Derived Equivalences for the Flops of Type C2 and AG4 via Mutation of Semiorthogonal Decomposition

DERIVED EQUIVALENCES FOR THE FLOPS OF TYPE C_2 AND A_4^G VIA MUTATION OF SEMIORTHOGONAL DECOMPOSITION

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Abstract. We give a new proof of the derived equivalence of a pair of varieties connected by the flop of type C_2 in the list of Kanemitsu [13], which is originally due to Segal [22]. We also prove the derived equivalence of a pair of varieties connected by the flop of type A_4^G in the same list. The latter proof follows that of the derived equivalence of Calabi–Yau 3-folds in Grassmannians $\mathrm{Gr}(2,5)$ and $\mathrm{Gr}(3,5)$ by Kapustka and Rampazzo [15] closely.

1. Introduction

Let G be a semisimple Lie group and B a Borel subgroup of G. For distinct maximal parabolic subgroups P and Q of G containing B, three homogeneous spaces G/P, G/Q, and $G/(P \cap Q)$ form the following diagram:

$$\begin{tikzcd} & \mathbf{F} := G/(P\cap Q) \arrow[dl, "\varpi_-"'] \arrow[dr, "\varpi_+"] & \\ \mathbf{P} := G/P & & \mathbf{Q} := G/Q \end{tikzcd}$$

We write the hyperplane classes of $\mathbf{P}$ and $\mathbf{Q}$ as h and H respectively. By abuse of notation, the pull-back to $\mathbf{F}$ of the hyperplane classes h and H will be denoted by the same symbol. The morphisms ϖ_- and ϖ_+ are projective morphisms whose relative $\mathcal{O}(1)$ are $\mathcal{O}(H)$ and $\mathcal{O}(h)$ respectively. We consider the diagram

$$\begin{tikzcd} & \mathbf{F} \arrow[dl, "\varpi_-"'] \arrow[d, hook, "\iota"] \arrow[dr, "\varpi_+"] & \\ \mathbf{P} \arrow[d, hook, "\iota_-"'] & \mathbf{V} \arrow[dl, "\varphi_-"'] \arrow[dr, "\varphi_+"] & \mathbf{Q} \arrow[d, hook, "\iota_+"] \\ \mathbf{V}_- \arrow[dr, "\phi_-"'] & & \mathbf{V}_+ \arrow[dl, "\phi_+"] \\ & \mathbf{V}_0 & \end{tikzcd} \tag{1.1}$$

where

- $\mathbf{V}_-$ is the total space of $((\varpi_-)_*\mathcal{O}(h+H))^\vee$ over $\mathbf{P}$,
- $\mathbf{V}_+$ is the total space of$((\varpi_+)_*\mathcal{O}(h+H))^\vee$ over $\mathbf{Q}$,
- $\mathbf{V}$ is the total space of $\mathcal{O}(-h-H)$ over $\mathbf{F}$,
- ι_-, ι_+, and ι are the zero-sections,
- φ_- and φ_+ are blow-ups of the zero-sections, and
- ϕ_- and ϕ_+ are the affinizations which contract the zero sections.

If $\mathbf{V}_-$ and $\mathbf{V}_+$ have the trivial canonical bundles, then one expects from [4, Conjecture 4.4] or [16, Conjecture 1.2] that $\mathbf{V}_-$ and $\mathbf{V}_+$ are derived-equivalent.

When G is the simple Lie group of type G_2, Ueda [24] used sequence of mutations of semiorthogonal decompositions of $D^b(\mathbf{V})$ obtained by applying Orlov's theorem [20] to the diagram (1.1) to prove the derived equivalence of $\mathbf{V}_-$ and $\mathbf{V}_+$. This sequence of mutations in turn follows that of Kuznetsov [18] closely.

In this paper, by using the same method, we give a new proof to the following theorem, which is originally due to Segal [22], where the flop was attributed to Abuaf:

Theorem 1.1. *Varieties connected by the flop of type C_2 are derived-equivalent.*

The term *the flop of type C_2* was introduced in [13], where simple K-equivalent maps in dimension at most 8 were classified. There are several ways to prove Theorem 1.1. In [22], Segal showed the derived equivalence by using tilting vector bundles. Hara [8] constructed alternative tilting vector bundles and studied the relation between functors defined by him and Segal.

The flop of type A^G_{2r-2} is also in the list of Kanemitsu[13]. It connects $\mathbf{V}_-$ and $\mathbf{V}_+$ for $\mathbf{P} = \mathrm{Gr}(r-1, 2r-1)$ and $\mathbf{Q} = \mathrm{Gr}(r, 2r-1)$. Similarly, we prove the following theorem:

Theorem 1.2. *Varieties connected by the flop of type A^G_4 are derived-equivalent.*

Although the proof of Theorem 1.2 is parallel to that of the derived equivalence of Calabi–Yau complete intersections in $\mathbf{P} = \mathrm{Gr}(2, 5)$ and $\mathbf{Q} = \mathrm{Gr}(3, 5)$ defined by global sections of the equivariant vector bundles dual to $\mathbf{V}_-$ and $\mathbf{V}_+$ in [15, Theorem 5.7], we write down a full detail for clarity. As explained in [24], the derived equivalence obtained in [15] in turn follows from Theorem 1.2 using matrix factorizations.

We also give a similar proof of derived equivalences for a Mukai flop and a standard flop. For a Mukai flop, Kawamata [16] and Namikawa [19] independently showed the derived equivalence by using the pull-back and the push-forward along the fiber product $\mathbf{V}_- \times_{\mathbf{V}_0} \mathbf{V}_+$. Addington, Donovan, and Meachan [1] introduced a generalization of the functor of Kawamata and Namikawa parametrized by an integer, and discovered that certain compositions of these functors give the $\mathbb{P}$-twist in the sense of Huybrechts and Thomas [11]. They also considered the case of a standard flop, where the derived equivalence is originally proved by Bondal and Orlov [5]. Our proof is obtained by proceeding the mutation performed in [5] and [1] a little further in a straightforward way. Hara [7] also studied a Mukai flop in terms of non-commutative crepant resolutions.

For a standard flop, Segal [21] showed the derived equivalence by using the grade restriction rule for variation of geometric invariant theory quotients (VGIT) originally introduced by Hori, Herbst, and Page [10]. VGIT method was subsequently developed by Halpern-Leistner [6] and Ballard, Favero, and Katzarkov [2]. It is an interesting problem to develop this method further to prove the derived equivalence for the flop of type C_2 and A^G_4, and a Mukai flop.

Notations and conventions. *We work over an algebraically closed field* $\mathbf{k}$ *of characteristic 0 throughout this paper. All pull-back and push-forward are derived unless otherwise specified. The complexes underlying* $\mathrm{Ext}^\bullet(-,-)$ *and* $\mathrm{H}^\bullet(-)$ *will be denoted by* $\mathbf{hom}(-,-)$ *and* $\mathbf{h}(-)$ *respectively.*

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2. Flop of type C_2

Let P and Q be the parabolic subgroups of the simple Lie group G of type C_2 associated with the crossed Dynkin diagrams $\times\!\Leftarrow\!\bullet$ and $\bullet\!\Leftarrow\!\times$. The corresponding homogeneous spaces are the projective space $\mathbf{P} = \mathbb{P}(V)$, the Lagrangian Grassmannian $\mathbf{Q} = \mathrm{LGr}(V)$, and the isotropic flag variety $\mathbf{F} = \mathbb{P}_{\mathbf{P}}\left(\mathscr{L}_{\mathbf{P}}^{\perp}/\mathscr{L}_{\mathbf{P}}\right) = \mathbb{P}_{\mathbf{Q}}\left(\mathscr{S}_{\mathbf{Q}}\right)$. Here V is a 4-dimensional symplectic vector space, $\mathscr{L}_{\mathbf{P}}^{\perp}$ is the rank 3 vector bundle given as the symplectic orthogonal to the tautological line bundle $\mathscr{L}_{\mathbf{P}} \cong \mathcal{O}_{\mathbf{P}}(-h)$ on $\mathbf{P}$, and $\mathscr{S}_{\mathbf{Q}}$ is the tautological rank 2 bundle on $\mathbf{Q}$. Note that $\mathbf{Q}$ is also a quadric hypersurface in $\mathbb{P}^4$. Tautological sequences on $\mathbf{Q} = \mathrm{LGr}(V)$ and $\mathbf{F} \cong \mathbb{P}_{\mathbf{Q}}\left(\mathscr{S}_{\mathbf{Q}}\right)$ give

$$0 \to \mathscr{S}_{\mathbf{Q}} \to \mathcal{O}_{\mathbf{Q}} \otimes V \to \mathscr{S}_{\mathbf{Q}}^{\vee} \to 0 \tag{2.1}$$

and

$$0 \to \mathcal{O}_{\mathbf{F}}(-h+H) \to \mathscr{S}_{\mathbf{F}}^{\vee} \to \mathcal{O}_{\mathbf{F}}(h) \to 0, \tag{2.2}$$

where $\mathscr{S}_{\mathbf{F}} := \varpi_+^* \mathscr{S}_{\mathbf{Q}}$. We have

$$(\varpi_-)_* \left(\mathcal{O}_{\mathbf{F}}(H)\right) \cong \left(\left(\mathscr{L}_{\mathbf{P}}^{\perp}/\mathscr{L}_{\mathbf{P}}\right) \otimes \mathscr{L}_{\mathbf{P}}\right)^{\vee}$$

and

$$(\varpi_+)_* \left(\mathcal{O}_{\mathbf{F}}(h)\right) \cong \mathscr{S}_{\mathbf{Q}}^{\vee},$$

whose determinants are given by $\mathcal{O}_{\mathbf{P}}(2h)$ and $\mathcal{O}_{\mathbf{Q}}(H)$ respectively. Since $\omega_{\mathbf{P}} \cong \mathcal{O}_{\mathbf{P}}(-4h)$, $\omega_{\mathbf{Q}} \cong \mathcal{O}_{\mathbf{Q}}(-3H)$, and $\omega_{\mathbf{F}} \cong \mathcal{O}_{\mathbf{F}}(-2h-2H)$, we have $\omega_{\mathbf{V}_-} \cong \mathcal{O}_{\mathbf{V}_-}$, $\omega_{\mathbf{V}_+} \cong \mathcal{O}_{\mathbf{V}_+}$, and $\omega_{\mathbf{V}} \cong \mathcal{O}_{\mathbf{V}}(-h-H)$.

Recall from [3] that

$$D^b(\mathbf{P}) = \langle \mathcal{O}_{\mathbf{P}}(-2h), \mathcal{O}_{\mathbf{P}}(-h), \mathcal{O}_{\mathbf{P}}, \mathcal{O}_{\mathbf{P}}(h) \rangle, \tag{2.3}$$

and from [17] (cf. also [14]) that

$$D^b(\mathbf{Q}) = \langle \mathcal{O}_{\mathbf{Q}}(-H), \mathscr{S}_{\mathbf{Q}}^{\vee}(-H), \mathcal{O}_{\mathbf{Q}}, \mathcal{O}_{\mathbf{Q}}(H) \rangle.$$

Since $\varphi_\pm$ are blow-ups along the zero-sections, it follows from [20] that

$$D^b(\mathbf{V}) = \langle \iota_* \varpi_-^* D^b(\mathbf{P}), \Phi_-(D^b(\mathbf{V}_-)) \rangle \tag{2.4}$$

and

$$D^b(\mathbf{V}) = \langle \iota_* \varpi_+^* D^b(\mathbf{Q}), \Phi_+(D^b(\mathbf{V}_+)) \rangle, \tag{2.5}$$

where

$$\Phi_- := ((-) \otimes \mathcal{O}_{\mathbf{V}}(H)) \circ \varphi_-^* \colon D^b(\mathbf{V}_-) \to D^b(\mathbf{V})$$

and

$$\Phi_+ := ((-) \otimes \mathcal{O}_{\mathbf{V}}(h)) \circ \varphi_+^* \colon D^b(\mathbf{V}_+) \to D^b(\mathbf{V}).$$

By abuse of notation, we use the same symbol for an object of $D^b(\mathbf{F})$ and its image in $D^b(\mathbf{V})$ by the push-forward ι_*. (2.3) and (2.4) give

$$D^b(\mathbf{V}) = \langle \mathcal{O}_{\mathbf{F}}(-2h), \mathcal{O}_{\mathbf{F}}(-h), \mathcal{O}_{\mathbf{F}}, \mathcal{O}_{\mathbf{F}}(h), \Phi_-(D^b(\mathbf{V}_-)) \rangle.$$

Since $\omega_{\mathbf{V}} \cong \mathcal{O}_{\mathbf{V}}(-h-H)$, by mutating the first term to the far right, and then $\Phi_-(D^b(\mathbf{V}_-))$ one step to the right, we obtain

$$D^b(\mathbf{V}) = \langle \mathcal{O}_{\mathbf{F}}(-h), \mathcal{O}_{\mathbf{F}}, \mathcal{O}_{\mathbf{F}}(h), \mathcal{O}_{\mathbf{F}}(-h+H), \Phi_1(D^b(\mathbf{V}_-)) \rangle,$$

where

$$\Phi_1 := R_{\langle \mathcal{O}_{\mathbf{F}}(-h+H) \rangle} \circ \Phi_-.$$

In the sequel, we will use the following fact.

Lemma 2.1. *Given two vector bundles $\mathcal{E}_{\mathbf{F}}, \mathcal{F}_{\mathbf{F}}$ on $\mathbf{F}$, if $\mathbf{h}\left(\mathcal{E}_{\mathbf{F}}^{\vee} \otimes \mathcal{F}_{\mathbf{F}}(-h-H)\right) \simeq 0$, then we have $\mathbf{hom}_{\mathcal{O}_{\mathbf{V}}}(\mathcal{E}_{\mathbf{F}}, \mathcal{F}_{\mathbf{F}}) \simeq \mathbf{h}\left(\mathcal{E}_{\mathbf{F}}^{\vee} \otimes \mathcal{F}_{\mathbf{F}}\right)$.*

Proof. We have

$$\begin{aligned}\mathbf{hom}_{\mathcal{O}_{\mathbf{V}}}(\mathcal{E}_{\mathbf{F}}, \mathcal{F}_{\mathbf{F}}) &\simeq \mathbf{hom}_{\mathcal{O}_{\mathbf{V}}}(\{\mathcal{E}_{\mathbf{V}}(h+H) \to \mathcal{E}_{\mathbf{V}}\}, \mathcal{F}_{\mathbf{F}}) \\ &\simeq \mathbf{h}(\{\mathcal{E}_{\mathbf{F}}^{\vee} \otimes \mathcal{F}_{\mathbf{F}} \to \mathcal{E}_{\mathbf{F}}^{\vee} \otimes \mathcal{F}_{\mathbf{F}}(-h-H)\}) \\ &\simeq \mathbf{h}(\mathcal{E}_{\mathbf{F}}^{\vee} \otimes \mathcal{F}_{\mathbf{F}}).\end{aligned}$$

□

Note that the canonical extension of $\mathcal{O}_{\mathbf{F}}(h)$ by $\mathcal{O}_{\mathbf{F}}(-h+H)$ associated with

$$\begin{aligned}\mathbf{hom}_{\mathcal{O}_{\mathbf{V}}}(\mathcal{O}_{\mathbf{F}}(h), \mathcal{O}_{\mathbf{F}}(-h+H)) &\simeq \mathbf{h}(\mathcal{O}_{\mathbf{F}}(-2h+H)) \\ &\simeq \mathbf{h}((\varpi_+)_* \mathcal{O}_{\mathbf{F}}(-2h) \otimes \mathcal{O}_{\mathbf{Q}}(H)) \\ &\simeq \mathbf{h}(\mathcal{O}_{\mathbf{Q}}[-1]) \\ &\simeq \mathbf{k}[-1]\end{aligned}$$

is given by the short exact sequence (2.2). By mutating $\mathcal{O}_{\mathbf{F}}(-h+H)$ one step to the left, $\mathcal{O}_{\mathbf{F}}(-h)$ to the far right, and then $\Phi_1(D^b(\mathbf{V}_-))$ one step to the right, we obtain

$$D^b(\mathbf{V}) = \langle \mathcal{O}_{\mathbf{F}}, \mathscr{S}_{\mathbf{F}}^{\vee}, \mathcal{O}_{\mathbf{F}}(h), \mathcal{O}_{\mathbf{F}}(H), \Phi_2(D^b(\mathbf{V}_-)) \rangle,$$

where

$$\Phi_2 := R_{\langle \mathcal{O}_{\mathbf{F}}(H) \rangle} \circ \Phi_1.$$

One can easily see that $\mathcal{O}_{\mathbf{F}}(h)$ and $\mathcal{O}_{\mathbf{F}}(H)$ are orthogonal, so that

$$D^b(\mathbf{V}) = \langle \mathcal{O}_{\mathbf{F}}, \mathscr{S}_{\mathbf{F}}^{\vee}, \mathcal{O}_{\mathbf{F}}(H), \mathcal{O}_{\mathbf{F}}(h), \Phi_2(D^b(\mathbf{V}_-)) \rangle. \tag{2.6}$$

By mutating $\Phi_2(D^b(\mathbf{V}_-))$ one step to the left, and then $\mathcal{O}_{\mathbf{F}}(h)$ to the far left, we obtain

$$D^b(\mathbf{V}) = \langle \mathcal{O}_{\mathbf{F}}(-H), \mathcal{O}_{\mathbf{F}}, \mathscr{S}_{\mathbf{F}}^{\vee}, \mathcal{O}_{\mathbf{F}}(H), \Phi_3(D^b(\mathbf{V}_-)) \rangle,$$

where

$$\Phi_3 := L_{\langle \mathcal{O}_{\mathbf{F}}(h) \rangle} \circ \Phi_2.$$

We have

$$\mathbf{hom}_{\mathcal{O}_{\mathbf{V}}}(\mathcal{O}_{\mathbf{F}}, \mathscr{S}_{\mathbf{F}}^{\vee}) \simeq \mathbf{h}(\mathscr{S}_{\mathbf{F}}^{\vee}) \simeq V^{\vee},$$

and the dual of (2.1) shows that the kernel of the evaluation map $\mathcal{O}_{\mathbf{F}} \otimes V^{\vee} \to \mathscr{S}_{\mathbf{F}}^{\vee}$ is $\mathscr{S}_{\mathbf{F}} \cong \mathscr{S}_{\mathbf{F}}^{\vee}(-H)$. By mutating $\mathscr{S}_{\mathbf{F}}^{\vee}$ one step to the left, we obtain

$$D^b(\mathbf{V}) = \langle \mathcal{O}_{\mathbf{F}}(-H), \mathscr{S}_{\mathbf{F}}^{\vee}(-H), \mathcal{O}_{\mathbf{F}}, \mathcal{O}_{\mathbf{F}}(H), \Phi_3(D^b(\mathbf{V}_-)) \rangle. \tag{2.7}$$

By comparing (2.7) with (2.5), we obtain a derived equivalence

$$\Phi := \Phi_+^! \circ \Phi_3 \colon D^b(\mathbf{V}_-) \xrightarrow{\sim} D^b(\mathbf{V}_+),$$

where

$$\Phi_+^!(-) := (\varphi_+)_* \circ ((-) \otimes \mathcal{O}_{\mathbf{V}}(-h)) : D^b(\mathbf{V}) \to D^b(\mathbf{V}_+)$$

is the left adjoint functor of Φ_+.

3. FLOP OF TYPE A_4^G

Let P and Q be the parabolic subgroups of the simple Lie group G of type A_4 associated with the crossed Dynkin diagrams $\bullet\!-\!\times\!-\!\bullet\!-\!\bullet$ and $\bullet\!-\!\bullet\!-\!\times\!-\!\bullet$. The corresponding homogeneous spaces are the Grassmannians $\mathbf{P} = \mathrm{Gr}(2,V)$, $\mathbf{Q} = \mathrm{Gr}(3,V)$, and the partial flag variety $\mathbf{F} = \mathbb{P}_{\mathbf{P}}\left(\wedge^2 \mathscr{Q}_{\mathbf{P}}^\vee\right) = \mathbb{P}_{\mathbf{Q}}\left(\wedge^2 \mathscr{S}_{\mathbf{Q}}\right)$. Here V is a 5-dimensional vector space, $\mathscr{Q}_{\mathbf{P}}^\vee$ is the dual of the universal quotient bundle on $\mathbf{P}$, and $\mathscr{S}_{\mathbf{Q}}$ is the tautological rank 3 bundle on $\mathbf{Q}$. We have

$$(\varpi_-)_* \left(\mathcal{O}_{\mathbf{F}}(H)\right) \cong \wedge^2 \mathscr{Q}_{\mathbf{P}}$$

and

$$(\varpi_+)_* \left(\mathcal{O}_{\mathbf{F}}(h)\right) \cong \wedge^2 \mathscr{S}_{\mathbf{Q}}^\vee,$$

whose determinants are given by $\mathcal{O}_{\mathbf{P}}(2h)$ and $\mathcal{O}_{\mathbf{Q}}(2H)$ respectively. Since $\omega_{\mathbf{P}} \cong \mathcal{O}_{\mathbf{P}}(-5h)$, $\omega_{\mathbf{Q}} \cong \mathcal{O}_{\mathbf{Q}}(-5H)$, and $\omega_{\mathbf{F}} \cong \mathcal{O}_{\mathbf{F}}(-3h-3H)$, we have $\omega_{\mathbf{V}_-} \cong \mathcal{O}_{\mathbf{V}_-}$, $\omega_{\mathbf{V}_+} \cong \mathcal{O}_{\mathbf{V}_+}$ and $\omega_{\mathbf{V}} \cong \mathcal{O}_{\mathbf{V}}(-2h-2H)$.

First, we adapt several lemmas in [15] to our situation. To distinguish vector bundles which are obtained as a pull-back to $\mathbf{F}$ from $\mathbf{P}$ or $\mathbf{Q}$, we put tilde on the pull-back from $\mathbf{Q}$. By abuse of notation, we use the same symbol for an object of $D^b(\mathbf{F})$ and its image in $D^b(\mathbf{V})$ by the push-forward ι_*.

Lemma 3.1. $\mathbf{hom}_{\mathcal{O}_{\mathbf{V}}}\left(\widetilde{\mathscr{Q}}_{\mathbf{F}}, \mathcal{O}_{\mathbf{F}}(h+aH)\right) \simeq 0$ *for integers* $-4 \le a \le -2$.

Proof. We have

$$\mathbf{hom}_{\mathcal{O}_{\mathbf{V}}}\left(\widetilde{\mathscr{Q}}_{\mathbf{F}}, \mathcal{O}_{\mathbf{F}}(h+aH)\right) \simeq \mathbf{h}\left(\widetilde{\mathscr{Q}}_{\mathbf{F}}^\vee(h+aH)\right) \simeq 0,$$

where the first and the second isomorphisms follow from Lemma 2.1, Borel-Bott-Weil theorem and [15, Lemma 5.1] respectively. □

Similarly, one can deduce Lemma 3.2 and Lemma 3.3 below from [15, Lemma 5.2, Lemma 5.3] by checking that $\mathcal{O}_{\mathbf{F}}((a-1)H)$, $\mathcal{E}_{\mathbf{F}}^\vee \otimes \mathcal{E}_{\mathbf{F}}'((a-1)h-2H)$, and $\widetilde{\mathcal{F}}_{\mathbf{F}}^\vee \otimes \widetilde{\mathcal{F}}_{\mathbf{F}}'(-2h+(a-1)H)$ are acyclic as an object of $D^b(\mathbf{F})$.

Lemma 3.2. $\mathbf{hom}_{\mathcal{O}_{\mathbf{V}}}\left(\mathcal{O}_{\mathbf{F}}, \mathcal{O}_{\mathbf{F}}(h+aH)\right) \simeq 0$ *for integers* $-3 \le a \le -1$.

Lemma 3.3. *Let* $\mathcal{E}_{\mathbf{F}}, \mathcal{E}_{\mathbf{F}}'$ *be the pull-back to* $\mathbf{F}$ *of vector bundles* $\mathcal{E}, \mathcal{E}'$ *on* $\mathbf{P}$*, and let* $\widetilde{\mathcal{F}}_{\mathbf{F}}, \widetilde{\mathcal{F}}_{\mathbf{F}}'$ *be the pull-back to* $\mathbf{F}$ *of vector bundles* $\mathcal{F}, \mathcal{F}'$ *on* $\mathbf{Q}$*. Then we have* $\mathbf{hom}_{\mathcal{O}_{\mathbf{V}}}\left(\mathcal{E}_{\mathbf{F}}, \mathcal{E}_{\mathbf{F}}'(ah-H)\right) \simeq 0$ *and* $\mathbf{hom}_{\mathcal{O}_{\mathbf{V}}}\left(\widetilde{\mathcal{F}}_{\mathbf{F}}, \widetilde{\mathcal{F}}_{\mathbf{F}}'(-h+aH)\right) \simeq 0$ *for all integers* a.

The parallel result to the following lemma was tacitly used in [15].

Lemma 3.4. *As an object of* $D^b(\mathbf{V})$*,* $\mathcal{O}_{\mathbf{F}}$*,* $\widetilde{\mathscr{Q}}_{\mathbf{F}}$*,* $\mathscr{S}_{\mathbf{F}}$*, and* $\mathscr{S}_{\mathbf{F}}^\vee$ *are left orthogonal to* $\widetilde{\mathscr{S}}_{\mathbf{F}}^\vee(h-2H)$*,* $\widetilde{\mathscr{S}}_{\mathbf{F}}^\vee(h-2H)$*,* $\mathcal{O}_{\mathbf{F}}(2h-2H)$*, and* $\mathscr{Q}_{\mathbf{F}}$ *respectively.*

Lemma 3.5 below and the tautological sequence show that $R_{\mathcal{O}_{\mathbf{F}}}\widetilde{\mathscr{Q}}_{\mathbf{F}}^\vee \simeq \widetilde{\mathscr{S}}_{\mathbf{F}}^\vee$ and $R_{\mathcal{O}_{\mathbf{F}}}\mathscr{S}_{\mathbf{F}} \simeq \mathscr{Q}_{\mathbf{F}}$ in $D^b(\mathbf{V})$.

Lemma 3.5. $\mathbf{hom}_{\mathcal{O}_{\mathbf{V}}}\left(\widetilde{\mathscr{Q}}_{\mathbf{F}}^\vee, \mathcal{O}_{\mathbf{F}}\right) \simeq V$ *and* $\mathbf{hom}_{\mathcal{O}_{\mathbf{V}}}\left(\mathscr{S}_{\mathbf{F}}, \mathcal{O}_{\mathbf{F}}\right) \simeq V$.

Again, both Lemma 3.4 and Lemma 3.5 follow from Lemma 2.1 and Borel-Bott-Weil theorem. Lemma 3.6 below and the exact sequences

$$0 \to \mathcal{O}_{\mathbf{F}}(h-H) \to \mathscr{Q}_{\mathbf{F}} \to \widetilde{\mathscr{Q}}_{\mathbf{F}} \to 0$$

and

$$0 \to \mathscr{S}_{\mathbf{F}} \to \widetilde{\mathscr{S}}_{\mathbf{F}} \to \mathcal{O}_{\mathbf{F}}(h-H) \to 0$$

obtained in [15] show that $R_{\mathcal{O}_{\mathbf{F}}(h-H)}\widetilde{\mathscr{Q}}_{\mathbf{F}} \simeq \mathscr{Q}_{\mathbf{F}}[1]$ and $L_{\mathcal{O}_{\mathbf{F}}(-h+H)}\widetilde{\mathscr{S}}_{\mathbf{F}}^\vee \simeq \mathscr{S}_{\mathbf{F}}^\vee$ in $D^b(\mathbf{V})$.

Lemma 3.6. $\mathbf{hom}_{\mathcal{O}_\mathbf{V}}\left(\widetilde{\mathscr{Q}}_\mathbf{F}, \mathcal{O}_\mathbf{F}(h-H)\right) \simeq \mathbf{k}[-1]$ *and* $\mathbf{hom}_{\mathcal{O}_\mathbf{V}}\left(\mathcal{O}_\mathbf{F}(-h+H), \widetilde{\mathscr{S}}_\mathbf{F}^\vee\right) \simeq \mathbf{k}$.

Proof. We have

$$\mathbf{hom}_{\mathcal{O}_\mathbf{V}}\left(\widetilde{\mathscr{Q}}_\mathbf{F}, \mathcal{O}_\mathbf{F}(h-H)\right) \simeq \mathbf{h}\left(\widetilde{\mathscr{Q}}_\mathbf{F}^\vee(h-H)\right) \simeq \mathbf{k}[-1],$$

where the isomorphisms follow from Lemma 2.1 and Borel-Bott-Weil theorem. Similarly, we have

$$\mathbf{hom}_{\mathcal{O}_\mathbf{V}}\left(\mathcal{O}_\mathbf{F}(-h+H), \widetilde{\mathscr{S}}_\mathbf{F}^\vee\right) \simeq \mathbf{h}\left(\widetilde{\mathscr{S}}_\mathbf{F}^\vee(h-H)\right) \simeq \mathbf{k}.$$

□

Recall from [17] (cf. also [14])

$$D^b(\mathbf{P}) = \langle \mathscr{S}_\mathbf{P}(-2h), \mathcal{O}_\mathbf{P}(-2h), \mathscr{S}_\mathbf{P}(-h), \mathcal{O}_\mathbf{P}(-h), \cdots, \mathscr{S}_\mathbf{P}(2h), \mathcal{O}_\mathbf{P}(2h)\rangle,$$

and

$$D^b(\mathbf{Q}) = \langle \mathcal{O}_\mathbf{Q}, \mathscr{Q}_\mathbf{Q}, \mathcal{O}_\mathbf{Q}(H), \mathscr{Q}_\mathbf{Q}(H), \cdots, \mathcal{O}_\mathbf{Q}(4H), \mathscr{Q}_\mathbf{Q}(4H)\rangle. \tag{3.1}$$

Since $\varphi_\pm$ are blow-ups along the zero-sections, it follows from [20] that

$$D^b(\mathbf{V}) = \langle \iota_*\varpi_-^* D^b(\mathbf{P}), \iota_*\varpi_-^* D^b(\mathbf{P})(h+H), \Phi_-(D^b(\mathbf{V}_-))\rangle \tag{3.2}$$

and

$$D^b(\mathbf{V}) = \langle \iota_*\varpi_+^* D^b(\mathbf{Q}), \iota_*\varpi_+^* D^b(\mathbf{Q})(h+H), \Phi_+(D^b(\mathbf{V}_+))\rangle, \tag{3.3}$$

where

$$\Phi_- := ((-)\otimes\mathcal{O}_\mathbf{V}(2H))\circ\varphi_-^* \colon D^b(\mathbf{V}_-) \to D^b(\mathbf{V})$$

and

$$\Phi_+ := ((-)\otimes\mathcal{O}_\mathbf{V}(2h))\circ\varphi_+^* \colon D^b(\mathbf{V}_+) \to D^b(\mathbf{V}).$$

We write $\mathcal{O}_{i,j} := \mathcal{O}_\mathbf{F}(ih+jH)$. (3.1) and (3.3) give a semiorthogonal decomposition of the form

$$\begin{aligned} D^b(\mathbf{V}) = \langle &\mathcal{O}_{0,0}, \widetilde{\mathscr{Q}}_{0,0}, \mathcal{O}_{0,1}, \widetilde{\mathscr{Q}}_{0,1}, \mathcal{O}_{0,2}, \widetilde{\mathscr{Q}}_{0,2}, \mathcal{O}_{0,3}, \widetilde{\mathscr{Q}}_{0,3}, \mathcal{O}_{0,4}, \widetilde{\mathscr{Q}}_{0,4} \\ &\mathcal{O}_{1,1}, \widetilde{\mathscr{Q}}_{1,1}, \mathcal{O}_{1,2}, \widetilde{\mathscr{Q}}_{1,2}, \mathcal{O}_{1,3}, \widetilde{\mathscr{Q}}_{1,3}, \mathcal{O}_{1,4}, \widetilde{\mathscr{Q}}_{1,4}, \mathcal{O}_{1,5}, \widetilde{\mathscr{Q}}_{1,5}, \Phi_+(D^b(\mathbf{V}_+))\rangle. \end{aligned}$$

Since $\omega_\mathbf{V} \cong \mathcal{O}_\mathbf{V}(-2h-2H)$, by mutating the first five terms to the far right, and then $\Phi_+(D^b(\mathbf{V}_+))$ five steps to the right, we obtain

$$\begin{aligned} D^b(\mathbf{V}) = \langle &\widetilde{\mathscr{Q}}_{0,2}, \mathcal{O}_{0,3}, \widetilde{\mathscr{Q}}_{0,3}, \mathcal{O}_{0,4}, \widetilde{\mathscr{Q}}_{0,4}, \mathcal{O}_{1,1}, \widetilde{\mathscr{Q}}_{1,1}, \mathcal{O}_{1,2}, \widetilde{\mathscr{Q}}_{1,2}, \mathcal{O}_{1,3} \\ &\widetilde{\mathscr{Q}}_{1,3}, \mathcal{O}_{1,4}, \widetilde{\mathscr{Q}}_{1,4}, \mathcal{O}_{1,5}, \widetilde{\mathscr{Q}}_{1,5}, \mathcal{O}_{2,2}, \widetilde{\mathscr{Q}}_{2,2}, \mathcal{O}_{2,3}, \widetilde{\mathscr{Q}}_{2,3}, \mathcal{O}_{2,4}, \Phi_1(D^b(\mathbf{V}_+))\rangle, \end{aligned}$$

where

$$\Phi_1 := R_{\langle \mathcal{O}_{2,2}, \widetilde{\mathscr{Q}}_{2,2}, \mathcal{O}_{2,3}, \widetilde{\mathscr{Q}}_{2,3}, \mathcal{O}_{2,4}\rangle} \circ \Phi_+.$$

One can easily see that $\mathcal{O}_{1,1}$ is orthogonal to $\mathcal{O}_{0,3}$, $\widetilde{\mathscr{Q}}_{0,3}$, $\mathcal{O}_{0,4}$, and $\widetilde{\mathscr{Q}}_{0,4}$ by Lemma 3.1 and Lemma 3.2, so that

$$\begin{aligned} D^b(\mathbf{V}) = \langle &\widetilde{\mathscr{Q}}_{0,2}, \mathcal{O}_{1,1}, \mathcal{O}_{0,3}, \widetilde{\mathscr{Q}}_{0,3}, \mathcal{O}_{0,4}, \widetilde{\mathscr{Q}}_{0,4}, \widetilde{\mathscr{Q}}_{1,1}, \mathcal{O}_{1,2}, \widetilde{\mathscr{Q}}_{1,2}, \mathcal{O}_{1,3} \\ &\widetilde{\mathscr{Q}}_{1,3}, \mathcal{O}_{2,2}, \mathcal{O}_{1,4}, \widetilde{\mathscr{Q}}_{1,4}, \mathcal{O}_{1,5}, \widetilde{\mathscr{Q}}_{1,5}, \widetilde{\mathscr{Q}}_{2,2}, \mathcal{O}_{2,3}, \widetilde{\mathscr{Q}}_{2,3}, \mathcal{O}_{2,4}, \Phi_1(D^b(\mathbf{V}_+))\rangle. \end{aligned}$$

By mutating $\widetilde{\mathscr{Q}}_{0,2}, \widetilde{\mathscr{Q}}_{1,3}, \widetilde{\mathscr{Q}}_{1,1}$, and $\widetilde{\mathscr{Q}}_{2,2}$ one step to the right, we obtain by $\widetilde{\mathscr{Q}}_{1,1} \cong \widetilde{\mathscr{Q}}_{1,2}^\vee$, Lemma 3.5, and Lemma 3.6

$$\begin{aligned} D^b(\mathbf{V}) = \langle &\mathcal{O}_{1,1}, \mathscr{Q}_{0,2}, \mathcal{O}_{0,3}, \widetilde{\mathscr{Q}}_{0,3}, \mathcal{O}_{0,4}, \widetilde{\mathscr{Q}}_{0,4}, \mathcal{O}_{1,2}, \widetilde{\mathscr{S}}_{1,2}^\vee, \widetilde{\mathscr{Q}}_{1,2}, \mathcal{O}_{1,3} \\ &\mathcal{O}_{2,2}, \mathscr{Q}_{1,3}, \mathcal{O}_{1,4}, \widetilde{\mathscr{Q}}_{1,4}, \mathcal{O}_{1,5}, \widetilde{\mathscr{Q}}_{1,5}, \mathcal{O}_{2,3}, \widetilde{\mathscr{S}}_{2,3}^\vee, \widetilde{\mathscr{Q}}_{2,3}, \mathcal{O}_{2,4}, \Phi_1(D^b(\mathbf{V}_+))\rangle. \end{aligned}$$

By mutating $\mathcal{O}_{1,2}$ and $\mathcal{O}_{2,3}$ four steps to the left, we obtain by Lemma 3.1, Lemma 3.2, and Lemma 3.6

$$\begin{aligned} D^b(\mathbf{V}) = \langle & \mathcal{O}_{1,1}, \mathcal{Q}_{0,2}, \mathcal{O}_{1,2}, \mathcal{O}_{0,3}, \mathcal{Q}_{0,3}, \mathcal{O}_{0,4}, \widetilde{\mathcal{Q}}_{0,4}, \widetilde{\mathcal{S}}_{1,2}^{\vee}, \widetilde{\mathcal{Q}}_{1,2}, \mathcal{O}_{1,3} \\ & \mathcal{O}_{2,2}, \mathcal{Q}_{1,3}, \mathcal{O}_{2,3}, \mathcal{O}_{1,4}, \mathcal{Q}_{1,4}, \mathcal{O}_{1,5}, \widetilde{\mathcal{Q}}_{1,5}, \widetilde{\mathcal{S}}_{2,3}^{\vee}, \widetilde{\mathcal{Q}}_{2,3}, \mathcal{O}_{2,4}, \Phi_1(D^b(\mathbf{V}_+))\rangle. \end{aligned}$$

One can easily see that $\widetilde{\mathcal{S}}_{1,2}^{\vee}$ is orthogonal to $\mathcal{O}_{0,4}$ and $\widetilde{\mathcal{Q}}_{0,4}$ by Lemma 3.4, so that

$$\begin{aligned} D^b(\mathbf{V}) = \langle & \mathcal{O}_{1,1}, \mathcal{Q}_{0,2}, \mathcal{O}_{1,2}, \mathcal{O}_{0,3}, \mathcal{Q}_{0,3}, \widetilde{\mathcal{S}}_{1,2}^{\vee}, \mathcal{O}_{0,4}, \widetilde{\mathcal{Q}}_{0,4}, \widetilde{\mathcal{Q}}_{1,2}, \mathcal{O}_{1,3} \\ & \mathcal{O}_{2,2}, \mathcal{Q}_{1,3}, \mathcal{O}_{2,3}, \mathcal{O}_{1,4}, \mathcal{Q}_{1,4}, \widetilde{\mathcal{S}}_{2,3}^{\vee}, \mathcal{O}_{1,5}, \widetilde{\mathcal{Q}}_{1,5}, \widetilde{\mathcal{Q}}_{2,3}, \mathcal{O}_{2,4}, \Phi_1(D^b(\mathbf{V}_+))\rangle. \end{aligned}$$

By mutating $\mathcal{O}_{0,3}$ and $\mathcal{O}_{1,4}$ two steps to the right, $\mathcal{O}_{1,3}$ and $\mathcal{O}_{2,4}$ three steps to the left, and then $\mathcal{O}_{0,4}$ and $\mathcal{O}_{1,5}$ two steps to the right, we obtain by Lemma 3.5 and Lemma 3.6

$$\begin{aligned} D^b(\mathbf{V}) = \langle & \mathcal{O}_{1,1}, \mathcal{Q}_{0,2}, \mathcal{O}_{1,2}, \mathcal{S}_{0,3}, \mathcal{S}_{1,2}^{\vee}, \mathcal{O}_{0,3}, \mathcal{O}_{1,3}, \mathcal{S}_{0,4}, \mathcal{S}_{1,3}^{\vee}, \mathcal{O}_{0,4} \\ & \mathcal{O}_{2,2}, \mathcal{Q}_{1,3}, \mathcal{O}_{2,3}, \mathcal{S}_{1,4}, \mathcal{S}_{2,3}^{\vee}, \mathcal{O}_{1,4}, \mathcal{O}_{2,4}, \mathcal{S}_{1,5}, \mathcal{S}_{2,4}^{\vee}, \mathcal{O}_{1,5}, \Phi_1(D^b(\mathbf{V}_+))\rangle. \end{aligned}$$

By mutating $\mathcal{O}_{1,1}$ to the far right, and then $\Phi_1(D^b(\mathbf{V}_+))$ one step to the right, we obtain

$$\begin{aligned} D^b(\mathbf{V}) = \langle & \mathcal{Q}_{0,2}, \mathcal{O}_{1,2}, \mathcal{S}_{0,3}, \mathcal{S}_{1,2}^{\vee}, \mathcal{O}_{0,3}, \mathcal{O}_{1,3}, \mathcal{S}_{0,4}, \mathcal{S}_{1,3}^{\vee}, \mathcal{O}_{0,4}, \mathcal{O}_{2,2} \\ & \mathcal{Q}_{1,3}, \mathcal{O}_{2,3}, \mathcal{S}_{1,4}, \mathcal{S}_{2,3}^{\vee}, \mathcal{O}_{1,4}, \mathcal{O}_{2,4}, \mathcal{S}_{1,5}, \mathcal{S}_{2,4}^{\vee}, \mathcal{O}_{1,5}, \mathcal{O}_{3,3}, \Phi_2(D^b(\mathbf{V}_+))\rangle, \end{aligned}$$

where

$$\Phi_2 \coloneqq R_{\langle \mathcal{O}_{3,3}\rangle} \circ \Phi_1.$$

By Lemma 3.2, Lemma 3.3, and Lemma 3.4, we obtain

$$\begin{aligned} D^b(\mathbf{V}) = \langle & \mathcal{Q}_{0,2}, \mathcal{O}_{1,2}, \mathcal{S}_{1,2}^{\vee}, \mathcal{O}_{2,2}, \mathcal{S}_{0,3}, \mathcal{O}_{0,3}, \mathcal{O}_{1,3}, \mathcal{S}_{1,3}^{\vee}, \mathcal{Q}_{1,3}, \mathcal{O}_{2,3} \\ & \mathcal{S}_{2,3}^{\vee}, \mathcal{O}_{3,3}, \mathcal{S}_{0,4}, \mathcal{O}_{0,4}, \mathcal{S}_{1,4}, \mathcal{O}_{1,4}, \mathcal{O}_{2,4}, \mathcal{S}_{2,4}^{\vee}, \mathcal{S}_{1,5}, \mathcal{O}_{1,5}, \Phi_2(D^b(\mathbf{V}_+))\rangle. \end{aligned}$$

By mutating $\Phi_2(D^b(\mathbf{V}_+))$ ten steps to the left, and then last ten terms to the far left, we obtain

$$\begin{aligned} D^b(\mathbf{V}) = \langle & \mathcal{S}_{0,1}^{\vee}, \mathcal{O}_{1,1}, \mathcal{S}_{-2,2}, \mathcal{O}_{-2,2}, \mathcal{S}_{-1,2}, \mathcal{O}_{-1,2}, \mathcal{O}_{0,2}, \mathcal{S}_{0,2}^{\vee}, \mathcal{S}_{-1,3}, \mathcal{O}_{-1,3} \\ & \mathcal{Q}_{0,2}, \mathcal{O}_{1,2}, \mathcal{S}_{1,2}^{\vee}, \mathcal{O}_{2,2}, \mathcal{S}_{0,3}, \mathcal{O}_{0,3}, \mathcal{O}_{1,3}, \mathcal{S}_{1,3}^{\vee}, \mathcal{Q}_{1,3}, \mathcal{O}_{2,3}, \Phi_3(D^b(\mathbf{V}_+))\rangle, \end{aligned}$$

where

$$\Phi_3 \coloneqq L_{\langle \mathcal{S}_{2,3}^{\vee}, \mathcal{O}_{3,3}, \mathcal{S}_{0,4}, \mathcal{O}_{0,4}, \mathcal{S}_{1,4}, \mathcal{O}_{1,4}, \mathcal{O}_{2,4}, \mathcal{S}_{2,4}^{\vee}, \mathcal{S}_{1,5}, \mathcal{O}_{1,5}\rangle} \circ \Phi_2.$$

By Lemma 3.3, we obtain

$$\begin{aligned} D^b(\mathbf{V}) = \langle & \mathcal{S}_{0,1}^{\vee}, \mathcal{O}_{1,1}, \mathcal{S}_{-2,2}, \mathcal{O}_{-2,2}, \mathcal{S}_{-1,2}, \mathcal{O}_{-1,2}, \mathcal{O}_{0,2}, \mathcal{S}_{0,2}^{\vee}, \mathcal{Q}_{0,2}, \mathcal{O}_{1,2} \\ & \mathcal{S}_{1,2}^{\vee}, \mathcal{O}_{2,2}, \mathcal{S}_{-1,3}, \mathcal{O}_{-1,3}, \mathcal{S}_{0,3}, \mathcal{O}_{0,3}, \mathcal{O}_{1,3}, \mathcal{S}_{1,3}^{\vee}, \mathcal{Q}_{1,3}, \mathcal{O}_{2,3}, \Phi_3(D^b(\mathbf{V}_+))\rangle. \end{aligned}$$

By mutating $\mathcal{Q}_{0,2}$ and $\mathcal{Q}_{1,3}$ two steps to the left, the first two terms to the far right, and then $\Phi_3(D^b(\mathbf{V}_+))$ two steps to the right, we obtain by $\mathcal{S}_{0,0}^{\vee} \simeq \mathcal{S}_{1,0}$, Lemma 3.4, and Lemma 3.6

$$\begin{aligned} D^b(\mathbf{V}) = \langle & \mathcal{S}_{-2,2}, \mathcal{O}_{-2,2}, \mathcal{S}_{-1,2}, \mathcal{O}_{-1,2}, \mathcal{S}_{0,2}, \mathcal{O}_{0,2}, \mathcal{S}_{1,2}, \mathcal{O}_{1,2}, \mathcal{S}_{2,2}, \mathcal{O}_{2,2} \\ & \mathcal{S}_{-1,3}, \mathcal{O}_{-1,3}, \mathcal{S}_{0,3}, \mathcal{O}_{0,3}, \mathcal{S}_{1,3}, \mathcal{O}_{1,3}, \mathcal{S}_{2,3}, \mathcal{O}_{2,3}, \mathcal{S}_{3,3}, \mathcal{O}_{3,3}, \Phi_4(D^b(\mathbf{V}_+))\rangle, \end{aligned} \tag{3.4}$$

where

$$\Phi_4 \coloneqq R_{\langle \mathcal{S}_{2,3}^{\vee}, \mathcal{O}_{3,3}\rangle} \circ \Phi_3.$$

By comparing (3.4) with (3.2), we obtain a derived equivalence

$$\Phi \coloneqq \Phi_-^! \circ \Phi_4 \colon D^b(\mathbf{V}_+) \xrightarrow{\sim} D^b(\mathbf{V}_-),$$

where

$$\Phi_-^!(-) := (\varphi_-)_* \circ ((-) \otimes \mathcal{O}_{\mathbf{V}}(-2H)) : D^b(\mathbf{V}) \to D^b(\mathbf{V}_-)$$

is the left adjoint functor of Φ_-.

4. Mukai flop

For $n \geq 2$, let P and Q be the maximal parabolic subgroups of the simple Lie group of type A_n associated with the crossed Dynkin diagrams $\times\!\!-\!\!\bullet\cdots\!\!-\!\!\bullet$ and $\bullet\!\!-\!\!\cdots\bullet\!\!-\!\!\times$. The corresponding homogeneous spaces are the projective spaces $\mathbf{P} = \mathbb{P}V$, $\mathbf{Q} = \mathbb{P}V^\vee$, and the partial flag variety $\mathbf{F} = \mathrm{F}(1, n; V)$, where V is an $(n+1)$-dimensional vector space. Since $\omega_{\mathbf{P}} \cong \mathcal{O}(-(n+1)h)$, $\omega_{\mathbf{Q}} \cong \mathcal{O}(-(n+1)H)$, and $\omega_{\mathbf{F}} \cong \mathcal{O}(-nh - nH)$, we have $\omega_{\mathbf{V}_-} \cong \mathcal{O}_{\mathbf{V}_-}$, $\omega_{\mathbf{V}_+} \cong \mathcal{O}_{\mathbf{V}_+}$, and $\omega_{\mathbf{V}} \cong \mathcal{O}(-(n-1)h - (n-1)H)$.

Lemma 4.1. *$\mathcal{O}_{\mathbf{F}}(-ih + jH)$ and $\mathcal{O}_{\mathbf{F}}(-(i+1)h + (j-1)H)$ are acyclic for $1 \leq j \leq n-1$ and $1 \leq i \leq n-j$.*

Proof. Since $j - n \leq -i \leq -1$ and $j - n - 1 \leq -i - 1 \leq -2$, the derived push-foward of $\mathcal{O}_{\mathbf{F}}(-ih + jH)$ and $\mathcal{O}_{\mathbf{F}}(-(i+1)h + (j-1)H)$ vanish by [9, Exercise III.8.4] unless $i = n-1$ and $j = 1$, in which case the acyclicity of $\mathcal{O}_{\mathbf{F}}(-nh)$ is obvious. □

Lemma 4.2. $\mathbf{hom}_{\mathcal{O}_{\mathbf{V}}}(\mathcal{O}_{\mathbf{F}}(ih - jH), \mathcal{O}_{\mathbf{F}}) \simeq 0$ *for $1 \leq j \leq n-1$ and $1 \leq i \leq n-j$.*

Proof. We have

$$\mathbf{hom}_{\mathcal{O}_{\mathbf{V}}}(\mathcal{O}_{\mathbf{F}}(ih - jH), \mathcal{O}_{\mathbf{F}}) \simeq \mathbf{h}\left(\{\mathcal{O}_{\mathbf{F}}(-ih + jH) \to \mathcal{O}_{\mathbf{F}}(-(i+1)h + (j-1)H)\}\right),$$

which vanishes by Lemma 4.1. □

Recall from [3] that

$$D^b(\mathbf{P}) = \langle \mathcal{O}_{\mathbf{P}}, \mathcal{O}_{\mathbf{P}}(h), \cdots, \mathcal{O}_{\mathbf{P}}(nh) \rangle \tag{4.1}$$

and

$$D^b(\mathbf{Q}) = \langle \mathcal{O}_{\mathbf{Q}}, \mathcal{O}_{\mathbf{Q}}(H), \cdots, \mathcal{O}_{\mathbf{Q}}(nH) \rangle. \tag{4.2}$$

Since $\varphi_\pm$ are blow-ups along the zero-sections, it follows from [20] that

$$D^b(\mathbf{V}) = \langle \iota_* \varpi_-^* D^b(\mathbf{P}), \cdots, \iota_* \varpi_-^* D^b(\mathbf{P}) \otimes \mathcal{O}_{\mathbf{V}}((n-2)H), \Phi_-(D^b(\mathbf{V}_-)) \rangle \tag{4.3}$$

and

$$D^b(\mathbf{V}) = \langle \iota_* \varpi_+^* D^b(\mathbf{Q}), \cdots, \iota_* \varpi_+^* D^b(\mathbf{Q}) \otimes \mathcal{O}_{\mathbf{V}}((n-2)h), \Phi_+(D^b(\mathbf{V}_+)) \rangle, \tag{4.4}$$

where

$$\Phi_- := ((-) \otimes \mathcal{O}_{\mathbf{V}}((n-1)H)) \circ \varphi_-^* \colon D^b(\mathbf{V}_-) \to D^b(\mathbf{V})$$

and

$$\Phi_+ := ((-) \otimes \mathcal{O}_{\mathbf{V}}((n-1)h)) \circ \varphi_+^* \colon D^b(\mathbf{V}_+) \to D^b(\mathbf{V}).$$

We write $\mathcal{O}_{i,j} := \mathcal{O}_{\mathbf{F}}(ih + jH)$. (4.1) and (4.3) give a semiorthogonal decomposition of the form

$$D^b(\mathbf{V}) = \langle \mathcal{A}_0, \Phi_-(D^b(\mathbf{V}_-)) \rangle$$

where $\mathcal{A}_0$ is given by

$$\begin{array}{ccccccccc}
\mathcal{O}_{0,0} & \mathcal{O}_{1,0} & \cdots & \mathcal{O}_{n-2,0} & \mathcal{O}_{n-1,0} & \mathcal{O}_{n,0} & & & \\
& \mathcal{O}_{1,1} & \cdots & \mathcal{O}_{n-2,1} & \mathcal{O}_{n-1,1} & \mathcal{O}_{n,1} & \mathcal{O}_{n+1,1} & & \\
& & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \\
& & & \mathcal{O}_{n-2,n-2} & \mathcal{O}_{n-1,n-2} & \mathcal{O}_{n,n-2} & \mathcal{O}_{n+1,n-2} & \cdots & \mathcal{O}_{2n-2,n-2}.
\end{array} \tag{4.5}$$

Note from Lemma 4.2 that there are no morphisms from right to left in (4.5). Since $\omega_{\mathbf{V}} \cong \mathcal{O}_{-(n-1),-(n-1)}$, by mutating first

$$\begin{array}{cccc} \mathcal{O}_{0,0} & \mathcal{O}_{1,0} & \cdots & \mathcal{O}_{n-2,0} \\ & \mathcal{O}_{1,1} & \cdots & \mathcal{O}_{n-2,1} \\ & & \ddots & \vdots \\ & & & \mathcal{O}_{n-2,n-2} \end{array}$$

to the far right, and then $\Phi_{-}(D^b(\mathbf{V}_{-}))$ to the far right, we obtain

$$D^b(\mathbf{V}) = \langle \mathcal{A}_1, \Phi_1(D^b(\mathbf{V}_{-}))\rangle,$$

where

$$\Phi_1(D^b(\mathbf{V}_{-})) \coloneqq R_{\langle \mathcal{O}_{n-1,n-1},\cdots,\mathcal{O}_{2n-3,2n-3}\rangle} \circ \Phi_{-}$$

and $\mathcal{A}_1$ is given by

$$\begin{array}{cccccc} \mathcal{O}_{n-1,0} & \mathcal{O}_{n,0} & & & & \\ \mathcal{O}_{n-1,1} & \mathcal{O}_{n,1} & \mathcal{O}_{n+1,1} & & & \\ \vdots & \vdots & \vdots & \ddots & & \\ \mathcal{O}_{n-1,n-2} & \mathcal{O}_{n,n-2} & \mathcal{O}_{n+1,n-2} & \cdots & \mathcal{O}_{2n-3,n-2} & \mathcal{O}_{2n-2,n-2} \\ \mathcal{O}_{n-1,n-1} & \mathcal{O}_{n,n-1} & \mathcal{O}_{n+1,n-1} & \cdots & \mathcal{O}_{2n-3,n-1} & \\ & \mathcal{O}_{n,n} & \mathcal{O}_{n+1,n} & \cdots & \mathcal{O}_{2n-3,n} & \\ & & \mathcal{O}_{n+1,n+1} & \cdots & \mathcal{O}_{2n-3,n+1} & \\ & & & \ddots & \vdots & \\ & & & & \mathcal{O}_{2n-3,2n-3}. & \end{array}$$

By mutating $\Phi_1(D^b(\mathbf{V}_{-}))$ one step to the left, and then $\mathcal{O}_{2n-2,n-2}$ to the far left, we obtain

$$D^b(\mathbf{V}) = \langle \mathcal{A}_2, \Phi_2(D^b(\mathbf{V}_{-}))\rangle, \tag{4.6}$$

where

$$\Phi_2(D^b(\mathbf{V}_{-})) \coloneqq L_{\mathcal{O}_{2n-2,n-2}} \circ \Phi_1$$

and $\mathcal{A}_2$ is given by

$$\begin{array}{ccccc} \mathcal{O}_{n-1,-1} & & & & \\ \mathcal{O}_{n-1,0} & \mathcal{O}_{n,0} & & & \\ \mathcal{O}_{n-1,1} & \mathcal{O}_{n,1} & \mathcal{O}_{n+1,1} & & \\ \vdots & \vdots & \vdots & \ddots & \\ \mathcal{O}_{n-1,n-2} & \mathcal{O}_{n,n-2} & \mathcal{O}_{n+1,n-2} & \cdots & \mathcal{O}_{2n-3,n-2} \\ \mathcal{O}_{n-1,n-1} & \mathcal{O}_{n,n-1} & \mathcal{O}_{n+1,n-1} & \cdots & \mathcal{O}_{2n-3,n-1} \\ & \mathcal{O}_{n,n} & \mathcal{O}_{n+1,n} & \cdots & \mathcal{O}_{2n-3,n} \\ & & \mathcal{O}_{n+1,n+1} & \cdots & \mathcal{O}_{2n-3,n+1} \\ & & & \ddots & \vdots \\ & & & & \mathcal{O}_{2n-3,2n-3}. \end{array}$$

By comparing (4.6) with (4.2) and (4.4), we obtain a derived equivalence

$$\Phi \coloneqq (\varphi_{+})_{*} \circ ((-) \otimes \mathcal{O}_{-(2n-2),0}) \circ \Phi_2 \colon D^b(\mathbf{V}_{-}) \xrightarrow{\sim} D^b(\mathbf{V}_{+}).$$

5. Standard flop

For $n \geq 1$, let P and Q be the maximal parabolic subgroups of the semisimple Lie group $G = \mathrm{SL}(V) \times \mathrm{SL}(V^\vee)$ associated with the crossed Dynkin diagram $\oplus$ and $\oplus$. The corresponding homogeneous spaces are the projective spaces $\mathbf{P} = \mathbb{P}V$, $\mathbf{Q} = \mathbb{P}V^\vee$, and their product $\mathbf{F} = \mathbb{P}V \times \mathbb{P}V^\vee$. Since $\omega_{\mathbf{P}} \cong \mathcal{O}(-(n+1)h)$, $\omega_{\mathbf{Q}} \cong \mathcal{O}(-(n+1)H)$, and $\omega_{\mathbf{F}} \cong \mathcal{O}(-(n+1)h - (n+1)H)$, we have $\omega_{\mathbf{V}_-} \cong \mathcal{O}_{\mathbf{V}_-}$, $\omega_{\mathbf{V}_+} \cong \mathcal{O}_{\mathbf{V}_+}$, and $\omega_{\mathbf{V}} \cong \mathcal{O}(-nh - nH)$.

Lemma 5.1. $\mathbf{hom}_{\mathcal{O}_{\mathbf{V}}}(\mathcal{O}_{\mathbf{F}}(ih - jH), \mathcal{O}_{\mathbf{F}}) \simeq 0$ *for* $1 \leq j \leq n-1$ *and* $1 \leq i \leq n - j$.

Proof. We have

$$\mathbf{hom}_{\mathcal{O}_{\mathbf{V}}}(\mathcal{O}_{\mathbf{F}}(ih - jH), \mathcal{O}_{\mathbf{F}}) \simeq \mathbf{h}\left(\{\mathcal{O}_{\mathbf{F}}(-ih + jH) \to \mathcal{O}_{\mathbf{F}}(-(i+1)h + (j-1)H)\}\right),$$

which vanishes for $1 \leq i \leq n - j \leq n - 1$. □

It follows from [20] that

$$D^b(\mathbf{V}) = \langle \iota_* \varpi_-^* D^b(\mathbf{P}), \cdots, \iota_* \varpi_-^* D^b(\mathbf{P}) \otimes \mathcal{O}((n-1)(h+H)), \Phi_-(D^b(\mathbf{V}_-)) \rangle \tag{5.1}$$

and

$$D^b(\mathbf{V}) = \langle \iota_* \varpi_+^* D^b(\mathbf{Q}), \cdots, \iota_* \varpi_+^* D^b(\mathbf{Q}) \otimes \mathcal{O}((n-1)(h+H)), \Phi_+(D^b(\mathbf{V}_+)) \rangle, \tag{5.2}$$

where

$$\Phi_- := (-) \otimes \mathcal{O}_{\mathbf{V}}(n(h+H)) \circ \varphi_-^* \colon D^b(\mathbf{V}_-) \to D^b(\mathbf{V})$$

and

$$\Phi_+ := (-) \otimes \mathcal{O}_{\mathbf{V}}(n(h+H)) \circ \varphi_+^* \colon D^b(\mathbf{V}_+) \to D^b(\mathbf{V}).$$

We write $\mathcal{O}_{i,j} := \mathcal{O}_{\mathbf{F}}(ih + jH)$. (4.1) and (5.1) give a semiorthogonal decomposition of the form

$$D^b(\mathbf{V}) = \langle \mathcal{A}_0, \Phi_-(D^b(\mathbf{V}_-)) \rangle$$

where $\mathcal{A}_0$ is given by

$$\begin{array}{cccccccccc}
\mathcal{O}_{0,0} & \mathcal{O}_{1,0} & \cdots & \mathcal{O}_{n-2,0} & \mathcal{O}_{n-1,0} & \mathcal{O}_{n,0} & & & & \\
 & \mathcal{O}_{1,1} & \cdots & \mathcal{O}_{n-2,1} & \mathcal{O}_{n-1,1} & \mathcal{O}_{n,1} & \mathcal{O}_{n+1,1} & & & \\
 & & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & & \\
 & & & \mathcal{O}_{n-2,n-2} & \mathcal{O}_{n-1,n-2} & \mathcal{O}_{n,n-2} & \mathcal{O}_{n+1,n-2} & \cdots & \mathcal{O}_{2n-2,n-2} & \\
 & & & & \mathcal{O}_{n-1,n-1} & \mathcal{O}_{n,n-1} & \mathcal{O}_{n+1,n-1} & \cdots & \mathcal{O}_{2n-2,n-1} & \mathcal{O}_{2n-1,n-1}.
\end{array} \tag{5.3}$$

Note from Lemma 5.1 that there are no morphisms from right to left in (5.3). Since $\omega_{\mathbf{V}} \cong \mathcal{O}_{\mathbf{V}}(-nh - nH)$, by mutating first

$$\begin{array}{cccc}
\mathcal{O}_{0,0} & \mathcal{O}_{1,0} & \cdots & \mathcal{O}_{n-2,0} \\
 & \mathcal{O}_{1,1} & \cdots & \mathcal{O}_{n-2,1} \\
 & & \ddots & \vdots \\
 & & & \mathcal{O}_{n-2,n-2}
\end{array}$$

to the far right, and then $\Phi_-(D^b(\mathbf{V}_-))$ to the far right, we obtain

$$D^b(\mathbf{V}) = \langle \mathcal{A}_1, \Phi_1(D^b(\mathbf{V}_-)) \rangle,$$

where

$$\Phi_1(D^b(\mathbf{V}_-)) := R_{\langle \mathcal{O}_{n,n}, \cdots, \mathcal{O}_{2n-2,2n-2} \rangle} \circ \Phi_-$$

and $\mathcal{A}_1$ is given by

$$\begin{array}{cccccc}
\mathcal{O}_{n-1,0} & \mathcal{O}_{n,0} & & & & \\
\mathcal{O}_{n-1,1} & \mathcal{O}_{n,1} & \mathcal{O}_{n+1,1} & & & \\
\vdots & \vdots & \vdots & \ddots & & \\
\mathcal{O}_{n-1,n-1} & \mathcal{O}_{n,n-1} & \mathcal{O}_{n+1,n-1} & \cdots & \mathcal{O}_{2n-2,n-1} & \mathcal{O}_{2n-1,n-1} \\
 & \mathcal{O}_{n,n} & \mathcal{O}_{n+1,n} & \cdots & \mathcal{O}_{2n-2,n} & \\
 & & \mathcal{O}_{n+1,n+1} & \cdots & \mathcal{O}_{2n-2,n+1} & \\
 & & & \ddots & \vdots & \\
 & & & & \mathcal{O}_{2n-2,2n-2}. &
\end{array}$$

By mutating $\Phi_1(D^b(\mathbf{V}_-))$ one step to the left, and then $\mathcal{O}_{2n-1,n-1}$ to the far left, we obtain

$$D^b(\mathbf{V}) = \langle \mathcal{A}_2, \Phi_2(D^b(\mathbf{V}_-)) \rangle, \tag{5.4}$$

where

$$\Phi_2(D^b(\mathbf{V}_-)) \coloneqq L_{\mathcal{O}_{2n-1,n-1}} \circ \Phi_1$$

and $\mathcal{A}_2$ is given by

$$\begin{array}{ccccc}
\mathcal{O}_{n-1,-1} & & & & \\
\mathcal{O}_{n-1,0} & \mathcal{O}_{n,0} & & & \\
\mathcal{O}_{n-1,1} & \mathcal{O}_{n,1} & \mathcal{O}_{n+1,1} & & \\
\vdots & \vdots & \vdots & \ddots & \\
\mathcal{O}_{n-1,n-1} & \mathcal{O}_{n,n-1} & \mathcal{O}_{n+1,n-1} & \cdots & \mathcal{O}_{2n-2,n-1} \\
 & \mathcal{O}_{n,n} & \mathcal{O}_{n+1,n} & \cdots & \mathcal{O}_{2n-2,n} \\
 & & \mathcal{O}_{n+1,n+1} & \cdots & \mathcal{O}_{2n-2,n+1} \\
 & & & \ddots & \vdots \\
 & & & & \mathcal{O}_{2n-2,2n-2}.
\end{array}$$

By comparing (5.4) with (4.2) and (5.2), we obtain a derived equivalence

$$\Phi \coloneqq (\varphi_+)_* \circ ((-) \otimes \mathcal{O}_{-(2n-1),0}) \circ \Phi_2 \colon D^b(\mathbf{V}_-) \xrightarrow{\sim} D^b(\mathbf{V}_+).$$

Remark 5.1. The way of presenting our proof in Section 4 and 5 is called chess game by some authors [12, 23].

References

[1] Addington, N., Donovan, W., Meachan, C.: Mukai flops and $\mathbb{P}$-twists. J. Reine. Angew. Math. 748, 227-240 (2019)

[2] Balllard, M., Favero, D., Katzarkov, L.: Variation of geometric invariant theory quotients and derived categories, J. Reine. Angew. Math. 746, 235-304 (2019)

[3] Beĭlinson, A.A.: Coherent sheaves on $\mathbb{P}^n$ and problems in linear algebra. Funct. Anal. Appl. + 12, 214-216 (1978)

[4] Bondal, A., Orlov, D.: Derived categories of coherent sheaves. Proceedings of the International Congress of Mathematicians. Vol. II (Beijing, 2002), Higher Ed. Press, Beijing, pp. 47-56 (2002)

[5] Bondal, A., Orlov, D.: *Semiorthogonal decomposition for algebraic varieties*, arXiv:alg-geom/9506012 (1995)

[6] Halpern-Leistner, D.: The derived category of a GIT quotient. .J. Am. Math. Soc. 28(3), 871-912 (2015)

[7] Hara, W.: Non-commutative crepant resolution of minimal nilpotent orbit closure of type A and Mukai flops. Adv. Math. 318, 355-410 (2017)

[8] Hara, W.: *On derived equivalence for Abuaf flop: mutation of non-commutative crepant resolutions and spherical twists*, arXiv:1706.04417 (2018)

[9] Hartshorne, R.: Algebraic geometry. Springer-Verlag (1977)

[10] Herbst, M., Hori, K., Page, D.: *Phases of N=2 theories in 1+1 dimensions with boundary*, arXiv:0803.2045 (2008)
[11] Huybrechts, D., Thomas, R.: P-objects and autoequivalences of derived categories. Math. Res. Lett. 13(1), 87-98 (2006)
[12] Jiang, Q., Leung, C.: *Derived category of projectivization and flops*, arXiv:1811.12525 (2018)
[13] Kanemitsu, A.: *Mukai pairs and simple K-equivalence*, arXiv:1812.05392 (2018)
[14] Kapranov, M.: On the derived categories of coherent sheaves on some homogenous spaces. Invent. Math. 92(3), 479-508 (1988)
[15] Kapustka, M., Rampazzo, M.: Torelli problem for Calabi-Yau threefolds with GLSM description, Commun. Num. Theor. Phys. 13(4), 725-761 (2019).
[16] Kawamata, Y.: D-equivalence and K-equivalence. J. Differ. Geom. 61(1), 147-171 (2002)
[17] Kuznetsov, A.: Exceptional collections for Grassmannians of isotropic lines. Proc. Lond. Math. Soc. 97(1), 155-182 (2008)
[18] Kuznetsov, A.: Derived equivalence of Ito–Miura–Okawa–Ueda Calabi–Yau 3-folds, J. Math. Soc. Jpn. 70(3), 1007-1013 (2018)
[19] Namikawa, Y.: Mukai flops and derived categories, J. Reine. Angew. Math. 560, 65-76 (2003)
[20] Orlov, D.: Projective bundles, monoidal transformations, and derived categories of coherent sheaves. Izv. Ross. Akad. Nauk Ser. Mat. 56(4), 852-862 (1992)
[21] Segal, E.: Equivalence between GIT quotients of Landau–Ginzburg B-models. Commun. Math. Phys. 304(2), 411-432 (2011)
[22] Segal, E.: A new 5-fold flop and derived equivalence. Bull. Lond. Math. Soc. 48(3), 533-538 (2016)
[23] Thomas, R.: Notes on HPD. Algebraic Geometry: Salt Lake City 2015. AMS (2018)
[24] Ueda, K.: G2-Grassmannians and derived equivalences. Manuscripta Math. 159(3-4), 549-559 (2019)

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