

# EXPLICIT RECONSTRUCTION IN QUANTUM COHOMOLOGY AND K-THEORY

ALEXANDER GIVENTAL

*To my friend Vadim Schechtman*

ABSTRACT. Cohomological genus-0 Gromov-Witten invariants of a given target space can be encoded by the “descendent potential,” a generating function defined on the space of power series in one variable with coefficients in the cohomology space of the target. Replacing the coefficient space with the subspace multiplicatively generated by degree-2 classes, we explicitly reconstruct the graph of the differential of the restricted generating function from one point on it. Using the Quantum Hirzebruch–Riemann–Roch Theorem from our joint work [10] with Valentin Tonita, we derive a similar reconstruction formula in genus-0 quantum K-theory. The results amplify the role in quantum cohomology and quantum K-theory of the structures, based on divisor equations, of  $\mathcal{D}$ -modules and  $\mathcal{D}_q$ -modules with respect to Novikov’s variables.

## 1. FORMULATIONS

Let  $X$  be a compact Kähler (or, more generally, symplectic) manifold. Its genus-0 *descendent potential* is defined by

$$\mathcal{F}(t) := \sum_{d \in \mathcal{M}} \sum_{n=0}^{\infty} \frac{Q^d}{n!} \langle t(\psi), \dots, t(\psi) \rangle_{0,n,d},$$

where  $\mathcal{M} \subset H_2(X, \mathbb{Z})$  is the Mori cone of  $X$ ,  $Q^d$  stands for the element corresponding to  $d$  in the semigroup ring of  $\mathcal{M}$ ,  $t := \sum_{k \geq 0} t_k z^k$  is a power series with coefficients  $t_k$  which are cohomology classes of  $X$ , and the correlator stands for the integral over the virtual fundamental class  $[X_{0,n,d}]$  of the moduli space of degree- $d$  stable maps to  $X$  of rational curves with  $n$  marked points:

$$\langle \phi_1 \psi^{k_1}, \dots, \phi_n \psi^{k_n} \rangle_{0,n,d} := \int_{[X_{0,n,d}]} \text{ev}_1^*(\phi_1) \psi_1^{k_1} \cdots \text{ev}_n^*(\phi_n) \psi_n^{k_n}.$$

---

*Date:* June 25, 2014, revised May 12 and August 1, 2015.

This material is based upon work supported by the National Science Foundation under Grant DMS-1007164.

Here  $\text{ev}_i^*$  is the pull-back of cohomology classes from  $X$  to  $X_{0,n,d}$  by the evaluation map at the  $i$ -th marked point, and  $\psi_i$  is the 1st Chern class of the line bundle over  $X_{0,n,d}$  formed by cotangent lines to the curves at the  $i$ -th marked point.

Following [8], we embed the graph of the differential of  $\mathcal{F}$  into the *symplectic loop space*  $\mathcal{H}$ . By definition, it consists of formal  $Q$ -series whose coefficients are Laurent series in one indeterminate  $z$  with vector coefficients from  $H^*(X, \mathbb{Q})$ .

The “loop space”  $\mathcal{H}$  (which is actually a  $\mathbb{Z}_2$ -graded module over the Novikov ring  $\mathbb{Q}[[Q]]$ ) is equipped with the  $\mathbb{Q}[[Q]]$ -valued even symplectic form

$$\Omega(f, g) := \text{Res}_{z=0}(f(-z), g(z)) dz,$$

where  $(\cdot, \cdot)$  is the Poincaré pairing (i.e.  $(a, b) = \int_X ab = \langle a, 1, b \rangle_{0,3,0}$ ). Decomposing  $\mathcal{H}$  into the sum  $\mathcal{H}_+ \oplus \mathcal{H}_-$  of complementary Lagrangian subspaces (by the standard splitting of a Laurent series into the sum of the power  $z$ -series, and the polar part), we identify  $\mathcal{H}$  with  $T^*\mathcal{H}_+$ . Translating the origin in  $\mathcal{H}_+$  from 0 to  $-1z$  (the operation, referred to as the *dilatón shift*), we embed the graph of  $d\mathcal{F}$  into  $\mathcal{H}$  as a Lagrangian submanifold. Explicitly (see [8]) it is given by the following *J-function*:

$$\mathcal{H}_+ \ni t \mapsto \mathcal{J}(t) := -z + t(z) + \sum_{n,d,\alpha} \frac{Q^d}{n!} \phi_\alpha \left\langle \frac{\phi^\alpha}{-z - \psi}, t(\psi), \dots, t(\psi) \right\rangle_{0,n,d},$$

where  $\{\phi_\alpha\}$  and  $\{\phi^\alpha\}$  are Poincaré-dual bases in  $H^*(X, \mathbb{Q})$ .

In fact, this construction leads to some (rather mild) divergence problem. To elucidate it, pick a graded basis  $\{\phi_\alpha\}$  in  $H^*(X, \mathbb{Q})$ , and assume that  $\phi_0 = 1$ , and  $\phi_\alpha$  with  $\alpha = 1, \dots, r = \text{rk } H^2(X)$  are integer degree-2 classes  $p_1, \dots, p_r$  taking non-negative values  $d_i := p_i(d)$  on degrees  $d \in \mathcal{M} \subset H_2(X)$  of holomorphic curves in  $X$ . Writing

$$t_k = \sum_{\alpha} t_{k,\alpha} \phi_\alpha = t_{k,0} 1 + t_{k,1} p_1 + \dots + t_{k,r} p_r + \text{the rest of the sum},$$

one can show (on the basis of string and divisor equations), that each  $Q^d$ -term in  $\mathcal{J}$  contains the factor  $e^{t_{0,0}/z}$  (which, unless expanded in powers of  $t_{0,0}$ , does not fit the space of formal Laurent series in  $z$ ), and besides comes with the factor  $e^{\sum_i d_i t_{0,i}}$  (which is not defined over  $\mathbb{Q}$ ). Also, as it follows from *dilatón equation*, with respect to the variable  $t_{1,0}$ , the series has convergence radius 1. It follows from dimensional considerations that the rest of each  $Q^d$ -term is a polynomial in  $1/z$  and in (finitely many of) the coefficients of the power series  $t(z)$ .

There are several ways to handle the problems. In this paper, we will ignore the convergence properties by interpreting the J-function (and other geometric generating objects) in the sense of formal geometry. That is,  $t \mapsto \mathcal{J}(t)$  is considered as the germ at  $-z$  of a formal series in the components of the vector variables  $t_k$  with coefficients which belong to the symplectic loop space.

We will take  $\mathbb{Q}[[Q_1, \dots, Q_r]]$  on the role of the Novikov ring, and represent  $Q^d$  by the monomial  $Q_1^{d_1} \dots Q_r^{d_r}$ . By virtue of the  $Q$ -adic convergence, one can specialize formal variables  $t_{k,\alpha}$  to their values in the Novikov ring, taken from its maximal ideal (which is necessary indeed in the case of  $t_{0,0}$ ,  $t_{0,i}$ , and  $t_{1,0}$ ). One can also make formal changes of the variables  $\{t_{k,\alpha}\}$  with coefficients in the Novikov ring.

**Theorem 1.** *Let  $\sum_d I_d Q^d$ , where  $I_d(z, z^{-1})$  are cohomology-valued Laurent  $z$ -series, represent a point on the graph of  $d\mathcal{F}$  in  $\mathcal{H}$ , and let  $\Phi_\alpha$  be polynomials in  $p_1, \dots, p_r$  (or, more generally, power  $z$ -series, with coefficients polynomial in  $p_1, \dots, p_r$ ). Then the family*

$$I(\tau) := \sum_d I_d Q^d \exp \left\{ \frac{1}{z} \sum_\alpha \tau_\alpha \Phi_\alpha(p_1 - zd_1, \dots, p_r - zd_r) \right\}$$

lies on the graph of  $d\mathcal{F}$ .

Furthermore, for arbitrary scalar power series  $c_\alpha(z) = \sum_{k \geq 0} \tau_{\alpha,k} z^k$ , the linear combination  $\sum_\alpha c_\alpha(z) z \partial_{\tau_\alpha} I$  of the derivatives also lies on the graph.

Moreover, in the case when  $p_1, \dots, p_r$  generate the entire cohomology algebra  $H^*(X, \mathbb{Q})$ , and  $\Phi_\alpha$  represent a linear basis, such linear combinations comprise the whole graph.

**Example 1.** Take  $X = \mathbb{C}P^{n-1}$ ,  $p$  to denote the hyperplane class (and hence  $p^n = 0$ ), and  $\Phi_i = p^i$ ,  $i = 0, \dots, n-1$ , for a basis in  $H^*(X, \mathbb{Q})$ . The “small J-function”

$$(-z) \sum_{d \geq 0} \frac{Q^d}{(p-z)^n (p-2z)^n \dots (p-dz)^n}$$

is known (see, for instance, [6]) to represent a point on the graph of  $d\mathcal{F}$ . It follows from Theorem 1 that the whole graph is comprised by

$$(-z) \sum_{d \geq 0} \frac{Q^d e^{(\tau_0 + \tau_1(p-dz) + \dots + \tau_{n-1}(p-dz)^{n-1})/z} \sum_{i=0}^{n-1} c_i(z) (p-dz)^i}{(p-z)^n (p-2z)^n \dots (p-dz)^n},$$

when  $c_i(z)$  run arbitrary power series. More explicitly, one equates the power  $z$ -series part of this formula to  $-z + t(z)$ :

$$\sum_{i=0}^{n-1} (\tau_i - z c_i(z)) p^i + (Q\text{-adically small terms}) = -z + \sum_{i=0}^{n-1} p^i \sum_{k=0}^{\infty} t_{k,i} z^k,$$

and expresses  $\tau_i$  and all coefficients of the series  $c_i$  (here  $c_0(0)$  needs to lie in a formal neighborhood of 1) in terms of  $\{t_{k,i}\}$ . Substituting these expressions back into the formula, one obtains (according to Theorem 1) the standard form of the J-function for  $\mathbb{C}P^{n-1}$ .

In K-theoretic version of GW-theory of a compact Kähler manifold  $X$ , the genus-0 descendent potential  $\mathcal{F}^K$  is defined by the same formula as its cohomological counterpart:

$$\mathcal{F}^K(t) = \sum_{d \in \mathcal{M}} \sum_{n=0}^{\infty} \frac{Q^d}{n!} \langle t(L, L^{-1}), \dots, t(L, L^{-1}) \rangle_{0,n,d}^K,$$

using the correlators

$$\langle \Phi_1 L^{k_1}, \dots, \Phi_k L^{k_n} \rangle_{0,n,d}^K := \chi(X_{0,n,d}; \mathcal{O}^{virt} \otimes \text{ev}_1^*(\Phi_1) L_1^{k_1} \dots \text{ev}_n^*(\Phi_n) L_n^{k_n}).$$

Here  $\chi$  is the holomorphic Euler characteristic (on  $X_{0,n,d}$ ),  $\mathcal{O}^{virt}$  is the virtual structure sheaf introduced by Yuan-Pin Lee [14],  $\Phi_i \in K^0(X)$  is a holomorphic vector bundle on  $X$ ,  $L_i^{k_i}$ ,  $k_i \in \mathbb{Z}$ , is the  $k_i$ th tensor power of the line bundle formed by the cotangent lines to the curves at the  $i$ th marked point. The input  $t$  in  $\mathcal{F}^K$  is a Laurent polynomial of  $L$  with coefficients in the K-ring of  $X$ .

Adapting the symplectic loop space formalism, we embed the graph of  $d\mathcal{F}^K$  as a Lagrangian submanifold into the “space”  $\mathcal{K}$  consisting of power  $Q$ -series whose coefficients are rational functions in one indeterminate,  $q$ , which take vector values in  $K^0(X) \otimes \mathbb{Q}$ . Each rational function of  $q$  is uniquely written as the sum of a Laurent polynomial and a rational function having no pole at  $q = 0$  and vanishing at  $q = \infty$ . The space  $\mathcal{K}$  is thereby decomposed into the direct sum of two subspaces,  $\mathcal{K}_+$  and  $\mathcal{K}_-$  respectively. They are Lagrangian with respect to the symplectic form

$$\Omega^K(f, g) = [\text{Res}_{q=0} + \text{Res}_{q=\infty}] (f(q), g(q^{-1})^K \frac{dq}{q}),$$

where  $(\cdot, \cdot)^K$  stands for the K-theoretic Poincaré pairing:

$$(A, B)^K = \chi(X; A \otimes B) = \int_X \text{ch}(A) \text{ch}(B) \text{td}(T_X).$$

Using this Lagrangian polarization to identify  $\mathcal{K}$  with  $T^*\mathcal{K}_+$ , and applying the dilaton shift  $1 - q$ , we identify the graph of  $d\mathcal{F}^K$  with a submanifold in  $\mathcal{K}$ , which is described explicitly by the  $J$ -function

$$\mathcal{K}_+ \ni t \mapsto \mathcal{J}^K(t) = 1 - q + t(q, q^{-1}) + \sum_{n,d,\alpha} \frac{Q^d}{n!} \Phi_\alpha \left\langle \frac{\Phi^\alpha}{1 - qL}, t(L, L^{-1}), \dots, t(L, L^{-1}) \right\rangle_{0,n+1,d}^K.$$

Here  $\Phi_\alpha$  and  $\Phi^\alpha$  run Poincaré-dual bases of  $K^0(X)$ . Similar to the cohomological case, we consider  $\mathcal{J}^K$  as a germ (at  $1 - q$ ) of a formal section of  $T^*\mathcal{H}_+$ . That is, it is a formal series of the coordinates  $t_{k,\alpha}$  (on the space of vector Laurent polynomials  $\sum_{k,\alpha} t_{k,\alpha} \Phi_\alpha q^k$ ), whose coefficients are  $Q$ -series with coefficients in rational functions of  $q$ .

Let  $P_1, \dots, P_r$  be line bundles over  $X$  such that  $c_1(P_i) = -p_i$ , i.e.  $d_i = -\int_d c_1(P_i)$ .

**Theorem 2.** *Let  $\sum_d I_d Q^d$  be a point in  $\mathcal{K}$ , lying on the graph of  $d\mathcal{F}^K$ , and let  $\Psi_\alpha$  be polynomials in  $P_1, \dots, P_r$  (with coefficients which could be Laurent polynomials in  $q$ ). Then the family*

$$I^K(\tau) = \sum_d I_d Q^d \exp\left\{ \frac{1}{1 - q} \sum_\alpha \tau_\alpha \Psi_\alpha(P_1 q^{d_1}, \dots, P_r q^{d_r}) \right\}$$

also lies on the graph.

Furthermore, for arbitrary scalar Laurent polynomials  $c_\alpha(q, q^{-1})$ , the linear combinations  $\sum_\alpha c_\alpha(q, q^{-1})(1 - q)\partial_{\tau_\alpha} I^K$  of the derivatives also lie on the graph.

Moreover, in the case when  $P_1, \dots, P_r$  generate the algebra  $K^0(X) \otimes \mathbb{Q}$ , and  $\Phi_\alpha$  form a linear basis in it, such linear combinations comprise the whole graph.

**Example 2.** Let  $X$  be  $\mathbb{C}P^{n-1}$ ,  $P = \mathcal{O}(-1)$  (and hence  $(1 - P)^n = 0$ ), and  $1, 1 - P, \dots, (1 - P)^{n-1}$  be the basis in  $K^0(X)$ . It was shown in [9] that the following series lies on the graph of  $d\mathcal{F}^K$ :

$$(1 - q) \sum_{d=0}^{\infty} \frac{Q^d}{(1 - Pq)^n (1 - Pq^2)^n \dots (1 - Pq^d)^n}.$$

It follows that the whole graph can be parameterized this way:

$$(1 - q) \sum_{d=0}^{\infty} \frac{Q^d e^{\sum_{i=0}^{n-1} \tau_i (1 - Pq^d)^i} / (1 - q) \sum_{i=0}^{n-1} c_i(q, q^{-1}) (1 - Pq^d)^i}{(1 - Pq)^n (1 - Pq^2)^n \dots (1 - Pq^d)^n}.$$

More explicitly, one equates the Laurent polynomial part of this formula to  $(1 - q) + t(q, q^{-1})$ :

$$\sum_{i=0}^{n-1} (1 - P)^i (\tau_i + (1 - q)c_i(q, q^{-1})) + \mathcal{O}(Q) = 1 - q + \sum_{k,i} t_{k,i} q^k (1 - P)^i$$

to express  $\tau_i$  and all coefficients of the Laurent polynomials  $c_i$  in terms of the variables  $\{t_{k,i}\}$ . Substituting these expressions back into the formula, one obtains the K-theoretic J-function of  $\mathbb{C}P^{n-1}$ .

**Remark.** For target spaces, whose 2nd cohomology multiplicatively generate the entire cohomology algebra, their cohomological and K-theoretic genus-0 GW-invariants are reconstructible from small degree data, as it is established by the reconstruction results of Kontsevich–Manin [13], Lee–Pandharipande [15], and Iritani–Milanov–Tonita [12]. Our results are closely related to them, and in a sense, explicate the reconstruction procedure.

**Added at revision.** A preliminary version of this paper was posted in May, 2014 to the author’s website. After that we learned that Theorem 1 appears: (a) in a toric context — in the earlier preprint [1], Section 5.4, by I. Ciocan-Fontanine and B. Kim, and (b) in a general context (though in a slightly less explicit form) — in the even earlier paper [11], Example 4.14, by H. Iritani. We are thankful to Ionut Ciocan-Fontanine for this communication.

## 2. PROOF OF THEOREM 1

Denote by  $\mathcal{L} \subset \mathcal{H}$  the dilaton-shifted graph of  $d\mathcal{F}$ .

**Step 1.** We begin by noting that modulo Novikov’s variables, the graph is known to have the form [8]

$$e^{-\tau/z} z \mathcal{H}_+,$$

where  $\tau = \sum_{\alpha} \tau_{\alpha} \phi_{\alpha}$  runs the cohomology space of  $X$ .

**Step 2.** The actual graph  $\mathcal{L}$  is known (see Appendix 2 in [4]) to have the form

$$S_{\tau}^{-1}(z) z \mathcal{H}_+,$$

where  $\tau \mapsto S_{\tau}(z)$  is a certain family of matrices (whose entries also depend on Novikov’s variables), which has the following properties. Firstly, it is an  $1/z$ -series:  $S = I + \mathcal{O}(1/z)$ . Secondly, it belongs to the “twisted” loop group:  $S^{-1}(z) = S^*(-z)$ , where “\*” denotes transposition with respect to the Poincaré pairing. Thirdly, it is a

fundamental solution to Dubrovin's connection on the tangent bundle of the cohomology space of  $X$ :

$$z\partial_\alpha S = \phi_\alpha \bullet S,$$

where  $\partial_\alpha := \partial/\partial\tau_\alpha$ , and  $\phi_\alpha \bullet$  is the matrix of quantum multiplication by  $\phi_\alpha$  (it depends on the application point  $\tau$  and on Novikov's variables, but not on  $z$ , and is self-adjoint). Finally  $S$  is constrained by the *string* and *divisor* equations. Namely, assuming as before, that  $\{\phi_\alpha\}$  is a graded basis in cohomology, with  $\phi_0 = 1$  and  $\phi_1 = p_1, \dots, \phi_r = p_r$ , we have:

$$z\partial_0 S = S, \quad \text{and} \quad z\partial_i S = zQ_i\partial_{Q_i} S + Sp_i, \quad i = 1, \dots, r.$$

(Here  $p_i$  means the operator of multiplication by  $p_i$  in the classical cohomology algebra of  $X$ .)

Moreover, according to the ‘‘descendent–ancestor correspondence’’ theorem [4]  $S_\tau \mathcal{L}$  is tangent to  $\mathcal{H}_+$  along  $z\mathcal{H}_+$ . This shows that  $\mathcal{L}$  is an *overruled Lagrangian cone*. By definition, this means that tangent spaces  $T_\tau$  to  $\mathcal{L}$  (which are  $S_\tau^{-1}\mathcal{H}_+$ ) are tangent to  $\mathcal{L}$  exactly along  $zT_\tau$ . We refer to [4, 8] for a more detailed discussion of this notion.

**Step 3.** Let  $\mathcal{D}$  be the algebra of differential operators in Novikov's variables. It follows from the above divisor equations for  $S$  that *tangent spaces*  $T_\tau = S_\tau^{-1}\mathcal{H}_+$  to  $\mathcal{L}$  are  $\mathcal{D}$ -modules with respect to the action of  $\mathcal{D}$  defined by the multiplication operators  $Q_j$  and differentiation operators  $zQ_i\partial_{Q_i} - p_i$ , where  $p_i$  stands for multiplication by  $p_i$  in the classical cohomology algebra of  $X$ . Consequently, the same is true about the *ruling spaces*  $zT_\tau$ .

Indeed, since  $S^{-1}(-z) = S^*(z)$ , and  $p_i^* = p_i$ , we have:

$$(p_i + zQ_i\partial_{Q_i})S^{-1}(-z) = (Sp_i + zQ_i\partial_{Q_i}S)^* = z\partial_i S^* = z\partial_i S^{-1}(-z).$$

Here  $S = S_\tau$  depends on  $\tau \in H^*(X)$  and independently on  $Q$ . Now fix a value of  $\tau = \tau(Q)$ , and consider  $f \in zT_\tau \subset \mathcal{L}$ , that is:  $f = S_\tau^{-1}h$ , where  $h \in z\mathcal{H}_+$ . Then

$$(zQ_i\partial_{Q_i} - p_i)f = z\partial_i S_\tau^{-1}h + \sum_\alpha (Q_i\partial_{Q_i}\tau_\alpha)z\partial_\alpha S_\tau^{-1}h + zS_\tau^{-1}(Q_i\partial_{Q_i}h),$$

where each summand on the right side lies in  $zT_\tau$ .

We arrive at the following conclusion.<sup>1</sup>

---

<sup>1</sup>This is a variant of Lemma from the proof of Quantum Lefschetz Theorem in Section 8 of [4]. As we've recently realized, the proof of it given in [4] was incorrect. Apparently, the argument was first corrected in [3] within the proof of the orbifold version of the Quantum Lefschetz Theorem.

**Lemma.** *Let  $\Phi$  be a polynomial expression in  $zQ_i\partial_{Q_i} - p_i$ . Then the flow  $f \mapsto e^{\epsilon\Phi/z}f$  preserves  $\mathcal{L}$ .*

**Proof.** If  $T$  denotes the tangent space to  $\mathcal{L}$  at  $f \in zT$ , then  $\Phi f/z \in T$ , i.e. the linear vector field on  $\mathcal{H}$ :  $f \mapsto \Phi f/z$  is tangent to  $\mathcal{L}$ .

**Remark.** Since we are using differentiations in  $Q$ , it is counter-intuitive to think of Novikov's variables as constants. In fact one can think of the symplectic loop space  $\mathcal{H}$  geometrically as the space of formal sections, over the spectrum of the Novikov ring, of the bundle whose fiber consists of Laurent  $z$ -series with vector coefficients. Likewise, the cone  $\mathcal{L} \subset \mathcal{H}$  consists of sections of the fibration whose fibers are overruled Lagrangian cones. The differential operators  $\Phi/z$  and their flows  $e^{\epsilon\Phi/z}$  act by linear transformations on the space of sections  $\mathcal{H}$ . In particular,  $g = e^{\epsilon\Phi/z}f$  is an  $\epsilon$ -family of sections  $Q \mapsto g(\epsilon, Q)$  of the fibration of overruled Lagrangian cones. One can choose any function  $Q \mapsto \epsilon(Q)$  and obtain section  $Q \mapsto g(\epsilon(Q), Q)$  lying in  $\mathcal{L}$ . We should note that it differs from  $e^{\epsilon(Q)\Phi/z}f$  since multiplication by  $\epsilon(Q)$  and  $\Phi$  do not commute.

**Step 4.** Write  $f = \sum_d f_d Q^d$ . Then

$$e^{\epsilon\Phi(\dots, p_i - zQ_i\partial_{Q_i}, \dots)/z} f = \sum_d f_d Q^d e^{\epsilon\Phi(\dots, p_i - z d_i, \dots)/z},$$

which according to Step 3 lies in  $\mathcal{L}$  whenever  $f$  does. Here one can consider  $\epsilon$  as a parameter, or take its value from the Novikov ring (or at least from its maximal ideal).

One obtains the first statement of Theorem 1 by replacing  $\epsilon\Phi$  with a linear combination  $\sum \tau_\alpha \Phi_\alpha$  of commuting differential operators.

The derivatives  $\partial_\alpha I(\tau)$  lie in the tangent space  $T$  to  $\mathcal{L}$  at  $I_\tau$ , and hence all linear combination  $\sum c_\alpha(z) z \partial_\alpha I(\tau)$ , where  $c_\alpha$  are scalar power  $z$ -series, lie in the same ruling space  $zT \subset \mathcal{L}$ .

When  $p_1, \dots, p_r$  generate the entire cohomology algebra of  $X$ , it follows from Step 1 that *modulo Novikov's variables*, such linear combinations comprise the whole of  $\mathcal{L}$ . Now the last statement of Theorem 1 follows the formal Implicit Function Theorem.

### 3. PROOF OF THEOREM 2

Let  $\mathcal{L}^K \subset \mathcal{K}$  denote the graph of  $d\mathcal{F}^K$ .

It is known (as explained in [10], Section 3) that  $\mathcal{L}^K$  is an overruled Lagrangian cone too. More precisely, as in the case of quantum cohomology theory, there is a family  $\tau \mapsto S_\tau(q, Q)$  of matrices depending on  $\tau \in K^*(X)$  which transform  $\mathcal{L}^K$  to  $S_\tau \mathcal{L}^K$  tangent to  $\mathcal{K}_+$



along  $(1 - q)\mathcal{K}_+$ . As a consequence,  $\mathcal{L}^K$  is a cone whose tangent spaces  $T_\tau = S_\tau^{-1}\mathcal{K}_+$  are  $\mathbb{Q}[q, q^{-1}]$  modules, and are tangent to  $\mathcal{L}^K$  exactly along  $(1 - q)T_\tau$ . Theorem 2 is based on the property of the tangent and ruling spaces of  $\mathcal{L}^K$  to be  $D_q$ -modules. Let us recall, following [10], how this is proved. Another approach to this result is contained in [12].

The main result of [10] (together with [16, 17]) is the Quantum Hirzebruch–Riemann–Roch Theorem which completely characterizes  $\mathcal{L}^K$  in terms of  $\mathcal{L}$  in the following, “adelic” way. For each complex value  $\zeta$  of  $q \neq 0$ , one introduces the localization space  $\mathcal{K}^\zeta$  which consists of series in  $Q$  whose coefficients are vectors in  $K^0(X) \otimes \mathbb{Q}(\zeta)$  and formal Laurent series in  $1 - q\zeta$ . The *adelic map*

$$\mathcal{K} \rightarrow \widehat{\mathcal{K}} := \prod_{\zeta} \mathcal{K}^\zeta$$

assigns to a rational function  $f$  of  $q$  the collection  $(f^{(\zeta)})$  of its Laurent series expansions (one at each  $q = \zeta^{-1}$ ).

Next, in each  $\mathcal{K}^\zeta$ , a certain cone  $\mathcal{L}^\zeta$  is described. For  $\zeta$  which is not a root of 1,  $\mathcal{L}^\zeta = \mathcal{K}_+^\zeta$ , the space of power series in  $1 - q\zeta$ . For  $\zeta = 1$ ,  $\mathcal{L}^1 \subset \mathcal{K}^1$  is the graph of the differential of  $\mathcal{F}^{fake}$ , the genus-0 descendent potential of *fake* quantum K-theory (studied in [8, 5, 2]). For  $\zeta \neq 1$ , which is a primitive  $m$ th root of 1,  $\mathcal{L}^\zeta$  is a certain linear subspace originating in a certain fake twisted quantum K-theory with the orbifold target space  $X/\mathbb{Z}_m$  (see [10] for more detail).

The adelic characterization of  $\mathcal{L}^K$  says that  $f \in \mathcal{L}^K$  if and only if  $f^{(\zeta)} \in \mathcal{L}^\zeta$  for each  $\zeta$ .

Furthermore,  $\mathcal{L}^\zeta$  have the following description in terms of the cone  $\mathcal{L} \subset \mathcal{H}$  of quantum cohomology theory.

First, the *quantum Chern character* defines an isomorphism  $\text{qch} : \mathcal{K}^1 \rightarrow \mathcal{H}^{even}$ . By definition,  $\text{qch}$  acts by the usual Chern character on the coefficients of Laurent  $q - 1$ -series, preserves Novikov’s variables, and transforms  $q$  into  $e^z$ . According to the “quantum HRR theorem” in *fake* quantum K-theory [2, 5],

$$\mathcal{L}^1 = \text{qch}^{-1} \Delta \mathcal{L}, \quad \text{where } \Delta \sim \prod_{\text{Chern roots } x \text{ of } T_X} \prod_{r=1}^{\infty} \frac{x - rz}{1 - e^{-x+rz}}.$$

Here  $\sim$  means taking the “Euler–Maclaurin asymptotic” of the right hand side. We won’t remind the reader what it is (see, for instance, [4, 10]), but note that (just as the expression on the right hand side suggests), it is multiplication by a series in  $z^{\pm 1}$  built of operators of multiplication in classical cohomology algebra of  $X$ , but *independent of Novikov’s variables*. As a consequence, all tangent and ruling spaces

of the overruled Lagrangian cone  $\mathcal{L}^{fake}$  are  $\mathcal{D}$ -modules (just like those of  $\mathcal{L}$  are).

Then, when  $\zeta \neq 1$  is a primitive  $m$ th root of 1, one can give the following (somewhat clumsy) description of  $\mathcal{L}^\zeta$ . On the cone  $\mathcal{L}^K$ , there is the point, denoted  $\mathcal{J}(0)$  which corresponds to the input  $t = 0$ . It is called the “small J-function,” and modulo  $\mathcal{K}_-$ , it is congruent to the dilaton shift  $1 - q$ . Expanding  $\mathcal{J}(0)$  into a Laurent series in  $q - 1$ , we obtain the corresponding point  $\mathcal{J}(0)^{(1)}$  in  $\mathcal{L}^{fake}$ . The tangent space to  $\mathcal{L}^{fake}$  at  $\mathcal{J}(0)^{(1)}$  has the form

$$\Delta(z)S_{\tau(Q)}^{-1}(z, Q)\mathcal{H}_+^{even}, \text{ where } z = \log q,$$

and  $S_\tau$  is the  $S$ -matrix of the cohomological theory computed at a certain value  $\tau = \tau(Q)$  (characterized by the application point  $\mathcal{J}(0)^{(1)}$ ). In this notation,  $f \in \mathcal{L}^\zeta$  if and only if for some  $h \in \mathcal{H}_+^{even}$

$$\text{qch}(\nabla_\zeta f(q^{1/m}/\zeta)) = \left( \Psi^m \Delta(mz)S_{\tau(Q^m)}^{-1}(mz, Q^m)\Psi^{1/m} \right) h,$$

where

$$\nabla_\zeta = e^{-\sum_{k>0} \left( \frac{\Psi^k(T_X^*)}{k(1-\zeta^{-k}q^{k/m})} - \frac{\Psi^{km}(T_X^*)}{k(1-q^{km})} \right)},$$

and  $\Psi^k$  are the Adams operations  $K^0(X) \rightarrow \mathcal{K}^0(X)$  acting (by way of the Chern isomorphism) on cohomology classes of degree  $2r$  as multiplication by  $k^r$ .

Let  $P_1, \dots, P_r$  be line bundles on  $X$  such that  $c_1(P_i) = -p_i$ , and let  $\mathcal{D}_q$  be the algebra of finite-difference operators in Novikov’s variables. By definition, it acts on  $\mathcal{K}$  by the “translation” operators  $P_i q^{Q_i \partial_{Q_i}} = \exp(-p_i + (\log q)Q_i \partial_{Q_i})$  and multiplications by  $Q_j$ . Let us show that  $\mathcal{L}^\zeta$  is a  $\mathcal{D}_q$ -module.

Indeed, first note that that  $\nabla_m$  and  $\Delta$  commute with  $\mathcal{D}$  (and hence with  $\mathcal{D}_q$ ). Next, on functions of  $Q^m$ , we have

$$\zeta^{-Q_i \partial_{Q_i}} = \zeta^{-mQ_i^m \partial_{Q_i^m}} = (\zeta^{-m})^{Q_i^m \partial_{Q_i^m}} = 1.$$

Therefore

$$(q^{1/m}/\zeta)^{Q_i \partial_{Q_i}} e^{-p_i} = q^{Q_i^m \partial_{Q_i^m}} e^{-p_i} = e^{-p_i + zQ_i^m \partial_{Q_i^m}}.$$

Since  $p_i \Psi^m = \Psi^m p_i / m$ , the operator  $zQ_i^m \partial_{Q_i^m} - p_i$ , when commuted across  $\Psi^m$ , becomes  $zQ_i^m \partial_{Q_i^m} - p_i / m$ . By the divisor equations for  $S$ , we have:

$$(zQ_i^m \partial_{Q_i^m} - p_i / m)S_\tau^{-1}(mz, Q^m) = z\partial_i S_\tau^{-1}(mz, Q^m).$$

The remaining part of the computation (such as differentiation in  $Q$  hidden in  $\tau = \tau(Q^m)$ ) works out the same way as in the cohomological

case. It is also essential here that  $\mathcal{H}_+^{even}$  is invariant under any differential of finite difference operators, including  $\zeta^{Q_i \partial_{Q_i}}$ .

As it was explained in [10], the adelic characterization of  $\mathcal{L}^K$  now implies that all tangent spaces  $T_\tau$  to  $\mathcal{L}^K$  (as well as the ruling subspaces  $(1-q)T_\tau \subset \mathcal{L}^K$  of the cone) are  $\mathcal{D}_q$ -modules.

Indeed, the whole space  $\mathcal{K}$  is  $\mathcal{D}_q$ -invariant. If  $f \in \mathcal{K}$  lies in a ruling space  $(1-q)T_f \subset \mathcal{L}^K$ , then the adelic components  $f^{(\zeta)}$  lie in  $\mathcal{L}^\zeta$ . By the previous discussion,  $P_i q^{Q_i \partial_{Q_i}} f^{(\zeta)} \in \mathcal{L}^\zeta$ . Therefore, by the adelic characterization,  $P_i q^{Q_i \partial_{Q_i}} f \in (1-q)T_f$ .

The proof of Theorem 2 proceeds now the same way as that of Theorem 1. If  $\Psi(\dots, P_i q^{Q_i \partial_{Q_i}}, \dots)$  is a polynomial expression in the translation operators, then the linear vector field on  $\mathcal{K}$  given by  $f \mapsto \Psi f / (1-q)$  is tangent to the cone  $\mathcal{L}^K$ , and therefore the flow  $f \mapsto e^{\epsilon \Psi / (1-q)} f$  preserves  $\mathcal{L}^K$ .

Decomposing  $f$  into  $Q$ -series  $\sum_d f_d Q^d$ , we find that

$$e^{\epsilon \Psi / (1-q)} f = \sum_d f_d Q^d e^{\epsilon \Psi(\dots, P_i q^{d_i}, \dots) / (1-q)}.$$

Replacing  $\epsilon \Psi$  with a linear combination  $\sum \tau_\alpha \Psi_\alpha$  of finite difference operators, one concludes that the family  $\tau \mapsto I^K(\tau)$  (introduced in Theorem 2) lies in  $\mathcal{L}^K$ . The derivatives  $\partial_\alpha I(\tau)$  lie in the tangent space  $T$  to  $\mathcal{L}^K$  at  $I^K(\tau)$ . Since  $T$  is a module over  $\mathbb{Q}[q, q^{-1}]$ , and  $(1-q)T \subset \mathcal{L}^K$ , one finds that  $\sum c_\alpha(q, q^{-1})(1-q)\partial_\alpha I^K(\tau)$  also lie in  $\mathcal{L}^K$ . Finally, assuming that  $P_1, \dots, P_r$  generate  $K^0(X)$ , one derives that such linear combinations comprise the whole of  $\mathcal{L}^K$  by checking this statement modulo Novikov's variables, and employing the formal Implicit Function Theorem.

#### 4. FURTHER IMPLICATIONS AND GENERALIZATIONS

**A. Birkhoff's factorization and mirror maps.** When  $H^*(X, \mathbb{Q})$  is generated by the degree-2 classes  $p_1, \dots, p_r$ , Theorems 1 and 2 can be reformulated as the following reconstruction results for the ‘‘S-matrix.’’ Starting with polynomials  $\Phi_\alpha(p)$  representing a basis in  $H^*(X, \mathbb{Q})$ , and with a point  $\sum I_d Q^d$  on the cone  $\mathcal{L}$ , one obtains a family of such points

$$I(\tau) = \sum I_d(z, z^{-1}) Q^d e^{-\sum \tau_\alpha \Phi_\alpha(p-dz)/z}.$$

We may assume here that  $I_0 = -z$ . The derivatives  $\partial_\alpha I$  form a  $\mathbb{Q}[[z]]$ -basis in the tangent spaces to  $\mathcal{L}$  (depending on  $\tau$ ). The square matrix  $U := [(\partial_\alpha I, \phi^\beta)]$ , formed by the components of these derivatives, can be factored into the product of  $U(z, z^{-1}) = V(z)W(z^{-1})$  of two matrix series (in the variables  $\tau$  and  $Q$ ), whose coefficients are power series

of  $z$  (on the left) and polynomial functions of  $z^{-1}$  (on the right). In the procedure (known as Birkhoff factorization), one may assume that  $W(0) = I$ . Then  $W$  coincides with  $S_\tau(-z^{-1})$  up to a change of variables  $\tau_\alpha \mapsto \tau_\alpha + \mathcal{O}(Q)$ , which generalizes the “mirror map” known in the mirror theory. To describe the change of variables, assume that  $\Phi_0 = 1$ , and note that the “first row” of  $W$  has the form

$$1 - z^{-1} \sum \Phi_\alpha(p)(\tau_\alpha + \mathcal{O}(Q)) + o(z^{-1}).$$

The mirror map is read off the  $z^{-1}$ -term of the expansion.

In quantum K-theory, a similar result is obtained by Birkhoff factorization  $U = VW$ , where the entries of  $U$ ,  $V$ , and  $W$  are built respectively of arbitrary rational functions, Laurent polynomials, and reduced rational functions of  $q$  regular at  $q = 0$ .

**B. Torus-equivariant theory.** It is often useful [7] to consider GW-invariants *equivariant* with respect to a torus action on  $X$ . The above results apply to this case without any significant changes. One only needs to extend the coefficient ring by the power series completion  $\mathbb{Q}[[\lambda]]$  of the coefficient ring of the equivariant theory. For example, when the torus  $T^n$  of diagonal matrices acts on  $X = \mathbb{C}P^{n-1} = \text{proj}(\mathbb{C}^n)$ , the  $T^n$ -equivariant cohomology algebra of  $X$  is described by the relation  $(p - \lambda_1) \cdots (p - \lambda_n) = 0$ . For the purpose of employing fixed-point localization, it is convenient to assume that the hyperplane class  $p$  localizes to each of the values  $\lambda_j$ . However, for the purpose of our proof it suffices to assume that  $\lambda_j$  are generators of the formal series ring  $\mathbb{Q}[[\lambda_1, \dots, \lambda_n]]$ , and obtain the following parameterization of the graph  $d\mathcal{F}$  in the  $T^n$ -equivariant GW-theory:

$$(-z) \sum_{d \geq 0} \frac{Q^d e^{(\tau_0 + \tau_1(p-dz) + \dots + \tau_{n-1}(p-dz)^{n-1})/z} \sum_{i=0}^{n-1} c_i(z)(p-dz)^i}{\prod_{j=1}^n (p - \lambda_j - z)(p - \lambda_j - 2z) \cdots (p - \lambda_j - dz)}.$$

Here the fractions  $1/(p - \lambda - rz)$  are to be interpreted as Laurent polynomials in  $z^{-1}$  modulo high powers of  $\lambda$ .

**C. Twisted GW-invariants.** Our results also extend to the case of twisted GW-invariants in the sense of [4] (e.g. “local” ones, i.e. GW-invariants of the non-compact total space of a vector bundle  $E \rightarrow X$ , or GW-invariants of the “super-bundle”  $\Pi E \rightarrow X$ , which in genus 0 are closely related to those of the zero locus of a section of  $E$ ). In such cases, to remove degenerations caused by non-compactness, one needs to act equivariantly, equipping  $E$  with the fiberwise scalar circle action. To adapt our arguments to this case, it suffices to work over the coefficient ring  $H^*(BS^1, \mathbb{Q}) = \mathbb{Q}[\lambda]$  localized to  $\mathbb{Q}((\lambda))$ . For example,

the graph of  $d\mathcal{F}$  of the local theory on the total space  $E$  of degree  $l$  line bundle over  $\mathbb{C}P^{n-1}$ , for  $l > 0$  obtains the following description:

$$(-z) \sum_{d \geq 0} \frac{Q^d e^{(\tau_0 + \tau_1(p-dz) + \dots + \tau_{n-1}(p-dz)^{n-1})/z} \sum_{i=0}^{n-1} c_i(z)(p-dz)^i}{\prod_{r=0}^{ld} (lp + \lambda - rz) \prod_{r=1}^d (p - rz)^n}.$$

Here  $p^n = 0$ , while the fractions  $1/(lp + \lambda - rz)$  should be expanded as power  $z$ -series, whose coefficients, however, can be Laurent series of  $\lambda$ .

## REFERENCES

- [1] I. Ciocan-Fontanine, B. Kim. *Big J-functions*. Preprint, 23pp., arXiv: 1401.7417
- [2] T. Coates. *Riemann–Roch theorems in Gromov–Witten theory*. PhD thesis, 2003, available at <http://math.harvard.edu/~tomc/thesis.pdf>
- [3] A. Corti, T. Coates, H. Iritani, H.-H. Tseng. *Computing twisted genus-zero Gromov–Witten invariants*. Duke Mathematical Journal, 147 (2009), no. 3, 377–438.
- [4] T. Coates, A. Givental. *Quantum Riemann–Roch, Lefschetz and Serre*. Ann. of Math. (2), 165 (2007), 15–53.
- [5] T. Coates, A. Givental. *Quantum cobordisms and formal group laws*. The unity of mathematics, 155–171, Progr. Math., 244, Birkhäuser Boston, Boston, MA, 2006.
- [6] A. Givental. *Homological geometry I. Projective hypersurfaces*. Selecta Math. (New Series) 1 (1995), 325–345.
- [7] A. Givental. *Equivariant Gromov–Witten invariants*. IMRN, 1996, 613–663.
- [8] A. Givental. *Symplectic geometry of Frobenius structures*. Frobenius manifolds, Aspects Math., E36, Vieweg, Wiesbaden, 2004, pp. 91–112.
- [9] A. Givental, Y.-P. Lee. *Quantum K-theory on flag manifolds, finite difference Toda lattices and quantum groups*. Invent. Math. 151, 193–219, 2003.
- [10] A. Givental, V. Tonita. *The Hirzebruch–Riemann–Roch theorem in true genus-0 quantum K-theory*. Preprint, arXiv:1106.3136
- [11] H. Iritani. *Quantum D-modules and generalized mirror transformations*. Topology 47 (2008), no. 4, 225 - 276.
- [12] H. Iritani, T. Milanov, V. Tonita. *Reconstruction and convergence in quantum K-theory via difference equations*. Preprint, 36 pp., arXiv:1309.3750
- [13] M. Kontsevich, Yu. Manin. *Gromov–Witten classes, quantum cohomology, and enumerative geometry*. In “Mirror Symmetry II,” AMS/IP Stud. Adv. Math., v. 1, AMS, Providence, RI, 1997, pp. 607–653.
- [14] Y.-P. Lee. *Quantum K-theory I. Foundations*. Duke Math. J. 121 (2004), no. 3, 389–424.
- [15] Y.-P. Lee, R. Pandharipande. *A reconstruction theorem in quantum cohomology and quantum K-theory*. Amer. J. Math. 126, no. 6 (2004): 1367–1379.
- [16] V. Tonita. *A virtual Kawasaki Riemann–Roch formula*. Pacif. J. Math. 268 (2014), no. 1, 249–255. arXiv:1110.3916.
- [17] V. Tonita. *Twisted orbifold Gromov–Witten invariants*. Nagoya Math. J. 213 (2014), 141–187, arXiv:1202.4778