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# NON-ABELIAN RECIPROCITY LAWS AND HIGHER BRAUER–MANIN OBSTRUCTIONS

J. P. PRIDHAM

ABSTRACT. We reinterpret Kim’s non-abelian reciprocity maps for algebraic varieties as obstruction towers of mapping spaces of étale homotopy types, removing technical hypotheses such as global basepoints and cohomological constraints. We then extend the theory by considering alternative natural series of extensions, one of which gives an obstruction tower whose first stage is the Brauer–Manin obstruction, allowing us to determine when Kim’s maps recover the Brauer–Manin locus. A tower based on relative completions yields non-trivial reciprocity maps even for Shimura varieties; for the stacky modular curve, these take values in Galois cohomology of modular forms, and give obstructions to an adélic elliptic curve with global Tate module underlying a global elliptic curve.

## INTRODUCTION

In [Kim], Minhyong Kim introduced a sequence of non-abelian reciprocity maps on the adélic points  $X(\mathbb{A}_F)$  of a variety  $X$  over a number field  $F$  equipped with a global point and satisfying certain cohomological conditions, with the global points contained within the kernel of all the maps. When  $X = \mathbb{G}_m$ , this sequence just consists of a single map, the Artin reciprocity law

$$\text{rec}: \mathbb{A}_F^\times \rightarrow G_F^{\text{ab}}$$

from the finite idèles of  $F$  to the abelianisation of its Galois group, with the property that  $\text{rec}(F^\times) = 0$ .

In this paper, we give a topological construction of the non-abelian reciprocity maps, based on homotopical obstruction theory. These are defined under more general hypotheses than those of [Kim]. In particular, we do not need to assume existence of a global point in order to define the maps, so our reciprocity laws can be used to test the Hasse principle. For arbitrary varieties, the reciprocity maps exist as a tower of spaces over  $X(\mathbb{A}_F)$ , with the cohomological conditions of [Kim] sufficing to ensure that the maps in the tower are injective.

Kim’s non-abelian reciprocity laws are based on the lower central series of the geometric fundamental group, but other variants are possible with our approach. One variant produces a tower starting with the Brauer–Manin obstruction, allowing us to compare it with Kim’s reciprocity laws. Another variant is based on relative completions, allowing us to study varieties whose geometric fundamental groups are perfect or nearly so.

For instance, the geometric fundamental group of the moduli stack  $\mathcal{M}_{1,1}$  of elliptic curves is the profinite completion  $\widehat{\text{SL}}_2(\mathbb{Z})$  of  $\text{SL}_2(\mathbb{Z})$ . This has finite abelianisation, so trivial pro-unipotent completion, which means the unipotent reciprocity maps of [Kim] are identically zero. However, the Malcev completion of  $\text{SL}_2(\mathbb{Z})$  relative to  $\text{SL}_2(\hat{\mathbb{Z}})$  (resp.

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$\mathrm{SL}_2(\mathbb{Q}_\ell)$ ) is a pro-unipotent extension of  $\mathrm{SL}_2(\hat{\mathbb{Z}})$  (resp.  $\mathrm{SL}_2(\mathbb{Q}_\ell)$ ) by a pro-unipotent group freely generated by duals of spaces of weight 2 (resp. level 1) modular forms. Elements in Galois cohomology of these tensors then give non-trivial obstructions to an adélic elliptic curve with global Tate module underlying a global elliptic curve.

Our point of view is that the reciprocity maps of [Kim] are obstruction towers in étale homotopy theory. The constructions of [AM, Fri] associate a pro-simplicial set  $X_{\text{ét}}$  to any locally Noetherian simplicial scheme  $X$ . When  $X$  is quasi-projective over a field  $F$ , with separable closure  $\bar{F}$ , [Fri, Theorem 11.5] shows that for  $\bar{X} := X \otimes_F \bar{F}$ , the geometric homotopy type  $(\bar{X})_{\text{ét}}$  is the homotopy fibre of  $X_{\text{ét}}$  over  $(\mathrm{Spec} F)_{\text{ét}}$ , because the space  $(\mathrm{Spec} \bar{F})_{\text{ét}}$  is contractible. Moreover,  $(\bar{X})_{\text{ét}}$  is equivalent to the profinite completion of the homotopy type of the manifold  $X(\mathbb{C})$ , for any embedding  $F \hookrightarrow \mathbb{C}$ , so  $(\bar{X})_{\text{ét}}$  is a  $K(\pi, 1)$  whenever  $X(\mathbb{C})$  is so.

We are interested in the simplicial set

$$\mathrm{map}_{(\mathrm{Spec} F)_{\text{ét}}}((\mathrm{Spec} F)_{\text{ét}}, X_{\text{ét}}),$$

i.e. the mapping space (or function complex) of pro-simplicial sets over  $(\mathrm{Spec} F)_{\text{ét}}$ . The space  $(\mathrm{Spec} F)_{\text{ét}}$  is a  $K(\pi, 1)$ , equivalent to the nerve  $BG_F$  of the Galois group  $G_F$ . Since morphisms of schemes give rise to morphisms of étale homotopy types, there is then a natural map

$$X(F) \rightarrow \mathrm{map}_{BG_F}(BG_F, X_{\text{ét}}).$$

When  $X$  is a  $K(\pi, 1)$  (such as any hyperbolic curve, surface of general type, or abelian variety) over  $F$ , we have (ignoring issues with basepoints)

$$\pi_i \mathrm{map}_{BG_F}(BG_F, X_{\text{ét}}) = \begin{cases} \mathrm{H}^{1-i}(F, \pi_1^{\text{ét}}(\bar{X})) & i \leq 1 \\ 0 & i \geq 2. \end{cases}$$

For smooth varieties  $X$ ,  $\pi_1^{\text{ét}}(\bar{X})$  will always be of strictly negative weights, so  $\mathrm{H}^0(F, \pi_1^{\text{ét}}(\bar{X})) = 0$ , and we have

$$\mathrm{map}_{BG_F}(BG_F, X_{\text{ét}}) \simeq \mathrm{H}^1(F, \pi_1^{\text{ét}}(\bar{X})),$$

a discrete set of points. This non-abelian cohomology set is the main focus of [Kim], and for hyperbolic curves  $X$ , Grothendieck's section conjecture amounts to the prediction that the morphism

$$X(F) \rightarrow \mathrm{map}_{BG_F}((BG_F, X_{\text{ét}}))$$

is an equivalence.

In this paper, we construct the reciprocity maps using obstruction theory analogous to [Bou]. The idea is to identify towers  $\{X_{\text{ét}}(n)\}_n$  of quotients of  $X_{\text{ét}}$  over  $BG_F$  for which there exist non-abelian spectral sequences converging to  $\mathrm{map}_{BG_F}(BG_F, X_{\text{ét}}(\infty))$ , where  $X_{\text{ét}}(\infty) := \varprojlim_n X_{\text{ét}}(n)$ . The crucial property making these spectral sequences special is that they incorporate fibre sequences

$$\pi_0 \mathrm{map}_{BG_F}((BG_F, X_{\text{ét}}(n))) \rightarrow \pi_0 \mathrm{map}_{BG_F}((BG_F, X_{\text{ét}}(n-1))) \xrightarrow{\mathrm{ob}_n} \mathrm{Ob}_n$$

giving obstructions to lifting homotopy classes of maps.

We can also take more general spaces as the source, considering a profinite homotopy type  $BG_{\mathbb{A}_F^{\infty \Sigma}}$  associated to the adèle ring  $\mathbb{A}_F^{\infty \Sigma} = \prod'_{v \in \Sigma} F_v$ , for a (possibly infinite) non-empty set  $\Sigma$  of finite places. Reciprocity maps then arise in non-abelian spectral sequences converging to the homotopy groups of

$$X(\mathbb{A}_F^{\infty \Sigma}) \times_{\mathrm{map}_{BG_F}(BG_{\mathbb{A}_F^{\infty \Sigma}}, X_{\text{ét}}(\infty))}^h \mathrm{map}_{BG_F}(BG_F, X_{\text{ét}}(\infty)),$$

and the spaces in the spectral sequence are compactly supported cohomology groups  $H_c^*(F, -)$ , which can be rewritten as duals of Galois cohomology groups by Poitou–Tate duality. Defining the tower  $\{X_{\text{ét}}(n)\}_n$  in terms of the lower central series of the geometric fundamental group  $\pi_1^{\text{ét}}(\bar{X})$  recovers Kim’s reciprocity maps [Kim]. Subtler towers based on relative completions give rise to reciprocity laws in more general situations.

Explicitly, for a modular curve  $Y_\Gamma$  we can consider the set  $Y_\Gamma(\mathbb{A}_F^{\infty\Sigma})_0$  of adelic points  $x$  for which the Tate module  $T_\ell E_{\bar{x}}$  of the associated elliptic curve lifts to a  $G_{F,\Sigma}$ -representation  $\Lambda$ . We then construct a sequence of subsets (glossing over subtleties related to potential higher automorphisms for now)

$$\dots \rightarrow Y_\Gamma(\mathbb{A}_F^{\infty\Sigma})_1 \rightarrow Y_\Gamma(\mathbb{A}_F^{\infty\Sigma})_0$$

containing  $Y_\Gamma(\mathcal{O}_{F,\Sigma})$ . These are defined inductively by  $Y_\Gamma(\mathbb{A}_F^{\infty\Sigma})_n = \text{ob}_n^{-1}(0)$ , for reciprocity maps

$$\text{ob}_n: Y_\Gamma(\mathbb{A}_F^{\infty\Sigma})_{n-1} \rightarrow H_c^2(G_{F,\Sigma}, T_n),$$

where the  $\mathbb{Q}_\ell$ -vector spaces  $T_n$  are given by homogeneous factors of a Lie algebra generated by

$$T_1 = \prod_m H^1(\Gamma, V_m)^* \otimes V_m,$$

for irreducible  $\text{SL}_2$ -representations  $V_m$ ; via Eichler–Shimura, the groups  $H^1(\Gamma, V_m)$  can be interpreted as  $\ell$ -adic realisations of motivic modular forms of weight  $m+2$  and level  $\Gamma$ . If we instead assume that the Tate modules  $T_p E_{\bar{x}}$  lift to  $G_{F,\Sigma}$ -representations  $\rho_p$  for all primes  $p$ , then we have a similar sequence, but with  $T_1$  now defined in terms of modular forms of all levels. In this case, [HV] shows that whenever there is an adelic elliptic curve compatible with the representations  $\rho_p$ , there must exist a rational elliptic curve giving rise to them, but our obstructions should measure the difference between these elliptic curves.

We can even incorporate higher homotopical information in constructing reciprocity laws for Deligne–Mumford stacks  $X$ , by looking at completions of étale homotopy types instead of their fundamental groups. The first obstruction map in the spectral sequence is then just the Brauer–Manin obstruction when we take the base  $X_{\text{ét}}(0)$  of the tower to be  $BG_F$ , with refinements for (pro-)étale covers given by the subtler obstruction towers.

The structure of the paper is as follows. Section 1 lays the topological foundations for constructing reciprocity laws, developing generalisations of Bousfield’s obstruction theory [Bou]. The most general statement is Proposition 1.5, giving obstruction spaces for homotopy limits of abelian extensions of simplicial groupoids.

Section 2 then applies this theory to give towers of obstructions to the existence of global points over a number field. The first such tower we consider is Example 2.5. Writing  $\Pi_n := \pi_1^{\text{ét}}(X, \bar{x})/[\pi_1^{\text{ét}}(\bar{X}, \bar{x})]_{n+1}$ ,  $\bar{\pi} := \pi_1^{\text{ét}}(\bar{X}, \bar{x})$ , and  $[\pi]_1 := \pi$ ,  $[\pi]_{k+1} := [\pi, [\pi]_k]$ , this gives a non-abelian spectral sequence

$$E_1^{s,t} = H^{1+s-t}(G_{F,\Sigma}, [\bar{\pi}]_s/[\bar{\pi}]_{s+1}) \implies \pi_{t-s} \text{map}_{BG_{F,\Sigma}}(BG_{F,\Sigma}, B\Pi_\infty),$$

encoding Ellenberg’s obstructions. There is a unipotent generalisation Example 2.12, and further refinements for relative completion. Notably, Examples 2.16 and 2.17 give obstructions, in terms of modular forms, to lifting a  $G_F$ -representation  $\Lambda$  to an elliptic curve  $E$  over  $F$  with Tate module  $\Lambda$ .

In Section 3, this approach is refined to consider the difference between the obstruction towers for  $F$  and  $\mathbb{A}_F^\Sigma$ , yielding reciprocity laws in terms of Poitou–Tate duality. The main examples of resulting spectral sequences appear in §3.2.2, with Examples 3.16

and 3.18 recovering and generalising Kim’s non-abelian reciprocity laws [Kim], while reciprocity laws for the stacky modular curve  $\mathcal{M}_{1,1}$  appear in Example 3.19, giving obstructions to an adélic elliptic curve being defined over  $F$  when its Tate module is known to be a  $G_F$ -representation.

Constructions in terms of higher homotopy types are then given in Example 3.21, with §3.2.3 showing how the spectral sequences for higher homotopy types start with the Brauer–Manin obstruction (or a pro-étale generalisation) as the first stage in the tower. Proposition 3.26 gives a sufficient condition for Kim’s non-abelian reciprocity laws to recover the Brauer–Manin locus. In §3.3, we then discuss more concrete ways to construct the reciprocity laws, with a fairly explicit description of the first obstruction for modular curves, and a discussion of the relation between higher Brauer–Manin obstructions and Massey products.

Appendix A contains the technicalities needed to work with higher étale homotopical invariants of adèle rings, giving a morphism from  $(\mathrm{Spec} \mathbb{A}_F^{\infty \Sigma})_{\acute{\mathrm{e}}\mathrm{t}}$  to the homotopy type  $BG_{\mathbb{A}_F^{\infty \Sigma}}$  governing restricted products of local cohomology groups.

Readers unfamiliar with abstract homotopy theory are advised to skip §1 entirely, starting with §3.3 for an overview before reading the examples in §§2, 3. We should warn at this stage that none of the examples exhibits explicit classes in Galois cohomology on which to evaluate the obstructions, but the weights of the Galois representations involved suggests they must exist in great generality.

I would like to thank Minhyong Kim for many helpful discussions.

**Notation.** We will write  $\cong$  for isomorphism and  $\simeq$  for weak equivalence. Let  $\mathbb{S}$  denote the category of simplicial sets with the Kan model structure, and  $s\mathbb{S}$  the category of bisimplicial sets. We denote mapping spaces in model categories by  $\mathrm{map}$ ; in the case of simplicial model categories, these simplicial sets are just given by derived functors of the simplicially enriched Hom bifunctor, and in general they are given by the function complexes of [Hov, §5.4].

We fix a number field  $F$ , and a (possibly infinite) non-empty set  $\Sigma$  of finite places of  $F$ . Then  $G_F$  denotes the Galois group of  $F$ , and  $G_{F,\Sigma}$  its subgroup of elements unramified outside  $\Sigma$ . We write  $\mathbb{A}_F^{\infty \Sigma}$  for the adèle ring

$$\mathbb{A}_F^{\infty \Sigma} := \prod_{v \in \Sigma}^{\prime} F_v = \varinjlim_{\substack{T \subset \Sigma \\ \text{finite}}} \left( \prod_{v \in T} F_v \times \prod_{v \in \Sigma - T} \mathcal{O}_{F,v} \right).$$

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## 1. OBSTRUCTION THEORY FROM ABELIAN EXTENSIONS

Given a fibration  $f: X \rightarrow Y$  of spaces with fibre  $Z$ , there is a long exact sequence

$$\dots \rightarrow \pi_2 Z \rightarrow \pi_2 X \rightarrow \pi_2 Y \rightarrow \pi_1 Z \rightarrow \pi_1 X \rightarrow \pi_1 Y \rightarrow \pi_0 Z \rightarrow \pi_0 X \rightarrow \pi_0 Y$$

of homotopy groups and sets, where the final map need not be surjective (and at this stage we are being deliberately vague about basepoints).

Our primary goal in this section is to look for cases where this sequence extends one stage further, giving an obstruction map from  $\pi_0 Y$  to some pointed set such that the fibre over the basepoint is the image of  $\pi_0 X \rightarrow \pi_0 Y$ . This will happen if there is some space  $B$  and a map  $Y \rightarrow B$  in the homotopy category of spaces, with  $X$  the homotopy fibre over a point  $b \in B$ , and in this case  $Z$  above is automatically the loop space  $\Omega(B, b)$ .

An obvious example of this phenomenon is when  $X$  is a principal  $G$ -bundle over  $Y$  for a topological group  $G$ , so arises as the homotopy fibre of a map  $Y \rightarrow BG$ . We then have a long exact sequence

$$\dots \rightarrow \pi_1 Y \rightarrow \pi_1 BG \rightarrow \pi_0 X \rightarrow \pi_0 Y \rightarrow \pi_0 BG,$$

noting that  $\pi_n BG = \pi_{n-1} G$ .

In this form, this statement is telling us nothing new, since  $\pi_0 X \rightarrow \pi_0 Y$  is automatically surjective in such cases. However the characterisation of  $X$  as a homotopy fibre also passes to homotopy limits of such diagrams. Given a small category  $I$ , together with  $I$ -diagrams  $Y$  and  $G$  in simplicial sets and simplicial groups, and a principal  $G$ -bundle  $X$  over  $Y$ , we can characterise  $X$  as the homotopy fibre of a map  $Y \rightarrow BG$  in the homotopy category, and then

$$\text{holim}_{i \in I} X(i) \rightarrow \text{holim}_{i \in I} Y(i) \rightarrow \text{holim}_{i \in I} BG(i).$$

is a homotopy fibre sequence, so gives rise to a long exact sequence of homotopy groups and sets of the desired form; this is essentially the content of Corollary 1.11 below.

### 1.1. Central and abelian extensions of simplicial groups.

1.1.1. *Central extensions.* We now look at principal fibrations in the category of groups. First observe that an internal group object in the category of groups is an abelian group  $A$  by the Eckmann–Hilton argument, with multiplication  $A \times A \rightarrow A$  being a group homomorphism.

An  $A$ -space in groups is then a group  $G$  equipped with a group homomorphism  $\mu: A \times G \rightarrow G$  such that the diagram

$$\begin{array}{ccc} A \times A \times G & \xrightarrow{(\text{id}_A, \mu)} & A \times G \\ (\cdot, \text{id}_G) \downarrow & & \downarrow \mu \\ A \times G & \xrightarrow{\mu} & G \end{array}$$

commutes. In other words,  $\mu(a, g) = \rho(a)g$ , for the group homomorphism  $\rho: A \rightarrow Z(G)$  to the centre of  $G$  given by  $\rho(a) = \mu(a, 1)$ . The  $A$ -action is faithful if  $\rho$  is injective, and then  $G$  is a principal  $A$ -space over  $G/A$ .

Applying the nerve functor, we have a simplicial abelian group  $BA$  (the group homomorphism  $A \times A \rightarrow A$  inducing a multiplication  $BA \times BA \rightarrow BA$ , and for every principal  $A$ -space  $G$  in groups over  $H$ , we get a principal  $BA$ -fibration  $BG$  over  $BH$ ).

**Definition 1.1.** Define  $\nabla: s\mathbb{S} \rightarrow \mathbb{S}$  to be the right adjoint to Illusie's total Dec functor given by  $\text{DEC}(X)_{mn} = X_{m+n+1}$ . Explicitly,

$$\nabla_p(X) = \{(x_0, x_1, \dots, x_p) \in \prod_{i=0}^p X_{i, p-i} \mid \partial_0^v x_i = \partial_{i+1}^h x_{i+1}, \forall 0 \leq i < p\}$$

with operations

$$\begin{aligned} \partial_i(x_0, \dots, x_p) &= (\partial_i^v x_0, \partial_{i-1}^v x_1, \dots, \partial_1^v x_{i-1}, \partial_i^h x_{i+1}, \partial_i^h x_{i+2}, \dots, \partial_i^h x_p), \\ \sigma_i(x_0, \dots, x_p) &= (\sigma_i^v x_0, \sigma_{i-1}^v x_1, \dots, \sigma_0^v x_i, \sigma_i^h x_i, \sigma_i^h x_{i+1}, \dots, \sigma_i^h x_p). \end{aligned}$$

Given a simplicial diagram  $\Gamma$  of groupoids, the nerve  $B\Gamma$  is a bisimplicial set, and we write  $\bar{W}\Gamma := \nabla B\Gamma$ , noting that this agrees with the definition of [GJ, §V.7] when  $\Gamma$  has constant objects.

Note that the loop space  $\Omega \bar{W}G$  of  $\bar{W}G$  is weakly equivalent to  $G$ , so in particular  $\pi_i \bar{W}G \cong \pi_{i-1} G$ , with  $\pi_0 G = *$ .

In [CR], it is established that the canonical natural transformation

$$\text{diag } X \rightarrow \nabla X$$

from the diagonal is a weak equivalence for all  $X$ . Thus  $\nabla X$  is a model for the homotopy colimit

$$\text{holim}_{n \in \Delta^{\text{opp}}} X_n,$$

and in particular  $\bar{W}\Gamma$  a model for  $\text{holim}_{n \in \Delta^{\text{opp}}} B(\Gamma_n)$ .

**Proposition 1.2.** *Given a surjection  $G \rightarrow H$  of simplicial groups with central kernel  $A$ , there is a simplicial set  $Y'$  weakly equivalent to  $\bar{W}H$  and a map  $f: Y' \rightarrow \bar{W}^2 A$  with fibre  $\bar{W}G$ , which is also the homotopy fibre. Moreover, the space  $Y'$  and weak equivalence  $w: Y' \rightarrow \bar{W}H$  can be chosen functorially.*

*Proof.* Writing  $K = \bar{W}A$ , the statement is essentially the well-known result ([GJ, Theorem V.3.9]) that  $\bar{W}K$  classifies principal fibrations. The reasoning above applied to simplicial groups gives us a bisimplicial abelian group  $BA$  and a principal  $BA$ -fibration  $BG$  over  $BH$ . Applying the codiagonal functor  $\nabla$  then gives us a simplicial abelian group  $\bar{W}A$  and a principal  $\bar{W}A$ -fibration  $\bar{W}G$  over  $\bar{W}H$ . The map  $f$  then just comes by taking the homotopy quotient of  $\bar{W}G \rightarrow \bar{W}H$  by the action of  $\bar{W}A$ .

Explicitly, we set  $Y' = \bar{W}[\bar{W}G/\bar{W}A]$ , for the simplicial groupoid  $[\bar{W}G/\bar{W}A]$  with objects  $\bar{W}G$  and morphisms given by  $\bar{W}A$  acting on the right. Applying  $\bar{W}$  twice to the map  $[G/A] \rightarrow [H/1]$  of groupoids in groups gives the weak equivalence  $Y' \rightarrow \bar{W}H$ , since  $\bar{W}[Y/1] = Y$  and the fibre  $\bar{W}[A/A]$  is contractible. Similarly, the Kan fibration  $Y' \rightarrow \bar{W}^2A$  comes from the map  $[G/A] \rightarrow [1/A]$  of groupoids in groups.  $\square$

1.1.2. *Abelian extensions.* More generally, given a group  $H$ , a group object  $\Gamma$  in the comma category  $\text{Gp} \downarrow H$  of groups over  $H$  is of the form  $\Gamma = H \times A$ , for an abelian group  $A$  equipped with an  $H$ -action.

Then a  $\Gamma$ -space in groups over  $H$  consists of a group  $G$  and a surjection  $G \rightarrow H$  together with an associative action  $\Gamma \times_H G \rightarrow G$  (all maps being group homomorphisms). Equivalently, for the group  $A$  above, we have a group homomorphism  $G \times A \rightarrow G$  over  $H$ , hence a  $G$ -equivariant map  $A \rightarrow \ker(G \rightarrow H)$ .

The condition for  $G$  to be a principal  $\Gamma$ -space is then just that the map  $A \rightarrow \ker(G \rightarrow H)$  be an isomorphism. In other words, a pair  $(\Gamma, G)$  is the same as an abelian group  $A$  equipped with an  $H$ -action together with a surjective group homomorphism  $G \rightarrow H$  with kernel  $A$ .

Given such a  $G$ , we can take the nerve, giving a surjective fibration  $BG \rightarrow BH$  of simplicial sets with fibre  $BA$  over the unique vertex of  $BH$ . The simplicial set  $B(H \times A)$  is a group object in simplicial sets over  $BH$ , and  $BG$  is a principal  $B(H \times A)$ -bundle.

**Proposition 1.3.** *Take a surjection  $G \rightarrow H$  of simplicial groups with abelian kernel  $A$ . Then there exists a fibration*

$$Y' \rightarrow \bar{W}[H \times \bar{W}A]$$

for which the projection  $Y' \rightarrow \bar{W}H$  is a weak equivalence, with

$$Y' \times_{\bar{W}[H \times \bar{W}A]} \bar{W}H \cong \bar{W}G.$$

Moreover, the space  $Y'$  and weak equivalence  $w: Y' \rightarrow Y$  can be chosen functorially.

*Proof.* We adapt the proof of Proposition 1.2. Set  $Y' = \bar{W}[\bar{W}(G \times A) \rightrightarrows \bar{W}G]$ , for the simplicial groupoid  $[\bar{W}(G \times A) \rightrightarrows \bar{W}G]$  with objects  $\bar{W}G$  and morphisms  $\bar{W}(G \times A)$ . Applying  $\bar{W}$  twice to the map  $[(G \times A) \rightrightarrows G] \rightarrow [H \rightrightarrows H]$  of groupoids in groups gives the weak equivalence  $Y' \rightarrow \bar{W}H$ , since  $\bar{W}[Y \rightrightarrows Y] = Y$  and the fibre  $\bar{W}[A/A] = \bar{W}[A \times A \rightrightarrows A]$  is contractible. Similarly, the Kan fibration  $Y' \rightarrow \bar{W}[H \times \bar{W}A]$  comes from the map  $[(G \times A) \rightrightarrows G] \rightarrow [(H \times A) \rightrightarrows H]$  of groupoids in groups.  $\square$

1.1.3. *Groupoids.* The constructions above generalise to groupoids, and we will not concern ourselves with the full generality of internal groups in groupoids. We just observe that any abelian group is *a fortiori* an internal group in groupoids with one object, and that for any groupoid  $H$ , an  $H$ -representation  $A$  in abelian groups has associated groupoid  $H \times A$ , which is a group object in groupoids over  $H$ .

**Definition 1.4.** Say that a morphism  $f: G \rightarrow H$  is an abelian extension if it is an isomorphism on objects, surjective on morphisms, and the groups  $A(x) := \ker(f: G(x, x) \rightarrow H(fx, fx))$  are abelian for all objects  $x$  of  $G$ .

Thus for any abelian extension  $G \rightarrow H$  of groupoids with kernel  $A$ , we get a surjective fibration  $BG \rightarrow BH$  of simplicial sets, and the fibre over  $fx \in (BH)_0$  is just  $A(x)$ . Moreover,  $B(H \times A)$  is a group object in simplicial sets over  $BH$ , and  $BG$  is a principal  $B(H \times A)$ -bundle.



**Proposition 1.5.** *Given an abelian extension  $G \rightarrow H$  of simplicial groupoids with abelian kernel  $A$ , there is fibration  $Y' \rightarrow \bar{W}[H \times A]$  such that the projection  $Y' \rightarrow \bar{W}H$  is a weak equivalence, with*

$$Y' \times_{\bar{W}[H \times A]} \bar{W}H \cong \bar{W}G.$$

Moreover, the space  $Y'$  and weak equivalence  $w: Y' \rightarrow Y$  can be chosen functorially.

*Proof.* The proof of Proposition 1.3 carries over.  $\square$

**1.2. Passage to homotopy limits.** For a small category  $I$ , we have a limit functor  $\varprojlim_I: \mathbb{S}^I \rightarrow \mathbb{S}$  from  $I$ -diagrams of simplicial sets to simplicial sets. Recall from [GJ, §VIII.2] or [Hir, Ch. 18] that  $\text{holim}_{\varprojlim_I}: \text{Ho}(\mathbb{S}^I) \rightarrow \text{Ho}(\mathbb{S})$  is the right-derived functor of  $\varprojlim_I$ ; in other words, it is the universal functor under  $\varprojlim_I$  preserving weak equivalences.

**Definition 1.6.** Given a small category  $I$  and simplicial group-valued functors  $G, H: I \rightarrow s\text{Gp}$ , we say that a natural transformation  $G \rightarrow H$  is a central (resp. abelian) extension if the maps  $G(i) \rightarrow H(i)$  are so, for all  $i \in I$ .

**Proposition 1.7.** *Given a central extension  $f: G \rightarrow H$  of  $I$ -diagrams with kernel  $A$ , there is a morphism  $\text{holim}_{\varprojlim_{i \in I}} \bar{W}H(i) \rightarrow \text{holim}_{\varprojlim_{i \in I}} \bar{W}^2A(i)$  in the homotopy category of simplicial sets with homotopy fibre  $\text{holim}_{\varprojlim_{i \in I}} \bar{W}G(i)$  over the distinguished point  $*$ .*

*Proof.* We just apply the derived functor  $\text{holim}_{\varprojlim_{i \in I}}$  to the diagrams from Proposition 1.2.  $\square$

Note that when  $I = \Delta$ , the simplex category, this recovers a fairly general case of Bousfield's obstruction maps from [Bou].

**Corollary 1.8.** *In the scenario of Proposition 1.7, there is a sequence*

$$\pi_0 \text{holim}_{\varprojlim_{i \in I}} \bar{W}G(i) \xrightarrow{f_*} \pi_0 \text{holim}_{\varprojlim_{i \in I}} \bar{W}H(i) \xrightarrow{\delta_*} \pi_0 \text{holim}_{\varprojlim_{i \in I}} \bar{W}^2A(i)$$

of sets, exact in the sense that the fibre of  $\delta_*$  over 0 is the image of  $f_*$ .

Moreover, there is a group action of  $\pi_0 \text{holim}_{\varprojlim_{i \in I}} \bar{W}A(i)$  on  $\pi_0 \text{holim}_{\varprojlim_{i \in I}} \bar{W}G(i)$  whose orbits are precisely the fibres of  $f_*$ .

For any  $x \in \text{holim}_{\varprojlim_{i \in I}} \bar{W}G(i)$ , with  $y = f_*x$ , the homotopy fibre of  $f$  over  $y$  is weakly equivalent to  $\text{holim}_{\varprojlim_{i \in I}} \bar{W}A(i)$ , and the sequence above extends to a long exact sequence

$$\begin{aligned} \cdots &\xrightarrow{f_*} \pi_n(\text{holim}_{\varprojlim_{i \in I}} \bar{W}H(i), y) \xrightarrow{\delta} \pi_{n-1} \text{holim}_{\varprojlim_{i \in I}} \bar{W}A(i) \longrightarrow \pi_{n-1}(\text{holim}_{\varprojlim_{i \in I}} X(i), x) \xrightarrow{f_*} \cdots \\ \cdots &\xrightarrow{f_*} \pi_1(\text{holim}_{\varprojlim_{i \in I}} \bar{W}H(i), y) \xrightarrow{\delta} \pi_0 \text{holim}_{\varprojlim_{i \in I}} \bar{W}A(i) \xrightarrow{-*x} \pi_0 \text{holim}_{\varprojlim_{i \in I}} \bar{W}G(i). \end{aligned}$$

*Proof.* This is just the long exact sequence of a fibration ([GJ, Lemma I.7.3]) applied to  $\delta: \text{holim}_{\varprojlim_{i \in I}} Y'(i) \rightarrow \text{holim}_{\varprojlim_{i \in I}} \bar{W}^2A(i)$ , and noting that

$$\Omega \text{holim}_{\varprojlim_{i \in I}} \bar{W}^2A(i) \simeq \text{holim}_{\varprojlim_{i \in I}} \Omega \bar{W}^2A(i) \simeq \text{holim}_{\varprojlim_{i \in I}} \bar{W}A(i),$$

so

$$\pi_n \text{holim}_{\varprojlim_{i \in I}} \bar{W}^2A(i) \cong \pi_{n-1} \text{holim}_{\varprojlim_{i \in I}} \bar{W}A(i)$$

for all  $i > 0$ .  $\square$

*Remark 1.9.* Were it not for the final term, Corollary 1.8 would just be the long exact sequence of homotopy for the map  $\text{holim}_{\leftarrow i \in I} \bar{W}G(i) \rightarrow \text{holim}_{\leftarrow i \in I} \bar{W}H(i)$ . The essential purpose of all our effort so far has thus been to incorporate the extra term  $\pi_0 \text{holim}_{\leftarrow i \in I} \bar{W}^2A(i)$ , giving an obstruction to lifting connected components.

**Proposition 1.10.** *Given an abelian extension  $G \rightarrow H$  of  $I$ -diagrams with kernel  $A$ , there is a morphism  $\delta: \text{holim}_{\leftarrow i \in I} \bar{W}H(i) \rightarrow \text{holim}_{\leftarrow i \in I} \bar{W}(H \times \bar{W}A(i))$  in the homotopy category of simplicial sets over  $\text{holim}_{\leftarrow i \in I} \bar{W}H(i)$  with a homotopy pullback diagram*

$$\begin{array}{ccc} \text{holim}_{\leftarrow i} \bar{W}G(i) & \longrightarrow & \text{holim}_{\leftarrow i} \bar{W}H(i) \\ \downarrow & & \downarrow \delta \\ \text{holim}_{\leftarrow i} \bar{W}H(i) & \xrightarrow{0} & \text{holim}_{\leftarrow i} \bar{W}(H(i) \times \bar{W}A(i)). \end{array}$$

*In particular, if the adjoint action of  $H$  on  $A$  factors through some quotient  $\bar{H}$ , then for any  $\bar{y} \in \text{holim}_{\leftarrow i} \bar{W}\bar{H}$ , we have a fibration sequence*

$$\left(\text{holim}_{\leftarrow i} \bar{W}G(i)\right)_{\bar{y}} \rightarrow \left(\text{holim}_{\leftarrow i} \bar{W}H(i)\right)_{\bar{y}} \rightarrow \text{holim}_{\leftarrow i} \bar{W}(\bar{H}(i) \times \bar{W}A(i))_{\bar{y}}$$

*on homotopy fibres over  $y$ .*

*Proof.* We just apply the derived functor  $\text{holim}_{\leftarrow i \in I}$  to the diagrams from Proposition 1.3.  $\square$

Now, given an  $I$ -diagram  $X$ , write  $\underline{X} := \text{holim}_{\leftarrow i} X(i)$ .

**Corollary 1.11.** *In the scenario of Proposition 1.10, an element  $y$  lies in the image of*

$$\pi_0 \underline{\bar{W}G} \xrightarrow{f_*} \pi_0 \underline{\bar{W}H}$$

*if and only if  $\delta_*(y) = 0 \in \pi_0(\underline{\bar{W}(H \times \bar{W}A)})_y$ , the homotopy fibre of  $\underline{\bar{W}(H \times \bar{W}A)} \rightarrow \underline{\bar{W}H}$  over  $y$ .*

*Moreover, for each such  $y$  there is a transitive group action of  $\pi_0(\underline{\bar{W}(H \times A)})_y$  on the fibre of  $f_*$ .*

*For any  $x \in \underline{\bar{W}G}$  with  $y = f_*x$ , the homotopy fibre of  $f$  over  $y$  is weakly equivalent to  $\underline{\bar{W}A}_{(y)} := \underline{\bar{W}(H \times A)}_y$ , and the sequence above extends to a long exact sequence*

$$\begin{array}{ccccccc} \cdots & \xrightarrow{f_*} & \pi_n(\underline{\bar{W}H}, y) & \xrightarrow{\delta} & \pi_{n-1}(\underline{\bar{W}A}_{(y)}) & \longrightarrow & \pi_{n-1}(\underline{\bar{W}G}, x) \xrightarrow{f_*} \cdots \\ \cdots & \xrightarrow{f_*} & \pi_1(\underline{\bar{W}H}, y) & \xrightarrow{\delta} & \pi_0(\underline{\bar{W}A}_{(y)}) & \xrightarrow{-*x} & \pi_0 \underline{\bar{W}G}. \end{array}$$

*Proof.* The proof of Corollary 1.8 carries over.  $\square$

## 2. TOWERS OF DIOPHANTINE OBSTRUCTIONS

Recall that we are fixing a number field  $F$ , and a (possibly infinite) non-empty set  $\Sigma$  of finite places of  $F$ . Given any profinite group  $\Pi$  and a pro-surjection  $\Pi \rightarrow G_{F, \Sigma}$  (such as when  $\Pi$  is the arithmetic fundamental group of an  $\mathcal{O}_{F, \Sigma}$ -scheme), we have a fibration  $B\Pi \rightarrow BG_{F, \Sigma}$  of pro-simplicial sets. Thus for any pro-simplicial set  $Y$  over  $BG_{F, \Sigma}$ , we may consider the mapping space

$$\text{map}_{BG_{F, \Sigma}}(Y, B\Pi)$$

for the model structure of [Isa]; when  $Y = BG_{F,\Sigma}$ , this is the space of sections of  $B\Pi \rightarrow BG_{F,\Sigma}$ . Via the equivalence  $BG_{F,\Sigma} \simeq (\text{Spec } \mathcal{O}_{F,\Sigma})_{\acute{e}t}$ , we may regard these as mapping spaces over  $(\text{Spec } F)_{\acute{e}t}$ .

For compatibility with [Isa], we consider only those pro-simplicial sets  $X$  which are isomorphic in  $\text{pro}(\mathbb{S})$  to the inverse limits  $\varprojlim_k P_k X$  of their Postnikov towers, as is automatically the case for  $B\Pi$ .

Explicitly, mapping spaces of pro-simplicial sets are defined as follows.

**Definition 2.1.** For pro-simplicial sets  $X = \varprojlim_i X(i), Y = \varprojlim_j Y(j)$ , we define the simplicial set  $\text{map}(X, Y)$  in terms of mapping spaces of simplicial sets by the homotopy limit

$$\text{map}(X, Y) := \text{holim}_j \varinjlim_i \text{map}(X(i), Y(j)),$$

and for a diagram  $X \xrightarrow{f} Z \leftarrow Y$  of pro-simplicial sets, the relative mapping space  $\text{map}_Z(X, Y)$  is the homotopy fibre of  $\text{map}(X, Y) \rightarrow \text{map}(X, Z)$  over  $f$ .

**2.1. Abelian extensions.** Assume that we have abelian extension  $\Pi'' \rightarrow \Pi'$  of profinite groups with kernel  $A$ , such that the conjugation action of  $\Pi'$  on  $A$  factors through some quotient  $G$  of  $\Pi'$ . When working with nilpotent completions of geometric fundamental groups, we may take  $G = G_{F,\Sigma}$ , but for relative completions (as needed for modular curves),  $G$  will be larger.

Writing  $B(G \ltimes BA) := \bar{W}(G \ltimes BA)$ , we have:

**Proposition 2.2.** *In the scenario above, and for any pro-simplicial set  $Y$  over  $BG$ , there is a natural fibration sequence*

$$\text{map}_{BG}(Y, B\Pi'') \rightarrow \text{map}_{BG}(Y, B\Pi') \rightarrow \text{map}_{BG}(Y, B(G \ltimes BA))$$

of mapping spaces, the fibre being taken over the zero map  $Y \rightarrow BG \rightarrow B(G \ltimes BA)$ .

*Proof.* The idea behind this statement is that the extension  $\Pi'' \rightarrow \Pi'$  defines an element of  $H^1(\Pi', A)$ , which we can write as a morphism  $\text{ob}: \Pi' \rightarrow G \ltimes BA$  in the homotopy category of simplicial profinite groups over  $G$ . We can then recover  $B\Pi''$  as a homotopy fibre product

$$B\Pi' \times_{\text{ob}, B(G \ltimes BA)}^h B\Pi',$$

leading to the fibration sequence above.

More formally, we write  $\Pi'' = \varprojlim_{j \in J} \Pi''(j)$  as a filtered limit of finite quotient groups, inducing compatible expressions  $A = \varprojlim_j A(j)$ ,  $\Pi'(j) = \Pi''(j)/A(j)$  and  $\Pi'(j) \twoheadrightarrow G(j)$  with  $G = \varprojlim_j G(j)$ .

The mapping spaces  $\text{map}(Y, B\Pi)$  are given by

$$\text{map}_{BG}(Y, B\Pi) \simeq \text{ho } \varprojlim_{(n,j) \in \Delta \times J} \text{Hom}_{\text{pro}(\text{Set})}(Y_n, B\Pi(j)),$$

so we apply Proposition 1.10 to the abelian extension

$$\text{Hom}_{\text{pro}(\text{Set})}(Y_n, \Pi''(j)) \rightarrow \text{Hom}_{\text{pro}(\text{Set})}(Y_n, \Pi'(j))$$

of  $(\Delta \times J)$ -diagrams in groups, and then take homotopy fibres over the canonical base-point of  $\text{map}(Y, BG)$ .  $\square$

We think of the base  $\text{map}_{BG}(Y, B(G \times BA))$  of the fibration as an obstruction space: its homotopy groups are given by equivariant cohomology groups

$$\pi_i \text{map}_{BG}(Y, B(G \times BA)) \cong H_G^{2-i}(Y, A),$$

so we have an exact sequence

$$\begin{aligned} 0 \rightarrow H_G^0(Y, A) \rightarrow \pi_1 \text{map}_{BG}(Y, B\Pi'') \rightarrow \pi_1 \text{map}_{BG}(Y, B\Pi') \\ \rightarrow H_G^1(Y, A) \rightarrow \pi_0 \text{map}_{BG}(Y, B\Pi'') \rightarrow \pi_0 \text{map}_{BG}(Y, B\Pi') \rightarrow H_G^2(Y, A) \end{aligned}$$

In particular, the obstruction to lifting a homotopy class of maps  $Y \rightarrow B\Pi'$  to  $B\Pi''$  lies in  $H_G^2(Y, A)$ , and the ambiguity in this lift is given by an action of  $H_G^1(Y, A)$  on the fibres.

*Remark 2.3.* Given an abelian extension  $\Pi'' \rightarrow \Pi'$  of pro-simplicial groups with kernel  $A$ , such that the conjugation action of  $\Pi'$  on  $A$  factors through some quotient  $G$  of  $\Pi'$ , there is a natural fibration sequence

$$\text{map}_{\bar{W}G}(Y, \bar{W}\Pi'') \rightarrow \text{map}_{\bar{W}G}(Y, \bar{W}\Pi') \rightarrow \text{map}_{\bar{W}G}(Y, \bar{W}(G \times \bar{W}A))$$

of mapping spaces, for any pro-space  $Y$  over  $\bar{W}G$ .

*Example 2.4.* In order to understand the first obstruction map  $\text{ob}: \pi_0 \text{map}_{BG}(Y, B\Pi') \rightarrow H_G^2(Y, A)$  explicitly, consider the case when  $Y$  is reduced and connected, so  $Y_0 = *$  and an element of  $\pi_0 \text{map}_{BG}(Y, B\Pi')$  is a conjugacy class of pro-group homomorphisms  $\alpha: \pi_1(Y) \rightarrow \Pi'$  over  $G$ . Here,  $\pi_1 Y$  is a pro-group with generators  $Y_1$  and relations  $\partial_1 y = \partial_0 y \partial_2 y$  for  $y \in Y_2$ . Since  $\Pi'' \rightarrow \Pi'$  is surjective, we may lift  $\alpha$  to a morphism  $\tilde{\alpha}: Y_1 \rightarrow \Pi''$  of pro-sets. The obstruction  $\text{ob}(\alpha)$  then measures the failure of  $\tilde{\alpha}$  to be a group homomorphism, in the form of the 2-cocycle

$$(y \in Y_2) \mapsto \tilde{\alpha}(\partial_2 y) \tilde{\alpha}(\partial_1 y)^{-1} \tilde{\alpha}(\partial_0 y).$$

**2.2. Nilpotent obstruction towers.** We can of course iterate the construction of Remark 2.3, by considering towers  $\dots \Pi_{n+1} \rightarrow \Pi_n \rightarrow \dots \rightarrow \Pi_0 = G$  of surjections whose kernels are abelian  $G$ -representations. The motivating examples are given by the quotients of  $\pi_1^{\text{ét}}(X)$  by the lower central series of  $\pi_1^{\text{ét}}(\bar{X})$ , and by their pro- $p$  completions relative to  $G_{F,\Sigma}$ .

Writing  $A_n$  for the kernel of  $\Pi_n \rightarrow \Pi_{n-1}$  and  $\Pi_\infty := \varprojlim_n \Pi_n$ , we then have an exact couple

$$\begin{array}{ccccccc} \dots & \longrightarrow & \pi_* \text{map}_{BG}(Y, B\Pi_n) & \longrightarrow & \pi_* \text{map}_{BG}(Y, B\Pi_{n-1}) & \longrightarrow & \dots \longrightarrow \pi_* \text{map}_{BG}(Y, B\Pi_1) \\ & & \uparrow & \swarrow \delta & \uparrow & \swarrow \delta & \uparrow \simeq \\ & & H_G^{1-*}(Y, A_n) & & H_G^{1-*}(Y, A_{n-1}) & & \dots & H_G^{1-*}(Y, A_1) \end{array}$$

similar to that in [GJ, §VI.2], but with the extra final terms  $H_G^2(Y, A_n)$ . Here, the connecting homomorphism  $\delta$  is of homological degree  $-1$ , so we have

$$\delta: \pi_i \text{map}_{BG}(Y, B\Pi_{n-1}) \rightarrow H_G^{2-i}(Y, A_n).$$

This induces a non-abelian spectral sequence

$$E_1^{s,t} = H_G^{1+s-t}(Y, A_s) \implies \pi_{t-s} \text{map}_{BG}(Y, B\Pi_\infty)$$

of groups and sets, where the terms  $E_1^{s,t}$  are only defined for  $t \geq \max(s-1, 0)$ , and the indexing convention follows [GJ, §VI.2], with  $d_r: E_r^{s,t} \rightarrow E_r^{s+r, t+r-1}$ . Unlike the fringed

Bousfield–Kan spectral sequence of [GJ, §VI.2], we have terms  $E_r^{t+1,t}$  ensuring that we can recover the images of

$$\pi_0 \text{map}_{BG}(Y, B\Pi_\infty) \rightarrow \pi_0 \text{map}_{BG}(Y, B\Pi_s)$$

from our spectral sequence.

Explicitly, writing

$$\pi_i M_s^{(r)} := \text{Im}(\pi_i \text{map}_{BG}(Y, B\Pi_{s+r}) \rightarrow \pi_i \text{map}_{BG}(Y, B\Pi_s)),$$

there are long exact sequences

$$\begin{aligned} \dots \rightarrow E_r^{s-r+1, t-r+2} \rightarrow \pi_{t-s+1} M_{s-r+1}^{(r-1)} \rightarrow \pi_{t-s+1} M_{s-r}^{(r-1)} \\ \rightarrow E_r^{s,t} \rightarrow \pi_{t-s} M_s^{(r-1)} \rightarrow \pi_{t-s} M_{s-1}^{(r-1)} \rightarrow \dots \end{aligned}$$

(as in [GJ, Lemma VI.2.8], but with extra final terms  $\pi_0 M_{t+1-r}^{(r-1)} \rightarrow E_r^{t+1,t}$ ).

The first page just corresponds to the exact sequences

$$\begin{aligned} 0 \rightarrow H_G^0(Y, A_s) \rightarrow \pi_1 M_s^{(0)} \rightarrow \pi_1 M_{s-1}^{(0)} \rightarrow \\ H_G^1(Y, A_s) \rightarrow \pi_0 M_s^{(0)} \rightarrow \pi_0 M_{s-1}^{(0)} \rightarrow H_G^2(Y, A_s). \end{aligned}$$

*Example 2.5* (Nilpotent completion of  $\pi_1^{\text{ét}}(\bar{X})$ ). If  $X$  is a scheme over  $\mathcal{O}_{F,\Sigma}$ , and  $\bar{X} := X \otimes_{\mathcal{O}_{F,\Sigma}} \mathcal{O}_{\bar{F},\Sigma}$ , with some geometric point  $\bar{x}$ , then the simplest examples are given by taking lower central series

$$\Pi_n := \pi_1^{\text{ét}}(X, \bar{x}) / [\pi_1^{\text{ét}}(\bar{X}, \bar{x})]_{n+1},$$

where for a group  $\pi$  we write  $[\pi]_1 := \pi$ ,  $[\pi]_{k+1} := [\pi, [\pi]_k]$ . Thus  $\Pi_0 = G_{F,\Sigma}$ , and taking  $Y = BG_{F,\Sigma}$ , we get the non-abelian spectral sequence

$$E_1^{s,t} = H^{1+s-t}(G_{F,\Sigma}, [\bar{\pi}]_s / [\bar{\pi}]_{s+1}) \implies \pi_{t-s} \text{map}_{BG_{F,\Sigma}}(BG_{F,\Sigma}, B\Pi_\infty)$$

of groups and sets, where we write  $\bar{\pi} := \pi_1^{\text{ét}}(\bar{X}, \bar{x})$ . If  $\bar{x}$  lies over a point in  $X(\mathcal{O}_{F,\Sigma})$ , then  $\Pi_\infty$  is just the semi-direct product of  $G_{F,\Sigma}$  and the pro-nilpotent completion of  $\pi_1^{\text{ét}}(\bar{X}, \bar{x})$ .

Since points in  $X(\mathcal{O}_{F,\Sigma})$  map to elements in  $\pi_0 \text{map}_{BG_{F,\Sigma}}(BG_{F,\Sigma}, B\Pi_\infty)$ , this spectral sequence gives obstructions to the existence of such rational points. The same constructions work when  $X$  is a Deligne–Mumford stack instead of a scheme, in which case we have a morphism from the groupoid  $X(\mathcal{O}_{F,\Sigma})$  to the fundamental groupoid  $\pi_f \text{map}_{BG_{F,\Sigma}}(BG_{F,\Sigma}, B\Pi_\infty)$ .

The maps  $d_r: E_r^{1,1} \rightarrow E_r^{r+1,r}$  are just Ellenberg’s obstructions, which can be described in terms of Massey products as in Wickelgren’s thesis [Wic1]. Another variant is given by taking the relative pro- $\ell$  completion of  $\pi_1^{\text{ét}}(X, \bar{x})$  over  $G_{F,\Sigma}$  in the sense of [HM], which will have the effect of replacing  $[\bar{\pi}]_s / [\bar{\pi}]_{s+1}$  with  $\ell$ -torsion groups — the corresponding maps are described in [Wic2].

If we replaced  $BG_{F,\Sigma}$  with the étale homotopy type of an  $F$ -scheme  $Z$ , we would instead obtain topological obstructions to the existence of a map  $Z \rightarrow X$  over  $F$ .

*Example 2.6* (Relative completion of  $\pi_1^{\text{ét}}(\bar{X})$  — descent obstructions). When the geometric fundamental group of  $X$  is perfect, its nilpotent completion is trivial, so the construction of Example 2.5 gives no information. However, we can remedy this by

taking the completion relative to a larger group than  $G_{F,\Sigma}$ . We may take any quotient  $P$  of  $\pi_1^{\acute{e}t}(X, \bar{x})$  bigger than  $G_{F,\Sigma}$ , then write  $K := \ker(\pi_1^{\acute{e}t}(X, \bar{x}) \rightarrow P)$ , and set  $\Pi_n := \pi_1^{\acute{e}t}(X, \bar{x})/[K]_{n+1}$ .

This gives a non-abelian spectral sequence

$$E_1^{s,t} = \begin{cases} \mathbb{H}^{1+s-t}(G_{F,\Sigma}, [K]_s/[K]_{s+1}) & s \geq 1 \\ \pi_t \text{map}_{BG_{F,\Sigma}}(BG_{F,\Sigma}, BP) \end{cases} \implies \pi_{t-s} \text{map}_{BG_{F,\Sigma}}(BG_{F,\Sigma}, B\Pi_\infty)$$

of groups and sets. Here, the Galois action on  $[K]_s/[K]_{s+1}$  depends on the relevant section  $\sigma \in \pi_0 \text{map}_{BG_{F,\Sigma}}(BG_{F,\Sigma}, BP)$ .

When  $P$  is a finite extension of  $G_{F,\Sigma}$ , each section  $\sigma$  as above gives a finite étale group scheme  $P^\sigma$  over  $F$  with  $P^\sigma(\bar{F}) \cong \ker(P \rightarrow G_{F,\Sigma})$ , and hence  $BP^\sigma$  having étale homotopy type  $BP$ . Even when  $P$  is not a finite extension of  $G_{F,\Sigma}$ , we can write it as a filtered limit  $\varprojlim_\alpha P_\alpha$  of such finite extensions, with each section  $\sigma$  giving a pro-(finite étale) group scheme  $P^\sigma = \varprojlim_\alpha P_\alpha^\sigma$  over  $F$ . Maps  $X_{\acute{e}t} \rightarrow BP$  then correspond to  $P^\sigma$ -torsors  $f^\sigma: Y^\sigma \rightarrow X$ , and we may substitute  $K \cong \pi_1(\bar{Y}^\sigma)$  in the spectral sequence above.

*Example 2.7* (Relative completion of  $\pi_1^{\acute{e}t}(\bar{Y}_\Gamma)$ ). As a special case of Example 2.6, take a congruence subgroup  $\Gamma \leq \text{SL}_2(\mathbb{Z})$ ; we may then form a stacky modular curve  $Y_\Gamma$  over some number field  $F$ , with geometric fundamental group the profinite completion  $\hat{\Gamma}$  of  $\Gamma$ . A point  $x \in Y_\Gamma(F^\Sigma)$  then gives  $\pi_1^{\acute{e}t}(Y_\Gamma, \bar{x}) \cong \hat{\Gamma} \rtimes G_{F,\Sigma}$ . The Tate module of the universal elliptic curve over  $Y_\Gamma$  gives rise to a  $\hat{\mathbb{Z}}$ -local system of rank 2 on  $Y_\Gamma$ , and hence a map

$$\pi_1^{\acute{e}t}(Y_\Gamma) \rightarrow \text{GL}_2(\hat{\mathbb{Z}})$$

(for any choice of basepoint).

Since the local system has determinant  $\hat{\mathbb{Z}}(1)$ , this induces a map

$$\pi_1^{\acute{e}t}(Y_\Gamma) \rightarrow \text{GL}_2(\hat{\mathbb{Z}}) \times_{\mathbb{G}_m(\hat{\mathbb{Z}})} G_{F,\Sigma},$$

and we may then take the relative pro-nilpotent completion over the image, or the relative pro- $\ell$  completion over the image in  $\text{GL}_2(\mathbb{Z}_\ell) \times_{\mathbb{G}_m(\mathbb{Z}_\ell)} G_{F,\Sigma}$ . Since the maps  $\text{GL}_2(\mathbb{Z}_\ell) \rightarrow \text{GL}_2(\mathbb{F}_\ell)$  are pro- $\ell$  extensions, completion relative to  $\text{GL}_2(\mathbb{F}_\ell)$  gives the same limit from a different tower.

For  $\Gamma = \text{SL}_2(\mathbb{Z})$ , with  $\Gamma(N) := \ker(\text{SL}_2(\mathbb{Z}) \rightarrow \text{SL}_2(\mathbb{Z}/N))$ , the spectral sequence resulting from the pro-nilpotent tower relative to  $\text{GL}_2(\mathbb{Z}/N) \times_{\mathbb{G}_m(\mathbb{Z}/N)} G_{F,\Sigma}$  is

$$\mathbb{H}^{1+s-t}(G_{F,\Sigma}, [\Gamma(N)]_s/[\Gamma(N)]_{s+1}) \implies \pi_{t-s} \text{map}_{B(\text{GL}_2(\mathbb{Z}/N) \times_{\mathbb{G}_m(\mathbb{Z}/N)} G_{F,\Sigma})} (BG_{F,\Sigma}, B\Pi_\infty),$$

where  $\Pi_\infty := \varprojlim_s \pi_1^{\acute{e}t}(Y_\Gamma)/[\hat{\Gamma}(N)]_s$ .

The spectral sequence relative to  $\text{GL}_2(\hat{\mathbb{Z}}) \times_{\mathbb{G}_m(\mathbb{Z}/N)} G_{F,\Sigma}$  instead has

$$\mathbb{H}^{1+s-t}(G_{F,\Sigma}, \varprojlim_N [\Gamma(N)]_s/[\Gamma(N)]_{s+1}) \implies \pi_{t-s} \text{map}_{B(\text{GL}_2(\hat{\mathbb{Z}}) \times_{\mathbb{G}_m(\hat{\mathbb{Z}})} G_F)} (BG_{F,\Sigma}, B\Pi_\infty),$$

for  $\Pi_\infty = \varprojlim_{s,N} \pi_1^{\acute{e}t}(Y_\Gamma)/[\hat{\Gamma}(N)]_s$ .

**2.3. Unipotent extensions.** We now look to consider towers  $\dots \Pi_{n+1} \rightarrow \Pi_n \rightarrow \dots \rightarrow \Pi_0$  of unipotent extensions of Lie groups over  $\mathbb{Q}_\ell$ .

**Definition 2.8.** Say that a simplicial group  $H$  is bounded if its Dold–Kan normalisation  $NH$  (given by  $N_n H = H_n \cap \ker_{i>0} \partial_i$ ) is so.

**Lemma 2.9.** *If  $U$  is a bounded simplicial unipotent algebraic group over  $\mathbb{Q}_\ell$ , equipped with a continuous action of a profinite group  $G$ , then  $U(\mathbb{Q}_\ell)$  is the filtered colimit of its bounded simplicial profinite  $G$ -equivariant subgroups.*

*Proof.* This is a slight generalisation of [Pri5, Lemmas 3.10 and 3.14], which address the case where the  $G$ -action is semisimple. Standard arguments give a  $G$ -equivariant bounded simplicial  $\mathbb{Z}_\ell$ -submodule  $\Lambda$  of the Lie algebra  $\mathfrak{u}$  of  $U$ , with  $\Lambda$  of finite rank and  $\Lambda \otimes \mathbb{Q}_\ell \rightarrow \mathfrak{u}$ . The closure  $g(\Lambda)$  of  $\Lambda$  under monomial operations in the Campbell–Baker–Hausdorff product is still bounded and of finite rank, as  $\mathfrak{u}$  is nilpotent, and the groups  $g(\ell^{-n}\Lambda)$  realise  $U(\mathbb{Q}_\ell)$  as a filtered colimit of the required form.  $\square$

**Corollary 2.10.** *Take an affine algebraic group  $T$  over  $\mathbb{Q}_\ell$  and a surjection  $\Pi \rightarrow T$  of simplicial affine group schemes, with  $U := \ker(\Pi \rightarrow T)$  bounded unipotent. Then for any Zariski-dense profinite group  $G \subset T(\mathbb{Q}_\ell)$ , the simplicial topological group*

$$\Pi(\mathbb{Q}_\ell) \times_{T(\mathbb{Q}_\ell)} G$$

*is a filtered colimit of those simplicial profinite subgroups which are bounded nilpotent extensions of  $G$ .*

*Proof.* Since  $\Pi(\mathbb{Q}_\ell) \times_{T(\mathbb{Q}_\ell)} G$  is the fibre of  $\Pi(\mathbb{Q}_\ell) \times_{T^{\text{red}}(\mathbb{Q}_\ell)} G \rightarrow T(\mathbb{Q}_\ell) \times_{T^{\text{red}}(\mathbb{Q}_\ell)} G$ , it suffices to prove this for  $T$  reductive. As in [Pri1], the simplicial unipotent extension  $\Pi \rightarrow T$  then admits a section (i.e. a Levi decomposition), unique up to conjugation by  $U(\mathbb{Q}_\ell)$ ; this gives an isomorphism  $\Pi \cong T \rtimes U$ . Since  $G$  is Zariski dense in the reductive group  $T$ , its action is semisimple so we may appeal to Lemma 2.9, writing

$$G \times_{T(\mathbb{Q}_\ell)} \Pi(\mathbb{Q}_\ell) \cong G \rtimes U \cong \varinjlim_{\alpha} G \rtimes N_{\alpha},$$

for bounded  $G$ -equivariant simplicial profinite subgroups  $N_{\alpha}$  of  $U$ .  $\square$

The nerve  $\bar{W}(\Pi(\mathbb{Q}_\ell) \times_{T(\mathbb{Q}_\ell)} G)$  is then an ind-pro-simplicial set, and defining mapping spaces for these by the usual convention

$$\text{map}(Y, \{Z_{\alpha}\}) := \varinjlim_{\alpha} \text{map}(Y, Z_{\alpha}),$$

for  $Y, Z_{\alpha}$  profinite, we may apply Proposition 2.2 to unipotent extensions, by passing to filtered colimits:

**Proposition 2.11.** *Take a unipotent extension  $\Pi'' \rightarrow \Pi'$  of algebraic groups over  $\mathbb{Q}_\ell$  with commutative kernel  $A$ , such that the conjugation action of  $\Pi'$  on  $A$  factors through some quotient  $\Pi$  of  $\Pi'$ . Then for any Zariski-dense map  $G \rightarrow \Pi(\mathbb{Q}_\ell)$  with  $G$  profinite, and for any pro-simplicial set  $Y$  over  $BG$ , there is a natural fibration sequence*

$$\text{map}_{BG}(Y, B(\Pi'' \times_{\Pi} G)) \rightarrow \text{map}_{BG}(Y, B(\Pi' \times_{\Pi} G)) \rightarrow \text{map}_{BG}(Y, B(G \rtimes BA))$$

*of mapping spaces, the fibre being taken over the zero map  $Y \rightarrow BG \rightarrow B(G \rtimes BA)$ .*

**Example 2.12** (Unipotent completion of  $\pi_1^{\text{ét}}(\bar{X})$ ). If  $X$  is a scheme over  $\mathcal{O}_{F,\Sigma}$ , and  $\bar{X} := X \otimes_{\mathcal{O}_{F,\Sigma}} \bar{\mathcal{O}}_{F,\Sigma}$ , with some geometric point  $\bar{x}$ , then we may use Proposition 2.11 to give a variant of Example 2.5. For simplicity, assume that we have a point  $x \in X(\mathcal{O}_{F,\Sigma})$

under  $\bar{x}$  (if not, we can recover the constructions below by taking a  $G_{F,\Sigma}$ -equivariant set  $\mathcal{B} \subset X(\bar{F})$ ), then consider the  $G_{F,\Sigma}$ -equivariant surjection from the groupoid  $\pi_1^{\text{ét}}(\bar{X}, \mathcal{B})$  to the contractible groupoid on objects  $\mathcal{B}$ .

We then have an isomorphism  $\pi_1^{\text{ét}}(X, \bar{x}) \cong G_{F,\Sigma} \times \pi_1^{\text{ét}}(\bar{X}, \bar{x})$ , and we consider the lower central series

$$\Pi_n := G_{F,\Sigma} \times (\pi_1^{\text{ét}}(\bar{X}, \bar{x}) \otimes \mathbb{Q}_\ell) / [\pi_1^{\text{ét}}(\bar{X}, \bar{x}) \otimes \mathbb{Q}_\ell]_n,$$

of the pro-unipotent Malcev completion  $\pi_1^{\text{ét}}(\bar{X}, \bar{x}) \otimes \mathbb{Q}_\ell$ .

Thus  $\Pi_0 = G_{F,\Sigma}$ , and taking  $Y = BG_{F,\Sigma}$ , we get a non-abelian spectral sequence

$$E_1^{s,t} = H^{1+s-t}(G_{F,\Sigma}, [\bar{\pi} \otimes \mathbb{Q}_\ell]_s / [\bar{\pi} \otimes \mathbb{Q}_\ell]_{s+1}) \implies \pi_{t-s} \text{map}_{BG_{F,\Sigma}}(BG_{F,\Sigma}, B\Pi_\infty)$$

of groups and sets, where we write  $\bar{\pi} := \pi_1^{\text{ét}}(\bar{X}, \bar{x})$ .

Although this gives weaker obstructions than Example 2.5, the obstruction spaces are easier to calculate. The vector spaces  $[\bar{\pi} \otimes \mathbb{Q}_\ell]_s / [\bar{\pi} \otimes \mathbb{Q}_\ell]_{s+1}$  are the graded pieces of a pro-nilpotent Lie algebra with generators  $H_1(\bar{X}, \mathbb{Q}_\ell)$  and relations non-canonically isomorphic to  $H_2(\bar{X}, \mathbb{Q}_\ell)$ . Since points in  $X(\mathcal{O}_{F,\Sigma})$  map to elements in  $\pi_0 \text{map}_{BG_{F,\Sigma}}(BG_{F,\Sigma}, B\Pi_\infty)$ , this spectral sequence gives obstructions to the existence of such rational points.

**2.4. Pro-unipotent extensions.** Relative Malcev completion was introduced by Hain in [Hai2] for discrete groups, and was slightly generalised to profinite groups in [Pri2], as follows:

**Definition 2.13.** Given a topological group  $\Gamma$ , a reductive pro-algebraic group  $R$  over  $\mathbb{Q}_\ell$ , and a Zariski-dense continuous representation  $\rho: \Gamma \rightarrow R(\mathbb{Q}_\ell)$ , Define the Malcev completion  $(\Gamma)^{\rho, \text{Mal}}$  to be the universal diagram

$$\Gamma \rightarrow \Gamma^{\rho, \text{Mal}}(\mathbb{Q}_\ell) \xrightarrow{p} R(\mathbb{Q}_\ell),$$

with  $p: \Gamma^{\rho, \text{Mal}} \xrightarrow{p} R$  a pro-unipotent extension, and the composition equal to  $\rho$ .

When the representation  $\rho$  is clear from the context, we will write  $\Gamma^{R, \text{Mal}} := \Gamma^{\rho, \text{Mal}}$ .

*Remark 2.14.* The pro-unipotent radical  $R_u(\Gamma, \rho)^{\text{Mal}}$  is then given by  $\exp(\mathfrak{u})$  for a pro-(finite-dimensional nilpotent) Lie algebra  $\mathfrak{u}$ . For  $O(R)$  the ring of algebraic functions on  $R$  over  $\mathbb{Q}_\ell$ , equipped with its left  $R$ -action, the abelianisation of  $\mathfrak{u}$  is dual to the continuous cohomology  $H^1(\Gamma, O(R))$ , and there is a presentation of  $\mathfrak{u}$  with relations dual to  $H^2(\Gamma, O(R))$ . In particular, if  $H^2(\Gamma, O(R)) = 0$ , then there are canonical isomorphisms

$$[R_u(\Gamma, \rho)^{\text{Mal}}]_n / [R_u(\Gamma, \rho)^{\text{Mal}}]_{n+1} \cong (\text{CoLie}_n H^1(\Gamma, O(R)))^*,$$

where  $\text{CoLie}_n(V) = \text{Lie}(n)^* \otimes_{S_n} V^{\otimes n}$  for the Lie operad  $\text{Lie}$ . Explicitly, when  $V$  is finite-dimensional,  $(\text{CoLie}_n V)^*$  is the subspace of the free Lie algebra on generators  $V^*$  consisting of homogeneous terms of bracket length  $n$ .

Also note that if  $\Gamma$  is a discrete group and  $\hat{\Gamma}$  its profinite completion, then for any representation  $\rho$  of  $\hat{\Gamma}$ , the map  $\Gamma^{\rho, \text{Mal}} \rightarrow \hat{\Gamma}^{\rho, \text{Mal}}$  is necessarily an isomorphism.

*Examples 2.15* ( $\widehat{\text{SL}}_2(\mathbb{Z})$ ). Our main motivating example is to take  $\Gamma = \text{SL}_2(\mathbb{Z})$  and its profinite completion  $\hat{\Gamma}$ , with  $R = \text{SL}_2$  (regarded as a group scheme over  $\mathbb{Q}_\ell$ ) and  $\hat{\Gamma} \rightarrow \text{SL}_2(\mathbb{Q}_\ell)$  the natural map.

Since the ring  $O(\text{SL}_2)$  of functions is given by  $\bigoplus_m V_m \otimes (UV_m)^*$ , for  $V_m$  the irreducible  $\text{SL}_2$ -representation of dimension  $m + 1$  over  $\mathbb{Q}_\ell$  and  $UV_m$  the underlying vector space,



we have

$$H^*(\Gamma, O(\mathrm{SL}_2)) \cong \bigoplus_m H^*(\Gamma, V_m) \otimes V_m^*.$$

Thus  $H^2(\Gamma, O(\mathrm{SL}_2)) = 0$ , and Eichler–Shimura gives a description of  $H^1(\Gamma, O(\mathrm{SL}_2)) \otimes \mathbb{C}$  in terms of the decomposition of  $H^1(\Gamma, V_m) \otimes \mathbb{C}$  into modular forms and cusp forms of weight  $m + 2$  and level 1.

Our groups of interest are  $H^1(\Gamma, V_m)$ . We may think of the spaces  $H^1(\Gamma, V_m)$  as  $\ell$ -adic realisations of motives of modular forms, as in [Del]. These  $\mathbb{Q}_\ell$ -vector spaces admit  $G_{\mathbb{Q}}$ -actions via the interpretation as summands of  $H_{\text{ét}}^{m+1}(\mathcal{M}_{1,m+1} \otimes \bar{\mathbb{Q}}, \mathbb{Q}_\ell)(m)$ , interpreting  $\mathcal{M}_{1,m+1}$  as the  $m$ -fold product of the universal elliptic curve  $\mathcal{M}_{1,2}$  over the moduli stack  $\mathcal{M}_{1,1}$  of elliptic curves (the Tate twists arise because we wish to regard  $V_1$  as a Tate module rather than its dual).

More generally, we can take  $\Gamma$  to be a congruence subgroup of  $\mathrm{SL}_2(\mathbb{Z})$ , giving a similar expression involving modular forms of higher levels, but with relations coming from  $H^2(\Gamma, O(\mathrm{SL}_2))$  whenever it is non-zero.

Alternatively, we can look at the relative completion of the canonical morphism

$$\mathrm{SL}_2(\mathbb{Z}) \rightarrow \mathrm{SL}_2(\hat{\mathbb{Z}}) \times \mathrm{SL}_2(\mathbb{Q}_\ell) =: R,$$

where we regard the profinite group  $\mathrm{SL}_2(\hat{\mathbb{Z}})$  as an affine group scheme over  $\mathbb{Q}_\ell$ . Then we still have  $H^2(\mathrm{SL}_2(\mathbb{Z}), O(R)) \otimes \mathbb{Q} = 0$ , and Leray–Serre gives

$$H^*(\mathrm{SL}_2(\mathbb{Z}), O(\mathrm{SL}_2(\hat{\mathbb{Z}})) \otimes V) \cong \varinjlim_N H^*(\Gamma(N!), V),$$

so

$$H^1(\mathrm{SL}_2(\mathbb{Z}), O(R)) \cong \bigoplus_m \varinjlim_N H^1(\Gamma(N!), V_m) \otimes V_m^*,$$

giving generators of  $R_{\mathrm{u}} \widehat{\mathrm{SL}_2(\mathbb{Z})}^{(\mathrm{SL}_2(\hat{\mathbb{Z}}) \times \mathrm{SL}_2), \mathrm{Mal}} = R_{\mathrm{u}} \mathrm{SL}_2(\mathbb{Z})^{(\mathrm{SL}_2(\hat{\mathbb{Z}}) \times \mathrm{SL}_2), \mathrm{Mal}}$  in terms of modular and cusp forms of all weights and levels.

We can also just look at the relative completion of the canonical morphism  $\mathrm{SL}_2(\mathbb{Z}) \rightarrow \mathrm{SL}_2(\hat{\mathbb{Z}})$ , again regarding  $\mathrm{SL}_2(\hat{\mathbb{Z}})$  as an affine group scheme over  $\mathbb{Q}_\ell$ . We then have

$$H^1(\mathrm{SL}_2(\mathbb{Z}), O(\mathrm{SL}_2(\hat{\mathbb{Z}}))) \cong \varinjlim_N H^1(\Gamma(N!), \mathbb{Q}_\ell)$$

with the corresponding  $H^2$  vanishing, giving generators for  $R_{\mathrm{u}} \mathrm{SL}_2(\mathbb{Z})^{\mathrm{SL}_2(\hat{\mathbb{Z}}), \mathrm{Mal}}$  in terms of modular and cusp forms of weight 2 and all levels.

For our purposes, Proposition 2.2 is now not quite general enough, as our group schemes might not be of finite type. Consider an affine group scheme  $T$  over  $\mathbb{Q}_\ell$  and a surjection  $\Pi \rightarrow T$  of simplicial affine group schemes, with  $U := \ker(\Pi \rightarrow R)$  bounded pro-unipotent, together with a Zariski-dense profinite group  $G \subset T(\mathbb{Q}_\ell)$ . We can then canonically write the morphism  $\Pi \rightarrow T$  as a filtered limit of unipotent extensions  $\Pi_a \rightarrow T_a$  of affine algebraic groups, with Corollary 2.10 giving that  $\Pi_a(\mathbb{Q}_\ell) \times_{T_a(\mathbb{Q}_\ell)} G$  is an ind-profinite group, so  $\Pi(\mathbb{Q}_\ell) \times_{T(\mathbb{Q}_\ell)} G$  is naturally a pro-ind-profinite group.

The nerve  $\bar{W}(\Pi(\mathbb{Q}_\ell) \times_{T(\mathbb{Q}_\ell)} G)$  is then a pro-ind-pro-simplicial set, and defining mapping spaces for these by the usual convention

$$\mathrm{map}(Y, \{Z_a\}) := \mathrm{holim}_{\leftarrow a} \mathrm{map}(Y, Z_a),$$

for  $Y$  profinite and  $Z_a$  ind-profinite, Proposition 2.11 extends verbatim to pro-unipotent extensions  $\Pi'' \rightarrow \Pi'$ .

*Example 2.16* (Modular forms of level 1). If  $X = \mathcal{M}_{1,1}$  is the stacky modular curve, and  $x \in X(\mathcal{O}_{F,\Sigma})$ , then the identification  $\pi_1^{\acute{e}t}(\bar{X}, \bar{x}) \cong \widehat{\mathrm{SL}_2(\mathbb{Z})}$  gives an action of  $G_{F,\Sigma}$  on  $\widehat{\mathrm{SL}_2(\mathbb{Z})}$ , and we may consider the pro-unipotent extension

$$G_{F,\Sigma} \times (\widehat{\mathrm{SL}_2(\mathbb{Z})})^{\mathrm{SL}_2, \mathrm{Mal}} \times_{\mathrm{SL}_2(\mathbb{Q}_\ell)} \mathrm{SL}_2(\mathbb{Z}_\ell) \rightarrow G_{F,\Sigma} \times \mathrm{SL}_2(\mathbb{Z}_\ell),$$

setting

$$\Pi_n := G_{F,\Sigma} \times ((\widehat{\mathrm{SL}_2(\mathbb{Z})})^{\mathrm{SL}_2, \mathrm{Mal}} / [\mathrm{R}_u]_{n+1}) \times_{\mathrm{SL}_2(\mathbb{Q}_\ell)} \mathrm{SL}_2(\mathbb{Z}_\ell).$$

As in Example 2.7, for the representation  $G_{F,\Sigma} \rightarrow \mathbb{Z}_\ell^*$  given by the Tate motive  $\mathbb{Z}_\ell(1)$ , we have  $G_{F,\Sigma} \times \mathrm{SL}_2(\mathbb{Z}_\ell) \cong G_{F,\Sigma} \times_{\mathbb{Z}_\ell^*} \mathrm{GL}_2(\mathbb{Z}_\ell)$ , so a section of the projection  $G_{F,\Sigma} \times \mathrm{SL}_2(\mathbb{Z}_\ell) \rightarrow G_{F,\Sigma}$  is equivalent to giving a  $G_{F,\Sigma}$ -representation  $\Lambda$  of rank 2 over  $\mathbb{Z}_\ell$ , with determinant  $\mathbb{Z}_\ell(1)$ .

For the universal elliptic curve  $f: E \rightarrow X$ , we have the Tate module  $\mathbb{T}_\ell := (\mathbf{R}^1 f_* \mathbb{Z}_\ell)^* \cong \mathbf{R}^1 f_* \mathbb{Z}_\ell(1)$ , a lisse  $\mathbb{Z}_\ell$ -sheaf of rank 2 on  $X$ , giving a  $G_{F,\Sigma}$ -action on  $\mathrm{H}^1(\mathrm{SL}_2(\mathbb{Z}), V_m)$  by identifying it with  $\mathbf{R}^1 q_*(S^m \mathbb{T}_\ell) \otimes \mathbb{Q}$ , for the structure morphism  $q: X \rightarrow \mathrm{Spec} \mathcal{O}_{F,\Sigma}$ .

Write

$$\begin{aligned} L_s &:= \mathrm{CoLie}_s\left(\bigoplus_m \mathrm{H}^1(\mathrm{SL}_2(\mathbb{Z}), V_m) \otimes S^m(\Lambda)^*\right), \\ &\cong \mathrm{CoLie}_s\left(\bigoplus_m \mathrm{H}^1(\mathrm{SL}_2(\mathbb{Z}), V_m) \otimes S^m(\Lambda)(-m)\right). \end{aligned}$$

Adapting Example 2.5, the pro-unipotent generalisation of Proposition 2.11 then combines with Examples 2.15 to give a non-abelian spectral sequence

$$E_1^{s,t} = \mathrm{H}^{1+s-t}(G_{F,\Sigma}, L_s^*) \implies \pi_{t-s} \mathrm{map}_{B(G_{F,\Sigma} \times_{\mathbb{G}_m(\mathbb{Z}_\ell)} \mathrm{GL}_2(\mathbb{Z}_\ell))} (BG_{F,\Sigma}, B\Pi_\infty),$$

where the map  $G_{F,\Sigma} \rightarrow \mathrm{GL}_2(\mathbb{Z}_\ell)$  is given by  $\Lambda$ . Note that  $\mathrm{H}^1(\mathrm{SL}_2(\mathbb{Z}), V_m)(-m)$  is mixed of weights  $m+1$  (cusp forms and their conjugates) and  $2m+2$  (Eisenstein series), and that  $S^m \Lambda_{\mathbb{Q}}$  is pure of weight  $-m$ . Thus  $\mathrm{H}^1(\mathrm{SL}_2(\mathbb{Z}), V_m) \otimes S^m(\Lambda)(-m)$  is mixed of weights 1 and  $m+2$ , so  $L_s$  is of strictly positive weights, and  $E_{s,s+1}^1 = 0$ .

Now set  $X_{(n)} := \mathrm{map}_{BG_{F,\Sigma}} (BG_{F,\Sigma}, B\Pi_n)$ ; thus  $X_{(0)}$  consists of representations  $G_{F,\Sigma} \rightarrow \mathrm{GL}_2(\mathbb{Z}_\ell)$  whose determinant is the Tate motive, conjugation by  $\mathrm{SL}_2(\mathbb{Z}_\ell)$  giving equivalences, so  $\pi_1(X_{(0)}, [\Lambda])$  consists of elements of  $\mathrm{SL}_2(\mathbb{Z}_\ell)$  commuting with the action of  $G_{F,\Sigma}$  on  $\Lambda$ . Since  $\pi_i X_{(n)} = 0$  for  $i > 1$ , we then have exact sequences

$$0 \rightarrow \pi_1 X_{(n)} \rightarrow \pi_1 X_{(n-1)} \rightarrow \mathrm{H}^1(F, L_n^*) \rightarrow \pi_0 X_{(n)} \rightarrow \pi_0 X_{(n-1)} \rightarrow \mathrm{H}^2(F, L_n^*),$$

with a map  $X(\mathcal{O}_{F,\Sigma}) \rightarrow X_{(\infty)}$ . Here,  $X(\mathcal{O}_{F,\Sigma})$  is the nerve of the groupoid of maps  $\mathrm{Spec} \mathcal{O}_{F,\Sigma} \rightarrow X$ , so  $\pi_0 X(\mathcal{O}_{F,\Sigma})$  is the set of isomorphism classes of elliptic curves over  $\mathcal{O}_{F,\Sigma}$ , and  $\pi_1(X(\mathcal{O}_{F,\Sigma}), x)$  the group of automorphisms of the elliptic curve  $E_x$  over  $\mathcal{O}_{F,\Sigma}$ ; the higher homotopy groups all vanish.

In other words, given a  $G_{F,\Sigma}$ -representation  $\Lambda$  of rank 2 over  $\mathbb{Z}_\ell$ , with determinant  $\mathbb{Z}_\ell(1)$ , these sequences give a tower of obstructions to lifting  $\Lambda$  to an elliptic curve over  $\mathcal{O}_{F,\Sigma}$  with Tate module  $\Lambda$ , and characterise the ambiguity of the lift at each stage. As in Examples 2.15, there is an entirely similar treatment for profinite completions of congruence subgroups  $\Gamma \leq \mathrm{SL}_2(\mathbb{Z})$ , replacing  $\mathcal{M}_{1,1}$  with the modular curve  $Y_\Gamma$ .

*Example 2.17* (Modular forms of all levels). Again taking  $X = \mathcal{M}_{1,1}$  to be the stacky modular curve, and  $x \in X(\mathcal{O}_{F,\Sigma})$ , we may consider the pro-unipotent extension

$$G_{F,\Sigma} \times (\widehat{\mathrm{SL}}_2(\mathbb{Z}))^{\mathrm{SL}_2 \times \mathrm{SL}_2(\hat{\mathbb{Z}}), \mathrm{Mal}} \times_{\mathrm{SL}_2(\mathbb{Q}_\ell) \times \mathrm{SL}_2(\hat{\mathbb{Z}})} \mathrm{SL}_2(\hat{\mathbb{Z}}) \rightarrow G_{F,\Sigma} \times \mathrm{SL}_2(\hat{\mathbb{Z}}),$$

setting

$$\Pi_n := G_{F,\Sigma} \times ((\widehat{\mathrm{SL}}_2(\mathbb{Z}))^{\mathrm{SL}_2 \times \mathrm{SL}_2(\hat{\mathbb{Z}}), \mathrm{Mal}} / [\mathrm{R}_u]_{n+1}) \times_{\mathrm{SL}_2(\mathbb{Q}_\ell) \times \mathrm{SL}_2(\hat{\mathbb{Z}})} \mathrm{SL}_2(\hat{\mathbb{Z}}).$$

Choose a section of the projection  $G_{F,\Sigma} \times \mathrm{SL}_2(\hat{\mathbb{Z}}) \rightarrow G_{F,\Sigma}$ ; this is equivalent to giving a  $G_{F,\Sigma}$ -representation  $\Lambda$  of rank 2 over  $\hat{\mathbb{Z}}$ , with determinant  $\hat{\mathbb{Z}}(1)$ . Write

$$M_s := \mathrm{CoLie}_s(\bigoplus_m \varinjlim_N \mathrm{H}^1(\Gamma(N!), V_m) \otimes_{\hat{\mathbb{Z}}} S_{\hat{\mathbb{Z}}}^m(\Lambda)(-m)).$$

As in Example 2.16, we then have a non-abelian spectral sequence

$$E_1^{s,t} = \mathrm{H}^{1+s-t}(G_{F,\Sigma}, M_s^*) \implies \pi_{t-s} \mathrm{map}_{B(G_{F,\Sigma} \times_{\mathbb{G}_m(\hat{\mathbb{Z}})} \mathrm{GL}_2(\hat{\mathbb{Z}}))} (BG_{F,\Sigma}, B\Pi_\infty),$$

where the map  $G_{F,\Sigma} \rightarrow \mathrm{GL}_2(\hat{\mathbb{Z}})$  is given by  $\Lambda$ . Since

$$O(\mathrm{SL}_2(\hat{\mathbb{Z}})) \otimes \mathrm{H}^1(\Gamma(N!), V_m) \otimes S^m(\Lambda)(-m)$$

is mixed of weights 1 (cusp forms of all levels and their conjugates) and  $m+2$  (Eisenstein series of all levels), so  $M_s$  is of strictly positive weights, and  $E_{s,s+1}^1 = 0$ .

Now set  $X_{(n)} := \mathrm{map}_{BG_{F,\Sigma}} (BG_{F,\Sigma}, B\Pi_n)$ ; thus  $X_{(0)}$  consists of representations  $G_{F,\Sigma} \rightarrow \mathrm{GL}_2(\hat{\mathbb{Z}})$  whose determinant is the Tate motive, conjugation by  $\mathrm{SL}_2(\hat{\mathbb{Z}})$  giving equivalences. Since  $\pi_i X_{(n)} = 0$  for  $i > 1$ , we then have exact sequences

$$0 \rightarrow \pi_1 X_{(n)} \rightarrow \pi_1 X_{(n-1)} \rightarrow \mathrm{H}^1(F, M_n^*) \rightarrow \pi_0 X_{(n)} \rightarrow \pi_0 X_{(n-1)} \rightarrow \mathrm{H}^2(F, M_n^*),$$

with a map  $X(\mathcal{O}_{F,\Sigma}) \rightarrow X_\infty$ .

*Example 2.18* (Modular forms of weight 2). Again taking  $X = \mathcal{M}_{1,1}$  to be the stacky modular curve, and  $x \in X(\mathcal{O}_{F,\Sigma})$ , we may consider the pro-unipotent extension

$$G_{F,\Sigma} \times (\widehat{\mathrm{SL}}_2(\mathbb{Z}))^{\mathrm{SL}_2(\hat{\mathbb{Z}}), \mathrm{Mal}} \rightarrow G_{F,\Sigma} \times \mathrm{SL}_2(\hat{\mathbb{Z}}),$$

setting

$$\Pi_n := G_{F,\Sigma} \times ((\widehat{\mathrm{SL}}_2(\mathbb{Z}))^{\mathrm{SL}_2(\hat{\mathbb{Z}}), \mathrm{Mal}} / [\mathrm{R}_u]_{n+1}).$$

As in Example 2.18, choose a  $G_{F,\Sigma}$ -representation  $\Lambda$  of rank 2 over  $\hat{\mathbb{Z}}$ , with determinant  $\hat{\mathbb{Z}}(1)$ . Write

$$M_s := \mathrm{CoLie}_s(\varinjlim_N \mathrm{H}^1(\Gamma(N!), \mathbb{Q}_\ell));$$

thus  $M_1$  is related to weight 2 modular forms; as a Galois representation it is mixed of weights 1 and 2. We then have a non-abelian spectral sequence

$$E_1^{s,t} = \mathrm{H}^{1+s-t}(G_{F,\Sigma}, M_s^*) \implies \pi_{t-s} \mathrm{map}_{B(G_{F,\Sigma} \times_{\mathbb{G}_m(\hat{\mathbb{Z}})} \mathrm{GL}_2(\hat{\mathbb{Z}}))} (BG_{F,\Sigma}, B\Pi_\infty),$$

where the map  $G_{F,\Sigma} \rightarrow \mathrm{GL}_2(\hat{\mathbb{Z}})$  is given by  $\Lambda$ .

Set  $X_{(n)} := \mathrm{map}_{BG_{F,\Sigma}} (BG_{F,\Sigma}, B\Pi_n)$ ; since  $\pi_i X_{(n)} = 0$  for  $i > 1$ , we then have exact sequences

$$0 \rightarrow \pi_1 X_{(n)} \rightarrow \pi_1 X_{(n-1)} \rightarrow \mathrm{H}^1(F, M_n^*) \rightarrow \pi_0 X_{(n)} \rightarrow \pi_0 X_{(n-1)} \rightarrow \mathrm{H}^2(F, M_n^*),$$

with a map  $X(\mathcal{O}_{F,\Sigma}) \rightarrow X_{(\infty)}$ .

*Example 2.19* (Étale fundamental groups). For any locally Noetherian Deligne–Mumford stack  $X$  over  $\mathcal{O}_{F,\Sigma}$  with  $x \in X(\mathcal{O}_{F,\Sigma})$ , we can generalise the examples above by considering any  $G_{F,\Sigma}$ -equivariant Zariski-dense representation  $\rho: \pi_1^{\text{ét}}(\bar{X}, \bar{x}) \rightarrow R(\mathbb{Q}_\ell)$  to a pro-reductive affine group scheme  $R$  over  $\mathbb{Q}_\ell$ . If there is no rational basepoint, we can instead take a  $G_{F,\Sigma}$ -equivariant set  $\mathcal{B} \subset X(\bar{F})$  of basepoints, then consider the  $G_{F,\Sigma}$ -equivariant surjection from the groupoid  $\pi_1^{\text{ét}}(\bar{X}, \mathcal{B})$  to the contractible groupoid on objects  $\mathcal{B}$ , with relative Malcev completions as in [Pri1, §3.2].

We may then set

$$\Pi_n := G_{F,\Sigma} \times (\pi_1^{\text{ét}}(\bar{X}, \bar{x})^{R, \text{Mal}} / [\mathbf{R}_u]_{n+1}) \times_{R(\mathbb{Q}_\ell)} \rho(\pi_1^{\text{ét}}(\bar{X}, \bar{x})),$$

with  $P_n := \ker(\Pi_n \rightarrow \Pi_{n-1})$  a quotient of  $(\text{CoLie}_n(\mathbf{H}^1(\bar{X}, O(R))))^*$  described as in Remark 2.14.

For any section  $\sigma$  of the projection  $G_{F,\Sigma} \times \rho(\pi_1^{\text{ét}}(\bar{X}, \bar{x})) \rightarrow G_{F,\Sigma}$ , we then have a non-abelian spectral sequence

$$E_1^{s,t} = \mathbf{H}^{1+s-t}(G_{F,\Sigma}, P_s) \implies \pi_{t-s} \text{map}_{B(G_{F,\Sigma} \times \rho(\pi_1^{\text{ét}}(\bar{X}, \bar{x})))} (BG_{F,\Sigma}, B\Pi_\infty),$$

where the map  $G_{F,\Sigma} \rightarrow G_{F,\Sigma} \times \rho(\pi_1^{\text{ét}}(\bar{X}, \bar{x}))$  is given by  $\sigma$ .

*Example 2.20* (Étale homotopy types). We may refine the previous example by considering étale homotopy types in place of fundamental groups. Take a locally Noetherian Deligne–Mumford stack  $X$  over  $\mathcal{O}_{F,\Sigma}$ , and a geometric point  $\bar{x}$ . We can then form the étale topological type  $X_{\text{ét}} \in \text{pro}(\mathbb{S})$  as defined in [Fri, Definition 4.4]. Note that  $(X_{\text{ét}})_0$  is the set of geometric points of  $X_0$  (with some bound imposed on the cardinalities of the associated fields). Consider the reduced pro-simplicial set  $(X_{\text{ét}}, \bar{x}) \subset X_{\text{ét}}$  given by setting  $(X_{\text{ét}}, \bar{x})_n$  to consist of  $n$ -simplices with fixed vertex  $\bar{x}$ . We may then apply the loop group construction of [GJ, §V.5] to get a pro-simplicial group  $G(X_{\text{ét}}, \bar{x})$  with  $\pi_0 G(X_{\text{ét}}, \bar{x}) \cong \pi_1^{\text{ét}}(X, \bar{x})$ .

Now fix a Zariski-dense representation  $\rho: \pi_1^{\text{ét}}(X, \bar{x}) \rightarrow S(\mathbb{Q}_\ell)$  to a pro-reductive pro-algebraic group  $S$ , and let  $R$  be the Zariski closure of  $\rho(\pi_1^{\text{ét}}(\bar{X}, \bar{x}))$ , and set  $T := S/R$ . We now need to consider fibre sequences, because  $G_{F,\Sigma}$  does not explicitly act on our model for  $\bar{X}_{\text{ét}}$ . If the  $G_{F,\Sigma}$ -representation  $\mathbf{H}^*(\bar{X}, V)$  is an extension of  $T$ -representations for all  $R$ -representations  $V$ , then [Pri5, Theorem 3.32] gives a fibre sequence

$$\bar{W}G(\bar{X}_{\text{ét}}, \bar{x})^{R, \text{Mal}} \rightarrow \bar{W}G(X_{\text{ét}}, \bar{x})^{S, \text{Mal}} \rightarrow G(\mathcal{O}_{F,\Sigma, \text{ét}})^{T, \text{Mal}}$$

of pro-algebraic homotopy types over  $\mathbb{Q}_\ell$ , and hence a long exact sequence

$$\begin{aligned} \dots \rightarrow \varpi_n(\bar{X}, \bar{x})^{R, \text{Mal}} \rightarrow \varpi_n(X, \bar{x})^{S, \text{Mal}} \rightarrow \varpi_n(BG_{F,\Sigma})^{T, \text{Mal}} \rightarrow \varpi_{n-1}(\bar{X}, \bar{x})^{R, \text{Mal}} \rightarrow \\ \dots \rightarrow \pi_1^{\text{ét}}(\bar{X}, \bar{x})^{R, \text{Mal}} \rightarrow \pi_1^{\text{ét}}(X, \bar{x})^{S, \text{Mal}} \rightarrow G_{F,\Sigma}^{T, \text{Mal}} \rightarrow 1 \end{aligned}$$

of pro-algebraic homotopy groups; in particular we will have an exact sequence of completed fundamental groups whenever  $\varpi_2(BG_{F,\Sigma})^{T, \text{Mal}} = 0$ , i.e. if  $G_{F,\Sigma}$  is 2-good relative to  $T$  in the sense of [Pri5, Definition 3.35] and [Pri6, §1.2.3].

We may then set  $\tilde{\Pi}_n$  to be the simplicial topological group given by the homotopy fibre product

$$\tilde{\Pi}_n := (G(X_{\text{ét}}, \bar{x})^{S, \text{Mal}} / [U]_{n+1}) \times_{G(\mathcal{O}_{F,\Sigma, \text{ét}})^{T, \text{Mal}}}^h G(\mathcal{O}_{F,\Sigma, \text{ét}}),$$

where  $U = R_{\mathfrak{u}}G(\bar{X}_{\acute{e}t}, \bar{x})^{R, \text{Mal}}$ ; in particular,  $\tilde{\Pi}_0 = S \times_T G(\mathcal{O}_{F, \Sigma, \acute{e}t})$ . Note that since  $B\tilde{\Pi}_\infty$  is equipped with a map from  $\bar{W}G(\bar{X}_{\acute{e}t}, \bar{x})$ , there is a canonical morphism

$$X(O_{F, \Sigma}) \rightarrow \text{map}_{B(G_{F, \Sigma})}(BG_{F, \Sigma}, B\tilde{\Pi}_\infty)$$

in the homotopy category of pro-ind-pro-simplicial sets.

We will then have a non-abelian spectral sequence

$$E_1^{s, t} \implies \pi_{t-s} \text{map}_{B(G_{F, \Sigma})}(BG_{F, \Sigma}, B\tilde{\Pi}_\infty),$$

with

$$E_1^{s, t} = \begin{cases} \mathbb{H}^{1+s-t}(G_{F, \Sigma}, [U]_s/[U]_{s+1}) & s \geq 1 \\ \pi_t \text{map}_{BT}(BG_{F, \Sigma}, BS) & s = 0, \end{cases}$$

where  $[U]_s/[U]_{s+1}$  is dual to  $\text{CoLie}_n((\mathbf{R}\Gamma(\bar{X}, O(R))/\mathbb{Q}_\ell)[1])$ , for  $\text{CoLie}$  now the cofree graded Lie coalgebra, and  $\tilde{H}^\bullet = H^\bullet/H^0$ . Beware that the terms  $E_1^{s, t}$  depend on an element of  $E_1^{0, 0}$  to determine the Galois action on  $U$ .

The filtration  $[U]_n$  corresponds to the good truncation filtration on  $\mathbf{R}\Gamma(\bar{X}, O(R))$ , but there are variants for other filtrations, replacing  $H^{1+\bullet}(\bar{X}, O(R))$  with the  $E_1$  page of the associated spectral sequence. For the case of the weight filtration on a quasi-projective variety, with representations tamely ramified around the divisor, see [Pri5, Corollary 6.16].

Note that taking path components of simplicial groups  $\tilde{\Pi}_n$  gives morphisms

$$\text{map}_{B(G_{F, \Sigma})}(BG_{F, \Sigma}, B\tilde{\Pi}_n) \rightarrow \text{map}_{B(G_{F, \Sigma})}(BG_{F, \Sigma}, B\Pi_n)$$

for the groups  $\Pi_n$  of Example 2.19. When  $H^{\geq 2}(\bar{X}, O(R)) = 0$  (such as for the stacky modular curve), the filtration  $[U]_n$  is just equivalent to the lower central series filtration of Example 2.19, so the morphisms are weak equivalences. For general  $X$ , the towers will be different, but whenever the higher relative Malcev homotopy groups of  $X$  vanish, the towers will converge to the same limit.

*Remark 2.21.* To recover Example 2.16 from Example 2.20, we take  $S$  to be the Zariski closure of the image of the representation

$$\pi_1^{\acute{e}t}(X, \bar{x}) \rightarrow \text{GL}(\mathbb{T}_{\ell, \bar{x}} \otimes \mathbb{Q}) \times \prod_m \text{GL}(H^1(\Gamma, V_m))$$

given by combining the monodromy representation on  $\mathbb{T}_{\ell, \bar{x}} \otimes \mathbb{Q}$  with the pullbacks of the  $G_{F, \Sigma}$ -representations  $H^1(\Gamma, V_m)$ . Then the Zariski closure  $R$  of the image of  $\pi_1^{\acute{e}t}(\bar{X}, \bar{x})$  is just  $\text{SL}_2 \times \{1\}$ , and the quotient  $T := S/R$  is the Zariski closure of the representation  $G_{F, \Sigma} \rightarrow \mathbb{G}_m(\mathbb{Q}_\ell) \times \prod_m \text{GL}(H^1(\Gamma, V_m))$ . The conditions of [Pri5, Theorem 3.32] are then satisfied by construction.

### 3. NON-ABELIAN RECIPROCITY LAWS AS OBSTRUCTION MAPS

#### 3.1. Adélic mapping spaces and compact supports.

**Definition 3.1.** In the category of pro-simplicial sets, we set

$$BG_{\mathbb{A}_F^{\infty \Sigma}} := \varprojlim_{\substack{T \subset \Sigma \\ \text{finite}}} \left( \prod_{v \in T} BG_v \sqcup \prod_{v \in \Sigma - T} B(G_v/I_v) \right),$$

where  $G_v = G_{F_v} \subset G_F$ , and  $I_v < G_v$  is the inertia subgroup; beware that both the coproduct and the limit are taken in the category of pro-simplicial sets.

Note that there is a natural map  $BG_{\mathbb{A}_F^{\infty\Sigma}} \rightarrow BG_{F,\Sigma}$ .

**Definition 3.2.** Given a finite abelian group  $U$  equipped with a continuous  $G_{F,\Sigma}$ -action, define

$$\begin{aligned} \mathbf{R}\Gamma(G_{\mathbb{A}_F^{\infty\Sigma}}, U) &:= \prod_v \mathbf{R}\Gamma(G_v, U) \\ &= \varinjlim_T \left( \prod_{v \in T} \mathbf{R}\Gamma(G_v, U) \times \prod_{v \in \Sigma - T} \mathbf{R}\Gamma(G_v/I_v, U) \right), \end{aligned}$$

where  $\mathbf{R}\Gamma(G, -)$  denotes the continuous cohomology complex,  $T$  ranges over all finite subsets of  $\Sigma$  containing the places at which the action on  $U$  is ramified, and  $I_v \subset G_v$  is the inertia subgroup.

**Definition 3.3.** Given a continuous profinite  $G_{F,\Sigma}$ -representation  $U$ , define

$$\mathbf{R}\Gamma(G_{\mathbb{A}_F^{\infty\Sigma}}, U) := \mathbf{R}\varprojlim_i \mathbf{R}\Gamma(G_{\mathbb{A}_F^{\infty\Sigma}}, U_i),$$

where the  $U_i$  range over the finite Galois equivariant quotients of  $U$ .

Similarly, given a continuous discrete torsion  $G_{F,\Sigma}$ -representation  $U$ , define

$$\mathbf{R}\Gamma(G_{\mathbb{A}_F^{\infty\Sigma}}, U) := \varinjlim_i \mathbf{R}\Gamma(G_{\mathbb{A}_F^{\infty\Sigma}}, U_i),$$

where the  $U_i$  range over the finite Galois equivariant subgroups of  $U$ .

**Definition 3.4.** Given a continuous  $G_{F,\Sigma}$ -representation  $V$  in finite-dimensional vector spaces over  $\mathbb{Q}_\ell$ , define

$$\mathbf{R}\Gamma(G_{\mathbb{A}_F^{\infty\Sigma}}, V) := \varinjlim_j \mathbf{R}\Gamma(G_{\mathbb{A}_F^{\infty\Sigma}}, V_j),$$

where the  $V_j$  range over the filtered direct system of all profinite subrepresentations of  $V$ .

Given a continuous  $G_{F,\Sigma}$ -representation  $V = \varprojlim_\alpha V_\alpha$  in profinite-dimensional vector spaces over  $\mathbb{Q}_\ell$ , define

$$\mathbf{R}\Gamma(G_{\mathbb{A}_F^{\infty\Sigma}}, V) := \mathbf{R}\varprojlim_\alpha \mathbf{R}\Gamma(G_{\mathbb{A}_F^{\infty\Sigma}}, V_\alpha).$$

Note that for any  $G_{F,\Sigma}$ -equivariant lattice  $\Lambda$  in a finite-dimensional  $G_{F,\Sigma}$ -representation  $V$  over  $\mathbb{Q}_\ell$ , the system  $\{\ell^{-n}\Lambda\}_n$  of profinite subrepresentations is cofinal, so

$$\mathbf{R}\Gamma(G_{\mathbb{A}_F^{\infty\Sigma}}, V) \simeq \mathbf{R}\Gamma(G_{\mathbb{A}_F^{\infty\Sigma}}, \Lambda) \otimes_{\mathbb{Z}_\ell} \mathbb{Q}_\ell.$$

*Remark 3.5.* Given a finite abelian group  $U$  equipped with a continuous  $G_{F,\Sigma}$ -action, observe that for all  $r$ ,

$$\begin{aligned} \text{map}_{BG_{F,\Sigma}}(BG_{\mathbb{A}_F^{\infty\Sigma}}, B(G_{F,\Sigma} \times B^r U)) &\simeq \\ \varinjlim_{\substack{T \subset \Sigma \\ \text{finite}}} \left( \prod_{v \in T} \text{map}_{BG_{F,\Sigma}}(BG_v, B(G_{F,\Sigma} \times B^r U)) \times \prod_{v \in \Sigma - T} \text{map}_{BG_{F,\Sigma}}(B(G_v/I_v), B(G_{F,\Sigma} \times B^r U)) \right), \end{aligned}$$

so  $\pi_i \text{map}_{BG_{F,\Sigma}}(BG_{\mathbb{A}_F^{\infty\Sigma}}, B(G_{F,\Sigma} \times B^r U)) \cong H^{r+1-i}(G_{\mathbb{A}_F^{\infty\Sigma}}, U)$ .

The convention of Definition 3.4 ensures that this equivalence extends to profinite groups or (pro-)finite-dimensional  $\mathbb{Q}_\ell$ -vector spaces  $U$  (regarding  $BU$  as a pro-simplicial set or a (pro-)ind-pro-simplicial set).

Beware that  $BG_{\mathbb{A}_F^{\infty\Sigma}}$  is not necessarily the same as the étale homotopy type  $(\text{Spec } \mathbb{A}_F^{\infty\Sigma})_{\text{ét}}$ . However, there is a map from the former to the profinite completion of the latter (see Corollary A.5); on the level of fundamental groups this is just the observation that a finite lisse étale sheaf on  $\mathbb{A}_F^{\infty\Sigma}$  is only ramified at  $F_v$  for finitely many places in  $v \in \Sigma$ .

We may now adapt all the examples from §2 to consider adélic points instead of rational points. In particular:

*Example 3.6* (Nilpotent completion of  $\pi_1^{\text{ét}}(\bar{X})$ ). Using the pro-simplicial set  $BG_{\mathbb{A}_F^{\infty\Sigma}}$ , we may adapt Example 2.5. If  $X$  is a Deligne–Mumford stack over  $\mathcal{O}_{F,\Sigma}$ , and  $\bar{X} := X \otimes_{\mathcal{O}_{F,\Sigma}} \mathcal{O}_{\bar{F},\Sigma}$ , with some geometric point  $\bar{x}$ , again consider the lower central series

$$\Pi_n := \pi_1^{\text{ét}}(X, \bar{x}) / [\pi_1^{\text{ét}}(\bar{X}, \bar{x})]_{n+1},$$

where we write  $[\pi]_1 := \pi$ ,  $[\pi]_{k+1} := [\pi, [\pi]_k]$ . Thus  $\Pi_0 = G_F$ , and taking  $Y = BG_{\mathbb{A}_F^{\infty\Sigma}}$  in the tower of §2.2, we get the non-abelian spectral sequence

$$E_1^{s,t} = H^{1+s-t}(\mathbb{A}_F^{\infty\Sigma}, [\bar{\pi}]_s / [\bar{\pi}]_{s+1}) \implies \pi_{t-s} \text{map}_{BG_{F,\Sigma}}(BG_{\mathbb{A}_F^{\infty\Sigma}}, B\Pi_{\infty})$$

of groups and sets, where we write  $\bar{\pi} := \pi_1^{\text{ét}}(\bar{X}, \bar{x})$ .

The reasoning above (without recourse to Corollary A.5) gives a morphism of groupoids from  $X(\mathbb{A}_F^{\infty\Sigma})$  to the fundamental groupoid  $\pi_f \text{map}_{BG_{F,\Sigma}}(BG_{\mathbb{A}_F^{\infty\Sigma}}, B\Pi_{\infty})$ , so the spectral sequence gives obstructions to the existence of such adélic points.

*Example 3.7* (Unipotent completion of  $\pi_1^{\text{ét}}(\bar{X})$ ). For unipotent adélic obstructions, we can adapt Example 2.12. In the setting of Example 3.6, assume that we have a point  $x \in X(\mathcal{O}_{F,\Sigma})$  under  $\bar{x}$  (if not, take a set of  $G_{F,\Sigma}$ -equivariant set  $\mathcal{B}$  of basepoints instead), and consider the lower central series

$$\Pi_n := G_{F,\Sigma} \times (\pi_1^{\text{ét}}(\bar{X}, \bar{x}) \otimes \mathbb{Q}_{\ell} / [\pi_1^{\text{ét}}(\bar{X}, \bar{x}) \otimes \mathbb{Q}_{\ell}]_n),$$

of the pro-unipotent Malcev completion  $\pi_1^{\text{ét}}(\bar{X}, \bar{x}) \otimes \mathbb{Q}_{\ell}$ .

Thus  $\Pi_0 = G_{F,\Sigma}$ , and taking  $Y = BG_{\mathbb{A}_F^{\infty\Sigma}}$ , we get a non-abelian spectral sequence

$$E_1^{s,t} = H^{1+s-t}(G_{\mathbb{A}_F^{\infty\Sigma}}, [\bar{\pi} \otimes \mathbb{Q}_{\ell}]_s / [\bar{\pi} \otimes \mathbb{Q}_{\ell}]_{s+1}) \implies \pi_{t-s} \text{map}_{BG_{F,\Sigma}}(BG_{\mathbb{A}_F^{\infty\Sigma}}, B\Pi_{\infty})$$

of groups and sets, where we write  $\bar{\pi} := \pi_1^{\text{ét}}(\bar{X}, \bar{x})$ . As in Example 3.6, there is a natural morphism  $X(\mathbb{A}_F^{\infty\Sigma}) \rightarrow \pi_f \text{map}_{BG_{F,\Sigma}}(BG_{F,\Sigma}, B\Pi_{\infty})$  of groupoids, but the obstruction spaces are easier to calculate in this setting.

*Example 3.8* (Modular forms of level 1). As in Example 2.16, let  $X = \mathcal{M}_{1,1}$  be the stacky modular curve, take  $x \in X(\mathcal{O}_{F,\Sigma})$ , and consider the resulting pro-unipotent extension

$$G_{F,\Sigma} \times (\widehat{\text{SL}}_2(\mathbb{Z})^{\text{SL}_2, \text{Mal}} \times_{\text{SL}_2(\mathbb{Q}_{\ell})} \text{SL}_2(\mathbb{Z}_{\ell})) \rightarrow G_{F,\Sigma} \times \text{SL}_2(\mathbb{Z}_{\ell}),$$

then set

$$\Pi_n := G_{F,\Sigma} \times ((\widehat{\text{SL}}_2(\mathbb{Z})^{\text{SL}_2, \text{Mal}} / [\text{Ru}]_{n+1}) \times_{\text{SL}_2(\mathbb{Q}_{\ell})} \text{SL}_2(\mathbb{Z}_{\ell})).$$

Using Example 2.7, a lift  $BG_{\mathbb{A}_F^{\infty\Sigma}} \rightarrow G_{F,\Sigma} \times \text{SL}_2(\mathbb{Z}_{\ell})$  of the homomorphism  $BG_{\mathbb{A}_F^{\infty\Sigma}} \rightarrow G_{F,\Sigma}$  is equivalent to giving  $G_v$ -representations  $\Lambda_v$  of rank 2 over  $\mathbb{Z}_{\ell}$  for  $v \in \Sigma$ , with determinant  $\mathbb{Z}_{\ell}(1)$ , such that for each  $n$ , there are only finitely many  $v \in \Sigma$  with  $\Lambda_v / \ell^n$  ramified. Write  $\Lambda$  for the system  $\{\Lambda_v\}_v$ .

As in Example 2.7, write  $L_s := \text{CoLie}_s(\bigoplus_m \mathbb{H}^1(\text{SL}_2(\mathbb{Z}), V_m) \otimes S^m(\Lambda)(-m))$ . The pro-unipotent generalisation of Proposition 2.11 then combines with Examples 2.15 to give a non-abelian spectral sequence

$$E_1^{s,t} = \mathbb{H}^{1+s-t}(G_{\mathbb{A}_F^{\infty\Sigma}}, L_s^*) \implies \pi_{t-s} \text{map}_{B(G_{F,\Sigma} \times_{G_m(\mathbb{Z}_\ell)} \text{GL}_2(\mathbb{Z}_\ell))} (BG_{\mathbb{A}_F^{\infty\Sigma}}, B\Pi_\infty),$$

where the map  $BG_{\mathbb{A}_F^{\infty\Sigma}} \rightarrow \text{GL}_2(\mathbb{Z}_\ell)$  is given by  $\Lambda$ . Note that  $E_{s,s+1}^1 = 0$  as  $L_s$  is of non-zero weights.

Now set  $X_{(n)} := \text{map}_{BG_{F,\Sigma}}(BG_{\mathbb{A}_F^{\infty\Sigma}}, B\Pi_n)$ ; thus  $X_{(0)}$  consists of sets  $\{\Lambda_v\}_v$  as above, conjugation by  $\text{SL}_2(\mathbb{Z}_\ell)$  giving equivalences, so  $\pi_1(X_{(0)}, [\Lambda])$  consists of elements of  $\text{SL}_2(\mathbb{Z}_\ell)$  commuting with the actions of the  $G_v$  on  $\Lambda$ . Since  $\pi_i X_{(n)} = 0$  for  $i > 1$ , we then have exact sequences

$$0 \rightarrow \pi_1 X_{(n)} \rightarrow \pi_1 X_{(n-1)} \rightarrow \mathbb{H}^1(G_{\mathbb{A}_F^{\infty\Sigma}}, L_n^*) \rightarrow \pi_0 X_{(n)} \rightarrow \pi_0 X_{(n-1)} \rightarrow \mathbb{H}^2(G_{\mathbb{A}_F^{\infty\Sigma}}, L_n^*),$$

with a map  $X(\mathbb{A}_F^{\infty\Sigma}) \rightarrow X_{(\infty)}$ . Here,  $\pi_0 X(\mathbb{A}_F^{\infty\Sigma})$  is the set of isomorphism classes of elliptic curves over  $\mathbb{A}_F^{\infty\Sigma}$ , and  $\pi_1(X(\mathbb{A}_F^{\infty\Sigma}), x)$  the group of automorphisms of the elliptic curve  $E_x$  over  $\mathbb{A}_F^{\infty\Sigma}$ .

In other words, given a system  $\Lambda = \{\Lambda_v\}_{v \in \Sigma}$  of rank 2 local Galois representations over  $\mathbb{Z}_\ell$  as above, these sequences give a tower of obstructions to lifting  $\Lambda$  to an elliptic curve over  $\mathbb{A}_F^{\infty\Sigma}$  with Tate module  $\Lambda$ , and characterise the ambiguity of the lift at each stage. As in Examples 2.15, there is an entirely similar treatment for profinite completions of congruence subgroups  $\Gamma \leq \text{SL}_2(\mathbb{Z})$ , replacing  $\mathcal{M}_{1,1}$  with the modular curve  $Y_\Gamma$ .

*Example 3.9* (Étale homotopy types). We now consider étale homotopy types in place of fundamental groups, as in Example 2.20. Take a locally Noetherian Deligne–Mumford stack  $X$  over  $F$ , a geometric point  $\bar{x}$  and a Zariski-dense representation  $\rho: \pi_1^{\text{ét}}(X, \bar{x}) \rightarrow S(\mathbb{Q}_\ell)$  to a pro-reductive pro-algebraic group  $S$ , let  $R$  be the Zariski closure of  $\rho(\pi_1^{\text{ét}}(\bar{X}, \bar{x}))$ , and set  $T := S/R$ .

We then look at the pro-simplicial group  $G(X_{\text{ét}}, \bar{x})$  associated to the étale topological type  $X_{\text{ét}} \in \text{pro}(\mathbb{S})$ . If the  $G_{F,\Sigma}$ -representation  $\mathbb{H}^*(\bar{X}, V)$  is an extension of  $T$ -representations for all  $R$ -representations  $V$ , then we may again set  $\Pi_n$  to be the simplicial topological group given by the homotopy fibre product

$$\Pi_n := (G(X_{\text{ét}}, \bar{x})^{S, \text{Mal}} / [U]_{n+1}) \times_{G_{(F_{\text{ét}})}^{T, \text{Mal}}}^h G(F_{\text{ét}}),$$

where  $U = R_{\text{u}}G(\bar{X}_{\text{ét}}, \bar{x})^{R, \text{Mal}}$ . Note that since  $B\Pi_\infty$  is equipped with a map from  $\bar{W}G(\bar{X}_{\text{ét}}, \bar{x})$ , Corollary A.5 gives a canonical morphism

$$X(\mathbb{A}_F^{\infty\Sigma}) \rightarrow \text{map}_{B(G_{F,\Sigma})} (BG_{\mathbb{A}_F^{\infty\Sigma}}, B\Pi_\infty).$$

in the homotopy category of pro-ind-pro-simplicial sets.

We then have a non-abelian spectral sequence

$$E_1^{s,t} \implies \pi_{t-s} \text{map}_{B(G_{F,\Sigma})} (BG_{\mathbb{A}_F^{\infty\Sigma}}, B\Pi_\infty),$$

with

$$E_1^{s,t} = \begin{cases} \mathbb{H}^{1+s-t}(\mathbb{A}_F^{\infty\Sigma}, [U]_s/[U]_{s+1}) & s \geq 1 \\ \pi_t \text{map}_{BT} (BG_{\mathbb{A}_F^{\infty\Sigma}}, BS) & s = 0, \end{cases}$$

where  $[U]_s/[U]_{s+1}$  is dual to  $\text{CoLie}_n((\mathbf{R}\Gamma(\bar{X}, \mathcal{O}(R)))/\mathbb{Q}_\ell)[1]$ .



**3.2. Reciprocity laws.** The idea behind non-abelian reciprocity laws is to compare the towers of obstructions for rational and adélic points, giving a relative obstruction tower for rational points over adélic points.

**Definition 3.10.** Given a continuous  $G_{F,\Sigma}$ -representation  $U$ , we set

$$\mathbf{R}\Gamma_c(G_{F,\Sigma}, U) := \text{cocone}(\mathbf{R}\Gamma(G_{F,\Sigma}, U) \rightarrow \mathbf{R}\Gamma(G_{\mathbb{A}_F^\Sigma}, U)),$$

where  $U$  can be any of the types of representation considered in Definitions 3.2–3.4.

3.2.1. *Abelian Poitou–Tate duality.*

**Definition 3.11.** Define a contravariant functor  $(-)^{\vee}$  on the category of abelian groups by

$$A^{\vee} := \text{Hom}_{\mathbb{Z}}(A, \mathbb{Q}/\mathbb{Z}).$$

**Definition 3.12.** Define a contravariant functor  $(-)^{\vee}(1)$  on the category of continuous  $G_{F,\Sigma}$ -representations in locally compact topological torsion abelian groups (in the sense of [HS]) by

$$A^{\vee}(1) := \text{Hom}_{\mathbb{Z}, \text{cts}}(A, \mu_{\infty}).$$

Note that  $(-)^{\vee}$  preserves the subcategory of finite representations, and interchanges profinite and discrete representations.

**Lemma 3.13.** *If  $\Sigma$  is a finite set of finite places containing all primes dividing  $\ell$ , and  $U$  a continuous pro- $\ell$   $G_{F,\Sigma}$ -representation, then there is a canonical equivalence*

$$\mathbf{R}\Gamma_c(G_{F,\Sigma}, U) \simeq \mathbf{R}\Gamma(G_{F,\Sigma}, U^{\vee}(1))^{\vee}[-3].$$

*If  $V$  is a continuous  $G_{F,\Sigma}$ -representation in finite-dimensional vector spaces over  $\mathbb{Q}_{\ell}$ , then we also have*

$$\mathbf{R}\Gamma_c(G_{F,\Sigma}, V) \simeq \mathbf{R}\Gamma(G_{F,\Sigma}, V^*(1))^*[-3].$$

*Proof.* The first statement is the formulation of Poitou–Tate duality given in [Lim], refining a homological isomorphism from [Nek]. For the second statement, take a  $G_{F,\Sigma}$ -equivariant lattice  $\Lambda \subset V$ , and then (writing  $\Lambda^* := \text{Hom}_{\mathbb{Z}_{\ell}}(\Lambda, \mathbb{Z}_{\ell})$ ),

$$\begin{aligned} \mathbf{R}\Gamma_c(G_{F,\Sigma}, V) &\simeq \mathbf{R}\Gamma_c(G_{F,\Sigma}, \Lambda) \otimes \mathbb{Q} \\ &\simeq \mathbf{R}\Gamma(G_{F,\Sigma}, \Lambda^{\vee}(1))^{\vee}[-3] \otimes \mathbb{Q} \\ &\simeq \mathbf{R}\underline{\text{Hom}}_{\mathbb{Z}_{\ell}}(\mathbf{R}\Gamma(G_{F,\Sigma}, \Lambda^*(1)) \otimes \mathbb{Q}_{\ell}/\mathbb{Z}_{\ell}, \mathbb{Q}_{\ell}/\mathbb{Z}_{\ell})[-3] \otimes \mathbb{Q} \\ &\simeq \mathbf{R}\underline{\text{Hom}}_{\mathbb{Z}_{\ell}}(\mathbf{R}\Gamma(G_{F,\Sigma}, \Lambda^*(1)), \mathbb{Z}_{\ell})[-3] \otimes \mathbb{Q} \\ &\simeq \mathbf{R}\underline{\text{Hom}}_{\mathbb{Z}_{\ell}}(\mathbf{R}\Gamma(G_{F,\Sigma}, \Lambda^*(1)), \mathbb{Q}_{\ell})[-3], \end{aligned}$$

the last isomorphism following because  $H^*(G_{F,\Sigma}, \Lambda^*(1))$  has finite rank,  $\Sigma$  being finite. The result now follows because  $V^* \cong \Lambda^* \otimes \mathbb{Q}_{\ell}$ .  $\square$

**Lemma 3.14.** *If  $\Sigma$  is a possibly infinite set of finite places, and  $U$  a continuous  $G_{F,\Sigma}$ -representation in profinite abelian groups whose order is a unit outside  $\Sigma$ , then there is a canonical equivalence*

$$\mathbf{R}\Gamma_c(G_{F,\Sigma}, U) \simeq \mathbf{R}\Gamma(G_{F,\Sigma}, U^{\vee}(1))^{\vee}[-3],$$

*following the continuous cohomology conventions of Definition 3.3.*

*Proof.* When  $U$  is finite, this is essentially the Poitou–Tate duality of [Mil, 1.4.10]. In general, writing  $U = \varprojlim_{\alpha} U_{\alpha}$  for  $U_{\alpha}$  finite, we have

$$\begin{aligned} \mathbf{R}\Gamma_c(G_{F,\Sigma}, U) &\simeq \mathbf{R}\varprojlim_{\alpha} \mathbf{R}\Gamma_c(G_{F,\Sigma}, U_{\alpha}) \\ &\simeq \mathbf{R}\varprojlim_{\alpha} \mathbf{R}\Gamma(G_{F,\Sigma}, U_{\alpha}^{\vee}(1))^{\vee}[-3] \\ &\simeq (\varinjlim_{\alpha} \mathbf{R}\Gamma(G_{F,\Sigma}, U_{\alpha}^{\vee}(1)))^{\vee}[-3] \\ &= \mathbf{R}\Gamma(G_{F,\Sigma}, U^{\vee}(1))^{\vee}[-3]. \end{aligned}$$

□

*Remark 3.15.* If we wanted to extend Lemma 3.14 to more general coefficients, we would have to pass to a larger category than the category  $\mathcal{TT}$  of locally compact topological torsion groups. The category  $\mathcal{TT}$  precisely consists of the Tate objects over the category of finite abelian groups in the sense of [BGW]. Since  $\mathbf{R}\Gamma(G_{F,\Sigma}, -)$  and  $\mathbf{R}\Gamma_c(G_{F,\Sigma}, -)$  are functors from finite groups to complexes of Tate objects, their natural extension to coefficients in  $\mathcal{TT}$  will take values in complexes of 2-Tate objects over finite abelian groups (or equivalently Tate objects over  $\mathcal{TT}$ ), and Poitou–Tate duality will extend formally to that category.

**3.2.2. Non-abelian reciprocity laws.** We may now adapt all the examples from §2 to obtain obstructions to adélic points being rational points, with terms in the spectral sequence given by Galois cohomology  $\mathbf{H}_c^*(G_{F,\Sigma}, -)$  with compact supports. Since the coefficients we consider have negative weights, the lower cohomology groups with compact supports tend to be small; when they vanish, the obstruction towers have no ambiguity in the lift at each stage.

*Example 3.16* (Nilpotent completion of  $\pi_1^{\text{ét}}(\bar{X})$ ). If  $X$  is a Deligne–Mumford stack over  $\mathcal{O}_{F,\Sigma}$ , and  $\bar{X} = X \otimes_{\mathcal{O}_{F,\Sigma}} \mathcal{O}_{\bar{F},\Sigma}$ , with some geometric point  $\bar{x}$ , as in Examples 2.5 and 3.6 we may consider the lower central series

$$\Pi_n := \pi_1^{\text{ét}}(X, \bar{x}) / [\pi_1^{\text{ét}}(\bar{X}, \bar{x})]_{n+1},$$

where we write  $[\pi]_1 := \pi$ ,  $[\pi]_{k+1} := [\pi, [\pi]_k]$ . Write  $\Pi_{\infty} = \varprojlim_n \Pi_n$ .

We then define the tower  $\dots X(\mathbb{A}_F^{\infty\Sigma})_n \rightarrow X(\mathbb{A}_F^{\infty\Sigma})_0 = X(\mathbb{A}_F^{\infty\Sigma})$  by the homotopy fibre products

$$X(\mathbb{A}_F^{\infty\Sigma})_n := X(\mathbb{A}_F^{\infty\Sigma}) \times_{\text{map}_{BG_{F,\Sigma}}(BG_{\mathbb{A}_F^{\infty\Sigma}}, B\Pi_n)}^h \text{map}_{BG_{F,\Sigma}}(BG_{F,\Sigma}, B\Pi_n),$$

defined using the morphism  $X(\mathbb{A}_F^{\infty\Sigma}) \rightarrow \text{map}_{BG_{F,\Sigma}}(BG_{\mathbb{A}_F^{\infty\Sigma}}, B\Pi_{\infty})$  from §3.1.

Taking homotopy fibres of the fibration sequences in §2.2, we then get a non-abelian spectral sequence

$$E_1^{s,t} = \begin{cases} \mathbf{H}_c^{1+s-t}(G_{F,\Sigma}, [\bar{\pi}]_s / [\bar{\pi}]_{s+1}) & s \geq 1 \\ \pi_t X(\mathbb{A}_F^{\infty\Sigma}) & s = 0 \end{cases} \implies \pi_{t-s} X(\mathbb{A}_F^{\infty\Sigma})_{\infty}$$

of groups and sets, where we write  $\bar{\pi} := \pi_1^{\text{ét}}(\bar{X}, \bar{x})$ . This comes from the exact couple

$$\begin{array}{ccccccc} \cdots & \longrightarrow & \pi_* X(\mathbb{A}_F^{\infty\Sigma})_s & \longrightarrow & \cdots & \longrightarrow & \pi_* X(\mathbb{A}_F^{\infty\Sigma})_1 & \longrightarrow & \pi_* X(\mathbb{A}_F^{\infty\Sigma})_0 \\ & & \uparrow & \swarrow \delta & & & \uparrow & \swarrow \delta & \parallel \\ & & \mathrm{H}_c^{1-*}(G_{F,\Sigma}, [\bar{\pi}]_s/[\bar{\pi}]_{s+1}) & & \cdots & & \mathrm{H}_c^{1-*}(G_{F,\Sigma}, \bar{\pi}/[\bar{\pi}]_2) & & \pi_* X(\mathbb{A}_F^{\infty\Sigma}) \end{array}$$

with  $\delta$  of cohomological degree  $+1$ .

As in §2, we have a map  $X(\mathcal{O}_{F,\Sigma}) \rightarrow X(\mathbb{A}_F^{\infty\Sigma})_\infty$ , so the spectral sequence gives obstructions to an adelic point being rational. When  $X$  is a scheme (or algebraic space),  $\pi_0 X(\mathbb{A}_F^{\infty\Sigma}) = \pi_* X(\mathbb{A}_F^{\infty\Sigma})$  and  $\pi_i(\mathbb{A}_F^{\infty\Sigma}) = 0$  for  $i > 0$ .

By Lemma 3.14,  $\mathrm{H}_c^{1+s-t}(G_{F,\Sigma}, [\bar{\pi}]_s/[\bar{\pi}]_{s+1})$  is isomorphic to  $\mathrm{H}^{2+t-s}(G_{F,\Sigma}, ([\bar{\pi}]_s/[\bar{\pi}]_{s+1})^\vee(1))^\vee$ . Thus elements of  $\mathrm{H}^1(G_{F,\Sigma}, ([\bar{\pi}]_s/[\bar{\pi}]_{s+1})^\vee(1))$  give obstructions to lifting points in  $\pi_0 X(\mathbb{A}_F^{\infty\Sigma})$  to  $X(\mathcal{O}_{F,\Sigma})$ , and the ambiguity of the lifts at each stage are dual to the groups  $\mathrm{H}^2(G_{F,\Sigma}, ([\bar{\pi}]_s/[\bar{\pi}]_{s+1})^\vee(1))$ , which are often finite for weight reasons as in [Jan]. The higher homotopy groups  $\pi_{\geq 2} X(\mathbb{A}_F^{\infty\Sigma})_n$  are necessarily 0, by vanishing of  $\mathrm{H}_c^{\leq 0}$ .

*Remark 3.17.* Since  $[\bar{\pi}]_n/[\bar{\pi}]_{n+1}$  is contained in the centre of  $\bar{\pi}/[\bar{\pi}]_{n+1}$ , it seems that the spectral sequence in Example 3.16 can alternatively be obtained as an inverse limit of the non-abelian Poitou–Tate exact sequence of [Sti, Theorem 168].

*Example 3.18* (Unipotent completion of  $\pi_1^{\text{ét}}(\bar{X})$ ). Examples 2.12 and 3.7 adapt along the lines of Example 3.16. Assuming we have a point  $x \in X(\mathcal{O}_{F,\Sigma})$  under  $\bar{x}$  (or replacing  $\bar{x}$  with a  $G_{F,\Sigma}$ -equivariant set of basepoints if not), set

$$\Pi_n := G_{F,\Sigma} \times (\pi_1^{\text{ét}}(\bar{X}, \bar{x}) \otimes \mathbb{Q}_\ell) / [\pi_1^{\text{ét}}(\bar{X}, \bar{x}) \otimes \mathbb{Q}_\ell]_n,$$

and

$$X(\mathbb{A}_F^{\infty\Sigma})_n := X(\mathbb{A}_F^{\infty\Sigma}) \times_{\mathrm{map}_{BG_{F,\Sigma}}(BG_{\mathbb{A}_F^{\infty\Sigma}}, B\Pi_n)}^h \mathrm{map}_{BG_{F,\Sigma}}(BG_{F,\Sigma}, B\Pi_n),$$

to give a non-abelian spectral sequence

$$E_1^{s,t} = \begin{cases} \mathrm{H}_c^{1+s-t}(G_{F,\Sigma}, [\bar{\pi} \otimes \mathbb{Q}_\ell]_s/[\bar{\pi} \otimes \mathbb{Q}_\ell]_{s+1}) & s \geq 1 \\ \pi_t X(\mathbb{A}_F^{\infty\Sigma}) & s = 0 \end{cases} \implies \pi_{t-s} X(\mathbb{A}_F^{\infty\Sigma})_\infty$$

of groups and sets, where we write  $\bar{\pi} := \pi_1^{\text{ét}}(\bar{X}, \bar{x})$ .

Lemma 3.14 shows that  $\mathrm{H}_c^{1+s-t}(G_{F,\Sigma}, [\bar{\pi} \otimes \mathbb{Q}_\ell]_s/[\bar{\pi} \otimes \mathbb{Q}_\ell]_{s+1})$  is isomorphic to  $\mathrm{H}^{2+t-s}(G_{F,\Sigma}, ([\bar{\pi}]_s/[\bar{\pi}]_{s+1})^\vee(1))^\vee \otimes \mathbb{Q}_\ell$ . If  $X$  is smooth, then  $[\bar{\pi} \otimes \mathbb{Q}_\ell]_s/[\bar{\pi} \otimes \mathbb{Q}_\ell]$  is a pro-finite-dimensional Galois  $\mathbb{Q}_\ell$ -representation of negative weights, so the local monodromy weight conjectures (as in the Poitou–Tate dual form of [Jan, Conjecture 6.3]) would imply  $E_{s,s}^1 = 0$  for  $s > 0$ , with the exact couple yielding the spectral sequence then degenerating to exact sequences

$$0 \rightarrow \pi_0 X(\mathbb{A}_F^{\infty\Sigma})_{(n)} \rightarrow \pi_0 X(\mathbb{A}_F^{\infty\Sigma})_{(n-1)} \rightarrow \mathrm{H}_c^2(G_{F,\Sigma}, [\bar{\pi} \otimes \mathbb{Q}_\ell]_s/[\bar{\pi} \otimes \mathbb{Q}_\ell]_{s+1}).$$

*Example 3.19* (Modular forms of level 1). As in Examples 2.16 and 3.8, let  $X = \mathcal{M}_{1,1}$  be the stacky modular curve, take  $x \in X(\mathcal{O}_{F,\Sigma})$ , and set

$$\Pi_n := G_{F,\Sigma} \times (\widehat{\mathrm{SL}_2(\mathbb{Z})}^{\mathrm{SL}_2, \mathrm{Mal}} / [\mathrm{R}_u]_{n+1}) \times_{\mathrm{SL}_2(\mathbb{Q}_\ell)} \mathrm{SL}_2(\mathbb{Z}_\ell).$$

We now write

$$X(\mathbb{A}_F^{\infty\Sigma})_n := X(\mathbb{A}_F^{\infty\Sigma}) \times_{\mathrm{map}_{BG_{F,\Sigma}}(BG_{\mathbb{A}_F^{\infty\Sigma}}, B\Pi_n)}^h \mathrm{map}_{BG_{F,\Sigma}}(BG_{F,\Sigma}, B\Pi_n).$$

Since  $\Pi_0 = G_{F,\Sigma} \times \mathrm{SL}_2(\mathbb{Z}_\ell)$ , the space  $X(\mathbb{A}_F^{\infty\Sigma})_0$  consists of pairs  $(x, \Lambda)$  with  $x$  an adélic point and  $\Lambda$  a  $G_{F,\Sigma}$ -representation of rank 2 over  $\mathbb{Z}_\ell$  with determinant  $\mathbb{Z}_\ell(1)$ , together with an isomorphism  $T_\ell E_{\bar{x}} \cong \Lambda$  of  $BG_{\mathbb{A}_F^{\infty\Sigma}}$ -representations.

Writing  $L_s := \mathrm{CoLie}_s(\bigoplus_m \mathrm{H}^1(\mathrm{SL}_2(\mathbb{Z}), V_m) \otimes S^m(\Lambda)(-m))$ , Proposition 2.11 and Examples 2.15 then give a non-abelian spectral sequence

$$E_1^{s,t} = \begin{cases} \mathrm{H}_c^{1+s-t}(G_{F,\Sigma}, L_s^*) & s \geq 1 \\ \pi_t X(\mathbb{A}_F^{\infty\Sigma})_0 & s = 0 \end{cases} \implies \pi_{t-s} X(\mathbb{A}_F^{\infty\Sigma})_\infty.$$

In other words, given a global Galois representation  $\Lambda$  and, for each  $v \in \Sigma$ , a local elliptic curve  $E_v$  lifting each underlying  $G_v$ -representation, with constraints on ramification, these sequences give a tower of obstructions to lifting  $(\Lambda, \{E_v\}_{v \in \Sigma})$  to an elliptic curve  $E$  over  $\mathcal{O}_{F,\Sigma}$  with Tate module  $T_\ell E(\bar{F}) \otimes \mathbb{Q} \cong \Lambda \otimes \mathbb{Q}$  and localisations  $E_v$ ; the sequences also characterise the ambiguity of the lift at each stage.

As in Example 2.15, the group  $\mathrm{H}^1(\Gamma, V_m)(-m)$  consists of modular forms and cusp forms of weight  $m+2$  and level 1. Thus  $L_s$  is a Galois  $\mathbb{Q}_\ell$ -representation of weights  $\geq s$ , so it follows that  $L_s^*$  is a pro-finite-dimensional Galois  $\mathbb{Q}_\ell$ -representation of weights  $\leq -s$ . As in Example 3.18, the local monodromy weight conjectures would cause the exact couple yielding the spectral sequence to degenerate to the exact sequences

$$0 \rightarrow \pi_0 X(\mathbb{A}_F^{\infty\Sigma})_{(n)} \rightarrow \pi_0 X(\mathbb{A}_F^{\infty\Sigma})_{(n-1)} \rightarrow \mathrm{H}_c^2(G_{F,\Sigma}, L_s^*)$$

equipped with a map  $X(\mathcal{O}_{F,\Sigma}) \rightarrow X(\mathbb{A}_F^{\infty\Sigma})_{(\infty)}$ .

As in Examples 2.15, there is an entirely similar treatment for congruence subgroups  $\Gamma \leq \mathrm{SL}_2(\mathbb{Z})$ , replacing  $\mathcal{M}_{1,1}$  with the modular curve  $Y_\Gamma$ . If we instead started from a representation over  $\hat{\mathbb{Z}}$ , relative Malcev completion of  $\mathrm{SL}_2(\mathbb{Z})$  over  $\mathrm{SL}_2 \times \mathrm{SL}_2(\hat{\mathbb{Z}})$  as in Example 2.17 would give rise to reciprocity laws associated to modular forms of all levels. Meanwhile, relative Malcev completion of  $\mathrm{SL}_2(\mathbb{Z})$  over  $\mathrm{SL}_2(\hat{\mathbb{Z}})$  as in Example 2.18 gives rise to reciprocity laws associated to weight 2 modular forms of all levels.

*Remark 3.20.* We may write

$$\mathrm{H}_c^i(G_{F,\Sigma}, L_s^*) \cong \mathrm{Lie}(n) \otimes^{S^n} \mathrm{H}_c^i(G_{F,\Sigma}, ((\bigoplus_m \mathrm{H}^1(\mathrm{SL}_2(\mathbb{Z}), V_m) \otimes S^m(\Lambda)(-m))^{\otimes n})^*)$$

As in Example 2.16, we may then consider the sheaf  $\mathbb{T}_\ell$  of relative Tate modules on  $Y_\Gamma$  as in Example 2.16, with  $\mathbf{R}q_* \mathbb{T}_\ell \otimes \mathbb{Q}[1] \simeq \mathbf{R}^1 q_* \mathbb{T}_\ell \otimes \mathbb{Q} \cong \mathrm{H}^1(\mathrm{SL}_2(\mathbb{Z}), V_m)$ , for the structure map  $q: Y_\Gamma \rightarrow \mathrm{Spec} \mathcal{O}_{F,\Sigma}$ . Applying Poitou–Tate duality in the form of Lemma 3.14 to this  $\mathbb{Z}_\ell$ -lattice then gives

$$\begin{aligned} & \mathbf{R}\Gamma_c(G_{F,\Sigma}, ((\bigoplus_m \mathrm{H}^1(\mathrm{SL}_2(\mathbb{Z}), V_m) \otimes S^m(\Lambda)(-m))^{\otimes s})^*) \\ & \simeq \mathbf{R}\Gamma(G_{F,\Sigma}, (\bigoplus_{m \geq 1} \mathbf{R}q_* S^m \mathbb{T}_\ell \otimes S^m(\Lambda)(-m))^{\otimes s} \otimes \mu_{\ell^\infty})^\vee \otimes \mathbb{Q}[3+s] \\ & \simeq \mathbf{R}\Gamma(X^s, \bigotimes_{i=1}^s (\bigoplus_{m \geq 1} \mathrm{pr}_i^* S^m \mathbb{T}_\ell \otimes q^* S^m(\Lambda)(-m)) \otimes \mu_{\ell^\infty})^\vee \otimes \mathbb{Q}[3+s], \end{aligned}$$

providing an expression for  $E_1^{s,t}$  as a summand of  $\mathrm{H}^{2+t}(X^s, \dots \otimes \mu_{\ell^\infty})^\vee \otimes \mathbb{Q}$ . As we will see in Example 3.24, the  $s=1$  case is a part of the Brauer–Manin obstruction, divisible elements in cohomology giving rise to obstructions.

By [HV], for  $\Sigma$  cofinite and  $\rho: G_{F,\Sigma} \rightarrow \mathrm{SL}_2(\hat{\mathbb{Z}})$ , non-emptiness of  $\mathcal{M}_{1,1}(\mathbb{A}_{\mathbb{Q}}^{\infty\Sigma})_{\rho}$  implies non-emptiness of  $X(\mathbb{Z}_{\Sigma})_{\rho}$ . The variants of example 3.19 for relative Malcev completions of  $\mathrm{SL}_2(\mathbb{Z})$  over  $\mathrm{SL}_2(\hat{\mathbb{Z}})$  or over  $\mathrm{SL}_2(\mathbb{Q}_{\ell}) \times \mathrm{SL}_2(\hat{\mathbb{Z}})$  will then help to identify  $X(\mathbb{Z}_{\Sigma})_{\rho} \subset \mathcal{M}_{1,1}(\mathbb{A}_{\mathbb{Q}}^{\infty\Sigma})_{\rho}$ . Following [Sto], we would expect the first map in the tower (a form of pro-étale Brauer–Manin obstruction) to be effective in cutting out the rational points.

*Example 3.21* (Relative Malcev étale homotopy types). As in Examples 2.20 and 3.9, we may consider étale homotopy types in place of fundamental groups. Take a locally Noetherian Deligne–Mumford stack  $X$  over  $\mathcal{O}_{F,\Sigma}$ , a geometric point  $\bar{x}$  and a Zariski-dense representation  $\rho: \pi_1^{\text{ét}}(X, \bar{x}) \rightarrow S(\mathbb{Q}_{\ell})$  to a pro-reductive pro-algebraic group  $S$ , let  $R$  be the Zariski closure of  $\rho(\pi_1^{\text{ét}}(\bar{X}, \bar{x}))$ , and set  $T := S/R$ .

Now set  $\Pi_n$  to be the simplicial topological group given by the homotopy fibre product

$$\Pi_n := (G(X_{\text{ét}}, \bar{x})^{S, \text{Mal}}/[U]_{n+1}) \times_{G(F_{\text{ét}})^{T, \text{Mal}}}^h G(F_{\text{ét}}),$$

where  $U = \mathrm{R}_{\mathrm{u}}G(\bar{X}_{\text{ét}}, \bar{x})^{R, \text{Mal}}$ .

The formula of Example 3.19 then gives a tower of spaces  $\{X(\mathbb{A}_F^{\infty\Sigma})_n\}_n$  and an associated non-abelian spectral sequence

$$E_1^{s,t} \implies \pi_{t-s}(X(\mathbb{A}_F^{\infty\Sigma}) \times_{\mathrm{map}_{B(G_{F,\Sigma})}(BG_{\mathbb{A}_F^{\infty\Sigma}, \bar{W}\Pi_{\infty})}^h \mathrm{map}_{B(G_{F,\Sigma})}(BG_{F,\Sigma}, \bar{W}\Pi_{\infty})$$

with

$$E_1^{s,t} = \begin{cases} \mathbb{H}_c^{1+s-t}(G_{F,\Sigma}, [U]_s/[U]_{s+1}) & s \geq 1 \\ \pi_t X(\mathbb{A}_F^{\infty\Sigma})_0 & s = 0, \end{cases}$$

where  $[U]_s/[U]_{s+1}$  is dual to  $\mathrm{CoLie}_s((\mathbf{R}\Gamma(\bar{X}, O(R)))/\mathbb{Q}_{\ell})[1]$  and

$$X(\mathbb{A}_F^{\infty\Sigma})_0 = (X(\mathbb{A}_F^{\infty\Sigma}) \times_{\mathrm{map}_{BT}(BG_{\mathbb{A}_F^{\infty\Sigma}, BS)}^h \mathrm{map}_{BT}(B(G_{F,\Sigma}), BS)).$$

*Remark 3.22.* As in [Pri5, Theorem 6.4], Lafforgue’s theorem and Esnault–Kerz ([Laf, Theorem VII.6 and Corollary VII.8] and [EK]) imply that the sheaf  $\rho^{-1}O(R)$  is pure of weight 0. If  $\bar{X}$  is smooth and proper, [Pri5, Corollary 6.7] then implies that the group  $\mathrm{H}^{-i}([U]_s/[U]_{s+1})$  in Example 3.21 is pure of weight  $-i - s$ .

The obstruction spaces for étale homotopy sections  $\pi_0 X(\mathbb{A}_F^{\infty\Sigma})_{(\infty)}$  are given in the spectral sequence by the terms  $E_1^{s,s-1}$ . Assuming that  $\rho$  is of geometric origin, the local monodromy weight conjectures (as in [Jan, Conjecture 6.3]) would imply that the groups  $\mathrm{H}_c^1$  vanish, so the only non-trivial contributions to  $E_1^{s,s-1}$  come from

$$\mathrm{H}_c^2(G_{F,\Sigma}, (\mathrm{CoLie}_s \mathrm{H}^1(\bar{X}, O(R)))^*)$$

as in Example 3.18, and from

$$\mathrm{H}_c^3(G_{F,\Sigma}, (\mathrm{H}^2(\bar{X}, O(R)) \otimes \mathrm{CoLie}_{s-1} \mathrm{H}^1(\bar{X}, O(R)))^*).$$

The latter group can only be non-zero for  $s = 1$ , when  $\mathrm{H}^2(\bar{X}, O(R))$  contains copies of the Tate motive, in which case the reciprocity map is detecting the Brauer–Manin obstruction of a pro-étale covering whose geometric fibres are  $\rho(\pi_1^{\text{ét}}(\bar{X}, \bar{x}))$ -torsors as in Example 3.27 below. These copies of the Tate motive then generate a large contribution  $\mathrm{H}_c^2(G_{F,\Sigma}, \mathrm{H}^2(\bar{X}, O(R)))^*$  to the  $E_1^{1,1}$  term, producing an ambiguity in the lift much larger than the new obstruction, meaning the map  $X(\mathbb{A}_F^{\infty\Sigma})_1 \rightarrow X(\mathbb{A}_F^{\infty\Sigma})$  would then be far from injective.

3.2.3. *Brauer–Manin obstructions.* We now look at Example 3.21 and analogous completions of étale homotopy types. A common feature is that the first obstruction map in the tower is just the Brauer–Manin obstruction, or related (pro-)étale refinements in the case of relative completion.

If  $O(R)_{\mathbb{Z}_\ell}$  is a  $\mathbb{Z}_\ell$ -form for the ring  $O(R)$  of functions on the reductive group featuring in Example 3.21, then we may use Poitou–Tate duality to rewrite the term  $E_1^{1,t}$  as

$$\begin{aligned} \mathbb{H}_c^{2-t}(G_{F,\Sigma}, [U]_1/[U]_2) &\cong \mathbb{H}^{2+t}(G_{F,\Sigma}, \mathbf{R}\Gamma(\bar{X}, O(R)_{\mathbb{Z}_\ell} \otimes \mu_{\ell^\infty})/\mu_{\ell^\infty})^\vee \otimes \mathbb{Q} \\ &\cong \begin{cases} \mathbb{H}_{\text{ét}}^2(X, O(R)_{\mathbb{Z}_\ell} \otimes \mu_{\ell^\infty})/\mathbb{H}^2(G_{F,\Sigma}, \mu_{\ell^\infty})^\vee & t = 0 \\ \mathbb{H}_{\text{ét}}^{2+t}(X, O(R)_{\mathbb{Z}_\ell} \otimes \mu_{\ell^\infty})^\vee & t > 0; \end{cases} \end{aligned}$$

when  $R = 1$  (unipotent completion of the geometric fibre), we have  $O(R)_{\mathbb{Z}_\ell} = \mathbb{Z}_\ell$ , and the first obstruction map  $d_1: E_1^{0,0} \rightarrow E_1^{1,0}$  is the rationalised Brauer–Manin obstruction

$$\pi_0 X(\mathbb{A}_F^{\infty\Sigma}) \rightarrow (\mathbb{H}_{\text{ét}}^2(X, \mu_{\ell^\infty})/\mathbb{H}^2(G_{F,\Sigma}, \mu_{\ell^\infty}))^\vee \otimes \mathbb{Q}.$$

*Remark 3.23.* We may write  $E_1^{s,t}$  as cohomology of a complex defined in terms of the Lie operad and the complexes  $\mathbf{R}\Gamma(X^n, \mu_{\ell^\infty})^\vee \otimes \mathbb{Q}$  for  $n \leq s$ . In particular,

$$E_1^{2,t} \cong \mathbb{H}^{2+t} \text{Tot}(\mathbf{R}\Gamma(X^2, \mu_{\ell^\infty})^\vee \otimes \mathbb{Q}/S_2 \xrightarrow{\text{pr}_{1*} - \text{pr}_{2*}} \mathbf{R}\Gamma(X, \mu_{\ell^\infty})^\vee \otimes \mathbb{Q}),$$

where  $S_2$  acts by switching the factors in  $X^2$ . For  $R \neq 1$ , the expression in Remark 3.20 for modular curves generalises whenever  $\mathbb{H}^{>0}(\bar{X}, \mathbb{Q}_\ell) = 0$ , but usually there are extra factors reflecting the difference between reduced and non-reduced cohomology.

Taking nilpotent completion instead of unipotent completion gives the following:

*Example 3.24* (Étale homotopy types and the Brauer–Manin obstruction). As in Examples 2.20, 3.9 and 3.21, we may consider étale homotopy types in place of fundamental groups. Take a locally Noetherian Deligne–Mumford stack  $X$  over  $\mathcal{O}_{F,\Sigma}$ , and a geometric point  $\bar{x}$ . Applying the profinite completion of [Pri5, §1] to the pro-simplicial group  $G(X_{\text{ét}}, \bar{x})$  of Example 2.20 gives a pro-(finite simplicial group)  $\hat{G}(X_{\text{ét}}, \bar{x})$ ; up to homotopy, this is independent of the choices made, by [Pri5, Proposition 1.32].

We now refine Example 3.16 by considering relative pro-nilpotent completions of the whole profinite homotopy type  $\hat{G}(X_{\text{ét}}, \bar{x})$  instead of the fundamental group. For completions relative to  $G_{F,\Sigma}$ , we set  $K := \ker(\hat{G}(X_{\text{ét}}, \bar{x}) \rightarrow G_{F,\Sigma})$  and

$$\Pi_n := \hat{G}(X_{\text{ét}}, \bar{x})/[K]_{n+1},$$

which is a pro-(finite simplicial group).

We then construct a tower  $\dots \rightarrow X(\mathbb{A}_F^{\infty\Sigma})_1 \rightarrow X(\mathbb{A}_F^{\infty\Sigma})_0 = X(\mathbb{A}_F^{\infty\Sigma})$  of homotopy fibre products

$$X(\mathbb{A}_F^{\infty\Sigma})_n := X(\mathbb{A}_F^{\infty\Sigma}) \times_{\text{map}_{BG_{F,\Sigma}}(BG_{\mathbb{A}_F^{\infty\Sigma}}, \bar{W}\Pi_n)}^h \text{map}_{BG_{F,\Sigma}}(BG_{F,\Sigma}, \bar{W}\Pi_n),$$

defined using the morphism  $X(\mathbb{A}_F^{\infty\Sigma}) \rightarrow \text{map}_{BG_{F,\Sigma}}(BG_{\mathbb{A}_F^{\infty\Sigma}}, B\Pi_\infty)$  from §3.1 and Corollary A.5.

This gives a non-abelian spectral sequence

$$E_1^{s,t} = \begin{cases} \mathbb{H}_c^{1+s-t}(G_{F,\Sigma}, [K]_s/[K]_{s+1}) & s \geq 1 \\ \pi_t X(\mathbb{A}_F^{\infty\Sigma}) & s = 0 \end{cases} \implies \pi_{t-s} X(\mathbb{A}_F^{\infty\Sigma})_\infty,$$

where we regard the simplicial abelian groups  $[K]_s/[K]_{s+1}$  as chain complexes.

Nielsen–Schreier implies that the simplicial group  $K$  is given levelwise by profinite completions of free groups, so the  $s = 1$  term is given by  $[K]_1/[K]_2 \simeq \hat{G}(\bar{X}_{\acute{e}t}, \bar{x})^{\text{ab}}$ , which is just the reduced homology complex of  $\bar{X}$  with  $\hat{\mathbb{Z}}$  coefficients. Poitou–Tate duality in the form of Lemma 3.14 applied to the complexes  $\hat{G}(\bar{X}_{\acute{e}t}, \bar{x})^{\text{ab}}$  thus gives

$$\mathbb{H}_c^{2-t}(G_{F,\Sigma}, [K]_1/[K]_2) \cong \begin{cases} \mathbb{H}_{\acute{e}t}^2(X, \mu_\infty)/\mathbb{H}^2(G_{F,\Sigma}, \mu_\infty)^\vee & t = 0 \\ \mathbb{H}_{\acute{e}t}^{2+t}(X, \mu_\infty)^\vee & t > 0, \end{cases}$$

where we follow the convention for continuous cohomology, regarding  $\mu_\infty$  as the ind-sheaf  $\varinjlim_n \mu_n$ .

Thus the first obstruction map  $d_1: E_1^{0,0} \rightarrow E_1^{1,0}$  is the map

$$\pi_0 X(\mathbb{A}_F^{\infty\Sigma}) \rightarrow (\mathbb{H}_{\acute{e}t}^2(X, \mu_\infty)/\mathbb{H}^2(G_{F,\Sigma}, \mu_\infty)^\vee),$$

induced by the Brauer–Manin obstruction  $\pi_0 X(\mathbb{A}_F^{\infty\Sigma}) \rightarrow \text{Br}(X)^\vee$  of [Man], for  $\text{Br}(X) := \text{Im}(\mathbb{H}_{\acute{e}t}^2(X, \mu_\infty) \rightarrow \mathbb{H}_{\acute{e}t}^2(X, \mathbb{G}_m))$  the cohomological Brauer group.

Writing  $\pi_0 X(\mathbb{A}_F^{\infty\Sigma})^{\text{Br}}$  for the kernel of the Brauer–Manin obstruction, we thus have

$$\pi_0 X(\mathbb{A}_F^{\infty\Sigma})^{\text{Br}} = \text{Im}(\pi_0 X(\mathbb{A}_F^{\infty\Sigma})_1 \rightarrow \pi_0 X(\mathbb{A}_F^{\infty\Sigma}))$$

for the tower above, and the later pages of the spectral sequence give obstructions to lifting further up the tower. Beware, however, that when  $E_1^{s,s} \neq 0$ , the lifts are not unique at each stage; in particular if a point lies in the kernel of the Brauer–Manin obstruction, we have an  $\mathbb{H}_{\acute{e}t}^3(X, \mu_\infty)^\vee$ -torsor of possible choices on which to apply the secondary obstruction.

When  $X$  is an algebraic space rather than a stack, we have  $\pi_0 X(\mathbb{A}_F^{\infty\Sigma}) = X(\mathbb{A}_F^{\infty\Sigma})$ , and may simply write  $X(\mathbb{A}_F^{\infty\Sigma})^{\text{Br}}$  for the image of  $\pi_0 X(\mathbb{A}_F^{\infty\Sigma})_1$ .

*Remark 3.25.* Because the simplicial pro-group  $K$  of Example 3.24 is given levelwise by profinite completions of free groups, the Magnus embedding (applied to profinite groups as in [Wic1]) gives an isomorphism  $[K]_s/[K]_{s+1} \cong \text{Lie}_s(\hat{K}^{\text{ab}})$ , where  $\bigoplus_{s \geq 1} \text{Lie}_s$  is the free Lie algebra functor, graded by bracket length, and  $\hat{\text{Lie}}_s$  the profinite completion of  $\text{Lie}_s$ , applied levelwise to the simplicial abelian group. These functors are homotopy invariant when applied to chain complexes of projective modules via the Dold–Kan correspondence, but are not easy to calculate; they give the terms arising in the unstable Adams spectral sequence.

Over  $\mathbb{Q}$ , the functor  $\bigoplus_s \text{Lie}_s$  corresponds via the Dold–Kan correspondence to the free Lie algebra functor on chain complexes. Thus the spaces  $E_1^{s,t} \otimes \mathbb{Q}$  are much simpler to describe in terms of free Lie algebras, but they correspond to the obstructions for the unipotent completion of Example 3.21 (with  $R = 1$ ).

We are now in a position to compare Kim’s non-abelian reciprocity laws with the Brauer–Manin obstruction. Replacing  $\mathbb{Q}/\mathbb{Z}$  with  $\mathbb{Q}_\ell/\mathbb{Z}_\ell$  would give a similar statement for the  $\ell$ -torsion part of the Brauer–Manin obstruction.

**Proposition 3.26.** *If the natural map*

$$\mathbb{H}_{\text{cts}}^2(\pi_1^{\acute{e}t}(\bar{X})/[\pi_1^{\acute{e}t}(\bar{X})]_{n+1}, \mathbb{Q}/\mathbb{Z}) \rightarrow \mathbb{H}_{\acute{e}t}^2(\bar{X}, \mathbb{Q}/\mathbb{Z})$$

*is surjective, then the image of the map  $X(\mathbb{A}_F^{\infty\Sigma})_n \rightarrow X(\mathbb{A}_F^{\infty\Sigma})$  from Example 3.16 is contained in the Brauer–Manin locus.*

*Proof.* Take a free pro-simplicial resolution  $\tilde{P}$  of  $P := \pi_1^{\text{ét}}(\bar{X})/[\pi_1^{\text{ét}}(\bar{X})]_{n+1}$ , and observe that the cofibrancy of  $G(\bar{X}_{\text{ét}})$  ensures that the natural map  $G(\bar{X}_{\text{ét}}) \rightarrow P$  lifts to a map  $G(\bar{X}_{\text{ét}}) \rightarrow \tilde{P}$ , unique up to homotopy.

Since a point of  $X(\mathbb{A})_n$  incorporates the datum of a  $P$ -valued Galois representation, the composite map

$$X(\mathbb{A})_n \rightarrow X(\mathbb{A}) \rightarrow \mathbb{H}_c^2(G_{F,\Sigma}, \hat{G}(\bar{X}_{\text{ét}})^{\text{ab}}) \rightarrow \mathbb{H}_c^2(G_{F,\Sigma}, P^{\text{ab}})$$

is necessarily 0. The kernel of the middle map is the Brauer–Manin locus as in Example 3.24, and via Poitou–Tate duality we can rewrite the final map as

$$\mathbb{H}^2(G_{F,\Sigma}, \mathbf{R}\tilde{\Gamma}(\bar{X}, \mu_\infty))^\vee \rightarrow \mathbb{H}^2(G_{F,\Sigma}, \mathbf{R}\tilde{\Gamma}(P, \mu_\infty))^\vee,$$

where  $\mathbf{R}\tilde{\Gamma}$  denotes the reduced cohomology complex.

It suffices to show that this map is injective, or equivalently that its dual is surjective. This will follow from the Leray spectral sequences provided the maps

$$\mathrm{H}_{\text{cts}}^i(P, \mathbb{Q}/\mathbb{Z}) \rightarrow \mathrm{H}_{\text{ét}}^i(\bar{X}, \mathbb{Q}/\mathbb{Z})$$

are an isomorphism for  $i = 1$  and surjective for  $i = 2$ . The first condition is automatic and the second is our hypothesis.  $\square$

Considering the relative merits of the higher Brauer–Manin obstructions of Example 3.24 and the non-abelian reciprocity laws of Example 3.16, the latter generally avoid ambiguity of lifts to the higher stages of the tower, but converge more slowly.

*Example 3.27* (Étale Brauer–Manin obstructions). While Example 3.24 considered completions of the étale homotopy type  $\hat{G}(X_{\text{ét}}, \bar{x})$  relative to  $G_{F,\Sigma}$ , it also makes sense to consider completions with respect to larger quotients  $P$  of  $\pi_0 \hat{G}(X_{\text{ét}}, \bar{x}) = \pi_1^{\text{ét}}(X, \bar{x})$  over  $G_{F,\Sigma}$ . We can write  $K := \ker(\hat{G}(X_{\text{ét}}, \bar{x}) \rightarrow P)$ , and set  $\Pi_n := \hat{G}(X_{\text{ét}}, \bar{x})/[K]_{n+1}$ .

As before, we define a tower  $\{X(\mathbb{A}_F^{\infty\Sigma})_n\}_n$  by

$$X(\mathbb{A}_F^{\infty\Sigma})_n := X(\mathbb{A}_F^{\infty\Sigma}) \times_{\text{map}_{BG_{F,\Sigma}}(BG_{\mathbb{A}_F^{\infty\Sigma}}, \bar{W}\Pi_n)}^h \text{map}_{BG_{F,\Sigma}}(BG_{F,\Sigma}, \bar{W}\Pi_n);$$

note that points in  $X(\mathbb{A}_F^{\infty\Sigma})_0$  now include the data of sections of  $P \rightarrow G_{F,\Sigma}$ , because  $\Pi_0 = P$ . The reasoning of Example 3.16 again gives a non-abelian spectral sequence

$$E_1^{s,t} = \begin{cases} \mathbb{H}_c^{1+s-t}(G_{F,\Sigma}, [K]_s/[K]_{s+1}) & s \geq 1 \\ \pi_t X(\mathbb{A}_F^{\infty\Sigma})_0 & s = 0 \end{cases} \implies \pi_{t-s} X(\mathbb{A}_F^{\infty\Sigma})_\infty$$

of groups and sets. The terms  $\mathbb{H}_c^{1+s-t}(G_{F,\Sigma}, [K]_s/[K]_{s+1})$  depend on the section  $\sigma$  of  $P \rightarrow G_{F,\Sigma}$  induced by the relevant element of  $\pi_0 X(\mathbb{A}_F^{\infty\Sigma})_0$ , the Galois action then coming from the natural  $P$ -action on  $[K]_s/[K]_{s+1}$ .

As in Example 2.6, each section  $\sigma$  above gives a pro-(finite étale) group scheme  $P^\sigma$  over  $\mathcal{O}_{F,\Sigma}$  with  $BP^\sigma$  having étale homotopy type  $BP$ , and maps  $X_{\text{ét}} \rightarrow BP$  correspond to  $P^\sigma$ -torsors  $f^\sigma: Y^\sigma \rightarrow X$ . The first obstruction map  $d_1: E_1^{0,0} \rightarrow E_1^{1,0}$  in the spectral sequence above is the disjoint union, over inner automorphism classes of sections  $\sigma$ , of the Brauer–Manin obstructions

$$\pi_0 Y^\sigma(\mathbb{A}_F^{\infty\Sigma})/P^\sigma(\mathcal{O}_{F,\Sigma}) \rightarrow (\mathrm{H}_{\text{pro}(\text{ét})}^2(Y^\sigma, \mu_\infty)/\mathrm{H}^2(G_{F,\Sigma}, \mu_\infty))^\vee$$

of the  $Y^\sigma$  (defined as derived limits unless  $\ker(P \rightarrow G_{F,\Sigma})$  is finite), so we have

$$\text{Im}(\pi_0 X(\mathbb{A}_F^{\infty\Sigma})_1 \rightarrow \pi_0 X(\mathbb{A}_F^{\infty\Sigma})) = \bigcup_{\substack{\sigma: G_{F,\Sigma} \rightarrow P \\ \text{a section}}} f^\sigma(\pi_0 Y^\sigma(\mathbb{A}_F^{\infty\Sigma})^{\text{Br}})$$



(when  $X$  is an algebraic space, we can drop the  $\pi_0$ 's). Combining these for all finite extensions  $P$  of  $G_{F,\Sigma}$  will thus give Skorobogatov's étale Brauer–Manin obstruction [Sko].

Since an inverse limit of non-empty sets can be empty, it seems that considering pro-étale covers in this way gives a strictly stronger obstruction than étale Brauer–Manin. The universal case to consider would take  $P = \pi_1^{\text{ét}}(X, \bar{x})$ , with the spectral sequence then detecting exclusively higher homotopical information, and  $\tilde{Y}^\sigma$  being a universal cover  $\tilde{X}$  of  $X$ . For this choice of  $P$ , we may therefore set

$$\begin{aligned} \pi_0 X(\mathbb{A}_F^{\infty\Sigma})^{\text{pro}(\text{ét}),\text{Br}} &:= \text{Im}(\pi_0 X(\mathbb{A}_F^{\infty\Sigma})_1 \rightarrow \pi_0 X(\mathbb{A}_F^{\infty\Sigma})) \\ &= \bigcup_{\substack{\sigma: G_{F,\Sigma} \rightarrow \pi_1^{\text{ét}}(X, \bar{x}) \\ \text{a section}}} f^\sigma(\pi_0 Y^\sigma(\mathbb{A}_F^{\infty\Sigma})^{\text{Br}}) \end{aligned}$$

(again, we can drop the  $\pi_0$ 's when  $X$  is an algebraic space).

Since  $G_{F,\Sigma}$  has cohomological dimension 2, the higher homotopy groups  $\pi_{\geq 2}([K]_s/[K]_{s+1})$  never contribute to the obstruction spaces  $E_1^{s,s-1}$  for  $\pi_0 X(\mathbb{A}_F^{\infty\Sigma})$  in the non-abelian spectral sequence above. For the universal case  $P = \pi_1^{\text{ét}}(X, \bar{x})$ , we have  $\pi_i K = \pi_{i+1}^{\text{ét}}(\tilde{X})$ , and  $\pi_1[K]_2 = 0$  (the Hurewicz map for  $\pi_2$  being an isomorphism). Thus  $E_1^{s,s-1} = 0$  for  $s > 1$ , meaning all higher obstructions vanish and

$$\pi_0 X(\mathbb{A}_F^{\infty\Sigma})^{\text{pro}(\text{ét}),\text{Br}} = \text{Im}(\pi_0 X(\mathbb{A}_F^{\infty\Sigma})_\infty \rightarrow \pi_0 X(\mathbb{A}_F^{\infty\Sigma})).$$

Moreover the sequence  $[K]_n$  is increasingly connected, so  $\Pi_\infty \simeq \hat{G}(X_{\text{ét}}, \bar{x})$ . Together, these phenomena imply that vanishing of the pro-étale Brauer–Manin obstruction alone implies the existence of a compatible section of the map  $X_{\text{ét}}^\wedge \rightarrow (\text{Spec } \mathcal{O}_{F,\Sigma})_{\text{ét}}^\wedge$  of profinite étale homotopy types.

This is not nearly as impressive as it might seem, since the construction of the pro-étale Brauer–Manin obstruction assumes a compatible section of  $\pi_1^{\text{ét}}(X) \rightarrow G_{F,\Sigma}$ . It does however seem plausible that Poonen's counterexamples [Poo] might fail for the pro-étale Brauer–Manin obstruction, because they are given by spaces fibred over curves, with the Brauer–Manin obstruction on the fibres detecting the failure of the Hasse principle.

**3.3. Alternative characterisations of the reciprocity laws.** We now give a more pedestrian interpretation of the obstruction maps from §1, and show how this can give rise to a more explicit description of the first obstruction map in cases of interest. We expect that this first obstruction map must already be known in some form, but are unable to find a reference.

**3.3.1. Cohomological obstruction classes.** Extensions  $e: 0 \rightarrow A \rightarrow \Pi'' \rightarrow \Pi' \rightarrow 1$  of a group  $\Pi'$  by an abelian  $\Pi'$ -representation  $A$  are classified by

$$H^2(\Pi', A),$$

by which we mean continuous cohomology when considering extensions of topological groups.

Given a group homomorphism  $\psi: G \rightarrow \Pi'$ , the obstruction to lifting  $\psi$  to a homomorphism  $\psi: G \rightarrow \Pi''$  is then given by

$$\psi^*[e] \in H^2(G, A).$$

If  $\psi^*[e] = 0$ , then the difference between two choices for  $\tilde{\psi}$  is a derivation, so the set of choices is a torsor for the group

$$H^1(G, A).$$

Taking  $\Pi', \Pi''$  to be suitable quotients of the arithmetic fundamental group of a scheme  $X$  over  $\mathcal{O}_{F,\Sigma}$ , the Diophantine obstruction maps on spaces of sections

$$\pi_0 \text{map}_{BG_{F,\Sigma}}(BG_{F,\Sigma}, B\Pi') \rightarrow H^2(G_{F,\Sigma}, A)$$

of §2 are all of this form. The adélic obstruction maps of §3.1 are a slight variant coming from looking at restricted products

$$\prod'_{v \in \Sigma} \pi_0 \text{map}_{BG_{F,\Sigma}}(BG_v, B\Pi') \rightarrow \prod'_{v \in \Sigma} H^2(G_v, A).$$

The reciprocity maps associated to an  $\mathbb{A}_F^{\infty\Sigma}$ -point in §3.2 then effectively look at the difference between these obstructions, yielding an obstruction in  $H_c^2(G_{F,\Sigma}, A)$  via the exact sequence

$$\prod'_{v \in \Sigma} H^1(G_v, A) \xrightarrow{\partial} H_c^2(G_{F,\Sigma}, A) \rightarrow H^2(G_{F,\Sigma}, A) \rightarrow \prod'_{v \in \Sigma} H^2(G_v, A).$$

In general, this is not very easy to work with, but when the extension  $e$  splits, so  $\Pi'' = \Pi' \times A$ , the adélic point defines a derivation in  $\alpha \in \prod'_{v \in \Sigma} H^1(G_v, A)$ , with associated abelian obstruction  $\partial(\alpha) \in H_c^2(G_{F,\Sigma}, A)$  to lifting the adélic point to a rational point.

*Example 3.28.* In nilpotent or unipotent settings such as Example 3.18, the first stage in the tower is a split extension

$$\begin{aligned} G_{F,\Sigma} \times \pi_1^{\text{ét}}(\bar{X}, \bar{x})^{\text{ab}} &\rightarrow G_{F,\Sigma}, \\ G_{F,\Sigma} \times (\pi_1^{\text{ét}}(\bar{X}, \bar{x}) \otimes \mathbb{Q}_\ell)^{\text{ab}} &\cong G_{F,\Sigma} \times H^1(\bar{X}, \mathbb{Q}_\ell)^* \rightarrow G_{F,\Sigma}. \end{aligned}$$

Then an  $\mathbb{A}_F^{\infty\Sigma}$ -point  $y$  defines a class in  $H^1(\mathbb{A}_F^{\infty\Sigma}, H^1(\bar{X}, \mathbb{Q}_\ell)^*)$  whose image in  $H_c^2(G_{F,\Sigma}, H^1(\bar{X}, \mathbb{Q}_\ell)^*)$  is the first unipotent obstruction to  $y$  being a rational point.

*Example 3.29.* Relative Malcev completions as in Example 3.19 are a little more complicated. For  $X = \mathcal{M}_{1,1}$  the stacky modular curve, take  $x \in X(\mathcal{O}_{F,\Sigma})$ , giving rise to a  $G_{F,\Sigma}$ -representation  $V$  of dimension 2 over  $\mathbb{Q}_\ell$ . We then set  $P_0 = G_{F,\Sigma} \times \text{SL}_2(\mathbb{Q}_\ell)$ , and

$$\begin{aligned} P_1 &:= G_{F,\Sigma} \times \widehat{(\text{SL}_2(\mathbb{Z}))}^{\text{SL}_2, \text{Mal}} / [\mathbb{R}_u]_2, \\ &= G_{F,\Sigma} \times (H^1(\text{SL}_2(\mathbb{Z}), O(\text{SL}_2))^* \rtimes \text{SL}_2(\mathbb{Q}_\ell)). \end{aligned}$$

with  $\Pi_i = P_i \times_{\text{SL}_2(\mathbb{Q}_\ell)} \text{SL}_2(\mathbb{Z}_\ell)$ , where we are writing  $O(\text{SL}_2)$  for the ring of algebraic functions on the scheme  $\text{SL}_2$  over  $\mathbb{Q}_\ell$ .

Now,  $P_1$  is an extension of  $P_0$  by  $H^1(\text{SL}_2(\mathbb{Z}), O(\text{SL}_2) \otimes \mathbb{Q}_\ell)^*$ , so is given by a class in  $H^2(P_0, H^1(\text{SL}_2(\mathbb{Z}), O(\text{SL}_2))^*)$ , where we may regard  $\text{SL}_2(\mathbb{Q}_\ell)$  as an algebraic group. Since  $\text{SL}_2$  is reductive, the Leray–Serre spectral sequence then gives

$$H^2(P_0, H^1(\text{SL}_2(\mathbb{Z}), O(\text{SL}_2))^*) \cong H^2(G_{F,\Sigma}, (H^1(\text{SL}_2(\mathbb{Z}), O(\text{SL}_2))^*)^{\text{SL}_2}),$$

which vanishes because  $H^1(\text{SL}_2(\mathbb{Z}), \mathbb{Q}_\ell) = 0$ .

We therefore have a split extension  $\Pi_1 \cong \Pi_0 \rtimes \mathrm{H}^1(\mathrm{SL}_2(\mathbb{Z}), O(\mathrm{SL}_2))^*$ . [For more general relative Malcev completions, a similar conclusion will still hold by combining Leray–Serre with the splitting of the extension  $\Pi_1 \rightarrow G_{F,\Sigma}$ .]

Thus an adélic elliptic curve  $E$  defines a class in  $\mathrm{H}^1(\mathbb{A}_F^{\infty\Sigma}, \mathrm{H}^1(\mathrm{SL}_2(\mathbb{Z}), O(\mathrm{SL}_2))^*)$ , whose image in  $\mathrm{H}_c^2(G_{F,\Sigma}, \mathrm{H}^1(\mathrm{SL}_2(\mathbb{Z}), O(\mathrm{SL}_2))^*)$  is the first obstruction to  $E$  being defined over  $\mathcal{O}_{F,\Sigma}$  with Tate module  $T_\ell(E(\bar{F})) \otimes \mathbb{Q} \simeq V$ .

**3.3.2. The first obstruction for modular curves.** We now give an explicit description of the abelian obstruction of Example 3.29, seeking elliptic curves with given Tate module.

On the modular curve  $q: Y_\Gamma \rightarrow \mathrm{Spec} \mathcal{O}_{F,\Sigma}$ , the Tate module of the universal elliptic curve  $f: E \rightarrow Y_\Gamma$  gives a lisse  $\mathbb{Z}_\ell$ -sheaf  $\mathbb{T}_\ell$  of rank 2, and we write  $\mathbb{T}_{\mathbb{Q}_\ell} := \mathbb{T}_\ell \otimes \mathbb{Q}$ . On pulling back to  $\bar{Y}_\Gamma$ , the sheaves  $S^m \mathbb{T}_{\mathbb{Q}_\ell}$  correspond to the irreducible representations  $V_m$  of  $\mathrm{SL}_2$ , and we consider the Galois representations  $\mathrm{H}^1(\Gamma, V_m) := \mathbf{R}^1 q_* S^m \mathbb{T}_{\mathbb{Q}_\ell}$ . For each  $m$ , the adjunction  $q^* \dashv \mathbf{R}q_*$  defines a class

$$\eta_m \in \mathrm{Ext}_{Y_\Gamma, \mathbb{Q}_\ell}^1(q^* \mathrm{H}^1(\Gamma, V_m), S^m \mathbb{T}_{\mathbb{Q}_\ell}).$$

Now take an adélic point  $x \in Y_\Gamma(\mathbb{A}_F^{\infty\Sigma})$ , and assume that there is a  $G_{F,\Sigma}$ -representation  $\Lambda$  with  $\det \Lambda = \mathbb{Z}_\ell(1)$  and an isomorphism  $\alpha: \Lambda \otimes \mathbb{Q} \cong \mathbb{T}_{\mathbb{Q}_\ell, x}$  which is  $G_v$ -equivariant for all  $v \in \Sigma$ . A necessary condition for  $x$  to lie in  $Y_\Gamma(\mathcal{O}_{F,\Sigma})$  compatibly with  $\alpha$  is that the class  $x^* \eta_m \in \prod_{v \in \Sigma} \mathrm{Ext}_{G_v}^1(\mathrm{H}^1(\Gamma, V_m), S^m \Lambda \otimes \mathbb{Q})$  lies in the image of  $\mathrm{Ext}_{G_{F,\Sigma}}^1(\mathrm{H}^1(\Gamma, V_m), S^m \Lambda \otimes \mathbb{Q})$ . Following the conventions of §3.2.1 to replace the product with a suitable restricted product, we get an obstruction

$$\partial(x^* \eta_m) \in \mathrm{H}_c^2(G_{F,\Sigma}, \mathrm{H}^1(\Gamma, V_m)^* \otimes S^m \Lambda).$$

Combining these gives a map

$$\mathrm{H}^1(G_{F,\Sigma}, \mathrm{GL}_2(\mathbb{Q}_\ell)) \times_{\mathrm{H}^1(\mathbb{A}_F^{\infty\Sigma}, \mathrm{GL}_2(\mathbb{Q}_\ell))} Y_\Gamma(\mathbb{A}_F^{\infty\Sigma}) \rightarrow \prod_{m \geq 1} \mathrm{H}_c^2(G_{F,\Sigma}, \mathrm{H}^1(\Gamma, V_m)^* \otimes S^m \Lambda),$$

which is the first reciprocity map associated to the relative completion of  $\Gamma \rightarrow \mathrm{SL}_2(\mathbb{Q}_\ell)$  in Example 3.19, via the isomorphism  $O(\mathrm{SL}_2) \otimes \mathbb{Q}_\ell \cong \bigoplus_m V_m \otimes V_m^*$ . We may then use Poitou–Tate duality as in Example 3.24 to rewrite the target of the map as

$$\prod_{m \geq 1} (\mathrm{H}_{\text{ét}}^2(Y_\Gamma, S^m \mathbb{T}_\ell \otimes q^* S^m \Lambda^* \otimes \mu_{\ell^\infty})^\vee \otimes \mathbb{Q});$$

adapting Example 3.27, this can be recovered from the Brauer–Manin obstruction of an inverse system of finite étale covers of  $Y_\Gamma$ , which in this case correspond to twisted level structures associated to the  $G_{F,\Sigma}$ -representations  $\Lambda/\ell^n$ .

*Remark 3.30.* An intermediate step in the construction above associates to each elliptic curve  $E$  over  $F$  a class in

$$\mathrm{Ext}_{G_{F,\Sigma}}^1(\mathrm{H}^1(\Gamma, V_m), S^m T_\ell(E(\bar{F})) \otimes \mathbb{Q}).$$

The corresponding construction for complex elliptic curves and mixed Hodge structures is given in [Hai1, Remark 13.3] (evaluating the section at the point  $[E]$ ). The extension arises geometrically as the relative cohomology group  $\mathrm{H}^1(\bar{Y}_\Gamma, [E]; S^m \mathbb{T}_{\mathbb{Q}_\ell})$ .

3.3.3. *Higher Brauer–Manin obstructions via cochain algebras.* The unipotent obstructions which we have considered were formulated in terms of morphisms of simplicial pro-unipotent groups, so could be thought of as a form of Quillen homotopy type [Qui]. An equivalent alternative formulation would be to look at morphisms of Sullivan homotopy types [Sul], which are just algebras of cochains.

Taking a Deligne–Mumford stack  $X$  over  $\mathcal{O}_{F,\Sigma}$  and writing  $\bar{X} := X \otimes \mathcal{O}_{\bar{F},\Sigma}$ , the cochain complex  $\mathbf{R}\Gamma(\bar{X}, \mathbb{Q}_\ell)$  carries a natural cup product, and is in fact naturally quasi-isomorphic to a commutative differential graded algebra over  $\mathbb{Q}_\ell$ . Equivalently this means that  $\mathbf{R}\Gamma(\bar{X}, \mathbb{Q}_\ell)$  carries the structure of a unital  $\mathrm{Com}_\infty$ -algebra (or strongly homotopy commutative algebra): it has a symmetric bilinear multiplication  $m_2$ , which is associative up to a homotopy  $m_3$ , and there is a hierarchy of higher homotopies  $m_n$  formulated in terms of the Lie operad. In the  $R = 1$  case, Example 3.21 looks at the morphism

$$\mathbf{R}\Gamma(\bar{X}, \mathbb{Q}_\ell) \rightarrow \mathbb{Q}_\ell$$

defined by an adélic point, and studies obstructions to lifting it to a  $\mathrm{Com}_\infty$ -morphism  $\{f_n\}_{n \geq 1}$  which is equivariant for the global Galois group  $G_{F,\Sigma}$ , rather than just the pro-groupoid

$$G_{\mathbb{A}_F^{\infty\Sigma}} := \varprojlim_{T \subset \Sigma \text{ finite}} \left( \prod_{v \in T} G_v \sqcup \prod_{v \in \Sigma - T} G_v / I_v \right)$$

formed from local Galois groups.

- (1) The first reciprocity law seeks just to lift this as a morphism of complexes, fixing  $\mathbb{Q}_\ell \subset \mathbf{R}\Gamma(\bar{X}, \mathbb{Q}_\ell)$ , so the first obstruction lies in

$$\mathbb{E}\mathrm{xt}_{G_{F,\Sigma},c}^1(\mathbf{R}\Gamma(\bar{X}, \mathbb{Q}_\ell)/\mathbb{Q}_\ell, \mathbb{Q}_\ell) \cong (\mathrm{H}^2(X, \mu_{\ell^\infty})/\mathrm{H}^2(G_{F,\Sigma}, \mu_{\ell^\infty}))^\vee \otimes \mathbb{Q};$$

this is just the rational Brauer–Manin obstruction.

- (2) The secondary obstruction of §3.2.3 depends on a choice  $f_1: \mathbf{R}\Gamma(\bar{X}, \mathbb{Q}_\ell) \rightarrow \mathbb{Q}_\ell$  of  $G_{F,\Sigma}$ -equivariant chain map, together with a homotopy  $h_1$  of  $G_{\mathbb{A}_F^{\infty\Sigma}}$ -representations making  $f_1$  compatible with our chosen adélic point. Such a lift exists whenever rational Brauer–Manin vanishes, and we now need to look at whether it respects the cup product. We thus ask whether the diagram

$$\begin{array}{ccc} \mathbf{R}\Gamma(\bar{X}, \mathbb{Q}_\ell) \otimes \mathbf{R}\Gamma(\bar{X}, \mathbb{Q}_\ell) & \xrightarrow{m_2} & \mathbf{R}\Gamma(\bar{X}, \mathbb{Q}_\ell) \\ & \searrow f_1 \otimes f_1 & \downarrow f_1 \\ & & \mathbb{Q}_\ell \end{array}$$

commutes, up to a homotopy  $f_2$ , in the derived category of  $G_{F,\Sigma}$ -representations, with a further  $G_{\mathbb{A}_F^{\infty\Sigma}}$ -equivariant homotopy  $h_2$  between  $f_2$  and the homotopy  $f_1 \otimes h_1 + h_1 \otimes f_1 + (h_1 d) \otimes h_1 - h_1 \circ m_2$  providing the known  $G_{\mathbb{A}_F^{\infty\Sigma}}$ -equivariant commutativity of  $f_1$ . The resulting obstruction lies in

$$\mathbb{E}\mathrm{xt}_{G_{F,\Sigma},c}^0(\mathbf{R}\Gamma(\bar{X}^2, \mathbb{Q}_\ell), \mathbb{Q}_\ell) \cong \mathrm{H}^3(X^2, \mu_{\ell^\infty})^\vee \otimes \mathbb{Q},$$

but this restricts to the finer obstruction described in Remark 3.23 when we take symmetry and the unit into account.

- (3) The third obstruction is more complicated, measuring obstructions to choosing the next component  $(f_3, h_3)$  of a  $\mathrm{Com}_\infty$ -morphism. If we choose a model  $A$  of

$\mathbf{R}\Gamma(\bar{X}, \mathbb{Q}_\ell)$  which is strictly (graded-)commutative, this means we seek a map  $f_3: A^{\otimes 3} \rightarrow A[-1]$  satisfying

$$(d \circ f_3 \mp f_3 \circ d)(a, b, c) = f_2(ab, c) \pm f_2(a, bc) \mp f_1(a)f_2(b, c) \mp f_2(a, b)f_2(c),$$

which must vanish on the unit  $1 \in A$  and on shuffle products. The right-hand side and associated  $G_{\mathbb{A}_F^{\infty \Sigma}}$ -equivariant homotopy in terms of  $h_2$  give rise to an obstruction class in

$$\mathbb{E}xt_{G_{F, \Sigma, c}}^{-1}(\mathbf{R}\Gamma(\bar{X}^3, \mathbb{Q}_\ell), \mathbb{Q}_\ell) \cong H^4(X^3, \mu_{\ell^\infty})^\vee \otimes \mathbb{Q},$$

which is closely related to Massey triple products

- (4) Explicit descriptions for the higher obstructions follow from the formulae for  $\text{Com}_\infty$ -morphisms as in [LV, §§10.2.2, 13.1.13] (take the expression for  $A_\infty$ -morphisms in [LV, Proposition 10.2.12] and replace  $\mathcal{A}s$  with  $\mathcal{L}ie$  by taking invariants under shuffle permutations). These are related to higher Massey products.

To express Example 3.21 in these terms beyond the  $R = 1$  case, we may reformulate via [Pri1, Proposition 3.15 and Corollary 4.41] to seek  $G_{F, \Sigma} \times R$ -equivariant morphisms

$$\mathbf{R}\Gamma(\bar{X}, O(R)) \rightarrow O(R),$$

for a pro-reductive algebraic groupoid  $R$  over  $\mathbb{Q}_\ell$  and a Zariski dense Galois-equivariant homomorphism  $\pi_1(\bar{X}, \mathcal{B}) \rightarrow R(\mathbb{Q}_\ell)$  with a Galois-equivariant set of basepoints  $\mathcal{B}$ . The descriptions above adapt, with the sheaf  $O(R)_{\mathbb{Z}_\ell} \otimes \mu_{\ell^\infty}$  (regarded as a  $\pi_1(\bar{X}, \mathcal{B}) \times R$ -representation via the left and right actions) replacing  $\mu_{\ell^\infty}$ .

*Remark 3.31.* If we wished to construct obstructions in the nilpotent, rather than unipotent setting, we should seek Galois-equivariant morphisms  $\mathbf{R}\Gamma(\bar{X}, \hat{\mathbb{Z}}) \rightarrow \hat{\mathbb{Z}}$  of cosimplicial commutative rings. The first obstruction is just Brauer–Manin, but the torsion in the higher obstructions is very difficult to describe, as discussed in Remark 3.25.

*Remark 3.32.* The description in terms of cochain algebras will readily adapt to more general cohomology theories with cup product. For instance, a motivic analogue of §2 would be given by seeking  $\text{Com}_\infty$ -morphisms  $M(Y_\Gamma) \rightarrow M(F)$  of cohomological  $F$ -motives, assuming existence of a suitable  $\text{Com}_\infty$ -structure enriching the cup product on motivic cohomology. The obstruction tower just depends on a filtration on the  $\text{Com}_\infty$ -operad, whereas Postnikov-type filtration in terms of motivic homotopy groups [Pri4, §4.5] would require a suitable  $t$ -structure. This approach could also be used to construct motivic obstructions to adélic points being global, along the lines of this section, but it is not obvious what the motivic analogue of Poitou–Tate duality should be.

## APPENDIX A. PRO-FINITE HOMOTOPY TYPES FOR ADELES

**Definition A.1.** Write  $s^b\text{Gpd}$  for the category consisting of simplicial groupoids  $G$  for which

- (1) The simplicial set  $\text{Ob}G$  of  $G$  is constant and finite;
- (2) each  $G_i(x, y)$  is finite;
- (3) the group  $N_i G(x, x) := G_i(x, x) \cap \bigcap_{j>0} \ker \partial_j$  is trivial for all but finitely many  $i$ .

Note that the second condition is equivalent to saying that the map  $G \rightarrow \text{cosk}_n G$  to the  $n$ -coskeleton is an isomorphism for sufficiently large  $n$ .

**Lemma A.2.** *The functor  $U$  from  $\text{pro}(s^b\text{Gpd})$  to simplicial profinite groupoids given by  $(U\{G(\alpha)\}_\alpha)_n := \{G(\alpha)_n\}_\alpha$  is an equivalence of categories; moreover, we may restrict to inverse systems in which all morphisms are surjective.*

*Proof.* Since  $s^b\text{Gp}$  is an Artinian category, the proofs of [Pri3, Proposition 1.19] (which dealt with Artinian local rings rather than finite groupoids) and of [Pri5, Lemma 1.17] carry over to this generality.  $\square$

**Definition A.3.** Given a simplicial scheme  $Y$ , define  $\Gamma^{\mathbb{S}}(Y, -)$  to be the global sections functor from simplicial étale presheaves on  $Y$  to simplicial sets. Write  $\mathbf{R}\Gamma_{\text{ét}}^{\mathbb{S}}(Y, -)$  for its right-derived functor with respect to the model structure for étale hypersheaves. Explicitly,

$$\mathbf{R}\Gamma_{\text{ét}}^{\mathbb{S}}(Y, \mathcal{F}) \simeq \text{holim}_{Y'_\bullet} \text{holim}_{n \in \Delta} \Gamma(Y'_n, \mathcal{F}),$$

where  $Y'_\bullet$  runs over simplicial étale hypercovers of  $Y$ .

Given an inverse system  $\mathcal{F} = \{\mathcal{F}_i\}_i$ , set

$$\mathbf{R}\Gamma_{\text{ét}}^{\mathbb{S}}(Y, \mathcal{F}) := \text{holim}_i \mathbf{R}\Gamma_{\text{ét}}^{\mathbb{S}}(Y, \mathcal{F}_i).$$

**Lemma A.4.** *There is a canonical morphism*

$$\mathbf{R}\Gamma_{\text{ét,cts}}^{\mathbb{S}}(\text{Spec } \mathbb{A}_F^{\infty\Sigma}, \bar{W}G) \rightarrow \text{map}(BG_{\mathbb{A}_F^{\infty\Sigma}}, \bar{W}G)$$

in  $\text{Ho}(\mathbb{S})$ , functorial in simplicial profinite groupoids  $G$ .

*Proof.* Because  $\text{Spec } \mathbb{A}_F^{\infty\Sigma}$  is quasi-compact, the category of quasi-compact hypercovers of  $\text{Spec } \mathbb{A}_F^{\infty\Sigma}$  is left filtering in the category of all hypercovers, by the argument of [Fri, Proposition 7.1]. Thus for all simplicial presheaves  $\mathcal{F}$ ,

$$\mathbf{R}\Gamma_{\text{ét}}^{\mathbb{S}}(\text{Spec } \mathbb{A}_F^{\infty\Sigma}, \mathcal{F}) \simeq \text{holim}_{Y'_\bullet \in \text{HR}(\text{Spec } \mathbb{A}_F^{\infty\Sigma})} \text{holim}_{n \in \Delta} \Gamma(Y'_n, \mathcal{F}) \leftarrow \text{holim}_{Y'_\bullet \in \text{qcHR}(\text{Spec } \mathbb{A}_F^{\infty\Sigma})} \text{holim}_{n \in \Delta} \Gamma(Y'_n, \mathcal{F})$$

is an equivalence, where  $\text{HR}(Y)$  is the category of simplicial hypercovers  $Y'_\bullet \rightarrow Y$  and  $\text{qcHR}(Y)$  the full subcategory of simplicial hypercovers  $Y'_\bullet \rightarrow Y$  with each  $Y'_n$  quasi-compact.

Given a simplicial presheaf  $\mathcal{F}$  for which the map  $\mathcal{F} \rightarrow \text{cosk}_m \mathcal{F}$  is an isomorphism, the map

$$\text{holim}_{Y'_\bullet \in \text{qcHR}(\text{Spec } \mathbb{A}_F^{\infty\Sigma})} \text{holim}_{n \in \Delta} \Gamma(Y'_n, \mathcal{F}) \leftarrow \text{holim}_{Y'_\bullet \in \text{qcHR}^b(\text{Spec } \mathbb{A}_F)} \text{holim}_{n \in \Delta} \Gamma(Y'_n, \mathcal{F})$$

is an equivalence, where  $\text{qcHR}^b(\text{Spec } \mathbb{A}_F^{\infty\Sigma})$  consists of quasi-compact hypercovers  $Y'$  which are truncated in the sense that  $Y' = \text{cosk}_r(Y'/\mathbb{A}_F^{\infty\Sigma})$  for some  $r$  (in fact  $r = m$  suffices for the case in hand).

Given a quasi-compact hypercover  $Y'_\bullet \rightarrow \text{Spec } \mathbb{A}_F^{\infty\Sigma}$ , write  $Y'_{\bullet,v}$  for its pullback along  $\text{Spec } F_v \rightarrow \text{Spec } \mathbb{A}_F^{\infty\Sigma}$ . Thus each  $Y'_{i,v}$  is the spectrum of a finite product of finite field extensions of  $F_v$ . Because  $Y'_i$  is of finite type over  $\mathbb{A}_F^{\infty\Sigma}$ , it is defined over  $(\prod_{v \in \Sigma} \mathcal{O}_v) \otimes_{\mathbb{Z}} \mathbb{Z}[S_i^{-1}]$  for some finite set  $S_i \subset \Sigma$  of primes. For  $v \in S_i$ , it then follows that  $Y'_{i,v}$  is the spectrum of a finite product of finite unramified field extensions of  $F_v$ . When the hypercover  $Y'_\bullet$  is  $r$ -truncated, we can set  $S = \bigcup_{i \leq r} S_i$ , and then see that

$$\{Y'_{\bullet,v}\}_v \in \left( \prod_{v \in \Sigma - S} \text{qcHR}^{\text{nr}}(\text{Spec } F_v) \right) \times \left( \prod_{v \in S} \text{qcHR}(\text{Spec } F_v) \right) \subset \prod_v \text{HR}(\text{Spec } F_v),$$

where  $qcHR^{\text{nr}}$  consists of quasi-compact hypercovers built from unramified field extensions.

Writing

$$\prod_v qcHR(\text{Spec } F_v) := \bigcup_{S \subset \Sigma \text{ finite}} \left( \prod_{v \in \Sigma - S} qcHR^{\text{nr}}(\text{Spec } F_v) \right) \times \left( \prod_{v \in S} qcHR(\text{Spec } F_v) \right),$$

we then get a map

$$\text{holim}_{Y' \in qcHR^b(\text{Spec } \mathbb{A}_F^{\infty \Sigma})} \text{holim}_{n \in \Delta} \Gamma(Y'_n, \mathcal{F}) \rightarrow \text{holim}_{Y' \in \prod'_v qcHR^b(\text{Spec } F_v)} \text{holim}_{n \in \Delta} \Gamma(Y'_n, \mathcal{F}).$$

Returning to the statement of the lemma, since both functors send filtered inverse limits to homotopy limits, Lemma A.2 allows us to restrict to the case where  $G \in s^b \text{Gpd}$ . Thus the map  $G \rightarrow \text{cosk}_{m-1} G$  is an isomorphism for some  $m$ , so  $\bar{W}G \cong \text{cosk}_m \bar{W}G$  and satisfies the conditions for  $\mathcal{F}$  above. Then we have

$$\mathbf{R}\Gamma_{\text{ét}}^{\mathbb{S}}(\text{Spec } \mathbb{A}_F^{\infty \Sigma}, \bar{W}G) \rightarrow \text{holim}_{Y' \in \prod'_v qcHR^b(\text{Spec } F_v)} \prod_v \text{holim}_{n \in \Delta} \Gamma((Y'_v)_n, \bar{W}G).$$

Now, we can rewrite the right-hand side as

$$\varinjlim_{S \subset \Sigma \text{ finite}} \text{holim}_{n \in \Delta} \left( \prod_{v \in \Sigma - S} \text{holim}_{(Y'_v)_\bullet \in qcHR^{\text{nr}}(\text{Spec } F_v)} \Gamma((Y'_v)_n, \bar{W}G) \right) \times \left( \prod_{v \in S} \text{holim}_{(Y'_v)_\bullet \in qcHR(\text{Spec } F_v)} \Gamma((Y'_v)_n, \bar{W}G) \right).$$

Since  $(\text{Spec } F_v)_{\text{ét}}^{\wedge} \simeq BG_v$  and  $(\text{Spec } \mathcal{O}_{F,v})_{\text{ét}}^{\wedge} \simeq B(G_v/I_v)$  this is weakly equivalent to

$$\varinjlim_{S \subset \Sigma \text{ finite}} \prod_{v \in \Sigma - S} \text{map}(B(G_v/I_v), \bar{W}G) \times \prod_{v \in S} \text{map}(BG_v, \bar{W}G),$$

which is just  $\text{map}(BG_{\mathbb{A}_F^{\infty \Sigma}}, \bar{W}G)$ , as required.  $\square$

**Corollary A.5.** *There is a canonical morphism*

$$BG_{\mathbb{A}_F^{\infty \Sigma}} \rightarrow (\text{Spec } \mathbb{A}_F^{\infty \Sigma})_{\text{ét}}^{\wedge}$$

in the homotopy category of pro-simplicial sets, where  $\wedge$  denotes profinite completion, and  $X_{\text{ét}}$  the étale topological type as in [Fri, Definition 4.4].

*Proof.* Since simplicial profinite groupoids model profinite homotopy types by [Pri5, Proposition 1.29], it suffices to show that we have natural morphisms

$$\text{map}((\text{Spec } \mathbb{A}_F^{\infty \Sigma})_{\text{ét}}, \bar{W}G) \rightarrow \text{map}(BG_{\mathbb{A}_F^{\infty \Sigma}}, \bar{W}G)$$

for simplicial profinite groupoids  $G$ , and this is precisely the content of Lemma A.4.  $\square$

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