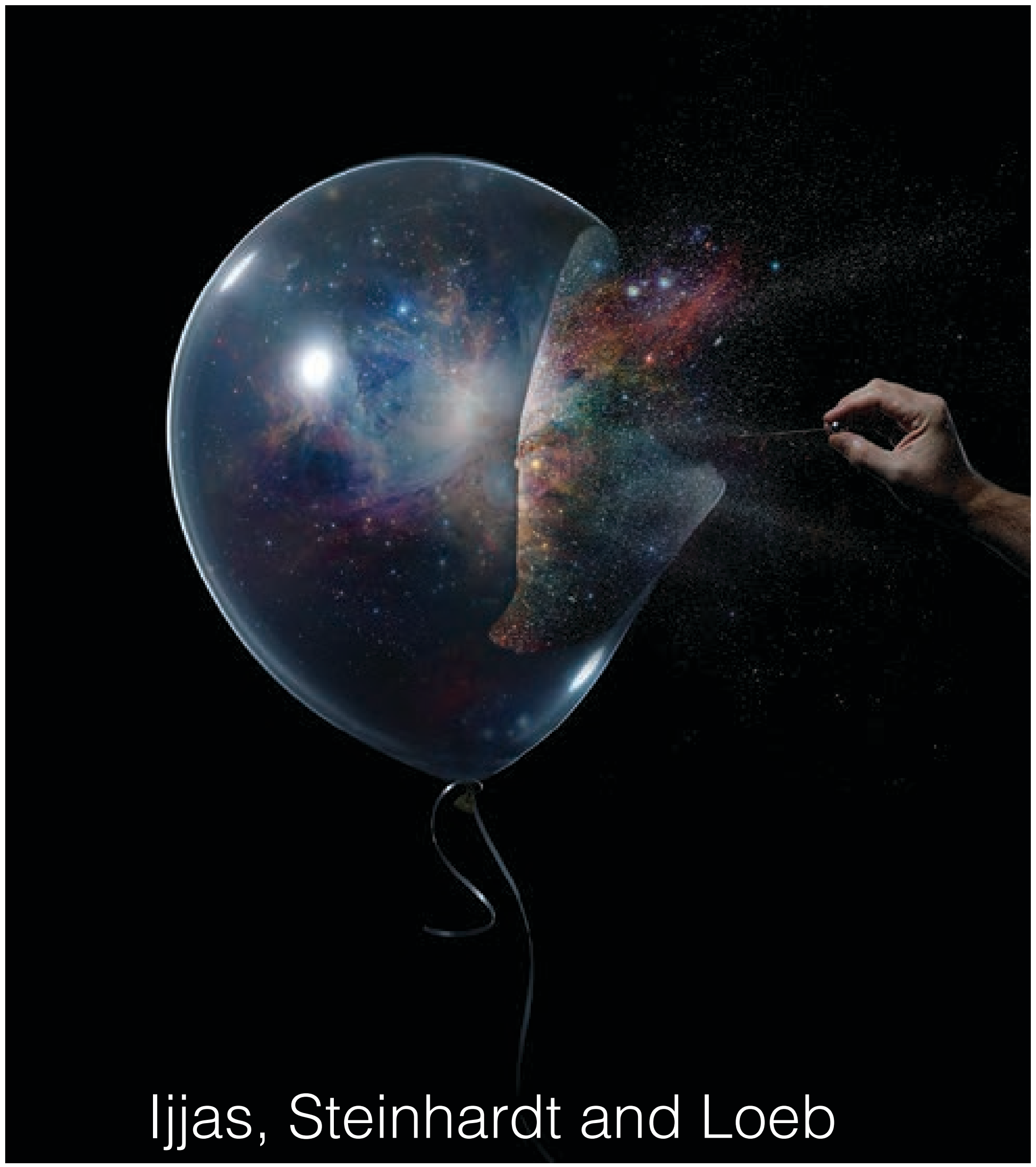
Inflation in String Theory & Quantum Gravity

Gary Shiu

This talk is ***not*** a critique of inflation …



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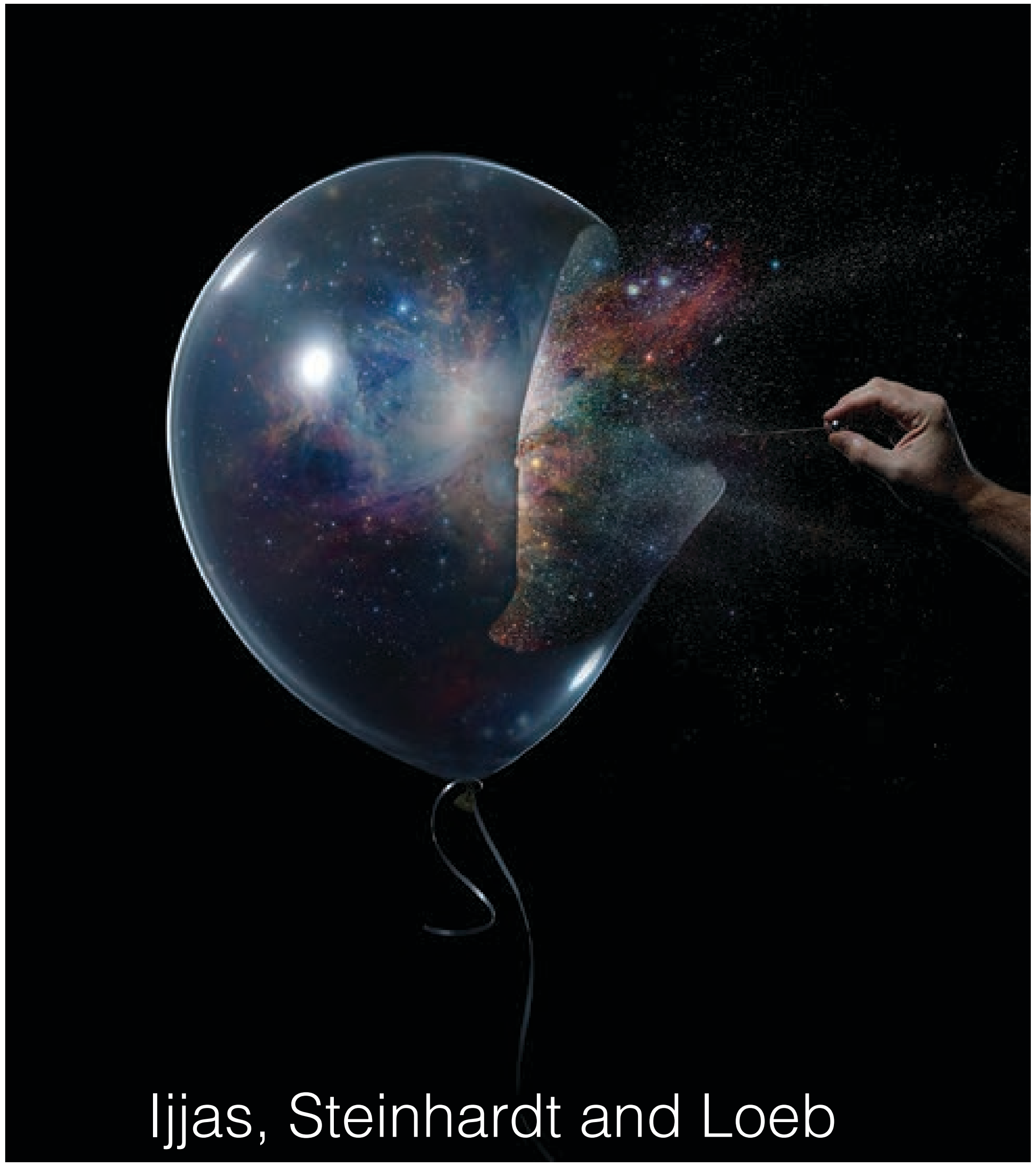

See reply from 33 physicists [Guth, Kaiser, Linde, Nomura, et al]

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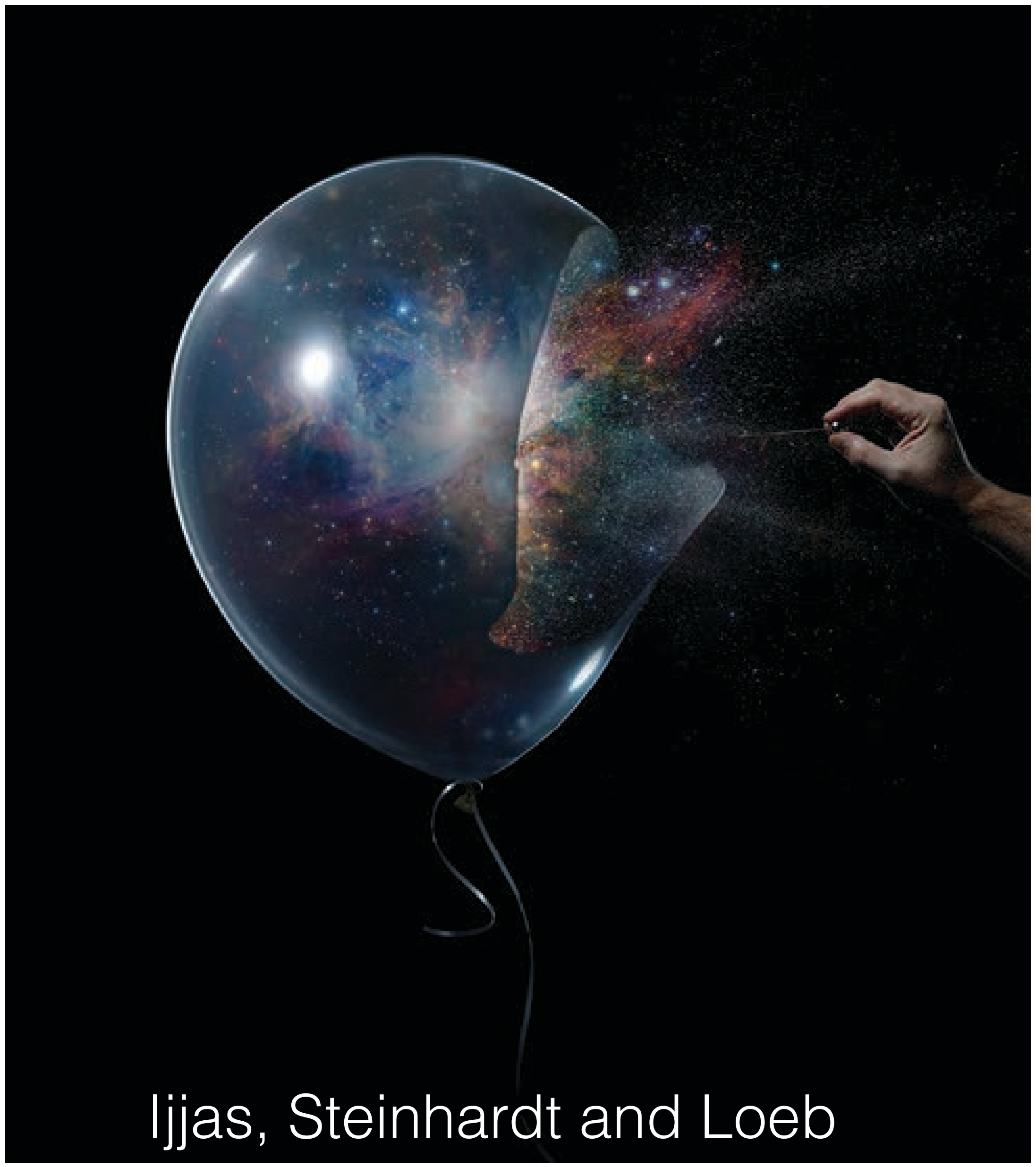

Experiment

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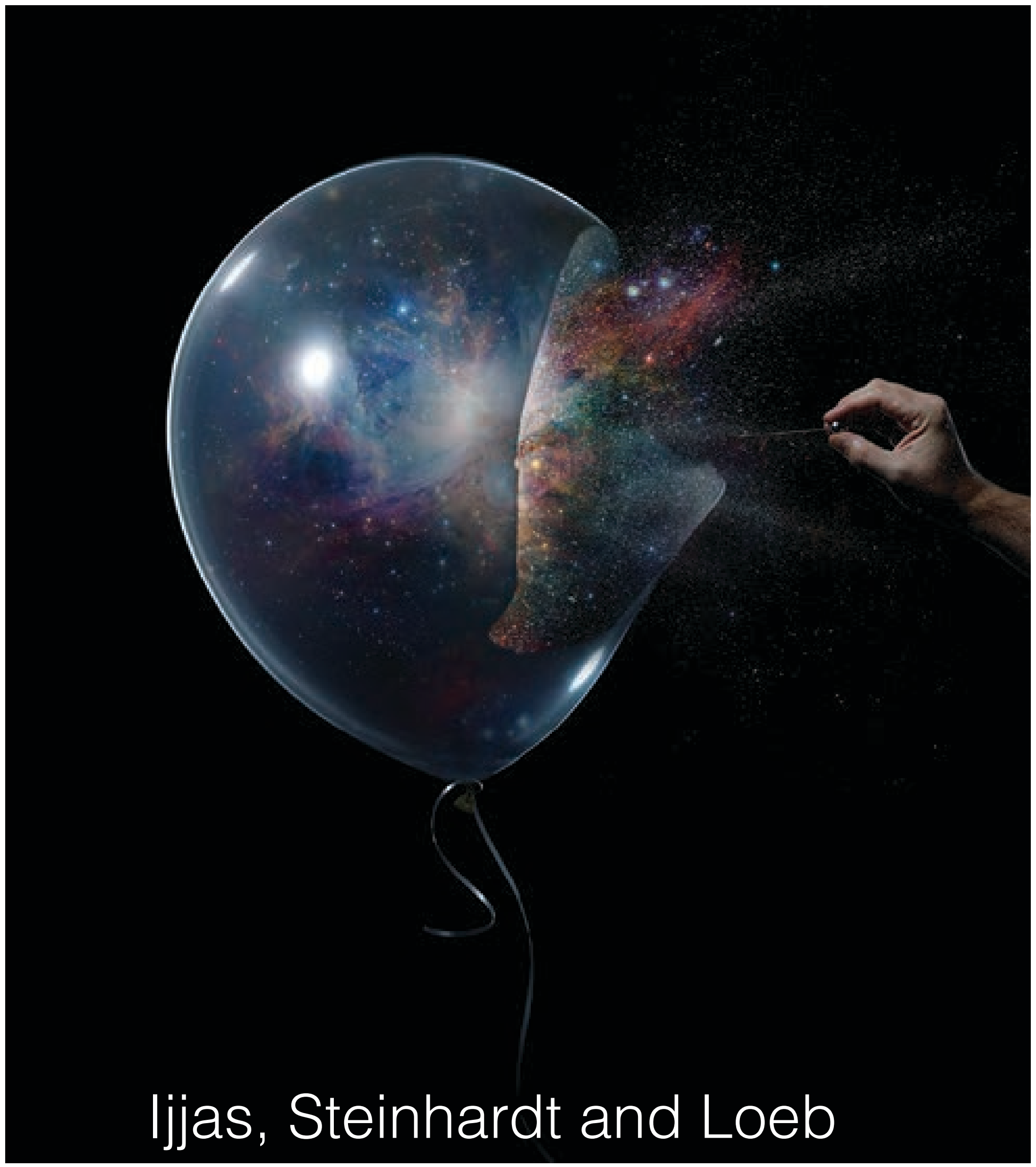

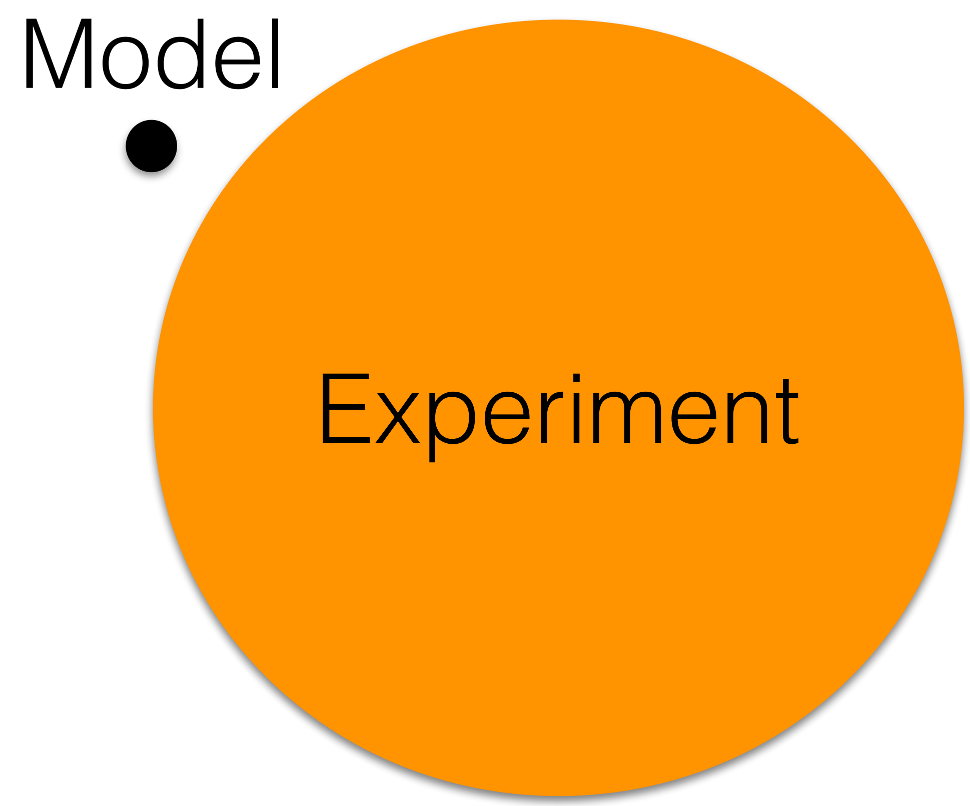

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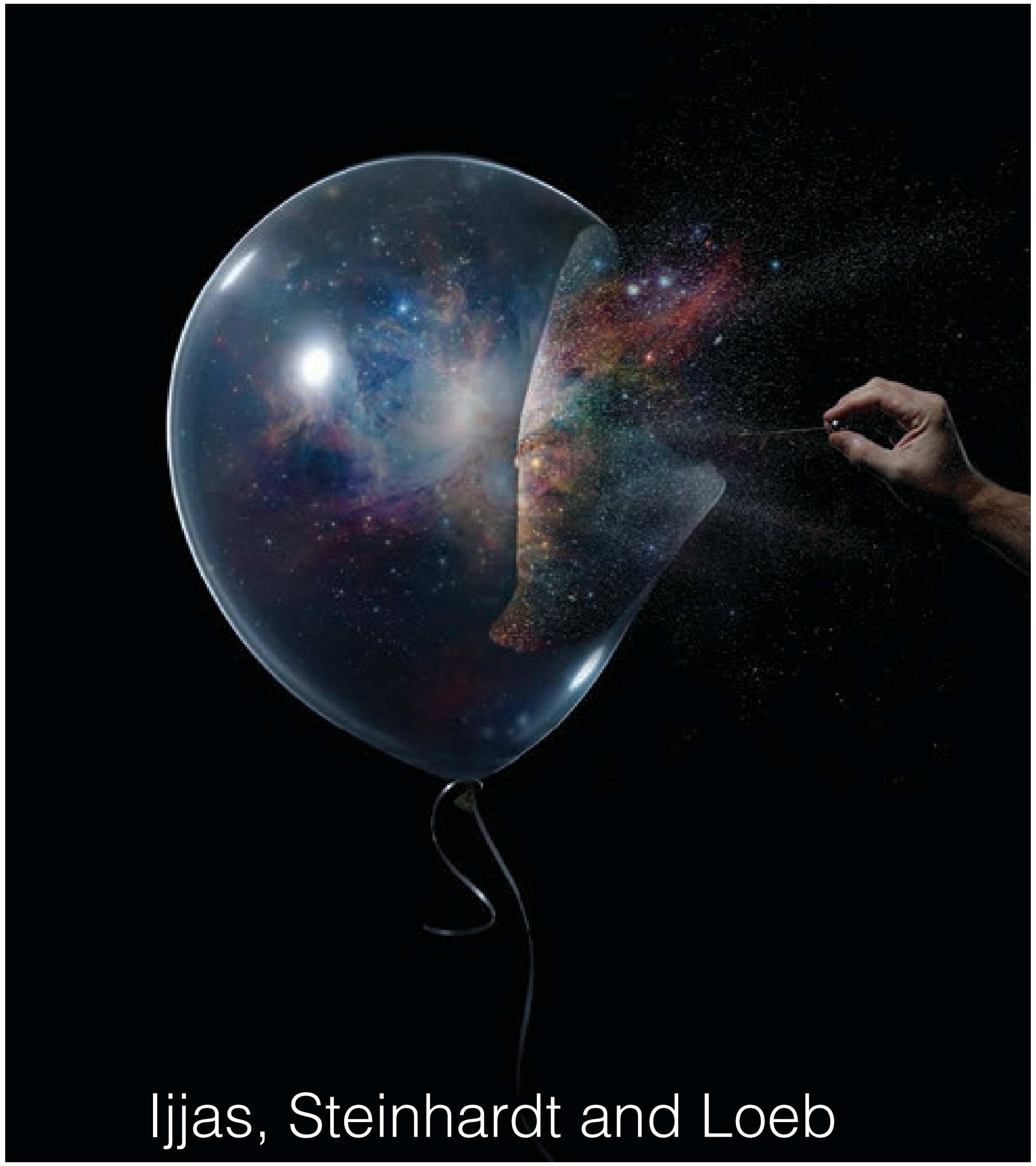

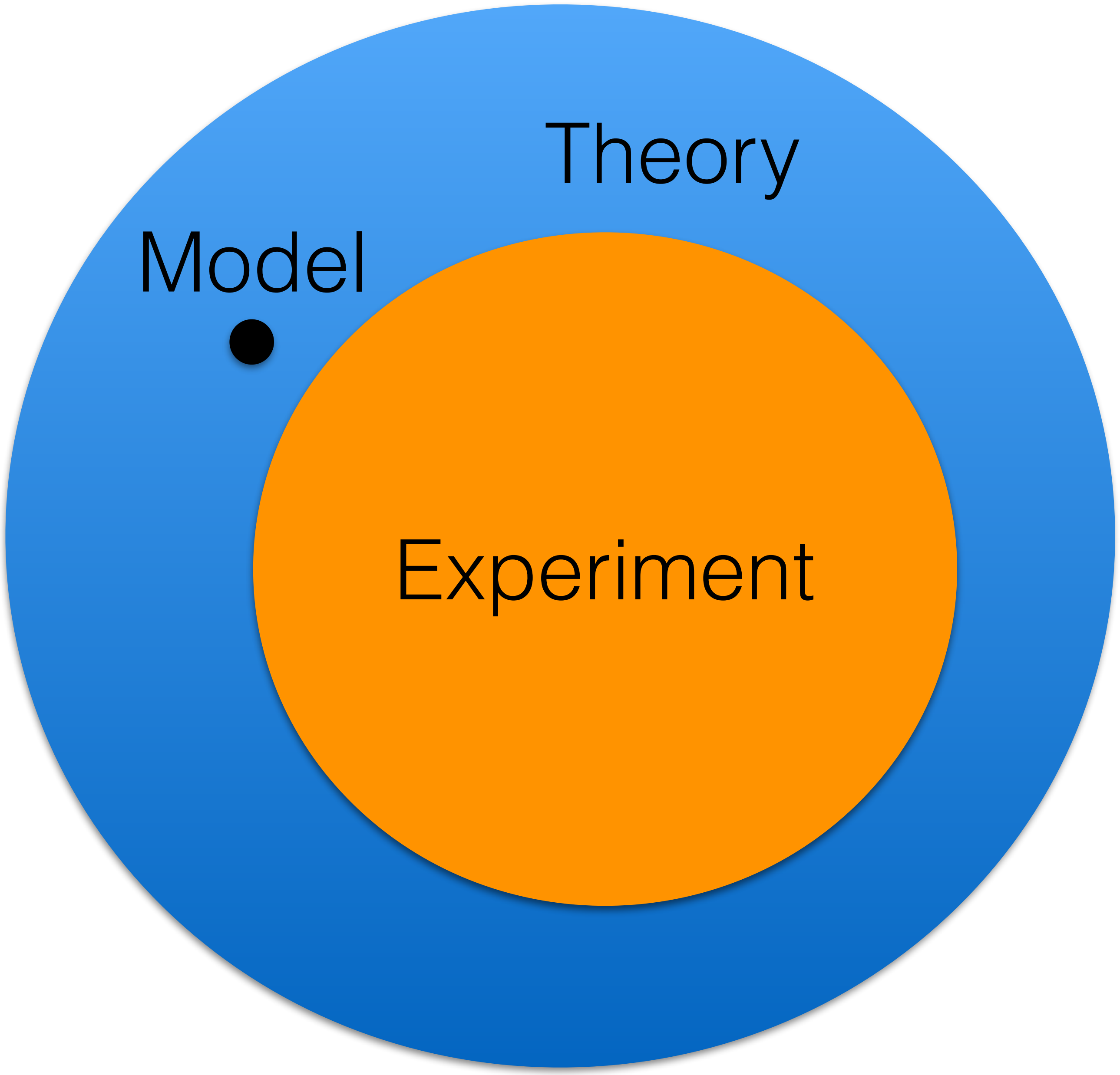

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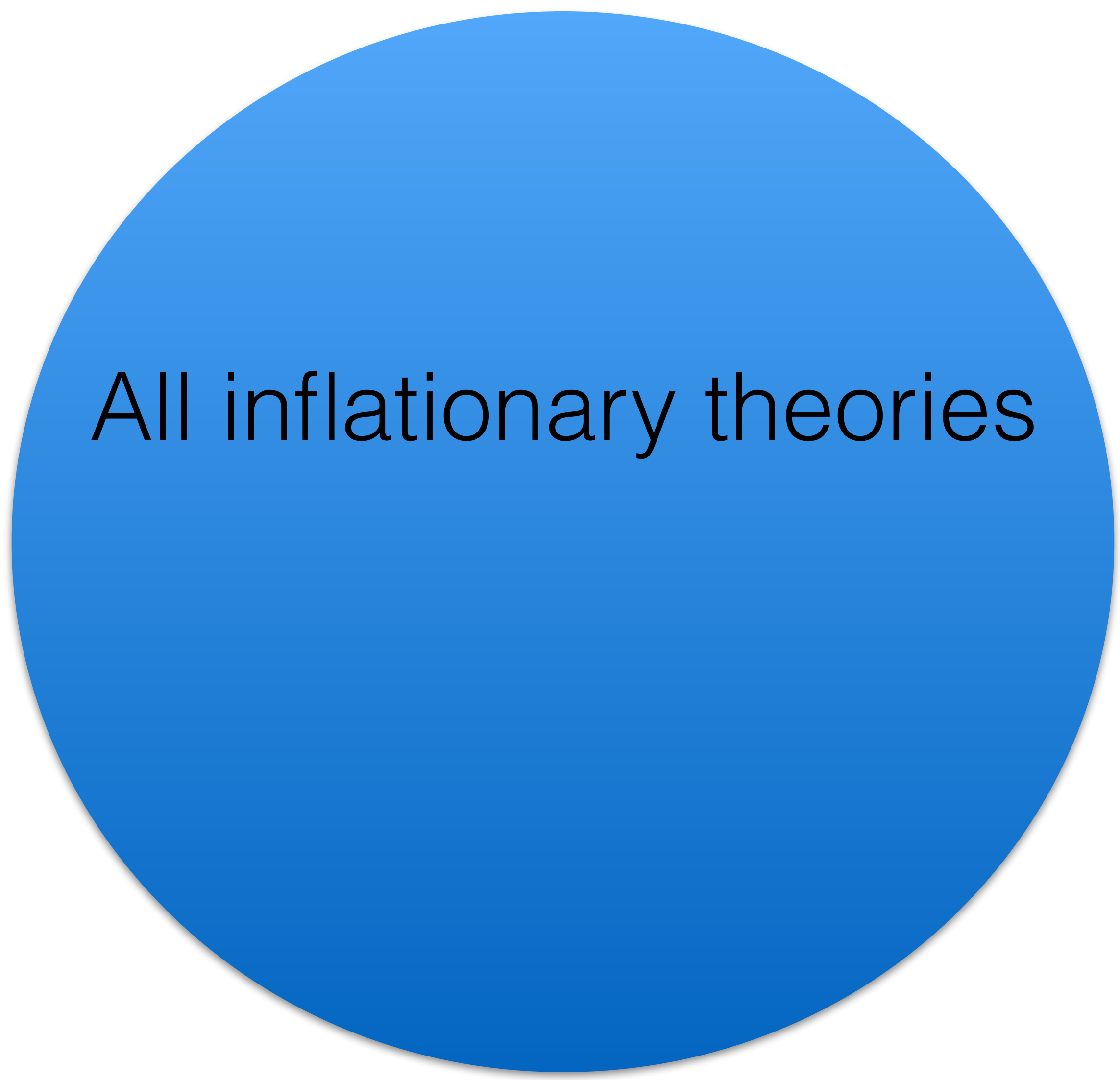

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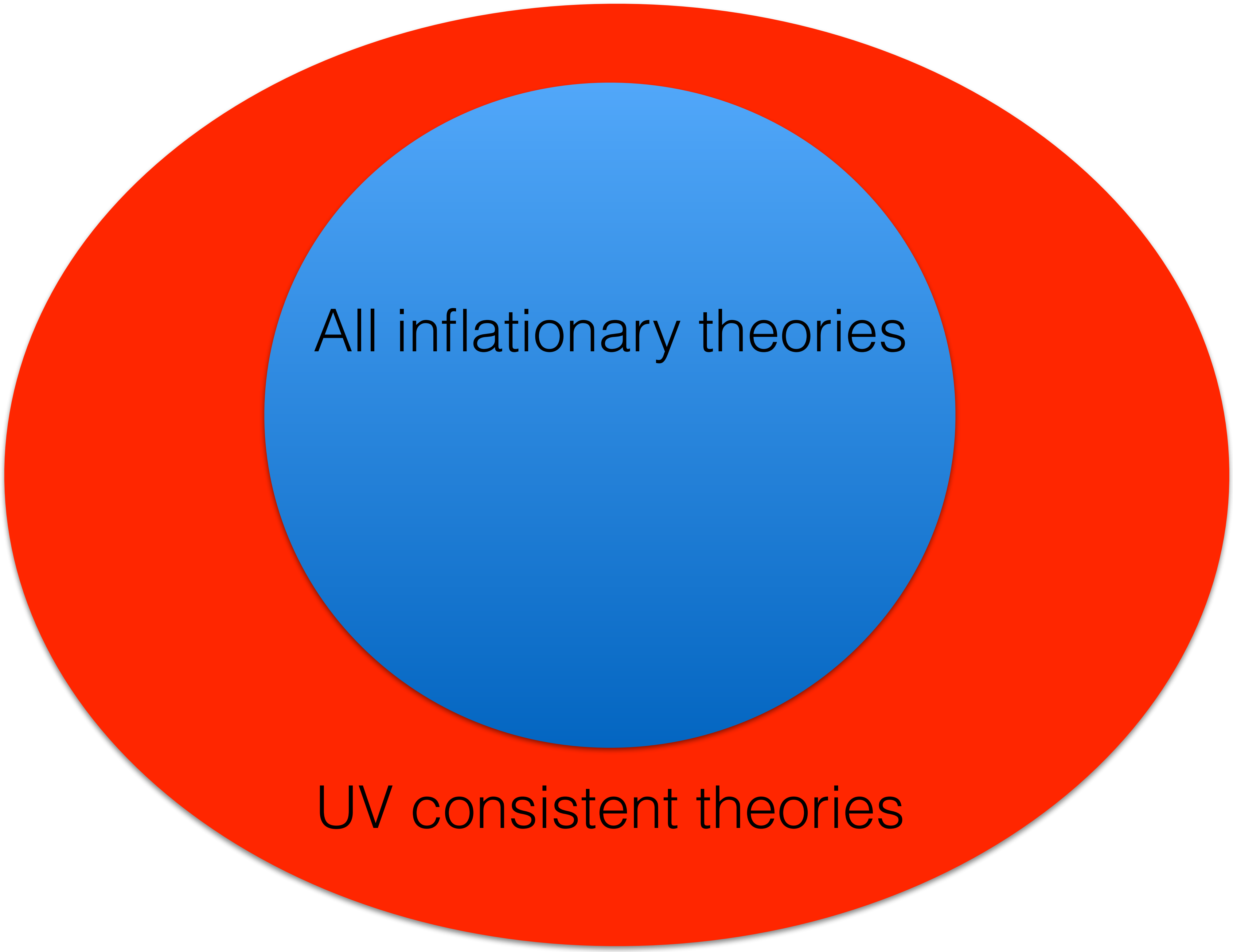

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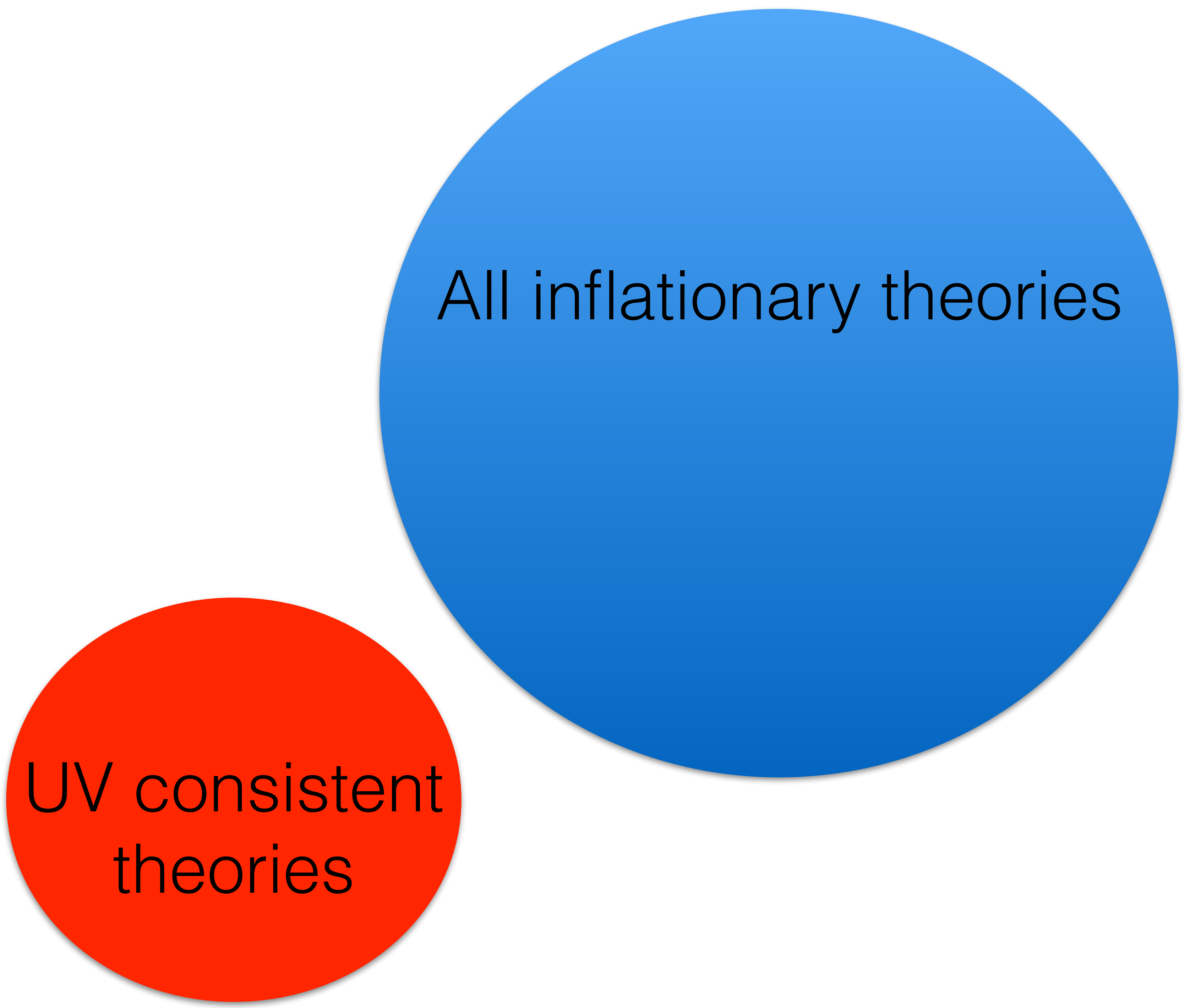

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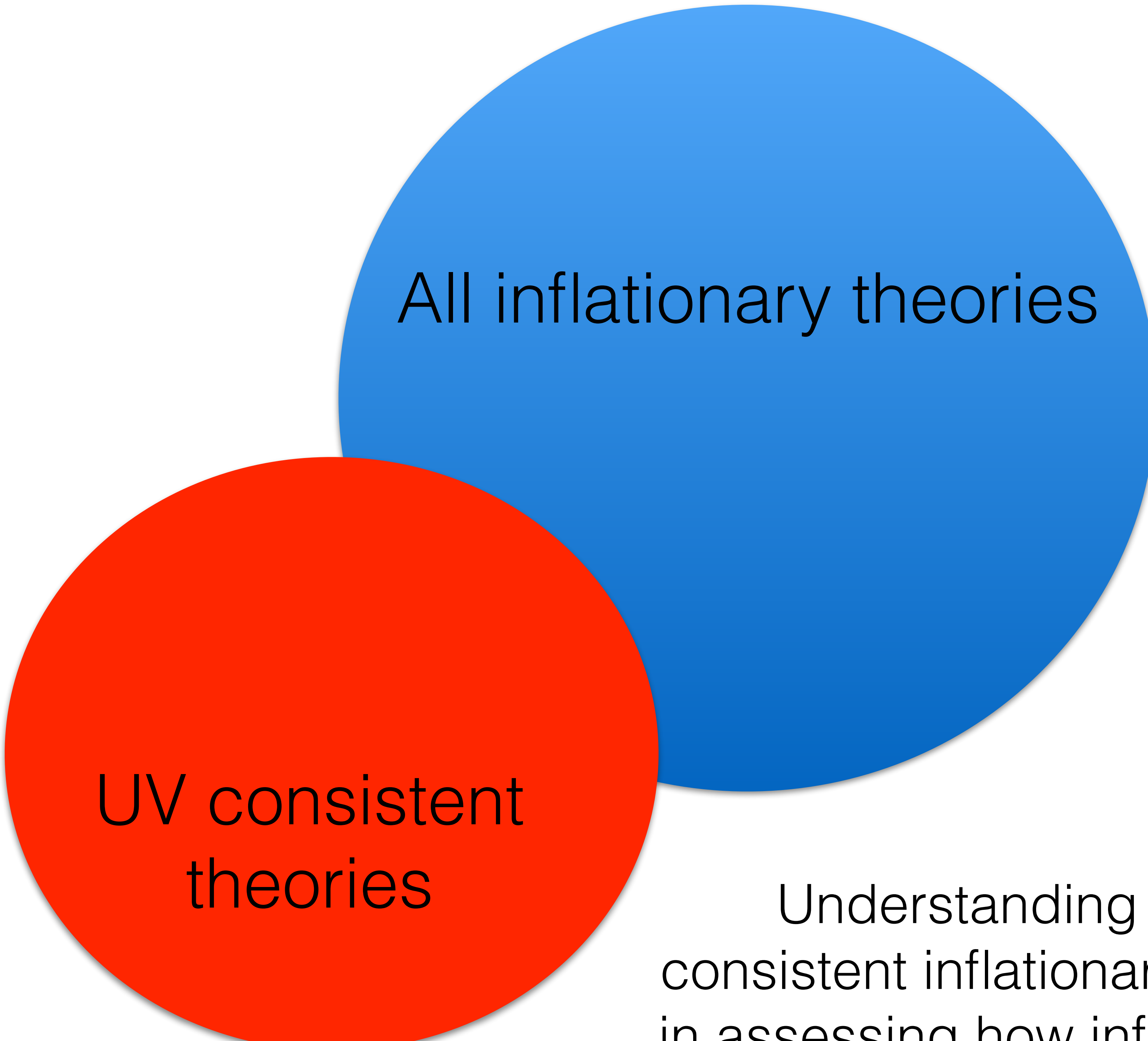


Understanding the space of UV consistent inflationary theories also helps in assessing how inflation fares with data.

Based on work with:

J. Brown

W. Cottrell

P. Soler

M. Montero

F. Marchesano

A. Uranga

A. Landete

G. Zoccarato

W. Staessens

J. Brown, W. Cottrell, GS, P. Soler, JHEP **1510**, 023 (2015), JHEP **1604**, 017 (2016), JHEP **1610** 025 (2016).

M. Montero, GS and P. Soler, JHEP **1610** 159 (2016).

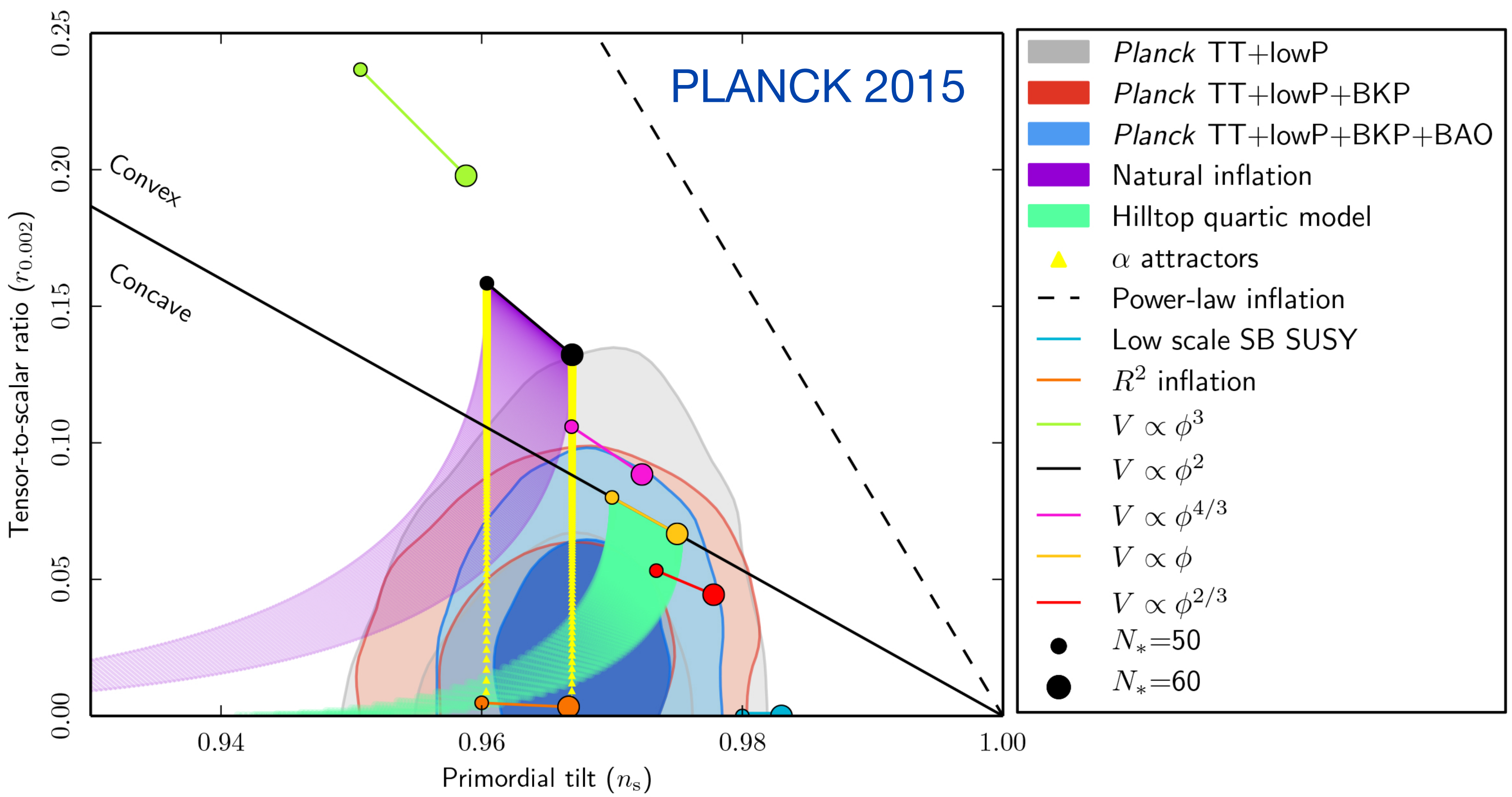
W. Cottrell, GS and P. Soler, arXiv:1611.06270 [hep-th].

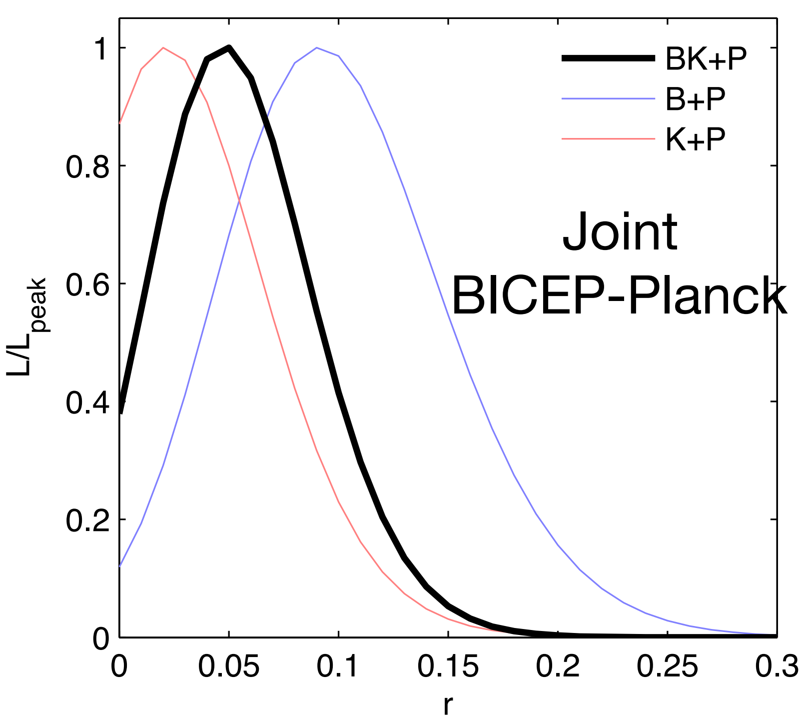
F. Marchesano, GS and A. Uranga, JHEP **1409**, 184 (2014).

A. Landete, F. Marchesano, GS, Gianluca Zoccarato, arXiv:1703.09729 [hep-th].

GS and W. Staessens, work in progress

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}.

UV Sensitivity of Large Field Inflation

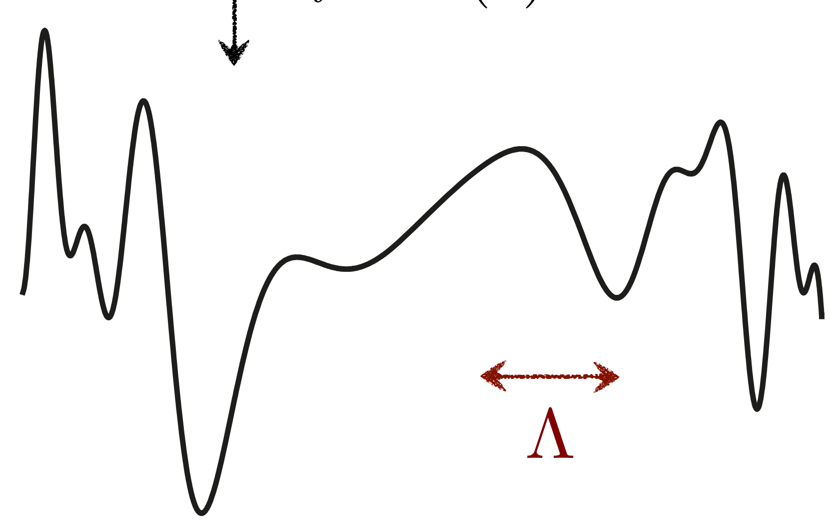
Lyth bound:

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

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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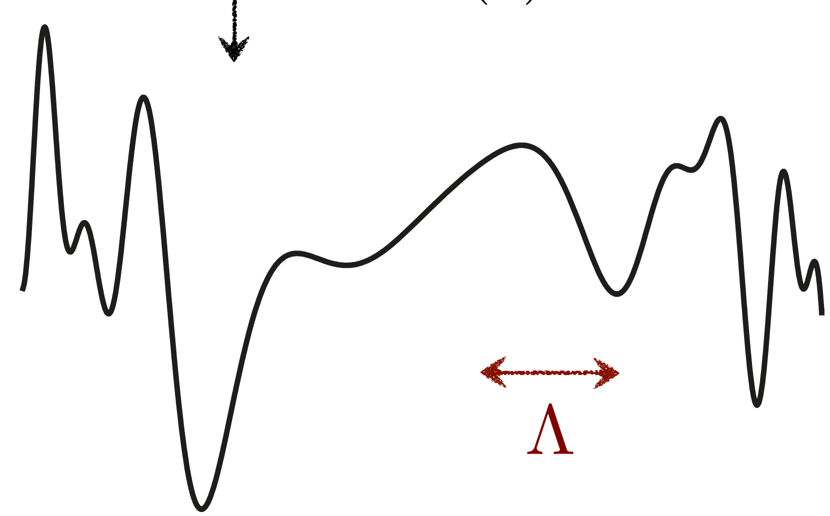
Quantum gravity forbids excursion > M_P?



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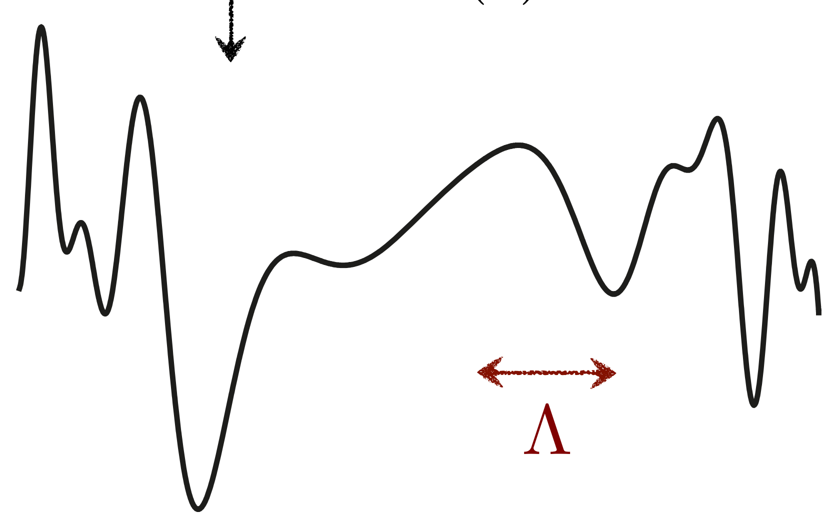
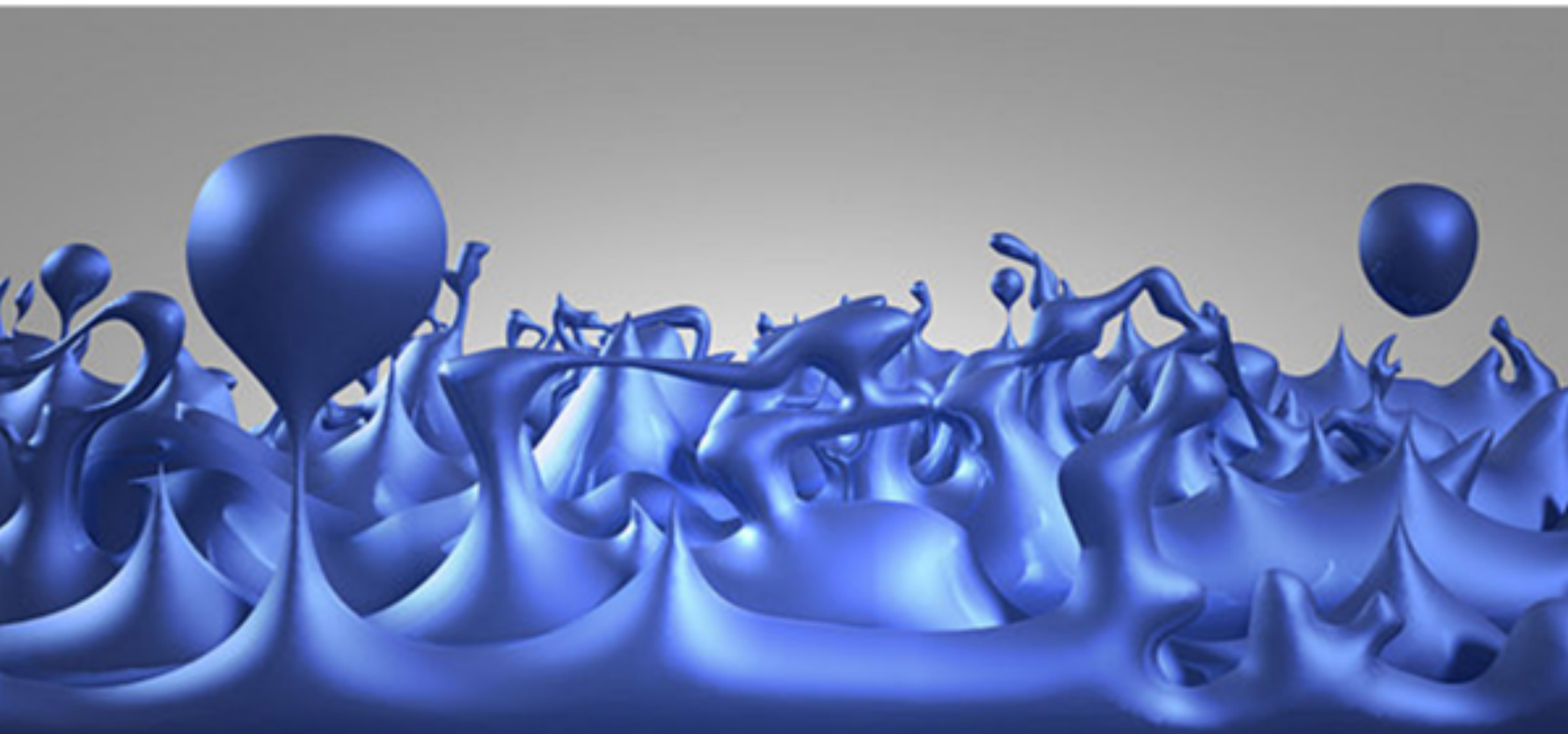


Quantum gravity forbids excursion > M_P?

UV completions control corrections?

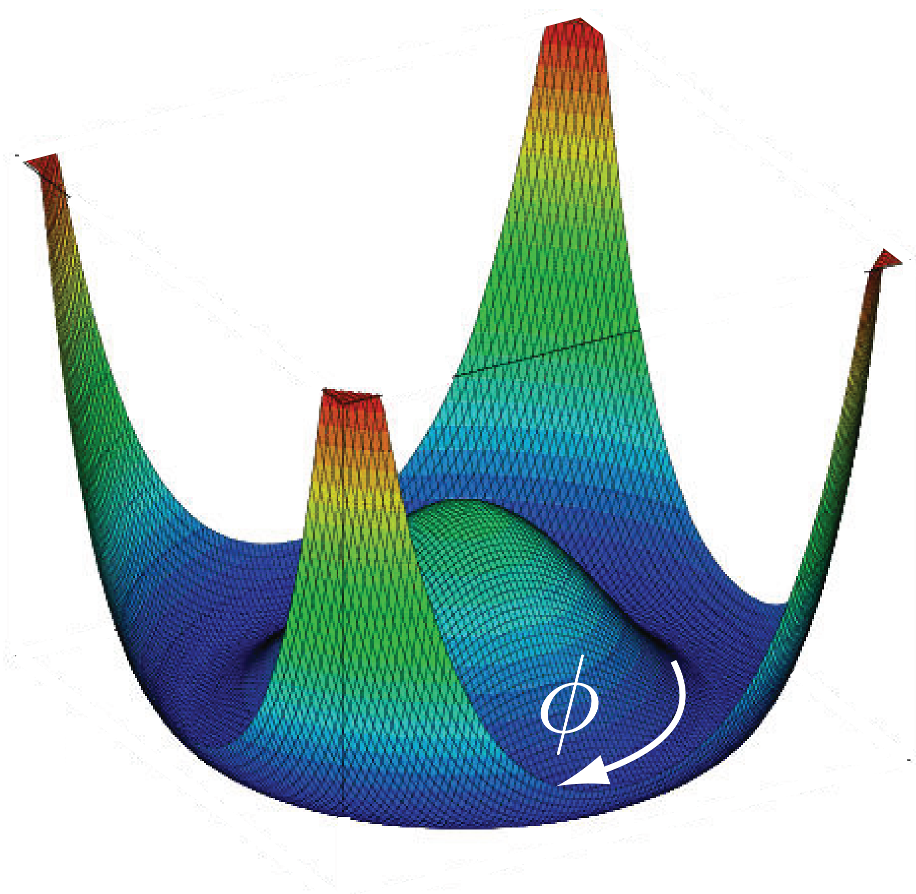
Quantum Gravity Considerations



Axions & Large Field Inflation

Natural Inflation [Freese, Frieman, Olinto]

Pseudo-Nambu-Goldstone bosons are natural inflaton candidates.



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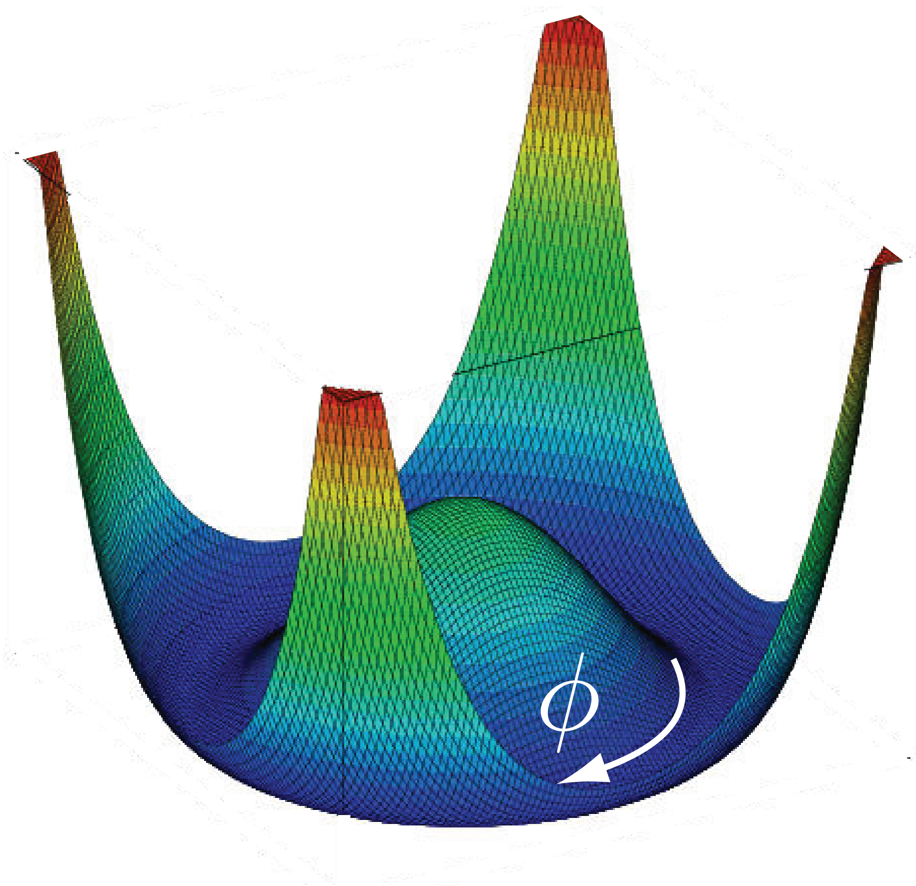
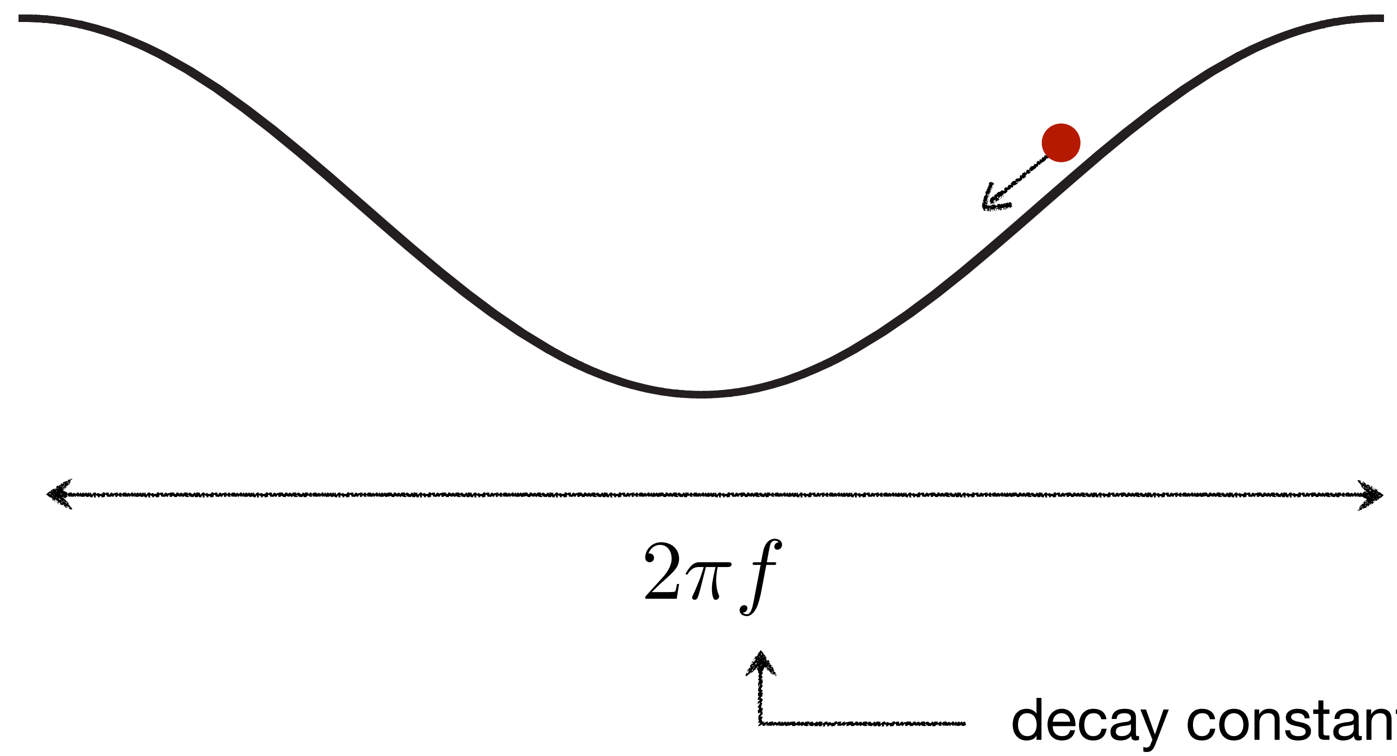


They satisfy a shift symmetry that is only broken by non-perturbative effects:



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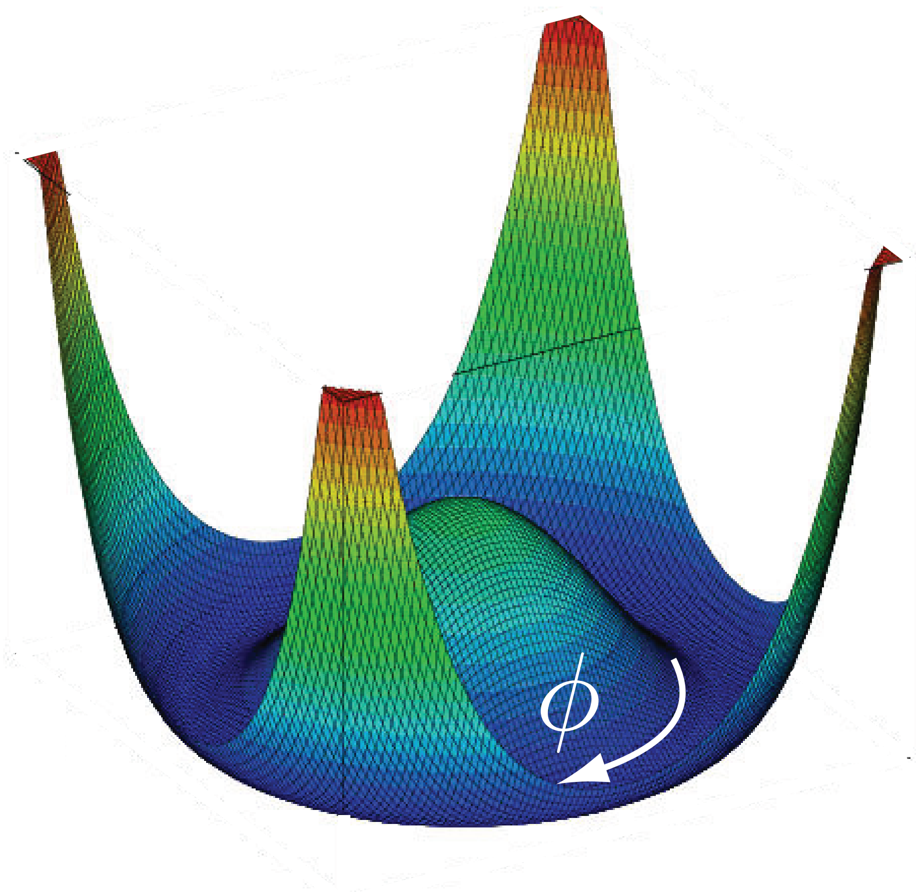

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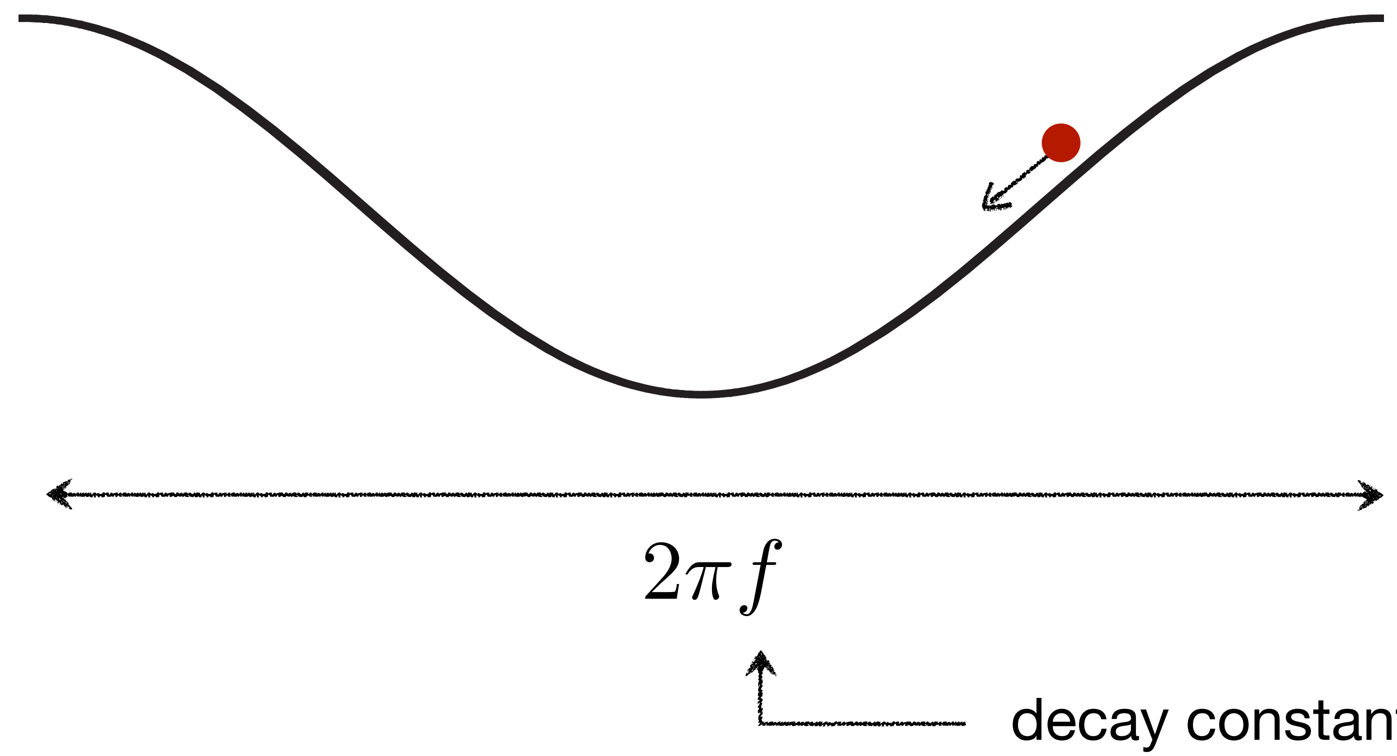

Slow roll: $f > M_P$

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

Axions in String Theory

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

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

3-form flux → F

2-form gauge potential: → A

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

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

See Ooguri, Palti and Montero's talks for other swampland conjectures

The Weak Gravity Conjecture

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.

$$\frac{q}{m} M_P \geq \text{``1''}$$

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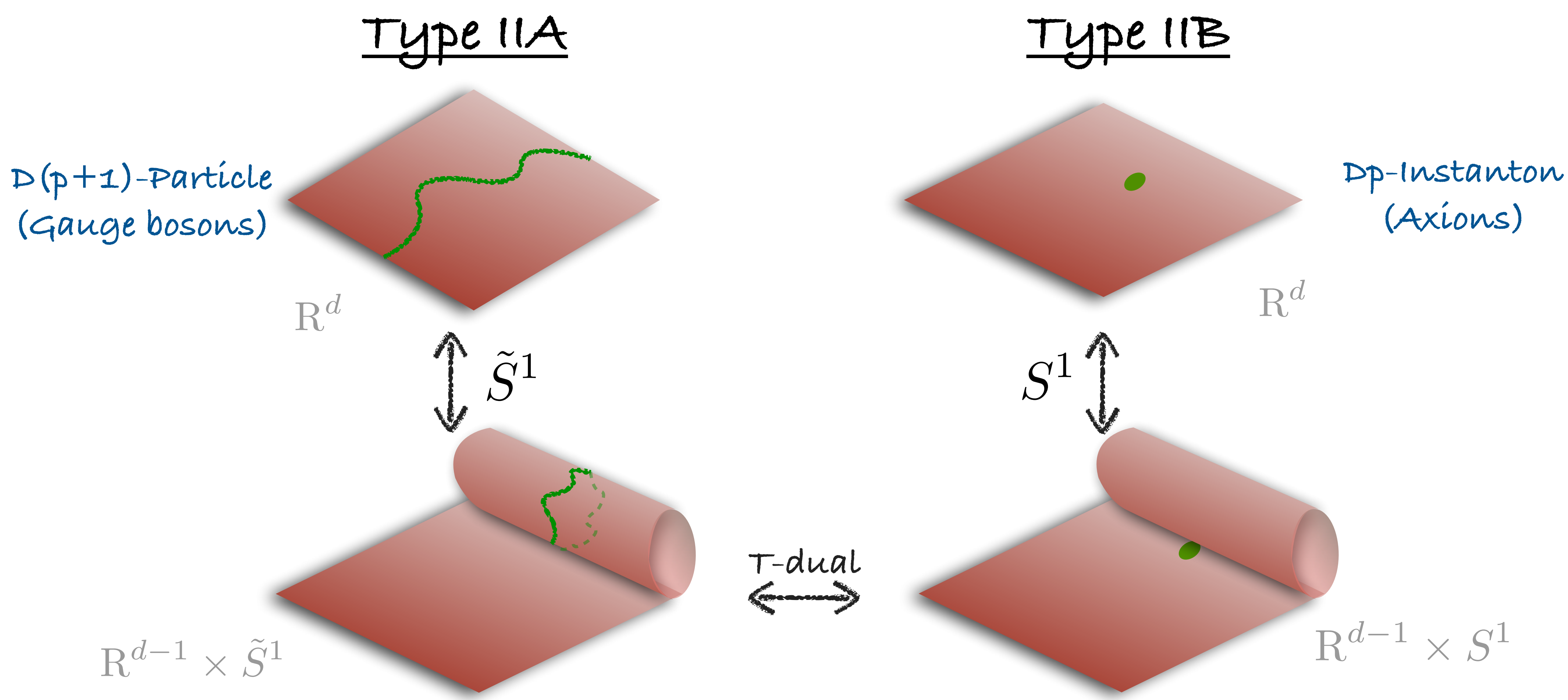
$$\frac{q}{m} M_P \geq \text{``}1\text{''} \equiv \frac{Q_{Ext}}{M_{Ext}}$$

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 $f \cdot S_{\mathrm{instanton}} \leq \mathcal{O}(1) M_P$ and generalizes to a convex hull condition for multiple axions.

Arguments for the Weak Gravity Conjecture

$M_P \equiv 1$

Heuristic Argument

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

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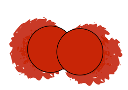
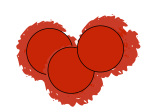
  - Infinitely many bound states

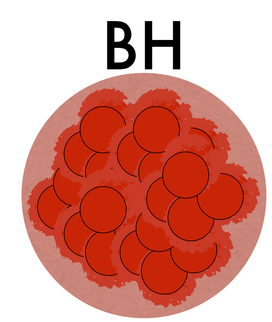


$2m > M_2 > 2q$



$3m > M_3 > 3q$

$\cdots$



$Nm > M_N > Nq$

$\cdots$

$M_\infty \to Q_\infty$

$M_P \equiv 1$

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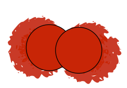
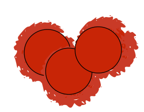
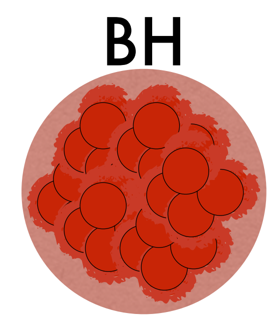




$\cdots$



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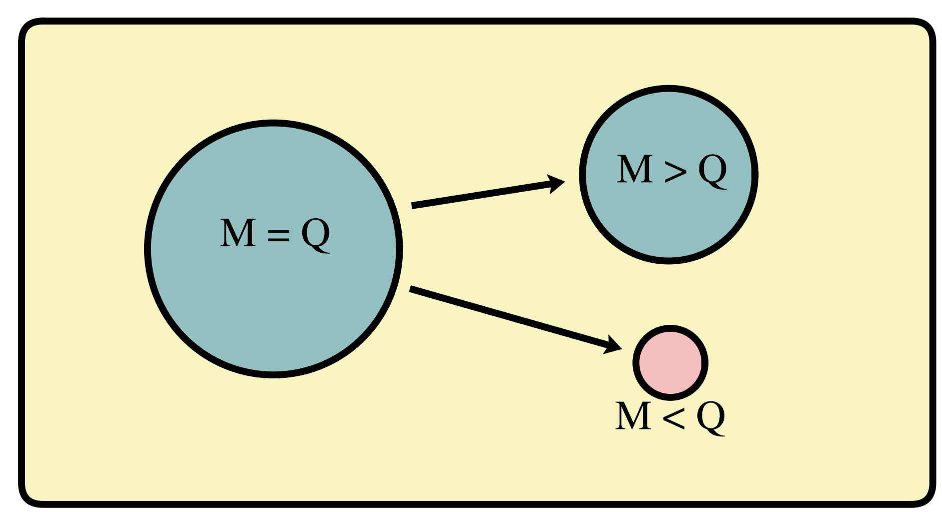
$2m > M_2 > 2q$ $\quad$ $3m > M_3 > 3q$ $\quad \cdots \quad$ $Nm > M_N > Nq$ $\quad \cdots \quad$ $M_\infty \to Q_\infty$

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

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



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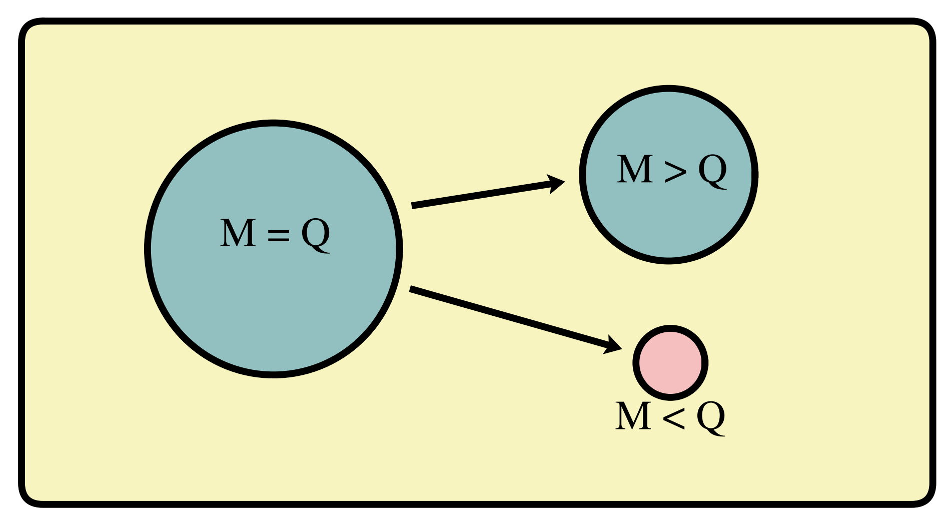
  - *Postulate* the existence of a state with ("mild form" of WGC)

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

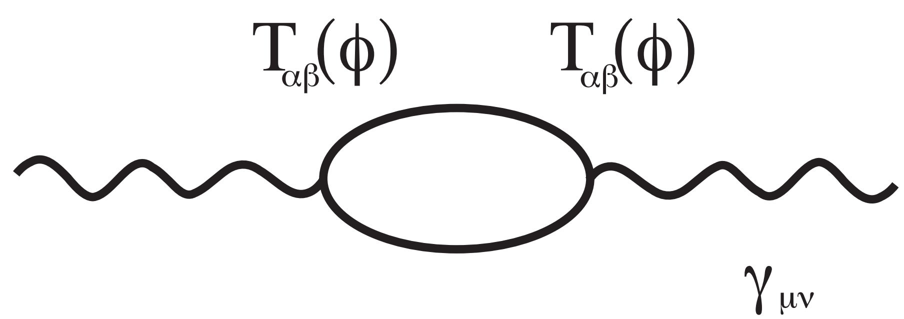
Magnetic WGC: $\Lambda \leq g M_P$

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



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]; [Cottrell, GS, Soler, '16]
- Axion Black Holes [Hebecker, Soler, '17]; [Montero, Uranga Valenzuela, '17]

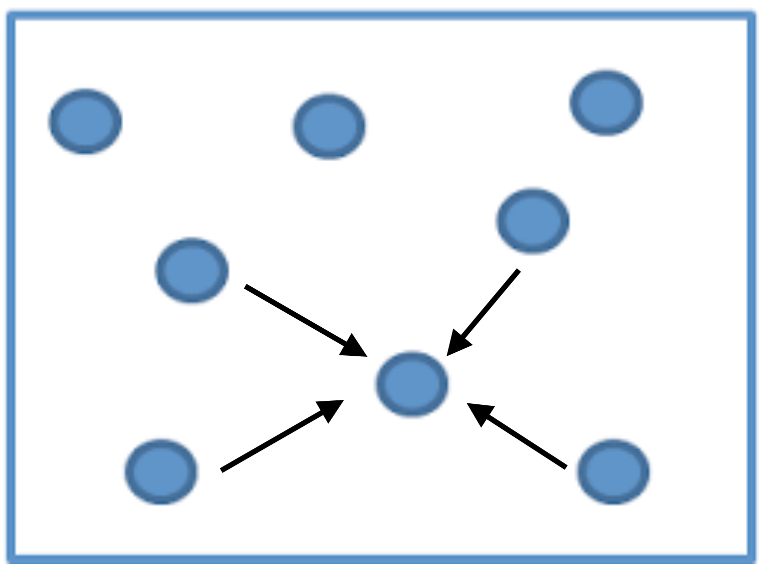
Evidences for *stronger* versions of the WGC:

- 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].

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.,

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

- 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:

$$\Lambda \lesssim q M_P$$

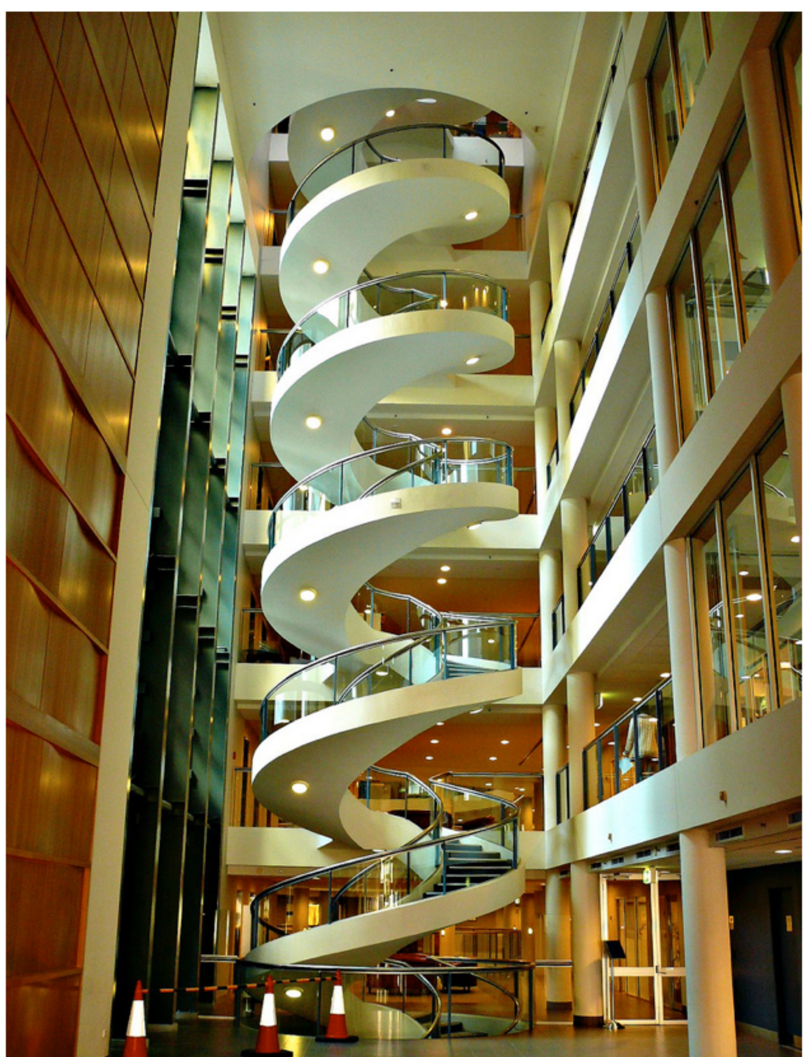
- A corollary is that in any UV complete theory of quantum gravity, an extremal particle cannot be fundamental, rather it must be a soliton.

- More in **Pablo Soler**'s parallel session talk on **Tuesday**.

String Theory Constructions

Large Field Inflation in String Theory

- Top-down models suggest mechanisms to evade these constraints:
  - "Infladron" (composite inflaton) **[GS, Staessens, Ye, '15], [GS, Staessens, work in progress]** **(see Wieland Staessens's parallel session talk on Tuesday)**.
  - Axion Mondromy Inflation **[McAllister, Silverstein, Westphal, '08]**

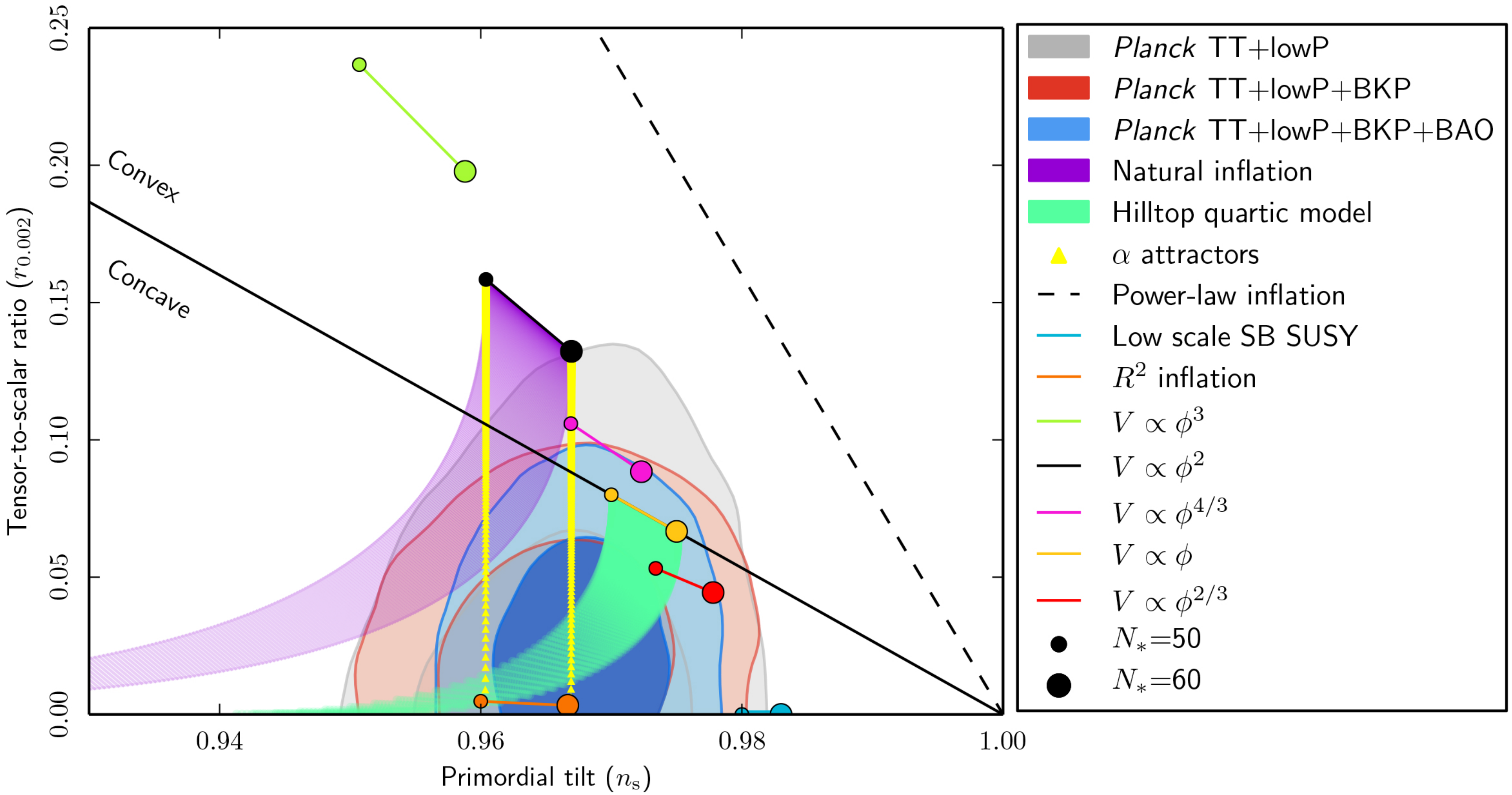


- Interesting exception to the WGC: the "monodromy axion" is mapped to a **massive U(1) gauge field**.
- **Backreaction** may limit the field range.
- **F-term axion monodromy** inflation **[Marchesano, GS, Uranga, '14]** provides explicit realizations in familiar **moduli stabilization** settings.

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

Axion Monodromy Inflation

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



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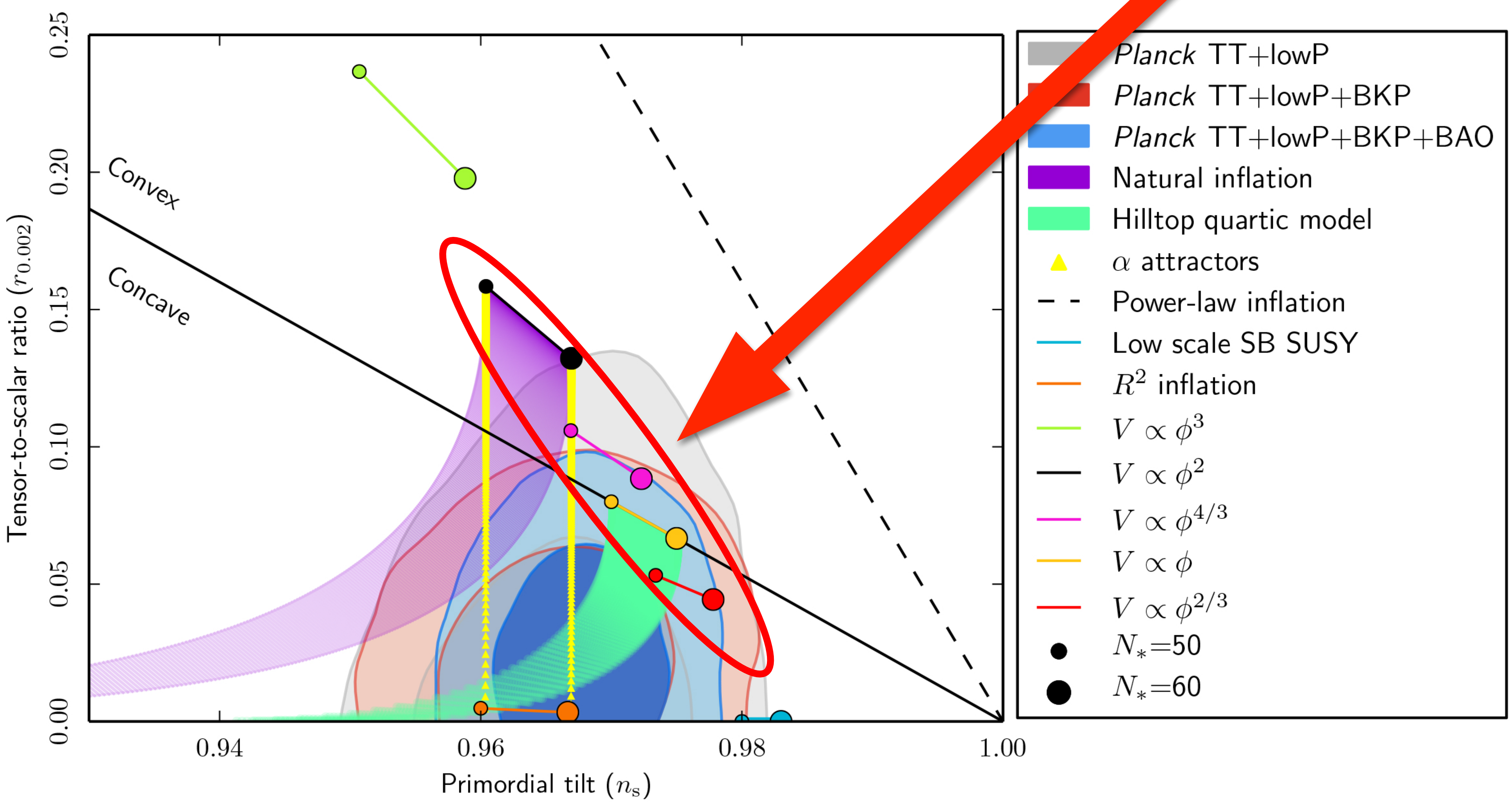

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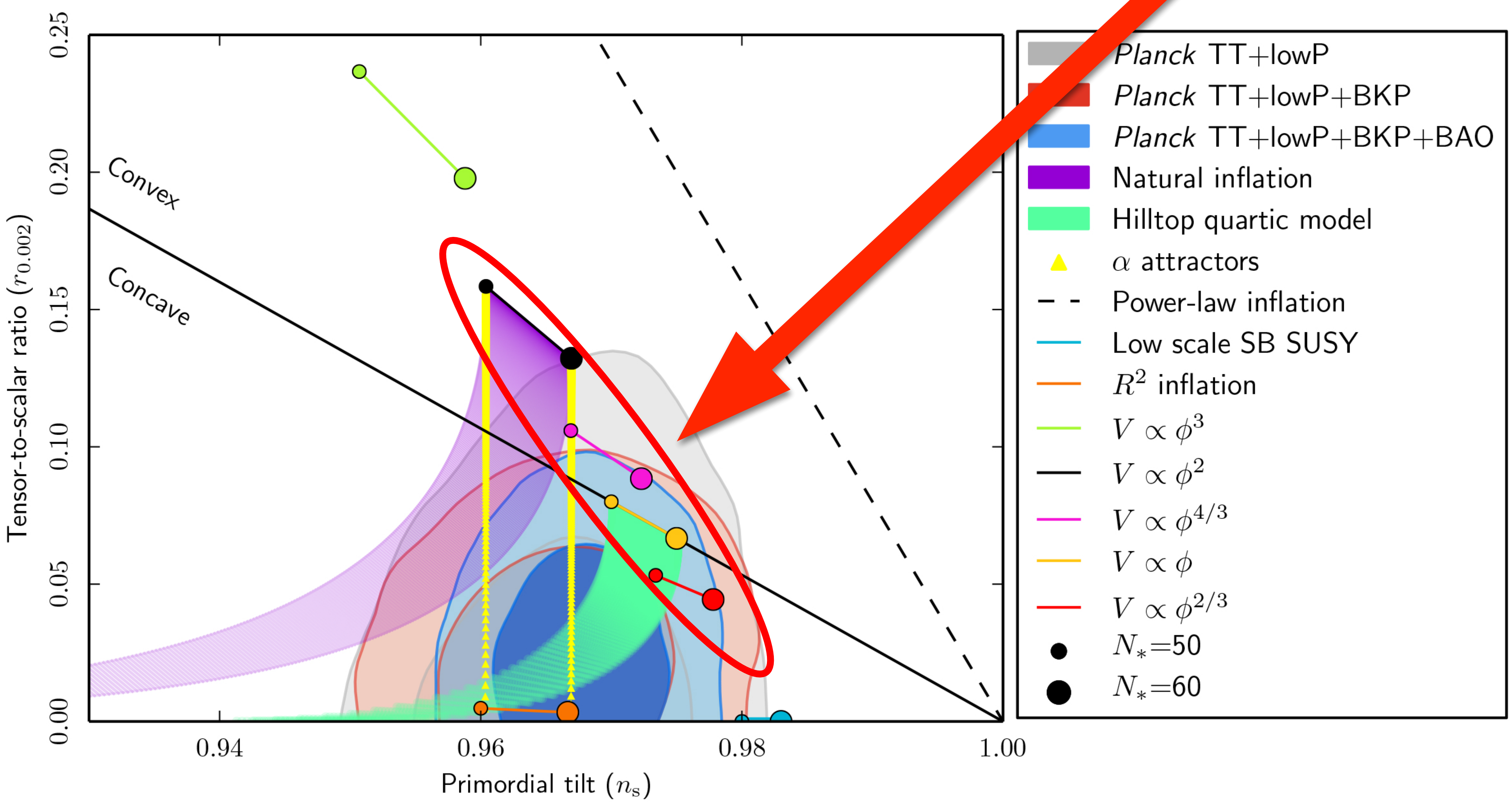


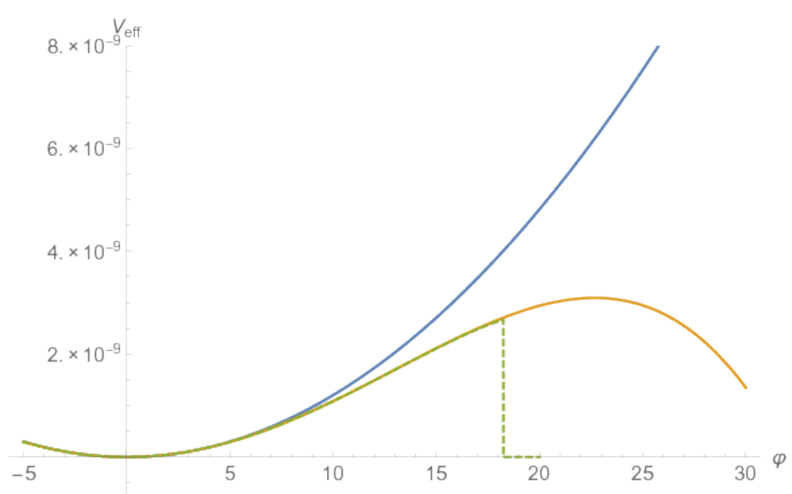
Current bound combining Planck+BICEP2/KECK+BAO: r < 0.07 (95% C.L.)

Sources of flattening

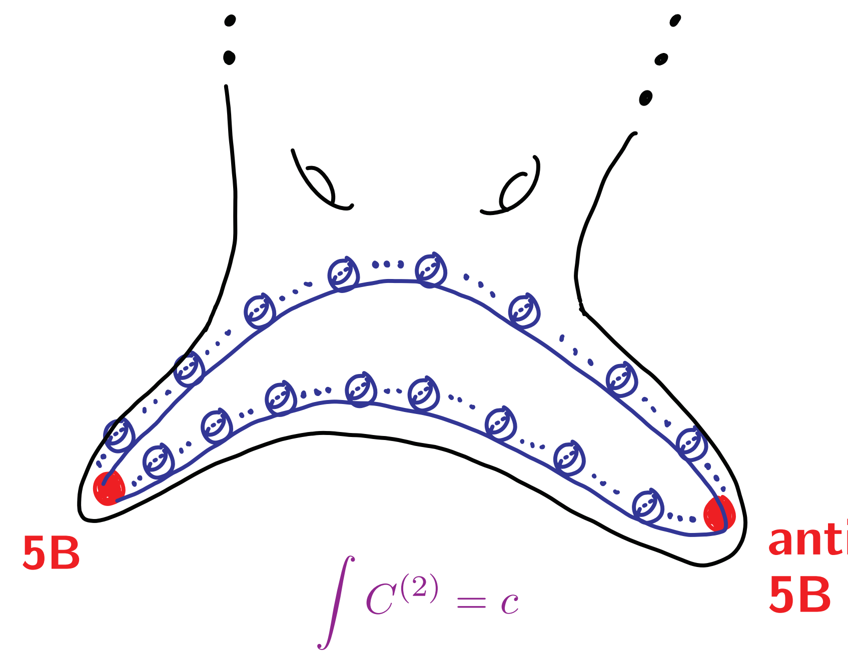
- Simple supergravity models of chaotic inflation yield polynomial potentials

$$W = a + b\Phi + c\Phi^2 + \ldots$$

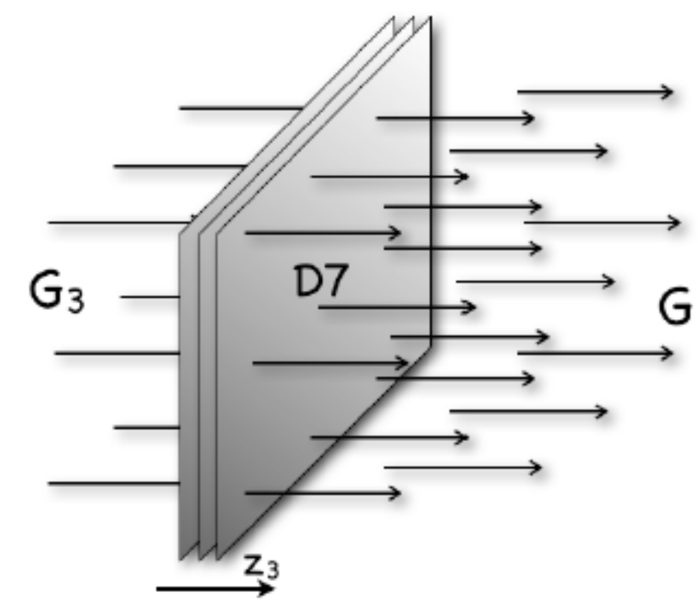
so one is led to consider sources of potential flattening:



4d sugra



DBI



open string kinetic terms

Dong et al.'10
Buchmuller et al.'14 & '15
...

McAllister, Silverstein, Westphal '08
Palti & Weigand'14
...

Silverstein, Westphal '08
Marchesano, GS, Uranga '14
Ibanez, Marchesano, Valenzuela '14

Sources of flattening

- Simple supergravity models of chaotic inflation yield polynomial potentials

$$W = a + b\Phi + c\Phi^2 + \ldots$$

so one is led to consider sources of potential flattening:

- The degree of flattening considered to date has been rather limited.
- We found new sources of flattening with more tensor lowering power [Landete, Marchesano, GS, Zoccarato, '17], which can bring $m^2 \phi^2$ inflation to

$$n_s \simeq 0.96 - 0.97 \text{ and } r \simeq 0.04 - 0.14$$

- This effect is invisible in supergravity, and is thus a ***stringy*** effect.

4d sugra

Dong et al.'10
Buchmuller et al.'14 & '15
...

DBI

McAllister, Silverstein, Westphal '08
Palti & Weigand'14
...

open string kinetic terms

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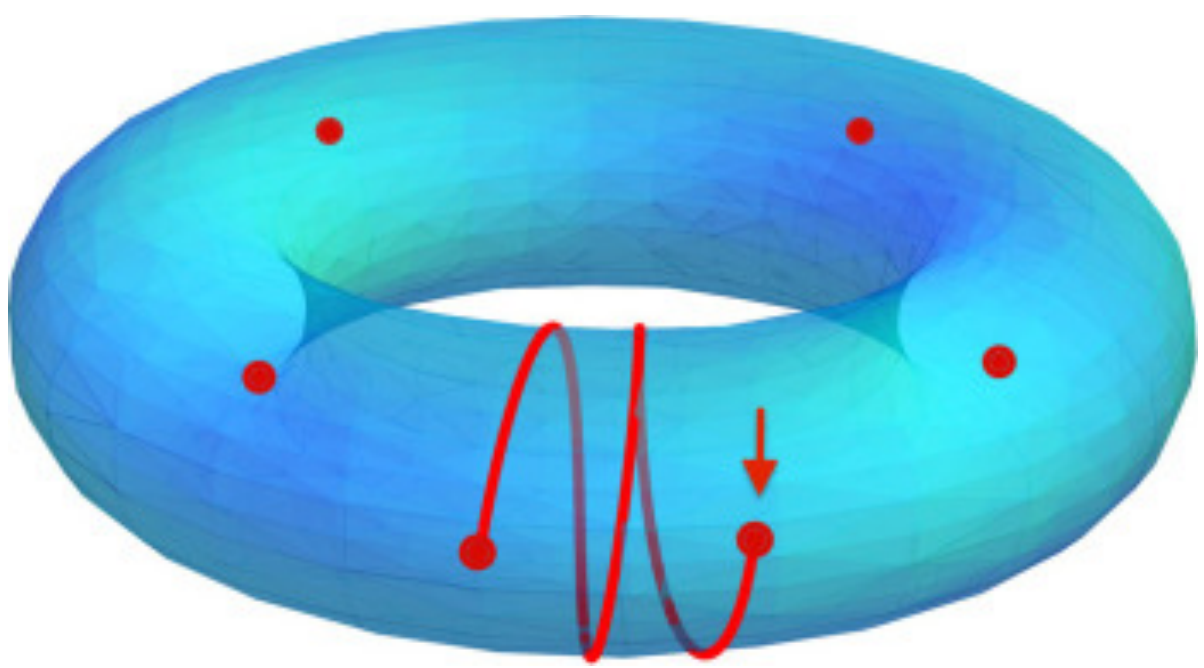
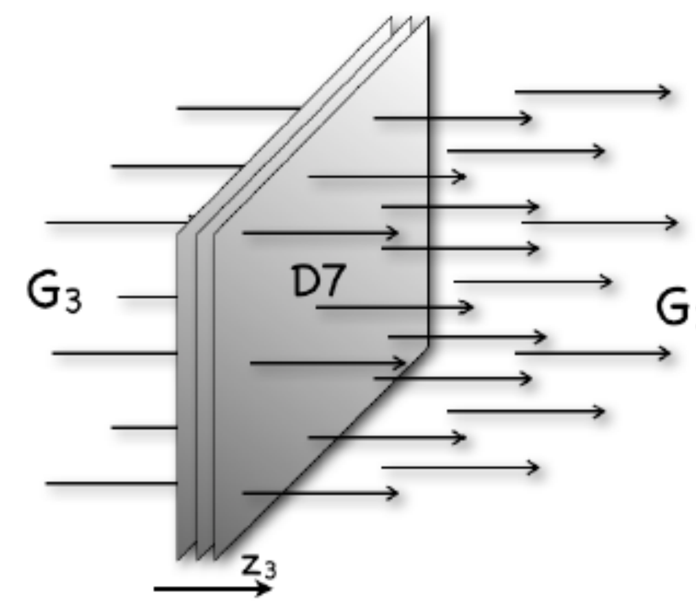
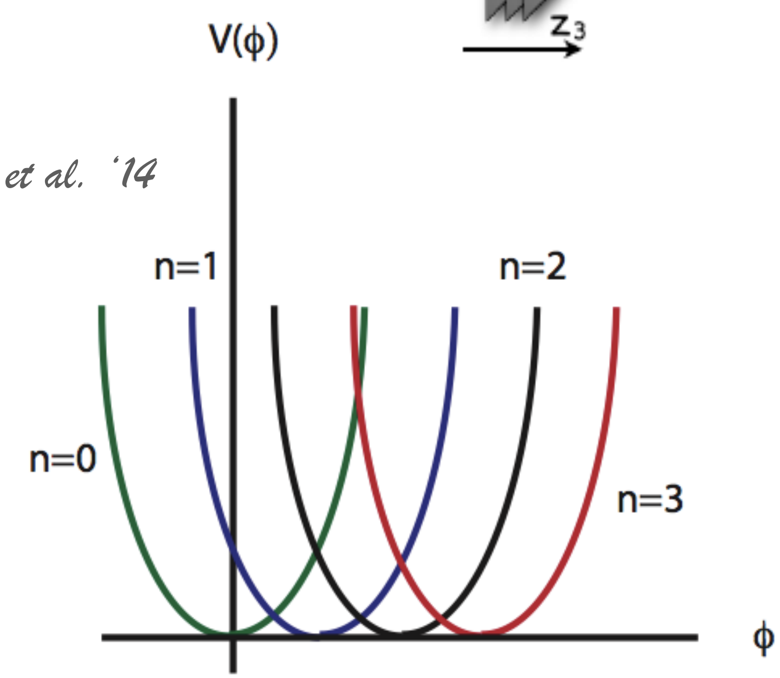
D7-brane positions and fluxes

- By adding background fluxes $G_3 = F_3 - \tau H_3$ we generate a potential for the position moduli Φ, because the induced B-field depends on the D7-brane position





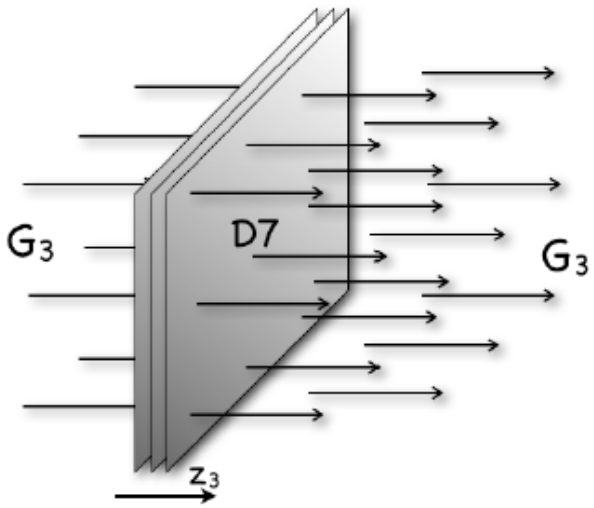
taken from Hebecker et al. '14



- When the D7-brane completes a period, the change in the B-field is an integer, so we can compensate it by a discrete change of F in $\mathcal{F} = F - B$ → multi-branched potential

- Gauge symmetries restrict the form of UV corrections [See Valenzuela's talk]

General flux flattening



- Fluxes enter both the **kinetic term** and the **potential**:

$$S_\Phi = -\int_{\mathbb{R}^{1,3}} \mathrm{dvol}_{\mathbb{R}^{1,3}} \left[g(\mathcal{F}) \partial_\mu \Phi \partial^\mu \overline{\Phi} + V(\mathcal{F}) \right]$$

- The larger the SD flux compared to the ASD the stronger the flattening effect

$$V(\Phi) = \left(\left[1 + (\mathcal{G} + \mathcal{H}) + \frac{1}{4} (\mathcal{G} - \mathcal{H})^2 \right]^{\frac{1}{2}} + \frac{1}{2}\mathcal{G} - \frac{1}{2}\mathcal{H} - 1 \right)$$

$\mathcal{H}$ SD

$$g(\Phi) = \left[1 + (\mathcal{G} + \mathcal{H}) + \frac{1}{4} (\mathcal{G} - \mathcal{H})^2 \right]^{\frac{1}{2}}$$

$\mathcal{G}$ ASD

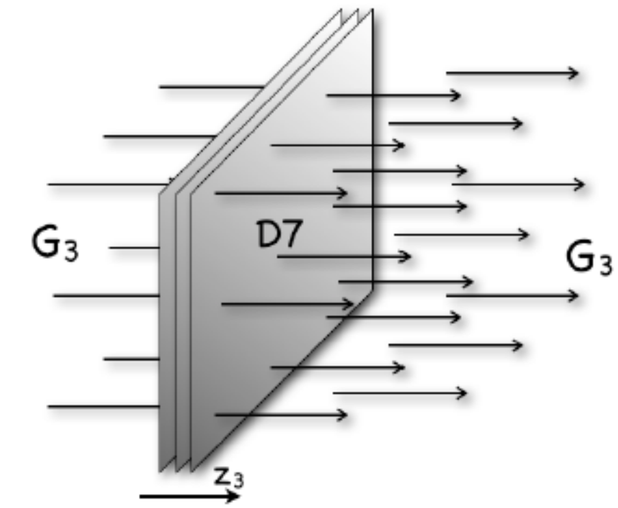
$1 \ll \mathcal{H} < \mathcal{G}$ $\qquad V \to \frac{1}{2}|\mathcal{G} - \mathcal{H}|$ $\qquad$ linear

$$g \to \frac{1}{2}|\mathcal{G} - \mathcal{H}|$$

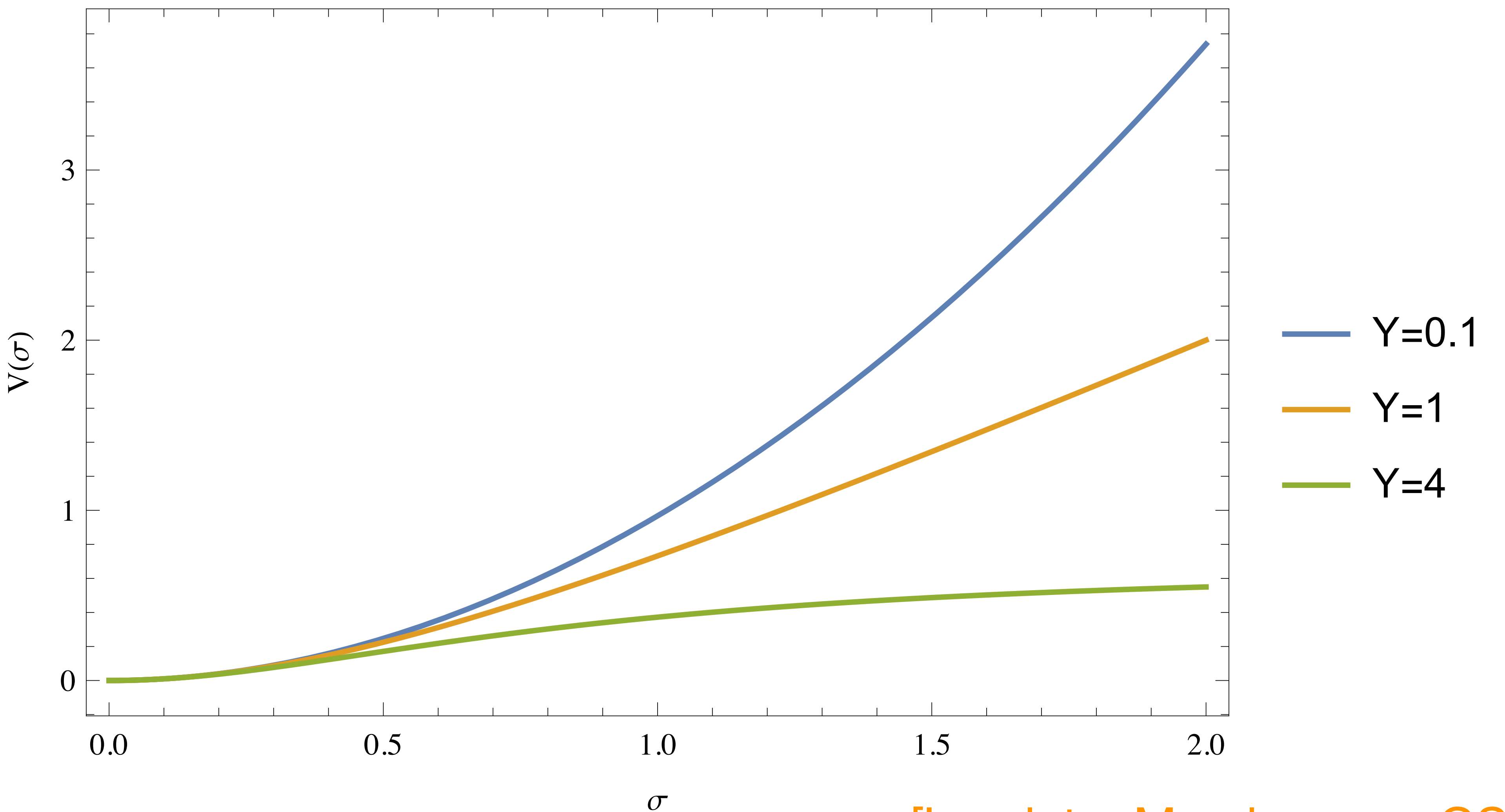
$1 \ll \mathcal{G} < \mathcal{H}$ $\qquad V \to \frac{2\mathcal{H}}{\mathcal{H} - \mathcal{G}} + \ldots$ $\qquad$ flux flattened

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

General flux flattening



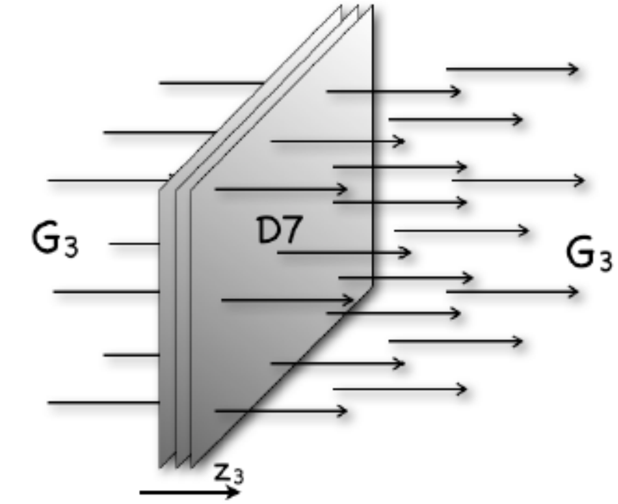
- For **ASD flux**, the growth of the kinetic term with large inflaton values matches that of the potential → **linear potential** [Ibanez, Marchesano, Valenzuela, '14]
- The larger the **SD flux** compared to the ASD the **stronger the flattening effect.**



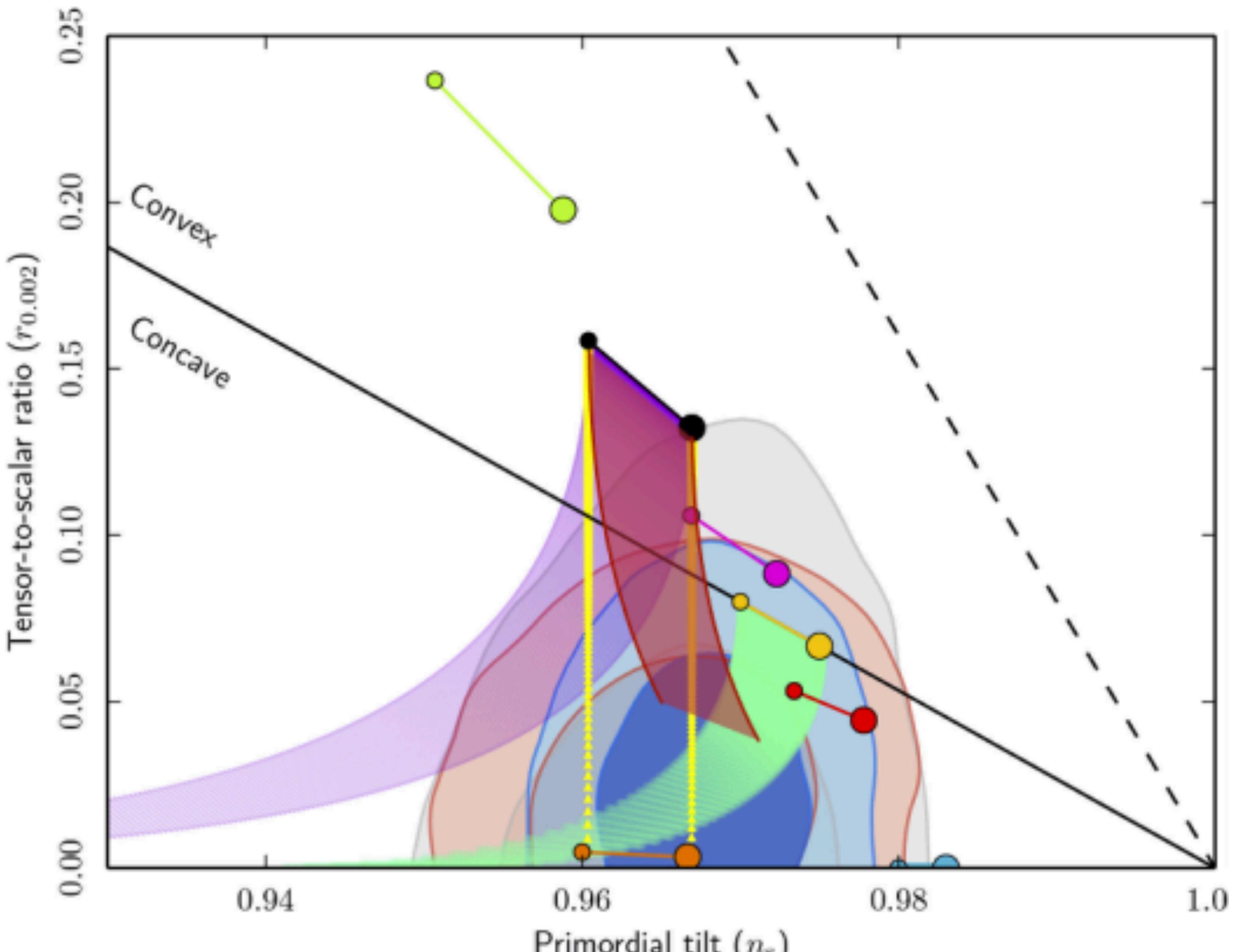
$$\Upsilon = \frac{\mathrm{SD}}{\mathrm{ASD}}$$

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

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

Conclusions

- 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 ≃ 0.04-0.14.
- We found evidence for 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)

Muchas Gracias!