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Algebraic geometry / *Géométrie algébrique*

# The equivariant Atiyah class

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**Abstract.** Let  $X$  be a complex scheme acted on by an affine algebraic group  $G$ . We prove that the Atiyah class of a  $G$ -equivariant perfect complex on  $X$ , as constructed by Huybrechts and Thomas, is  $G$ -equivariant in a precise sense. As an application, we show that, if  $G$  is reductive, the obstruction theory on the fine relative moduli space  $M \rightarrow B$  of simple perfect complexes on a  $G$ -invariant smooth projective family  $Y \rightarrow B$  is  $G$ -equivariant. The results contained here are meant to suggest how to check the equivariance of the natural obstruction theories on a wide variety of moduli spaces equipped with a torus action, arising for instance in Donaldson–Thomas theory and Vafa–Witten theory.

**Résumé.** Soit  $X$  un schéma complexe sur lequel agit un groupe algébrique affine  $G$ . Nous démontrons que la classe d'Atiyah d'un complexe parfait  $G$ -équivariant au dessus de  $X$ , construite par Huybrechts et Thomas, est  $G$ -équivariante dans un sens précis. Comme application, nous démontrons que, si  $G$  est réductif, la théorie d'obstruction sur l'espace de modules relatif fin  $M \rightarrow B$  des complexes parfaits simples sur une famille lisse projective  $Y \rightarrow B$  est  $G$ -équivariante. Les résultats contenus ici vont suggérer comment vérifier l'équivariance de la théorie d'obstruction naturelle sur un nombre d'espaces de modules munis de l'action d'un tore, notamment ceux qui sont construits en théorie de Donaldson–Thomas et en théorie de Vafa–Witten.

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## Introduction

### Overview

The *Atiyah class* of a vector bundle  $V$  on a complex algebraic variety  $X$ , introduced in [1], is an extension class

$$\text{At}_V \in \text{Ext}_X^1(V, V \otimes \Omega_X)$$

whose vanishing is equivalent to the existence of an algebraic connection on  $V$ . A general definition of Atiyah class was given by Illusie for every complex of sheaves on a scheme [24]. The Atiyah class is classically linked with the theory of jet bundles and sheaves of principal parts [13].

In this paper all schemes, stacks and group schemes are defined over  $\mathbb{C}$ . Let  $G$  be an algebraic group acting on a scheme  $X$ . Our first goal is to make sense of, and prove (see Theorem A), a rigorous version of the following slogan:

*The Atiyah class of a  $G$ -equivariant perfect complex on  $X$  is  $G$ -equivariant.*

Our main motivation comes from enumerative geometry: the Atiyah class is a crucial ingredient in the construction of the *obstruction theory* [4, 29] on various moduli spaces of sheaves, such as those appearing as main characters in Donaldson–Thomas theory, Pandharipande–Thomas theory, Vafa–Witten theory. When the moduli space is acted on by a torus  $\mathbb{G}_m^r$ , a powerful tool to compute the virtual invariants defined via these obstruction theories is the *virtual localisation formula*, proved in equivariant Chow cohomology by Graber and Pandharipande [15] and in K-theory by Fantechi and Göttsche [11]. The localisation theorem requires as input an *equivariant obstruction theory*. After confirming an equivariant version of Grothendieck duality (Section 2.5), we show in a general example that the equivariance of the Atiyah class ensures that the obstruction theory it induces is itself equivariant, at least for reductive groups; since  $\mathbb{G}_m^r$  is reductive, this is enough to apply the virtual localisation formula.

By the above slogan, in a typical situation a “working mathematician” would only have to verify the equivariance of the universal sheaf<sup>1</sup> (or complex) on the moduli space under consideration in order to apply the localisation theorem. This procedure is explained in detail in Section 4, where we prove the equivariance of the universal object on the moduli space of simple perfect complexes on a  $G$ -invariant smooth projective family (Proposition 52). A special case of our construction will be considered in [12] in the context of Quot schemes over 3-folds, in order to produce equivariant virtual fundamental classes and prove a special case of a formula conjectured in [40]. Quot schemes have already appeared in many equivariant and non-equivariant calculations in enumerative geometry [3, 8, 9, 14, 36–39], and this work is meant to make the foundations of their virtual equivariant theory rigorous, as well as that of other moduli spaces of sheaves.

### Main result

Let  $X$  be a separated noetherian scheme over  $\mathbb{C}$ , and let  $\mathrm{QCoh}_X$  be the abelian category of quasi-coherent  $\mathcal{O}_X$ -modules. Let  $E \in \mathrm{Perf} X \subset \mathbf{D}(\mathrm{QCoh}_X)$  be a perfect complex. Assuming  $X$  admits a closed embedding in a smooth scheme, Huybrechts and Thomas defined the *truncated Atiyah class* of  $E$  as an element

$$\mathrm{At}_E \in \mathrm{Ext}_X^1(E, E \otimes \mathbb{L}_X), \quad (1)$$

where  $\mathbb{L}_X \in \mathbf{D}^{[-1,0]}(\mathrm{QCoh}_X)$  is the truncated cotangent complex. If  $X$  carries an action of a complex algebraic group  $G$ , one can form the abelian category  $\mathrm{QCoh}_X^G$  of  $G$ -equivariant quasi-coherent sheaves on  $X$ . There is an exact functor  $\Phi: \mathbf{D}(\mathrm{QCoh}_X^G) \rightarrow \mathbf{D}(\mathrm{QCoh}_X)$  forgetting the equivariant structure. We say that  $\mathrm{At}_E$  is  *$G$ -equivariant* if the corresponding morphism  $E \rightarrow E \otimes \mathbb{L}_X[1]$  in  $\mathbf{D}(\mathrm{QCoh}_X)$  can be lifted to  $\mathbf{D}(\mathrm{QCoh}_X^G)$  along  $\Phi$ .

Our first main result is the following.

**Theorem A (Theorem 48).** *Let  $G$  be a complex affine algebraic group acting on a separated noetherian  $\mathbb{C}$ -scheme  $X$  admitting a  $G$ -equivariant embedding in a smooth  $G$ -scheme. Fix a perfect complex  $E \in \mathrm{Perf} X$ . Then every lift of  $E$  to  $\mathbf{D}(\mathrm{QCoh}_X^G)$  makes  $\mathrm{At}_E$  canonically  $G$ -equivariant.*

Note that the assumption on  $X$  is satisfied as soon as, for instance,  $X$  is quasi-projective and carries at least one  $G$ -equivariant line bundle.

<sup>1</sup>Most sheaf-theoretic moduli problems, including those for which one does not have a universal sheaf (but only a universal *twisted* sheaf), should behave in a way that is entirely parallel to our discussion in Section 4.

*Application to equivariant obstruction theories*

As we briefly recall below, the Atiyah class is the main ingredient in the construction of an *obstruction theory* on moduli spaces of simple perfect complexes on a smooth projective family  $Y \rightarrow B$ , see [22, Thm. 4.1]. An obstruction theory [4, Def. 4.4] on a scheme  $X$  is a morphism  $\phi: \mathbb{E} \rightarrow \mathbb{L}_X$  in  $\mathbf{D}(\mathrm{QCoh}_X)$  such that  $\mathcal{H}^0(\phi)$  is an isomorphism and  $\mathcal{H}^{-1}(\phi)$  is a surjection. See [4, §7] for a relative version.

In case  $X$  is acted on by an algebraic group  $G$ , the complex  $\mathbb{L}_X$  has a canonical lift to  $\mathbf{D}(\mathrm{QCoh}_X^G)$  (see Section 3.1.1), and one has the following notion.

**Definition 1 (cf. [5, 15]).** *Let  $G$  be an algebraic group acting on  $X$ . An obstruction theory  $\phi: \mathbb{E} \rightarrow \mathbb{L}_X$  is  $G$ -equivariant if  $\phi$  can be lifted to a morphism in  $\mathbf{D}(\mathrm{QCoh}_X^G)$ .*

To make a statement about equivariant obstruction theories, one needs to get a handle on Hom-sets in  $\mathbf{D}(\mathrm{QCoh}_X^G)$ . For this, we restrict to  $G$  reductive (in order to exploit a technical result, Lemma 37). For instance, the theory works for a torus  $G = \mathbb{G}_m^r$ , which includes most applications we have in mind.

Here is the statement of our second main result.

**Theorem B (Theorem 53).** *Let  $G$  be an affine reductive algebraic group. Let  $Y \rightarrow B$  be a  $G$ -invariant smooth projective family of varieties. Let  $M \rightarrow B$  be a fine moduli space of simple perfect complexes on the fibres of  $Y \rightarrow B$ . Then the relative obstruction theory on  $M \rightarrow B$  is  $G$ -equivariant.*

We refer to [22, §4.1] (or our Section 4.1) for the precise assumptions on  $M \rightarrow B$ . We briefly outline here the role of the Atiyah class and of Grothendieck duality in the construction of the relative obstruction theory on  $M \rightarrow B$ . Set  $X = Y \times_B M$ , let  $E \in \mathrm{Perf} X$  be the universal perfect complex and let  $\pi_M: X \rightarrow M$  be the projection. The Atiyah class one has to consider is the “ $M$ -component” of (1), namely

$$\mathrm{At}_{E/Y} \in \mathrm{Ext}_X^1(E, E \otimes \pi_M^* \mathbb{L}_{M/B}).$$

Via the distinguished triangle

$$\mathbf{R}\mathcal{H}om_X(E, E)_0 \longrightarrow \mathbf{R}\mathcal{H}om_X(E, E) \xrightarrow{\mathrm{trace}} \mathcal{O}_X,$$

the class  $\mathrm{At}_{E/Y}$  projects onto an element of

$$\mathrm{Ext}_X^1(\mathbf{R}\mathcal{H}om_X(E, E)_0, \pi_M^* \mathbb{L}_{M/B}) \cong \mathrm{Ext}_M^{1-d}(\mathbf{R}\pi_{M*}(\mathbf{R}\mathcal{H}om_X(E, E)_0 \otimes \omega_{\pi_M}), \mathbb{L}_{M/B}), \tag{2}$$

where  $d$  is the relative dimension of  $Y \rightarrow B$  and the isomorphism is given by Grothendieck duality. The image of  $\mathrm{At}_{E/Y}$  along this journey is a morphism

$$\phi: \mathbf{R}\pi_{M*}(\mathbf{R}\mathcal{H}om_X(E, E)_0 \otimes \omega_{\pi_M})[d-1] \longrightarrow \mathbb{L}_{M/B},$$

and it is shown in [22, Thm. 4.1] that  $\phi$  is a relative obstruction theory in the sense of [4, §7]. The following strategy will prove Theorem B:

- (1)  $X$  has a  $G$ -action such that  $E$  is  $G$ -equivariant (Proposition 52).
- (2)  $\mathrm{At}_{E/Y}$  is a  $G$ -invariant extension (thanks to Theorem A).
- (3) The Grothendieck duality isomorphism (2) is  $G$ -equivariant (Corollary 44).
- (4)  $G$ -invariant extensions correspond to morphisms in  $\mathbf{D}(\mathrm{QCoh}_M^G)$ .

Step (4) uses the reductivity of  $G$  via Lemma 37.

**Conventions.** All schemes are noetherian and defined over  $\mathbb{C}$ . By an *algebraic group*  $G$  we mean a connected group scheme of finite type over  $\mathbb{C}$  (often affine). We follow Olsson [35, Ch. 8] for conventions on algebraic stacks (in particular, we make no separation assumptions). For an algebraic stack  $\mathcal{X}$ , we denote by  $\mathrm{QCoh}_{\mathcal{X}}$  the abelian category of quasi-coherent sheaves on the lisse-étale site of  $\mathcal{X}$  [35, Ch. 9], and  $\mathbf{D}(\mathcal{X})$  will denote the unbounded derived category of the abelian category  $\mathrm{Mod}_{\mathcal{O}_{\mathcal{X}}}$  of all  $\mathcal{O}_{\mathcal{X}}$ -modules.

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**1. Equivariant sheaves and complexes**

1.1. *The category of equivariant sheaves*

We work in the algebraic category throughout. A standard reference for the background material covered here, in the topological setup, is the book [6].

Let  $X$  be a noetherian scheme over  $\mathbb{C}$ ,<sup>2</sup> equipped with an action  $\sigma: G \times X \rightarrow X$  of a group scheme  $G$ . We call such a pair  $(X, \sigma)$  a  $G$ -scheme. The abelian category  $\text{Mod}_{\mathcal{O}_X}$  of  $\mathcal{O}_X$ -modules contains the abelian subcategories  $\text{QCoh}_X$  (resp.  $\text{Coh}_X$ ) of quasi-coherent (resp. coherent)  $\mathcal{O}_X$ -modules. We will mostly focus on  $\text{QCoh}_X$  in this paper.

Denoting by  $m: G \times G \rightarrow G$  the group law of  $G$ , there is a commutative diagram

$$\begin{array}{ccc} G \times G \times X & \xrightarrow{m \times \text{id}_X} & G \times X \\ \text{id}_G \times \sigma \downarrow & & \downarrow \sigma \\ G \times X & \xrightarrow{\sigma} & X \end{array} \tag{3}$$

translating the condition  $g \cdot (h \cdot x) = (gh) \cdot x$ .

Let  $p_i: G \times X \rightarrow X$  and  $p_{ij}: G \times G \times X \rightarrow G \times X$  denote the projections onto the labeled factors.

**Definition 2.** A  $G$ -equivariant quasi-coherent sheaf on  $X$  is a pair  $(\mathcal{F}, \vartheta)$  where  $\mathcal{F} \in \text{QCoh}_X$  and  $\vartheta: p_2^* \mathcal{F} \xrightarrow{\sim} \sigma^* \mathcal{F}$  is an isomorphism in  $\text{QCoh}_{G \times X}$  compatible with the diagram (3). In other words,  $\vartheta$  is required to satisfy the cocycle condition

$$(m \times \text{id}_X)^* \vartheta = (\text{id}_G \times \sigma)^* \vartheta \circ p_{23}^* \vartheta. \tag{4}$$

The isomorphism  $\vartheta$  is called a  $G$ -equivariant structure on  $\mathcal{F}$ .

Explicitly, the cocycle condition (4) means that the diagram of isomorphisms

$$\begin{array}{ccc} (m \times \text{id}_X)^* p_2^* \mathcal{F} & \xrightarrow{(m \times \text{id}_X)^* \vartheta} & (m \times \text{id}_X)^* \sigma^* \mathcal{F} \\ \parallel & & \parallel \\ p_{23}^* p_2^* \mathcal{F} & & (\text{id}_G \times \sigma)^* \sigma^* \mathcal{F} \\ \downarrow p_{23}^* \vartheta & & \uparrow (\text{id}_G \times \sigma)^* \vartheta \\ p_{23}^* \sigma^* \mathcal{F} & \xlongequal{\quad} & (\text{id}_G \times \sigma)^* p_2^* \mathcal{F} \end{array}$$

commutes in  $\text{QCoh}_{G \times G \times X}$ .

<sup>2</sup>The theory works relatively to a fixed base scheme  $B$  (see Remark 6). This requires all relative operations (such as fibre products) to be performed over  $B$ , as well as the requirement that  $G \rightarrow B$  be flat (this would be needed e.g. in the construction of  $f_*$  and  $\mathcal{H}om_X$  in Section 1.3).

**Remark 3.** Let  $(X, \sigma)$  be a  $G$ -scheme. Then  $\sigma$  is flat. Indeed, it agrees with the composition

$$G \times X \xrightarrow{\gamma} G \times X \xrightarrow{p_2} X$$

where  $\gamma$  is the automorphism  $(g, x) \mapsto (g, \sigma(g, x))$ , having  $(g, x) \mapsto (g, \sigma(g^{-1}, x))$  as inverse.

**Definition 4.** A morphism  $(\mathcal{F}, \vartheta) \rightarrow (\mathcal{F}', \vartheta')$  of  $G$ -equivariant quasi-coherent sheaves is a morphism  $\phi: \mathcal{F} \rightarrow \mathcal{F}'$  in  $\text{QCoh}_X$  such that the diagram

$$\begin{array}{ccc} p_2^* \mathcal{F} & \xrightarrow{p_2^* \phi} & p_2^* \mathcal{F}' \\ \vartheta \downarrow & & \downarrow \vartheta' \\ \sigma^* \mathcal{F} & \xrightarrow{\sigma^* \phi} & \sigma^* \mathcal{F}' \end{array} \tag{5}$$

commutes in  $\text{QCoh}_{G \times X}$ .

**Notation 5.** Let  $\mathcal{C}$  be any of the categories  $\text{Mod}_{\mathcal{O}_X}$ ,  $\text{QCoh}_X$  or  $\text{Coh}_X$ . We let  $\mathcal{C}^G$  denote the corresponding category of  $G$ -equivariant sheaves  $(\mathcal{F}, \vartheta)$  where  $\mathcal{F} \in \mathcal{C}$ . We mainly focus on  $\mathcal{C} = \text{QCoh}_X$ . The category  $\text{QCoh}_X^G$  is a  $\mathbb{C}$ -linear abelian category (see also Lemma 27 for a stronger statement). Its (unbounded) derived category will be denoted  $\mathbf{D}(\text{QCoh}_X^G)$ .

Consider the composite isomorphism

$$\rho_g: X \xrightarrow{\sim} \{g\} \times X \hookrightarrow G \times X \xrightarrow{\sigma} X, \quad x \mapsto \sigma(g, x).$$

Every object  $(\mathcal{F}, \vartheta) \in \text{QCoh}_X^G$  comes with a collection of isomorphisms

$$\vartheta_g: \mathcal{F} \xrightarrow{\sim} \rho_g^* \mathcal{F}, \quad g \in G,$$

satisfying  $\vartheta_{hg} = \rho_g^* \vartheta_h \circ \vartheta_g$ , where  $\vartheta_g$  is the restriction of  $\vartheta$  along  $X \xrightarrow{\sim} \{g\} \times X \subset G \times X$ .

**Remark 6 (Relative version).** In general, when working with a flat group scheme  $G \rightarrow B$  acting on a scheme  $X \rightarrow B$ , where  $B$  is a base scheme, a  $G$ -equivariant sheaf  $(\mathcal{F}, \vartheta)$  can be described in the following equivalent fashion. Some notation first. For every  $B$ -scheme  $T$ , set  $X_T = T \times_B X = T \times_T X_T$  and let  $\mathcal{F}_T$  denote the pullback of  $\mathcal{F}$  along the projection  $X_T \rightarrow X$ . For every  $T$ -valued point  $g: T \rightarrow G_T = T \times_B G$  of  $G$  one has an isomorphism of  $T$ -schemes

$$\rho_g: X_T \xrightarrow{g \times \text{id}_{X_T}} G_T \times_T X_T \xrightarrow{\sigma_T} X_T, \quad (t, x) \mapsto (t, \sigma_T(g(t), x)).$$

The condition “ $\mathcal{F}$  is  $G$ -equivariant” is equivalent to the following condition: for every  $T$ -valued point  $g \in G_T(T)$  as above there is an isomorphism  $\vartheta_g: \mathcal{F}_T \xrightarrow{\sim} \rho_g^* \mathcal{F}_T$  such that for every pair of  $T$ -valued points  $g, h \in G_T(T)$  one has a commutative diagram of isomorphisms

$$\begin{array}{ccc} \rho_g^* \rho_h^* \mathcal{F}_T & \xleftarrow{\rho_g^* \vartheta_h} & \rho_g^* \mathcal{F}_T \\ \parallel & & \uparrow \vartheta_g \\ \rho_{hg}^* \mathcal{F}_T & \xleftarrow{\vartheta_{hg}} & \mathcal{F}_T \end{array} \tag{6}$$

in  $\text{QCoh}_{X_T}$ .

**Example 7.** Let  $(X, \sigma)$  be a  $G$ -scheme over a scheme  $B$ . Then the structure sheaf  $\mathcal{O}_X$  is  $G$ -equivariant in a natural way. For a  $B$ -scheme  $T$ , set  $X_T = T \times_B X$ . Then the inverse of the natural isomorphisms  $\rho_g^* \mathcal{O}_{X_T} \xrightarrow{\sim} \rho_g^* \rho_{g^*} \mathcal{O}_{X_T} \xrightarrow{\sim} \mathcal{O}_{X_T}$  is a  $G$ -equivariant structure on  $\mathcal{O}_X$ .

**Example 8.** Let  $(X, \sigma)$  be a  $G$ -scheme over a scheme  $B$ . Then the sheaf  $\Omega_{X/B}$  of relative differentials is  $G$ -equivariant in a natural way. Indeed, for a  $B$ -scheme  $T$ , consider the natural isomorphisms  $\alpha_T: (\Omega_{X/B})_T \xrightarrow{\sim} \Omega_{X_T/T}$  and  $\ell_g: \rho_g^* \Omega_{X_T/T} \xrightarrow{\sim} \Omega_{X_T/T}$ , where  $g \in G_T(T)$ . Then the composition

$$\vartheta_g: (\Omega_{X/B})_T \xrightarrow{\alpha_T} \Omega_{X_T/T} \xrightarrow{\ell_g^{-1}} \rho_g^* \Omega_{X_T/T} \xrightarrow{\rho_g^* \alpha_T^{-1}} \rho_g^* (\Omega_{X/B})_T$$

defines an equivariant structure on  $\Omega_{X/B}$ .

**Notation 9.** For an object  $(\mathcal{F}, \vartheta) \in \text{QCoh}_X^G$ , we will often somewhat sloppily omit the  $G$ -equivariant structure “ $\vartheta$ ” from the notation. We will also write  $\text{Hom}_X$  instead of  $\text{Hom}_{\text{QCoh}_X}$  or  $\text{Hom}_{\mathbf{D}(\text{QCoh}_X)}$ , and write  $g^*$  instead of  $\rho_g^*$ .

**Remark 10.** If  $(\mathcal{F}, \vartheta_{\mathcal{F}}), (\mathcal{F}', \vartheta_{\mathcal{F}'}) \in \text{QCoh}_X^G$ , the  $\mathbb{C}$ -vector space

$$\text{Hom}_X(\mathcal{F}, \mathcal{F}')$$

is naturally a  $G$ -representation. Indeed, for a morphism  $\phi: \mathcal{F} \rightarrow \mathcal{F}'$  in  $\text{QCoh}_X$ , one defines  $g \cdot \phi$  by means of the composition

$$\begin{array}{ccc} \mathcal{F} & \xrightarrow{g \cdot \phi} & \mathcal{F}' \\ \vartheta_{\mathcal{F},g} \downarrow & & \uparrow \vartheta_{\mathcal{F}',g}^{-1} \\ g^* \mathcal{F} & \xrightarrow{g^* \phi} & g^* \mathcal{F}' \end{array} \tag{7}$$

exploiting the invertibility of  $\vartheta_{\mathcal{F}',g}$ . The structure of  $G$ -representation on  $\text{Hom}_X(\mathcal{F}, \mathcal{F}')$  clearly depends on the chosen equivariant structures  $\vartheta_{\mathcal{F}}$  and  $\vartheta_{\mathcal{F}'}$ .

**Remark 11.** It is immediate to see that, in  $\text{QCoh}_X^G$ , the morphisms are the  $G$ -invariant morphisms between the underlying quasi-coherent sheaves. In symbols,

$$\text{Hom}_{\text{QCoh}_X^G}((\mathcal{F}, \vartheta_{\mathcal{F}}), (\mathcal{F}', \vartheta_{\mathcal{F}'})) = \text{Hom}_X(\mathcal{F}, \mathcal{F}')^G. \tag{8}$$

Indeed, the diagram (5) becomes precisely

$$\begin{array}{ccc} \mathcal{F} & \xrightarrow{\phi} & \mathcal{F}' \\ \vartheta_{\mathcal{F},g} \downarrow & & \downarrow \vartheta_{\mathcal{F}',g} \\ g^* \mathcal{F} & \xrightarrow{g^* \phi} & g^* \mathcal{F}' \end{array}$$

when restricted to  $\{g\} \times X \cong X$ . Again, in the right hand side of (8) the “ $G$ -invariant part” depends on the  $G$ -structure on  $\text{Hom}_X(\mathcal{F}, \mathcal{F}')$ , which in turn is determined by the pair  $(\vartheta_{\mathcal{F}}, \vartheta_{\mathcal{F}'})$ .

The following result is classical, and is key to this paper. It is proved in [28, Ex. 12.4.6], but see also [35, Exercise 9.H].

**Proposition 12.** *Let  $G$  be a smooth group scheme,  $X$  a  $G$ -scheme. There is an equivalence*

$$\text{QCoh}_X^G \cong \text{QCoh}_{[X/G]}.$$

**Example 13.** Let  $X = \text{Spec } k$ , for a field  $k$ . Then  $\text{QCoh}_{\text{Spec } k}^G \cong \text{QCoh}_{\text{B}_k G}$ , which in turn is equivalent to the category  $\text{Rep}_k(G)$  of locally finite  $k$ -linear representations of  $G$ .

### 1.2. Forgetful functor

There is an exact functor  $\Phi: \mathbf{D}(\text{QCoh}_X^G) \rightarrow \mathbf{D}(\text{QCoh}_X)$  that forgets the equivariant structure. This results in a commutative diagram

$$\begin{array}{ccc} \text{QCoh}_X^G & \xrightarrow{\Phi} & \text{QCoh}_X \\ \downarrow & & \downarrow \\ \mathbf{D}(\text{QCoh}_X^G) & \xrightarrow{\Phi} & \mathbf{D}(\text{QCoh}_X) \end{array}$$

where the vertical arrows are the inclusions of the standard hearts. We write  $\Phi_X$  when we wish to emphasise the scheme. More concretely, if  $p: X \rightarrow [X/G]$  is the standard smooth atlas, we can identify  $\Phi$  as the composition

$$\mathbf{D}(\mathrm{QCoh}_X^G) \xrightarrow{\sim} \mathbf{D}(\mathrm{QCoh}_{[X/G]}) \xrightarrow{p^*} \mathbf{D}(\mathrm{QCoh}_X), \tag{9}$$

where  $p^* = \mathbf{L}p^*$  is the pullback functor as defined in [34, §7] and the first equivalence comes from Proposition 12.

**Remark 14.** The forgetful functor  $\Phi$  reflects exactness: a sequence in  $\mathrm{QCoh}_X^G$  that becomes exact in  $\mathrm{QCoh}_X$  was already exact in  $\mathrm{QCoh}_X^G$ . We will not need this fact.

### 1.3. Geometric functors

Fix two noetherian  $G$ -schemes  $(X, \sigma_X)$  and  $(Y, \sigma_Y)$ . All morphisms  $X \rightarrow Y$  in this subsection are assumed to be  $G$ -equivariant. Since  $X$  and  $Y$  are noetherian, pushforward preserves quasi-coherence.

Let  $(\mathcal{F}, \vartheta)$  and  $(\mathcal{F}', \vartheta')$  be two objects of  $\mathrm{QCoh}_X^G$ . Then there is a canonical lift

$$(\mathcal{F} \otimes \mathcal{F}', \vartheta \otimes \vartheta') \in \mathrm{QCoh}_X^G$$

of the object  $\mathcal{F} \otimes \mathcal{F}' \in \mathrm{QCoh}_X$ . This gives a bi-functor

$$\mathrm{QCoh}_X^G \times \mathrm{QCoh}_X^G \xrightarrow{\otimes} \mathrm{QCoh}_X^G.$$

If  $f: X \rightarrow Y$  is a morphism of  $G$ -schemes, there is a pullback functor

$$\mathrm{QCoh}_Y^G \xrightarrow{f^*} \mathrm{QCoh}_X^G, \quad (\mathcal{E}, \vartheta_{\mathcal{E}}) \mapsto (f^* \mathcal{E}, (\mathrm{id}_G \times f)^* \vartheta_{\mathcal{E}}).$$

By flat base change along  $p_2, \sigma_Y: G \times Y \rightrightarrows Y$  (cf. Remark 3 for flatness of  $\sigma_Y$ ), one constructs a pushforward functor

$$\mathrm{QCoh}_X^G \xrightarrow{f_*} \mathrm{QCoh}_Y^G, \quad (\mathcal{F}, \vartheta_{\mathcal{F}}) \mapsto (f_* \mathcal{F}, (\mathrm{id}_G \times f)_* \vartheta_{\mathcal{F}}),$$

such that  $(f^*, f_*)$  is an adjoint pair.

Finally, given  $(\mathcal{F}, \vartheta) \in \mathrm{Coh}_X^G$  and  $(\mathcal{F}', \vartheta') \in \mathrm{QCoh}_X^G$ , there is a canonical  $G$ -equivariant structure on the quasi-coherent sheaf  $\mathcal{H}om_X(\mathcal{F}, \mathcal{F}')$ ,<sup>3</sup> given by  $\mathcal{H}om_{G \times X}(\vartheta, \vartheta')$ . More precisely, the isomorphism

$$\mathcal{H}om_{G \times X}(\vartheta, \vartheta'): \mathcal{H}om_{G \times X}(p_2^* \mathcal{F}, p_2^* \mathcal{F}') \xrightarrow{\sim} \mathcal{H}om_{G \times X}(\sigma_X^* \mathcal{F}, \sigma_X^* \mathcal{F}')$$

can be used to define the equivariant structure

$$\begin{array}{ccc} p_2^* \mathcal{H}om_X(\mathcal{F}, \mathcal{F}') & \xrightarrow{\vartheta_{\mathcal{H}om_X(\mathcal{F}, \mathcal{F}')}} & \sigma_X^* \mathcal{H}om_X(\mathcal{F}, \mathcal{F}') \\ \downarrow \wr & & \wr \uparrow \\ \mathcal{H}om_{G \times X}(p_2^* \mathcal{F}, p_2^* \mathcal{F}') & \xrightarrow{\mathcal{H}om_{G \times X}(\vartheta, \vartheta')} & \mathcal{H}om_{G \times X}(\sigma_X^* \mathcal{F}, \sigma_X^* \mathcal{F}') \end{array}$$

in the top row, where to obtain the vertical isomorphisms one exploits the flatness of  $p_2$  and of  $\sigma_X$ , as well as the coherence of  $\mathcal{F}$ , see [16, (6.7.6)]. This construction defines a bi-functor

$$\mathrm{Coh}_X^G \times \mathrm{QCoh}_X^G \xrightarrow{\mathcal{H}om_X(\cdot, \cdot)} \mathrm{QCoh}_X^G.$$

<sup>3</sup>Note that  $\mathcal{H}om_X(\mathcal{F}, \mathcal{F}')$  is quasi-coherent because we assumed  $\mathcal{F}$  is coherent.

## 2. Equivariant derived functors and Grothendieck duality

This section contains the technical material needed to prove Theorems A and B. It can be skipped at a first reading.

Throughout this section we fix an affine (connected) algebraic group  $G$  over  $\mathbb{C}$ . In particular  $G$  is smooth by Cartier's theorem. Moreover,  $G$  is *linear*. We also assume (with the exception of Section 2.2, which just records some general definitions) that all schemes are noetherian and separated over  $\mathbb{C}$ .

### 2.1. Ample families of equivariant line bundles

Given a  $G$ -scheme  $X$ , the following condition will be crucial:

$$X \text{ has an ample family of } G\text{-equivariant line bundles.} \quad (\dagger)$$

Condition  $(\dagger)$  means that there exists a family  $\{\mathcal{L}_i\}_{i \in I}$  of  $G$ -equivariant line bundles such that, for every object  $\mathcal{E} \in \text{QCoh}_X$ , the evaluation map yields a surjective morphism

$$\bigoplus_i \bigoplus_{n>0} H^0(X, \mathcal{E} \otimes \mathcal{L}_i^{\otimes n}) \otimes_{\mathbb{C}} (\mathcal{L}_i^\vee)^{\otimes n} \rightarrow \mathcal{E}.$$

Here the index set  $I$  is arbitrary, but since  $X$  is quasi-compact taking  $I$  to be finite yields an equivalent definition.

**Example 15.** If  $X$  is a quasi-projective scheme with a linear  $G$ -action, then  $(\dagger)$  holds. If  $X$  is quasi-projective and there exists at least one  $G$ -equivariant line bundle on  $X$ , then  $X$  admits a  $G$ -equivariant embedding in a smooth scheme.

**Lemma 16.** *If  $X$  admits a  $G$ -equivariant immersion in a smooth separated  $\mathbb{C}$ -scheme, then  $X$  satisfies  $(\dagger)$ .*

**Proof.** Let  $i: X \hookrightarrow A$  be a  $G$ -equivariant locally closed embedding, where  $A$  is a smooth separated  $\mathbb{C}$ -scheme. By [7, II.2.2.7.1],  $A$  has an ample family of line bundles  $\{\mathcal{L}_i\}_i$ . By GIT [31] (but see also the result [45, Thm. 1.6] of Sumihiro), every line bundle  $\mathcal{L}$  on a normal scheme, such as  $A$ , has a tensor power  $\mathcal{L}^{\otimes s}$  that is  $G$ -linearisable (this also uses smoothness of  $G$ ). So  $A$  has an ample family of  $G$ -equivariant line bundles. Since  $i$  is a quasi-affine morphism (and is  $G$ -equivariant), pulling back this family along  $i$  yields an ample family of  $G$ -equivariant line bundles.  $\square$

**Remark 17.** By a result of Thomason [46], we have the implication

$$X \text{ satisfies } (\dagger) \implies [X/G] \text{ has the resolution property,}$$

where the condition on the right means that every  $G$ -equivariant *coherent*  $\mathcal{O}_X$ -module is the quotient of a  $G$ -equivariant locally free  $\mathcal{O}_X$ -module of finite type.

**Remark 18.** For a  $G$ -scheme  $X$ , Condition  $(\dagger)$  is *not* equivalent to the resolution property for the stack  $[X/G]$ . In [48, §9] an example is given of a projective variety  $X$  (a nodal cubic curve) acted on by an algebraic group  $G$  (the torus  $\mathbb{G}_m$ ), such that  $X$  does not admit a family of  $G$ -equivariant line bundles. However, the quotient stack  $[X/G]$  does have the resolution property [48, Prop. 9.1].

### 2.2. Quasi-coherent sheaves on quotient stacks

For the sake of completeness, and for future reference, we record here a few properties of (quotient) stacks and their derived categories.

2.2.1. *Perfect complexes on schemes*

Let  $X$  be an arbitrary scheme.

**Definition 19** (cf. [47, Section 2]). *A complex  $E \in \mathbf{D}(X)$  is called perfect (resp. strictly perfect) if it is locally (resp. globally) quasi-isomorphic to a bounded complex of locally free  $\mathcal{O}_X$ -modules of finite type. We let  $\text{Perf } X$  denote the triangulated category of perfect complexes on  $X$ .*

**Remark 20.** As long as  $X$  is quasi-compact, quasi-separated and has an ample family of line bundles, there is no difference between perfect and strictly perfect [47, Prop. 2.3.1 (d)]. For  $G$ -schemes satisfying condition  $(\dagger)$ , every perfect complex is then a *bounded* complex.

By [44, Tag 08DB], if  $X$  is quasi-compact and semi-separated (i.e. has affine diagonal), the canonical functor  $\mathbf{D}(\text{QCoh}_X) \rightarrow \mathbf{D}_{\text{qc}}(X)$  is an equivalence. The same holds true for any noetherian scheme [44, Tag 09TN]. Here the decoration “qc” means that the cohomology sheaves of the complexes lie in  $\text{QCoh}_X$ . Our schemes will be noetherian, so all statements usually made about  $\mathbf{D}_{\text{qc}}(X)$  can, and will be rephrased here using  $\mathbf{D}(\text{QCoh}_X)$ .

2.2.2. *Separation and noetherianity for algebraic stacks*

Let  $S$  be a scheme. Recall that a morphism of schemes  $X \rightarrow S$  is *quasi-separated* if the diagonal  $X \rightarrow X \times_S X$  is quasi-compact. On the other hand, an algebraic stack  $\mathcal{X} \rightarrow S$  is *quasi-separated* if the diagonal  $\mathcal{X} \rightarrow \mathcal{X} \times_S \mathcal{X}$  is quasi-compact *and quasi-separated*, see [35, Def. 8.2.12].

Let  $G \rightarrow S$  be a smooth quasi-compact separated group scheme acting on a quasi-compact quasi-separated  $S$ -scheme  $X \rightarrow S$ . An algebraic stack of the form  $[X/G] \rightarrow S$  has representable, quasi-compact and separated diagonal [28, Ex. 4.6.1], therefore it is quasi-separated.

An algebraic stack is *noetherian* if it is quasi-compact, quasi-separated and admits a noetherian atlas. For instance, if  $X$  is a noetherian scheme acted on by a smooth affine algebraic group, then  $[X/G]$  is a noetherian algebraic stack. Indeed,  $X \rightarrow [X/G]$  is an atlas; we just established quasi-separatedness, and quasi-compactness can be checked on an atlas [44, Tag 04YA].

2.2.3. *Compact generation for derived categories*

For an algebraic stack  $\mathcal{X}$ , the inclusion  $\text{QCoh}_{\mathcal{X}} \subset \text{Mod}_{\mathcal{O}_{\mathcal{X}}}$  of the abelian category of quasi-coherent  $\mathcal{O}_{\mathcal{X}}$ -modules on the lisse-étale site of  $\mathcal{X}$  (cf. [35, Def. 9.1.6]) inside the abelian category of all  $\mathcal{O}_{\mathcal{X}}$ -modules induces a canonical functor

$$\mathbf{D}(\text{QCoh}_{\mathcal{X}}) \longrightarrow \mathbf{D}_{\text{qc}}(\mathcal{X}) \subset \mathbf{D}(\mathcal{X}).$$

We now briefly recall the notion of compact generation. It will be essential in the proof of equivariant Grothendieck duality (Theorem 41).

**Definition 21** (cf. [32, Def. 1.7]). *A triangulated category  $\mathcal{S}$  with small coproducts is said to be compactly generated if there is a set of objects  $\mathcal{S}' \subset \mathcal{S}$  such that for every  $s \in \mathcal{S}'$  the functor  $\text{Hom}_{\mathcal{S}}(s, -)$  commutes with coproducts, and whenever  $y$  is an object of  $\mathcal{S}$  such that  $\text{Hom}_{\mathcal{S}}(s, y) = 0$  for all  $s \in \mathcal{S}'$ , then it follows that  $y = 0$ .*

**Proposition 22.** *Let  $X$  be a noetherian scheme over  $\mathbb{C}$ , acted on by an affine algebraic group  $G$  and satisfying  $(\dagger)$ . Set  $\mathcal{X} = [X/G]$ . The derived category  $\mathbf{D}(\text{QCoh}_{\mathcal{X}})$  has small coproducts and is compactly generated.*

**Proof.** First of all,  $\mathbf{D}(\text{QCoh}_{\mathcal{X}})$  has small coproducts because  $\text{QCoh}_{\mathcal{X}}$  is a Grothendieck abelian category [44, Tag 06WU].

Next,  $\mathcal{X}$  is quasi-separated and noetherian: this was established in Section 2.2.2. Since  $G$  is affine,  $\mathcal{X}$  has affine stabiliser groups at closed points. By [48, Prop. 1.3], a noetherian algebraic

stack with affine stabiliser groups at closed points, and having the resolution property, has affine diagonal. Therefore, by Remark 17,  $\mathcal{X}$  has affine diagonal.

Since we work in characteristic 0 and  $X$  has an ample family  $\{\mathcal{L}_i\}$  of  $G$ -equivariant line bundles,  $\mathcal{X}$  is concentrated (see [19, Ex. 8.6], and [19, Def. 2.4] for the definition of concentrated), thus it has the compact resolution property; therefore we can apply [19, Prop. 8.4] to conclude that the family of line bundles  $\{\mathcal{L}_i\}$  (including their shifts), viewed as line bundles over  $\mathcal{X}$ , form a family of compact generators for  $\mathbf{D}_{\text{qc}}(\mathcal{X})$ .

Summing up,  $\mathcal{X}$  is a quasi-compact algebraic stack with affine diagonal and such that  $\mathbf{D}_{\text{qc}}(\mathcal{X})$  is compactly generated: by [17, Thm. 1.2] this implies that the canonical functor  $\mathbf{D}(\text{QCoh}_{\mathcal{X}}) \rightarrow \mathbf{D}_{\text{qc}}(\mathcal{X})$  is an equivalence. Thus  $\mathbf{D}(\text{QCoh}_{\mathcal{X}})$  is compactly generated.  $\square$

**Remark 23.** See also [19, Rem. 8.7] for the statement (an example of application of [19, Prop. 8.4]) that for a quasi-compact concentrated algebraic stack  $\mathcal{X}$  having affine diagonal and the resolution property, the category  $\mathbf{D}_{\text{qc}}(\mathcal{X})$  is compactly generated.

**Corollary 24.** *The category  $\mathbf{D}(\text{QCoh}_X^G)$  is compactly generated.*

**Proof.** This follows directly from Proposition 12.  $\square$

**Remark 25.** Combining Proposition 12 with the proof of Proposition 22 shows that if  $X$  is a noetherian  $\mathbb{C}$ -scheme acted on by an affine algebraic group  $G$ , and satisfying  $(\dagger)$ , then we have equivalences

$$\mathbf{D}(\text{QCoh}_X^G) \xrightarrow{\sim} \mathbf{D}(\text{QCoh}_{[X/G]}) \xrightarrow{\sim} \mathbf{D}_{\text{qc}}([X/G]). \tag{10}$$

The literature on derived functors for algebraic stacks usually refers to  $\mathbf{D}_{\text{qc}}$ , but given the equivalences (10) implied by our assumptions, we will state the results we need for  $\mathbf{D}(\text{QCoh}^G)$ .

**Example 26.** Let  $G$  be a group scheme of finite type over a field  $k$  of characteristic 0. Then  $\mathbf{D}_{\text{qc}}(\text{B}_k G)$  is compactly generated. Moreover, if  $G$  is affine, it is compactly generated by the irreducible  $k$ -representations of  $G$ , see [18, Thm. A]. Let  $\text{Rep}_k(G)$  be the abelian category of  $k$ -linear locally finite representations of  $G$ . Then by [17, Thm. 1.2] the natural functor  $\mathbf{D}(\text{Rep}_k(G)) = \mathbf{D}(\text{QCoh}_{\text{B}_k G}) \rightarrow \mathbf{D}_{\text{qc}}(\text{B}_k G)$  is an equivalence.

### 2.3. Equivariant derived functors

In this subsection  $G$  denotes an affine (connected) complex algebraic group. All  $G$ -schemes are noetherian, separated over  $\mathbb{C}$ , and satisfy  $(\dagger)$ . In particular all morphisms, which we always assume to be  $G$ -equivariant, are quasi-compact and separated.

The following result lies at the foundations of the construction of derived versions of the geometric functors recalled in Section 1.3.

**Lemma 27 (cf. [49, Prop. 1.5.7 (a) and Prop. 1.5.6 (a)]).** *Let  $X$  be a  $G$ -scheme. The category  $\text{QCoh}_X^G$  is a Grothendieck abelian category with enough injectives. Moreover, any complex of objects in  $\text{QCoh}_X^G$  has a  $K$ -injective resolution and a  $K$ -flat resolution.*

**Remark 28.** Serpé proved that, in fact, unbounded complexes on any Grothendieck category admit  $K$ -injective resolutions [42, Thm. 3.13].

**Remark 29.** The resolutions mentioned in Lemma 27 (which are carefully defined in [49, Def. 1.5.3 (c), (d)]) are precisely the  $G$ -equivariant analogues of those used by Spaltenstein to construct derived functors for unbounded derived categories in the non-equivariant case, see in particular Definitions 1.1 and 5.1 in [43].

K-flat and K-injective resolutions allow one to define equivariant derived functors. As explained in [49, §1.5], K-flat resolutions are needed to construct derived tensor product and derived pullback, whereas K-injective resolutions are used to construct derived pushforward.

**Proposition 30 (cf. [49, Prop. 1.5.6, 1.5.7]).** *Let  $X$  be a  $G$ -scheme. There is a left derived functor*

$$\otimes^{\mathbf{L}}: \mathbf{D}(\mathrm{QCoh}_X^G) \times \mathbf{D}(\mathrm{QCoh}_X^G) \longrightarrow \mathbf{D}(\mathrm{QCoh}_X^G).$$

*If  $f: X \rightarrow Y$  is a morphism of  $G$ -schemes, there is a left derived functor*

$$\mathbf{L}f^*: \mathbf{D}(\mathrm{QCoh}_Y^G) \longrightarrow \mathbf{D}(\mathrm{QCoh}_X^G),$$

*and a right derived functor*

$$\mathbf{R}f_*: \mathbf{D}(\mathrm{QCoh}_X^G) \longrightarrow \mathbf{D}(\mathrm{QCoh}_Y^G).$$

To construct the equivariant derived sheaf Hom functor, we proceed as follows. We consider the quotient stack  $\mathcal{X} = [X/G]$  and the category  $\mathrm{Perf}(\mathcal{X}) \subset \mathbf{D}_{\mathrm{qc}}(\mathcal{X})$  of perfect complexes. We also let  $\mathrm{Perf}^G(X) \subset \mathbf{D}(\mathrm{QCoh}_X^G)$  be the image of  $\mathrm{Perf}(\mathcal{X})$  under the equivalence  $\mathbf{D}_{\mathrm{qc}}(\mathcal{X}) \xrightarrow{\sim} \mathbf{D}(\mathrm{QCoh}_X^G)$ .

By [19, Lemma 4.3 (2)], the bifunctor

$$\mathbf{R}\mathcal{H}om_{\mathcal{X}}(\cdot, \cdot): \mathbf{D}(\mathcal{X}) \times \mathbf{D}(\mathcal{X})^{\mathrm{op}} \longrightarrow \mathbf{D}(\mathcal{X}) \tag{11}$$

calculated in  $\mathcal{O}_{\mathcal{X}}$ -modules restricts to

$$\mathbf{R}\mathcal{H}om_{\mathcal{X}}(\cdot, \cdot): \mathrm{Perf}(\mathcal{X}) \times \mathbf{D}(\mathrm{QCoh}_{\mathcal{X}})^{\mathrm{op}} \longrightarrow \mathbf{D}(\mathrm{QCoh}_{\mathcal{X}}).$$

Let  $p: X \rightarrow \mathcal{X}$  denote the standard atlas. Exploiting the equivalences (10) and the factorisation (9), we obtain a diagram

$$\begin{array}{ccc}
 \mathrm{Perf}(\mathcal{X}) \times \mathbf{D}(\mathrm{QCoh}_{\mathcal{X}})^{\mathrm{op}} & \xrightarrow{\mathbf{R}\mathcal{H}om_{\mathcal{X}}(\cdot, \cdot)} & \mathbf{D}(\mathrm{QCoh}_{\mathcal{X}}) \\
 \downarrow \wr & & \downarrow \wr \\
 \mathrm{Perf}^G(X) \times \mathbf{D}(\mathrm{QCoh}_X^G)^{\mathrm{op}} & \xrightarrow{\mathbf{R}\mathcal{H}om_X(\cdot, \cdot)} & \mathbf{D}(\mathrm{QCoh}_X^G) \\
 \downarrow \Phi \times \Phi & & \downarrow \Phi \\
 \mathrm{Perf}(X) \times \mathbf{D}(\mathrm{QCoh}_X)^{\mathrm{op}} & \xrightarrow{\mathbf{R}\mathcal{H}om_X(\cdot, \cdot)} & \mathbf{D}(\mathrm{QCoh}_X)
 \end{array}$$

$\left( \begin{array}{c} \text{Left side of diagram} \\ \text{Right side of diagram} \end{array} \right) \begin{array}{c} p^* \times p^* \\ p^* \end{array}$

where the bottom row is the ordinary derived sheaf Hom functor. The top square is used to *define* the  $G$ -equivariant  $\mathbf{R}\mathcal{H}om_X(\cdot, \cdot)$  in the middle row, so it commutes by construction, whereas the commutativity of the whole diagram, which is equivalent to the statement

$$p^* \mathbf{R}\mathcal{H}om_{\mathcal{X}}(\mathcal{E}^\bullet, \mathcal{F}^\bullet) = \mathbf{R}\mathcal{H}om_X(p^* \mathcal{E}^\bullet, p^* \mathcal{F}^\bullet), \tag{12}$$

is used to observe that the lower square is also commutative: this means that the  $G$ -equivariant  $\mathbf{R}\mathcal{H}om_X(\cdot, \cdot)$  commutes with the forgetful functor  $\Phi$ .

We thank David Rydh for pointing out the following.

**Remark 31.** The “quasi-coherent” derived sheaf Hom functor

$$\mathbf{R}\mathcal{H}om_{\mathcal{X}}^{\mathrm{qc}}(\cdot, \cdot): \mathbf{D}_{\mathrm{qc}}(\mathcal{X}) \times \mathbf{D}_{\mathrm{qc}}(\mathcal{X})^{\mathrm{op}} \longrightarrow \mathbf{D}_{\mathrm{qc}}(\mathcal{X})$$

considered in [19, §1.2], defined by composing the restriction of (11) with the *quasi-coherator*  $\mathbf{D}(\mathcal{X}) \rightarrow \mathbf{D}_{\mathrm{qc}}(\mathcal{X})$ , does not commute with pullback in general. However, (12) holds true precisely because we restricted to perfect complexes in the first entry. In this case, if we take  $(\mathcal{E}^\bullet, \mathcal{F}^\bullet) \in \mathrm{Perf}(\mathcal{X}) \times \mathbf{D}_{\mathrm{qc}}(\mathcal{X})$ , we have indeed

$$\mathbf{R}\mathcal{H}om_{\mathcal{X}}(\mathcal{E}^\bullet, \mathcal{F}^\bullet) = \mathbf{R}\mathcal{H}om_{\mathcal{X}}^{\mathrm{qc}}(\mathcal{E}^\bullet, \mathcal{F}^\bullet) = \mathcal{E}^{\bullet \vee} \otimes^{\mathbf{L}} \mathcal{F}^\bullet,$$

and (12) follows since duals of perfect complexes, which are dualisable, commute with arbitrary pullback. See [19, Lem. 4.3] and the paragraph before it for more details.

The  $G$ -equivariant derived functors listed above satisfy the usual compatibilities. Here are some of them: given a morphism  $f: X \rightarrow Y$  of  $G$ -schemes,

- (1)  $\mathbf{L}f^*$  is left adjoint to  $\mathbf{R}f_*$ ,
- (2)  $\mathbf{R}f_*$  preserves cohomologically bounded complexes,
- (3)  $\mathbf{L}f^*$ ,  $\mathbf{R}f_*$ ,  $\otimes^{\mathbf{L}}$  and  $\mathbf{R}\mathcal{H}om_X(\cdot, \cdot)$  commute with the forgetful functor  $\Phi$  (cf. [49, §1.5.8]).
- (4) The projection formula

$$\mathcal{E}^\bullet \otimes^{\mathbf{L}} \mathbf{R}f_* \mathcal{F}^\bullet = \mathbf{R}f_*(\mathbf{L}f^* \mathcal{E}^\bullet \otimes^{\mathbf{L}} \mathcal{F}^\bullet)$$

holds, for all  $\mathcal{F}^\bullet \in \mathbf{D}(\mathrm{QCoh}_X^G)$  and  $\mathcal{E}^\bullet \in \mathbf{D}(\mathrm{QCoh}_Y^G)$ .

For us, the most important property is (3).

### 2.4. Equivariant Ext groups

For a  $G$ -scheme  $X$  with structure morphism  $\pi: X \rightarrow \mathrm{Spec} \mathbb{C}$ , we write  $\mathbf{R}\Gamma_X = \mathbf{R}\pi_*$ . Since the  $G$ -equivariant derived functors commute with the forgetful morphism, given  $(\mathcal{E}^\bullet, \mathcal{F}^\bullet) \in \mathrm{Perf}^G(X) \times \mathbf{D}(\mathrm{QCoh}_X^G)$ , the complex

$$\mathbf{R}\Gamma_X \mathbf{R}\mathcal{H}om_X(\mathcal{E}^\bullet, \mathcal{F}^\bullet) \in \mathbf{D}(\mathrm{QCoh}_{\mathrm{pt}}^G) = \mathbf{D}(\mathrm{Rep}_{\mathbb{C}}(G))$$

is a complex of  $G$ -representations with  $\mathbf{R}\mathrm{Hom}_X(\Phi_X(\mathcal{E}^\bullet), \Phi_X(\mathcal{F}^\bullet))$  as underlying complex of vector spaces. We will often omit  $\Phi_X$  from the notation.

**Remark 32.** The cohomology functors  $H^k: \mathbf{D}(\mathrm{QCoh}_{\mathrm{pt}}^G) \rightarrow \mathrm{QCoh}_{\mathrm{pt}}^G$  also commute with the forgetful functor. In other words, for any object  $V^\bullet \in \mathbf{D}(\mathrm{QCoh}_{\mathrm{pt}}^G)$ , there is a natural structure of  $G$ -representation on the vector spaces  $H^k(\Phi_{\mathrm{pt}}(V^\bullet))$ . Thus, given  $(\mathcal{E}^\bullet, \mathcal{F}^\bullet) \in \mathrm{Perf}^G(X) \times \mathbf{D}(\mathrm{QCoh}_X^G)$ , all Ext groups

$$\mathrm{Ext}_X^k(\mathcal{E}^\bullet, \mathcal{F}^\bullet) := H^k(\mathbf{R}\mathrm{Hom}_X(\Phi_X(\mathcal{E}^\bullet), \Phi_X(\mathcal{F}^\bullet))) \in \mathrm{QCoh}_{\mathrm{pt}} \tag{13}$$

have a natural structure of  $G$ -representations. Therefore the  $G$ -invariant part

$$\mathrm{Ext}_X^k(\mathcal{E}^\bullet, \mathcal{F}^\bullet)^G \subset \mathrm{Ext}_X^k(\mathcal{E}^\bullet, \mathcal{F}^\bullet)$$

is well-defined.

We now describe the  $G$ -representation structure on (13) explicitly. We set  $k = 0$ , the general case being obtained by replacing  $\mathcal{F}^\bullet$  with  $\mathcal{F}^\bullet[k]$ .

Fix a pair  $(\mathcal{E}^\bullet, \mathcal{F}^\bullet) \in \mathrm{Perf}^G(X) \times \mathbf{D}(\mathrm{QCoh}_X^G)$  and a morphism  $\alpha: \mathcal{E}^\bullet \rightarrow \mathcal{F}^\bullet$  in  $\mathbf{D}(\mathrm{QCoh}_X)$ . For simplicity, assume  $\alpha$  is represented by a cochain map

$$\begin{array}{ccccccc} \dots & \longrightarrow & \mathcal{E}^i & \xrightarrow{d_{\mathcal{E}^\bullet}^i} & \mathcal{E}^{i+1} & \longrightarrow & \dots \\ & & \alpha_i \downarrow & & \downarrow \alpha_{i+1} & & \\ \dots & \longrightarrow & \mathcal{F}^i & \xrightarrow{d_{\mathcal{F}^\bullet}^i} & \mathcal{F}^{i+1} & \longrightarrow & \dots \end{array} \tag{14}$$

where all arrows are in the category  $\mathrm{QCoh}_X$ . The sheaves  $\mathcal{E}^i$  (resp.  $\mathcal{F}^i$ ) carry a  $G$ -equivariant structure  $\vartheta_{\mathcal{E}^i}$  (resp.  $\vartheta_{\mathcal{F}^i}$ ). We let  $g \in G$  act on  $\alpha = (\alpha_i)_{i \in \mathbb{Z}}$  by  $g \cdot \alpha = (g \cdot \alpha_i)_{i \in \mathbb{Z}}$ , where the element

$g \cdot \alpha_i = \vartheta_{\mathcal{F}^i, g}^{-1} \circ g^* \alpha_i \circ \vartheta_{\mathcal{E}^i, g} \in \text{Hom}_X(\mathcal{E}^i, \mathcal{F}^i)$  was defined via Diagram (7). For fixed  $g \in G$  and  $i \in \mathbb{Z}$ , the diagram

$$\begin{array}{ccc}
 \mathcal{E}^i & \xrightarrow{d_{\mathcal{E}^\bullet}^i} & \mathcal{E}^{i+1} \\
 \downarrow \vartheta_{\mathcal{E}^i, g} & & \downarrow \vartheta_{\mathcal{E}^{i+1}, g} \\
 g^* \mathcal{E}^i & \xrightarrow{g^* d_{\mathcal{E}^\bullet}^i} & g^* \mathcal{E}^{i+1} \\
 \downarrow g^* \alpha_i & & \downarrow g^* \alpha_{i+1} \\
 g^* \mathcal{F}^i & \xrightarrow{g^* d_{\mathcal{F}^\bullet}^i} & g^* \mathcal{F}^{i+1} \\
 \downarrow \vartheta_{\mathcal{F}^i, g}^{-1} & & \downarrow \vartheta_{\mathcal{F}^{i+1}, g}^{-1} \\
 \mathcal{F}^i & \xrightarrow{d_{\mathcal{F}^\bullet}^i} & \mathcal{F}^{i+1}
 \end{array}
 \tag{15}$$

in  $\text{QCoh}_X$  illustrates the situation: since  $(\mathcal{E}^\bullet, d_{\mathcal{E}^\bullet})$  and  $(\mathcal{F}^\bullet, d_{\mathcal{F}^\bullet})$  are objects of  $\mathbf{D}(\text{QCoh}_X^G)$ , the morphisms  $d_{\mathcal{E}^\bullet}^i$  and  $d_{\mathcal{F}^\bullet}^i$ , as soon as we view them in  $\text{QCoh}_X$ , satisfy

$$\begin{aligned}
 d_{\mathcal{E}^\bullet}^i &= g \cdot d_{\mathcal{E}^\bullet}^i = \vartheta_{\mathcal{E}^{i+1}, g}^{-1} \circ g^* d_{\mathcal{E}^\bullet}^i \circ \vartheta_{\mathcal{E}^i, g} \\
 d_{\mathcal{F}^\bullet}^i &= g \cdot d_{\mathcal{F}^\bullet}^i = \vartheta_{\mathcal{F}^{i+1}, g}^{-1} \circ g^* d_{\mathcal{F}^\bullet}^i \circ \vartheta_{\mathcal{F}^i, g}
 \end{aligned}$$

respectively, for all  $g \in G$  (cf. Remark 11). Therefore the top and bottom squares commute. So does the middle square, by the commutativity of (14). Therefore the outer square commutes, thus defining the morphism  $g \cdot \alpha \in \text{Hom}_X(\mathcal{E}^\bullet, \mathcal{F}^\bullet)$ .

**Remark 33.** Let  $\mathcal{E}^\bullet$  be an object of  $\text{Perf}^G(X)$ . Then

$$\text{id}_{\mathcal{E}^\bullet} \in \text{Hom}_X(\mathcal{E}^\bullet, \mathcal{E}^\bullet)^G \subset \text{Hom}_X(\mathcal{E}^\bullet, \mathcal{E}^\bullet).$$

This is clear by looking at the diagram (15) where all  $\alpha_i = \text{id}_{\mathcal{E}^i}$ .

**Lemma 34.** *The following statements hold.*

(1) Fix  $\mathcal{F}^\bullet \in \text{Perf}^G(X)$ . A distinguished triangle  $\mathcal{E}_1^\bullet \rightarrow \mathcal{E}_2^\bullet \rightarrow \mathcal{E}_3^\bullet \rightarrow \mathcal{E}_1^\bullet[1]$  in  $\mathbf{D}(\text{QCoh}_X^G)$  induces a long exact sequence

$$\dots \rightarrow \text{Ext}_X^k(\mathcal{F}^\bullet, \mathcal{E}_1^\bullet) \rightarrow \text{Ext}_X^k(\mathcal{F}^\bullet, \mathcal{E}_2^\bullet) \rightarrow \text{Ext}_X^k(\mathcal{E}_3^\bullet, \mathcal{F}^\bullet) \rightarrow \text{Ext}_X^{k+1}(\mathcal{F}^\bullet, \mathcal{E}_1^\bullet) \rightarrow \dots$$

of  $G$ -representations.

(2) Fix  $\mathcal{F}^\bullet \in \mathbf{D}(\text{QCoh}_X^G)$ . A distinguished triangle  $\mathcal{E}_1^\bullet \rightarrow \mathcal{E}_2^\bullet \rightarrow \mathcal{E}_3^\bullet \rightarrow \mathcal{E}_1^\bullet[1]$  in  $\text{Perf}^G(X)$  induces a long exact sequence

$$\dots \rightarrow \text{Ext}_X^k(\mathcal{E}_3^\bullet, \mathcal{F}^\bullet) \rightarrow \text{Ext}_X^k(\mathcal{E}_2^\bullet, \mathcal{F}^\bullet) \rightarrow \text{Ext}_X^k(\mathcal{E}_1^\bullet, \mathcal{F}^\bullet) \rightarrow \text{Ext}_X^{k+1}(\mathcal{E}_3^\bullet, \mathcal{F}^\bullet) \rightarrow \dots$$

of  $G$ -representations.

**Proof.** To prove (1), apply the composition  $\mathbf{R}\Gamma_X \circ \mathbf{R}\mathcal{H}om_X(\mathcal{F}^\bullet, \cdot)$  of equivariant derived functors, and then cohomology  $H^\bullet : \mathbf{D}(\text{Rep}_\mathbb{C}(G)) \rightarrow \text{Rep}_\mathbb{C}(G)$ , to the given distinguished triangle: exploiting Remark 32, this yields the first sequence. To prove (2), use  $\mathbf{R}\mathcal{H}om_X(\cdot, \mathcal{F}^\bullet)$ .  $\square$

We will only need the following special case.

**Corollary 35.** *The following statements hold.*

(1) Fix  $\mathcal{F}^\bullet \in \text{Perf}^G(X)$ . A morphism  $j : \mathcal{E}_1^\bullet \rightarrow \mathcal{E}_2^\bullet$  in  $\mathbf{D}(\text{QCoh}_X^G)$  induces a morphism of  $G$ -representations

$$j_* : \text{Hom}_X(\mathcal{F}^\bullet, \mathcal{E}_1^\bullet) \rightarrow \text{Hom}_X(\mathcal{F}^\bullet, \mathcal{E}_2^\bullet), \quad \alpha \mapsto j \circ \alpha.$$

(2) Fix  $\mathcal{F} \in \mathbf{D}(\mathrm{QCoh}_X^G)$ . A morphism  $i: \mathcal{E}_1^\bullet \rightarrow \mathcal{E}_2^\bullet$  in  $\mathrm{Perf}^G(X)$  induces a morphism of  $G$ -representations

$$i^*: \mathrm{Hom}_X(\mathcal{E}_2^\bullet, \mathcal{F}^\bullet) \longrightarrow \mathrm{Hom}_X(\mathcal{E}_1^\bullet, \mathcal{F}^\bullet), \quad \beta \longmapsto \beta \circ i.$$

The following definition will be central in the next sections.

**Definition 36.** Fix  $(\mathcal{E}^\bullet, \mathcal{F}^\bullet) \in \mathbf{D}(\mathrm{QCoh}_X^G) \times \mathbf{D}(\mathrm{QCoh}_X^G)$ . We say that an extension class

$$\alpha \in \mathrm{Ext}_X^k(\mathcal{E}^\bullet, \mathcal{F}^\bullet)$$

is  $G$ -equivariant if the corresponding morphism  $\mathcal{E}^\bullet \rightarrow \mathcal{F}^\bullet[k]$  admits a lift to  $\mathbf{D}(\mathrm{QCoh}_X^G)$ , i.e. if it lies in the image of the natural morphism  $\mathrm{Hom}_{\mathbf{D}(\mathrm{QCoh}_X^G)}(\mathcal{E}^\bullet, \mathcal{F}^\bullet[k]) \rightarrow \mathrm{Hom}_X(\mathcal{E}^\bullet, \mathcal{F}^\bullet[k])$ . Recall that we omit  $\Phi$  from the notation in the target Hom-set. We say that  $\alpha$  is  $G$ -invariant if it belongs to  $\mathrm{Ext}_X^k(\mathcal{E}^\bullet, \mathcal{F}^\bullet)^G$ .

### 2.4.1. The case of reductive groups

Recall from [31, App. A] that, over a field of characteristic 0, a linear algebraic group  $G$  is *reductive* if and only if it is linearly reductive. This means that the functor

$$(\cdot)^G: \mathrm{QCoh}_{\mathrm{pt}}^G \longrightarrow \mathrm{QCoh}_{\mathrm{pt}}, \quad V \longmapsto V^G,$$

taking a  $G$ -representation to its  $G$ -invariant part, is exact.

Reductivity has the following important property.

**Lemma 37 (cf. [2, Lem. 2.2.8]).** Let  $G$  be a reductive algebraic group acting on a complex noetherian separated  $G$ -scheme  $X$ . Set  $\mathcal{X} = [X/G]$  and fix  $k \in \mathbb{Z}$  and two objects  $\mathcal{E}^\bullet, \mathcal{F}^\bullet \in \mathbf{D}(\mathrm{QCoh}_X^G) = \mathbf{D}(\mathrm{QCoh}_{\mathcal{X}})$ . Then there are natural isomorphisms

$$\mathrm{Hom}_{\mathcal{X}}(\mathcal{E}^\bullet, \mathcal{F}^\bullet[k]) \xrightarrow{\sim} \mathrm{Hom}_X(\mathcal{E}^\bullet, \mathcal{F}^\bullet[k])^G.$$

The Hom-set on the left hand side is taken in  $\mathbf{D}(\mathrm{QCoh}_{\mathcal{X}})$ , the Hom-set on the right hand side is taken in  $\mathbf{D}(\mathrm{QCoh}_X)$ .

**Remark 38.** If  $G$  is reductive, then by Lemma 37 an extension class  $\alpha$  is  $G$ -equivariant if and only if it is  $G$ -invariant.

### 2.5. Equivariant Grothendieck duality

Classically, one says that Grothendieck duality holds for a morphism of schemes  $f$  if the right derived functor  $\mathbf{R}f_*$  has a right adjoint. Such adjoint is usually denoted  $f^\times$ , or  $f^!$  if  $f$  is a proper morphism. We will stick to the  $f^!$  notation.

The most general statement we are aware of is due to Neeman. Note that this is stated for  $\mathbf{D}_{\mathrm{qc}}$  in [32], but (as we observed in Section 2.2.1) with our assumptions these categories are equivalent to  $\mathbf{D}(\mathrm{QCoh})$ .

**Theorem 39 (Grothendieck duality [32]).** Let  $f: X \rightarrow Y$  be a morphism of quasi-compact separated schemes. Then  $\mathbf{R}f_*: \mathbf{D}(\mathrm{QCoh}_X) \rightarrow \mathbf{D}(\mathrm{QCoh}_Y)$  has a right adjoint  $f^!$ . If  $f$  is a proper morphism of noetherian separated schemes, the natural morphism

$$\mathbf{R}f_* \mathbf{R}\mathcal{H}om_X(\mathcal{F}^\bullet, f^! \mathcal{E}^\bullet) \longrightarrow \mathbf{R}\mathcal{H}om_Y(\mathbf{R}f_* \mathcal{F}^\bullet, \mathcal{E}^\bullet) \tag{16}$$

is an isomorphism in  $\mathbf{D}(Y)$  for all  $\mathcal{F}^\bullet \in \mathbf{D}(\mathrm{QCoh}_X)$  and  $\mathcal{E}^\bullet \in \mathbf{D}(\mathrm{QCoh}_Y)$ .

**Proof.** The first assertion is [32, Ex. 4.2]. The sheafified Grothendieck duality isomorphism (16) is obtained in [32, §6]. A proof of (16) assuming  $f$  is a morphism essentially of finite type between noetherian separated schemes can be found in [26, Eq. 1.6.1].  $\square$

We refer the reader to Neeman [32] and Lipman [30] for very informative discussions around the history of Grothendieck duality, as well its more modern versions.

In this section we prove a  $G$ -equivariant version of Theorem 39. We follow Neeman’s strategy entirely. See also [19, Thm. 4.14 (1)] for a generalisation, proving the existence of a right adjoint of  $\mathbf{R}h_* : \mathbf{D}_{\text{qc}}(\mathcal{X}) \rightarrow \mathbf{D}_{\text{qc}}(\mathcal{Y})$  for  $h: \mathcal{X} \rightarrow \mathcal{Y}$  an arbitrary concentrated morphism (cf. [19, Def. 2.4]) of algebraic stacks.

The main tool used by Neeman is the following version of Brown’s representability theorem.

**Theorem 40 (Brown representability [32, Thm. 4.1]).** *Let  $\mathcal{S}$  be a compactly generated triangulated category,  $\mathcal{T}$  any triangulated category. Let  $F: \mathcal{S} \rightarrow \mathcal{T}$  be a triangulated functor respecting coproducts. Then  $F$  has a right adjoint.*

**Theorem 41 (Equivariant Grothendieck duality).** *Let  $f: X \rightarrow Y$  be a morphism of noetherian separated  $G$ -schemes satisfying  $(\dagger)$ . Then  $\mathbf{R}f_* : \mathbf{D}(\text{QCoh}_X^G) \rightarrow \mathbf{D}(\text{QCoh}_Y^G)$  has a right adjoint  $f^!$ .*

**Proof.** Recall that  $\mathbf{D}(\text{QCoh}_X^G)$  is compactly generated by Corollary 24. Set  $\mathcal{X} = [X/G]$  and  $\mathcal{Y} = [Y/G]$ . The morphism  $f: X \rightarrow Y$  induces a *representable* morphism of algebraic stacks

$$\bar{f}: \mathcal{X} \longrightarrow \mathcal{Y},$$

that by our assumptions on  $X$  and  $Y$  is quasi-compact and quasi-separated. In particular, by [19, Lem. 2.5],  $\bar{f}$  is a *concentrated* morphism. Then, by [19, Thm. 2.6(3)], the direct image  $\mathbf{R}\bar{f}_* : \mathbf{D}_{\text{qc}}(\mathcal{X}) \rightarrow \mathbf{D}_{\text{qc}}(\mathcal{Y})$  preserves coproducts. Under the equivalences (10), the functor  $\mathbf{R}\bar{f}_*$  corresponds precisely to  $\mathbf{R}f_* : \mathbf{D}(\text{QCoh}_X^G) \rightarrow \mathbf{D}(\text{QCoh}_Y^G)$ . Thus the existence of  $f^! : \mathbf{D}(\text{QCoh}_Y^G) \rightarrow \mathbf{D}(\text{QCoh}_X^G)$  follows by Theorem 40.  $\square$

**Lemma 42 (Sheafified Grothendieck duality).** *Let  $f: X \rightarrow Y$  be a proper morphism of noetherian separated  $G$ -schemes satisfying  $(\dagger)$ . Fix objects  $\mathcal{F}^\bullet \in \text{Perf}^G(X)$  and  $\mathcal{E}^\bullet \in \mathbf{D}(\text{QCoh}_Y^G)$ . Then there is a natural isomorphism*

$$\mathbf{R}f_* \mathbf{R}\mathcal{H}om_X(\mathcal{F}^\bullet, f^! \mathcal{E}^\bullet) \xrightarrow{\sim} \mathbf{R}\mathcal{H}om_Y(\mathbf{R}f_* \mathcal{F}^\bullet, \mathcal{E}^\bullet) \tag{17}$$

in  $\mathbf{D}(\text{QCoh}_Y^G)$ .

**Proof.** This is a special case of [33, Lem. 5.3].  $\square$

One can ask whether the right adjoint  $f^! : \mathbf{D}(\text{QCoh}_Y^G) \rightarrow \mathbf{D}(\text{QCoh}_X^G)$  commutes with the forgetful functor. This question can be restated as follows. Given the 2-cartesian diagram

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ \text{p}_X \downarrow & \square & \downarrow \text{p}_Y \\ \mathcal{X} & \xrightarrow{\bar{f}} & \mathcal{Y} \end{array}$$

we ask whether the natural transformation  $\eta: \text{p}_X^* \bar{f}^! \rightarrow f^! \text{p}_Y^*$  is an isomorphism of functors. This is answered in full generality in [33, Lem. 5.20]. For the purpose of this paper, we content ourselves with a special case of that result: the answer is positive, i.e.  $\eta_{\mathcal{E}^\bullet}$  is an isomorphism, when  $f$  is proper and  $\mathcal{E}^\bullet \in \mathbf{D}_{\text{qc}}^+(\mathcal{Y})$  is bounded below. Under these assumptions one has

$$\Phi_X(f^!(\mathcal{E}^\bullet)) = f^!(\Phi_Y(\mathcal{E}^\bullet)) \tag{18}$$

in  $\mathbf{D}(\text{QCoh}_X)$ , where  $f^!$  in the left hand side (resp. in the right hand side) is the  $G$ -equivariant right adjoint (resp. the ordinary right adjoint) of  $\mathbf{R}f_*$ .

**Remark 43.** In a little more detail, properness of  $f$  implies properness of  $\bar{f}$  (reason:  $\bar{f}$  is separated by [44, Tag 04YV], universally closed by [44, Tag 0CL3] and of finite type by [44, Tag 06FR]); since  $\mathcal{X}$  and  $\mathcal{Y}$  are noetherian and  $\bar{f}$  is representable, it follows that  $\bar{f}$  is *quasi-proper*, which together with  $\mathcal{E}^\bullet \in \mathbf{D}_{\text{qc}}^+(\mathcal{Y})$  is one of the conditions in [33, Lem. 5.20] ensuring that  $\eta_{\mathcal{E}^\bullet}$  is an isomorphism.

Note that restricting attention to bounded below complexes does not affect the applications we have in mind, which involve perfect complexes: we already observed in Section 2.2.1 that by assumption (†) perfect complexes are *bounded*.

**Corollary 44.** *Let  $f: X \rightarrow Y$  be a proper morphism of noetherian separated  $G$ -schemes satisfying (†). Given  $\mathcal{F}^\bullet \in \text{Perf}^G(X)$  and  $\mathcal{E}^\bullet \in \mathbf{D}_{\text{qc}}^+(\mathcal{Y}) \subset \mathbf{D}(\text{QCoh}_Y^G)$ , for all  $k \in \mathbb{Z}$  there is a canonical isomorphism of  $G$ -representations*

$$\text{Ext}_X^k(\mathcal{F}^\bullet, f^! \mathcal{E}^\bullet) \xrightarrow{\sim} \text{Ext}_Y^k(\mathbf{R}f_* \mathcal{F}^\bullet, \mathcal{E}^\bullet).$$

Taking  $G$ -invariant parts, it restricts to an isomorphism of  $\mathbb{C}$ -vector spaces

$$\text{Ext}_X^k(\mathcal{F}^\bullet, f^! \mathcal{E}^\bullet)^G \xrightarrow{\sim} \text{Ext}_Y^k(\mathbf{R}f_* \mathcal{F}^\bullet, \mathcal{E}^\bullet)^G.$$

**Proof.** It is enough to apply  $H^k \circ \mathbf{R}\Gamma_Y$  to the isomorphism (17) and to observe that all functors involved commute with the forgetful functor. For  $f^!$ , we exploit (18).  $\square$

**Example 45.** Keep the assumptions of Corollary 44. If  $G$  is reductive, by Lemma 37 we have a commutative diagram of isomorphisms

$$\begin{array}{ccc} \text{Ext}_X^k(\mathcal{F}^\bullet, f^! \mathcal{E}^\bullet)^G & \xrightarrow{\sim} & \text{Ext}_Y^k(\mathbf{R}f_* \mathcal{F}^\bullet, \mathcal{E}^\bullet)^G \\ \uparrow \wr & & \uparrow \wr \\ \text{Hom}_{\mathbf{D}(\text{QCoh}_X^G)}(\mathcal{F}^\bullet, f^! \mathcal{E}^\bullet[k]) & \xrightarrow{\sim} & \text{Hom}_{\mathbf{D}(\text{QCoh}_Y^G)}(\mathbf{R}f_* \mathcal{F}^\bullet, \mathcal{E}^\bullet[k]) \end{array}$$

where the bottom map is the adjunction isomorphism obtained via Theorem 41.

### 3. Equivariance of the truncated Atiyah class

#### 3.1. Truncated Atiyah classes after Huybrechts–Thomas

In this section all schemes are noetherian and separated over  $\mathbb{C}$ .

##### 3.1.1. The relative truncated cotangent complex

The goal of this subsection is to revisit the classical fact that the truncated cotangent complex, though defined through the choice of a smooth embedding, does not depend on this choice. We review this from [22, §2] since the argument reveals that the same feature occurs in the equivariant setting.

Let  $B$  be a scheme. Let  $X \subset A_1$  be a closed embedding inside a smooth  $B$ -scheme  $A_1$ . Let  $J_1 \subset \mathcal{O}_{A_1}$  be the ideal sheaf of the embedding. Consider the exterior derivative

$$d: J_1 \hookrightarrow \mathcal{O}_{A_1} \longrightarrow \Omega_{A_1/B}$$

and restrict it to  $X$  to obtain the (relative) *truncated cotangent complex*

$$\mathbb{L}_{X/B} = [J_1/J_1^2 \longrightarrow \Omega_{A_1/B}|_X] \in \mathbf{D}^{[-1,0]}(\text{QCoh}_X). \tag{19}$$

Suppose  $X$  admits an embedding in another smooth  $B$ -scheme  $A_2$ . Then the composition  $X \hookrightarrow A_1 \times_B A_2 \rightarrow A_1$ , where  $X \hookrightarrow A_1 \times_B A_2$  is the diagonal embedding defined by an ideal  $J_{12} \subset \mathcal{O}_{A_1 \times_B A_2}$ , induces a quasi-isomorphism of two-term complexes

$$\begin{array}{ccc} J_1/J_1^2 & \longrightarrow & \Omega_{A_1/B}|_X \\ \downarrow & & \downarrow \\ J_{12}/J_{12}^2 & \longrightarrow & \Omega_{A_1/B}|_X \oplus \Omega_{A_2/B}|_X \\ \downarrow & & \downarrow \\ \Omega_{A_2/B}|_X & \xlongequal{\quad} & \Omega_{A_2/B}|_X \end{array} \tag{20}$$

showing that replacing  $X \subset A_1$  with  $X \subset A_1 \times_B A_2$  does not change the isomorphism class of  $\mathbb{L}_{X/B}$  in the derived category.

We recalled this argument in order to make the following observation. Suppose  $\iota_i: X \hookrightarrow A_i$  is a  $G$ -equivariant closed embedding, for  $i = 1, 2$ . Then

$$0 \longrightarrow J_i \longrightarrow \mathcal{O}_{A_i} \longrightarrow \iota_{i*} \mathcal{O}_X \longrightarrow 0$$

is a  $G$ -equivariant short exact sequence, and similarly for  $\iota_{12}: X \hookrightarrow A_1 \times_B A_2$ . Since the exterior derivative  $d: \mathcal{O}_{A_i} \rightarrow \Omega_{A_i/B}$  is also  $G$ -equivariant, the whole diagram (20) can be canonically lifted to  $\mathbf{QCoh}_X^G$ . This yields a well-defined element

$$\mathbb{L}_{X/B} \in \mathbf{D}^{[-1,0]}(\mathbf{QCoh}_X^G), \tag{21}$$

whose isomorphism class again does not depend on the choice of equivariant embedding. The equivariant truncated cotangent complex is also discussed by Illusie in [25, Ch. VII, §2.2.5].

Let  $L_{S/T}^\bullet$  denote the full (possibly  $G$ -equivariant) cotangent complex of a (possibly  $G$ -equivariant) morphism of schemes (or algebraic stacks)  $S \rightarrow T$ .

**Lemma 46.** *Let  $f: X \rightarrow Y$  and  $g: Y \rightarrow Z$  be  $G$ -equivariant morphisms. Then there is a sequence of morphisms*

$$\tau_{\geq -1} \mathbf{L}f^* L_{Y/Z}^\bullet \longrightarrow \mathbb{L}_{X/Z} \longrightarrow \mathbb{L}_{X/Y}$$

in  $\mathbf{D}^{[-1,0]}(\mathbf{QCoh}_X^G)$ .

**Proof.** Let us shorten  $\mathcal{X} = [X/G]$ ,  $\mathcal{Y} = [Y/G]$  and  $\mathcal{Z} = [Z/G]$ . The given  $G$ -equivariant morphisms induce 2-cartesian diagrams of algebraic stacks

$$\begin{array}{ccccc} X & \xrightarrow{f} & Y & \xrightarrow{g} & Z \\ \downarrow p_X & \square & \downarrow p_Y & \square & \downarrow p_Z \\ \mathcal{X} & \xrightarrow{\bar{f}} & \mathcal{Y} & \xrightarrow{\bar{g}} & \mathcal{Z} \end{array}$$

where the morphisms  $\bar{f}$  and  $\bar{g}$  are quasi-compact, quasi-separated and of Deligne–Mumford type [44, Tag 04YW]. Hence their cotangent complexes live in  $\mathbf{D}^{\leq 0}(\mathbf{QCoh})$ . By [34, Thm. 8.1], there is an exact triangle

$$\mathbf{L}\bar{f}^* L_{\mathcal{Y}/\mathcal{Z}}^\bullet \longrightarrow L_{\mathcal{X}/\mathcal{Z}}^\bullet \longrightarrow L_{\mathcal{X}/\mathcal{Y}}^\bullet \tag{22}$$

in  $\mathbf{D}(\mathbf{QCoh}_{\mathcal{X}})$ , where  $L^\bullet$  denotes the full cotangent complex. If we applied the pullback functor

$$p_X^*: \mathbf{D}(\mathbf{QCoh}_{\mathcal{X}}) \xrightarrow{\sim} \mathbf{D}(\mathbf{QCoh}_X^G) \xrightarrow{\Phi} \mathbf{D}(\mathbf{QCoh}_X)$$

to the triangle (22), we would get the usual triangle of full cotangent complexes

$$\mathbf{L}f^* L_{Y/Z}^\bullet \longrightarrow L_{X/Z}^\bullet \longrightarrow L_{X/Y}^\bullet \tag{23}$$

in  $\mathbf{D}^{\leq 0}(\mathbf{QCoh}_X)$ . Instead, we get a lift to  $\mathbf{D}(\mathbf{QCoh}_X^G)$  of the triangle (23) by applying the exact equivalence  $\mathbf{D}(\mathbf{QCoh}_{\mathcal{X}}) \xrightarrow{\sim} \mathbf{D}(\mathbf{QCoh}_X^G)$  to (22). Applying the truncation functor  $\tau_{\geq -1}$  on  $\mathbf{D}(\mathbf{QCoh}_X^G)$  yields the desired sequence of morphisms

$$\tau_{\geq -1} \mathbf{L}f^* L_{Y/Z}^\bullet \longrightarrow \mathbb{L}_{X/Z} \longrightarrow \mathbb{L}_{X/Y}$$

in  $\mathbf{D}^{[-1,0]}(\mathbf{QCoh}_X^G)$ , as required. □

3.1.2. *Absolute setting*

Let  $X \hookrightarrow A$  be a closed immersion of a scheme  $X$  inside a smooth  $\mathbb{C}$ -scheme  $A$ . Let  $J \subset \mathcal{O}_A$  be the corresponding sheaf of ideals. The (absolute) truncated cotangent complex is the two term complex

$$\mathbb{L}_X = [J/J^2 \longrightarrow \Omega_{A|X}] \in \mathbf{D}^{[-1,0]}(\mathrm{QCoh}_X). \tag{24}$$

Let  $\mathcal{I}_A \subset \mathcal{O}_{A \times A}$  and  $\mathcal{I}_X \subset \mathcal{O}_{X \times X}$  be the ideal sheaves of the diagonal embeddings

$$A \xrightarrow{i_{\Delta_A}} A \times A, \quad X \xrightarrow{i_{\Delta_X}} X \times X,$$

respectively. Huybrechts–Thomas [22, §2] show how to construct a canonical morphism

$$\alpha_X: \mathcal{O}_{\Delta_X} \longrightarrow i_{\Delta_X*} \mathbb{L}_X[1]. \tag{25}$$

It is represented in degrees  $[-2, 0]$  by the morphism of complexes

$$\begin{array}{ccccc} i_{\Delta_X*}(J/J^2) & \longrightarrow & \mathcal{I}_A|_{X \times X} & \longrightarrow & \mathcal{O}_{X \times X} \\ \parallel & & \downarrow & & \\ i_{\Delta_X*}(J/J^2) & \longrightarrow & \mathcal{I}_A/\mathcal{I}_A^2|_{X \times X} & & \end{array} \tag{26}$$

where the quasi-isomorphism between the top complex and  $\mathcal{O}_{\Delta_X}$  is proved as a consequence of [22, Lem. 2.2]. The extension class

$$\alpha_X \in \mathrm{Ext}_{X \times X}^1(\mathcal{O}_{\Delta_X}, i_{\Delta_X*} \mathbb{L}_X)$$

corresponding to (25) is called the *truncated universal Atiyah class*. It does not depend on the choice of embedding  $X \subset A$ .

The main observation in [22], at this point, is that the map (25) can be seen as a map of Fourier–Mukai kernels. In particular, for a perfect complex  $E$  on  $X$ , one can view  $\mathbf{R}\pi_{2*}(\pi_1^* E \otimes \alpha_X)$  as a canonical morphism

$$\mathrm{At}_E: E \longrightarrow E \otimes \mathbb{L}_X[1]$$

in  $\mathbf{D}(\mathrm{QCoh}_X)$ , where  $\pi_i: X \times X \rightarrow X$  are the projections. This is, by definition, the *truncated Atiyah class* of  $E$  introduced in [22, Def. 2.6]. It can of course be seen as an element

$$\mathrm{At}_E \in \mathrm{Ext}_X^1(E, E \otimes \mathbb{L}_X). \tag{27}$$

Under the canonical morphism  $\mathbb{L}_X \rightarrow h^0(\mathbb{L}_X) = \Omega_X$ , the extension  $\mathrm{At}_E$  projects onto the classical Atiyah class in  $\mathrm{Ext}_X^1(E, E \otimes \Omega_X)$ .

3.1.3. *Relative setting*

We consider the following setup, which we recall verbatim from [22, §2] and [23].

Let  $B$  be a scheme,  $X \rightarrow B$  a  $B$ -scheme equipped with a closed immersion  $X \hookrightarrow A$  with ideal  $J \subset \mathcal{O}_A$ . We assume we have a commutative diagram

$$\begin{array}{ccccc} X & \hookrightarrow & A_B & \hookrightarrow & A \\ & \searrow & \downarrow & \square & \downarrow \\ & & B & \hookrightarrow & \tilde{B} \end{array} \tag{28}$$

where  $\tilde{B}$  and  $A \rightarrow \tilde{B}$  are smooth and the square is cartesian. In particular, both  $A$  and  $A_B \rightarrow B$  are smooth. Let  $J_B \subset \mathcal{O}_{A_B}$  be the ideal sheaf of  $X \subset A_B$ . Then there is a natural morphism of complexes

$$\begin{CD} J/J^2 @>>> J_B/J_B^2 \\ @VVV @VVV \\ \Omega_A|_X @>>> \Omega_{A/\tilde{B}}|_X = \Omega_{A_B/B}|_X \end{CD} \tag{29}$$

inducing a morphism

$$j: \mathbb{L}_X \longrightarrow \mathbb{L}_{X/B}.$$

The *relative truncated Atiyah class* of a perfect complex  $E \in \text{Perf } X$  is, by definition, the composition

$$\text{At}_{E/B}: E \xrightarrow{\text{At}_E} E \otimes \mathbb{L}_X[1] \xrightarrow{\text{id}_E \otimes j[1]} E \otimes \mathbb{L}_{X/B}[1].$$

It corresponds to the element

$$\text{At}_{E/B} \in \text{Ext}_X^1(E, E \otimes \mathbb{L}_{X/B})$$

obtained as the image of  $\text{At}_E$  under the map  $(\text{id}_E \otimes j[1])_*: \text{Ext}_X^1(E, E \otimes \mathbb{L}_X) \rightarrow \text{Ext}_X^1(E, E \otimes \mathbb{L}_{X/B})$ .

### 3.2. Adding in the group action

In this section we prove Theorem A (which builds on the situation of Section 3.1.2), along with its relative analogue (which builds on the situation of Section 3.1.3).

#### 3.2.1. Absolute setting

We first go back to the absolute setting of Section 3.1.2.

Let  $G$  be an affine algebraic group, and let

$$X \subset A$$

be a  $G$ -equivariant embedding of noetherian separated schemes, where  $A$  is smooth. Recall (cf. Example 15) that this situation is achieved if  $X$  is quasi-projective and has a  $G$ -equivariant line bundle. Under these assumptions, we have seen that the truncated cotangent complex is canonically  $G$ -equivariant, i.e. there is a canonical lift

$$\mathbb{L}_X \in \mathbf{D}^{[-1,0]}(\text{QCoh}_X^G)$$

of the complex (24).

Let  $i_{\Delta_X}: X \hookrightarrow X \times X$  be the diagonal embedding. The  $G$ -action on  $X$  determines a  $G$ -equivariant structure on the structure sheaf  $\mathcal{O}_X$  (Example 7), and on the short exact sequence

$$\mathcal{I}_X \hookrightarrow \mathcal{O}_{X \times X} \twoheadrightarrow \mathcal{O}_{\Delta_X} = i_{\Delta_X*} \mathcal{O}_X.$$

**Lemma 47.** *The morphism*

$$\alpha_X: \mathcal{O}_{\Delta_X} \longrightarrow i_{\Delta_X*} \mathbb{L}_X[1]$$

*is naturally  $G$ -equivariant.*

**Proof.** Since  $X \subset A$  is a  $G$ -equivariant embedding, the diagram of closed immersions

$$\begin{CD} X @<<< A \\ @V i_{\Delta_X} VV @VV i_{\Delta_A} V \\ X \times X @<<< A \times A \end{CD}$$

along with its associated ideal sheaf short exact sequences, are also  $G$ -equivariant in a natural way. Therefore Diagram (26), which is built out of these equivariant short exact sequences

through the  $G$ -equivariant geometric functors (cf. Section 1.3), inherits a  $G$ -equivariant structure. But Diagram (26) represents precisely  $\alpha_X$ . The claim follows.  $\square$

We finally have all the tools to complete the proof of Theorem A.

**Theorem 48.** *Let  $G$  be a complex affine algebraic group acting on a separated noetherian  $\mathbb{C}$ -scheme  $X$  admitting a  $G$ -equivariant embedding in a smooth  $G$ -scheme. Fix a perfect complex  $E \in \text{Perf } X$ . Then every lift of  $E$  to  $\mathbf{D}(\text{QCoh}_X^G)$  makes  $\text{At}_E$  canonically  $G$ -equivariant.*

Recall (cf. Definition 36) that by “ $\text{At}_E$  is  $G$ -equivariant” we mean that the corresponding morphism  $E \rightarrow E \otimes_{\mathbb{L}_X}[1]$  admits a lift to  $\mathbf{D}(\text{QCoh}_X^G)$ .

**Proof.** Endow  $X \times X$  with the diagonal action. Then the projections  $\pi_i: X \times X \rightarrow X$  are  $G$ -equivariant and both  $X$  and  $X \times X$  satisfy Condition  $(\dagger)$  by Lemma 16. Since  $\alpha_X$  is  $G$ -equivariant by Lemma 47, using equivariant pushforward  $\mathbf{R}\pi_{2*}$ , pullback  $\pi_1^*$  and tensor product  $\otimes$  (cf. Section 2.3), we deduce that the morphism

$$\mathbf{R}\pi_{2*}(\pi_1^*E \otimes \alpha_X): E \longrightarrow E \otimes_{\mathbb{L}_X}[1]$$

is canonically lifted to  $\mathbf{D}(\text{QCoh}_X^G)$ , which proves the result.  $\square$

### 3.2.2. Relative setting

Suppose we are in the situation depicted in Diagram (28), and assume  $X \hookrightarrow A_B \hookrightarrow A$  are  $G$ -equivariant embeddings. Then we obtain the following consequence of Theorem 48.

**Corollary 49.** *The relative truncated Atiyah class  $\text{At}_{E/B}$  is  $G$ -equivariant.*

**Proof.** The assumption that  $X \hookrightarrow A_B \hookrightarrow A$  are  $G$ -equivariant implies that the morphism  $j: \mathbb{L}_X \rightarrow \mathbb{L}_{X/B}$ , induced by Diagram (29), is  $G$ -equivariant. Therefore

$$\text{At}_{E/B}: E \longrightarrow E \otimes_{\mathbb{L}_X}[1] \xrightarrow{\text{id}_E \otimes j[1]} E \otimes_{\mathbb{L}_{X/B}}[1]$$

lives in  $\mathbf{D}(\text{QCoh}_X^G)$  entirely.  $\square$

**Remark 50.** By Corollary 35, the morphism  $\text{At}_{E/B}$  can be seen as an element of

$$\text{Ext}^1(E, E \otimes_{\mathbb{L}_{X/B}})^G \subset \text{Ext}^1(E, E \otimes_{\mathbb{L}_{X/B}}).$$

Indeed, since both  $\text{At}_E$  and  $\text{id}_E \otimes j[1]$  are morphisms in  $\mathbf{D}(\text{QCoh}_X^G)$ , the composition

$$\text{Hom}_X(E, E) \xrightarrow{\text{At}_E} \text{Hom}_X(E, E \otimes_{\mathbb{L}_X}[1]) \xrightarrow{(\text{id}_E \otimes j[1])^*} \text{Hom}_X(E, E \otimes_{\mathbb{L}_{X/B}}[1])$$

is a morphism of  $G$ -representations, and as such it preserves  $G$ -invariant parts. Therefore  $\text{id}_E \in \text{Hom}_X(E, E)^G$  gets sent to  $\text{At}_{E/B} \in \text{Ext}^1(E, E \otimes_{\mathbb{L}_{X/B}})^G$ .

## 4. Application to moduli spaces of perfect complexes

In this section we shall prove Theorem B, whose statement we recall below (Theorem 53) for the reader’s convenience.

### 4.1. The moduli space of perfect complexes

Fix an affine algebraic group  $G = \text{Spec } A$ , for  $A$  a (noetherian) unique factorisation domain (e.g.  $G$  could be a torus), and fix a noetherian separated  $\mathbb{C}$ -scheme  $B$  carrying the trivial  $G$ -action  $p_2: G \times B \rightarrow B$ . Let  $f: Y \rightarrow B$  be a smooth (connected) projective  $G$ -invariant morphism of relative dimension  $d$ , where the  $G$ -action on  $Y$  is denoted  $\sigma_Y: G \times Y \rightarrow Y$ . By assumption,  $G$  preserves the fibres of  $f$ .

As in [22, §4.1], let  $M \rightarrow B$  be a relative fine separated moduli space of simple perfect complexes of rank  $r \neq 0$  on the fibres of  $f$ , with fixed determinant  $\mathcal{L} \in \text{Pic } Y$  and fixed numerical invariants. Then  $M$  is an algebraic space, locally complete as a moduli space, and there is a universal perfect complex

$$E \in \text{Perf}(Y \times_B M).$$

Denote by  $\iota_b: Y_b \hookrightarrow Y$  the inclusion of a fibre of  $f$ . If a point  $m \in M$  sits over  $b \in B$ , let  $i_m: Y_b \xrightarrow{\sim} Y_b \times \{m\} \hookrightarrow Y \times_B M$  denote the corresponding inclusion.

For a scheme  $S \rightarrow B$ , the universal property of the pair  $(M, E)$  translates into a bijection between

- morphisms  $S \rightarrow M$  over  $B$ , and
- equivalence classes of complexes  $F \in \text{Perf}(Y \times_B S)$  such that for all  $s \in S$  (say, sitting over  $b \in B$ ) the derived restriction  $F|_{Y_b}$  is isomorphic to  $\mathbf{L}i_m^* E$  for some  $m \in M$  (sitting over  $b$ ), and such that  $\det F = \pi_S^* \mathcal{L}' \otimes \pi_Y^* \mathcal{L}$  for some  $\mathcal{L}' \in \text{Pic } S$  (where  $\pi_S$  and  $\pi_Y$  are the projections from  $Y \times_B S$ ).

Two complexes  $F$  and  $F'$  in  $\text{Perf}(Y \times_B S)$  are considered equivalent if there exists a line bundle  $\mathcal{H} \in \text{Pic } S$  such that  $F = F' \otimes \pi_S^* \mathcal{H}$ . The correspondence assigns to a  $B$ -morphism  $h: S \rightarrow M$  the equivalence class of the perfect complex  $(\text{id}_Y \times h)^* E \in \text{Perf}(Y \times_B S)$ .

### 4.2. Equivariance of the universal complex

From now on we set  $X = Y \times_B M$ . We will define a suitable  $G$ -action on  $X$ , with respect to which the universal complex is equivariant. Before doing so, we state a fact that we will need during the proof.

**Fact 51.** *A theorem of Rosenlicht [41, Thm. 2], whose proof is sketched in [10, Rem. 7.1], says that if  $Z$  and  $Z'$  are irreducible varieties over an algebraically closed field, the natural homomorphism  $\mathcal{O}(Z)^\times \otimes \mathcal{O}(Z')^\times \rightarrow \mathcal{O}(Z \times Z')^\times$  is surjective. In fact, [10, Rem. 7.1] shows more: one can write every function  $\alpha \in \mathcal{O}(Z \times Z')^\times$  as  $\alpha = \beta \boxtimes \beta'$  for  $\beta \in \mathcal{O}(Z)^\times$  and  $\beta' \in \mathcal{O}(Z')^\times$ .*

**Proposition 52.** *The universal complex  $E \in \text{Perf } X$  is naturally  $G$ -equivariant.*

**Proof.** First of all, we lift the  $G$ -action  $\sigma_Y: G \times Y \rightarrow Y$  to a  $G$ -action on  $M$ . Pulling back  $E$  along

$$\sigma_Y \times \text{id}_M: G \times Y \times_B M \longrightarrow Y \times_B M$$

gives a family of perfect complexes parameterised by  $G \times M$ . By the universal property of  $(M, E)$ , this induces a  $B$ -morphism

$$\sigma_M: G \times M \longrightarrow M,$$

which is a  $G$ -action on  $M$ . (Note that, since  $G$  is connected and affine, the determinant does not change under the action.) We have

$$(\text{id}_Y \times \sigma_M)^* E \cong (\sigma_Y \times \text{id}_M)^* E \otimes \pi_{G,M}^* \mathcal{H}$$

for some  $\mathcal{H} \in \text{Pic}(G \times M)$ , where  $\pi_{G,M}: G \times Y \times_B M \rightarrow G \times M$  is the projection. We claim that  $\mathcal{H}$  is the trivial line bundle. Consider the projection  $\pi_2: G \times M \rightarrow M$ . Since  $G = \text{Spec } A$  where  $A$  is a UFD

(by our assumption at the beginning of this section), by [20, Ch. II, Prop. 6.2] we deduce that the class group  $\text{Cl}(G)$  is trivial; but by [20, Ch. II, Cor. 6.16] we have an isomorphism  $\text{Cl}(G) \cong \text{Pic}(G)$ , so we deduce that  $\text{Pic} G = 0$ , thus  $\mathcal{H} = \pi_2^* \mathcal{H}'$  for some  $\mathcal{H}' \in \text{Pic} M$ . However,  $\mathcal{H}'|_{\{g\} \times M}$  is trivial for all  $g \in G$ , in particular for  $g = e$ , where  $e \in G$  is the group identity. Thus  $\mathcal{H}'$  is trivial and hence so is  $\mathcal{H}$ . Then the previous isomorphism becomes

$$(\text{id}_Y \times \sigma_M)^* E \cong (\sigma_Y \times \text{id}_M)^* E.$$

Next, we have to make  $E$  equivariant. We consider the  $G$ -action

$$\tau: G \times Y \times_B M \longrightarrow Y \times_B M, \quad (g, y, m) \longmapsto (\sigma_Y(g, y), \sigma_M(g^{-1}, m))$$

on  $X = Y \times_B M$ . The pullback  $\tau^* E$  corresponds to a  $B$ -morphism  $\phi_\tau: G \times M \rightarrow M$ . In fact,  $\phi_\tau$  is the second projection. Indeed,

$$\tau^* E|_{\{g\} \times Y_b \times \{m\}} = \mathbf{L}i_n^* E,$$

where  $n = \sigma_M(g, \sigma_M(g^{-1}, m)) = \sigma_M(e, m) = m$ . Thus  $\tau^* E|_{\{g\} \times Y_b \times \{m\}} = \mathbf{L}i_m^* E$ , and we obtain an isomorphism  $\tau^* E \cong (\text{id}_Y \times \phi_\tau)^* E \otimes \pi_{G,M}^* \mathcal{H}$  for some  $\mathcal{H} \in \text{Pic}(G \times M)$ . For the same reason as before,  $\mathcal{H}$  is trivial. Therefore, since  $\phi_\tau$  is the projection, we obtain an isomorphism

$$\vartheta: p_2^* E \xrightarrow{\sim} \tau^* E \tag{30}$$

of perfect complexes on  $G \times X$ , where  $p_2 = \text{id}_Y \times \phi_\tau: G \times X \rightarrow X$  is the projection.

Finally, we need to verify that  $\vartheta$  satisfies the cycle condition. We follow [27, Prop. 4.4], but we have to adapt the argument because the universal complex  $E$  is not necessarily simple. By [27, Prop. 2.4], it is enough to check the cocycle condition (in the form of Remark 6) on closed points of  $G$ . Let us normalise  $\vartheta$ , if necessary, to achieve  $\vartheta_e = \text{id}_E$ . We need to show that the function

$$F: G \times G \longrightarrow \text{Aut} E, \quad (g, h) \longmapsto \vartheta_{hg}^{-1} \circ \rho_g^* \vartheta_h \circ \vartheta_g$$

is the constant  $1 \in \mathbb{C}^* \subset \text{Aut} E$  where, as in Section 1.1,  $\rho_g$  denotes the composition

$$X \xrightarrow{\sim} \{g\} \times X \hookrightarrow G \times X \xrightarrow{\tau} X.$$

We proceed as follows. Fix a closed point  $m \in M$ , sitting over  $b \in B$ . Set  $E_m = \mathbf{L}i_m^* E$ , a perfect complex on  $Y_b \xrightarrow{\sim} Y_b \times \{m\} \hookrightarrow X$ . Consider the commutative diagram

$$\begin{array}{ccccc} Y_b \times \{m\} & \xrightarrow{\sim} & \{g\} \times Y_b \times \{m\} & \hookrightarrow & G \times (Y_b \times \{m\}) & \xrightarrow[\rho_{2,m}]{\sigma_{Y,m}} & Y_b \times \{m\} \\ \downarrow i_m & & \downarrow g \times i_m & & \downarrow \text{id}_G \times i_m & & \downarrow i_m \\ X & \xrightarrow{\sim} & \{g\} \times X & \hookrightarrow & G \times X & \xrightarrow[\rho_2]{\tau} & X \end{array} \tag{31}$$

where  $\sigma_{Y,m}$  is the restriction of the action  $\sigma_Y$  to the fibre  $Y_b \subset Y$ , identified with  $Y_b \times \{m\}$ . Restricting the isomorphism  $\vartheta$  in (30) to the slice  $G \times (Y_b \times \{m\}) \subset G \times X$  we obtain an isomorphism

$$\vartheta(m) = \vartheta|_{G \times Y_b \times \{m\}}: p_{2,m}^* E_m \xrightarrow{\sim} \sigma_{Y,m}^* E_m,$$

and restricting  $\vartheta(m)$  further to  $Y_b \times \{m\} \xrightarrow{\sim} \{g\} \times Y_b \times \{m\}$  we obtain

$$\vartheta_g(m): E_m \xrightarrow{\sim} \rho_g(m)^* E_m,$$

where  $\rho_g(m)$  is, as ever, the composition

$$\rho_g(m): Y_b \times \{m\} \xrightarrow{\sim} \{g\} \times Y_b \times \{m\} \hookrightarrow G \times Y_b \times \{m\} \xrightarrow{\sigma_{Y,m}} Y_b \times \{m\}.$$

Now, for  $g$  and  $h$  varying in  $G$ , we consider the diagrams

$$\begin{array}{ccc} \rho_g(m)^* \rho_h(m)^* E_m & \xleftarrow{\rho_g(m)^* \vartheta_h(m)} & \rho_g(m)^* E_m \\ \parallel & & \uparrow \vartheta_g(m) \\ \rho_{hg}(m)^* E_m & \xleftarrow{\vartheta_{hg}(m)} & E_m \end{array}$$

and we ask whether these commute. As before, we translate this condition as follows. We consider the function

$$F_m: G \times G \longrightarrow \text{Aut } E_m = \mathbb{C}^*, \quad (g, h) \longmapsto \vartheta_{hg}(m)^{-1} \circ \rho_g(m)^* \vartheta_h(m) \circ \vartheta_g(m).$$

Thanks to the fact that  $E_m$  is simple, which implies  $\text{Aut } E_m = \mathbb{C}^*$ , the function  $F_m$  can be seen as a regular nowhere vanishing function in  $\mathcal{O}(G \times G)^\times$ . Thus by Fact 51 (applied to  $Z = Z' = G$ , which is irreducible since it is smooth and connected) we can write  $F_m(g, h) = F_{1,m}(g) \cdot F_{2,m}(h)$  for  $F_{i,m} \in \mathcal{O}(G)^\times$ . Since  $F_m(g, 1) = 1 = F_m(1, h)$  for all closed points  $g, h \in G$  (we have used  $\rho_e(m) = \text{id}$  as well as the normalisation  $\vartheta_e(m) = \text{id}_{E_m}$ ), it follows that  $F_m$  is constantly equal to  $1 \in \mathbb{C}^*$ . To finish the proof, it is enough to observe that by Diagram (31) we have  $\vartheta_g(m) = i_m^* \vartheta_g$ , in particular we have a commutative diagram

$$\begin{array}{ccc} G \times G & \xrightarrow{F} & \text{Aut } E \\ & \searrow 1 \equiv F_m & \downarrow i_m^* \\ & & \text{Aut } E_m \end{array}$$

and since  $i_m^*$  is an isomorphism on  $\mathbb{C}^\times \subset \text{Aut } E$  we conclude that  $F \equiv 1$ , as required. □

### 4.3. The Atiyah class of the universal complex

From now on, we endow  $E \in \text{Perf } X$  with the  $G$ -equivariant structure produced in (30). We endow  $M$  with the  $G$ -action  $g \cdot m = \sigma_M(g^{-1}, m)$ , so that the projection  $\pi_M: X \rightarrow M$  is  $G$ -equivariant. We also assume that  $M$  admits a  $G$ -equivariant embedding inside a smooth scheme.<sup>4</sup> By Lemma 16 it follows that  $M$  (and hence  $X$ , by [47, Ex. 2.1.2(h)]) satisfy  $(\dagger)$ . Finally, notice that since the projection  $\pi_M: X \rightarrow M$  is a proper (in fact, smooth and projective) morphism of  $G$ -schemes satisfying condition  $(\dagger)$ , equivariant Grothendieck duality applies to  $\pi_M$ .

Our goal is to prove the following result, which is Theorem B from the Introduction.

**Theorem 53.** *Let  $M \rightarrow B$  be as in Section 4.1, and assume  $G$  is reductive. Then the relative obstruction theory on  $M \rightarrow B$  is naturally  $G$ -equivariant.*

We recalled in the Introduction how the relative obstruction theory is obtained via the Atiyah class of the universal complex. We review this below, directly in the equivariant setting.

The complex  $E$  has a well-defined (absolute) truncated Atiyah class (27)

$$\text{At}_E \in \text{Ext}_X^1(E, E \otimes \mathbb{L}_X),$$

and our first task is now to prove its equivariance. The proof of Theorem 53 will follow almost immediately by equivariant Grothendieck duality. In fact, the equivariance of the Atiyah class is now an easy corollary of Proposition 52 and the main result of the paper.

**Corollary 54.** *The Atiyah class  $\text{At}_E$  is naturally  $G$ -equivariant.*

**Proof.** Follows by combining Proposition 52 with Theorem 48. □

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<sup>4</sup>Recall from Example 15 that this is easily achieved in many practical applications, where the moduli space is actually quasi-projective. However, this assumption can be removed, just as in [22, §4.5]. We leave the details to the reader.

The  $G$ -equivariant maps  $\pi_Y: X \rightarrow Y$  and  $Y \rightarrow \text{Spec } \mathbb{C}$  induce a morphism  $j: \mathbb{L}_X \rightarrow \mathbb{L}_{X/Y}$  in  $\mathbf{D}(\text{QCoh}_X^G)$  by Lemma 46. Composing  $\text{At}_E$  with  $\text{id}_E \otimes j[1]$  gives the relative Atiyah class

$$\text{At}_{E/Y}: E \longrightarrow E \otimes \mathbb{L}_X[1] \longrightarrow E \otimes \mathbb{L}_{X/Y}[1].$$

Therefore Corollary 54 immediately implies the following.

**Corollary 55.** *The relative Atiyah class  $\text{At}_{E/Y}$  is naturally  $G$ -equivariant.*

By taking the image of  $\text{id}_E \in \text{Hom}_X(E, E)^G$  under the composition  $(\text{id}_E \otimes j[1])_* \circ \text{At}_{E*}$  we can view the relative truncated Atiyah class as an element

$$\text{At}_{E/Y} \in \text{Ext}_X^1(E, E \otimes \mathbb{L}_{X/Y})^G = \text{Ext}_X^1(E, E \otimes \pi_M^* \mathbb{L}_{M/B})^G,$$

where we have observed that  $\mathbb{L}_{X/Y} = \pi_M^* \mathbb{L}_{M/B}$  by [44, Tag 09DJ].

#### 4.4. Proof of Theorem B

From now on, we assume  $G$  to be *reductive* (cf. Section 2.4.1). We shall exploit the splitting

$$\mathbf{R}\mathcal{H}om_X(E, E) = \mathcal{O}_X \oplus \mathbf{R}\mathcal{H}om_X(E, E)_0, \quad (32)$$

which we wish to prove to be  $G$ -equivariant. Recall (see e.g. [21, §10.1] for more details on this construction) how (32) is obtained in the non-equivariant setup: the trace map  $\text{tr}: \mathbf{R}\mathcal{H}om_X(E, E) \rightarrow \mathcal{O}_X$  splits the identity homomorphism  $\text{id}_E: \mathcal{O}_X \rightarrow \mathbf{R}\mathcal{H}om_X(E, E)$ , and the composition  $\text{tr} \circ \text{id}_E$  is multiplication by the rank  $r$  (which we assumed nonzero in Section 4.1). We now show that the induced distinguished triangle

$$\mathbf{R}\mathcal{H}om_X(E, E)_0 \longrightarrow \mathbf{R}\mathcal{H}om_X(E, E) \xrightarrow{\text{tr}} \mathcal{O}_X, \quad (33)$$

defining the *traceless*  $\mathbf{R}\mathcal{H}om$ , is naturally lifted to  $\mathbf{D}(\text{QCoh}_X^G)$ .

Consider the element

$$\text{id}_E \in \text{Hom}_X(E, E) = \text{Hom}_X(\mathcal{O}_X, \mathbf{R}\mathcal{H}om_X(E, E)).$$

By Remark 33 and Lemma 37, we know that

$$\text{id}_E \in \text{Hom}_X(\mathcal{O}_X, \mathbf{R}\mathcal{H}om_X(E, E))^G \cong \text{Hom}_{\mathbf{D}(\text{QCoh}_X^G)}(\mathcal{O}_X, \mathbf{R}\mathcal{H}om_X(E, E)).$$

Then take  $\mathcal{F}^\bullet = \mathcal{O}_X$  and  $i = \text{id}_E$  in Corollary 35 (2) to observe that

$$\text{id}_E^*: \text{Hom}_X(\mathbf{R}\mathcal{H}om_X(E, E), \mathcal{O}_X) \longrightarrow \text{Hom}_X(\mathcal{O}_X, \mathcal{O}_X)$$

is  $G$ -equivariant. In particular, it preserves the  $G$ -invariant parts. Since the trace map  $\text{tr} \in \text{Hom}_X(\mathbf{R}\mathcal{H}om_X(E, E), \mathcal{O}_X)$  gets sent to  $r \cdot \text{id}_{\mathcal{O}_X}$ , which is  $G$ -invariant in virtue of Remark 33, it follows that  $\text{tr}$  must be  $G$ -invariant, too. In other words,

$$\text{tr} \in \text{Hom}_X(\mathbf{R}\mathcal{H}om_X(E, E), \mathcal{O}_X)^G \cong \text{Hom}_{\mathbf{D}(\text{QCoh}_X^G)}(\mathbf{R}\mathcal{H}om_X(E, E), \mathcal{O}_X).$$

We can then take the shifted cone of  $\text{tr}$  in  $\mathbf{D}(\text{QCoh}_X^G)$  to obtain a distinguished triangle

$$\mathbf{R}\mathcal{H}om_X(E, E)_0 \longrightarrow \mathbf{R}\mathcal{H}om_X(E, E) \xrightarrow{\text{tr}} \mathcal{O}_X$$

in  $\text{Perf}^G(X) \subset \mathbf{D}(\text{QCoh}_X^G)$ , lifting (33).

We have proved that the splitting (32) is  $G$ -equivariant. This in particular implies that the projection

$$\mathfrak{q}: \text{Ext}_X^1(E, E \otimes \pi_M^* \mathbb{L}_{M/B}) \longrightarrow \text{Ext}_X^1(\mathbf{R}\mathcal{H}om_X(E, E)_0, \pi_M^* \mathbb{L}_{M/B})$$

from the full Ext group containing the element  $\text{At}_{E/Y}$ , is a morphism of  $G$ -representations, in particular it preserves  $G$ -invariant parts. Therefore,  $\text{At}_{E/Y}$  maps to an element

$$\mathfrak{q}(\text{At}_{E/Y}) \in \text{Ext}_X^1(\mathbf{R}\mathcal{H}om_X(E, E)_0, \pi_M^* \mathbb{L}_{M/B})^G.$$

Note that the dualising line bundle  $\omega_{\pi_M} = \pi_Y^* \omega_{Y/B}$  is naturally  $G$ -equivariant. By equivariant Grothendieck duality along the proper morphism  $\pi_M$  (Corollary 44), the latter group is canonically isomorphic to

$$\begin{aligned} \text{Ext}_X^1(\mathbf{R}\mathcal{H}om_X(E, E)_0 \otimes \omega_{\pi_M}[d], \pi_M^* \mathbb{L}_{M/B} \otimes \omega_{\pi_M}[d])^G & \\ &= \text{Ext}_X^{1-d}(\mathbf{R}\mathcal{H}om_X(E, E)_0 \otimes \omega_{\pi_M}, \pi_M^! \mathbb{L}_{M/B})^G \\ &\cong \text{Ext}_M^{1-d}(\mathbf{R}\pi_{M*}(\mathbf{R}\mathcal{H}om_X(E, E)_0 \otimes \omega_{\pi_M}), \mathbb{L}_{M/B})^G \\ &= \text{Hom}_M(\mathbb{E}, \mathbb{L}_{M/B})^G \\ &\cong \text{Hom}_{\mathbf{D}(\text{QCoh}_M^G)}(\mathbb{E}, \mathbb{L}_{M/B}) \end{aligned}$$

where  $d$  is the relative dimension of  $Y \rightarrow B$  and we have set

$$\mathbb{E} = \mathbf{R}\pi_{M*}(\mathbf{R}\mathcal{H}om_X(E, E)_0 \otimes \omega_{\pi_M})[d - 1].$$

We have also used again that  $G$  is reductive for the last isomorphism. The morphism  $\phi \in \text{Hom}_M(\mathbb{E}, \mathbb{L}_{M/B})$  determined as the image of the relative truncated Atiyah class  $\text{At}_{E|Y}$  is a relative obstruction theory on  $M \rightarrow B$  by [22, Thm. 4.1]. Therefore we have shown its equivariance in the sense of Definition 1.

The proof of Theorem B is complete.

**Example 56.** Let  $Y$  be a smooth complex projective toric 3-fold. Let  $G = \mathbb{G}_m^3 \subset Y$  be the open torus. The above result confirms the  $G$ -equivariance of the (perfect) obstruction theory on the following classical moduli spaces:

- (1) the Hilbert scheme of points  $\text{Hilb}^n Y$ ,
- (2) the moduli space  $I_m(Y, \beta)$  of ideal sheaves  $\mathcal{I}$  with  $\text{ch } \mathcal{I} = (1, 0, -\beta, -m)$ ,
- (3) the moduli space  $P_m(Y, \beta)$  of stable pairs  $(\mathcal{F}, s)$  with  $\chi(\mathcal{F}) = m$  and  $[\mathcal{F}] = \beta$ ,
- (4) higher rank analogues of (2) and (3),
- (5) the Quot scheme  $\text{Quot}_Y(F, n)$  of length  $n$  quotients of a  $G$ -equivariant exceptional locally free sheaf  $F$ , as in [40]. This will be exploited in [12].

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