Wall-crossing from quantum multi-centered BPS black holes

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based on work with J. Manschot and A. Sen,

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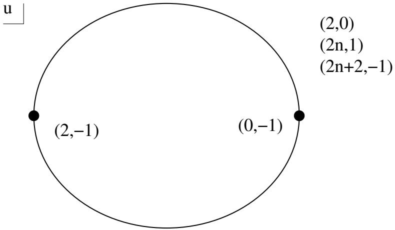
Introduction I

- In $D = 4$, $N = 2$ supersymmetric field and string theories, the exact spectrum of BPS states can often be determined at weak coupling, and extrapolated to strong coupling.
- E.g., in pure $SU(2)$ Seiberg-Witten theory,



Seiberg Witten; Bilal Ferrari

Introduction II

- In following the BPS spectrum from weak to strong coupling, one must be wary of two issues:
  - short multiplets may pair up into a long multiplet,
  - single-particle states may decay into multi-particle states.
- The first issue can be avoided by considering a suitable index $\Omega(\gamma, t)$, designed such that contributions from long multiplets cancel. $\Omega(\gamma, t)$ is then a piecewise constant function of the charge vector γ and couplings/moduli t.
- To deal with the second issue, one must understand how $\Omega(\gamma, t)$ changes across a wall of marginal stability W, where a single-particle state with charge γ can decay into a multi-particle state with charges $\{\alpha_i\}$, such that $\gamma = \sum_i \alpha_i$.

Introduction III

- Initial progress came from physics, by noting that single-particle states (in a certain limit) can be represented by multi-centered solitonic solutions. Those exist only on one side of the wall and decay into the continuum of multi-particle states on the other side.
- The simplest decay $\gamma \to \gamma_1 + \gamma_2$, where γ_1, γ_2 are primitive charge vectors, involves only two-centered configurations, whose index is easily computed:

$$\Delta\Omega(\gamma \to \gamma_1 + \gamma_2) = (-1)^{\gamma_{12}+1} \, |\gamma_{12}| \, \Omega(\gamma_1) \, \Omega(\gamma_2)$$

Denef Moore

- In the non-primitive case $\gamma = M\gamma_1 + N\gamma_2$ where $M, N > 1$, many multi-centered configurations in general contribute, and computing their index is non-trivial.

Introduction IV

- A general answer to this problem has come from the mathematical study of the wall-crossing properties of (generalized) Donaldson-Thomas invariants for Calabi-Yau three-folds, believed to be the mathematical translation of the BPS index $\Omega(\gamma)$ in type IIA CY vacua.
- Notably, Kontsevich & Soibelman (KS) and Joyce & Song (JS) gave two different-looking formulae for $\Delta\Omega(\gamma \to M\gamma_1 + N\gamma_2)$.
- The KS formula has already been derived/interpreted in several ways, e.g. by considering instanton corrections to the moduli space metric in 3D after compactification on a circle.

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- Our goal will be to derive new wall-crossing formulae, based on the quantization of multi-centered solitonic configurations.

Outline

1. Introduction
2. Generalities, and a Boltzmannian view of wall-crossing
3. The Kontsevich-Soibelman-Joyce-Song formula
4. Non-primitive wall-crossing from localization
5. Away from the wall

Outline

1. Introduction
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Preliminaries I

- We consider $\mathcal{N}=2$ supergravity in 4 dimensions (this includes field theories with rigid $\mathcal{N}=2$ as a special case). Let $\Gamma = \Gamma_e \oplus \Gamma_m$ be the lattice of electric and magnetic charges, with antisymmetric (Dirac-Schwinger- Zwanziger) integer pairing

$$\langle \gamma, \gamma' \rangle = \langle (p^\Lambda, q_\Lambda), (p'^\Lambda, q'_\Lambda) \rangle \equiv q_\Lambda p'^\Lambda - q'_\Lambda p_\Lambda \in \mathbb{Z}$$

- BPS states preserve 4 out of 8 supercharges, and saturate the bound $M \geq |Z(\gamma, t^a)|$ where $Z(\gamma, t^a) = e^{\mathcal{K}/2}(q_\Lambda X^\Lambda - p^\Lambda F_\Lambda)$ is the central charge/stability data.
- We are interested in the index $\Omega(\gamma; t^a) = \mathrm{Tr}_{\mathcal{H}'_\gamma(t^a)}(-1)^{2J_3}$ where $\mathcal{H}'_\gamma(t^a)$ is the Hilbert space of one-particle states with charge $\gamma \in \Gamma$ in the vacuum with vector moduli t^a.

Preliminaries II

- The BPS invariants $\Omega(\gamma; t^a)$ are locally constant functions of t^a, but may jump across codimension-one subspaces

$$W(\gamma_1, \gamma_2) = \{t^a \,/\, \arg[Z(\gamma_1)] = \arg[Z(\gamma_2)]\}$$

  where γ_1 and γ_2 are two primitive (non-zero) vectors such that $\gamma = M\gamma_1 + N\gamma_2$, $M, N \geq 1$. Assume for definiteness that $\gamma_{12} < 0$.
- We choose γ_1, γ_2 such that $\Omega(\gamma; t^a)$ has support only on the positive cone (root basis property)

$$\tilde{\Gamma}: \quad \{M\gamma_1 + N\gamma_2, \quad M, N \geq 0, \quad (M, N) \neq (0, 0)\} \; .$$

- Let $c_\pm$ be the chamber in which $\arg(Z_{\gamma_1}) \gtrless \arg(Z_{\gamma_2})$. Our aim is to compute $\Delta\Omega(\gamma) \equiv \Omega^-(\gamma) - \Omega^+(\gamma)$ as a function of $\Omega^+(\gamma)$ (say).

Wall-crossing from semi-classical solutions I

- Assume that $M(\gamma_1), M(\gamma_2) \gg \Lambda, m_P$. Single-particle states which are potentially unstable across W are described by classical configurations with n centers of charge $\alpha_i = M_i\gamma_1 + N_i\gamma_2 \in \tilde{\Gamma}$, satisfying $(M, N) = \sum_i (M_i, N_i)$.
- Such bound states exist only on one side of the wall, and the distances r_{ij} diverge at the wall. Across the wall, the single-particle bound state has decayed into the continuum of multi-particle states. $\Delta\Omega(\gamma)$ is given by the index of such configurations.
- *In addition, in either chamber, there may be multi-centered configurations whose charge vectors do not lie in $\tilde{\Gamma}$. However, they remain bound across W and do not contribute to $\Delta\Omega(\gamma)$.*

Wall-crossing from semi-classical solutions II

- In $\mathcal{N} = 2$ supergravity (and presumably also in $\mathcal{N} = 2$ Abelian gauge theories), the locations of the centers are constrained by

$$\sum_{j=1\dots n, j\neq i}^{n} \frac{\alpha_{ij}}{|\vec{r}_i - \vec{r}_j|} = c_i \,, \qquad \begin{cases} c_i = 2\,\mathrm{Im}\left[e^{-i\phi} Z(\alpha_i, t^a)\right] \\ \phi \equiv \arg[Z(\alpha_1 + \cdots \alpha_n, t^a)] \\ \alpha_{ij} \equiv \langle \alpha_i, \alpha_j \rangle \end{cases}$$

Denef

If all $\alpha_i \in \tilde{\Gamma}$, the constants c_i are given by $c_i = \Lambda \sum_{i\neq j} \alpha_{ij}$, with $\Lambda \to 0$ near the wall.

- After factoring out an overall translational mode, the solution space is (generically) a $(2n-2)$-dimensional symplectic manifold $(\mathcal{M}_n(\alpha_{ij}, c_i), \omega)$, with $\omega = \frac{1}{2} \sum_{i<j} \alpha_{ij} \sin\theta_{ij}\, \mathrm{d}\theta_{ij} \wedge \mathrm{d}\phi_{ij}$.

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Wall-crossing from semi-classical solutions III

- Up to issues of statistics, $\Delta\Omega(\gamma)$ is equal to the index of the SUSY quantum mechanics on $\mathcal{M}_n$, multiplied by the index $\Omega(\gamma_i)$ of the internal d.o.f. carried by each center.
- For primitive decay $\gamma \to \gamma_1 + \gamma_2$, the quantization of the phase space $(\mathcal{M}_2, \omega) = (S^2, \frac{1}{2}\gamma_{12} \sin\theta \, \mathrm{d}\theta \mathrm{d}\phi)$ reproduces the primitive WCF

$$\Delta\Omega(\gamma \to \gamma_1 + \gamma_2) = (-1)^{\gamma_{12}+1} \, |\gamma_{12}| \, \Omega^+(\gamma_1) \, \Omega^+(\gamma_2) \; ,$$

where $(-1)^{\gamma_{12}+1} \, |\gamma_{12}|$ is the index of the angular momentum multiplet of spin $j = \frac{1}{2}(\gamma_{12} - 1)$.

Wall-crossing from semi-classical solutions IV

- This generalizes to semi-primitive wall-crossing $\gamma \to \gamma_1 + N\gamma_2$: unstable configurations consist of a halo of n_s particles of charge $s\gamma_2$, with total charge $\sum s n_s \gamma_2 = n\gamma_2$, orbiting around a core of charge $\gamma_1 + (N-n)\gamma_2$. The phase space is

$$\mathcal{M}_n = \prod_s (\mathcal{M}_2)^{n_s} / S_{n_s}$$

- Taking into account the Bose/Fermi statistics of the n_s identical particles, one arrives at a Mac-Mahon type partition function,

$$\frac{\sum_{N\geq 0} \Omega^-(1,N)\, q^N}{\sum_{N\geq 0} \Omega^+(1,N)\, q^N} = \prod_{k>0} \left(1 - (-1)^{k\gamma_{12}} q^k\right)^{k\,|\gamma_{12}|\;\Omega^+(k\gamma_2)} .$$

Denef Moore

Wall-crossing from semi-classical solutions V

- E.g. for $\gamma \mapsto \gamma_1 + 2\gamma_2$,

$$\begin{aligned}\Delta\Omega(1,2) =&(-1)^{\gamma_{12}}\gamma_{12}\Omega^+(0,1)\,\Omega^+(1,1) + 2\gamma_{12}\,\Omega^+(0,2)\,\Omega^+(1,0)\\ &+ \frac{1}{2}\gamma_{12}\,\Omega^+(0,1)\left(\gamma_{12}\Omega^+(0,1)+1\right)\Omega^+(1,0)\ .\end{aligned}$$

In particular, the term $\frac{1}{2}d(d+1)$ with $d = \gamma_{12}\Omega^+(0,1)$, reflects the projection on (anti)symmetric wave functions.

Wall-crossing from semi-classical solutions VI

- It is instructive to rewrite the semi-primitive WCF using the rational BPS invariants, related to the usual integer invariants via

$$\bar{\Omega}(\gamma) \equiv \sum_{d|\gamma} \Omega(\gamma/d)/d^2 \;, \qquad \Omega(\gamma) = \sum_{d|\gamma} \mu(d)\,\bar{\Omega}(\gamma/d)/d^2$$

  where $\mu(d) \in \{1, -1, 0\}$ is the Möbius function.
- The rational DT invariants $\bar{\Omega}(\gamma)$ appear in the JS formula, in constructions of modular invariant black hole partition functions, and in instanton corrections to hypermultiplet moduli spaces.

Joyce Song; Manschot; Alexandrov BP Saueressig Vandoren

Wall-crossing from semi-classical solutions VII

- Using the identity $\prod_{d=1}^{\infty}(1-q^d)^{\mu(d)/d} = e^{-q}$, or working backwards, one arrives at the Boltzmann-type partition function

$$\frac{\sum_{N\geq 0} \bar\Omega^-(1,N)\, q^N}{\sum_{N\geq 0} \bar\Omega^+(1,N)\, q^N} = \exp\left[\sum_{s=1}^{\infty} q^s (-1)^{\langle\gamma_1, s\gamma_2\rangle} \langle\gamma_1, s\gamma_2\rangle \bar\Omega^+(s\gamma_2)\right] .$$

- This can also be interpreted as the partition of distinguishable particles of charge $s\gamma_2$, each carrying an effective index $\bar\Omega(s\gamma_2)$, and satisfying Boltzmann statistics !
- One advantage is that $\Delta\bar\Omega(\gamma)$ takes a simpler form, and makes charge conservation manifest. E.g for $\gamma \mapsto \gamma_1 + 2\gamma_2$,

$$\Delta\bar\Omega(1,2) = (-1)^{\gamma_{12}}\gamma_{12}\bar\Omega^+(0,1)\,\bar\Omega^+(1,1) + 2\gamma_{12}\,\bar\Omega^+(0,2)\,\bar\Omega^+(1,0) + \frac{1}{2}\gamma_{12}\,\bar\Omega^+(0,1)^2\,\bar\Omega^+(1,0) .$$

The main conjecture I

- In general, we expect that the jump to be given by a finite sum

$$\Delta\bar{\Omega}(\gamma) = \sum_{n\geq 2} \sum_{\substack{\{\alpha_1,\dots\alpha_n\}\in\tilde{\Gamma} \\ \gamma=\alpha_1+\dots+\alpha_n}} \frac{g(\{\alpha_i\})}{|\mathrm{Aut}(\{\alpha_i\})|} \prod_{i=1}^{n} \bar{\Omega}^+(\alpha_i) \ ,$$

  over all unordered decompositions of the total charge vector γ into a sum of n vectors $\alpha_i \in \tilde{\Gamma}$. The symmetry factor $|\mathrm{Aut}(\{\alpha_i\})|$ reflects Boltzmannian statistics.
- $g(\{\alpha_i\})$ are universal factors depending only on the charges α_i, which should be given by the index of the supersymmetric quantum mechanics on $\mathcal{M}_n$.
- The KS and JS formulae give a mathematical prediction for these coefficients $g(\{\alpha_i\})$, which we shall compare with the index.

Outline

The Kontsevich-Soibelman formula I

- Consider the Lie algebra $\mathcal{A}$ spanned by abstract generators $\{e_\gamma, \gamma \in \Gamma\}$, satisfying the commutation rule

$$[e_{\gamma_1}, e_{\gamma_2}] = (-1)^{\langle \gamma_1, \gamma_2 \rangle} \langle \gamma_1, \gamma_2 \rangle \, e_{\gamma_1+\gamma_2} \, .$$

- For a given charge vector γ and value of the VM moduli t^a, consider the operator $U_\gamma(t^a)$ in the Lie group $\exp(\mathcal{A})$

$$U_\gamma(t^a) \equiv \exp\left(\Omega(\gamma; t^a) \sum_{d=1}^{\infty} \frac{e_{d\gamma}}{d^2} \right)$$

- The operators e_γ / U_γ can be realized as Hamiltonian vector fields / symplectomorphisms of a twisted torus.

The Kontsevich-Soibelman formula II

- The KS wall-crossing formula states that

$$\prod_{\substack{M\geq 0, N\geq 0,\\ M/N\downarrow}} U^{+}_{M\gamma_1+N\gamma_2} = \prod_{\substack{M\geq 0, N\geq 0,\\ M/N\uparrow}} U^{-}_{M\gamma_1+N\gamma_2} ,$$

  Starting from the l.h.s and reordering the product using the Baker-Campbell-Hausdorff (BCH) formula, one may express $\Omega^{-}(\gamma)$ in terms of $\Omega^{+}(\gamma)$.
- Both sides may be infinite, but only a finite number of factors contribute to the projection onto the finite dimensional quotient

$$\mathcal{A}_{M,N} = \mathcal{A}/\{ \sum_{m>M \text{ or } n>N} \mathbb{R} \cdot e_{m\gamma_1+n\gamma_2} \} .$$

The Kontsevich-Soibelman formula III

- For example, the primitive WCF

$$\Omega^-(\gamma_1+\gamma_2) - \Omega+(\gamma_1+\gamma_2) = (-1)^{\gamma_{12}+1}\,|\gamma_{12}|\,\Omega^+(\gamma_1)\,\Omega^+(\gamma_2)$$

follows from projecting the KS formula to $\mathcal{A}_{1,1}$

$$\begin{aligned} &\exp(\bar\Omega^+(\gamma_1)e_{\gamma_1})\,\exp(\bar\Omega^+(\gamma_1+\gamma_2)e_{\gamma_1+\gamma_2})\,\exp(\bar\Omega^+(\gamma_2)e_{\gamma_2})\\ =\,&\exp(\bar\Omega^-(\gamma_2)e_{\gamma_2})\,\exp(\bar\Omega^-(\gamma_1+\gamma_2)e_{\gamma_1+\gamma_2})\,\exp(\bar\Omega^-(\gamma_1)e_{\gamma_1})\end{aligned}$$

and using the order 2 truncation of the BCH formula

$$e^X\,e^Y = e^{X+Y+\frac{1}{2}[X,Y]}\,.$$

- The semi-primitive WCF follows similarly using the Hadamard formula

$$e^Y\,X\,e^{-Y} = X + [Y,X] + \frac{1}{2!}[Y,[Y,X]] + +\frac{1}{3!}[Y,[Y,[Y,X]]] + \dots$$

The Kontsevich-Soibelman formula IV

- In some simple cases, related to cluster algebras, one may establish the WCF in the full algebra $\mathcal{A}$, e.g. for $\gamma_{12} = 1$,

$$
\begin{aligned}
A_2 \quad &: \qquad U_{1,0}\, U_{0,1} = U_{0,1}\, U_{1,1}\, U_{1,0}\ , \\
B_2 \quad &: \qquad U_{1,0} U_{0,1}^{(2)} = U_{0,1}^{(2)} U_{1,2} U_{1,1}^{(2)} U_{1,0} \\
G_2 \quad &: \qquad U_{1,0} U_{0,1}^{(3)} = U_{0,1}^{(3)} U_{1,3} U_{1,2}^{(3)} U_{2,3} U_{1,1}^{(3)} U_{1,0}
\end{aligned}
$$

or for $\gamma_{12} = 2$,

$$
U_{2,-1} \cdot U_{0,1} = U_{0,1} \cdot U_{2,1} \cdot U_{4,1} \dots U_{2,0}^{(-2)} \dots U_{3,-1} \cdot U_{2,-1} U_{1,-1}
$$

The last identity captures the BPS spectrum of Seiberg-Witten theory with $G = SU(2)$, no flavor !

Denef Moore; Dimofte Gukov Soibelman

The Kontsevich-Soibelman formula V

- Noting that the operators $U_{k\gamma}$ for different $k \geq 1$ commute, one may combine them into a single factor

$$V_\gamma \equiv \prod_{k=1}^{\infty} U_{k\gamma} = \exp\left(\sum_{\ell=1}^{\infty} \bar{\Omega}(\ell\gamma)\, e_{\ell\gamma} \right) , \qquad \bar{\Omega}(\gamma) = \sum_{d|\gamma} \Omega(\gamma/d)/d^2 \, .$$

and rewrite the KS formula as a product over primitive charge vectors only,

$$\prod_{\substack{M\geq 0, N\geq 0, \\ \gcd(M,N)=1, M/N\downarrow}} V^{+}_{M\gamma_1+N\gamma_2} = \prod_{\substack{M\geq 0, N\geq 0, \\ \gcd(M,N)=1, M/N\uparrow}} V^{-}_{M\gamma_1+N\gamma_2} \, ,$$

The Kontsevich-Soibelman formula VI

- Using the BCH formula, one easily derives the semi-primitive wcf formula, and generalizations to $\gamma \to 2\gamma_1 + N\gamma_2, \ldots$.
- The fact that the algebra is graded by the charge lattice and the expression of V_γ guarantees that the jumps in the rational invariant will take the form

$$\Delta\bar{\Omega}(\gamma) = \sum_{n\geq 2} \sum_{\substack{\{\alpha_1,\ldots\alpha_n\}\in\tilde{\Gamma} \\ \gamma=\alpha_1+\cdots+\alpha_n}} \frac{g(\{\alpha_i\})}{|\mathrm{Aut}(\{\alpha_i\})|} \prod_{i=1}^{n} \bar{\Omega}^{+}(\alpha_i) \;,$$

  for some universal coefficients $g(\{\alpha_i\})$.
- The Joyce-Song wall-crossing formula expresses $g(\{\alpha_i\})$ as a complicated sum over trees, permutations, etc.

Generic decay I

- When α_i have generic phases, $g(\{\alpha_i\})$ can be computed by projecting the KS formula to the subalgebra spanned by $e_{\sum \alpha_j}$ where $\{\alpha_j\}$ runs over all subsets of $\{\alpha_i\}$.
- E.g., for $n = 3$, assuming that the phase of the charges are ordered according to

$$\alpha_1,\ \alpha_1+\alpha_2,\ \alpha_1+\alpha_3,\ \alpha_1+\alpha_2+\alpha_3,\ \alpha_2,\ \alpha_2+\alpha_3,\ \alpha_3\ ,$$

we find

$$g(\{\alpha_1,\alpha_2,\alpha_3\}) = (-1)^{\alpha_{12}+\alpha_{23}+\alpha_{13}}\,\alpha_{12}\,(\alpha_{13}+\alpha_{23})$$

As we shall see later, this fits the macroscopic index of 3-centered configurations !

The motivic Kontsevich-Soibelman formula I

- KS have proposed a quantum deformation of their formula, which governs wall-crossing properties of motivic DT invariants $\Omega_{\rm ref}(\gamma; y, t)$. Physically, these correspond to the "refined index"

$$\Omega_{\rm ref}(\gamma, y) = {\rm Tr}'_{\mathcal{H}(\gamma)}(-y)^{2J_3} \equiv \sum_{n\in\mathbb{Z}}(-y)^n\, \Omega_{{\rm ref},n}(\gamma)\,,$$

  where J_3 is the angular momentum in 3 dimensions along the z axis. As $y \to 1$, $\Omega_{\rm ref}(\gamma; y, t) \to \Omega(\gamma; t)$.

  Dimofte Gukov; D G Soibelman

- Caution: this index (rather, a variant of it using a combination of angular momentum and $SU(2)_R$ quantum numbers) is protected in $\mathcal{N} = 2, D = 4$ field theories, but not in supergravity/string theory, where $SU(2)_R$ is generically broken.

  Gaiotto Moore Neitzke

The motivic Kontsevich-Soibelman formula II

- To state the formula, consider the Lie algebra $\mathcal{A}(y)$ spanned by generators $\{\tilde{e}_\gamma, \gamma \in \Gamma\}$, satisfying the commutation rule

$$[\tilde{e}_{\gamma_1}, \tilde{e}_{\gamma_2}] = \kappa(\langle\gamma_1, \gamma_2\rangle)\, \tilde{e}_{\gamma_1+\gamma_2}\ , \qquad \kappa(x) = \frac{(-y)^x - (-y)^{-x}}{y - 1/y}\ .$$

- To any primitive charge vector γ, attach the operator

$$\tilde{V}_\gamma = \prod_{k\geq 1} \tilde{U}_{k\gamma} = \exp\left[\sum_{\ell=1}^{\infty} \bar{\Omega}_{\rm ref}(\ell\gamma, y)\, \tilde{e}_{\ell\gamma}\right]$$

where $\bar{\Omega}_{\rm ref}(\gamma, y)$ are the "rational motivic invariants", defined by

$$\bar{\Omega}^+_{\rm ref}(\gamma, y) \equiv \sum_{d|\gamma} \frac{(y - y^{-1})}{d(y^d - y^{-d})} \Omega^+_{\rm ref}(\gamma/d, y^d)\, .$$

The motivic Kontsevich-Soibelman formula III

- The motivic version of the KS wall-crossing formula states that

$$\prod_{\substack{M\geq 0, N\geq 0>0,\\ \gcd(M,N)=1, M/N\downarrow}} \tilde{V}^{+}_{M\gamma_1+N\gamma_2} = \prod_{\substack{M\geq 0, N\geq 0>0,\\ \gcd(M,N)=1, M/N\uparrow}} \tilde{V}^{-}_{M\gamma_1+N\gamma_2},$$

- $\Delta\bar{\Omega}_{\rm ref}(\gamma, y)$ can be computed using the same techniques as before, e.g. the primitive wcf read

$$\Delta\Omega_{\rm ref}(\gamma_1+\gamma_2, y) = \frac{(-y)^{\langle\gamma_1,\gamma_2\rangle} - (-y)^{-\langle\gamma_1,\gamma_2\rangle}}{y-1/y}\,\Omega_{\rm ref}(\gamma_1, y)\,\Omega_{\rm ref}(\gamma_2, y)$$

- The general formula for $\Delta\bar{\Omega}_{\rm ref}$ involves universal factors $g(\{\alpha_i\}, y)$, which reduce to $g(\{\alpha_i\})$ in the limit $y\to 1$. We expect that they are given by $\mathrm{Tr}'(-y)^{2J_3}$ in the corresponding SUSY quantum mechanics.

Outline

Quantum mechanics of multi-centered solutions I

- The moduli space $\mathcal{M}_n$ of BPS configurations with n centers in $\mathcal{N} = 2$ SUGRA is described by solutions to Denef's equations

$$\sum_{j=1\dots n, j\neq i}^{n} \frac{\alpha_{ij}}{|\vec{r}_i - \vec{r}_j|} = c_i \,, \qquad \begin{cases} c_i = 2\,\mathrm{Im}\left[e^{-i\phi} Z(\alpha_i)\right] \\ \phi = \arg[Z(\alpha_1 + \cdots \alpha_n)] \end{cases} .$$

- $\mathcal{M}_n$ is a symplectic manifold of dimension $2n-2$, and carries an Hamiltonian action of $SU(2)$:

$$\omega = \frac{1}{2} \sum_{i<j} \alpha_{ij} \sin\theta_{ij}\, \mathrm{d}\theta \wedge \mathrm{d}\phi_{ij} \,, \qquad \vec{J} = \frac{1}{2} \sum_{i<j} \alpha_{ij} \frac{\vec{r}_{ij}}{|r_{ij}|}$$

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- Crucially, when the α_i's lie in the positive cone $\tilde{\Gamma}$ (more generally, whenever $\mathrm{sign}(\alpha_{ij})$ defines an ordering of the α_i), $\mathcal{M}_n$ is compact, and the fixed points of J_3 are isolated.

Quantum mechanics of multi-centered solutions II

- The symplectic form $\omega/2\pi \in H^2(\mathcal{M}_n, \mathbb{Z})$ is the curvature of a complex line bundle $\mathcal{L}$ over $\mathcal{M}_n$, with connection

$$\lambda = \frac{1}{2} \sum_{i<j} \alpha_{ij} \left(1 - \cos\theta_{ij}\right) \mathrm{d}\phi_{ij} \;, \quad \mathrm{d}\lambda = \omega \;.$$

- Assuming that $\mathcal{M}_n$ is spin, let $S = S_+ \oplus S_-$ be the spin bundle. Let $D = D_+ \oplus D_-$ be the Dirac operator for the metric obtained by restricting the flat metric on $\mathbb{R}^{3n-3}$ to $\mathcal{M}_n$, with $D_\pm : S_\pm \mapsto S_\mp$. The action of $SO(3)$ on $\mathcal{M}_n$ lifts to an action of $SU(2)$ on $S_\pm$.
- We assume that BPS states correspond to harmonic spinors, i.e. sections of $S \otimes \mathcal{L}$ annihilated by the Dirac operator D.

Quantum mechanics of multi-centered solutions III

- The 'refined index' is then given by

$$g_{\rm ref}(\{\alpha_i\}; y) = \mathrm{Tr}_{{\rm Ker} D_+}(-y)^{2J_3} + \mathrm{Tr}_{{\rm Ker} D_-}(-y)^{2J_3} \ .$$

- We further assume that ${\rm Ker} D_- = 0$, so that the refined index $g_{\rm ref}(\{\alpha_i\}; y)$ reduces to the equivariant index

$$g_{\rm ref}(\{\alpha_i\}; y) = \mathrm{Tr}_{{\rm Ker} D_+}(-y)^{2J_3} - \mathrm{Tr}_{{\rm Ker} D_-}(-y)^{2J_3} \ .$$

- The vanishing of ${\rm Ker} D_-$ can be shown to hold in special cases where $\mathcal{M}_n$ is Kähler. In gauge theories, the protected spin character presumably reduces to the equivariant index without further assumption.

Quantum mechanics of multi-centered solutions IV

- The refined/equivariant index can be computed by the Atiyah-Bott Lefschetz fixed point formula:

$$g_{\rm ref}(\{\alpha_i\}, y) = \sum_{\text{fixed pts}} \frac{y^{2J_3}}{\det((-y)^L - (-y)^{-L})}$$

  where L is the matrix of the action of J_3 on the holomorphic tangent space around the fixed point.

- In the large charge limit, $\mathcal{L} \to k\mathcal{L}$ with $k \to \infty$, this reduces to the Duistermaat-Heckmann formula for the equivariant volume,

$$\frac{\int_{\mathcal{M}_n} \omega^{n-1}\, y^{2J_3}}{(2\pi)^{n-1}(n-1)!} = \sum_{\text{fixed pts}} \frac{y^{2J_3}}{\det(L \log(-y))}$$

Quantum mechanics of multi-centered solutions V

- The fixed points of the action of J_3 are collinear multi-centered configurations along the z-axis, such that

$$\sum_{j=1\dots n, j\neq i}^{n} \frac{\alpha_{ij}}{|z_i - z_j|} = c_i\,, \quad J_3 = \frac{1}{2}\sum_{i<j} \alpha_{ij}\,\mathrm{sign}(z_j - z_i)\,.$$

- Equivalently, fixed points are critical points of the 'superpotential'

$$W(\lambda, \{z_i\}) = -\sum_{i<j} \mathrm{sign}[z_j - z_i]\,\alpha_{ij}\,\ln|z_j - z_i| - \sum_i (c_i - \frac{\lambda}{n}) z_i$$

These are isolated, and classified by permutations describing the order of z_i along the axis.

Quantum mechanics of multi-centered solutions VI

- This leads to the Coulomb branch formula

$$g_{\rm ref}(\{\alpha_i\}, y) = \frac{(-1)^{\sum_{i<j}\alpha_{ij}+n-1}}{(y-y^{-1})^{n-1}} \sum_{p:\partial_I W(p)=0} s(p)\, y^{\sum_{i<j}\alpha_{ij}\,{\rm sign}(z_j-z_i)}$$

where $s(p) = -{\rm sign}(\det W_{IJ})$ is (minus) the Morse index.

- For $n \leq 5$, we find perfect agreement with JS/KS !

$$g_{\rm ref}(\alpha_1,\alpha_2;y) = (-1)^{\alpha_{12}} \frac{\sinh(\nu\alpha_{12})}{\sinh\nu} \qquad (y=e^\nu)$$

$$g_{\rm ref}(\alpha_1,\alpha_2,\alpha_3;y) = (-1)^{\alpha_{13}+\alpha_{23}+\alpha_{12}} \frac{\sinh(\nu(\alpha_{13}+\alpha_{23}))\,\sinh(\nu\alpha_{12})}{\sinh^2\nu}$$

Higgs branch picture I

- An alternative formula can be given using the Higgs branch description of the multi-centered configuration, namely the quiver with n nodes $\{1 \dots n\}$ of dimension 1 and α_{ij} arrows from i to j.
- Since α_i lie on a 2-dimensional sublattice $\tilde{\Gamma}$, the quiver has no oriented closed loop. Reineke's formula gives

$$g_{\rm ref} = \frac{(-y)^{-\sum_{i<j}\alpha_{ij}}}{(y-1/y)^{n-1}} \sum_{\rm partitions} (-1)^{s-1} y^{2\sum_{a\le b}\sum_{j<i}\alpha_{ji}\, m_i^{(a)}\, m_j^{(b)}} \,,$$

where $\sum$ runs over all ordered partitions of $\gamma = \alpha_1 + \dots + \alpha_n$ into s vectors $\beta^{(a)}$ ($1 \le a \le s$, $1 \le s \le n$) such that

1. $\beta^{(a)} = \sum_i m_i^{(a)} \alpha_i$ with $m_i^{(a)} \in \{0, 1\}$, $\sum_a \beta^{(a)} = \gamma$
2. $\langle \sum_{a=1}^{b} \beta^{(a)}, \gamma \rangle > 0 \quad \forall \quad b \quad \text{with} \quad 1 \le b \le s-1$

Higgs branch picture II

- The Higgs branch formula agrees with KS/JS/Coulomb for $n = 2, 3, 4, 5$!
- The formula gives a prescription for what permutations are allowed in the Coulomb problem, and for their Morse index.
- It is perhaps not surprising that the Higgs branch formula agrees with KS/JS, since quiver categories are an example of Abelian categories. Unlike the JS formula, the Higgs branch formula works at $y \neq 1$.

Outline

Away from the wall I

- Having understood the jump $\Delta\Omega(\gamma; y)$ in terms of the index of multi-centered solutions, one would like to compute the BPS index $\Omega(\gamma; y, t^a)$ on either side of the wall, from the index $\Omega_S(\alpha_i)$ of single-centered black holes. Since spherically symmetric SUSY black holes cannot decay and carry zero angular momentum, $\Omega_S(\alpha_i)$ must be independent of t^a and y.

Manchot BP Sen II

- Naively, one may expect

$$\bar{\Omega}(\gamma; y, t^a) = \sum_{n\geq 2} \sum_{\substack{\{\alpha_1,\dots\alpha_n\}\in\Gamma \\ \gamma=\alpha_1+\dots+\alpha_n}} \frac{g(\{\alpha_i\}; y, c_i)}{|\mathrm{Aut}(\{\alpha_i\})|} \prod_{i=1}^n \bar{\Omega}_S(\alpha_i) \,,$$

where $g(\{\alpha_i\}; y, c_i)$ is the refined index of the SUSY quantum mechanics on $\mathcal{M}_n(\alpha_i, c_i)$. This is similar to the formula for $\Delta\bar{\Omega}(\gamma)$, but with some important differences.

Away from the wall II

- Unlike the formula for $\Delta\bar{\Omega}(\gamma)$, the charges α_i of the constituents are no longer restricted to a two-dimensional subspace of the charge lattice, and there are a priori an infinite number of possible splittings $\gamma = \sum \alpha_i$. It is plausible that requiring that the multi-centered solution be regular may leave only a finite number of splittings. In addition, for a given splitting, the regularity constraint may rule out certain components of $\mathcal{M}_n(\alpha_i, c_i)$.
- The space $\mathcal{M}_n(\alpha_i, c_i)$ is in general no longer compact. In particular, there can be scaling regions in $\mathcal{M}_n$, when some or all of the n centers approach each other at arbitrary small distances. Classically, these scaling solutions carry zero angular momentum and are invariant under $SO(3)$.

Away from the wall III

- In spite a potential logarithmic divergence due to these scaling regions, it appears that $\mathcal{M}_n$ admits a compactification $\overline{\mathcal{M}}_n$ with finite volume. However, this introduces new (non-collinear) fixed points of the action of J_3 which are no longer isolated, leading to additional contributions to the equivariant index.
- Rather than trying to compute these new contributions directly, we propose to determine them by requiring 1) that the resulting $\Omega(\gamma; y, t^a)$ is a finite Laurent polynomial in y and 2) that they carry the minimal angular momentum J_3 compatible with condition 1). This minimal modification hypothesis fixes $\Omega(\gamma; y, t^a)$ uniquely.
- We have checked that the minimal modification hypothesis works for an infinite class of 'dipole halo' configurations, where $\mathcal{M}_n$ is a toric manifold and can be quantized directly.

Conclusion I

- Multi-centered solitonic configurations provide a simple picture to derive and understand wall-crossing formulae for the BPS (refined) index.
- We have not proven the equivalence between the Coulomb branch, Higgs branch, JS and KS wall-crossing formula, but there is overwhelming evidence that they all agree.
- Our derivation was made in the context of $\mathcal{N}=2$ supergravity, it would be interesting to develop our understanding of multi-centered dyonic solutions in $\mathcal{N}=2$ gauge theories.

Lee Yi

- In principle, our formulae can be used to extract the degeneracies $\Omega_S(\gamma)$ of single-centered black holes from the moduli-dependent BPS index $\Omega(\gamma)$. The former is the one that should be compared with Sen's quantum entropy function.

THANK YOU !