Is Gravity the Weakest Force?

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Pacific 2019, Moorea
2019/Sep/1

Thanks to collaborations :

Satoshi Shirai + MY

1904.10577 [hep-th]

Alexander Kusenko, Volodymyr Takhistov, Masaki Yamada + MY

1908.10930 [hep-th]

My rule today:

No complicated equations/figures

No systematic references

Loose in factors $(2 = \pi = 1)$

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No complicated equations/figures

No systematic references

Loose in factors ($2 = \pi = 1$)

OK to be naive/speculative

Attempt for big picture/
fundamental questions

Be relaxed!

Motivation

Forces in Nature

Gravity

EM

Weak

Strong

Forces in Nature

Gravity	$g_{\mu\nu}$	
EM	A_μ	$U(1)$
Weak	A_μ^a	$SU(2)$
Strong	A_μ^a	$SU(3)$

Forces in Nature

Gravity	$g_{\mu\nu}$		long-ranged
EM	A_μ	$U(1)$	
Weak	A_μ^a	$SU(2)$	short-ranged (NOT today)
Strong	A_μ^a	$SU(3)$	

Forces in Nature

spin 2   spin 1

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??	ϕ ?		

spin 0

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

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

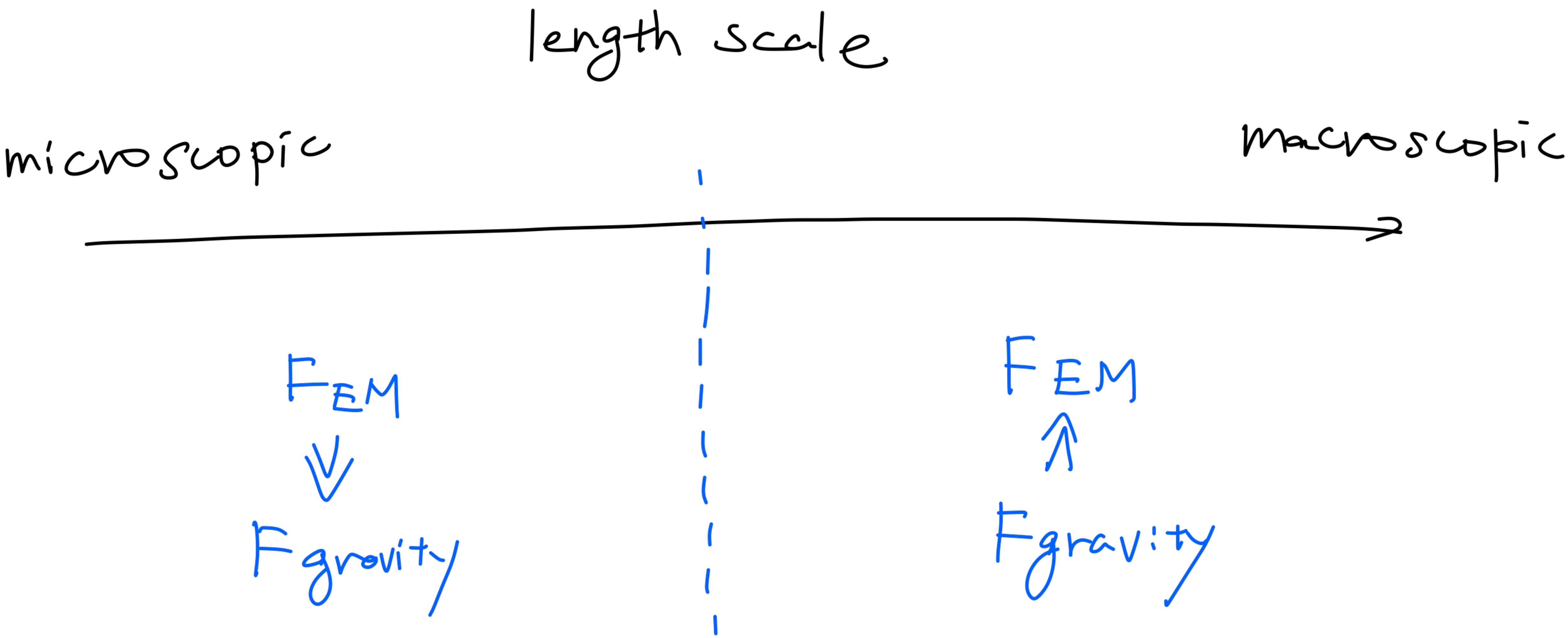
(m : huge
gravity
accumulates)

$$\Downarrow$$

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

(e ~ 0
cancellation of
opposite charges)

Gravity versus EM



Gravity versus EM

length scale

microscopic $\longrightarrow$ macroscopic

F_{EM}

$\Uparrow$

$F_{gravity}$

everywhere ?

F_{EM} small means e : gauge coupling small

e.g. electron

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

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

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) WGC

No Global Symmetry

In the extreme limit $e \to 0$

then U(1) gauge sym. $\longrightarrow$ U(1) global sym.

No Global Symmetry

In the extreme limit $e \to 0$

then $U(1)$ gauge sym. $\longrightarrow$ $U(1)$ global sym.

However, semiclassical GR / string forbids exact global sym.

$\rightsquigarrow$ $e \to 0$ not possible

["known" from long ago; see e.g. Banks–Seiberg ('10)]

(Gauge) Weak Gravity Conjecture

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

$\boxed{\text{GWGC}}$

$\exists$ a particle s.t.

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

(q : charge, m : mass)

"gravity as the weakest force"

(Gauge) Weak Gravity Conjecture

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

$\boxed{\text{GWGC}}$

$\exists$ a particle s.t.

$$m \leq \sqrt{2}\, e q$$

(q : charge, m : mass)

This bound

$$M \leq \sqrt{2}\, Q$$

is opposite from BH extremality bound

$$M \geq \sqrt{2}\, Q$$

Decay of extremal BH (if it happens) requires WGC particle

extremal BH

$M = \sqrt{2}\, Q$

decay

(M_1, Q_1)

(M_2, Q_2)

$\vdots$

(M_n, Q_n)

$\left(\sum M_i = M, \ \sum Q_i = Q \right)$

$\left(M_i \leq \sqrt{2}\, Q_i \right.$ for some $\left. i \right)$

Gauge-Scalar WGC

Forces in Nature

spin 2

spin 1

- Gravity $g_{\mu\nu}$
- EM A_μ $U(1)$

long-ranged

Weak A_μ^a $SU(2)$

Strong A_μ^a $SU(3)$

short-ranged

(NOT today)

??

ϕ ?

spin 0

Scalar ?

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

however, typically not "long-range"

since scalar ϕ is massive

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

$\downarrow$

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since scalar ϕ is massive

a) SUSY

b) very light $(m \lesssim H^{-1})$

IR

c) "IR/UV"

Let's assume

a) SUSY

for the moment

BPS extremal BH in 4d $\mathcal{N}=2$ SUGRA

$$
\begin{tikzcd}
 & g_{\mu\nu} \arrow[dl, "Q_1"'] \arrow[dr, "Q_2"] & \\
\lambda_1 \arrow[dr, "Q_2"'] & & \lambda_2 \arrow[dl, "Q_1"] \\
 & \phi &
\end{tikzcd}
$$

BH extremality bound

[Ceresole, d'Auria, Ferrara ('95)]

$$\underbrace{Q^2}_{\text{gauge}} \geq |Z|^2 + g^{i\bar{j}} D_i Z \, D_{\bar{j}} \bar{Z}$$

$$= \underbrace{M^2}_{\text{gravity}} + \underbrace{g^{i\bar{j}} (\partial_i M)(\partial_{\bar{j}} M)}_{\text{scalar}}$$

$$|Z| = M$$

Scalar Force

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

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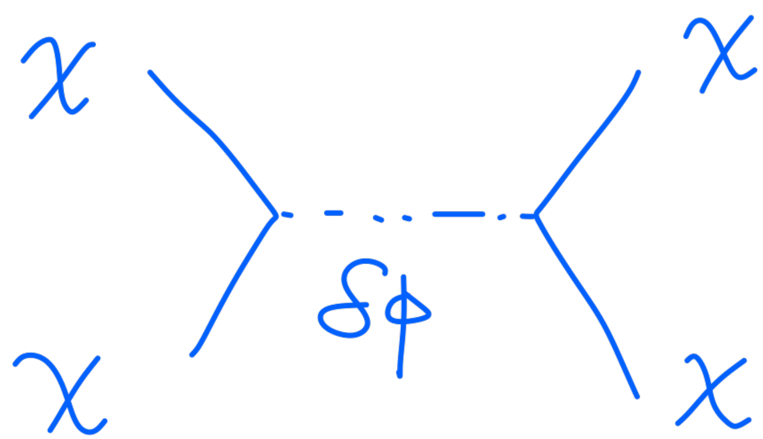
$$\mathcal{L} \supset m(\phi)\bar{\chi}\chi \underset{\uparrow}{=} m(\langle\phi\rangle)\bar{\chi}\chi + \boxed{(\partial_\phi m)\,\delta\phi\,\bar{\chi}\chi}$$

$$+ \cdots$$

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

Scalar Force

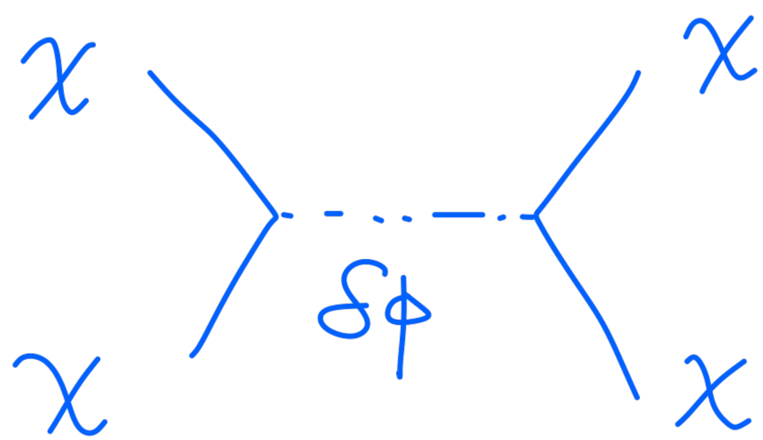
$$\mathcal{L} \supset m(\phi)\,\bar{\chi}\chi \underset{\phi = \langle\phi\rangle + \delta\phi}{=} m(\langle\phi\rangle)\,\bar{\chi}\chi + \boxed{(\partial_\phi m)\,\delta\phi\,\bar{\chi}\chi} + \cdots$$



Scalar Force

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

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



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

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

$\boxed{\text{GSWGC 1}}$ (repulsive force conjecture)

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

$\boxed{\text{GSWGC 2}}$

[Palti ('17), ...]

$$\frac{Q}{M} \geq \left(\frac{Q}{M}\right)_{\text{extremal BH}}$$

※ GSWGC 1 ≠ GSWGC 2 but closely related.

[Heidenreich, Reece, Rudelius ('19)]

Scalar WGC

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

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

competition ?

We can again start w/ a) SUSY

Previously for extremal BH

$$Q^2 = M^2 + g^{i\bar{j}} D_i M \, D_{\bar{j}} \overline{M}$$

There is a similar relation

[Ceresole, d'Auria, Ferrara ('95)]

$$\left(Q \Big|_{N_{IJ} \to F_{IJ}} \right)^2 = M^2 - g^{i\bar{j}} D_i M \, D_{\bar{j}} \overline{M}$$

$\boxed{\text{SWGC 1}}$ [Palti ('17, 19)]

$\exists$ particle

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

$$\| \qquad\qquad \|$$

$$\frac{|\partial_\phi m|^2}{4\pi r^2} \qquad \frac{m^2}{8\pi M_{pl} r^2}$$

i.e.

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

$\boxed{\text{SWGC 1}'}$ [Palti ('17, 19)]

$\forall$ (GWGC) particle

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

Let's also go beyond a): SUSY

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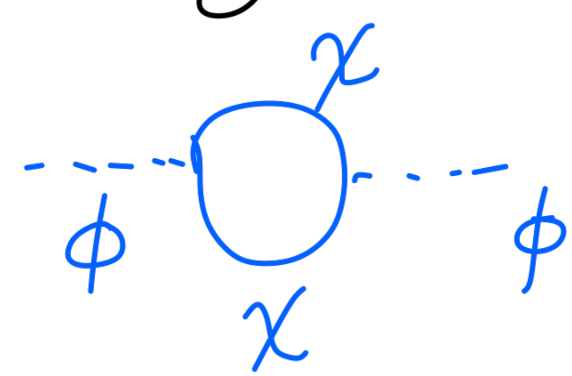
Hard to expect exactly massless scalar

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



)

but can expect very light scalar ϕ

(e.g. ALP, quintessence ....)

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

b): very light $m \lesssim H^{-1}$

[cf. Shirai-Y ('19)]

$\boxed{\text{SWGC } 1'}$

$\forall$ (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

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

general

ϕ: very light

long-range forces

What if we use self-interaction?

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

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

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

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

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

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

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

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

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

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$\boxed{\text{SWGC 2}}$ [Gonzalo, Ibanez ('19)]

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

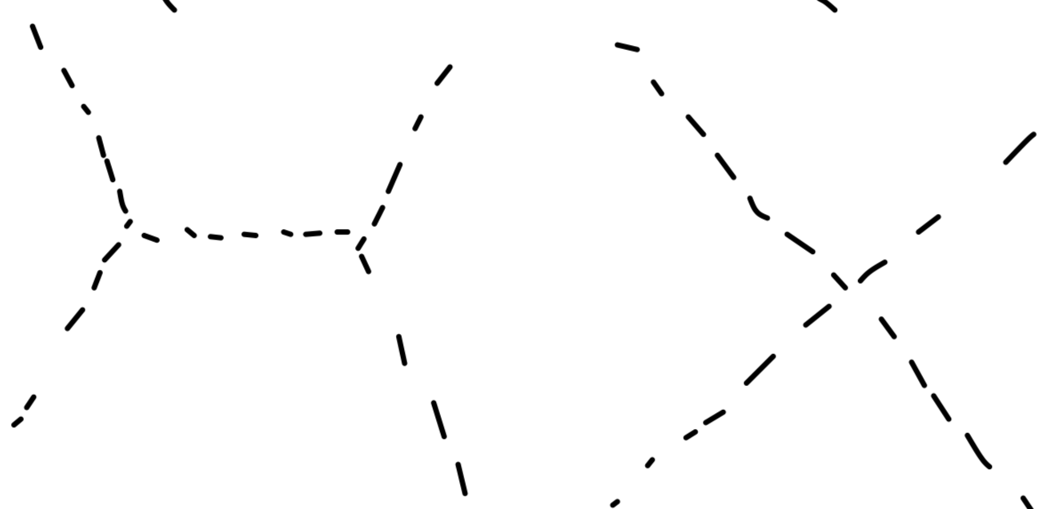
$\boxed{\text{SWGC 2}}$ [Gonzalo, Ibanez ('19)]

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

if $V''>0$

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

gravity



repulsion attraction

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

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

$$\Big\downarrow \quad \text{if } V''>0$$

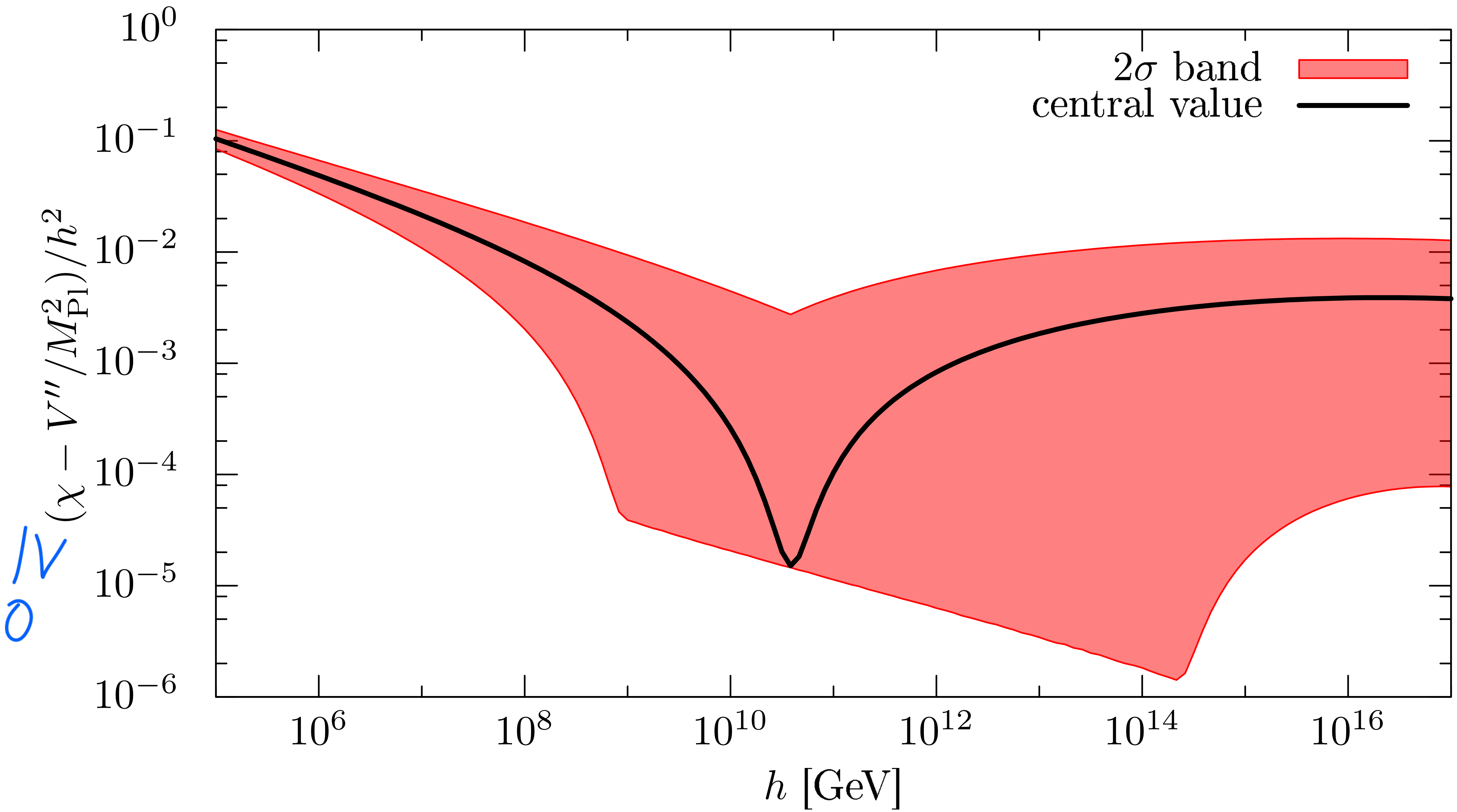
$$2\,\frac{\left(V'''\right)^2}{V''} - V'''' \geq \frac{\left(V''\right)^2}{M_{pl}^2}$$

i.e. schematically

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

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

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



SWGC 2

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

- This does NOT require a very light scalar (in general no long-range scalar force)

- hence c) "UV/IR" statement

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

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

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

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

still non-trivial constraint

VERY different from other swampland conjectures

(Not a swampland conjecture?)

Currently little support for SWGC2,
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?

String moduli

In String Theory, "generically"

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

Often assumed: gravitational interaction

(cf. moduli problem)

String moduli

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Scenario changed if $F_{scalar} \gtrsim F_{grav}$.

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

$V''' \qquad V''''$

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

V''

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

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

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

V'' $\quad$ V''' $\quad$ V''''

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 $\qquad$ gravity small

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

Q-ball formation $\qquad$ oscillon formation

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

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

scalar fields fragment into localized lumps

after inflation

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

Q-ball / oscillon [Kusenko-Shaposhnikov ('97), ⋯]

PBH [Alex's talk]

⋮

as DM ?

Summary

GWGC

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

Swampland

QG / string ?

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?