Two Symmetries & a Mechanism: UV Info at Low Energies

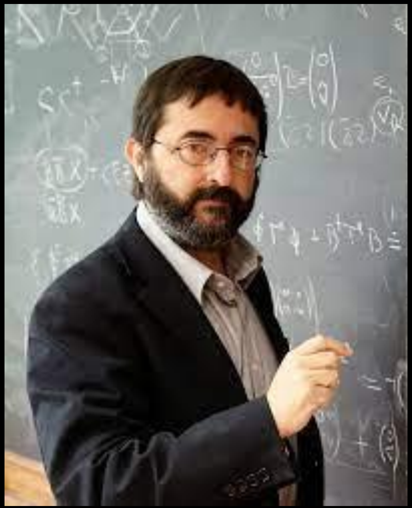
(*the Highland Program*)

Relaxation, Scaling and Supersymmetry

CERN Aug 31, 2023

CPB @ McMaster University PI Perimeter Institute for Theoretical Physics

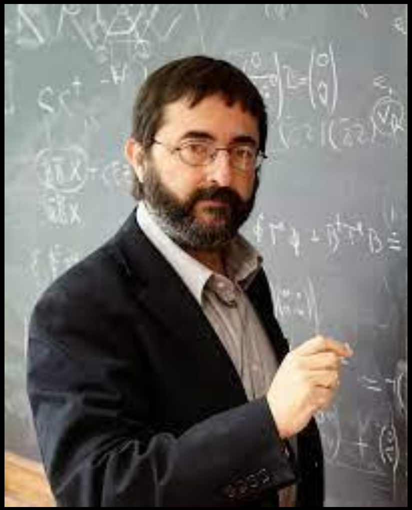
D. Dineen



F. Quevedo

2111.07286 *Yoga DE*

2202.05344 *dS & inflation*

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S. Krippendorf M. Cicoli

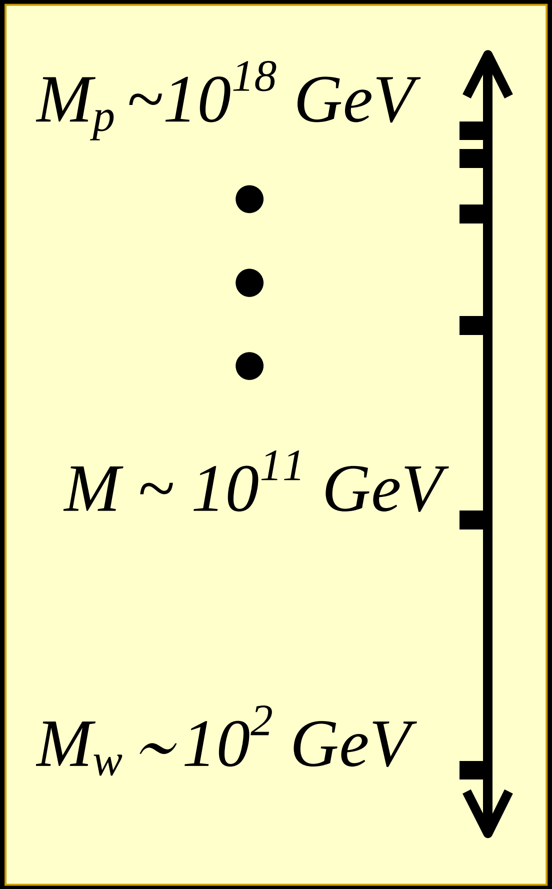
M. Ciupke

Builds on earlier work on ubiquity of accidental scale invariance and supersymmetry in EFTs for string vacua

2006.06694

Life at Low Energies



Nature comes to us with many scales

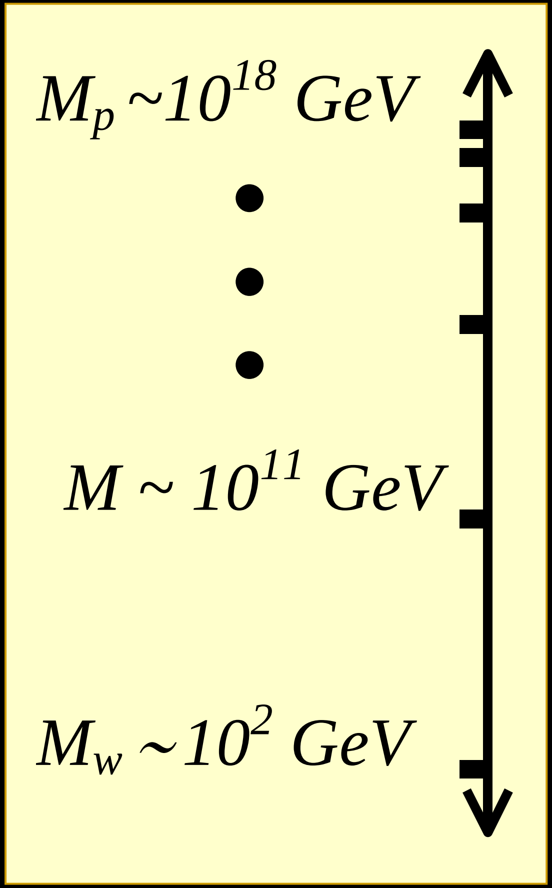
EFTs show why most low-energy predictions are robust and some are UV sensitive

eg for QCD

UV sensitive: value of proton mass

UV insensitive: soft pion theorems

Life at Low Energies



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UV insensitive: soft pion theorems

Swampland hypothesis

Difficulty finding dS is UV informative

Swampland Program

Vafa 05

Swampland Hypothesis:

Many EFTs (eg those with dS solutions) have no UV completion (making it useful to identify which ones are which)

Some things indeed seem rare:

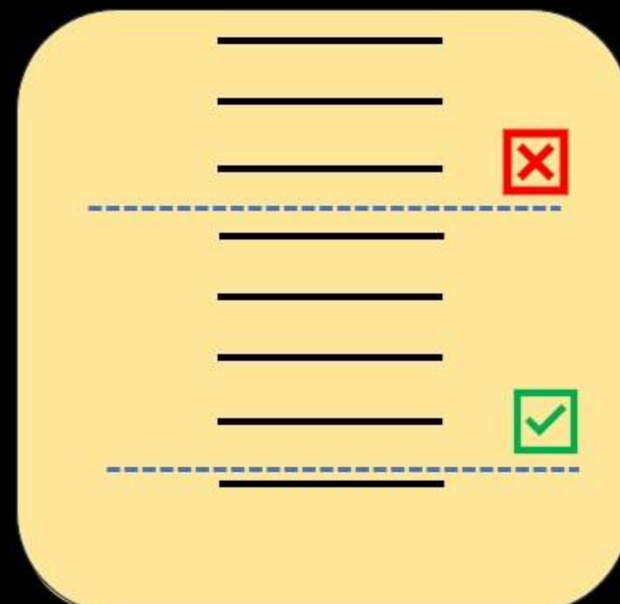
- Global symmetries
- Non-supersymmetric control
- Standard Model & no extras
- de Sitter solutions (possibly)

Swamplementarity:

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

Stringy `non-EFT' surprises

Most seem examples of EFTs never being valid descriptions of physics part way up a tower



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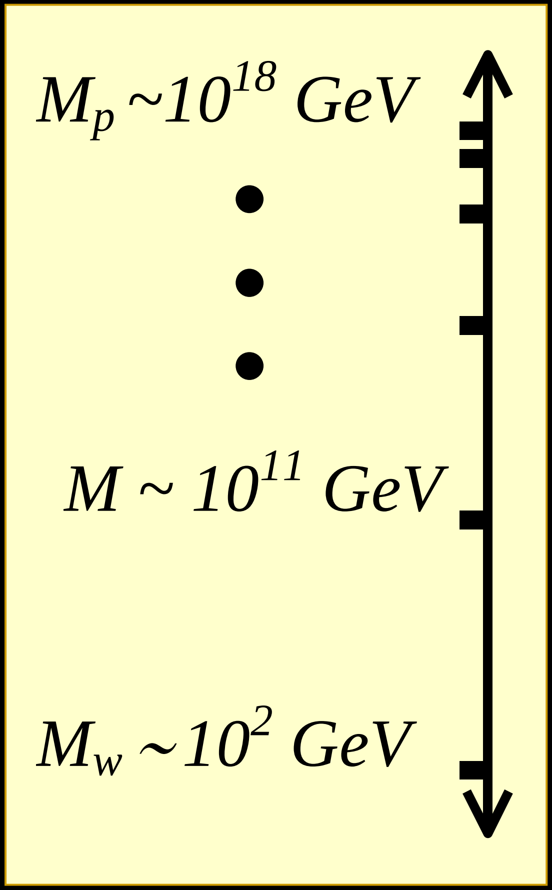
Life at Low Energies



Nature comes to us with many scales

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UV sensitive: value of proton mass

UV insensitive: soft pion theorems

Swampland hypothesis

Difficulty finding dS is UV informative

Will instead use symmetries to extract robust *low-energy implications of strings*

Key generic approximate symmetries

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

Key generic approximate symmetries

Supersymmetry (especially of the gravity sector)

Rigid scaling symmetries

MECHANISM FOR SUPPRESSING V:

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

Outline

UV Motivations

Two symmetries and a mechanism

Low-energy EFT

RG modulus stabilization

de Sitter vacua

Yoga exercises: adding relaxation

Features

Challenges

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$$V_{\rm min} \sim 10^{-91} M_p^4$$

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$$V_{\rm min} \sim 10^{-91} M_p^4$$

$$\boxed{m_e = m_e(t)}$$

(Hubble Tension)

Challenges

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

(tests of gravity)

UV Motivations

Two symmetries and a mechanism

Scaling Symmetries

String vacua (and therefore also essentially all extra-dimensional supergravities) share a class of accidental approximate scaling symmetries

$$g_{\mu\nu} \to \lambda^r \, g_{\mu\nu} \qquad \Phi \to \lambda^s \, \Phi \qquad \mathscr{L} \to \lambda^p \, \mathscr{L}$$

Witten 85
CPB, Font & Quevedo 85
2006.06694

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

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

$$\Phi \to \lambda^p \Phi \qquad \Psi \to \lambda^q \Psi \qquad \mathscr{L}_{mn} \to \lambda^{mp+nq} \mathscr{L}_{mn}$$

Evidence for Accidental Scaling

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: $\mathscr{L}_B \to \lambda^{4u} \mathscr{L}_B$

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

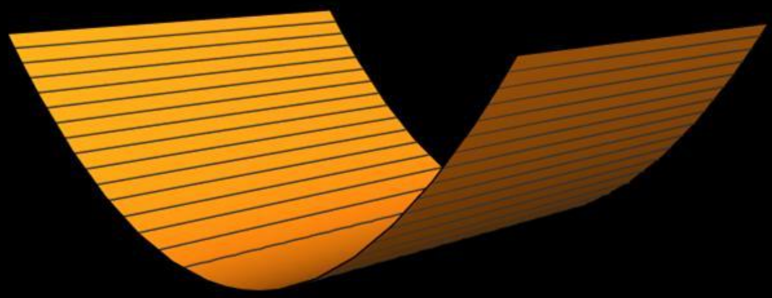
$$C_{MN} \to \lambda^w C_{MN} \qquad \tau \to \lambda^{2(w-u)} \tau$$

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

+ fermion transfns

and so on for Type I and IIA and heterotic vacua corresponding to g_s and α' expansions..

Accidental Scaling can enforce V = 0 at extremum



V = 0 despite scaling symmetry being spontaneously broken!

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

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

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

Corrections to scaling

Not actually a symmetry

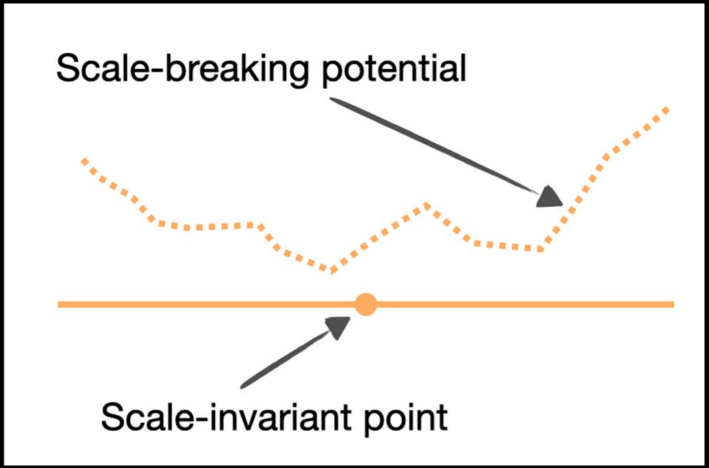
$$\mathscr{L} \to \lambda^w \mathscr{L}$$

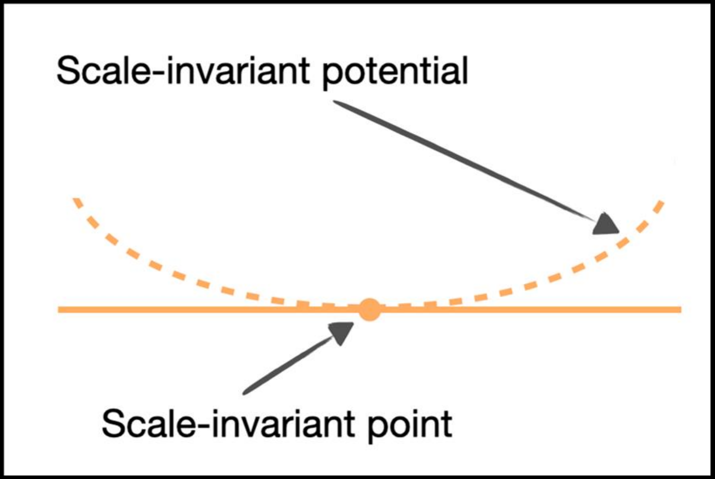
Even if it were a classical symmetry, it is usually anomalous

Peccei et al 87
Wetterich 88

Weinberg No Go: Even if unbroken, scale inv cannot forbid lifting of flat direction

Weinberg 89





Restricting the lifting of flat directions is where supersymmetry might help

2006.06694

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),* $f_{ab}(z)$

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

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

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

$$D_i W = W_i + K_i W$$

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

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

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

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Scaling and 4D Supersymmetry

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

if $W_i = 0$ then

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

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

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'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

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

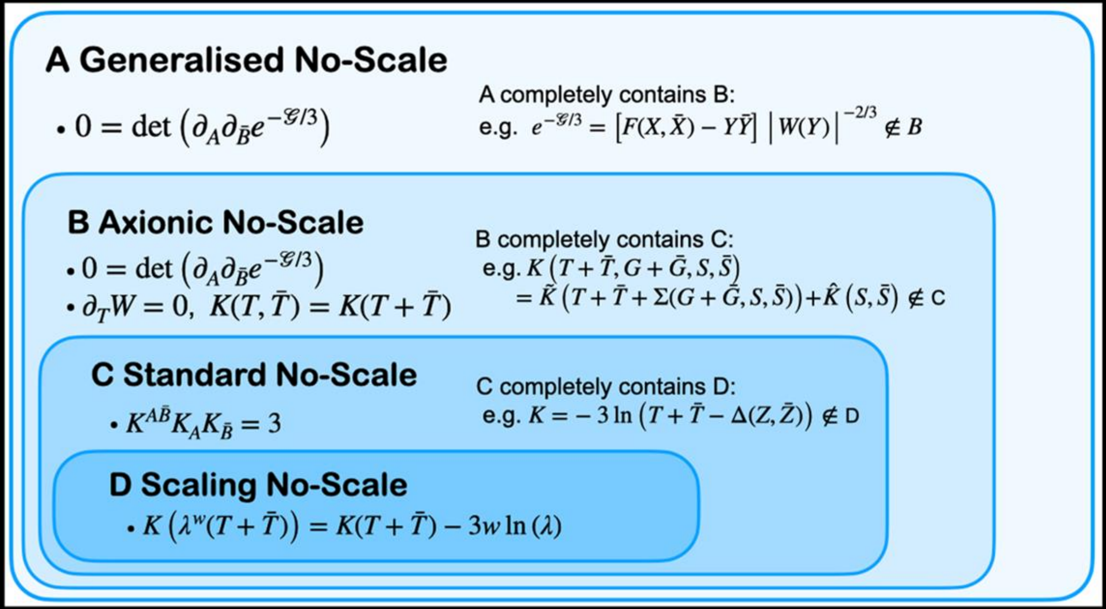
$$D_i W = W_i + K_i W = K_i W \neq 0$$

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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A mechanism

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

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

scale invariant & no-scale

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

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Not scale invariant but still no-scale

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

though are eventually lifted

neither

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

Extended No-Scale Structure

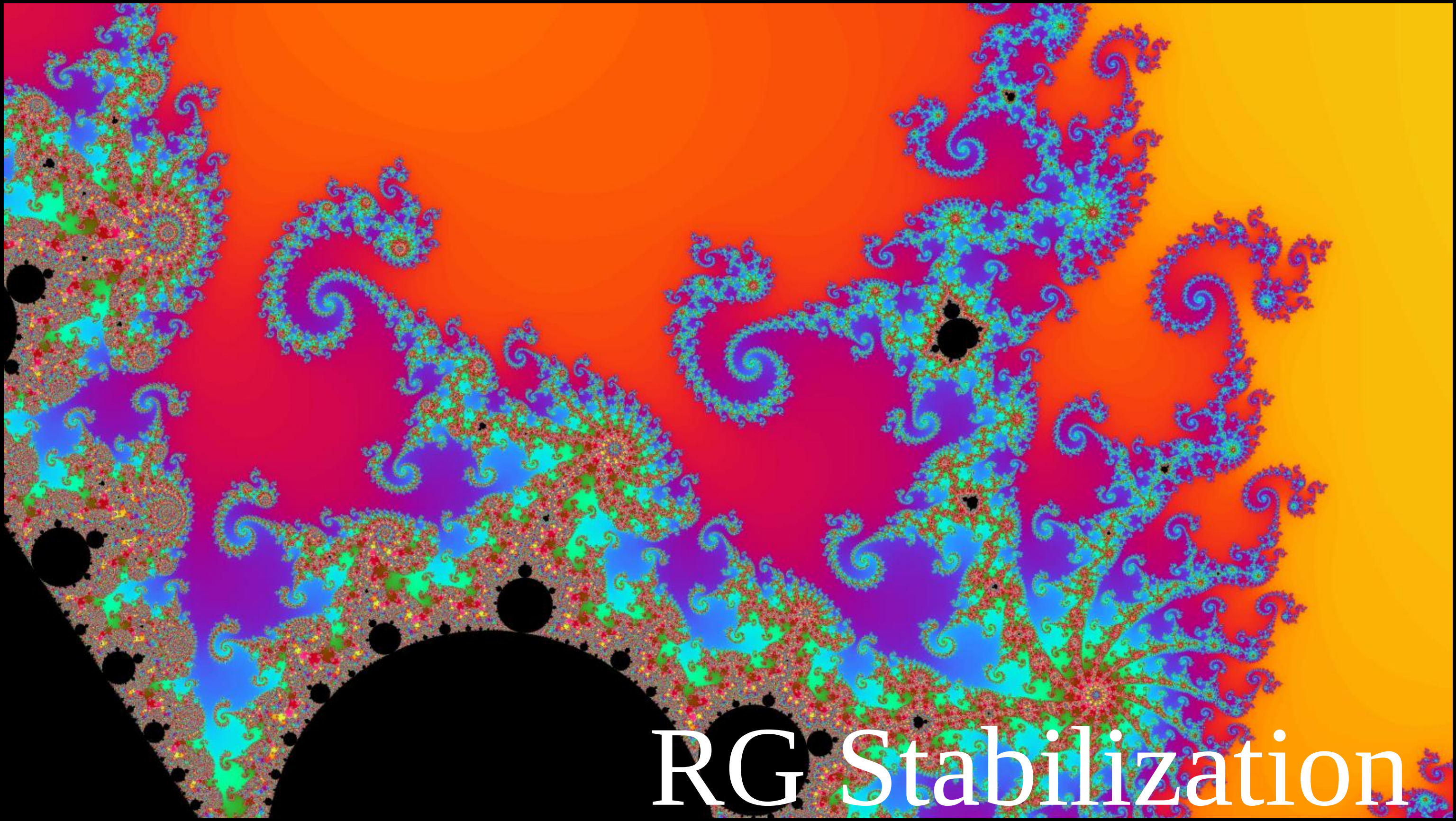
This actually happens in some string compactifications

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

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

corresponding to an α'^2 string loop correction

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



RG Stabilization

Exponentially large dimensions

de Sitter vacua

Toy Model

Supersymmetry and accidental scale invariance:

There is a dilaton supermultiplet: $T = \{\tau + i\, a\, ,\ \xi\}$

Action arises as expansion in dilaton field $\tau = T + T^*$

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2202.05344

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Axion symmetry ensures W independent of *T*

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Weyl scaling makes particle masses depend on τ in EF:

$$m = \tilde{m}\, e^{K/6} = \frac{\tilde{m}}{\sqrt{\mathcal{P}}} \sim \frac{\tilde{m}}{\sqrt{\tau}} + \cdots$$

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$$k = k(Y, \overline{Y}) \qquad h = h(Y, \overline{Y}) \qquad W = w_0 + w(Y)$$

k, h 'independent' of τ though loops can give *k* and *h* dependence on $\ln(m_1/m_2) \sim \ln \mathcal{P}$

Toy Model

Scalar potential for τ

$$V = -\frac{3k_{T\overline{T}}}{\mathcal{P}^2}\left[1 + \mathcal{O}(\mathcal{P}^{-1})\right] \simeq \frac{3(k' - k'')}{\mathcal{P}^4}$$

where primes denote differentiation with respect to $\ln \mathcal{P}$

RG Stabilization

log τ dependence can stabilize the dilaton.

$$V \simeq \frac{U[\log \tau]}{\tau^4}$$

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eg suppose log τ dependence arises due to loop effects:

$$k \simeq k_0 + k_1 \alpha(\tau) + k_2 \alpha^2(\tau) + \cdots$$

with $$\frac{1}{\alpha(\tau)} = \frac{1}{\alpha_0} + \hat{b} \log\left(\frac{m_1}{m_2}\right) = \frac{1}{\alpha_0} + b \log \tau$$

This implies $$U \simeq U_0 \alpha^2 + U_1 \alpha^3 + U_2 \alpha^4 + \cdots$$

RG Stabilization

Generates minima at exponentially large values for τ

$$U(\ln \tau) \simeq U_0 \alpha^2 + U_1 \alpha^3 + U_2 \alpha^4 + \cdots$$

eg if $\frac{U_0}{U_1} \sim \frac{U_1}{U_2} \sim O(\epsilon)$

can have U minimized at $\alpha(\tau) \sim \epsilon$ and so $\log \tau \sim \frac{1}{\epsilon}$

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can have U minimized at $\alpha(\tau) \sim \epsilon$ and so $\log \tau \sim \frac{1}{\epsilon}$

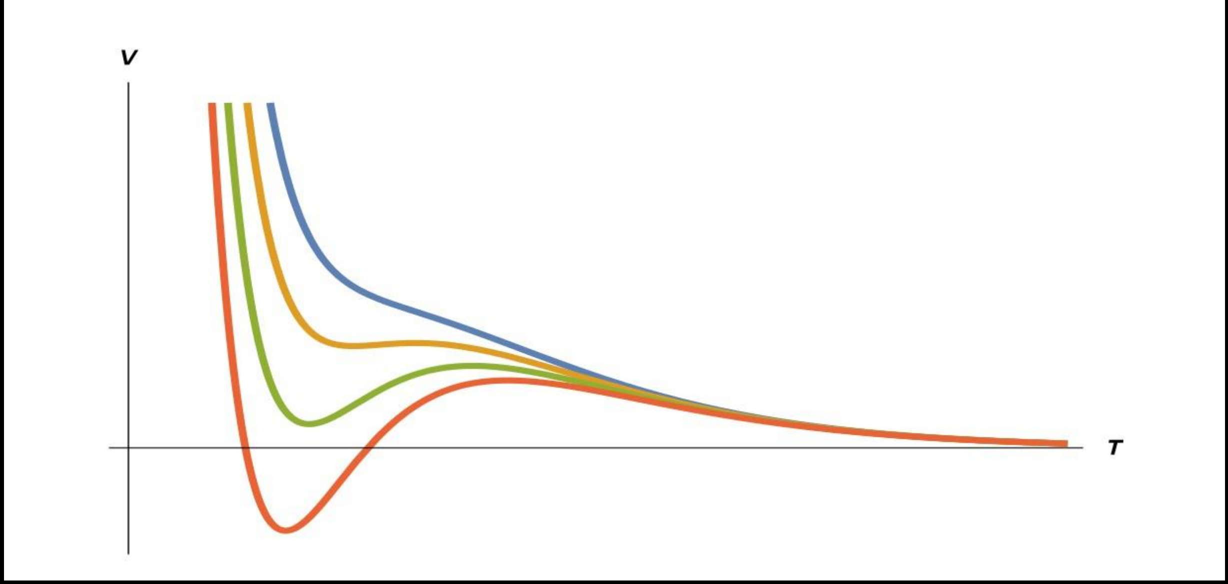
Notice RG ensures can still trust $\frac{1}{\alpha(\tau)} = \frac{1}{\alpha_0} + b \log \tau$

Potential at minimum: $U \sim \epsilon^5$

RG Stabilization

Minimum can be dS or AdS depending on coefficients U_i

$$U(\ln\tau) \simeq U_0\alpha^2 + U_1\alpha^3 + U_2\alpha^4 + \cdots$$



RG Stabilization

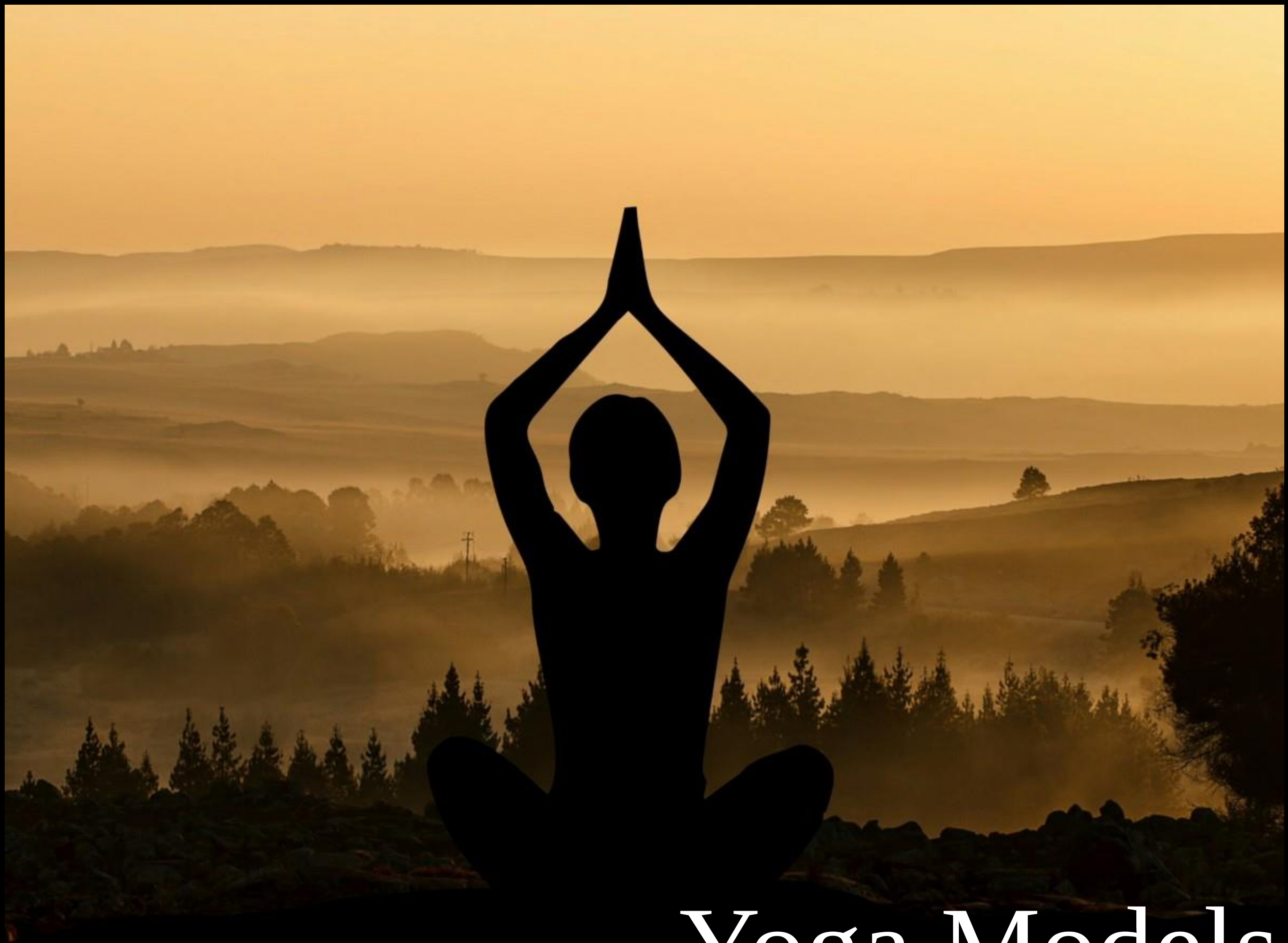
Two reasons why dS not disfavoured relative to AdS:

1. Perturbing around scale invariance starts one ‘near’ V = 0

2. Supersymmetry always broken at minimum because

$$D_T W = K_T w_0 = -\frac{3w_0}{\mathcal{P}} \neq 0$$

Preference for AdS lost because W(T) is not used to stabilize potential and so not drawn to supersymmetric minima



Yoga Models

SM fields and natural relaxation

Supergravity Coupled to nonSUSY matter

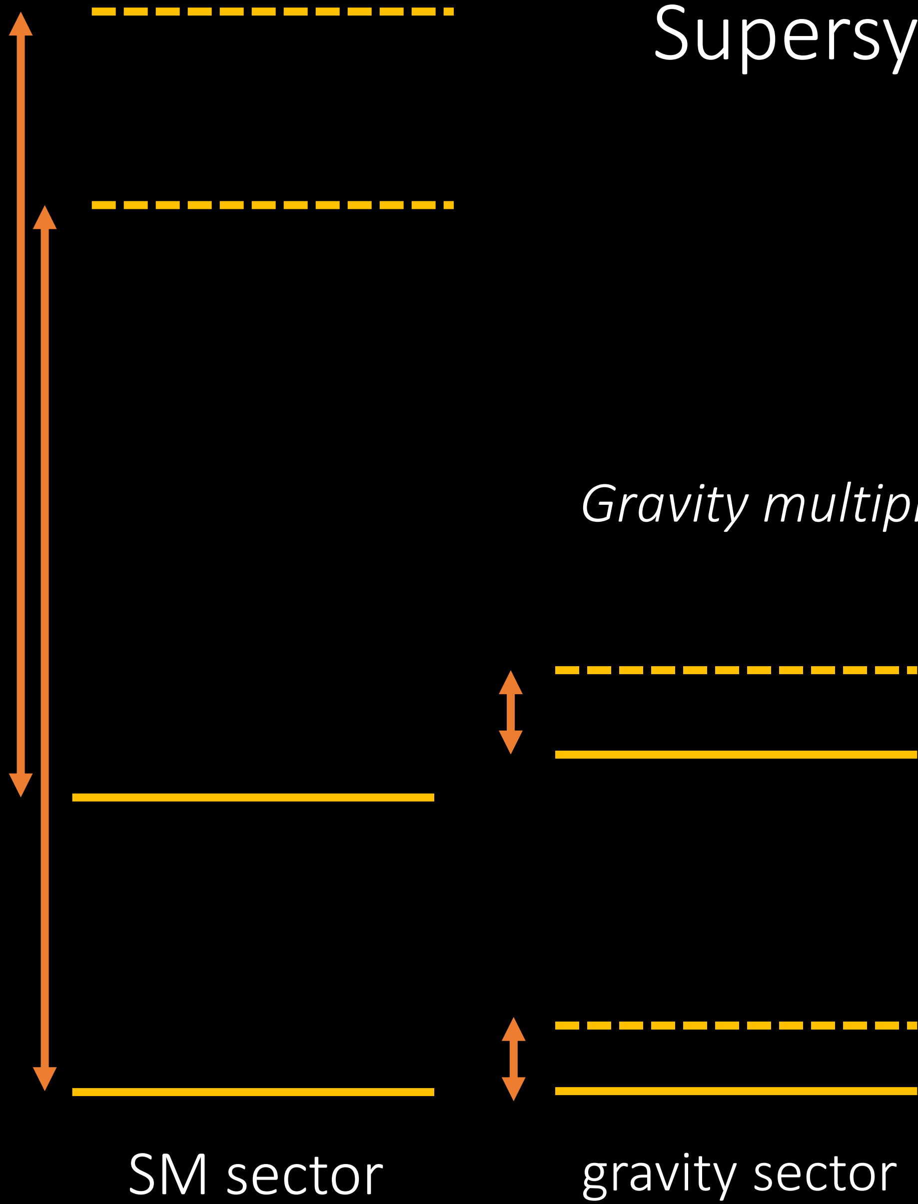
How to couple this to SM fields?

How can supersymmetry play a role at low energies when we know the Standard Model is not supersymmetric?

Supersymmetric Gravity Sector

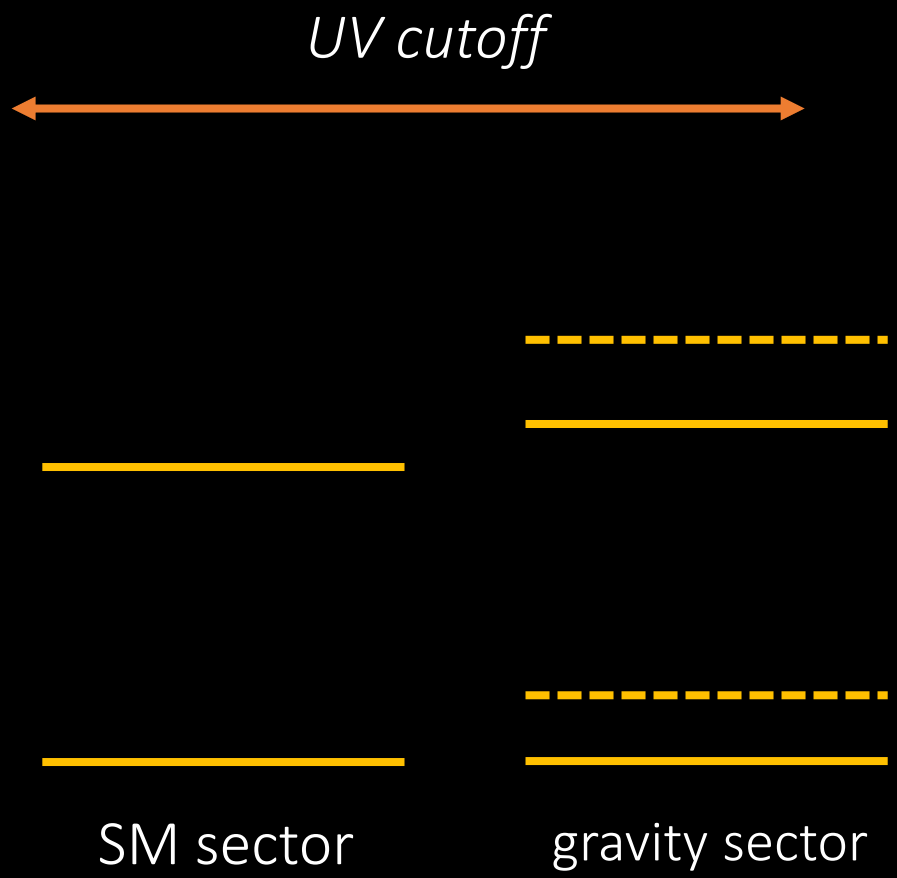
$$\Delta m^2 = m_B^2 - m_F^2 \sim gF$$

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

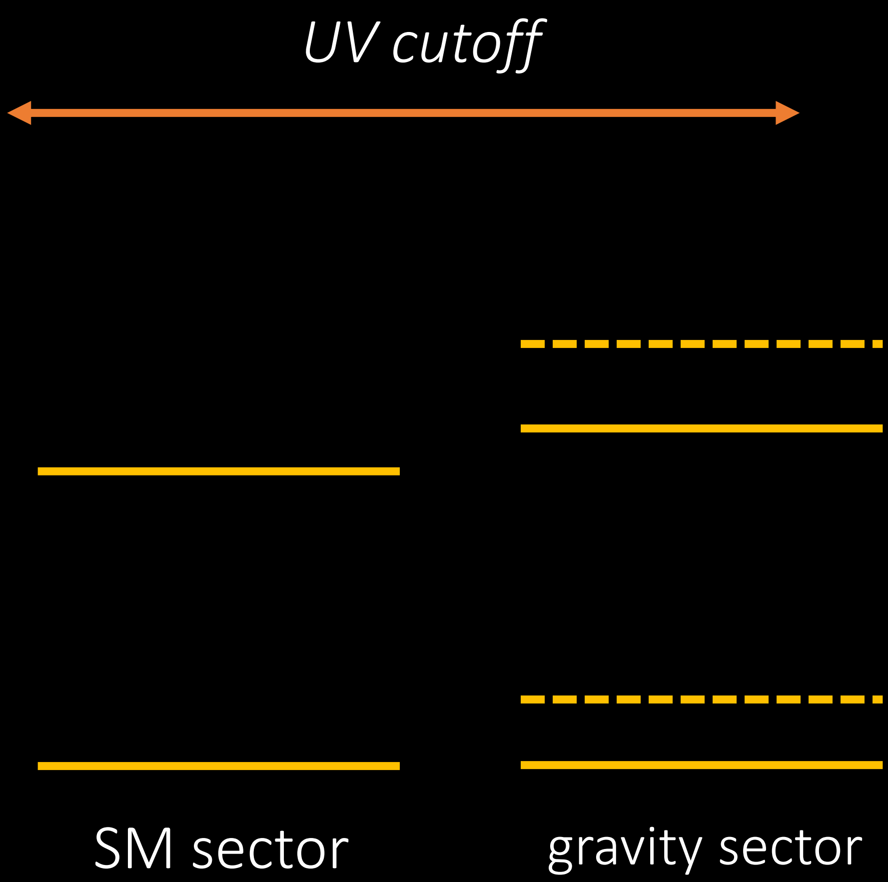


Supersymmetric Gravity Sector

General coupling of supergravity to nonsupersymmetric matter is known



Supersymmetric Gravity Sector



$$X = \frac{G^2}{F} + \Theta G + \Theta^2 F$$

$$X^2 = 0$$ (goldstino)

and similar constraints for other nonSUSY fields

eg $XY = 0$ (SM fermion)

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

Supersymmetric 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)

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

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

Auxiliary fields actually start life as topological fields in higher dimensions

Bielleman, Ibanez & Valenzuela 15
1509.04209

Yoga Models

Coupling to SM fields

There is a dilaton supermultiplet: $T = \{\tau + i\, a\,,\ \xi\}$

Action arises as expansion in dilaton field $\tau = T + T^*$

Goldstino X and other fields Y enter in nonsupersymmetric way

$$\mathcal{P} := e^{-K/3} = \tau - k + \frac{h}{\tau} + \cdots$$

$$k = k_0(Y,\overline{Y}) + \boxed{[k_X(Y,\overline{Y})X + \text{h.c.}] + \overline{X}X\ \text{term}}$$

$$W = w_0(Y) + \boxed{w_X(Y,\overline{Y})X}$$

NEW

2111.07286

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$$W = w_0(Y) + w_X(Y, \overline{Y})X$$

$$F^X = e^{K/2} K^{X\overline{B}}(w_{\overline{B}} + K_{\overline{B}} w_0)$$

Must keep this large to use nonlinearly realized susy

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$$k = k_0(Y, \overline{Y}) + [k_X(Y, \overline{Y})X + \cdots$$

As opposed to just this

$$W = w_0(Y) + w_X(Y, \overline{Y})X$$

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Yoga Overview

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

Leading part of the matter/dark interactions has the form:

axio-dilaton: T = τ + i a

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

Yoga Overview

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

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

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This can work if: $\tau \sim 10^{28}$

BUT:

- Can potential generate this large a vev?
- Where would such a large number come from in the UV?

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This can work if: $\tau \sim 10^{28}$

BUT:

- Can potential generate this large a vev?
- Where would such a large number come from in the UV?
- Axion decay constant is also very small: $f_a = M_p/\tau \sim m_\nu$

Aside on UV completions

Possible UV completion exists at eV energies (2 large extra dimensions):

- SM particles must be localized on a non-SUSic brane
- SUSY in bulk broken by KK scale (supersymmetric gravity)

(th/0304256)

$$\tilde{g}_{MN}\mathrm{d}x^M\mathrm{d}x^N = \frac{1}{r^2}\, g_{\mu\nu}\mathrm{d}x^\mu\mathrm{d}x^\nu + r^2 g_{mn}\mathrm{d}x^m\mathrm{d}x^n$$

Missing energy constraints require $M_g > 10\ \mathrm{TeV}$

- so for eV sized dimensions volume in natural units is

Hannesteed & Raffelt 02

$$\mathcal{V} = (M_g r)^2 \sim 10^{26}$$

Large value for τ corresponds in UV to size of extra dimensions

Aside on UV completions

Axions in such theories arise as 2-form gauge potentials

- For instance in bulk

$$S = \int \mathrm{d}^6x \,\sqrt{-\tilde{g}}\; e^{-2\phi} H_{LMN}H^{LMN} + \frac{1}{M^2}\int_{M_4} {}^\star H \wedge J$$

$$\widetilde{B}_{MN}\mathrm{d}x^M \mathrm{d}x^N = \frac{b(x)}{r}\,\omega_{mn}\mathrm{d}x^m \mathrm{d}x^n$$

This gives effective 4D description

$$S = \int \mathrm{d}^4x \,\sqrt{-g}\left[\frac{(\partial\tau)^2+(\partial b)^2}{\tau^2} + \frac{1}{F}\partial_\mu b\, J^\mu\right]$$

with $\tau = r^2\, e^\phi$ and $F \sim M^2 r \sim M_p$

Decay constant is M_p because interaction also depends on r

Aside on UV completions

Axions in such theories arise as 2-form gauge potentials

- For instance in bulk

$$S = \int \mathrm{d}^6x \, \sqrt{-\tilde{g}} \, e^{-2\phi} H_{LMN} H^{LMN} + \frac{1}{M^2} \int_{M_4} {}^\star H \wedge J$$

$$\widetilde{B}_{MN} \mathrm{d}x^M \mathrm{d}x^N =$$

This gives effective 4D description

$$S = \int \mathrm{d}^4x \, \sqrt{-g} \, \Big[\frac{(\partial\tau)}{}$$

with $\tau = r^2 \, e^{\phi}$ and $F \sim M \, \tau \sim M_p$

But if instead use

$$\widetilde{B}_{MN} \mathrm{d}x^M \mathrm{d}x^N = b_{\mu\nu}(x) \, \mathrm{d}x^\mu \mathrm{d}x^\nu$$

and $$S_{\text{int}} = \frac{1}{M^2} \int_{M_4} H \wedge J$$

then $$F \sim M_p / \tau$$

Decay constant is M_p because interaction also depends on *r*

Aside on UV completions

Such completions inherit promising features of SLED models

- 4D SM behaviour for particle physics on brane and only gravity sector knows about extra dimensions
- Large SM vacuum energy on branes can curve extra dimensions rather than the 4 dimensions seen by cosmology

Explains why SLED models never quite succeeded: did not stabilize moduli in a way consistent with no-scale structure

Stabilization mechanism (fluxes) broke accidental symmetries

$K = -\ln(STU) \quad W = W(U)$ Fayet Iliopoulos term

Yoga Overview

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

$$m_{sm} \propto \frac{M_p}{\sqrt{\tau}} \quad m_\nu \propto \frac{M_p}{\tau} \quad m_{3/2} \propto \frac{M_p}{\tau}$$

What about the potential for τ *?*

Yoga Overview

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$$m_{sm} \propto \frac{M_p}{\sqrt{\tau}} \quad m_\nu \propto \frac{M_p}{\tau} \quad m_{3/2} \propto \frac{M_p}{\tau}$$

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

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

Yoga Overview

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$\mathcal{O}(m_{sm}^4)$

NOT SMALL BECAUSE OF SUSY BREAKING

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Introduce 'relaxation' field ϕ that seeks minimum of w_x terms

Yoga Overview

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

ASIDE: the field ϕ can play double duty as an inflaton

2202.05304

$$\frac{M_p}{\tau} \qquad m_{3/2} \propto \frac{M_p}{\tau}$$

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

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$$m_{sm} \propto \frac{M_p}{\sqrt{\tau}} \qquad V(\tau) \simeq \frac{M_p^4}{\tau^4} U(\ln\tau)$$

$$\ln\tau_{\rm min} \sim 65 \qquad \tau_{\rm min} \sim 10^{28}$$

Yoga Overview

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$$m_{sm} \propto \frac{M_p}{\sqrt{\tau}} \qquad V(\tau) \simeq \frac{M_p^4}{\tau^4} U(\ln \tau)$$

Suggestive numerology!

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

Yoga Overview

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

$$F \sim \frac{w_0}{\tau^{3/2} M_p} \qquad w_0 \sim M_p^3\, \tau_{\rm min}^{1/2}$$

More honest comparison:

$$V_{\rm min} \sim \frac{\epsilon^5 |w_0|^2}{\tau_{\rm min}^4 M_p^2} \sim \frac{\epsilon^5}{\tau_{\rm min}}\, F^* F$$

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

Yoga Overview

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

Yoga Overview

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Small V_{min} implies small τ mass: below 10^{-80} M_p^4 must worry about long-range forces in the solar system (WIP)

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Interesting axio-dilaton cosmology for DE and H tension

NASA

Yoga Models

Screening and solar system tests

Implications for astrophysics and cosmology

$$\mathcal{L} = -\sqrt{-g}\left\{M_p^2\left[\frac{\mathcal{R}}{2} + \frac{3}{4}\frac{(\partial\tau)^2+(\partial a)^2}{\tau^2}\right] + \frac{U}{\tau^4}\right\} + \mathcal{L}_m$$

Dilaton mass $m_D \simeq \sqrt{V}_{\min}/M_p \sim H_0$

Implications for astrophysics and cosmology

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Dilaton mass $m_D \simeq \sqrt{V}_{\min}/M_p \sim H_0$

Generically true for any Planck coupled scalar if potential energy dominates universe

$\mathcal{L} = M_p^2(\partial\theta)^2 + v^4 f(\theta)$ and $f(\theta) \sim f'(\theta) \sim f''(\theta) \sim 1$

imply $m \sim v^2/M_p$

Implications for astrophysics and cosmology

$$\mathcal{L} = -\sqrt{-g}\left\{M_p^2\left[\frac{\mathcal{R}}{2} + \frac{3}{4}\frac{(\partial\tau)^2+(\partial a)^2}{\tau^2}\right] + \frac{U}{\tau^4}\right\} + \mathcal{L}_m$$

Dilaton mass $m_D \simeq \sqrt{V}_{\text{min}}/M_p \sim H_0$

These become relevant to solar system tests for Compton wavelengths > 1000 km and so

$$V_{\text{min}} < (10\text{ MeV})^4 \sim 10^{-80} M_p^4$$

The Brans-Dicke Problem

When V = 0: dilaton is a Brans-Dicke scalar

$$\tilde{g}_{\mu\nu} = \Omega^2(\tau) g_{\mu\nu} \qquad \Omega(\tau) = \exp\Big(g\chi\Big)$$

$$2g^2 = (3 + 2\omega)^{-1}$$

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$$\tilde{g}_{\mu\nu} = \Omega^2(\tau) g_{\mu\nu} \qquad \Omega(\tau) = \exp\Big(g\chi\Big) = \tau^{-1/2}$$

Brans-Dicke coupling

$$g = -\frac{1}{\sqrt{6}} \simeq -0.41 \qquad 2g^2 = (3 + 2\omega)^{-1} = \frac{1}{3}$$

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$$g = -\frac{1}{\sqrt{6}} \simeq -0.41 \qquad 2g^2 = (3+2\omega)^{-1} = \frac{1}{3}$$

BD scalar is constrained by solar system tests, eg Cassini bound

$$1 - \gamma \simeq 4g^2 < 10^{-5}$$

Bertotti et al 03

Why isn't *g* too large?

The Brans-Dicke Problem

Presence of axion w dilaton interactions changes PPN predictions

$$\mathcal{L} = -\frac{3}{4}\, M_p^2 \sqrt{-g}\, \frac{(\partial\tau)^2 + (\partial a)^2}{\tau^2}$$

$$g = -\frac{1}{\sqrt{6}} \simeq -0.41 \qquad \cancel{1 - \gamma \simeq 4g^2} < 10^{-5}$$

Seek a screening mechanism, in which macroscopic objects couple to dilaton more weakly than does each of their constituents.

Existing screening mechanism (eg chameleon) seem not useful.

Little known about multi-field screening – Open Problem.

Multi-field Screening Mechanisms

Best example so far:

$$\mathcal{L} = -\frac{1}{2} M_p^2 \sqrt{-g} \Big[(\partial\phi)^2 + W^2(\phi)(\partial a)^2 \Big]$$

If axion experiences different minimum inside/outside of matter

Hook & Huang 17

then axion necessarily has gradient near object's surface, whose interaction with the dilaton reduces the object's dilaton charge

$$\phi'(R_+) \simeq \phi'(R_-) + \left(\frac{WW'}{2\ell} \right)_{r=R} (a_+ - a_-)^2$$

(narrow width approximation)

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If axion experiences different mi atter

uang 17

Why aren't required axion-matter couplings ruled out?

then axion necessarily has gradient near object's surface, whose interaction with the dilaton reduces the object's dilaton charge

$$\phi'(R_+) \simeq \phi'(R_-) + \left(\frac{WW'}{2\ell} \right)_{r=R} (a_+ - a_-)^2$$

(narrow width approximation)

Screening

Good news: very general methods exist to generate exterior solutions:

$$\mathcal{L} = -\tfrac{1}{2} M_p^2 \sqrt{-g} \Big[\mathcal{R} + \mathcal{G}_{ab}(\phi)\, \partial_\mu \phi^a \, \partial_\nu \phi^b \Big]$$

Any target-space geodesic

$$\phi^a(\sigma) \qquad \text{with} \qquad \ddot{\phi}^a + \Gamma^a_{bc}(\phi)\, \dot{\phi}^b \, \dot{\phi}^c = 0$$

is an exact solution provided *σ(x)* solves the Klein-Gordon/Einstein equations

$$\mathcal{R}_{\mu\nu} + \tfrac{3}{4}\, \partial_\mu \sigma \, \partial_\nu \sigma = 0 \qquad\qquad \Box \sigma = 0$$

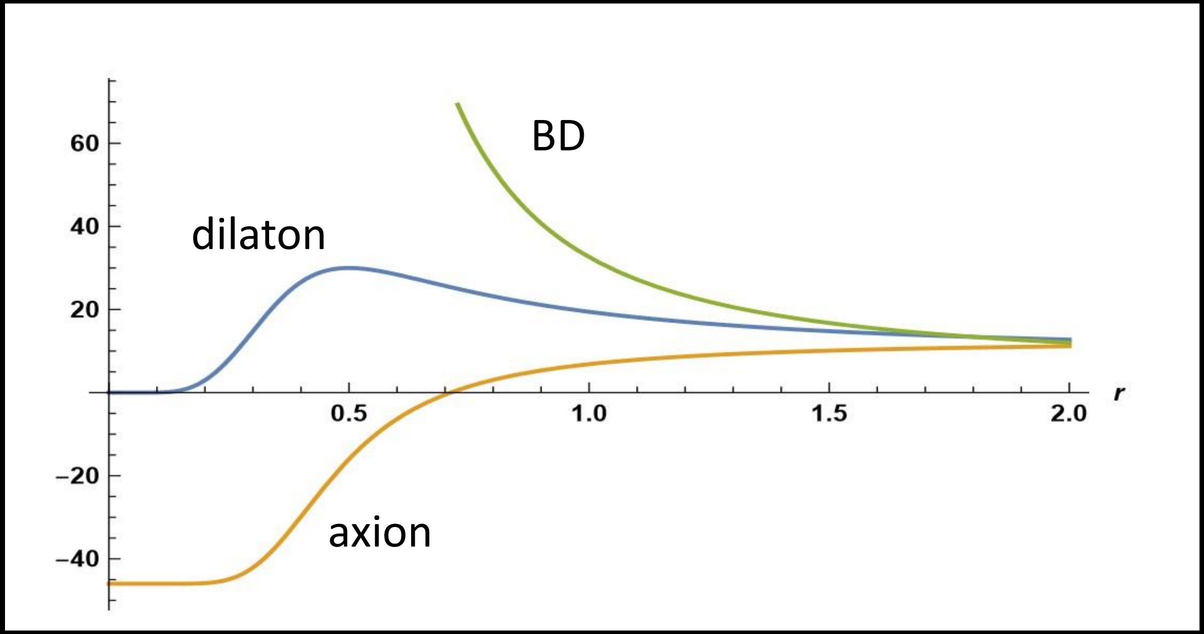
Screening

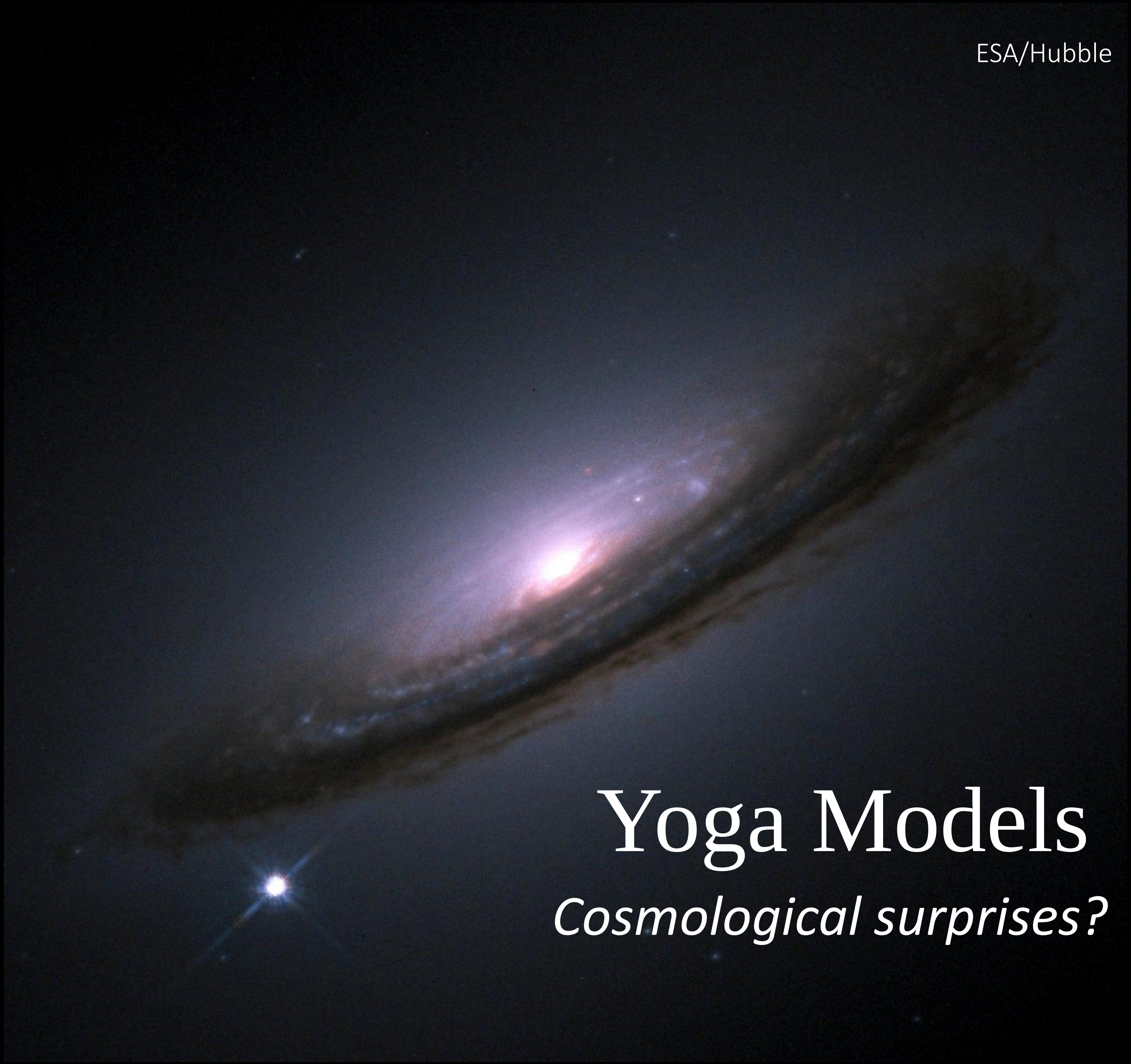
For instance for the Yoga axio-dilaton system:

$$a(r) = A - B\tanh X$$
$$\tau(r) = B\,\mathrm{sech}X$$

$$\tau^2 + (a - A)^2 = B^2$$

$$X(r) = D + (BC/r)$$





ESA/Hubble

Yoga Models

Cosmological surprises?

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

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

5% increase in all masses at recombination helps with H0

Sekiguchi & Takahashi 2007.03381

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

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

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

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Leaves BAO unchanged if small spatial curvature

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

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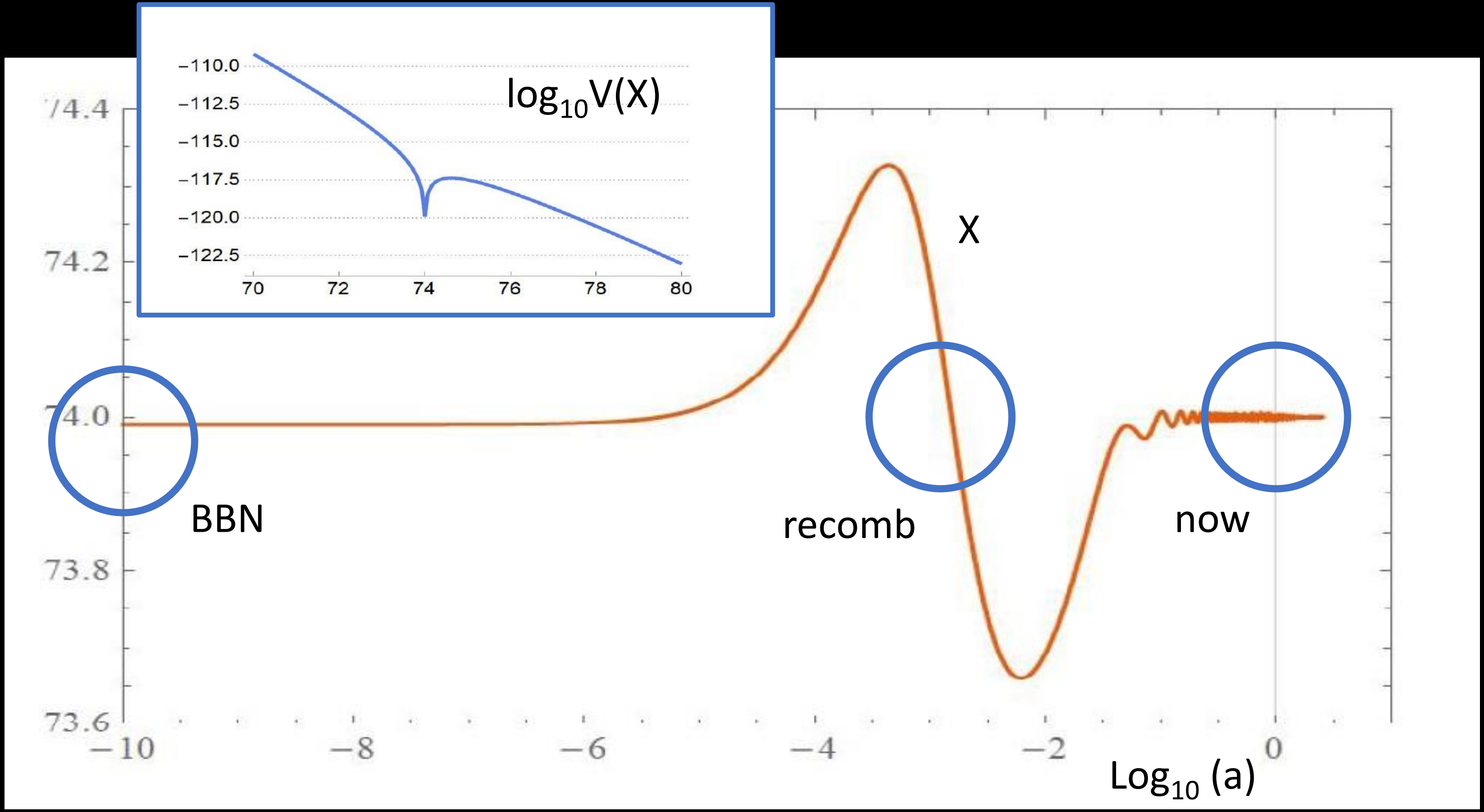
Leaves BAO unchanged if small spatial curvature

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

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



Conclusions

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

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Suppressed DE density; possibly light axio-dilaton; screening mechanisms; dark fermions; and so on

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Much to check and many directions to explore

Framework to trade progress on the cc problem for model-building issues elsewhere

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Thanks for your time & attention!