기초과학연구원
Institute for Basic Science

The unrefined dS swampland conjecture with EW symmetry and QCD chiral symmetry breaking

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Based on work [arXiv:1809.01475 JHEP published]
with Kiwoon Choi and Dongjin Chway (IBS-CTPU)

At APCTP
Nov. 30, 2018

Outline

Low energy implications of the original dS SWC

Two examples of a scalar potential with local maxima in the SM

Phenomenological constraints

Conclusions

Low energy implications of the dS SWC

For a scalar potential $V(\phi)$ of any consistent theory of quantum gravity
(→ not only for the fundamental scalar fields in string theory)

strong/unrefined version [1806.08362]

$$|\nabla V| \geq \frac{c}{M_{Pl}} V \quad \text{with } c = O(1) > 0$$

No exponential expansion
weak/refined version [1810.05506]

$$|\nabla V| \geq \frac{c}{M_{Pl}} V \quad \text{with } c = O(1) > 0$$

$$\text{or } \min \nabla_i \nabla_j V \leq -\frac{c'}{M_{Pl}^2} V \quad \text{with } c' = O(1) > 0$$

Images from http://www.demiak.nl/?project=swampland

Low energy implications of the dS SWC

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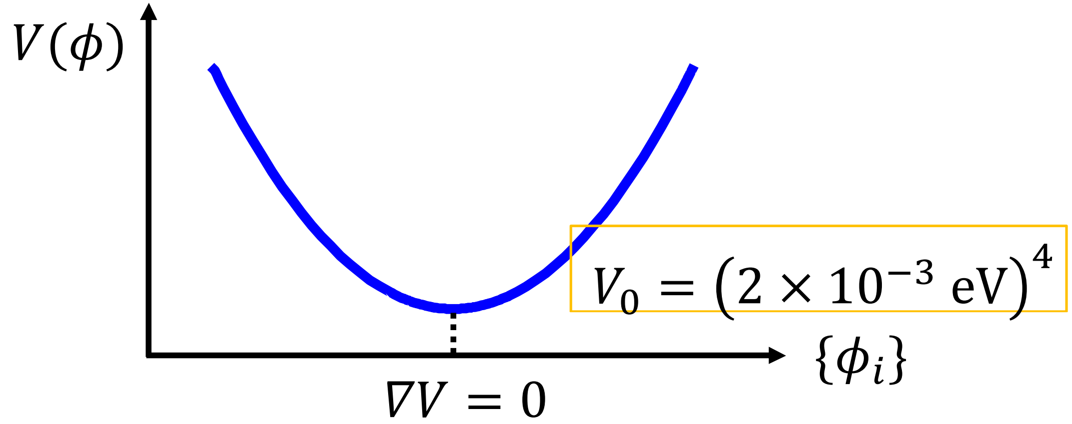
Quintessence from accelerating Universe

The present accelerating Universe → a positive vacuum energy: $V(\langle\phi\rangle) > 0$

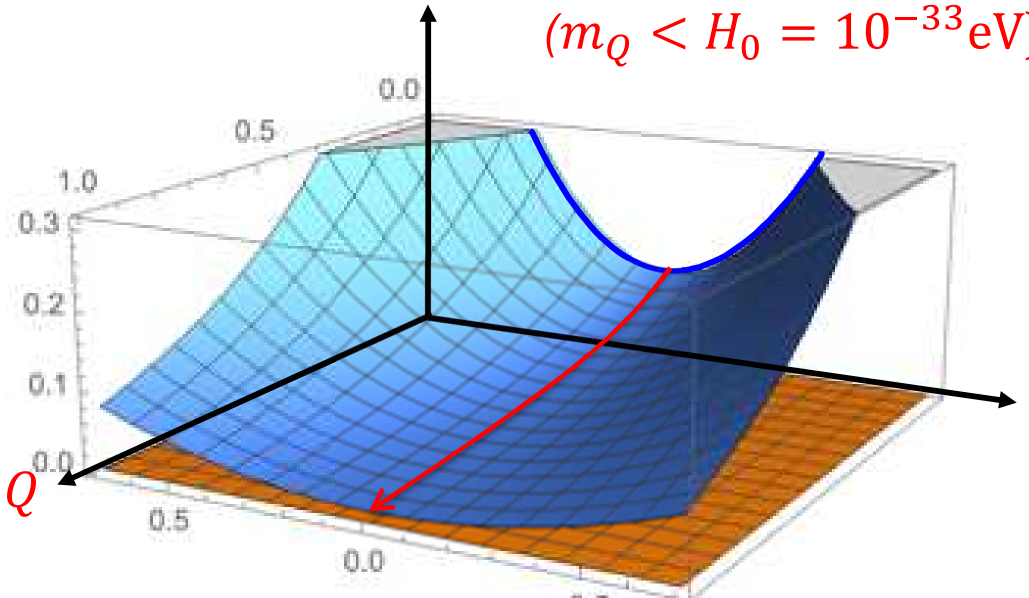


It is natural to think that all fields are stabilized at their vacuum values

However then $|\nabla V| = 0 \not\geq \frac{c}{M_{Pl}} V$ *with* $c = O(1) > 0$ *(conflicts with the dS SWC).*

The dS SWC implies there should be scalar field directions (Q) with $\left|\partial_Q V\right| > \frac{c}{M_{Pl}} V_0$*.*

$(m_Q < H_0 = 10^{-33}\mathrm{eV})$

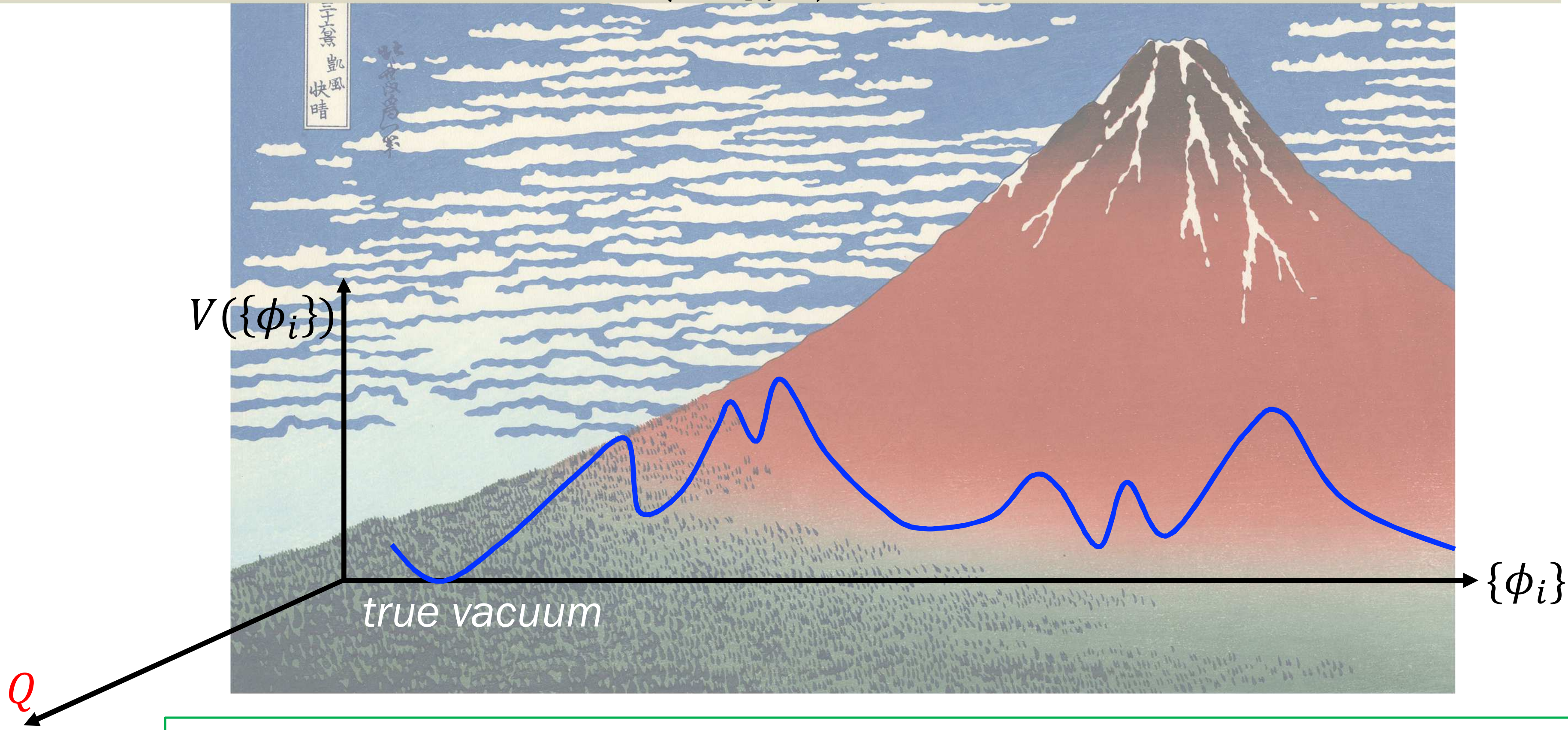


$$V(Q) \sim \exp\left(-\frac{c}{M_{Pl}} Q\right) V_0$$

Trouble with local maxima

The inequality of the original conjecture applies to all the field space: No local minima, maxima are allowed in any field space point. The quintessence should couple nontrivially to scalar fields whose potential has several local dS extrema.

$$V(Q,\{\phi_i\}) \neq V(\{\phi_i\}) + \exp\left(-\frac{c}{M_{Pl}}Q\right)V_0 \;\; \text{for} \;\; V(\{\phi_i\})_{\text{extremum}} \gg V_0$$



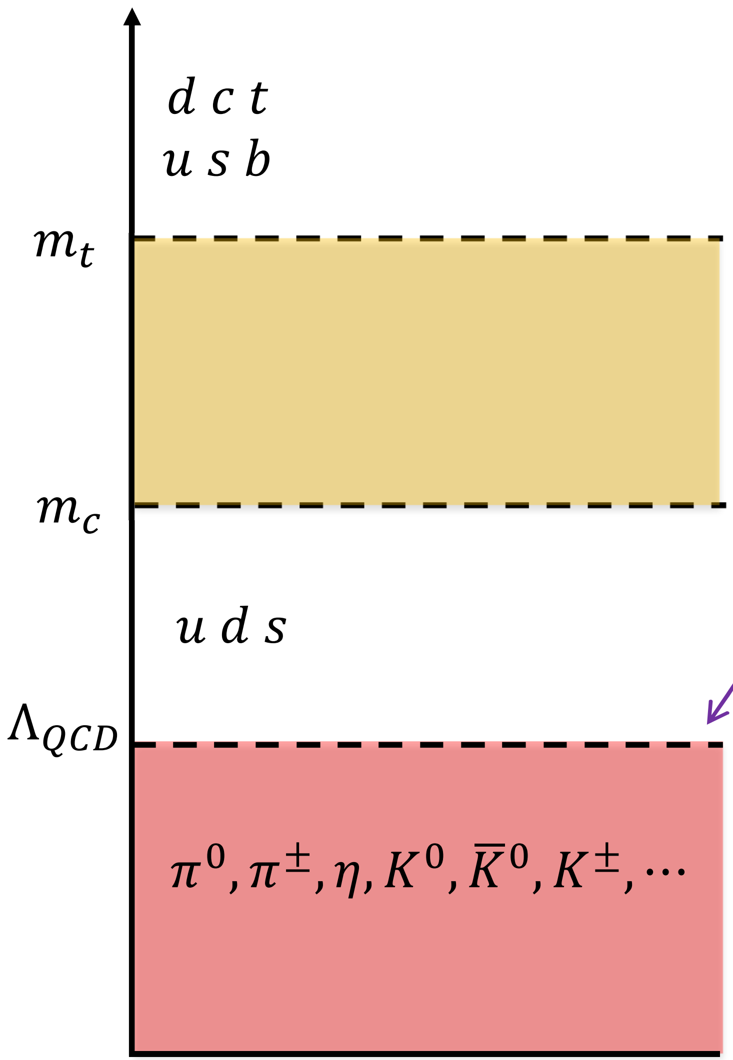
$$\text{e.g. } V(Q,\{\phi_i\}) \sim \exp\left(-\frac{c}{M_{Pl}}Q\right)(V(\{\phi_i\}) + V_0) \rightarrow |\nabla V| \geq |\partial_Q V| \simeq \frac{c}{M_{Pl}}V$$

Two examples of a scalar potential with local maxima in the SM

[Choi, Chway, CSS 18]

The pions as the low energy degrees of freedom

The dS SWC is related with the vacuum structure of the Universe: a low energy consequence of quantum gravity. It is natural to play the game with all the low energy scalar degrees of freedom including composite particles.



$$\boxed{\langle q_i \bar{q}_j \rangle \neq 0:\ SU(3)_L \times SU(3)_R \to SU(3)_V}$$

$$q_i \bar{q}_j = \delta_{ij} \Lambda^3\, U(x)$$

$$U(x) = \exp\left[\frac{i}{F_\pi} \begin{pmatrix} \pi^0 + \frac{\eta}{\sqrt{3}} & \sqrt{2}\pi^+ & \sqrt{2}K^+ \\ \sqrt{2}\pi^- & -\pi^0 + \frac{\eta}{\sqrt{3}} & \sqrt{2}K^0 \\ \sqrt{2}K^- & \sqrt{2}\bar{K}^0 & -\frac{2\eta}{\sqrt{3}} \end{pmatrix}\right]$$

$$\mathcal{L}_{eff} = -\frac{F_\pi^2}{4} \mathrm{Tr}\left[\partial_\mu U \partial^\mu U^+\right] - \frac{\langle q_i \bar{q}_i \rangle}{2} \mathrm{Tr}\left[M_q U + M_q U^+\right] + \cdots$$

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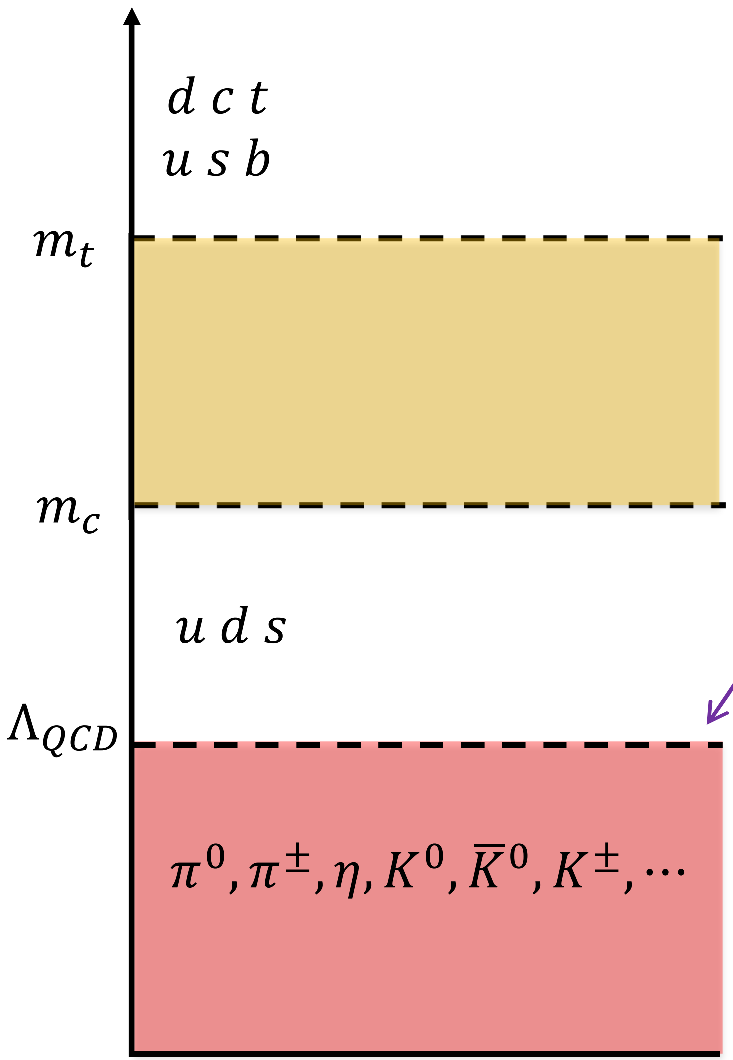

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A neutral pion effective potential

At a scale below Λ_{QCD}, the light quarks are confined, and the relevant degrees of freedom are mesons and baryons. The pions are good low energy degrees of freedom:

$$m_{\pi_0} = 135\ \mathrm{MeV}, \qquad \tau_{\pi_0} \simeq 10^{-16}\,\mathrm{sec} = \left(10^{-6}\ \mathrm{MeV}\right)^{-1} \gg m_{\pi_0}^{-1}$$

The effective scalar potential of the pion is calculable

$$\mathcal{L}_{eff}(\pi^0) = -\frac{(\partial_\mu \pi^0)(\partial^\mu \pi^0)}{2(1 + (\pi^0/F_\pi)^2 + \cdots)^2} \underbrace{- (m_u + m_d)\Lambda^3 \left(1 - \cos\frac{\pi^0}{F_\pi}\right)}_{V_{eff}(\pi^0)} + \cdots$$

A periodicity of the pion potential is the natural consequence of spontaneous breaking of $SU(2)_L \times SU(2)_R \to SU(2)_V$ by quark condensation.

At the top of the pion potential

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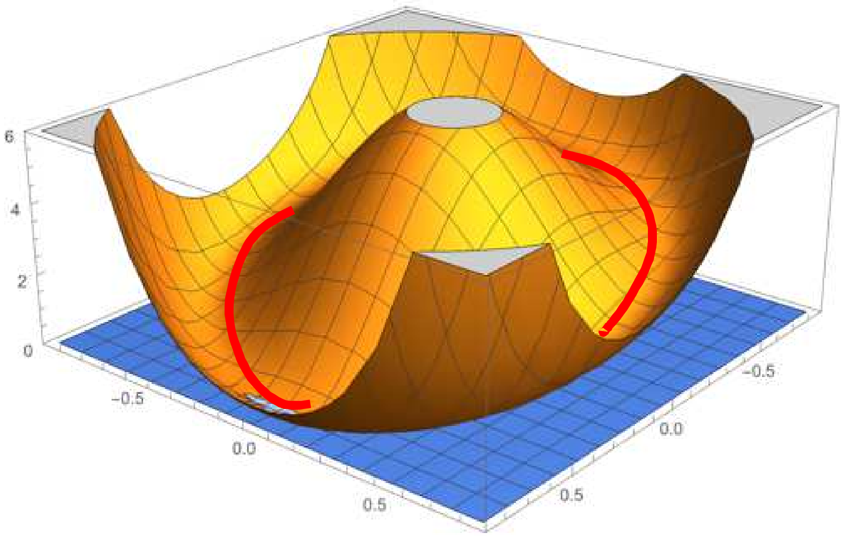
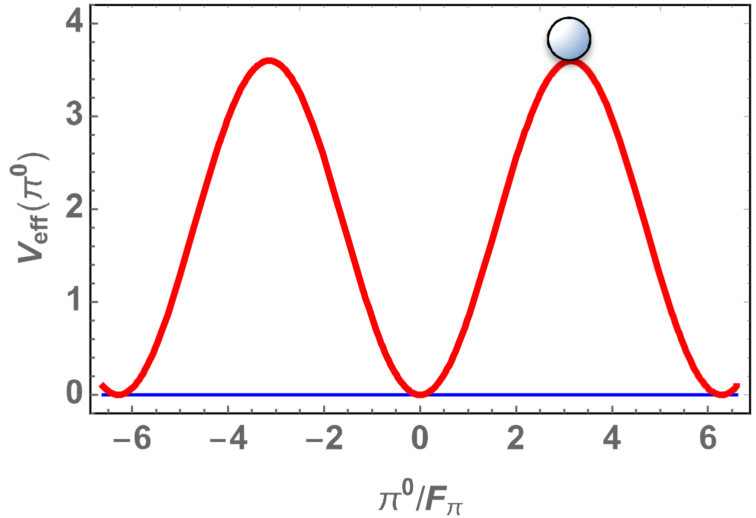




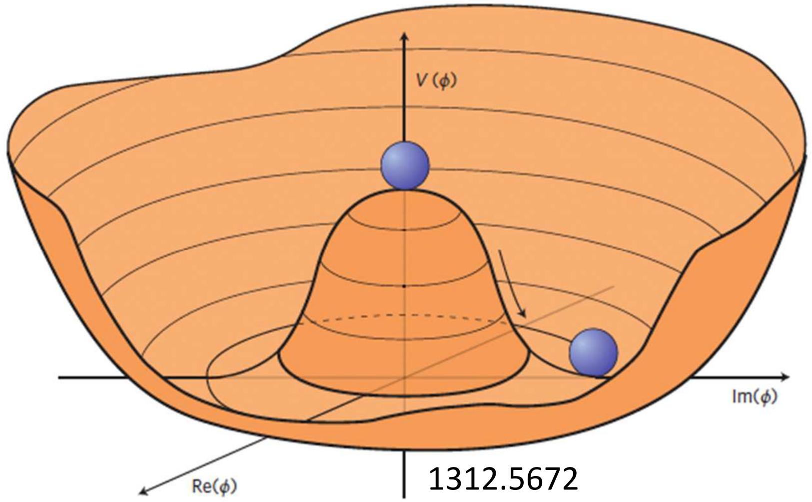
Applying the dS SWC to the local maximum of the pion potential ($\pi^0/F_\pi = \pi$) implies the sizable coupling between the quintessence and the QCD sector.

$$V(Q,\pi^0) \sim \exp\left(-\frac{c}{M_{Pl}}Q\right)\left(V_{eff}(\pi^0) + V_0\right)$$

Higgs at the origin

1807.06581 Denef, Hebecker, Wrase

The scalar potential of the Higgs can be written as $V(h) = \lambda\left(|H|^2 - \frac{v^2}{2}\right)^2$



$$H = \frac{1}{\sqrt{2}}\begin{bmatrix} 0 \\ h \end{bmatrix}$$

Applying the dS SWC to the point $\langle H \rangle = 0$ *:*

$$V(Q,h) \sim \exp\left(-\frac{c}{M_{Pl}}Q\right)(V(h) + V_0)$$

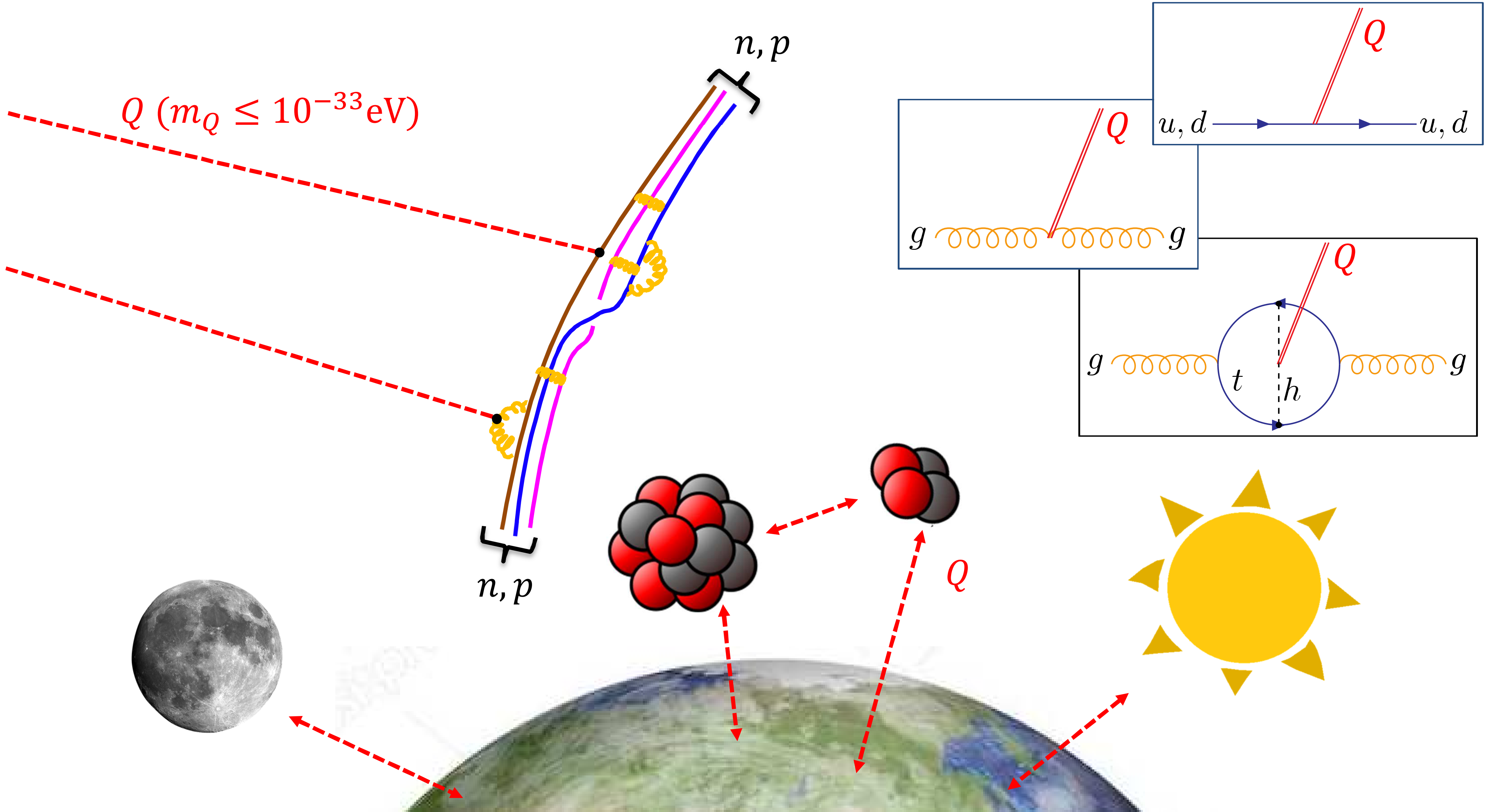
The original dS SWC :
inevitable couplings between the quintessence and the SM fields

Phenomenological constraints

[Choi, Chway, CSS 18]

Constraints on the quintessence couplings

The quintessence coupling to the pion and the Higgs induces a long range force between macroscopic objects (nucleus, earth, sun, etc): The gluon and light quark couplings to the Quintessence at a scale $\mu \simeq \Lambda_{QCD}$ is essential.



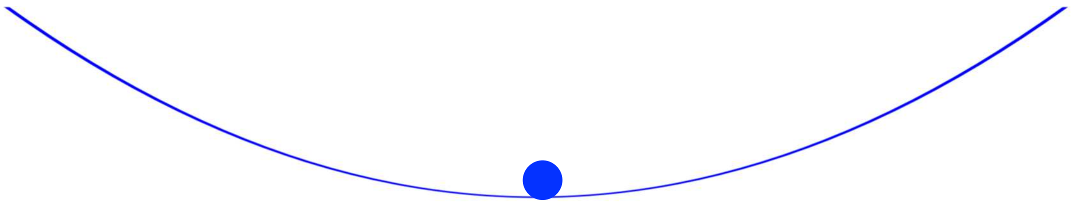
Predictions?

For the pion case, there is the direct relation between the long range force and the bound on "c" for the dS SWC (e.g. $c \leq O(10^{-5}, 10^{-2})$ as discussed in Kiwoon's talk).

Caveat : valid if there is no other light scalar field (moduli with $m_\chi > H_0$) whose scalar potential is largely shifted by changing the pion expectation value.

$$\mathcal{L} = -\frac{1}{2}(\partial_\mu Q)^2 + \frac{c_Q(\chi)}{M_{Pl}} Q\, V_{eff}(\pi^0) - \frac{1}{2}(\partial_\mu \chi)^2 - \frac{1}{2} m_\chi^2 \chi^2 + \frac{c_\chi}{M_{Pl}} \chi\, V_{eff}(\pi^0) + \cdots$$

$\boxed{\pi^0 = 0}$



Fifth force constraints are for $c_Q(\chi = 0)$ *(present value) . The dS SWC needs* $\nabla V|_{\text{pion top}} = \sqrt{(\partial_Q V)^2 + (\partial_\chi V)^2}$. *At* $\chi = 0$, $\partial_\chi V = \frac{c_\chi}{M_{Pl}} V$: $\sqrt{c_Q(0)^2 + c_\chi^2} > c$. *Constraints on* c_χ *is needed. On the other hand, at a new extremum for* χ ($\partial_\chi V = 0$), $\nabla V|_{\text{pion top}} = c_Q(\chi \neq 0) > c$, *whose value could be quite different from* $c_Q(\chi = 0)$.

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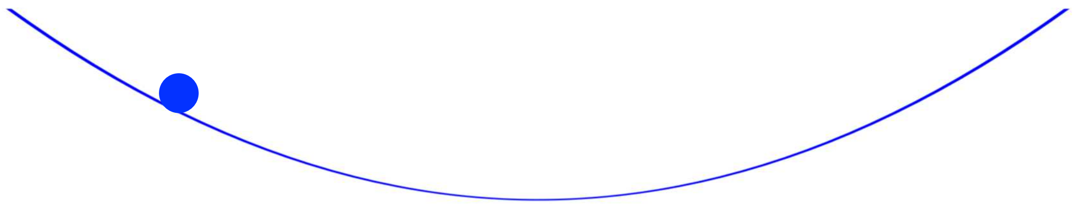
$$\boxed{\pi^0 = \pi\, F_\pi}$$



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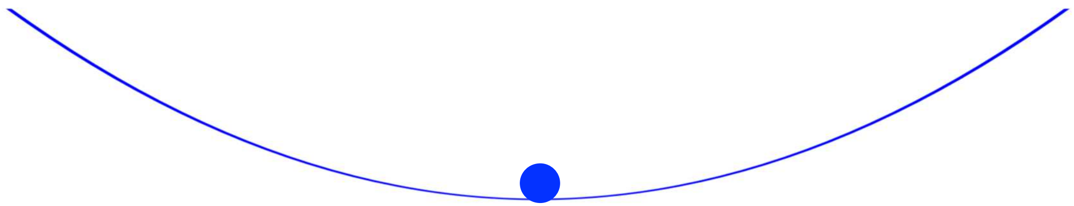

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Constraining the coupling between the light moduli and the SM fields is also crucial for predictions.

Fifth force constraints for light scalar coupling

The only known long range force for neutral objects: gravity

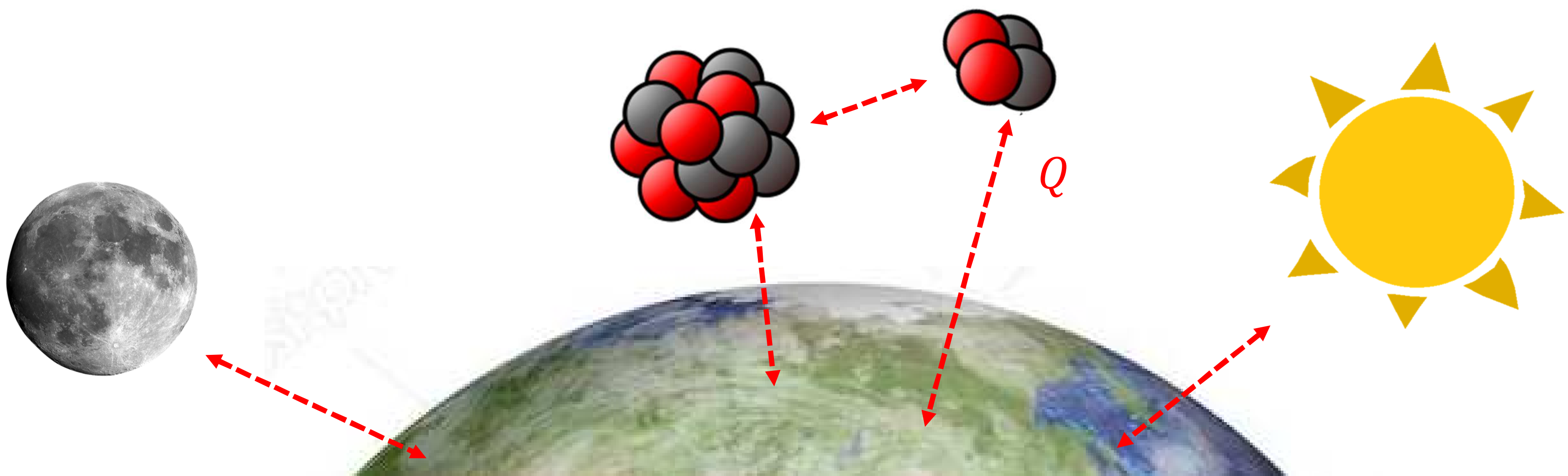
1) inertial mass = gravitational mass (universal acceleration)

2) gravitational force = spacetime curvature

3) inverse-square law at large distances (Force $\propto 1/r^2$)

Any phenomena deviated from 1)-3) imply a modification of Einstein Gravity or an additional long range force. In other words, if there is no deviation, it gives strong constraints.

$$V_i = -G\frac{M_* m_i}{r}(1 + \alpha_{*i} e^{-m_Q r}), \qquad \eta_{ij} = 2\frac{|\vec{a}_i - \vec{a}_j|}{|\vec{a}_i + \vec{a}_j|}$$



No violation of the weak equivalence principle

If the light scalar couples to the trace of energy momentum tensor, the force is proportional to the mass of the object : does not violate WEP for the objects at rest.

$$\frac{c}{M_{Pl}} Q\, T^{\mu}{}_{\mu} \rightarrow \frac{c}{M_{Pl}} Q\, m_{\psi}\, \bar{\psi}\psi$$

However Q is not coupled to photons at low energies.

Photons only feel gravity (gravitational mass).

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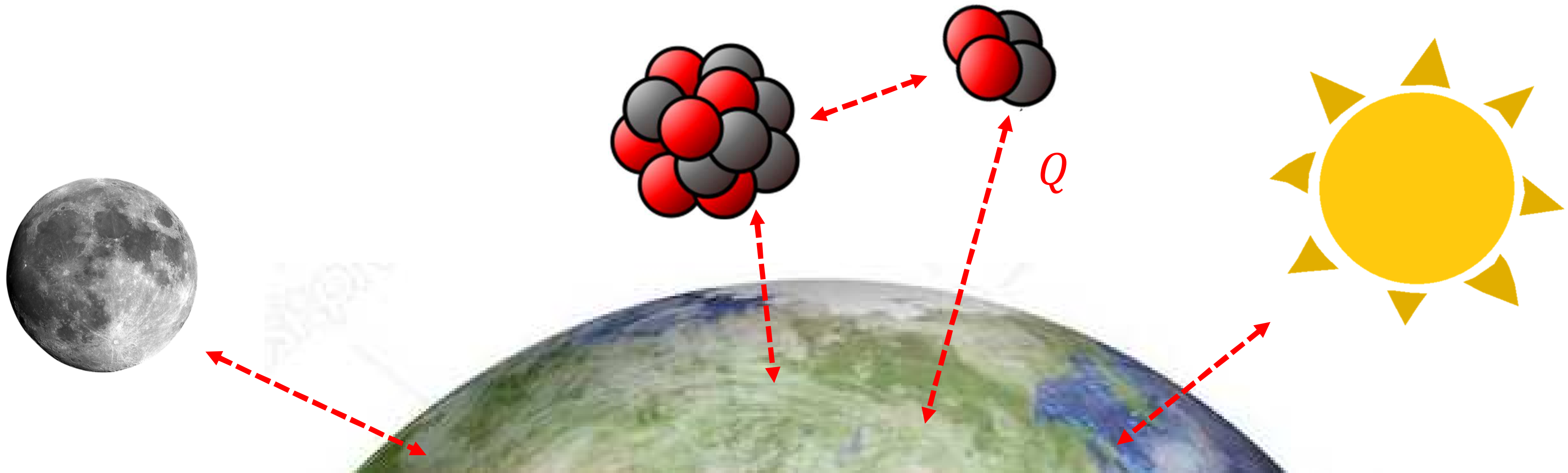
$$V_i = -G\frac{M_* m_i}{r}(1 + \alpha e^{-m_Q r}), \qquad GM_*(r_1) \neq GM_*(r_2)$$

$$ds^2_{eff} = -\left(1 - \frac{2GM_*}{r}\right)dt^2 + \left(1 + (1 + \delta\gamma)\frac{2GM_*}{r}\right)d\vec{x}^2$$

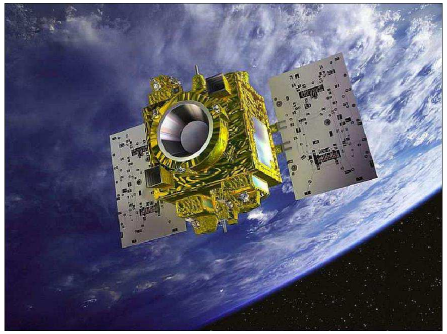
from Kepler mass *from light ray deflection*



Violation of the weak equivalence principle

Measurement of the Eötvös *parameter* $\eta = (\Delta a/a)_{ij}$

MICROSCOPE experiment : $\eta(\mathrm{Ti},\mathrm{Pt}) < (-1 \pm 27) \times 10^{-15} (2\sigma)$ *for* $m_Q < 10^{-12}$ eV



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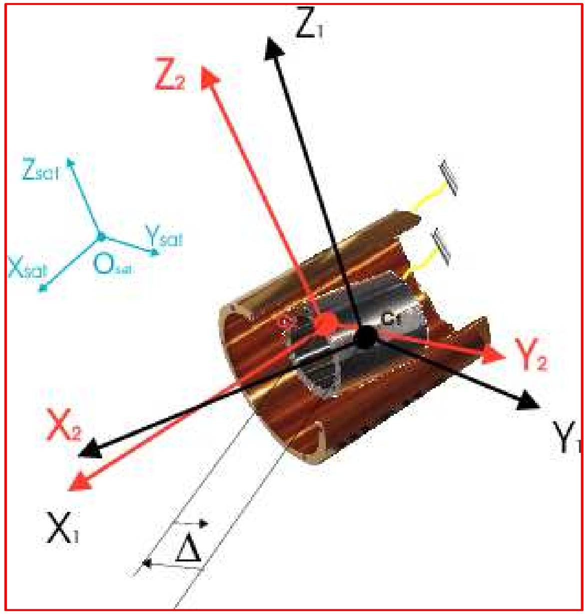
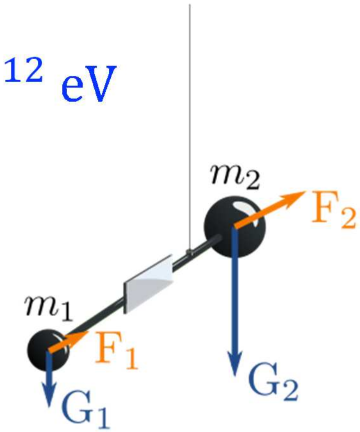
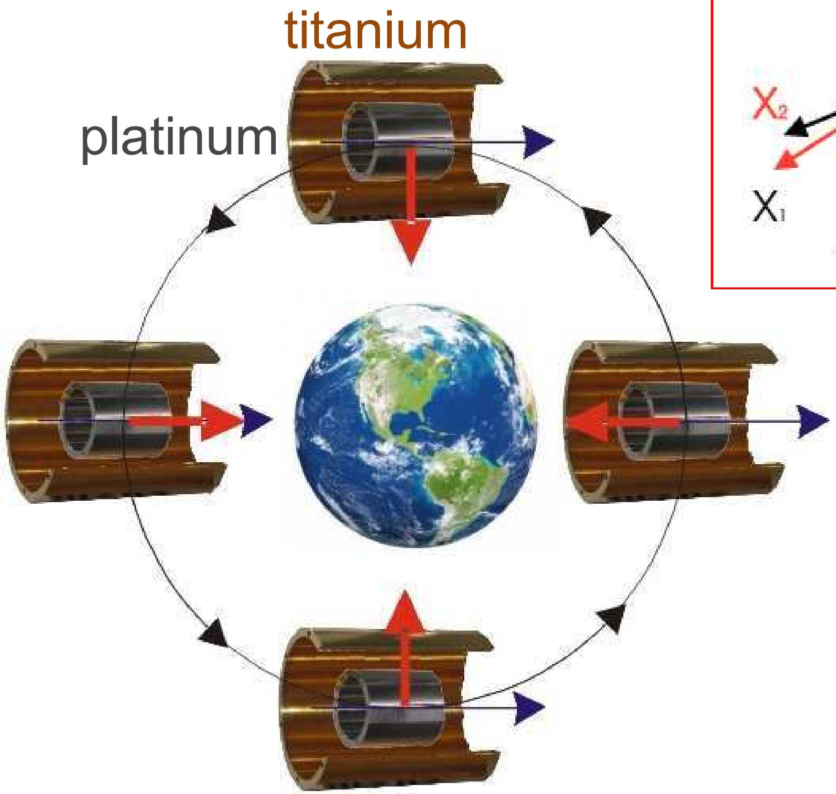
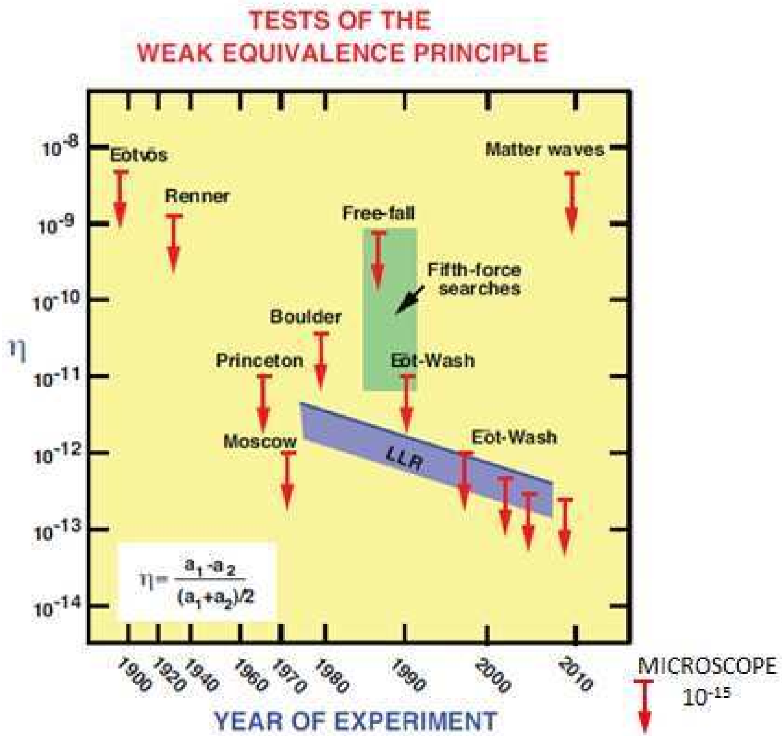






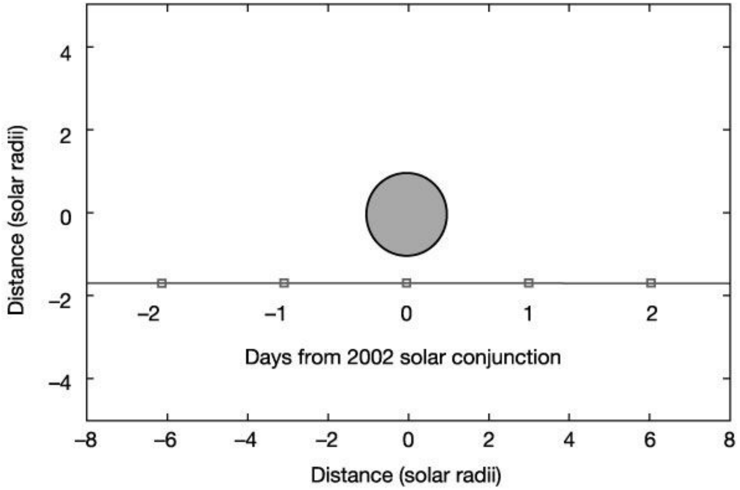


1501.01644

Violation of general relativity

"A massive object like the Sun causes space-time to curve, and a light ray (radio wave) that passes by the Sun has to travel further because of the curvature. The extra distance that the radio waves travel from Cassini past the Sun to the Earth delays their arrival; the amount of the delay provides a sensitive test of the predictions of Einstein's theory."

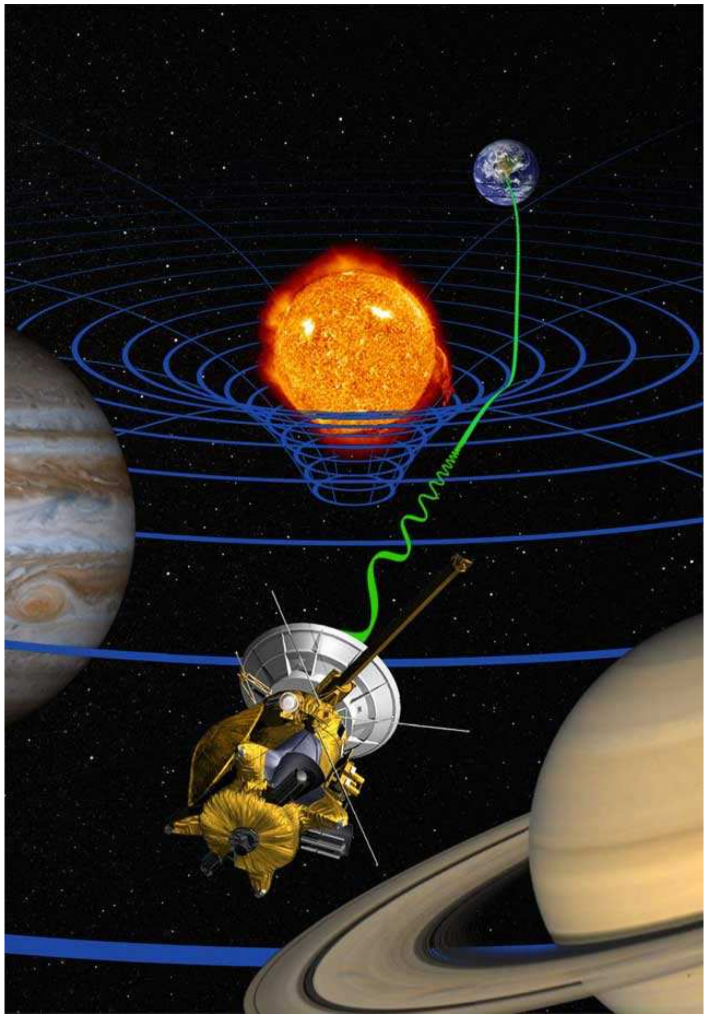
for $m_Q < 10^{-18} eV$



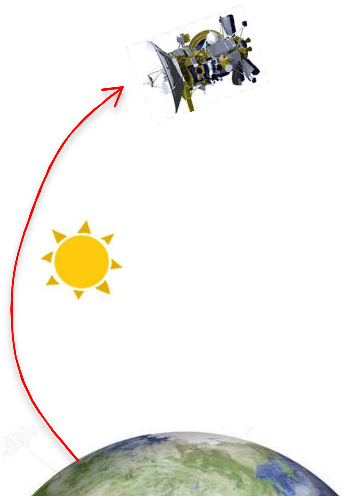
$$\delta\gamma = (2.1 \pm 2.3) \times 10^{-5}$$

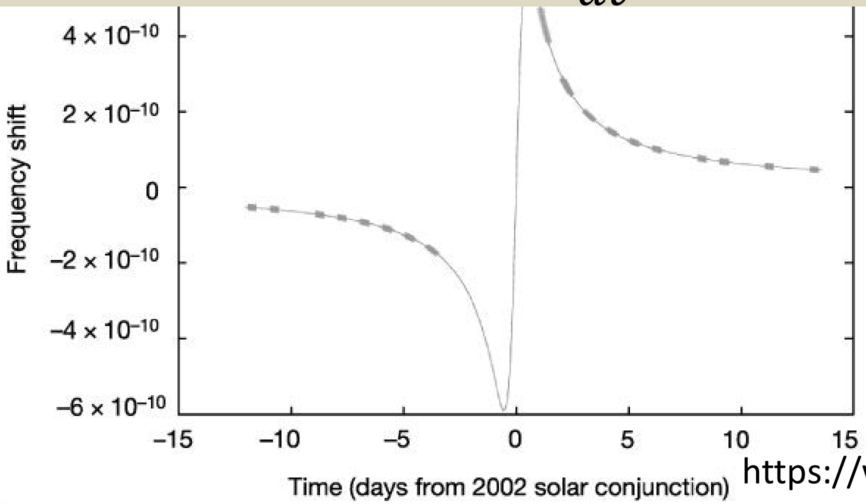
Cassini spacecraft

Nature 425 (2003) 374



$$\frac{d\Delta t}{dt} = \frac{\Delta\nu}{\nu} = -(10^{-5}\text{sec})(2+\delta\gamma)\frac{\text{d ln impact parameter}}{dt}$$





https://www.jpl.nasa.gov/news/news.php?feature=230

Violation of inverse-square law

Newton's constant at laboratory experiments ($G_{\rm lab}$) and that for space measurements ($G_{\rm sp}$)

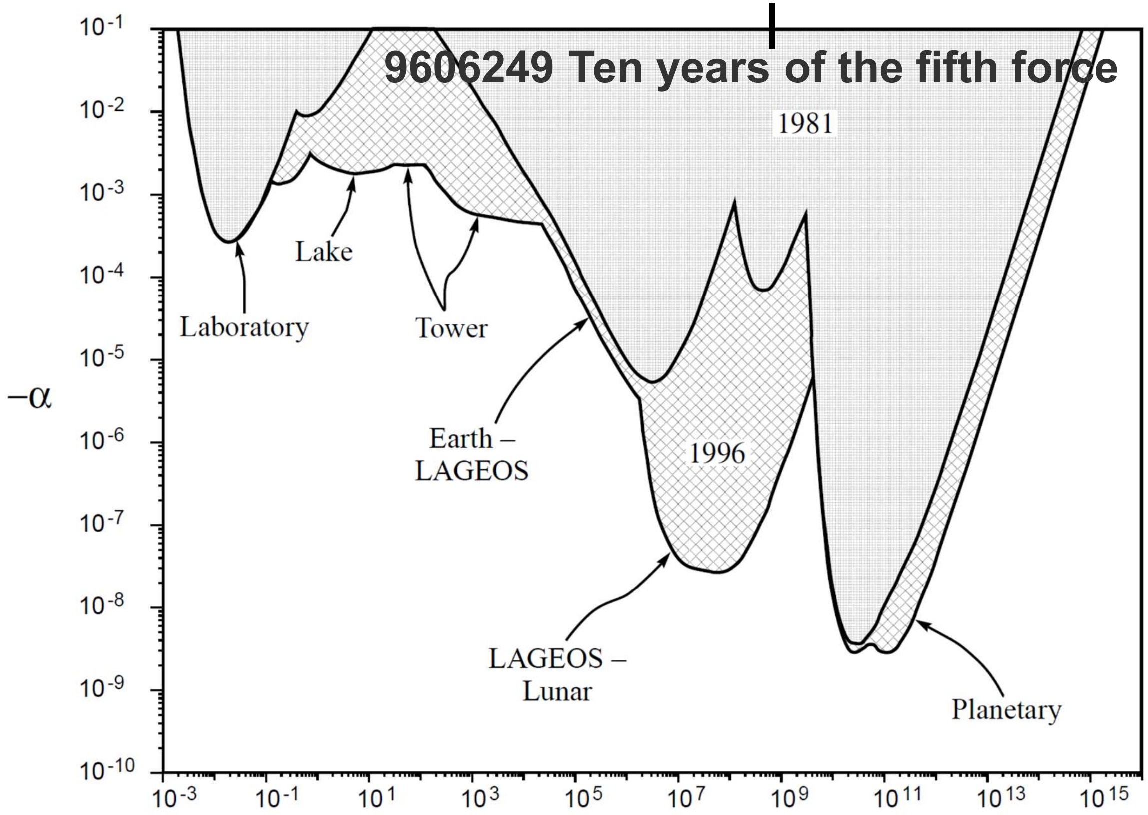
$$V_i = -G\frac{M_* m_i}{r}\left(1+\alpha e^{-m_Q r}\right) = -G(r)\frac{M_* m_i}{r}, \qquad G(0) = G(\infty)(1+\alpha)$$

It is mostly sensitive for a mass range: $m_Q r_{\rm lab} \ll 1 \ll m_Q r_{\rm sp}$

$$\mathrm{r_{moon}} \simeq 3.8\times 10^{8}\ \mathrm{m} \;\to\; m_Q = 5\times 10^{-15}\ \mathrm{eV}$$

10^{-15} eV

$$G_{\rm sp} \simeq G(\infty) = \frac{G(0)}{(1+\alpha_{*i})}$$

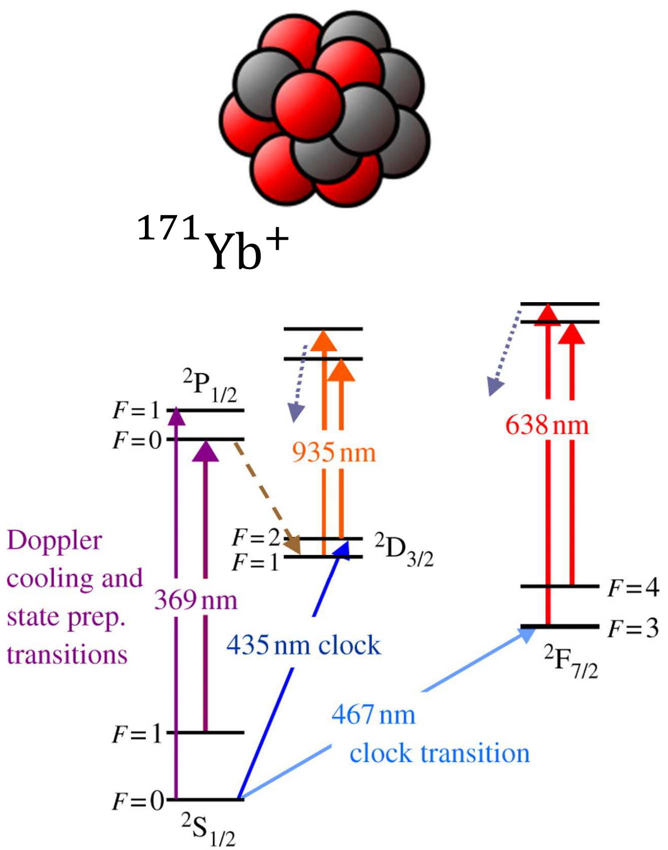


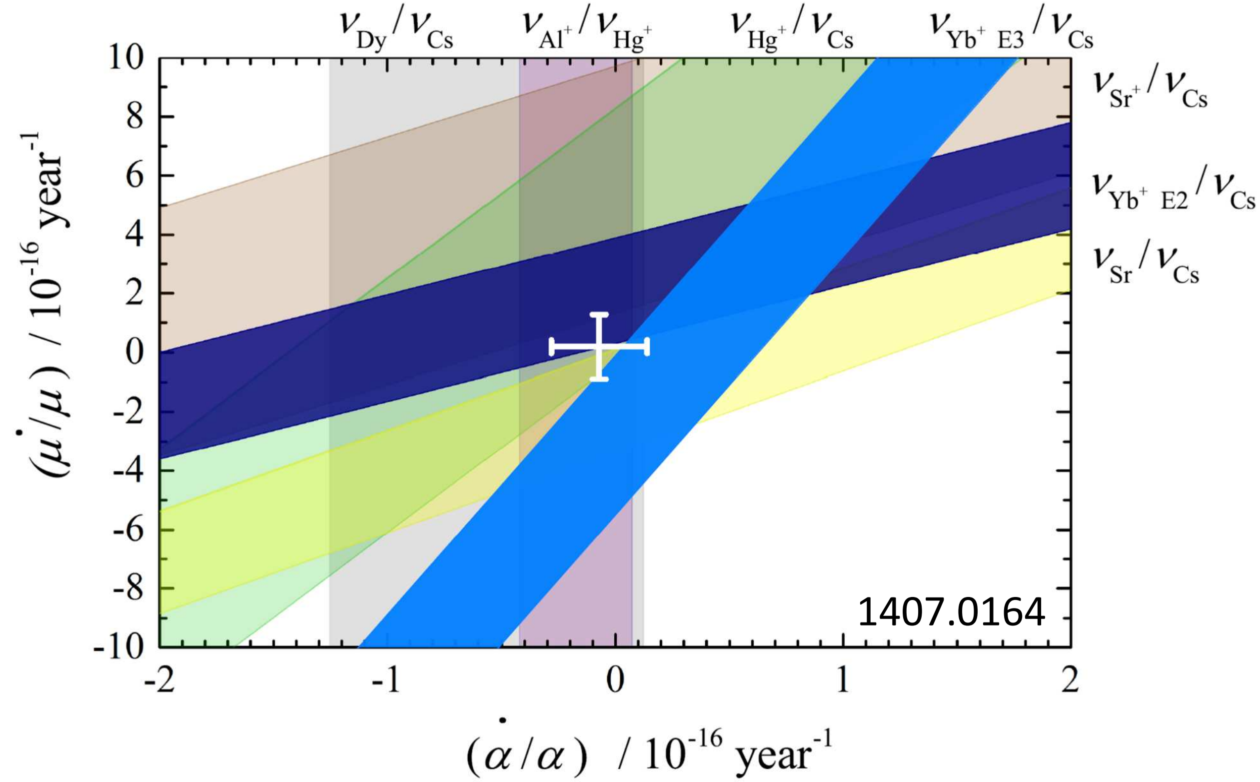
$= 1/m_Q$

$$G_{\rm lab} \simeq G(0)$$

Time varying coupling constant

Fine structure constant, $\alpha(Q)$, and nucleon mass, $m_N(Q)$, electron mass, $m_e(Q)$ can change as the quintessence vacuum value changes ($\dot{Q} \neq 0$)





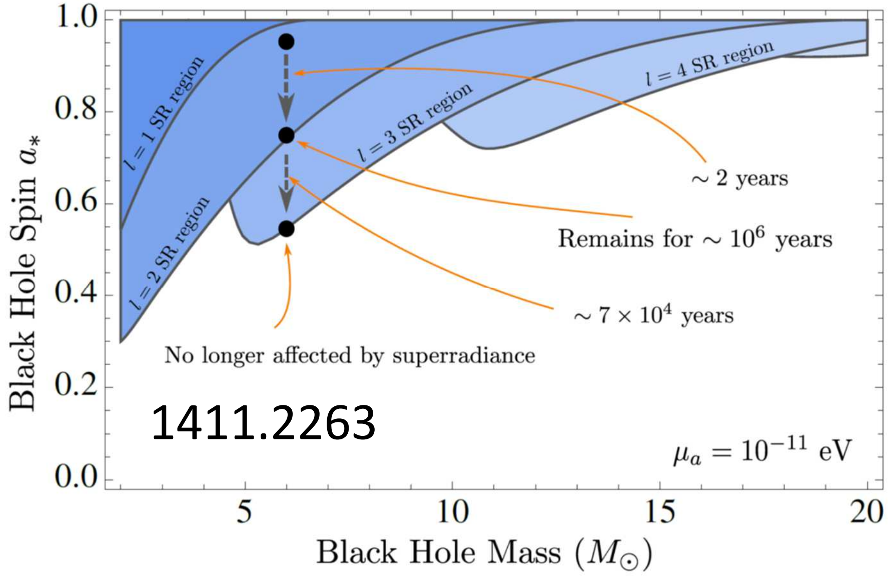
$$\dot{\alpha}/\alpha = -0.7(2.1) \times 10^{-17}\ \mathrm{year}^{-1}$$
$$\dot{\mu}/\mu = 0.2(1.1) \times 10^{-16}\ \mathrm{year}^{-1}$$

$\nu_i \propto \mu^{B_i}\alpha^{A_i}$ *(A_i, B_i from numerical calculation, $\mu \equiv m_e/m_p$)*

$$\frac{1}{(\nu_i/\nu_j)}\frac{d(\nu_i/\nu_j)}{dt} \propto (A_i - A_j)\frac{\dot{\alpha}}{\alpha} + (B_i - B_j)\frac{\dot{\mu}}{\mu}$$

Blackhole superradiance

A spinning black hole with a bosonic field whose Compton wavelength is around its Schwarzschild radius is cosmologically unstable. Observation of spinning blackholes gives the constraints on certain mass ranges of the scalar field



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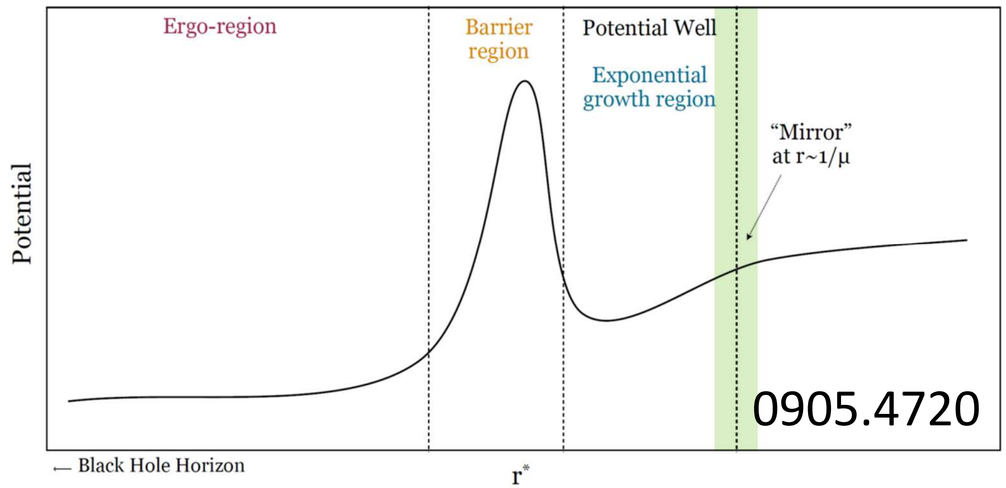

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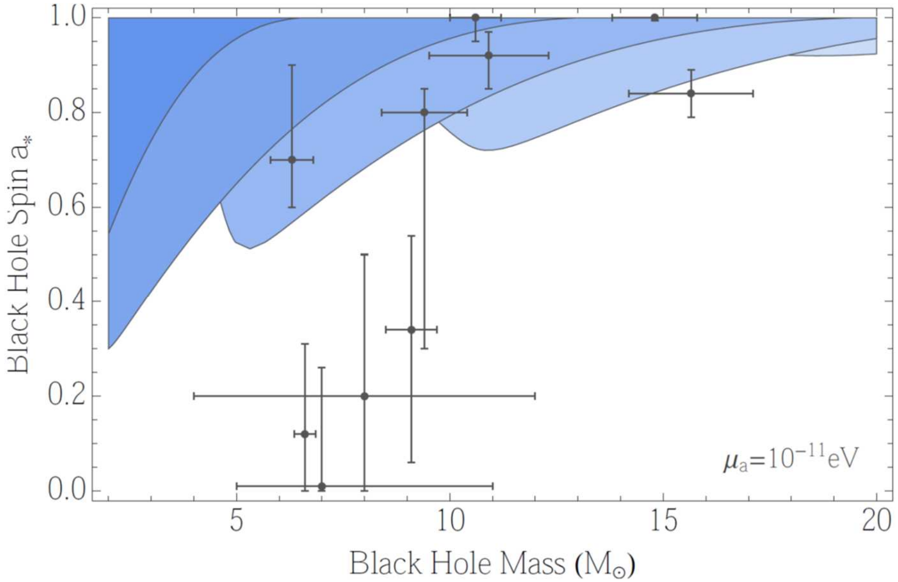

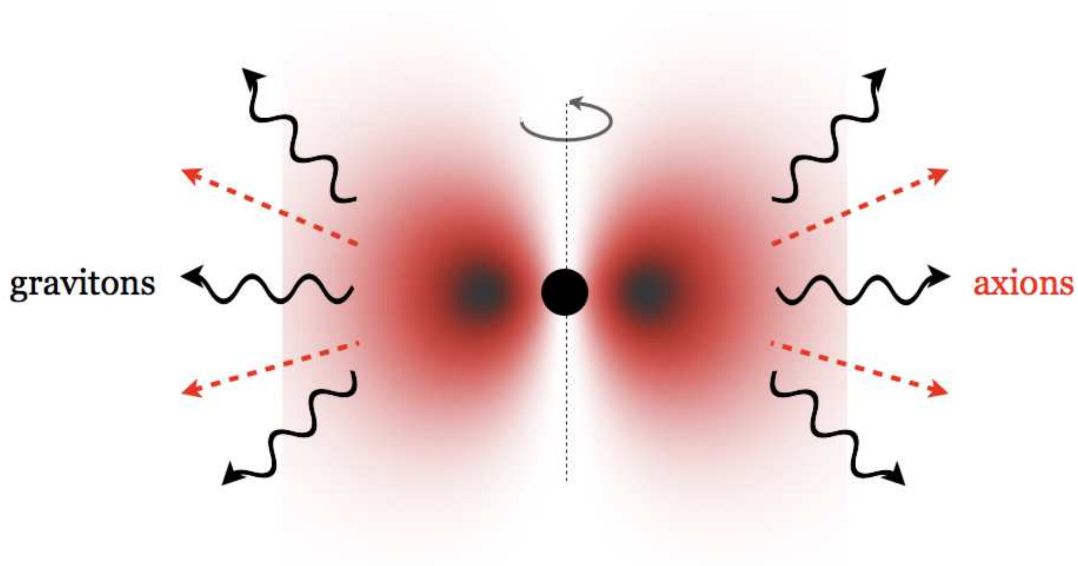

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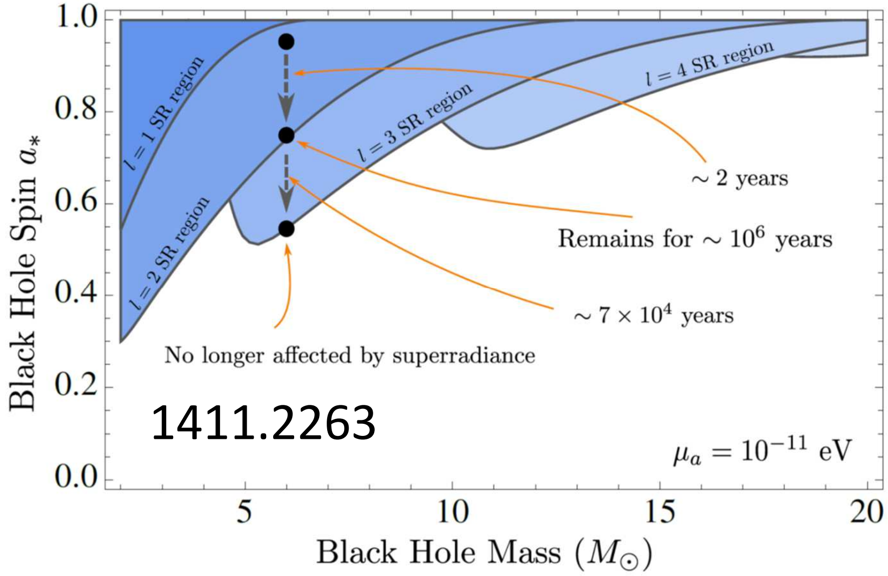
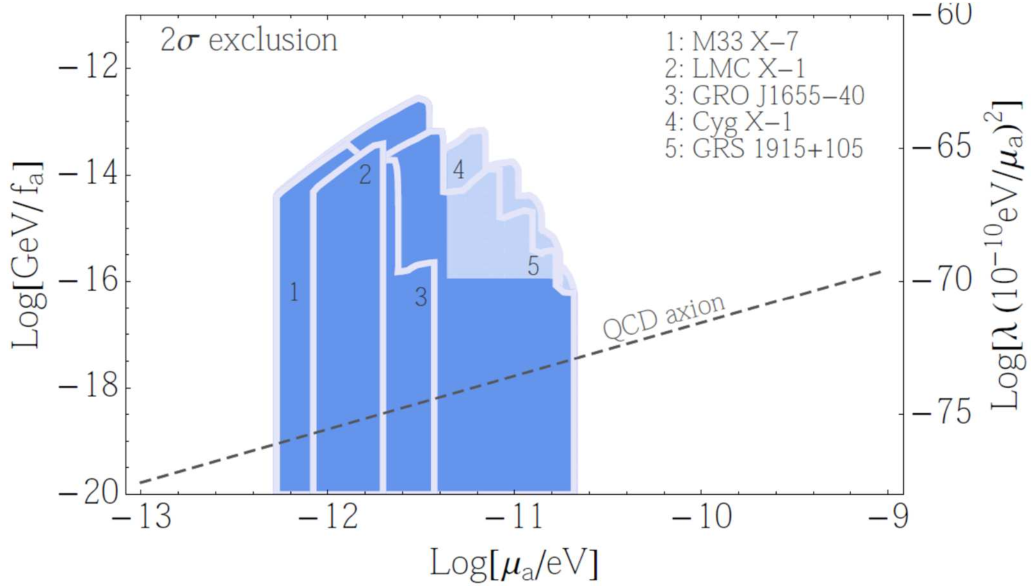
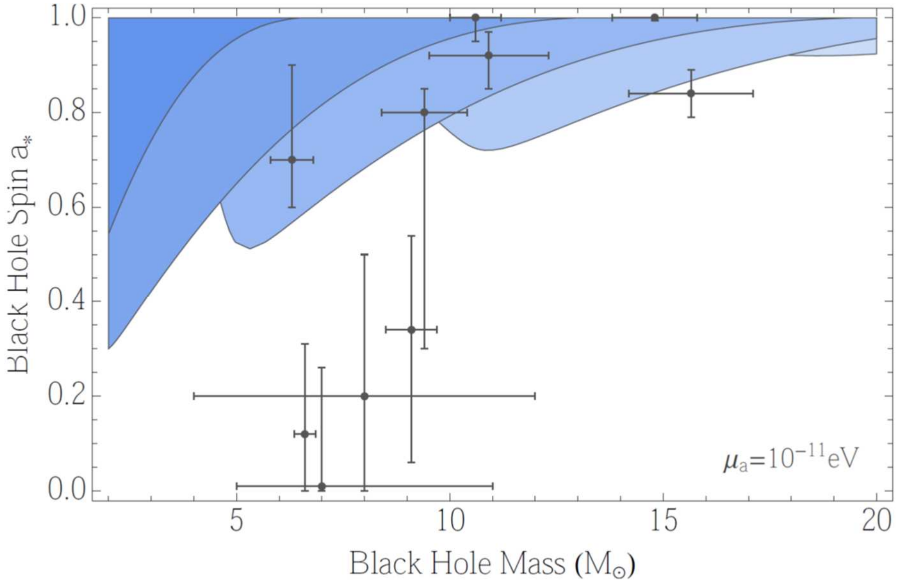
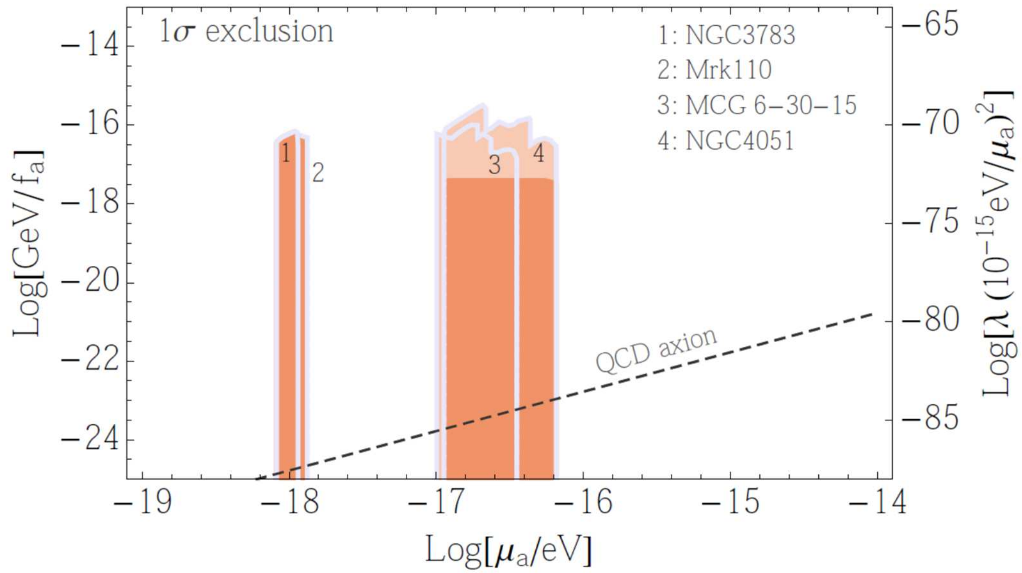
Blackhole superradiance

A spinning black hole with a bosonic field whose Compton wavelength is around its Schwarzschild radius is cosmologically unstable. Observation of spinning blackholes gives the constraints on certain mass ranges of the scalar field









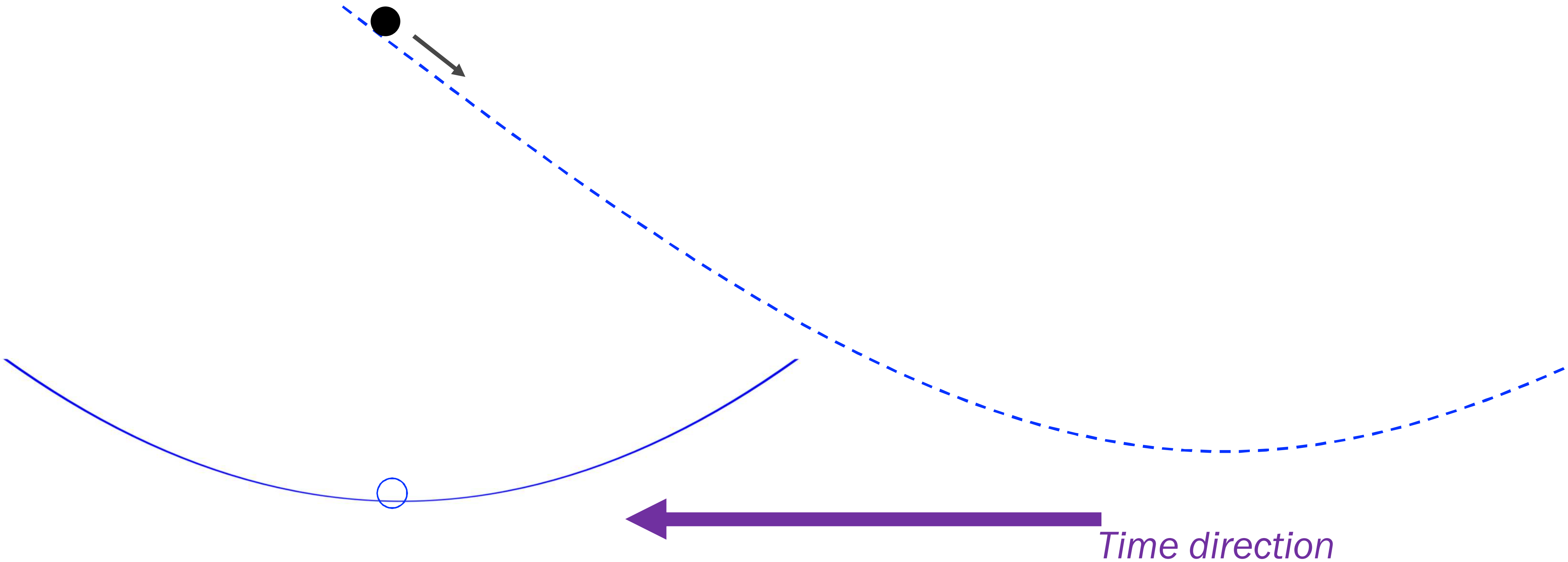
Cosmological history of the moduli

Coherent oscillation of light moduli becomes a problem if its abundance is greater than the observed dark matter abundance : $\Omega_\chi \leq \Omega_{DM}$

$$\mathcal{L} = -\frac{1}{2}\left(\partial_\mu \chi\right)^2 - \frac{1}{2} m_\chi^2 \chi^2 + \frac{c_\chi}{M_{Pl}} \chi \; \langle V_{SM} \rangle_T$$

Time dependent

For $m_\chi \ll H$



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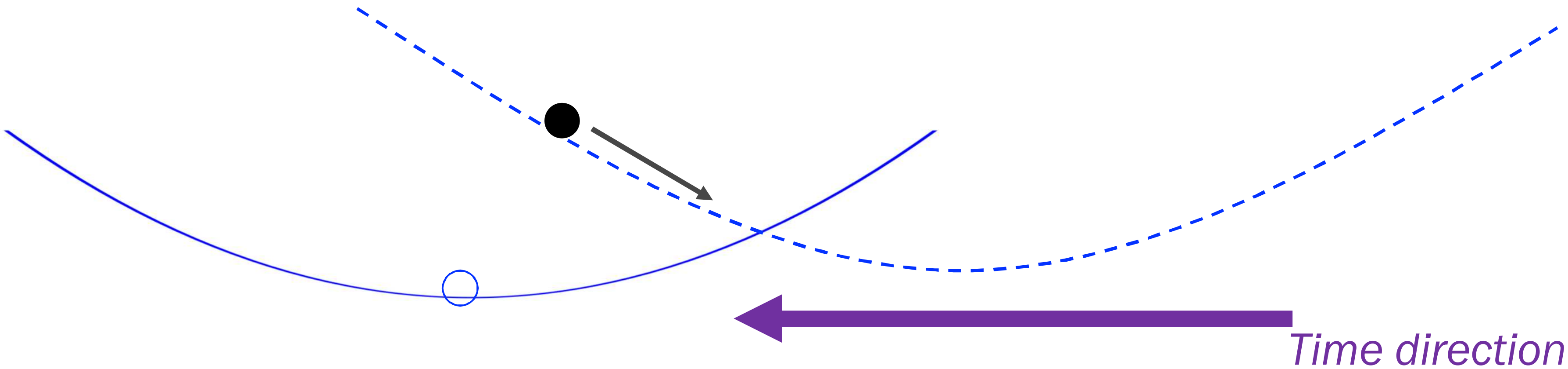
<u>*Time dependent*</u>

For $m_\chi < H$



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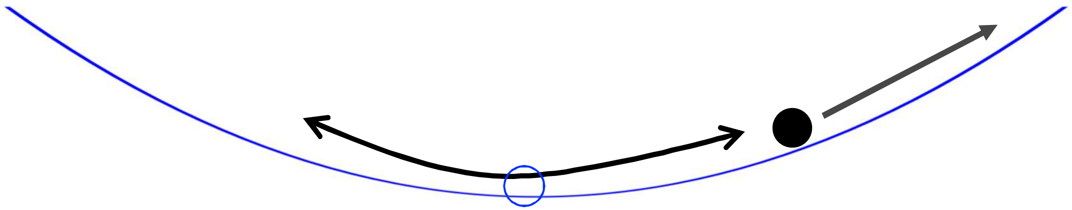
Time dependent

For $m_\chi \geq H$



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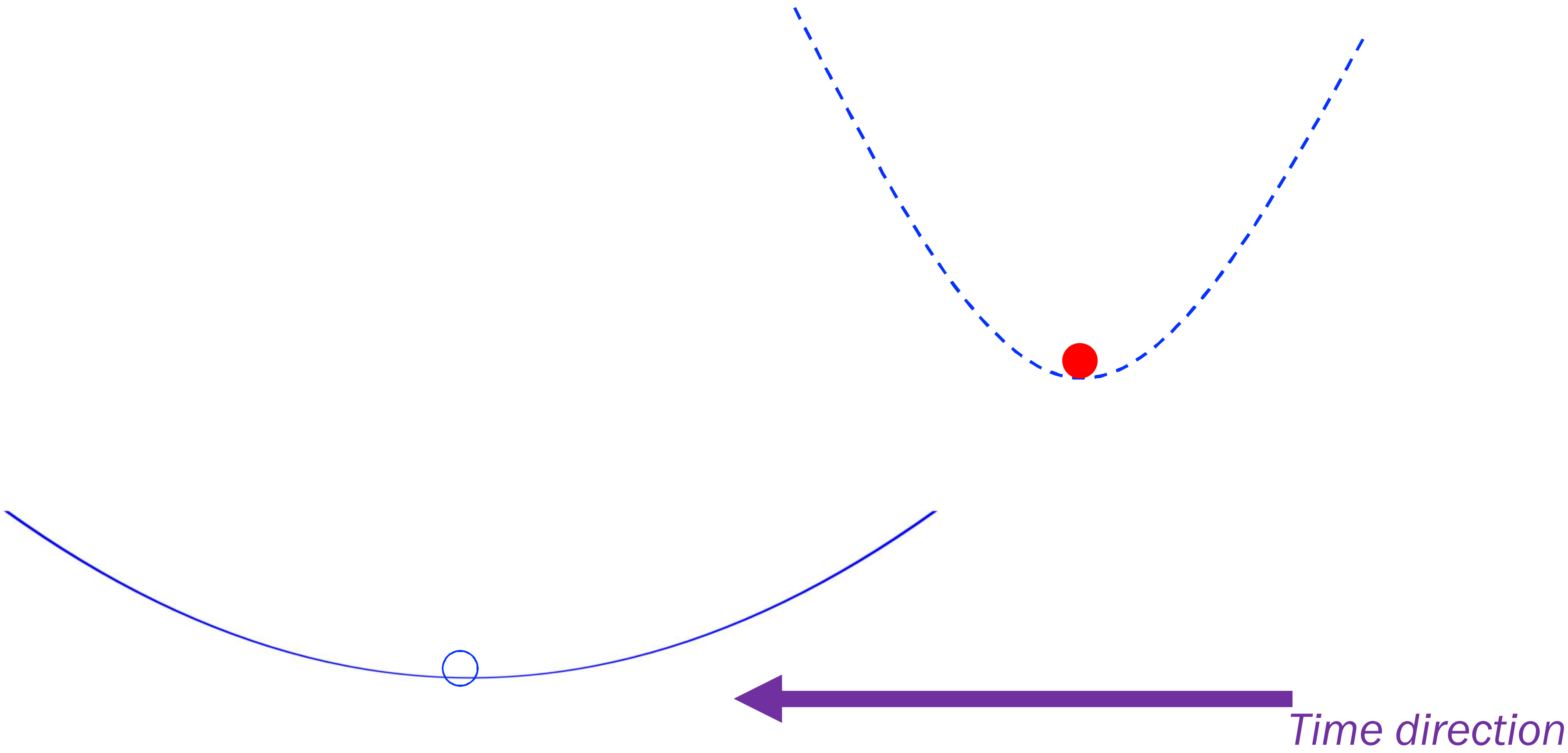
For $m_\chi \ll H$ with a Hubble induced mass term



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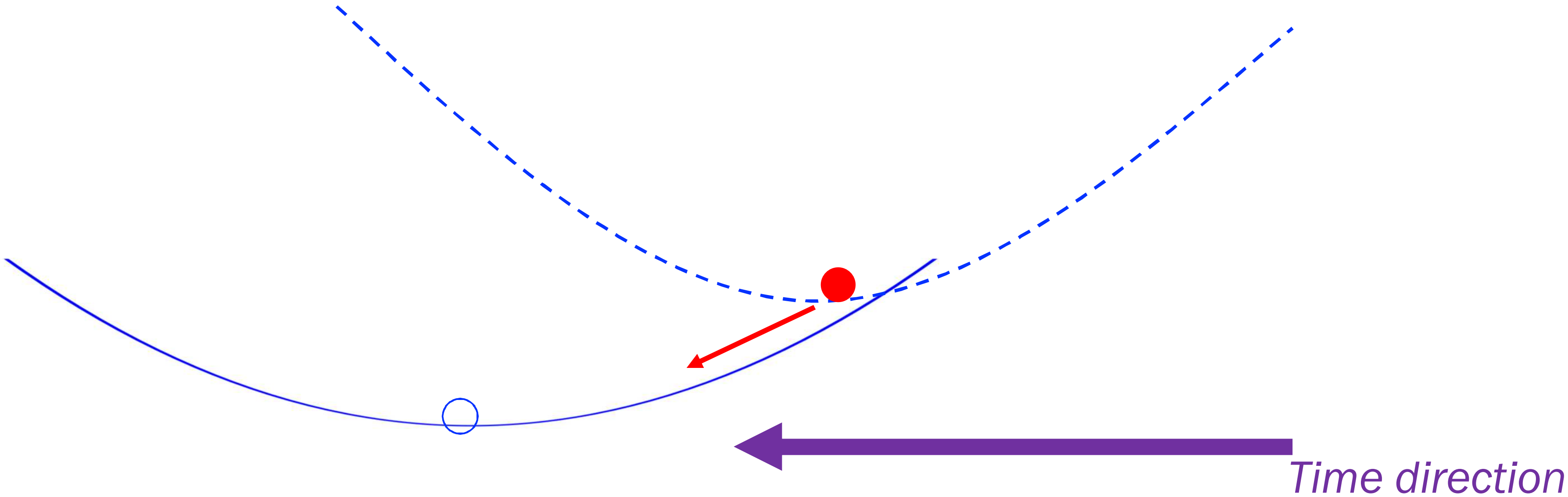

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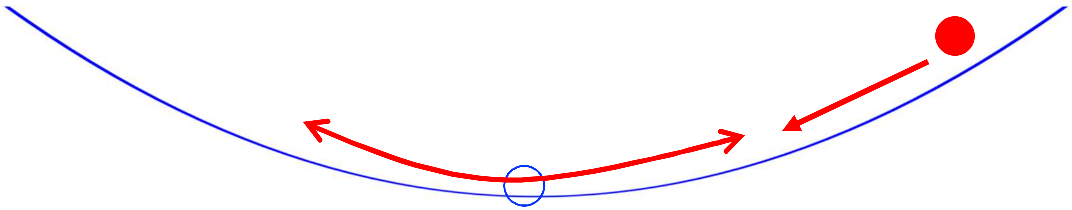
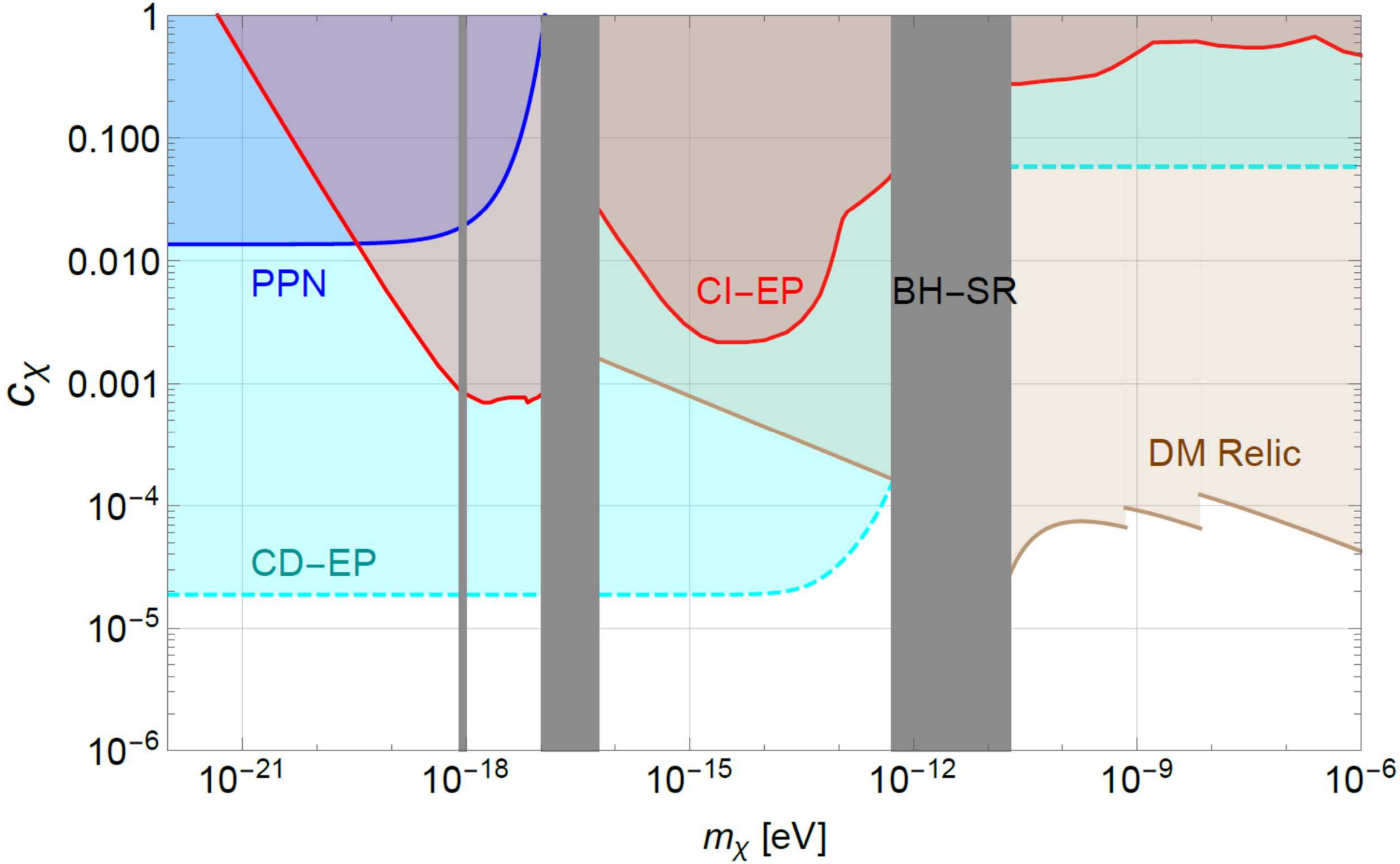
For $m_\chi \geq H$ with a Hubble induced mass term



Summary plot

[Choi, Chway, CSS 1809.01475]



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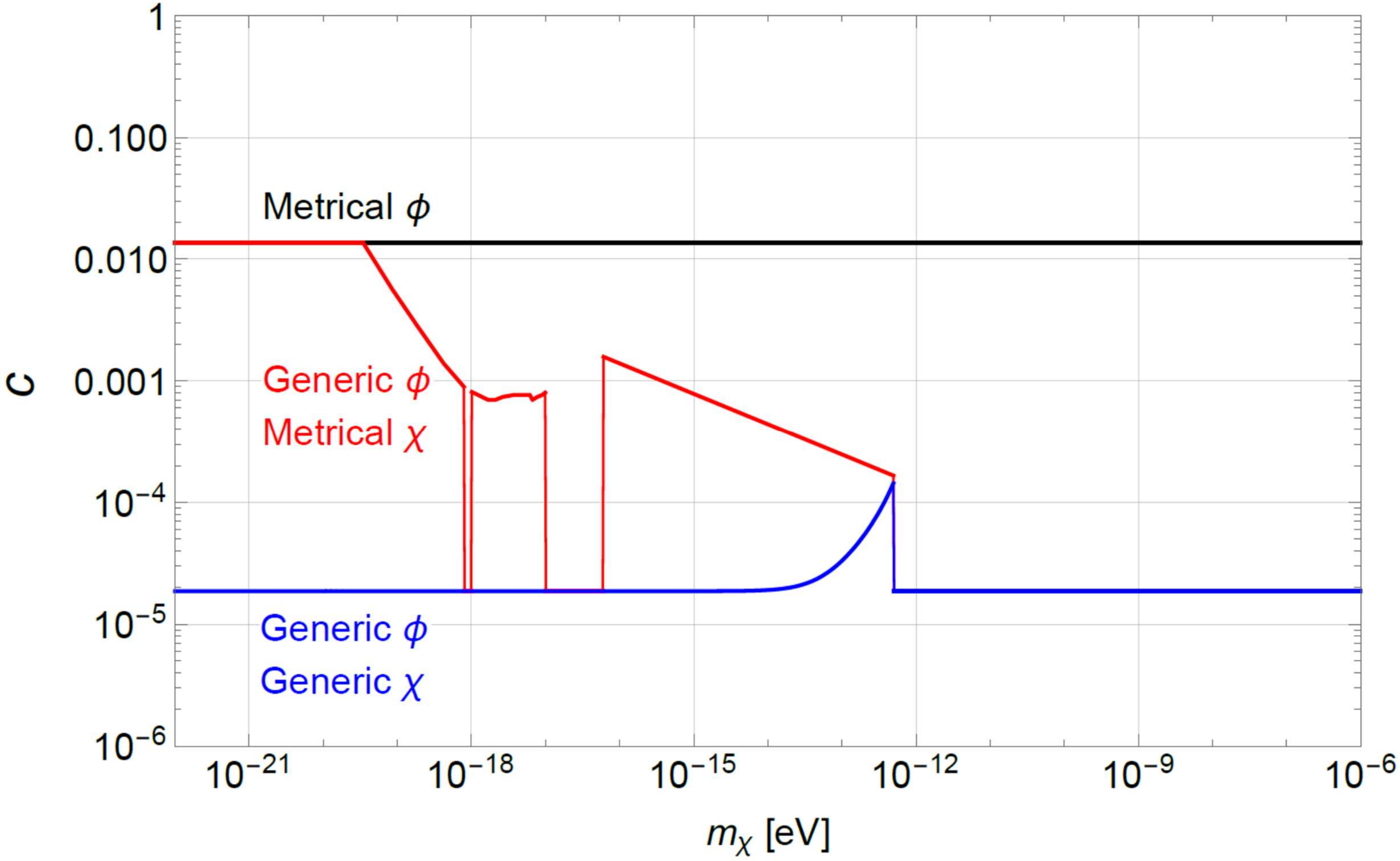

Conclusions

- *The original dS SWC gives interesting implications for the present Universe, whose claim can be tested by fifth force constraints*

- *Various experiments with the pion effective potential provides a very predictive bound on the parameter of the dS SWC.*

- *This gives the phenomenological motivation of refining the dS SWC.*

- *I did not yet figure out concrete phenomenological constraints on the refined version.*