Festina-Lente Bound on Higgs vacuum structure, inflation and dark photon
Why electron is not massless?

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S.M.Lee, D.Y.Cheong, M.S.Seo, SCP, 2111.04010 (JHEP 22)
K. Ban, D. Y. Cheong, H. Okada, H. Otsuka,J-C Park, SCP, 2206.00890 (PTEP 23)

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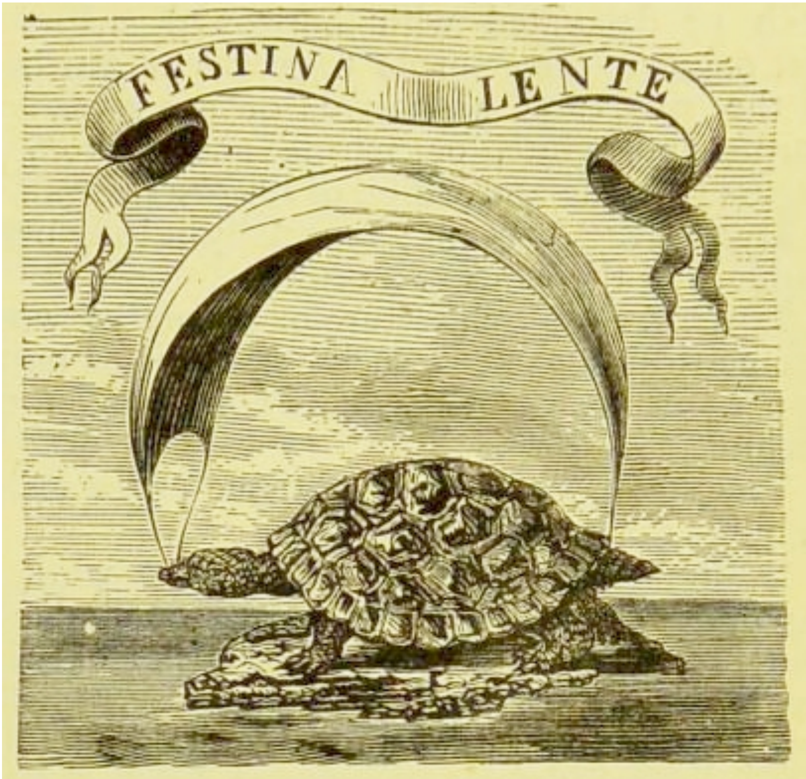
$m_e = 0$ is not acceptable

$m_e = 0$ spoils all chemistry and biology. You cannot exist.

However, is there a fundamental reason against a massless electron?

'Festina Lente bound' gives a hint

Festina lente symbol has been widely used in Europe since middle ages



Festina Lente

My army, march
Festina Lente!

- ***Festina lente*** (Classical Latin: [fɛsˈtiː.naː ˈlɛn.teː]) is a classical adage meaning “***make haste slowly***”

-wikipedia

“급할 수록 돌아가라” in Korean

“ゆっくり急げ” in Japanese

- ***If tasks are rushed too quickly then mistakes are made, and good long-term results are not achieved.***
  “move quickly but not too quickly!”

- It was adopted as a motto by the emperor Augustus.

'Festina Lente bound' in physics

#1

Festina Lente: EFT Constraints from Charged Black Hole Evaporation in de Sitter

Miguel Montero (Leuven U. and Harvard U.), Thomas Van Riet (Leuven U.), Gerben Venken (Leuven U.)

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DOI: 10.1007/JHEP01(2020)039

#2

The FL bound and its phenomenological implications

Miguel Montero (Harvard U.), Cumrun Vafa (Harvard U.), Thomas Van Riet (Leuven U. and Uppsala U.), Gerben Venken (Heidelberg U.)

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Festina Lente: EFT Constraints from Charged Black Hole Evaporation in de Sitter

Montero, Riet, Venken 1910.01648

In the Swampland philosophy of constraining EFTs from black hole mechanics we study charged black hole evaporation in de Sitter space. We establish how the black hole mass and charge change over time due to both Hawking radiation and Schwinger pair production as a function of the masses and charges of the elementary particles in the theory. **We find a lower bound on the mass of charged particles by demanding that large charged black holes evaporate back to empty de Sitter space**, in accordance with the thermal picture of the de Sitter static patch…. **All in all, charged black holes in de Sitter should make haste to evaporate, but they should not rush it.**

Festina Lente

//Review//

Charged BH in dS space

Reissner-Nordstrom-de Sitter black holes $(-,+,+,+)$

- BH solution in asymptotically dS space $\Lambda_{\rm cc} = \frac{3}{\ell_{\rm dS}^2} > 0$ with a gauged $U(1)$ field

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{16\pi G}(R - 2\Lambda_{\rm cc}) - \frac{1}{4g^2}F_{\mu\nu}F^{\mu\nu} + \mathscr{L}_M\right]$$

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + \Lambda_{\rm cc}g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

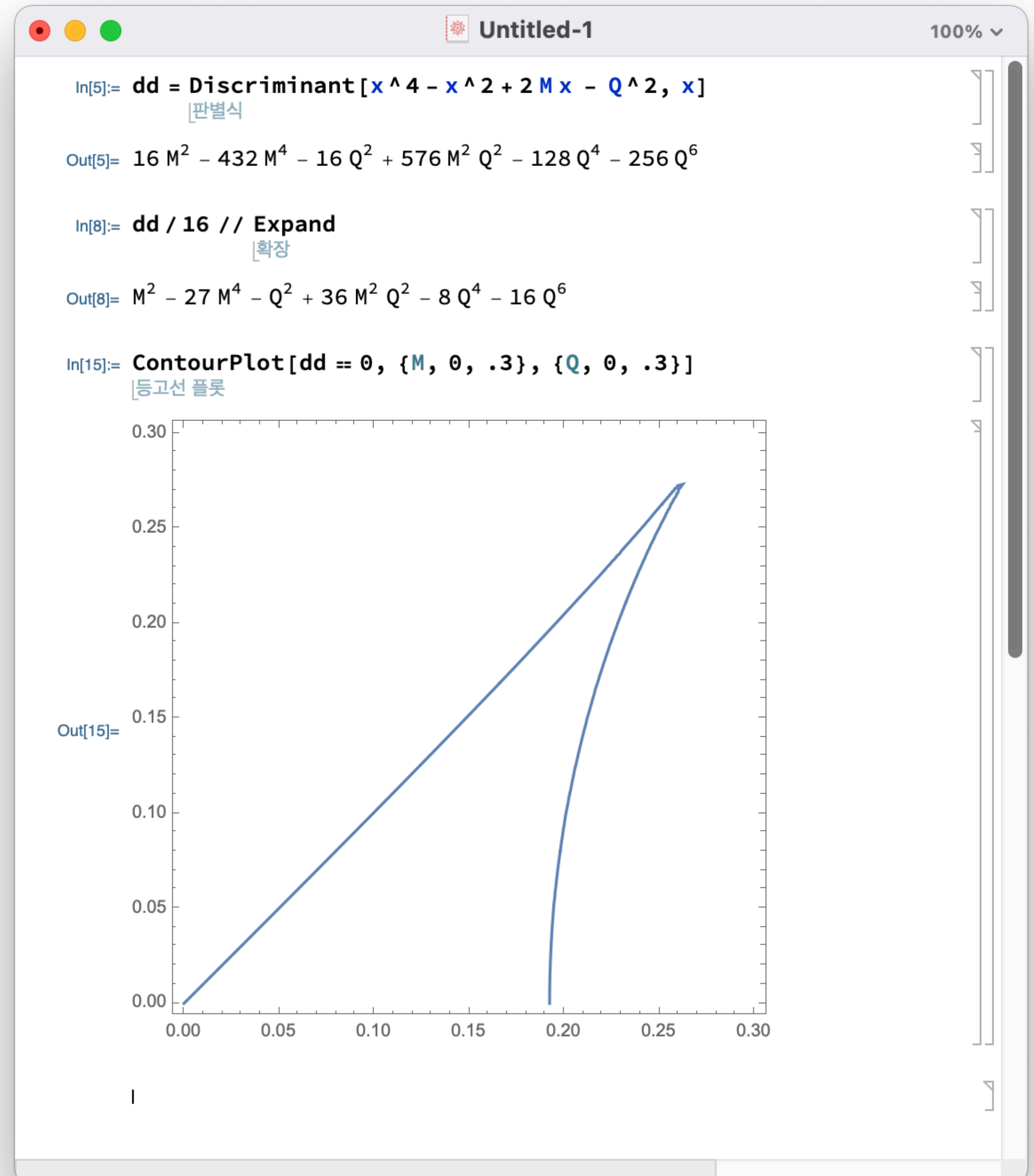
$$T_{\mu\nu} := \frac{-2}{\sqrt{-g}}\frac{\delta(\sqrt{-g}\mathscr{L}_M)}{\delta g^{\mu\nu}} = g_{\mu\nu}\mathscr{L}_M - 2\frac{\partial\mathscr{L}_M}{\partial g^{\mu\nu}}$$

- $ds^2_{\rm RN-dS} = -U(r)dt^2 + \frac{dr^2}{U(r)} + r^2 d\Omega^2$
- Lapse function : $U(r) = 1 - \frac{2GM_r}{r} + \frac{G(gQ_r)^2}{4\pi r^2} - \frac{r^2}{\ell_{\rm dS}^2}$ with $r \in (0, \ell_{\rm dS})$
- Event horizon sets at $U(r) = 0$ (cf) Schwarzschild limit $\ell_{\rm dS} \to \infty, Q_r \to 0$

Solving $0 = U(r) = 1 - \frac{2GM_r}{r} + \frac{G(gQ_r)^2}{4\pi r^2} - \frac{r^2}{\ell_{\mathrm{dS}}^2}$

Setting $Q = \frac{\sqrt{G}(gQ_r)}{\sqrt{4\pi}\ell_{\mathrm{dS}}}$, $M = \frac{GM_r}{\ell_{\mathrm{dS}}^2}$, $\ell_{\mathrm{dS}} = 1$

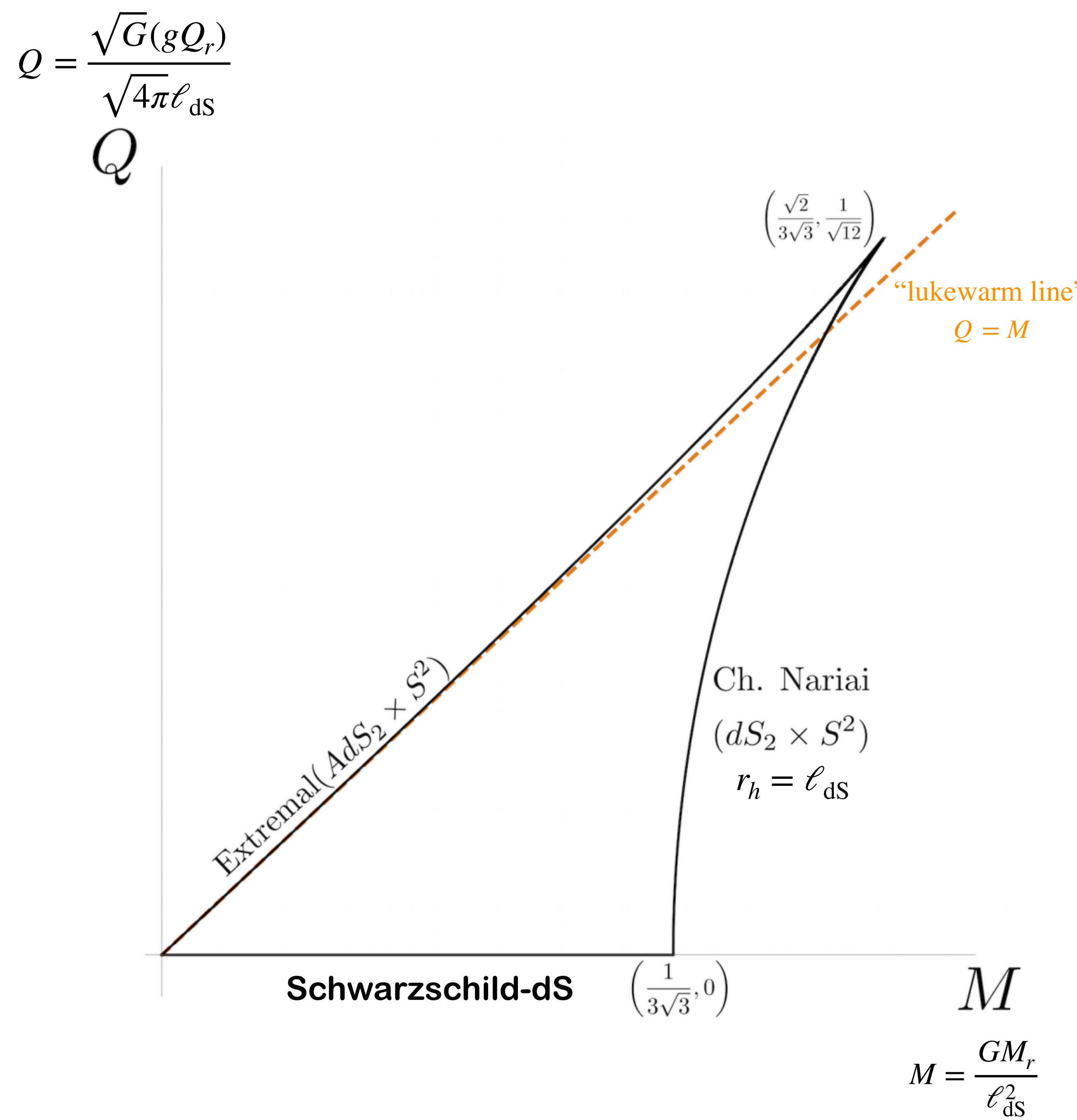
- $0 = -r^2U(r) = r^4 - r^2 + 2Mr - Q^2$
- discriminant for quartic eq.
  $\Delta = M^2 - Q^2 - 27M^4 + 36M^2Q^2 - 8Q^4 - 16Q^6$
- A real solution exists when $\Delta \geq 0$
- $\Delta = 0$ defines the boundary of the physical domain in (Q, M) plane.



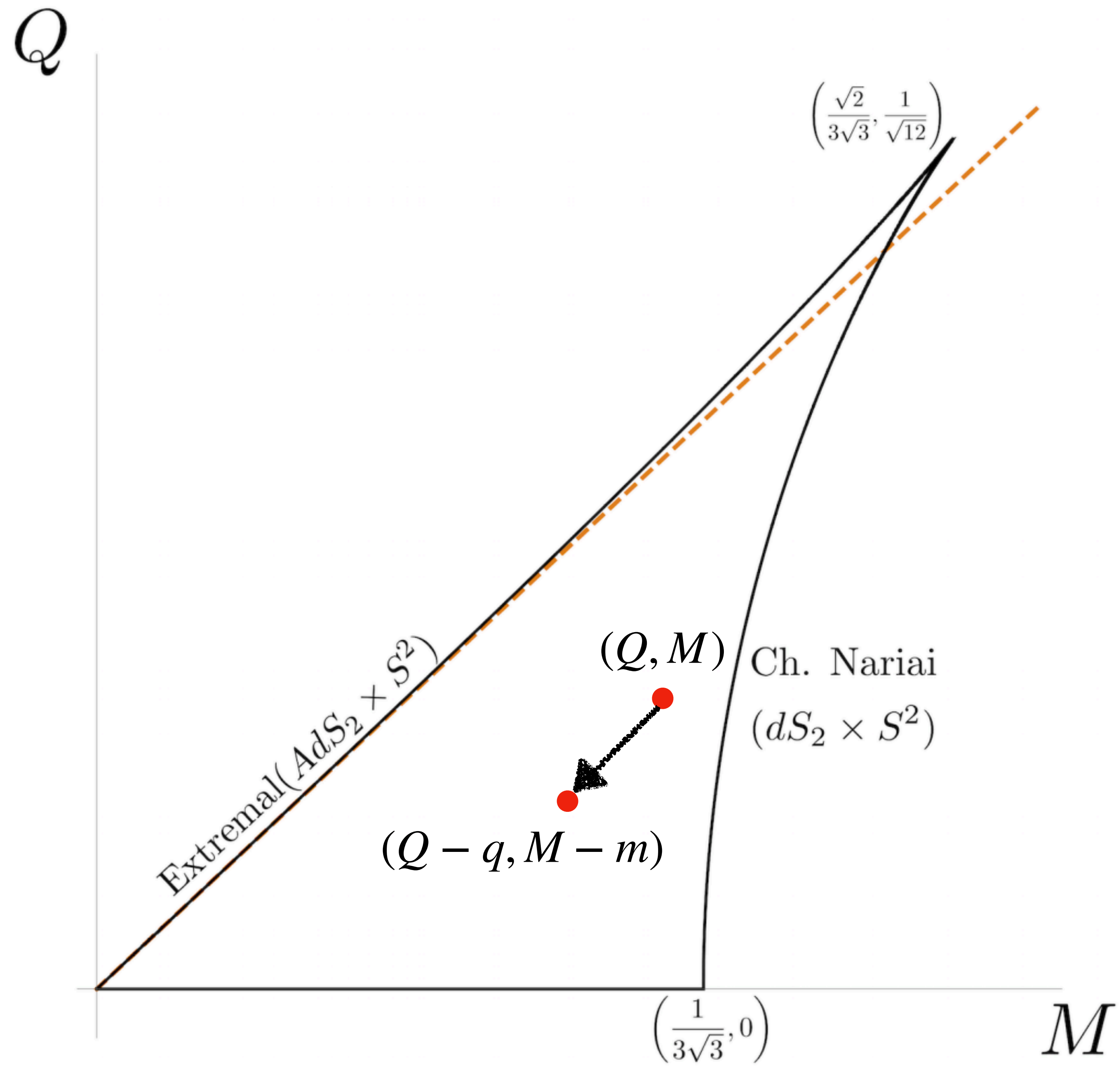
Phase diagram of RN-dS bh

'Shark fin'

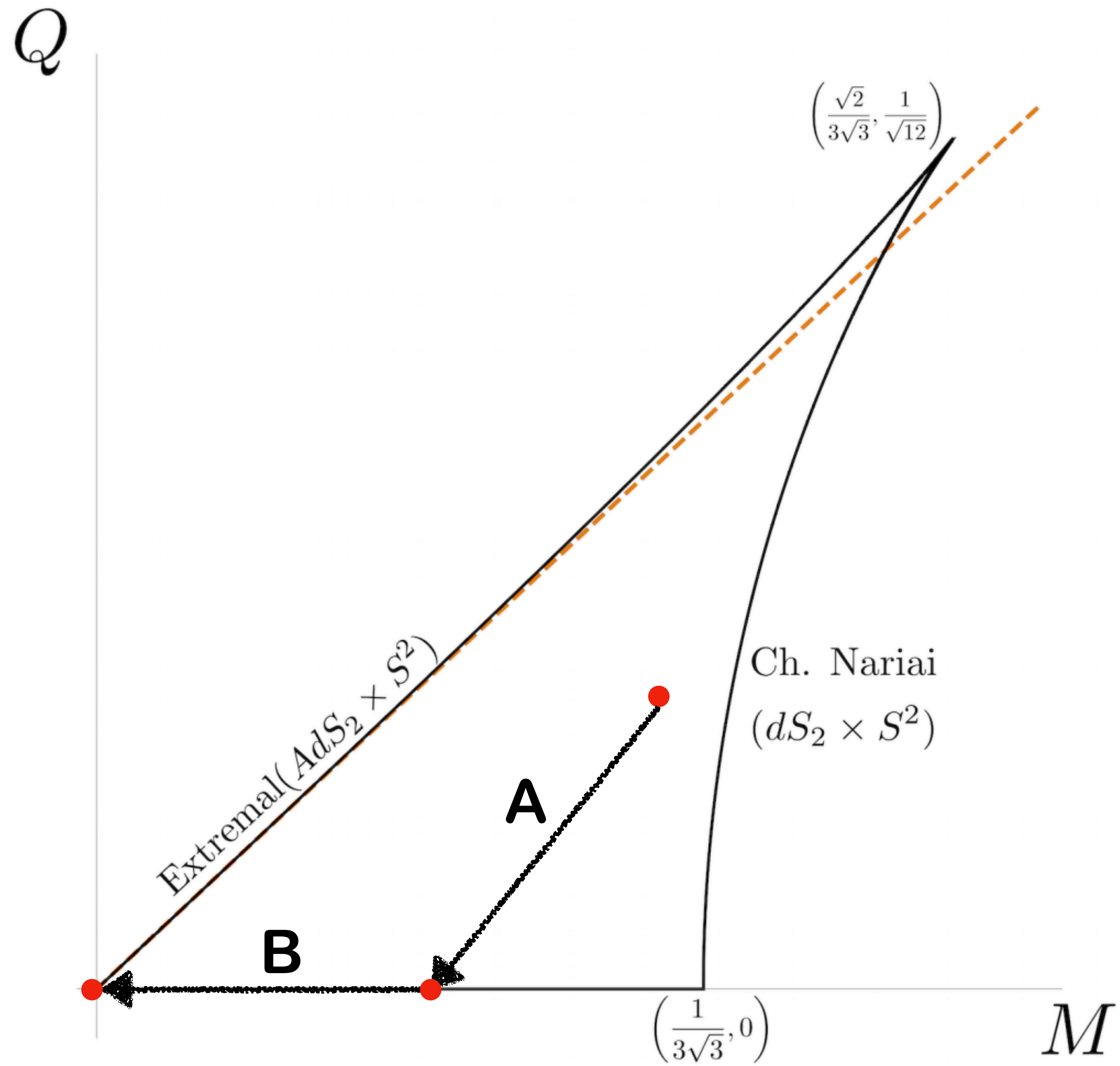
- Outside of the shark fin is unphysical (super-extremal or naked singularity appears)
  - ✓ Extremal branch ~ $AdS_2 \times S^2$
  - ✓ Nariai branch ~ $dS_2 \times S^2$
  - ✓ Schwarzschild-dS branch along Q=0



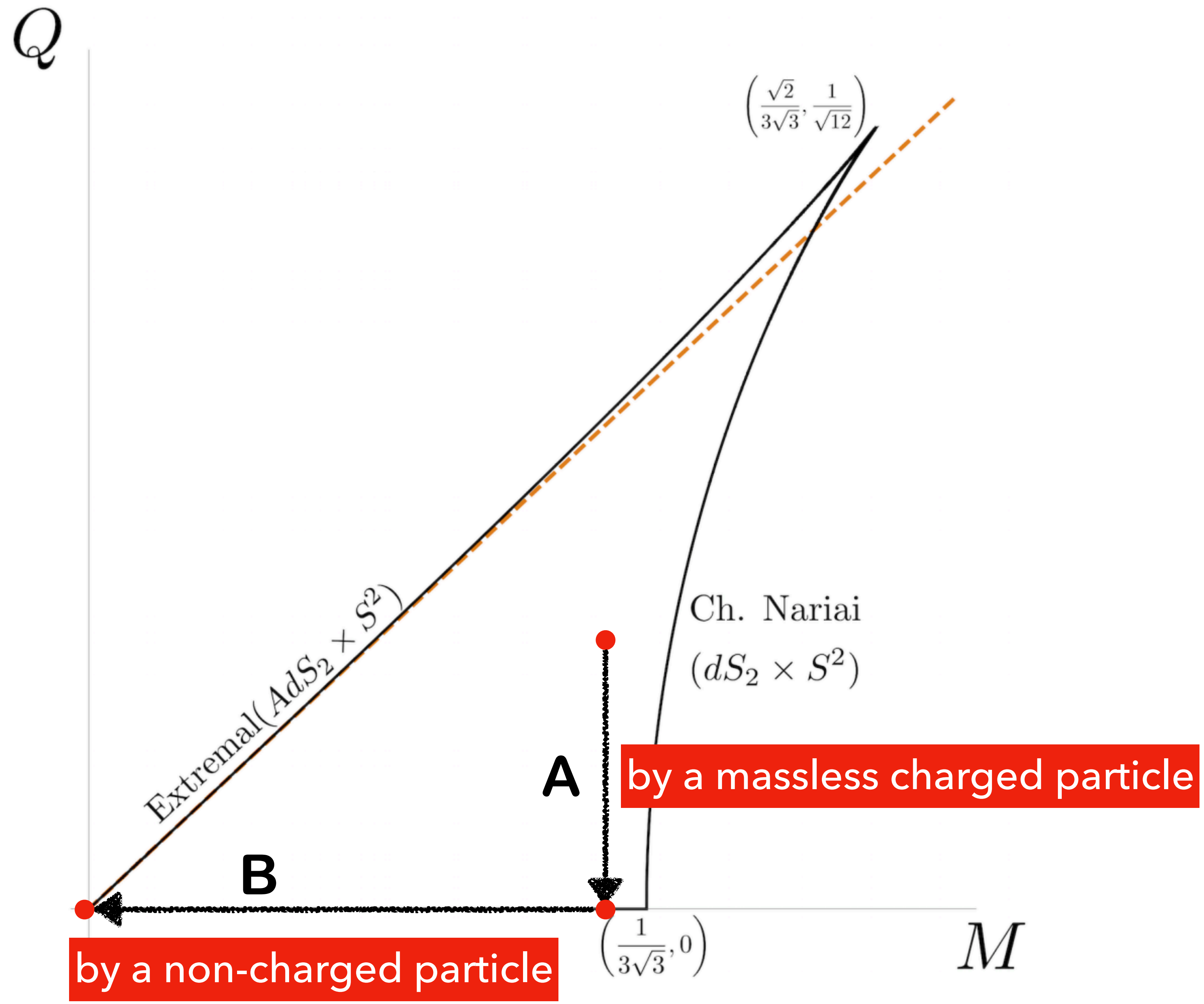
(EX) Radiating a charged particle with (q,m)



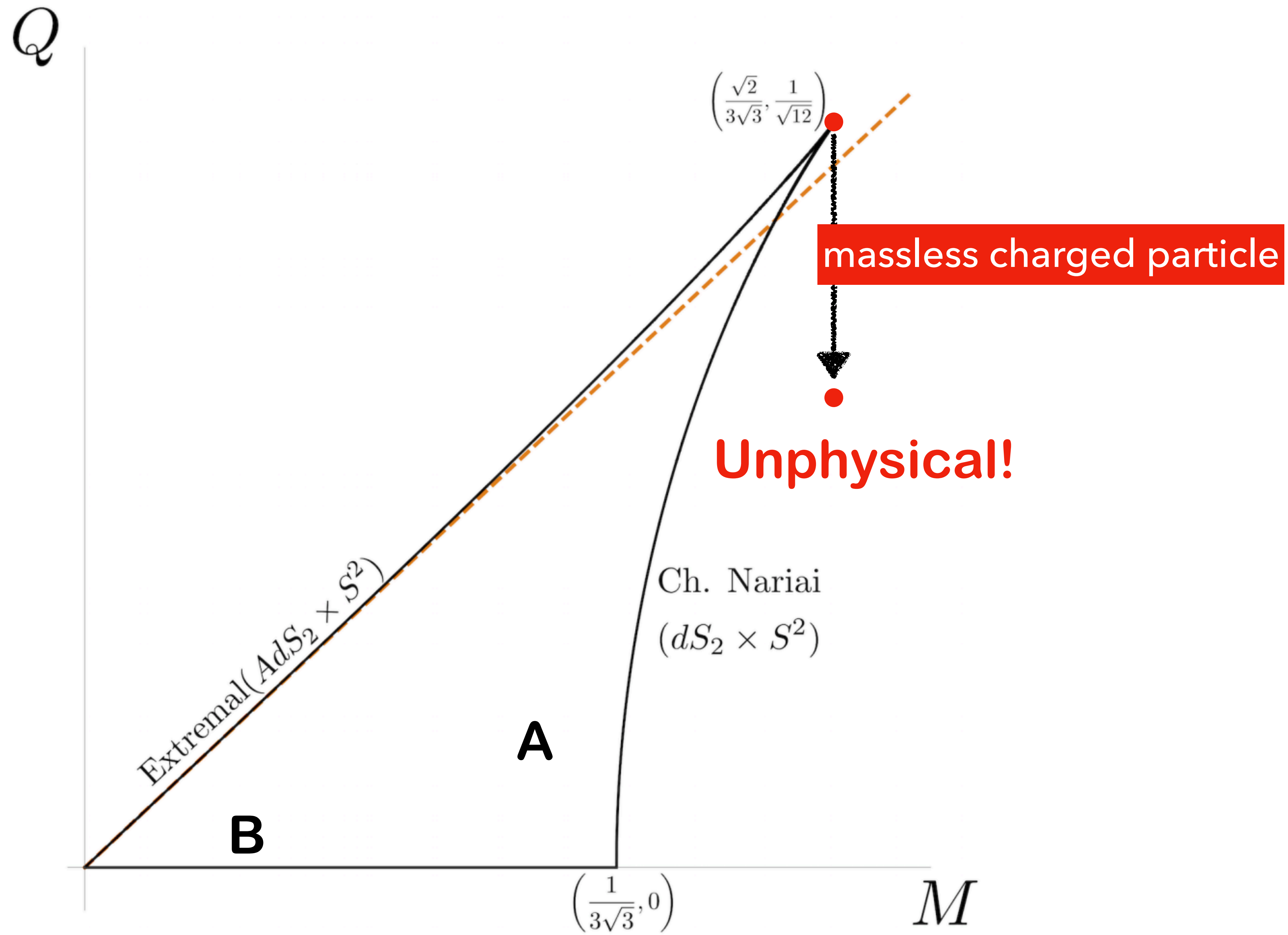
(EX) Evaporation



(EX2) Evaporation with $m = 0, q \neq 0$)



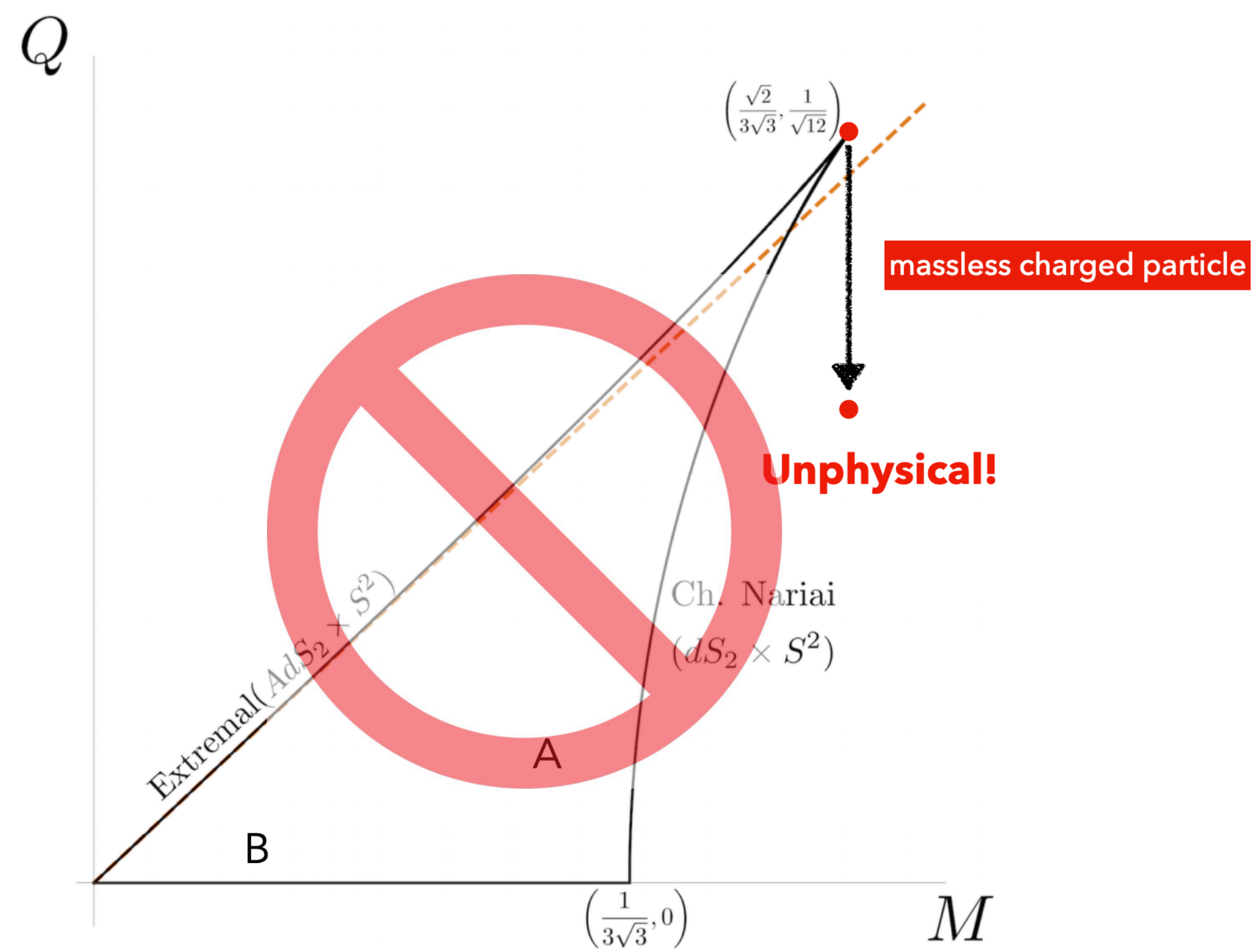
(EX3) Unphysical evaporation with $m = 0, q \neq 0$)



FL bound

1910.01648 & 2106.07650

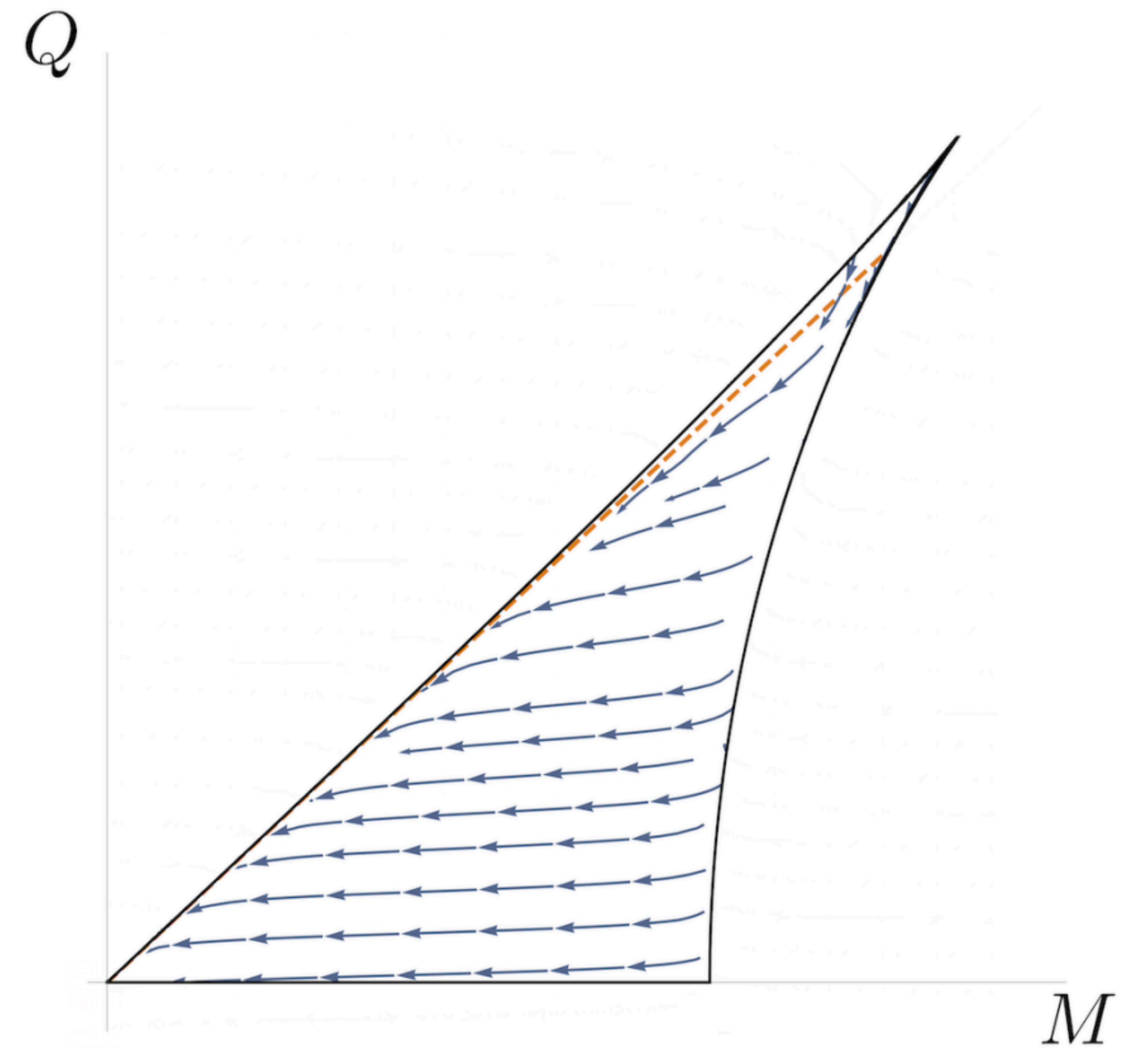
- **BH decays fast but not too fast!**
- To forbid the unphysical evolution of BH, there should be a lower bound on the mass of a charged particle.



FL bound

1910.01648 & 2106.07650

- One can read the lower bound on mass by analyzing the flow of the decay process
- The process should remain inside the shark fin region.

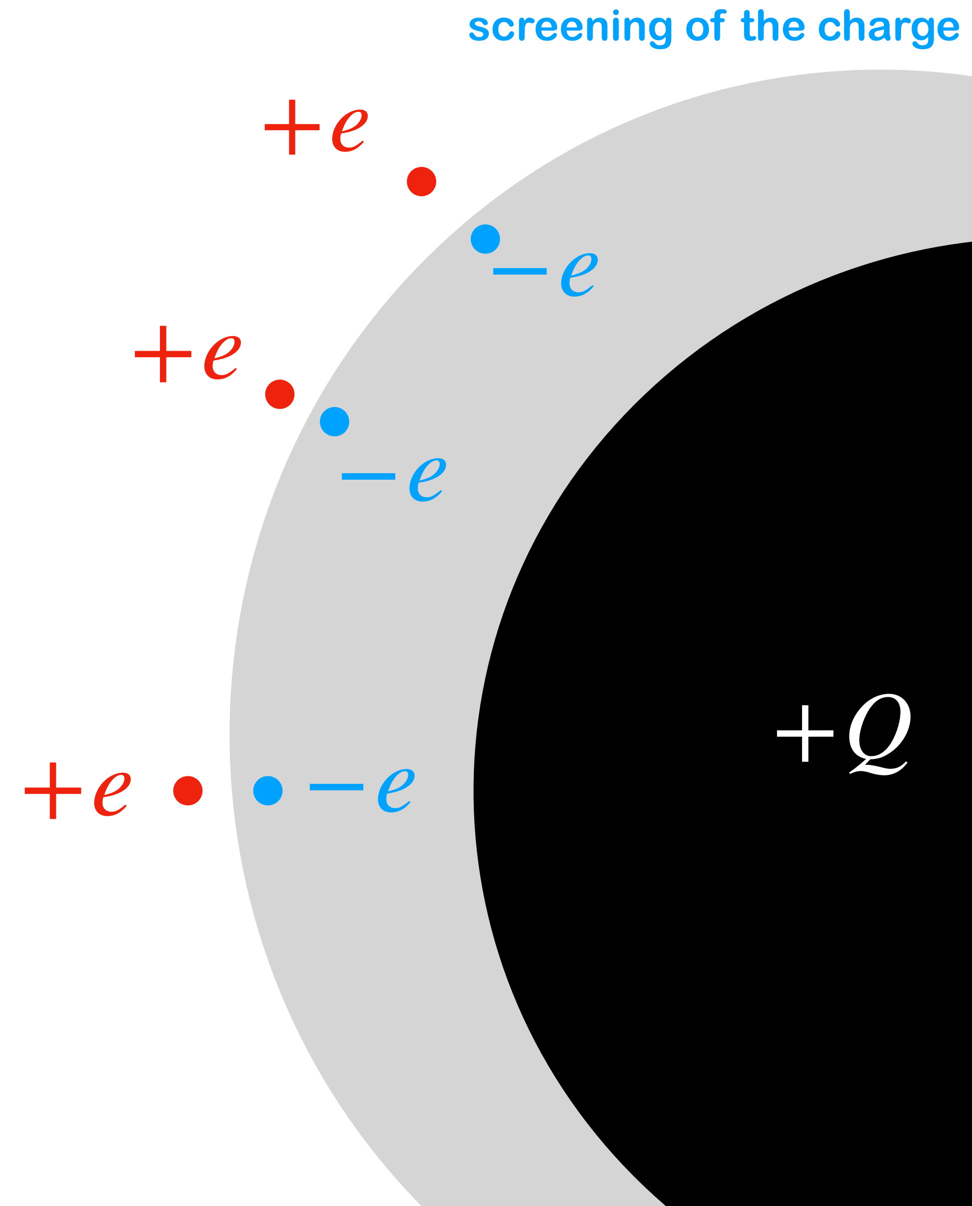


Schwinger process

M. Montero, C. Vafa, T. V. Riet, G. Venken JHEP10 (2021) 009

- The decay of BH can be triggered by Schwinger pair production in the near-horizon electric field (E)
- $\Gamma_{\text{Schwinger}} \propto \exp(-m^2/qE) = \exp(-m^2/gq\sqrt{V})$ with $E \sim gM_P H = g\sqrt{V}$ along Nariai branch
- When Γ is sizable, the electric field is quickly screened by Schwinger pair production. BH loses its charge but not the mass therefore does not decay into the empty space. :-(
- By contrast, if $m^2 > qE = qg\sqrt{V}$ is satisfied, $\Gamma \to 0$ then all black holes slowly evaporate towards empty de Sitter space in the usual fashion. :-)

=> The FL bound.



FL bound : $m^4 > 8\pi\alpha q^2 V$ for any charged particle

- m : mass of a charged particle under unbroken $U(1)$ gauge symmetry
- $\alpha = e^2/4\pi$: fine-structure constant of the $U(1)$ interaction
- q : charge of the particle in unit charge $q = Q/e$
- V : scalar potential energy (or CC) of dS background

FL & EW symmetry breaking

- Within the SM, the lightest charged particle is the electron

$m_e = 0.511\text{MeV}, q = e$ for $U(1)_{\text{em}}$

- At current universe, $V = \dfrac{\Lambda_{cc}}{8\pi G} = \rho_{vac}$ from cosmological measurement:

$\Lambda_{cc} = 8\pi G \rho_{vac} = 3(H_0)^2 \Omega_\Lambda = 2.8 \times 10^{-122} M_P^2$ (Planck 2018)

- FL bound $m_e^4 > 8\pi\alpha V$, and $m_e = \dfrac{y_e}{\sqrt{2}}\langle H \rangle$

$$\Longrightarrow \langle H \rangle > \left[\frac{32\pi\alpha V}{y_e^4}\right]^{1/4} \sim \left(\frac{10^{-6}}{y_e}\right) \text{keV}$$

- This is consistent with the fact that we are in a broken phase $\langle H \rangle = 246\ \text{GeV}.$
- **FL bound implies EW symmetry must be broken!**

More on Higgs potential

S.M.Lee, D.Y.Cheong, S.C.Hyun, SCP, M.-S.Seo

arXiv 2111.04010, JCAP 2022

- Effective potential of the Higgs with the RG running of λ, and higher order operators

$$V_{\text{eff}}(h) = \Lambda_{\text{DE}} + \frac{\lambda(h)}{4} h^4 + \frac{c_6}{\Lambda^2} h^6 + \frac{c_8}{\Lambda^4} h^8 + \cdots .$$

- 1 : the unique EW vacuum
- 2” : inflection point $V' = 0 = V''$
- 2, 2’ : 2nd dS vacuum at UV
- 3 : 2nd AdS vacuum

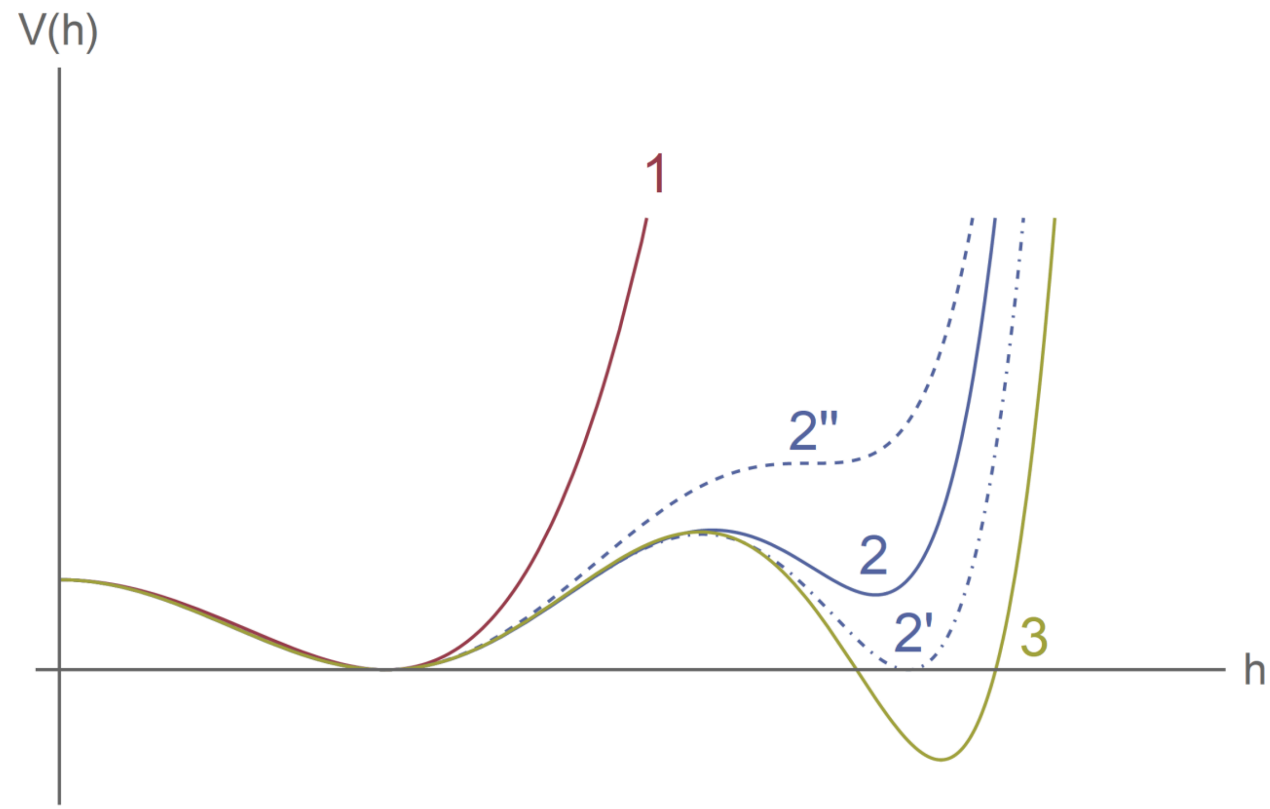


Figure 1: Schematic shape of the Higgs potential.

More on Higgs potential

S.M.Lee, D.Y.Cheong, S.C.Hyun, SCP, M.-S.Seo

arXiv 2111.04010, JCAP 2022

- Case 1 : the unique EW vacuum.
- FL bound:
  $$\Lambda_{cc} \leq \frac{Gm_e^4}{\alpha} \sim 10^{-90} M_P^2$$
- cf) $\Lambda_{cc}^{\text{obs}} = 2.8 \times 10^{-122} M_P^2$ (Planck 2018) is consistent with FL bound

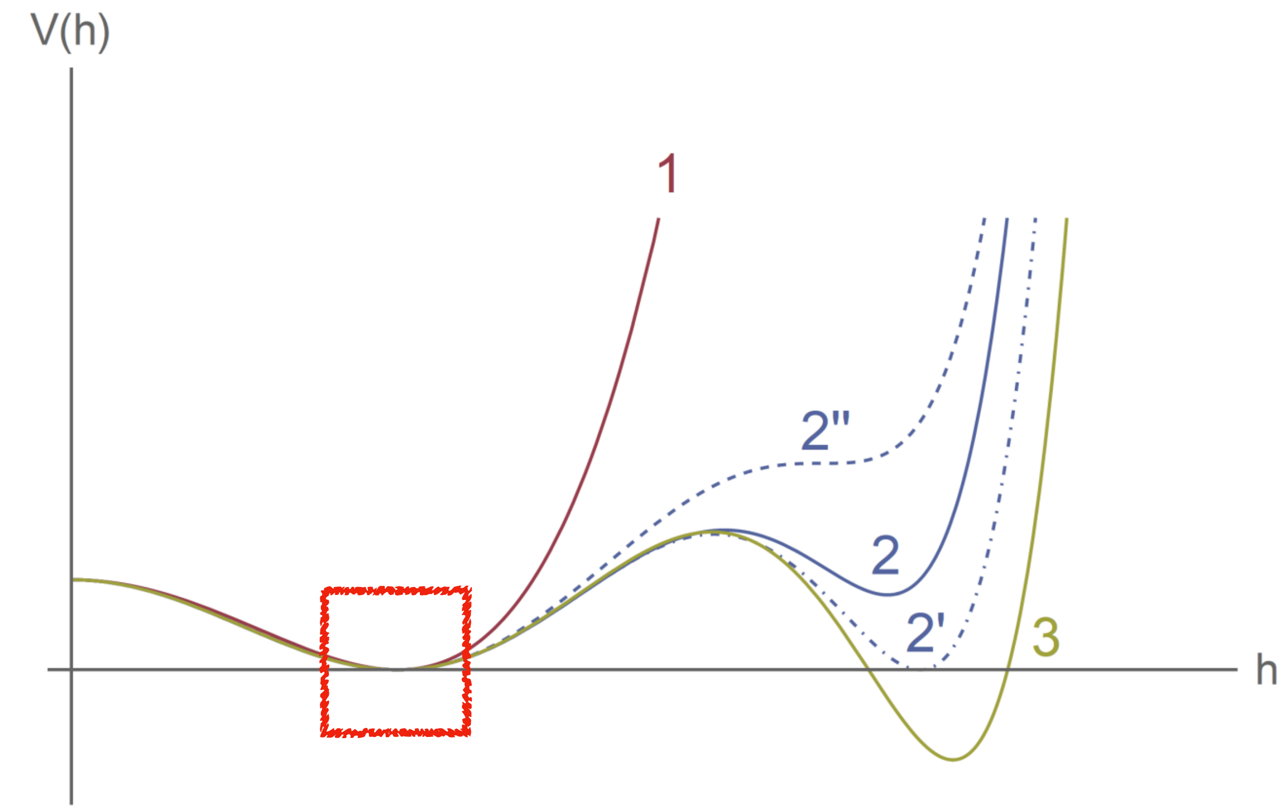


Figure 1: Schematic shape of the Higgs potential.

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- 3 : AdS vacuum

  => FL bound is not applied.

  We don't exclude this possibility here, but we are not in this vacuum.

-Who cares about this (most probably) unreal case?

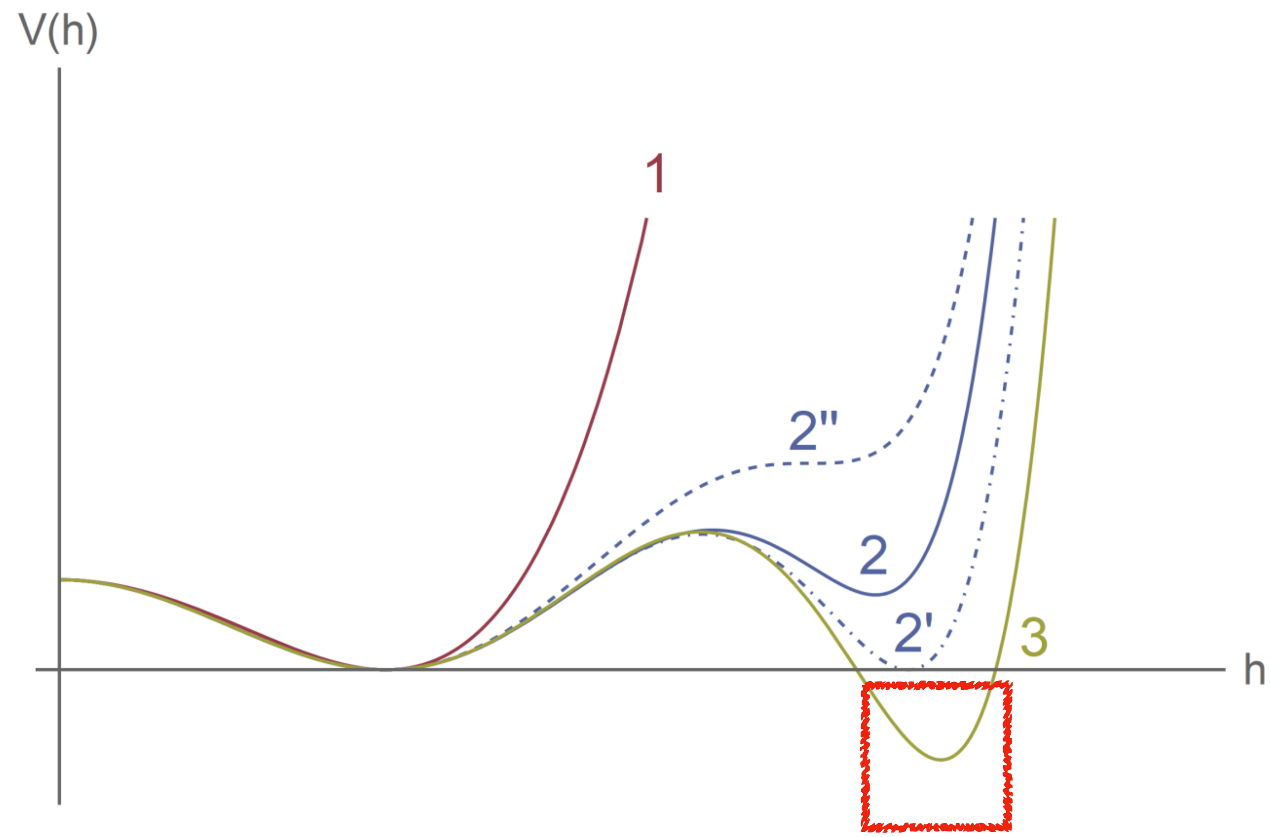

Figure 1: Schematic shape of the Higgs potential.

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arXiv 2111.04010, JCAP 2022

- 2” ~ inflection point at UV
- 2, 2’ ~ 2nd Vacuum at UV

$$\min_{i\in \mathrm{SM}} \frac{m_i^4}{8\pi\alpha_i} = \frac{y_e^4 v_{\mathrm{UV}}^4/4}{8\pi\alpha_{\mathrm{EM}}} \geq \frac{\lambda_{\mathrm{eff}}(v_{\mathrm{UV}})}{4} v_{\mathrm{UV}}^4$$

$$\Rightarrow \quad \lambda_{\mathrm{eff}}(v_{\mathrm{UV}}) \leq \frac{y_e^4}{8\pi\alpha_{\mathrm{EM}}} \simeq \mathcal{O}\left(10^{-22}\right).$$

- Nearly degenerate vacuum (2’) is particularly interesting where FL bound is consistent.

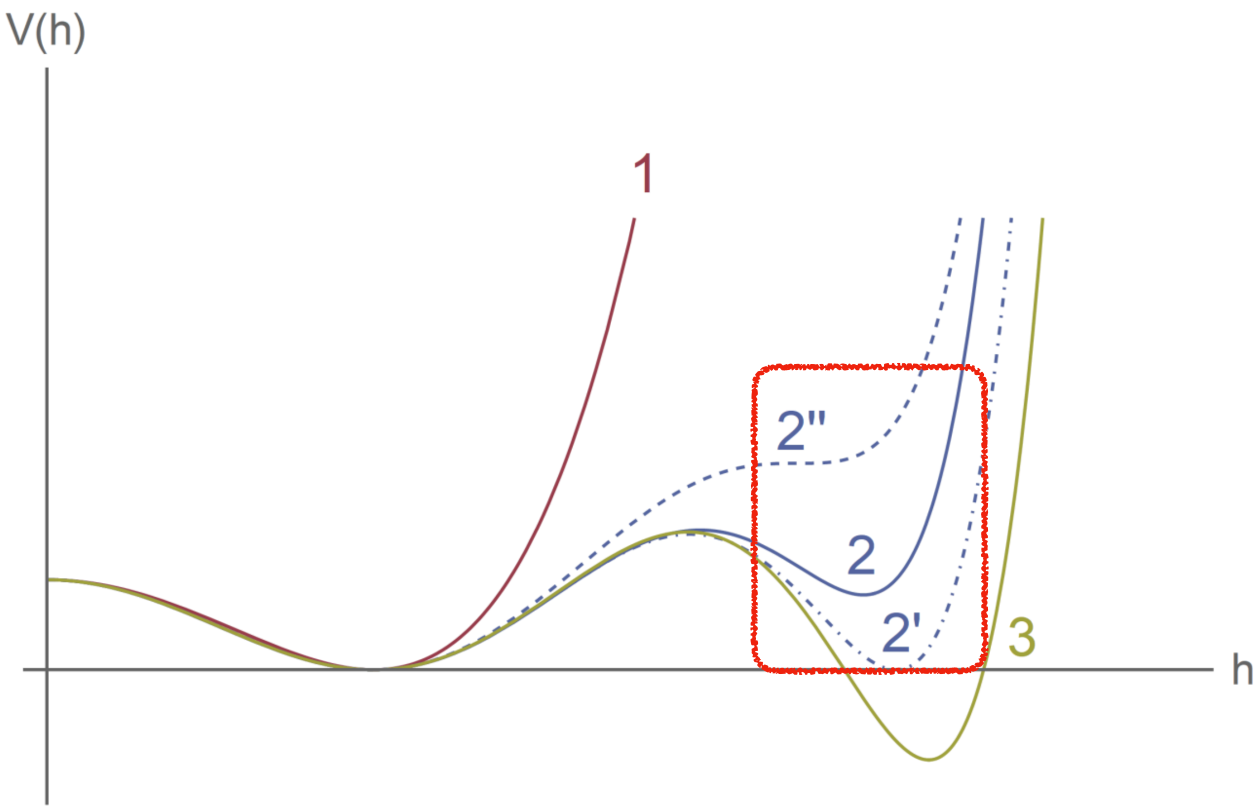

Figure 1: Schematic shape of the Higgs potential.

More on Higgs potential

at degenerate vacuum (2′)

S.M.Lee, D.Y.Cheong, S.C.Hyun, SCP, M.-S.Seo
arXiv 2111.04010, JCAP 2022

$$\boxed{V_{\rm eff}(h) = \Lambda_{\rm DE} + \frac{\lambda(h)}{4}h^4 + \frac{c_6}{\Lambda^2}h^6 + \frac{c_8}{\Lambda^4}h^8 + \cdots .}$$

- at the degenerate vacuum
  $V_{\rm eff}(v_{UV}) = 0 = V'_{\rm eff}(v_{UV})$
- Taking the RG running effect $\lambda(h) = -\dfrac{b_1(m_t)}{32\pi^2}$ (uncertainty α_S= 0.1179 ± 0.0010) with respect to top mass provides the relations to the parameters $h_0, v_{UV}, \Lambda_{UV}$.

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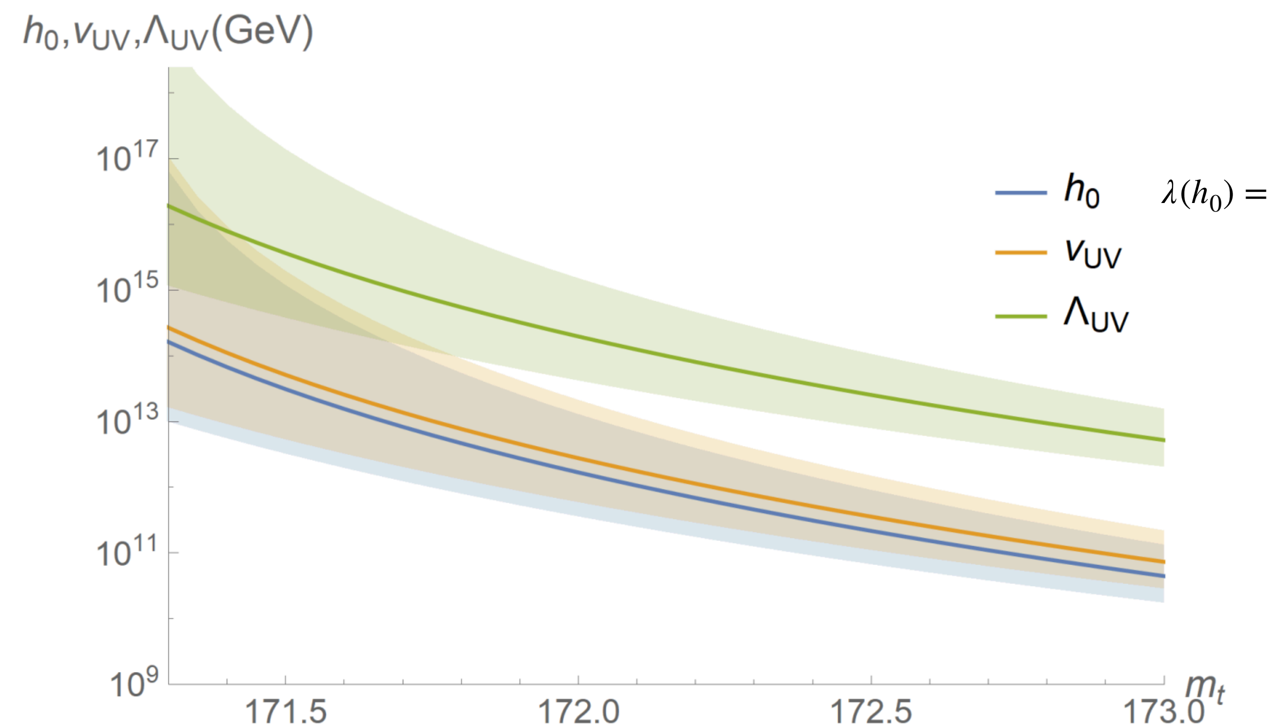

==> By measuring the top quark mass, we will learn about the high scale behavior of the Higgs potential

Applicability of FL bound

- Pseudo dS with slow-roll potential (meta stable) satisfying a short lifetime of blackhole $\tau_{\mathrm{BH}} \ll \tau_{\mathrm{Universe}}$ is also subject to FL bound.
- ==>The nearly constant cosmological horizon .
- Slow-roll parameter $\epsilon_V \equiv \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1$ enables the inflation to take place.

Inflation

with additional fields

- During inflation, $V(\phi) = \dfrac{3}{8\pi G} H_I^2 = 3M_P^2 H_I$, and we take $m_e(h) = y_e h/2$
- The FL bound leads $\dfrac{y_e^4 h^4/4}{8\pi\alpha} \geq 3M_P^2 H_I^2$

$$==> h \geq \left(\frac{96\pi\alpha}{y_e^4}\right)^{1/4} \sqrt{M_P H_I} \gg O(100)\mathrm{GeV}$$

==> Higgs cannot stay at EW vacuum during inflation

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arXiv 2111.04010, JCAP 2022

Inflation

small tensor-to-scalar ratio

- $H_I^2/M_P^2 \simeq \dfrac{\pi^2}{2}A_S r$ and FL bound $\dfrac{y_e^4 h^4/4}{8\pi\alpha} \geq 3M_P^2 H_I^2$ requests small tensor-to-scalar ratio

$$r \lesssim 3 \times 10^{-15}\left(\frac{10^{-2}}{\alpha_{EM}}\right)\left(\frac{2\cdot 10^{-9}}{A_S}\right)\left(\frac{y_e}{3\cdot 10^{-6}}\right)^4 \frac{h^4}{M_P^4}$$

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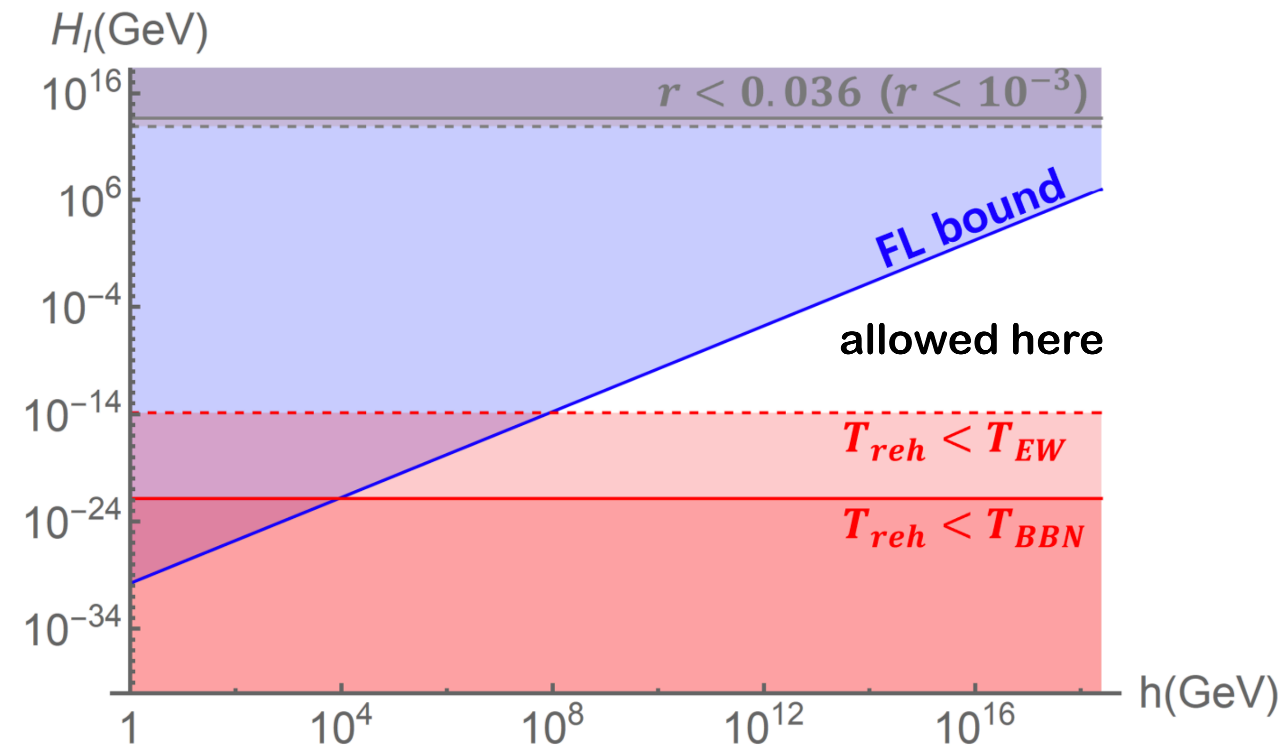
arXiv 2111.04010, JCAP 2022

Inflation

- Requesting reheating temperature high enough, we learn the lower bound on $H_I^2 = 3M_P^2\rho > 3M_P^2\rho_R \sim 3M_P^2 k T^4$
- FL bound set upper bound on H_I (potential cannot be too high) $$\frac{m_e^4}{3M_P^2 \cdot 8\pi\alpha} \geq H_I^2$$
- ==> The window of consistency is identified $$\frac{y_e^4 h^4/4}{3M_P^2 \cdot 8\pi\alpha} \geq H_I^2 \geq 3M_P^2 k T^4$$



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arXiv 2111.04010

Dark gauged $U(1)_D$

- A dark matter is stable if it is the lightest charged particle under $U(1)_D$
- FL bound forbids too light DM:

$$m_D \geq \left(8\pi\alpha_D q_D^2 V_{cc}\right)^{1/4} = \left(8\pi\alpha_D q_D^2 \frac{\Lambda_{cc}}{8\pi G}\right)^{1/4} = \left(\alpha_D q_D^2 \Lambda_{cc}\right)^{1/4} \sim 10^{-31} M_P \sim 10^{-3}\mathrm{eV}$$

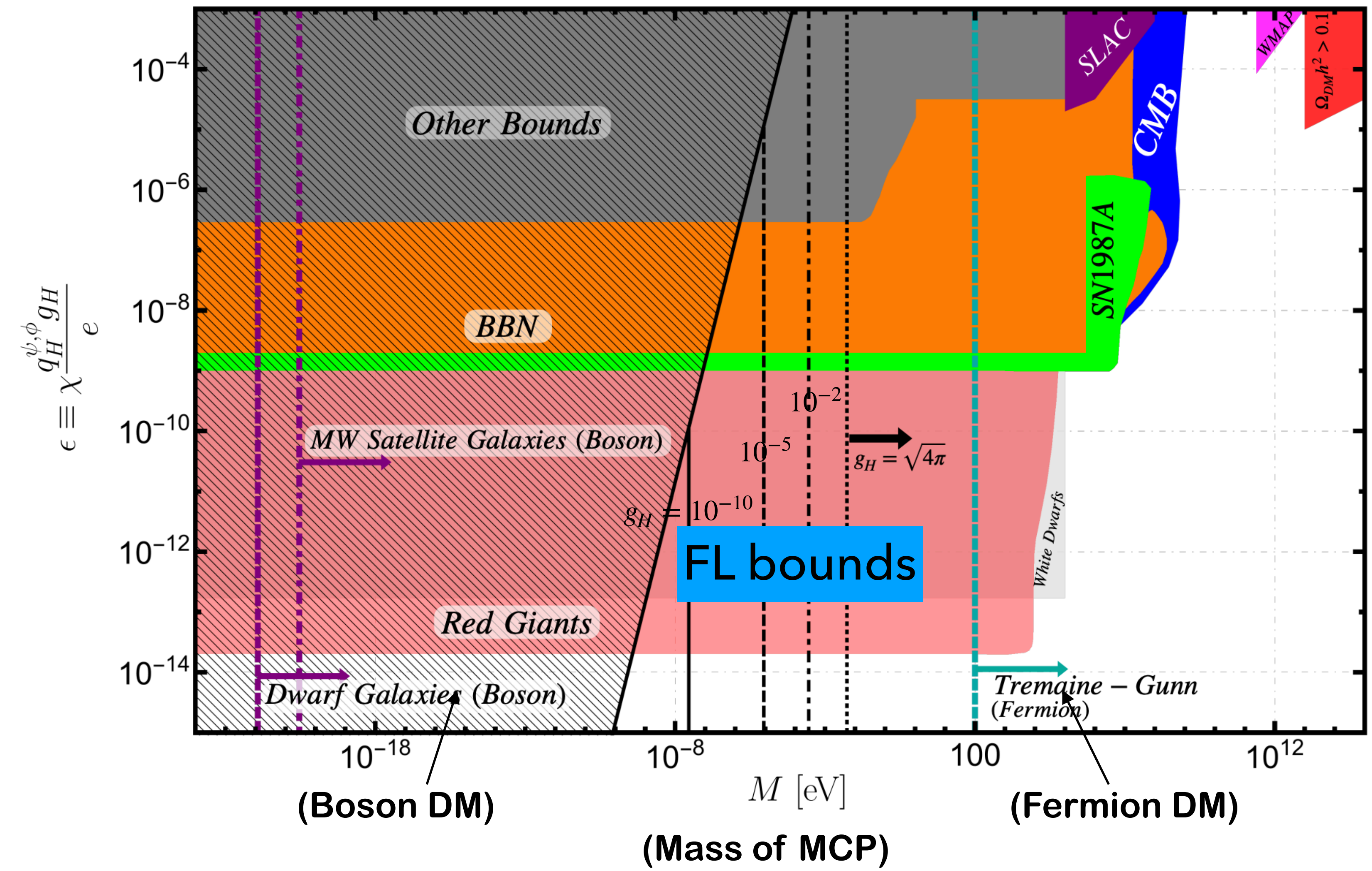
with $\alpha_D \sim \alpha, q_D = 1$

- FL excludes FIMP at $m_{FIMP} \sim 10^{-22}\mathrm{eV}$
- We can think of $U(1)^N$ then the corresponding FL bound $m_D > N^{1/4}\mathrm{meV}$

K. Ban, D. Y. Cheong, H. Okada, H. Otsuka, J-C. Park, SCP, 2206.00890

Milli-charged particles (MCP)

$$q = \epsilon e$$



K. Ban, D. Y. Cheong, H. Okada, H. Otsuka, J-C Park, SCP, 2206.00890

Conclusion

- FL bound : All charged particles must be massive $m_q \geq (8\pi\alpha q^2 V)^{1/4}$

✓The electron should be heavy enough with EWSB

✓(if exists,) The almost degenerate vacuum at high scale $(y_e v_{high})^4 > \alpha\lambda(v_{high})v_{high}^4$

✓Higgs cannot stay at the EW vacuum during inflation $h > \sqrt{\alpha M_P H_I}/y_e$

✓Tensor-to-scalar-ratio is small $r \sim A_s^2 H_I^2/M_P^2 < m_e^4/\alpha M_P^4$

✓Dark U(1) is constrained by MCP searches

✓If $U(1)_D$ protected, $m_{DM} \gtrsim 10^{-3}\alpha_D^{1/4}\mathrm{eV}$ thus Fuzzy DM is ruled out

✓You may find more interesting results..

Weak gravity conjecture

N. Arkani-Hamed, L. Motl, A. Nicolis and C. Vafa, JHEP 06, 060 (2007)[arXiv:hep-th/0601001].

- Gravity is the weakest force of all
- $m \leq \sqrt{2} g q M_P$ for a particle A review (https://inspirehep.net/files/16b1f684e1f68c0c54a88021e3d3f57d)