Physics Beyond Colliders
Exploring Beyond the Standard Model

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

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 also to Gaia Lanfranchi!

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What is PBC?

What is PBC?

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Study group mandated by CERN management to prepare for the 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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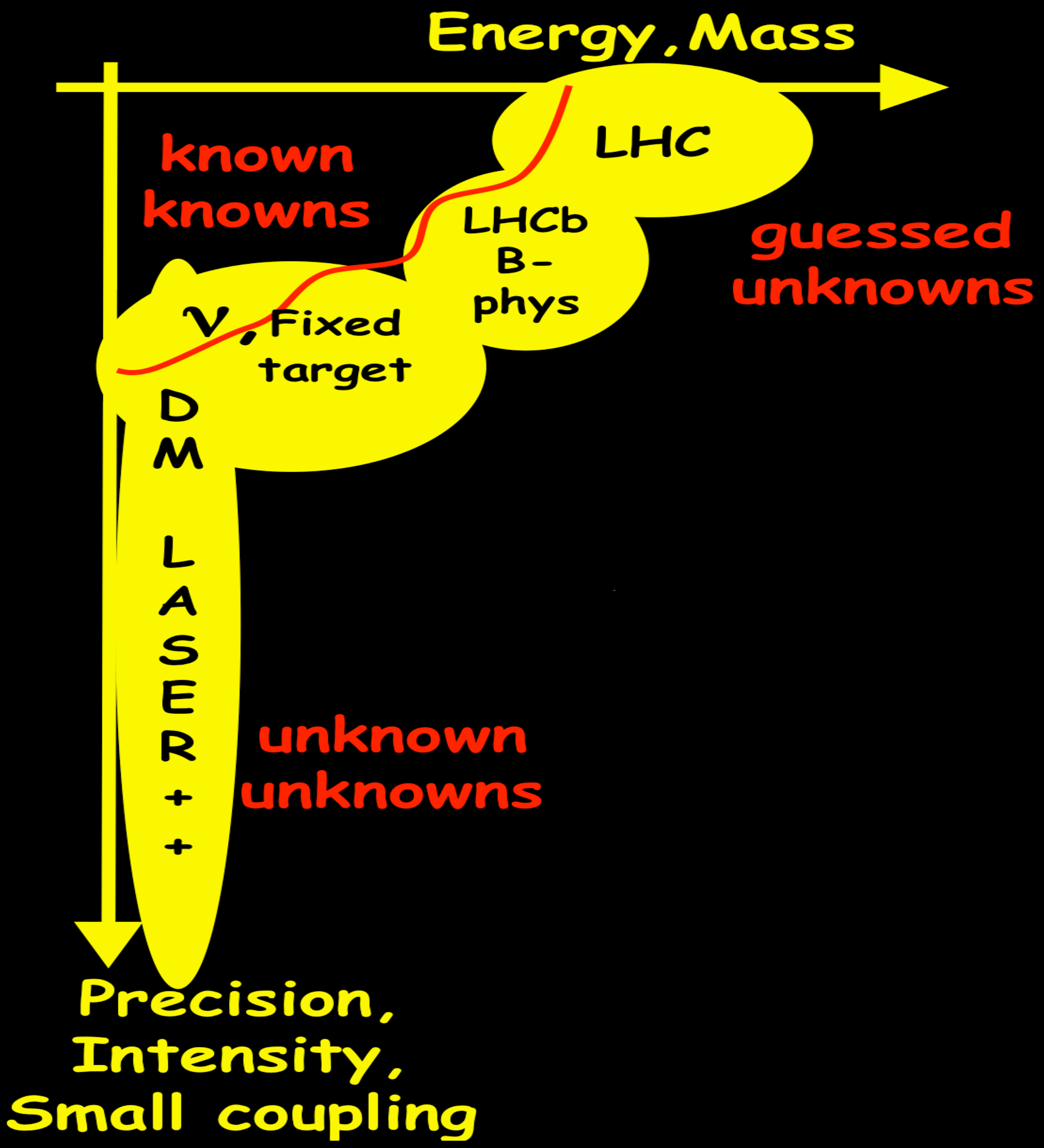

Exploring is (at least) 2 dimensional

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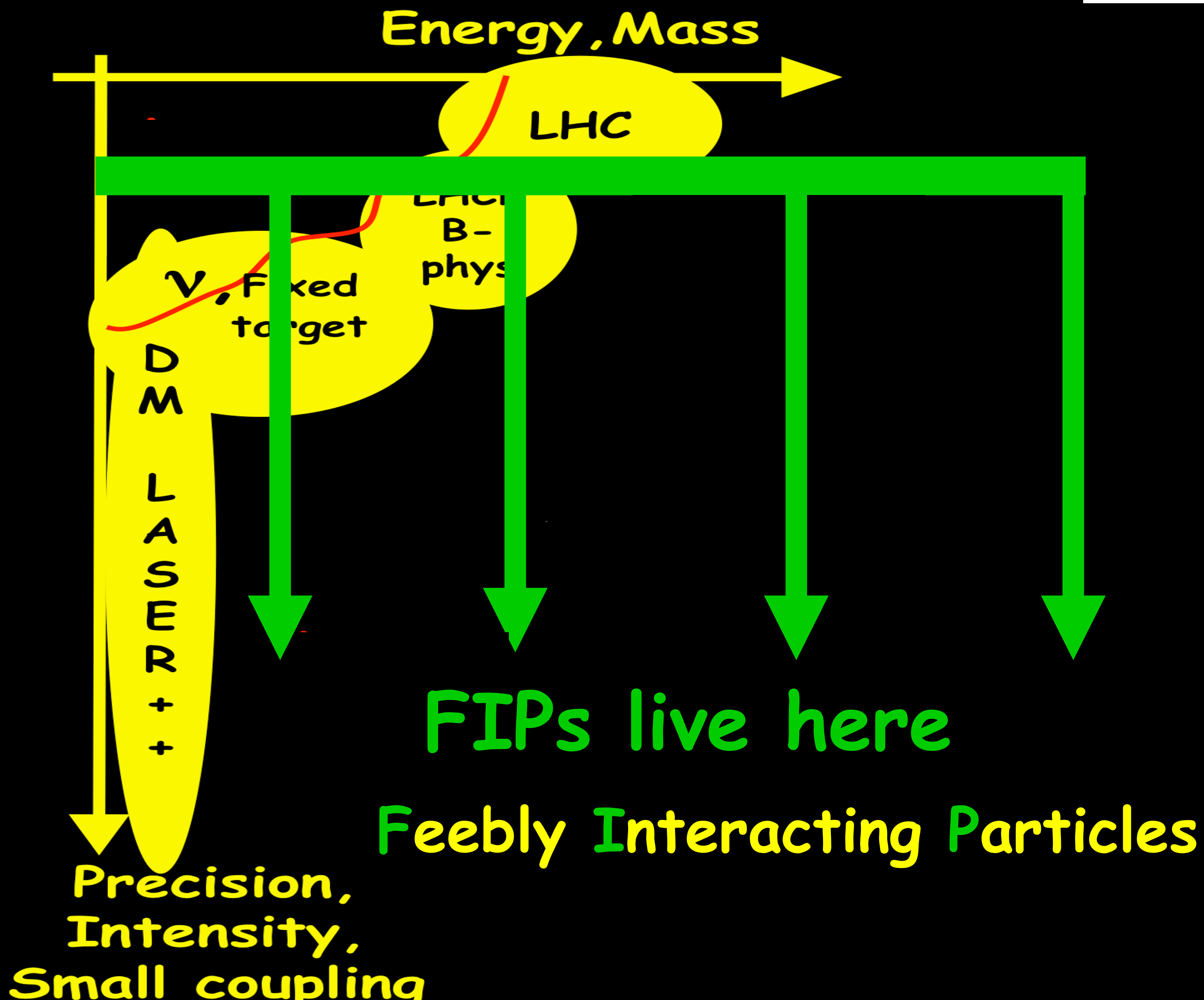
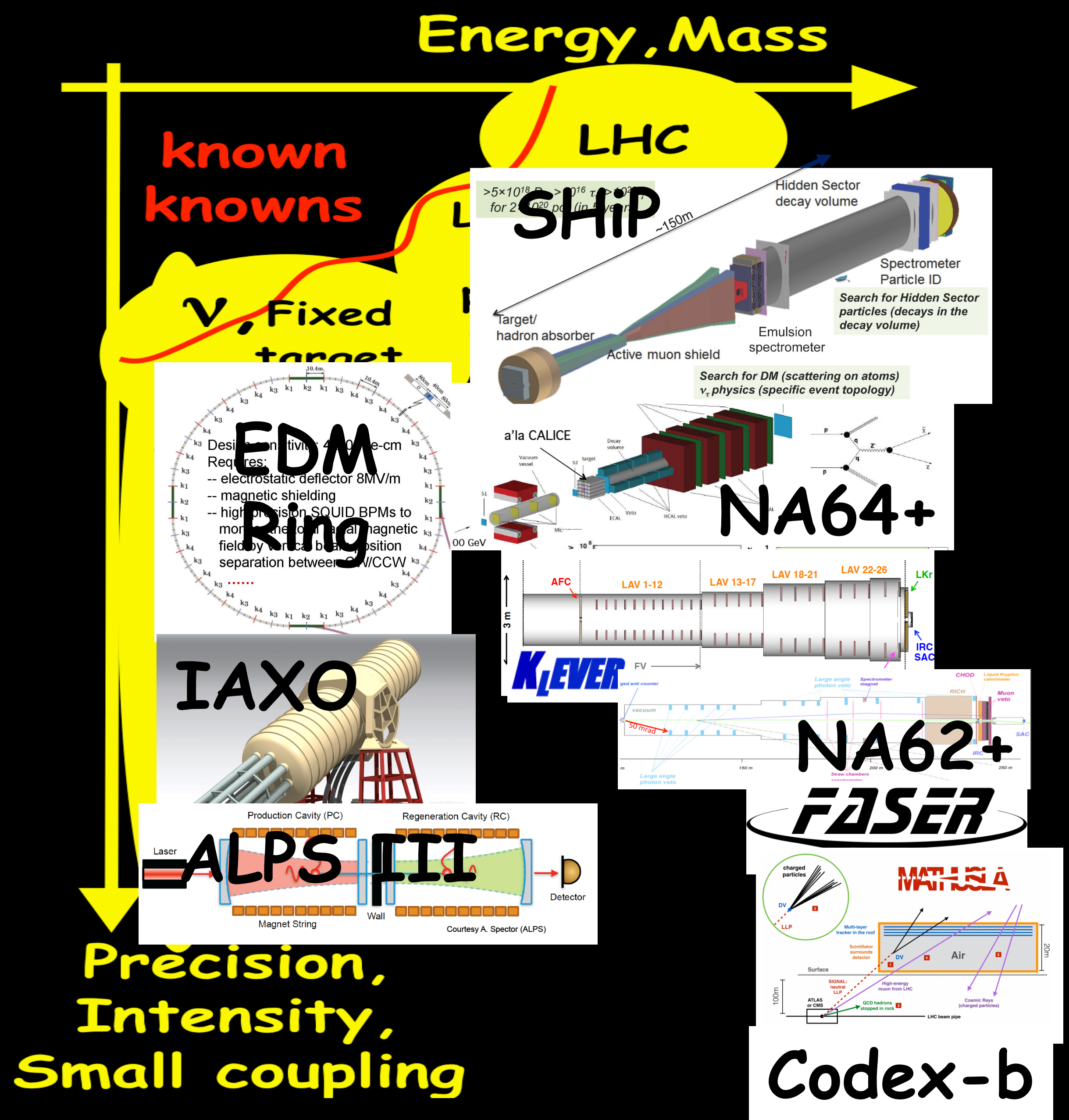


Here we want to go today…



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**

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

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

- **Gluon coupling**

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

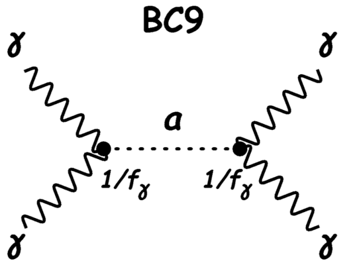
$$g_{agg} \sim \frac{\alpha_s}{2\pi f_a}$$

- **Fermion couplings**

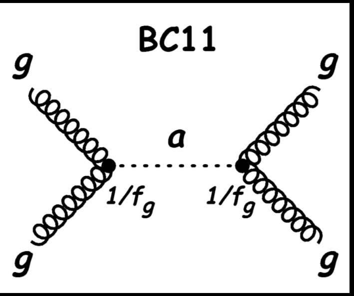
$$\mathcal{L} \supset \frac{\partial_\mu a}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$$

In pictures...

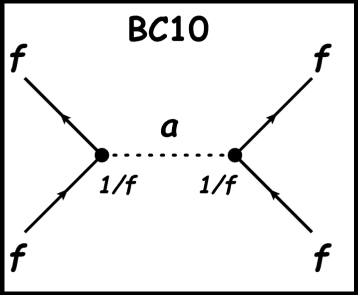
photons



gluons



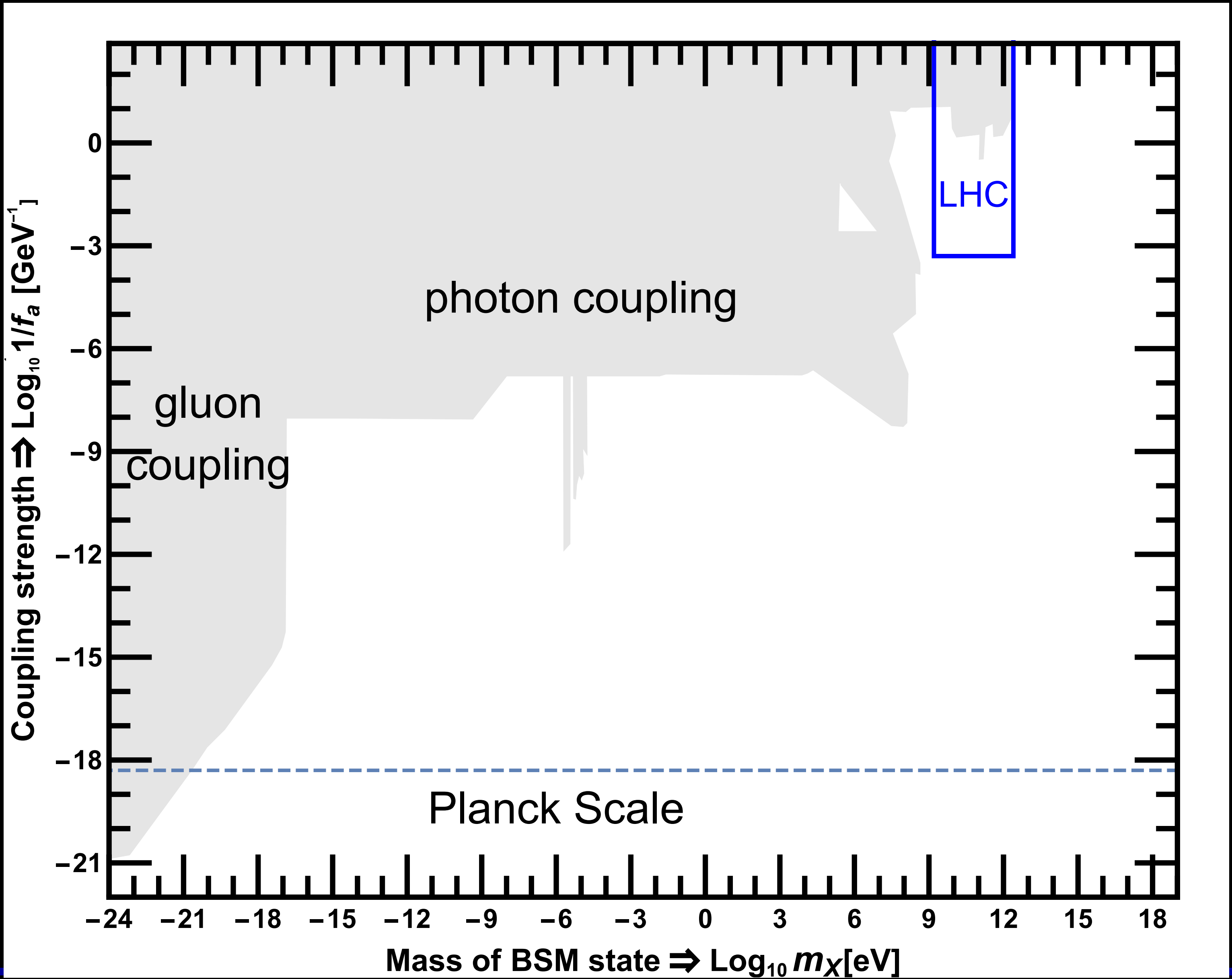
fermions



Most definitely an LLP ;-)

$$\Gamma_{a\gamma\gamma} \sim 10^{31}\,\mathrm{s}\left(\frac{\mathrm{eV}}{m_a}\right)^3\left(\frac{f_a}{10^{10}\,\mathrm{GeV}}\right)^2 .$$

Target space



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PBC exploration

Measurement of proton EDM

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Storage ring based EDM search

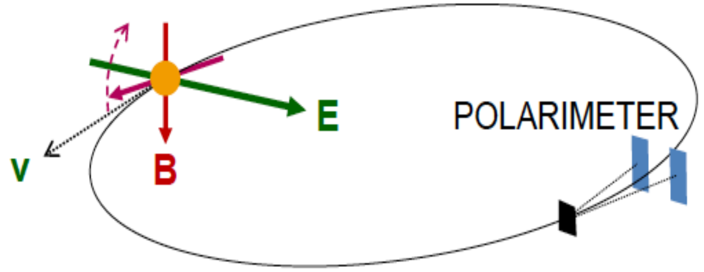
- In the presence of EDM,

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

- **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**

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

$\Downarrow$



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?

- Proton electric dipole moment ~Θ_{QCD}

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

($\frac{1}{4} g_{agg} a \to \Theta_{QCD}$)

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

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

Sensitivity

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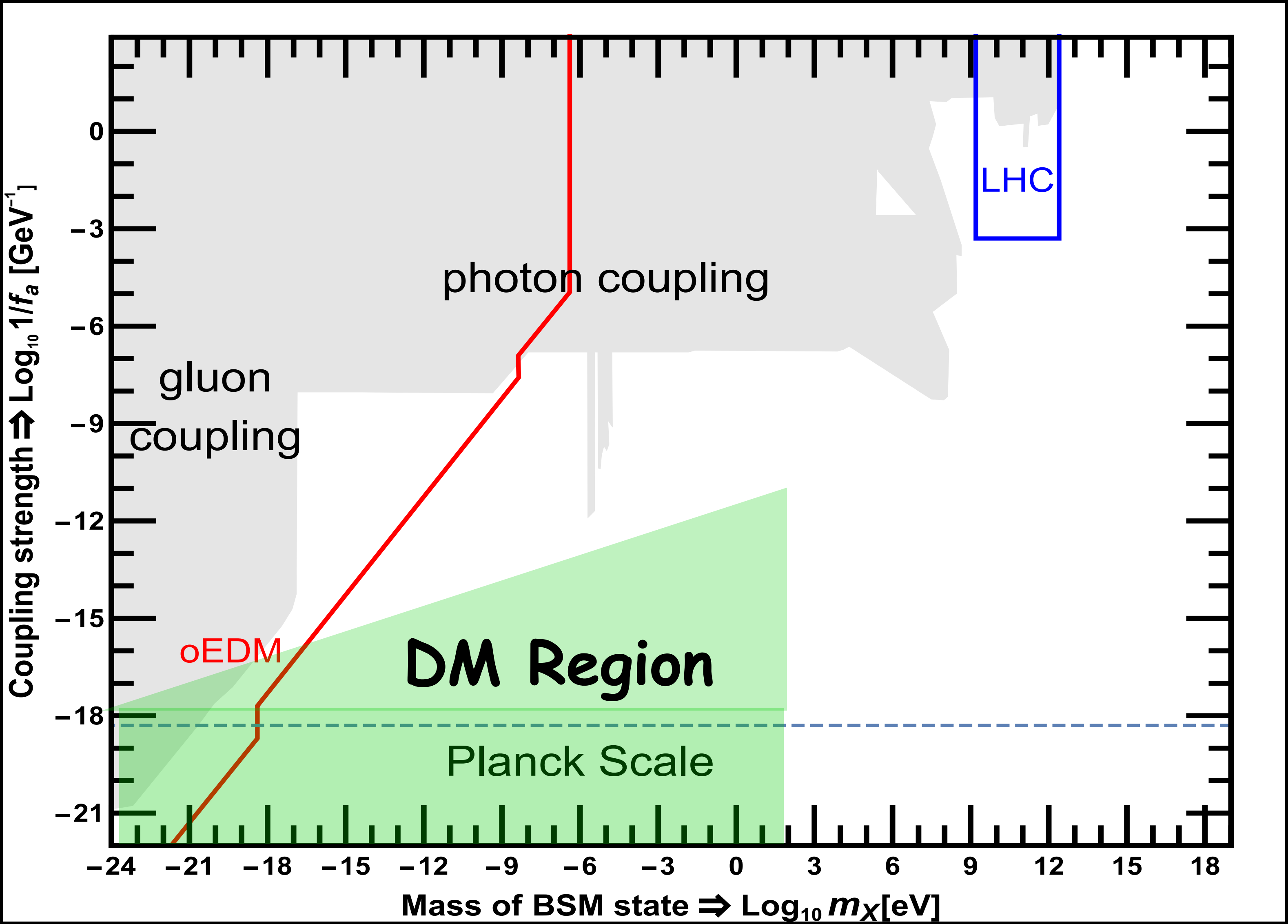

International Axion Observatory = IAXO

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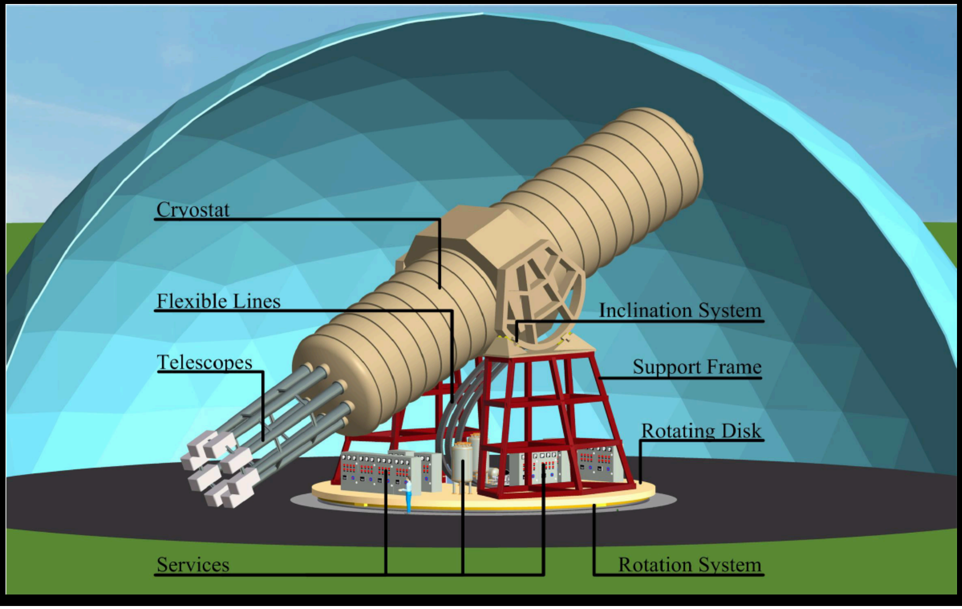
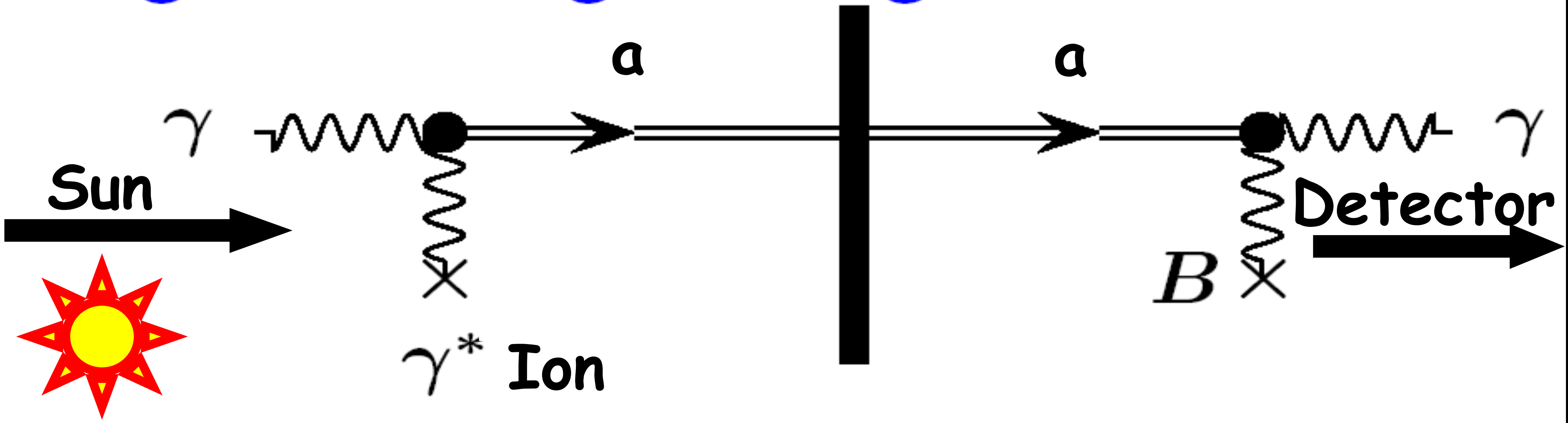
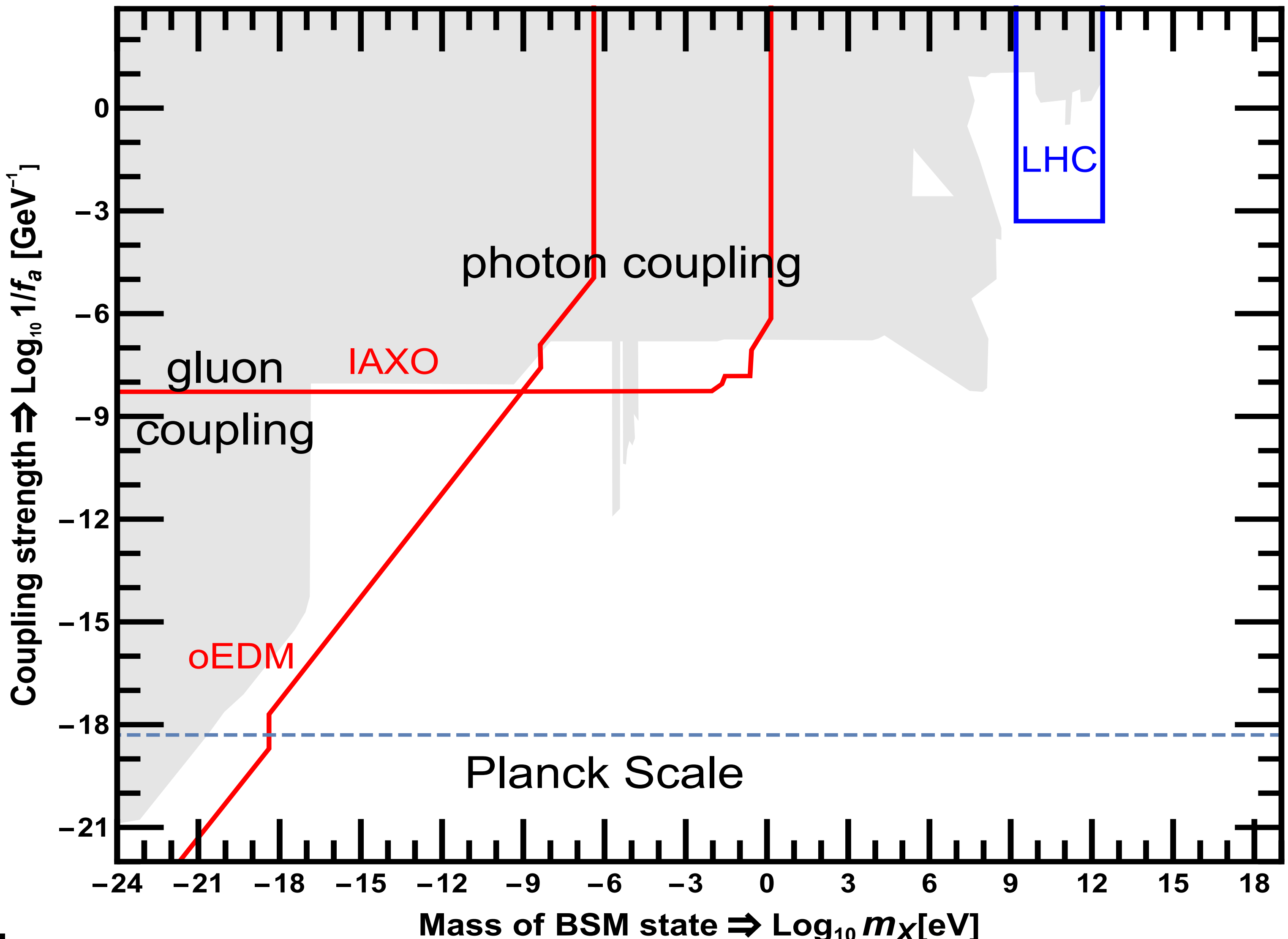


$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma} a F^{\mu} \tilde{F}_{\mu\nu}$$

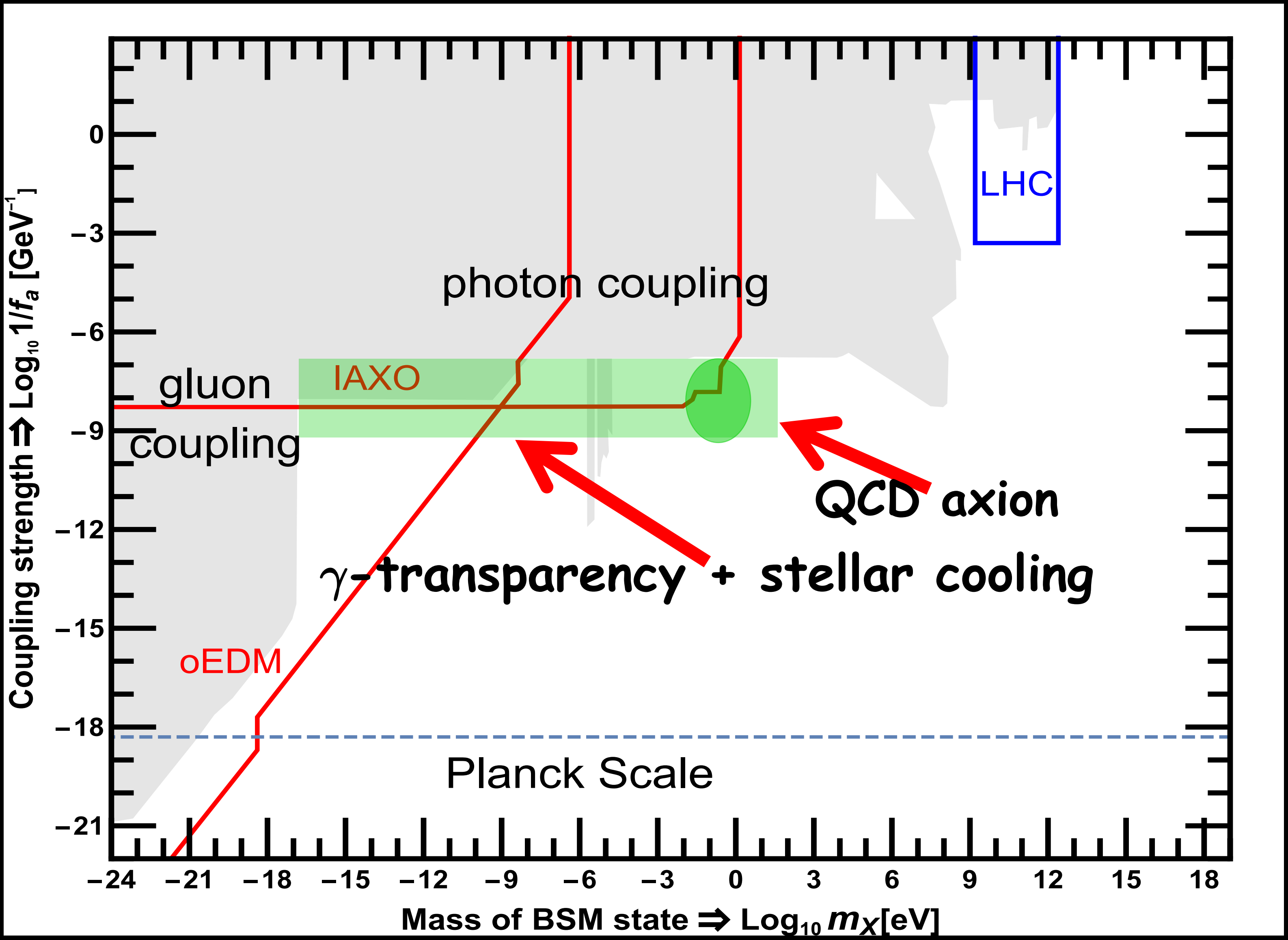
"Light shining through a wall"



Sensitivity



Sensitivity



More : Light shining through walls JURA

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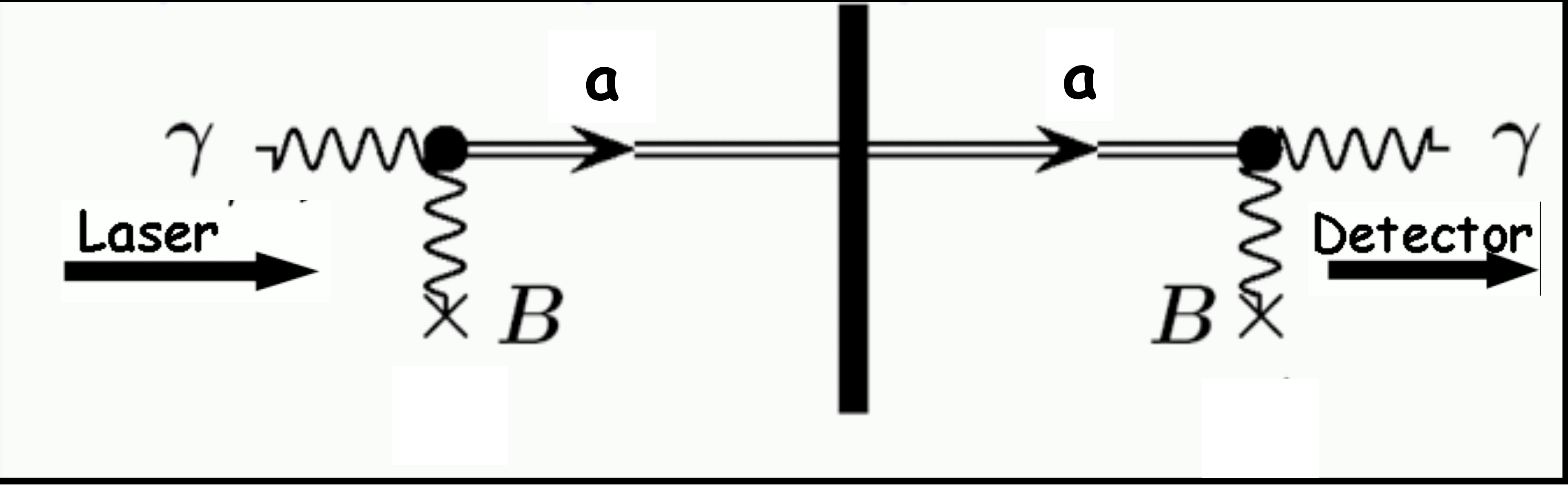

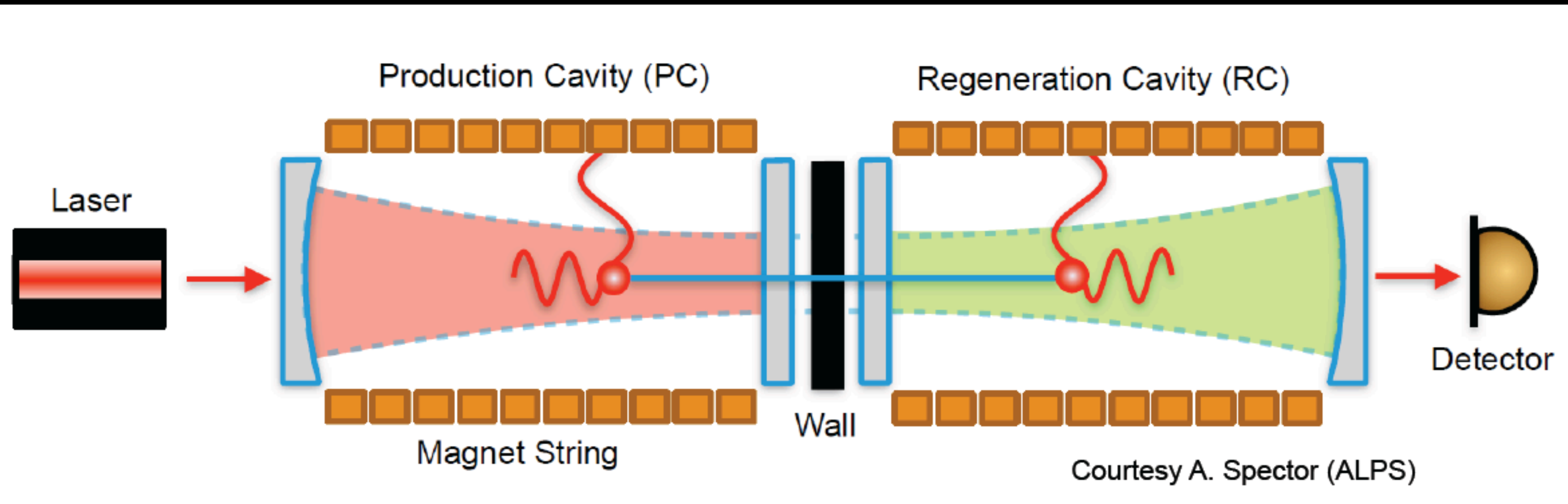

Sensitivity

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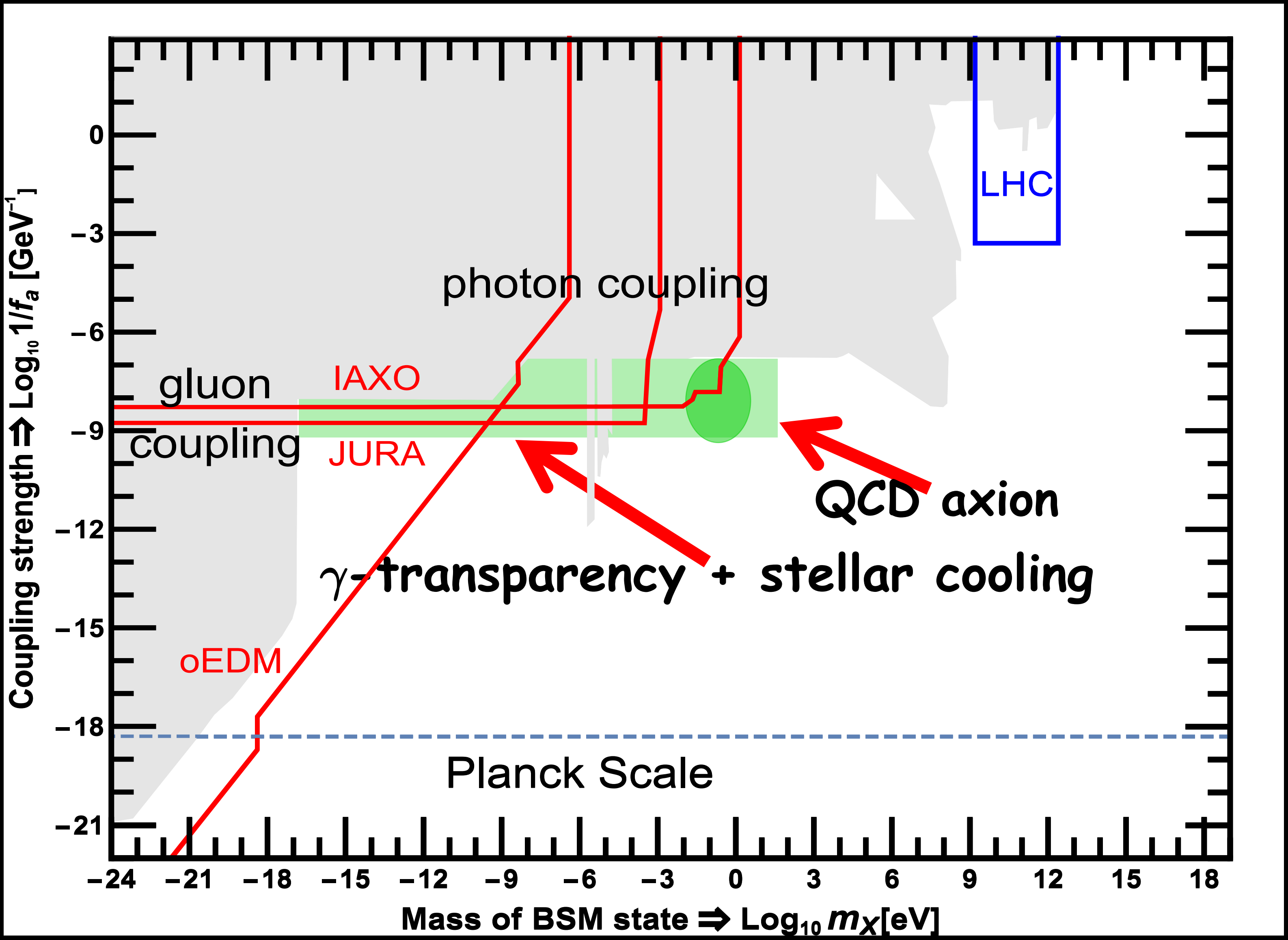

Search for Hidden Particls = SHiP

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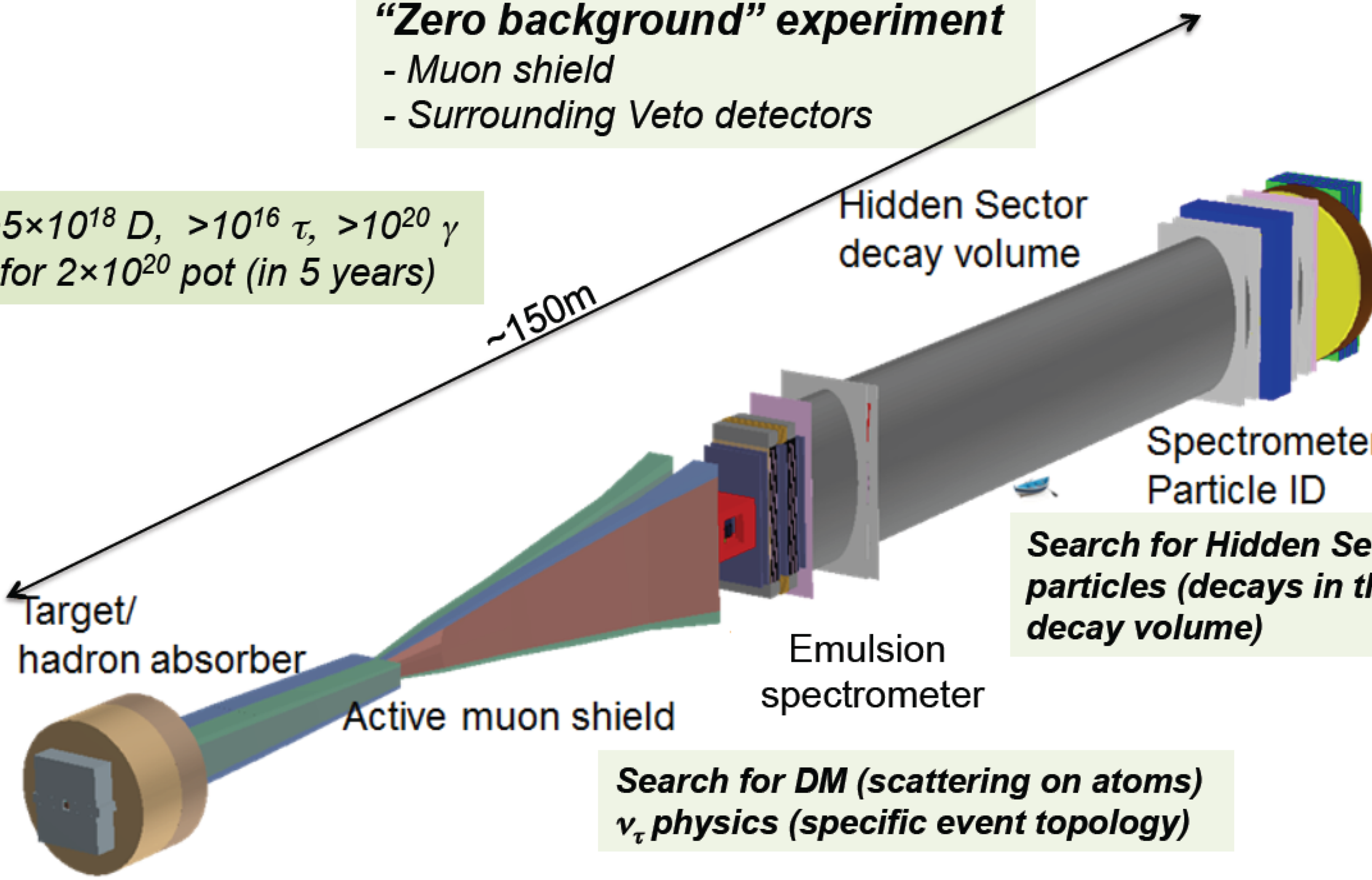
SHiP
Search for Hidden Particles

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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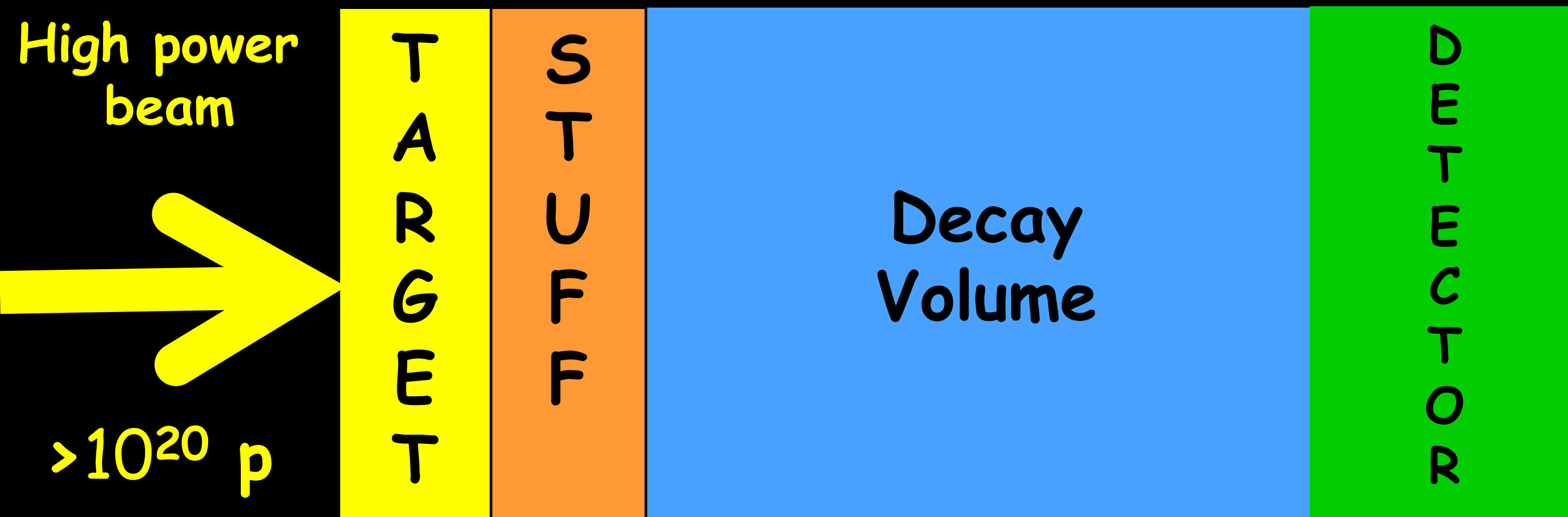

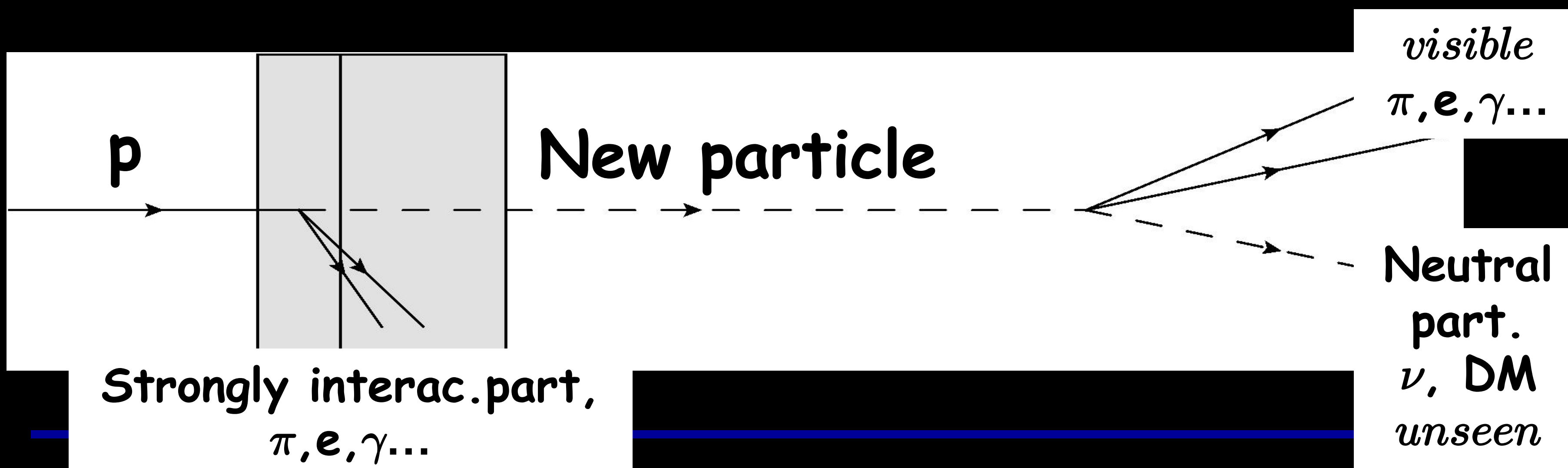

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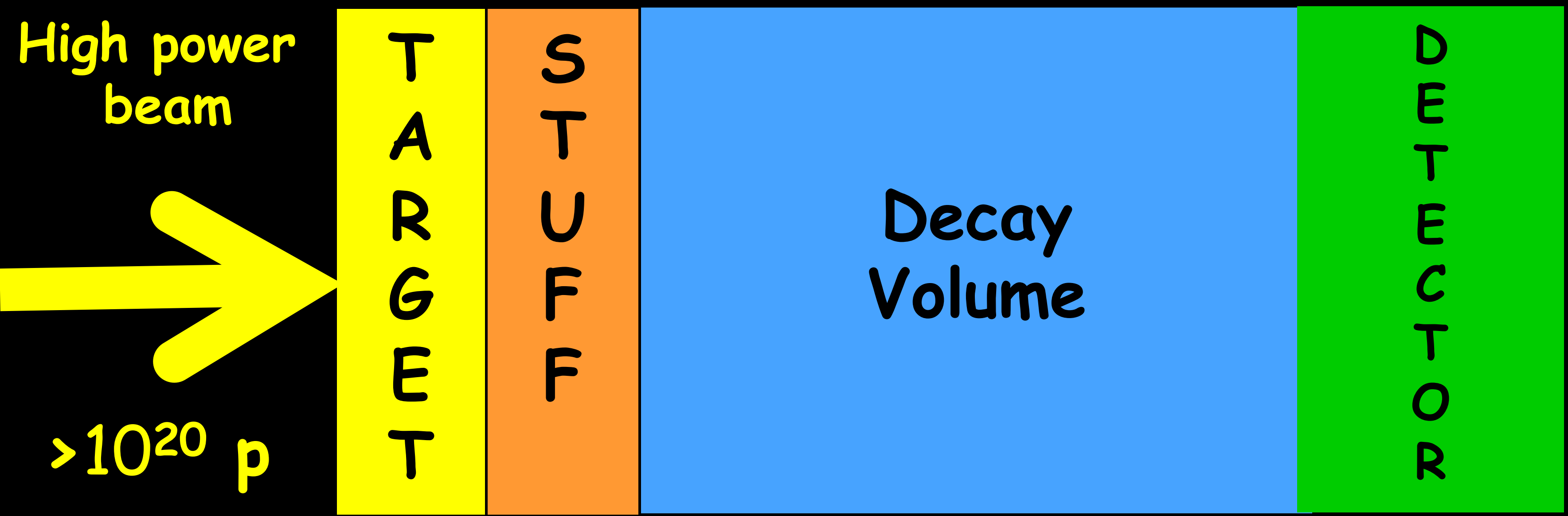
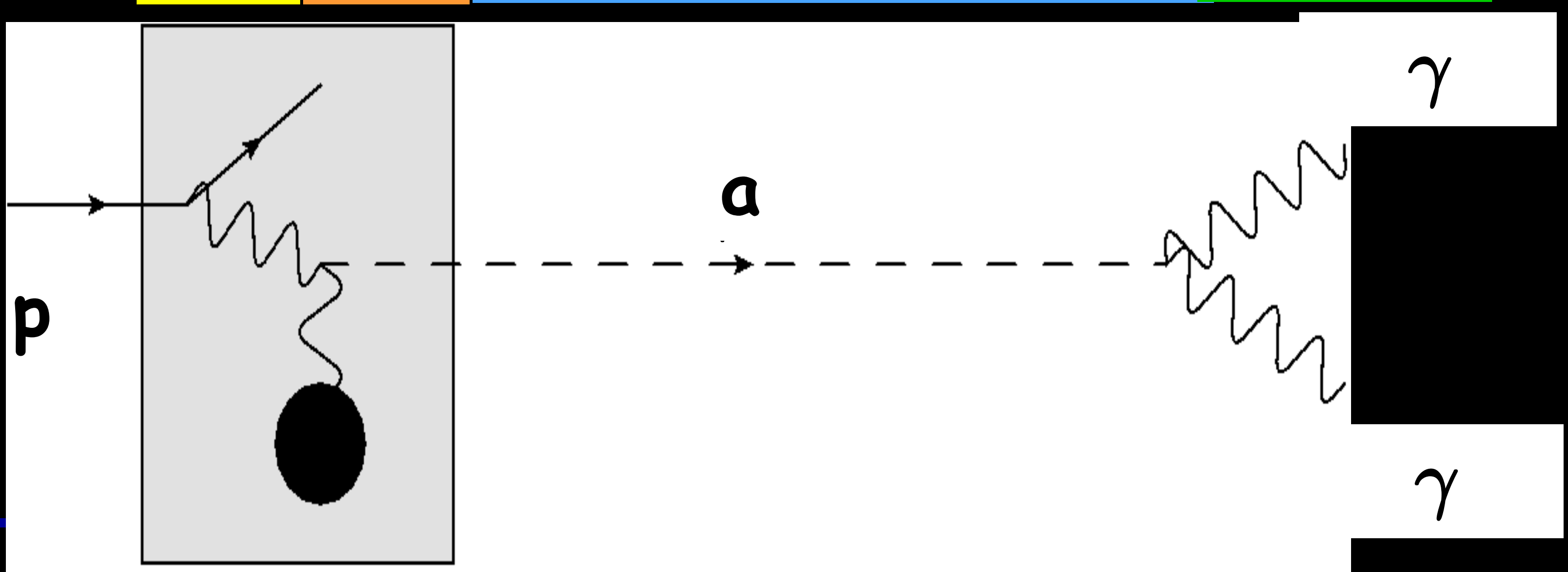
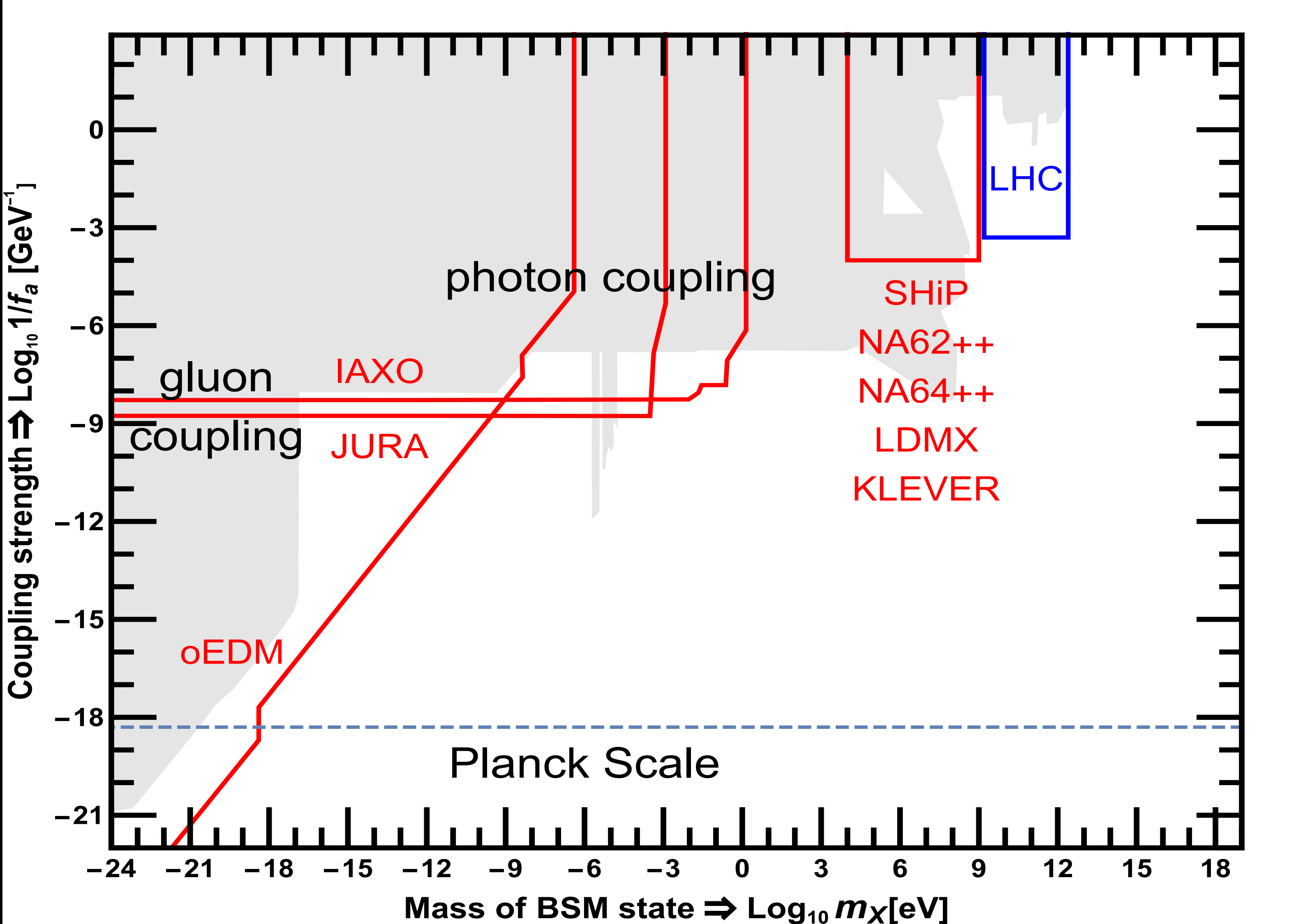




SHiP + NA62+, NA64+ and KLEVER



“Seeing” the dark stuff NA 64+

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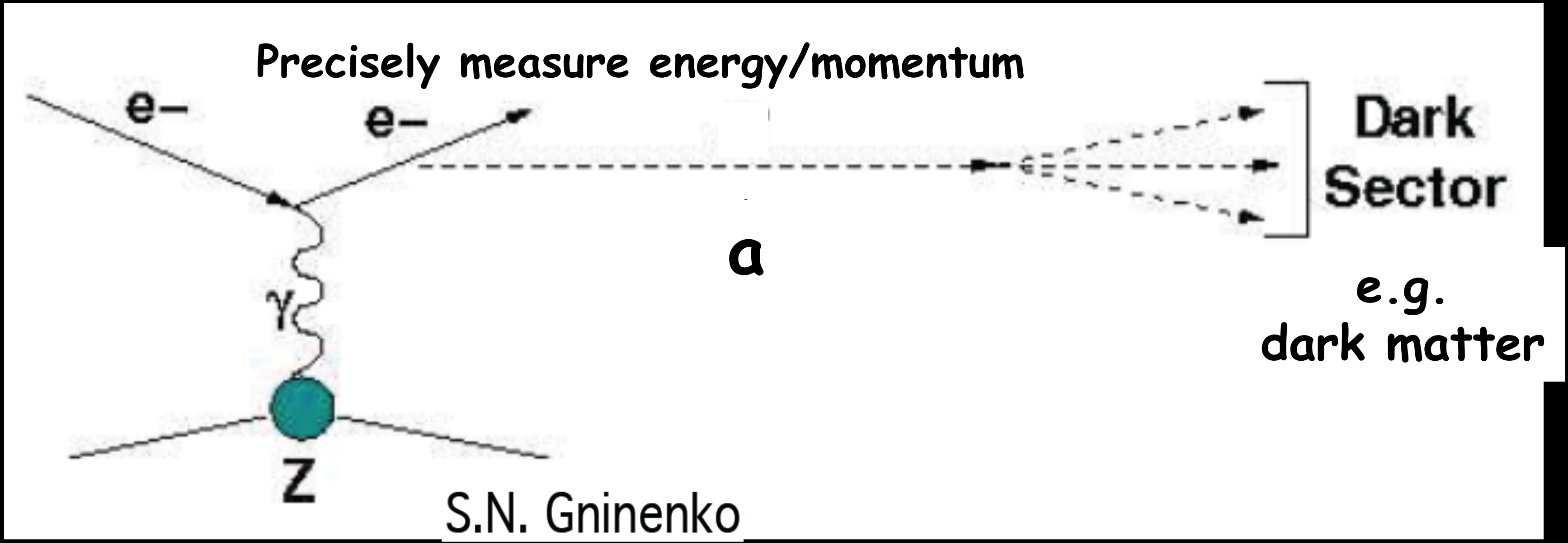
$$\mathcal{L} \supset g_{a\psi\psi} a \bar{\psi} \gamma^5 \psi$$



+ “dark matter” detector @ SHiP

Messengers for dark matter?

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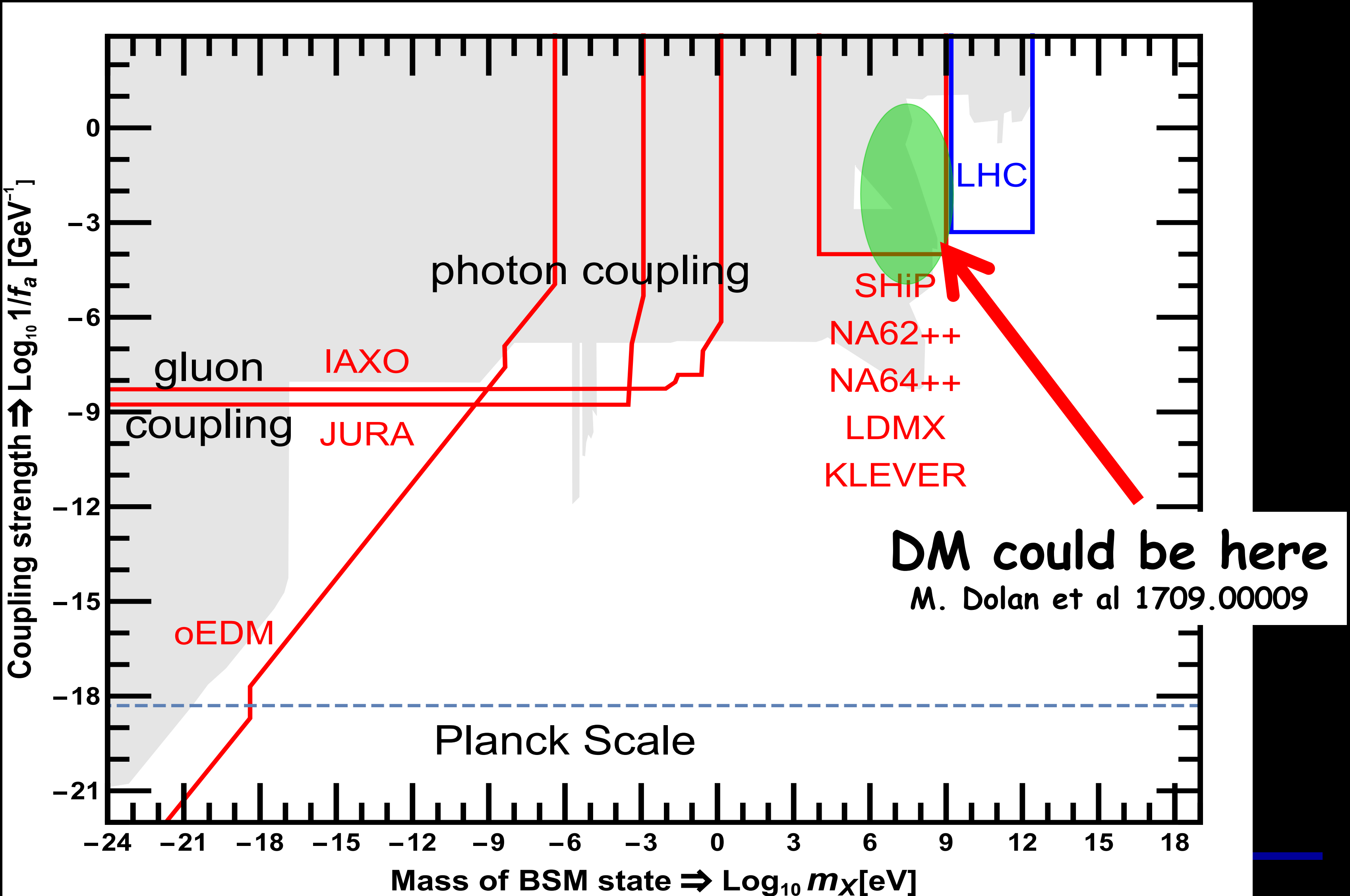

$(g-2)_\mu$ and proton radius anomaly

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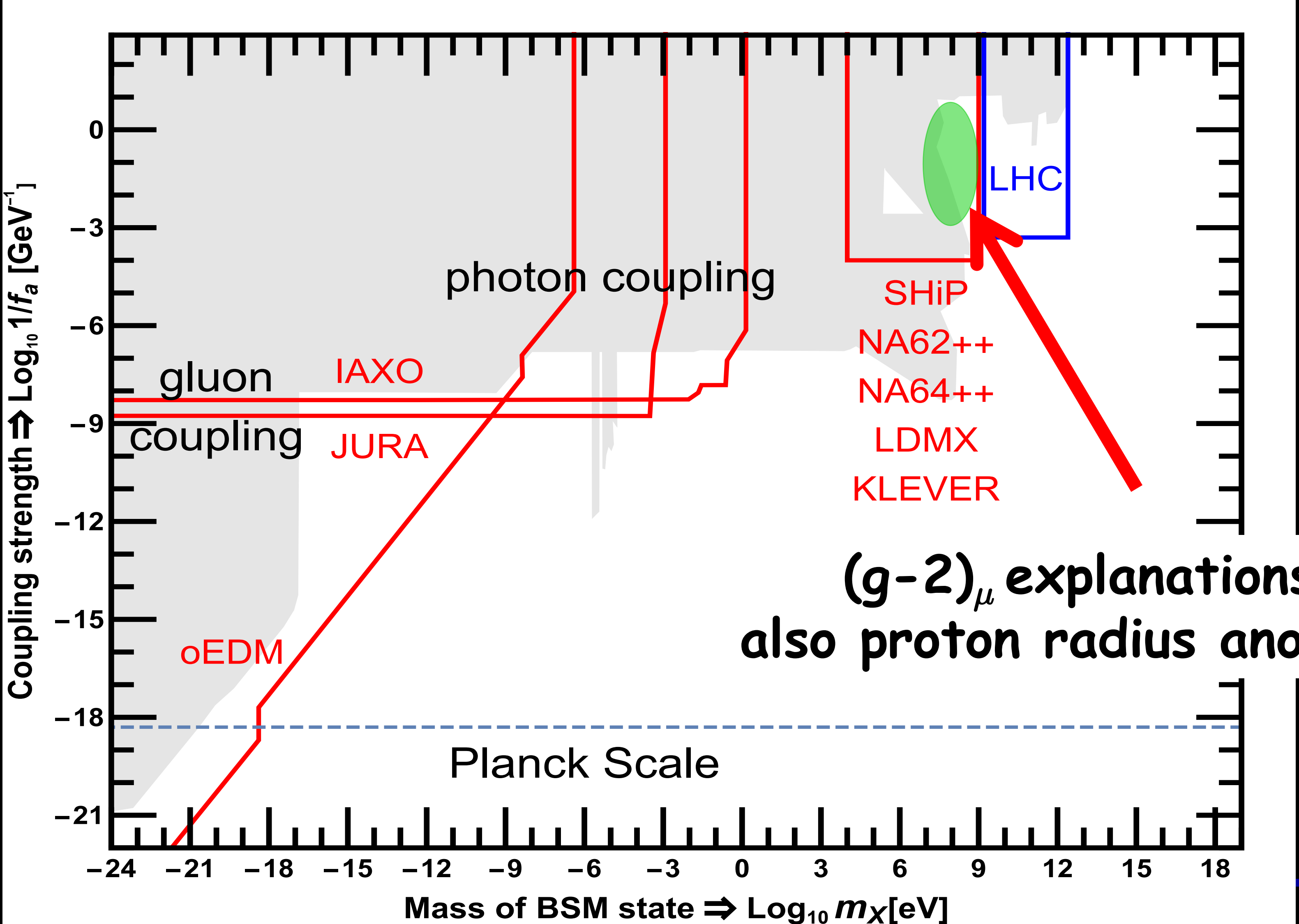

$(g-2)_\mu$ explanations
also proton radius anomaly

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

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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.

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

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

→ improvement needed

Could be "pure theory"
Lattice: 2002.12347

➔ (3-4)σ discrepancy

mu on e

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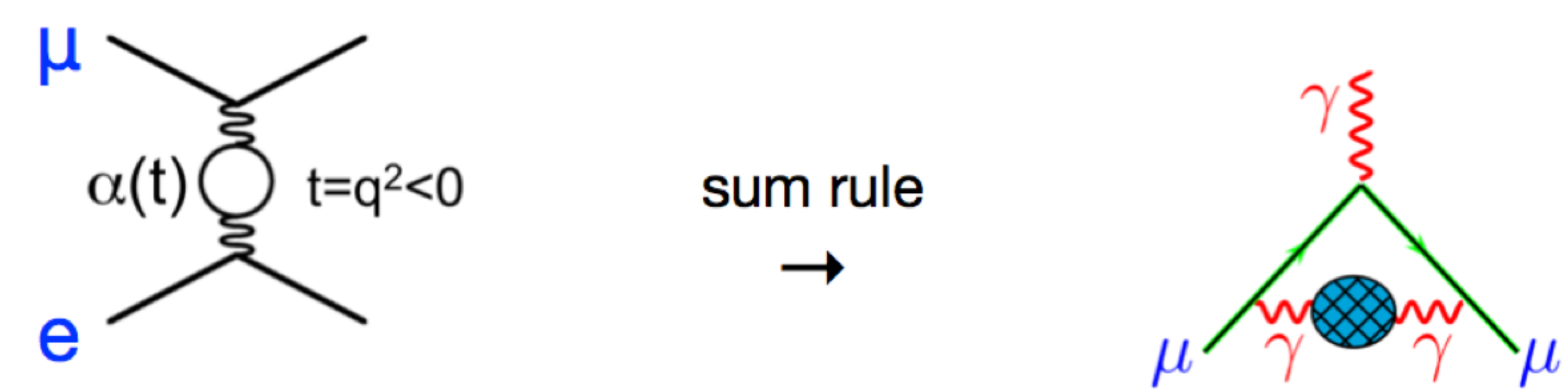
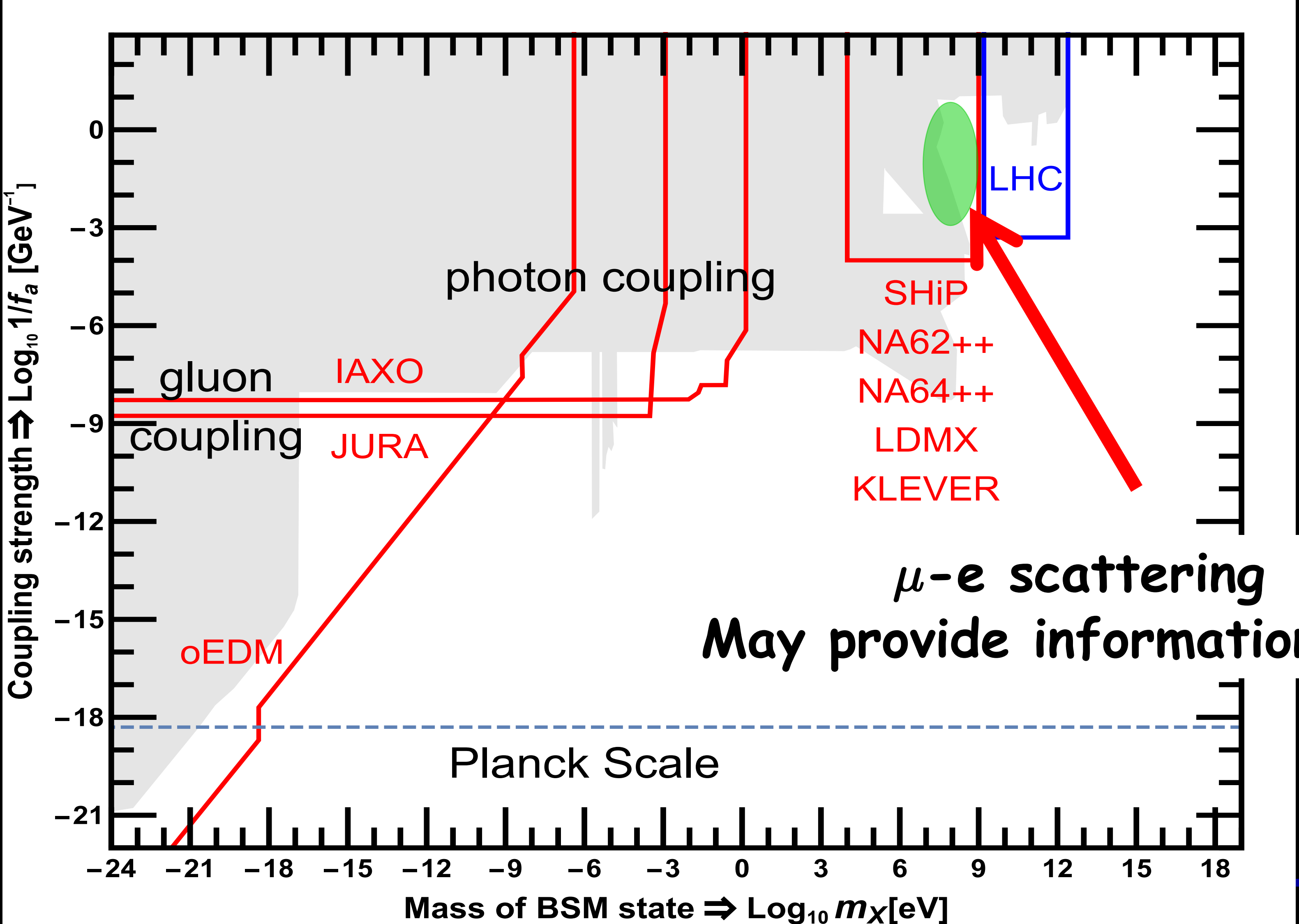
- To improve "Theory" we need to Measure hadronic corrections for $(g-2)_\mu$
- Crucial input for using $(g-2)_\mu$ to search for BSM!
- New way: Measure scattering of μ on e



see Gunar Schnell @ PBC Workshop Nov. 2017

$(g-2)_\mu$



μ-e scattering May provide information here

Long Lived Particles @ LHC

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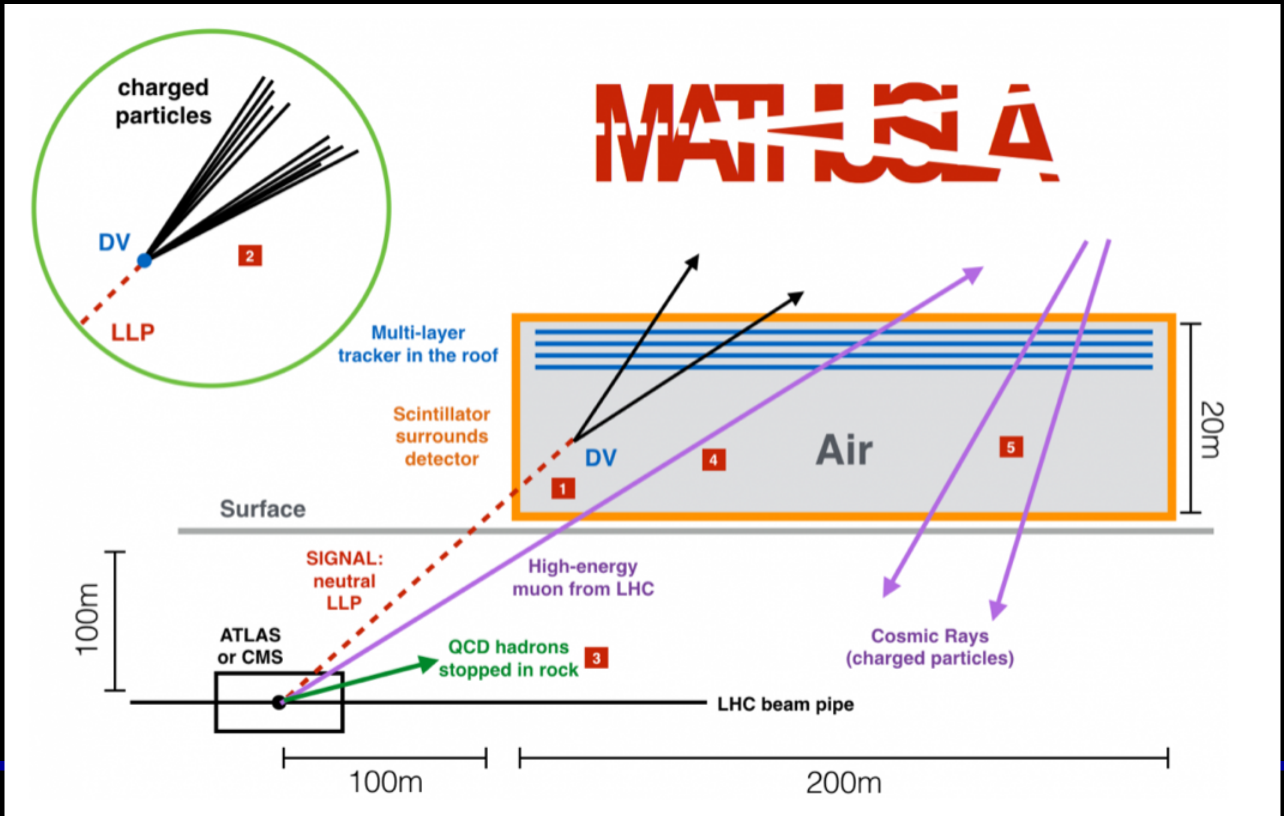
- Idea: Look for very long lived particles produced in LHC collissions
- Recent proposals:

  MATHUSLA, FASER, CodexB, MilliCan



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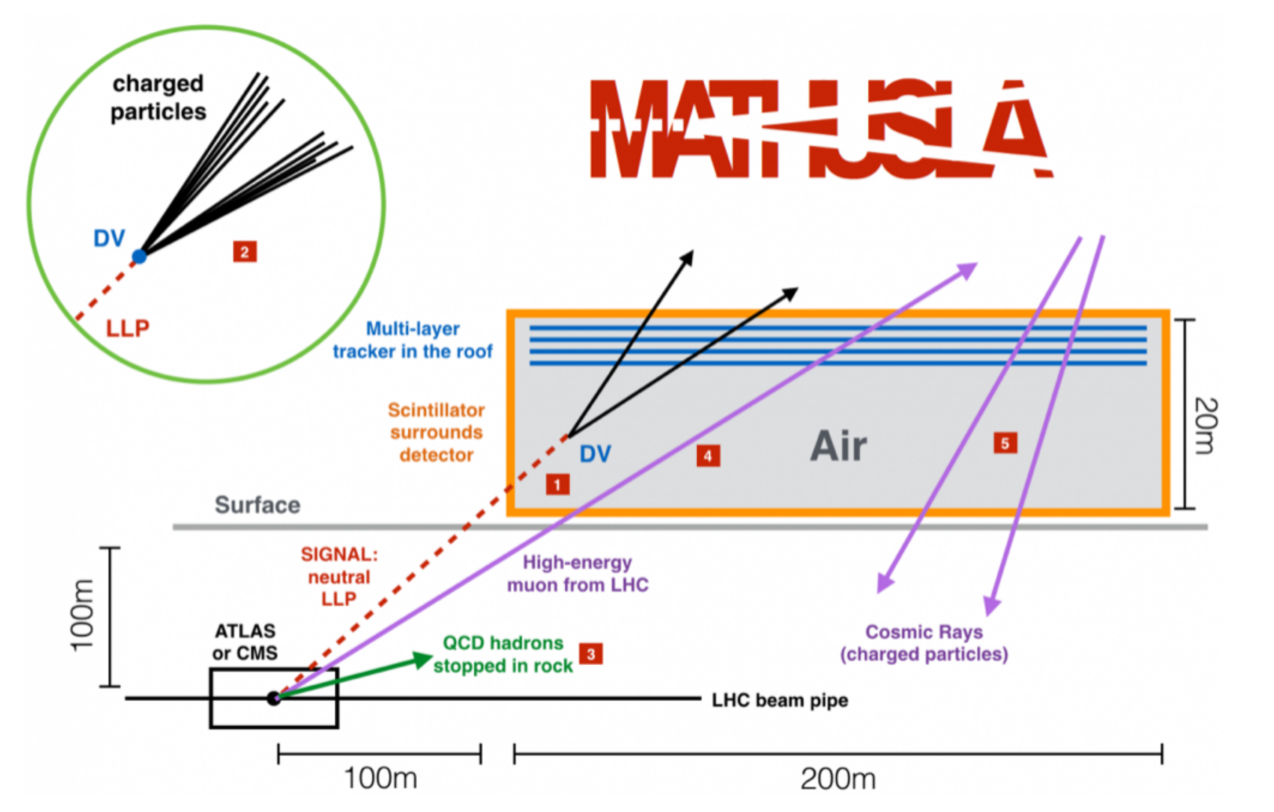

FASER

Long Lived Particles @ LHC

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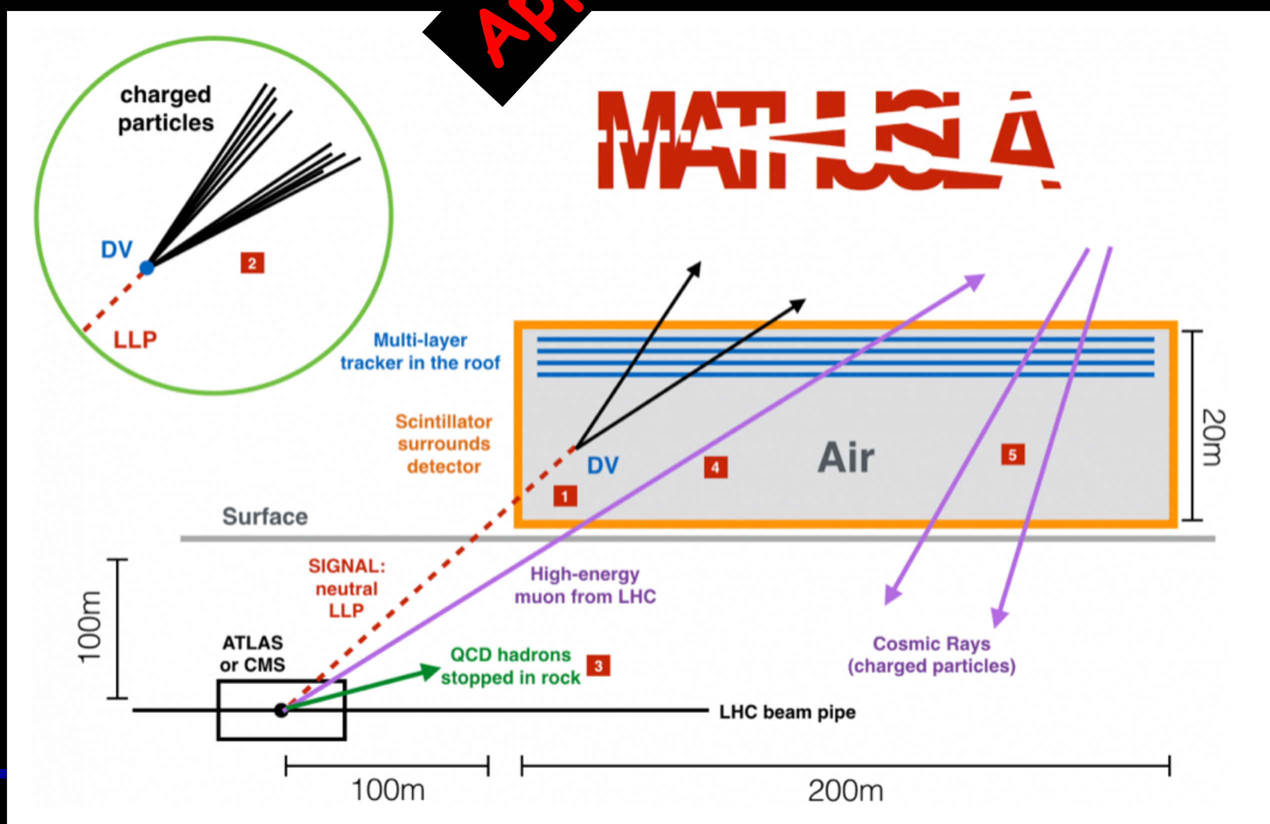
- Idea: Look for very long lived particles produced in LHC collissions
- Recent proposals:

  MATHUSLA, F[illegible]R, CodexB, MilliCan

Approved



FASER

Long Lived Particle searches also explore MeV-GeV region

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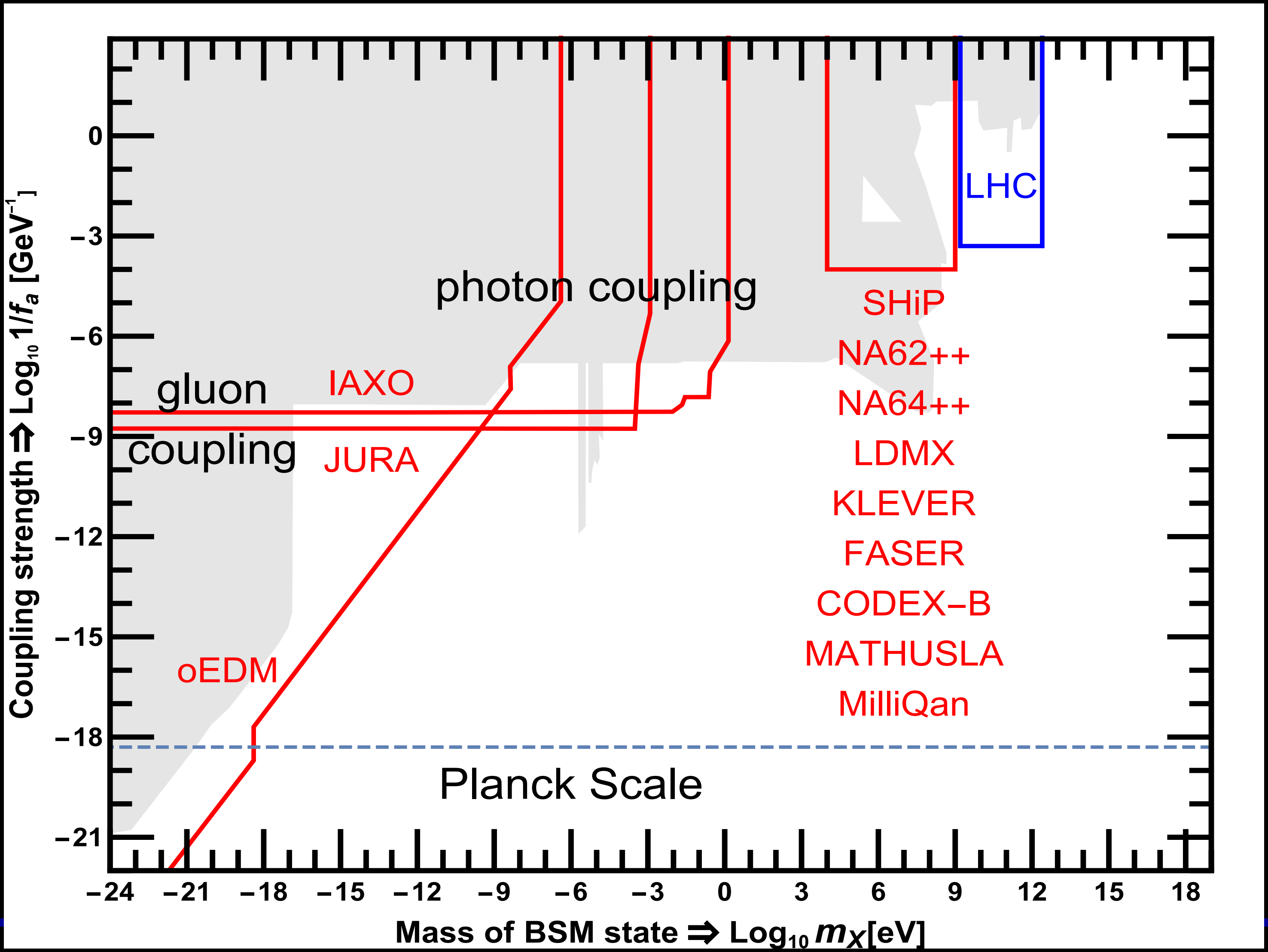

Much more cool physics can be probed !!!

Example

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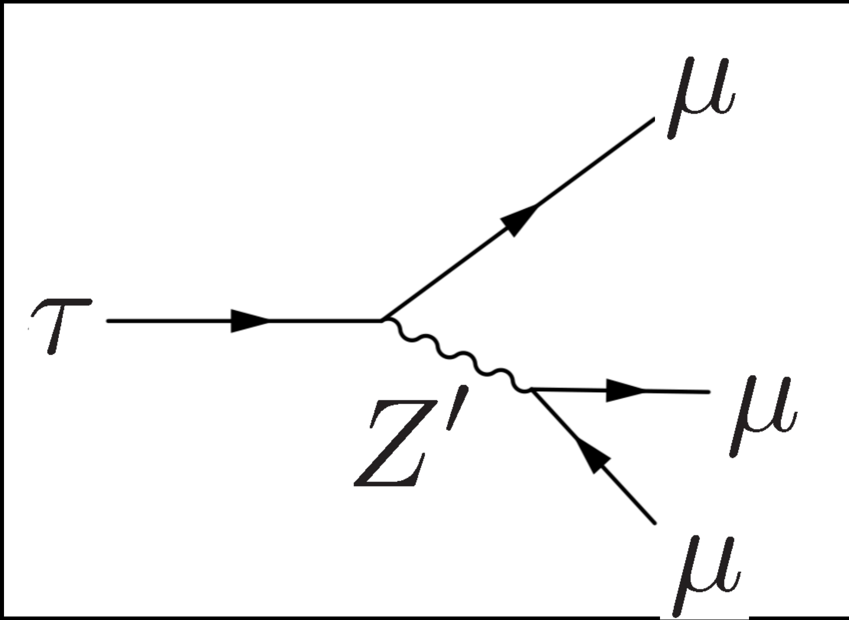
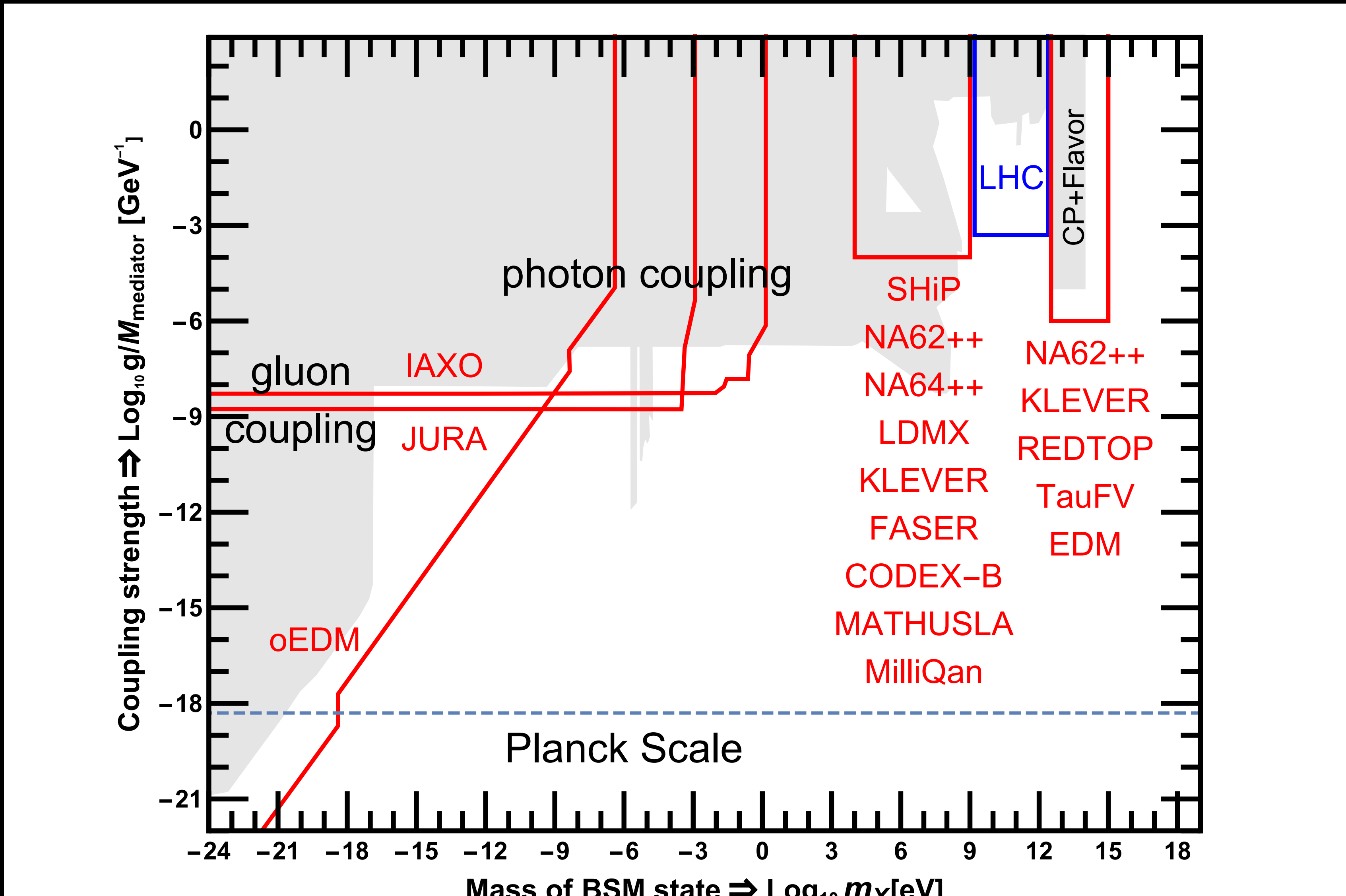
- Rare decays:

$K^+ \to \pi^+ + \nu\nu$	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...



Example 2:
Dark Photon without dark decays

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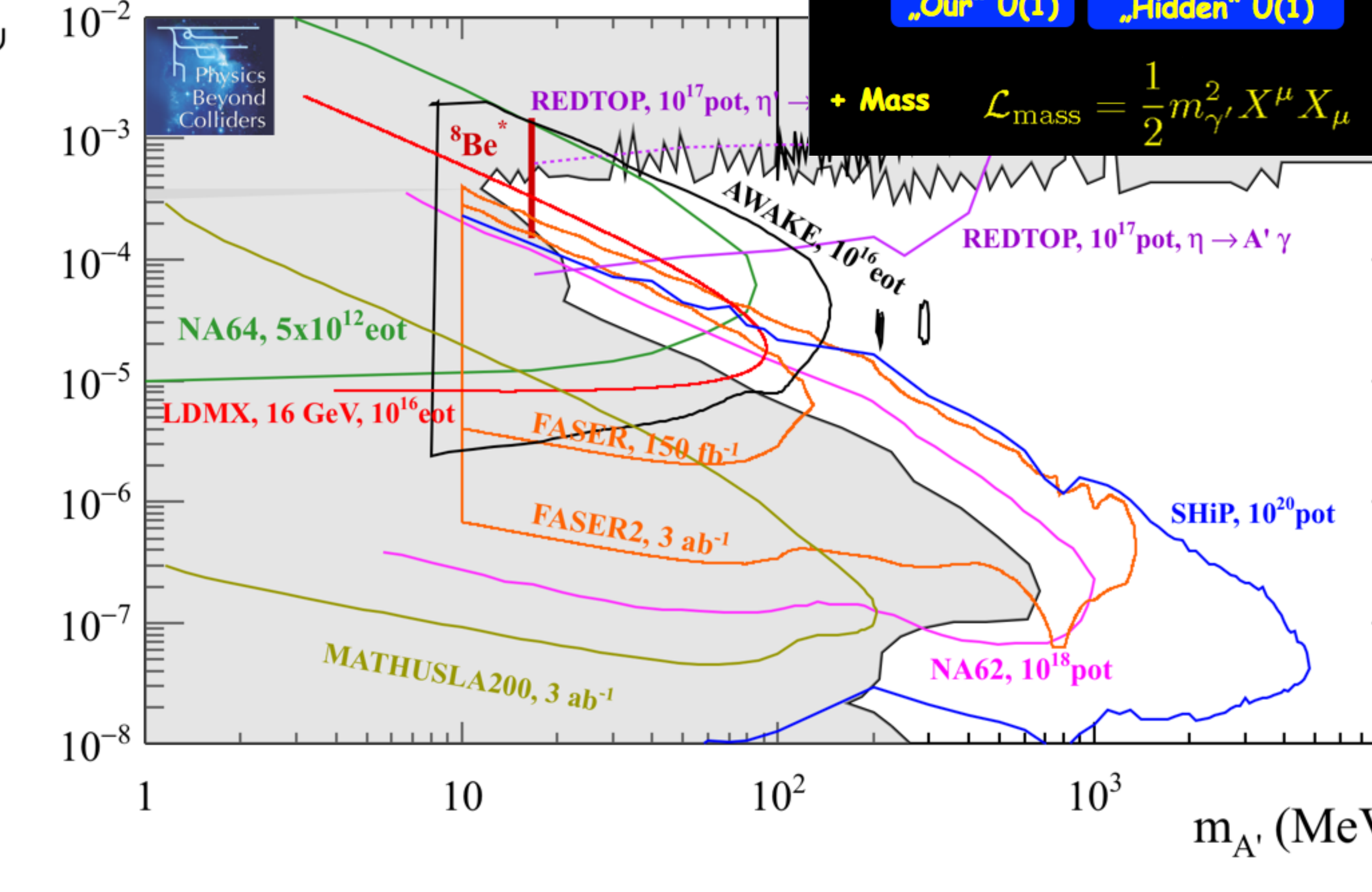
$$\mathcal{L}_{\rm gauge} = -\frac{1}{4}F^{\mu\nu}_{(A)}F_{(A)\mu\nu} - \frac{1}{4}F^{\mu\nu}_{(B)}F_{(B)\mu\nu} + \frac{\epsilon}{2}F^{\mu\nu}_{(A)}F_{(B)\mu\nu},$$

„Our" U(1) — „Hidden" U(1) — Mixing

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



Example 3: Heavy Neutral Leptons

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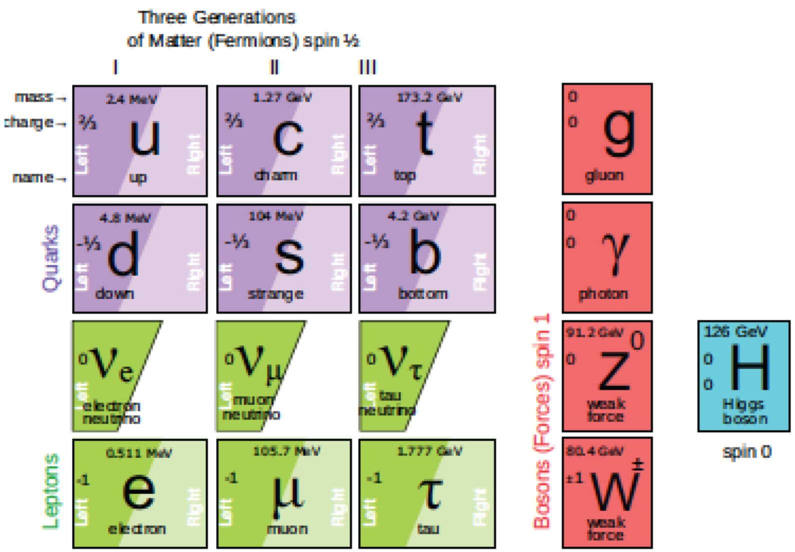
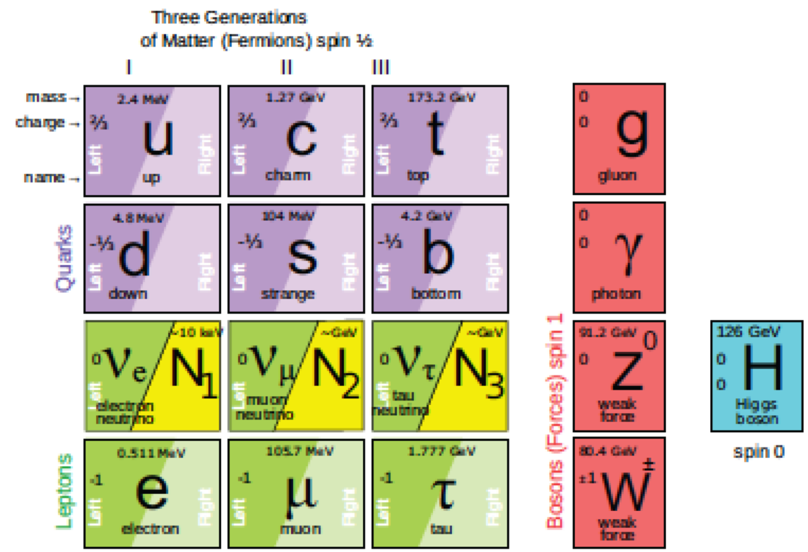
A new ν (Minimal) Standard Model





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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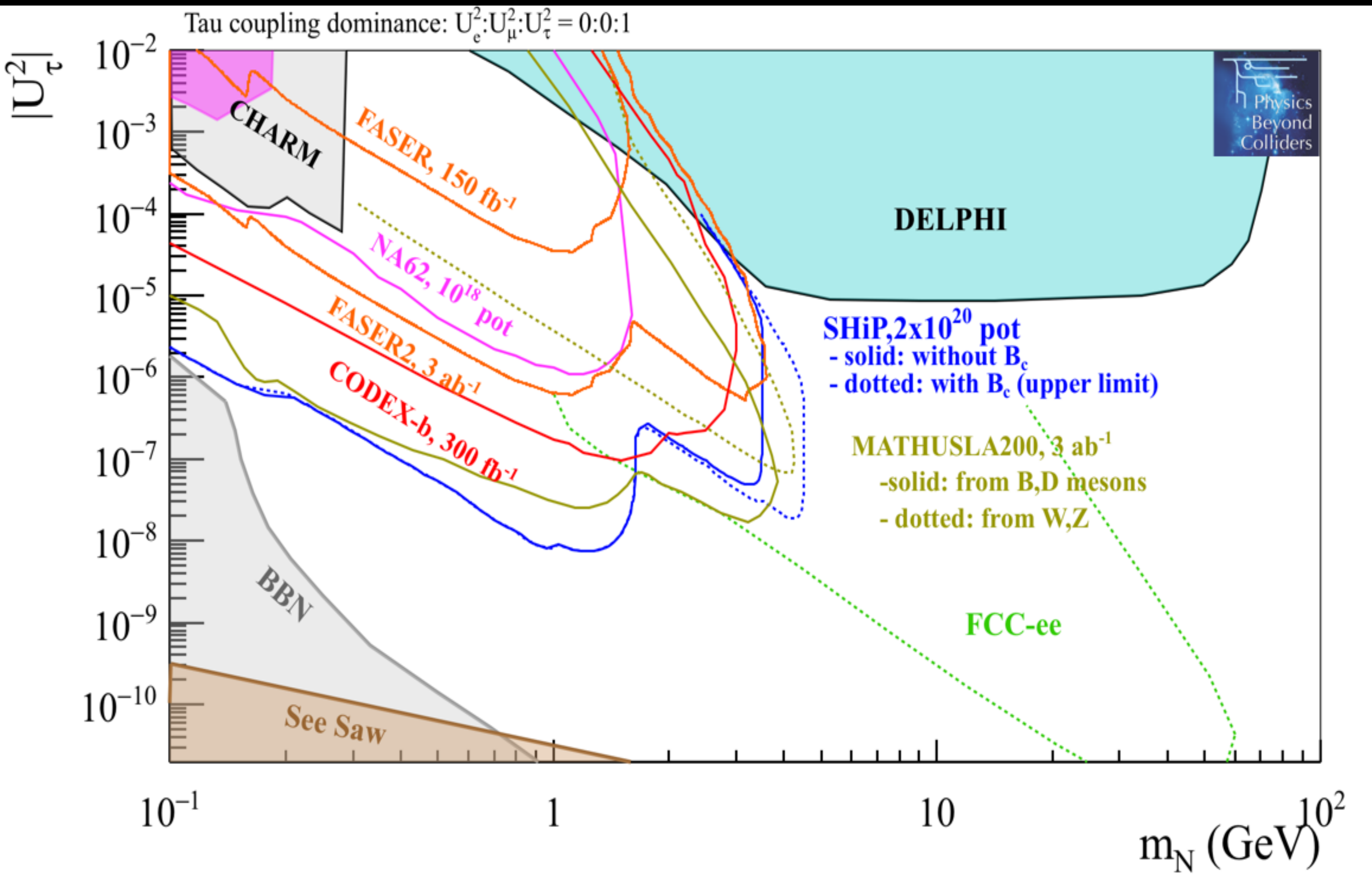
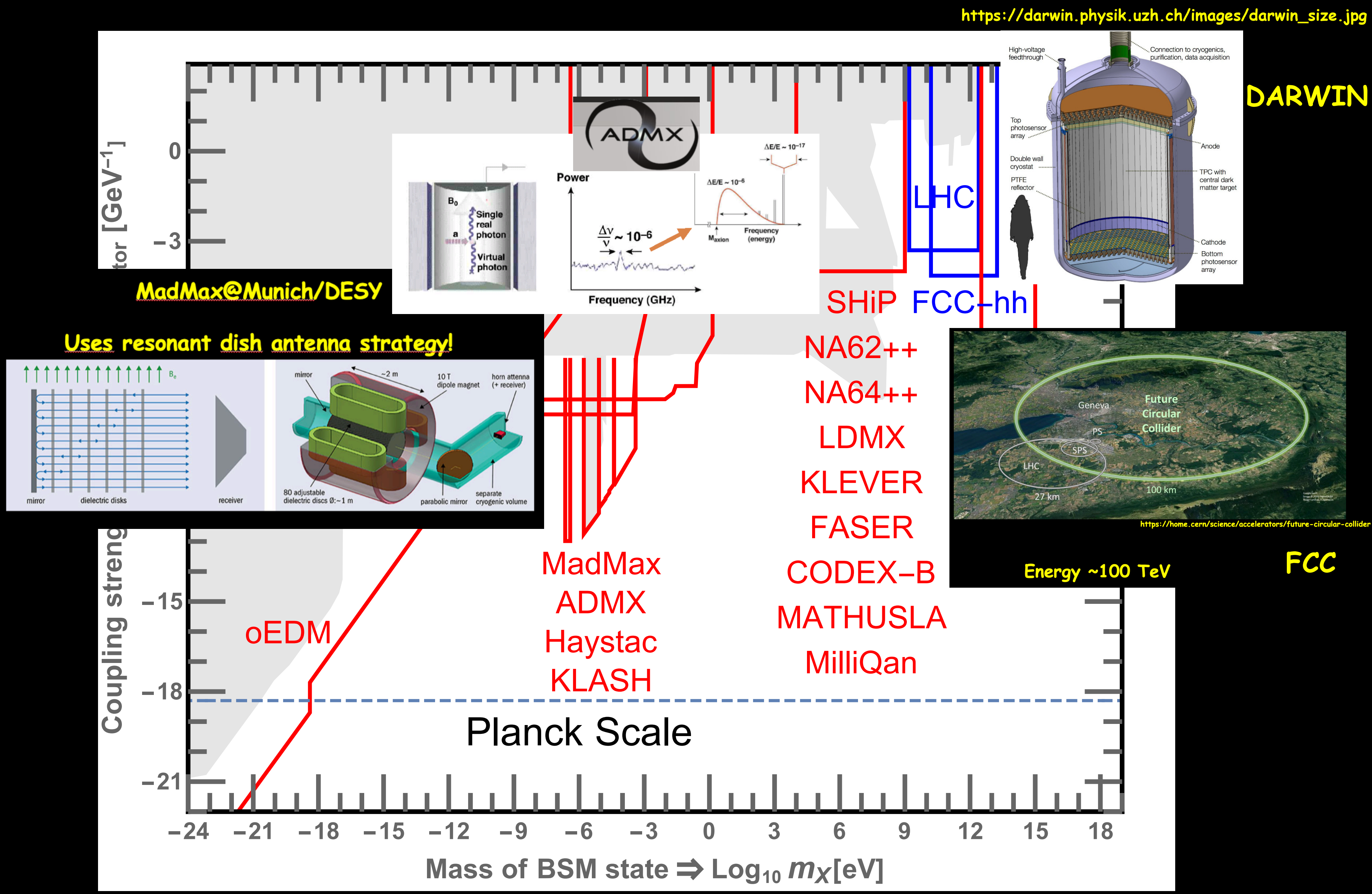


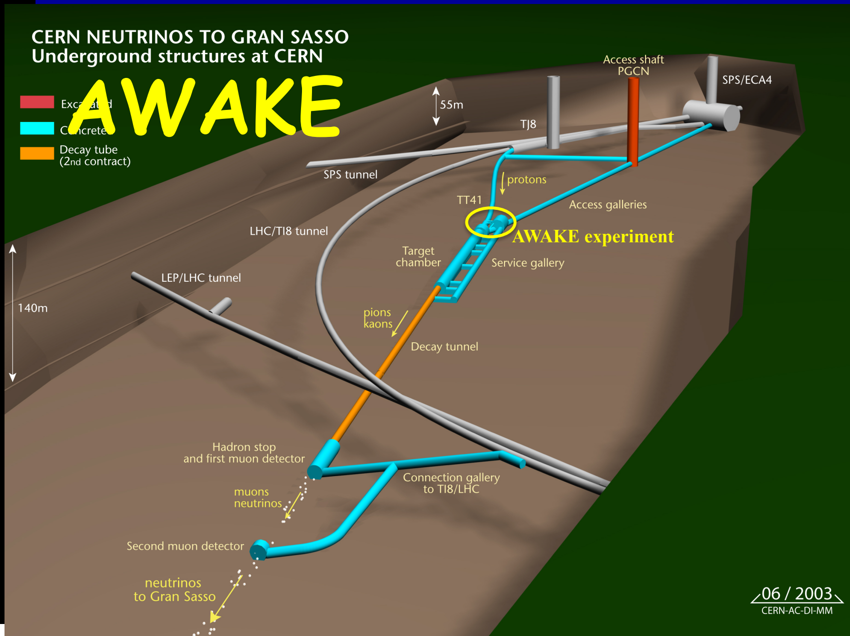
Beyond PBC

Many more exciting things going on...



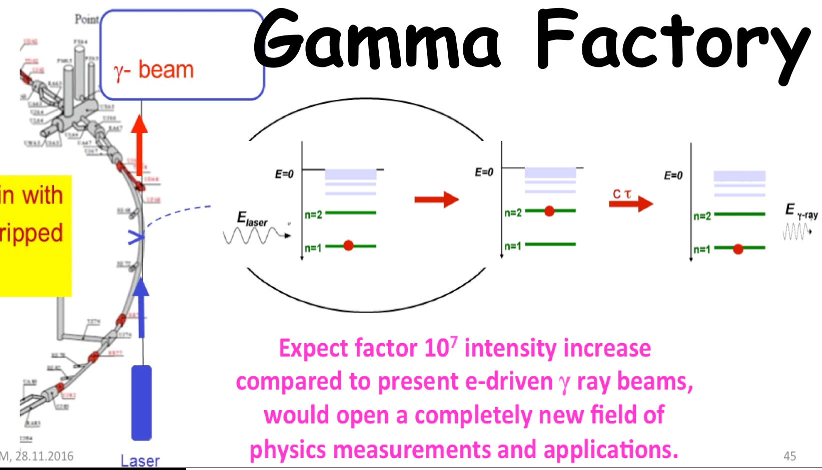
Many more cool things out there!

Cool things…



New idea: Gamma Factory

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

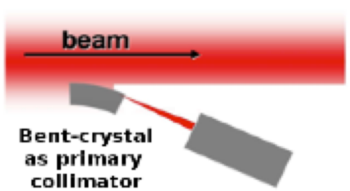


LHC filled in with partially stripped ion beams

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.

C. Vallée, CPPM, 28.11.2016 45

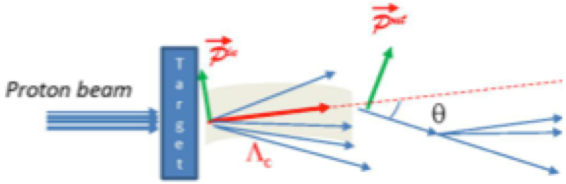
Crystal extraction

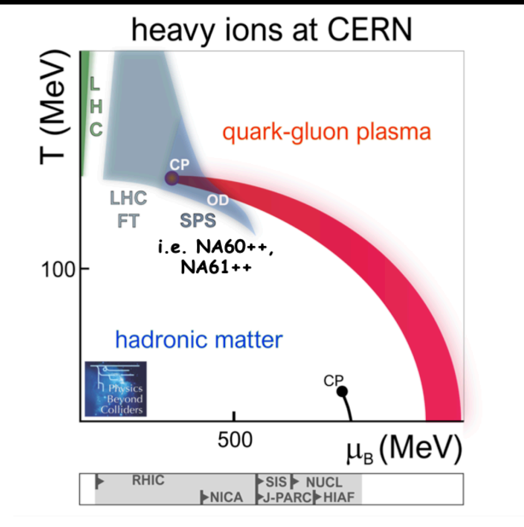


UA9

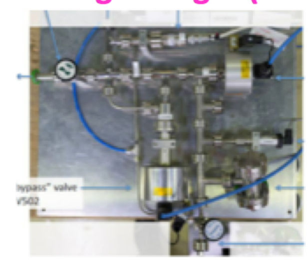
Upstream of LHCb and/or ALICE

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





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

The future: FIPs

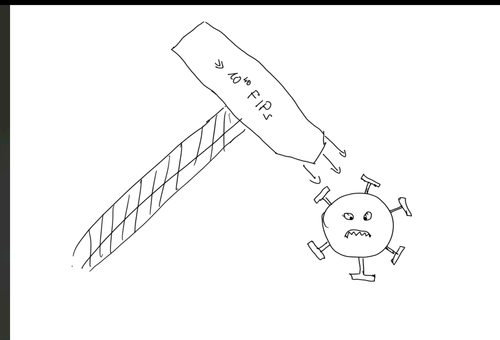
FIPs ←→ coupling <<<<<1

- So far most searches have been concentrated on low mass region
- But colliders are getting into the game.

- Bring together as unified framework


FIPs 2020
Workshop on
Feebly-Interacting
Particles
27-29 May 2020
CERN
FIPS at colliders (including
ATLAS, CMS, LHCb)
extracted beams /
fixed-target experiments
neutrino experiments
direct and indirect
dark matter detectors
axion/ALP experiments
and beyond
Organizers:
Martin Bauer
James Beacham
Albert De Roeck
Gian Francesco Giudice
Pilar Hernandez
Igor Irastorza
Joerg Jaeckel
Gordan Krnjaic
Gaia Lanfranchi
Jocelyn Monroe
Silvia Pascoli
Joshua Ruderman
Philip Schuster
Mikhail Shaposhnikov
Jessie Shelton
indico.cern.ch/e/FIPs_May_2020
CERN

FIPs strike back soon at a location near you



FIPS at colliders (including ATLAS, CMS, LHCb)

extracted beams / fixed-target experiments

neutrino experiments

direct and indirect dark matter detectors

axion/ALP experiments

and beyond

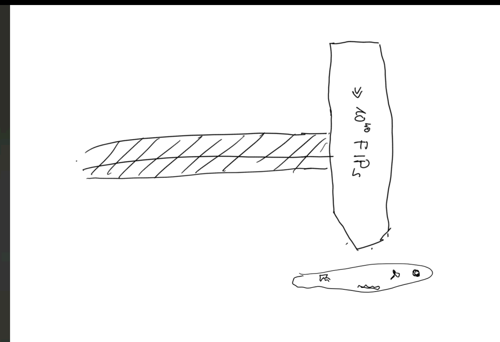
Organizers:

Martin Bauer
James Beacham
Albert De Roeck
Gian Francesco Giudice
Pilar Hernandez
Igor Irastorza
Joerg Jaeckel
Gordan Krnjaic
Gaia Lanfranchi
Jocelyn Monroe
Silvia Pascoli
Joshua Ruderman
Philip Schuster
Mikhail Shaposhnikov
Jessie Shelton

indico.cern.ch/e/FIPs_May_2020

CERN

FIPs strike back soon at a location near you



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CERN

Even Earlier ☺: 8-10 June 2020

Physics Beyond Colliders meets theory: informal discussions about PBC selected topics

8-10 June 2020
CERN
Europe/Zurich timezone

Search...

- Overview
- Registration
- Timetable
- Contribution List
- Participant List
- Videoconference Rooms

With FIPS 2020 being postponed to the Fall of 2020, this virtual workshop aims to host a few talks and informal discussions related to searches for feebly interacting light particles. The scope is primarily on accelerator-based probes of hidden sectors, with a mix of theory and experiment.

The workshop will be fully virtual and consist out of 3 sessions of each 2 hours, taking place from 4pm to 6pm CERN time on the 3 days of the workshop. The timing is chosen to maximize the workshop's accessibility to as many time zones as possible. Talks are by invitation only.

If the status of the COVID crisis permits this, a conference room will be provided for CERN-based physicists to attend the talks. No in-person visits to CERN for the purpose of this workshop can be accommodated.

Starts 8 Jun 2020, 16:00
Ends 10 Jun 2020, 18:00
Europe/Zurich

Simon Knapen
Diego Redigolo
Gaia Lanfranchi

https://indico.cern.ch/event/910753/overview

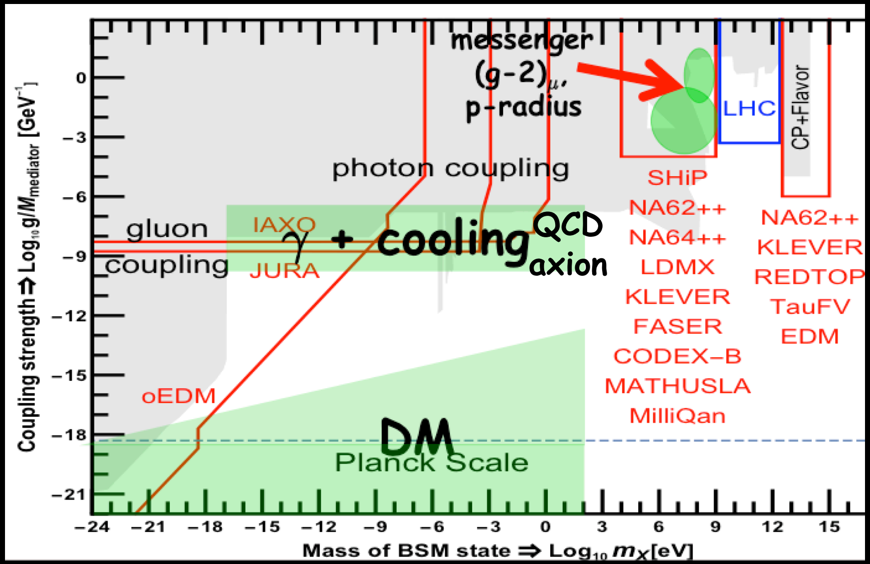
Conclusions

Conclusions

- 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!