Light dark matter in cosmological relaxation scenario

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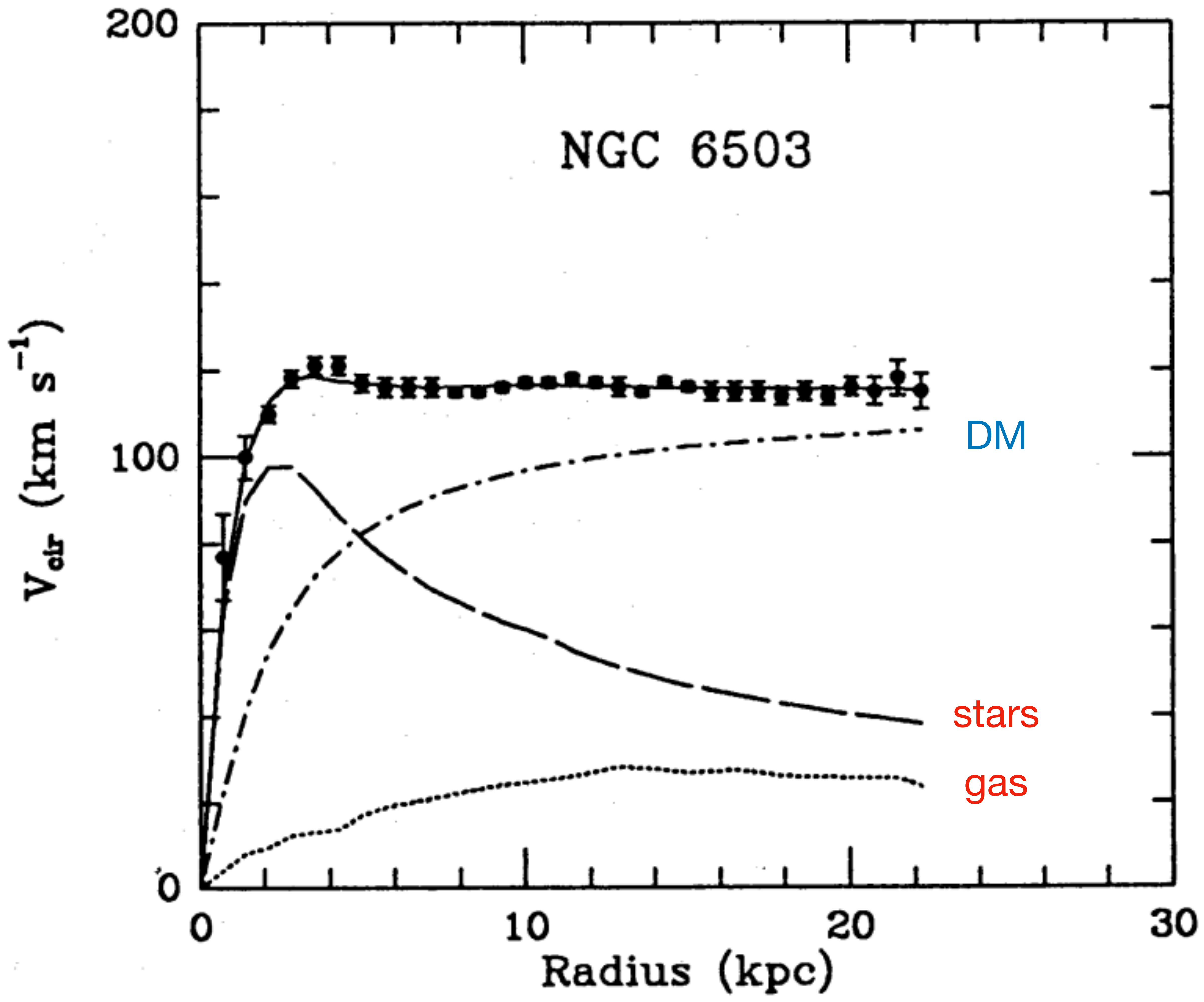
DESY

9 Aug. 2021

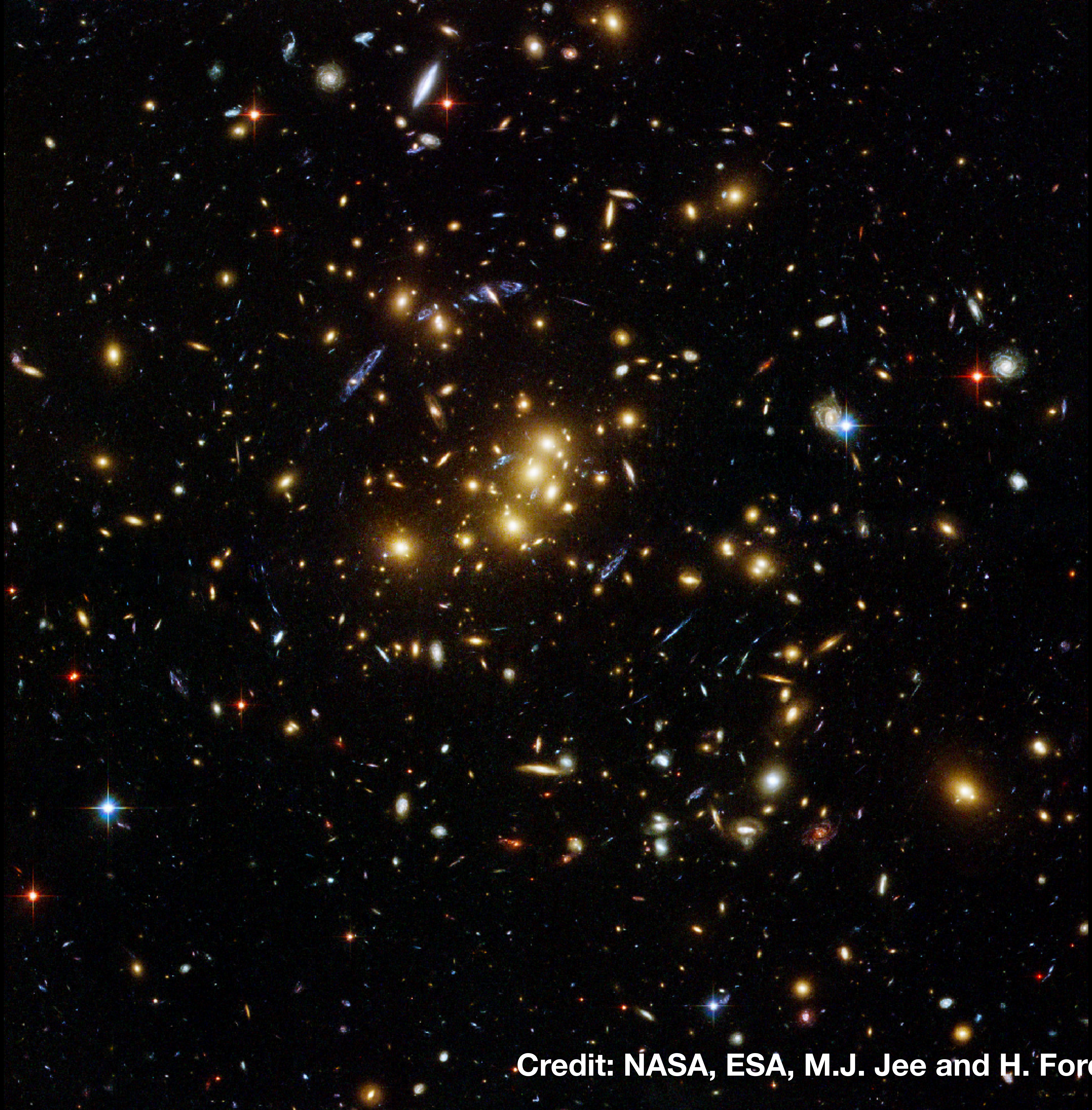
NGC 6503

Credit: NASA/ESA



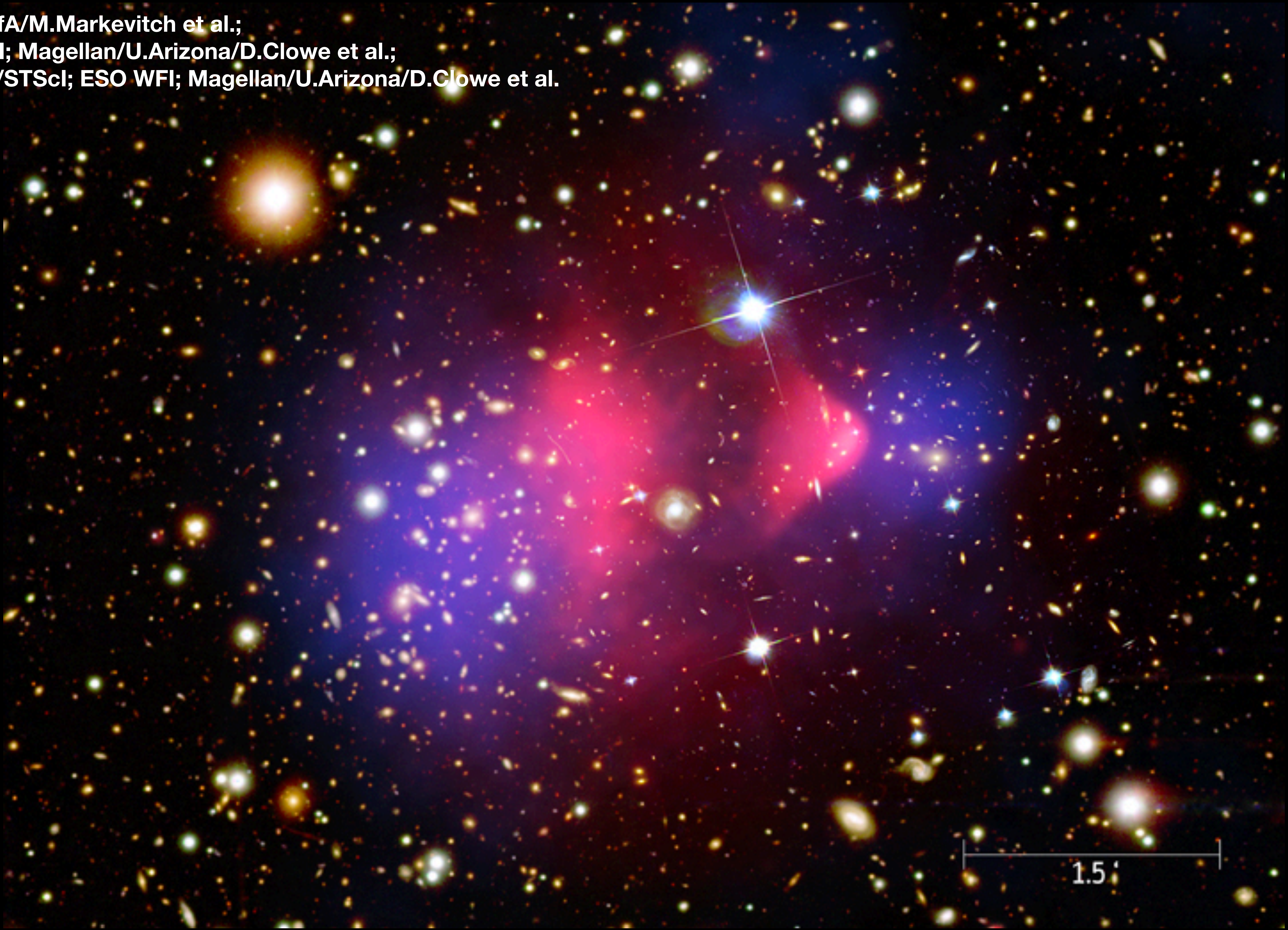
Begeman et al 1991

CL0024+1654



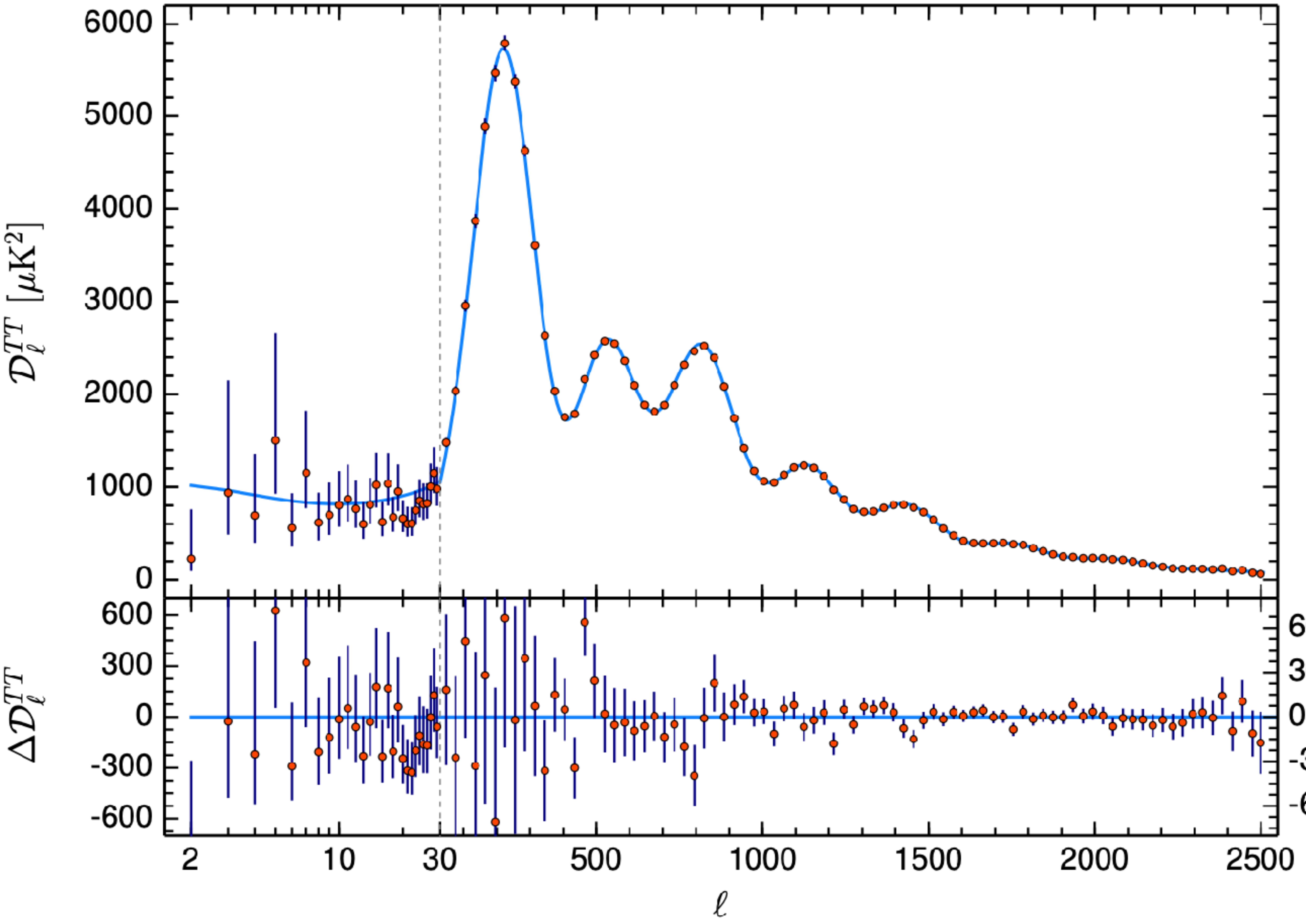
Credit: NASA, ESA, M.J. Jee and H. Ford (Johns Hopkins University)

Credit:
X-ray: NASA/CXC/CfA/M.Markevitch et al.;
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

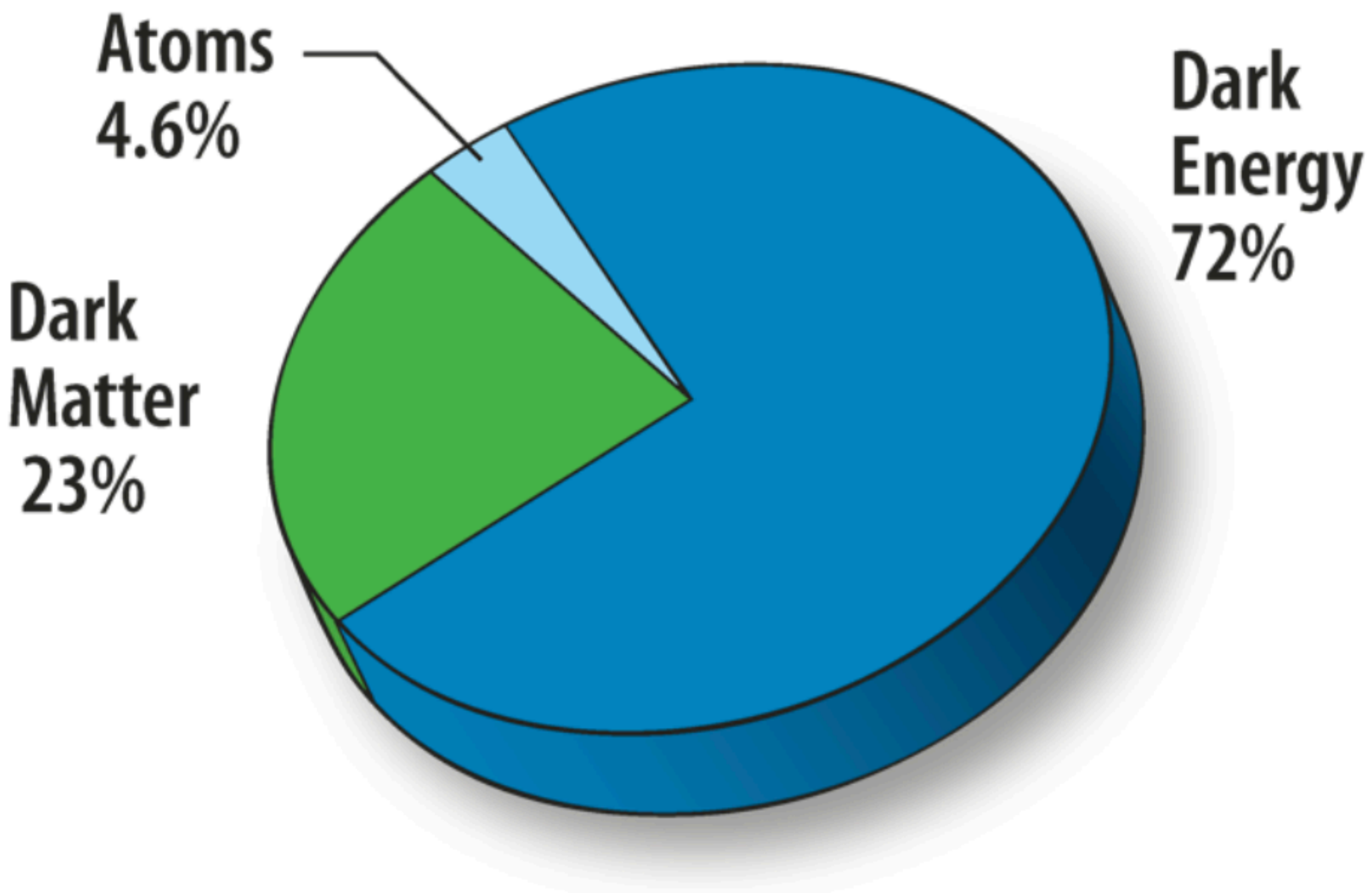


Credit: ESA and the Planck Collaboration

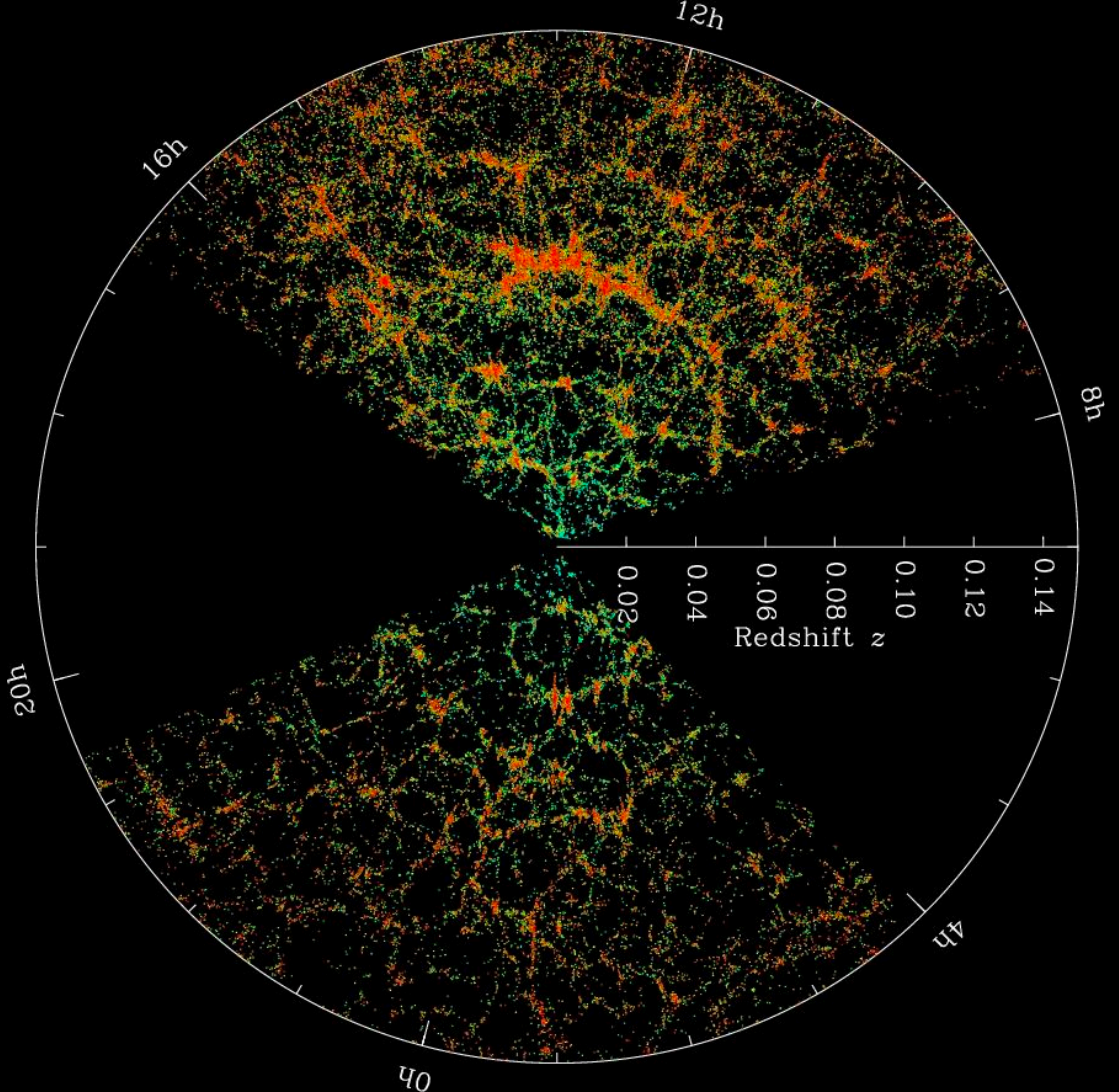
$\Omega_c h^2$ . . . . 0.1206 ± 0.0021



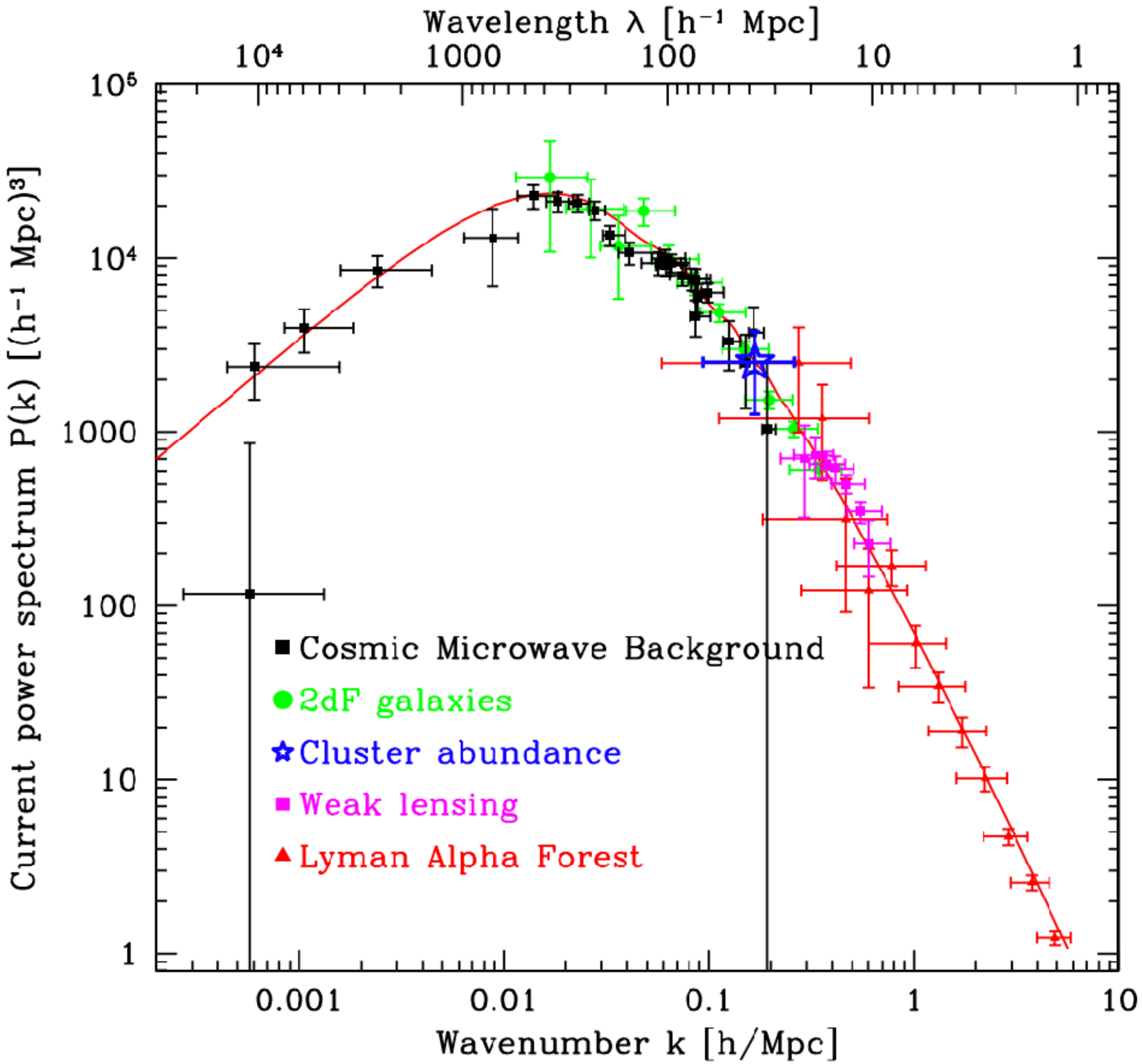
[Planck Collaboration 2018]



TODAY



SDSS



[Tegmark & Zaldarriaga 02]

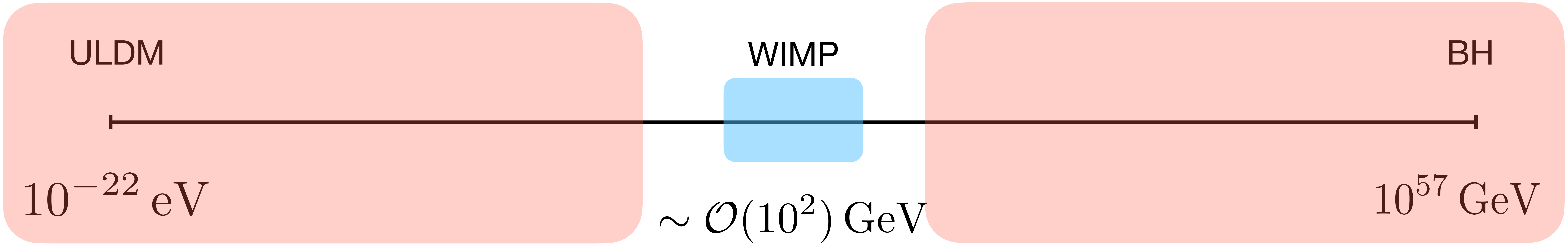
where are they?

ULDM — BH

$10^{-22}\,\mathrm{eV}$ — $10^{57}\,\mathrm{GeV}$

the possible mass range of DM $\sim \mathcal{O}(10^{80})$

where are they?



the possible mass range of DM $\sim \mathcal{O}(10^{80})$

$$\mathcal{L} \supset \Lambda_{\mathrm{cc}} + m_H^2 |H|^2$$

these parameters are radiatively unstable solutions proposed to explain them may be categorized

- symmetry
- anthropic
- dynamics

solutions proposed to explain them may be categorized

- symmetry
- anthropic
- dynamics

fundamental constants may not be constants

but may be dynamical variables

$$\mathcal{L} \supset \Lambda_{\rm cc} + m_H^2 |H|^2$$

$$= \Lambda_{\rm cc}(\langle\phi_i\rangle) + m_H^2(\langle\phi_i\rangle)|H|^2$$

dynamical selection of EW scale

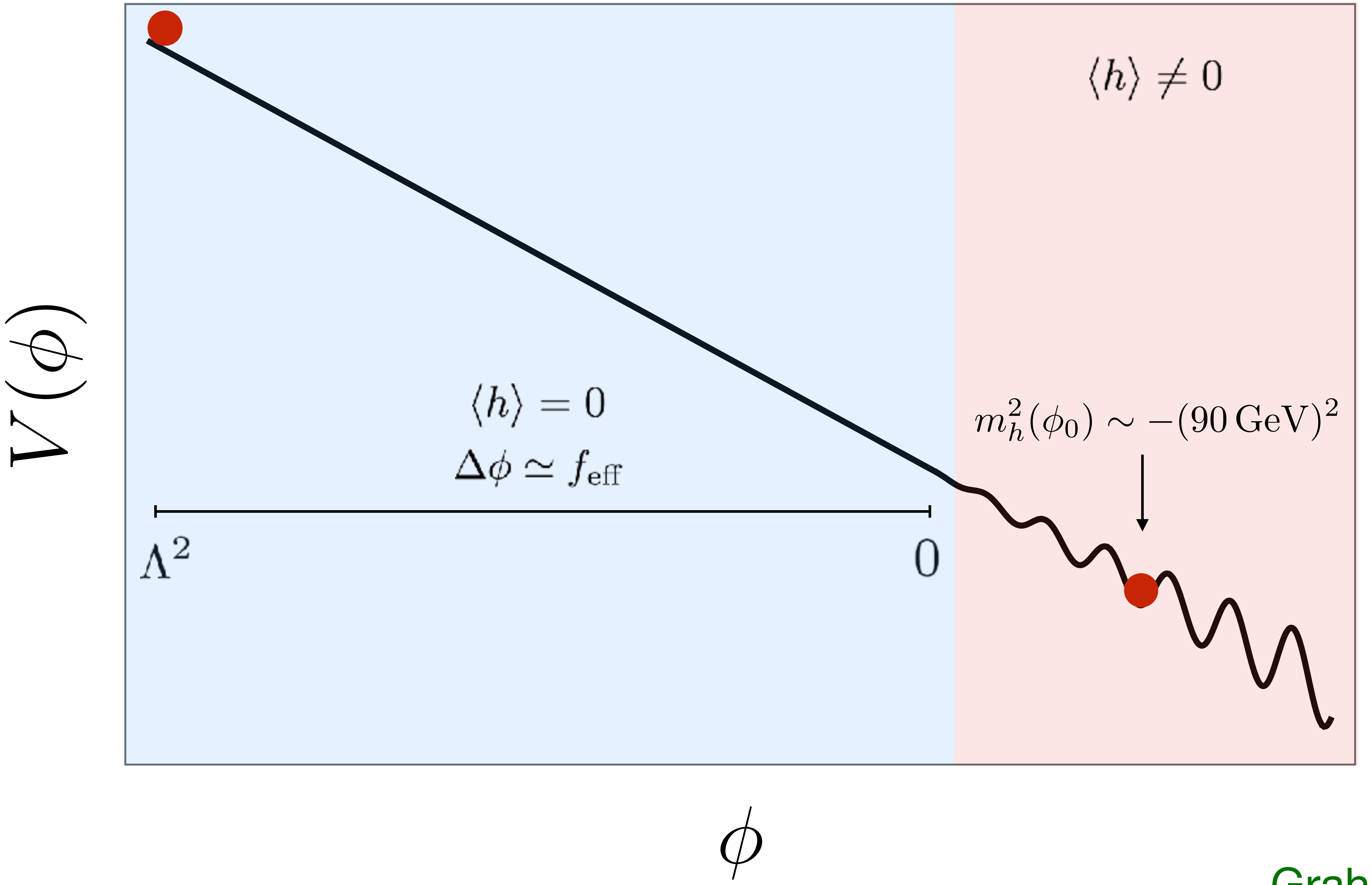
$$V(H,\phi) = m_H^2(\phi)|H|^2 + V(\phi) + V_{\rm br}(H,\phi)$$

$$= \left(\Lambda^2 - \Lambda^2 \frac{\phi}{f_{\rm eff}}\right)|H|^2 - \Lambda^4 \frac{\phi}{f_{\rm eff}} + \mu^2 |H|^2 \cos(\phi/f)$$

Graham, Rajendran, Kaplan 2015

Dynamical selection of EW scale

$$V(\phi) = \left(\Lambda^2 - \frac{\Lambda^2}{f_{\rm eff}}\phi\right)|h|^2 - c\frac{\Lambda^4}{f_{\rm eff}}\phi \;+ \mu_b^2|h|^2\cos(\phi/f)$$



Graham, Rajendran, Kaplan 2015

The smallness of the Higgs mass

$$v_{\rm ew}^2 \ll \Lambda^2$$

is due to dynamical relaxation in the early universe unlike models based on symmetry principle

the relaxation mechanism includes

one IR degree of freedom: *relaxion*

$$m_{\rm IR} < v_{\rm ew} \left(\frac{v_{\rm ew}}{\Lambda}\right)^{3/2}$$

Banerjee, HK, Matsedonskyi, Perez, Safronova 2020 for low-phenomenology we need to know

(i) the mass

(ii) the couplings to SM particles

most of information can be extracted from *wiggles*

$$V_{\rm br} = -\mu_b^2 |H|^2 \cos(\phi/f)$$

some (*rough*) dimensional analysis

$$V_{\rm br} = -\mu_b^2 |H|^2 \cos(\phi/f)$$

its mass might be estimate

$$m_\phi^2 \sim \partial_\phi^2 V_{\rm br} \sim \mu_b^2 v^2/f^2 \cos(\phi_0/f) \sim \mu_b^2 v^2/f^2$$

it does also have a mass mixing

$$m_{h\phi}^2 \sim \partial_\phi \partial_h V_{\rm br} \sim \mu_b^2 v/f \sin(\phi_0/f) \sim \mu_b m_\phi$$

the mass matrix

$$M^2 = \begin{pmatrix} m_h^2 & m_{h\phi} \\ m_{h\phi} & m_\phi^2 \end{pmatrix}$$

$$m_{h\phi}^2 \sim \mu_b m_\phi$$

$$m_\phi^2 \sim \mu_b^2 v^2 / f^2$$

diagonalize the mass matrix

$$h \to h \cos\theta_{h\phi} + \phi \sin\theta_{h\phi}$$

$$\phi \to \phi \cos\theta_{h\phi} - h \sin\theta_{h\phi}$$

mixing angle

$$\sin\theta_{h\phi} \sim \frac{m_{h\phi}^2}{m_h^2} \sim \frac{\mu_b}{v} \frac{m_\phi}{v}$$

based on this *rough* estimation …

the mass is given by

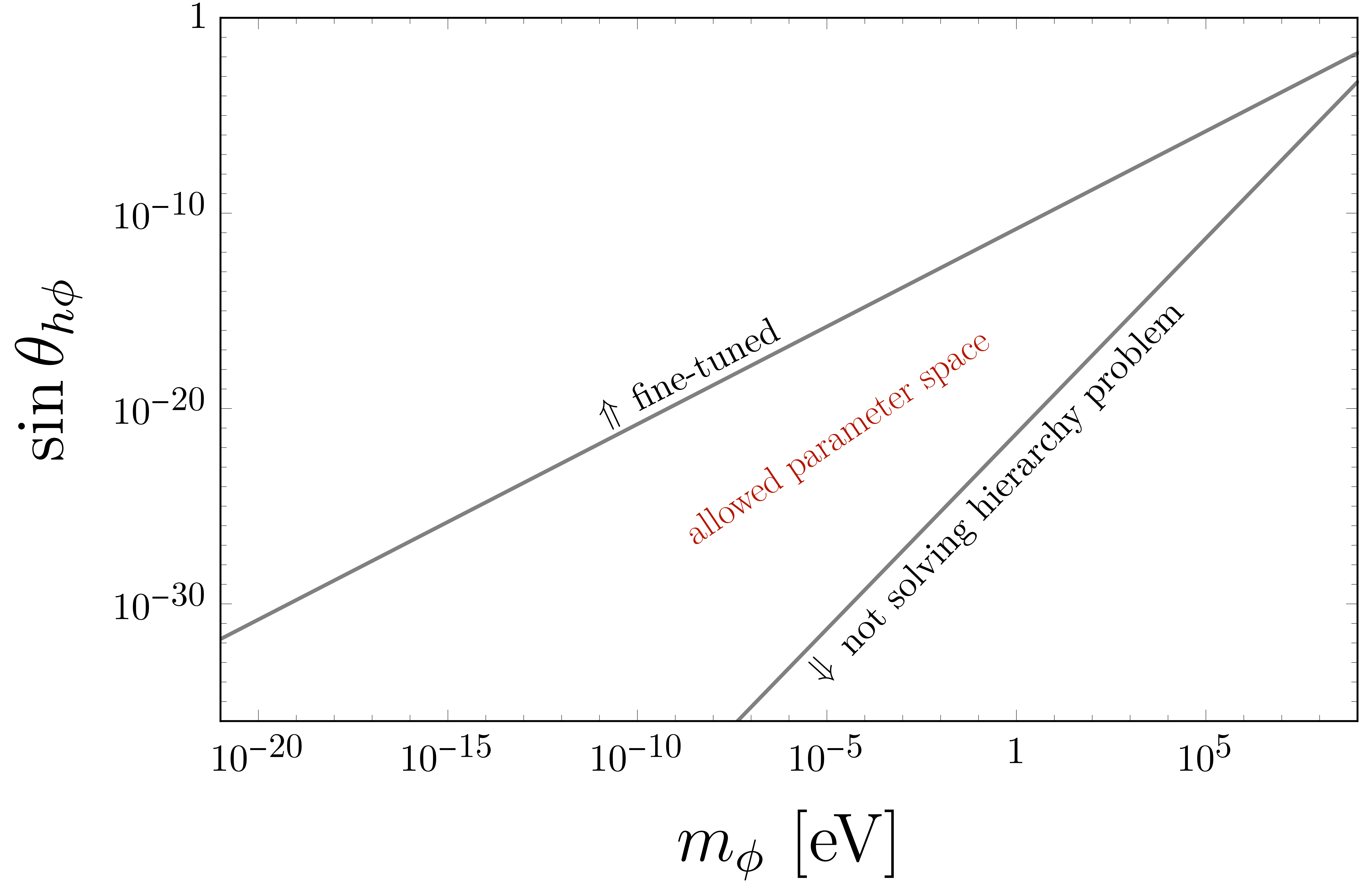
$$m_\phi^2 \sim \mu_b^2 v^2 / f^2$$

the couplings are given by

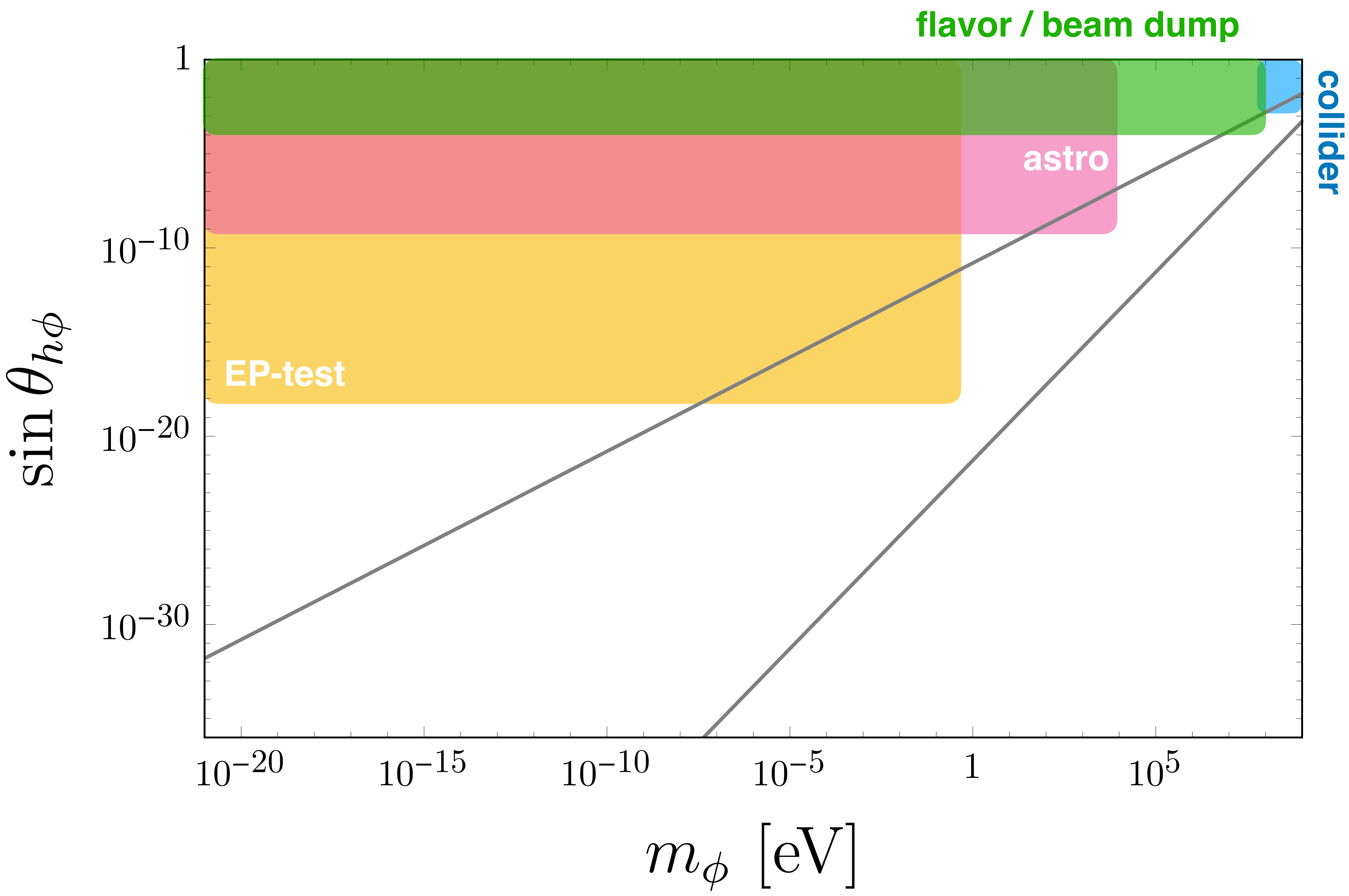
$$\mathcal{L} \supset h\mathcal{O}_{\rm SM} \to \sin\theta_{h\phi}\phi\mathcal{O}_{\rm SM}$$

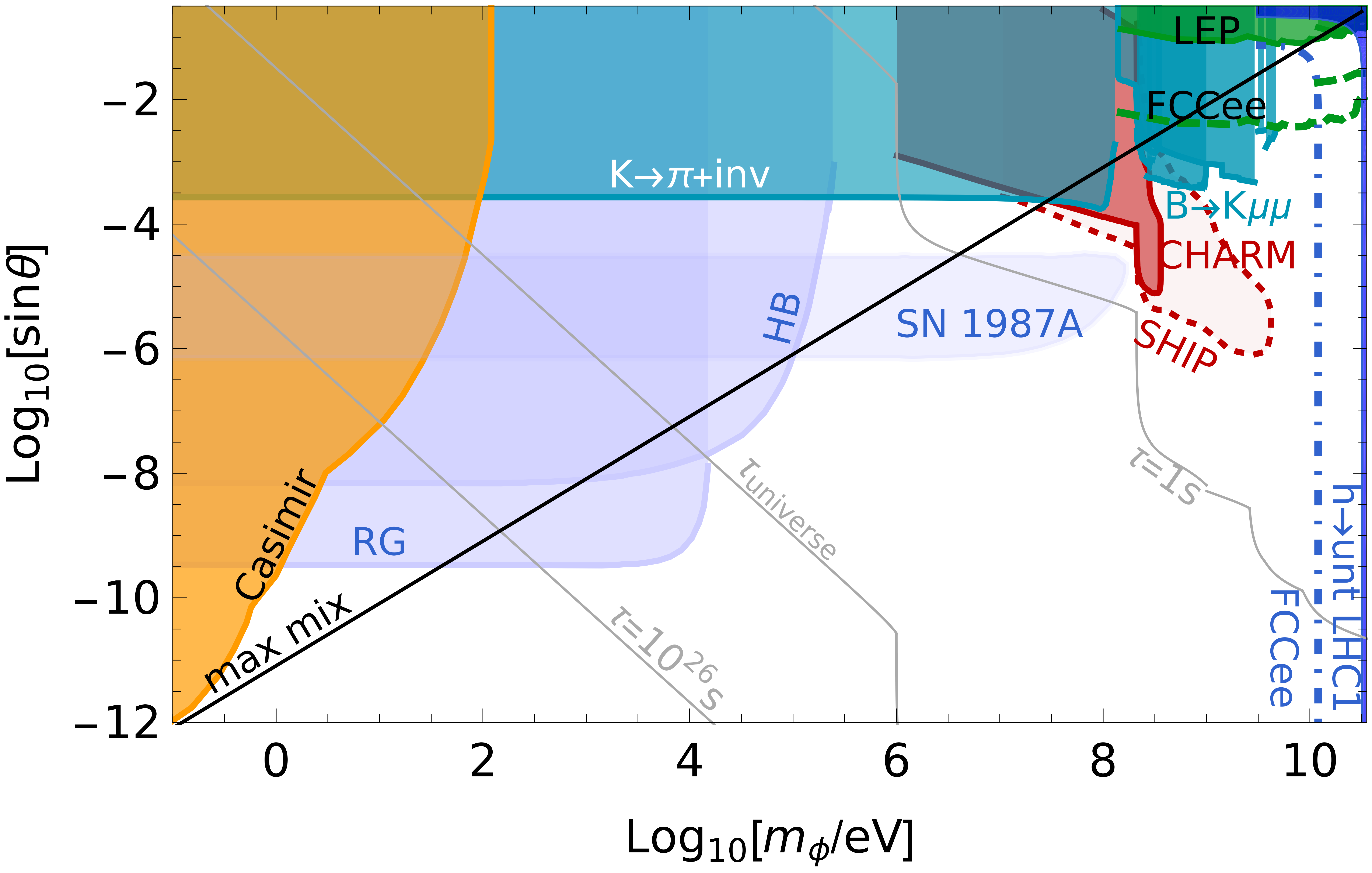
$$\mathcal{O}_{\rm SM} = \frac{1}{v}\Big(-\sum_f m_f \bar{f} f + c_\gamma \frac{\alpha}{4\pi} FF + c_g \frac{\alpha_s}{4\pi} GG \Big)$$

$$\sin\theta_{h\phi} \sim \frac{m_{h\phi}^2}{m_h^2} \sim \frac{\mu_b}{v}\frac{m_\phi}{v}$$



Schematically





Frugiuele, Fuchs, Perez, Schlaffer 2018

identification of available parameter space is based on

the relaxion mass is naively

$$m_\phi^2 \sim \mu_b^2 v^2 / f^2$$

the mixing angle is

$$\sin\theta_{h\phi} \sim \mu_b^2 / v f$$

identification of available parameter space is based on

the relaxion mass is naively

$$m_\phi^2 \sim \mu_b^2 v^2 / f^2 \times (\mu_b / \Lambda)$$

the mixing angle is

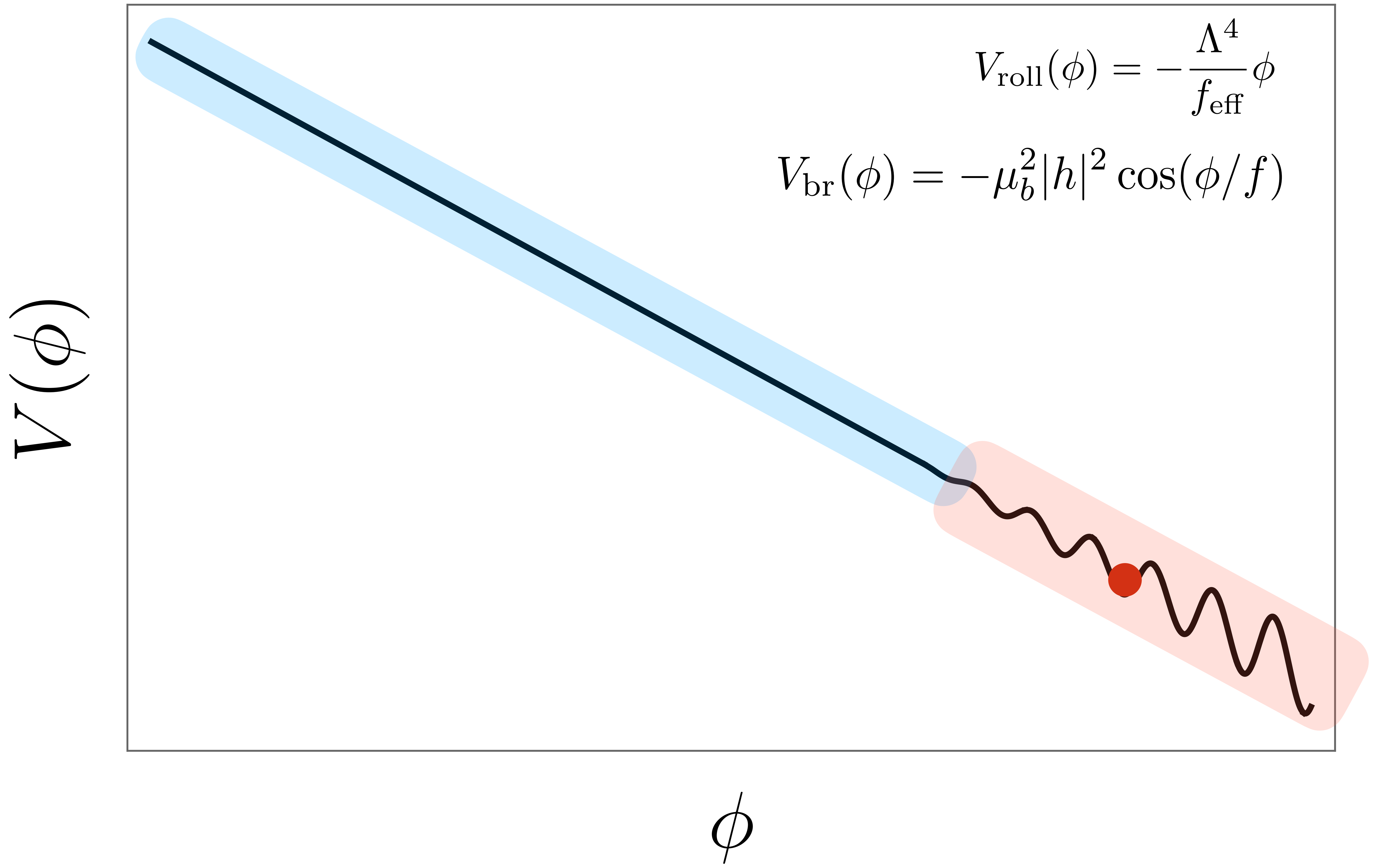
$$\sin\theta_{h\phi} \sim \mu_b^2 / v f$$

the relaxion is also relaxed

[Banerjee, HK, Matsedonskyi, Perez and Safronova 20]

How is relaxion relaxed ?

$$V(\phi) = \left(\Lambda^2 - \Lambda^2 \frac{\phi}{f_{\rm eff}}\right)|h|^2 - \frac{\Lambda^4}{f_{\rm eff}}\phi - \mu_b^2 |h|^2 \cos(\phi/f)$$



How is relaxion relaxed ?

$$V(\phi) = \left(\Lambda^2 - \Lambda^2 \frac{\phi}{f_{\rm eff}}\right)|h|^2 - \frac{\Lambda^4}{f_{\rm eff}}\phi - \mu_b^2 |h|^2 \cos(\phi/f)$$

Relaxion stops when

$$0 = V'_{\rm roll} + V'_{\rm br}$$

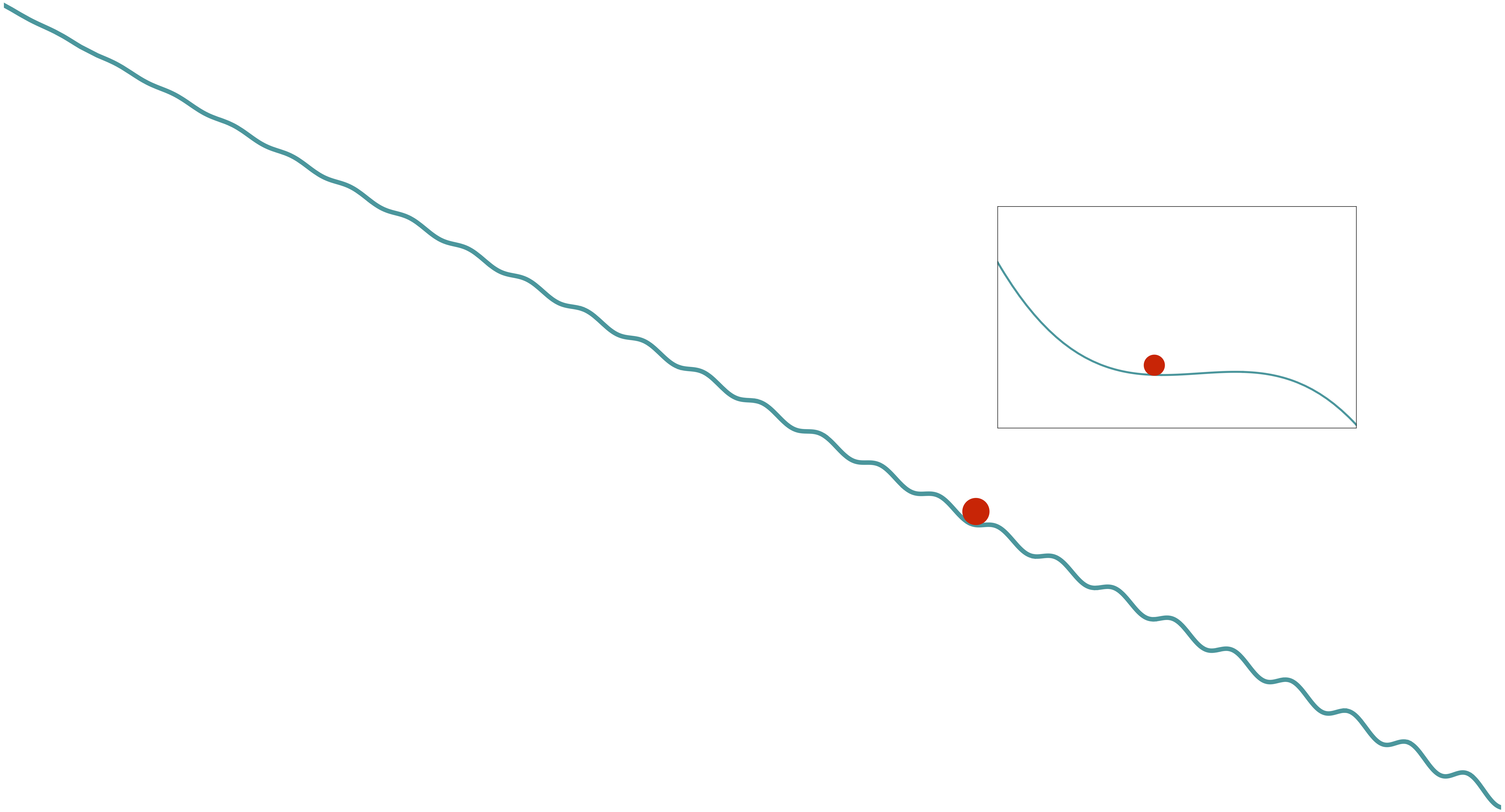
$$= -\frac{\Lambda^4}{f_{\rm eff}} + \frac{\mu_b^2 |h|^2}{f} \sin(\phi/f)$$

Relaxion should stop at the electroweak Higgs mass

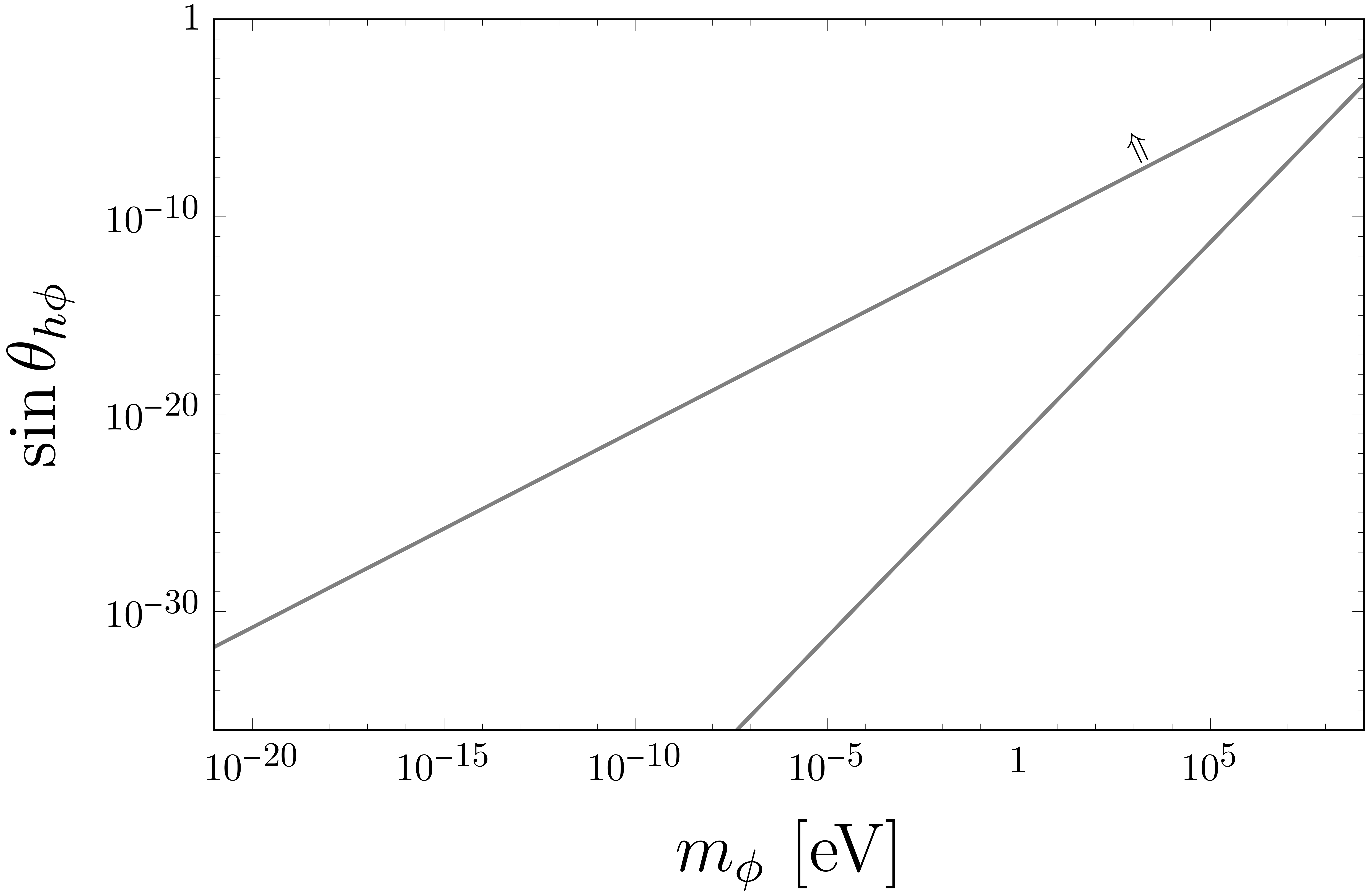
$$\frac{\Lambda^4}{f_{\rm eff}} \simeq \frac{\mu_b^2 v^2}{f}$$

The potential height increases *incrementally*

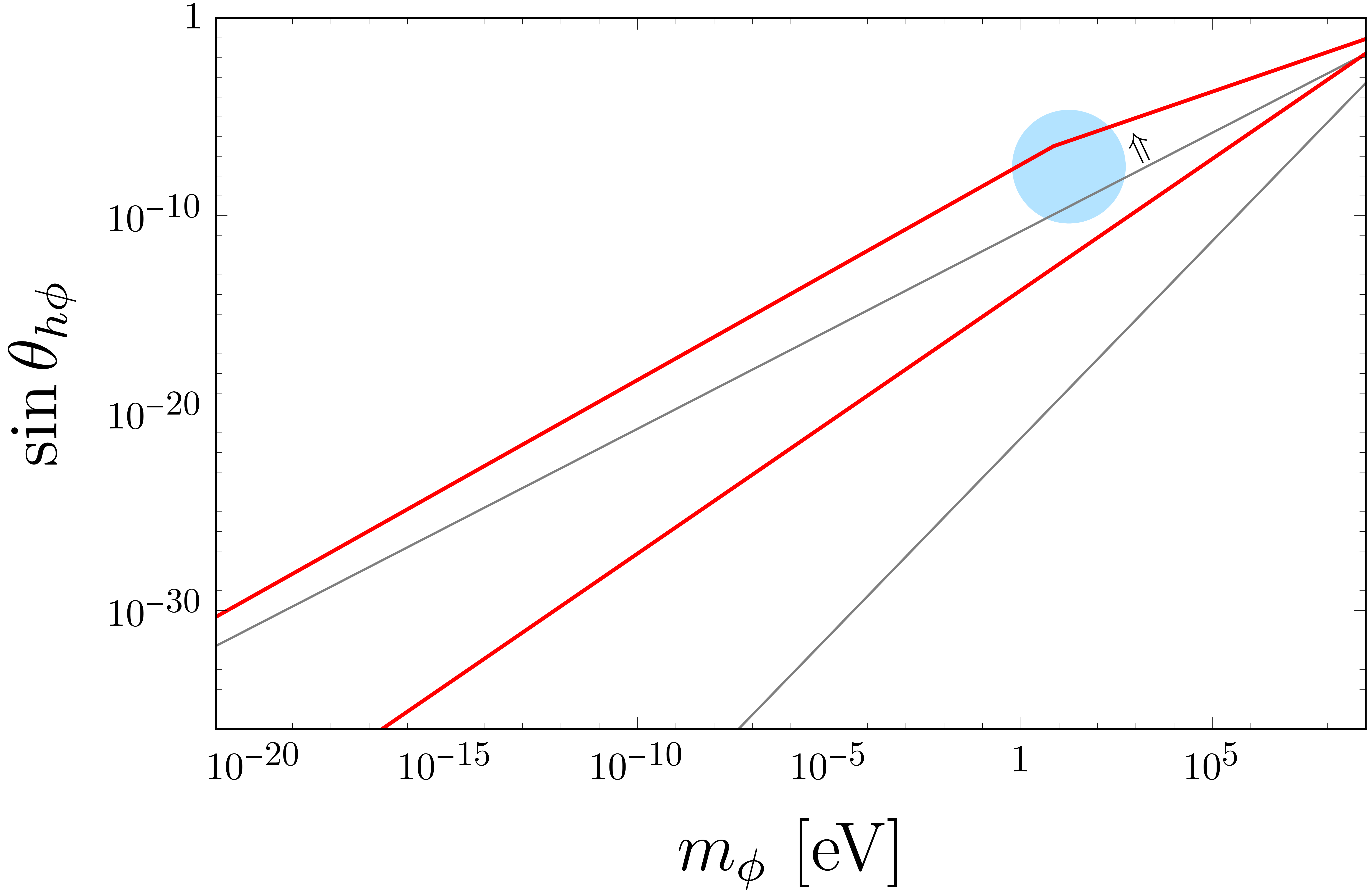
and the relaxion stops at the shallow part of the potential



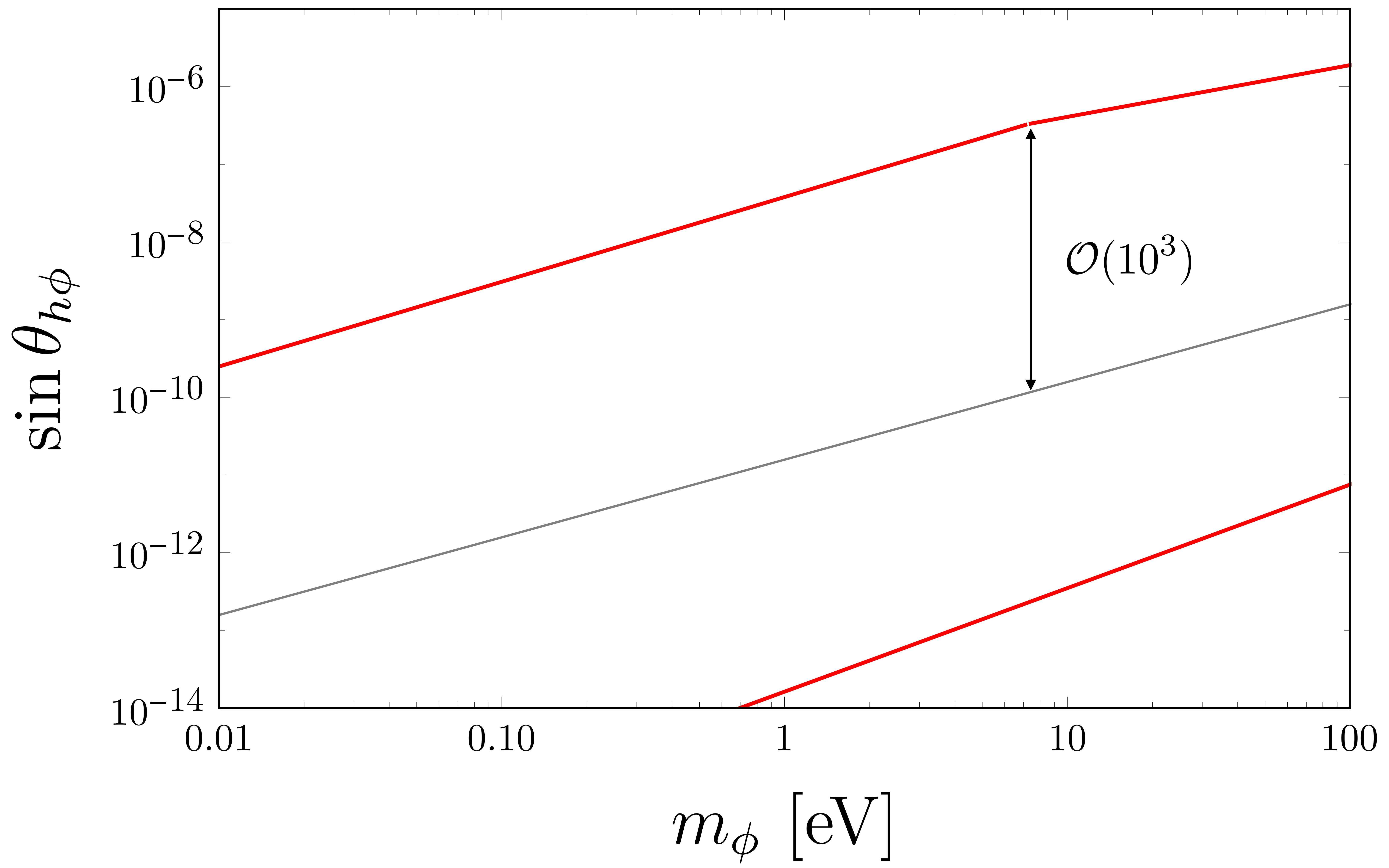
available parameter space shifts accordingly

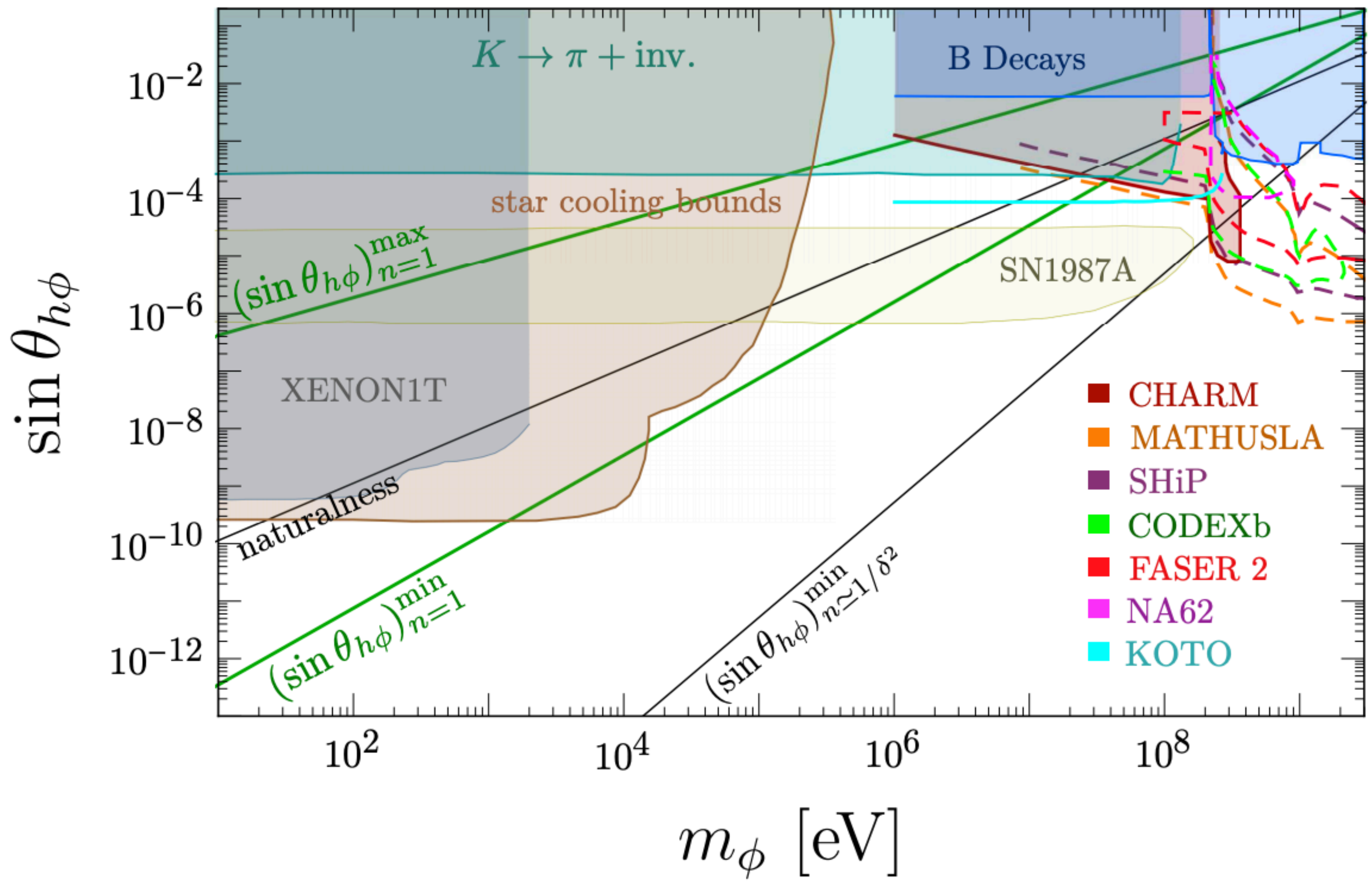


available parameter space shifts accordingly



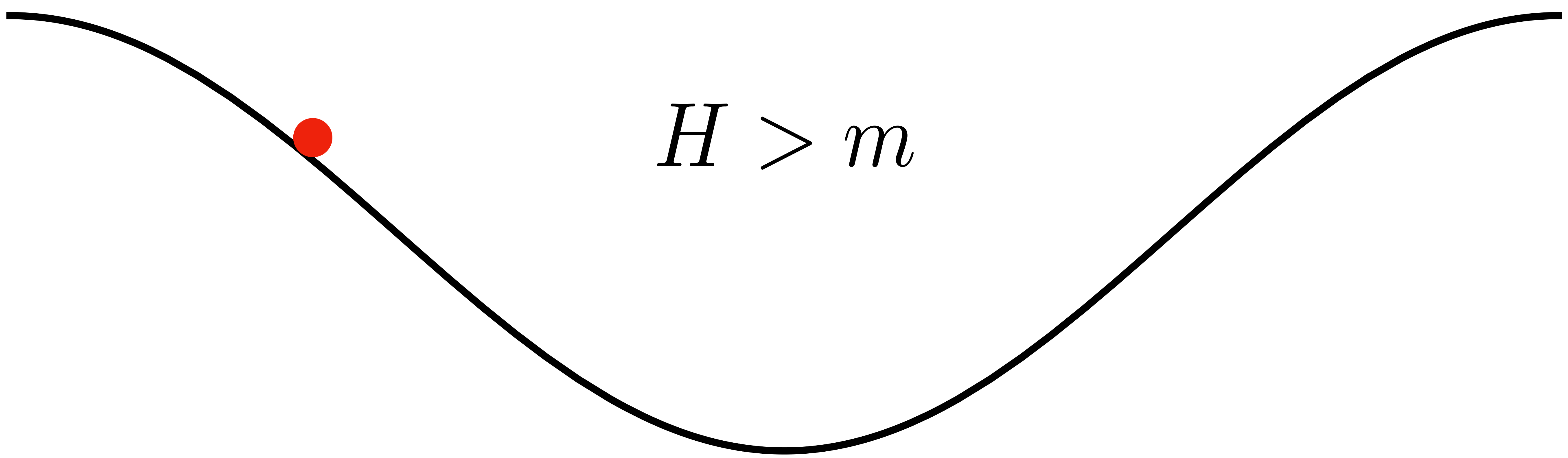
available parameter space shifts accordingly





[Banerjee, HK, Matsedonskyi, Perez and Safronova 20]

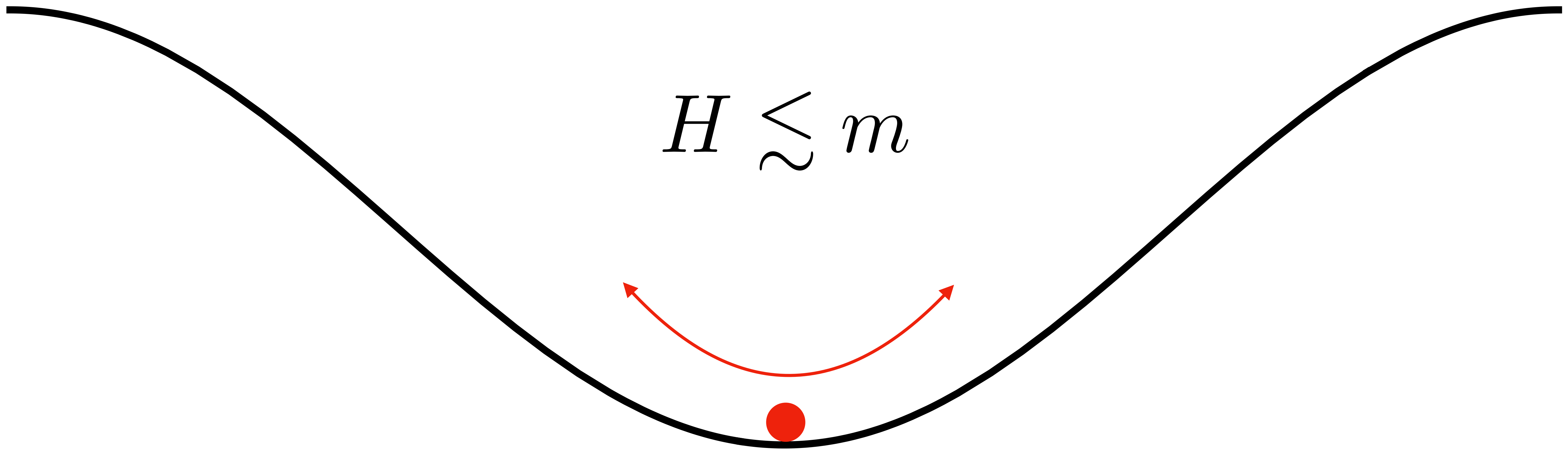
misaligned axion dark matter



$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$$

[Abbott & Sikivie 83]
[Dine & Fischler 83]
[Preskill, Wise and Wilczek 83]

misaligned axion dark matter

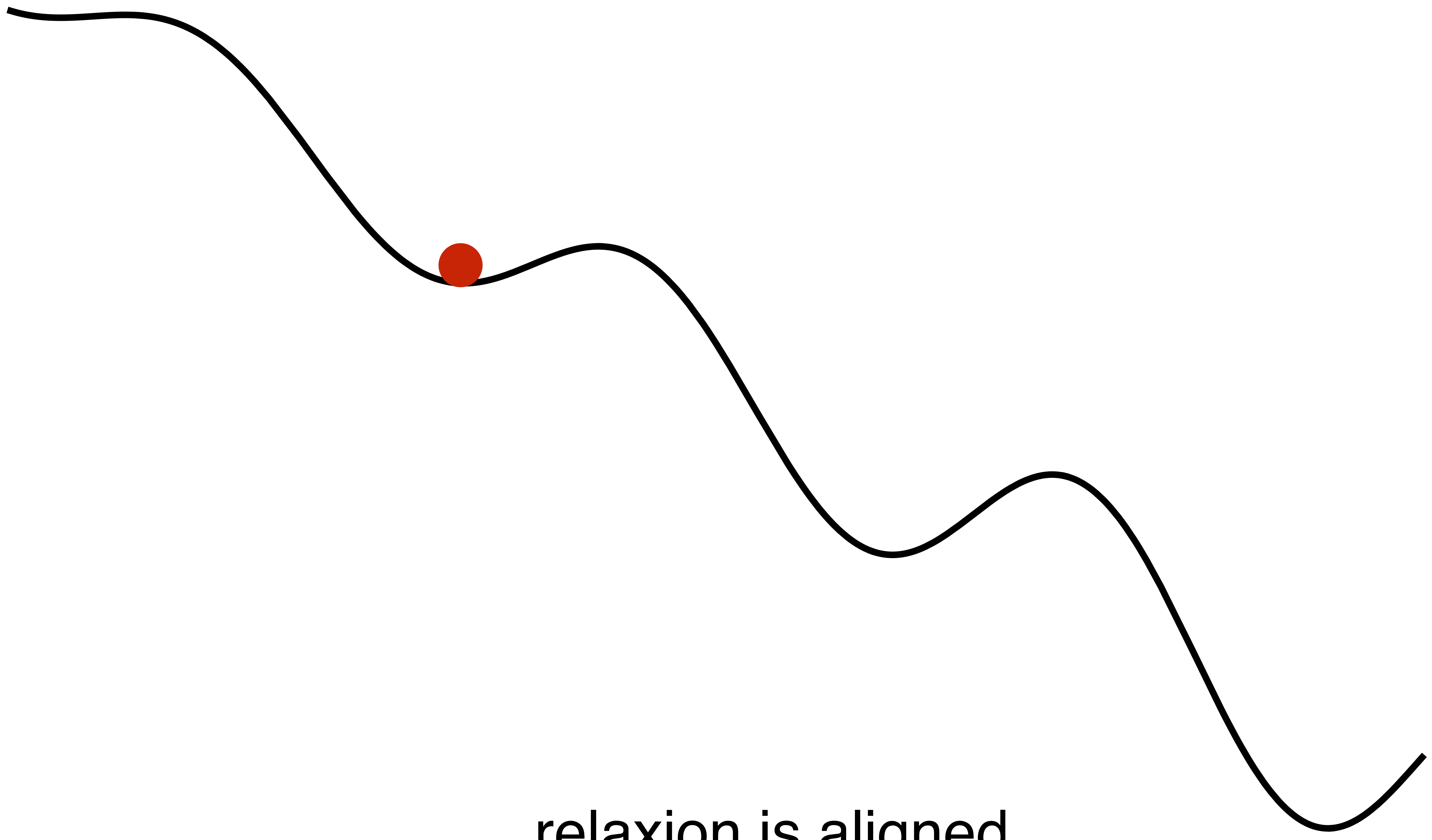


$$H \lesssim m$$

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$$

coherent scalar oscillation constitutes dark matter in the universe after a long period of inflation

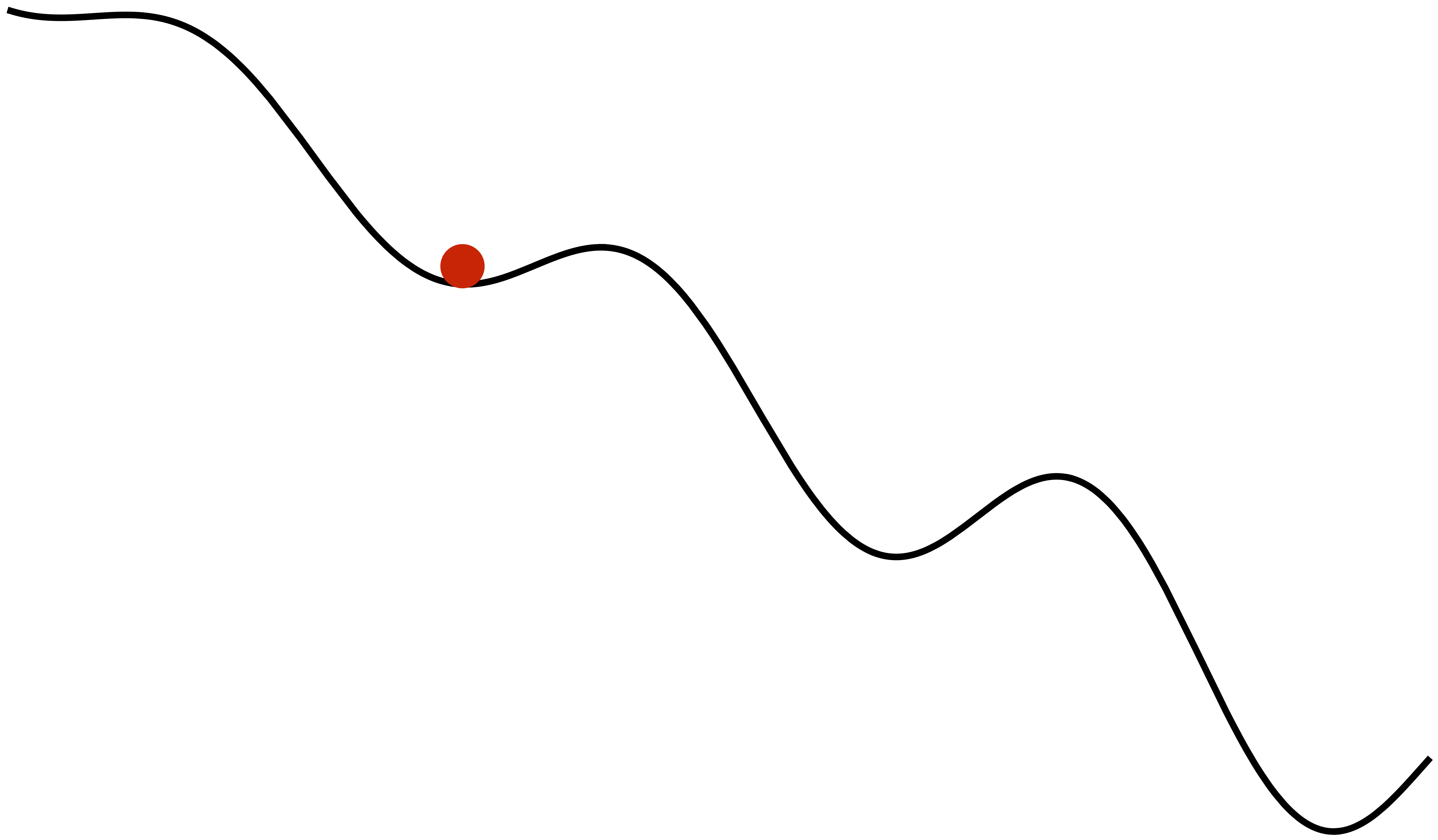
the relaxion is settled down to one of local minima



relaxion is aligned

no misalignment at all

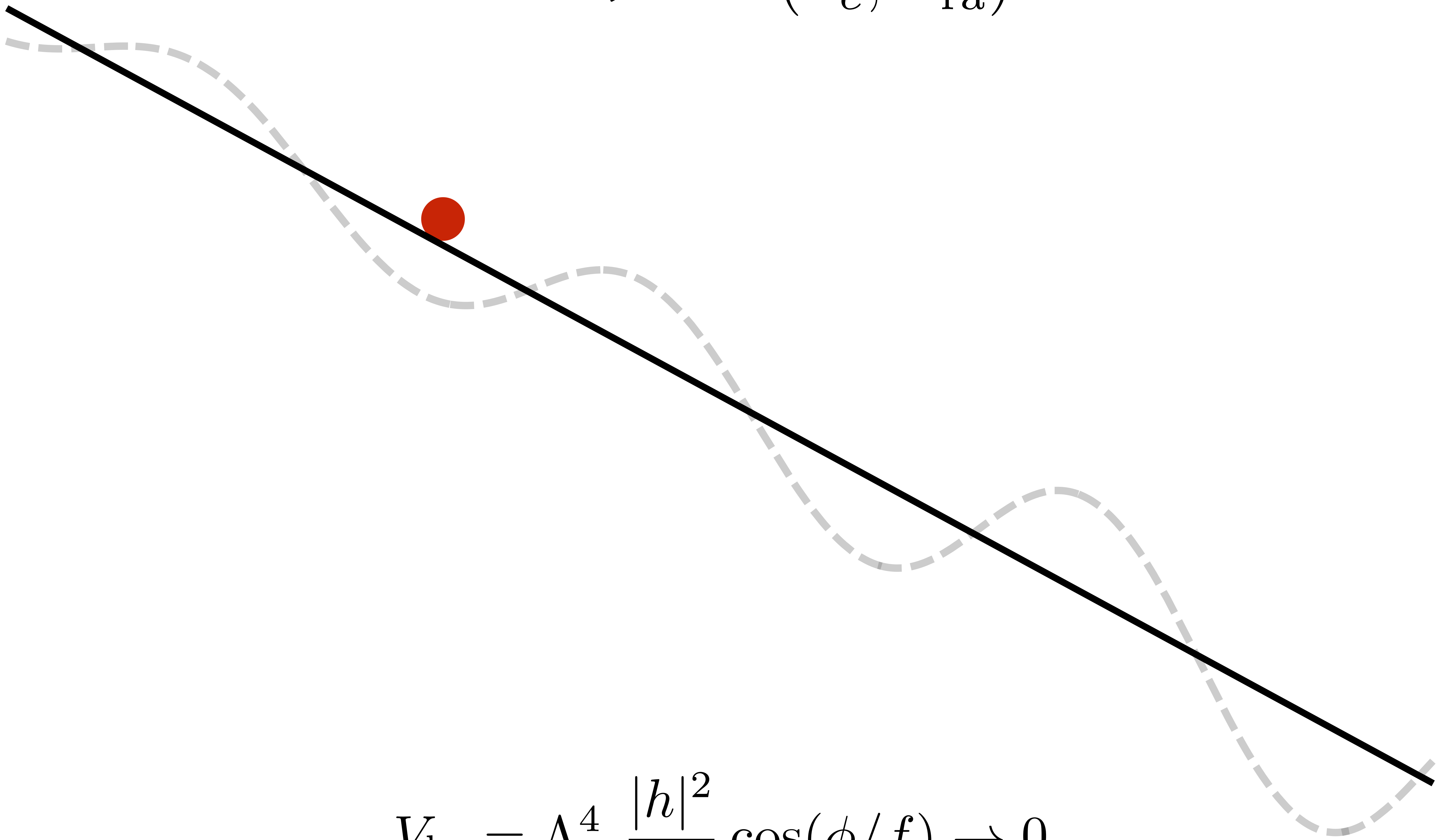
A challenge is to generate non-zero misalignment angle



misalignment angle can be generated

if the reheating temperature is high

$$T > \min(T_c, T_{\rm ra})$$



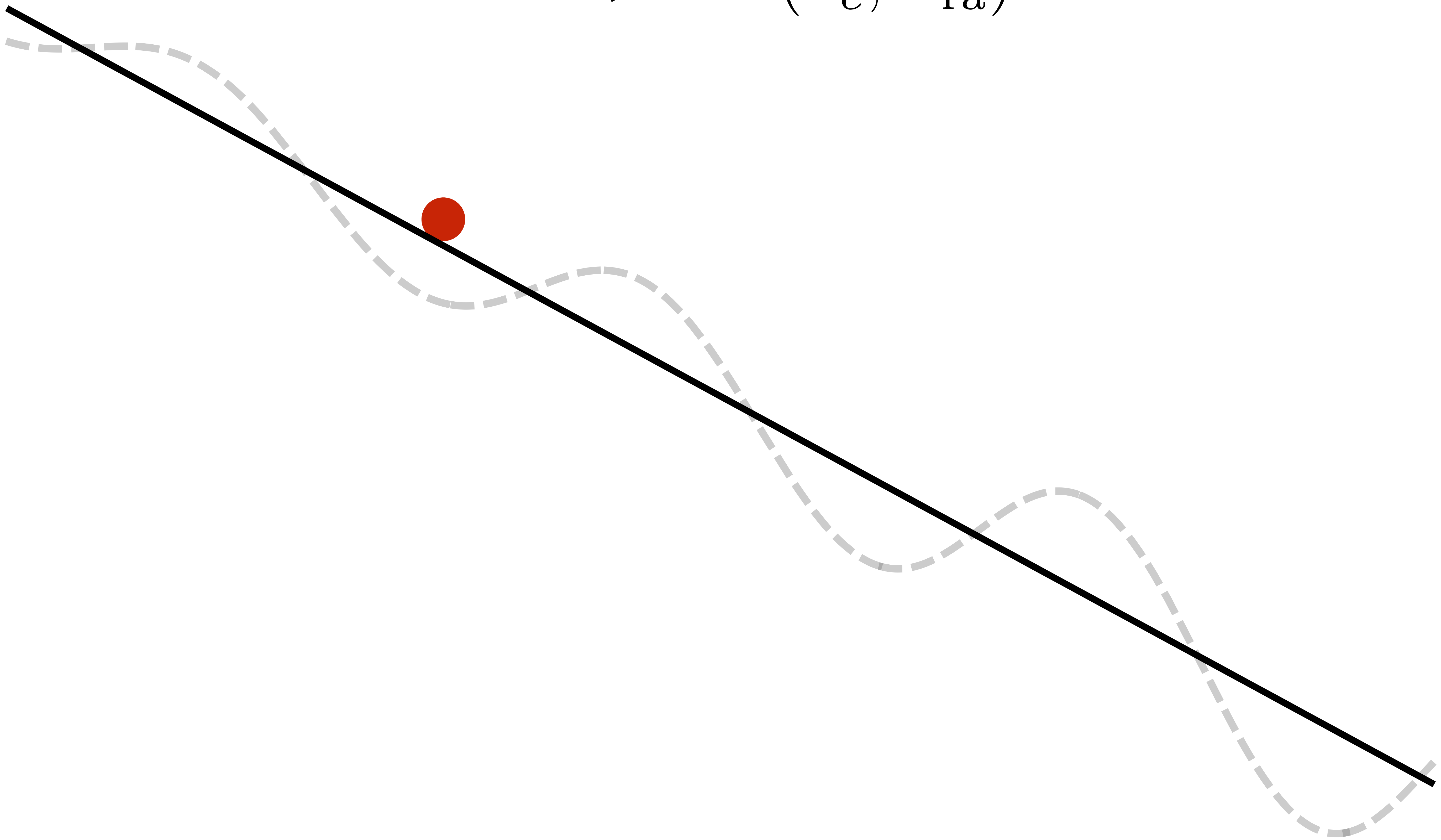
$$V_{\rm br} = \Lambda_{\rm br}^4 \frac{|h|^2}{v^2} \cos(\phi/f) \to 0$$

backreaction potential vanishes

misalignment angle can be generated

if the reheating temperature is high

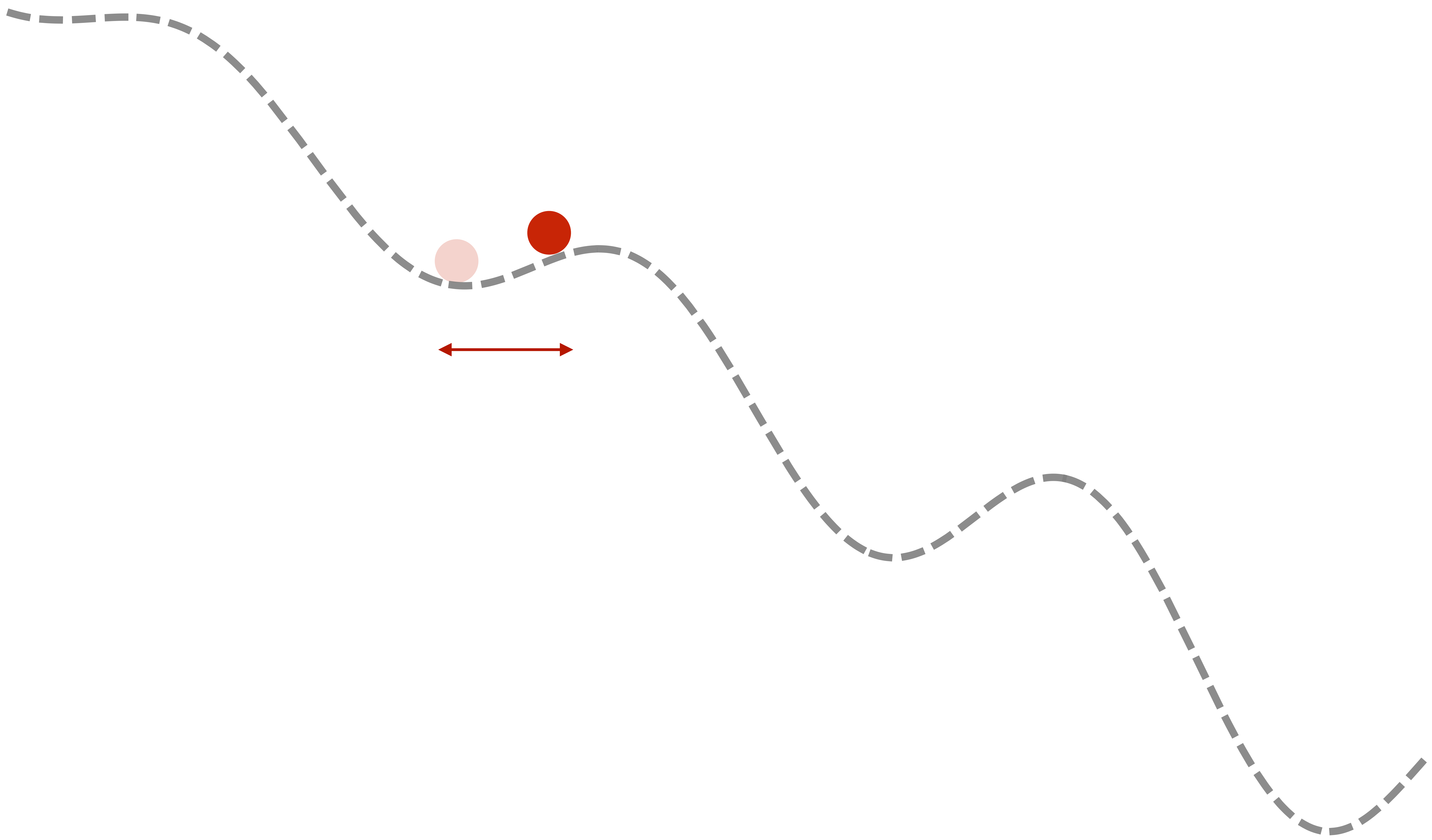
$$T > \min(T_c, T_{\rm ra})$$



relaxion begins to roll again

As temperature drops, the backreaction potential appears again

misalignment is dynamically generated



[Banerjee, HK and Perez 18]

the relaxion DM induces

an oscillation of fundamental constants

$$\mathcal{L} \supset \sin\theta_{h\phi} \frac{\phi}{v} \left[-m_f \bar{f} f + \frac{c_\gamma}{4\pi} FF + \frac{c_g}{4\pi} GG \right]$$

for instance

$$\frac{\Delta m_f}{m_f} \sim \sin\theta_{h\phi} \frac{\phi}{v} \simeq \sin\theta_{h\phi} \frac{\sqrt{\rho_{\rm dm}}}{m_\phi v} \cos(m_\phi t)$$

one way to probe such oscillation is

to use atomic clocks

[Arvanitaki, Huang, Tilburg 14]

[Banerjee, HK, Perez 18]

[Banerjee, HK, Matsedonskyi, Perez and Safronova 20]