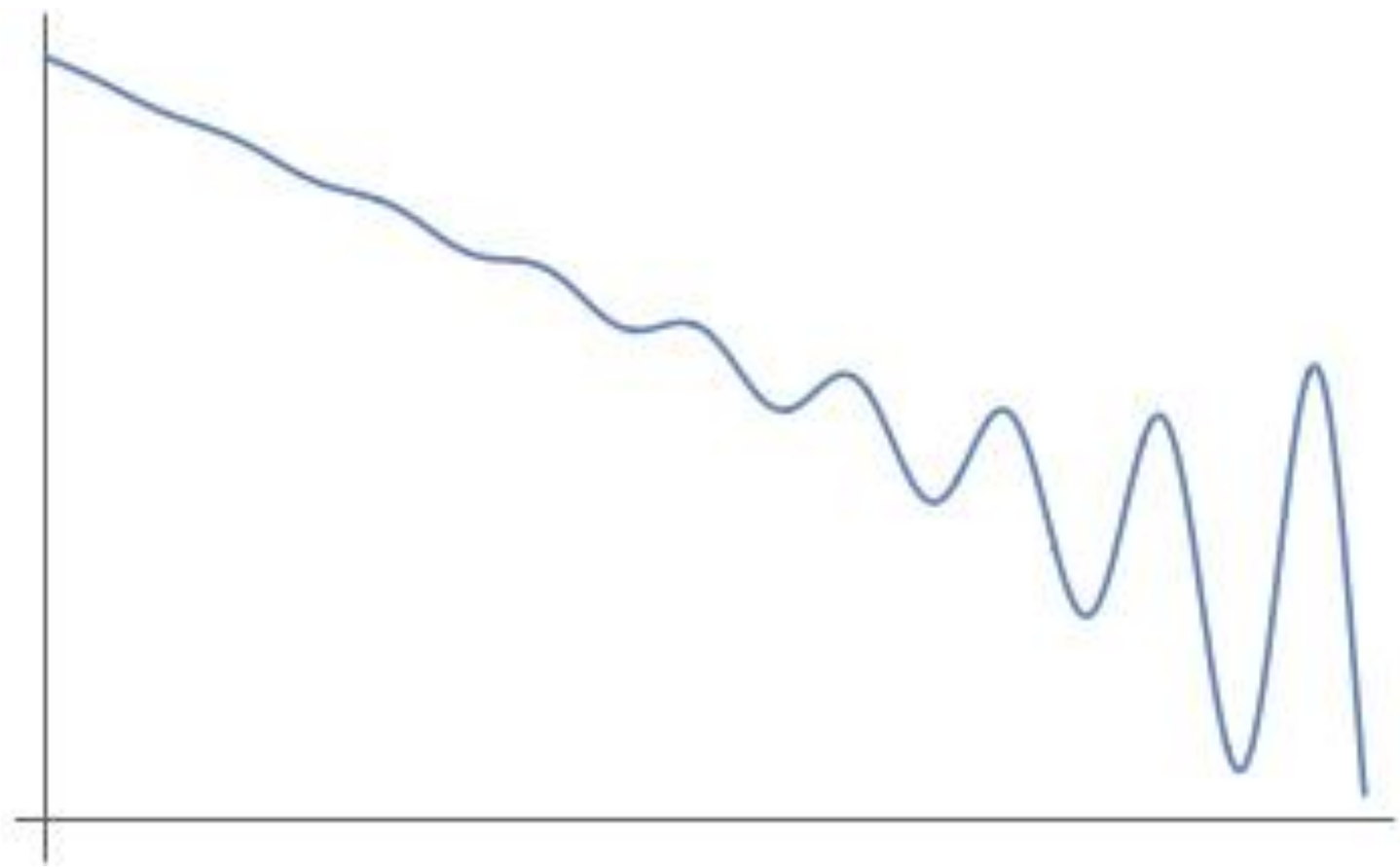
Relaxion Phenomenology



TEL AVIV UNIVERSITY אוניברסיטת תל אביב

Institute for Advanced Study

WEIZMANN INSTITUTE OF SCIENCE

Diego Redigolo

10/08/2018

TEL AVIV UNIVERSITY אוניברסיטת תל אביב

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Relaxion = New Playground for Naturalness

new theoretical challenges ⟷ new phenomenological probes

Relaxion = New Playground for Naturalness

new theoretical challenges

hopefully another example after Nate's talk

new phenomenological probes

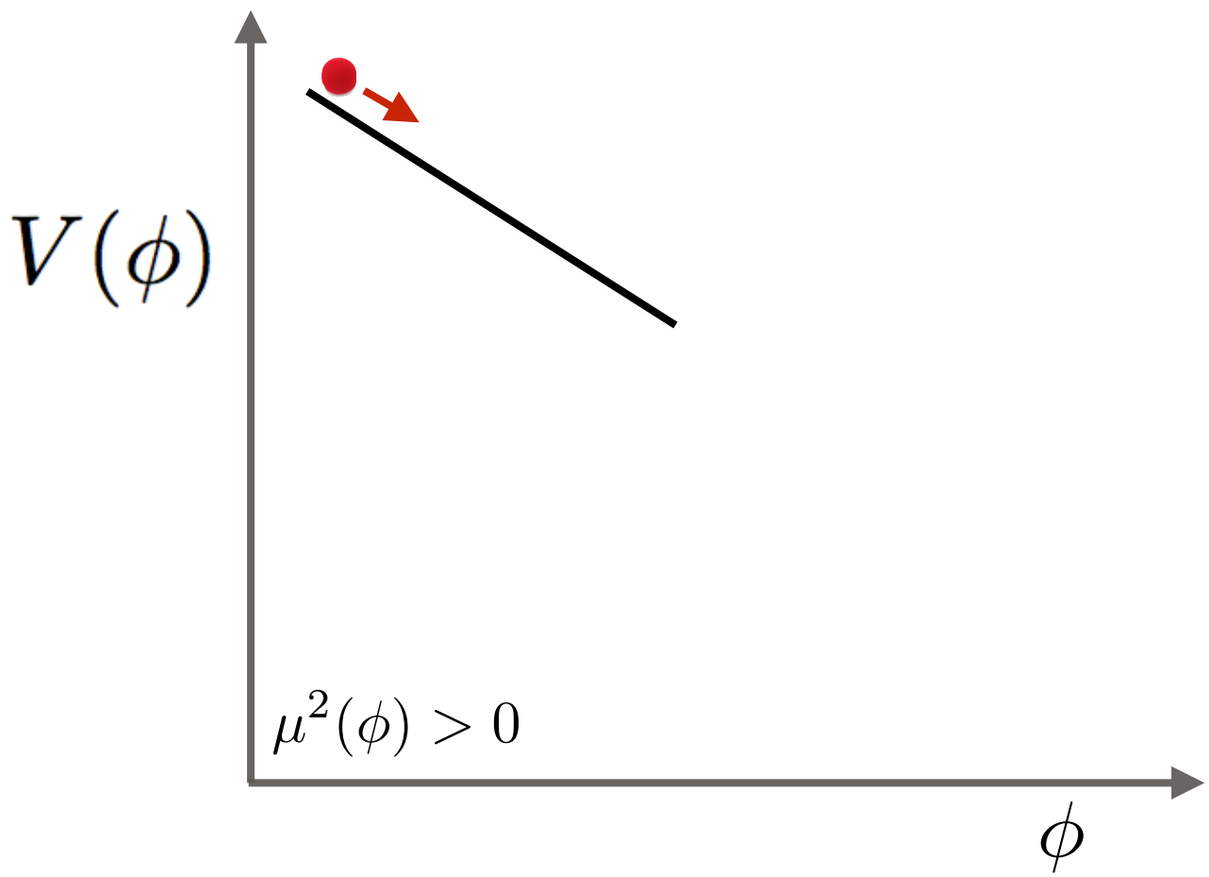
Relaxion = New Playground for Naturalness

Setting the stage

I

The Relaxion rolling

(Graham, Kaplan & Rajendran)



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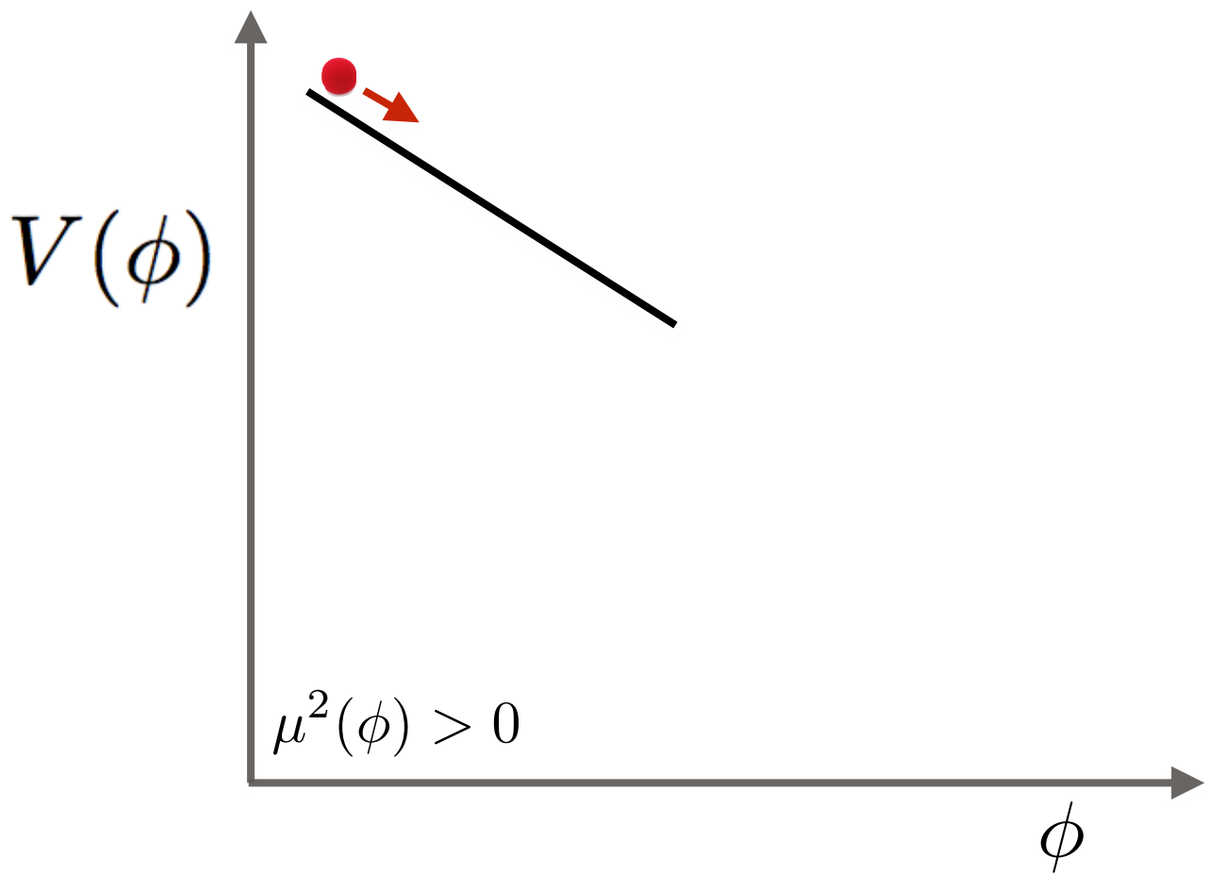

ϕ rolling potential:

$$\Lambda_{\rm roll}^4 \cos \frac{\phi}{F}$$

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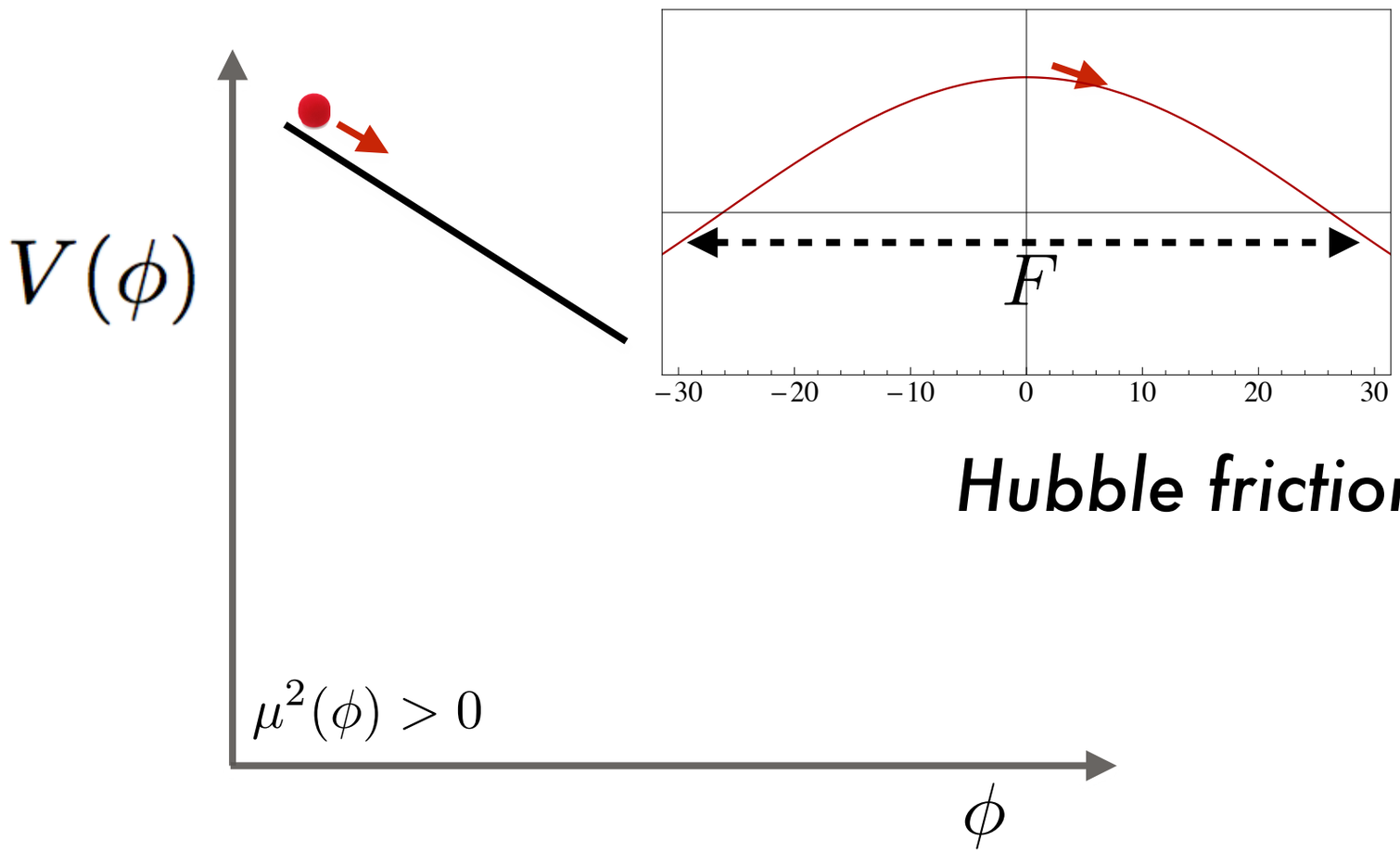

Hubble friction

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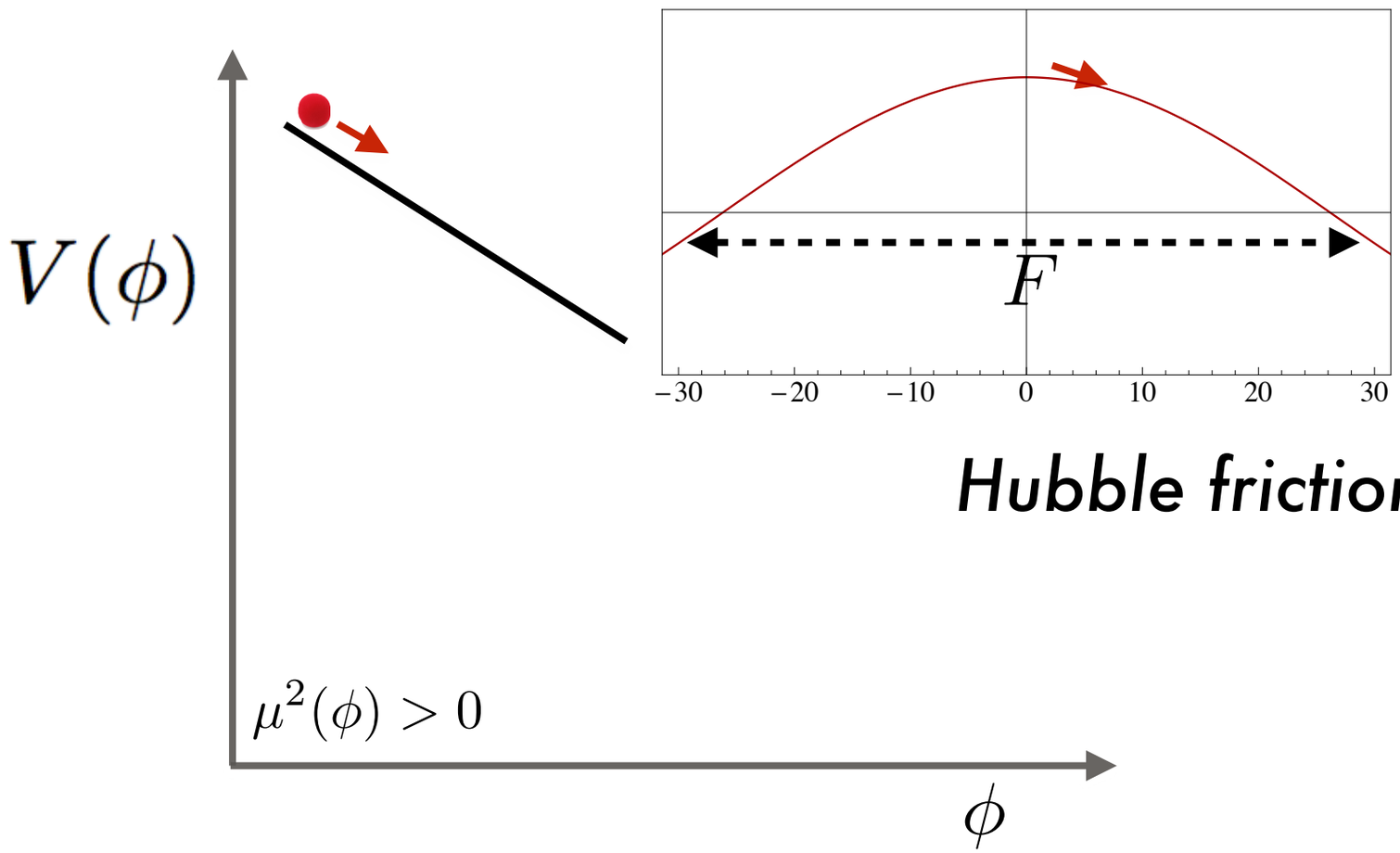

Hubble friction

ϕ- *dependent Higgs mass*

$$\Lambda_H^2 \underbrace{(\kappa - \cos\frac{\phi}{F})}_{\mu^2(\phi)} H^\dagger H$$

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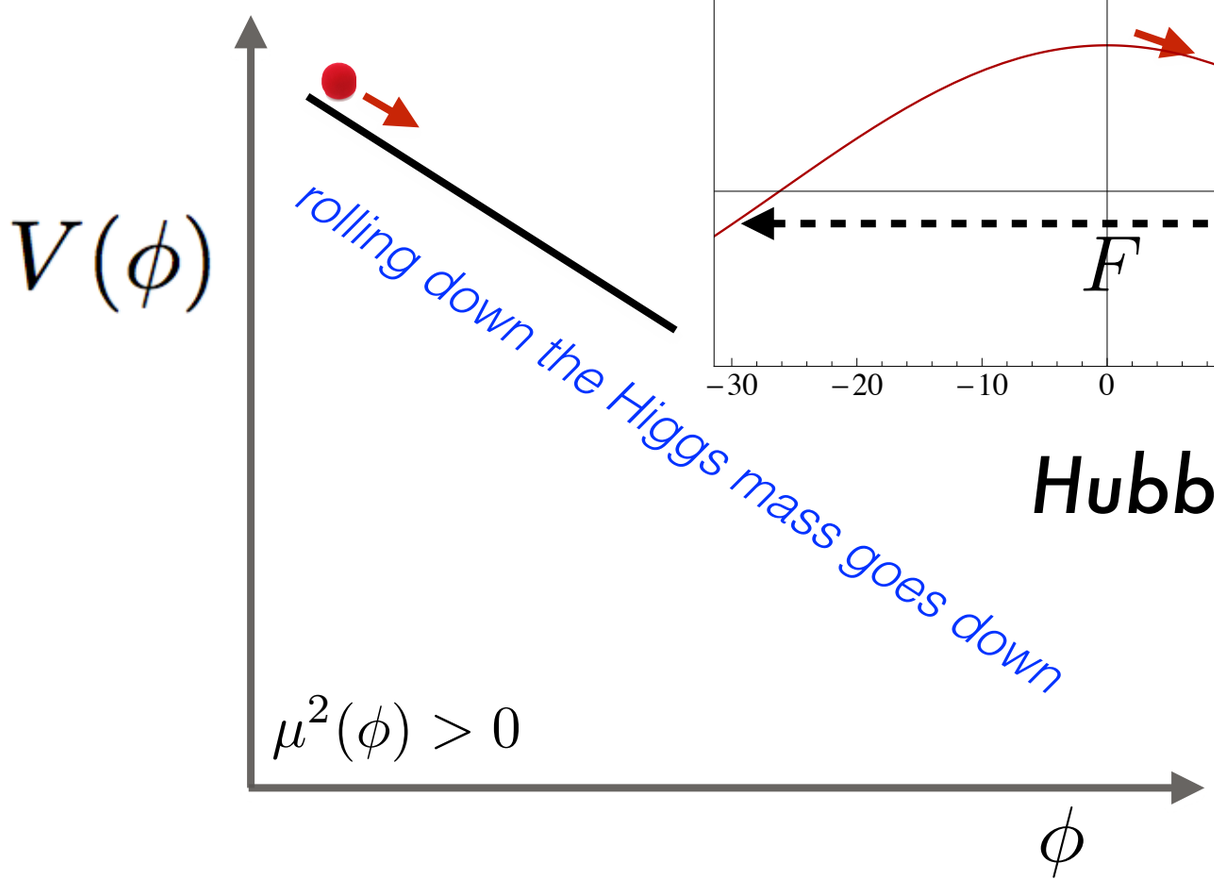

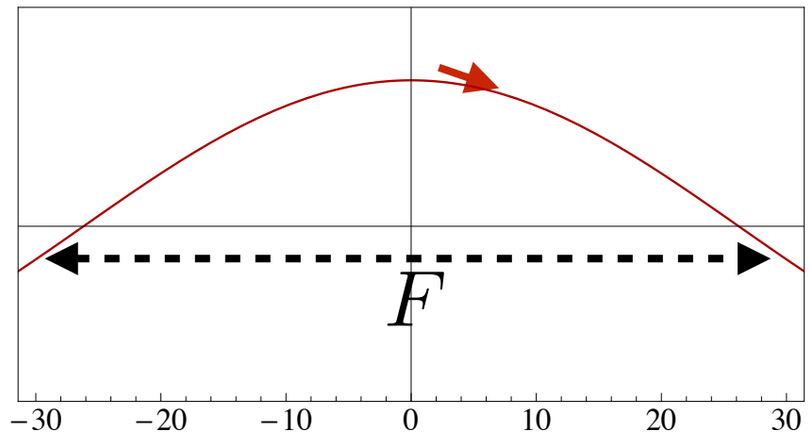

Hubble friction $\dot{\phi}_{\rm roll} \sim \frac{\Lambda_{\rm roll}^4}{3H_I F}$

ϕ- dependent Higgs mass

$$\Lambda_H^2 \underbrace{(\kappa - \cos\frac{\phi}{F})}_{\mu^2(\phi)} H^\dagger H \simeq (\kappa\Lambda_H^2 - \underbrace{g\phi}) H^\dagger H$$

ϕ rolling potential:

$$\Lambda_{\rm roll}^4 \cos\frac{\phi}{F} \simeq \underbrace{g\Lambda_H^3\phi}$$

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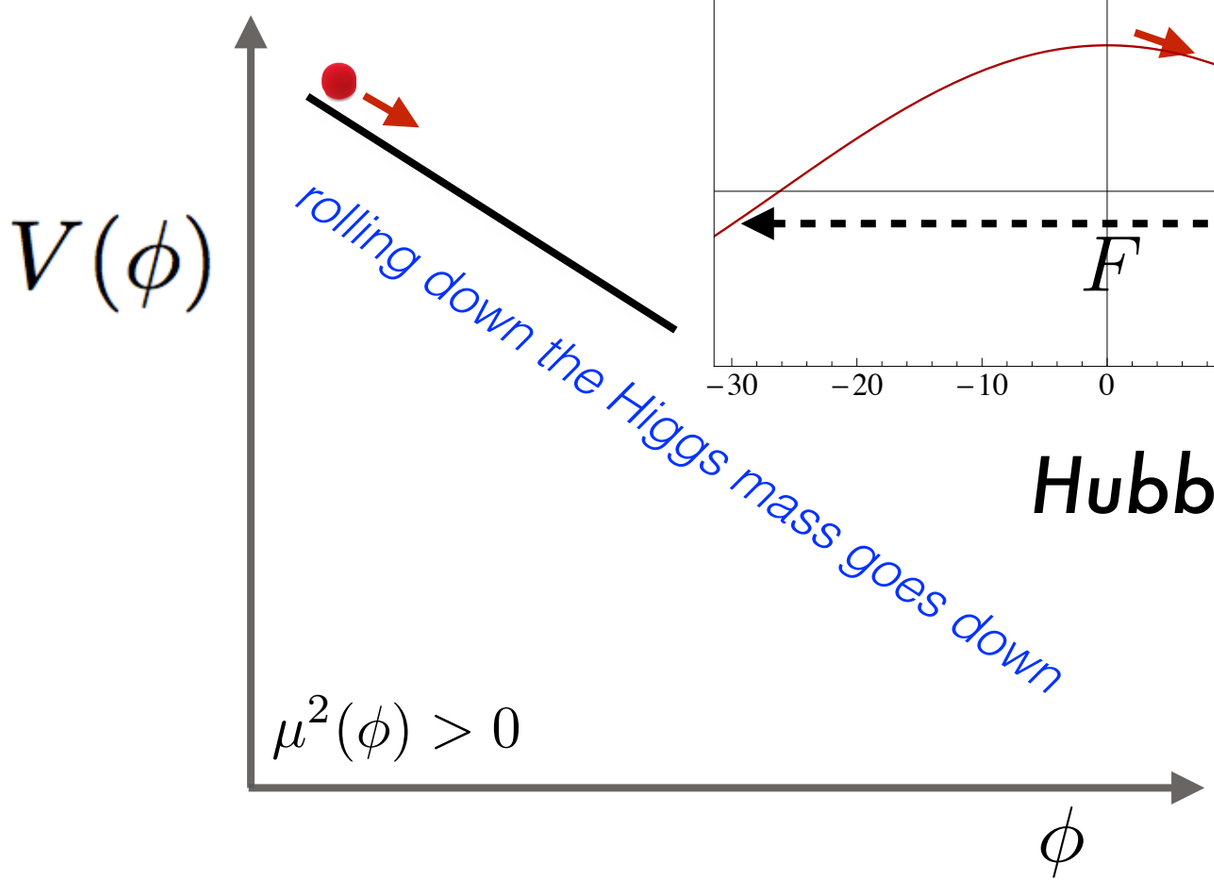

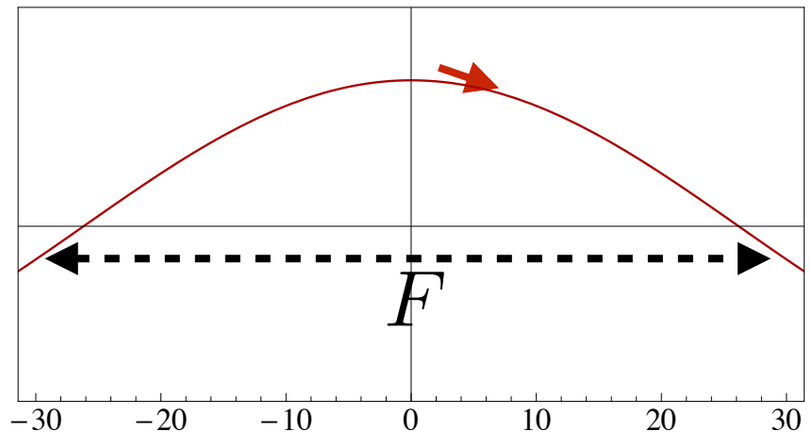

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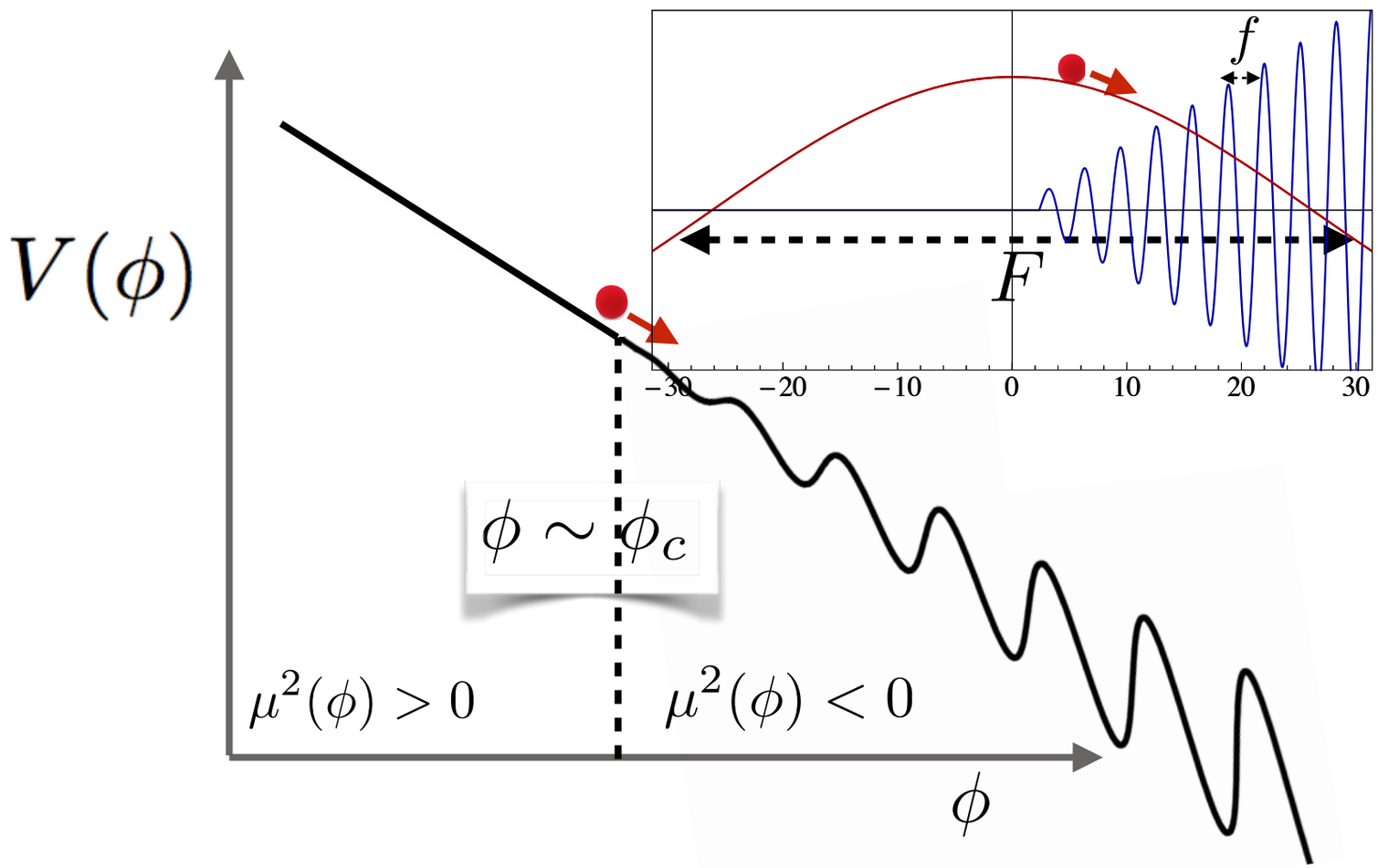
ϕ rolling potential:

$$\Lambda_{\rm roll}^4 \cos\frac{\phi}{F} \simeq \underbrace{g\Lambda_H^3\phi}\ \times \underbrace{r_{\rm roll}^2}$$

the pace of the scanning: $r_{\rm roll} \equiv \frac{\Lambda_{\rm roll}^2}{\Lambda_H^2} \gtrsim \frac{1}{4\pi}$

II

The Relaxion wiggles



ϕ gets a "backreaction" potential after EWSB

Periodicity of this potential smaller than the "rolling"

$$\Lambda_{\rm br}^4 \cos \frac{\phi}{f}$$

II

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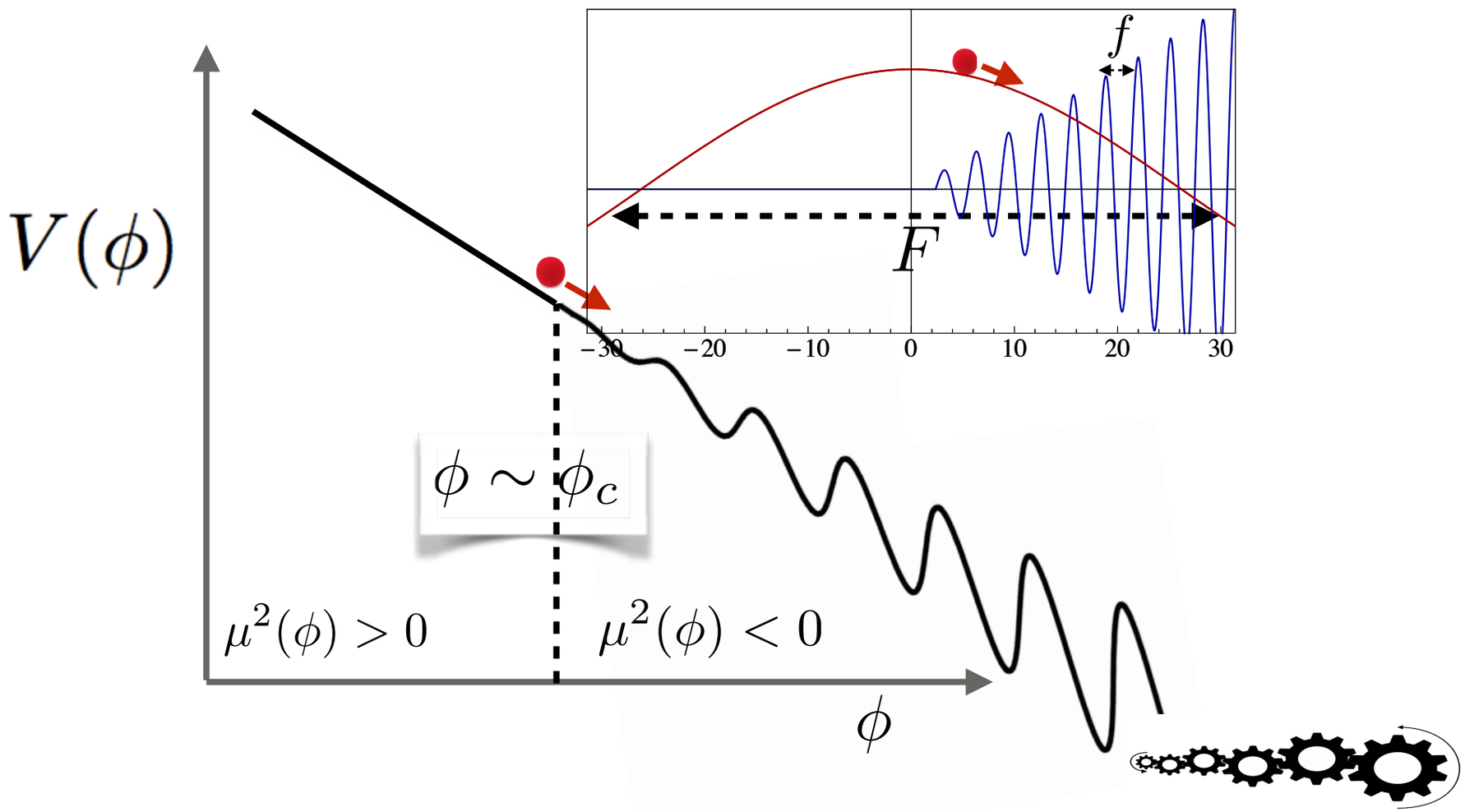


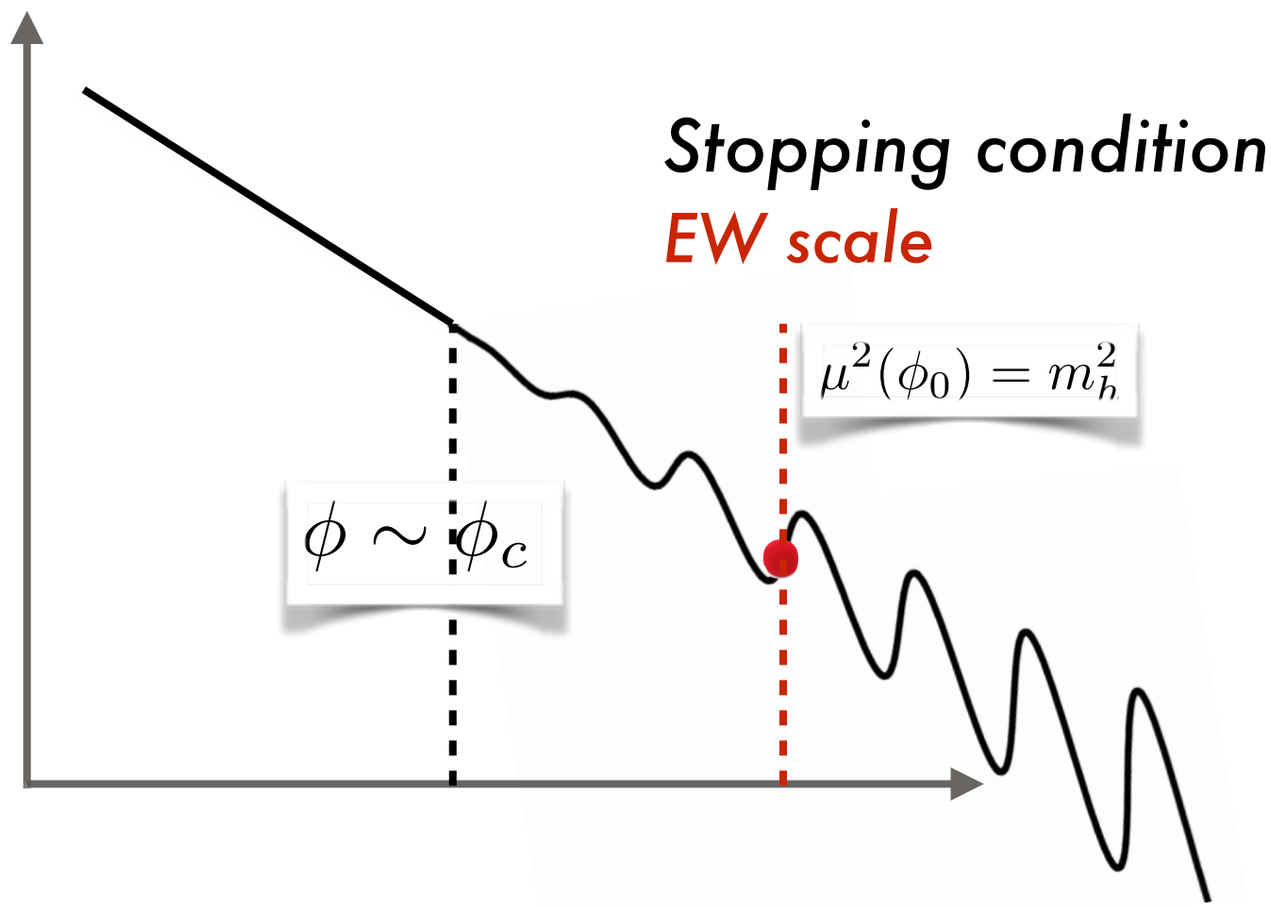
ϕ gets a "backreaction" potential after EWSB

Periodicity of this potential smaller than the "rolling"

$$\Lambda_{\rm br}^4 \cos\frac{\phi}{f} \Big\} \; \Lambda_{\rm br} \text{ model dependent}$$

$$f/F \simeq \underbrace{Q} \ll 1$$

I + II = rolling + wiggles



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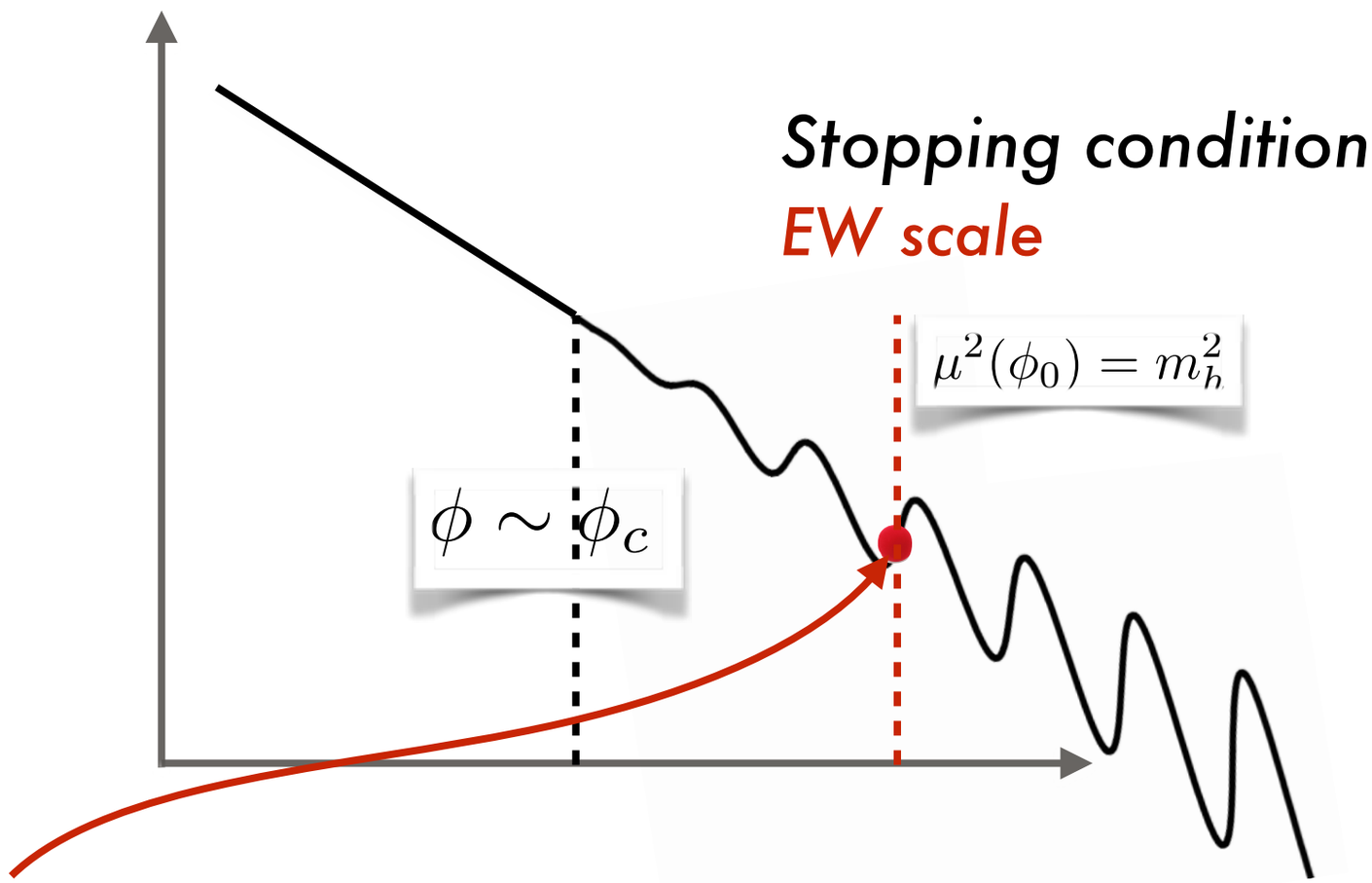

CP violating phase

$$\sin\frac{\phi_0}{f} \sim \sin\frac{\phi_0}{F} \sim \mathcal{O}(1)$$

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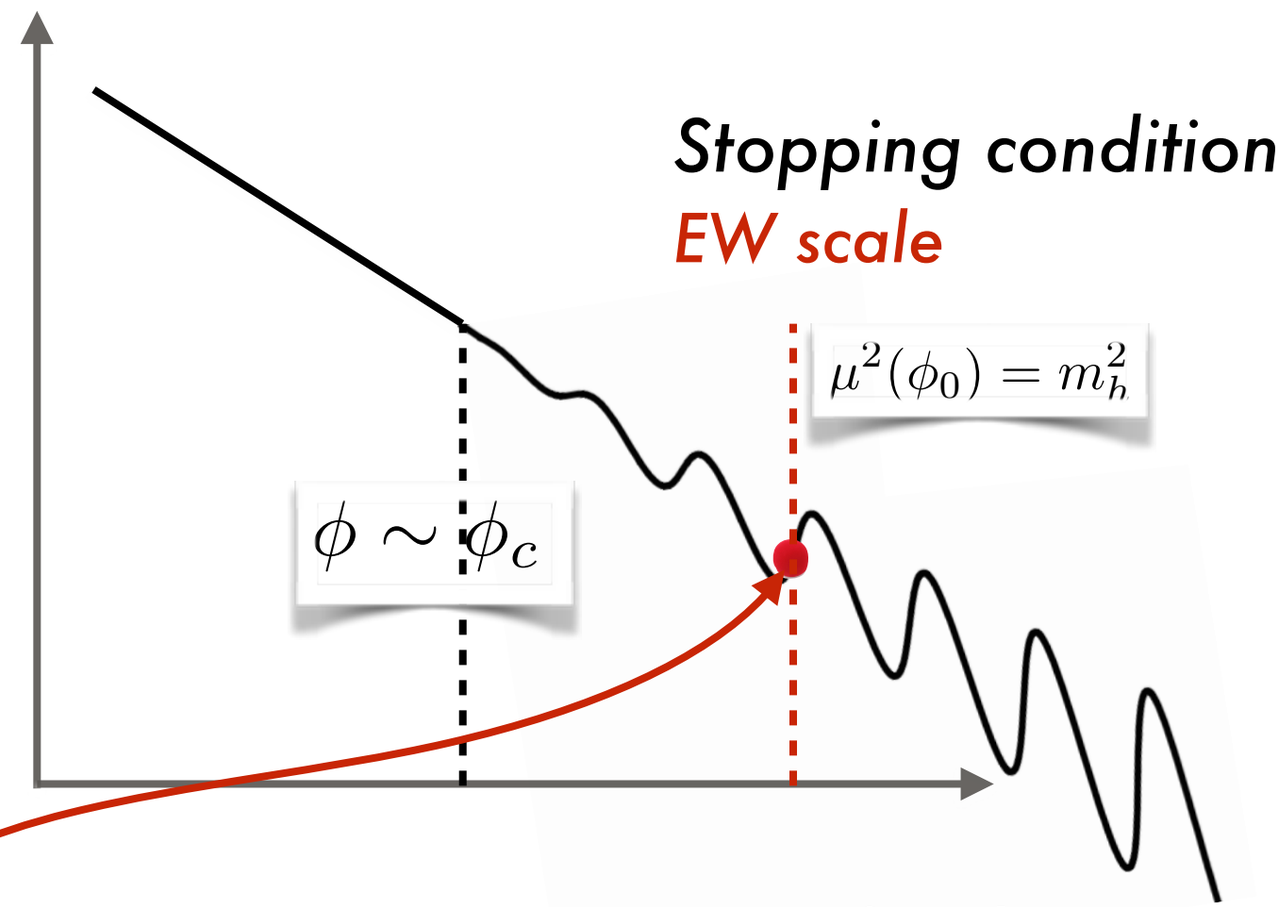

Stopping condition

EW scale

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Ratio of scales = Ratio of vevs

$$\frac{\Lambda_{\rm roll}}{\Lambda_{\rm br}} \sim \left(\frac{F}{f}\right)^{1/4}$$

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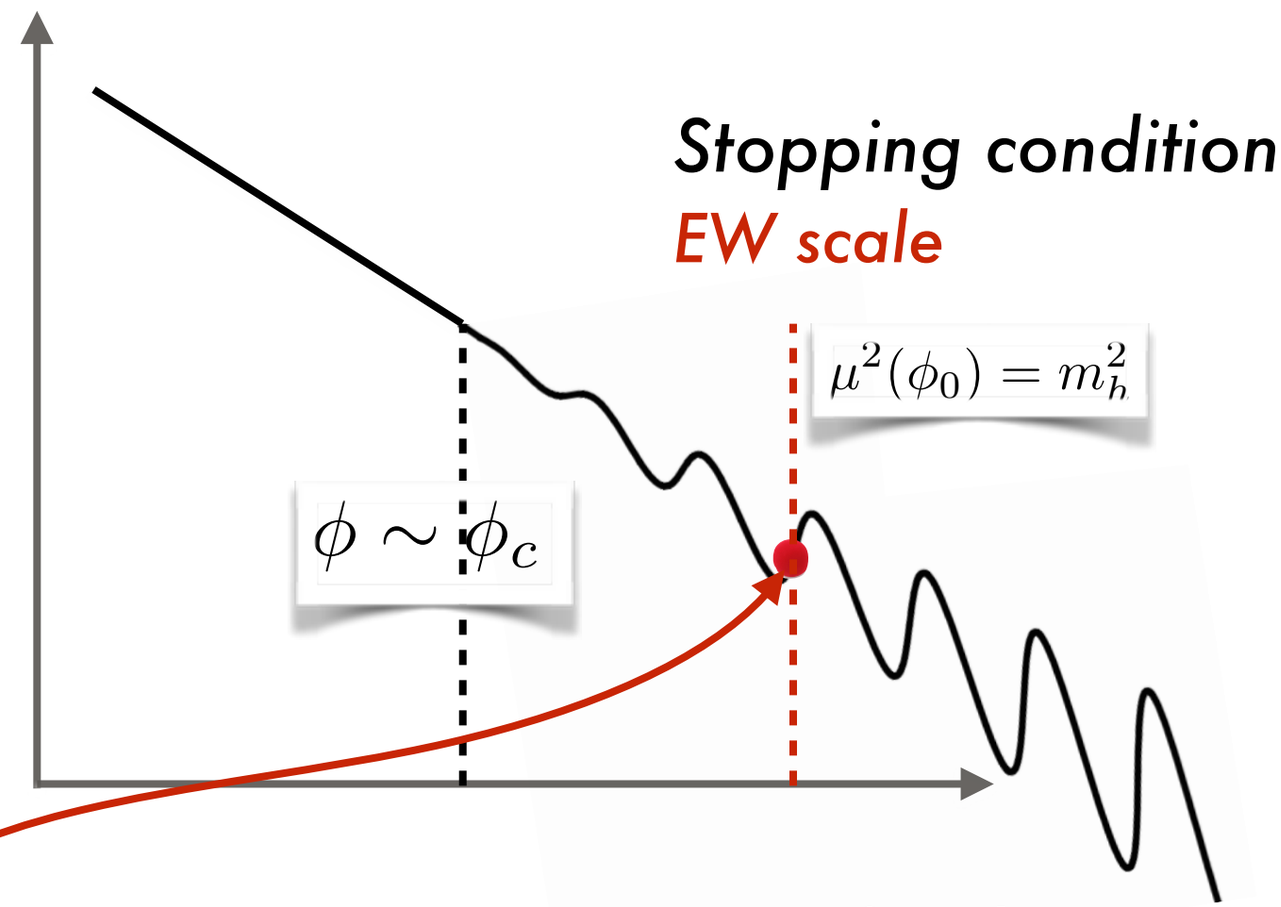

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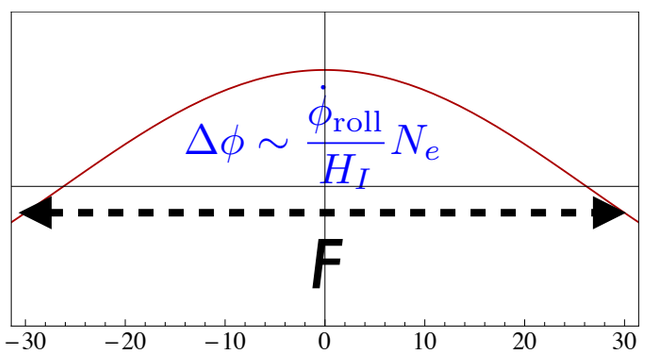
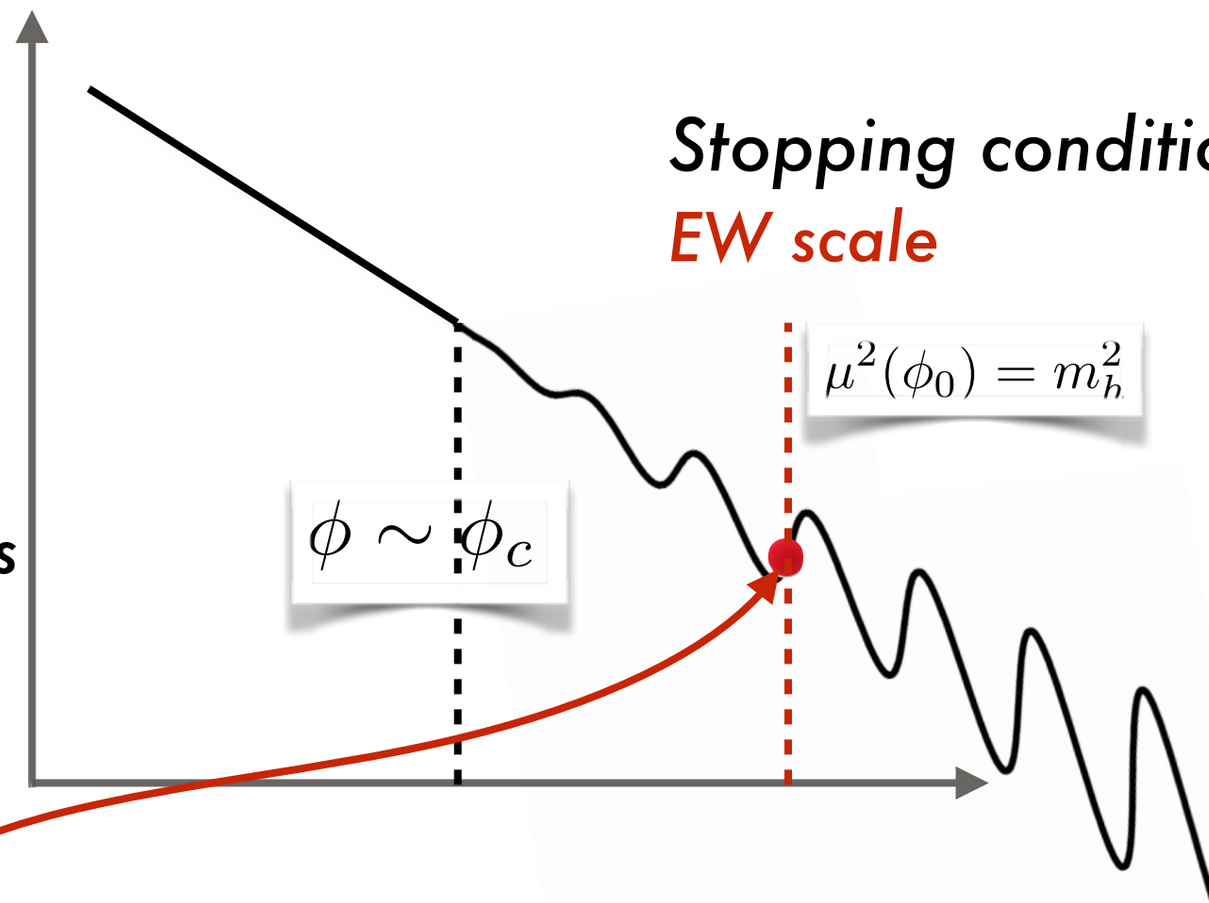
Price to pay:



huge number of e-folds

$$N_e \sim \left(\frac{F H_I}{\Lambda_{\rm roll}^2}\right)^2 \ggg 1$$



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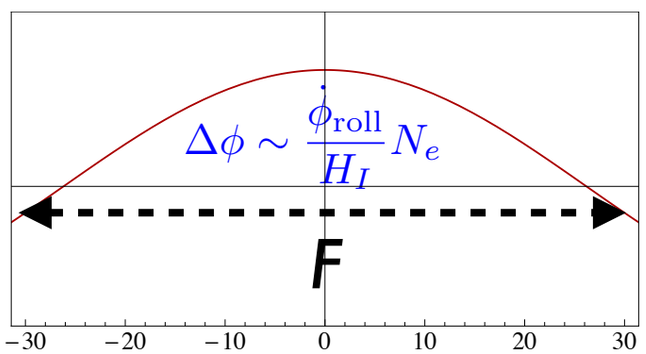

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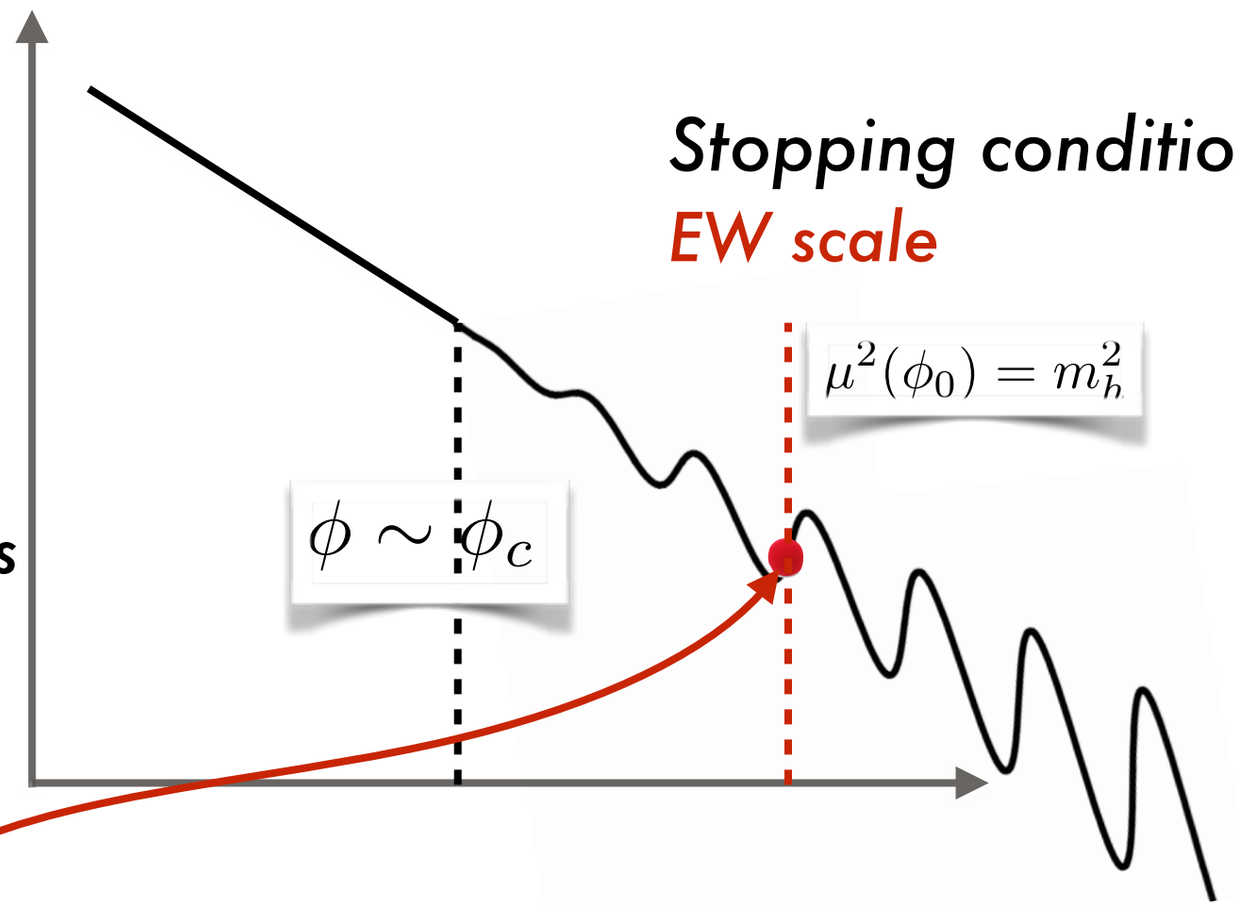

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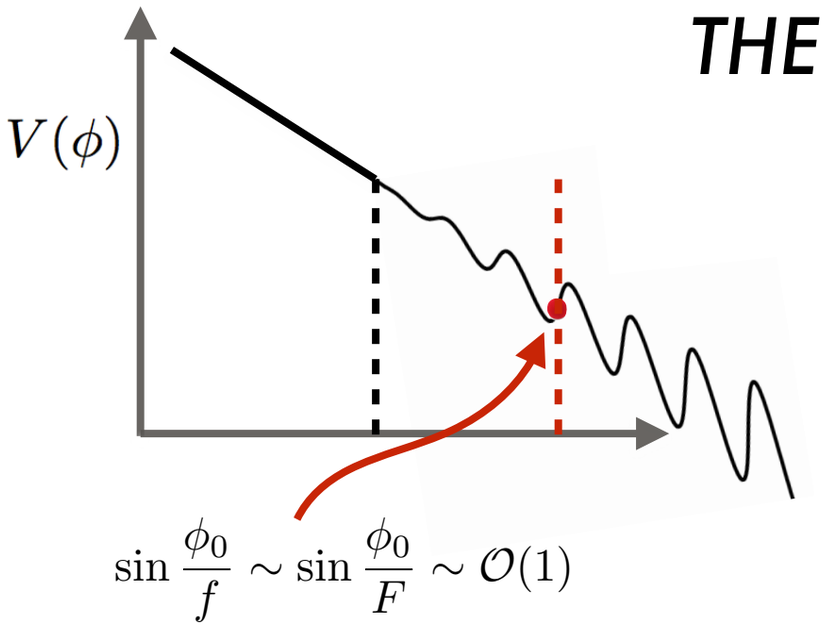
there is a price to pay for to large pace $\frac{\Lambda_H}{\Lambda_{\rm br}} \simeq 1/\sqrt{r_{\rm roll}} \cdot 1/Q$

THE RELAXION CP PROBLEM



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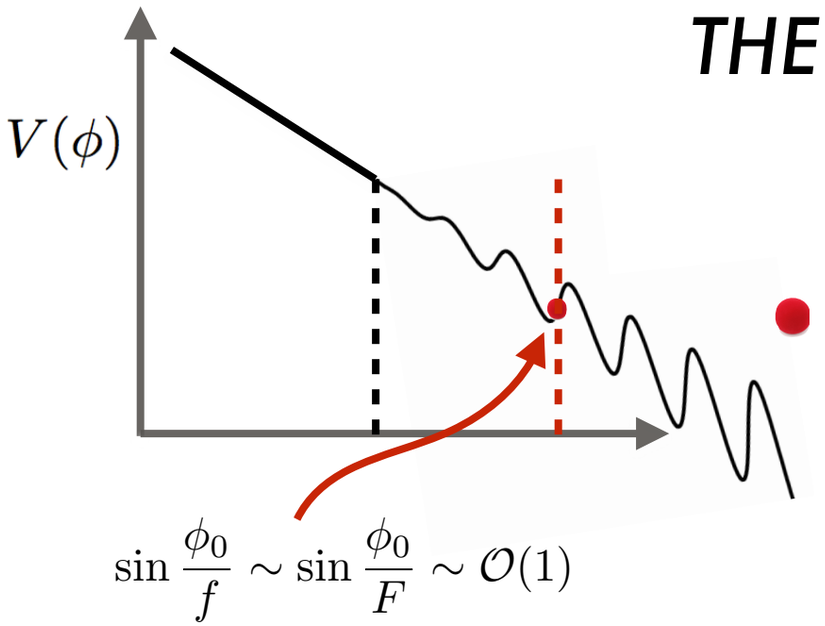

- *if classical rolling + Hubble friction set the Cosmo*

$$\dot{\phi}_{\rm roll} \gtrsim H_I^2 \qquad\qquad V_{\rm infl} \gtrsim \Delta V_{\rm roll}$$

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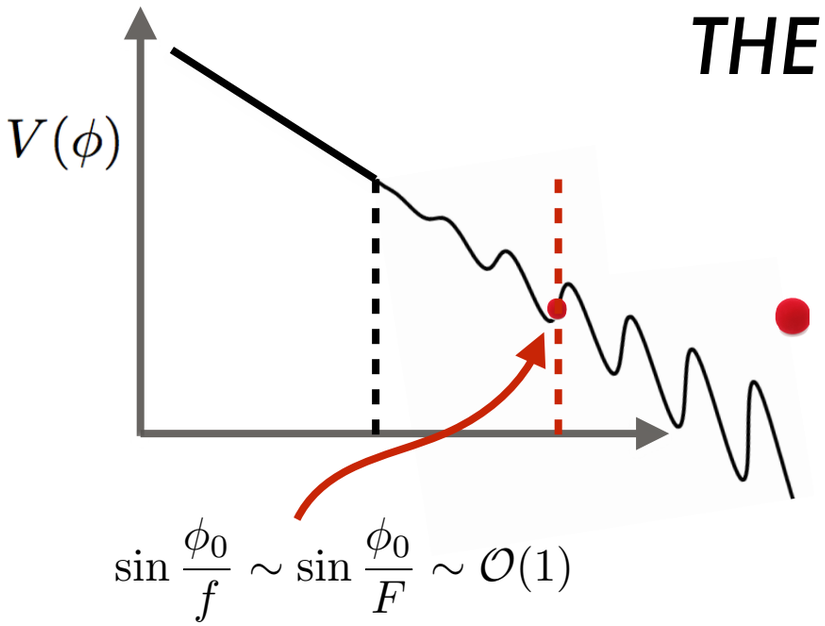

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- *if QCD anomaly generates the wiggles*

$$\frac{\phi}{f} G\tilde{G} \;\longleftrightarrow\; m_\pi^2 f_\pi^2 \cos\frac{\phi}{f} \;\longleftrightarrow\; \theta_{\rm QCD} \sim \mathcal{O}(1)$$

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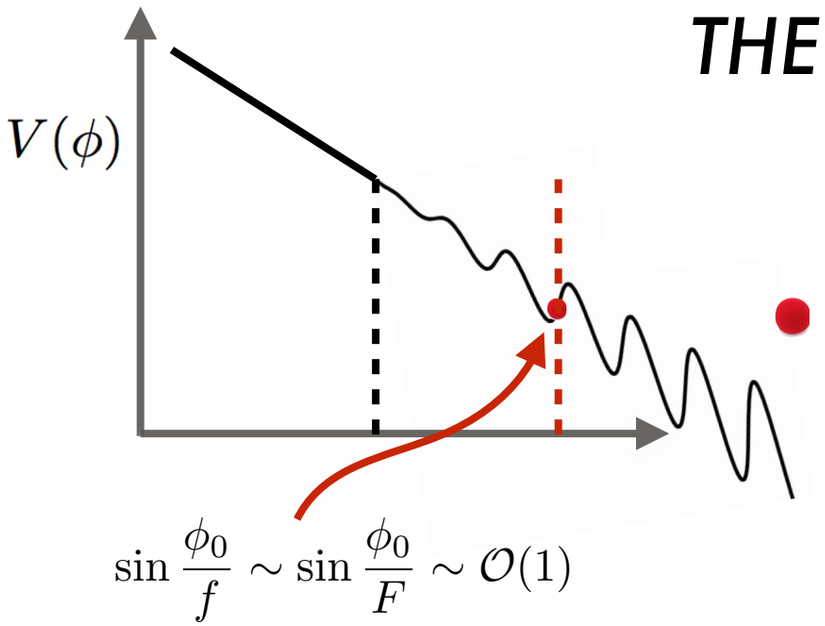

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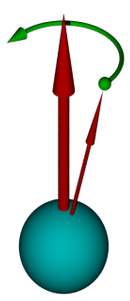

Then the relaxion is excluded by neutron EDM

$$d_n = \frac{e}{m_p}\frac{g_{\pi NN}\bar{g}_{\pi NN}}{4\pi^2}\log\frac{m_\rho}{m_\pi} \approx \theta \cdot 10^{-15}\ \text{e cm}$$

$$d_n < 10^{-26} e\ \text{cm}$$ Pendlebury '15

POSSIBLE SOLUTIONS

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- *changing the Cosmo:*

  - ★ *particle production: no slope vs wiggles* *Hook &Tavares*
  - ★ *relaxing the vev* *Graham, Kaplan & Rajendran*
  - ★ *inflation between EW & QCD PT* *Nelson & Prescod-Weinstein*

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- *changing the Field Theory:*
  - ★ *ignoring CP: no QCD anomaly* *(Gupta, Komargodski, Perez, Ubaldi)*
  - ★ *solving CP: Nelson-Barr relaxion* *(Davidi,Gupta, Perez,DR, Shalit)*

POSSIBLE SOLUTIONS

- *changing the Cosmo:*

see Nayara's talk { ★ *particle production: no slope vs wiggles* *Hook &Tavares*

if we have time… { ★ *relaxing the vev* *Graham, Kaplan & Rajendran*

★ *inflation between EW & QCD PT* *Nelson & Prescod-Weinstein*

- *changing the Field Theory:*

my focus here { ★ *ignoring CP: no QCD anomaly* *(Gupta, Komargodski, Perez, Ubaldi)*

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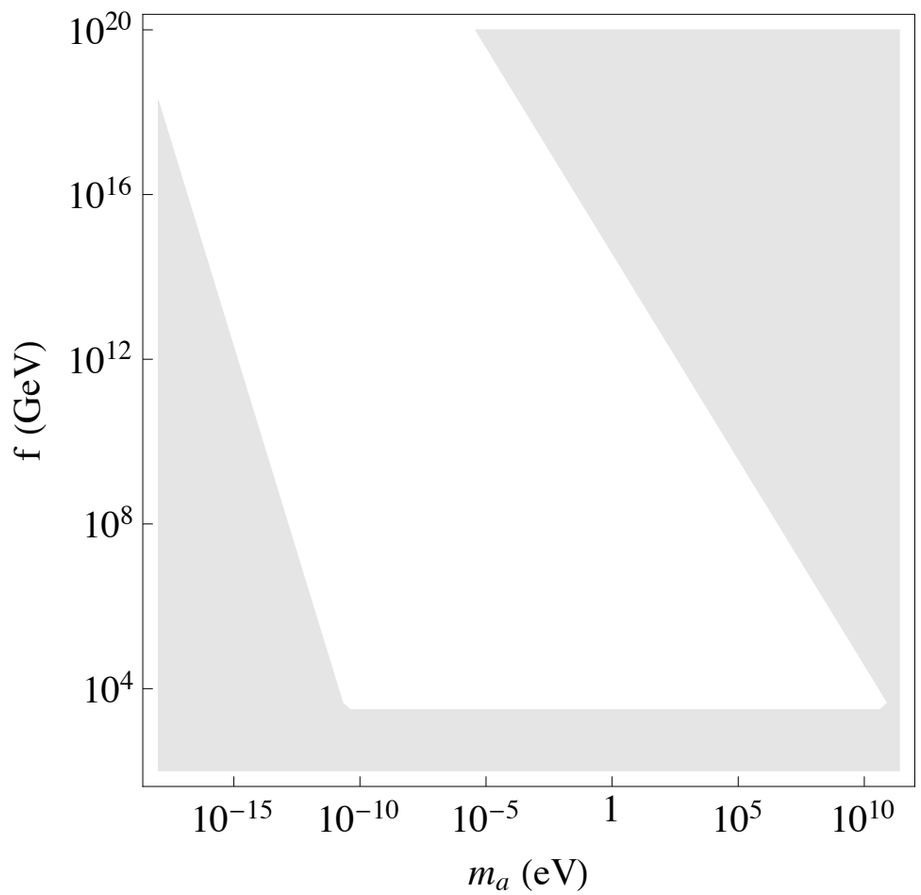
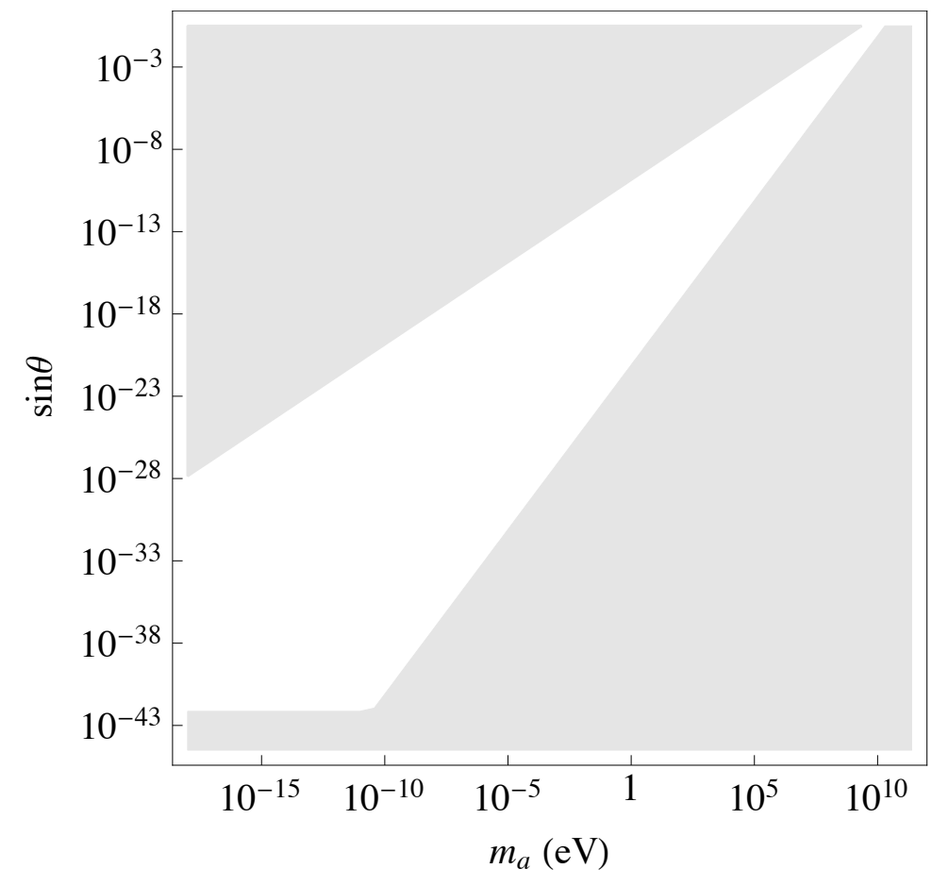
Relaxion = New Playground for Naturalness

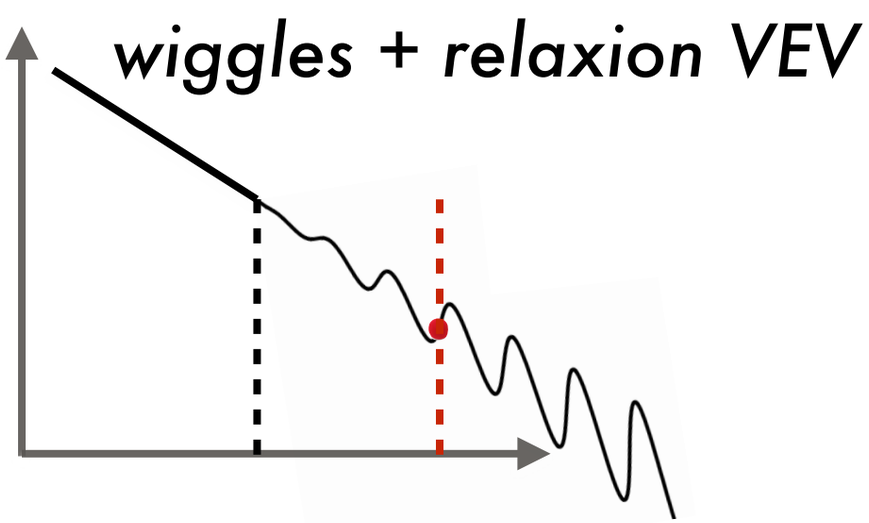
How do we test the relaxion paradigm?

The relaxion parameter space

Model-independent PHENO depends on explicit breaking from wiggles

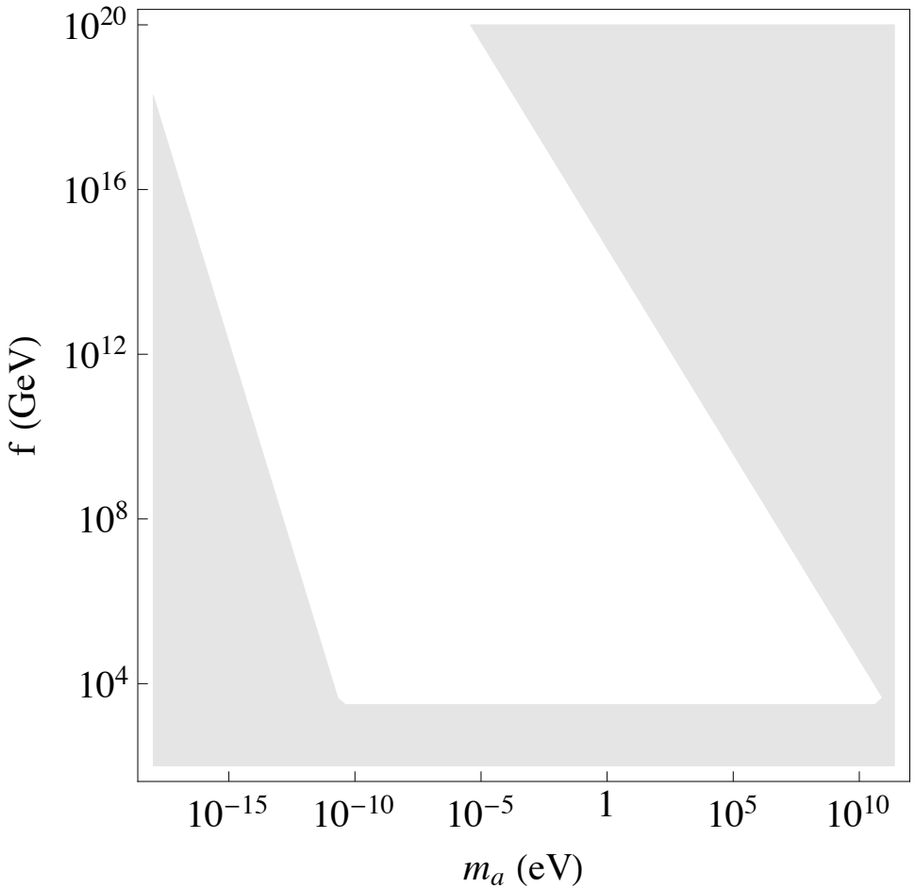


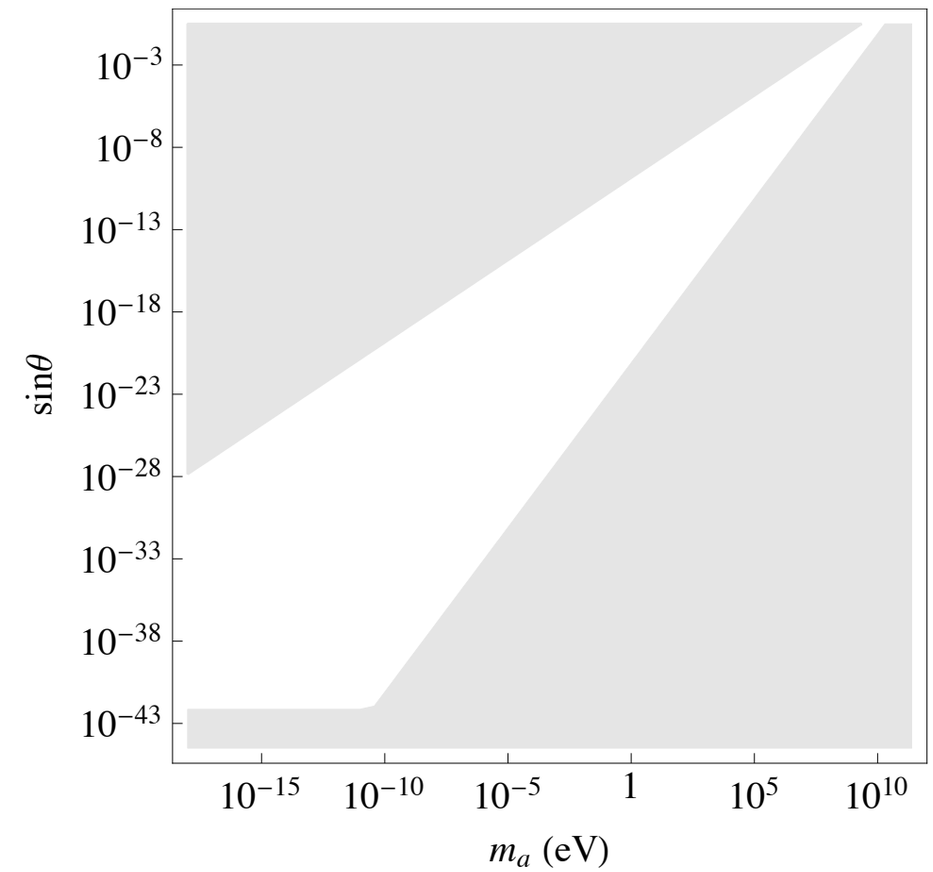


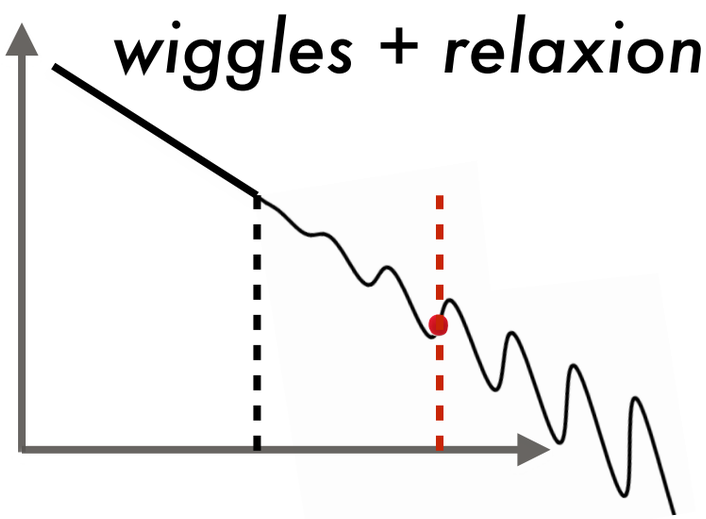


The relaxion parameter space

Model-independent PHENO depends on explicit breaking from wiggles







wiggles + relaxion VEV ---→ *relaxion mass*

$$m_a \simeq \frac{\overbrace{M_{\rm br}^2}}{f}$$

The relaxion parameter space

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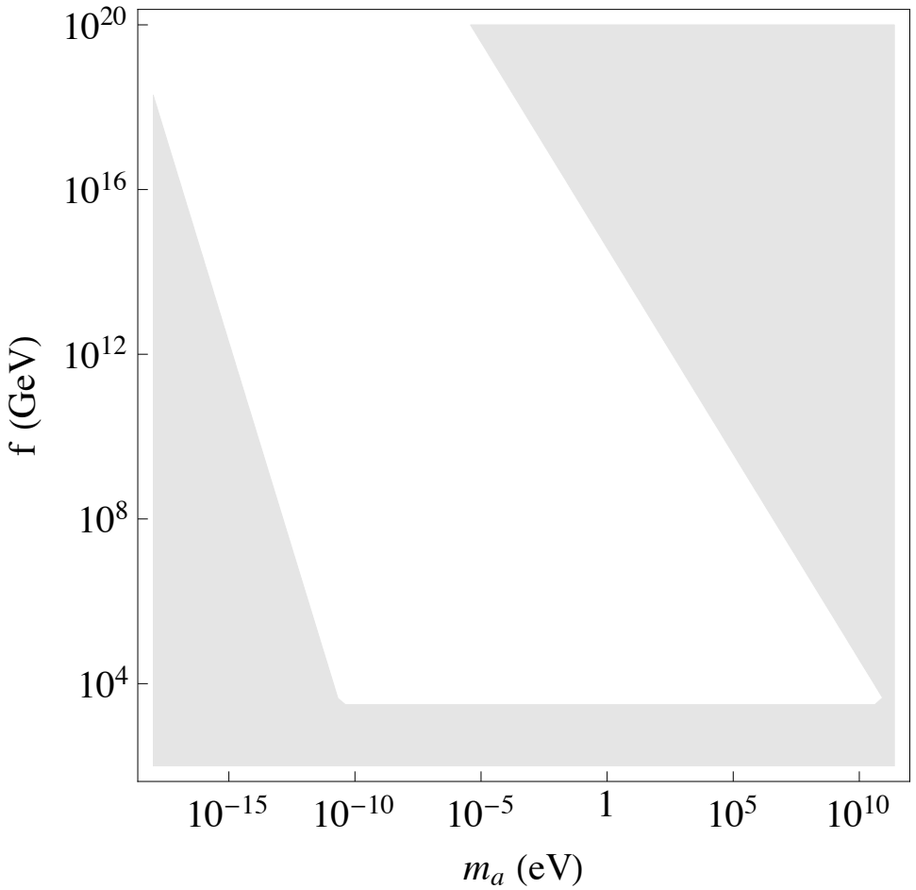
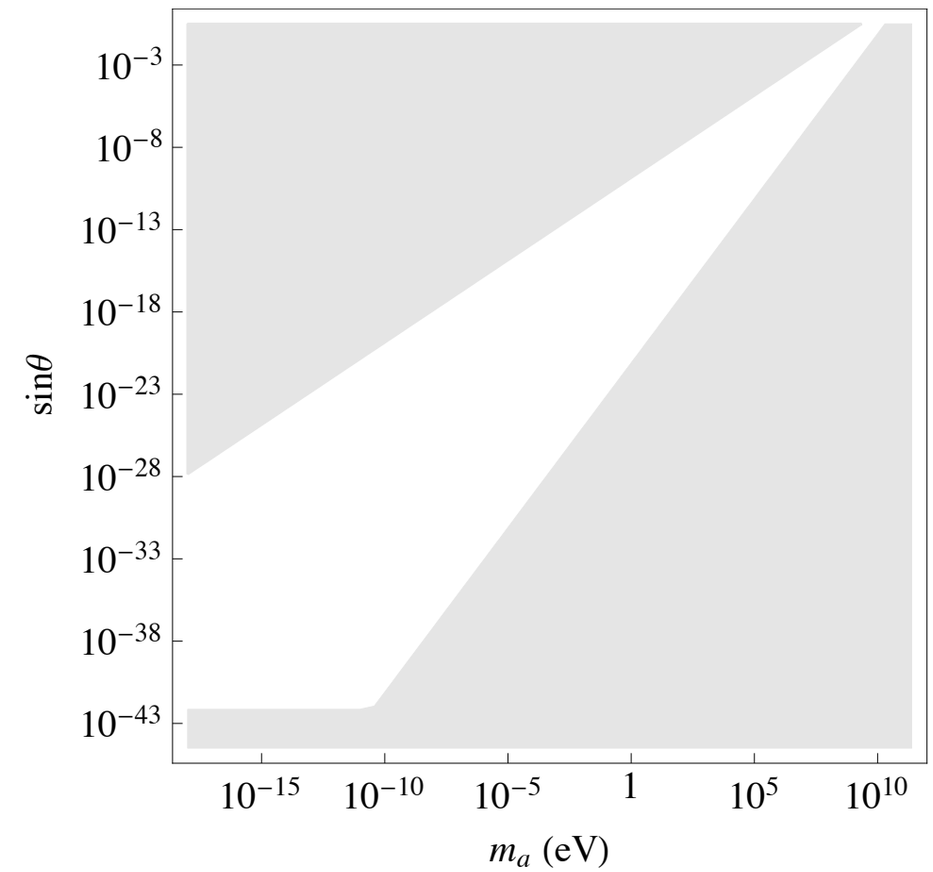
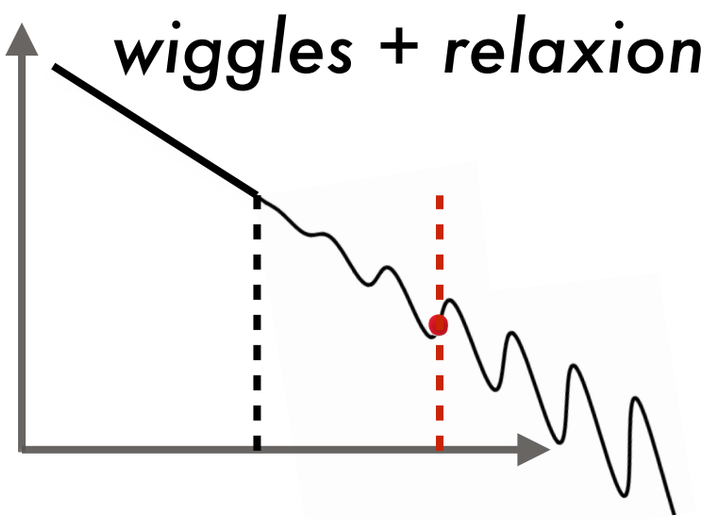






wiggles + relaxion VEV ---→ *relaxion mass* $m_a \simeq \frac{\overbrace{M_{\rm br}^2}}{f}$

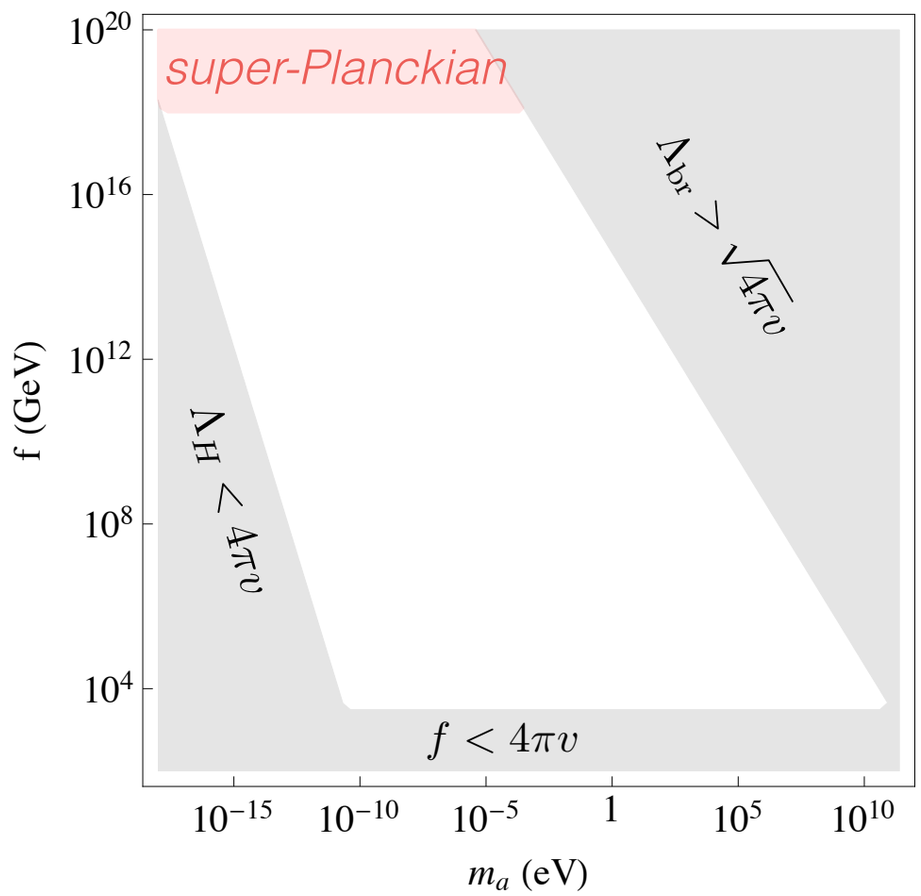
---→ *relaxion-Higgs mixing* $\sin\theta \simeq \frac{v}{f} \cdot \frac{\overbrace{M_{\rm br}^2}}{m_h^2}$

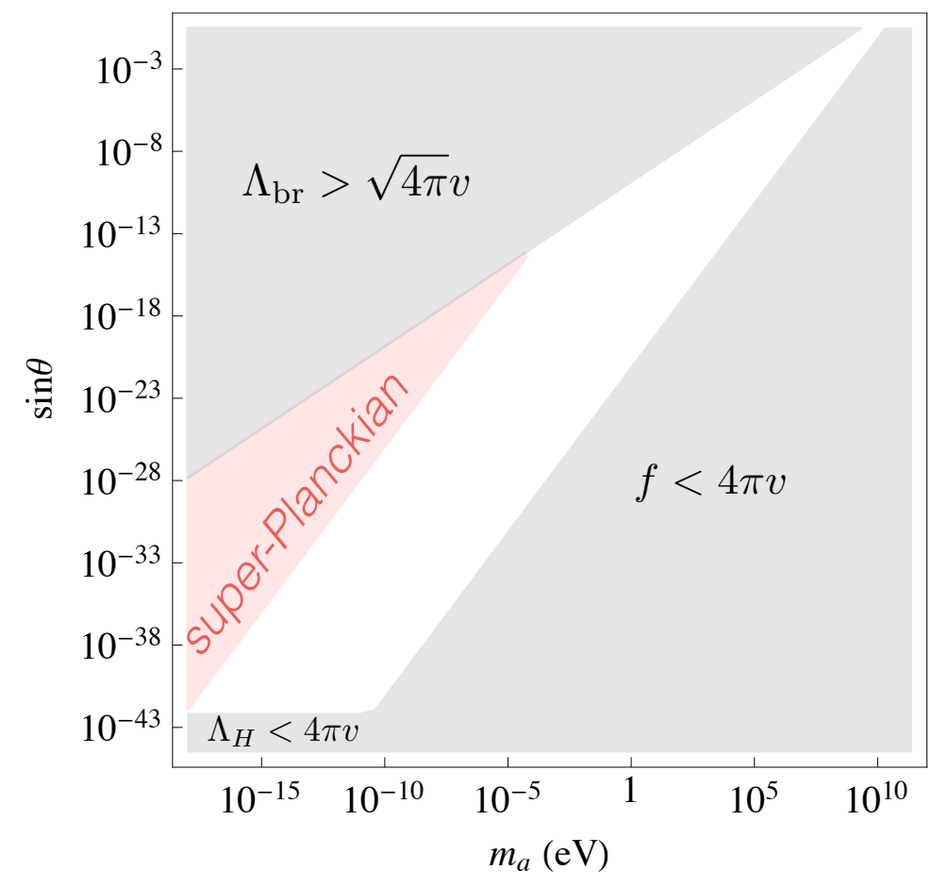
Flacke,Gupta, Frugiuele, Fuchs,Perez

Choi and Im

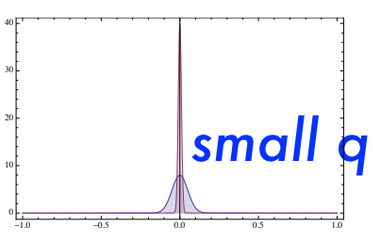
The relaxion parameter space

Model-independent boundaries





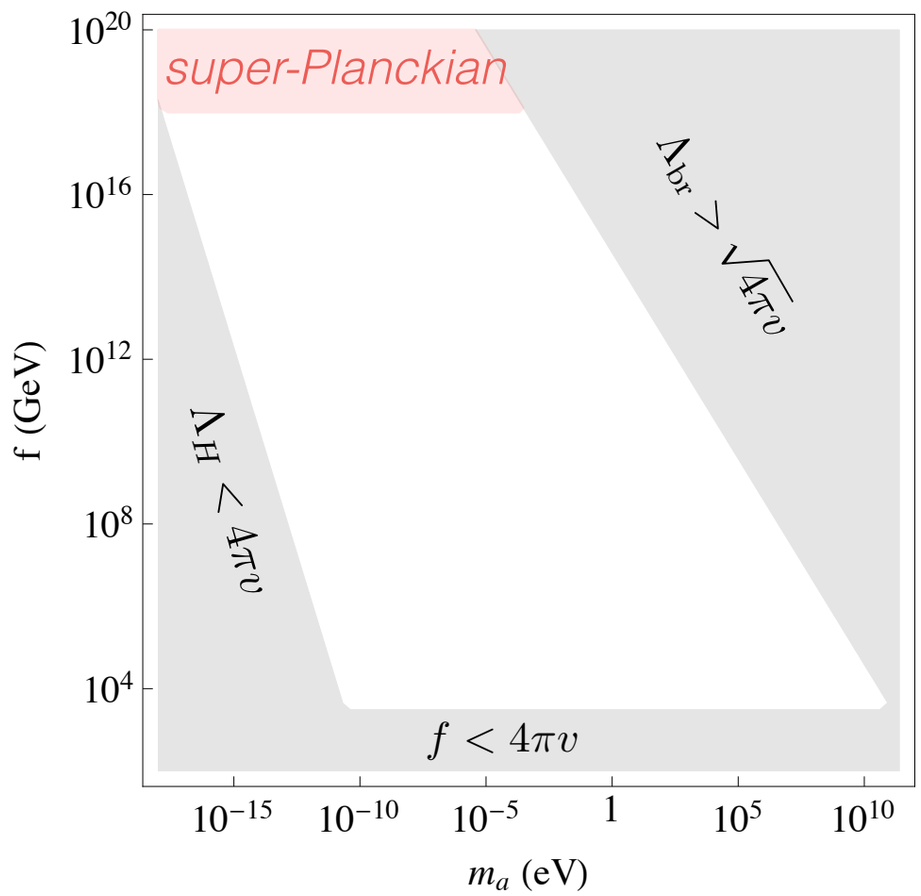
inflation OK $\Lambda_{\rm roll}^4 \lesssim H_I^2 M_{\rm Pl}^2$

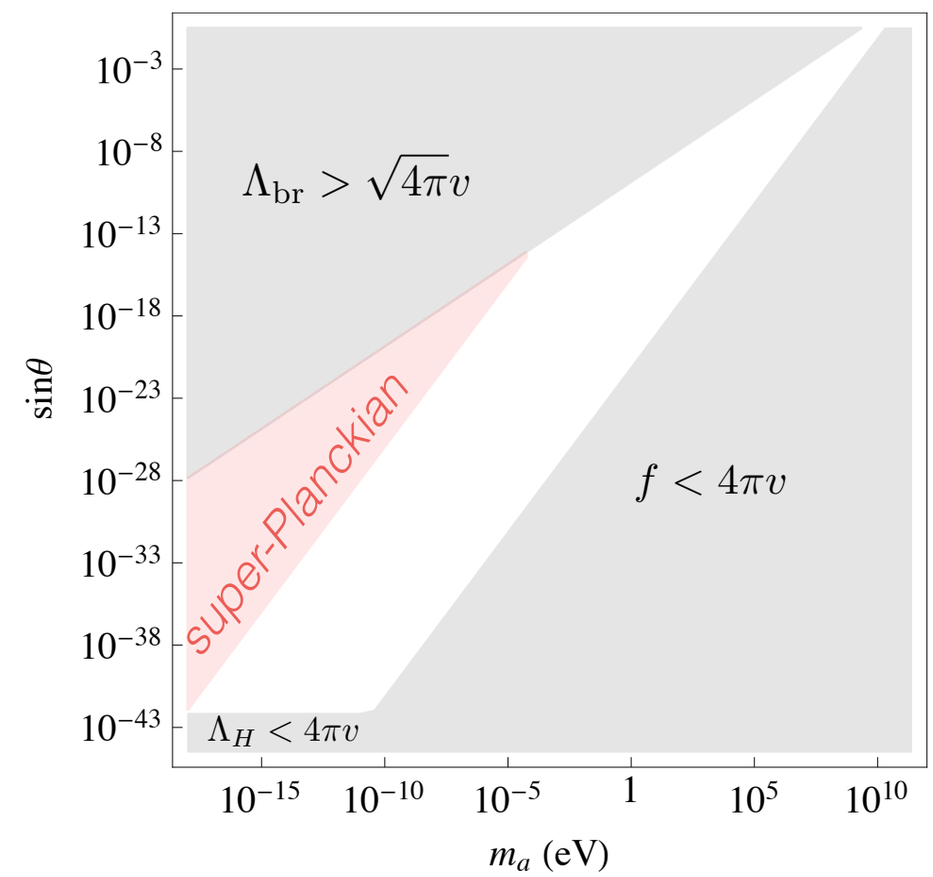


small quantum spread $\dot{\phi} \gtrsim H_I^2$

The relaxion parameter space

Model-independent boundaries





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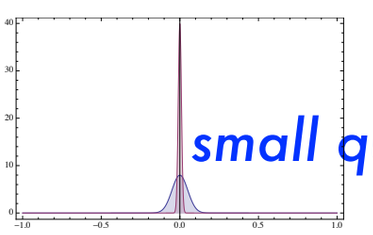

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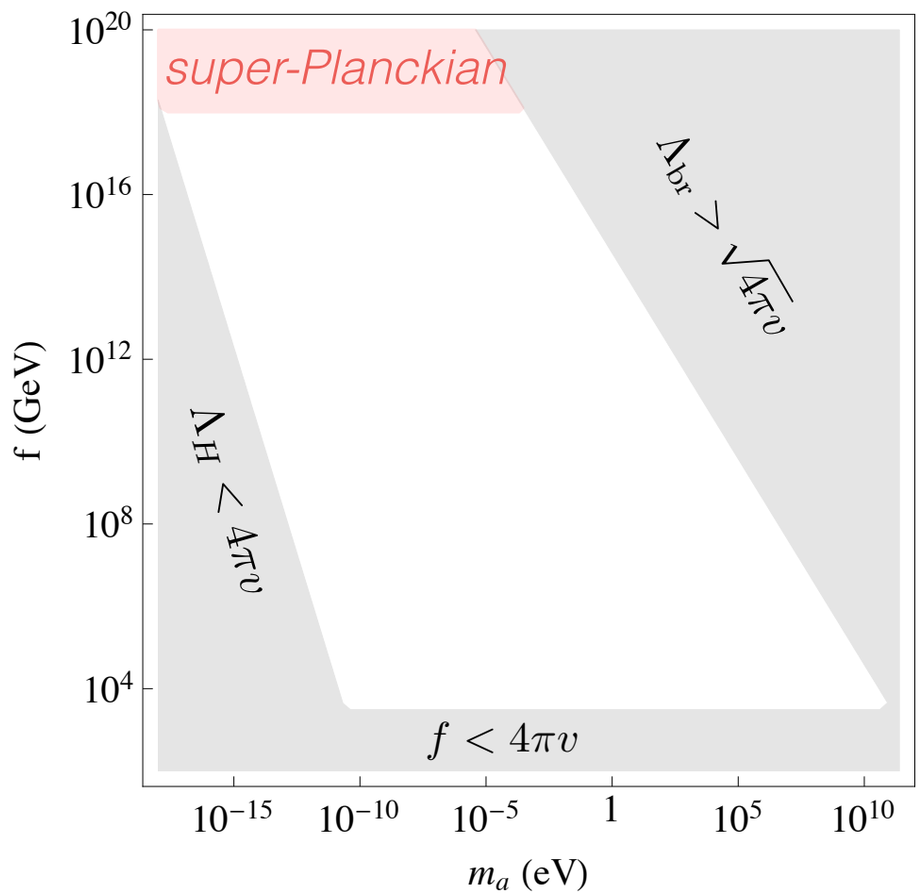
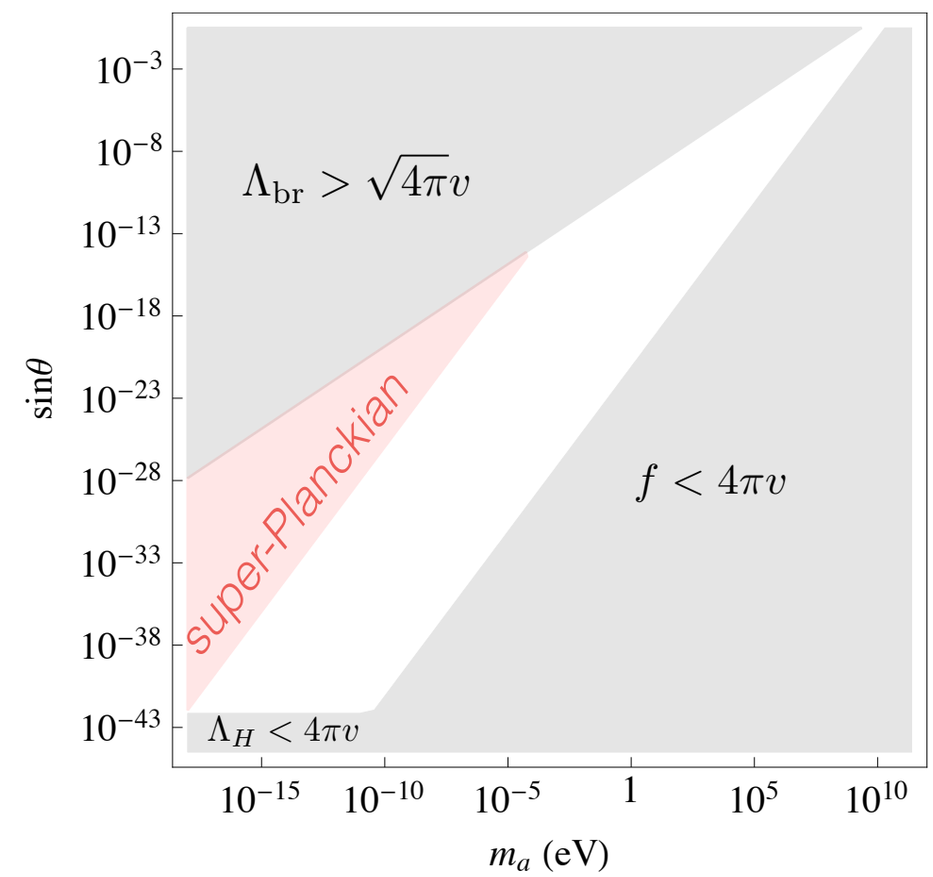
$$\begin{cases} 4\pi v \lesssim \Lambda_H \lesssim \left(\dfrac{M_{\rm Pl}}{r_{\rm roll}}\right)^{1/2} \left(\dfrac{\Lambda_{\rm br}^4}{f}\right)^{1/6} \\ \sqrt{\dfrac{M_{\rm Pl}}{f}} \cdot 10^{-18}\ \text{eV} \lesssim m_a \lesssim v \end{cases}$$

The relaxion parameter space

Model-independent boundaries





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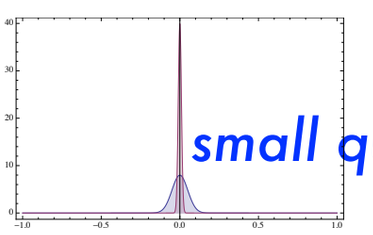


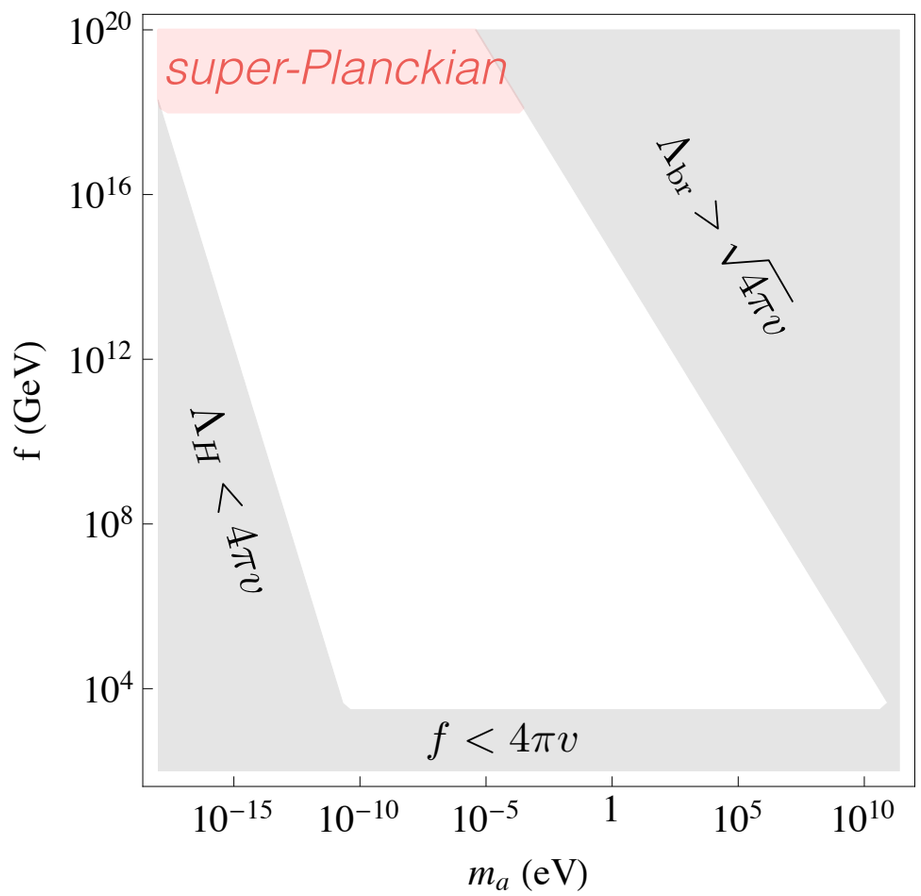
small quantum spread $\dot{\phi} \gtrsim H_I^2$

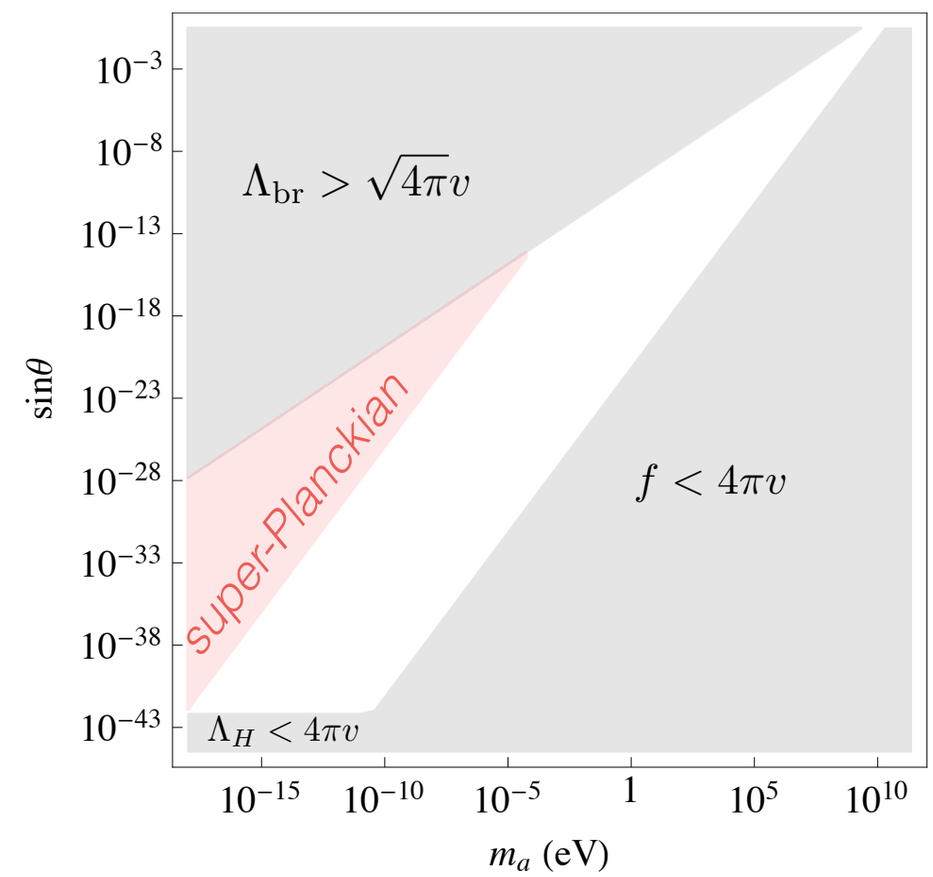
$$\begin{cases} 4\pi v \lesssim \Lambda_H \lesssim \underbrace{\left(\frac{M_{\rm Pl}}{r_{\rm roll}}\right)^{1/2} \left(\frac{\Lambda_{\rm br}^4}{f}\right)^{1/6}} \\ \sqrt{\frac{M_{\rm Pl}}{f}} \cdot 10^{-18}\ {\rm eV} \lesssim m_a \lesssim v \end{cases}$$

maximal gain in cut-off

The relaxion parameter space

Model-independent boundaries





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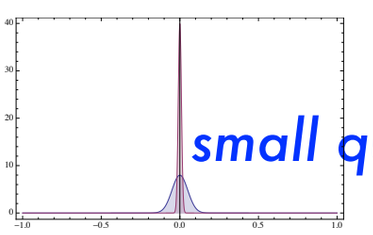

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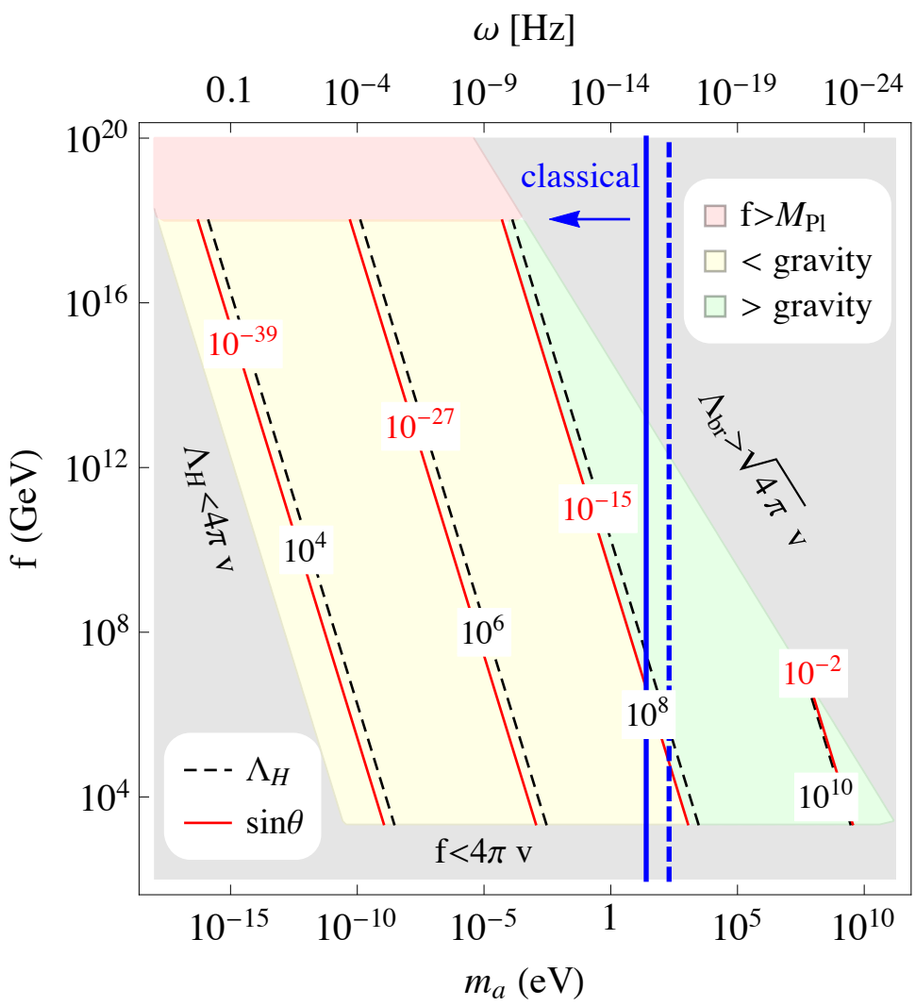
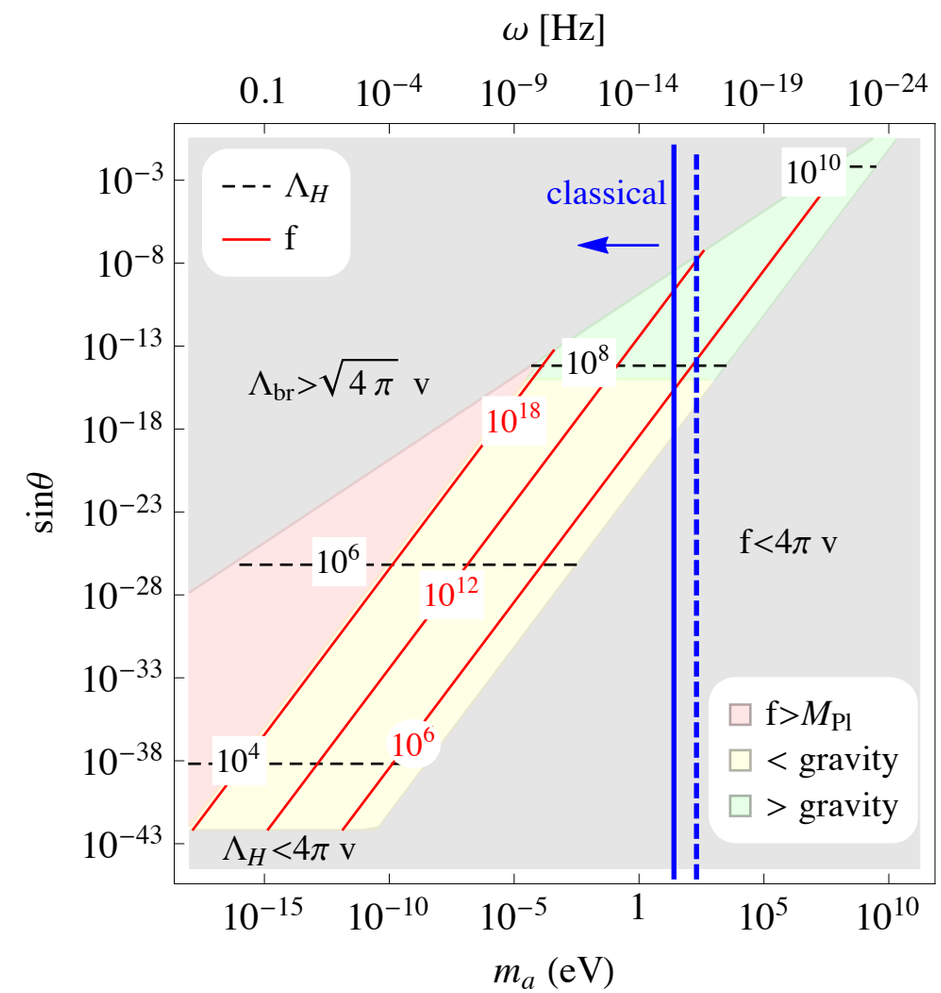
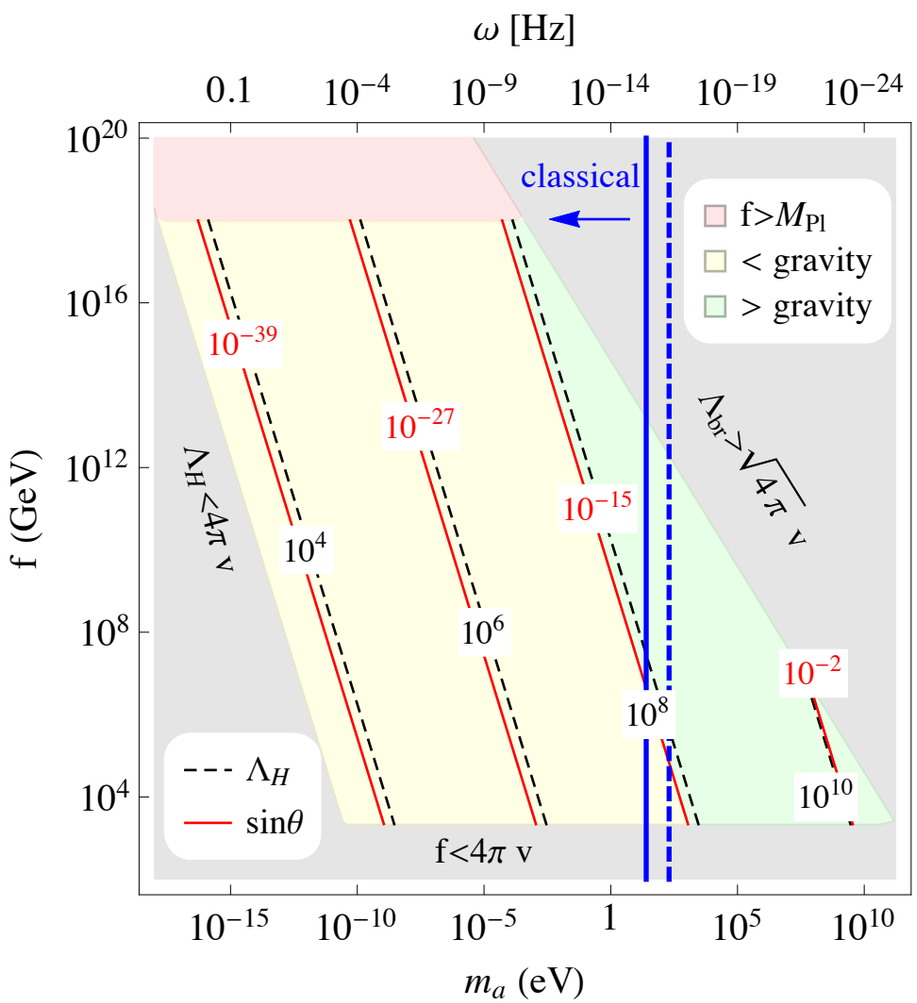


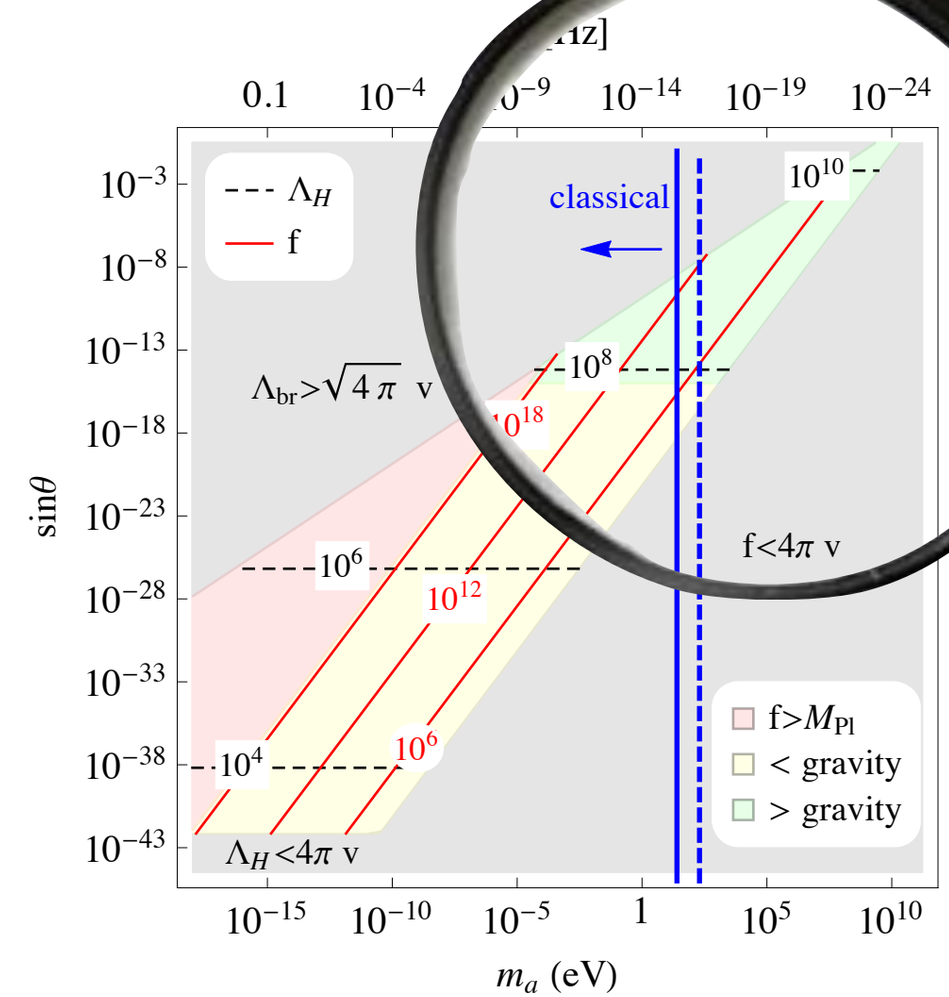


highest cut-off ⟷ *highest mixing*

TESTABLE SETUP

The relaxion parameter space





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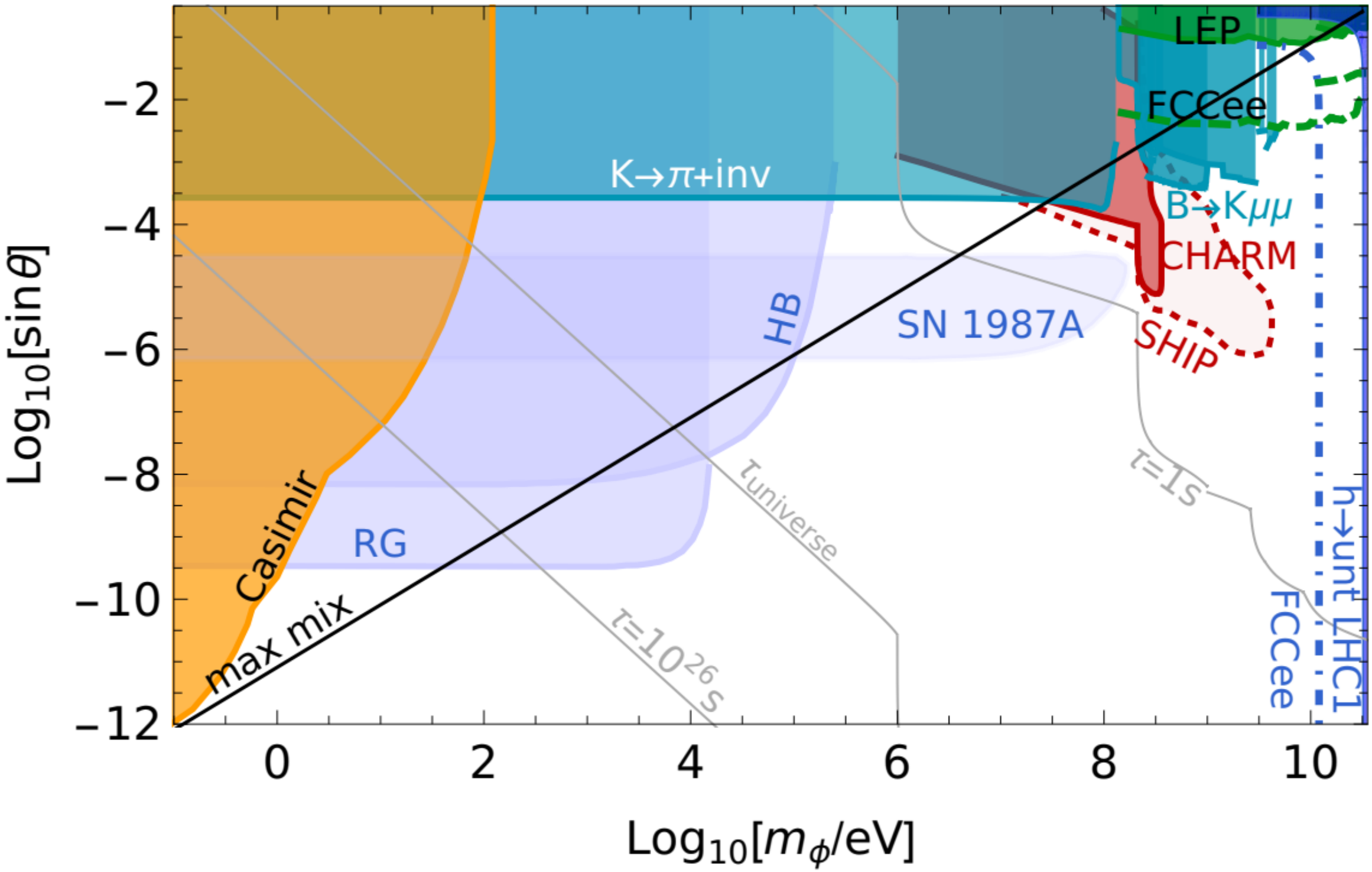
TESTABLE SETUP

The Phenomenology is the one of a light Higgs portal

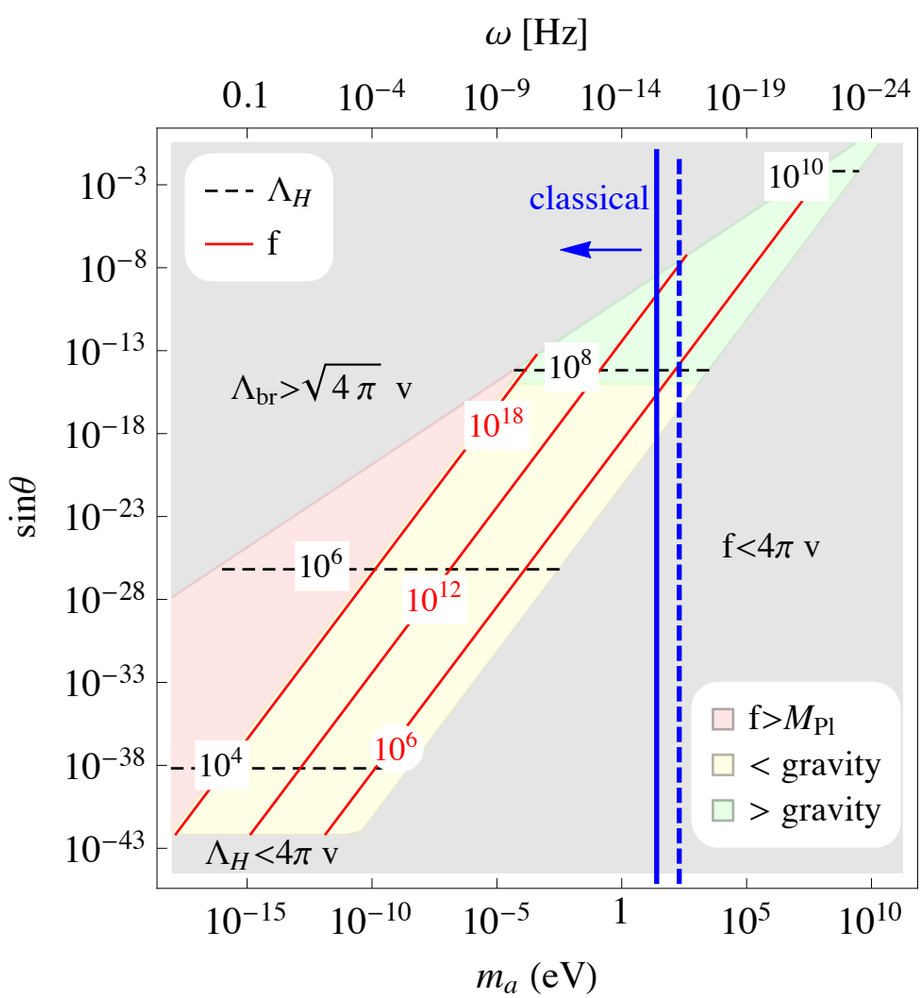
Frugiuele, Fuchs,Perez,Schlaffer



Can the Relaxion be a relic?

if produced cold (misalignment, during inflation etc..) it would be a classical background

$$m_\phi \lesssim 10 \text{ eV}$$



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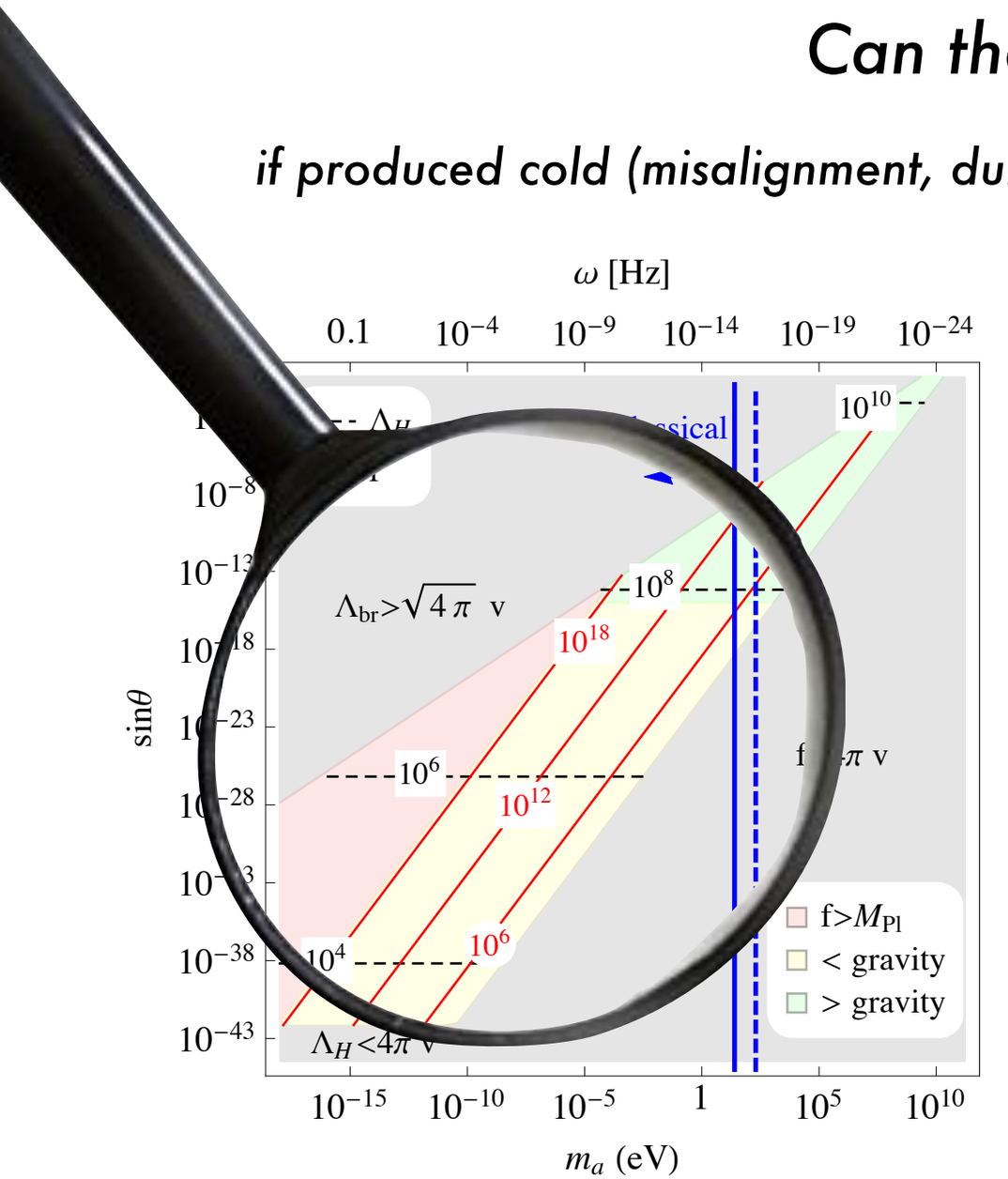

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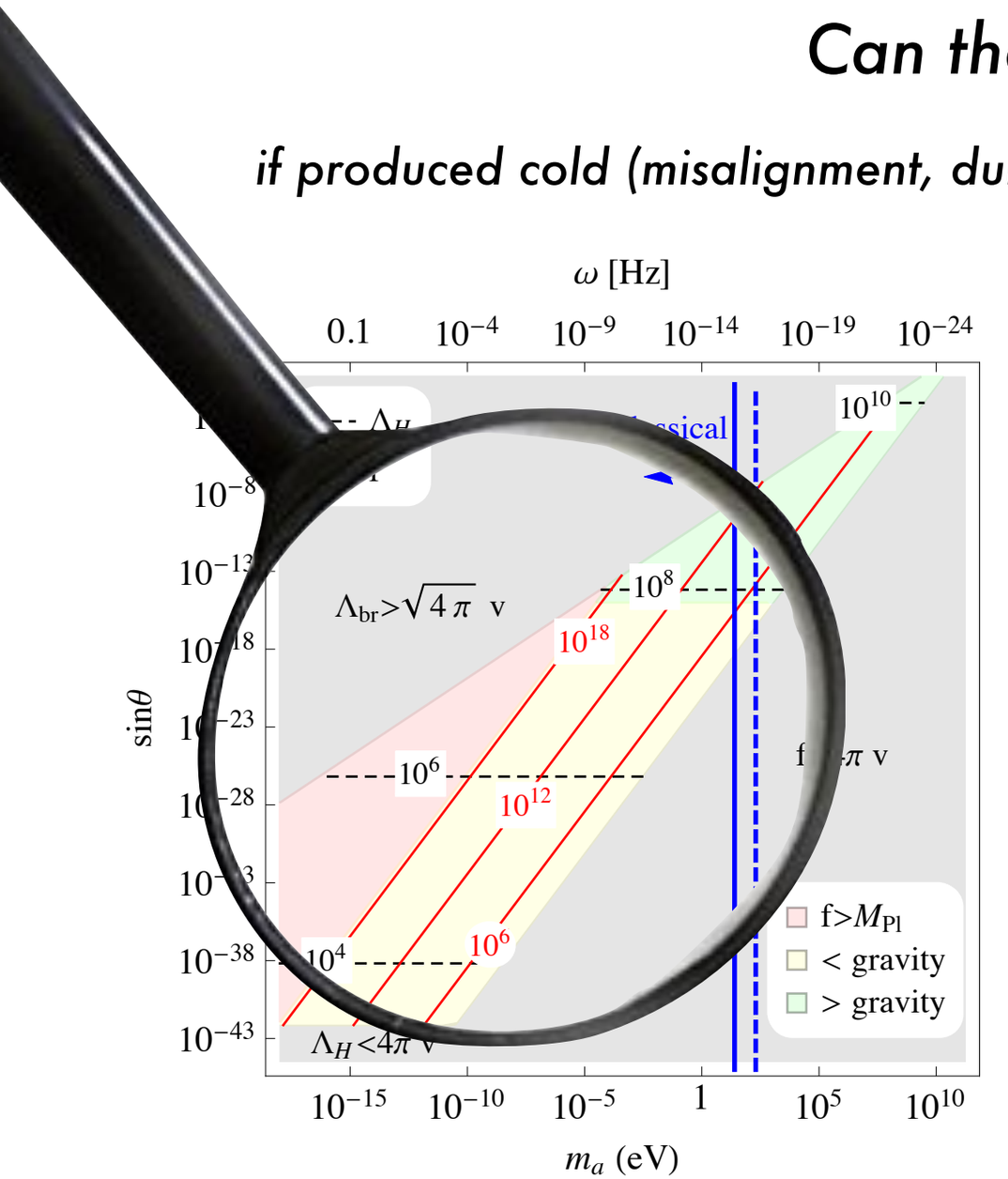

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- *atomic clock experiments*
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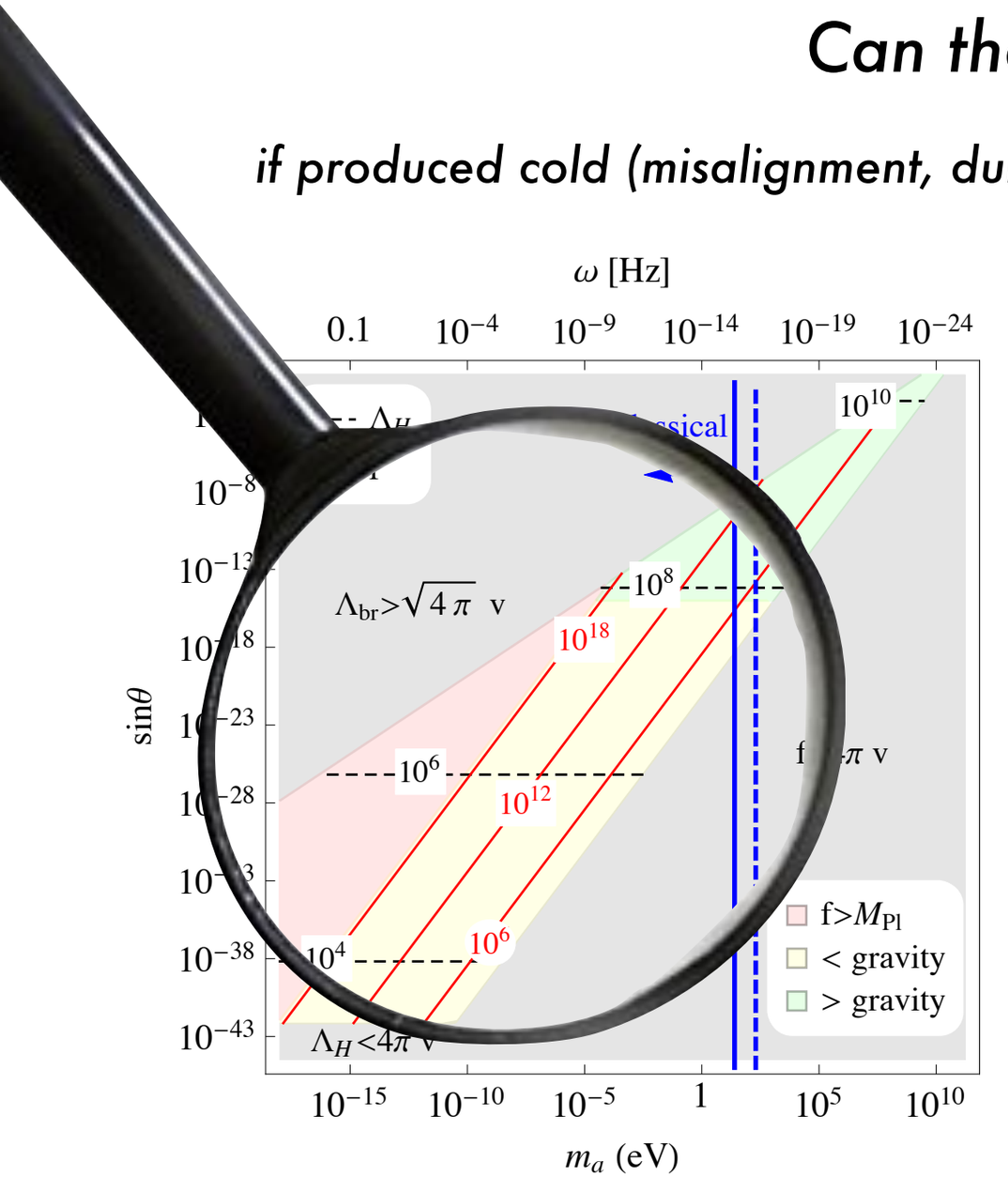
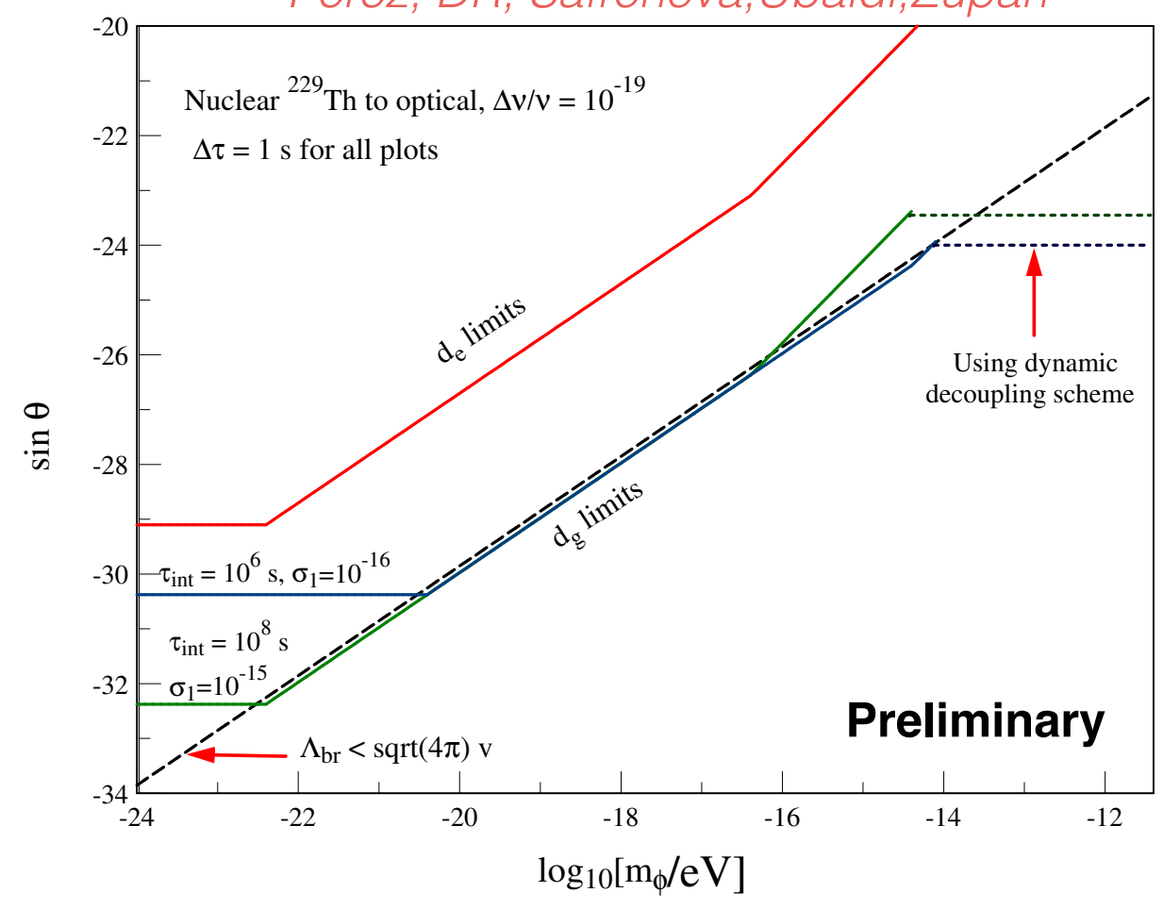


Perez, DR, Safronova,Ubaldi,Zupan



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The Nelson Barr relaxion

$$\phi_0 \sim \delta_{\rm CKM}$$ *(see Gilad's talk)*

narrows down the relaxion parameter space

(certainly not the only way but it is one well motivated way)

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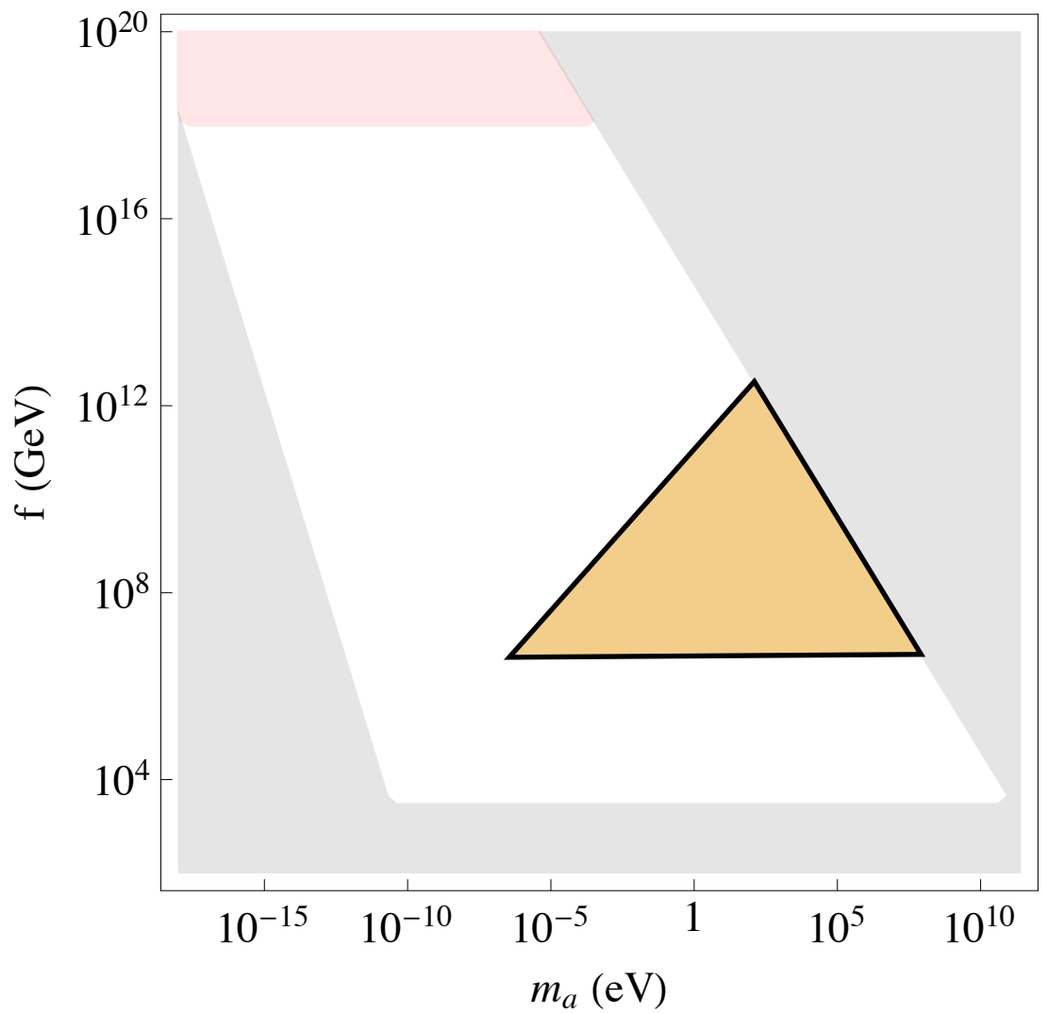
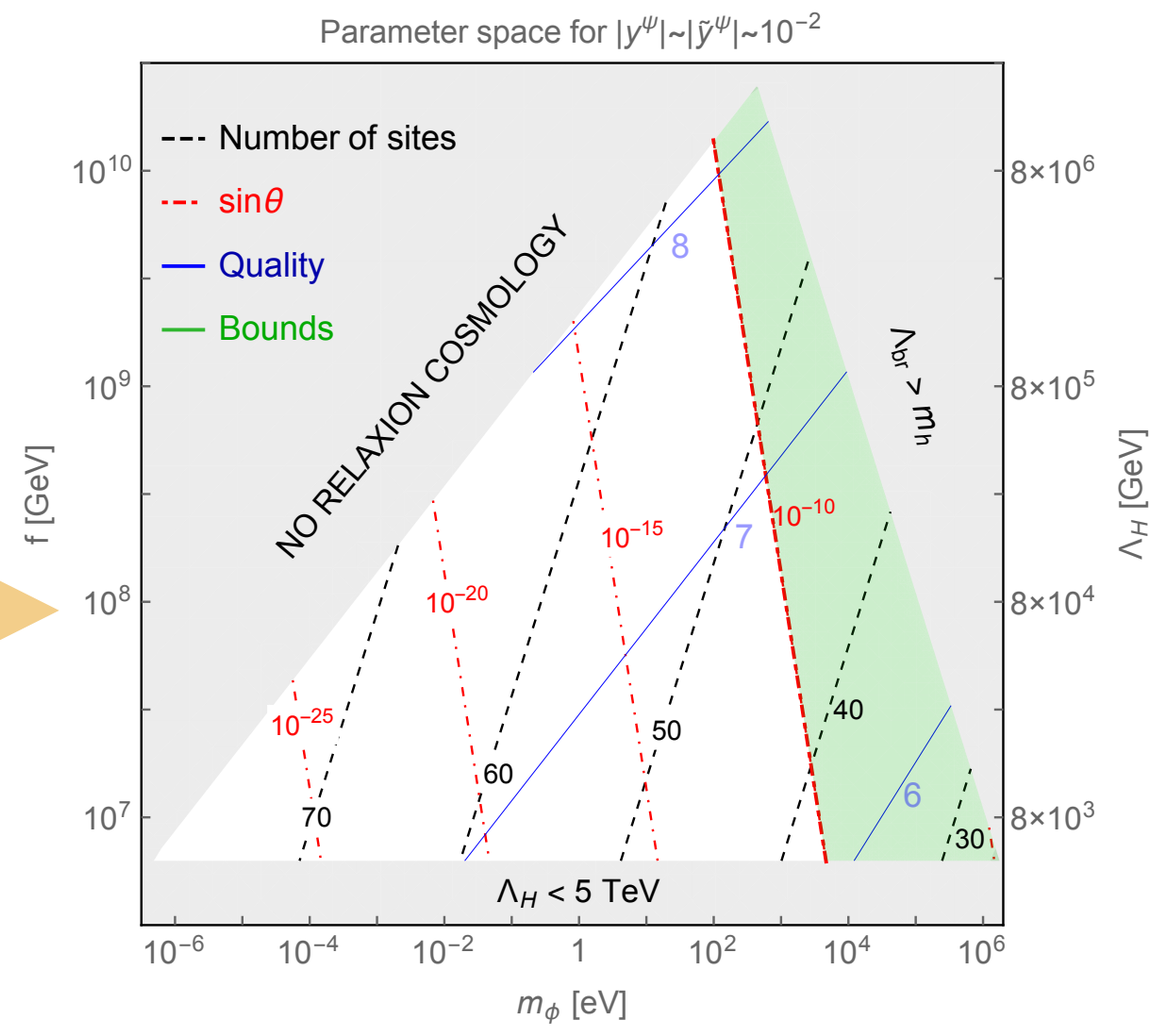
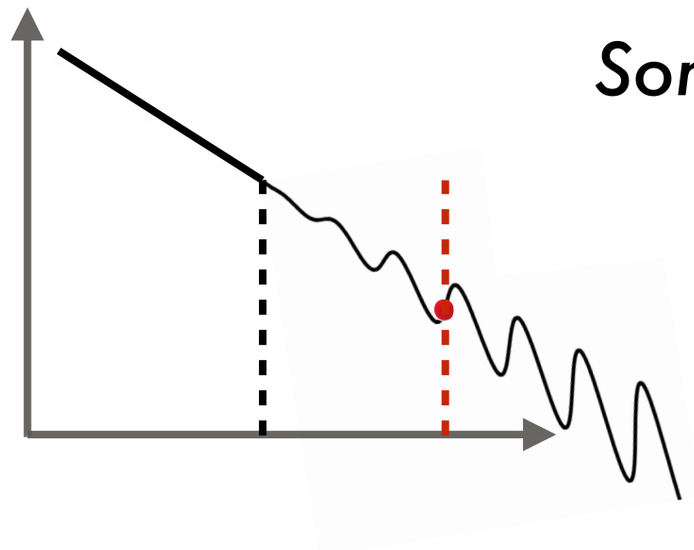




New Playground for Naturalness

Can we formulate a no-lose theorem for other states?

(see Hinchliffe's rule)

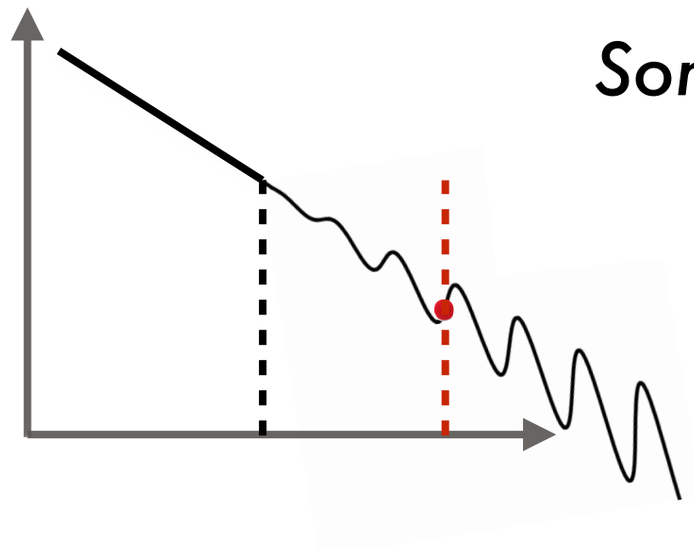


Something else than QCD generates the wiggles

Espinosa, Grojean, Panico, Pomarol,Pujolas, Servant

Komargodski, Gupta, Perez, Ubaldi

$$V_{\rm br} = -M_{\rm br}^2 H^\dagger H \cos\frac{\phi}{f} + r_{\rm br} M_{\rm br}^4 \cos\frac{\phi}{f}$$



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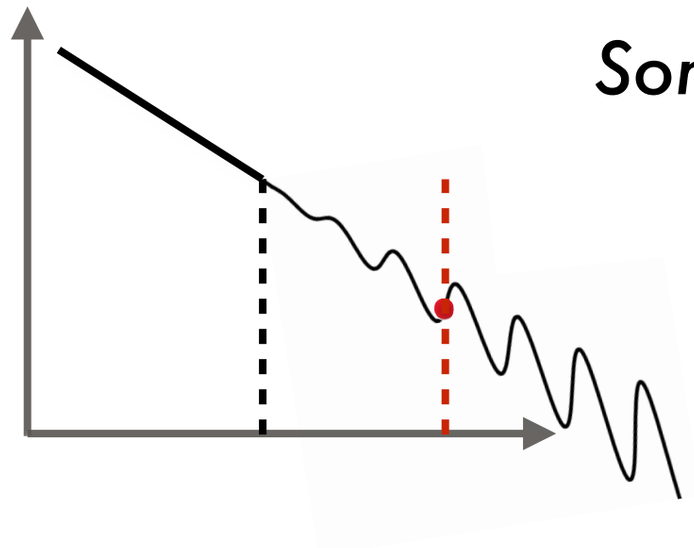

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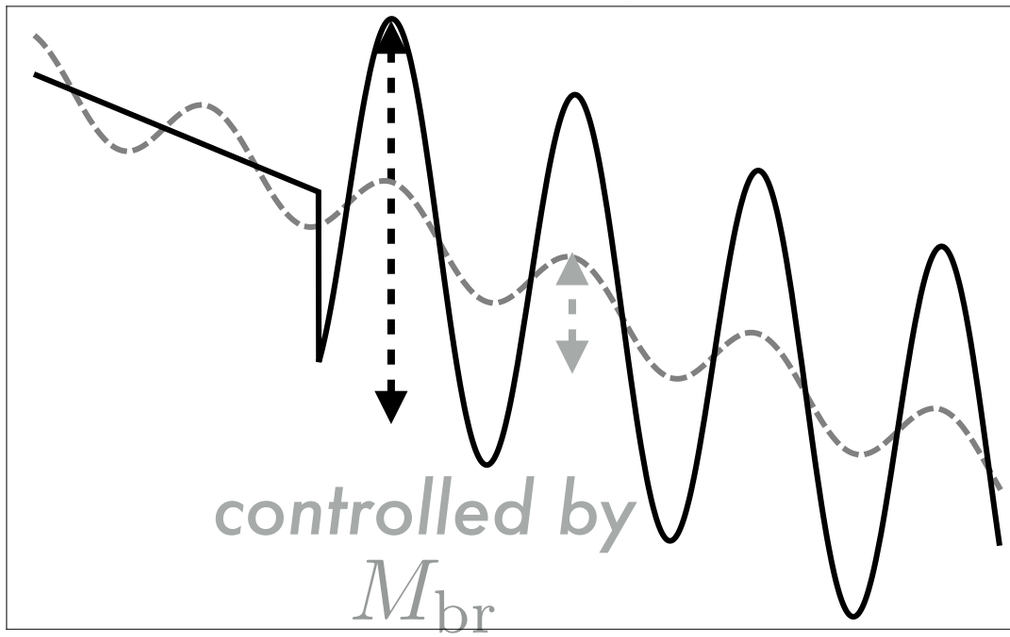
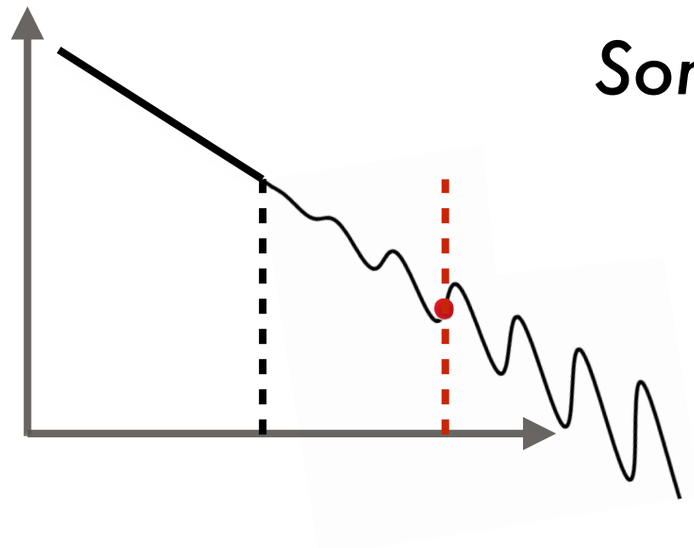
$\Lambda_{\rm br} \gtrsim M_{\rm br}$ ***to make it work***

(coincidence problem)

controlled by $\Lambda_{\rm br}$





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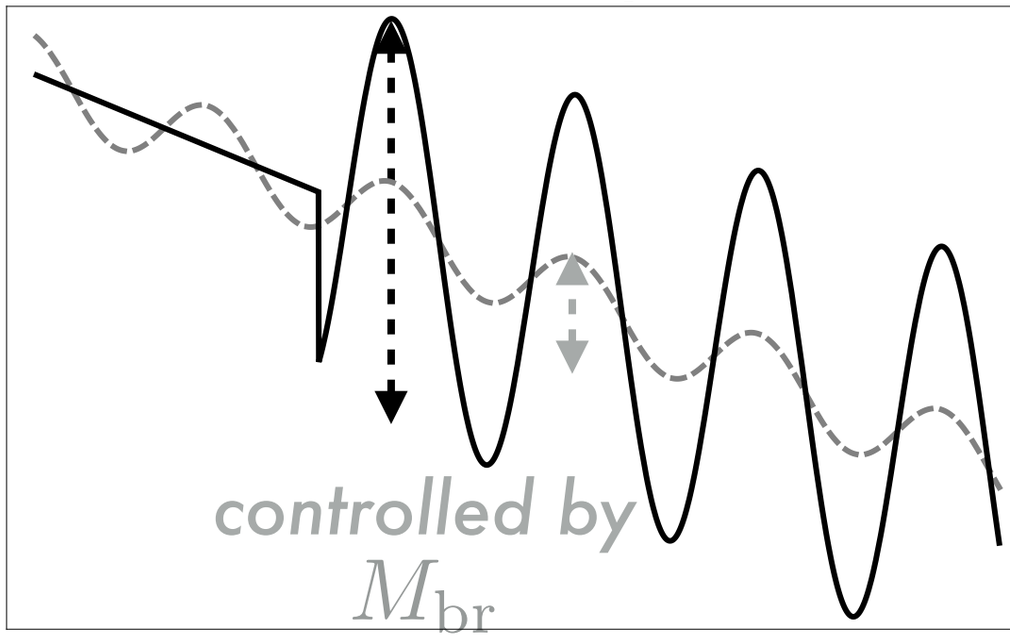
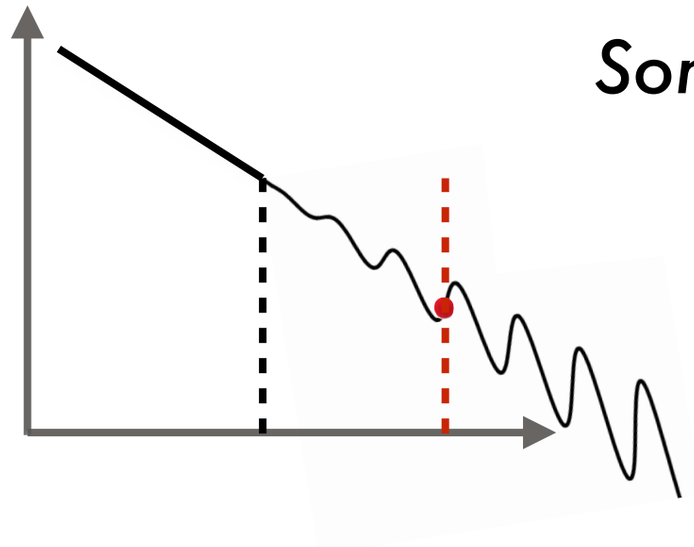


no loose theorem



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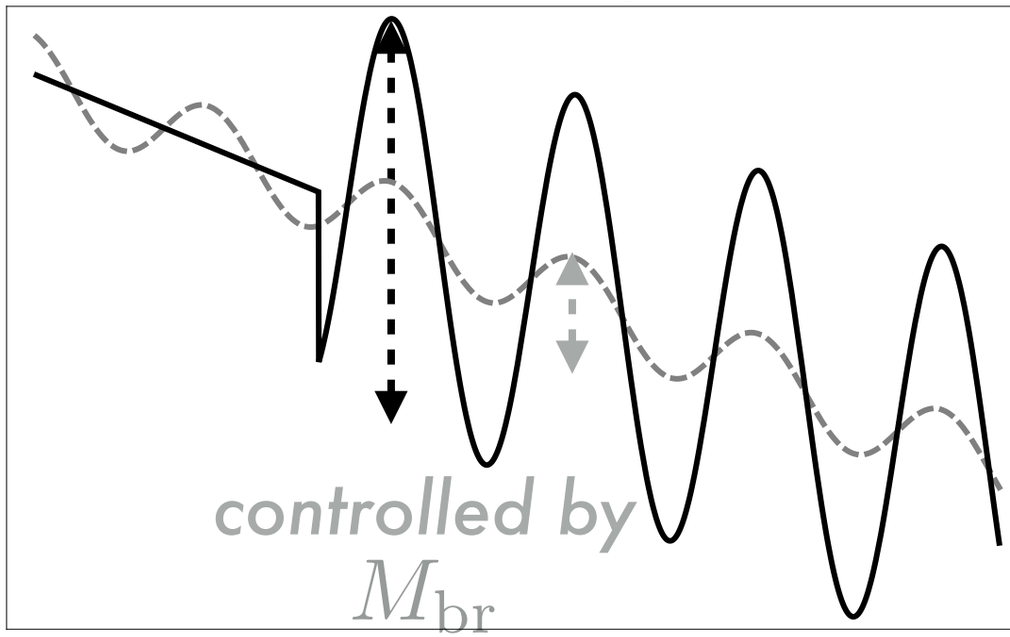

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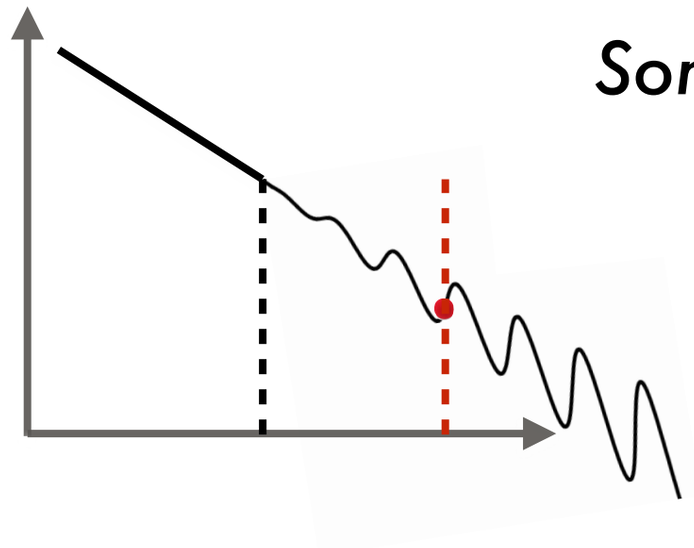

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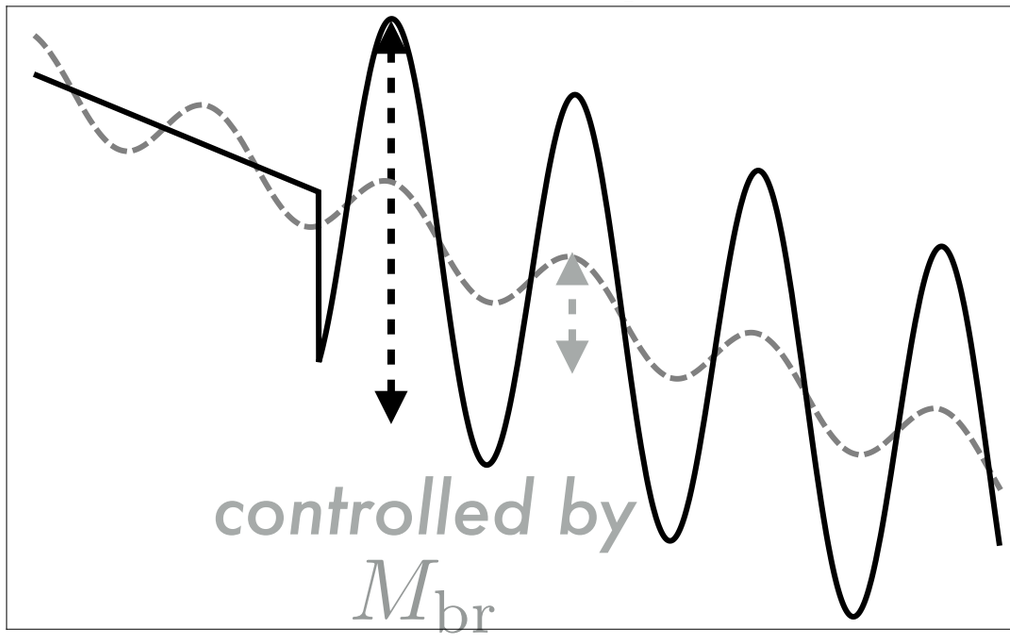

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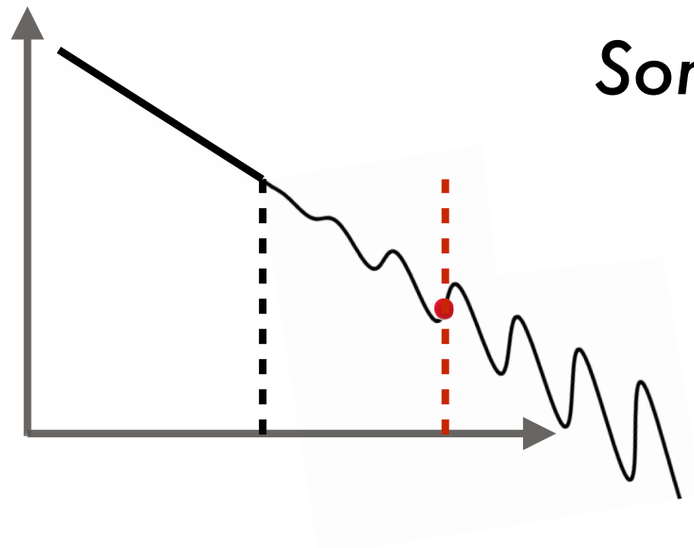

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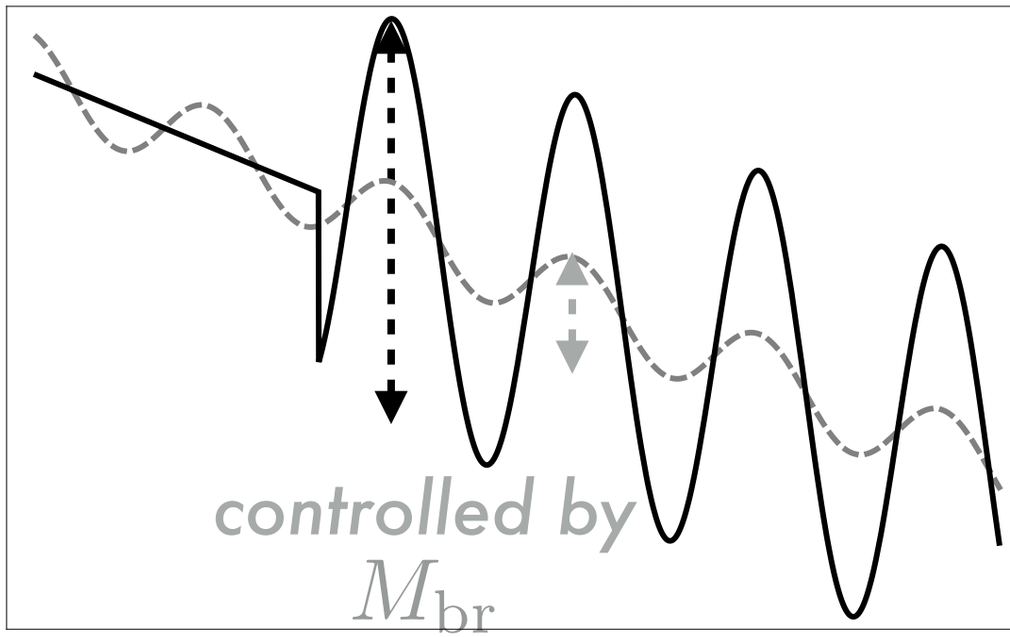

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Counter-Example

(Davidi,Gupta, Perez,DR, Shalit)

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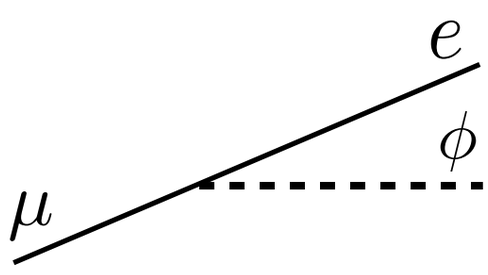
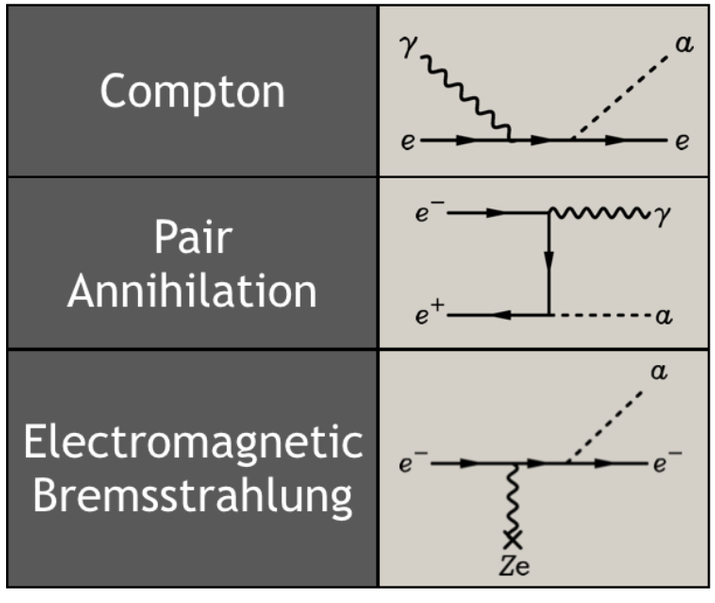
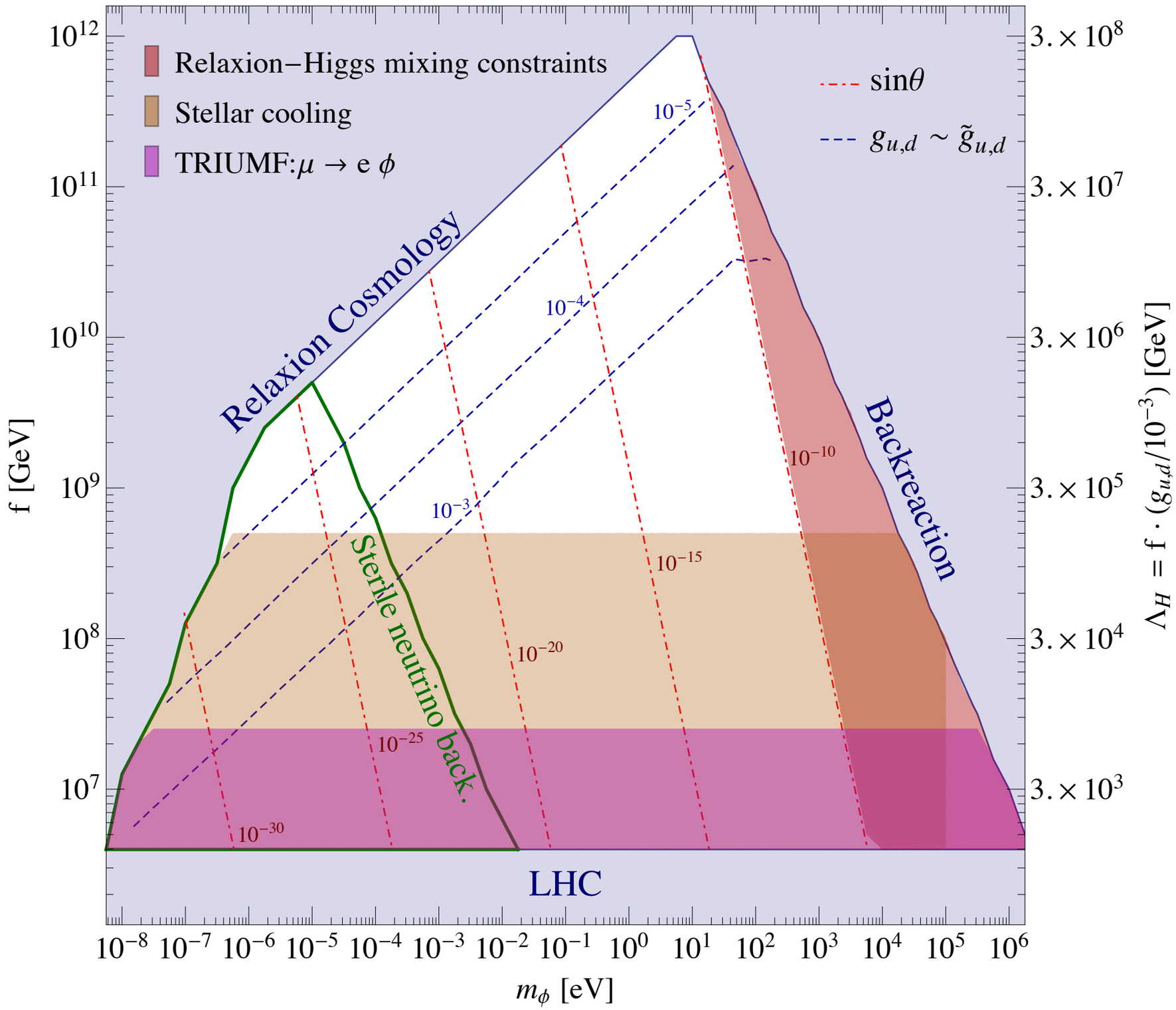
FV lepton decays *VS* *star cooling*



$$\Gamma(\mu \to e\phi) \simeq \frac{m_e^2 m_\mu}{16\pi f^2}$$



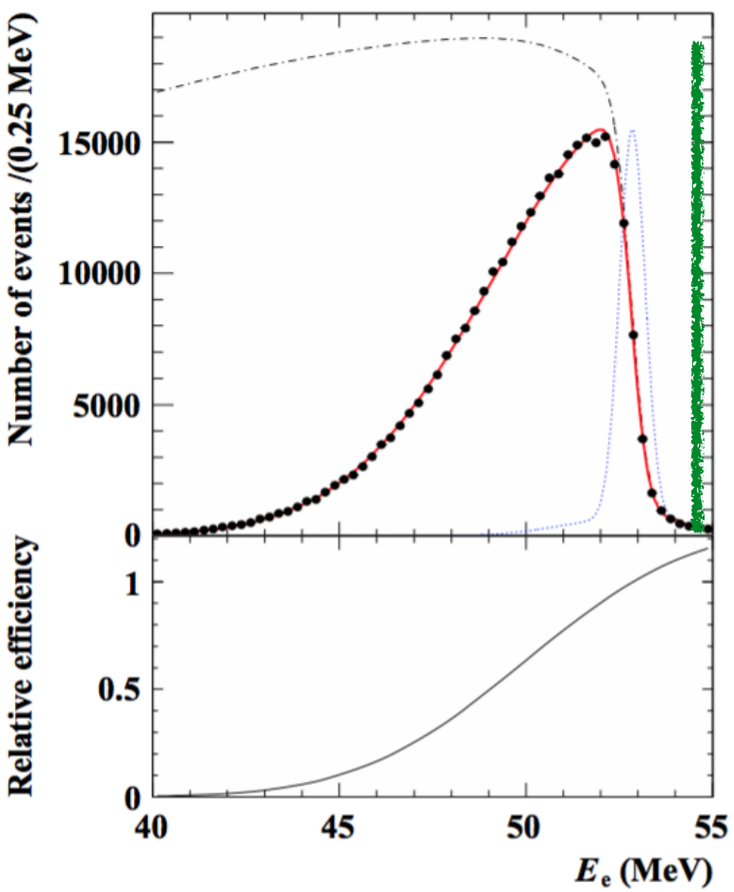
Star cooling gives the most stringent bound!



Can we increase the sensitivity of future experiments?

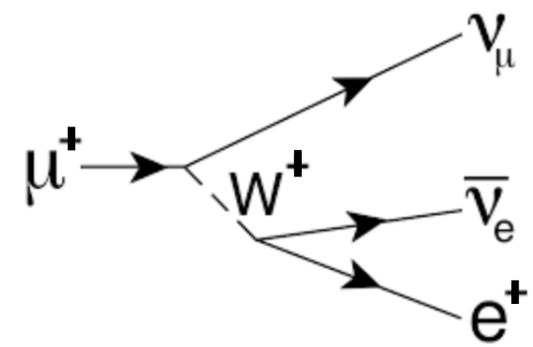
Learning from the past...

TRIUMF (1988) $\approx 10^7\ \mu$	$\mathrm{BR}(\mu \to e + a) \lesssim 3 \cdot 10^{-6}$	$f_a \gtrsim 10^7$ GeV



The signal is a line at $E_e \approx \frac{m_\mu}{2}$

The background comes from



The peak of the Michel spectrum depend on the muon polarization

IT IS ZERO in the OPPOSITE direction to the muon polarization!

More recent experiments...

CRYSTAL BOX (1988) 10^{12} μ	$\mathrm{BR}(\mu \to e + a + \gamma) \lesssim 1 \cdot 10^{-9}$	$f_a \gtrsim 10^6$ GeV

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GENERAL LESSON HERE:

- Flavor experiment can be extremely good at probing light new states
- They compete/complement with astro in some region of the par. space
- Optimised searches on many motivated final states need still to be done

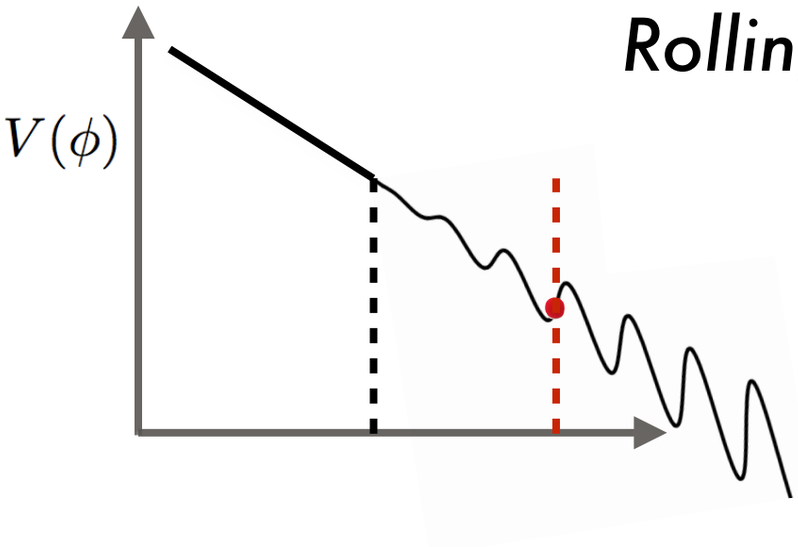
(I have more examples @ NA62 and LHCb)

Relaxion = New Playground for Naturalness

- *Switches the focus to very light weakly coupled states*
- *Worst case we would have ameliorated our sensitivity on light weakly coupled scalars*
- *Many cosmological and UV problems to be taken more seriously*


Thanks everyone for the amazing
Workshop

BACKUP



Rolling generated by Nelson-Barr sector

(see Gilad's talk)

ϕ ***rolling potential:***

$$V_{\rm roll} = \frac{g_{u,d}\tilde{g}_{u,d} f^4}{16\pi^2} \cos\frac{\phi}{F}$$

ϕ***- dependent Higgs mass:***

$$\Lambda_H^2 \underbrace{(\kappa - \cos\frac{\phi}{F})}_{\mu^2(\phi)} H^\dagger H$$

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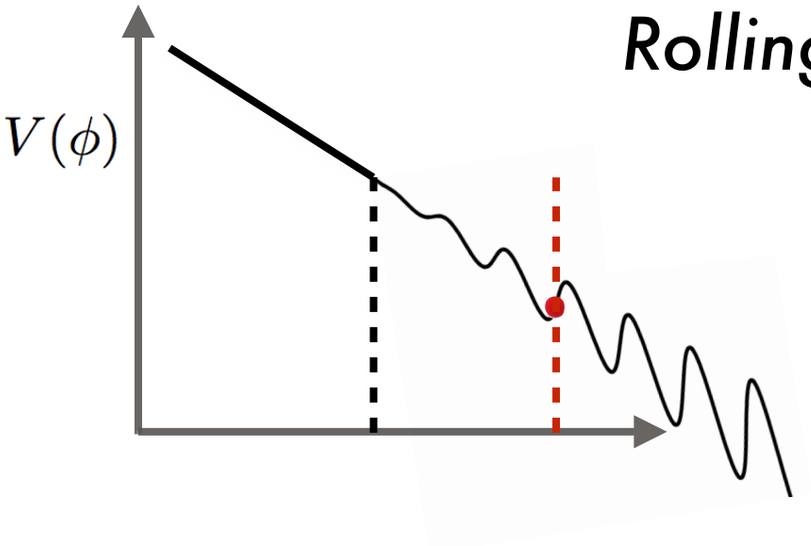

Rolling generated by Nelson-Barr sector

(see Gilad's talk)

ϕ ***rolling potential:***

$$V_{\rm roll} = \frac{g_{u,d}\tilde{g}_{u,d}\overbrace{f^4}}{16\pi^2}\cos\frac{\phi}{F}$$

ϕ***- dependent Higgs mass:***

$$\underbrace{\Lambda_H^2(\kappa - \cos\frac{\phi}{F})}_{\mu^2(\phi)}H^\dagger H$$

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hard-breaking

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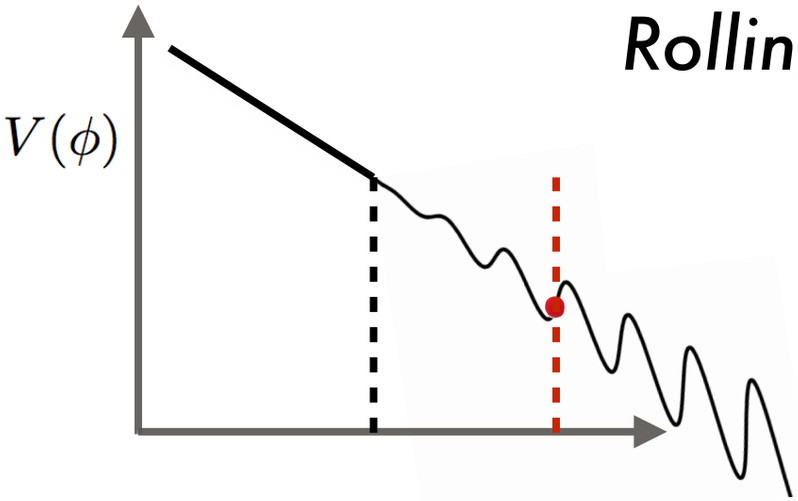

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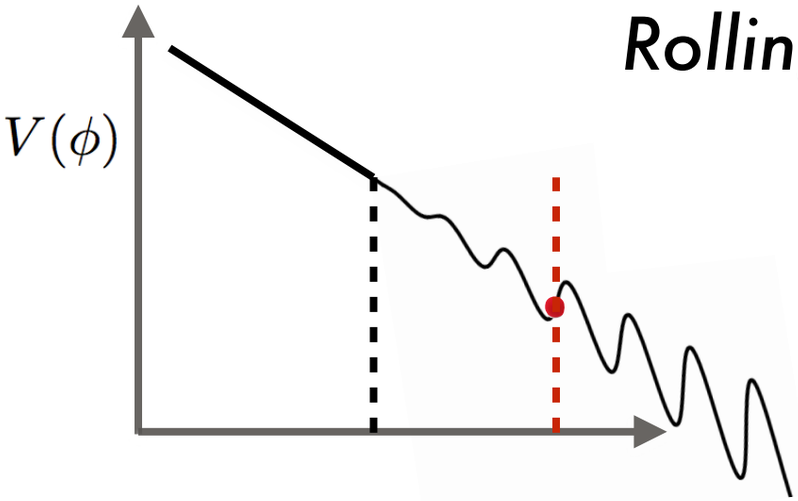

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$$\sqrt{g_{u,d}\,\tilde{g}_{u,d}} \lesssim 10^{-3}$$

(depends on the flavor structure)

see M. Dine & P. Draper and L. Vecchi