Electroweak Quintessence Axion

and

Swampland Conjectures

Masahito Yamazaki

(Kavli IPMU, Univ. Tokyo)

PASCOS 2019, Manchester

Based on

arXiv: 1811.04664 [hep-th]

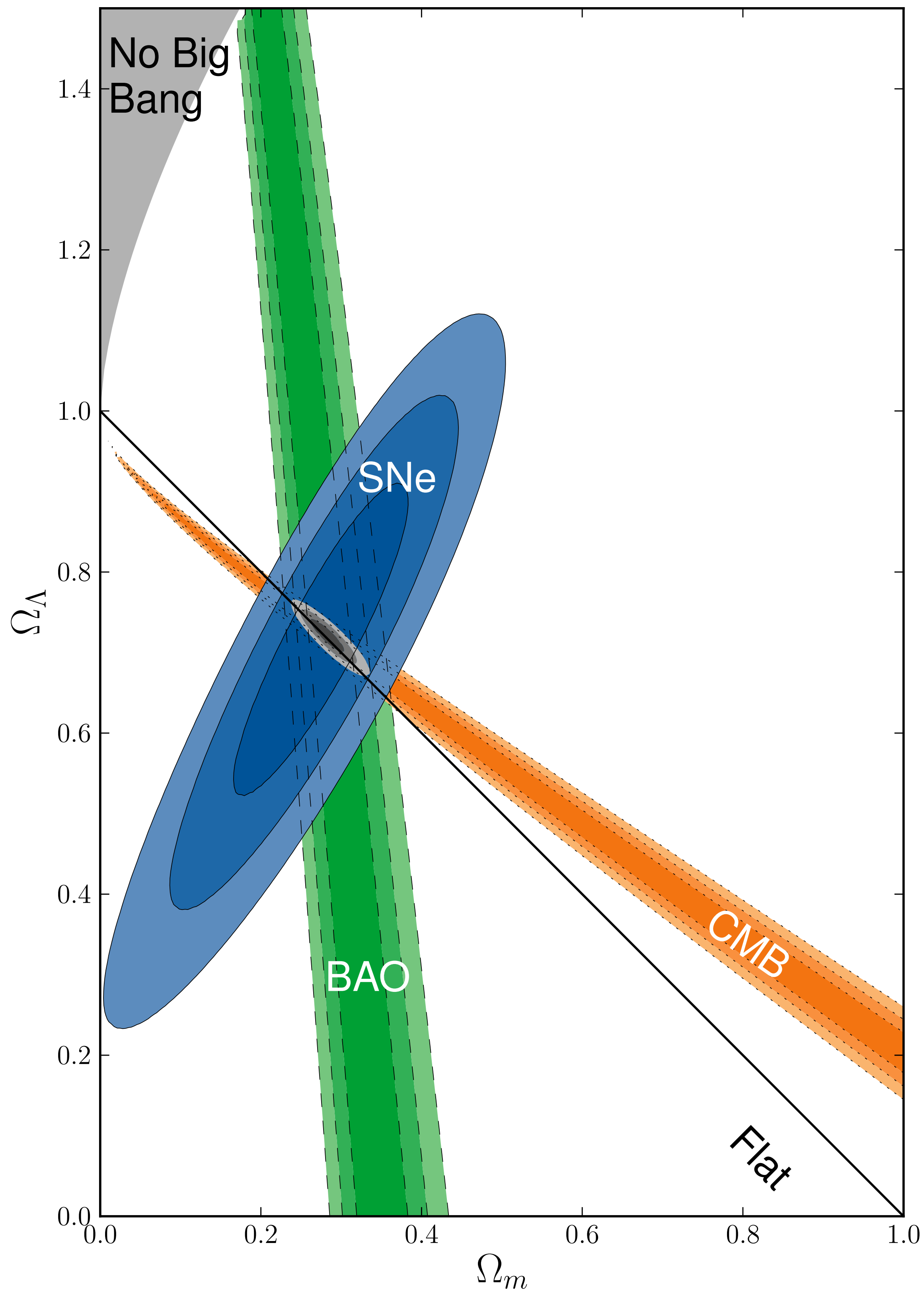
w/ Masahiro Ibe, Tsutomu T. Yanagida

(ICRR Tokyo)

(IPMU Tokyo → TD Lee Inst, Shanghai)

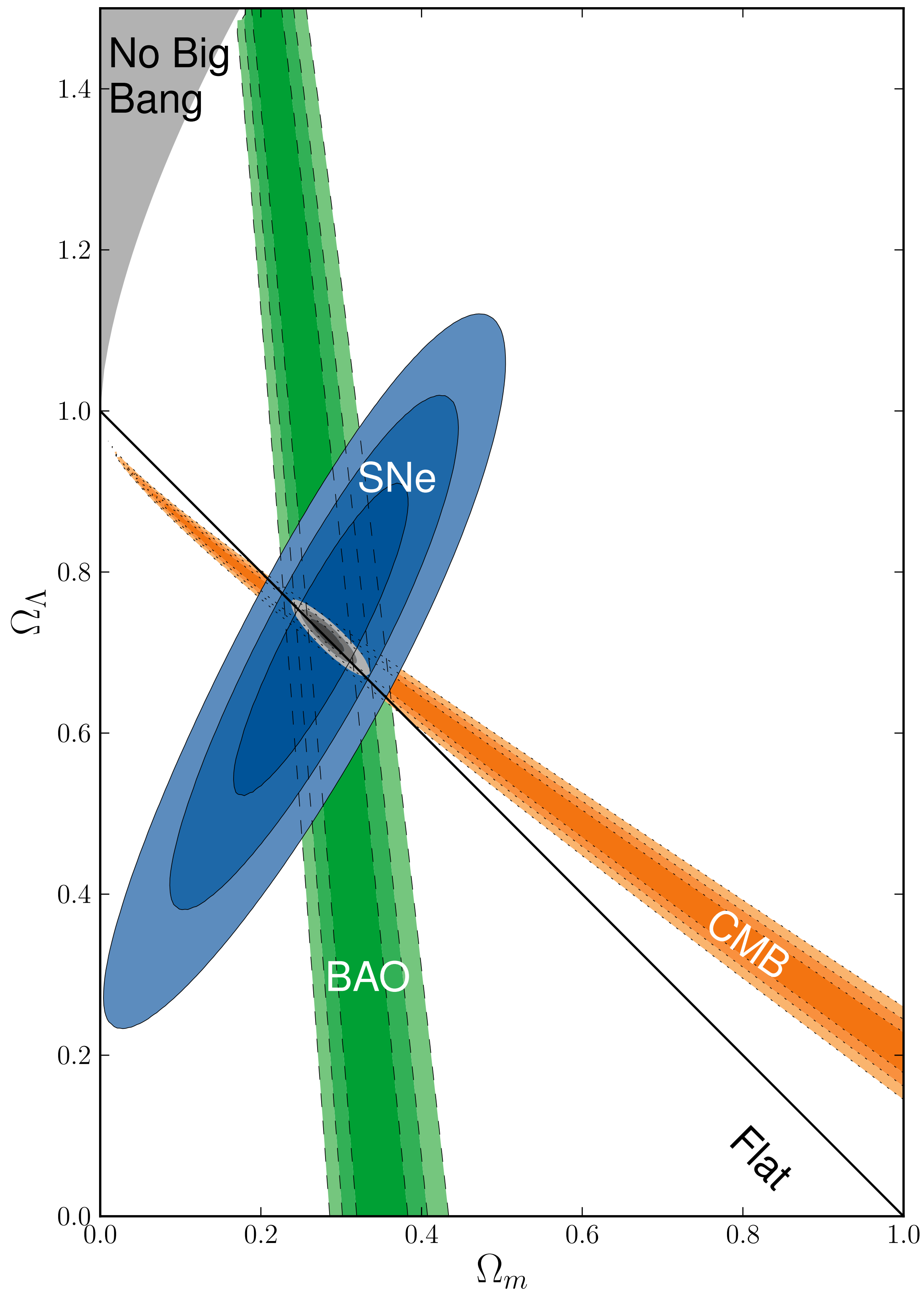
... and many earlier papers

Dark Energy



[Suzuki et al, ('11)]

$\Lambda > 0$!



[Suzuki et al, ('11)]

$\Lambda > 0$!

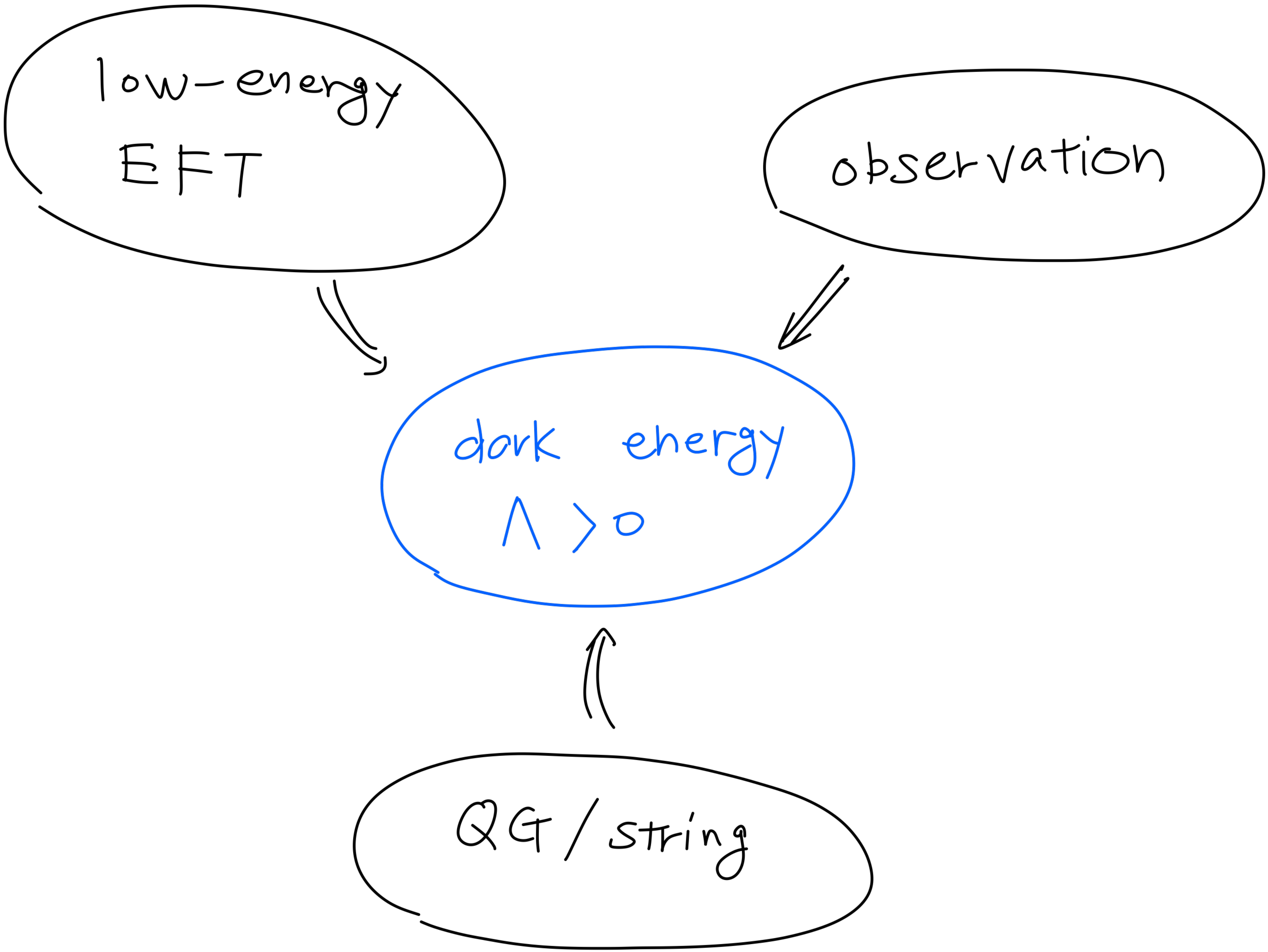
$\Lambda^4 \simeq \mathcal{O}(10^{-120}) M_{pl}^4$

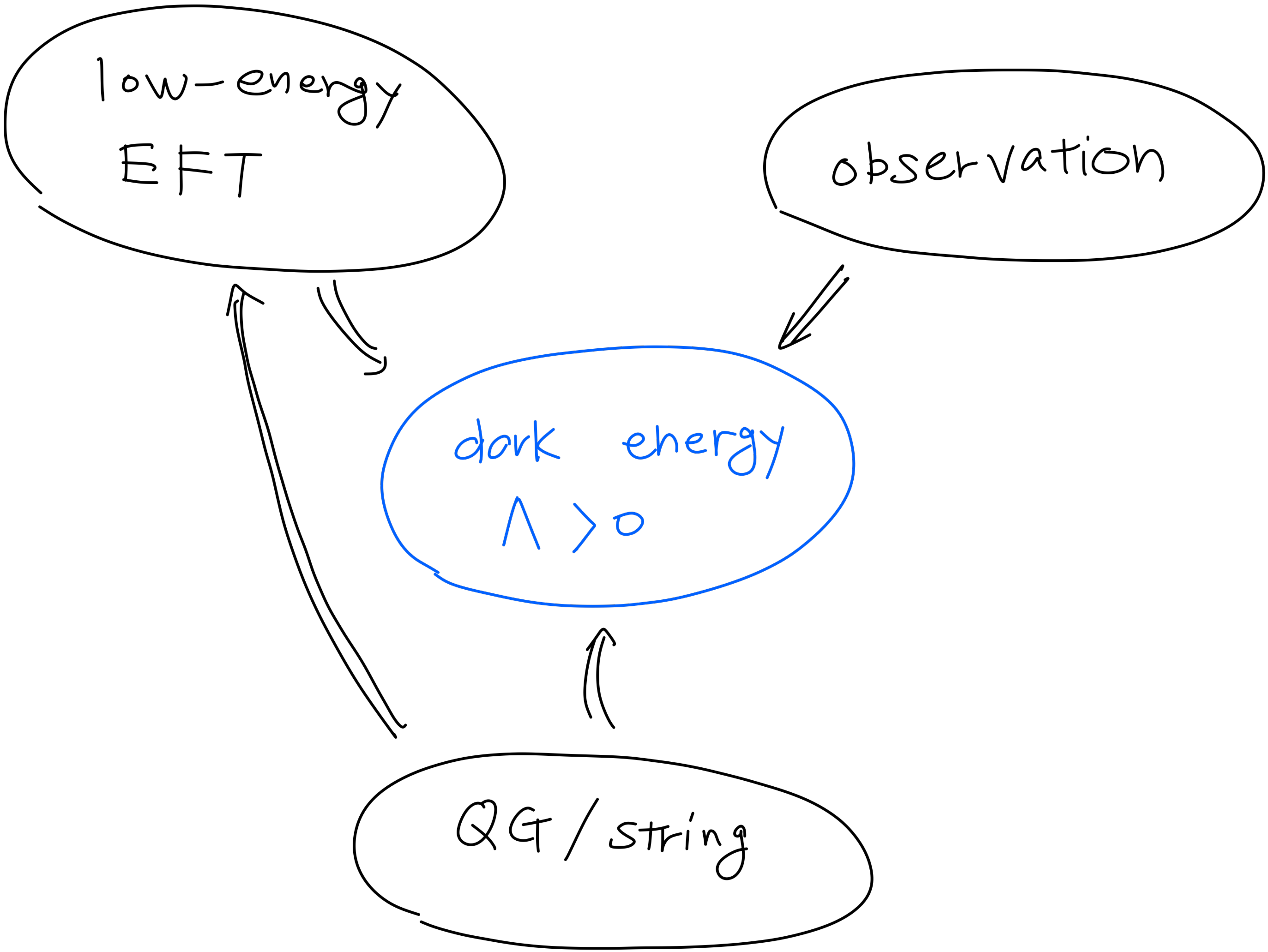
$\ll M_{pl}^4$!!

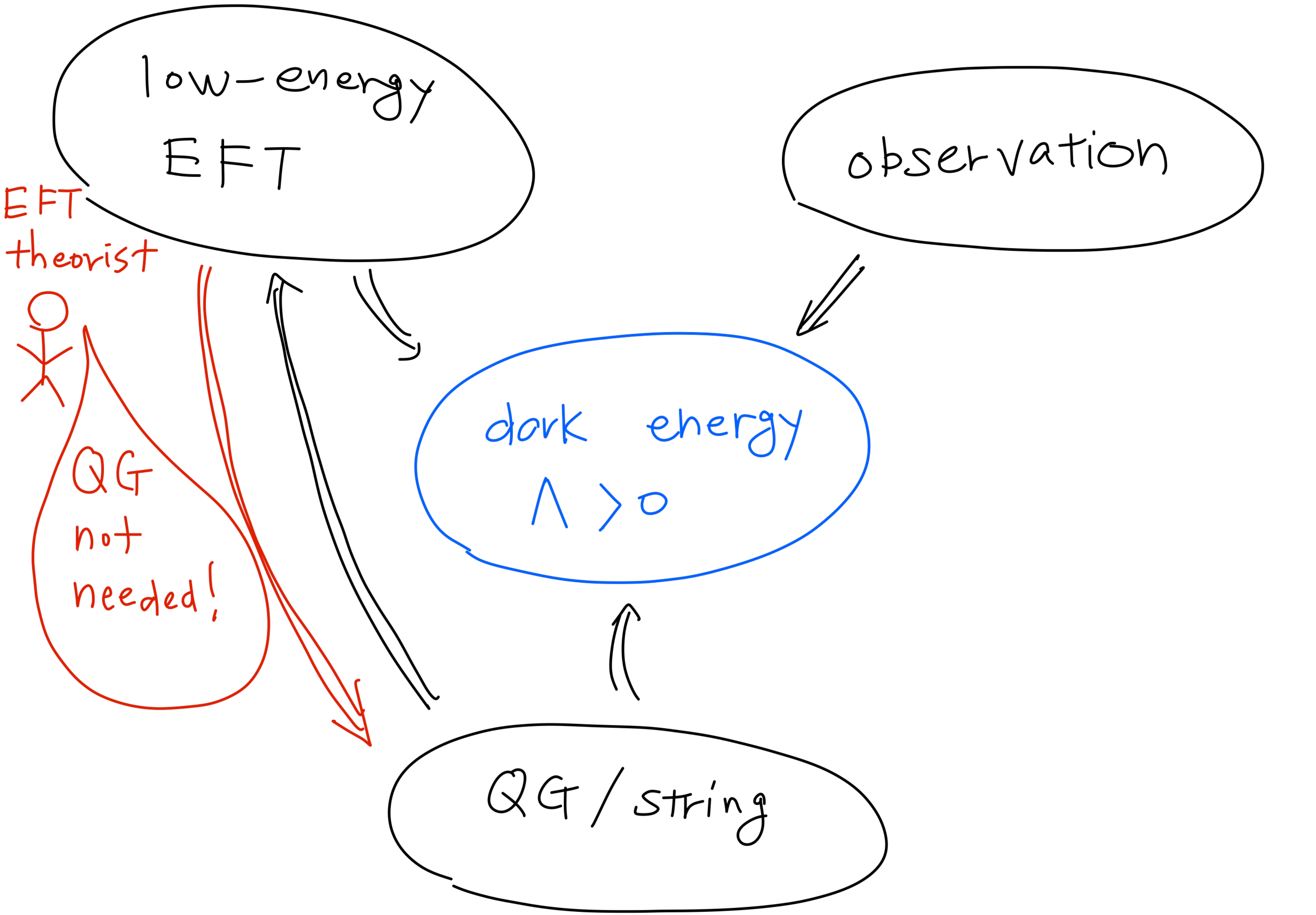
$$\Lambda^4 \simeq \mathcal{O}(10^{-120})\, M_{Pl}^4 \ll M_{Pl}^4$$

while dark energy is IR phenomenon

it is partly about $\underbrace{\text{UV}}_{\text{QG, string, ...}}$


low-energy EFT
observation
dark energy
Λ > 0
QG / string


low-energy EFT
observation
dark energy
Λ > 0
QG / string

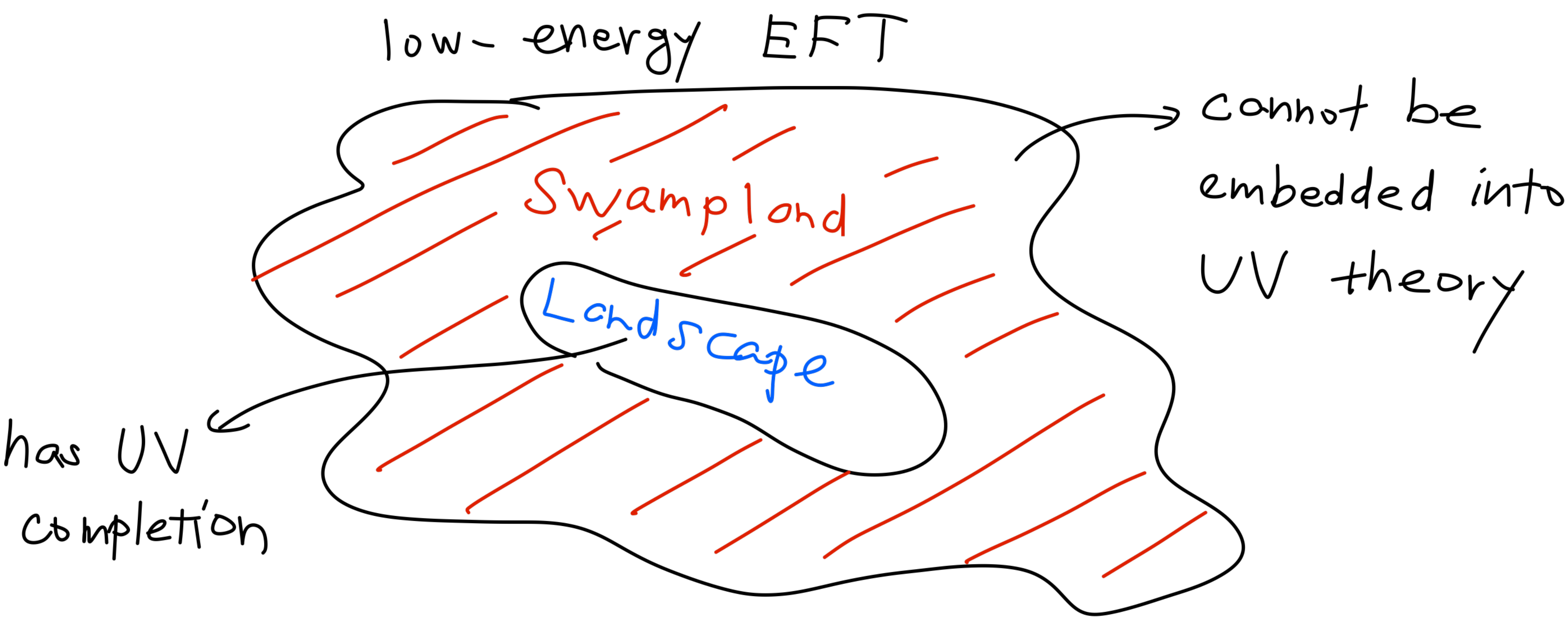


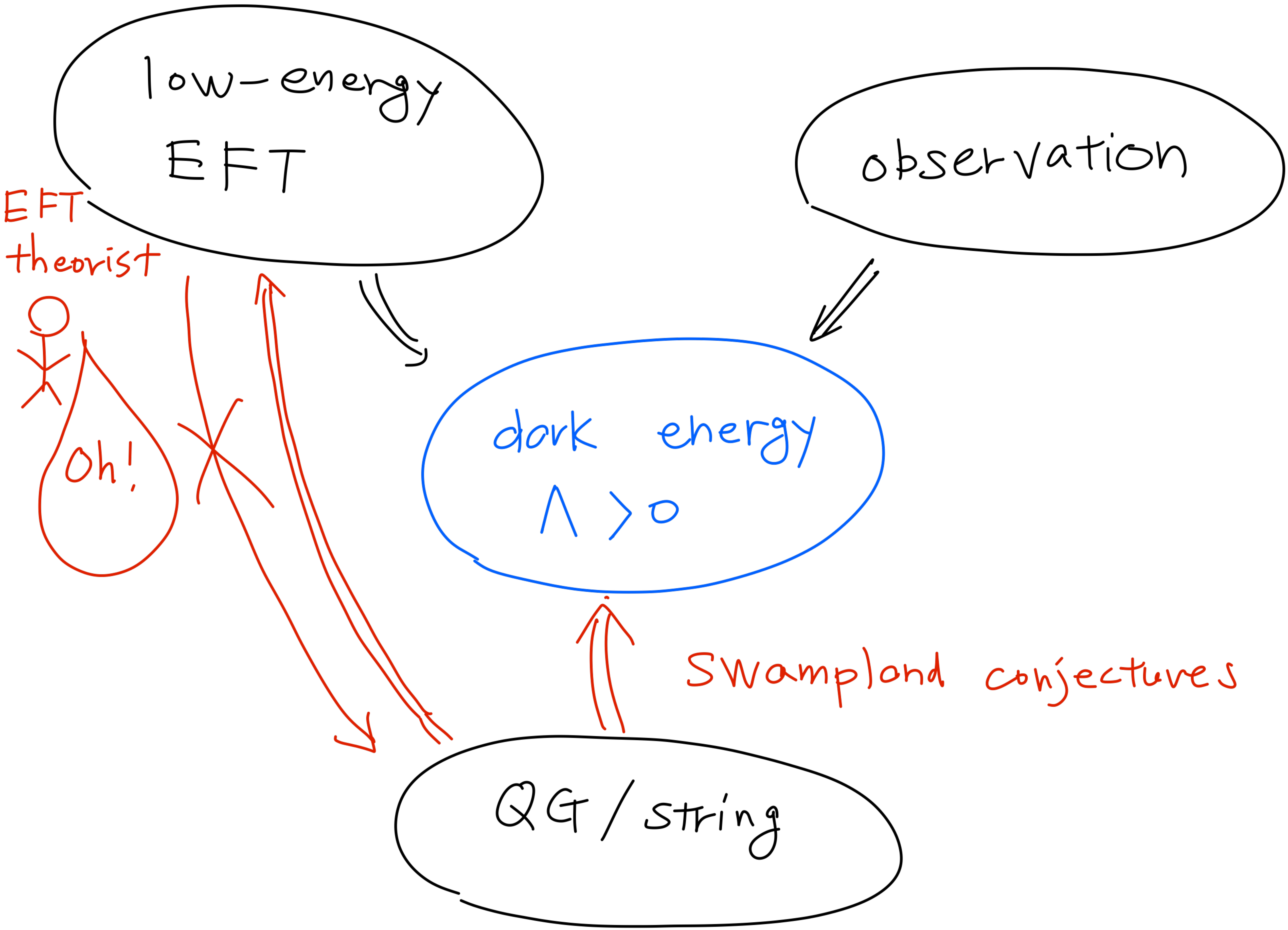
low-energy EFT
observation
EFT theorist
QG not needed!
dark energy
$\Lambda > 0$
QG / string

Swampland Conjectures:

[Vafa ('05), Ooguri–Vafa ('06), ⋯]

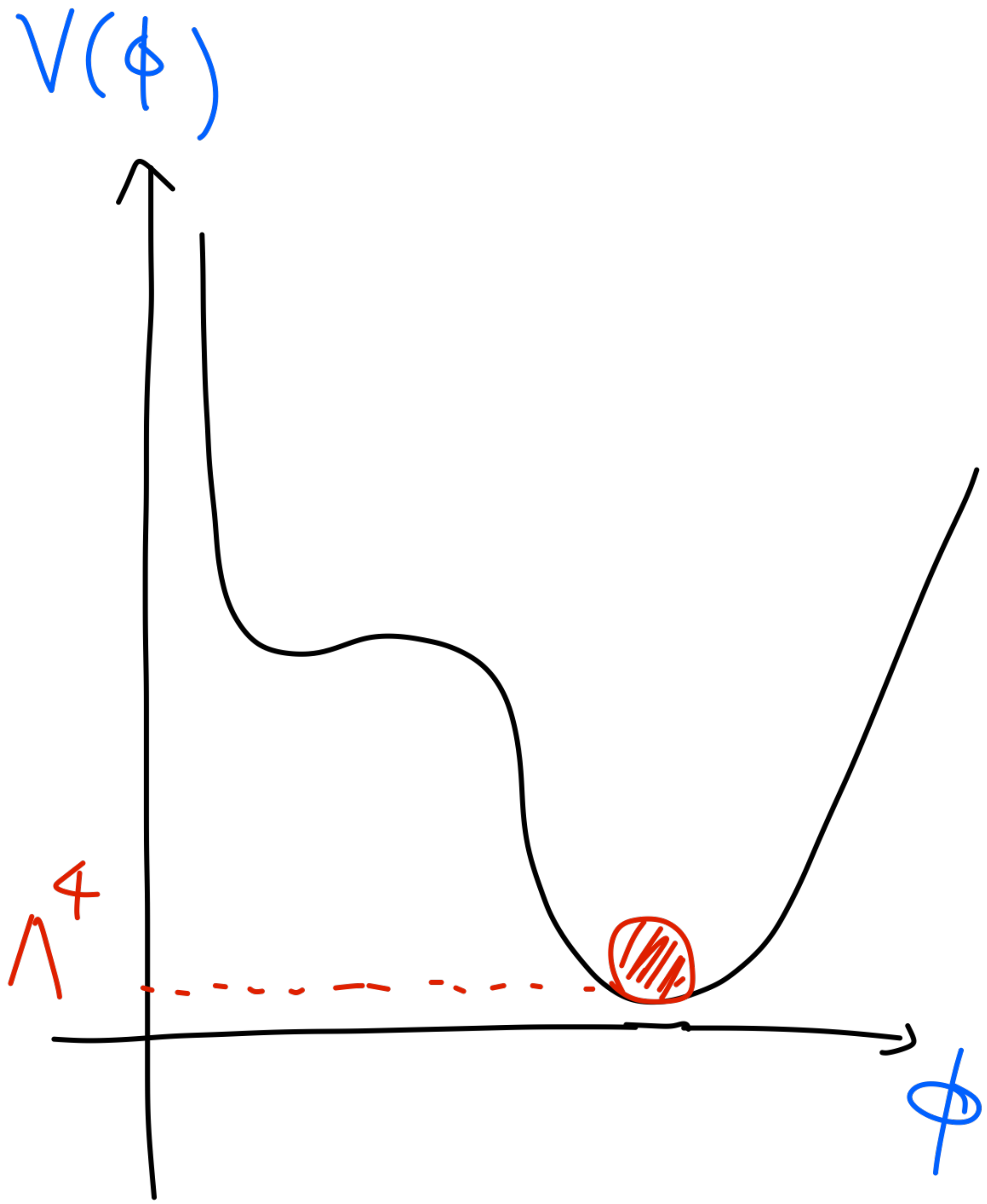
existence of UV completion in QG constrains low-energy EFT



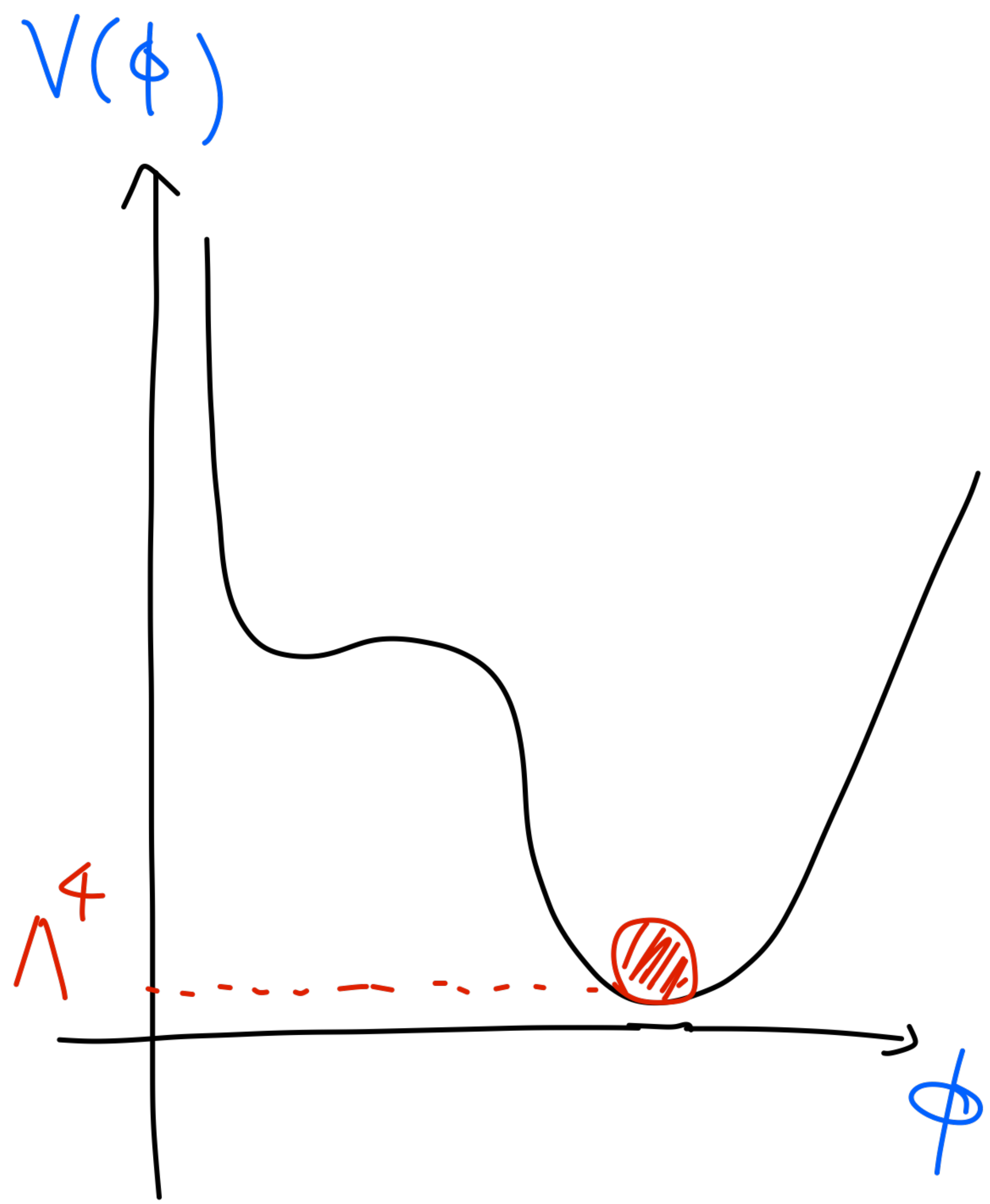

low-energy EFT
observation
EFT theorist
Oh!
dark energy
$\Lambda > 0$
Swampland conjectures
QG / string

How to Realize $\wedge$?

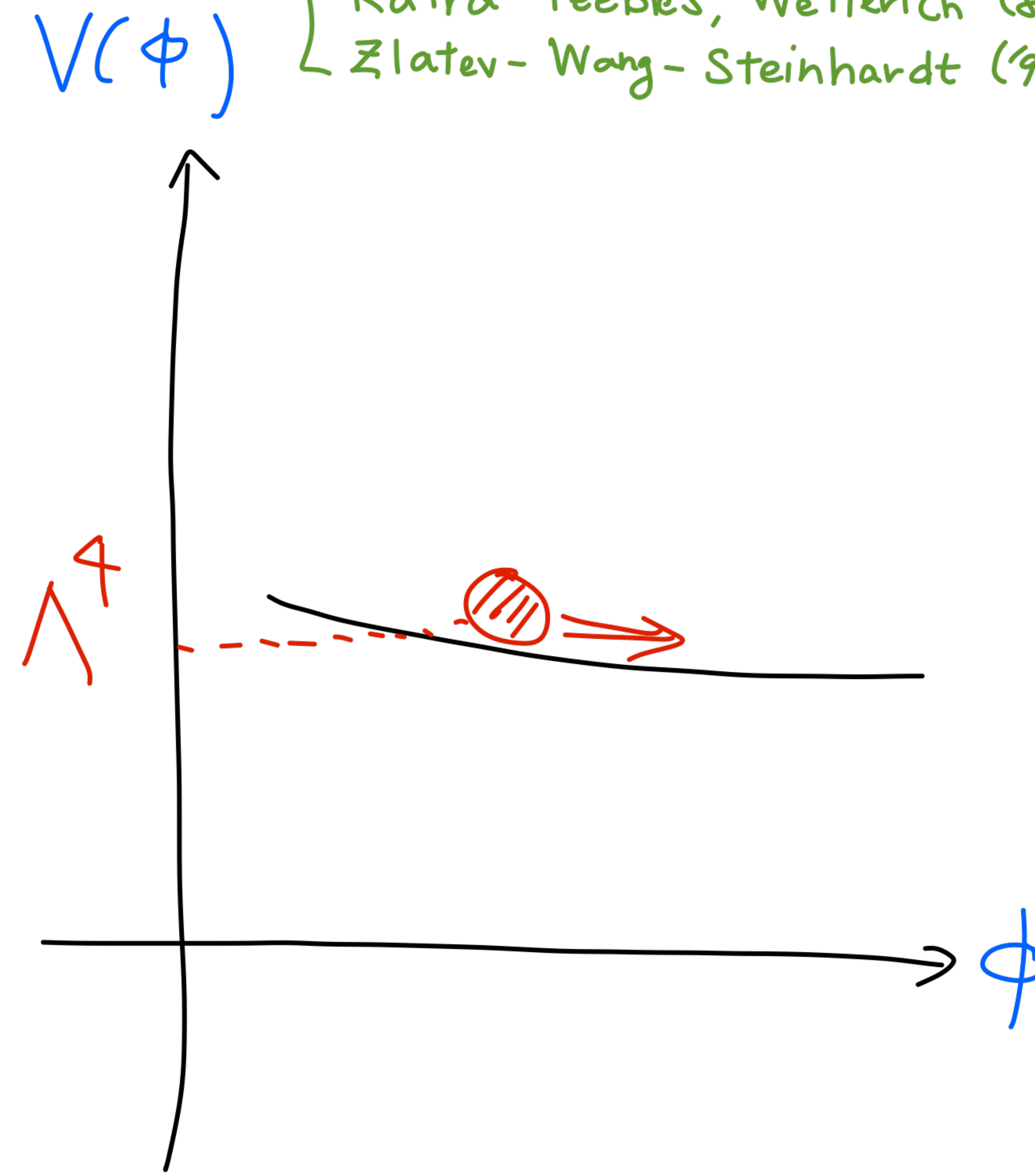
cosmological constant



cosmological constant vs. quintessence



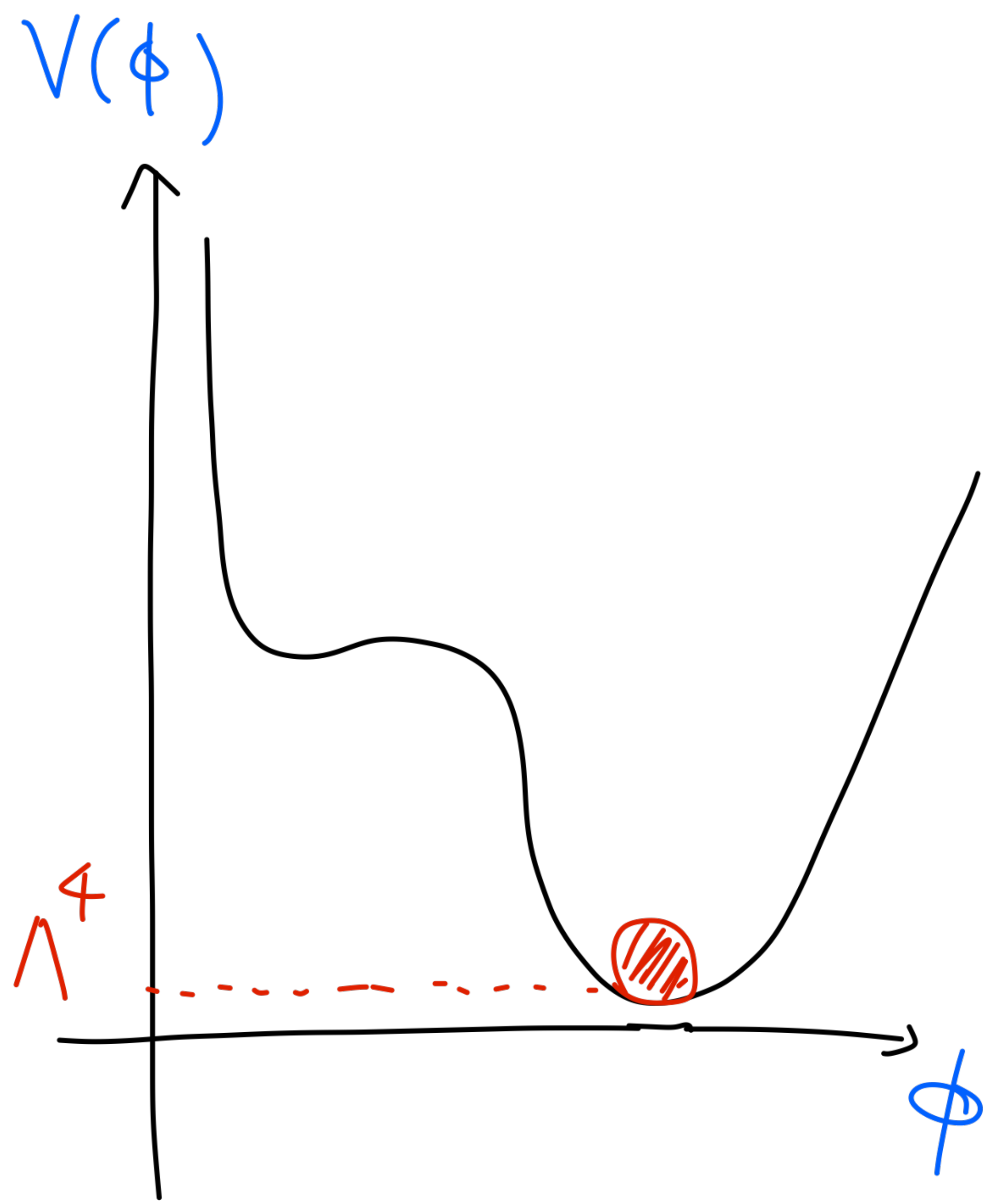
[Ratra-Peebles, Wetterich ('88)
Zlatev-Wang-Steinhardt ('98)]

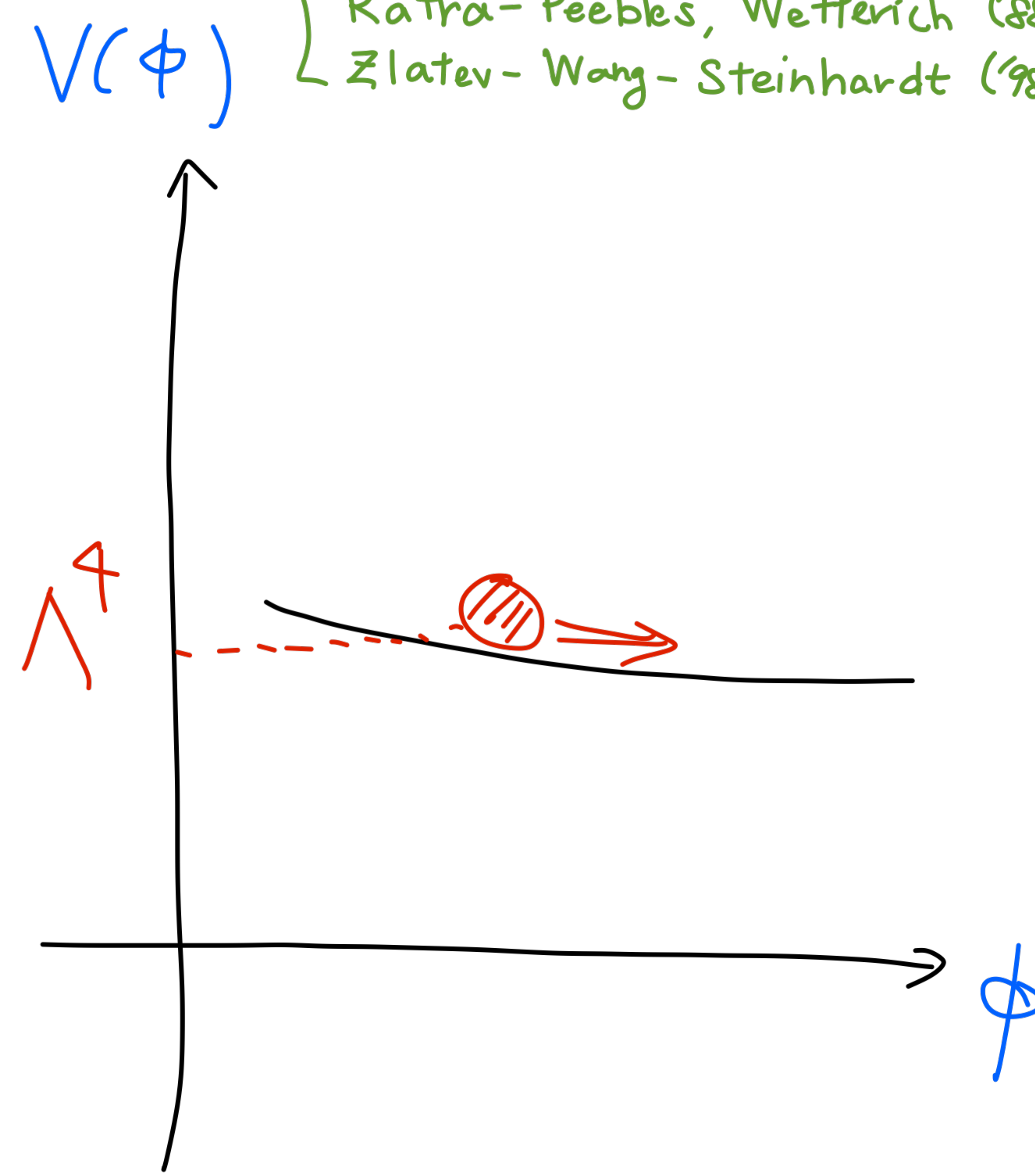


TODAY!!

cosmological constant vs. quintessence

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





de Sitter swampland conjecture

[Obied-Ooguri-Spodyneiko-Vafa ('18)]

$$M_{Pl} \, \|\nabla V\| \geq c \, V \qquad (c \sim \mathcal{O}(1), \; c > 0)$$

excludes dS vacua $(\nabla V = 0 \, , \quad V > 0)$

$\rightsquigarrow$ motivates quintessence [Agrawal-Obied-Steinhardt-Vafa ('18)]

de Sitter swampland conjecture

[Obied-Ooguri-Spodyneiko-Vafa ('18)]

$$M_{Pl} \|\nabla V\| \geq c\, V \qquad (c \sim \mathcal{O}(1),\ c>0)$$

excludes dS vacua $(\nabla V = 0\ ,\ V > 0)$

⇝ motivates quintessence [Agrawal-Obied-Steinhardt-Vafa ('18)]

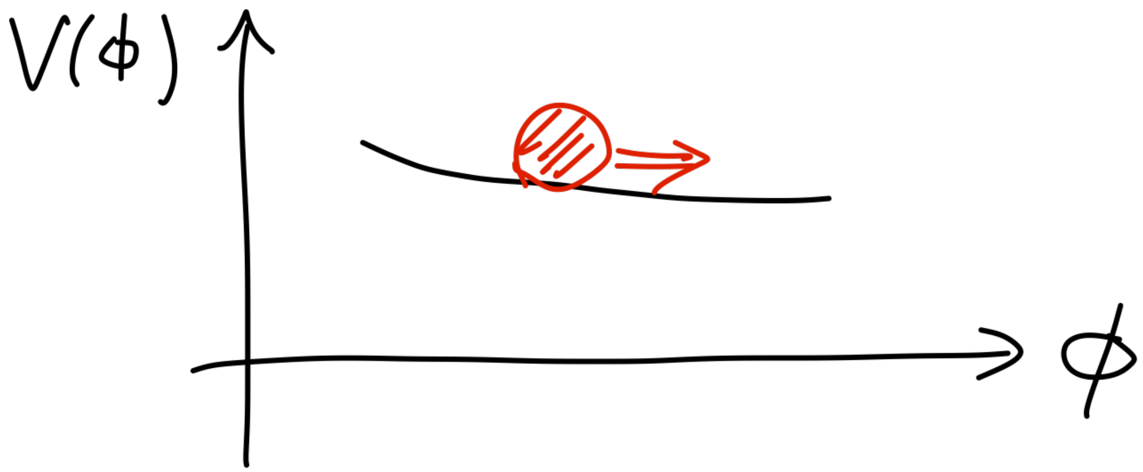
* speculative, better motivated in asymptotic region

[cf. Dine-Seiberg ('85), Maldacena-Nunez ('00), Wesley-Steinhardt ('08), ...
Ooguri-Palti-Shiu-Vafa, Hebecker-Wrase ('18), ...]

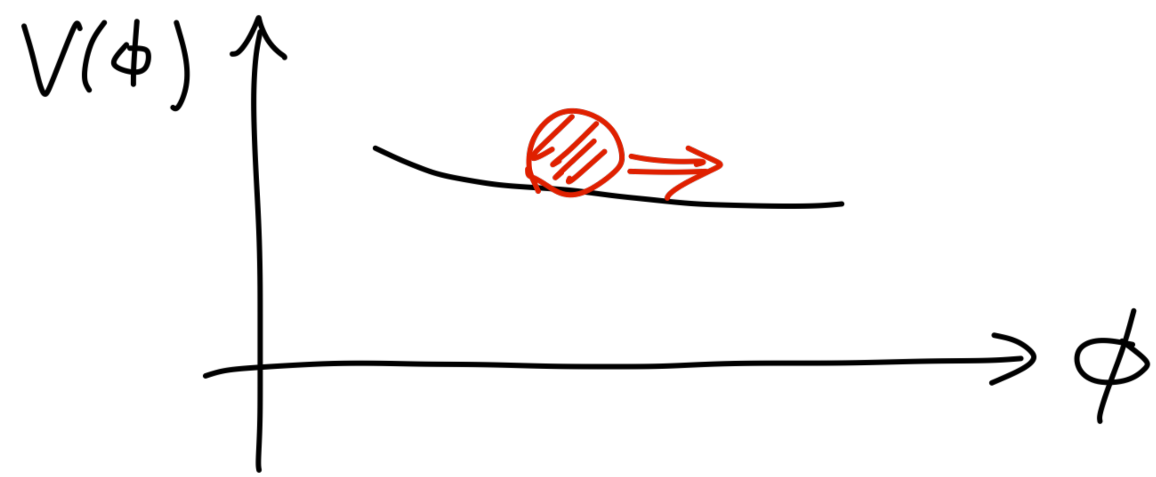
(This talk does not directly rely on this conjecture)

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), …]

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

$\frac{a}{f}$: dynamical θ angle

F: non-Abelian gauge field

(※ this is the ONLY coupling of a)

shift symmetry

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

broken by non-pert. effect

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

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

shift symmetry

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

broken by non-pert. effect

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

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

Q: which non-Abelian gauge field?

why particular value of α?

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

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

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

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

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

(※ 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)]

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

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

* Weak gravity conjecture implies

[Arkani-Hamed-Motl-Nicolis-Vafa ('06)]

[See also Banks-Dine-Fox-Gorbatov ('03)]

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

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

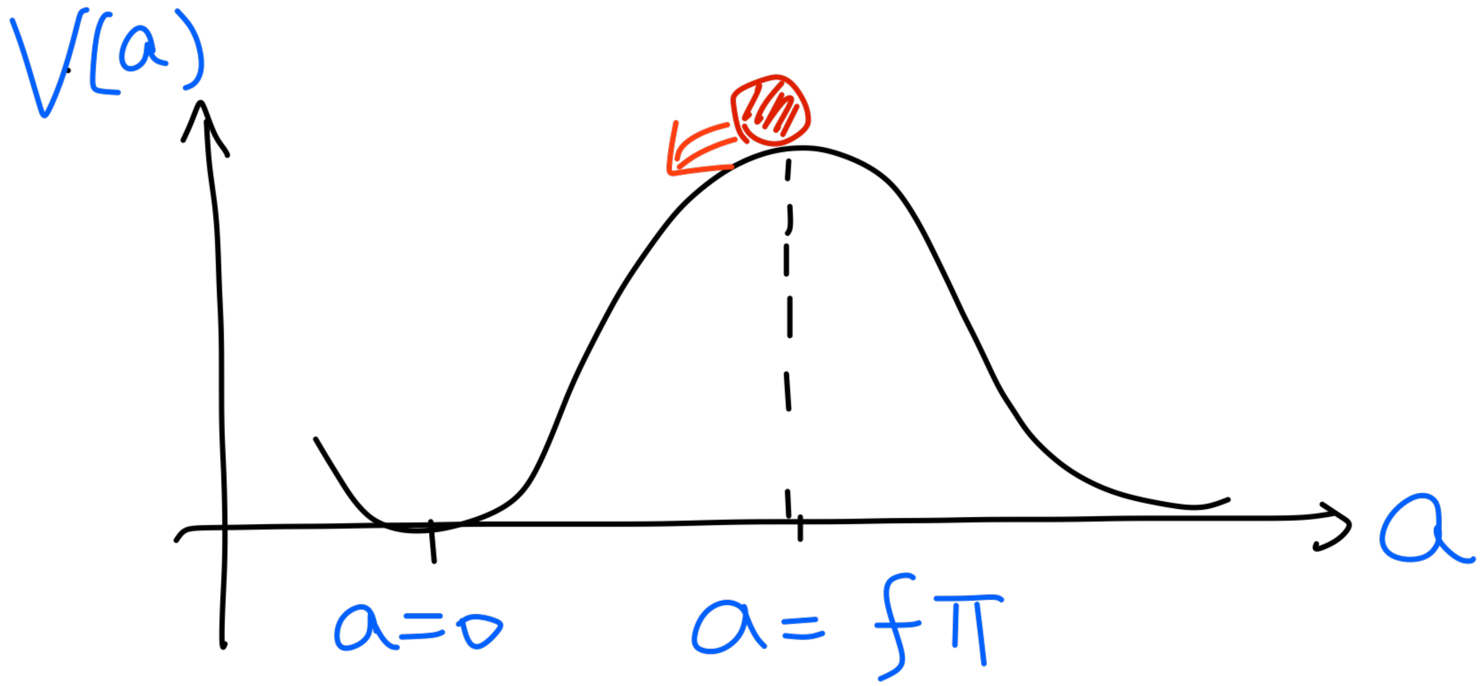
* However, we need small quintessence mass

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

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

Hilltop Quintessence?

[Dutta-Scherrer ('08), ⋯]



Choose

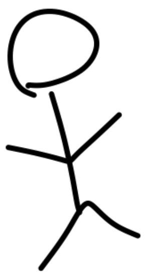
$\delta a = |a - f\pi| \ll f\pi$ to avoid too much rolling

However, this requires

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

(e^{100} ← S_{inst})

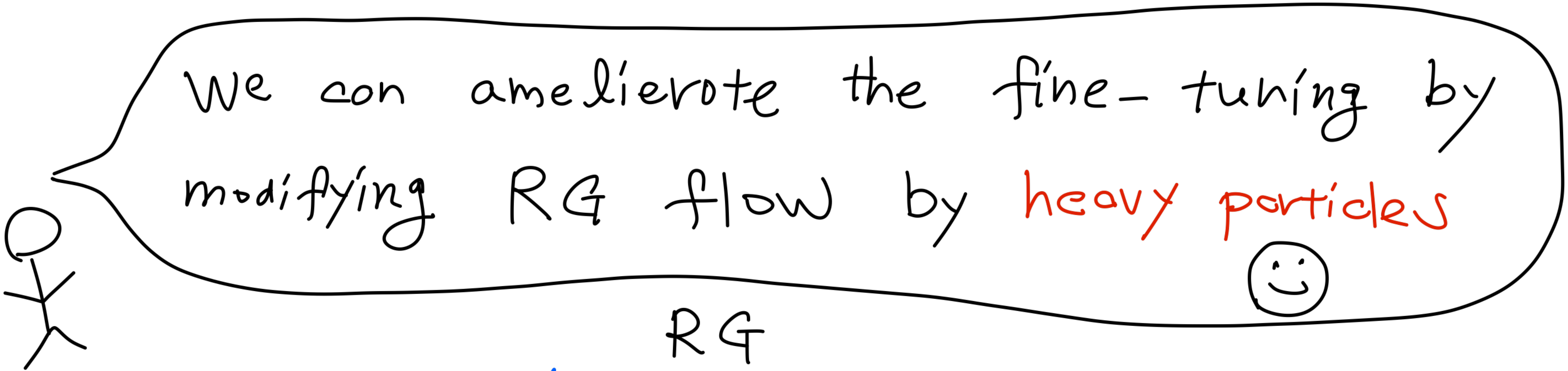
[see e.g. Choi ('99), Svrcek ('06), Ibe-Yanagida-MY ('18)]



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

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

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



$$\alpha_2(M_Z) \simeq \frac{1}{29} \quad \overset{\text{RG}}{\rightsquigarrow} \quad \alpha_2(M_Z) \sim \mathcal{O}(1)$$

w/ heavy particles

$$S_{inst} \sim \mathcal{O}(10)$$

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

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

w/ heavy particles

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

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

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

Supersymmetric Miracle

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

EW θ-angle

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

EW θ-angle ⟵ (B+L)-breaking

dim 5 op. $QQQL$

dangerous for proton decay

[Sakai-Yanagida, Weinberg ('82)]

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

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

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

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

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

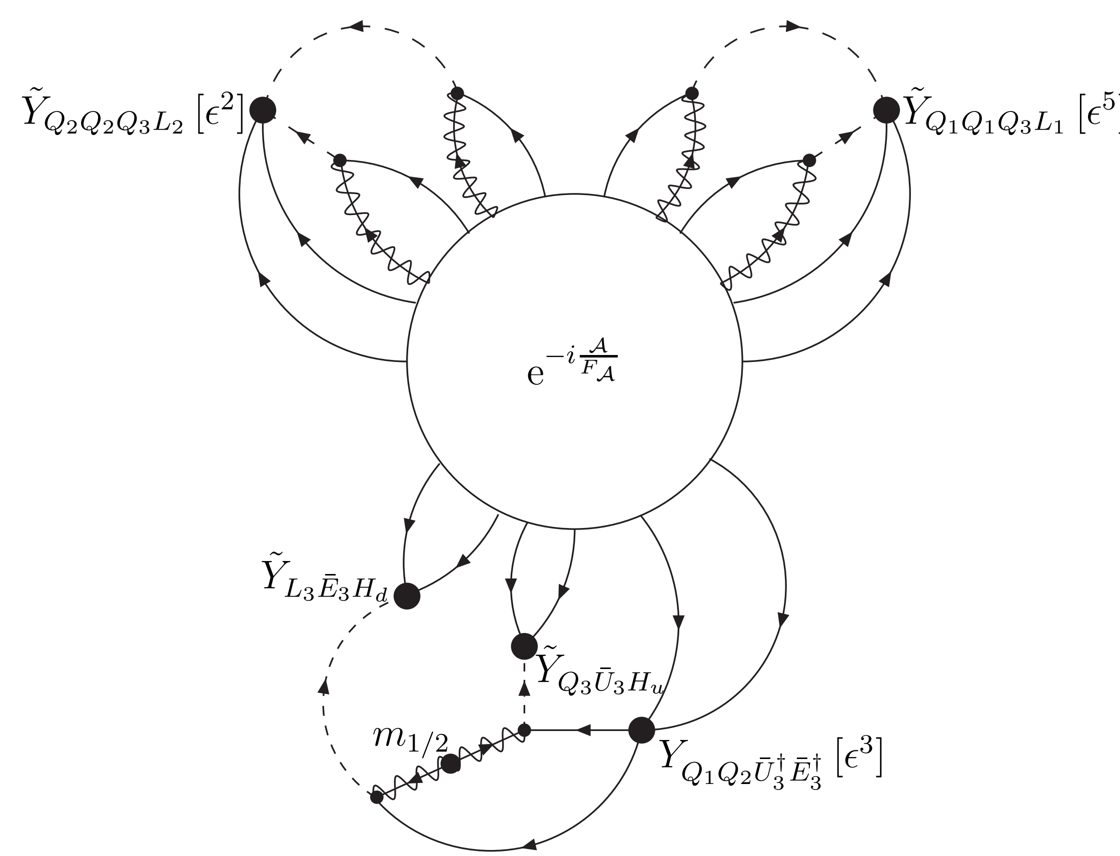
instanton calculus gives [Nomura-Watari-Yanagida ('00)]

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

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

↑

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

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

← Dynkin index

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

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 (the two $\left(\cdot\right)^{2T_R}$ factors)

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

→ 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 $\mathcal{O}(10^7\,\text{GeV})$

② 1 SU(2) triplet

1 SU(3) octet

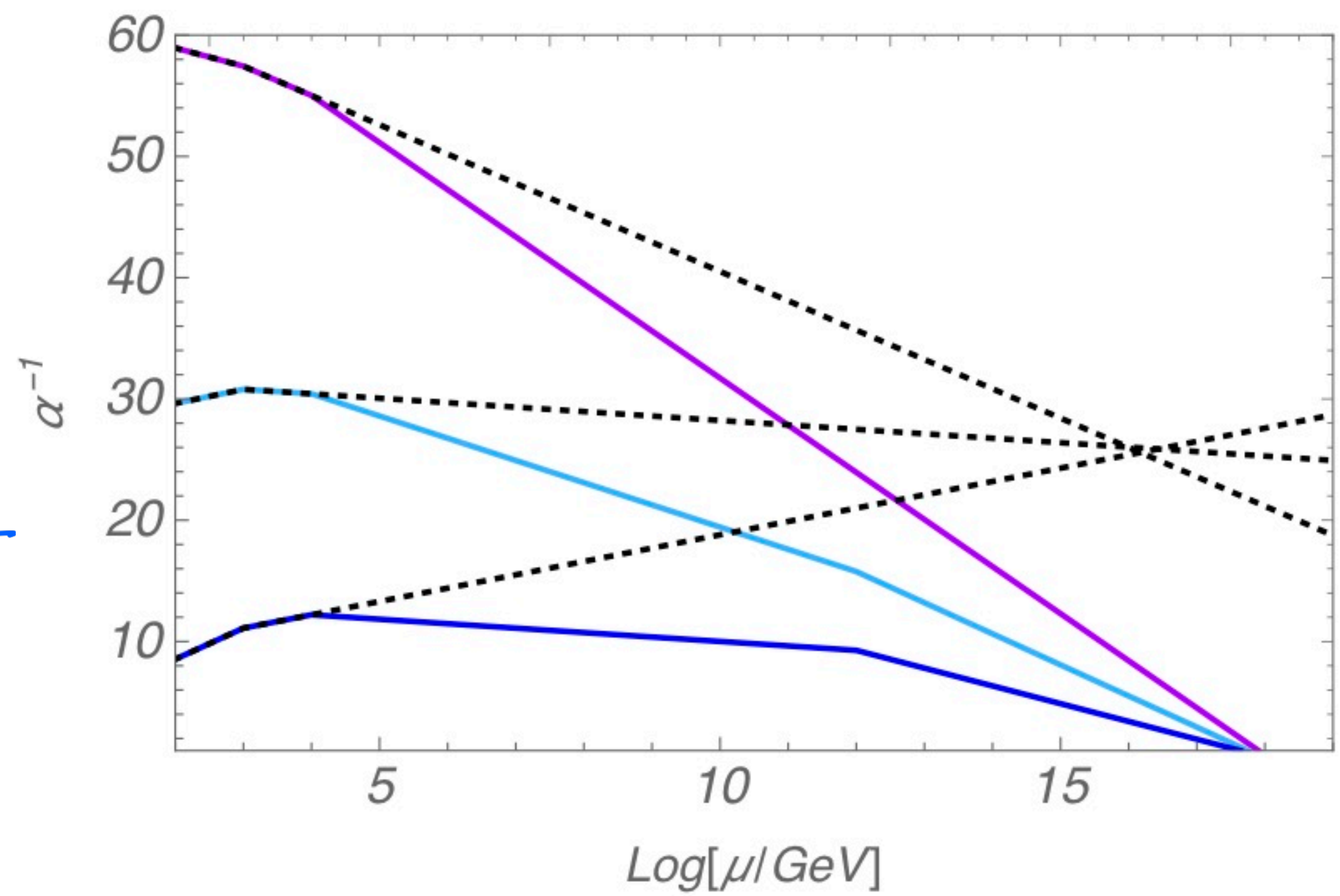
at $\mathcal{O}(10^{12}\,\text{GeV})$

+

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

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

gauge coupling unification



More Swampland Conjectures

「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,

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)]

However, consistent w/ refined dS conjecture

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

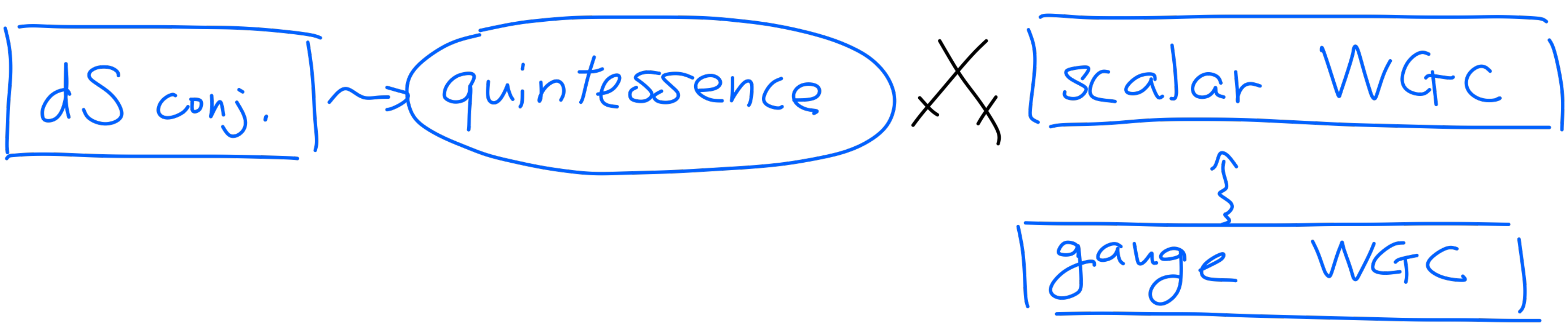
[Garg - Krishnan, Murayama - Yanagida - MY, Ooguri - Palti - Shiu - Vafa, ... ('18)
See also Fukuda - Saito - Shirai - MY ('18)]

「Scalar WGC」

* Some versions of weak gravity conjecture with scalar fields claim [Palti ('17), Shiraishi-MY ('19)]

$$\text{“} F_{\text{scalar}} \geq F_{\text{gravity}} \text{”}$$

This requires $\mathcal{O}(1)$ coupling of quintessence to SM particles, and is highly constrained by fifth-force searches [⋯, Shiraishi-MY ('19)]



「No NON-SUSY AdS」

SM + Majorana neutrinos on S^1 creates

$AdS_3 \times S^1$ vacua [Arkani-Hamed – Dubovsky – Nicolis – Villadoro ('07)],

which is conjecturally forbidden

[Ooguri – Vafa ('16), Ibanez – Martin – Lozano – Venezuela ('17)]

This "problem" removed by two light bosons

(EW axion and QCD axion)

($\rightsquigarrow$ observation ?)

$$\ulcorner \pi_1 = 0 \lrcorner$$

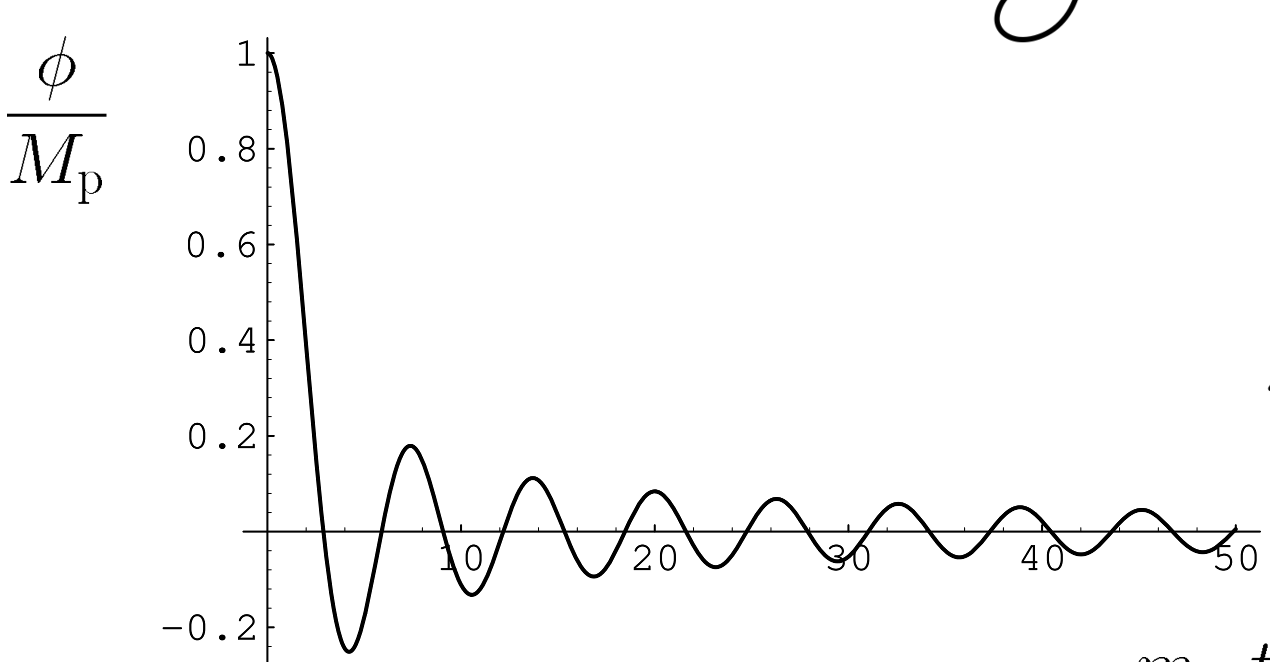
※ axion is complexified into saxion S

[in SUSY / swampland conjecture (Ooguri–Vafa '06)]

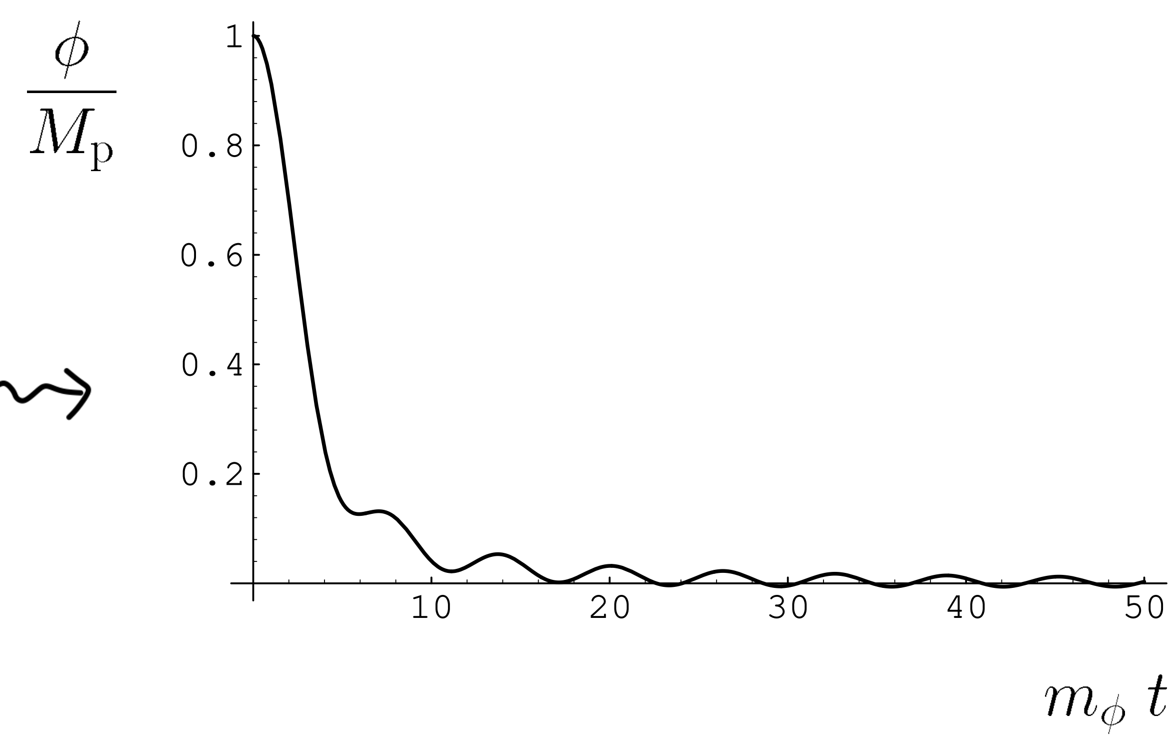
$(\pi_1(S^1) = \mathbb{Z},\ \pi_1(\mathbb{C}) = 0)$

Saxion decay causes moduli/Polonyi problem

This can be saved e.g. by enhancing the coupling w/ inflaton [Linde ('96)]



$\rightsquigarrow$



Summary

electroweak quintessence axion

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

* Electroweak Quintessence Axion :

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

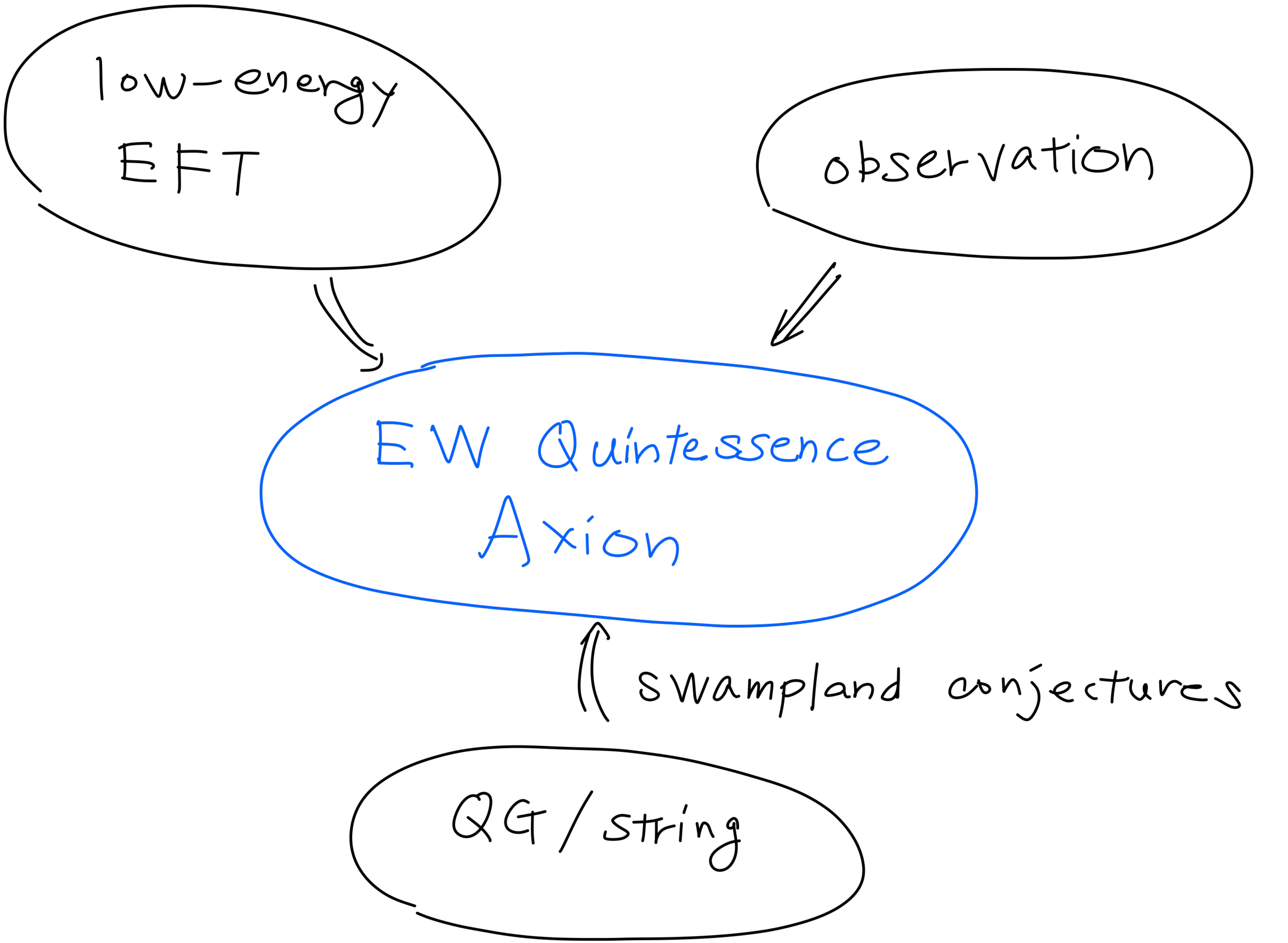
* Consistent w/ de Sitter swampland conjecture

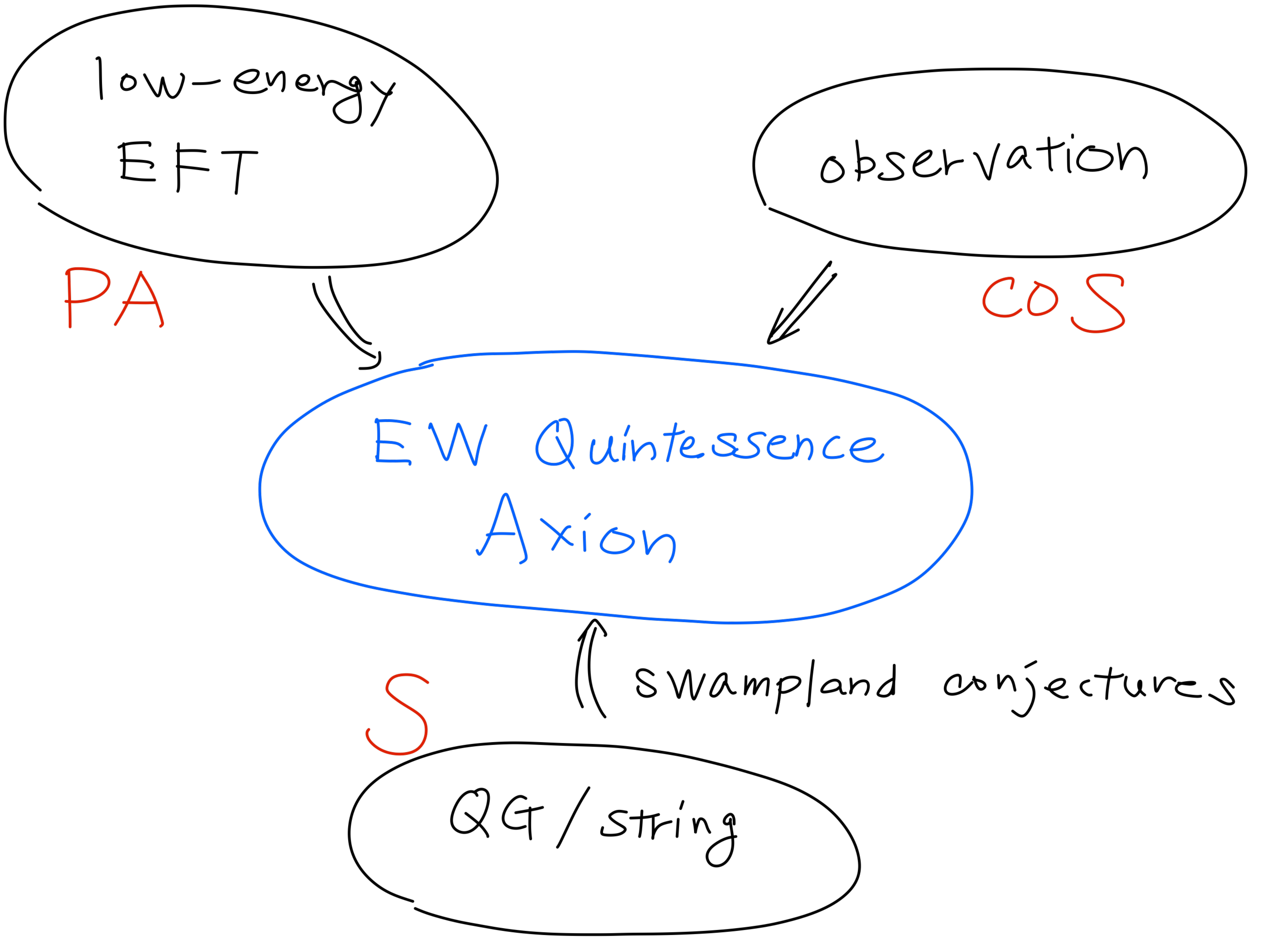
* Consistency w/ weak gravity conjecture

requires fine-tuning into hilltop region

* However, fine-tuning ameliorated in

MSSM + heavy matter (SUSY miracle" Λ robust)


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



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