

# Feebly interacting particles (FIPs): Pheno overview & new ideas

Gilad Perez

Weizmann Inst.



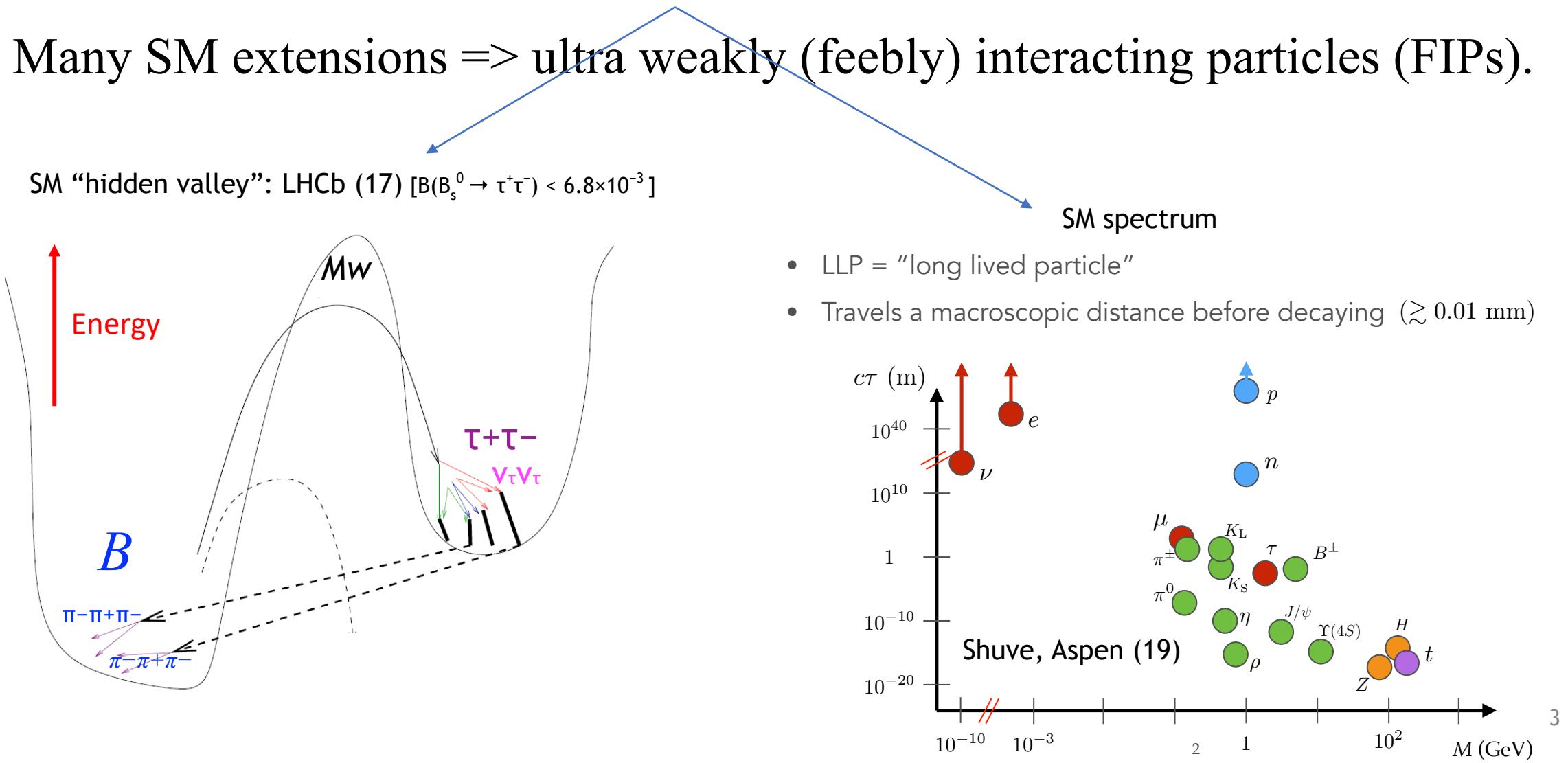
# Outline

---

- Generic motivation, why new feebly interacting particles (FIPs)?
- FIPs & the log crisis/opportunity, where & how to look for them?
- FIPs (spin-0) searches, timely description with new approaches
- Conclusions

# Generic motivation, the feeble-front

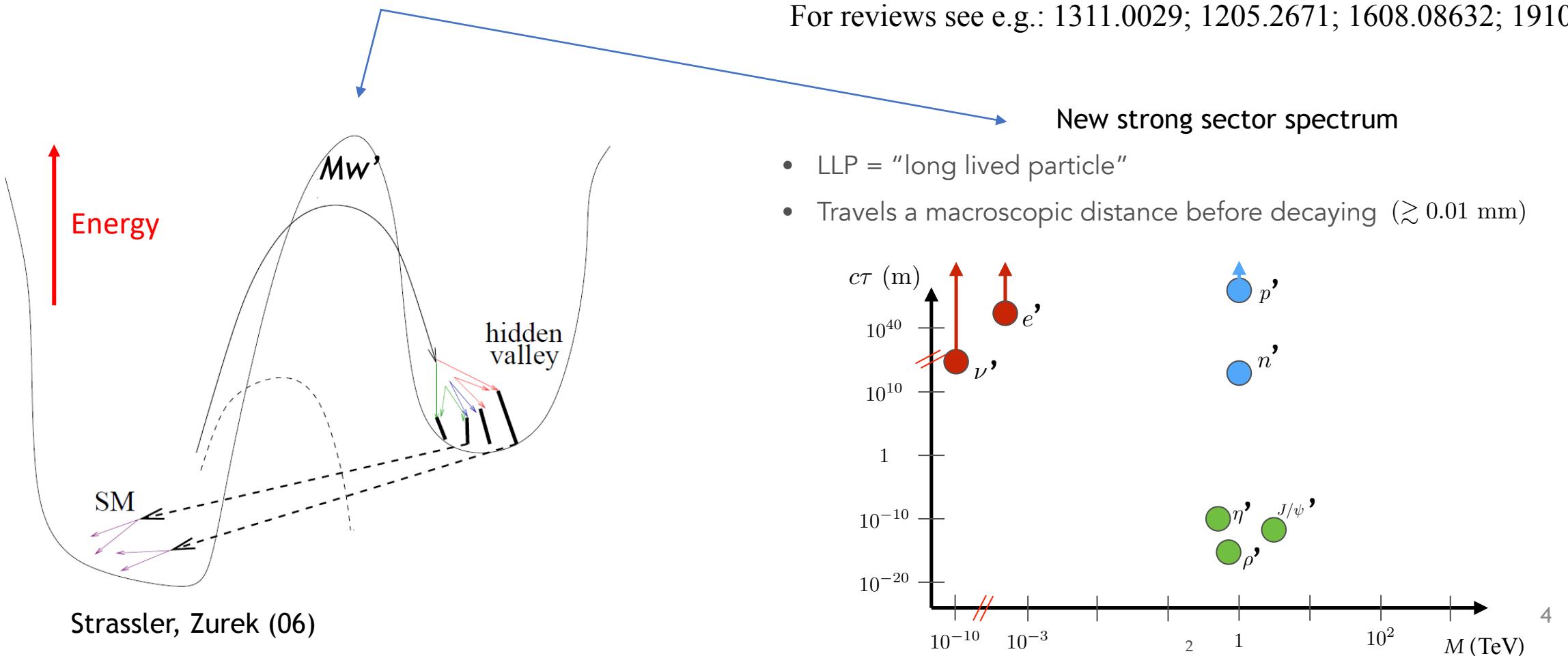
- The standard model (SM) consists of weakly interacting & long-lived particles.
- Many SM extensions => ultra weakly (feeble) interacting particles (FIPs).



# Generic motivation, the feeble-front

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

For reviews see e.g.: 1311.0029; 1205.2671; 1608.08632; 1910.11775



# Theoretical perspective, the feeble-front

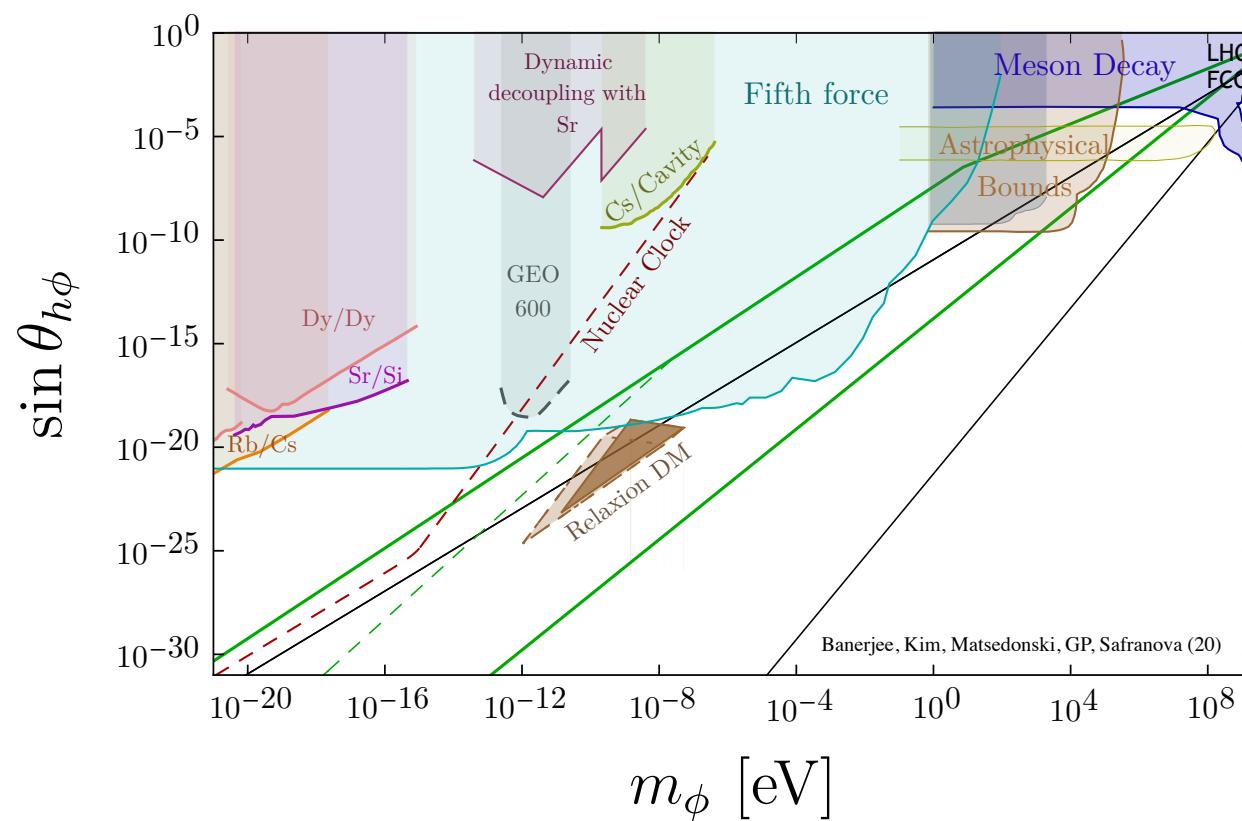
---

- ➊ Heavy FIPs are hard to observe, possibly in energy frontier
- ➋ Light FIPs can be copiously produced & probed across frontiers: energy, luminosity, precision
- ➌ 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') ...

# Searching for FIPs => Log crisis/opportunity

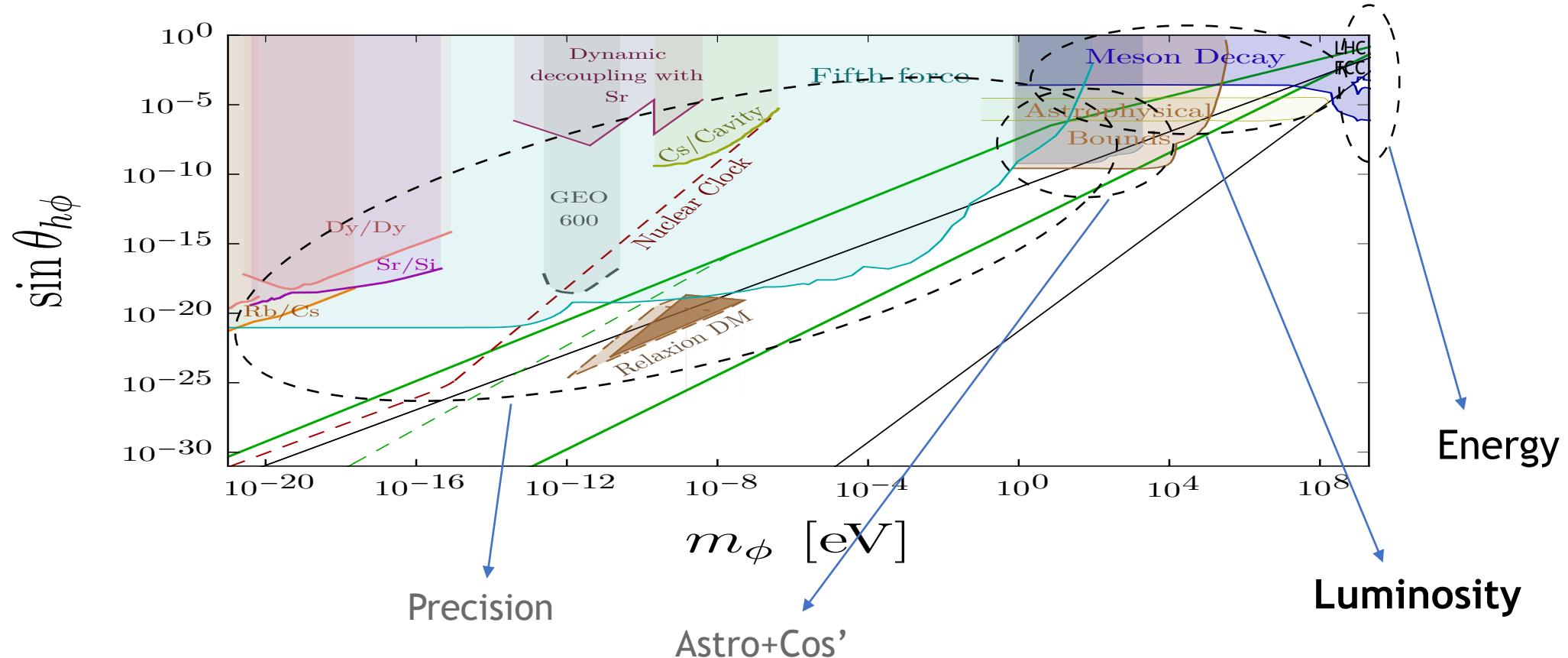
- FIPs coupling can be very small & mass result of soft sym' breaking => model dependent => could span many orders of mag' => log crisis/opportunity

Example: scalar that mixes w Higgs (relaxion/ALP+CP violation) 30-decade-open parameter space



# Log crisis / opportunity => diverse approach with searches across frontiers

Example: scalar that mixes \w Higgs (relaxion/ALP+CP violation) 30-decade-open parameter space

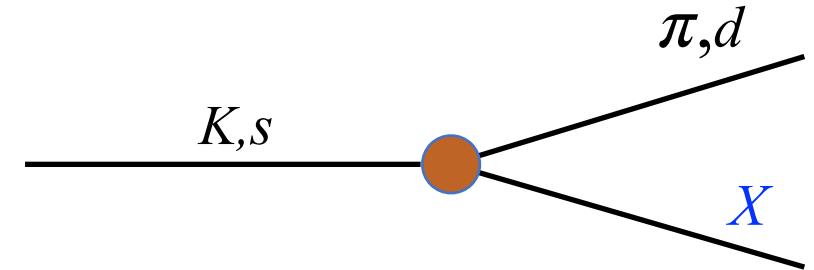


# Present/near future progress

- (i) Dark sector searches @ the Kaon factories
- (ii) The  $(g - 2)_\mu$  : call for accelerators (+precision) of muon (e) forces
- (iii) nPOD @ LUXE: new Physics searches with Optical Dump at LUXE

- Kaon factories:  $10^{19}$  protons on target &  $O(10^{13}) K$ 's  $\Rightarrow$  BR of  $O(10^{-11})$

- Ideal for FIPs searches:  $(K \rightarrow \pi\nu\bar{\nu}) \Leftrightarrow (K \rightarrow \pi X)$



- The Grossman-Nir (GN) bound (97) [scalar; Leutwyler and M. A. Shifman (90)]:

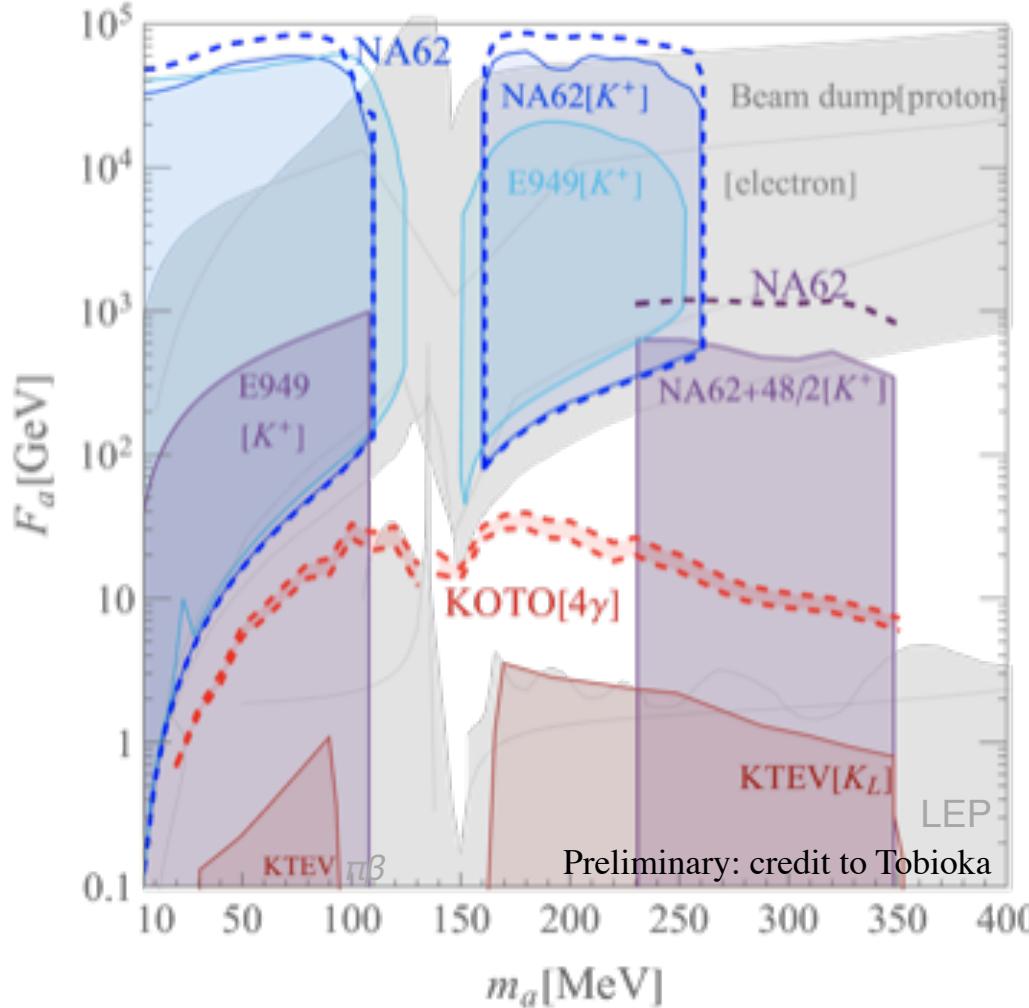
$$K_L \rightarrow \pi^0 \nu \bar{\nu} \text{ and } K^+ \rightarrow \pi^+ \nu \bar{\nu} \text{ are related via sym., } \text{BR} (K_L \rightarrow \pi^0 \nu \bar{\nu}) \leq 4.3 \text{ BR} (K^+ \rightarrow \pi^+ \nu \bar{\nu}) .$$

With FIPs the relation can be violated by orders of mag.:  
 makes the searches at KOTO and NA62 independent & interesting

# Complementarity of Kaon factories in searching for NP

Searching to 2-photons decay from ALP-gluon coupling:  $\mathcal{L} \subset \frac{\alpha_s}{8\pi F_a} a G \tilde{G}$

Based on Gori, GP & Tobioka (20);



However previous calculation, based on basis-dep.  
missed the non-mixed pion-ALP contributions,  
Bauer, Neubert, Renner, Schnubel & Thamm (21)

Update by Tobioka; based on discussions \w Gori:

Present and future (dashed) bounds  
on the parameter space. Beam-  
dumped in gray, present bound; in  
red and purple  $4\gamma$  &  $\pi^+ + 2\gamma$   
signatures; light blue & blue we show  
 $\pi^+ + \text{invisible}$

# Current status of $(g - 2)_\mu$

---

$$a_\mu^{\text{exp}} = 116592061(41) \times 10^{-11}$$

BNL : [hep-ex/0602035](#)  
Fermilab : [2104.03281](#)

$$\Delta a_\mu^R \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM},R} = 251(59) \times 10^{-11}$$
 4.2\*  $\sigma$

For instance: Aoyama et al Phys Rep. (20)

$$\Delta a_\mu^{\text{lattice}} \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM,lattice}} = 109(71) \times 10^{-11}$$
 1.6  $\sigma$

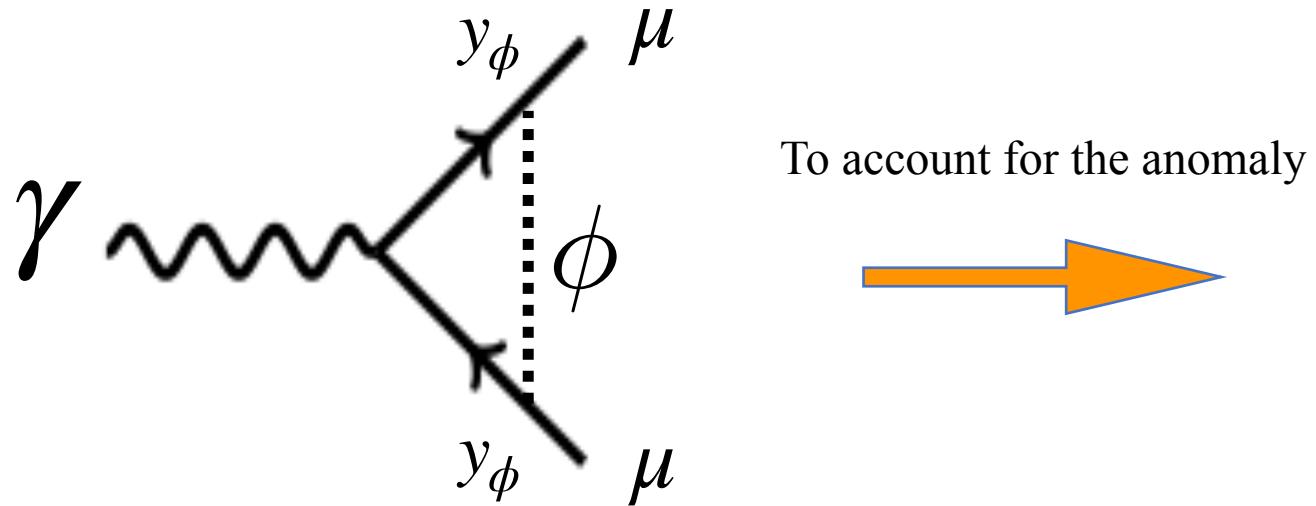
Borsanyi et al. (20)

\* Supported indirectly by the electroweak precision tests used to extract  $\alpha(M_Z)$

e.g.: Crivellin, Hoferichter, Manzari & Montull; Keshavarzi, Marciano, & Passera (20)

# $(g - 2)_\mu$ vs. beyond the standard model (BSM) physics

- In vanilla models it is induced at one loop (virtual), for instance for a light scalar:



To account for the anomaly

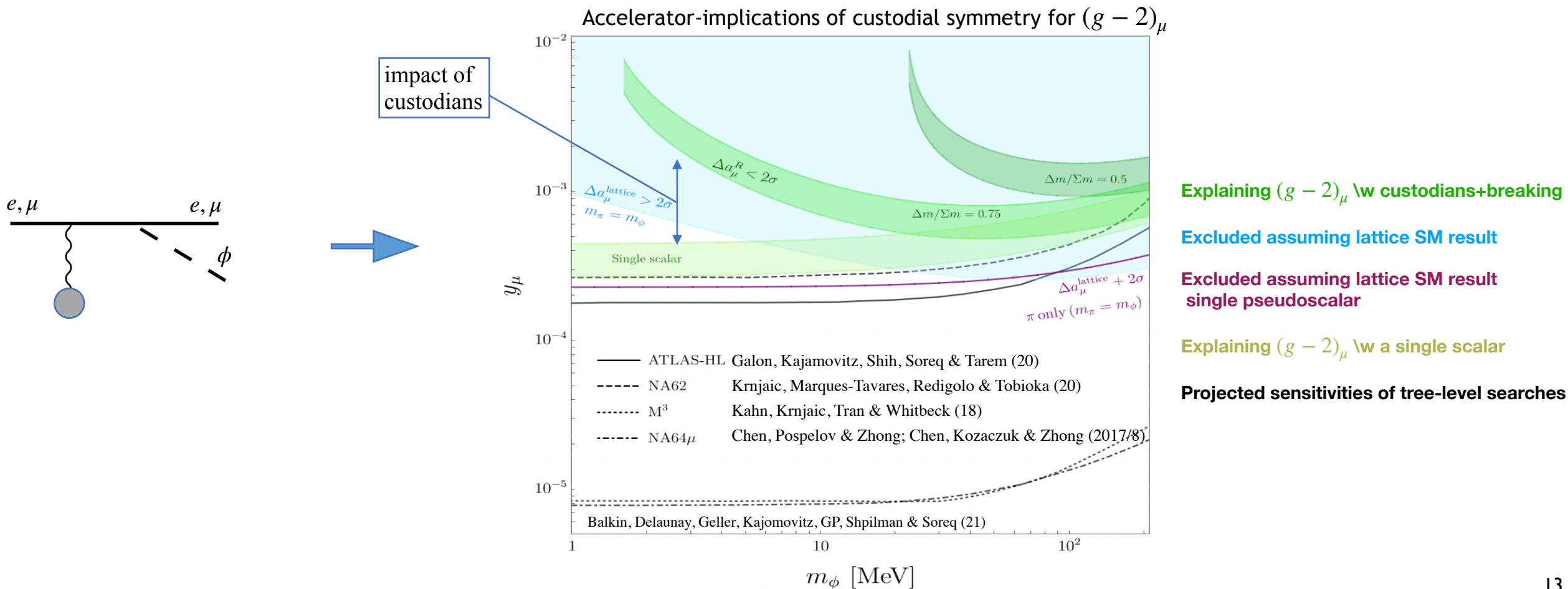
$\longrightarrow$   $y_\phi \approx$  or  $\lesssim 4 \times 10^{-4}$

- This relation/bound is strong; however, as it comes from one loop, is it robust?

Possible to build models that due to symmetry or structural properties the loop vanishes

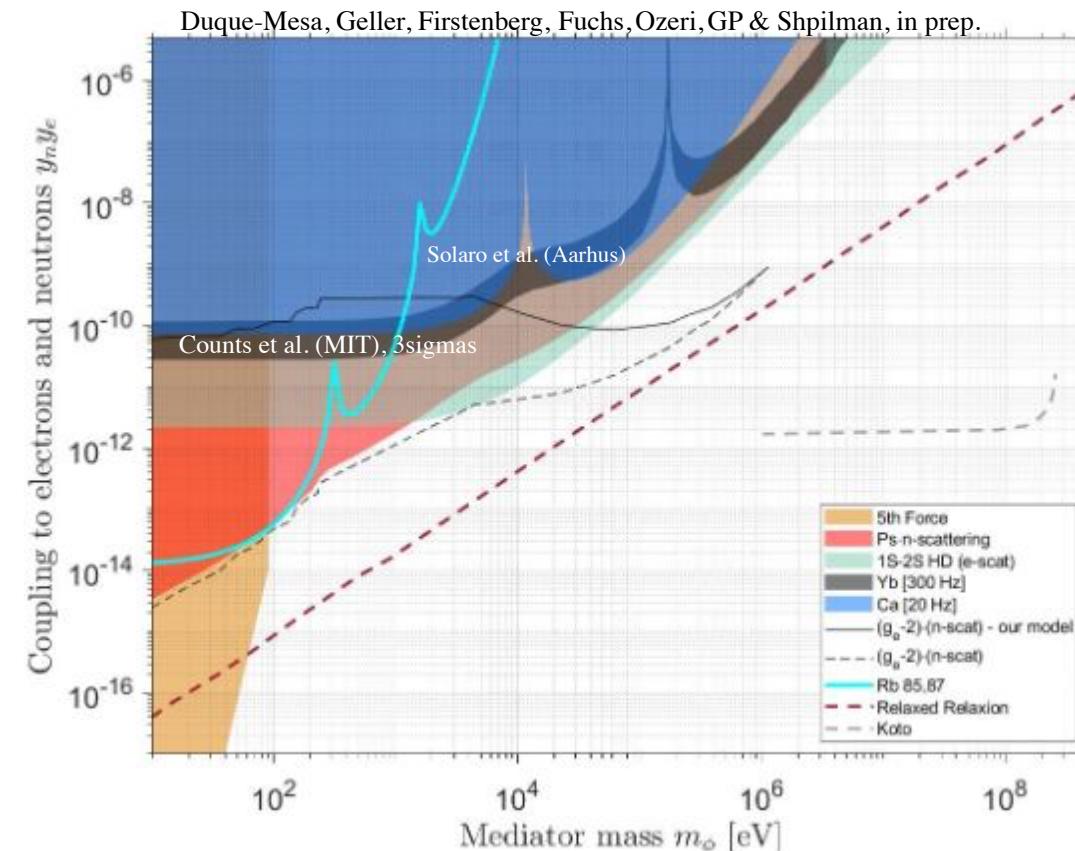
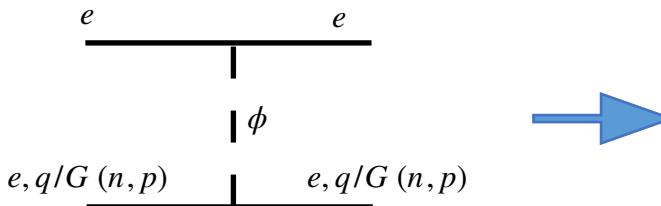
# Naturally cancelling the 1-loop $(g - 2)_{\mu,e}$ contributions

- Tree level contributions, say  $\phi$ -strahlung are unavoidable  $\Rightarrow$  may be tested in accelerators:



# Naturally cancelling the 1-loop $(g - 2)_{\mu,e}$ contributions

- Tree level contributions, which induce intermediate-range force are unavoidable => tested in spectroscopy:



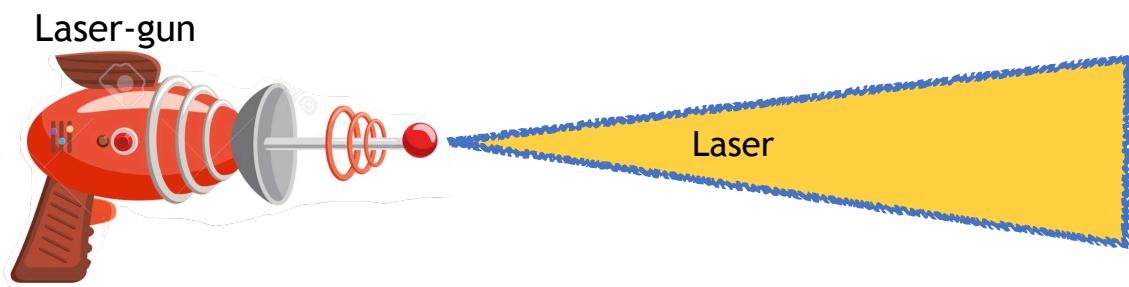
King (1963)  
Delaunay, Ozeri, GP & Soreq (16);  
Delaunay, Fuchs, Fruguele, Soreq (17)  
Berengut et al. (18)  
Manovitz et al (19) have demonstrated  
that precision below 100 mHz is possible.

# nPOD @ LUXE: new physics searches with optical dump at LUXE

LUXE CDR, arXiv: 2102.02032

- LUXE (Laser Und XFEL Experiment) proposed experiment to study non-perturbative QED: via studying electron-laser and photon-laser collisions See more in poster by: F. Meloni for the LUXE collab.
- For FIPs @ LUXE, let's consider the electron-laser collision:

The strong laser act as a dump for the electron  
(LUXE: relevant mean free path is  $O(1)$ )



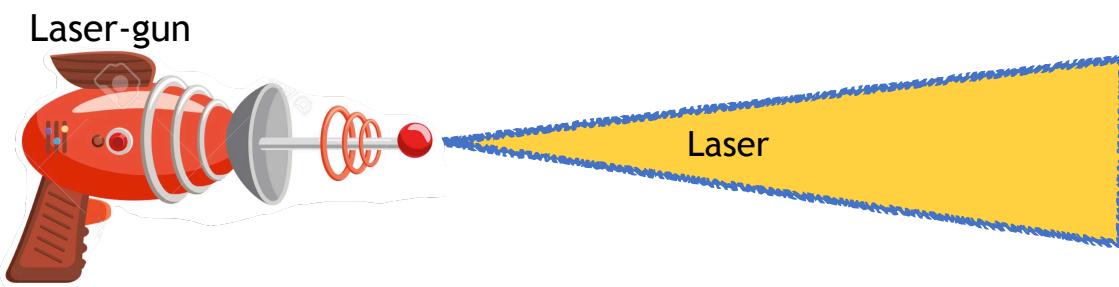
# Electron strong-laser collision @ LUXE

LUXE CDR, arXiv: 2102.02032

- LUXE (Laser Und XFEL Experiment) proposed experiment to study non-perturbative QED: via studying electron-laser and photon-laser collisions
- For FIPs @ LUXE, let's consider the electron-laser collision:

See more in poster by: F. Meloni for the LUXE collab.

The strong laser act as a dump for the electron  
(LUXE: relevant mean free path is  $O(1)$ )

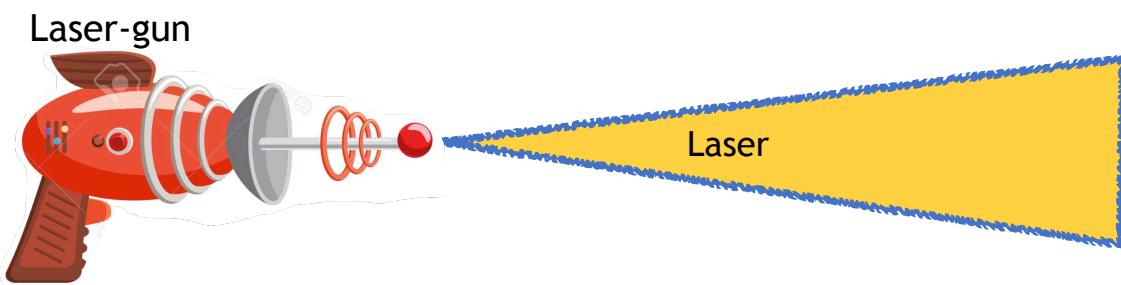


# Electron strong-laser collision @ LUXE

LUXE CDR, arXiv: 2102.02032

- LUXE (Laser Und XFEL Experiment) proposed experiment to study non-perturbative QED: via studying electron-laser and photon-laser collisions See more in poster by: F. Meloni for the LUXE collab.
- For FIPs @ LUXE, let's consider the electron-laser collision:

The strong laser act as a dump for the electron  
(LUXE: relevant mean free path is  $O(1)$ )

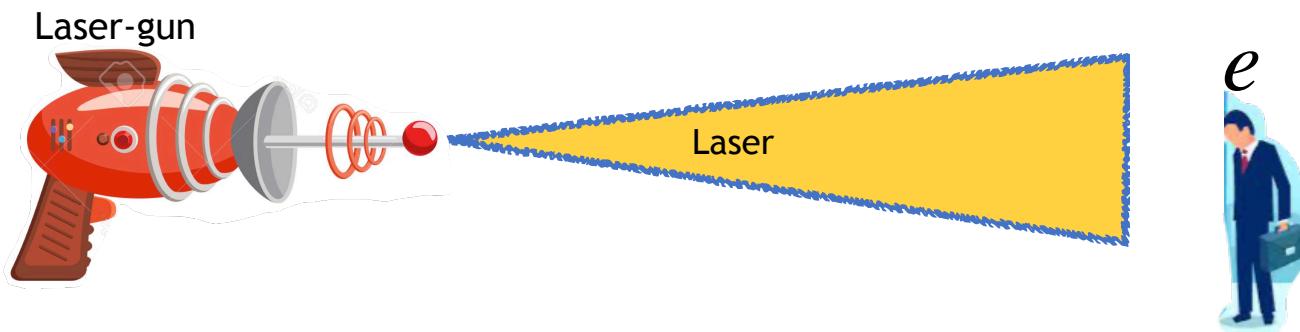


# Electron strong-laser collision @ LUXE

LUXE CDR, arXiv: 2102.02032

- LUXE (Laser Und XFEL Experiment) proposed experiment to study non-perturbative QED: via studying electron-laser and photon-laser collisions See more in poster by: F. Meloni for the LUXE collab.
- For FIPs @ LUXE, let's consider the electron-laser collision:

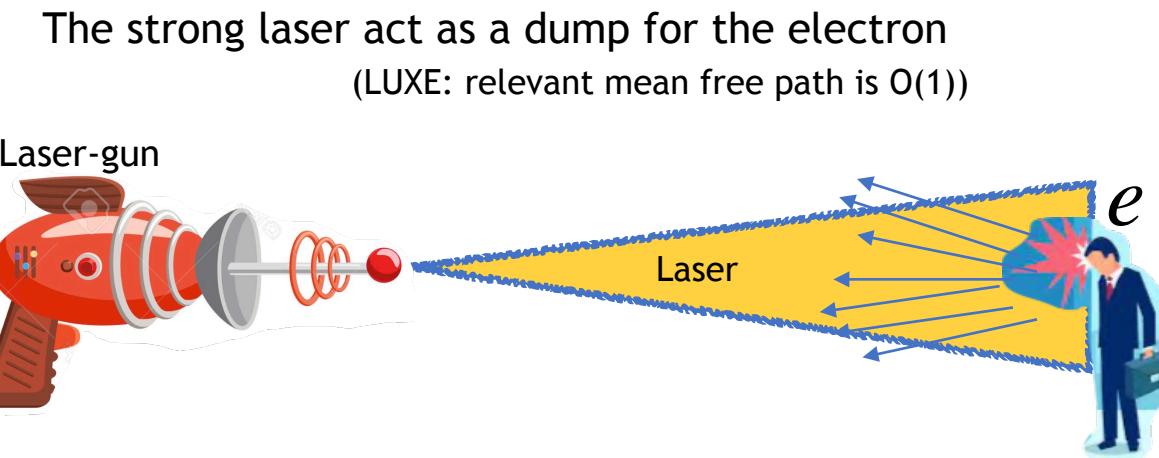
The strong laser act as a dump for the electron  
(LUXE: relevant mean free path is  $O(1)$ )



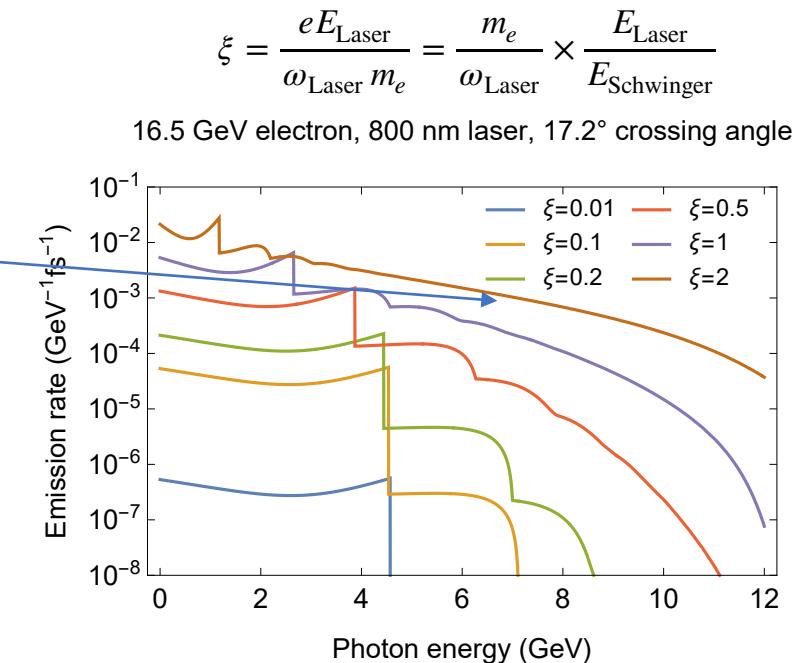
# Electron strong-laser collision @ LUXE

LUXE CDR, arXiv: 2102.02032

- LUXE (Laser Und XFEL Experiment) proposed experiment to study non-perturbative QED: via studying electron-laser and photon-laser collisions
- For FIPs @ LUXE, let's consider the electron-laser collision:

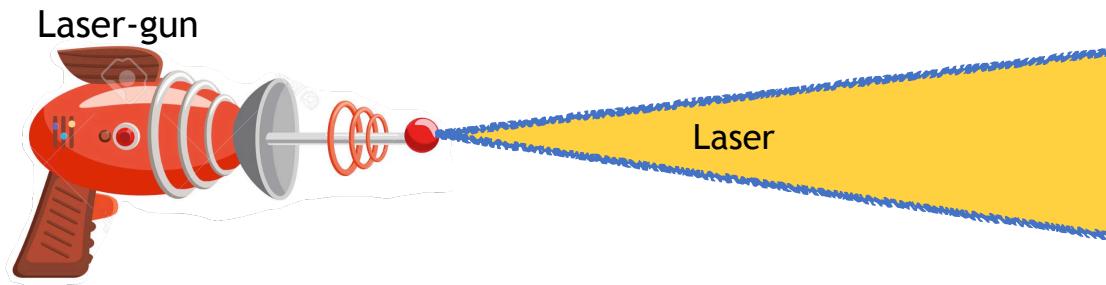


Excellent hard  
photon-source



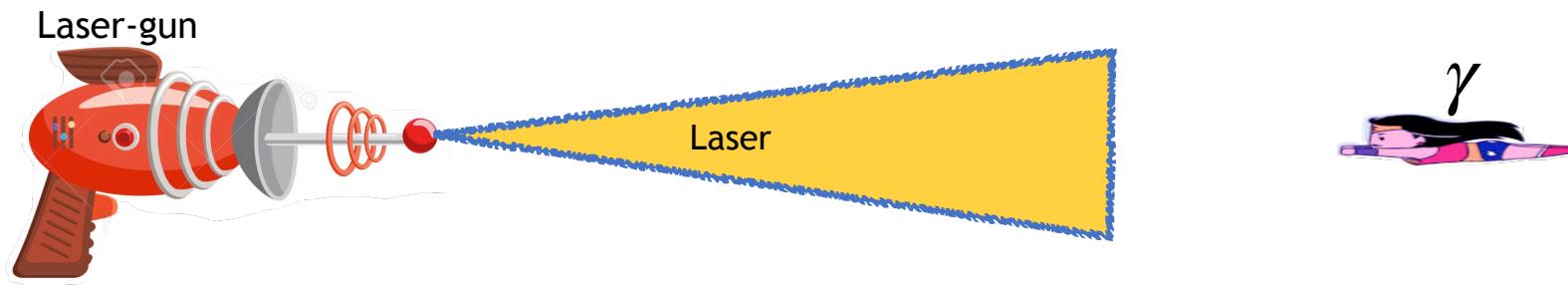
# Photons strong-laser (effectively no)-collision @ LUXE

Unlike the electron case, photons free stream in the strong laser (LUXE: relevant mean free path is  $O(10^4)$ )



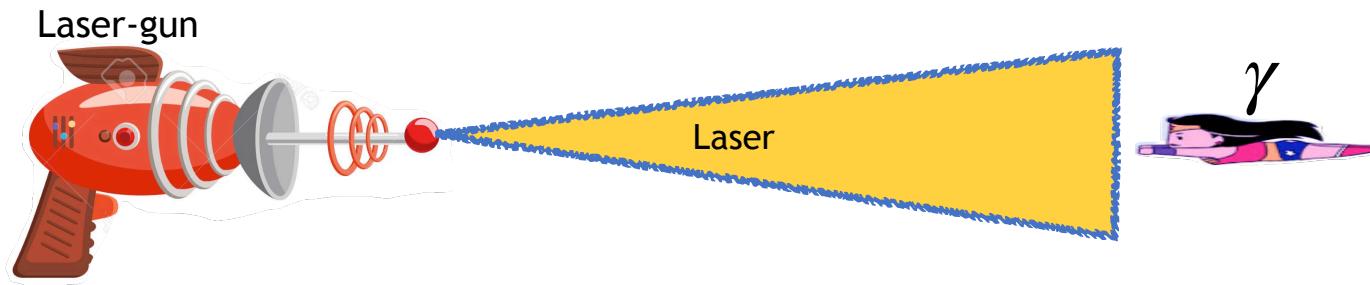
# Photons strong-laser (effectively no)-collision @ LUXE

Unlike the electron case, photons free stream in the strong laser (LUXE: relevant mean free path is  $O(10^4)$ )



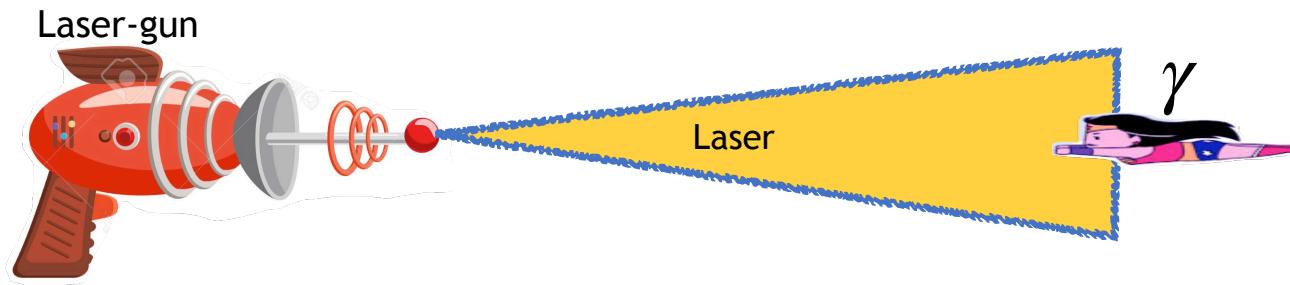
# Photons strong-laser (effectively no)-collision @ LUXE

Unlike the electron case, photons free streaming in the strong laser (LUXE: relevant mean free path is  $O(10^4)$ )



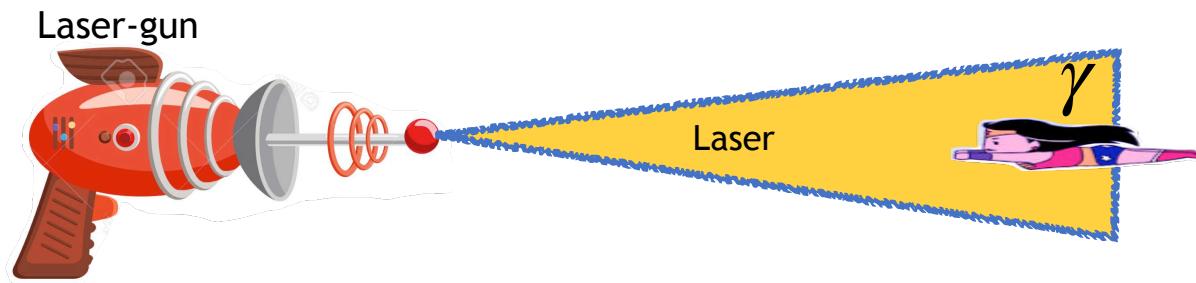
# Photons strong-laser (effectively no)-collision @ LUXE

Unlike the electron case, photons free stream in the strong laser (LUXE: relevant mean free path is  $O(10^4)$ )



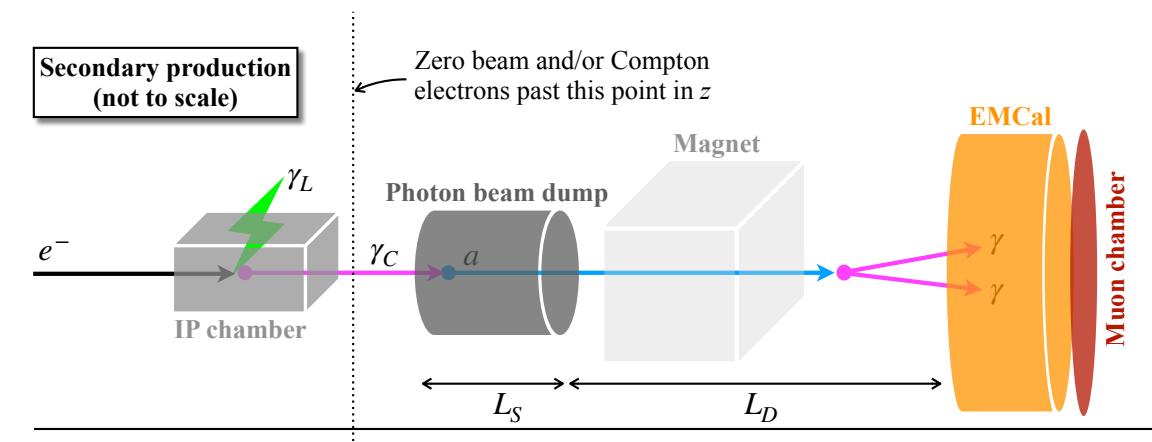
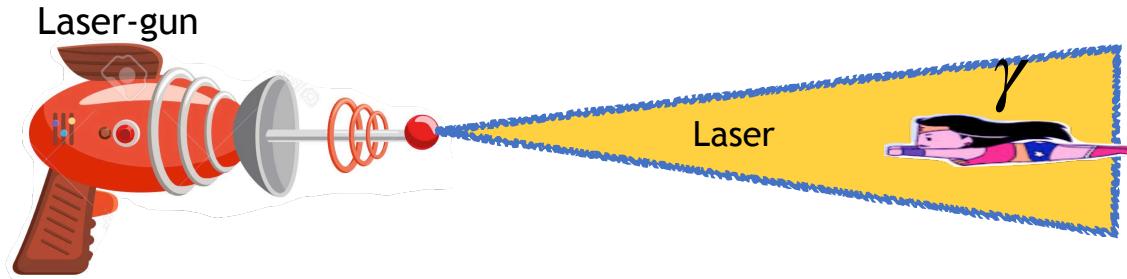
# Photons strong-laser (effectively no)-collision @ LUXE

Unlike the electron case, photons free stream in the strong laser (LUXE: relevant mean free path is  $O(10^4)$ )



# Photons strong-laser (effectively no)-collision @ LUXE

Unlike the electron case, photons free streaming in the strong laser (LUXE: relevant mean free path is  $> 10^4$ )

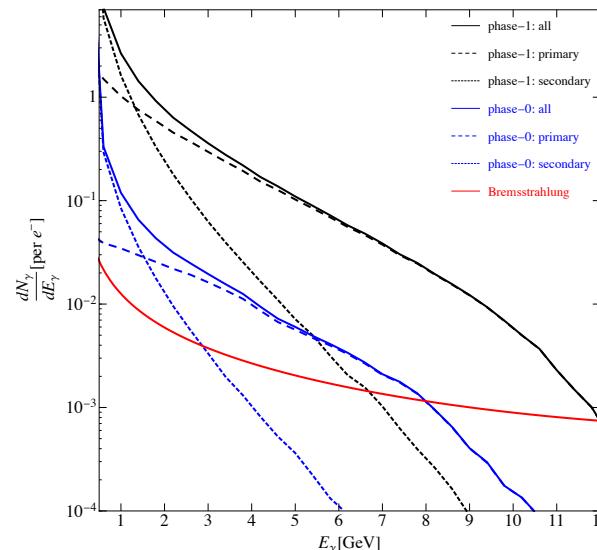


Let's combine both properties to create optical dump to search for FIPs

# nPOD @ LUXE: new physics searches with optical dump at LUXE

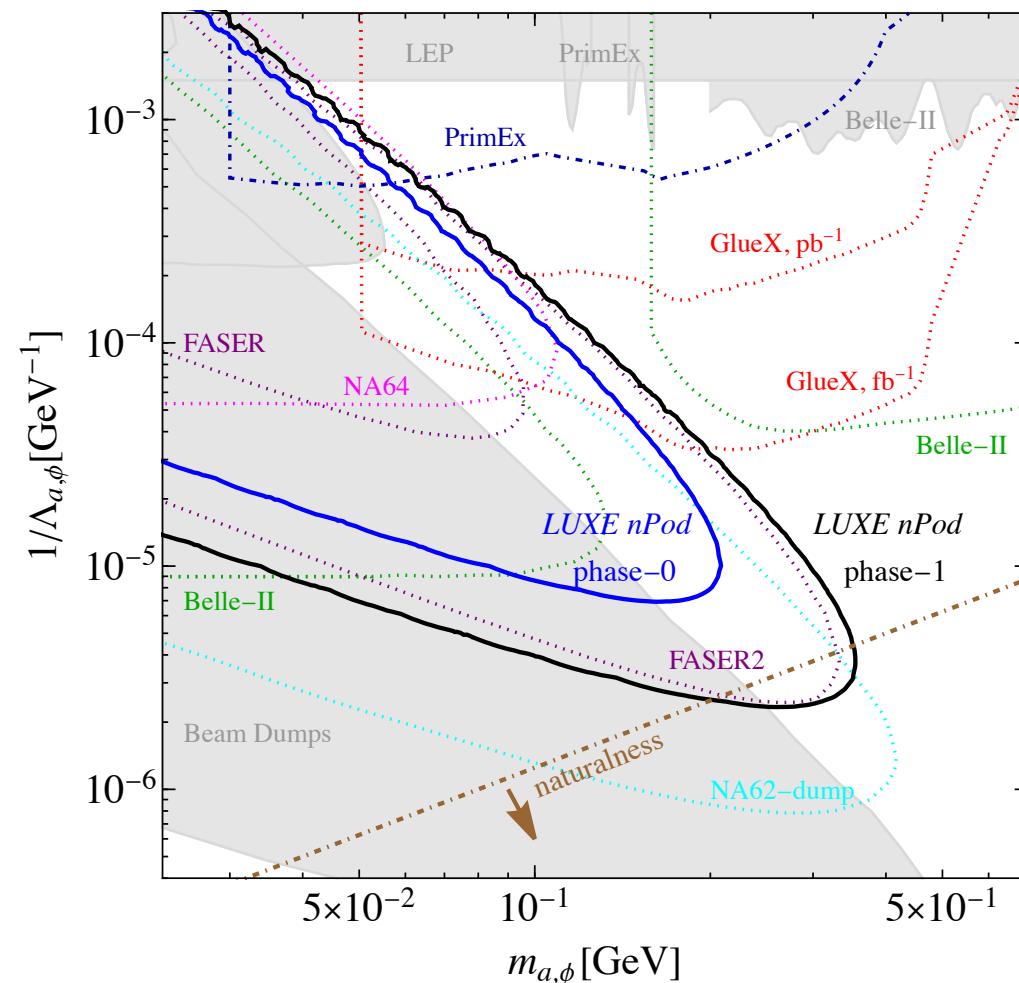
Bai, Blackburn, Borysov, Davidi, Hartin, Heinemann, Ma, GP, Santra, Soreq & Tal-Hod to appear

source	# photons, E>1 GeV	backgrounds
LUXE-0/1	0.12 / 2.5	effectively free
e-beam thin	0.03	effectively free
e-beam thick	6.7	0(100) larger



Photon spectrum for phase-0(1) in blue(black) vs. brem spec. w  $E_e = 16.5$  GeV & target length of 0.01 rad'-length in red.

The prelim money plot: record sensitivity to scalar/ALP-photon coupling



# 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
- Interesting complementarity \w tabletop @ precision frontier
- New approach: nPOD @ LUXE, FIPs searches via optical dump

# *Backups*

# 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  $\sim 10^{-5}$  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.

# Simplified models: relevant/marginal portals

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

Portal	Coupling
Dark Photon, $A_\mu$	$-\frac{\epsilon}{2 \cos \theta_W} F'_{\mu\nu} B^{\mu\nu}$
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).

# Naturally cancelling the 1-loop $(g - 2)_{\mu,e}$ contributions

## A Custodial Symmetry for Muon $g - 2$

Reuven Balkin,<sup>a</sup> Cédric Delaunay,<sup>b</sup> Michael Geller,<sup>c</sup> Enrique Kajomovitz,<sup>a</sup> Gilad Perez,<sup>d</sup> Yosef Shpilman,<sup>d</sup> and Yotam Soreq<sup>a</sup>

<sup>a</sup>Physics Department, Technion – Israel Institute of Technology, Haifa 3200003, Israel

<sup>b</sup>LAPTh, CNRS – USMB, BP 110 Annecy-le-Vieux, F-74941 Annecy, France

<sup>c</sup>Department of Physics, Tel Aviv University, Tel Aviv, Israel

<sup>d</sup>Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot 7610001, Israel

E-mail: [reuven.b@campus.technion.ac.il](mailto:reuven.b@campus.technion.ac.il), [cedric.delaunay@lapth.cnrs.fr](mailto:cedric.delaunay@lapth.cnrs.fr),  
[micgeller@tauex.tau.ac.il](mailto:micgeller@tauex.tau.ac.il), [enrique@physics.technion.ac.il](mailto:enrique@physics.technion.ac.il),  
[gilad.perez@weizmann.ac.il](mailto:gilad.perez@weizmann.ac.il), [yosef.shpilman@weizmann.ac.il](mailto:yosef.shpilman@weizmann.ac.il),  
[soreq@physics.technion.ac.il](mailto:soreq@physics.technion.ac.il)

**ABSTRACT:** We discuss the recent results on the muon anomalous magnetic moment in the context of new physics models with light scalars. We propose a model in which the one-loop contributions to  $g - 2$  of a scalar and a pseudoscalar naturally cancel in the massless limit due to the symmetry structure of the model. This model allows to interpolate between two possible interpretations. In the first interpretation, the results provide a strong evidence of the existence of new physics, dominated by the positive contribution of a CP-even scalar. In the second one, supported by the recent lattice result, the data provides a strong upper bound on new physics, specifically in the case of (negative) pseudoscalar contributions. We emphasize that tree-level signatures of the new degrees of freedom of the model are enhanced relative to conventional explanations of the discrepancy. As a result, this model can be tested in the near future with accelerator-based experiments and possibly also at the precision frontier.

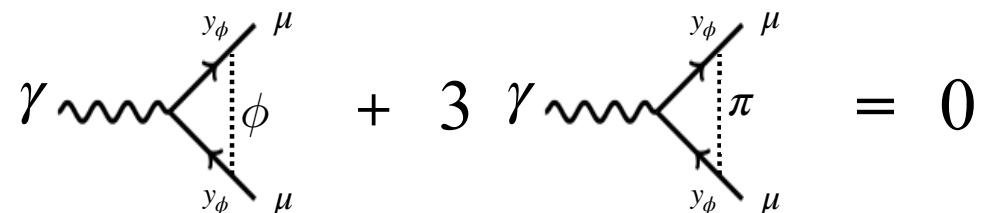
## The model

$$-\mathcal{L} \supset \frac{1}{2} m_\sigma^2 \sigma^T \cdot \sigma + (\sigma^T \cdot \hat{y} \cdot \varepsilon \ell^c + m^\dagger \cdot \varepsilon \ell^c + \text{h.c.})$$



$$\sigma = \begin{pmatrix} \phi \\ \pi_1 \\ \pi_2 \\ \pi_3 \end{pmatrix}$$

Model requires 3 light pseudo scalars & 1 scalar



# Experimental status, NA62 vs KOTO

$$\text{BR} (K^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{NA62}} = (11.0 \pm 4.0) \times 10^{-11} \implies 3.5 \sigma! \quad [\text{SM} : (9.1 \pm 0.7) \times 10^{-11}]$$

$$''\text{BR} (K_L \rightarrow \pi^0 \nu \bar{\nu})_{\text{KOTO}} \lesssim 4 \times 10^{-9}'' \quad [\text{SM} : (3.0 \pm 0.3) \times 10^{-11}]$$

Update (this year) 2012.07571:

$$\text{BR} (K_L \rightarrow \pi^0 \nu \bar{\nu})_{\text{KOTO}} \lesssim 5 \times 10^{-9}$$

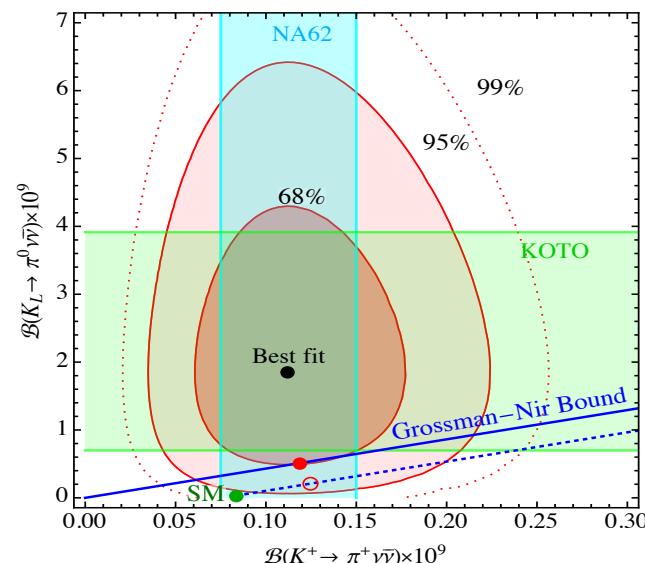
BG  $\sim 1.22$

Kitahara, Okui, GP, Soreq & Tobioka (19)

Tobioka, POST ICHEP 20:

(A)  $K^+$  BG based on MC

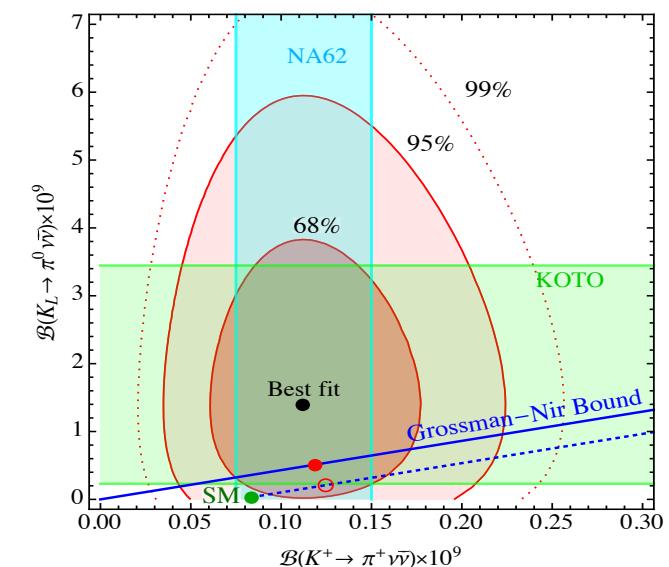
$$B = \mathbf{0.39} \pm 0.10$$



- SM:  $2.6\sigma$
- GN tension:  $1.5\sigma$

(B)  $K^+$  BG MC **x3** [special run]

$$B = \mathbf{1.05} \pm 0.28$$



- $1.7\sigma$
- $0.9\sigma$

# Luminosity & precision: the era of Kaon factories

Power of Kaons: scalar that mixes with the Higgs.

