Electroweak Quintessence Axion

as

Dark Energy

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15th Rencontres du Vietnam

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Based on

arXiv: 1811.04664 [hep-th]

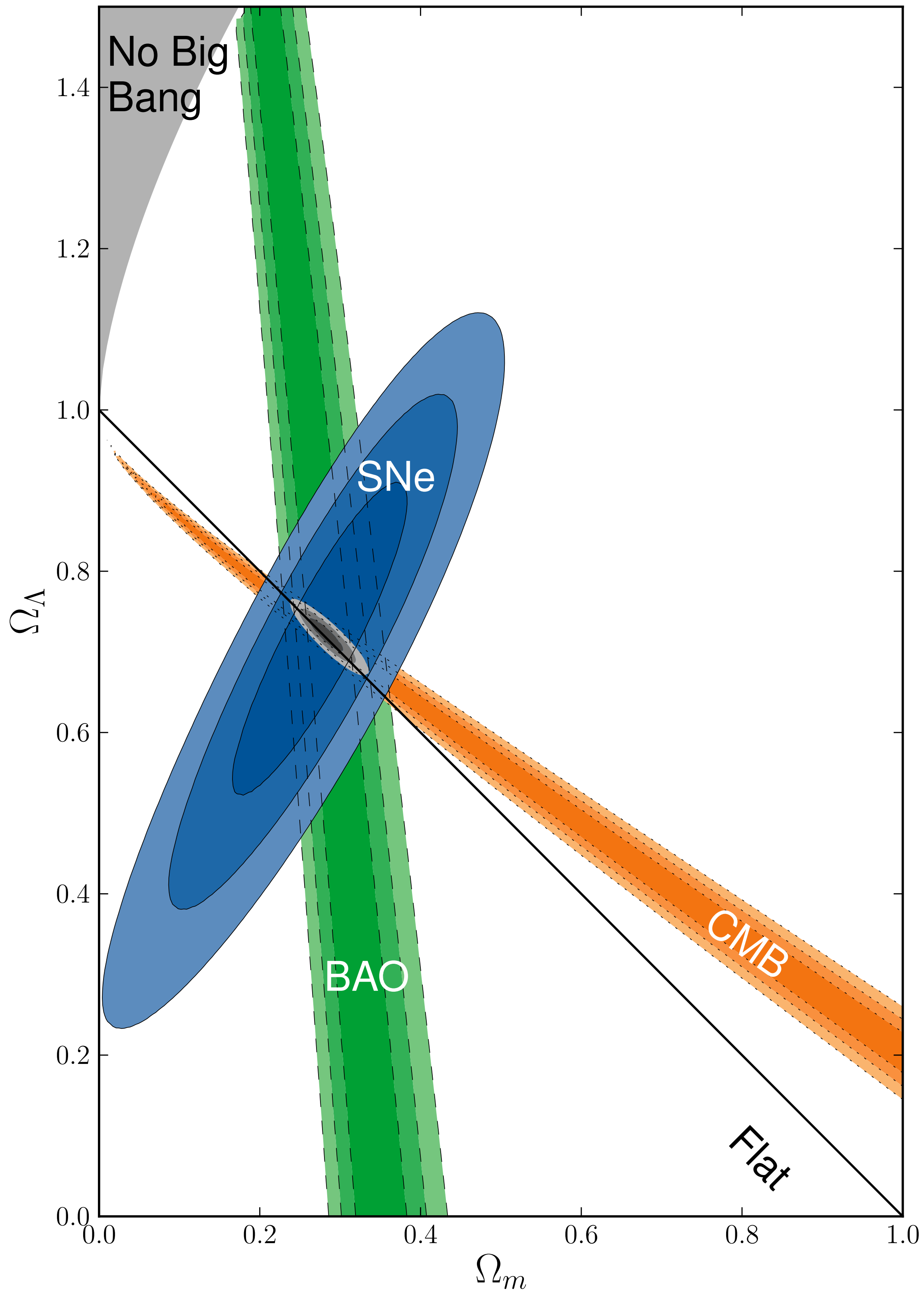
w/ Masahiro Ibe, Tsutomu T. Yanagida

(ICRR Tokyo)

(IPMU → TD Lee Inst, Tokyo Shanghai)

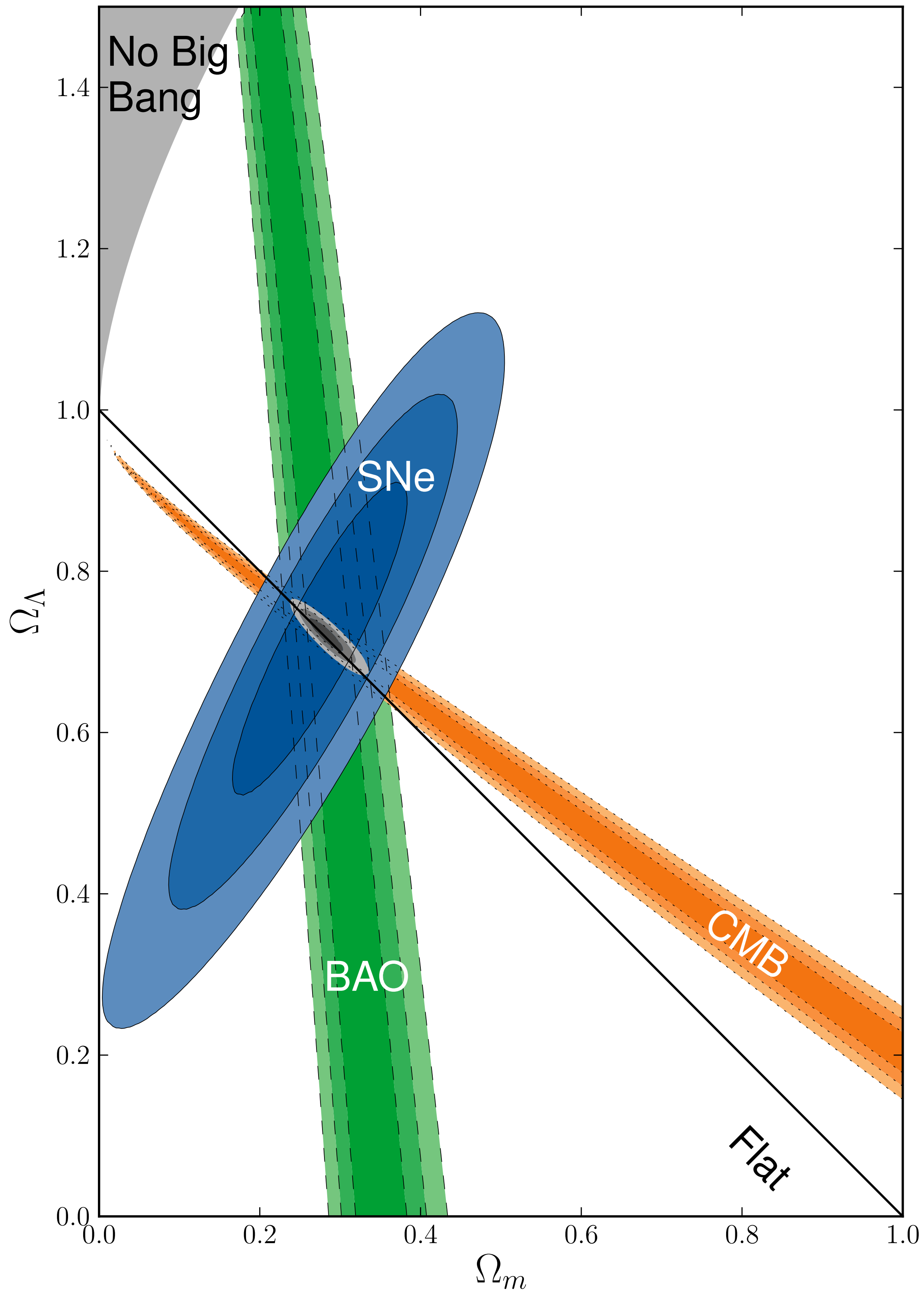
... and many earlier papers

Dark Energy



[Suzuki et al, ('11)]

$\Lambda > 0$!



[Suzuki et al, ('11)]

$\Lambda > 0$!

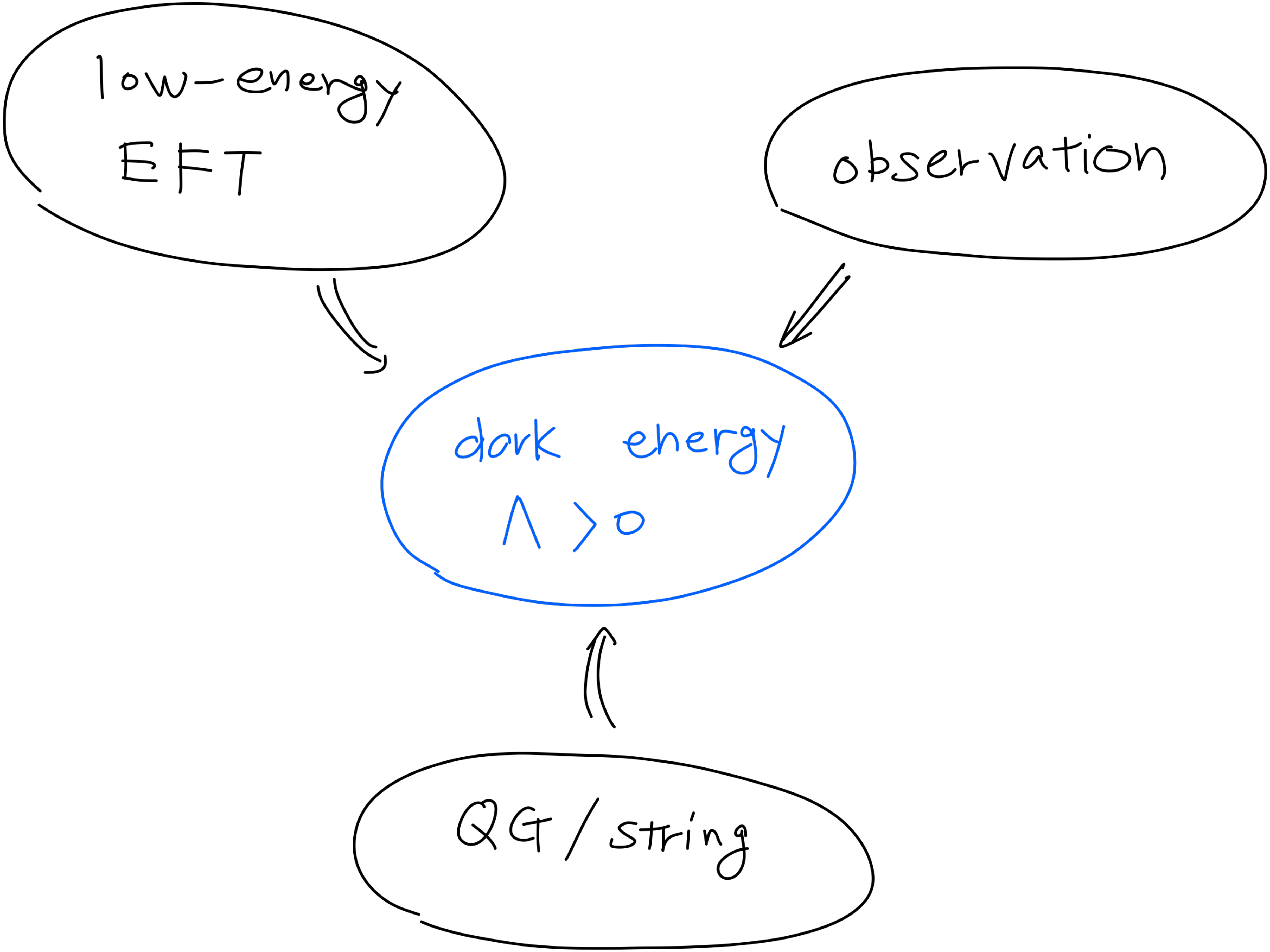
$\Lambda^4 \simeq \mathcal{O}(10^{-120}) M_{pe}^4$

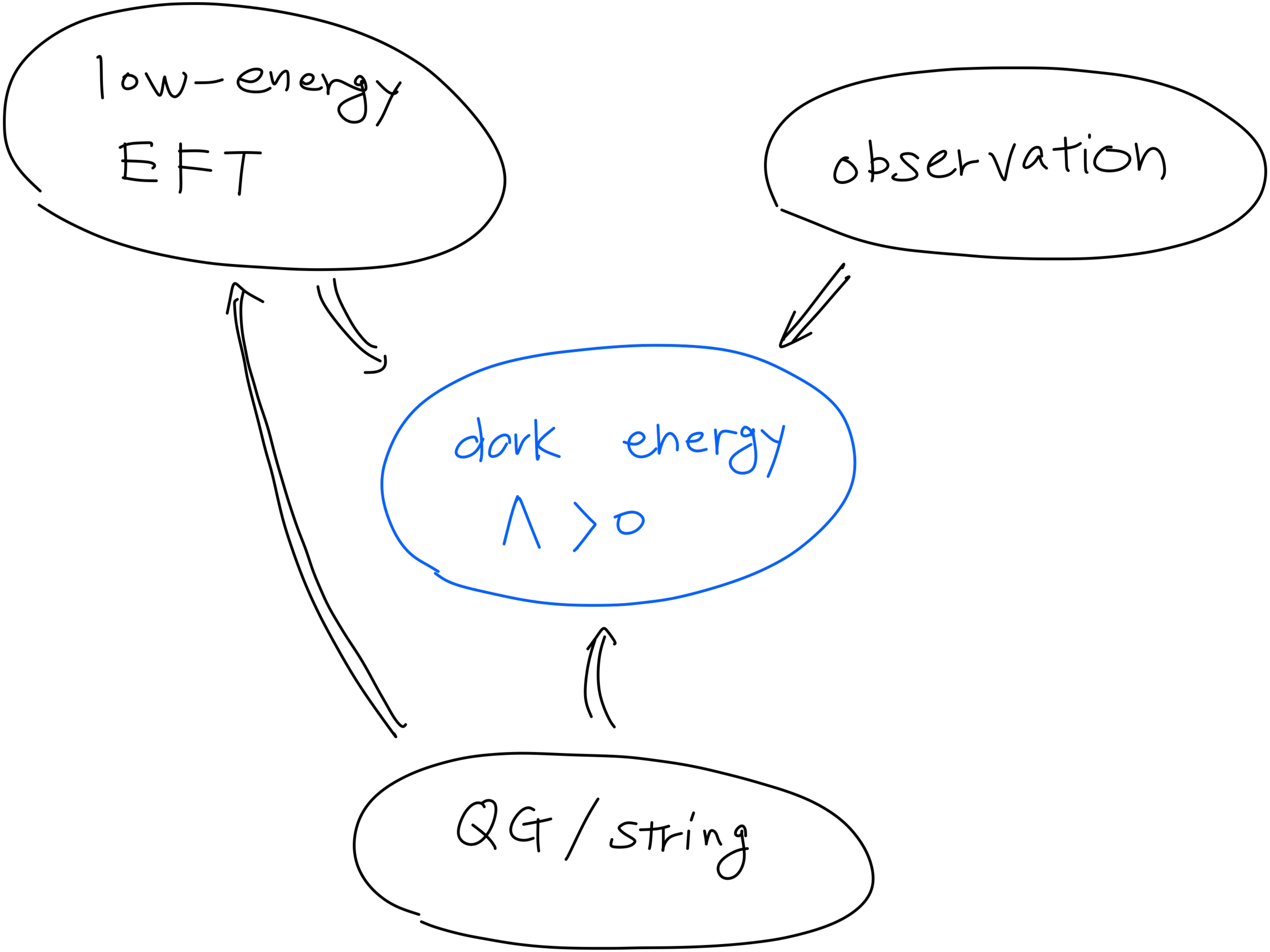
$\ll M_{pe}^4$!!

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

while dark energy is IR phenomenon

it is partly about $\underbrace{\text{UV}}_{\substack{\text{quantum gravity}\\ \text{string}}}$


low-energy EFT
observation
dark energy
$\Lambda > 0$
QG / string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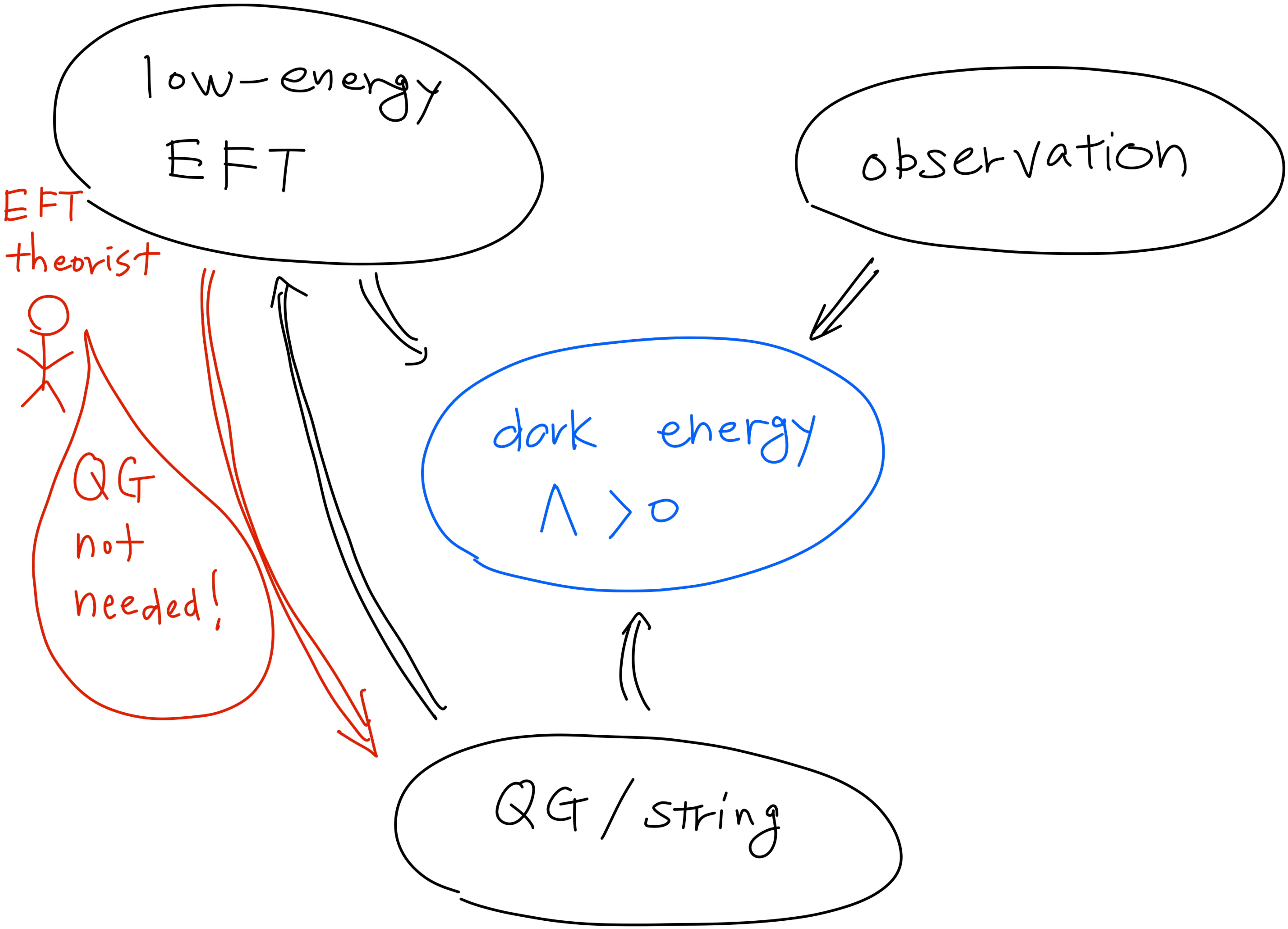
low-energy EFT
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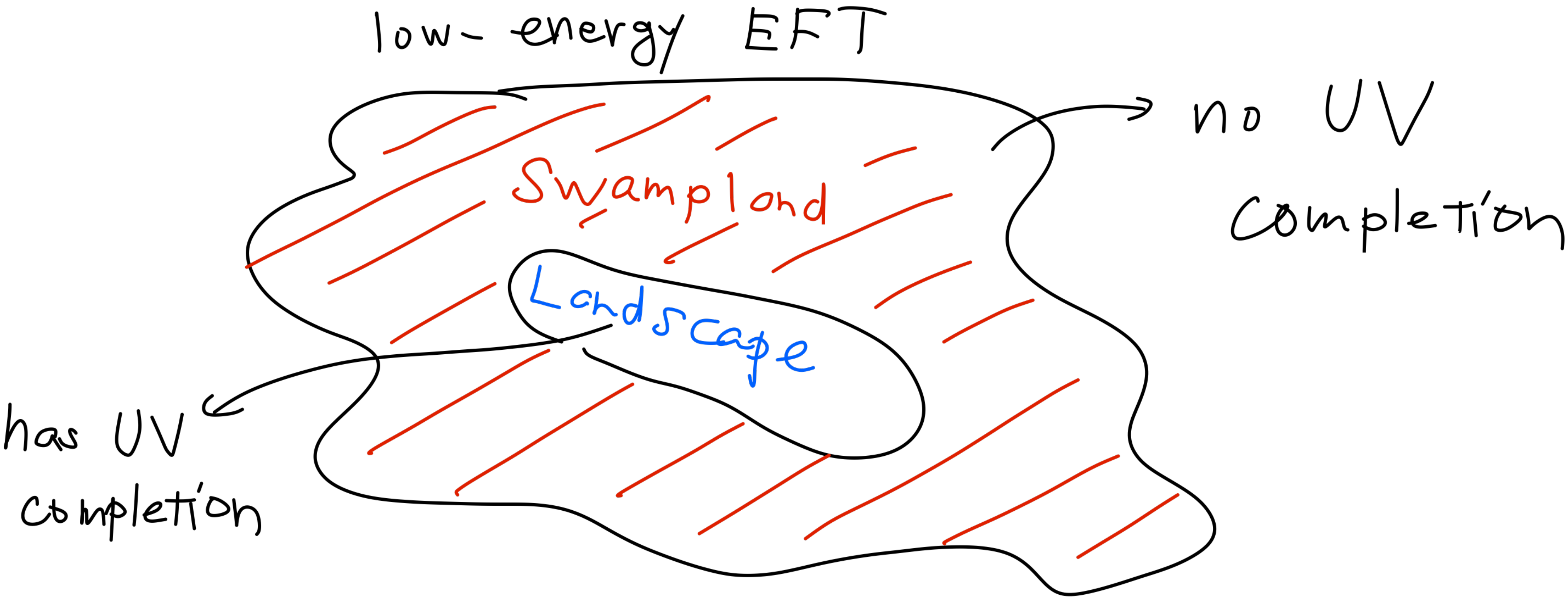
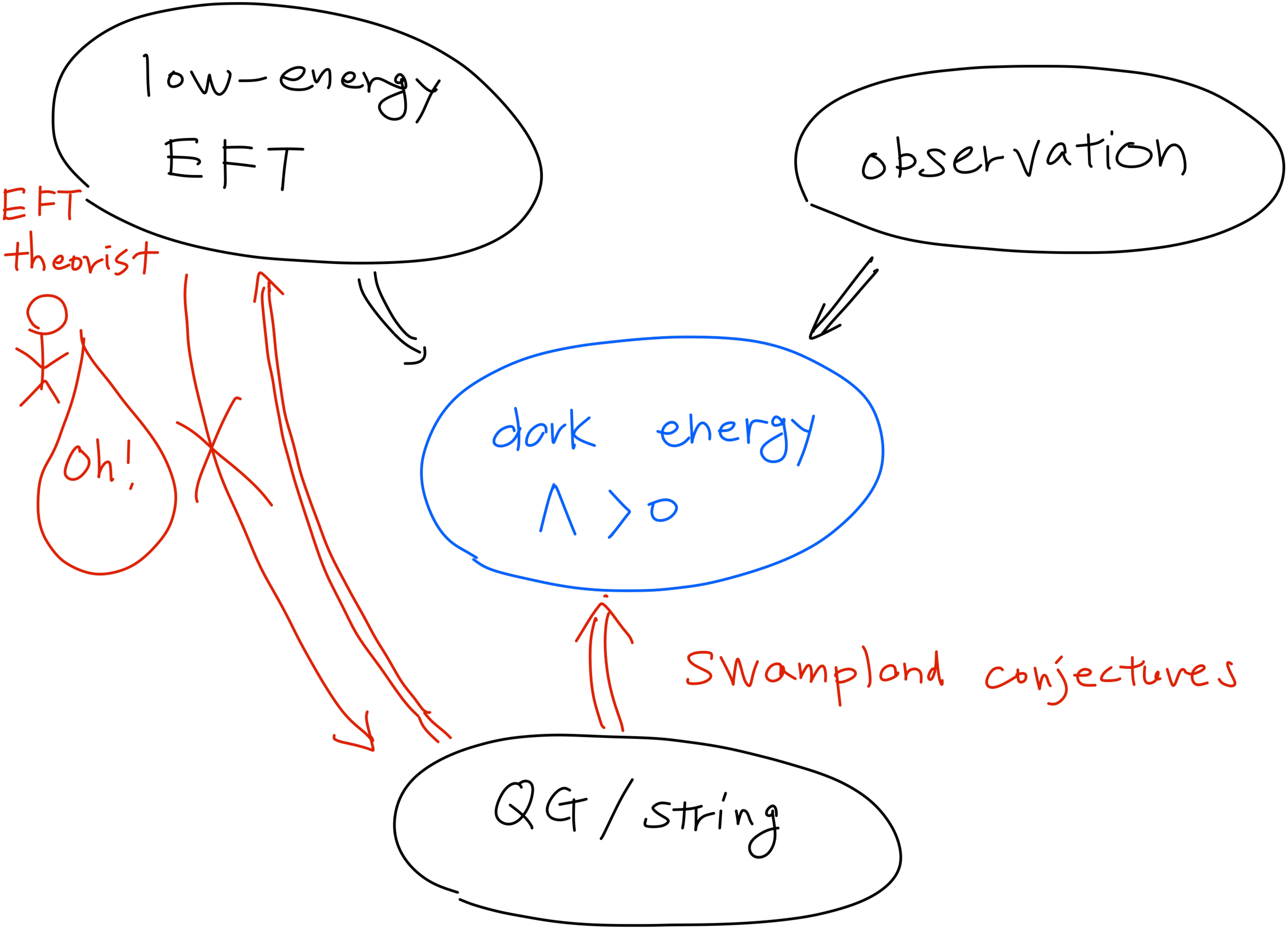
dark energy
$\Lambda > 0$
QG / string
EFT theorist
QG not needed!

Swampland Conjectures:

[Vafa ('05), Ooguri-Vafa ('06), ⋯⋯]

Necessary condition for $^{\exists}$ UV completion in Quantum Gravity

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Oh!
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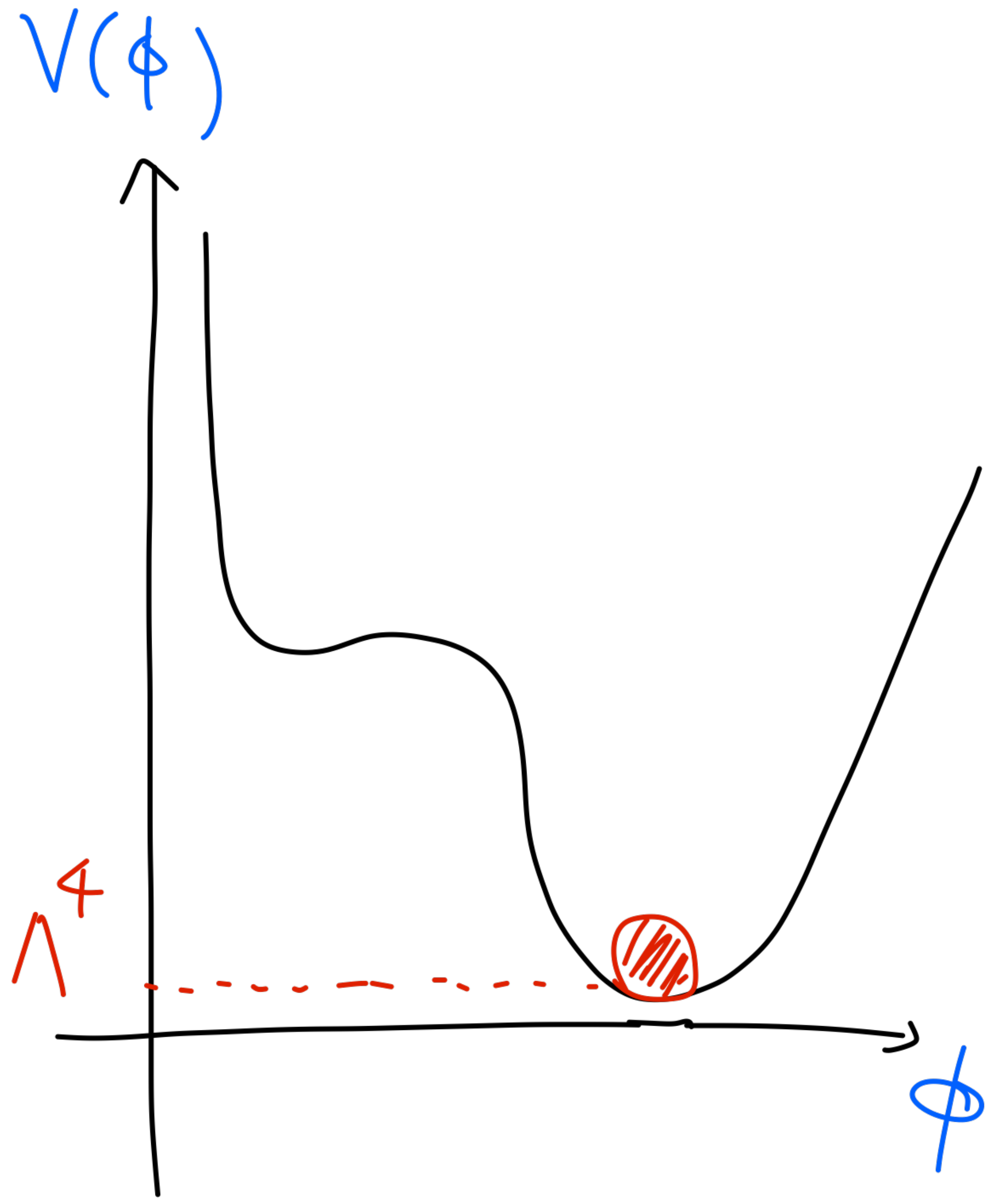
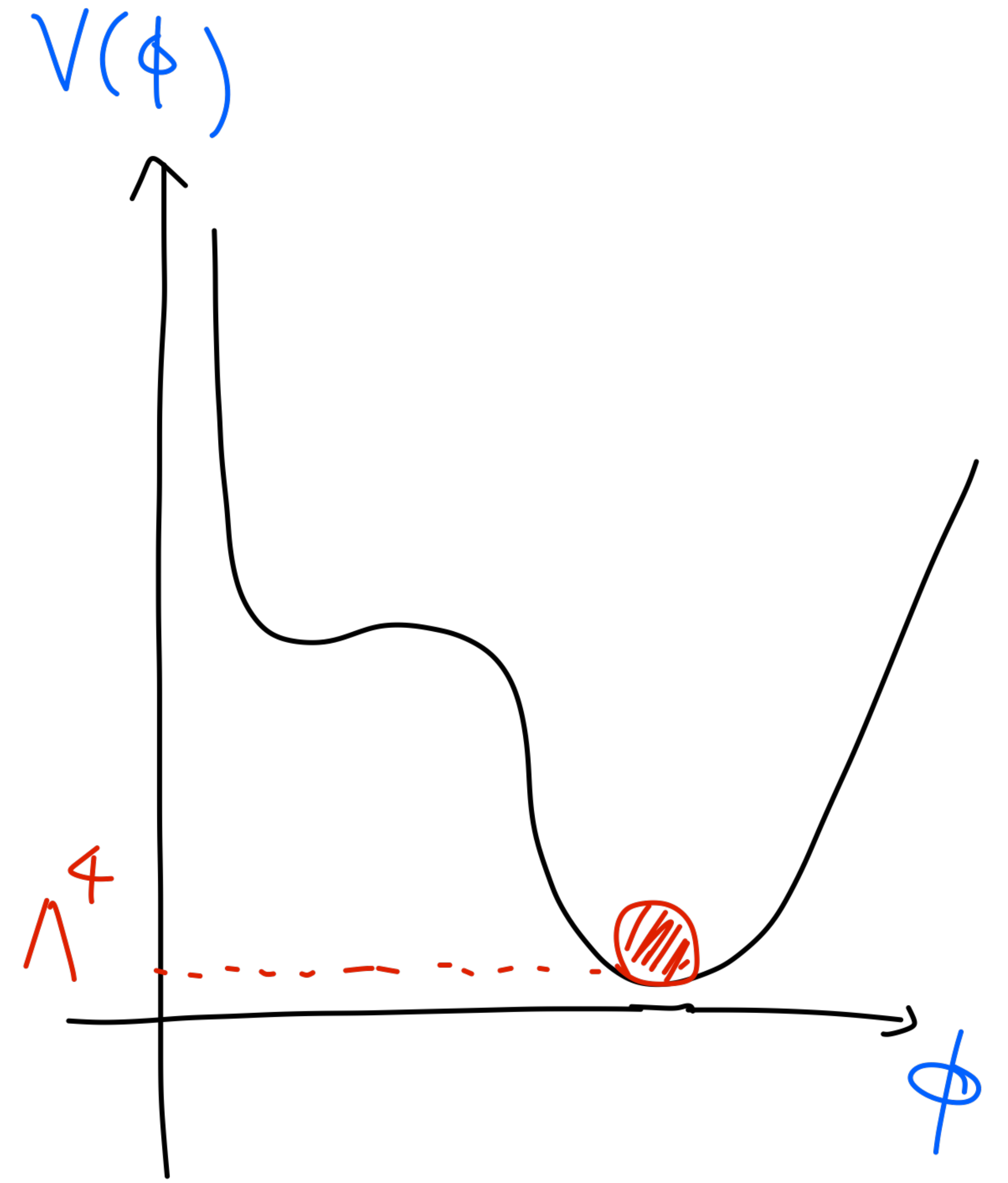
$\Lambda > 0$
Swampland conjectures
QG / string

How to Realize Λ ?

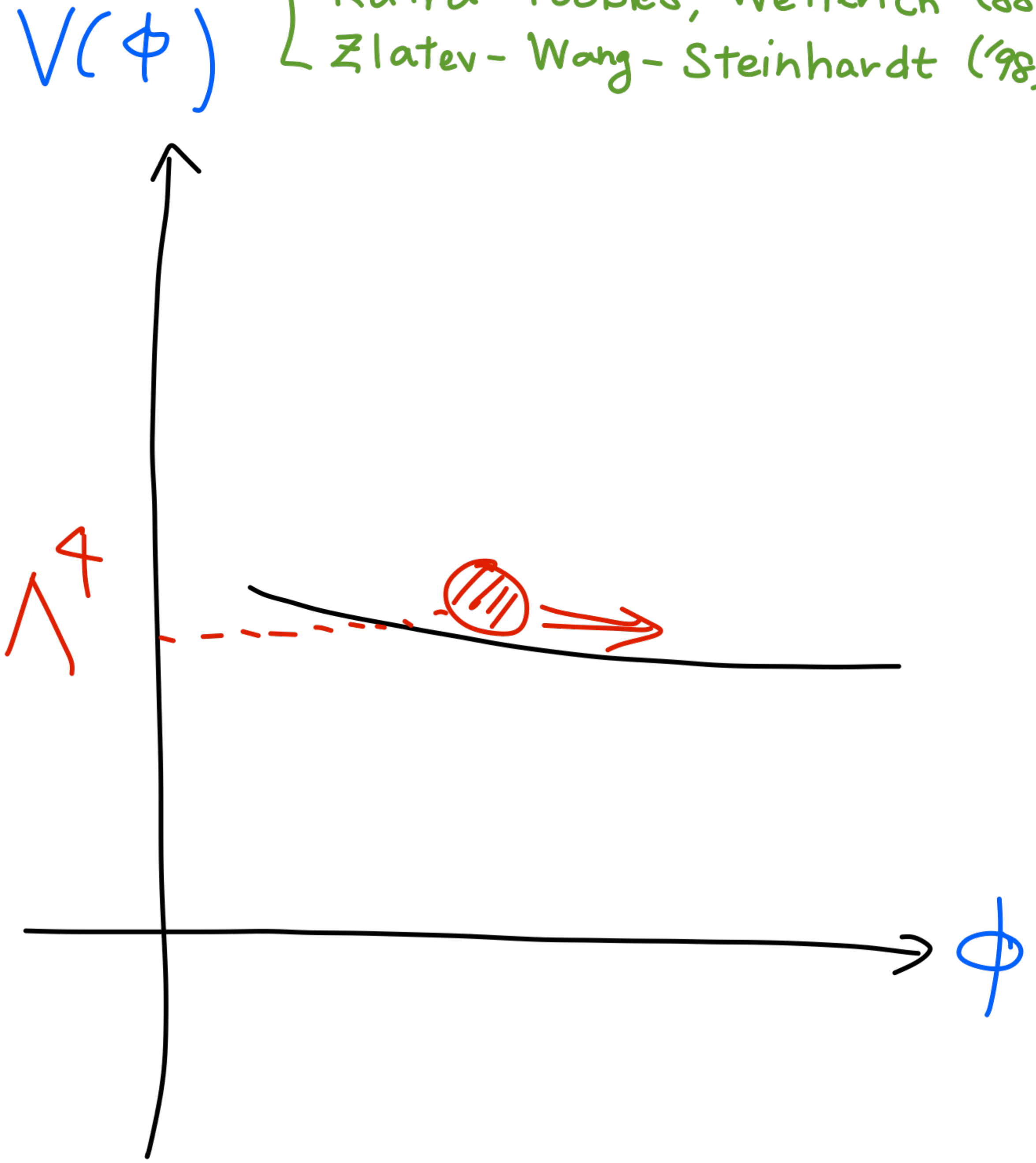
cosmological constant



cosmological constant vs. quintessence



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



TODAY!!

cosmological constant vs. quintessence

[Ratra-Peebles, Wetterich ('88)
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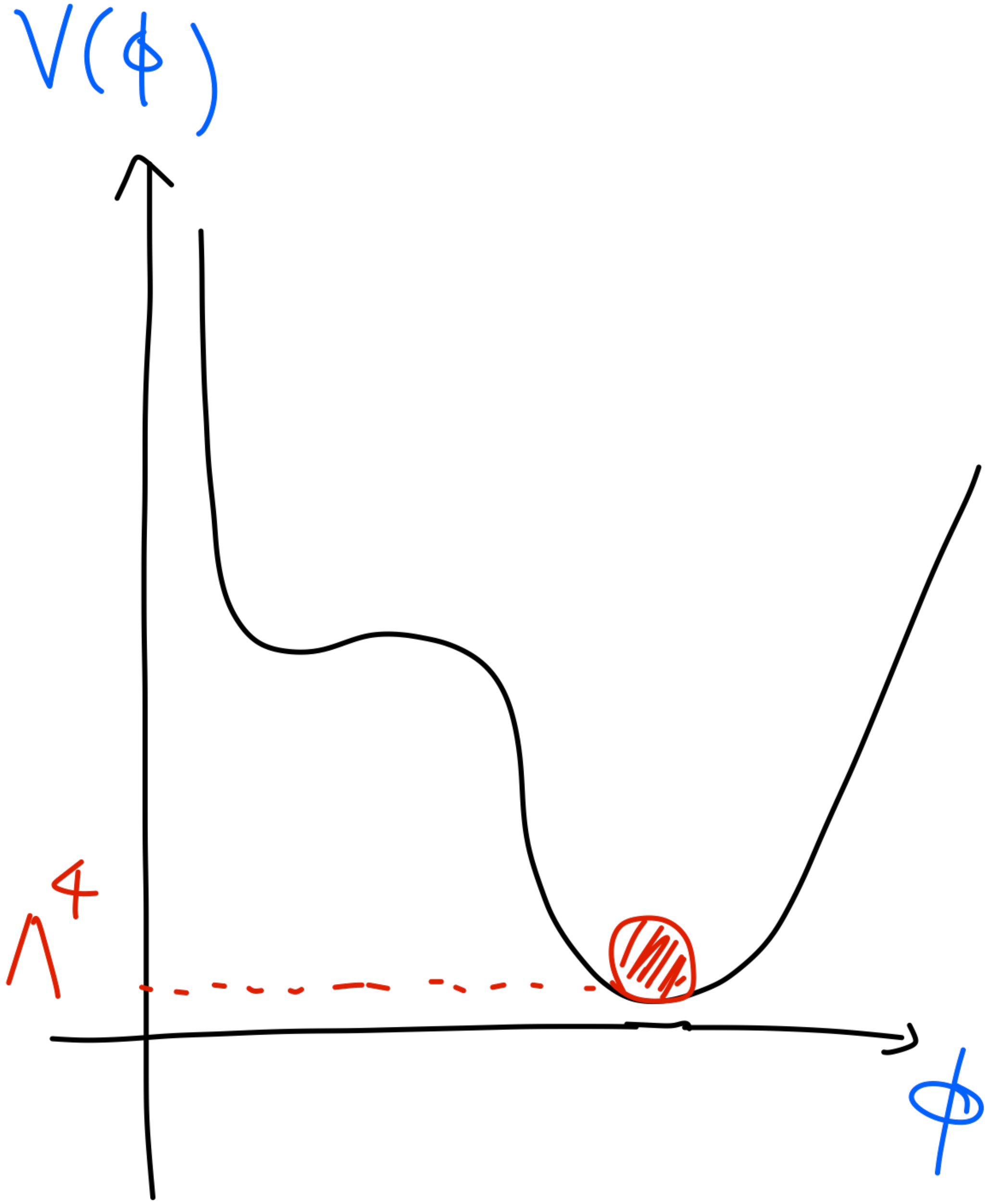
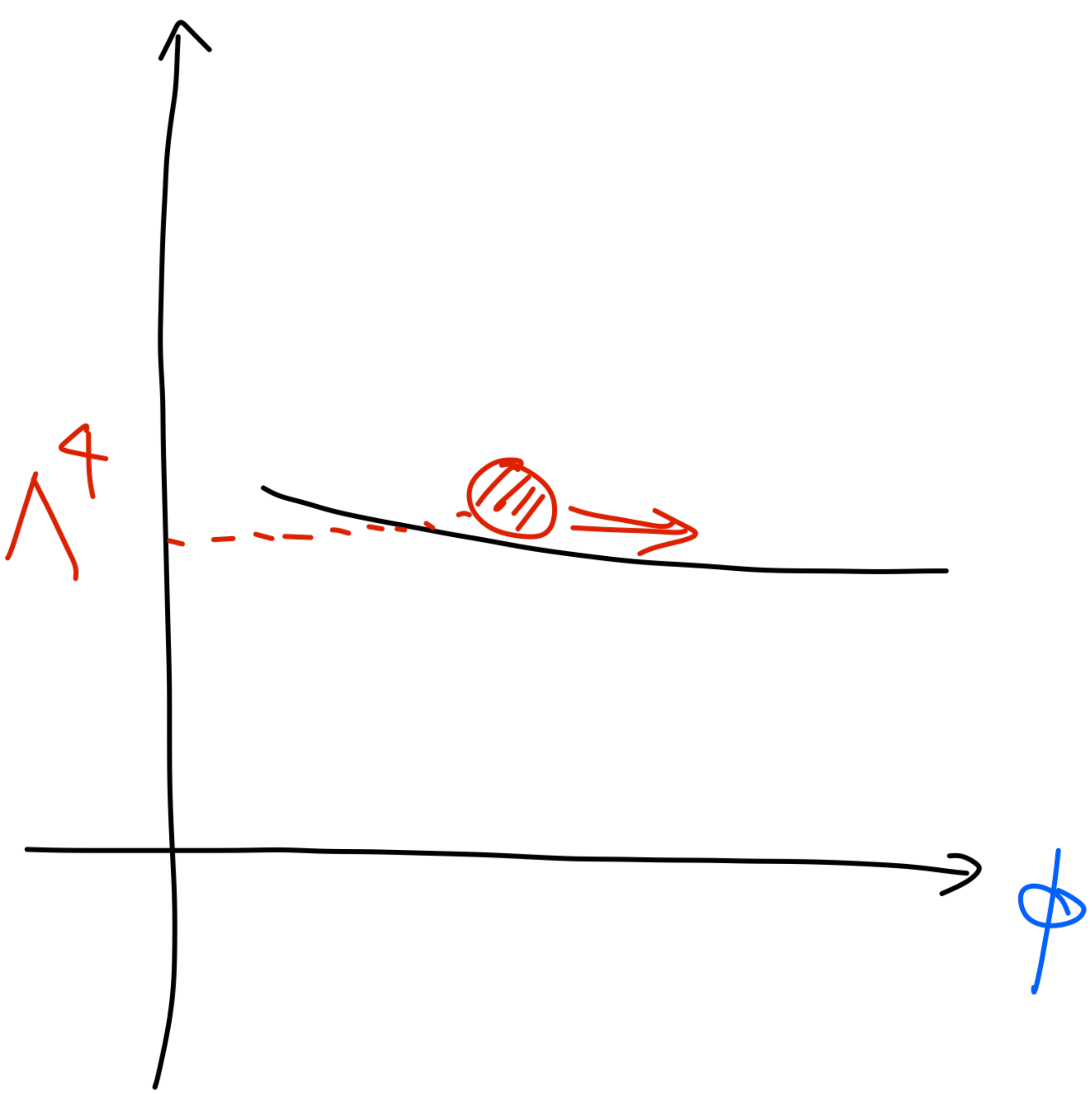




* Very few discussion of quintessence in QG/String (... until recently)

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

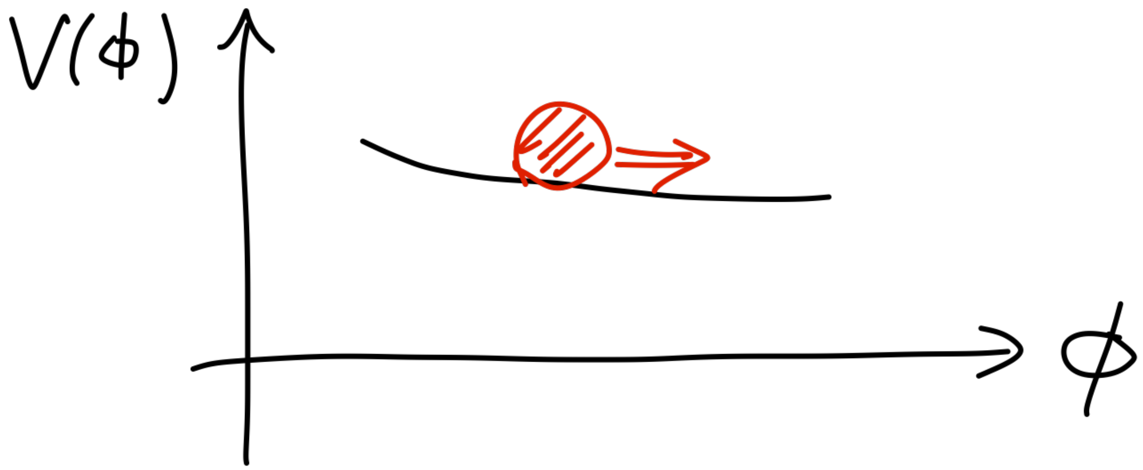
$$M_{pl} |\nabla V| \geq c V \quad \text{or} \quad \min(\nabla^2 V) \leq -c' V$$

$(c, c' \sim \mathcal{O}(1))$

(This talk does NOT directly rely on this conjecture)

Quintessence

Q : if quintessence, why flat potential?



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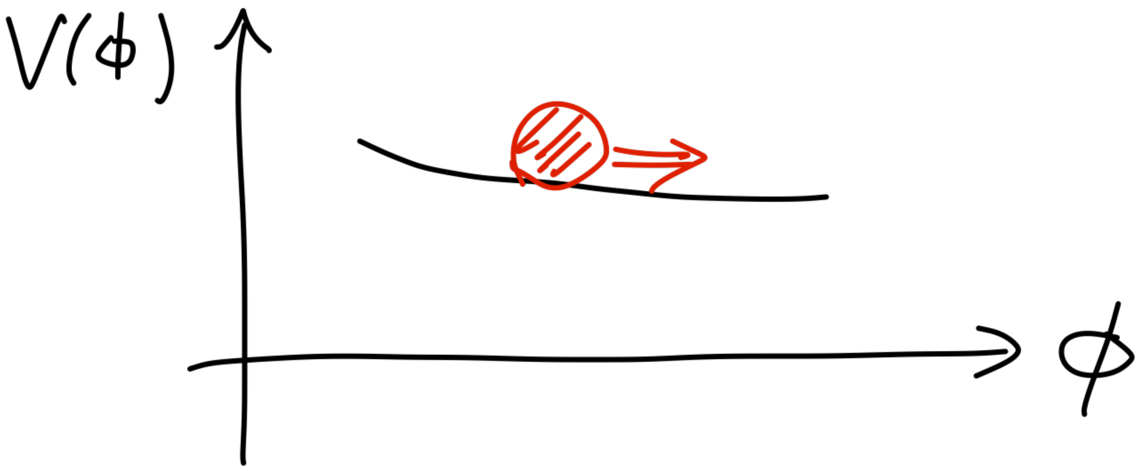

possible answer: quintessence axion

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

$$\mathcal{L} \supset \frac{1}{32\pi^2}\underbrace{\frac{a}{f}}_{\text{dynamical }\theta\text{ angle}}\,\mathrm{Tr}\,\underbrace{F_{\mu\nu}\tilde{F}^{\mu\nu}}_{\text{non-Abelian gauge field}}$$

(※ this is the ONLY coupling of a)

shift symmetry

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

broken by non-pert. effect

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

$$\parallel$$

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

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

Q: which non-Abelian gauge field?

why particular value of α?

Surprisingly, electroweak SU(2) gauge group

in the standard model does the job!!

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

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

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

(※ 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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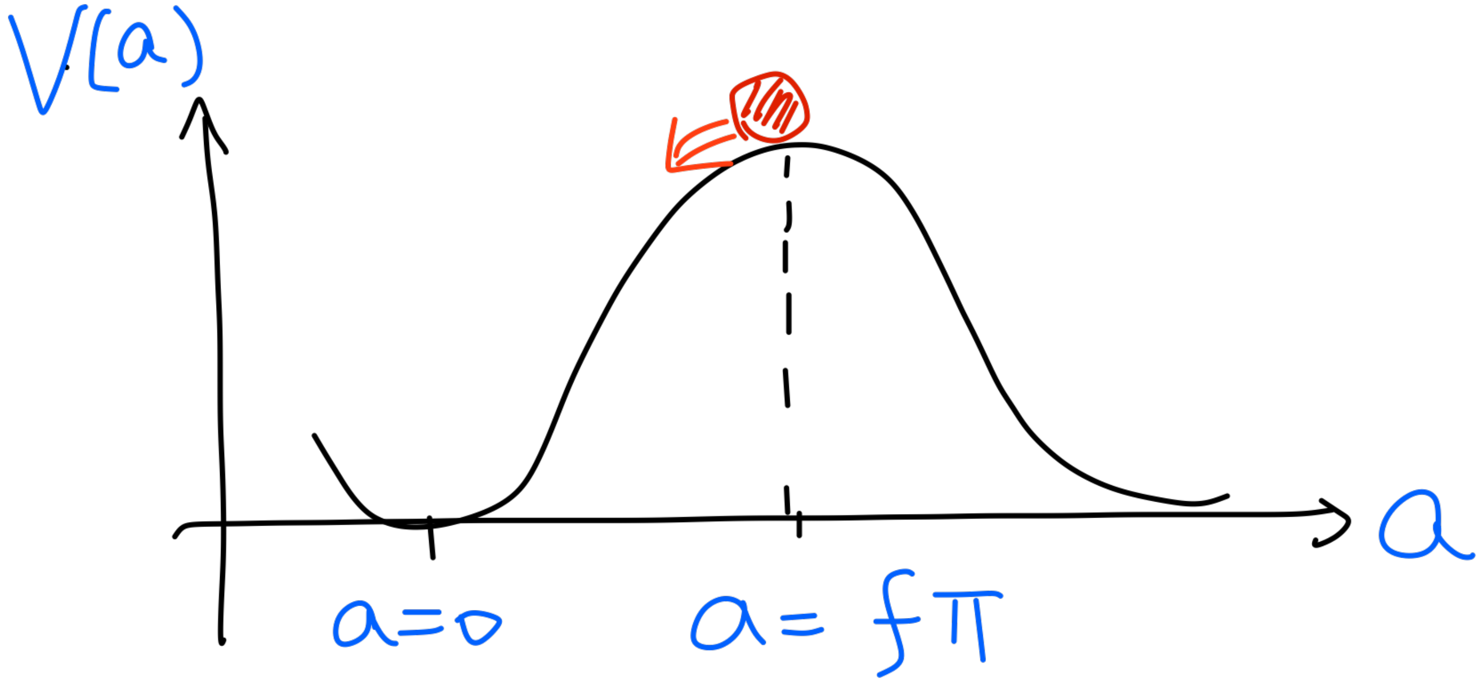
* However, we need small quintessence mass

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

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

Hilltop Quintessence ?

[Dutta - Scherrer ('08), ...]



Choose

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

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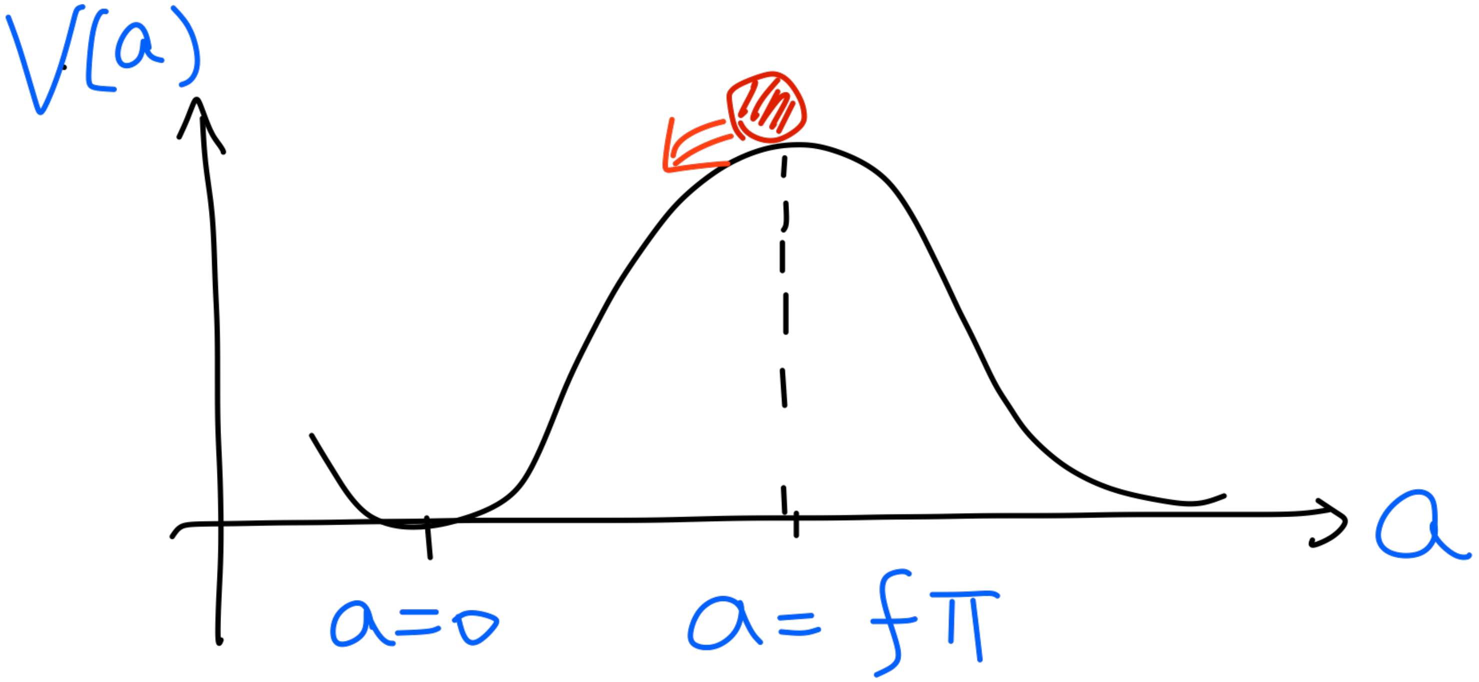

Choose

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

However, this requires

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

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

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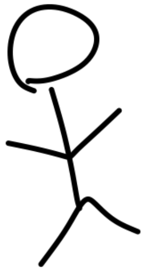
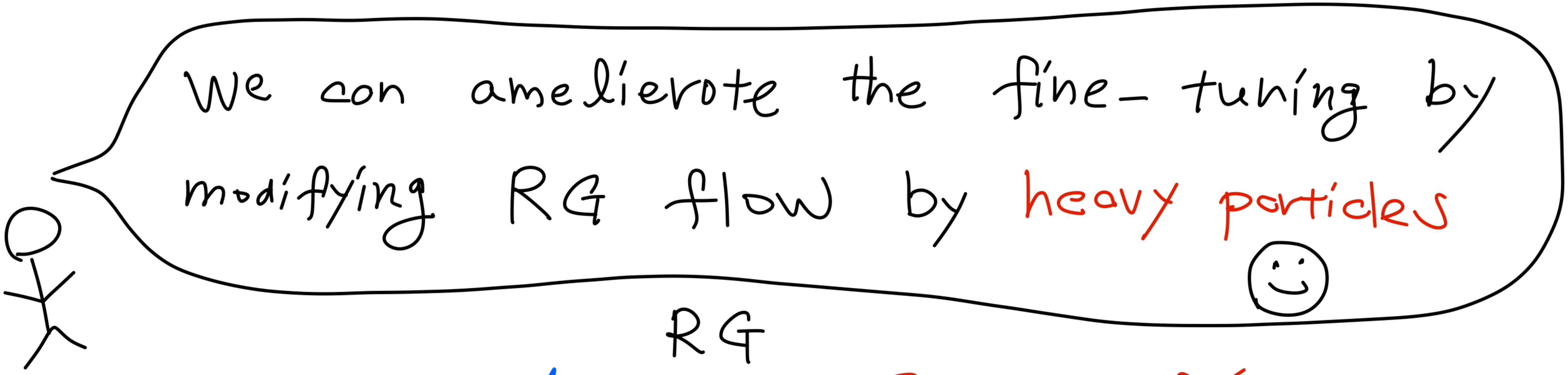


We can amelierate the fine-tuning by modifying RG flow by heavy particles

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

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



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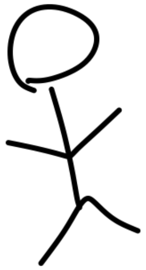
$$\alpha_2(M_Z) \simeq \frac{1}{29} \overset{RG}{\rightsquigarrow} S_{inst} \simeq \mathcal{O}(10)$$

w/ heavy particles

or even

$$\mathcal{O}(1)$$

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



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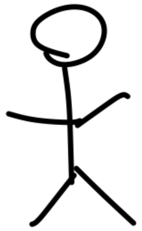
s.t. $f \sim M_{pl}$

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



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

Supersymmetric Miracle

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

EW θ-angle

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

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

dim 5 op. $QQQL$

dangerous for proton decay

[Sakai-Yanagida, Weinberg ('82)]

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

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

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

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

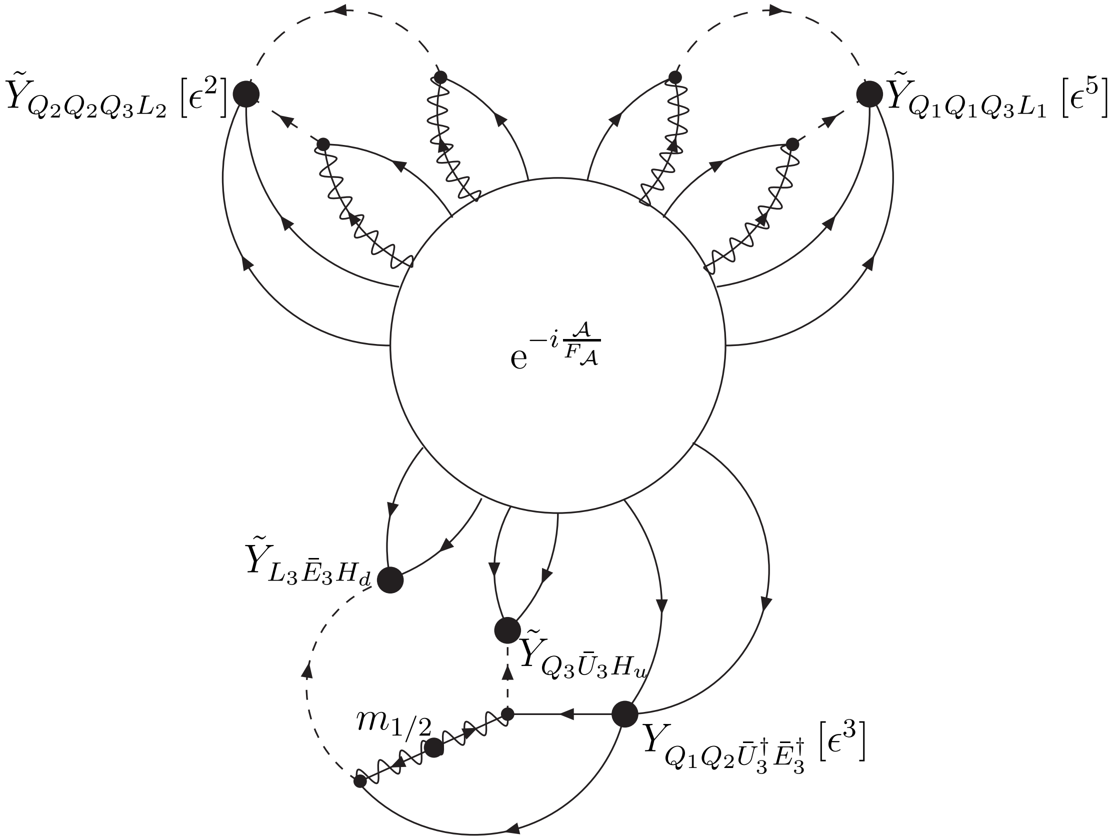
$$\alpha_2(M_{pl})\Big|_{MSSM} = \frac{1}{23} \quad \text{cf.} \quad \alpha_2(M_{pl})\Big|_{SM} = \frac{1}{48}$$

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

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

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

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



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

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

↙ Dynkin index

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

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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)]

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

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

② 1 SU(2) triplet

1 SU(3) octet

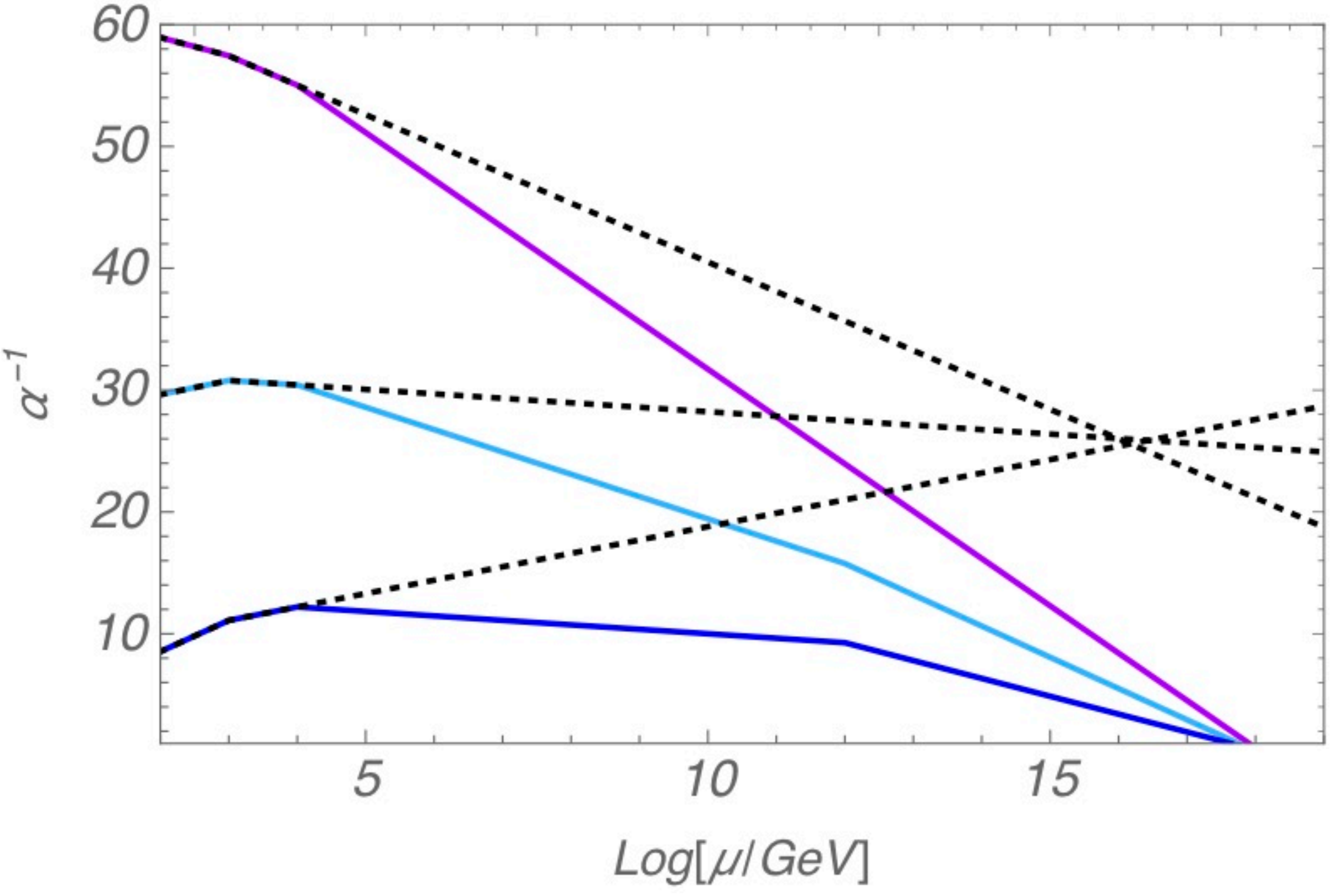
at $\mathcal{O}(10^{12}\,\mathrm{GeV})$

$+$

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

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

gauge coupling unification



Dark ~~Energy~~

Matter

If $m_{SUSY} \gg \text{TeV}$ then

no need for FN suppression

for dim 5 proton decay

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

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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

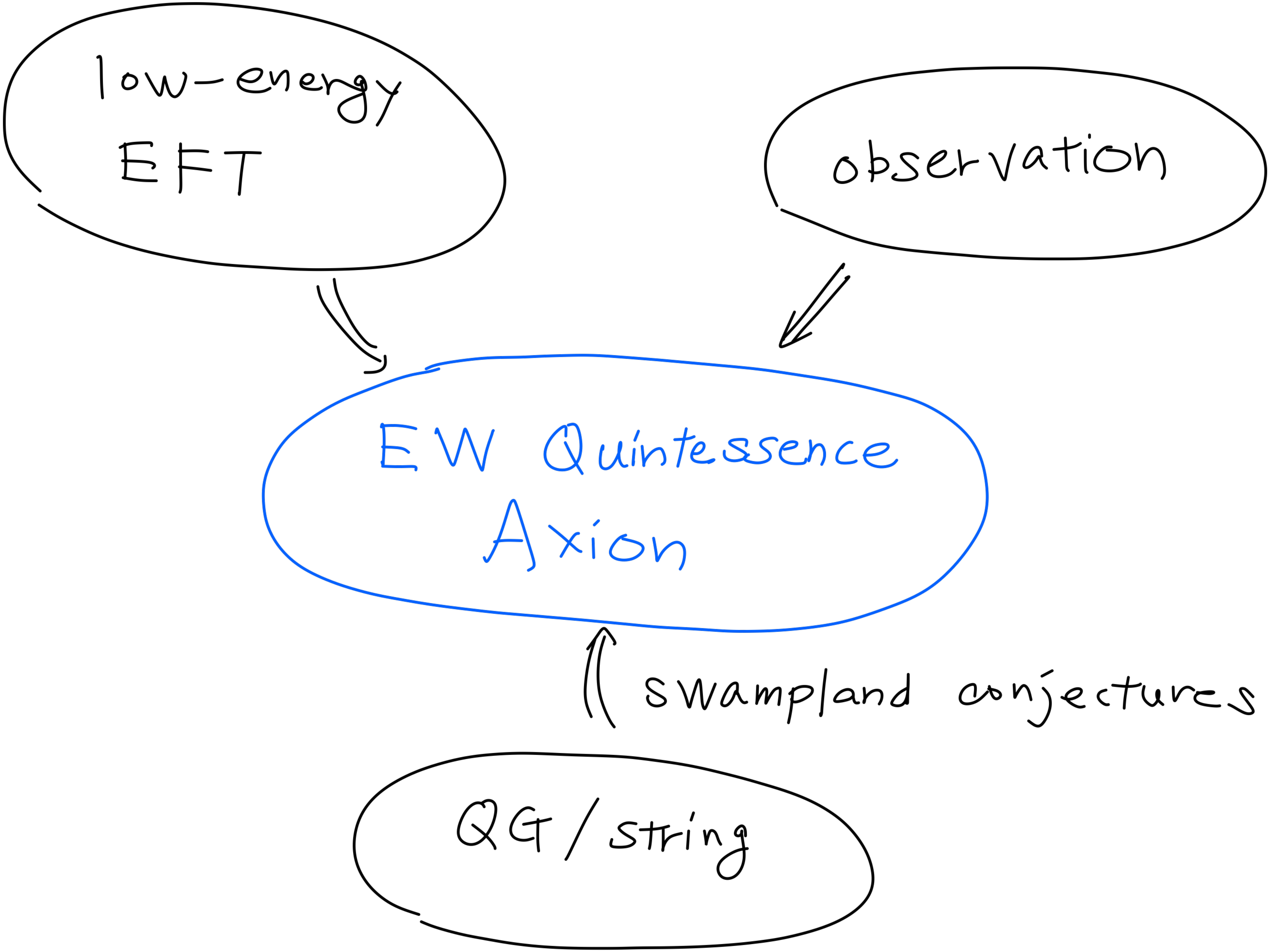
$$\Lambda^4 \simeq M_{pl}^2 \, e^{-\frac{2\pi}{\alpha_2(M_{pl})}} \simeq \mathcal{O}(10^{-130}) M_{pl}^4 \; !$$

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

- 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" $\wedge$ robust)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「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)]

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

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

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 - Shirai - MY ('18)]