Comments on Axions and Swampland Conjectures

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Disclaimer:

original plan:

swampland conjectures $\rightsquigarrow$ axions/ALPs

e.g.

weak gravity conjecture $\rightsquigarrow$ $f_a \lesssim \mathcal{O}(M_{pl})$

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weak gravity conjecture $\rightsquigarrow$ $f_a \lesssim \mathcal{O}(M_{pl})$

instead

scalar weak gravity conjecture $\rightsquigarrow$ moduli (including ALPs)

Thanks to collaborations :

Satoshi Shirai + MY

1904.10577 [hep-th]

Alexander Kusenko, Volodymyr Takhistov,

Masaki Yamada + MY

1908.10930 [hep-th]

Motivation

Gravity versus EM

Microscopically

$$F_{gravity} = \frac{m^2}{8\pi M_{Pl}^2} \frac{1}{r^2}$$

$$\Uparrow$$

$$F_{EM} = \frac{e^2}{4\pi} \frac{1}{r^2}$$

Gravity versus EM

Macroscopically

$$F_{gravity} = \frac{m^2}{8\pi M_{pe}^2}\frac{1}{r^2}$$

(m : huge
gravity accumulates)

$$\Downarrow$$

$$F_{EM} = \frac{e^2}{4\pi}\frac{1}{r^2}$$

($e \sim 0$
cancellation of opposite charges)

Q : Can we have e : gauge coupling small

s.t. $F_{EM} \lesssim F_{gravity}$?

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s.t. $F_{EM} \lesssim F_{gravity}$?

e.g. electron

$$e \lesssim \frac{m}{M_{pl}} \sim \frac{0.5\,\text{MeV}}{10^{18}\,\text{GeV}} \sim 10^{-21}$$

sounds very unnatural,

but is technically natural

$$\mathcal{L} = \int \sqrt{g}\left(\frac{1}{e^2} F_{\mu\nu}F^{\mu\nu} + R + \Lambda\right)$$

things are different if we consider quantum gravity / strings

(swampland paradigm)

(Gauge) Weak Gravity Conjecture

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

$\boxed{\text{GWGC}}$

$\exists$ a particle s.t.

$$F_{gauge} = \frac{(eq)^2}{4\pi r^2} \geq F_{gravity} = \frac{m^2}{8\pi M_{pl}^2}$$

(q : charge, m : mass)

"gravity as the weakest force"

Scalar Force

Scalar Force

$$\mathcal{L} \supset m(\phi)\bar{\chi}\chi$$

Scalar Force

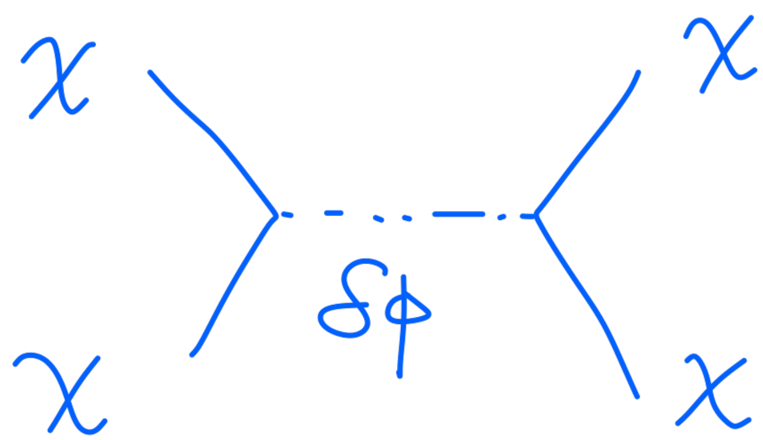
$$\mathcal{L} \supset m(\phi)\bar{\chi}\chi \underset{\substack{\uparrow \\ \phi = \langle\phi\rangle + \delta\phi}}{=} m(\langle\phi\rangle)\bar{\chi}\chi + \boxed{(\partial_\phi m)\,\delta\phi\,\bar{\chi}\chi}$$

$$+ \cdots$$

Scalar Force

$$\mathcal{L} \supset m(\phi)\,\bar{\chi}\chi = m(\langle\phi\rangle)\,\bar{\chi}\chi + \boxed{(\partial_\phi m)\,\delta\phi\,\bar{\chi}\chi} + \dots$$

$$\phi = \langle\phi\rangle + \delta\phi$$



Scalar Force

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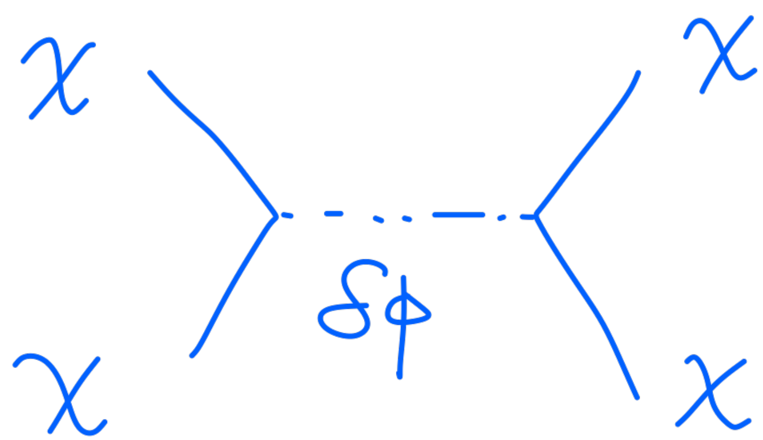


$$F \sim \frac{(\partial_\phi m)^2}{r^2}$$

"$\partial_\phi m$: scalar charge"

In String Theory, "generically"

$\mathcal{O}(100)$ scalar moduli

$\rightsquigarrow$

$F_{\text{grav.}}$, F_{gauge}, F_{scalar}

In many situations, Coulomb repulsions cost energy and charges tends to neutralize

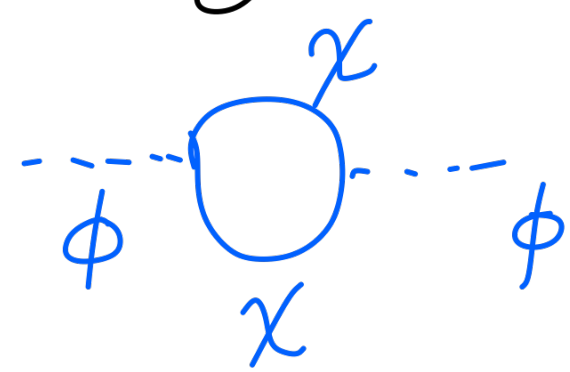
$\cancel{F_{gauge}}$ $\quad F_{gravity} \quad F_{scalar}$

- competition?
- more dramatic cosmological consequence?

However, in general

hard to expect **exactly** massless scalar

($\mathcal{L} \supset \phi \bar{\chi} \chi$ generates mass



)

$\rightsquigarrow$ no long-range scalar force

Scalar WGC

$\boxed{\text{SWGC 1}}$ [Palti ('17)] $\leftarrow$ BPS BH in 4d $\mathcal{N}=2$ SUSY

$\forall$ (GWGC) particle

$$F_{scalar} \geq F_{gravity}$$

$$\frac{|\partial_\phi m|^2}{4\pi r^2} = F_{scalar}, \qquad F_{gravity} = \frac{m^2}{8\pi M_{pl} r^2}$$

i.e.

$$|\partial_\phi m| \geq \frac{m}{M_{pl}}$$

$\boxed{\text{SWGC2}}$ [Shiraiー-Y ('19)]

Let's assume a very light scalar ϕ

e.g. $m^{-1} \gtrsim \mathcal{O}(H_0^{-1})$

(e.g. ALPs, quintessence ....)

cf. dS conjecture
[Obied-Ooguri-Spodyneiko
-Vafa ('18)]

$\boxed{\text{SWGC2}}$ [Shiraz-Y ('19), cf. Palti ('17)]

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$$F_{scalar} \geq F_{gravity}$$

$\boxed{\text{SWGC2}}$ [Shirai-Y ('19), cf. Palti ('17)]

$\forall$ (GWGC) particle

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

This version is too strong

in tension w/ fif-th force searches

[Shirai-Y ('19)]

(※ Loophole by screening mechanism
e.g. chameleon)

different version?

Previously we considered

$$\mathcal{L} \supset \underbrace{m(\phi)}_{\phi:\ \text{very light}} \underbrace{\bar{\chi}\chi}_{\text{general}}$$

long-range forces

What if we use self-interaction?

$$\mathcal{L} \supset m^2(\phi)\,\phi^2$$

$$= m^2\phi^2 - A\phi^3 + \lambda\phi^4 + \cdots$$

$\boxed{\text{SWGC } 1/2}$

$$(\partial_\phi m)^2 \geq \frac{m^2}{M_{pl}^2}$$

$$m = V'' = V_{\phi\phi}$$

$$(V''')^2 \geq \frac{(V'')^2}{M_{pl}^2}$$

$\boxed{\text{SWGC 1/2}}$

$$(\partial_\phi m)^2 \geq \frac{m^2}{M_{pl}^2}$$

$$\rightsquigarrow \quad m = V'' = V_{\phi\phi}$$

$$(V''')^2 \geq \frac{(V'')^2}{M_{pl}^2}$$

$\boxed{\text{SWGC 3}}$

[Gonzalo, Ibanez ('19)]

$$2(V''')^2 - V'' V'''' \geq \frac{(V'')^2}{M_{pl}^2}$$

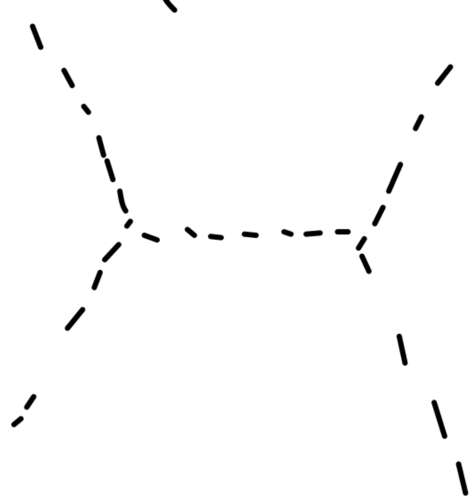
$\boxed{\text{SWGC 3}}$ [Gonzalo, Ibanez ('19)]

$$2(V''')^2 - V''V'''' \geq \frac{(V'')^2}{M_{pl}^2}$$

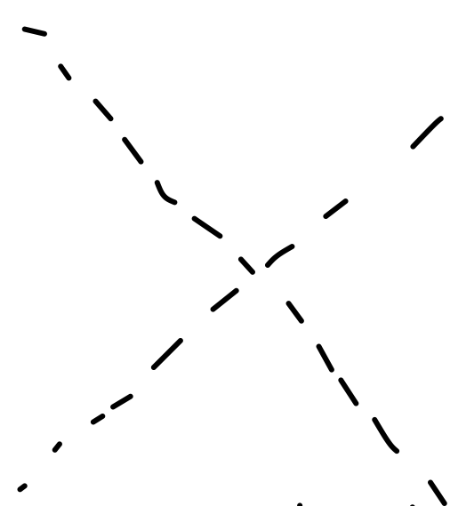
if $V''>0$

$$2\frac{(V''')^2}{V''} - V'''' \geq \frac{V''}{M_{pl}^2}$$

gravity



attraction



repulsion

SWGC 3

$$2(V''')^2 - V'' V'''' \geq \frac{(V'')^2}{M_{pl}^2}$$

$\Big\downarrow$ if $V''>0$

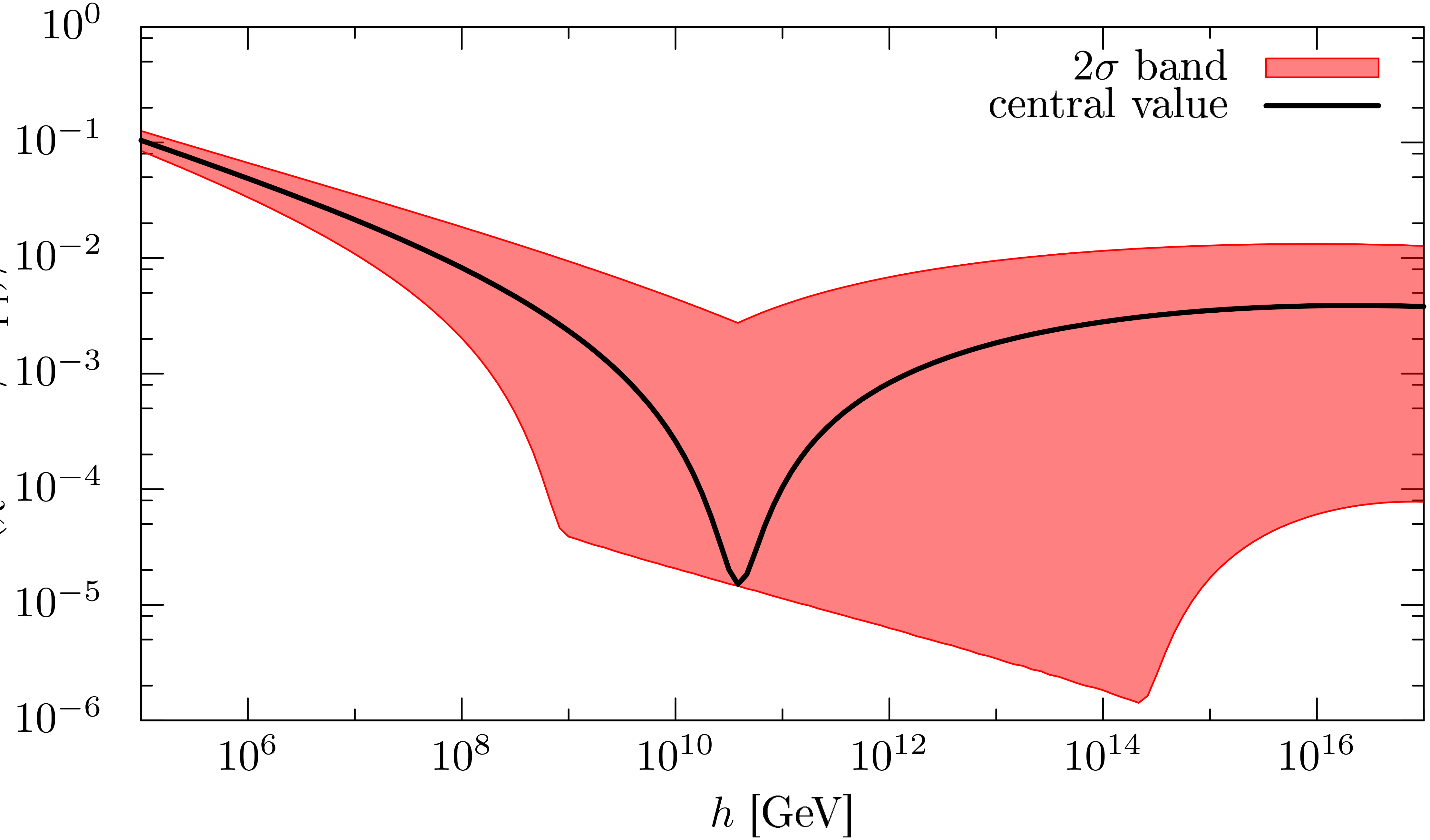
$$2\frac{(V''')^2}{V''} - V'''' \geq \frac{(V'')^2}{M_{pl}^2}$$

i.e. schematically

$$F^{net}_{scalar} = F^{att.}_{scalar} - F^{rep.}_{scalar} \geq F_{grav.}$$

SWGC 3

e.g. Higgs [Shirai - Y ('19)]



≥ 0

SWGC 3

$$2\left(V'''\right)^2 - V'' V'''' \geq \frac{\left(V''\right)^2}{M_{pl}^2}$$

- This does NOT require a very light scalor

(in general no long-range scalor force)

SWGC 3

$$2(V''')^2 - V''V'''' \geq \frac{(V'')^2}{M_{Pl}^2}$$

$$\Big\downarrow \; M_{Pl} \to \infty$$

$$2(V''')^2 - V''V'''' \geq 0$$

still non-trivial constraint

VERY different from other swampland conjectures

(Not a swampland conjecture?)

General Lesson?

Currently little support for SWGC3,

likely not true as a general statement?

contrary to the claims of [Gonzalo ('19), Ibanez]

However, the main point

$$F_{scalar} \gtrsim F_{gravity}$$

could be true in many cases?

If $F_{scalar} \geq F_{grav.}$

for $V(\phi) = \frac{1}{2}\underbrace{m^2}_{V''}\phi^2 - \frac{\overbrace{A}^{V'''}}{3}\phi^3 + \frac{\overbrace{\lambda}^{V''''}}{4}\phi^4$

If $F_{scalar} \geq F_{grav.}$

for $V(\phi) = \frac{1}{2} \underset{V''}{m^2} \phi^2 - \frac{\overset{V'''}{A}}{3} \phi^3 + \frac{\overset{V''''}{\lambda}}{4} \phi^4$

SWGC $\longrightarrow$ $\underbrace{A^2}_{F^{att.}_{scalar}} - \underbrace{\lambda m^2}_{F^{rep.}_{scalar}} \gtrsim \underbrace{\left(\frac{m^2}{M_{pl}}\right)^2}_{F_{grav.}}$

If $F_{scalar} \geq F_{grav.}$

for $V(\phi) = \frac{1}{2}\underbrace{m^2}_{V''}\phi^2 - \frac{\overbrace{A}^{V'''}}{3}\phi^3 + \frac{\overbrace{\lambda}^{V''''}}{4}\phi^4$

SWGC $\longrightarrow$ $\underbrace{A^2}_{F^{att.}_{scalar}} - \underbrace{\lambda m^2}_{F^{rep.}_{scalar}} \gtrsim \underbrace{\left(\frac{m^2}{M_{pl}}\right)^2}_{F_{grav.}}$

λ: small $\swarrow$ $\searrow$ gravity small

$A \gtrsim \frac{m^2}{M_{pl}}$ $\qquad\qquad$ $A^2 \gtrsim \lambda m^2$

Q-ball formation $\qquad\qquad$ oscillon formation

(Floquet exponent $\gtrsim H$) $\qquad$ [Kusenko – Takistov – Yamada – Y (19)]

If $F_{scalar} \geq F_{grav.}$

scalar fields fragment into localized lumps

after inflation

[Kusenko-Takhistov-Yamada-Y ('19)]

Q-ball / oscillon

PBH

⋮

as DM ?

Summary

GWGC

$$F_{gauge} \geq F_{gravity}$$

Swampland

QG/string ?

GSWGC

$$F_{gauge} \geq F_{scalar} + F_{gravity}$$

SWGC

$$F_{scalar} \geq F_{gravity}$$

most controversial but most powerful

Q: Is gravity the weakest force?

Q: If so, in what sense? why?