The Gravity of Particle Physics

CPB @ McMaster University

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

UV Implications for Low Energy Gravity

CATCH 22+2, May 5, 2024

The Gravity of Particle Physics
(*the Highland Program*)

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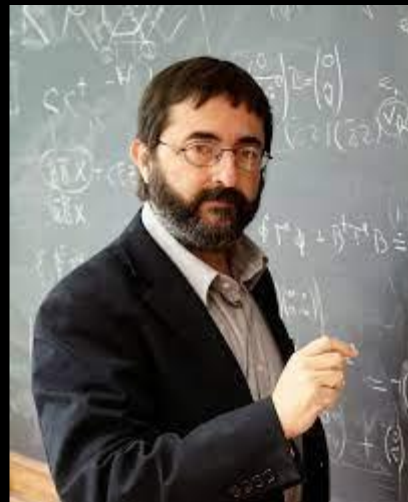
D. Dineen



F. Quevedo

P. Brax

Yoga models

2111.07286

dS & inflation

2202.05344

Axiodilaton tests

2212.14870

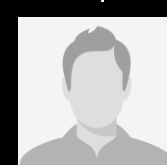
Screening

2310.02092

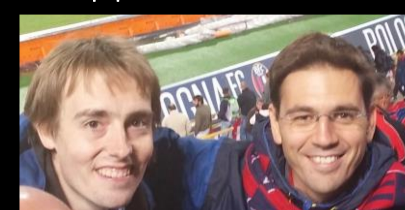
Based on earlier work on ubiquity of accidental symmetries in EFTs for string vacua

2006.06694

M. Ciupke



S. Krippendorf M. Cicoli



Outline

Can UV usefully inform tests of gravity?

EFTs & Decoupling

More is different (against Horndeski)

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Can UV usefully inform tests of gravity?

EFTs & Decoupling

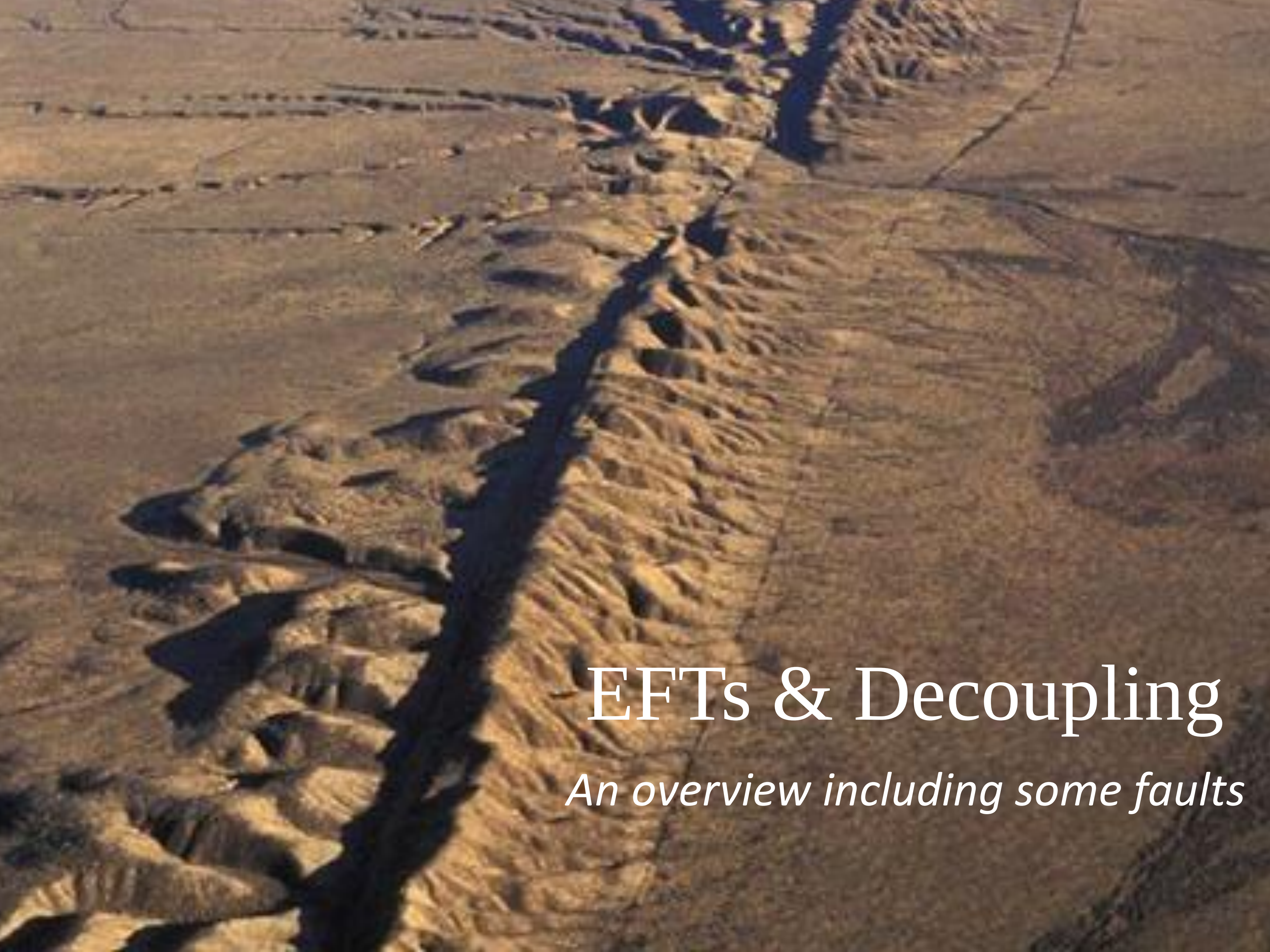
More is different (against Horndeski)

Two symmetries and a mechanism

Natural relaxation and DE

Cosmic surprises (Hubble tension, birefringence)

Challenges (tests of GR & screening)



EFTs & Decoupling

An overview including some faults

A Light-Scalar Surprise

Particle physicists usually argue that light scalar fields are NOT generic at low energies

A technically natural Dark Energy density makes them more likely rather than less likely

BUT we are likely looking for them in the wrong way (by doing so using eg Horndeski models).

Light Gravitating Scalars

What should the low-energy dynamics of gravitating scalars look like?

$$\mathcal{L}_W = -\sqrt{-g}\Big[v^4 U(\phi) + \tfrac{1}{2} M_p^2 R + \tfrac{1}{2} M_p^2\, \mathcal{G}_{ab}(\phi)\partial_\mu \phi^a \partial^\mu \phi^b + c_2 R^2 + \cdots\Big]$$

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Zero derivative terms

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Two derivative terms

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Four derivative terms and so on

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It is technically natural for *v* to be large, but we must keep $v^2 = H\,M_p$ with $H \ll M_p$ if the derivative expansion is to be valid (*the cc problem*)

$$M_p^2\,R_{\mu\nu} + M_p^2\,\mathcal{G}_{ab}(\phi)\partial_\mu\phi^a\partial_\nu\phi^b + v^4 U(\phi) g_{\mu\nu} + \cdots = 0$$

But small v also tends to suppress scalar masses

$$M_p^2\Big[\nabla^\mu\nabla_\mu\phi^a + \Gamma^a_{bc}\partial_\mu\phi^b\partial^\mu\phi^c\Big] - v^4\mathcal{G}^{ab}\partial_b U + \cdots = 0$$

Light Gravitating Scalars

What should the low-energy dynamics of gravitating scalars look like?

$$\mathcal{L}_W = -\sqrt{-g}\Big[v^4 U(\phi) + \tfrac{1}{2} M_p^2 R + \tfrac{1}{2} M_p^2 \, \mathcal{G}_{ab}(\phi) \partial_\mu \phi^a \partial^\mu \phi^b + c_2 R^2 + \cdots \Big]$$

If v is small and if U and G_{ab} are order unity then the scalar mass is generically:

$$\mu \sim \frac{v^2}{M_p}$$

In a world where it is understood why the cc problem is solved **any** *gravitationally coupled scalar has a Hubble-scale mass!*

astro-ph/0107573

Light Gravitating Scalars

Will now argue why the derivative expansion is *compulsory*
if one works semiclassically (as everyone does)

$$\mathcal{L}_W = -\sqrt{-g}\Big[v^4 U(\phi) + \tfrac{1}{2}M_p^2 R + \tfrac{1}{2}M_p^2\, \mathcal{G}_{ab}(\phi)\partial_\mu\phi^a\partial^\mu\phi^b + c_2 R^2 + \frac{c_3}{m^2}R^3 + \cdots\Big]$$

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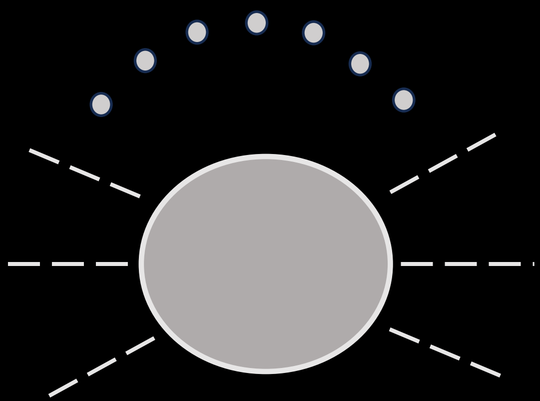

Evaluate a correlation function with *E* external lines, *L* loops and V_n vertices involving d_n derivatives with curvature *H* and external momenta *k/a=H*

Light Gravitating Scalars

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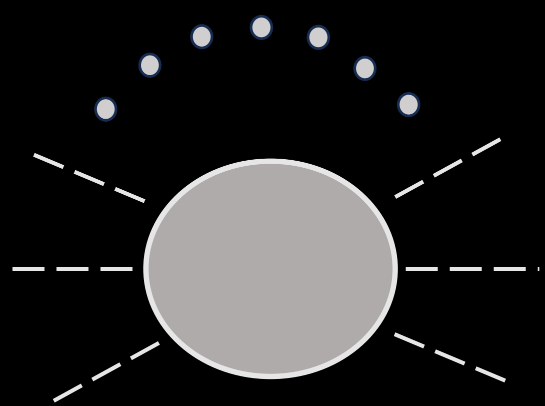


Evaluate a correlation function with *E* external lines, *L* loops and V_n vertices involving d_n derivatives with curvature *H* and external momenta *k/a=H*

0902.4465

1708.07443

$$\mathcal{B}_E(H) \simeq M_p \left(\frac{H^2}{M_p}\right)^{E-1}\left(\frac{H}{4\pi\,M_p}\right)^{2L} \times \prod_{d_n\geq 4}\left[\left(\frac{H}{M_p}\right)^2\left(\frac{H}{m}\right)^{d_n-4}\right]^{V_n}\prod_{d_n=0}\left(\frac{v^4}{H^2M_p^2}\right)^{V_n}$$

Light Gravitating Scalars

This shows what controls semiclassical perturbation theory

$$\mathcal{B}_E(H) \simeq M_p \left(\frac{H^2}{M_p}\right)^{E-1} \boxed{\left(\frac{H}{4\pi\, M_p}\right)^{2L}}$$
$$\times \prod_{d_n \geq 4} \left[\left(\frac{H}{M_p}\right)^2 \left(\frac{H}{m}\right)^{d_n - 4}\right]^{V_n} \prod_{d_n = 0} \left(\frac{v^4}{H^2 M_p^2}\right)^{V_n}$$

Each loop costs: $\left(\frac{H}{4\pi\, M_p}\right)^2$

The semiclassical approximation *relies* on the derivative expansion

Light Gravitating Scalars

This shows what controls semiclassical perturbation theory

$$\mathcal{B}_E(H) \simeq M_p \left(\frac{H^2}{M_p}\right)^{E-1} \left(\frac{H}{4\pi\, M_p}\right)^{2L}$$

$$\times \prod_{d_n \geq 4} \left[\left(\frac{H}{M_p}\right)^2 \left(\frac{H}{m}\right)^{d_n - 4}\right]^{V_n} \prod_{d_n = 0} \left(\frac{v^4}{H^2 M_p^2}\right)^{V_n}$$

Each higher-derivative interaction costs an *additional*: $\left(\frac{H}{M_p}\right)^2 \left(\frac{H}{m}\right)^{d_n - 4}$

4- and higher-derivative interactions are ***always*** suppressed at low energies when the semiclassical approximation is under control

Light Gravitating Scalars

This shows what controls semiclassical perturbation theory

$$\mathcal{B}_E(H) \simeq M_p \left(\frac{H^2}{M_p}\right)^{E-1} \left(\frac{H}{4\pi\, M_p}\right)^{2L} \times \prod_{d_n \geq 4} \left[\left(\frac{H}{M_p}\right)^2 \left(\frac{H}{m}\right)^{d_n-4}\right]^{V_n} \prod_{d_n=0} \left(\frac{v^4}{H^2 M_p^2}\right)^{V_n}$$

Each zero-derivative interaction ***amplifies*** by an *additional*: $\frac{v^4}{H^2 M_p^2}$

This generically undermines the derivative expansion (and semiclassical control)

It need not be a problem ***if*** $v^2 = HM_p$ or smaller

Light Gravitating Scalars

This shows what controls semiclassical perturbation theory

$$\mathcal{B}_E(H) \simeq M_p \left(\frac{H^2}{M_p}\right)^{E-1} \left(\frac{H}{4\pi\, M_p}\right)^{2L} \times \prod_{d_n \geq 4} \left[\left(\frac{H}{M_p}\right)^2 \left(\frac{H}{m}\right)^{d_n - 4}\right]^{V_n} \prod_{d_n = 0} \left(\frac{v^4}{H^2 M_p^2}\right)^{V_n}$$

There is *no penalty* for fields being large

This is why trans-Planckian field excursions need not be a problem

Light Gravitating Scalars

This shows what controls semiclassical perturbation theory

$$\mathcal{B}_E(H) \simeq M_p \left(\frac{H^2}{M_p}\right)^{E-1} \left(\frac{H}{4\pi\, M_p}\right)^{2L} \times \prod_{d_n \geq 4} \left[\left(\frac{H}{M_p}\right)^2 \left(\frac{H}{m}\right)^{d_n-4}\right]^{V_n} \prod_{d_n=0} \left(\frac{v^4}{H^2 M_p^2}\right)^{V_n}$$

There is *no penalty* for 2-derivative terms

This is why GR nonlinearities cannot be neglected at low energies

It also shows that 2-derivative scalar interactions scale the same as does GR (and are similar in size when $f = M_p$)

Light Gravitating Scalars

We should expect two-derivative scalar self-interactions to compete with GR for any scalars light enough to be relevant to cosmology

Light Gravitating Scalars

We should expect two-derivative scalar self-interactions to compete with GR for any scalars light enough to be relevant to cosmology

BAD NEWS

Almost all efforts at testing scalar-tensor theories for simplicity specialize to a single scalar

Two-derivative interactions can be removed using a field redefinition if the metric G_{ab} is flat

For all single-field models the metric G_{ab} is flat

This is why it seems so difficult to get single-scalar (eg Horndeski models) to be competitive with gravity at low energies


Adventure Sports Magazine
Clues from the UV
Accidental Symmetries
(Scaling the Landscape)

UV Strategies

What *can* be learned from UV completions to gravity?

Some things seem common:

Garden-variety low-spin fields (spins 0,1/2,1,3/2) and possibly extra dimensions (only down to eV energies)

Often find accidental approximate symmetries and these can lead to light fields (axions, dilatons, and often many of them)

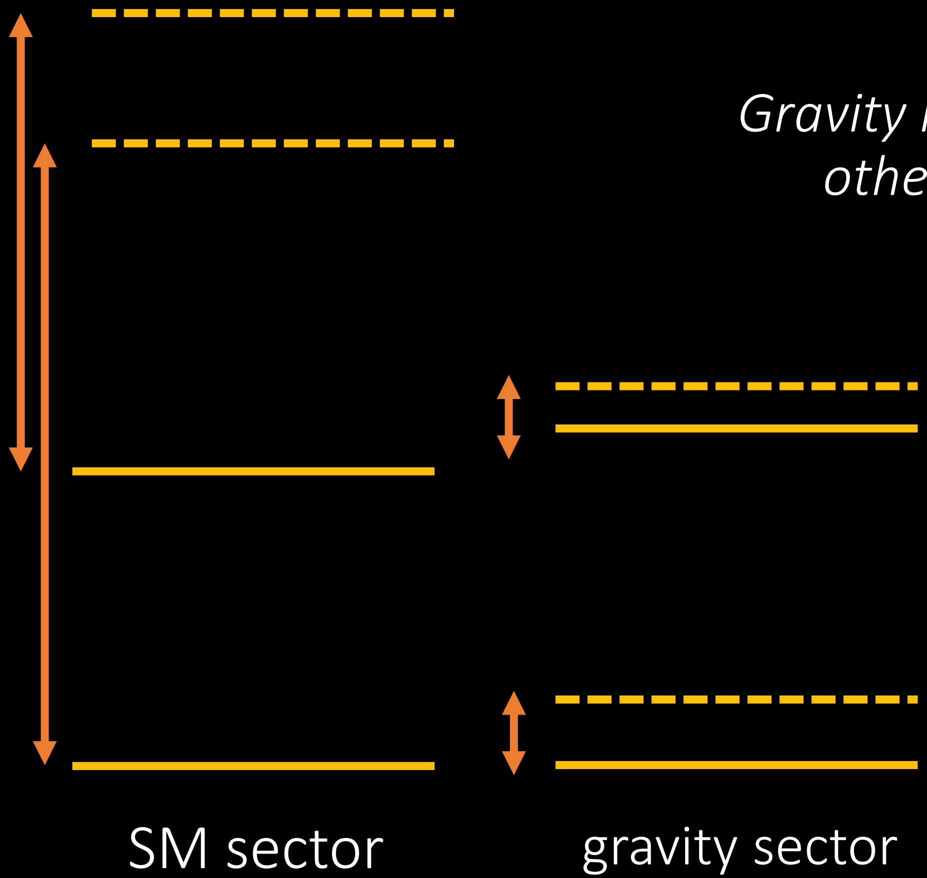
Supersymmetry present but broken

Will argue: surprising progress on cc and other unexpectedly rich IR limit (well-motivated candidates when testing GR)

Supersymmetry of the gravity sector

How can supersymmetry play a role at low energies when LHC finds no evidence for supersymmetry?

Gravity multiplet typically split by less than others because gravity is weakest force



$$\Delta m^2 = m_B^2 - m_F^2 \sim gF$$

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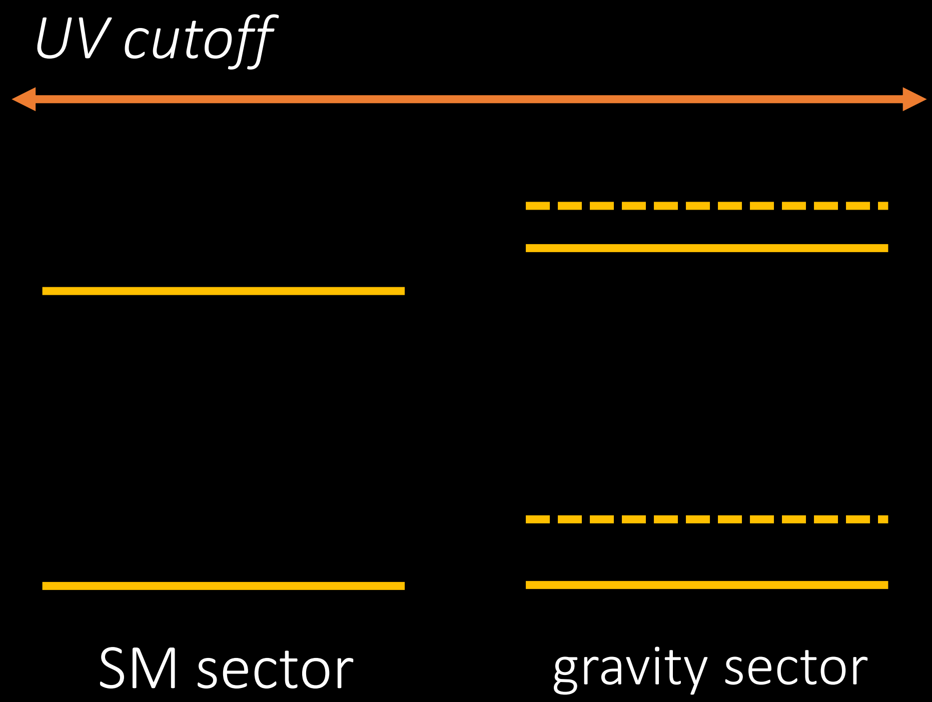
How can supersymmetry play a role at low energies when LHC finds no evidence for supersymmetry?

ph/0404135 | 2110.13275



Should expect gravity sector to be more supersymmetric at low energies than particle physics sector

We now know how to couple supergravity to matter that is not supersymmetric

Komargodsky & Seiberg 09
Bergshoeff et al 15
Dallagata & Farakos 15
Schillo et al 15
Antoniadis et al 21
Dudas et al 21

Supersymmetry of the gravity sector

Why should it matter if gravity is supersymmetric when the SM sector is not supersymmetric anyway?

Auxiliary fields are important in the low-energy scalar potential (and so also for naturalness arguments)

Non-propagating – topological – fields play similarly important roles in eg Quantum Hall systems.

Auxiliary fields similarly start life as topological fields in higher dimensions within string theory.

Bielleman, Ibanez & Valenzuela 15
1509.04209

Semiclassical Scaling Symmetries

Allows more traditional EFT approach to rarity of inflationary solutions in string theory: it is a reflection of robust low-energy 'symmetries'?

2006.06694

$$g_{\mu\nu} \to \lambda\, g_{\mu\nu}$$

$$\Phi \to \lambda^s\, \Phi$$

$$\mathscr{L} \to \lambda^p\, \mathscr{L}$$

String theory has no parameters so all perturbative expansions are in powers of fields

$$\mathscr{L} = \sum_{mn} f_{mn}\, \Phi^m\, \Psi^n$$

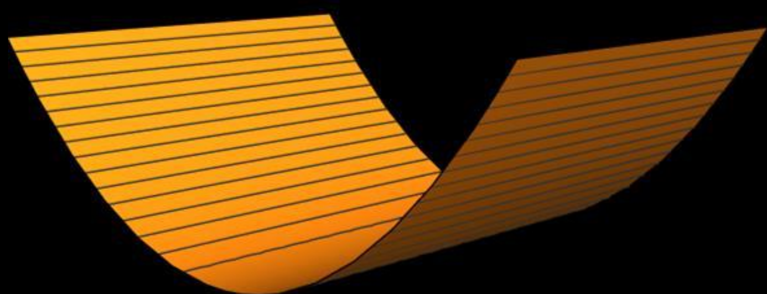
$$\Phi \to \lambda^p \Phi \qquad \Psi \to \lambda^q \Psi$$

$$\mathscr{L}_{mn} \to \lambda^{mp+nq}\, \mathscr{L}_{mn}$$

Accidental Scaling enforces V = 0 (so fights dS)

Does so despite symmetry being spontaneously broken!

$$V(\lambda^p \Psi) = \lambda^w V(\Psi)$$



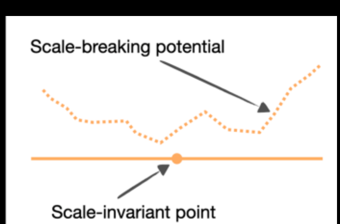
$$\sum_i p_i \phi^i \left(\frac{\partial V}{\partial \phi^i} \right) = w V(\phi)$$

$$\text{if} \quad \frac{\partial V}{\partial \phi^i} = 0 \quad \text{then}^* \quad V = 0$$

$$p_j \frac{\partial V}{\partial \phi^j} + \sum_i p_i \phi^i \frac{\partial^2 V}{\partial \phi^i \partial \phi^j} = w \frac{\partial V}{\partial \phi^j}$$

$$\text{if} \quad \phi^i = 0 \quad \text{then}^* \quad \frac{\partial V}{\partial \phi^i} = 0$$

Must quantify effects due to explicit symmetry breaking



Peccei et al 87 Wetterich 88

Weinberg 89

arXiv:2006.06694

Scaling and 4D Supersymmetry

Can supersymmetry combine with scale invariance to suppress lifting of flat directions?

$$\mathscr{L} = \int d^4\theta\, \overline{\Phi}\,\Phi\, e^{-K/3} + \int d^2\theta \left[\Phi^3 W + f_{ab}\overline{\mathscr{F}}^a \mathscr{F}^b\right] + \text{c.c.}$$

4D susy specified by functions *K(z,z*), W(z),* $f_{ab}(z)$

$$\mathscr{L}_{\rm kin} = -\sqrt{-g}\, K_{i\bar{j}}\, \partial_\mu z^i\, \partial^\mu \bar{z}^j$$

$$V(z,\bar{z}) = e^K\left[K^{i\bar{j}}\, D_i W\, \overline{D_j W} - 3\,|W|^2\right]$$

$$D_i W = W_i + K_i W$$

Scale invariance implies rules for how *W*, f_{ab} and $e^{-K/3}$ scale as the fields *z* scale

Scaling and 4D Supersymmetry

Special things happen if $e^{-K/3}$ is homogeneous degree 1:

Sufficient condition for flat direction along which susy breaks

0811.1503

if $z^i \to \lambda z^i$ implies $e^{-K/3} \to \lambda e^{-K/3}$

then $K^{i\bar{j}} K_i K_{\bar{j}} = 3$

'no-scale' model

No-Scale supergravity: scalar potential has a flat direction along which susy breaks

Cremmer et al 83
Barbieri et al 85

if $W_i = 0$ then

$$V = e^K \left[K^{i\bar{j}} K_i K_{\bar{j}} - 3 \right] |W|^2 = 0$$

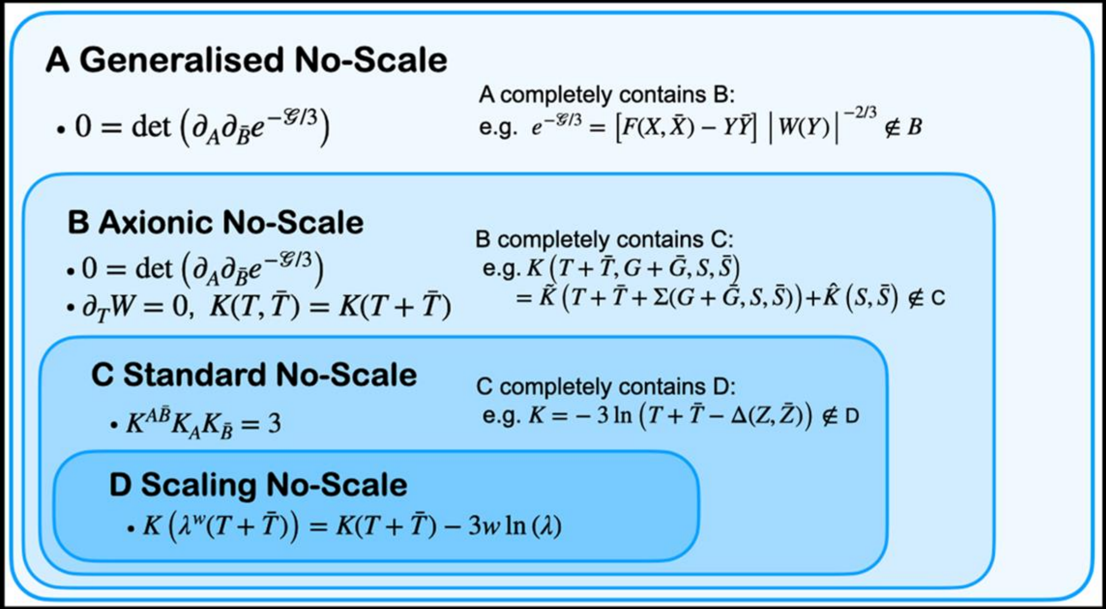
$$D_i W = W_i + K_i W = K_i W \neq 0$$

Scaling and 4D Supersymmetry

Scale invariance is ***sufficient*** for no-scale supergravity, but is ***not necessary***.

$$e^{-K/3} = T + T^* + f(z, z^*)$$

No-scale condition is sufficient for flat directions, but is also not necessary



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Symmetry Insights into rarity of dS solutions

Supersymmetry (especially of the gravity sector)

Rigid scaling symmetries

Usual approach (for which dS is hard to obtain):
SCALE BREAKING >> susy breaking

KKLT 03
LVS 05

More promising approach:
SUSY BREAKING >> scale breaking

2202.05344

Symmetry Insights into rarity of dS solutions

Berg, Haack & Kors 05
Berg, Haack & Pajer 07
Cicoli, Conlon & Quevedo 08

Supersymmetry (especially

Rigid scaling symmetries

Scale invariant with a flat scalar potential

Not scale invariant but still with a flat scalar potential

Not scale invariant & flatness of scalar potential is lifted

MECHANISM FOR SUPPRESSING V:

Together these can be more than the sum of their parts…

Interplay of scaling and supersymmetry provides a new mechanism for suppressing vacuum energies:

$$e^{-K(\tau)/3} = A\tau + B + \frac{C}{\tau} + \cdots$$

Symmetry Insights into rarity of dS solutions

Supersymmetry (especially of the gravity sector)

Rigid scaling symmetries

Yoga Models: low-energy EFT exploiting this mechanism

2111.07286

Expand in inverse powers of very large dilaton field τ

Imagine gravity sector (including dilaton) is more supersymmetric than the SM sector

Allows a relaxation mechanism


Yoga Models
SM fields and natural relaxation

An example Low-energy framework

Yoga Models

2111.07286

2212.14870

Low-energy dynamics involves matter coupled to gravity and axio-dilaton (plus possible relaxon field)

axio-dilaton: $T = \tau + i\, a$

$$\mathcal{L}_{\rm ad} \sim M_p^2 \left[\mathcal{R} + \frac{(\partial\tau)^2 + (\partial a)^2}{\tau^2} \right] + V(\tau) + \mathcal{L}_m(\tilde{g}_{\mu\nu}, \psi)$$

$$\tilde{g}_{\mu\nu} = e^{-K/3} g_{\mu\nu} \simeq \frac{g_{\mu\nu}}{\tau}$$

$$m_{sm} \propto \frac{M_p}{\sqrt{\tau}} \qquad m_\nu \propto \frac{M_p}{\tau}$$

This works if

$$\tau_{\rm min} \sim 10^{28}$$

Scalar Potential

Yoga Models

2111.07286

2212.14870

$$V(\tau) \simeq M_p^4 \left[\frac{w_X^2}{\tau^2} + \frac{A w_X}{\tau^3} + \frac{B}{\tau^4} + \cdots \right]$$

w_X, A, B functions of other fields and $\ln \tau$

Scalar Potential

Yoga Models

2111.07286

2212.14870

$$V(\tau) \simeq M_p^4 \left[\frac{w_X^2}{\tau^2} + \frac{A w_X}{\tau^3} + \frac{B}{\tau^4} + \cdots \right]$$

$\mathcal{O}(m_{sm}^4)$ NOT SMALL, BUT POSITIVE

$$m_{sm} \propto \frac{M_p}{\sqrt{\tau}}$$

Scalar Potential

Yoga Models

2111.07286

2212.14870

$$V(\tau) \simeq M_p^4 \left[\frac{w_X^2}{\tau^2} + \frac{A w_X}{\tau^3} + \frac{B}{\tau^4} + \cdots \right]$$

Introduce 'relaxation' field that seeks minimum of w_X terms

$$V(\tau) \simeq \frac{M_p^4}{\tau^4} U(\ln \tau)$$

Scalar Potential

Yoga Models

2111.07286

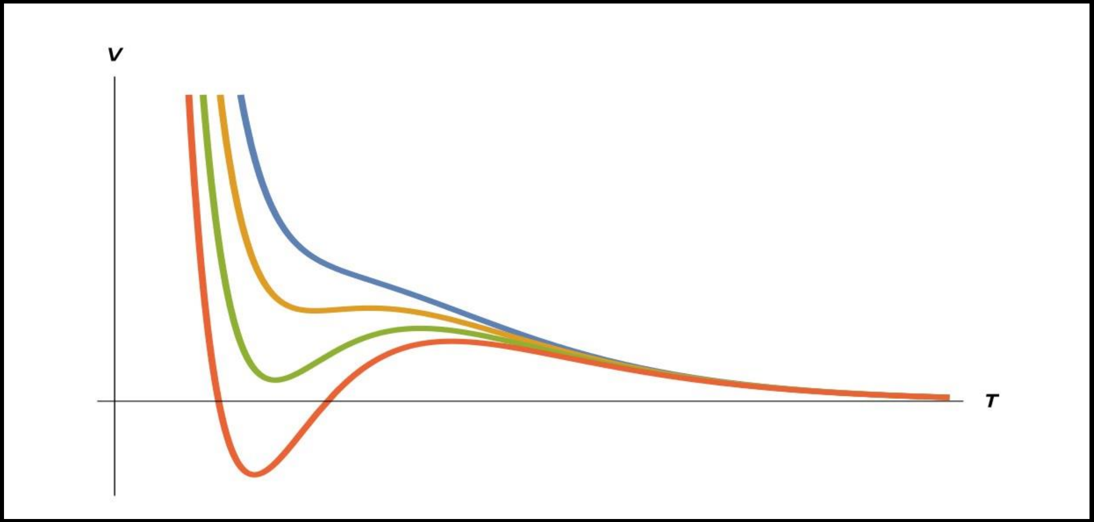
2212.14870

$$V(\tau) \simeq \frac{M_p^4}{\tau^4} U(\ln \tau)$$

$$\ln \tau_{\min} \sim 65$$

$$\tau_{\min} \sim 10^{28}$$

1/τ expansion still under control



Scalar Potential

Yoga Models

2111.07286

2212.14870

$$V(\tau) \simeq \frac{M_p^4}{\tau^4} U(\ln \tau)$$

$$m_{sm} \propto \frac{M_p}{\sqrt{\tau}}$$

$$V_{\min} \propto \frac{M_p^4}{\tau_{\min}^4} \propto \left(\frac{m_{sm}^2}{M_p}\right)^4$$ 👀

Scalar Potential

Yoga Models

2111.07286

2212.14870

$$V(\tau) \simeq \frac{M_p^4}{\tau^4} U(\ln \tau)$$

$$V_{\min} \sim \frac{\epsilon^5}{\tau_{\min}} F^* F \qquad F > (10\ \mathrm{TeV})^2$$

$$\epsilon \sim 1/(\log \tau_{\min})$$

Out of the box: $V_{min} = 10^{-91}\ M_p^4$ (not *quite 10^{-120}, but…)*

Many tantalizing low-energy implications

Yoga Models
2111.07286
2212.14870

Best models of inflation (goldstone boson agreeing with data)

1603.06789 2202.05344

Novel late-time cosmology (axion birefringence; H0 tension;...)

Requires UV completion at eV scales, and match there to Supersymmetric Large Extra-Dimension models

Possible implications for colliders (resemble SLED)

th/0304256 (SLED)
ph/0404135 (MSLED)
ph/0401125 (Higgs)
ph/0508156 (neutrinos)
and more

Biggest current challenge: tests of GR (new screening mechanisms)

2310.02092

Conclusions

Conclusions

High road to UV properties can be predictive

But it is robust properties like accidental scale invariance and supersymmetric gravity sector that are informative

Remarkably rich physics possible at very low energies

EFT arguments are restrictive but not prohibitive for predicting things to be tested in GW (and other gravity) tests

Much to explore

2-derivative interactions & multi-scalar models are an opportunity

GW and other GR tests can probe physics well-motivated by UV completions & strongly constrain approaches to the cc problem

Thanks for your time & attention!

Extra Slides

Relevance to inflation

Practical consequences for inflationary models

Two kinds of low-energy pseudo-Goldstone bosons with which to build technically natural inflationary string potentials, one class of which arises due to approximate scale invariances

Axions Dilatons

Practical consequences for inflationary models

Axions Dilatons

Axionic inflationary models

- axions are ubiquitous
- axions have protected masses

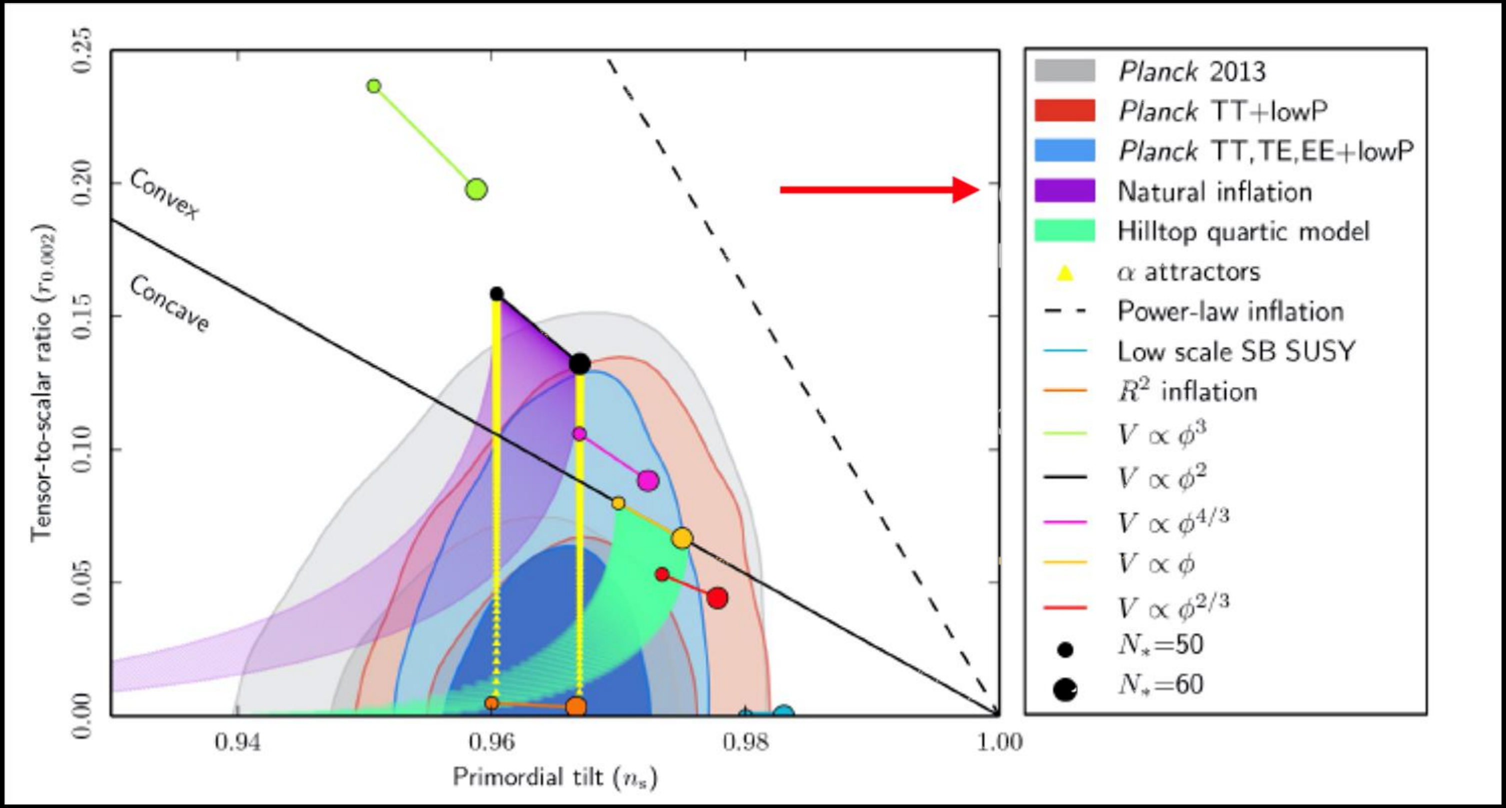
$$V(a) = A + B\cos\left(\frac{a}{f}\right)$$

Freese et.al. 90; Kachru et.al. 03;
Silverstein & Westphal 08 and more

Practical consequences for inflationary models

But: need $f \gg M_p$ disfavoured by data

Axions Dilatons



Planck collaboration

Practical consequences for inflationary models

Axions *Dilatons*

Scaling inflationary models

- Fibre moduli are ubiquitous
- F. mod have protected masses

$$V(a) = A - B\, e^{-a/f}$$

Goncharov & Linde 84; Kallosh & Linde 13 & 15

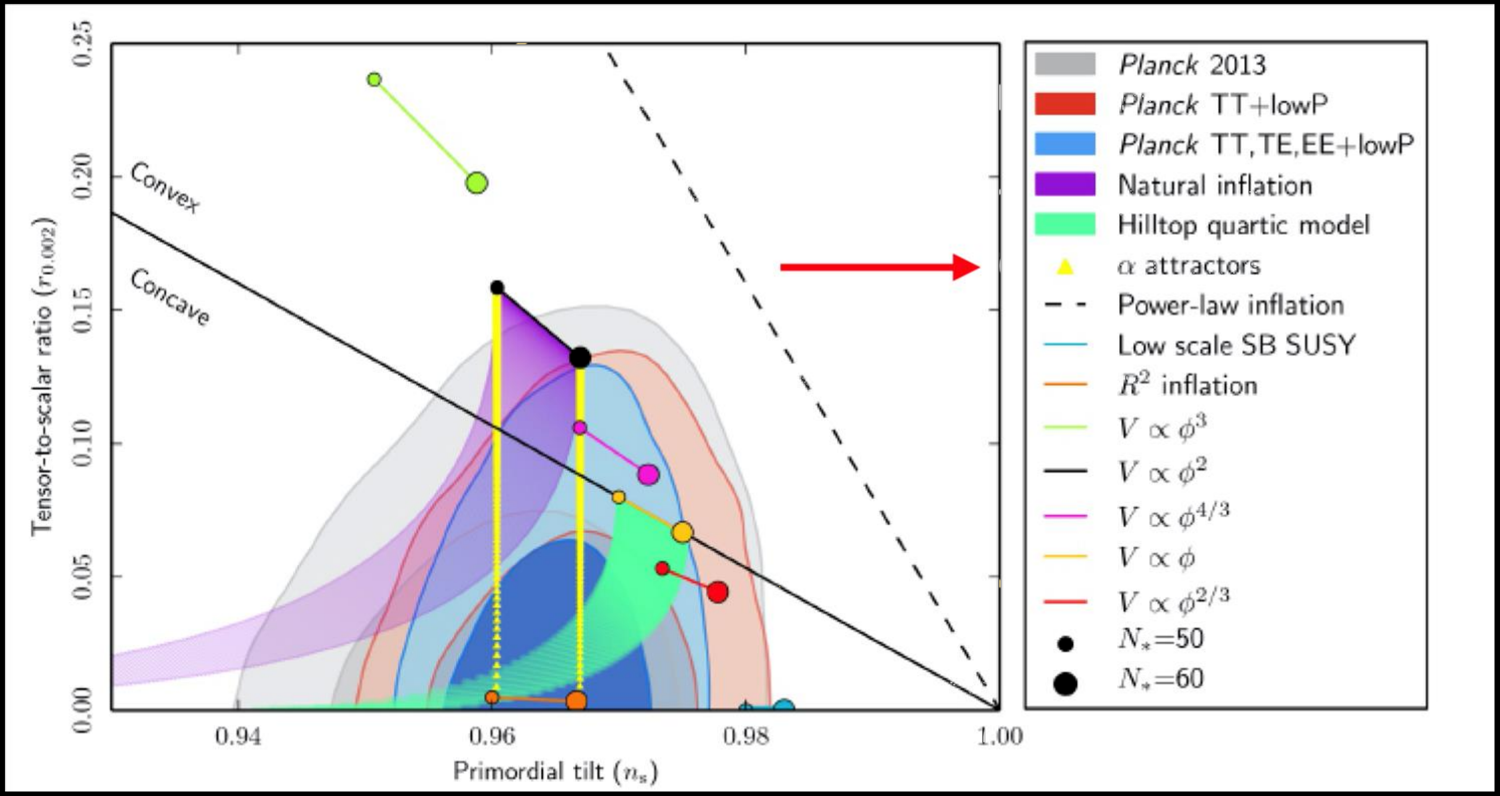
hep-th/0111025; 0808.0691; 1603.06789

Practical consequences for inflationary models

need $f \simeq M_p$
loved by data
predicts $r \simeq (n_s - 1)^2$

Axions

Dilatons



Planck collaboration

All This and More!

For microscopic inflationary models allows progress on the eta problem in ***two*** ways:

because of use of K for modulus stabilization

because flatness of potential is due to large field and not small parameter