String Phenomenology 2018 - University of Warsaw

The Refined Swampland Distance Conjecture in Calabi-Yau Moduli Spaces

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Outline

The string swampland and associated conjectures

Testing the Refined Swampland Distance Conjecture (RSDC)

Outlook on implications for phenomenology

The Swampland and Related Ideas

String theory has just celebrated its **50th birthday** 🎉 in Okinawa! String Phenomenology is a well-developed subject, addressing many problems in particle physics and cosmology from a top-down perspective.

Many detailed constructions have been developed to obtain: dS vacua, inflation, GUTs, etc…

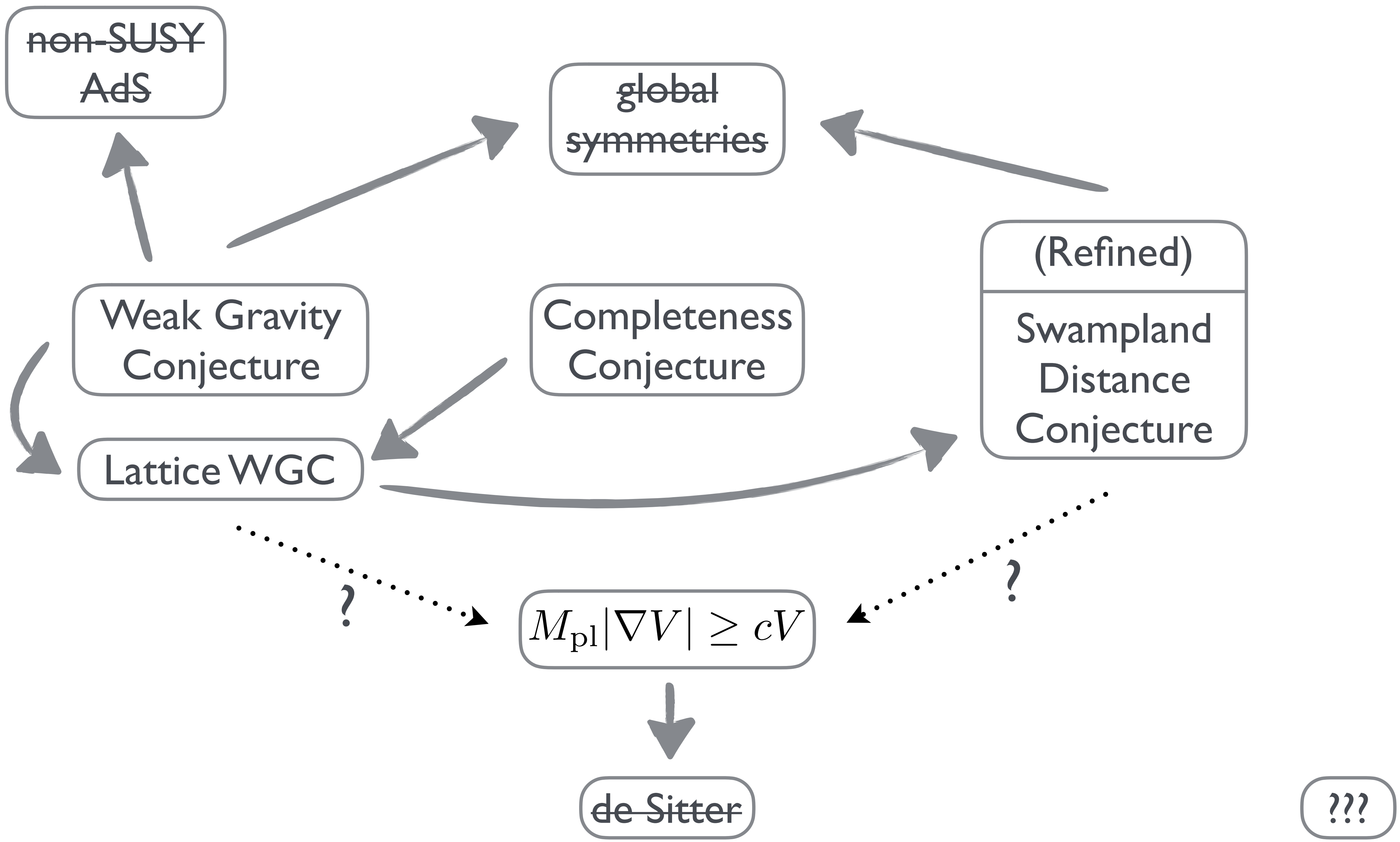
Yet **general ideas about quantum gravity** and its realization in string theory appear to **challenge many of these models.**

The **(string) swampland** is the set of (seemingly consistent) effective field theories, which cannot be obtained from a consistent string construction.

Maybe our wishful thinking about connecting string theory to observations has led us astray. As we don't want to get stuck in the swampland, we need to **map out its boundary**.

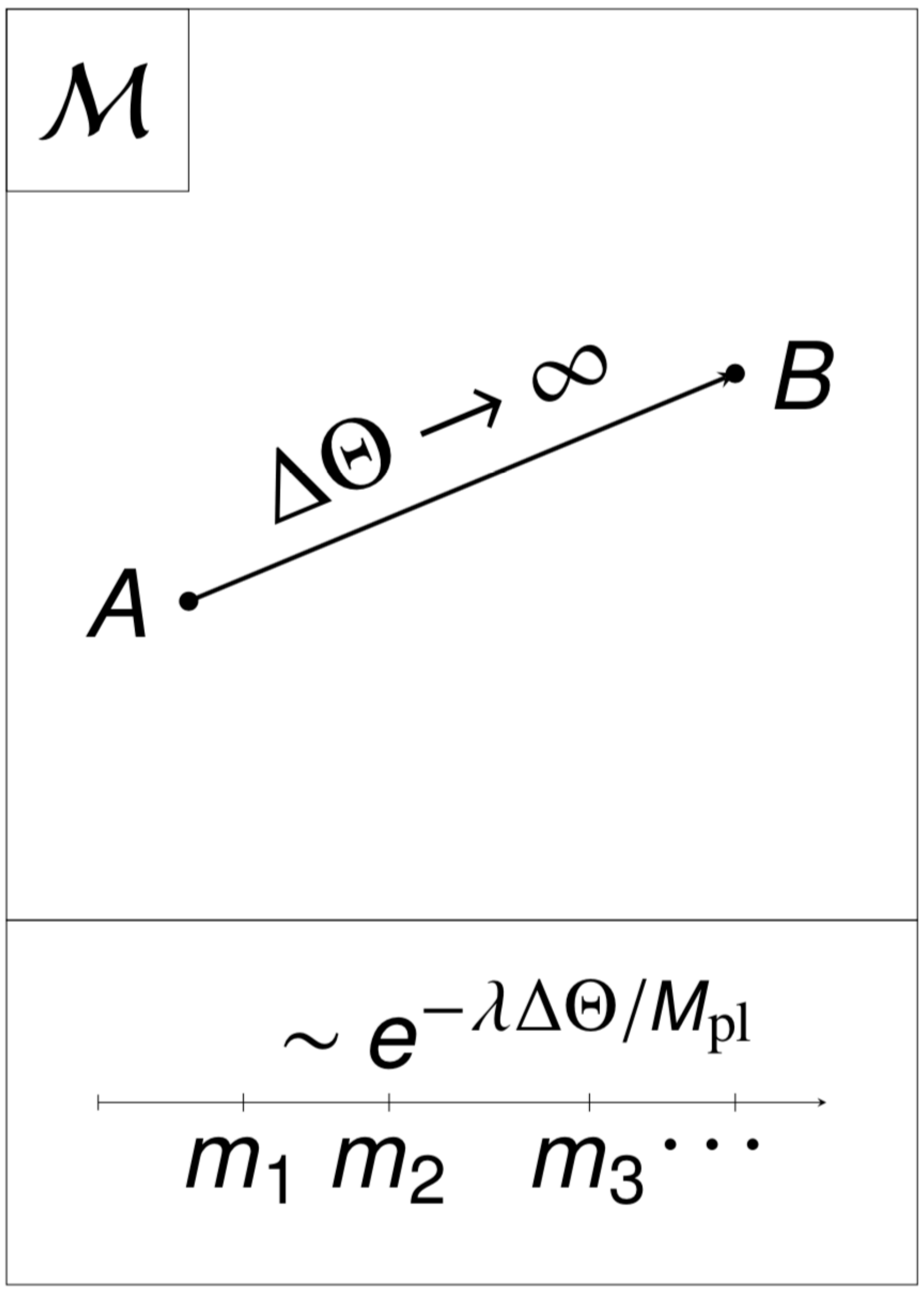
The **swampland as a blessing**: Knowing which field theories cannot be realized could actually lead to falsifiable predictions!!!

A Web of Conjectures…



The Swampland Distance Conjecture

[Ooguri, Vafa '06]



- Asymptotic displacements A → B in continuous moduli space of quantum gravity
- Conjectured **universal behavior of mass scale of an infinite tower of states**

$$\Theta = \int_{\tau_A}^{\tau_B} d\tau \sqrt{G_{\alpha\beta}\frac{dx^\alpha}{d\tau}\frac{dx^\beta}{d\tau}}$$

- Casts **doubt on validity of EFT** for large field displacements

$$\Theta > \Theta_\lambda = \frac{1}{\lambda} = \mathcal{O}(1) M_{\rm pl}$$

Evidence

- Well known for **string theory on tori** (IIB on S[1]) [Ooguri, Vafa '06]

$$M_{\mathrm{KK}} \sim \frac{1}{R^{\frac{8}{7}}} \qquad M_{\mathrm{W}} \sim R^{\frac{6}{7}} \qquad G_{\mathrm{RR}} \sim \frac{1}{R^2} \qquad \Theta \sim \log\left(\frac{R_B}{R_A}\right)$$

- **Holds for N > 8 supercharges** (moduli space is coset) [Cecotti '15]
- **Evidence also for N = 8 supercharges** [Grimm, Palti, Valenzuela '18] [Blumenhagen, DK, Schlechter, Wolf '18]
- Evidence from **semi-classical arguments**, relating it to WGC: [DK, Palti '16]
- (Sub-)Lattice WGC predicts infinite tower of states with $m \sim qgM_{\mathrm{pl}}$
- In gravitational theory, scalar fields can grow at most logarithmically [Nicolis '08]

$$\Delta\phi < \frac{1}{\alpha}\log(r/r_*)$$

- Together with magnetic WGC bound on the energy density $g(r) > \rho(r)^{\frac{1}{2}}$

Find that gauge coupling = mass drops at least exponentially in $\Delta\phi$

The Refined Swampland Distance Conjecture

[Baume, Palti ’16; DK, Palti ‘16]

- SDC holds globally in simple moduli spaces (toroidal compactification)
- Generically expect the SDC to be **badly violated** at finite distances

Refined SDC quantifies this:

The universal exponential behavior sets in for

finite displacements Θ_0

of order the Planck scale or earlier

Evidence

- Even **less evidence than for the SDC**
- The semi-classical argument gives a **hint**: Free Scalars can only support sub-Planckian variations. Inside sources $\Delta\Theta > M_{\rm pl}$ is indeed possible, but only logarithmic growth!
- Solid **evidence from string theory** has been **lacking**

→ **fill this gap!**

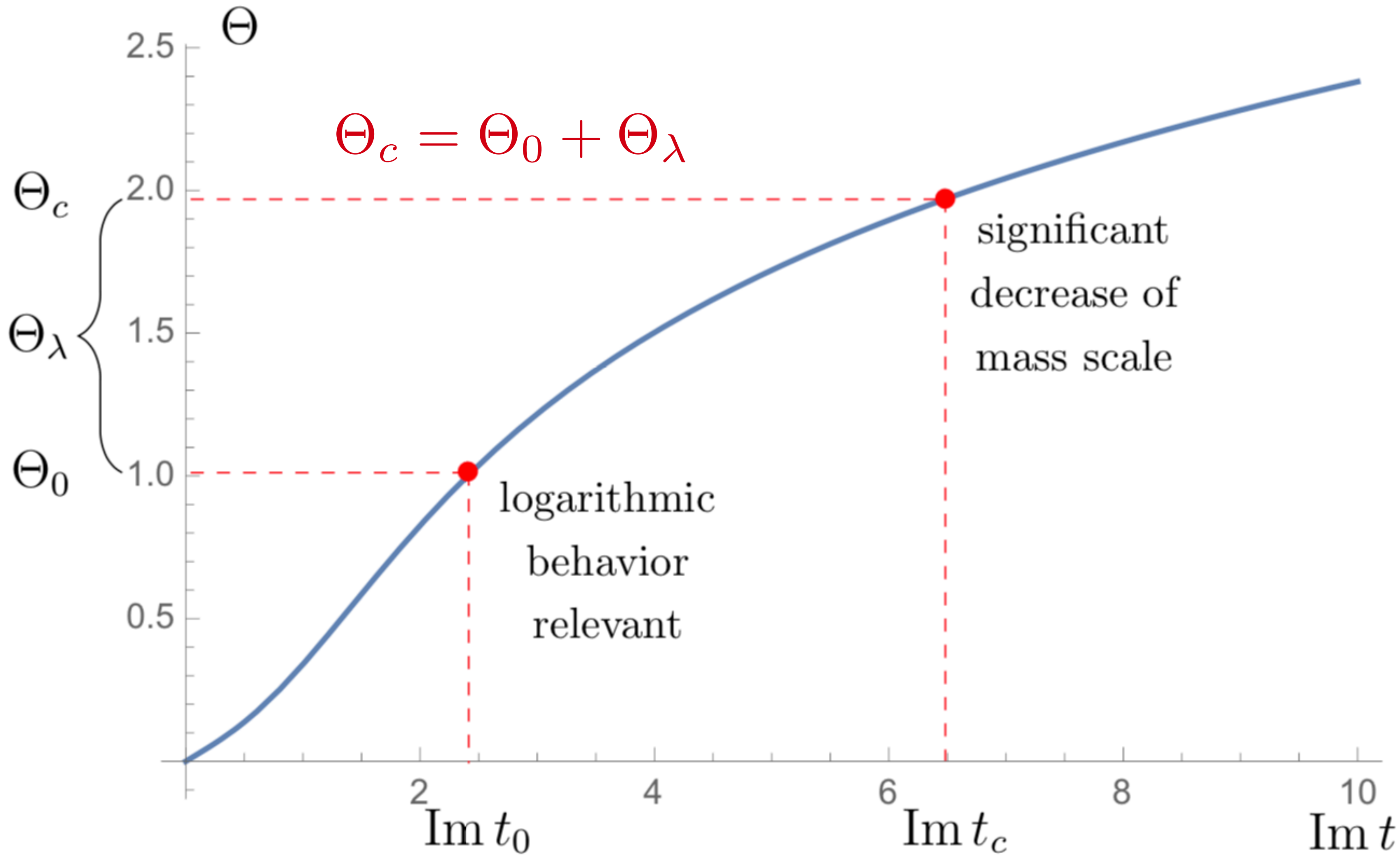
Additional Evidence?

- The RSDC applies to moduli, i.e. flat directions. For Pheno, we really want it to apply it to fields with a potential (Inflaton,…).
- In fact, there is evidence that a similar mechanism is at work.
- (F-term) axion monodromy inflation: [Silverstein, Westphal '08; Marchesano, Shiu, Uranga '14] [Palti, Baume '16; Blumenhagen, Valenzuela, Wolf '17]
- Break axion shift symmetry by fluxes, but corrections to the effective potential controlled even in the trans-Planckian regime $\Delta\Theta > M_{\text{pl}}$
- Axions do not control mass scales, should be safe from SDC
- For trans-Planckian axion, the axion valley moves into saxion direction (backreaction). $s(\theta) = \lambda\theta$
- This implies the behavior predicted by the refined SDC

$$\Theta = \int K_{\theta\theta}^{1/2}(s) d\theta \sim \int \frac{d\theta}{s(\theta)} \sim \frac{1}{\lambda} \log(\theta)$$

Objectives

- **Test the Refined Swampland Distance Conjecture in CY moduli spaces**



Prediction: $\Theta_0 < \mathcal{O}(1) M_{\mathrm{pl}}$ | $\Theta_\lambda < \mathcal{O}(1) M_{\mathrm{pl}}$

Calabi Yau Moduli Spaces

- IIA/IIB string theory on a Calabi-Yau M manifold with
$$h^{11} = \dim\left(H^{1,1}\right)$$
$$h^{21} = \dim\left(H^{2,1}\right)$$
- Low energy EFT: N=2 supergravity
- Moduli space of deformations of M splits into

Kähler x **complex structure**

IIA: h^{11} vector multiplets h^{21} hypermultiplets

IIB: h^{11} hypermultiplets h^{21} vector multiplets

- **Mirror symmetry:** duality between IIA on M and IIB on W (mirror CY)
    - Exchanges Kähler and CS moduli spaces

Calabi Yau Moduli Spaces

- Metric on moduli space is determined by **Kähler potential** $g_{\alpha\bar{\beta}} = \partial_\alpha \partial_{\bar{\beta}} \mathcal{K}$

$$\mathcal{K}_K = -\log\left(-\frac{i}{6}\kappa^{abc}(t_a - \bar{t}_a)(t_b - \bar{t}_b)(t_c - \bar{t}_c) + \xi + \mathcal{O}\left(e^{-2\pi i t_a}\right)\right)$$

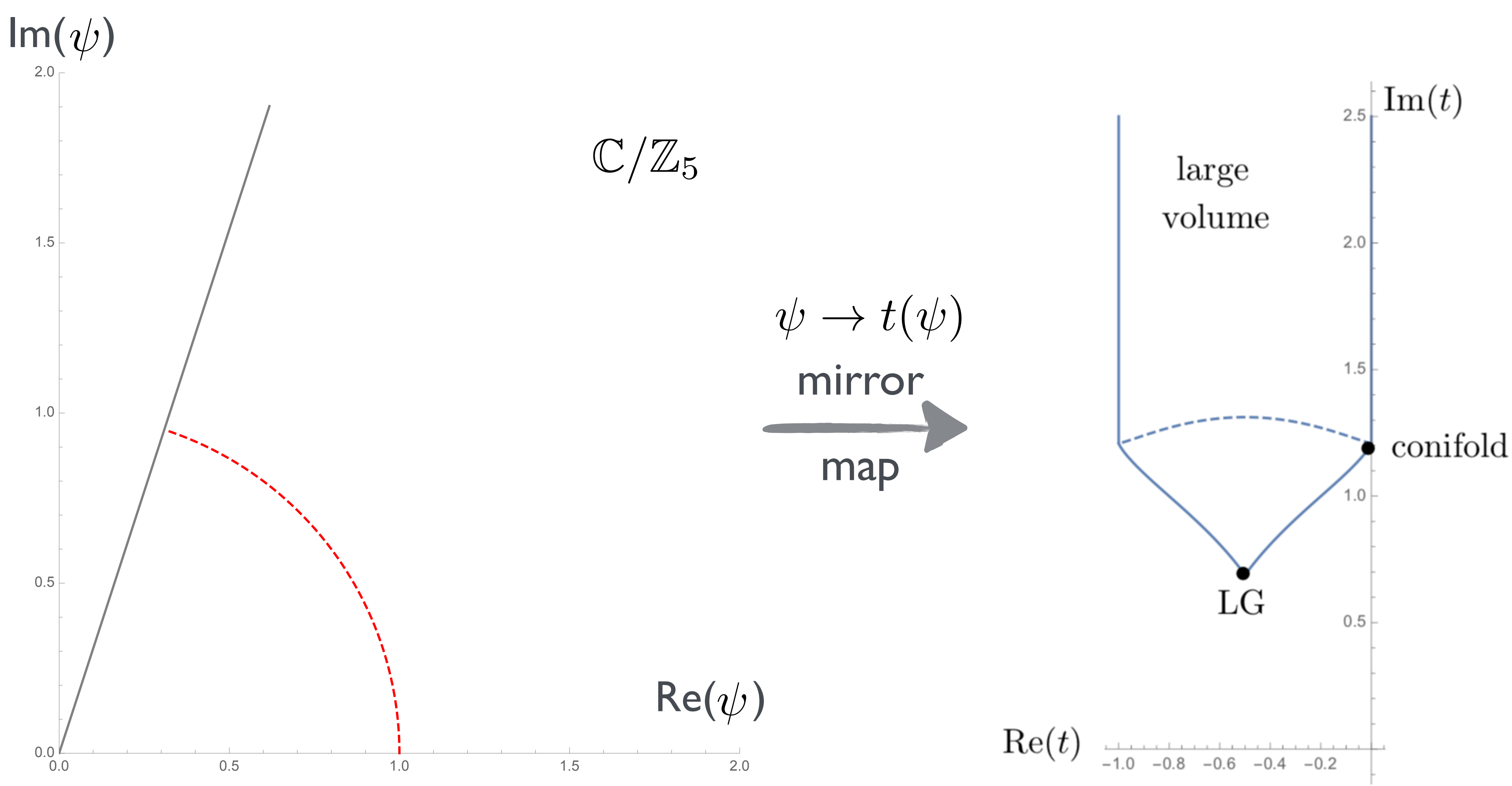
$$t_a = \int_{\Sigma_a} B + i\int_{\Sigma_a} J \qquad a = 1, \ldots, h^{11}$$ compl. Kähler moduli

$$\mathcal{K}_{CS} = -\log(-i\overline{\Pi}\Sigma\Pi) \quad \Pi_i(\Phi_\alpha) = \int_{A_i} \Omega(\Phi_\alpha) \quad i = 1, \ldots, 2h^{2,1} + 2$$ periods

- The **Kähler side receives** perturbative and non-perturbative **corrections**
- The classical result for the complex structure side is **exact**
- We focus on the Kähler side because of the obvious associated **tower of Kaluza-Klein states** (similar results apply for the CS sector)
- Use mirror symmetry as tool to compute the fully corrected Kähler potential and explore non-geometric regions of moduli space $\mathrm{Im}(t_j) = \mathcal{O}(1)$

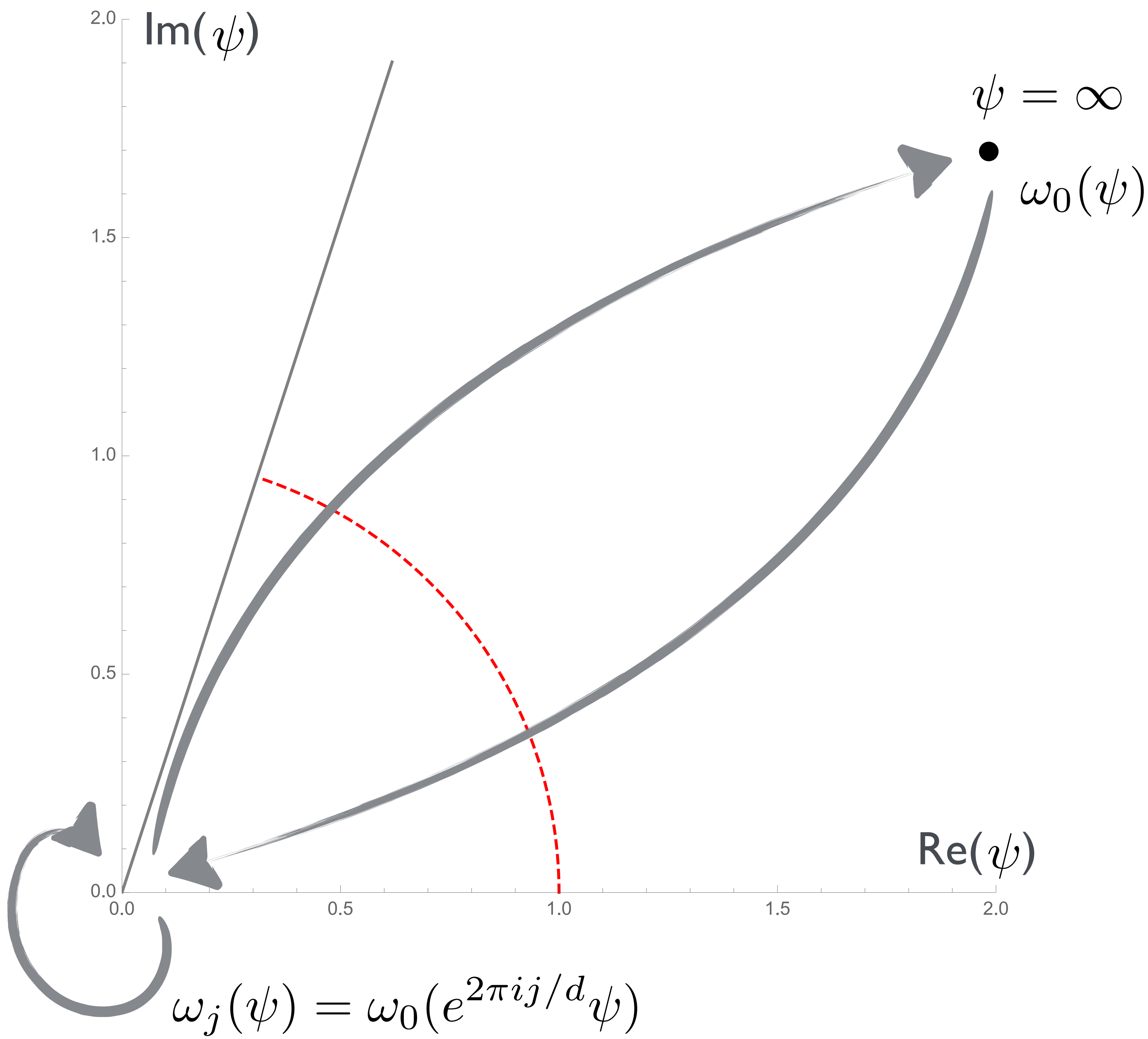
CY moduli spaces and the RSDC

- **Example: (mirror) quintic** $x_1^5 + x_2^5 + x_3^5 + x_4^5 + x_5^5 + 5\psi x_1 x_2 x_3 x_4 x_5 = 0$



Periods

- Well-known method to obtain **Kähler potential on CS side and mirror map:**



Tedious, but can be done in a case by case analysis for h[11] small

[Berglund, Candelas, de la Ossa, Font, Hübsch, Jancic, Quevedo '93]

[Hosono, Klemm, Theisen, Yau '93]

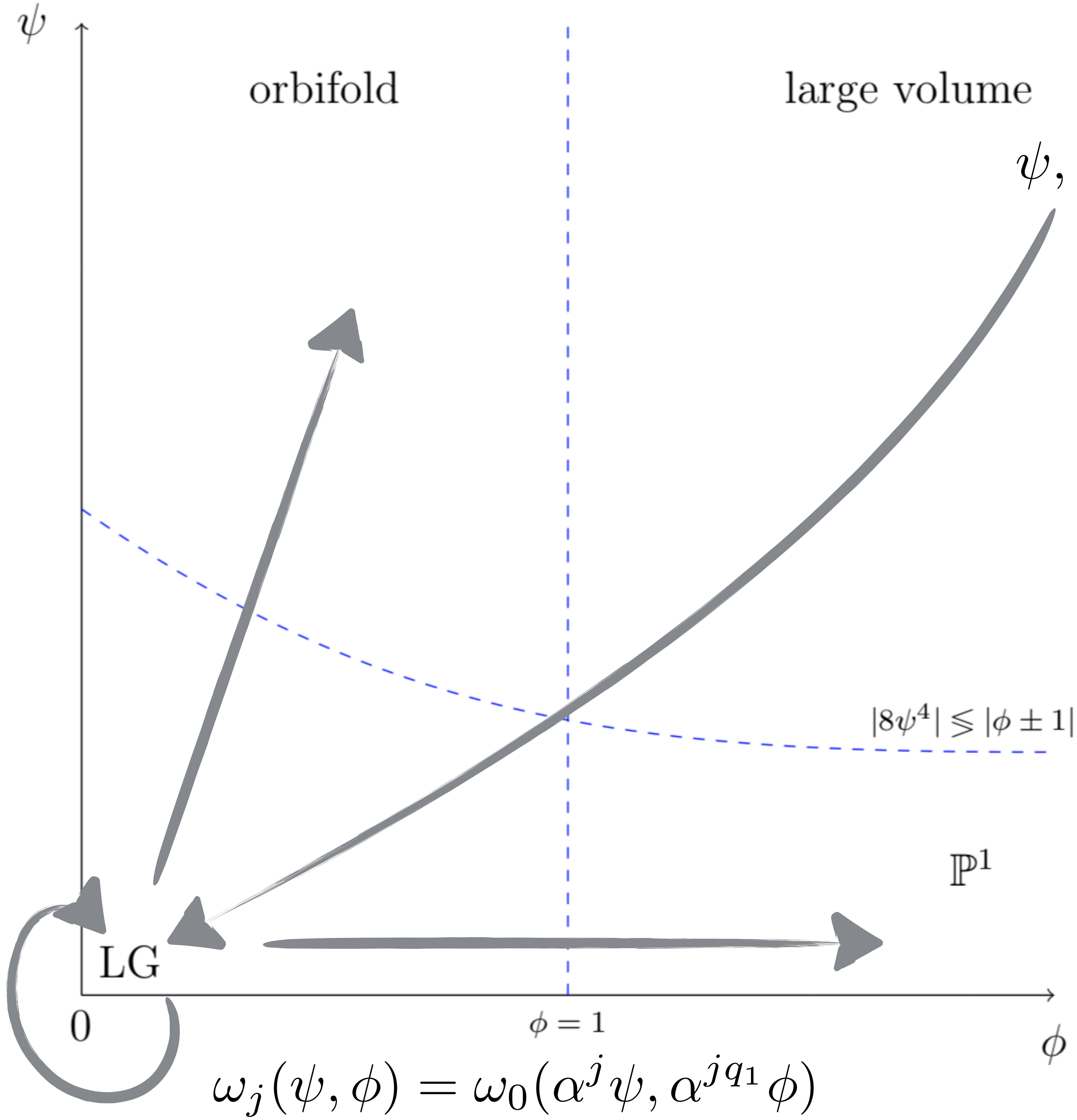
[Candelas, de la Ossa, Font, Katz, Morrison '94]

$$t = t(\psi)$$

$$\Pi = m\,\omega$$

Periods for 2-dimensional moduli spaces

$$P = x_1^8 + x_2^8 + x_3^4 + x_4^4 + x_5^4 + \psi x_1 x_2 x_3 x_4 x_5 + \phi x_1^4 x_2^4$$



Analytic continuation is subtle, but periods can be written in terms of hypergeometric functions in different ways and standard techniques apply

The Gauged Linear Sigma Model

- Can also compute directly on the Kähler side, using Witten's **gauged linear sigma model** (GLSM) description [Witten '93] [Jockers, Kumar, Lapan, Morrison, Romo '13]
- GLSM is N=(2,2) SUSY gauge theory in 2d. Varying the FI parameters leads to phase transitions, corresponding to phases of Kähler moduli space
- **Kähler potential is given by sphere partition function** $e^{-\mathcal{K}} = Z_{S^2}$

$$Z_{S^2}(\xi, \bar{\xi}, Q, R) = \sum_{m_1 \in \mathbb{Z}} \dots \sum_{m_s \in \mathbb{Z}} \int_{-i\infty}^{i\infty} da_1 \dots \int_{-i\infty}^{i\infty} da_s \, Z_{\text{class}} \, Z_{\text{gauge}} \, Z_{\text{chiral}}$$

$$Z_{\text{chiral}} = \prod_{i=1}^{M} \frac{\Gamma\left(R_i/2 + \sum_{j=1}^{s} Q_{i,j} \cdot (a_j - m_j/2)\right)}{\Gamma\left(1 - R_i/2 - \sum_{j=1}^{s} Q_{i,j} \cdot (a_j + m_j/2)\right)} \qquad Z_{\text{class}} = \prod_{j=1}^{s} e^{-4\pi i r_j a_j + i\theta_j m_j} \qquad Z_{\text{gauge}} = 1$$

[Doroud, Gomis, Le Floch, Lee '13] [Benini, Cremonesi '15]

- Allows for **direct and algorithmic computation of the Kähler potential** without knowing the periods. Subtleties of analytic continuation are traded for subtleties in the evaluation of the integrals.

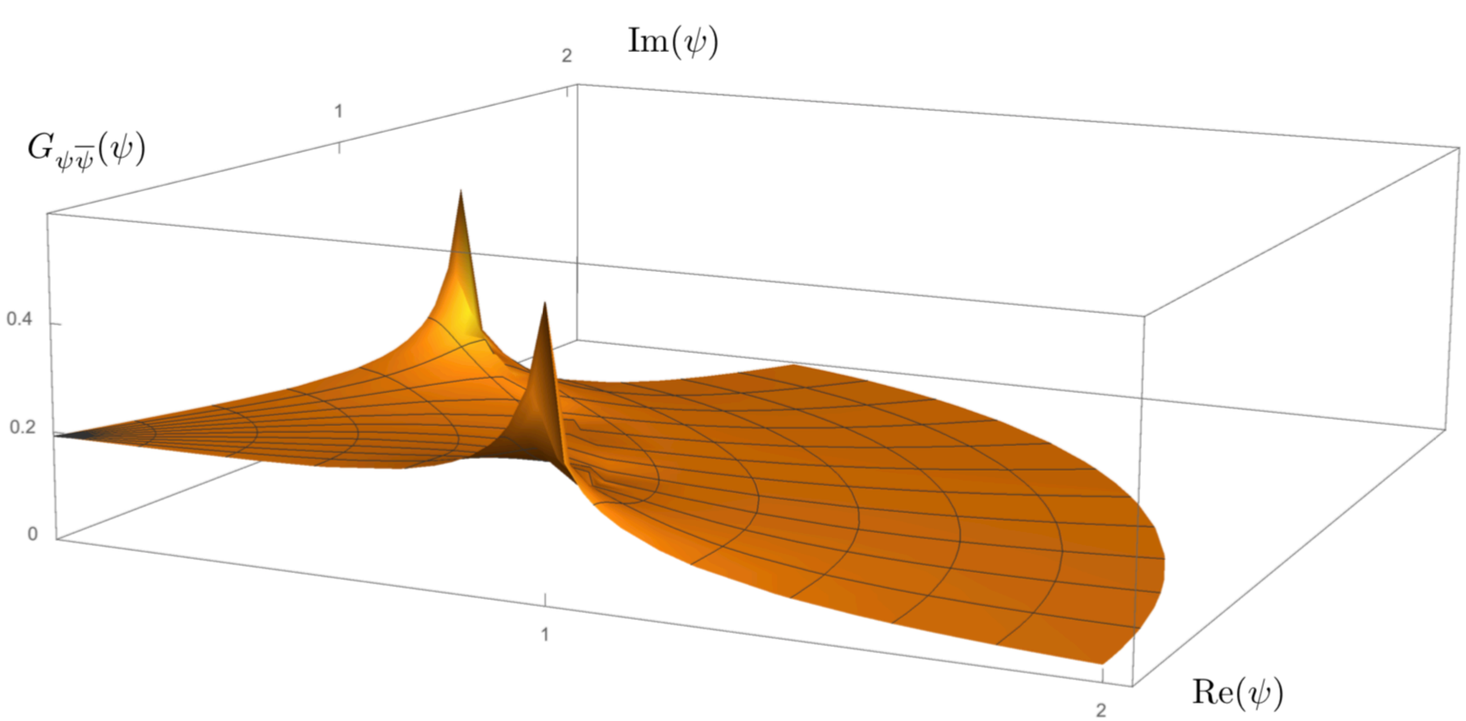
The Quintic

$$\boxed{x_1^5 + x_2^5 + x_3^5 + x_4^5 + x_5^5 + 5\psi x_1 x_2 x_3 x_4 x_5 = 0}$$

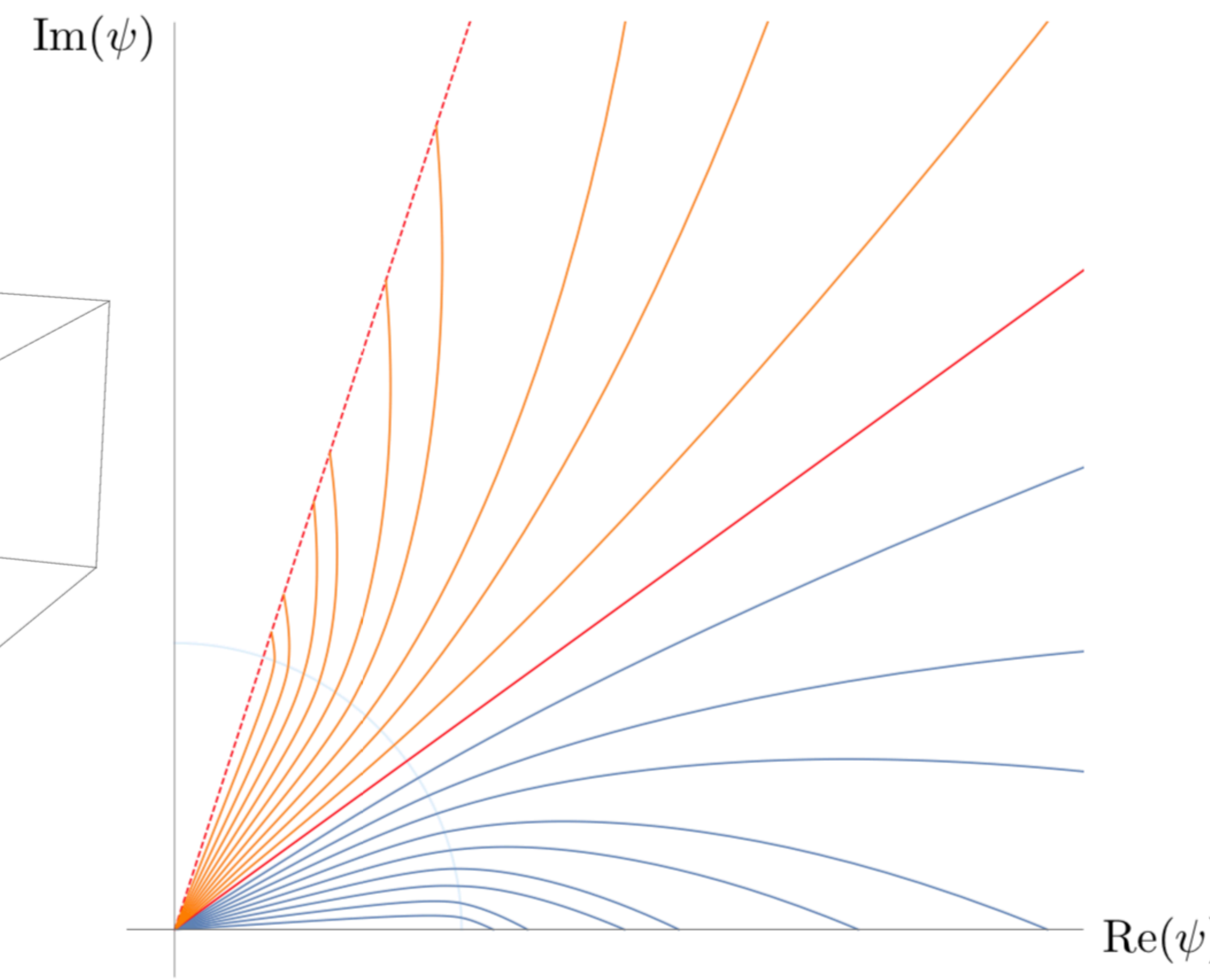
- **Necessary steps:**
- Compute metric, mirror map as described
- Determine the interesting regions in the moduli space (here: Landau-Ginzburg)
- Solve the geodesic equation numerically $\frac{d^2 x^\mu}{d\tau^2} + \Gamma^\mu_{\alpha\beta} \frac{dx^\alpha}{d\tau} \frac{dx^\beta}{d\tau} = 0$
- Check consistency with the RSDC

The Quintic

Metric



Geodesics



Results

- **Find distances 0.42-0.45** inside the LG phase
- Θ_λ varies because geodesics curve in axion direction

$$\boxed{\Theta_0 \leq 0.45} \qquad \boxed{\Theta_\lambda < 1}$$

$\theta_{\text{init}} \cdot 60/\pi$	α_0	α_1	λ^{-1}	Θ_0	Θ_c
3	0.1315	0.2043	0.9605	0.4262	1.3866
4	0.1127	0.2099	0.9865	0.4261	1.4125
5	0.0998	0.2213	0.9780	0.4260	1.4040
6	0.0955	0.2294	0.9567	0.4259	1.3827
7	0.0818	0.2475	0.9611	0.4259	1.3869
8	0.0877	0.2592	0.9275	0.4258	1.3533
9	0.0808	0.2825	0.9253	0.4257	1.3510
10	0.0929	0.3093	0.8969	0.4257	1.3226
11	0.0998	0.3497	0.8845	0.4257	1.3102
12	0.1234	0.1662	0.8657	0.4256	1.2914

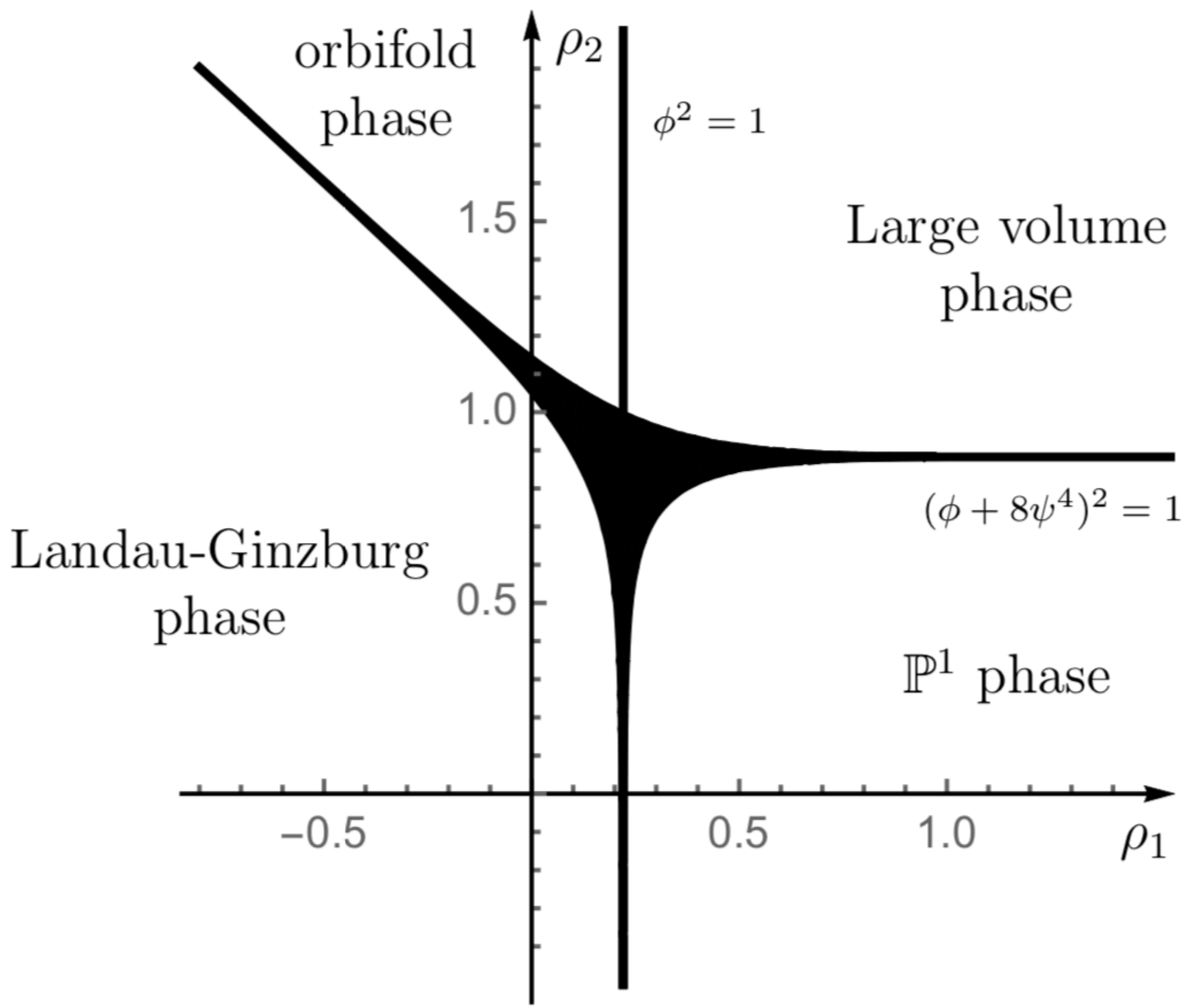
- Analyse all CYs with $h^{11} = 1$ given by hypersurfaces in $W\mathbb{C}P$, namely

$$\mathbb{P}^4_{11112}[6] \qquad \mathbb{P}^4_{11114}[8] \qquad \mathbb{P}^4_{11125}[10]$$

- **All results in agreement with the RSDC, quintic is extremal**

$$\boxed{\Theta_c \equiv \Theta_0 + \Theta_\lambda \leq 1.4}$$

Models With $h^{11} = 2$



[Aspinwall '94]

new feature:
hybrid phases

Everything consistent with the RSDC!

See talk by Florian Wolf

The Mirror Quintic: $h^{11} = 101$

$$P = x_1^5 + x_2^5 + x_3^5 + x_4^5 + x_5^5 + \psi x_1 x_2 x_3 x_4 x_5 + 100 \text{ other terms}$$

- Recent advances allow us to compute the **Kähler metric for the Landau-Ginzburg phase of the mirror quintic** [Aleshkin, Belavin '17]
- Computing geodesics in a 101 dimensional space numerically is hopeless
- Group deformations into equivalence classes under coordinate permutations

  $\longrightarrow$ left with 5 sets of deformations of cardinality (1, 20, 30, 30, 20)
- Compute proper lengths of collective displacements
- Compelling: $\Theta_0 \sim \dfrac{1}{\#\text{fields}}$
- No parametric enhancement of Θ_0 in this way.

direction	$\Delta\Theta$
Φ_0	0.4656
Φ_1	0.0082
Φ_2	0.0670
Φ_3	0.0585
Φ_4	0.0089

$$\boxed{\frac{\Theta_0}{\text{phase}} \#(\text{phases}) \leq M_{\text{pl}} \ ?}$$

Implications for Cosmology

Large Field Inflation

- Under pressure from several swampland conjectures
  - WGC constrains natural inflation
  - All models of large field inflation in tension with RSDC
  - OOSV $|V'|/V > c = \mathcal{O}(1)$ puts pressure on slow roll [Obied, Ooguri, Spodyneiko, Vafa '18]

Dark Energy

- If dS is in the swampland, what about quintessence?
- Borderline consistent with the OOSV conjecture, RSDC [Agrawal, Obied, Steinhardt, Vafa '18]

Are we missing something fundamental?

Conclusion

- Refined Swampland Distance Conjecture passes many non-trivial tests in Calabi-Yau moduli spaces
- Diameter of non-geometric phases seems to approach zero as $h^{11} \to \infty$
- Our analysis is case by case - it would be good to have a general argument!
- Many of the swampland conjectures turn out to be tightly related. Does this fact rely on supersymmetry? Are there further relations?

Thank You