Higgs BSM (fringy perspective)

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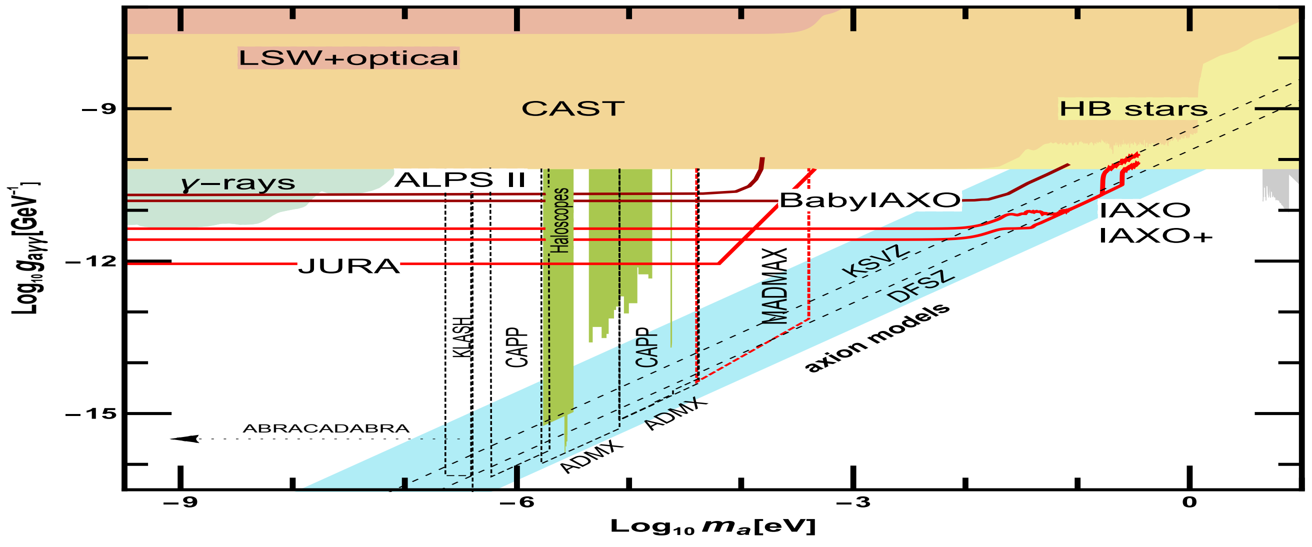
Outline

- Intro Higgs physics @ 21st century: the (relaxion) log crisis/opportunity.
- Why accelerators & colliders are important ?
- Ultra light DM & oscillating Higgs VEV - the precision front.
- [Probing Higgs-strange couplings.]
- Conclusions.

Prologue: ex. the axion's log crisis

- Axion or axion-like particles (ALPs) are well motivated fields.
- However, challenging to find, ALP mass is protected & its scale is undetermined.
- Required searches across scales & frontier => The well known axion's log crisis:

Log crisis: Search region shown on a *log-log scale*



Light Pseudoscalars, Particle Physics and Cosmology
Jihn E. Kim (Seoul Natl. U.).
Published in **Phys.Rept. 150 (1987) 1-177**
SNUHE-86-09
DOI: 10.1016/0370-1573(87)90017-2
- References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
- KEK scanned document; ADS Abstract Service

Detailed record - **Cited by 1085 records**

See eg: A European Strategy Towards Finding Axions and Other WISPs

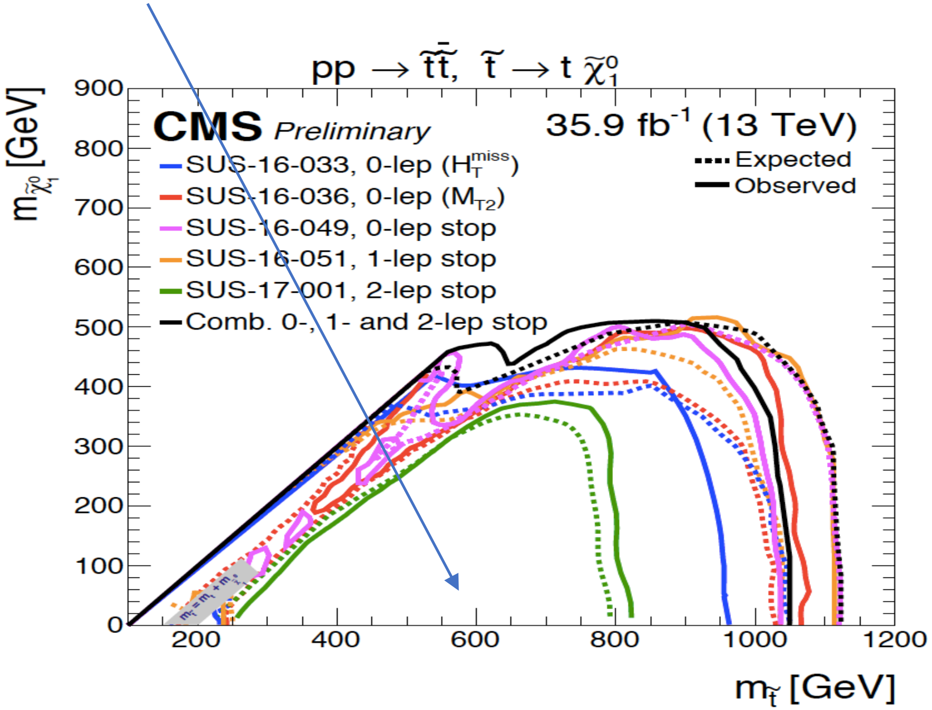
Desch, Döbrich, Irastorza, Jaeckel, Lindner, Majorovits & Ringwald

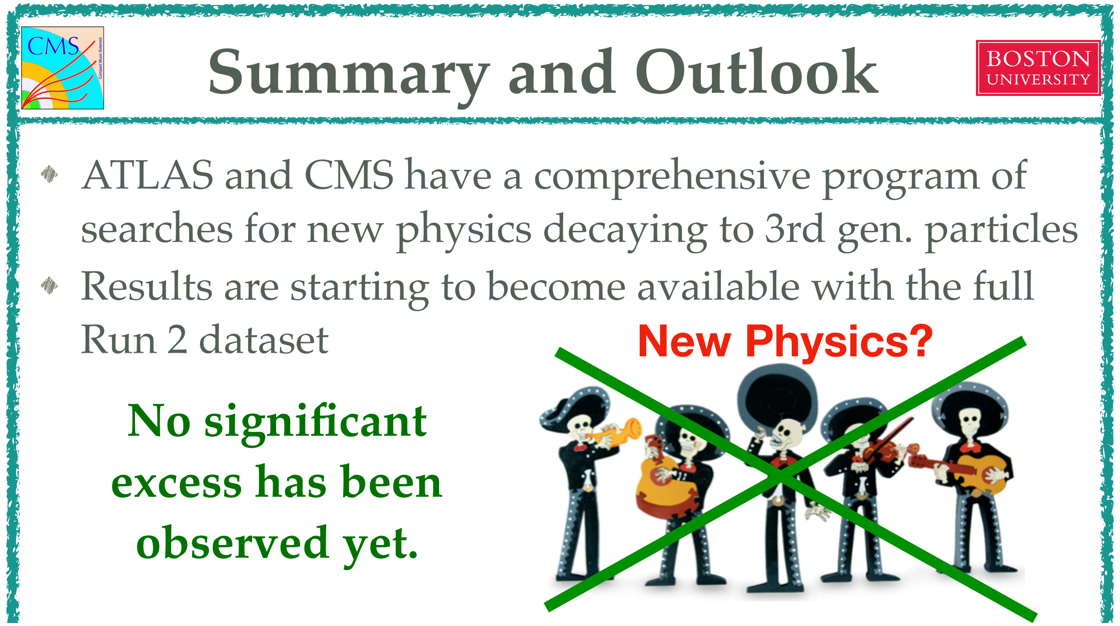
Higgs & new physics

- For > 40 yrs Higgs served us as anchor to determine the new phys. (NP) scale.

Naturalness <=> TeV NP

- NP searches according to leading paradigm, driven by E-frontier on linear scale:





LHCP19: Suarez on behalf of the ATLAS & CMS

Higgs @ 21st century => crisis & opportunity

- New ideas & null LHC results cast tiny doubt on this paradigm.

  eg: "Cosmic attractors", "dynamical relaxation", "N-naturalness", "relating the weak-scale to the CC" & "inflating the Weak scale".

- New scalar common to all of above: concretely let us consider the relaxion:

  Graham, Kaplan & Rajendran (15)

  under some assumption allows for a concrete QFT realisation.

- Bottomline here: relaxion is ALP that (due to CP violation) can be described as scalar mixes \w the Higgs.

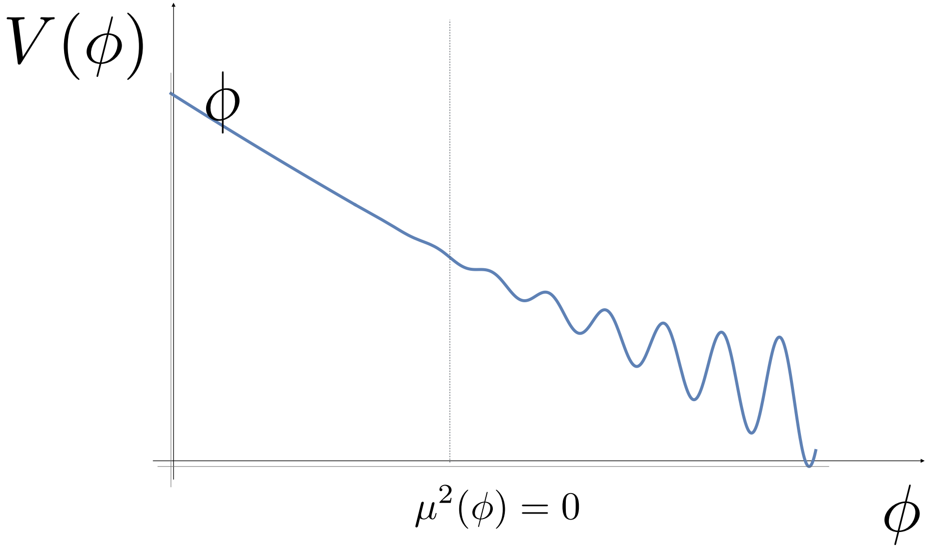
  Flacke, Frugiuele, Fuchs, Gupta & GP; Choi & Im (16)

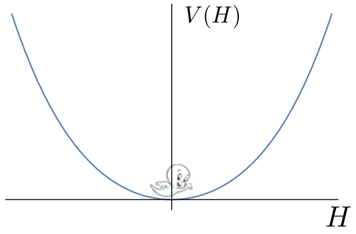
Relaxion mechanism (inflation based)

Graham, Kaplan & Rajendran (15)

(i) Add a scalar (relaxion) Higgs dependent mass: $\overbrace{\left(\Lambda^2 - g^2\phi^2\right)}^{\mu^2(\phi)} H^\dagger H$

(ii) ϕ roles till μ^2 changes sign $\Rightarrow \langle H \rangle \neq 0 \Rightarrow$ stops rolling.





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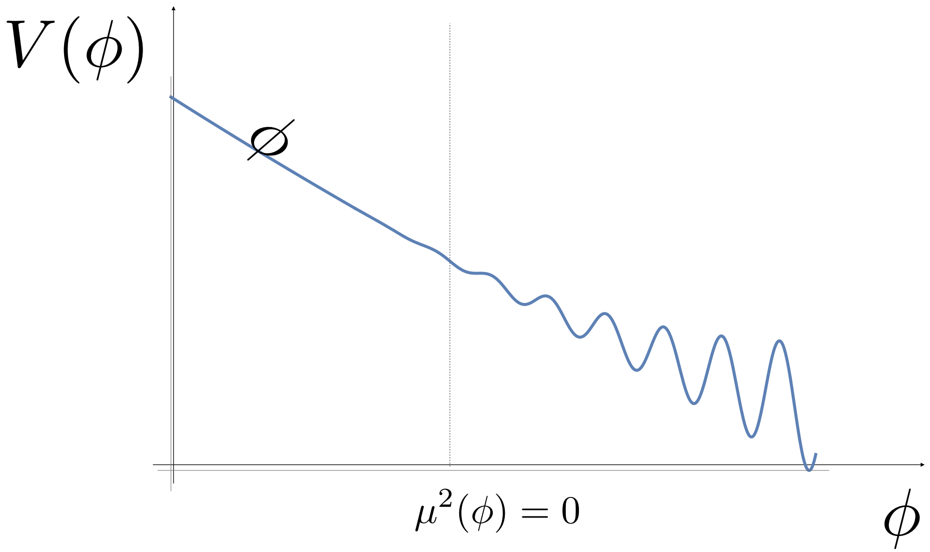

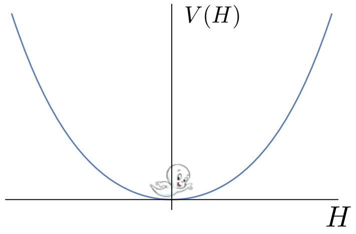

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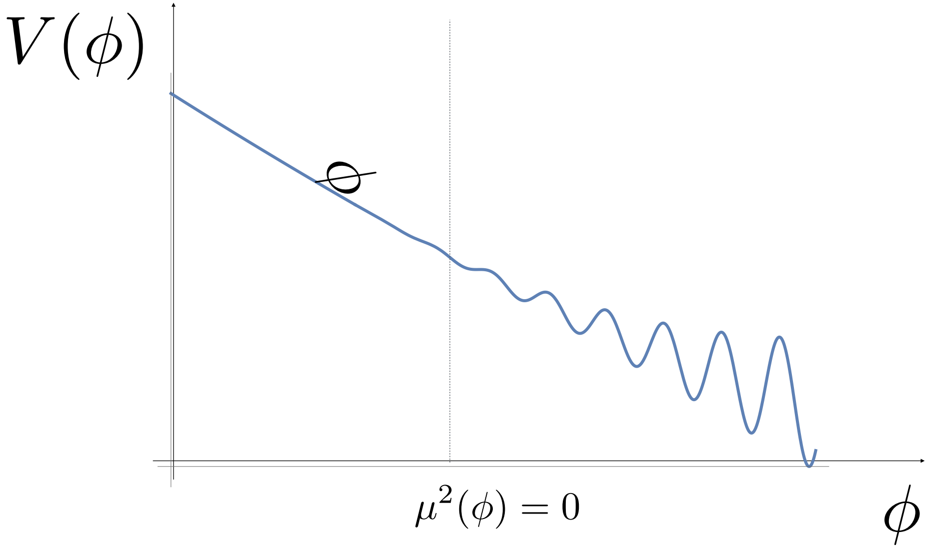

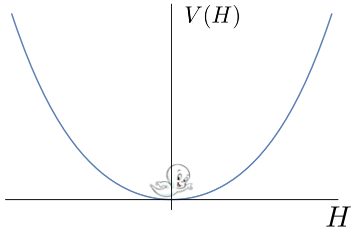

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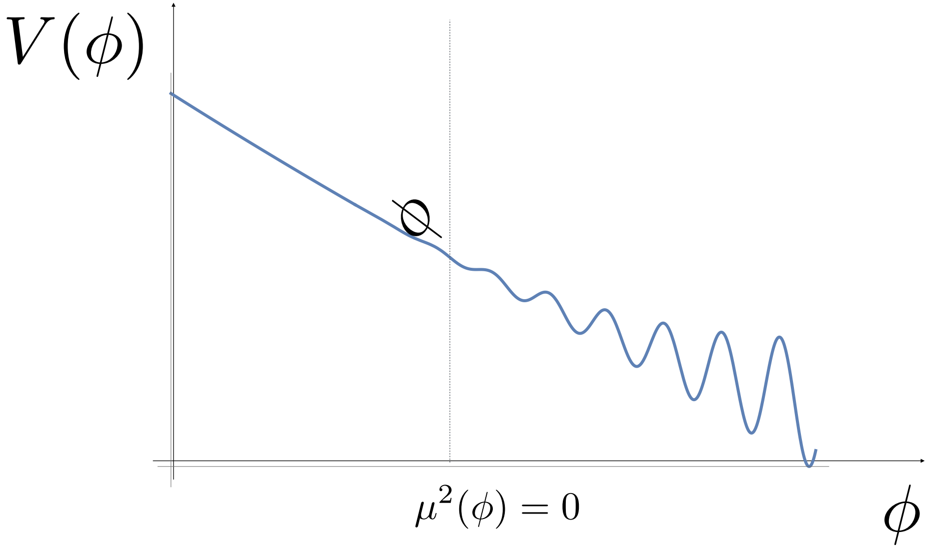

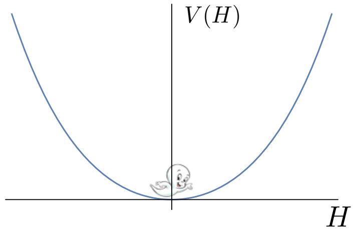

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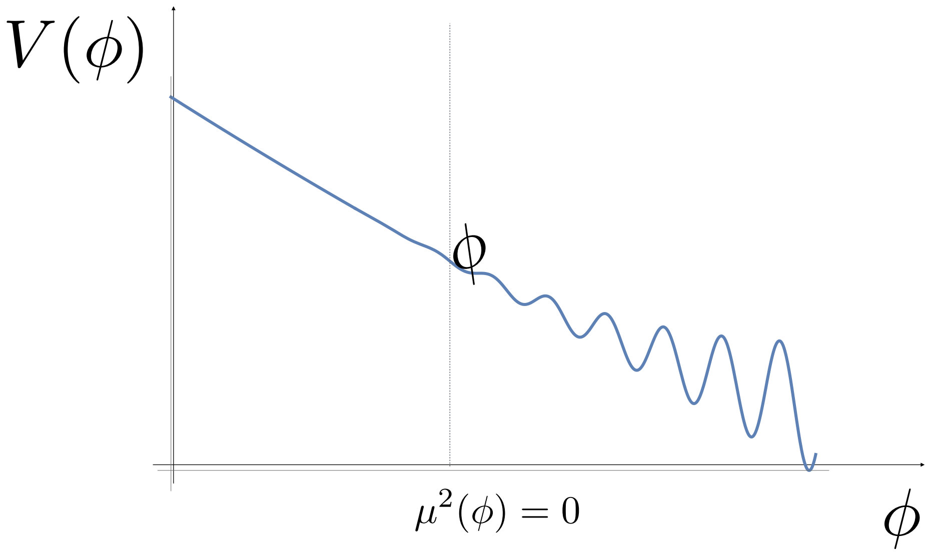

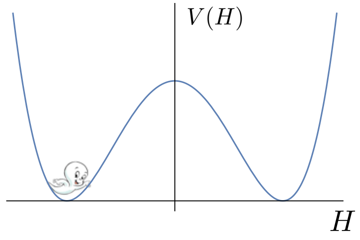

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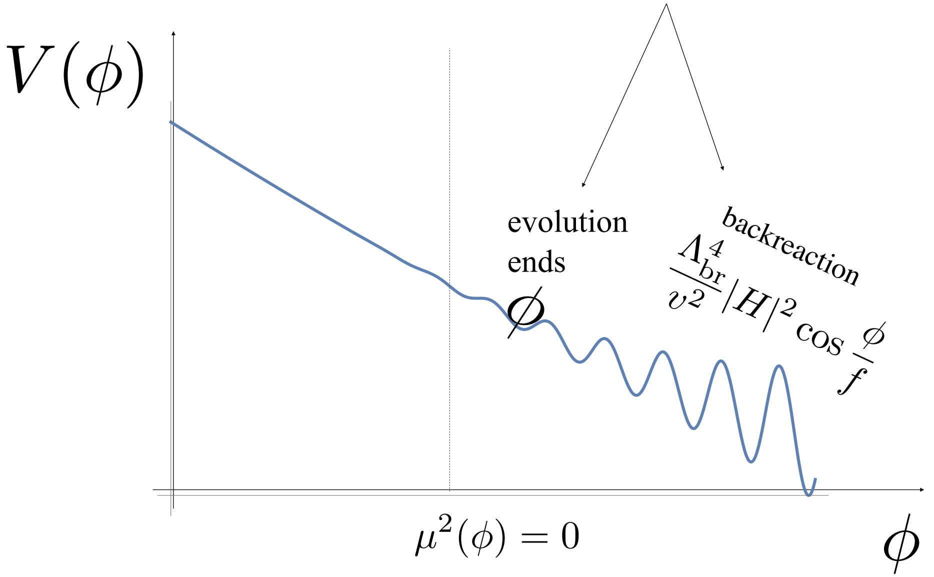

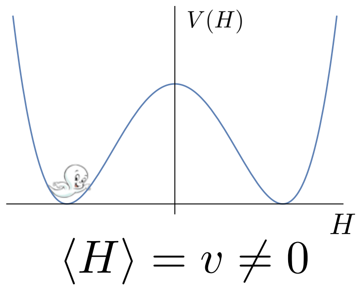

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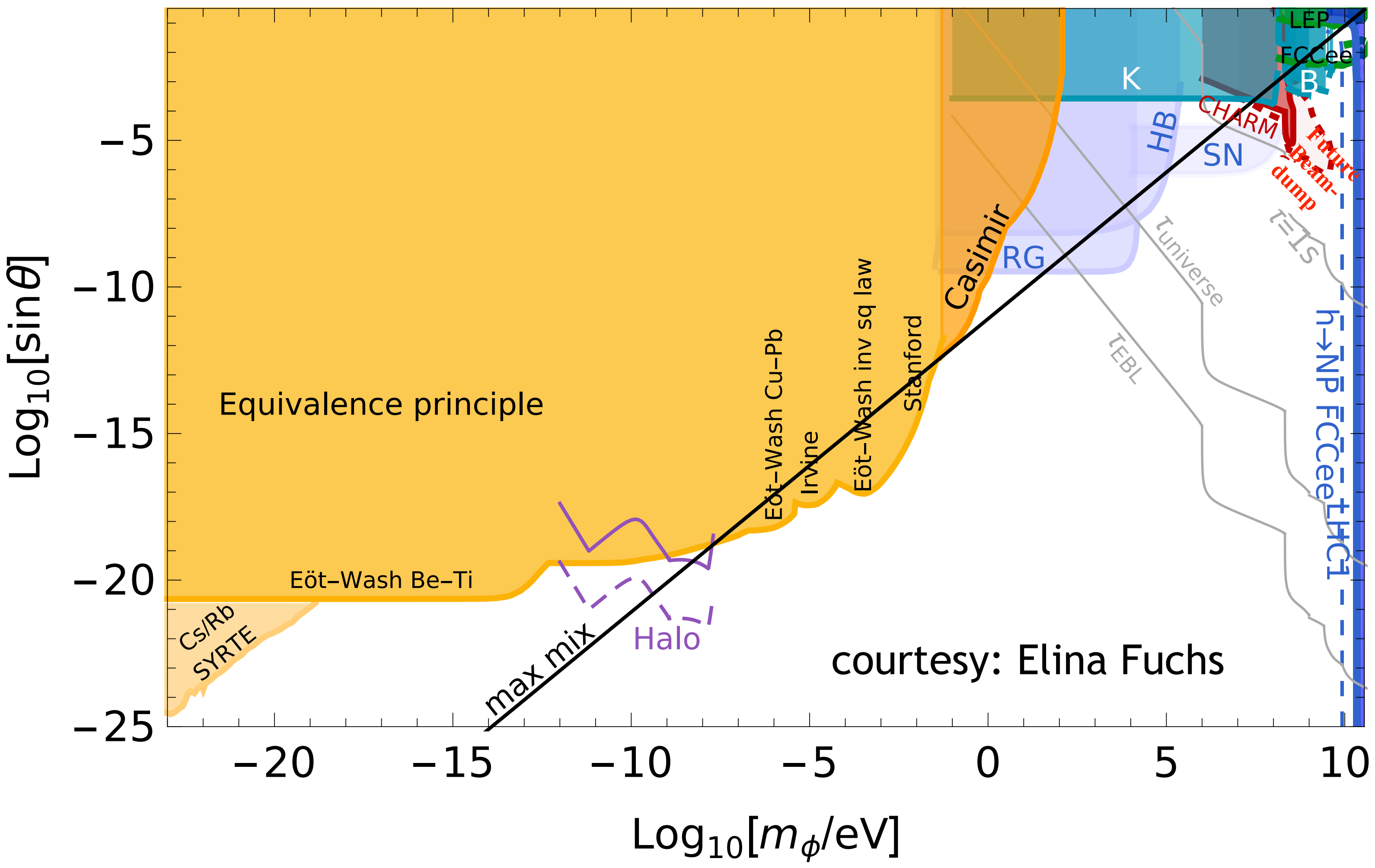
  Flacke, Frugiuele, Fuchs, Gupta & GP; Choi & Im (16)

- However, searching the relaxion => *log crisis* as follows:

The relaxion (Higgs portal) parameter space & the *log crisis*

Overview plot: the relaxion 30-decade-open parameter space



Two reasons for what makes accelerators relaxion-based searches special

(i) Penetrating the natural region

(ii) Relaxion quality problem

Reason 1: Penetrating the (naive) relaxion natural region

- As effective relaxion models can be described via a Higgs portal they suffer from their own naturalness problem which can be summarised as follows:

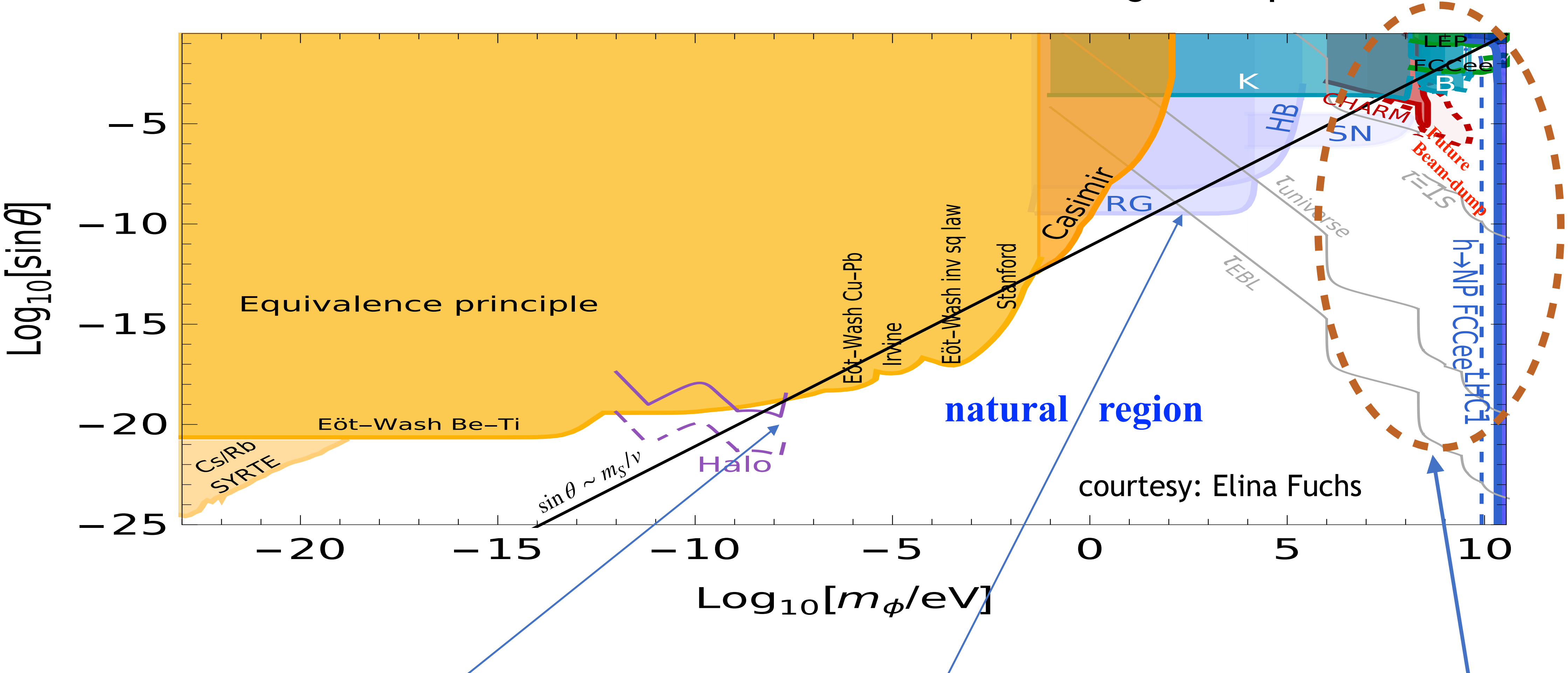
$$L_S \in m_S^2 SS + \mu S H^\dagger H + \lambda S^2 H^\dagger H \,, \quad \text{with } S = \text{light scalar \& } H = \text{SM Higgs} \,.$$

Naive naturalness implies: $\sin\theta \simeq \mu/\langle H \rangle \lesssim \frac{m_S}{\langle H \rangle}$ & $\lambda \lesssim \frac{m_S^2}{\langle H \rangle^2}$.

- As you see in following plot it is very hard to probe the natural region:

Accelerators: 1 among only 3 probes of naive physical models

The 3 fronts where natural models of mixing can be probed

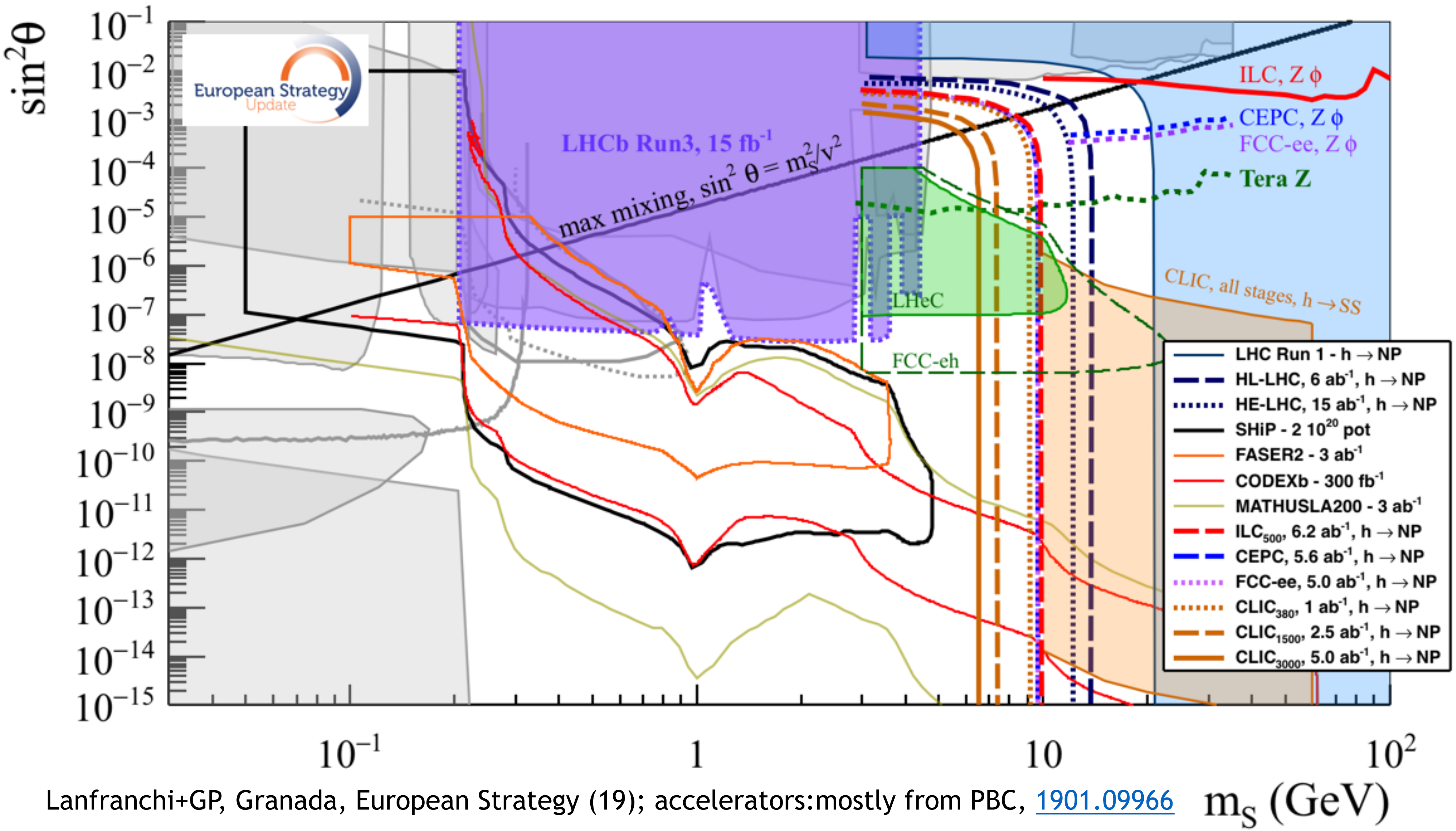


Precision frontier

Astro frontier

Accelerator frontier

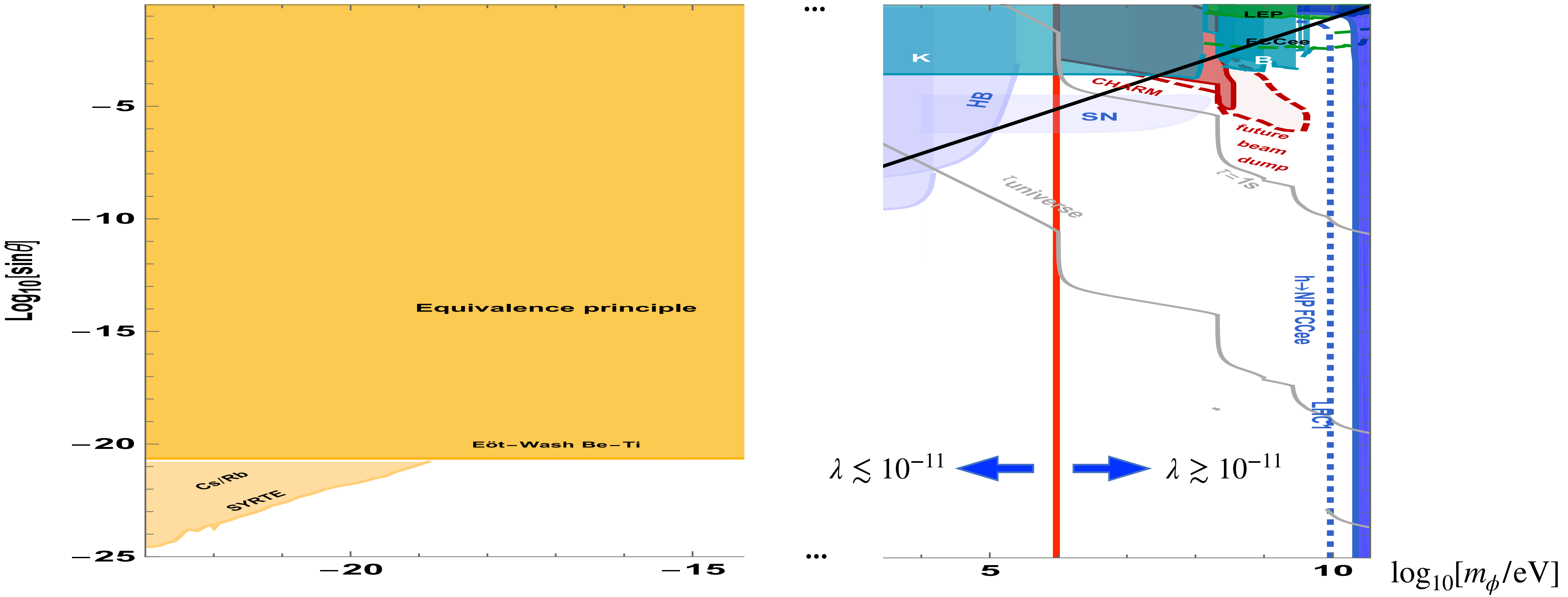
Overview: accelerator probes of relaxion



Lanfranchi+GP, Granada, European Strategy (19); accelerators:mostly from PBC, 1901.09966

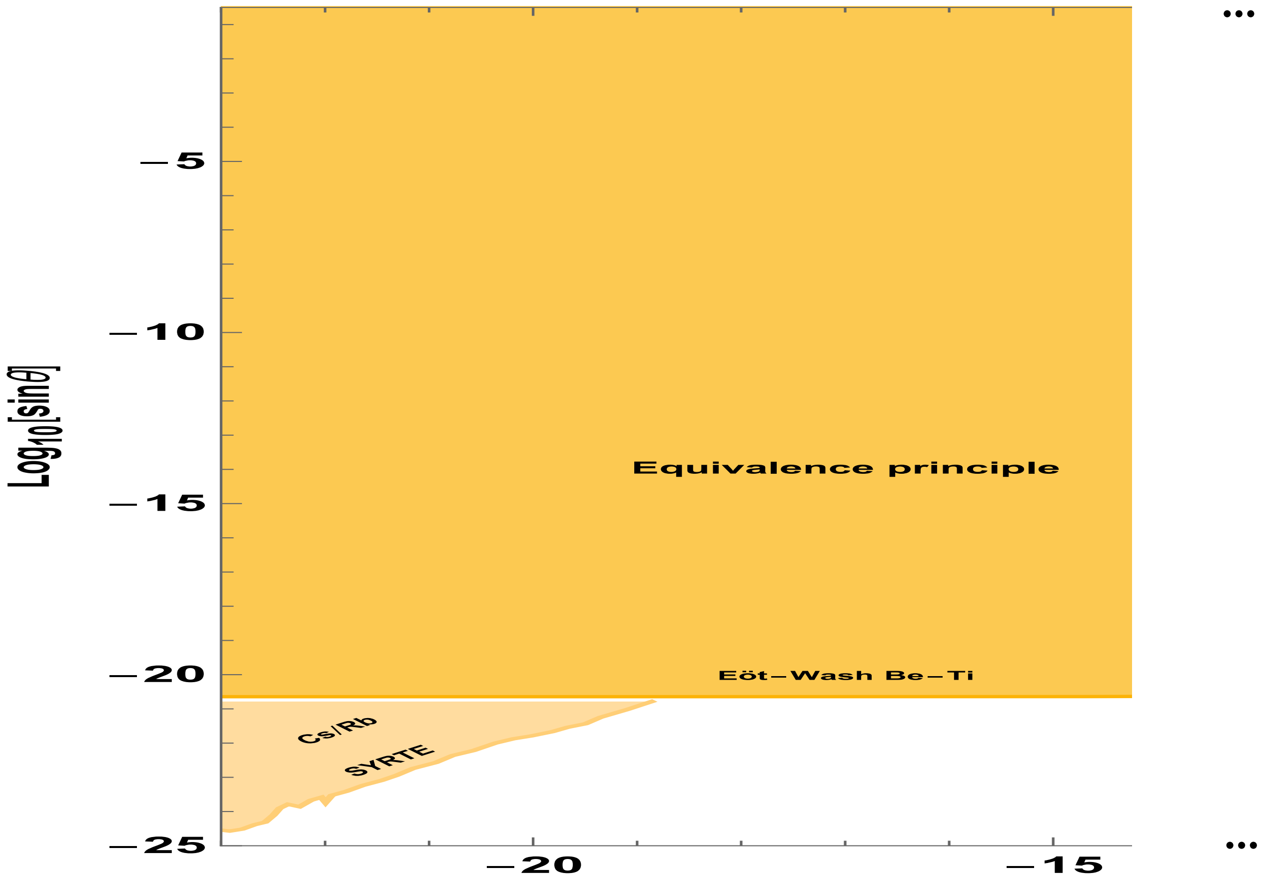
Naturalness in the Z_2 limit $(S \to -S\,,\ \sin\theta \to 0)$

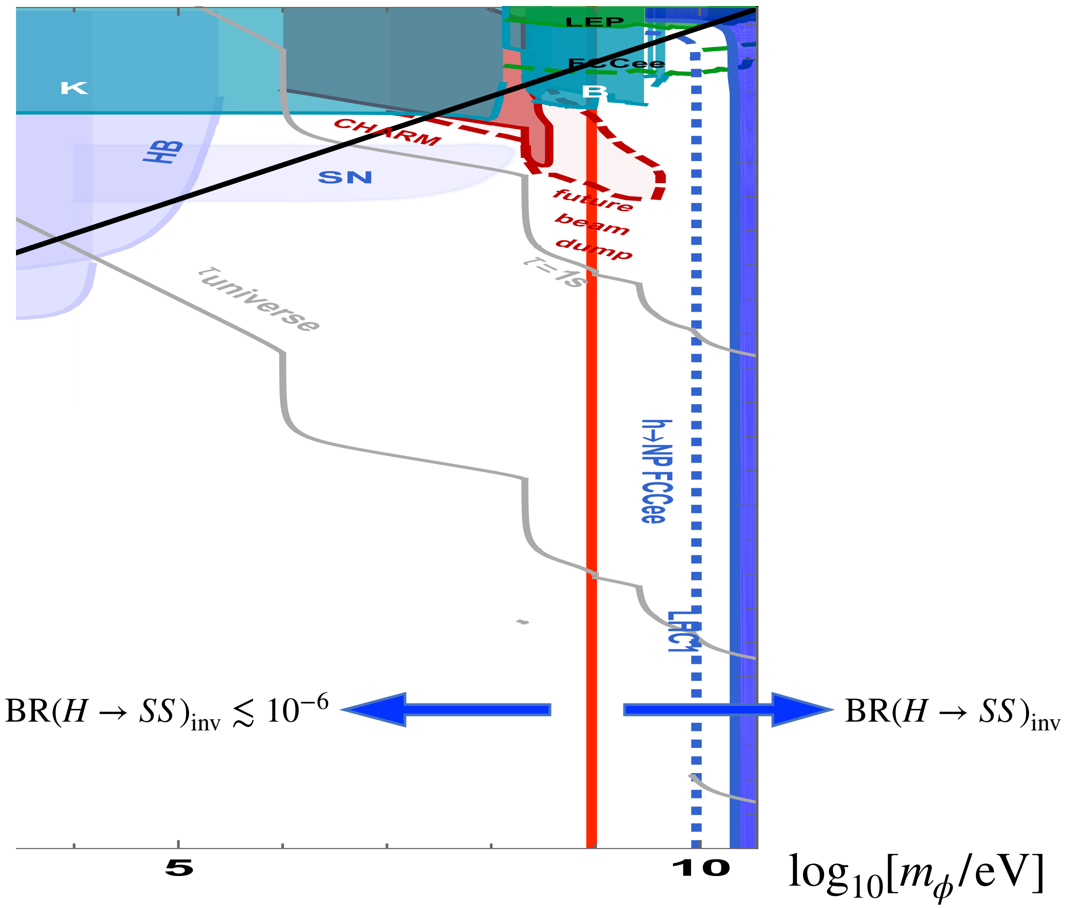
$$\text{Natural region for } H^\dagger H S^2 \text{ term}:\ \lambda \lesssim \frac{m_S^2}{\langle H\rangle^2} \sim 10^{-5} \times \left(\frac{m_s}{\text{GeV}}\right)^2$$



Naturalness, Z_2 limit: sizeable BR only for large masses

$$\text{Natural region for } \lambda \lesssim \frac{m_S^2}{\langle H\rangle^2} \sim 10^{-5} \times \left(\frac{m_s}{\text{GeV}}\right)^2 \Longrightarrow \text{BR}(H \to SS)_{\text{inv}} \lesssim 10^{-6} \times \left(\frac{m_s}{\text{GeV}}\right)^4$$





Z_2 <=> heavy masses: mostly relevant for colliders + parasites

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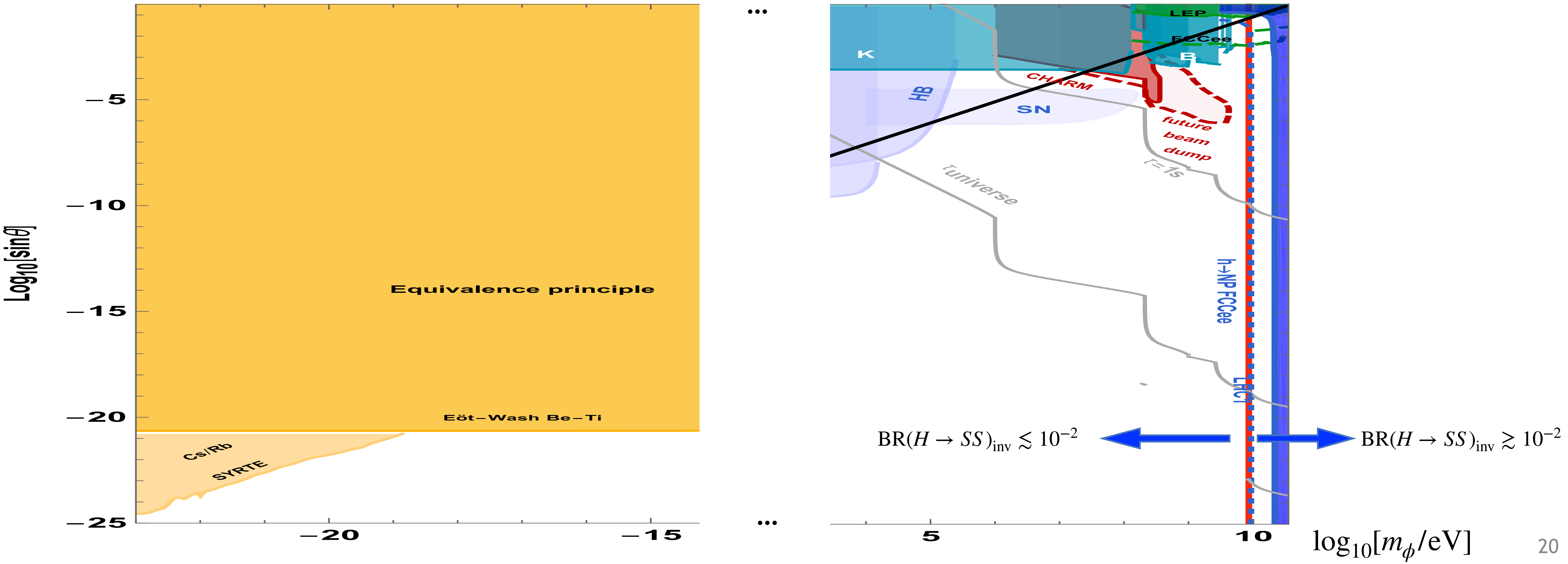

Future colliders probe this Z_2 in a strong manner via H->invisible

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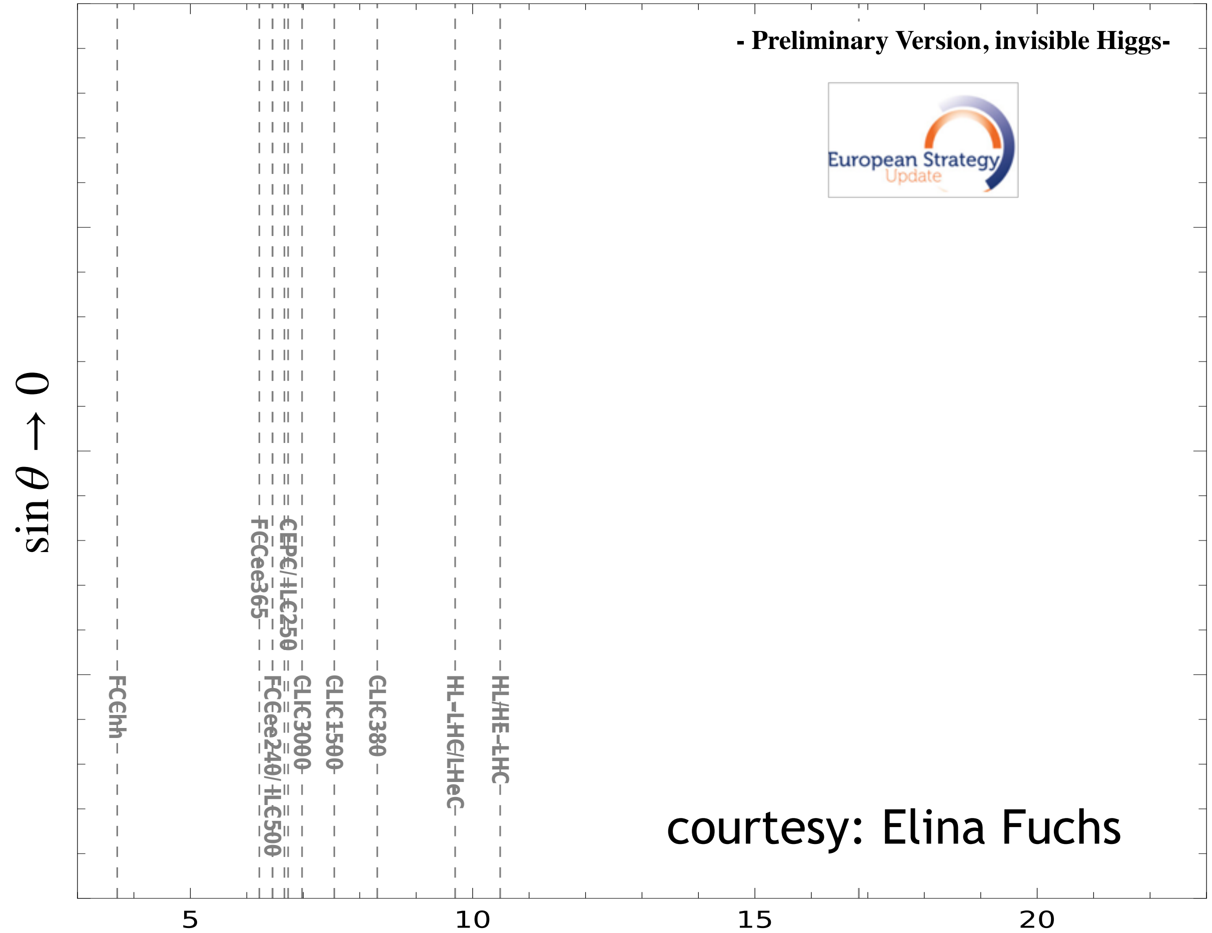
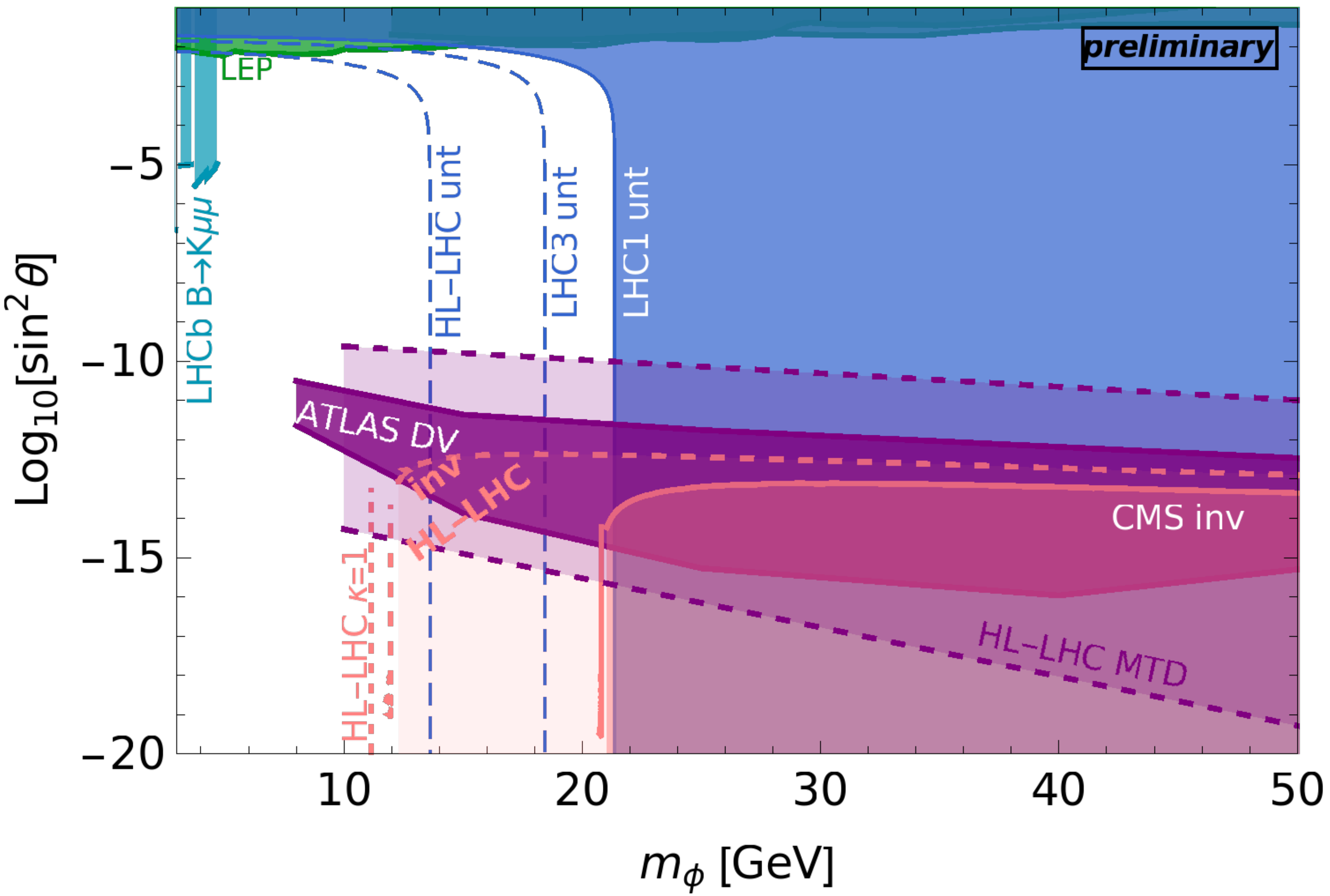
Numbers from:

Higgs Boson studies at future particle colliders

1905.03764v1 (prelim ver.)



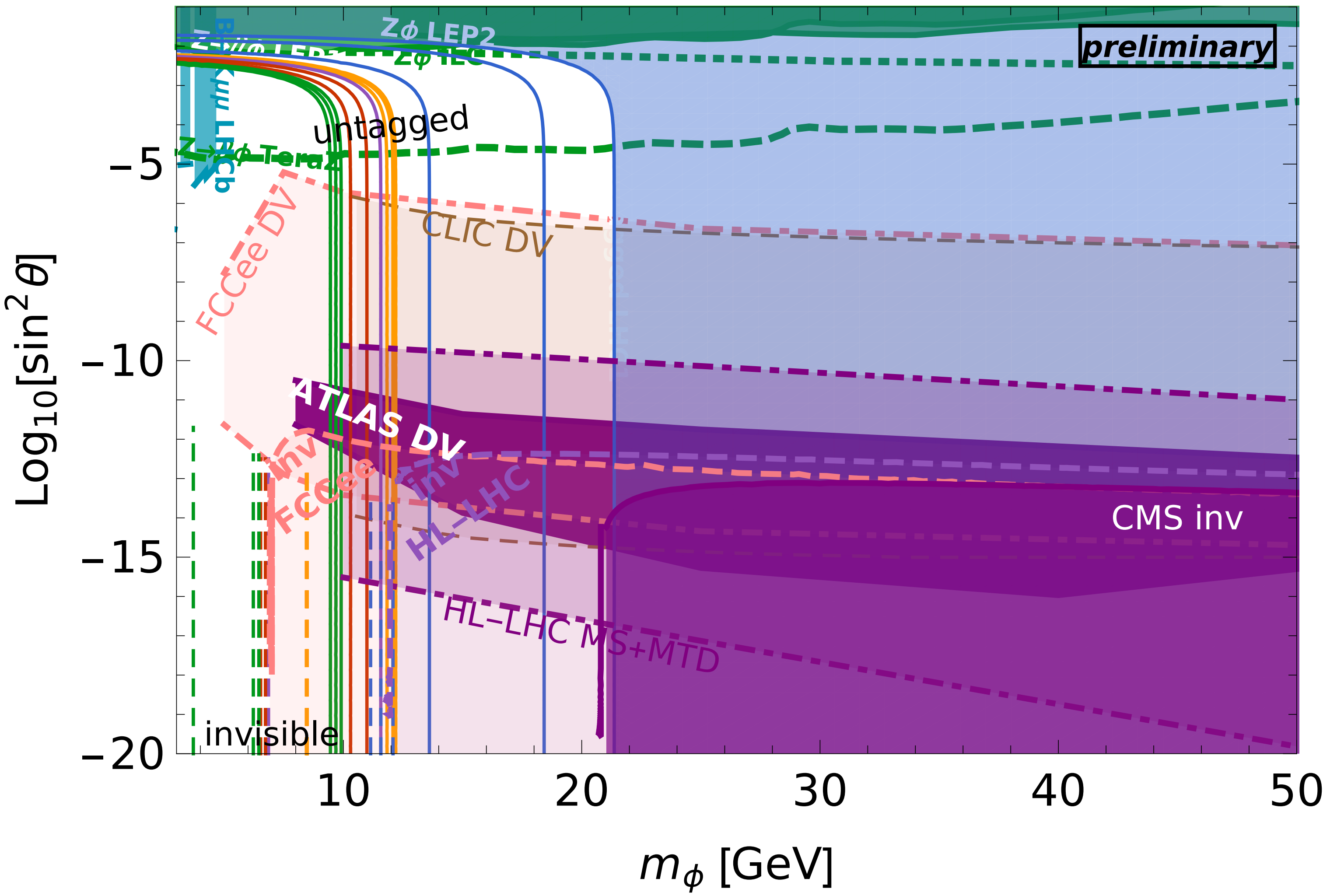
Zooming in LHC probes of "ultra-heavy" relaxion (naive)



Liu, Liu & Wang; Frugiuele, Fuchs, GP & Schlaffer; Alipour-fard, Craig, Gori, Koren, Redigolo (18); HWG: 1905.03764

Preliminary, in prep': Fuchs, Matsedonskyi, GP, Savoray, Schlaffer

Zooming in collider probes of “ultra-heavy”relaxion (naive)



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Reason 2: ALP/axion quality problem

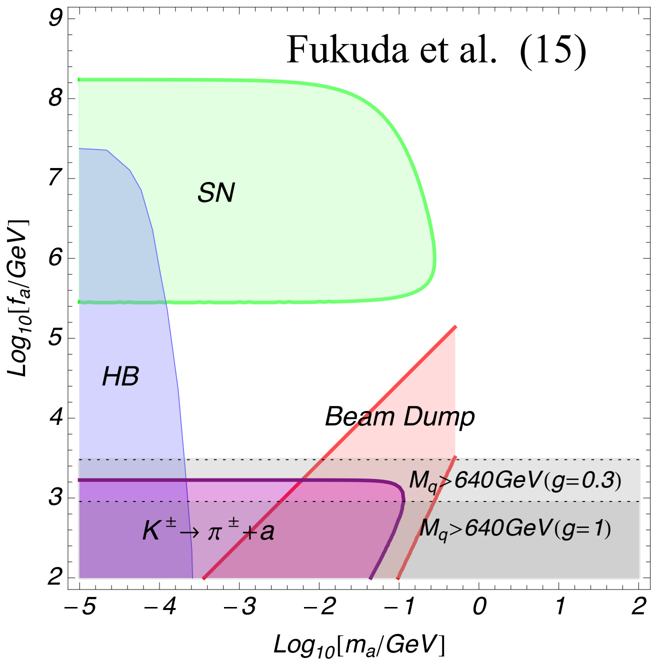
Barr & Seckel; Kamionkowski & March-Russell (92); see also talk by Dine …

- Planck suppressed operators typically destroy the axion potential.

$$\Delta V_{P\!\!\!/Q} = \lambda_\Delta \frac{\Phi^\Delta}{\Lambda_{UV}^{\Delta-4}} + \text{h.c.} \quad \Rightarrow \quad V_a \simeq -\Lambda_{QCD}^4 \cos\frac{Na}{f} + \frac{1}{2^{\frac{\Delta}{2}-1}} \frac{|\lambda_\Delta| f^\Delta}{\Lambda_{UV}^{\Delta-4}} \cos\left(\alpha_\Delta + \Delta \frac{a}{f}\right)$$

where with Δ<12 operators, strong CP problem is not solve!

- Can be addressed if the axion has additional contribution to its mass (lowering *f*):



Rybakov (97); Berezhiani, Gianfagna & Giannotti (01); Hook (14);

Fukuda, Harigaya, Ibe & Yanagida (15); Alves & Weiner (17) …

We note also that for the relaxion case the quality problem is much worse, due to special QFT structure denoted as clockworking.

Clockwork: Choi, Kim & Yun (14) Rattazzi & Kaplan; Choi & Im (15)

Clock-quality: Davidi, Gupta, GP, Redigolo & Shalit (18)

2 differences from generic Higgs portal

(i) Lower bound on mixing angle (implications of compact parameter manyfold)

(ii) Parity-odd-ALP coupling (not discussed today …)

Naive lower bound on relaxion-Higgs mixing

- Naively you can think about the relaxion as dominated by its "backreacion" potential, similar to the axion:

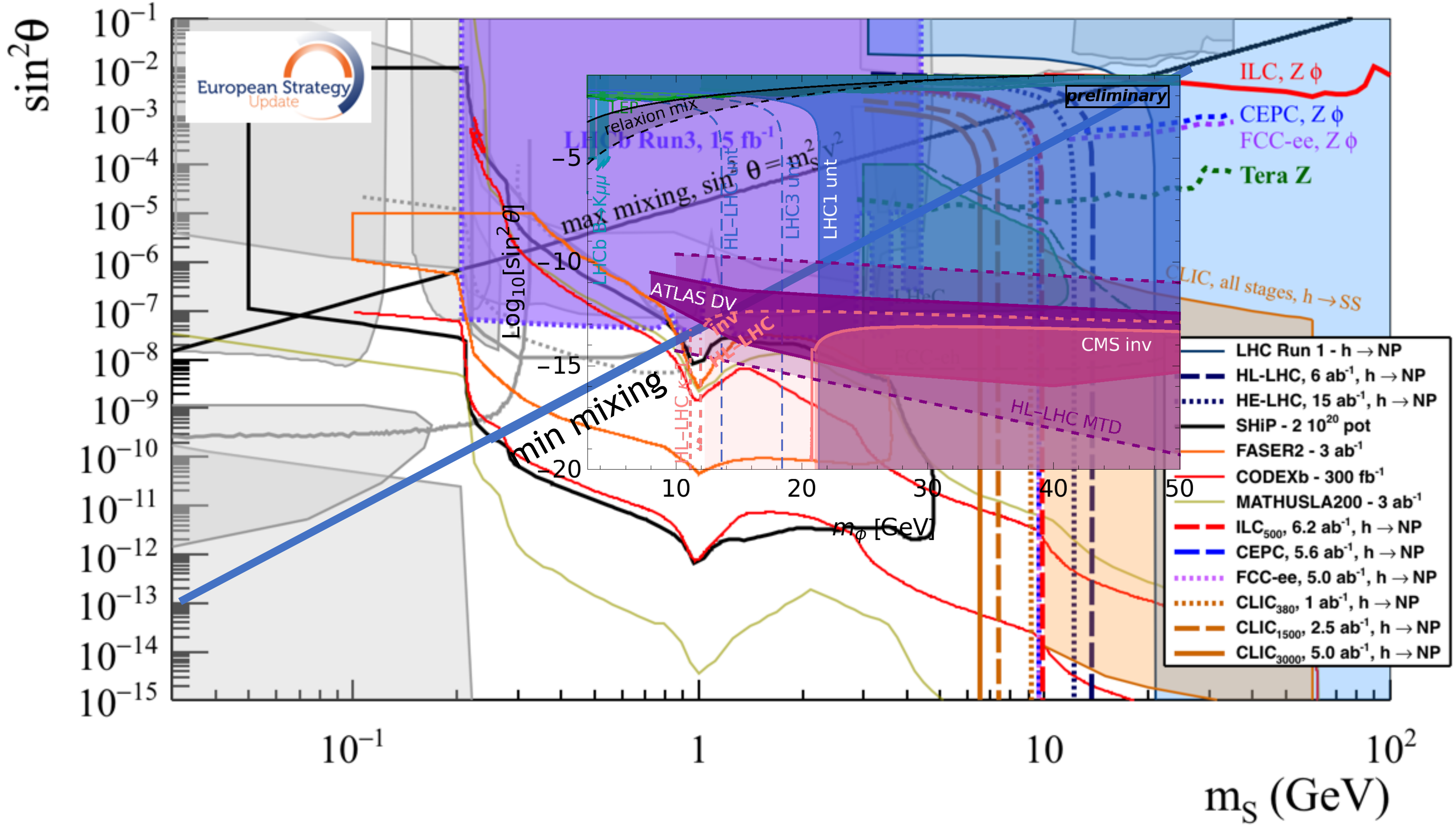
$$V(H,\phi)_{J=2} \sim \Lambda_{\rm BR}^4/v^2 \times H^\dagger H \cos(\phi/f)\,, \quad (H = \text{ Higgs}, v = \langle H\rangle,\ \phi = \text{ relaxion})$$

- Which implies: $m \sim \Lambda_{\rm BR}^2/f$ and $\sin\theta \sim m/v \times \Lambda_{\rm BR}^2/v^2$.

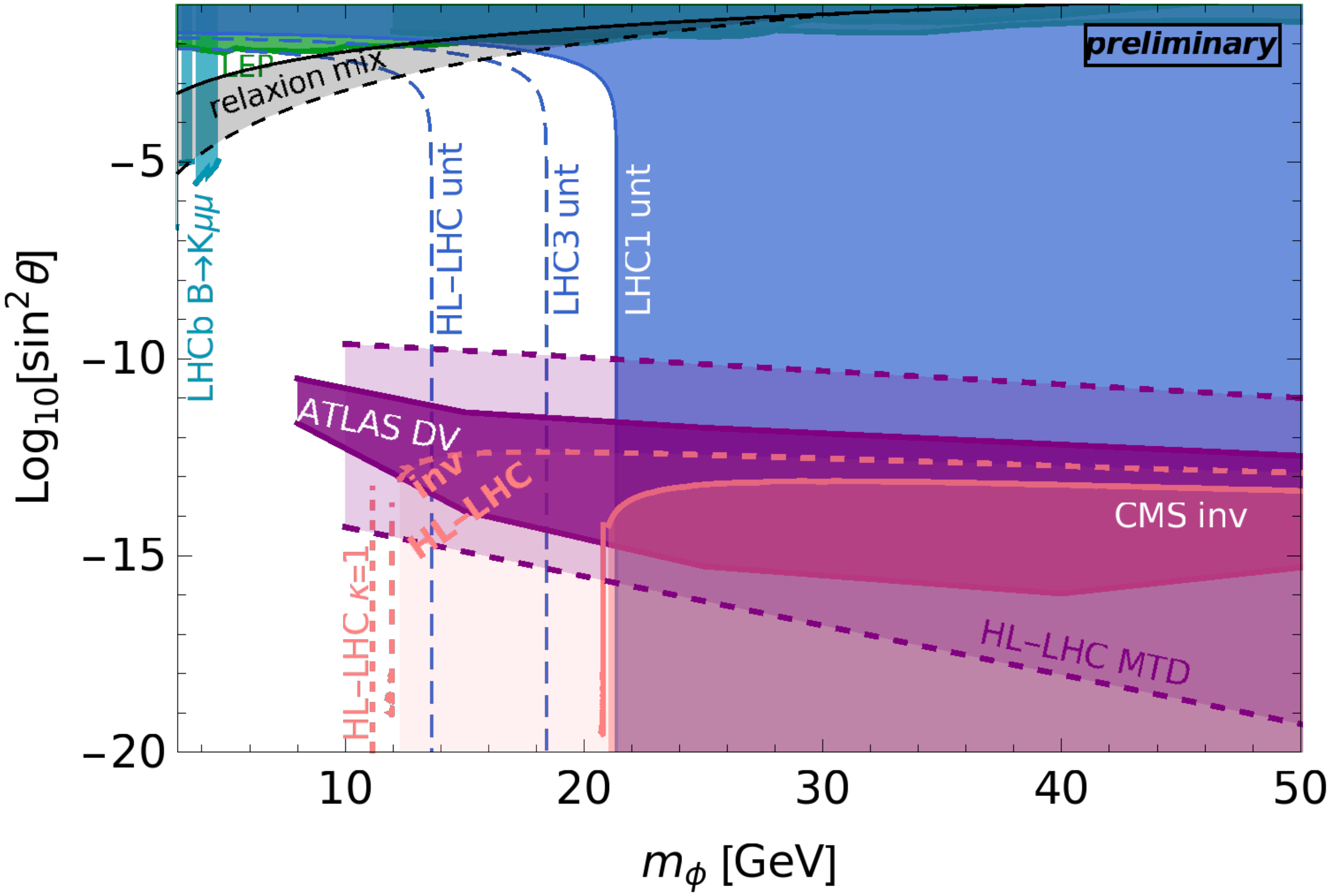
- As $f \gtrsim \Lambda \gtrsim$ TeV $\Rightarrow \sin\theta \gtrsim m^2/v^2 \times f/v \gtrsim 10 \times m^2/v^2$.

Discussion \w Grojean …

Excluding the relaxion with accelerators (naive)

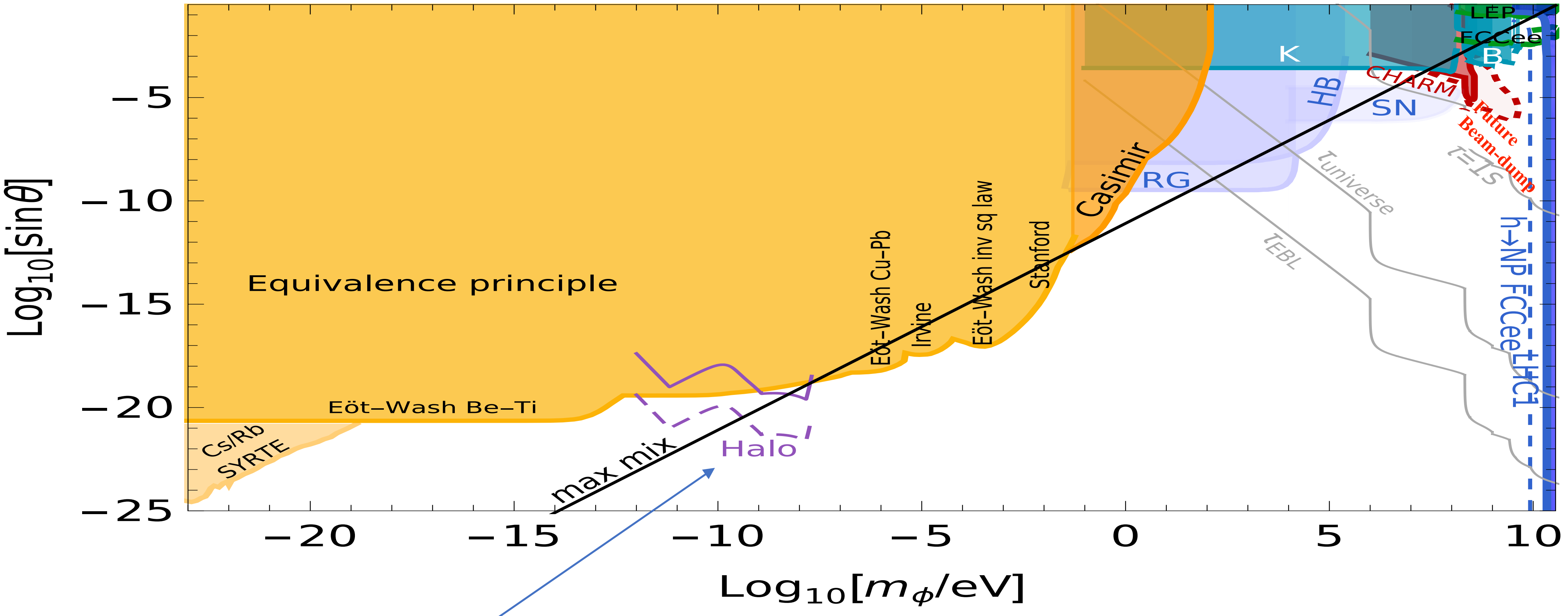


Excluding the heavy relaxion with collider (exact)



Preliminary, in prep': Fuchs, Matsedonskyi, GP, Savoray, Schlaffer

What if the relaxion is super light?
Probing the relaxion at the precision front.



Precision frontier

Ultra light relaxion

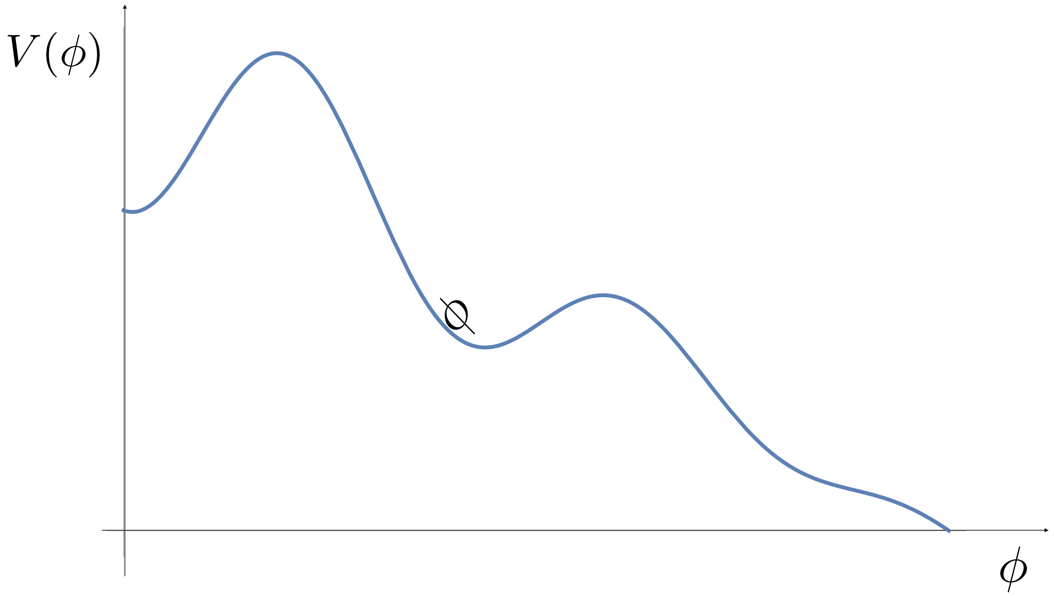
- When the relaxion is very light, via its Higgs-mixing it induces deviation from equivalence principle, which is constrained.
- In addition, even minimal models form an axion-like dark matter oscillating field (\w dynamical misalignment angle) => Higgs VEV oscillates .

Banerjee, Kim & GP (18)

Concrete ex.: relaxion dark matter (DM)

- Basic idea is similar to axion DM (but avoiding missalignment problem):

  Now the relaxion not at the min' and start to oscillates = DM.



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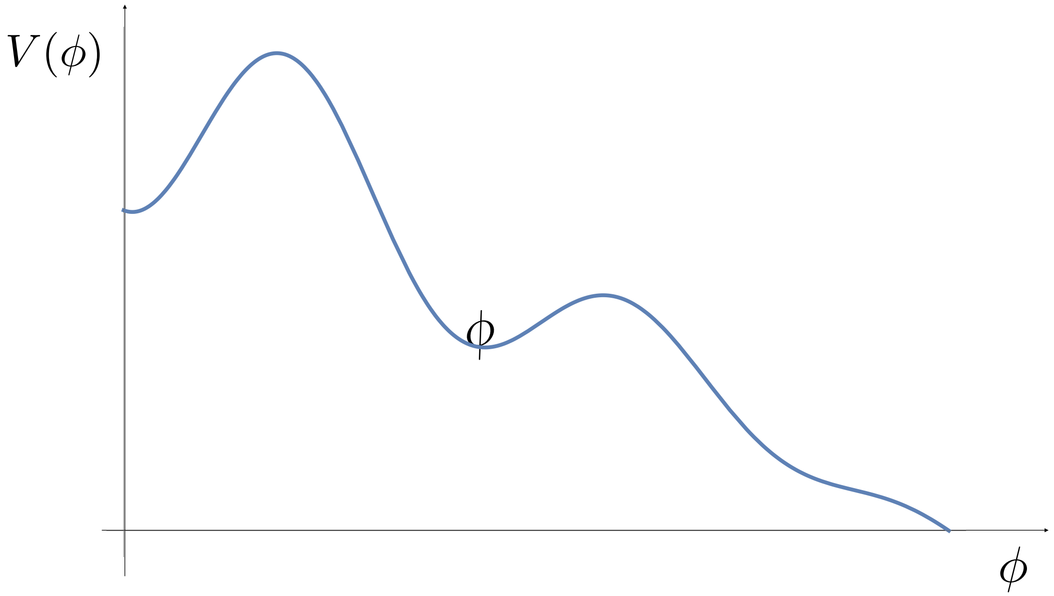

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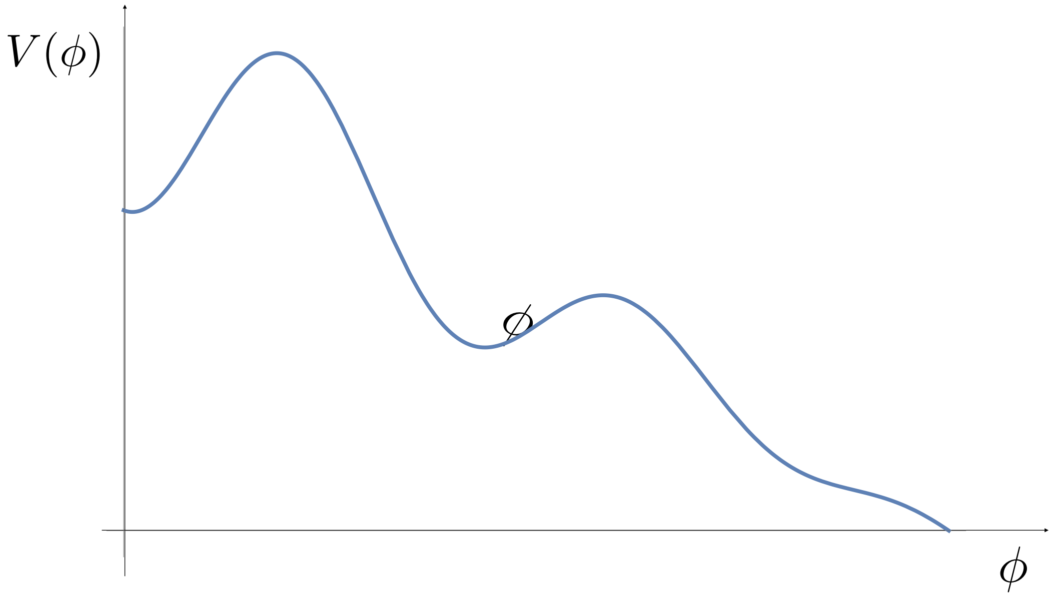

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Banerjee, Kim & GP (18)

- It implies that all coupling constants $(m_e, \alpha, \alpha_s \dots)$ oscillate:

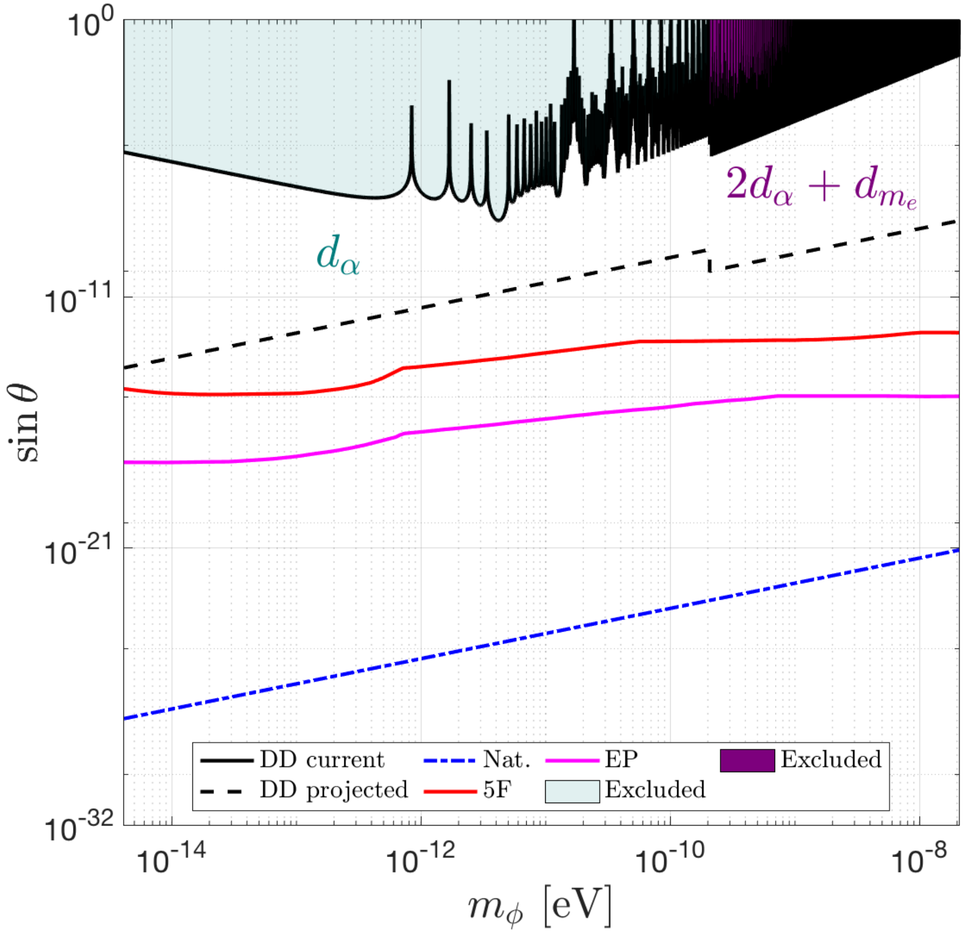
$$\frac{\delta m_e}{m_e} \lesssim y_e \sin_{\phi h} \frac{\sqrt{\rho_{\rm DM}}}{m_e\, m_\phi} \sin\left(m_\phi t\right)$$

Arvanitaki, Huang & Van Tilburg (15)

See also: Graham, Kaplan, Mardon, Rajendran & Terrano; Arvanitaki, Dimopoulos & Van Tilburg; Van Tilburg, Leefer, Bougas & Budker (15)

Beyond 1Hz DM mass \w dynamical decoupling

Aharony, Akerman, Ozeri, GP & Shaniv & Savoray (19) [via ion-cavity comparison]

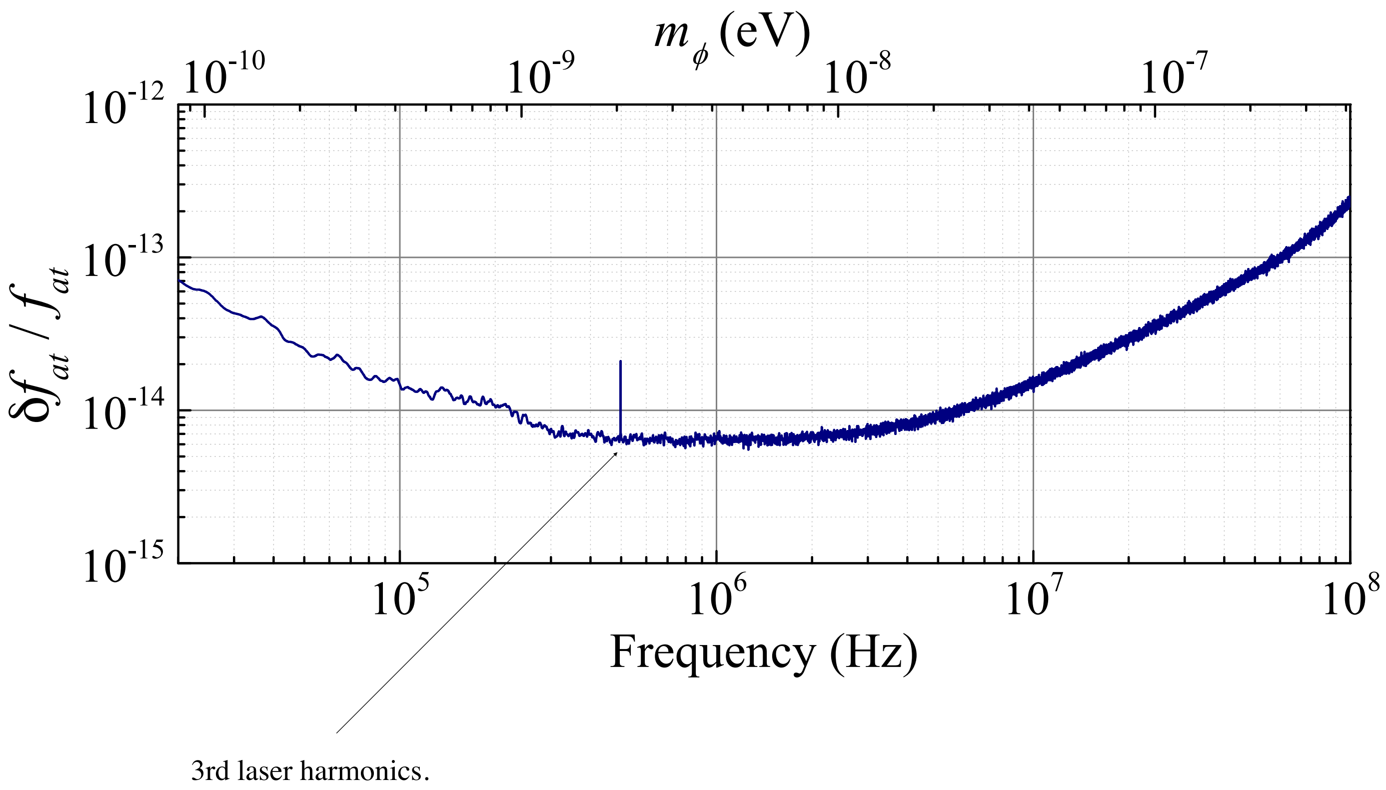


The bounds on the mixing angle of a relaxion DM: Black – current and projected bounds from DD experiments at 95% CL. Red – Bounds from fifth force experiments. Magenta – EP-tests bounds. Dash-dotted – Bounds from Naturalness.

Beyond 1Hz DM mass \w polarization spectroscopy

Antypas, Tretiak, Garcon, Ozeri, GP & Budker, (19)

Cs $6S_{1/2} \rightarrow 6P_{3/2}$ transition frequency (10 GHz)



Probing/measuring the strange Yukawa with future lepton colliders

Duarte-Campderros, GP, Schlaffer & Soffer (19)

Strange Yukawa at lepton colliders, strange tagger

- Already applied to Z:

Measurement of the strange quark forward backward asymmetry around the Z0 peak

DELPHI Collaboration, Eur.Phys.J. C14 (2000)

Light quark fragmentation in polarized Z0 decays

SLD Collaboration, Nucl.Phys.Proc.Suppl. 96 (2001)

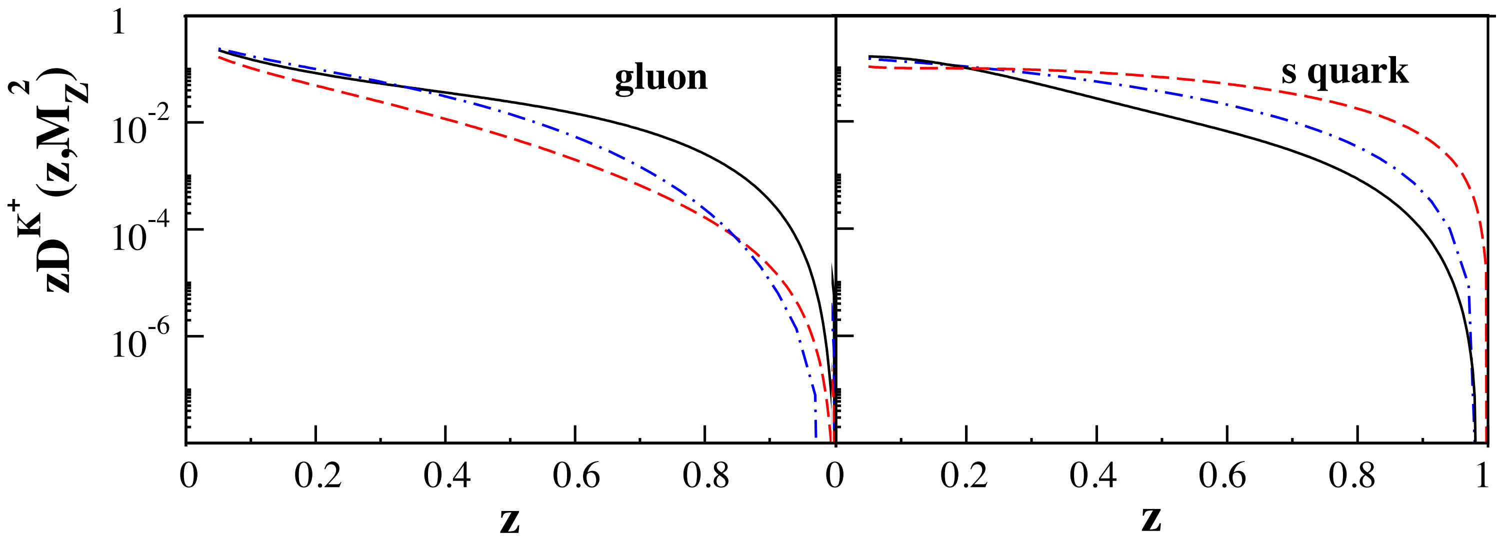
- $\mathrm{BR}(h \to s\bar{s}) \simeq 0.02\%$ more than 2000 events with 10^7 Higgses.

- $$\frac{S_{s\bar{s}}}{\sqrt{B_{b\bar{b}}}, \sqrt{B_{gg}}} \sim 1.0, 2.8\,. \quad (10^7 \text{ Higgses})$$

jordi Duarte-Campderros, GP, Schlaffer & A. Soffer (19)

Strategy for digging out higgs to strange decay

♦ Looking for 2 leading Kaons that are (i) hard; (ii) prompt.



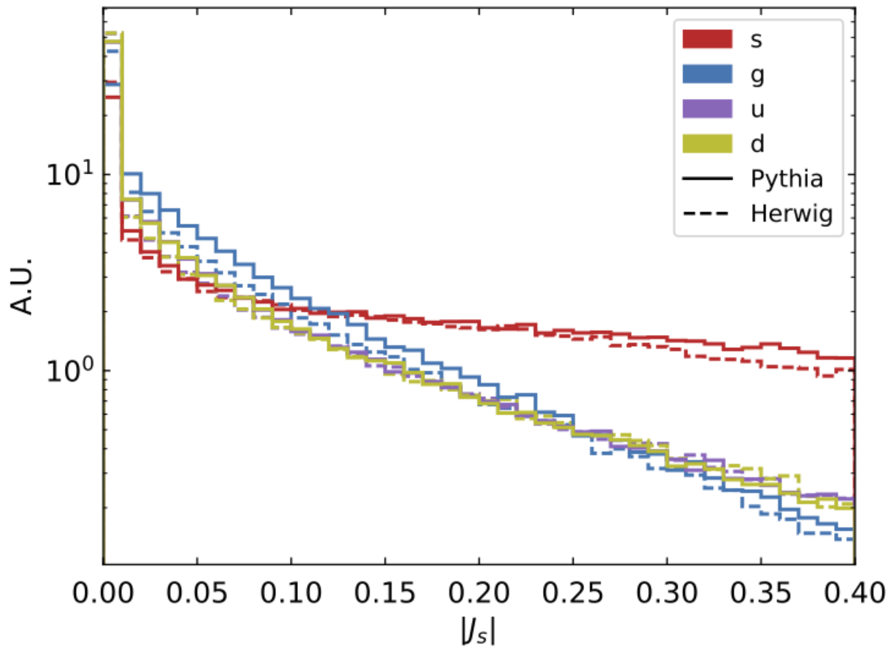
For ex: Soleymaninia et al. (13)

Defining a new IR-safe collinear-unsafe jet-flavour variable

jordi Duarte-Campderros, GP, Schlaffer & A. Soffer (19)

$$J_F = \frac{\sum_H \mathbf{p}_H \cdot \hat{\mathbf{s}}\, R_H}{\sum_H \mathbf{p}_H \cdot \hat{\mathbf{s}}}.$$

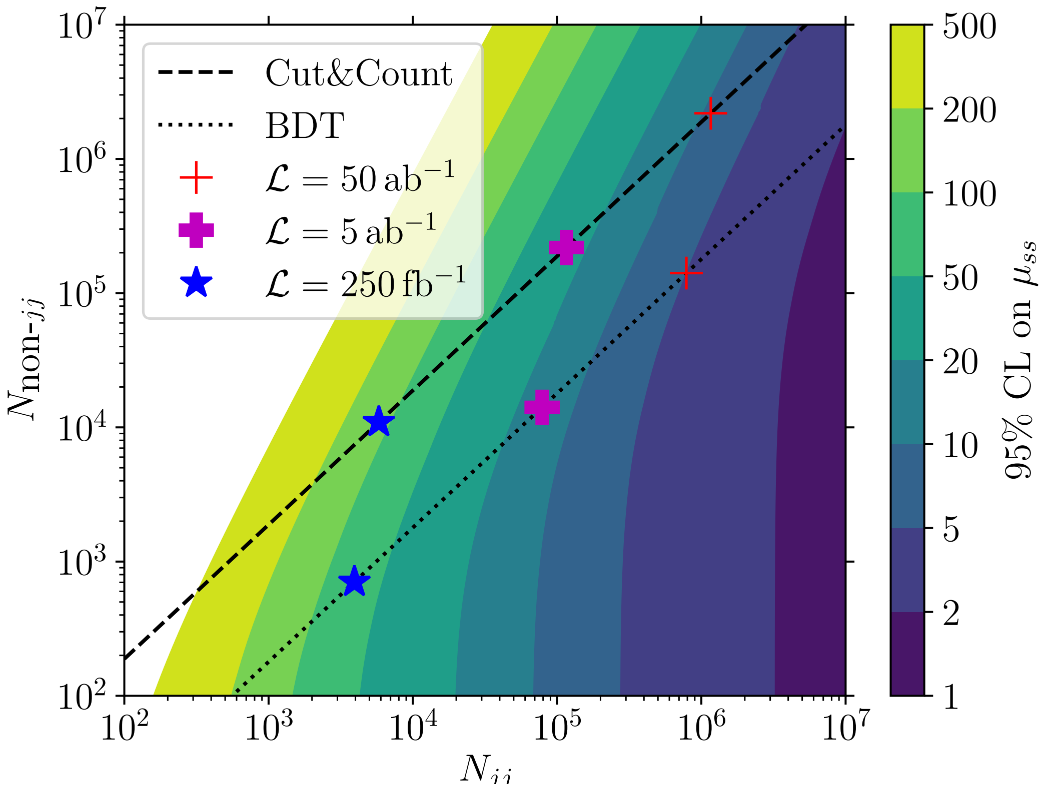
(Sum is over hadrons H within the jet, $\vec{p}_H$ is the hadron's momentum, R_H is its flavor)



Comparison of simulated $|J_s|$ distributions for $h \to s\bar{s}$, $d\bar{d}$, $u\bar{u}$, and gg decays. The values are computed in the Higgs rest-frame with $R_{K^\pm} = \mp 1$, $R_{K_s} = \pm 1$ such that $|J_s|$ is minimized and only if the K_s decays into charged pions, and $R_H = 0$ for all other hadrons.

Adding displacement-veto & particle ID

jordi Duarte-Campderros, GP, Schlaffer & A. Soffer (19)



Higgs candidate	W	bb	uu	dd	cc	ss
Fraction [%]	65.3	9.8	6.1	6.0	6.4	6.0

Relative composition of the hadronic part of the non-$h \to jj$ event that is assumed to fake the $h \to jj$ candidate. W refers to the case where a W boson is falsely identified as Higgs, in both $e^+e^- \to W^+W^-$ and $h \to$ non-jj events. The other compositions stem mainly from $Z/\gamma^* \to q\bar{q}$.

Best sensitivities: $d_0 \sim 18\mu m$, $p_{\parallel} \sim 10GeV$, and $\varepsilon_{K^\pm} \approx 96\%$.

Conclusions

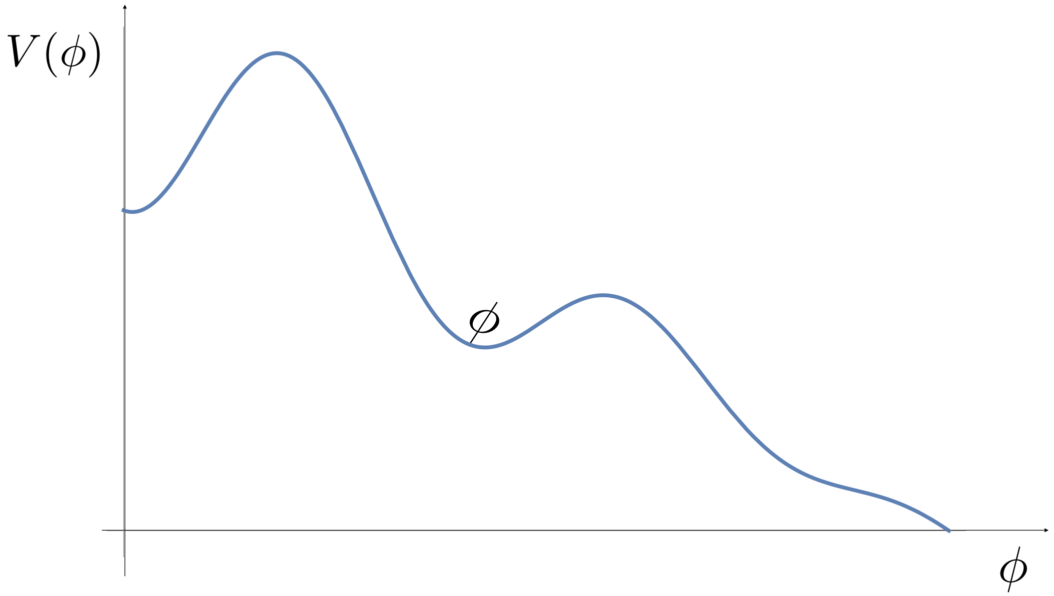
- Higgs physics has been always our beacon for new physics.
- Null-results + new theories (ex.: relaxion) => log crisis/opportunity, calls for experimental diversity.
- Accelerators provided a unique opportunity to search for relaxion.
- Ultra-light relaxion DM => Higgs VEV oscillating => exciting signals …
- Higgs to strange within the SM => potentially be probed at lepton colliders.

Backups

Concrete ex.: relaxion dark matter (DM)

Banerjee, Kim & GP (18)

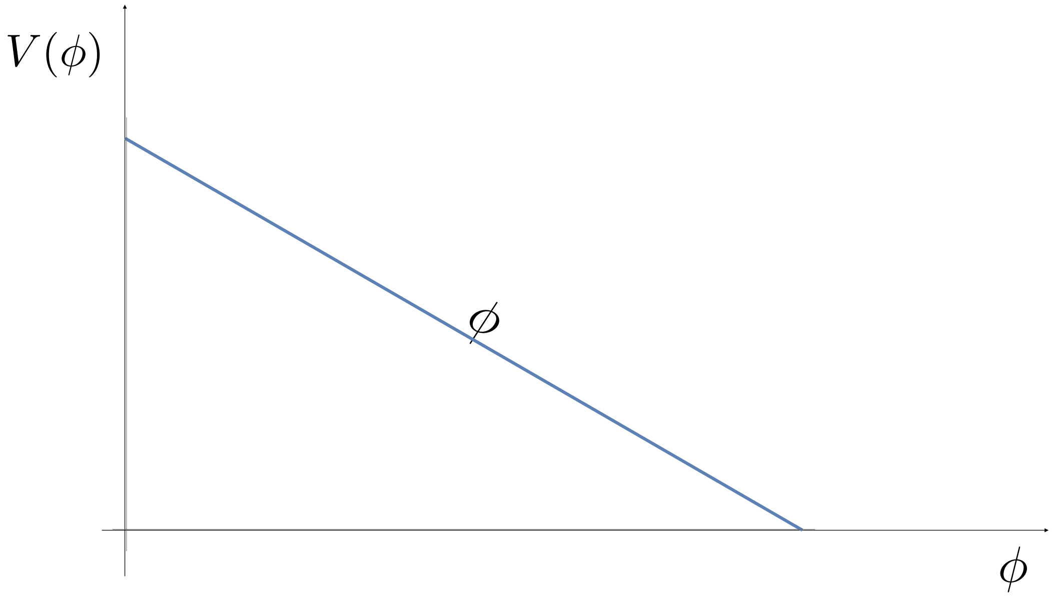
- Basic idea is similar to axion DM (but avoiding missalignment problem):



Concrete ex.: relaxion dark matter (DM)

- Basic idea is similar to axion DM (but avoiding missalignment problem):

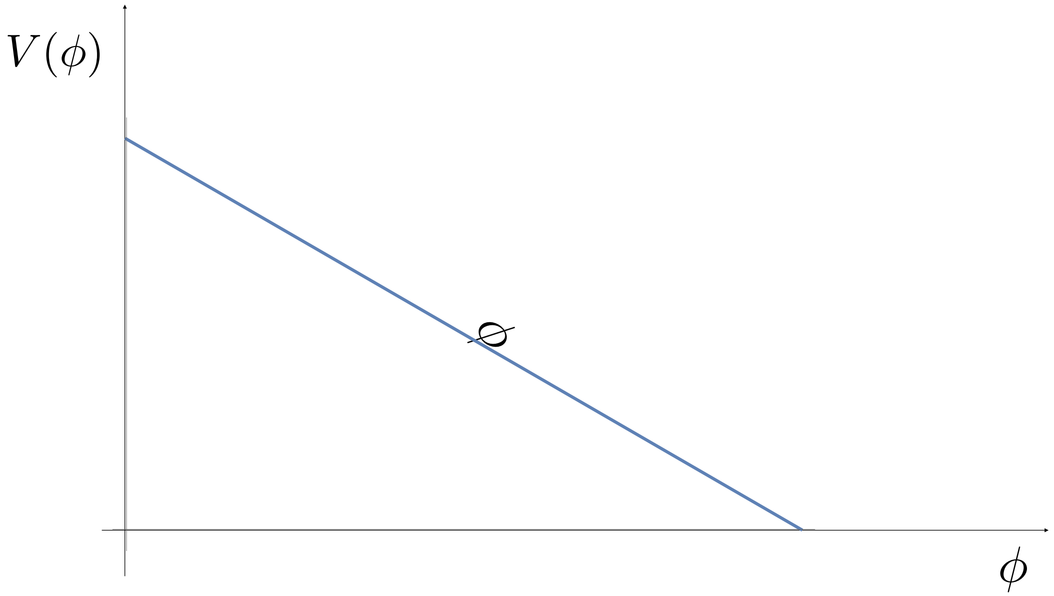
  After reheating the wiggles disappear (sym' restoration):



Concrete ex.: relaxion dark matter (DM)

- Basic idea is similar to axion DM (but avoiding missalignment problem):

  After reheating the wiggles disappear: and the relaxion roles a bit.



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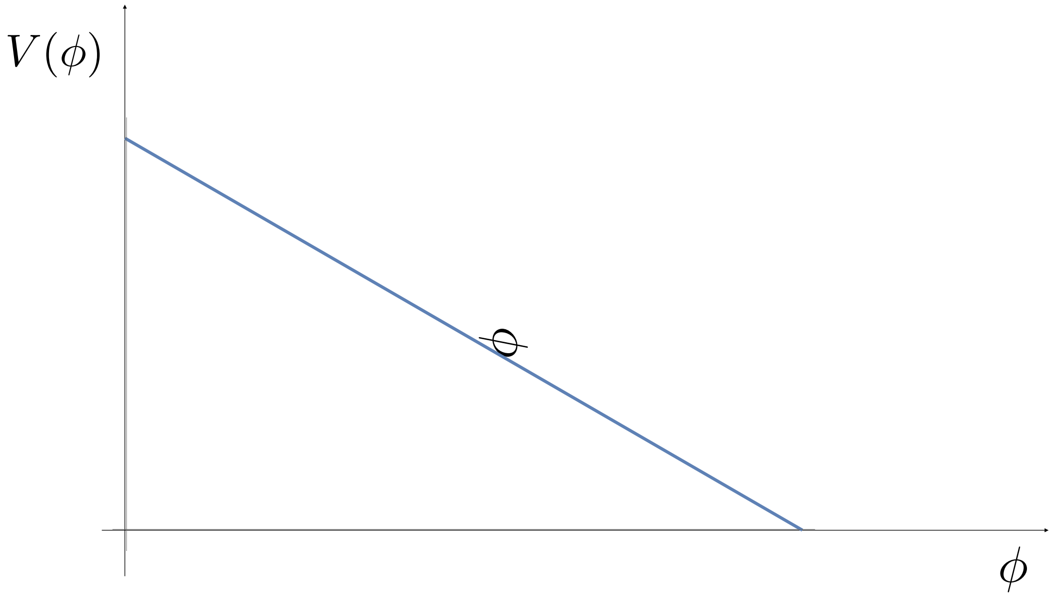

Concrete ex.: relaxion dark matter (DM)

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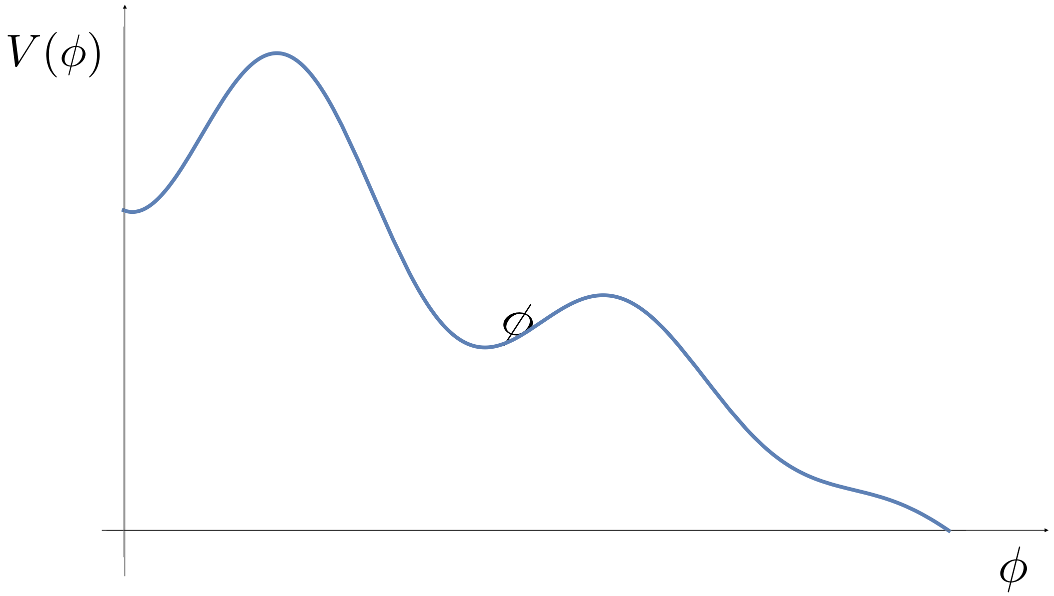
  Now the relaxion not at the min' and start to oscillates = DM.



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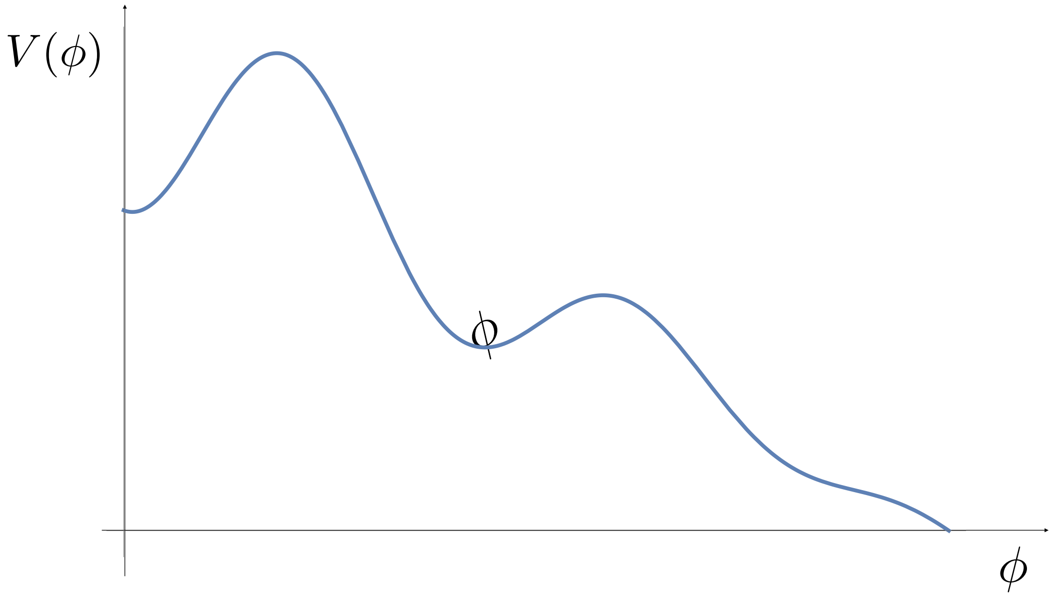

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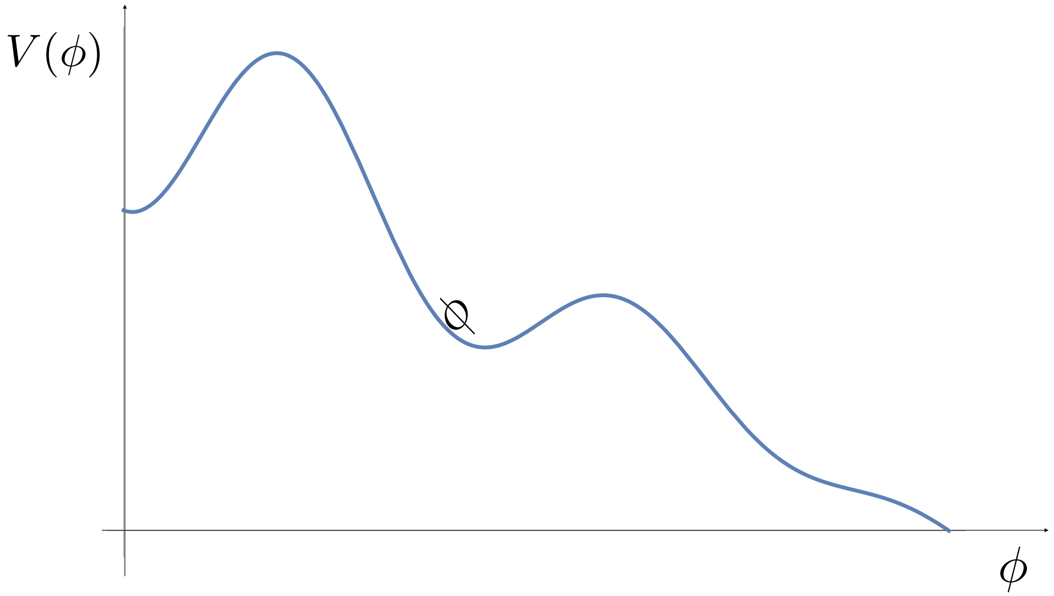

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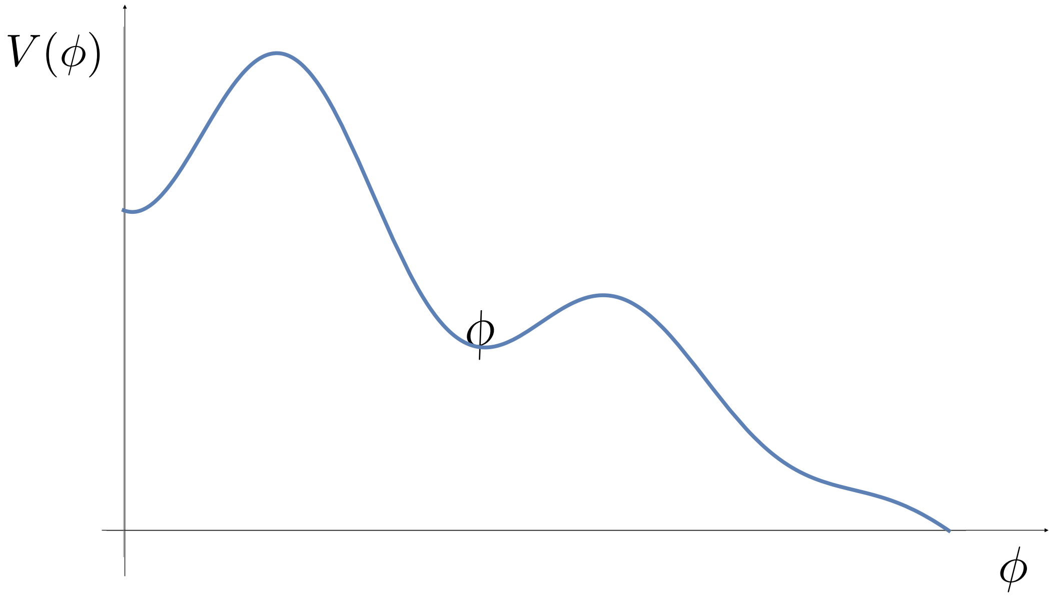

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