

# QUASIMAP QUANTUM LEFSCHETZ VIA RELATIVE QUASIMAPS

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**ABSTRACT.** We define moduli spaces of relative toric quasimaps in genus zero, in the spirit of A. Gathmann. When  $X$  is a smooth toric variety and  $Y$  is a very ample hypersurface in  $X$  we construct a virtual class on the moduli space of relative quasimaps to  $(X, Y)$  which can be used to define relative quasimap invariants of the pair. We obtain a recursion formula which expresses each relative invariant in terms of invariants of lower multiplicity. Finally we apply this formula to derive a quantum Lefschetz theorem for quasimaps, expressing the restricted quasimap invariants of  $Y$  in terms of those of  $X$ .

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## 1. INTRODUCTION

In this paper we construct moduli spaces of relative quasimaps as substacks of moduli spaces of (absolute) quasimaps. This provides a common generalisation of two different theories: stable quasimaps on the one hand, and relative stable maps (in the sense of A. Gathmann) on the other. In this introductory section we briefly recall these, putting our work in its proper context.

**1.1. Stable quasimaps.** The moduli space of *stable toric quasimaps*  $\mathcal{Q}_{g,n}(X, \beta)$  was constructed by I. Ciocan-Fontanine and B. Kim [CFK10] as a compactification of the moduli space of smooth curves in a smooth and complete toric variety  $X$ . Roughly speaking, the objects are rational maps  $C \dashrightarrow X$  where  $C$  is a nodal curve, subject to a stability condition; the precise definition depends on the description of  $X$  as a GIT quotient. The space  $\mathcal{Q}_{g,n}(X, \beta)$  is

a proper Deligne–Mumford stack of finite type. It admits a virtual fundamental class, which is used to define curve-counting invariants for  $X$  called *quasimap invariants*.

This theory agrees with that of stable quotients [MOP11] when both are defined, namely when  $X$  is a projective space. There is a common generalisation given by the theory of stable quasimaps to GIT quotients [CFKM14]. For simplicity, we will work mostly in the toric setting; however, this restriction is not essential for our arguments. Thus in this paper when we say “quasimaps” we are implicitly talking about toric quasimaps. Quasimap invariants provide an alternative system of curve counts to the more well-known Gromov–Witten invariants. These latter invariants are defined via moduli spaces of stable maps, and as such we will often refer to them as *stable map invariants*.

For  $X$  sufficiently positive, the quasimap invariants coincide with the Gromov–Witten invariants, in all genera. This has been proven in the following cases:

- $X$  a projective space or a Grassmannian: see [MOP11, Theorems 3 and 4], and [Man14] for an alternative proof.
- $X$  a projective complete intersection of Fano index at least 2: see [CFK16, Corollary 1.7], and [CZ14] for an earlier approach.
- $X$  a projective toric Fano variety: see [CFK17, Corollary 1.3].

In general, however, the invariants differ, the difference being encoded by certain wall-crossing formulae, which can be interpreted in the context of toric mirror symmetry [CFK14].

**1.2. Relative stable maps.** Let  $Y$  be a smooth very ample hypersurface in a smooth projective variety  $X$ . In [Gat02] A. Gathmann constructs a space of relative stable maps to the pair  $(X, Y)$  as a closed substack of the moduli space of (absolute) stable maps to  $X$ :

$$\overline{\mathcal{M}}_{0,\alpha}(X|Y, \beta) \hookrightarrow \overline{\mathcal{M}}_{0,n}(X, \beta)$$

The relative space parametrises stable maps with prescribed tangencies to  $Y$  at the marked points. Unfortunately this space does not admit a natural perfect obstruction theory. Nevertheless, because  $Y$  is very ample it is still possible to construct a virtual fundamental class by intersection-theoretic methods, and hence one can define relative stable map invariants.

Gathmann establishes a recursion formula for these virtual classes which allows one to express any relative invariant of  $(X, Y)$  in terms of absolute invariants of  $Y$  and relative invariants with lower contact multiplicities. By successively increasing the contact multiplicities from zero to the maximum possible value, this gives an algorithm expressing the (restricted) invariants of  $Y$  in terms of those of  $X$ : see [Gat02, Corollary 5.7]. In [Gat03b] this result is applied to give an alternative proof of the mirror theorem for projective hypersurfaces [Giv96] [LLY97].

**1.3. Relative stable quasimaps.** In this paper we construct moduli spaces of relative quasimaps in genus zero. We prove a recursion relation similar to Gathmann’s formula, and use this to derive a quantum Lefschetz formula for quasimap invariants. Our construction carries over to the setting of  $\epsilon$ -stable quasimaps [CFK10]; since for  $\epsilon > 1$  these moduli spaces agree with the space of stable maps, one can view our construction as giving a common generalisation of the two stories outlined above.

The plan of the paper is as follows. In §§2.1 and 2.2 we provide a brief review of the theories of stable quasimaps and relative stable maps. Then in §2.3 we define the space of relative quasimaps as a substack of the moduli space of (absolute) quasimaps:

$$\mathcal{Q}_{0,\alpha}(X|Y, \beta) \hookrightarrow \mathcal{Q}_{0,n}(X, \beta).$$

Here  $X$  is a smooth toric variety,  $Y$  is a smooth very ample hypersurface and  $\alpha = (\alpha_1, \dots, \alpha_n)$  encodes the orders of tangency of the marked points to  $Y$ . Note that we *do not* require  $Y$  to be toric.

In §3 we examine the special case of a hyperplane  $H \subseteq \mathbb{P}^N$ . We find that the relative space is irreducible of the expected dimension (in fact, more than this: it is the closure of the so-called “nice locus” consisting of maps from a  $\mathbb{P}^1$  whose image is not contained in  $H$ ). Thus it has an actual fundamental class, which we can use to define relative quasimap invariants. Another useful fact about this special case is that there exists a birational comparison morphism:

$$\chi : \overline{\mathcal{M}}_{0,n}(\mathbb{P}^N, d) \rightarrow \mathcal{Q}_{0,n}(\mathbb{P}^N, d)$$

This restricts to a birational morphism between the relative spaces, which we use to push down Gathmann’s formula to obtain a recursion formula for relative stable quasimaps.

In §4 we turn to the case of an arbitrary pair  $(X, Y)$  with  $Y$  very ample. We use the embedding  $X \hookrightarrow \mathbb{P}^N$  defined by  $\mathcal{O}_X(Y)$  to construct a virtual class  $[\mathcal{Q}_{0,\alpha}(X|Y, \beta)]^{\text{virt}}$ . We then prove the recursion formula for  $(X, Y)$  by pulling back the formula for  $(\mathbb{P}^N, H)$ . This requires several comparison theorems for virtual classes, extending results in Gromov–Witten theory to the setting of quasimaps. The full statement of the recursion formula is:

**Theorem 4.1.** Let  $X$  be a smooth projective toric variety and let  $Y \subseteq X$  be a very ample hypersurface (not necessarily toric). Then

$$(\alpha_k \psi_k + \text{ev}_k^*[Y]) \cap [\mathcal{Q}_{0,\alpha}(X|Y, \beta)]^{\text{virt}} = [\mathcal{Q}_{0,\alpha+e_k}(X|Y, \beta)]^{\text{virt}} + [\mathcal{D}_{\alpha,k}^{\mathcal{Q}}(X|Y, \beta)]^{\text{virt}}$$

in the Chow group of  $\mathcal{Q}_{0,\alpha}(X|Y, \beta)$ .

Here  $\mathcal{D}_{\alpha,k}^{\mathcal{Q}}(X|Y, \beta)$  is a certain *quasimap comb locus* sitting inside the boundary of the relative space (see §4.3); its virtual class should be thought of as a correction term. Such terms also appear in Gathmann’s stable map recursion formula; however, in our setting the stronger stability condition for quasimaps considerably reduces the number of such contributions.

Finally in §5 we apply the recursion formula of §4 to obtain a quantum Lefschetz theorem for quasimap invariants. This takes two forms: first we have a general result which holds without any special restrictions on  $Y$ .

**Theorem 5.1.** Let  $X$  be a smooth projective toric variety and  $Y \subseteq X$  a smooth very ample hypersurface. Then there is an explicit algorithm to recover the (restricted) quasimap invariants of  $Y$  from the quasimap invariants of  $X$ .

If, however, we are willing to impose some (semi)positivity assumptions, we can do better and actually obtain a closed formula (rather than just an algorithm) for this relationship.

**Theorem 5.4.** Let  $X$  be a smooth projective toric Fano variety and let  $i: Y \hookrightarrow X$  be a very ample hypersurface. Assume that  $-K_Y$  is nef and that  $Y$  contains all curve classes (see §5.3). Then

$$\frac{\sum_{\beta \geq 0} q^\beta \prod_{j=0}^{Y \cdot \beta} (Y + jz) S_0^X(z, \beta)}{P_0^X(q)} = \tilde{S}_0^Y(z, q)$$

where  $S_0^X(z, \beta)$  and  $\tilde{S}_0^Y(z, q)$  are the following generating functions for 2-pointed quasimap invariants

$$S_0^X(z, \beta) = (\text{ev}_1)_* \left( \frac{1}{z - \psi_1} [\mathcal{Q}_{0,2}(X, \beta)]^{\text{virt}} \right)$$

$$\tilde{S}_0^Y(z, q) = i_* \sum_{\beta \geq 0} q^\beta (\text{ev}_1)_* \left( \frac{1}{z - \psi_1} [\mathcal{Q}_{0,2}(Y, \beta)]^{\text{virt}} \right)$$

and  $P_0^X(q)$  is given by:

$$P_0^X(q) = 1 + \sum_{\substack{\beta > 0 \\ K_Y \cdot \beta = 0}} q^\beta (Y \cdot \beta)! \langle [\text{pt}_X] \psi_1^{Y \cdot \beta - 1}, \mathbb{1}_X \rangle_{0,2,\beta}^X$$

The argument is similar in spirit to the one given in [Gat03b], however the stronger stability condition considerably simplifies both the proof and the final result. This formula can also be obtained as a consequence of [CFK14, Corollary 5.5.1]; see §5.6.

In Appendix A we define the *diagonal pull-back* along a morphism whose target is smooth, and verify that it agrees with the more modern concept of virtual pull-back [Man12a] when both are defined. The diagonal pull-back was employed implicitly in [Gat02], but we find it useful here to give a more explicit treatment.

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**1.4. Table of notation.** We will use the following notation, most of which is introduced in the main body of the paper.

$X$	a smooth projective toric variety
$Y$	a smooth very ample hypersurface in $X$
$\Sigma, \Sigma(1)$	the fan of $X$ , and the set of 1-dimensional cones of $\Sigma$
$\rho, D_\rho$	an element of $\Sigma(1)$ , and the toric divisor in $X$ associated to it
$\overline{\mathcal{M}}_{g,n}(X, \beta)$	the moduli space of stable maps to $X$
$\overline{\mathcal{M}}_{0,\alpha}(X Y, \beta)$	the moduli space of relative stable maps to $(X, Y)$ ; see §2.2
$\mathcal{Q}_{g,n}(X, \beta)$	the moduli space of toric quasimaps to $X$ ; see §2.1
$\mathcal{Q}_{0,\alpha}^\circ(X Y, \beta)$	the nice locus of relative quasimaps to $(X, Y)$ ; see §3.1
$\mathcal{Q}_{0,\alpha}(X Y, \beta)$	the moduli space of relative quasimaps to $(X, Y)$ ; see §2.3
$\mathcal{D}_{\alpha,k}^\mathcal{Q}(X Y, \beta)$	the quasimap comb locus; see §3.2
$\mathcal{D}^\mathcal{Q}(X Y, A, B, M)$	(a component of) the comb locus; see §3.2
$\mathcal{E}^\mathcal{Q}(X Y, A, B, M)$	the total product for the comb locus; see §4.3
$\mathcal{D}^\mathcal{Q}(X, A, B)$	the quasimap centipede locus; see §4.3
$\mathcal{E}^\mathcal{Q}(X, A, B)$	the total product for the centipede locus; see §4.3
$\mathfrak{M}_{g,n}^{\text{wt}}$	the moduli stack of weighted prestable curves; see §4.3
$\text{Bun}_G^{g,n}$	the moduli stack of principal $G$ -bundles on the universal curve over $\mathfrak{M}_{g,n}$ ; see Remark 4.4
$\mathcal{Q}(f)$	the push-forward morphism between quasimap spaces; see §4.1
$\chi$	the comparison morphism from stable maps to quasimaps; see §3.1
$f_v^!$	virtual pull-back for $f$ virtually smooth; see Appendix A
$f_\Delta^!$	diagonal pull-back; see Appendix A

## 2. RELATIVE STABLE QUASIMAPS

**2.1. Review of absolute stable quasimaps.** We briefly recall the definition and basic properties of the moduli space of toric quasimaps; see [CFK10] for more details.

**Definition 2.1.** [CFK10, Definition 3.1.1] Let  $N$  be a lattice, let  $\Sigma \subseteq N_\mathbb{Q}$  be a fan, and let  $X = X_\Sigma$  be the corresponding toric variety. Suppose that  $X$  is smooth and projective. Let  $M = N^\vee = \text{Hom}(N, \mathbb{Z})$  and let  $\mathcal{O}_{X_\Sigma}(1)$  be a fixed polarisation, which we can write (non-uniquely) in terms of the

torus-invariant divisors as:

$$\mathcal{O}_{X_\Sigma}(1) = \otimes_{\rho \in \Sigma(1)} \mathcal{O}_{X_\Sigma}(D_\rho)^{\otimes \alpha_\rho}$$

for some  $\alpha_\rho \in \mathbb{Z}$ . We fix the following numerical invariants: a genus  $g \geq 0$ , a number of marked points  $n \geq 0$ , and an effective curve class  $\beta \in H_2^+(X)$ . A *stable (toric) quasimap* is given by the data

$$\left( (C, x_1, \dots, x_n), (L_\rho, u_\rho)_{\rho \in \Sigma(1)}, (\varphi_m)_{m \in M} \right)$$

where:

- (1)  $(C, x_1, \dots, x_n)$  is a prestable curve of genus  $g$  with  $n$  marked points;
- (2) the  $L_\rho$  are line bundles on  $C$  of degree  $d_\rho = D_\rho \cdot \beta$ ;
- (3) the  $u_\rho$  are global sections of  $L_\rho$ ;
- (4)  $\varphi_m: \bigotimes_{\rho \in \Sigma(1)} L_\rho^{\otimes \langle \rho, m \rangle} \rightarrow \mathcal{O}_C$  are isomorphisms, such that  $\varphi_m \otimes \varphi_{m'} = \varphi_{m+m'}$  for all  $m, m' \in M$ .

These are required to satisfy the following two conditions:

- (1) *nondegeneracy*: there is a finite (possibly empty) set of smooth and non-marked points  $B \subseteq C$ , called the *basepoints* of the quasimap, such that for all  $x \in C \setminus B$  there exists a maximal cone  $\sigma \in \Sigma_{\max}$  with  $u_\rho(x) \neq 0$  for all  $\rho \notin \sigma$ ;
- (2) *stability*: if we let  $L = \otimes_{\rho} L_\rho^{\otimes \alpha_\rho}$  then the following  $\mathbb{Q}$ -divisor is ample

$$\omega_C(x_1 + \dots + x_n) \otimes L^{\otimes \epsilon}$$

for every rational  $\epsilon > 0$ . This does not depend on the choice of polarisation. Note that necessarily  $2g - 2 + n \geq 0$ .

**Remark 2.2.** This definition is motivated by D. A. Cox's description of the functor of points of a toric variety in terms of  $\Sigma$ -collections [Cox95a]. A quasimap defines a rational map  $C \dashrightarrow X$  with base locus equal to  $B$ . In fact, a quasimap is a map to the stack quotient  $[\mathbb{A}^{\Sigma(1)}/\mathbb{G}_m^r]$ , with  $B$  the preimage of the unstable locus. In particular a quasimap without any basepoints defines a morphism  $C \rightarrow X$ . Thus maps with basepoints appear in the (virtual) boundary of the moduli space of quasimaps, in much the same way as maps with rational tails appear in the boundary of the moduli space of stable maps. This is something more than just a vague analogy; these loci correspond to each other under the comparison morphism when  $X \cong \mathbb{P}^N$ ; see the start of §3.1.

More generally, one can define the notion of a family of quasimaps over a base scheme  $S$ , and what it means for two such families to be isomorphic; one thus obtains a moduli stack

$$\mathcal{Q}_{g,n}(X, \beta)$$

of stable (toric) quasimaps to  $X$ , which is a proper Deligne–Mumford stack of finite type [CFK10, §3].

As with the case of stable maps, there is a combinatorial characterisation of stability which is easy to check in practice; a prestable quasimap is stable if and only if the following conditions hold:

- (1) the line bundle  $L = \otimes_{\rho} L_{\rho}^{\otimes \alpha_{\rho}}$  must have strictly positive degree on any rational component with fewer than three special points, and on any elliptic component with no special points (case  $(g, n) = (1, 0)$ );
- (2)  $C$  cannot have any rational components with fewer than two special points (that is, no *rational tails*).

Condition (1) is analogous to the ordinary stability condition for stable maps. Condition (2) is new, however, and gives quasimaps a distinctly different flavour to stable maps; we shall sometimes refer to it as the *strong stability condition*.

**Remark 2.3.** Unlike in Gromov–Witten theory,  $\mathcal{Q}_{g,n+1}(X, \beta)$  is *not* the universal curve over  $\mathcal{Q}_{g,n}(X, \beta)$  since markings cannot be basepoints. In fact there is not even a morphism between these spaces in general.

The moduli space  $\mathcal{Q}_{g,n}(X, \beta)$  admits a perfect obstruction theory relative to the moduli space  $\mathfrak{M}_{g,n}$  of source curves [CFK10, §5], and hence one can construct a virtual class

$$[\mathcal{Q}_{g,n}(X, \beta)]^{\text{virt}} \in A_{\text{vdim } \mathcal{Q}_{g,n}(X, \beta)}(\mathcal{Q}_{g,n}(X, \beta))$$

where the virtual dimension is the same as for stable maps:

$$\text{vdim } \mathcal{Q}_{g,n}(X, \beta) = (\dim X - 3)(1 - g) - (K_X \cdot \beta) + n$$

Since the markings are not basepoints, there exist evaluation maps

$$\text{ev}_i : \mathcal{Q}_{g,n}(X, \beta) \rightarrow X$$

and there are  $\psi$ -classes defined in the usual way by pulling back the relative dualising sheaf of the universal curve

$$\psi_i = c_1(x_i^* \omega_{\mathcal{C}/\mathcal{Q}})$$

where  $\mathcal{C} \rightarrow \mathcal{Q} = \mathcal{Q}_{g,n}(X, \beta)$  is the universal curve and  $x_i : \mathcal{Q} \rightarrow \mathcal{C}$  is the section defining the  $i$ th marked point. Putting all these pieces together, we can define *quasimap invariants*:

$$\langle \gamma_1 \psi_1^{k_1}, \dots, \gamma_n \psi_n^{k_n} \rangle_{g,n,\beta}^X = \int_{[\mathcal{Q}_{g,n}(X, \beta)]^{\text{virt}}} \prod_{i=1}^n \text{ev}_i^*(\gamma_i) \cdot \psi_i^{k_i}$$

We use the same correlator notation as in Gromov–Witten theory; this should not cause any confusion.

**Example 2.4.** Consider  $\mathcal{Q}_{0,2}(\mathbb{P}^2, 1)$ . What are its objects? By the strong stability condition (2) above, we see that the source curve must be irreducible. On the other hand since  $\mathbb{P}^2$  has Picard rank 1 we may exploit the isomorphisms  $\varphi_m$  to reduce ourselves to considering one line

bundle equipped with three sections. Thus the data of the quasimap is  $((C, x_1, x_2), L, u_0, u_1, u_2)$  where  $(C, L) \cong (\mathbb{P}^1, \mathcal{O}_{\mathbb{P}^1}(1))$ .

Pick coordinates  $[s : t]$  on  $\mathbb{P}^1$  such that the marked points are  $[1 : 0]$  and  $[0 : 1]$ . We can express the sections as  $u_i = a_i s + b_i t$ ; the requirement that the markings are not basepoints then translates into the following stability condition:

$$(a_0, a_1, a_2) \neq (0, 0, 0) \quad \text{and} \quad (b_0, b_1, b_2) \neq (0, 0, 0).$$

The group  $\text{Aut}(C; x_1, x_2) \cong \mathbb{G}_m$  acts by rotation  $\lambda : [s : t] \mapsto [s : \lambda t]$ , while  $\text{Aut}(L) \cong \mathbb{G}_m$  acts by scalar multiplication on  $\underline{a}$  and  $\underline{b}$ . Thus the  $\mathbb{G}_m^2$  action on  $\mathbb{A}_{\underline{a}, \underline{b}}^6$  is encoded by the following weight matrix:

$$\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 \end{bmatrix}$$

It is now clear that the quotient is  $\mathbb{P}^2 \times \mathbb{P}^2$ ; in fact, we see that the evaluation map

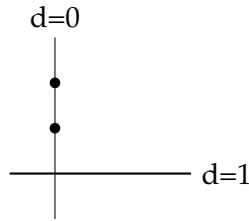
$$(\text{ev}_1, \text{ev}_2) : \mathcal{Q}_{0,2}(\mathbb{P}^2, 1) \rightarrow \mathbb{P}^2 \times \mathbb{P}^2$$

is an isomorphism. It is given in the above notation by:

$$((\mathbb{P}^1; [1 : 0], [0 : 1]); \mathcal{O}_{\mathbb{P}^1}(1); u_0, u_1, u_2) \mapsto ([a_0 : a_1 : a_2], [b_0 : b_1 : b_2])$$

Notice that the locus where  $(a_0, a_1, a_2) = \mu(b_0, b_1, b_2)$ , i.e. the diagonal in  $\mathbb{P}^2 \times \mathbb{P}^2$  is precisely the locus of quasimaps which have a basepoint. The point  $[a_0 : a_1 : a_2] = [b_0 : b_1 : b_2] \in \mathbb{P}^2$  is the image of the underlying “residual map” of degree 0, obtained by dividing all the sections by a local equation of the basepoint (equivalently, by extending the rational map  $C \dashrightarrow \mathbb{P}^2$  to a morphism  $C \rightarrow \mathbb{P}^2$ ).

On the other hand,  $(\text{ev}_1, \text{ev}_2) : \overline{\mathcal{M}}_{0,2}(\mathbb{P}^2, 1) \rightarrow \mathbb{P}^2 \times \mathbb{P}^2$  is *not* an isomorphism. Off the diagonal, the images of the two marked points determine uniquely the image of the stable map, i.e. the line through them. On the diagonal however, the following maps with a rational tail appear:



The image of the degree 1 component under  $f$  can be any line passing through the point of  $\mathbb{P}^2$  to which the other component is contracted. Hence  $\overline{\mathcal{M}}_{0,2}(\mathbb{P}^2, 1) \cong \text{Bl}_{\Delta}(\mathbb{P}^2 \times \mathbb{P}^2)$ . The comparison morphism  $\chi$  (see §3.1) can be interpreted as the blow-down map, and it induces an isomorphism of the rational tail-free locus with the basepoint-free locus.



**Remark 2.5.** There is a more general notion of  $\epsilon$ -stable quasimap [CFKM14, §7.1]. Here the stability condition, namely that the line bundle

$$\omega_C(x_1 + \dots + x_n) \otimes L^{\otimes \epsilon}$$

is ample, is only required to hold for a fixed  $\epsilon \in \mathbb{Q}_{>0}$  (instead of for arbitrary  $\epsilon$ , as was the case with ordinary quasimaps).

This has the effect of allowing some rational tails to appear, as long as their degree is high enough with respect to  $\epsilon$ . In order to keep the moduli space Deligne–Mumford and separated, one also has to bound the multiplicity of the basepoints that can occur.

By boundedness and the fact that the degree is an integer-valued function, there exist finitely many critical values of  $\epsilon$  which divide  $\mathbb{Q}_{>0}$  into chambers inside which the moduli spaces  $\mathcal{Q}_{g,n}^\epsilon(X, \beta)$  do not change. For  $\epsilon$  sufficiently small we recover the space of (ordinary) quasimaps, and for  $\epsilon$  sufficiently large we obtain the moduli space of stable maps. Thus one can view the spaces of  $\epsilon$ -stable quasimaps as interpolating between these two extremes, and they have proven successful as a tool for comparing quasimap invariants to stable map invariants [Tod11] [CFK14].

Another variant of the theory, which will play a role in later sections, is that of *parametrised quasimaps* [CFK10, §7]. A parametrised quasimap comes with a preferred rational component, which is equipped with the extra data of an isomorphism with  $\mathbb{P}^1$ , and the stability condition is imposed *on all but the preferred component*. This mimics the construction of graph spaces in Gromov-Witten theory – for example, there is a  $\mathbb{G}_m$ -action on  $\mathcal{Q}G_{g,n}(X, \beta)$  by rotating the preferred component, which plays the role of the  $\mathbb{G}_m$ -action that rotates the graph. The fixed loci and their equivariant normal bundles are well-understood, at least in the toric setting [CFK10, §7]. In the parametrised case we no longer require  $2g - 2 + n \geq 0$ , due to the modified stability condition. In particular it makes sense, and turns out to be very useful, to consider unmarked parametrised quasimaps  $\mathcal{Q}G_{0,0}(X, \beta)$ . In this case the source curve is necessarily irreducible.

**Example 2.6.**  $\mathcal{Q}G_{0,0}(\mathbb{P}^N, d) = \mathbb{P}^K$  with  $K = (N + 1)(d + 1) - 1$ . Indeed, the curve and line bundle must be  $(\mathbb{P}^1, \mathcal{O}_{\mathbb{P}^1}(d))$  and we are left with choosing  $N + 1$  sections of  $\mathcal{O}_{\mathbb{P}^1}(d)$  (not all zero) up to automorphisms of  $\mathcal{O}_{\mathbb{P}^1}(d)$ , i.e. up to scaling. For early appearances of such spaces, see for instance [MP95] [Giv98] [Ber00].

**2.2. Review of relative stable maps.** Given a smooth projective variety  $X$  and a smooth very ample divisor  $Y$ , Gathmann’s space of relative stable maps parametrises stable maps to  $X$  with specified tangencies to  $Y$  at the marked points.

**Definition 2.7.** [Gat02, Definition 1.1] Let  $X$  be a smooth projective variety and  $Y \subseteq X$  a smooth very ample divisor. Fix a number  $n \geq 0$  of marked points, an effective curve class  $\beta \in H_2^+(X)$  and an  $n$ -tuple  $\alpha = (\alpha_1, \dots, \alpha_n)$

of non-negative integers such that  $\sum_i \alpha_i \leq Y \cdot \beta$ . The space

$$\overline{\mathcal{M}}_{0,\alpha}(X|Y, \beta)$$

of relative stable maps to  $(X, Y)$  consists of those points  $(C, (x_i \in C)_{i=1}^n, f : C \rightarrow X)$  in  $\overline{\mathcal{M}}_{0,n}(X, \beta)$  satisfying the following two conditions:

- (1) if  $x_i$  is a marked point such that  $\alpha_i > 0$  then  $f(x_i) \in Y$ ;
- (2) if we consider the class  $f^*[Y] \in A_0(f^{-1}Y)$  then the difference  $f^*[Y] - \sum_i \alpha_i [x_i]$  is an effective class.

These conditions define a closed substack of  $\overline{\mathcal{M}}_{0,n}(X, \beta)$ .

There is an equivalent, more combinatorial definition which is more useful in practice (see [Gat02, Remark 1.4]): a stable map  $(C, x_1, \dots, x_n, f)$  is a relative stable map if and only if, for each connected component  $Z$  of  $f^{-1}(Y) \subseteq C$ :

- (1) if  $Z$  is a point and is equal to a marked point  $x_i$ , then the multiplicity of  $f$  to  $Y$  at  $x_i$  is greater than or equal to  $\alpha_i$ ;
- (2) if  $Z$  is one-dimensional (hence a union of irreducible components of  $C$ ) and if we let  $C^{(i)}$  for  $1 \leq i \leq r$  denote the irreducible components of  $C$  adjacent to  $Z$  and  $m^{(i)}$  denote the multiplicity of  $f|_{C^{(i)}}$  to  $Y$  at the node  $Z \cap C^{(i)}$ , then:

$$(*) \quad Y \cdot f_*[Z] + \sum_{i=1}^r m^{(i)} \geq \sum_{x_i \in Z} \alpha_i$$

**Remark 2.8.** In case (2) above we call  $Z$  an *internal* component and the  $C^{(i)}$  *external* components. Note that  $Z$  is not necessarily irreducible.

**Remark 2.9.** Effectivity can be translated into a purely numerical condition because we are working in genus zero, hence  $\text{Pic}(Z) = \mathbb{Z}$ .

**Remark 2.10.** When  $\alpha = (0, \dots, 0)$ , condition (2) becomes  $Y \cdot \beta \geq 0$ , so  $\overline{\mathcal{M}}_{0,(0,\dots,0)}(X|Y, \beta) = \overline{\mathcal{M}}_{0,n}(X, \beta)$  as long as  $Y$  is nef.

**Remark 2.11.** In the case of maximal multiplicity  $\sum_i \alpha_i = Y \cdot \beta$ , all the inequalities in the above definition must be equalities.

In the case  $X = \mathbb{P}^N$  and  $Y = H$  a hyperplane, Gathmann showed [Gat02, Proposition 1.14] that  $\overline{\mathcal{M}}_{0,\alpha}(\mathbb{P}^N|H, d)$  is irreducible with dimension equal to the expected dimension:

$$\text{vdim } \overline{\mathcal{M}}_{0,\alpha}(X|Y, \beta) = \text{vdim } \overline{\mathcal{M}}_{0,n}(X, \beta) - \sum_{i=1}^n \alpha_i$$

Hence it has a fundamental class from which one can define relative Gromov–Witten invariants. More generally if  $Y \subseteq X$  is very ample one can use the embedding  $X \hookrightarrow \mathbb{P}^N$  given by  $|\mathcal{O}_X(Y)|$  to obtain a cartesian diagram:

$$\begin{array}{ccc}
\overline{\mathcal{M}}_{0,\alpha}(X|Y, \beta) & \longrightarrow & \overline{\mathcal{M}}_{0,\alpha}(\mathbb{P}^N|H, d) \\
\downarrow & \square & \downarrow \\
\overline{\mathcal{M}}_{0,n}(X, \beta) & \xrightarrow{\varphi} & \overline{\mathcal{M}}_{0,n}(\mathbb{P}^N, d)
\end{array}$$

Then the fact that  $\overline{\mathcal{M}}_{0,n}(\mathbb{P}^N, d)$  is smooth allows one to define a virtual class on  $\overline{\mathcal{M}}_{0,\alpha}(X|Y, \beta)$  by diagonal pull-back (see Appendix A of the current paper):

$$[\overline{\mathcal{M}}_{0,\alpha}(X|Y, \beta)]^{\text{virt}} := \varphi^! [\overline{\mathcal{M}}_{0,\alpha}(\mathbb{P}^N|H, d)]$$

Thus one can define relative Gromov–Witten invariants in the usual way, by capping the virtual class with products of evaluation classes and psi classes.

In [Gat02, §§2-4] Gathmann establishes a recursion relation inside the Chow group of  $\overline{\mathcal{M}}_{0,\alpha}(X|Y, \beta)$ . This describes what happens when we increase the multiplicity at one of the marked points by 1. Let us therefore fix a marked point  $x_k \in \{x_1, \dots, x_n\}$  and let  $e_k = (0, \dots, 1, \dots, 0)$ . Then

$$(\alpha_k \psi_k + \text{ev}_k^*[Y]) \cap [\overline{\mathcal{M}}_{0,\alpha}(X|Y, \beta)]^{\text{virt}} = [\overline{\mathcal{M}}_{0,\alpha+e_k}(X|Y, \beta)]^{\text{virt}} + [\mathcal{D}_{\alpha,k}(X, \beta)]^{\text{virt}}$$

where  $\mathcal{D}_{\alpha,k}(X, \beta)$  is an appropriate *comb locus*. This parametrises relative stable maps where the component containing  $x_k$  is mapped entirely into  $Y$ , and which satisfy inequality (\*) for  $\alpha$  but not for  $\alpha + e_k$ ; these form a virtual divisor in  $\overline{\mathcal{M}}_{0,\alpha}(X|Y, \beta)$ .

Repeated application of this result shows that both the relative Gromov–Witten invariants of  $(X, Y)$  and the (restricted) Gromov–Witten invariants of  $Y$  are completely determined by the Gromov–Witten invariants of  $X$  [Gat02, Corollary 5.7]. This result is then applied in [Gat03b] to obtain a new proof of the mirror theorem for projective hypersurfaces.

**Remark 2.12.** There are many other approaches to defining relative stable maps besides Gathmann’s: the moduli space of maps to expanded degenerations of J. Li [Li01] [Li02], the twisted stable maps of D. Abramovich and B. Fantechi [AF16], the logarithmic stable maps with expansions of B. Kim [Kim10] and the logarithmic stable maps (without expansions) of M. Gross and B. Siebert [GS13], Q. Chen [Che14] and D. Abramovich and Q. Chen [AC14]. However, the invariants defined via these theories are all known to coincide [AMW14] [Gat03a], so the choice of which moduli space to work with mainly depends on one’s intended application.

**2.3. Definition of relative stable quasimaps.** We now give the main definition of the paper. From here on  $X$  will denote a smooth projective toric variety and  $Y \subseteq X$  a very ample hypersurface. We *do not* require that  $Y$  is toric. Consider the line bundle  $\mathcal{O}_X(Y)$  and the section  $s_Y$  cutting out  $Y$ . By [Cox95b] we have a natural isomorphism of  $\mathbb{C}$ -vector spaces

$$H^0(X, \mathcal{O}_X(Y)) = \left\langle \prod_{\rho} z_{\rho}^{a_{\rho}} : \sum_{\rho} a_{\rho} [D_{\rho}] = [Y] \right\rangle_{\mathbb{C}}$$

where the  $z_\rho$  for  $\rho \in \Sigma(1)$  are the generators of the Cox ring of  $X$  and the  $a_\rho$  are non-negative integers. We can therefore write  $s_Y$  as

$$s_Y = \sum_{\underline{a}=(a_\rho)} \lambda_{\underline{a}} \prod_{\rho} z_\rho^{a_\rho}$$

where the  $\underline{a} = (a_\rho) \in \mathbb{N}^{\Sigma(1)}$  are exponents and the  $\lambda_{\underline{a}}$  are scalars. The idea is that a quasimap

$$((C, x_1, \dots, x_n), (L_\rho, u_\rho)_{\rho \in \Sigma(1)}, (\varphi_m)_{m \in M})$$

should “map” a point  $x \in C$  into  $Y$  if and only if the section

$$(1) \quad u_Y := \sum_{\underline{a}} \lambda_{\underline{a}} \prod_{\rho} u_\rho^{a_\rho}$$

vanishes at  $x$ . We now explain how to make sense of expression (1). For each exponent  $\underline{a}$  appearing in  $s_Y$  we have a well-defined section:

$$u_{\underline{a}} := \lambda_{\underline{a}} \prod_{\rho} u_\rho^{a_\rho} \in H^0(C, \otimes_{\rho} L_\rho^{\otimes a_\rho})$$

Furthermore, given two such  $\underline{a}$  and  $\underline{b}$ , since  $\sum_{\rho} a_\rho [D_\rho] = [Y] = \sum_{\rho} b_\rho [D_\rho]$  in  $\text{Pic } X$  it follows from the exact sequence

$$0 \rightarrow M \rightarrow \mathbb{Z}^{\Sigma(1)} \rightarrow \text{Pic } X \rightarrow 0$$

that  $\underline{a}$  and  $\underline{b}$  differ by an element  $m$  of  $M$ . Thus the isomorphism  $\varphi_m$  allows us to view the sections  $u_{\underline{a}}$  and  $u_{\underline{b}}$  as sections of the same bundle, which we denote by  $L_Y$  (there is a choice for  $L_Y$  here, but up to isomorphism it does not matter). We can thus sum the  $u_{\underline{a}}$  together to obtain  $u_Y$ .

The upshot is that we obtain a line bundle  $L_Y$  on  $C$ , which plays the role of the “pull-back” of  $\mathcal{O}_X(Y)$  along the “map”  $C \rightarrow X$ , and a global section

$$u_Y \in H^0(C, L_Y)$$

which plays the role of the “pull-back” of  $s_Y$ .

**Definition 2.13.** With notation as above, let  $n \geq 2$  be a number of marked points,  $\beta \in H_2^+(X)$  be an effective curve class and  $\alpha = (\alpha_1, \dots, \alpha_n)$  be a collection of non-negative integers such that  $\sum_i \alpha_i \leq Y \cdot \beta$ . The *space of relative stable quasimaps*

$$\mathcal{Q}_{0,\alpha}(X|Y, \beta) \subseteq \mathcal{Q}_{0,n}(X, \beta)$$

is defined to be the locus of quasimaps

$$((C, (x_i \in C)_{i=1}^n), (L_\rho, u_\rho)_{\rho \in \Sigma(1)}, (\varphi_m)_{m \in M})$$

such that:

- (1) if  $x_i$  is a marking such that  $\alpha_i > 0$ , then  $x_i^* u_Y = 0$ ;
- (2) if we let  $u_Y^*(0) \in A_0(u_Y^{-1}(0))$  denote the class defined by the Gysin map for  $L_Y$ , then the difference  $u_Y^*(0) - \sum_i \alpha_i [x_i]$  is an effective class.

The class  $u_Y^*(0)$  is defined as follows. Consider the cartesian diagram

$$\begin{array}{ccc}
u_Y^{-1}(0) & \longrightarrow & C \\
\downarrow & \square & \downarrow u_Y \\
C & \xrightarrow{0_Y} & L_Y
\end{array}$$

where  $0_Y$  is the zero section. There is a Gysin map [Ful98, §2.6]

$$0_Y^! : A_*(C) \rightarrow A_*(u_Y^{-1}(0))$$

and we define  $u_Y^*(0) := 0_Y^!([C])$ .

**Remark 2.14.** As in the case of relative stable maps (see §2.2) there is an equivalent definition which is more useful in practice: a quasimap is an  $\alpha$ -relative quasimap if and only if for every connected component  $Z$  of  $u_Y^{-1}(0)$  we have that:

- (1) if  $Z$  is a point and is equal to a marked point  $x_i$ , then the order of vanishing of  $u_Y$  at  $x_i$  is greater than or equal to  $\alpha_i$ ;
- (2) if  $Z$  is one-dimensional (hence a union of irreducible components) and if we let  $C^{(i)}$  for  $1 \leq i \leq r$  denote the irreducible components of  $C$  adjacent to  $Z$  and  $m^{(i)}$  the order of vanishing of  $u_Y$  at the node  $Z \cap C^{(i)}$ , then:

$$(**) \quad \deg L_Y|_Z + \sum_{i=1}^r m^{(i)} \geq \sum_{x_i \in Z} \alpha_i$$

**Remark 2.15.** The above discussion also makes sense for  $\epsilon$ -stable quasimaps where  $\epsilon > 0$  is an arbitrary rational number. We therefore have a notion of  $\epsilon$ -stable relative quasimap. For  $\epsilon = 0+$  we recover relative quasimaps as above, whereas for  $\epsilon > 1$  we recover relative stable maps in the sense of Gathmann.

For simplicity we restrict ourselves to the case  $\epsilon = 0+$ . However, all of the arguments can be adapted to the general case. As  $\epsilon$  increases, the recursion formula (see §4) becomes progressively more complicated due to the presence of rational tails of lower and lower degree. Consequently the quantum Lefschetz theorem (see §5) also becomes more complicated.

### 3. RECURSION FORMULA FOR $\mathbb{P}^N$ RELATIVE A HYPERPLANE

At this stage we do not know much about the moduli space of relative quasimaps. In this section we will examine the case  $X = \mathbb{P}^N$  and  $Y = H$  a hyperplane in detail.

**3.1. Basic properties of the moduli space.** We now show that the moduli space

$$\mathcal{Q}_{0,\alpha}(\mathbb{P}^N|H, d)$$

is irreducible of the expected dimension, and thus admits a fundamental class. We then prove a recursion formula for these fundamental classes by

pushing d Gathmann's recursion formula along the comparison morphism:

$$\chi : \overline{\mathcal{M}}_{0,n}(\mathbb{P}^N, d) \rightarrow \mathcal{Q}_{0,n}(\mathbb{P}^N, d)$$

Let us briefly recall what this morphism does. Every stable map defines a quasimap which is stable except for the fact that it may have rational tails.  $\chi$  has the effect of contracting these rational tails and introducing a basepoint at the corresponding node, with multiplicity equal to the degree of the rational tail.

For more details, see [MOP11, Theorem 3] and [Man12b, Section 4.3] (earlier manifestations of these ideas can be found in [Ber00] and [PR03]).

For the remainder of this section we set  $X = \mathbb{P}^N$ , denote the projective coordinates on  $X$  by  $[z_0 : \dots : z_N]$  and set  $Y = H = \{z_0 = 0\}$ . Given a quasimap

$$((C, x_1, \dots, x_n), L, u_0, \dots, u_N) \in \mathcal{Q}_{0,n}(\mathbb{P}^N, d)$$

the line bundle  $L_Y$  of the previous section is equal to  $L$  and the section  $u_Y$  is equal to  $u_0$ .

**Lemma 3.1.** The comparison morphism restricts to a morphism

$$\chi : \overline{\mathcal{M}}_{0,\alpha}(\mathbb{P}^N|H, d) \rightarrow \mathcal{Q}_{0,\alpha}(\mathbb{P}^N|H, d)$$

*Proof.* We need to verify that a relative stable map is sent to a relative stable quasimap by  $\chi$ . Since the contraction of a rational tail  $R$  always occurs away from the markings, we only need to examine the internal components  $Z$  of the quasimap. To be more precise, we have to show that the inequality  $(**)$  is satisfied, using the fact that the inequality  $(*)$  is satisfied by the stable map that we started with. Let us describe this stable map around  $Z$ . For each basepoint  $x$  on  $Z$  there is a rational tail  $R$  of the stable map attached to  $Z$  at  $x$ . This is either internal (mapped into  $H$ ) or external (not mapped entirely into  $H$ ).

If  $R$  is internal then both  $R$  and  $Z$  live inside the same connected component  $Z'$  of  $f^{-1}(H)$ . Applying  $\chi$  has the effect of contracting  $R$  and increasing the degree of the line bundle on  $Z$  by  $H \cdot f_*[R]$ . Thus the left hand side of inequality  $(*)$  is left unchanged, and since the right hand side is also unaltered we obtain inequality  $(**)$ .

On the other hand if  $R$  is external then the multiplicity  $m^{(R)}$  of  $R \cap Z$  satisfies:

$$m^{(R)} \leq H \cdot f_*[R]$$

Since applying  $\chi$  has the effect of replacing  $m^{(R)}$  by  $H \cdot f_*[R]$  in the left hand side of  $(*)$ , inequality  $(**)$  holds a fortiori for the quasimap. Thus we obtain a morphism from the relative stable map space to the relative quasimap space, as claimed.  $\square$

Let us denote by

$$\mathcal{Q}_{0,\alpha}^\circ(\mathbb{P}^N|H, d) \subseteq \mathcal{Q}_{0,\alpha}(\mathbb{P}^N|H, d)$$

the *nice locus*, consisting of those quasimaps with irreducible source curve  $C \cong \mathbb{P}^1$  and no basepoints (so that we have an actual map  $u : C \rightarrow \mathbb{P}^N$ ) such that the curve is not mapped inside  $H$  and  $u$  has tangency at least  $\alpha_i$  to  $H$  at the marking  $x_i$ .

This is an irreducible, locally closed substack of  $\mathcal{Q}_{0,n}(\mathbb{P}^N, d)$  of codimension  $\sum_i \alpha_i$ , by essentially the same argument as in [Gat02, Lemma 1.8]. In fact it is isomorphic to the nice locus inside the stable map space, denoted  $\mathcal{M}_{0,\alpha}(\mathbb{P}^N|H, d)$  by Gathmann (see [Gat02, Def. 1.6]); the stricter stability condition has no effect when the source curve is irreducible.

**Lemma 3.2.**  $\mathcal{Q}_{0,\alpha}(\mathbb{P}^N|H, d)$  is the closure of the nice locus  $\mathcal{Q}_{0,\alpha}^\circ(\mathbb{P}^N|H, d)$  inside  $\mathcal{Q}_{0,n}(\mathbb{P}^N, d)$ .

*Proof.*  $\mathcal{Q}_{0,\alpha}(\mathbb{P}^N|H, d) \subseteq \overline{\mathcal{Q}_{0,\alpha}^\circ(\mathbb{P}^N|H, d)}$ : we show that any relative stable quasimap can be infinitesimally deformed to a relative stable quasimap with no basepoints. This is in particular a relative stable map; we then appeal to [Gat02, Prop. 1.14] to deform this stable map and obtain a point in the nice locus. Since this deformation does not introduce any rational tails, this is also a deformation of quasimaps, and the statement follows.

We induct on the number of components containing at least one basepoint. Suppose this number is non-zero (otherwise there is nothing to prove) and pick such a component  $C_0$ , with base-points  $y_1, \dots, y_k$ . Recall that this means that  $u_i(y_j) = 0$  for all  $i$  and  $j$ . We will deform the section  $u_N|_{C_0}$  to a new section  $u'_N|_{C_0}$  in such a way that  $u'_N|_{C_0}(y_j) \neq 0$  and in such a way that we do not introduce any new basepoints. Notice that since the relative condition only depends on  $u_0$ , the resulting deformed quasimap will still be a relative quasimap.

Now, by nondegeneracy and the fact that there exists a basepoint, we must have  $\deg(L|_{C_0}) > 0$ , and since  $C_0 \cong \mathbb{P}^1$  we can find a section  $w_0$  of  $L|_{C_0} \cong \mathcal{O}_{\mathbb{P}^1}(d_0)$  not vanishing at any of the base-points  $y_i$ . We then set

$$u'_N|_{C_0} := u_N|_{C_0} + \epsilon w_0$$

and  $u'_i|_{C_0} = u_i|_{C_0}$  for all other  $i$ . Notice that  $u'_N|_{C_0}(y_j) \neq 0$  for all  $j$  as claimed. It is also clear that we do not introduce any new basepoints, since  $u'_N|_{C_0}(y) = 0$  implies  $u_N|_{C_0}(y) = 0$  (put differently: being a basepoint is a closed condition).

It remains to extend the section  $u'_N|_{C_0}$  to a section  $u'_N$  on the whole curve. Let  $C_1, \dots, C_r$  be the components of  $C$  adjacent to  $C_0$  and let  $q_i = C_0 \cap C_i$ . We need to modify the sections  $u_N|_{C_i}$  in such a way that  $u'_N|_{C_i}(q_i) = u'_N|_{C_0}(q_i)$ .

By nondegeneracy, we can choose a section  $w_i$  of  $L|_{C_i}$  such that  $w_i(q_i) \neq 0$ . Then set:

$$u'_N|_{C_i} := u_N|_{C_i} + \epsilon \left( \frac{w_0(q_i)}{w_i(q_i)} \right) \cdot w_i$$

Then indeed we have:

$$u'_N|_{C_i}(q_i) = u_N(q_i) + \epsilon \left( \frac{w_0(q_i)}{w_i(q_i)} \right) \cdot w_i(q_i) = u_N(q_i) + \epsilon w_0(q_i) = u'_N|_{C_0}(q_i)$$

We can continue this process, replacing  $C_0$  by  $C_i$ ; since the genus of the curve is zero there are no cycles in the dual intersection graph, and so we will never come to the same component twice. In this way we obtain a new quasimap

$$((C, x_1, \dots, x_n), L, u_0, \dots, u_{N-1}, u'_N)$$

over  $\text{Spec } \mathbb{C}[\epsilon]/(\epsilon^2)$  which has no basepoints on  $C_0$ . We can repeat this process for all the components of  $C$  (using higher powers of  $\epsilon$  each time in order to ensure that we never introduce additional basepoints) and thus we obtain an infinitesimal deformation of our original quasimap which has no basepoints, as required.

$\overline{\mathcal{Q}}_{0,\alpha}^\circ(\mathbb{P}^N|H, d) \subseteq \mathcal{Q}_{0,\alpha}(\mathbb{P}^N|H, d)$ : consider a family of stable quasimaps over a smooth curve  $S$ , such that the generic fibre lies in the nice locus. We may blow-up the source curve (a fibred surface over  $S$ ) in the locus of basepoints (which consists of finitely many smooth points of the central fibre) and repeat this process a finite number of times in order to obtain an actual morphism to  $\mathbb{P}^N$ . This has the effect of adding rational trees at the basepoints in the central fibre. If the morphism is constant on any of these newly introduced rational tails or bridges we may contract them, and thus we obtain a family of stable maps which pushes down along  $\chi$  to our original family of quasimaps.

The general fibre is not modified at all, and so is still in the nice locus. By [Gat02, Lemma 1.9] it follows that the central fibre is a relative stable map, and then by applying  $\chi$  and appealing to Lemma 3.1 it follows that the same is true for the central fibre of the family of quasimaps.  $\square$

**Corollary 3.3.** The moduli space  $\mathcal{Q}_{0,\alpha}(\mathbb{P}^N|H, d)$  is irreducible of the expected dimension. Hence it has a fundamental class.

*Proof.* This holds because the moduli space is equal to the closure of the nice locus, which is irreducible of the expected dimension.  $\square$

Since the moduli space of relative quasimaps has a fundamental class, we can define *relative quasimap invariants* for the pair  $(\mathbb{P}^N, H)$ :

$$\langle \gamma_1 \psi_1^{k_1}, \dots, \gamma_n \psi_n^{k_n} \rangle_{0,\alpha,d}^{\mathbb{P}^N|H} := \int_{[\mathcal{Q}_{0,\alpha}(\mathbb{P}^N|H,d)]} \prod_{i=1}^n \text{ev}_i^* \gamma_i \cdot \psi_i^{k_i}$$

We will now establish a number of properties of the fundamental class.

**Corollary 3.4.** The comparison morphism from relative stable maps to relative quasimaps is birational. In particular it sends the fundamental class to the fundamental class, and thus the invariants coincide.



*Proof.* This follows because the comparison morphism restricts to an isomorphism on the nice locus, which by Lemma 3.2 is a dense open subset of both spaces. Notice that by setting  $\alpha = 0$  we recover the absolute case.  $\square$

**3.2. Proof of the recursion formula.** We wish to obtain a recursion formula relating the quasimap invariants of multiplicity  $\alpha$  with the quasimap invariants of multiplicity  $\alpha + e_k$ , as in [Gat02, Theorem 2.6]. For  $m = \alpha_k + 1$  the following section (of the pull-back of the jet bundle of the universal line bundle)

$$\sigma_k^m := x_k^* d_{C/Q}^m(u_0) \in H^0(Q, x_k^* \mathcal{P}_{C/Q}^m(\mathcal{L}))$$

vanishes along  $\mathcal{Q}_{0,\alpha+e_k}(\mathbb{P}^N|H, d)$  inside  $\mathcal{Q} = \mathcal{Q}_{0,\alpha}(\mathbb{P}^N|H, d)$ , and also along a number of *comb loci*. The latter parametrise quasimaps for which  $x_k$  belongs to an internal component  $Z \subseteq C$  (a connected component of the vanishing locus of  $u_0$ ), such that:

$$\deg(L|_Z) + \sum_{i=1}^r m^{(i)} = \sum_{x_i \in Z} \alpha_i$$

The strong stability condition means that quasimaps in the comb loci cannot contain any rational tails; this is really the only difference with the case of stable maps.

Indeed, we can push forward Gathmann's recursion formula for stable maps along the comparison morphism

$$\chi: \overline{\mathcal{M}}_{0,\alpha}(\mathbb{P}^N|H, d) \rightarrow \mathcal{Q}_{0,\alpha}(\mathbb{P}^N|H, d)$$

and, due to Corollary 3.4 above, the only terms which change are the comb loci containing rational tails. In fact these disappear, since the restriction of the comparison map to these loci has positive-dimensional fibres:

**Lemma 3.5.** Consider a rational tail component in the comb locus of the moduli space of stable maps, i.e. a moduli space of the form:

$$\overline{\mathcal{M}}_{0,(m^{(i)})}(\mathbb{P}^N|H, d)$$

and assume that  $Nd > 1$ . Then

$$\dim \left( [\overline{\mathcal{M}}_{0,(m^{(i)})}(\mathbb{P}^N|H, d)] \cap \text{ev}_1^*(\text{pt}_H) \right) > 0$$

where  $\text{pt}_H \in A^{N-1}(H)$  is a point class. Thus the pushforward along  $\chi$  of any comb locus with a rational tail is zero.

*Proof.* This is a simple dimension count. We have

$$\begin{aligned} \dim \left( [\overline{\mathcal{M}}_{0,(m^{(i)})}(\mathbb{P}^N|H, d)] \cap \text{ev}_1^*(\text{pt}_H) \right) &= (N-3) + d(N+1) + (1-m^{(i)}) - (N-1) \\ &= (Nd-1) + (d-m^{(i)}) \end{aligned}$$

from which the lemma follows because  $m^{(i)} \leq d$ .  $\square$

**Remark 3.6.** With an eye to the future, we remark that these rational tail components contribute nontrivially to the Gromov–Witten invariants of a Calabi–Yau hypersurface in projective space, and so their absence from the quasimap recursion formula accounts for the divergence between Gromov–Witten and quasimap invariants in the Calabi–Yau case [Gat03b, Rmk. 1.6].

Since we wish to apply the projection formula to Gathmann’s recursion relation, we should express the cohomological terms which appear as pull-backs:

**Lemma 3.7.** We have:

$$\begin{aligned}\chi^*(\psi_k) &= \psi_k \\ \chi^*(\text{ev}_k^* H) &= \text{ev}_k^* H\end{aligned}$$

*Proof.* It suffices to show that

$$\begin{aligned}\chi^* x_k^* \omega_{\mathcal{C}/\mathcal{Q}} &= x_k^* \omega_{\mathcal{C}/\mathcal{M}} \\ \chi^* x_k^* \mathcal{L} &= \text{ev}_k^* \mathcal{O}_{\mathbb{P}^N}(H)\end{aligned}$$

where  $\mathcal{L}$  is the universal line bundle on  $\mathcal{C}_{\mathcal{Q}}$ . This follows by considering the following diagram:

$$\begin{array}{ccccc} & & & \mathbb{P}^N & \\ & \nearrow f & & \nwarrow & \\ \mathcal{C}_{\mathcal{M}} & \xrightarrow{\sigma^{\text{ss}}} & \chi^* \mathcal{C}_{\mathcal{Q}} & \xrightarrow{\quad} & \mathcal{C}_{\mathcal{Q}} \\ & \searrow x_k & \downarrow x_k & \square & \downarrow x_k \\ & \mathcal{M}_{0,\alpha}(\mathbb{P}^N|H,d) & \xrightarrow{\chi} & \mathcal{Q}_{0,\alpha}(\mathbb{P}^N|H,d) & \end{array}$$

where  $\sigma^{\text{ss}}$  is the strong stabilisation map which contracts the rational tails. Note that  $\sigma^{\text{ss}}$  is an isomorphism near the markings.  $\square$

**Proposition 3.8.** Define the *quasimap comb locus*  $\mathcal{D}_{\alpha,k}^{\mathcal{Q}}(\mathbb{P}^N|H,d)$  as the union of the moduli spaces

$$\mathcal{D}^{\mathcal{Q}}(\mathbb{P}^N|H,A,B,M) := \mathcal{Q}_{0,A^{(0)} \cup \{q_1^0, \dots, q_r^0\}}(H,d_0) \times_{H^r} \prod_{i=1}^r \mathcal{Q}_{0,\alpha^{(i)} \cup (m^{(i)})}(\mathbb{P}^N|H,d_i)$$

where the union runs over all splittings  $A = (A^{(0)}, \dots, A^{(r)})$  of the markings (inducing a splitting  $(\alpha^{(0)}, \dots, \alpha^{(r)})$  of the corresponding tangency conditions),  $B = (d_0, \dots, d_r)$  of the degree and all valid multiplicities  $M = (m^{(1)}, \dots, m^{(r)})$  such that the above spaces are all well-defined (in particular we require that  $|A^{(0)}| + r$  and  $|A^{(i)}| + 1$  are all  $\geq 2$ ) and such that

$$d_0 + \sum_{i=1}^r m^{(i)} = \sum \alpha^{(0)}$$

Write  $[\mathcal{D}_{\alpha,k}^{\mathcal{Q}}(\mathbb{P}^N|H,d)]$  for the sum of the (product) fundamental classes, where each term is weighted by:

$$\frac{m^{(1)} \dots m^{(r)}}{r!}$$

Then

$$(\alpha_k \psi_k + \text{ev}_k^* H) \cdot [\mathcal{Q}_{0,\alpha}(\mathbb{P}^N|H,d)] = [\mathcal{Q}_{0,\alpha+e_k}(\mathbb{P}^N|H,d)] + [\mathcal{D}_{\alpha,k}^{\mathcal{Q}}(\mathbb{P}^N|H,d)].$$

*Proof.* This follows from [Gat02, Thm. 2.6] by pushing forward along  $\chi$ , using the projection formula and Lemmas 3.4, 3.5 and 3.7.  $\square$

**Remark 3.9.** In the discussion above we have implicitly used the fact that there exists a commuting diagram of comb loci:

$$\begin{array}{ccc} \mathcal{D}^{\mathcal{M}}(\mathbb{P}^N|H,A,B,M) & \longrightarrow & \overline{\mathcal{M}}_{0,\alpha}(\mathbb{P}^N|H,d) \\ \downarrow & & \downarrow \\ \mathcal{D}^{\mathcal{Q}}(\mathbb{P}^N|H,A,B,M) & \longrightarrow & \mathcal{Q}_{0,\alpha}(\mathbb{P}^N|H,d) \end{array}$$

The vertical arrow on the left is a product of comparison morphisms (notice that  $H \cong \mathbb{P}^{N-1}$ ). The horizontal arrow at the top is the gluing morphism which glues together the various pieces of the comb to produce a single relative stable map. Here we explain how to define the corresponding gluing morphism for quasimaps, that is, the bottom horizontal arrow.

Suppose for simplicity that  $r$ , the number of teeth of the comb, is equal to 1. Consider an element of the quasimap comb locus, consisting of two quasimaps:

$$\begin{aligned} &((C^0, x_1^0, \dots, x_{n_0}^0, q^0), L^0, u_0^0, \dots, u_N^0) \\ &((C^1, x_1^1, \dots, x_{n_1}^1, q^1), L^1, u_0^1, \dots, u_N^1) \end{aligned}$$

such that  $u^0(q^0) = u^1(q^1)$  in  $\mathbb{P}^N$ . We want to glue these quasimaps together at  $q^0, q^1$ . The definition of the curve is obvious; we simply take:

$$C = C^0 \sqcup_{q^1} C^1$$

On the other hand, gluing together the line bundles  $L^0$  and  $L^1$  to obtain a line bundle  $L$  over  $C$  requires a choice of scalar  $\lambda \in \mathbb{G}_m$ , in order to match up the fibres over  $q^i$ . Furthermore, if the sections are to extend as well, then this scalar must be chosen in such a way that it takes  $(u_0^0(q^0), \dots, u_N^0(q^0)) \in (L_{q^0}^0)^{\oplus(N+1)}$  to  $(u_0^1(q^1), \dots, u_N^1(q^1)) \in (L_{q^1}^1)^{\oplus(N+1)}$ . Since neither  $q^0$  nor  $q^1$  are basepoints (because they are markings), these tuples are nonzero, and so  $\lambda$  is unique if it exists. Furthermore it exists if and only if these tuples belong to the same  $\mathbb{G}_m$ -orbit in  $\mathbb{A}^{N+1}$ . This is precisely the statement that  $u^0(q^0) = u^1(q^1) \in \mathbb{P}^N$ .

Similar arguments apply for  $r > 1$ , and for more general toric varieties.

## 4. RECURSION FORMULA IN THE GENERAL CASE

In this section we prove the main result of this paper: a recursion formula for relative quasimap invariants of a general pair  $(X, Y)$ .

**Theorem 4.1.** Let  $X$  be a smooth projective toric variety and let  $Y \subseteq X$  be a very ample hypersurface (not necessarily toric). Then

$$(\alpha_k \psi_k + \text{ev}_k^*[Y]) \cap [\mathcal{Q}_{0,\alpha}(X|Y, \beta)]^{\text{virt}} = [\mathcal{Q}_{0,\alpha+e_k}(X|Y, \beta)]^{\text{virt}} + [\mathcal{D}_{\alpha,k}^{\mathcal{Q}}(X|Y, \beta)]^{\text{virt}}$$

in the Chow group of  $\mathcal{Q}_{0,\alpha}(X|Y, \beta)$ .

We begin by defining the terms that appear in the statement.

**4.1. The virtual class on the space of relative quasimaps.** Let  $X$  and  $Y$  be as in the statement of Theorem 4.1. The complete linear system associated to  $\mathcal{O}_X(Y)$  defines an embedding  $i : X \hookrightarrow \mathbb{P}^N$  such that  $i^{-1}(H) = Y$  for a certain hyperplane  $H$ . By the functoriality property of quasimap spaces (see [CFK14, §3.1]) we have a map:

$$k := \mathcal{Q}(i) : \mathcal{Q}_{0,n}(X, \beta) \rightarrow \mathcal{Q}_{0,n}(\mathbb{P}^N, d)$$

where  $d = i_*\beta$ .

**Remark 4.2.** I. Ciocan-Fontanine has kindly pointed out that, contrary to the case of stable maps,  $k$  might not be a closed embedding, even though  $i$  is. For instance, consider the Segre embedding

$$\begin{aligned} \mathbb{P}^1 \times \mathbb{P}^1 &\xrightarrow{i} \mathbb{P}^3 \\ ([x : y], [z : w]) &\mapsto [xz : xw : yz : yw] \end{aligned}$$

and the induced morphism between quasimap spaces:

$$k : \mathcal{Q}_{0,3}(\mathbb{P}^1 \times \mathbb{P}^1, (2, 2)) \rightarrow \mathcal{Q}_{0,3}(\mathbb{P}^3, 4)$$

If we take the following two objects of  $\mathcal{Q}_{0,3}(\mathbb{P}^1 \times \mathbb{P}^1, (2, 2))$ :

$$\begin{aligned} &\left( (\mathbb{P}_{[s:t]}^1, 0, 1, \infty), (L_1 = \mathcal{O}_{\mathbb{P}^1}(2), u_1 = s^2, v_1 = st), (L_2 = \mathcal{O}_{\mathbb{P}^1}(2), u_2 = st, v_2 = t^2) \right) \\ &\left( (\mathbb{P}_{[s:t]}^1, 0, 1, \infty), (L_1 = \mathcal{O}_{\mathbb{P}^1}(2), u_1 = st, v_1 = t^2), (L_2 = \mathcal{O}_{\mathbb{P}^1}(2), u_2 = s^2, v_2 = st) \right) \end{aligned}$$

then these two quasimaps are non-isomorphic, but they both map to the same object under  $k$ , namely:

$$\left( (\mathbb{P}_{[s:t]}^1, 0, 1, \infty), (L = \mathcal{O}_{\mathbb{P}^1}(4), z_0 = s^3t, z_1 = s^2t^2, z_2 = s^2t^2, z_3 = st^3) \right)$$

Notice that this only happens on the locus of quasimaps with basepoints.

It is easy to see that  $k$  restricts to a morphism between moduli space of relative quasimaps, and thus we have a diagram

$$\begin{array}{ccc} \mathcal{Q}_{0,\alpha}(X|Y, \beta) & \longrightarrow & \mathcal{Q}_{0,\alpha}(\mathbb{P}^N|H, d) \\ \downarrow & \square & \downarrow \\ \mathcal{Q}_{0,n}(X, \beta) & \xrightarrow{k} & \mathcal{Q}_{0,n}(\mathbb{P}^N, d) \end{array}$$

which one can show is cartesian. Since  $\mathcal{Q}_{0,n}(\mathbb{P}^N, d)$  is unobstructed, the morphism  $k$  admits a natural perfect obstruction theory, and so there is a virtual pull-back morphism  $k^\dagger_\vee$ . Alternatively, we may use the presence of a virtual class on  $\mathcal{Q}_{0,n}(X, \beta)$  to define a diagonal pull-back morphism  $k^\dagger_\Delta$ . The discussion in Appendix A shows that these two maps coincide, and from now on we will denote them both by  $k^\dagger$ .

We now define the virtual class on  $\mathcal{Q}_{0,\alpha}(X|Y, \beta)$  by pull-back along  $k$

$$[\mathcal{Q}_{0,\alpha}(X|Y, \beta)]^{\text{virt}} := k^\dagger[\mathcal{Q}_{0,\alpha}(\mathbb{P}^N|H, d)]$$

and use this class to define relative quasimap invariants in general:

$$\langle \gamma_1 \psi_1^{k_1}, \dots, \gamma_n \psi_n^{k_n} \rangle_{0,\alpha,\beta}^{X|Y} := \int_{[\mathcal{Q}_{0,\alpha}(X|Y, \beta)]^{\text{virt}}} \prod_{i=1}^n \text{ev}_i^*(\gamma_i) \cdot \psi_i^{k_i}$$

These invariants will play a role in our proof of the quasimap quantum Lefschetz formula in §5.

**4.2. Relative spaces pull back.** The idea is to prove the recursion formula for general  $(X, Y)$  by pulling back the formula for  $(\mathbb{P}^N, H)$  along  $k$ . In order to do this, we need to understand how the various virtual classes involved in the formula pull back along this map. The first two terms pull back by the very definition of the virtual class:

**Lemma 4.3.**  $k^\dagger[\mathcal{Q}_{0,\alpha}(\mathbb{P}^N|H, d)] = [\mathcal{Q}_{0,\alpha}(X|Y, \beta)]^{\text{virt}}$

It thus remains to consider the third term, namely the virtual class of the comb locus. This is the technical heart of the proof.

**4.3. Comb loci pull back.** As in the previous section, we define  $\mathcal{D}_{\alpha,k}^{\mathcal{Q}}(X|Y, \beta)$  to be the union of the moduli spaces

$$\mathcal{D}^{\mathcal{Q}}(X|Y, A, B, M) := \mathcal{Q}_{0,A^{(0)} \cup \{q_1, \dots, q_r\}}(Y, \beta^{(0)}) \times_{Y^r} \prod_{i=1}^r \mathcal{Q}_{0,\alpha^{(i)} \cup (m_i)}(X|Y, \beta^{(i)})$$

where the union runs over all splittings  $A = (A^{(0)}, \dots, A^{(r)})$  of the markings (inducing a splitting  $(\alpha^{(0)}, \dots, \alpha^{(r)})$  of the corresponding tangency requirements),  $B = (\beta^{(0)}, \dots, \beta^{(r)})$  of the curve class  $\beta$  and all valid multiplicities  $M = (m^{(1)}, \dots, m^{(r)})$  such that the above spaces are non-empty and such that:

$$Y \cdot \beta^{(0)} + \sum_{i=1}^r m^{(i)} = \sum \alpha^{(0)}$$

We refer to the  $\mathcal{D}^{\mathcal{Q}}(X|Y, A, B, M)$  as *comb loci*.

**Remark 4.4.** Note that  $Y$  is not in general toric, and so we should clarify the meaning of the factor

$$\mathcal{Q}_{0,A^{(0)} \cup \{q_1, \dots, q_n\}}(Y, \beta^{(0)})$$

above. There are two possibilities here: one is to *define* this space as the cartesian product

$$\begin{array}{ccc} \mathcal{Q}_{0,n}(Y, \beta) & \longrightarrow & \mathcal{Q}_{0,n}(H, d) \\ \downarrow & \square & \downarrow \\ \mathcal{Q}_{0,n}(X, \beta) & \xrightarrow{k} & \mathcal{Q}_{0,n}(\mathbb{P}^N, d) \end{array}$$

and equip it with the virtual class pulled back along  $k$ :

$$[\mathcal{Q}_{0,n}(Y, \beta)]^{\text{virt}} := k^! [\mathcal{Q}_{0,n}(H, d)]$$

Using this definition,  $\mathcal{Q}_{0,n}(Y, \beta)$  consists of those quasimaps in  $\mathcal{Q}_{0,n}(X, \beta)$  for which the section  $u_Y$  (constructed in §2.3) is identically zero. This has obvious advantages from the point of view of our computations, but is conceptually unsatisfying.

On the other hand, in [CFKM14] moduli spaces of stable quasimaps are constructed for GIT quotient targets satisfying a number of conditions. Since  $Y$  is a hypersurface in a toric variety, it has a natural presentation as such a GIT quotient

$$Y = C(Y) // G$$

where  $C(Y) \subseteq \mathbb{A}^{\Sigma_X(1)}$  is the affine cone over  $Y$  and  $G = \text{Hom}_{\mathbb{Z}}(\text{Pic}(X), \mathbb{G}_m) \cong \mathbb{G}_m^{r_X}$  acts on  $C(Y)$  via the natural inclusion

$$\mathbb{G}_m^{r_X} \hookrightarrow \mathbb{G}_m^{\Sigma_X(1)}$$

(here  $C(Y) \subseteq \mathbb{A}^{\Sigma_X(1)}$  is preserved by  $G$  because it is cut out by a homogeneous polynomial in the Cox ring of  $X$ ). Thus, we have two possible definitions of  $\mathcal{Q}_{0,n}(Y, \beta)$  and its virtual class; we will now show that they agree.

Objects of  $\mathcal{Q}_{0,n}^{\text{GIT}}(Y, \beta)$  are diagrams of the form

$$\begin{array}{c} P \times_G C(Y) \\ \downarrow p \uparrow u \\ C \end{array}$$

where  $C$  is a prestable curve,  $P$  is a principal  $G$ -bundle on  $C$ , and  $u$  is a section of the associated  $C(Y)$ -bundle. Given this data, there is a  $G$ -equivariant embedding

$$\begin{array}{ccc} P \times_G C(Y) & \xhookrightarrow{j} & P \times_G \mathbb{A}^{\Sigma_X(1)} = \bigoplus_{\rho \in \Sigma_X(1)} L_{\rho} \\ \downarrow p \uparrow u & \nearrow & \\ C & & \end{array}$$

which expresses  $P \times_G C(Y)$  as the vanishing locus of  $u_Y$ , viewed as a section of a line bundle on the total space of  $\bigoplus_{\rho \in \Sigma_X(1)} L_{\rho}$ . This shows that the two definitions of the moduli space agree.

It remains to compare the virtual classes. The obstruction theory on the GIT space is defined relative to the stack  $\mathfrak{Bun}_{0,n}^G$  parametrising principal  $G$ -bundles on the universal curve  $\mathcal{C}_{\mathfrak{M}_{0,n}} \rightarrow \mathfrak{M}_{0,n}$ . It is given by

$$\mathbf{E}_{\mathcal{Q}/\mathfrak{Bun}_{0,n}^G}^\vee = \mathbf{R}^\bullet \pi_*(u^* \mathbf{T}_p)$$

where  $\pi$  is the universal curve over  $\mathcal{Q} = \mathcal{Q}_{0,n}^{\text{GIT}}(Y, \beta)$  and  $\mathbf{T}_p$  is the relative tangent complex of the projection map  $\rho$ . There is a natural isomorphism

$$\mathfrak{Bun}_{0,n}^G = \underbrace{\mathfrak{Pic}_{0,n} \times_{\mathfrak{M}_{0,n}} \cdots \times_{\mathfrak{M}_{0,n}} \mathfrak{Pic}_{0,n}}_{r_X}$$

given by sending  $P$  to the  $r_X$  individual factors of the affine bundle  $P \times_G \mathbb{A}^{r_X}$ . Using the normal sheaf sequence for the inclusion  $j$  in the diagram above (all relative to the base  $C$ ) we obtain a short exact sequence on  $C$ :

$$0 \rightarrow u^* \mathbf{T}_p \rightarrow \bigoplus_{\rho \in \Sigma_X(1)} L_\rho \rightarrow u^* \mathbf{N}_{P \times_G C(Y)/\oplus_{\rho \in \Sigma_X(1)} L_\rho} \rightarrow 0$$

Since  $P \times_G C(Y)$  is defined by the vanishing of  $u_Y$ , we see that the final term is isomorphic to the line bundle  $L_Y$  discussed above. Thus we have a natural isomorphism of objects of the derived category:

$$u^* \mathbf{T}_p = \left[ \bigoplus_{\rho \in \Sigma_X(1)} L_\rho \rightarrow L_Y \right]$$

Applying  $\mathbf{R}^\bullet \pi_*$  we obtain on the left hand side the obstruction theory for  $\mathcal{Q}_{0,n}^{\text{GIT}}(Y, \beta)$  relative  $\mathfrak{Bun}_{0,n}^G$ . On the other hand, the first term on the right hand side is the obstruction theory for the toric quasimap space  $\mathcal{Q}_{0,n}(X, \beta)$  relative to the fibre product of the Picard stacks, whereas the second term is the relative obstruction theory for  $\mathcal{Q}_{0,n}(Y, \beta)$  inside  $\mathcal{Q}_{0,n}(X, \beta)$ . Thus the virtual classes agree as well.

**Aside 4.5.** In Remark 4.2 we saw that if  $Y = \mathbb{P}^1 \times \mathbb{P}^1$  and  $X = \mathbb{P}^3$ , with  $Y \hookrightarrow X$  given by the Segre embedding, then the induced map

$$\mathcal{Q}_{0,3}^{\text{GIT}}(Y, (2, 2)) \rightarrow \mathcal{Q}_{0,3}^{\text{GIT}}(X, 4)$$

is not injective. However, there is no contradiction between this and the discussion above. The somewhat subtle point is that the definition of the quasimap space depends on the presentation of the target as a GIT quotient [CFKM14, §4.6]. In Remark 4.2 we expressed  $Y$  as a toric GIT quotient

$$Y \cong \mathbb{A}^4 // \mathbb{G}_m^2$$

whereas in the context of Remark 4.4,  $Y$  would be expressed as a more parsimonious quotient:

$$Y \cong C(Y) // \mathbb{G}_m$$

The map  $\mathcal{Q}_{0,3}^{\text{GIT}}(\mathbb{A}^4 // \mathbb{G}_m^2) \rightarrow \mathcal{Q}_{0,3}^{\text{GIT}}(X)$  is not an embedding, but it factors through  $\mathcal{Q}_{0,3}^{\text{GIT}}(C(Y) // \mathbb{G}_m) \rightarrow \mathcal{Q}_{0,3}^{\text{GIT}}(X)$  which is.

We have thus shown that the comb locus  $\mathcal{D}^{\mathcal{Q}}(X|Y, A, B, M)$  makes sense for general  $(X, Y)$ . Our next task is to construct a virtual class on this locus. Consider the product (*not* the fibre product over  $Y^r$ )

$$\mathcal{E}^{\mathcal{Q}}(X|Y, A, B, M) := \mathcal{Q}_{0, A^{(0)} \cup \{q_1, \dots, q_r\}}(Y, \beta^{(0)}) \times \prod_{i=1}^r \mathcal{Q}_{0, \alpha^{(i)} \cup (m_i)}(X|Y, \beta^{(i)})$$

which we may endow with the product virtual class (with weighting as before):

$$[\mathcal{E}^{\mathcal{Q}}(X|Y, A, B, M)]^{\text{virt}} := \left( \frac{m^{(1)} \dots m^{(r)}}{r!} \right) \cdot \left( [\mathcal{Q}_{0, A^{(0)} \cup \{q_1, \dots, q_r\}}(Y, \beta^{(0)})]^{\text{virt}} \times \prod_{i=1}^r [\mathcal{Q}_{0, \alpha^{(i)} \cup (m_i)}(X|Y, \beta^{(i)})]^{\text{virt}} \right)$$

We have the following cartesian diagram

$$\begin{array}{ccc} \mathcal{D}^{\mathcal{Q}}(X|Y, A, B, M) & \longrightarrow & \mathcal{E}^{\mathcal{Q}}(X|Y, A, B, M) \\ \downarrow & \square & \downarrow \\ X^r & \xrightarrow{\Delta_{X^r}} & X^r \times X^r \end{array}$$

and we can use this to define a virtual class on the comb locus:

$$[\mathcal{D}^{\mathcal{Q}}(X|Y, A, B, M)]^{\text{virt}} := \Delta_{X^r}^! [\mathcal{E}^{\mathcal{Q}}(X|Y, A, B, M)]^{\text{virt}}$$

The virtual class on the union  $\mathcal{D}_{\alpha, k}^{\mathcal{Q}}(X|Y, \beta)$  of the comb loci is defined to be the sum of the virtual classes  $[\mathcal{D}^{\mathcal{Q}}(X|Y, A, B, M)]^{\text{virt}}$ .

**Remark 4.6.** This is the same definition of the virtual class of the comb locus that we gave in §3.2 in the case  $(X, Y) = (\mathbb{P}^N, H)$ .

On the other hand, there is another cartesian diagram:

$$\begin{array}{ccc} \coprod_{B: i_* B = B'} \mathcal{D}^{\mathcal{Q}}(X|Y, A, B, M) & \longrightarrow & \mathcal{D}^{\mathcal{Q}}(\mathbb{P}^N|H, A, B', M) \\ \downarrow & \square & \downarrow \\ \mathcal{Q}_{0, n}(X, \beta) & \xrightarrow{k} & \mathcal{Q}_{0, n}(\mathbb{P}^N, d) \end{array}$$

Recall that we are trying to show that the virtual class of the comb locus pulls back nicely along  $k$ . The result that we need is:

**Lemma 4.7.**  $k^! [\mathcal{D}^{\mathcal{Q}}(\mathbb{P}^N|H, A, B', M)]^{\text{virt}} = \sum_{B: i_* B = B'} [\mathcal{D}^{\mathcal{Q}}(X|Y, A, B, M)]^{\text{virt}}$



For the proof of Lemma 4.7, let us introduce the following shorthand notation. We fix the data of  $A, B', M$  for a comb locus of  $(\mathbb{P}^N, H)$ , and set:

$$\begin{aligned} \mathcal{D}(X|Y) &:= \coprod_{B: i_*B=B'} \mathcal{D}^{\mathcal{Q}}(X|Y, A, B, M) & \mathcal{D}(\mathbb{P}^N|H) &:= \mathcal{D}^{\mathcal{Q}}(\mathbb{P}^N|H, A, B', M) \\ \mathcal{E}(X|Y) &:= \coprod_{B: i_*B=B'} \mathcal{E}^{\mathcal{Q}}(X|Y, A, B, M) & \mathcal{E}(\mathbb{P}^N|H) &:= \mathcal{E}^{\mathcal{Q}}(\mathbb{P}^N|H, A, B', M) \\ \mathcal{D}(X) &:= \coprod_{B: i_*B=B'} \mathcal{D}^{\mathcal{Q}}(X, A, B) & \mathcal{D}(\mathbb{P}^N) &:= \mathcal{D}^{\mathcal{Q}}(\mathbb{P}^N, A, B') \\ \mathcal{E}(X) &:= \coprod_{B: i_*B=B'} \mathcal{E}^{\mathcal{Q}}(X, A, B) & \mathcal{E}(\mathbb{P}^N) &:= \mathcal{E}^{\mathcal{Q}}(\mathbb{P}^N, A, B') \\ \mathcal{Q}(X) &:= \mathcal{Q}_{0,n}(X, \beta) & \mathcal{Q}(\mathbb{P}^N) &:= \mathcal{Q}_{0,n}(\mathbb{P}^N, i_*\beta) \end{aligned}$$

Here  $\mathcal{D}(X)$  and  $\mathcal{E}(X)$  are the so-called centipede loci; they are defined in the same way as the comb loci, except that we replace both the quasimaps to  $Y$  and the relative quasimaps to  $(X, Y)$  by quasimaps to  $X$ . There is a cartesian diagram:

$$\begin{array}{ccc} \mathcal{E}(X|Y) & \longrightarrow & \mathcal{E}(\mathbb{P}^N|H) \\ \downarrow & \square & \downarrow \theta \\ \mathcal{E}(X) & \longrightarrow & \mathcal{E}(\mathbb{P}^N) \end{array}$$

Since  $\mathcal{E}(\mathbb{P}^N)$  is smooth (being a product of spaces of quasimaps to  $\mathbb{P}^N$ ) and there is a natural fundamental class on  $\mathcal{E}(\mathbb{P}^N|H)$ , we have a diagonal pull-back morphism  $\theta^! = \theta_{\Delta}^!$  (see Appendix A).

**Lemma 4.8.**  $[\mathcal{E}(X|Y)]^{\text{virt}} = \theta^![\mathcal{E}(X)]^{\text{virt}}$

*Proof.* It follows from the discussion in §4.1.  $\square$

Now consider the following cartesian diagram

$$\begin{array}{ccccc} \mathcal{D}(X) & \longrightarrow & \mathcal{D}(\mathbb{P}^N) & \longrightarrow & \mathfrak{M}_{A,B}^{\text{wt}} \\ \downarrow \varphi_X & \square & \downarrow \varphi_{\mathbb{P}^N} & \square & \downarrow \psi \\ \mathcal{Q}(X) & \xrightarrow{k} & \mathcal{Q}(\mathbb{P}^N) & \longrightarrow & \mathfrak{M}_{0,n,\beta}^{\text{wt}} \end{array}$$

where  $\mathfrak{M}_{0,n,\beta}^{\text{wt}}$  is the moduli space of prestable curves weighted by the class  $\beta$  [Cos06, §2] and:

$$\mathfrak{M}_{A,B}^{\text{wt}} := \mathfrak{M}_{0,A^{(0)} \cup \{q_1^0, \dots, q_r^0\}, \beta^{(0)}}^{\text{wt}} \times \prod_{i=1}^r \mathfrak{M}_{0,A^{(i)} \cup \{q_i^1\}, \beta^{(i)}}^{\text{wt}}$$

The vertical maps in the above diagram are given by gluing together curves (in the case of  $\psi$ ) and quasimaps (in the case of  $\varphi_X$  and  $\varphi_{\mathbb{P}^N}$ ). The maps  $\mathcal{D}(X) \rightarrow \mathfrak{M}_{A,B}^{\text{wt}}$  and  $\mathcal{Q}(X) \rightarrow \mathfrak{M}_{0,n,\beta}^{\text{wt}}$  admit relative perfect obstruction theories which are the same as the usual perfect obstruction theories relative to the moduli spaces of *unweighted* curves. Furthermore the morphism  $\psi$  admits a perfect obstruction theory. Thus there are virtual pull-back morphisms  $\psi^!$ , and by the splitting axiom (which is the same in quasimap theory

as in Gromov–Witten theory; see [CFK17, §2.3.3]) we have:

$$[\mathcal{D}(X)]^{\text{virt}} := \Delta_{X^r}^! [\mathcal{E}(X)]^{\text{virt}} = \psi^! [\mathcal{Q}(X)]^{\text{virt}}$$

Commutativity of virtual pull-backs then implies that:

$$(2) \quad [\mathcal{D}(X)]^{\text{virt}} = \psi^! [\mathcal{Q}(X)]^{\text{virt}} = \psi^! k^! [\mathcal{Q}(\mathbb{P}^N)] = k^! \psi^! [\mathcal{Q}(\mathbb{P}^N)] = k^! [\mathcal{D}(\mathbb{P}^N)]$$

*Proof of Lemma 4.7.* Putting all the preceding results together, we consider the cartesian diagram:

$$\begin{array}{ccccc} \mathcal{D}(X|Y) & \longrightarrow & \mathcal{E}(X|Y) & \longrightarrow & \mathcal{E}(\mathbb{P}^N|H) \\ \downarrow & \square & \downarrow & \square & \downarrow \theta \\ \mathcal{D}(X) & \longrightarrow & \mathcal{E}(X) & \longrightarrow & \mathcal{E}(\mathbb{P}^N) \\ \downarrow & \square & \downarrow & & \\ X^r & \xrightarrow{\Delta_{X^r}} & X^r \times X^r & & \end{array}$$

We then have:

$$\begin{aligned} [\mathcal{D}(X|Y)]^{\text{virt}} &= \Delta_{X^r}^! [\mathcal{E}(X|Y)]^{\text{virt}} && \text{by definition} \\ &= \Delta_{X^r}^! \theta^! [\mathcal{E}(X)]^{\text{virt}} && \text{by Lemma 4.8} \\ &= \theta^! \Delta_{X^r}^! [\mathcal{E}(X)]^{\text{virt}} && \text{by commutativity} \\ &= \theta^! [\mathcal{D}(X)]^{\text{virt}} && \text{by definition} \\ &= \theta^! k^! [\mathcal{D}(\mathbb{P}^N)] && \text{by formula (2) above} \\ &= \theta^! k^! \Delta_{(\mathbb{P}^N)^r}^! [\mathcal{E}(\mathbb{P}^N)] && \text{by definition} \\ &= k^! \Delta_{(\mathbb{P}^N)^r}^! \theta^! [\mathcal{E}(\mathbb{P}^N)] && \text{by commutativity} \\ &= k^! \Delta_{(\mathbb{P}^N)^r}^! [\mathcal{E}(\mathbb{P}^N|H)] && \text{by Lemma 4.8} \\ &= k^! [\mathcal{D}(\mathbb{P}^N|H)] && \text{by definition} \end{aligned}$$

Summing over all the components of  $\mathcal{D}_{\alpha,k}^{\mathcal{Q}}(\mathbb{P}^N|H, d)$  we obtain the result.  $\square$

*Proof of Theorem 4.1.* Apply  $k^!$  to Proposition 3.8, using Lemmas 4.3 and 4.7.  $\square$

## 5. QUASIMAP QUANTUM LEFSCHETZ THEOREM

The recursion formula shows that the relative quasimap invariants of  $(X, Y)$  are completely determined, in an algorithmic way, from the absolute invariants of  $X$  and  $Y$ ; by repeatedly applying the recursion formula, we can remove all the tangency conditions, leaving us with an expression which only involves the invariants of  $X$  and  $Y$ .

However, we can do much more than this. In this section we will prove (two variations of) a *quantum Lefschetz theorem for quasimap invariants*, that is, a result which expresses the quasimap invariants of  $Y$  in terms of those

of  $X$ . This is the quasimap analogue of the quantum Lefschetz hyperplane principle in Gromov–Witten theory and, on the face of it, has nothing to do with relative invariants.

**5.1. General quasimap quantum Lefschetz.** First we state the most general form of the theorem, without any additional assumptions on  $X$  and  $Y$ .

**Theorem 5.1** (Quasimap quantum Lefschetz theorem). Let  $X$  be a smooth projective toric variety and  $Y \subseteq X$  a smooth very ample hypersurface. Then there is an explicit algorithm to recover the (restricted) absolute quasimap invariants of  $Y$ , as well as the relative quasimap invariants of  $(X, Y)$ , from the absolute quasimap invariants of  $X$ .

The corresponding result in Gromov–Witten theory is due to Gathmann [Gat03a, Corollary 2.5.6]; the proof we present in the quasimap setting is very similar to his. The term “*restricted*” here means that we only integrate against cohomology classes pulled back from  $H^*(X)$ , rather than allowing arbitrary classes from  $H^*(Y)$ .

*Proof.* The idea, of course, is to repeatedly apply the recursion formula. The proof is by induction, and in order for the argument to work it is essential that we determine simultaneously the absolute invariants of  $Y$  and the relative invariants of  $(X, Y)$ .

We induct on: the intersection number  $d = Y \cdot \beta$ , the number of marked points  $n$ , and the total tangency  $\sum_i \alpha_i$ , in that order. This means that when we come to compute an absolute or relative invariant, we assume that all of the absolute *and* relative invariants with

- (1) smaller  $d$ , or
- (2) the same  $d$ , but smaller  $n$ , or
- (3) the same  $d$ , the same  $n$ , but smaller  $\sum_i \alpha_i$

are known. For the purposes of this ordering, we set  $\sum_i \alpha_i = d + 1$  for any absolute invariant of  $Y$ . This means that when we come to compute such an invariant, we assume that all the relative invariants with the same  $d$  and  $n$  are known.

We first prove the induction step for the relative invariants; suppose then that we want to compute some invariant:

$$\langle \gamma_1 \psi_1^{k_1}, \dots, \gamma_n \psi_n^{k_n} \rangle_{0, \alpha, \beta}^{X|Y}$$

We assume  $\sum_i \alpha_i > 0$ , since otherwise this is just an absolute invariant of  $X$ . Pick some  $k \in \{1, \dots, n\}$  with  $\alpha_k > 0$ , and apply Theorem 4.1 to obtain:

$$((\alpha_k - 1) \psi_k + \text{ev}_k^*[Y]) \cap [\mathcal{Q}_{0, \alpha - e_k}(X|Y, \beta)]^{\text{virt}} = [\mathcal{Q}_{0, \alpha}(X|Y, \beta)]^{\text{virt}} + [\mathcal{D}_{\alpha - e_k, k}^{\mathcal{Q}}(X|Y, \beta)]^{\text{virt}}$$

Capping this with the appropriate product of evaluation and psi classes, we obtain from the first term on the right-hand side the invariant that we are looking for.

It remains to show that the other terms are known by the induction hypothesis. Clearly, this is true for the term on the left-hand side, which

has the same  $d$ , the same  $n$ , but smaller  $\sum_i \alpha_i$ . Consider on the other hand a component of the comb locus. This contributes a product of an absolute invariant of  $Y$  (corresponding to the internal component) with a number of relative invariants of  $(X, Y)$  (corresponding to the external components). One can check that each of these invariants either has smaller  $d$ , or the same  $d$  and smaller  $n$ . Thus, they are also determined. Therefore the relative invariant is determined inductively.

Now we prove the induction step for the absolute invariants of  $Y$ . Suppose then that we want to compute a restricted invariant:

$$\langle \gamma_1 \psi_1^{k_1}, \dots, \gamma_n \psi_n^{k_n} \rangle_{0,n,\beta}^Y$$

If we apply Theorem 4.1 with  $\alpha = (d+1, 0, \dots, 0)$  we obtain

$$(d\psi_1 + \text{ev}_1^*[Y]) \cap [\mathcal{Q}_{0,\alpha-e_1}(X|Y, \beta)]^{\text{virt}} = [\mathcal{D}_{\alpha,1}^{\mathcal{Q}}(X|Y, \beta)]^{\text{virt}}$$

where the comb locus on the right-hand side has a connected component isomorphic to the moduli space

$$\mathcal{Q}_{0,n}(Y, \beta)$$

(corresponding to a “comb with no teeth”). Capping as before with an appropriate class, we obtain the invariant that we are looking for. The term on the left-hand side is known since  $\sum_i \alpha_i$  is smaller, while any other terms coming from the comb locus either involve invariants with smaller  $d$  or with the same  $d$  but smaller  $n$ , and so are also known inductively. This completes the proof.  $\square$

**Remark 5.2.** There is a subtle but extremely important point which we have ignored in the proof above. While the statement of Theorem 5.1 only concerns the *restricted* quasimap invariants, i.e. those with insertions from  $H^*(X)$ , when we calculate contributions from the comb loci we are forced to consider unrestricted invariants, due to classes in the diagonal in  $H^*(Y \times Y)$  which do not come from  $H^*(X \times X)$ . This is problematic, since in general these terms cannot be computed inductively.

However, a careful analysis of the recursion formula shows that any term which appears in this way must in fact be zero. The argument is the same as the one given for Gromov–Witten invariants in [Gat03a, §2.5]; the details are left to the reader. The key idea is to show that any absolute or relative quasimap invariant which has precisely one insertion from outside of  $H^*(X)$  must be zero, and then to show that any term arising from the comb locus and involving unrestricted classes is equal to a product of invariants, at least one of which takes this form.

**5.2. A mirror theorem for quasimap invariants.** Although the algorithm presented in the previous section is completely explicit, it is in general quite involved, since the combinatorics can become arbitrarily complicated. We would like to be able to find a closed formula which expresses the quasimap invariants of  $Y$  in terms of those of  $X$ . This is our goal over the next few

sections, culminating in Theorem 5.4, which provides such a closed formula, under some additional restrictions.

In [Gat03b] Gathmann applies the stable map recursion formula to obtain a new proof of the mirror theorem for hypersurfaces [Giv96]. This can be viewed as a partial quantum Lefschetz formula, expressing certain stable map invariants of  $Y$  in terms of those of  $X$ .

In this section we carry out a similar computation in the quasimap setting. We work with generating functions for 2-pointed quasimap invariants (the minimal number of markings, due to the strong stability condition). The absence of rational tails in the quasimap moduli space makes the quasimap recursion much simpler than Gathmann's.

Our formula can be viewed as a special case of [CFK14, Corollary 5.5.1], and thus as a relation between certain residues of the  $\mathbb{G}_m$ -action on spaces of 0-pointed and 1-pointed parametrised quasimaps to  $Y$ . Some of the consequences of this formula are explored in [CFK14, Section 5.5]; for instance, it follows in the semipositive case that all primary  $\epsilon$ -quasimap invariants with a fundamental class insertion can be expressed in terms of 2-pointed invariants.

**5.3. Setup.** As before, we let  $X = X_\Sigma$  be a smooth projective toric variety and  $i: Y \hookrightarrow X$  a smooth very ample hypersurface. We also make the following two assumptions:

- (1)  $Y$  is semi-positive:  $-K_Y$  is nef;
- (2)  $Y$  contains all curve classes: the map  $i_*: A_1(Y) \rightarrow A_1(X)$  is surjective.

By adjunction,  $-K_X$  pairs strictly positively with every curve class coming from  $Y$ , hence with every curve class by Assumption (2). Thus  $-K_X$  is ample by Kleiman's criterion (since the effective cone of a toric variety is finitely generated), so  $X$  is Fano. Also note that if  $\dim X \geq 3$  then Assumption (2) always holds, due to the classical Lefschetz hyperplane theorem; on the other hand if  $\dim X = 2$  then Assumption (2) forces  $X$  to be  $\mathbb{P}^2$ .

We fix a homogeneous basis  $\eta_0, \dots, \eta_k$  for  $H^*(X) = H^*(X, \mathbb{Q})$  and let  $\eta^0, \dots, \eta^k$  denote the dual basis with respect to the Poincaré pairing. Without loss of generality we may suppose that  $\eta^0 = \mathbb{1}_X$  and  $\eta^1 = [Y]$ . We get an induced basis  $\rho_1 = i^*\eta_1, \dots, \rho_k = i^*\eta_k$  for  $i^*H^*(X)$ . Notice that  $\rho_0 = i^*\eta_0 = i^*[\text{pt}_X] = 0$ ,  $\rho_1 = i^*\eta_1 = [\text{pt}_Y]$ . We can extend the  $\rho_i$  to a basis  $\rho_1, \dots, \rho_l$  for  $H^*(Y)$  by adding  $\rho_{k+1}, \dots, \rho_l$ . Let  $\rho^1, \dots, \rho^l$  denote the dual basis; notice that  $\rho^i$  is *not* equal to  $i^*\eta^i$  (they do not even have the same degree!). Note also that  $\rho^1 = \mathbb{1}_Y$ .

**5.4. Generating functions for quasimap invariants.** As with many results in enumerative geometry, the quasimap Lefschetz formula is most conveniently stated in terms of generating functions. Here we define several such generating functions for the absolute quasimap invariants of  $X$  and  $Y$ . We work with two marked points since this is the minimum number required in order for the quasimap space to be nonempty. However since

we only take insertions at the first marking we would like to think of these, morally speaking, as 1-pointed invariants (in Gromov–Witten theory the corresponding statement is literally true, due to the string equation).

For any smooth projective toric variety  $X$  (or more generally, any space for which the quasimap invariants are defined), and any effective curve class  $\beta \in H_2^+(X)$ , we define

$$S_0^X(z, \beta) = (\text{ev}_1)_* \left( \frac{1}{z - \psi_1} [\mathcal{Q}_{0,2}(X, \beta)]^{\text{virt}} \right)$$

and

$$S_0^X(z, q) = \sum_{\beta \geq 0} q^\beta S_0^X(z, \beta)$$

where by convention  $S_0^X(z, 0) = \mathbb{1}_X$ , and  $q$  is a Novikov variable. These are generating functions for quasimap invariants of  $X$  which take values in  $H^*(X)$ .

The same definition applies to  $Y$ . However, as noted in §5.1, quantum Lefschetz theorems only work if we study *restricted quasimap invariants*. The generating function for these is defined as

$$\tilde{S}_0^Y(z, \beta) = (\text{ev}_1)_* \left( \frac{1}{z - \psi_1} [\mathcal{Q}_{0,2}(Y, \beta)]^{\text{virt}} \right)$$

where crucially  $\text{ev}_1$  is viewed as *mapping to*  $X$  instead of to  $Y$ . Thus  $\tilde{S}_0^Y(z, \beta)$  takes values in  $H^*(X)$  and involves only quasimap invariants of  $Y$  with insertions coming from  $i^* H^*(X)$ ; this is in contrast to  $S_0^Y(z, \beta)$ , which takes values in  $H^*(Y)$  and involves quasimap invariants of  $Y$  with arbitrary insertions. As earlier, we can also define  $\tilde{S}_0^Y(z, q)$ .

Now, since  $X$  and  $Y$  are smooth, we may use Poincaré duality to define a push-forward map on cohomology,  $i_*: H^k(Y) \rightarrow H^{k+2}(X)$ .

**Lemma 5.3.**  $i_* S_0^Y(z, \beta) = \tilde{S}_0^Y(z, \beta)$ .

*Proof.* This follows from functoriality of cohomological push-forwards and the fact that we have a commuting triangle:

$$\begin{array}{ccc} \mathcal{Q}_{0,2}(Y, \beta) & \xrightarrow{\text{ev}_1} & Y \\ & \searrow \text{ev}_1 & \swarrow i \\ & X & \end{array}$$

Let us spell this out explicitly, in order to help the reader familiarise with the generating functions involved. First, it is easy to see from the projection formula that:

$$i_* \rho^i = \begin{cases} \eta^i & \text{for } i = 1, \dots, k \\ 0 & \text{for } i = k+1, \dots, l \end{cases}$$

Now, we can write  $S_0^Y(z, \beta)$  as:

$$S_0^Y(z, \beta) = \sum_{i=1}^l \left\langle \frac{\rho_i}{z - \psi_1}, \mathbb{1}_Y \right\rangle_{0,2,\beta}^Y \rho^i$$

Thus applying  $i_*$  gives

$$i_* S_0^Y(z, \beta) = \sum_{i=1}^l \left\langle \frac{\rho_i}{z - \psi_1}, \mathbb{1}_Y \right\rangle_{0,2,\beta}^Y i_* \rho^i = \sum_{i=1}^k \left\langle \frac{\eta_i}{z - \psi_1}, \mathbb{1}_X \right\rangle_{0,2,\beta}^Y \eta^i = \tilde{S}_0^Y(z, \beta)$$

as claimed.  $\square$

**5.5. Quasimap quantum Lefschetz formula.** We now turn to our main result: a formula expressing the generating function  $\tilde{S}_0^Y(z, q)$  for restricted quasimap invariants of  $Y$  in terms of the quasimap invariants of  $X$ .

**Theorem 5.4.** Let  $X$  and  $Y$  be as above. Then

$$(3) \quad \frac{\sum_{\beta \geq 0} q^\beta \prod_{j=0}^{Y \cdot \beta} (Y + jz) S_0^X(z, \beta)}{P_0^X(q)} = \tilde{S}_0^Y(z, q)$$

where:

$$P_0^X(q) = 1 + \sum_{\substack{\beta > 0 \\ K_Y \cdot \beta = 0}} q^\beta (Y \cdot \beta)! \langle [\text{pt}_X] \psi_1^{Y \cdot \beta - 1}, \mathbb{1}_X \rangle_{0,2,\beta}^X$$

Notice that  $P_0^X(q)$  depends not only on  $X$  but also on the divisor class of  $Y$  in  $X$ ; the superscript is supposed to indicate that the definition only involves quasimap invariants of  $X$ .

*Proof.* For  $m = 0, \dots, Y \cdot \beta$ , define the following generating function for 2-pointed relative quasimap invariants

$$S_{0,(m)}^{X|Y}(z, \beta) = (\text{ev}_1)_* \left( \frac{1}{z - \psi_1} [\mathcal{Q}_{0,(m,0)}(X|Y, \beta)]^{\text{virt}} \right)$$

where we view  $\text{ev}_1$  as mapping to  $X$ . Note that  $S_{0,(0)}^{X|Y}(z, \beta) = S_0^X(z, \beta)$ . Also define the following generating function for “comb loci invariants”

$$T_{0,(m)}^{X|Y}(z, \beta) = (\text{ev}_1)_* \left( m [\mathcal{Q}_{0,(m,0)}(X|Y, \beta)]^{\text{virt}} + \frac{1}{z - \psi_1} [\mathcal{D}_{(m,0),1}^{\mathcal{Q}}(X|Y, \beta)]^{\text{virt}} \right)$$

where again we view  $\text{ev}_1$  as mapping to  $X$ . As in [Gat03b, Lemma 1.2], it follows from Theorem 4.1 that

$$(4) \quad (Y + mz) S_{0,(m)}^{X|Y}(z, \beta) = S_{0,(m+1)}^{X|Y}(z, \beta) + T_{0,(m)}^{X|Y}(z, \beta)$$

and we can apply this repeatedly to obtain:

$$(5) \quad \prod_{j=0}^{Y \cdot \beta} (Y + jz) S_0^X(z, \beta) = \sum_{m=0}^{Y \cdot \beta} \prod_{j=m+1}^{Y \cdot \beta} (Y + jz) T_{0,(m)}^{X|Y}(z, \beta)$$

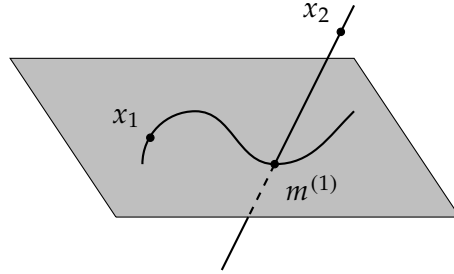
We now examine the right-hand side in detail. By definition,  $T_{0,(m)}^{X|Y}(z, \beta)$  splits into two parts: those terms coming from the relative space and those terms coming from the comb loci.

Let us first consider the contribution of the comb loci. Since there are only two marked points and the first is required to lie on the internal component of the comb, it follows from the strong stability condition that there are only two options: a comb with zero teeth or a comb with one tooth.

First consider the case of a comb with zero teeth. The moduli space is then  $\mathcal{Q}_{0,2}(Y, \beta)$  and we require that  $Y \cdot \beta = m$ . Thus this piece only contributes to  $T_{0,(Y \cdot \beta)}^{X|Y}(z, \beta)$ , and the contribution is:

$$\sum_{i=1}^k \left\langle \frac{\rho_i}{z - \psi_1}, \mathbb{I}_Y \right\rangle_{0,2,\beta}^Y \eta^i$$

Next consider the case of a comb with one tooth. Let  $\beta^{(0)}$  and  $\beta^{(1)}$  denote the curve classes of the internal and external components, respectively, and let  $m^{(1)}$  be the contact order of the external component with  $Y$ . The picture is as follows



and the invariants which contribute take the form

$$\left\langle \frac{\rho_i}{z - \psi_1}, \rho^h \right\rangle_{0,2,\beta^{(0)}}^Y \left\langle \rho_h, \mathbb{I}_X \right\rangle_{0,(m^{(1)},0),\beta^{(1)}}^{X|Y} \eta^i$$

for  $i = 1, \dots, k$  and  $h = 1, \dots, l$ . By computing dimensions, we find

$$\begin{aligned} 0 &\leq \text{codim } \rho^h = \dim Y - \text{codim } \rho_h \\ &= \dim Y - \text{vdim } \mathcal{Q}_{0,(m^{(1)},0)}(X|Y, \beta^{(1)}) \\ &= \dim Y - (\dim X - 3 - K_X \cdot \beta^{(1)} + 2 - m^{(1)}) \\ &= K_Y \cdot \beta^{(1)} - Y \cdot \beta^{(1)} + m^{(1)} \\ &\leq 0 \end{aligned}$$

where the final equality follows from adjunction and the final inequality holds because  $-K_Y$  is nef and  $m^{(1)} \leq Y \cdot \beta_1$ . This shows that the only non-trivial contributions come from curve classes  $\beta^{(1)}$  such that  $K_Y \cdot \beta^{(1)} = 0$ , and that in this case the order of tangency must be maximal, i.e.  $m^{(1)} = Y \cdot \beta^{(1)}$ .



Furthermore we must have  $\text{codim } \rho^h = 0$  and so  $\rho^h = \rho^1 = \mathbb{1}_Y$  which implies  $\rho_h = \rho_1 = [\text{pt}_Y]$ . Finally since  $m^{(1)} = Y \cdot \beta^{(1)}$  we have

$$m = Y \cdot \beta^{(0)} + m^{(1)} = Y \cdot (\beta^{(0)} + \beta^{(1)}) = Y \cdot \beta$$

and so again this piece only contributes to  $T_{0,(Y \cdot \beta)}^{X|Y}(z, \beta)$ , and the contribution is:

$$\sum_{i=1}^k \left( \sum_{\substack{0 < \beta^{(1)} < \beta \\ K_Y \cdot \beta^{(1)} = 0}} (Y \cdot \beta^{(1)}) \left\langle \frac{\rho_i}{z - \psi_1}, \mathbb{1}_Y \right\rangle_{0, 2, \beta - \beta^{(1)}}^Y \left\langle \rho_1, \mathbb{1}_X \right\rangle_{0, (Y \cdot \beta^{(1)}, 0), \beta^{(1)}}^{X|Y} \right) \eta^i$$

where the  $Y \cdot \beta^{(1)}$  factor comes from the weighting on the virtual class of the comb locus. Finally, we must examine the terms of  $T_{0,(m)}^{X|Y}(z, \beta)$  coming from:

$$\text{ev}_{1*}(m[\mathcal{Q}_{0,(m,0)}(X|Y, \beta)]^{\text{virt}})$$

Notice that we only have insertions from  $i^* H^*(X) \subseteq H^*(Y)$ , since  $\text{ev}_1$  is viewed as mapping to  $X$ . On the other hand

$$\begin{aligned} \text{vdim } \mathcal{Q}_{0,(m,0)}(X|Y, \beta) &= \dim X - 3 - K_X \cdot \beta + 2 - m \\ &= \dim X - 1 - K_Y \cdot \beta + Y \cdot \beta - m && \text{by adjunction} \\ &\geq \dim X - 1 + Y \cdot \beta - m && \text{since } -K_Y \text{ is nef} \\ &\geq \dim X - 1 && \text{since } m \leq Y \cdot \beta \end{aligned}$$

where in the second line we have applied the projection formula to  $i$ , and thus have implicitly used Assumption (2), discussed in §5.3; namely that every curve class on  $X$  comes from a class on  $Y$ .

Consequently the only insertions that can appear are those of dimension 0 and 1. However, the restriction of the 0-dimensional class  $\eta_0 = [\text{pt}_X]$  to  $Y$  vanishes, as do the restrictions of all 1-dimensional classes except for  $\eta_1$  (by the definition of the dual basis, since  $\eta^1 = Y$ ). Thus the only insertion is  $i^* \eta_1 = \rho_1 = [\text{pt}_Y]$ , and since  $\eta^1$  has dimension 1 all the inequalities above must actually be equalities. Thus we only have a contribution if  $-K_Y \cdot \beta = 0$  and  $m = Y \cdot \beta$ . The contribution to  $T_{0,(Y \cdot \beta)}^{X|Y}(z, \beta)$  in this case is:

$$(Y \cdot \beta) \langle \rho_1, \mathbb{1}_X \rangle_{0, (Y \cdot \beta, 0), \beta}^{X|Y} \eta^1$$

Thus we have calculated  $T_{0,(m)}^{X|Y}(z, \beta)$  for all  $m$ ; substituting into equation (5) we obtain

$$\begin{aligned} \prod_{j=0}^{Y \cdot \beta} (Y + jz) S_0^X(z, \beta) &= T_{0,(Y \cdot \beta)}^{X|Y}(z, \beta) \\ &= \sum_{i=1}^k \left\langle \frac{\rho_i}{z - \psi_1}, \mathbb{1}_Y \right\rangle_{0,2,\beta}^Y \eta^i + \\ &\quad \sum_{i=1}^k \left( \sum_{\substack{0 < \beta^{(1)} < \beta \\ K_Y \cdot \beta^{(1)} = 0}} (Y \cdot \beta^{(1)}) \left\langle \frac{\rho_i}{z - \psi_1}, \mathbb{1}_Y \right\rangle_{0,2,\beta-\beta^{(1)}}^Y \left\langle \rho_1, \mathbb{1}_X \right\rangle_{0,(Y \cdot \beta^{(1)},0),\beta^{(1)}}^{X|Y} \right) \eta^i + \\ &\quad (Y \cdot \beta) \langle \rho_1, \mathbb{1}_X \rangle_{0,(Y \cdot \beta,0),\beta}^{X|Y} \eta^1 \end{aligned}$$

where the third term only appears if  $K_Y \cdot \beta = 0$ . We can rewrite this as:

$$\begin{aligned} \prod_{j=0}^{Y \cdot \beta} (Y + jz) S_0^X(z, \beta) &= \tilde{S}_0^Y(z, \beta) + \sum_{\substack{0 < \beta^{(1)} \leq \beta \\ K_Y \cdot \beta^{(1)} = 0}} \left( (Y \cdot \beta^{(1)}) \left\langle \rho_1, \mathbb{1}_X \right\rangle_{0,(Y \cdot \beta^{(1)},0),\beta^{(1)}}^{X|Y} \right) \tilde{S}_0^Y(z, \beta - \beta^{(1)}) \end{aligned}$$

It is now clear from the expression above that equation (3) in the statement of Theorem 5.4 holds, with:

$$P_0^X(q) = 1 + \sum_{\substack{\beta > 0 \\ K_Y \cdot \beta = 0}} q^\beta (Y \cdot \beta) \langle \rho_1, \mathbb{1}_X \rangle_{0,(Y \cdot \beta,0),\beta}^{X|Y}$$

To complete the proof it thus remains to show that:

$$P_0^X(q) = 1 + \sum_{\substack{\beta > 0 \\ K_Y \cdot \beta = 0}} q^\beta (Y \cdot \beta)! \langle \psi_1^{Y \cdot \beta - 1} [\mathbf{pt}_X], \mathbb{1}_X \rangle_{0,2,\beta}^X$$

The aim therefore is to express the relative invariants

$$\langle \rho_1, \mathbb{1}_X \rangle_{0,(Y \cdot \beta,0),\beta}^{X|Y}$$

in terms of absolute invariants of  $X$ . Unsurprisingly, we once again do this by applying Theorem 4.1. We have:

$$\begin{aligned} [\mathcal{Q}_{0,(Y \cdot \beta,0)}(X|Y, \beta)]^{\text{virt}} &= ((Y \cdot \beta - 1) \psi_1 + \text{ev}_1^* Y) [\mathcal{Q}_{0,(Y \cdot \beta - 1,0)}(X|Y, \beta)]^{\text{virt}} - \\ &\quad [\mathcal{D}_{(Y \cdot \beta - 1,0),1}^{\mathcal{Q}}(X|Y, \beta)]^{\text{virt}} \end{aligned}$$

We begin by examining the contributions from the comb loci. As before, we have only contributions coming from combs with 0 teeth and combs with 1 tooth. The former contributions take the form

$$\langle \rho_1, \mathbb{1}_Y \rangle_{0,2,\beta}^Y$$

which vanish because  $\text{vdim } \mathcal{Q}_{0,2}(Y, \beta) = \dim Y - 1 - K_Y \cdot \beta = \dim Y - 1$  whereas the insertion has codimension  $\dim Y$ . The latter contributions take the form

$$\langle \rho_1, \rho^h \rangle_{0,2,\beta^{(0)}}^Y \langle \rho_h, \mathbb{1}_X \rangle_{0,(Y \cdot (\beta - \beta^{(0)}) - 1, 0), \beta - \beta^{(0)}}^{X|Y}$$

and these must also vanish since:

$$\begin{aligned} \text{codim } \rho^h &= \dim Y - \text{codim } \rho_h \\ &= \dim Y - \text{vdim } \mathcal{Q}_{0,(Y \cdot (\beta - \beta^{(0)}) - 1, 0)}(X|Y, \beta - \beta^{(0)}) \\ &= \dim Y - (\dim X - 3 - K_X \cdot (\beta - \beta^{(0)}) + 2 - Y \cdot (\beta - \beta^{(0)}) + 1) \\ &= -1 + K_X \cdot (\beta - \beta^{(0)}) + Y \cdot (\beta - \beta^{(0)}) \\ &= -1 + K_Y \cdot (\beta - \beta^{(0)}) \\ &\leq -1 \end{aligned}$$

Thus the comb loci do not contribute at all. Applying this recursively (the same argument as above shows that we never get comb loci contributions), we find that

$$\begin{aligned} (Y \cdot \beta) \langle \rho_1, \mathbb{1}_X \rangle_{0,(Y \cdot \beta, 0), \beta}^{X|Y} &= (Y \cdot \beta) \langle \eta_1 \prod_{j=0}^{Y \cdot \beta - 1} (Y + j\psi_1), \mathbb{1}_X \rangle_{0,2,\beta}^X \\ &= (Y \cdot \beta)! \langle [\text{pt}_X] \psi_1^{Y \cdot \beta - 1}, \mathbb{1}_X \rangle_{0,2,\beta}^X \end{aligned}$$

where the second equality holds because  $Y \cdot \eta_1 = \eta_1^1 \cdot \eta_1 = [\text{pt}_X]$  and  $Y^2 \cdot \eta_1 = 0$ . This completes the proof of Theorem 5.4.  $\square$

**Corollary 5.5.** If  $Y$  is Fano then there is no correction term:

$$\sum_{\beta \geq 0} q^\beta \prod_{j=0}^{Y \cdot \beta} (Y + jz) S_0^X(z, \beta) = \tilde{S}_0^Y(z, q)$$

**Corollary 5.6.** Let  $Y = Y_5 \subseteq X = \mathbb{P}^4$  be the quintic three-fold. Then

$$\tilde{S}_0^{Y_5}(z, q) = \frac{I_{\text{small}}^{Y_5}(z, q)}{P(q)}$$

where

$$I_{\text{small}}^{Y_5}(z, q) = 5H + \sum_{d>0} \frac{\prod_{j=0}^{5d} (H + jz)}{\prod_{j=0}^d (H + jz)^5} q^d$$

and:

$$P(q) = 1 + \sum_{d>0} \frac{(5d)!}{(d!)^5} q^d$$

*Proof.* Apply Theorem 5.4 and use the fact that the quasimap invariants of  $\mathbb{P}^4$  coincide with the Gromov–Witten invariants, which are well-known from mirror symmetry.  $\square$

**Remark 5.7.** Theorem 5.4 agrees with [CZ14, Theorem 1] when  $X$  is a projective space.

**5.6. Comparison with the work of Ciocan-Fontanine and Kim.** Here we briefly explain how to compare our Theorem 5.4 to a formula obtained by Ciocan-Fontanine and Kim. We assume that the reader is familiar with the paper [CFK14], in particular §4 and §5 thereof. There they introduce (in the more general context of  $\epsilon$ -stable quasimaps) the following generating functions for quasimap invariants of  $Y$ :

(1) The  $J^\epsilon$ -function

$$J^\epsilon(\mathbf{t}, z) = \sum_{m \geq 0, \beta \geq 0} \frac{q^\beta}{m!} (\text{ev}_\bullet)_* \left( \prod_{i=1}^m \text{ev}_i^*(\mathbf{t}) \cap \text{Res}_{F_0} [\mathcal{Q}G_{0,m}^\epsilon(Y, \beta)]^{\text{virt}} \right)$$

for  $\mathbf{t} \in H^*(X)$ . Here  $\mathcal{Q}G_{0,m}^\epsilon(Y, \beta)$  is the moduli space of  $\epsilon$ -stable quasimaps with a parametrised component,  $F_0$  is a certain fixed locus of the natural  $\mathbb{G}_m$ -action on this space, and  $\text{ev}_\bullet$  is the evaluation at the point  $\infty \in \mathbb{P}^1$  on the parametrised component.  $\text{Res}_{F_0}$  is the residue of the virtual class, i.e. the virtual class of the fixed locus divided by the Euler class of the virtual normal bundle (see [GP99] for details on virtual localisation). The variable  $z$  is the  $\mathbb{G}_m$ -equivariant parameter.

(2) The  $S^\epsilon$ -operator

$$S^\epsilon(\mathbf{t}, z)(\gamma) = \sum_{m \geq 0, \beta \geq 0} \frac{q^\beta}{m!} (\text{ev}_1)_* \left( \frac{\text{ev}_2^*(\gamma) \cdot \prod_{j=3}^{2+m} \text{ev}_j^*(\mathbf{t})}{z - \psi_1} \cap [\mathcal{Q}_{0,2+m}^\epsilon(Y, \beta)]^{\text{virt}} \right)$$

where  $\mathbf{t}, \gamma \in H^*(X)$  and  $z$  is a formal variable.

(3) The  $P^\epsilon$ -series

$$P^\epsilon(\mathbf{t}, z) = \sum_{h=1}^k \rho^h \sum_{m \geq 0, \beta \geq 0} \frac{q^\beta}{m!} (\text{ev}_1^*(\rho_h \boxtimes p_\infty) \cap [\mathcal{Q}G_{0,1+m}^\epsilon(Y, \beta)]^{\text{virt}})$$

where  $\mathbf{t} \in H^*(X)$  and  $z$  is the  $\mathbb{G}_m$ -equivariant parameter. Here we view  $\text{ev}_1$  as mapping to  $Y \times \mathbb{P}^1$ , and  $p_\infty \in H_{\mathbb{G}_m}^*(\mathbb{P}^1)$  is the equivariant cohomology class defined by setting  $p_\infty|_0 = 0$  and  $p_\infty|_\infty = -z$ .

Given these definitions, Ciocan-Fontanine and Kim use localisation with respect to the  $\mathbb{G}_m$ -action on the parametrised space to prove the following formula [CFK14, Theorem 5.4.1]:

$$J^\epsilon(\mathbf{t}, z) = S^\epsilon(\mathbf{t}, z)(P^\epsilon(\mathbf{t}, z))$$

They observe that if we set  $\mathbf{t} = 0$  and restrict to semi-positive targets, then the only class that matches non-trivially with  $P^\epsilon|_{\mathbf{t}=0}$  is  $[\text{pt}_Y]$ . Hence the above formula takes the simple form

$$(6) \quad \frac{J^\epsilon|_{\mathbf{t}=0}}{\langle [\text{pt}_Y], P^\epsilon|_{\mathbf{t}=0} \rangle} = S^\epsilon(\mathbb{1}_Y)|_{\mathbf{t}=0} = \mathbb{1}_Y + \sum_{h=1}^k \rho^h \left( \sum_{\beta>0} q^\beta \left\langle \frac{\rho_h}{z - \psi}, \mathbb{1}_Y \right\rangle_{0,2,\beta}^{Y,\epsilon} \right)$$

see [CFK14, Corollary 5.5.1]. In our setting,  $\epsilon = 0+$  and  $Y$  embeds as a very ample hypersurface in a toric Fano variety  $X$ . Our Theorem 5.4 makes explicit a consequence of formula (6). More precisely:

**Lemma 5.8.** We have the following relations between our generating functions and the generating functions of Ciocan-Fontanine and Kim:

$$(7) \quad i_* J^{0+}|_{\mathbf{t}=0} = \sum_{\beta \geq 0} q^\beta \prod_{j=0}^{Y \cdot \beta} (Y + jz) S_0^X(z, \beta)$$

$$(8) \quad \langle [\text{pt}_Y], P^{0+}|_{\mathbf{t}=0} \rangle = P_0^X(q)$$

$$(9) \quad i_* S^{0+}(\mathbb{1}_Y)|_{\mathbf{t}=0} = \tilde{S}_0^Y(z, q)$$

*Proof.* (9) is clear from the second equality of (6) and the definition of  $\tilde{S}_0^Y(z, q)$ . To show (7), let us look more closely at the left-hand side:

$$J^{0+}|_{\mathbf{t}=0} = \sum_{\beta \geq 0} q^\beta (\text{ev}_\bullet)_* \left( \text{Res}_{F_0} [\mathcal{Q}G_{0,0}(Y, \beta)]^{\text{virt}} \right)$$

We have a diagram of fixed loci and evaluation maps

$$\begin{array}{ccccc} \mathcal{Q}G_{0,0}(Y, \beta) & \longleftarrow & F_0^Y & \xrightarrow{\text{ev}_\bullet} & Y \\ \downarrow i & & \square & & \downarrow i \\ \mathcal{Q}G_{0,0}(X, \beta) & \longleftarrow & F_0^X & \xrightarrow{\text{ev}_\bullet} & X \end{array}$$

and by a mild generalisation of [CFKM14, Propositions 6.2.2 and 6.2.3], we have an equality of  $\mathbb{G}_m$ -equivariant classes

$$i_* [\mathcal{Q}G_{0,0}(Y, \beta)]^{\text{virt}} = e(\pi_* E_{0,0,\beta}^Y) \cap [\mathcal{Q}G_{0,0}(X, \beta)]^{\text{virt}}$$

where  $\pi$  is the universal curve on  $\mathcal{Q}G_{0,0}(X, \beta)$  and  $E_{0,0,\beta}^Y$  is the equivariant line bundle on this curve associated to  $\mathcal{O}_X(Y)$ . This is the parametrised analogue of the bundle  $L_Y$  constructed in the definition of relative quasimaps; see §2.3.

We would like to pull back this equation to the fixed locus  $F_0^X$  in order to obtain an equation involving the residues. Let us first briefly recall the definition of  $F_0^X$ . Since there are no markings, any quasimap in  $\mathcal{Q}G_{0,0}(X, \beta)$  has irreducible source curve. For such a quasimap to be  $\mathbb{G}_m$ -fixed we need that the induced rational map is constant; this means that the degree of the quasimap is concentrated at the basepoints (i.e. the sum of the lengths of

the basepoints should be equal to the degree). Furthermore only the points 0 and  $\infty$  of the parametrised component are allowed to be basepoints. The fixed loci are thus indexed by ordered partitions of the degree which record the length of the basepoints at 0 and  $\infty$ .  $F_0^X$  is the locus on which all the degree is concentrated at 0. This means that  $\infty$  is not a basepoint and we have an evaluation map  $\text{ev}_\infty$  (denoted  $\text{ev}_\bullet$  earlier). See [CFK14, §4] for more details: our  $F_0^X$  is there denoted  $F_{0,0,\beta}^{0,0,0}$ .

Since the fibres of  $\pi$  are irreducible and rational, the degree of the universal line bundle on the parametrised component is constant; therefore we have for  $0 < j \leq Y \cdot \beta + 1$  an exact sequence:

$$0 \rightarrow \pi_*(E_{0,0,\beta}^Y(-j\sigma_\infty)) \rightarrow \pi_*E_{0,0,\beta}^Y \rightarrow \sigma_\infty^* \mathcal{P}^{j-1}(E_{0,0,\beta}^Y) \rightarrow 0$$

where  $\mathcal{P}^{j-1}$  denotes the bundle of  $(j-1)$ -jets, and  $\sigma_\infty$  is the section given by the point  $\infty \in \mathbb{P}^1$  of the parametrised component. The right-hand map is given by evaluating a section of  $E_{0,0,\beta}^Y$  (as well as its derivatives up to order  $j-1$ ) at the point  $\infty$ . The left-hand term consists of sections of  $E_{0,0,\beta}^Y$  which vanish at  $\sigma_\infty$  to order  $j$ . If we set  $j = Y \cdot \beta + 1$  then this term vanishes and we have:

$$\pi_*E_{0,0,\beta}^Y = \sigma_\infty^* \mathcal{P}^{Y \cdot \beta}(E_{0,0,\beta}^Y)$$

On the other hand, we have

$$0 \rightarrow E_{0,0,\beta}^Y \otimes \omega_\pi^{\otimes j} \rightarrow \mathcal{P}^j(E_{0,0,\beta}^Y) \rightarrow \mathcal{P}^{j-1}(E_{0,0,\beta}^Y) \rightarrow 0$$

see [Gat02, §2]. Pulling back along  $\sigma_\infty$  and taking Euler classes, we can compute recursively from  $j = Y \cdot \beta$  to 0 and obtain a splitting

$$e(\pi_*E_{0,0,\beta}^Y) = \prod_{j=0}^{Y \cdot \beta} c_1(\sigma_\infty^*E_{0,0,\beta}^Y \otimes \omega_\infty^{\otimes j})$$

where  $\omega_\infty = \sigma_\infty^* \omega_\pi$  gives the cotangent space at the point  $\infty$ . The bundle  $\omega_\infty$  is (non-equivariantly) trivial since the source curves in  $F_0^X$  are rigid; on the other hand the weight of the  $\mathbb{G}_m$ -action on the cotangent space at  $\infty$  is  $z$ . We thus obtain:

$$i_*[F_0^Y]^{\text{virt}} = \prod_{j=0}^{Y \cdot \beta} (\text{ev}_\infty^* Y + jz) \cap [F_0^X]^{\text{virt}}$$

Furthermore, the Euler classes of the virtual normal bundles match under  $i$ . Substituting into  $i_*J^{0+}|_{t=0}$  we find that:

$$\begin{aligned} i_*J^{0+}|_{t=0} &= \sum_{\beta \geq 0} q^\beta (i \circ \text{ev}_\bullet)_* \left( \text{Res}_{F_0^Y} [\mathcal{Q}G_{0,0}(Y, \beta)]^{\text{virt}} \right) \\ &= \sum_{\beta \geq 0} q^\beta \prod_{j=0}^{Y \cdot \beta} (Y + jz) (\text{ev}_\bullet)_* \left( \text{Res}_{F_0^X} [\mathcal{Q}G_{0,0}(X, \beta)]^{\text{virt}} \right) \end{aligned}$$

On the other hand, if we apply (6) with  $X$  instead of  $Y$ , then the denominator on the left-hand side vanishes since  $X$  is Fano. Comparing coefficients of  $q^\beta$  we thus obtain

$$(\mathrm{ev}_\bullet)_* \mathrm{Res}_{F_0^X} [\mathcal{Q}G_{0,0}(X, \beta)]^{\mathrm{virt}} = S_0^X(z, \beta)$$

from which it follows that:

$$i_* J^{0+}|_{t=0} = \sum_{\beta \geq 0} q^\beta \prod_{j=0}^{Y \cdot \beta} (Y + jz) S_0^X(z, \beta)$$

This proves (7). It remains to show (8). According to Ciocan-Fontanine and Kim, if we write the  $1/z$ -expansion of  $J^\epsilon|_{t=0}$  as

$$J^\epsilon|_{t=0} = J_0^\epsilon(q) \mathbb{1}_Y + O(1/z)$$

then  $\langle [\mathrm{pt}_Y], P^\epsilon|_{t=0} \rangle = J_0^\epsilon(q)$ . It thus remains to prove that  $J_0^{0+}(q) = P_0^X(q)$ .

Since  $X$  is a toric Fano variety, we have the following calculation of residues due to Givental [Giv98] (see also [CFK10, Definition 7.2.8]):

$$S_0^X(z, \beta) = \prod_{\rho \in \Sigma_X(1)} \frac{\prod_{j=-\infty}^0 (D_\rho + jz)}{\prod_{j=-\infty}^{D_\rho \cdot \beta} (D_\rho + jz)} = \frac{\prod_{\rho: D_\rho \cdot \beta \leq 0} \prod_{j=D_\rho \cdot \beta}^0 (D_\rho + jz)}{\prod_{\rho: D_\rho \cdot \beta > 0} \prod_{j=1}^{D_\rho \cdot \beta} (D_\rho + jz)}$$

We can then apply equation (7) to find  $i_* J^{0+}|_{t=0}$ , and hence also to find  $J_0^{0+}(q)$ . In the end we obtain:

$$J_0^{0+}(q) = \sum_{\beta \geq 0} q^\beta (Y \cdot \beta)! \frac{\prod_{\rho: D_\rho \cdot \beta < 0} (-1)^{-D_\rho \cdot \beta} (-D_\rho \cdot \beta)!}{\prod_{\rho: D_\rho \cdot \beta > 0} (D_\rho \cdot \beta)!}$$

On the other hand the coefficient

$$\langle [\mathrm{pt}_X] \psi_1^{Y \cdot \beta - 1}, \mathbb{1}_X \rangle_{0,2,\beta}^X$$

which appears in our  $P_0^X(q)$ -series also appears in  $S_0^X(z, \beta)$ . So again we can find it by appealing to Givental's calculation of  $S_0^X(z, q)$ .

$$\begin{aligned} \langle [\mathrm{pt}_X] \psi_1^{Y \cdot \beta - 1}, \mathbb{1}_X \rangle_{0,2,\beta}^X &= \mathrm{coeff}_{q^\beta z^{-Y \cdot \beta}} \langle [\mathrm{pt}_X], S_0^X(z, q) \rangle \\ &= \frac{\prod_{\rho: D_\rho \cdot \beta < 0} (-1)^{-D_\rho \cdot \beta} (-D_\rho \cdot \beta)!}{\prod_{\rho: D_\rho \cdot \beta > 0} (D_\rho \cdot \beta)!} \end{aligned}$$

which proves (8). We thus conclude that (6) implies our Theorem 5.4.  $\square$

## APPENDIX A. INTERSECTION-THEORETIC LEMMAS

In this appendix we explicitly define the *diagonal pull-back* along a morphism whose target is unobstructed (used in [Gat02]) and verify that this agrees with the virtual pull-back of [Man12a] when both are defined. We also check that it satisfies some expected compatibility properties.

Consider a morphism of DM stacks  $f: Y \rightarrow X$  over a smooth base  $\mathfrak{M}$ , such that  $X$  is smooth over  $\mathfrak{M}$  and  $Y$  carries a virtual class given by a perfect obstruction theory  $\mathbf{E}_{Y/\mathfrak{M}}$ . Then, for every cartesian diagram

$$\begin{array}{ccc} G & \xrightarrow{g} & F \\ \downarrow q & \square & \downarrow p \\ Y & \xrightarrow{f} & X \end{array}$$

and every class  $\alpha \in A_*(F)$ , we may define

$$f_{\Delta}^!(\alpha) = \Delta_X^!([Y]^{\text{vir}} \times \alpha) \in A_*(G)$$

which we call the *diagonal pull-back*. We first show that it coincides with the usual virtual pull-back along  $f$  in the presence of a compatible perfect obstruction theory for  $f$ .

**Lemma A.1.** Assume that there exists a relative obstruction theory  $\mathbf{E}_f$  compatible with  $\mathbf{E}_{Y/\mathfrak{M}}$  and the standard (unobstructed) obstruction theory for  $X$ , i.e:

$$\begin{array}{ccccc} f^*\mathbf{L}_{X/\mathfrak{M}} & \longrightarrow & \mathbf{E}_{Y/\mathfrak{M}} & \longrightarrow & \mathbf{E}_f \xrightarrow{[1]} \\ \downarrow \text{Id} & & \downarrow & & \downarrow \\ f^*\mathbf{L}_{X/\mathfrak{M}} & \longrightarrow & \mathbf{L}_{Y/\mathfrak{M}} & \longrightarrow & \mathbf{L}_f \xrightarrow{[1]} \end{array}$$

Then for every cartesian diagram and every class  $\alpha \in A_*(F)$  as above,

$$f_v^!(\alpha) = f_{\Delta}^!(\alpha).$$

*Proof.* Consider the following cartesian diagram:

$$\begin{array}{ccccc} G & \xrightarrow{q \times g} & Y \times_{\mathfrak{M}} F & \xrightarrow{\text{pr}_1} & Y \\ \downarrow g & \square & \downarrow f \times \text{Id} & \square & \downarrow f \\ F & \xrightarrow{p \times \text{Id}} & X \times_{\mathfrak{M}} F & \xrightarrow{\text{pr}_1} & X \\ \downarrow p & \square & \downarrow \text{Id} \times p & & \\ X & \xrightarrow{\Delta_X} & X \times_{\mathfrak{M}} X & & \end{array}$$

Then, by commutativity of (virtual) pull-backs, we have

$$\begin{aligned} \Delta_X^!([Y]^{\text{vir}} \times \alpha) &= \Delta_X^!((f_v^![X]) \times \alpha) \\ &= \Delta_X^!(f_v^!([X] \times \alpha)) \\ &= f_v^!(\Delta_X^!([X] \times \alpha)) \\ &= f_v^!(\alpha) \end{aligned}$$

as required.  $\square$



Secondly, we show that the diagonal pull-back behaves similarly to an ordinary virtual pull-back (e.g. commutes with other virtual pull-backs) even in the absence of a compatible perfect obstruction theory.

**Lemma A.2.** The diagonal pull-back morphism as defined above commutes with ordinary Gysin maps and with virtual pull-backs.

*Proof.* First consider the case of ordinary Gysin maps. We must consider a cartesian diagram:

$$\begin{array}{ccccc} Y'' & \longrightarrow & X'' & \longrightarrow & S \\ \downarrow & \square & \downarrow & \square & \downarrow k \\ Y' & \longrightarrow & X' & \longrightarrow & T \\ \downarrow & \square & \downarrow & & \\ Y & \xrightarrow{f} & X & & \end{array}$$

with  $k$  a regular embedding and  $f: Y \rightarrow X$  as before. We need to show that for all  $\alpha \in A_*(X')$ :

$$k^! f_{\Delta}^!(\alpha) = f_{\Delta}^! k^!(\alpha)$$

We form the cartesian diagram

$$\begin{array}{ccccc} Y'' & \longrightarrow & Y \times X'' & \longrightarrow & S \\ \downarrow & \square & \downarrow & \square & \downarrow k \\ Y' & \longrightarrow & Y \times X' & \longrightarrow & T \\ \downarrow & \square & \downarrow & & \\ X & \xrightarrow{\Delta_X} & X \times X & & \end{array}$$

and apply commutativity of usual Gysin morphisms. In the case where  $k$  is not a regular embedding but rather is equipped with a relative perfect obstruction theory, the same argument works with  $k^!$  replaced by  $k_v^!$ .  $\square$

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