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Heidelberg University

Physics Beyond Colliders

Exploring the Fundamental Questions

J. Jaeckel

Huge Thanks to ALL participants of the PBC study!

Many slides, pictures etc from talks at PBC workshops.

Physics Beyond Colliders

Exploring the Fundamental Questions

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J. Jaeckel

Extra special thanks to
Gaia, Babette, Clare, Maxim, Klaus^2, Sasha, Felix, Gunnar, Markus, Jan, Claude and Mike

Many slides, pictures etc from talks at PBC workshops.

Asking the Big Questions

Three Big Open Questions

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- The origin of (our) mass
- The origin of us (baryon asymmetry + $\not{C}\not{P}$)
- Dark Matter

➔ What can we learn with PBC experiments

Understanding
The origin of (our) mass

Our mass

- Only ~1% of the mass of the ordinary matter around us originates from the Higgs mechanism

- ➔ 99% arises from QCD!!

➔ We want to understand confinement and chiral symmetry breaking

Exploring the QCD phase diagram

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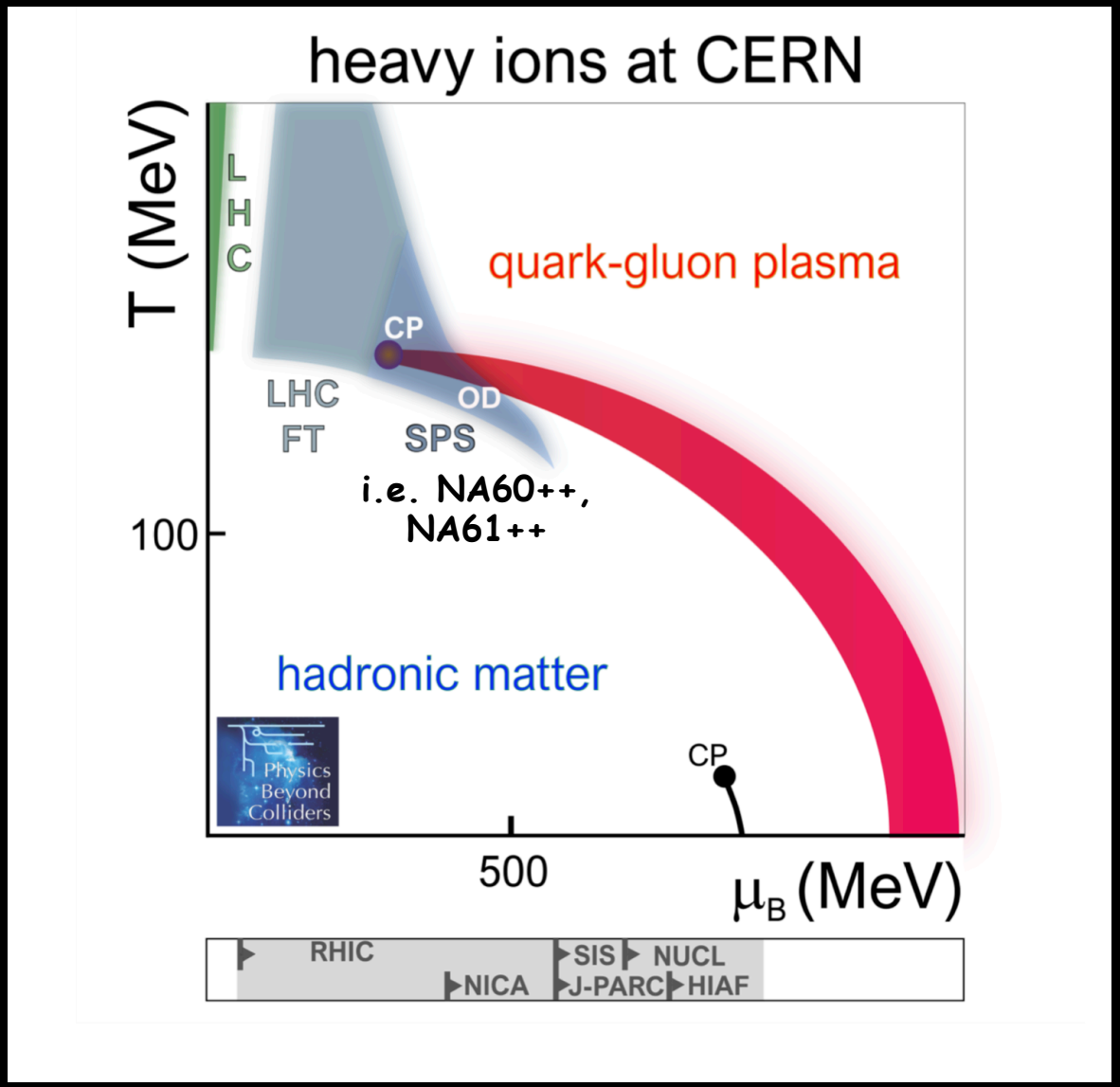

Exploring the QCD phase diagram

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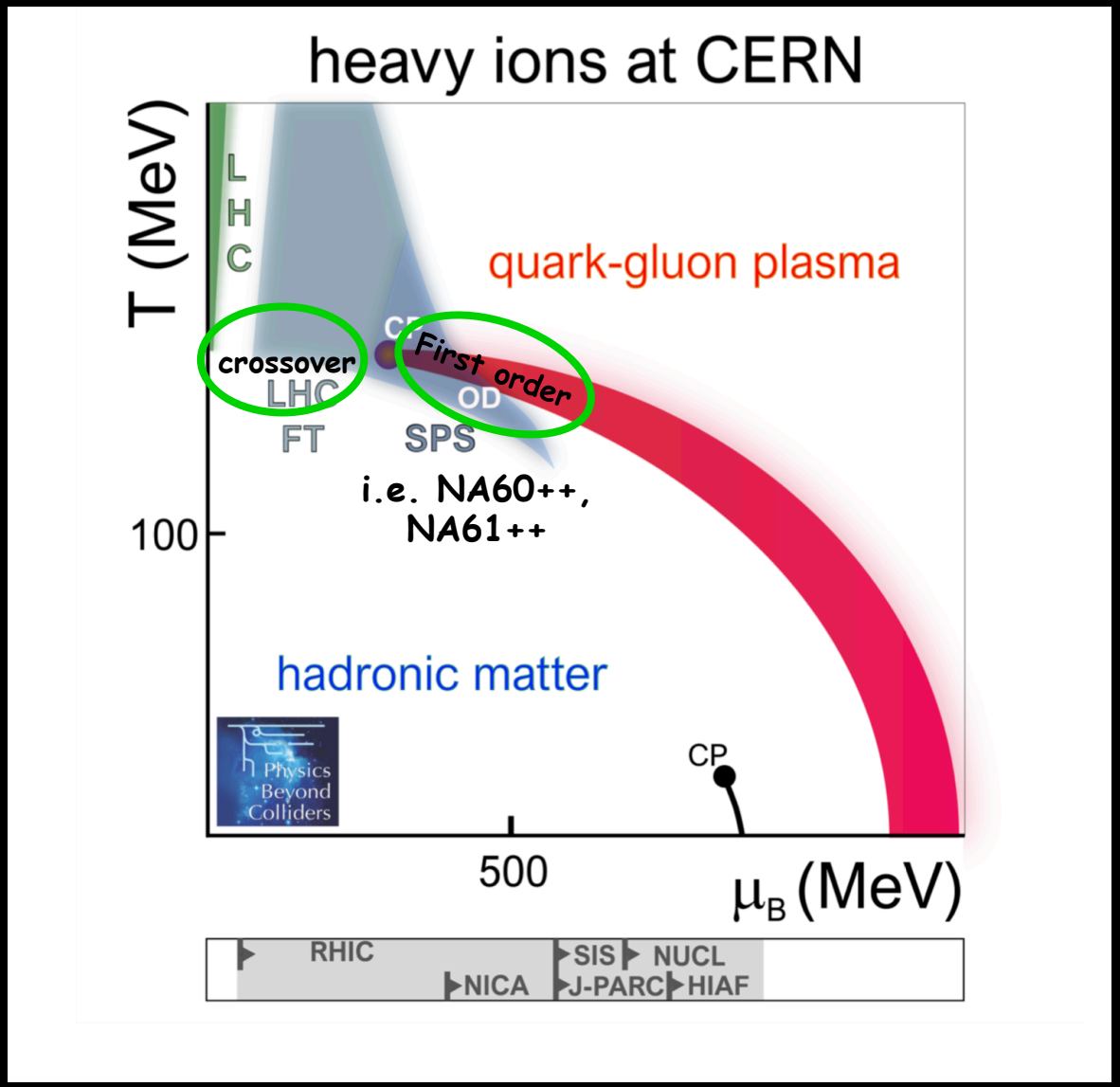

Exploring the QCD phase diagram

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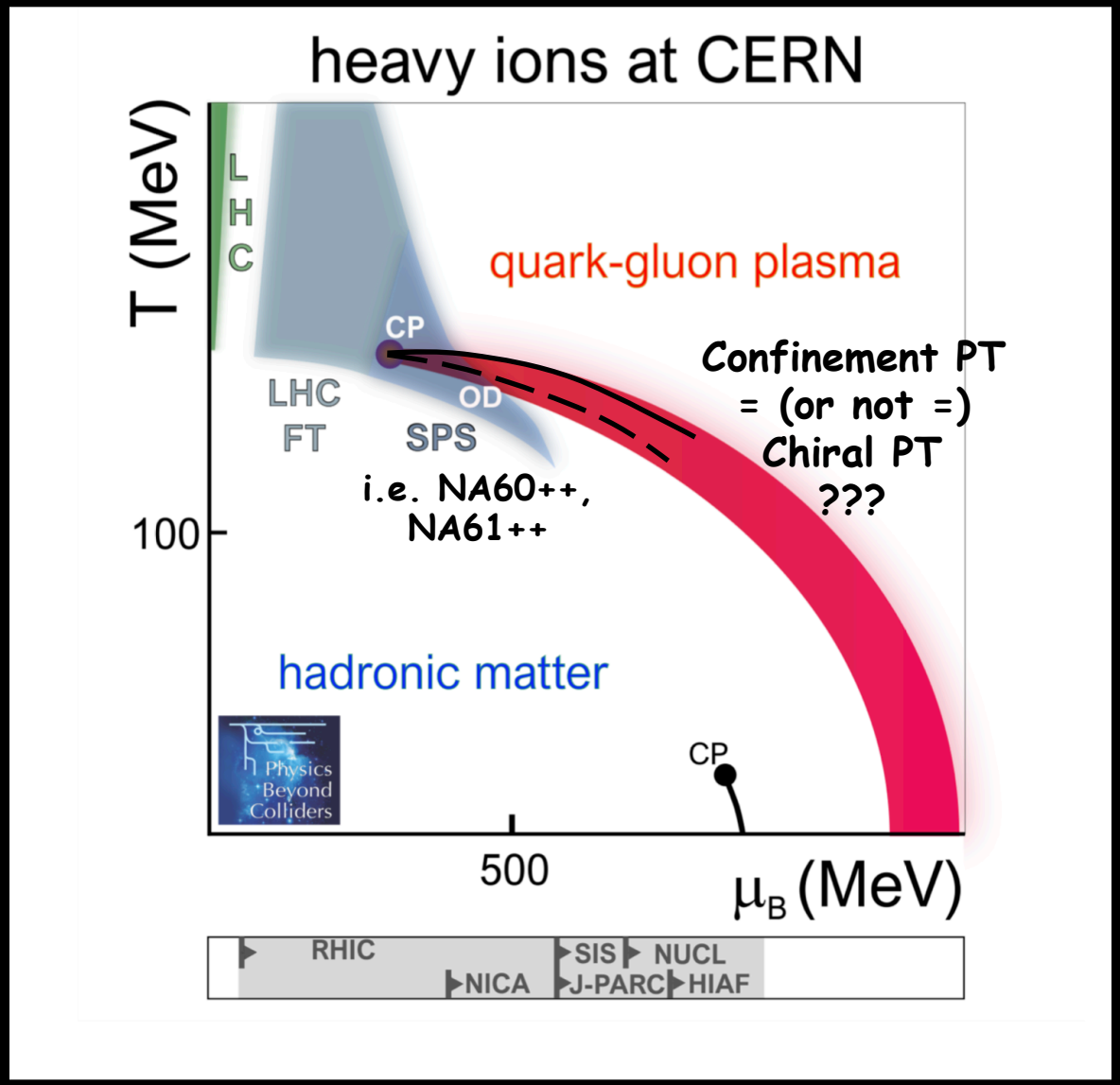

Bound state masses and interactions

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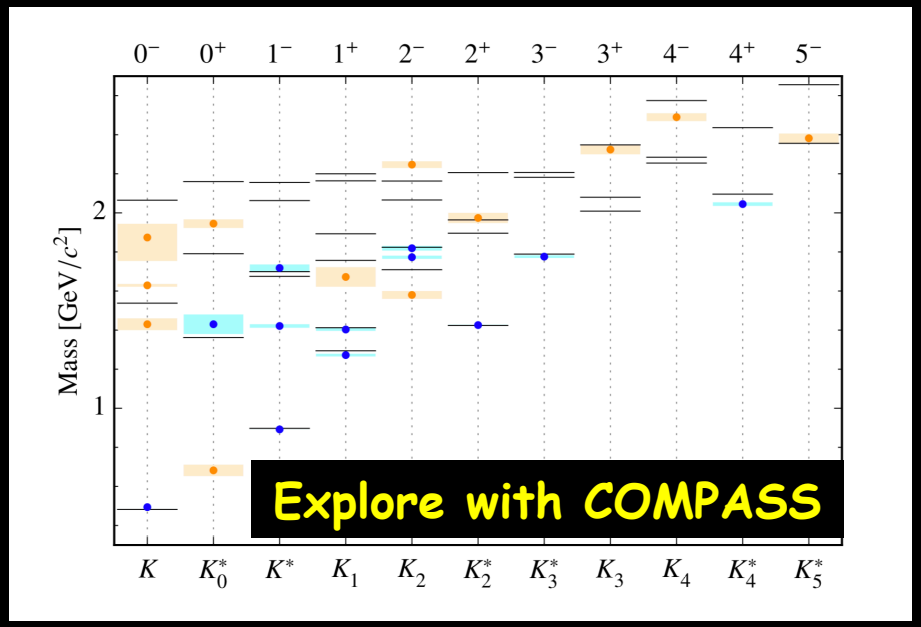
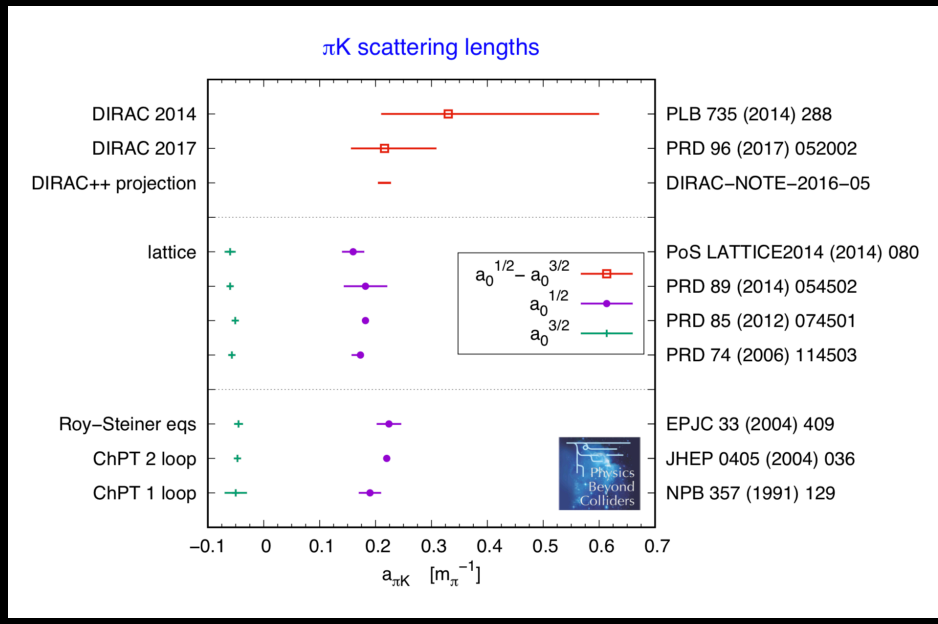
- Compare theory vs Measurement





The origin of us

baryon asymmetry + $\not{C}\not{P}$

Reminder Sakharov conditions

- 1. B violation
  (The SM violates B+L → L violation is sufficient)
- 2. CP and C violation
- 3. Out of Thermal equilibrium

Leptogenesis

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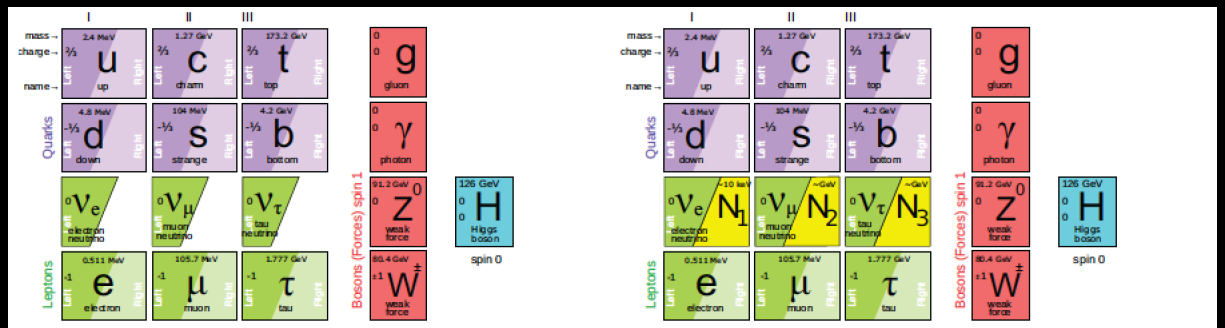
Baryogenesis via Leptogenesis:

(Violate L and use B+L violation of SM ➔ Violate B)

Right Handed Majorana Neutrino = Heavy Neutral Lepton

Violate L!

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

Probing with PBC

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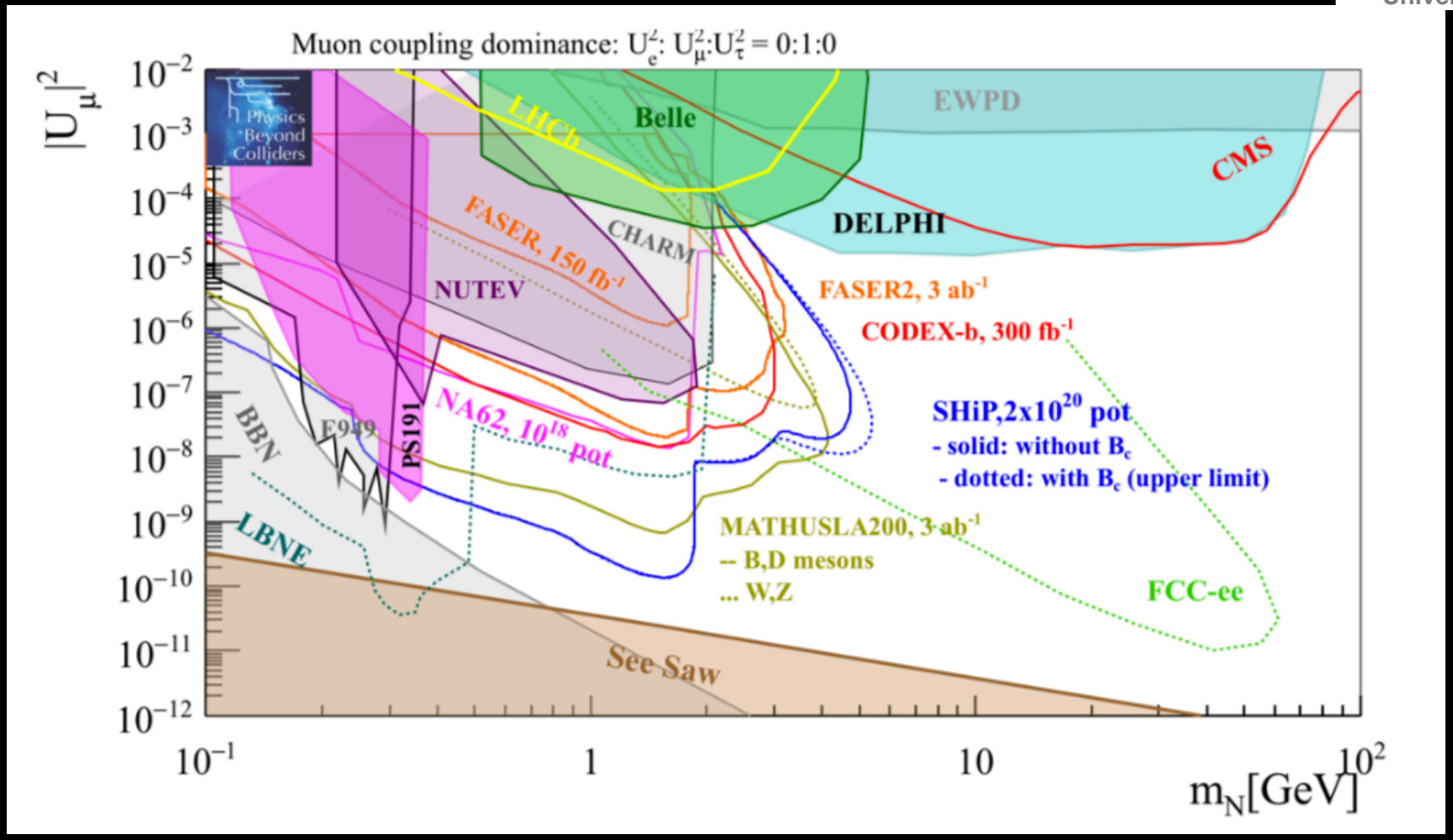
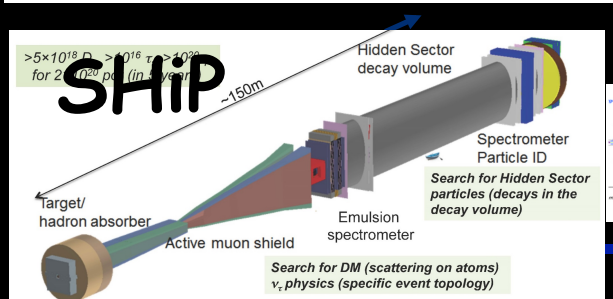
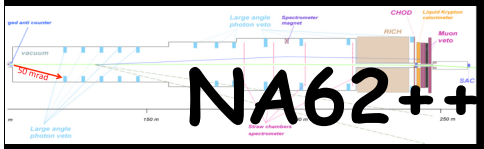
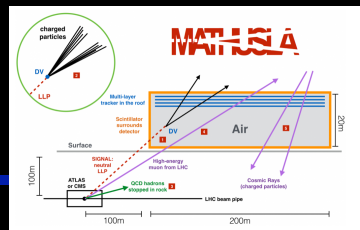






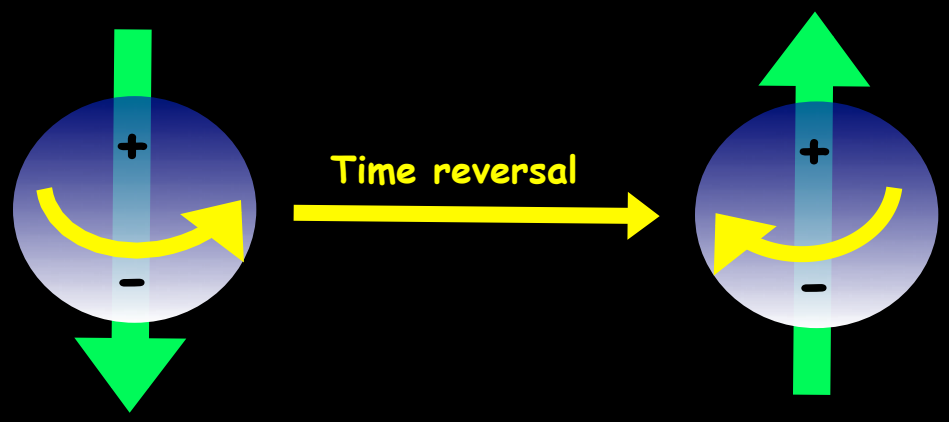
CODEX-b

FASER



Probing CP violation

- Electric Dipole Moment (of more or less elementary particle) violates T and CP



Measurement of proton EDM

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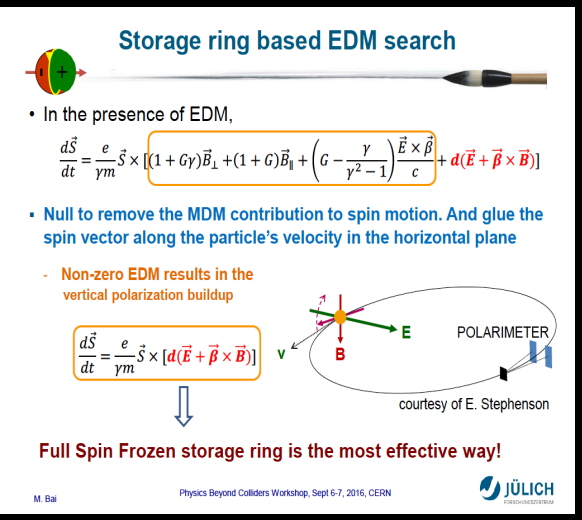
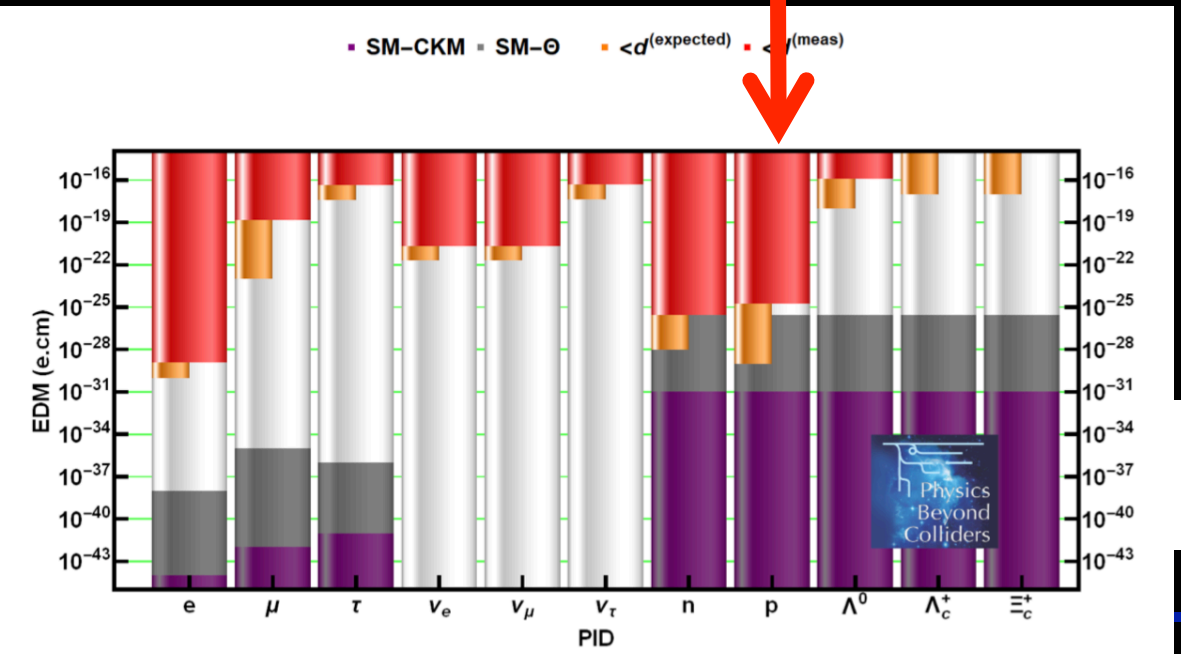


Sensitivity

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



Test new CP violating particles m~1000 TeV

$$\frac{|\sin(\phi^{(q)})|}{\Lambda_q^2} \sim \frac{1}{(7\times 10^5\,\mathrm{TeV})^2} \times \left(\frac{d_p}{10^{-29} e\mathrm{cm}}\right)^{1/2}$$

Strong CP problem: Probing the axion

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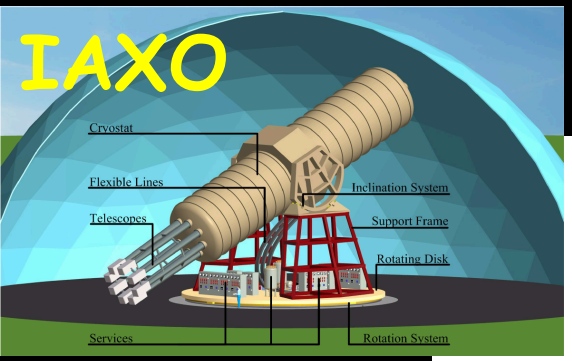

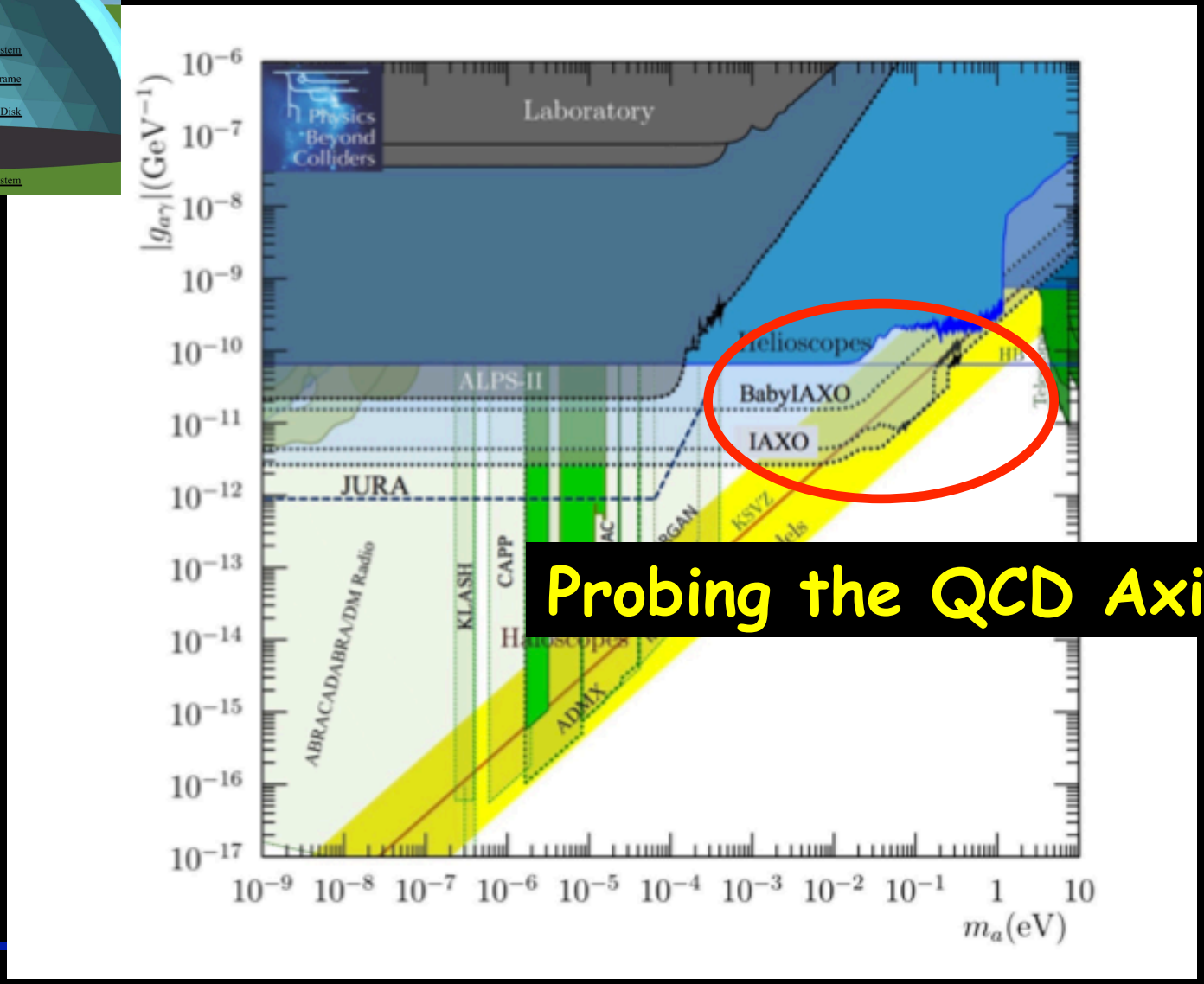

Probing the QCD Axion!

Speculation: Learning about Quantum Gravity?

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- Let us say the Axion is found
- CKM effects cause

$$d_p \sim 10^{-32} e\,cm$$ (SM background)

- What would a measurement of $d_p \sim 10^{-29} e\,cm$ tell us?

  1) other sources of CP violation
     (can be probed by other EDMs)

  2) PQ symmetry not exact
     (expected from Quantum Gravity for global symmetry)

➔ Probe QG

Dark Matter

Dark Matter: Not quite there yet

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- We know:
  - It exists
  - About 27% of energy
- We don't know:
  - What particle (or other?)
  - Mass of "particle"

$$m_{DM} \sim 10^{-22}\,\mathrm{eV} - 10 M_{sun}$$
$$\sim 10^{-22}\,\mathrm{eV} - 10^{67}\,\mathrm{eV}$$

~90 orders of magnitude...

Direct Detection oscillating EDM

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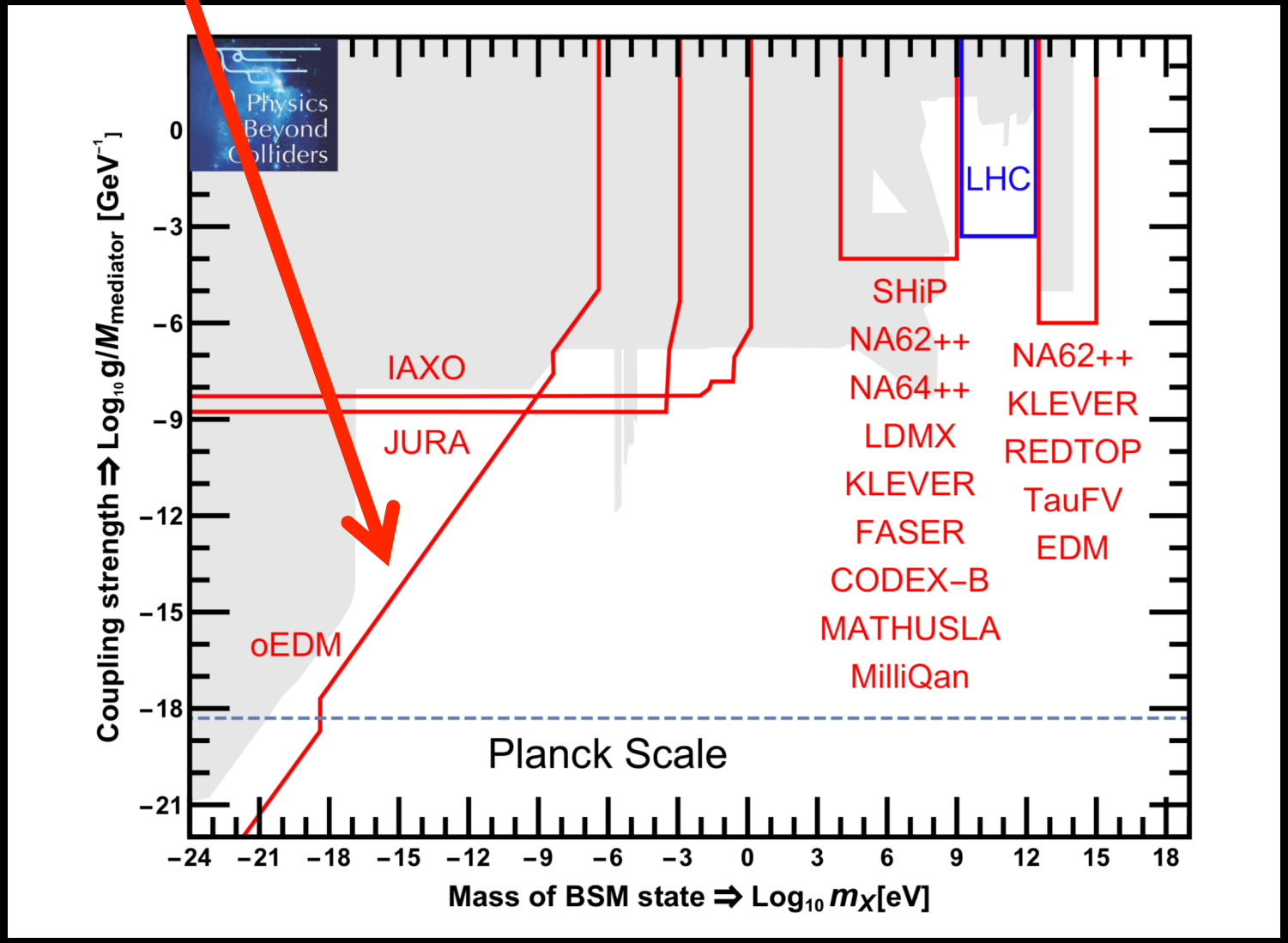

(Messengers to) Dark Matter Sector

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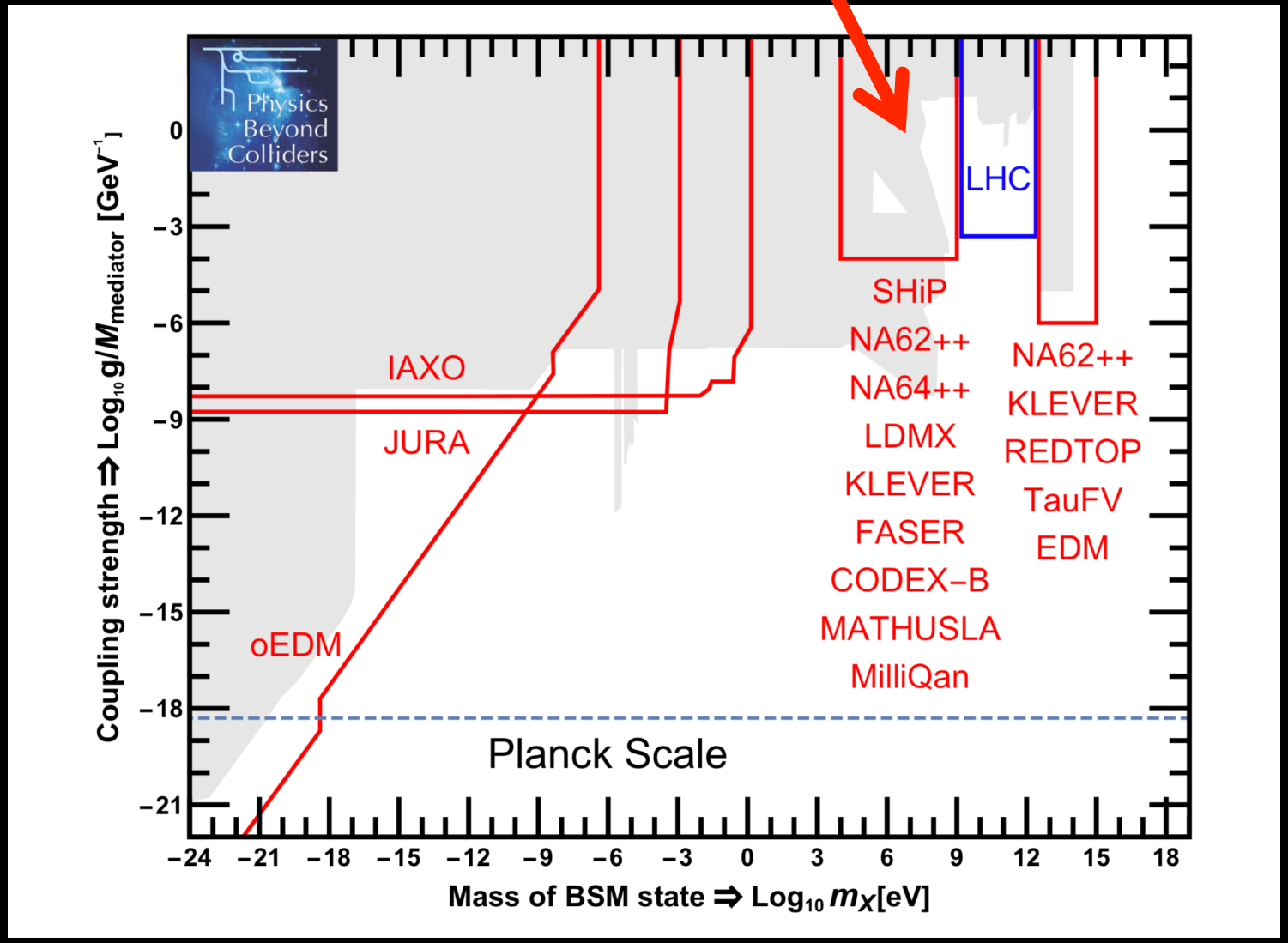

NA61++ Contributes to indirect detection

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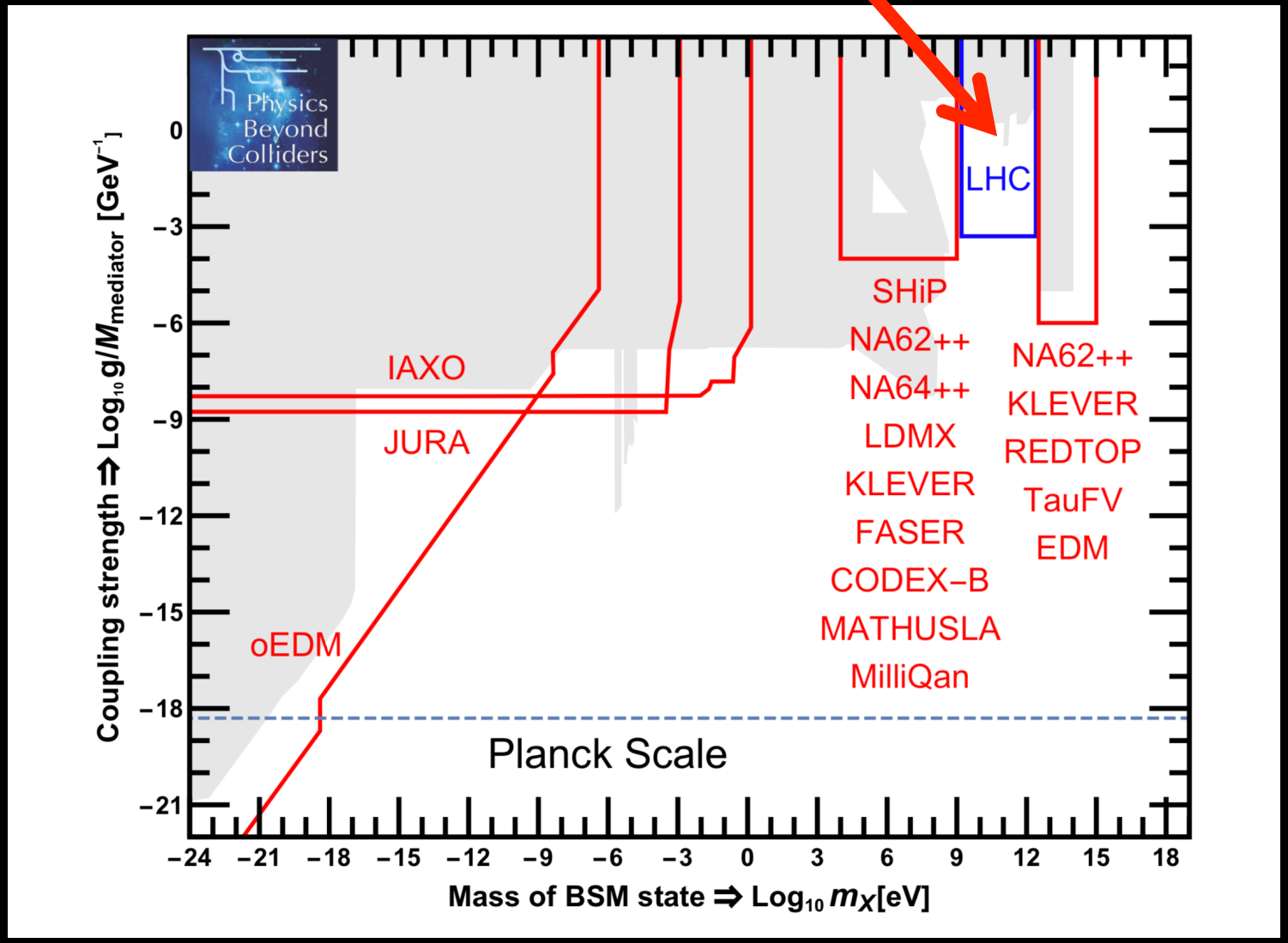

Hunting Hints

Astrophysical hints for ALPs

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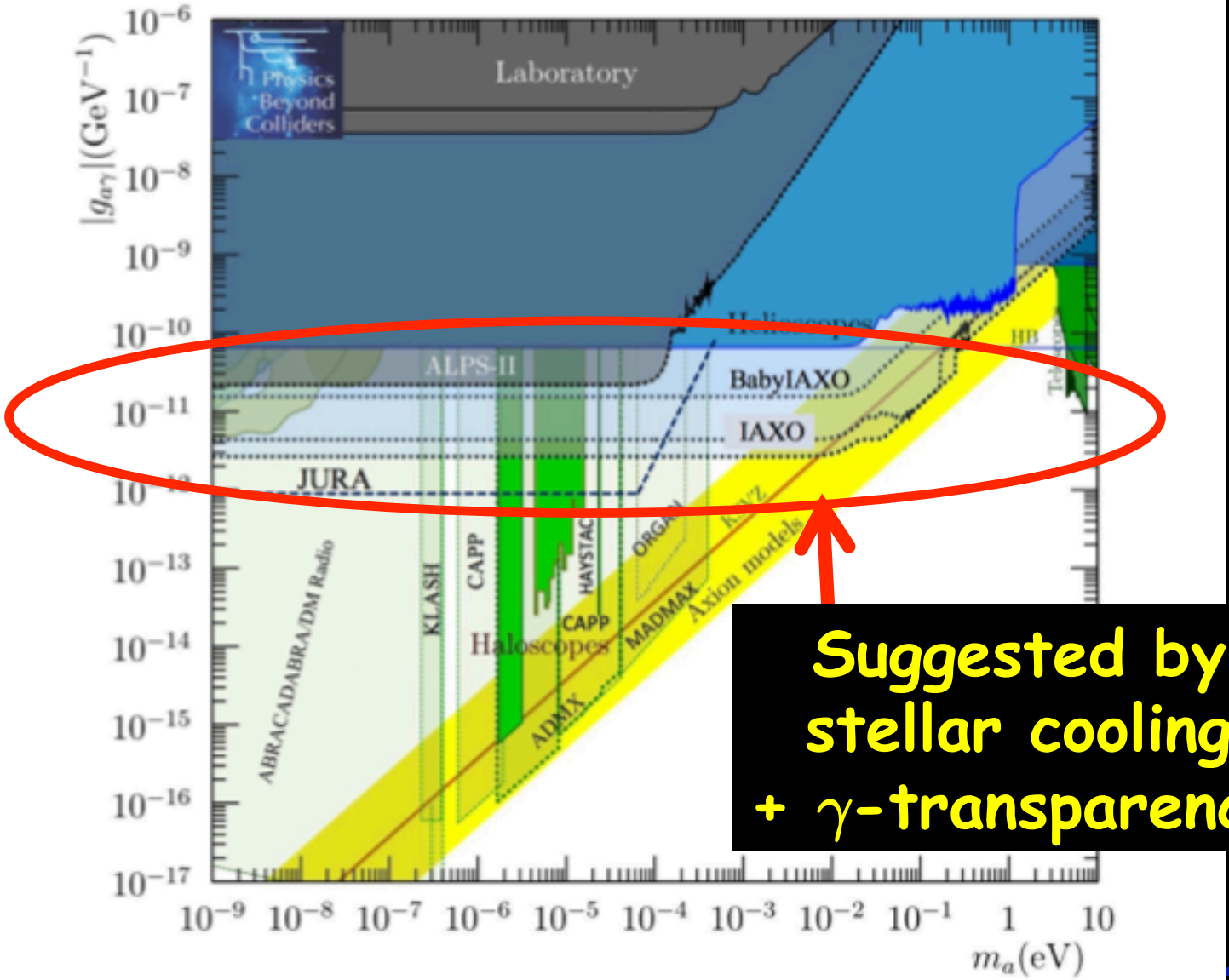

Suggested by stellar cooling + γ-transparency

The $(g-2)_\mu$ anomaly

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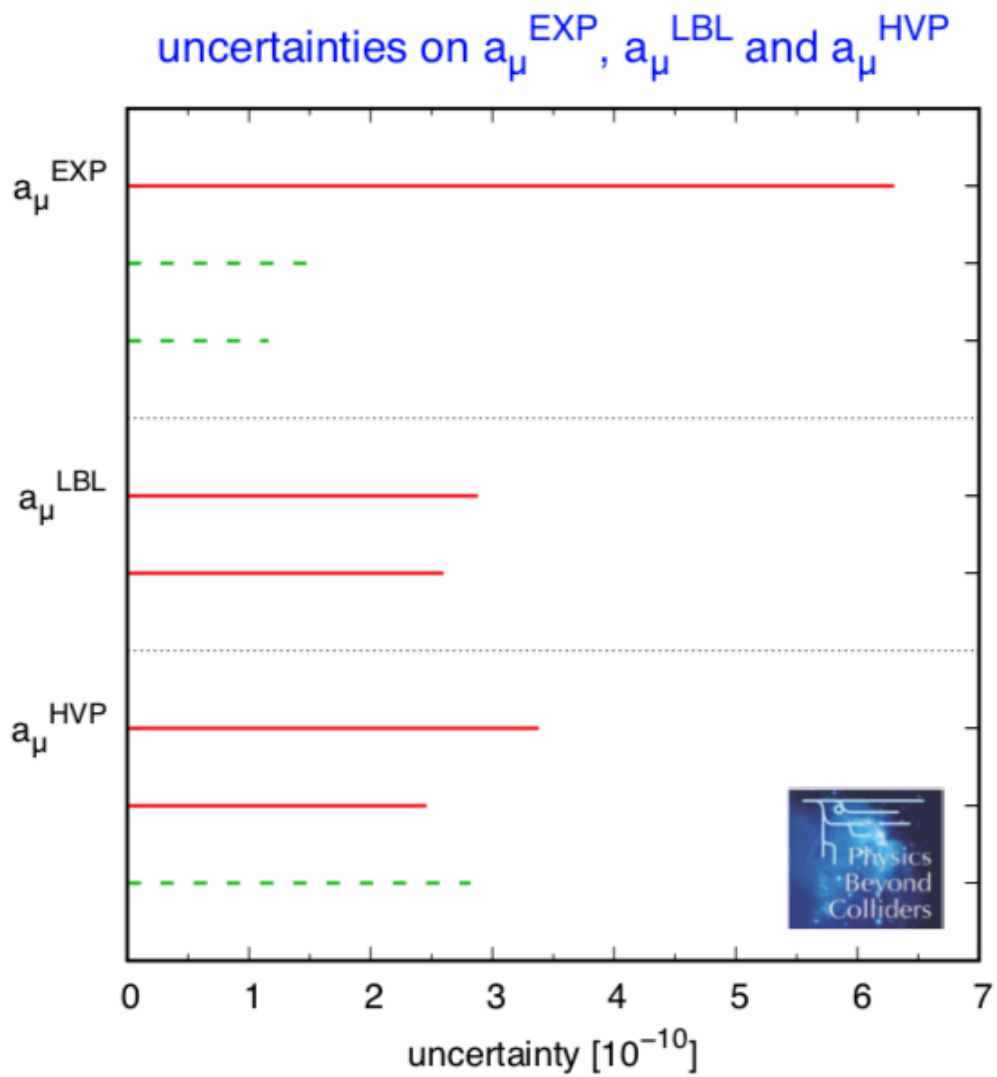
- Hints want to be found + confirmed + supported



BNL E821 [Phys.Rev., D73 (2006) 072003]

FNAL g−2 goal [arXiv:1801.00084]

J-PARC E34 goal [JPS Conf. Proc. 8, 025008 (2015)]

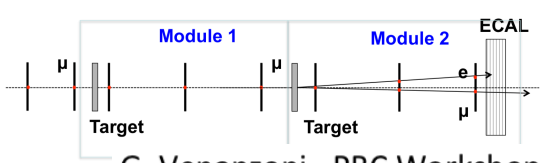
Jegerlehner [arXiv:1804.07409]

Prades, de Rafael, Vainstein [arXiv:0901.0306]

Jegerlehner [EPJ Web Conf. 166 (2018) 00022]

Keshavarzi, Nomura, Teubner [PRD 97 (2018) 114025]

MUonE precision goal



G. Venanzoni, PBC Workshop

The $(g-2)_\mu$ anomaly

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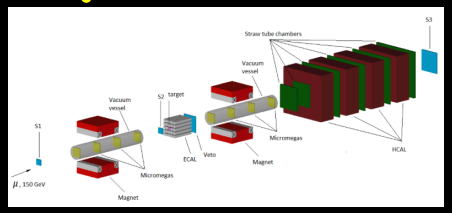
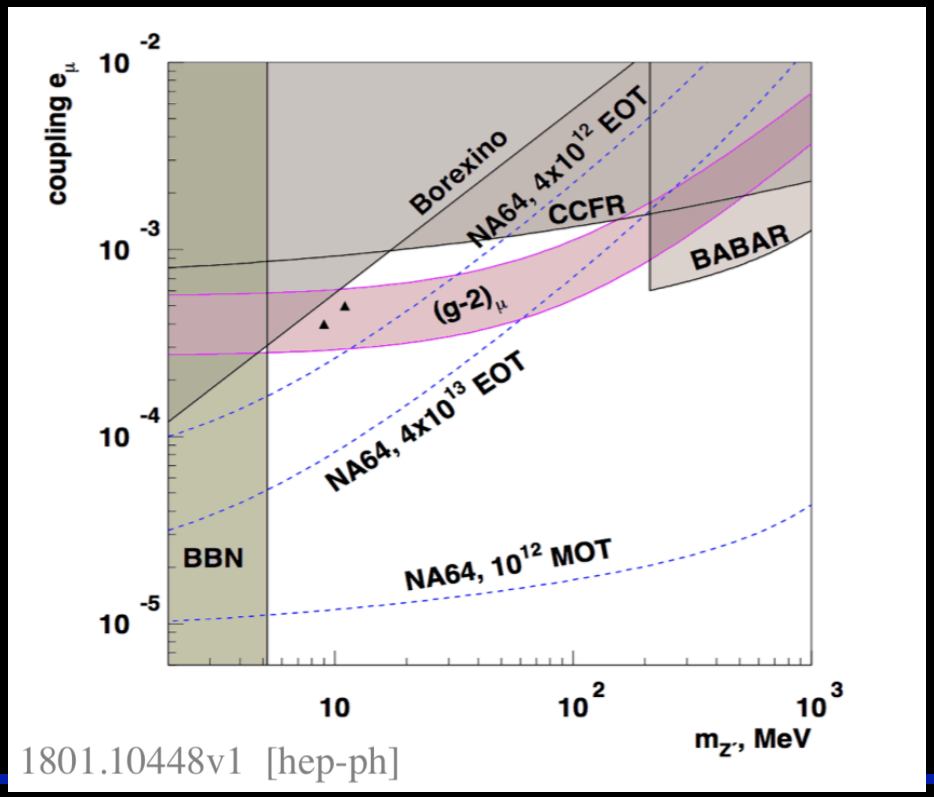
- Deviation in $(g-2)_\mu$ can be explained by dark boson dominantly coupled to μ

➔ Probe with NA64(μ)++





1801.10448v1 [hep-ph]

Exploring Beyond

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

Sometimes a bad theory „works“:

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

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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

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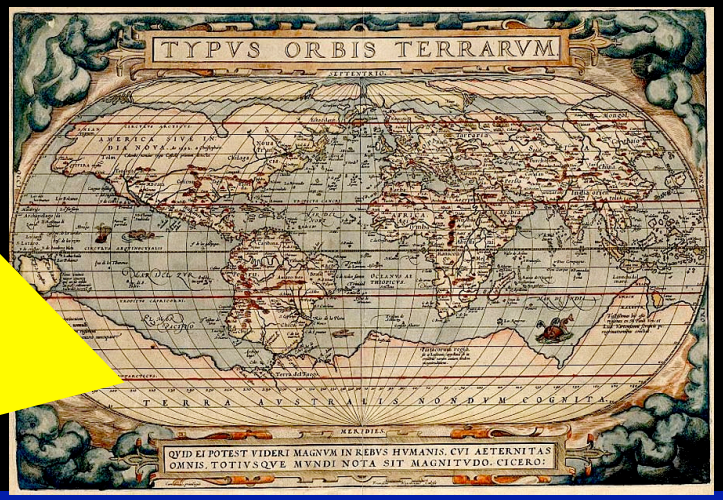
Draw Map with Predicted Terra Australis



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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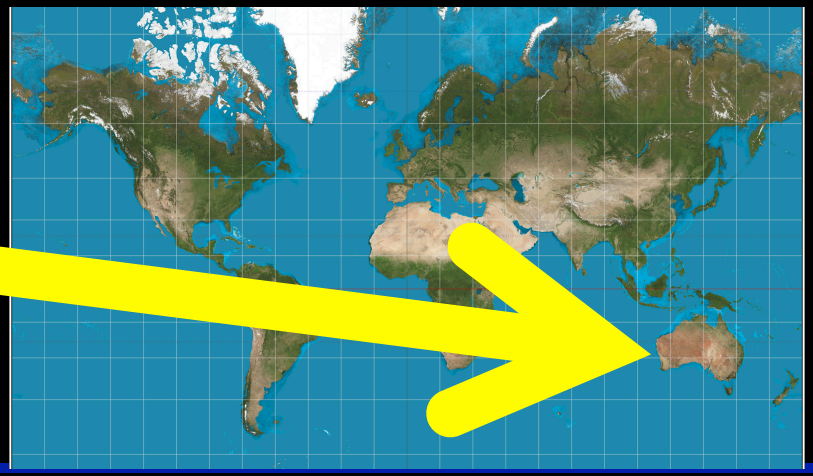
„Experimentally“ Discovered: Australia



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

Testing of models fostering Exploration

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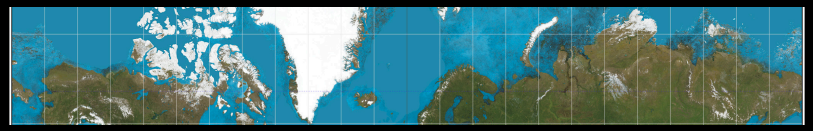
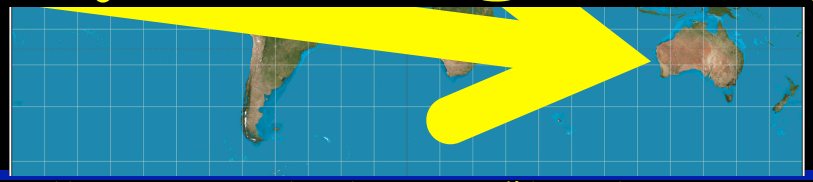


➔ Draw a Map and go explore

Australia



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

Sometimes it's good to draw a map
The "PBC projection"
➔ benchmark models

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- **Photon coupling**

  BC 9

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

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

- **Gluon coupling**

  BC 11

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

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

- **Fermion couplings**

  BC 10

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

PBC explores wide and deep

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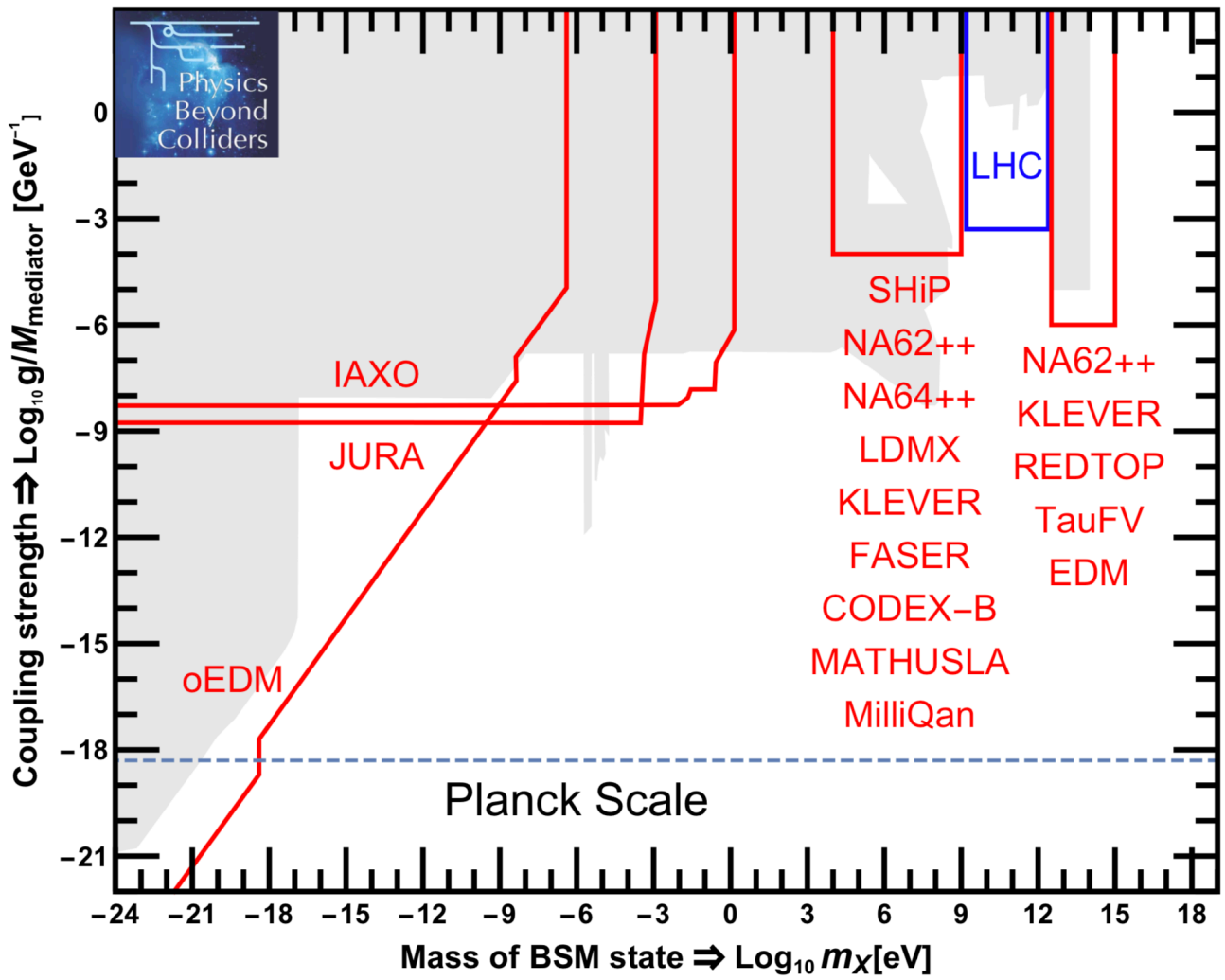

PBC explores wide and deep

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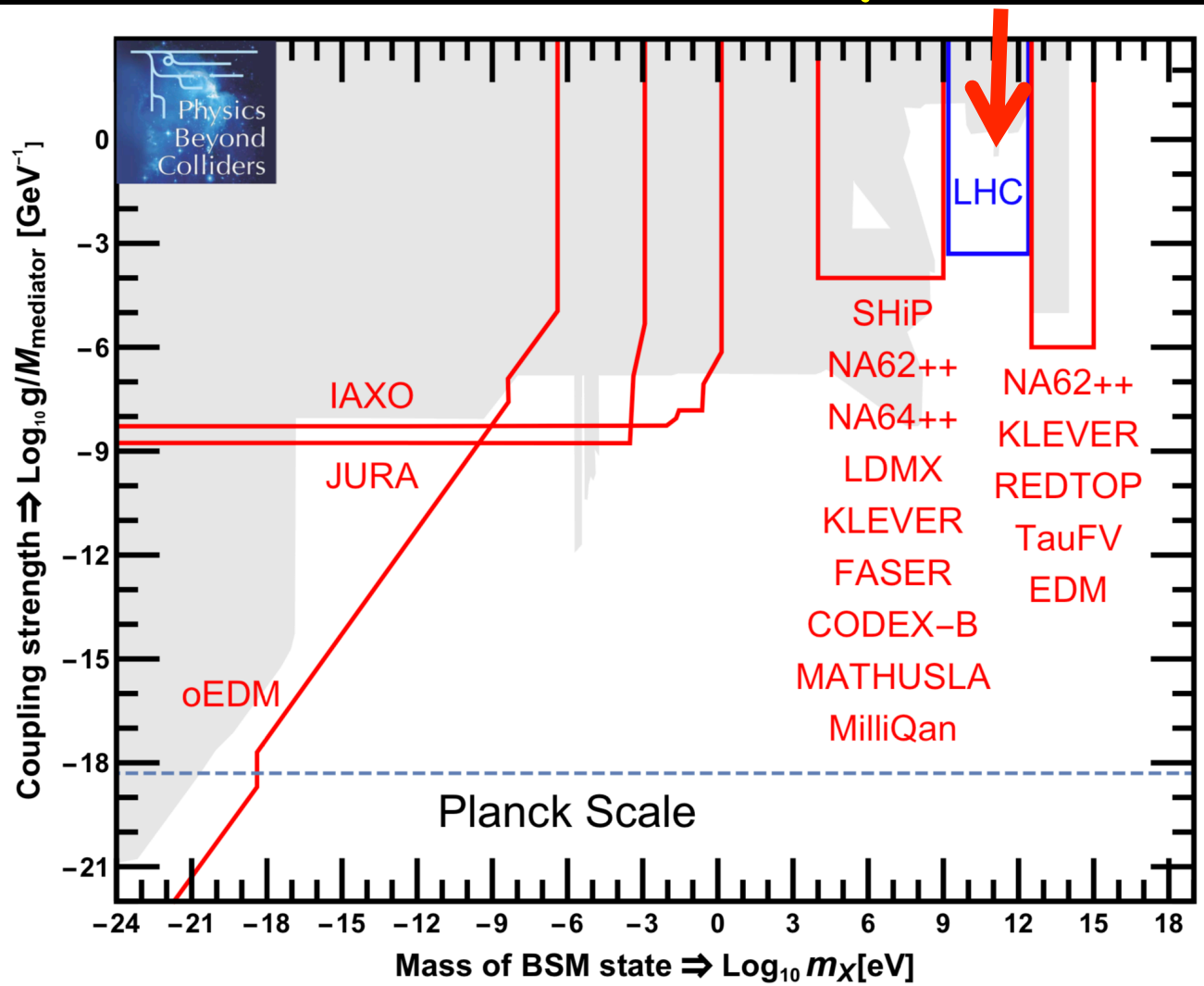
Information on PDFs provided by LHC-FT



PBC explores wide and deep

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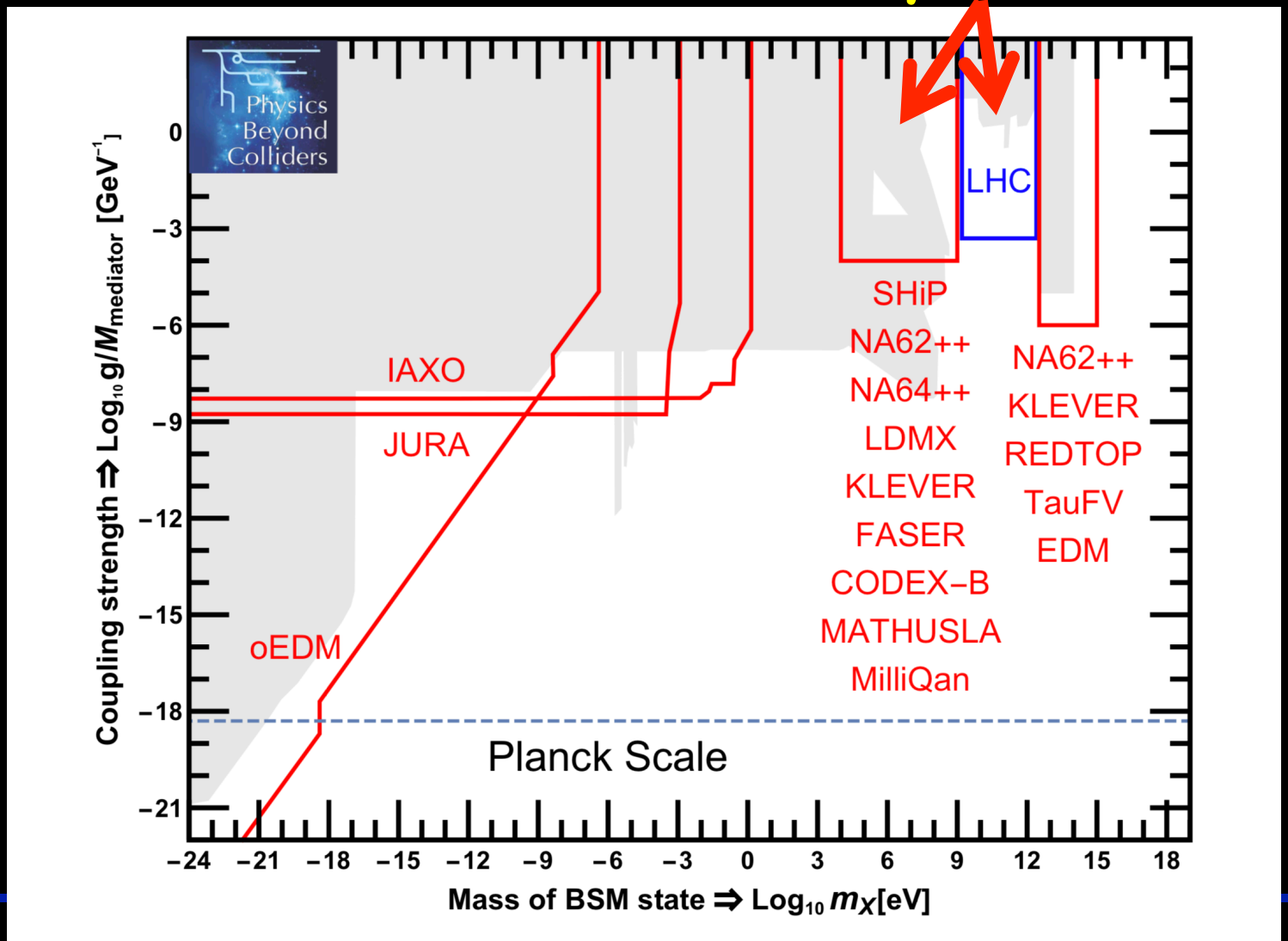
Information on $(g-2)_\mu$ provided By MuonE



PBC explores wide and deep

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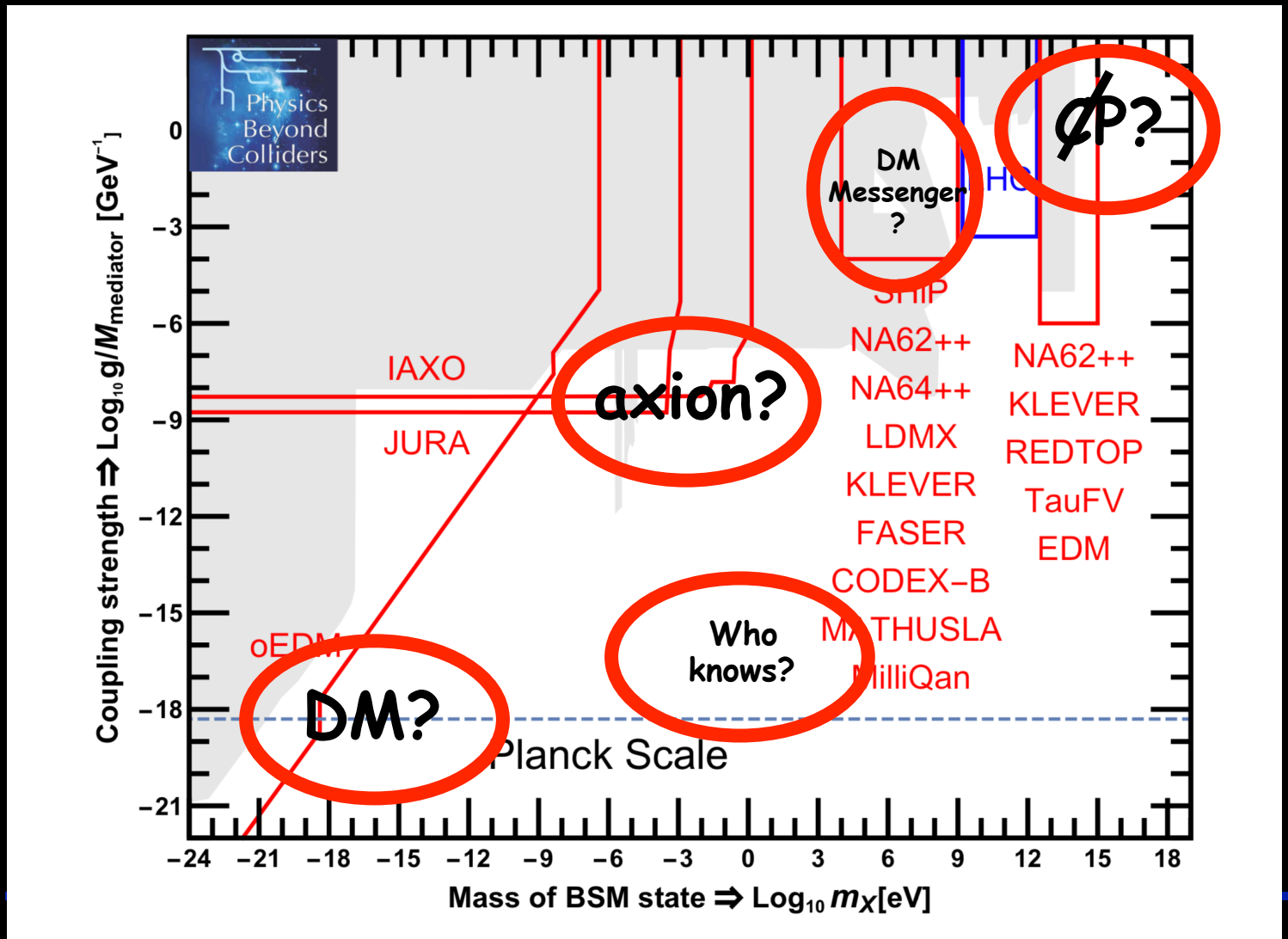

Conclusions

Conclusions + The Future

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PBC experiments:

- are fully complementary to collider studies
- are stronger together with each other and other experiments (LHC, indirect detection etc.)
- have the potential to answer fundamental open questions!
- investigate existing anomalies + hints
- have broad + deep coverage of theory space

➔ Discover "Particula Obscura"

Thanks again
to Everybody!!!