Feebly interacting particles: theory landscape

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European Strategy Update

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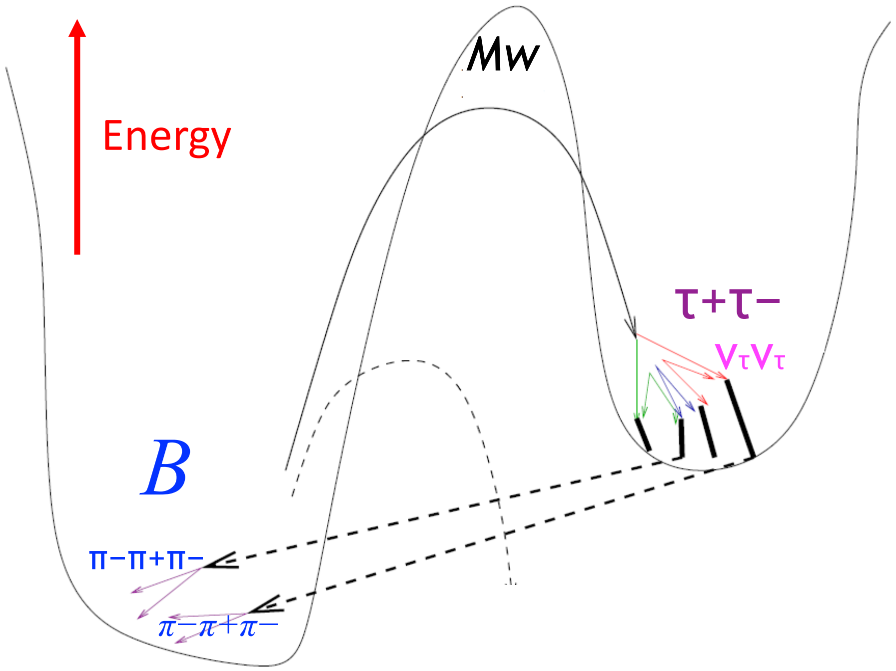
Outline

- Generic motivation, why new feebly interacting particles (FIPs)?
- FIPs & the log crisis/opportunity, where & how to look for them?
- Why accelerators & colliders are important for FIP-searches?
- Practical compromise - FIPs benchmarks (results shown in following talk).
- Conclusions

Generic motivation, the feeble-front

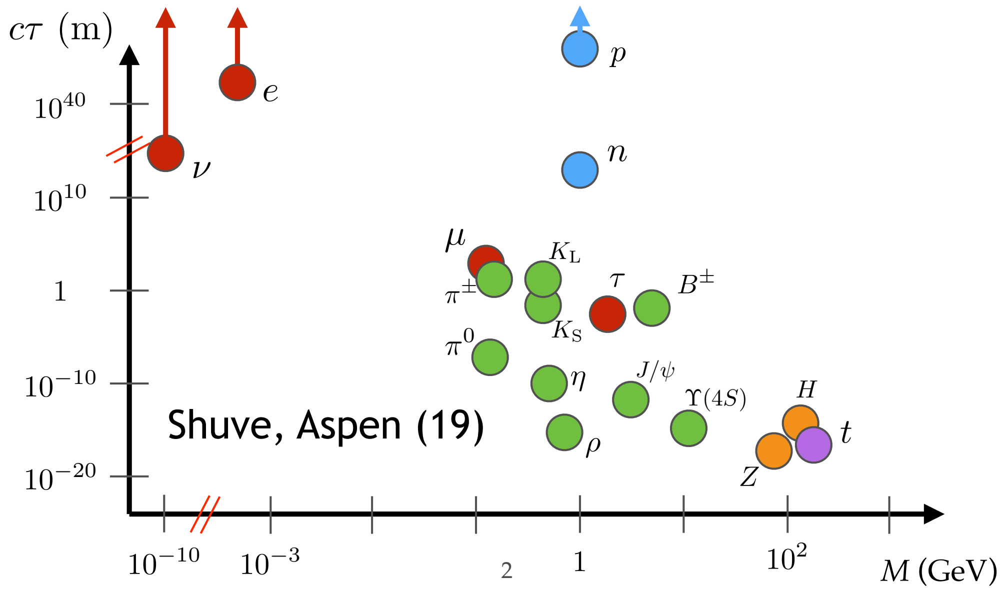
- The standard model (SM) consists of weakly interacting & long-lived particles.
- Many SM extensions => ultra weakly (feebly) interacting particles (FIPs).

SM "hidden valley": LHCb (17) [$B(B_s^0 \to \tau^+\tau^-) < 6.8\times10^{-3}$]



SM spectrum

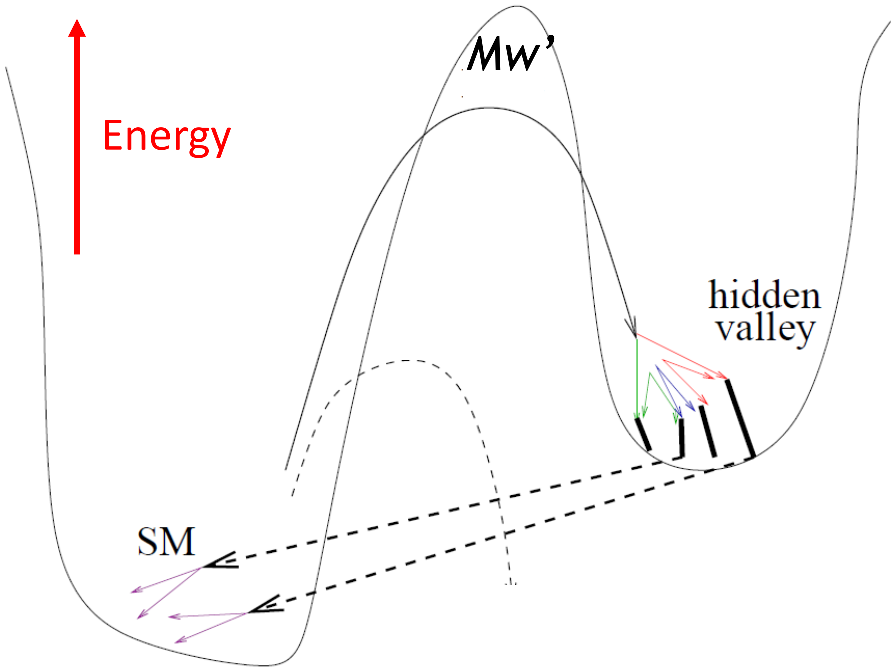
- LLP = "long lived particle"
- Travels a macroscopic distance before decaying ($\gtrsim$ 0.01 mm)



Generic motivation, the feeble-front

- The standard model (SM) consists of weakly interacting & long-lived particles.
- Many SM extensions => ultra weakly (feebly) interacting particles (FIPs).

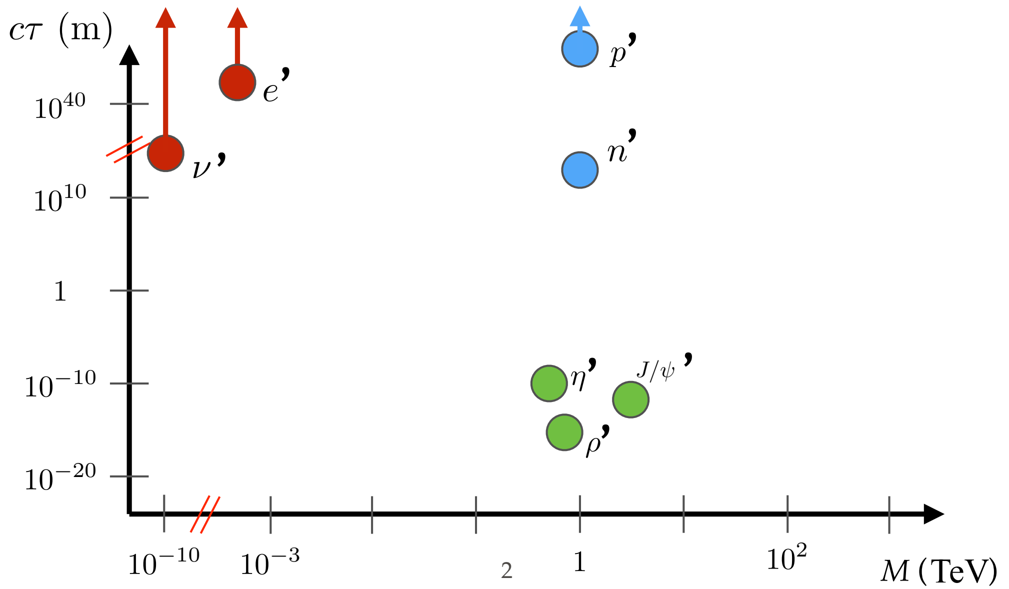
For reviews see e.g.: 1311.0029; 1205.2671; 1608.08632



Strassler, Zurek (06)

New strong sector spectrum

- LLP = "long lived particle"
- Travels a macroscopic distance before decaying ($\gtrsim 0.01$ mm)



Generic motivation, the feeble-front

- Heavy FIPs are hard to observe, possibly in energy frontier.
- Light FIPs can be copiously produced & probed across frontiers, relevant to this study: energy, luminosity, precision => *our mandate - focus on this case*.
- Are such light particles motivated by basic principles? Absolutely:

  pseudo-scalars (Goldstones, axion-like=ALP),

  scalars (SUSY, dilatons, Goldstones+CP violation),

  fermions (axial sym’),

  vectors (gauge sym’) …

Axion's log crisis

- It is hard to predict FIPs properties => *log crisis*;

log crisis: requires cross-frontier search over decades of energy <=> opportunity.

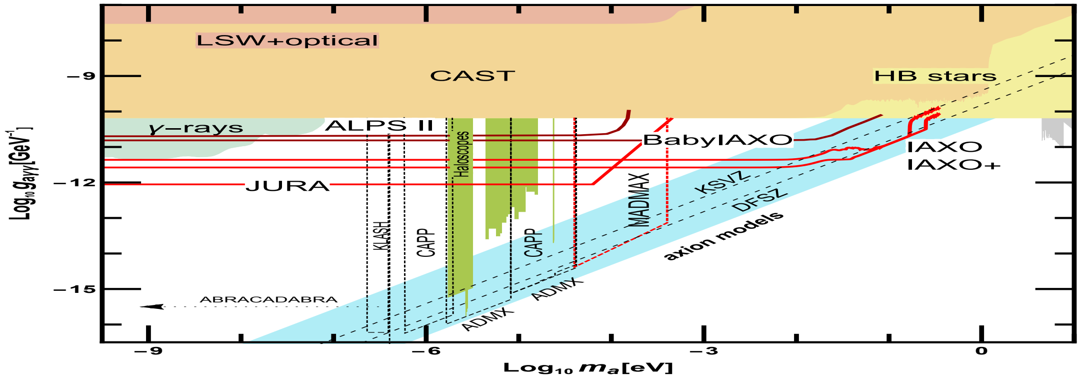
- Well known for axion like particle (ALP) or dark photon models.

(see talks by: Agrawal, Dine, Lindner, Irastorza …)

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

Naturalness @ 21st century => FIPS & new crisis

- Not common for naturalness-based models; the anchor for energy frontier which conventionally satisfies the equation:

Naturalness <=> TeV new physics (NP)

Talks by: Rattazzi, Weiler, Wulzer …

- New ideas cast doubt on this "equation".

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

- New scalar-FIPs common to all of above: consider for ex. the relaxion.

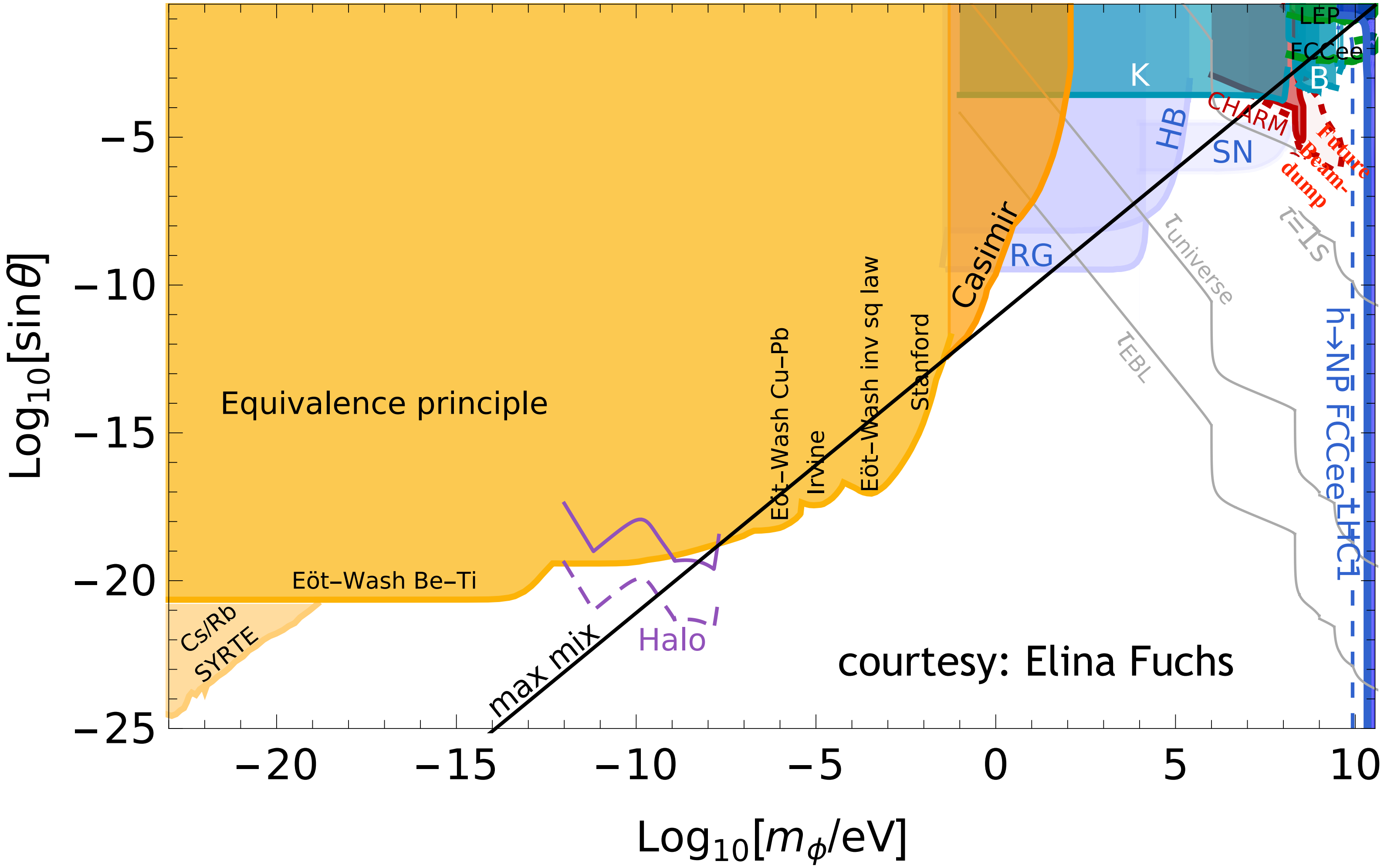
Graham, Kaplan & Rajendran (15)

- Relaxion models can be described via a scalar that mixes with the Higgs:

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

The relaxion (Higgs portal) Log crisis

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



What makes accelerator FIP-searches special?

(*i*) Case for (thermal) dark matter (DM) & its portal

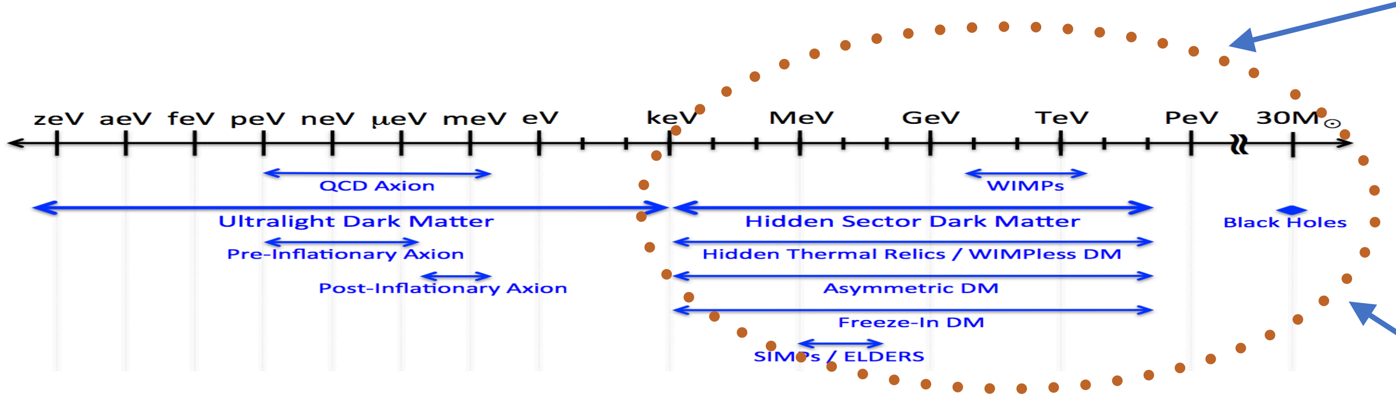
(*ii*) Case for ALP & its quality problem

(*iii*) Case for relaxion/scalar-portal & its natural parameter space

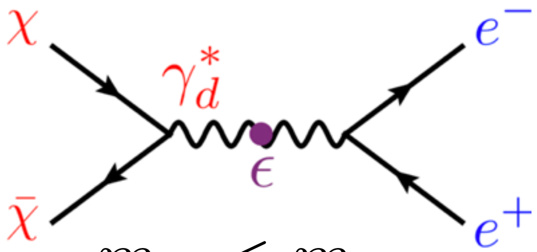
Case (i): The thermal dark-matter-sector target

- Among the attractive solutions to DM problem is to make it boundary condition indep’ <=> thermal relic, acquires abundance via thermal int’ if m_{DM} > keV:

See talks by Frugiuele, Mccullough, Murayama, Rossi, Stapnes …



- Furthermore, light DM typically => light mediator, see for instance dark-photon:



$m_\chi < m_{A'}$

$$\langle \sigma v \rangle \propto m_\chi^{-2} \left(\frac{m_\chi}{m'_A} \right)^4$$

See talk by Frugiuele

Case (*ii*): ALP/axion quality problem

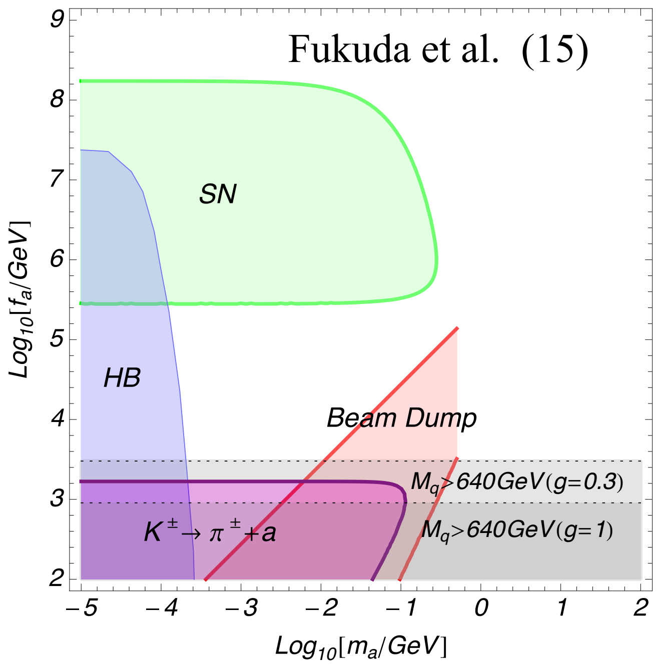
Barr & Seckel; Kamionkowski & March-Russell (92); see also talk by Dine …

- Planck suppressed operators typically destroy the axion potential.

$$\Delta V_{\not{PQ}} = \lambda_\Delta \frac{\Phi^\Delta}{\Lambda_{\rm UV}^{\Delta-4}} + {\rm h.c.} \quad \Rightarrow \quad V_a \simeq -\Lambda_{\rm QCD}^4 \cos\frac{Na}{f} + \frac{1}{2^{\frac{\Delta}{2}-1}} \frac{|\lambda_\Delta| f^\Delta}{\Lambda_{\rm UV}^{\Delta-4}} \cos\left(\alpha_\Delta + \Delta\frac{a}{f}\right)$$

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) …

Case (*iii*): Penetrating the relaxion physical 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:

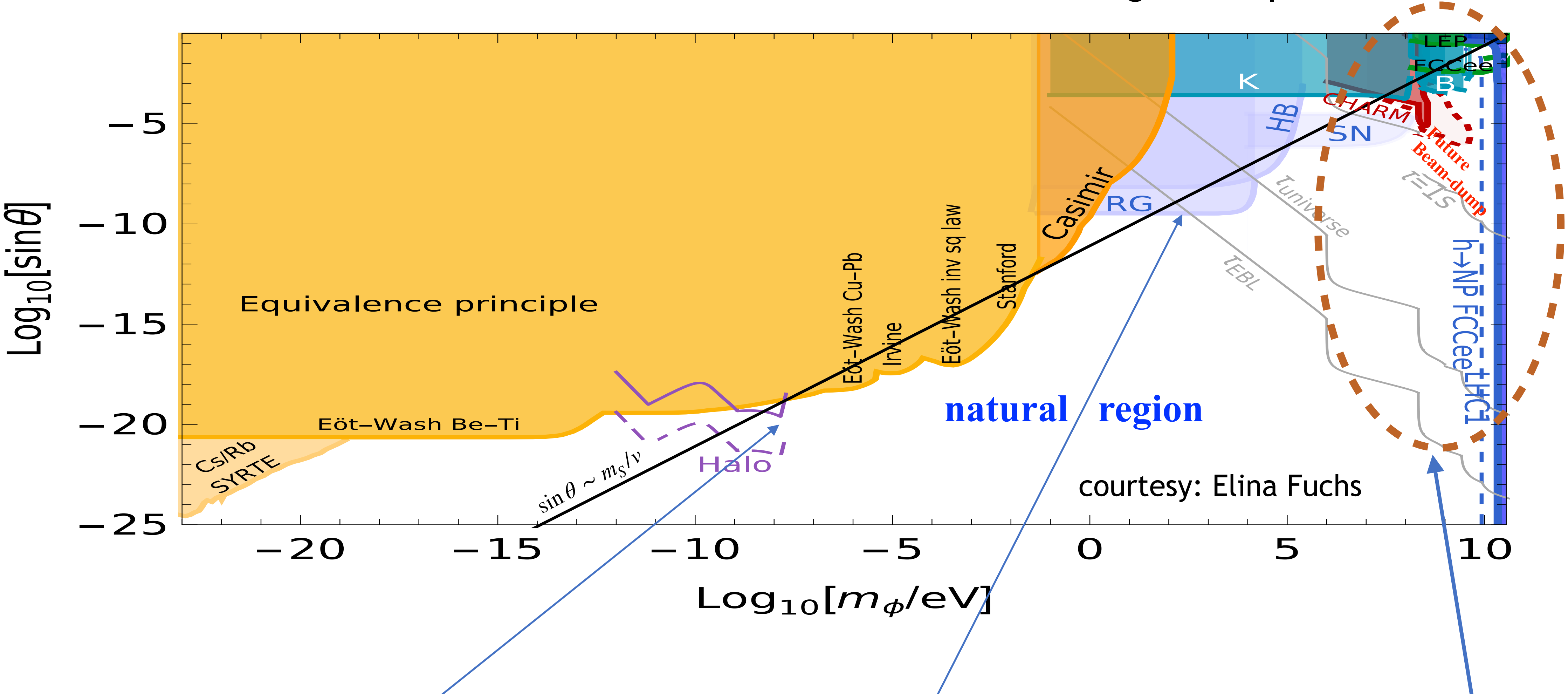
$$L_S \in m_S^2 SS + \mu S H^\dagger H + \lambda S^2 H^\dagger H\,, \quad \text{with } S = \text{light scalar \& } H = \text{SM Higgs}\,.$$

$$\text{Naturalness implies:} \quad \sin\theta \simeq \mu/\langle H\rangle \lesssim \frac{m_S}{\langle H\rangle} \quad \& \quad \lambda \lesssim \frac{m_S^2}{\langle H\rangle^2}\,.$$

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

Accelerators: 1 among only 3 probes of physical models

The 3 fronts where natural models of mixing can be probed



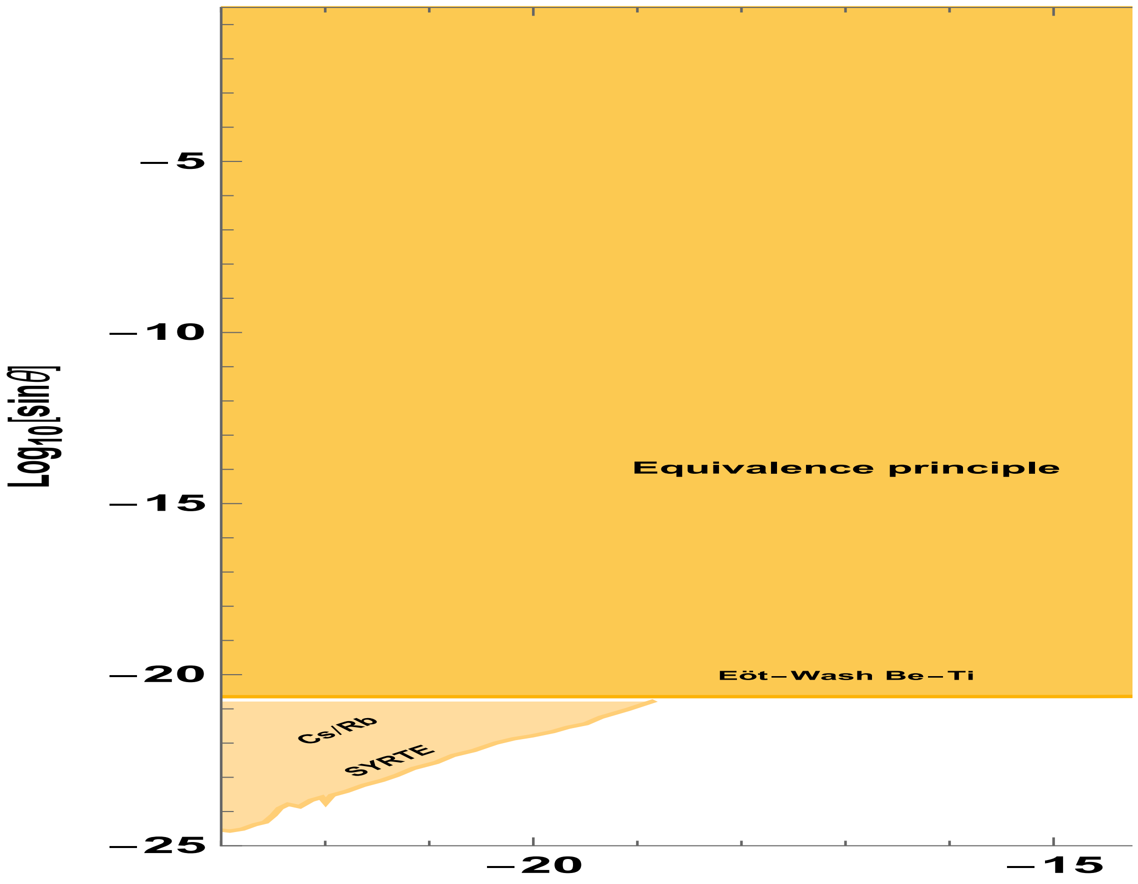
Precision frontier

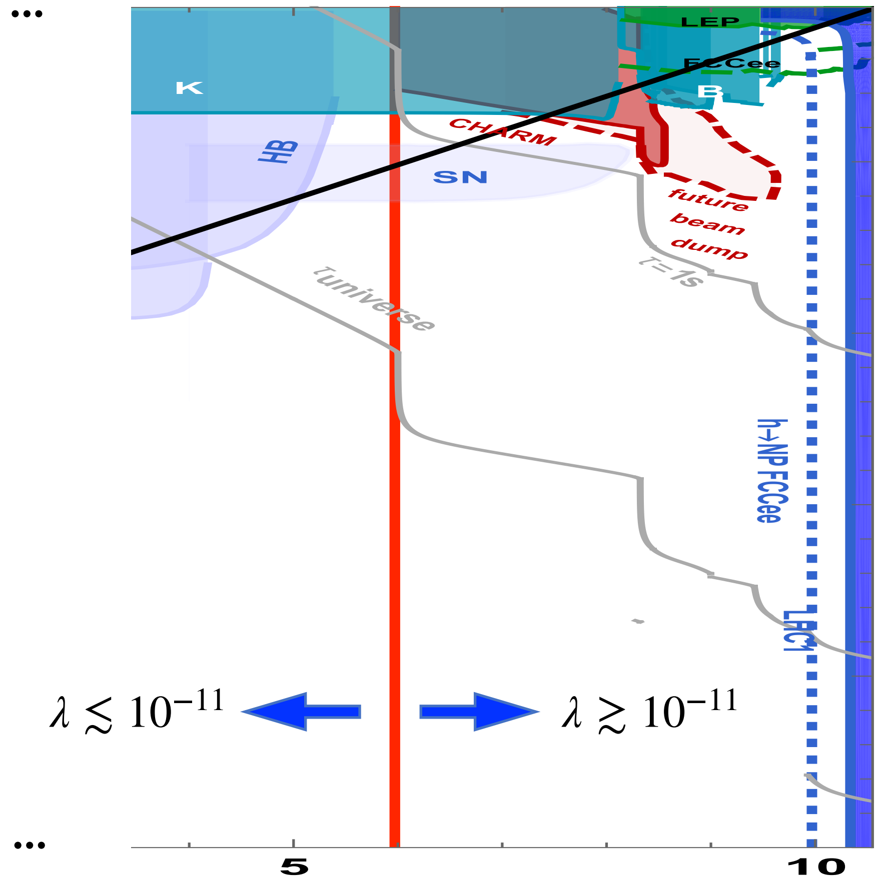
Astro frontier

Accelerator frontier

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

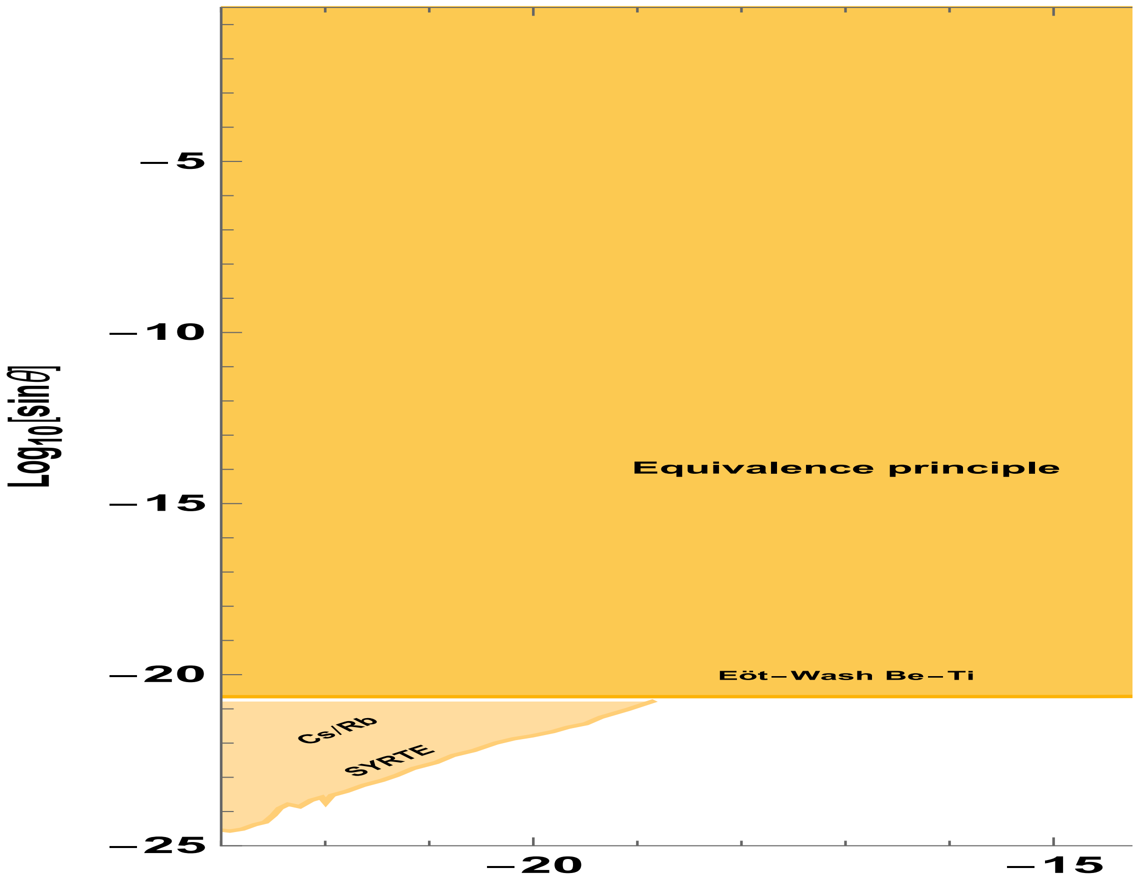
$$\text{Natural region for } H^\dagger H S^2 \text{ term}: \lambda \lesssim \frac{m_S^2}{\langle H \rangle^2} \sim 10^{-5} \times \left(\frac{m_s}{\text{GeV}}\right)^2$$





Naturalness, Z_2 limit: sizeable BR only for large masses

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



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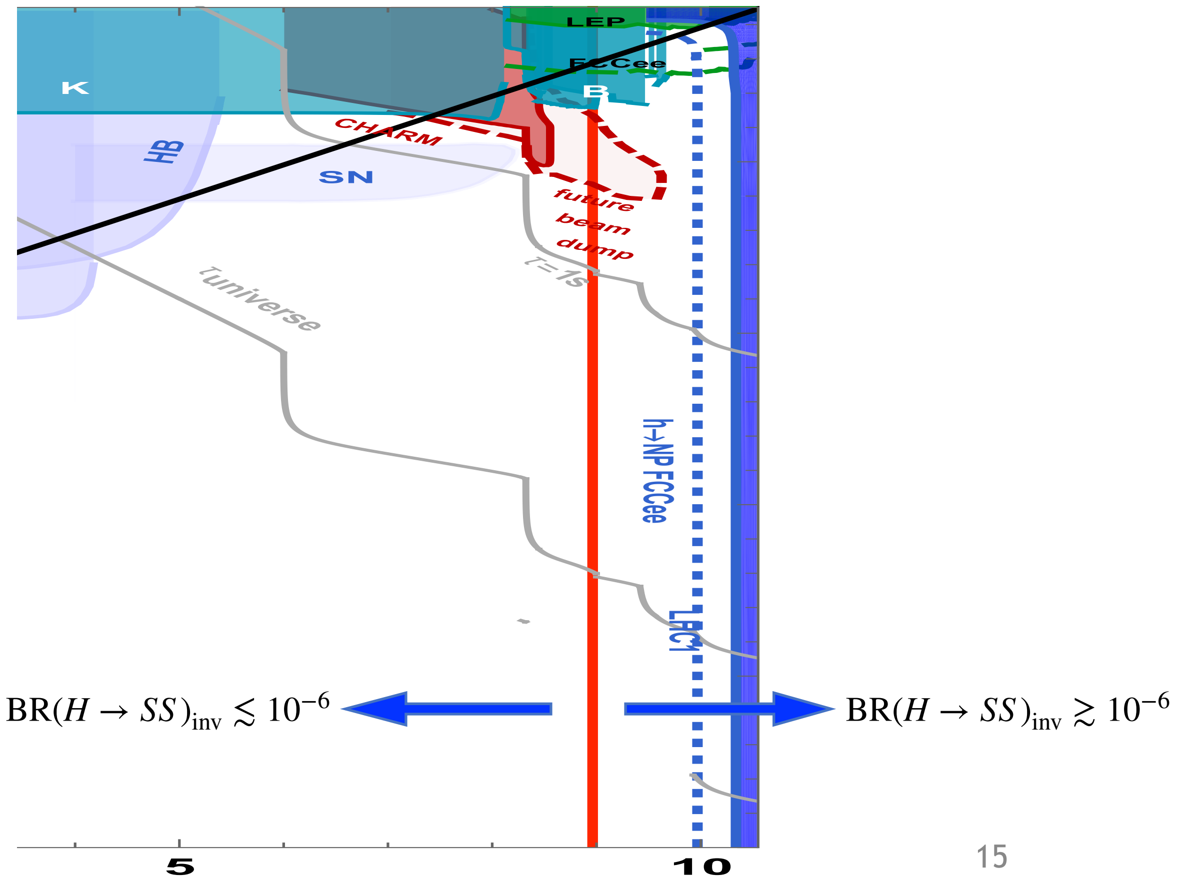
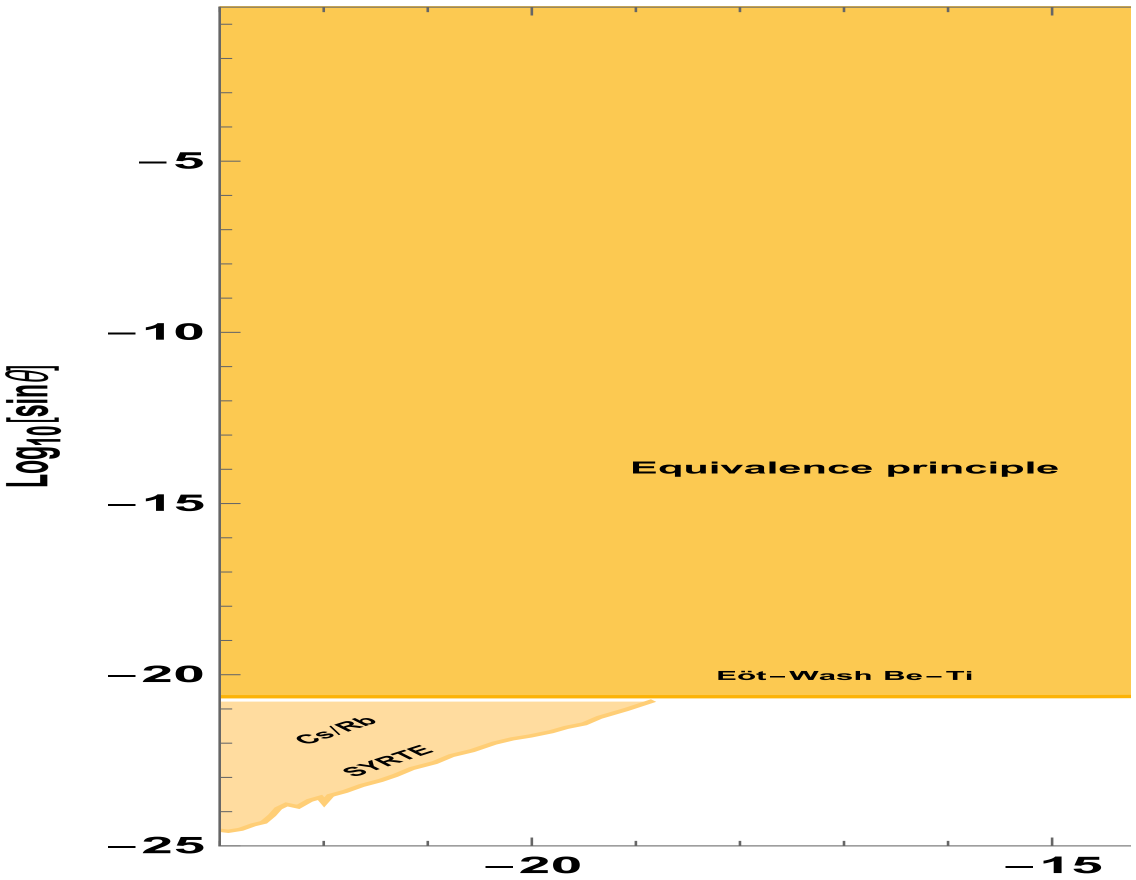


...

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

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



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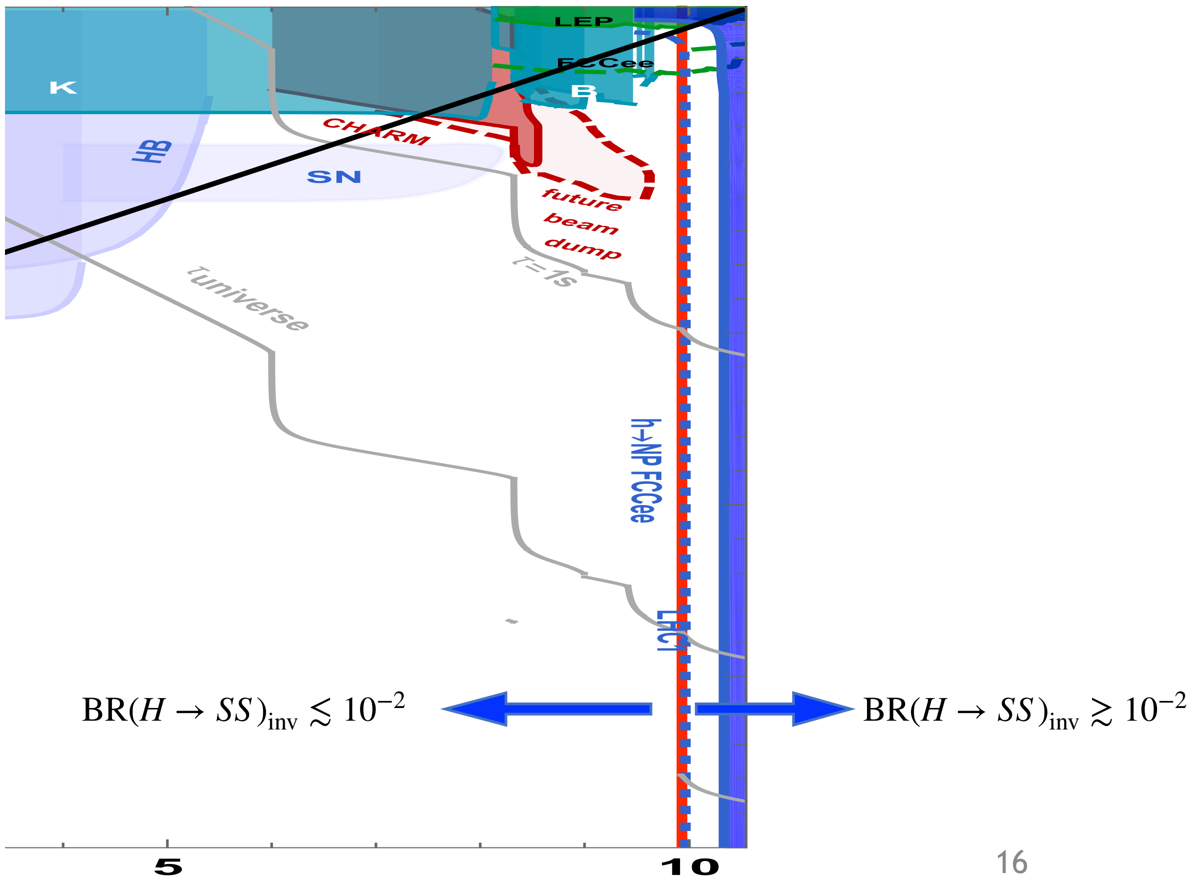


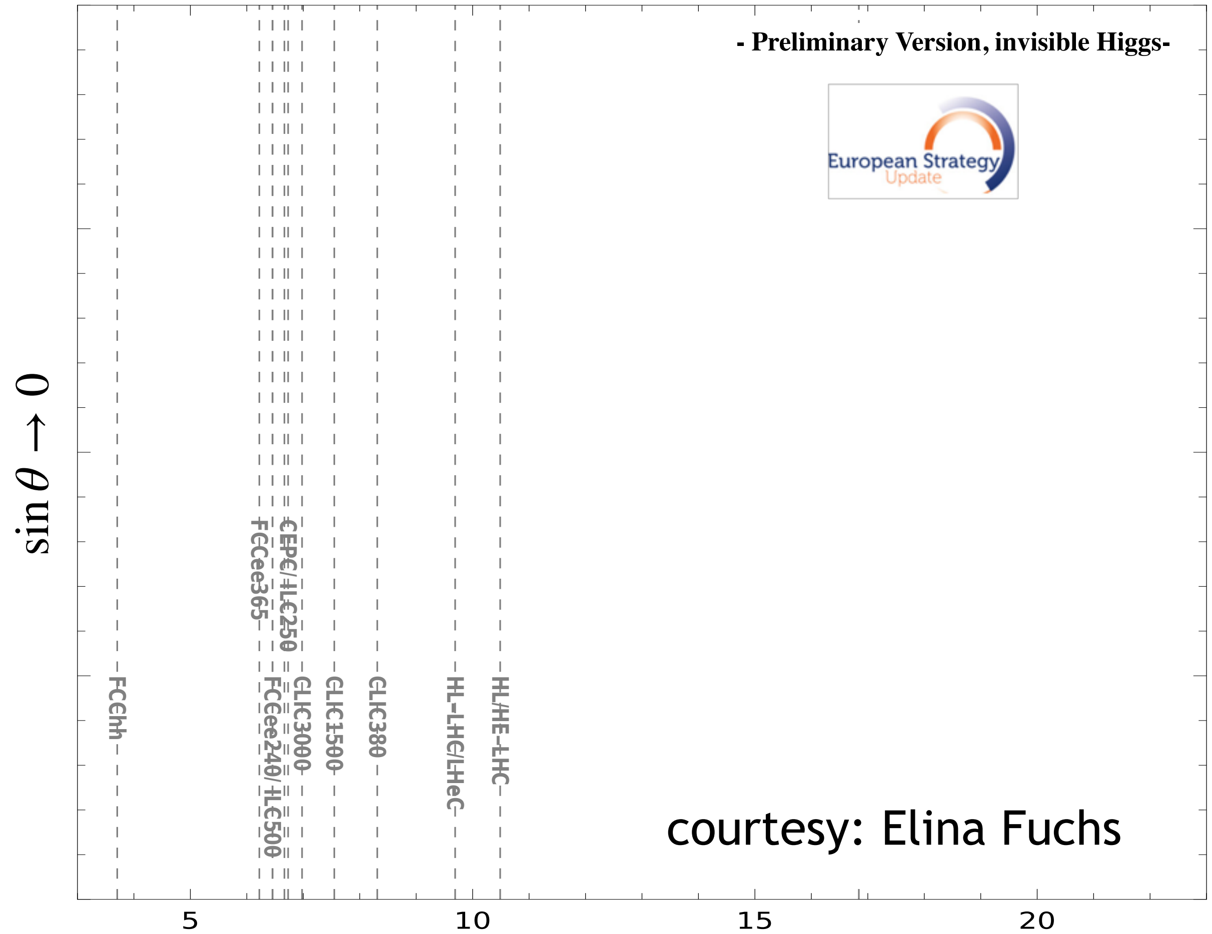
Future colliders probe this Z_2 in a strong manner via *H*->invisible

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

Numbers from:

Higgs Boson studies at future particle colliders

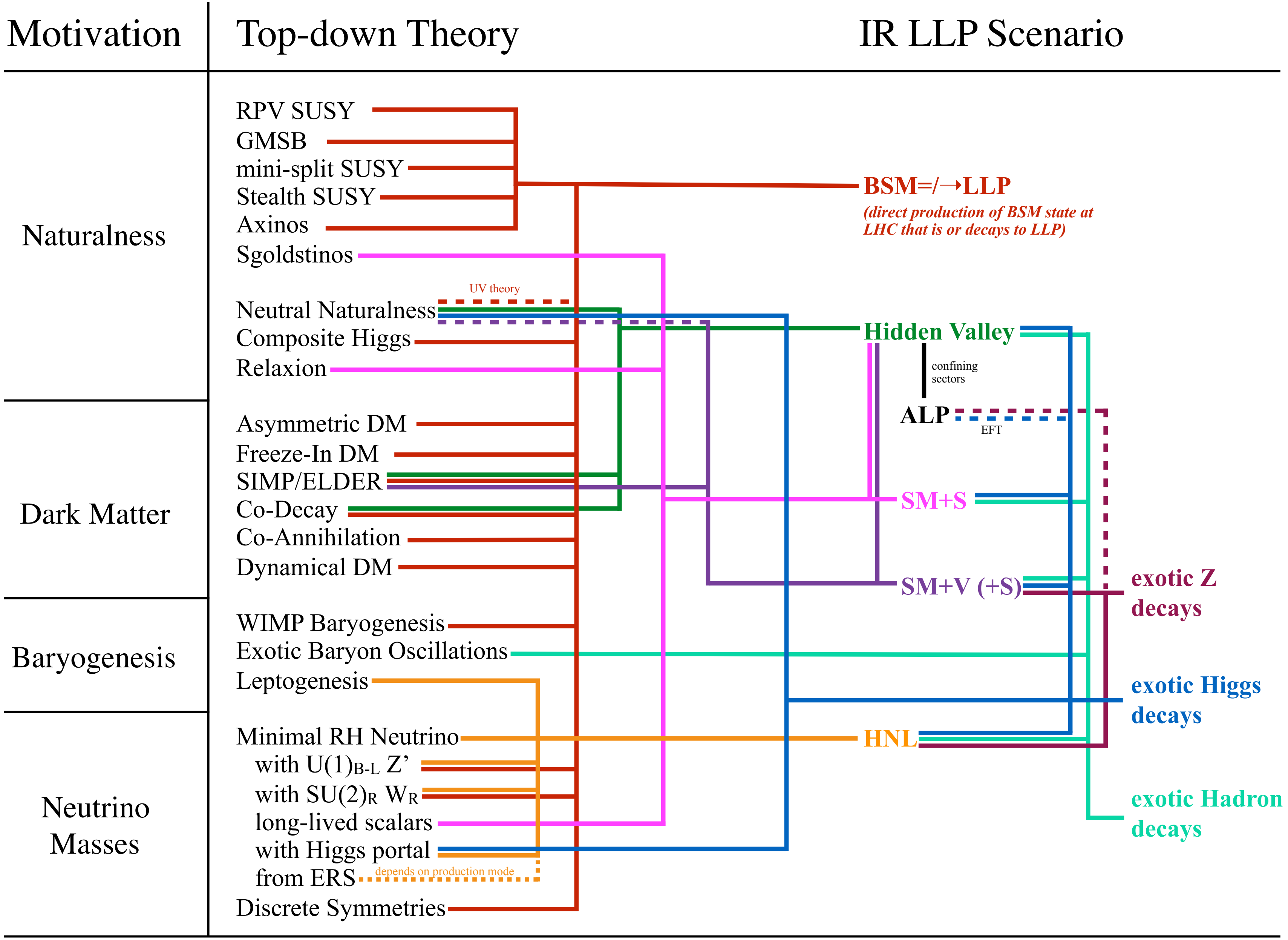
1905.03764v1 (prelim ver.)



3/4 summary

Zoo of microscopic models giving FIPs+ long lived particles (LLPs)

1806.07396



Observational & theoretical motivation for BSM & its scale

Experimental facts

Dark Matter:
candidates \w mass from 10^{-22} eV (light feeble scalars)
to 10^{20} GeV (black holes).

Neutrino masses and oscillations
explanation: (feeble) RH neutrinos from 10^{-2} eV to 10^{15} GeV.

Matter-antimatter asymmetry:
hard to associate scale, solutions of many orders of mag'.

Theoretical

Fine tuning:
Sym' based solutions => TeV partners;
relaxion => light feeble goldstone (ALPs).

Strong CP problem:
axion = goldstone mass ~ 10^{-5} eV;
spont' CP, Nelson-Barr = heavy states.

Fermion masses hierarchy
light feeble familons=ALPS or vector bosons;
or heavy states (extra dim' geography)

Etc …

Unknown mass-scale;
Feeble light particles are common and motivated.

Feebly-interacting long-lived particles: very popular topic across the ESPP inputs

- BSM at colliders (B5):

160 - HE-LHC
152 - HL-LHC
145 - CLIC
135 - FCC-int
101 - FCC-ee
94 - FASER
75 - MATHUSLA
29 - CEPC

- Dark Matter and Dark Sector (B8)

1 - Sterile Neutrinos at CERN (NA62/SHiP) - Albert Shrock
9 - NA64
11 - Belle II
12 – SHiP
34 - Diversification (Israeli input)
36 - Dark Sector Physics with primary electron beam (eSPS)
42 - Physics Beyond Colliders
50 - Particle Physics with AWAKE

- Flavor (B2):

11 – Belle-II experiment at super KEK-B
28 – REDTOP
153 - KLEVER

How to search for such broad class of models?

Following PBC: Simplified models (some tweaks).

How to compare frontiers? Experiments?

Use benchmarks.

Dark Sectors and New, Light, Weakly-Coupled Particles Conveners: Rouven Essig,[1,*] John A. Jaros,[2,†] William Wester,

Simplified models: relevant/marginal portals

PBC: Beacham, et al., CERN-PBC-REPORT-2018-007, 1901.09966

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$
Sterile Neutrino, N	$y_N L H N$

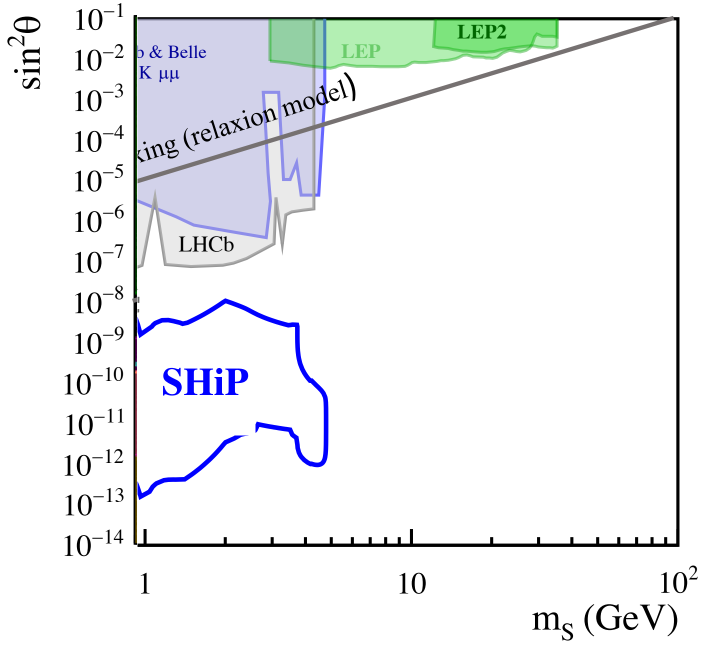
Allowing CP violation => axion acquires scalar couplings (not included).

Conclusions

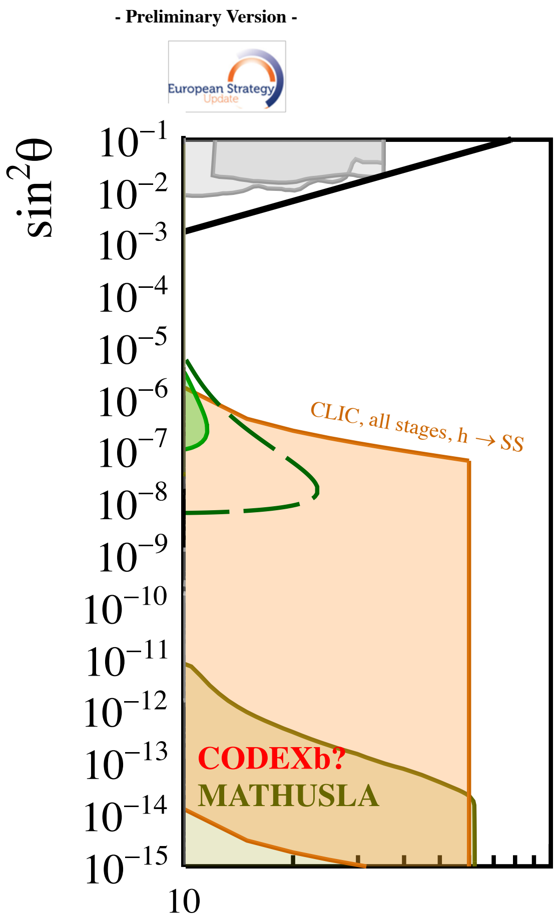
- Feebly interacting particles (FIPs) are generically motivated.
- FIPs bring with them log crisis/opportunity calls for experimental diversity.
- Accelerator provided a unique opportunity to look for well motivated FIPs.
- Practical compromise - FIPs benchmarks.
- Results & sensitivity plots shown in following talk by Gaia Lanfranchi .

Backups

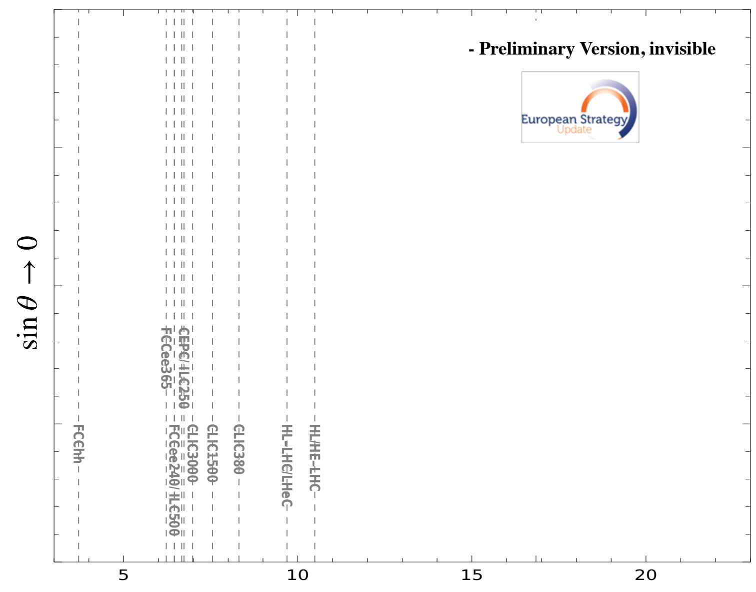
Interplay



sin²θ
b & Belle
K μμ
LEP
LEP2
king (relaxion model)
LHCb
SHiP
m_S (GeV)



- Preliminary Version -
European Strategy Update
sin²θ
CLIC, all stages, h → SS
CODEXb?
MATHUSLA



- Preliminary Version, invisible
European Strategy Update
sin θ → 0
FCChh
FCCee365
CEPC/ILC250
FCCee240/ILC500
CLIC3000
CLIC1500
CLIC380
HL-LHC/LHeC
HL/HE-LHC