The Gravity of Particle Physics (Naturally)

GWEFT

CPB @ McMaster University PI PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Benasque Aug 2023

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Warner Bros

Be vewy, vewy quiet…we're hunting for *GWEFT*

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Warner Bros

very, very

Be ~~vewy, vewy~~ quiet…we're hunting for ~~GWEFT~~

GREFT

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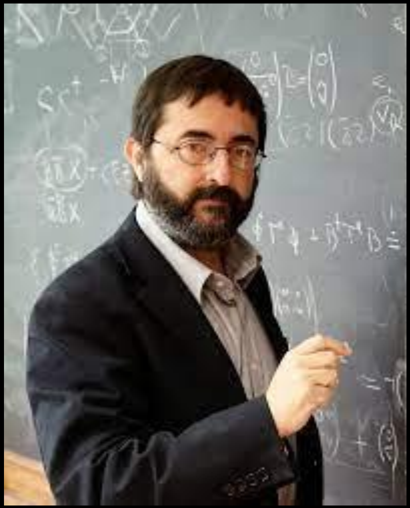
D. Dineen



F. Quevedo

P. Brax

Yoga models

2111.07286

dS & inflation

2202.05344

Axiodilaton tests

2212.14870

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

2006.06694

M. Ciupke

S. Krippendorf M. Cicoli

Contents

- EFTs & Gravitational physics
  - *What is done and what is wrong with it?*
  - *When is the classical approximation good?*
  - *Decoupling and UV sensitivity*

- Understanding the gravity of our situation
  - *Don't get swamped*
  - *Robust low-energy implication from the UV?*
  - *Challenges*

EFTs & GW physics

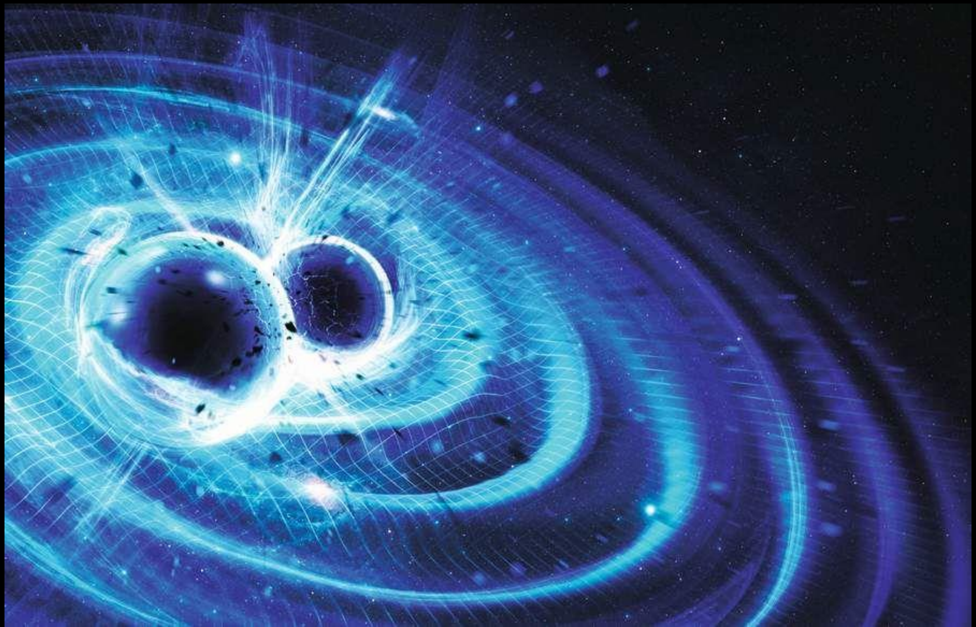
An overview including some faults

A New Window on the Universe

- ***We've seen gravitational waves!!!***
- More than once! In more than one way!

What do we learn?

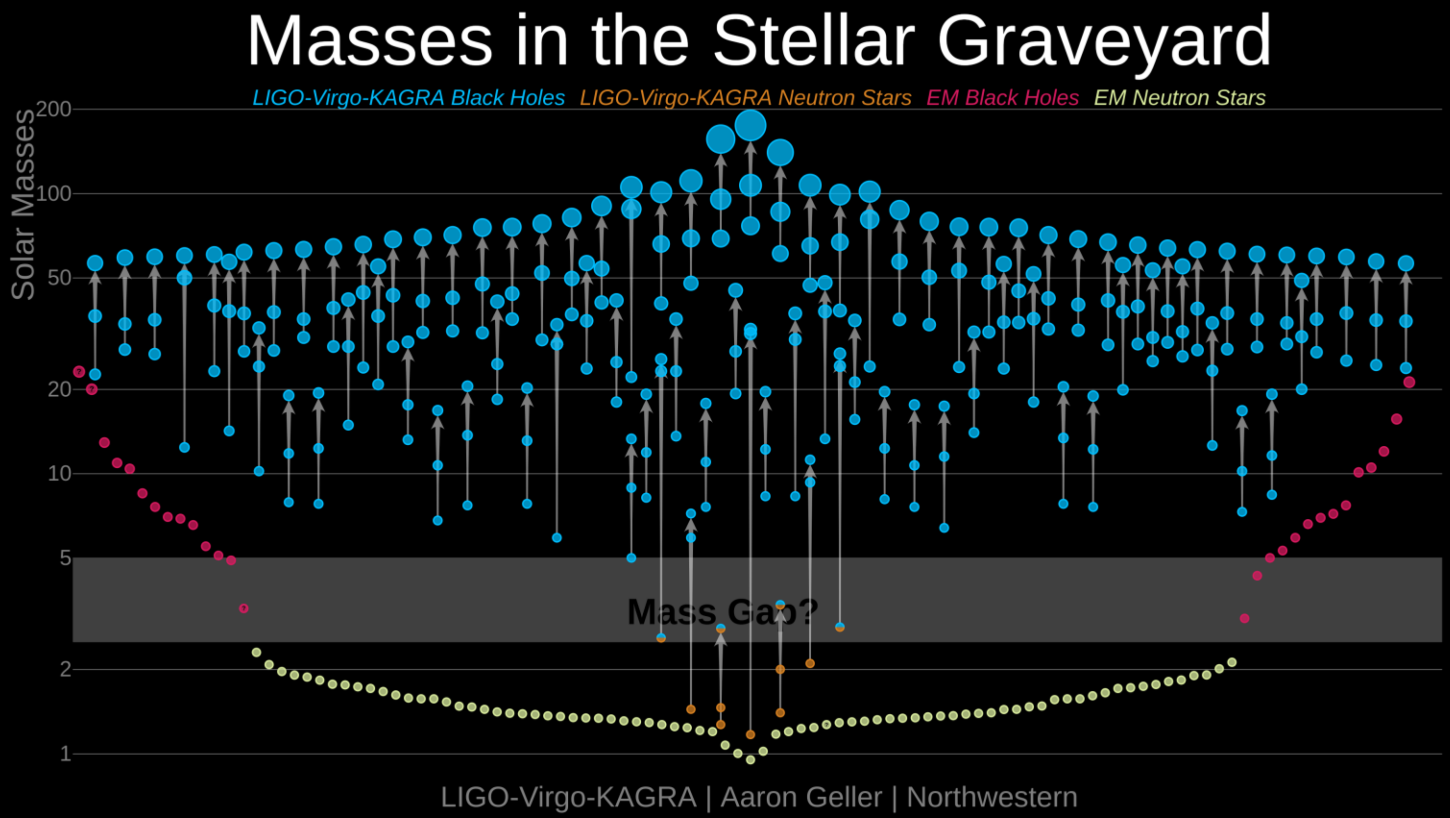
(fig science.com) LIGO/VIRGO/KAGRA



NANOGRAV (fig cornell.edu)

What Do We Learn?

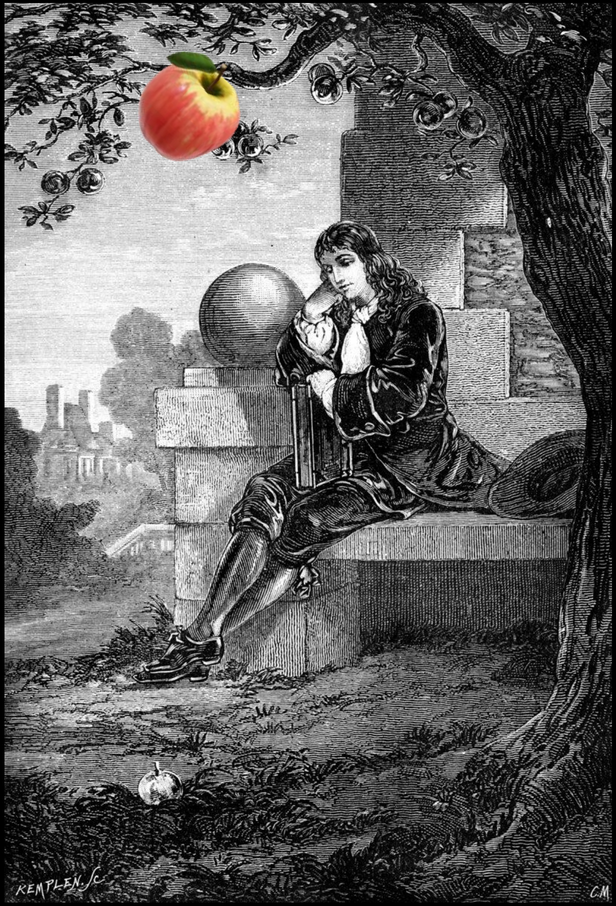
Black hole physics; Cosmology; …



What Do We Learn?

About how gravity itself works?

Rowe (Roy Soc)



What Do We Learn?

About how gravity itself works?

Rowe (Roy Soc)

Woolthorpe Manor & The Apple Tree

The Core Theory (SM + GR)

Supremely successful Core Theory:

- Renormalizable $SU_3 \times SU_2 \times U_1$ gauge theory
- Coupled to gravity described by GR

Which we believe is probably wrong

- Neutrino oscillations
- Gravity is not renormalizable
- Dark Matter and Dark Energy
- Primordial initial conditions
  - Baryon asymmetry; primordial fluctuations (inflation);…

The Core Theory (SM + GR)

- All but the neutrino problem involve gravity
  - ~~Neutrino oscillations~~
  - Gravity is not renormalizable
  - Dark Matter and Dark Energy
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The Core Theory (SM + GREFT)

- All but the neutrino problem involve gravity
  - ~~Neutrino oscillations~~
  - *Gravity is not renormalizable*
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Not M_p!

GR+QM point to unprobed high-energy scales

$$\frac{L}{\sqrt{-g}} = \Lambda + \frac{M_p^2}{2}R + c_1 R^2 + c_2 R_{\mu\nu}R^{\mu\nu} + \frac{c_3}{m^2}R^3 + \cdots$$

The Core Theory (SM + GREFT)

- GREFT: *explains why* classical *GR works*

e.g. compute amplitude for scattering *E* gravitons with energy *Q* at *L* loops using V_{ik} vertices involving *i* fields and *k* derivatives:

$$A_E(Q) \propto \left(\frac{Q^2}{M_p^{E-2}}\right)\left(\frac{Q}{4\pi M_p}\right)^{2L} \prod_{i;k>2}\left(\frac{Q}{M_p}\right)^{2V_{ik}}\left(\frac{Q}{m}\right)^{(k-4)V_{ik}}$$

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Leading contribution: $L = 0$ and $V_{ik} = 0$ unless $k=2$ (ie classical GR)

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EFTs Encode Decoupling

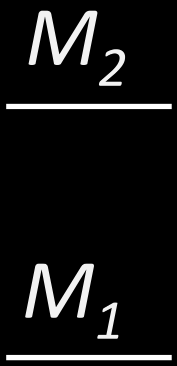
- Ef as

  re

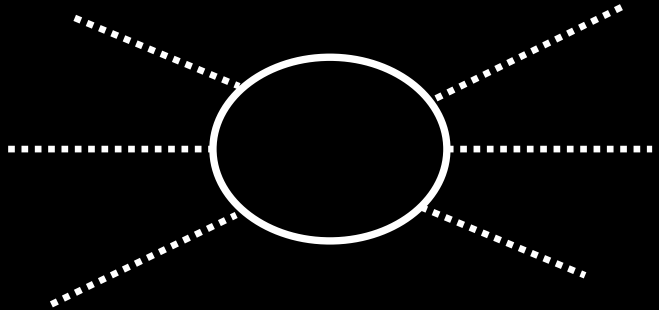
  - ll

GR+QM point to unprobed high-energy scales

$$\frac{L}{\sqrt{-g}} \boxed{= \Lambda +} \frac{M_p^2}{2} R + c_1 R^2 + c_2 R_{\mu\nu} R^{\mu\nu} + \frac{c_3}{m^2} R^3 + \cdots$$



$$g_{\text{eff}} = \frac{c_1}{M_1^p} + \frac{c_2}{M_2^p}$$

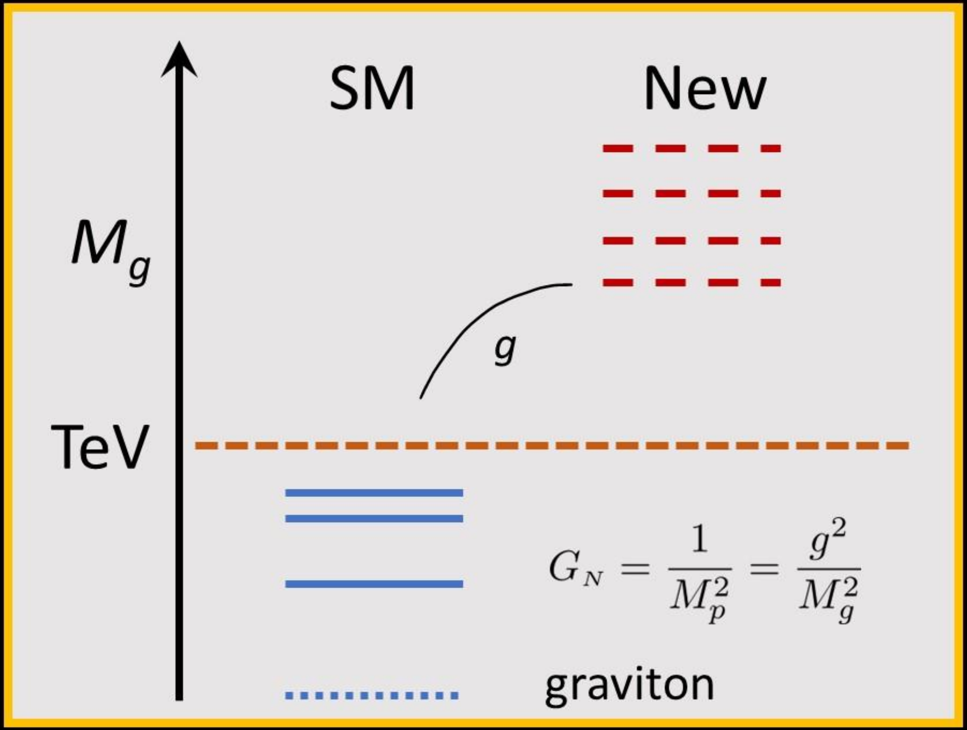


Decoupling: when *p > 0 smallest* mass *consist w sym* wins

***BUT** when p < 0 biggest mass wins*

Core Theory: GREFT

- *GR behaves like low-E limit of something fundamental*
  - nonrenormalizability *forces* an EFT interpretation
  - Possible UV completion (eg String Theory) exists



Core Theory: GREFT + SMEFT

- *GR behaves like low-E limit of something fundamental*
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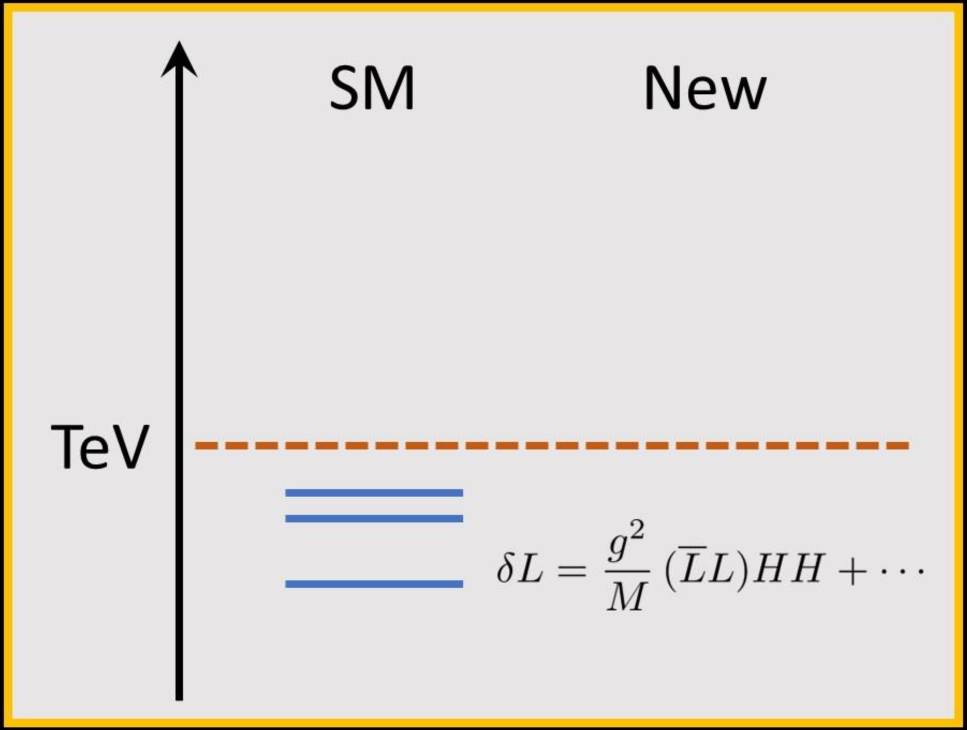
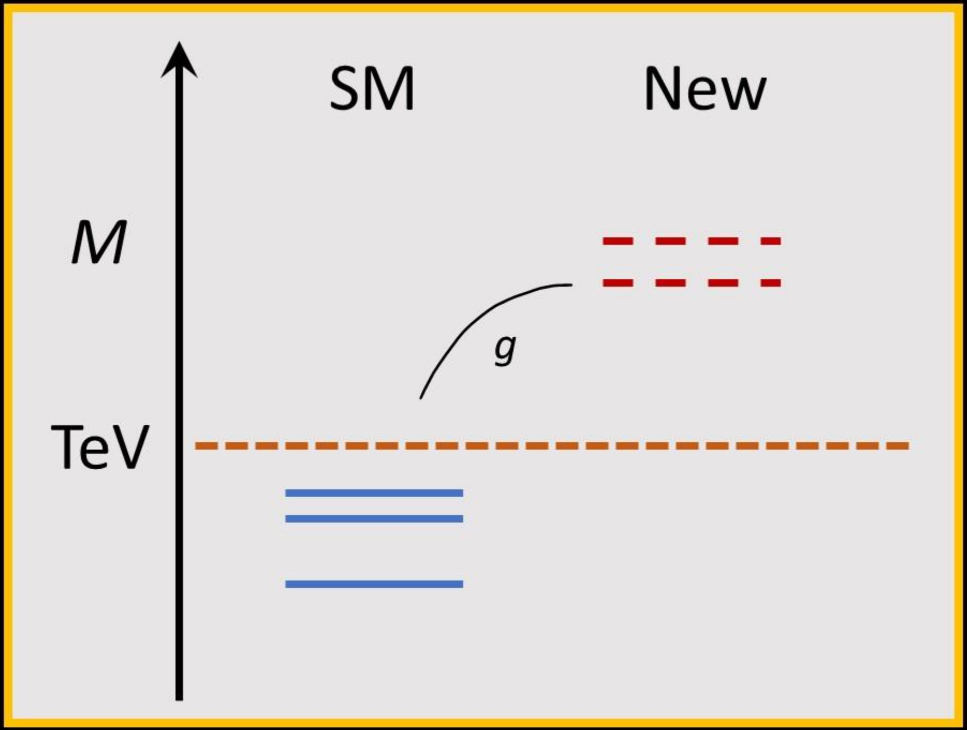
  - Including SM fields too immediately gives ν mass (SMEFT)



$$\delta L = \frac{g^2}{M}(\overline{L}L)HH + \cdots$$

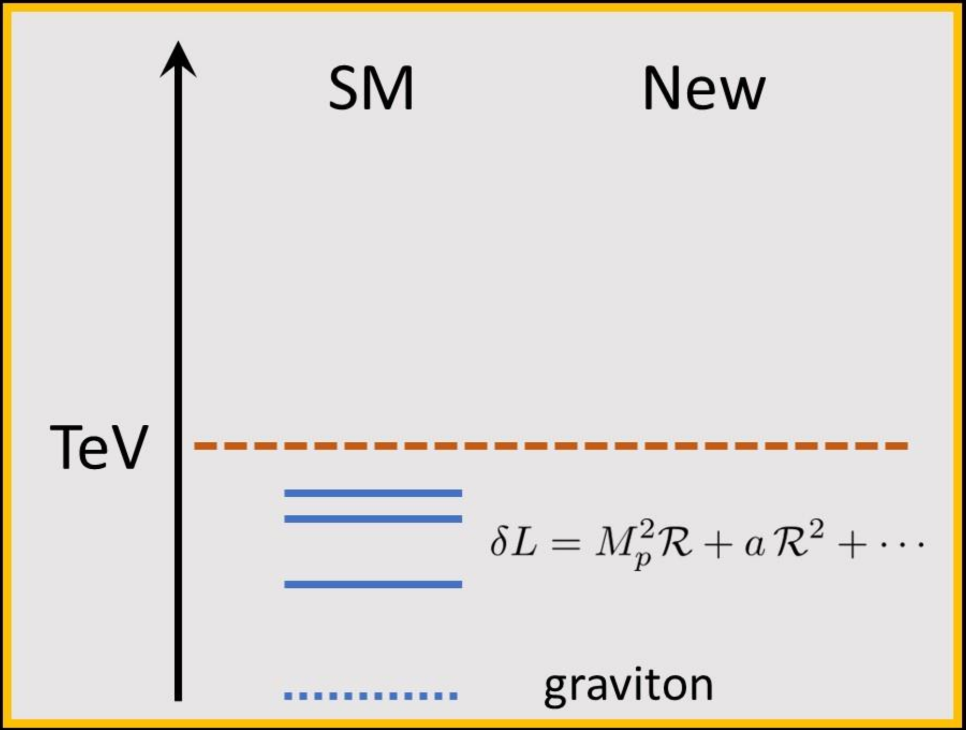
Core Theory: GREFT + SMEFT

- *GR behaves like low-E limit of something fundamental*
  - nonrenormalizability *forces* an EFT interpretation
  - Possible UV completion (eg String Theory) exists
  - Including SM fields too immediately gives ν mass (SMEFT) (also as expected from heavy new physics)



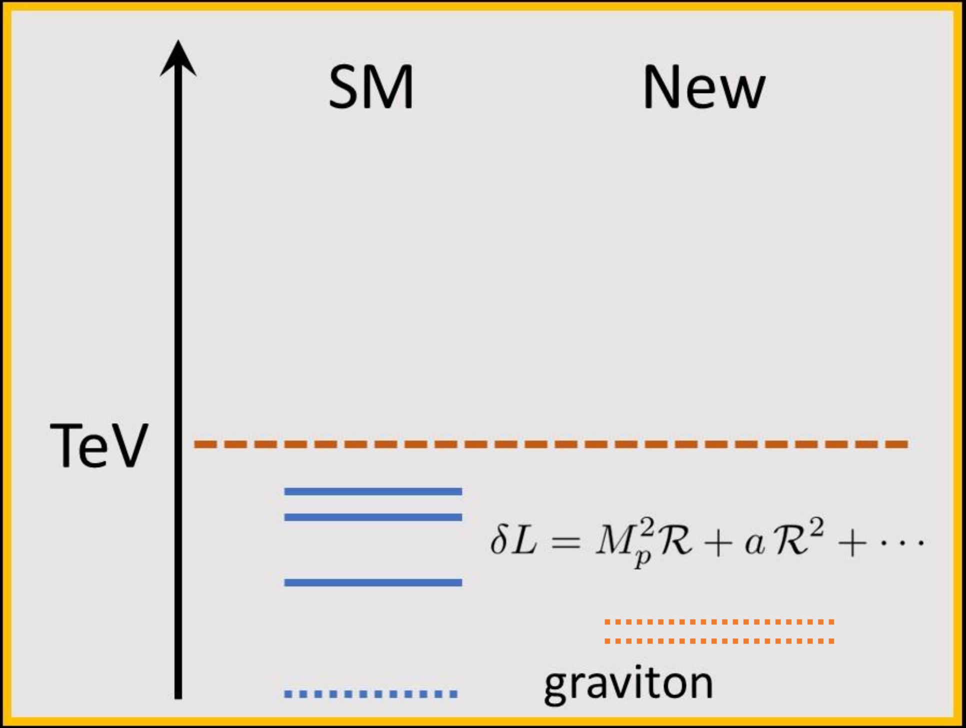
So what does this mean for GWs?

- *Two approaches:*
  - Seek implications of new interactions in GREFT



So what does this mean for GWs?

- *Two approaches:*
  - Seek implications of new interactions in GREFT
  - Seek implications of new light states



New GREFT interactions

- *Good news:* These almost certainly exist!
- *Bad news:*
  - Influence arises as a series in $1/(mL) = \lambda/L$ where L is a typical length scale in the process of interest and $\lambda = 1/m$ is a *microscopic* length scale

- *Conceptually interesting:*
  - Quantify how well GR works
  - New interactions (eg higher time derivatives) complicate numerical predictiveness

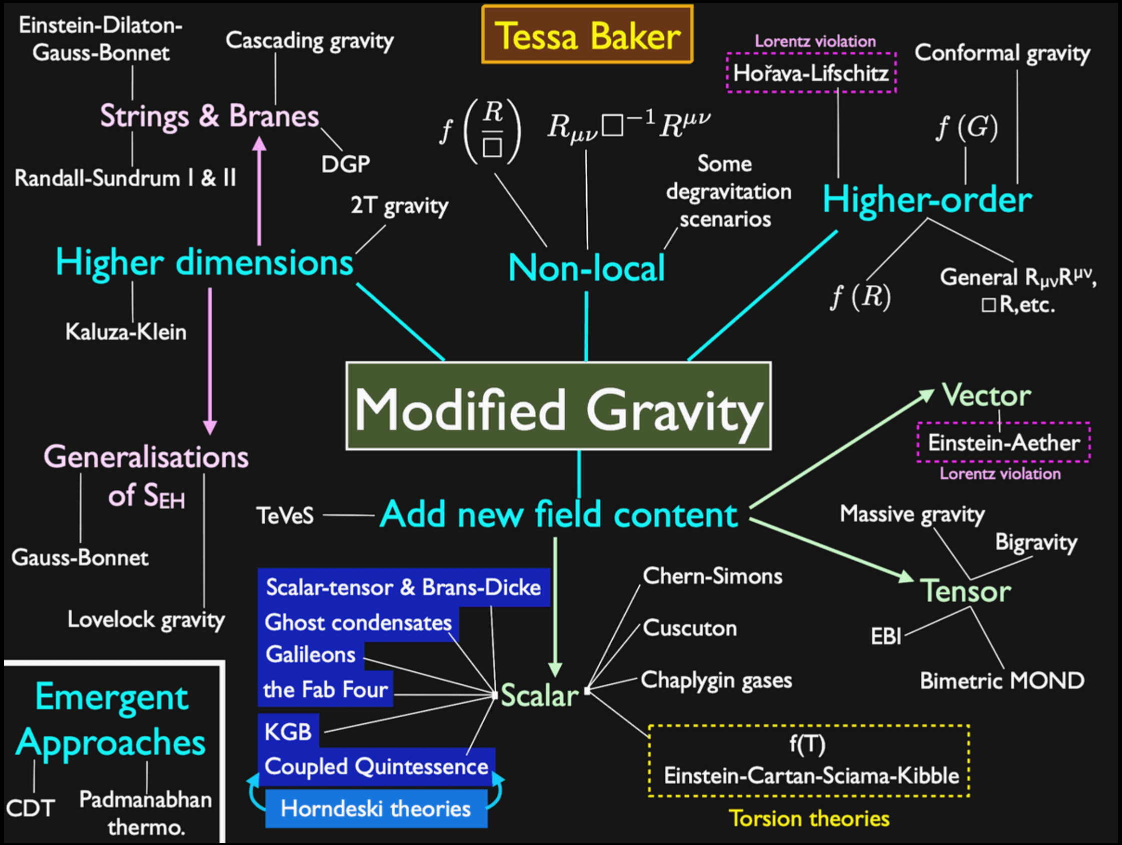
$$\boxed{\frac{L}{\sqrt{-g}} = \Lambda + \frac{M_p^2}{2} R + c_1 R^2 + c_2 R_{\mu\nu} R^{\mu\nu} + \frac{c_3}{m^2} R^3 + \cdots}$$

New Light States

- *Requires:*
  - Introduce new boson (to mediate macroscopic force) with mass $m < 10^{-10}$ eV so that $\lambda = 1/m > 1$ km.
- *Potential opportunity:*
  - Scalars much lighter than this are often invoked in cosmology for phenomenological reasons
  - Light scalar masses (and small potentials) are famously UV sensitive (ie rare in the low-energy limit of complicated systems, so their presence requires explanation)
- *Constrained:*
  - New states should not damage our understanding of why classical methods work in GR at low energies

The Wild West

- *Many many proposals*
  - Procedure: make up new fields; make up new lagrangian; solve *classical* field equations



Tessa Baker

Modified Gravity

Higher dimensions

Strings & Branes

Einstein-Dilaton-Gauss-Bonnet

Cascading gravity

DGP

Randall-Sundrum I & II

2T gravity

Kaluza-Klein

Generalisations of S_{EH}

Gauss-Bonnet

Lovelock gravity

Non-local

$f\left(\frac{R}{\Box}\right)$

$R_{\mu\nu}\Box^{-1}R^{\mu\nu}$

Some degravitation scenarios

Higher-order

Lorentz violation

Hořava-Lifschitz

Conformal gravity

$f(G)$

$f(R)$

General $R_{\mu\nu}R^{\mu\nu}$, $\Box R$, etc.

Add new field content

TeVeS

Vector

Einstein-Aether

Lorentz violation

Tensor

Massive gravity

Bigravity

EBI

Bimetric MOND

Scalar

Scalar-tensor & Brans-Dicke

Ghost condensates

Galileons

the Fab Four

KGB

Coupled Quintessence

Horndeski theories

Chern-Simons

Cuscuton

Chaplygin gases

f(T)

Einstein-Cartan-Sciama-Kibble

Torsion theories

Emergent Approaches

CDT

Padmanabhan thermo.

The Wild West

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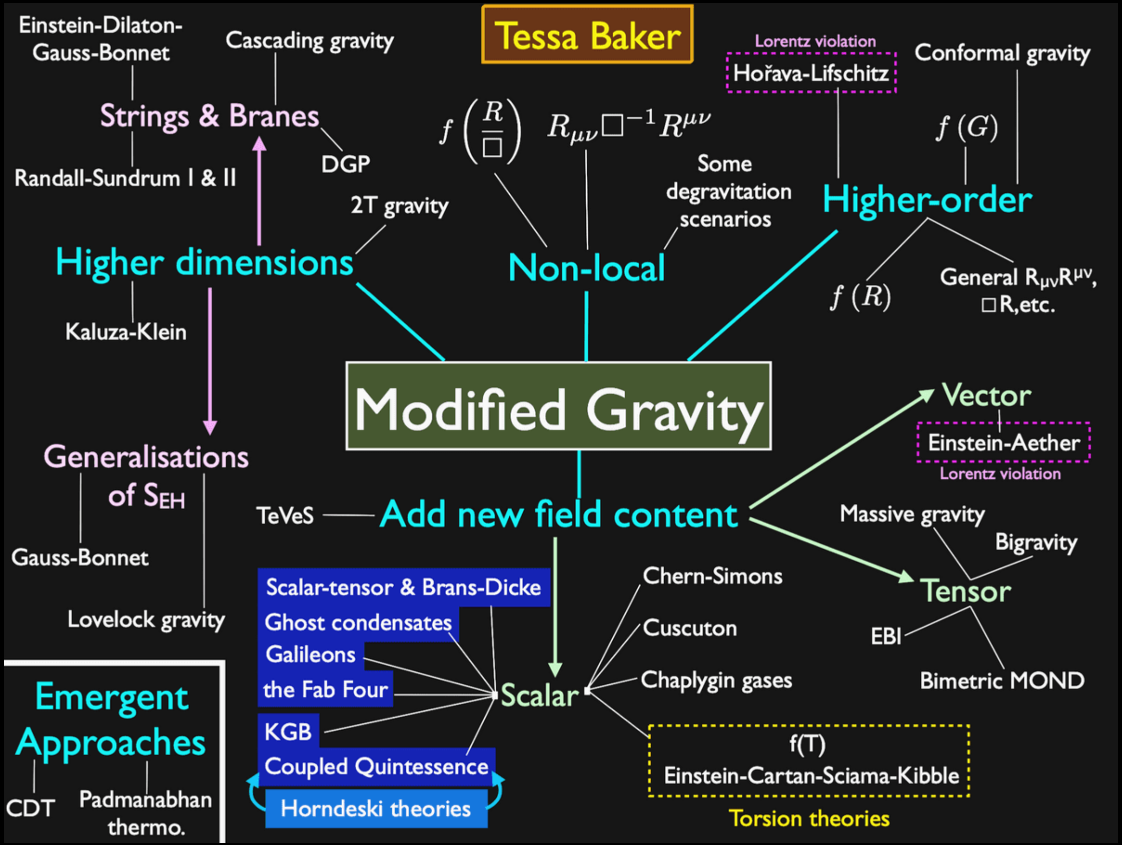

Most are inconsistent with low-energy GREFT control over quantum effects

- Many admit no EFT framework at all
- Those with EFT framework often break down above fairly low (sub eV) energies
- Many have no mechanism for why new field is so light

The Wild West

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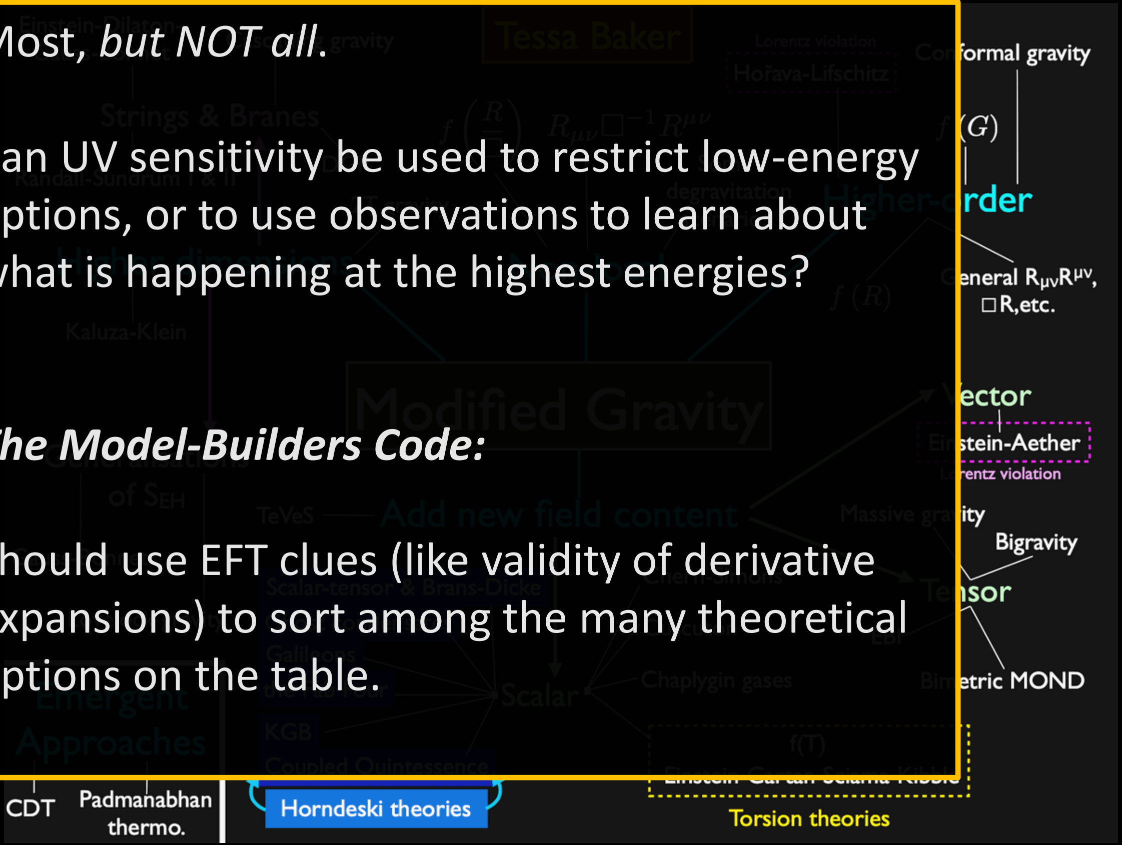

Most, *but NOT all*.

Can UV sensitivity be used to restrict low-energy options, or to use observations to learn about what is happening at the highest energies?

The Model-Builders Code:

Should use EFT clues (like validity of derivative expansions) to sort among the many theoretical options on the table.

Most are inconsistent with low-energy GREFT control over quantum effects

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The Wild West

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The Model-Builders Code:

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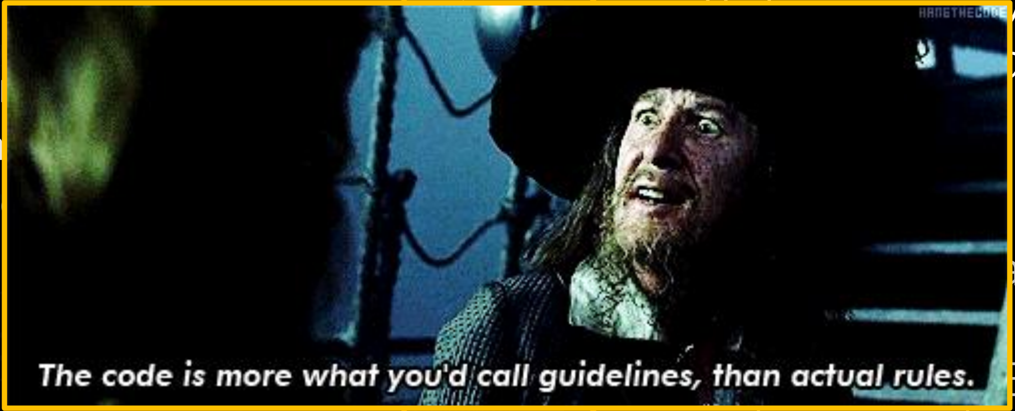
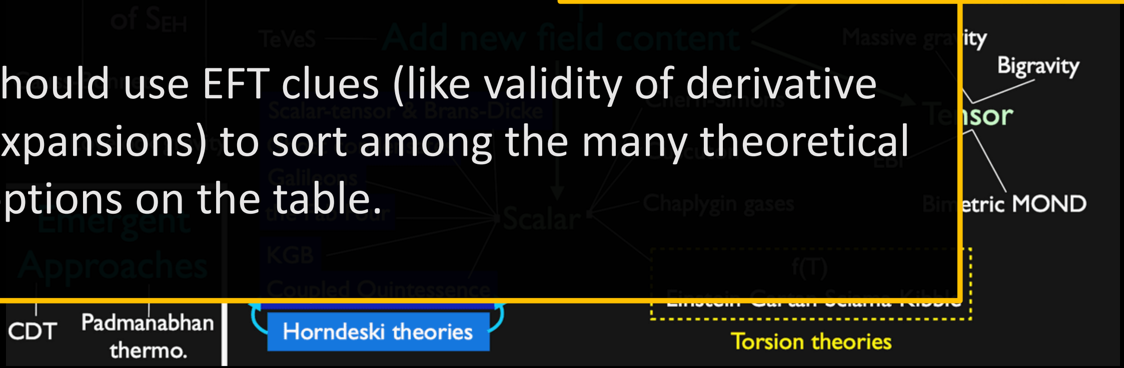

The code is more what you'd call guidelines, than actual rules.

Most are inconsistent

GREFT

antum

- no EFT
  at all
- EFT
  framework often break down above fairly low (sub eV) energies
- Many have no mechanism for why new field is so light



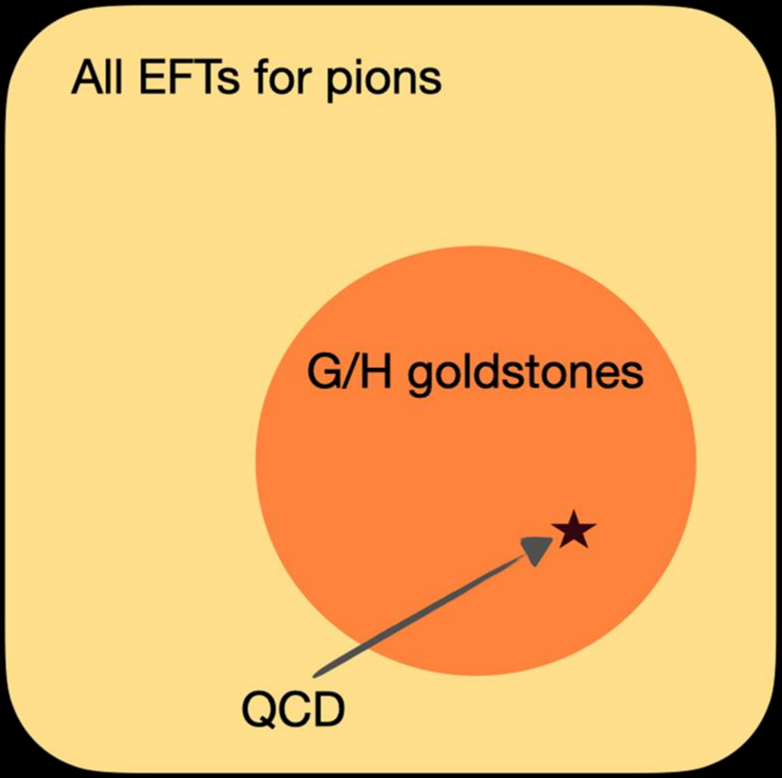
Clues from the UV?

Part I: Dropping apples in the Swamp

UV Robust vs UV Specific Predictions

EFTs identify which predictions are UV sensitive and which are not (consider the QCD example)

$$SU(2) \times SU(2) \to SU(2)$$



UV insensitive prediction from QCD: soft pion theorems

UV specific prediction from QCD: proton mass

UV Information from Gravity?

What can be learned from UV completions to gravity?

Examples exist! (in practice use string theory as a guide)

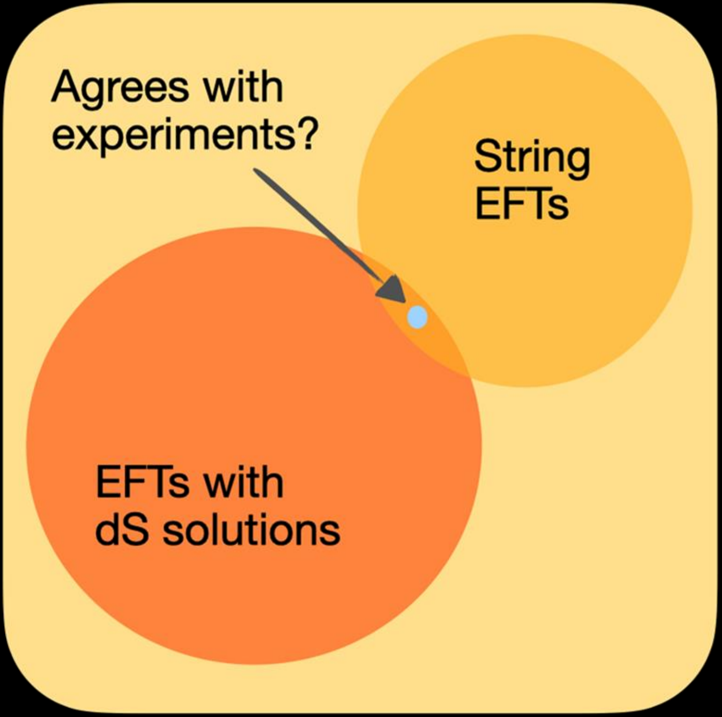
Some things also seem rare:

Global symmetries

Non-supersymmetric control

Standard Model & no extras

de Sitter solutions



Swampland Program

Swampland Hypothesis:

dS solutions are UV informative (like proton mass in QCD)

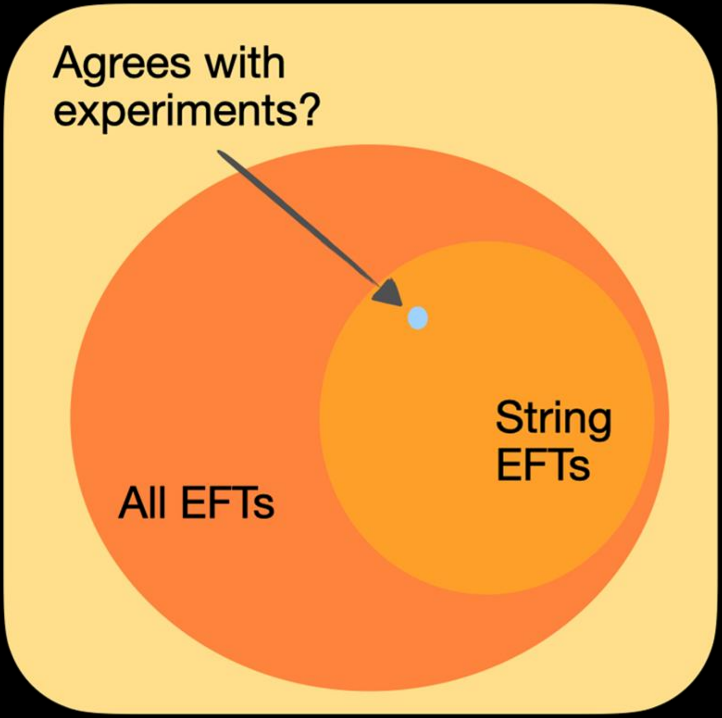
Many EFTs (eg those with dS sol

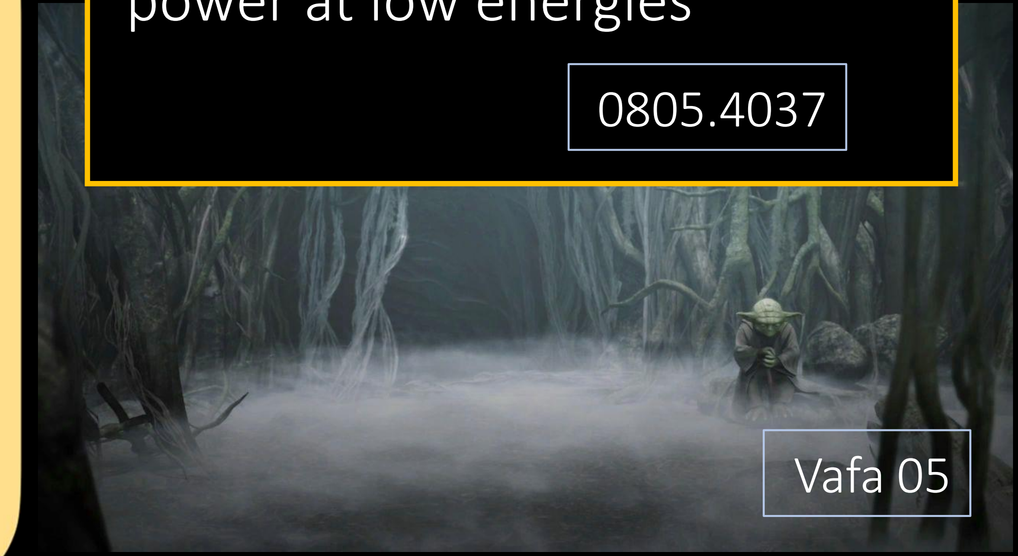
(making it useful to identify whi

Principle of Swamplementarity:

A conjectured swampland feature's plausibility is inversely proportional to its predictive power at low energies

0805.4037





Vafa 05

Adventure Sports Magazine

Clues from the UV?

Part II: 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)

Possibly extra dimensions (only down to eV energies)

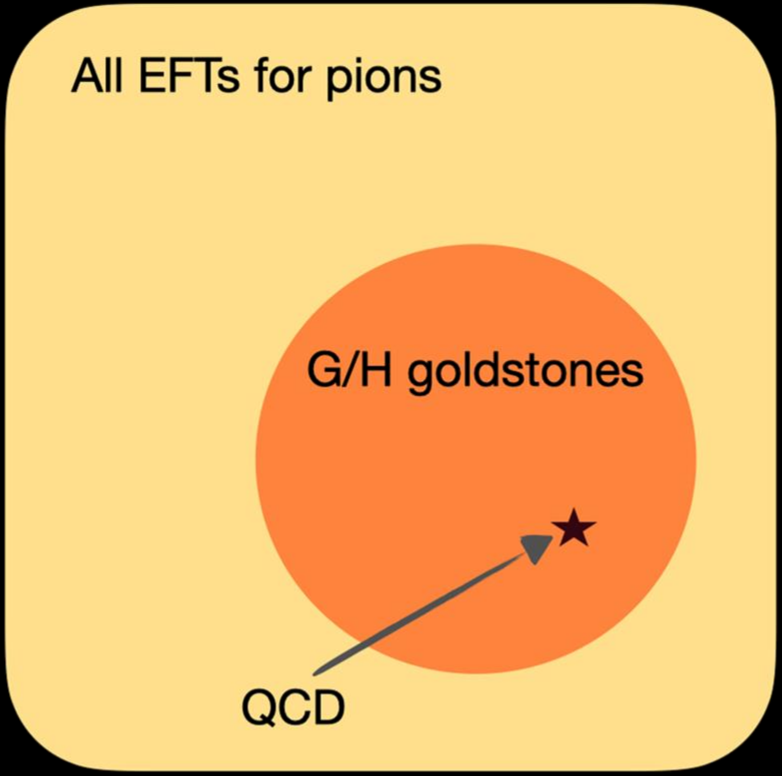
Often find accidental approximate symmetries and these can lead to light fields (axions, dilatons, and often many of them)

Supersymmetry present but broken

Accidental symmetries from the UV

Similar to QCD, accidental low-energy string symmetries often provide natural candidates for new low-energy fields

$$SU(2) \times SU(2) \to SU(2)$$



Axions are a common example

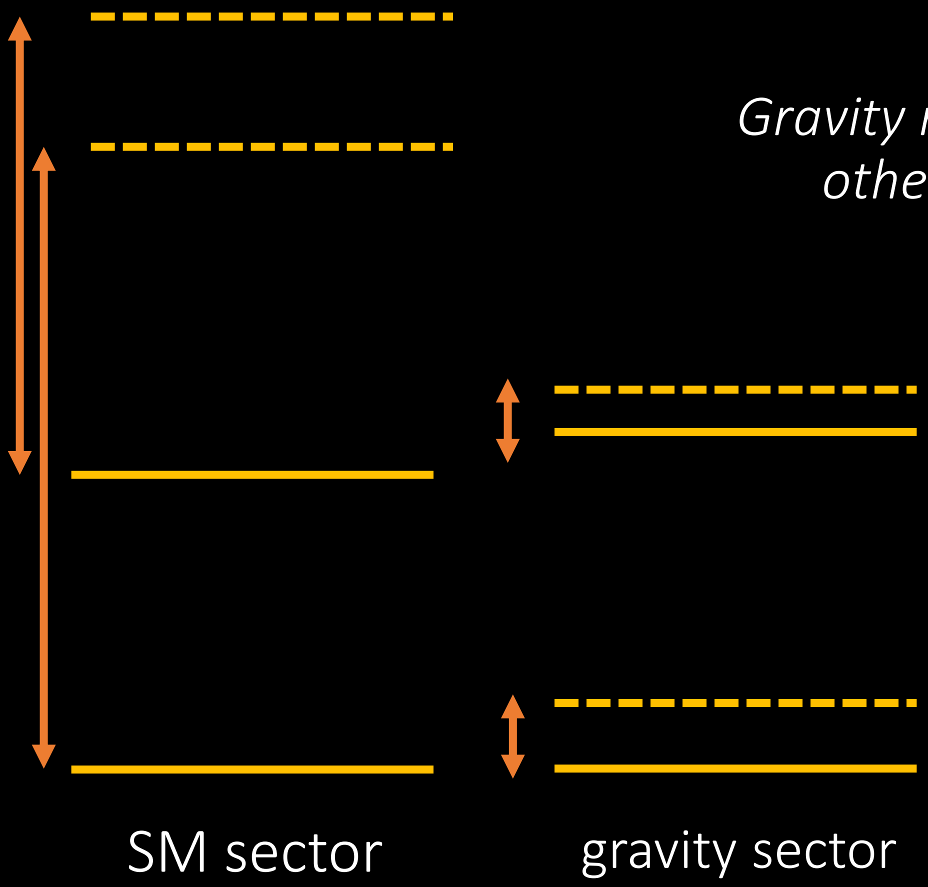
Two other accidental symmetries equally generic & relevant to dS solutions but relatively poorly explored

Supersymmetry in gravity sector;

Semiclassical scaling symmetries

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

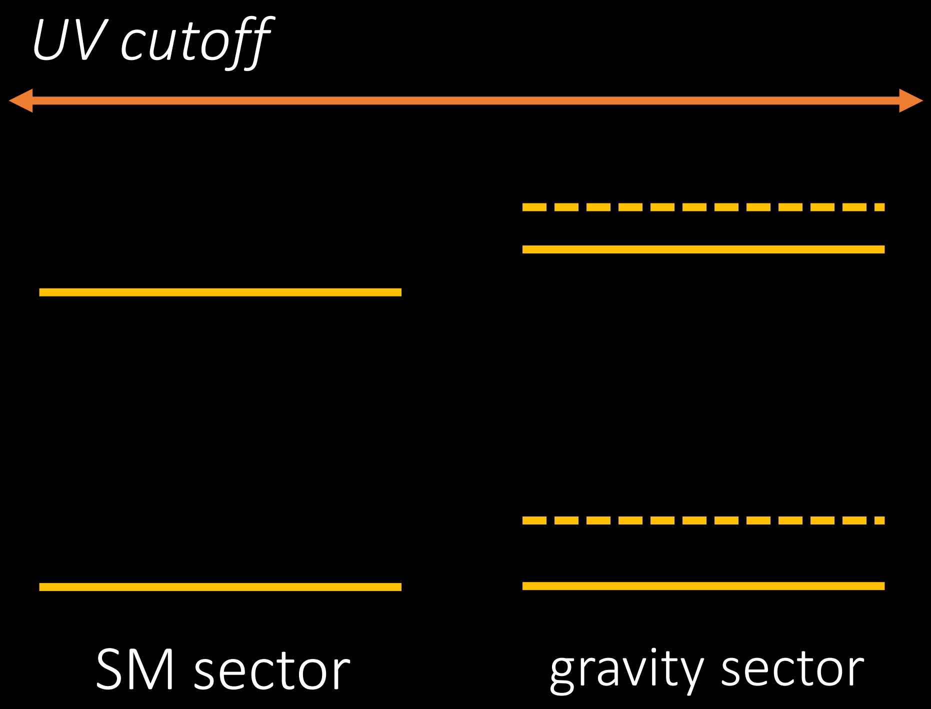
$$\Delta m^2 = m_B^2 - m_F^2 \sim gF$$

Supersymmetry of the gravity sector

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

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

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

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

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

Evidence for Accidental Scaling

11D SUGRA admits single scaling corresponding to the α' expansion

11D sugra: $\mathscr{L}_{11} \to \lambda^9 \mathscr{L}_{11}$

$$g_{MN} \to \lambda^2 g_{MN}$$

$$A_{MNP} \to \lambda^3 A_{MNP}$$

\+ fermion transfns

10D IIB SUGRA similarly admits single scaling corresponding to the α' and g_s expansions

10D IIB sugra: $\mathscr{L}_B \to \lambda^{4u} \mathscr{L}_B$

$$g_{MN} \to \lambda^u g_{MN} \qquad B_{MN} \to \lambda^{2u-w} B_{MN}$$

$$C_{MN} \to \lambda^w C_{MN} \qquad \tau \to \lambda^{2(w-u)} \tau$$

$$C_{MNPR} \to \lambda^{2u} C_{MNPR}$$

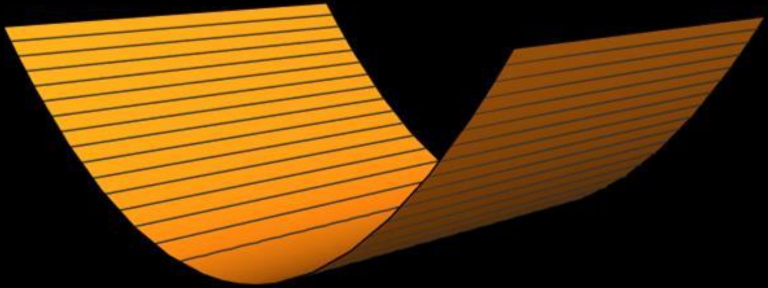
\+ fermion transfns

and so on for IIA, heterotic and other perturbative vacua…

Accidental Scaling enforces V = 0 (so fights dS)

Does so despite symmetry being spontaneously broken!

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



Must quantify effects due to explicit symmetry breaking

Peccei et al 87 Wetterich 88

Weinberg 89

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

if $\dfrac{\partial V}{\partial \phi^i} = 0$ then* $V = 0$

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

if $\phi^i = 0$ then* $\dfrac{\partial V}{\partial \phi^i} = 0$

arXiv:2006.06694

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

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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

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

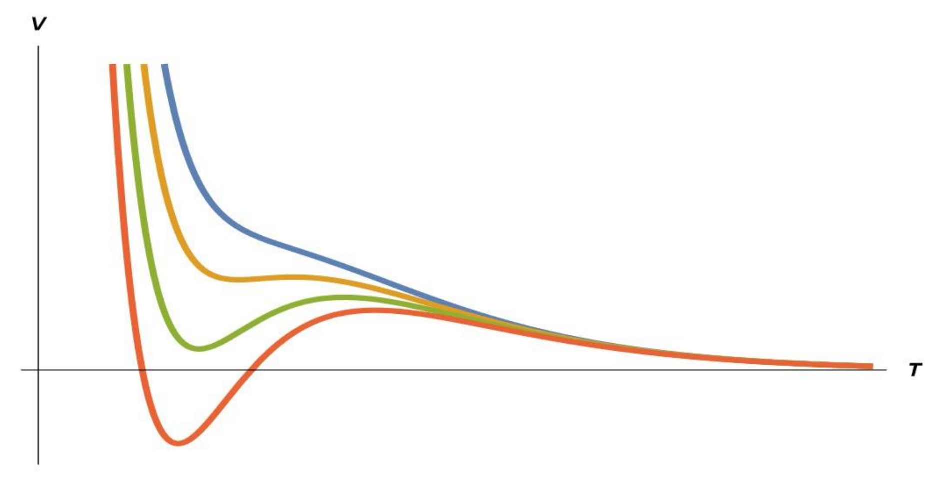
2212.14870

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

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

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

1/τ expansion still under control



Scalar Potential

Yoga Models

2111.07286

2212.14870

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

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

Scalar Potential

Yoga Models

2111.07286

2212.14870

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

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

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

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

These model cry out for tests of GR

Yoga Models
2111.07286
2212.14870

Both axions and dilatons are pseudo-Goldstone bosons and so can naturally be in low-energy theory

Unlike axions, low energy dilatons tend to couple to matter like Brans-Dicke scalars and want to couple with gravitational strength (which is a problem if they are light enough to mediate macroscopic forces)

Any progress on the cosmological constant problem generically makes at least one dilaton extremely light:

$$m^2 \sim V_{\rm min}/M_p^2 \sim H^2$$

Technically natural: astro-ph/0107573

Not yet known whether screening mechanisms can allow them to have escaped detection (multiple scalars allow new possibilities)

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 approach to the Hubble problem (time-dependent m)

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 approach to the Hubble problem (time-dependent m)

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

Implications for colliders (resemble SLED)

Recently rediscovered by swampland program

Montero, Vafa & Valenzuela 22

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

Conclusions

UV properties can be predictive

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

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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

Conclusions

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

GW and other GR tests can probe plausible physics well-motivated by UV completions, providing among the strongest constraints on models relevant to the cosmological constant problem

Thanks for your time & attention!

Extra Slides

Suppression of the potential

Scaling and 4D Supersymmetry

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

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

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

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

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

$$D_i W = W_i + K_i W$$

Scaling and 4D Supersymmetry

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

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

$$\mathcal{L}_g = \sqrt{-\tilde{g}}\, e^{-K/3}\,\widetilde{R}$$

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

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Scaling and 4D Supersymmetry

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

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

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

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

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$$D_i W = W_i + K_i W$$

Scaling and 4D Supersymmetry

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

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

Sufficient condition for no-scale model, so provides flat directions along which susy is broken

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

if $W_i = 0$ then

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

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

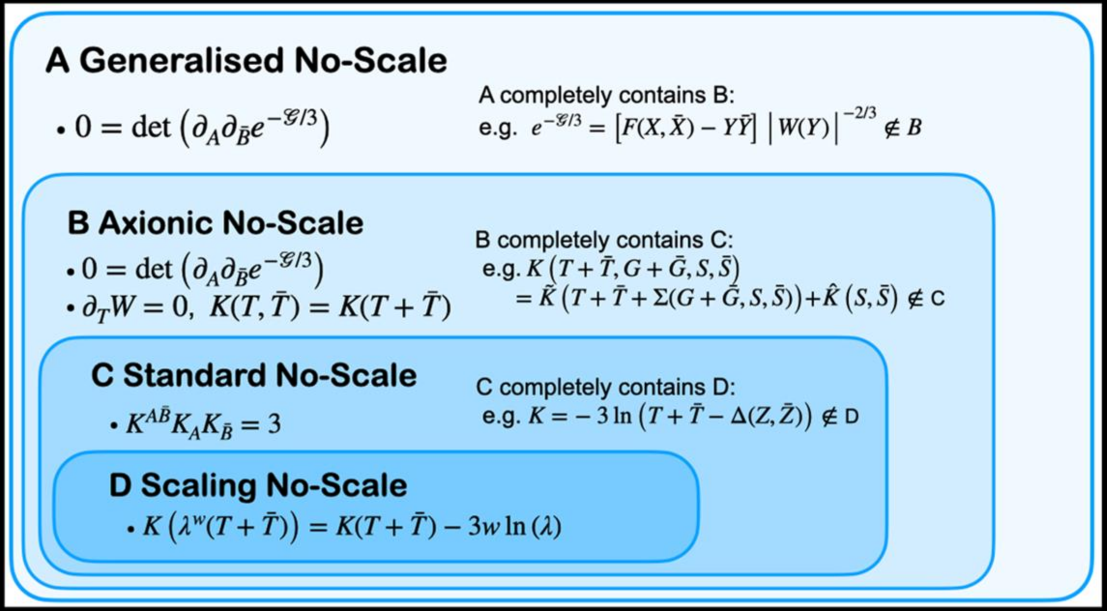
Cremmer et al 83
Barbieri et al 85
0811.1503

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



A Generalised No-Scale

- $0 = \det\left(\partial_A \partial_{\bar{B}} e^{-\mathscr{G}/3}\right)$

A completely contains B:
e.g. $e^{-\mathscr{G}/3} = \left[F(X,\bar{X}) - Y\bar{Y}\right] \left|W(Y)\right|^{-2/3} \notin B$

B Axionic No-Scale

- $0 = \det\left(\partial_A \partial_{\bar{B}} e^{-\mathscr{G}/3}\right)$
- $\partial_T W = 0,\ K(T,\bar{T}) = K(T+\bar{T})$

B completely contains C:
e.g. $K\left(T+\bar{T}, G+\bar{G}, S, \bar{S}\right) = \tilde{K}\left(T+\bar{T}+\Sigma(G+\bar{G},S,\bar{S})\right) + \hat{K}\left(S,\bar{S}\right) \notin$ C

C Standard No-Scale

- $K^{A\bar{B}} K_A K_{\bar{B}} = 3$

C completely contains D:
e.g. $K = -3\ln\left(T+\bar{T}-\Delta(Z,\bar{Z})\right) \notin$ D

D Scaling No-Scale

- $K\left(\lambda^w (T+\bar{T})\right) = K(T+\bar{T}) - 3w\ln(\lambda)$

2006.06694

A mechanism

Flat directions can persist in no-scale models to higher orders than naively expected

e.g. suppose Φ^{-1} is an expansion field and scale invariance gives leading scale invariant result

scale invariant & no-scale

$$e^{-K/3} = A_0 \, \Phi$$

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$$e^{-K/3} = A_0\,\Phi$$

Flat directions can persist at subleading order ‘by accident’

Not scale invariant

but still no-scale

$$e^{-K/3} = A_0\,\Phi + A_1$$

A mechanism

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scale invariant & no-scale

$$e^{-K/3} = A_0 \, \Phi$$

Flat directions can persist at subleading order ‘by accident’

Not scale invariant

but still no-scale

$$e^{-K/3} = A_0 \, \Phi + A_1$$

though are eventually lifted

neither

$$e^{-K/3} = A_0 \, \Phi + A_1 + \frac{A_2}{\Phi}$$

Extended No-Scale Structure

This actually happens in some string compactifications

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

$$e^{-K/3} = (\tau - \tau^*)^{1/3} A_0 \mathcal{V}^{2/3} \left[1 + \frac{B_n}{\mathcal{V}^{2/3}} (\tau - \tau^*)^{1-n} + \cdots \right]$$

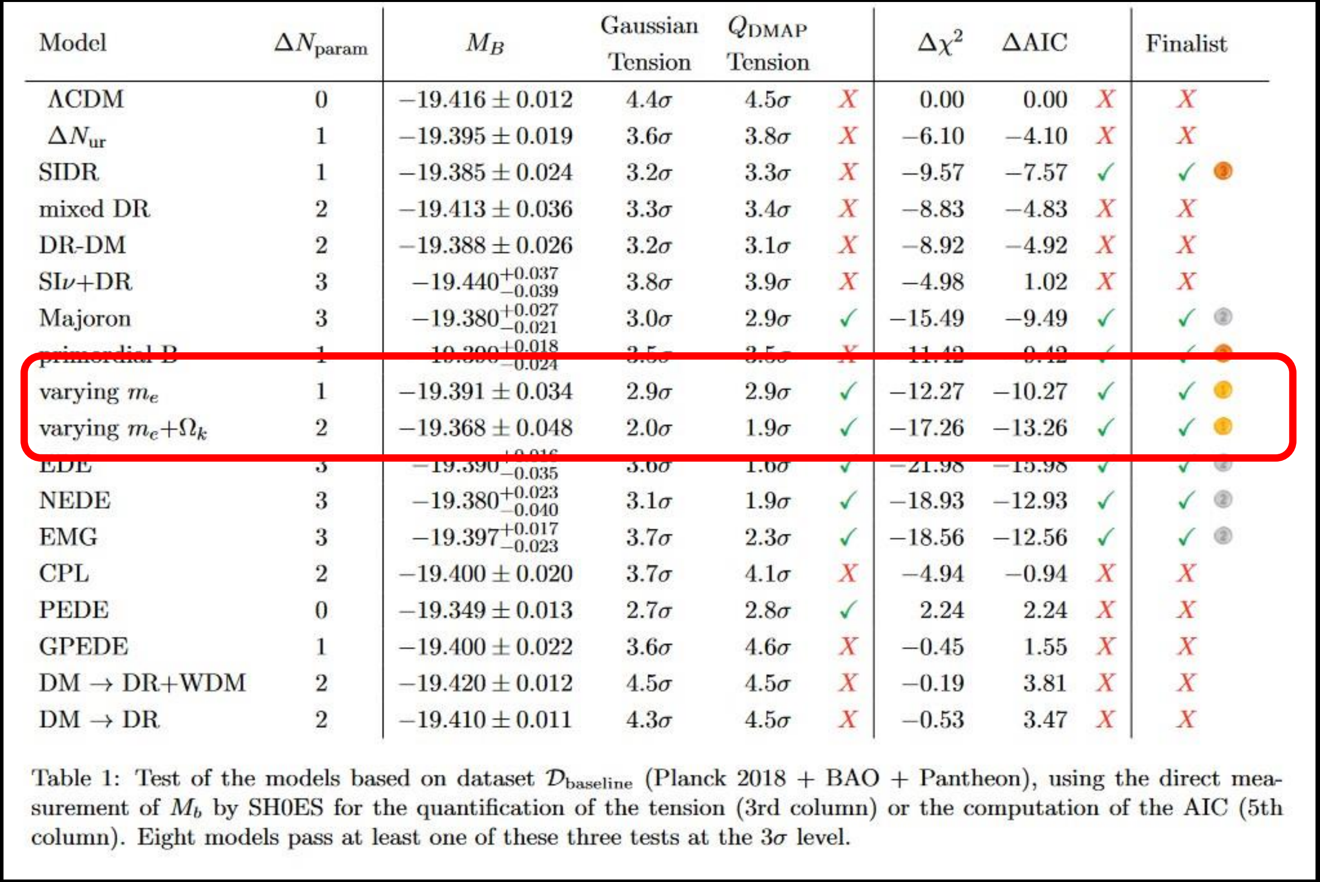
corresponding to an α'^2 string loop correction

These corrections preserve the flat direction for V to order α'^3 when evaluated at $D_\tau W = D_a W = 0$

Relevance to the Hubble Tension

Axiodilaton cosmology

5% increase in all masses at recombination helps with H0



Model	$\Delta N_{\rm param}$	M_B	Gaussian Tension	$Q_{\rm DMAP}$ Tension		$\Delta\chi^2$	ΔAIC		Finalist
ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	X	0.00	0.00	X	X
$\Delta N_{\rm ur}$	1	-19.395 ± 0.019	3.6σ	3.8σ	X	-6.10	-4.10	X	X
SIDR	1	-19.385 ± 0.024	3.2σ	3.3σ	X	-9.57	-7.57	✓	✓ ③
mixed DR	2	-19.413 ± 0.036	3.3σ	3.4σ	X	-8.83	-4.83	X	X
DR-DM	2	-19.388 ± 0.026	3.2σ	3.1σ	X	-8.92	-4.92	X	X
SIν+DR	3	$-19.440^{+0.037}_{-0.039}$	3.8σ	3.9σ	X	-4.98	1.02	X	X
Majoron	3	$-19.380^{+0.027}_{-0.021}$	3.0σ	2.9σ	✓	-15.49	-9.49	✓	✓ ②
primordial B	1	$-19.390^{+0.018}_{-0.024}$	3.5σ	3.5σ	X	-11.42	-9.42	✓	✓ ③
varying m_e	1	-19.391 ± 0.034	2.9σ	2.9σ	✓	-12.27	-10.27	✓	✓ ①
varying m_e+Ω_k	2	-19.368 ± 0.048	2.0σ	1.9σ	✓	-17.26	-13.26	✓	✓ ①
EDE	3	$-19.390^{+0.016}_{-0.035}$	3.6σ	1.6σ	✓	-21.98	-15.98	✓	✓ ②
NEDE	3	$-19.380^{+0.023}_{-0.040}$	3.1σ	1.9σ	✓	-18.93	-12.93	✓	✓ ②
EMG	3	$-19.397^{+0.017}_{-0.023}$	3.7σ	2.3σ	✓	-18.56	-12.56	✓	✓ ②
CPL	2	-19.400 ± 0.020	3.7σ	4.1σ	X	-4.94	-0.94	X	X
PEDE	0	-19.349 ± 0.013	2.7σ	2.8σ	✓	2.24	2.24	X	X
GPEDE	1	-19.400 ± 0.022	3.6σ	4.6σ	X	-0.45	1.55	X	X
DM $\to$ DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	X	-0.19	3.81	X	X
DM $\to$ DR	2	-19.410 ± 0.011	4.3σ	4.5σ	X	-0.53	3.47	X	X

Table 1: Test of the models based on dataset $\mathcal{D}_{\rm baseline}$ (Planck 2018 + BAO + Pantheon), using the direct measurement of M_b by SH0ES for the quantification of the tension (3rd column) or the computation of the AIC (5th column). Eight models pass at least one of these three tests at the 3σ level.

H0 Olympics: 2107.10291

Axiodilaton cosmology

Need not be bad news (relevance to Hubble tension?)

5% increase in all masses at recombination helps with H0

Sekiguchi & Takahashi 2007.03381

CMB does not change (except small nonequilibrium effects) if:

$$\boxed{\Delta_{m_e} = \Delta_{\omega_b} = \Delta_{\omega_c}}$$

Changes H_0 because it changes epoch of recombination

$$\Delta_{a_*} = -\Delta_{m_e}$$

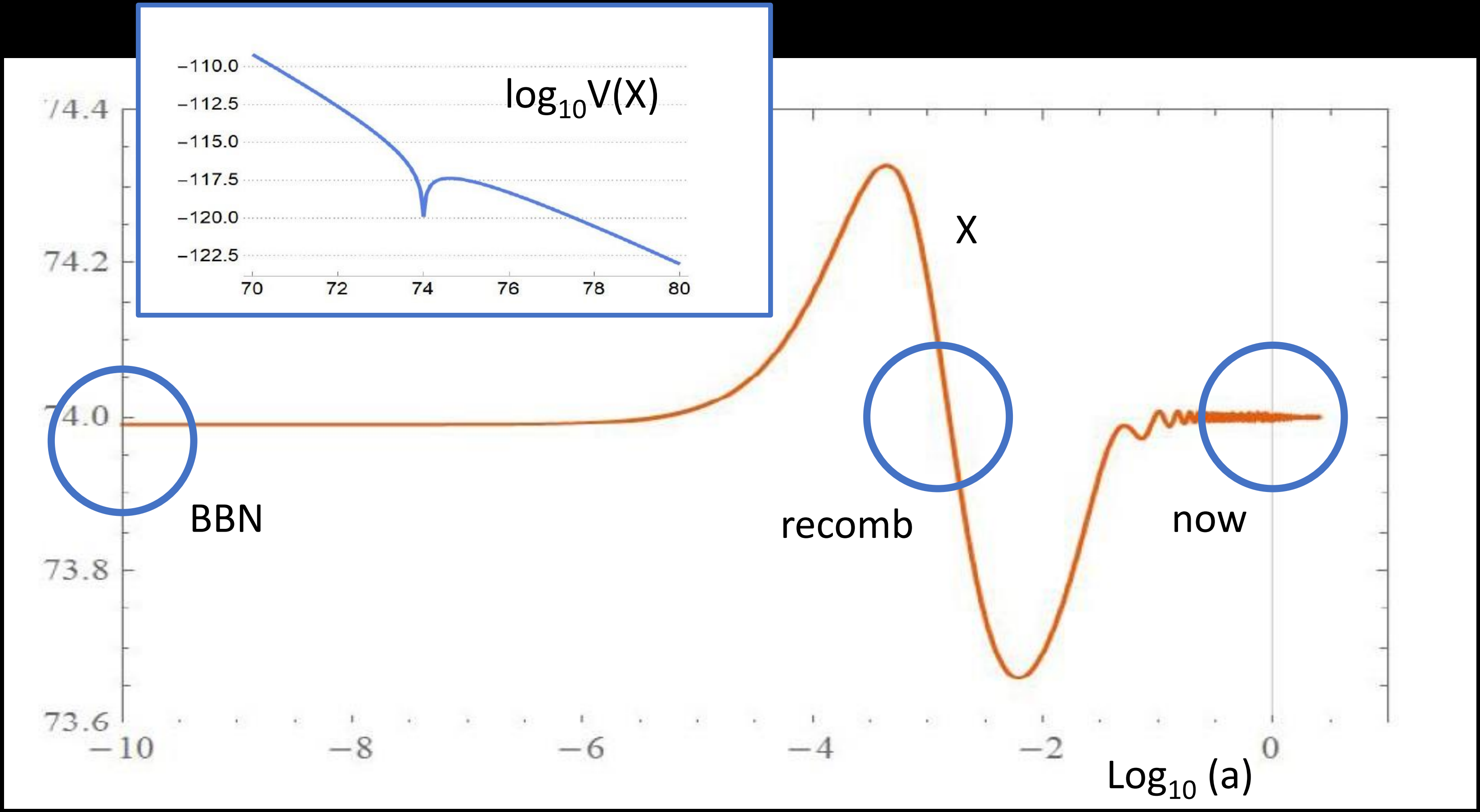
Leaves BAO unchanged if small spatial curvature

$$\Delta_h = 1.5\Delta_{m_e} \qquad \omega_k = -0.125\Delta_{m_e}$$

Requires 10% reduction in τ ; equal abundance-shifts automatic

Axiodilaton cosmology

Dilaton evolution constrained because it changes particle masses relative to the Planck mass, leaving mass ratios unchanged



Relevance to inflation

Practical consequences for inflationary models

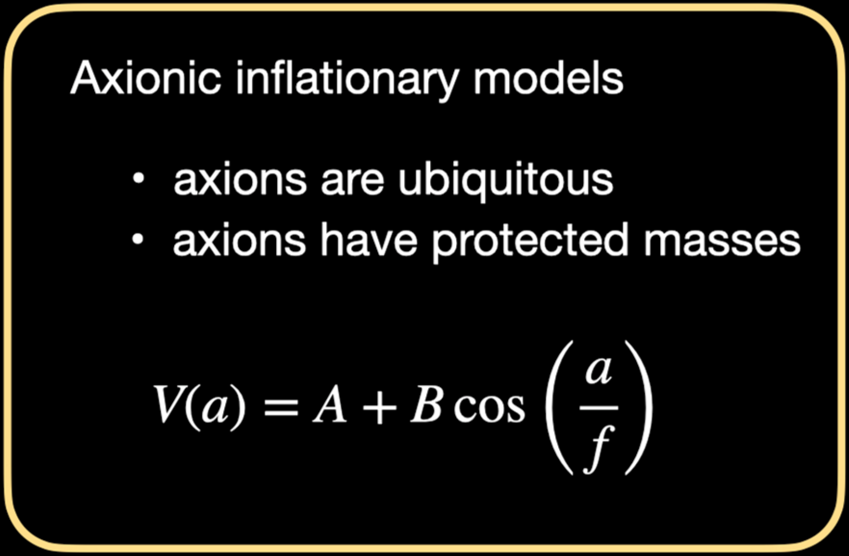
Two kinds of low-energy pseudo-Goldstone bosons with which to build technically natural inflationary string potentials, one class of which arises due to approximate scale invariances

Axions

Dilatons

Practical consequences for inflationary models

Axions Dilatons



Axionic inflationary models

- axions are ubiquitous
- axions have protected masses

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

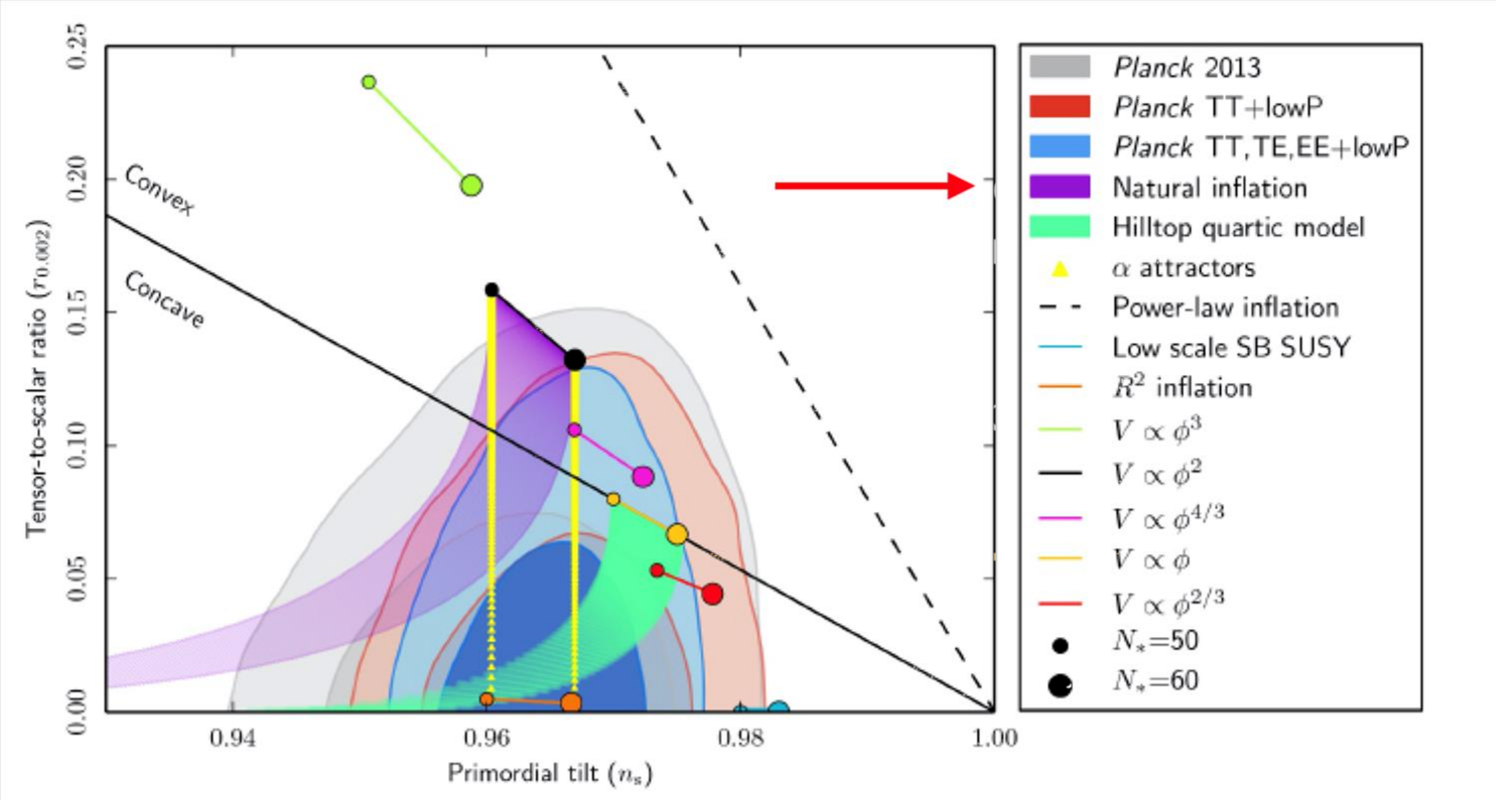
Freese et.al. 90; Kachru et.al. 03;
Silverstein & Westphal 08 and more

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

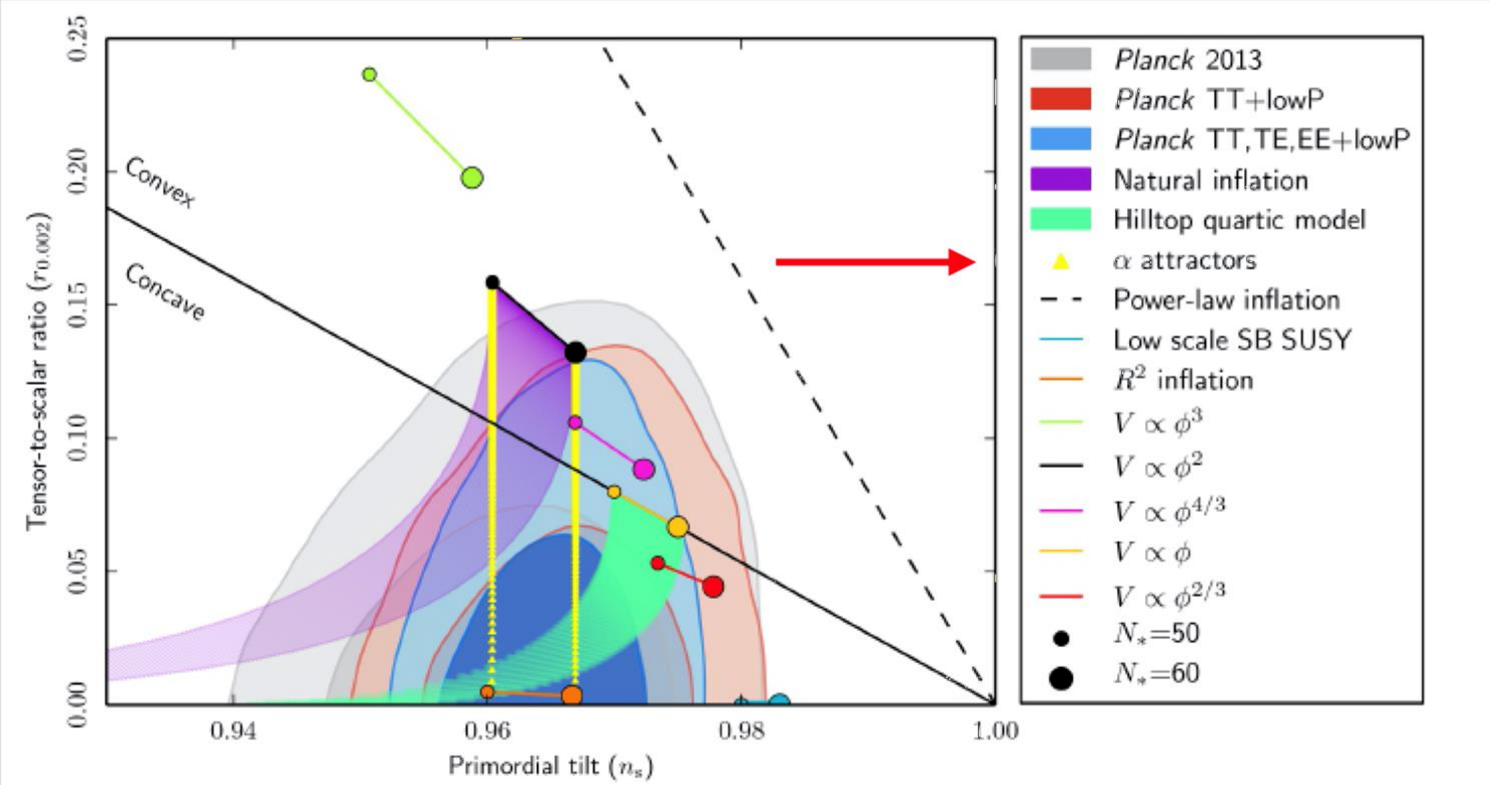
need $f \simeq M_p$

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