Electroweak Quintessence Axion

as

Dark Energy

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Based on

arXiv: 1811.04664 [hep-th]

w/ Masahiro Ibe, Tsutomu T. Yanagida

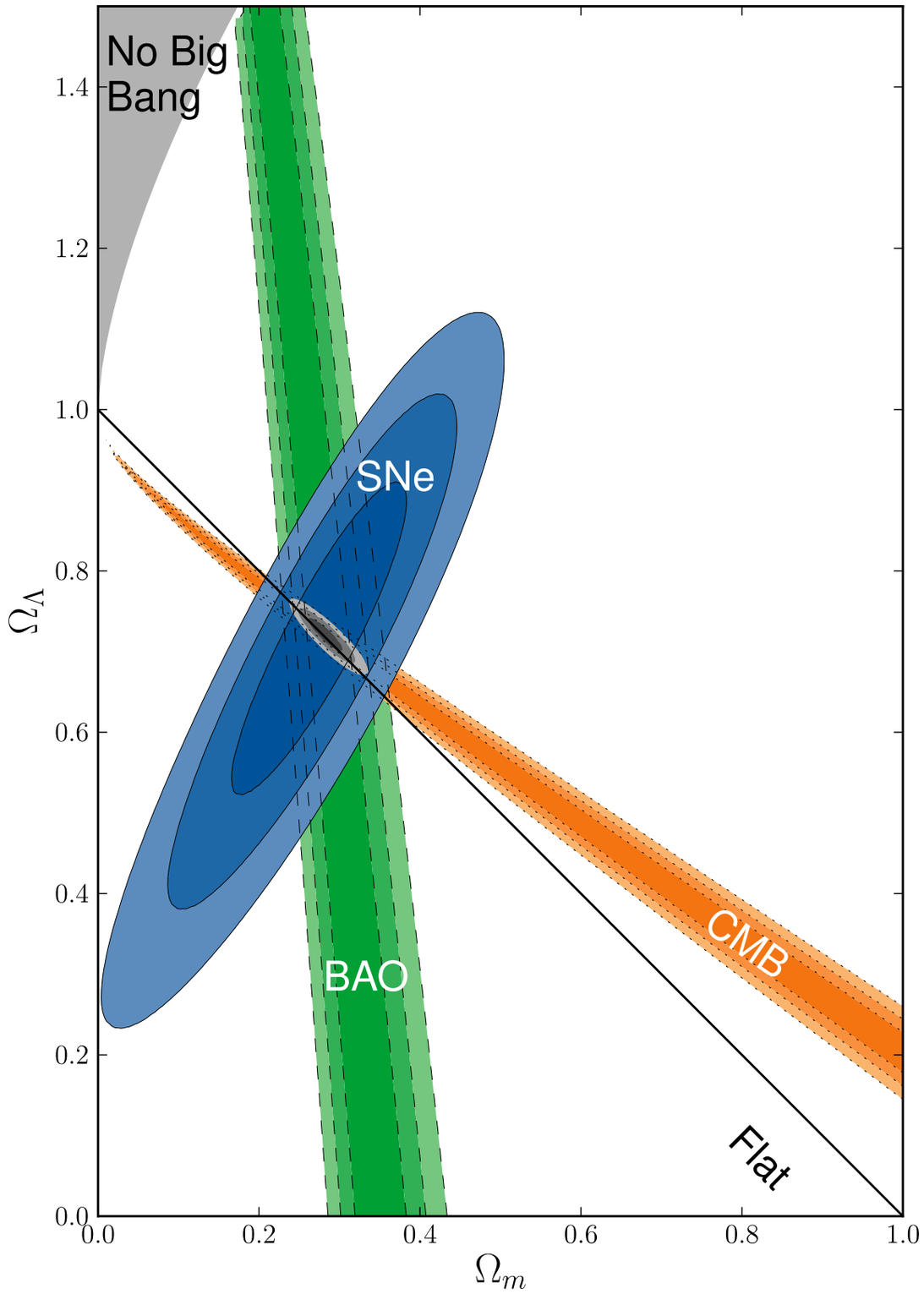
(ICRR Tokyo) (IPMU Tokyo → TD Lee Inst. Shanghai)





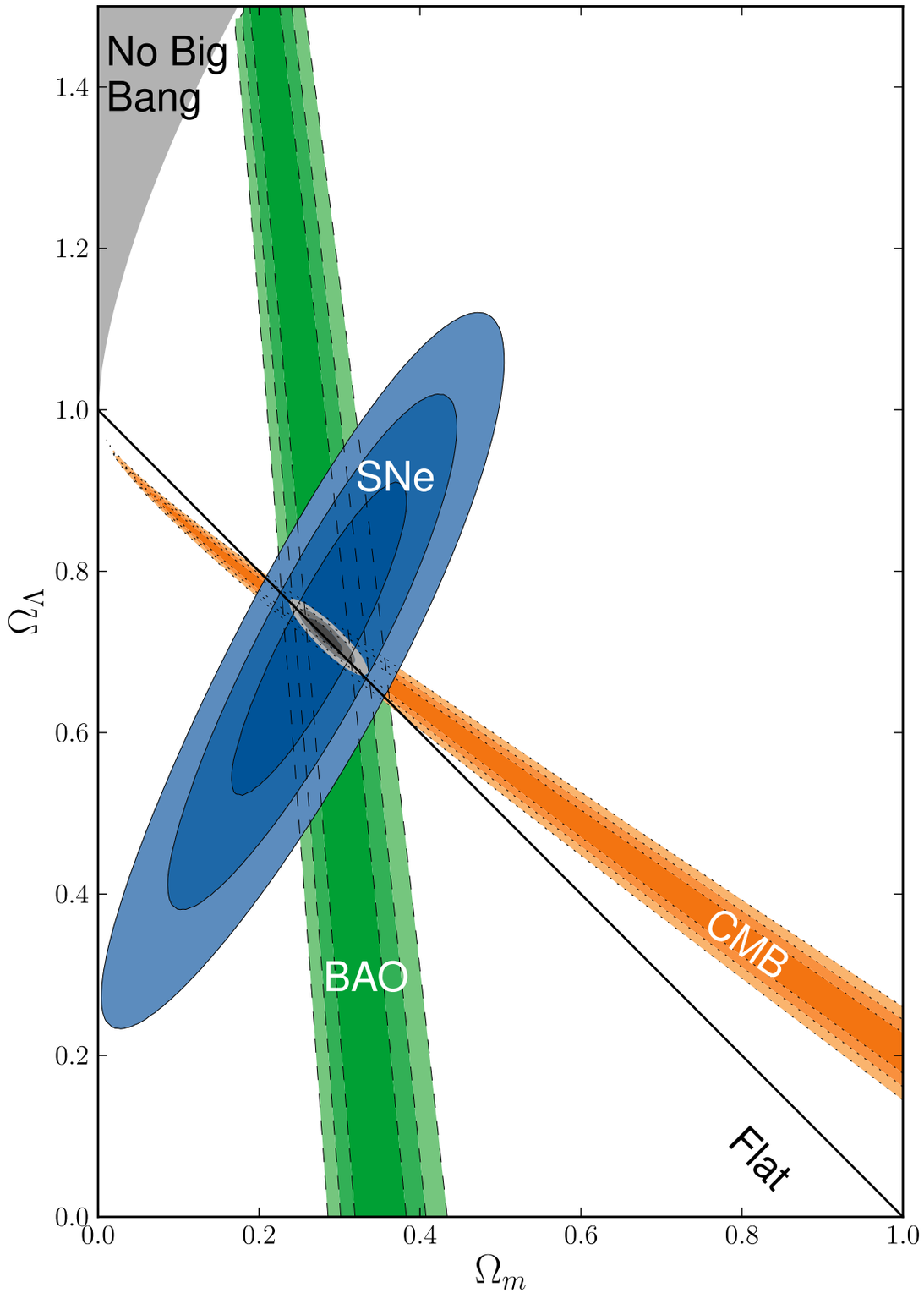
... and many earlier papers

Dark Energy



[Suzuki et al, ('11)]

$\Lambda > 0$!



[Suzuki et al, ('11)]

$\Lambda > 0$!

$\Lambda^4 \simeq O(10^{-120}) M_{pl}^4$

$\ll M_{pl}^4$!!

$$\Lambda^4 \simeq O(10^{-120}) M_{Pl}^4 \ll M_{Pl}^4$$

while dark energy is IR phenomenon

it is partly about UV

quantum gravity

string

low-energy EFT

observation

dark energy

$\Lambda > 0$

QG / string

low-energy EFT

observation

dark energy

$\Lambda > 0$

QG / string

low-energy EFT

observation

EFT theorist

QG not needed!

dark energy

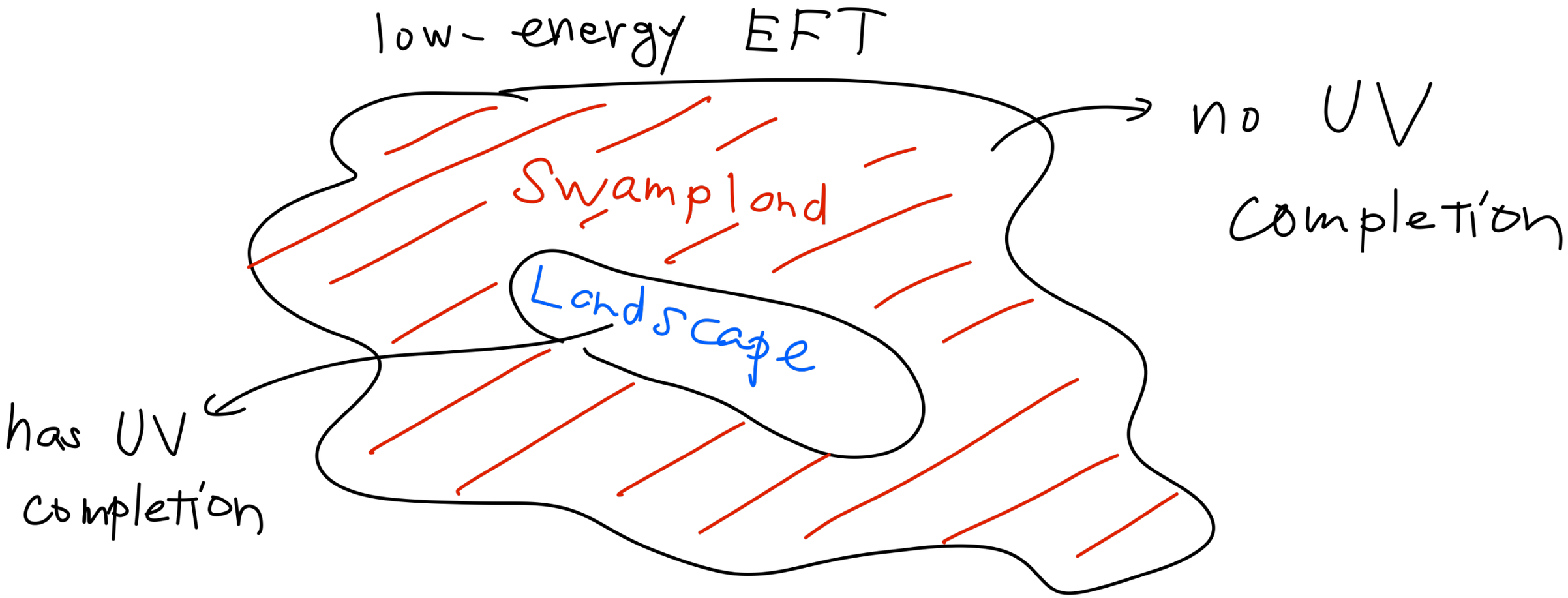
$\Lambda > 0$

QG / string

Swampland Conjectures :

[Vafa ('05), Ooguri – Vafa ('06), ····]

Necessary condition for $\exists$ UV completion in Quantum Gravity



low-energy EFT

observation

EFT theorist

Oh!

dark energy

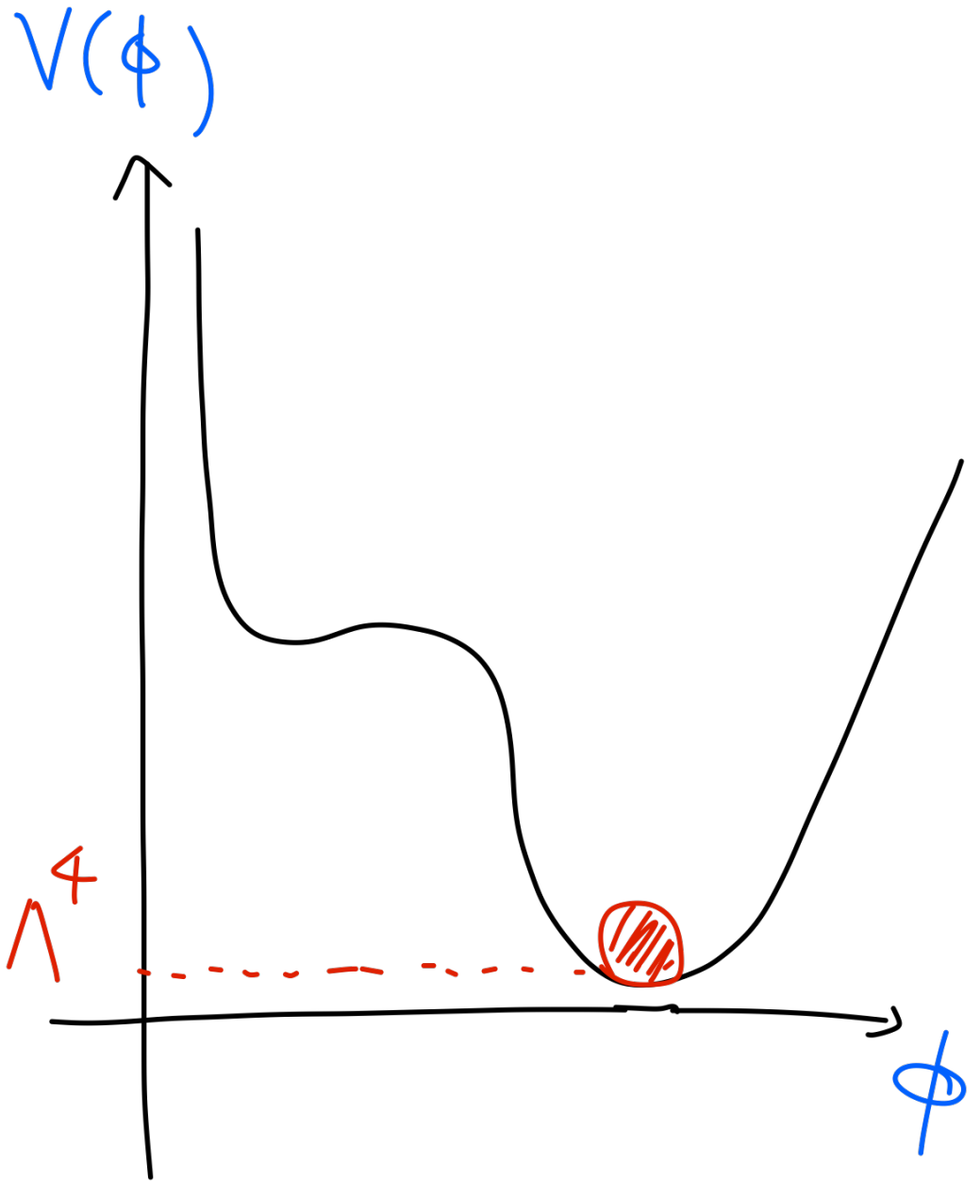
$\Lambda > 0$

Swampland conjectures

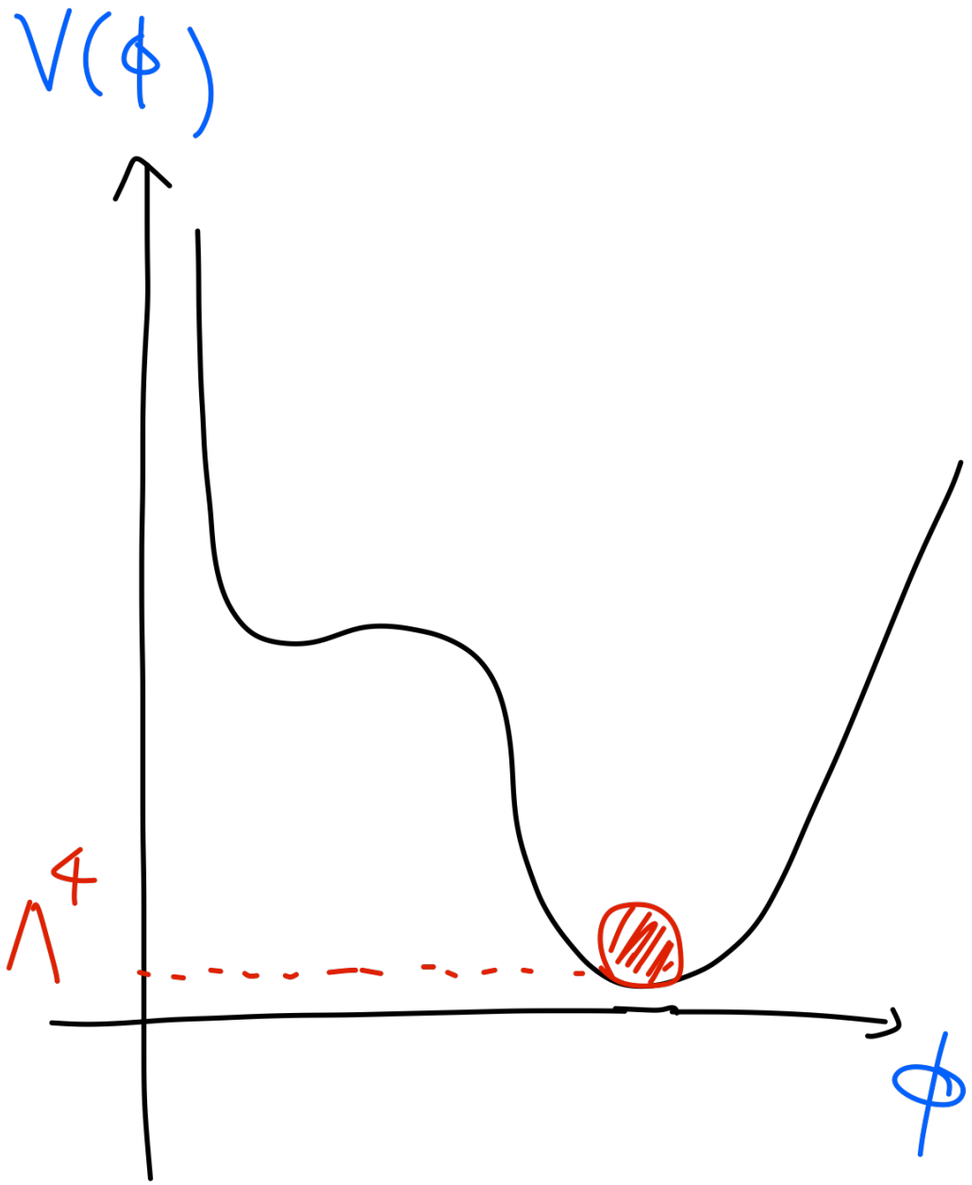
QG / string

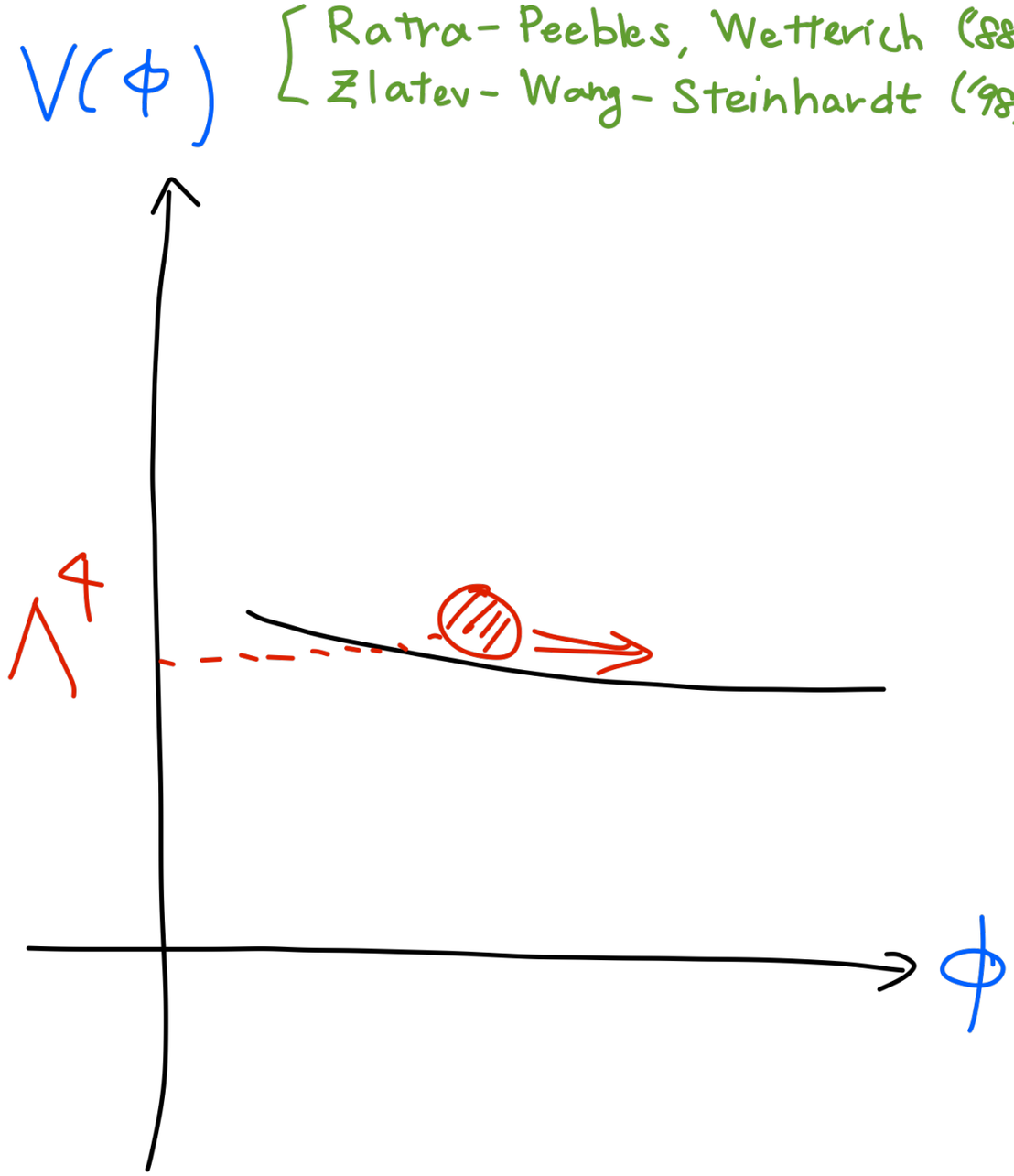
How to Realize  ?

cosmological constant



cosmological constant vs. quintessence



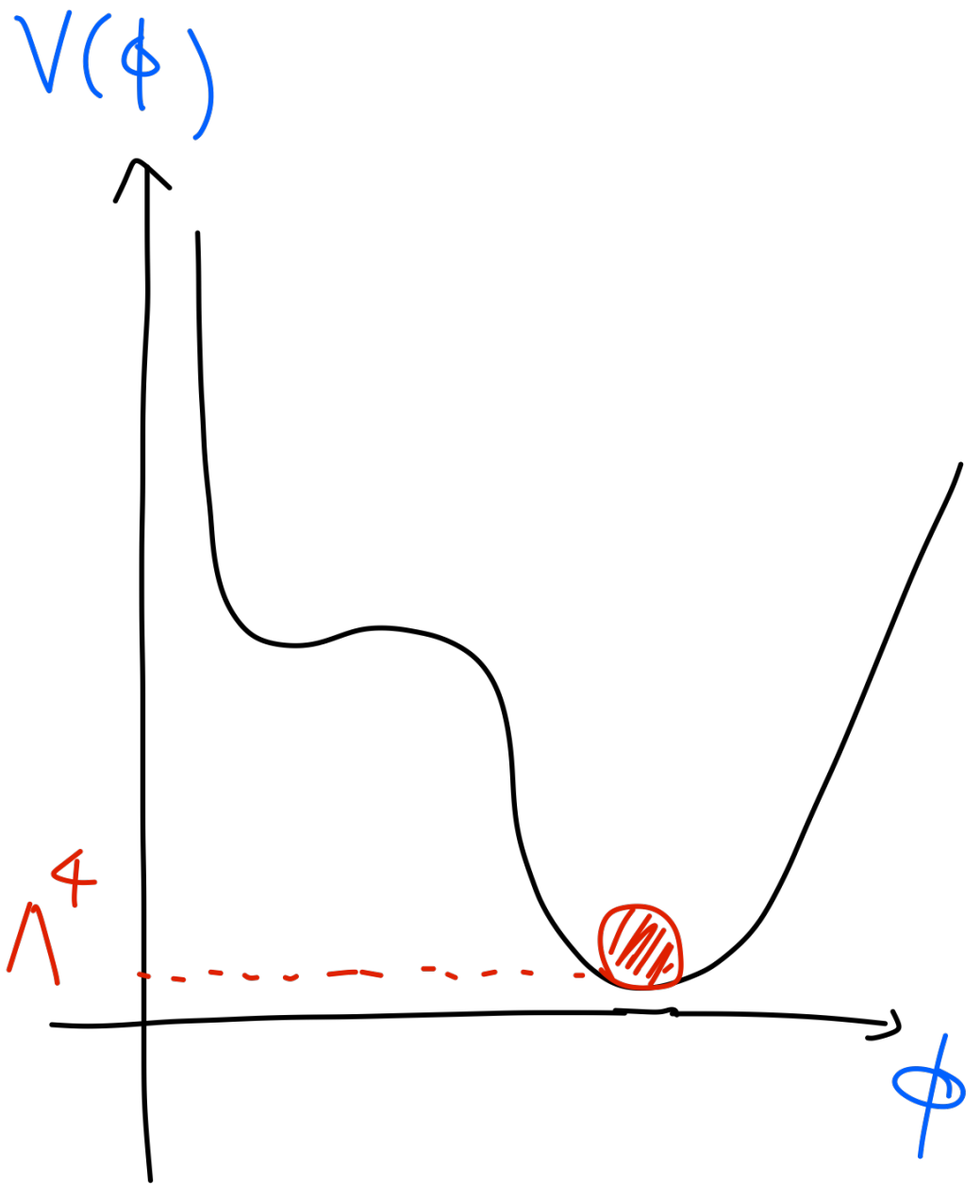


cosmological constant

vs.

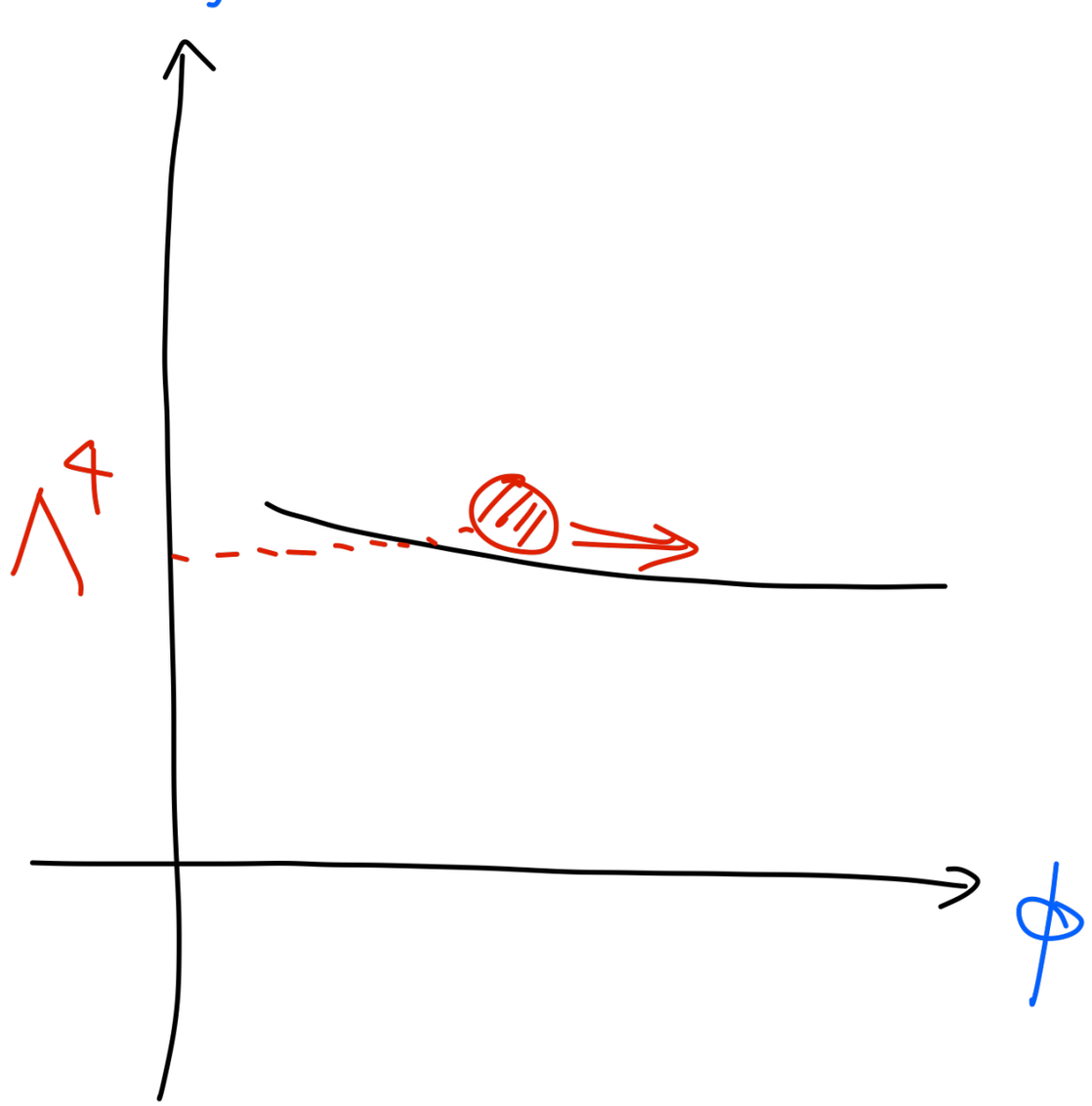
TODAY!!

quintessence



V(ϕ)

[Ratra-Peebles, Wetterich ('88)
Zlatev-Wang-Steinhardt ('98)]



* Very few discussion of quintessence
  in QG/String (... until recently)

* Motivated by
  refined de Sitter swapland conjecture
  [Obied-Ooguri-Spodyneiko-Vafa, Garg-Krishnan,
  Murayama-Yanagida-Y, Ooguri-Palti-Shiu-Vafa, ('18)]

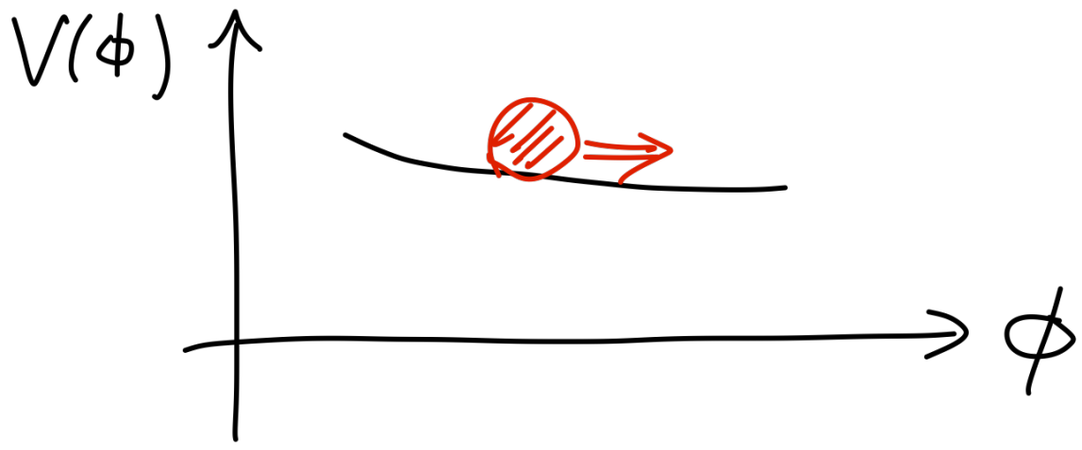
$$M_{pl}|\nabla V| \geq c\,V \quad \text{or} \quad \min(\nabla^2 V) \leq -c'V$$

($c, c' \sim O(1)$)

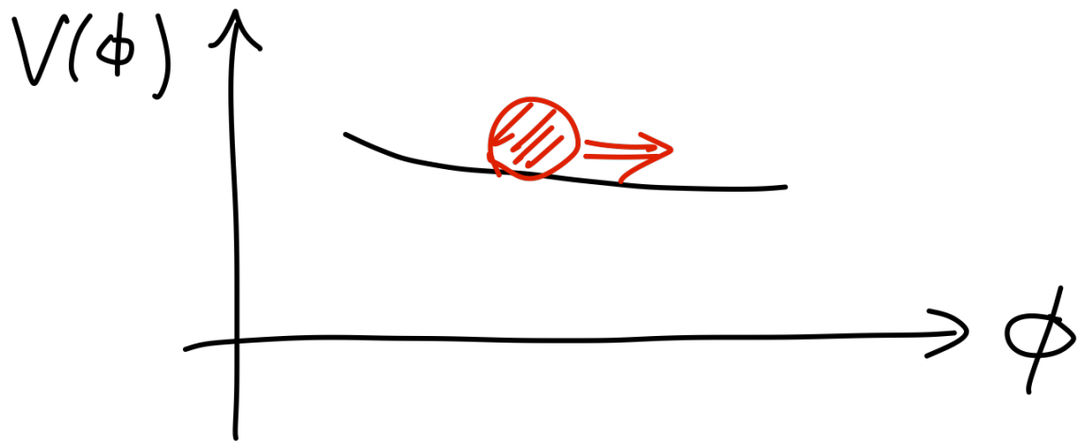
(This talk does NOT directly rely on this conjecture)

Quintessence

Q: if quintessence, why flat potential?



Q : if quintessence, why flat potential?



possible answer : quintessence axion

[Fukugita-Yanagida ('94) Frieman-Hill-Stebbins-Waga (95), Choi ('99), ···]

$$\mathcal{L} \supset \frac{1}{32\pi^2}\frac{a}{f}\,\mathrm{Tr}\,\underbrace{F_{\mu\nu}\tilde{F}^{\mu\nu}}_{\mathcal{Q}}$$

dynamical θ angle

non-Abelian gauge field

(※ this is the ONLY coupling of a)

shift symmetry

$$a \longrightarrow a + (\text{const.})$$

broken by non-pert. effect

$$V(a) = \Lambda^4 \cos\left(\frac{a}{f_a}\right) + \cdots\cdots$$

$$M_{pl}^4 \, e^{-2\pi/\alpha} \ll M_{pl}^4 \quad ! \qquad \left(\alpha = \frac{g^2}{4\pi}\right)$$

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$$\Lambda^4 = M_{pl}^4 \, e^{-2\pi/\alpha} \ll M_{pl}^4 \quad / \quad \left(\alpha = \frac{g^2}{4\pi}\right)$$

Q: which non-Abelian gauge field?

why particular value of α ?

Surprisingly, electroweak $SU(2)$ gauge group in the standard model does the job !!

$$\alpha_2(M_Z) \simeq \frac{1}{29} \xrightarrow{\text{RG}} \alpha_2(M_{Pl}) \simeq \frac{1}{48}$$

Surprisingly, electroweak $SU(2)$ gauge group in the standard model does the job !!

$$\alpha_2(M_Z) \simeq \frac{1}{29} \overset{\text{RG}}{\rightsquigarrow} \alpha_2(M_{pl}) \simeq \frac{1}{48}$$

$$\Lambda^4 \simeq M_{pl}^4 \, e^{-\frac{2\pi}{\alpha_2(M_{pl})}} \simeq \mathcal{O}(10^{-130}) M_{pl}^4 \; !!$$

(※ dominant contribution comes from small-size instanton)

electroweak quintessence axion scenario

[Fukugita-Yanagida ('94), Nomura-Watari-Yanagida ('00), McLerran-Pisarski-Skokov ('12), ···]

Q: Isn't the EW θ-angle unphysical!?

(θ can be rotated away by anomalies of
(B+L)-global symmetry [cf. Anselm-Johansen ('92)])

A. (B+L)-sym. is broken by higher-dim.
operator, e.g. $\mathcal{L} \supset \frac{1}{\Lambda^2} qqql$

[Anselm-Johansen ('93)]

(cf. no exact global symmetry in QG)

[Misner-Wheeler ('57), ⋯, Polchinski ('03), Banks-Seiberg ('10), Harlow-Ooguri ('18), ⋯]

Weak Gravity Conjecture

* Weak gravity conjecture implies

[Arkani-Hamed-Motl-Nicolis-Vafa ('06)]
[See also Banks-Dine-Fox-Gorbatov ('03)]

$$f \lesssim \frac{M_{Pl}}{S_{inst}} \sim \mathcal{O}(10^{-2}) M_{Pl} \ll M_{Pl}$$

$$S_{inst} = \frac{2\pi}{\alpha_2(M_{Pl})} \cong 300$$

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* However, we need small quintessence mass

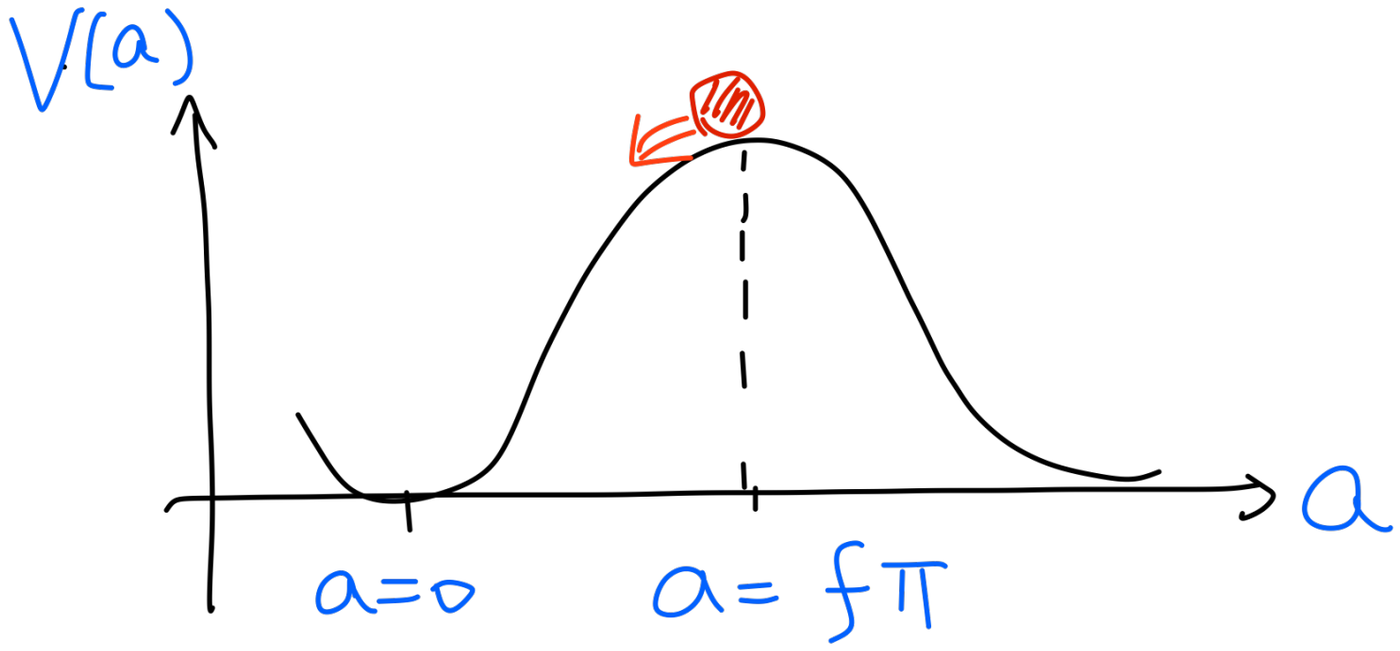
$$m^2 \simeq \frac{\Lambda^4}{f^2} \simeq \frac{H_0^2 M_P^2}{f^2} \lesssim H_0^2$$

$\rightsquigarrow$ $f \gtrsim M_{Pl}$ needed



Hilltop Quintessence ?

[Putta - Scherrer ('08), ···]

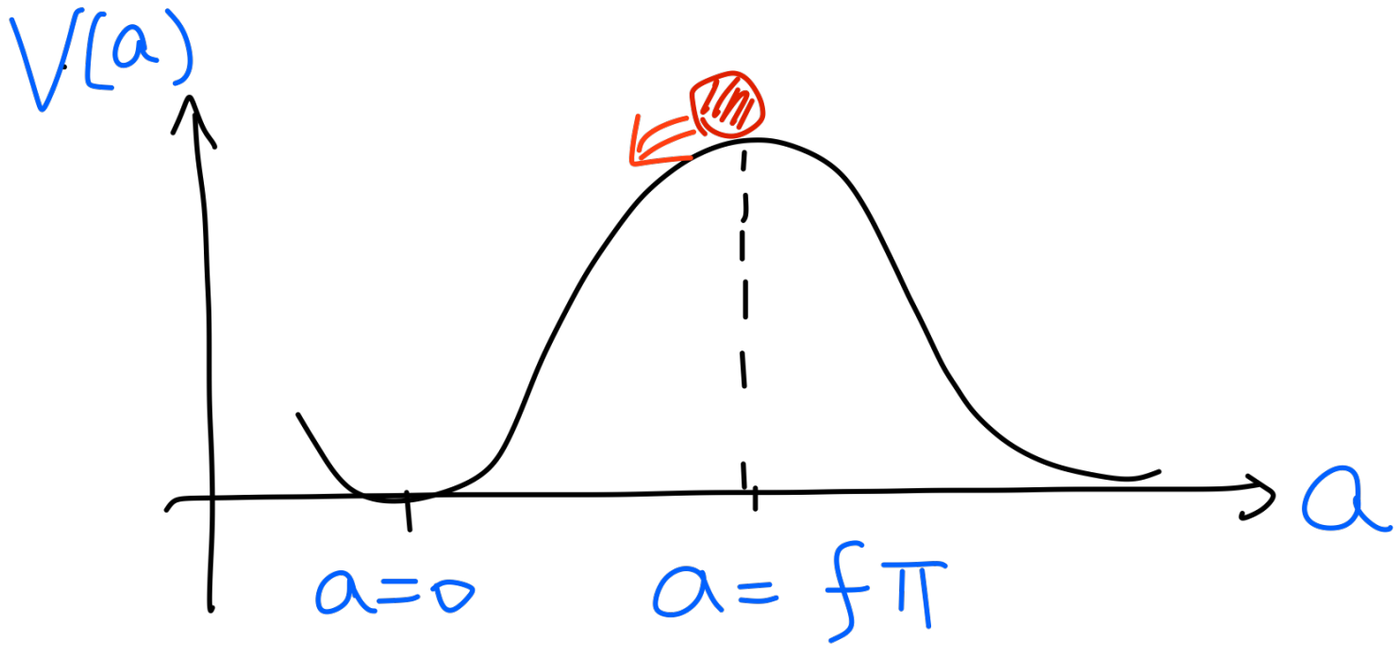


Choose

$\delta a = |a - f\pi| \ll f\pi$ to avoid too much rolling

Hilltop Quintessence ?

[Dutta - Scherrer ('08), ···]



Choose

$\delta a = |a - f\pi| \ll f\pi$ to avoid too much rolling

However, this requires

$$\mathcal{O}\left(\exp\left(M_{Pl}/f\right)\right) \sim \mathcal{O}\left(e^{100}\right)$$ fine-tuning

Sinst

[see e.g. Choi ('99), Svrcek ('06), Ibe-Yanagida-MY ('18)]

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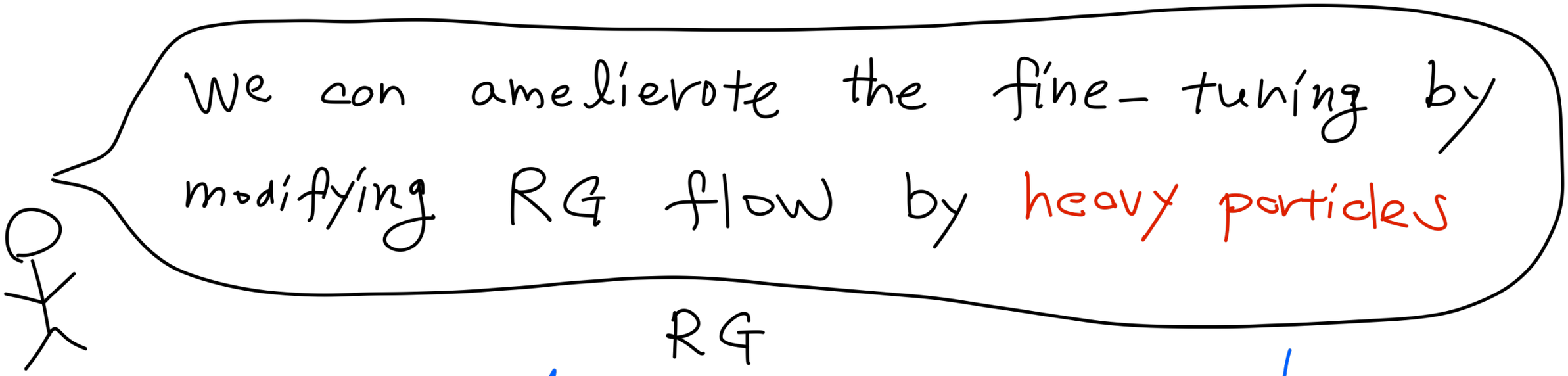
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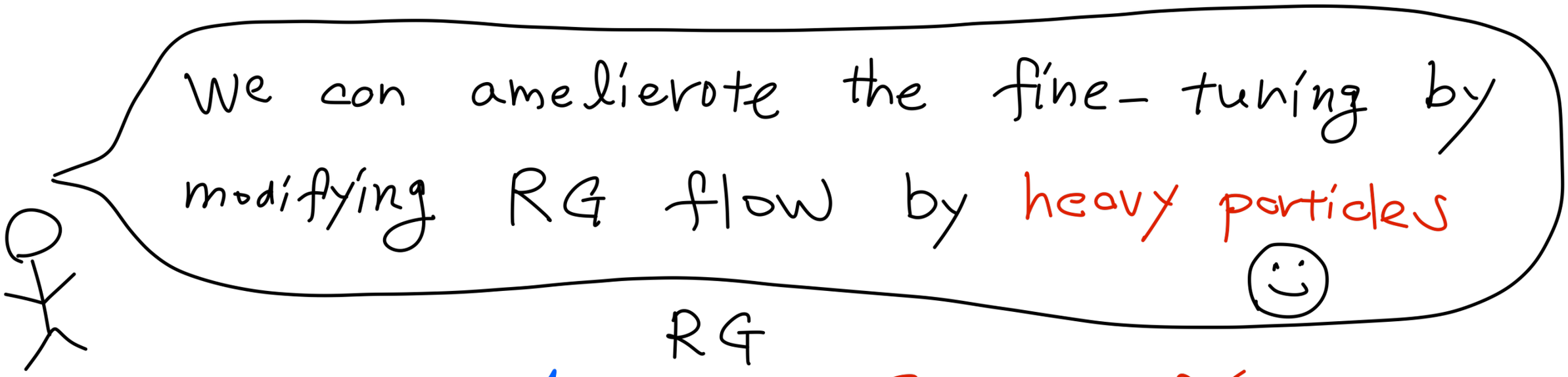
$\rightsquigarrow$ $f \gtrsim M_{Pl}$ needed





$$\alpha_2(M_Z) \simeq \frac{1}{29} \rightsquigarrow \alpha_2(M_{pl}) \simeq \frac{1}{48}$$

$$S_{inst} \simeq \frac{2\pi}{\alpha_2(M_{pl})} \simeq 300$$



RG

$\alpha_2(M_Z) \simeq \frac{1}{29}$ ⟿ $S_{inst} \simeq O(10)$

w/ heavy particles

or even $O(1)$

s.t. $f \sim M_{Pl}$

We can ameliorate the fine-tuning by modifying RG flow by heavy particles

RG

$\alpha_2(M_Z) \simeq \frac{1}{29}$ ⇝ $S_{inst} \simeq O(10)$ w/ heavy particles

or even $O(1)$

s.t. $f \sim M_{Pl}$

But.... this spoils the successful estimate for Λ

$\Lambda^4 \sim M_{Pl}^4 \, e^{-S_{inst}} \sim O(10^{-120}) M_{Pl}^4$

Supersymmetric Miracle

Consider MSSM w/ $m_{SUSY} \simeq \mathcal{O}(\mathrm{TeV})$

EW θ-angle

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EW θ-angle $\leftsquigarrow$ (B+L)-breaking

dim 5 op. QQQL

dangerous for proton decay

[Sakai-Yanagida, Weinberg ('82)]

Consider MSSM w/ $m_{SUSY} \simeq \mathcal{O}(TeV)$

EW θ-angle ⟵ (B+L)-breaking

dim 5 op. QQQL

dangerous for proton decay [Sakai-Yanagida, Weinberg ('82)]

impose Frogatt-Nielsen sym.

with breaking parameter

$$\epsilon \simeq \frac{\langle \Phi_{FN} \rangle}{M_{Pl}} \simeq \frac{1}{17}$$

for quark/lepton mixing matrix

$U(1)_{FN}$
10_1	+2
10_2	+1
10_3	0
5_1^*	1
5_2^*	0
5_3^*	0
H_u	0
H_d	0

$$\alpha_2(M_{pl})\Big|_{MSSM} = \frac{1}{23} \quad \text{cf.} \quad \alpha_2(M_{pl})\Big|_{SM} = \frac{1}{48}$$

$$\Lambda^4 \simeq e^{-\frac{2\pi}{\alpha_2(M_{pl})}}$$

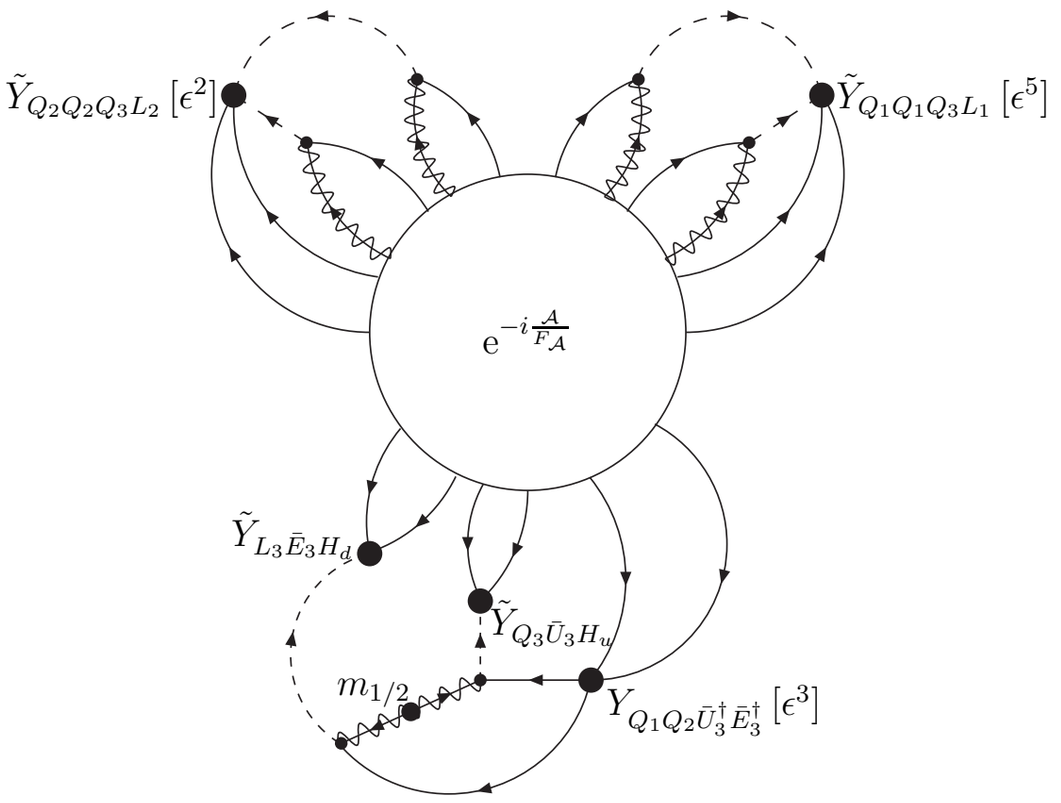
$$\alpha_2(M_{pl})\Big|_{MSSM} = \frac{1}{23} \quad \text{cf.} \quad \alpha_2(M_{pl})\Big|_{SM} = \frac{1}{48}$$

instanton calculus gives [Nomura-Watari-Yanagida ('00)]

$$\Lambda^4 \simeq e^{-\frac{2\pi}{\alpha_2(M_{pl})}} \epsilon^{10} m_{SUSY}^3 M_{pl}$$

$$\simeq \mathcal{O}(10^{-120}) M_{pl}^4 \;!!$$

$\epsilon \simeq 1/17$, $m_{SUSY} \simeq$ TeV



Now, back to inclusion of heavy particles ....

Include a pair $X, \bar{X}$ of heavy particles with intermediate mass M_X

$$\alpha_2^{-1}(M_{Pl})\Big|_{X\bar{X}} = \alpha_2^{-1}(M_{Pl}) + \frac{2T_R}{2\pi}\log\frac{M_X}{M_{Pl}}$$

← Dynkin index

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← Dynkin index

Heavy particles also generate extra zero modes

Insertion of operators $M_X X \bar{X}$

$$\rightsquigarrow \left(\frac{M_X}{M_{Pl}}\right)^{2T_R}$$

It turns out 2 effects cancel out!

[Nomura-Watari-Yanagida ('00)]

$$\Lambda^4\big|_{X\bar{X}} \simeq \underbrace{e^{-\frac{2\pi}{\alpha_2(M_{pl})|_{X\bar{X}}}}\left(\frac{M_X}{M_{pl}}\right)^{2T_R}}_{=\; e^{-\frac{2\pi}{\alpha_2(M_{pl})}}\left(\frac{M_{pl}}{M_X}\right)^{2T_R}} \epsilon^{10} m_{susy}^3 M_{pl}$$

cancel

$$\simeq \Lambda^4\big|_{MSSM}$$

WGC ☺

We can change the RG running of α_2 while keeping the size of Λ^4 ☺

robust !!

We have many choices for heavy particles

s.t. $\alpha_2(M_{pl}) \simeq 4\pi$

e.g.

① 3 SU(2) triplets

at $O(10^7\,\mathrm{GeV})$

② 1 SU(2) triplet

1 SU(3) octet

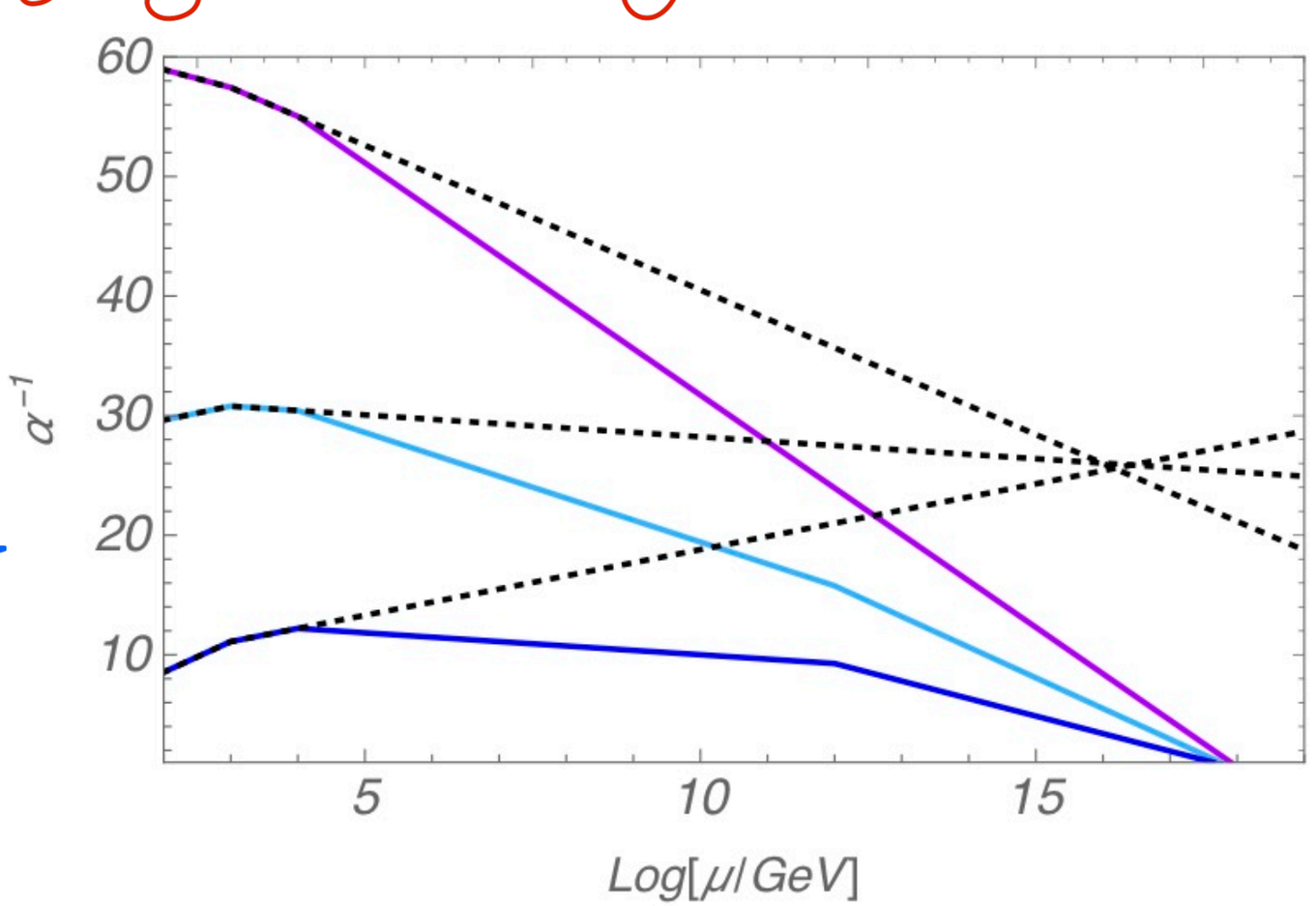
at $O(10^{12}\,\mathrm{GeV})$

+

4 pairs of SU(5) $5, \bar{5}$

at $O(1\,\mathrm{TeV})$

gauge coupling unification



Dark Energy

Matter

If $m_{SUSY} \gg$ TeV then

no need for FN suppression

for dim 5 proton decay

$$\Lambda^4 \simeq e^{-\frac{2\pi}{\alpha_2(M_{Pl})}} m_{SUSY}^3 M_{Pl}$$

If $m_{SUSY} \gg$ TeV then

no need for FN suppression

for dim 5 proton decay

$$\Lambda^4 \simeq e^{-\frac{2\pi}{\alpha_2(M_{pl})}} m_{SUSY}^3 M_{pl}$$

$$m_a \simeq \frac{\Lambda^2}{M_{pl}} \simeq \mathcal{O}(10^{-22}\,\mathrm{eV})$$

for $m_{SUSY} \simeq \mathcal{O}(1000\,\mathrm{TeV})$

Fuzzy DM

[Ibe-Yanagida-Y]

Summary

electroweak quintessence axion

$$\Lambda^4 \simeq M_{pe}^2 \, e^{-\frac{2\pi}{\alpha_2(M_{pe})}} \simeq \mathcal{O}(10^{-130}) M_{pl}^4 \; !$$

$$\Lambda^4\Big|_{MSSM} \simeq \epsilon^{10} e^{-\frac{2\pi}{\alpha_2(M_{pl})}} m_{susy}^3 M_{pl} \simeq \mathcal{O}(10^{-120}) M_{pl}^4 \; !!$$

* Electroweak Quintessence Axion:

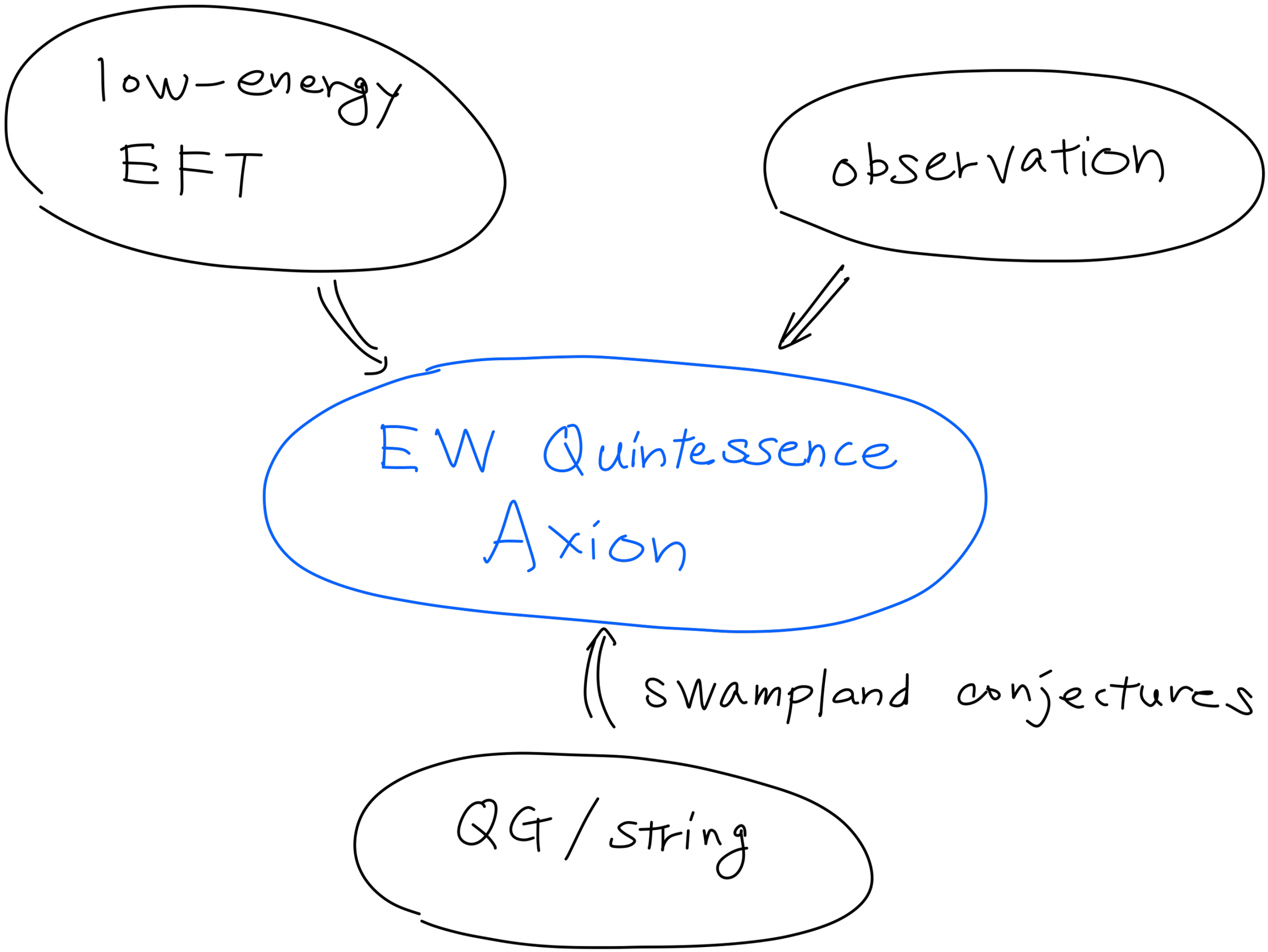
simple scenario to explain $\Lambda^4 \simeq 10^{-120} M_{Pl}^4$

* Consistency w/ weak gravity conjecture

requires fine-tuning into hilltop region

* However, fine-tuning ameliorated in

MSSM + heavy matter ("SUSY miracle" ∧ robust)


low-energy
EFT
observation
EW Quintessence
Axion
swampland conjectures
QG / string

「de Sitter Conjecture」

※ $V(a) \sim \Lambda^4 \cos\left(\frac{a}{f}\right)$ has local maximum,

hence violates original dS conjecture

$$M_{Pl} \|\nabla V\| \geq c\, V$$

[Murayama-Yanagida-MY (18)
see also Denef-Hebecker-Wrase, Conlon, Choi-Chway-Sin (18)]

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However, consistent w/ refined dS conjecture

$$M_{Pl} \|\nabla V\| \geq c\, V \quad \text{or} \quad M_{Pl}^2 \min(\nabla^2 V) \leq -c' V$$

[Garg-Krishnan, Murayama-Yanagida-MY, Ooguri-Palti-Shiu-Vafa, ---- ('18)
See also Fukuda-Saito-Shiraf-MY ('18)]