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Axion Where Are You?

J. Jaeckel

Special Thanks to all my collaborators,
the Physics Beyond Colliders Study Group,
Claude Vallee, Mike Lamont and Gianluigi Arduini
and especially also Gaia Lanfranchi
as well as all participants of the PBC workshops

Many slides, pictures etc from talks at PBC workshops

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Axion/ALP/FIP Where Are You?

Axion-like particle → ALP

Feebly Interacting Particle → FIP

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Many slides, pictures etc from talks at PBC workshops

There is treasure to be found:

Open questions

Inventory of the (mostly INVISIBLE) Universe

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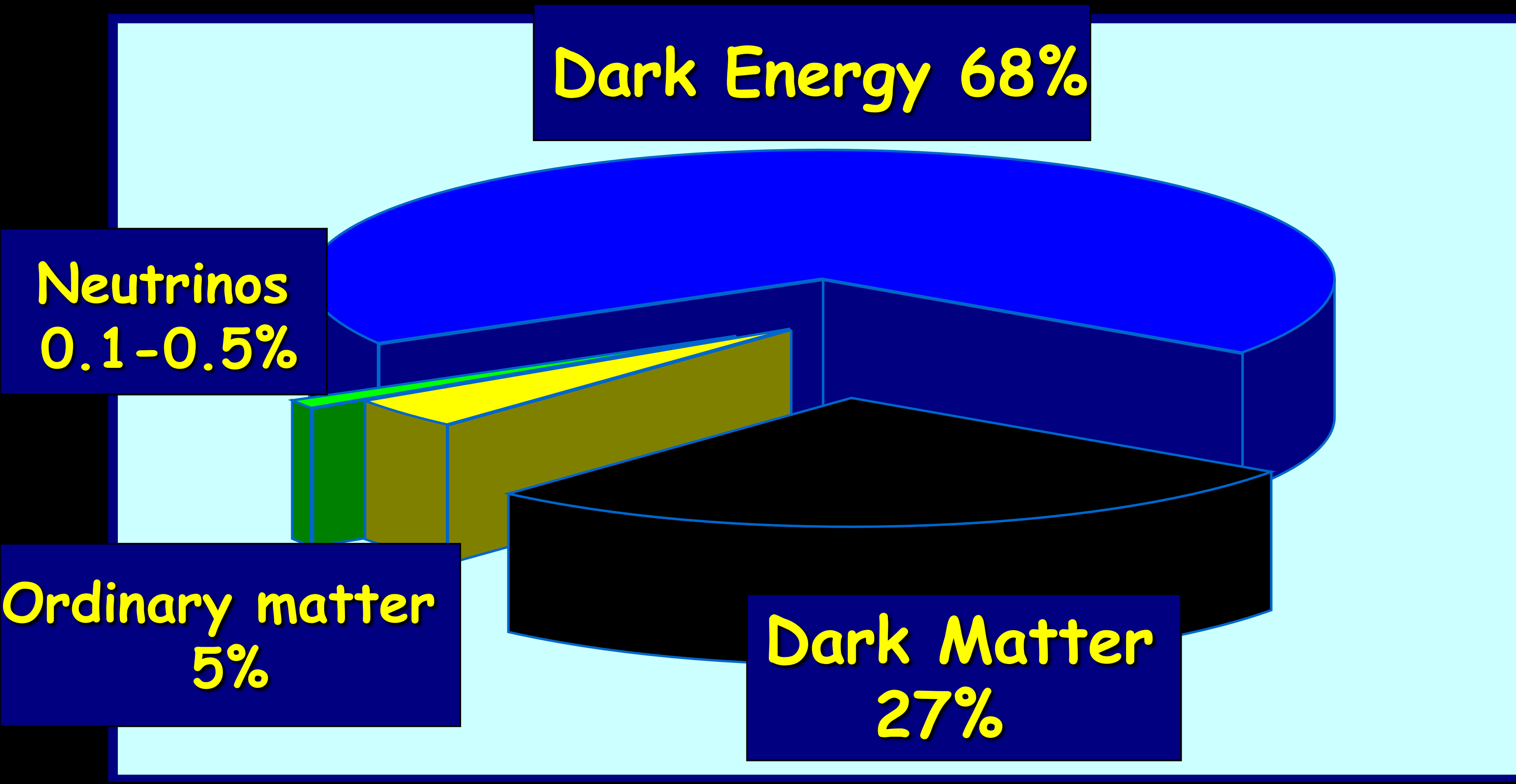
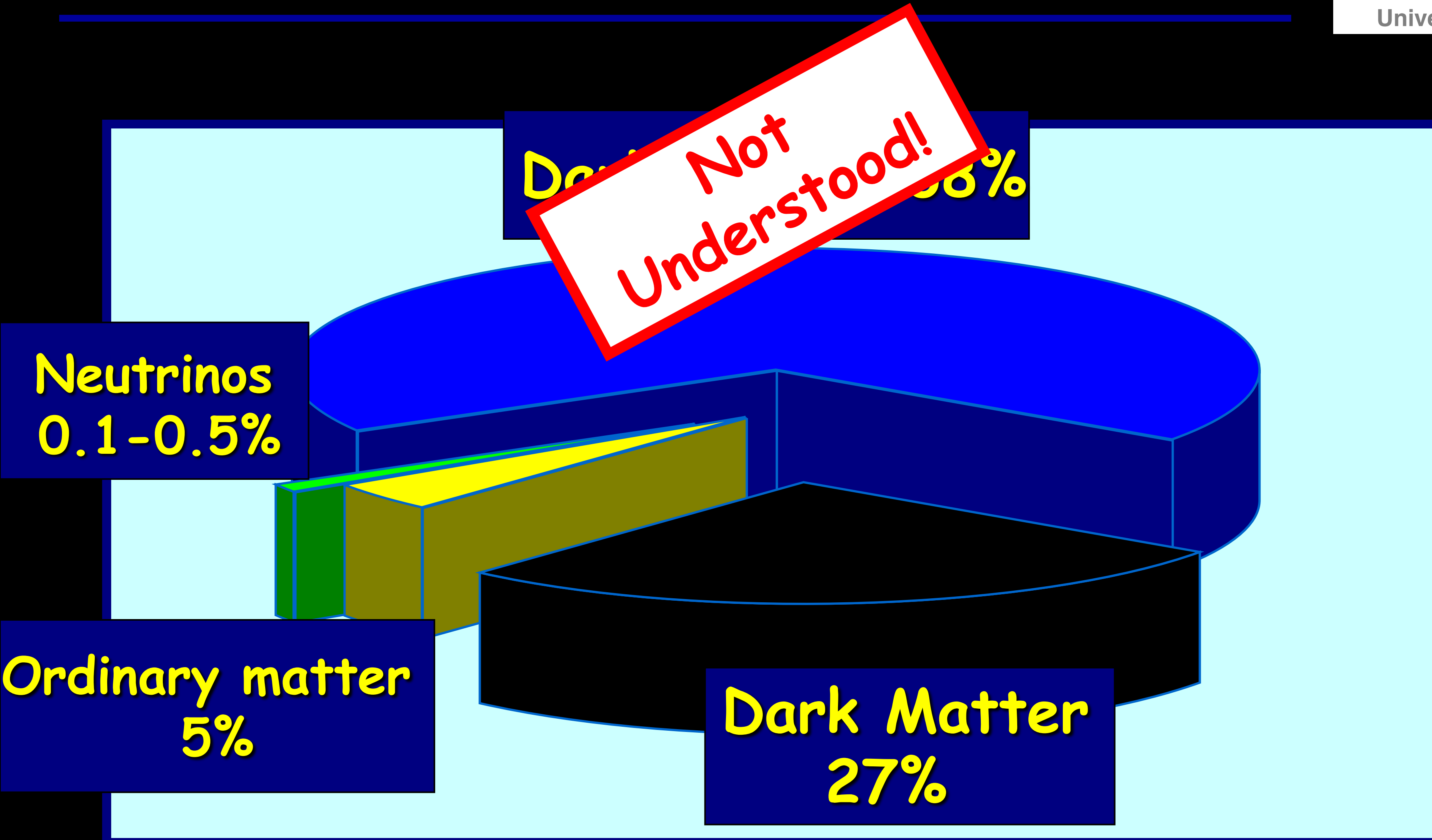


Inventory of the (mostly INVISIBLE) Universe



Inventory of the (mostly INVISIBLE) Universe

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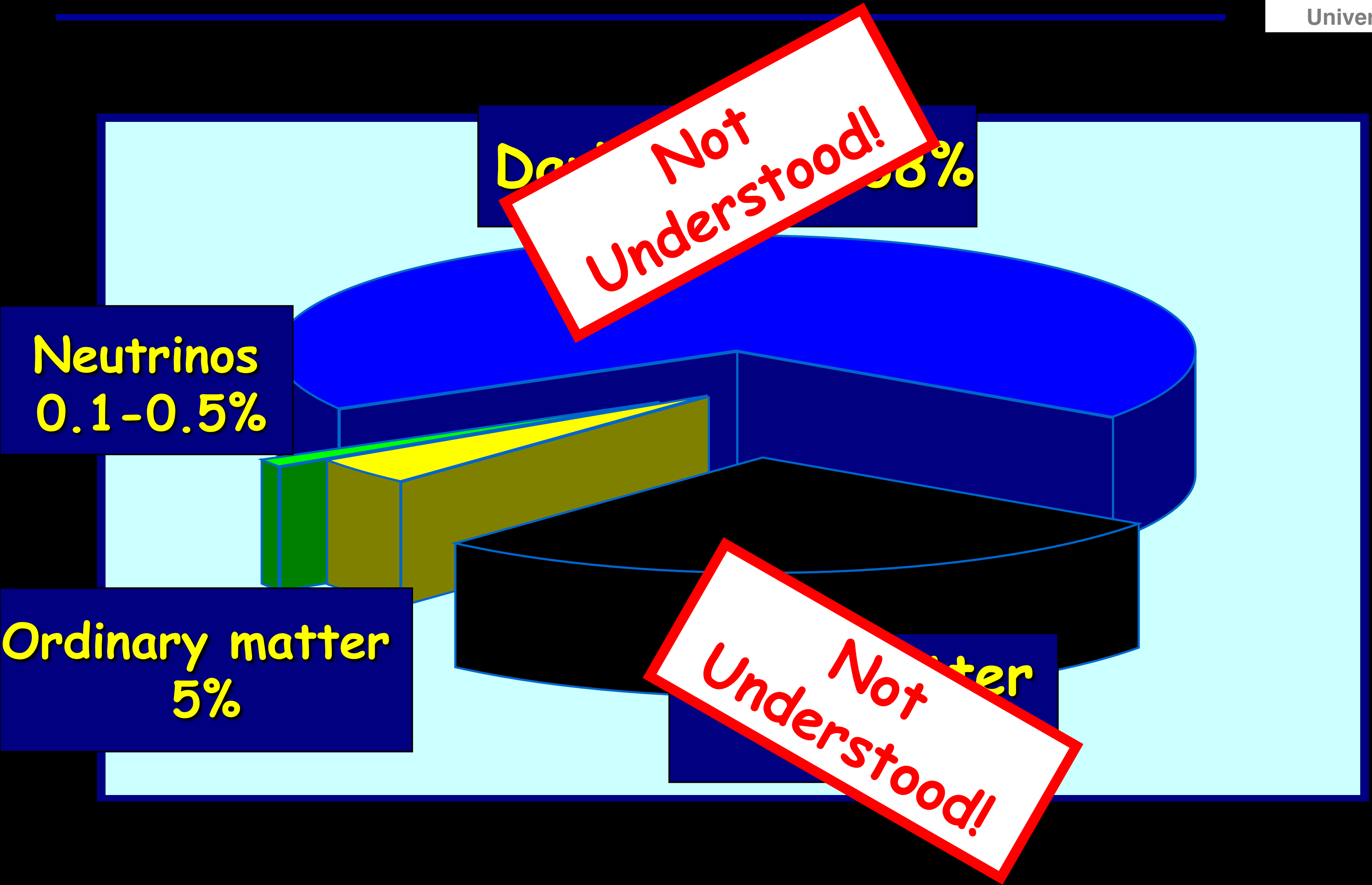

Inventory of the (mostly INVISIBLE) Universe

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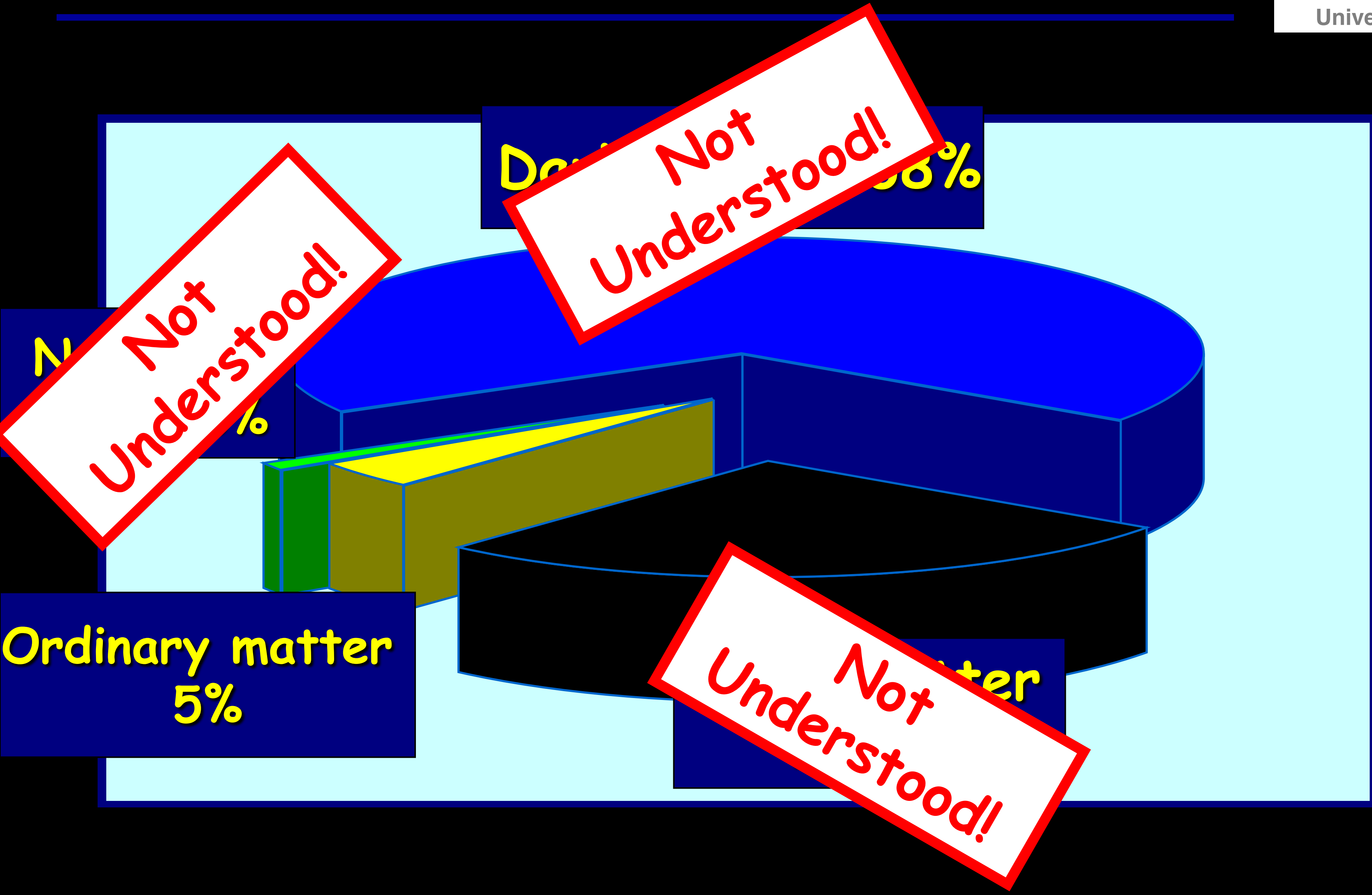

Inventory of the (mostly INVISIBLE) Universe

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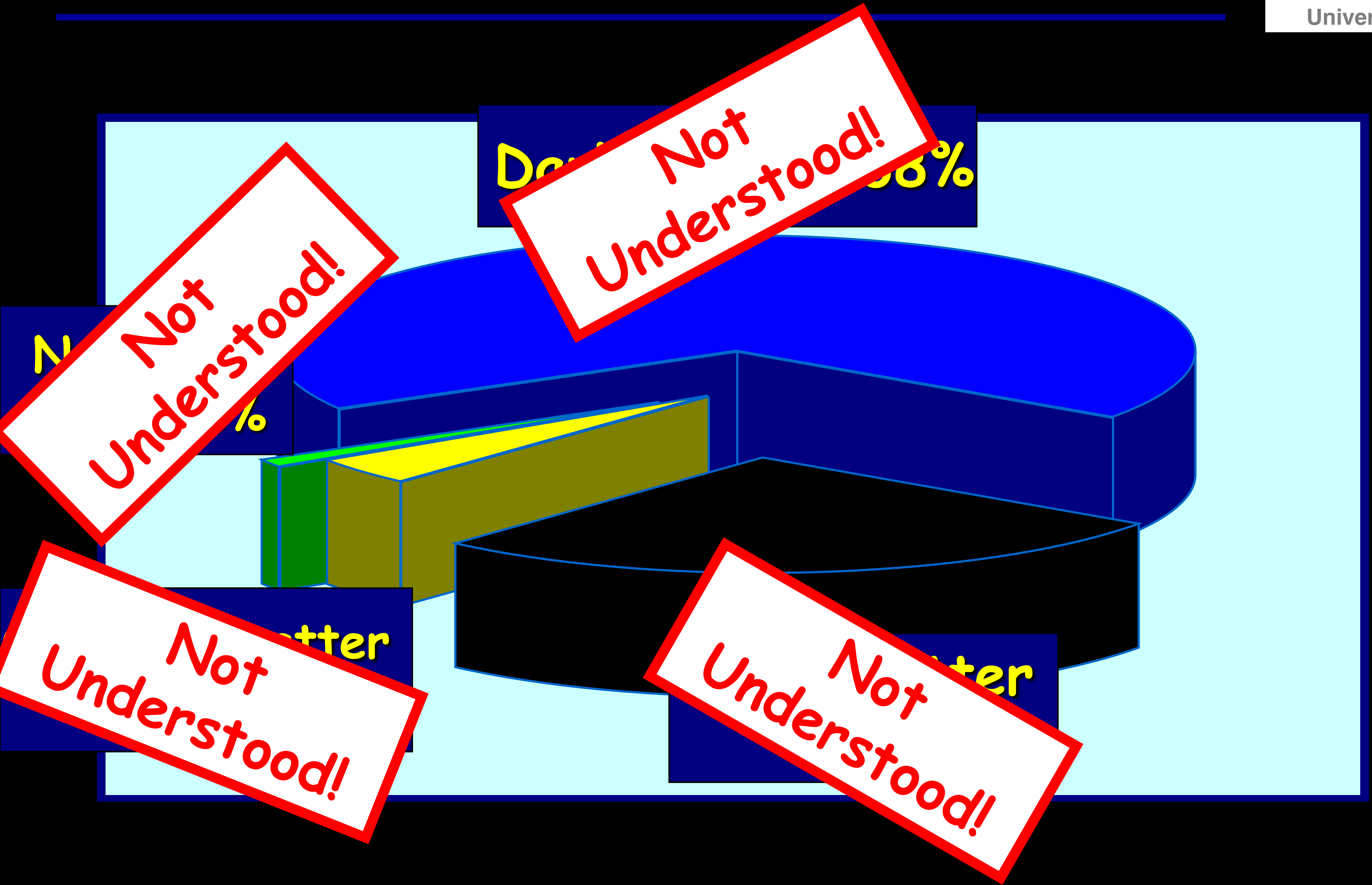

Inventory of the (mostly INVISIBLE) Universe

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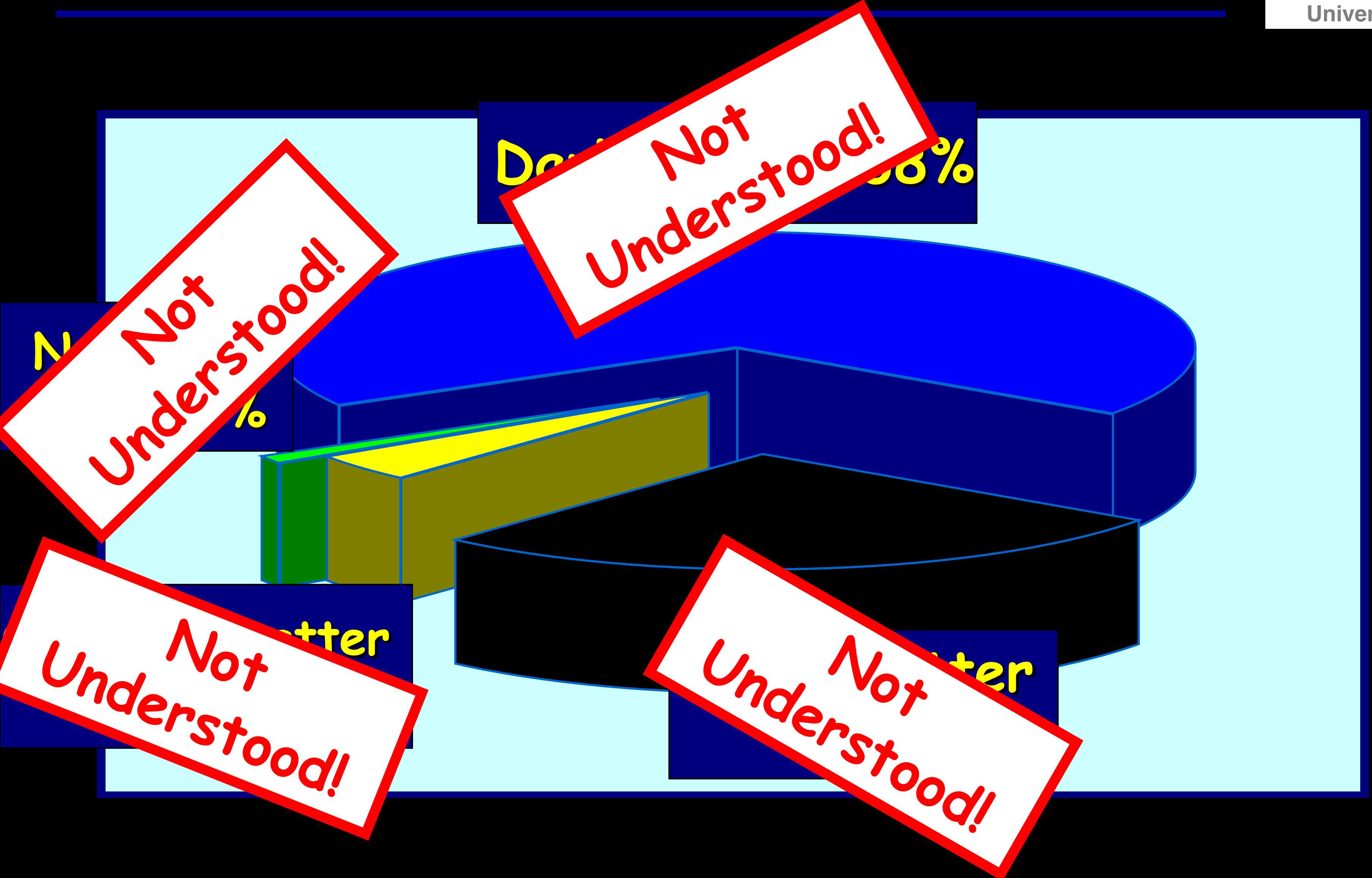

Unimaginable Riches to be found ;-) → Go Explore

Dreaming about the treasure

https://en.wikipedia.org/wiki/Treasure#/media/File:Tesoro_de_Villena.jpg

Some answers with axions/ALPs

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- Dark Energy: Quintessential Axion

A Quintessential axion
Jihn E. Kim (Bonn U. and Seoul Natl. U.), Hans Peter Nilles (Bonn U.) (Oct, 2002)
Published in: *Phys.Lett.B* 553 (2003) 1-6 • e-Print: hep-ph/0210402 [hep-ph]

- Dark Matter: QCD axion or ALP Dark Matter via misalignment mechanism

Cosmology of the Invisible Axion
John Preskill (Harvard U.), Mark B. Wise (Harvard U.), Frank Wilczek (Santa Barbara, KITP)
Phys.Lett.B 120 (1983) 127-132 • DOI: 10.1016/0370-2693(83)90637-8

A Cosmological Bound on the Invisible Axion
L.F. Abbott (Brandeis U.), P. Sikivie (Florida U.)
Phys.Lett.B 120 (1983) 133-136 • DOI: 10.1016/0370-2693(83)90638-X

The Not So Harmless Axion
Michael Dine (Princeton, Inst. Advanced Study), Willy Fischler (Pennsylvania U.)
Phys.Lett.B 120 (1983) 1

WISPy Cold Dark Matter
Paola Arias (DESY and Chile U., Catolica), Davide Cadamuro (Munich, Max Planck Inst.), Mark Goodsell (DESY and CERN), Joerg Jaeckel (Durham U., IPPP), Javier Redondo (Munich, Max Planck Inst.) et al. (Jan, 2012)
Published in: *JCAP* 06 (2012) 013 • e-Print: 1201.5902 [hep-ph]

- ALP Baryogenesis

Baryon asymmetry and gravitational waves from pseudoscalar inflation
Daniel Jiménez (Heidelberg, Max Planck Inst.), Kohei Kamada (Arizona State U., Tempe), Kai Schmitz (Heidelberg, Max Planck Inst.), Xun-Jie Xu (Heidelberg, Max Planck Inst.) (Jul 25, 2017)
Published in: *JCAP* 12 (2017) 011 • e-Print: 1707.07943 [hep-ph]

Baryogenesis from axion inflation
Valerie Domcke (DESY), Benedict von Harling (DESY and Barcelona, IFAE), Enrico Morgante (DESY), Kyohei Mukaida (DESY) (May 30, 2019)
Published in: *JCAP* 10 (2019) 032 • e-Print: 1905.13318 [hep-ph]

- Neutrino Masses and everything explained with axions/ALPs: SMASH

Standard Model—axion—seesaw—Higgs portal inflation. Five problems of particle physics and cosmology solved in one stroke
Guillermo Ballesteros (IPhT, Saclay), Javier Redondo (Zaragoza U. and Munich, Max Planck Inst.), Andreas Ringwald (DESY), Carlos Tamarit (Durham U., IPPP) (Oct 5, 2016)
Published in: *JCAP* 08 (2017) 001 • e-Print: 1610.01639 [hep-ph]

- And much much more to be imagined...

More ALPy answers to more questions

- The strong CP Problem

CP Conservation in the Presence of Instantons
R.D. Peccei (Stanford U., ITP), Helen R. Quinn (Stanford U., ITP) (Mar, 1977)
Published in: *Phys.Rev.Lett.* 38 (1977) 1440-1443,

- Axion (Natural) Inflation

Natural inflation with pseudo - Nambu-Goldstone bosons
Katherine Freese (MIT, LNS), Joshua A. Frieman (Fermilab), Angela V. Olinto (Fermilab) (Aug, 1990)
Published in: *Phys.Rev.Lett.* 65 (1990) 3233-3236, Phys. Rev. Lett. 65 (1990) 3233-3236 and Fermilab Batavia - FERMILAB-Pub-90-177 (90,rec.Nov.) 8 p

The ALP miracle: unified inflaton and dark matter
Ryuji Daido (Tohoku U.), Fuminobu Takahashi (Tohoku U. and Tokyo U., IPMU), Wen Yin (Beijing, Inst. High Energy Phys.) (Feb 10, 2017)
Published in: *JCAP* 05 (2017) 044 • e-Print: 1702.03284 [hep-ph]

- Astrophysical puzzles: Energy Loss of stars, gamma ray transparency of the Universe

Axion cooling of white dwarfs
J. Isern (ICE, Bellaterra), S. Catalan (Hertfordshire U.), E. Garcia--Berro (Barcelona, IEEC), M. Salaris (Liverpool John Moores U., ARI), S. Torres (Barcelona, IEEC) (Apr 29, 2013)
e-Print: 1304.7652 [astro-ph.SR]

Hardening of TeV gamma spectrum of AGNs in galaxy clusters by conversions of photons into axion-like particles
Dieter Horns (Hamburg U.), Luca Maccione (Munich U. and Munich, Max Planck Inst.), Manuel Meyer (Hamburg U.), Alessandro Mirizzi (Hamburg U., Inst. Theor. Phys. II), Daniele Montanino (Salento U. and INFN, Lecce) et al. (Jul, 2012)
Published in: *Phys.Rev.D* 86 (2012) 075024 • e-Print: 1207.0776 [astro-ph.HE]

- $(g-2)_\mu$

Contributions of axionlike particles to lepton dipole moments
W.J. Marciano (Brookhaven Natl. Lab.), A. Masiero (Padua U. and INFN, Padua), P. Paradisi (Padua U. and INFN, Padua), M. Passera (INFN, Padua) (Jul 4, 2016)
Published in: *Phys.Rev.D* 94 (2016) 11, 115033 • e-Print: 1607.01022 [hep-ph]

- ...

Your paper here

Drawing a Map:

Where is the New Physics Treasure?

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

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

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↑

All other theories are, of course, completely wrong

Testing of models fostering Exploration

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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

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

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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

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)

→ Draw a Map and go explore

Australia

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

Exploring is (at least) 2 dimensional

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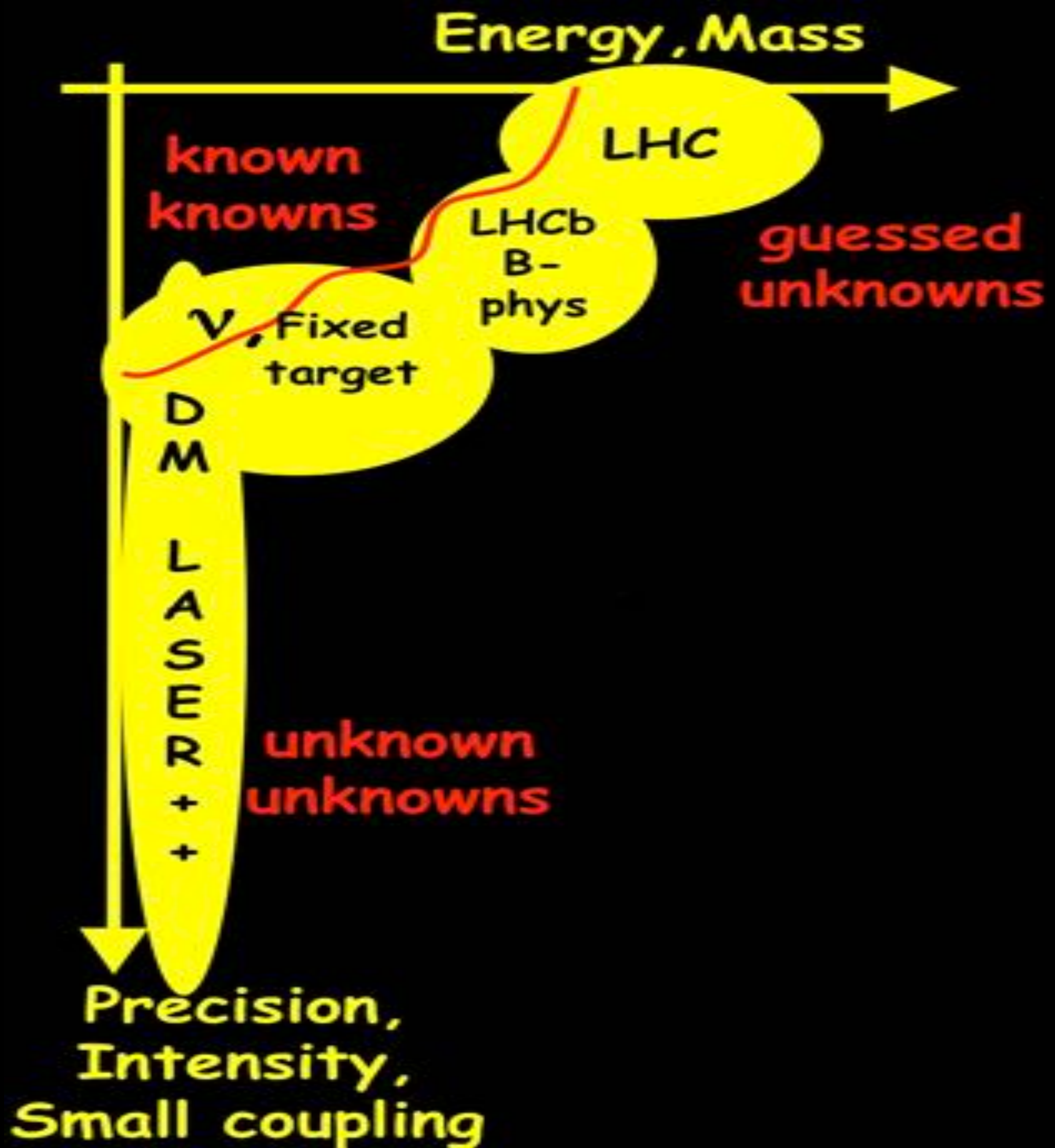

The future...

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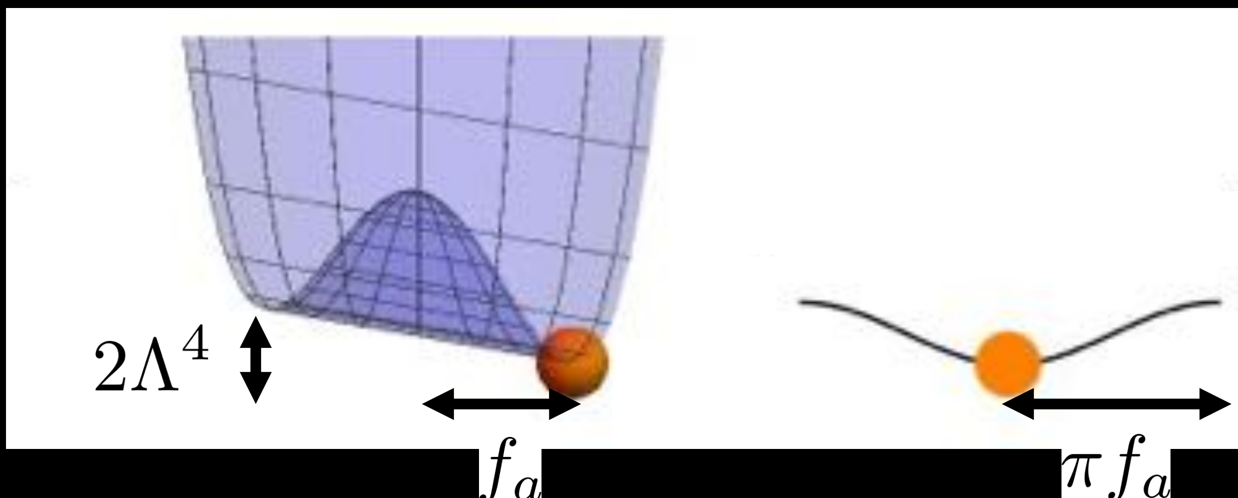
ISOLDE, AD...e.g.

An example of a FIP:
Axions,
axion like particles,
general pseudo-Goldstone bosons

ALP/Pseudo-Goldstone Boson?

- Start with U(1) symmetric potential
- Add a small breaking of U(1) 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

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

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

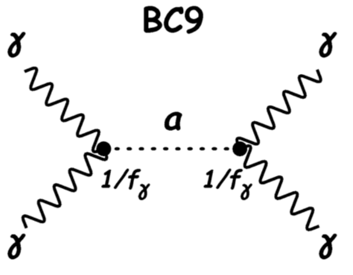
$$g_{agg} \sim \frac{\alpha_s}{2\pi f_a}$$

- Fermion couplings

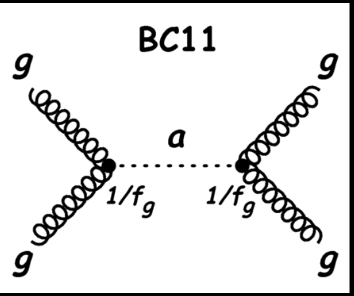
$$\mathcal{L} \supset \frac{\partial_\mu \phi}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$$

In pictures...

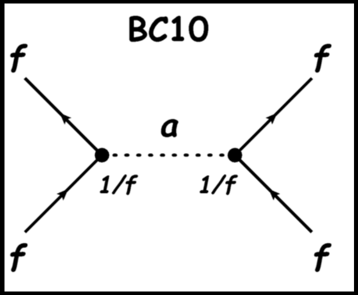
photons



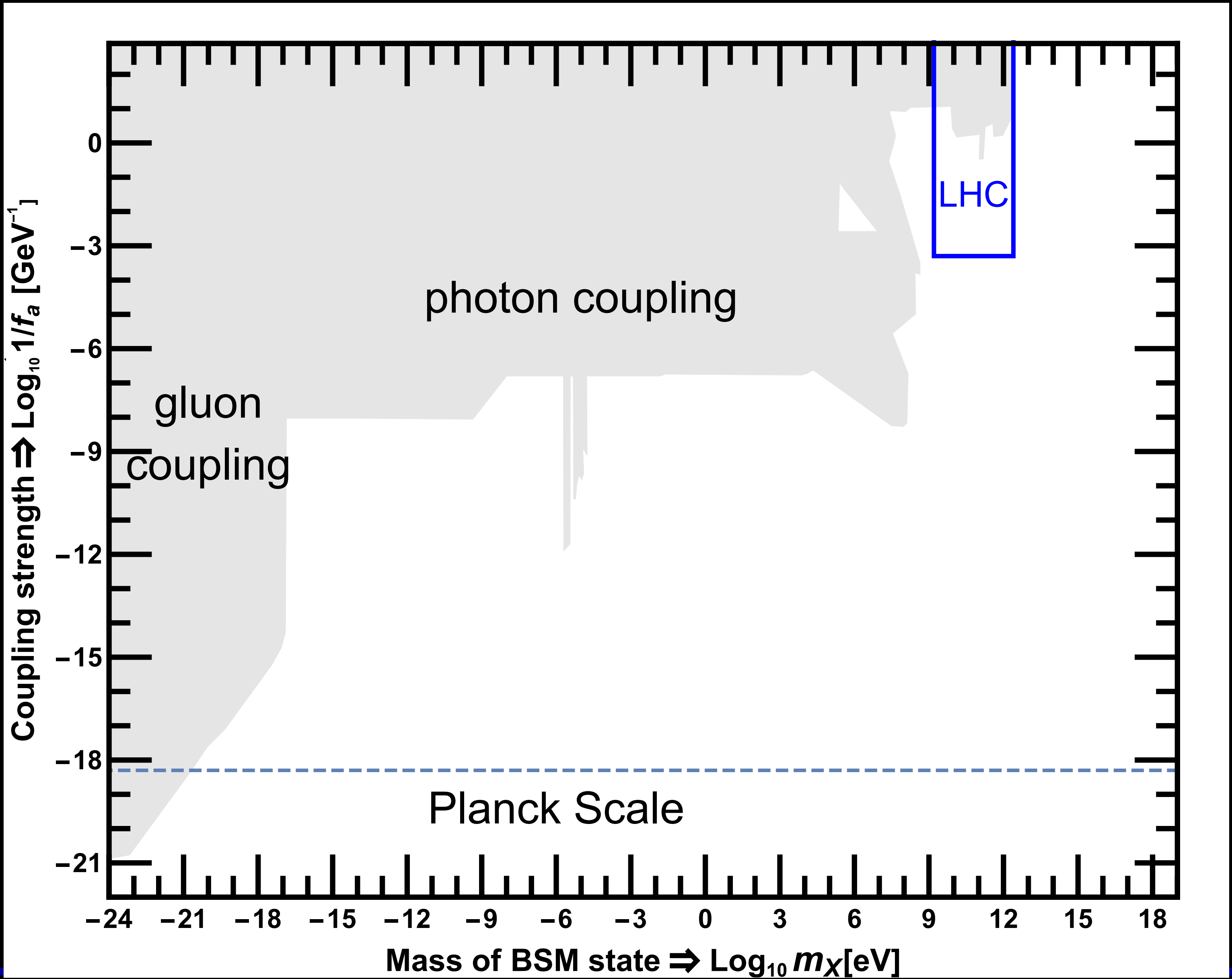
gluons



fermions



Target space



Target space

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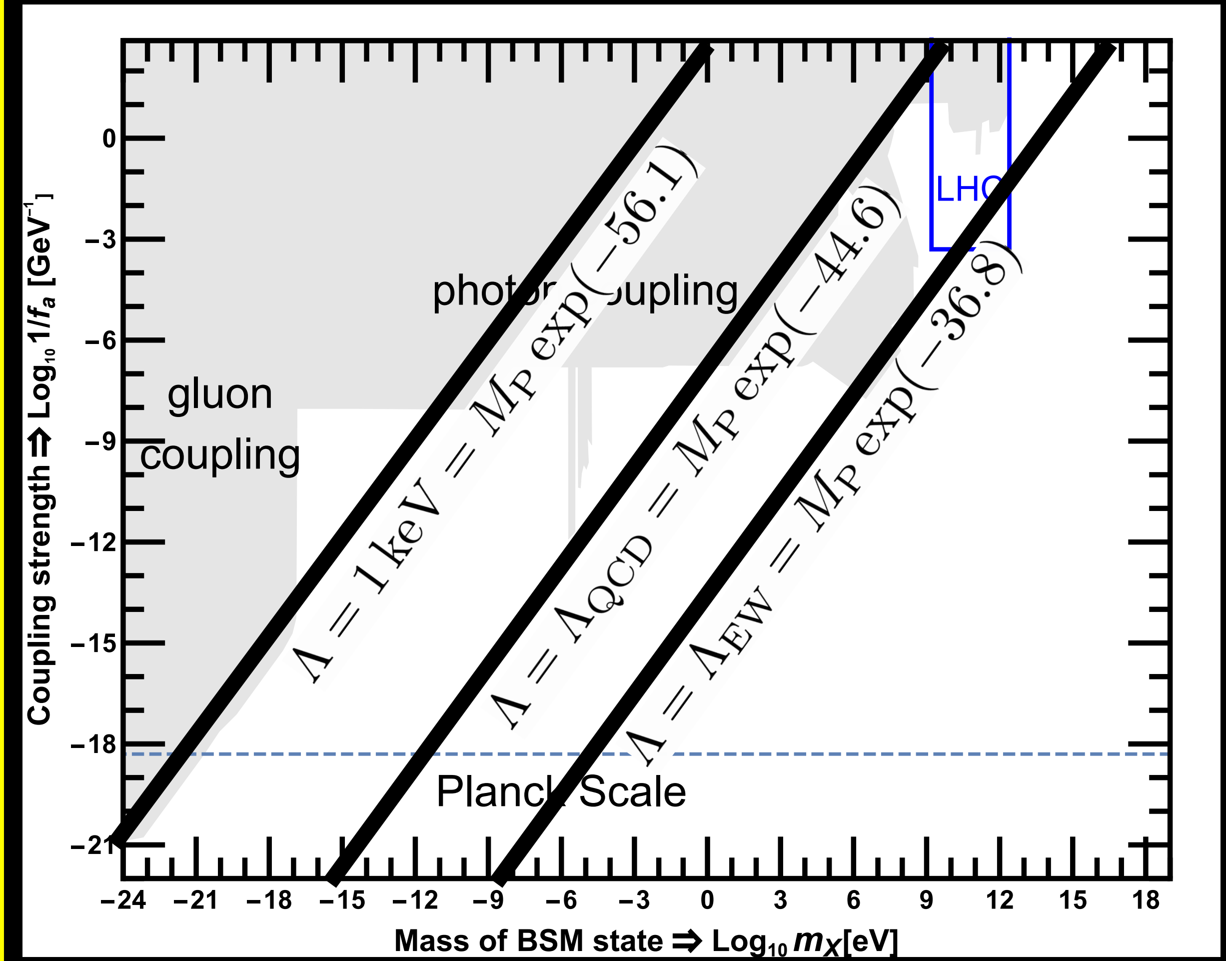
High mass



Small coupling

Go Explore

Measurement of proton EDM

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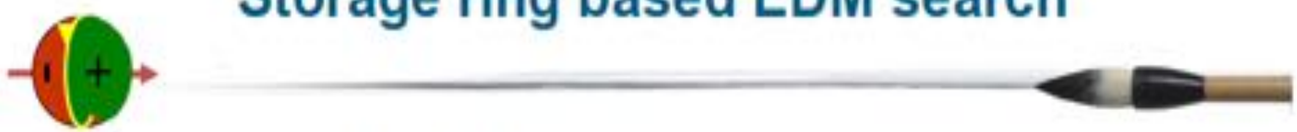
Storage ring based EDM search



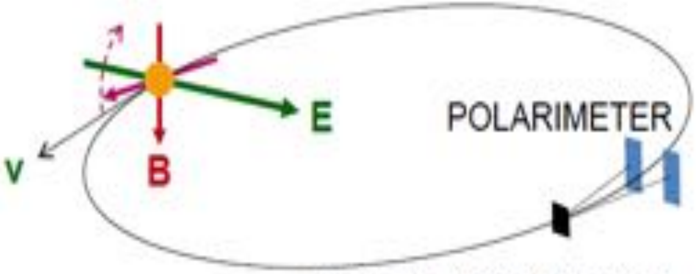
- In the presence of EDM,

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

- 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

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

⇩



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}

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

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

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

Sensitivity

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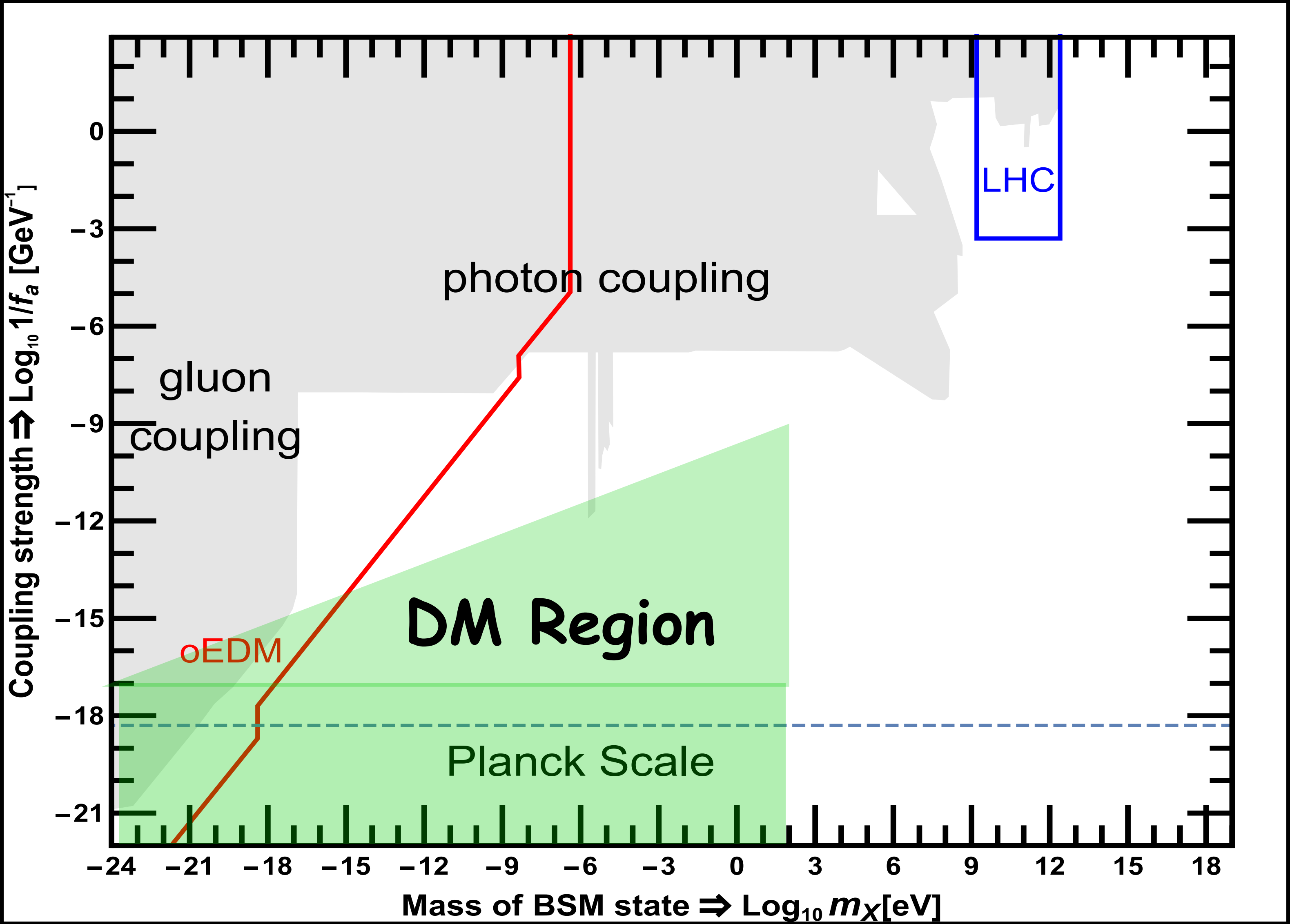

International Axion Observatory = IAXO

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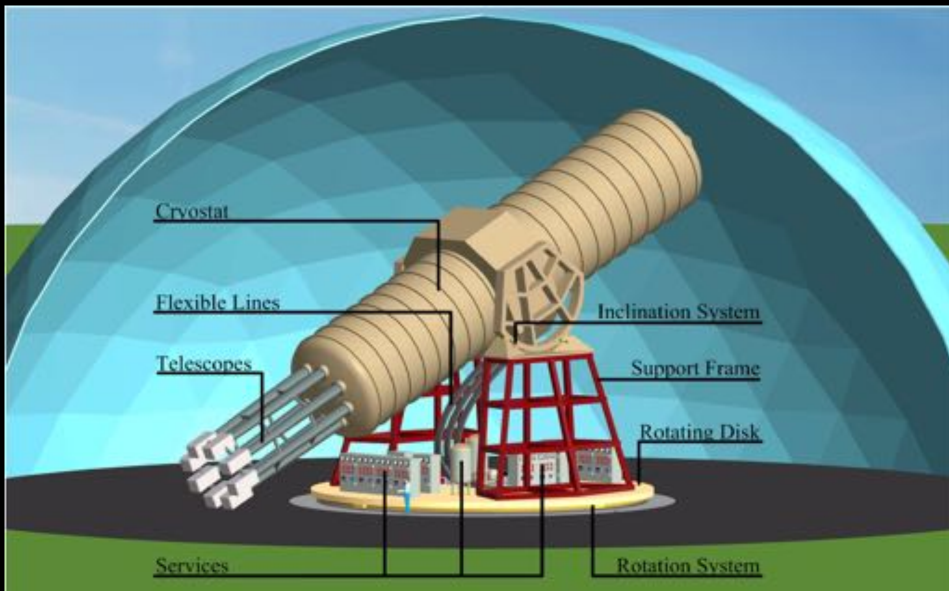
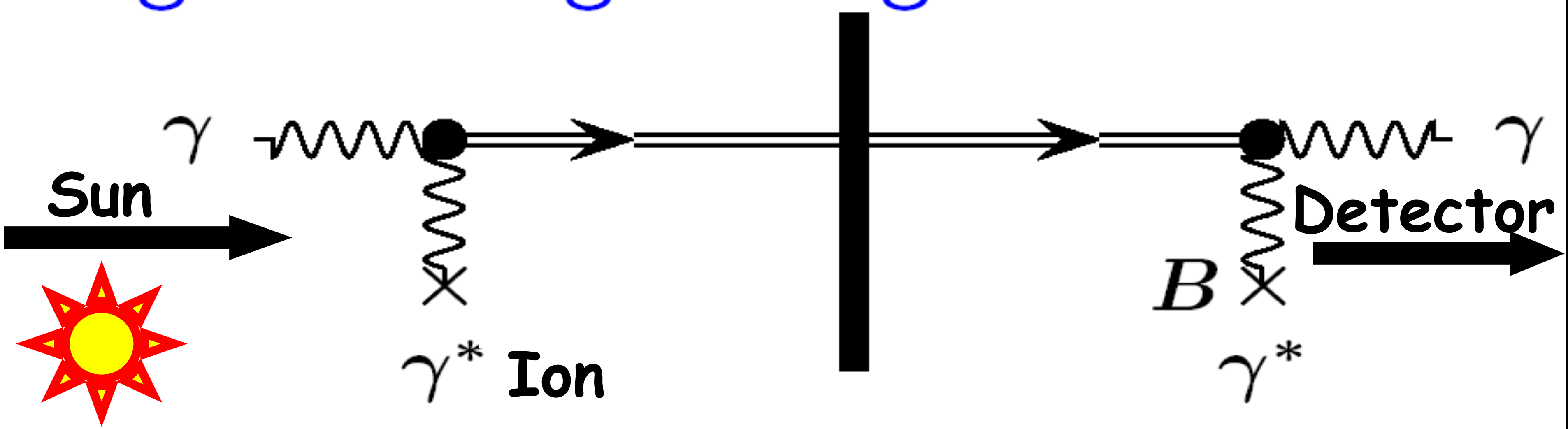


$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma} \phi F^{\mu} \tilde{F}_{\mu\nu}$$

“Light shining through a wall”



Baby IAXO comes soon

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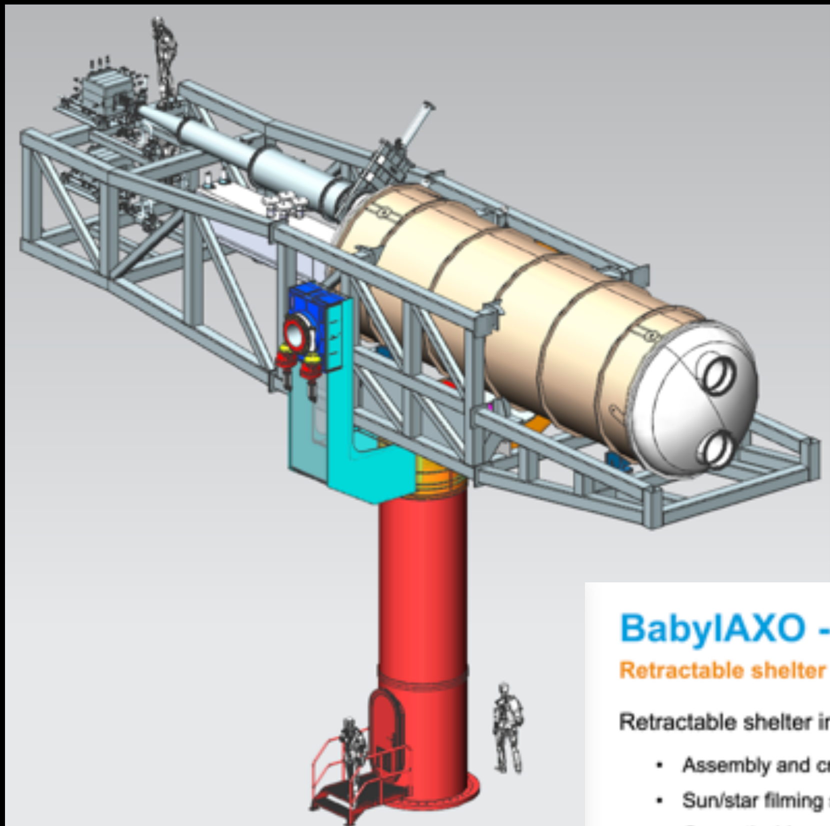

Pictures and slides from IAXO collaboration meeting,
talks by Igor Irastorza and Uwe Schneekloth
https://indico.cern.ch/event/1011471/

Sensitivity

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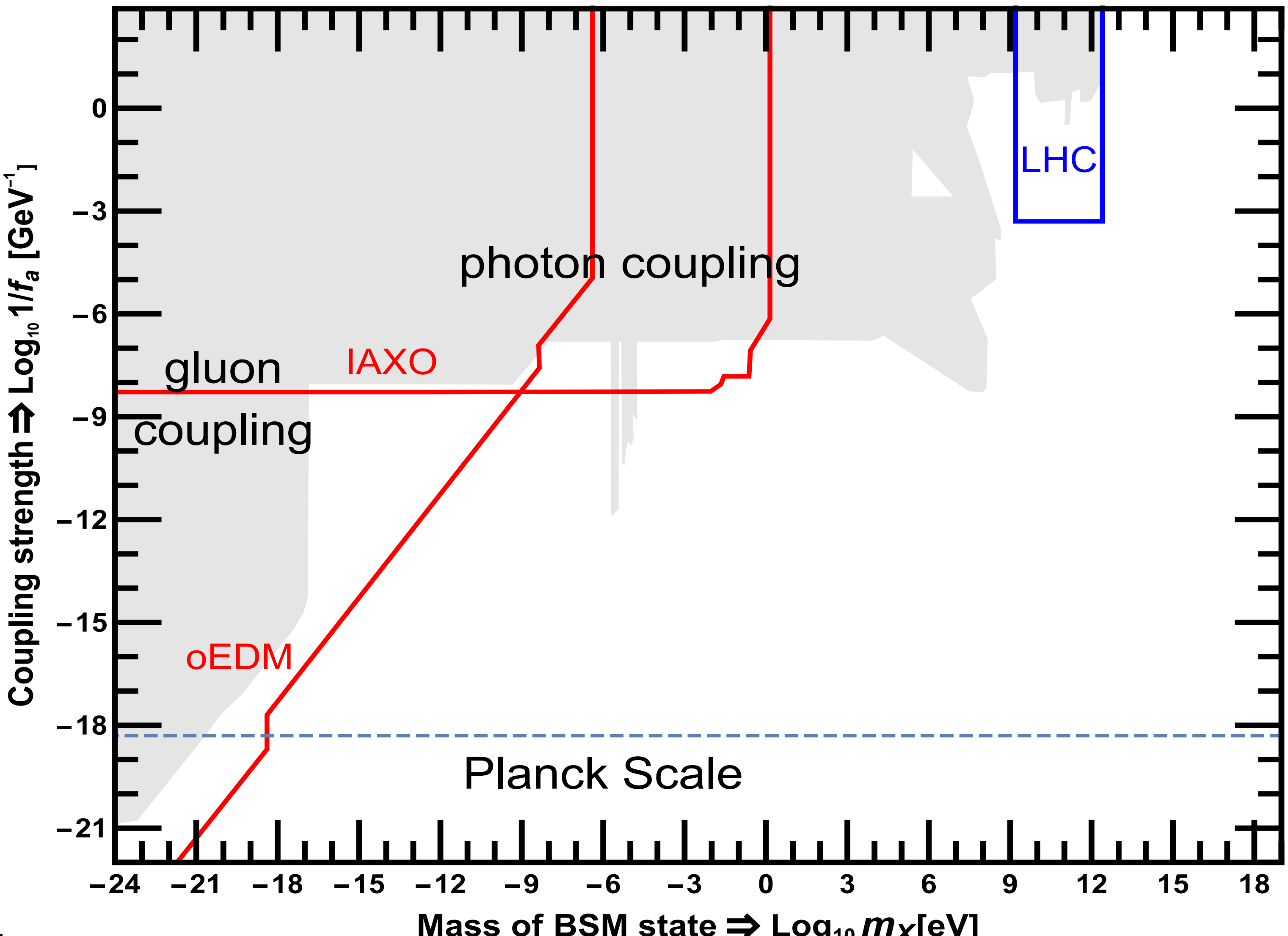
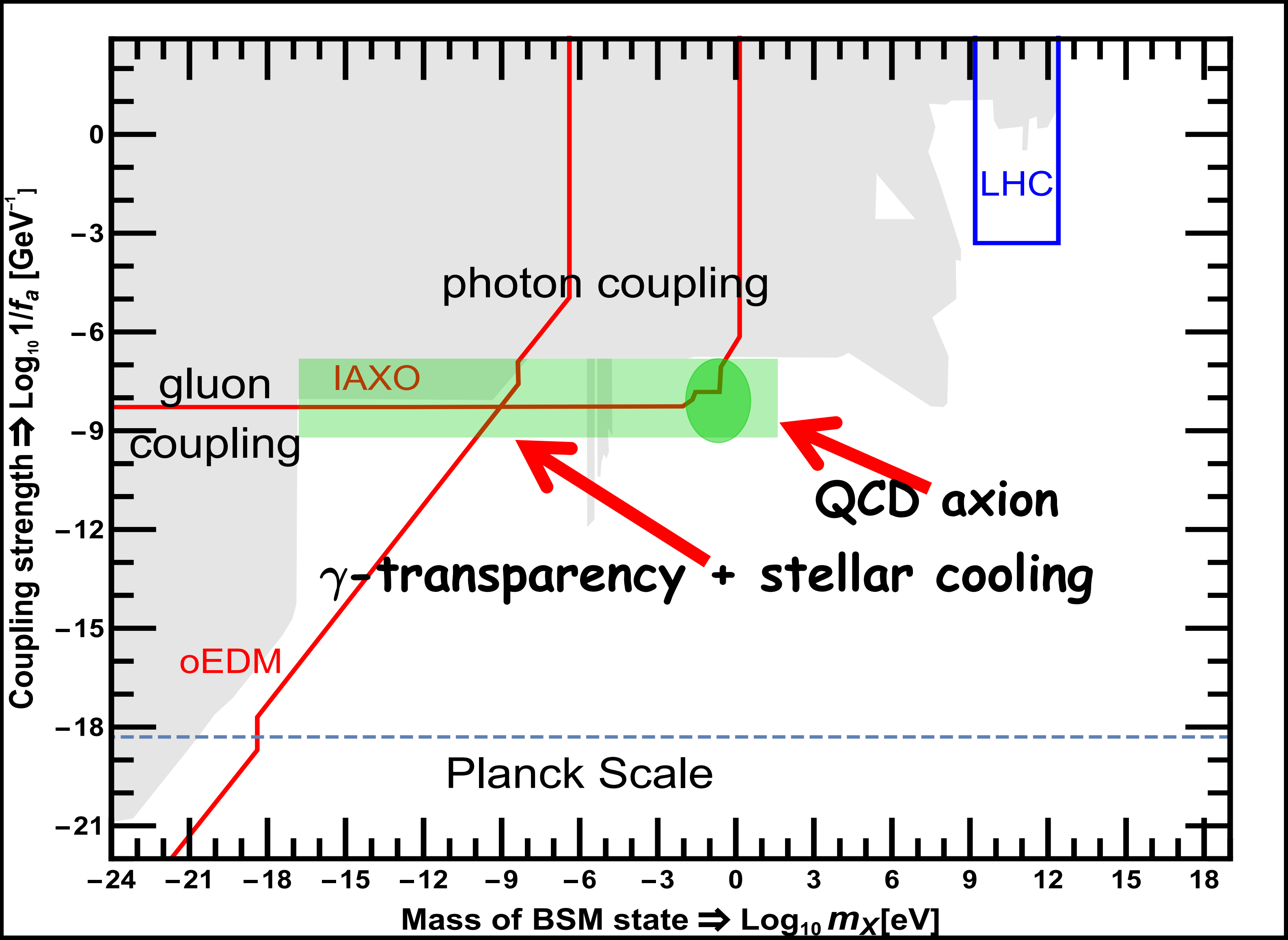


Sensitivity



More : Light shining through walls JURA

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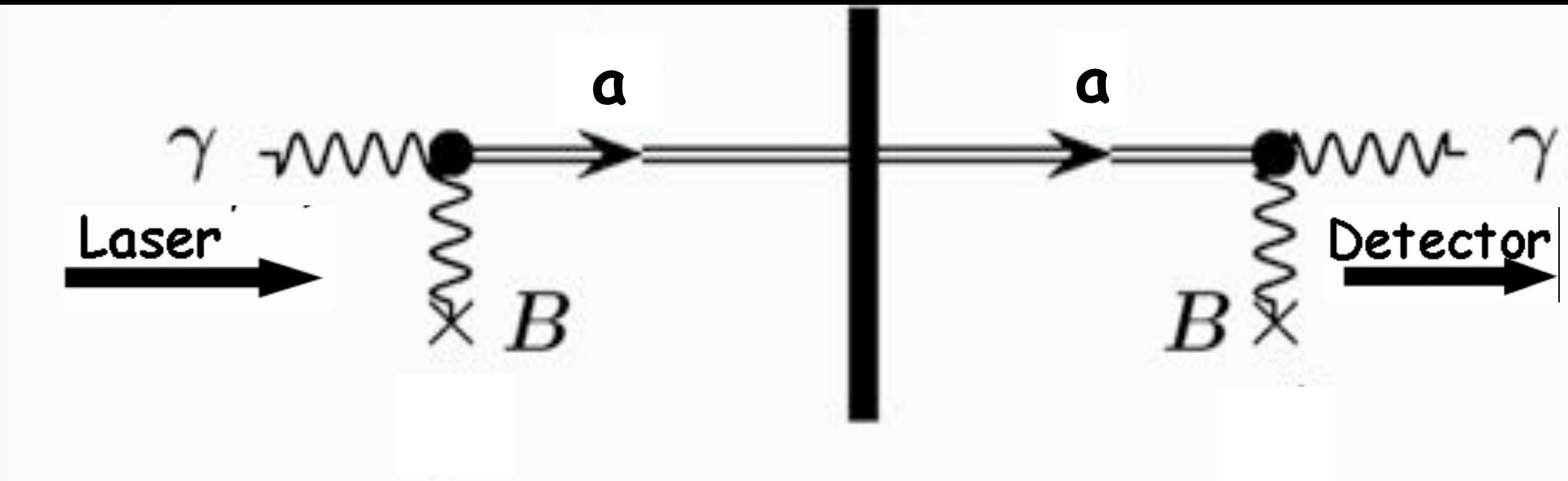

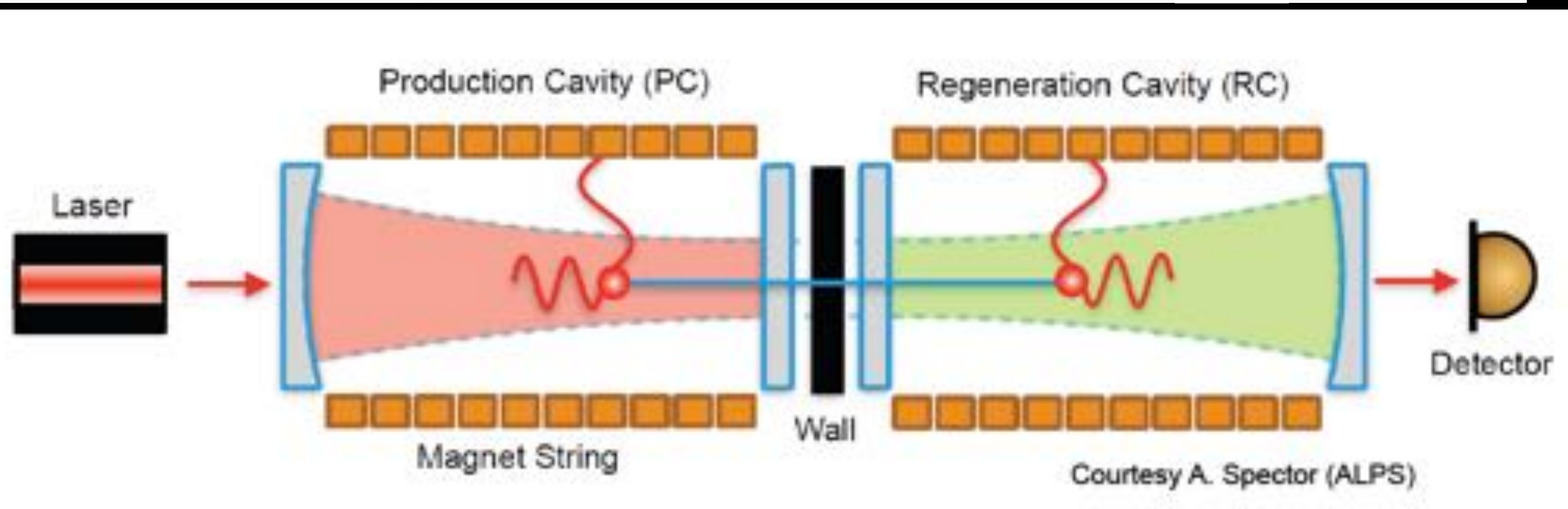

Sensitivity

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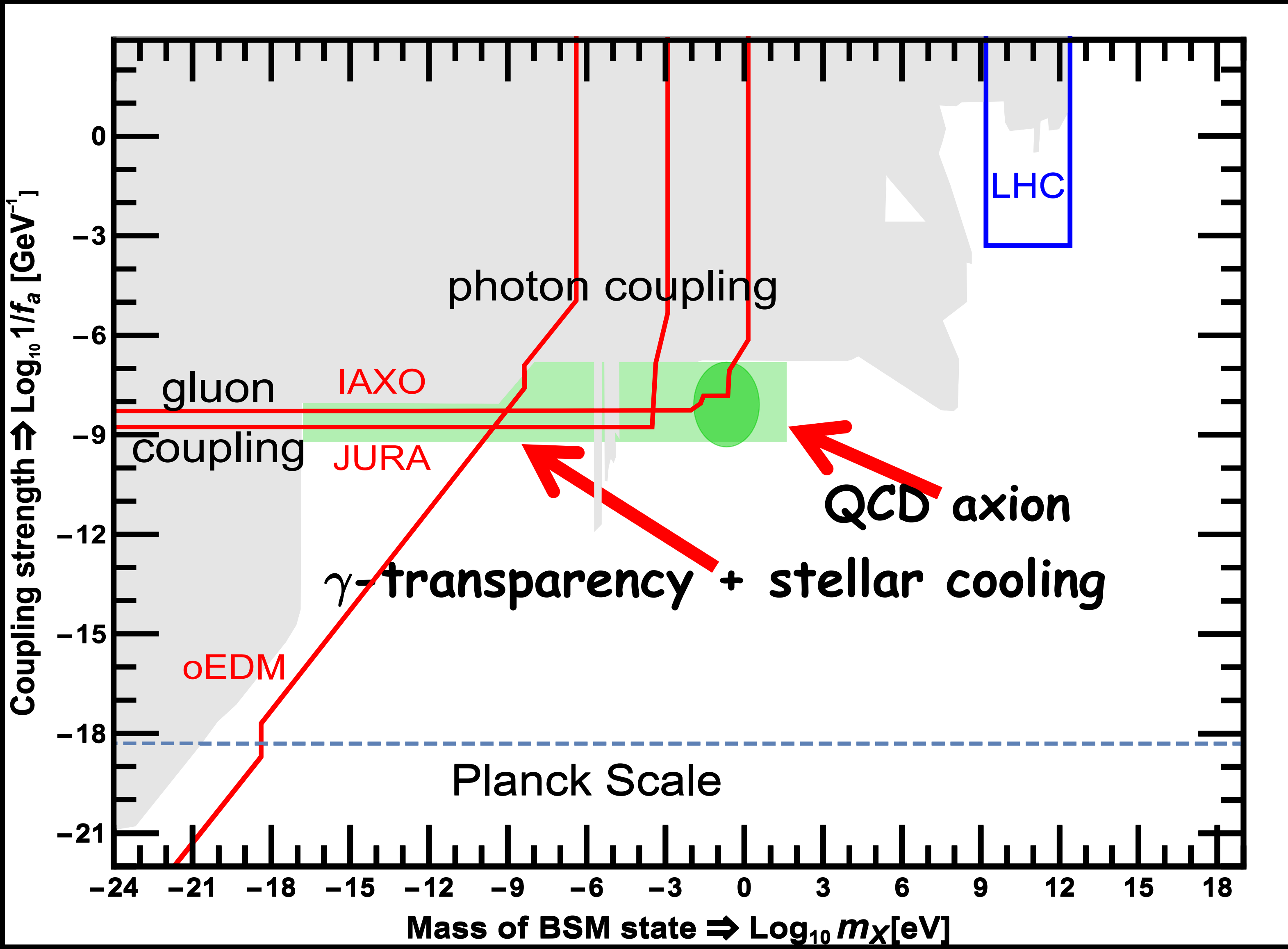
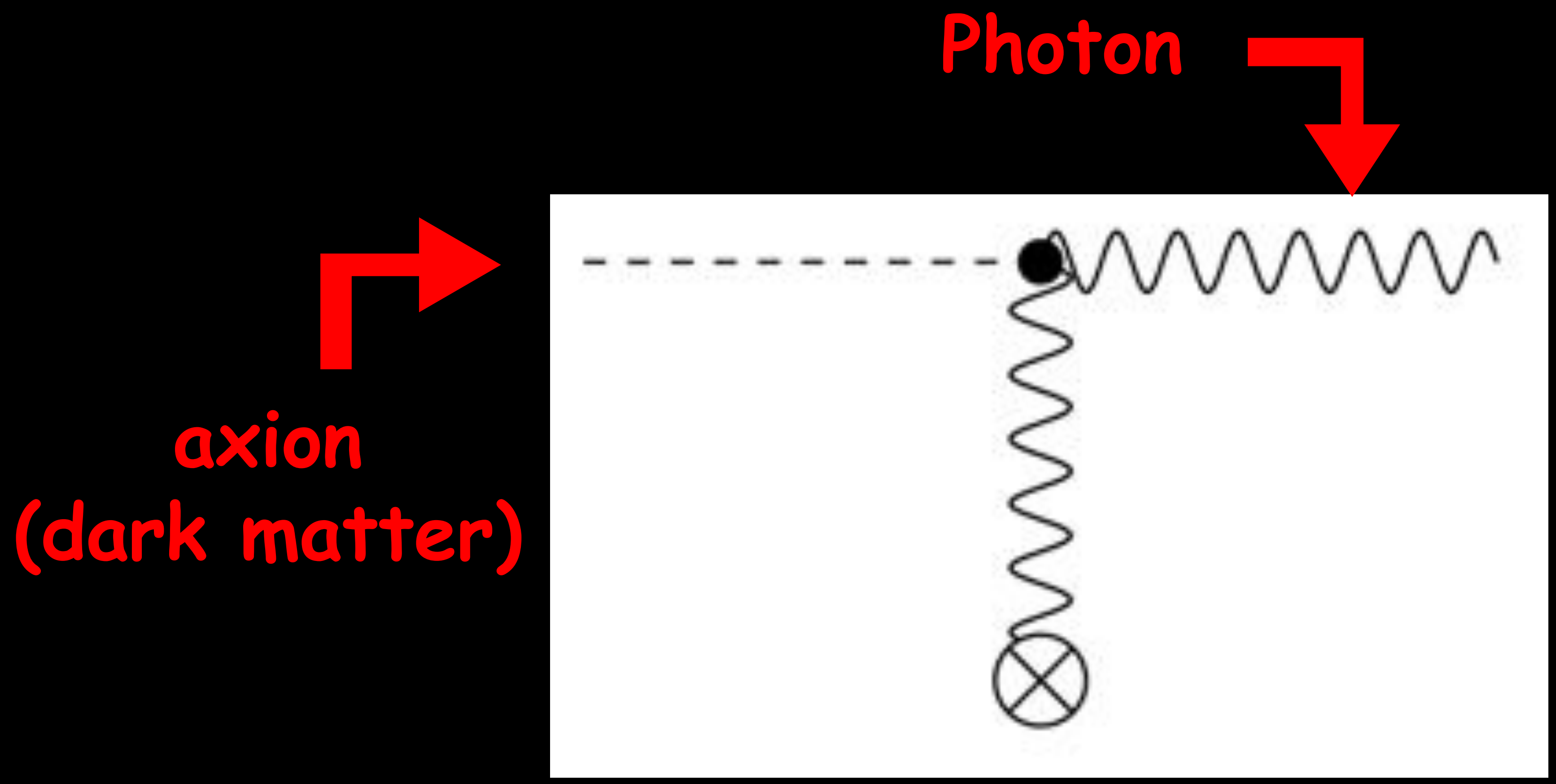
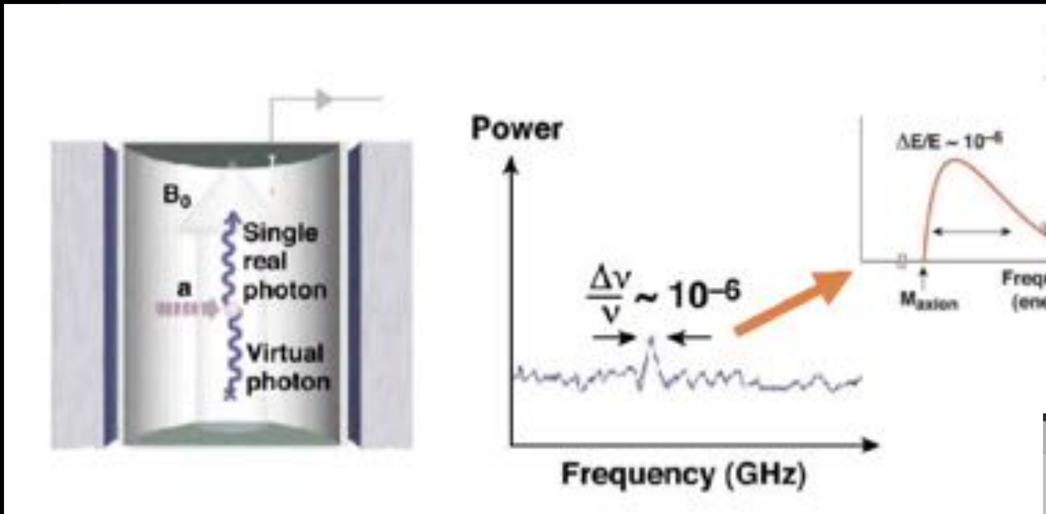


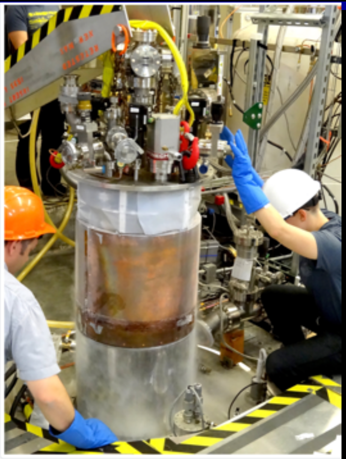
Searching Axion DM

- Photon Regeneration



Searching for Axion DM





The ADMX insert being extracted from the magnet bore for upgrades. The mist pouring off the edges is air condensing on the cryogenic surface as the insert warms.

Photo Credit: Rakshya Khatiwada, UW

https://depts.washington.edu/admx/gallery.shtml

Going Quantum:HAYSTAC

A quantum-enhanced search for dark matter axions

K. M. Backes,[1,*] D. A. Palken,[2,3,*] S. Al Kenany,[4] B. M. Brubaker,[2,3] S. B. Cahn,[1] A. Droster,[4] Gene C. Hilton,[5] Sumita Ghosh,[1] H. Jackson,[4] S. K. Lamoreaux,[1] A.F. Leder,[4] K. W. Lehnert,[2,3,5] S. M. Lewis,[4] M. Malnou,[2,5] R. H. Maruyama,[1] N. M. Rapidis,[4] M. Simanovskaia,[4] Sukhman Singh,[1] D. H. Speller,[1] I. Urdinaran,[4] Leila R. Vale,[5] E. C. van Assendelft,[1] K. van Bibber,[4] and H. Wang[1]

[1]*Department of Physics, Yale University, New Haven, Connecticut 06511, USA*
[2]*JILA, National Institute of Standards and Technology and the University of Colorado, Boulder, Colorado 80309, USA*
[3]*Department of Physics, University of Colorado, Boulder, Colorado 80309, USA*
[4]*Department of Nuclear Engineering, University of California Berkeley, California 94720, USA*
[5]*National Institute of Standards and Technology, Boulder, Colorado 80305, USA*

https://arxiv.org/pdf/2008.01853.pdf

Sensitivity

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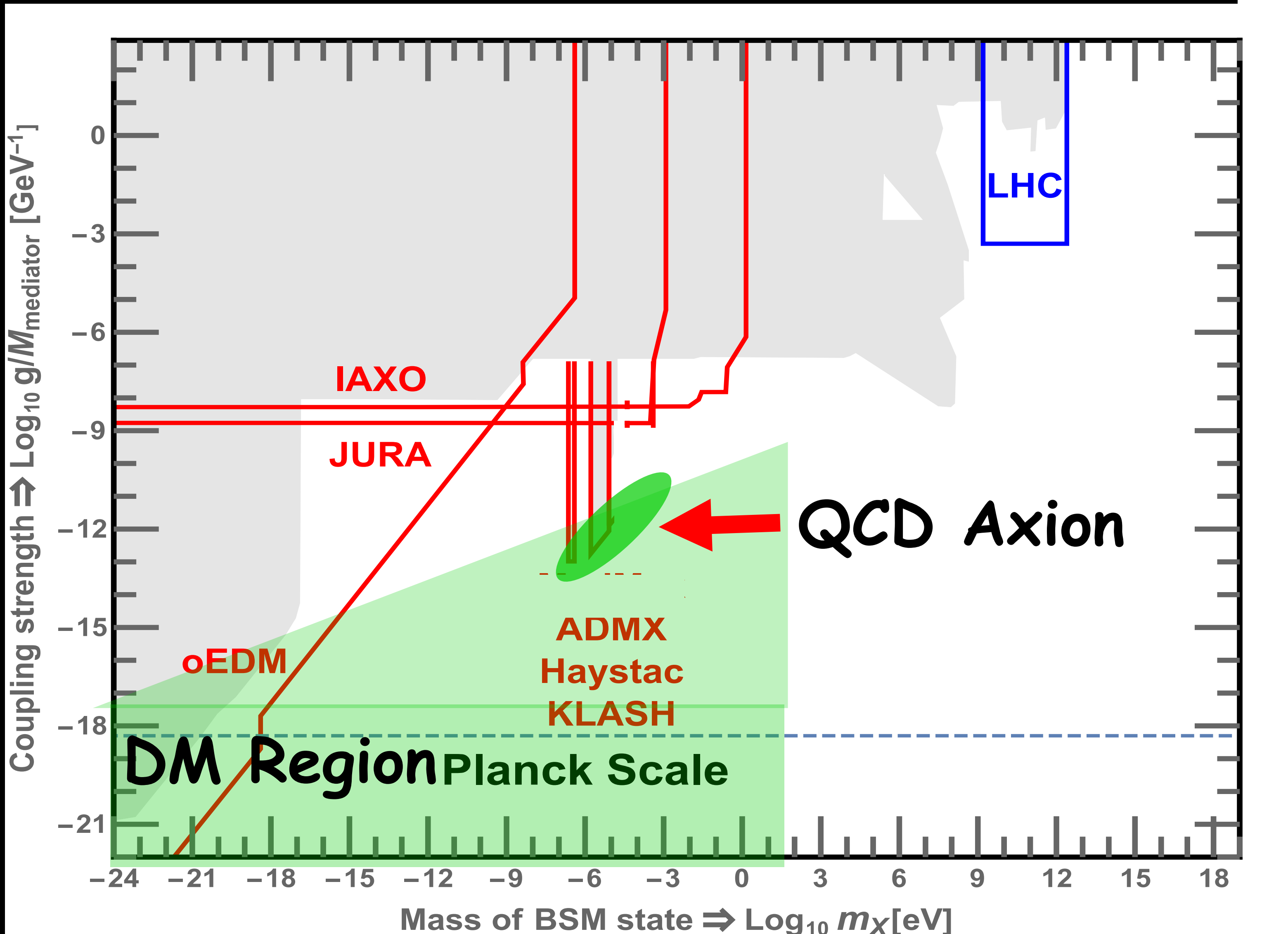
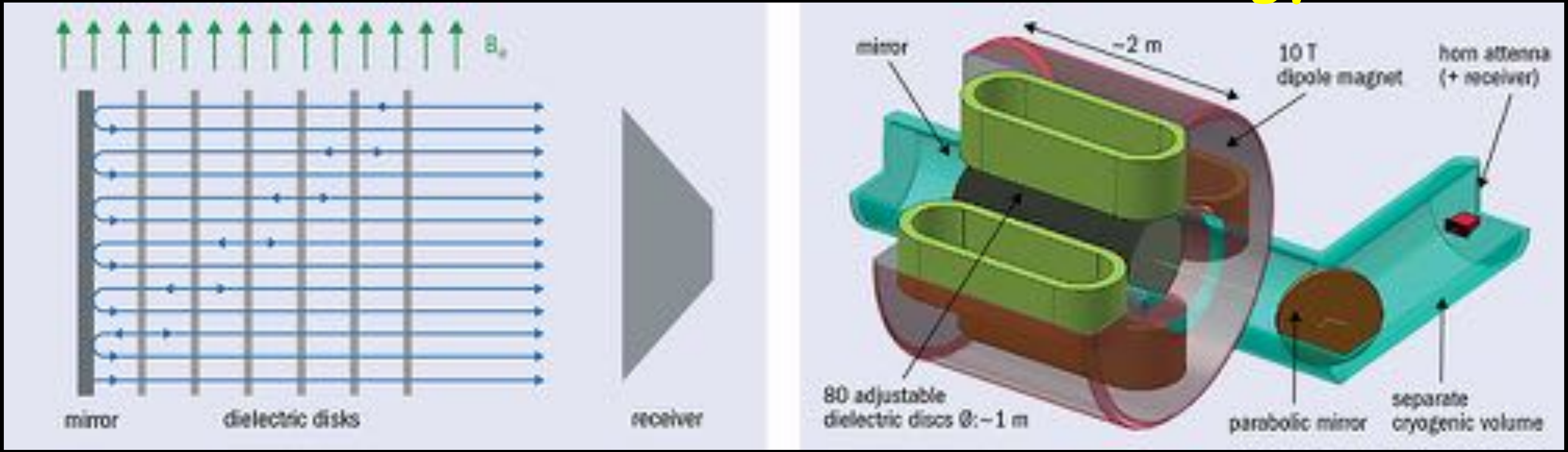
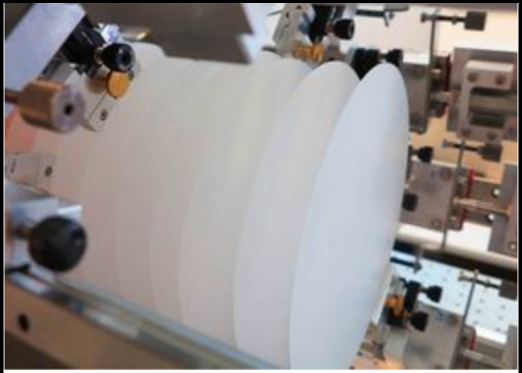


Going to higher masses

MadMax@Munich/DESY
Uses resonant dish antenna strategy!



https://cerncourier.com/a/search-for-wisps-gains-momentum/



Testaufbau des MADMAX-Experiments: Der Photonenanteil der Axionen erzeugt beim Übergang von Luft zum Material der Scheiben Radiowellen, die sich messen lassen. (Foto: MADMAX Collaboration)

https://www.mpp.mpg.de/en/research/astroparticle-physics-and-cosmology/dark-matter-experiments/madmax-searching-for-axion-dark-matter

Sensitivity

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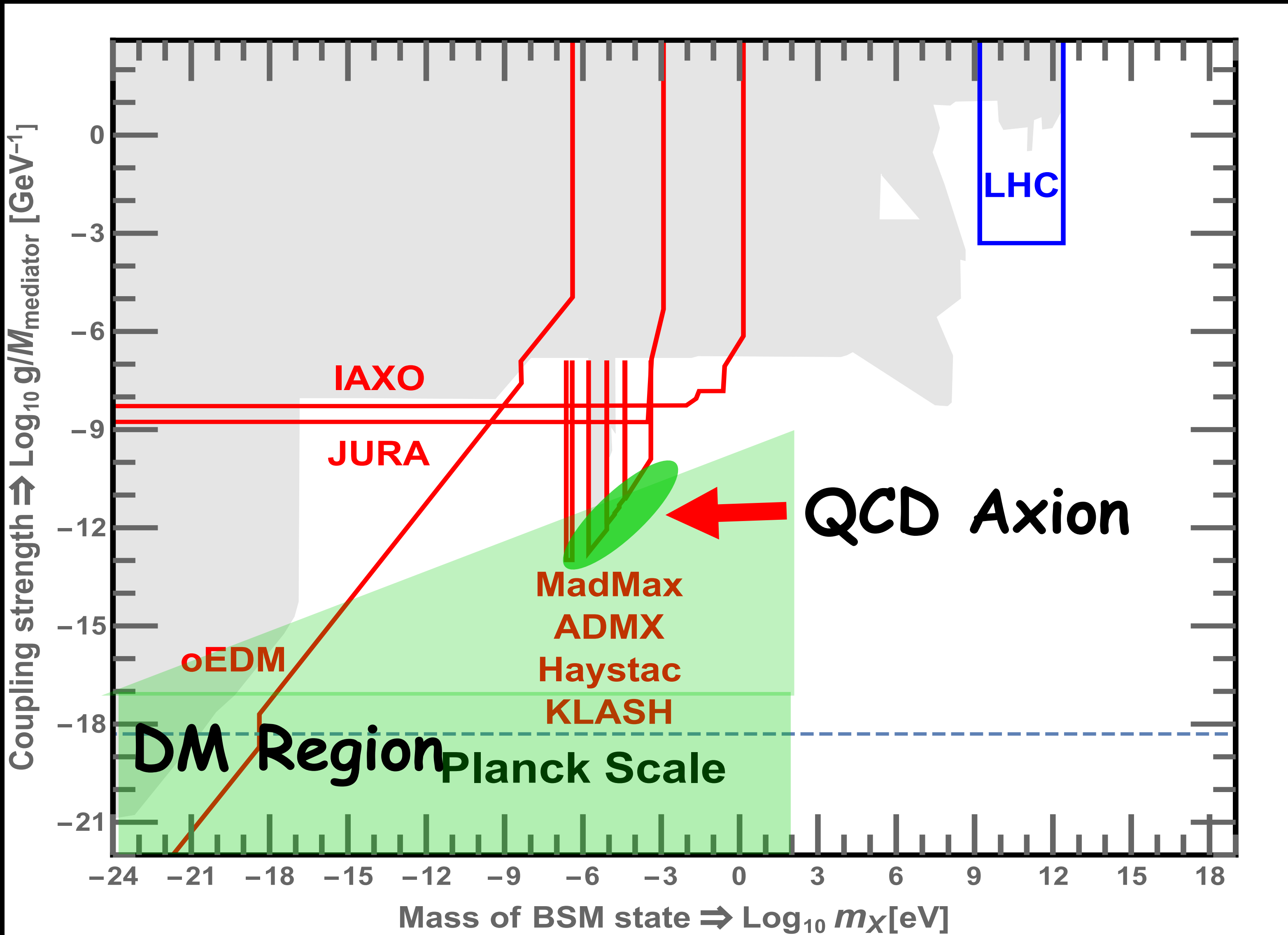
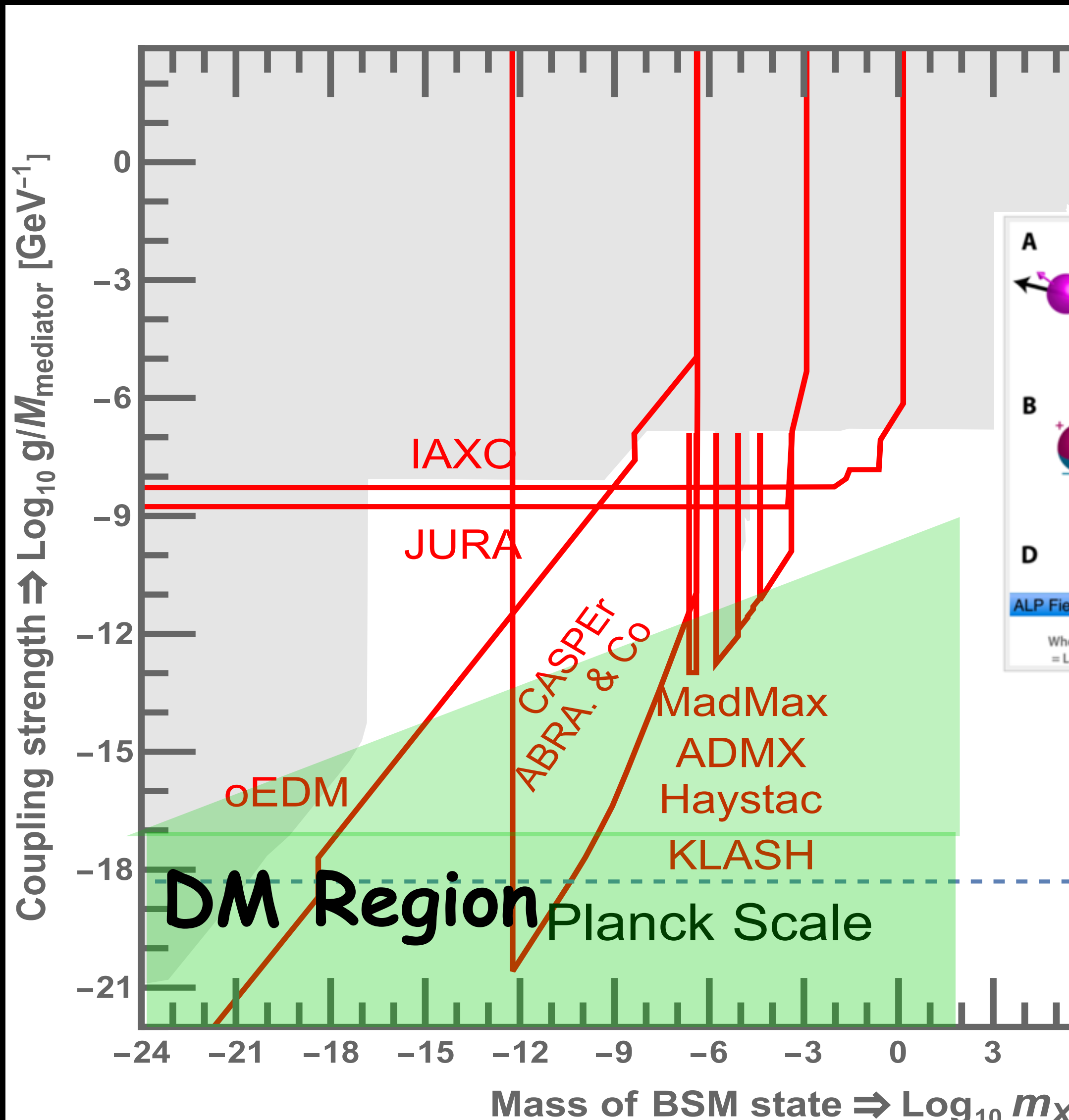
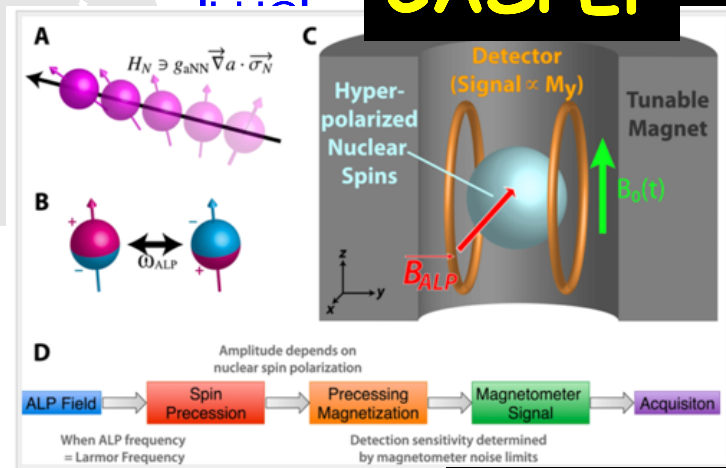


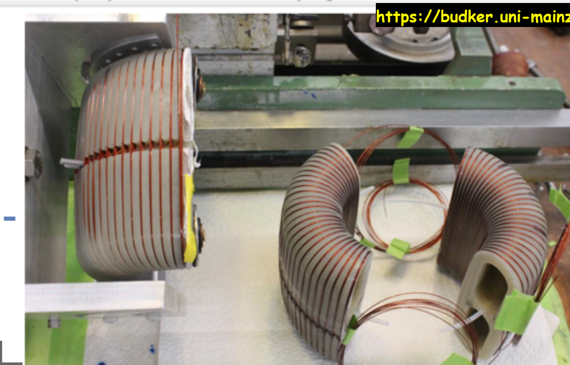
Sensitivity



CASPEr



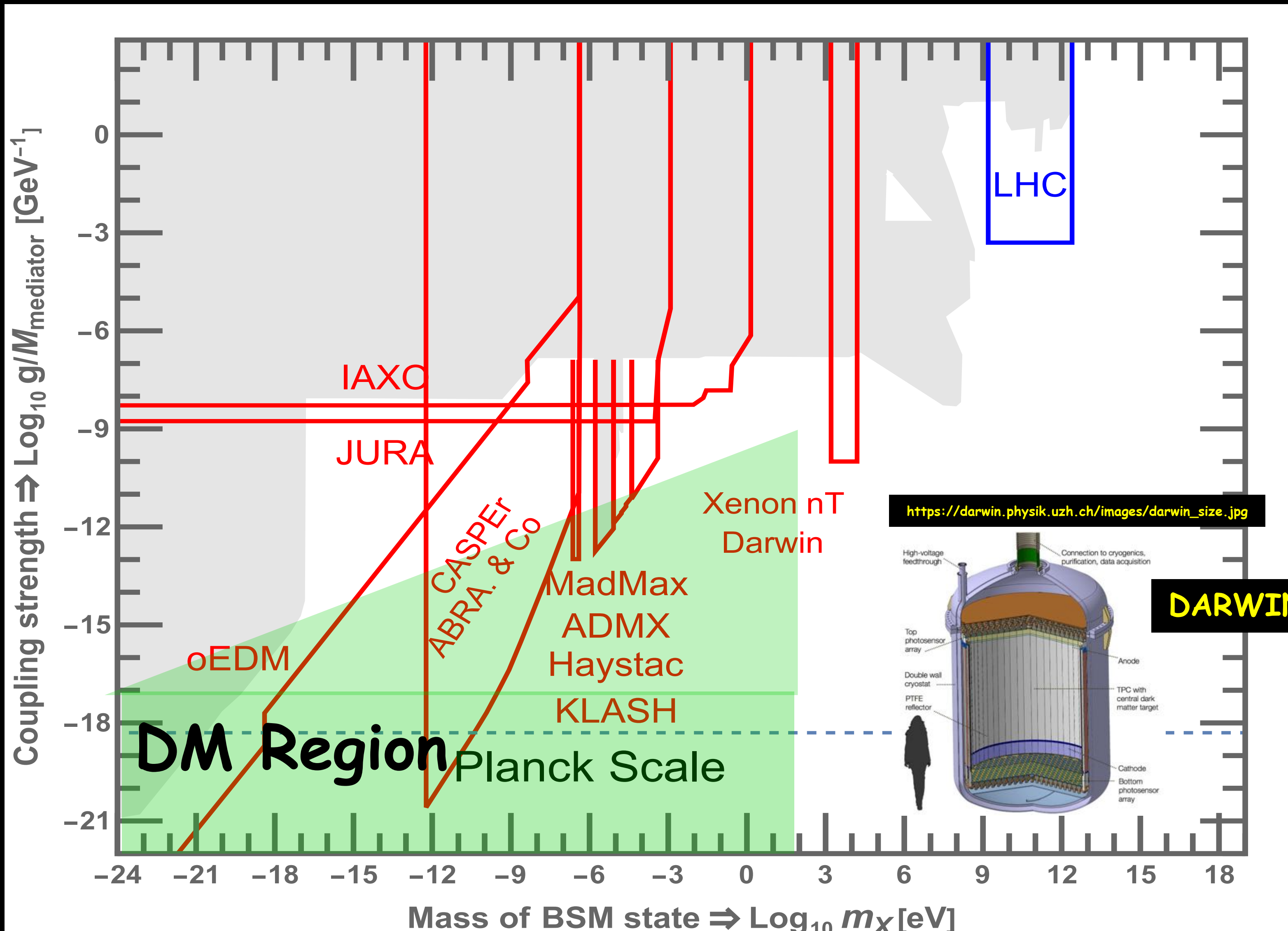
https://budker.uni-mainz.de/?page_id=7



ABRACADABRA

https://abracadabra.mit.edu

Sensitivity: WIMP DM detectors



Search for Hidden Particls = SHiP

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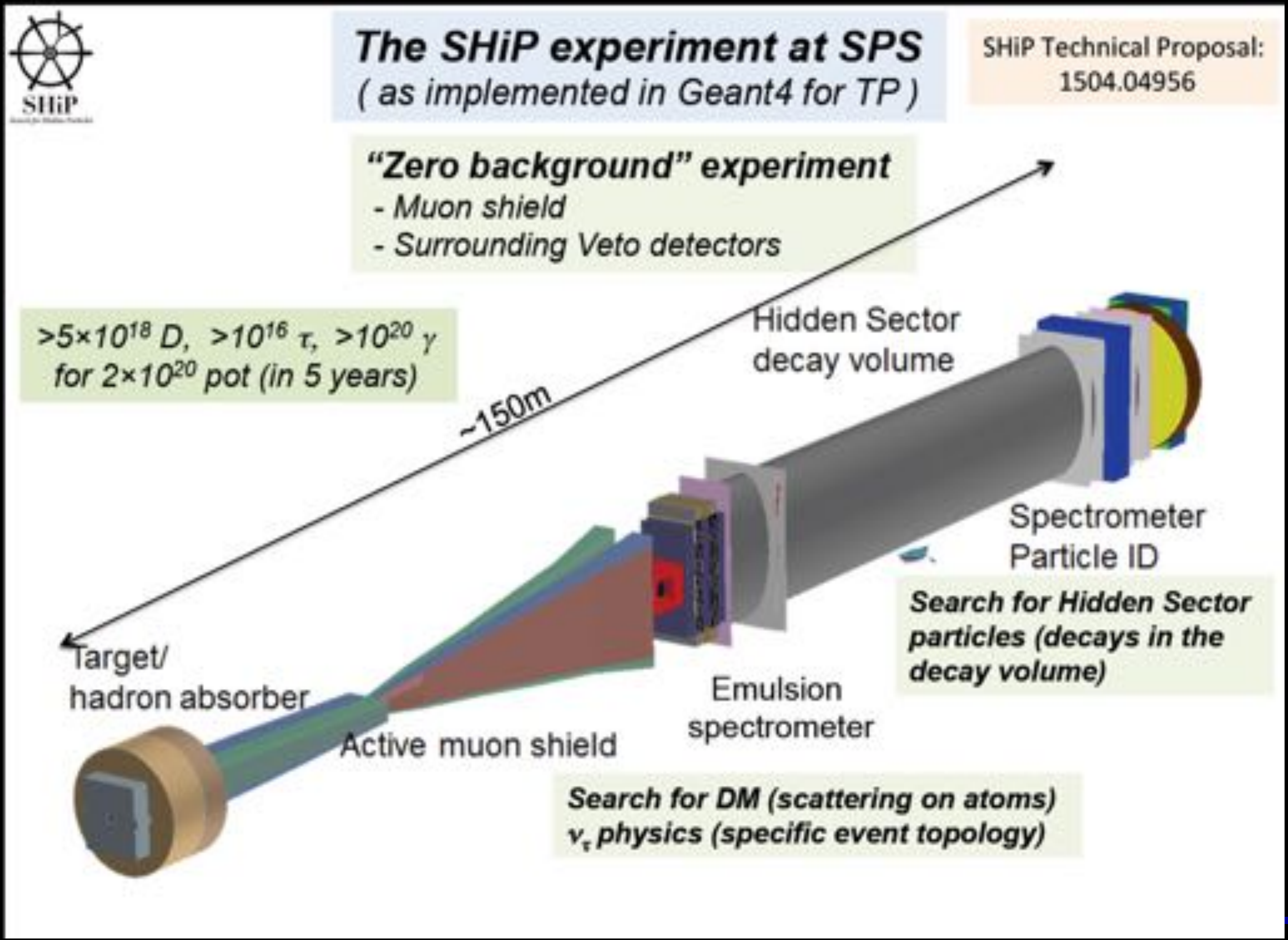
Heidelberg University



A theorist's picture...

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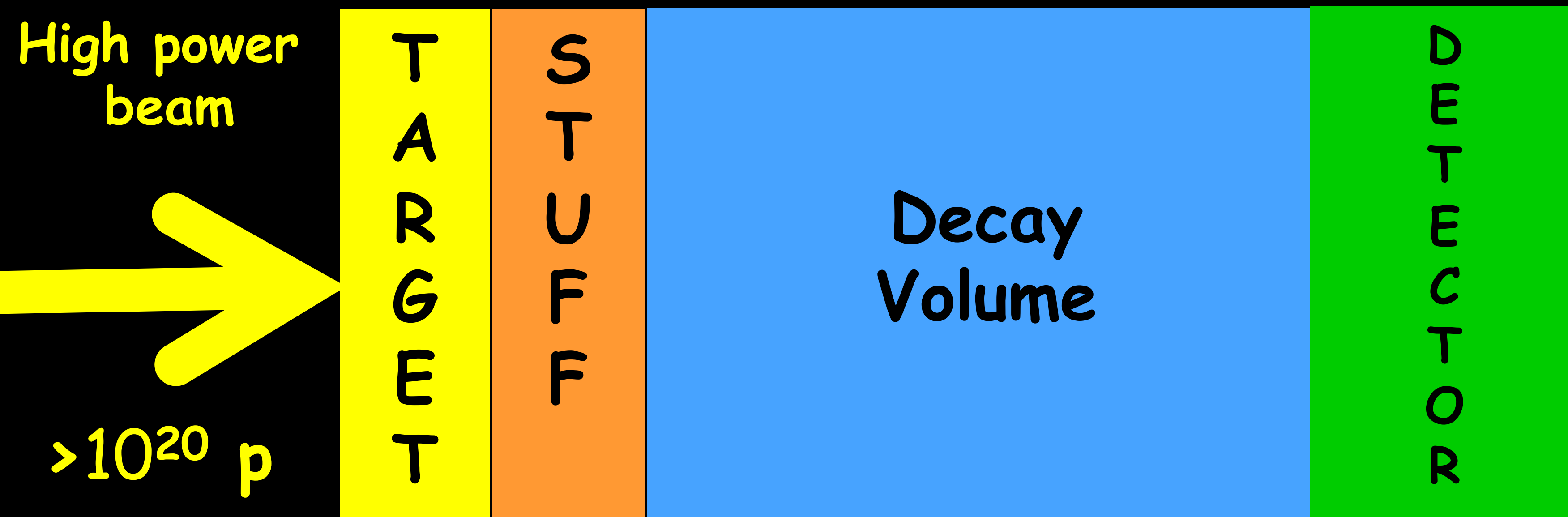

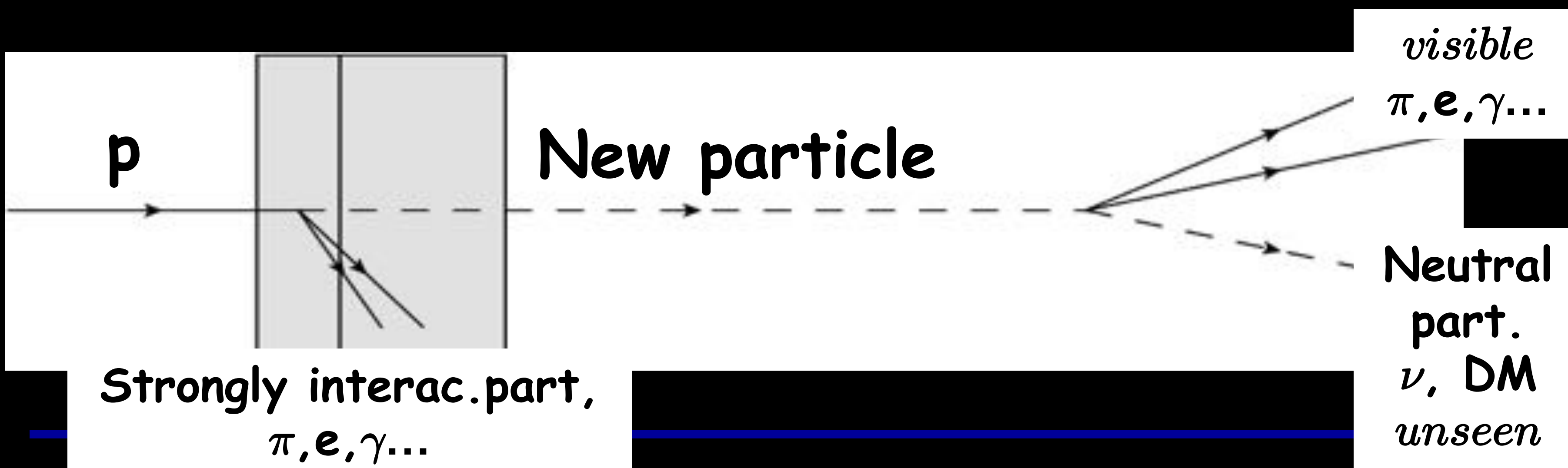

A theorist's picture...

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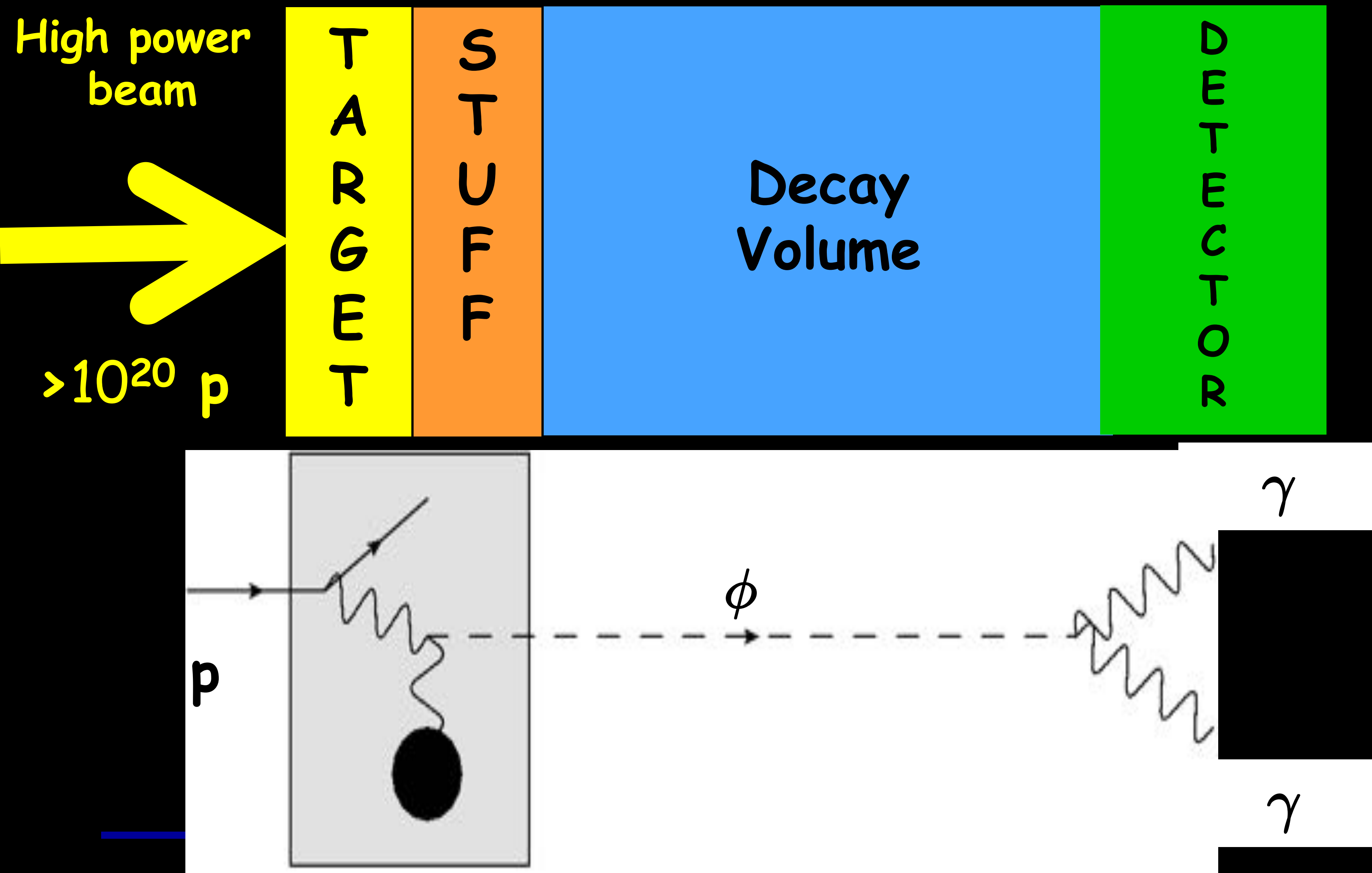

SHiP + NA62+, NA64+ and KLEVER

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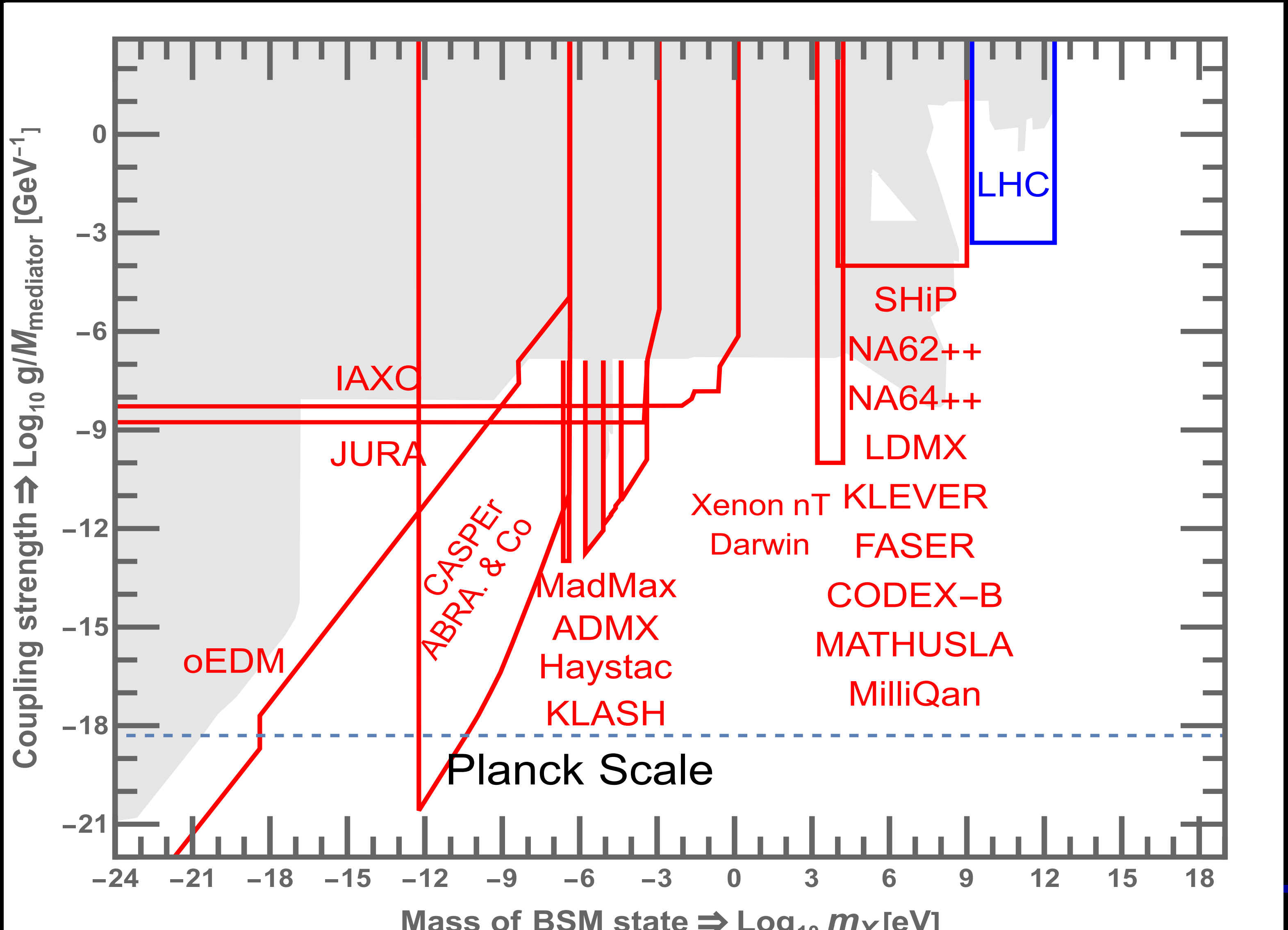

“Seeing” the dark stuff NA 64+

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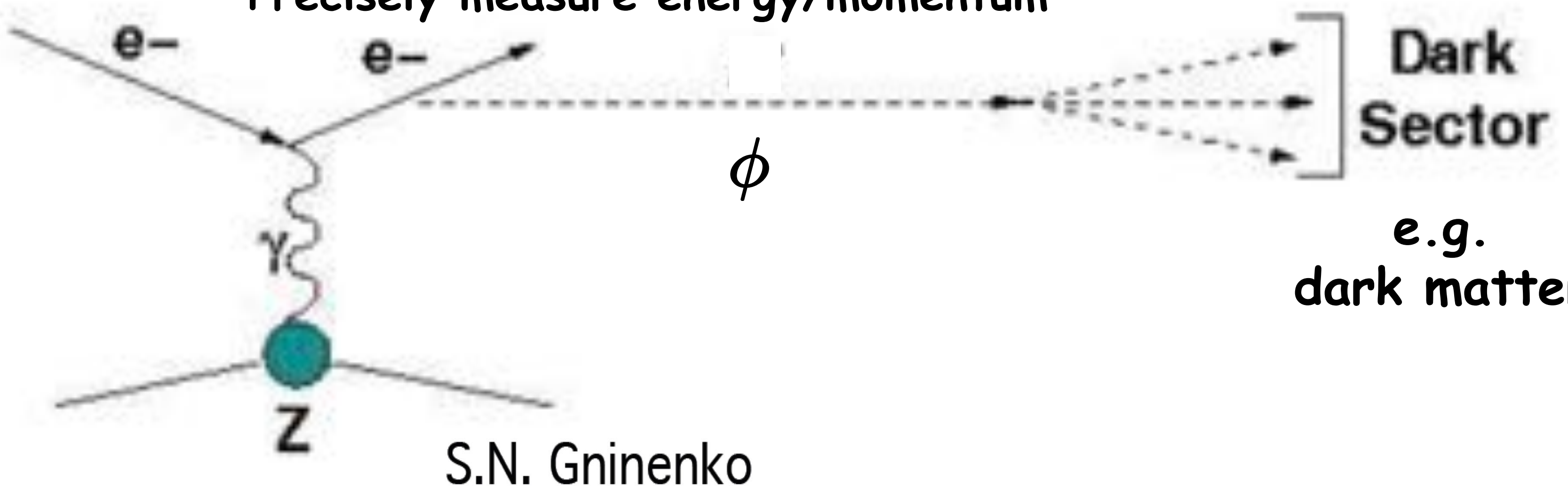
$$\mathcal{L} \supset \frac{\partial_\mu \phi}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$$

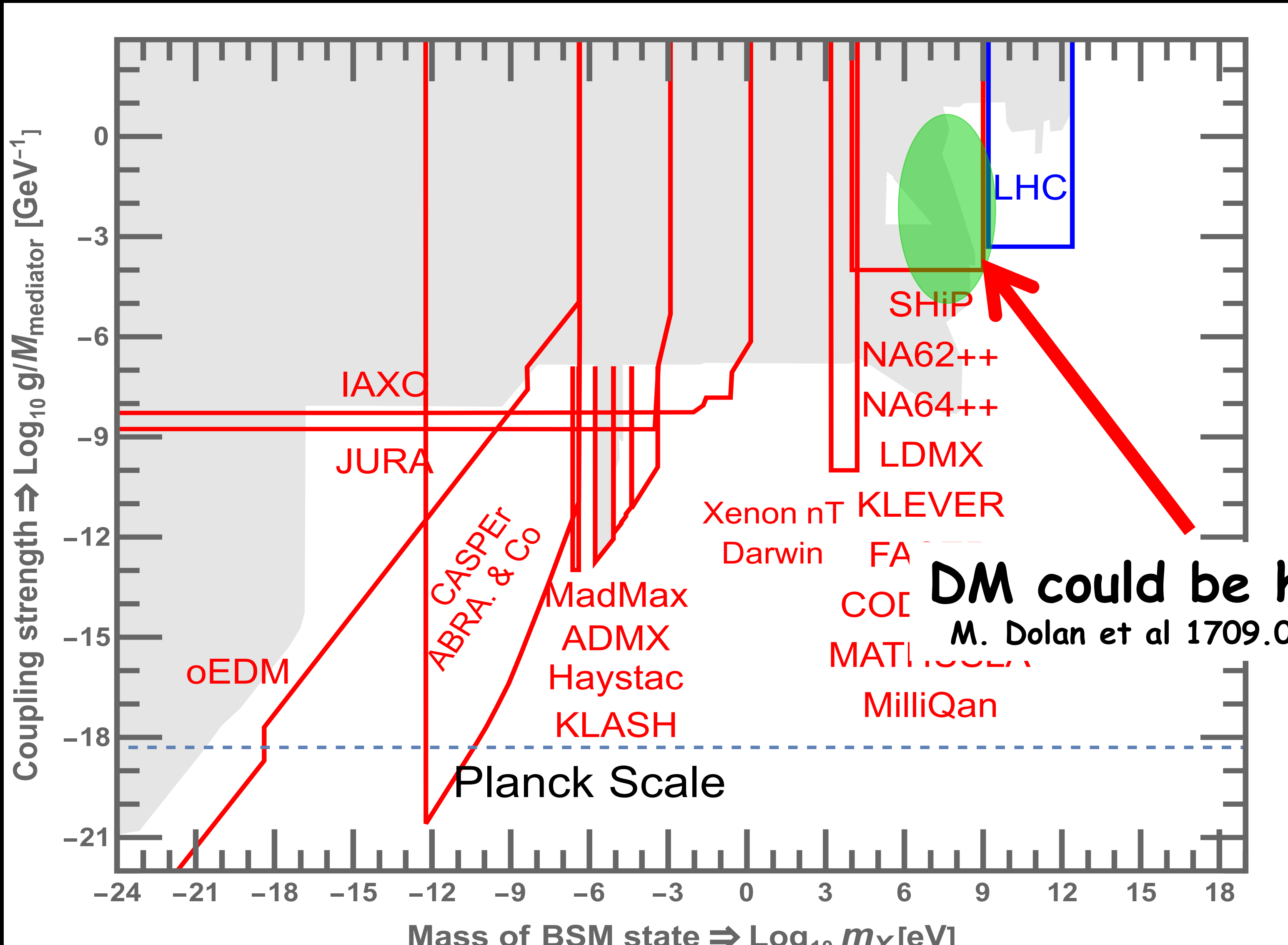
Precisely measure energy/momentum



e.g.
dark matter

+ “dark matter” detector @ SHiP

Messengers for dark matter?



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Long Lived Particles @ LHC

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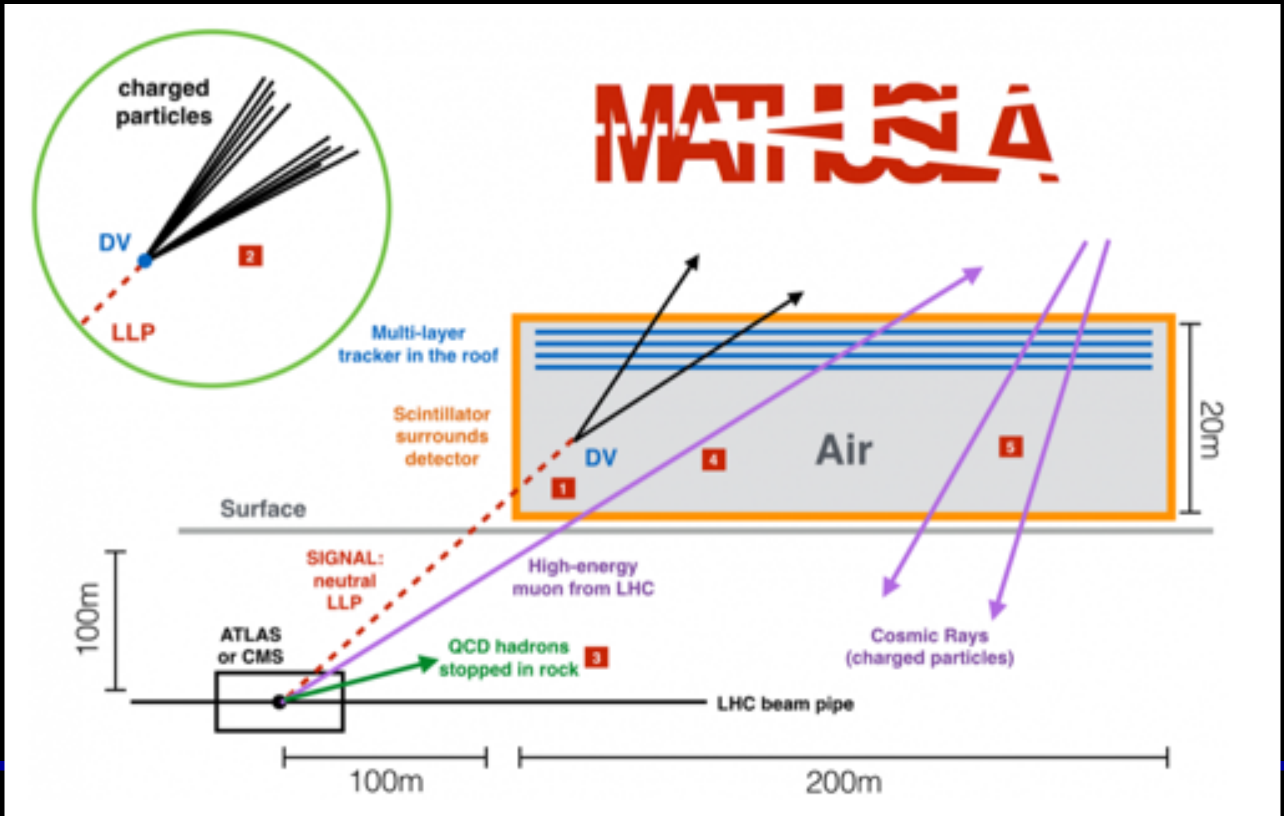
- Idea: Look for very long lived particles produced in LHC collissions
- Recent proposals:

  MATHUSLA, FASER, CodexB, MilliCan



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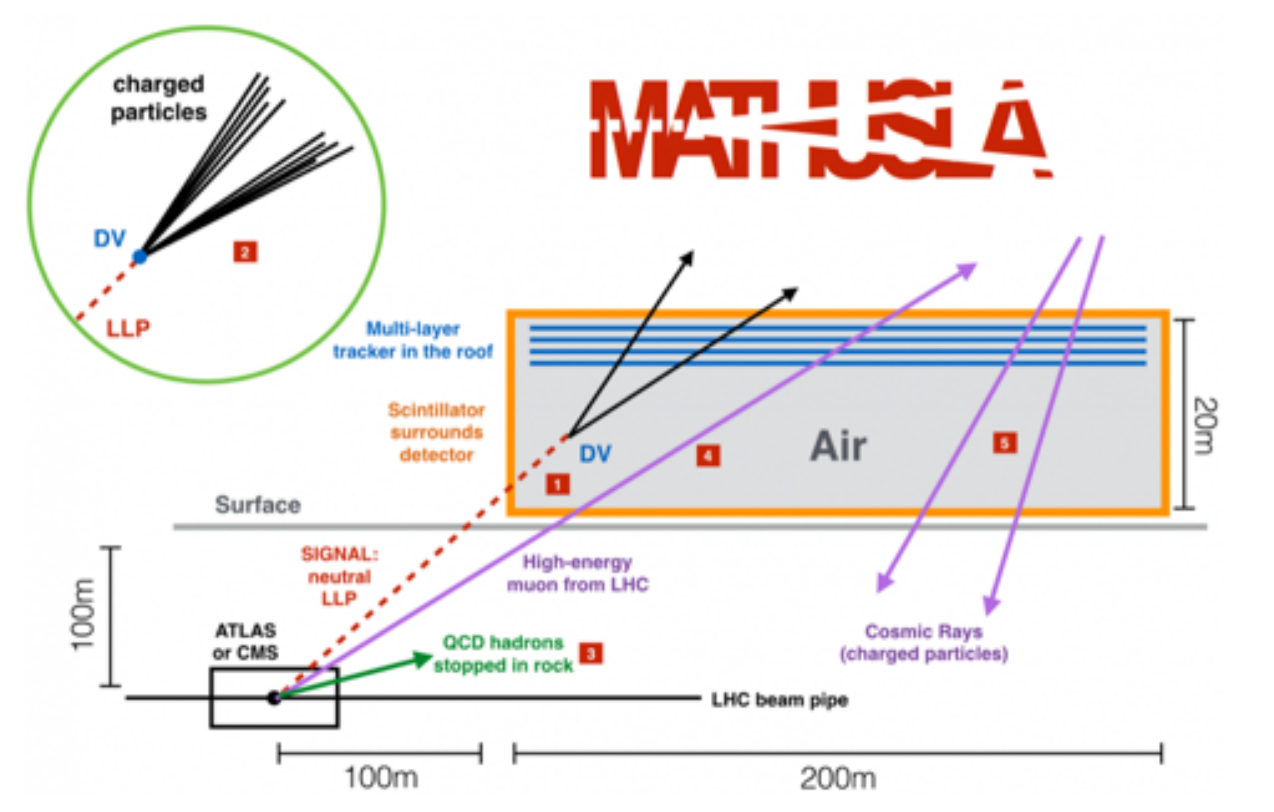

FASER

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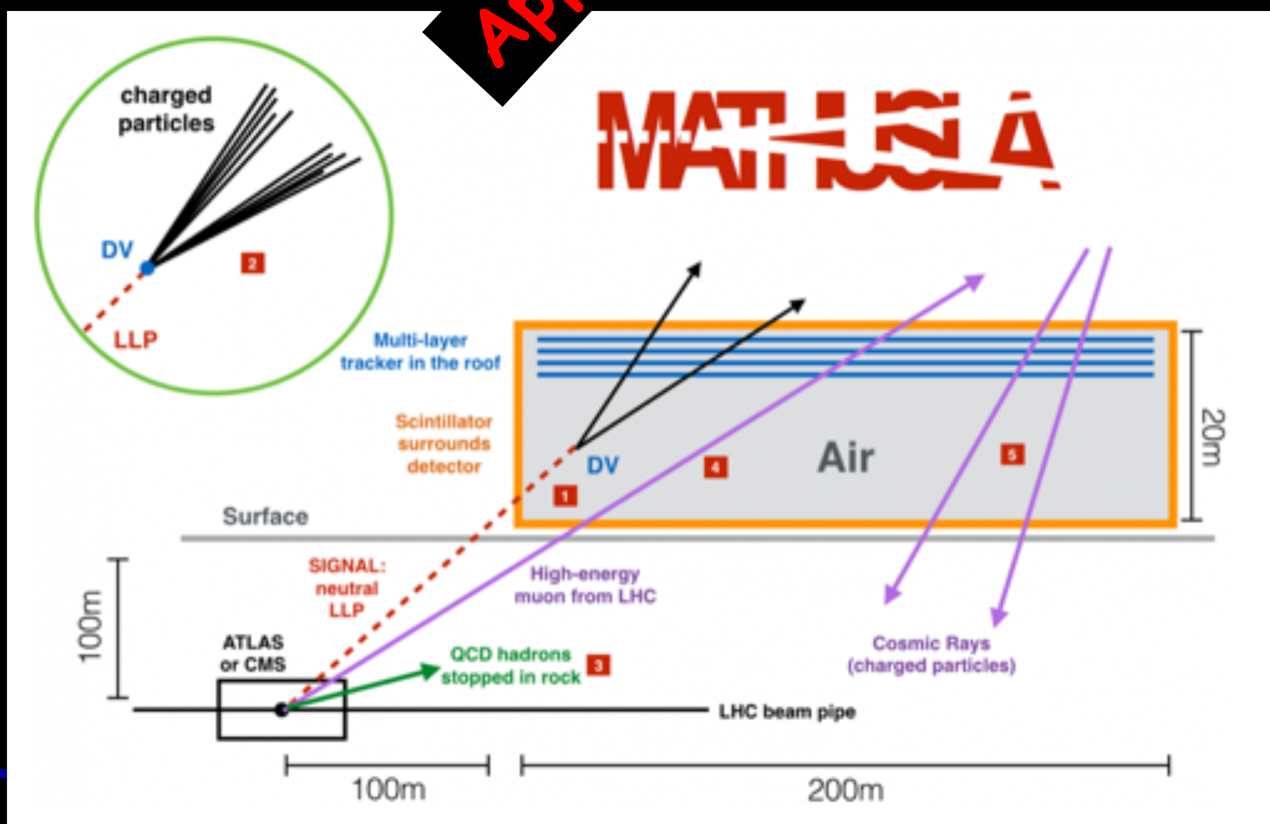
Heidelberg University

Long Lived Particles @ LHC

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

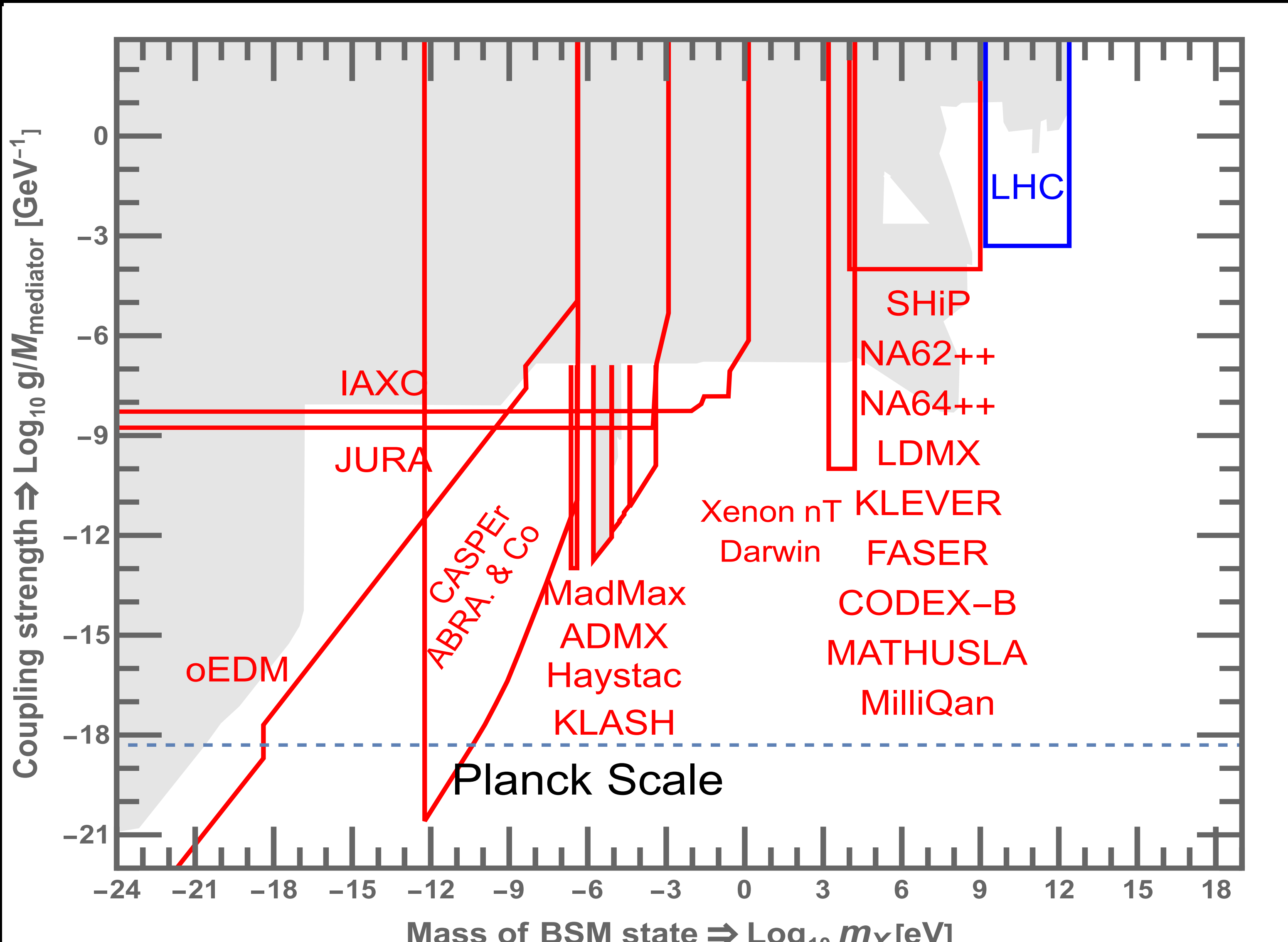
MATHUSLA, F R, CodexB, MilliCan

Approved

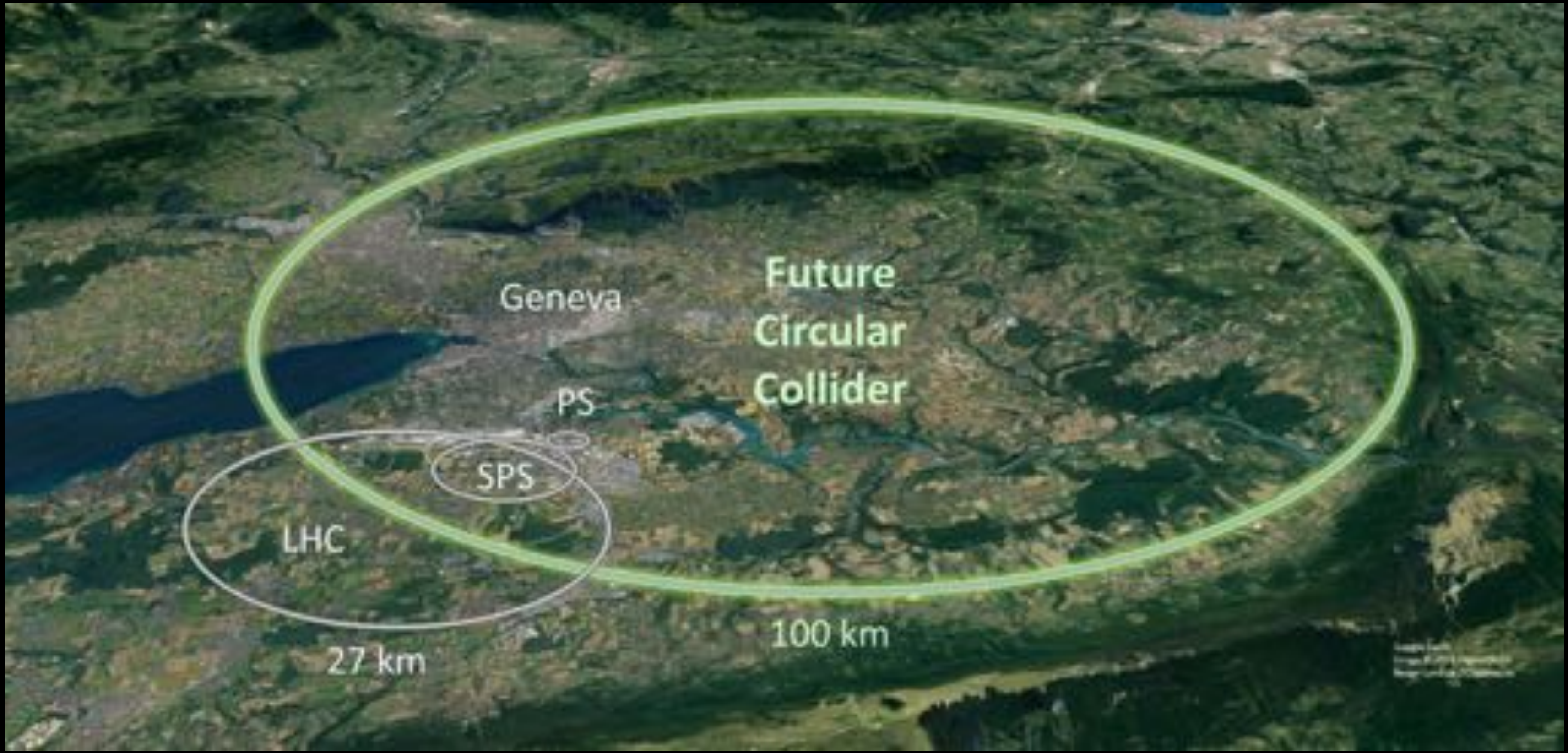


FASER

Long Lived Particle searches also explore MeV-GeV region

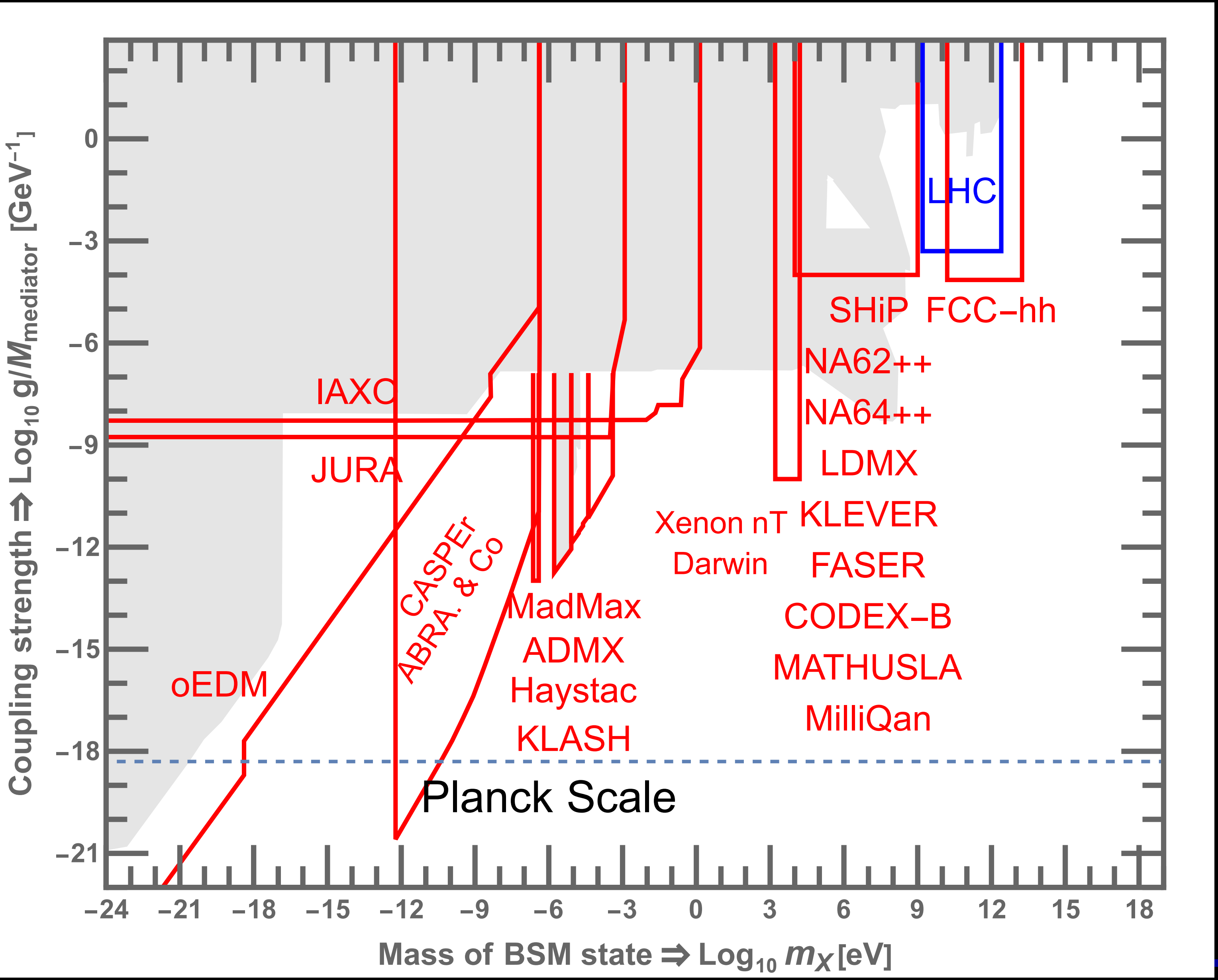


Future Circular Collider



https://home.cern/science/accelerators/future-circular-collider

Energy ~100 TeV



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Coupling strength ⇒ Log10 g/Mmediator [GeV-1]
Mass of BSM state ⇒ Log10 mX [eV]
0
−3
−6
−9
−12
−15
−18
−21
−24
−21
−18
−15
−12
−9
−6
−3
0
3
6
9
12
15
18
IAXO
JURA
oEDM
CASPEr
ABRA. & Co
MadMax
ADMX
Haystac
KLASH
Xenon nT
Darwin
LHC
SHiP
FCC−hh
NA62++
NA64++
LDMX
KLEVER
FASER
CODEX−B
MATHUSLA
MilliQan
Planck Scale

Flavor searches

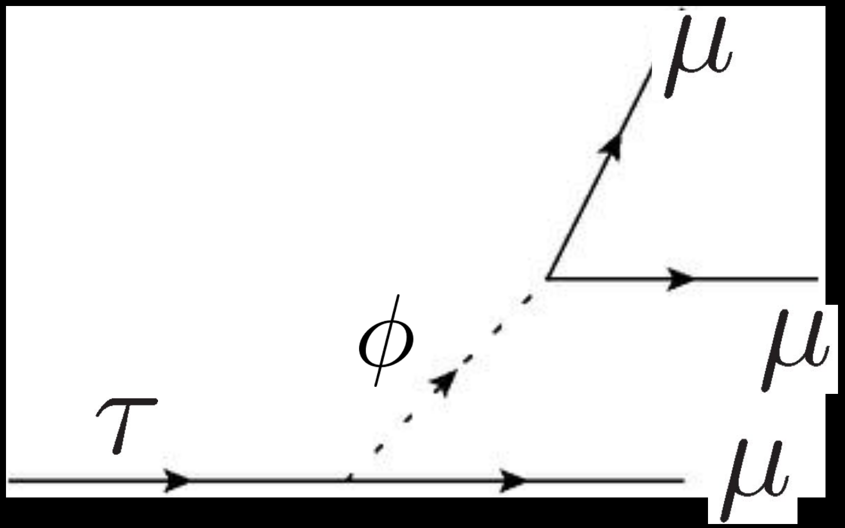
- Rare decays:

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

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

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

  $\eta \rightarrow \mu^+ + e^-$ RedTop



➔ Probe 1-1000TeV scales

Where do we explore...

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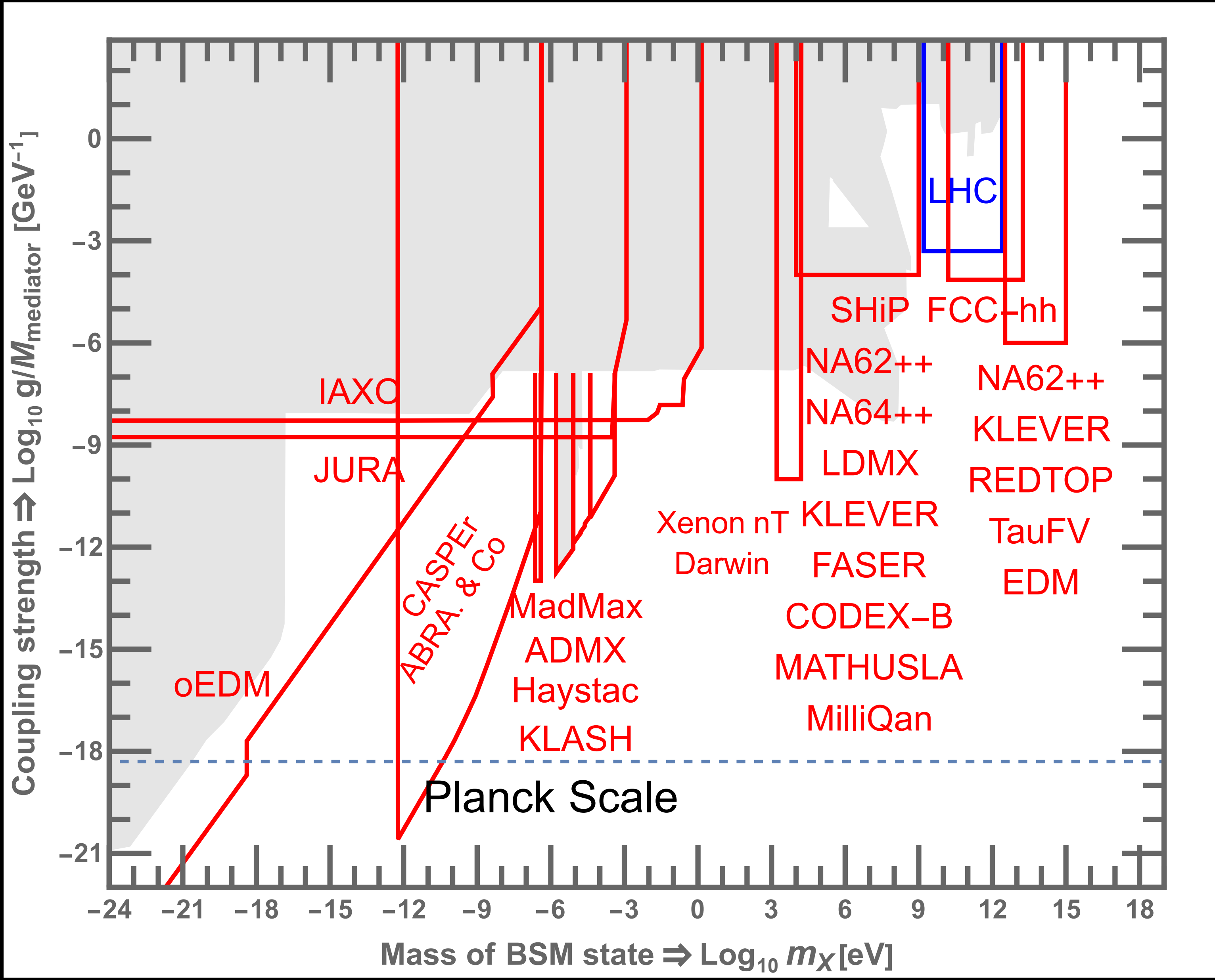

Much more to come... for example

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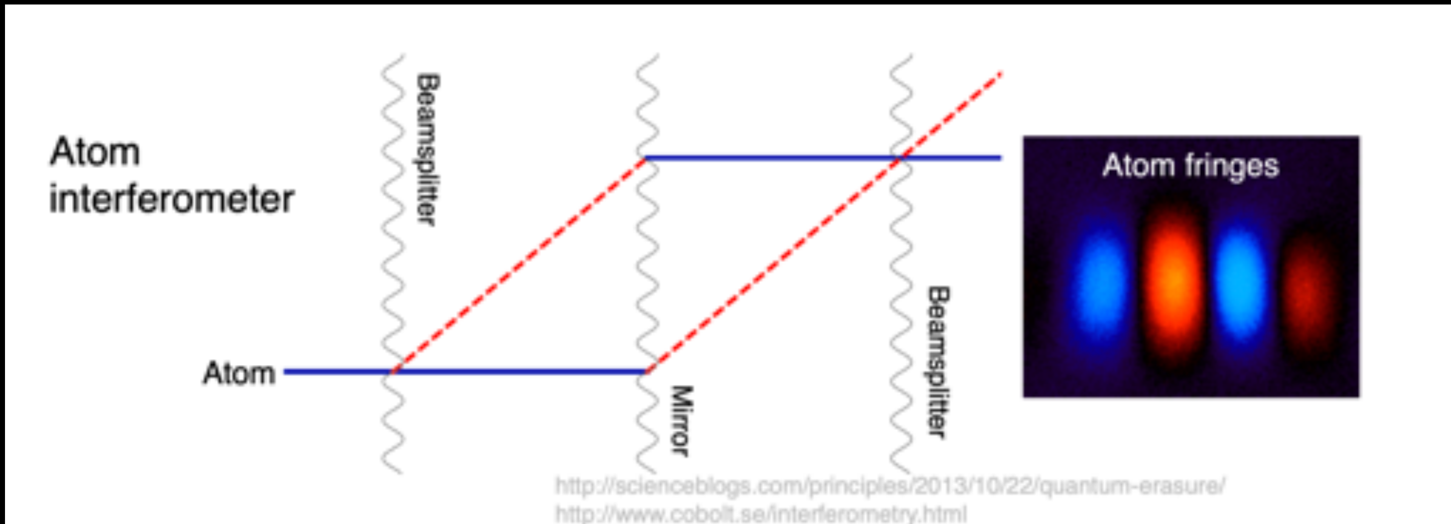
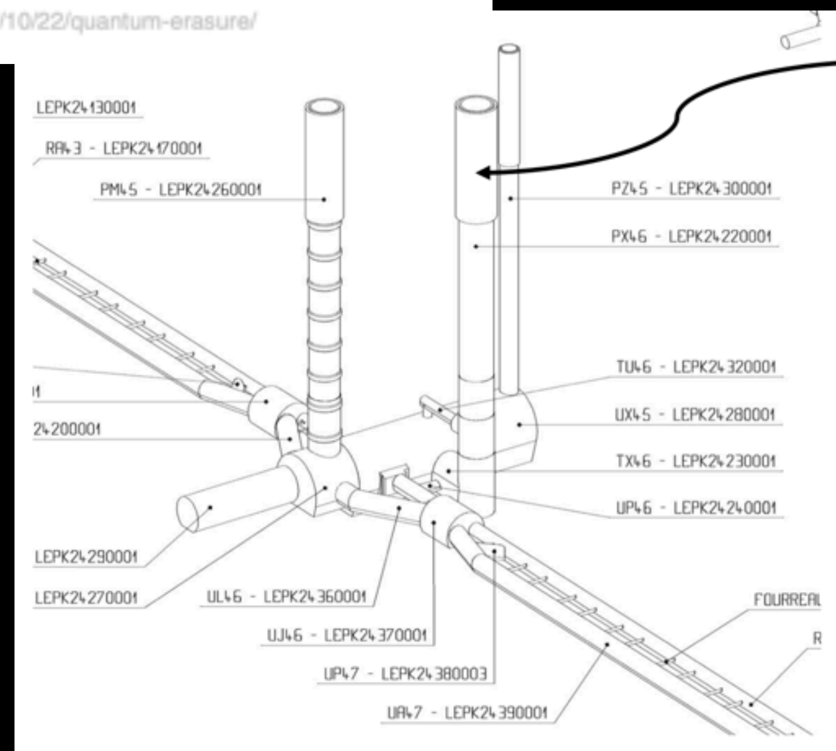
AION



From O. Buchmueller @ PBC 2021



From O. Buchmueller @ PBC 2021

Theory Experiments: The FIPC

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Physics Beyond Colliders

https://pbc.web.cern.ch/fpc-mandate

Feebly Interacting Particles Physics Centre

Introduction

Small numbers are ubiquitous in Nature. Prominent examples of small numbers are:

1. Higgs mass: $m^2(\text{Higgs})/m^2(\text{Planck}) = 10^{-33}$
2. theta(QCD): $\text{theta}_{QCD} < 10^{-10}$
3. cosmological constant: rho ~ 10^{-120} m^4 (Planck)
4. matter-antimatter asymmetry: $(n_B - n_{antiB})/n_{gamma} = 10^{-9}$
5. DM abundance: $n_{DM}/n_{gamma} \sim 10^{-12}\, m_{DM}/\text{TeV}$
6. primordial density fluctuations: delta rho/rho ~ 10^{-5}
7. flavor (all the Yukawa's couplings): eg: y(electron) /y(top) ~ 10^{-6}.

New Physics may interact with the SM particles through small, very feeble, dimensionless or dimensional couplings. These are Feebly-Interacting Particles or FIPs. The smallness of the couplings can be due either to an approximate symmetry slightly broken or to a large separation of scales (as data seem to suggest).

CERN - 24 February 2021

**Feebly-Interacting Particles:
FIPs 2020 Workshop Report**

P. Agrawal[1], M. Bauer[2,a], J. Beacham[3,a], A. Berlin[4], A. Boyarsky[5], S. Cebrian[6], X. Cid-Vidal[7], D. d'Enterria[3], A. De Roeck[3,a], M. Drewes[8], B. Echenard[9], M. Giannotti[10], G. F. Giudice[3,a], S. Gninenko[11], S. Gori[12,13], E. Goudzovski[14], J. Heeck[15], P. Hernandez[16,a], M. Hostert[24,25,38], I. Irastorza[6,a], A. Izmaylov[11], J. Jaeckel[17,a], F. Kahlhoefer[18], S. Knapen[3,b], G. Krnjaic[19,20,a], G. Lanfranchi[21,a,b,*], J. Monroe[22,a], V. Martinez-Outschoorn[23], J. Lopez-Pavon[16], S. Pascoli[2,39,a], M. Pospelov[24,25], D. Redigolo[3,26,b], A. Ringwald[27], O. Ruchayskiy[28] J. Ruderman[4,27,a], H. Russell[3], J. Salfeld-Nebgen[29], P. Schuster[30,a], M. Shaposhnikov[31,a], L. Shchutska[31], J. Shelton[32,a], Y. Soreq[33] Y. Stadnik[34], J. Swallow[14], K. Tobioka[35,36], Y.-D. Tsai[23,37]

Abstract: With the establishment and maturation of the experimental programs searching for new physics with sizeable couplings at the LHC, there is an increasing interest in the broader particle and astrophysics community for exploring the physics of light and feebly-interacting particles as a paradigm complementary to a New Physics sector at the TeV scale and beyond. FIPs 2020 has been the first workshop fully dedicated to the physics of feebly-interacting particles and was held virtually from 31 August to 4 September 2020. The workshop has gathered together experts from collider, beam dump, fixed target experiments, as well as from astrophysics, axions/ALPs searches, current/future neutrino experiments, and dark matter direct detection communities to discuss progress in experimental searches and underlying theory models for FIPs physics, and to enhance the cross-fertilisation across different fields. FIPs 2020 has been complemented by the topical workshop "Physics Beyond Colliders meets theory", held at CERN from 7 June to 9 June 2020. This document presents the summary of the talks presented at the workshops and the outcome of the subsequent discussions held immediately after. It aims to provide a clear picture of this blooming field and proposes a few recommendations for the next round of experimental results.

[a] Member of the Organising Committee of FIPs2020 workshop, https://indico.cern.ch/event/864648/.
[b] Member of the Organising Committee of "PBC meets theory" workshop, https://indico.cern.ch/event/910753/.
[*] Corresponding author, email: Gaia.Lanfranchi@lnf.infn.it

arXiv:2102.12143v1 [hep-ph] 24 Feb 2021

Conclusions

Conclusions

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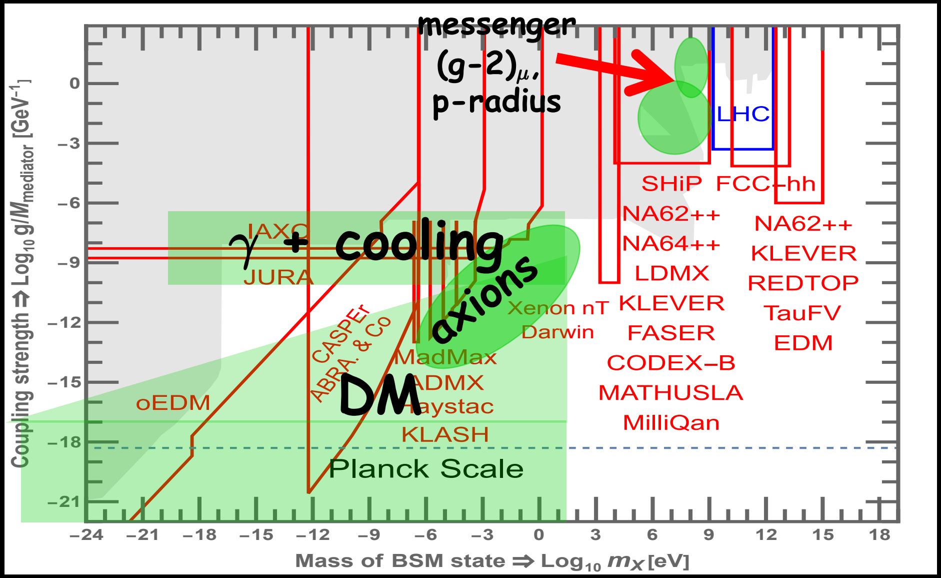
- Exploration for New Physics benefits from both high energy as well as high sensitivity

➔Different experiments complement each other

➔Interesting Hints



Many (more) cool things to explore!

Conclusions

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