Relaxion dark matter, relaxion stars, and table-top experiments
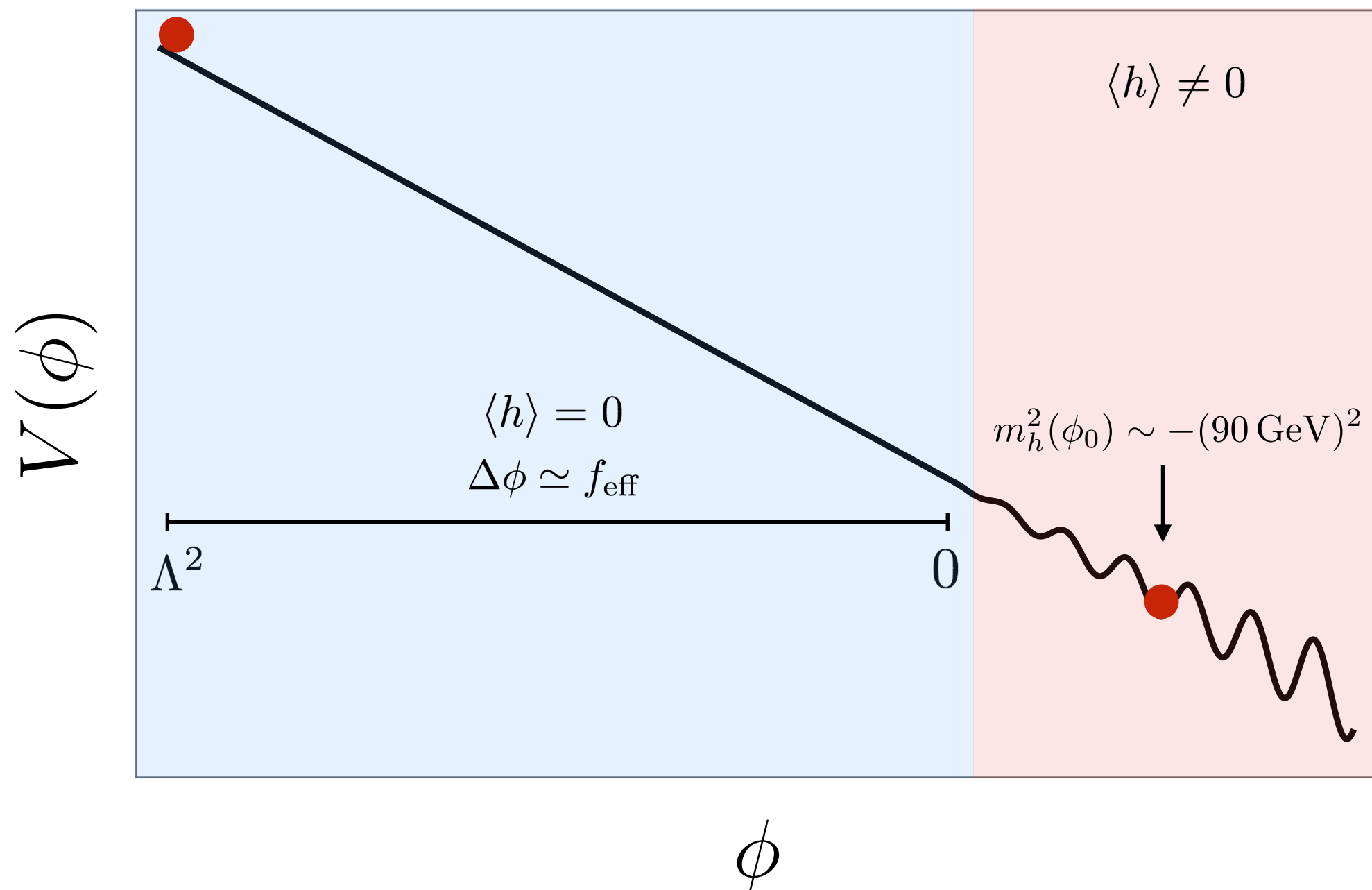
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Dynamical selection of EW scale

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

[Graham, Kaplan, Rajendran 15]

Relaxion can explain a little hierarchy problem

Can relaxion also explain dark matter in the universe?

how to populate them?

thermally
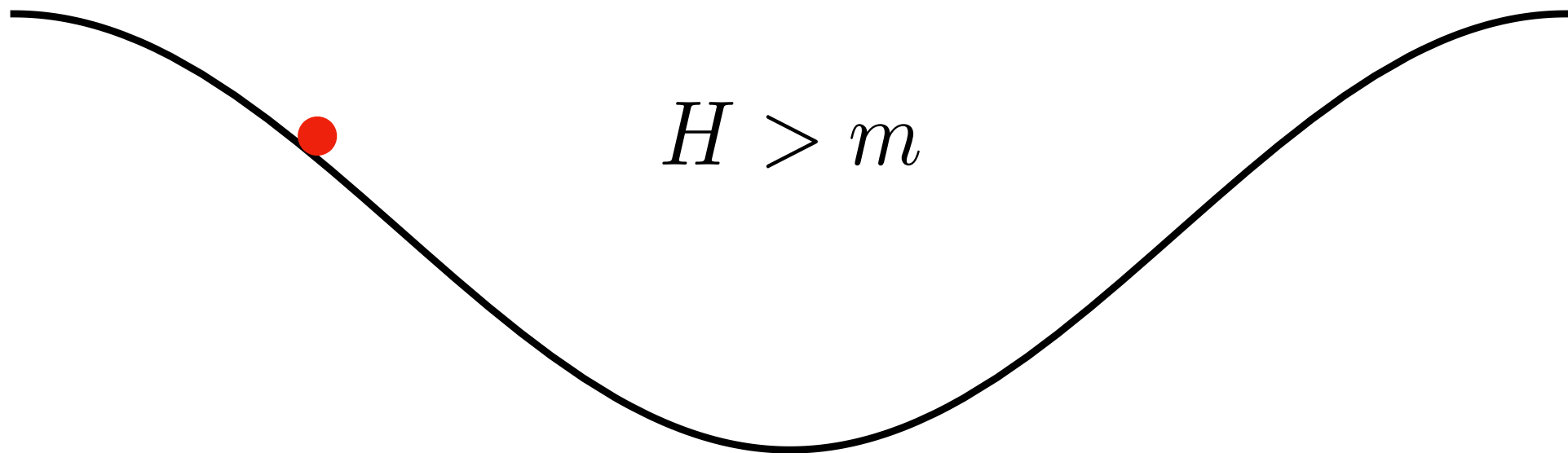
freeze-out

freeze-in   [Fonseca and Morgante 18]

non-thermally

misalignment   [Banerjee, HK and Perez 18]
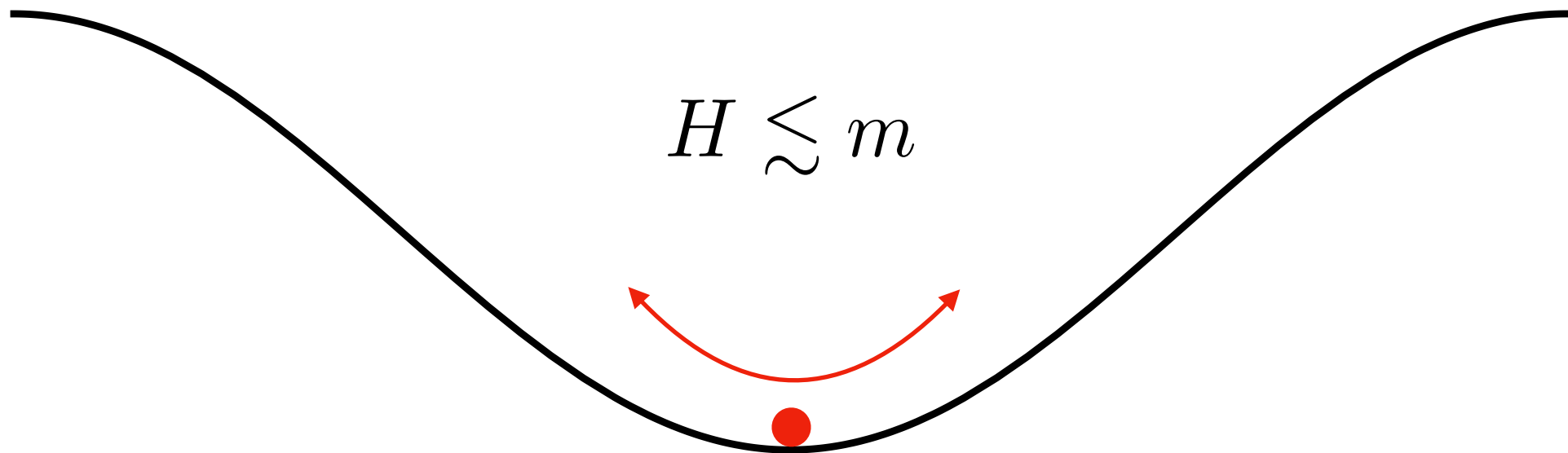
… …

misaligned axion dark matter

$$H > m$$

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

[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

misaligned axion dark matter

initial mis. angle needs to be properly chosen
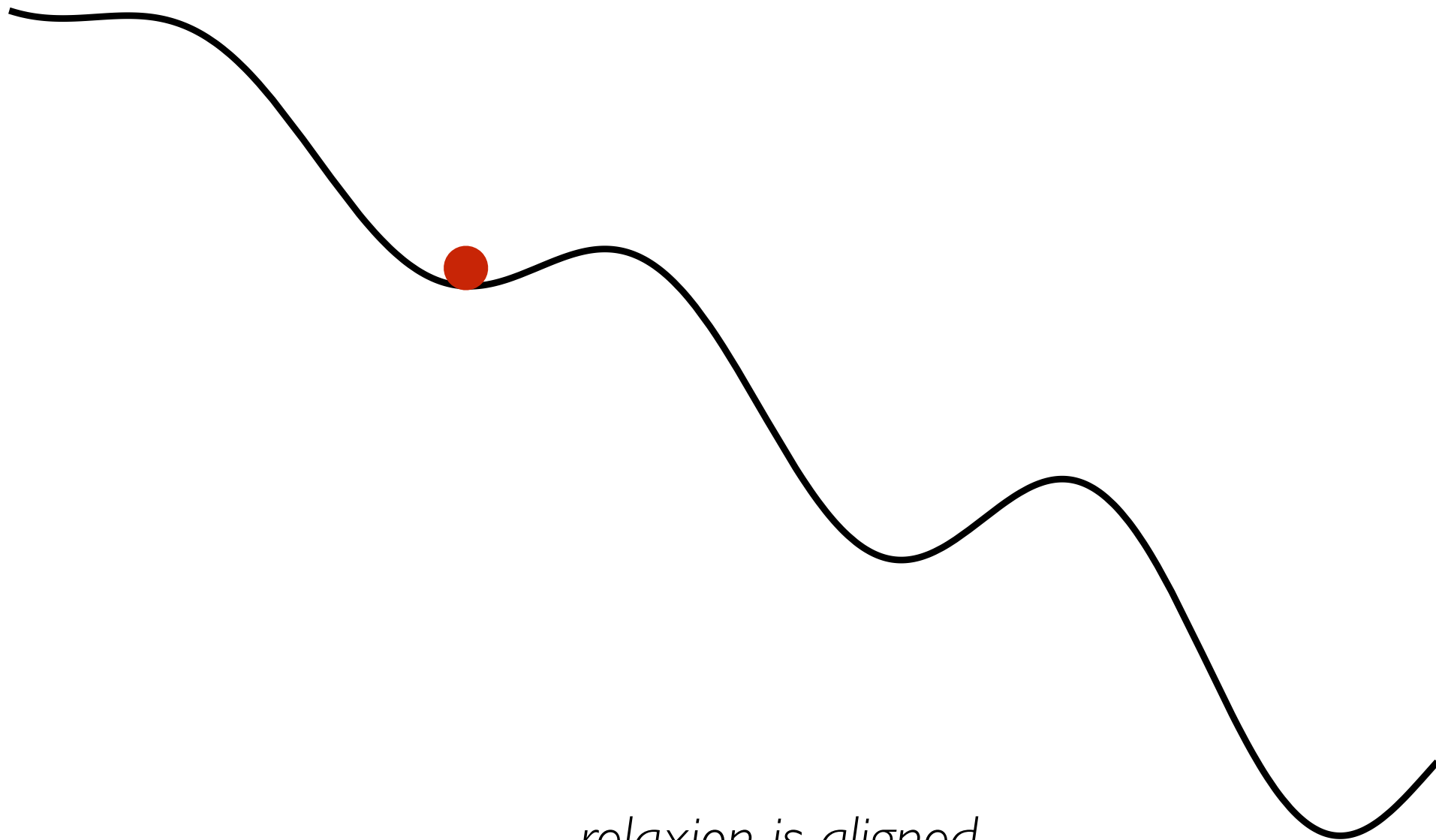*to account observed dark matter relic density*

$$(\Delta\theta)_{\mathrm{ini}} = g(\Omega_{\mathrm{cdm}}, m, f, \cdots)$$

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

coherent scalar oscillation constitutes dark matter in the universe

after a long period of inflation
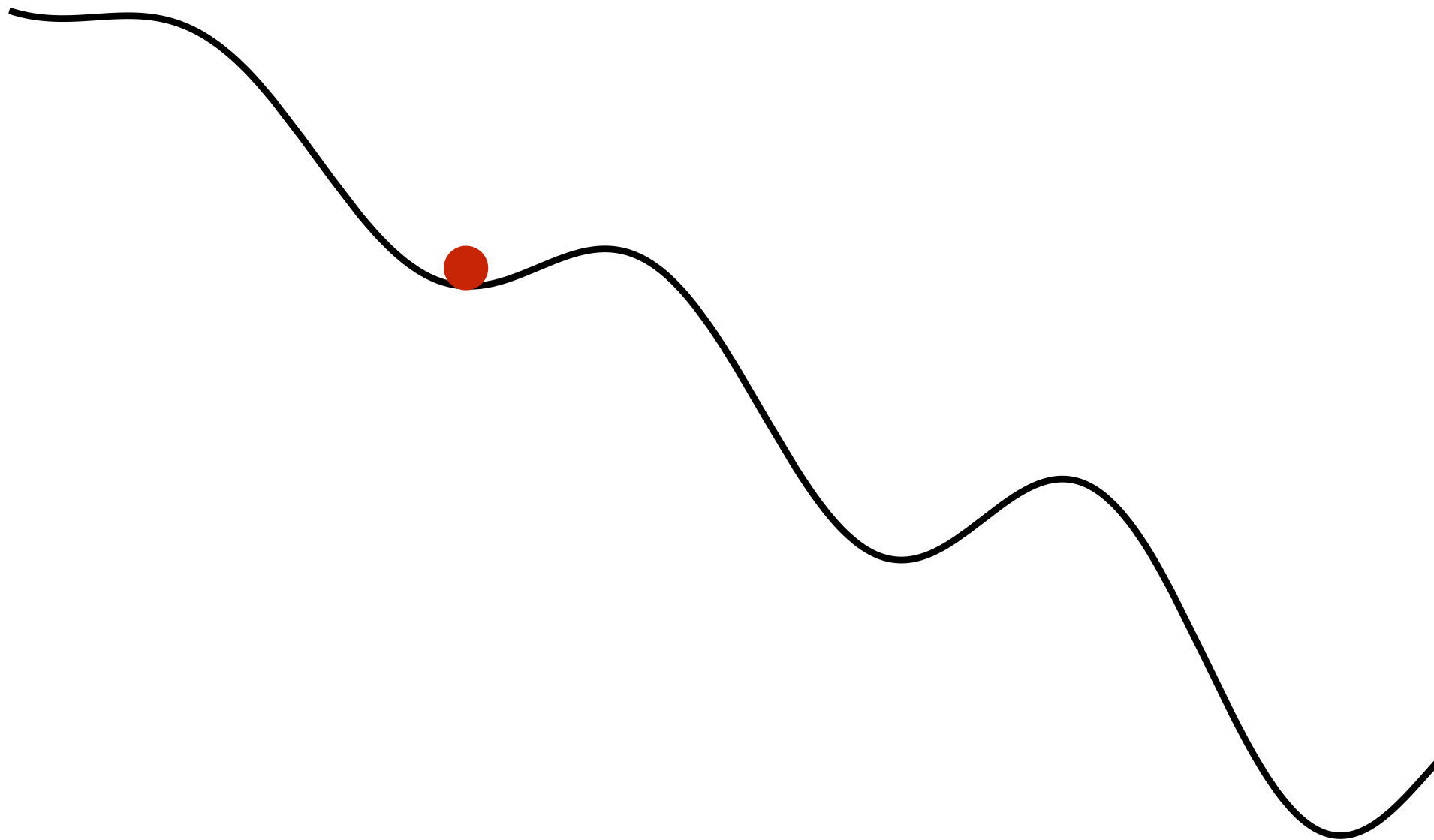
the relaxion is settled down to one of local minima

relaxion is aligned

no misalignment at all
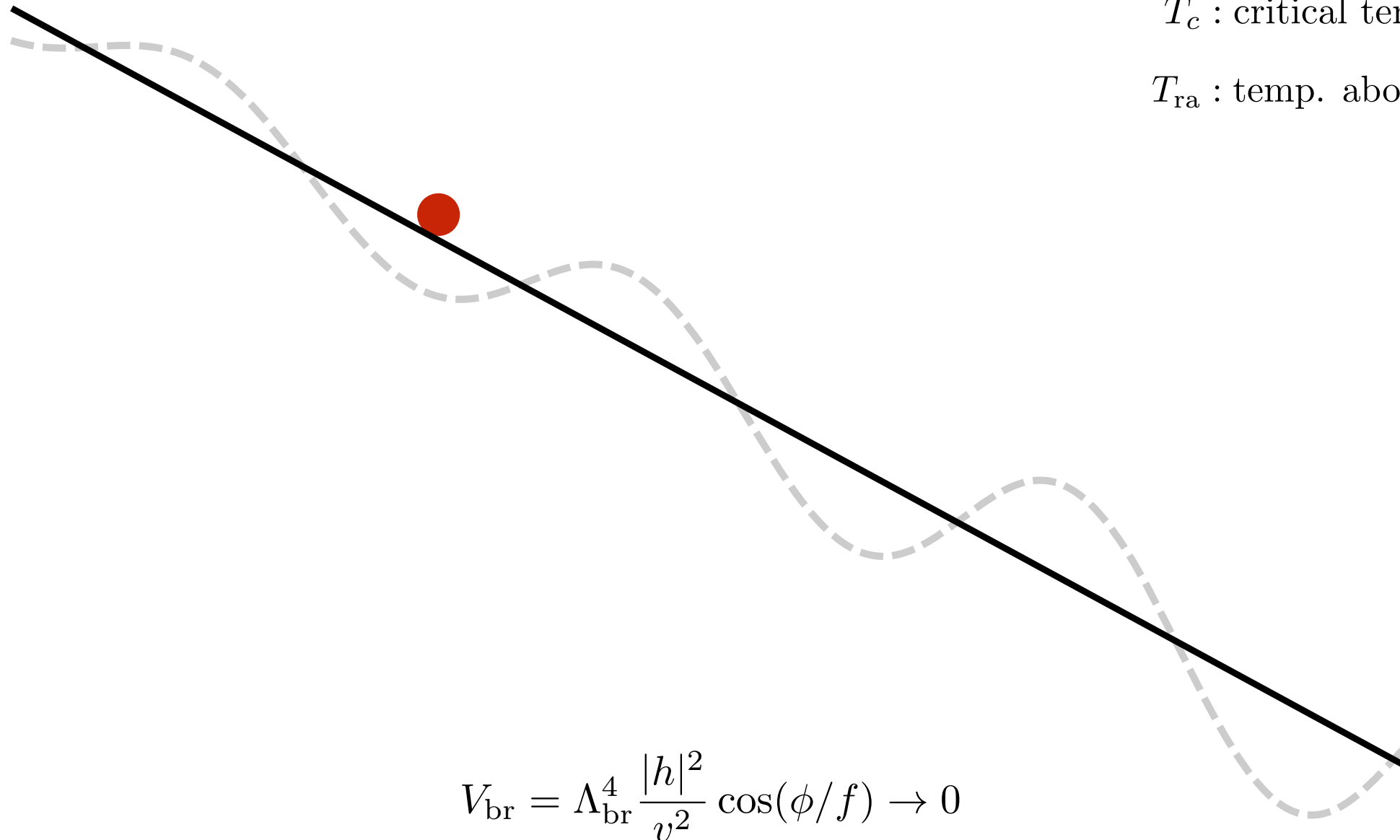
to generate misalignment angle

we need a 'kick'

a kick or a nudge is realized when the universe is reheated with

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

T_c : critical temp. for EWPT

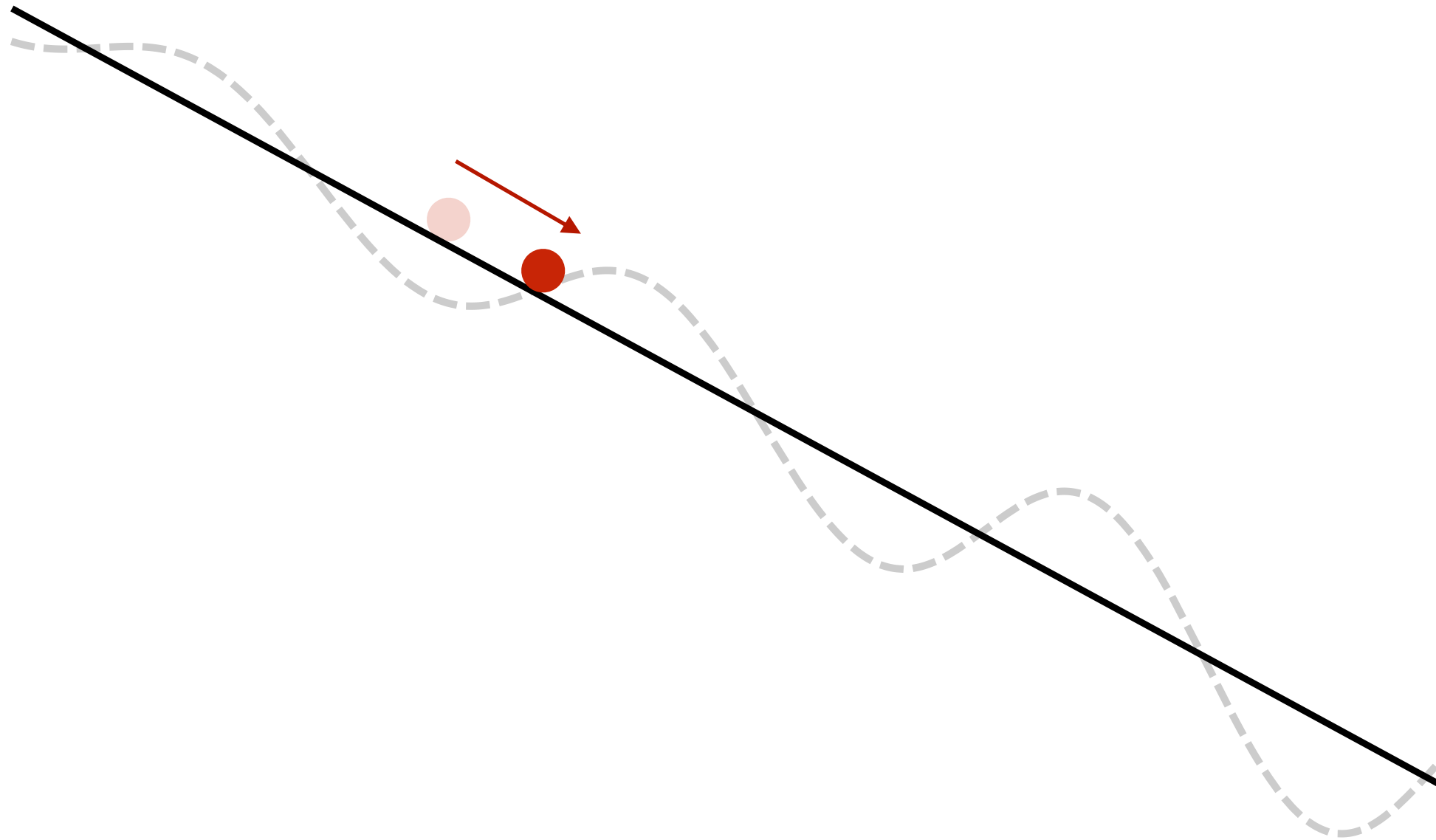T_{ra} : temp. above which $V_{\mathrm{br}} \approx 0$

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

backreaction potential vanishes

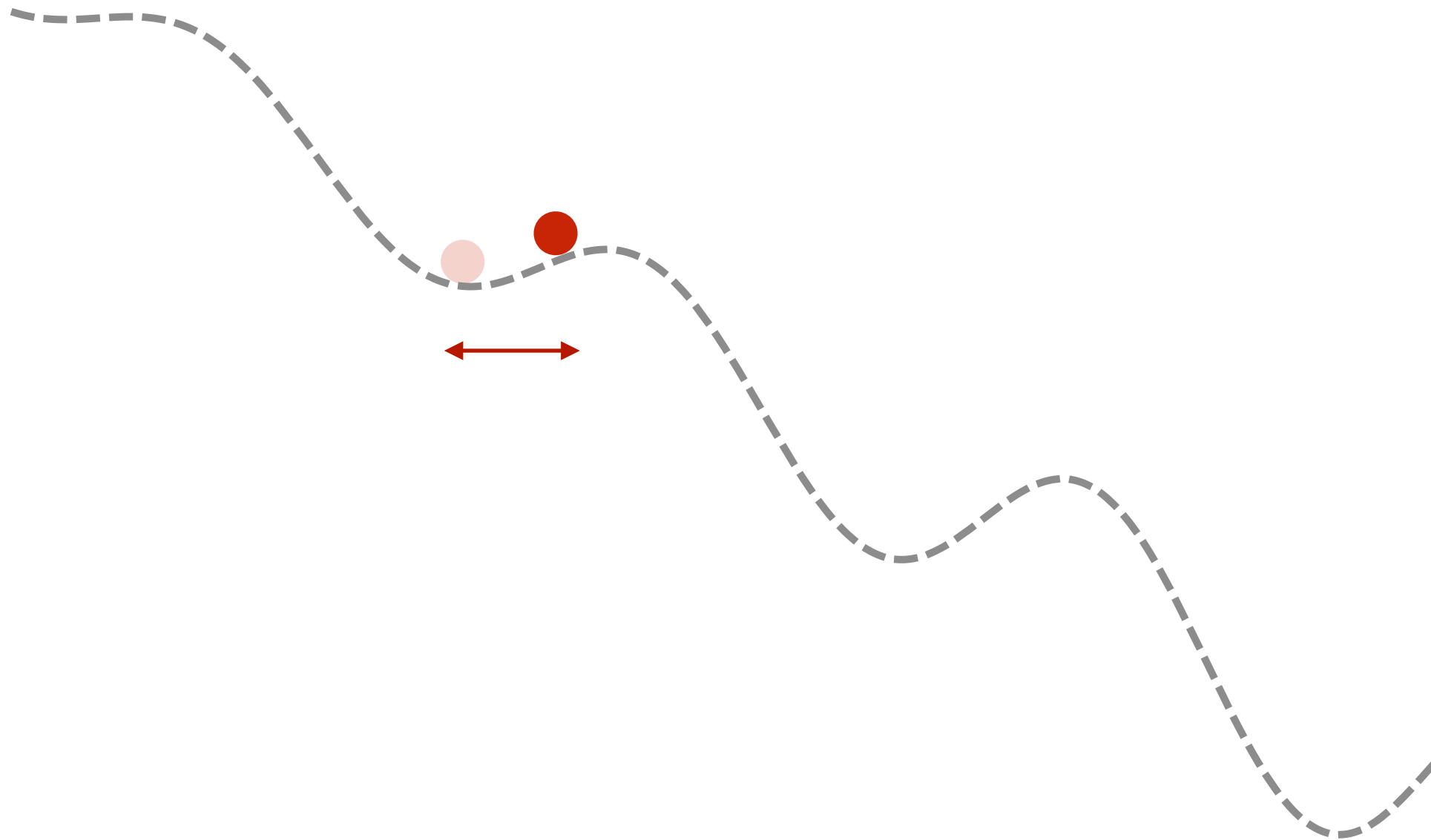*a kick or a nudge is realized when the universe is reheated with*

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

relaxion begins to roll again

continues until

$$T \simeq \min(T_c, T_{\mathrm{ra}})$$

misalignment is dynamically generated

two things should be guaranteed :

(i) EW scale must be preserved

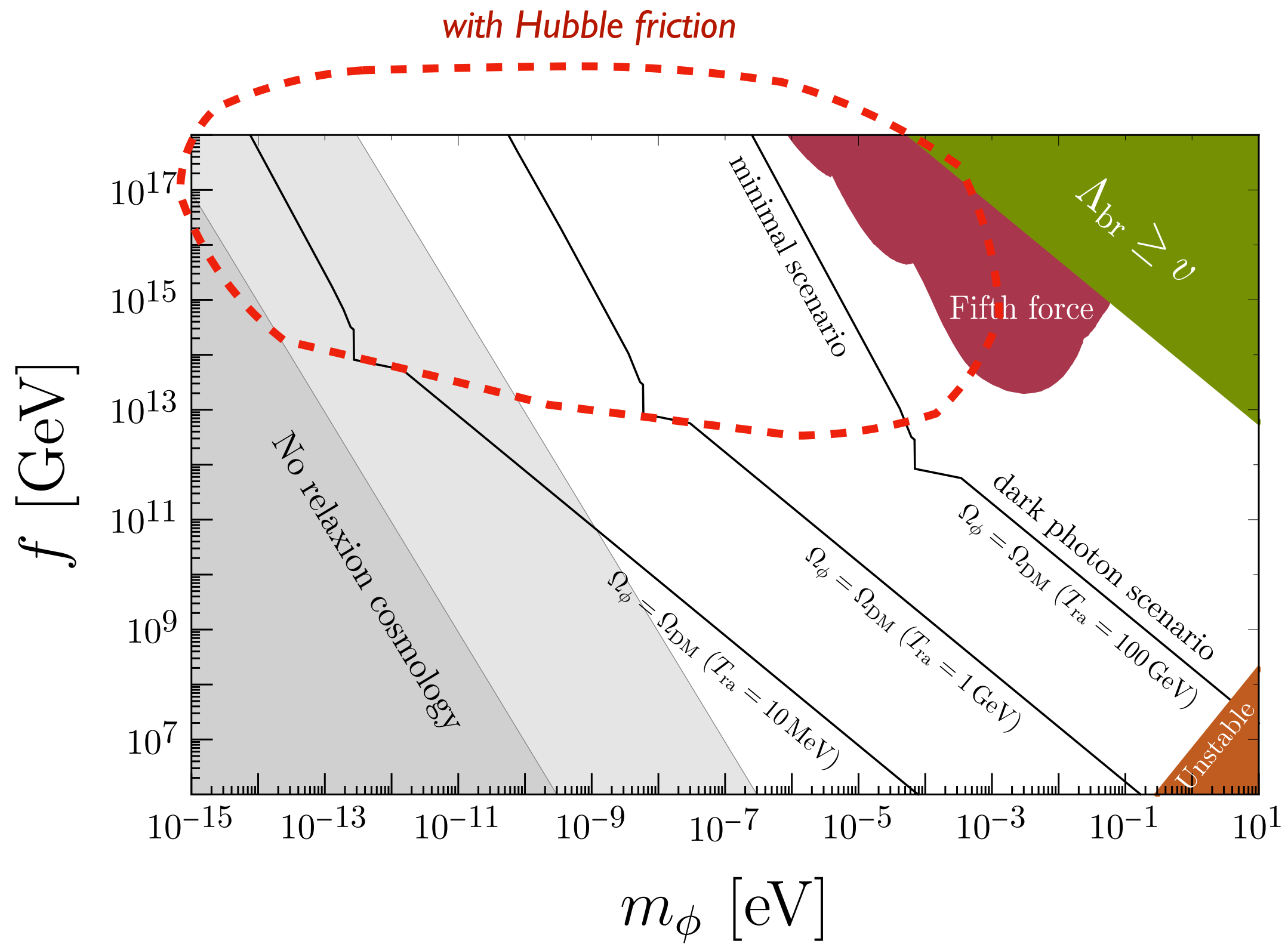*(ii) kinetic energy should be small enough to be trapped*

$$\dot{\phi} \simeq \frac{V'}{H} \lesssim \Lambda_{\mathrm{br}}^2$$

which can be written as … …

$$m_\phi \lesssim H \ \sim 10^{-5}\,\mathrm{eV} \quad @\ T = 100\ GeV$$

For this mass range, the Hubble friction is enough to trap relaxion again

For heavier mass, additional friction is needed (e.g. particle production)

with Hubble friction

f [GeV]

m_ϕ [eV]

$\Lambda_{\rm br} \gtrsim v$

Fifth force

minimal scenario

No relaxion cosmology

$\Omega_\phi = \Omega_{\rm DM}$ ($T_{\rm ra} = 10\,{\rm MeV}$)

$\Omega_\phi = \Omega_{\rm DM}$ ($T_{\rm ra} = 1\,{\rm GeV}$)

$\Omega_\phi = \Omega_{\rm DM}$ ($T_{\rm ra} = 100\,{\rm GeV}$)

dark photon scenario

Unstable

[Banerjee, HK and Perez 18]

f [GeV]

m_ϕ [eV]

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No relaxion cosmology

Unstable

with particle production

[Banerjee, HK and Perez 18]
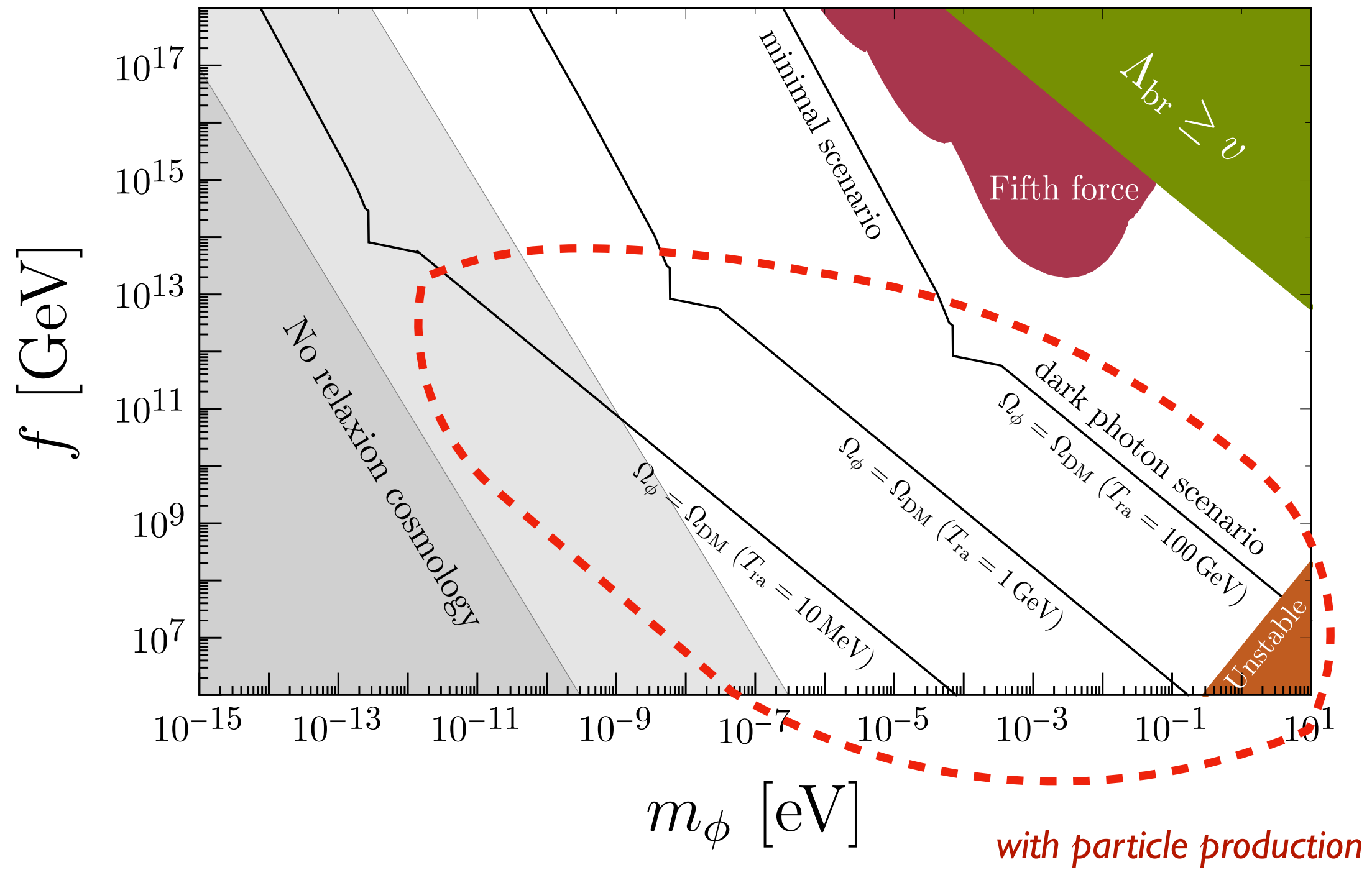
we see the same field can be responsible for

(i) scanning EW scale

(ii) dark matter in the universe

then how can we find them?

observe relaxion mixes with Higgs

this leads to

$$-\mathcal{L} \supset \phi \sin\theta \left(\frac{m_f}{v} \bar{f} f + \frac{\alpha}{4\pi v} FF + \cdots \right)$$

$$\equiv g_e \phi \bar{f} f + \frac{g_\gamma}{4} \phi FF + \cdots$$

if relaxion is dark matter in the universe

we are sitting on the coherently oscillating relaxion condensate

$$\phi = \frac{\sqrt{\rho}}{m} \cos(mt)$$

leading to oscillating fundamental constants

$$\frac{\delta m_e}{m_e} = \frac{g_e \phi}{m_e} \qquad\qquad \frac{\delta\alpha}{\alpha} = g_\gamma \phi$$

these effects are tiny, and only measurable for small scalar mass

$$\frac{\delta m_e}{m_e} = g_e \frac{\phi}{m_e} = g_e \frac{\sqrt{\rho_\phi}/m_\phi}{m_e} \sim 10^6 g_e \times \left(\frac{10^{-15}\,\text{eV}}{m_\phi} \right)$$

a coupling to electron is already constrained by EP-violation tests

$$g_e \lesssim 10^{-24}$$

electron mass is oscillating with the amplitude
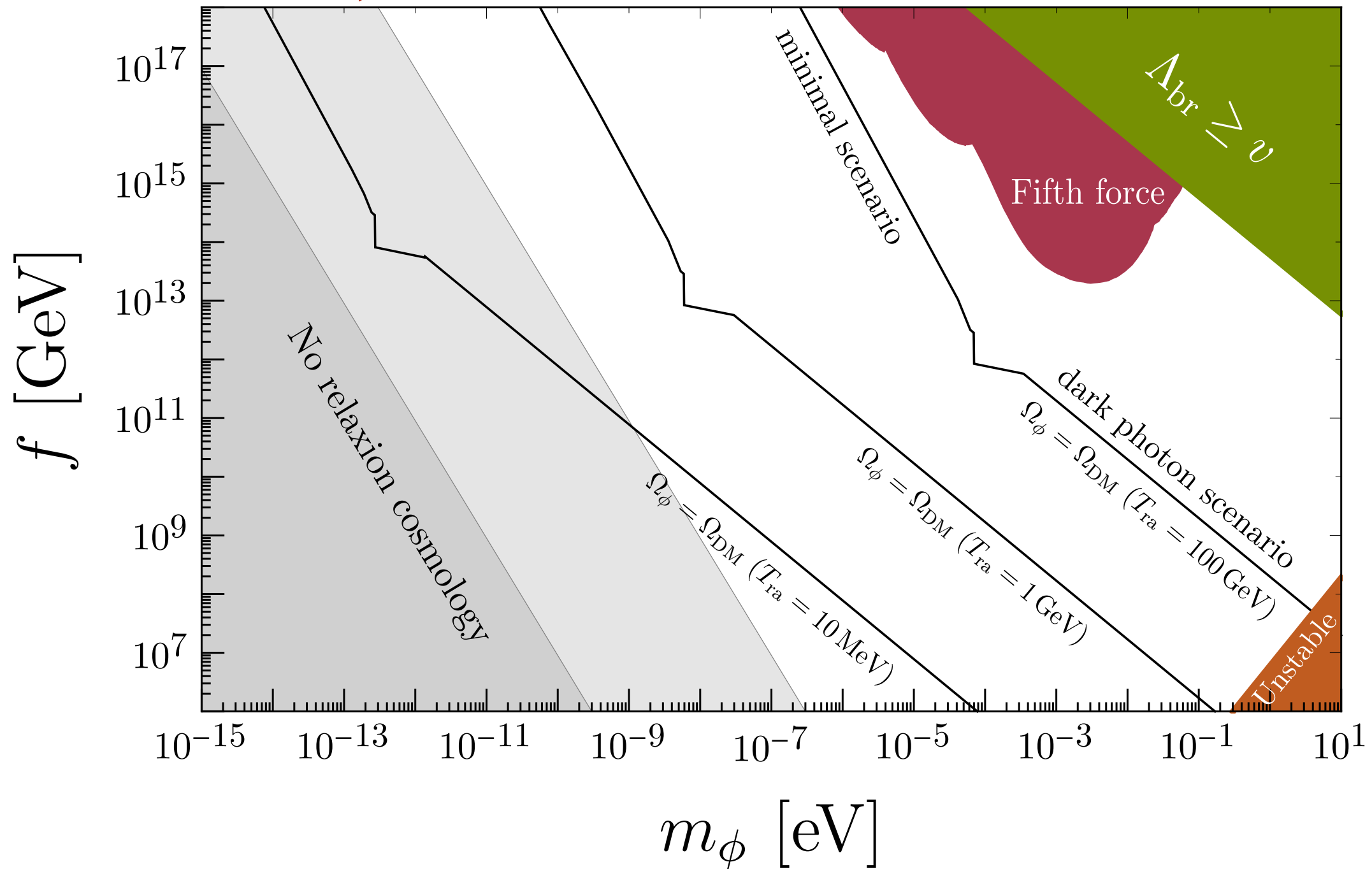
$$\frac{\delta m_e}{m_e} \simeq 10^{-18}$$

state-of-art atomic clocks, atomic interferometry …

have a chance to probe unexplored regime of parameter space

[Arvanitaki et al 15] [Graham et al 15] [For a review, Safronova et al 17]

We are interested in more heavier mass range

$$m_\phi \gtrsim 10^{-15}\,\mathrm{eV} \sim 1\,\mathrm{Hz}$$

1 Hz

We are interested in more heavier mass range

$$m_\phi \gtrsim 10^{-15}\,\mathrm{eV} \sim 1\,\mathrm{Hz}$$

$$\phi = \frac{\sqrt{\rho}}{m}\cos(mt)$$

oscillation frequency is higher

field amplitude/coherence time is smaller

to find them

(i) experiments should be sensitive to such oscillation frequencies

(ii) sensitivity should be enough to compensate decreases in field amplitude

this will be very challenging only with background DM … …

what if relaxion DM form gravitationally bounded compact object?

we consider **relaxion stars** *with* **larger density** *relative to background DM*

[Banerjee, Budker, Eby, HK and Perez 19]

it is a classical solution of the system of gravity+scalar field

$$S = \int d^4x \sqrt{-g} \left(\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - \frac{1}{2} m^2 \phi^2 \right)$$
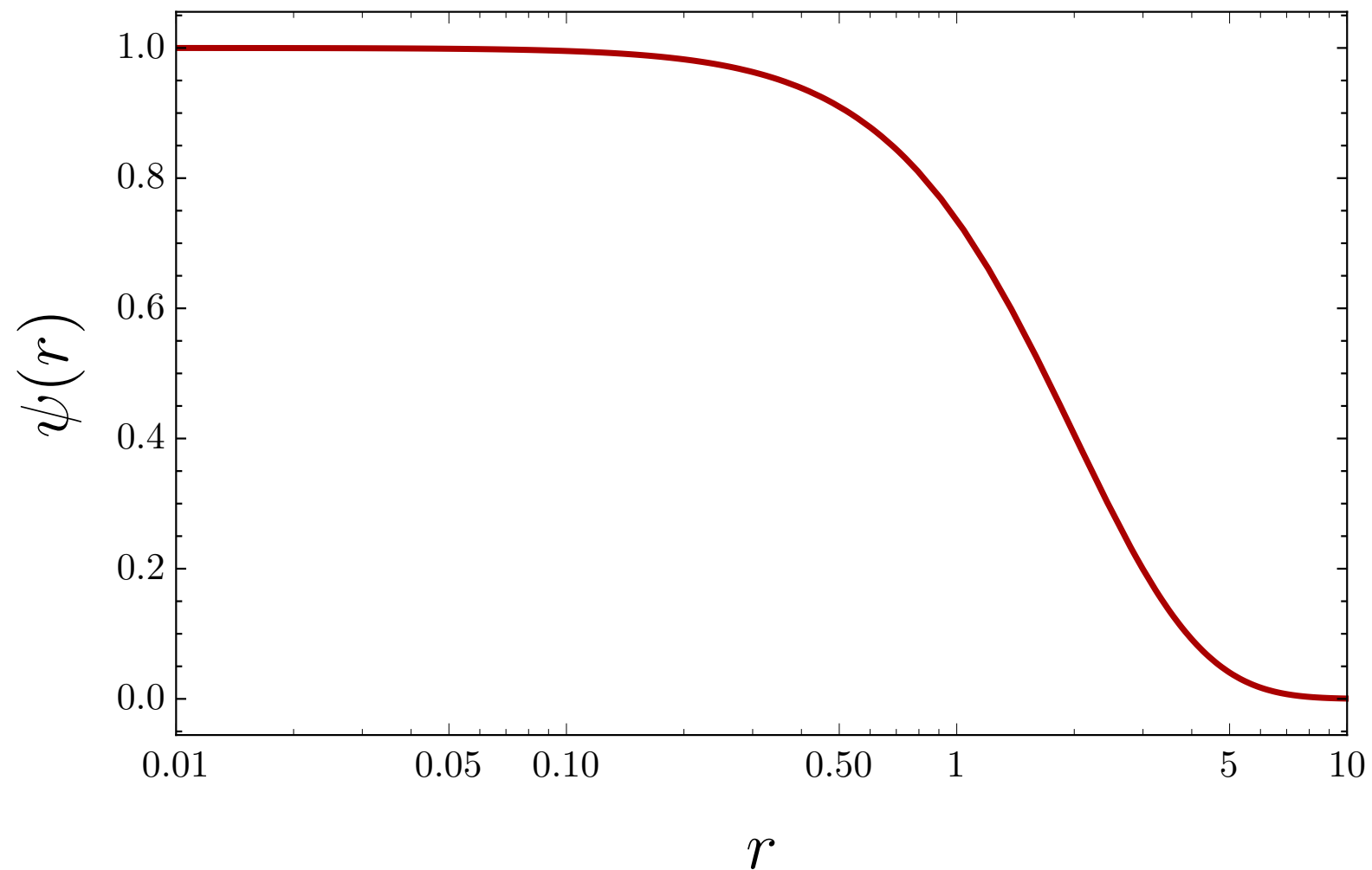
the equation of motion in nonrel. limit is

$$i\dot{\psi} = \left[-\frac{\nabla^2}{2m} + V_{\mathrm{grav}} \right] \psi$$

where

$$\phi = \frac{1}{\sqrt{2m}} (\psi e^{-imt} + \mathrm{h.c.})$$

$$V_{\mathrm{grav}} = -Gm^2 \int d^3r' \frac{|\psi|^2}{|\vec{r} - \vec{r}'|^2}$$

*one find a classical solution: **relaxion stars***

has a unique mass-radius relation

$$R_\star = \frac{M_P^2}{m^2 M_\star}$$

[Chavanis 11]

[Eby et al 18]

now the density of relaxion star could be much higher than the background DM

$$\delta \equiv \frac{\rho_\star}{\rho_{\text{local}}} \sim \frac{M_\star/R_\star^3}{\rho_{\text{local}}} \sim 10^{22} \times \left(\frac{10^{-10}\,\text{eV}}{m}\right)^2 \left(\frac{10^5\,\text{km}}{R_\star}\right)^4$$

Recall that

$$\left(\frac{\delta m_e}{m_e}, \frac{\delta \alpha}{\alpha}\right) \propto \phi = \frac{\sqrt{\rho}}{m} = \sqrt{\delta}\phi_{\text{local}}$$
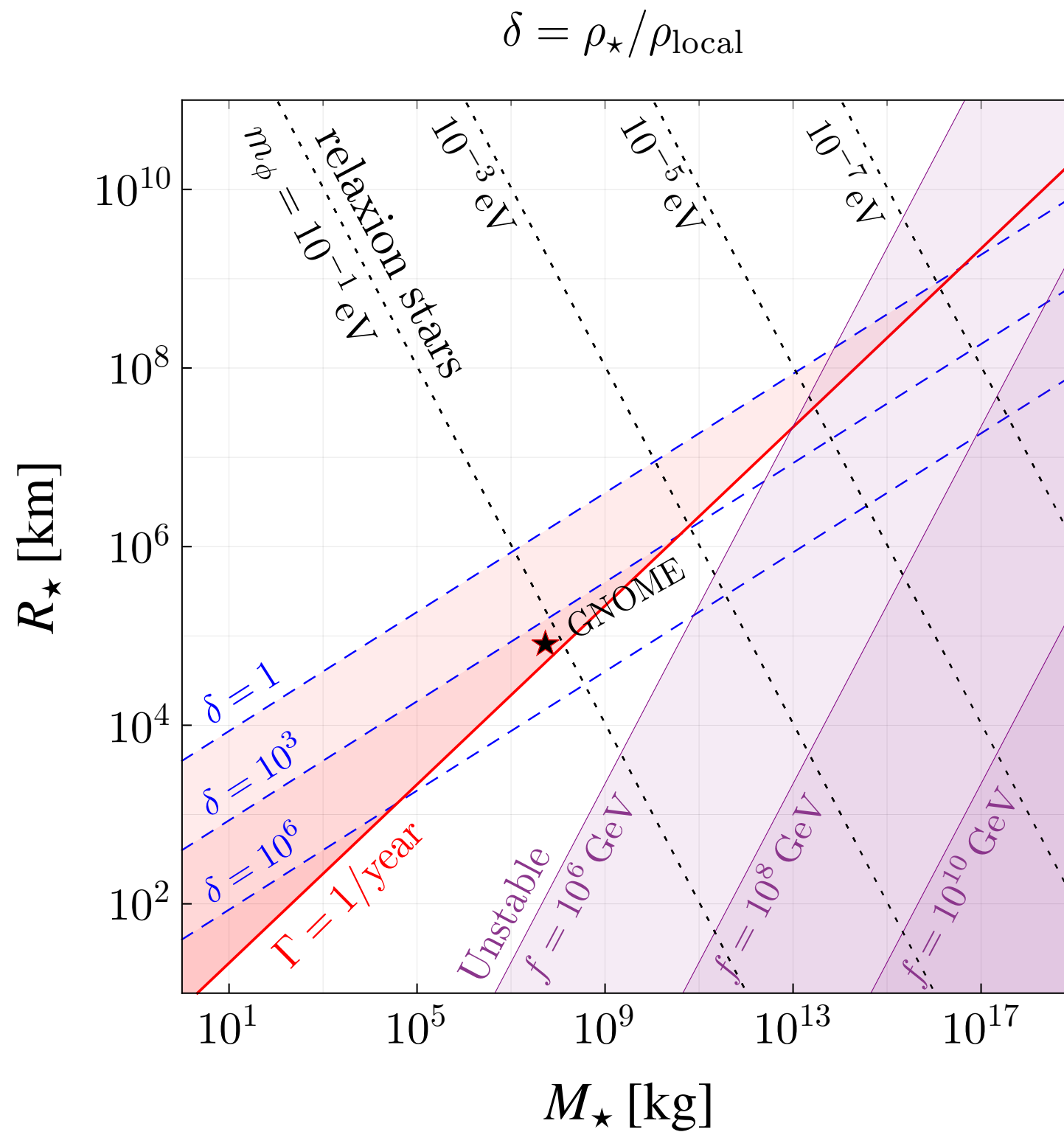
this leads to gigantic enhancement in signal

but unfortunately … …

$$\Gamma = \frac{\rho_{\text{local}}}{M_\star}\sigma_\star v_\star \simeq 10^{-18}\,\text{yr}^{-1} \left(\frac{m_\phi}{10^{-10}\,\text{eV}}\right)^2 \left(\frac{R_\star}{10^5\,\text{km}}\right)^3$$

for this choice of parameters

not even a single event in the entire history of the universe happens

[Banerjee, Budker, Eby, HK and Perez 19]

$\delta = \rho_\star / \rho_{\rm local}$

[Banerjee, Budker, Eby, HK and Perez 19]

moderately large density contrast and reasonable collision rate can be achieved

for relatively heavy relaxion mass

a more exotic scenario:

relaxion stars captured by Earth or Sun

equation of motion is

$$i\dot{\psi} = \left[-\frac{\nabla^2}{2m} + V_{\text{grav}} + \boxed{V_{\text{ext}}} \right] \psi$$

everything is the same except that it is now gravitationally bounded

by the potential of external gravitating body

mass-radius relation changes as
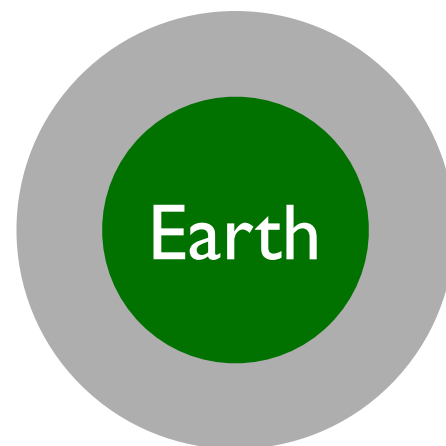
$$R_{\star} = \frac{M_P^2}{m^2 M_{\text{ext}}}$$

[Banerjee, Budker, Eby, HK and Perez 19]

radius must be large enough

such that we should be surrounded by this relaxion halo …

$$R_\star = \frac{M_P^2}{m^2 M_{\text{ext}}}$$

when bounded by the Earth

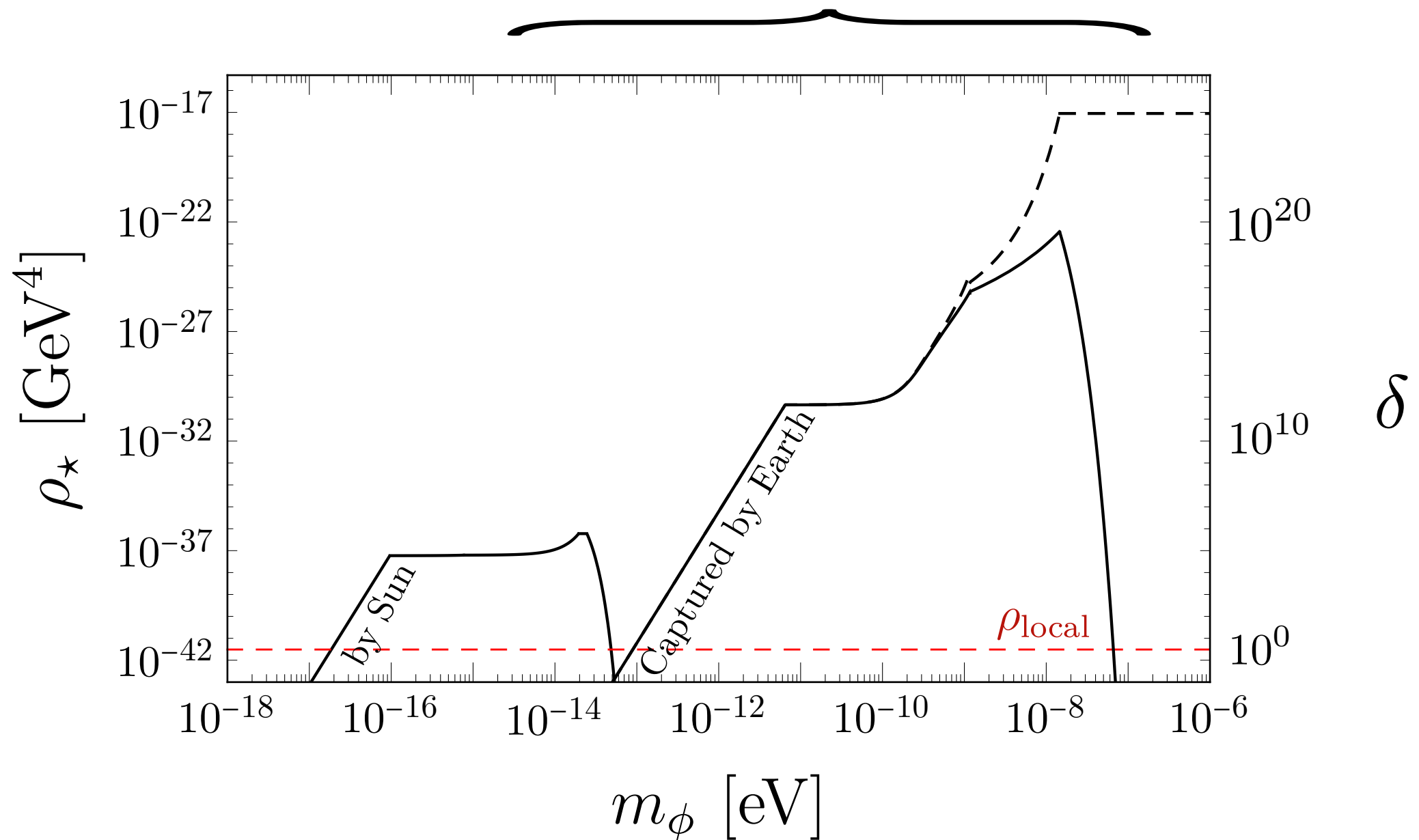$$R_\star \gtrsim R_\oplus$$

$$m \sim 10^{-9} \text{ eV}$$

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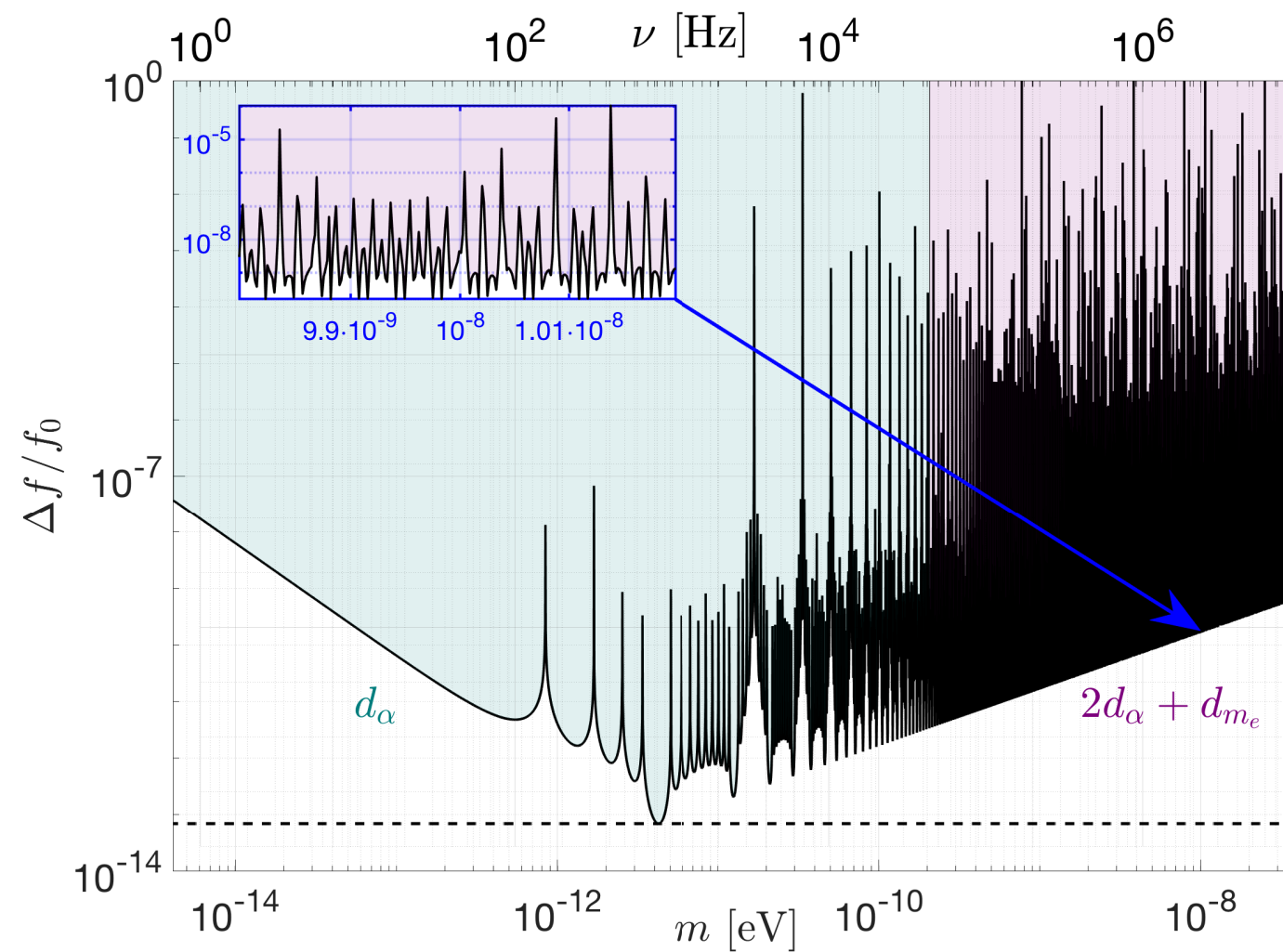*when bounded by the Sun*

$$R_\star \gtrsim 1\,\text{AU}$$

$$m \sim 10^{-14}\,\text{eV}$$

what exps are sensitive to this frequency of oscillations?

Hz - MHz freq.

with dynamic decoupling

[Shaniv and Ozeri 17]
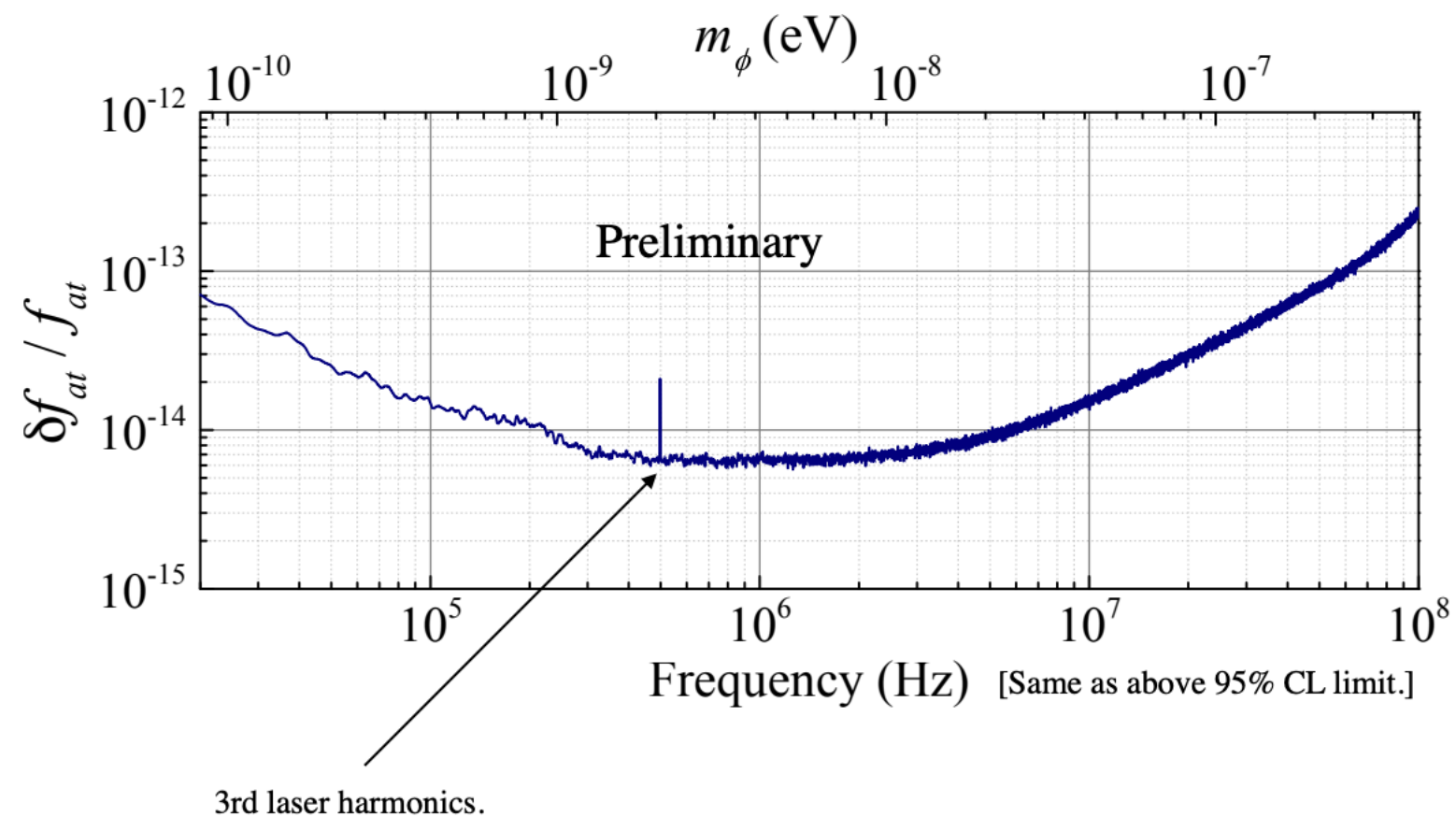
[Aharony, Akerman, Ozeri, Perez and Savoray 19]

with atomic spectroscopy

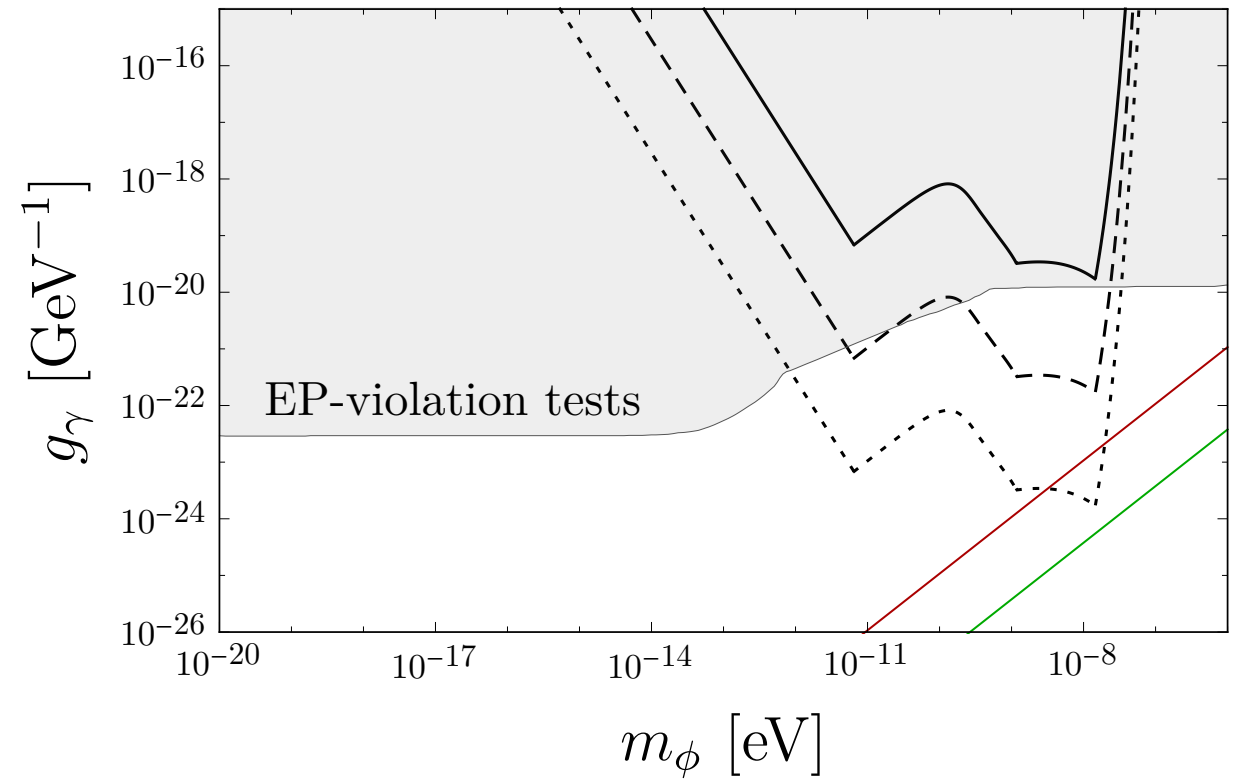*(preliminary)*

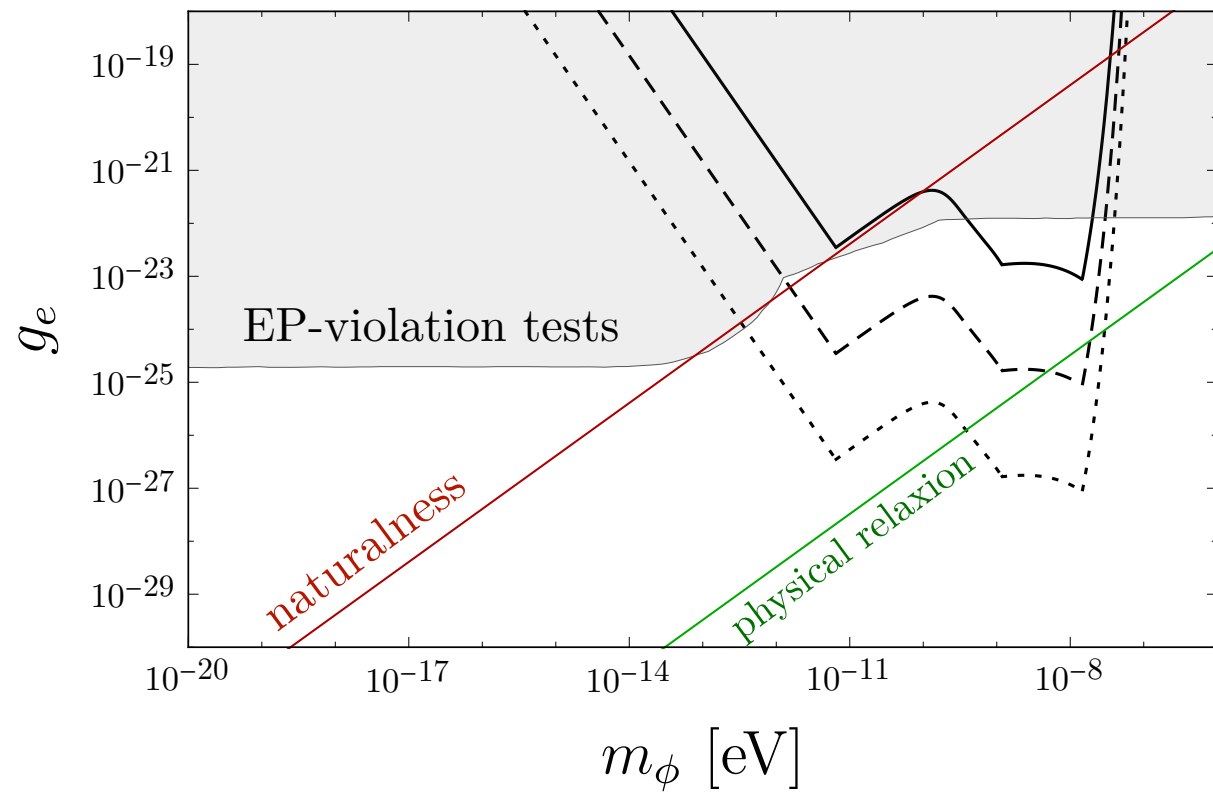# Beyond 1Hz DM mass \w polarization spectroscopy

Antypas, Tretiak, Garcon, Ozeri, GP & Budker, to appear
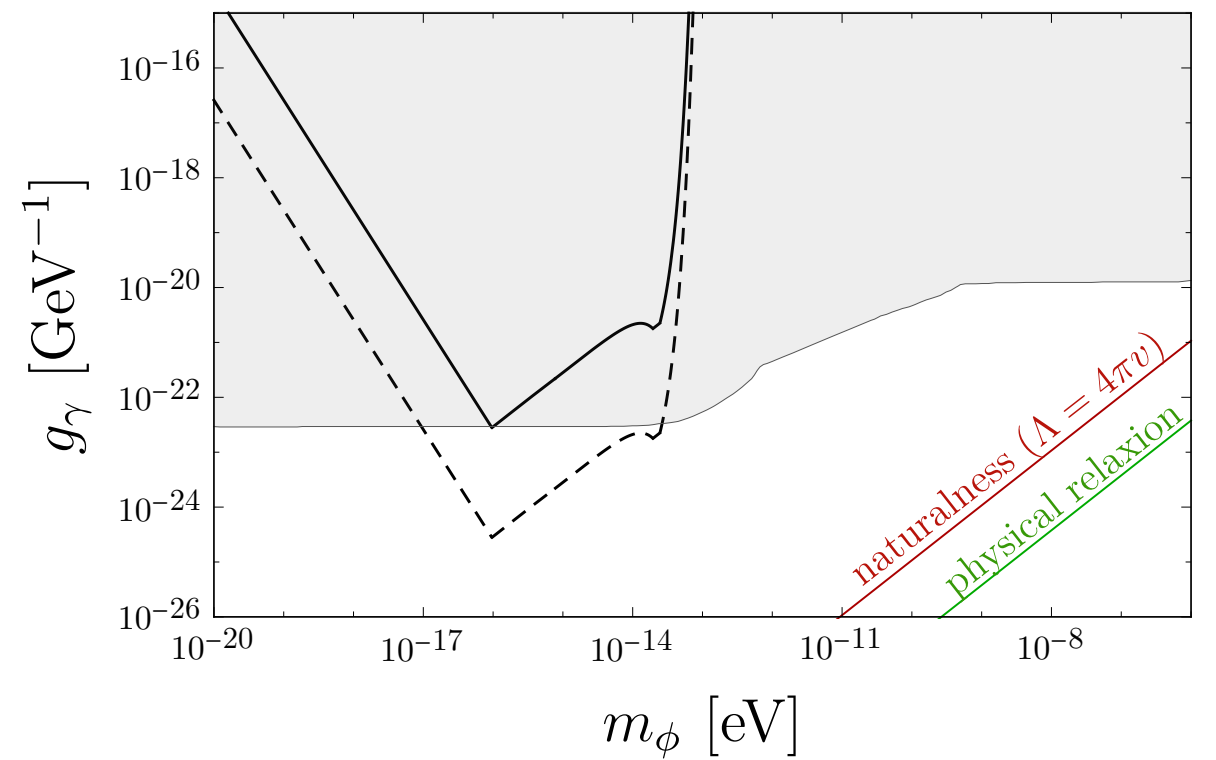
Cs $6S_{1/2} \to 6P_{3/2}$ transition frequency (10 GHz)

3rd laser harmonics.
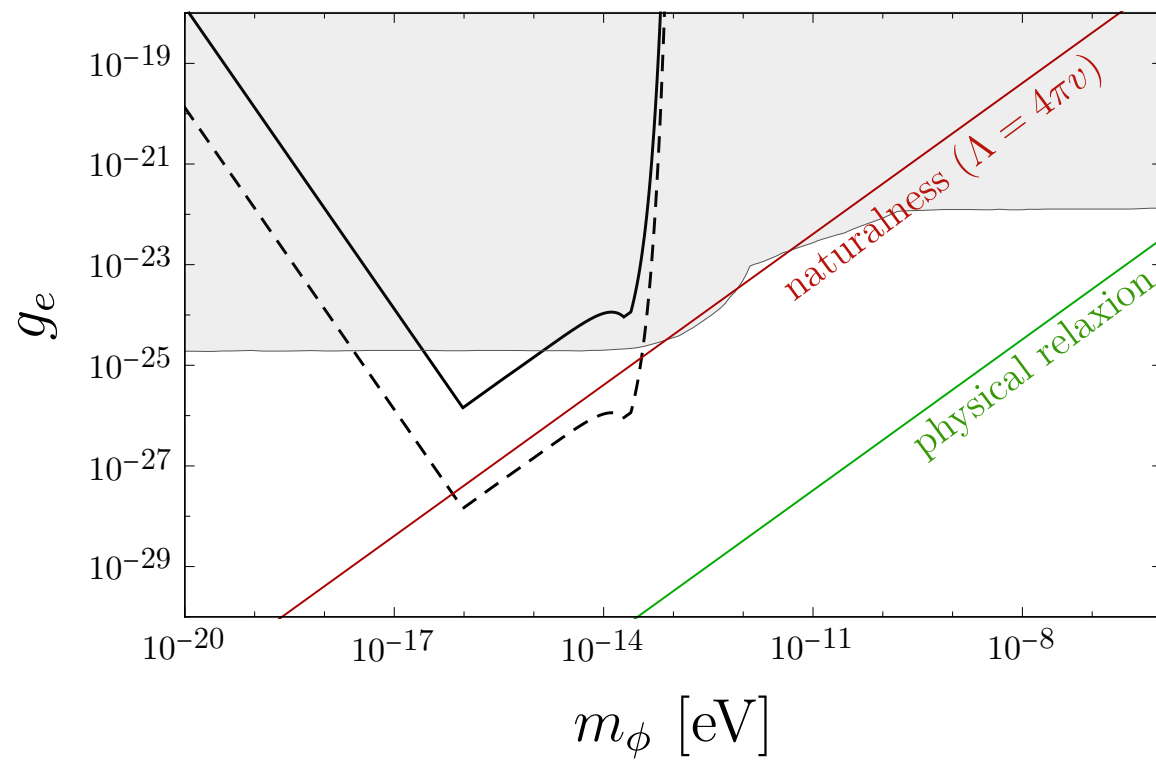
[Same as above 95% CL limit.]

[Slide from G. Perez]

captured by the Earth

sensitivities in $\delta m_e / \langle m_e \rangle$ and $\delta \alpha / \alpha$ are taken to be 10^{-14}, 10^{-16}, 10^{-18}

[Banerjee, Budker, Eby, HK and Perez 19]

captured by the Sun

sensitivities in $\delta m_e / \langle m_e \rangle$ and $\delta\alpha / \alpha$ are taken to be 10^{-16}, 10^{-18}

[Banerjee, Budker, Eby, HK and Perez 19]

Summary

- *relaxion could explain hierarchy problem in the standard model*

- *could also be coherent dark matter in the universe*

- *oscillating background DM induces oscillations of fundamental constants*

- *but for the mass range m>10^-15 eV, sensitivity of table-top exps cannot compete with that of EP-violation tests*

- *In cases where it forms relaxion stars and captured within solar system, table-top exps is able to probe unexplored region of parameter space*