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Physics Beyond Colliders

Exploring Physics Beyond the Standard Model

J. Jaeckel

Special Thanks to all my collaborators,
the Physics Beyond Colliders Study Group,
Claude Vallee, Gianluigi Arduini and Mike Lamont
and in particular also Gaia Lanfranchi and Felix Kahlhoefer
+ all participants of the many PBC workshops

Many slides, pictures etc from talks at PBC workshops

PBC is all about Exploration

Very wrong...

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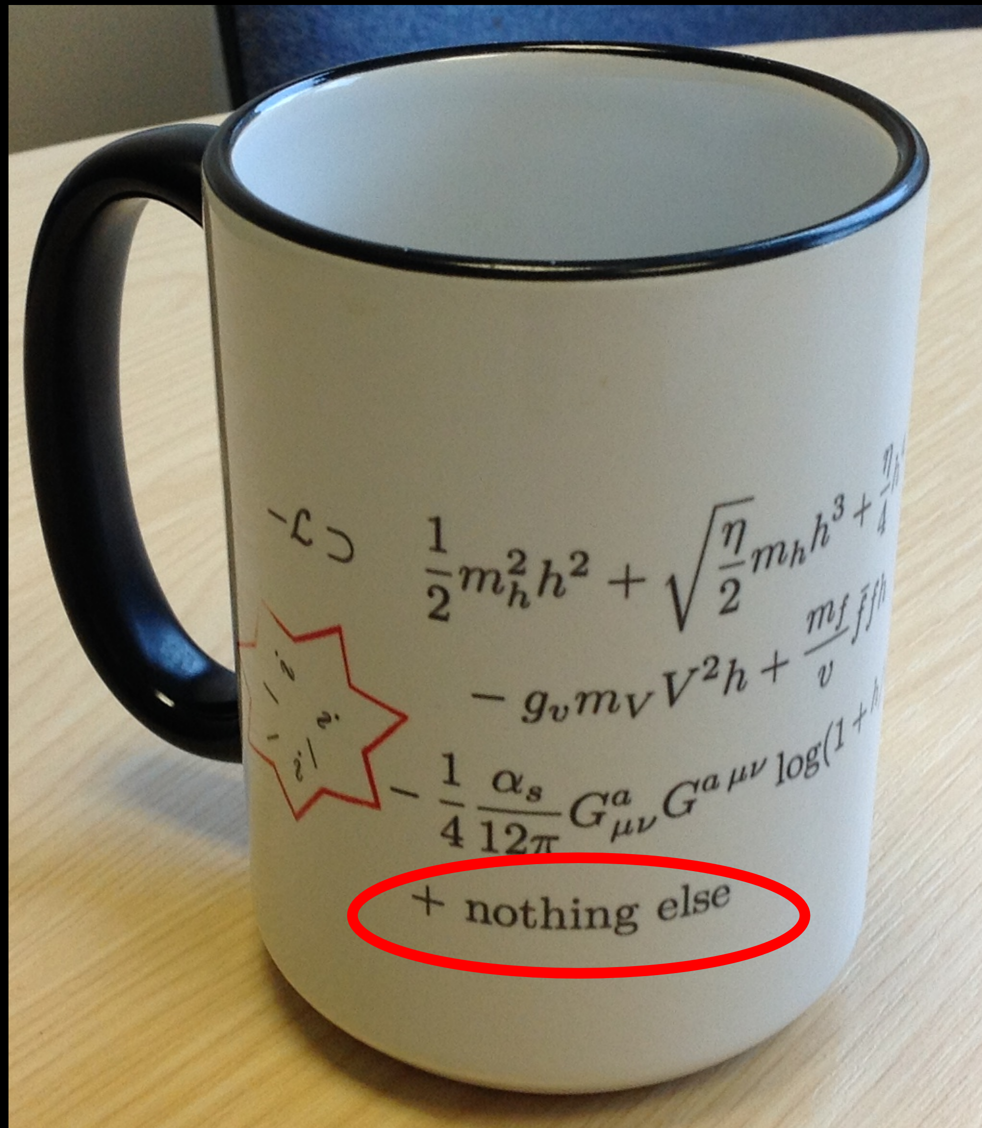

Inventory of the (mostly INVISIBLE) Universe

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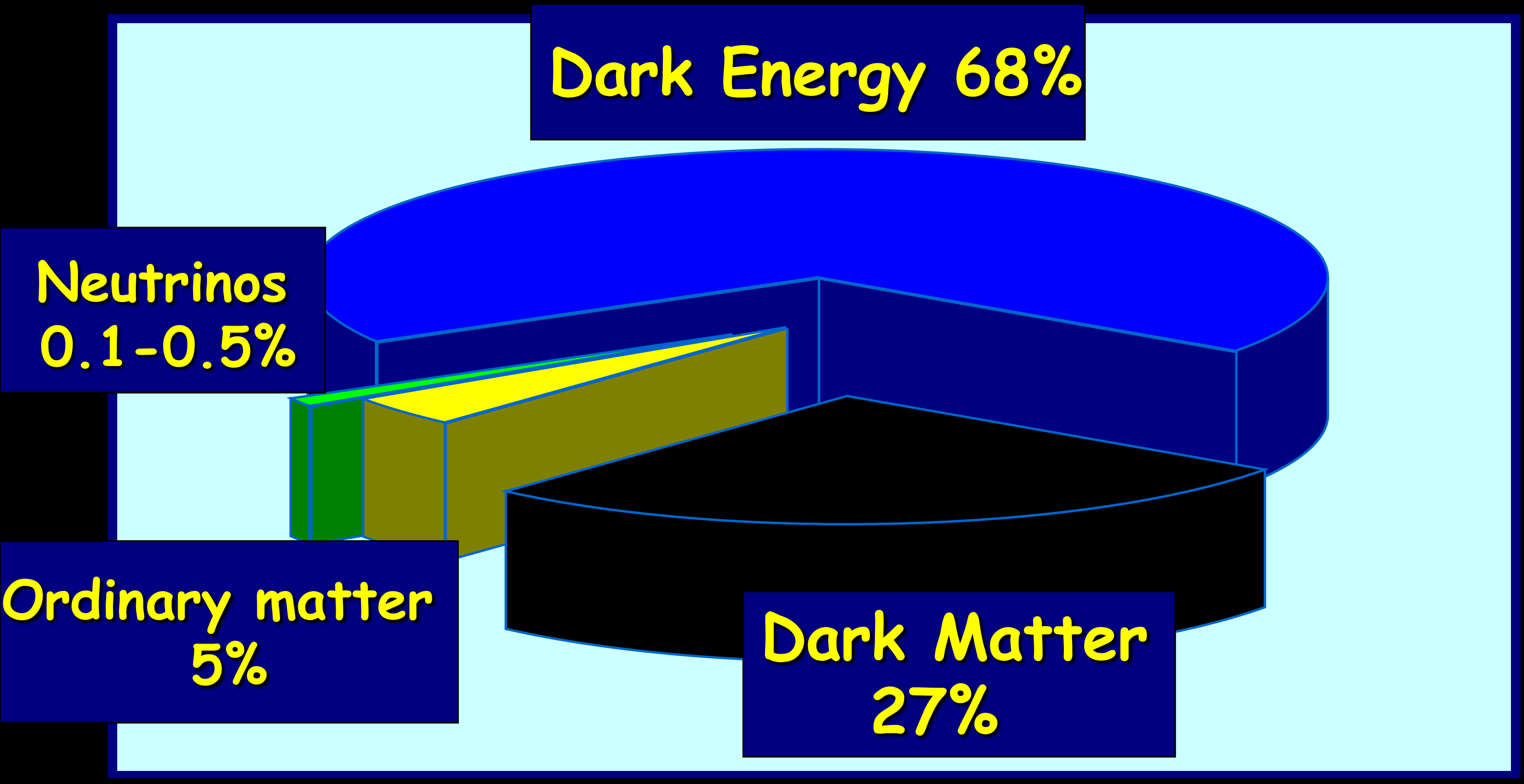

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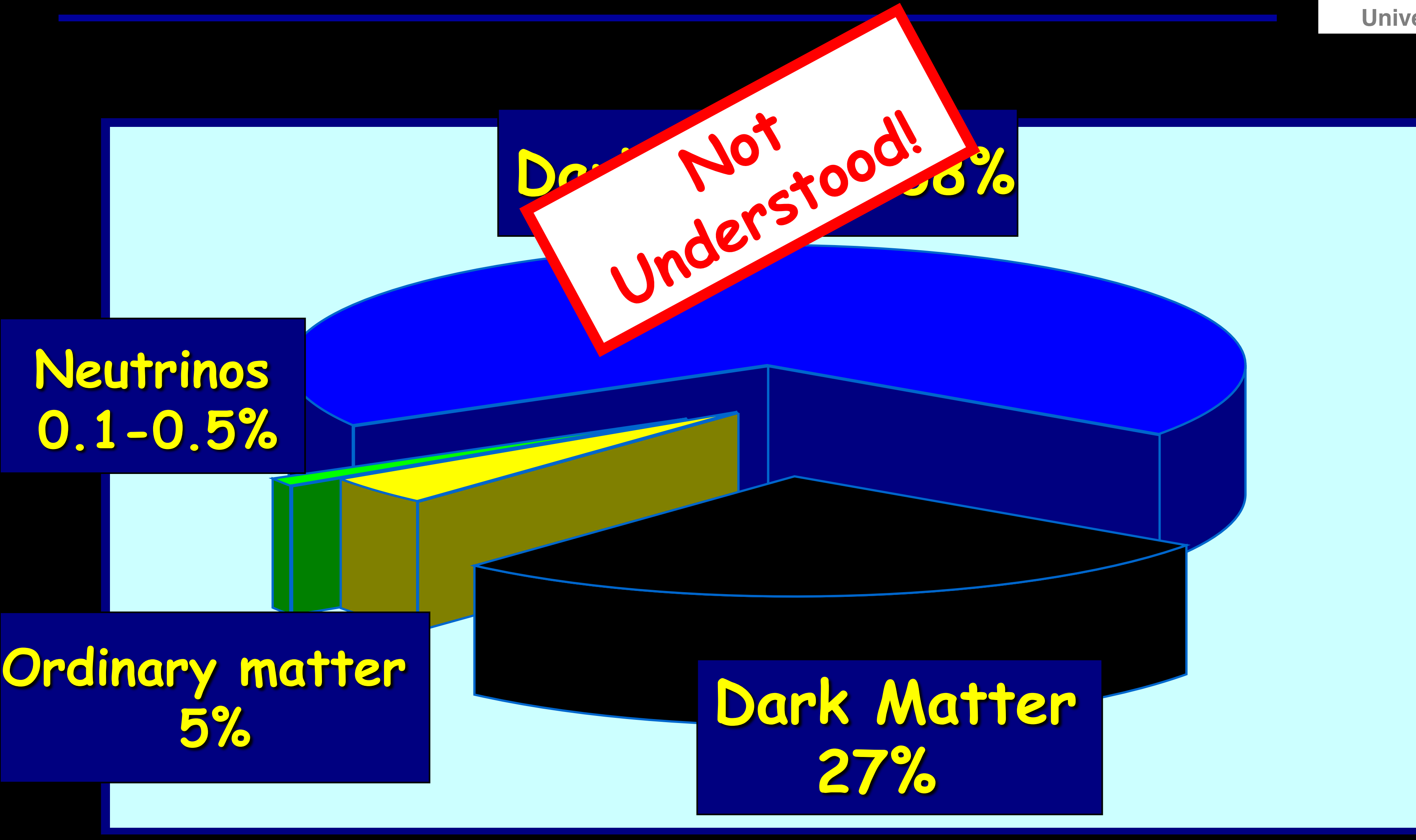

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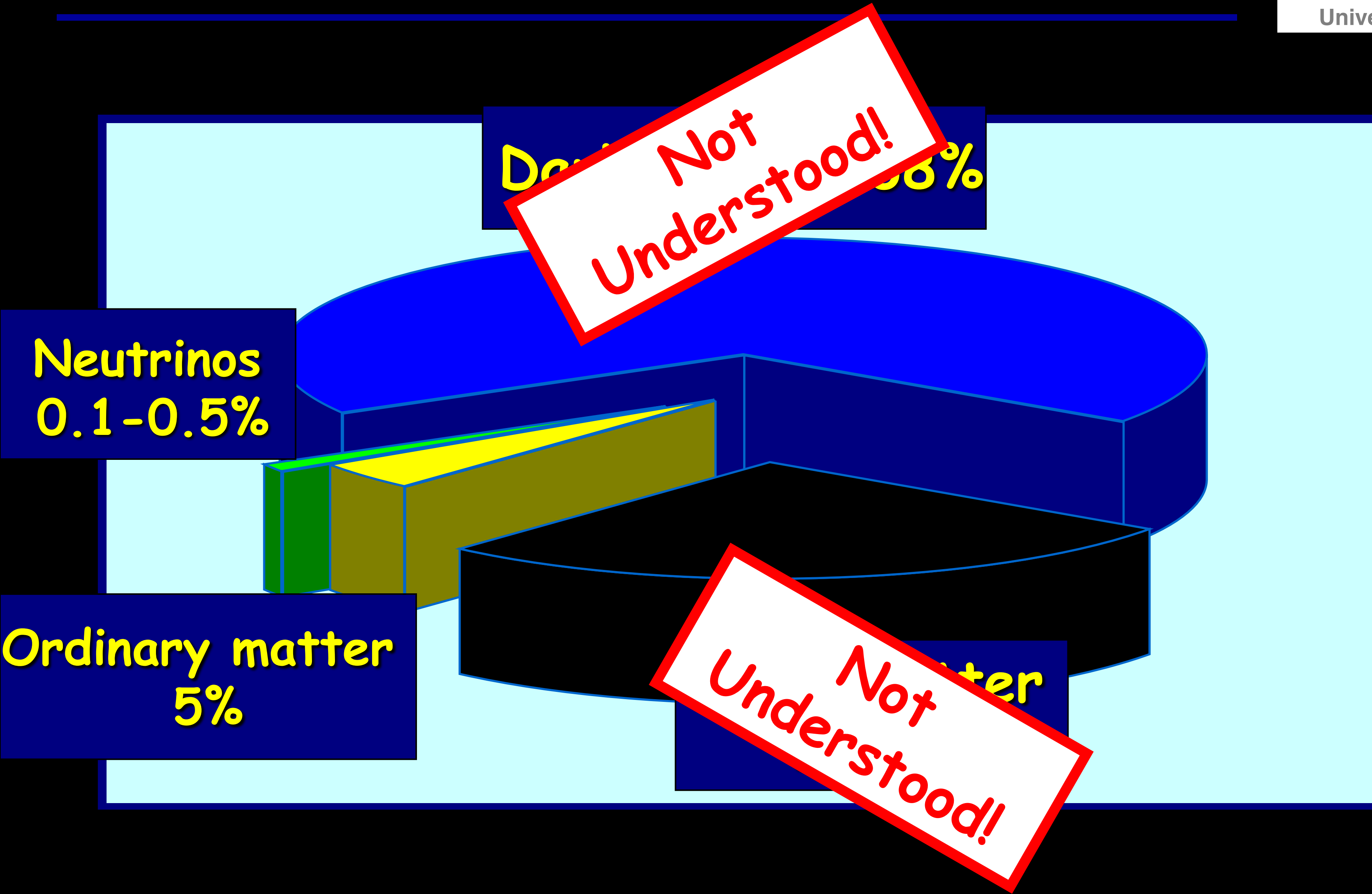

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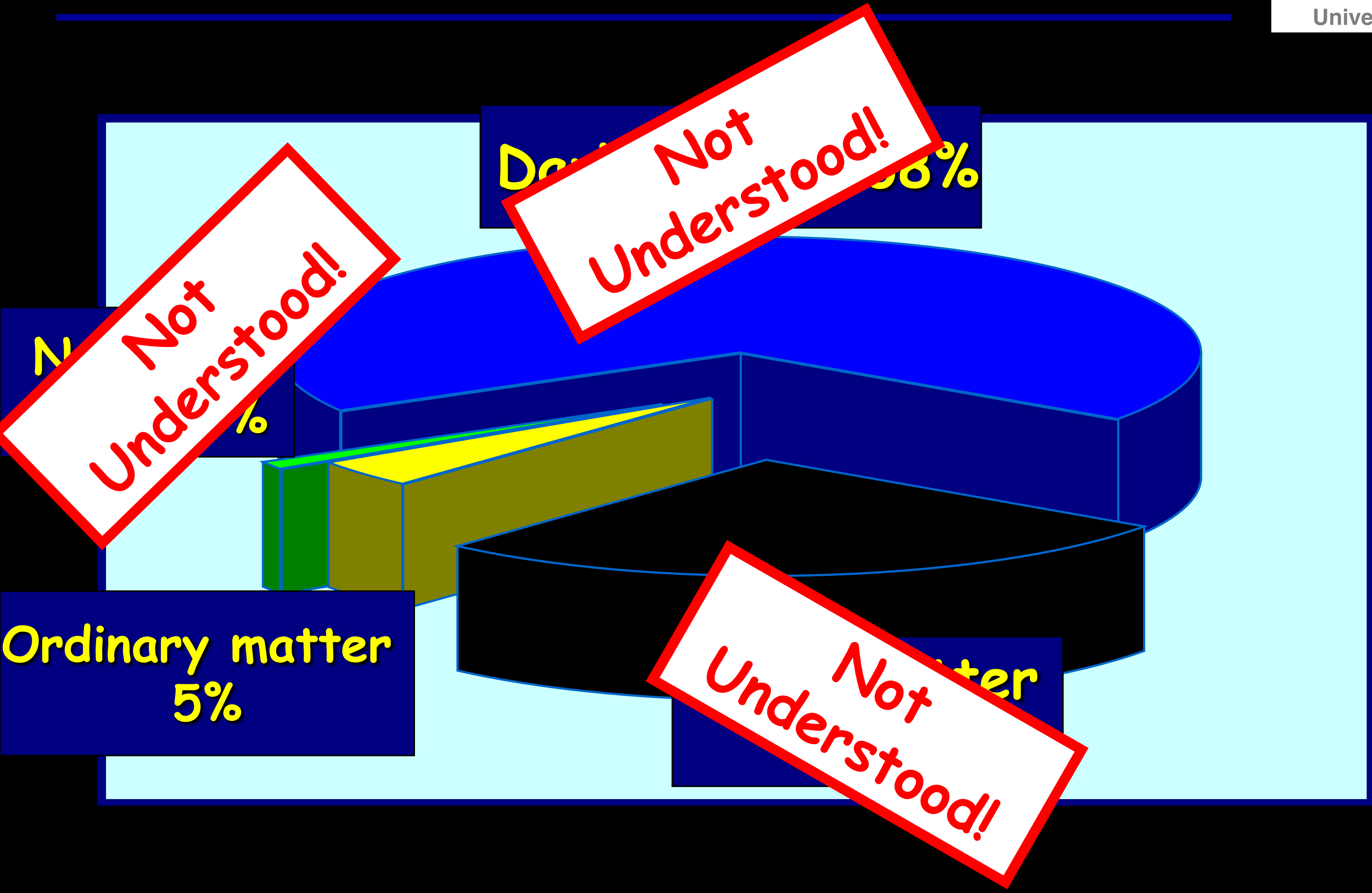

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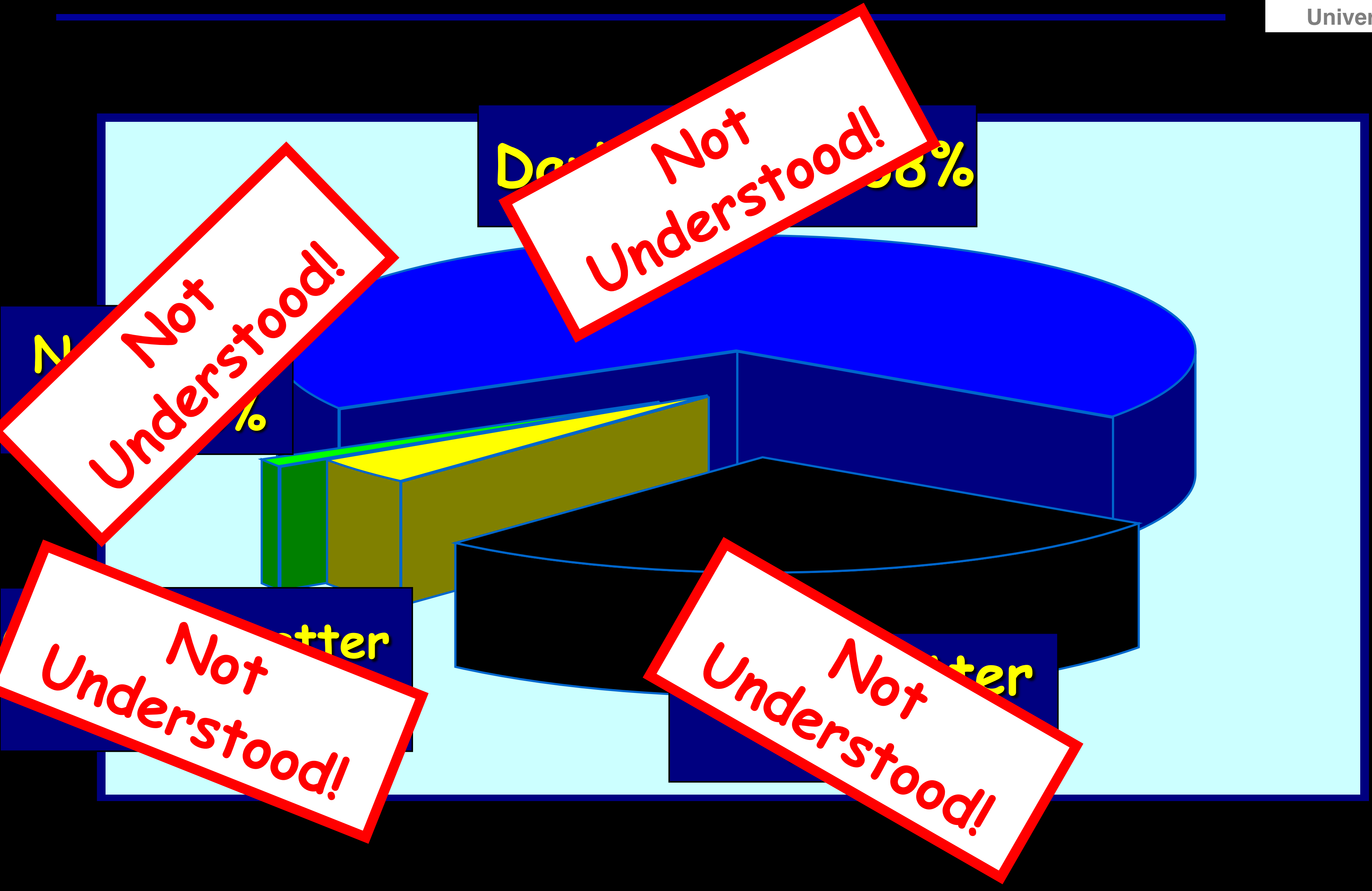

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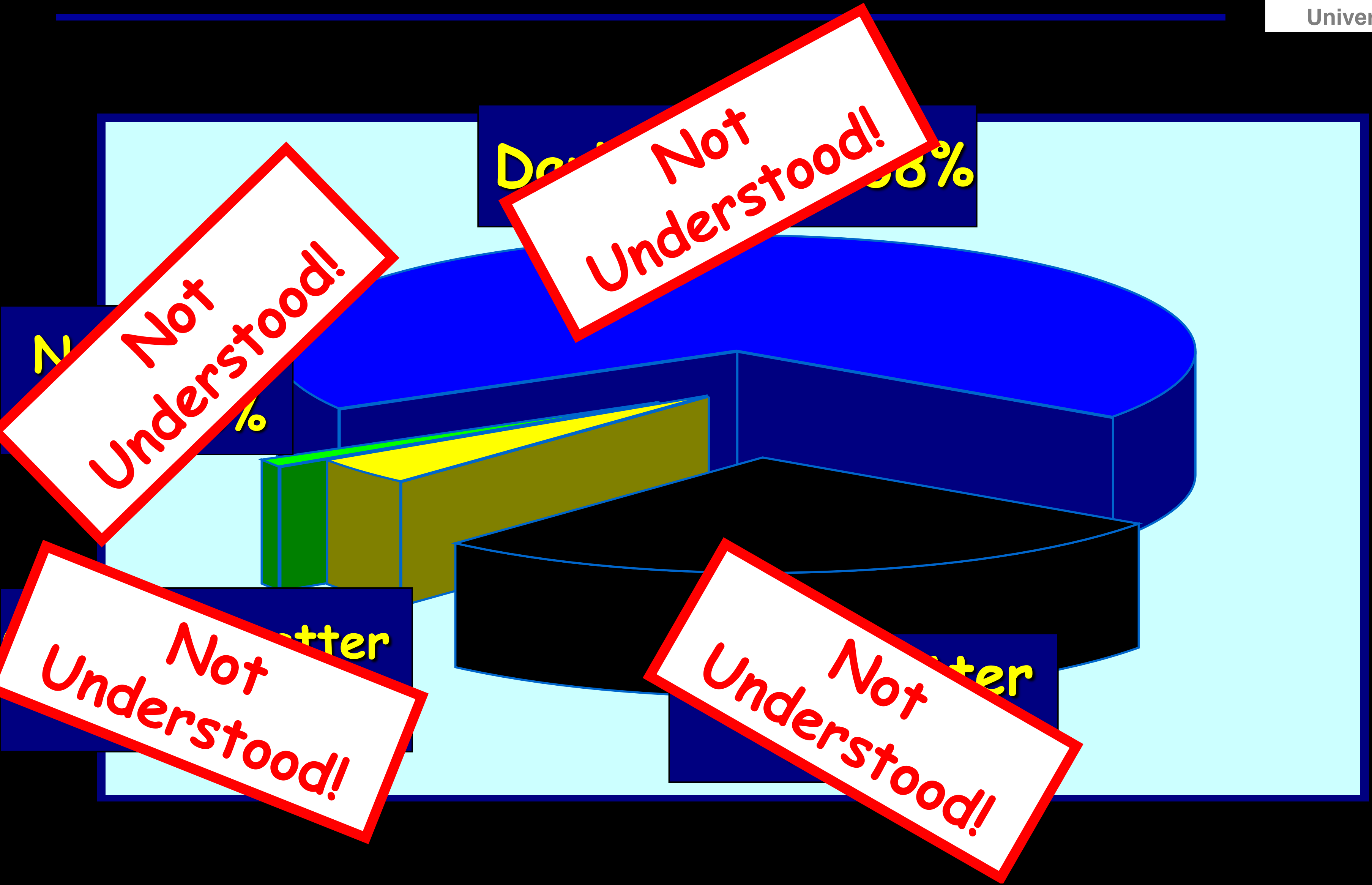

Unimaginable riches to be found ;-) → Go Explore

Testing of models fostering Exploration

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An early example (16th-18th Century):

You want to go to explore the southern hemisphere

If you want to explore: ask a theorist ;-)

16th Century Theorist: Gerardus Mercator

16th Century Theory: Terra Australis

https://en.wikipedia.org/wiki/Gerardus_Mercator#/media/File:Gerardus_Mercator_3.jpg

Testing of models fostering Exploration

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Gerardus Mercator on the need for the existence of Terra Australis:

„...demonstrated and proved by solid reasons and arguments to yield in its geometric proportions, size and weight, and importance to neither of the other two, nor possibly to be lesser or smaller, otherwise the constitution of the world could not hold together at its centre.“ (according to Walter Ghim cf. Wikipedia Terra Australis)

Theorists don't lack confidence in their results

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Testing of models fostering Exploration

Gerardus Mercator on the need for the existence of Terra Australis:

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Some theory gibberish

Testing of models fostering Exploration

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All other theories are, of course, completely wrong

Testing of models fostering Exploration

Gerardus Mercator on the need for the existence of Terra Australis:

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Draw Map with Predicted Terra Australis

https://en.wikipedia.org/wiki/Terra_Australis#/media/File:Typus_Orbis_Terrarum_drawn_by_Abraham_Ortelius.jpg

Testing of models fostering Exploration

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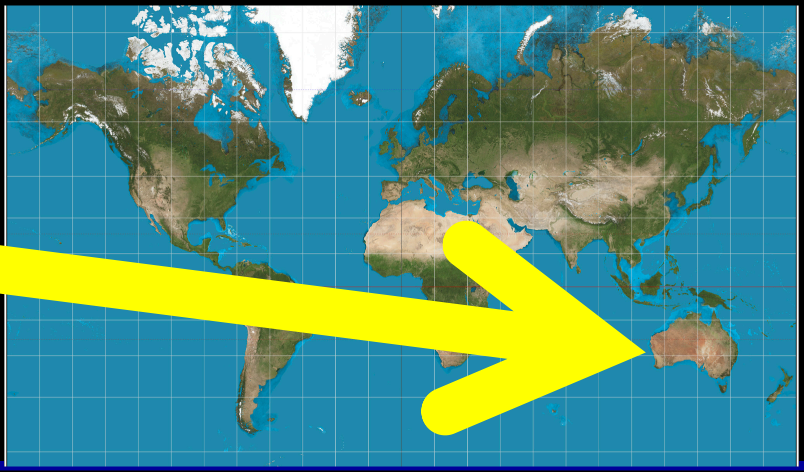
„Experimentally“ Discovered: Australia



https://en.wikipedia.org/wiki/World_map#/media/File:Mercator_projection_SW.jpg

Testing of models fostering Exploration

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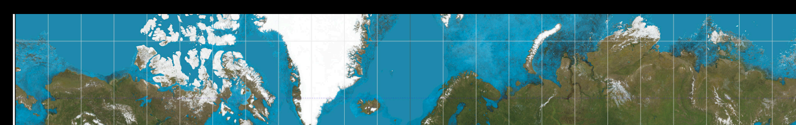
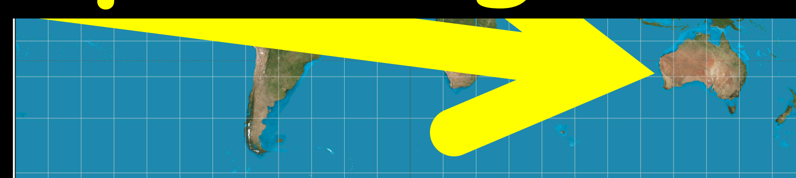


➔ **Draw a Map and go explore**

Australia



https://en.wikipedia.org/wiki/World_map#/media/File:Mercator_projection_SW.jpg

Drawing a Map:
Where is the New Physics?

Exploring is (at least) 2 dimensional

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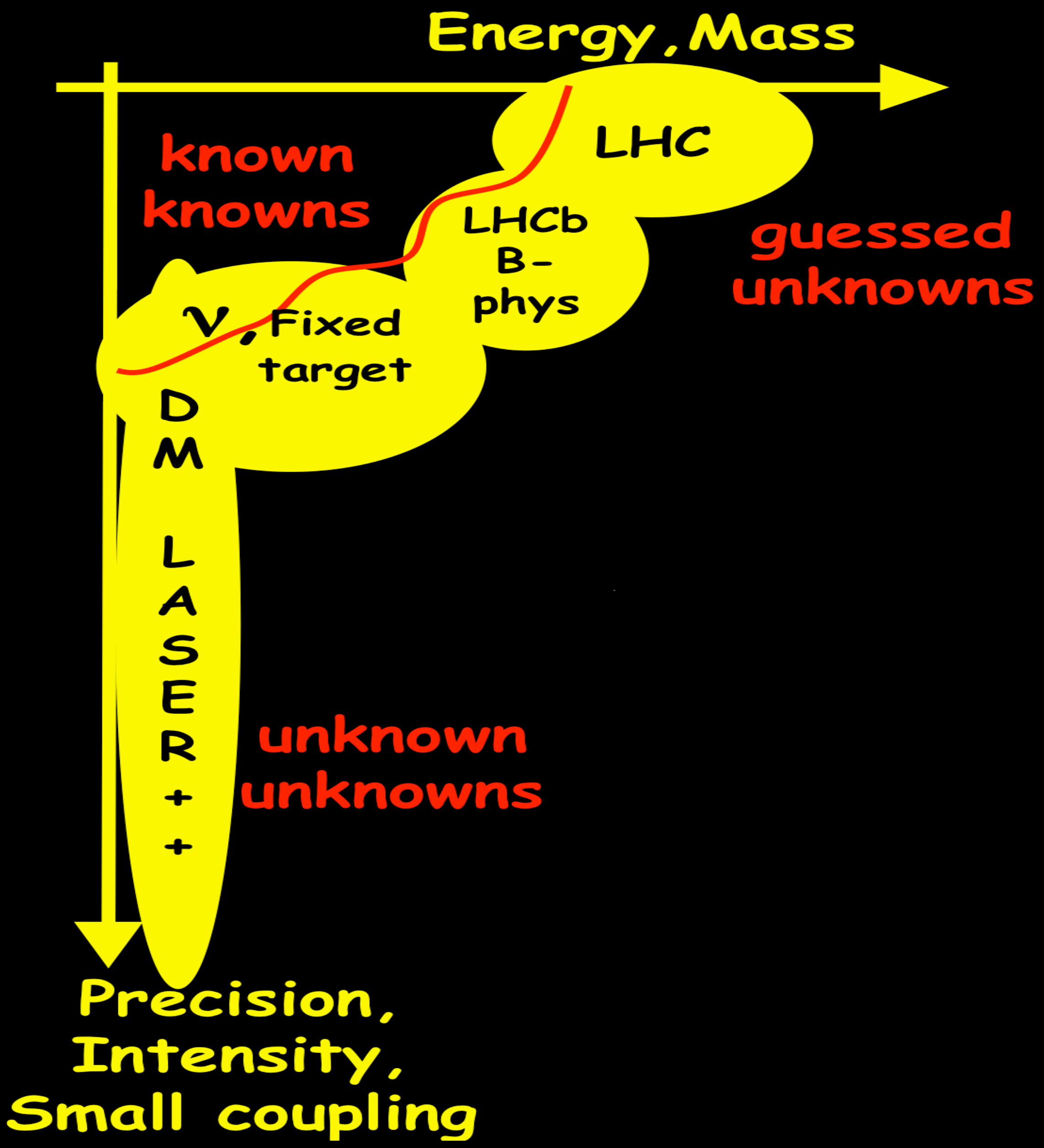

Exciting times

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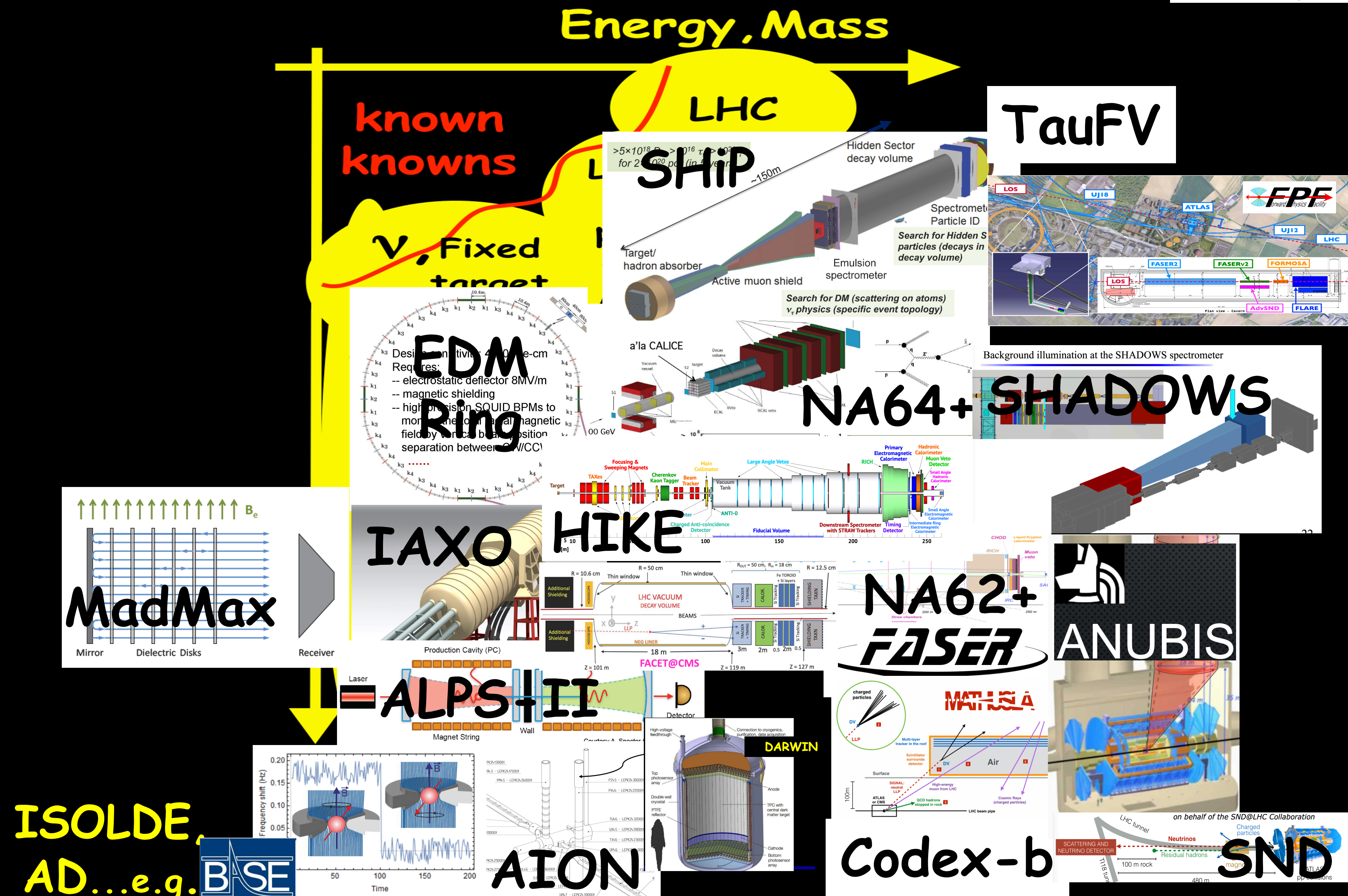

An example:

Axions,
axion like particles,
general pseudo-Goldstone bosons

This is only an example

Many more cool and interesting models to test!!!

see, e.g., 1901.09966

The example:
Axions,
axion like particles,
general pseudo-Goldstone bosons

On the Elliptic Calabi-Yau Fourfold with Maximal $h^{1,1}$

Yi-Nan Wang[a]

ABSTRACT: In this paper, we explicitly construct the smooth compact base threefold for the elliptic Calabi-Yau fourfold with the largest known $h^{1,1} = 303\,148$. It is generated by blowing up a smooth toric "seed" base threefold with (E_8, E_8, E_8) collisions. The 4d F-theory compactification model over it has the largest geometric gauge group, $E_8^{2\,561} \times F_4^{7\,576} \times G_2^{20\,168} \times SU(2)^{30\,200}$, and the largest number of axions, 181 820, in the known 4d $\mathcal{N} = 1$ supergravity landscape. We also prove that there are at least $1100^{15\,048} \approx 7.5 \times 10^{45\,766}$ different flop phases of this base threefold. Moreover, we find that many other base threefolds with large $h^{1,1}$ in the 4d F-theory landscape can be constructed in a similar way as well.

https://arxiv.org/pdf/2001.07258.pdf

What is a Goldstone Boson?

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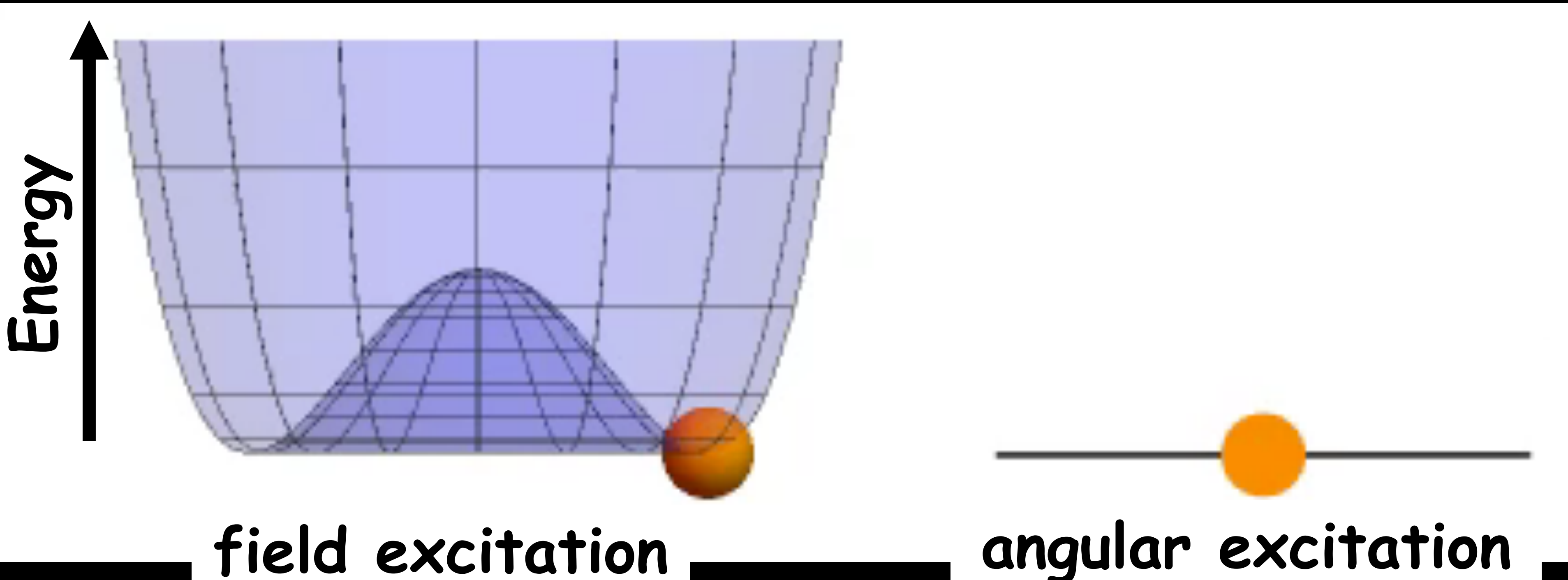
- Let us start with a U(1)/rotation symmetric potential



→ If you move along the minimum, it costs no energy to move around

→ Particle is massless

What is a pseudo-Goldstone Boson?

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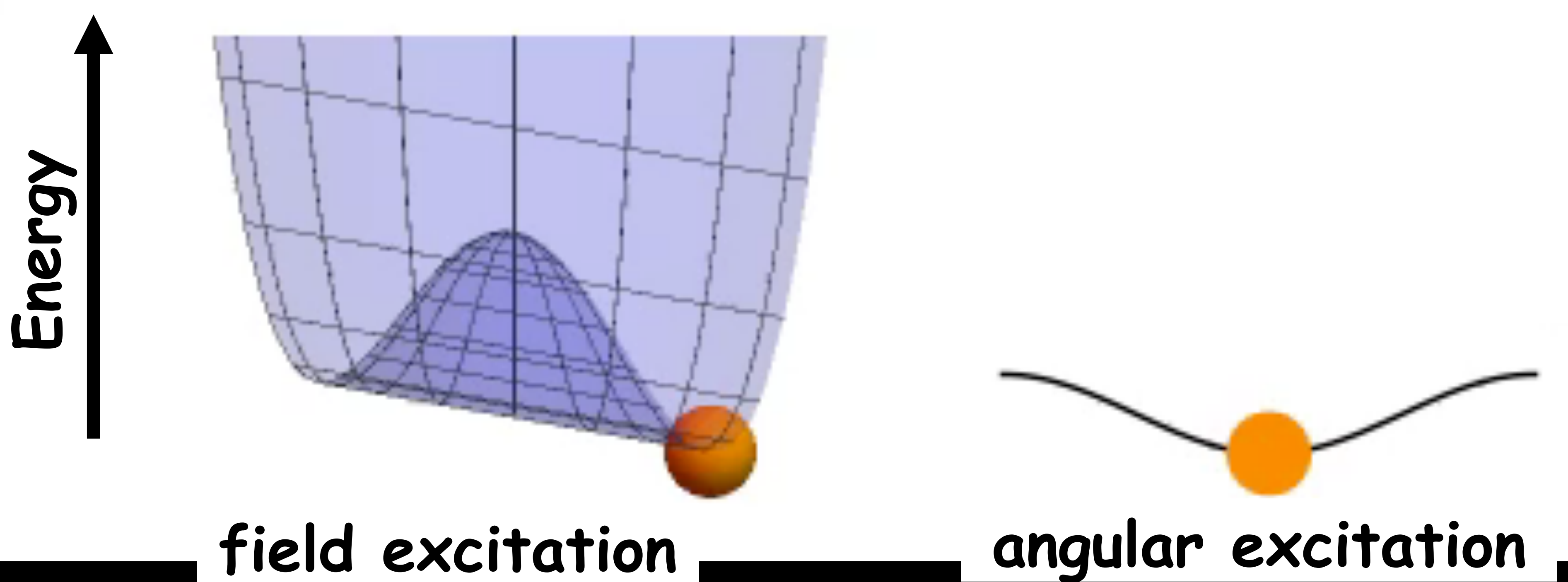
- Add a small breaking of U(1)/rotation symmetry



➔ If you move along the minimum, it costs a little bit of energy

➔ Particle has a small mass

What is a pseudo-Goldstone Boson?

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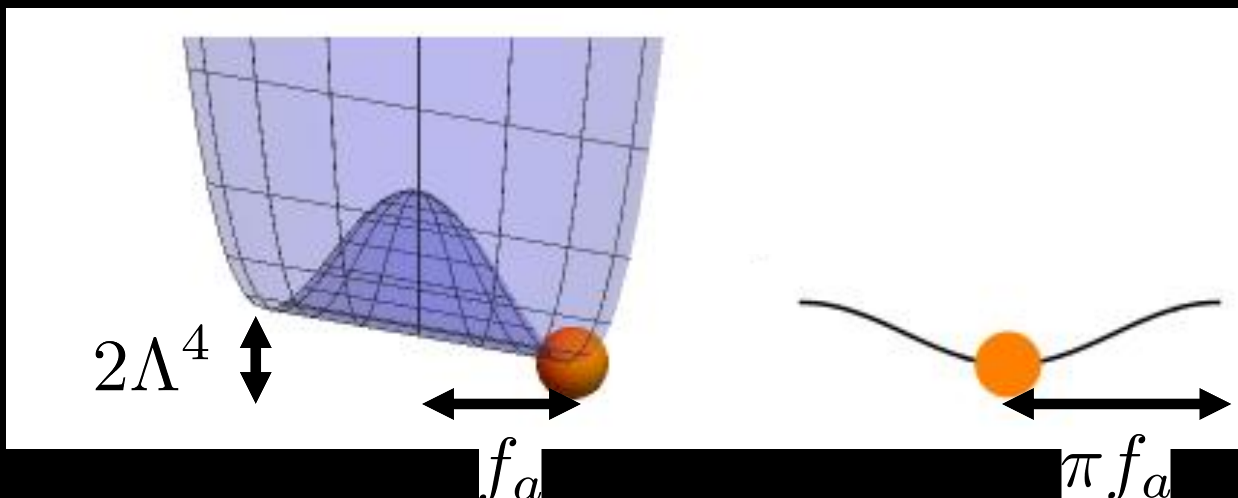
- Add a small breaking of U(1)/rotation symmetry



$$V(a) = \Lambda^4 \left[1 - \cos\left(\frac{a}{f_a}\right)\right]$$

very small

$$\text{mass}^2 = m_X^2 = V''(0) = \frac{\Lambda^4}{f_a^2}$$

small

large

Message:

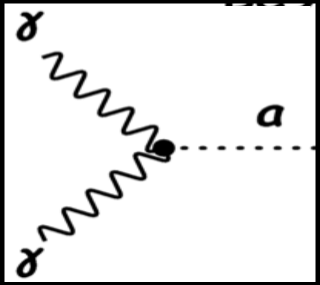
Large scale f_a

↓

Small mass

Couplings fixed by scale of symmetry breaking: f_a

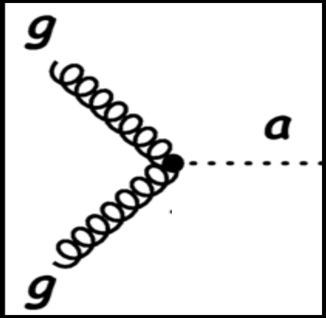
- Photon coupling



$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma} a F^{\mu} \tilde{F}_{\mu\nu}$$

$$g_{a\gamma\gamma} \sim \frac{\alpha}{4\pi f_a}$$

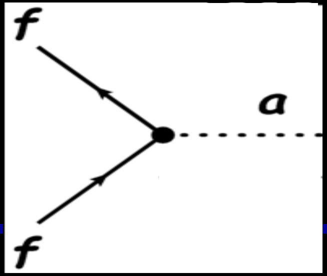
- Gluon coupling



$$\mathcal{L} \supset \frac{1}{4} g_{agg} a G^{\mu} \tilde{G}_{\mu\nu}$$

$$g_{agg} \sim \frac{\alpha_s}{2\pi f_a}$$

- Fermion couplings



$$\mathcal{L} \supset g_{a\psi\psi} a \bar{\psi} \gamma^5 \psi$$

$$g_{a\psi\psi} \sim \frac{m_\psi}{f_a}$$

Couplings fixed by scale of symmetry breaking: f_a

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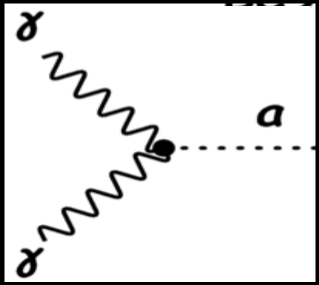
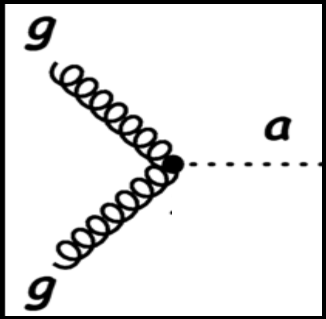
- Photon coupling



$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma} a F^{\mu} \tilde{F}_{\mu\nu}$$

small → $$g_{a\gamma\gamma} \sim \frac{\alpha}{4\pi f_a}$$ ← large

- Gluon coupling



$$\mathcal{L} \supset \frac{1}{4} g_{agg} a G^{\mu} \tilde{G}_{\mu\nu}$$

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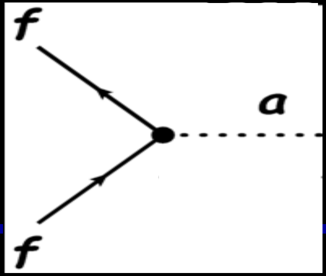
- Fermion couplings



$$\mathcal{L} \supset g_{a\psi\psi} a \bar{\psi} \gamma^5 \psi$$

small → $$g_{a\psi\psi} \sim \frac{m_\psi}{f_a}$$ ← large

Message:

Large scale f_a

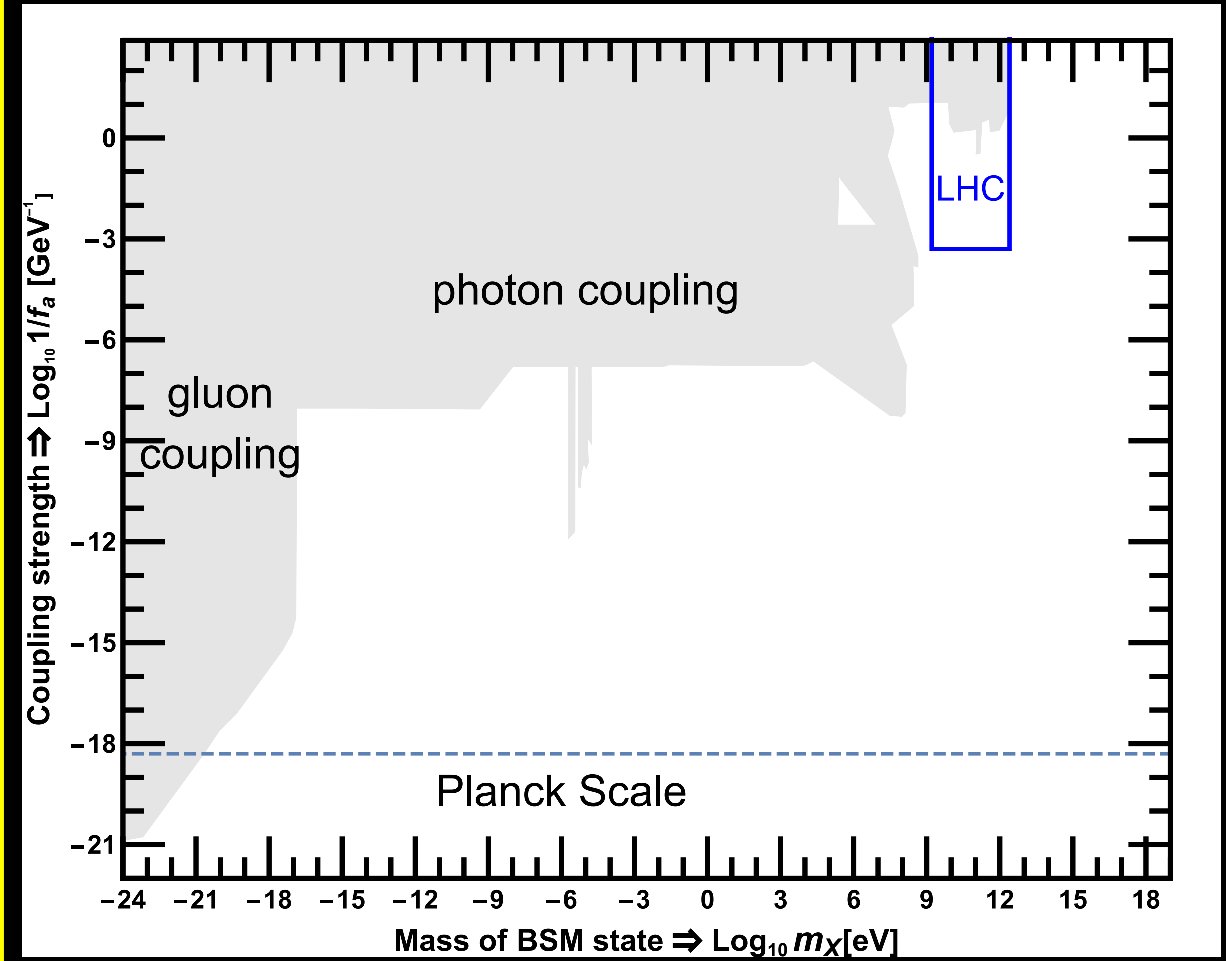
↓

Small coupling

Drawing our map

Target space

High mass



Small coupling

String theory: Moduli and Axions

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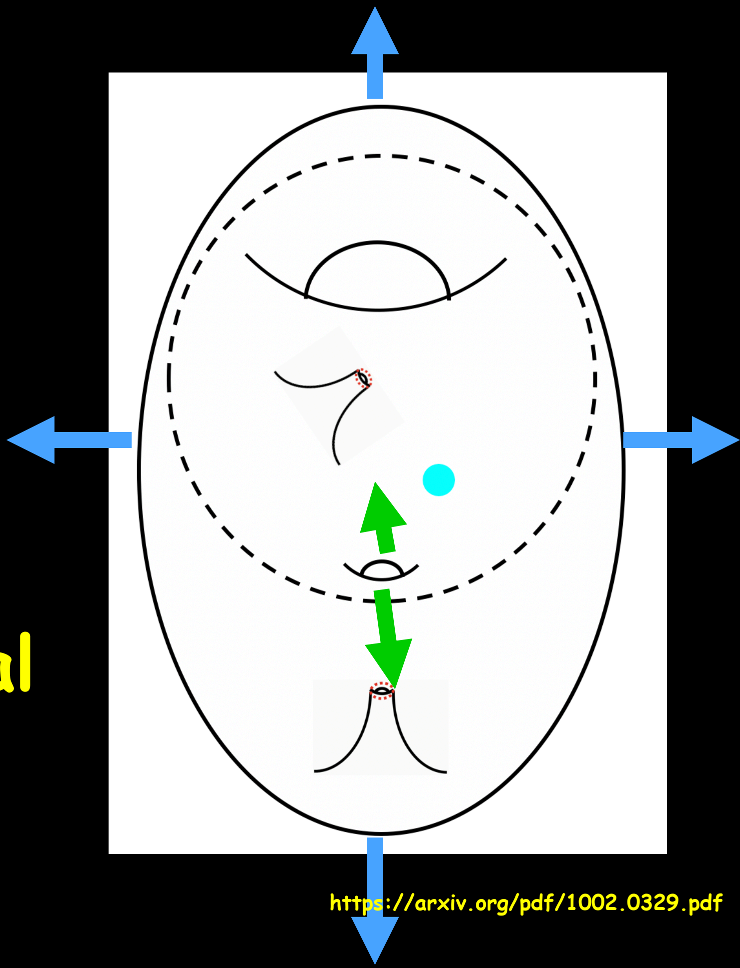
- String theory needs Extra Dimensions

Must compactify

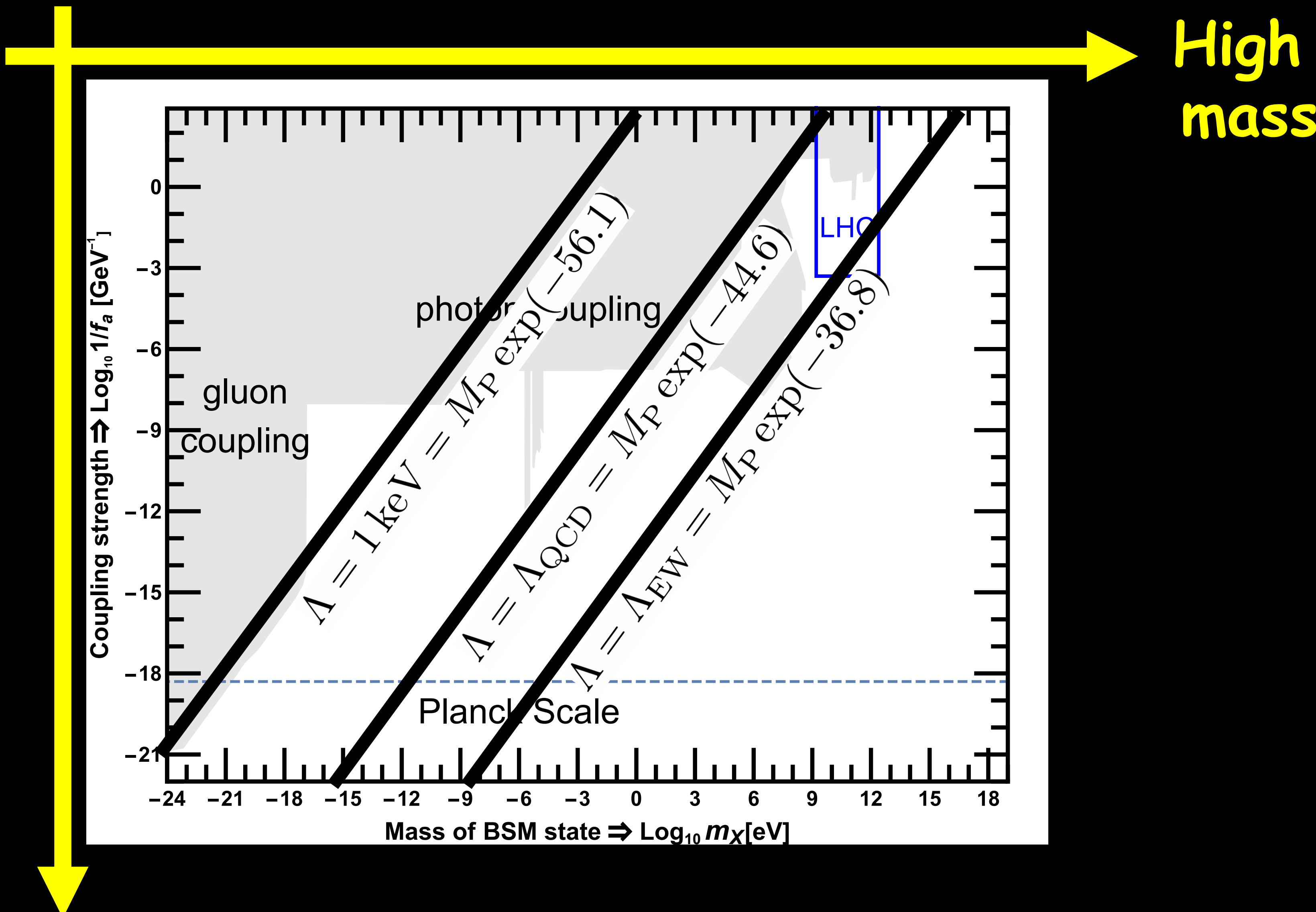
- Shape and size deformations correspond to fields:
  Moduli (WISPs) and Axions
  Connected to the fundamental scale, here string scale



https://arxiv.org/pdf/1002.0329.pdf

WISPs candidates

Target space



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PBC exploration

Measurement of proton EDM

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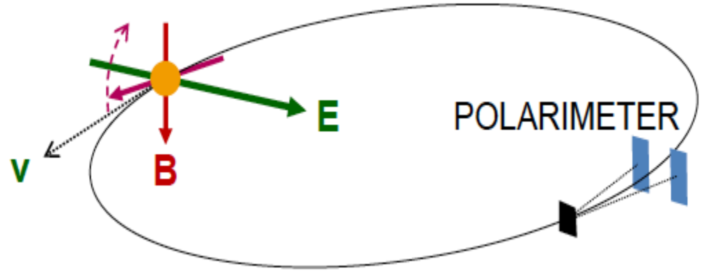
Storage ring based EDM search

- In the presence of EDM,

$$\frac{d\vec{S}}{dt} = \frac{e}{\gamma m}\vec{S} \times \left[(1+G\gamma)\vec{B}_{\perp} + (1+G)\vec{B}_{\parallel} + \left(G - \frac{\gamma}{\gamma^2-1}\right)\frac{\vec{E}\times\vec{\beta}}{c} + \boldsymbol{d}(\vec{\boldsymbol{E}} + \vec{\boldsymbol{\beta}} \times \vec{\boldsymbol{B}}) \right]$$

- **Null to remove the MDM contribution to spin motion. And glue the spin vector along the particle's velocity in the horizontal plane**
  - **Non-zero EDM results in the vertical polarization buildup**

$$\frac{d\vec{S}}{dt} = \frac{e}{\gamma m}\vec{S} \times [\boldsymbol{d}(\vec{\boldsymbol{E}} + \vec{\boldsymbol{\beta}} \times \vec{\boldsymbol{B}})]$$



courtesy of E. Stephenson

⇩

Full Spin Frozen storage ring is the most effective way!

M. Bai

Physics Beyond Colliders Workshop, Sept 6-7, 2016, CERN

JÜLICH FORSCHUNGSZENTRUM

Sensitivity

$$d_p \sim 4 \times 10^{-29} e\,\mathrm{cm}$$

What is measured?

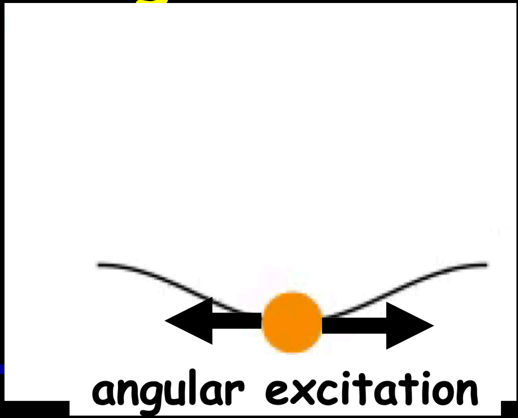
- Proton electric dipole moment ~Θ_{QCD}

$$\mathcal{L} \supset \frac{1}{4} g_{agg} a G^{\mu\nu} \tilde{G}_{\mu\nu}$$

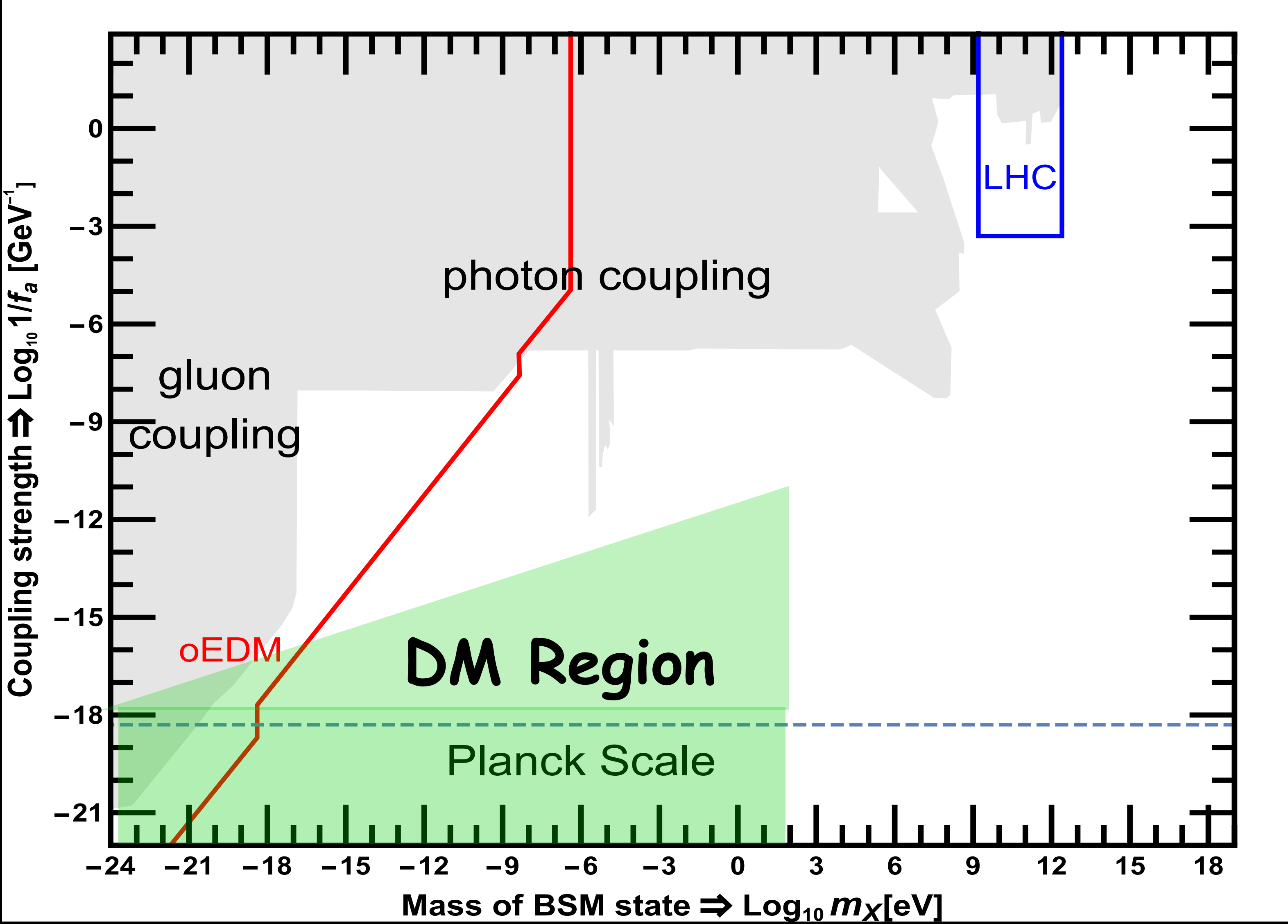
Θ_{QCD}

$$d_p \sim \theta_{QCD} 10^{-16} e\,\mathrm{cm}$$

- Sensitive to static and slowly oscillating EDM.
- If a = Dark Matter → oscillating



Sensitivity



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International Axion Observatory = IAXO

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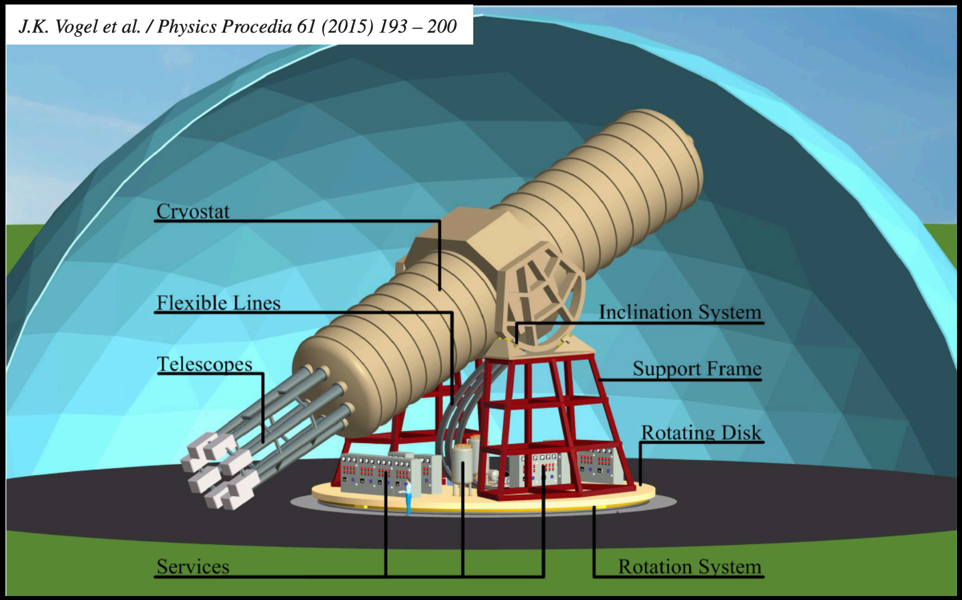
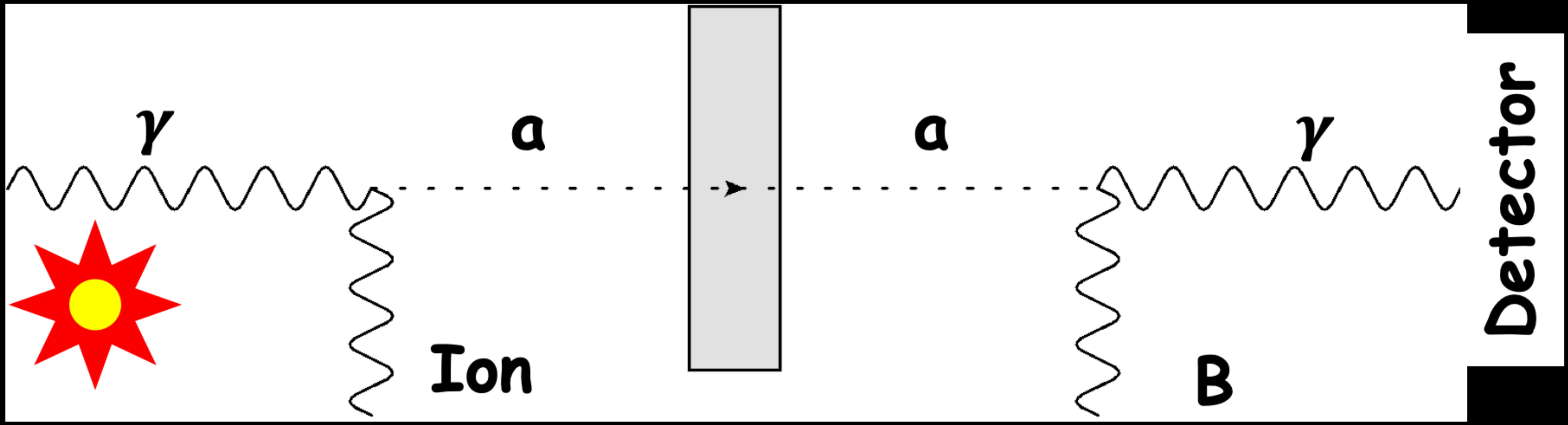
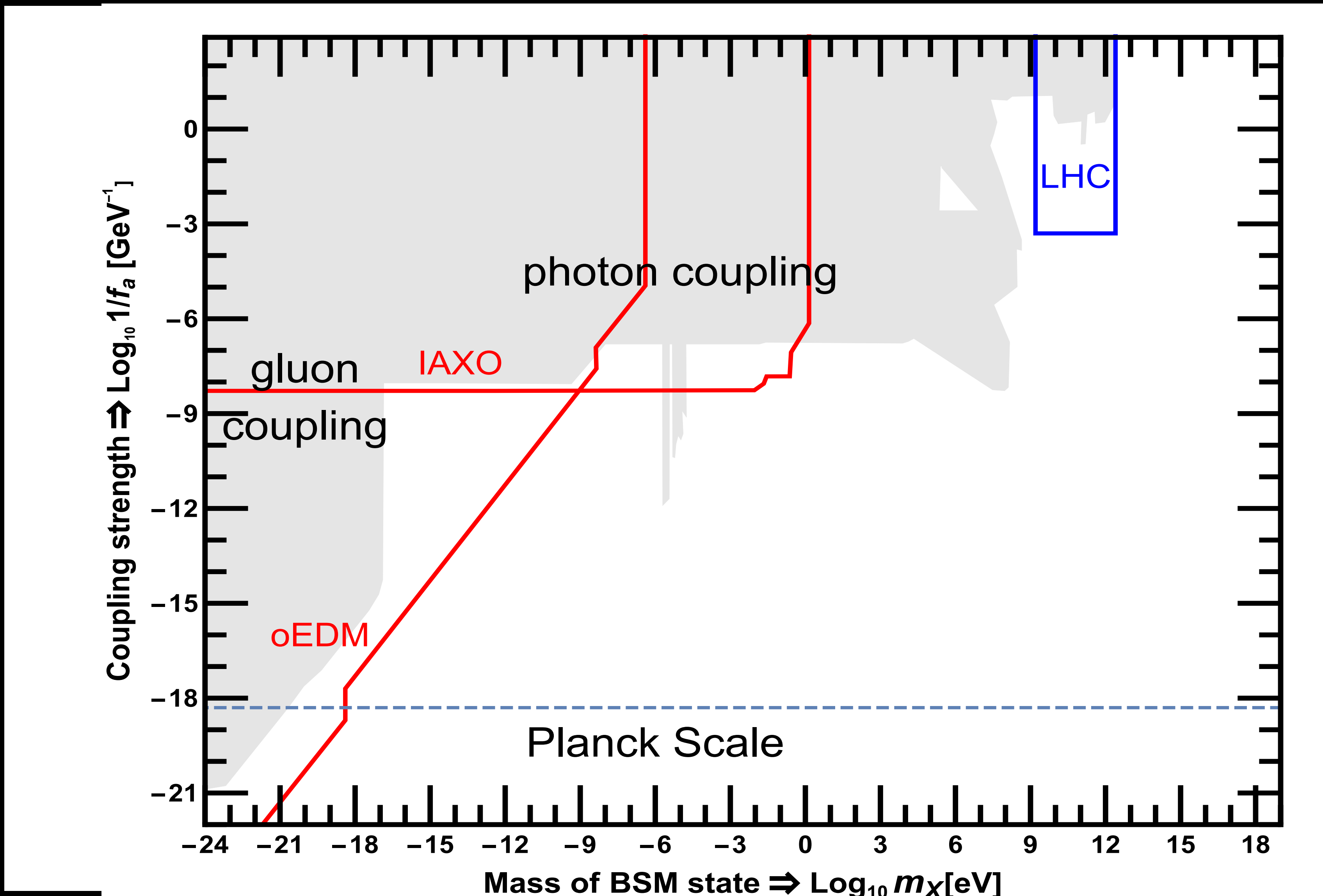


$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma} a F^{\mu} \tilde{F}_{\mu\nu}$$

Light shining through walls



Sensitivity



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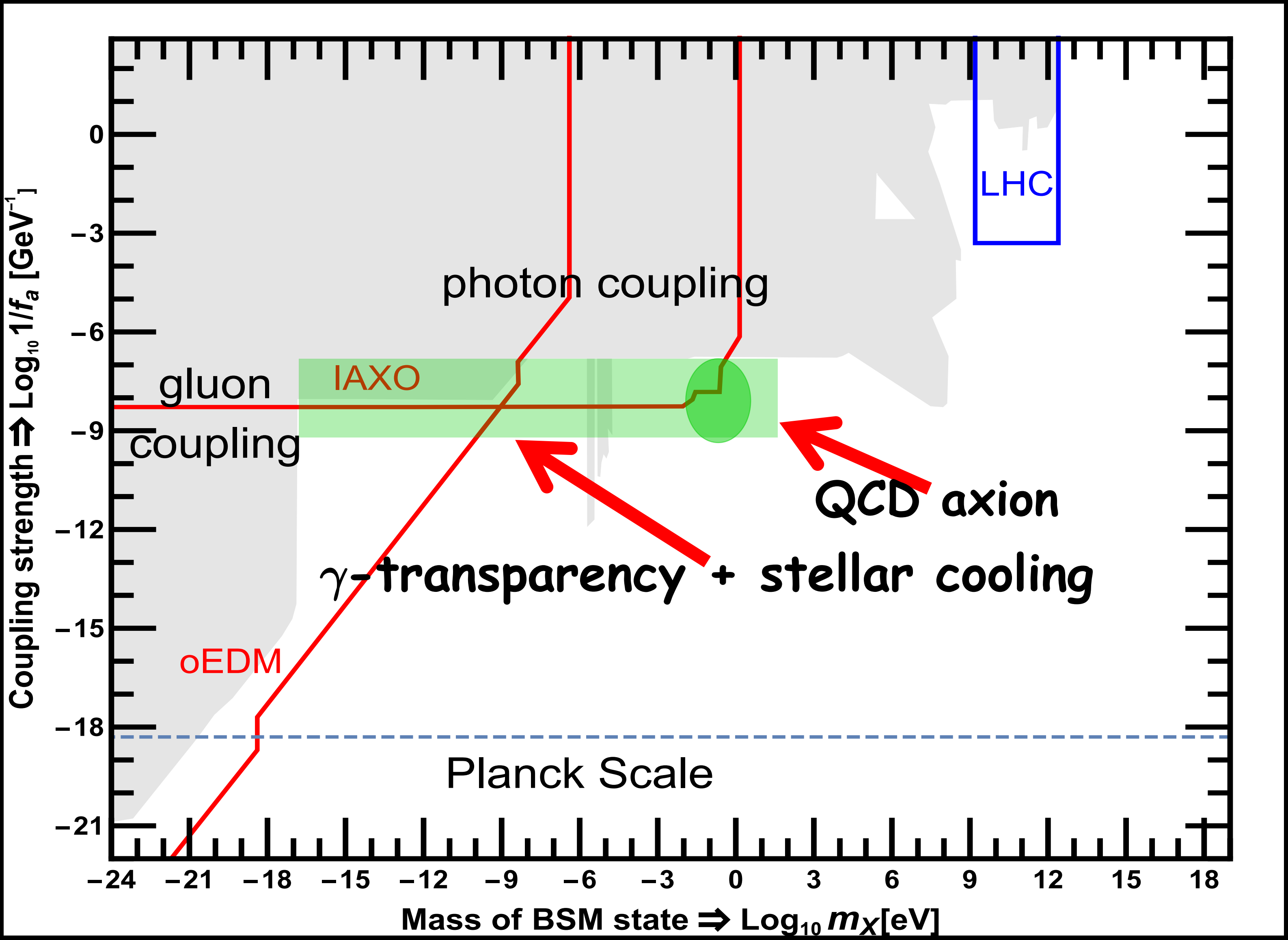
Sensitivity



More : Light shining through walls JURA

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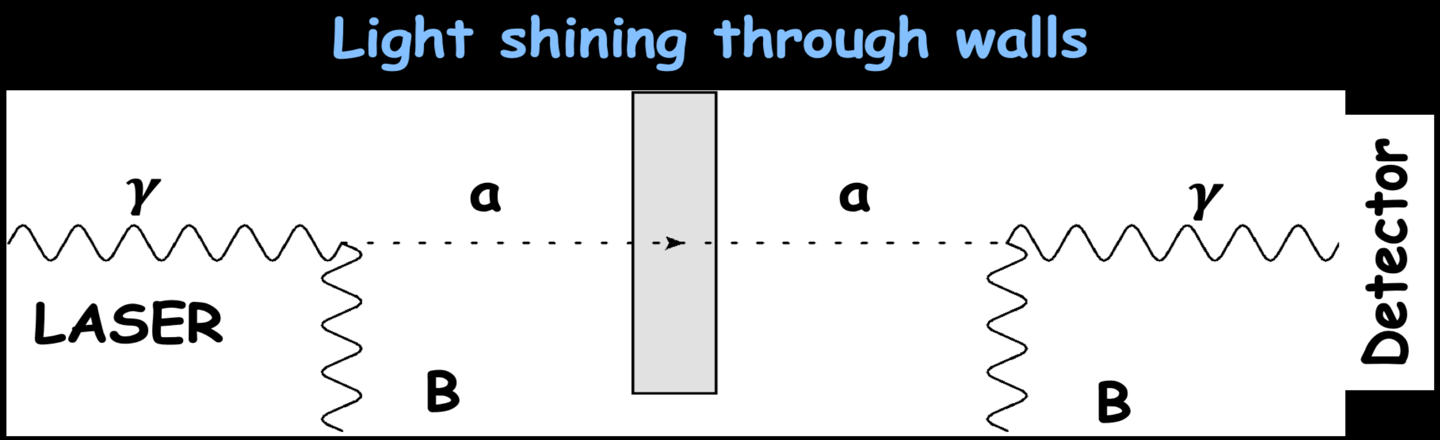

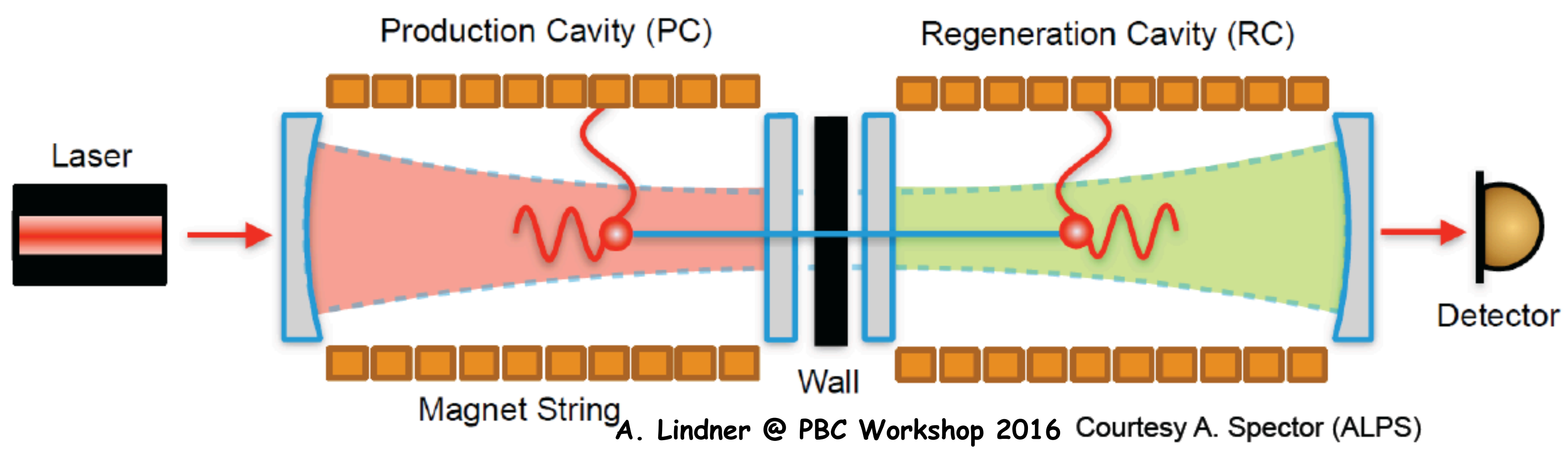

A. Lindner @ PBC Workshop 2016

Sensitivity

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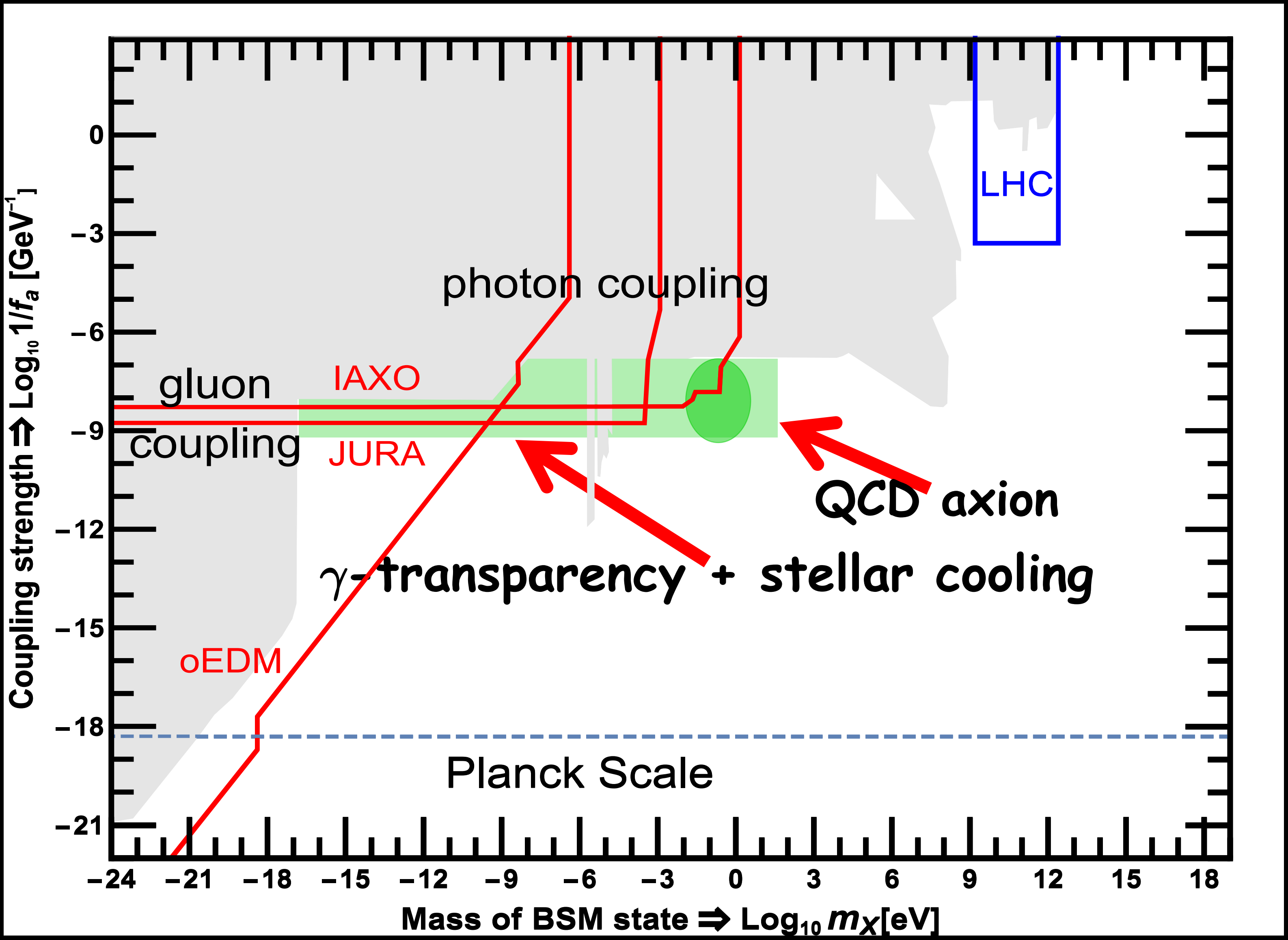

Search for Hidden Particls = SHiP

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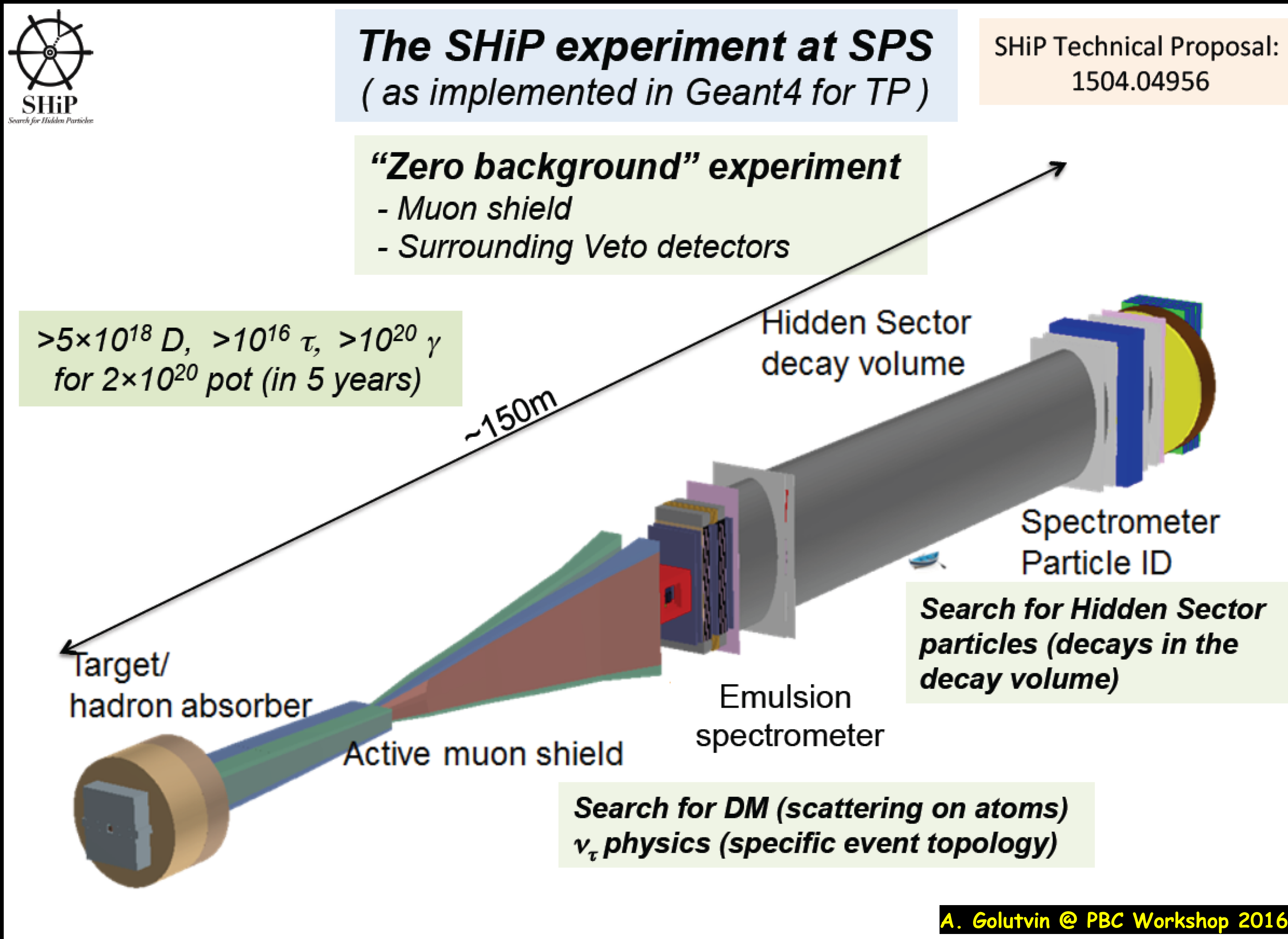

A. Golutvin @ PBC Workshop 2016

SHADOWS and HIKE

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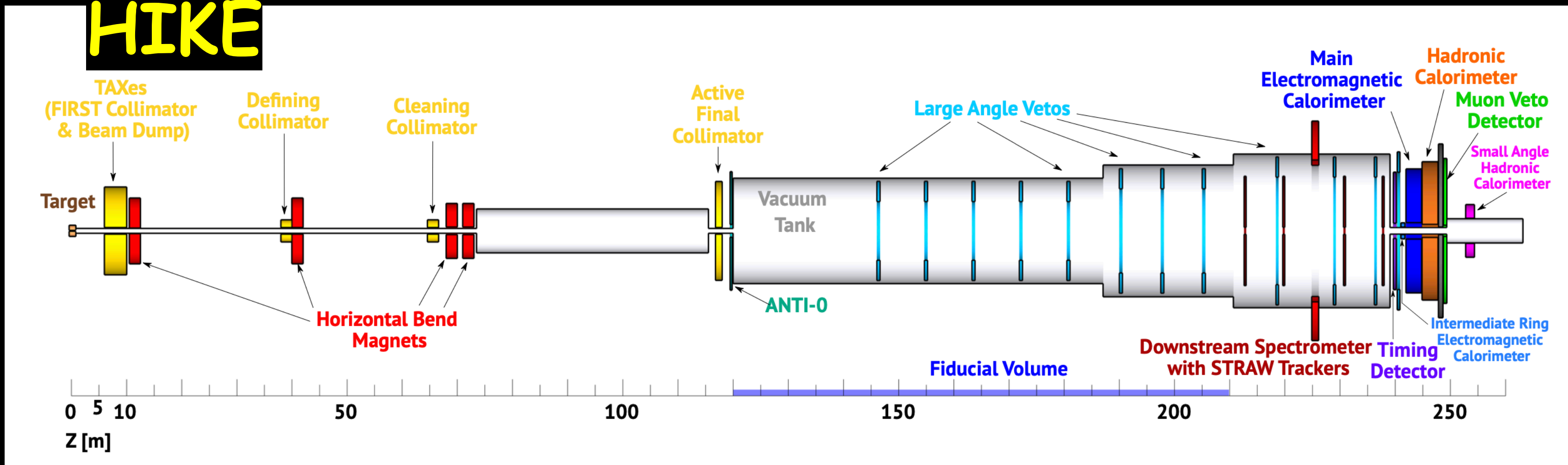
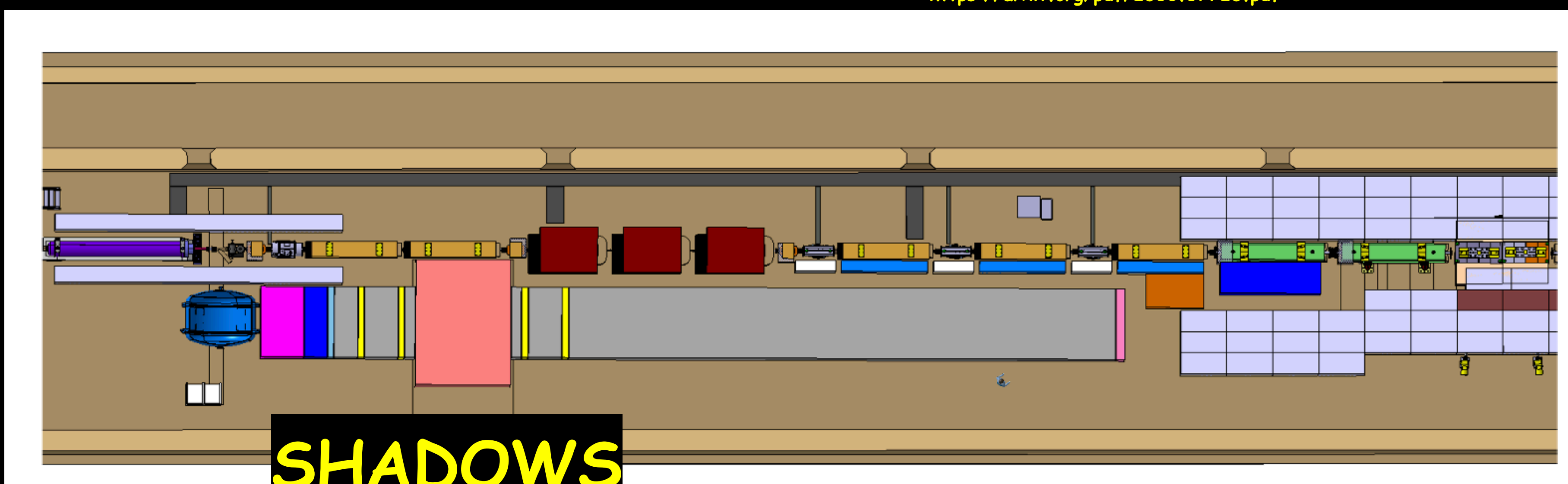


https://arxiv.org/pdf/2310.17726.pdf



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A theorist's picture...

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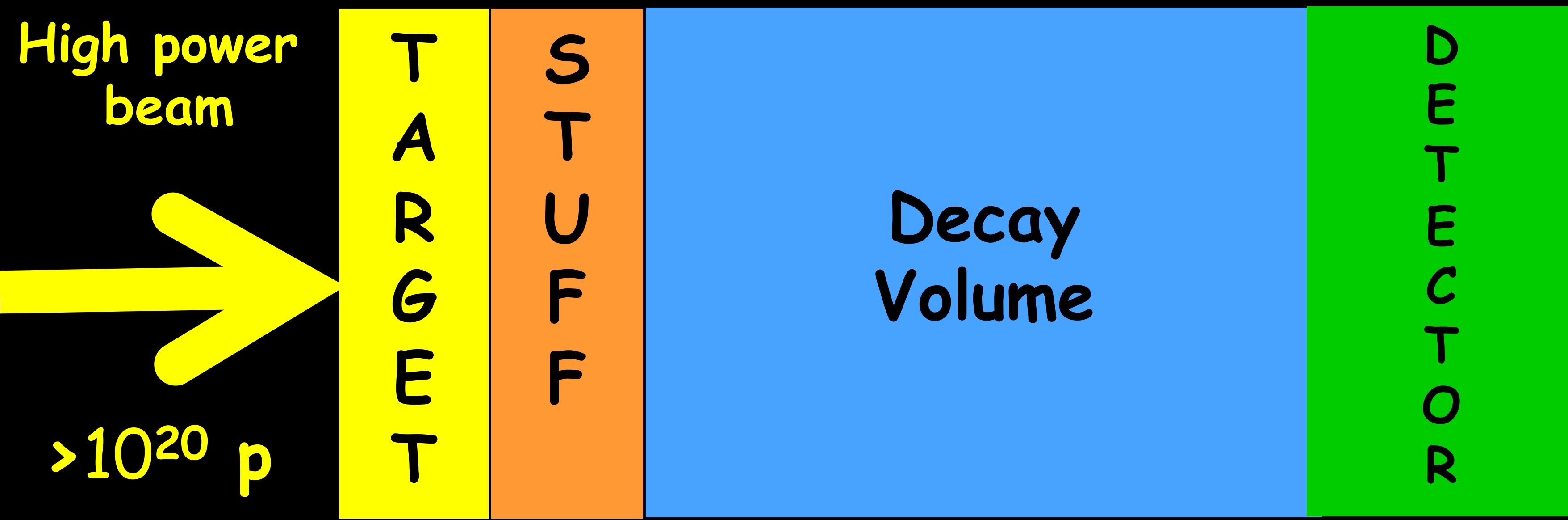

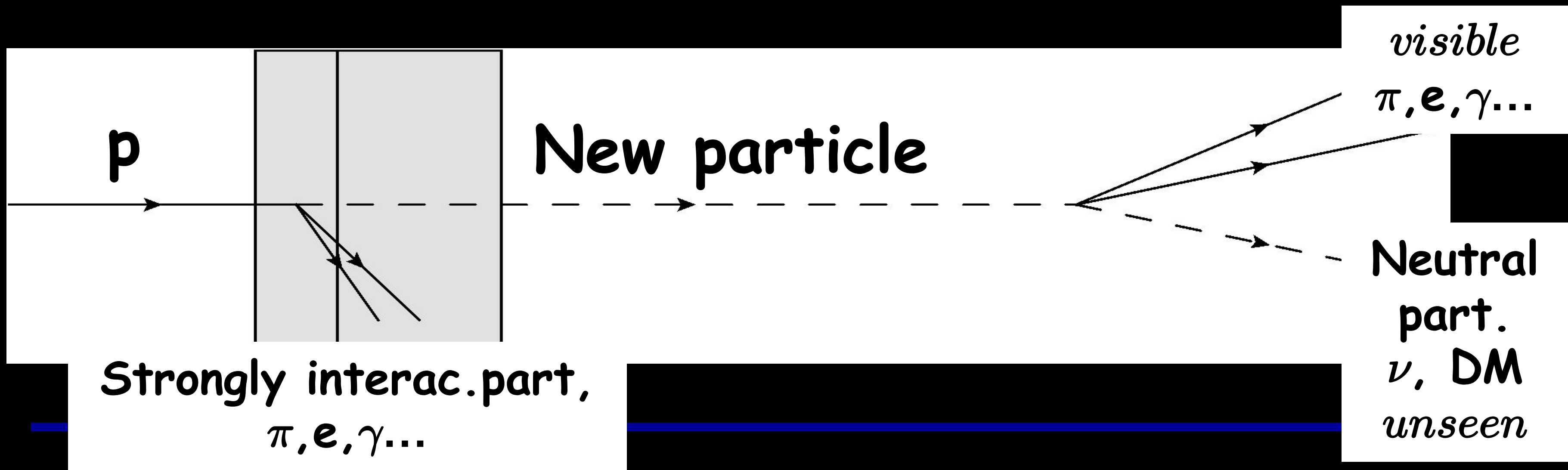

A theorist's picture…

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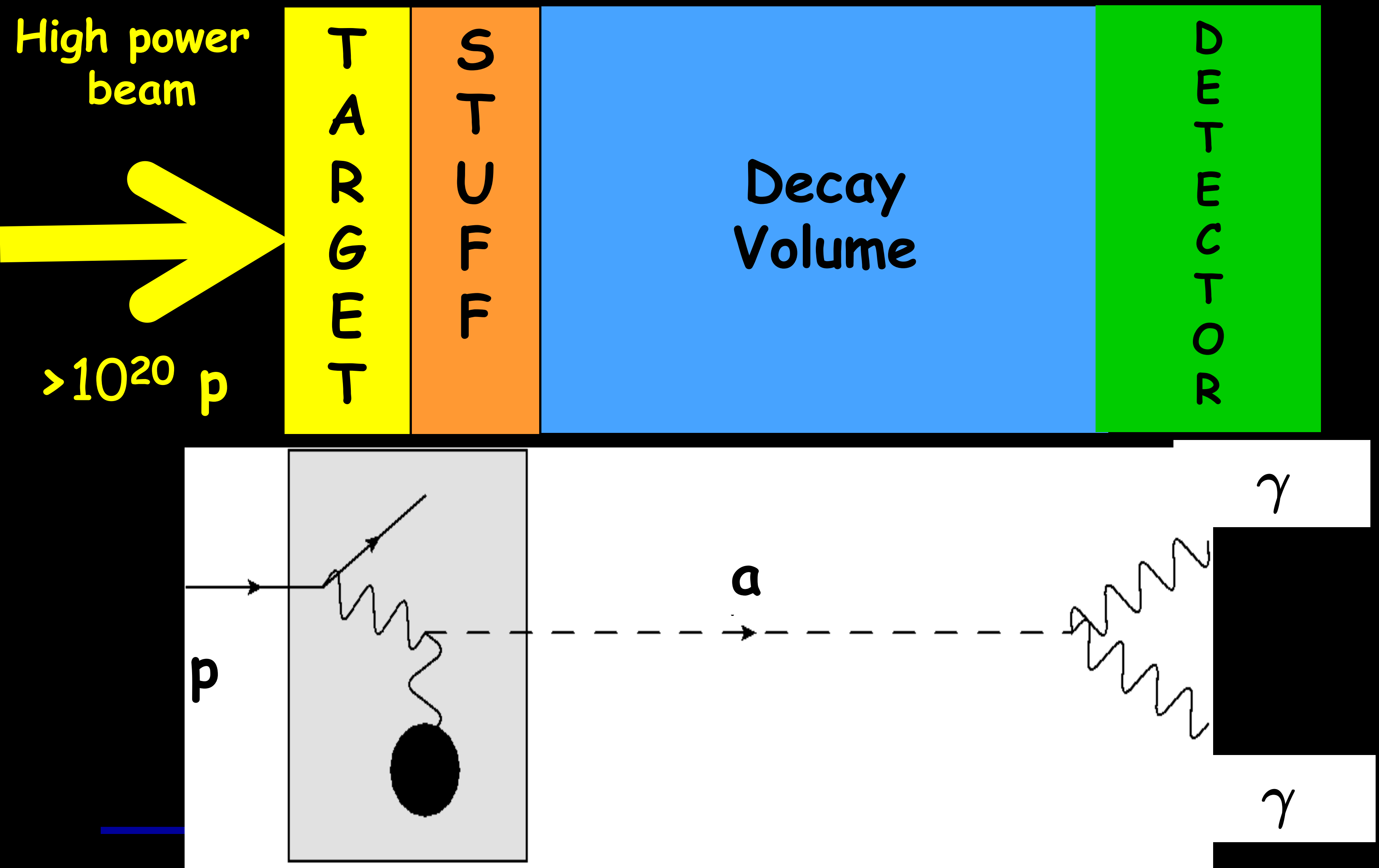
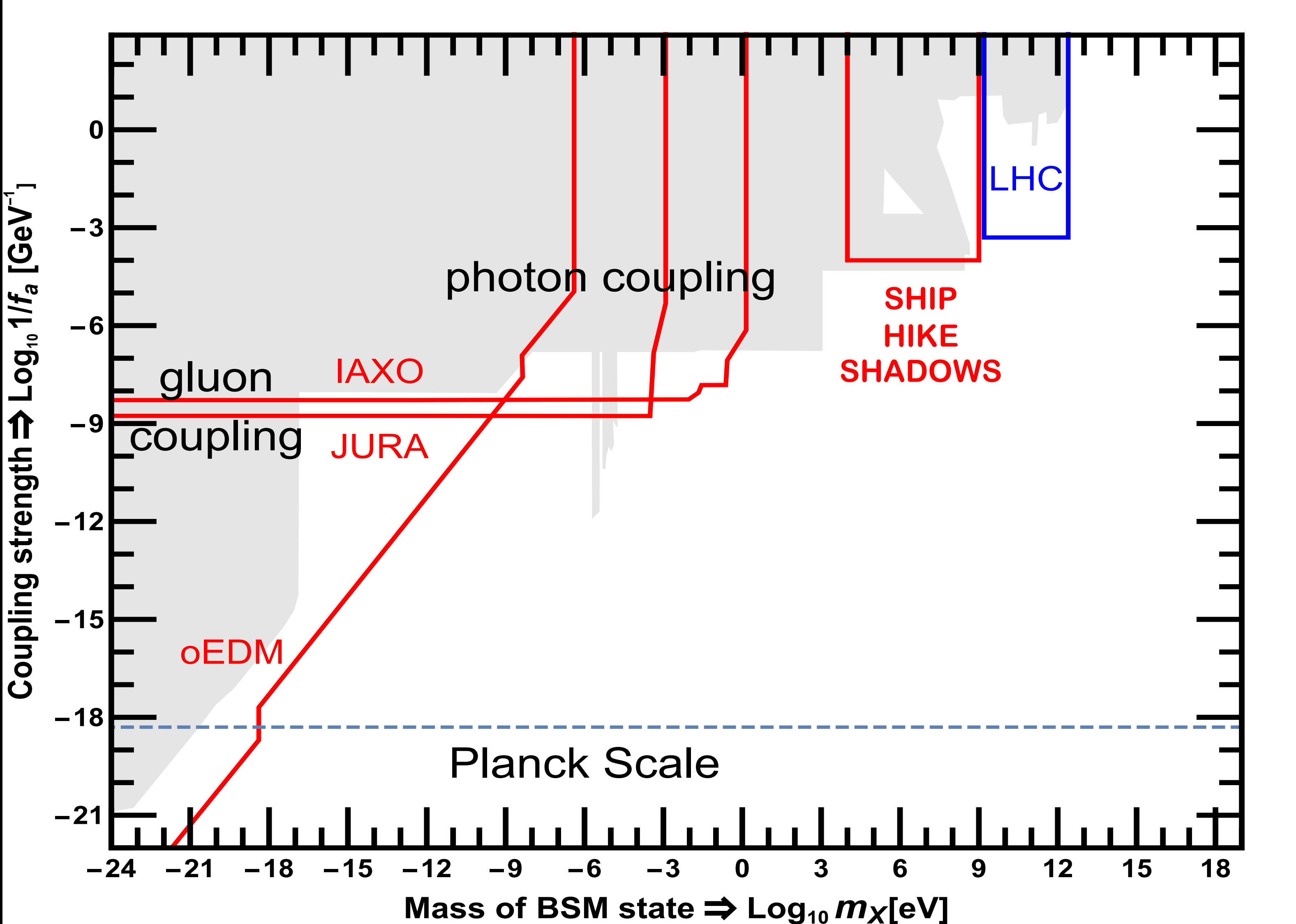


SHiP, HIKE, SHADOWS



A real plot...

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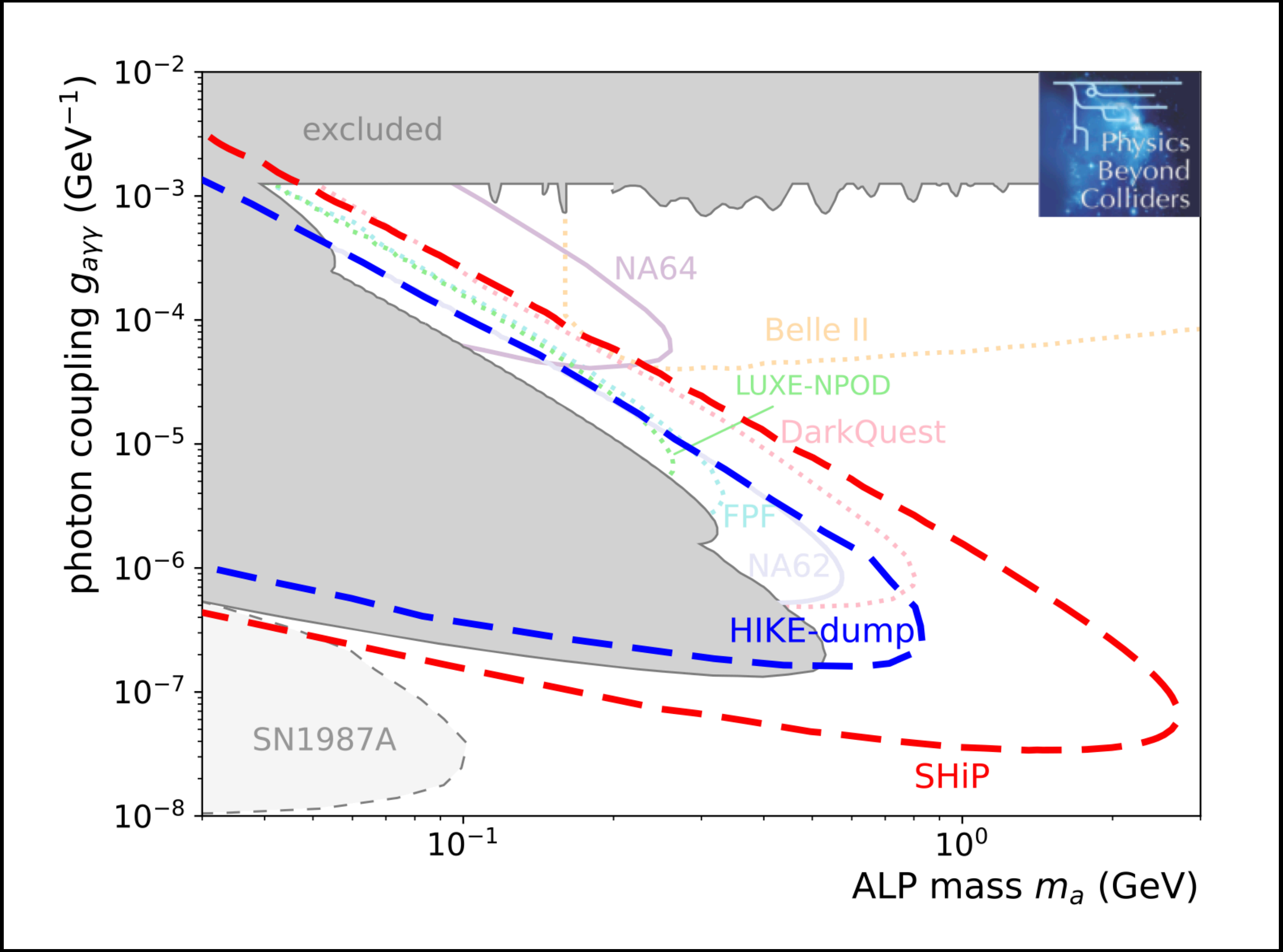
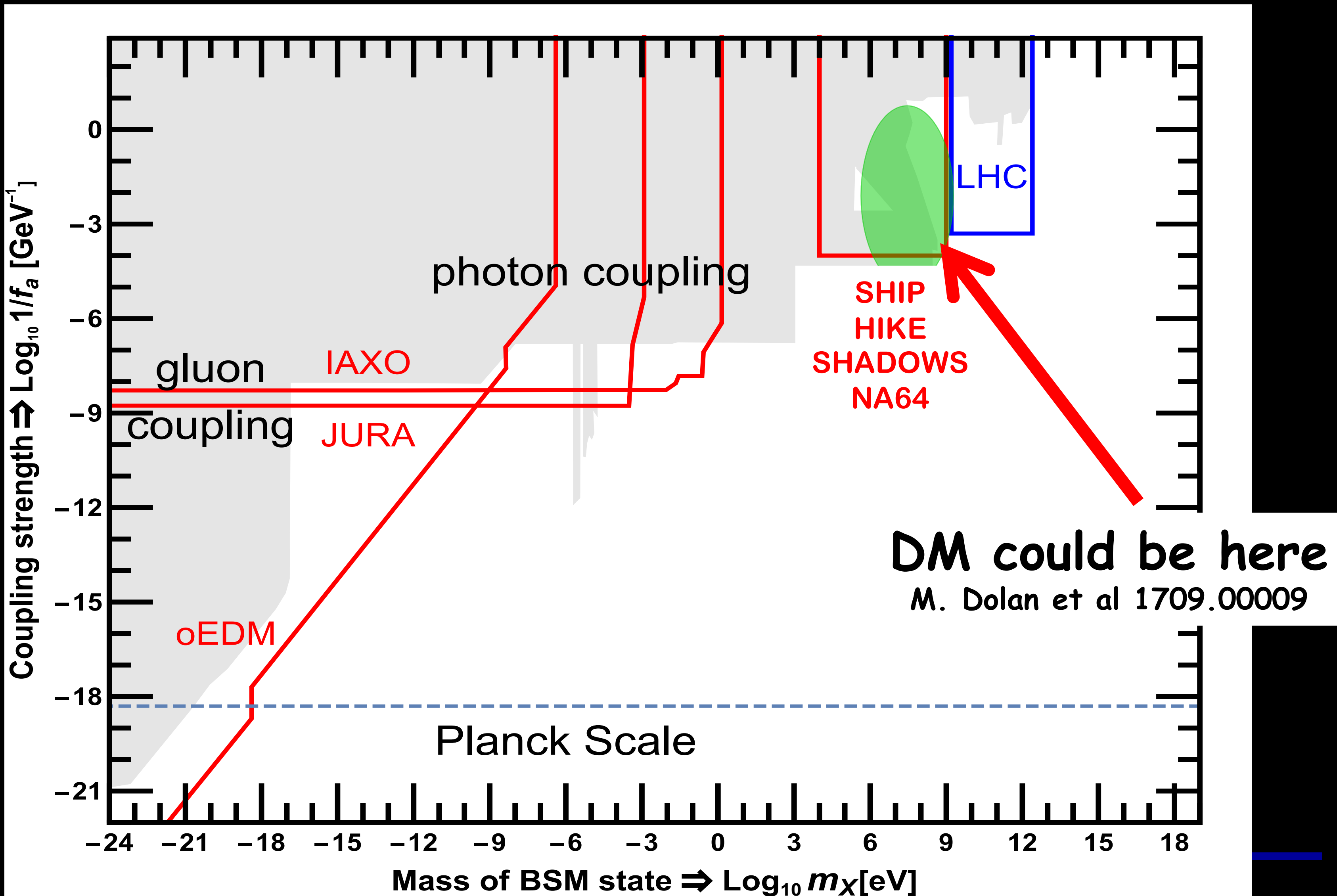


https://arxiv.org/pdf/2310.17726.pdf

Messengers for dark matter?



$(g-2)_\mu$ and proton radius anomaly

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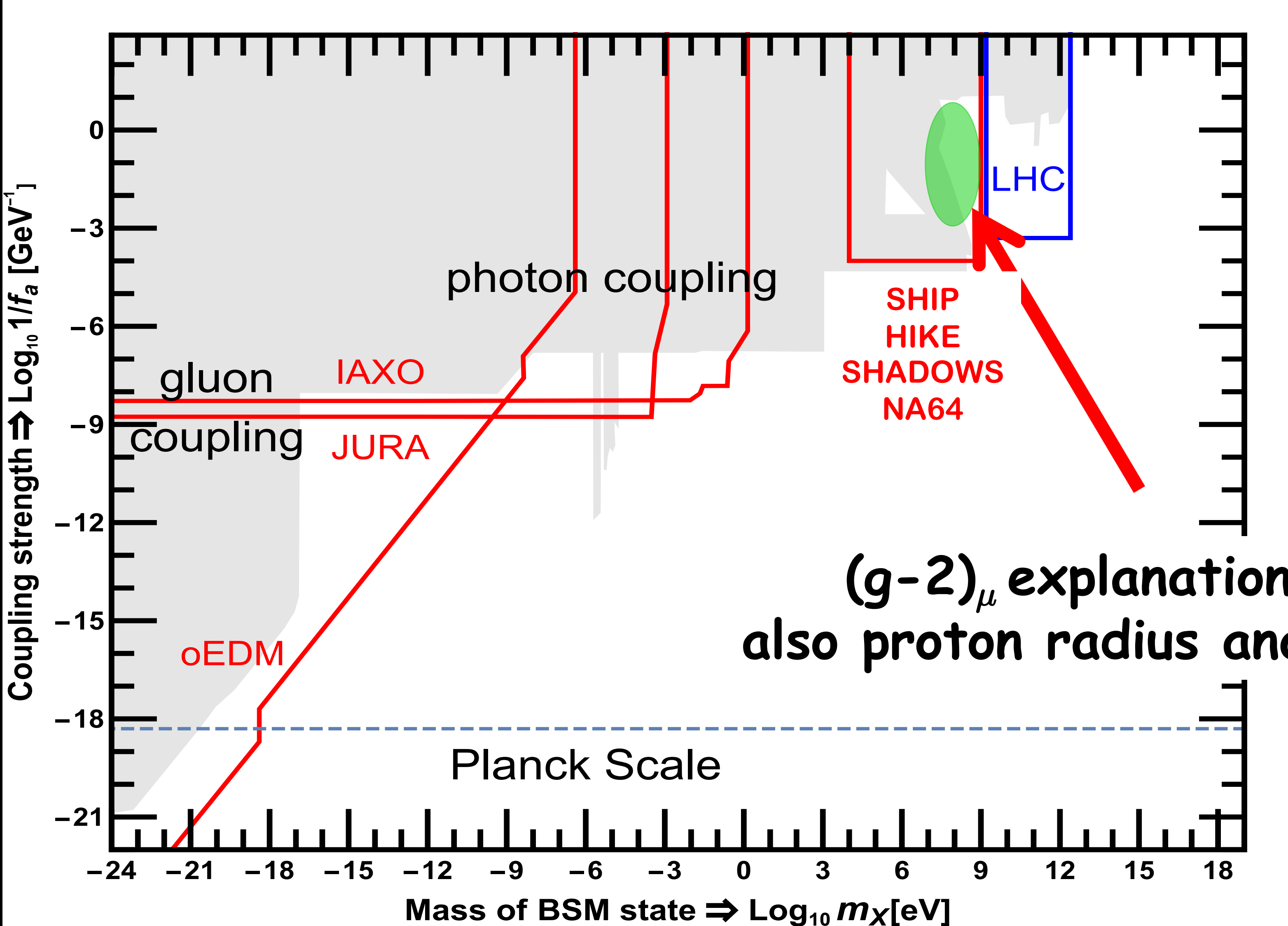

$(g-2)_\mu$ explanations
also proton radius anomaly

What is $(g\text{-}2)_\mu$?

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- The SM predicts the value of the magnetic dipole moment of the muon:

$$\mu_\mu = \frac{e}{2m_\mu}\left(2 + (g-2)_\mu\right)$$

➔ Measure and calculate veeery precisely

$$\left(\frac{(g-2)_\mu}{2}\right)_{\rm exp} = 11659209.1 \pm 6.3$$

→ To be halved by Fermilab exp.

Jegerlehner, https://arxiv.org/pdf/1804.07409.pdf

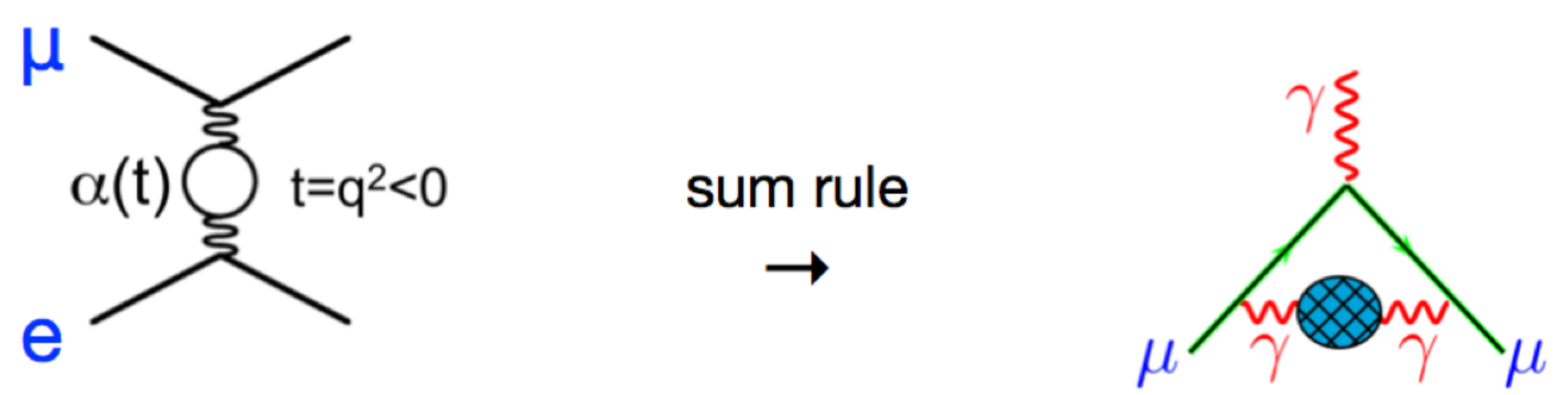
$$\left(\frac{(g-2)_\mu}{2}\right)_{\rm th} = 11659178.3 \pm 4.3$$

→ improvement needed

➔ $(3\text{-}4)\sigma$ discrepancy

mu on e

- To improve "Theory" we need to Measure hadronic corrections for $(g-2)_\mu$
- Crucial input for using $(g-2)_\mu$ to search for BSM!
- New way: Measure scattering of μ on e



see Gunar Schnell @ PBC Workshop Nov. 2017

$(g-2)_\mu$

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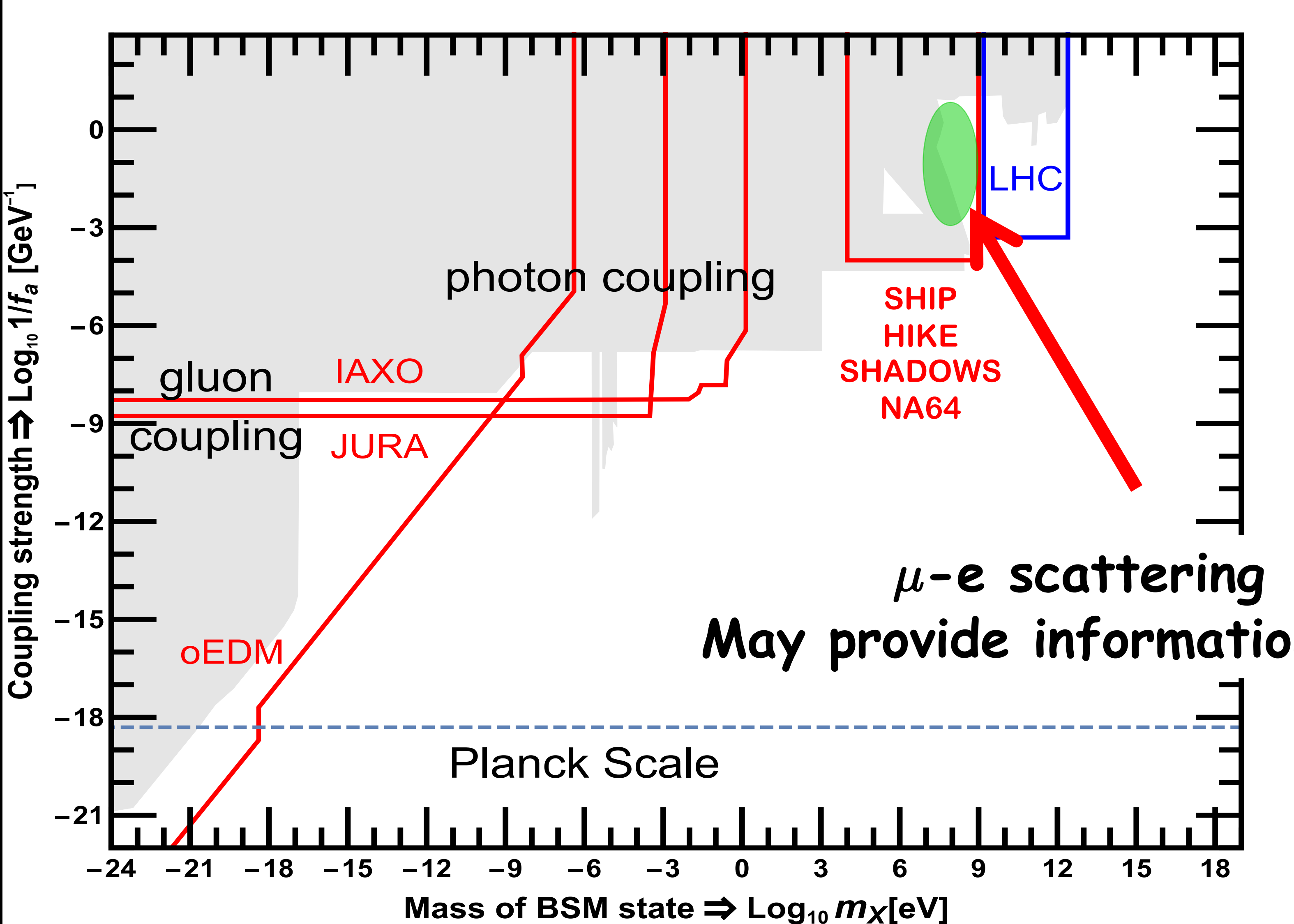

μ-e scattering
May provide information here

Long Lived Particles @ LHC

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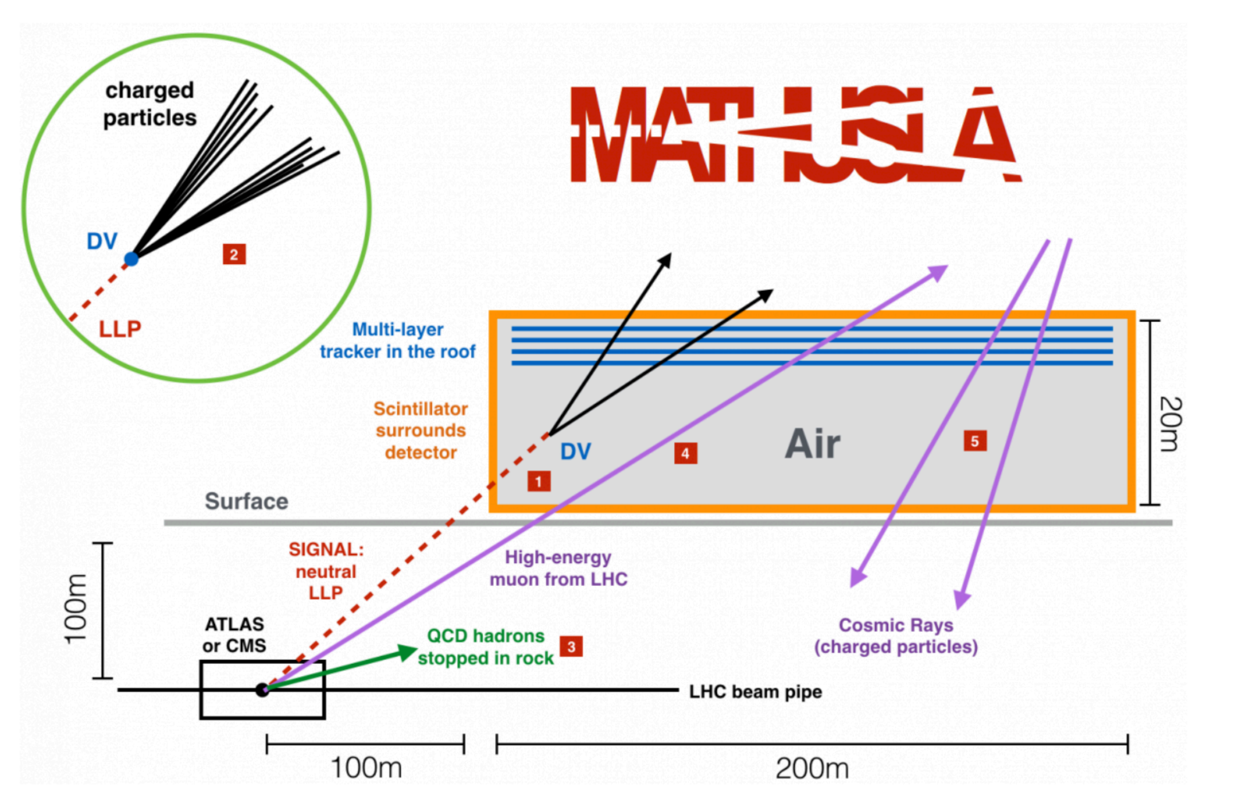
- Idea: Look for very long lived particles produced in LHC collissions
- Recent proposals:

  MATHUSLA, FASER, CodexB, MilliCan



https://ep-news.web.cern.ch/content/lifetime-frontier

The Forward Physics Facility

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- Idea: Look for very long lived particles produced in LHC collissions
- Recent proposals:

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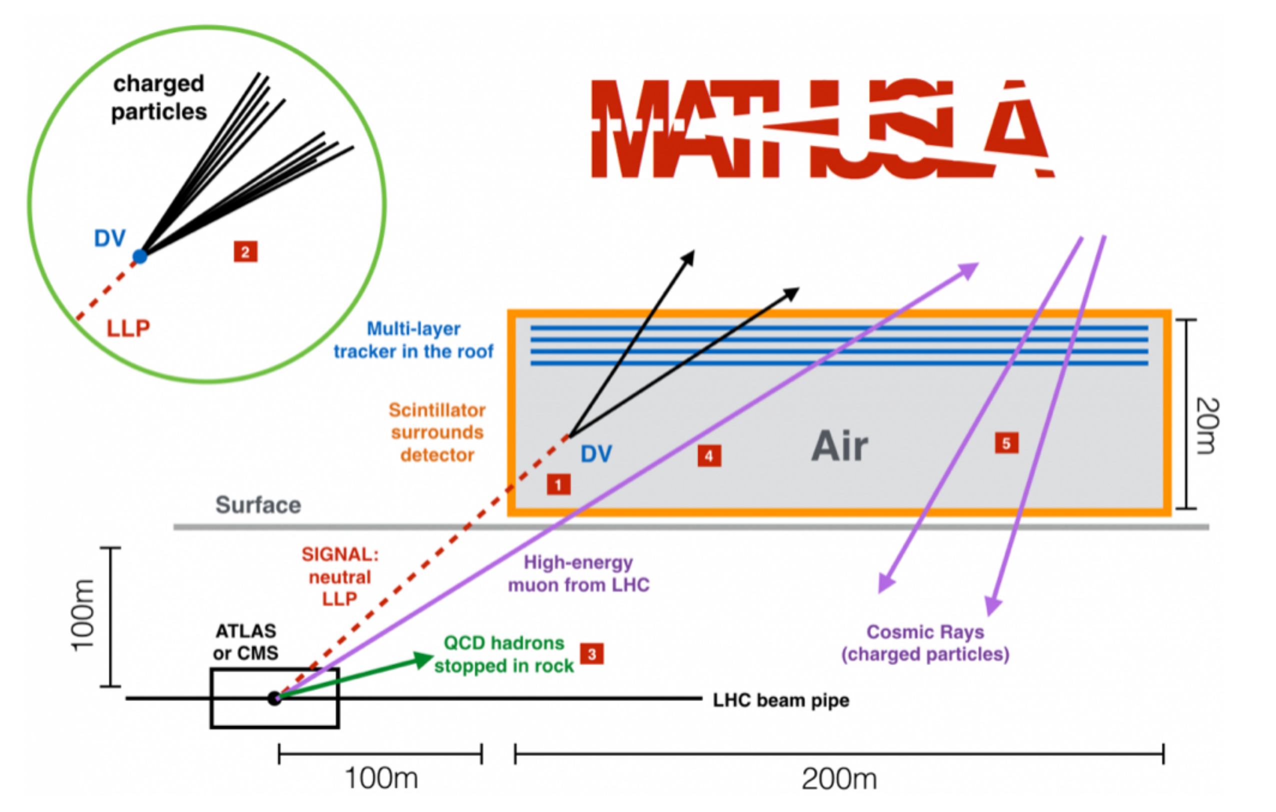

Look Forward

FASER

https://ep-news.web.cern.ch/content/lifetime-frontier

Long Lived Particles @ LHC

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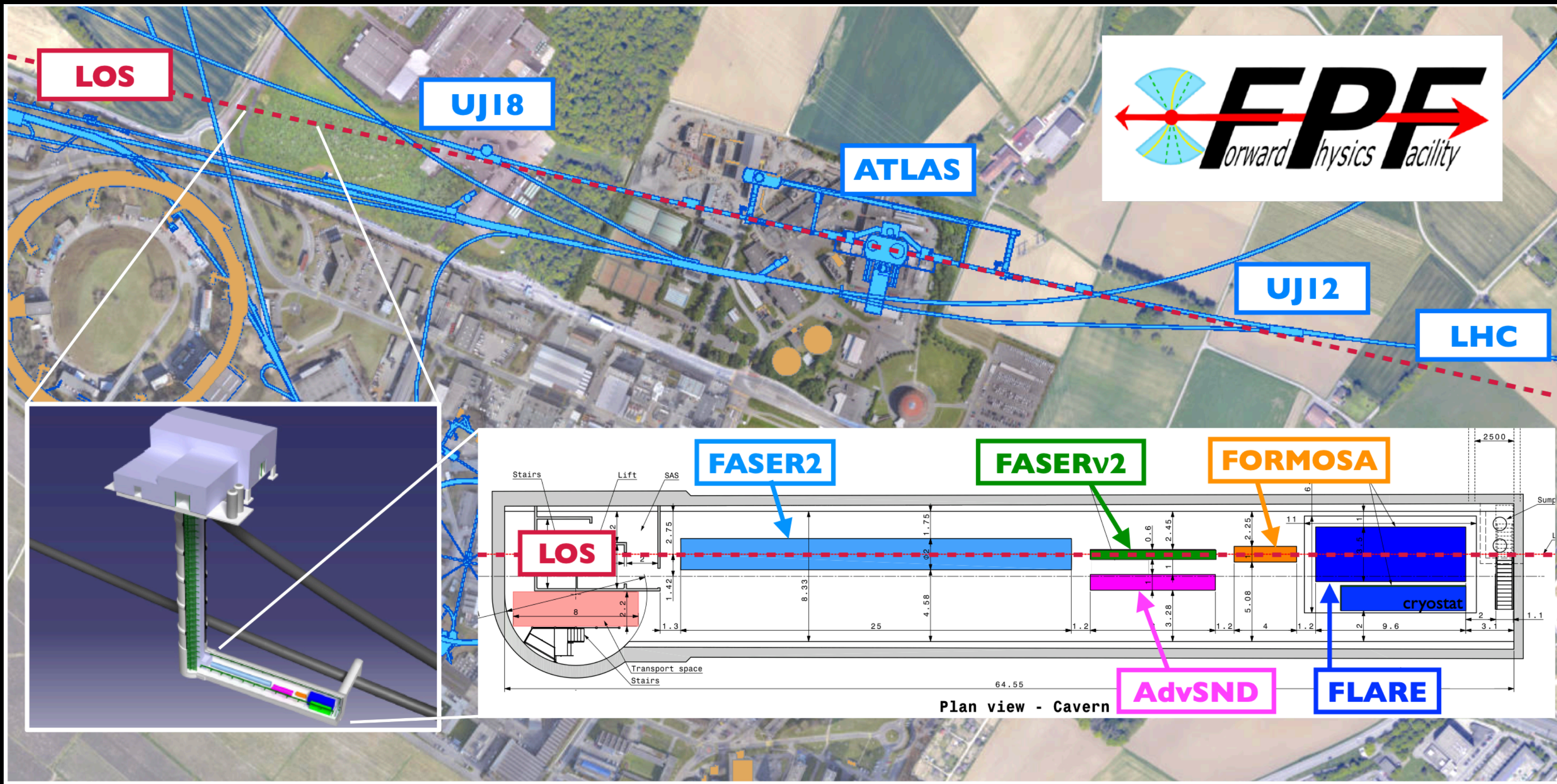
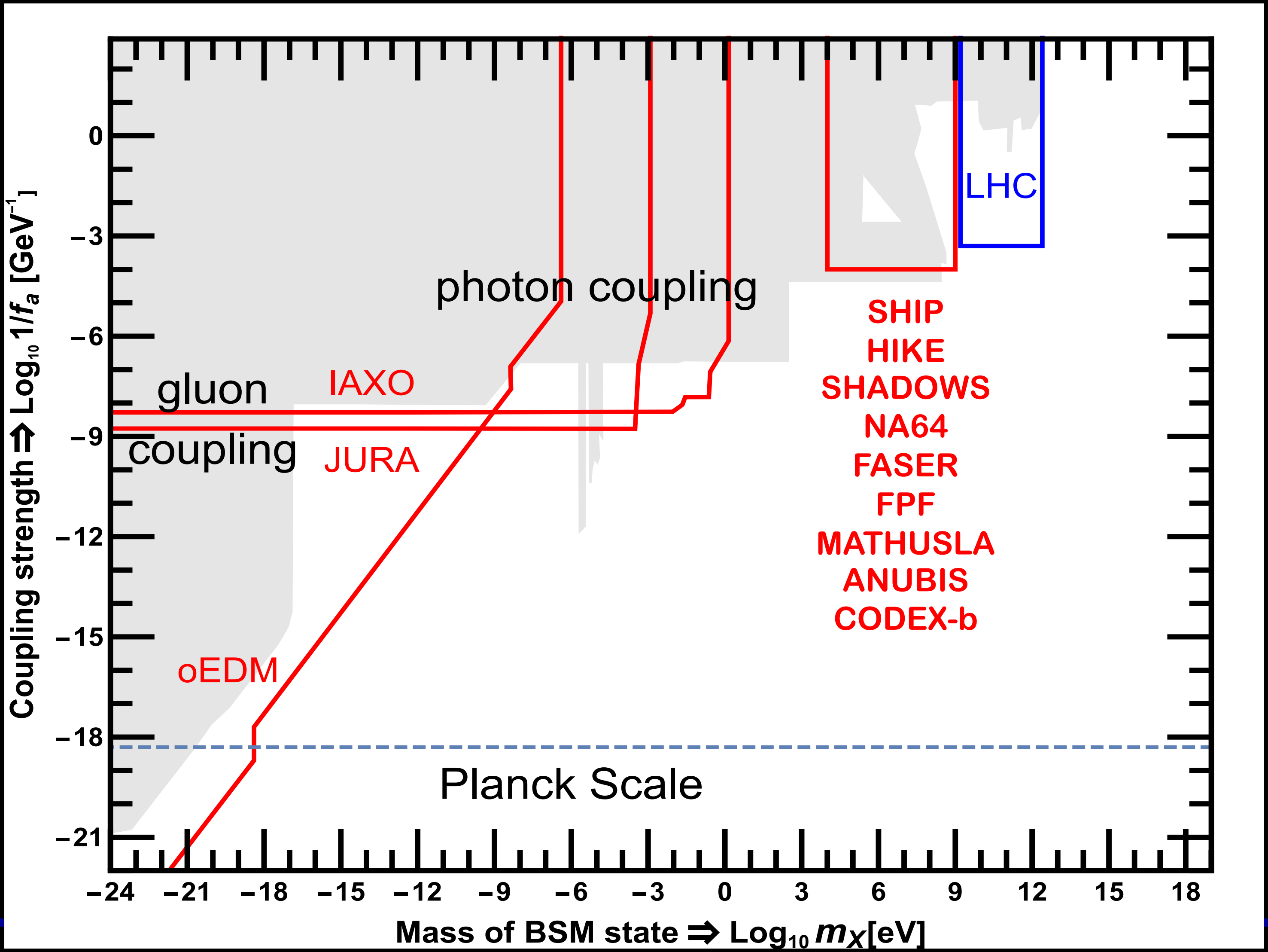
A lot of interesting stuff flies in the forward direction → FPF



FPF, J. Feng, F. Kling et al. https://arxiv.org/pdf/2203.05090.pdf

Long Lived Particle searches also explore MeV-GeV region



A real plot...

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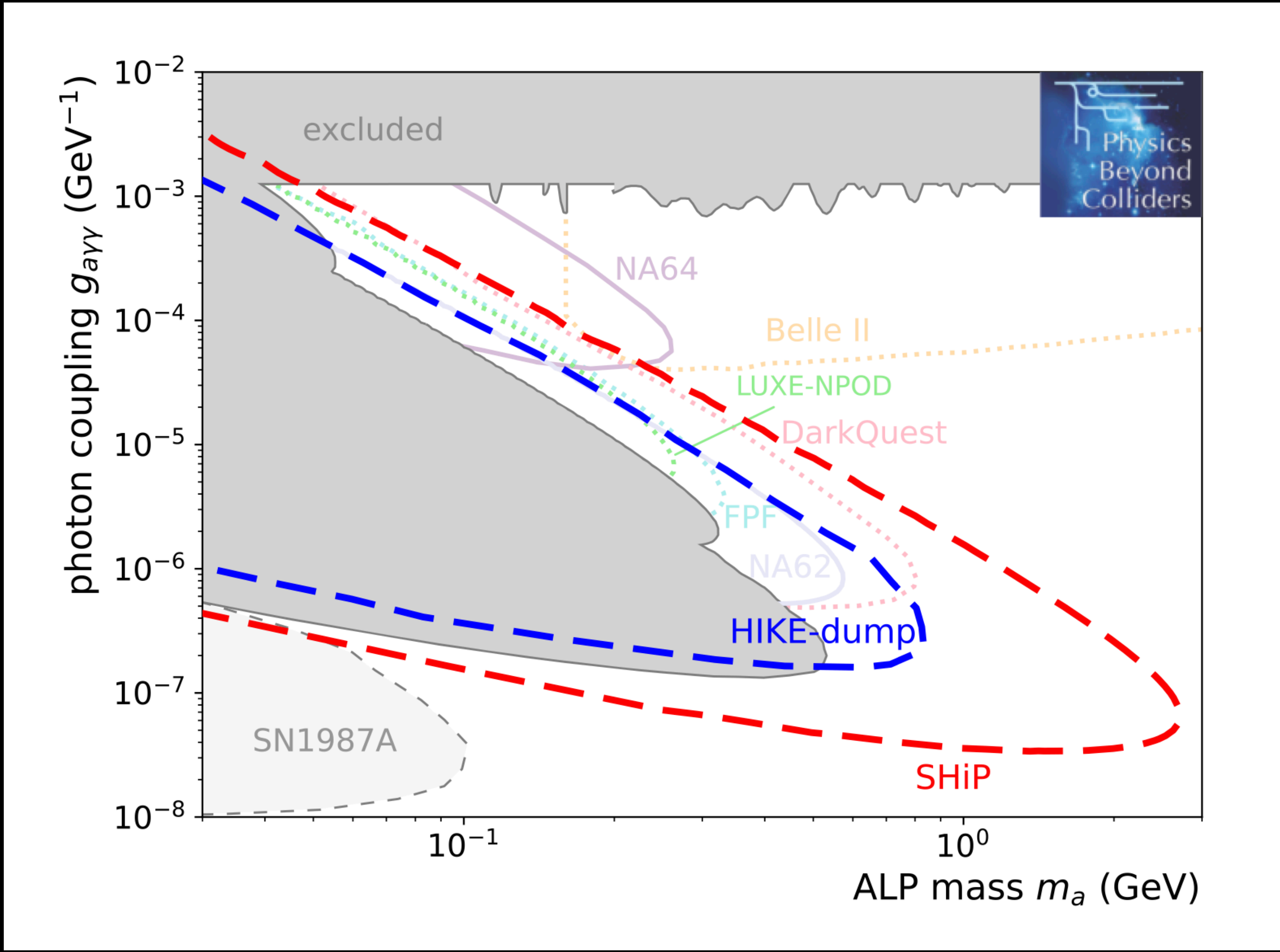

https://arxiv.org/pdf/2310.17726.pdf

Many more
Maps and Particles

More concrete:

Portals to the "Dark Sector"

The 3+x portals to new physics

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Portal	Coupling
Dark Photon, A'	$-\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Axion-like particles, a	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Dark Higgs, S	$(\mu S + \lambda_{\rm HS} S^2) H^\dagger H$
Heavy Neutral Lepton, N	$y_N L H N$
milicharged particle, χ	$\epsilon A^\mu \bar{\chi}\gamma_\mu\chi$

https://arxiv.org/pdf/2102.12143.pdf

Constructed to be the lowest dimensional connections between SM particles and new particles uncharged under SM gauge groups + some symmetry prejudices

The 3+x portals to new physics

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https://arxiv.org/pdf/2102.12143.pdf

Constructed to be the lowest dimensional connections between SM particles and new particles uncharged under SM gauge groups + some symmetry prejudices

Note: We expect a very broad range of underlying new physics models to give signatures close to that of Benchmarks

Dark Photon without dark decays

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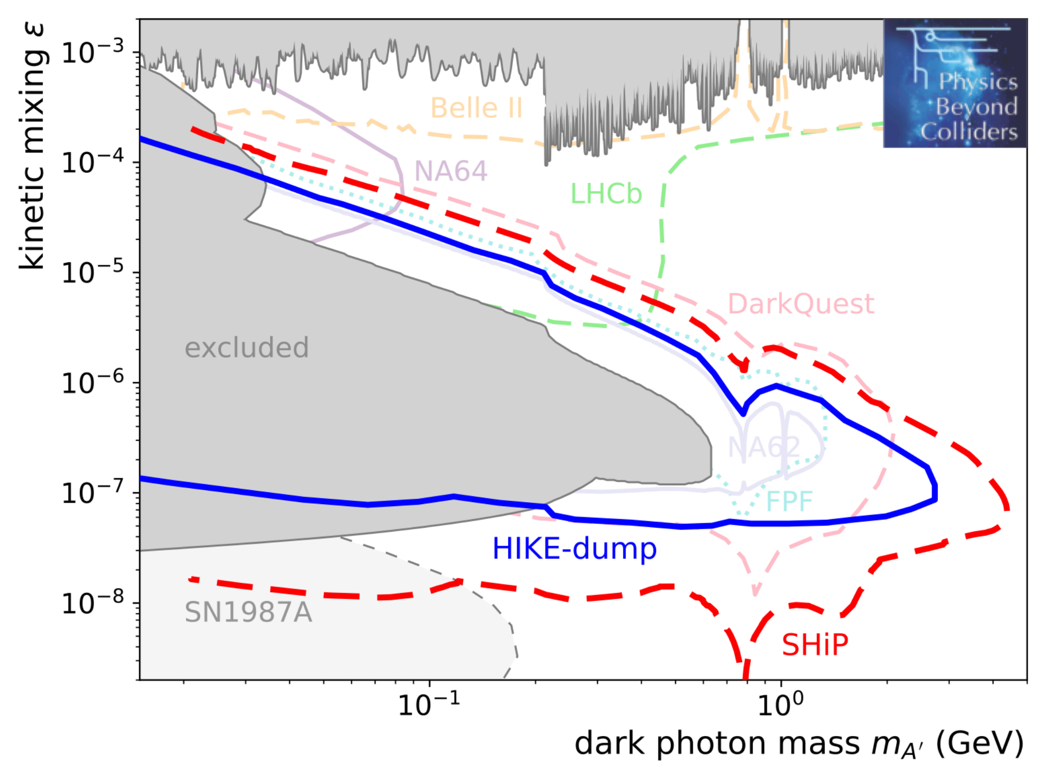
- Motivation: Model building and dark matter
- Target areas for dark matter



$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}F^{\mu\nu}_{(\text{A})}F_{(\text{A})\mu\nu} - \frac{1}{4}F^{\mu\nu}_{(\text{B})}F_{(\text{B})\mu\nu} + \frac{\chi}{2}F^{\mu\nu}_{(\text{A})}F_{(\text{B})\mu\nu},$$

„Our" U(1) | „Hidden" U(1) | Mixing

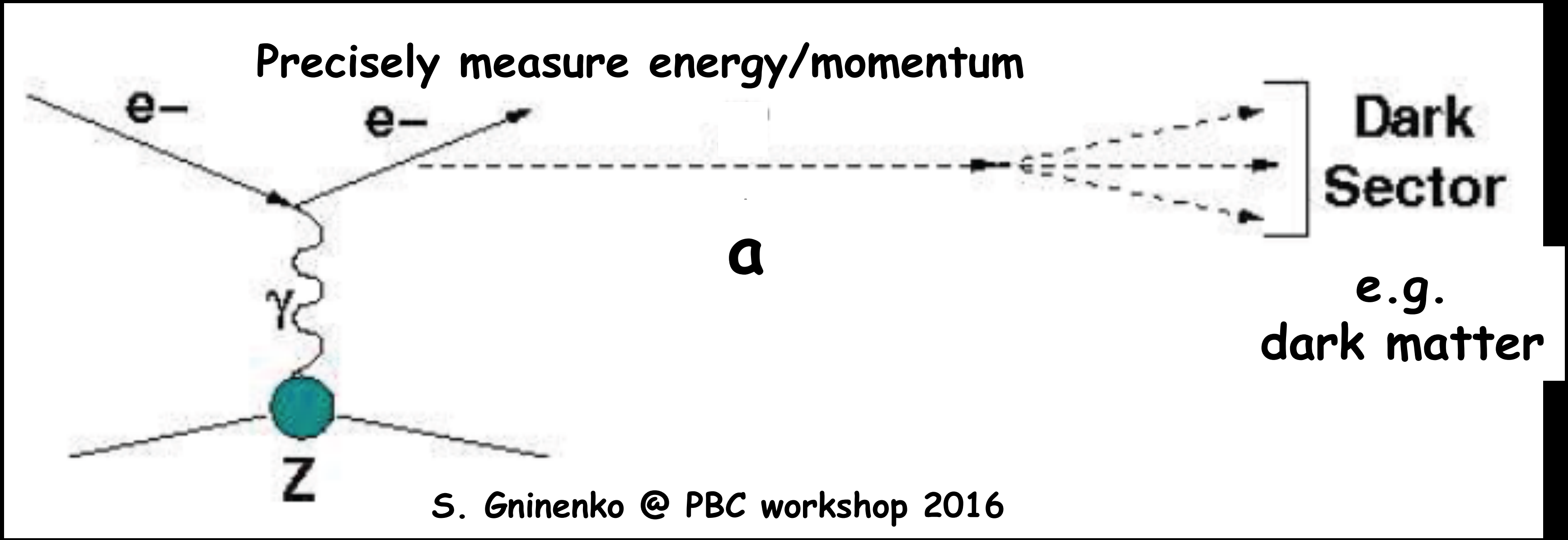
+ Mass $$\mathcal{L}_{\text{mass}} = \frac{1}{2}m^2_{\gamma'}X^\mu X_\mu$$

Experiments:
HIKE, NA64,
SHiP,
ALPS-III (low mass)

https://arxiv.org/pdf/2310.17726.pdf

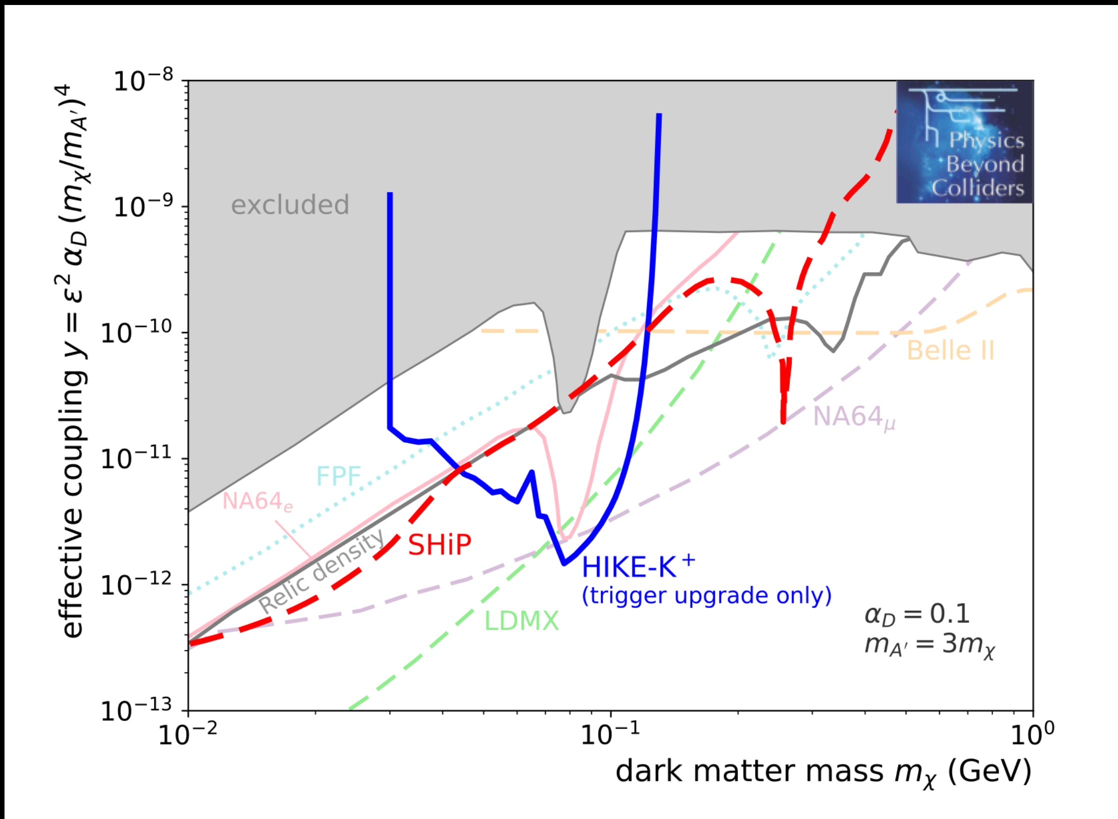
“Seeing” the dark stuff NA 64+

$$\mathcal{L} \supset g_{a\psi\psi} a\bar{\psi}\gamma^5\psi$$



+ “dark matter” detector @ SHiP

Dark photon with dark decays



https://arxiv.org/pdf/2310.17726.pdf

Dark photon

$$+e_h \bar{\psi} X^\mu \gamma_\mu \psi$$

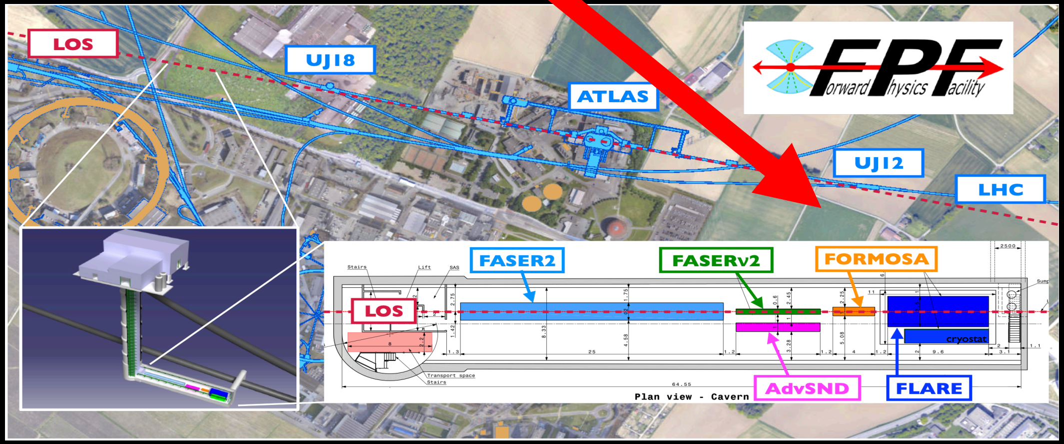
Experiments concerned: HIKE (from kaon decays), NA64, SHiP (with detector for decay products…)

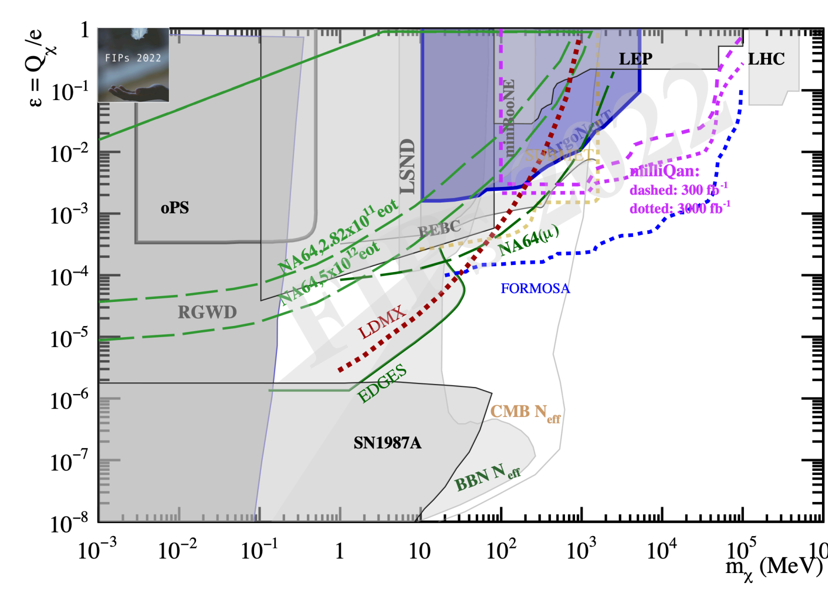
Massless Dark photon + hidden matter

Massless Dark photon

$$+e_h\bar{\psi}X^{\mu}\gamma_{\mu}\psi$$

→ Millicharged particle





FPF, J. Feng, F. Kling et al.
https://arxiv.org/pdf/2203.05090.pdf

C. Antel,...,G. Lanfranchi...et al.
https://arxiv.org/pdf/2305.01715.pdf

Experiments concerned: milliQan, FPF

Heavy Neutral Leptons

A new ν (Minimal) Standard Model

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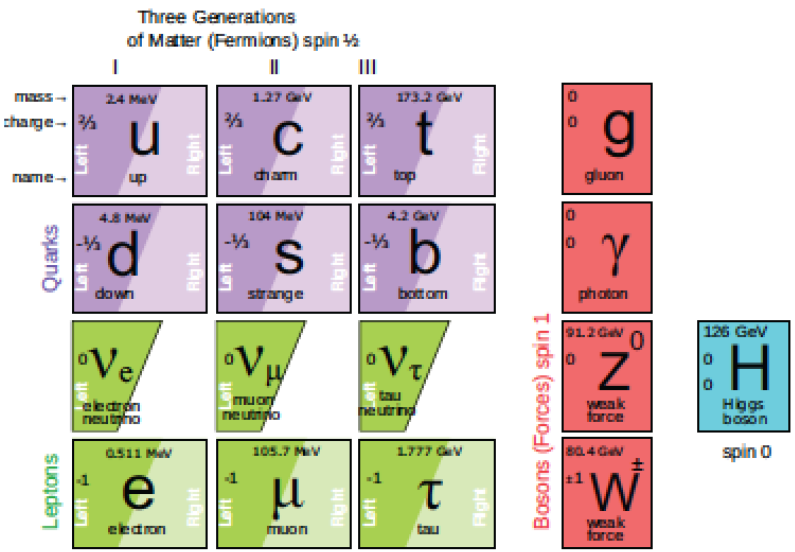
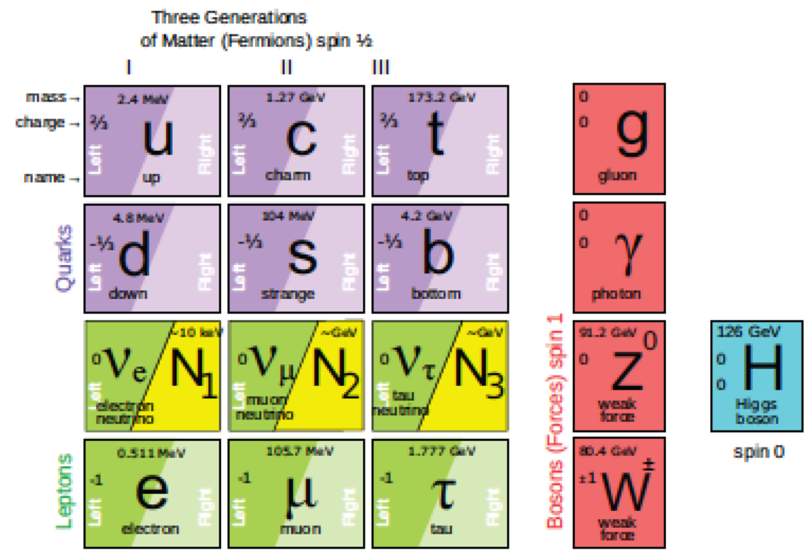




N = Heavy Neutral Lepton - HNL, Majorana fermion

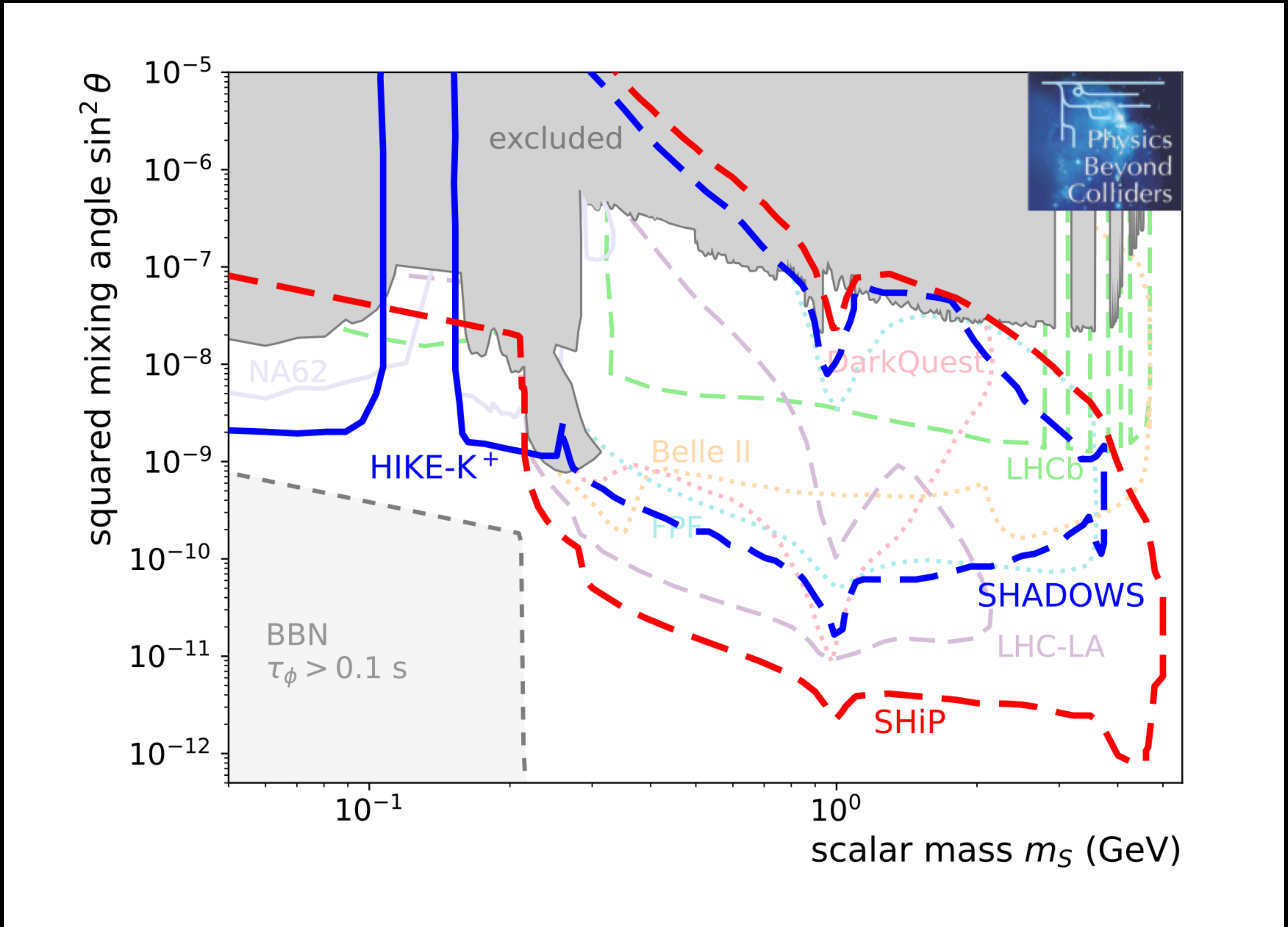
Role of N_1 with mass in keV region: dark matter

Role of $N_2,\ N_3$ with mass in 100 MeV – 100 GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe

Role of the Higgs: give masses to quarks, leptons, Z and W and inflate the Universe.

M. Shaposhnikov @ PBC workshop 2016

Heavy Neutral Leptons



https://arxiv.org/pdf/2310.17726.pdf

Experiments concerned: HIKE, SHADOWS, SHiP

Back to extremely low masses

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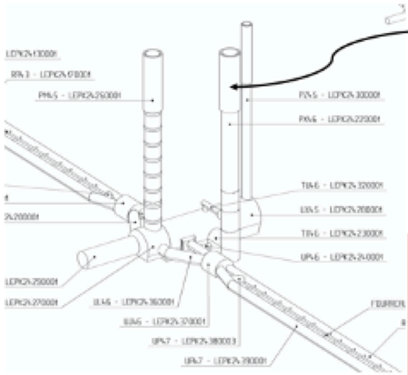


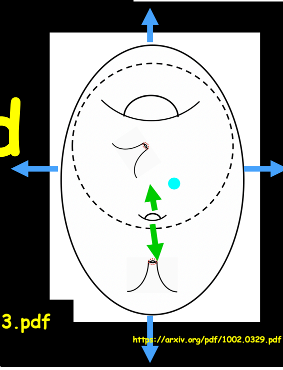
PX46 – P4 Support shaft
Lengths 143m
D = 10.10m
➢ Ideal basic parameters for AION100

Supported by CERN PBC Team
(Gianluigi Arduini, Sergio Calatroni …)
on feasibility study:
Seismology
Temperature
Ventilation
Radiation protection
Electromagnetic interference
Access & safety

J. Ellis @ PBC workshop 2022

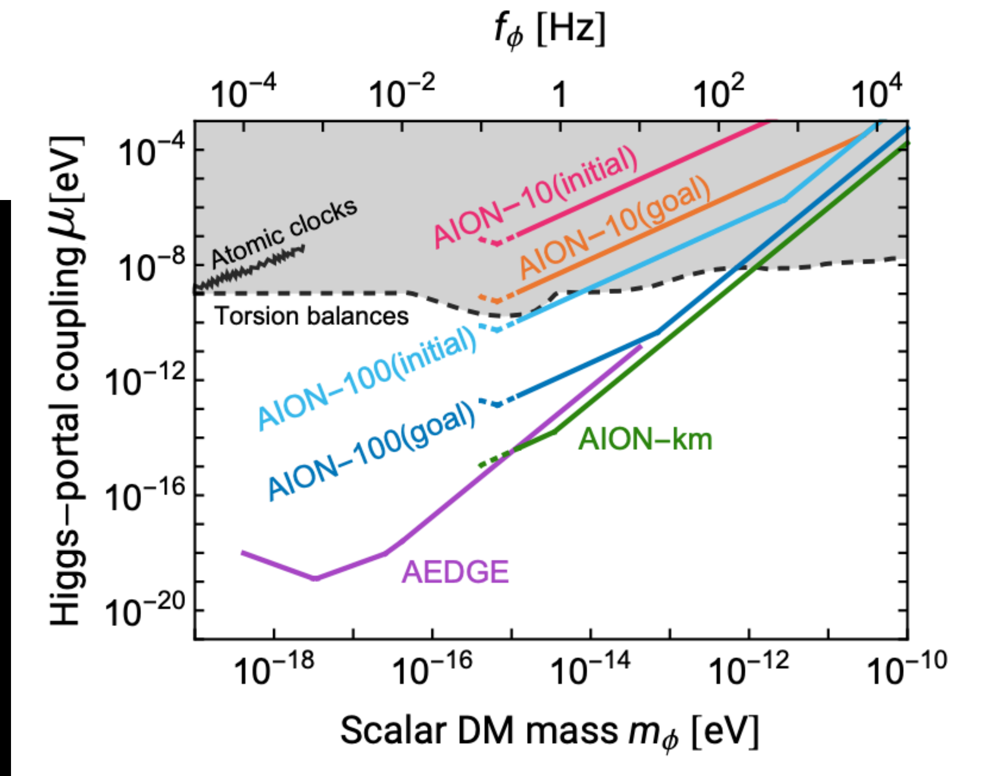
Volume modulus naturally coupled to Higgs

M. Cicoli, A. Hebecker et al, https://arxiv.org/pdf/2203.08833.pdf



https://arxiv.org/pdf/1002.0329.pdf

AION:
An Atom Interferometry Observatory and Network

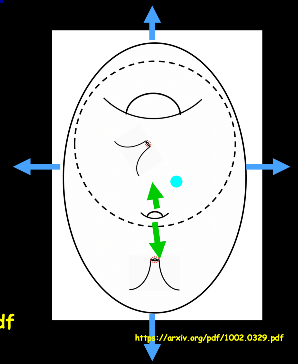


L. Badurina et al, https://arxiv.org/pdf/1911.11755.pdf

Back to extremely low masses

Volume modulus naturally coupled to Higgs

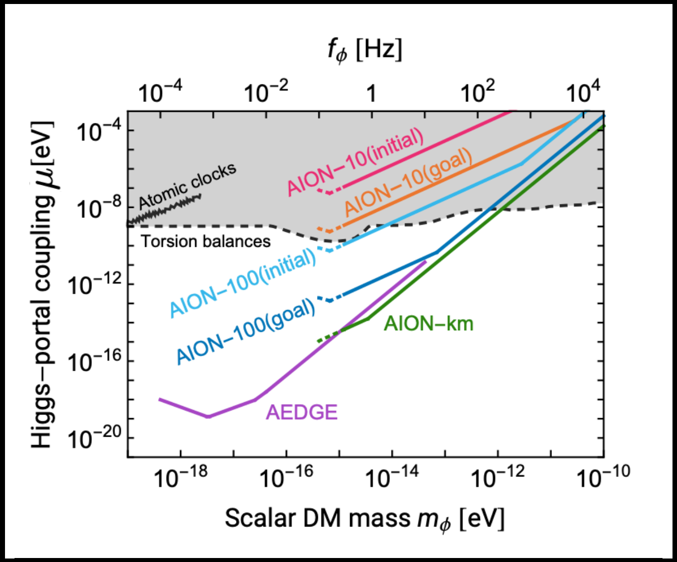
M. Cicoli, A. Hebecker et al, https://arxiv.org/pdf/2203.08833.pdf



https://arxiv.org/pdf/1002.0329.pdf

Dark Higgs, S $\quad (\mu S + \lambda_{\rm HS} S^2) H^\dagger H$

https://arxiv.org/pdf/2102.12143.pdf



L. Badurina et al, https://arxiv.org/pdf/1911.11755.pdf

Much more cool physics can be probed !!!

Flavor

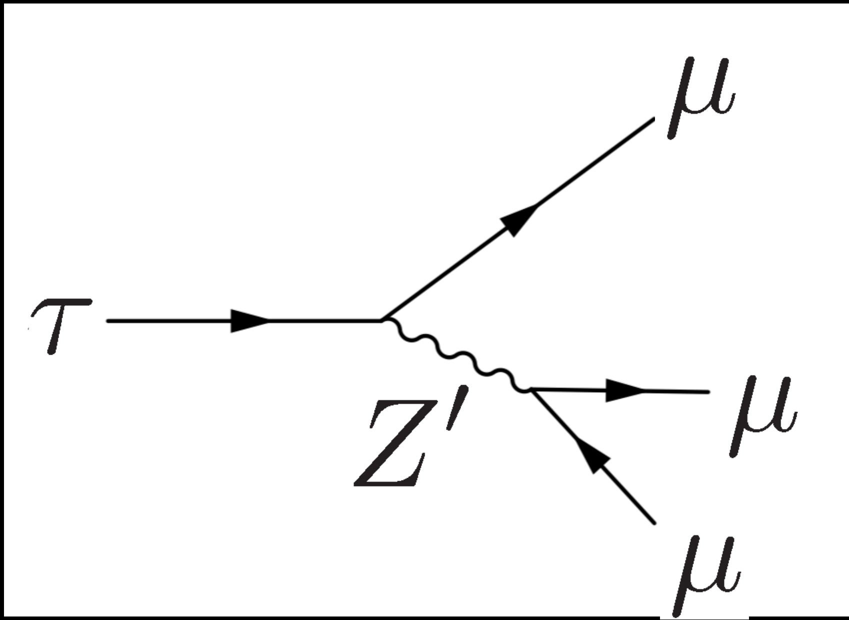
Example

- Rare decays:

$K^+ \rightarrow \pi^+ + \nu\nu$ NA62 (currently running)

$K^0 \rightarrow \pi^0 + \nu\nu$ KLEVER

$\tau \rightarrow \mu^+ \mu^- \mu^+$ TauFV



➔ Probe 1-1000TeV scales

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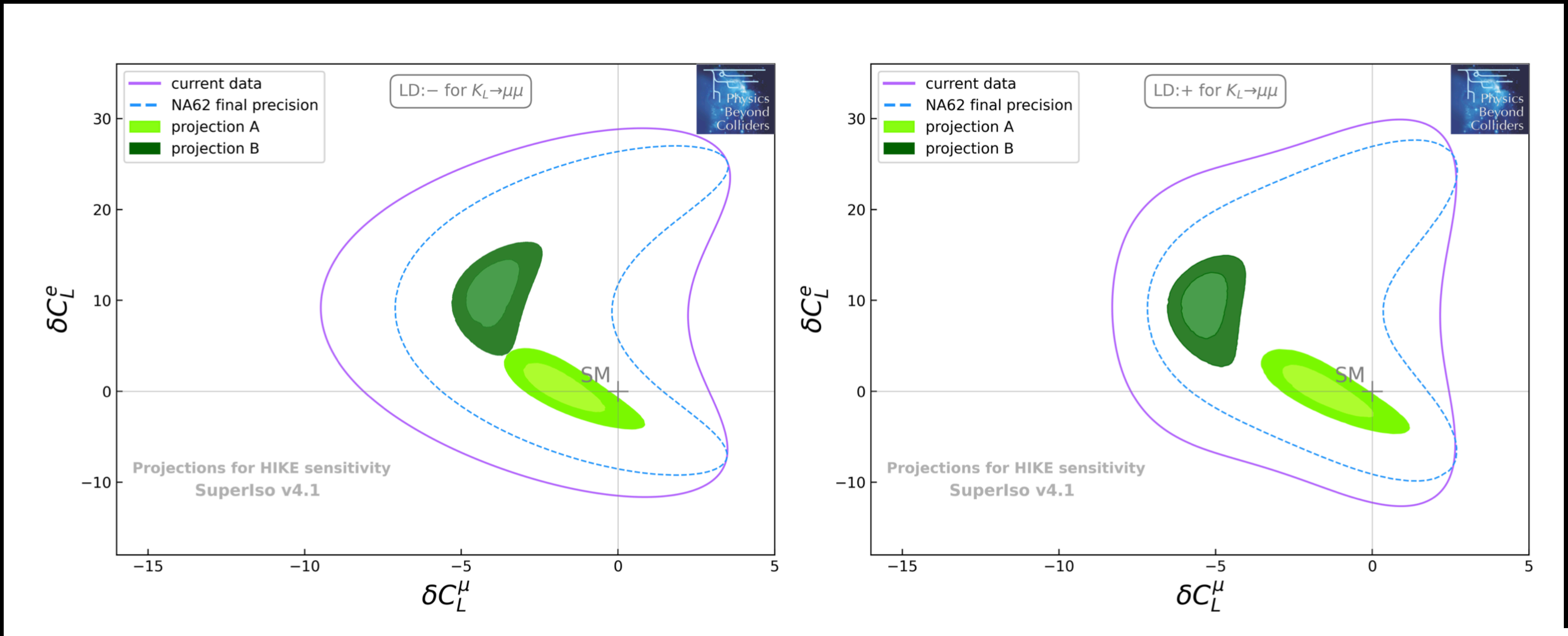
HIKE progress in the flavor sector



$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{td} V_{ts}^* \frac{\alpha_e}{4\pi} \sum_k C_k^\ell O_k^\ell$$

$$\{\delta C_L^e, \delta C_L^\mu (= \delta C_L^\tau)\}$$

https://arxiv.org/pdf/2310.17726.pdf

Neutrinos

New kinematic regimes ☺

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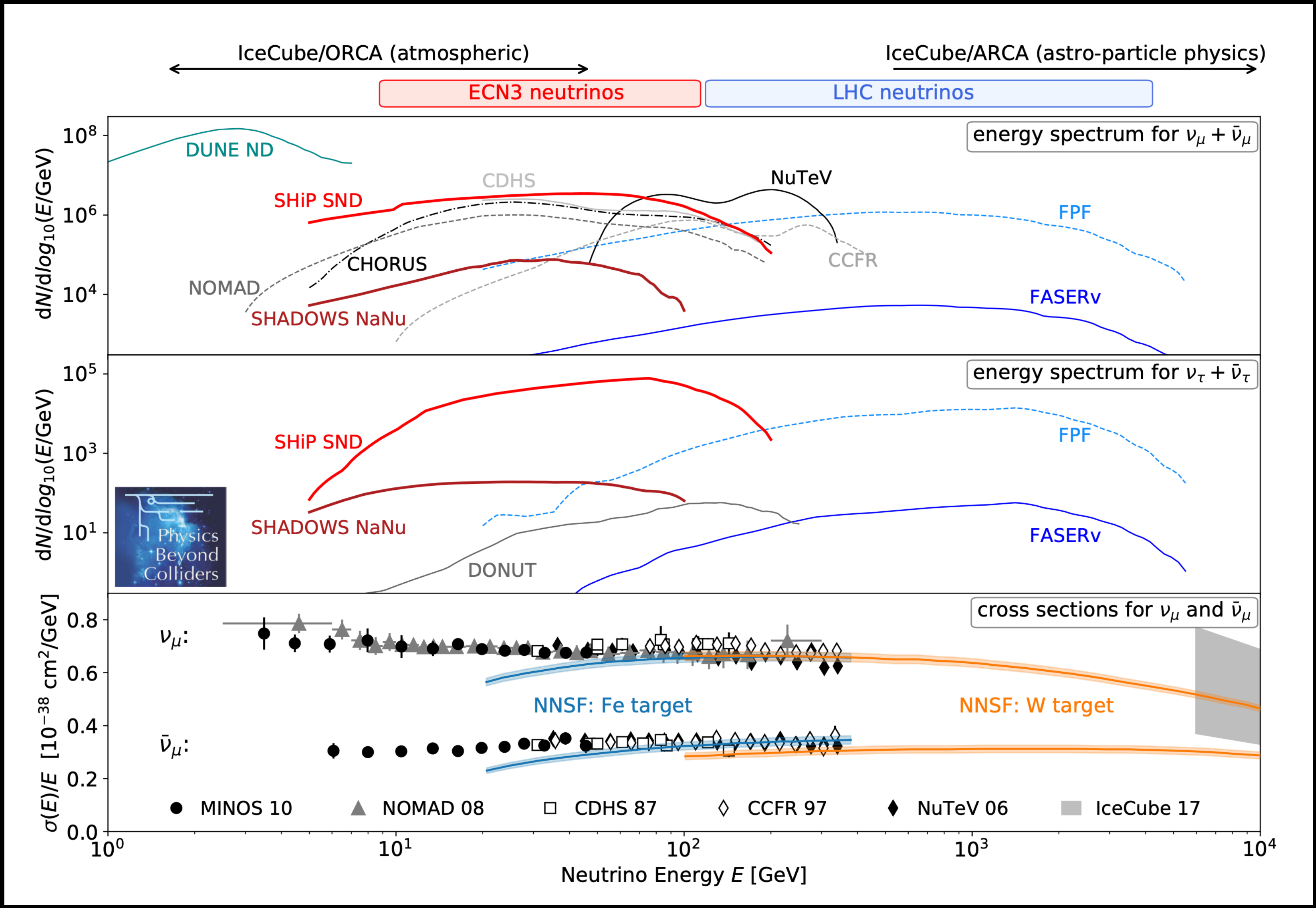

https://arxiv.org/pdf/2310.17726.pdf

Many more cool things out there!

Some cool things…

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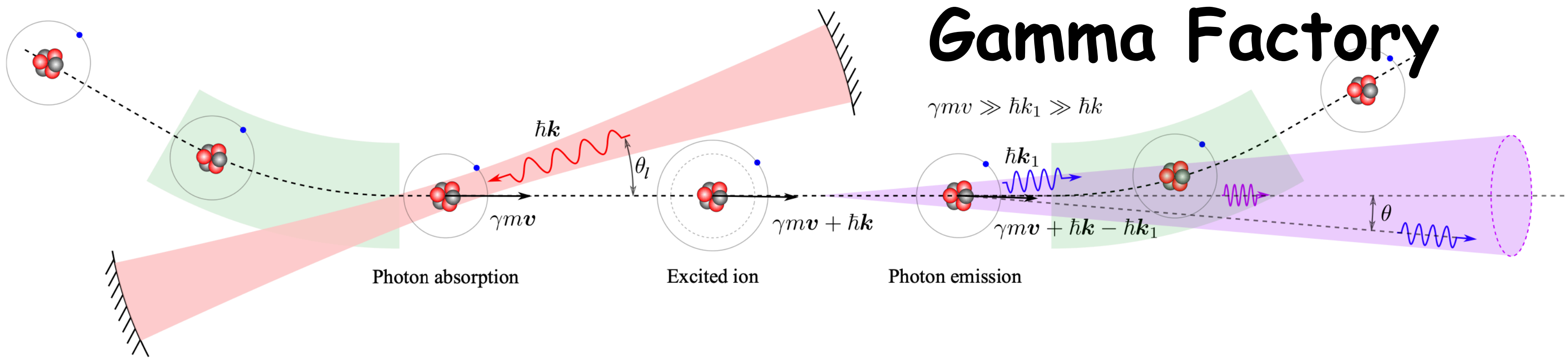
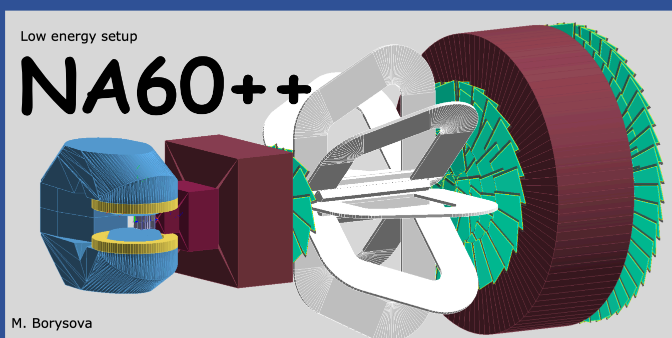
Gamma Factory



D. Budker… W. Krasny… et al. https://arxiv.org/pdf/2106.06584.pdf

Overview of the setup in Geant4



NA60+status report, PBC annual meeting, Nov 2022 G. Usai

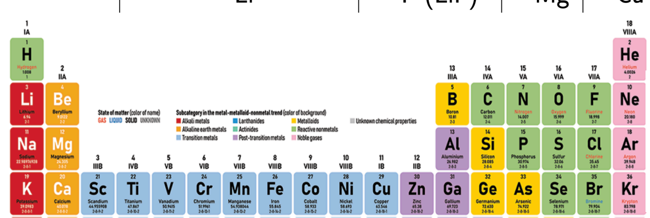
G. Usai
@ PBC
workshop 2022

M. K. Mackowiak-Pawlowska
@ PBC
workshop 2022

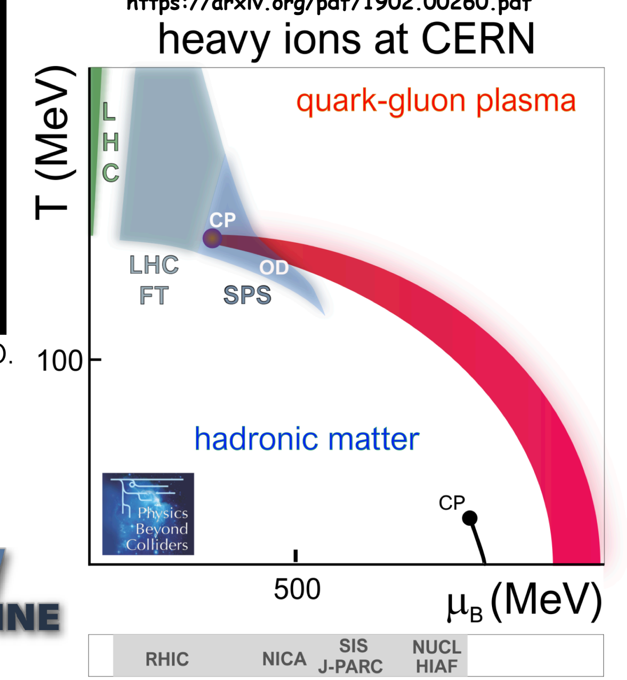
NA61++/SHINE

- The solid/compact targets are in favor due to possibility of installation in VD.

projectile	^{4}He/^{10}B	^{16}O	^{24}Mg	^{40}Ar
target	^{4}He(liquid)/^{9}Be-^{12}C ^{7}Li	^{16}O(water) ^{19}F (LiF)	^{32}S ^{24}Mg	^{45}Sc ^{40}Ca



https://arxiv.org/pdf/1902.00260.pdf



Conclusions

Conclusions

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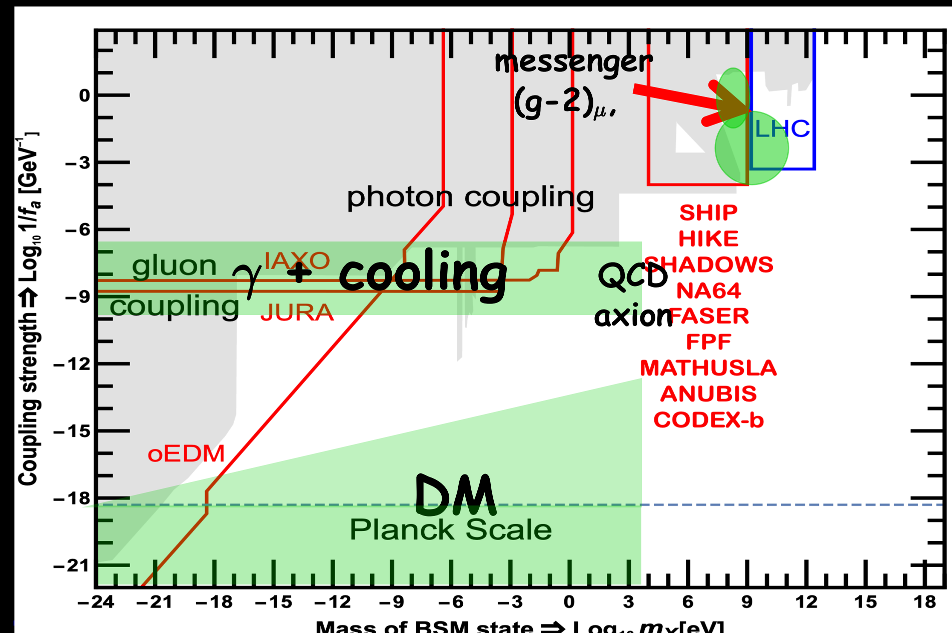
- Exploration for New Physics benefits from both high energy as well as high sensitivity

➔Different experiments complement each other

➔Interesting Hints



Many (more) cool things to explore!

More things going on @ PBC

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- Here mostly direct BSM searches but more things going on…

- QCD experiments
- Technology development

- This can also have crucial impact on BSM searches, e.g.
  - mu-e scattering → essential for $(g-2)_\mu$
  - Fixed target measurements with LHC beam → PDF's for collider searches

Conclusions

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Columbus' Theory: Tenerife – Jakarta ~ 3000 miles
Actual distance: ~ 7300 miles

https://spectrum.ieee.org/tech-talk/at-work/test-and-measurement/columbuss-geographical-miscalculations

Lesson:
Theory doesn't have to be correct in order to find something ;-).
➔ Go Explore + Be prepared for surprises

https://en.wikipedia.org/wiki/Christopher_Columbus#/media/File:Emanuel_Gottlieb_Leutze_-_Columbus_Before_the_Queen.JPG

More to come

- Stay tuned: pbc.web.cern.ch

Your Ideas Welcome