Fun ways to relax and unwind

New directions in cosmologica relaxation

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+ BSM blues…

- For the last few decades a major part of particle physics research has been driven by the expectation of new physics at the TeV scale.
- But LHC has found no new physics yet ! No superpartners or composite top partners..
- This might change soon with more data.
- The LHC null results have brought the High-Energy-Physics community to a point of introspection.

+ No new physics at TeV scale ?

- Suggested not just by LHC null results…
- Electroweak precision constrains certain kind of new physics to few TeV scale.
- New Physics with generic flavour structure constrained to ~1000 TeV.
- B, L violating new physics constrained to much higher scales $\sim 10^{15}$ GeV

Can we have an explanation for a light Higgs with no new physics up to high scales?

Relaxions: basic ingredients

1. In relaxion models the value of μ^2, the Higgs mass squared term in the Higgs potential changes during the course of inflation.

$$V(H) = \mu^2 H^\dagger H + \lambda (H^\dagger H)^2 \,,$$

$$\mu^2 = -\Lambda^2 + g\phi\Lambda + g^2\phi^2 + \ldots \,,$$

2. It varies with the classical value of a scalar field Φ, which slowly rolls because of a potential:

$$V(\phi) = g\phi\Lambda^3 + g^2\phi^2\Lambda^2 + \ldots$$

3. In the simplest model Φ is the QCD axion and has the coupling:

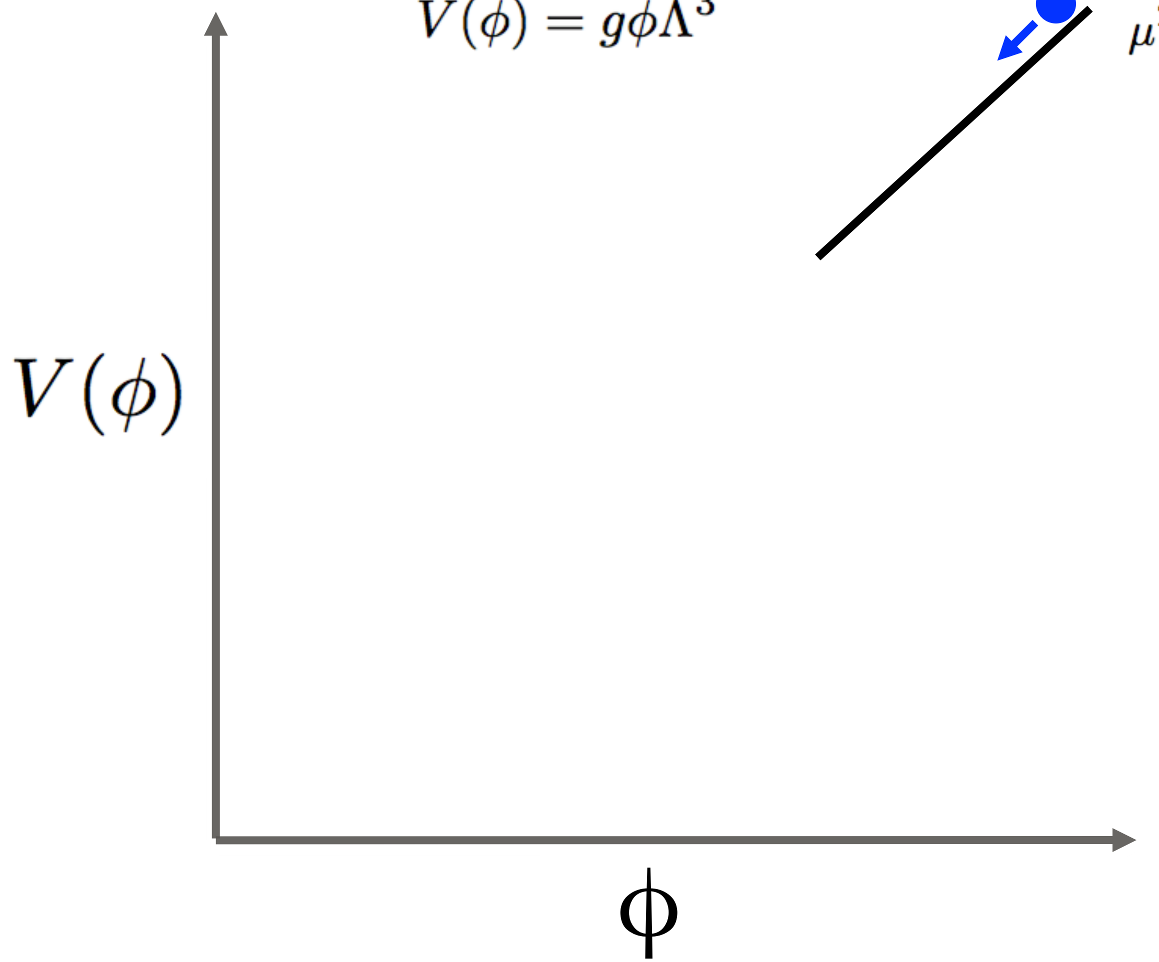
(more generally it is a PNGB).

$$\frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

Graham, Kaplan & Rajendran, 2015

The Relaxion Mechanism

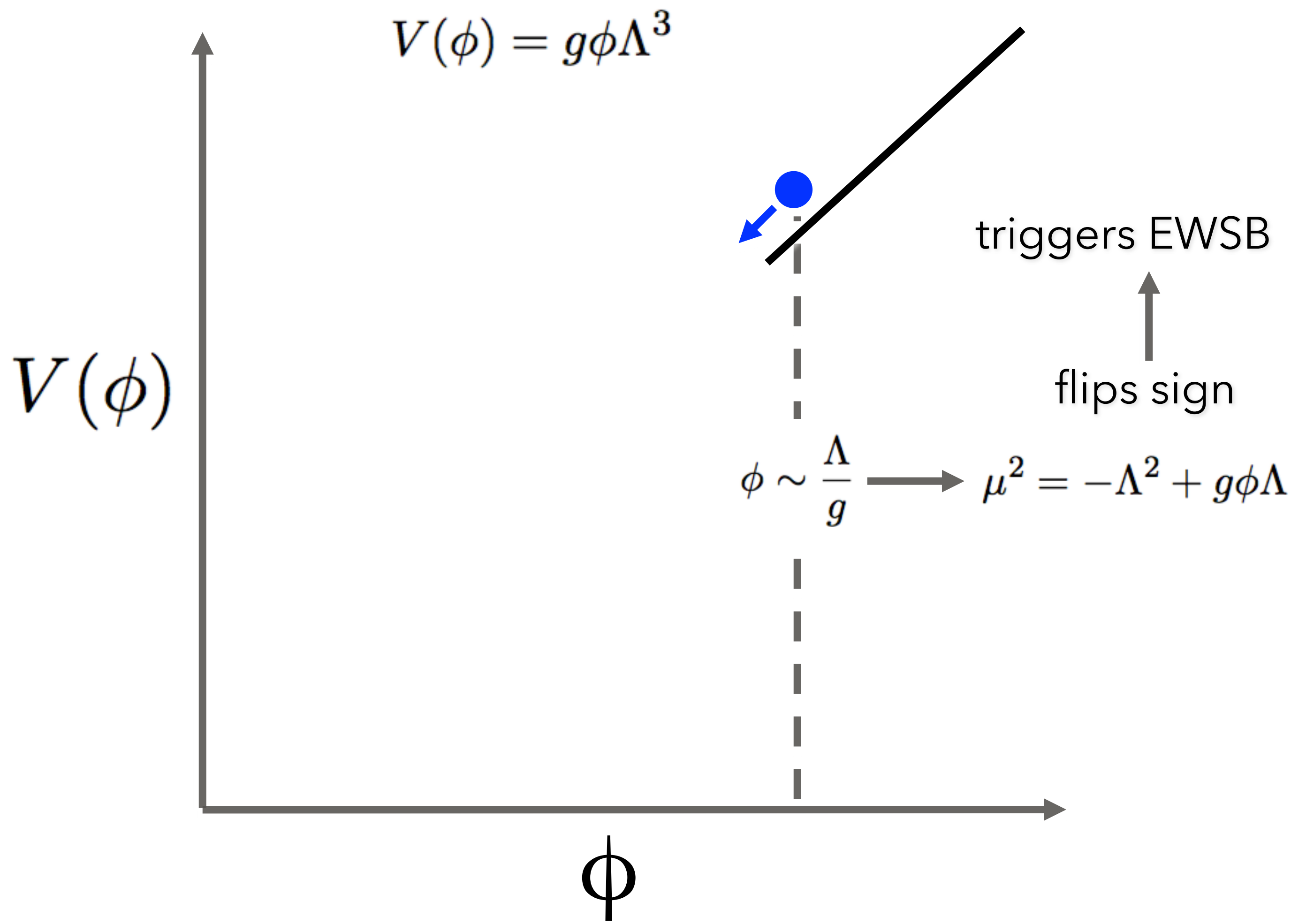
$$V(\phi) = g\phi\Lambda^3$$



$$\mu^2 = -\Lambda^2 + g\phi\Lambda > 0$$

$$\phi \gtrsim \frac{\Lambda}{g}$$

The Relaxion Mechanism



Backreaction potential

- Backreaction term in the potential turns on only when upon EWSB.

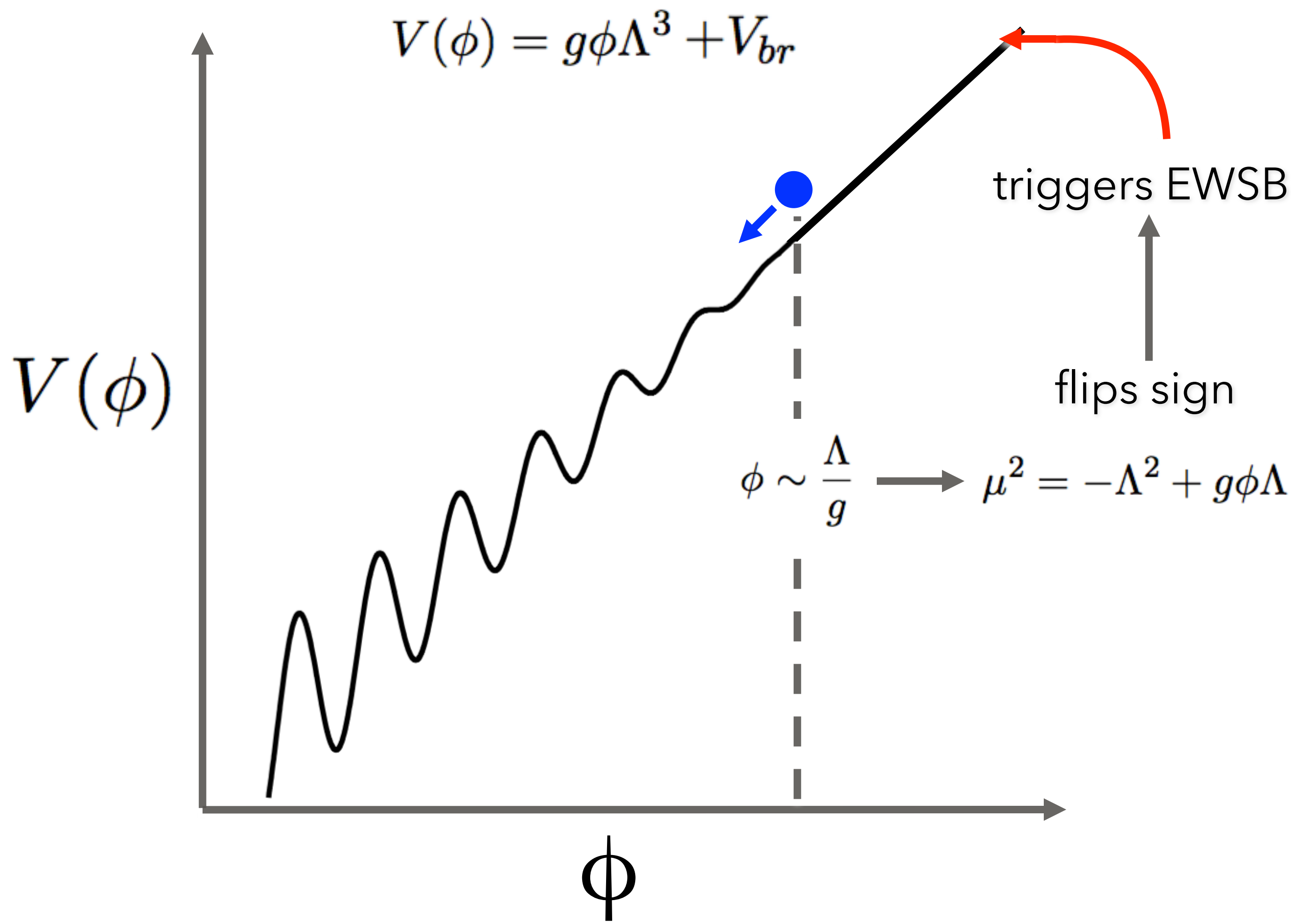
$$V_{\rm br} = -\Lambda_{\rm br}^4 \cos\frac{\phi}{f}\,, \quad \Lambda_{\rm br}^4 \sim M_{\rm br}^{4-j}(v+h)^j$$

- Example: QCD axion potential

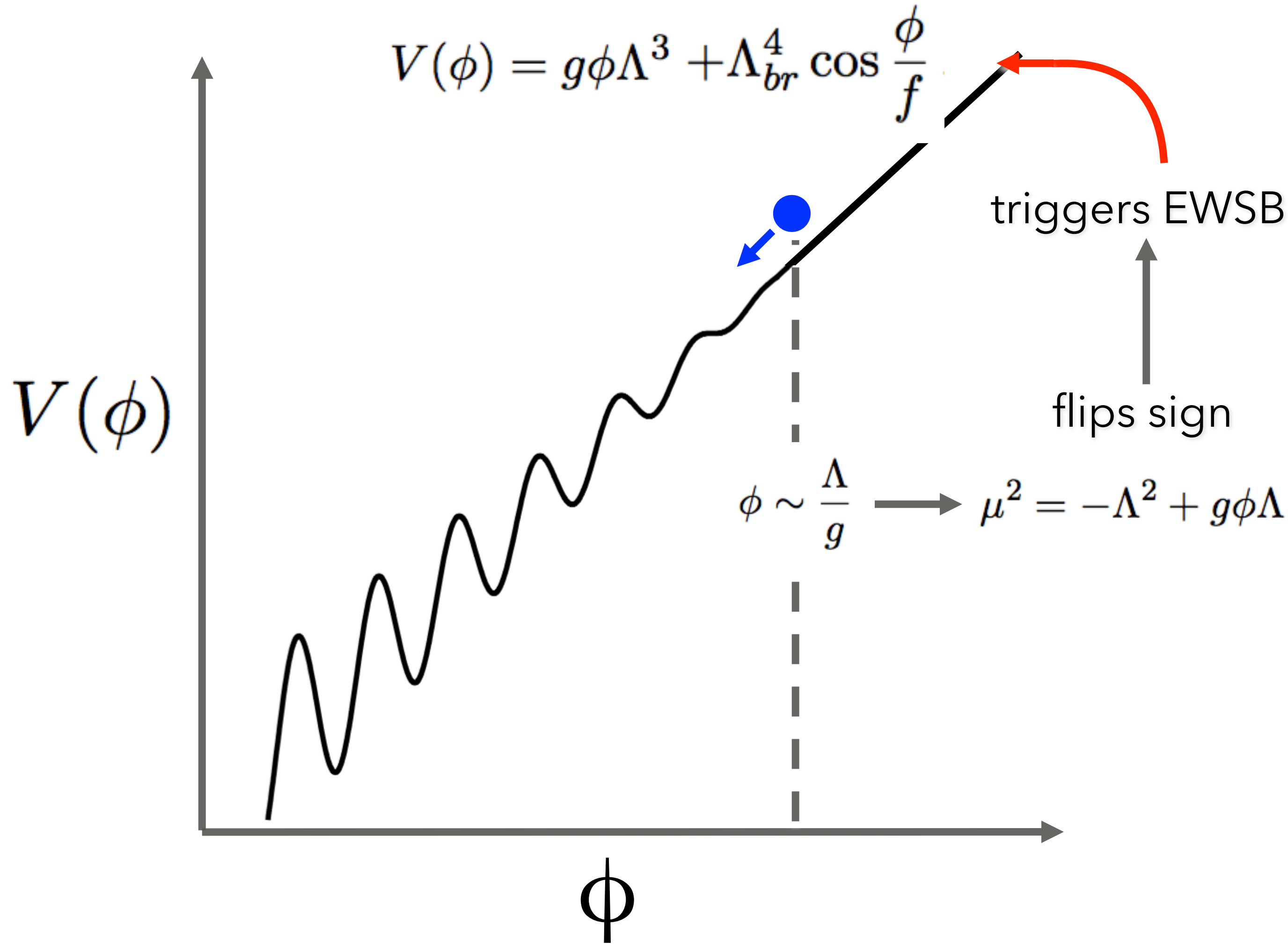
$$\Delta V \sim y_u v f_\pi^3 \cos\left(\frac{\phi}{f_a}\right)$$

- In simplest model relaxion is QCD axion.

The Relaxion Mechanism

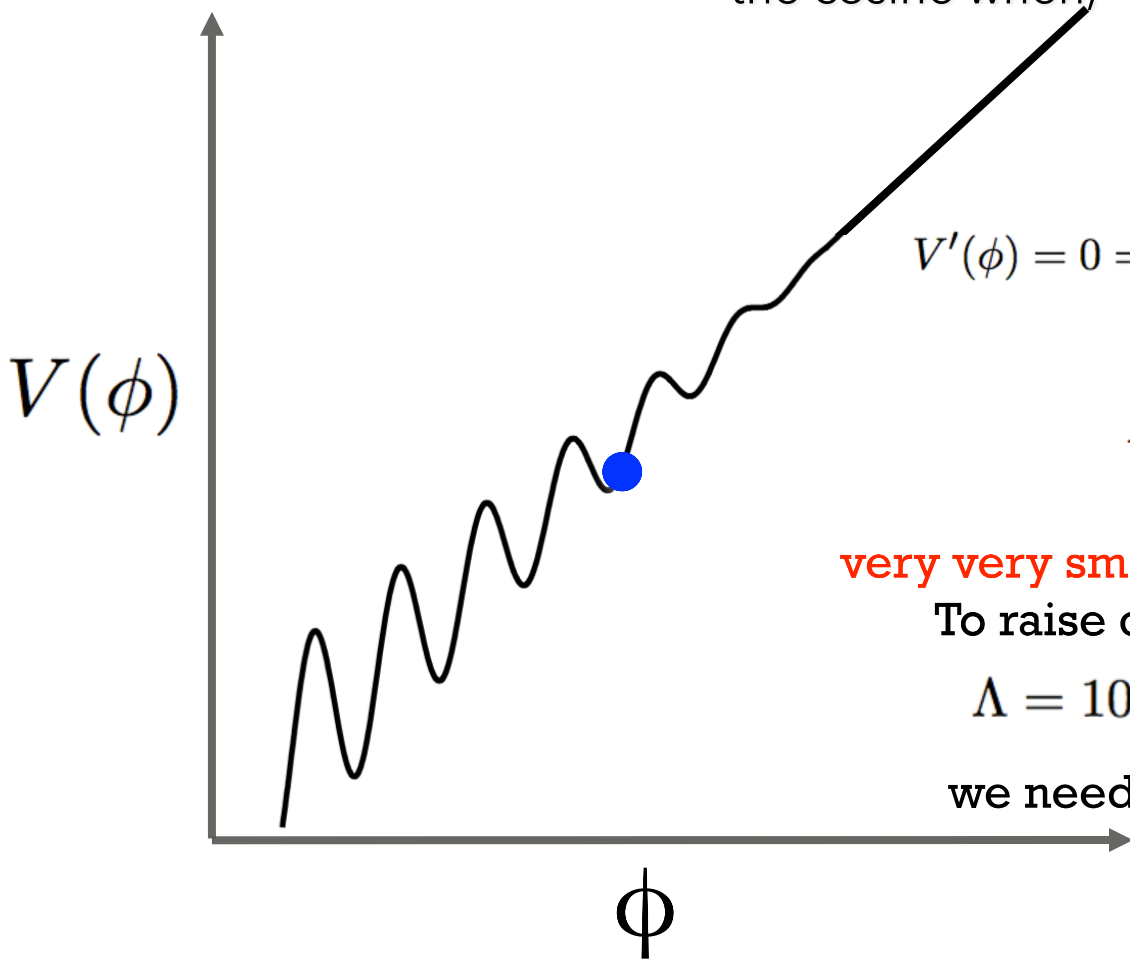


The Relaxion Mechanism



The Relaxion Mechanism

Relaxion stops at O(1) phase of the cosine when,



$$V'(\phi) = 0 \Rightarrow g\Lambda^3 - \frac{\Lambda_{br}^4}{f} \sin\frac{\phi}{f} = 0$$

$$\Lambda \sim \left(\frac{\Lambda_{br}^4}{gf}\right)^{1/3}$$

very very small g required!

To raise cut-off to

$$\Lambda = 10^7 \text{ GeV}$$

we need g= 10^{-33}

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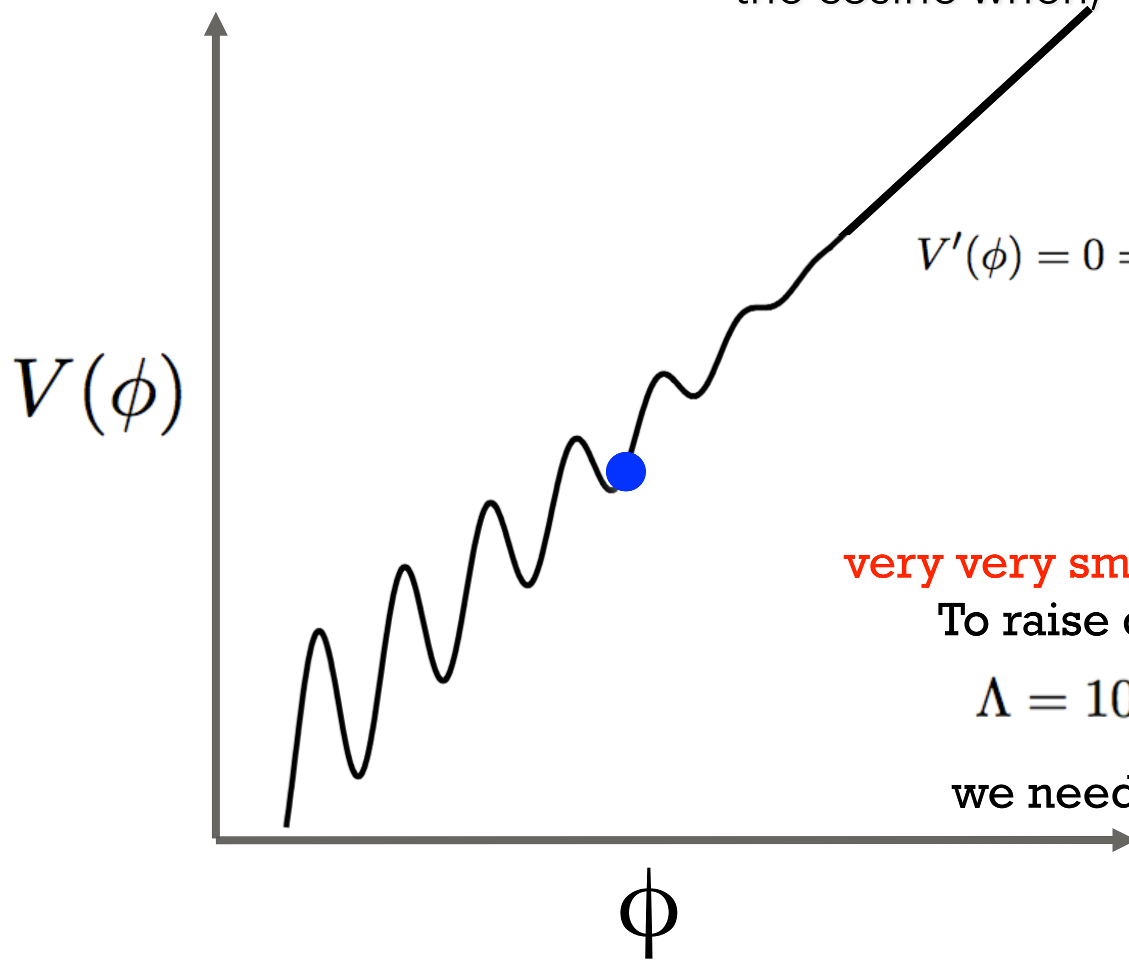

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While the relaxion mechanism pushes the scale that cuts off the Higgs quadratic divergence to very high values it also gives a light scalar degree of freedom that can be probed at the `low energy- high intensity' frontier.

Relaxion-Higgs mixing

- Potential: $$V = \left[-\Lambda^2 + g\Lambda\phi ...\right] \hat{h}^2 - \tilde{M}^2 \hat{h}^2 \cos\left(\frac{\phi}{f}\right) + \lambda \hat{h}^4 + rg\Lambda^3\phi + rg^2\Lambda^2\phi^2 \ldots .$$
- Mass Matrix elements:

$$M^2_{h'h'} \equiv \frac{\partial^2 V}{\partial h' \partial h'} = 3\lambda v^2 - \Lambda^2 + g\Lambda\phi + \tilde{M}^2 \cos\left(\frac{\phi_0}{f}\right) = 2\lambda v^2 \,,$$

$$M^2_{h'\phi'} \equiv \frac{\partial^2 V}{\partial h' \partial \hat{\phi}} = g\Lambda v + \frac{\tilde{M}^2 v}{f} \sin\left(\frac{\phi_0}{f}\right) \simeq \frac{\tilde{M}^2 v}{f} \sin\left(\frac{\phi_0}{f}\right) \,,$$

$$M^2_{\phi'\phi'} \equiv \frac{\partial^2 V}{\partial \phi' \partial \phi'} = \frac{v^2}{2} \frac{\tilde{M}^2}{f^2} \cos\left(\frac{\phi_0}{f}\right) + rg^2\Lambda^2 \simeq \frac{v^2}{2} \frac{\tilde{M}^2}{f^2} \cos\left(\frac{\phi_0}{f}\right)$$

$$\tilde{M}^2 = \frac{\Lambda^4_{br}}{v^2}$$

Flacke, Frugiuele, Fuchs, RSG, and Perez (arXiv:1610.02025)

+

Relaxion-Higgs mixing

- Potenti… $\phi + rg^2\Lambda^2\phi^2\ldots.$
- Mass M… elemen… $\Big) = 2\lambda v^2\,,$ …in$\left(\frac{\phi_0}{f}\right)\,,$ … $\frac{\tilde{M}^2}{f^2}\cos\left(\frac{\phi_0}{f}\right)$

Mass and Mixing:

$$\sin\theta \approx \tan\theta \approx \frac{M^2_{h\hat{\phi}}}{M^2_{hh}} \approx \frac{v}{f}\frac{\tilde{M}^2}{m_h^2}\sin\left(\frac{\phi_0}{f}\right)$$

$$m_\phi^2 \approx \frac{\tilde{M}^2 v^2}{2f^2}\left(1 - \frac{\tilde{M}^2}{\lambda v^2}\right) = \frac{\tilde{M}^2 v^2}{2f^2}\left(1 - \frac{2\tilde{M}^2}{m_h^2}\right).$$

Spontaneous CP violation

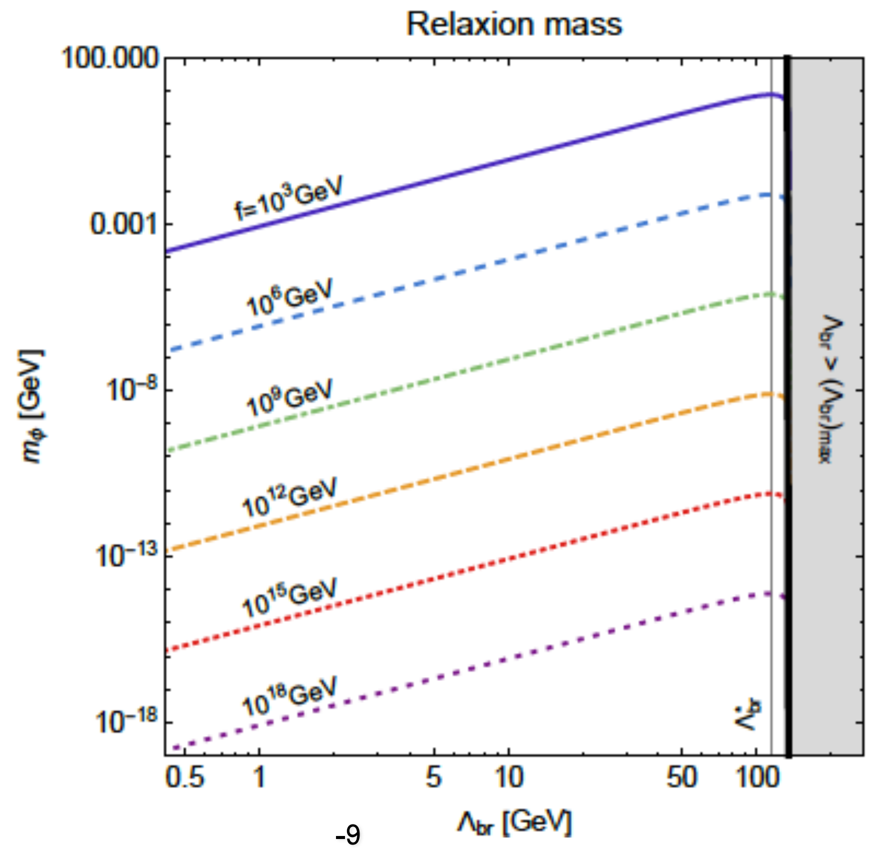
Flacke, Frugiuele, Fuchs, RSG, and Perez (arXiv:1610.02025)

Relaxion, a weakly coupled light particle

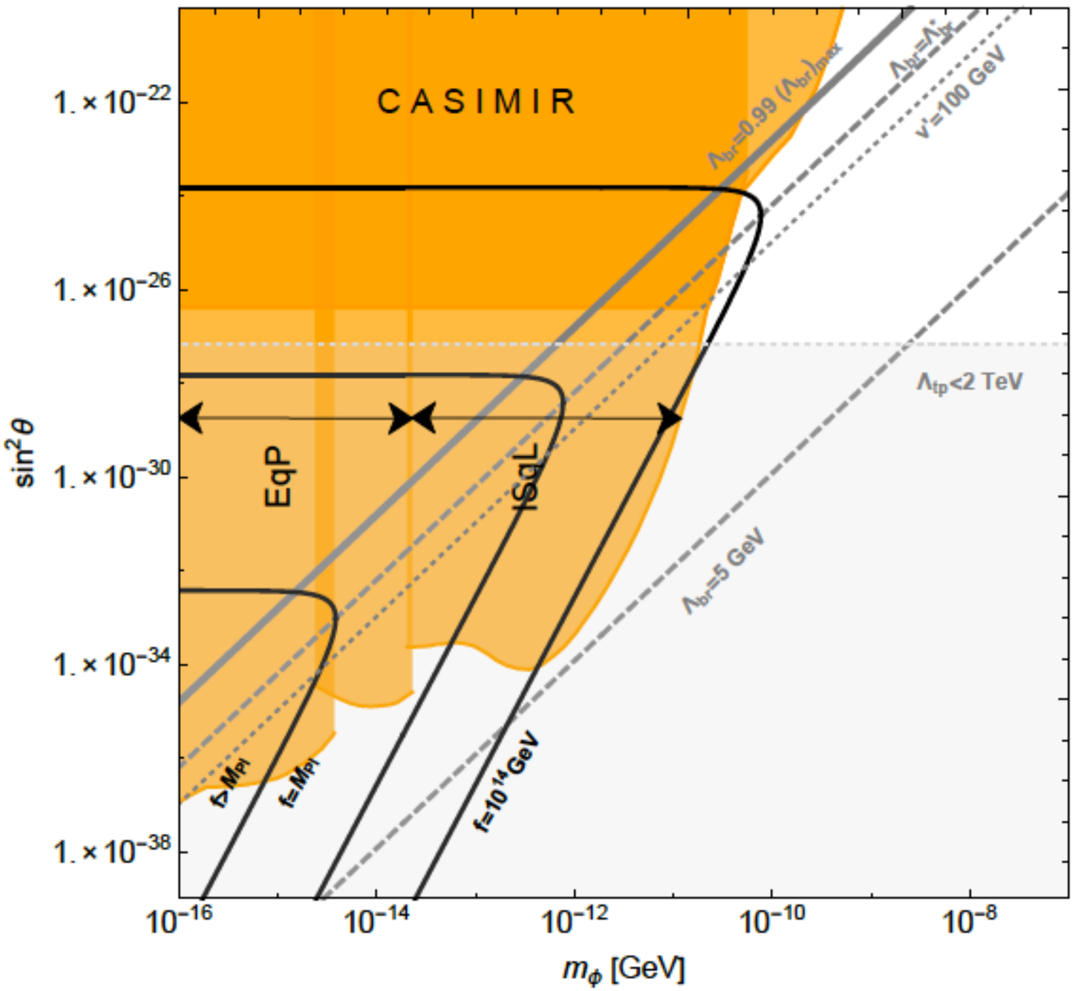
- Relaxion mass varies from less than 10 eV to 60 GeV .
- Weakly coupled:

$$s_\theta < 0.04\,\frac{m_\phi}{1\,\mathrm{GeV}}$$

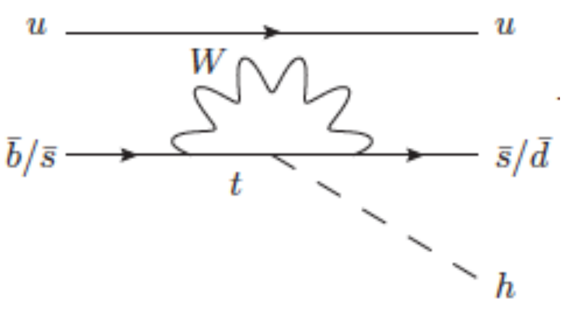
- Rich variety of constraints depending on the mass range.



+ Sub-eV experiments: Fifth force experiments



Flavour Bounds



$$Br(K^+ \to \pi^+ h) \approx \sin^2\rho \times 0.002 \times \frac{2|\vec{p}_h|}{m_K},$$
$$Br(B^+ \to K^+ h) \approx \sin^2\rho \times 0.5 \times \frac{2|\vec{p}_h|}{m_B} \times \mathcal{F}_K^2(m_h)$$

Relaxions can be probed by meson decays

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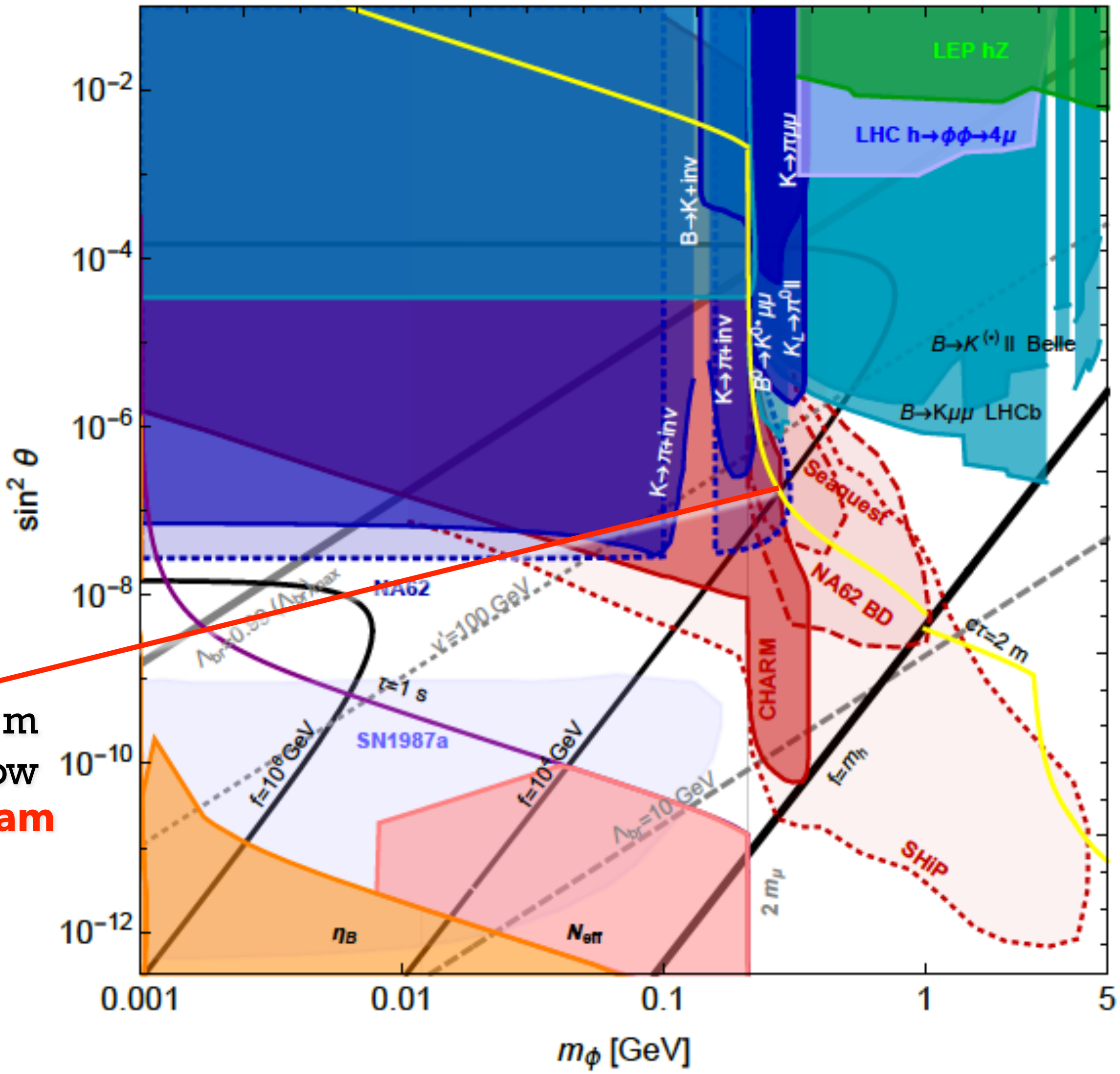
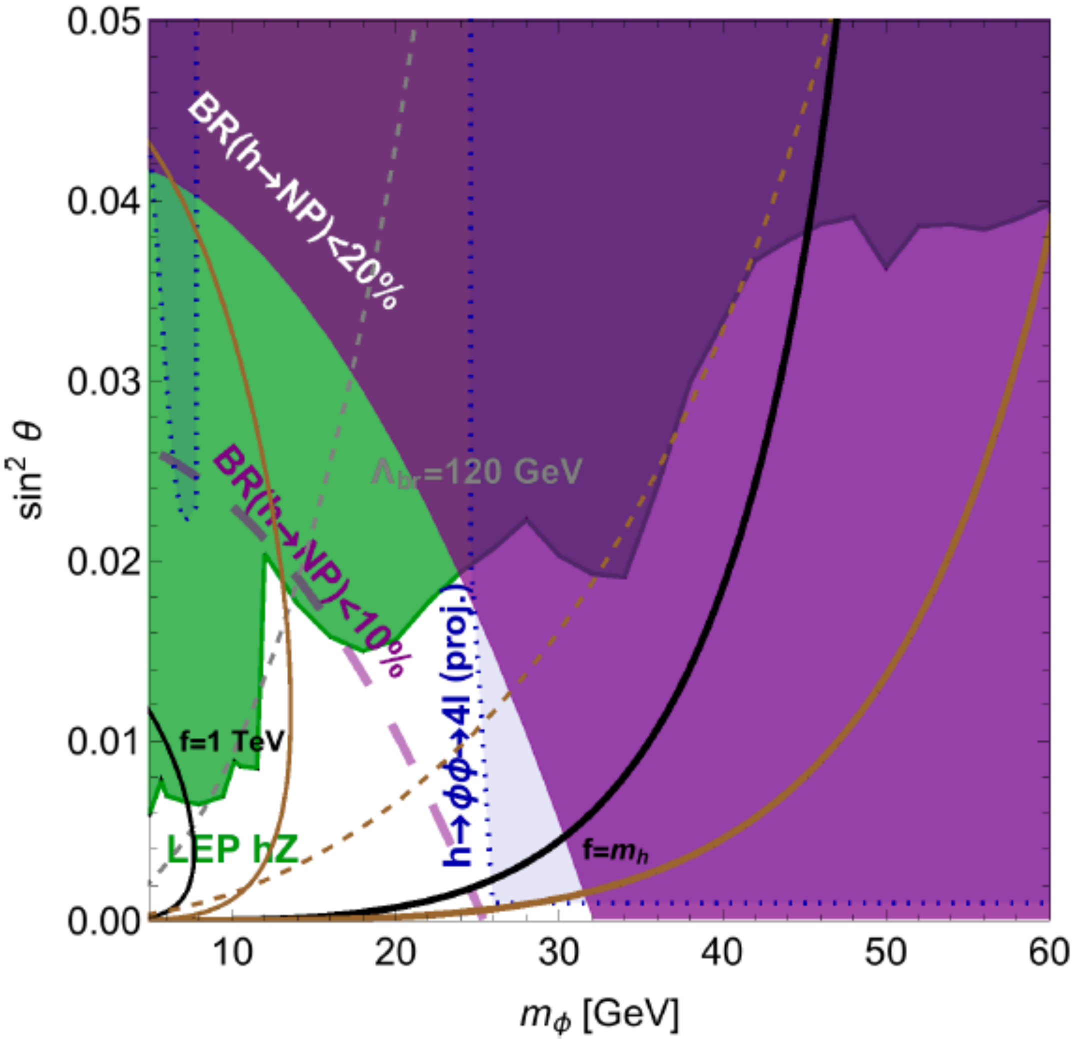
MeV-GeV Range



Decay length greater than 100 m to the left of yellow line, ideal for **Beam Dump** experiments!

Flacke, Frugiuele, Fuchs, RSG, and Perez (arXiv:1610.02025)

GeV Range

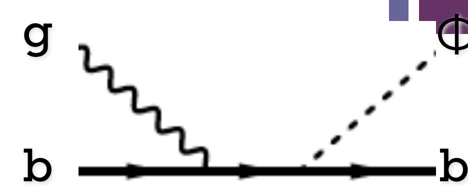


Flacke, Frugiuele, Fuchs, RSG, and Perez (arXiv:1610.02025)

- *No constraints in the eV-MeV region from lab experiments.*

Cosmology: Relaxion abundance

- Before EWSB only process: HH->$\Phi\Phi$
- During EWSB: finite temperature effects make it hard to calculate the contribution to abundance.
- In EW broken phase (T<20 GeV) mixing with Higgs turned on: b+g->b+Φ



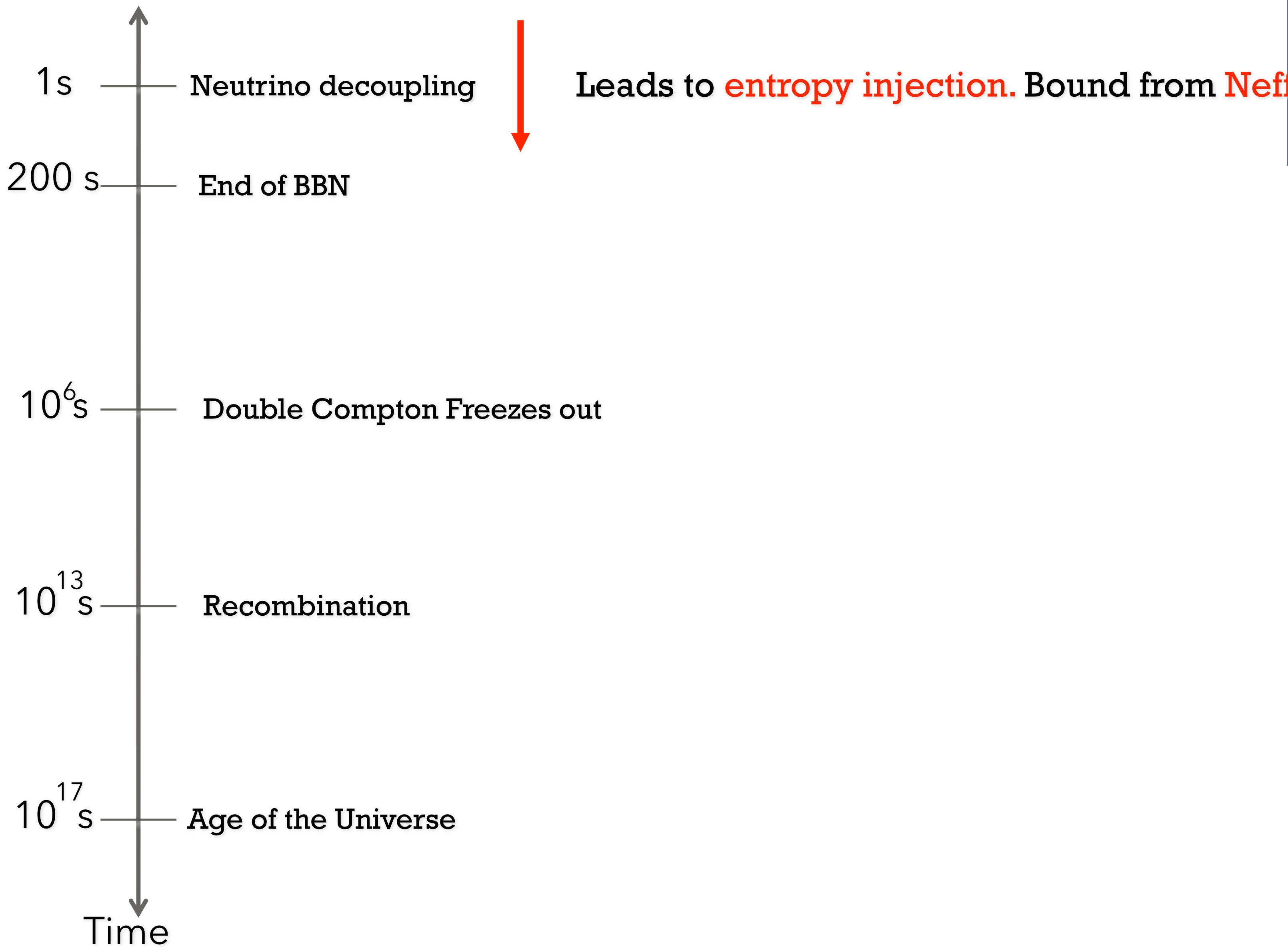
$$Y' = \frac{\Gamma}{xH}(Y_{eq} - Y)$$

$$0.003\left[1 - \exp\left(-6.1 \times 10^{10} s_\theta^2\right)\right]$$

$$Y_{h\phi} = 2.0 \times 10^8 s_\theta^2.$$

Flacke, Frugiuele, Fuchs, RSG, and Perez (arXiv:1610.02025)

Cosmology: Relaxion late decays



Cosmology: Relaxion late decays

1 s — Neutrino decoupling

200 s — End of BBN

10^6 s — Double Compton Freezes out

10^{13} s — Recombination

10^{17} s — Age of the Universe

Time

Leads to entropy injection. Bound from Neff

+

BBN bounds

Relaxion decay produces a cascade of electrons and photons which can cause photodissociation of nuclei and alter BBN predictions.

Cosmology: Relaxion late decays

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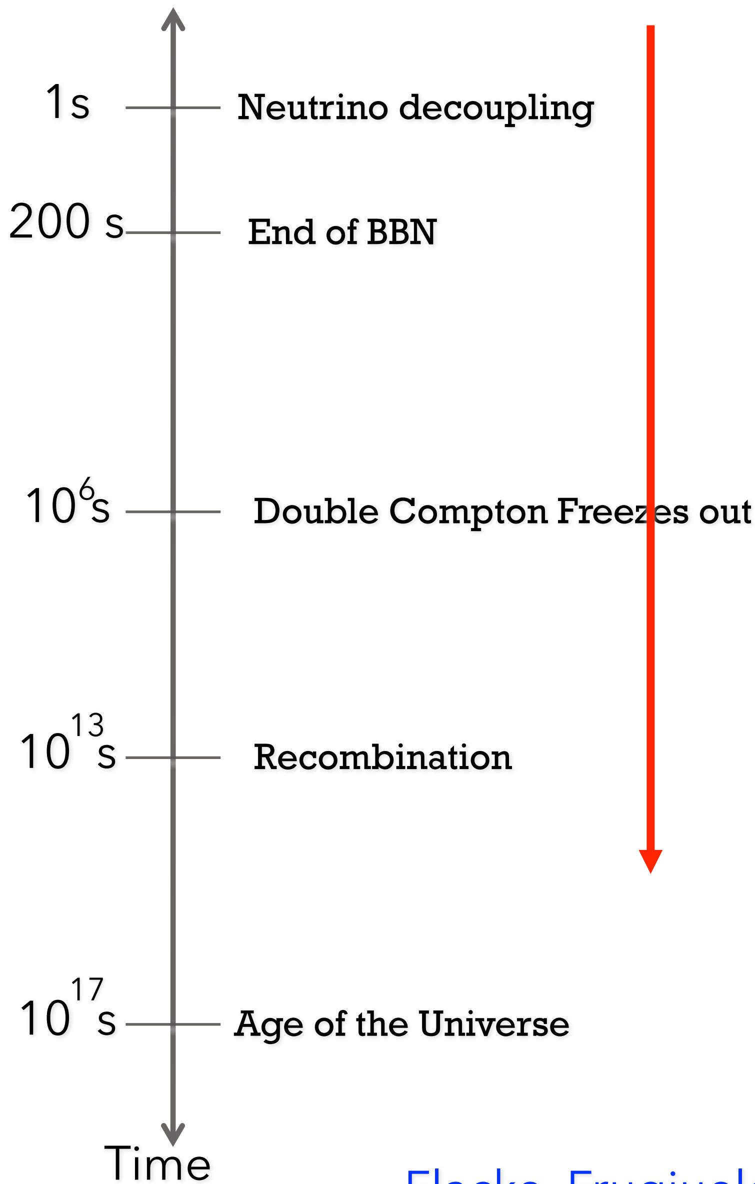
CMB spectral distortions

Decays to photons after this time lead to a distortion of planck spectrum, For decays before DC freezes out, photons just re-equilibrate.

+ Cosmology: Relaxion late decays

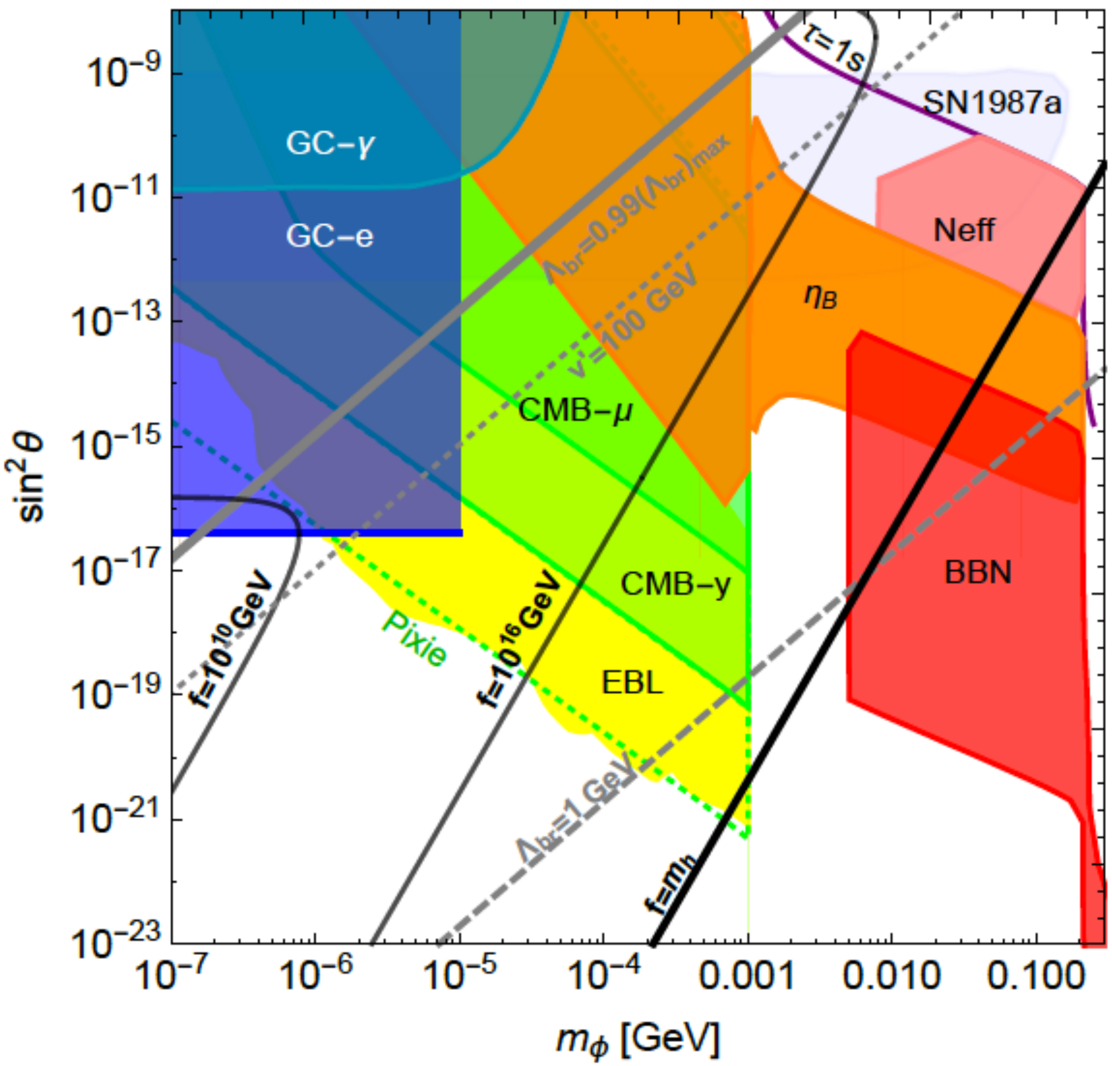


Only EBL distortion bounds

After reombination universe becomes transparent to radiation. Any decays after this point can still be seen today as a distortion of the extragalactic background light (EBL) spectrum.

Flacke, Frugiuele, Fuchs, RSG, and Perez (arXiv:1610.02025)

Sub-eV-MeV



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Connection to other BSM puzzles

- The hierarchion, a model where we solve all the hierarchies in SM plus neutrino masses.
- We find a way to combine

1. The Relaxion solution to Higgs mass hierarchy problem
2. The Nelson Barr Solution to the strong CP problem
3. The Froggatt-Nielsen solution for the SM flavour puzzle
4. The see-saw mechanism for neutrino masses

in a unified framework with a single light degree of freedom that we call the hierarchion.

Davidi, RSG, Perez, Redigolo and Shalit (arXiv:1711.00858)
Davidi, RSG, Perez, Redigolo and Shalit (arXiv:1806.08791)

Connection to other BSM puzzles: Spontaneous Relaxion Baryogenesis

- Standard relaxion models have all the ingredients for successful baryogenesis if we add the coupling to SM fermions,

$$\frac{\partial_\mu \phi}{f} J^\mu$$

must contain

SM B+L current

Abel, RSG, Scholtz (arXiv:1809.XXXXX)

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already present in hierarchion model with
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Connection to other BSM puzzles: Spontaneous Relaxion Baryogenesis

- Standard relaxion models have all the ingredients for successful baryogenesis if we add the coupling

No additional CP or B violating required.
No departure from equilibrium required.

SM B+L current

already present in hierarchion model with
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Abel, RSG, Scholtz (arXiv:1809.XXXXX)

Spontaneous Relaxion Baryogenesis

- In the background of the the rolling relaxion field this term alters particle distribution wrt to antiparticle ones provided there is a source for B-violation.

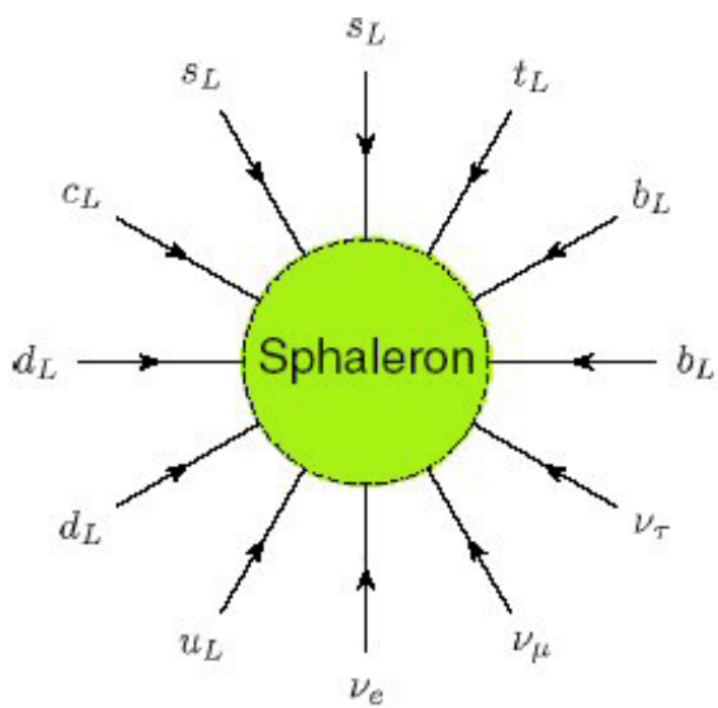
$$\frac{\partial_\mu \phi}{f} J^\mu \longrightarrow \text{Particles/Anti-particles obtain a chemical potential} \longrightarrow \mu = \pm \frac{\dot{\phi}}{f}$$

$$j_i^0 = n_i - \bar{n}_i = \frac{g_i}{(2\pi)^3} \int d^3p \left[\left\{ \exp\left(\frac{p-\mu_i}{T}\right) + 1 \right\}^{-1} - \left\{ \exp\left(\frac{p+\mu_i}{T}\right) + 1 \right\}^{-1} \right]$$
$$= \frac{g_i}{6} \mu_i T^2 \left\{ 1 + \mathcal{O}\left(\frac{\mu_i}{T}\right)^2 \right\}.$$

Cohen & Kaplan (1987)

+ Spontaneous Relaxion Baryogenesis

- With this term the rolling relaxion field alters particle distribution wrt to antiparticle ones provided there is a source for B-violation.

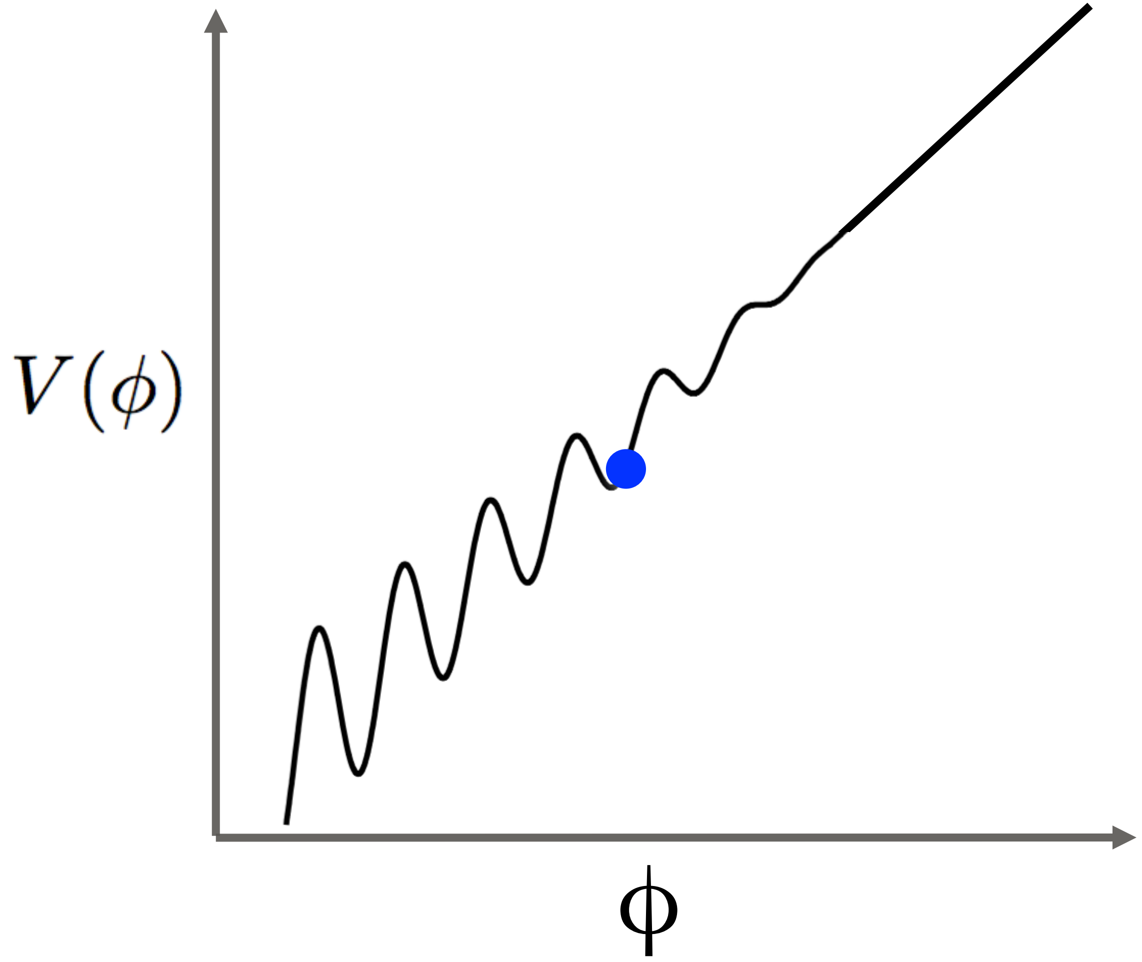


Sphalerons !!!

Not possible during inflation !

- *Sphalerons not active unless we are at high temperatures.*
- *Any B asymmetry will be diluted by rapid expansion*

What happens to relaxion after inflation?



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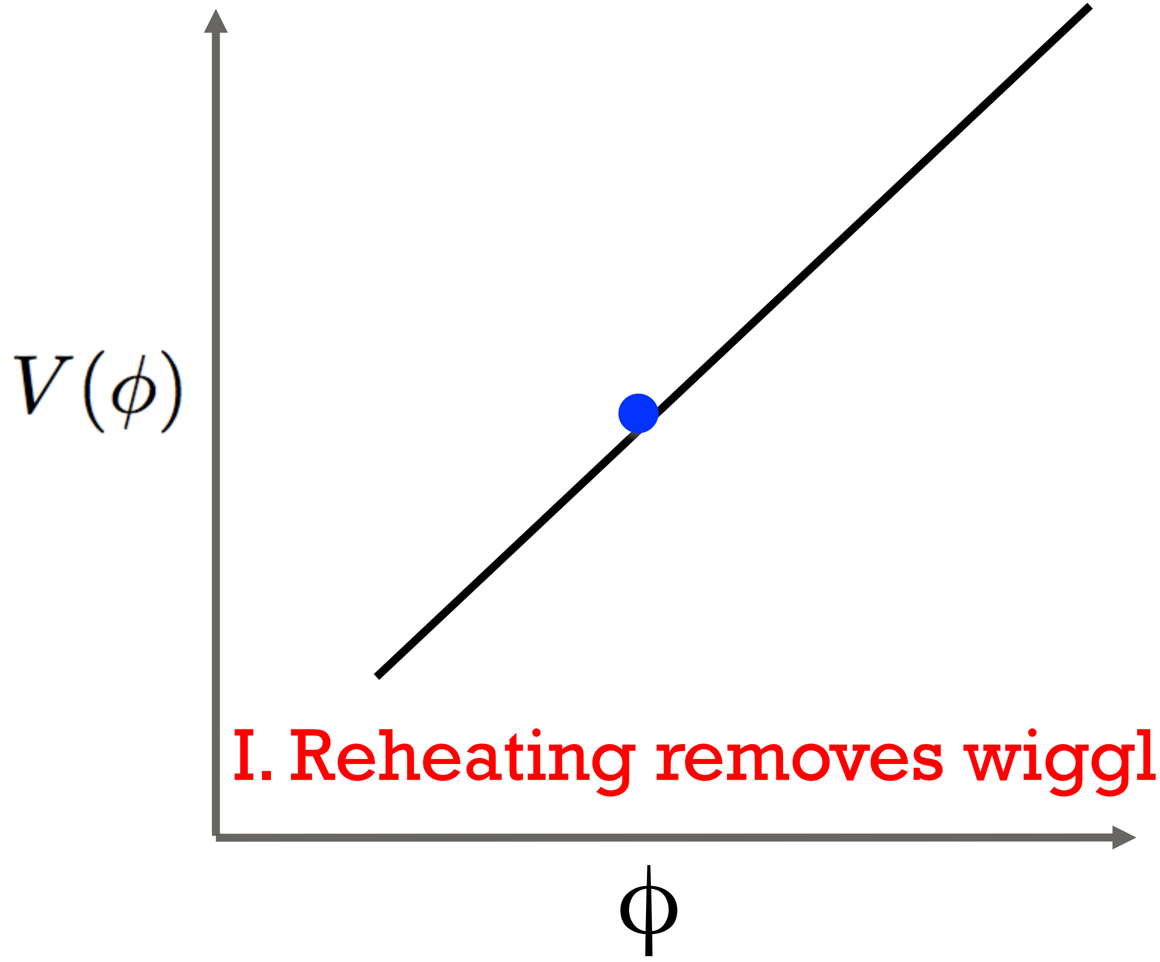

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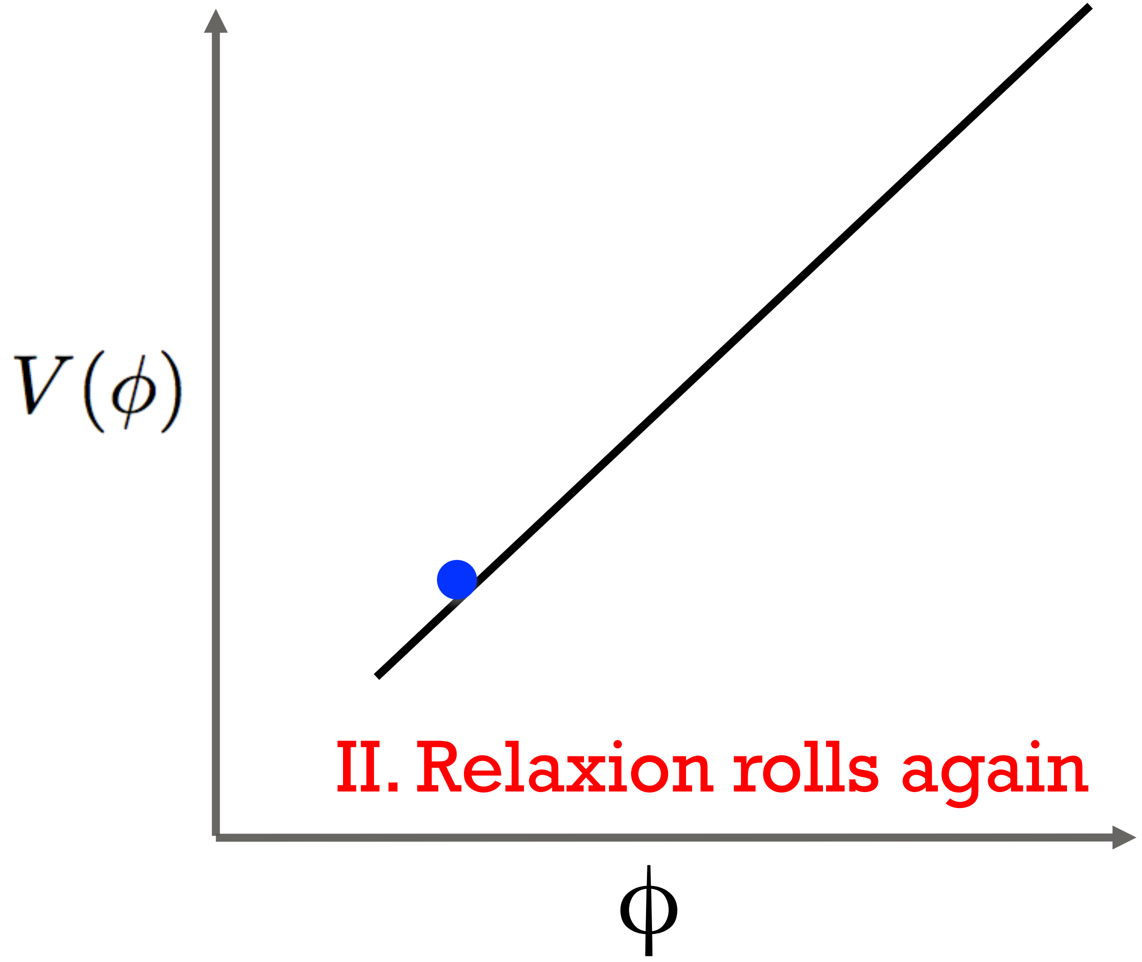

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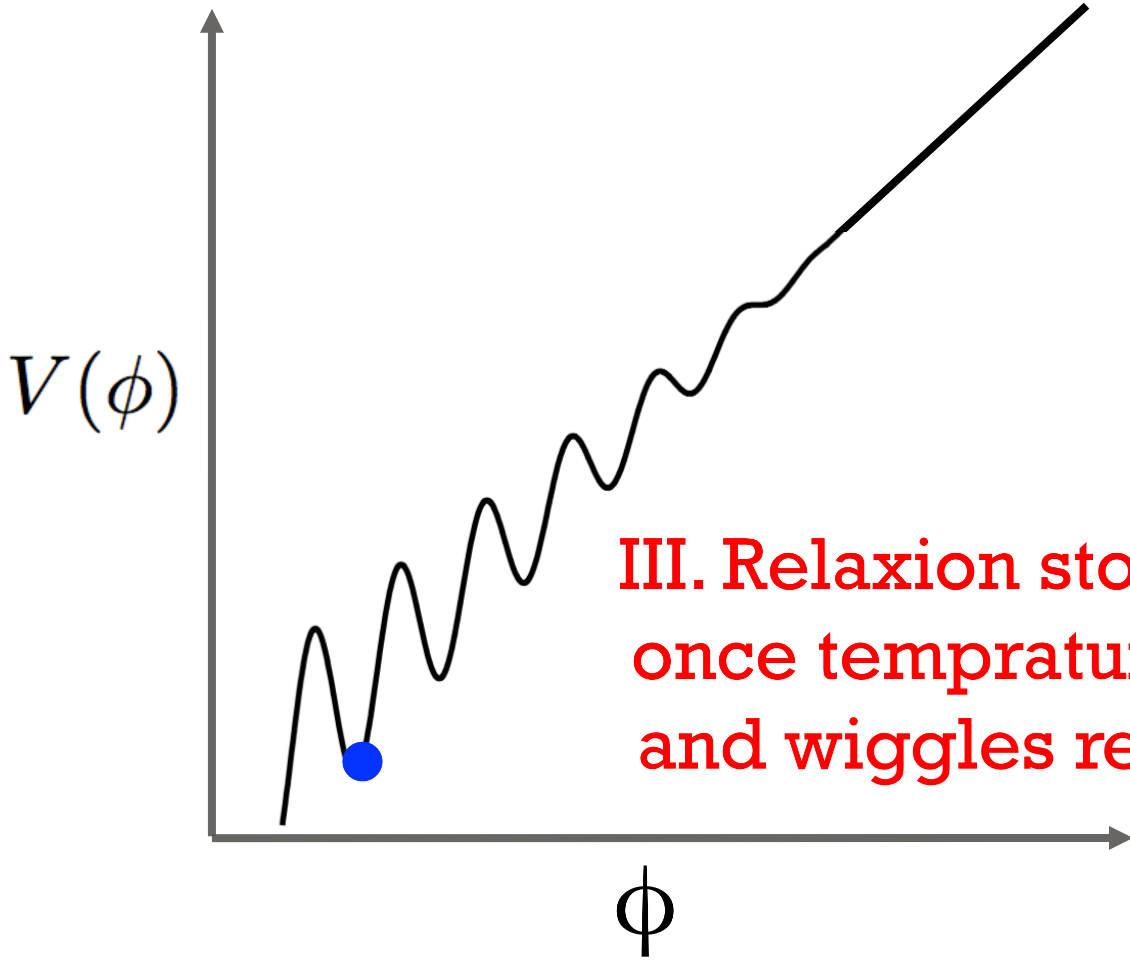


Does this spoil relaxion mechanism?

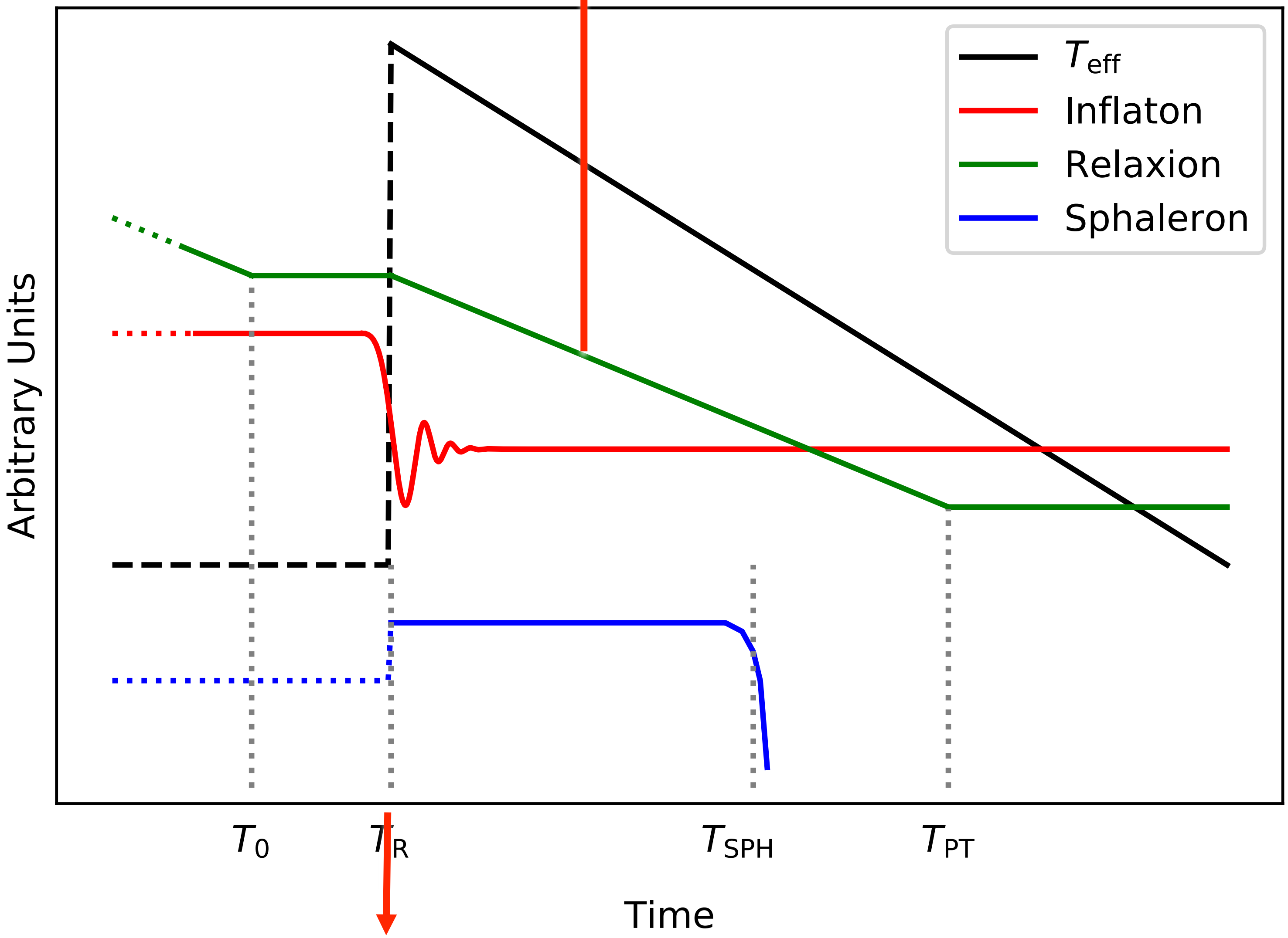
NO!

1) The shifting of the relaxion shifts Higgs VEV by miniscule amount ~eV

2) Slow roll conditions can still hold in large parts of parameter space.

Spontaneous baryogenesis occurs here

(after inflation)



Inflation ends here

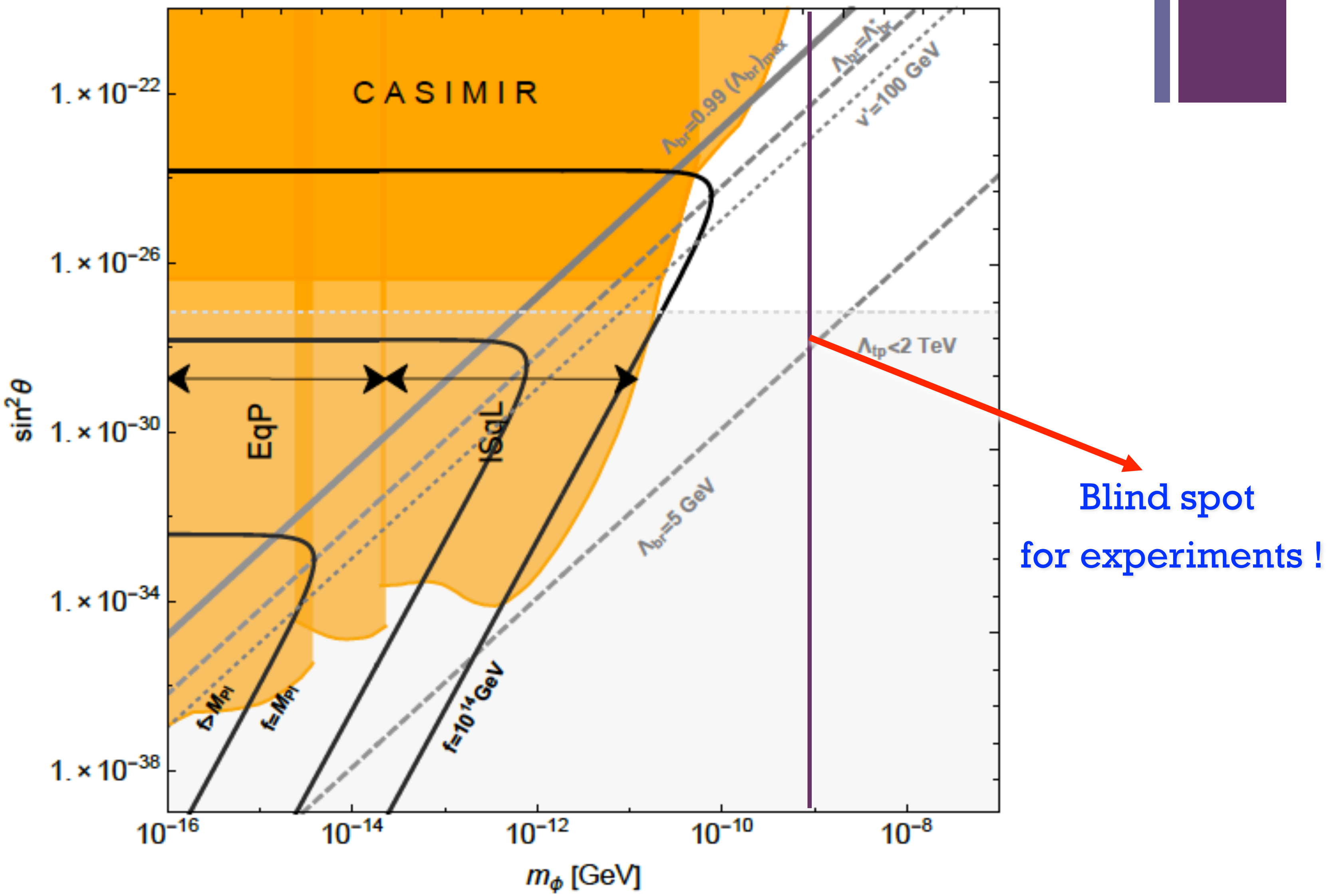
Prediction for mass !

$$\left.\frac{n_B}{s}\right|_{\rm dec} = \frac{15}{4\pi^2}\frac{\sum_i B_i c_i g_i}{g_{s*}}\left.\frac{\dot{\phi}}{Tf}\right|_{\rm dec} . = \quad 8.6\times 10^{-11}$$

Relaxion mass squared

The requirement to obtain correct value for B-asymmetry fixes relaxion mass to 1 eV !

Prediction for mass !



Conclusions

- Relaxion mechanism a new way to address the Higgs hierarchy problem which requires no TeV scale states to cut off Higgs quadratic divergence
- Relaxions can be probed by a variety of low energy probes because they mix with the SM Higgs.
- Generic relaxion models can give observed baryon asymmetry if relaxion couples to SM fermions. This gives a prediction for relaxion mass ~1 eV