INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

Physics Beyond Colliders

Exploring Beyond the Standard Model

J. Jaeckel

Special Thanks to all my collaborators,
the Physics Beyond Colliders Study Group,
Claude Vallee and Mike Lamont
and all participants of the PBC workshops

Many slides, pictures etc from talks at PBC workshops

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Extra special thanks to Clare Burrage!

Many slides, pictures etc from talks at PBC workshops

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Physics Beyond Colliders

Exploring Beyond the Standard Model

CERN

Physics Beyond Colliders

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Extra special thanks also to Gaia Lanfranchi!

Many slides, pictures etc from talks at PBC workshops

No no no!!!!!!!!

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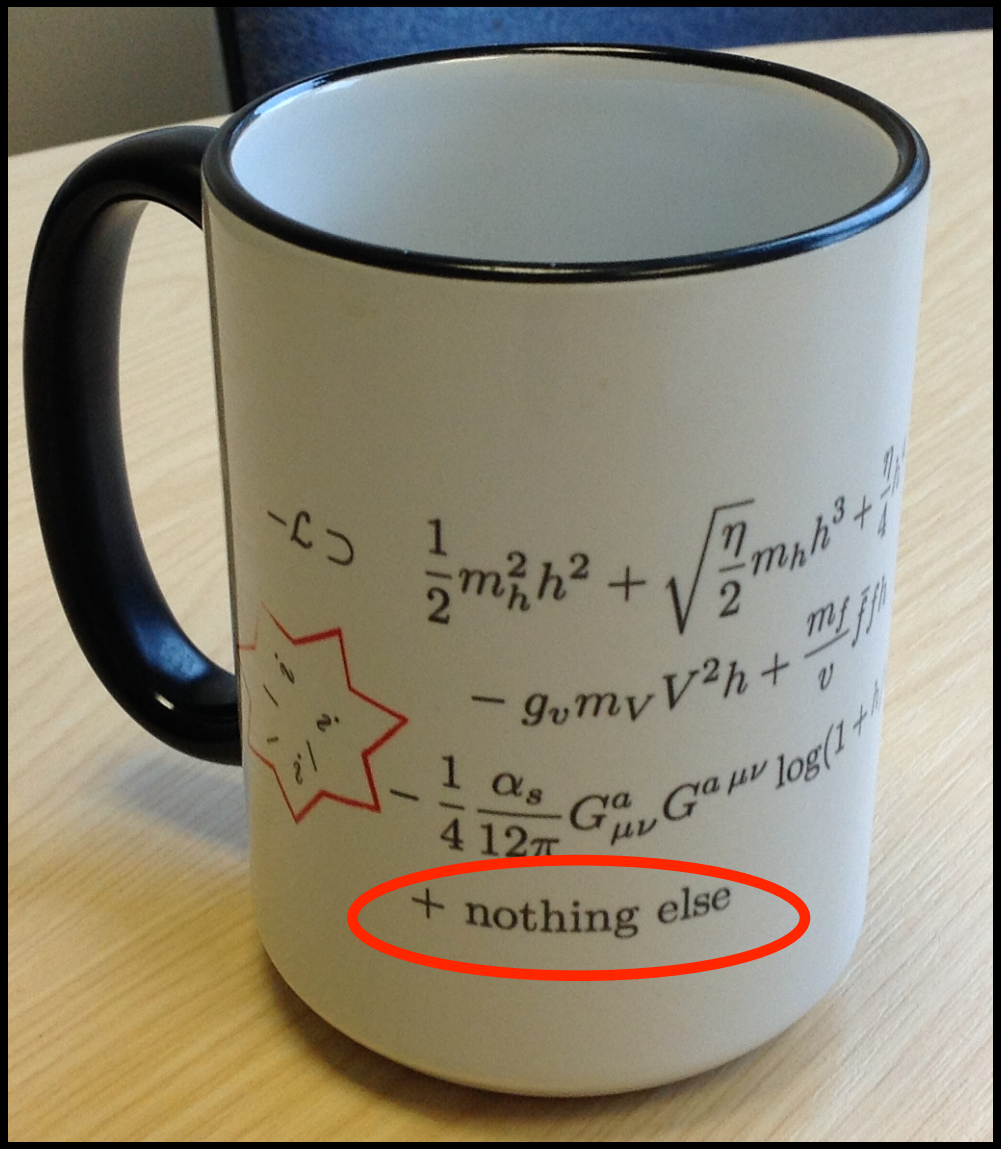

No no no!!!!!!!!

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What is PBC?

What is PBC?

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Study group mandated by CERN management to prepare for the next European HEP strategy update

(coordinators Mike Lamont, Claude Vallee, JJ)

"Explore the opportunities offered by the CERN accelerator complex to address some of today's outstanding questions in particle physics through experiments complementary to high-energy colliders and other initiatives in the world" (Excerpt from the mandate)

Time scale ~ 20 years

pbc.web.cern.ch

Where is the New Physics?

Exploring is (at least) 2 dimensional

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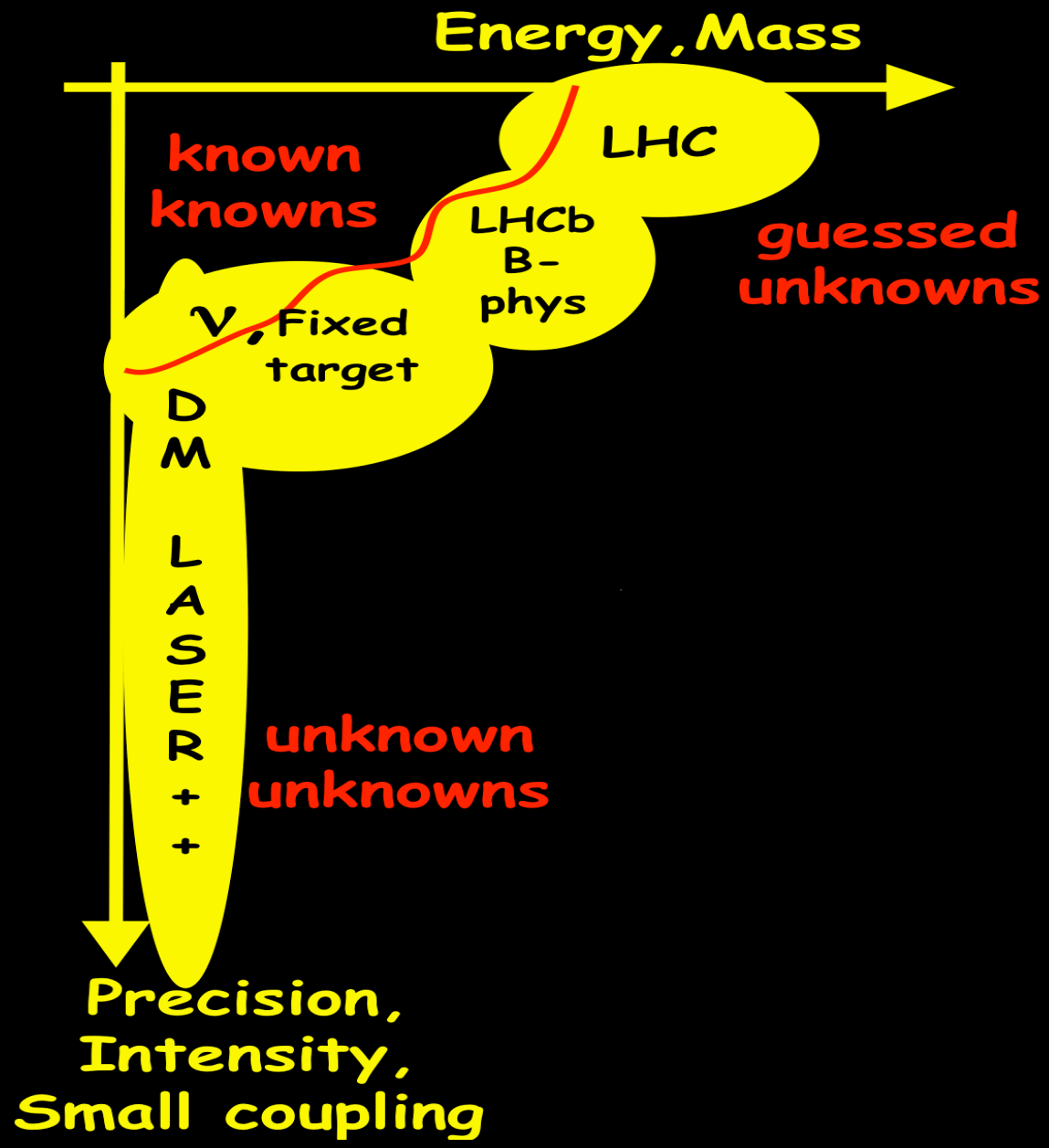

Here we want to go today…

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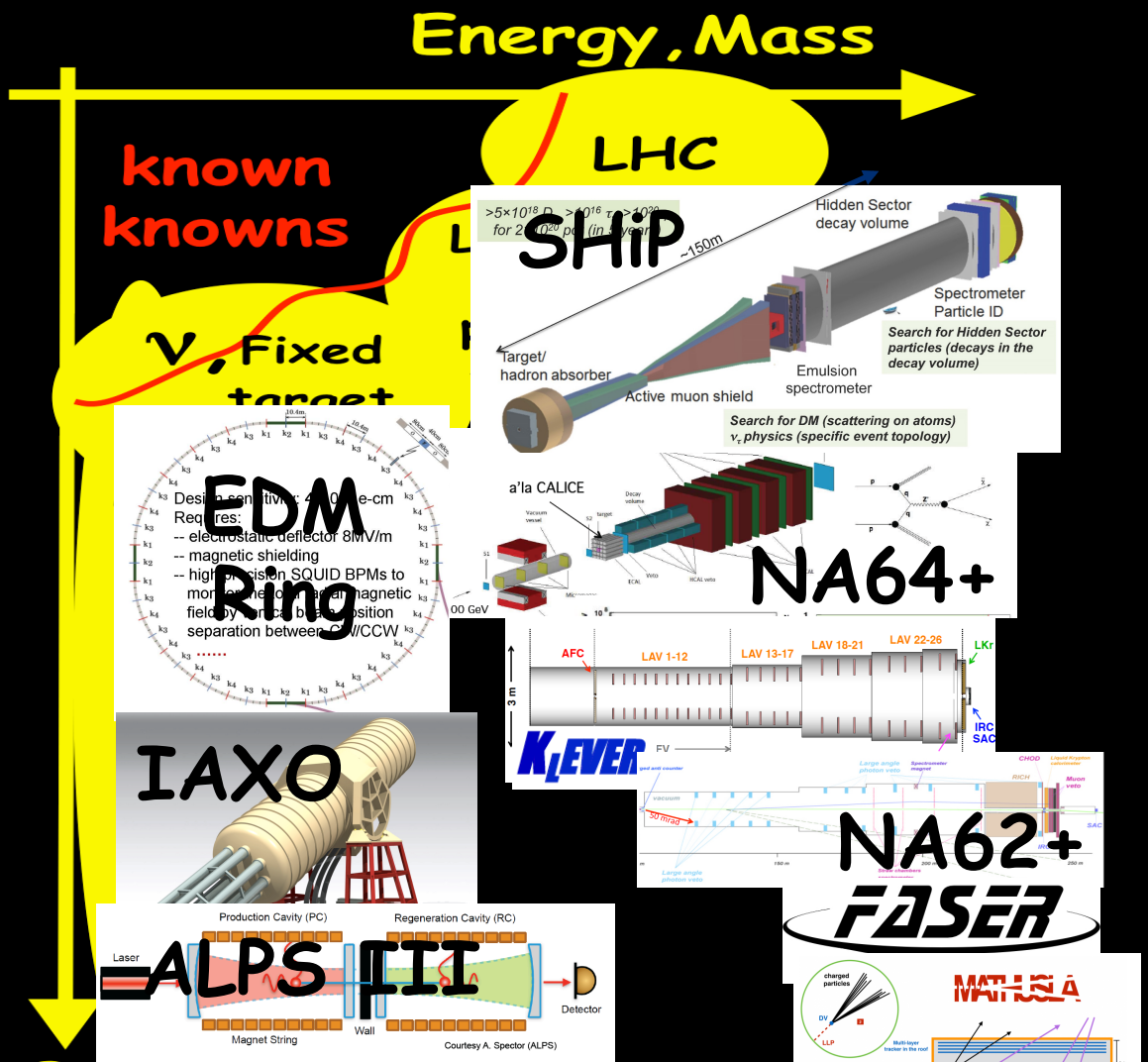

PBC exploration

An example:

Axions,
axion like particles,
general pseudo-Goldstone bosons

This is only an example
Many more cool and interesting models to test!!!

Couplings fixed by scale of symmetry breaking: f_a

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- **Photon coupling**

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

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

- **Gluon coupling**

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

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

- **Fermion couplings**

$$\mathcal{L} \supset \frac{\partial_\mu \phi}{f_a} \bar{\psi} \gamma^{\mu} \gamma^{5} \psi$$

In pictures...

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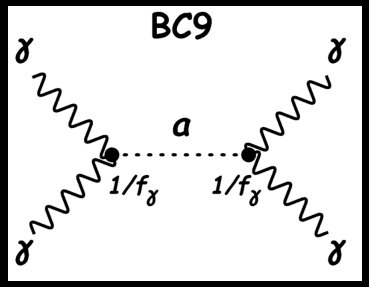
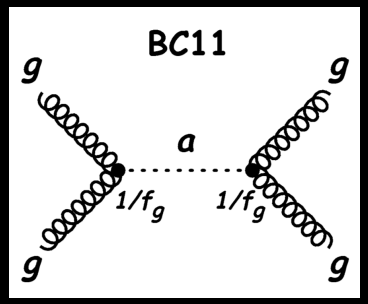
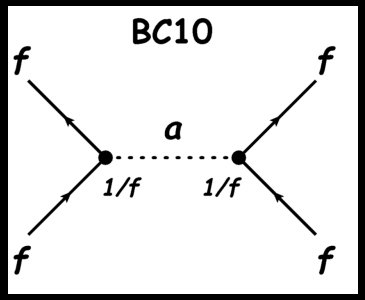
photons



gluons



fermions



Target space

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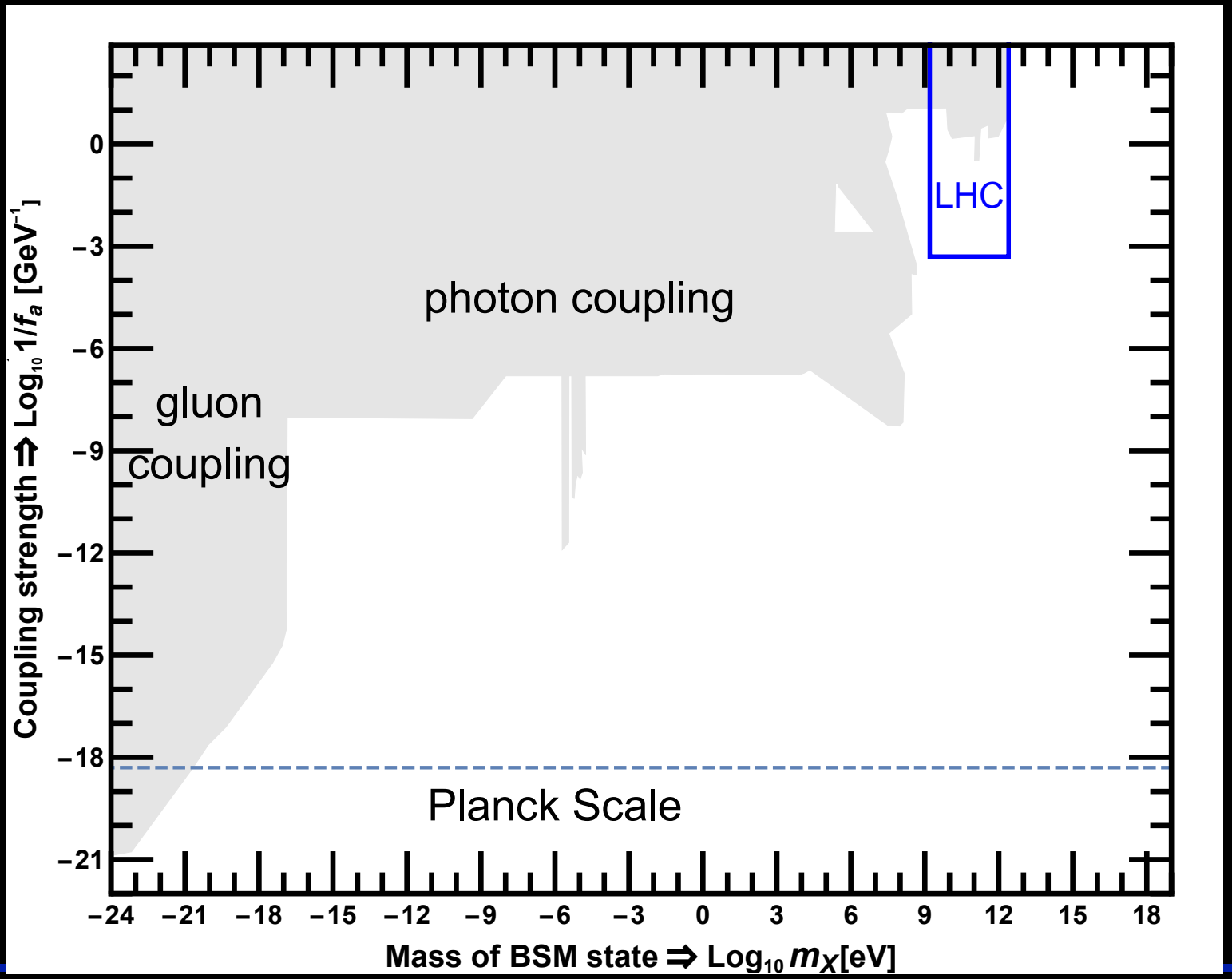

Measurement of proton EDM

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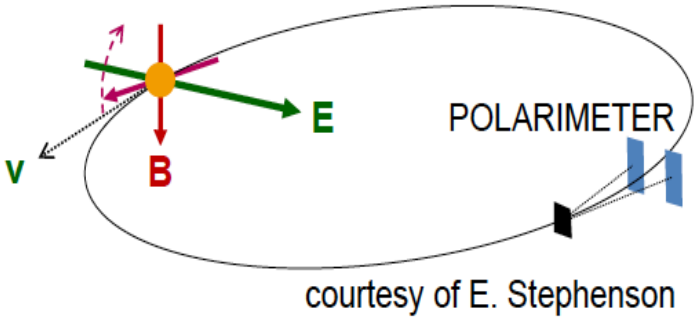
Storage ring based EDM search

- In the presence of EDM,

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

- **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**

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



courtesy of E. Stephenson

Full Spin Frozen storage ring is the most effective way!

Sensitivity

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

What is measured?

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- Proton electric dipole moment ~Θ_{QCD}

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

Θ_{QCD}

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

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

Sensitivity

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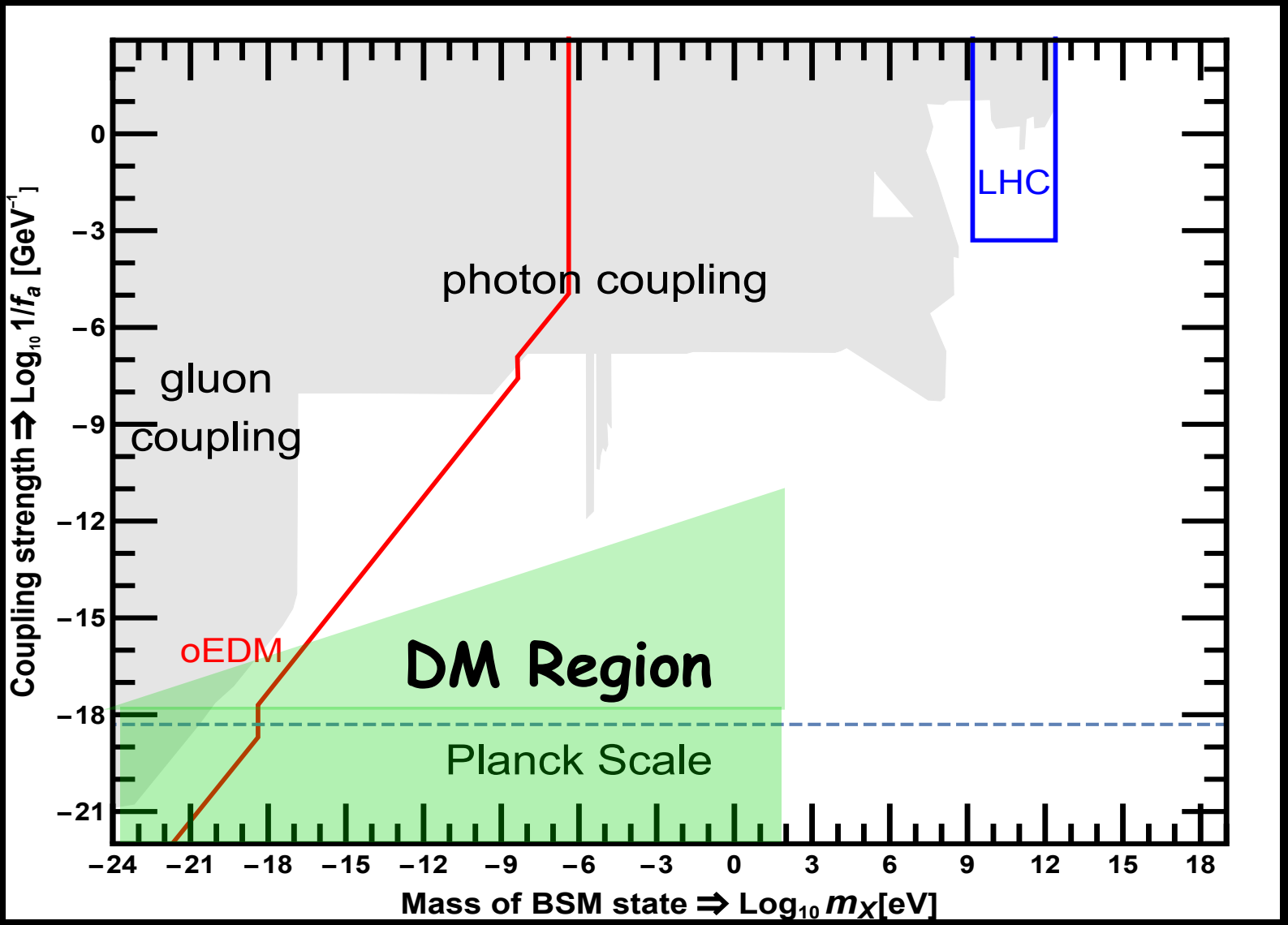

International Axion Observatory = IAXO

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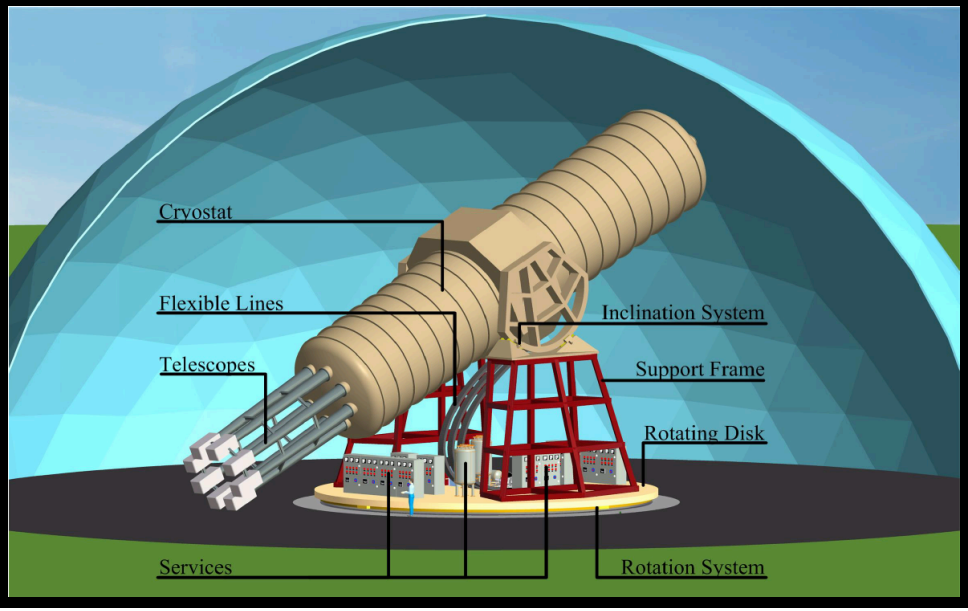
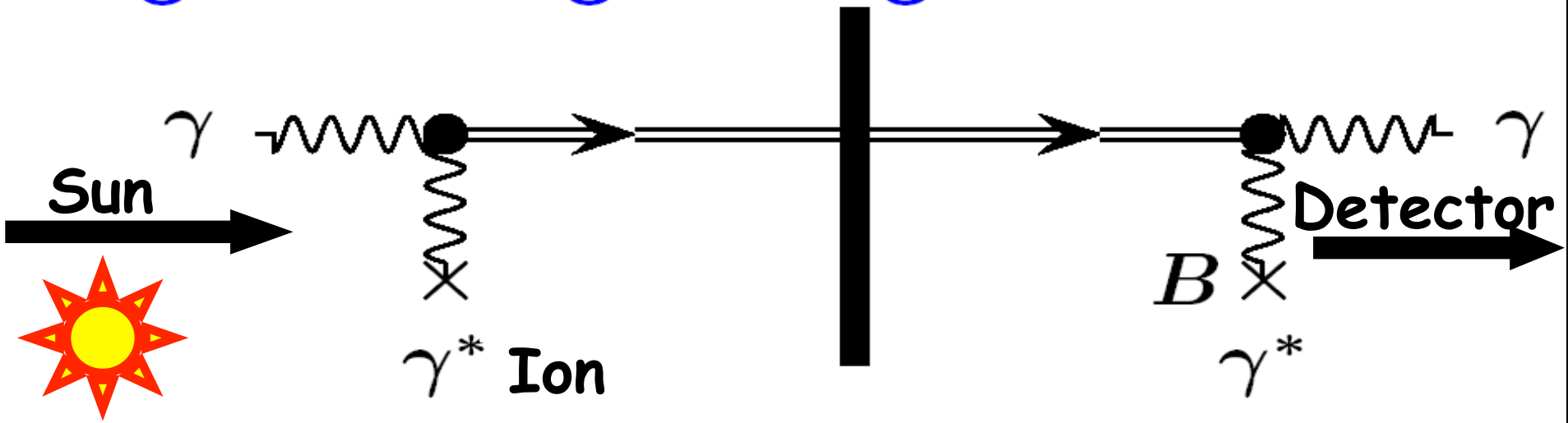


$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma} \phi F^{\mu} \tilde{F}_{\mu\nu}$$

"Light shining through a wall"



Sensitivity

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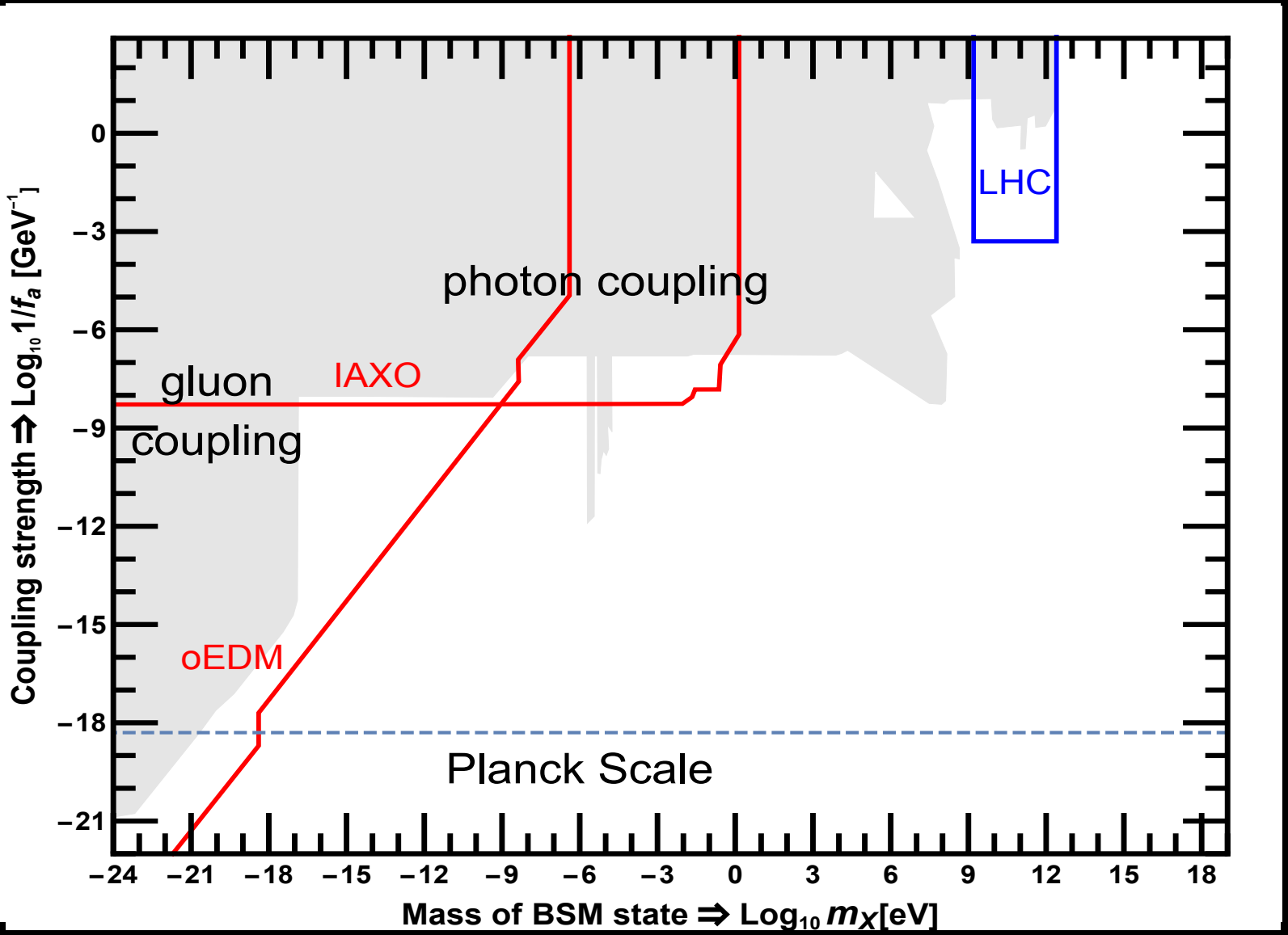

Sensitivity

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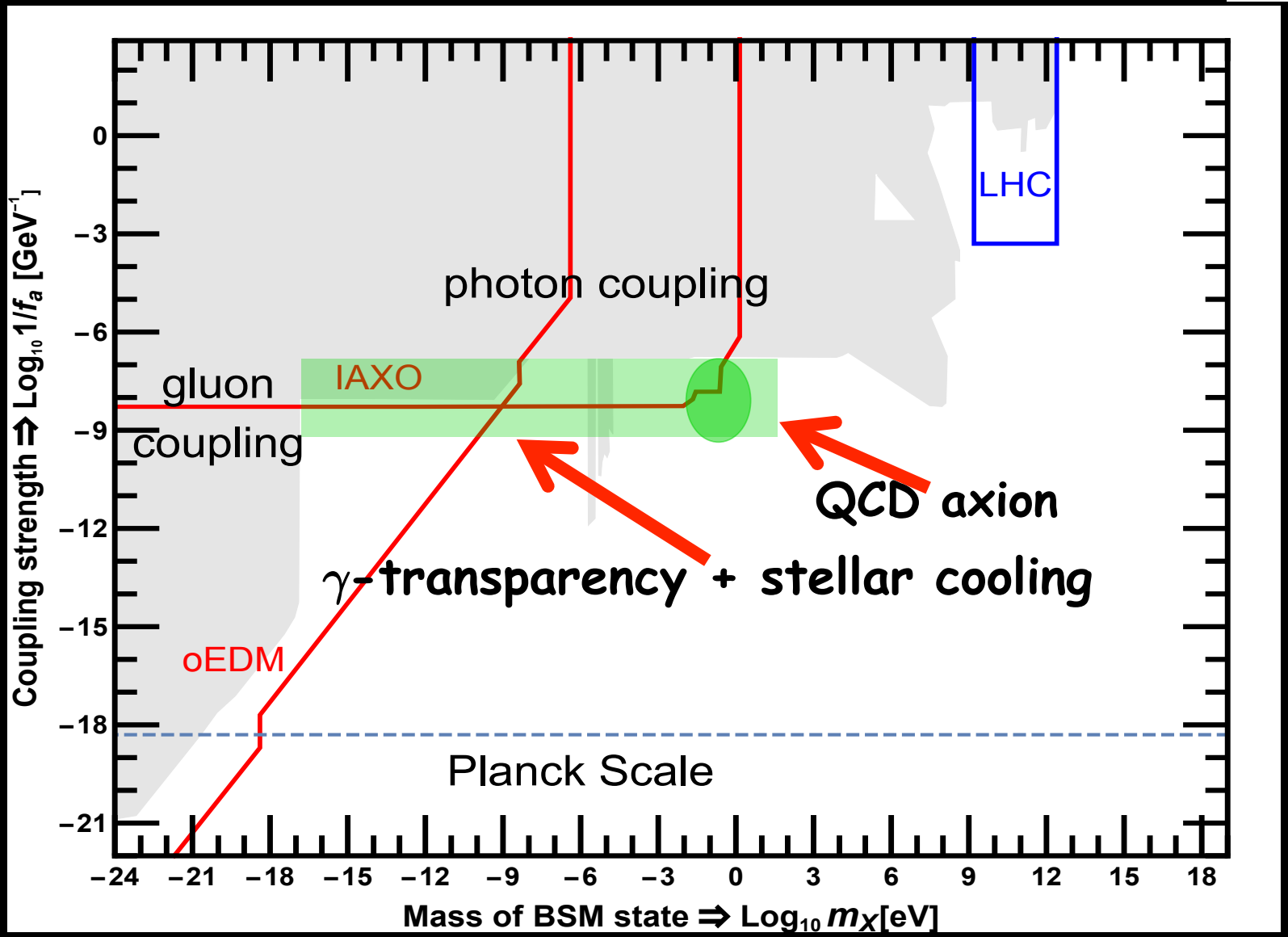

More : Light shining through walls
JURA

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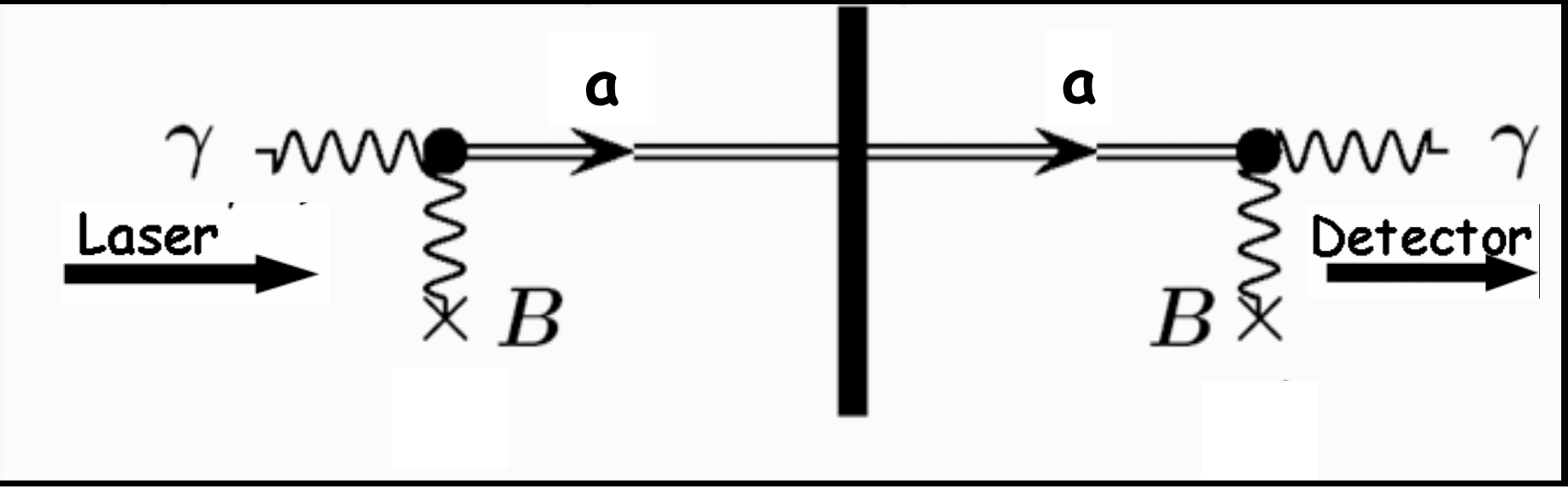

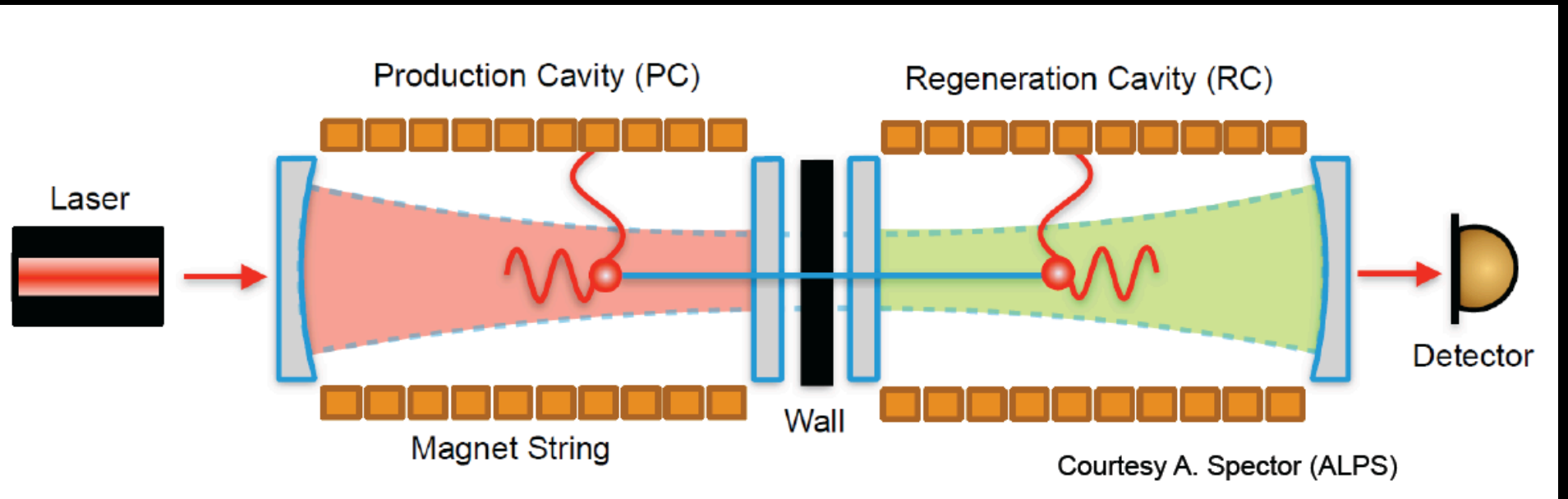

Sensitivity

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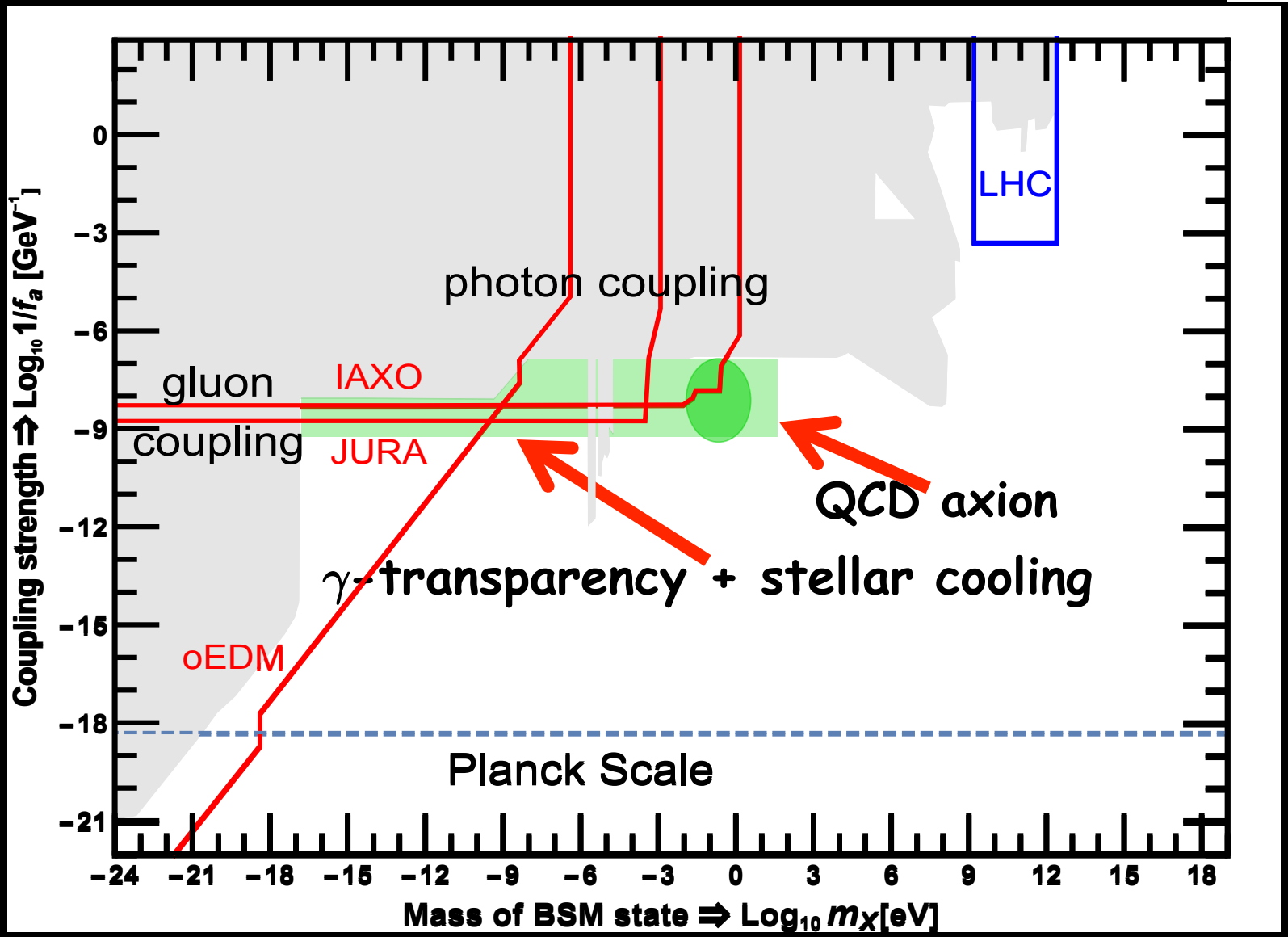

Search for Hidden Particls = SHiP

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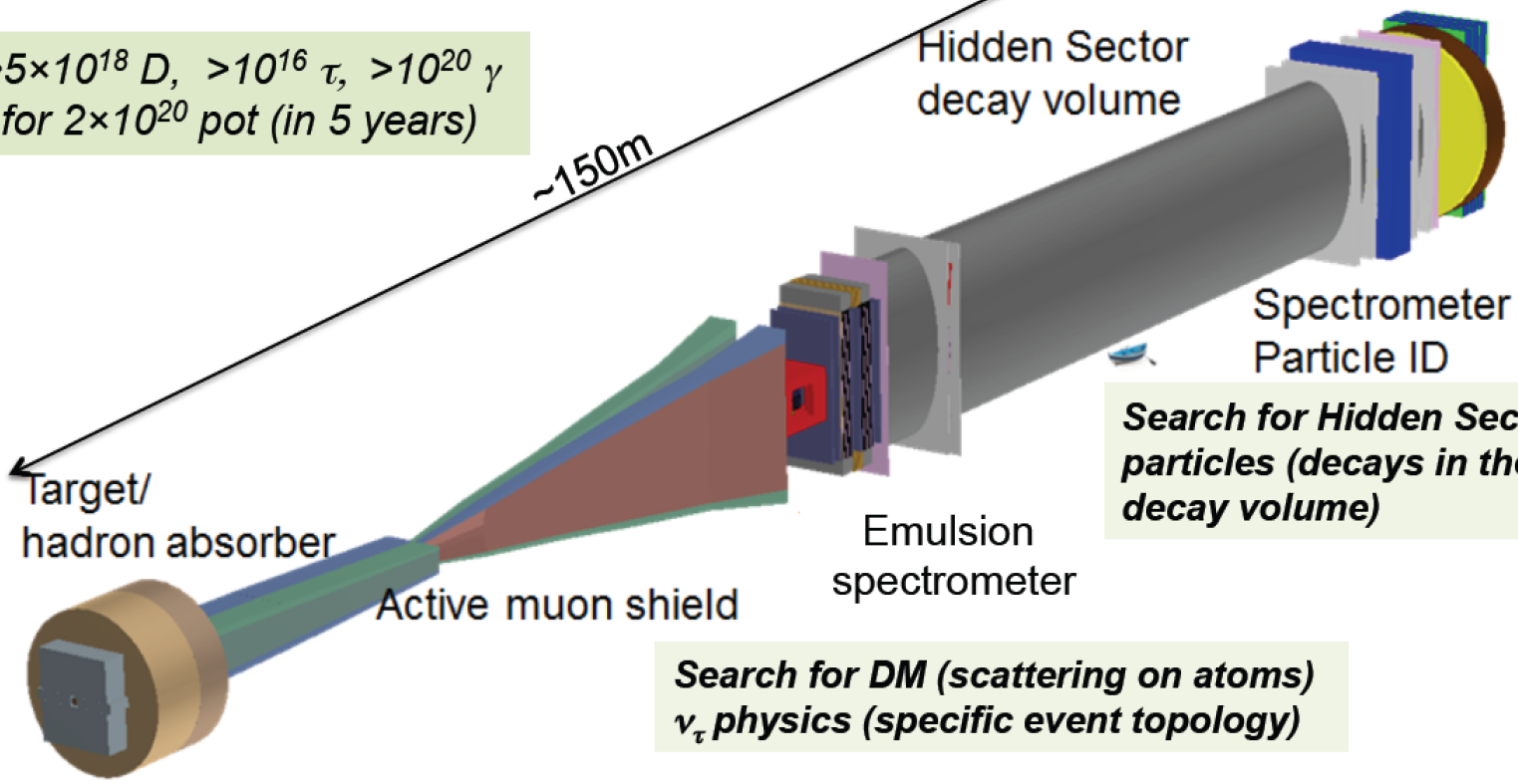
SHiP
Search for Hidden Particles

The SHiP experiment at SPS
(as implemented in Geant4 for TP)

SHiP Technical Proposal: 1504.04956

"Zero background" experiment
- *Muon shield*
- *Surrounding Veto detectors*

>5×10^{18} D, >10^{16} τ, >10^{20} γ for 2×10^{20} pot (in 5 years)



Search for Hidden Sector particles (decays in the decay volume)

Search for DM (scattering on atoms)
ν_τ physics (specific event topology)

A theorist's picture...

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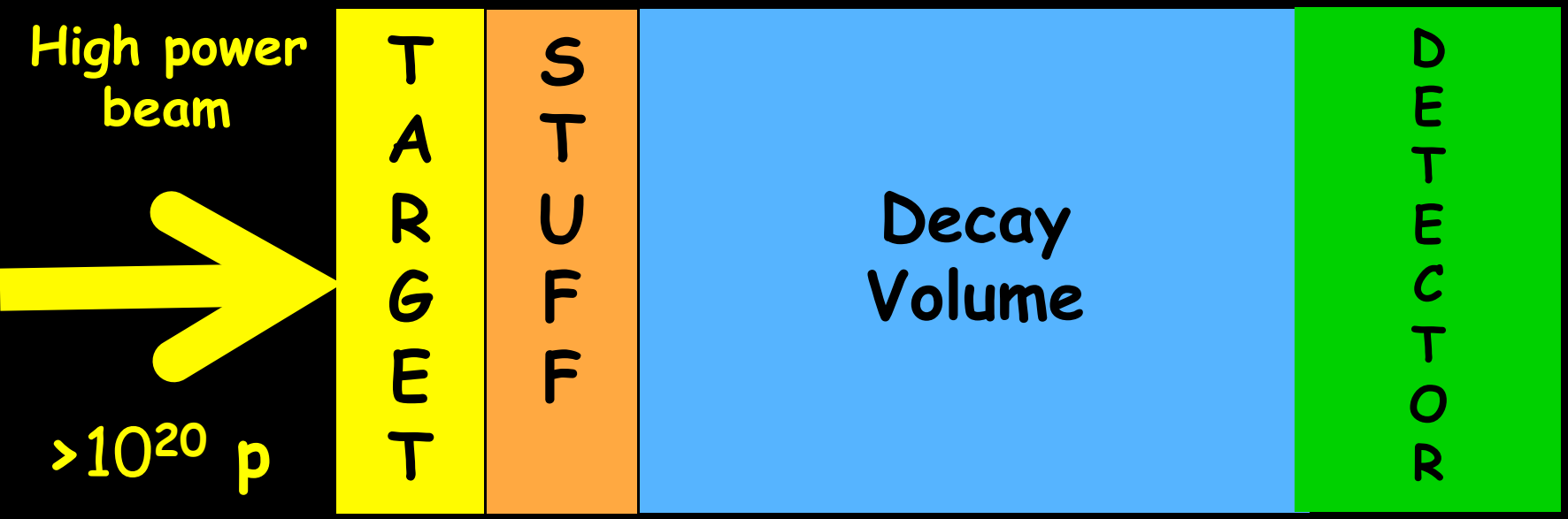

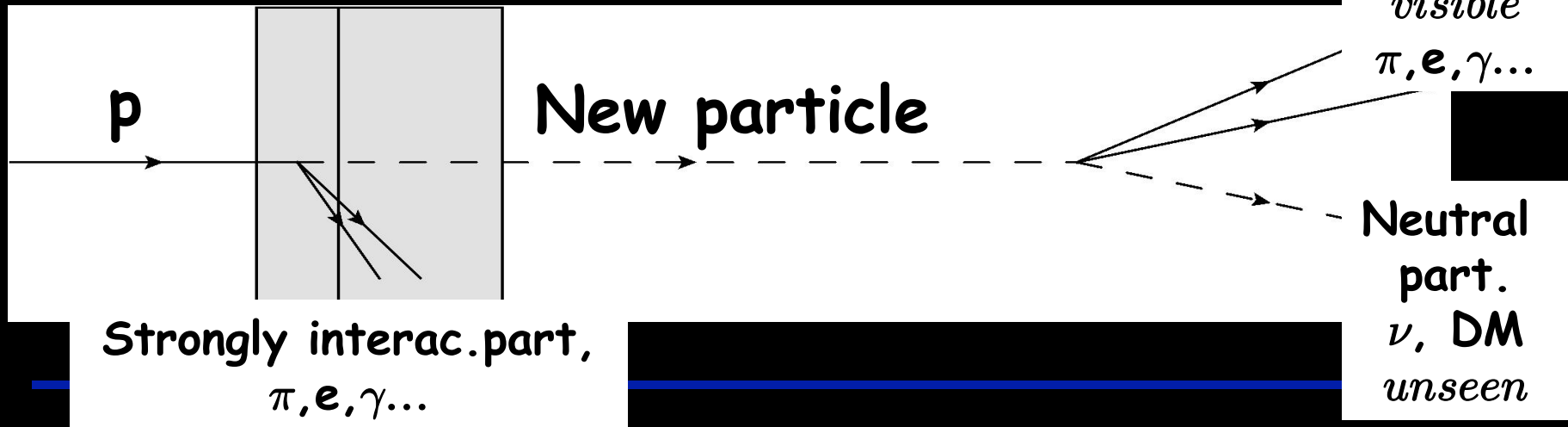

A theorist's picture...

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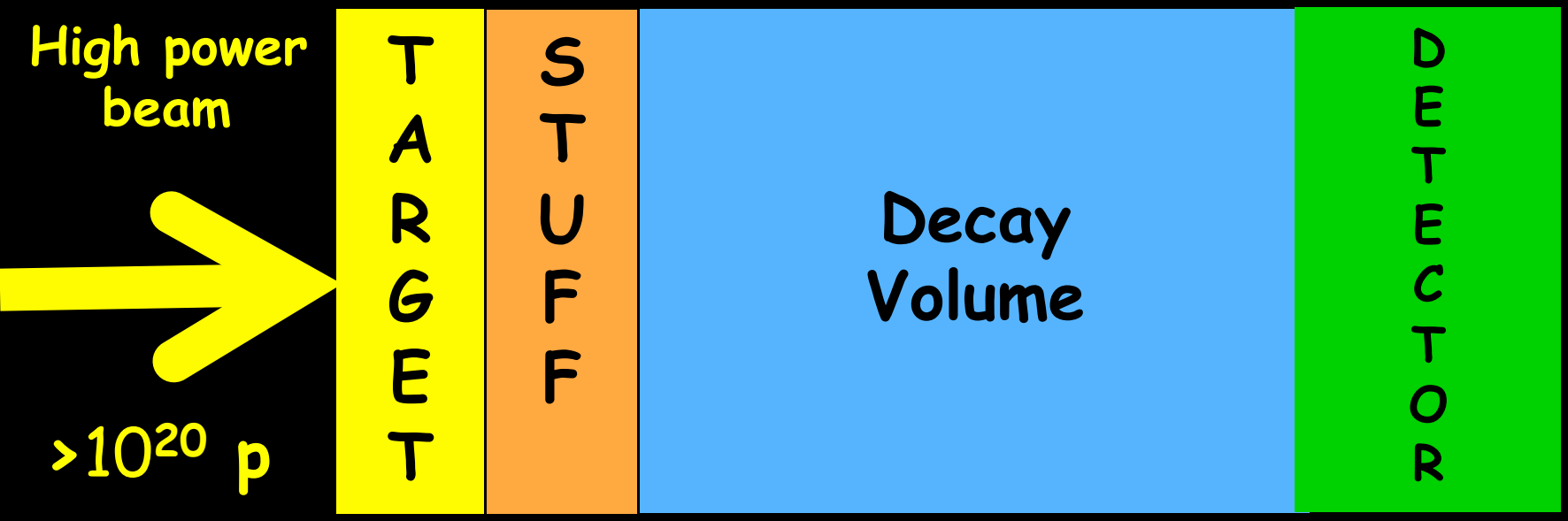
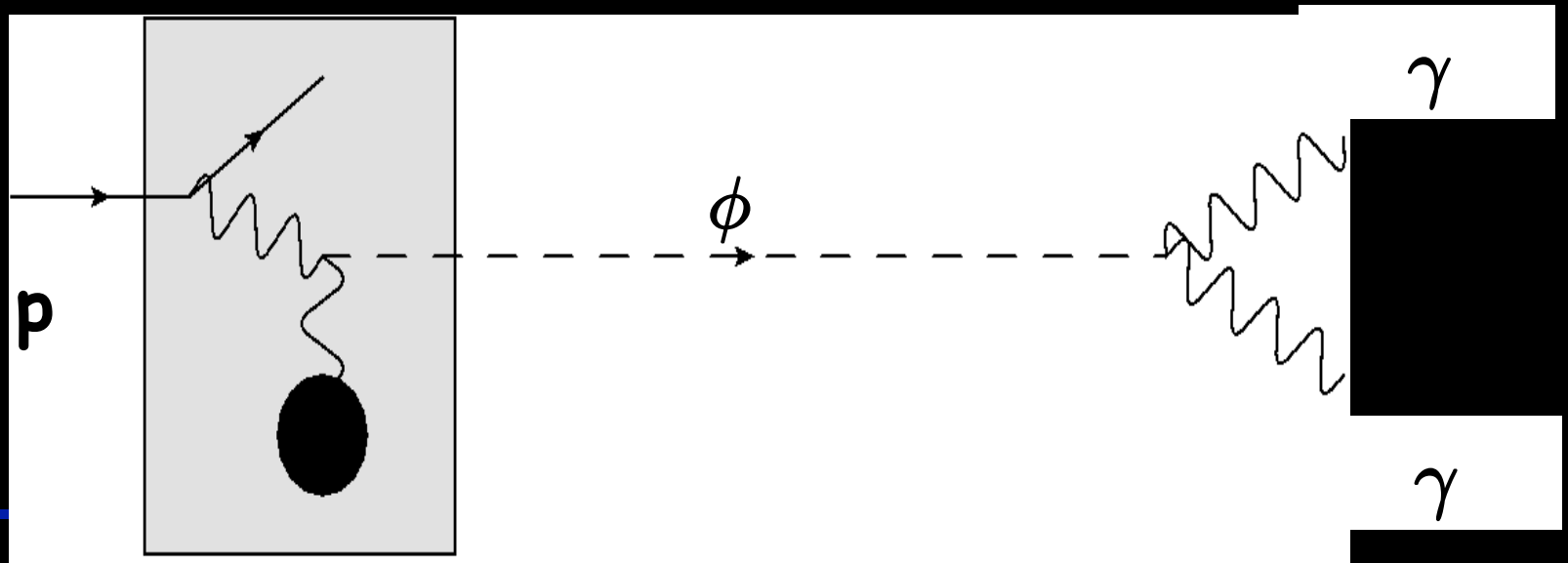
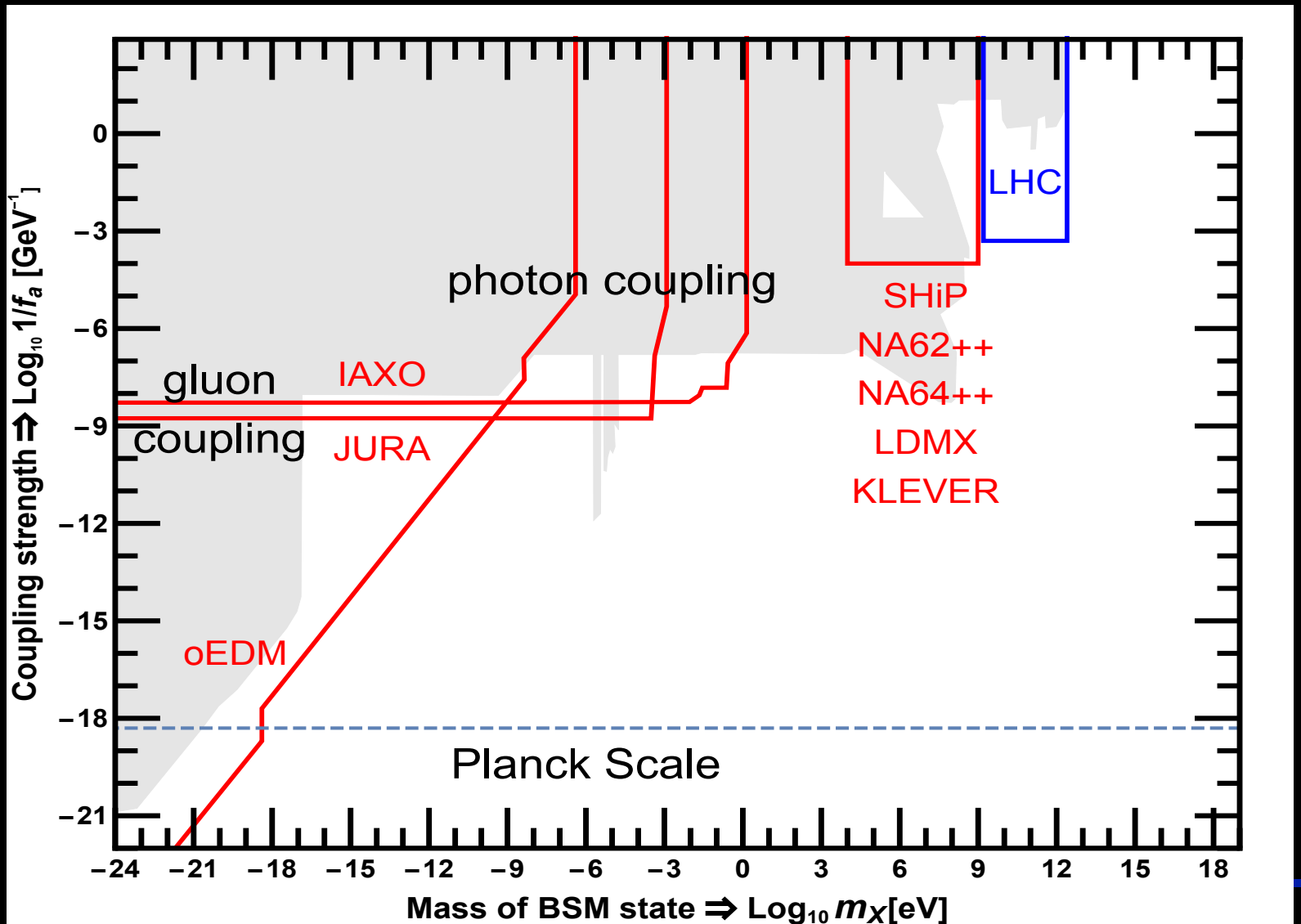




SHiP + NA62+, NA64+ and KLEVER



"Seeing" the dark stuff NA 64+

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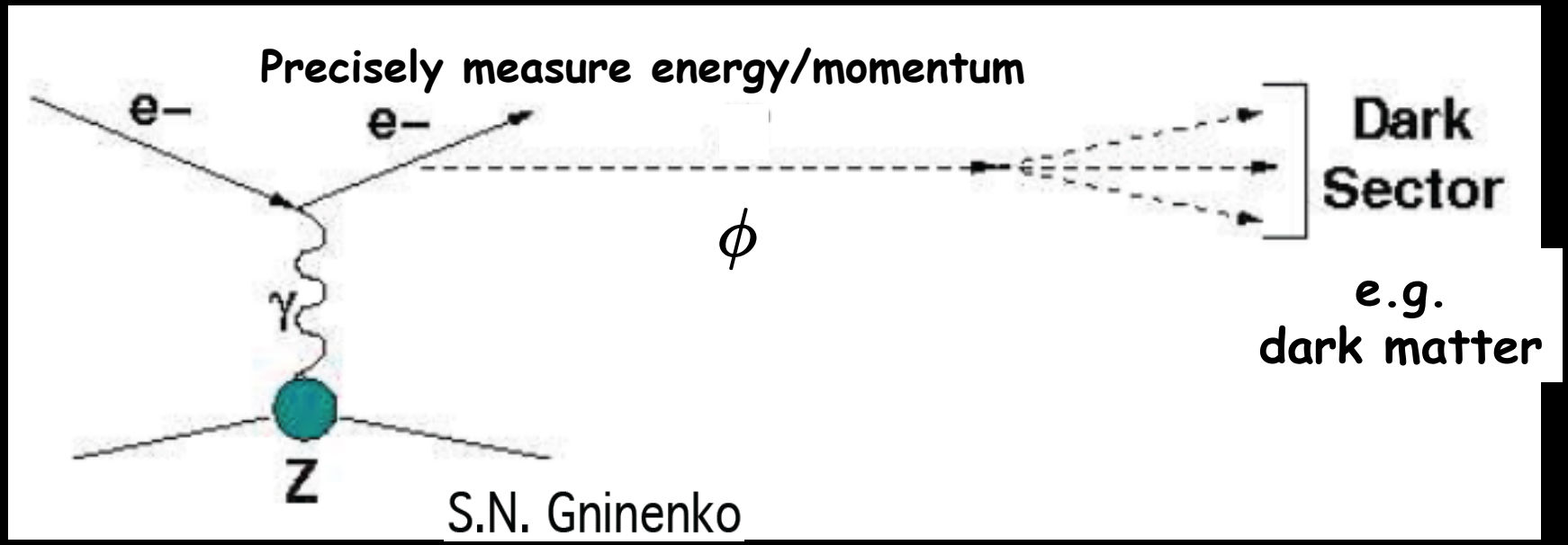
$$\mathcal{L} \supset \frac{\partial_\mu \phi}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$$



+ "dark matter" detector @ SHiP

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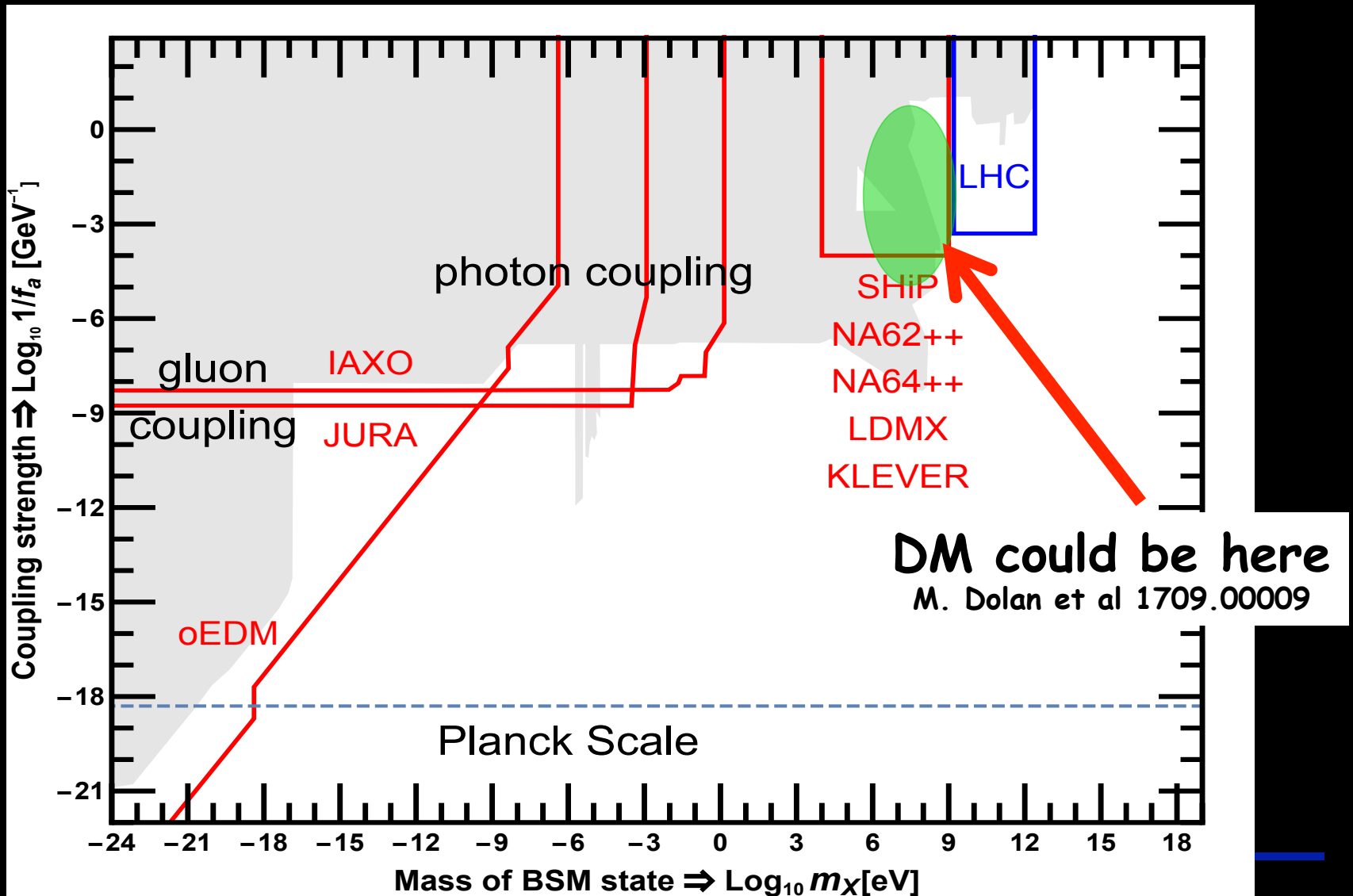
Messengers for dark matter?



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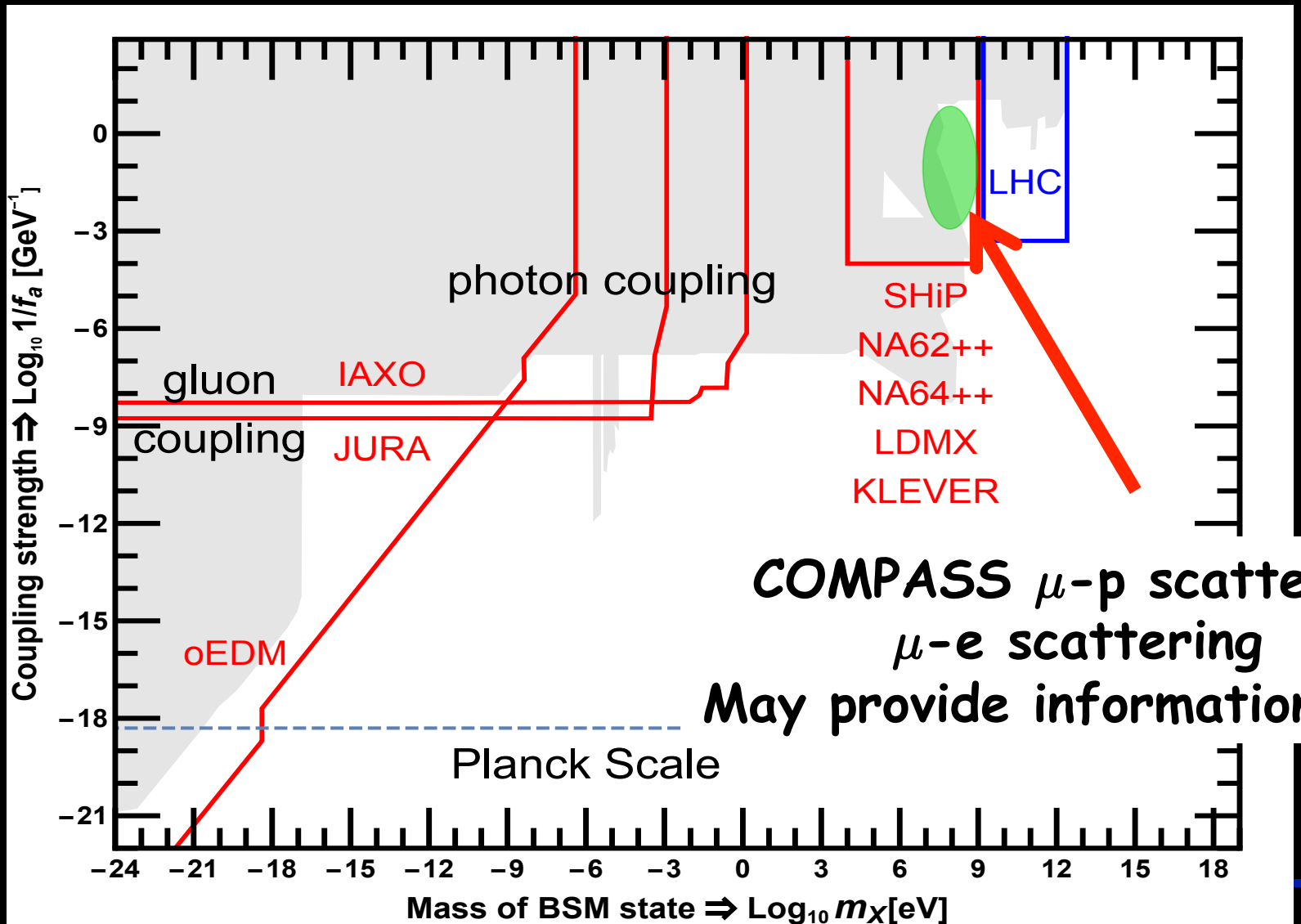
$(g-2)_\mu$ and proton radius anomaly



COMPASS μ-p scattering
μ-e scattering
May provide information here

mu on e

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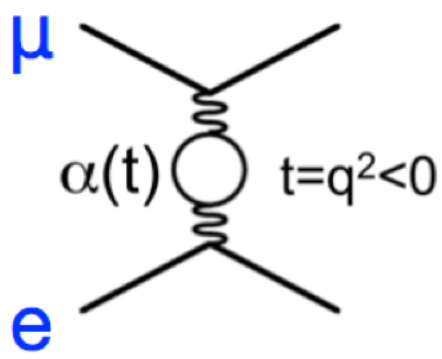
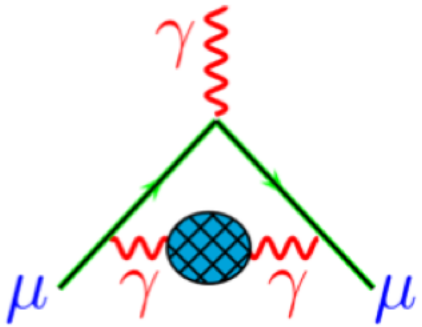
- Measure hadronic corrections for $(g-2)_\mu$
- Crucial input for using $(g-2)_\mu$ to search for BSM!
- New way: Measure scattering of μ on e



sum rule →



see Gunar Schnell @ PBC Workshop Nov. 2017

Long Lived Particles @ LHC

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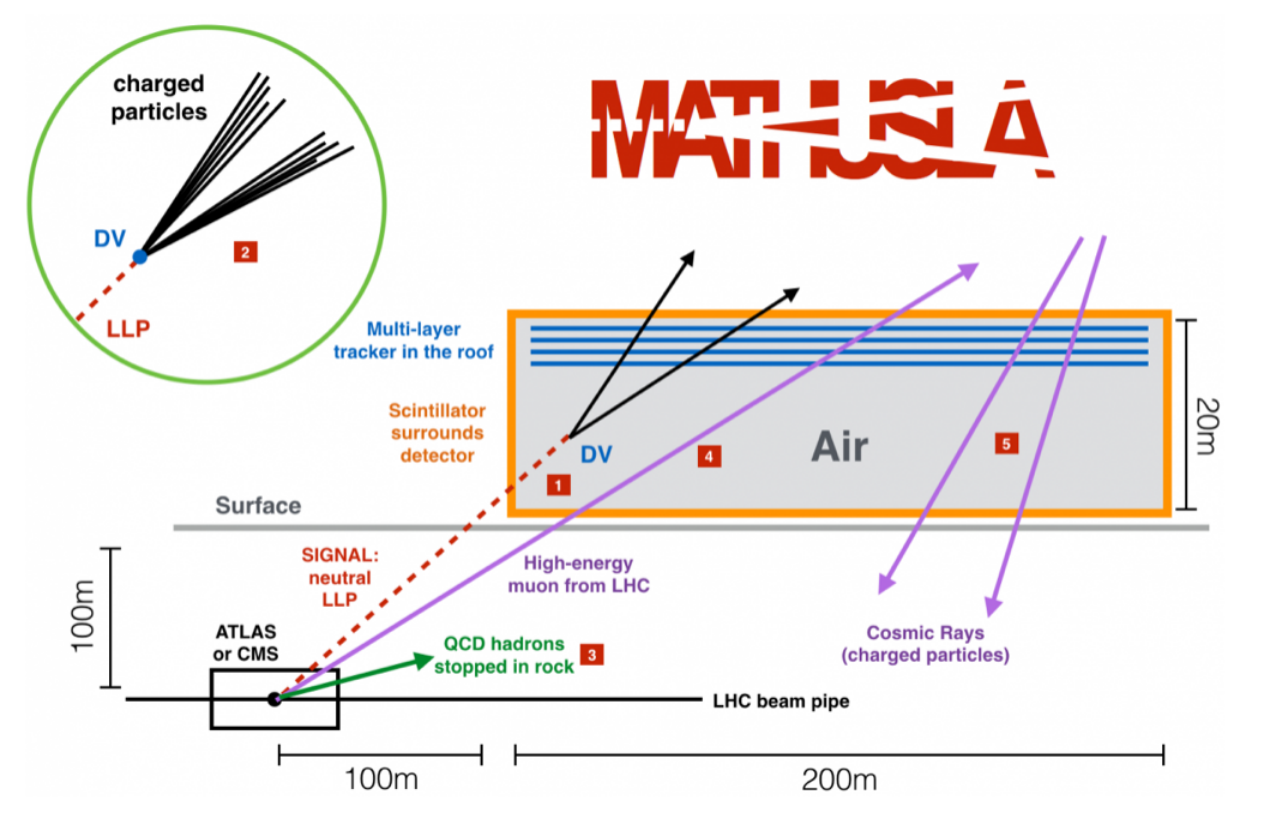
- Idea: Look for very long lived particles produced in LHC collissions
- Recent proposals:

  MATHUSLA, FASER, CodexB



Long Lived Particle searches also explore MeV-GeV region

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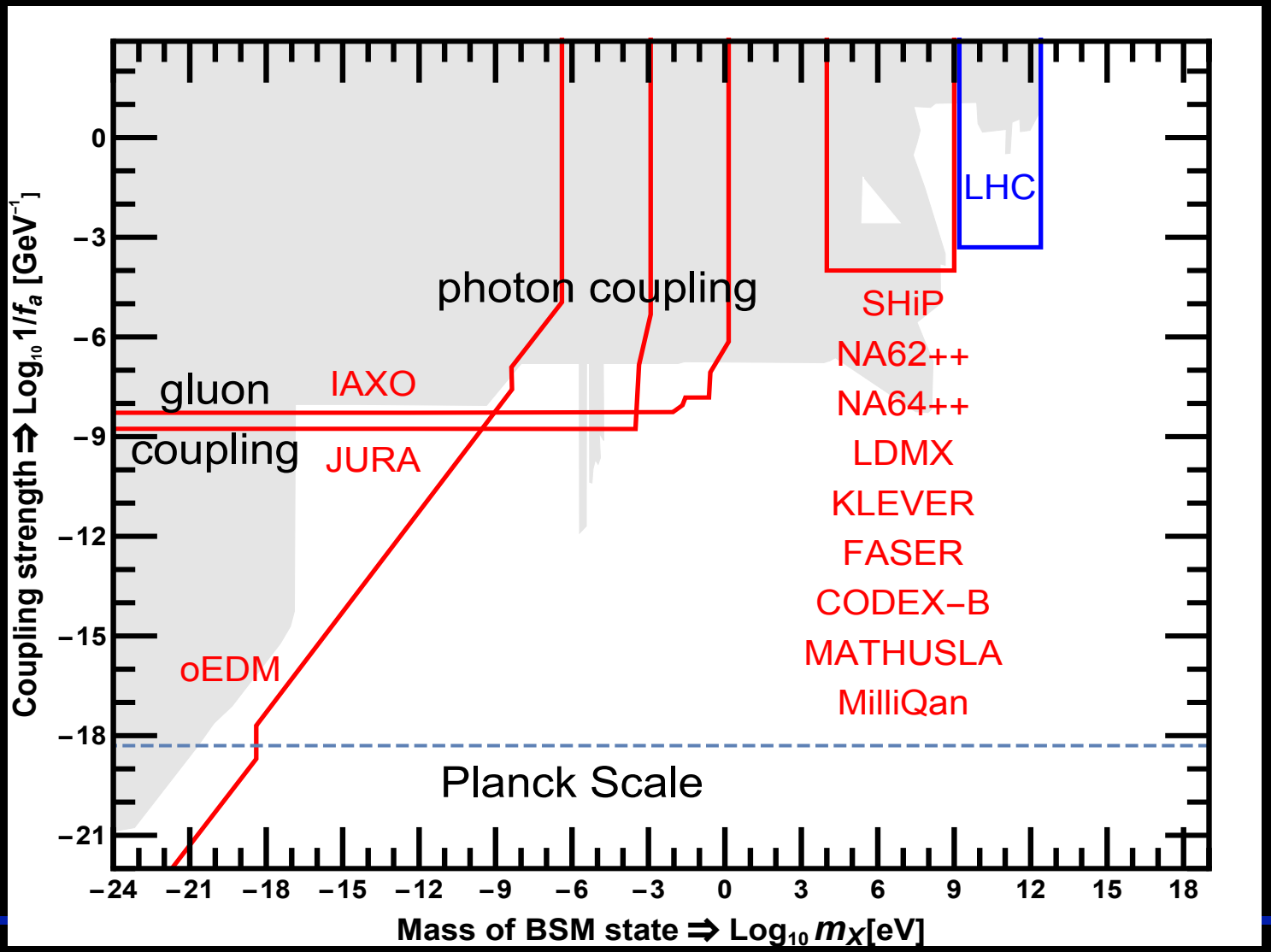

Much more cool physics can be probed !!!

Example 1

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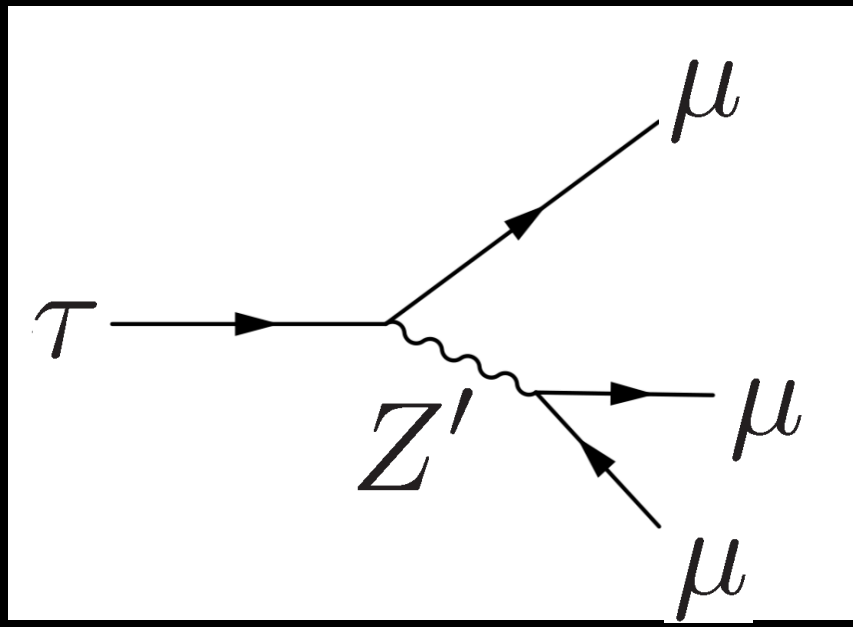
- Rare decays:

$K^+ \to \pi^+ + \nu\nu$	NA62 (currently running)
$K^0 \to \pi^0 + \nu\nu$	KLEVER
$\tau \to \mu^+\mu^-\mu^+$	TauFV
$\eta \to \mu^+ + e^-$	RedTop



➔ Probe 1-1000TeV scales

Where do we explore...

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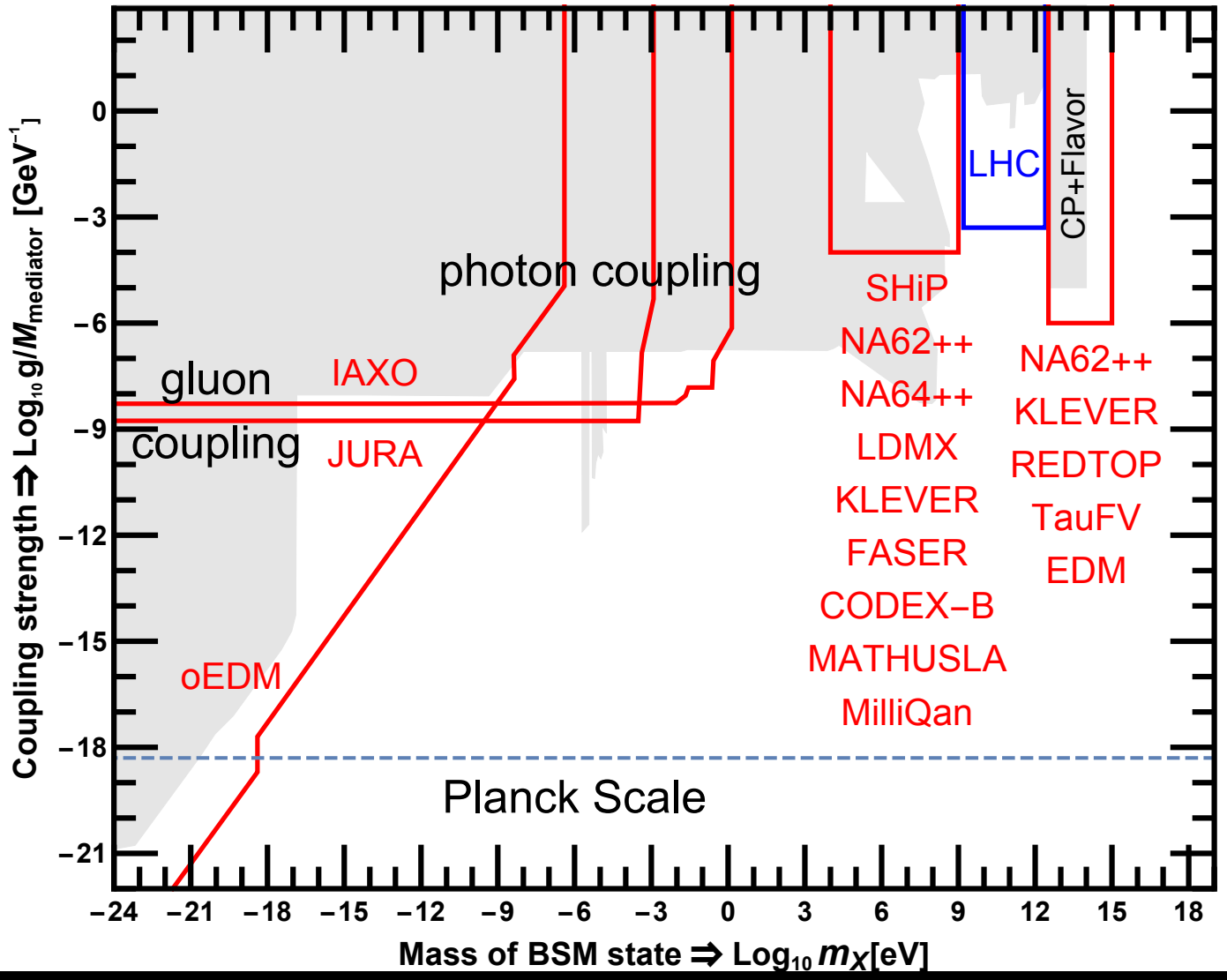

Example 2:
Dark Photon without dark decays

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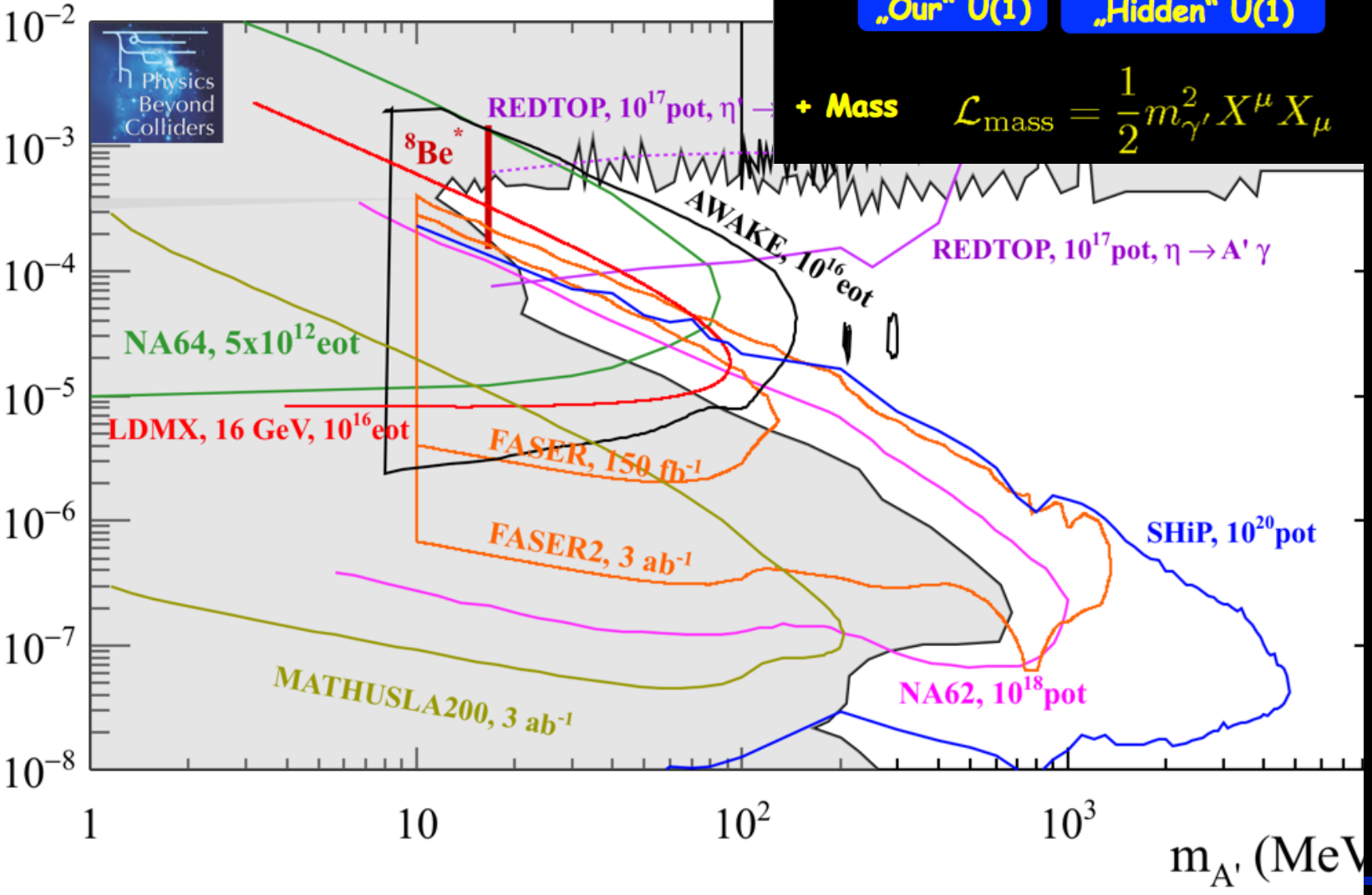
$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}F^{\mu\nu}_{(A)}F_{(A)\mu\nu} - \frac{1}{4}F^{\mu\nu}_{(B)}F_{(B)\mu\nu} + \frac{\epsilon}{2}F^{\mu\nu}_{(A)}F_{(B)\mu\nu},$$

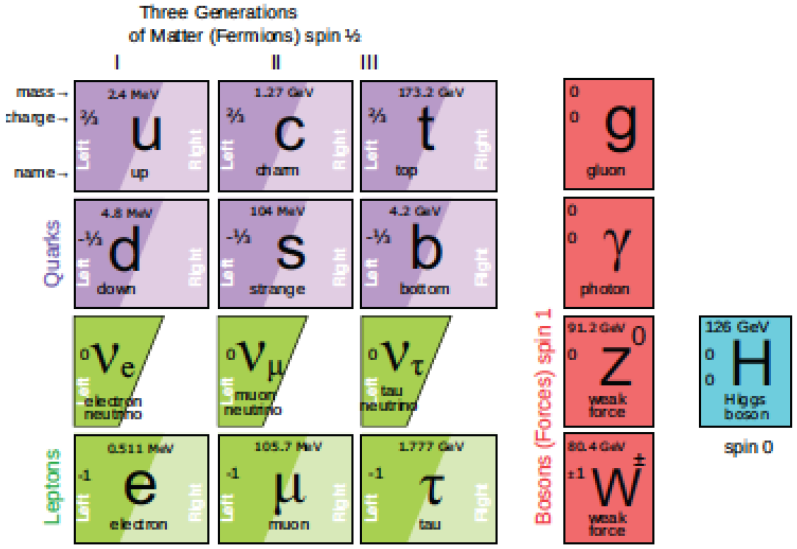
„Our" U(1) | „Hidden" U(1) | Mixing

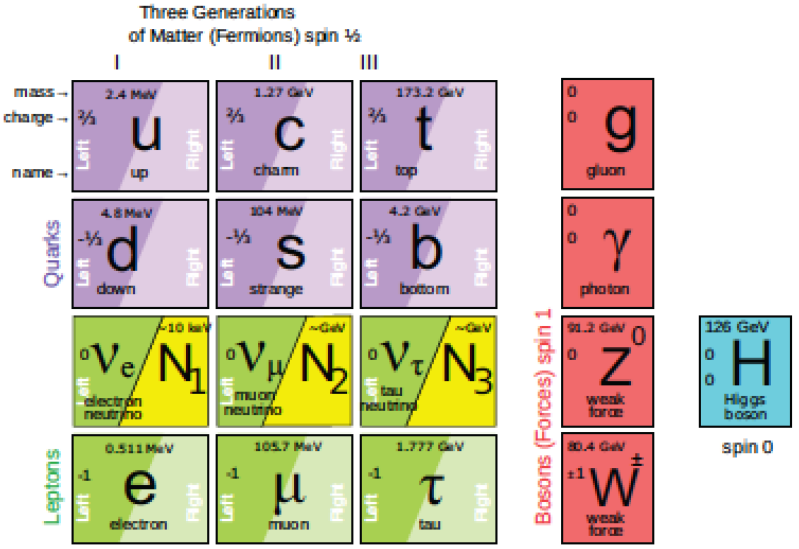
+ Mass $\mathcal{L}_{\text{mass}} = \frac{1}{2}m^2_{\gamma'}X^\mu X_\mu$



Example 3: Heavy Neutral Leptons

A new ν (Minimal) Standard Model





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.

From M. Shaposhnikov

PBC experiments@work

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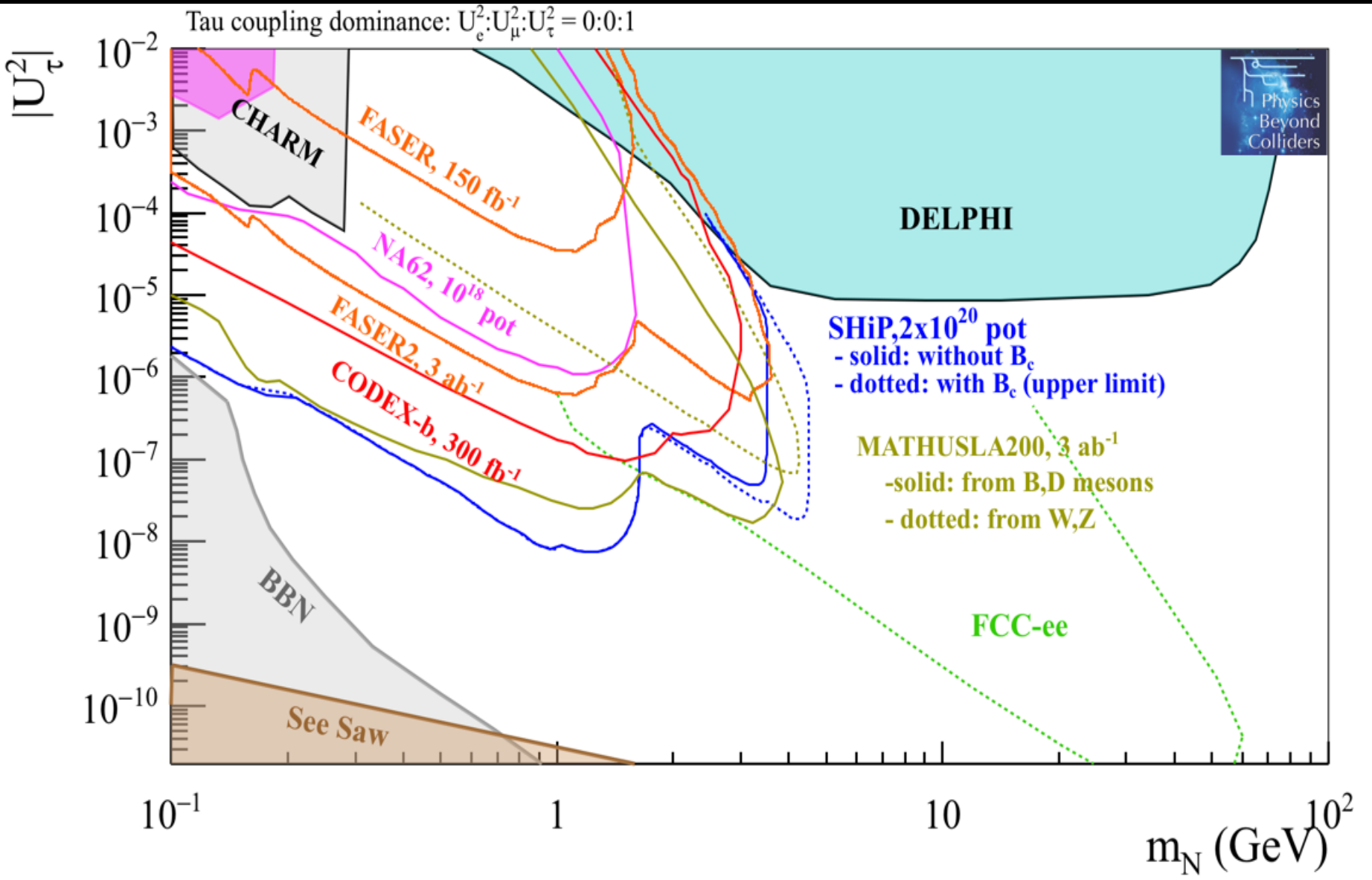

A few words on QCD

LHC fixed target studies

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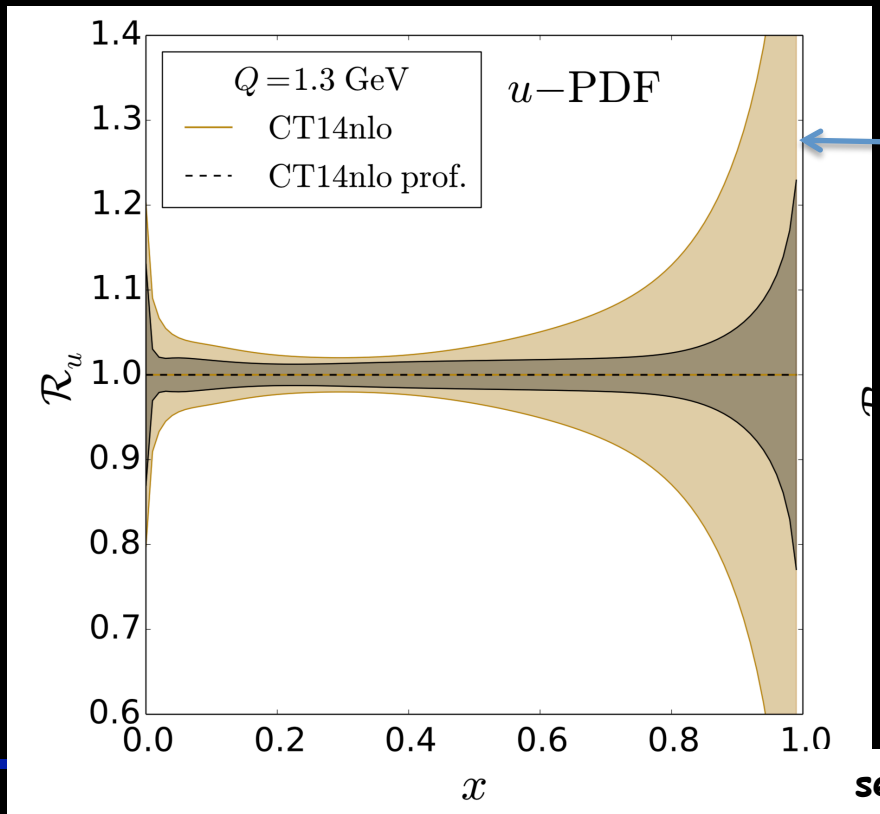
- AFTER but also @LHCb and ALICE

- Example measure parton densities in p, Pb etc.!
- Crucial input for searches with high-lumi LHC!



high mass particles

see Gunar Schnell @ PBC Workshop Nov. 2017

COMPASS

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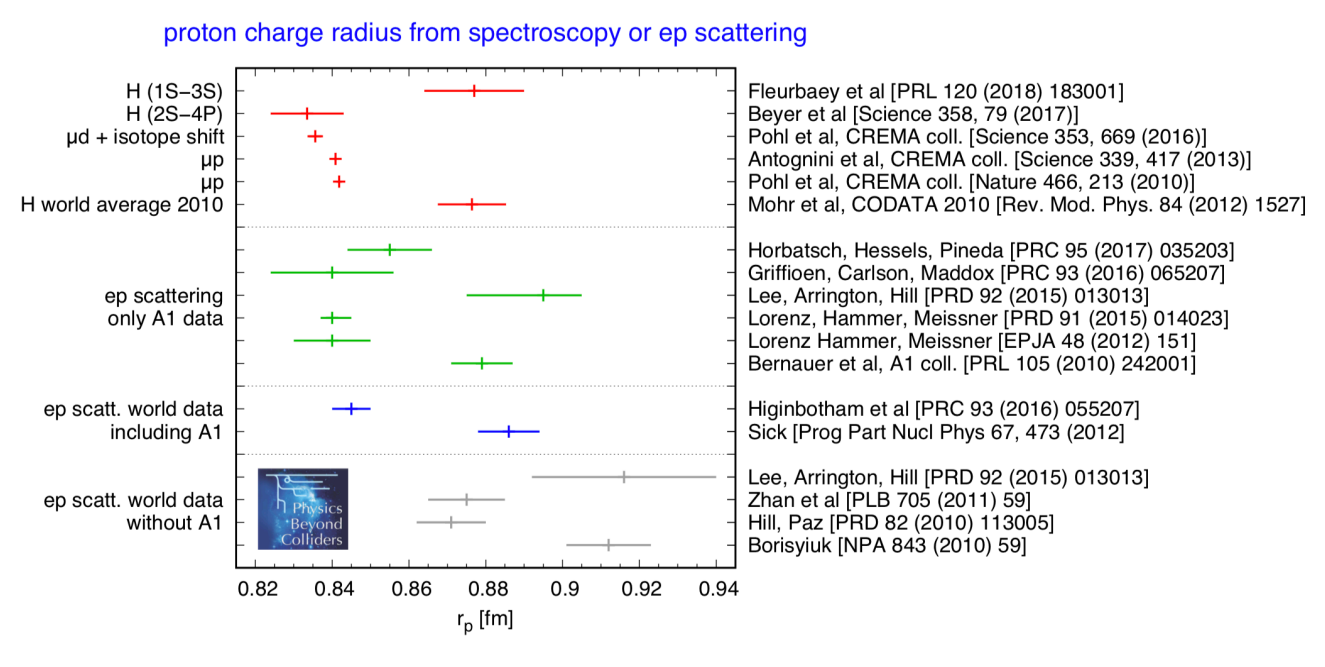
- Measure μ-p scattering at Q~0
- This allows to determine the "muonic" proton radius
- Investigate proton radius puzzle



NA60 + NA61

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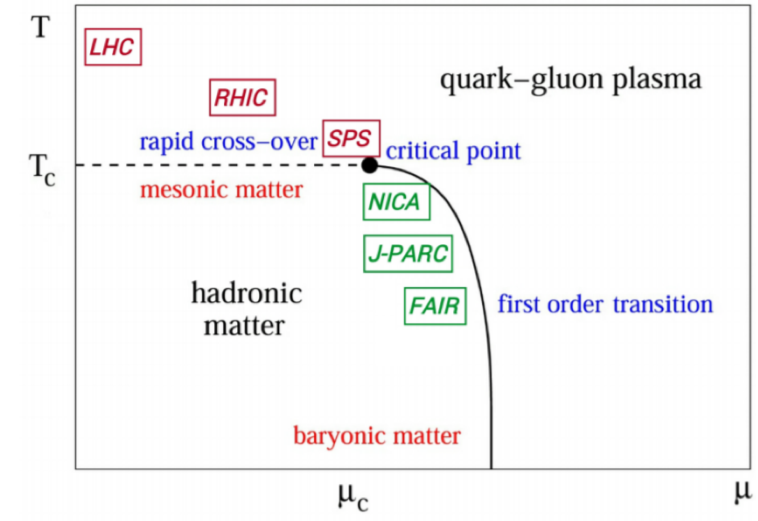
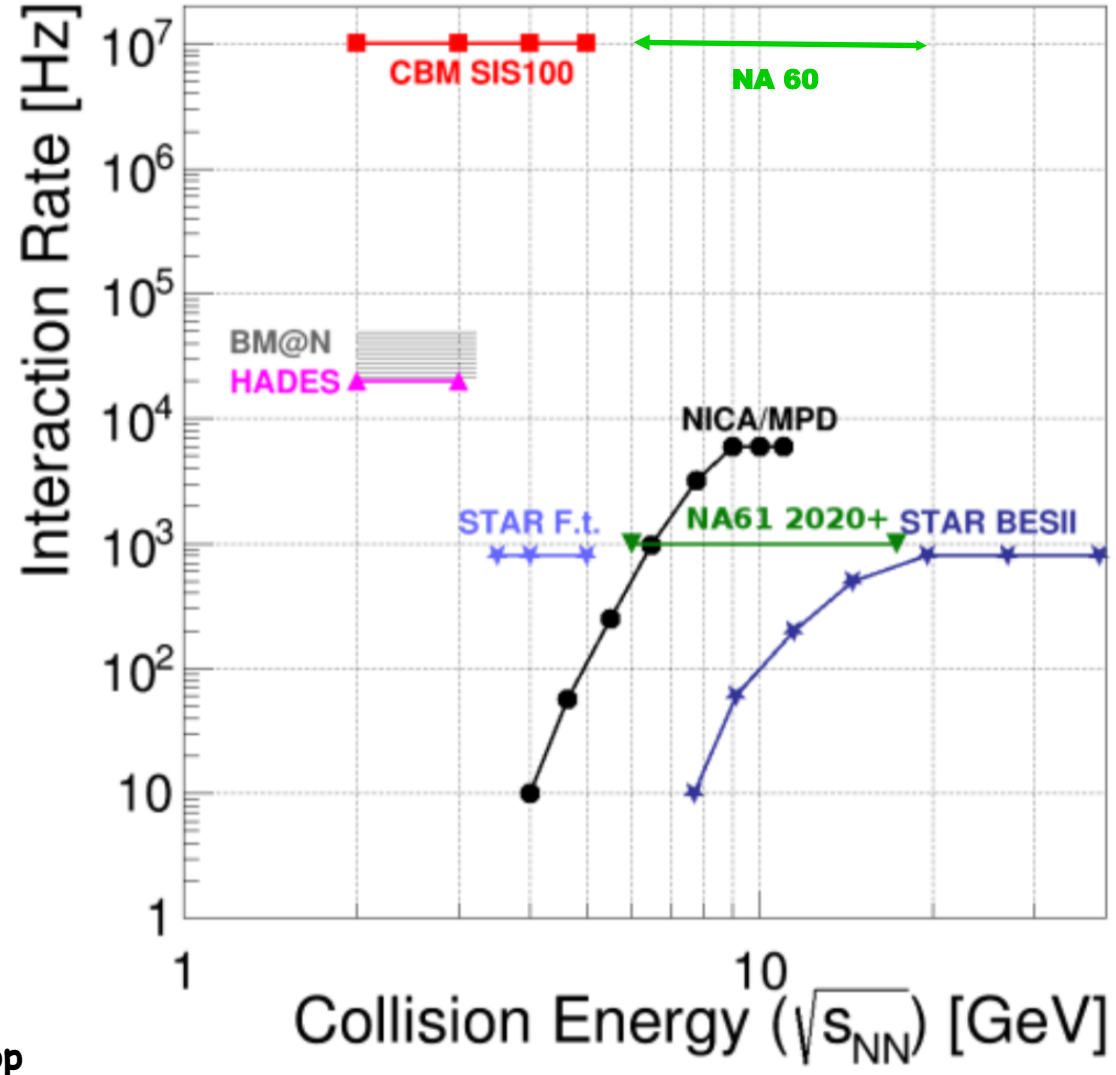
- Explore QCD phase diagram





Adapted from
Szymon Pulawski @ internal PBC Workshop

Many more cool things out there!

Cool things…

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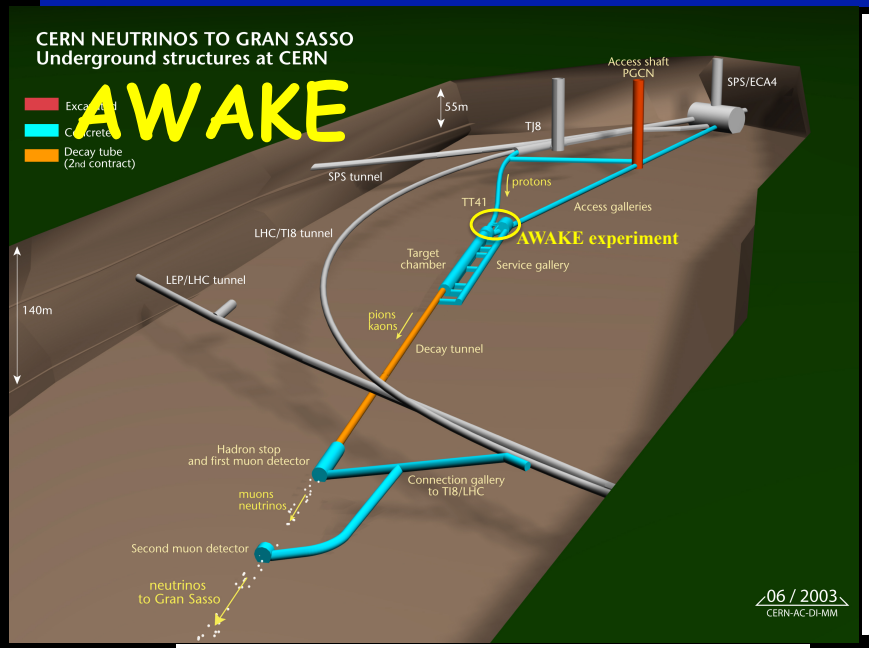
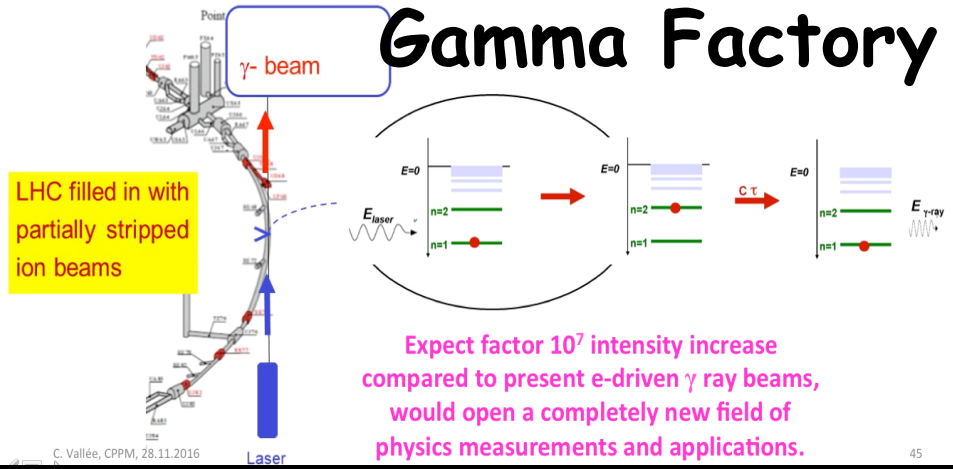


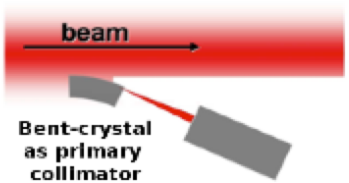
New idea: Gamma Factory

Use LHC beam to convert laser photons into 0.1 - 400 MeV γ rays



Expect factor 10^7 intensity increase compared to present e-driven γ ray beams, would open a completely new field of physics measurements and applications.

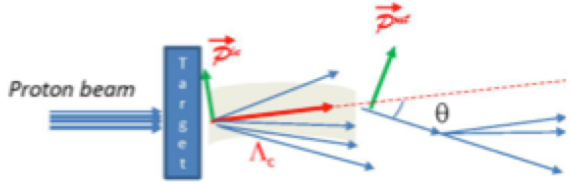
Crystal extraction



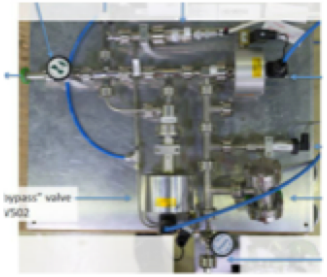
UA9

Upstream of LHCb and/or ALICE

$$\frac{dN_i}{N_{0i}\,d\cos\theta_i} = \frac{1}{2}(1+\alpha P_i \cos_i\theta_i)$$



Internal gas target (AFTER)



e.g. SMOG

Upstream of LHCb and/or ALICE

p-p: High precision TMD measurements (polarized target) and charm at high x

p-A: Nuclear PDFs

Conclusions

Conclusions

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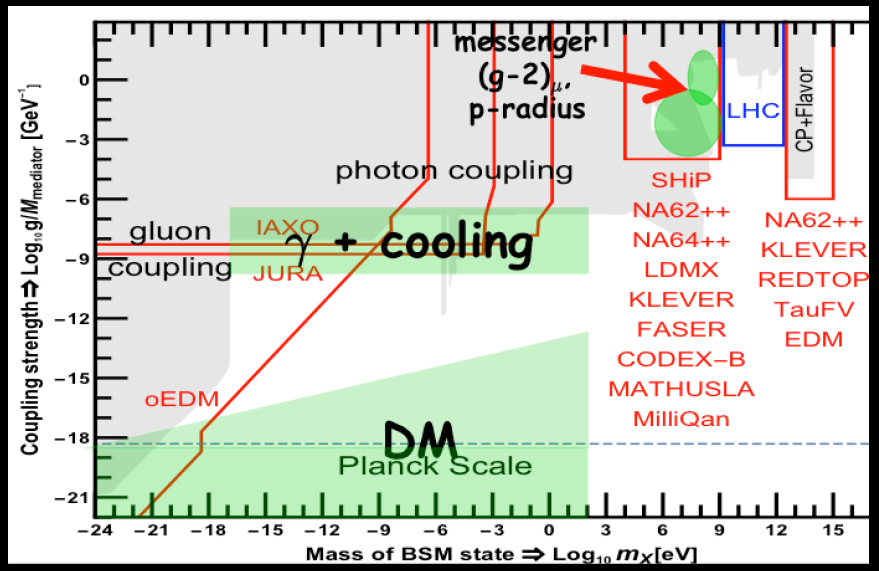
- Exploration for New Physics benefits from both high energy as well as high sensitivity

➔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