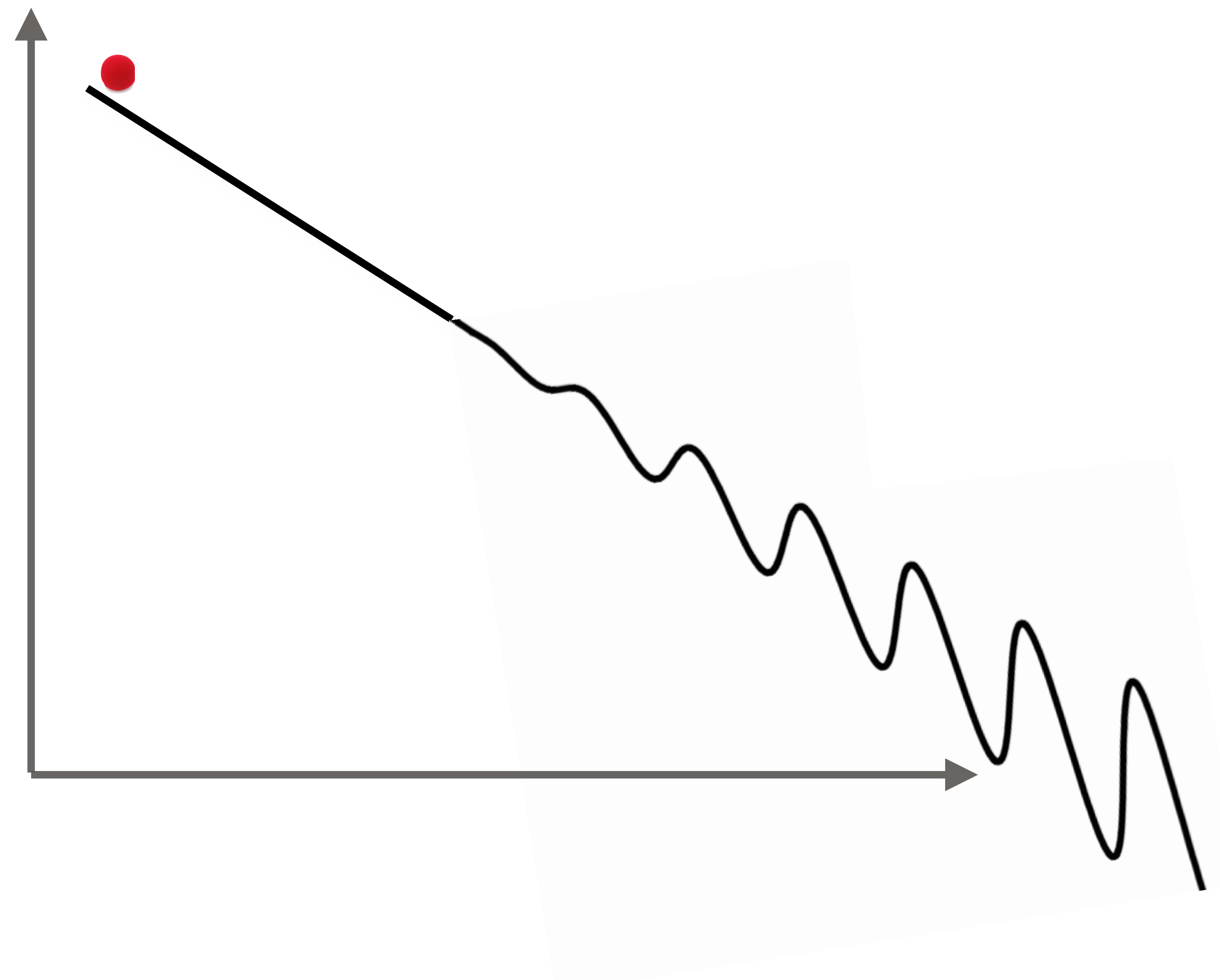
Relaxions



TEL AVIV UNIVERSITY אוניברסיטת תל אביב

Institute for Advanced Study

WEIZMANN INSTITUTE OF SCIENCE

Diego Redigolo

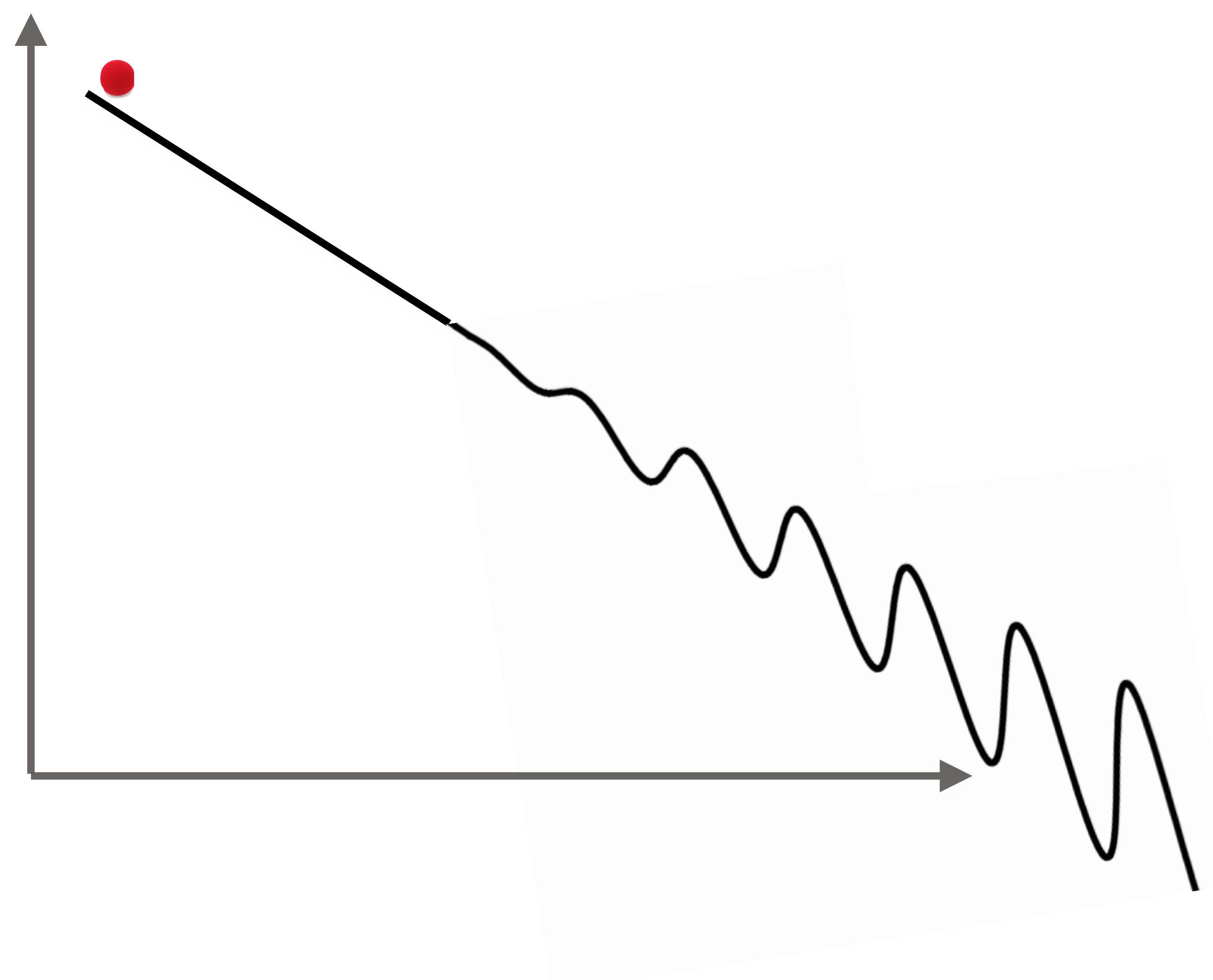
2/10/2018

TEL AVIV UNIVERSITY אוניברסיטת תל אביב

Institute for Advanced Study

WEIZMANN INSTITUTE OF SCIENCE

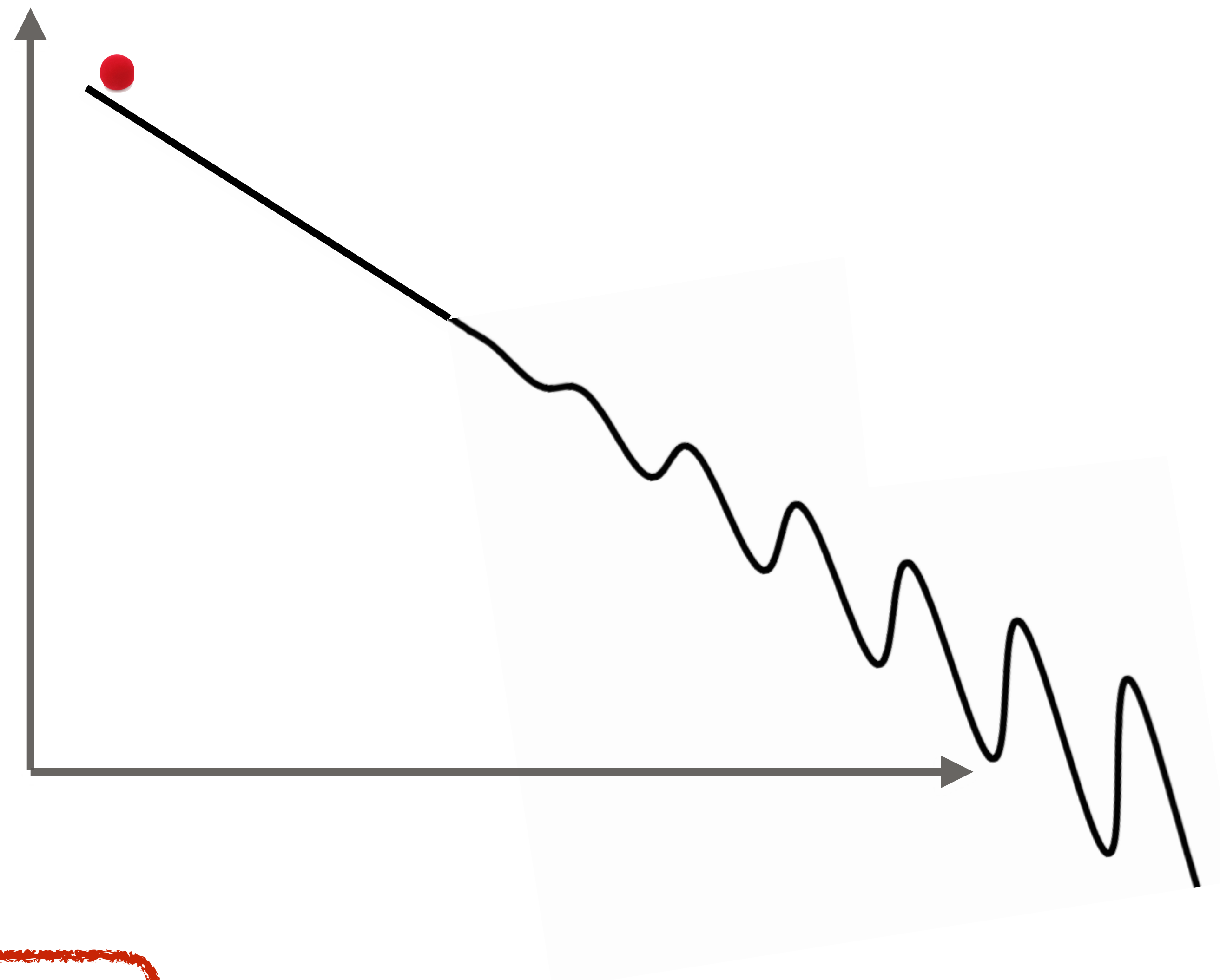
New playground for Naturalness



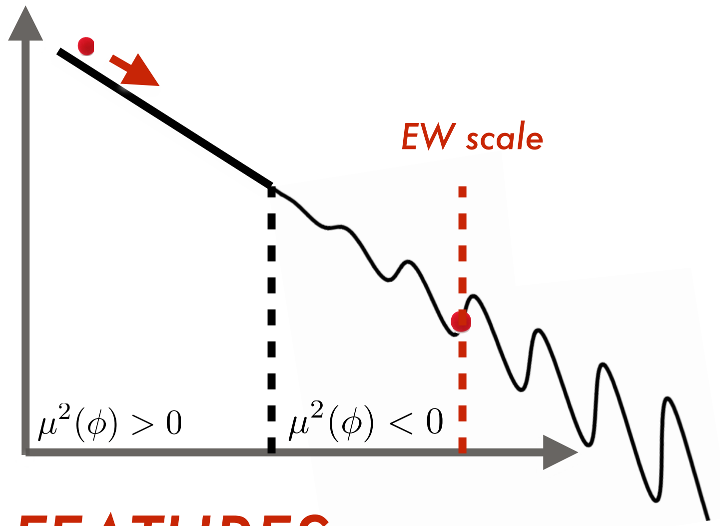
new theoretical challenges ⟷ new phenomenological probes

New playground for Naturalness

going on from David's talk



new theoretical challenges ⟷ new phenomenological probes

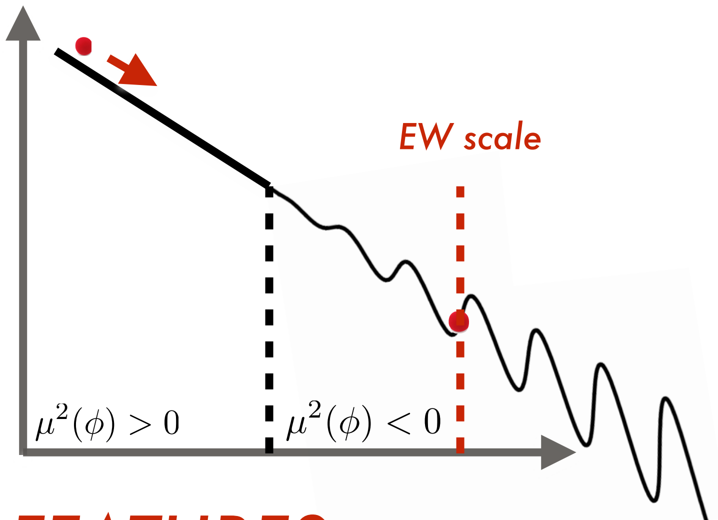


The simplest version

(Graham, Kaplan & Rajendran '15)

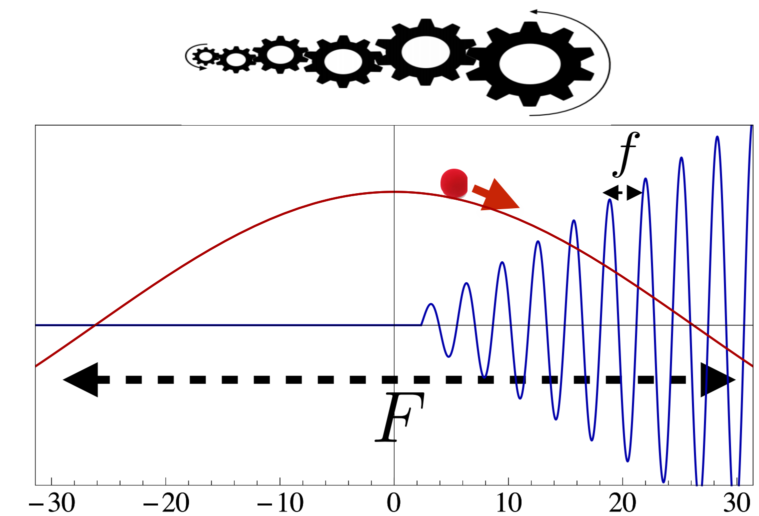
FEATURES:

- *classical rolling + Hubble friction set the Cosmo*
- *EWSB triggers potential barriers*
- *stopping point: Ratio of scales $=$ Ratio of vevs*
- *abelian symmetry with O(1) and $(1/3)^N$ charges*



The simplest version

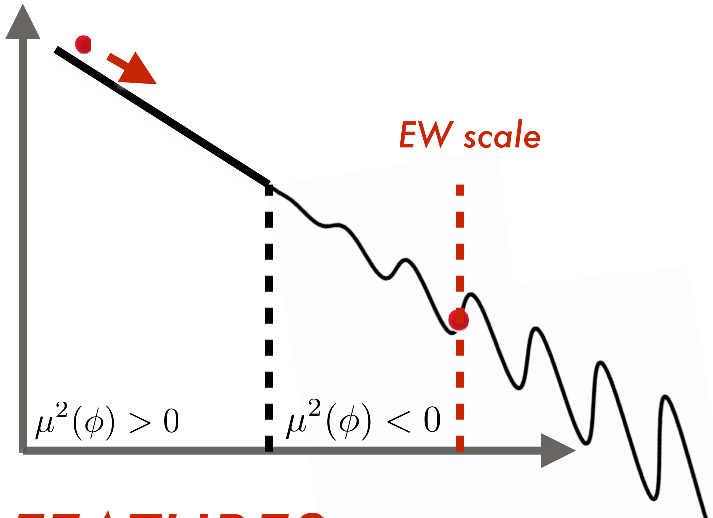
(Graham, Kaplan & Rajendran '15)



$$\frac{\Lambda^4_{\rm UV}}{F}\sin\frac{\phi_0}{F} = \frac{\Lambda^4_{\rm wig}}{f}\sin\frac{\phi_0}{f}$$

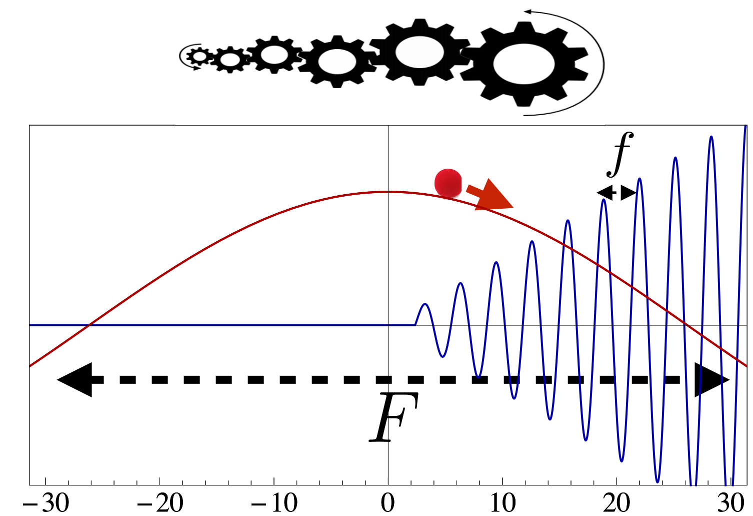
FEATURES:

- *classical rolling + Hubble friction set the Cosmo*
- *EWSB triggers potential barriers*
- *stopping point: Ratio of scales = Ratio of vevs*
- *abelian symmetry with O(1) and* $(1/3)^N$ *charges*



The simplest version

(Graham, Kaplan & Rajendran '15)



$$\frac{\Lambda_{\rm UV}^4}{F}\sin\frac{\phi_0}{F} = \frac{\Lambda_{\rm wig}^4}{f}\sin\frac{\phi_0}{f}$$

FEATURES:

- *classical rolling + Hubble friction set the Cosmo*
- *EWSB triggers potential barriers*
- *stopping point: Ratio of scales = Ratio of vevs*
- *abelian symmetry with O(1) and $(1/3)^N$ charges*

CONSEQUENCES:

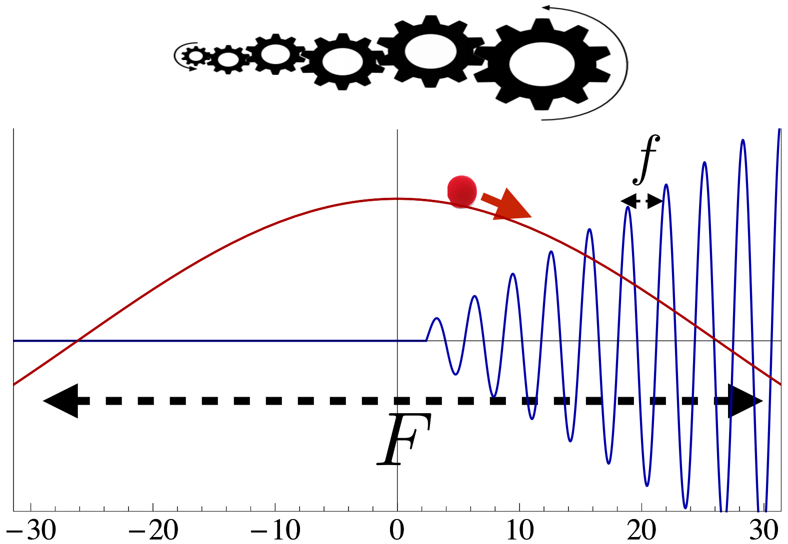
- *works for generic initial conditions*
- *CP violating phase ⟷ Higgs-Relaxion mixing*
- *Lots of e-folds ⟷ Transplanckian field excursion*

The simplest version

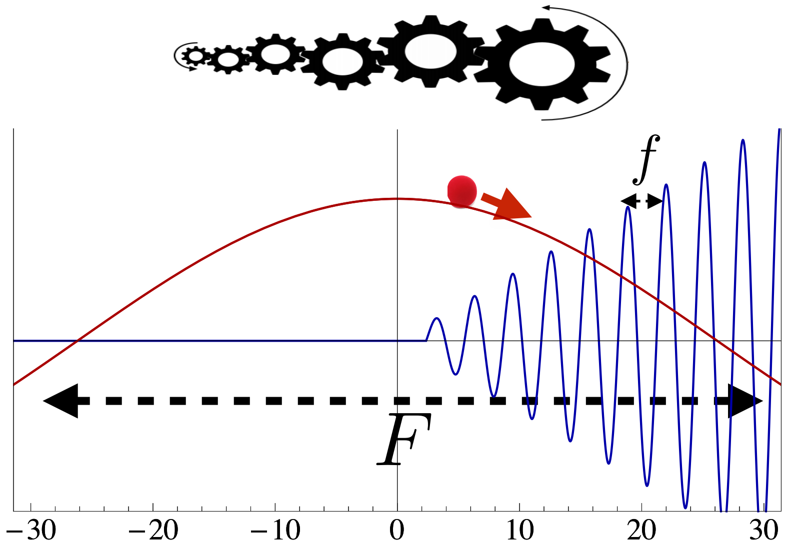
(Graham, Kaplan & Rajendran '15)

The simplest version

(Graham, Kaplan & Rajendran '15)



$$\frac{\Lambda_{\rm UV}^4}{F}\sin\frac{\phi_0}{F} = \frac{\Lambda_{\rm wig}^4}{f}\sin\frac{\phi_0}{f}$$



$$\frac{\Lambda_{\rm UV}^4}{F}\sin\frac{\phi_0}{F} = \frac{\Lambda_{\rm wig}^4}{f}\sin\frac{\phi_0}{f}$$

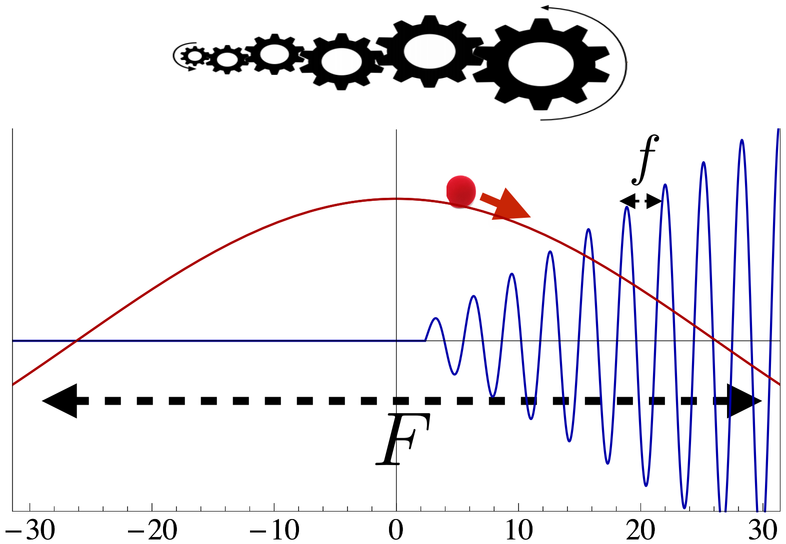
The simplest version

(Graham, Kaplan & Rajendran '15)

if QCD anomaly generates the wiggles

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

Then the relaxion is excluded by neutron EDM



$$\frac{\Lambda_{\rm UV}^4}{F}\sin\frac{\phi_0}{F} = \frac{\Lambda_{\rm wig}^4}{f}\sin\frac{\phi_0}{f}$$

The simplest version

(Graham, Kaplan & Rajendran '15)

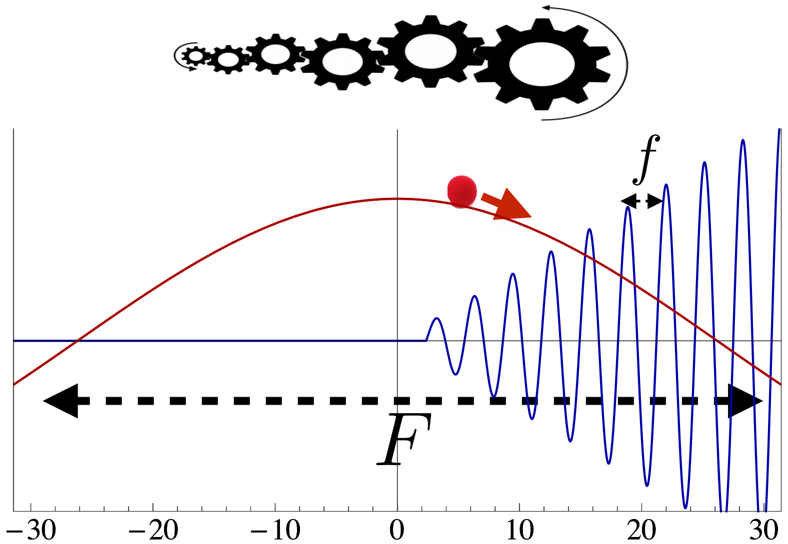
if QCD anomaly generates the wiggles

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

Then the relaxion is excluded by neutron EDM

WAYS OUT:

- *changing the Cosmo:*
  - ★ *smaller slope after inflation*
    Graham, Kaplan Rajendran '15
  - ★ *inflation between EW & QCD PT*
    Nelson & Prescod-Weinstein '17



$$\frac{\Lambda_{\rm UV}^4}{F}\sin\frac{\phi_0}{F} = \frac{\Lambda_{\rm wig}^4}{f}\sin\frac{\phi_0}{f}$$

The simplest version

(Graham, Kaplan & Rajendran '15)

if QCD anomaly generates the wiggles

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

Then the relaxion is excluded by neutron EDM

WAYS OUT:

- *changing the Cosmo:*
  - ★ *smaller slope after inflation* — Graham, Kaplan Rajendran '15
  - ★ *inflation between EW & QCD PT* — Nelson & Prescod-Weinstein '17
- *changing the Field Theory:*
  - ★ *ignoring CP: NP generates wiggles* — Gupta, Komargodski, Perez, Ubaldi '15; Espinosa, Panico, Pomarol,Pujolas, Servant '15 ...
  - ★ *solving CP: Nelson-Barr relaxion* — Davidi,Gupta, Perez,DR, Shalit '17

CHANGING THE COSMOLOGY

$$\frac{\Lambda_{\rm UV}^4}{F}\sin\frac{\phi_0}{F} = \frac{\Lambda_{\rm wig}^4}{f}\sin\frac{\phi_0}{f}$$

$\frac{\phi_0}{f}$ → $\theta_{\rm QCD}$

CHANGING THE COSMOLOGY

$$\frac{\Lambda_{\rm UV}^4}{F}\sin\frac{\phi_0}{F} = \frac{\Lambda_{\rm wig}^4}{f}\sin\frac{\phi_0}{f}$$

$\theta_{\rm QCD}$

If we fix the R.H.S ⟶ *slope during inflation* $\gg$ *slope after inflation*

Graham, Kaplan & Rajendran '15

$$\underbrace{\dot\phi_{\rm roll}}_{\text{eom } \frac{V'}{H_I^2}} \gtrsim H_I^2 \quad + \quad \Delta V_{\rm roll} \lesssim V_{\rm infl} \quad \longleftrightarrow \quad \Lambda_{\rm UV} \lesssim \left(\frac{\Lambda_{\rm QCD}^4 M_{\rm Pl}^3}{f}\right)^{1/6} \theta^{1/4}$$

low cut-off (at most 30 TeV)

CHANGING THE COSMOLOGY

$$\frac{\Lambda_{\rm UV}^4}{F}\sin\frac{\phi_0}{F} = \frac{\Lambda_{\rm wig}^4}{f}\sin\frac{\phi_0}{f} \quad \theta_{\rm QCD}$$

If we fix the R.H.S ⟶ *slope during inflation* $\gg$ *slope after inflation*

Graham, Kaplan & Rajendran '15

$\underbrace{\dot\phi_{\rm roll}}_{\text{eom } \frac{V'}{H_I^2}} \gtrsim H_I^2 \quad + \quad \Delta V_{\rm roll} \lesssim V_{\rm infl} \quad \longleftrightarrow \quad \Lambda_{\rm UV} \lesssim \left(\frac{\Lambda_{\rm QCD}^4 M_{\rm Pl}^3}{f}\right)^{1/6} \theta^{1/4}$

low cut-off (at most 30 TeV)

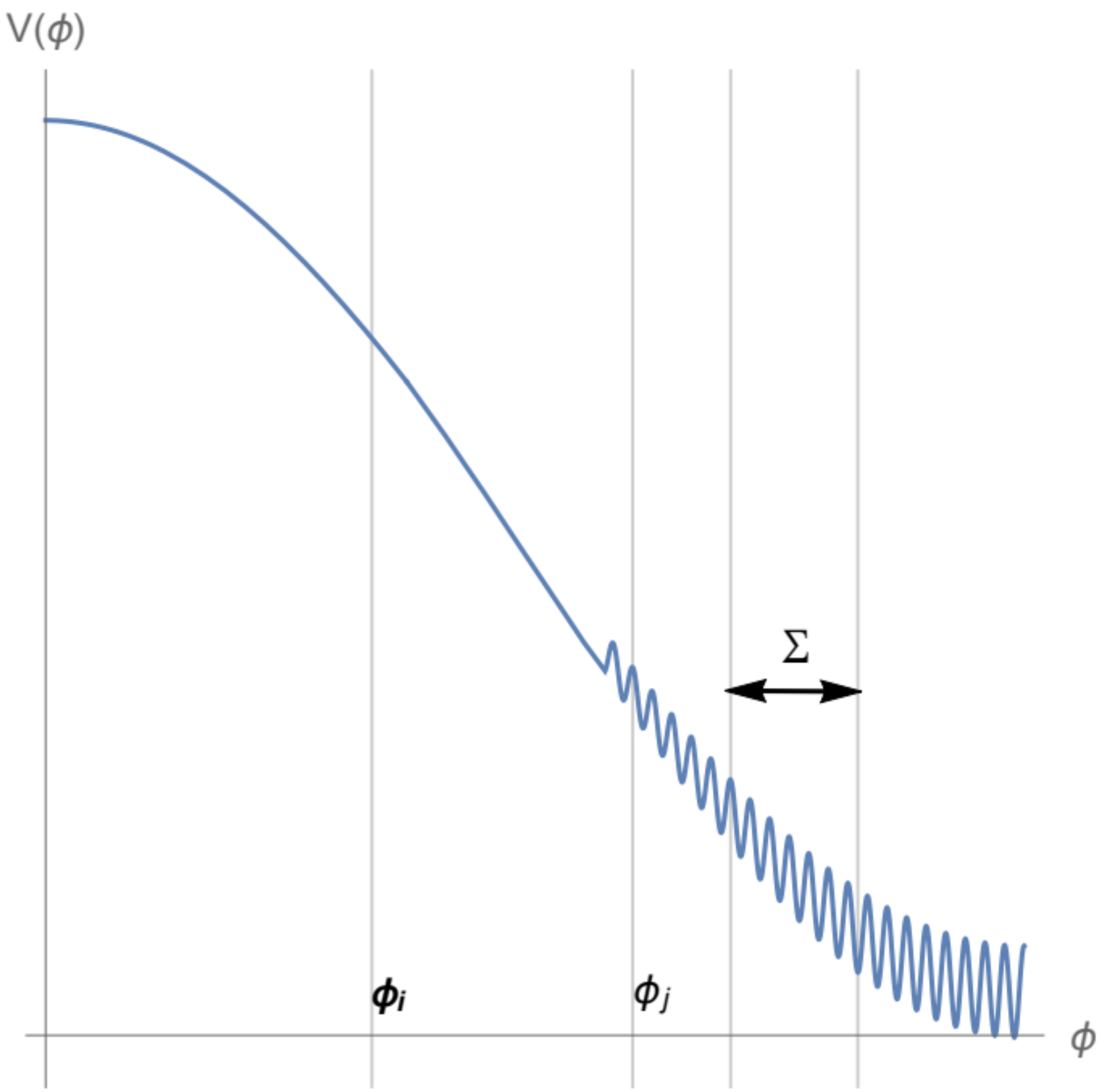
If we fix the L.H.S ⟶ *wiggles during inflation* $\ll$ *wiggles after inflation*

Nelson & Prescod-Weinstein '17

$H_I \gtrsim 3$ GeV ⟷ *high enough Hubble to suppress QCD wiggles with T-effects*

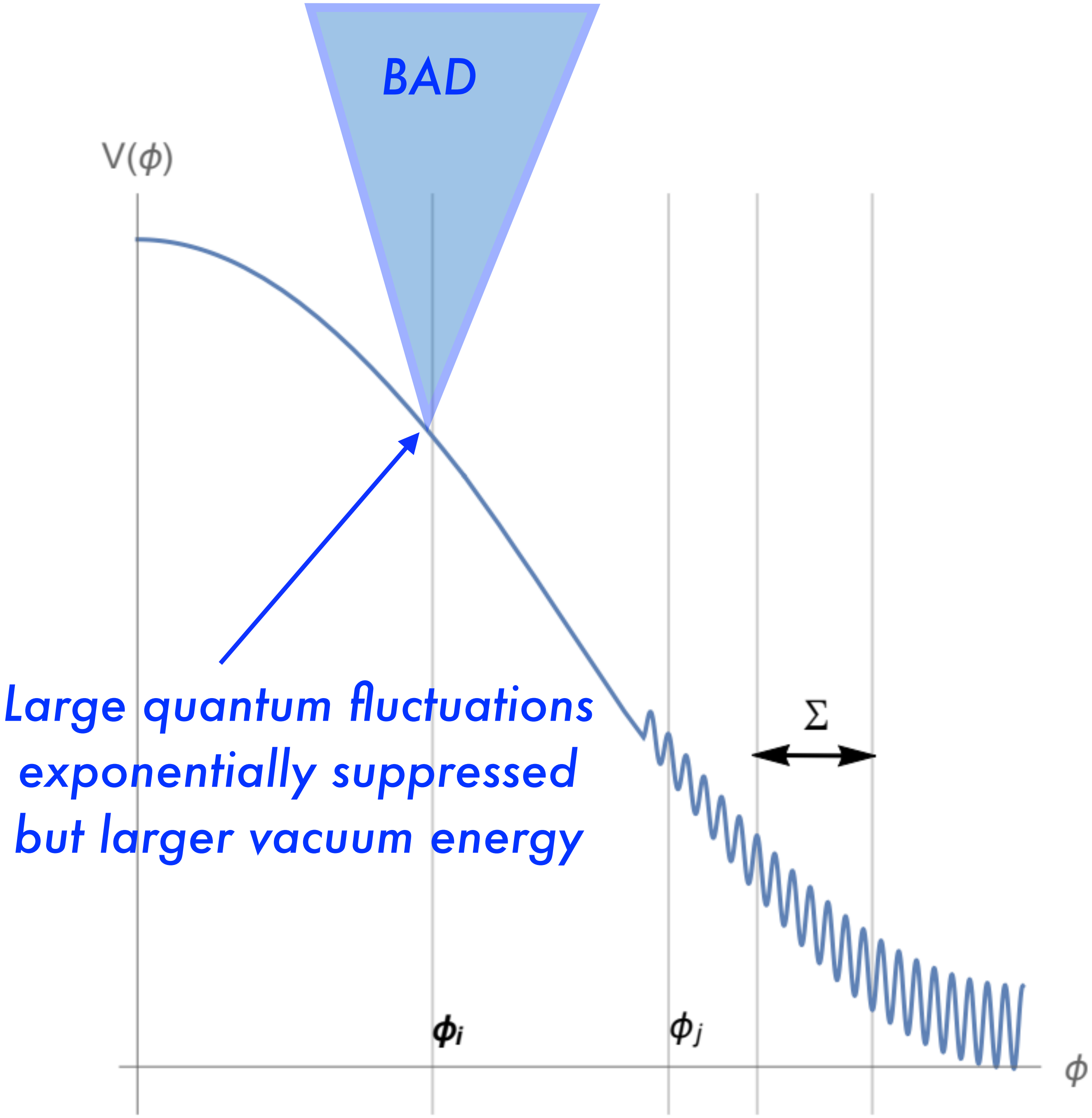
CAN WE achieve that?

~~$\dot{\phi}_{\rm roll} \lesssim H_I^2$~~ $+$ $\Delta V_{\rm roll} \lesssim V_{\rm infl}$ ⟷ $\Lambda_{UV} \lesssim (H_I M_{Pl})^{1/2}$



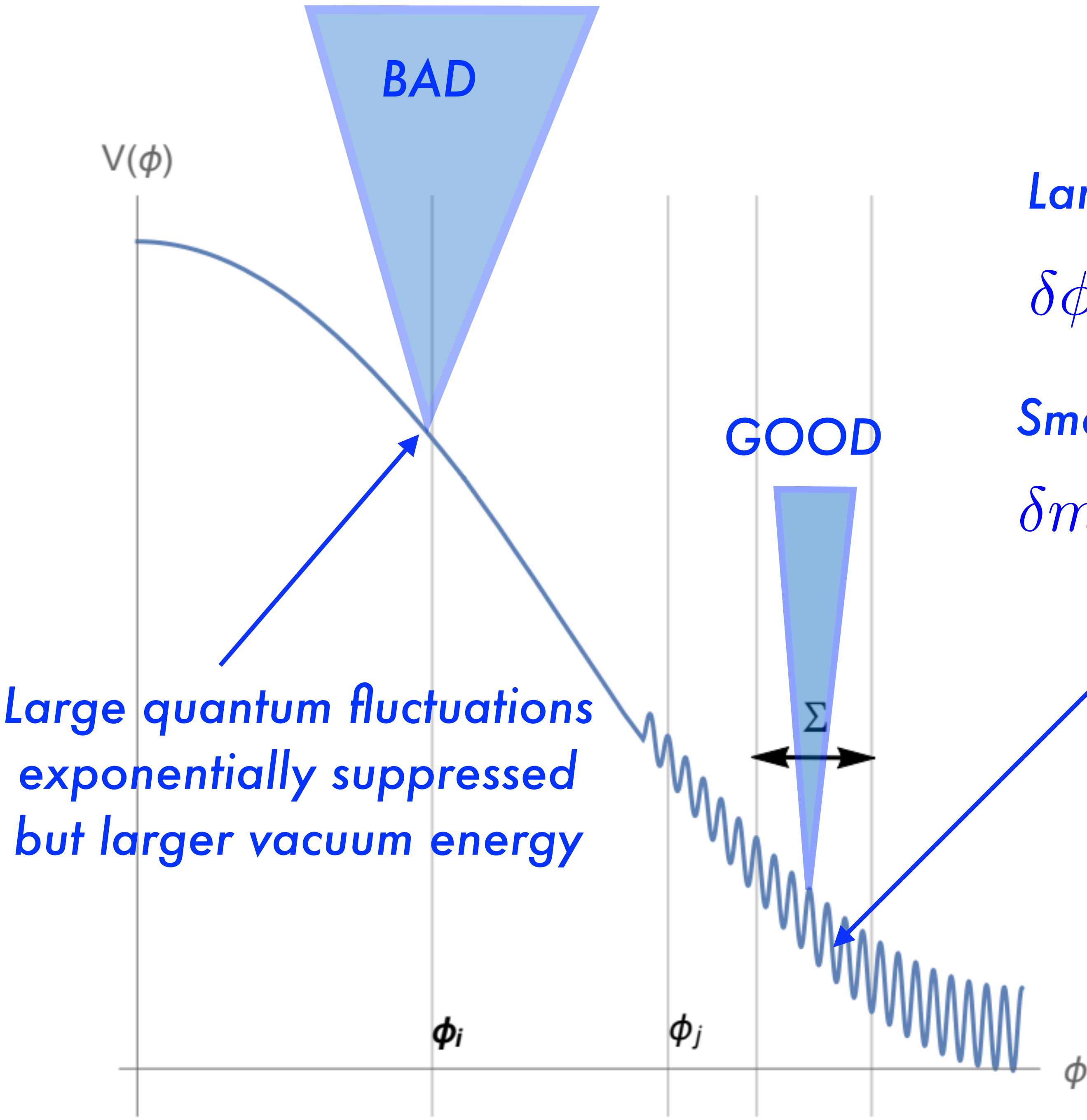
CAN WE achieve that?

~~$\dot{\phi}_{\rm roll} \lesssim H_I^2$~~ $+$ $\Delta V_{\rm roll} \lesssim V_{\rm infl}$ ⟷ $\Lambda_{UV} \lesssim (H_I M_{Pl})^{1/2}$



CAN WE achieve that?

~~$\dot{\phi}_{\rm roll} \lesssim H_I^2$~~ $+$ $\Delta V_{\rm roll} \lesssim V_{\rm infl}$ ⟷ $\Lambda_{UV} \lesssim (H_I M_{Pl})^{1/2}$



Large quantum spread

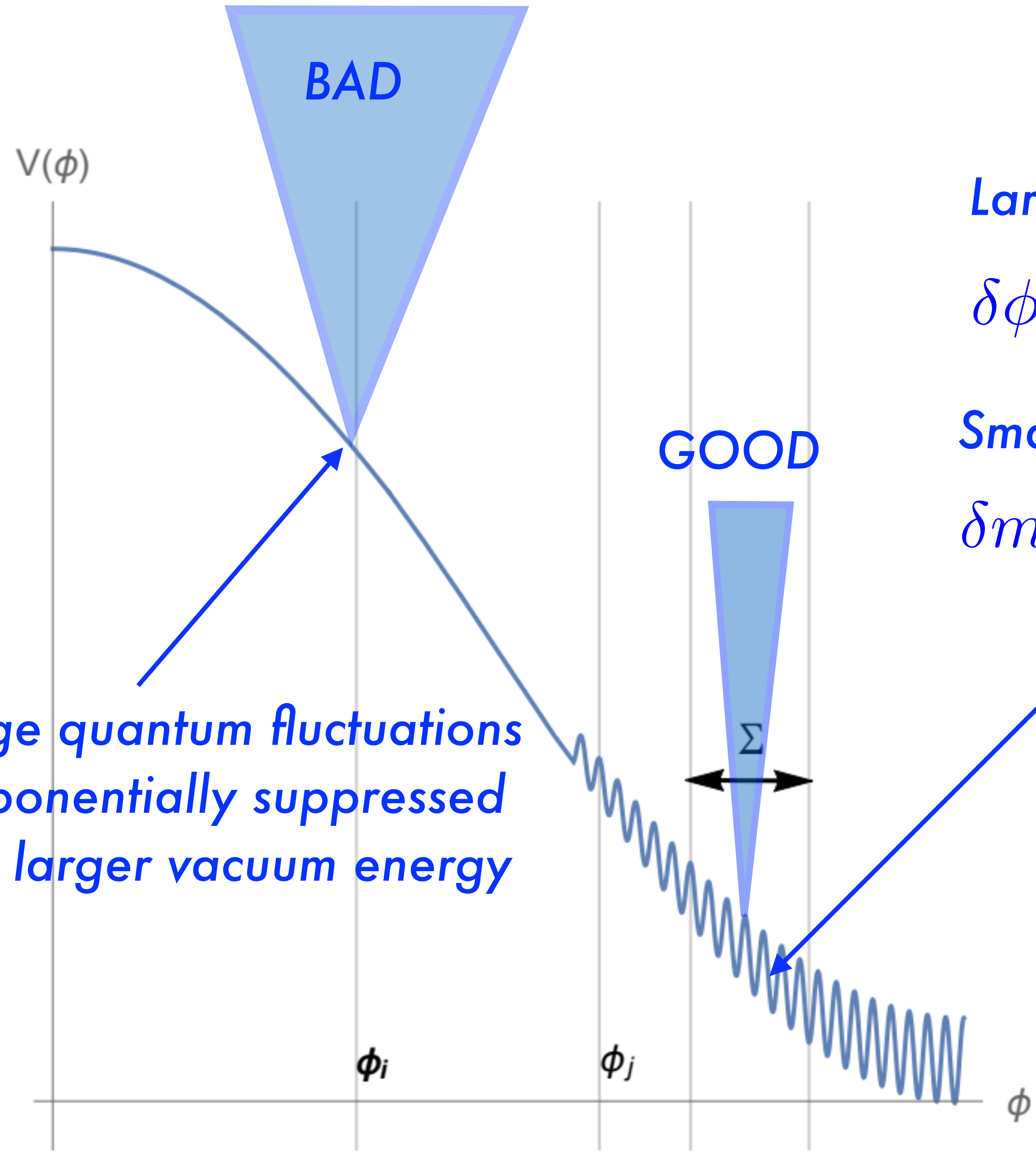
$$\delta\phi \sim F \cdot \frac{H_I^2}{\Lambda_{UV}^2}$$

Small variation of the EW scale

$$\delta m^2 \sim H_I^2 \lesssim v^2$$

CAN WE achieve that?

~~$\dot{\phi}_{\rm roll} \lesssim H_I^2$~~ $+$ $\Delta V_{\rm roll} \lesssim V_{\rm infl}$ ⟷ $\Lambda_{UV} \lesssim (H_I M_{Pl})^{1/2}$



Large quantum spread

$$\delta\phi \sim F \cdot \frac{H_I^2}{\Lambda_{UV}^2}$$

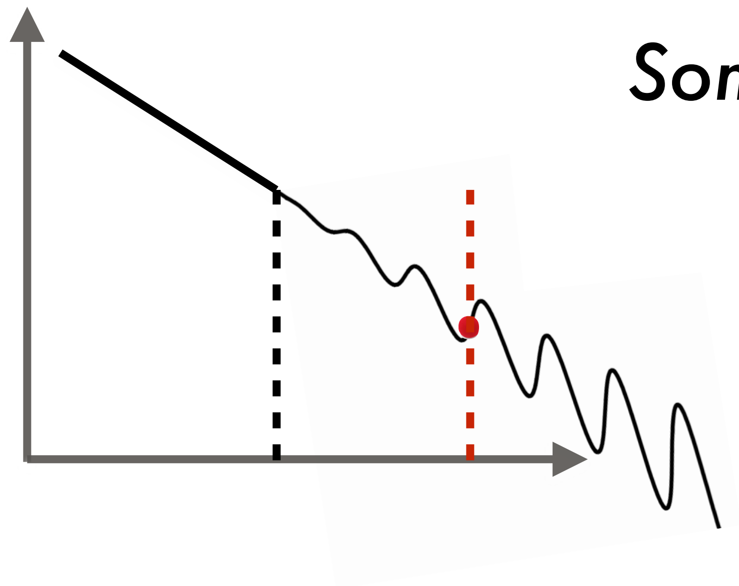
Small variation of the EW scale

$$\delta m^2 \sim H_I^2 \lesssim v^2$$

Large quantum fluctuations
exponentially suppressed
but larger vacuum energy

Volume BAD> Volume GOOD?

The fate of these large quantum fluctuations
suffer from measure problems... Gupta '18



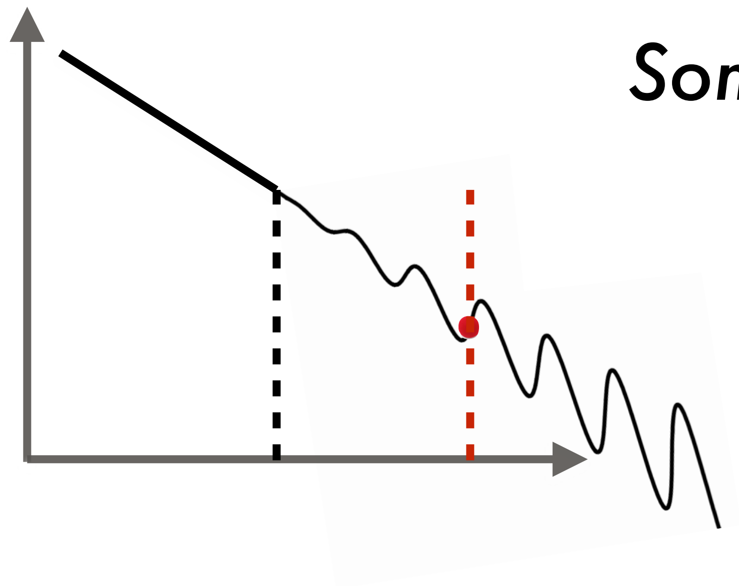
Something else than QCD generates the wiggles

Espinosa, Grojean, Panico, Pomarol,Pujolas, Servant '15

Komargodski, Gupta, Perez, Ubaldi '15

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

$$\Lambda_{\rm wig} \equiv \sqrt{M_{\rm br} v}$$

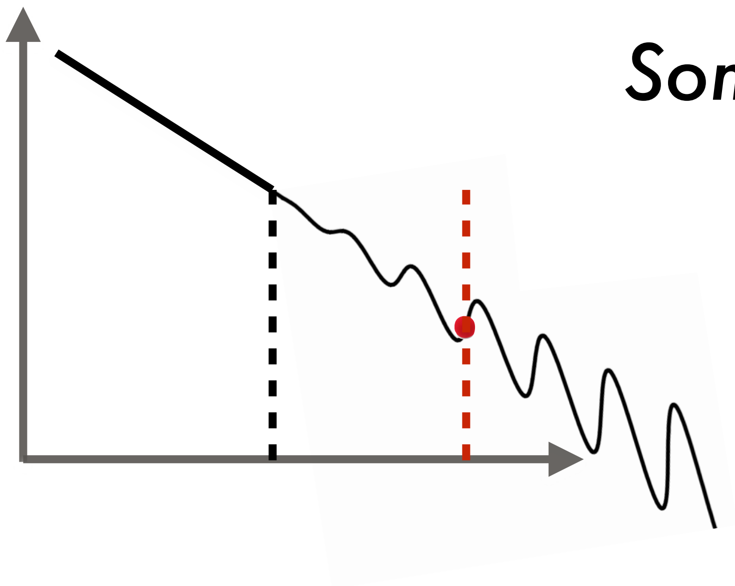


Something else than QCD generates the wiggles

Espinosa, Grojean, Panico, Pomarol,Pujolas, Servant '15

Komargodski, Gupta, Perez, Ubaldi '15

$$V_{\rm br} = -\underbrace{M_{\rm br}^2 H^\dagger H}_{\Lambda_{\rm wig} \equiv \sqrt{M_{\rm br} v}} \cos\frac{\phi}{f} + \underbrace{r_{\rm br} M_{\rm br}^4}\cos\frac{\phi}{f}$$



Something else than QCD generates the wiggles

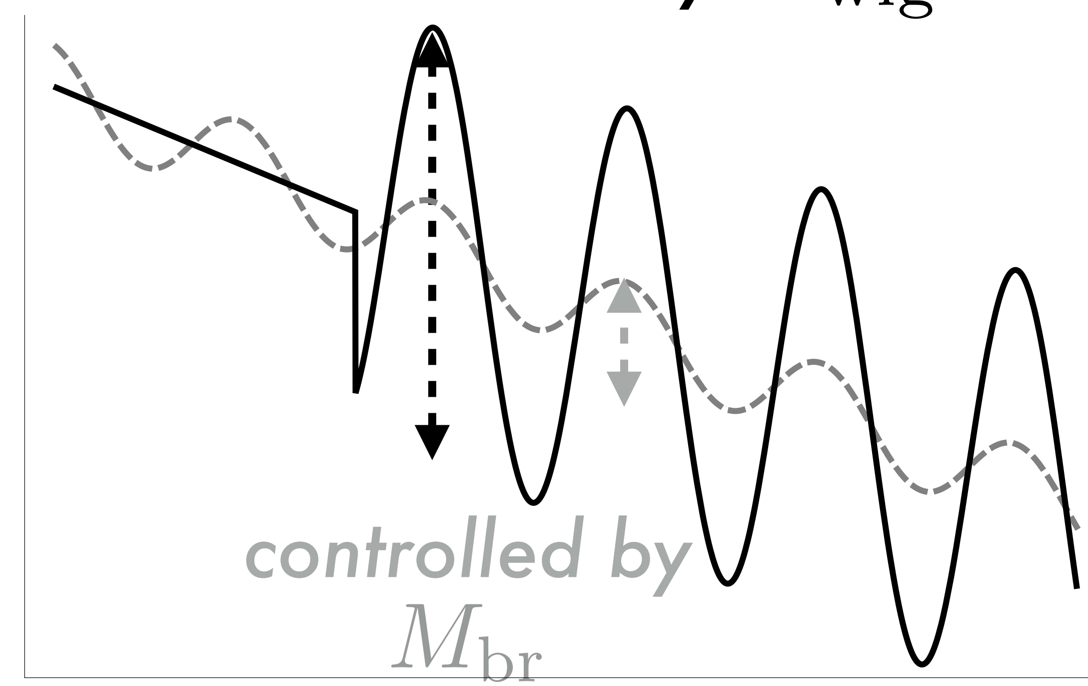
Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant '15

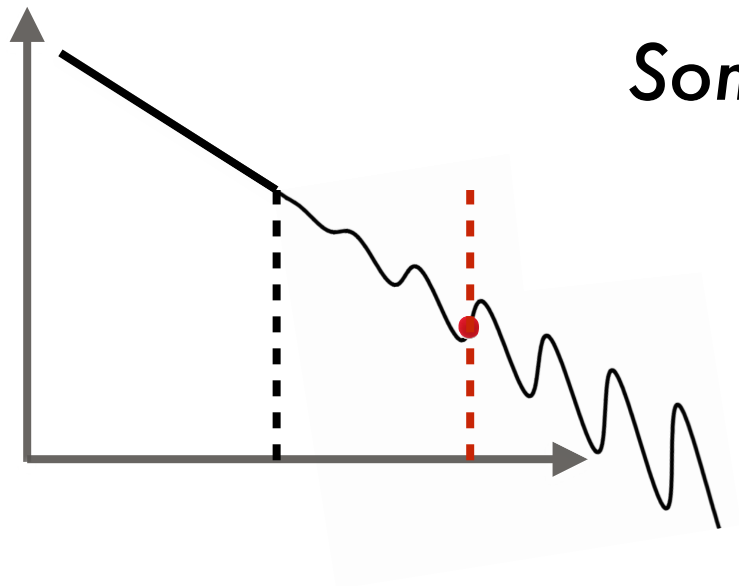
Komargodski, Gupta, Perez, Ubaldi '15

$$V_{\rm br} = -\underbrace{M_{\rm br}^2 H^\dagger H}_{\Lambda_{\rm wig} \equiv \sqrt{M_{\rm br} v}} \cos\frac{\phi}{f} + \underbrace{r_{\rm br} M_{\rm br}^4}\cos\frac{\phi}{f}$$

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

controlled by $\Lambda_{\rm wig}$





Something else than QCD generates the wiggles

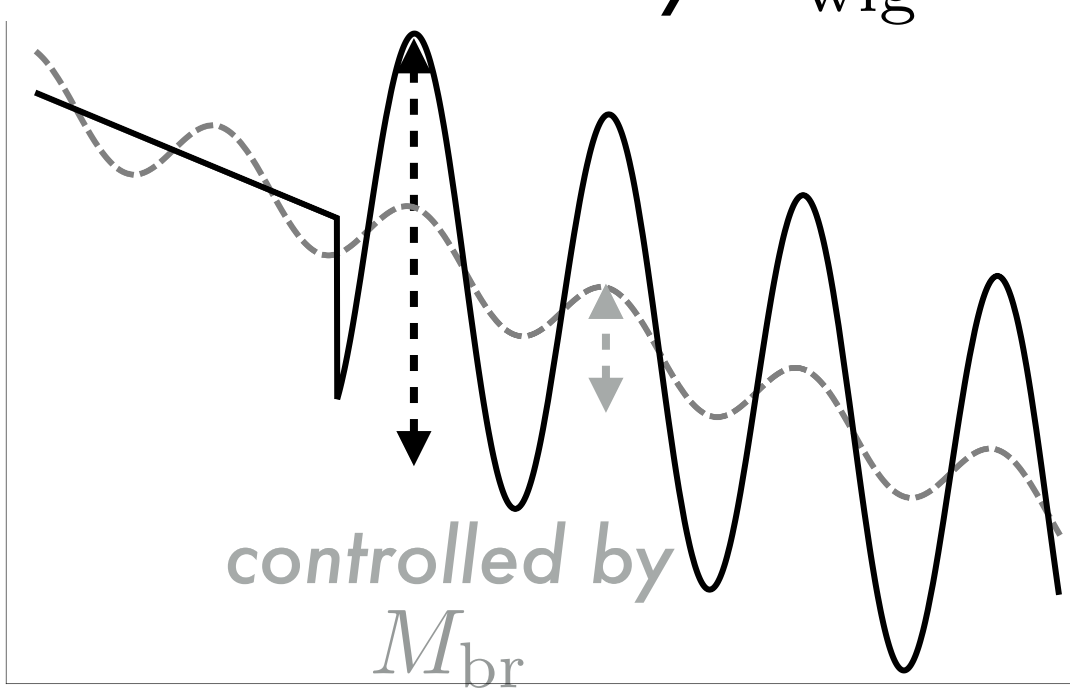
Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant '15

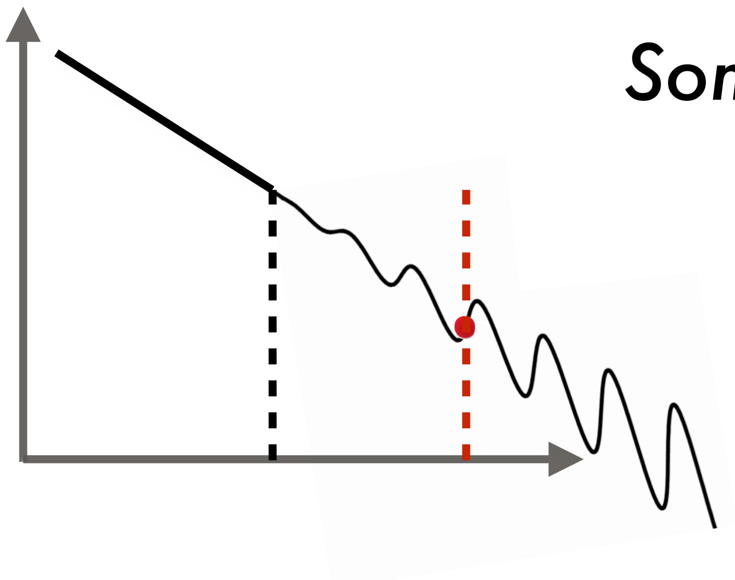
Komargodski, Gupta, Perez, Ubaldi '15

$$V_{\rm br} = -\underbrace{M_{\rm br}^2 H^\dagger H}_{\Lambda_{\rm wig} \equiv \sqrt{M_{\rm br} v}} \cos\frac{\phi}{f} + \underbrace{r_{\rm br} M_{\rm br}^4}_{} \cos\frac{\phi}{f}$$

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

no loose theorem



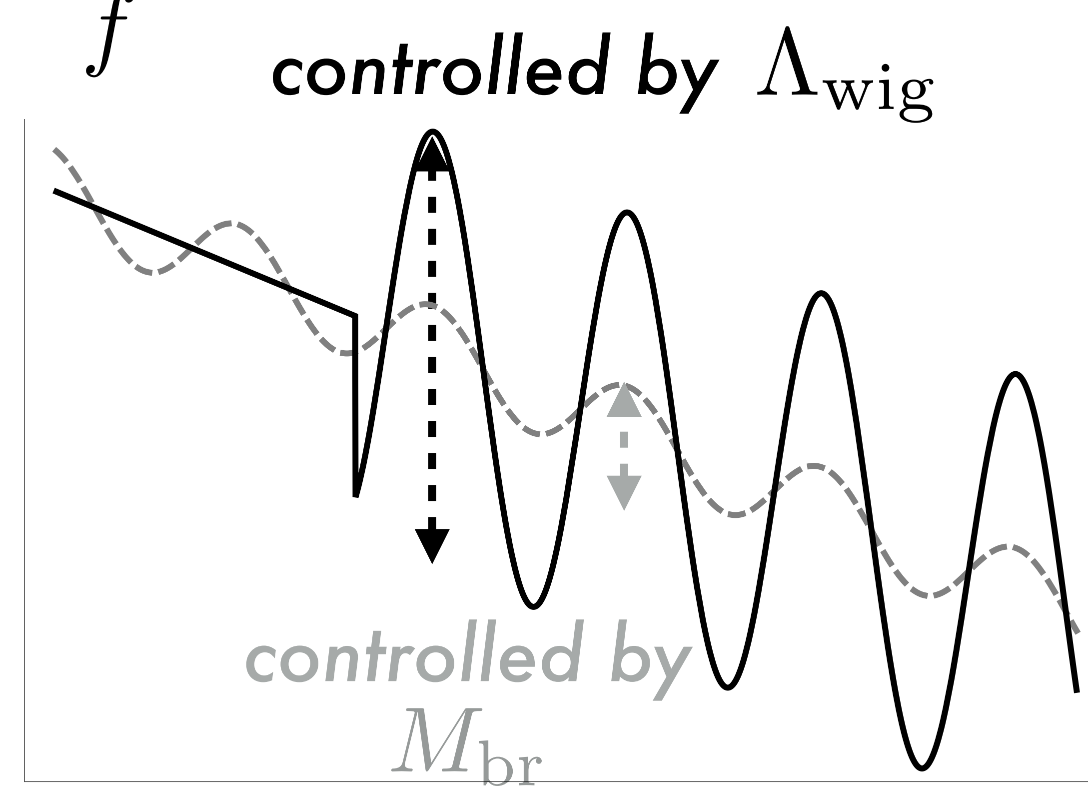


Something else than QCD generates the wiggles

Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant '15

Komargodski, Gupta, Perez, Ubaldi '15

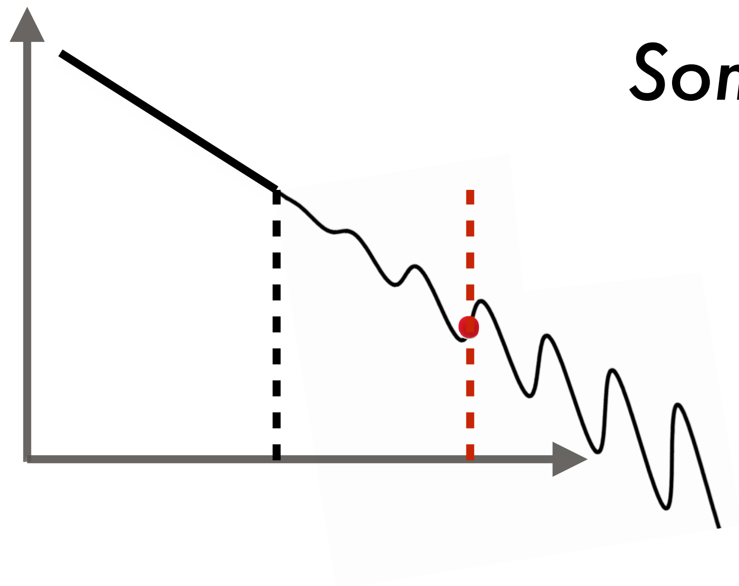
$$V_{\rm br} = -\underbrace{M_{\rm br}^2 H^\dagger H}_{\Lambda_{\rm wig} \equiv \sqrt{M_{\rm br} v}} \cos\frac{\phi}{f} + \underbrace{r_{\rm br} M_{\rm br}^4}\cos\frac{\phi}{f}$$



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

no loose theorem

New states @ the EW scale $\mathcal{L}_{\rm NP} \supset H f^{SM} f^{NP}$



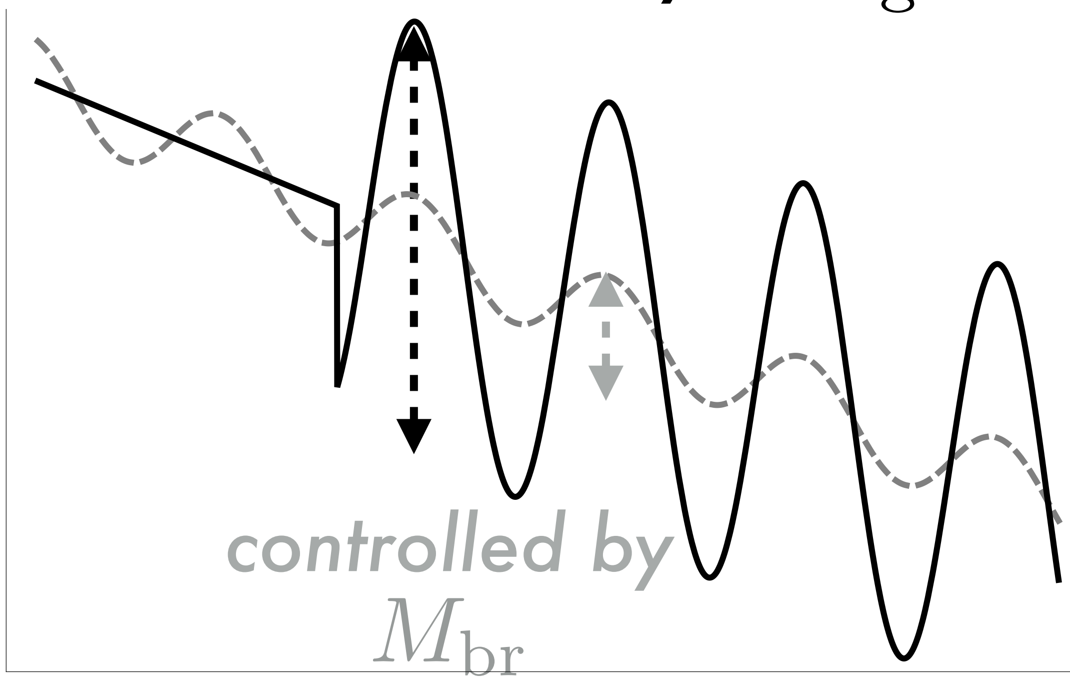
Something else than QCD generates the wiggles

Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant '15

Komargodski, Gupta, Perez, Ubaldi '15

$$V_{\rm br} = -\underbrace{M_{\rm br}^2 H^\dagger H}_{\Lambda_{\rm wig} \equiv \sqrt{M_{\rm br} v}} \cos\frac{\phi}{f} + \underbrace{r_{\rm br} M_{\rm br}^4}\cos\frac{\phi}{f}$$

controlled by $\Lambda_{\rm wig}$

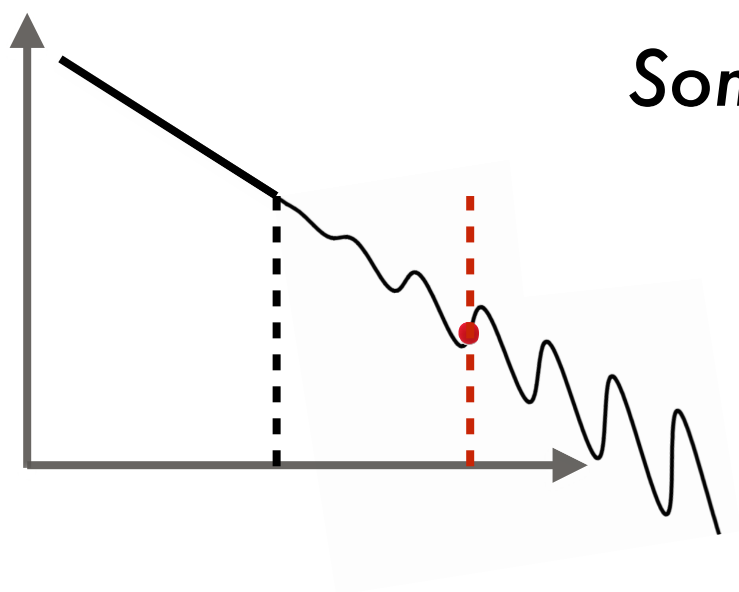


$\Lambda_{\rm wig} \gtrsim M_{\rm br}$ *to make it work*

no loose theorem

New states @ the EW scale $\mathcal{L}_{\rm NP} \supset H f^{SM} f^{NP}$

Generically these states are EW-charged



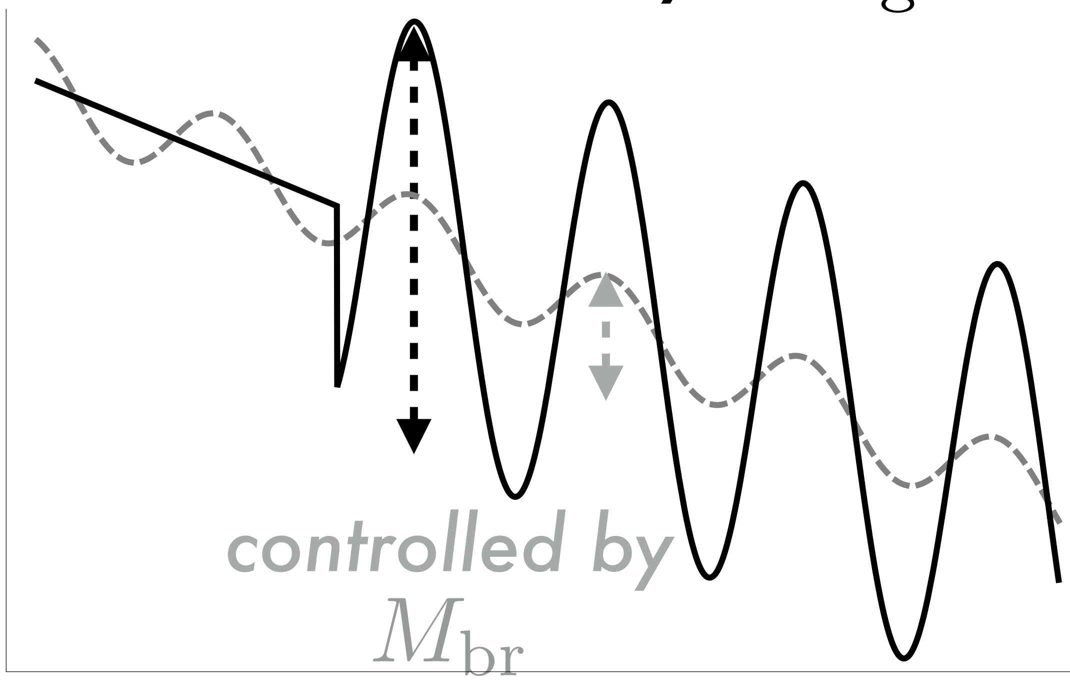
Something else than QCD generates the wiggles

Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant '15

Komargodski, Gupta, Perez, Ubaldi '15

$$V_{\rm br} = -\underbrace{M_{\rm br}^2 H^\dagger H}_{\Lambda_{\rm wig} \equiv \sqrt{M_{\rm br} v}} \cos\frac{\phi}{f} + \underbrace{r_{\rm br} M_{\rm br}^4}\cos\frac{\phi}{f}$$

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

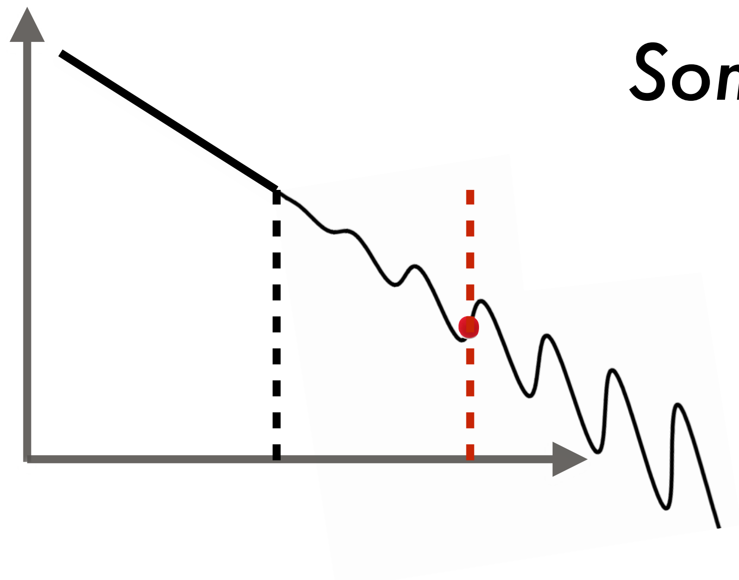


no loose theorem

New states @ the EW scale $\mathcal{L}_{\rm NP} \supset H f^{SM} f^{NP}$

Generically these states are EW-charged

We can test them @ collider



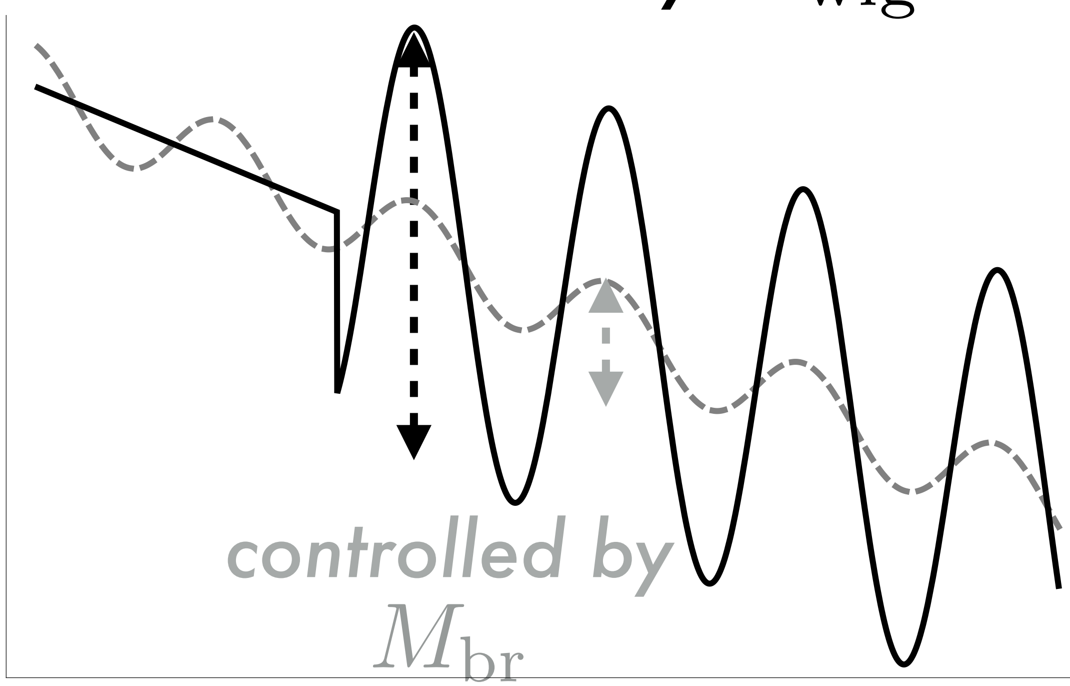
Something else than QCD generates the wiggles

Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant '15

Komargodski, Gupta, Perez, Ubaldi '15

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

$\Lambda_{\rm wig} \equiv \sqrt{M_{\rm br} v}$



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

no loose theorem

New states @ the EW scale $\mathcal{L}_{\rm NP} \supset H f^{SM} f^{NP}$

Generically these states are EW-charged

We can test them @ collider

I will show a counter-example later...

addressing strong CP

Something else than QCD generates the wiggles

+

Nelson-Barr sector generates the rolling

addressing strong CP

Something else than QCD generates the wiggles

+

Nelson-Barr sector generates the rolling

CP is a symmetry of the UV theory

it is spontaneously broken by the relaxion VEV

a discrete symmetry forbids the coupling to $G\tilde{G}$

} Nelson-Barr solution to the strong CP problem

(Nelson '84, Barr '84)

addressing strong CP

Something else than QCD generates the wiggles

+

Nelson-Barr sector generates the rolling

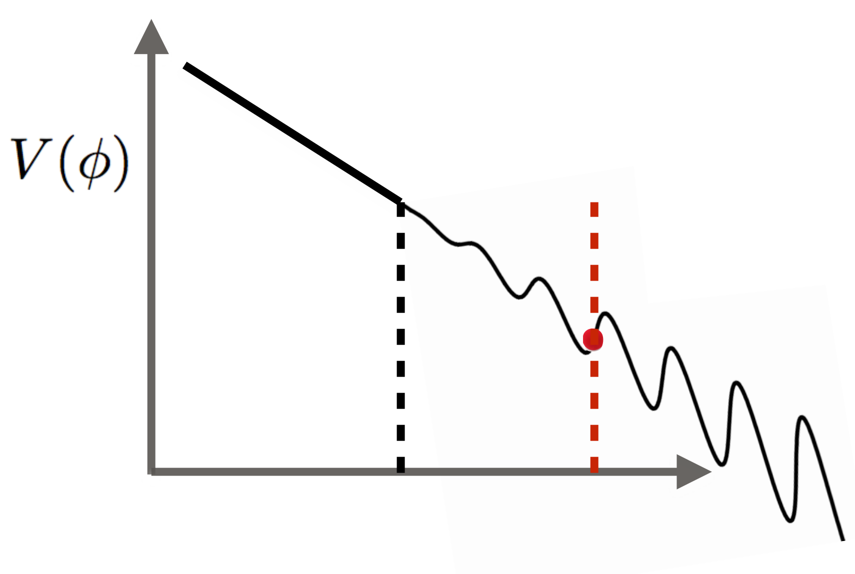
CP is a symmetry of the UV theory

it is spontaneously broken by the relaxion VEV

a discrete symmetry forbids the coupling to $G\tilde{G}$

} Nelson-Barr solution to the strong CP problem (Nelson '84, Barr '84)

The U(1) on the N-site of the clockwork chain is broken explicitly $g_{u,d}\tilde{g}_{u,d}$

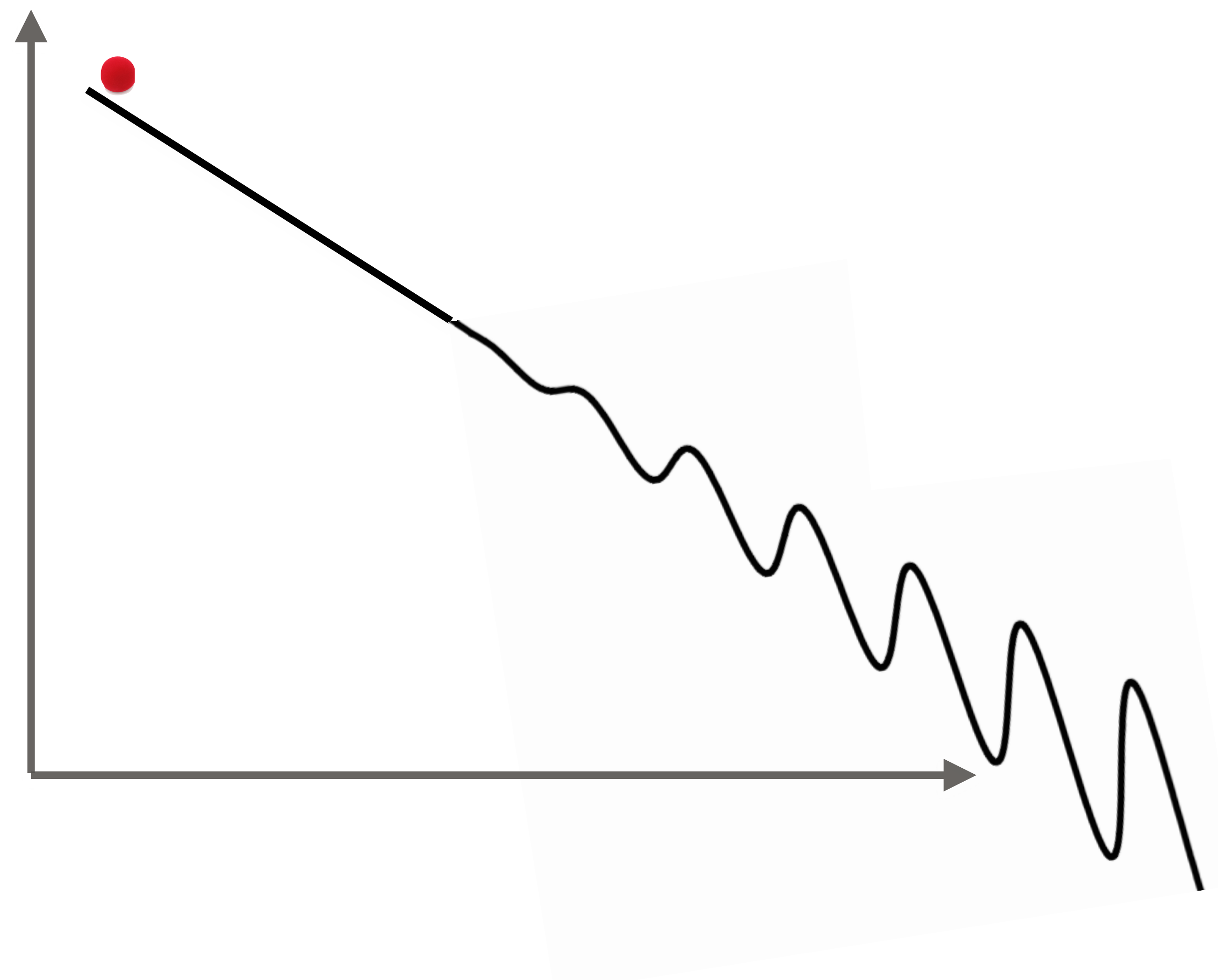


ϕ ***rolling potential:*** $V_{\rm roll} = \frac{g_{u,d}\tilde{g}_{u,d} f^4}{16\pi^2} \cos\frac{\phi}{F}$

$$\cos\frac{\phi_0}{F} \sim \delta_{\rm CKM} \sim \mathcal{O}(1)$$

Davidi,Gupta, Perez,DR, Shalit '17

New playground for Naturalness

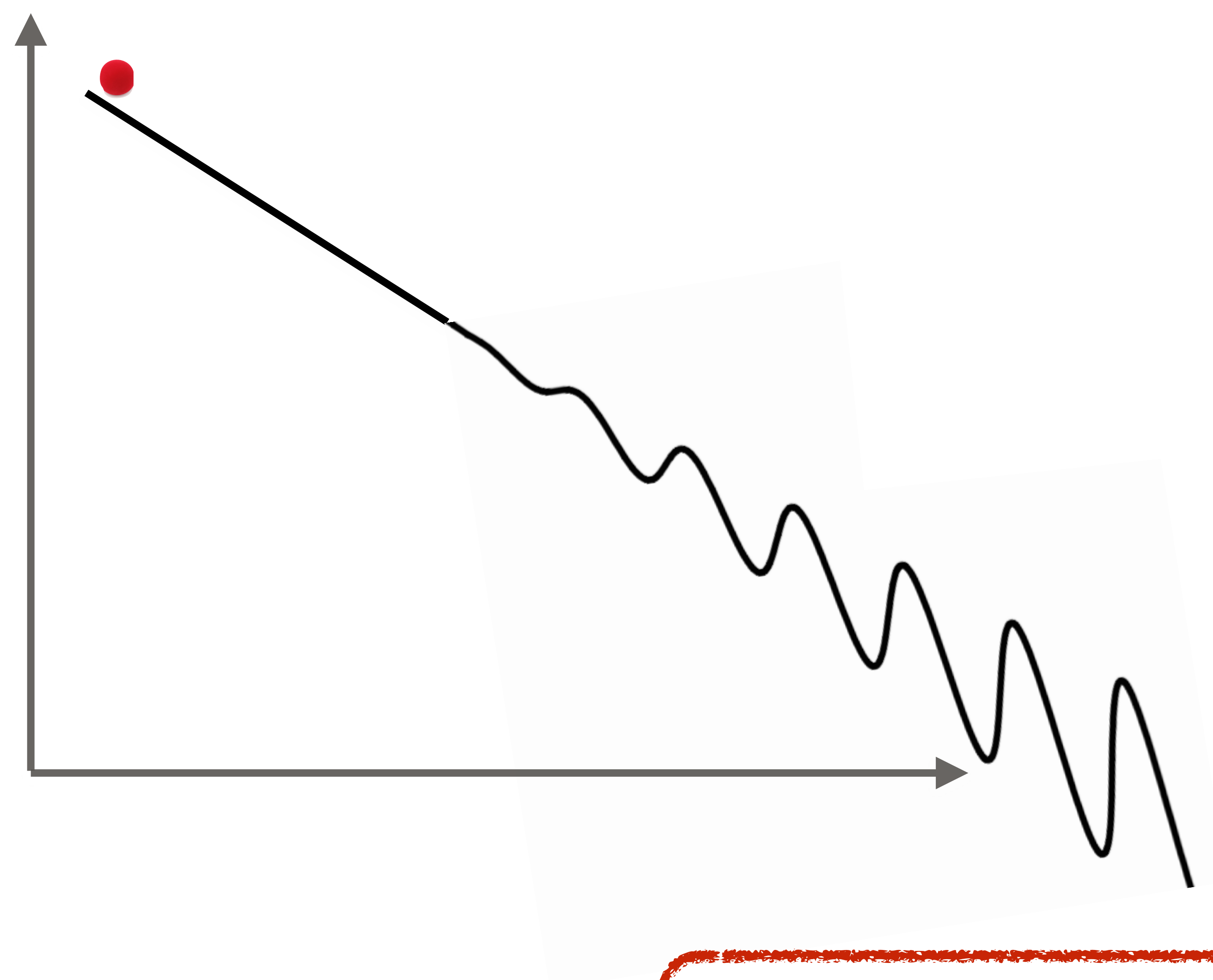


new
theoretical
challenges

↔

new
phenomenological
probes

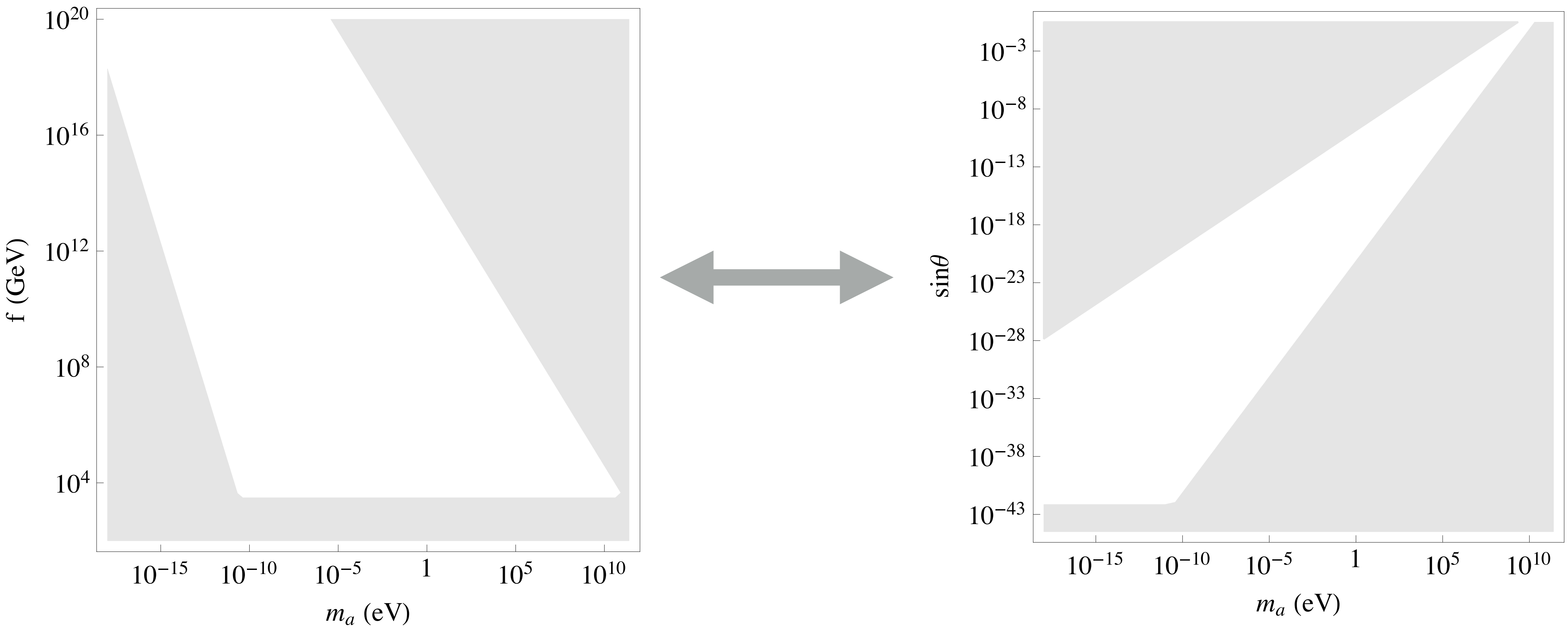
New playground for Naturalness

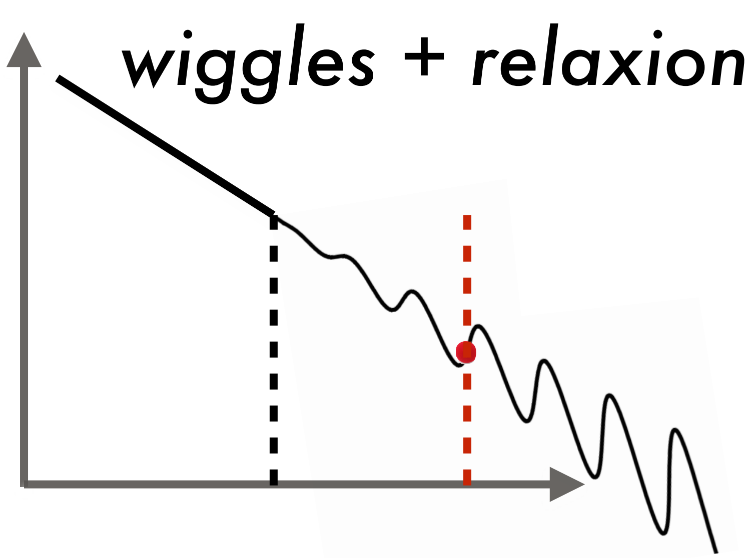


new theoretical challenges ⟷ new phenomenological probes

The relaxion parameter space

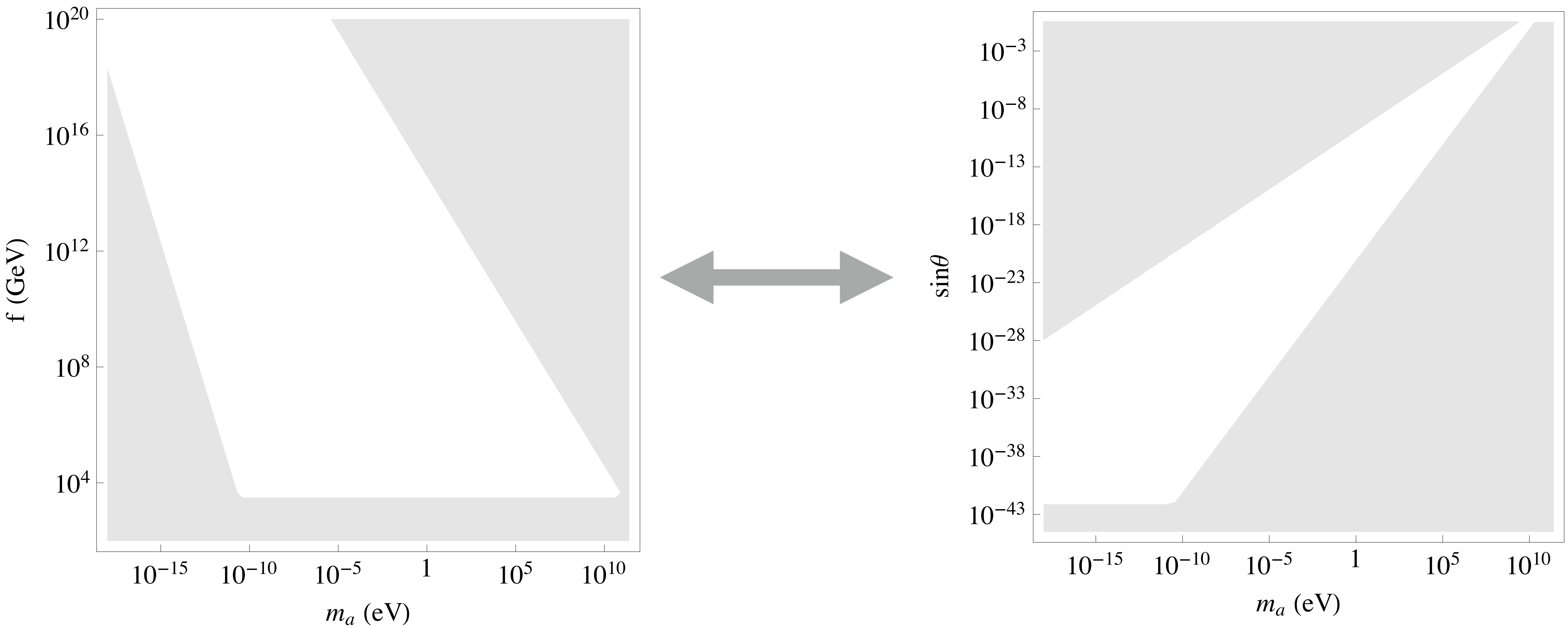
Model-independent PHENO depends on explicit breaking from wiggles

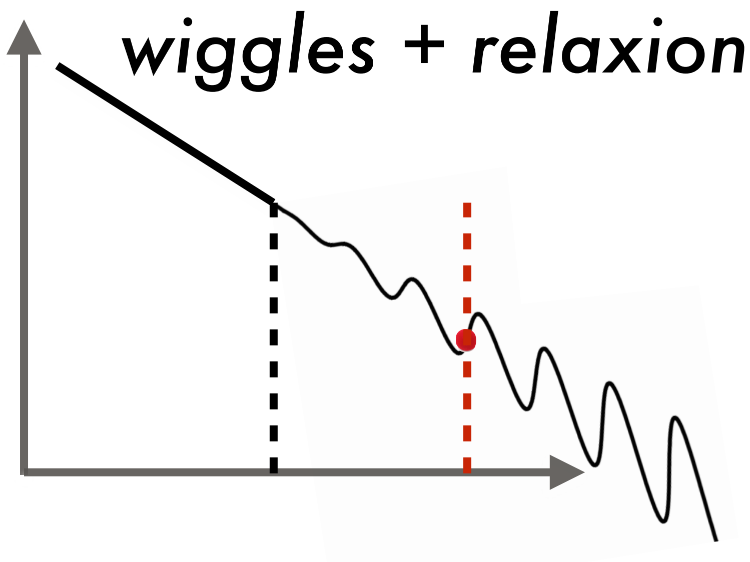




The relaxion parameter space

Model-independent PHENO depends on explicit breaking from wiggles



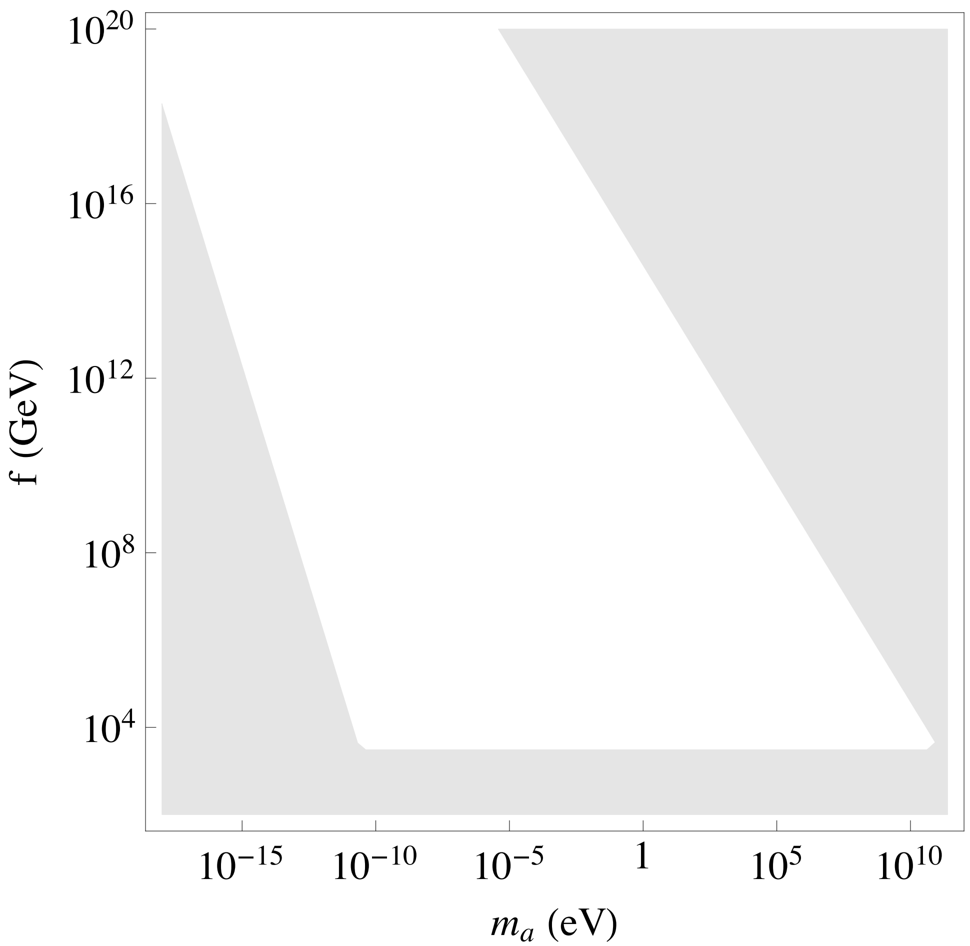


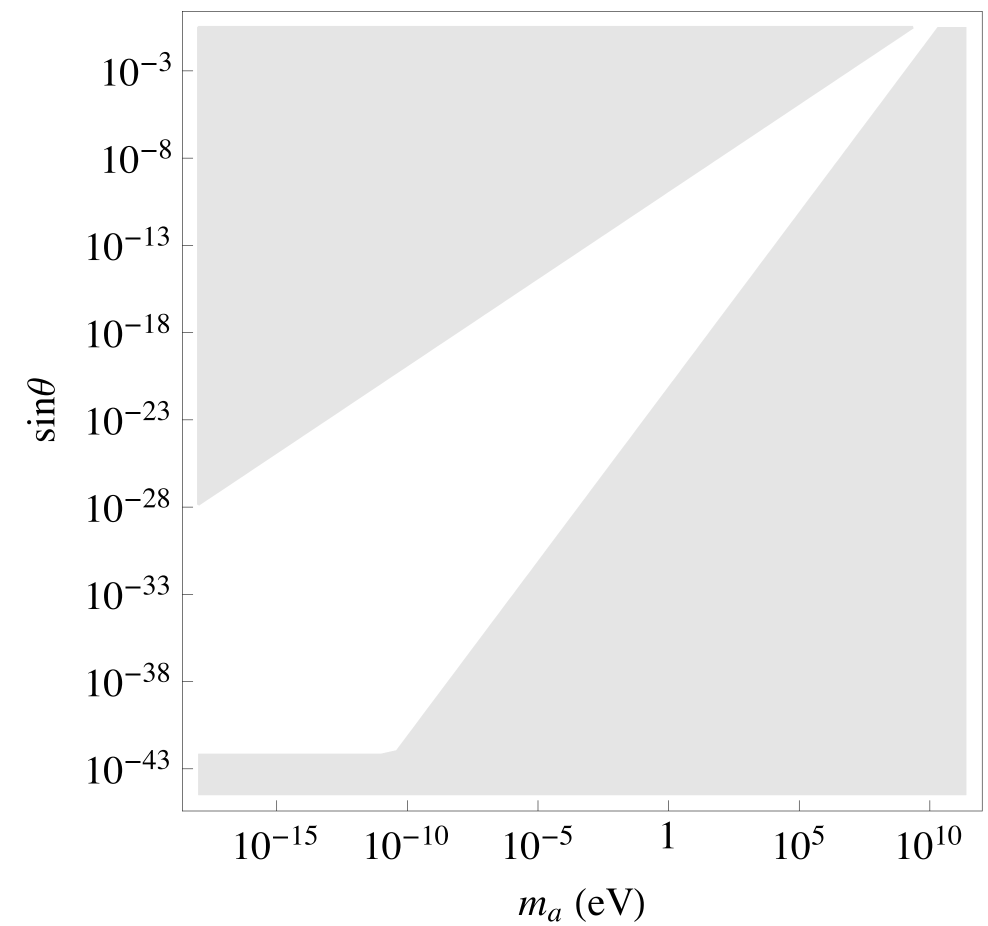
wiggles + relaxion VEV ---▸ relaxion mass

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

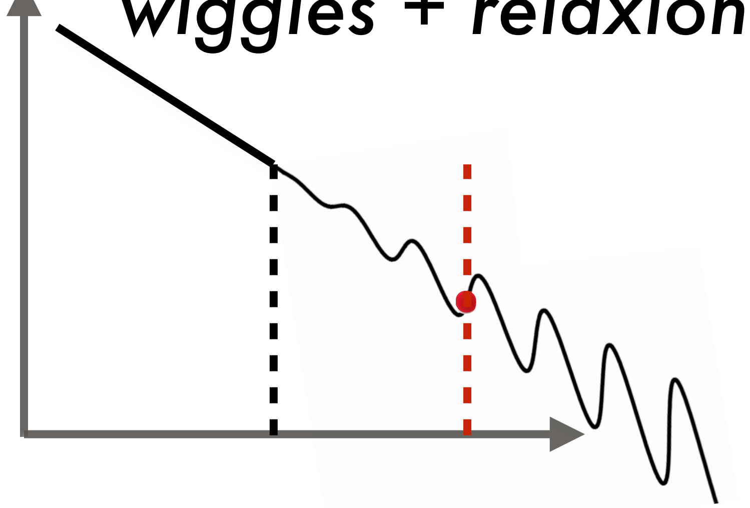
The relaxion parameter space

Model-independent PHENO depends on explicit breaking from wiggles





wiggles + relaxion VEV



- - -▸ relaxion mass $$m_a \simeq \frac{\overbrace{M_{\rm br}^2}}{f}$$

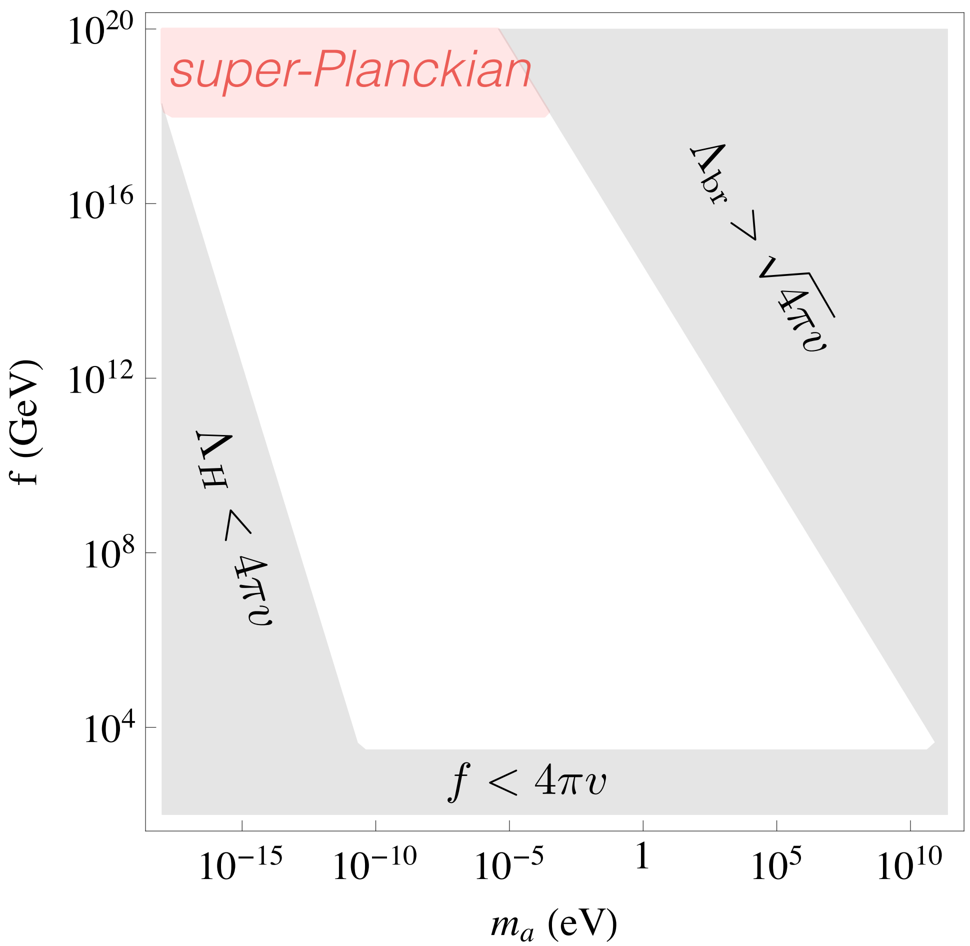
- - -▸ relaxion-Higgs mixing $$\sin\theta \simeq \frac{v}{f} \cdot \frac{\overbrace{M_{\rm br}^2}}{m_h^2}$$

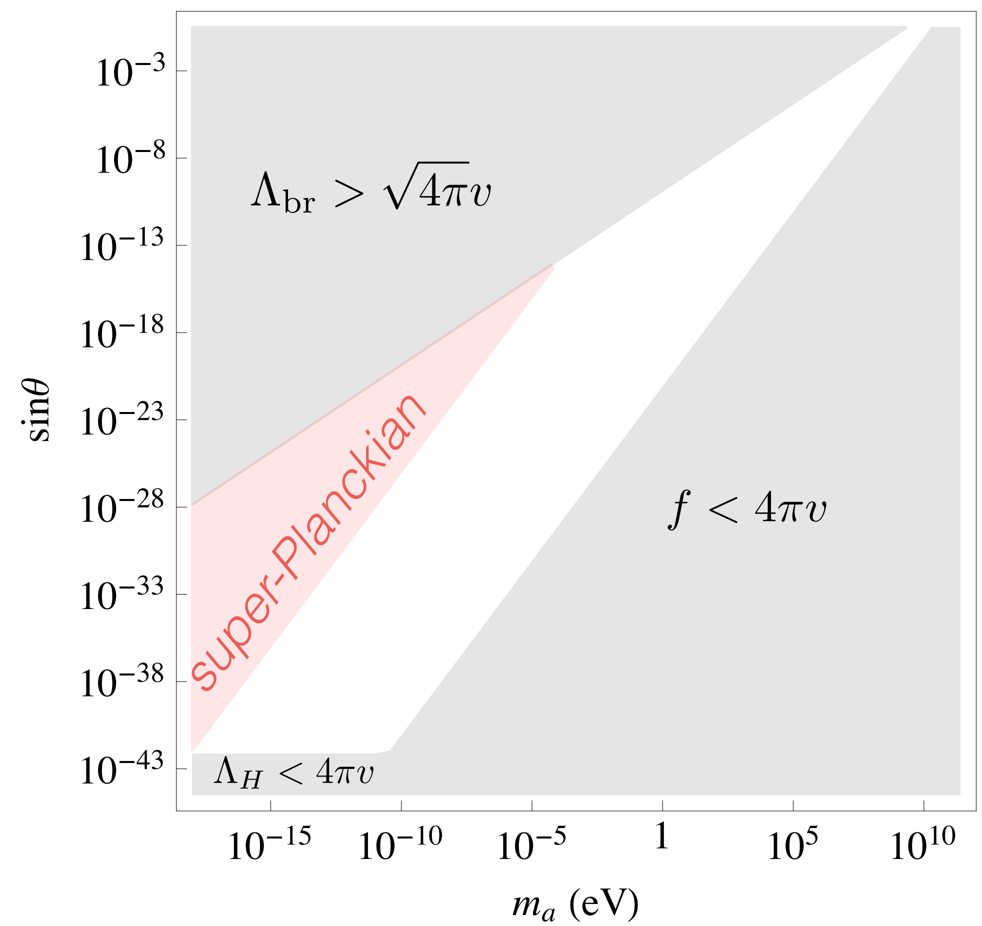
Flacke,Gupta, Frugiuele, Fuchs,Perez ‘16

Choi and Im ‘17

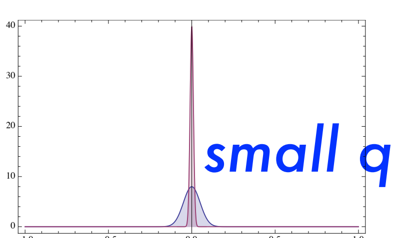
The relaxion parameter space

Model-independent boundaries





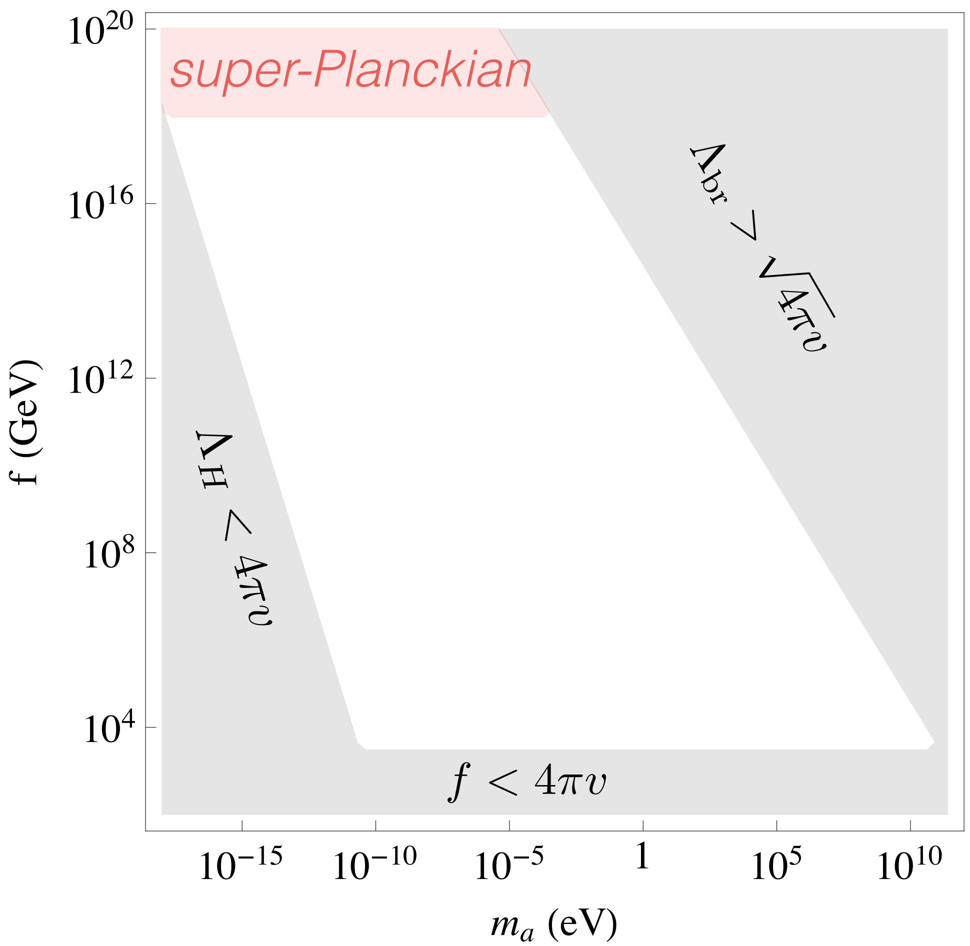
inflation OK $\Lambda_{\rm roll}^4 \lesssim H_I^2 M_{\rm Pl}^2$

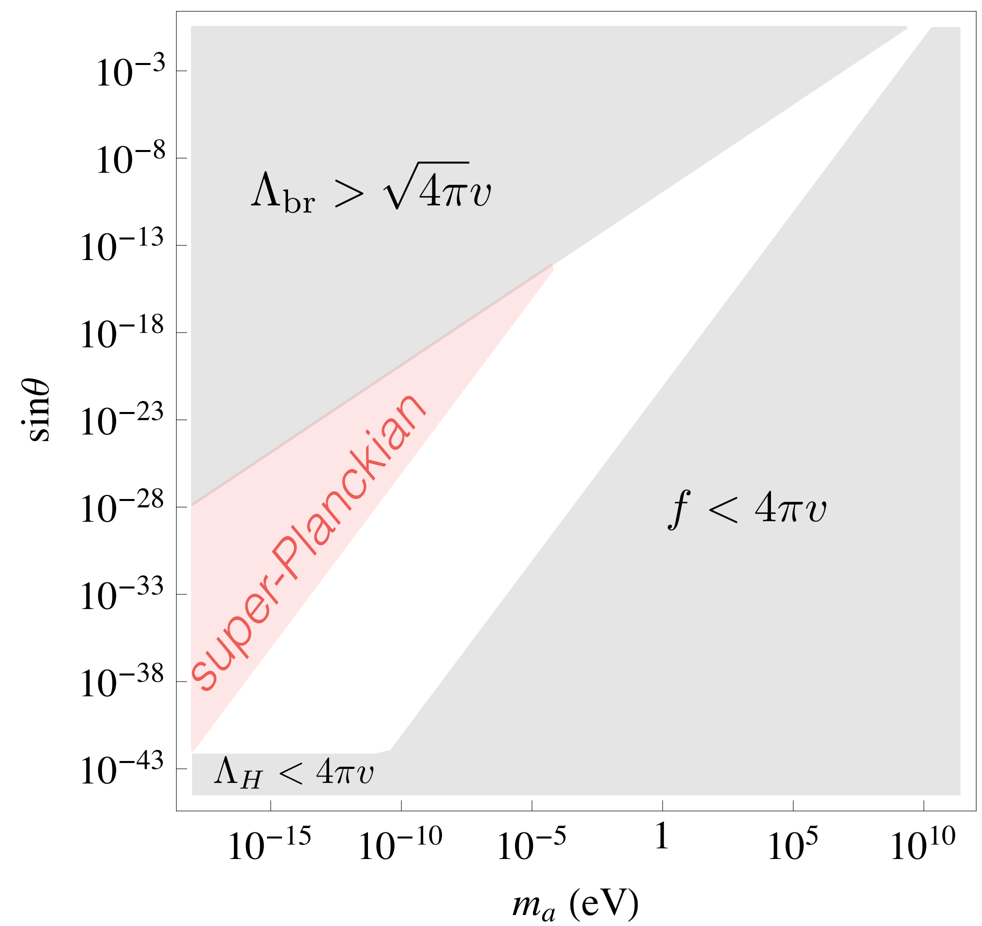


small quantum spread $\dot{\phi} \gtrsim H_I^2$

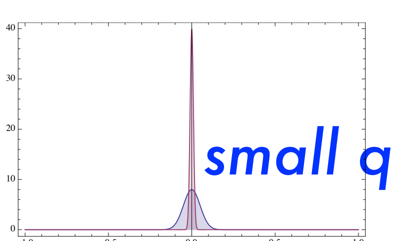
The relaxion parameter space

Model-independent boundaries





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

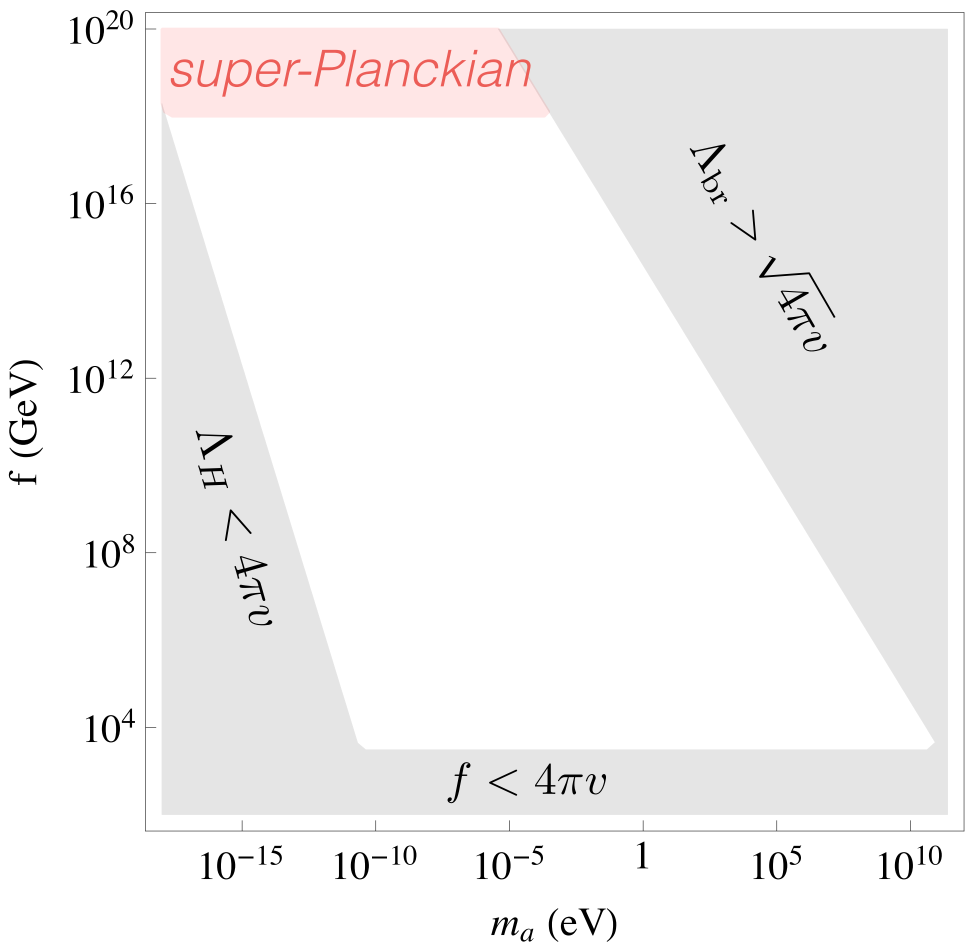


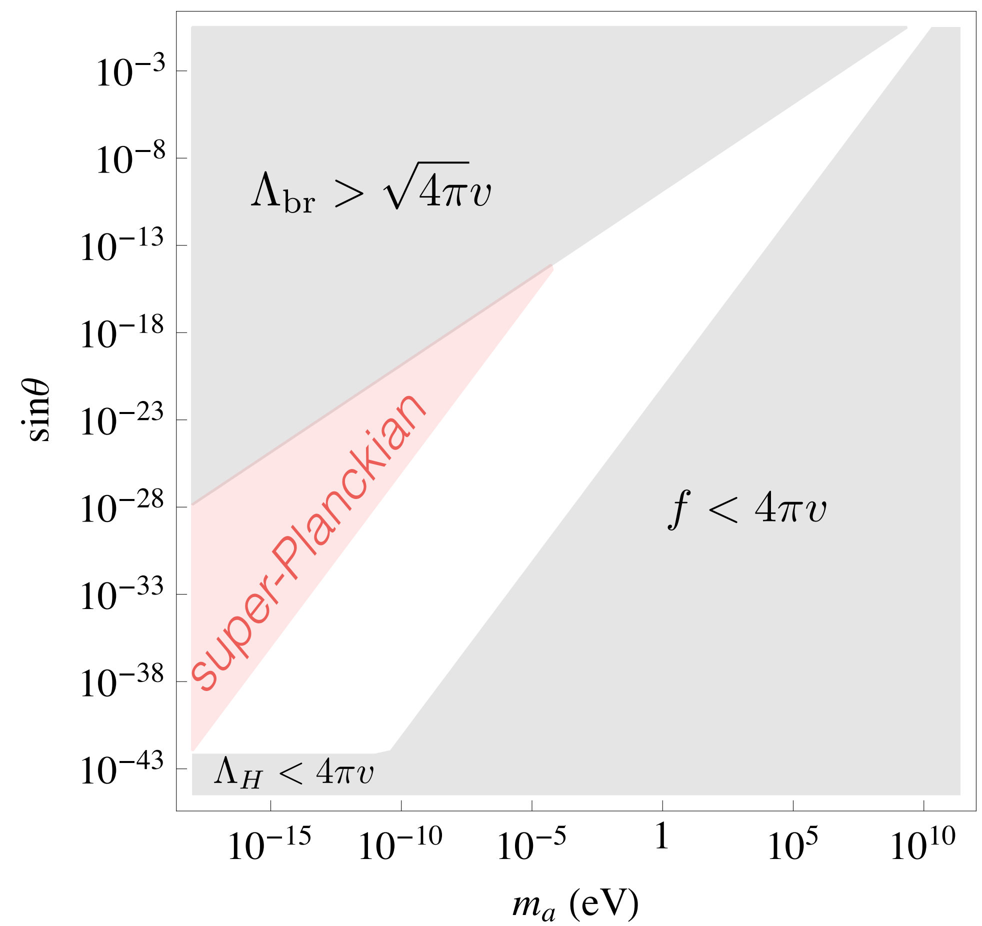
small quantum spread $\dot{\phi} \gtrsim H_I^2$

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

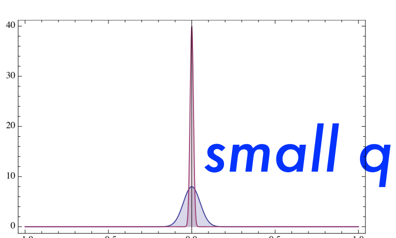
The relaxion parameter space

Model-independent boundaries





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



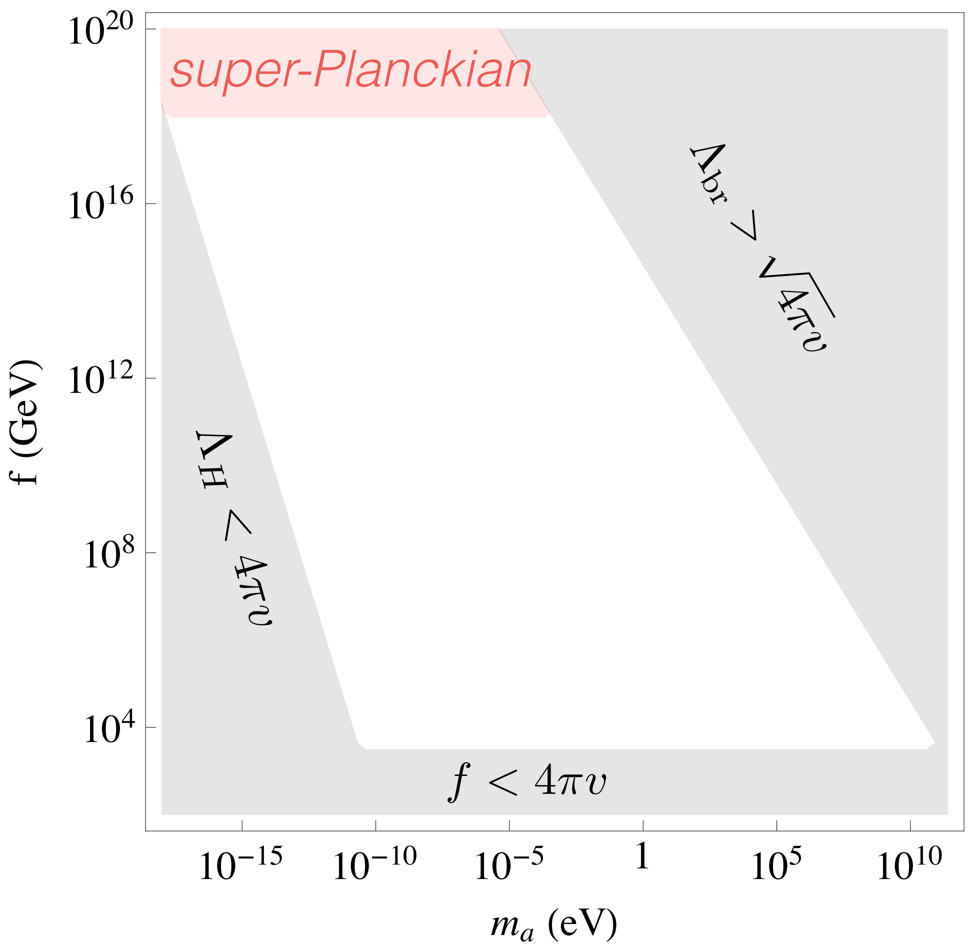
small quantum spread $\dot{\phi} \gtrsim H_I^2$

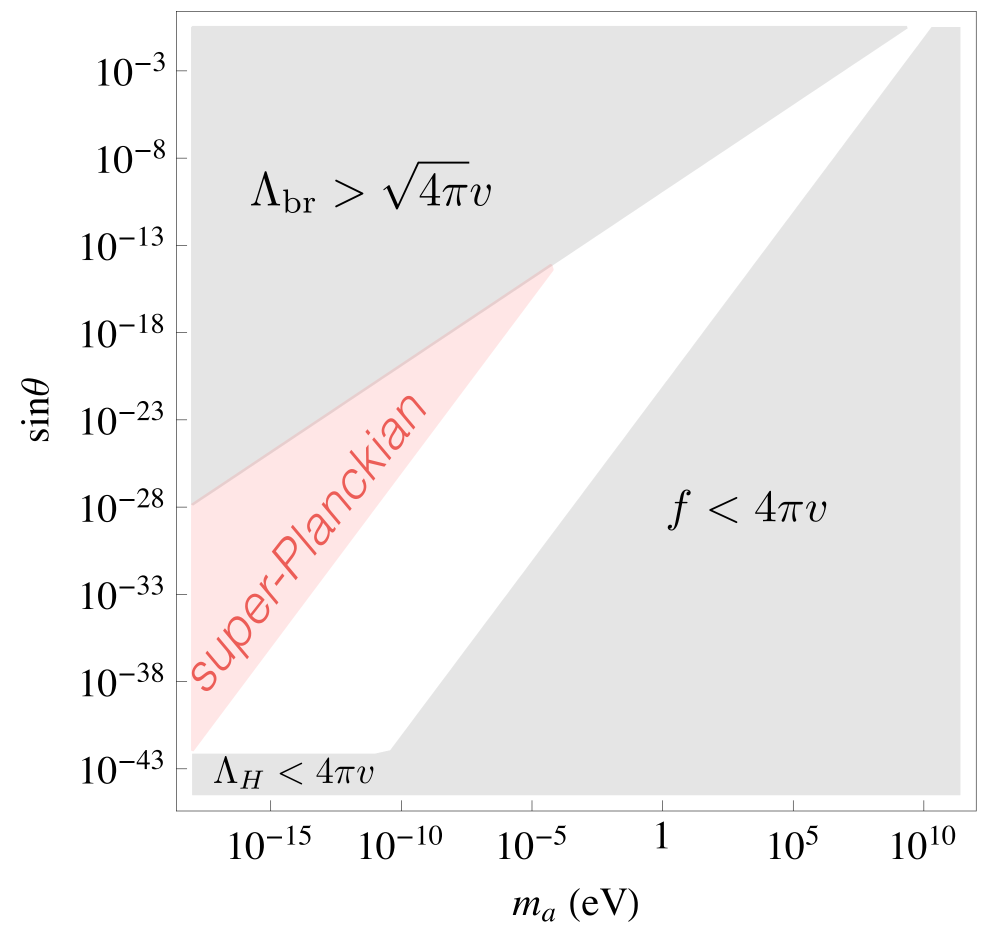
$$\begin{cases} 4\pi v \lesssim \Lambda_H \lesssim \underbrace{\left(\frac{M_{Pl}}{r_{roll}}\right)^{1/2} \left(\frac{\Lambda_{br}^4}{f}\right)^{1/6}} \\ \sqrt{\frac{M_{Pl}}{f}} \cdot 10^{-18}\ \text{eV} \lesssim m_a \lesssim v \end{cases}$$

maximal gain in cut-off

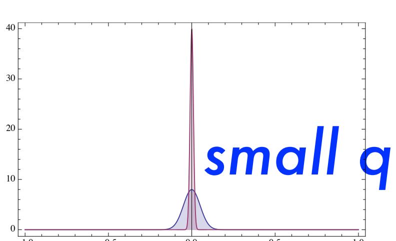
The relaxion parameter space

Model-independent boundaries





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



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

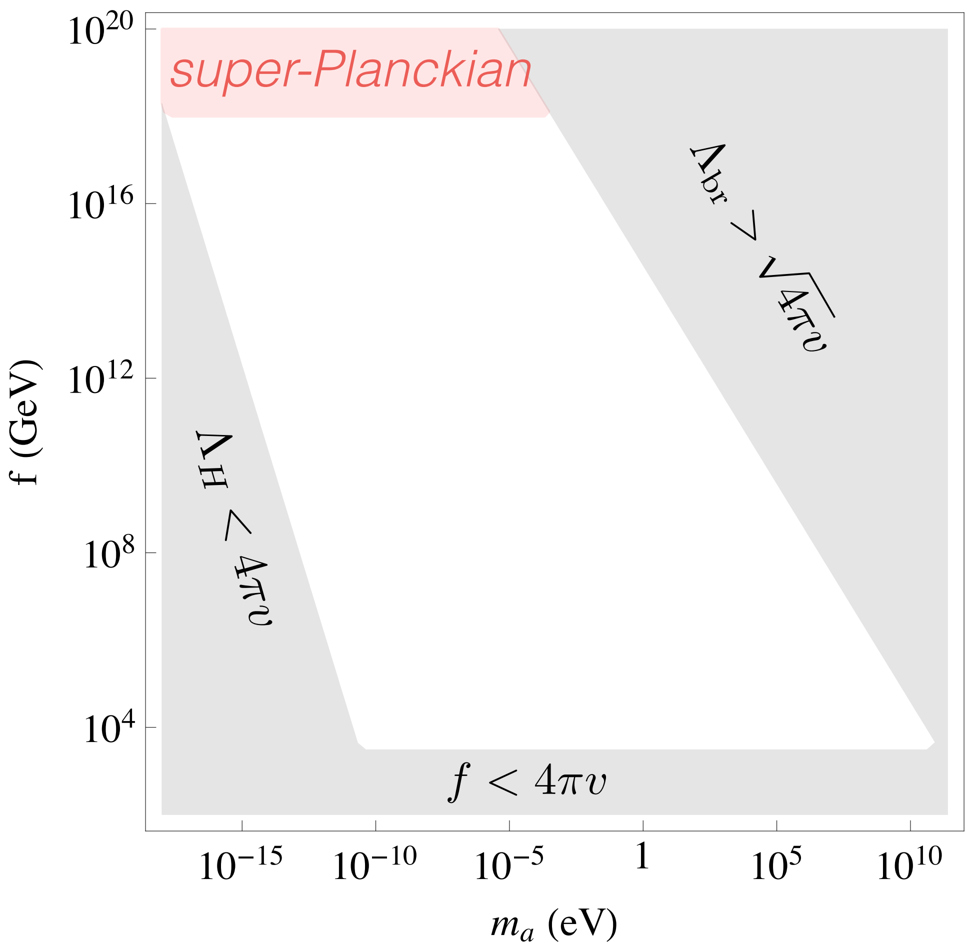
$$\begin{cases} 4\pi v \lesssim \Lambda_H \lesssim \underbrace{\left(\dfrac{M_{Pl}}{r_{roll}}\right)^{1/2} \left(\dfrac{\Lambda_{br}^4}{f}\right)^{1/6}}_{\text{maximal gain in cut-off}} \\ \underbrace{\sqrt{\dfrac{M_{Pl}}{f}} \cdot 10^{-18}\ \text{eV}}_{\text{minimal mass}} \lesssim m_a \lesssim v \end{cases}$$

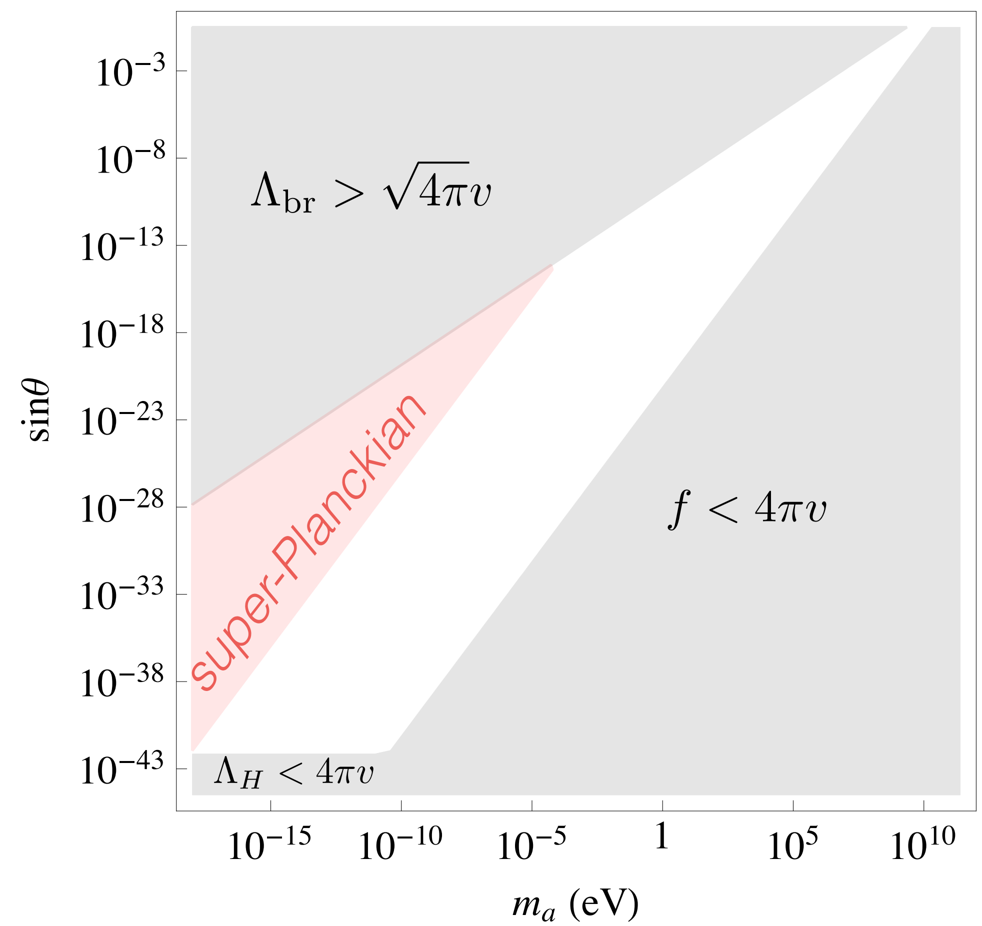
maximal gain in cut-off

minimal mass

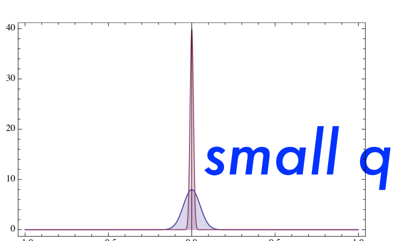
The relaxion parameter space

Model-independent boundaries





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



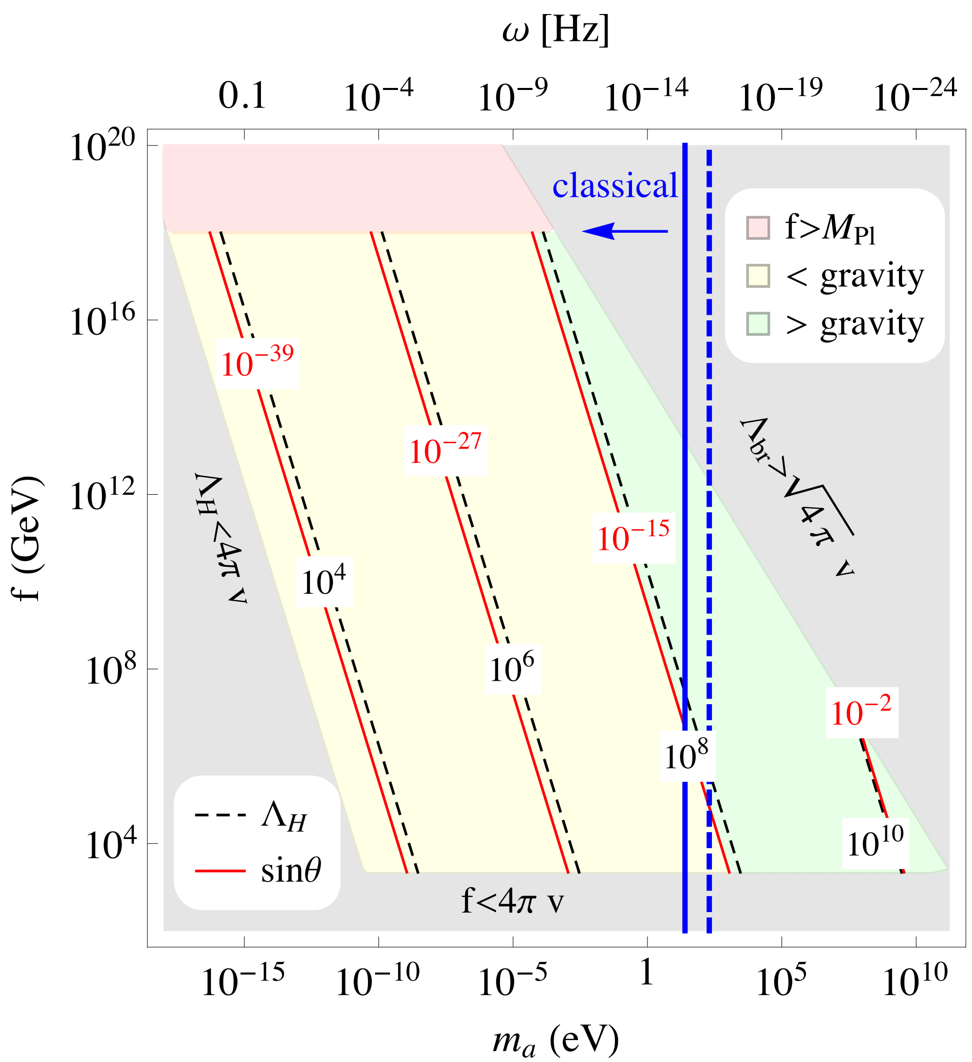
small quantum spread $\dot\phi \gtrsim H_I^2$

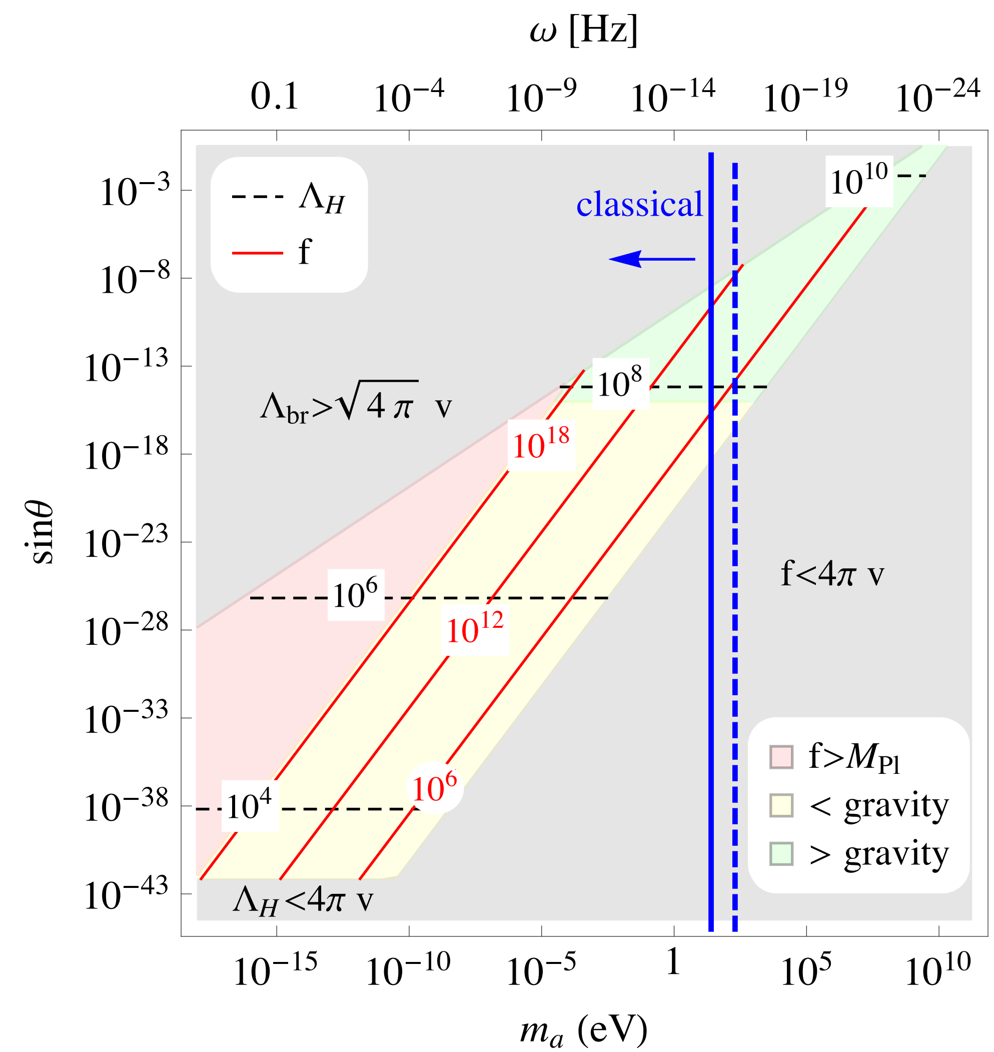
$$\begin{cases} 4\pi v \lesssim \Lambda_H \lesssim \underbrace{\left(\dfrac{M_{\rm Pl}}{r_{\rm roll}}\right)^{1/2}\left(\dfrac{\Lambda_{\rm br}^4}{f}\right)^{1/6}}_{\text{maximal gain in cut-off}} \\ \underbrace{\sqrt{\dfrac{M_{\rm Pl}}{f}}\cdot 10^{-18}\ {\rm eV}}_{\text{minimal mass}} \lesssim m_a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

maximal gain in cut-off

minimal mass (heavier than bounds from Ly-a power spectrum)

The relaxion parameter space

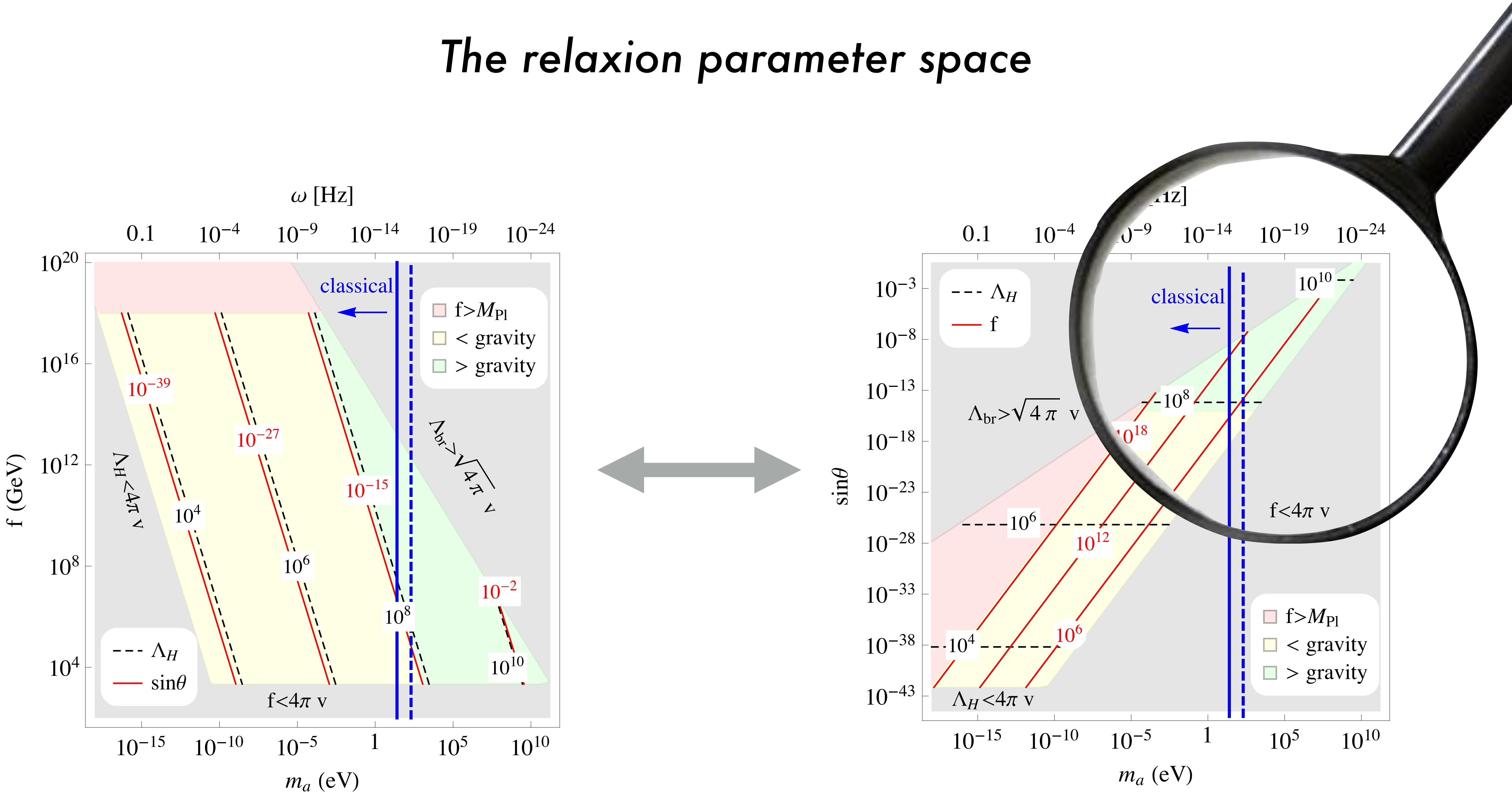




highest cut-off ⟷ *highest mixing*

TESTABLE SETUP

The relaxion parameter space

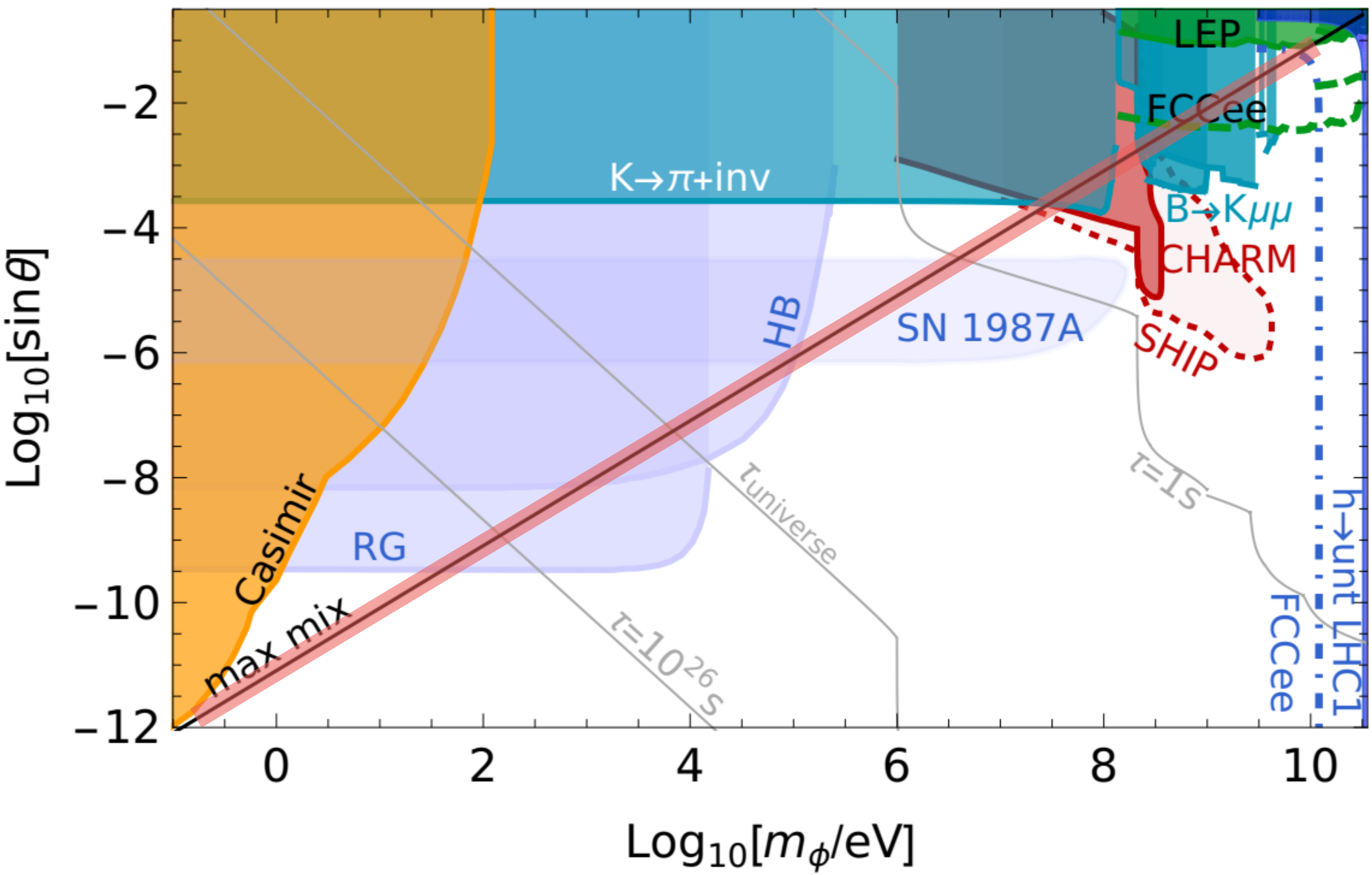


highest cut-off ⟷ ***highest mixing***

TESTABLE SETUP

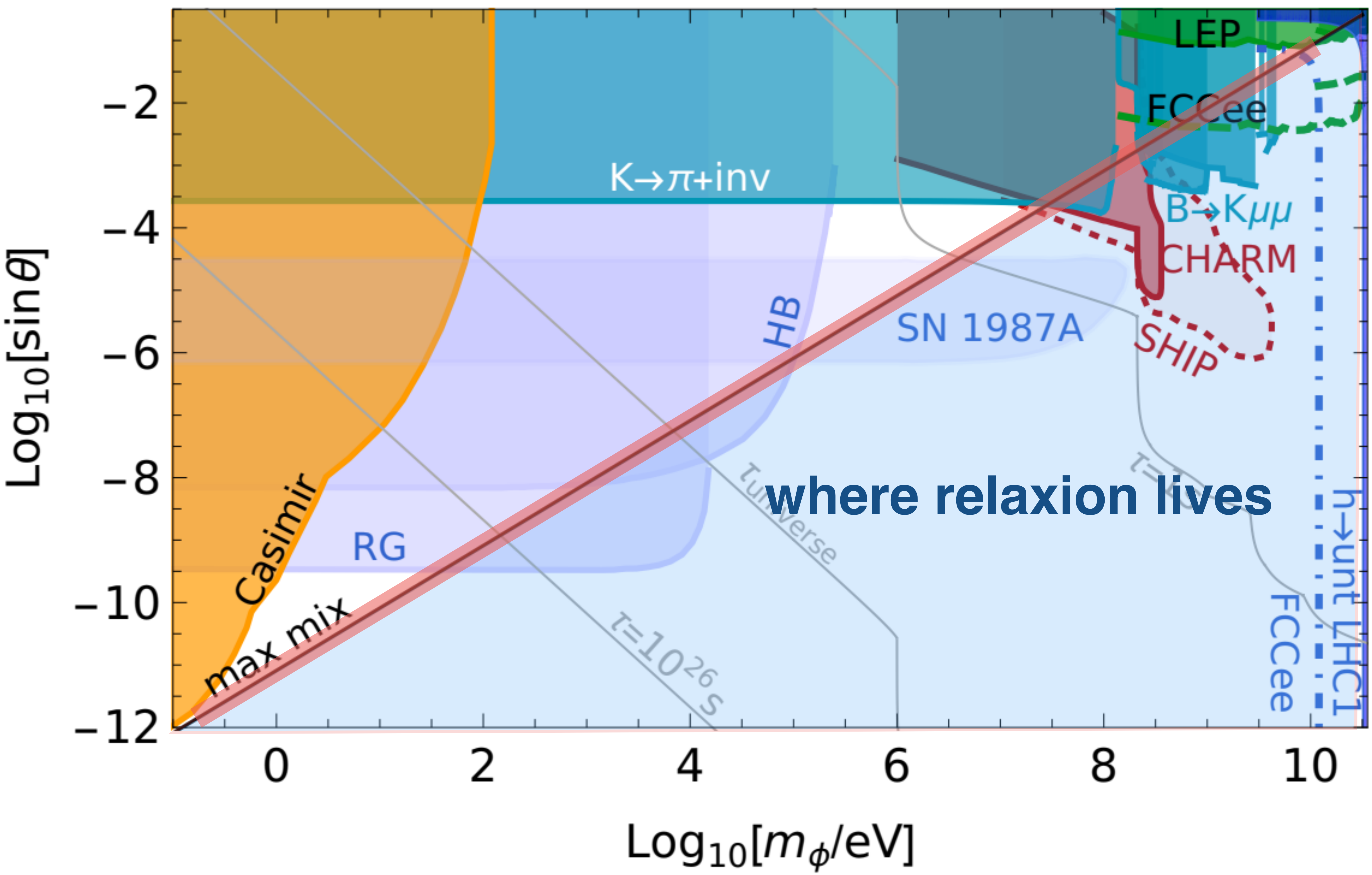
The Phenomenology is the one of a light Higgs portal

Frugiuele, Fuchs,Perez,Schlaffer '18



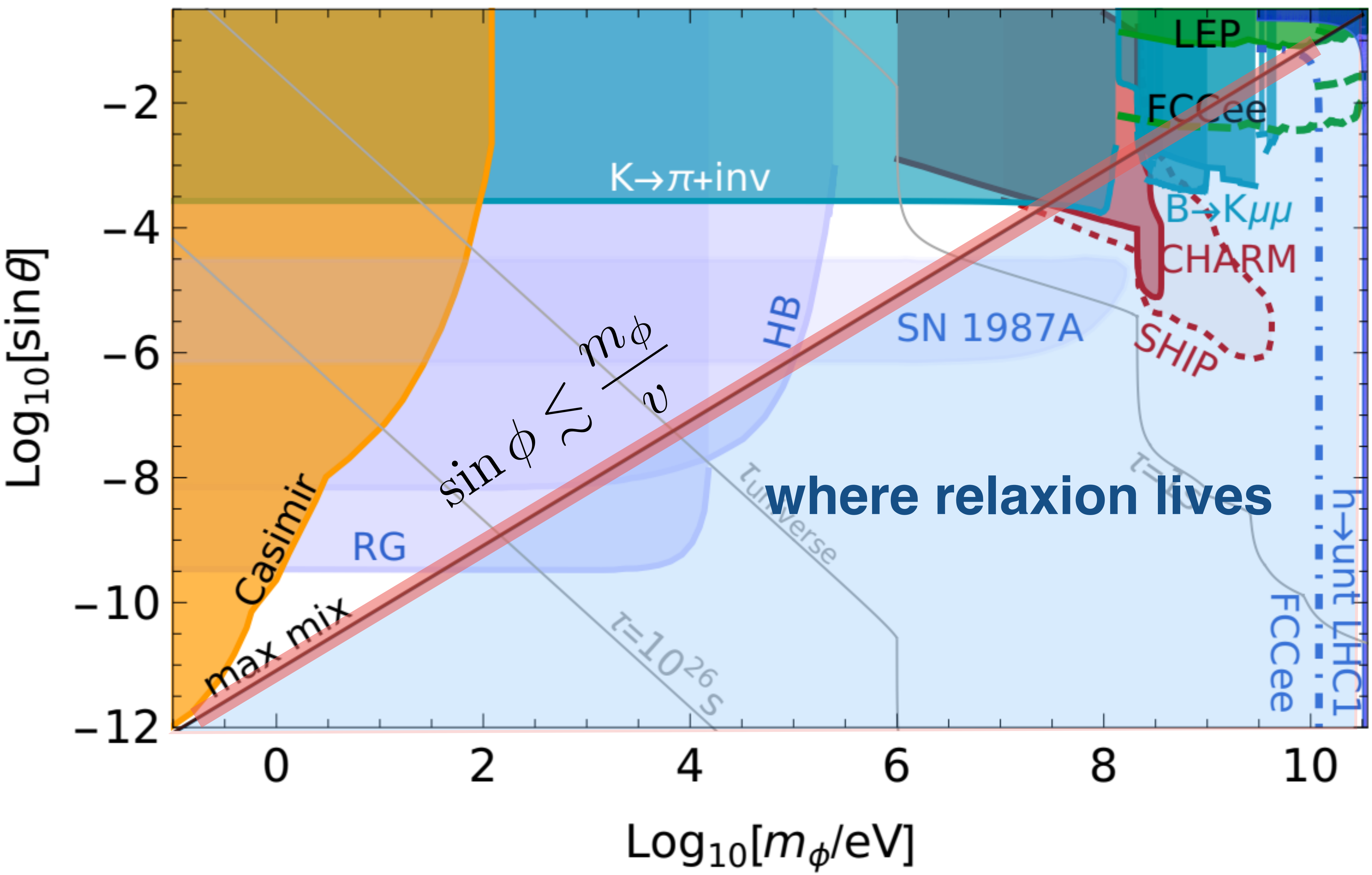
The Phenomenology is the one of a light Higgs portal

Frugiuele, Fuchs,Perez,Schlaffer '18



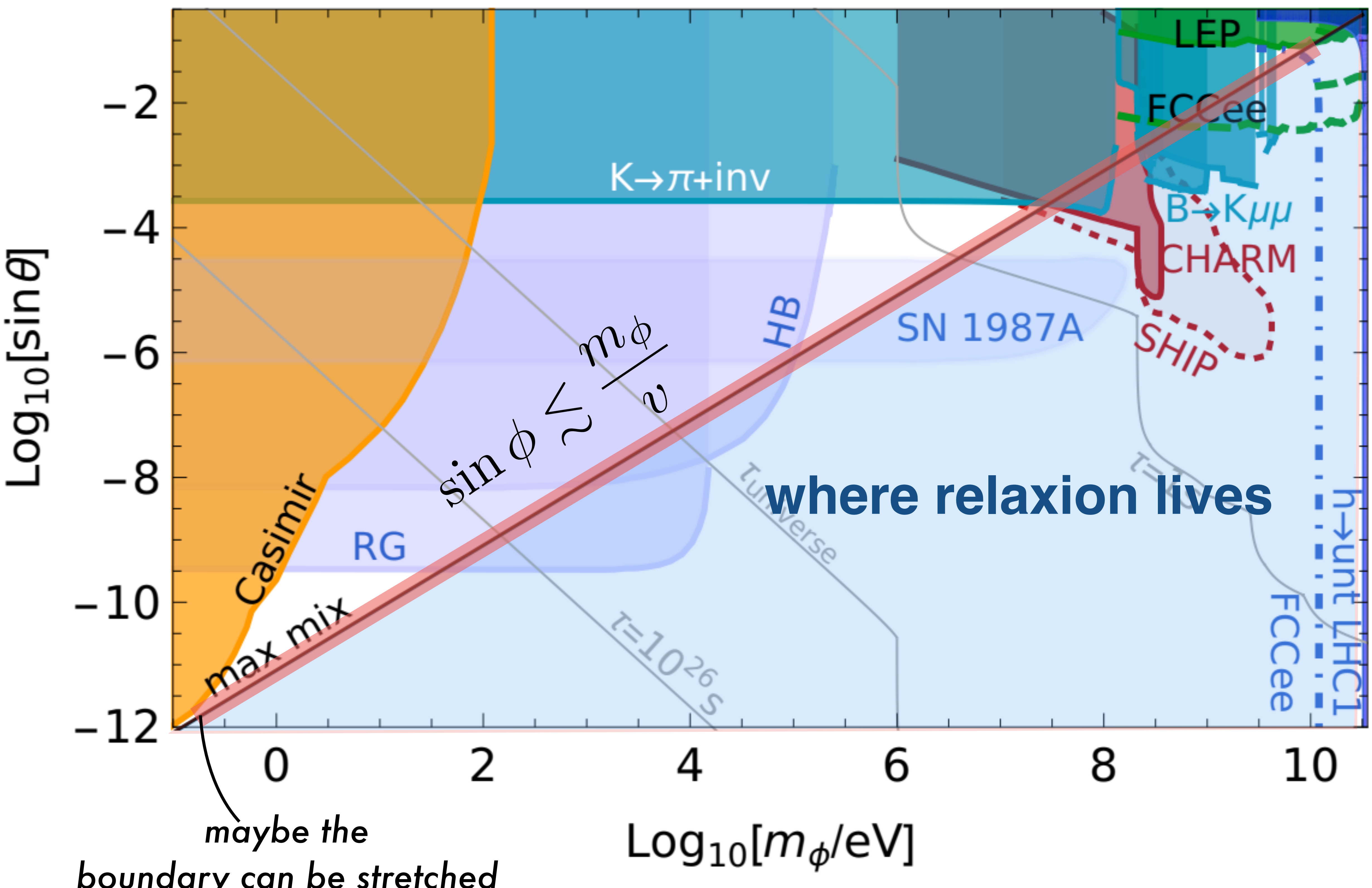
The Phenomenology is the one of a light Higgs portal

Frugiuele, Fuchs,Perez,Schlaffer '18

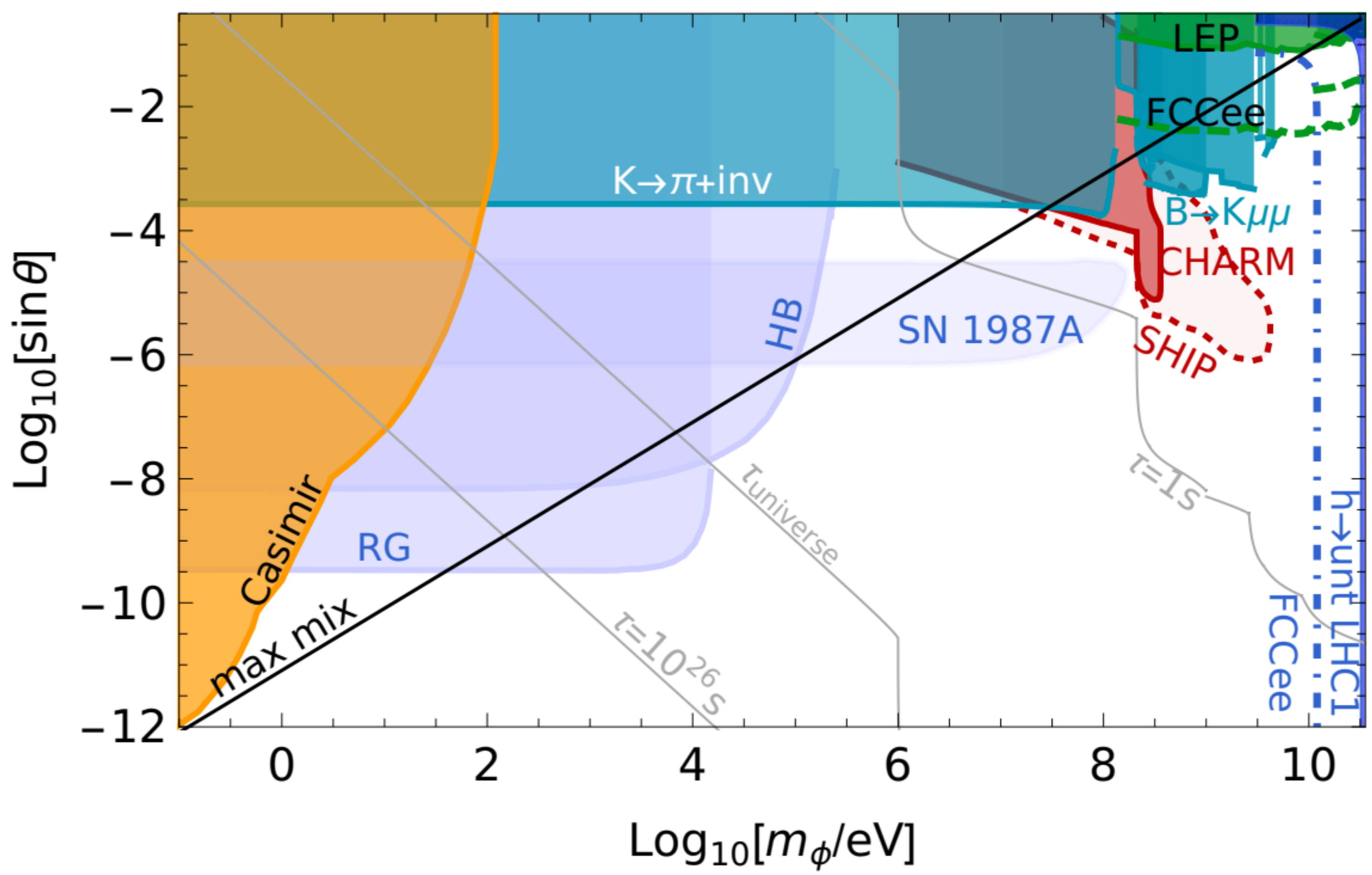


The Phenomenology is the one of a light Higgs portal

Frugiuele, Fuchs,Perez,Schlaffer '18

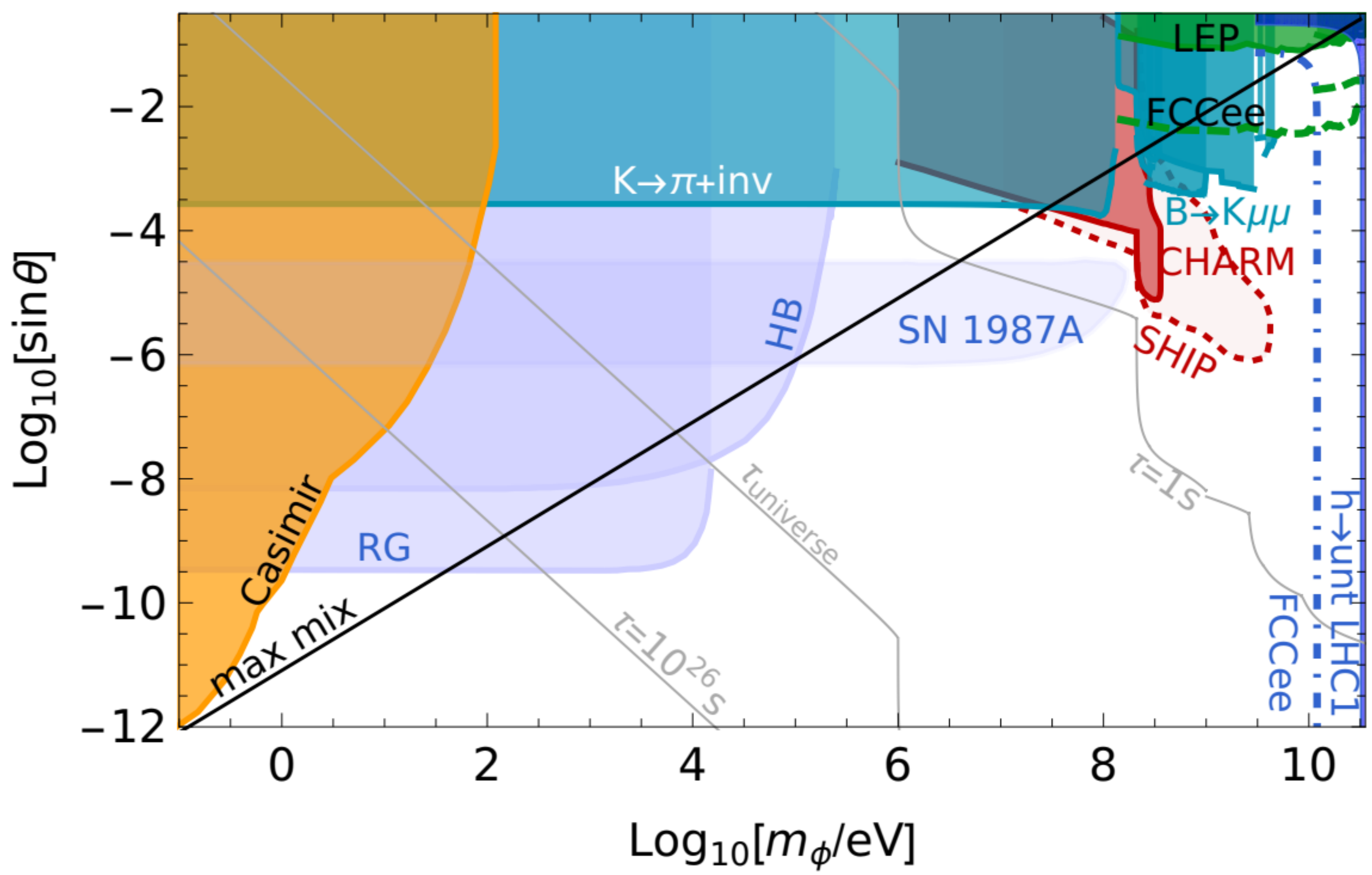


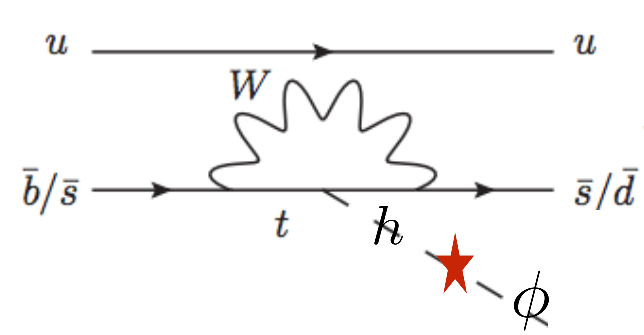
Different probes depending on the mass range



Different probes depending on the mass range

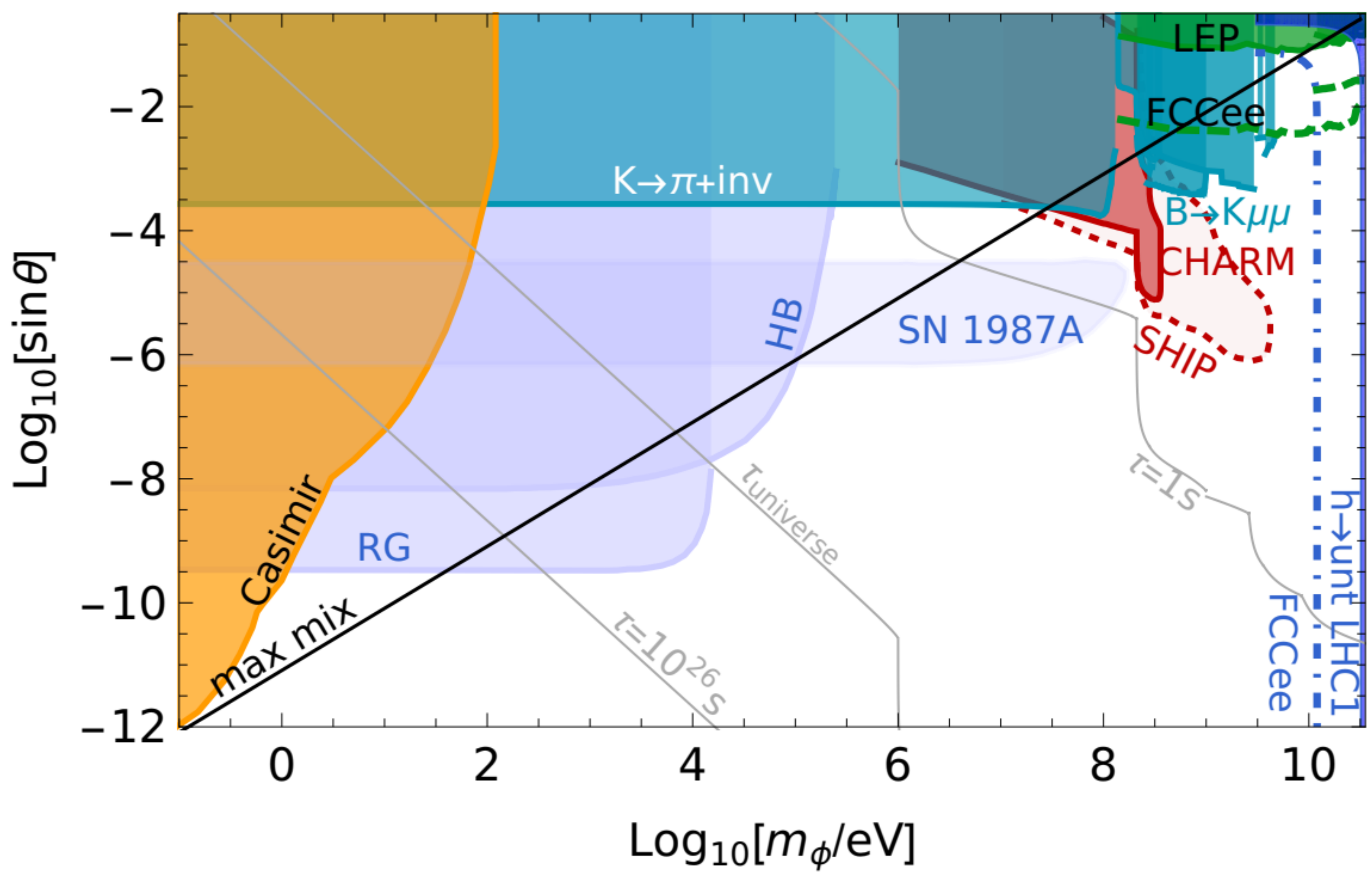
$$m_\phi > 0.1 \text{ GeV}$$



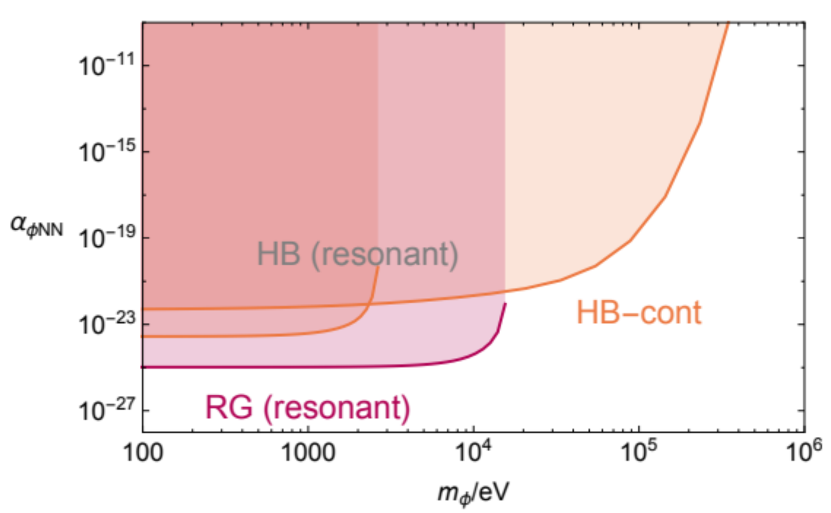
• *Proton Beam Dump*	• *Flavor transitions*	• *colliders*
$N_{\text{dec}} \approx N_\phi \cdot \text{BR}(\phi \to l^+ l^-) \cdot e^{\frac{-L}{\tau}}$		$\mu_h = \mu_h^{\text{SM}} \cos^2 \gamma$ $Z \to f \bar{f} \phi$

Different probes depending on the mass range

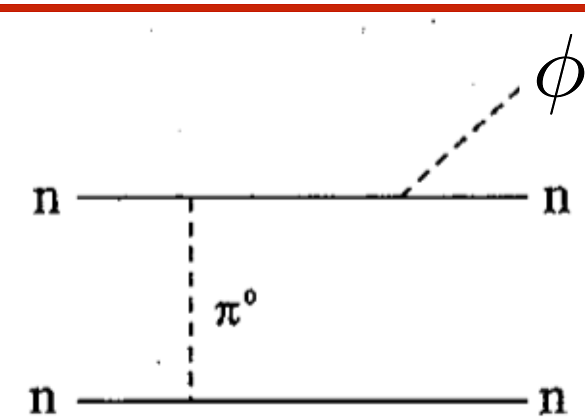
$$0.1 \text{ KeV} < m_\phi < 0.1 \text{ GeV}$$



- *Star cooling* Hardy, Lasenby '17



- *Supernova neutrino flux*

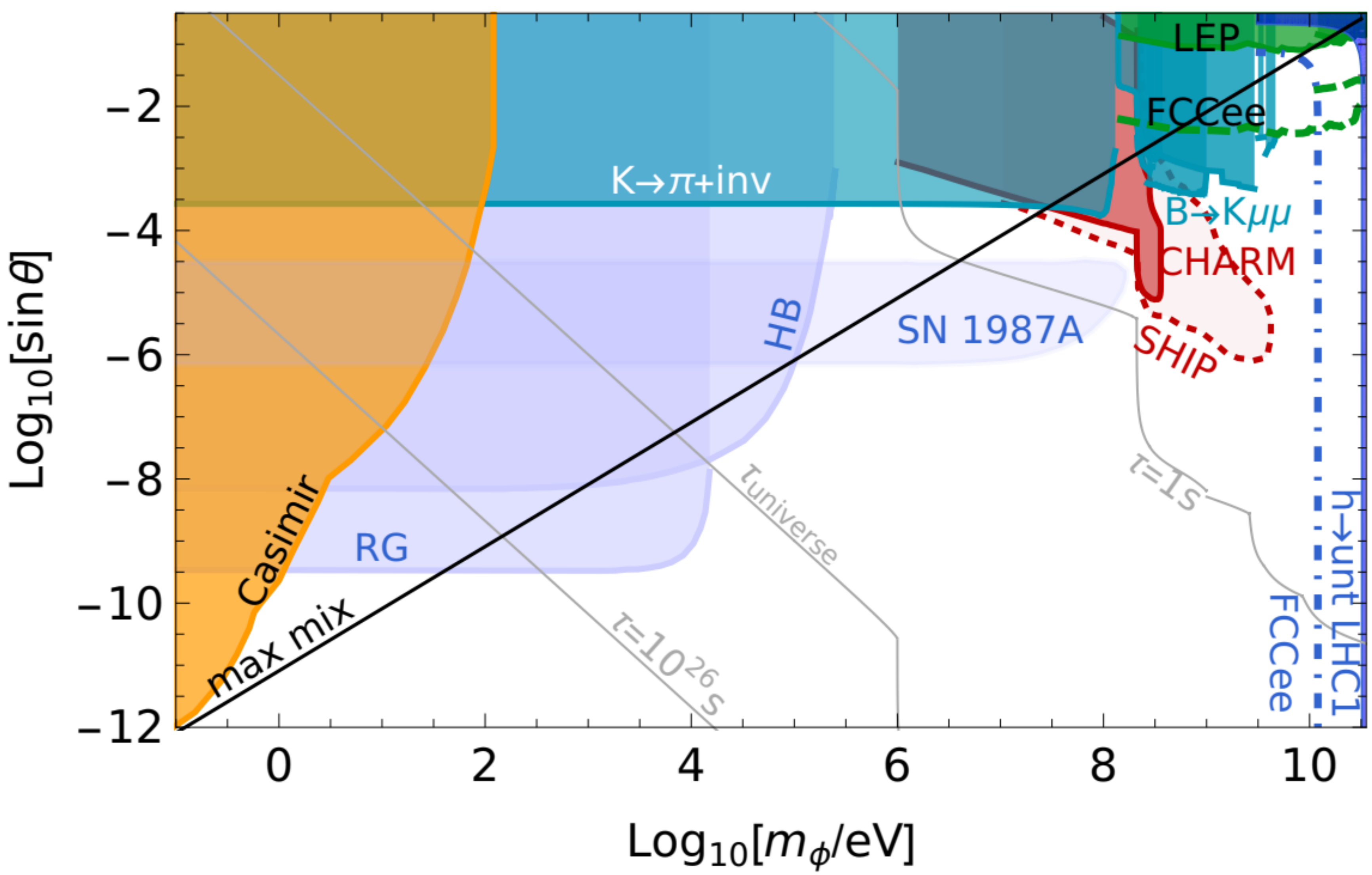


Ishizuka, Yoshimura '90

$$L_{NP} \lesssim 3 \cdot 10^{52} \text{erg}/s$$

Different probes depending on the mass range

$$m_\phi < 100\ \mathrm{eV}$$



- ***5th force experiments*** *see Andrew's talk*

$$V(r) = \frac{\alpha_{\mathrm{eff}}}{r} e^{-m_\phi r}.$$

through Higgs mixing we induce a long range force

The Nelson Barr relaxion

narrows down the relaxion parameter space

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

The Nelson Barr relaxion

narrows down the relaxion parameter space

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

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

flavor structure dependent

see M. Dine & P. Draper '15
L. Vecchi '14

The Nelson Barr relaxion

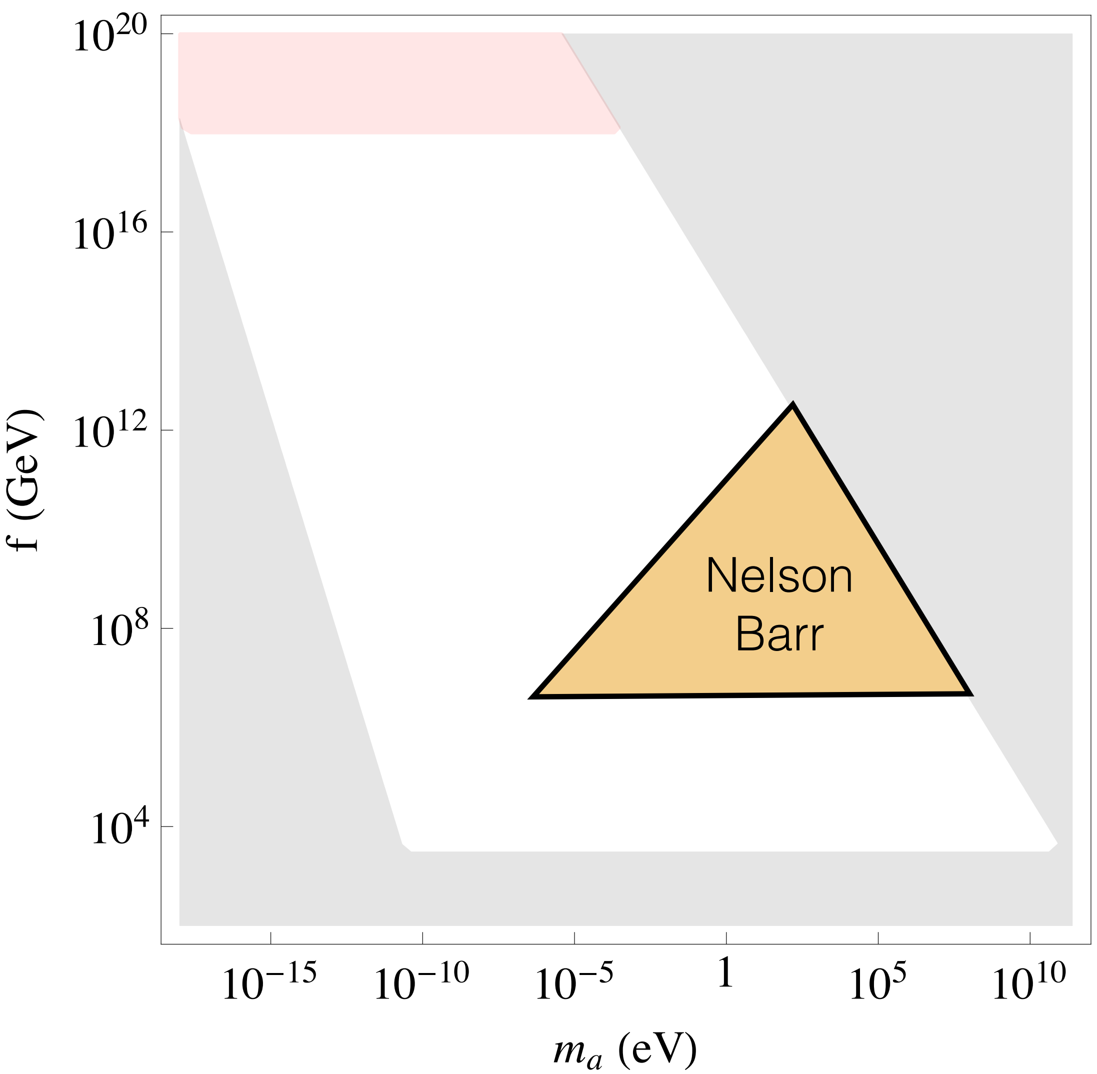
narrows down the relaxion parameter space

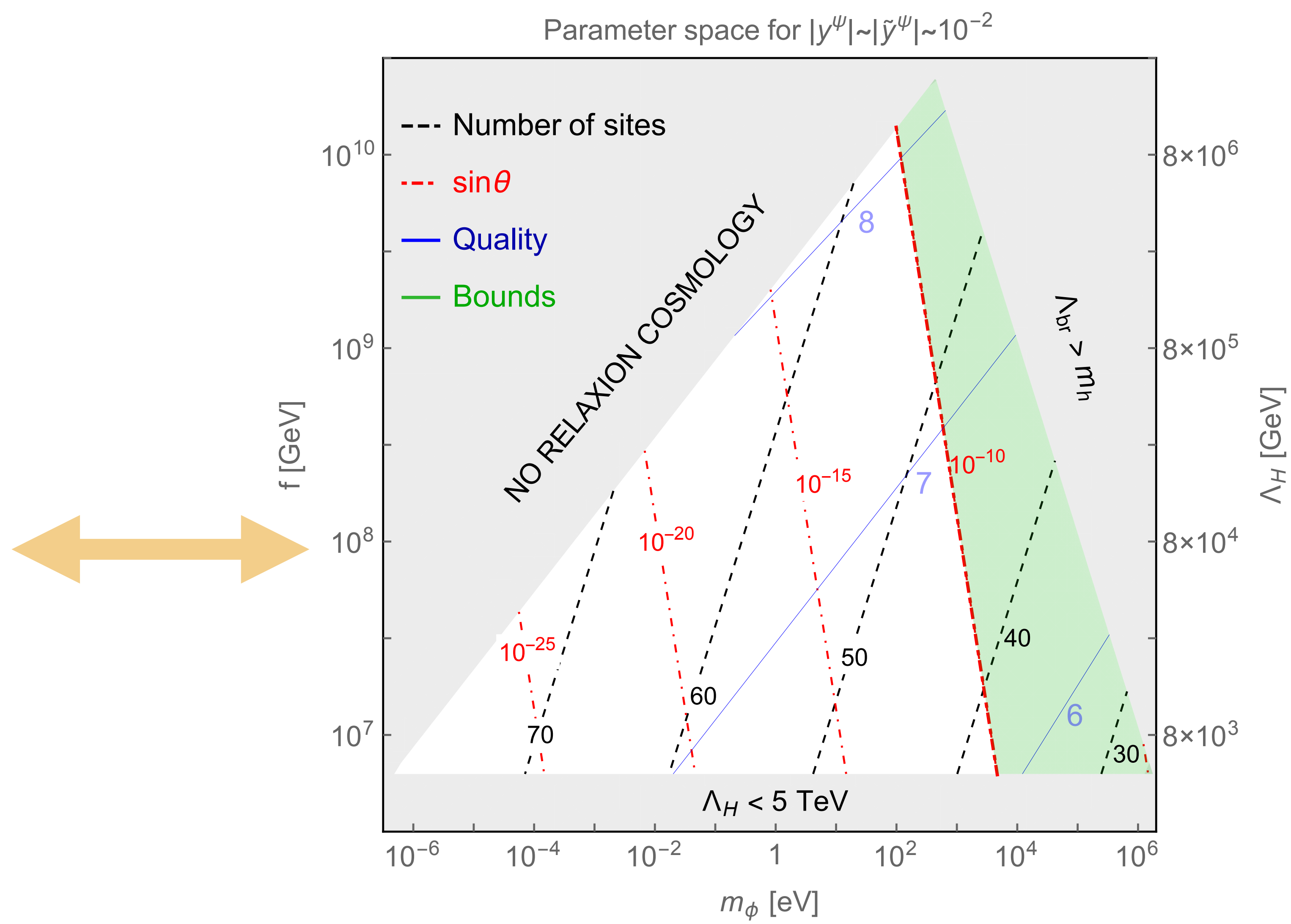
$$V_{\rm roll} = \frac{\overbrace{g_{u,d}\tilde{g}_{u,d}}f^4}{16\pi^2}\cos\frac{\phi}{F}$$

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

flavor structure dependent

see M. Dine & P. Draper '15
L. Vecchi '14

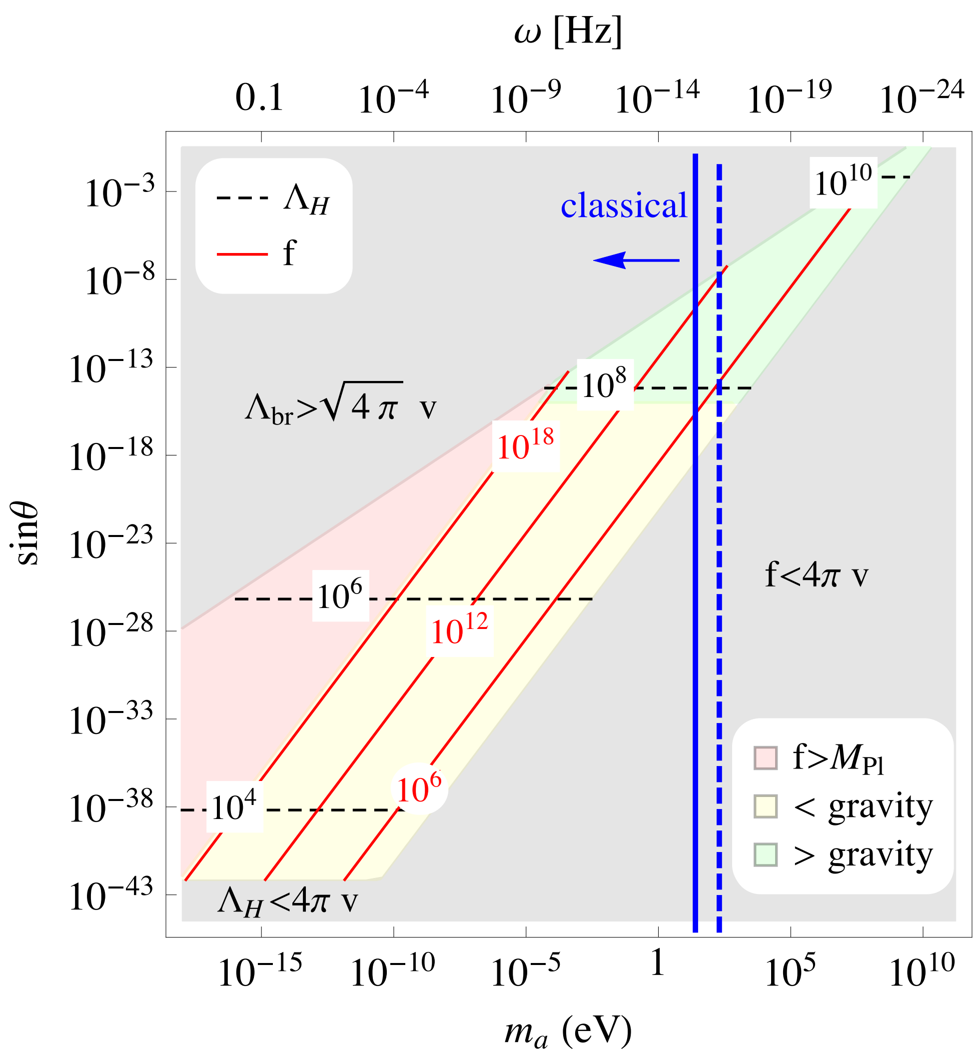




Davidi, Gupta, Perez, DR, Shalit '17

Can the Relaxion be a relic?

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

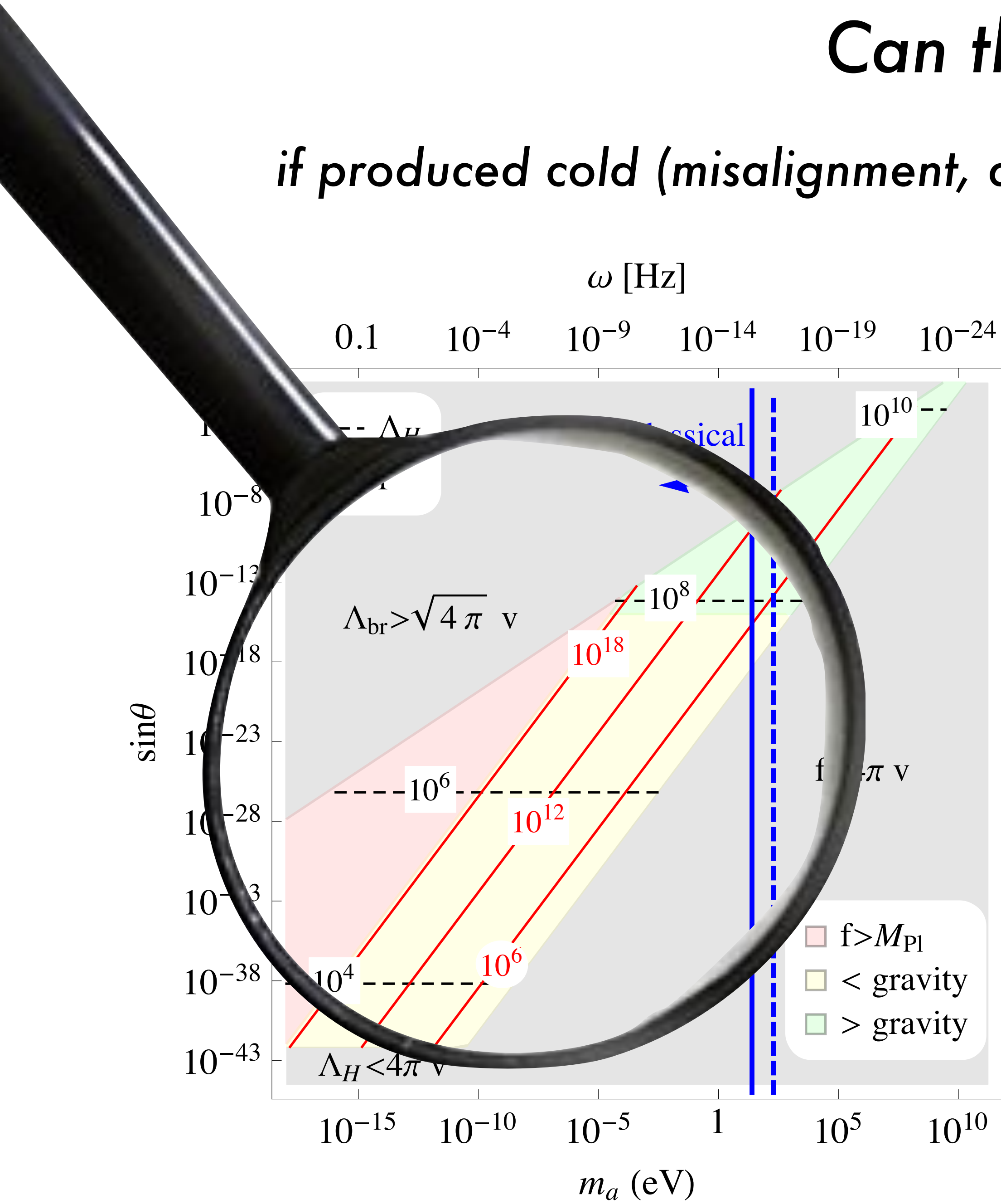


$$m_\phi \lesssim 10\ \mathrm{eV}$$

Can the Relaxion be a relic?

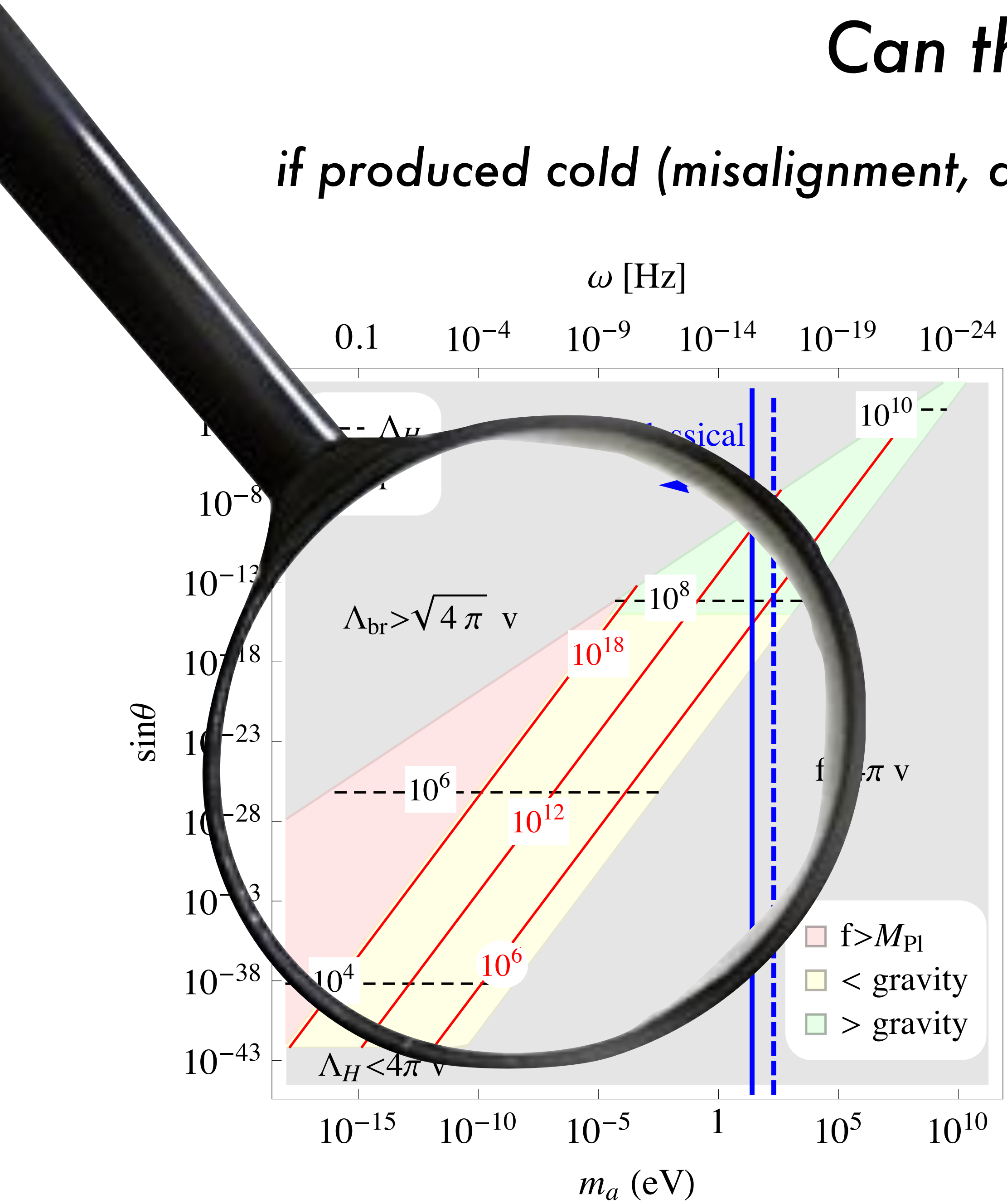
if produced cold (misalignment, during inflation,other?...) it would be a classical background

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



Can the Relaxion be a relic?

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



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

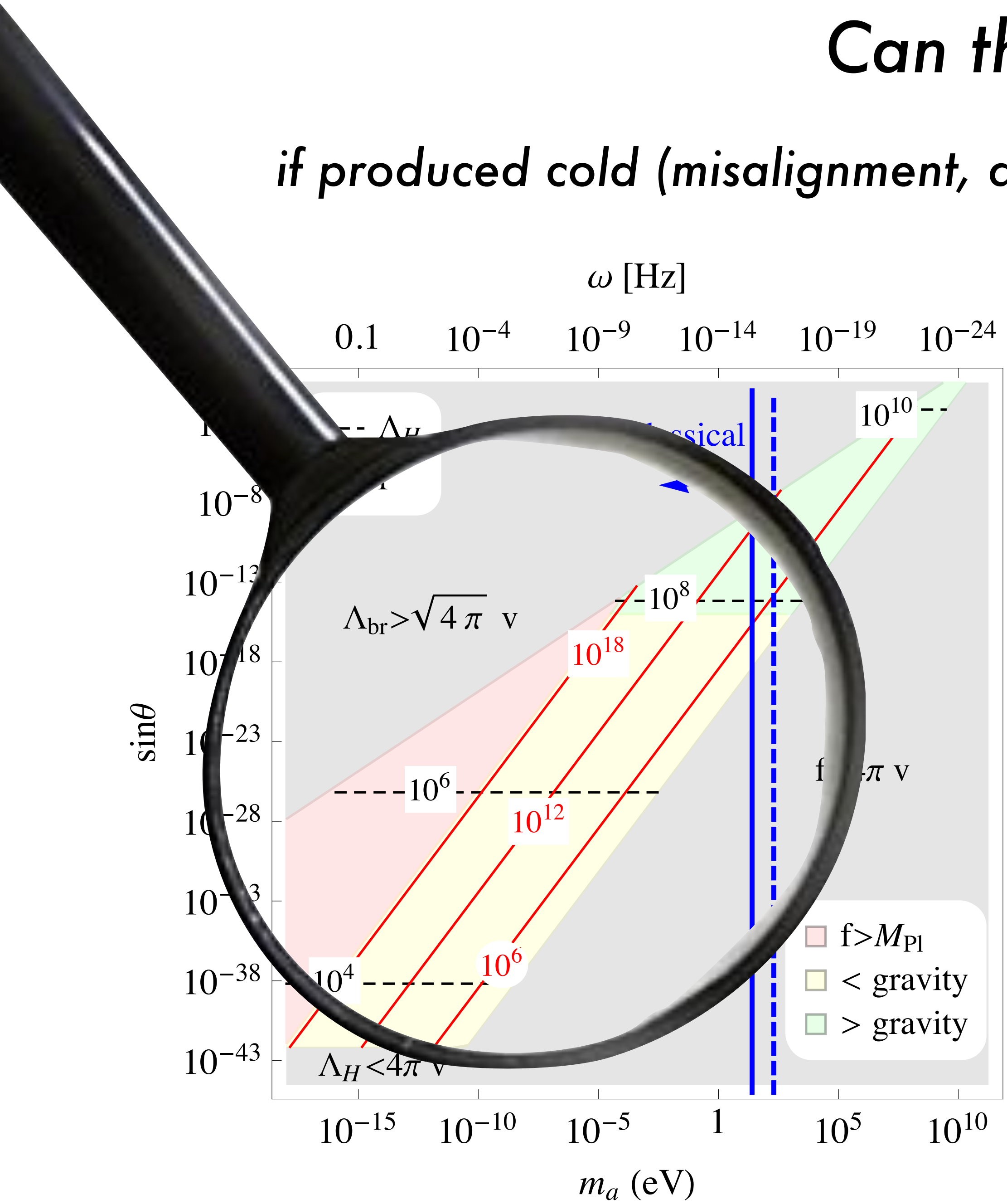
this might enhance detectability in the near future

- *atomic clock experiments*
- *absorption*
- *...*

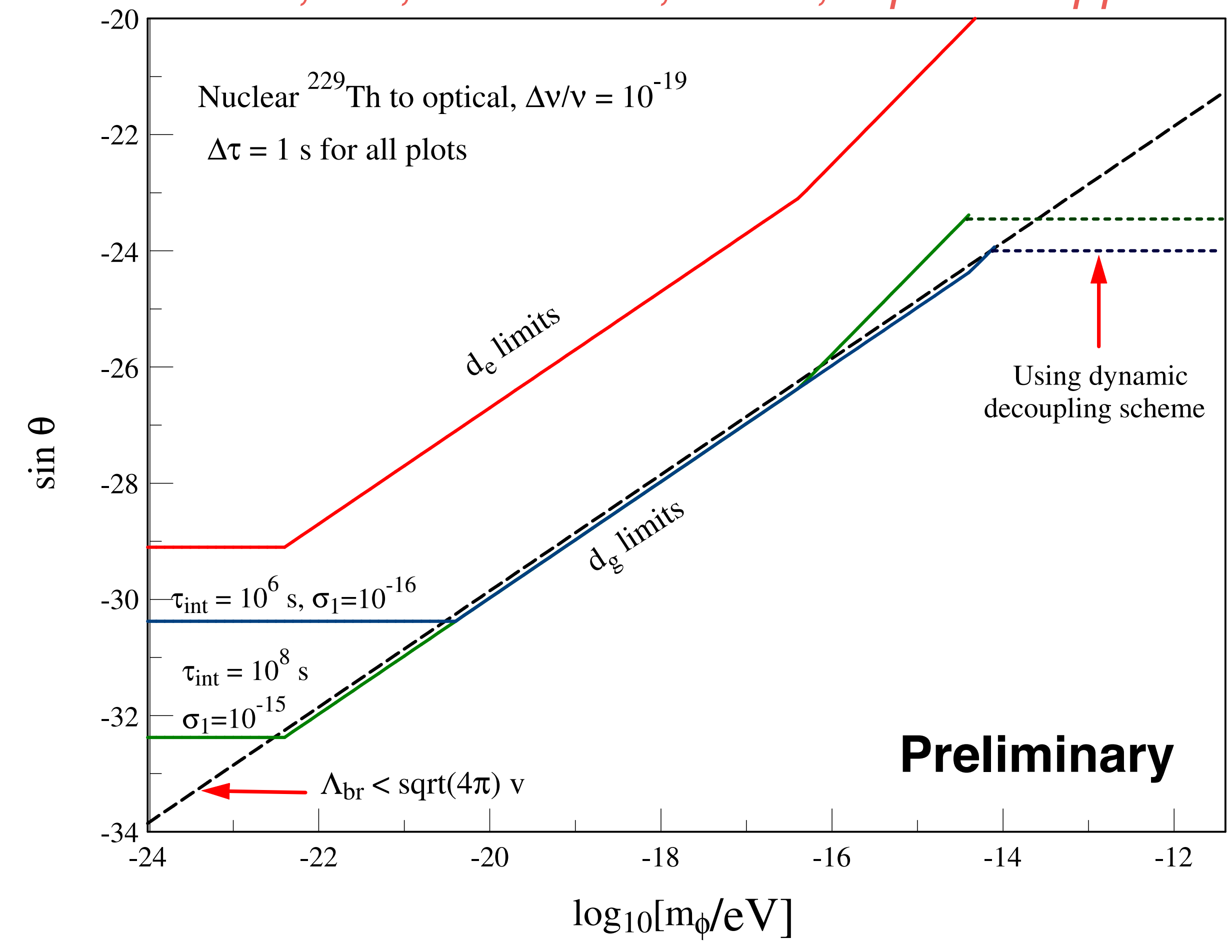
Can the Relaxion be a relic?

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

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



Perez, DR, Safronova,Ubaldi,Zupan to appear



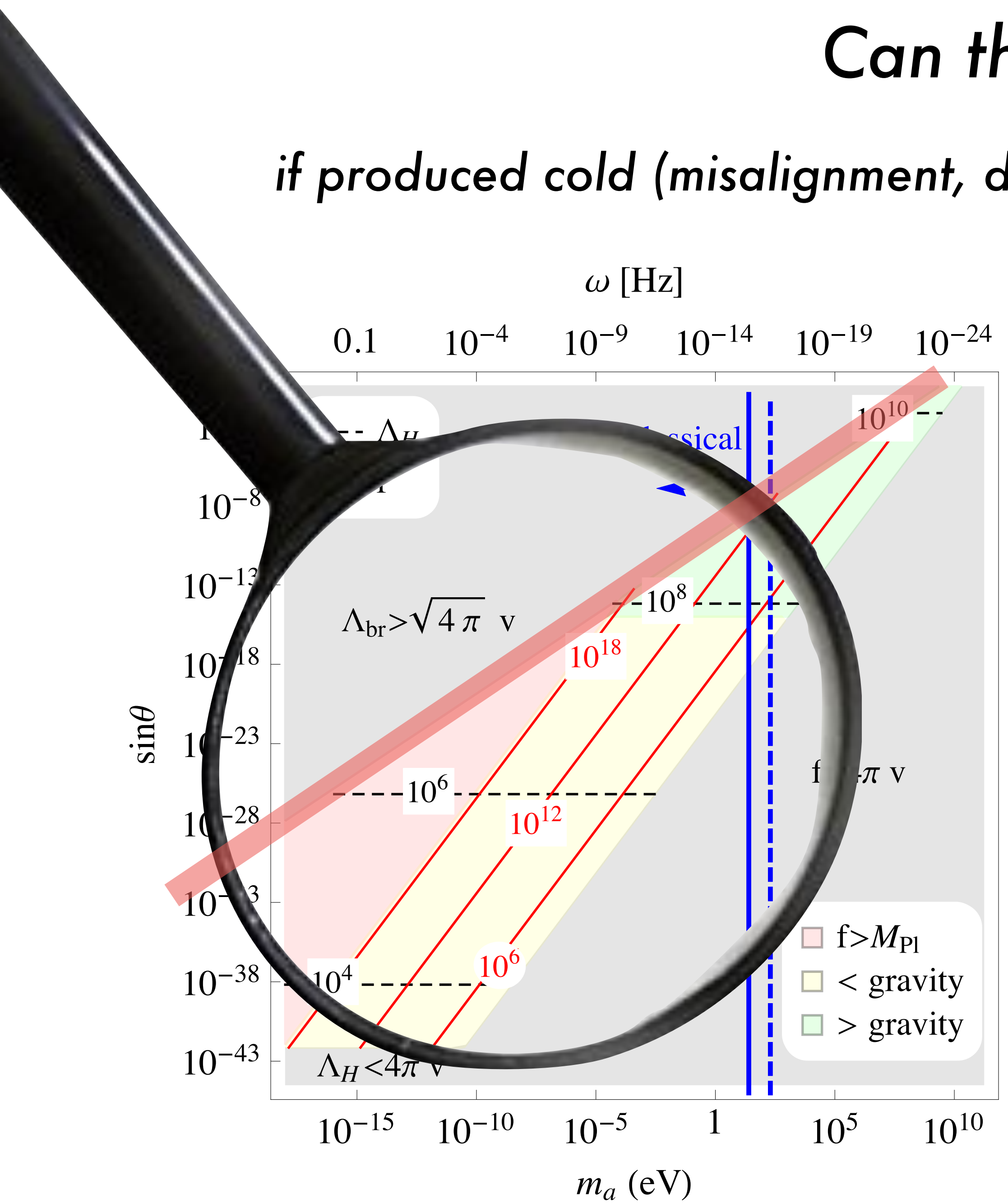
this might enhance detectability in the near future

- *atomic clock experiments*
- *absorption*
- ...

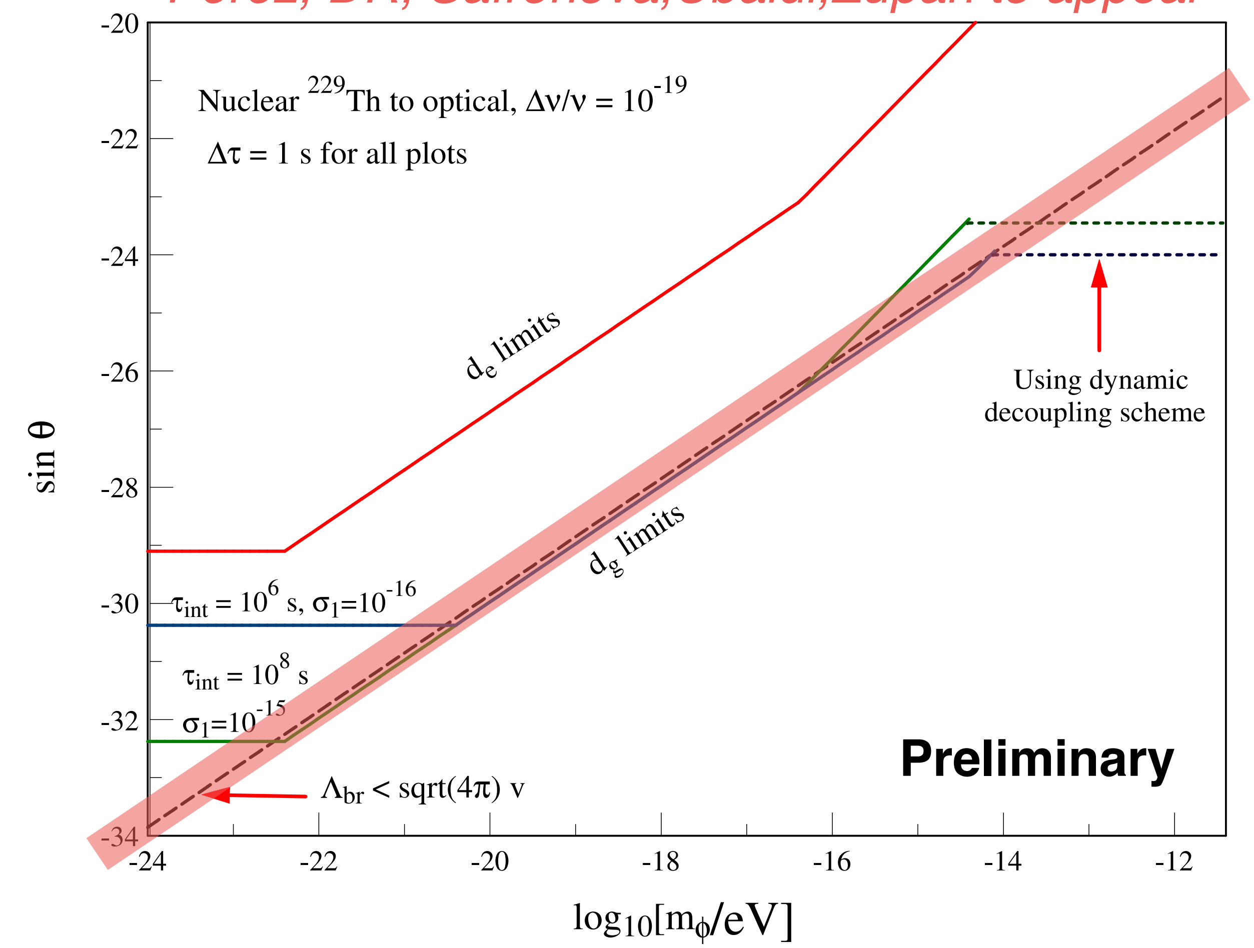
Can the Relaxion be a relic?

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

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



Perez, DR, Safronova, Ubaldi, Zupan to appear



this might enhance detectability in the near future

- *atomic clock experiments*
- *absorption*
- *...*

It touches the boundary of the parameter space!

Wiggles without EW states

(Davidi,Gupta, Perez,DR, Shalit '18)

We use sterile neutrinos $\mathcal{L}_{\rm NP} \supset Y_N \tilde{H} L N^c$

Wiggles without EW states

(Davidi,Gupta, Perez,DR, Shalit '18)

We use sterile neutrinos $\mathcal{L}_{\rm NP} \supset Y_N \tilde{H} L N^c$

Froggatt-Nielsen texture to ensure
- $\Lambda_{\rm br} \gtrsim M_{\rm br}$ (where $M_{\rm br}$ is the scale of sterile neutrinos)
- neutrino masses for free

Wiggles without EW states

(Davidi,Gupta, Perez,DR, Shalit '18)

We use sterile neutrinos $\mathcal{L}_{\rm NP} \supset Y_N \tilde{H} L N^c$

Froggatt-Nielsen texture to ensure
- $\Lambda_{\rm br} \gtrsim M_{\rm br}$ (where $M_{\rm br}$ is the scale of sterile neutrinos)
- neutrino masses for free

The relaxion is the PNGB of a U(1) flavor symmetry acting on leptons

Wiggles without EW states

(Davidi,Gupta, Perez,DR, Shalit ‘18)

We use sterile neutrinos $\mathcal{L}_{\rm NP} \supset Y_N \tilde{H} L N^c$

Froggatt-Nielsen texture to ensure
- $\Lambda_{\rm br} \gtrsim M_{\rm br}$ (where $M_{\rm br}$ is the scale of sterile neutrinos)
- neutrino masses for free

The relaxion is the PNGB of a U(1) flavor symmetry acting on leptons

$$\mathcal{L}_\phi \supset \frac{iv\phi}{f}(L_j + e^c_k)(Y_e)_{jk} e_j e^c_k$$

Wiggles without EW states

(Davidi, Gupta, Perez, DR, Shalit '18)

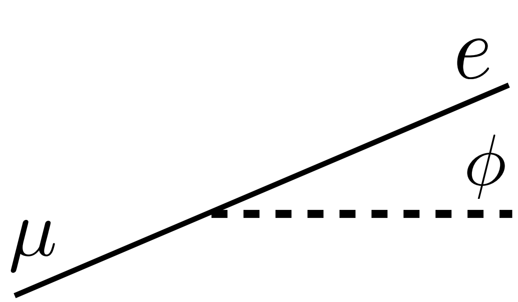
We use sterile neutrinos $\mathcal{L}_{\rm NP} \supset Y_N \tilde{H} L N^c$

Froggatt-Nielsen texture to ensure
- $\Lambda_{\rm br} \gtrsim M_{\rm br}$ (where $M_{\rm br}$ is the scale of sterile neutrinos)
- neutrino masses for free

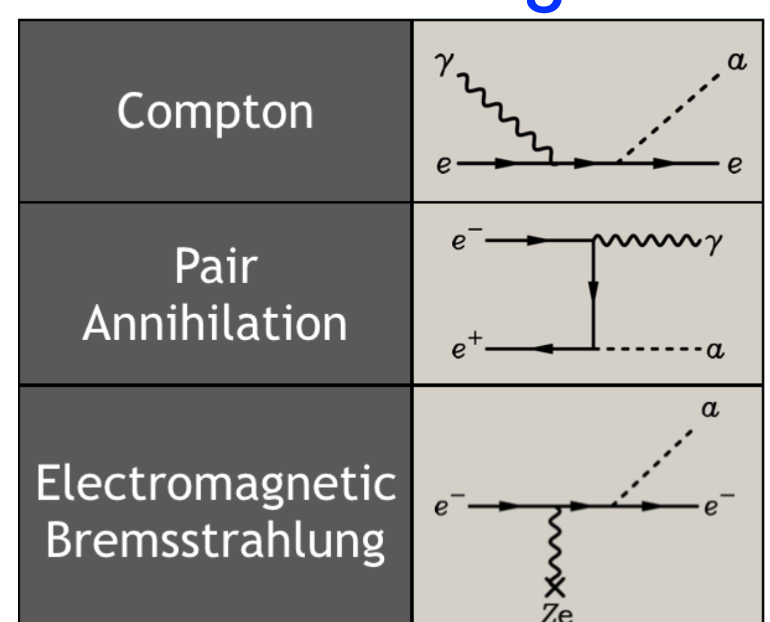
The relaxion is the PNGB of a U(1) flavor symmetry acting on leptons

$$\mathcal{L}_\phi \supset \frac{iv\phi}{f}(L_j + e^c_k)(Y_e)_{jk} e_j e^c_k$$

FV lepton decays VS **star cooling**



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



Wiggles without EW states

(Davidi,Gupta, Perez,DR, Shalit ‘18)

We use sterile neutrinos $\mathcal{L}_{\rm NP} \supset Y_N \tilde{H} L N^c$

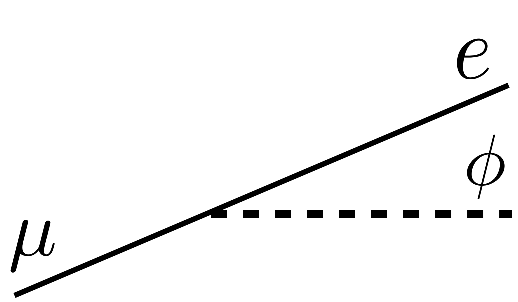
Froggatt-Nielsen texture to ensure
- $\Lambda_{\rm br} \gtrsim M_{\rm br}$ *(where $M_{\rm br}$ is the scale of sterile neutrinos)*
- *neutrino masses for free*

The relaxion is the PNGB of a U(1) flavor symmetry acting on leptons

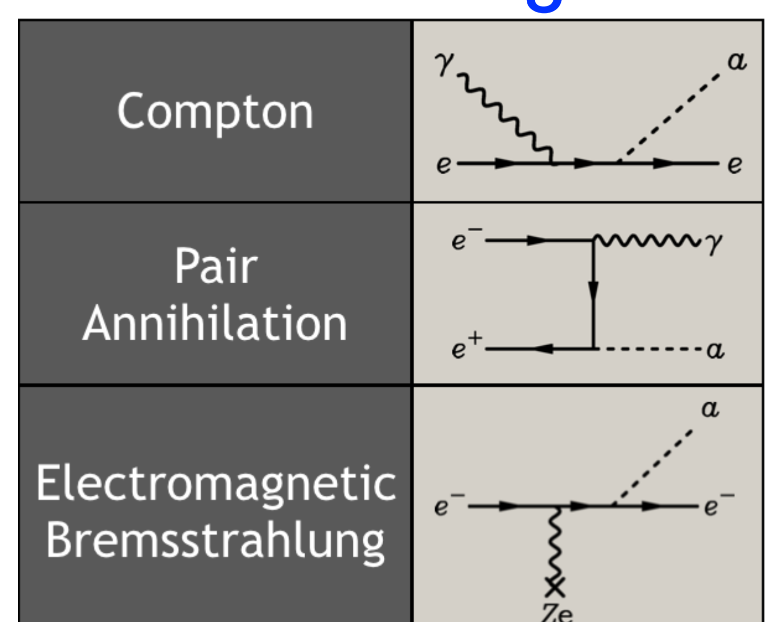
$$\mathcal{L}_\phi \supset \frac{iv\phi}{f}(L_j + e^c_k)(Y_e)_{jk} e_j e^c_k$$

This is an axion-like coupling!

FV lepton decays VS star cooling

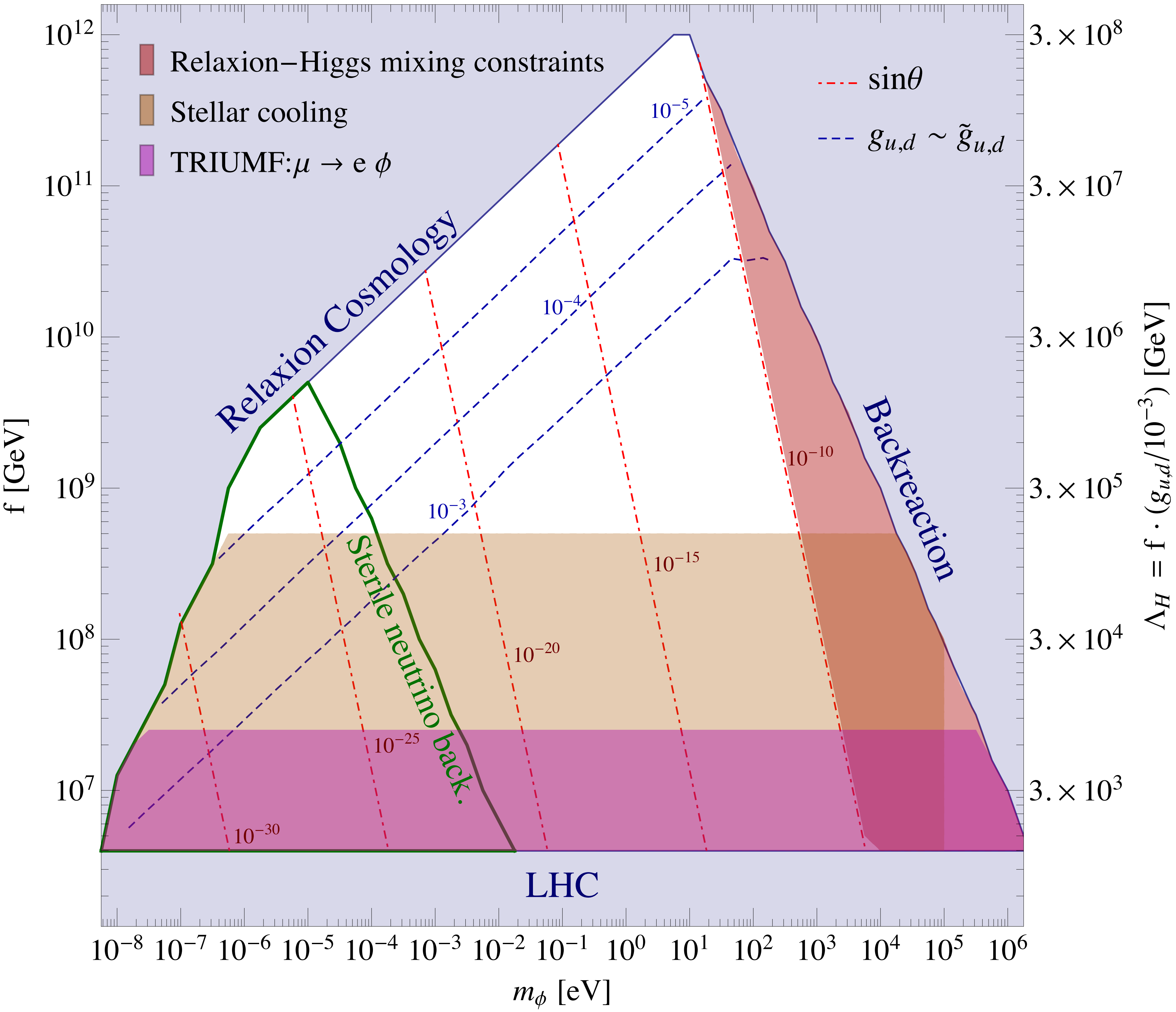


$$\Gamma(\mu \to e\phi) \simeq \frac{m_e^2 m_\mu}{16\pi f^2}$$



Star cooling gives the most stringent bound!

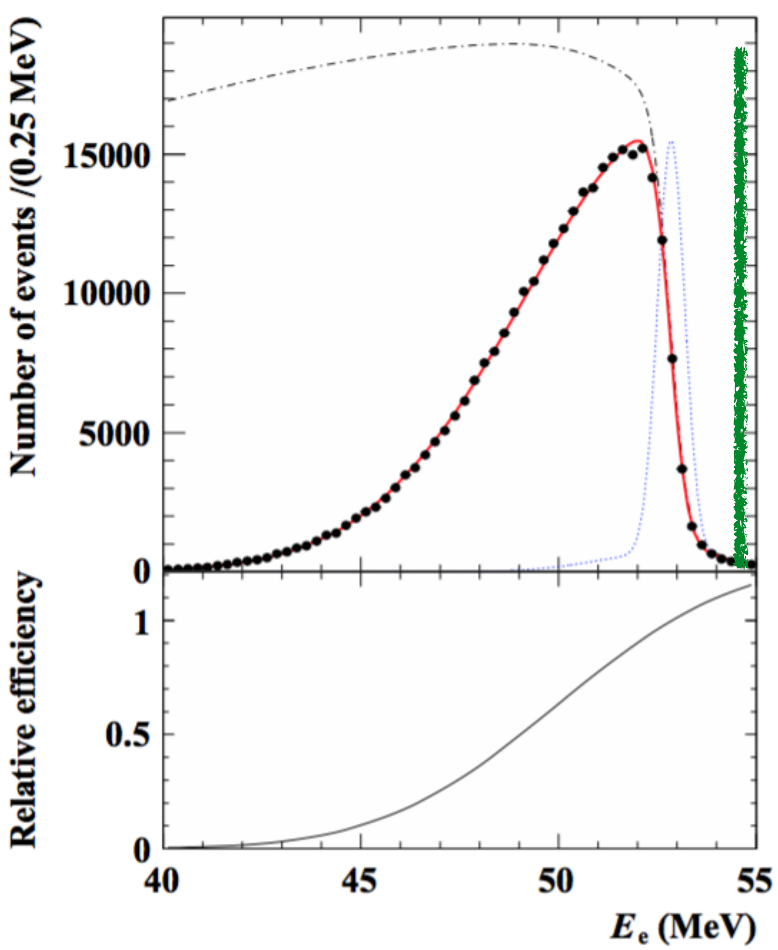
Davidi, Gupta, Perez, DR, Shalit '17



Can we increase the sensitivity of future experiments?

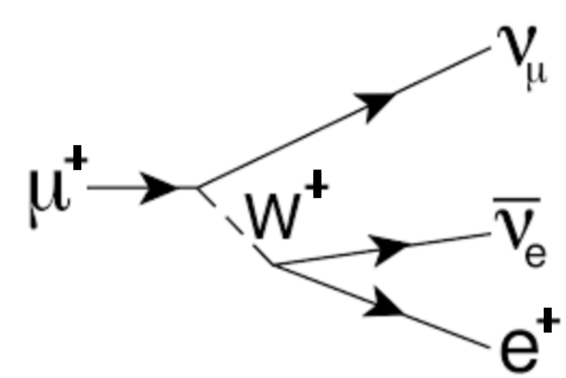
Learning from the past...

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 $E_e \approx \dfrac{m_\mu}{2}$

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

More recent experiments...

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

MEG with $10^{14}\ \mu$?   **no analysis but naively:** $\mathrm{BR}(\mu \to e + a + \gamma) \lesssim 1 \cdot 10^{-9} \cdot \frac{1}{\sqrt{100}}$

More recent experiments...

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

MEG with $10^{14}\ \mu$? **no analysis but naively:** $\mathrm{BR}(\mu \to e + a + \gamma) \lesssim 1 \cdot 10^{-9} \cdot \frac{1}{\sqrt{100}}$

MEG II ? Mu3e ?

More recent experiments...

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

MEG with $10^{14}\ \mu$? **no analysis but naively:** $\mathrm{BR}(\mu \to e + a + \gamma) \lesssim 1 \cdot 10^{-9} \cdot \frac{1}{\sqrt{100}}$

MEG II ? Mu3e ?

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

(more examples @ NA62 and LHCb)

See talk by Filippo Sala

NA62 highly constraint the quark FV interactions

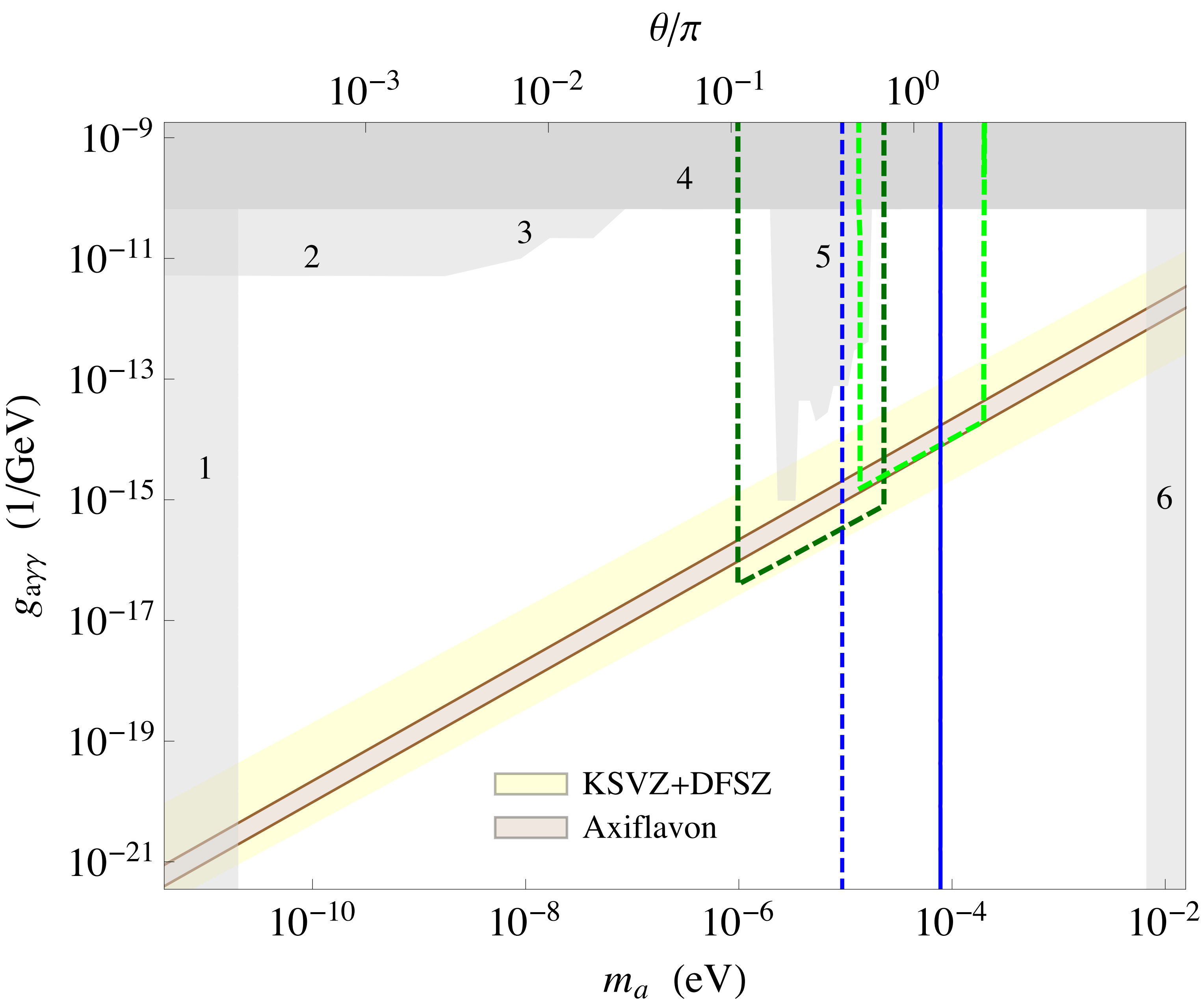
$$\mathcal{L}_\phi \supset \frac{iv\phi}{f}(Q_j + u_k^c)(Y_u)_{jk}u_j u_k^c$$

FV Kaon decays are super-powerful probes of NP $f \gtrsim 10^{11}\ \mathrm{GeV}$

NA62 highly constraint the quark FV interactions

$$\mathcal{L}_\phi \supset \frac{iv\phi}{f}(Q_j + u_k^c)(Y_u)_{jk} u_j u_k^c$$

FV Kaon decays are super-powerful probes of NP $f \gtrsim 10^{11}$ GeV

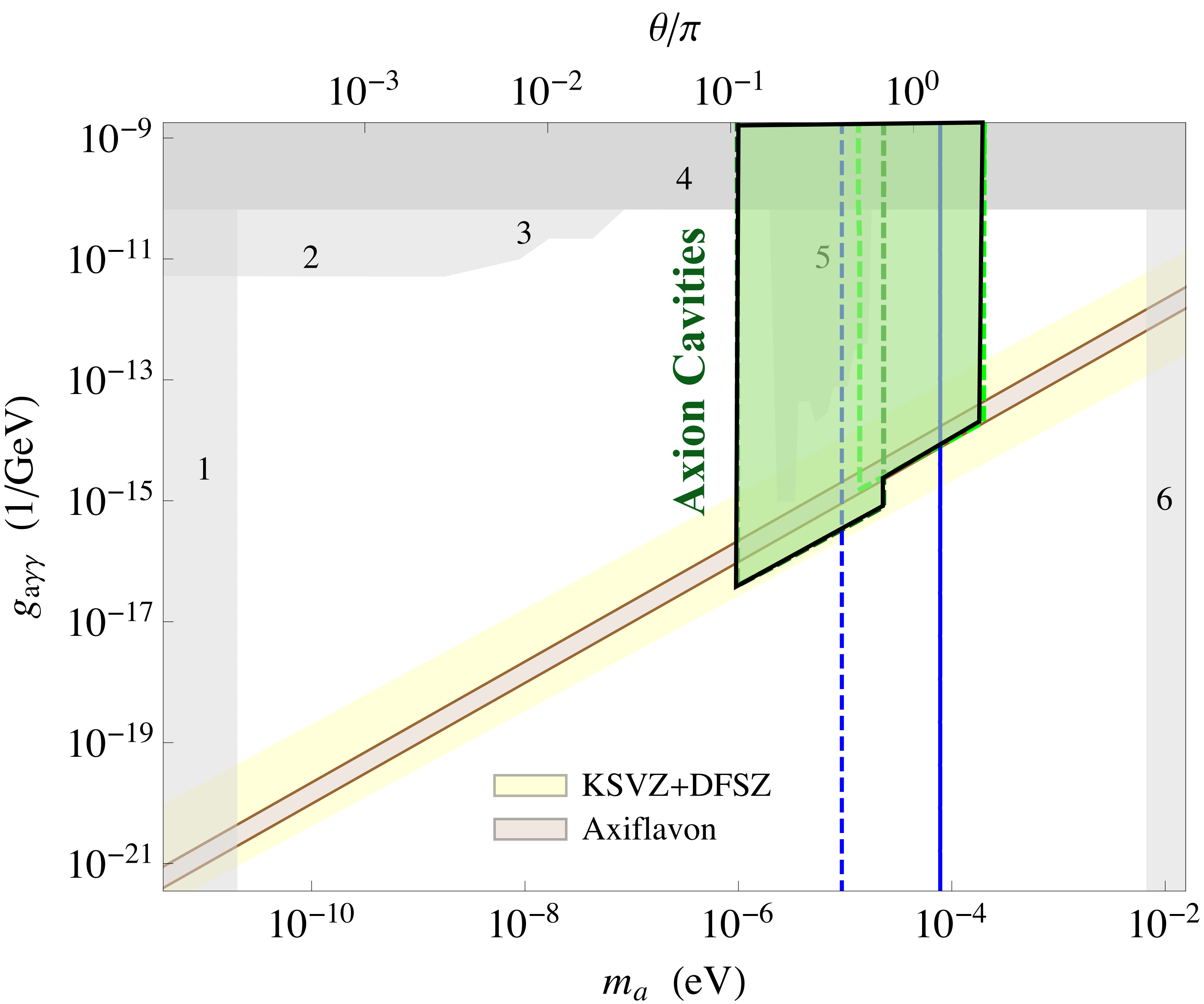


Calibbi,Goertz,DR,Ziegler,Zupan

NA62 highly constraint the quark FV interactions

$$\mathcal{L}_\phi \supset \frac{iv\phi}{f}(Q_j + u_k^c)(Y_u)_{jk} u_j u_k^c$$

FV Kaon decays are super-powerful probes of NP $f \gtrsim 10^{11}$ GeV

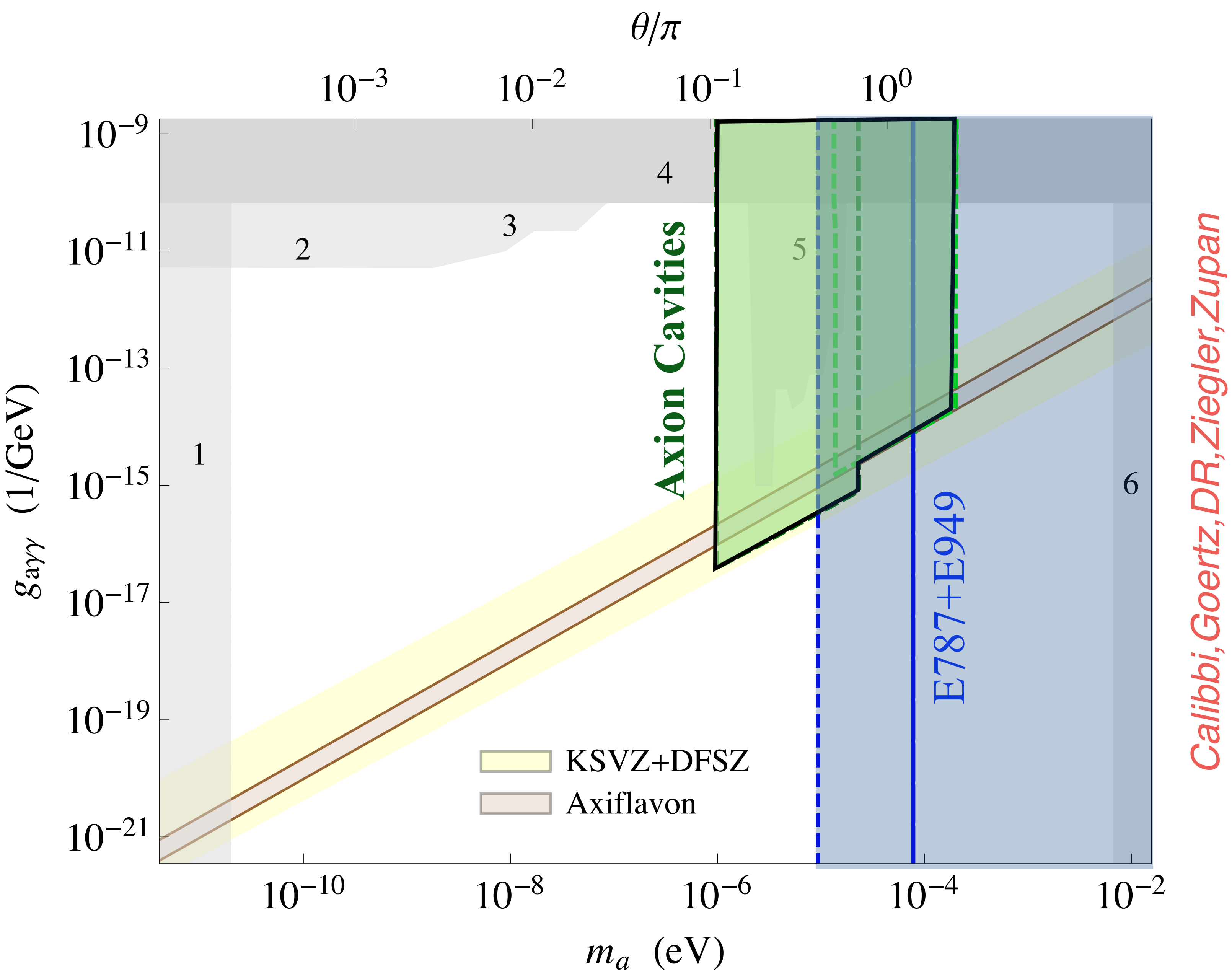


Calibbi,Goertz,DR,Ziegler,Zupan

NA62 highly constraint the quark FV interactions

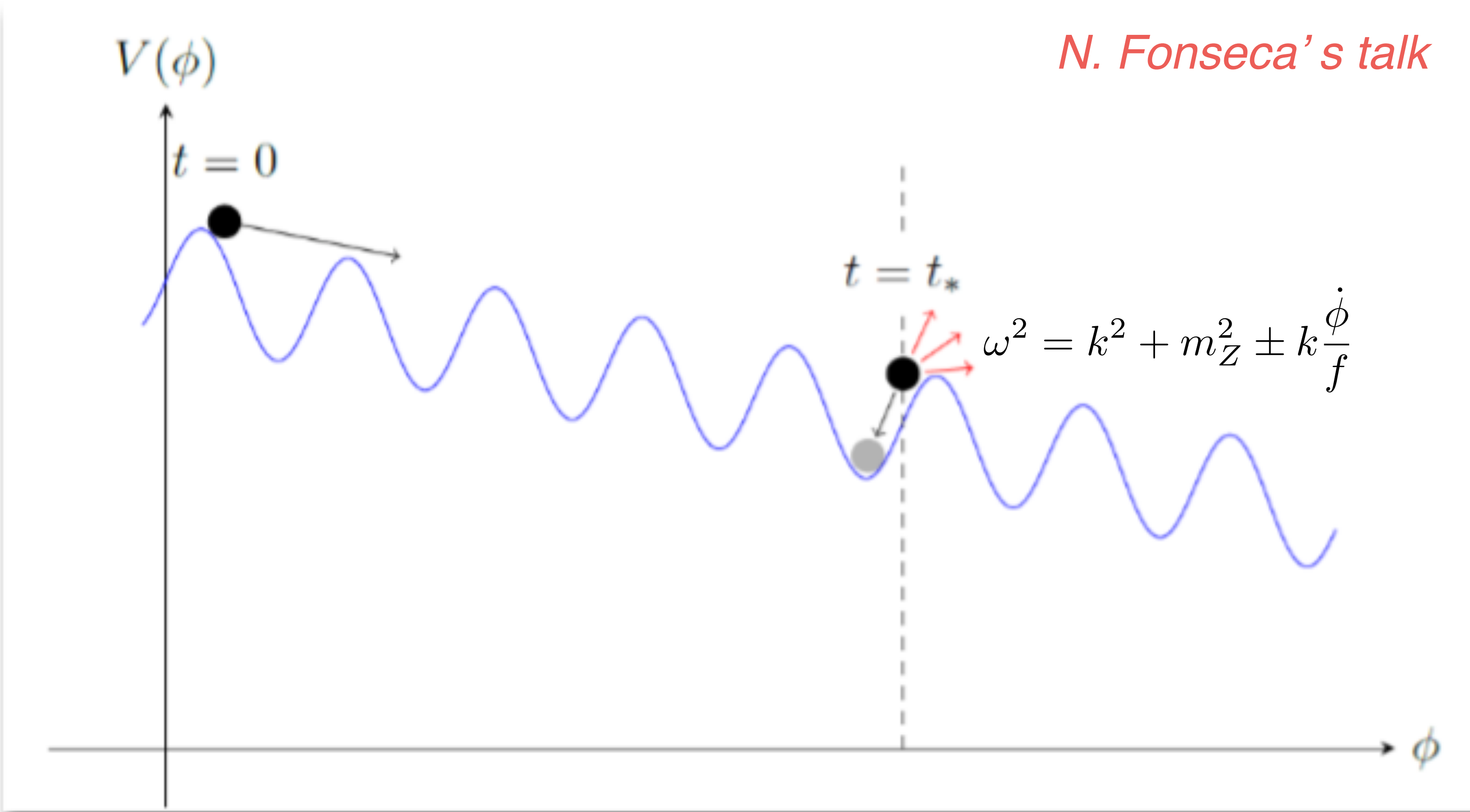
$$\mathcal{L}_\phi \supset \frac{iv\phi}{f}(Q_j + u_k^c)(Y_u)_{jk} u_j u_k^c$$

FV Kaon decays are super-powerful probes of NP $f \gtrsim 10^{11}\ \text{GeV}$



The "thermal" relaxion

A. Hook, G. Marquez Tavares '16



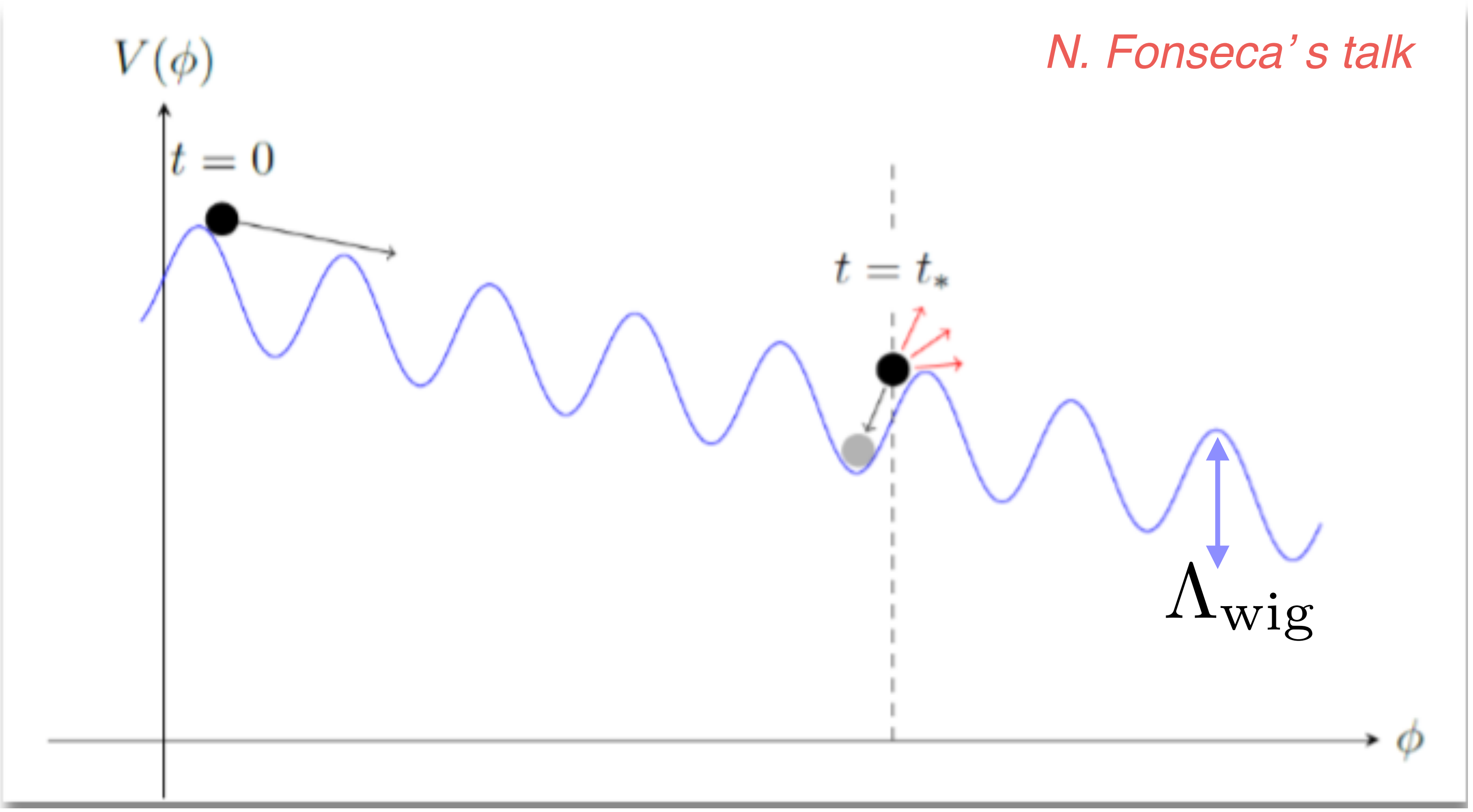
$$\mathcal{L} \supset -\frac{\phi}{f}\left(\alpha_Y B\tilde{B} - \alpha_2 W\tilde{W}\right)$$

FEATURES:

- *classical rolling + production of massive gauge bosons*
- *EW VEV goes down and enhance particle production*
- *particle production relevant* $\dot\phi_s \sim f v$
- *no coupling to photons*

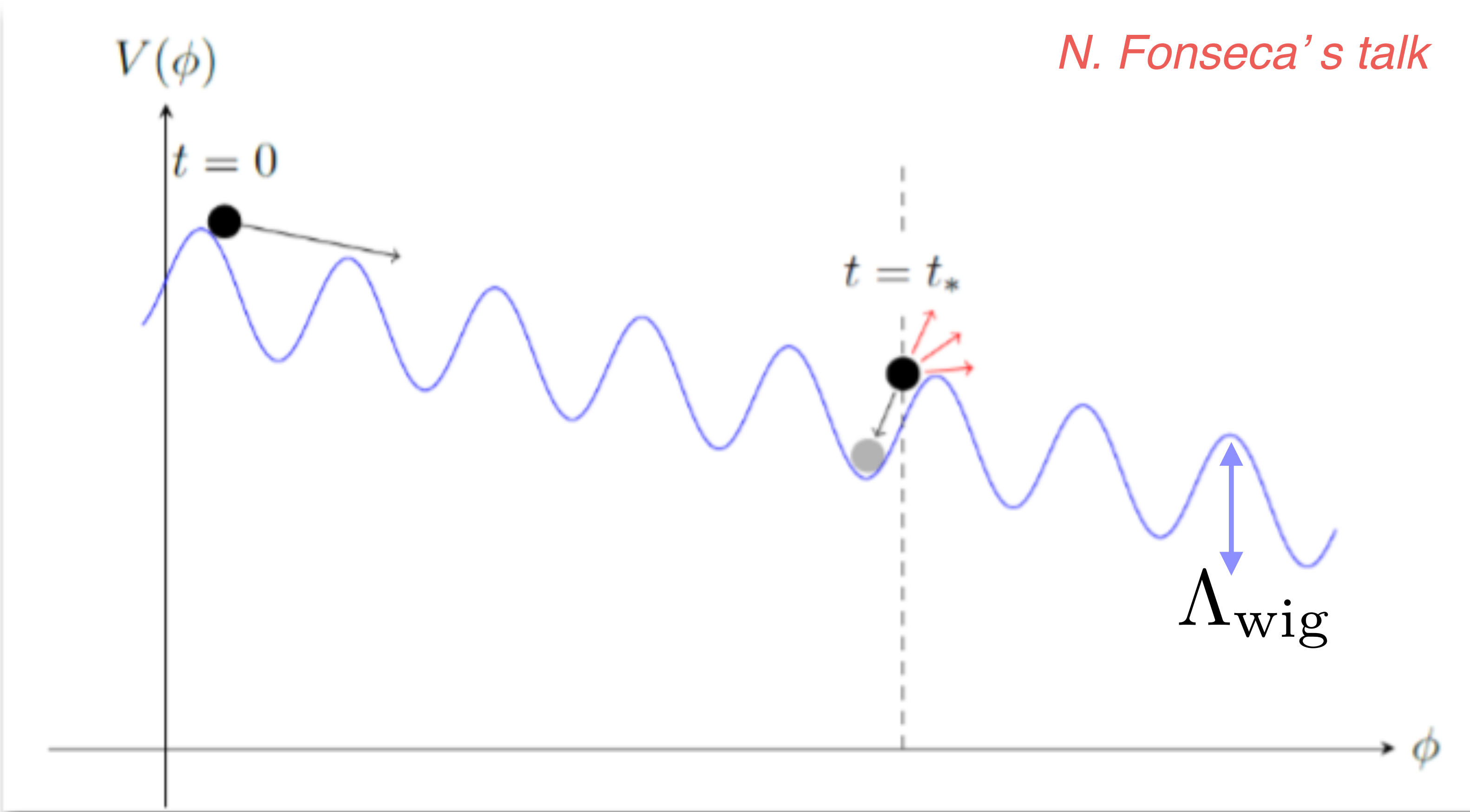
The “thermal” relaxion

A. Hook, G. Marquez Tavares ‘16



The "thermal" relaxion

A. Hook, G. Marquez Tavares '16

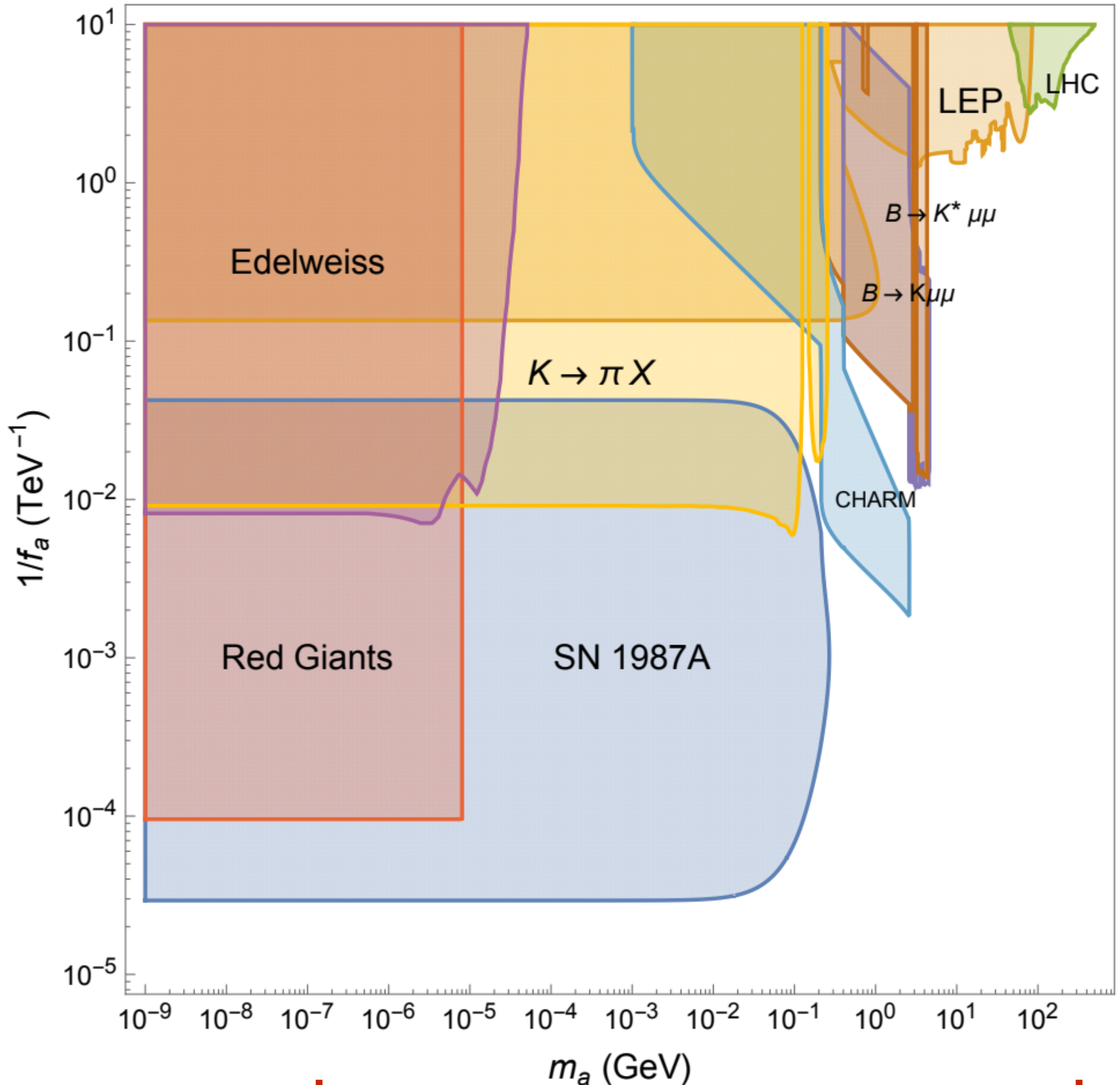


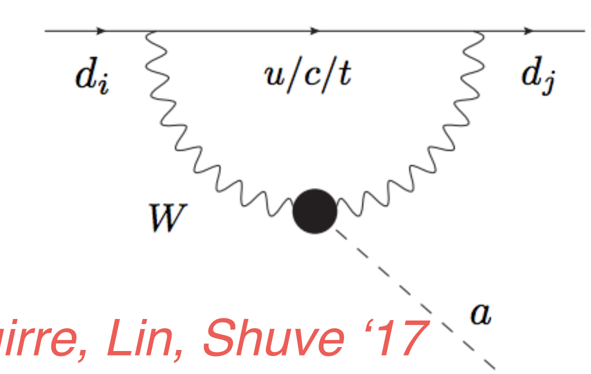
- $F \lesssim M_{\rm Pl}$
- $\Lambda_{\rm UV} \lesssim \sqrt{M_{Pl} v} \cdot \left(\frac{\Lambda_{\rm wiggles}}{f}\right)^2$
- $\dot\phi_i^2 \gtrsim \Lambda_{\rm wig}^4 \quad , \quad \dot\phi_f^2 \gtrsim \Lambda_{\rm wig}^4$
- $F \lesssim \left(\frac{T_{\rm RH}}{\Lambda_{\rm UV}}\right)^2 \cdot M_{\rm Pl}$

CONSEQUENCES:

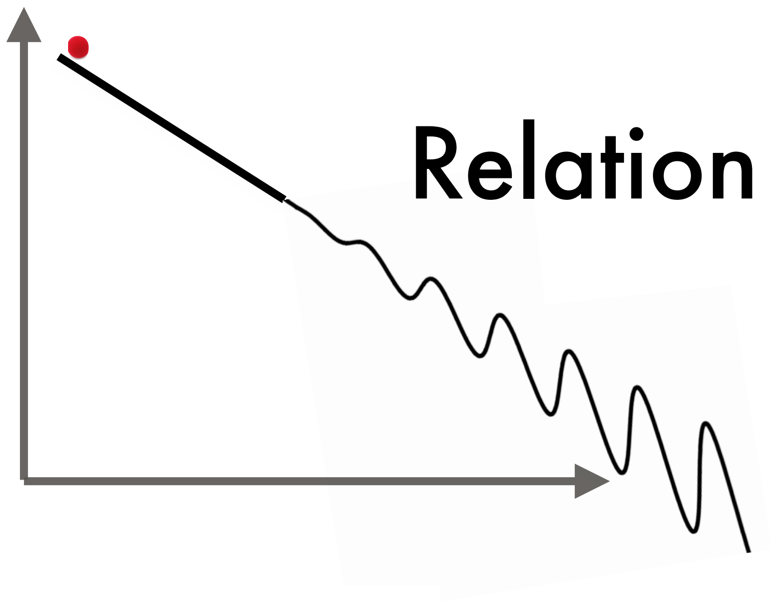
- *Subplanckian field excursion*
- *Large wiggles* ⟷ *heavy relaxion*
- *non-generic initial velocity* ⟷ *tuning in the initial conditions?*
- *relaxation without inflation* N. Fonseca, E. Morgante, G. Servant '18

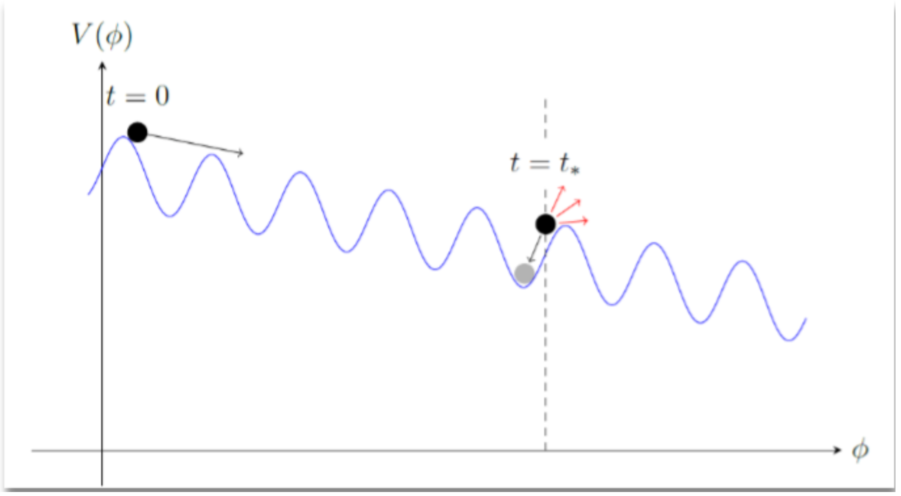
Craig, Hook, Kasko '18

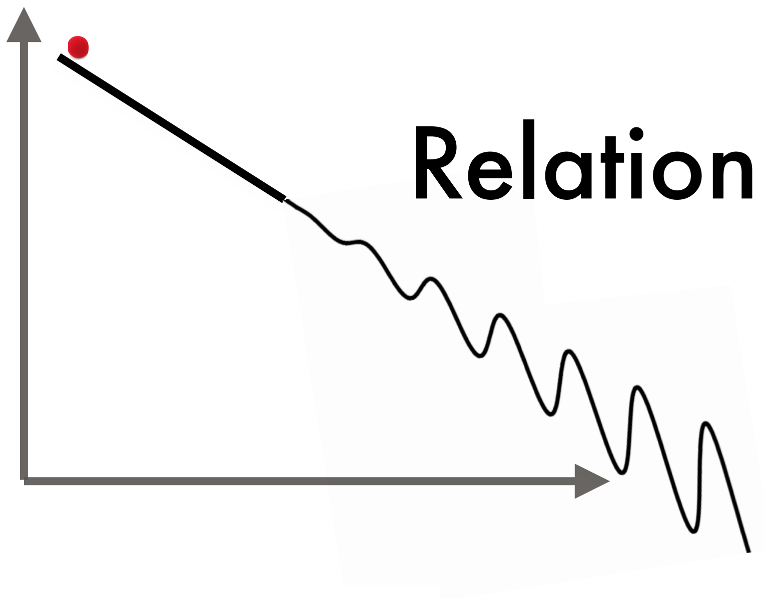


• Bolometers/Red Giants	• Flavor transitions	• colliders
production of axion in the Sun $e + Ze \to Ze + e + a$	 Izaguirre, Lin, Shuve '17	$pp \to Z 2\gamma$ $pp \to 3W$

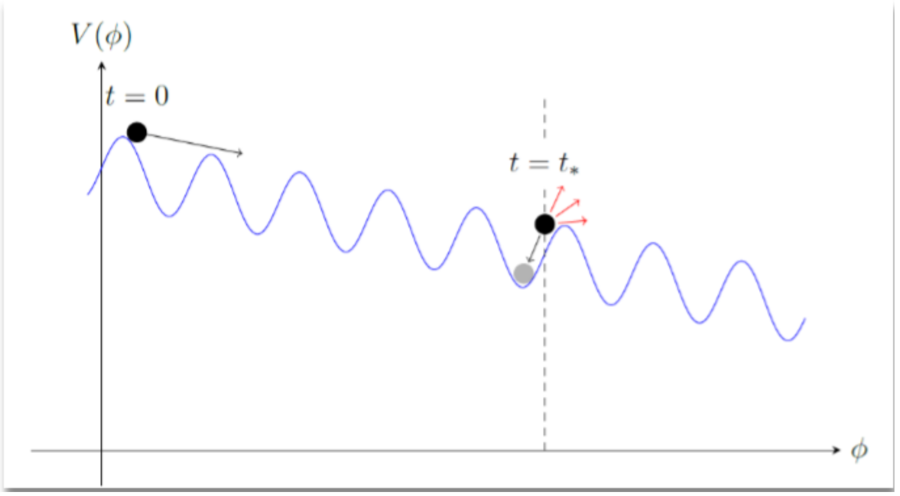
Relation as playground for Naturalness







Relation as playground for Naturalness

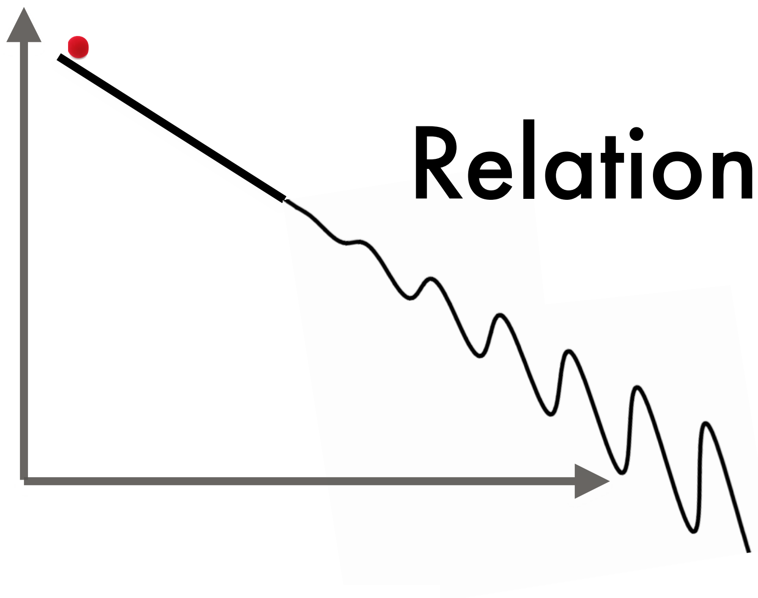


new theory challenges

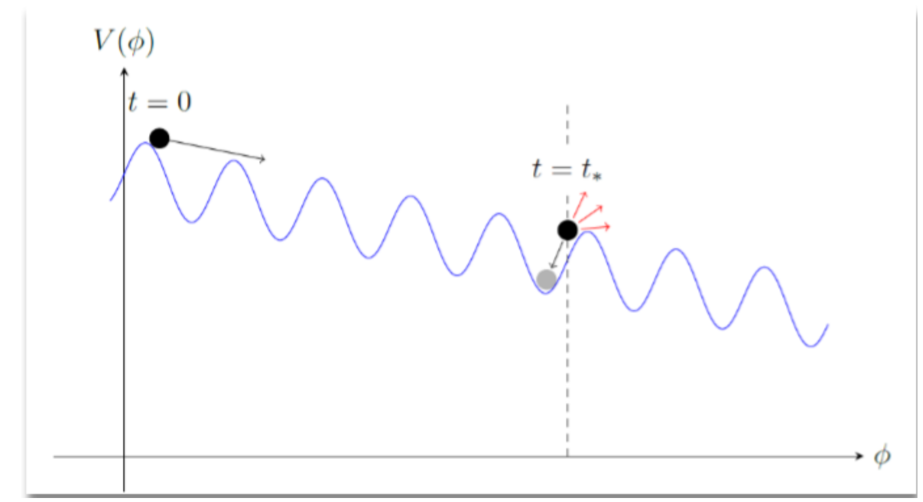
- *Raises new cosmological and field theory questions*

  CC? Is there a bound on small global charges?

  inflation? baryogengesis? relaxion DM?



Relation as playground for Naturalness



new theory challenges

- *Raises new cosmological and field theory questions*

  CC? Is there a bound on small global charges?

  inflation? *baryogengesis?* *relaxion DM?*

new pheno probes

- *Switches the focus to very light weakly coupled states*
- *Higgs portal phenomenology for the original relaxion*
- *ALP phenomenology for the thermal relaxion*

BACKUP

How Atomic Clock experiments work?

Arvanitaki, Dimopoulos, Van Tilburg

$$\phi(t,\vec{x}) = \phi_0 \cos(m_\phi t - \vec{k}_\phi \cdot \vec{x} + \dots)$$

$$\phi_0 \approx \frac{1}{m_\phi}\sqrt{2\xi_\phi \rho_{DM}}$$

Fluctuations on the fundamental constant of Nature

The mass controls the frequency

$$\frac{\delta(f_A/f_B)}{(f_A/f_B)} \simeq [d_{m_e} - d_g + M_A d_{\hat{m}} + d_e(\xi_A - \xi_B)]\,\kappa\phi(t)$$

1 sec   3.25 years

$$\Delta\tau < \frac{2\pi}{m_\phi} < \tau_{\rm int}. \longrightarrow m_\phi \lesssim 10^{-15}\ {\rm eV}$$

Backreaction from NP sector

$$\mathcal{L} = -y_1 e^{i\frac{2n\phi}{f_{\rm UV}}} \epsilon^{\alpha\beta} h_\alpha L_\beta N - y_2 h^{\dagger\alpha} L^c_\alpha N - m_L \epsilon^{\alpha\beta} L_\alpha L^c_\beta - \frac{m_N}{2} NN + \text{h.c.}$$

$$V_{\rm CW}(\phi) \simeq -\frac{1}{4\pi^2} m_L m_N y_1 y_2 |h^0|^2 \cos\left(\frac{\phi}{f}\right) \log\left(\frac{\Lambda^2}{\tilde{m}^2}\right) , \quad \text{VS} \quad V^{2-\rm loop}_{\rm CW}(\phi) \sim -\frac{1}{4\pi^2} m_L m_N y_1 y_2 \left(\frac{\Lambda_c^2}{16\pi^2}\right) \cos\left(\frac{\phi}{f}\right)$$

screen the Higgs loop

$$\Delta\mathcal{L} = m_D N N^c - \frac{m_{N^c}}{2} N^c N^c \dashrightarrow m_N \approx \frac{m_D^2}{m_{N^c}}$$

no quadratic divergences above m_{N^c} $\quad m_L \approx m_N \lesssim m_{N^c} \approx 4\pi v$

Backreaction from neutrino sector

$$\mathcal{L}_N^{\text{br}} = y_{jk}^D \cdot \left(\frac{\hat{\Phi}_0}{\Lambda_n}\right)^{\left|[N_j]+[N_k^c]\right|-1} \hat{\Phi}_0 N_j N_k^c + \frac{1}{2} M_{jk}^M N_j N_k + \text{h.c.}$$
$$\supseteq M_{jk}^D \cdot U_0^{[N_j]+[N_k^c]} N_j N_k^c + \frac{1}{2} M_{jk}^M N_j N_k + \text{h.c.}\,,$$

The potentials:

$$V_D \sim \frac{\text{Tr}(M^D M^{D\dagger} \overline{M}^M \overline{M}^{M\dagger})}{16\pi^2} \log \frac{m_{\text{clock}}^2}{M^2}$$
$$V_{\text{br}} \sim H^\dagger H \left[\frac{\text{Tr}(Y^n M^{D\dagger} \overline{M}^M \overline{M}^{M\dagger} M^D Y^{n\dagger})}{16\pi^2 M^2} + \ldots\right]$$

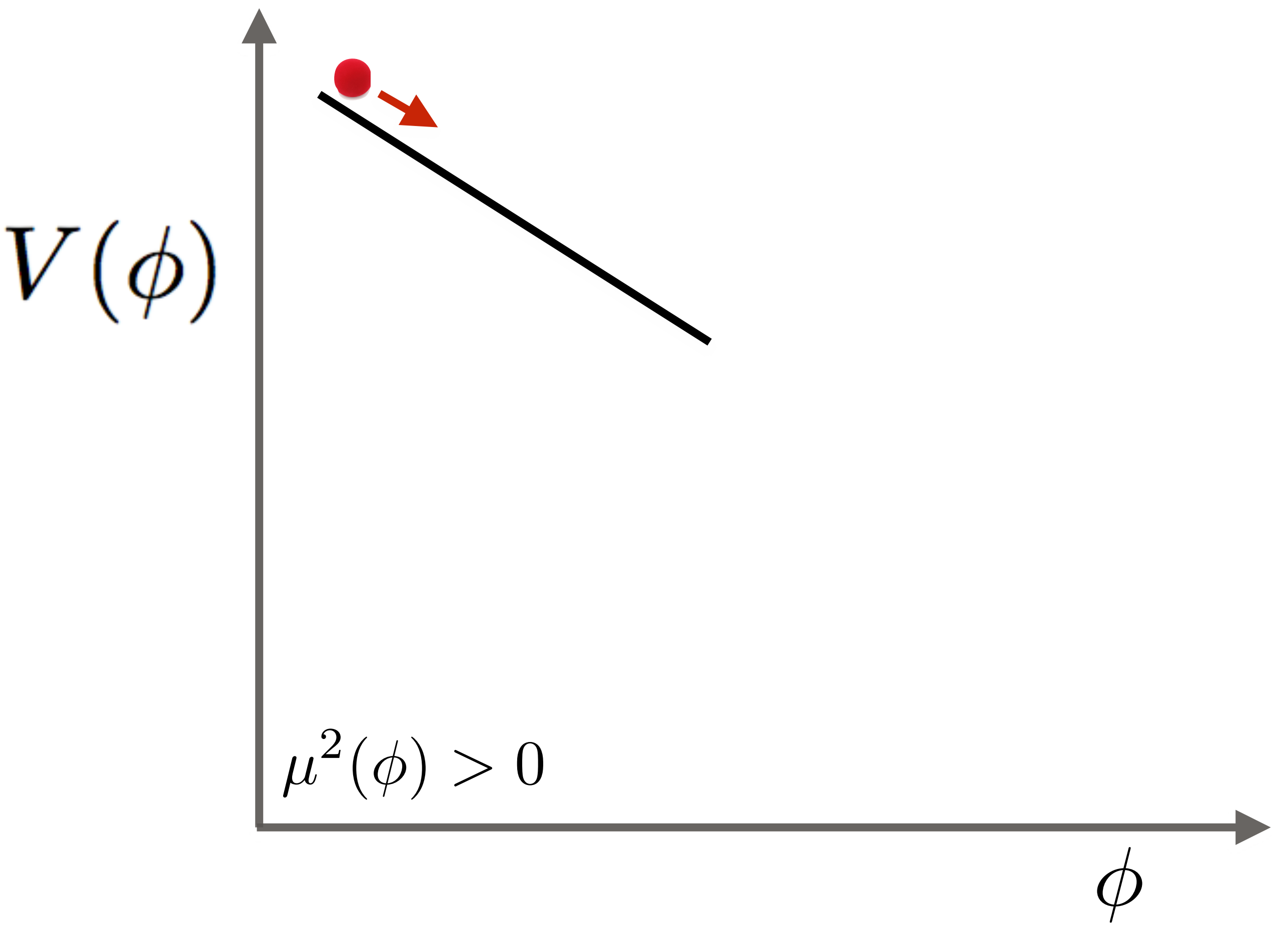
The trick: $V_D < V_{\text{br}}$ -----▸ M_D diagonal

The consequence: $\Lambda_{\text{br}} \sim \left(\frac{y_N^2 v^2 M^2}{16\pi^2}\right)^{1/4} \sim \left(\frac{m_\nu M^3}{16\pi^2}\right)^{1/4} \lesssim 10 \text{ MeV}\,.$

I

The Relaxion rolling

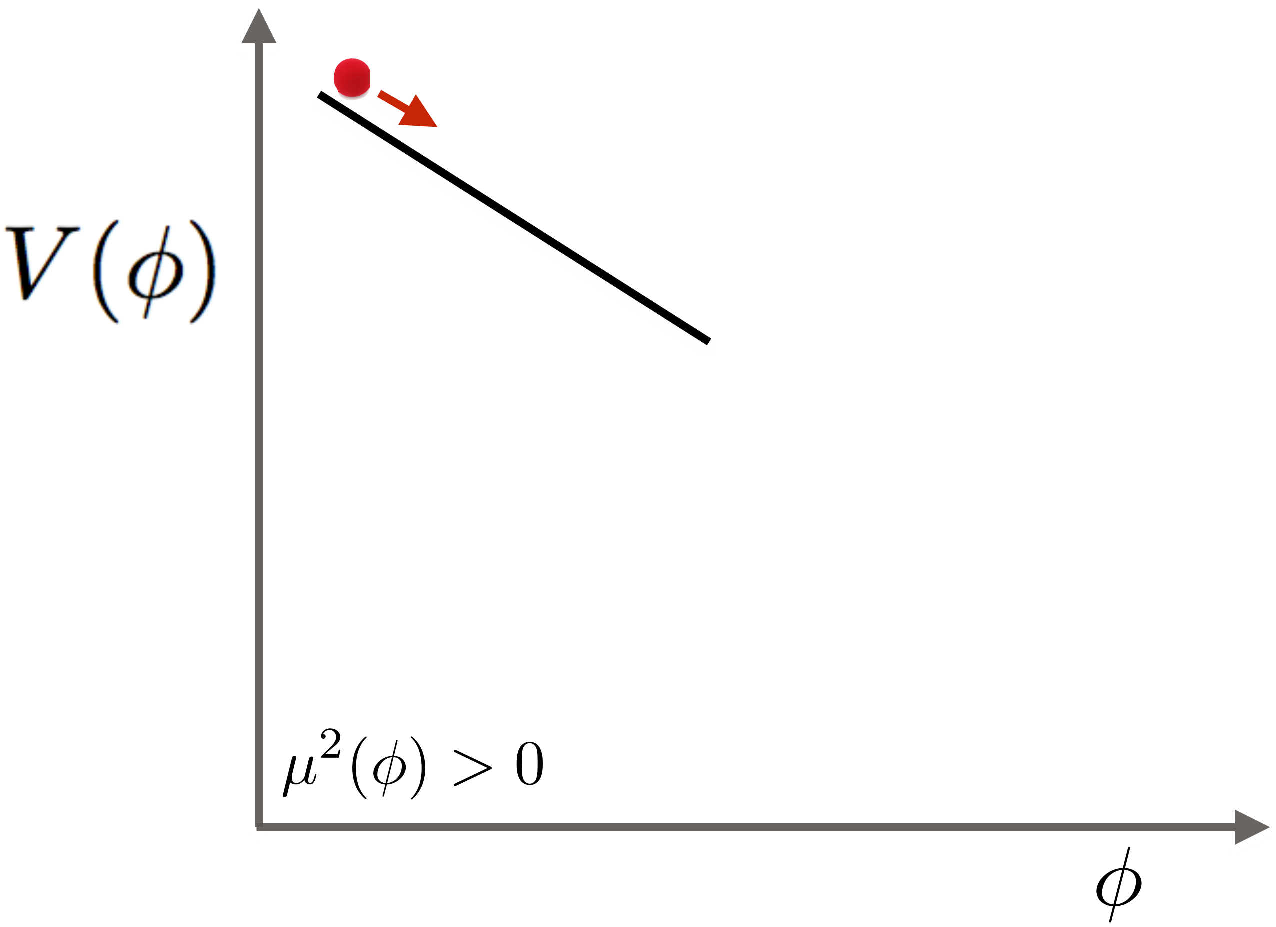
(Graham, Kaplan & Rajendran)



I

The Relaxion rolling

(Graham, Kaplan & Rajendran)



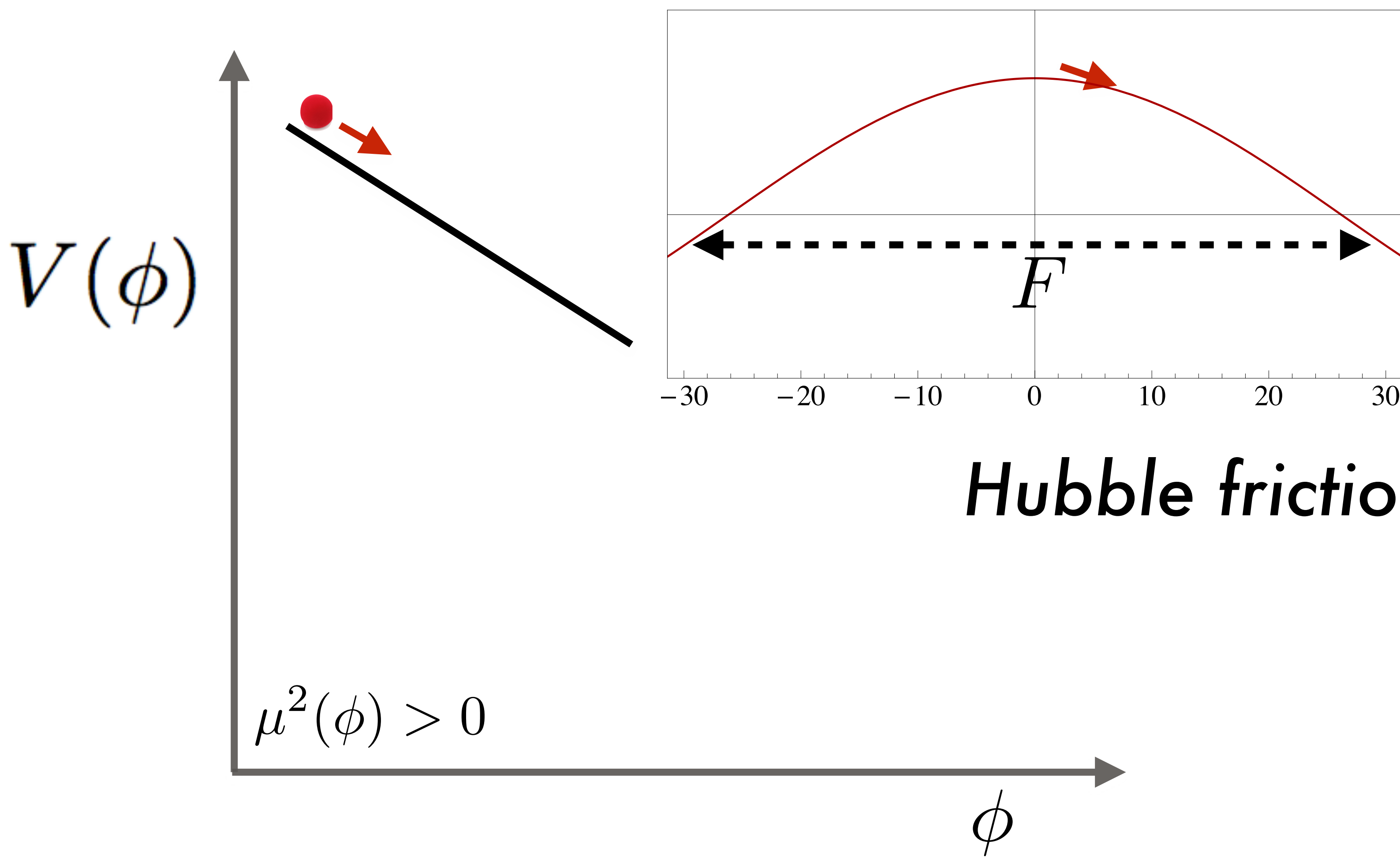
ϕ ***rolling potential:***

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

I

The Relaxion rolling

(Graham, Kaplan & Rajendran)



Hubble friction

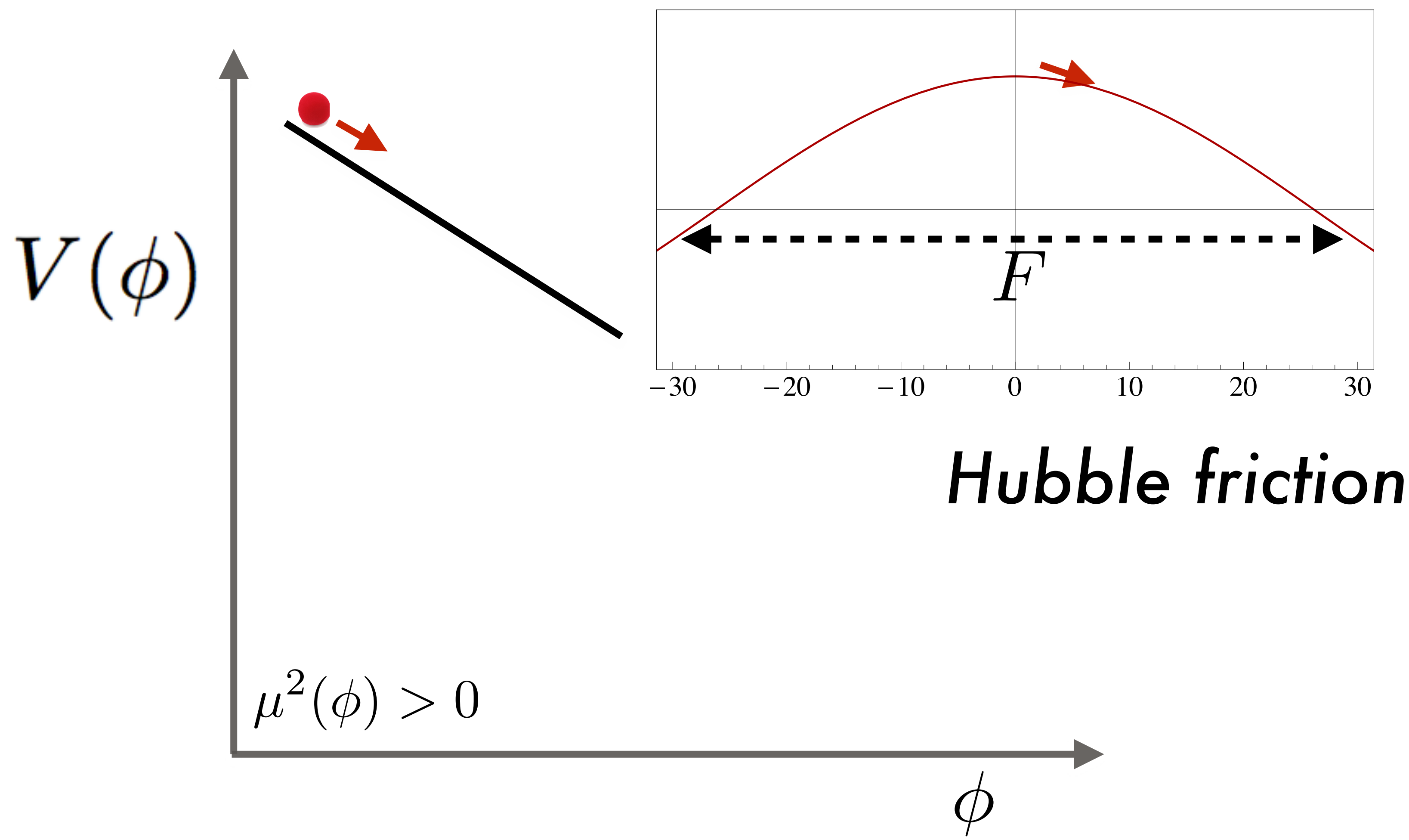
ϕ ***rolling potential:***

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

I

The Relaxion rolling

(Graham, Kaplan & Rajendran)



ϕ- dependent Higgs mass

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

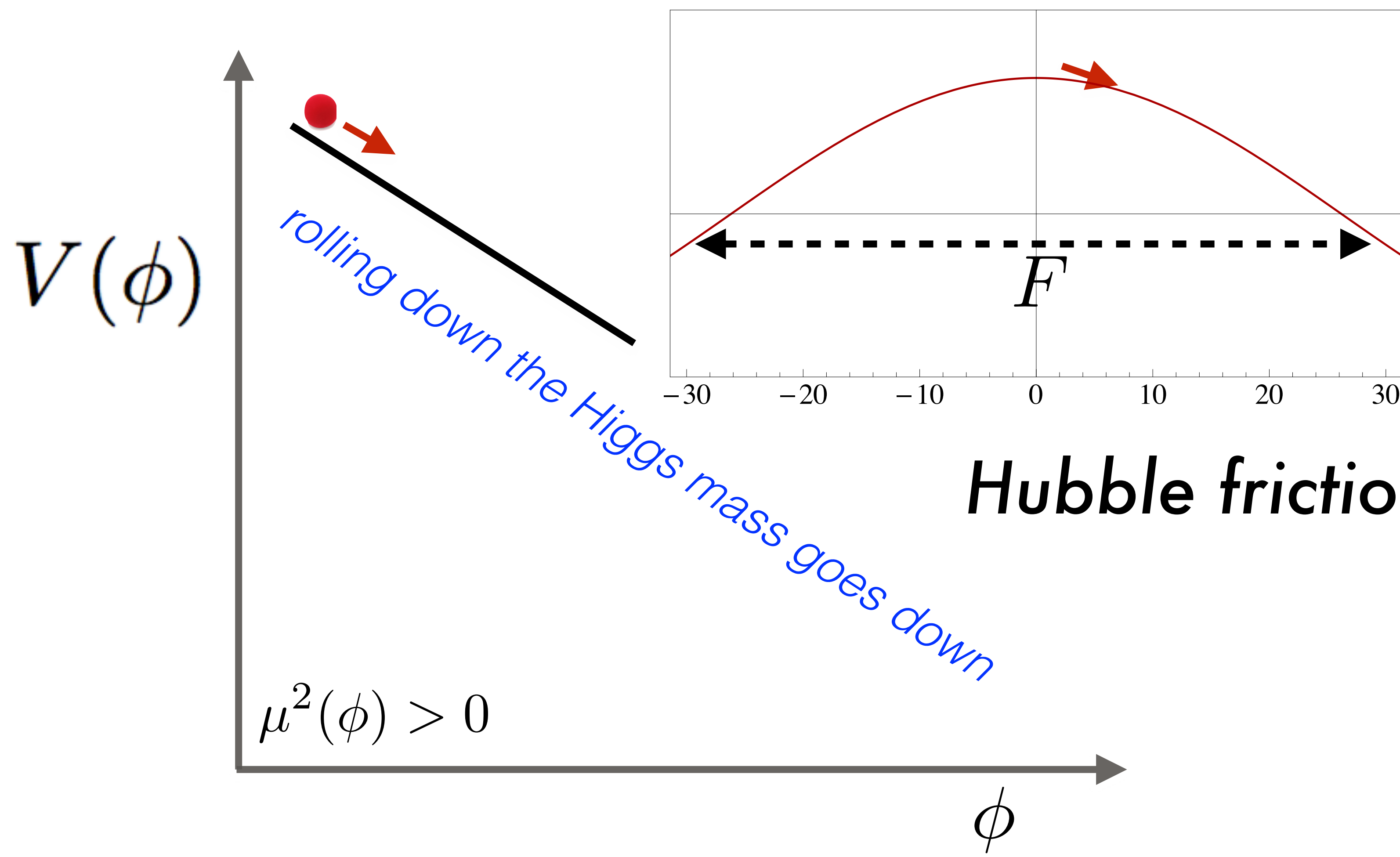
ϕ rolling potential:

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

I

The Relaxion rolling

(Graham, Kaplan & Rajendran)



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

ϕ- dependent Higgs mass

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

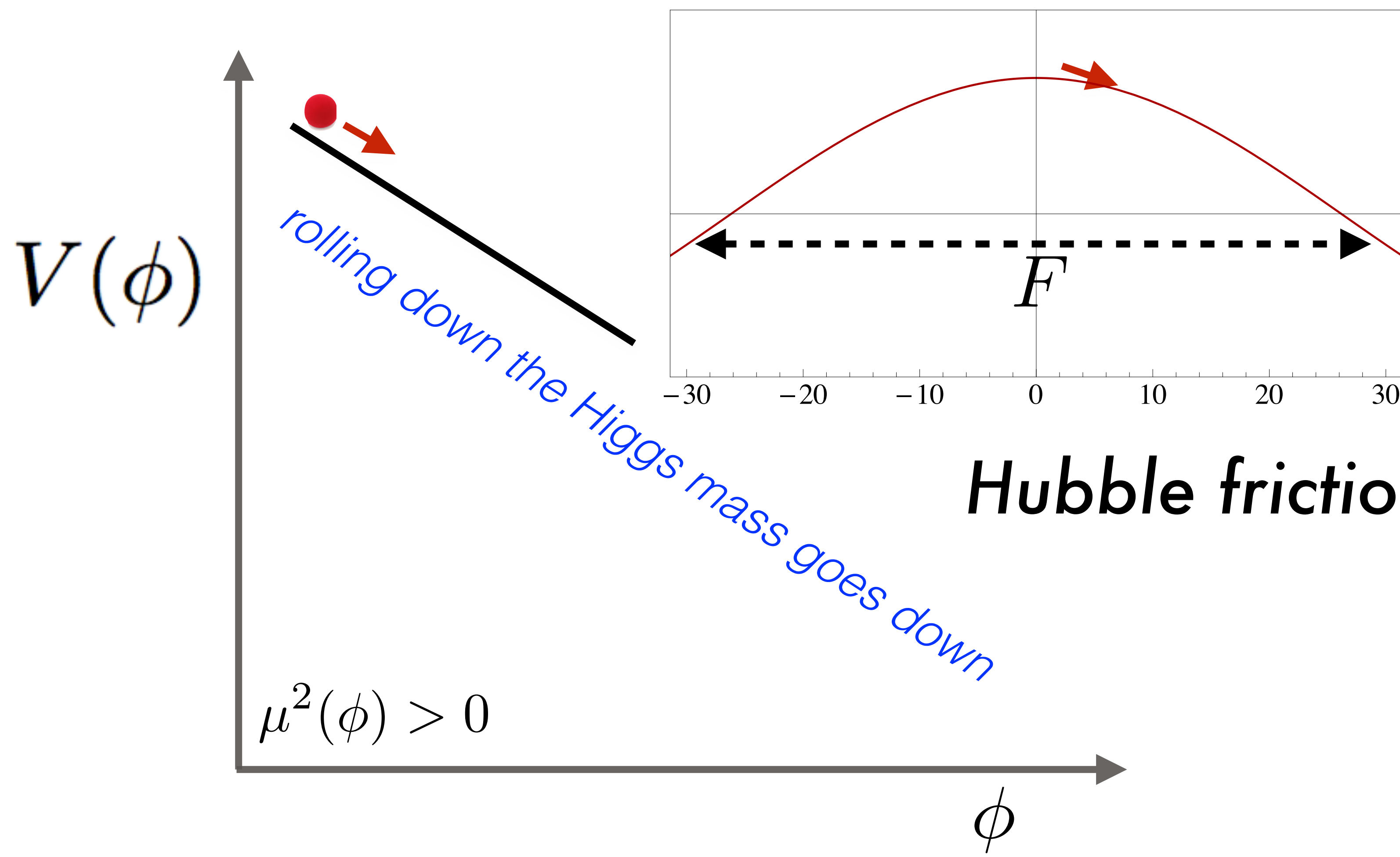
ϕ rolling potential:

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

I

The Relaxion rolling

(Graham, Kaplan & Rajendran)



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

ϕ- dependent Higgs mass

$$\underbrace{\Lambda_H^2(\kappa - \cos\frac{\phi}{F})}_{\mu^2(\phi)} H^\dagger H \simeq (\kappa\Lambda_H^2 - \underbrace{g\phi}_{\frac{g}{\Lambda_H} \lll 1})H^\dagger H$$

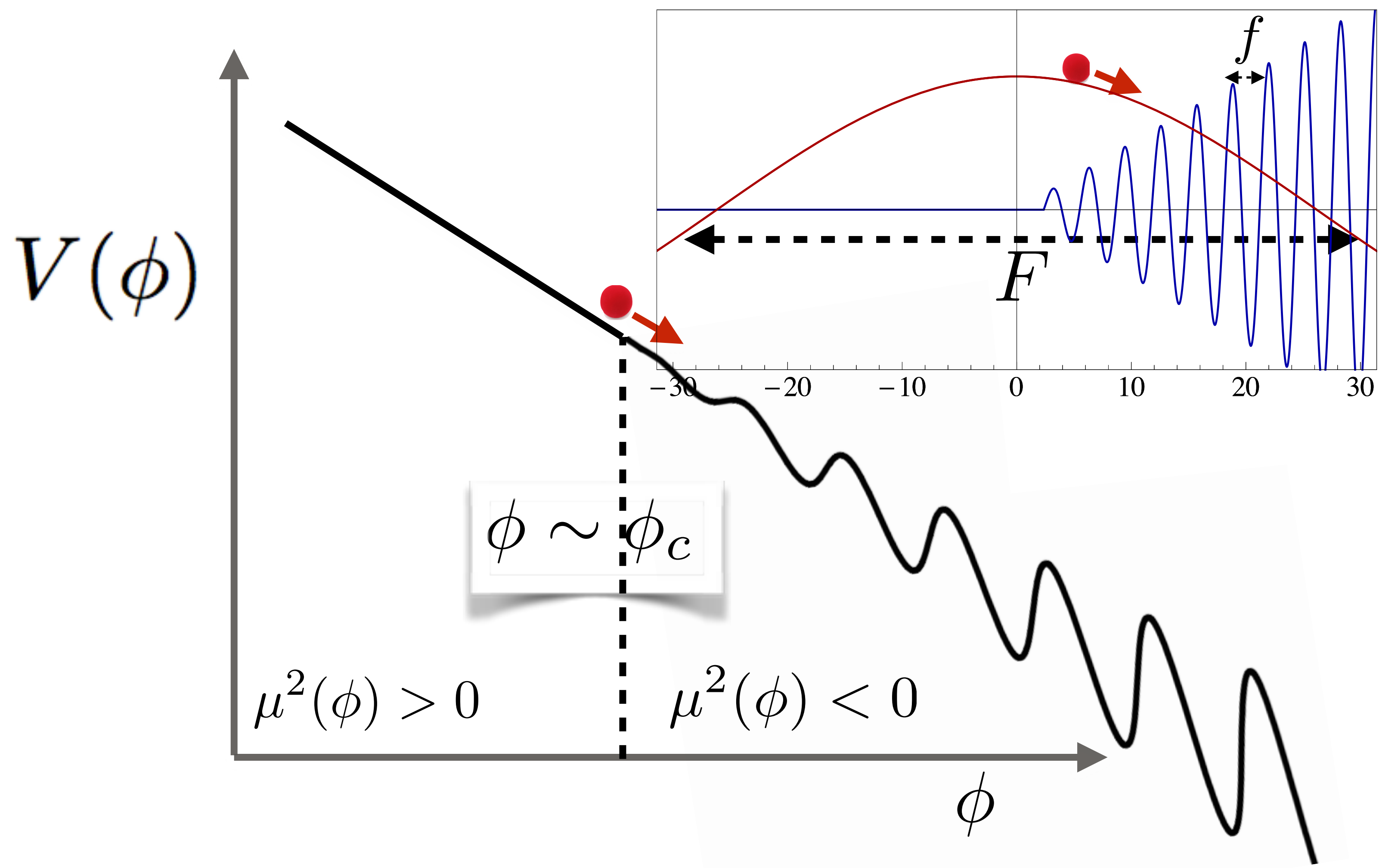
ϕ rolling potential:

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

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

II

The Relaxion wiggles



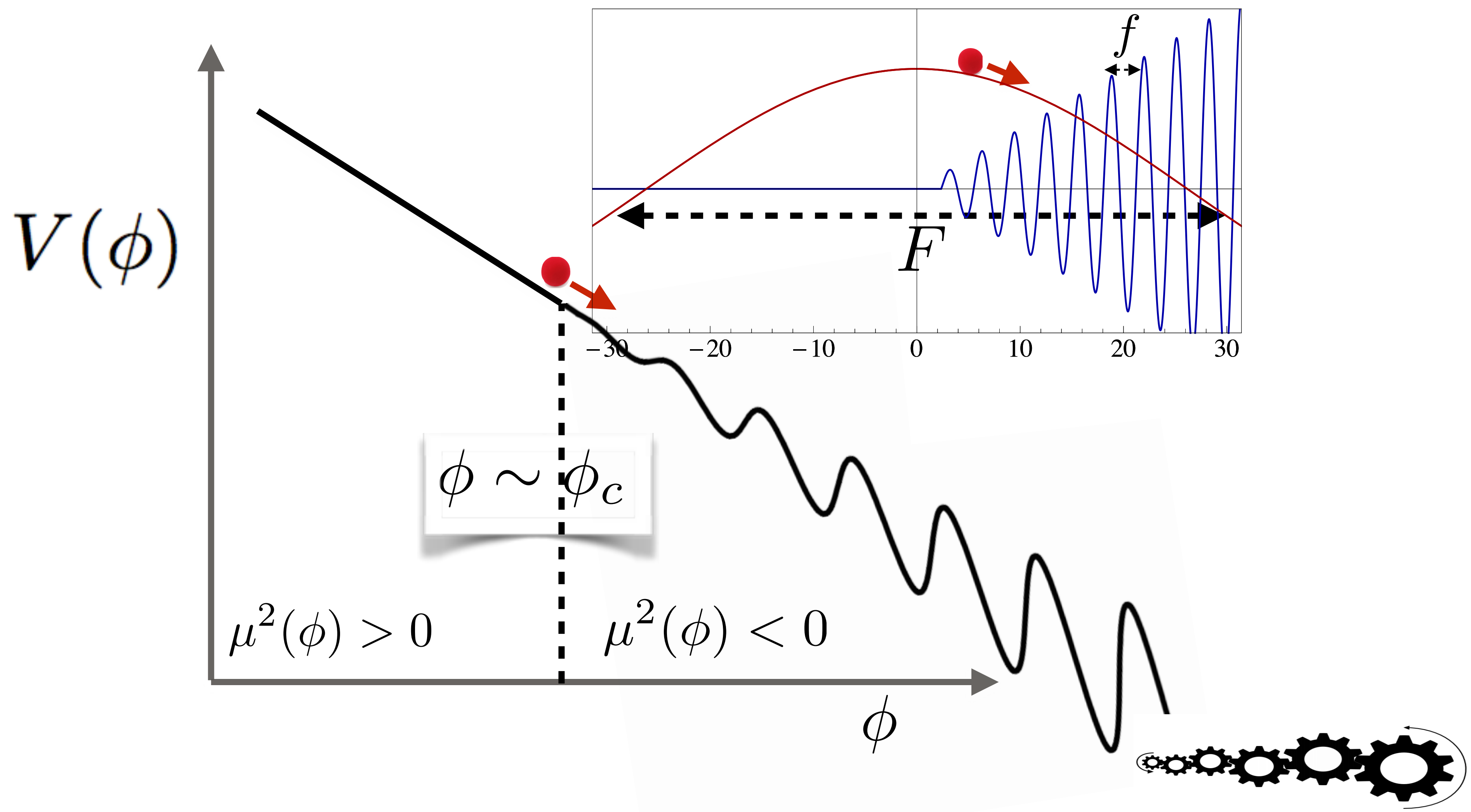
ϕ gets a "backreaction" potential after EWSB

Periodicity of this potential smaller than the "rolling"

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

II

The Relaxion wiggles



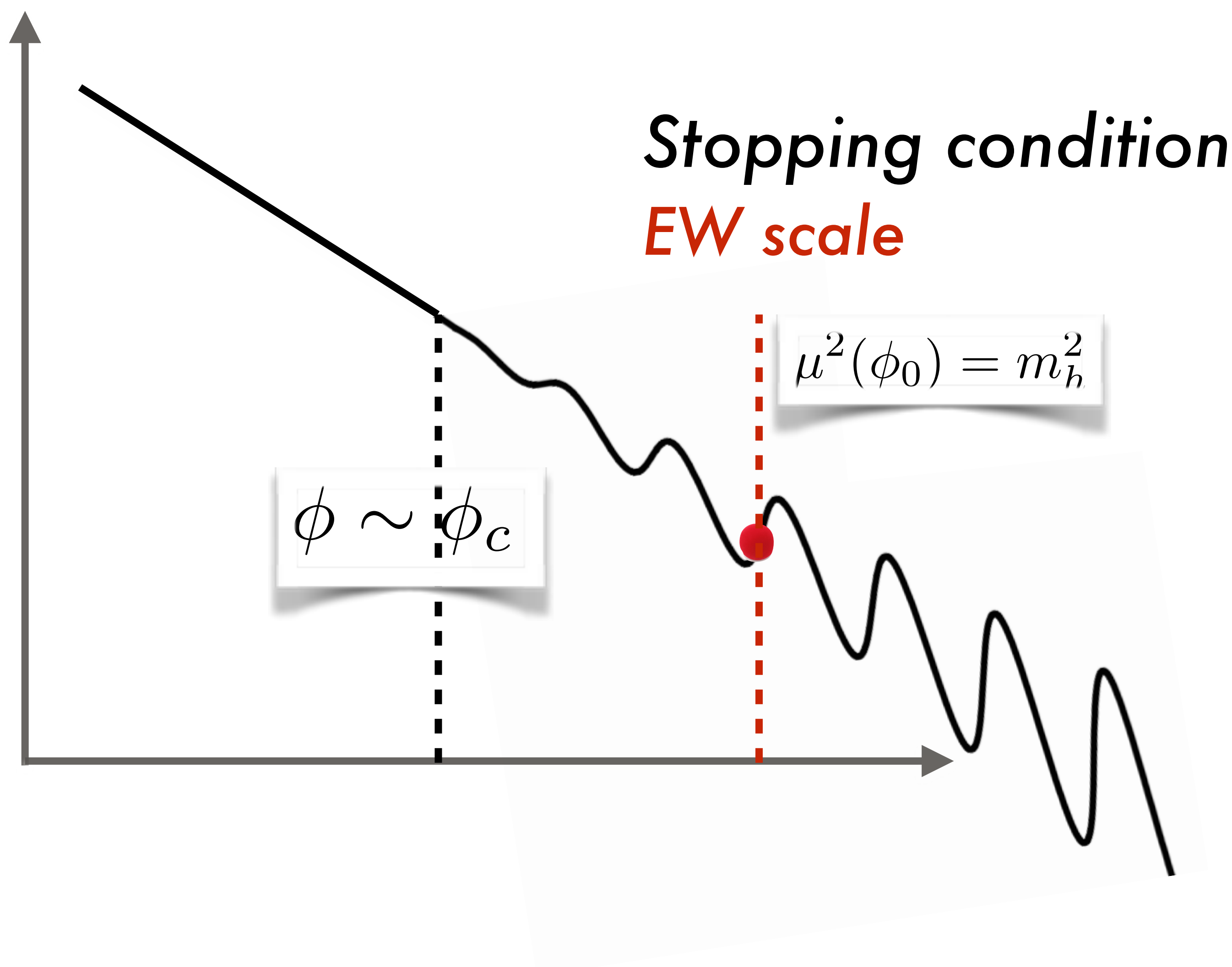
ϕ gets a "backreaction" potential after EWSB

Periodicity of this potential smaller than the "rolling"

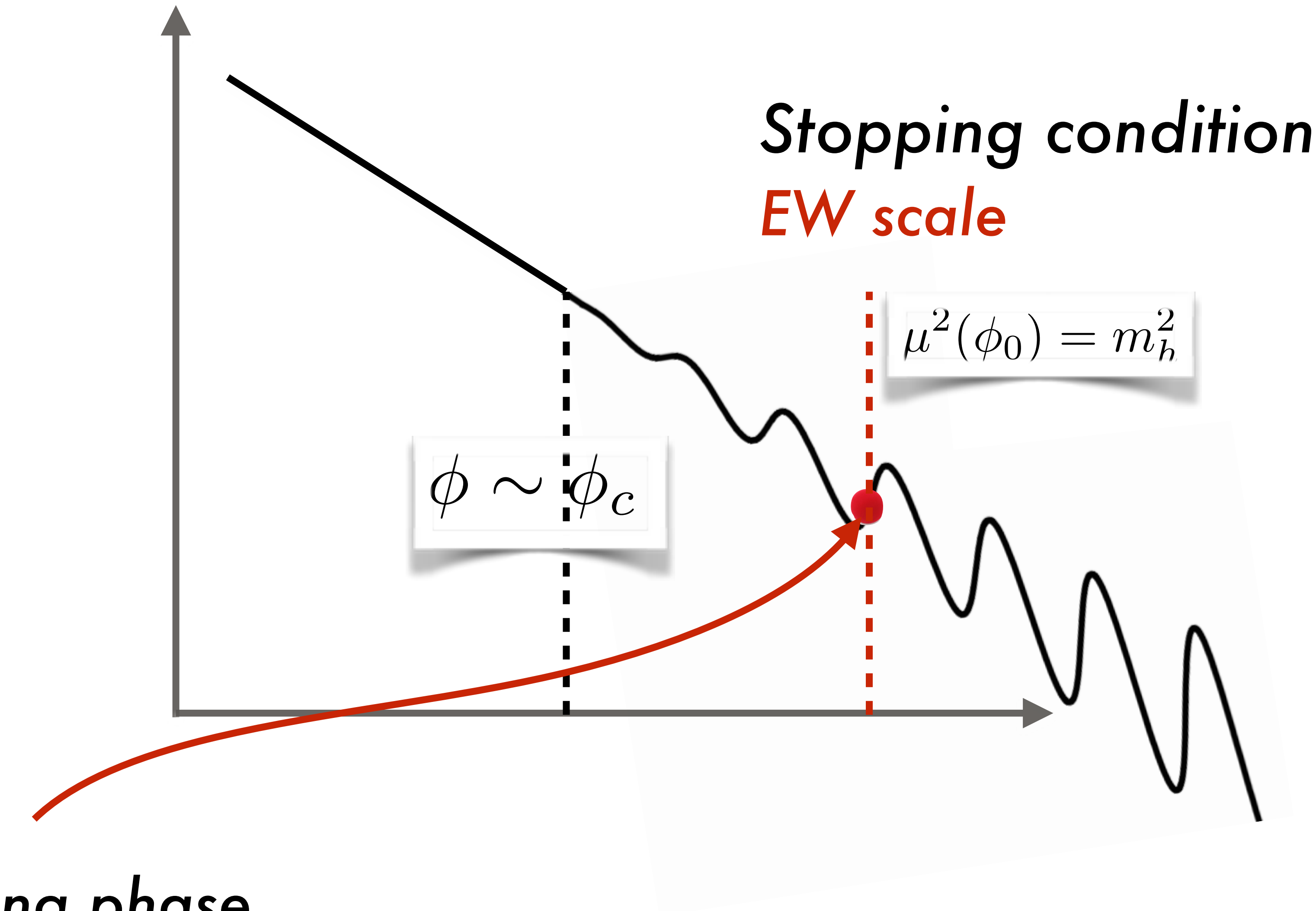
$$\Lambda_{\rm br}^4 \cos\frac{\phi}{f}$$ } $\Lambda_{\rm br}$ **model dependent**

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

I + II = rolling + wiggles



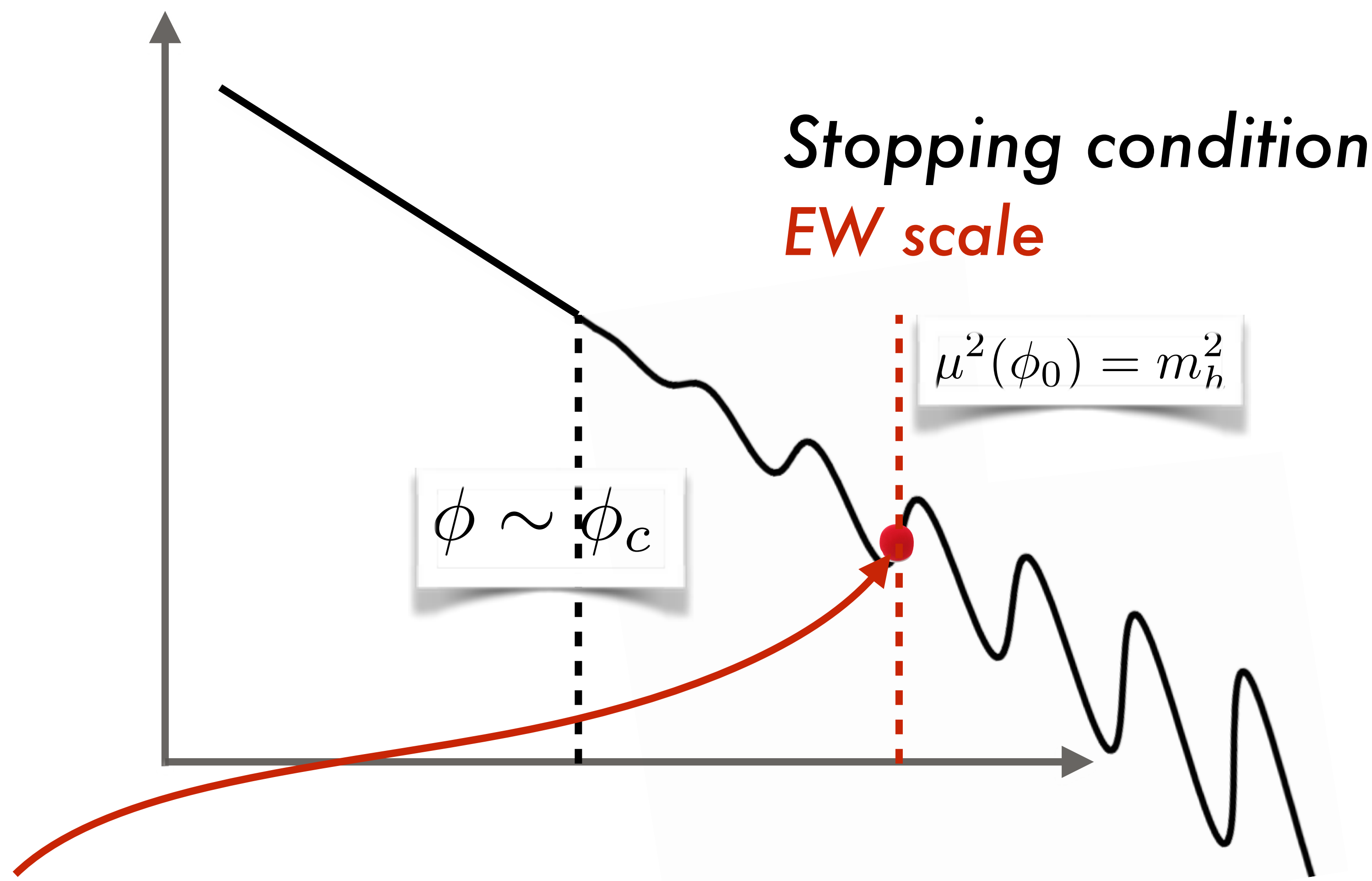
I + II = rolling + wiggles



CP violating phase

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

I + II = rolling + wiggles



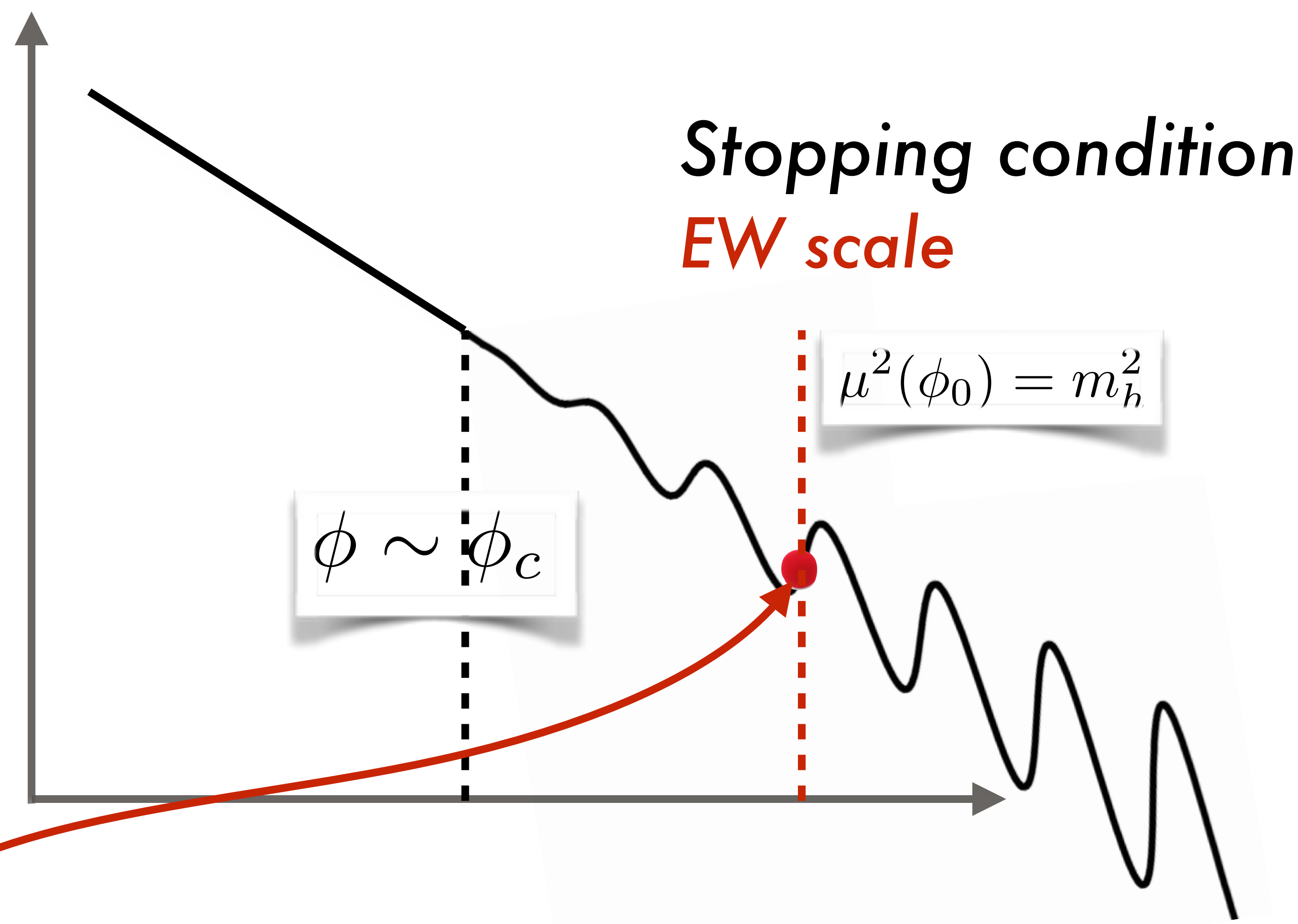
CP violating phase

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

Ratio of scales $=$ *Ratio of vevs*

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

I + II = rolling + wiggles



CP violating phase

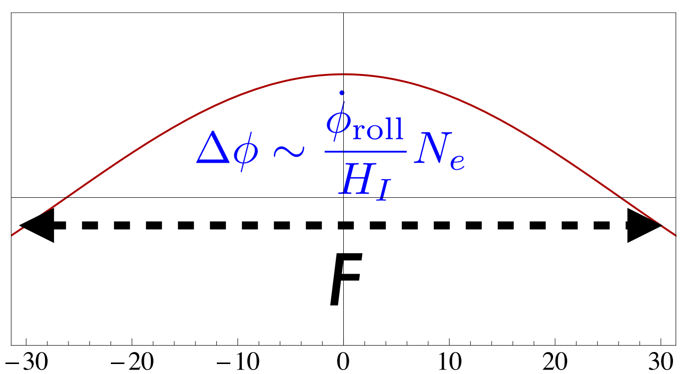
$$\sin\frac{\phi_0}{f} \sim \sin\frac{\phi_0}{F} \sim \mathcal{O}(1)$$

Ratio of scales = Ratio of vevs

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

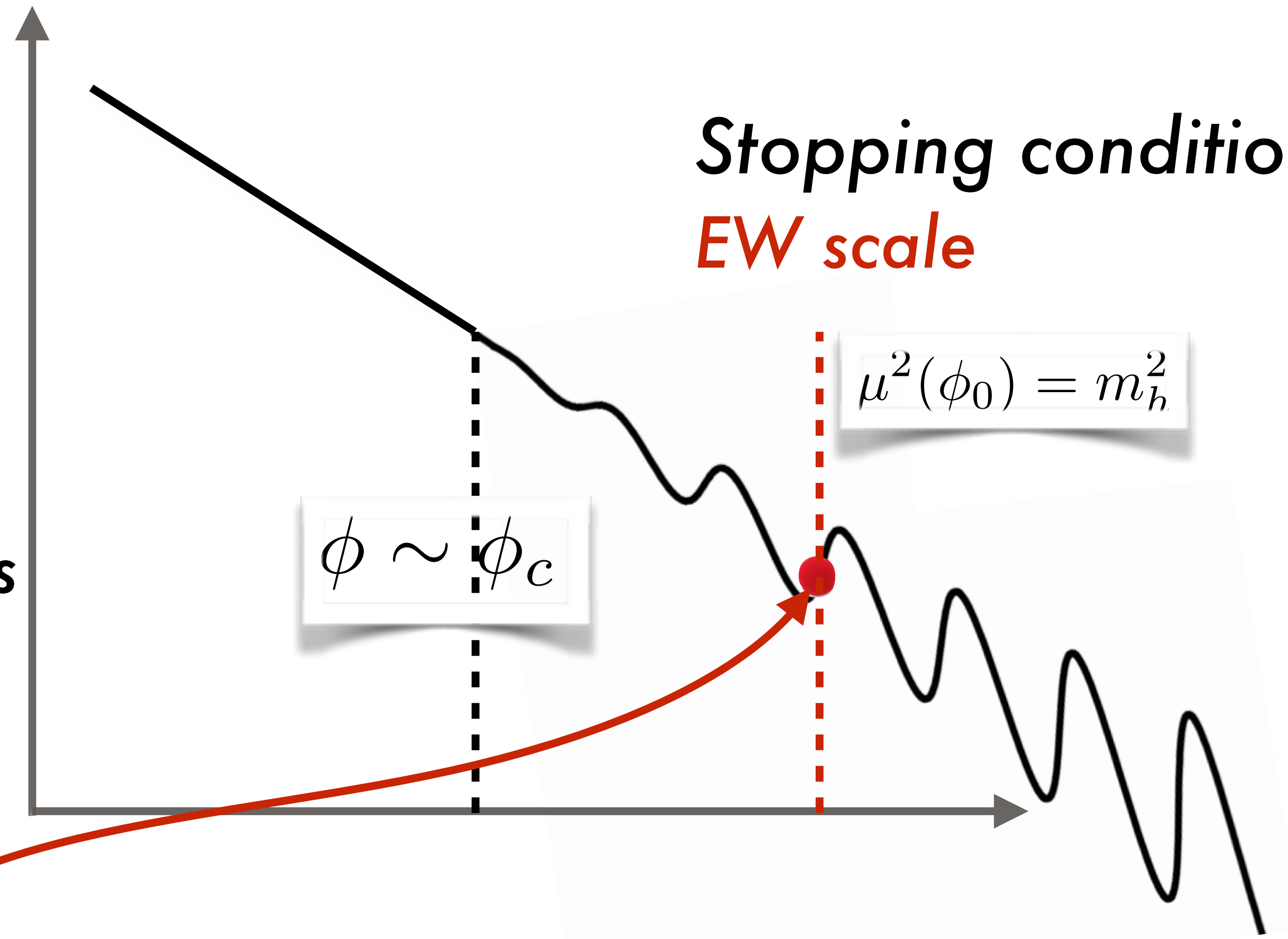
I + II = rolling + wiggles

Price to pay:



huge number of e-folds

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



Stopping condition

EW scale

CP violating phase

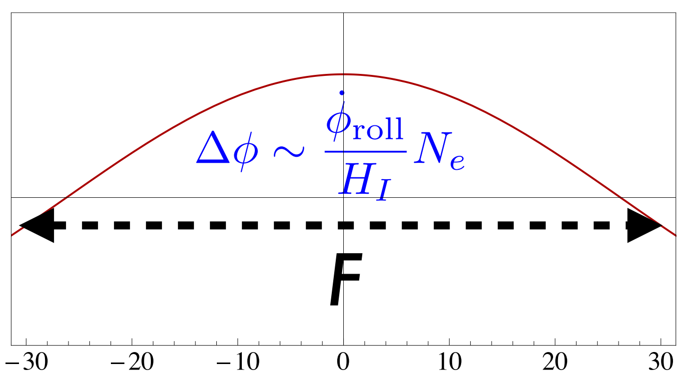
$$\sin\frac{\phi_0}{f} \sim \sin\frac{\phi_0}{F} \sim \mathcal{O}(1)$$

Ratio of scales = Ratio of vevs

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

I + II = rolling + wiggles

Price to pay:

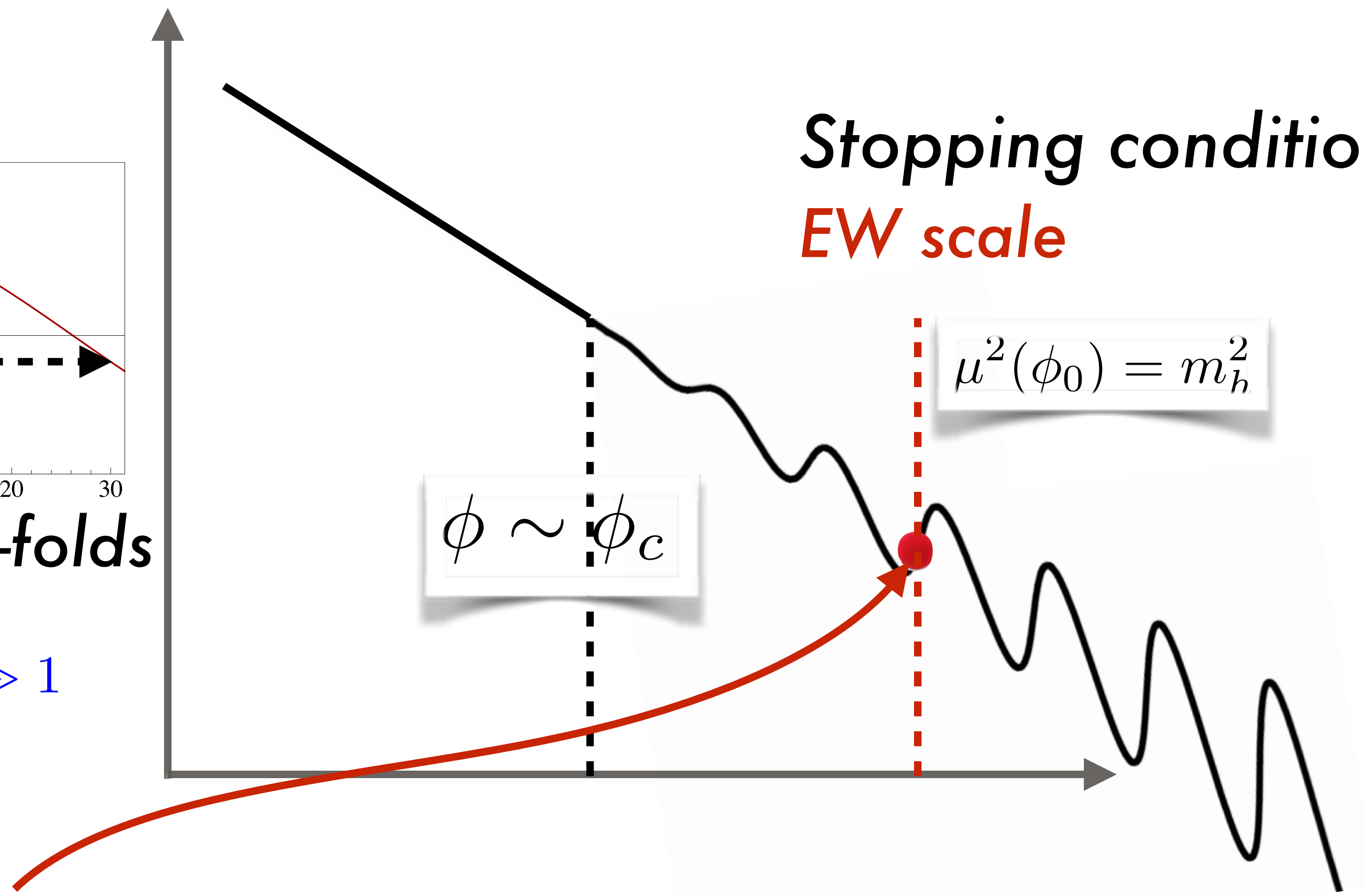


huge number of e-folds

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

Stopping condition

EW scale



CP violating phase

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

Ratio of scales $=$ Ratio of vevs

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

there is a price to pay
for the large pace

$$\frac{\Lambda_H}{\Lambda_{\rm br}} \simeq 1/\sqrt{r_{\rm roll}} \cdot 1/Q$$