Gravity's instantons
&
ultra-light dark matter

Rodrigo Alonso

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

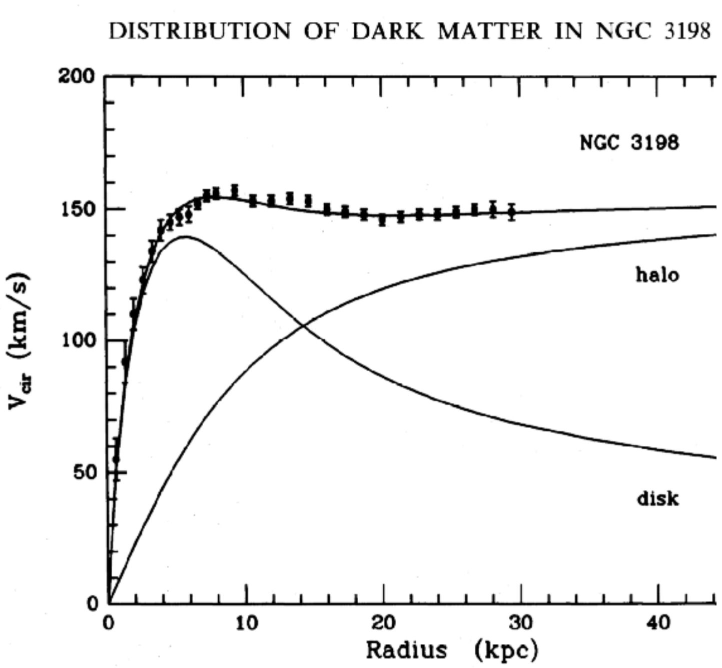
Berkeley week

Largely based on work with **A. Urbano**

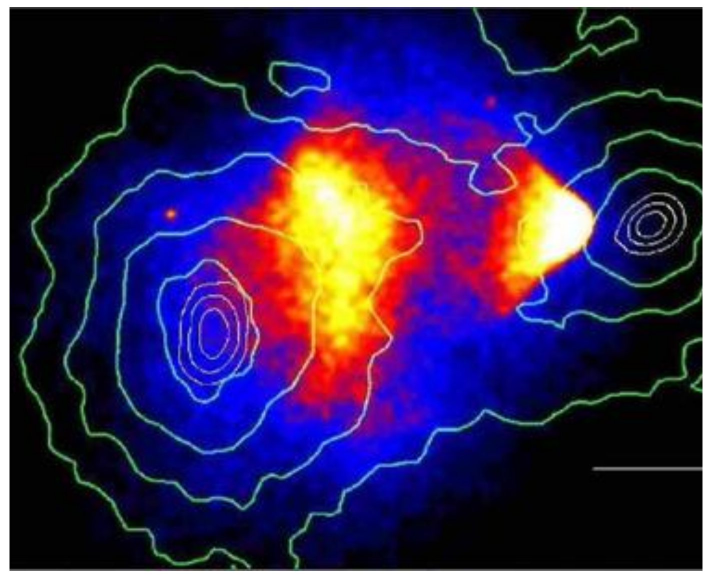
Frontiers in particle physics

Evidence for another massive species

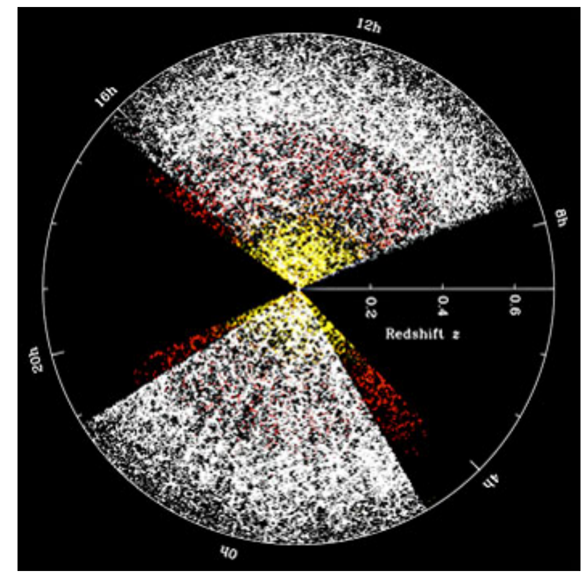
Rotation curves



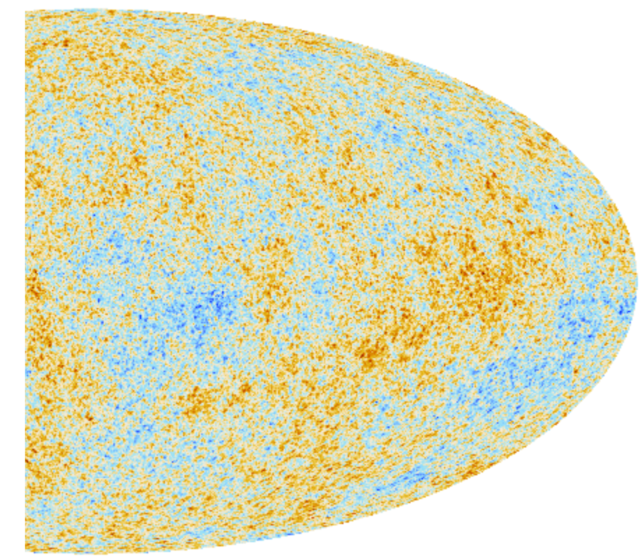
Lensing



Structure formation

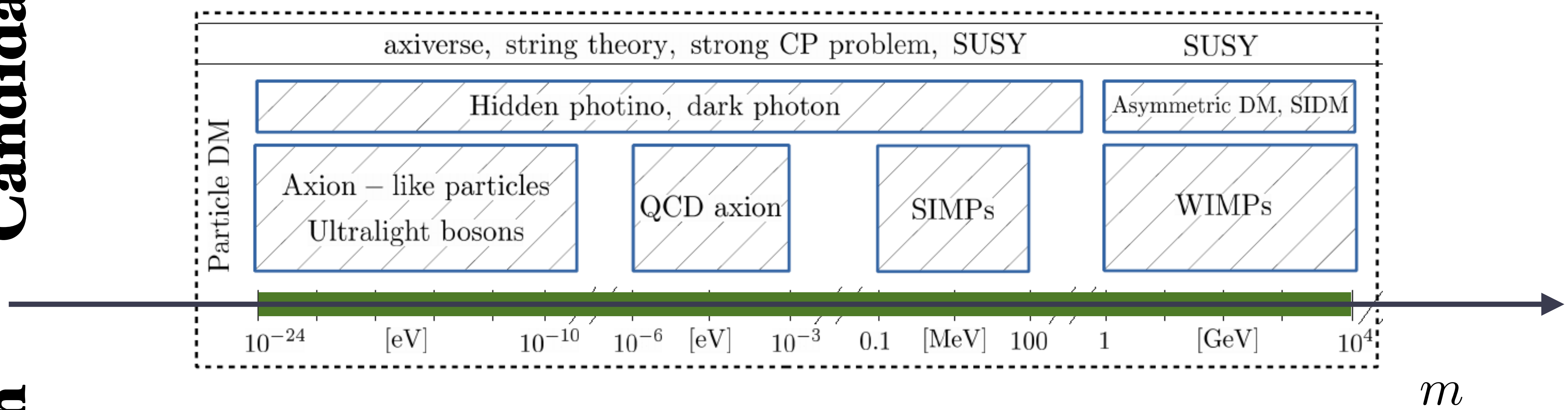


CMB



Dark matter: que sera, sera?

Candidates



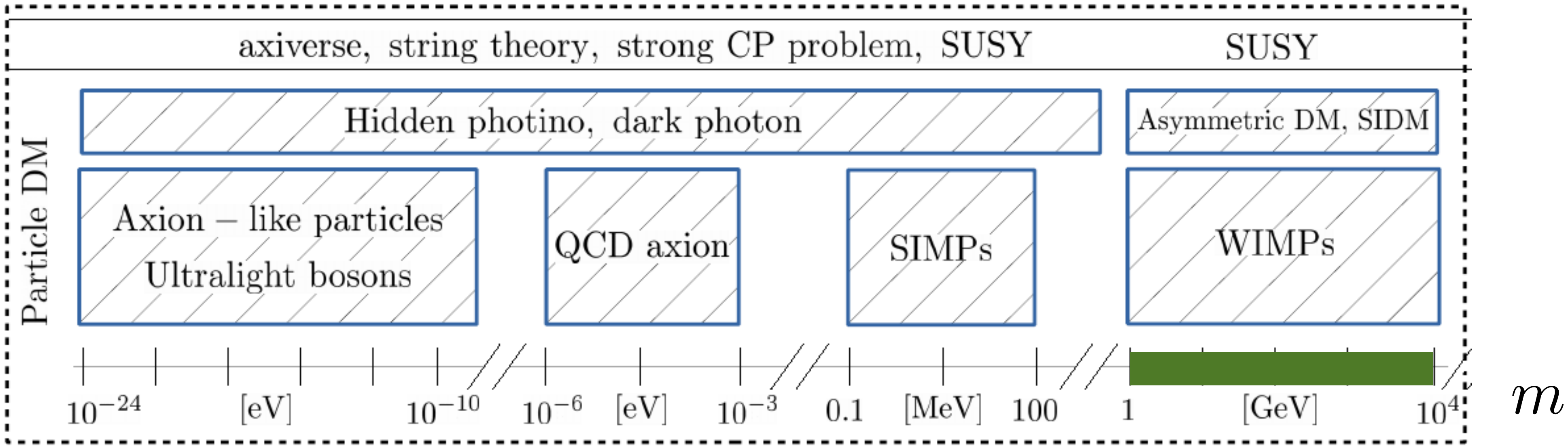
Production

Misalignment

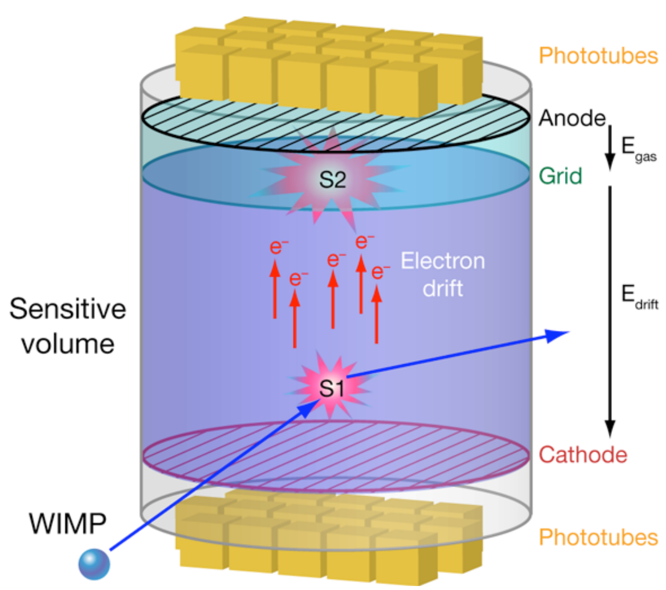
Freeze-in

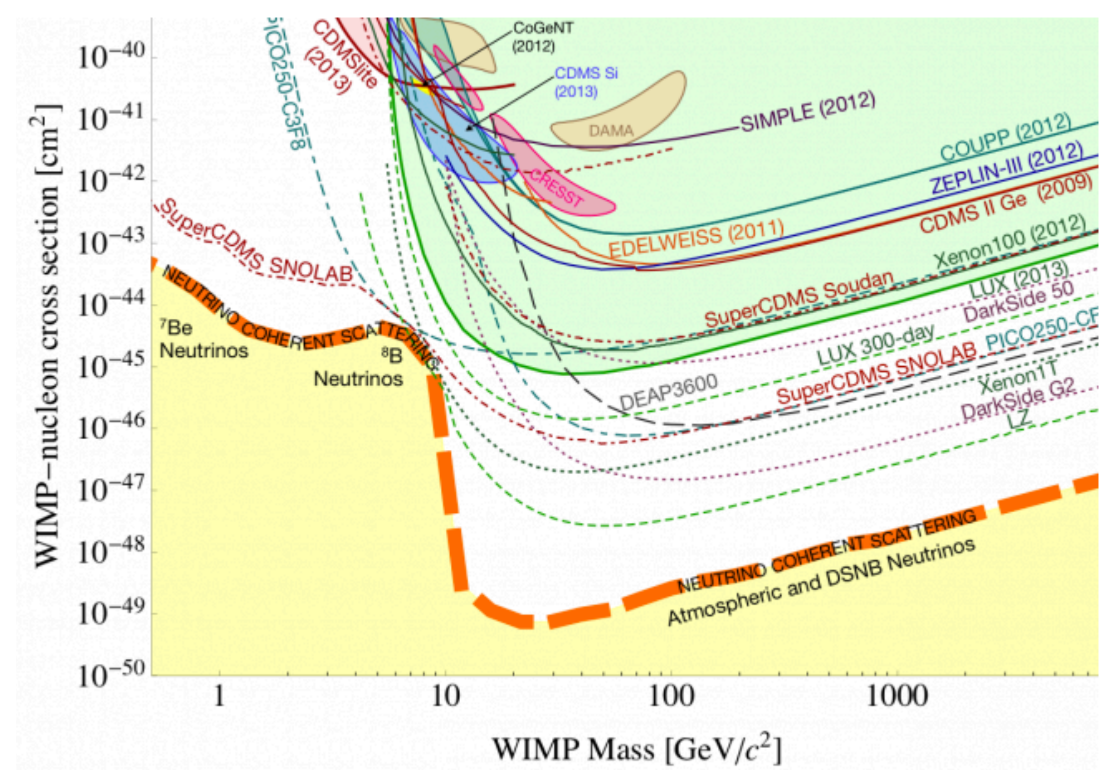
Freeze-out

Que sera, sera? WIMP?

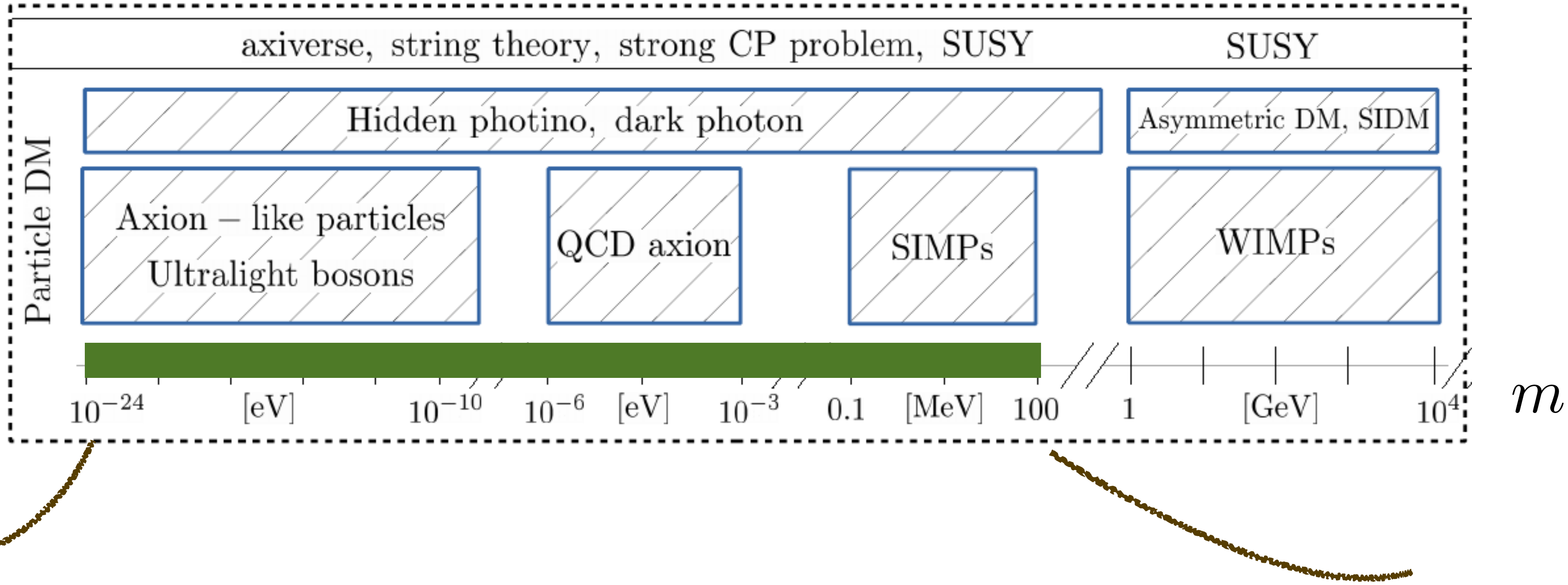


- ★ Most 'natural' candidate: connection to Hierarchy Problem
- ★ Thermal production banner bearer





Que sera, sera? Materia oscura ligera?



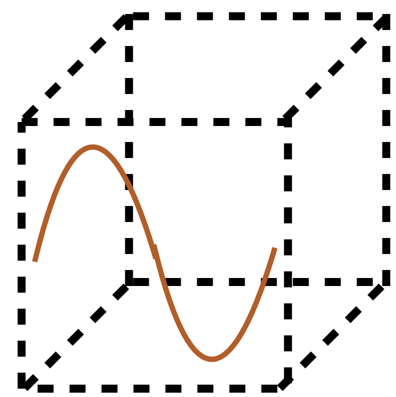
Blooming both experimentally and theoretically

Electron scattering, semiconductors, helioscopes,
Haloscopes, oscillating EDM, comagnetometers

Field vs particle

Take the dark matter mass and dial it down

$$\Delta p \sim p = \frac{1}{\lambda}$$



$$N_{ps} \sim 4\pi n^2 \Delta n \sim 4\pi \left(\frac{\ell}{\lambda}\right)^3$$

$$N_\chi = n_\chi \ell^3 = \frac{\rho_\chi \ell^3}{m_\chi}$$

Occupancy

$$\frac{N_\chi}{N_{ps}} \sim 10^2 \frac{eV^4}{m_\chi^4}$$

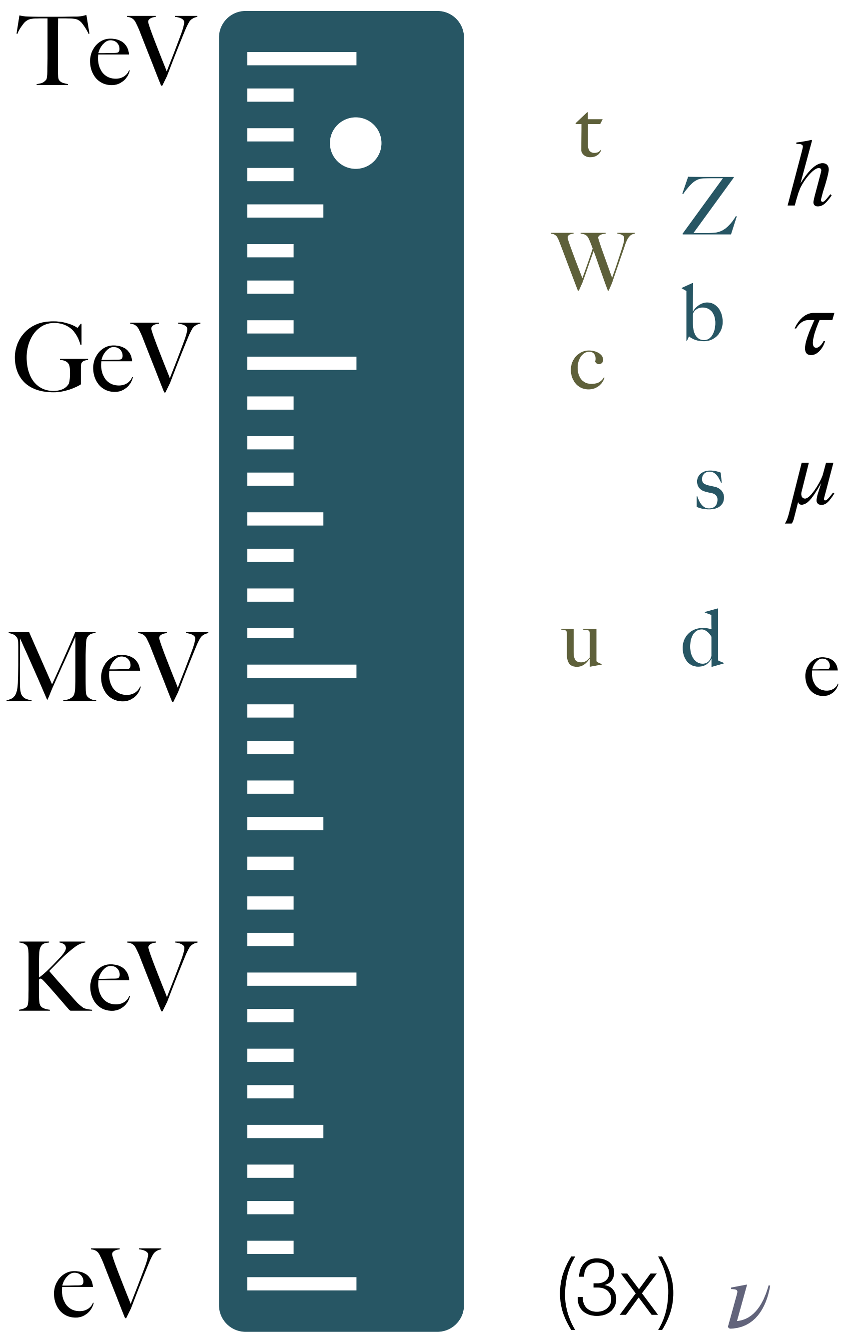
For high occupation number → field description

Field given by solution to E.O.M.

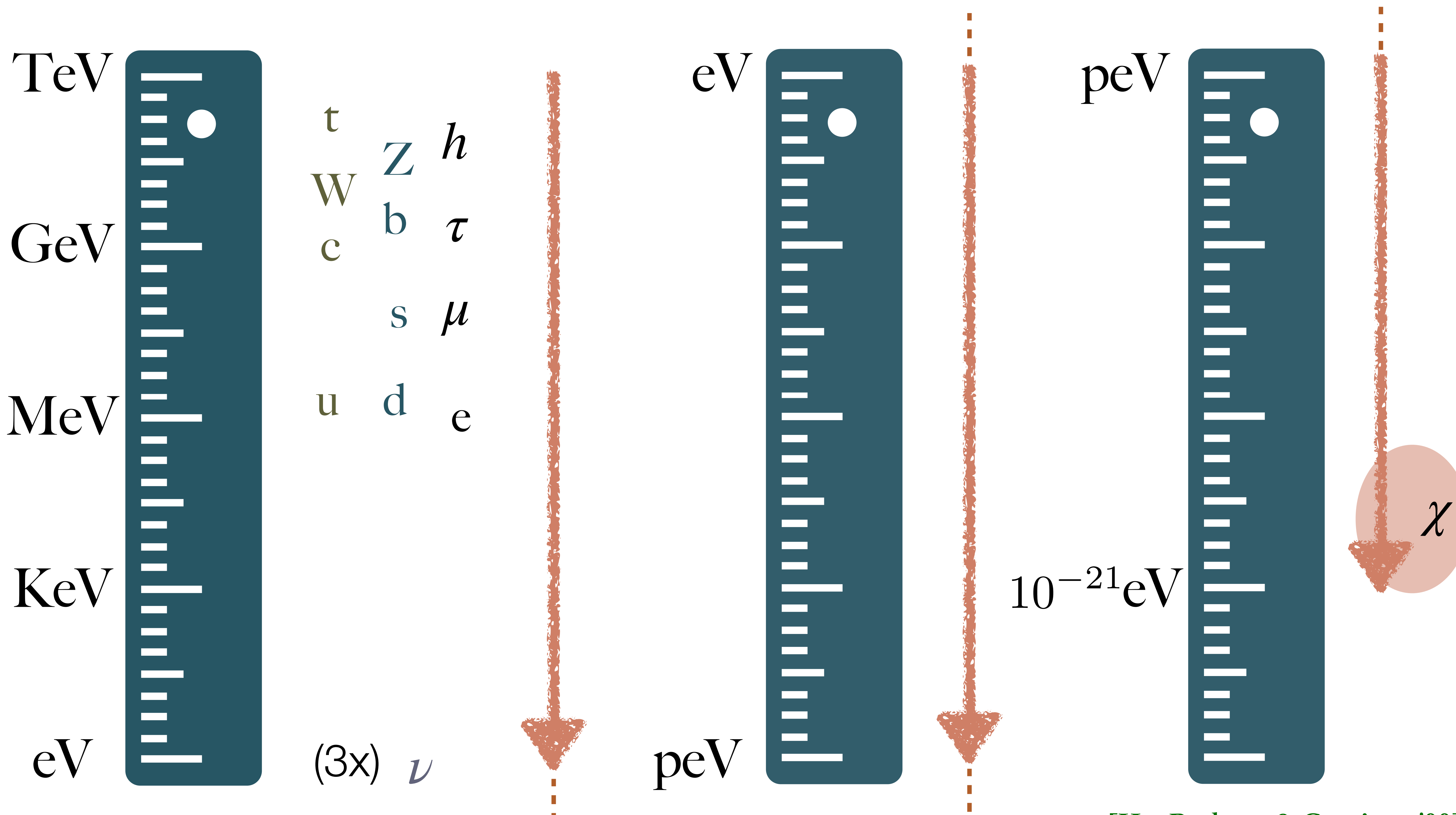
e.g. **massive scalar case** $\phi(x,t)$

$$\Box\phi(x,t) + m^2\phi(x,t) = 0$$

Que sera, sera? Materia oscura ligera?



Que sera, sera? Materia oscura ligera?



[Hu, Barkana & Gruzinov '00]
[Hui, Ostriker, Tremaine & Witten, '17]

Says the naturalist: why would it be so light?

a) It is as unnatural as it can get!

b) it has one single motivation

Says the naturalist: why would it be so light?

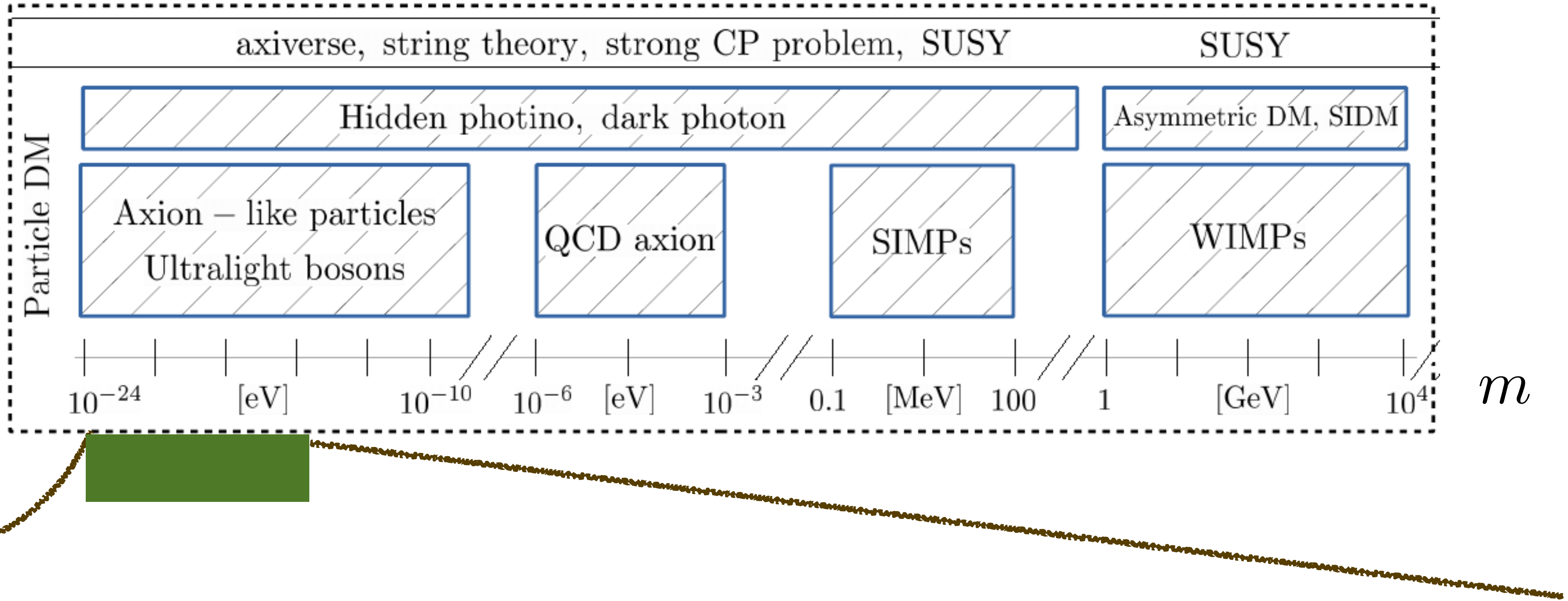
a) It is as unnatural as it can get!

Actually... ✓

b) it has one single motivation

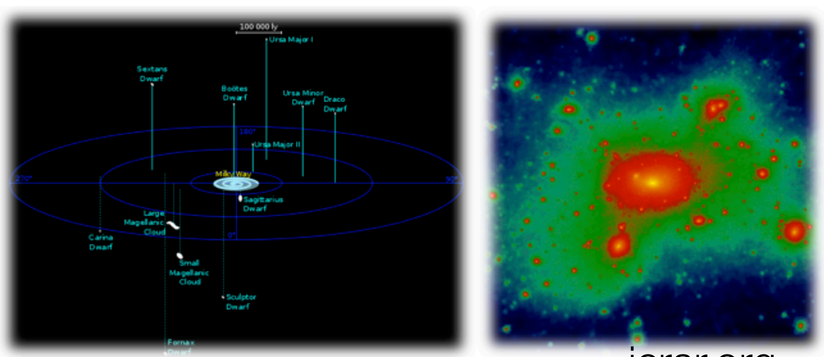
¯_(^_^)_/¯

The experimental case of UDM



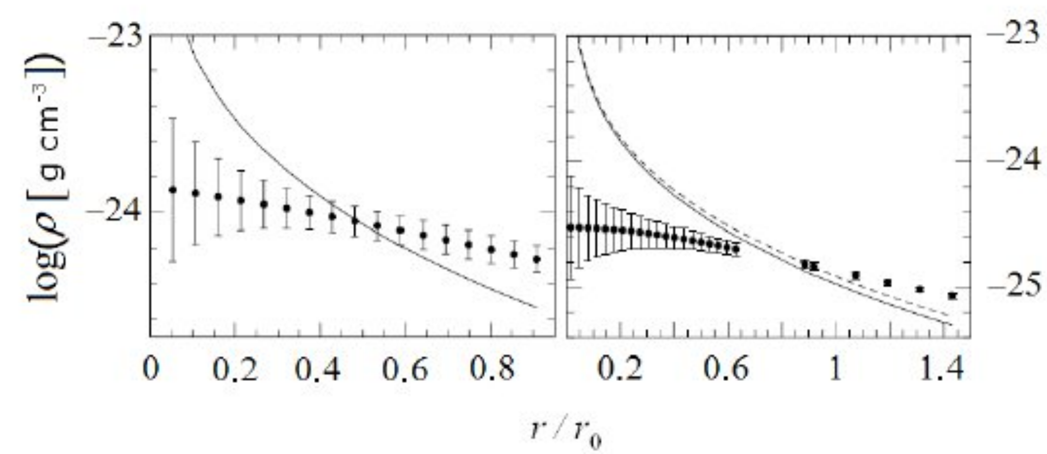
[Hu, Barkana & Gruzinov '00]

[Hui, Ostriker, Tremaine & Witten, '17]



icrar.org

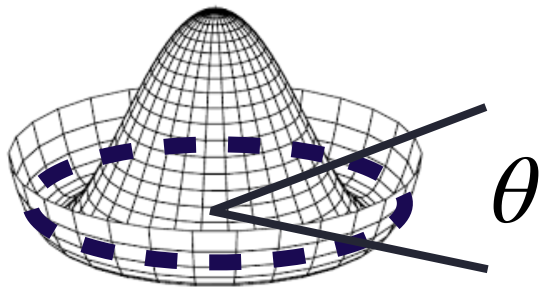
Missing satellite



Core/Cusp

Why would it be so light?

Goldstone bosons !



have their masses protected by shift symmetry

$$\theta \to \theta + \alpha$$

Still, how does it get its mass though?

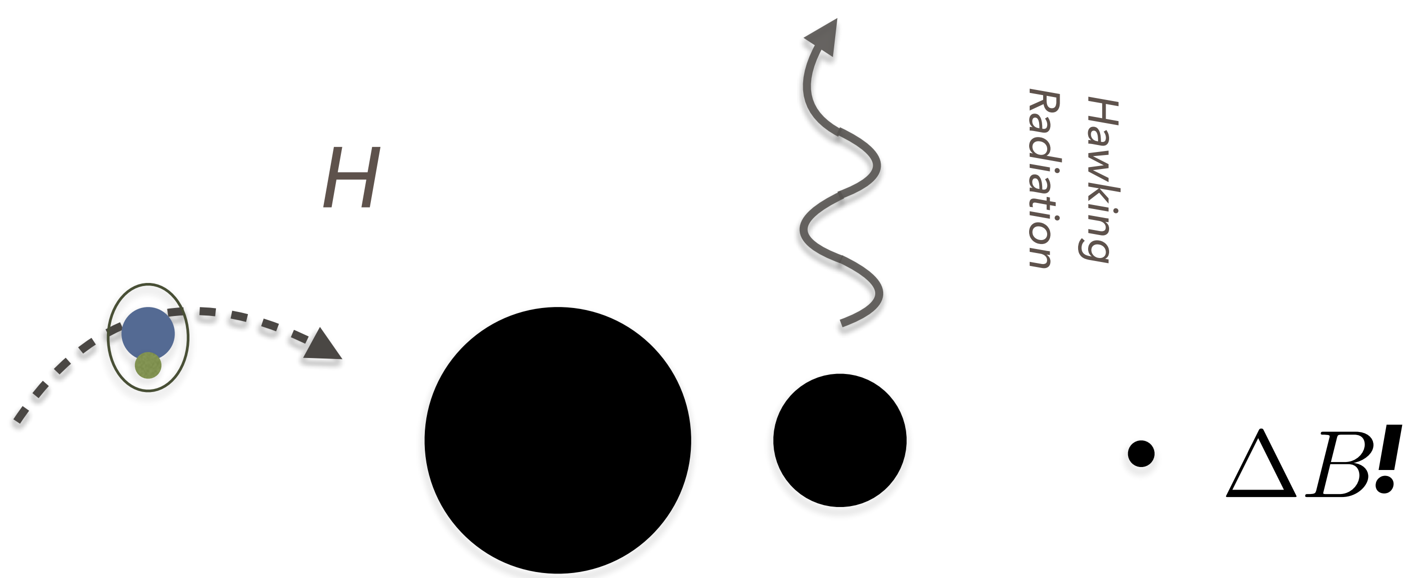
Why would it be so light?

Still, how does it get its mass though?

…there is one unavoidable source of breaking

Gravity!

Recall
the folk theorem



Estimating the effect

The naive expectation for an EFTist

The graviton couples with M_{PL}

so..,

$$\hat{V} = \frac{cf^5}{M_{\text{PL}}}\cos(\theta) \qquad \text{Or maybe} \qquad \left(\frac{f}{M_{\text{PL}}}\right)^n$$

[Kamionkowski, March-Russel, 92']

But the argument we have involves black holes
i.e. non perturbative!

Looking the effect: semi-classical

Let's turn to Euclidean, and look for non-perturbative dynamics

$$\int d^4x_E\sqrt{g}\left(-\frac{M_{PL}^2R}{16\pi}+\frac{f^2}{2}\partial_\mu\theta\partial^\mu\theta\right)$$

Are there non-trivial EOM solutions?

Instantons (wormholes)

Gravitational instanton

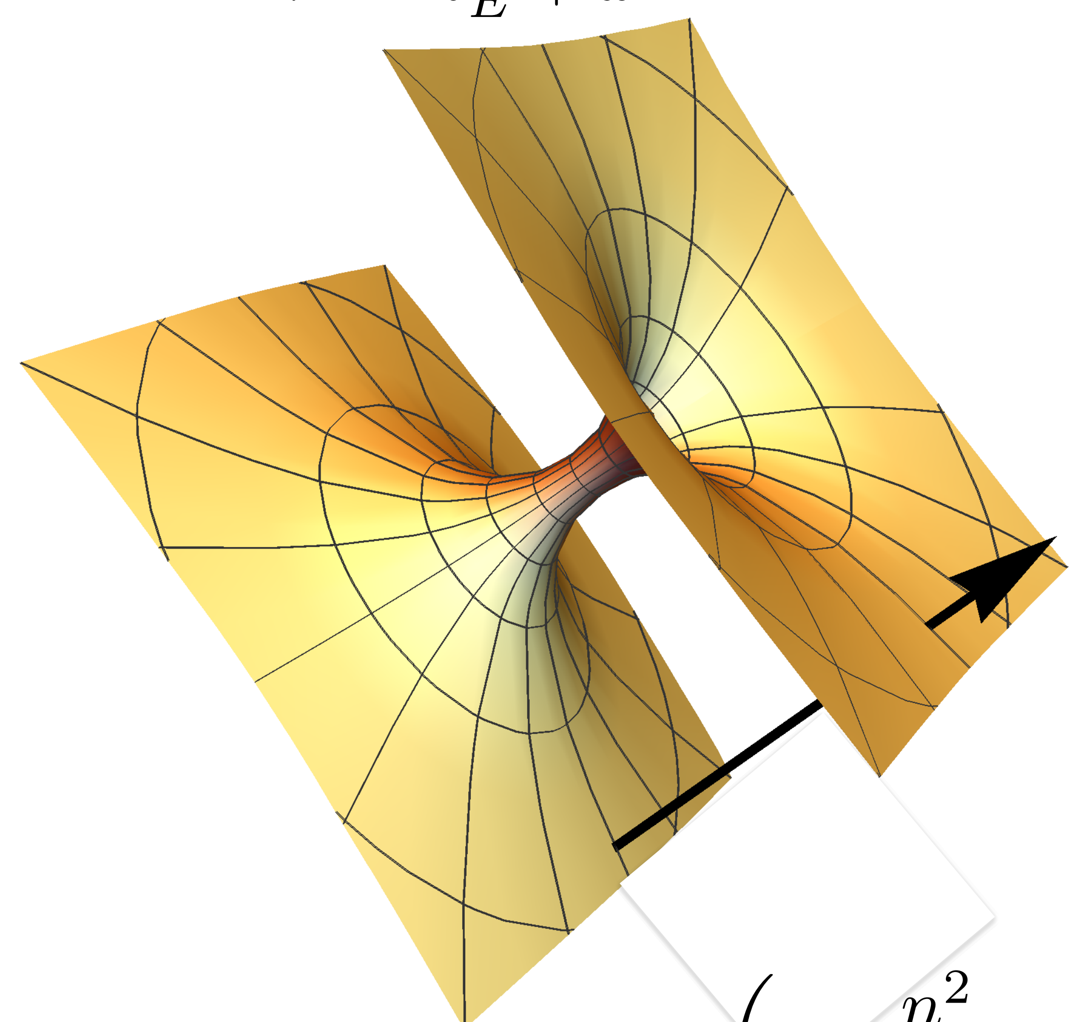
$$ds^2 = \left(\frac{1}{1 - L^4/r^4}\right) dr^2 + r^2 d\Omega_{3,1}$$

Noether current

$$J^\mu \rightarrow \quad \partial^r \theta = \frac{n}{2\pi^2 r^3}$$

Charge

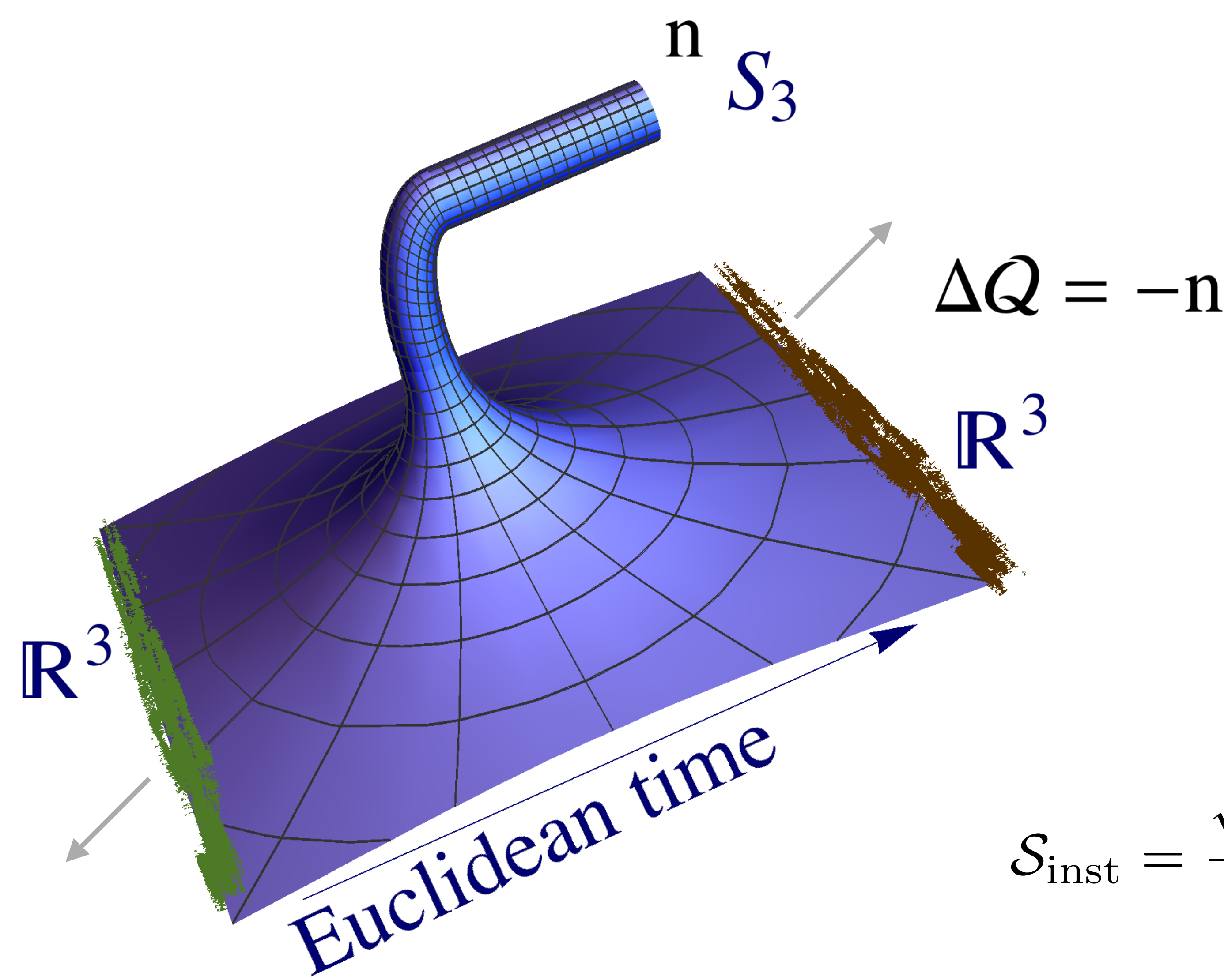
$$\int J^0 = \int d\Omega_3 \sqrt{g} \partial^r \theta = n$$



$$L \equiv \left(\frac{n^2}{3\pi^3 M_{\rm Pl}^2 f_a^2}\right)^{1/4}$$

[Giddings & Strominger NPB **306** 890 (1988)]

What is going on?

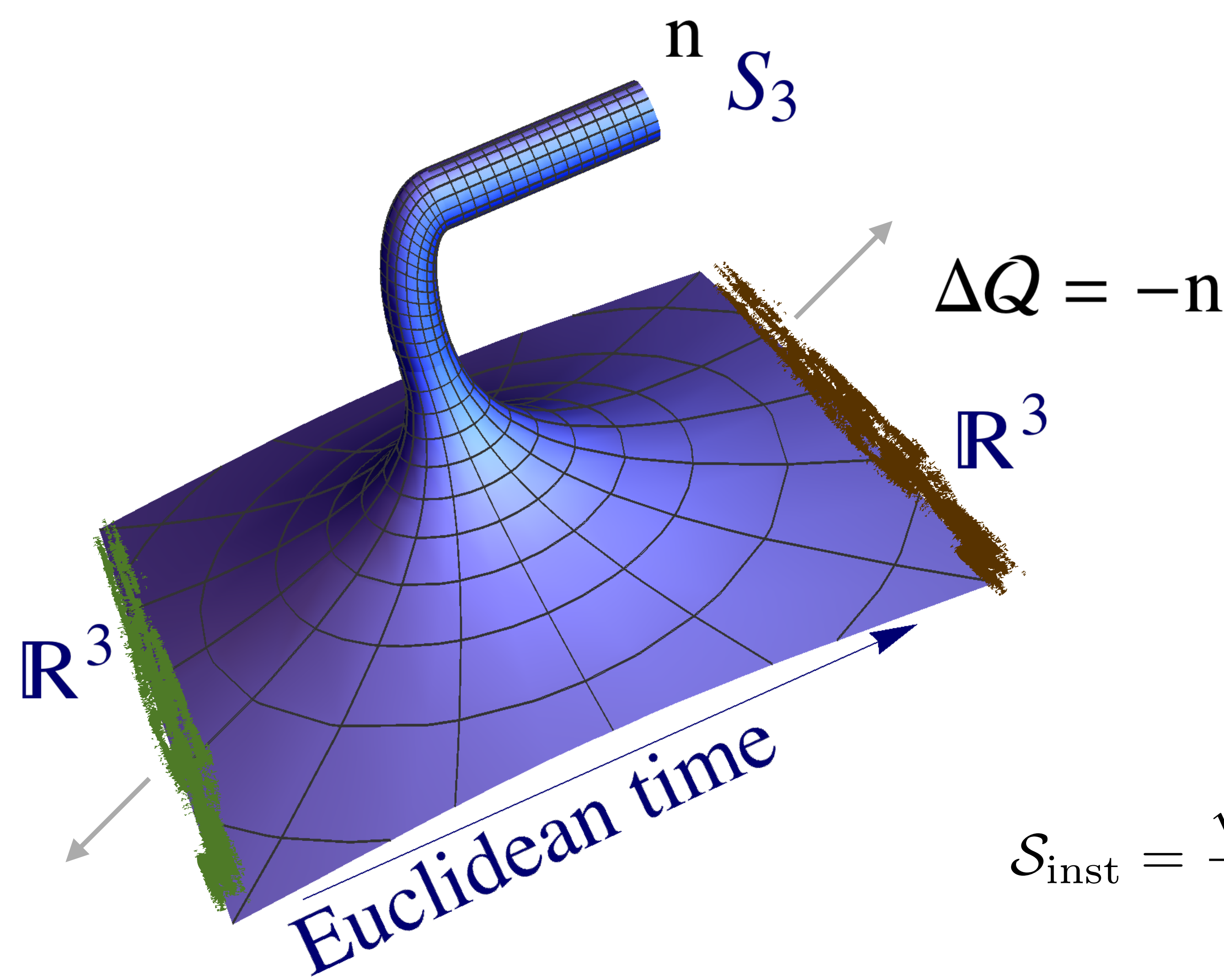


$$\mathcal{S}_{\text{inst}} = \frac{\sqrt{3\pi} n M_{\text{Pl}}}{8 f_a}\left(1 - \frac{2}{\pi}\right)$$

"Any reasonable theory of quantum gravity will allow closed universes to branch off from our nearly flat region of spacetime"

[Hawking PRD **37** 904 (1988)]

What is going on?



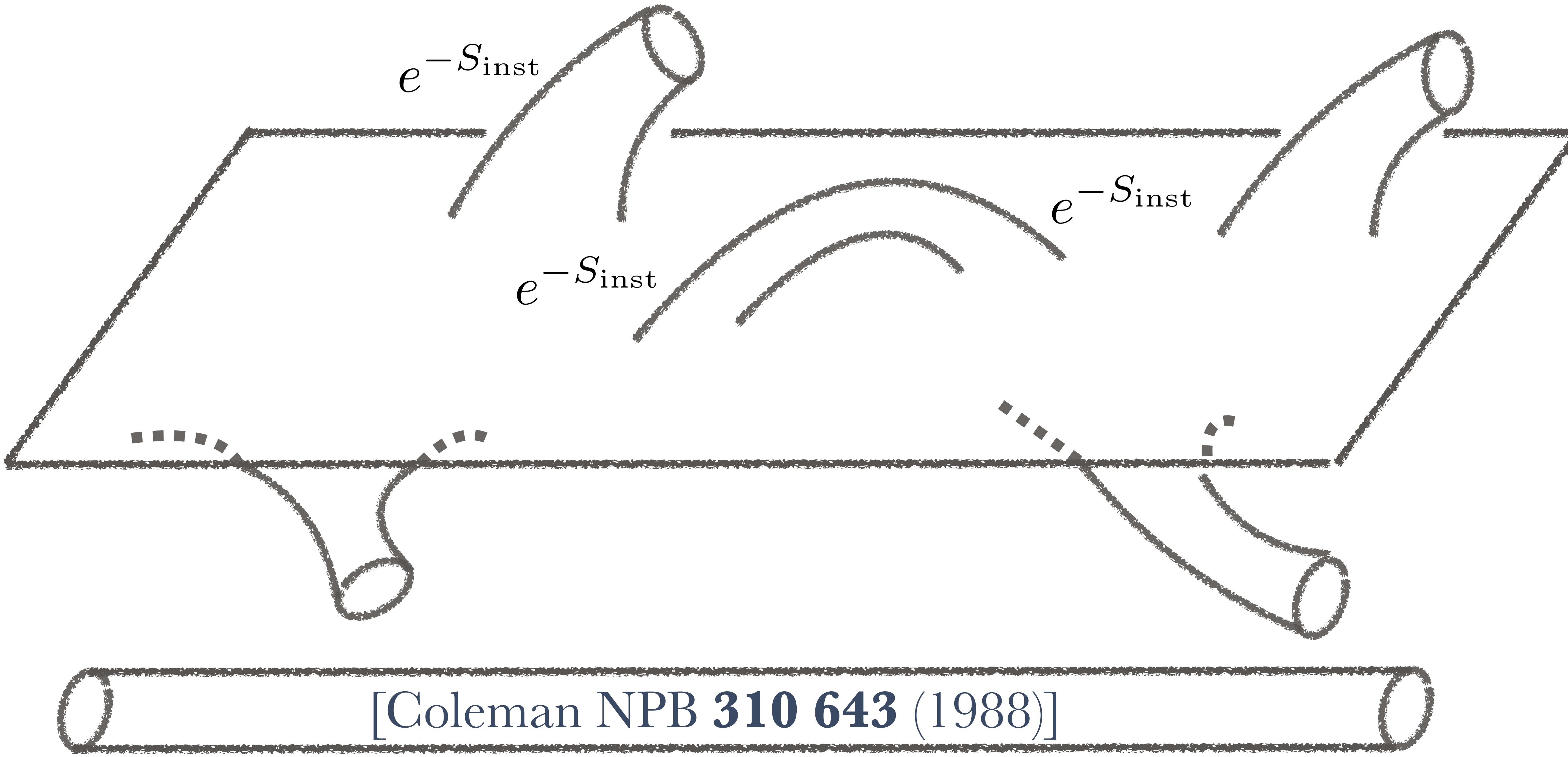
$$\mathcal{S}_{\text{inst}} = \frac{\sqrt{3\pi} n M_{\text{Pl}}}{8 f_a}\left(1 - \frac{2}{\pi}\right)$$

$$S[\theta_{\text{inst}} + \delta\theta] = S_{\text{inst}} + \delta\theta \int dS \cdot J$$

Prob~ $e^{-S_{\text{inst}}}(1 + Q\delta\theta)$

Summing over instantons

$$\sum_{inst} e^{-S} = e^{-S_{eff}}$$



[Coleman NPB **310 643** (1988)]

$$V = L^{-4} e^{-\sqrt{3\pi} M_{\rm PL}/8f} \cos(\theta)$$

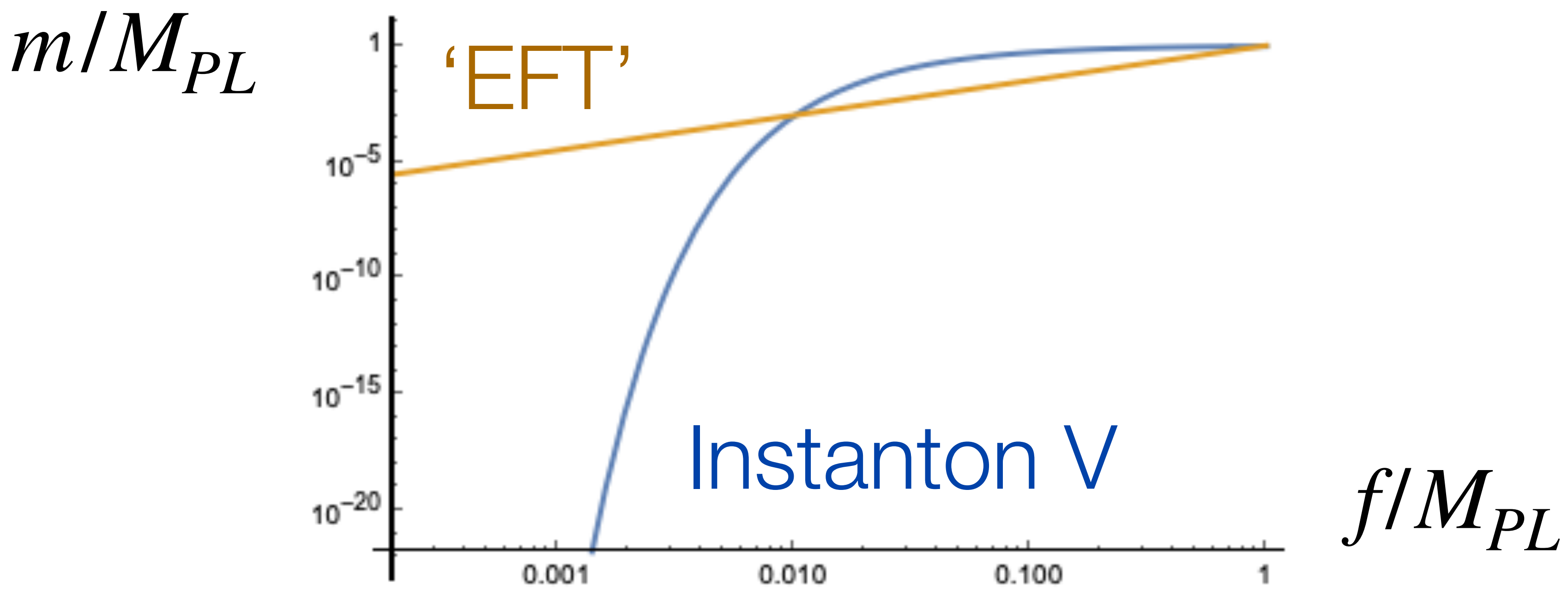
Comparative of estimates

Gravity generates a potential for the NGB:

$$V = L^4 e^{-S_{inst}} \cos\theta = M_{\rm PL}^2 f^2 e^{-\sqrt{3\pi} M_{\rm PL}/8f} \cos(\theta)$$

The naive expectation for an EFTist

$$\hat{V} = \frac{c f^5}{M_{\rm PL}} \cos(\theta)$$



$$10^{-0.03 M_{PL}/f}$$

[RA & A. Urbano, '17]

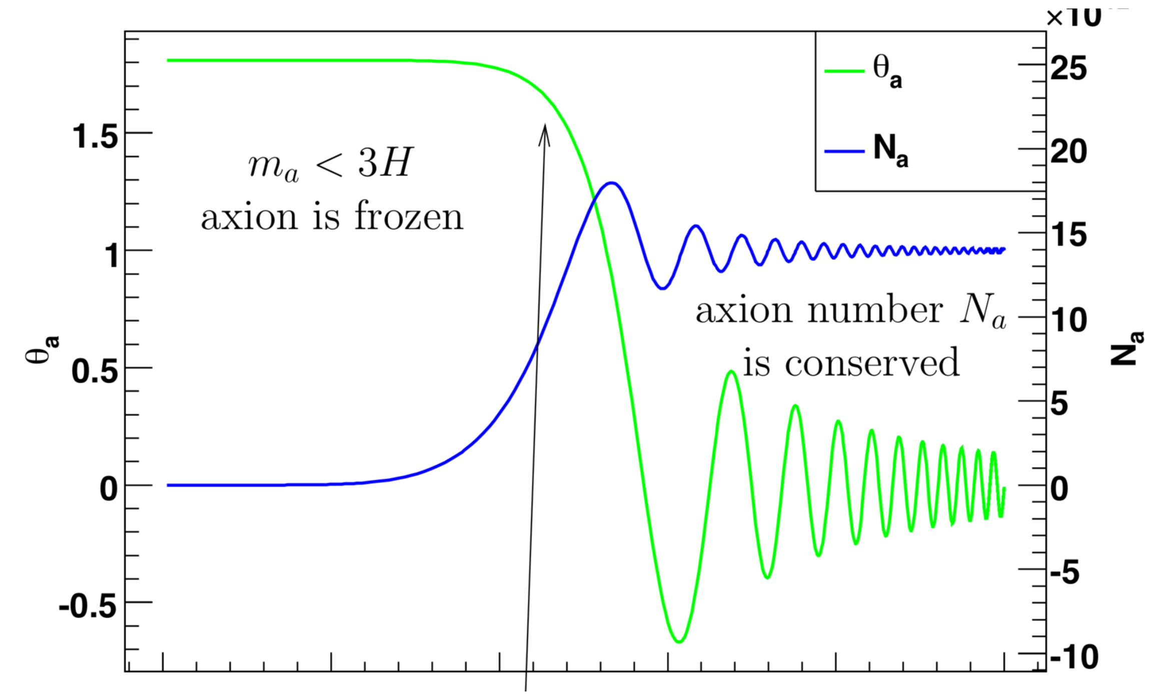
Gravity as mass source

$$m^2 = M_{\rm PL}^2 e^{-\sqrt{3\pi} M_{\rm PL}/8f}$$

Could this be dark matter?

Production? misalignment

$$\partial^2\theta + 3H\dot{\theta} + m^2\theta = 0$$



1/T

$$\Omega = 0.1\left(\frac{f}{10^{17}\text{GeV}}\right)^2\sqrt{\frac{m}{10^{-22}\text{eV}}}$$

For the mass generation via instantons

$$f \simeq 8\times 10^{15}\text{GeV}$$

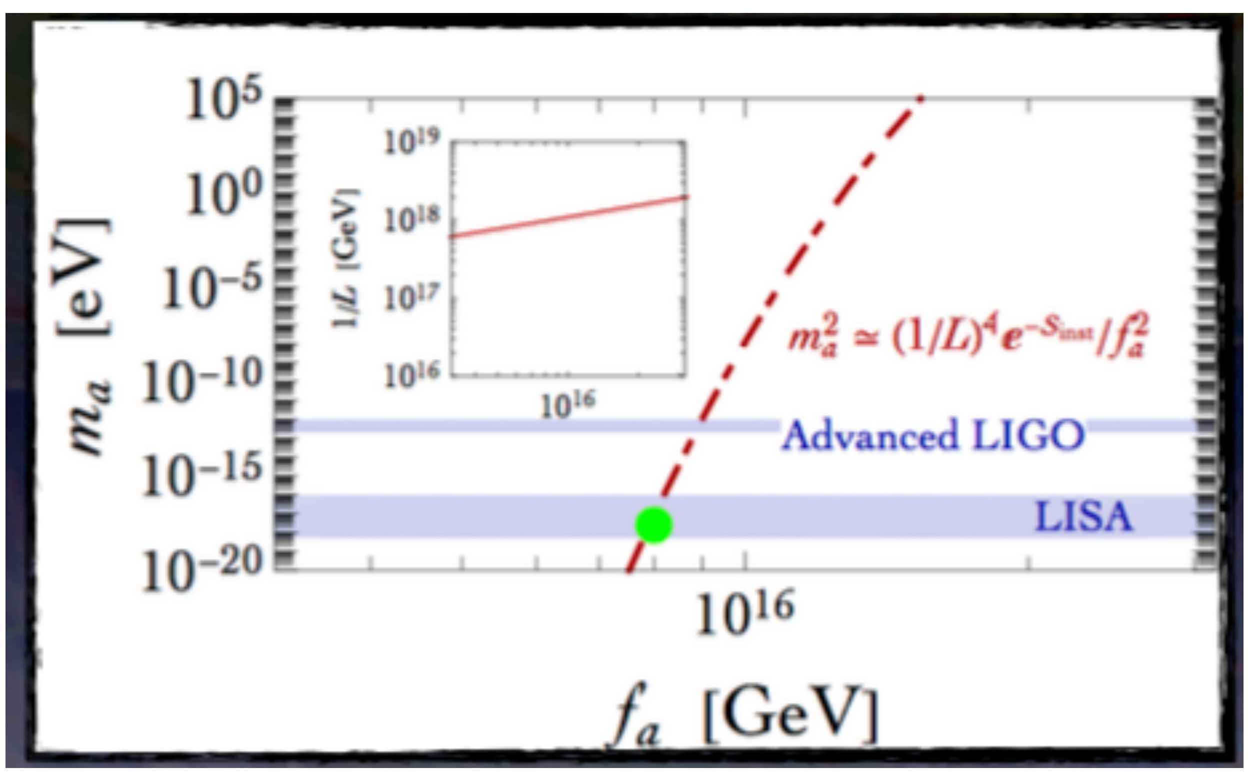
$$m = 2.5\times 10^{-18}\text{eV}$$

Comparative of estimates

Hard to see on laboratories...

Testable via its gravitational interactions
e.g. Gravitational Waves from super-radiance

[Brito, Ghosh, Barausse, Berti, Cardoso, Dvorkin, Klein, Pani '17]



$$m = 2.5 \times 10^{-18}\text{eV}$$

$$f \simeq 8 \times 10^{15}\text{GeV}$$

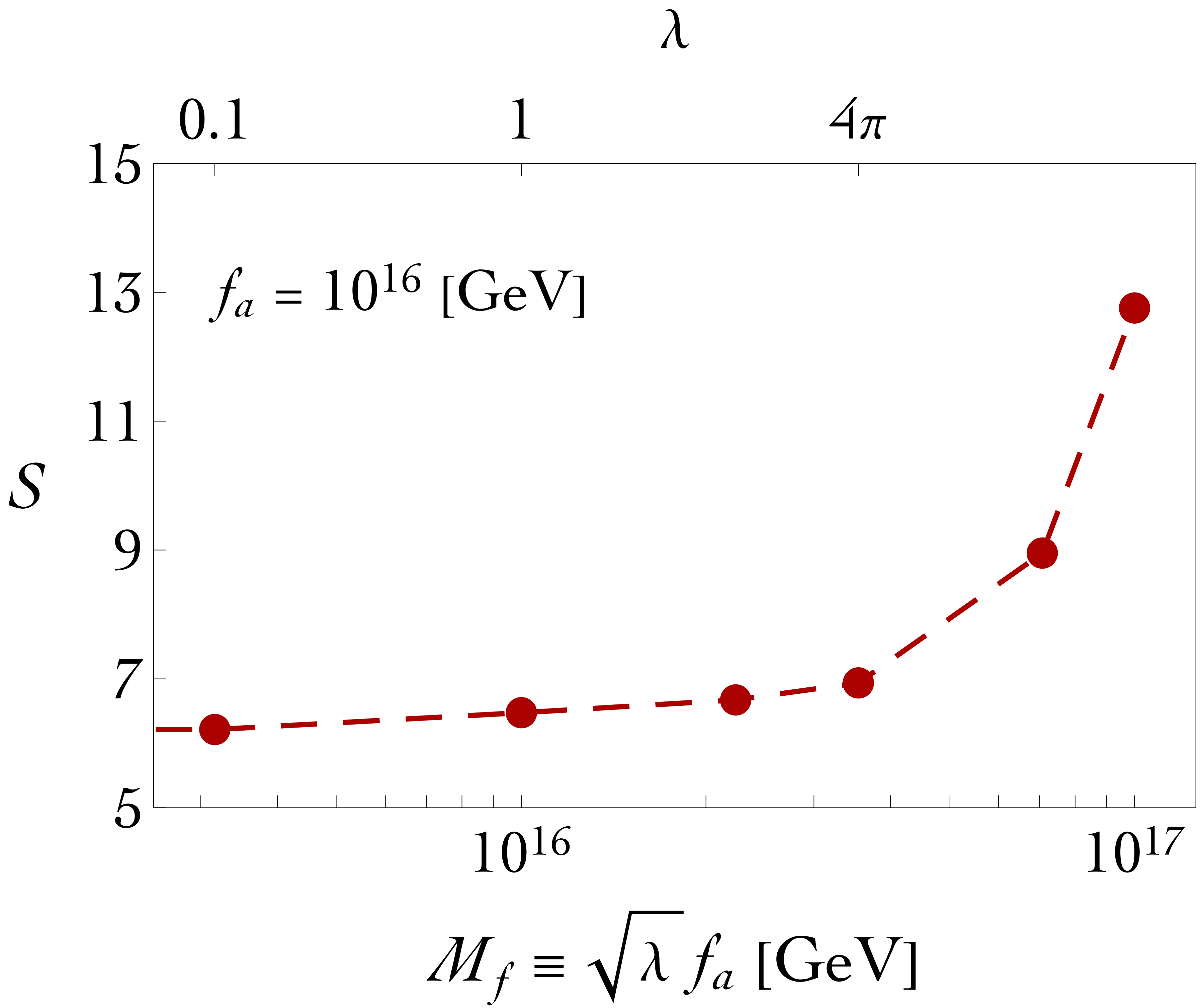
Summary

U(1) Goldstone + Gravity

=

Dark Matter

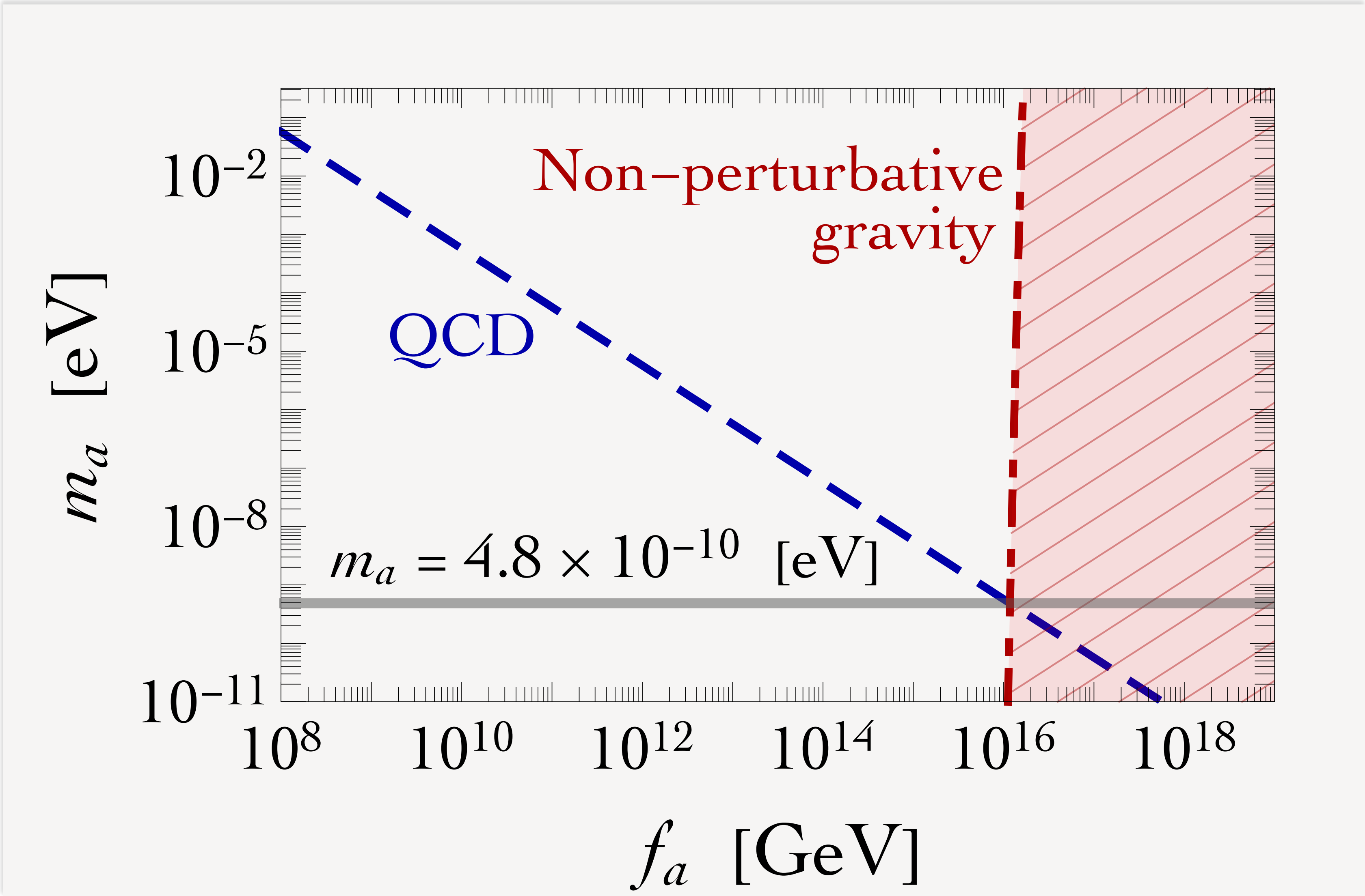
Radial mode



λ
0.1
1
4π
15
13
11
9
7
5
S
$f_a = 10^{16}$ [GeV]
10^{16}
10^{17}
$M_f \equiv \sqrt{\lambda}\, f_a$ [GeV]

Other applications: QCD axion

$$m_a^2 = \frac{\Lambda_{\rm QCD}^4}{f^2} \overset{*}{+} 3\pi^3 M_{\rm PL}^2 e^{-\sqrt{3\pi} M_{\rm PL}/f8}$$



[RA & A. Urbano, '17]

Effective action below L

Transitions described by the action:

$$S_{\text{eff}} = \int dV \sum_n K e^{-S_n} \left(e^{-in\theta}\mathcal{O}(x)a_n^\dagger + h.c.\right)$$

$$[a_n, a_{n'}^\dagger] = \delta_{nn'}$$

$$\left(a_n^\dagger + a_n\right)|\alpha\rangle = \alpha|\alpha\rangle$$

Vacuum state

$$\langle\alpha|\mathcal{S}_{\text{eff}}|\alpha\rangle = \int d^4x\sqrt{g}Ke^{-\mathcal{S}_{\text{inst}}}\alpha\cos\left(\frac{\phi}{f} + \delta_q\right)$$

$$\frac{M_{\text{PL}}}{f} \qquad \text{vs} \qquad \frac{1}{g_s^2}$$

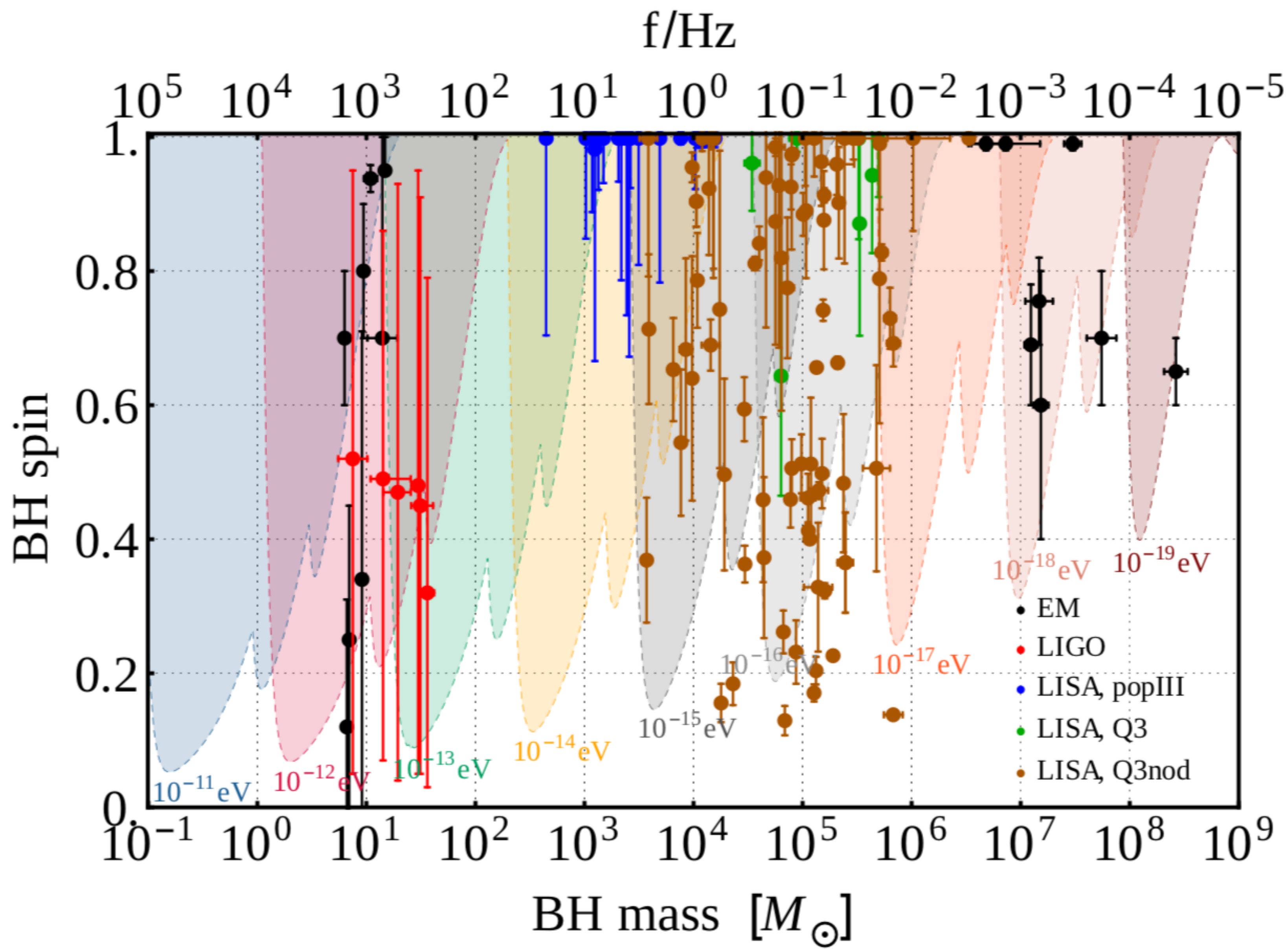


FIG. 1. Exclusion regions in the BH mass-spin plane (Regge plane) for a massive scalar field. For each mass m_s, the instability threshold is obtained by setting the superradiant instability time scales for $l = m = 1, 2, 3$ equal to a typical accretion time scale, taken to be $\tau = 50\,\mathrm{Myr}$ (see main text for details). Black data points (with error bars) are spin estimates of stellar and massive BHs obtained through the Kα or continuum fitting methods [37, 38]. Red data points are GW measurements of the primary and secondary BHs from the three LIGO detections (GW150914, GW151226 and GW170104 [3, 4]). Blue, green and brown data points are projected LISA measurements under the assumption that there are no light bosons for three different astrophysical black hole population models (popIII, Q3 and Q3-nod from [39]), as discussed in the text. We assume a LISA observation time $T_{\rm obs} = 1\,\mathrm{yr}$, and to avoid cluttering we only show events for which LISA spin measurement errors are relatively small ($\Delta\chi/\chi \leq 2/3$). The top horizontal line is a frequency scale corresponding to the BH mass, $f \approx \mu/\pi$ with $\mu \sim 0.2/M$ as a reference value.