Title: Electroweak Quintessence Axion Revisited in Light of Swampland Conjectures

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Series: Quantum Fields and Strings

Date: November 12, 2019 - 2:30 PM

URL: http://pirsa.org/19110047

Abstract: It is a curious numerology that the dynamical scale associated with the instanton of the electroweak SU(2) gauge group is approximately the energy scale of dark energy. We revisit this electroweak quintessence axion scenario, taking into account observational as well as swampland constraints.

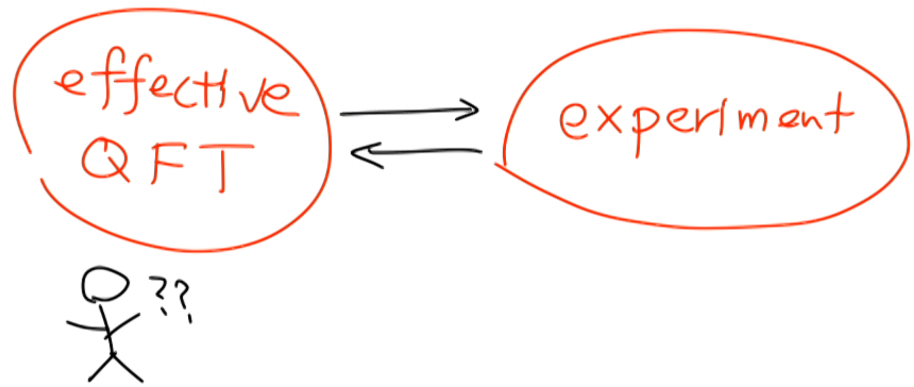
Electroweak Quintessence Axion Revisited

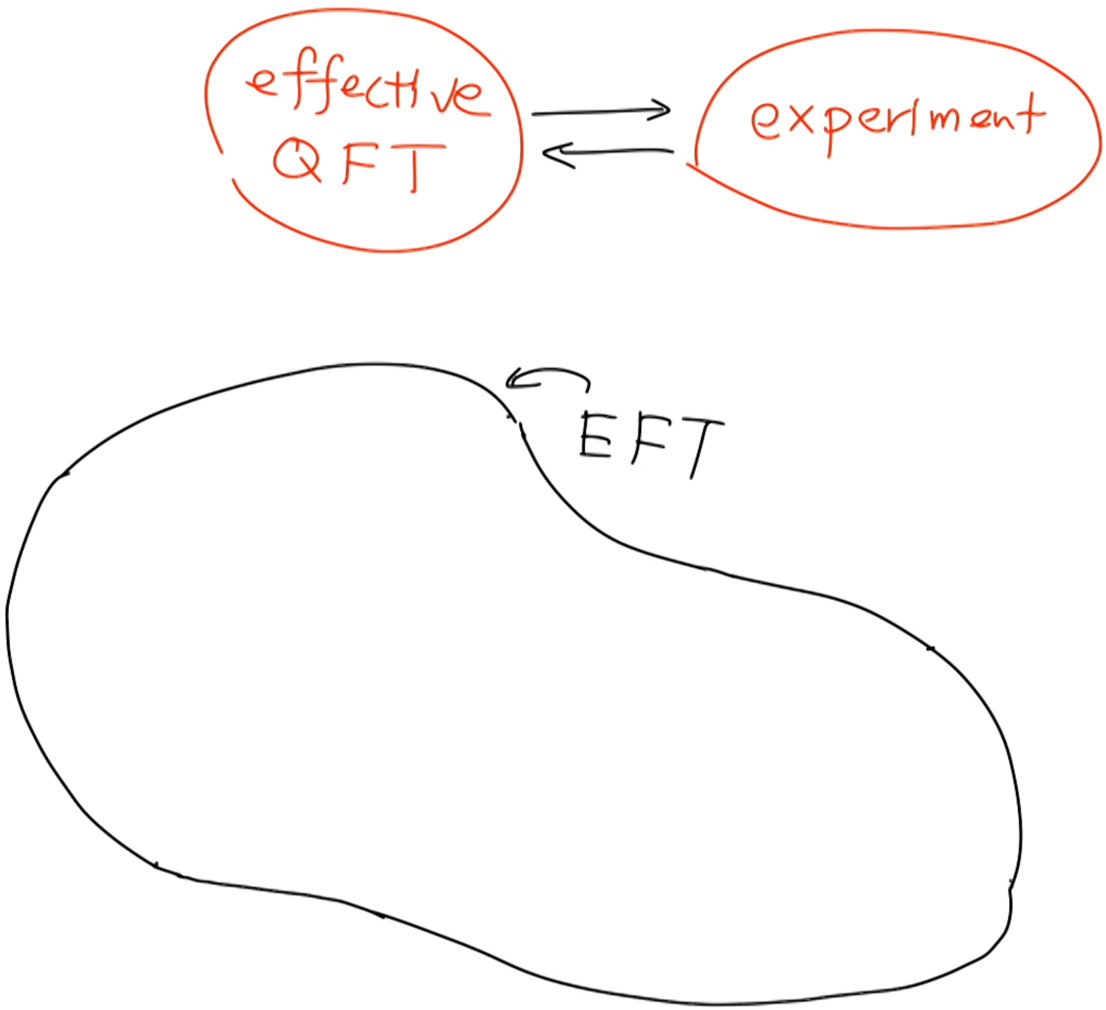
in Light of Swampland Conjectures

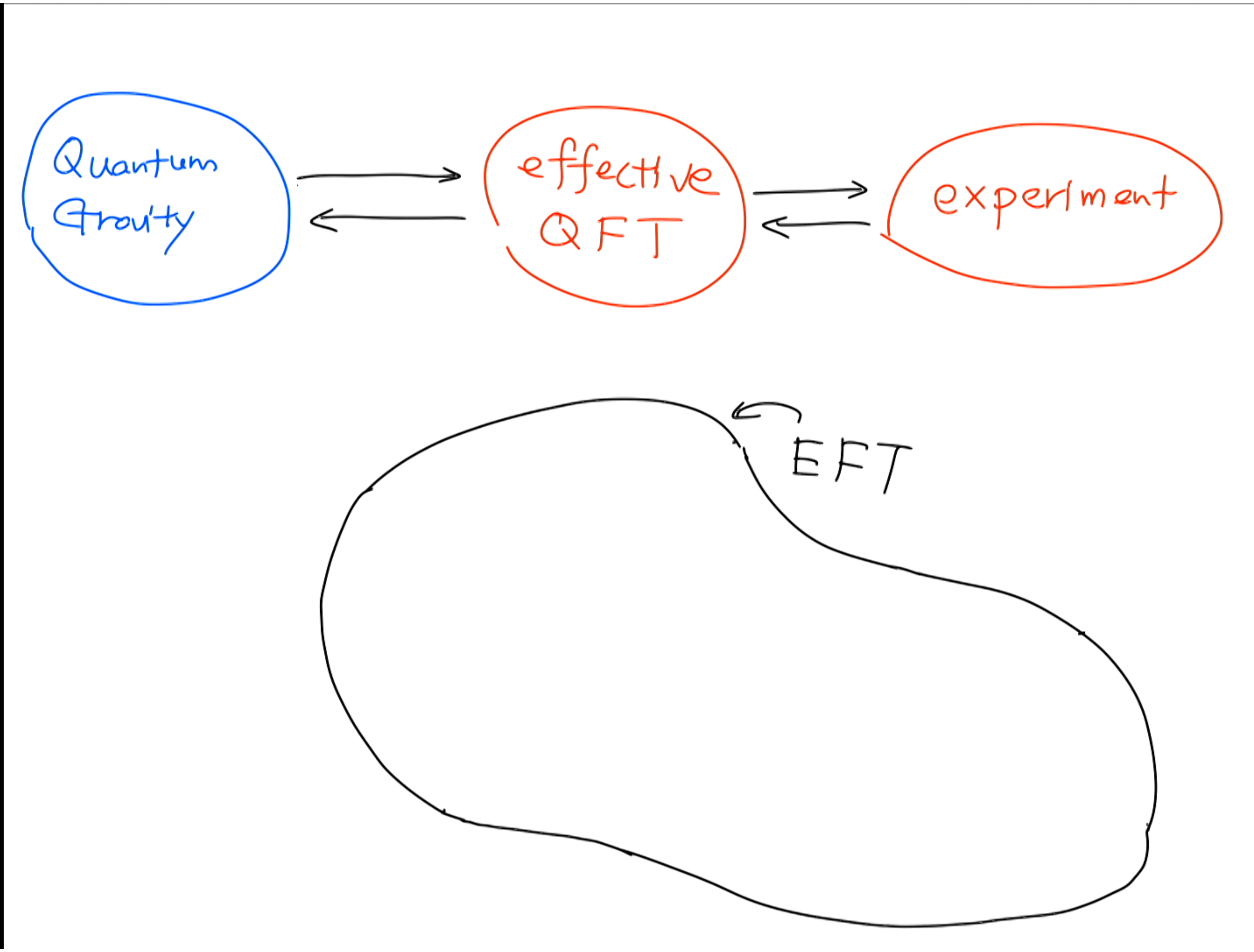
Masahito Yamazaki
(Kavli IPMU, Univ. Tokyo)

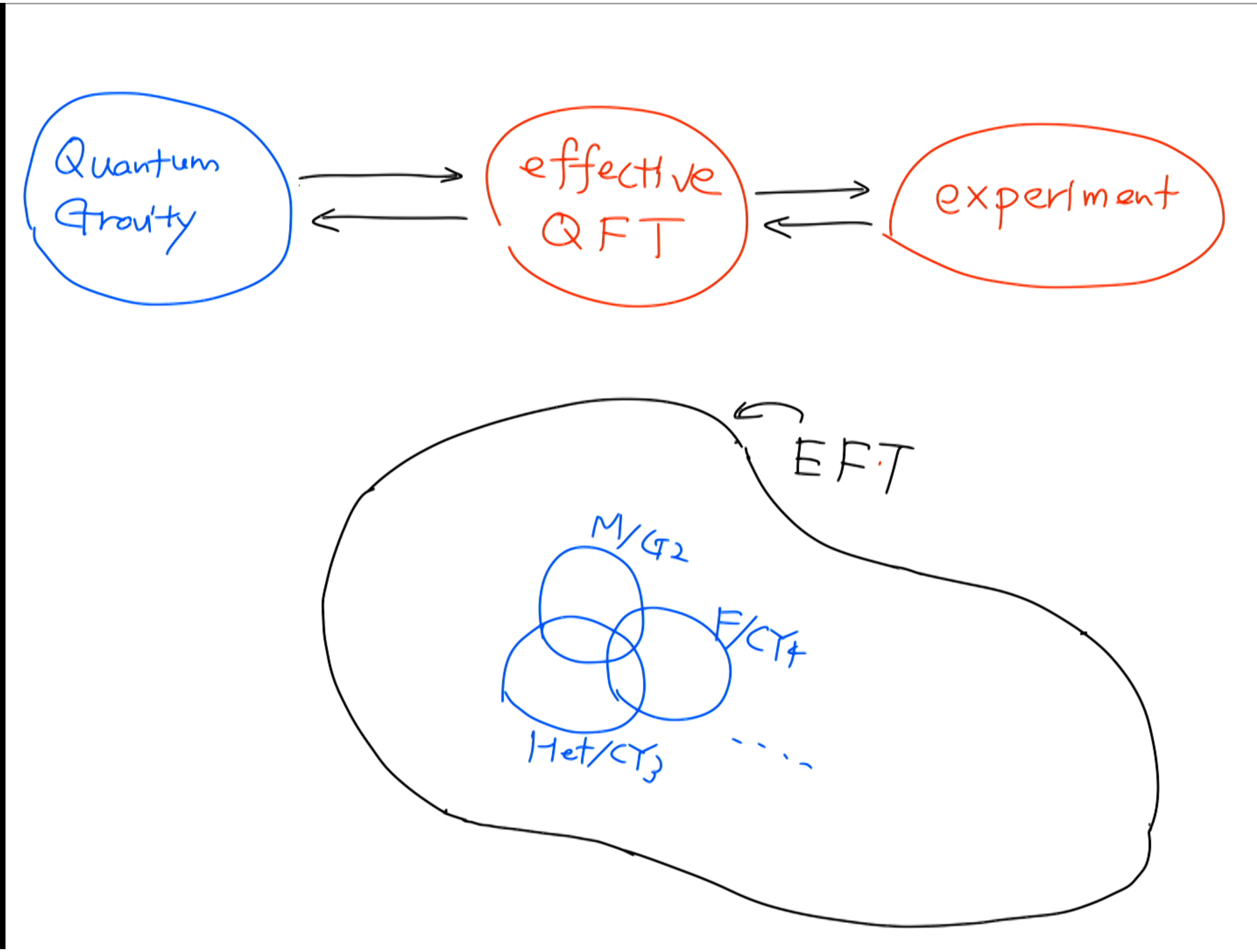
Quantum Fields and String + cosmology seminar
Nov / 12 / 2019, PI

Swampland

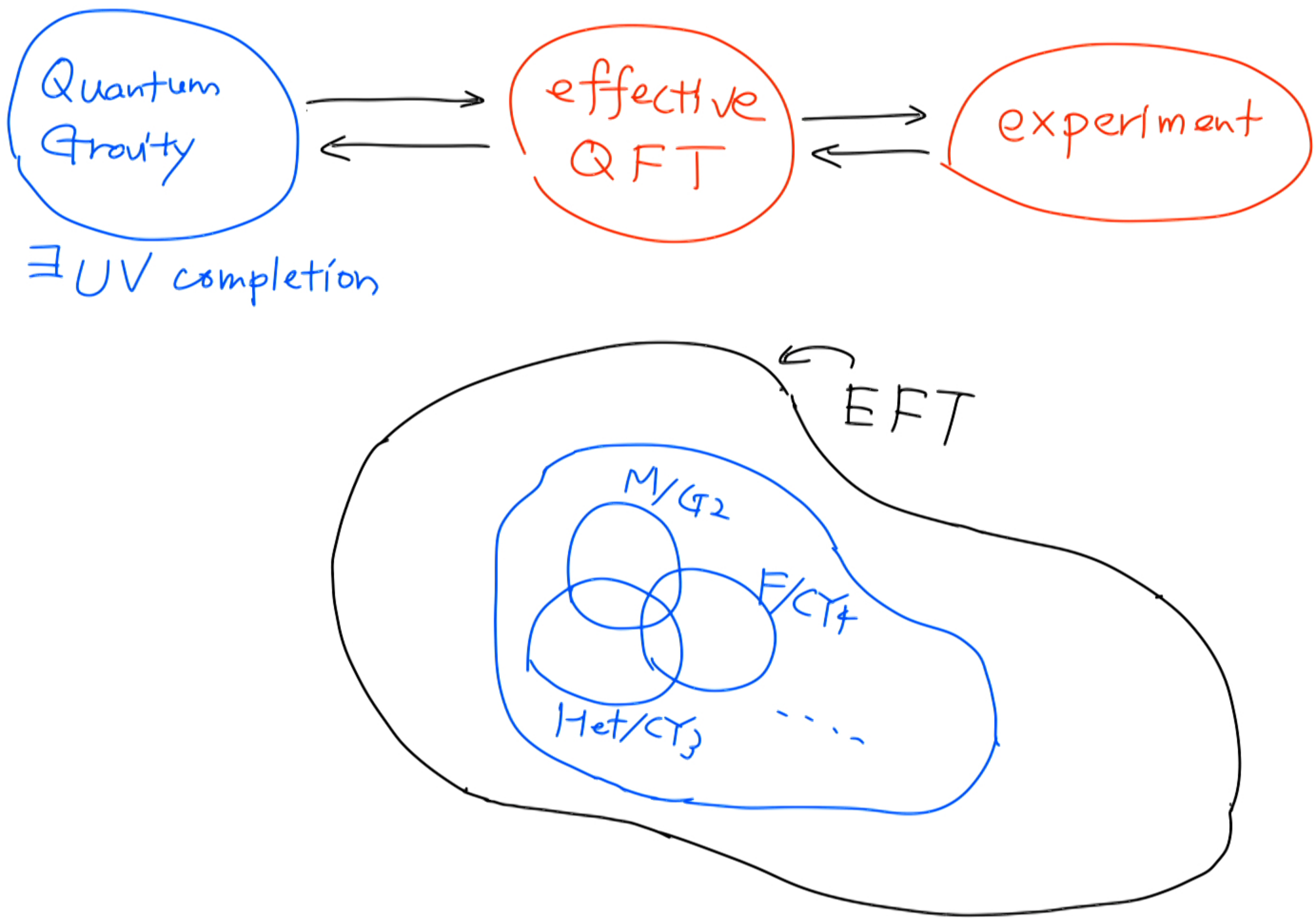

effective
QFT
experiment
??

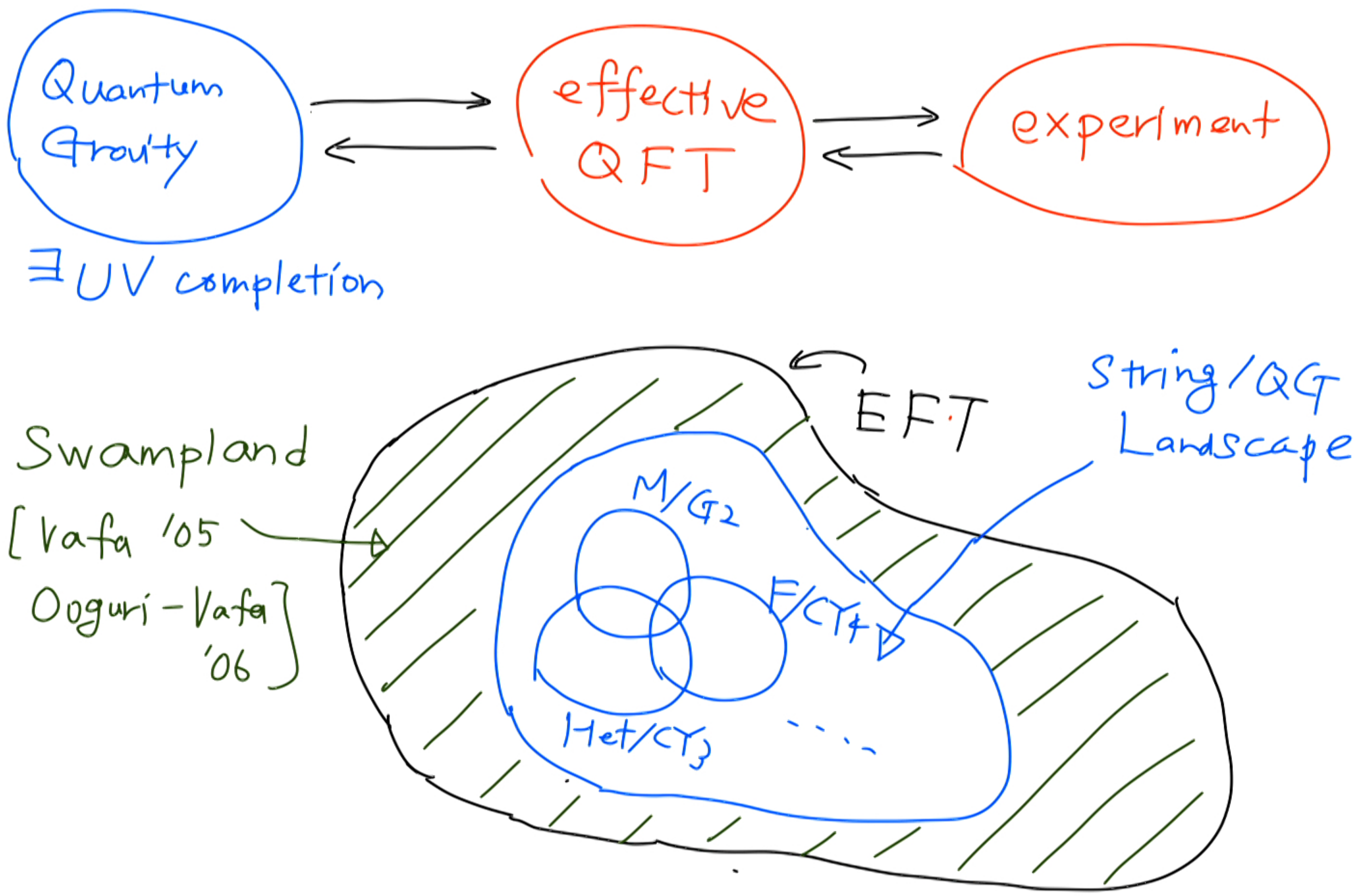

effective
QFT
experiment
EFT

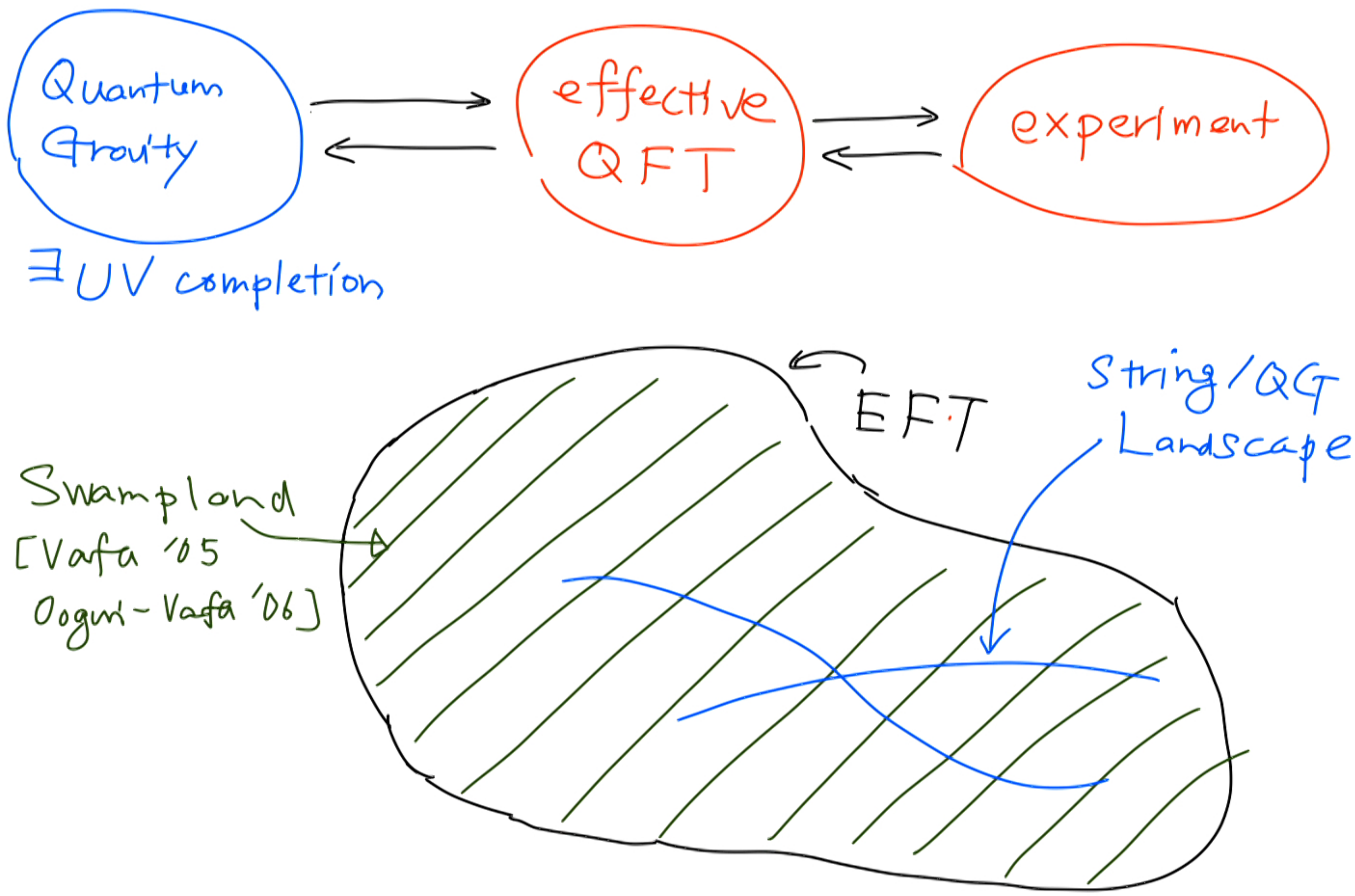

Quantum Gravity
effective QFT
experiment
EFT



Quantum Gravity
effective QFT
experiment
EFT
M/G2
F/CY4
Het/CY3
. . . .


Quantum Gravity
effective QFT
experiment
∃ UV completion
EFT
M/G2
F/CY4
Het/CY3
. . . . .


Quantum Gravity
effective QFT
experiment
∃ UV completion
Swampland
[Vafa '05
Ooguri-Vafa '06]
EFT
String/QG Landscape
M/G2
F/CY4
Het/CY3
. . . . .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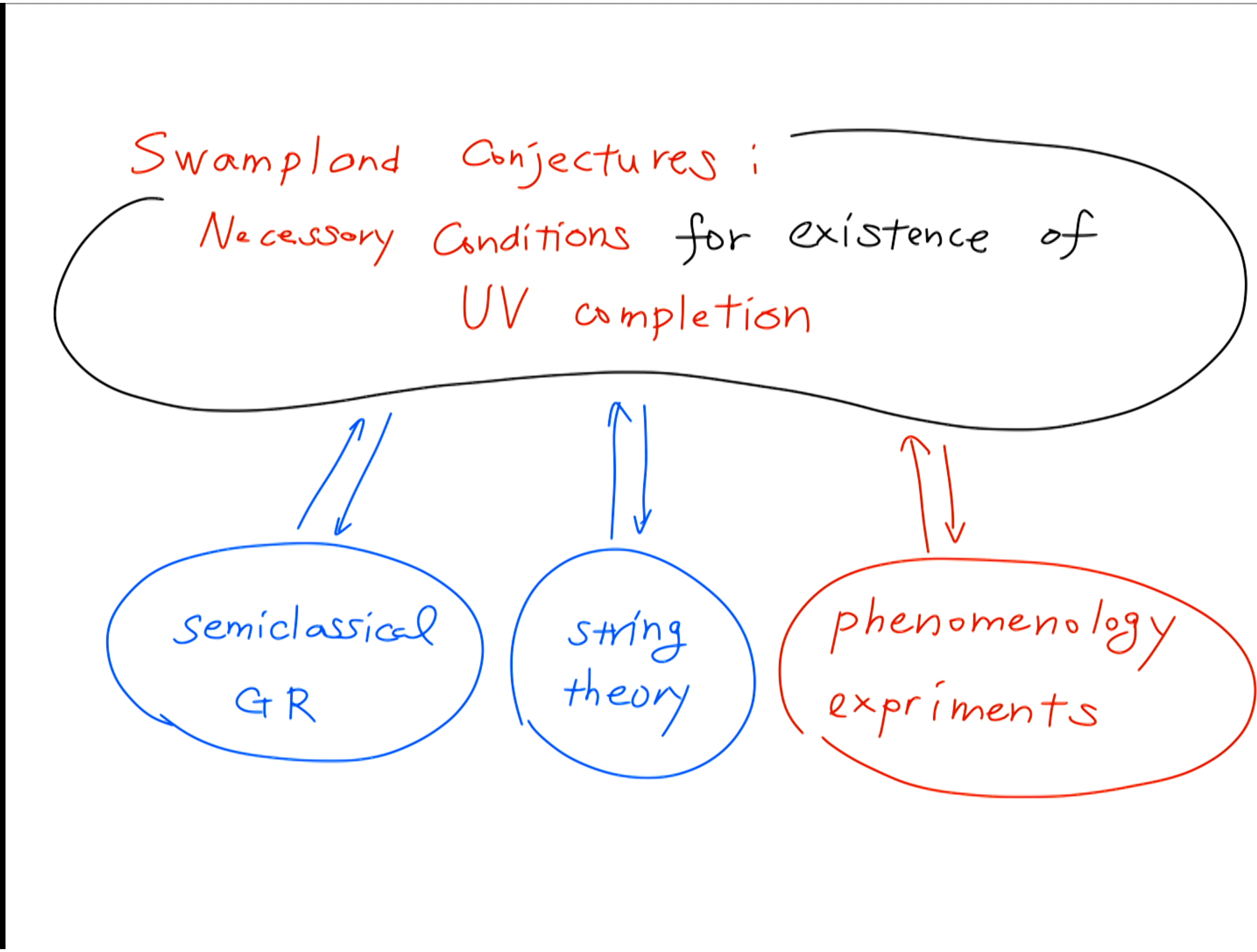
String/QG Landscape
Swampland
[Vafa '05
Oogur-Vafa '06]


Swampland Conjectures :
Necessary Conditions for existence of
UV completion
semiclassical
GR
string
theory
phenomenology
expriments

de Sitter swampland conjecture

[Obied - Ooguri - Spodyneiko - Vafa '18]

V : total potential of an EFT

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

M_{pl}: Planck scale $\sim 2 \times 10^{18}$ GeV

c: $\mathcal{O}(1)$ const.

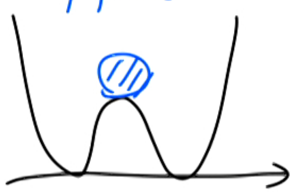
$\rightsquigarrow$ de Sitter vacua ruled out

$$(\nabla V = 0, \ \underset{\Lambda}{\underset{\shortparallel}{V}} > 0)$$

Problem

the conjecture ($|\nabla V| \geq cV$) rules out local maximum w/ $V > 0$

e.g. Higgs in the SM!



$$V(H) = \lambda \left(|H|^2 - v^2\right)^2$$

Loopholes almost closed

Denef-Hebecker-Wrase
Murayama-Yanagida-Y
Choi-Chwa-Shin
Hamaguchi-Ibe-Moroi '18

* EW modification?

$$V(S,H) = \lambda(H^2-v^2)^2 + \kappa(S-a)(H^2-\omega^2) + \frac{m^2}{2}S^2 + \Lambda^4$$

$\Leftarrow$ some no-go theorems

* Coupling w/ quintessence?

$$V(Q,H) = e^{-\frac{cQ}{M_{pl}}} V(H)$$

$\Leftarrow$ fifth force, $\frac{m_p}{m_e}$ time dependence

Murayama-Yanagida-Y 1809.00478

Fukuda-Saito-Shirai-Y 1810.06532

Ibe-Yanagida-Y 1811.04664

Y 1904.04976

Shirai-Y 1904.10577

Kusenko-Takhistov-Yamada-Y 1908.10930

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TODAY

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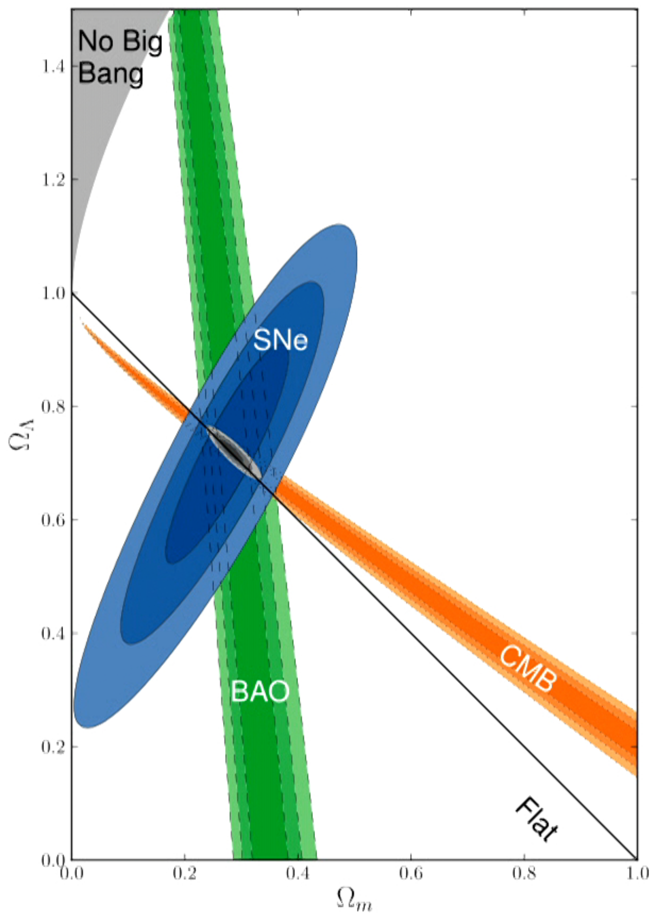
Dark Energy



[Suzuki et al, ('11)]

$\Lambda > 0$!

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

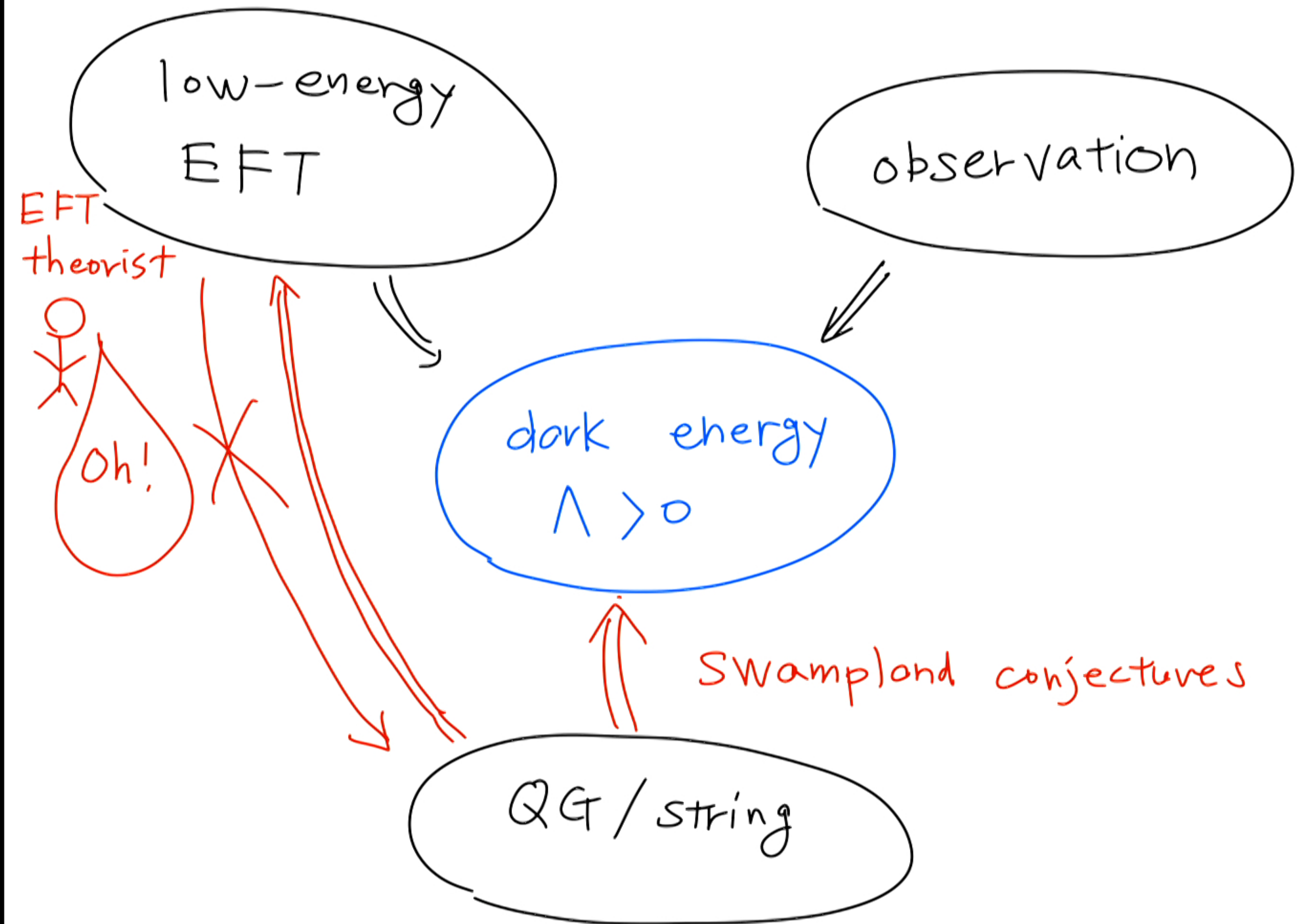
$$\ll M_{pl}^4 \ !!$$

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

while dark energy is IR phenomenon

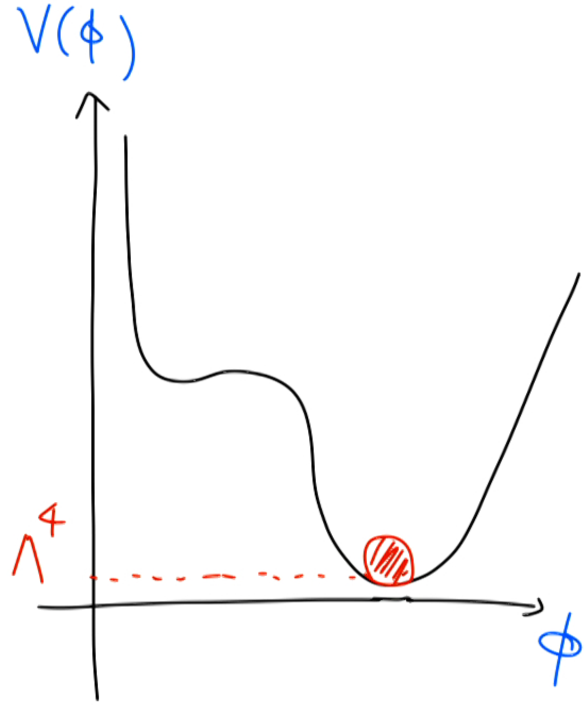
it is partly about $\underbrace{\text{UV}}_{\text{quantum gravity}}$

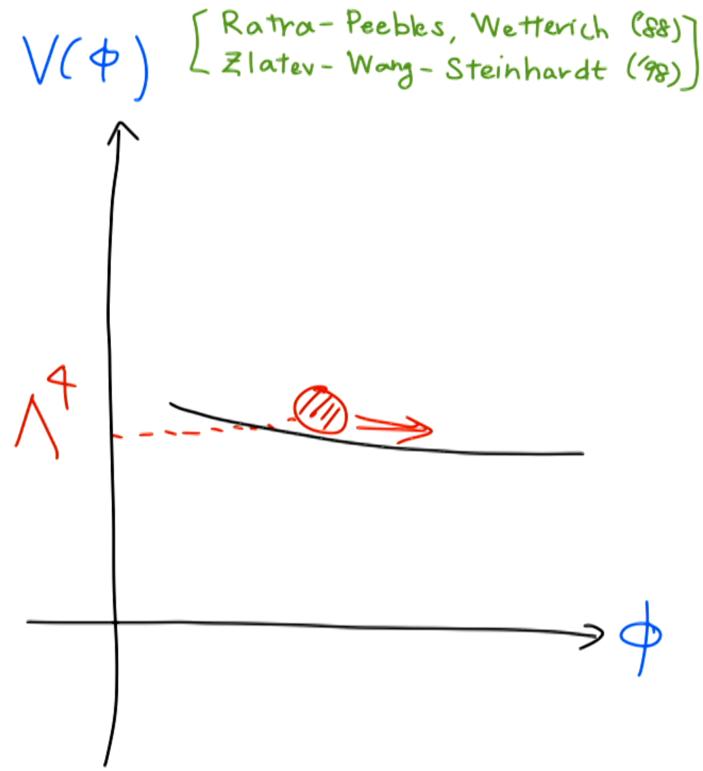
string


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

How to Realize Λ ?

cosmological constant vs. quintessence





* Very few discussion of quintessence

in QG / String (... until recently)

* dS vacua difficult in weak coupling

[Dine-Seiberg, Maldacena-Nunez, ...]

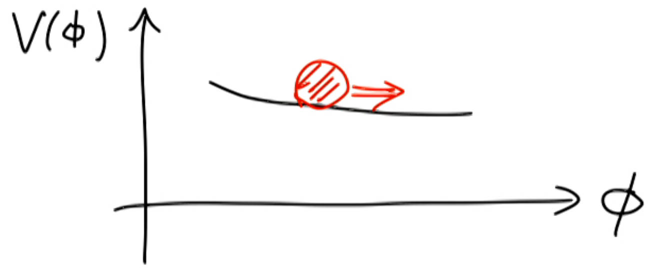
cf. refined de Sitter conjecture(s)

[Obied-Ooguri-Spodyneiko-Vafa, Garg-Krishnan,
Murayama-Yanagida-Y, Ooguri-Palti-Shiu-Vafa, ('18)]

* It's the Nature to decide

Quintessence

Q: if quintessence, why flat potential?



possible answer: $\boxed{\text{quintessence axion}}$

[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

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

$$\parallel$$

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

Q: which non-Abelian gauge field?

why particular value of α?

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

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

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

(※ dominant contribution comes from small-size instanton)

$\boxed{\text{electroweak quintessence axion scenario}}$

[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. $\mathcal{L} \supset \frac{1}{M_{Pl}^2} qqql$

[Anselm-Johansen ('93)]

(cf. no exact global symmetry in QG)

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

For QCD

$$V \sim \int^{\infty} \frac{d\rho}{\rho^5} e^{-\frac{2\pi}{\alpha(\rho)}} = \int^{\infty} \frac{d\rho}{\rho^5} e^{-\frac{2\pi}{\alpha(\rho_0)}} \left(\frac{\rho}{\rho_0}\right)^7 \sim \int^{\infty} d\rho\, \rho^2 \cdots$$

dominant contribution from IR

For EW SU(2)

$$V \sim \int_{M_{pl}^{-1}} \frac{d\rho}{\rho^5} \underbrace{\frac{1}{(\rho M_{pl})^6}} e^{-\frac{2\pi}{\alpha(\rho_0)}} \left(\frac{\rho}{\rho_0}\right)^{\frac{19}{6}} \sim \int_{M_{pl}^{-1}} \frac{d\rho}{\rho^{\frac{47}{6}}} \cdots$$

dominant contribution from IR

$$\mathcal{L} \supset \frac{O(1)}{M_{pl}^2} qqq\ell$$

for each generation

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

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$\boxed{\text{electroweak quintessence axion scenario}}$

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

Weak Gravity Conjecture

* Weak gravity conjecture implies

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

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

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

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

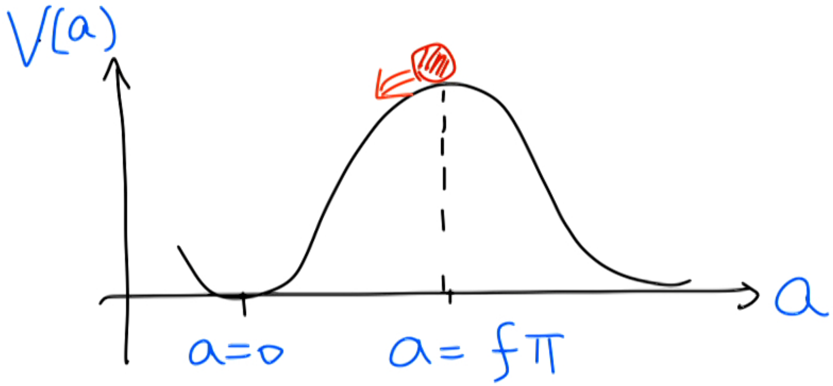
* However, we need small quintessence mass

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

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

S_{inst}

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

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

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

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

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

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

$$\alpha_2(M_Z) \simeq \frac{1}{29} \xrightarrow[\text{w/ heavy particles}]{RG} S_{inst} \simeq \mathcal{O}(10)$$

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

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

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

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

Supersymmetric Miracle

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

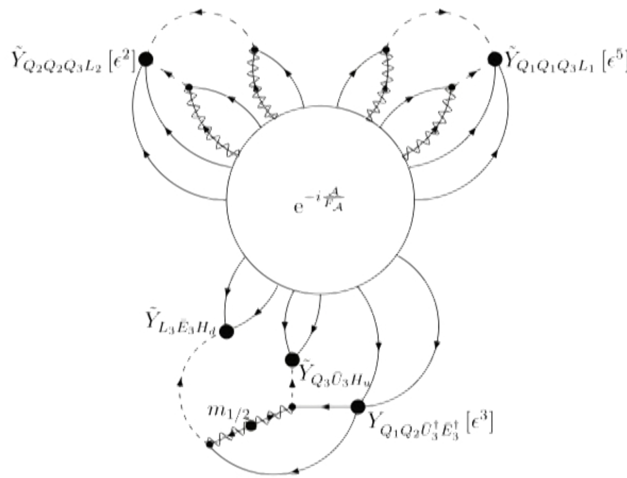
$$\alpha_2(M_{pl})\Big|_{MSSM} = \frac{1}{23} \quad \text{cf.} \quad \alpha_2(M_{pl})\Big|_{SM} = \frac{1}{48}$$

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

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

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

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



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

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

← 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)]

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

cancel

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

WGC ☺

$$\boxed{\text{We can change the RG running of } \alpha_2 \text{ while keeping the size of } \Lambda^4 ☺}$$

robust !!

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

Summary

electroweak quintessence axion

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

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

* 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" / Λ robust)

* Weak gravity conjecture implies

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

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

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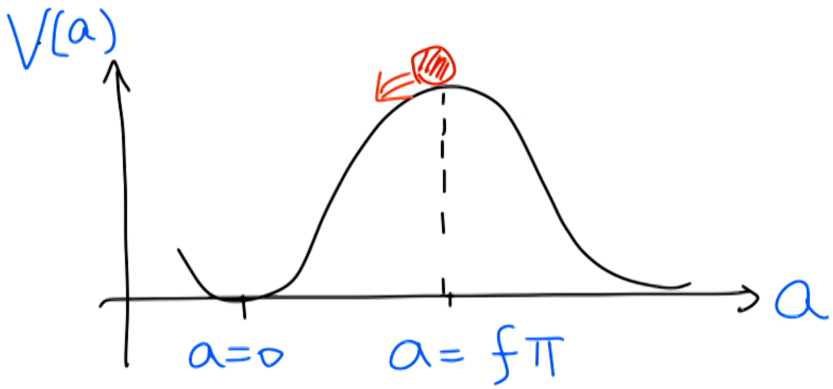

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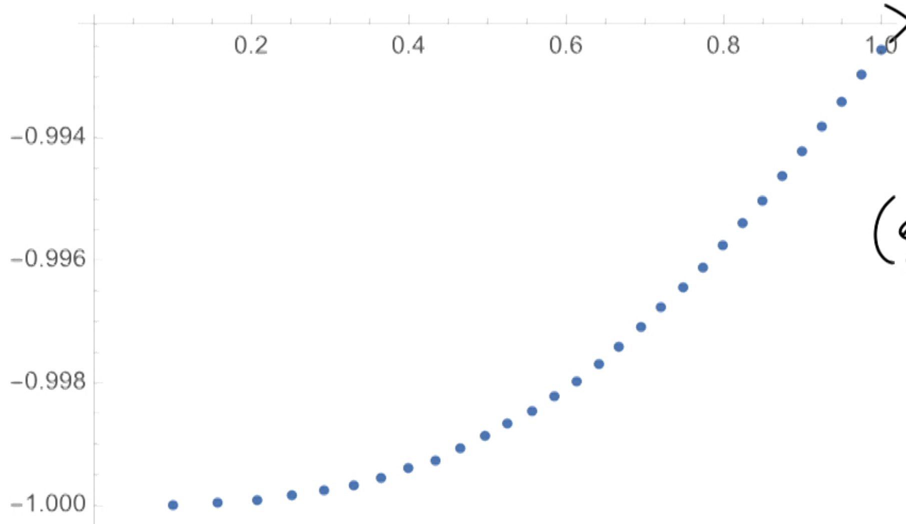
S_{inst}

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

* Future measurement of $\omega = \frac{P}{\rho}$?



a

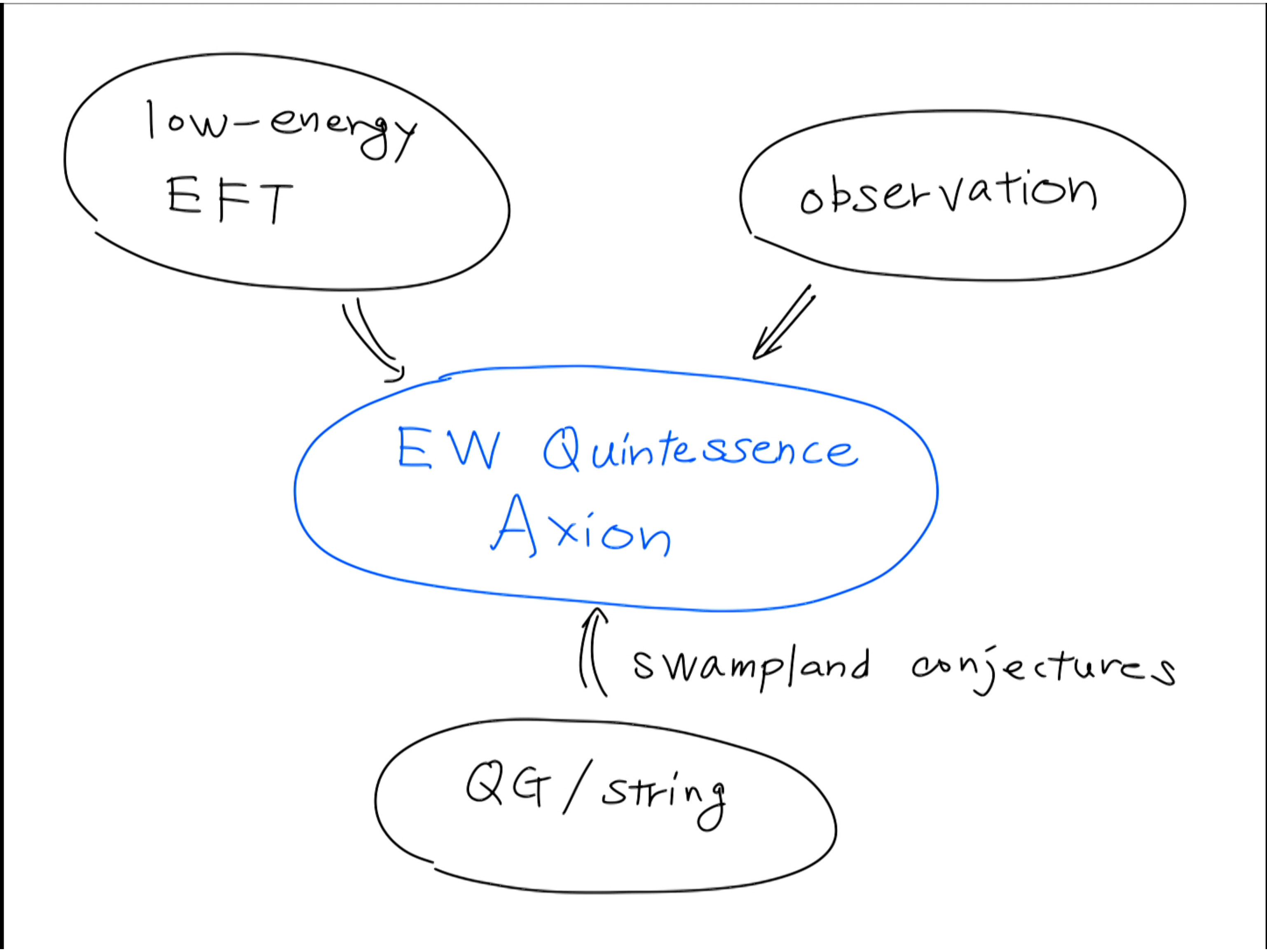
$1+\omega$

(eg w/ $f_a = M_{pl}$)

* Constraints from birefringence ?

$\left(\mathcal{L} \supset \frac{a}{f} \mathbb{E} \cdot \mathbb{B} \right)$

* QCD axion + EW axion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QG / string