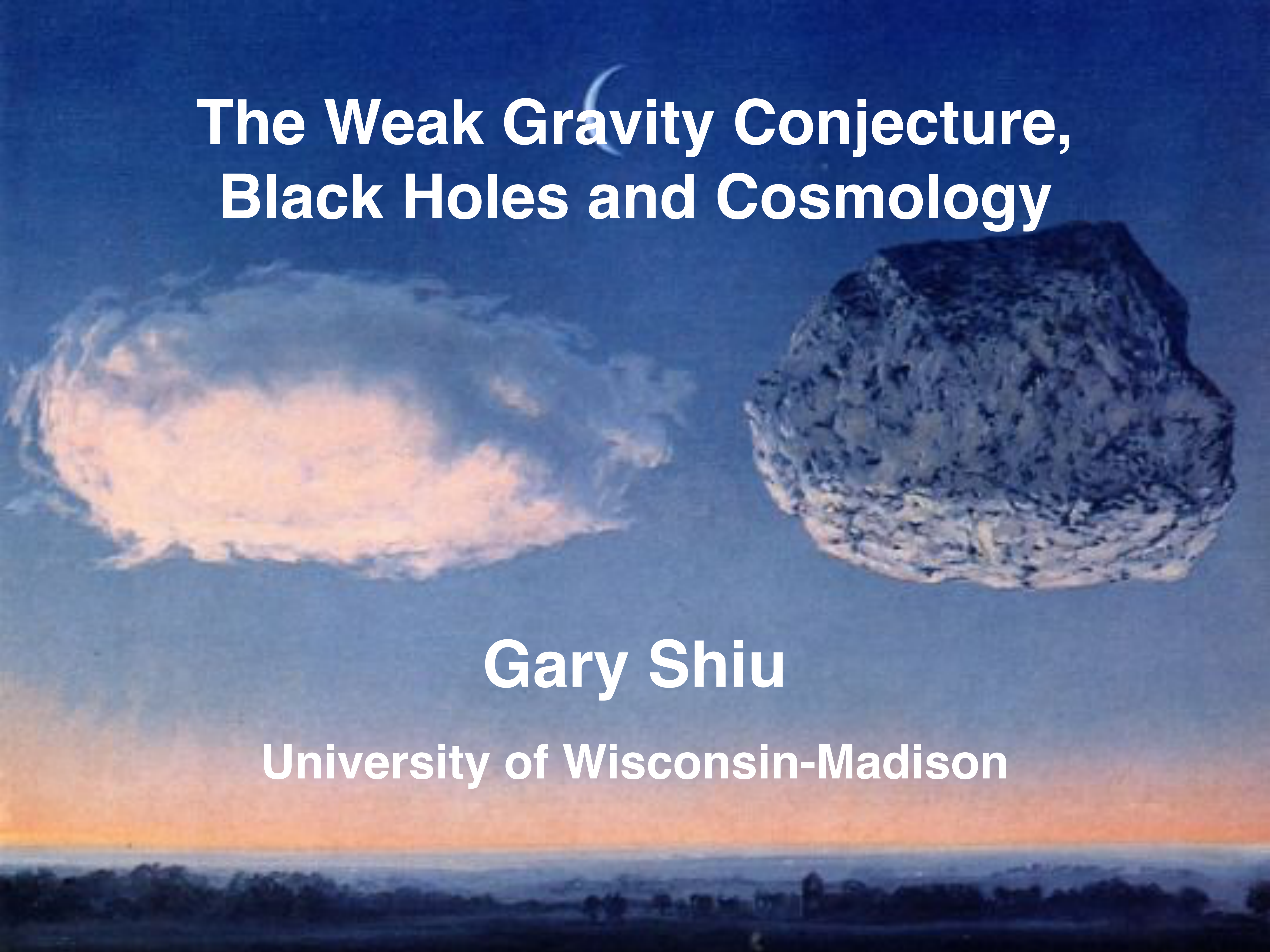


# The Weak Gravity Conjecture, Black Holes and Cosmology

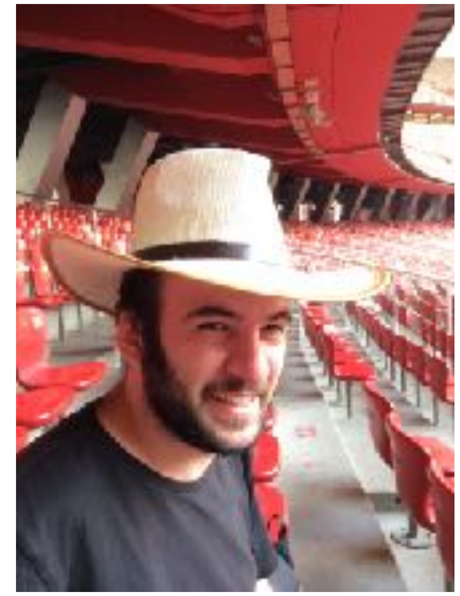
Gary Shiu

University of Wisconsin-Madison

# Based on work with:

**J. Brown**

**W. Cottrell**



**P. Soler**

**M. Montero**

**F. Marchesano**

**A. Landete**

**G. Zoccarato**

**Y. Hamada**

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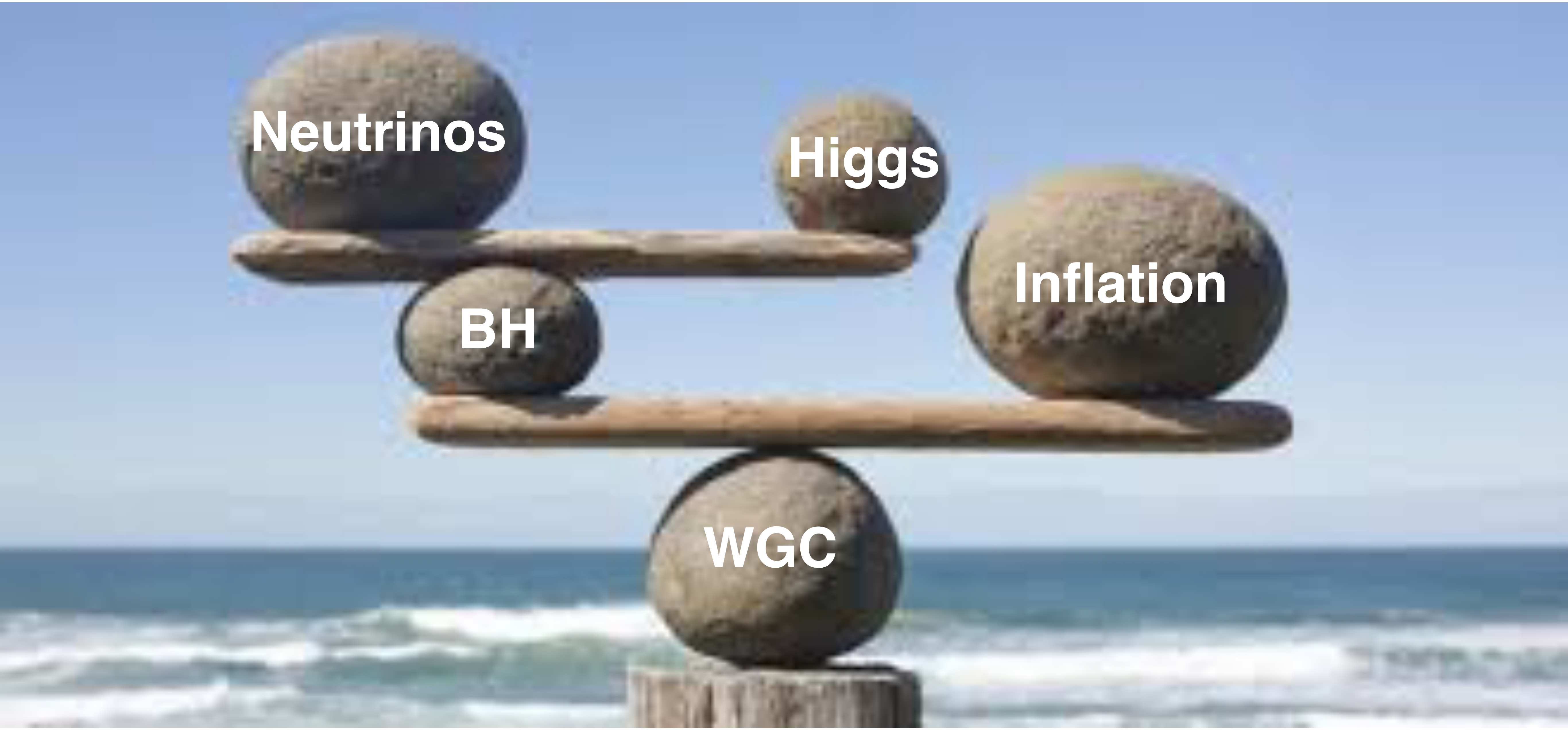

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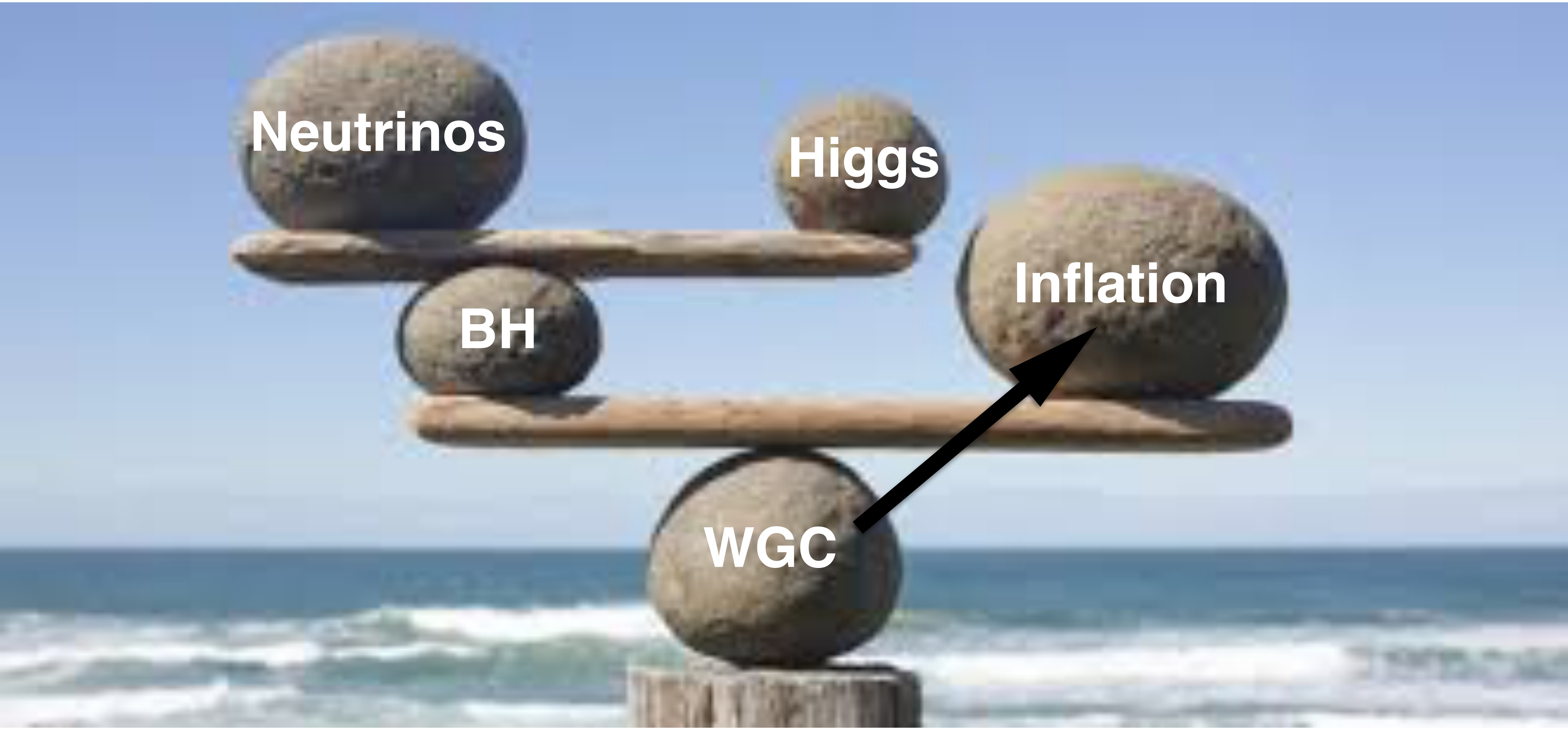


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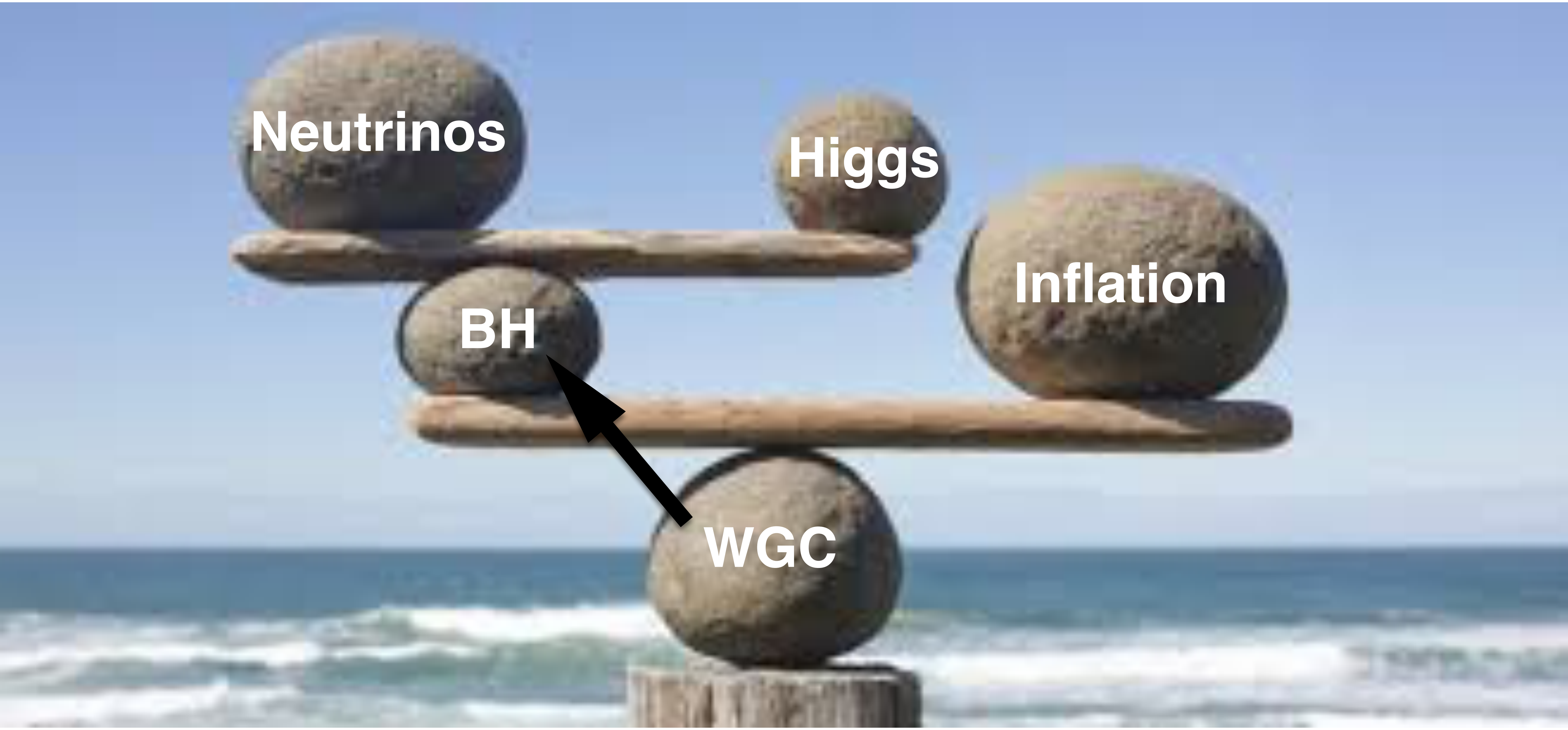


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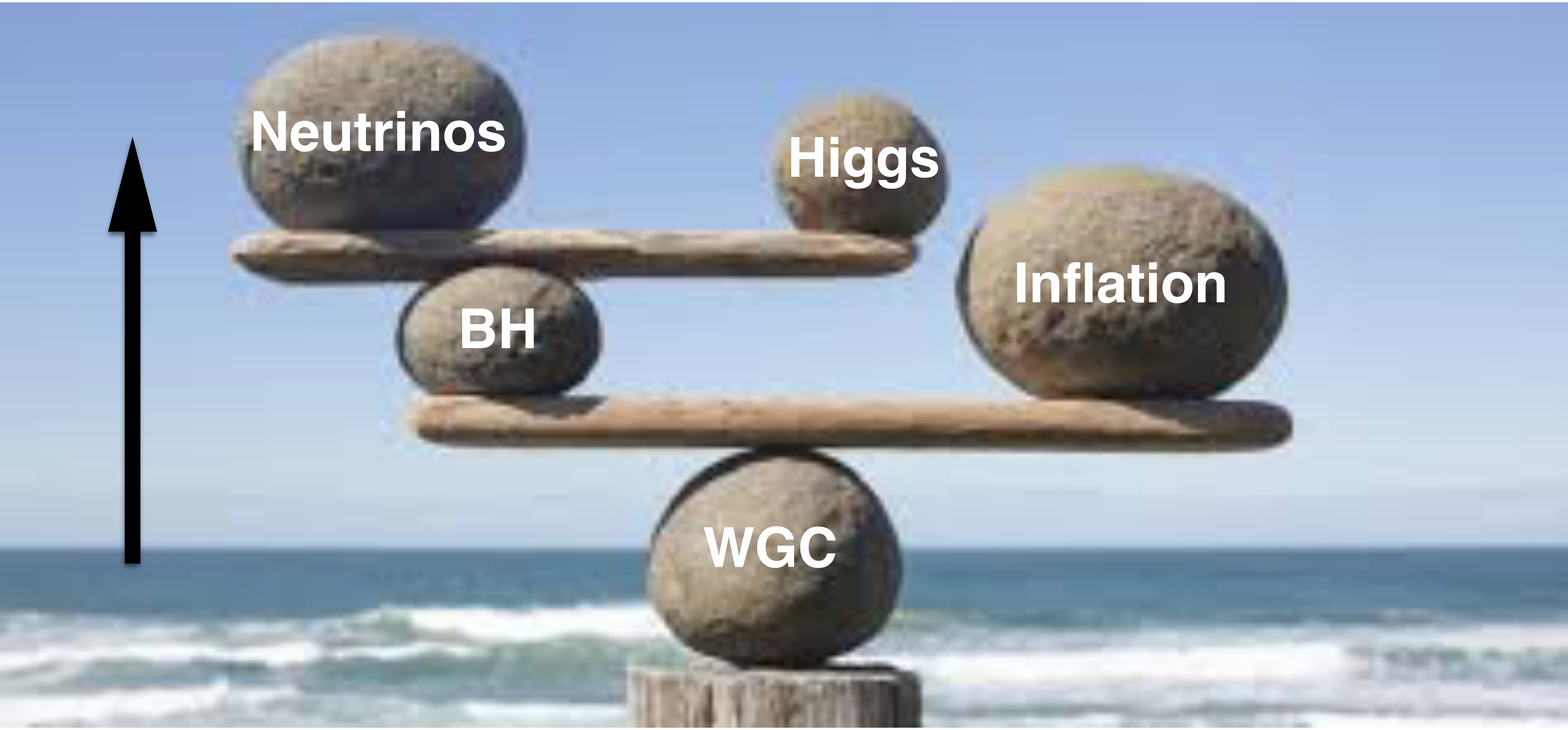


**WGC, Multiple Point Principle, and the Standard Model Landscape**

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# String Theory Landscape

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An even vaster Swampland?

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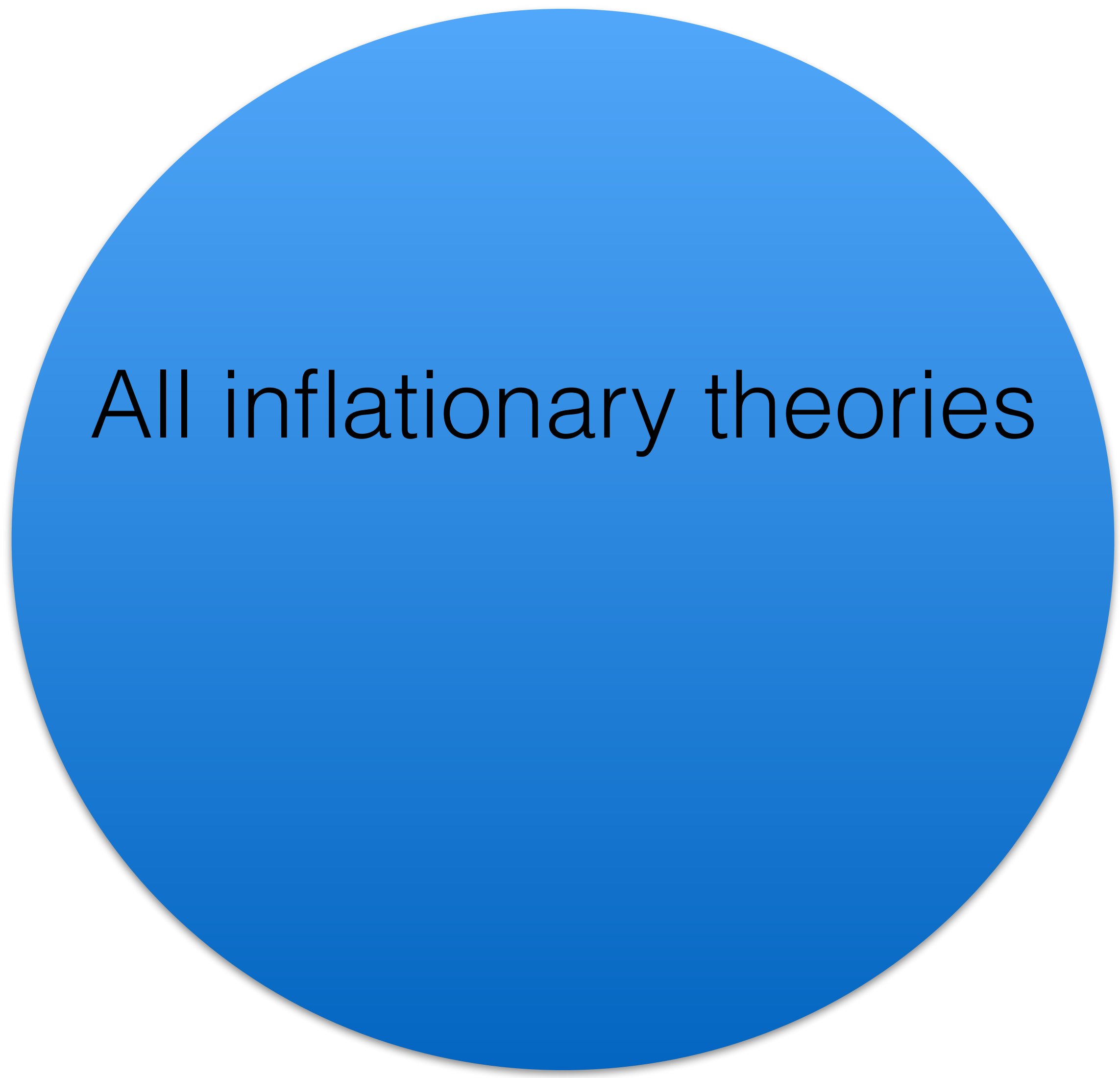
These questions can be asked sharply in the context of inflation:



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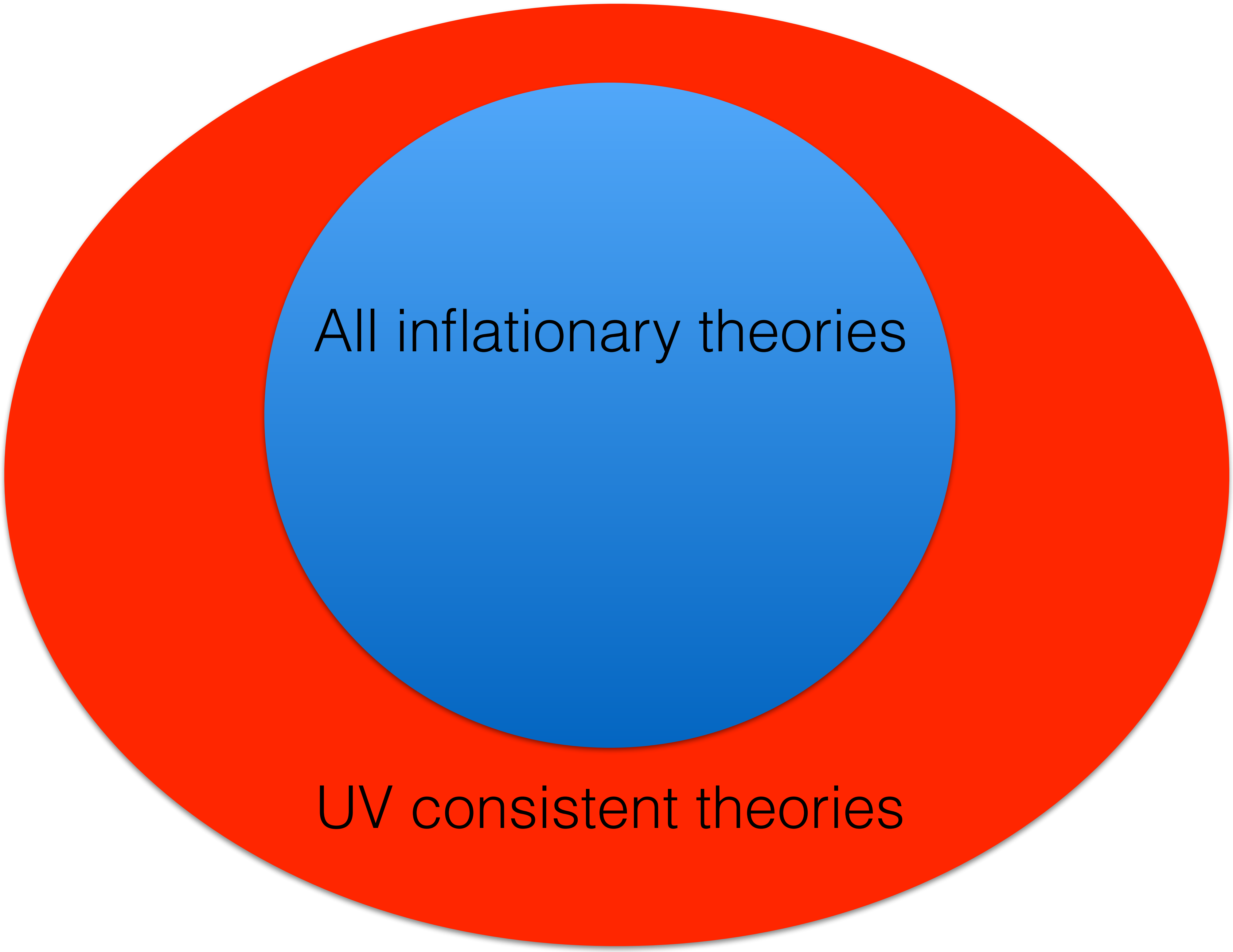

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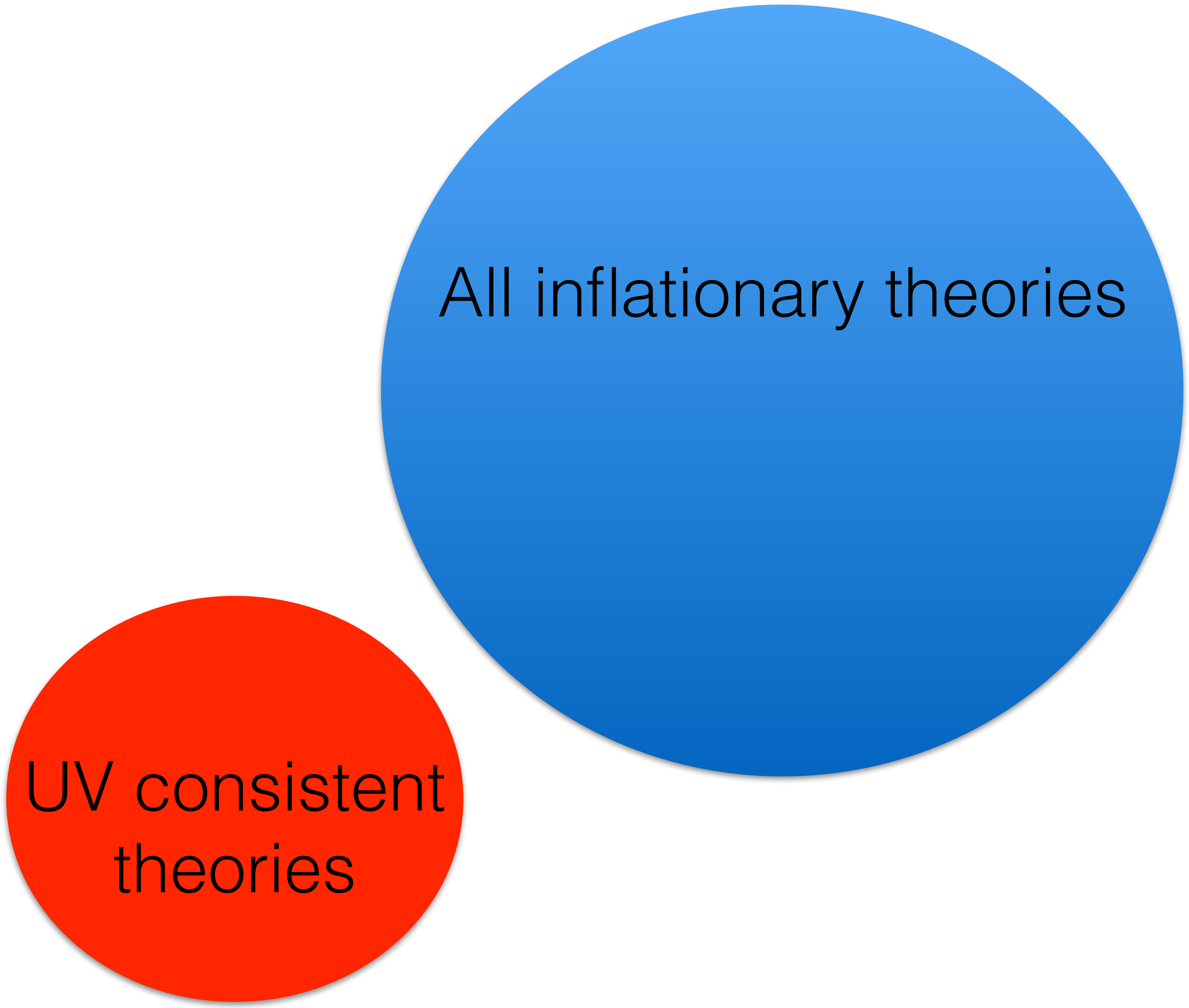

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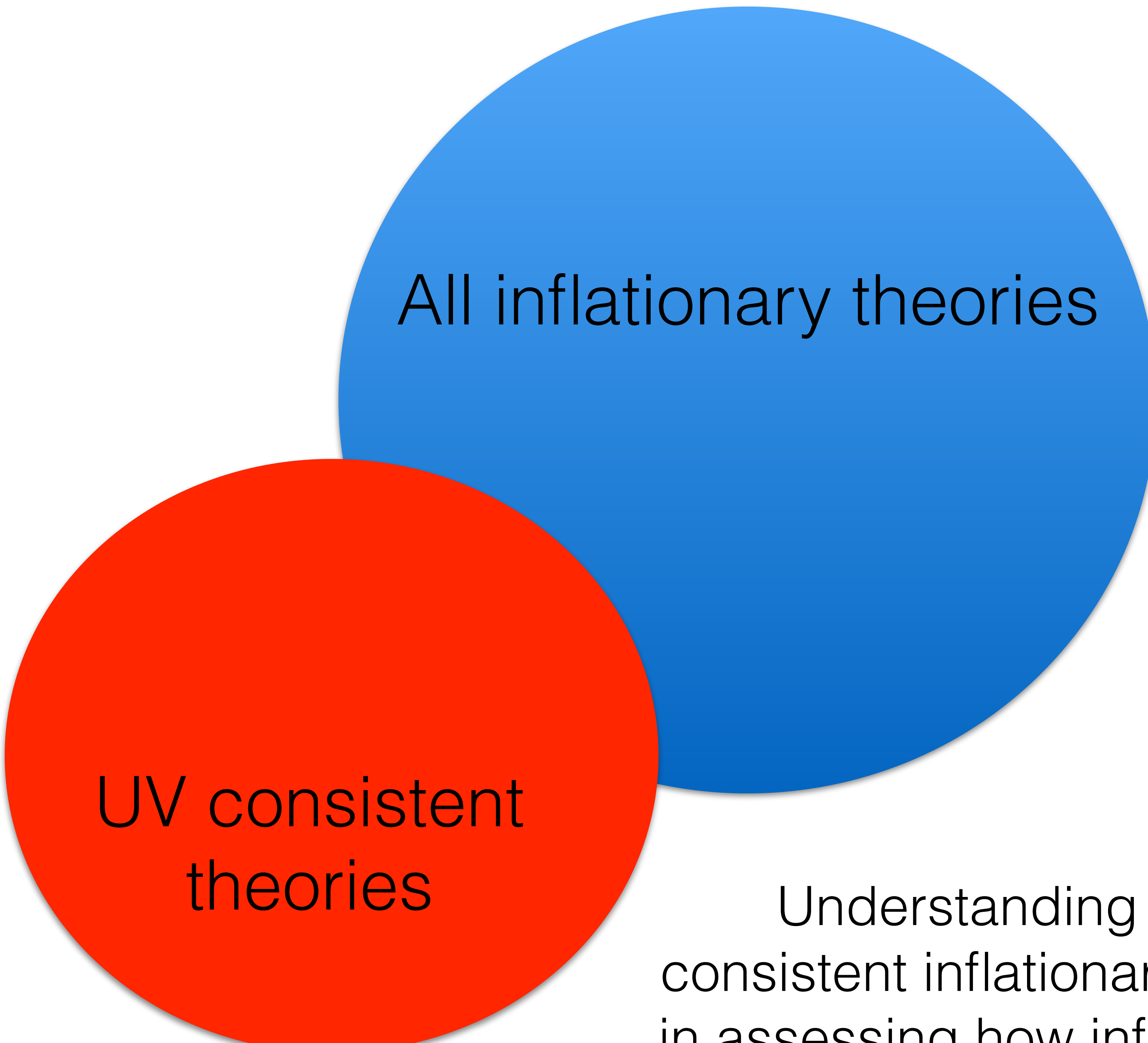
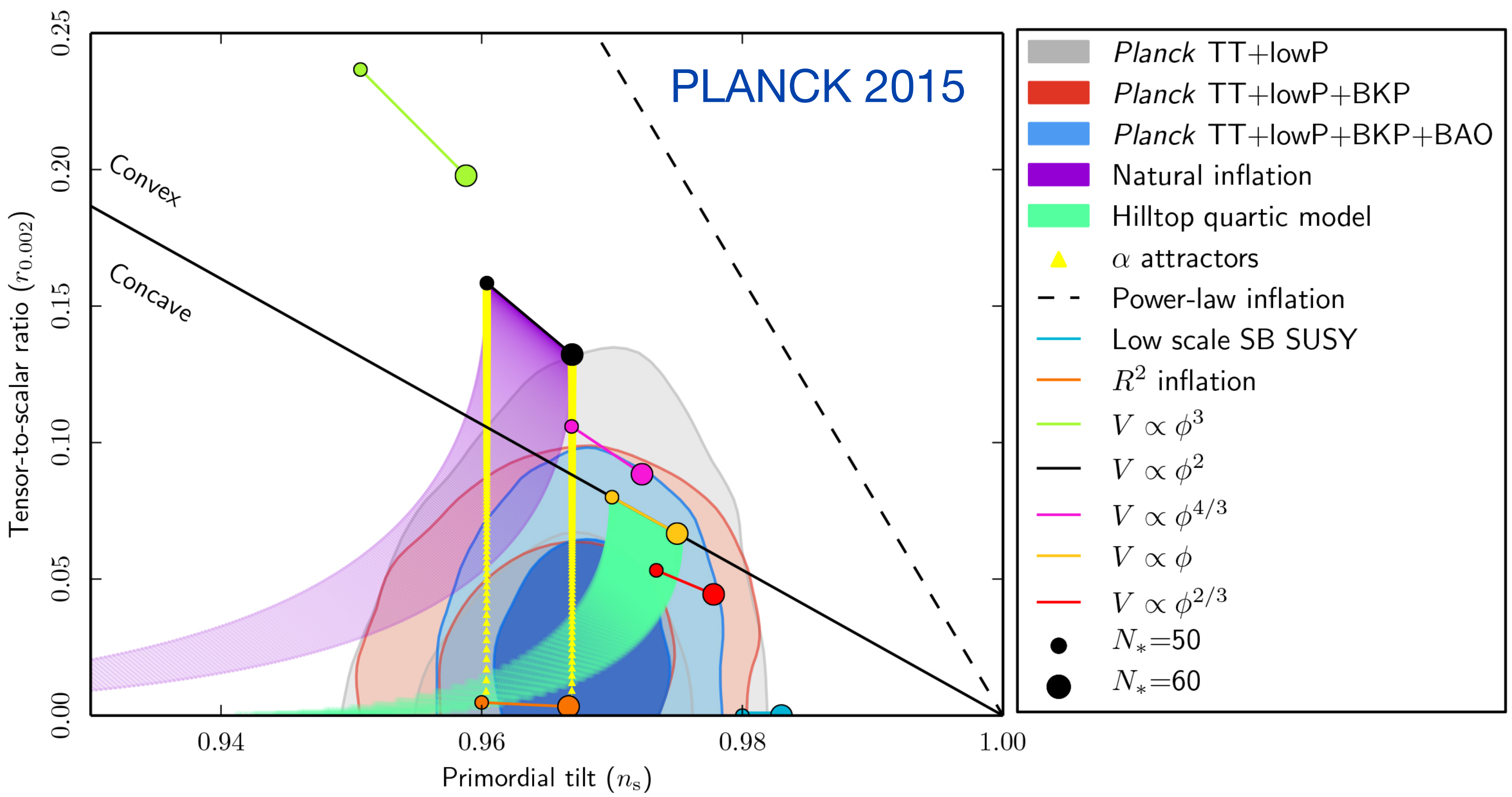
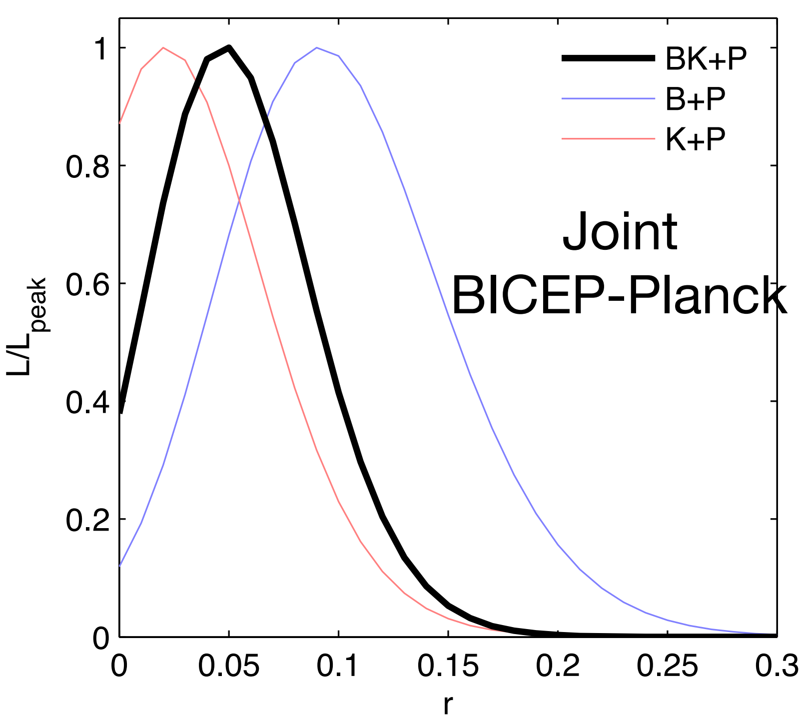



Understanding the space of UV consistent inflationary theories also helps in assessing how inflation fares with data.

# 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 $r \sim 10^{-2}$.

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

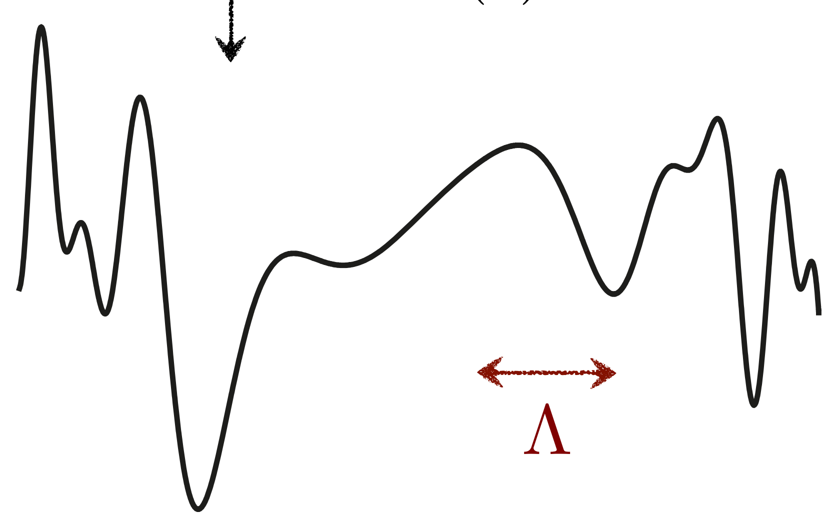
# UV Sensitivity of Large Field Inflation

Lyth bound: $$\frac{\Delta\phi}{M_{\rm pl}} \gtrsim 2 \times \left(\frac{r}{0.01}\right)^{1/2}$$

**Coupling the inflaton to the UV degrees of freedom in quantum gravity:**

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

$c_i \sim \mathcal{O}(1)$



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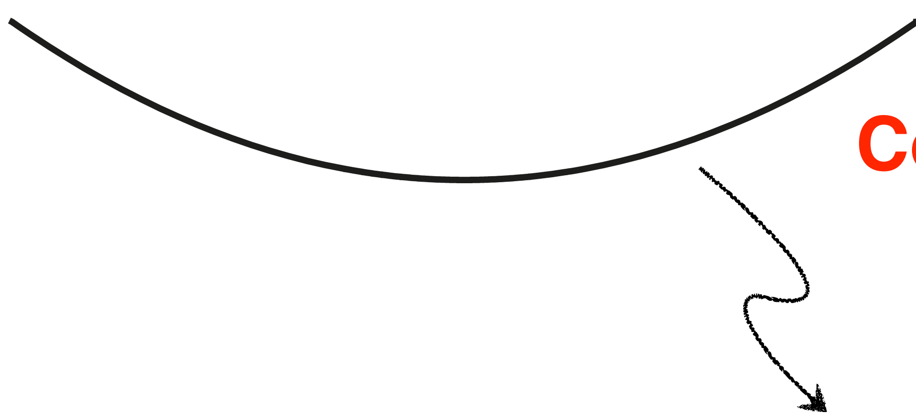

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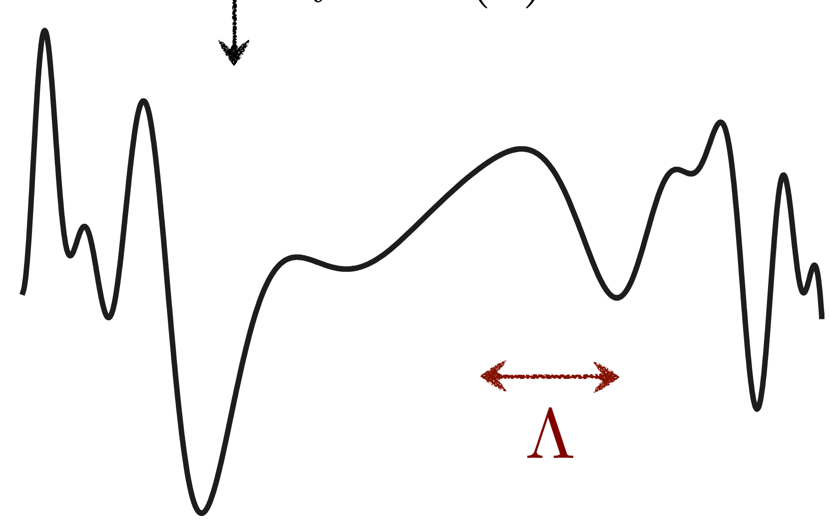

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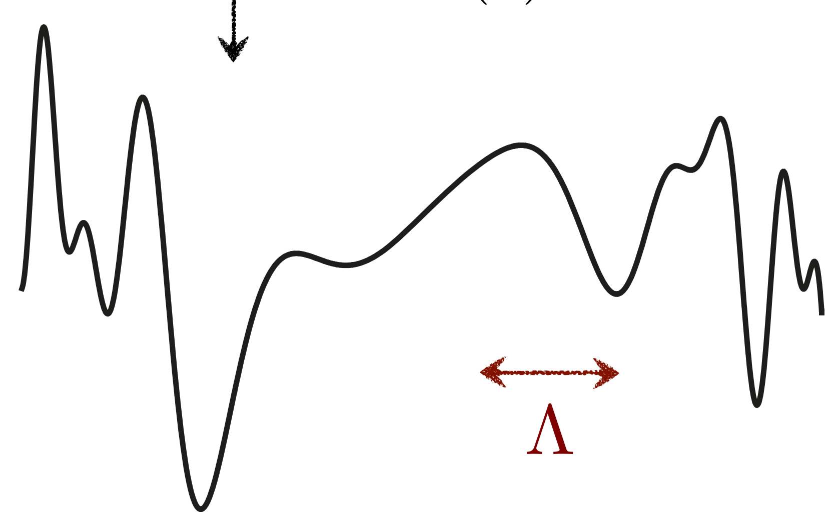


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**UV completions control corrections?**

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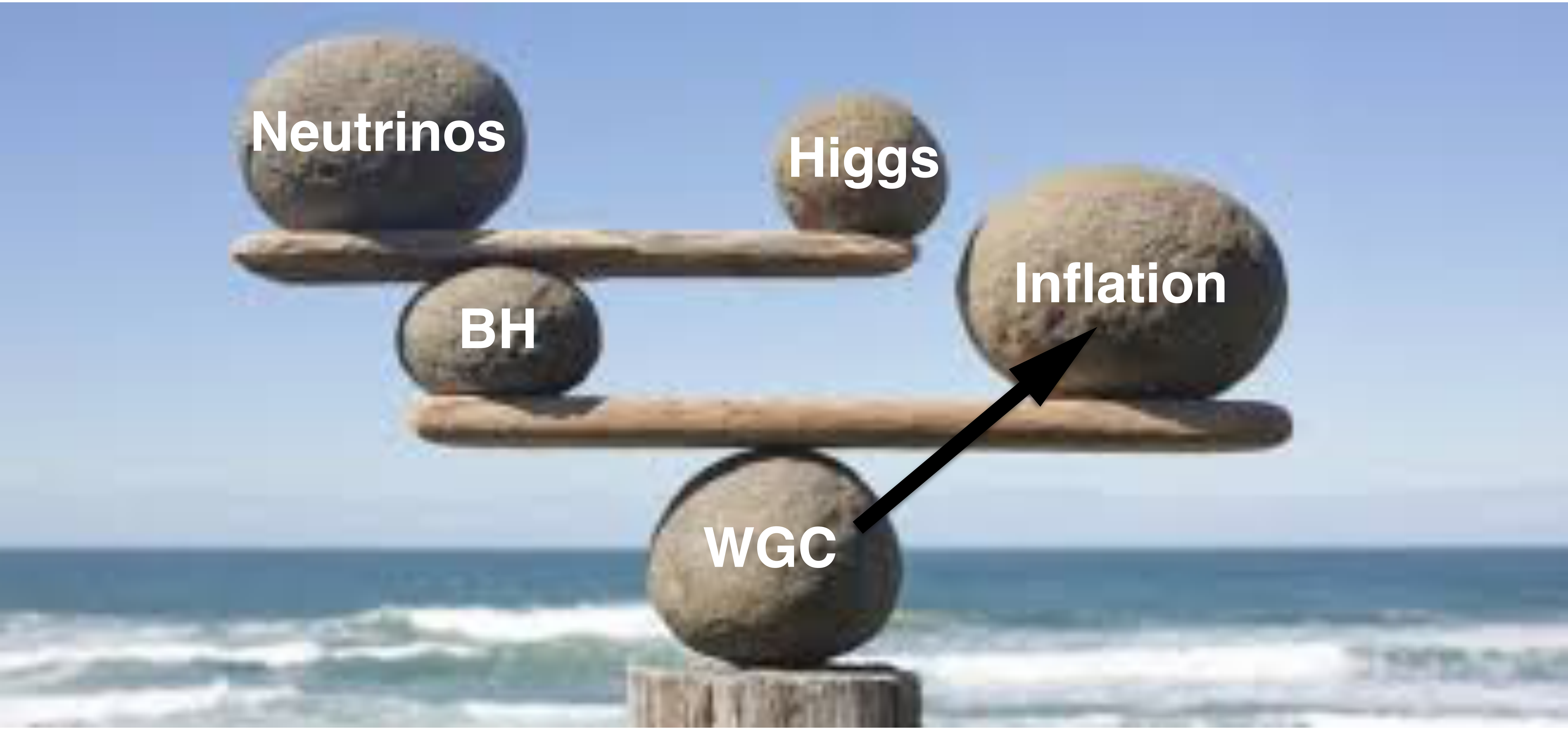


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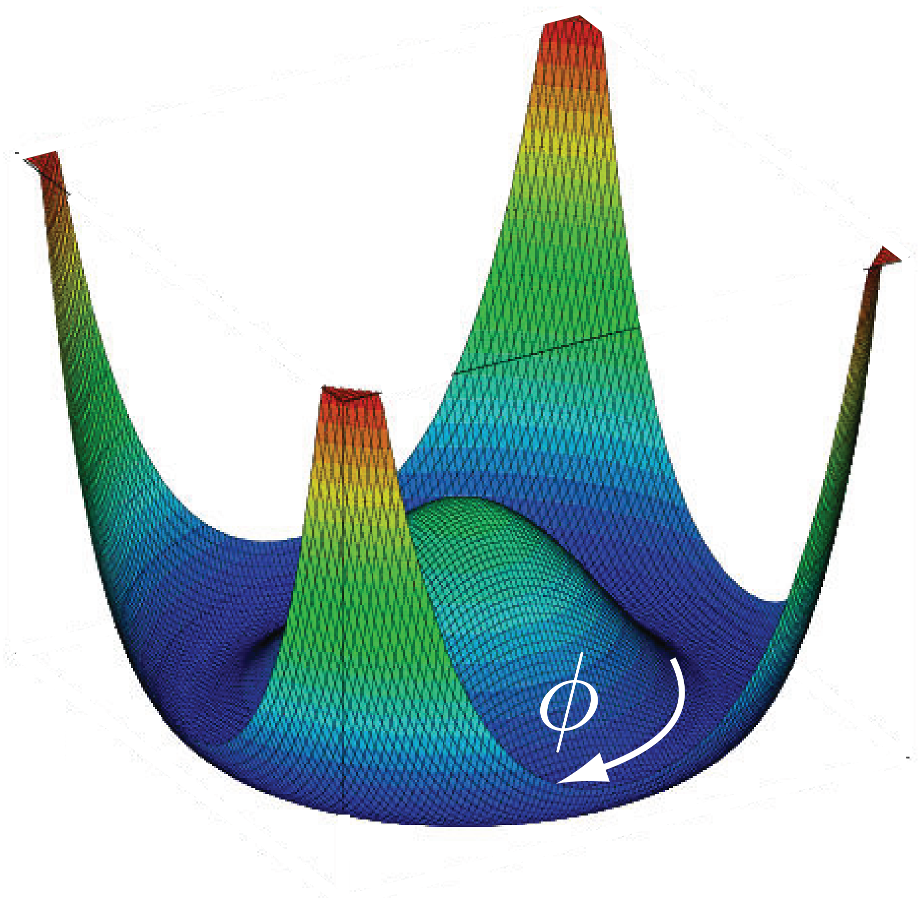
# Axions & Large Field Inflation

Natural Inflation [Freese, Frieman, Olinto]

Pseudo-Nambu-Goldstone bosons are natural inflaton candidates.



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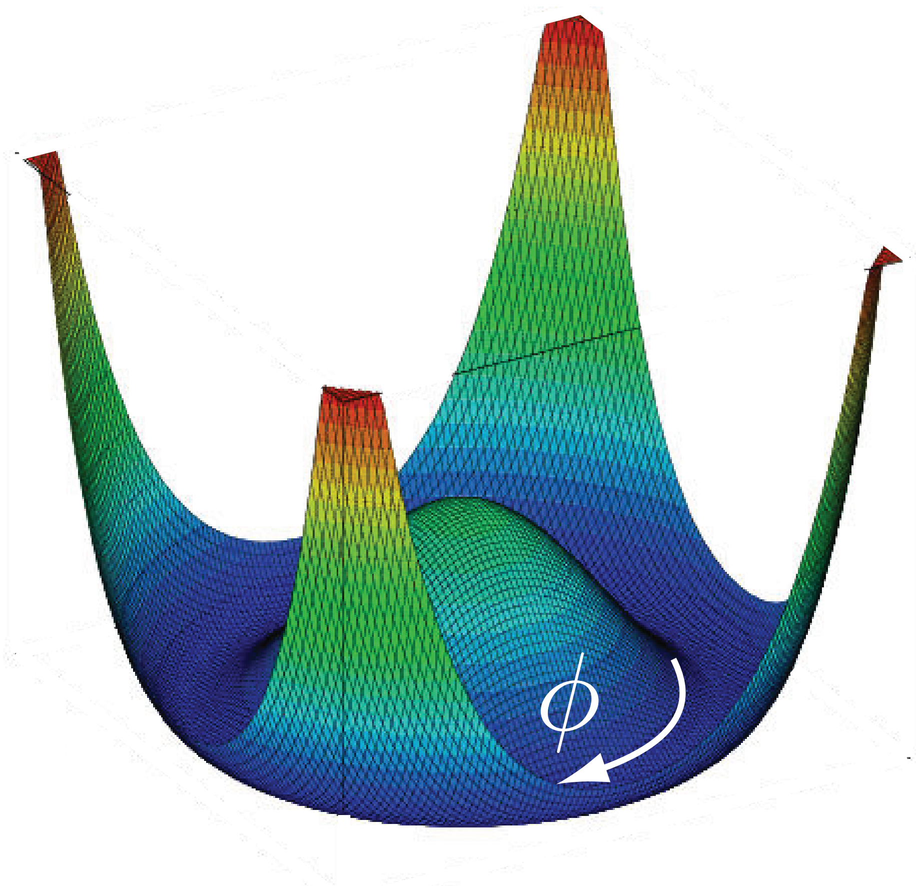
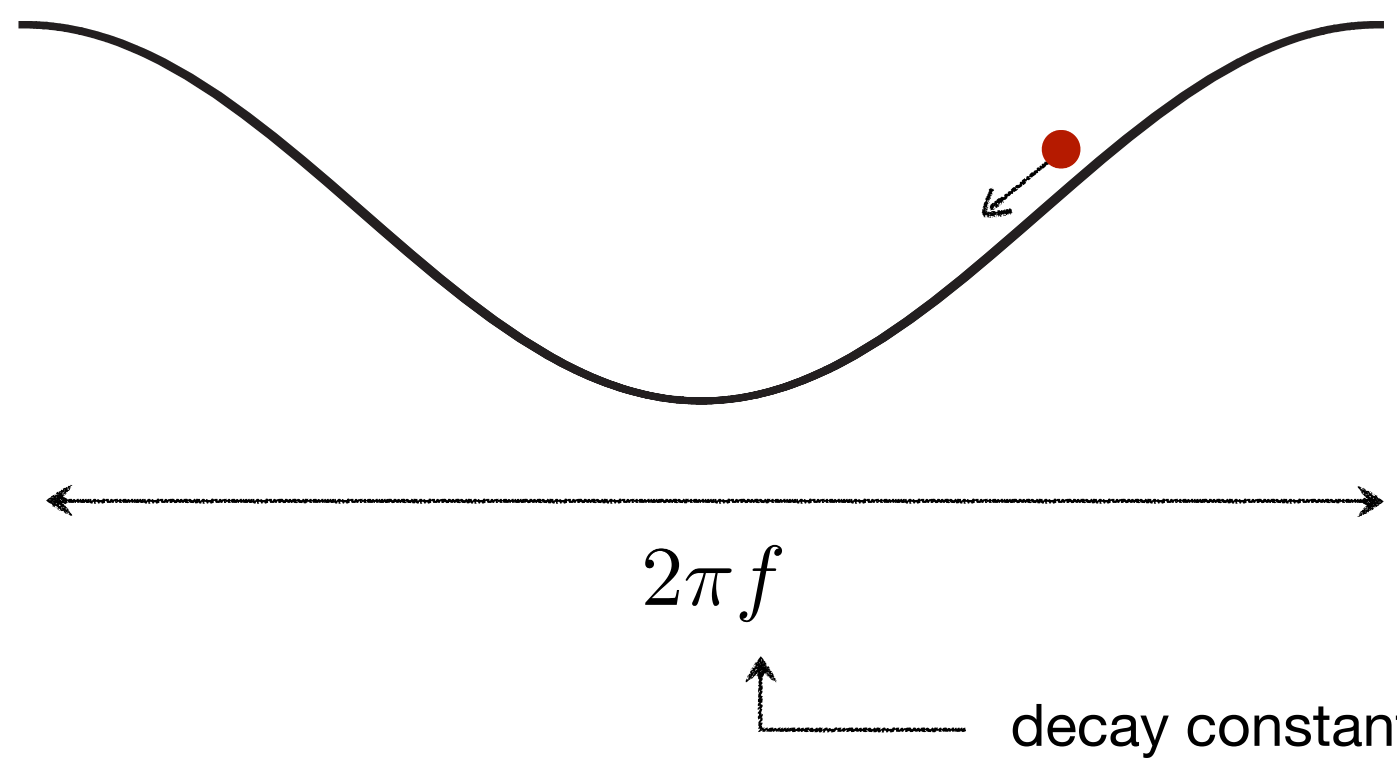



They satisfy a shift symmetry that is only broken by non-perturbative effects:



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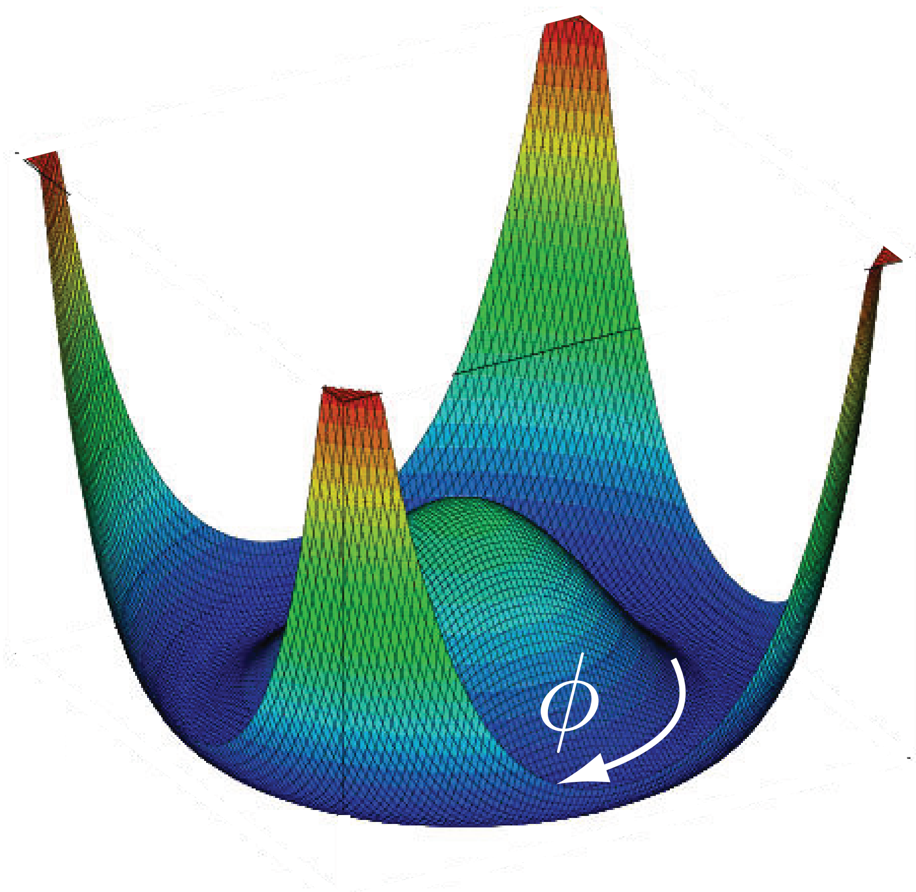


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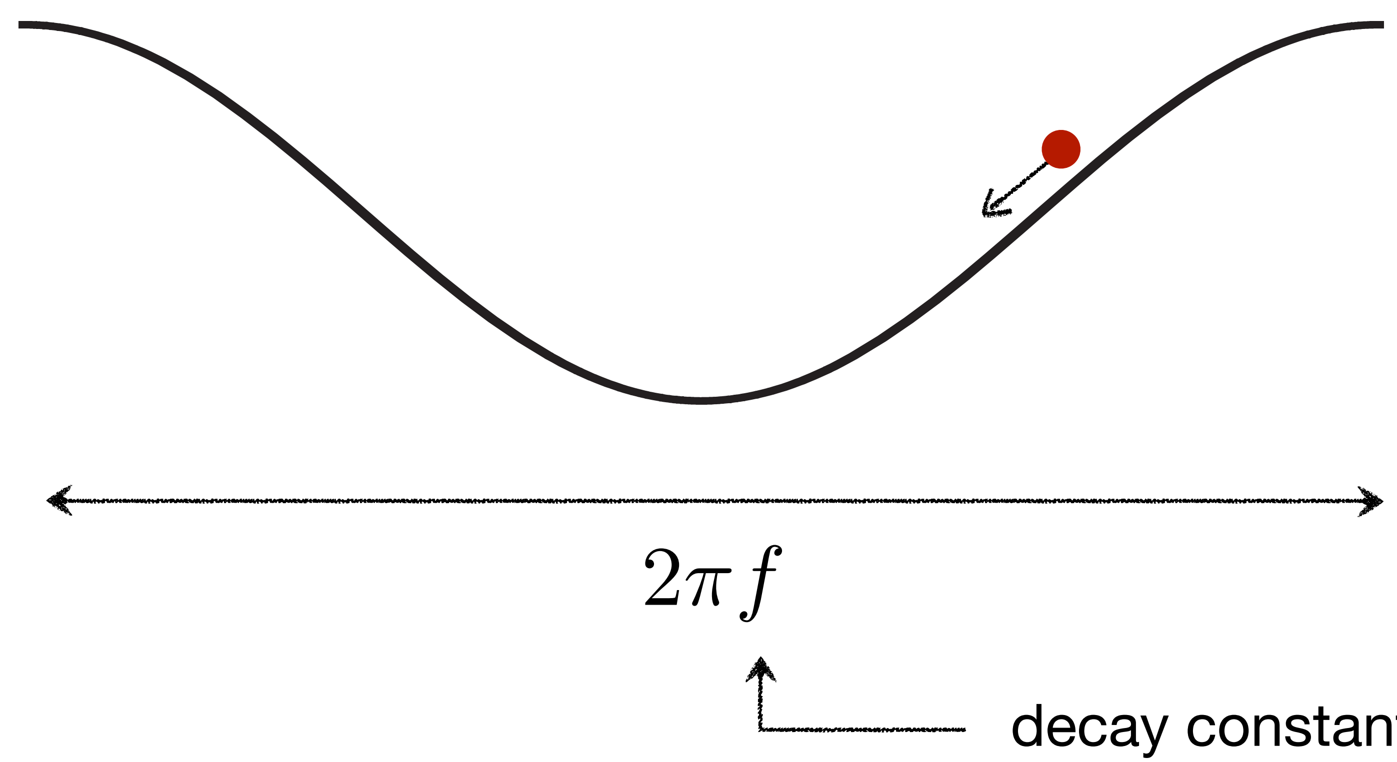


**Slow roll:** $f > M_P$

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

# Axions in String Theory

String theory has many **higher-dimensional form-fields**:

e.g. $$F = \mathrm{d}A$$

3-form flux → $F$

$A$ ← 2-form gauge potential:

gauge symmetry: $A \rightarrow A + \mathrm{d}\Lambda$

Integrating the 2-form over a 2-cycle gives an **axion**:

$$a(x) \equiv \int_{\Sigma_2} A$$

The gauge symmetry becomes a **shift symmetry**.

Axions with super-Planckian decay constants don't seem to exist in controlled limits of string theory.

Banks, Dine, Fox, Gorbatov, '03

# The Weak Gravity Conjecture

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Arkani-Hamed, Motl, Nicolis, Vafa ‘06

- The conjecture:

**“Gravity is the Weakest Force”**

- For every long range gauge field there exists a particle of charge q and mass m, s.t.

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$$\frac{q}{m} M_P \geq \text{``1''} \equiv \frac{Q_{Ext}}{M_{Ext}}$$

$M_P \equiv 1$

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- Take a U(1) and a single family with q < m ( ~~WGC~~ )

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  - Infinitely many bound states


$2m > M_2 > 2q$ $\quad$ $3m > M_3 > 3q$ $\quad \cdots \quad$ $Nm > M_N > Nq$ $\quad \cdots \quad$ $M_\infty \to Q_\infty$

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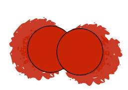
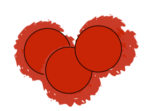
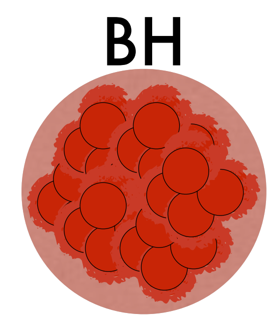




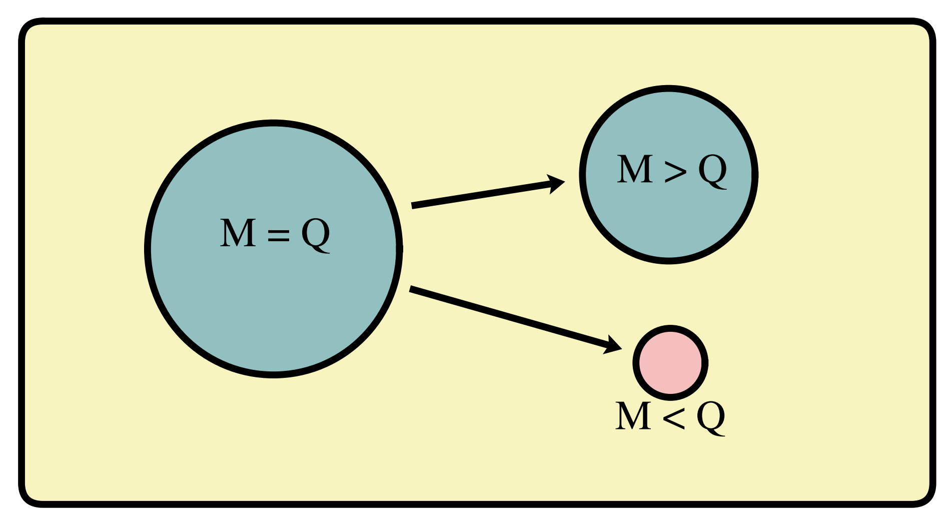




$2m > M_2 > 2q$ $\quad$ $3m > M_3 > 3q$ $\quad \cdots \quad$ $Nm > M_N > Nq$ $\quad \cdots \quad$ $M_\infty \to Q_\infty$

  - *Postulate* the existence of a state with ("mild form" of WGC)

$$\frac{q}{m} \geq \text{“}1\text{”} \equiv \frac{Q_{Ext}}{M_{Ext}}$$



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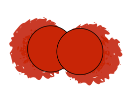

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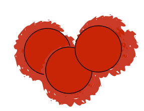

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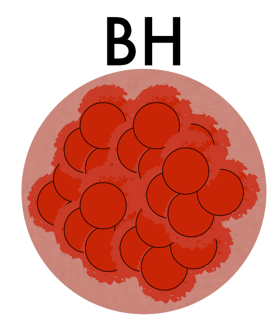



$Nm > M_N > Nq$

$\cdots$

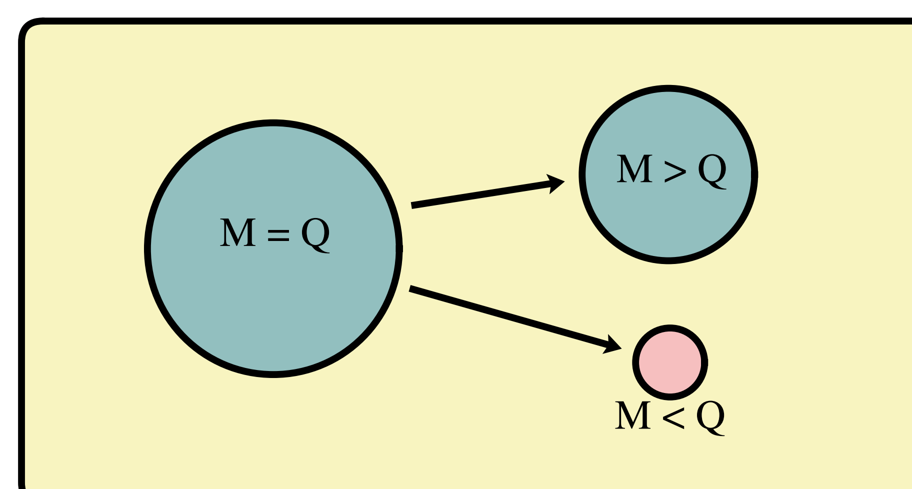

$M_\infty \to Q_\infty$

- *Postulate* the existence of a state with ("mild form" of WGC)

Electric WGC: $\frac{q}{m} \geq \text{“}1\text{”} \equiv \frac{Q_{Ext}}{M_{Ext}}$

Magnetic WGC: $\Lambda \leq g M_P$

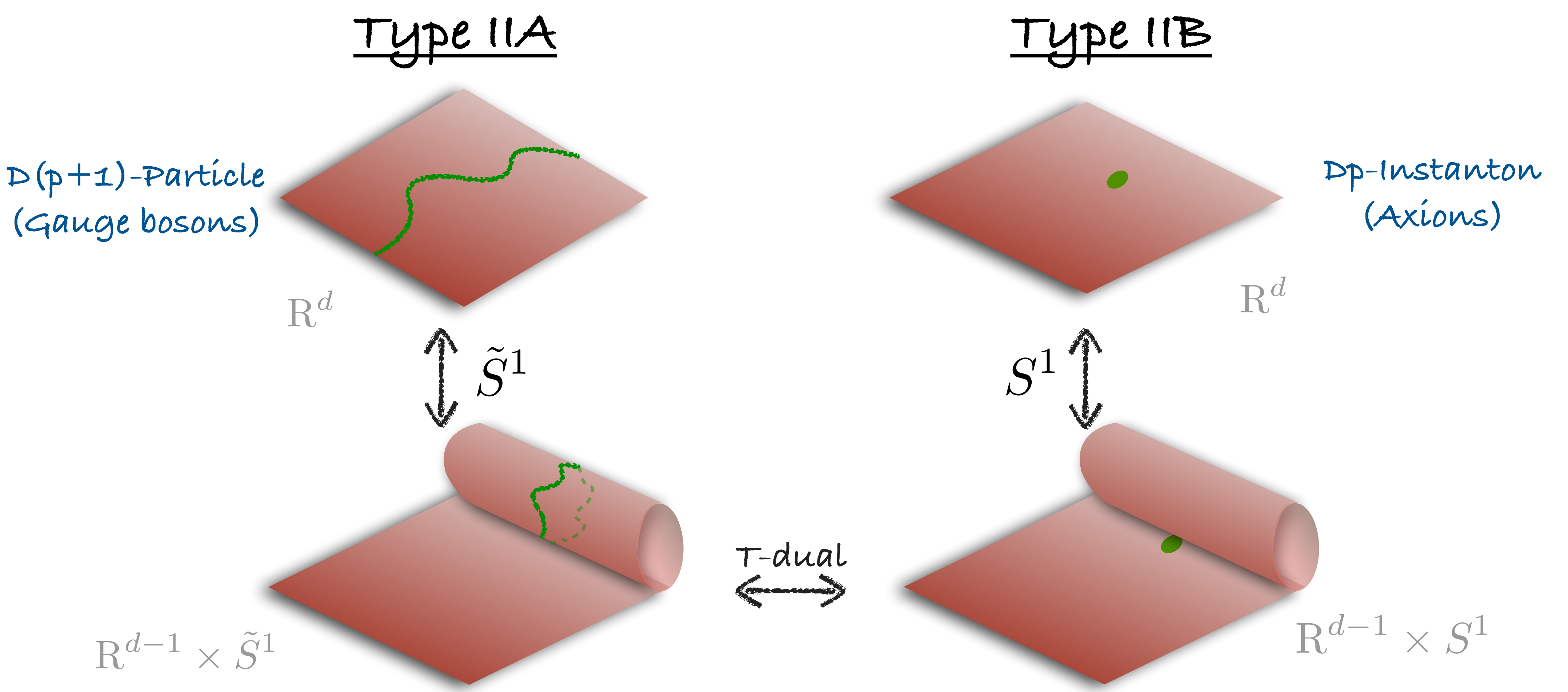
$[m_{mag} \sim \Lambda / g^2 \;, q_{mag} \sim 1/g]$



# WGC and Axions

Brown, Cottrell, GS, Soler

- Formulate the WGC in a duality frame where the axions and instantons turn into gauge fields and particles, e.g.

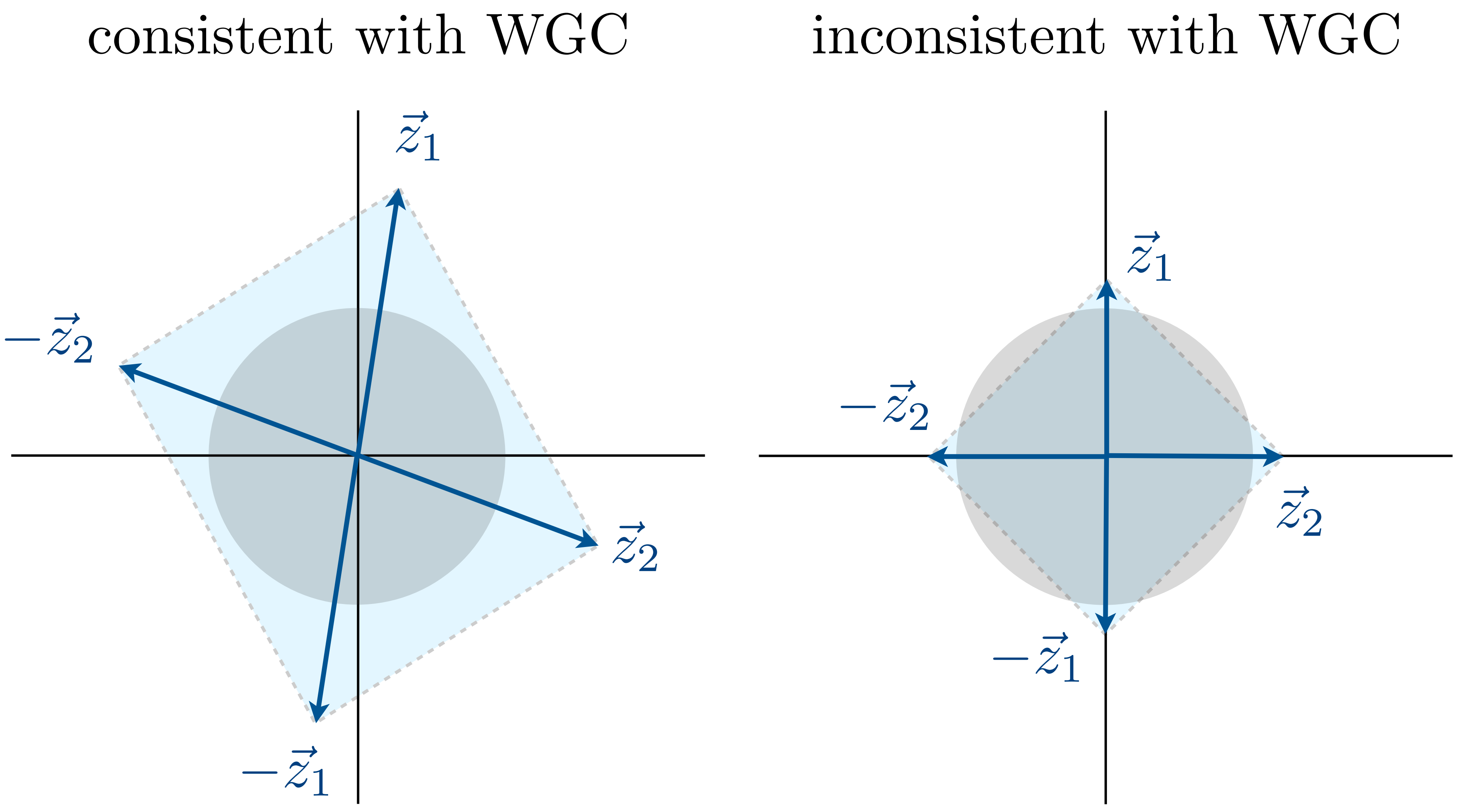



model-dependent, calculable

- The WGC takes the form $f \cdot S_{\text{instanton}} \leq \mathcal{O}(1) M_P$ and generalizes to a convex hull condition for multiple axions.

# Multiple Axions and Convex Hull

- Generalization of the WGC to multiple U(1)'s is a convex hull condition [Cheung, Remmen], which has been dualized to the WGC for multiple axions [Brown, Cottrell, GS, Soler];[Rudelius]



# Strong vs Mild Form

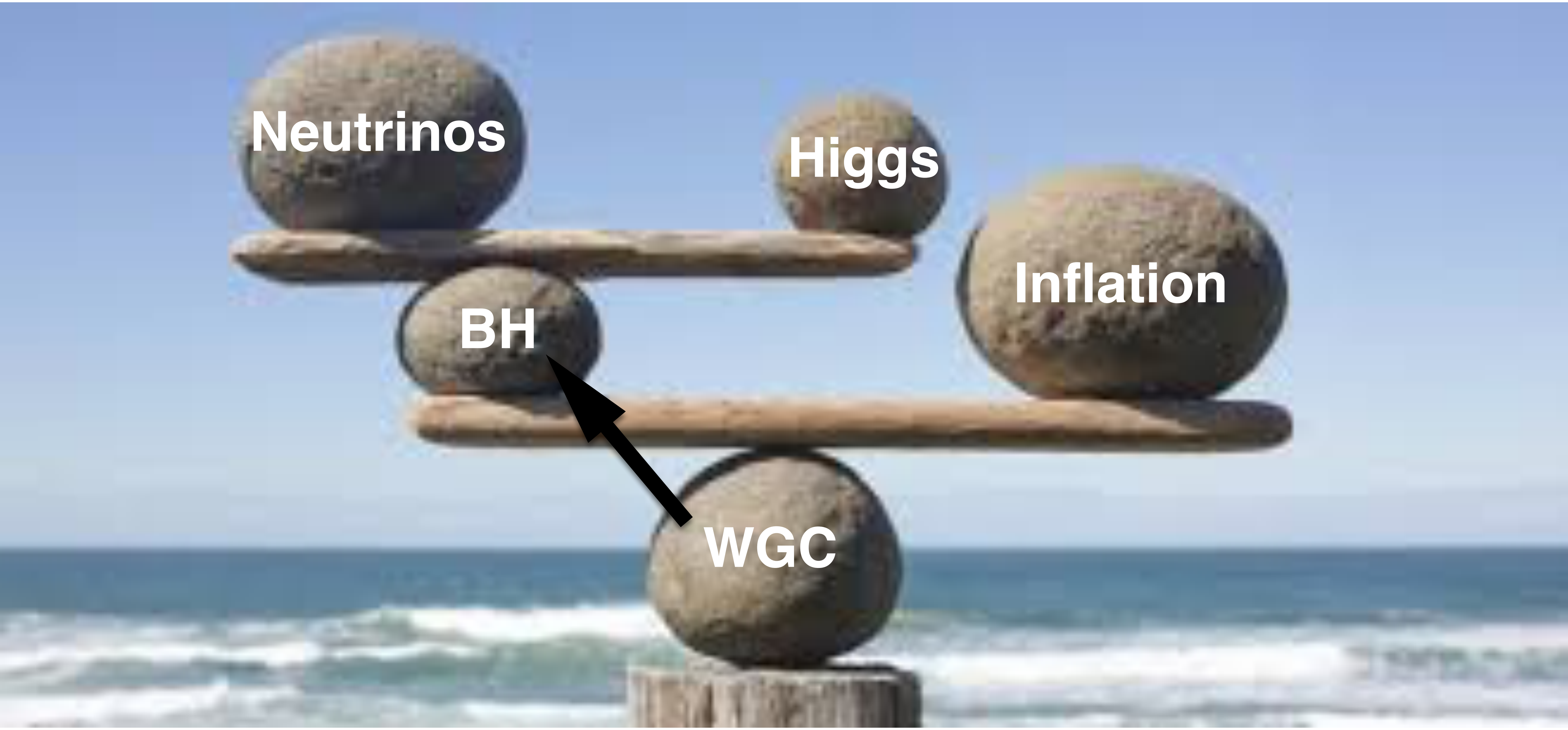
- Consistencies suggested that the WGC takes stronger forms:
  - **Madison Strong Form (1503.04783)** [Brown, Cottrell, GS, Soler]:

    *"The lightest (possibly multi-particle) state in any given direction in charge space satisfies* $|z_{lightest}| \geq 1$*"*
  - **Harvard Strong Form (1509.06374)** [Heidenreich, Reece, Rudelius]:

    Lattice WGC: For every point $\vec{Q}$ on the charge lattice, there is particle of charge $\vec{Q}$ with charge-to-mass ratio at least as large as that of a large, semi-classical, non-rotating extremal black hole with charge $\vec{Q}_{BH} \propto \vec{Q}$.
- **The Lattice WGC was shown to be false**. There are counter examples where the conjecture holds only by a proper sublattice **(sublattice WGC)**

  [Montero, GS, Soler];[Heidenreich, Reece, Rudelius]
- The precise form of the WGC is still being formulated.

# Road Map

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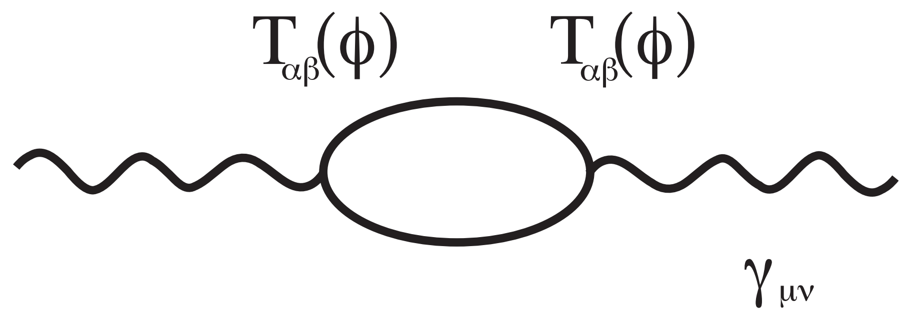
# Arguments for the Weak Gravity Conjecture

# Heuristic Argument

- Heuristic argument suggests ∃ a state w/ $\frac{q}{m} \geq \text{“}1\text{”} \equiv \frac{Q_{Ext}}{M_{Ext}}$
- One often invokes the remnants argument [Susskind] for the WGC but the situations are different (finite vs infinite mass range).




- Perfectly OK for some extremal BHs to be stable [e.g., Strominger, Vafa] as q ∊ central charge of SUSY algebra.
  - No q>m states possible (∵ BPS bound).
  - BPS BHs ***are*** the WGC states (boring option)
  - More subtle for theories with some q ∉ central charge
- The WGC is a conjecture on the ***finiteness of the # of stable states that are <u>not</u> protected by a symmetry principle.***

# Evidences for the Weak Gravity Conjecture

**Several lines of argument have been taken (so far):**

- Holography [Nakayama, Nomura, '15];[Harlow, '15];[Benjamin, Dyer, Fitzpatrick, Kachru, '16]; [Montero, GS, Soler, '16]
- IR Consistencies (unitarity & causality) [Cheung, Remmen, '14];[Andriolo,Junghans, Noumi, GS,'17, to appear].
- Cosmic Censorship [Horowitz, Santos, Way, '16];[Crisford, Horowitz, Santos, '17]
- Axion Black Holes [Hebecker, Soler, '17]; [Montero, Uranga Valenzuela, '17]

**Evidences for _**stronger**_ versions of the WGC:**

- Consistencies with T-duality [Brown, Cottrell, GS, Soler, '15] and dimensional reduction [Heidenreich, Reece, Rudelius '15].
- Modular invariance + charge quantization suggest a **sub-lattice WGC** [Montero, GS, Soler, '16] (see also [Heidenreich, Reece, Rudelius '16])

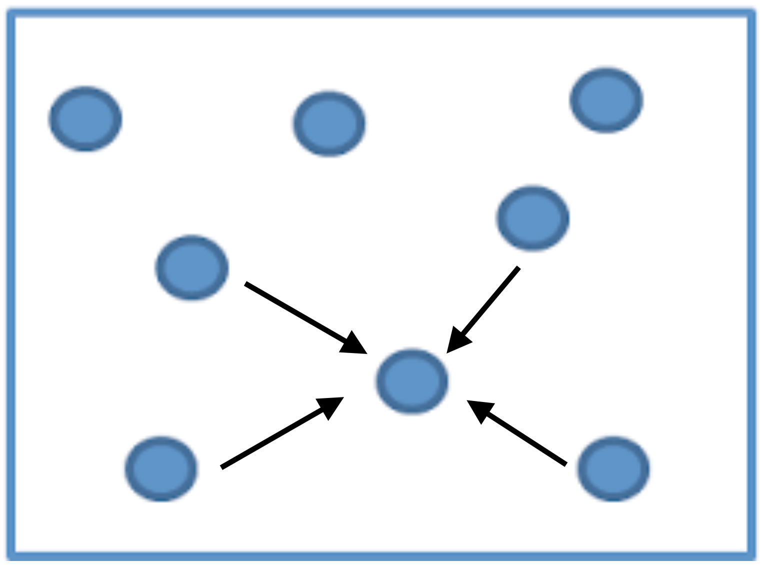
***Further evidence*** based on **entropy considerations** [Cottrell, GS, Soler, '16].
**(I'll comment on some recent erroneous claims in** [Fisher, Mogni, '17]**)**

# Back to the Basic

What's wrong if the WGC is violated in the *4D Einstein-Maxwell theory*?

# Microscopic Intuition

- In the semi-classical, Newton limit, the microcanonical entropy for a system of N stable particles with $\Delta m^2 \equiv m^2 - q^2 > 0$ is ***unbounded***.



'gravo-thermal catastrophe'

[Antonov, '62]; [Padmanabhan, '89]

- A divergence in entropy, if real, would undermine the consistency of the theory, but an upgrade of this analysis to include GR + quantum is hindered by the presence of horizons.
- We cannot exclude a UV completion saving us from this catastrophe but the WGC suggests that no such consistent UV framework exists.

# Horizon Entropy

- No reason a priori for it to agree with the microcanonical entropy but the equivalence was shown in some cases [Lewkowycz, Maldacena '13].
- We computed the 1-loop corrected BH geometry and entropy using the **quantum entropy function** formalism [Sen, '05-'12].
- The **Wald formula** [Wald, '93] computes the horizon entropy for an arbitrary *local* Lagrangian, e.g.,

$$S = 2\pi \int_{\rho^2} \frac{\delta I}{\delta R_{\mu\nu\alpha\beta}} \epsilon^{\mu\alpha} \epsilon^{\nu\beta} \sqrt{h} d^2\Omega \qquad \text{for} \qquad I = \frac{1}{16\pi} \int (R + R^2 + R^4 F^4 + \cdots)$$

- Sen's entropy function formalism instructs us to apply Wald's formula to the quantum corrected 1PI effective action, which is not necessarily local.
- For a near horizon geometry that approaches $AdS_2$ x X, we can rewrite Wald's formula in terms of a **Legendre transform of the near-horizon Lagrangian density**. This method applies even to non-local Lagrangians.

# Summary of Findings

- While corrections from ***neutral particles*** have been obtained previously, integrating out ***charged particles*** introduce some **new features:**

  ***Loops of massive charged particles can induce 'unexpected' contributions to the horizon entropy of extremal black holes.***

- Our previous paper (1611.06270) established this result for N=0,1 BHs.
- In a forthcoming paper, we demonstrate that this feature persists even with the full structure of N=2 SUGRA.
- This finding is puzzling because:
  - Intuitively, we don't expect loops of massive particles could alter the area law of a *macroscopic BH*.
  - How do we reconcile this finding w/ the results on the entropy of N≥2 BHs in string theory?

# Summary of Findings

- A resolution to this puzzle: we should ***not*** integrate out these extremal particles to begin with. For RR U(1)'s in string theory, they are the ***D-brane states*** that have ***already been integrated out.***

- This is how the conifold singularity is resolved [Strominger, '95]. At special points in the moduli space (e.g., conifold), these D-brane states are massless, hence the effective action exhibits singularity.

- This gives evidence for the **magnetic WGC** which identifies the UV cutoff to the mass scale of the extremal particles:

$$\Lambda \lesssim qM_P$$

- A corollary is that in any UV complete theory of quantum gravity, an extremal particle cannot be fundamental, rather it must be a soliton.

# Sketch of the Argument

- The near-horizon geometry is $AdS_2$ x $S_2$

$$\begin{aligned} ds^2 &\equiv g_{\mu\nu} dx^\mu dx^\nu = a^2 \left( -r^2 dt^2 + \frac{dr^2}{r^2} \right) + b^2 \left( d\theta^2 + \sin^2\theta d\phi^2 \right) \\ F &= E dt \wedge dr \end{aligned}$$

- The **heat kernel** is defined by:

$$(\partial_s - D) K(x, y; s) = 0 \qquad K(x, y; 0) = \delta^4(x - y)$$

where D is a generalized laplacian of the field to be integrated out.

- The 1-loop correction: $\mathcal{L}^{(1)} = \frac{1}{2} \int_{\epsilon^2}^{\infty} \frac{ds}{s} K(s)$ where $\epsilon$ = **UV cutoff**.

- Quantum corrected entropy can be obtained by extremizing:

$$\mathcal{E}(Q; E, a, b) = 2\pi \left[ QE - 4\pi a^2 b^2 \mathcal{L}_{GR+EM}(E, a, b) \right]$$

# Heat Kernel

- Since the near horizon is $AdS_2$ x $S_2$ the heat kernel factorizes. We can apply results of [Banerjee, Gupta, Sen];[Comtet, Houston];[Pioline, Troost]:

- **Charged Scalars:**

$$K_s(s) = \frac{e^{-s\Delta m^2}}{4\pi^2 a^2 b^2} \sum_{l=0}^{\infty} (2l+1) \int_0^\infty d\lambda\, \lambda\, \rho_s(\lambda) e^{-s\left[\left(\lambda^2+\frac{1}{4}\right)/a^2 + l(l+1)/b^2\right]}$$

$$\rho_s(\lambda) = \frac{\sinh(2\pi\lambda)}{\cosh(2\pi\lambda) + \cosh(2\pi qE)}$$

- **Chiral Fermions:**

$$K_f(s) = \frac{e^{-s\Delta m^2}}{4\pi^2 a^2 b^2} \sum_{l=0}^{\infty} (2l+2) \int_0^\infty d\lambda\, \lambda\, \rho_f(\lambda)\, e^{-s\left[\lambda^2/a^2 + (l+1)^2/b^2\right]}$$

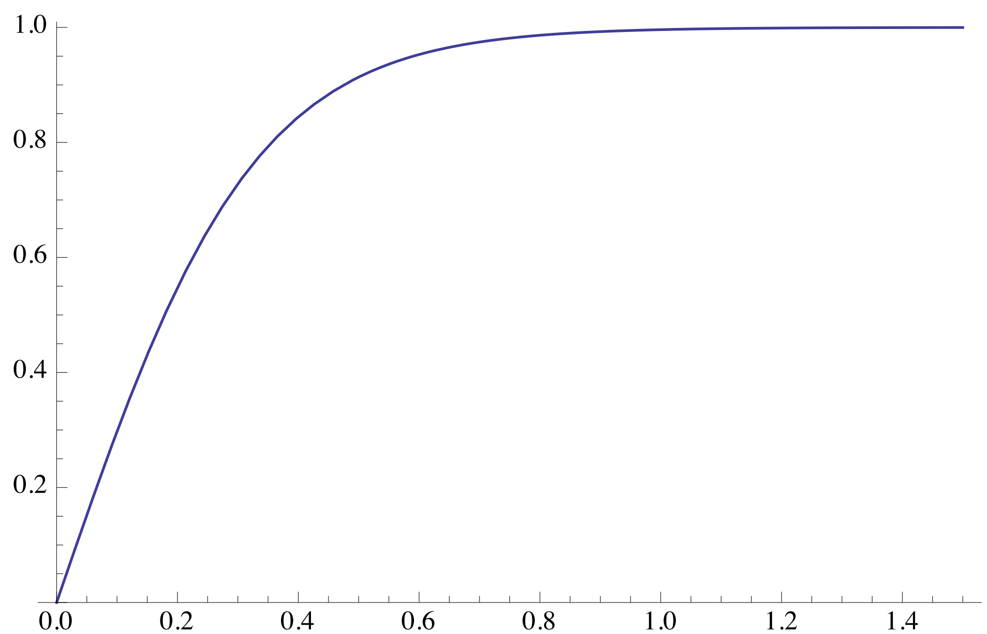
$$\rho_f(\lambda) = \frac{\sinh(2\pi\lambda)}{\cosh(2\pi qE) - \cosh(2\pi\lambda)}$$

where $\Delta m^2 = m^2 - \frac{q^2E^2}{a^2} \rightarrow m^2 - 2q^2M_P^2$ **(classical value)**

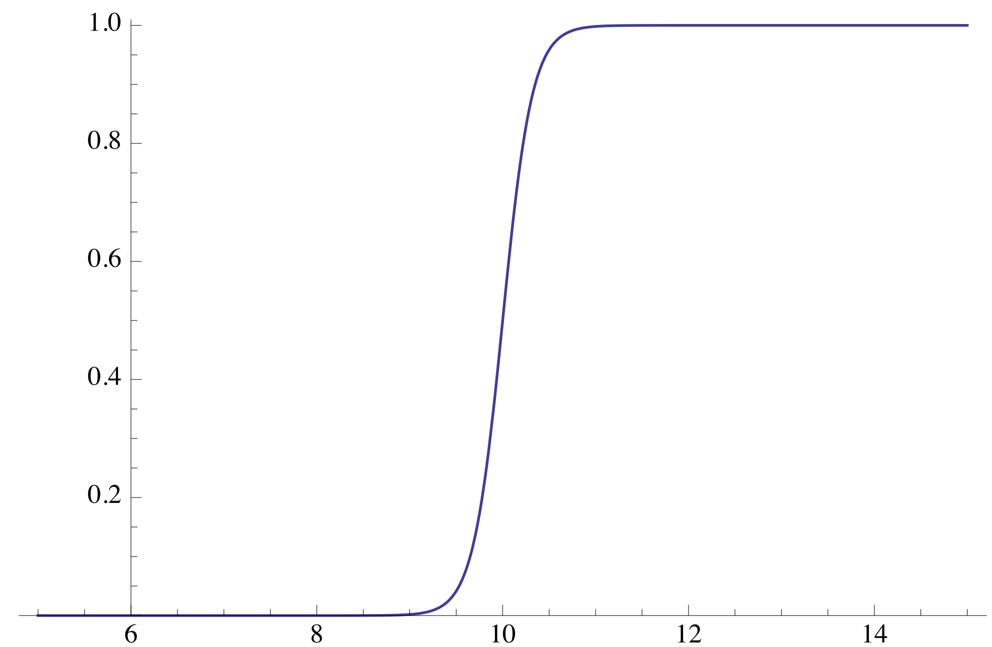
- The heat kernel is **IR divergent** for $\Delta m^2 < 0$, signaling an **instability** to Schwinger pair production of superextremal particles.

# (Sub)Extremal Particles

- One has to be careful in expanding the heat kernel:




(a) Intermediate Black Hole ($qE = 0.1$)




(b) Large Black Hole ($qE = 10$)

- A qE expansion is *only valid* for **intermediate BHs** where:

$$\Lambda_{WGC} = qM_P << 1/a << M_P$$

even both intermediate and large BHs have a >> $1/M_P$, so a semi-classical treatment of gravity should remain valid.

# Relation to the WGC

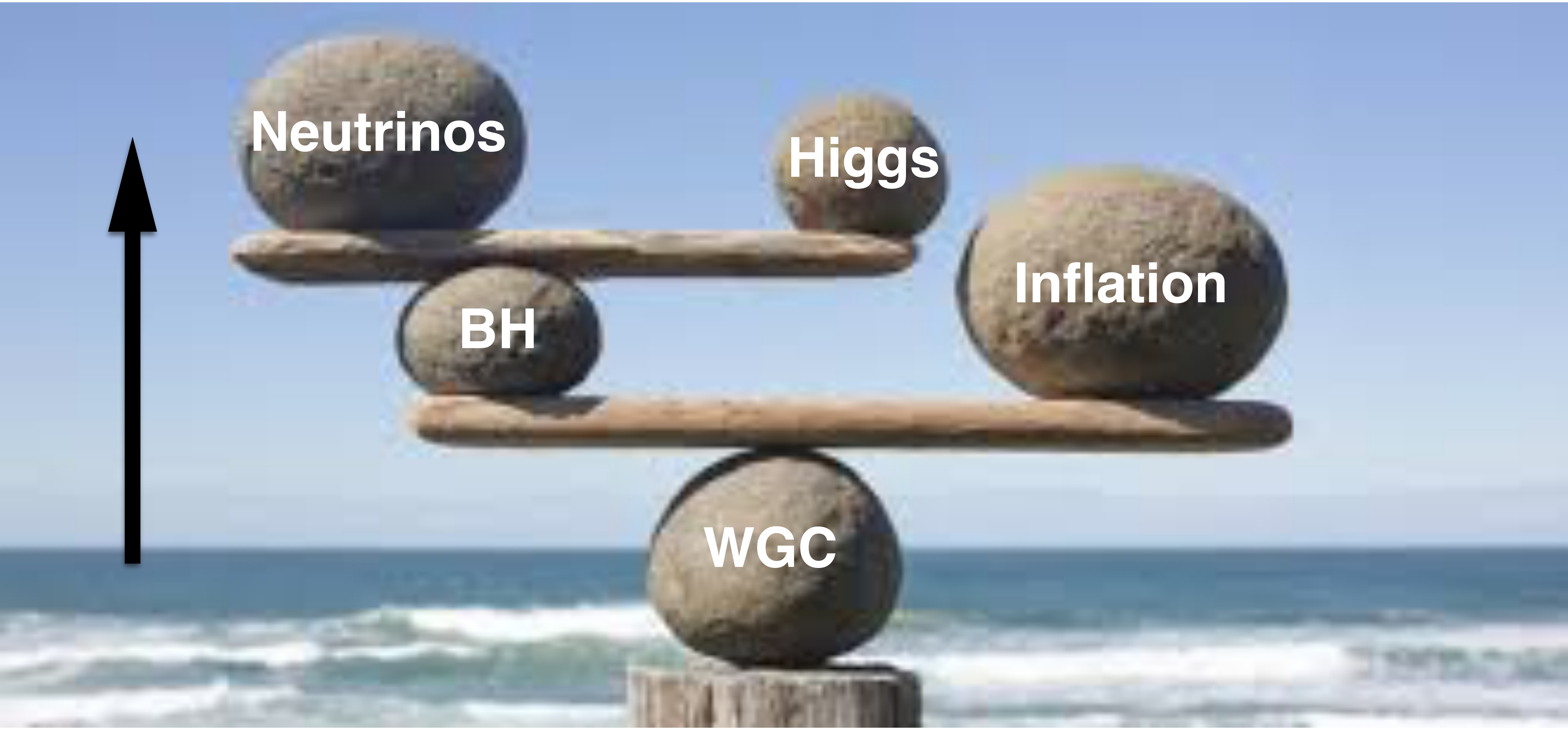
- See [Cottrell, GS, Soler, '16] for results of various cases (intermediate/ large BHs, loops of (sub)extremal bosons/fermions, SUSY or not).
- As an example, we found that for an **intermediate BH**, including loop corrections from an **extremal scalar**:

$$\mathcal{S}_s \approx \mathcal{E}(Q; E_0, a_0, b_0) = \frac{Q^2}{4} - \left(\frac{1}{90} + \frac{q^2 Q^2}{192\pi^2} + \frac{q^4 Q^4}{1024\pi^4}\right) \ln(q^2 Q^2) + \mathcal{O}(Q^0)$$

- For large BHs, loops of (sub)extremal particles do not induce corrections to the entropy, other than renormalizing the couplings.

- {Fisher, Mogni, '17] recently repeated our computations for an extremal scalar and confirmed our formulae in the valid region.
- However they made an **erroneous claim** of proving the WGC: they found the second law of thermodynamics is violated for large Q, but this is the regime where the qE expansion breaks down.

# Road Map




**WGC, Multiple Point Principle, and the Standard Model Landscape**

Y. Hamada and GS, arXiv:1707.06326 [hep-th].

# WGC for Branes

- We have seen the evidences for and applications of the WGC for particles (and instantons). Analogously for branes, the WGC is:

$$``T_p \leq Q_p"$$

where = applies only to BPS, otherwise <

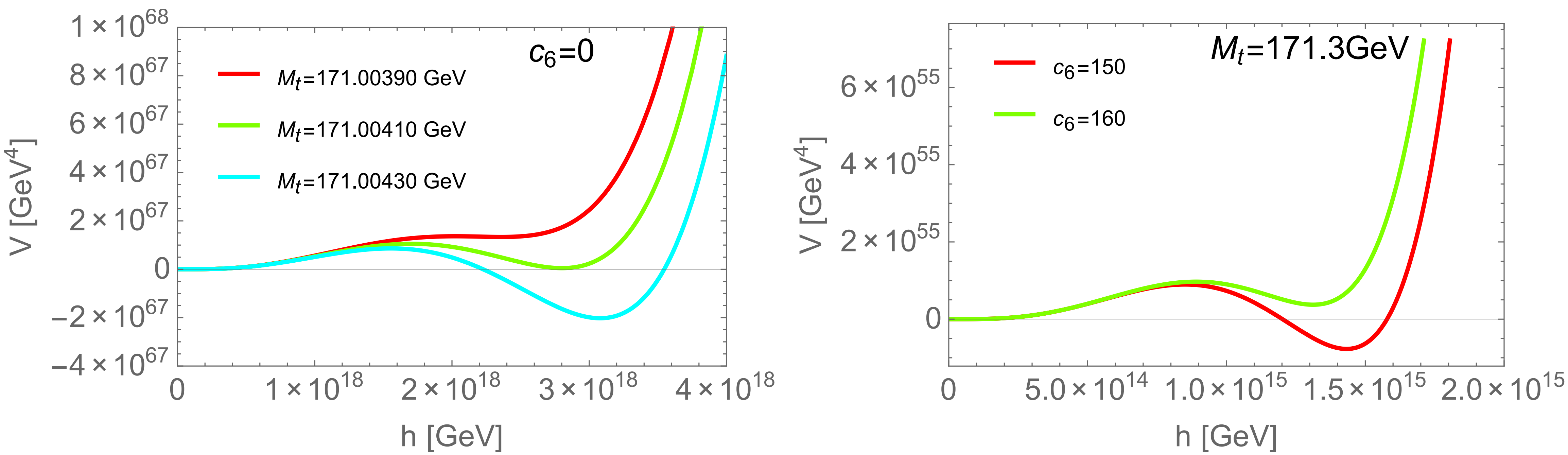
- This led [Ooguri,Vafa, '16] to conjecture that non-SUSY AdS vacua supported by fluxes are unstable (AdS fragmentation).
- This conjecture is best supported by the lack of counter examples in string theory, but is supposed to hold more generally.
- A stronger form of their conjecture:

**"all non-SUSY AdS** (in theories whose low energy description is Einstein gravity coupled to a finite # of fields) **are unstable"**

- **How do we test this conjecture?**

# Standard Model Landscape

- After the Higgs discovery, we know that there is an additional Higgs vacuum at high scale, other than the EW vacuum:




- This high scale vacuum can be $AdS_4$, $M_4$, or $dS_4$ depending on the top quark mass and the higher-dimensional operators.
- Applying this conjecture to the SM landscape, we can constrain the **Higgs potential** and **BSM physics**. [Hamada, GS].

# Standard Model Landscape

- The SM gives rise to a rich landscape of vacua in 2d & 3d upon compactification, dependent on the type (Majorana or Dirac) and masses of the neutrinos [Arkani-Hamed, Dubovsky, Nicolis, Villadoro].
- The SM with minimal Majorana neutrino masses seems to give rise to a non-SUSY AdS vacuum [Arkani-Hamed et al]. This led [Ooguri, Vafa, '16] to conjecture that this model is in the swampland.
- We carried out a systematic study of the SM landscape in 2d and 3d, including more general BCs and Wilson lines [Hamada, GS].
- We found a runaway behavior at small compactification radii ($\lesssim \text{GeV}^{-1}$). These candidate non-SUSY AdS neutrino vacua are subject to quantum tunneling instabilities, a possibility overlooked in [Arkani-Hamed, Dubovsky, Nicolis, Villadoro]; [Ibanez, Martin-Lozano, Valenzuela]
- Our result is consistent with the OV conjecture.

# Multiple Point Criticality Principle

- There may nonetheless be an interesting correlation between the neutrino mass and the 4d cosmological constant scale,
- The **Multiple Point Criticality principle** [Froggatt, Nielsen, '96]; [Bennett, '96] which demands the coexistence of degenerate phases had some successes in predicting the Higgs mass.

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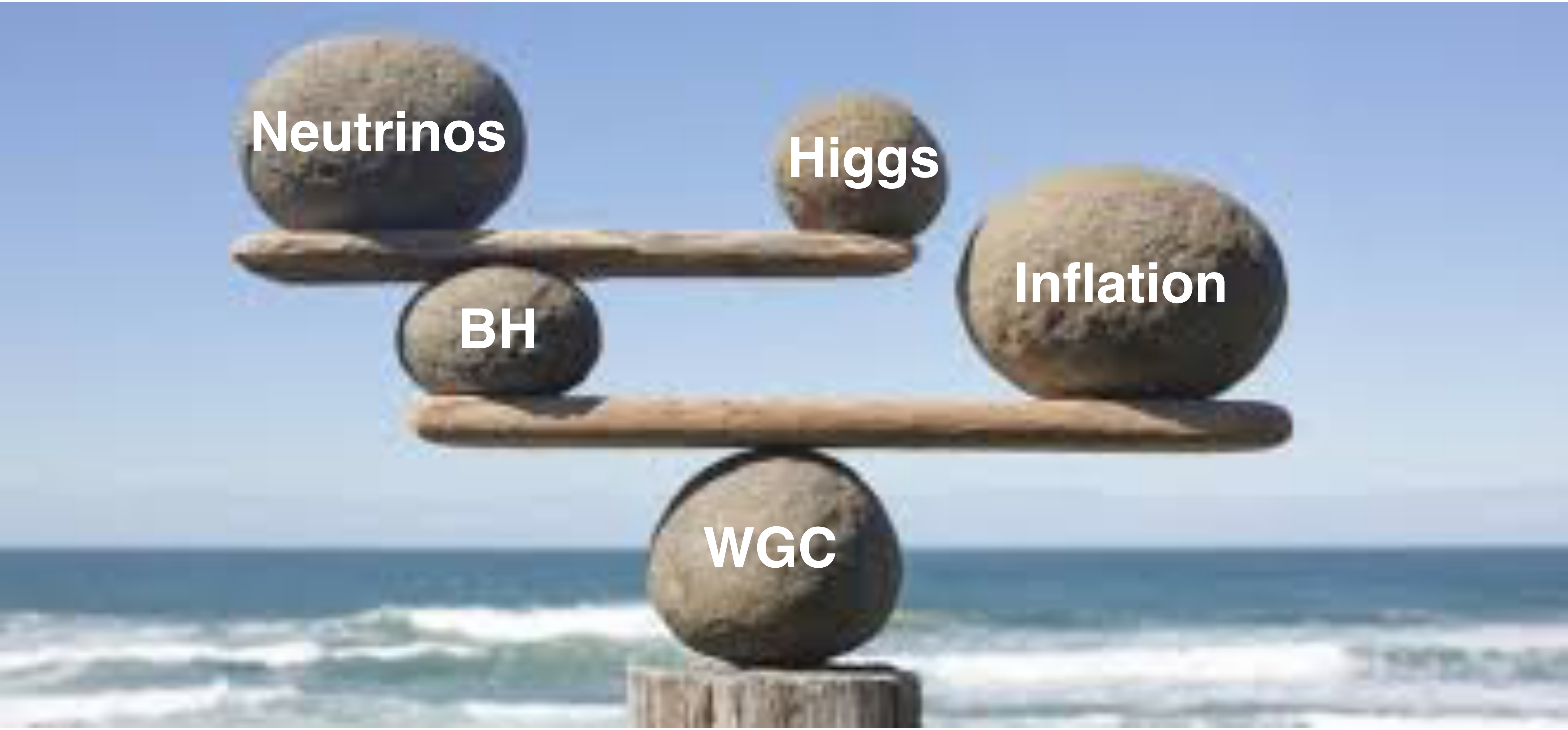
PHYSICS LETTERS B

Standard model criticality prediction top mass 173 ± 5 GeV and Higgs mass 135 ± 9 GeV

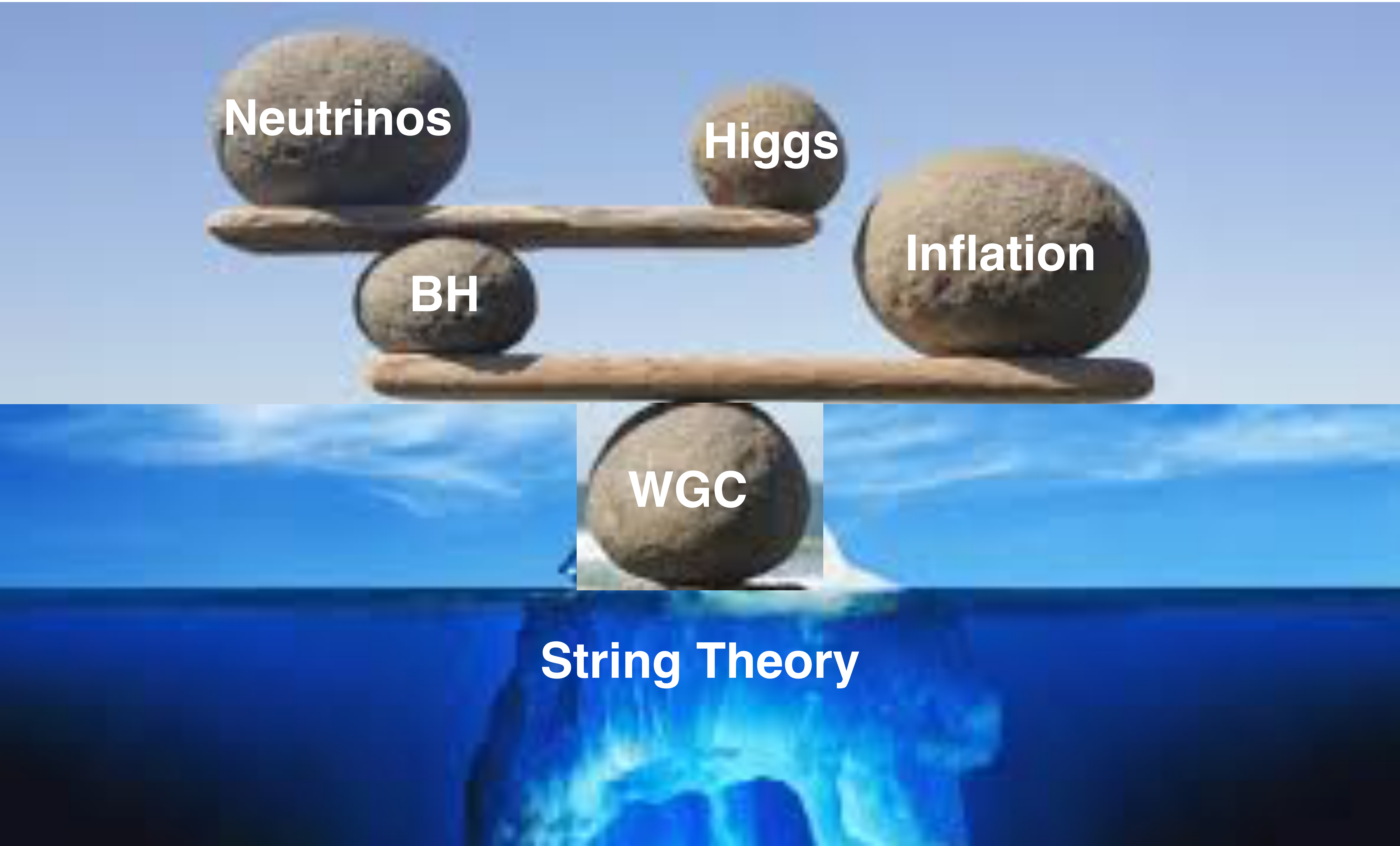
C.D. Froggatt [a], H.B. Nielsen [b]

- Applying the multiple point criticality principle to 2/3d and 4d vacua, we predicted that the **$\nu$s are Dirac w/ mass of lightest $\nu \simeq \mathcal{O}$ (1-10) meV**.
- Our predictions can be tested by future CMB, large-scale structure, and 21cm line observations.

# Road Map



# Road Map



# String Theory Constructions

# Axion Monodromy

**Monodromy by brane coupling**
[Silverstein, Westphal, '08];
[McAllister, Silverstein, Westphal, 08]

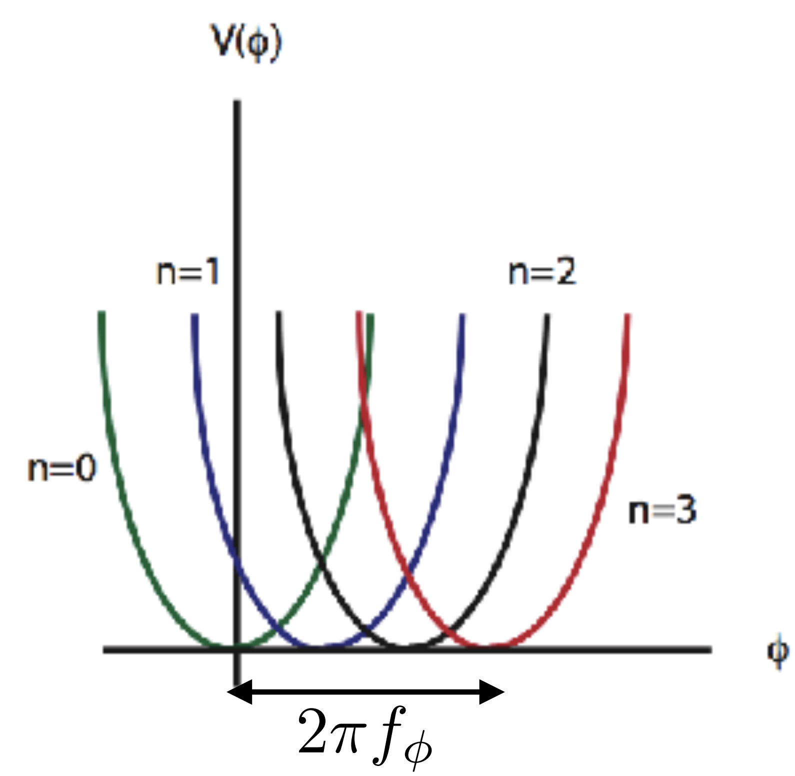
**F-term axion monodromy**
(embeddable in SUGRA of string theory)
[Marchesano, GS, Uranga '14]

See also [Blumenhagen, Plauschinn '14];
[Hebecker, Kraus, Witowski, '14]

- Axion is mapped to a ***massive*** gauge field.
- Gauge symmetry:

$$\phi \to \phi + 2\pi f$$

$$F \to F - n$$



# Effective 4d Description

- Coupling the axion to a 4-form field strength $F_4 = dC_3$

$$L = -\frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}|F_4|^2 + g\phi F_4,$$

- Upon integrating out $C_3$

$$* F_4 = f_0 + g\phi, \qquad f_0 = ne \quad \text{where } n \in \mathbb{Z}$$

one finds a quadratic potential

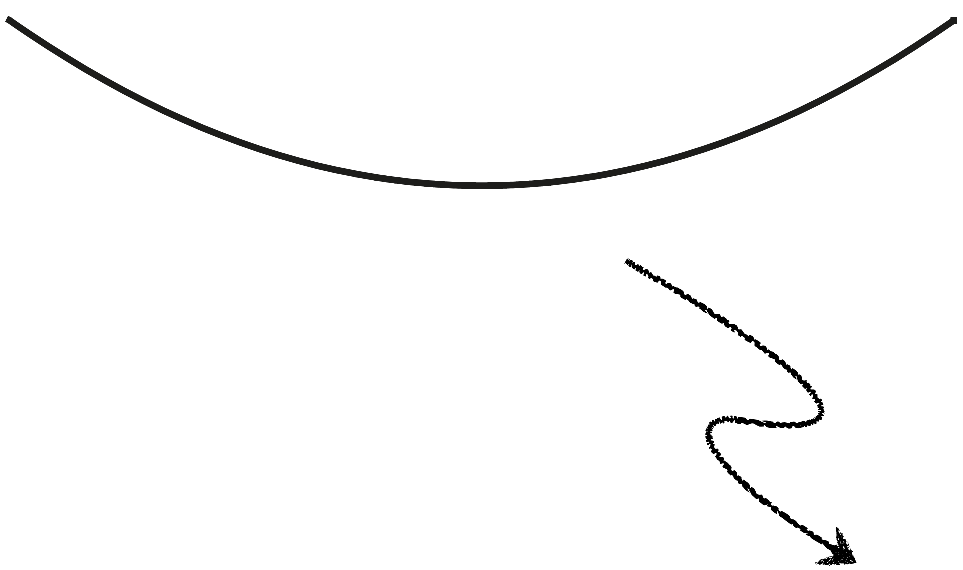
$$V = \frac{1}{2}\left(f_0 + g\phi\right)^2$$

with a shift symmetry: $\phi \to \phi + \frac{e}{\mu}$ $\quad n \to n-1 \quad n \in \mathbb{Z}$

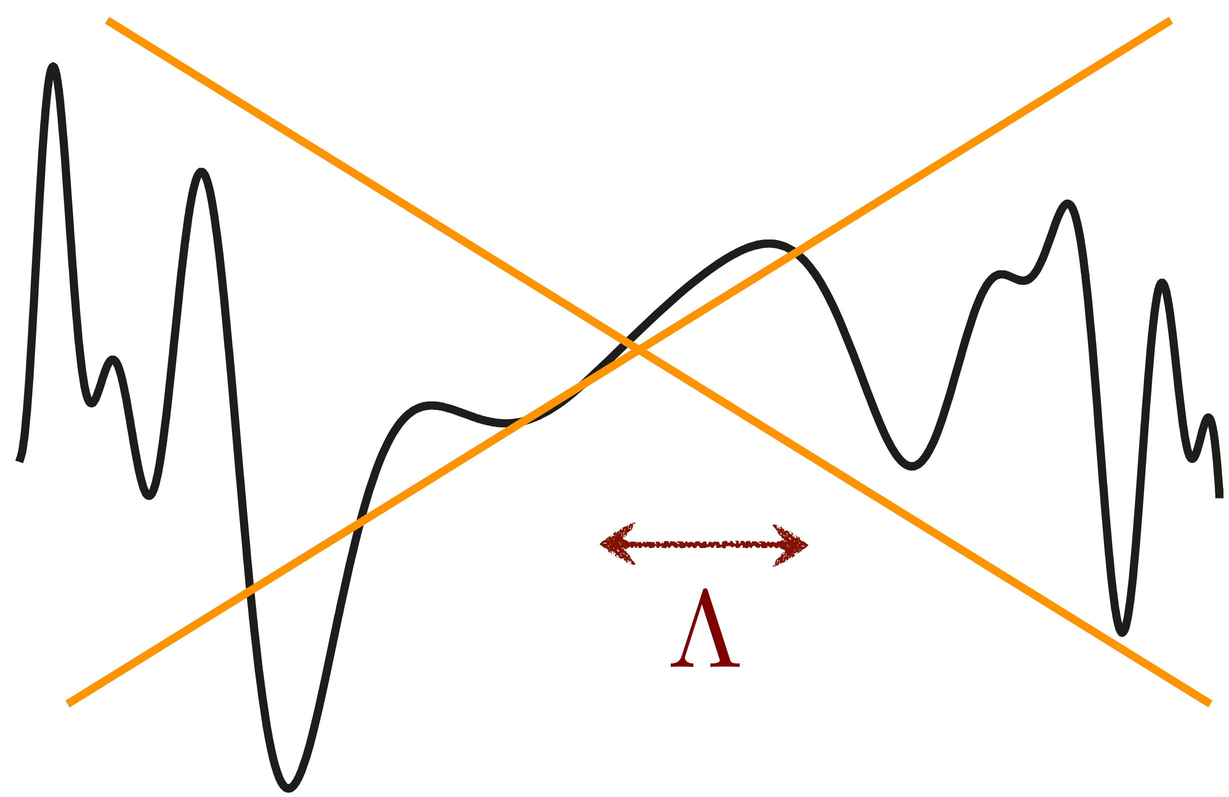
# Planck-suppressed Corrections

- ✤ Gauge symmetry ⇒ UV corrections only depend on $F_4$

$$\sum_n c_n \frac{F^{2n}}{\Lambda^{4n}} \longrightarrow \mu^2\phi^2 \sum_n c_n \left(\frac{\mu^2\phi^2}{\Lambda^4}\right)^n$$

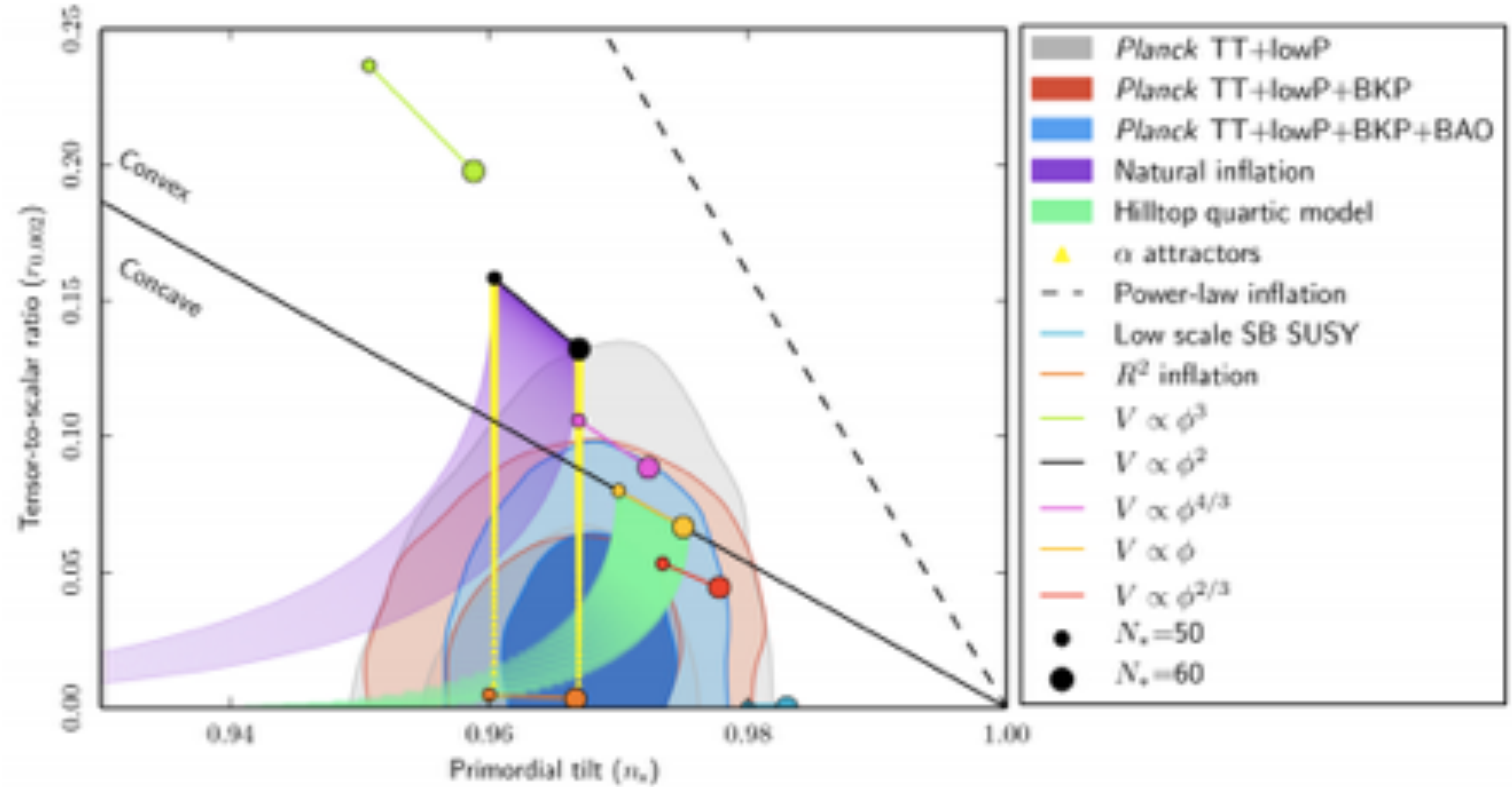


$$\Lambda \rightarrow \Lambda_{\text{eff}} = \Lambda\left(\frac{\Lambda}{\mu}\right)$$



# Axion Monodromy Inflation

$$\mathcal{L} = \frac{1}{2}\left(\partial\phi\right)^2 - \Lambda^4\left(1 - \cos\left(\frac{\phi}{f}\right)\right) - \mu^{4-p}\phi^p$$



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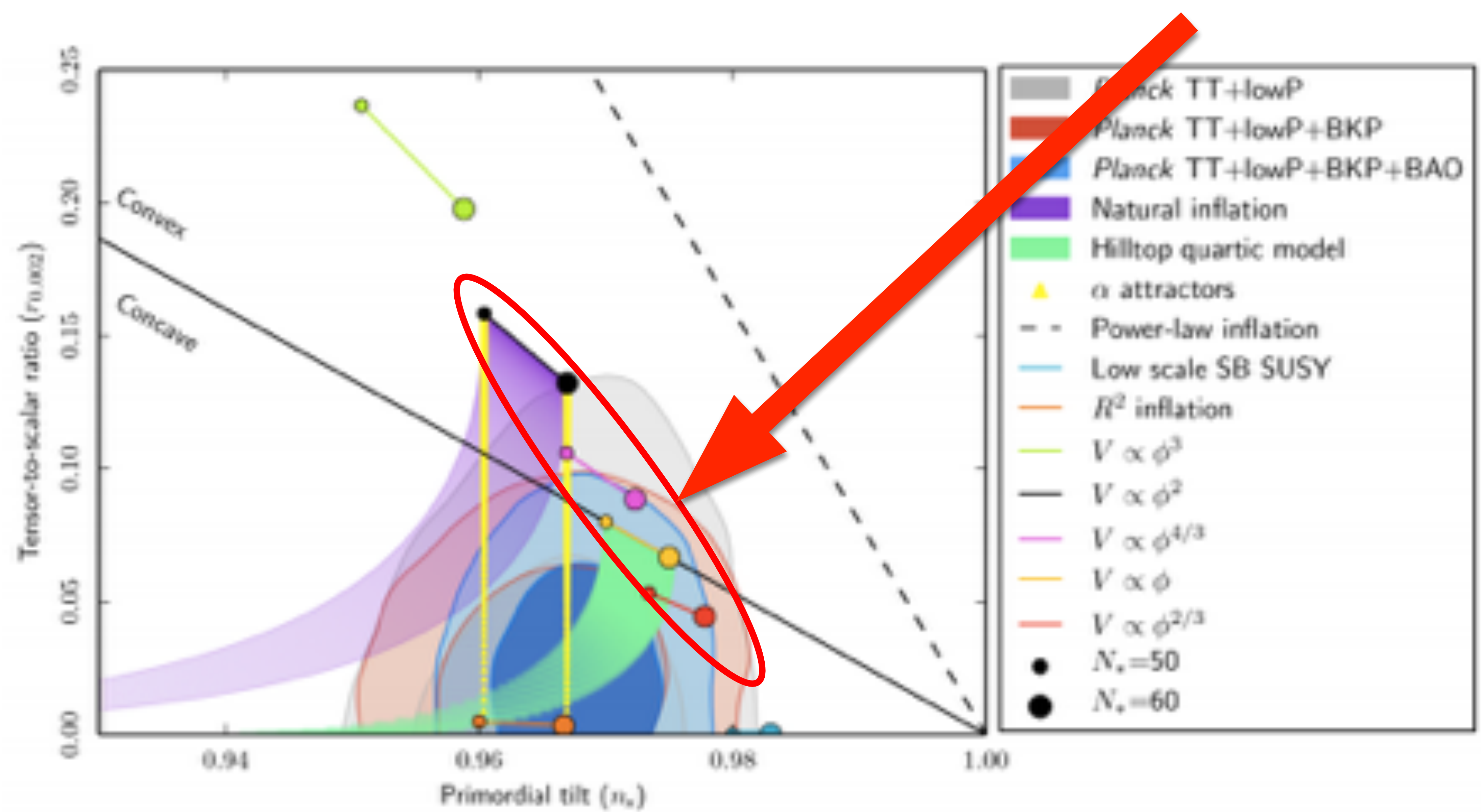

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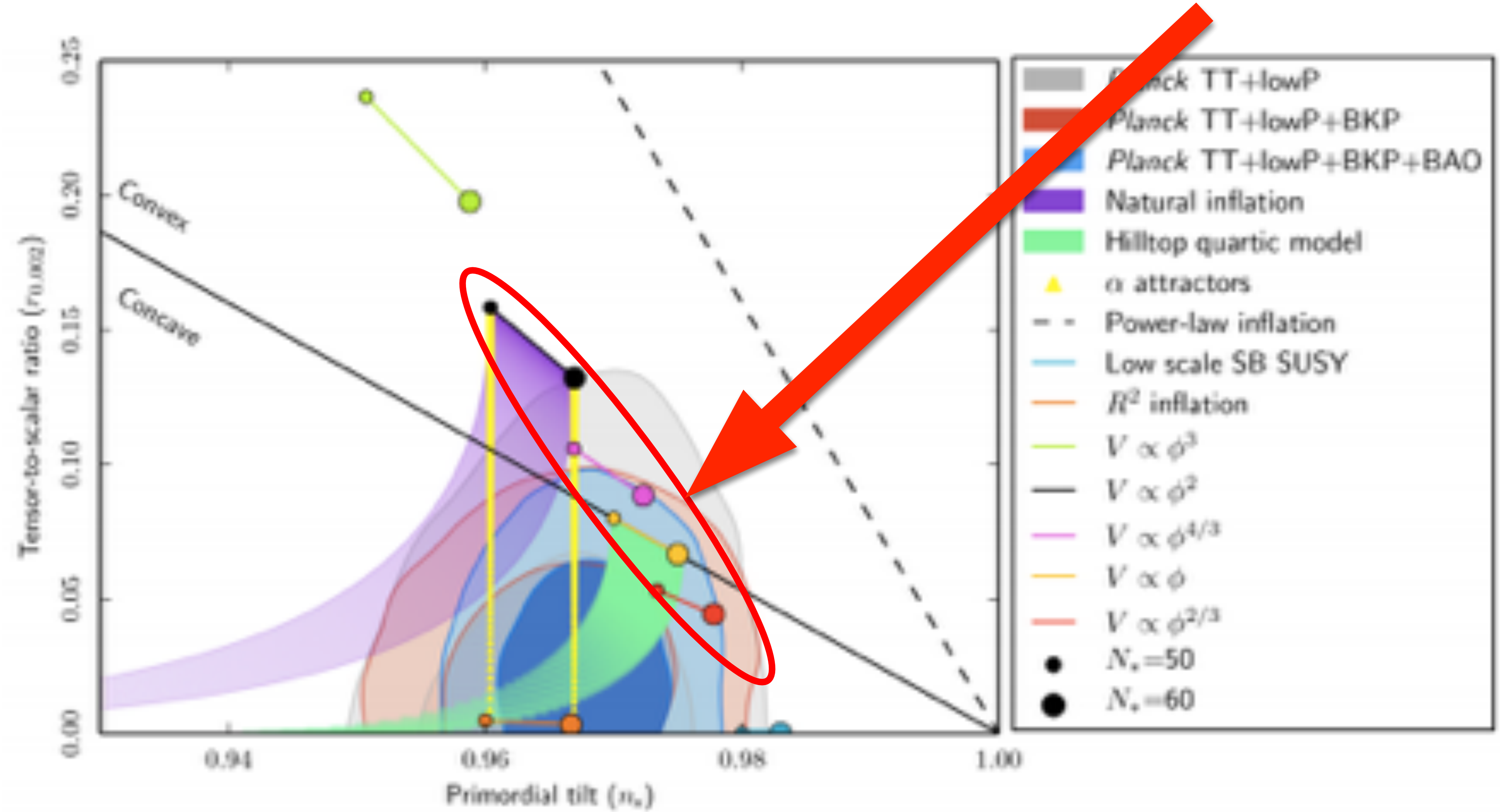
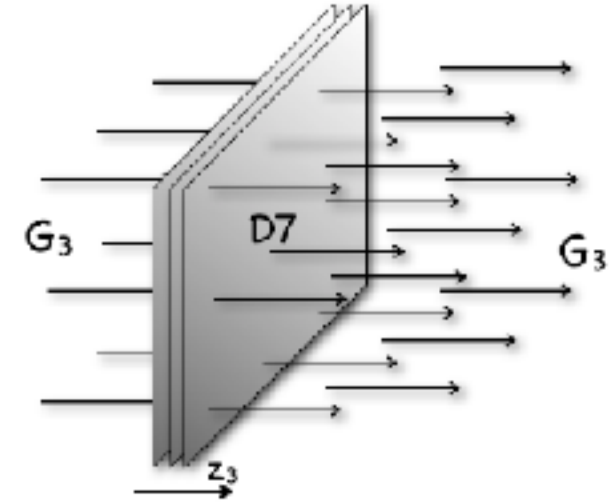
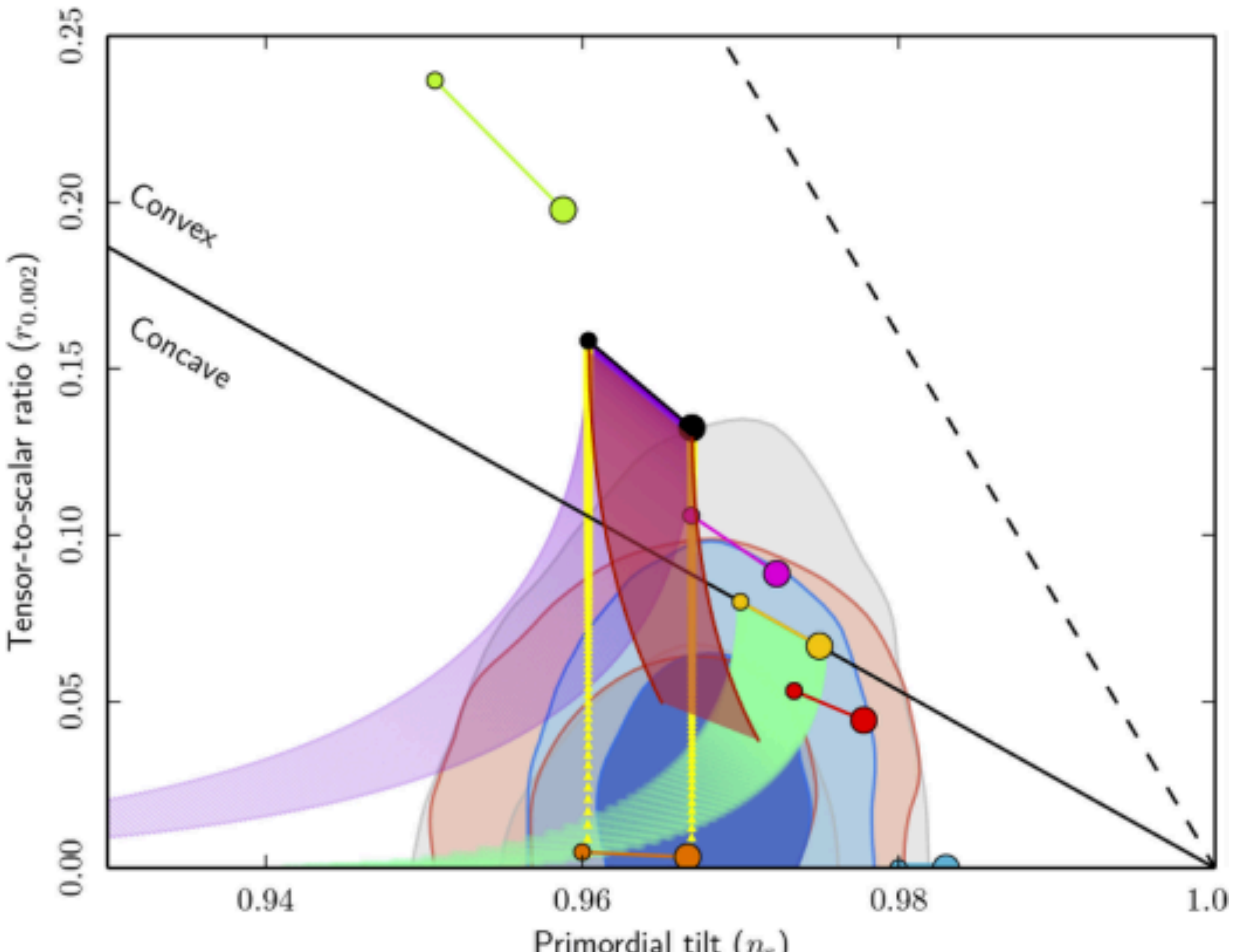



**Current bound combining Planck+BICEP2/KECK+BAO: r < 0.07**

# Inflationary Observables




- Taking into account constraints from **moduli stabilization**:




**Flux flattening** generates a ***family*** of $m^2\phi^2$ inflation with:

$$n_s \simeq 0.96 - 0.97$$
$$r \simeq 0.04 - 0.14$$

[Landete, Marchesano, GS, Zoccarato, '17]

# Conclusions

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- Progress in **experimental cosmology** and **string theoretical considerations** may help narrow down the range of r.
- We have formulated the WGC for (a large class of) axions which can be dualized to U(1) gauge fields.
- **Axion Monodromy** is an interesting exception to the WGC, though there may be other considerations (e.g., backreaction) that limit r.
- **Flux flattening** can lower r to within current experimental bound and yet detectable in the foreseeable future, e.g., the flux flattened $m^2\phi^2$ family has $r \simeq 0.04$-$0.14$.
- We test the WGC from **entropic considerations**.
- Loops of charged particles can lead to unexpected corrections to the classical geometry and entropy of a large extremal BH unless:
  - ∃ super-extremal particle for the BH to decay (electric WGC)
  - or, ∃ a UV cutoff set by extremal states (magnetic WGC)
- WGC & Multiple Point Principle offer interesting predictions about Higgs and neutrino physics.

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