String Theory

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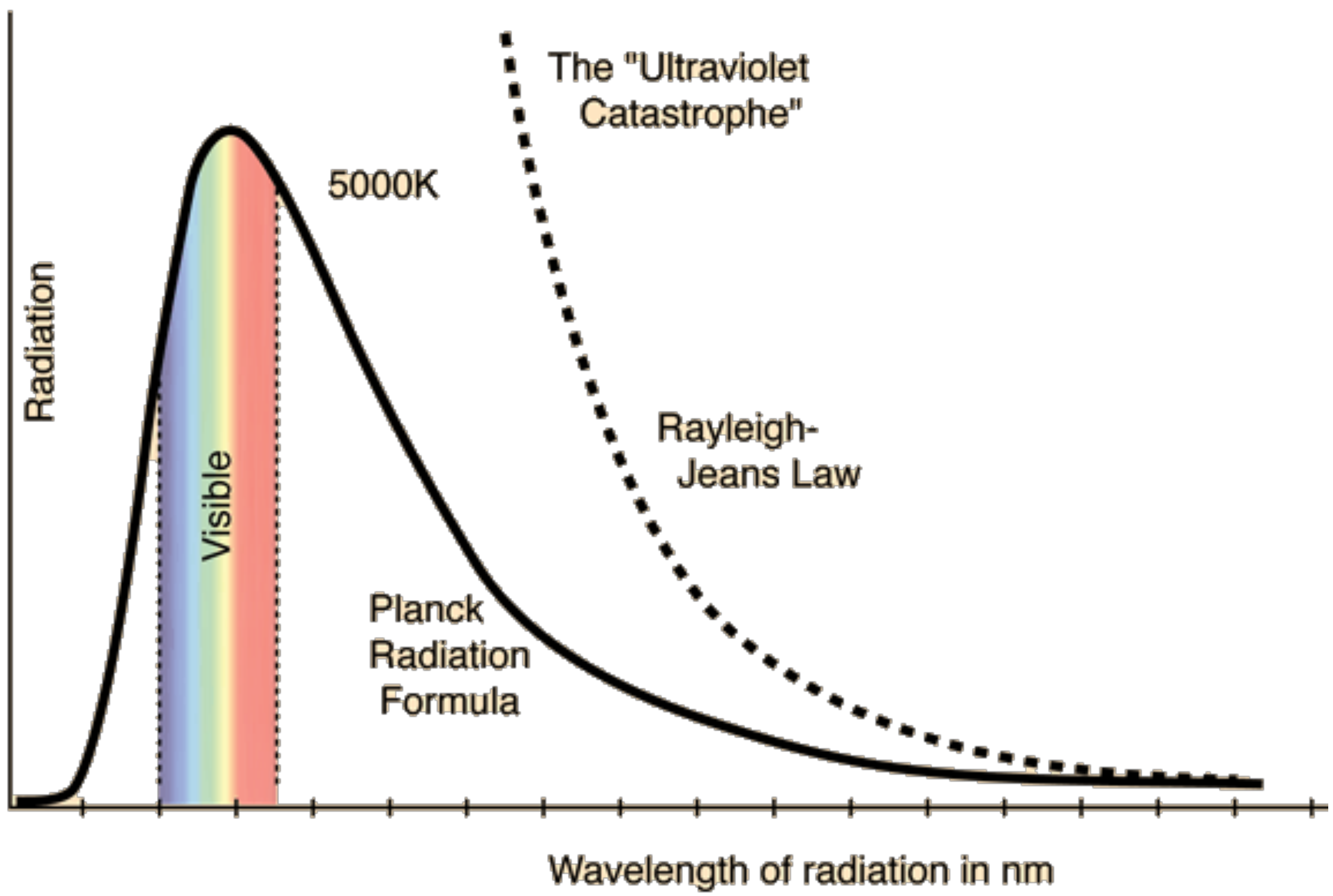
The beginning

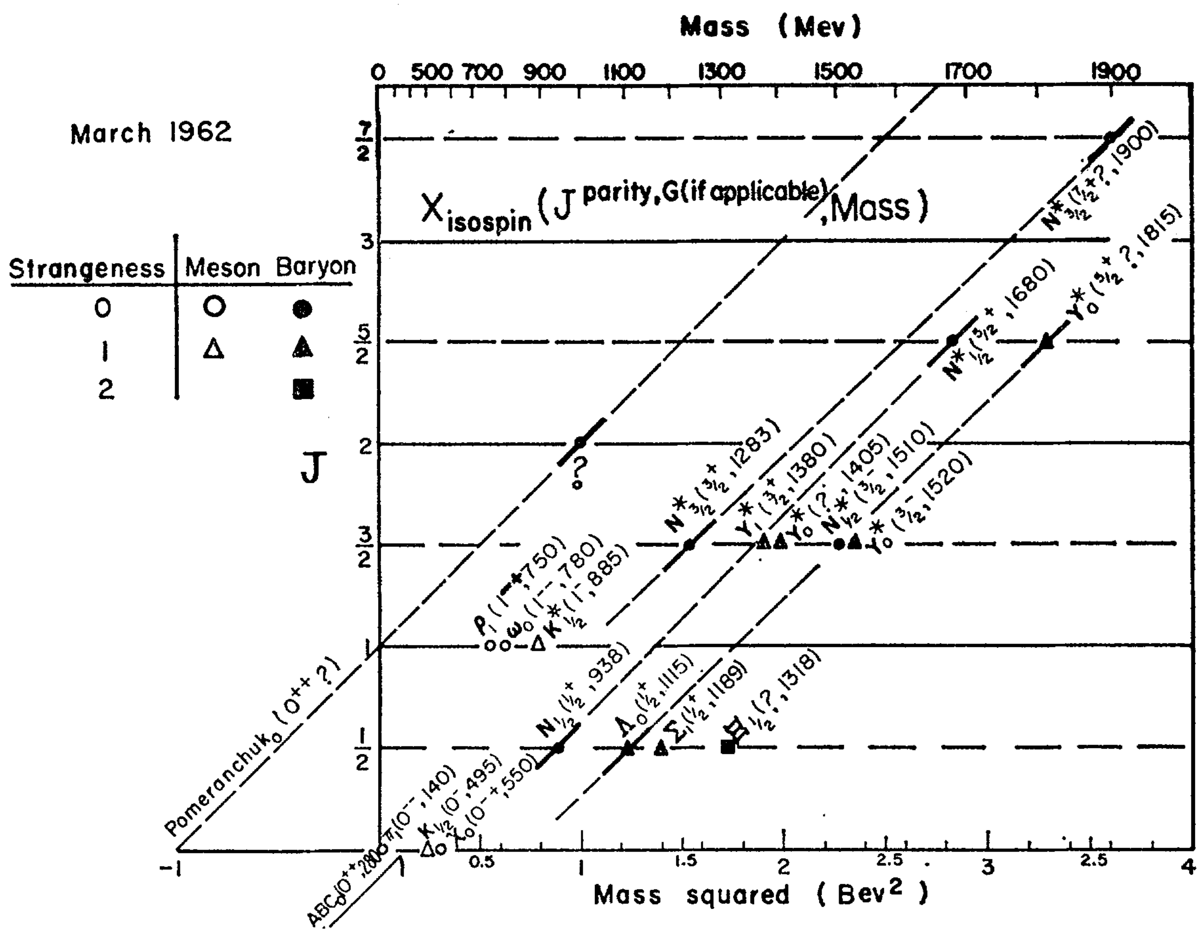
- Physicists are great in turning lemons into lemonade:



- This ingenious observation of Planck gave birth to the quantum revolution.

The beginning

- String theory owes its roots to **particle physics**:



$$M^2 \sim J/\alpha'$$

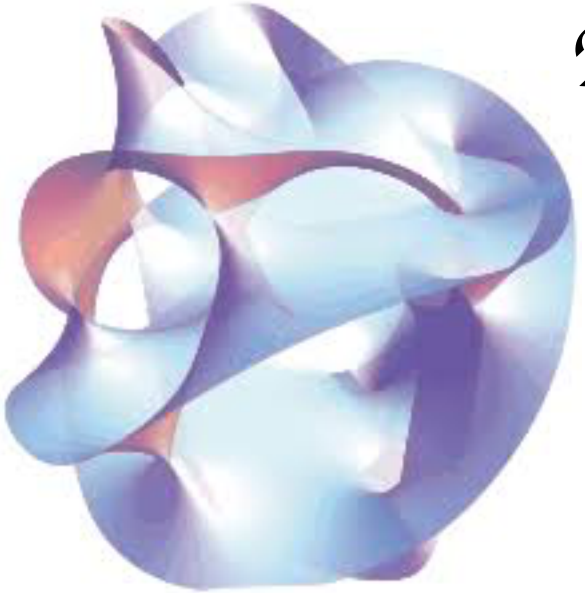
$$\text{where } \alpha' \sim 1(GeV)^{-2}$$

- There always ∃ a massless spin 2 resonance, which is not in the observed hadron spectrum.
- This is the **graviton** **[Yoneya, '73];[Scherk, Schwarz, '74]**: string theory is not only a theory of elementary particles but a **quantum theory of gravity**!

Strings Meet Phenomenology

- After the discovery of anomaly cancellation **[Green, Schwarz, '84]**, it was soon realized that string theory provides a consistent framework for **unifying particle physics with gravity.**
- This is followed by **the heterotic string** **[Gross, Harvey, Martinec, Rohm,'85]** and **Calabi-Yau compactification** **[Candelas, Horowitz, Strominger, Witten, '85].**
- To make contact with phenomenology:

X



$\mathcal{M}_{6d}$

- Physical properties of our universe (# of families, particle's quantum numbers and couplings, etc) are encoded by the size and shape of the extra dimensions.

String Theory Landscape

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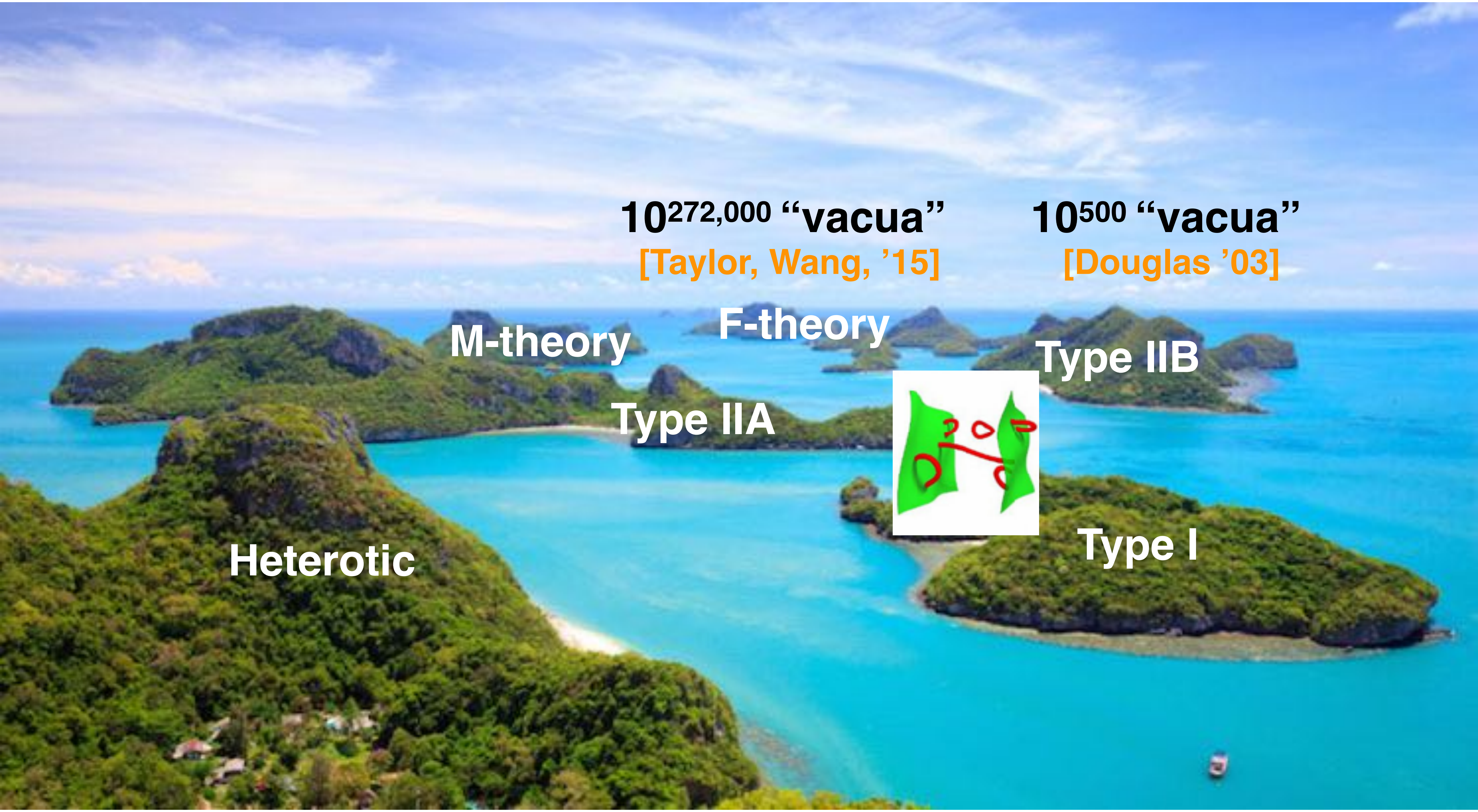


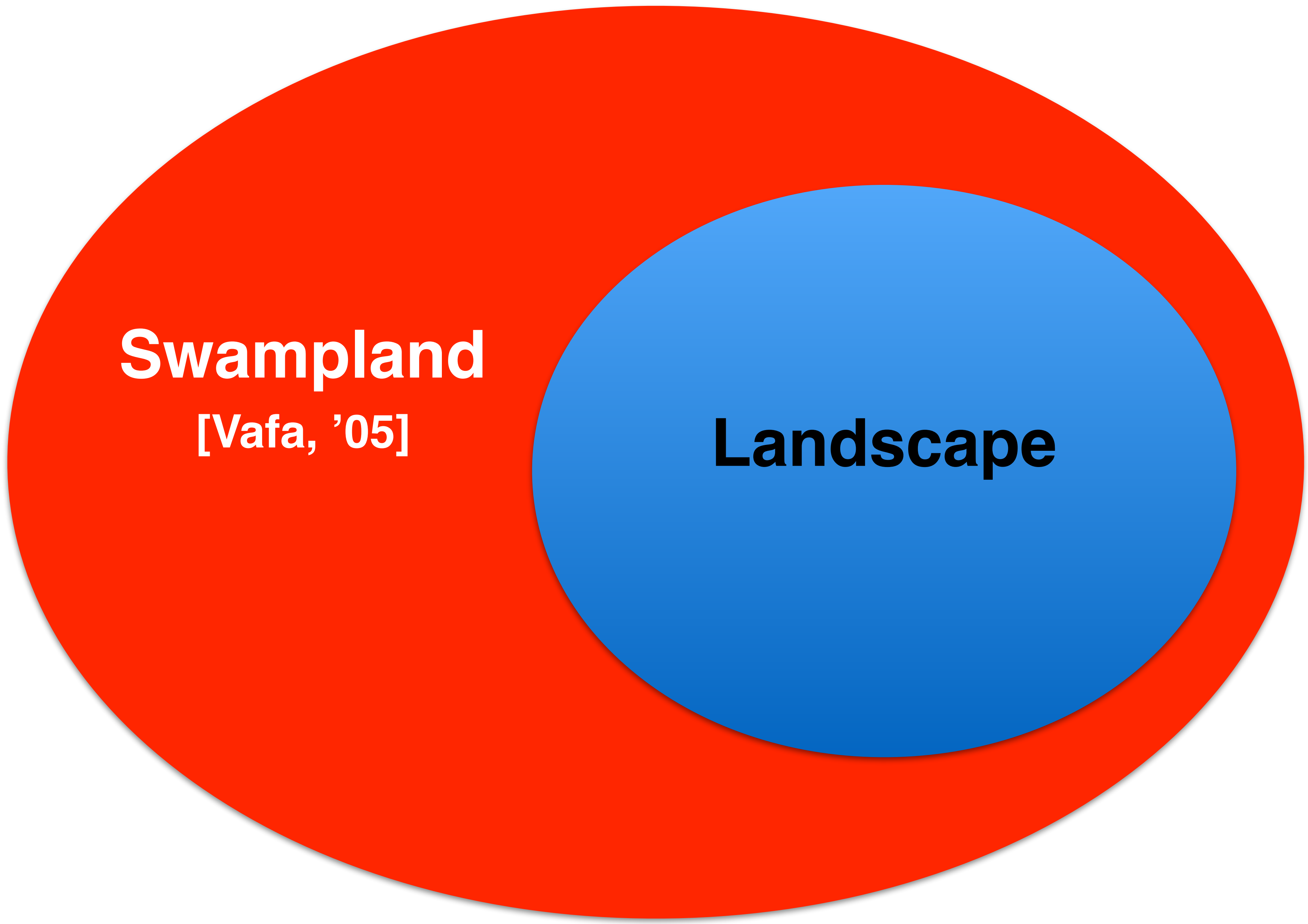
String Landscape and Phenomenology

- String theory seems to admit a vast number of 4d solutions
- They represent an enormously rich landscape of EFTs
  - Field theoretical ideas in particle physics and cosmology have found their UV realizations in string theory.
  - New scenarios have been uncovered along the way.
- This traditional approach leaves the impression that every consistent-looking EFT can be embedded in string theory

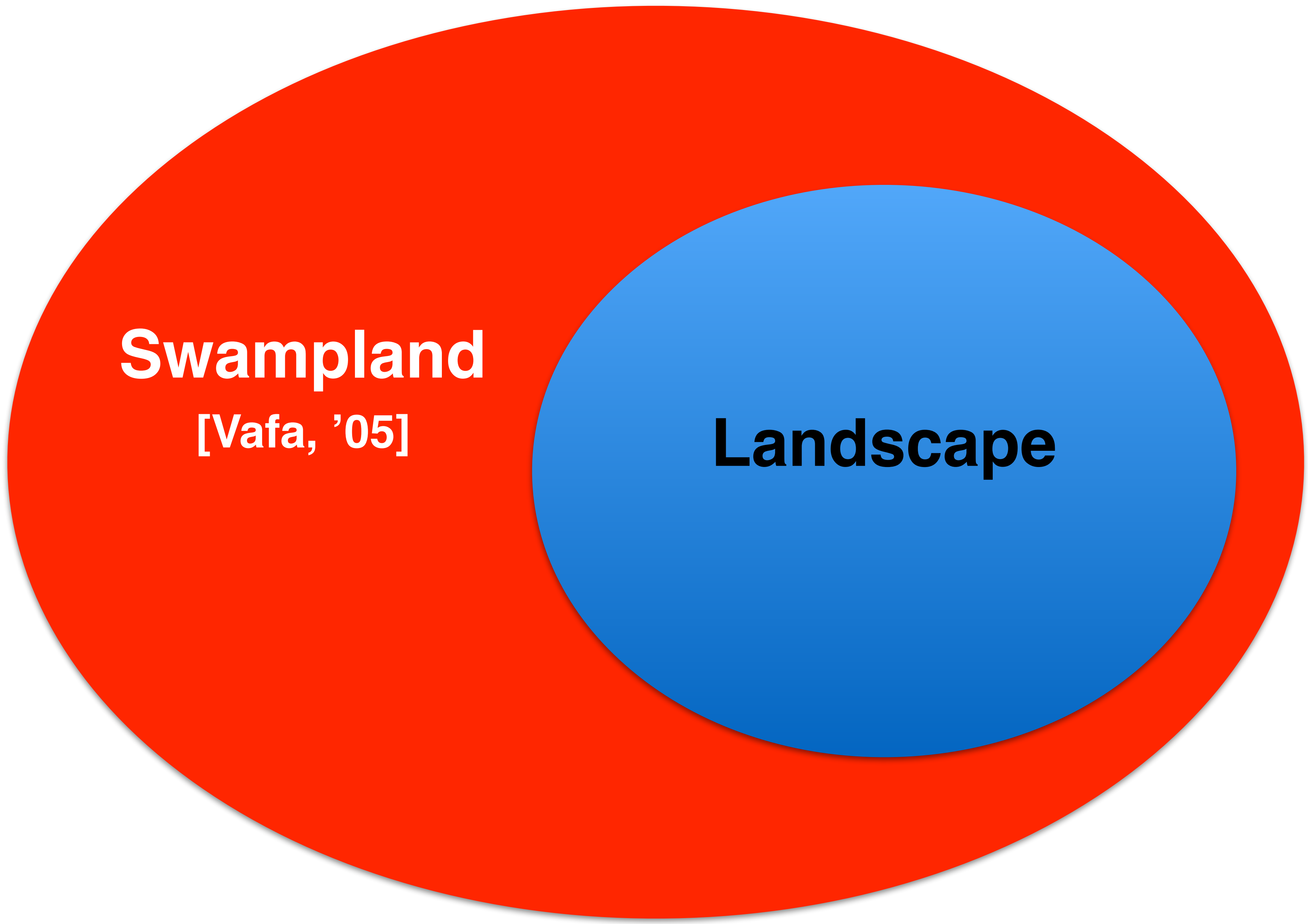
Are there low energy effective theories that are ***not*** embeddable in string theory?

Landscape vs Swampland

Landscape vs Swampland



Landscape vs Swampland



What properties delineate the landscape from the swampland?

What are the phenomenological consequences?

Swampland Conjectures

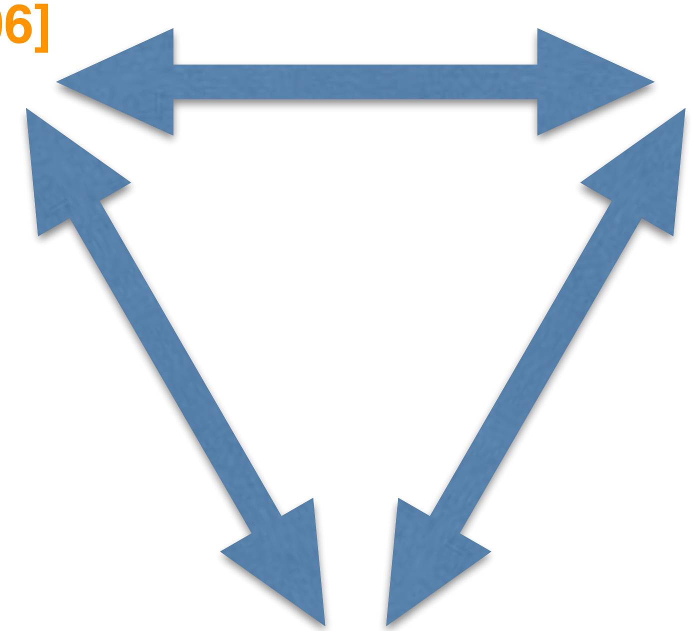
We don't have yet theorems that fully delineate the landscape from the swampland, but ∃ an intricate web of well-tested conjectures:

Weak Gravity Conjecture

[Arkani-Hamed, Motl, Nicolis, Vafa. '06]

Distance Conjecture

[Ooguri, Vafa. '06]



dS Conjecture

[Obied, Ooguri, Spodyneiko, Vafa,'18]; [Ooguri, Palti, GS, Vafa, '18]

These conjectures were developed based on general properties of quantum gravity (e.g., black holes) and string constructions.

Quantum Gravity and Global Symmetries

Quantum Gravity and Global Symmetries

- **Global symmetries** are expected to be violated by gravity:

  - **No hair theorem:** Hawking radiation is insensitive to Q.
    - ➡ Infinite number of states (remnants) with $m \lesssim M_p$
    - ➡ Violation of entropy bounds. At finite temperature (e.g. in Rindler space), the density of states blows up.

      Susskind '95

  - **Swampland conjecture**: theories with exact global symmetries are not UV-completable.

  - In (perturbative) string theory, all symmetries are gauged **[Banks, Dixon, '88];** recently revisited using holography **[Harlow, Ooguri, '18].**

  - Many phenomenological ramifications, e.g., milli-charged DM comes with a new massless gauge boson **[GS, Soler, Ye, '13].**

The Weak Gravity Conjecture

Arkani-Hamed, Motl, Nicolis, Vafa '06

The Weak Gravity Conjecture

- The conjecture: **[Arkani-Hamed, Motl, Nicolis, Vafa]**

"Gravity is the Weakest Force"

- This is a scale-dependent statement, but as we'll see, the WGC comes with a UV cutoff Λ (magnetic WGC).
- For every long range gauge field there exists a particle of charge q and mass m, s.t.

$$\frac{q}{m} M_P \geq \text{“}1\text{”}$$

- Proving and sharpening this conjecture has been an active research area **[Brown, Cottrell, GS, Soler];[Cottrell, GS, Soler];[Montero, GS, Soler]; [Andriolo, Junghans, Noumi, GS]; [Hamada, Noumi, GS] (and many others…).**
- Applying the WGC to magnetically charged states imply:

$$q_{mag} \sim 1/g, \quad m_{mag} \sim \Lambda/g^2 \quad \Rightarrow \quad \Lambda \lesssim g(\Lambda) M_P$$

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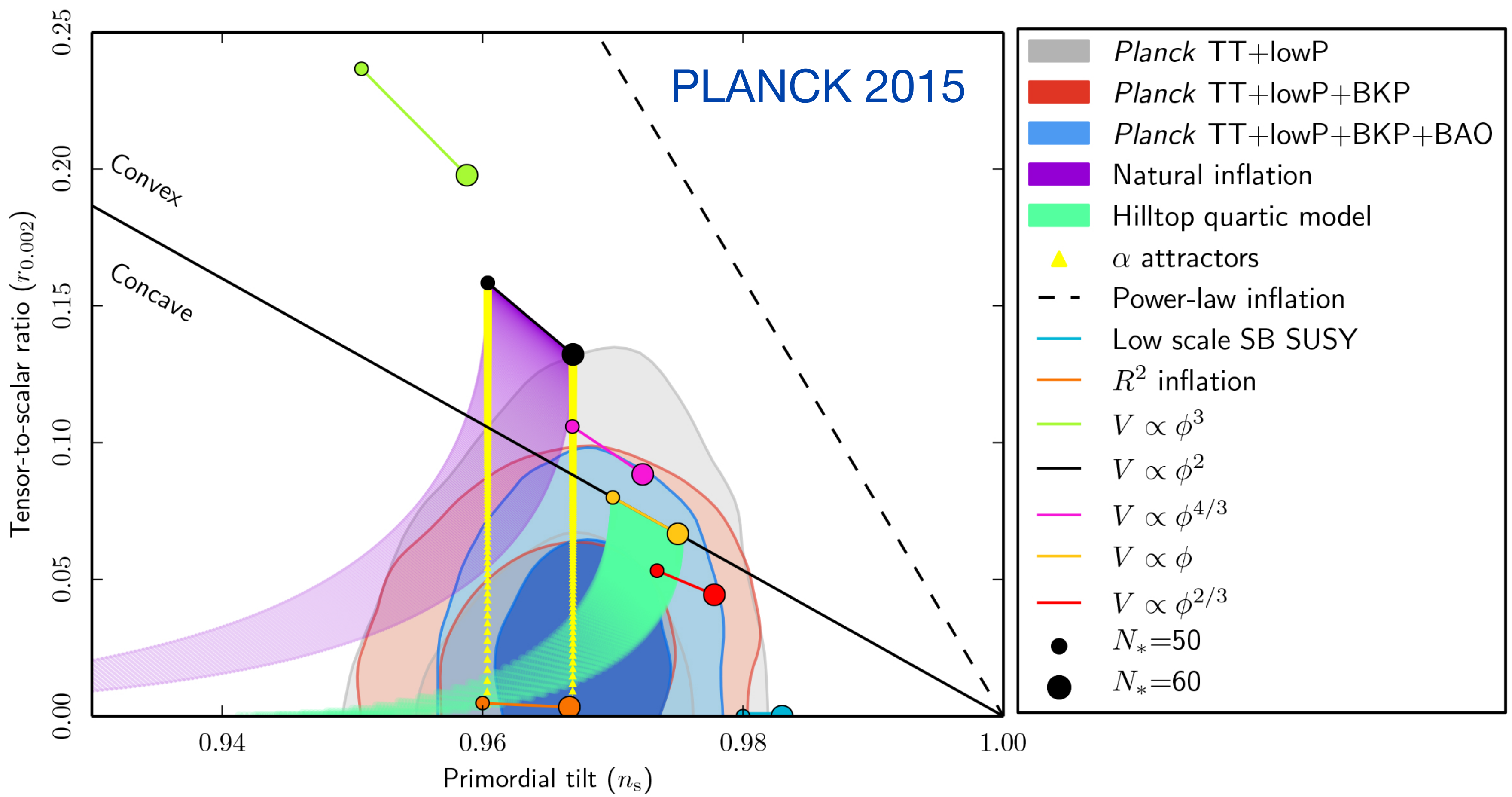
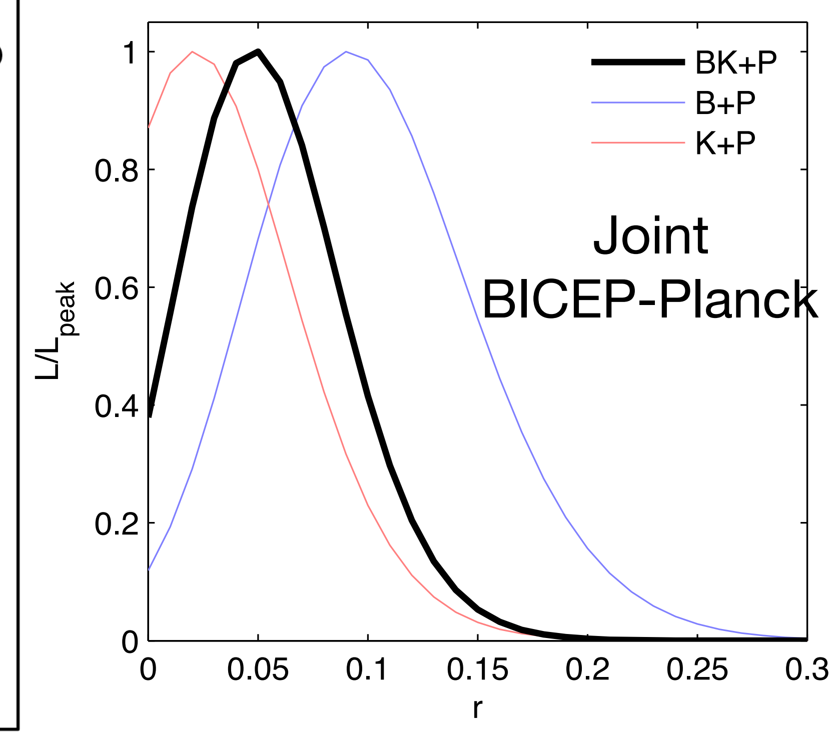
WGC and Inflation

Primordial Gravitational Waves





Many experiments including BICEP/KECK, PLANCK, ACT, PolarBeaR, SPT, SPIDER, QUEIT, Clover, EBEX, QUaD, … can potentially detect primordial B-mode at the sensitivity r~10^{-2}.

Further experiments, such as CMB-S4, PIXIE, LiteBIRD, DECIGO, Ali, .. may improve further the sensitivity to eventually reach r ~ 10^{-3}.

B-mode and UV Sensitivity

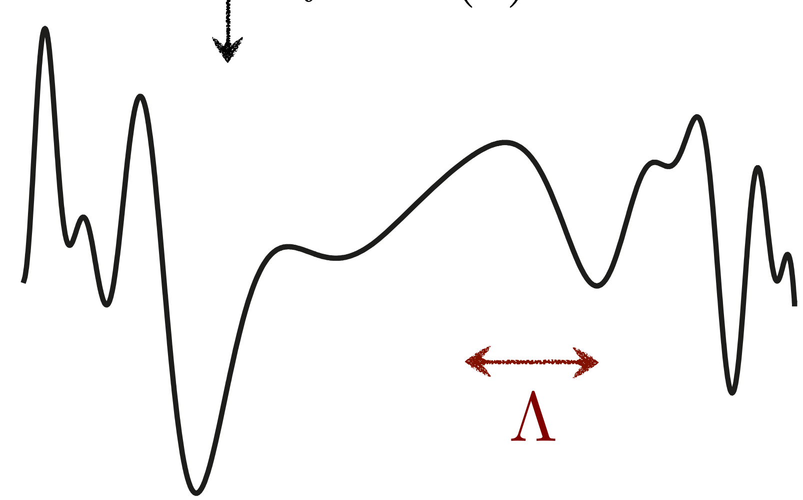
A detection at the targeted level implies that the inflaton potential is nearly flat over a **super-Planckian** field range:

$$\Delta\phi \gtrsim \left(\frac{r}{0.01}\right)^{1/2} M_{\rm Pl}$$

Lyth '96

$$\mathcal{L}_{\rm eff}[\phi] = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2\left(1 + \sum_{i=1}^{\infty} c_i \frac{\phi^{2i}}{\Lambda^{2i}} + \cdots\right)$$

$$\Big\downarrow \; c_i \sim \mathcal{O}(1)$$



"Large field inflation" are highly **sensitive to UV physics**

Axions and ALPs

The QCD axion [Wilczek, '78]; [Weinberg, '78] was introduced in the context of the Pecci-Quinn mechanism and the strong CP problem.

An axion enjoys a **perturbative shift symmetry.**

String theory has many **higher-dimensional form-fields,** which when reduced on the internal space give 0-form ***axion-like particles* (ALPs)**:

$$a(x) \equiv \int_{\Sigma_p} A_p$$

The gauge symmetry becomes a **shift symmetry,** that is broken by non-perturbative (instanton) effects**.**

The WGC for a 0-form field:

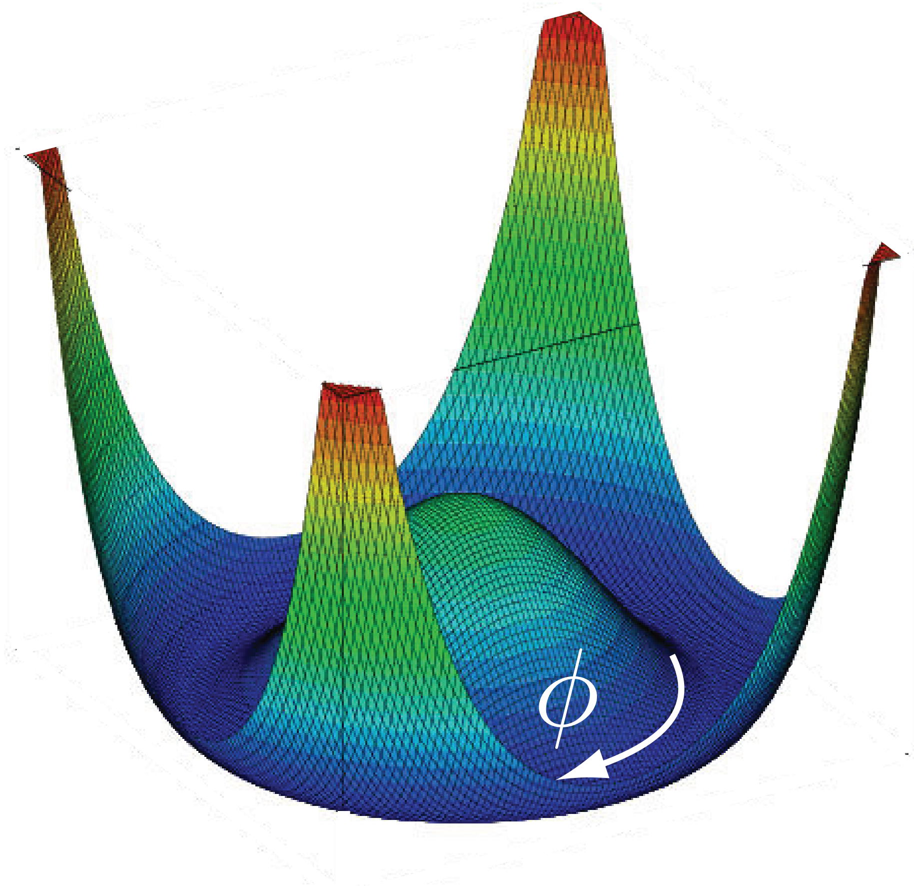
$$\boxed{f \cdot S_{inst} \leq M_p}$$

More generally, using duality: Brown, Cottrell, GS, Soler, '15

Axions & Large Field Inflation

Natural Inflation [Freese, Frieman, Olinto]

Pseudo-Nambu-Goldstone bosons are natural inflaton candidates.



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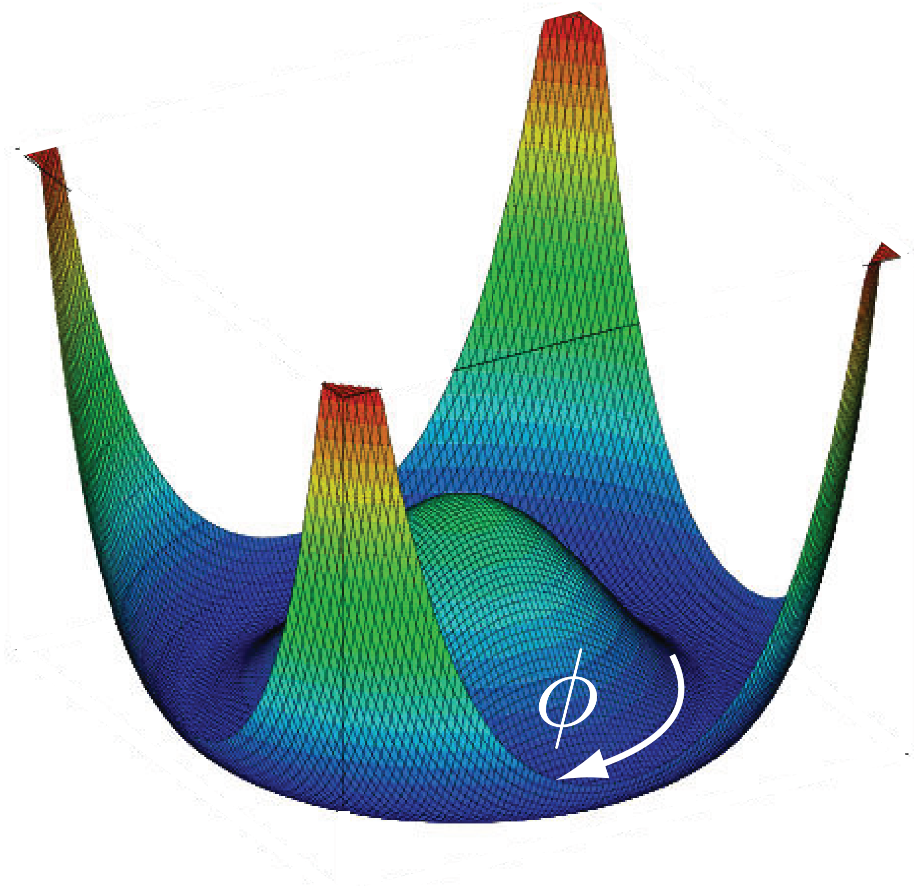
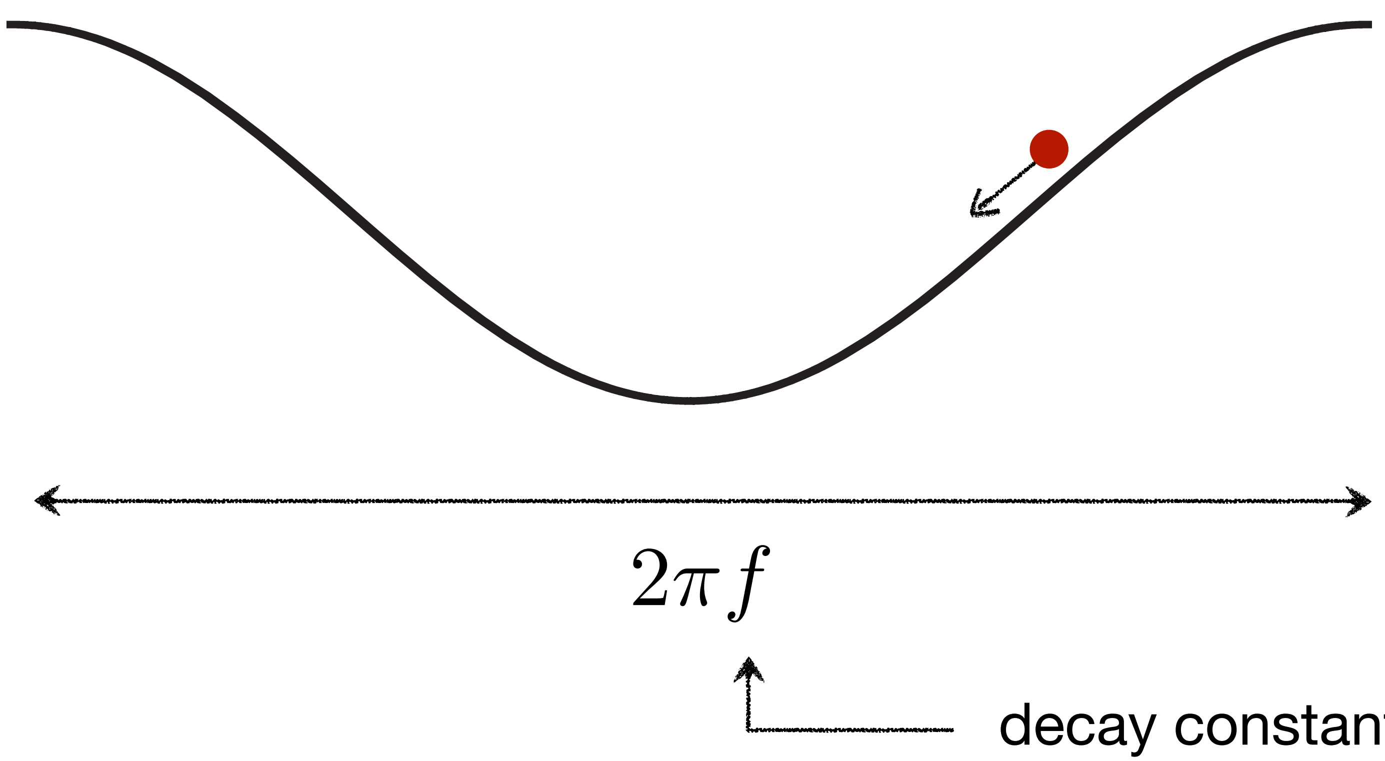


They satisfy a shift symmetry that is only broken by non-perturbative effects:



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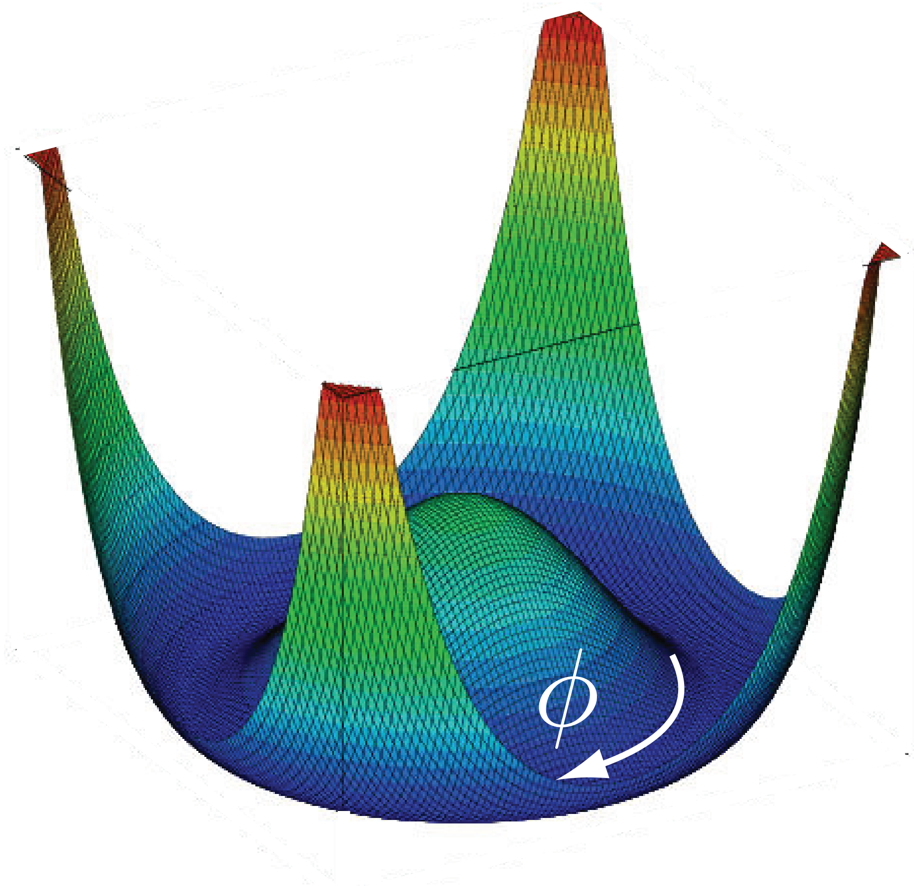

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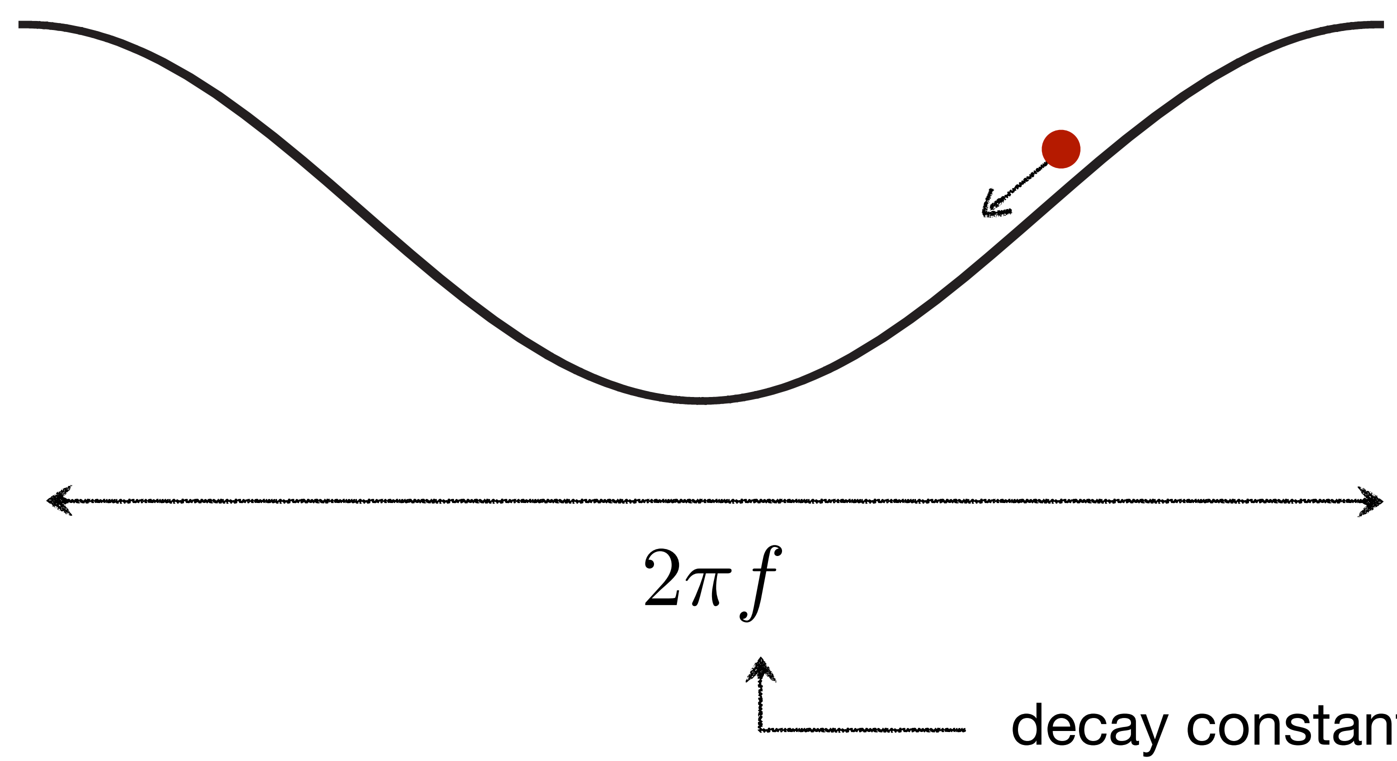

Slow roll: $f > M_P$

$$V(\phi) = 1 - \Lambda^{(1)} \cos\left(\frac{\phi}{f}\right) + \cancel{\sum_{k>1} \Lambda^{(k)} \left[1 - \cos\left(\frac{k\phi}{f}\right)\right]} \quad \text{if} \quad \frac{\Lambda^{(n+1)}}{\Lambda^{(n)}} \sim e^{-S_{\text{inst}}} << 1$$

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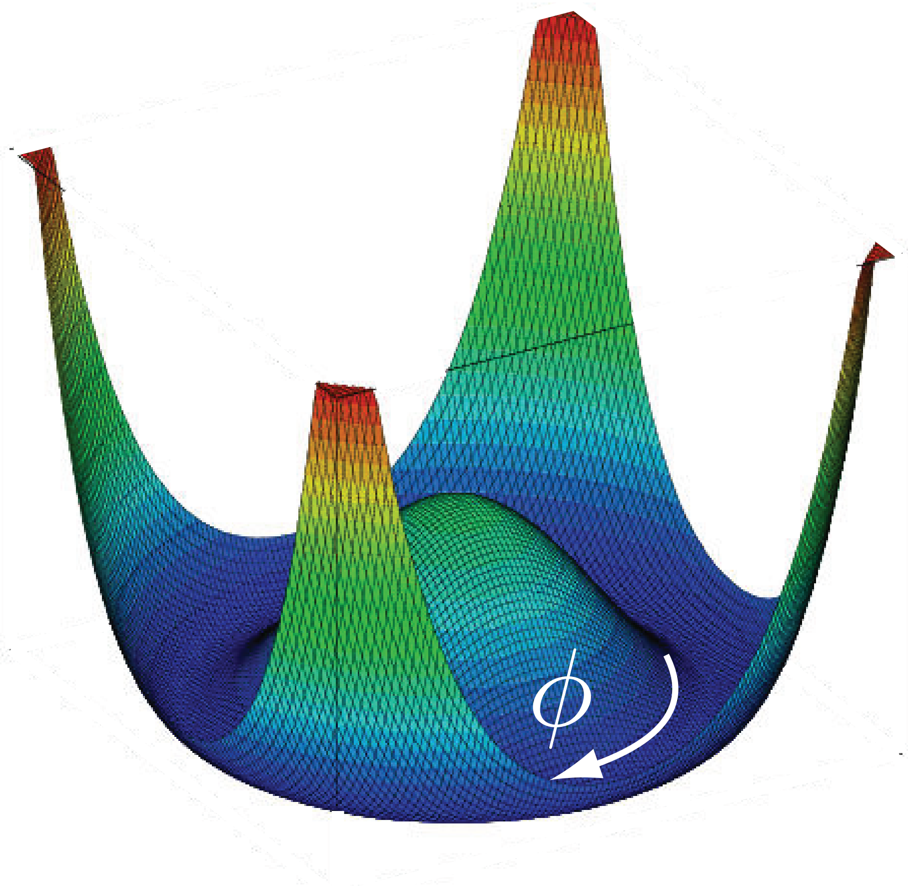

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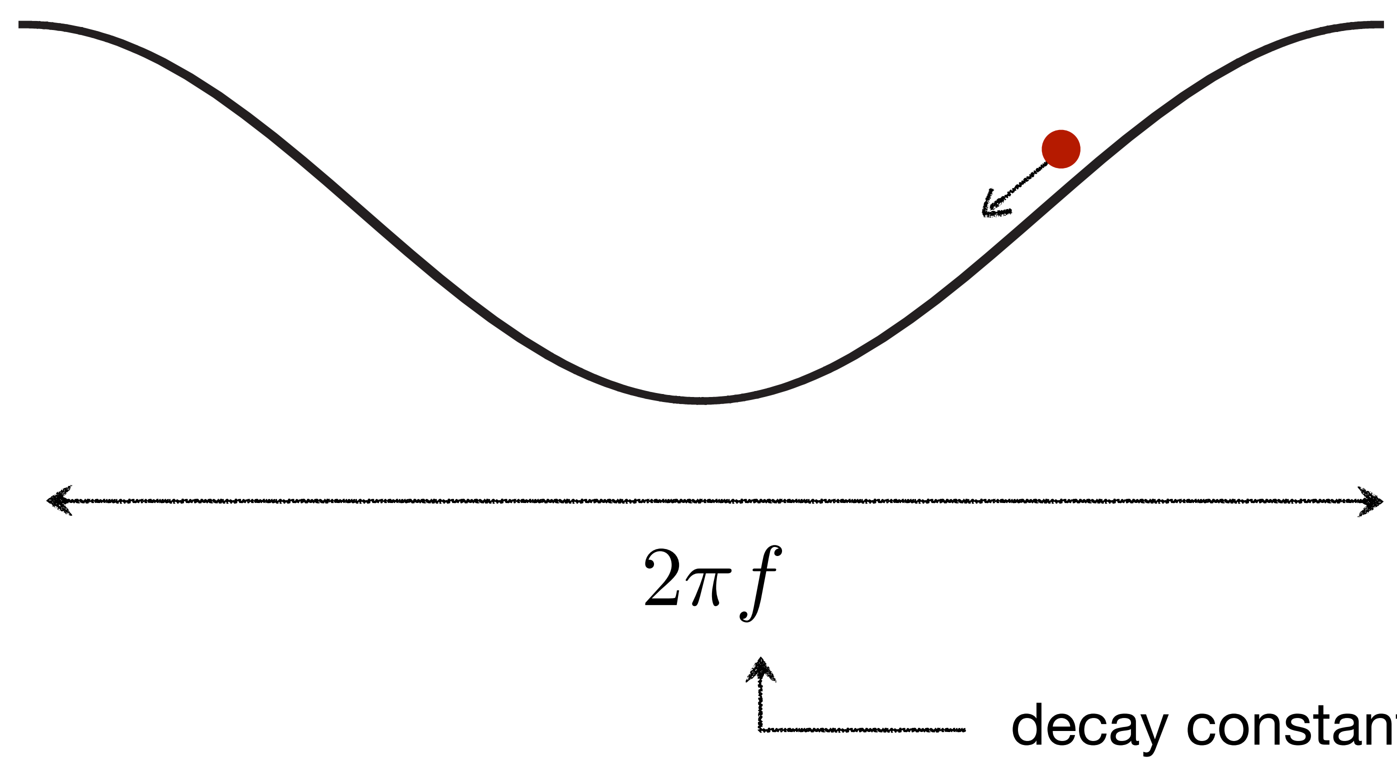

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The WGC implies that these conditions cannot be *simultaneously* satisfied.

WGC and Axion Inflation

- Models with multiple axions (N-flation, KNP-alignment,…) have been proposed to obtain large field ranges
  - The WGC in all direction in charge space (i.e. requiring all extremal black holes to be unstable) constrains these models

Brown, Cottrell, GS, Soler, '15…

- ∃ Loopholes (e.g., spectator instantons).
- Axion monodromy is an interesting exception.

[Silverstein, Westphal];[McAllister, Silverstein, Westphal]; [Marchesano, GS, Uranga]

It is however subject to other swampland constraints (e.g., distance conjecture) though models with $\Delta\phi \sim$ 5-10 M_P seems compatible with quantum gravity [Landete, GS, '18]

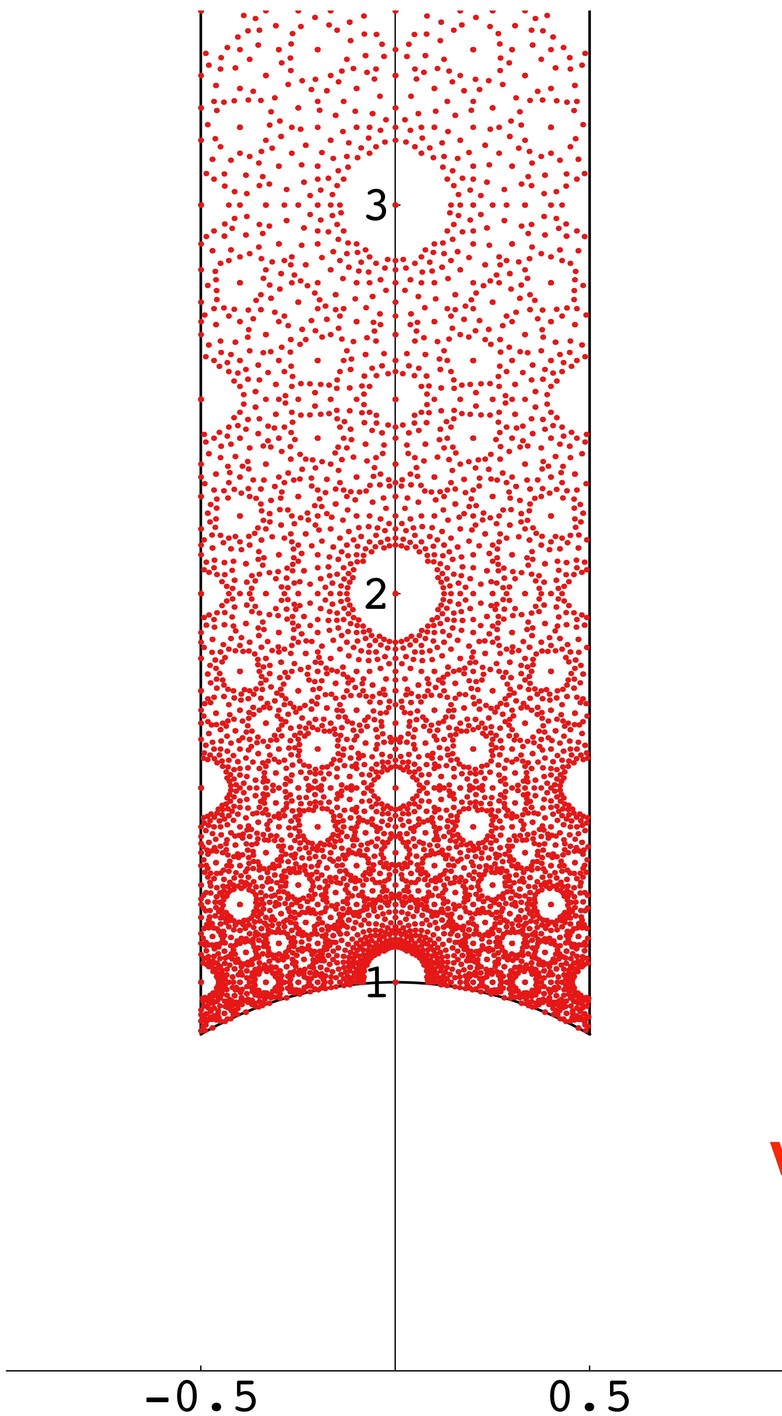
Other Swampland Applications

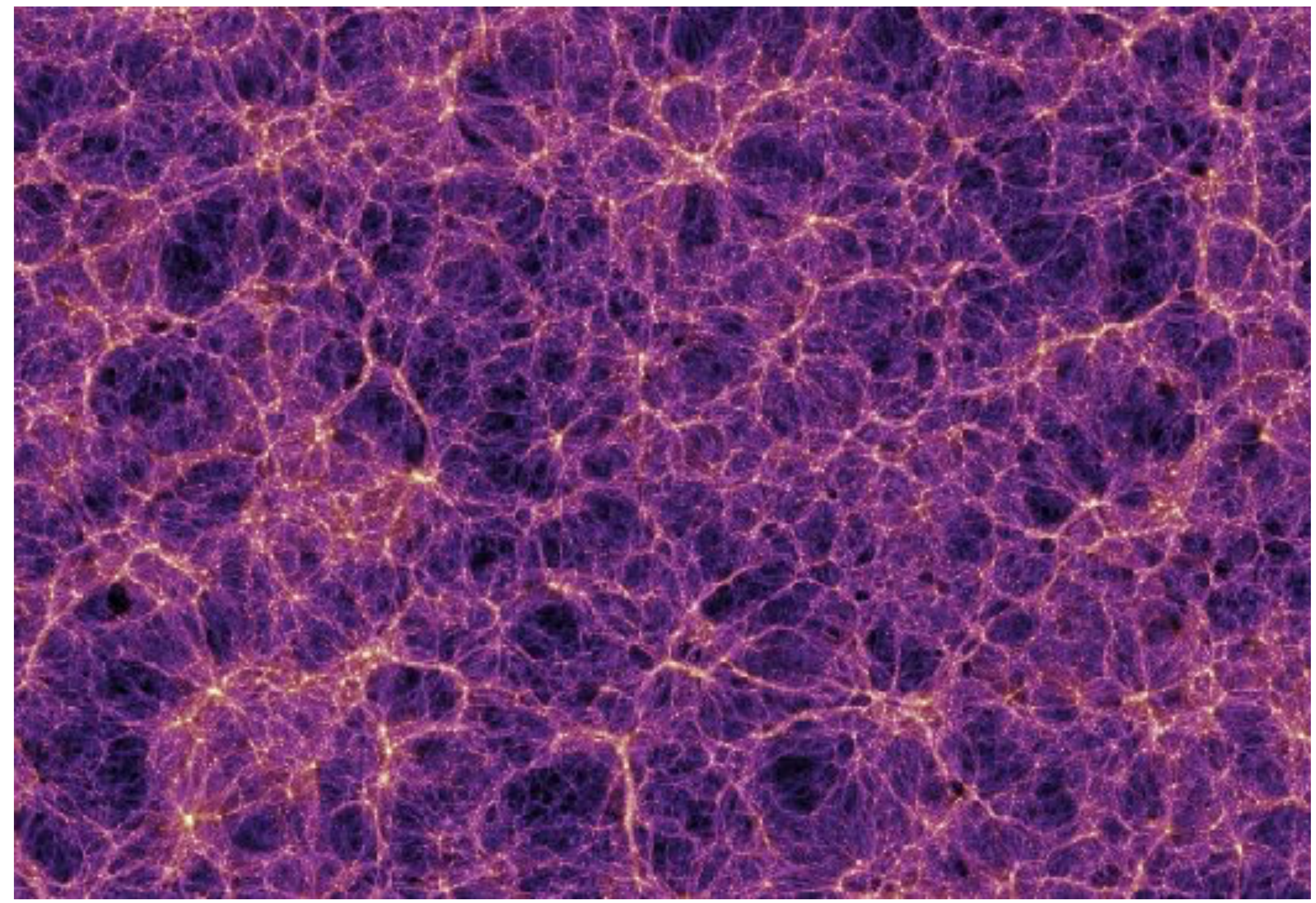
- The Swampland program attempts to clarify the formulation, motivation and applications of several consistency criteria:
  - No global symmetries -> Mini-charged DM.
  - Weak Gravity Conjecture -> Large field (natural) inflation, Fuzzy DM
  - Large distances in moduli space -> Axion monodromy inflation.
  - Instability of non-SUSY AdS -> Neutrino physics? **[Ooguri, Vafa, '16]; [Ibanez, Martin-Lozano, Valenzuela, '17];[Hamada, GS, '17]**
  - No dS -> Inflation, CC, quintessence **[Obied, Ooguri, Spodyneiko, Vafa, '18]; [Ooguri, Palti, GS, Vafa, '18]**
  - Consistency of string/brane probes limit the particle spectrum coupled to quantum gravity **[Kim, GS, Vafa, '19]**
- Despite recent intense effort, much work remains to be done to fully understand the origin and consequences of these conjectures.

String Theory and Data Science

About 25 papers written since 2017, ranging from using **topological data analysis** to analyze the structure of the landscape **[Cole, GS '17, '18]** to using **genetic algorithms** **[Cole, Schachner, GS, '19]** and **machine learning** **[Ruhle, '17]; [Mutter, Parr, Vaudrevange, '18];[Halverson, Nelson, Ruhle, '19]** to search for phenomenologically interesting string vacua

Structure of the String Landscape

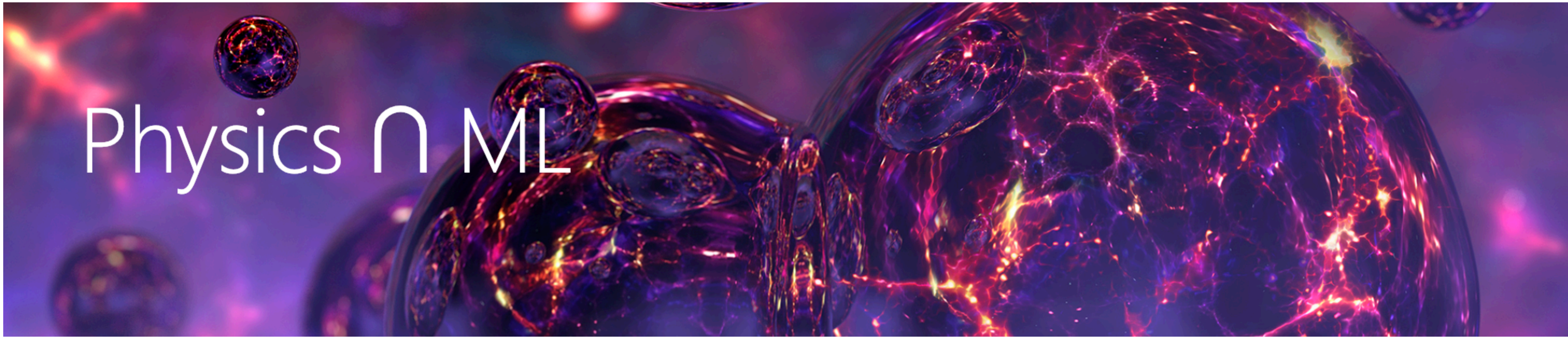




Distribution of string vacua (projected to 2D) contains voids and clusters, resembling the LSS of our universe!

Topological data analysis has been used to analyze the structure of the landscape [Cole, GS, ’17, ’18].

Microsoft | Research



Overview

Region: North America

Date: April 25, 2019 - April 26, 2019

Location: Redmond, Washington, USA

Venue: Microsoft Research Building 99/1919
Redmond, Washington, USA

About Agenda

The goal of *Physics ∩ ML* (read 'Physics Meets ML') is to bring together researchers from machine learning and physics to learn from each other and push research forward together. In this inaugural edition, we will especially highlight some amazing progress made in string theory with machine learning and in the understanding of deep learning from a physical angle. Nevertheless, we invite a cast with wide ranging expertise in order to spark new ideas. Plenary sessions from experts in each field and shorter specialized talks will introduce existing research. We will hold moderated discussions and breakout groups in which participants can identify problems and hopefully begin new collaborations in both directions. For example, physical insights can motivate advanced algorithms in machine learning, and analysis of geometric and topological datasets with machine learning can yield critical new insights in fundamental physics.

Please contact an organizing member if you wish to participate in this workshop.

Organizers

Greg Yang, Microsoft Research
Jim Halverson, Northeastern University
Sven Krippendorf, LMU Munich
Fabian Ruehle, CERN, Oxford University
Rak-Kyeong Seong, Tsinghua University
Gary Shiu, University of Wisconsin

Microsoft Advisers

Chris Bishop, Microsoft Research
Jennifer Chayes, Microsoft Research
Michael Freedman, Microsoft Research
Paul Smolensky, Microsoft Research

5 international meetings on this theme have taken place and more to come:
Boston (11/17), Munich (03/18), Sanya (06/18), Trieste (12/18), Seattle (04/19)

Summary

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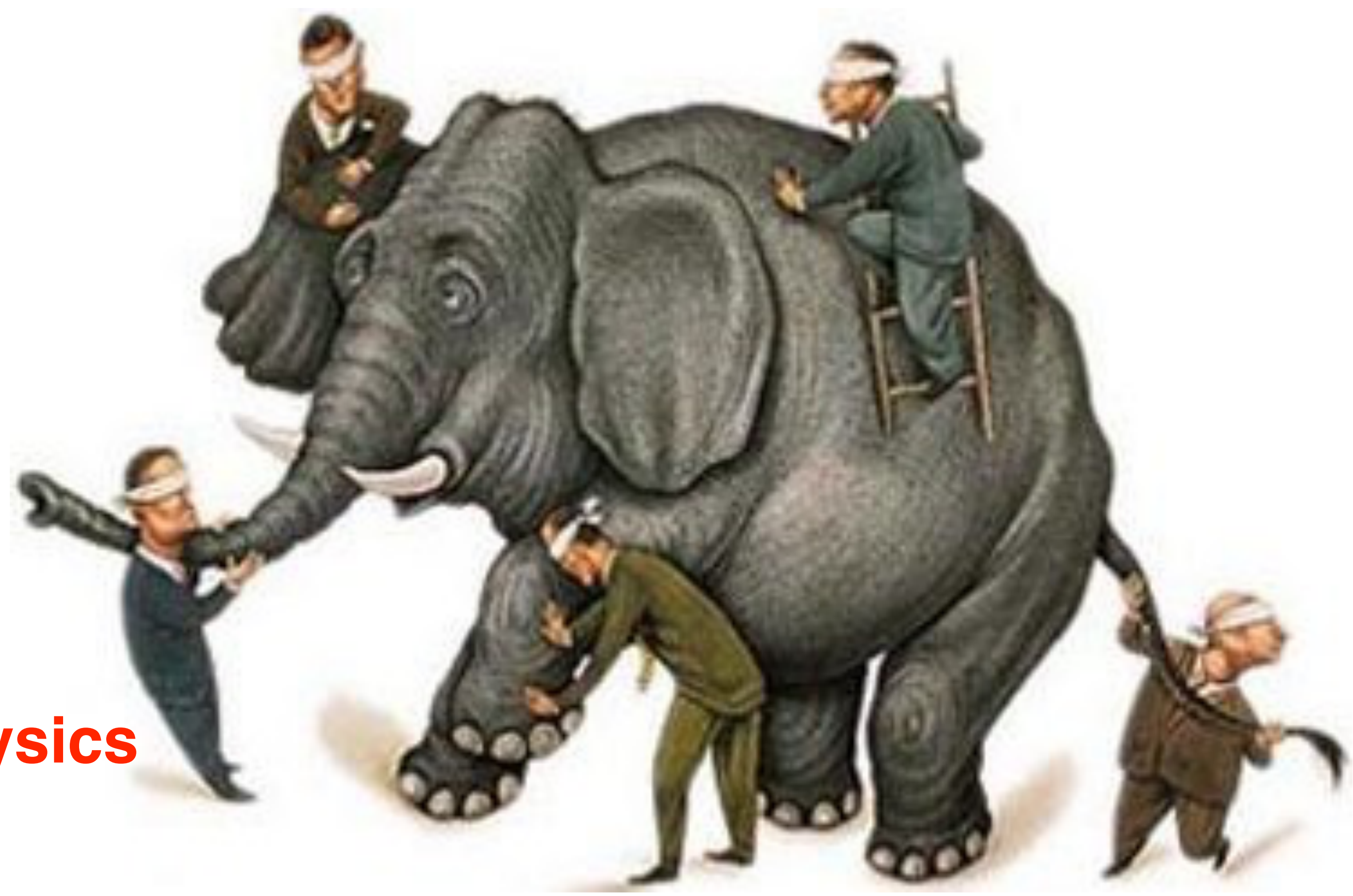
- String theory continues to be a vital field that offers insight into particle physics and cosmology, but it has become much more than one'd have anticipated:



Particle Physics

Cosmology

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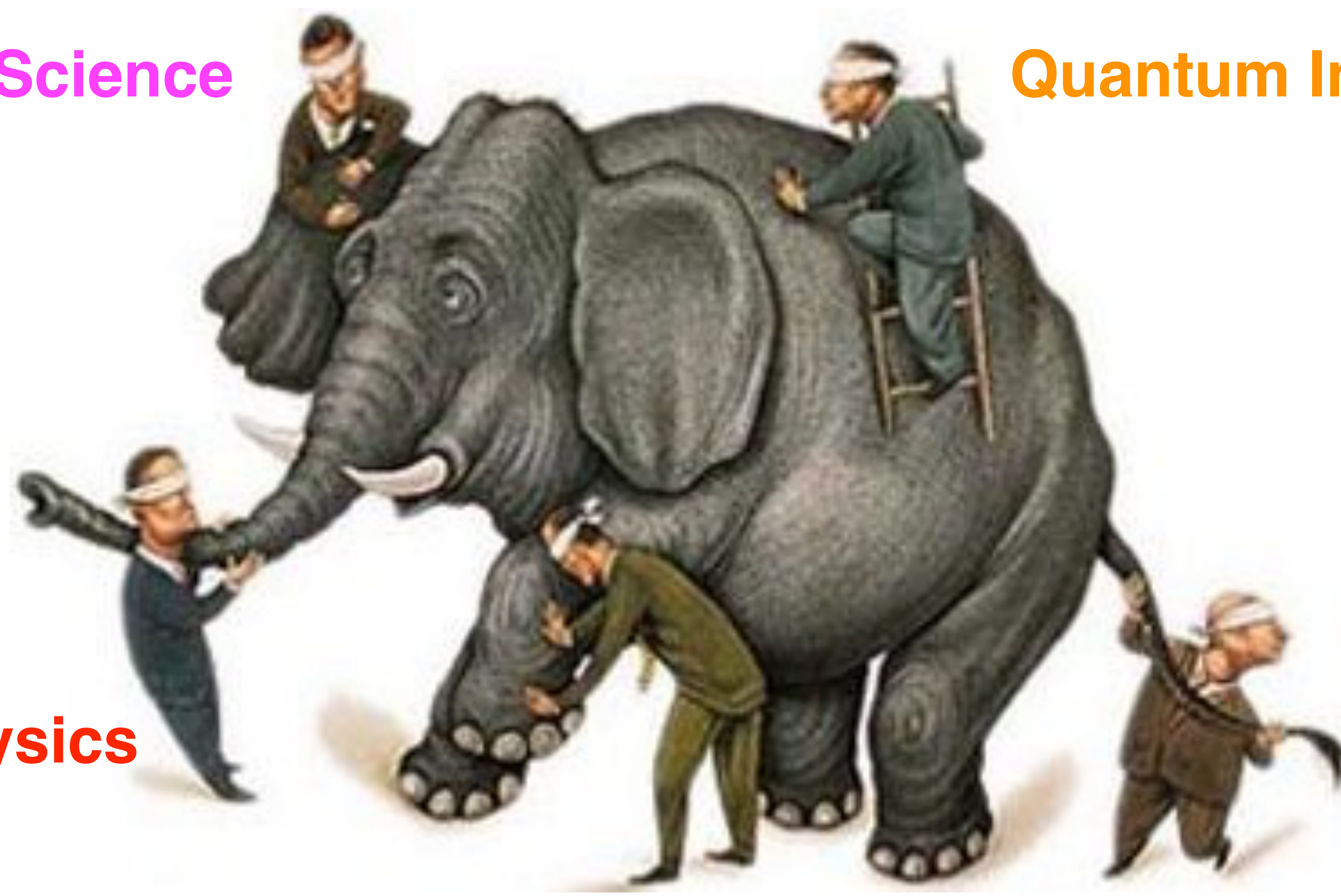
Data Science

Quantum Information



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