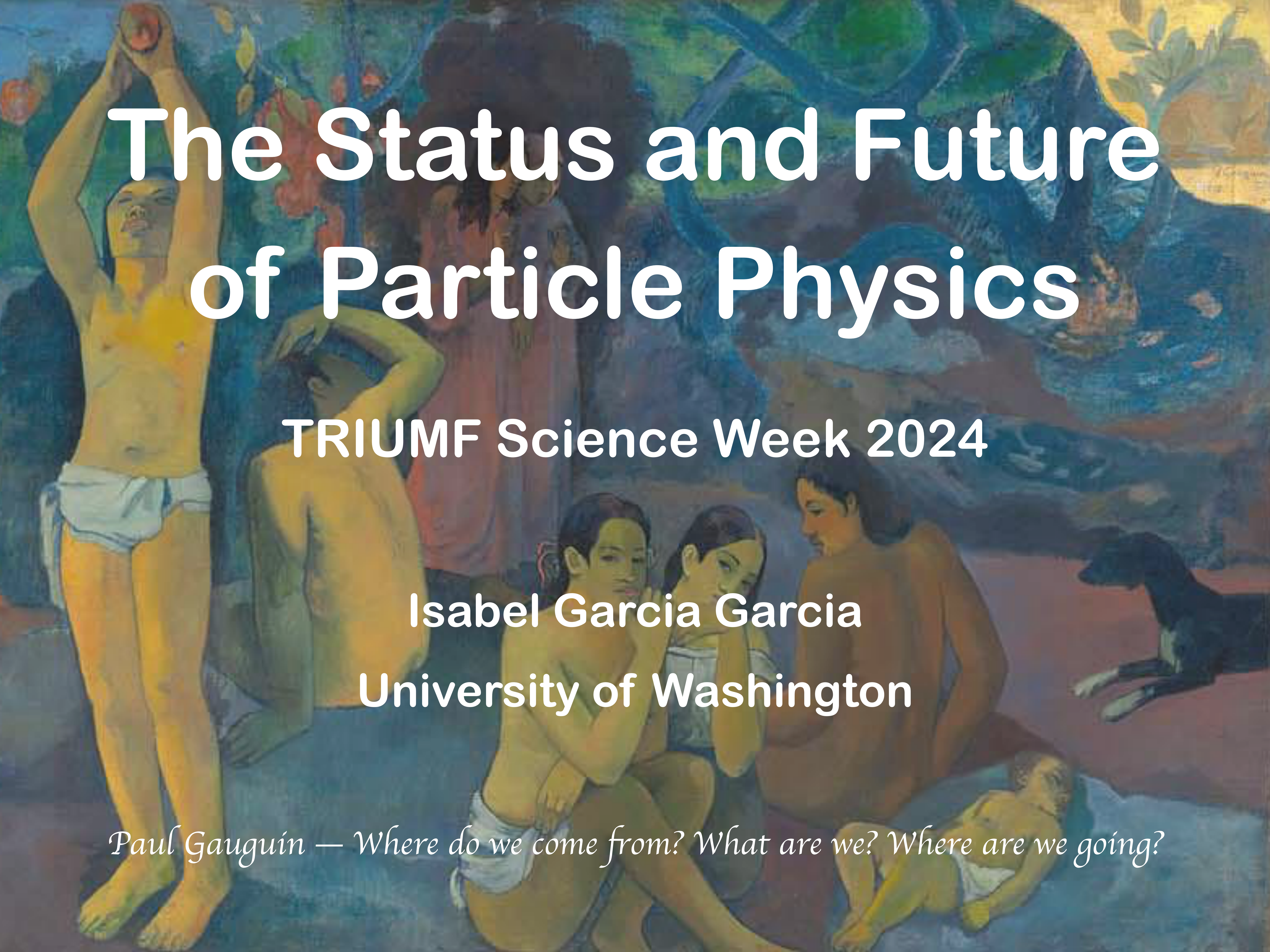


The Status and Future of Particle Physics

TRIUMF Science Week 2024

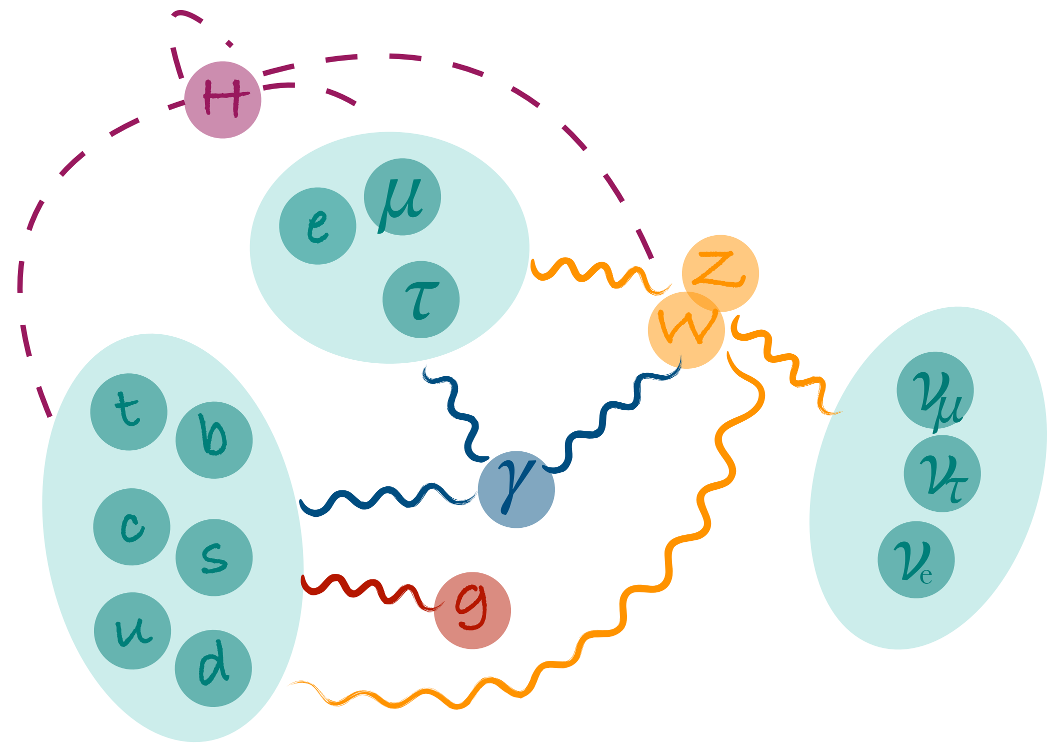
Isabel Garcia Garcia

University of Washington

Paul Gauguin — Where do we come from? What are we? Where are we going?

Where are we?

Standard Model



$SU(3) \times SU(2) \times U(1)$

General Relativity

$$G_{\mu\nu} = \frac{1}{M_{Pl}^2} 8\pi T_{\mu\nu}$$

" geometry = matter "

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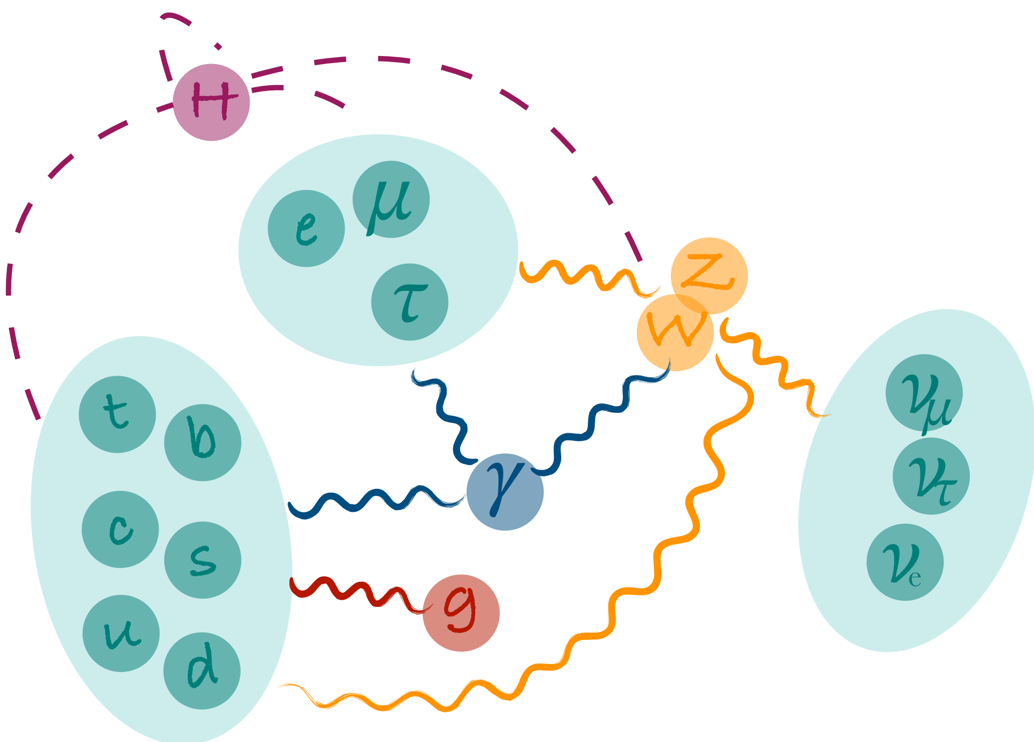

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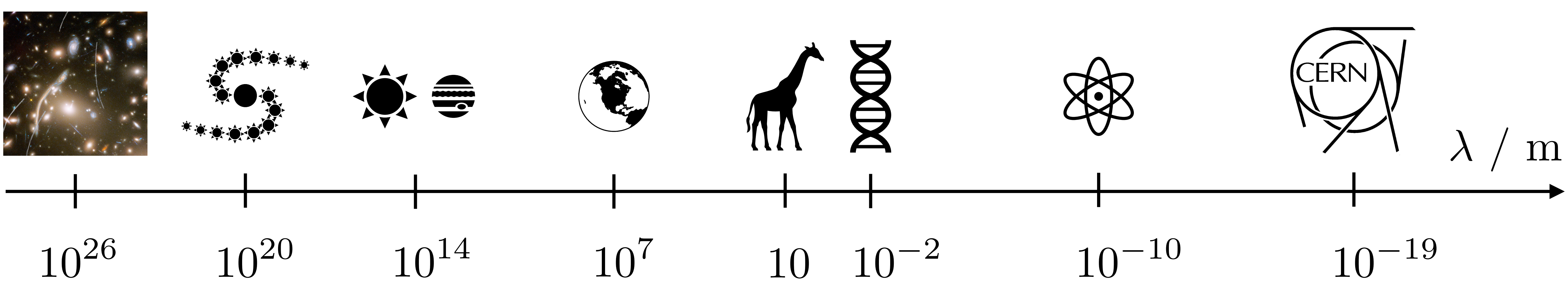

Why go beyond?

- neutrino masses
- Why 3 generations?
- cosmological constant problem
- why smooth, low-entropy spacetime?
- matter anti-matter asymmetry
- strong CP problem
- why $\delta\rho/\rho \sim 10^{-6}$ and approx. scale-invariant?
- weak scale
- Why 3+1 dimensions?
- dark matter
- who is the Higgs boson?

etc, etc...

Why go beyond?

neutrino masses

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why $\delta\rho/\rho \sim 10^{-6}$ and approx. scale-invariant?

weak scale

Why 3+1 dimensions?

dark matter

who is the Higgs boson?

etc, etc...

challenge: provide solutions that can be experimentally probed...

Outline

1. (My) highlights from the US P5 report

2. Gravitational waves and particle physics

3. Dark matter cornucopia

4. Strong-CP and flavor — beyond the QCD axion

5. Gravity and Effective Field Theory

6. QFT in the non-perturbative regime

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biased, and not comprehensive!

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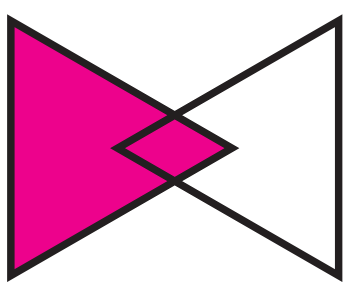
P5 = Particle Physics Project Prioritization Panel

Task: develop 10-year strategic plan for US particle physics

Input: 2021 Snowmass Community Planning Exercise (US and global community)

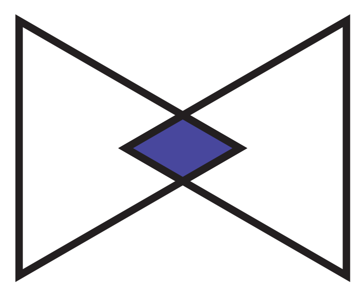
Output: ~ 150 page report with specific recommendations for funding agencies

3 overarching science themes, with 2 focus areas each:



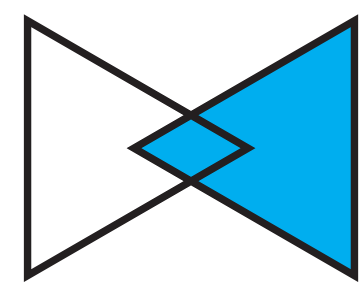
Decipher the Quantum Realm

- Elucidate the Mysteries of Neutrinos
- Reveal the Secrets of the Higgs Boson



Explore New Paradigms in Physics

- Search for Direct Evidence of New Particles
- Pursue Quantum Imprints of New Phenomena



Illuminate the Hidden Universe

- Determine the Nature of Dark Matter
- Understand What Drives Cosmic Evolution

Impact: TBD — but report best summary of community consensus at present

The Higgs at Colliders

Strong collider program central for present and future of particle physics

&

Exploring the properties of the Higgs as a path to advance particle physics

Higgs properties — and the Higgs potential — linked to many of the outstanding puzzles in particle physics

EWSB, flavor, baryogenesis…

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  - Higgs to SM couplings (~1% or less)
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- Higgs factory: FCC-ee or ILC $\Rightarrow$ Higgs physics as a precision science

Towards a 10 TeV parton-COM Collider

Future progress requires higher energies

- R&D towards a 10 TeV parton-COM — e.g. 100 TeV proton collider (FCC-hh), or 10 TeV muon or e+e collider

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* For more, see: "Inaugural US Muon collider Meeting" @ Fermilab August 2024

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In the end: only way to directly probe physics at the smaller distances

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Precision Cosmology

Continue strong support for cosmology as a precision science
via galaxy surveys and precision CMB measurements

- CMB-S4 → $\Sigma\, m_\nu <$ few $\times$ 0.01eV
  → $\Delta N_{\rm eff} \sim$ few $\times$ 0.01
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Most powerful when combined: galaxy surveys and CMB measurements will provide strongest test of ΛCDM paradigm

The search for Dark Matter continues…

- For WIMPs, via direct detection experiments like DarkSide-20k, LZ, SuperCDMS, XENONnT

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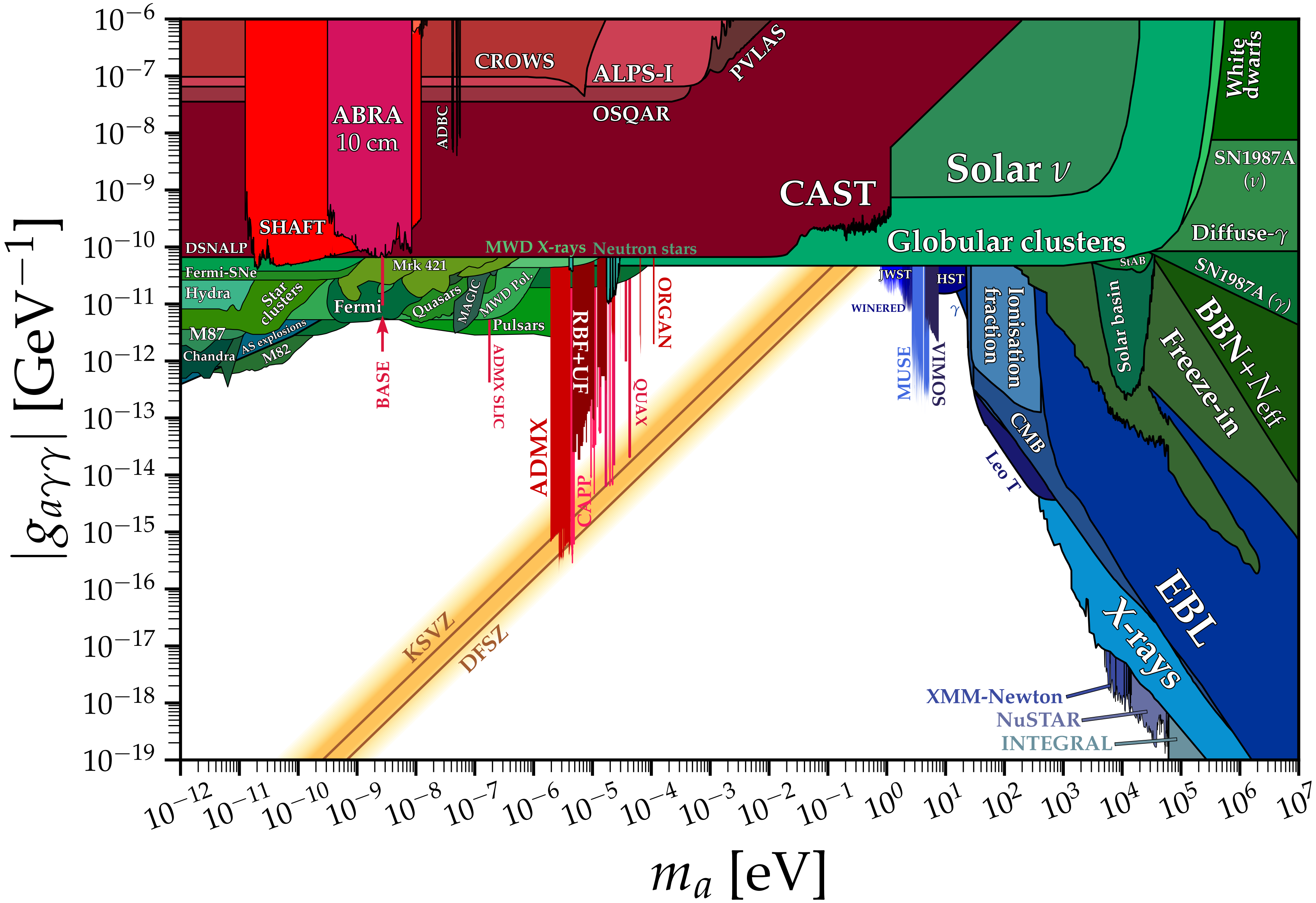

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  ⇒ Recommendation to implement new small-project portfolio (ASTAE)

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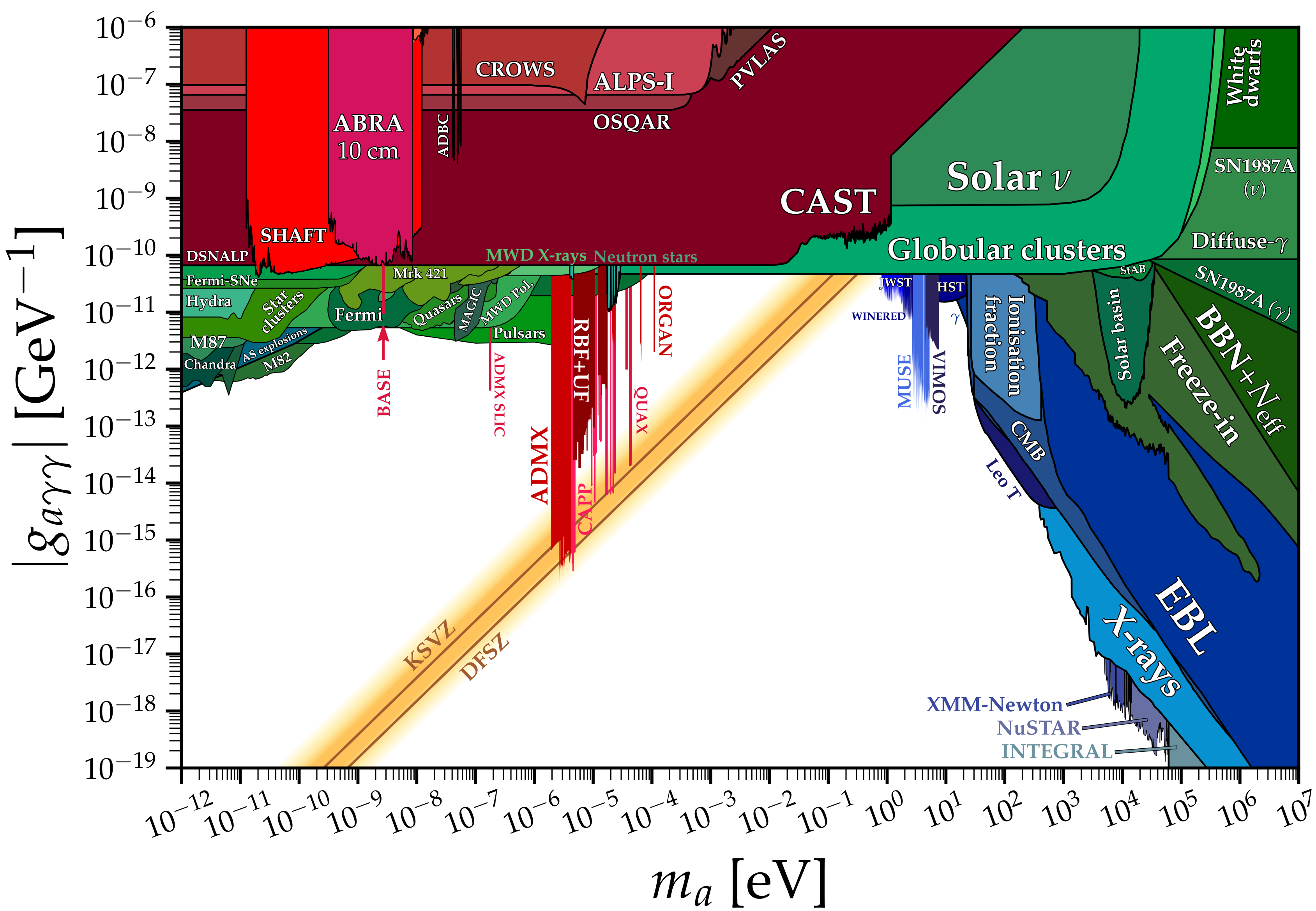

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Medium-scale precision experiments

- Strong commitment to LHCb and Belle II (and upgrades)

- Muon g-2, Mu2e

Flavor and CP structure of the SM one of the enduring mysteries of particle physics

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Theory

- Recognition of multiple exciting theoretical developments
- Vital to provide framework/motivation for experiments and their interpretation
- Emphasis on critical role of theory to drive field forward, beyond its connection to individual experimental projects: new answers, new questions

more later...

Today…

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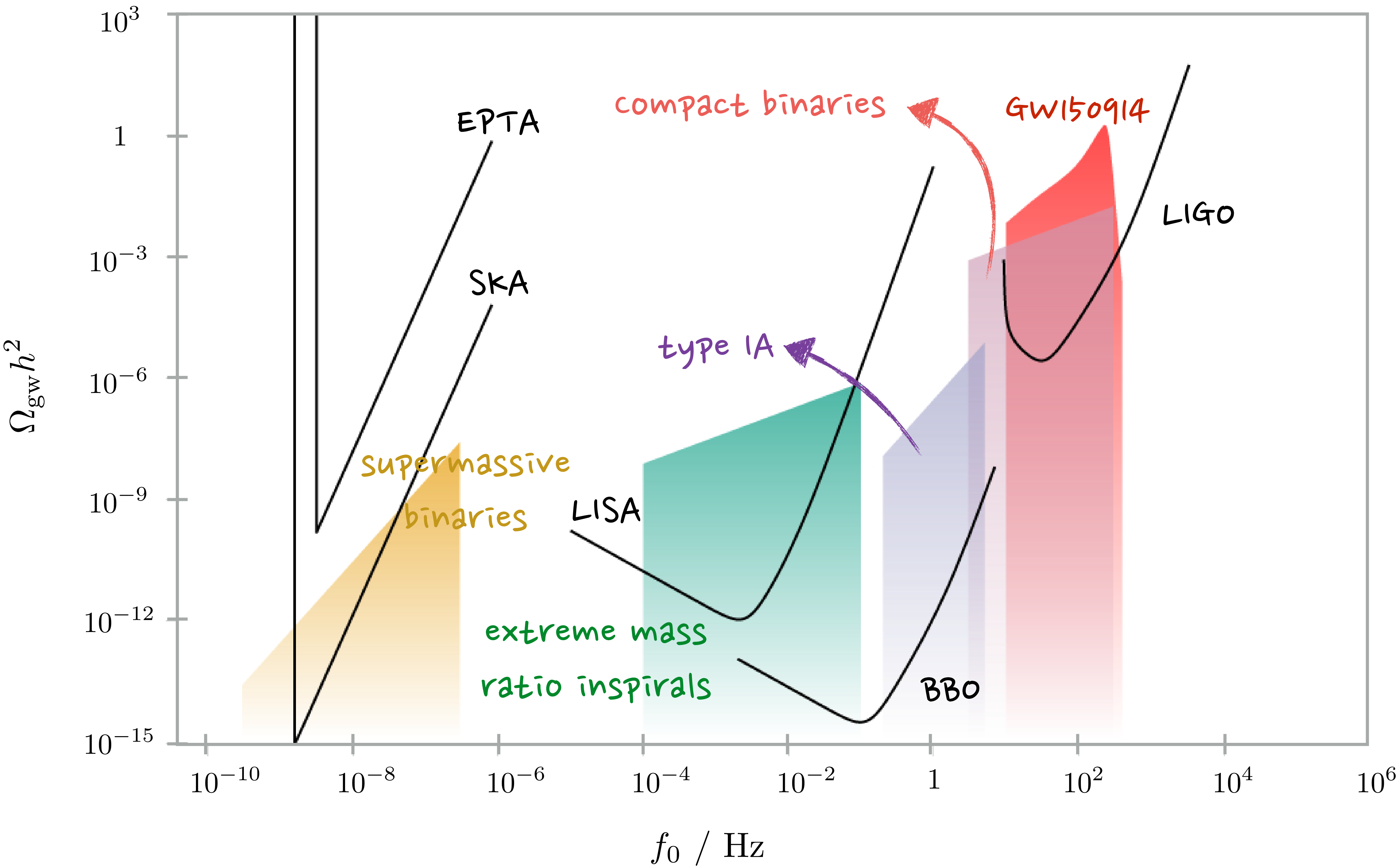
Gravitational Waves and Particle Physics

Gravitational wave detectors provide a new window into our Universe



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Current frequency of primordial gravitational waves: $f \sim H(T_*) \times \frac{T_0}{T_*} \sim \frac{T_* T_0}{M_{\rm Pl}^2}$

$\Rightarrow \quad f \sim 1 \text{ nHz} - 1 \text{ kHz}$ corresponds to temperatures $T_* \sim 10 \text{ MeV} - 10^7 \text{ TeV}$

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- Observation of primordial gravitational waves would be first direct probe of the early Universe prior to BBN

- Gravitational wave detectors probe the existence of new d.o.f./hidden sectors even if they only interact with the Standard Model gravitationally

Gravitational Waves and Particle Physics

Cosmological phase transitions that occur via bubble nucleation a well-motivated possibility

both in (minimal) extensions of the SM and in more general hidden sectors

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Bubble wall collisions a significant source of gravitational waves

Hogan (1986); Kosowsky, Turner, Watkins (1992); Kamionkowski, Kosowsky, Turner [astro-ph/9310044]

Several collisions per Hubble volume, plus $\frac{H(T_*)^{-3}}{H(T_0)^{-3}} \lll 1 \quad \Rightarrow$ stochastic background

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$$\text{e.g.} \quad f_0 \sim R^{-1} \times \frac{T_0}{T_*} \sim 1\ \text{mHz} \times \frac{T_*}{100\ \text{GeV}}$$

LISA will probe the nature of the electroweak scale

see e.g. [1512.06239] & [1910.13125] by LISA Cosmology Working Group

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- Cosmic string dynamics

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At the moment: stochastic GW signal seen by pulsar timing arrays, with origin TBD…

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- Beyond-the-SM sources of gravitational waves at $f > 1\,\mathrm{kHz}$ and $f < 1\,\mathrm{nHz}$, but no competitive experiments

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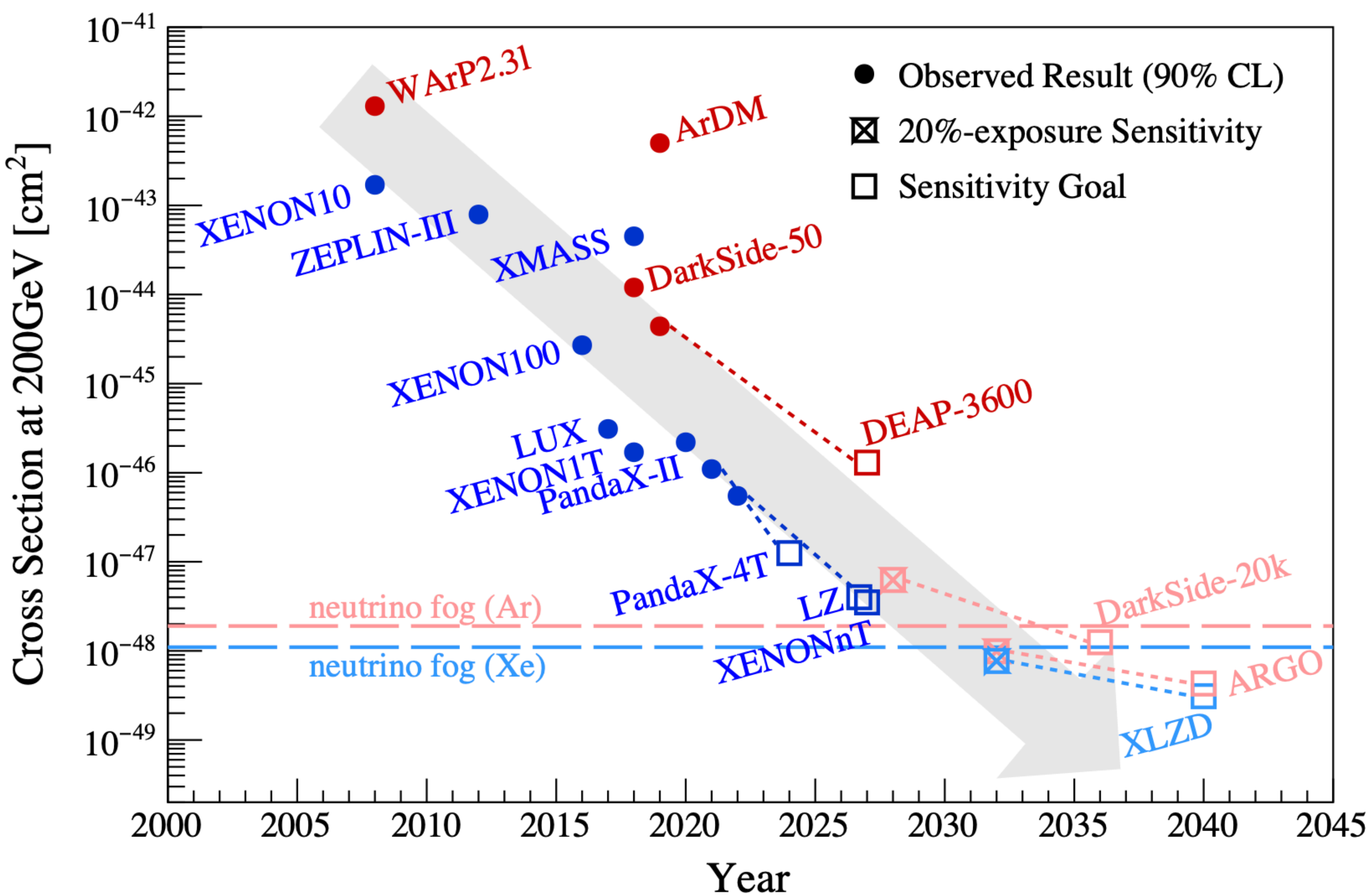
WIMPs

- A lot of WIMP parameter space explored by direct detection experiments…

all the way down to the "neutrino fog" (XENONnT)



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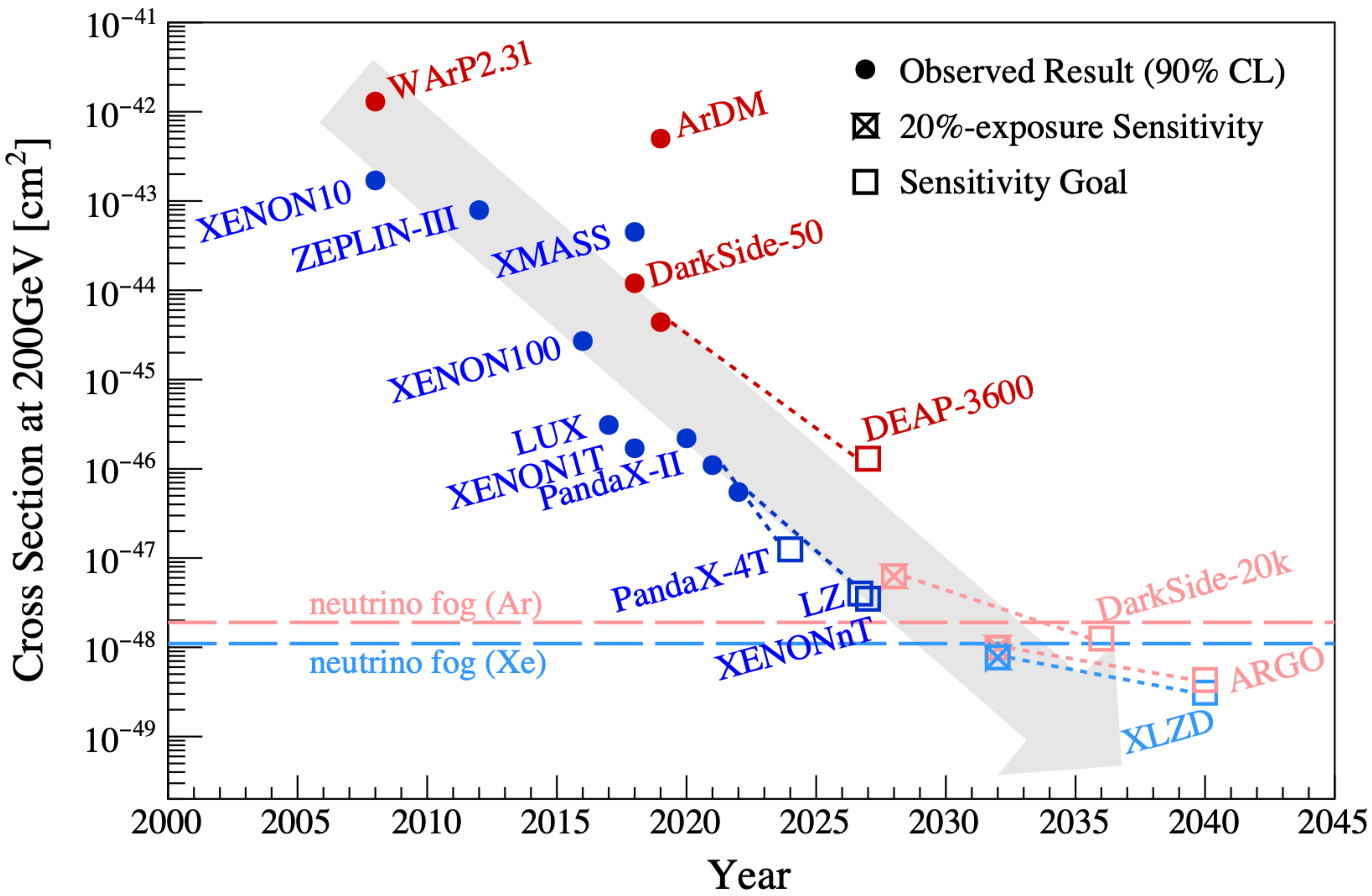

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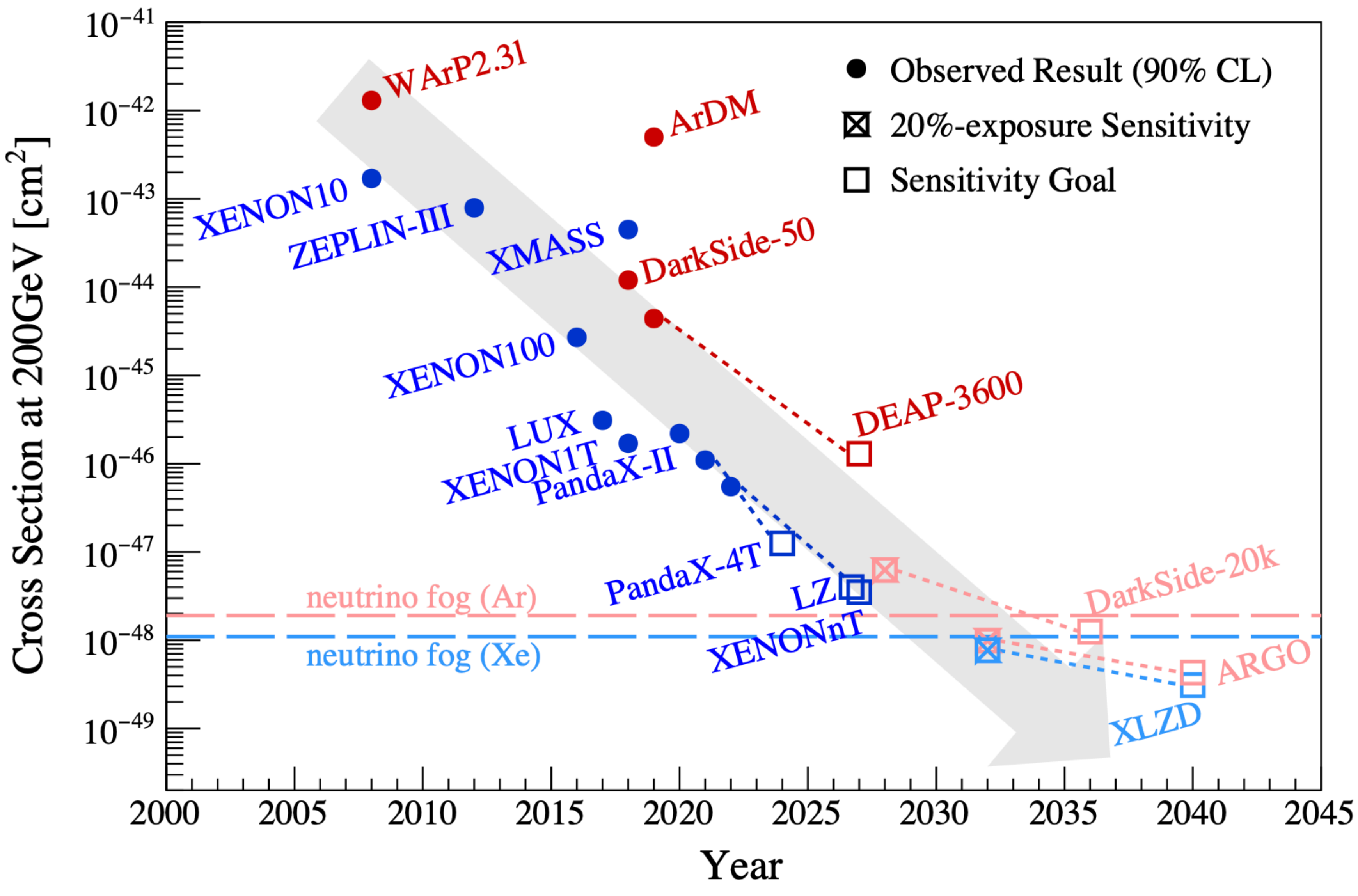
- Also important to consider other dark matter candidates…



Light bosonic dark matter

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- Axion-Like-Particles (ALPs) are naturally light and present in UV-completions of the SM

e.g. QCD axion, "string axiverse" axions, etc…

- Natural production mechanism: e.g. "misalignment" (produced cold) or emission by cosmic strings (produced relativistic)

if axions exists, they will make *some* fraction of the dark matter

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- Difficulty: vast parameter space of mass and couplings…

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Observationally:

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easy to arrange if "connector interaction" active in early universe

needs to be dynamically realized, otherwise haven't explained the DM to baryon ratio!

Where to look…?

- In specific implementations , DM often inside the "neutrino fog"

see e.g. **IGG**, Lasenby, March-Russell [1505.07410]; Farina [1506.03520]
Bodas *et al* [2401.12286], etc…

- There is no DM annihilation, and DM can build to form composite objects: from atomic DM… all the way up to black holes

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Need new dark matter "paradigms" that provide theoretical guidance in our search for dark matter

see e.g. Brzeminski, Hook [2310.07777]

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Strong CP problem: It is not possible to understand the absence of strong CP violation based on the underlying symmetries of the Standard Model

$$\bar{\theta} = \theta_s + \theta_q \lesssim 10^{-10}$$

$$\mathcal{L} \supset \frac{\theta_s g^2}{32\pi^2} \mathrm{tr}\left(G_{\mu\nu}\tilde{G}^{\mu\nu}\right)$$

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what about alternative solutions to the strong CP problem?

Spacetime symmetry solutions to strong CP

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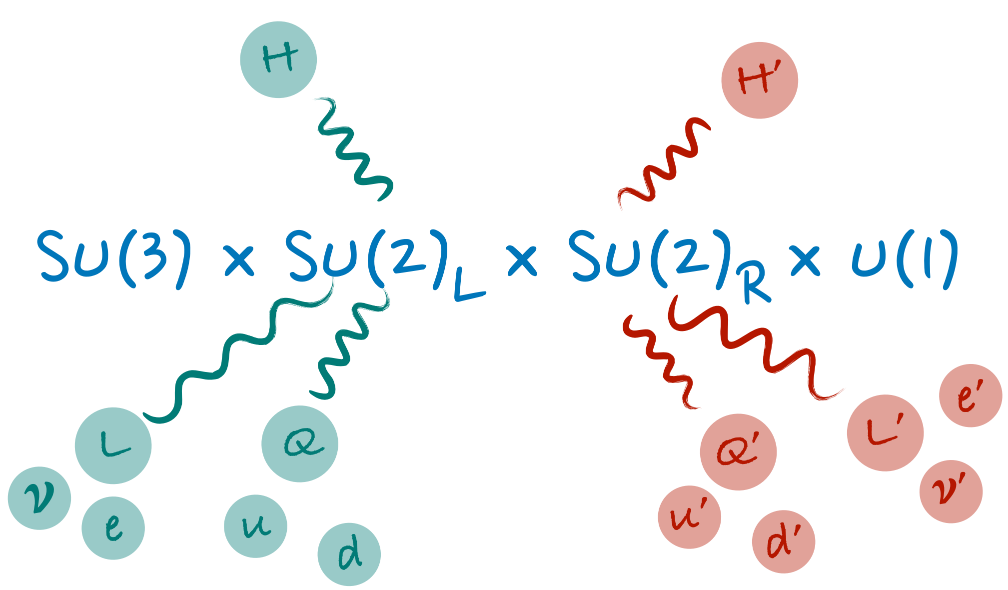
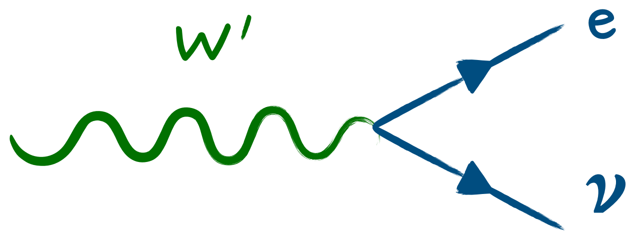


"Mirror" sector is an exact copy of the Standard Model, except that $SU(2)_L$ doublets become doublets of $SU(2)_R$

Parity solutions to strong CP

- Leading constraint on the parity-breaking scale from direct production of exotic gauge bosons at the LHC

ATLAS; 1906.05609



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Craig, **IGG**, Koszegi, McCune [2012.13416]

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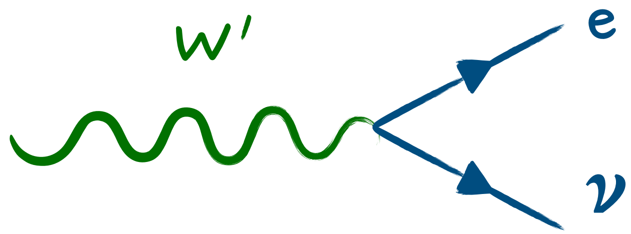

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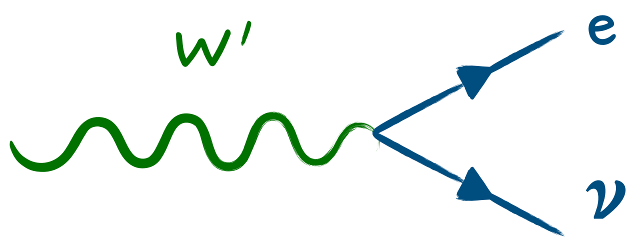

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- Interesting cosmological signatures, including gravitational waves

etc…

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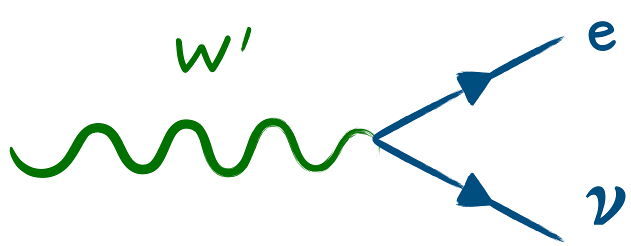

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Critical to explore new solutions to strong CP problem and their experimental implications

Craig, **IGG**, Koszegi, McCune [2012.13416]

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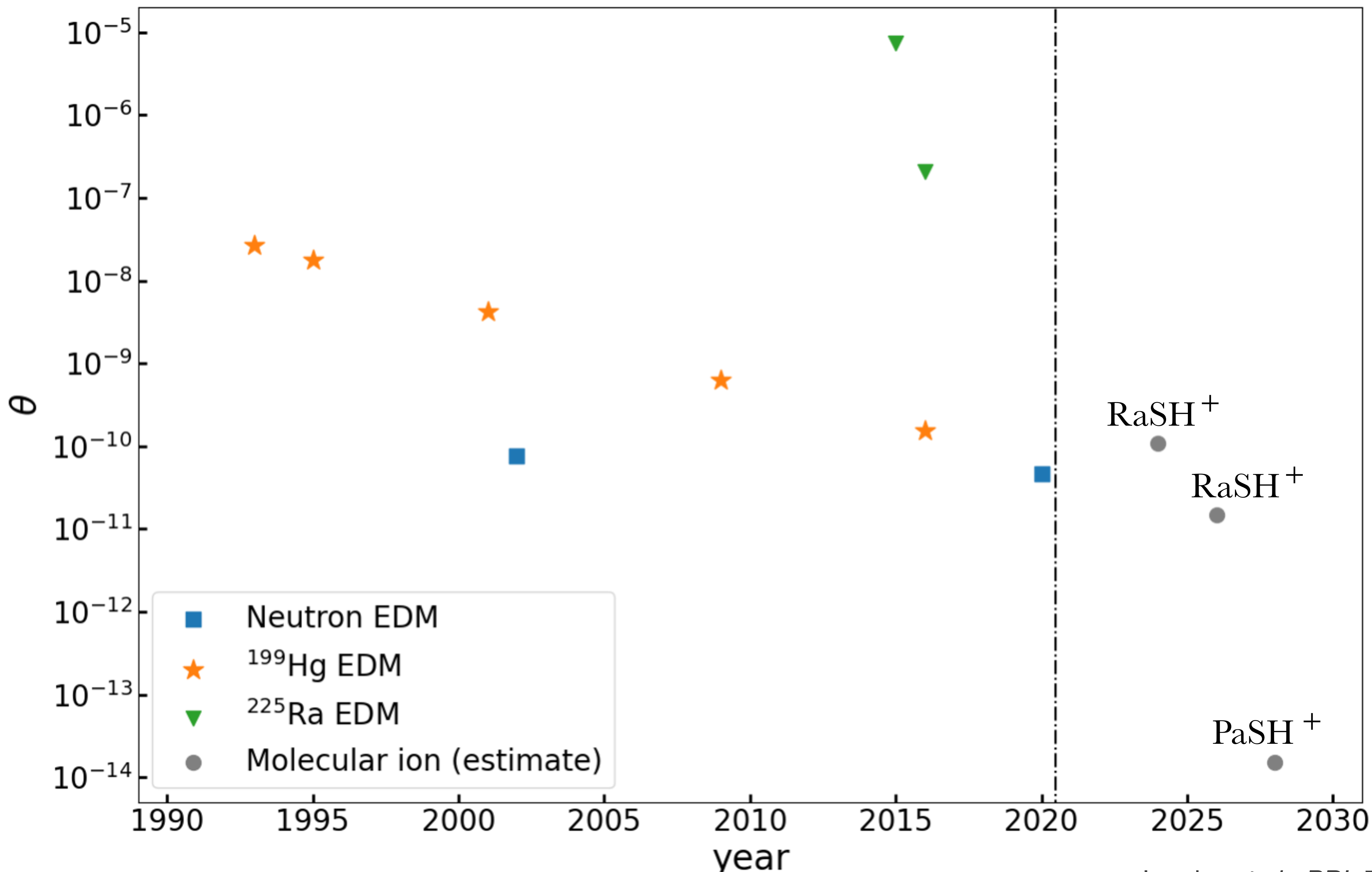

Pendlebury *et al.*, *PRD* **92**, 092003 (2015)
Abel *et al.*, *PRL* **124**, 081803 (2020)
Parker *et al.*, *PRL* **114**, 233002 (2015)
Bishof *et al.*, *PRC* **94**, 025501 (2016)

Jacobs *et al.*, *PRL* **71**, 3782 (1993)
Jacobs *et al.*, *PRA* **52**, 3521 (1995)
Romalis *et al.*, *PRL* **86**, 2505 (2001)
Griffith *et al.*, *PRL* **102**, 101601 (2009)
Graner *et al.*, *PRL* **116**, 161601 (2016)

Plot courtesy of A. Jayich's lab at UCSB (see also arXiv:2010.08709)

Today…

1. (My) highlights from the US P5 report

2. Gravitational waves and particle physics

3. Dark matter cornucopia

4. Strong-CP and flavor — beyond the QCD axion

5. Gravity and Effective Field Theory

6. QFT in the non-perturbative regime

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Rules of EFT need to be modified in a gravitational theory

evidence from black hole thought experiments
and formal research on string theory

Gravity and EFT

- Sub-extensive entropy:

$$S_{\rm BH} = \frac{A}{4\hbar G_N} \sim L^2 M_{\rm Pl}^2 \qquad \text{vs} \qquad S_{\rm QFT} \sim L^3 T^3 \lesssim L^3 \Lambda^3$$

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Can deviations from the EFT paradigm provide new light on some of the problems of the SM?

A few ideas… but a lot of room for exploration!

CC problem: Cohen, Kaplan, Nelson [9803132] + Banks, Draper [1911.05778]

EW hierarchy: Cheung, Remmen [1402.2287] + Craig, **IGG**, Koren [1904.08426]

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QFT beyond perturbation theory

Non-perturbative QFT crucial to understand
the Standard Model and beyond

- Despite numerical lattice simulations, still no proof of QCD confinement

- Soliton-like defects absent in the SM, but common in many extensions

e.g. domain walls, cosmic strings…

- Evolution and interactions of non-perturbative defects crucial to understand their evolution in the early universe

with implications for gravitational wave signatures and DM production

- Interest in new (generalized) symmetries — may play a role in particle physics

see e.g. [2205.09545] and refs.

- Quantum computer as simulators of strongly interacting theories and QFT in medium

Conclusions

Success in particle physics means never losing the drive to explore places we have never been before — at smaller distances or higher intensities

At the moment: many major puzzles + theoretical developments + diversity of experiments — an exciting time to be a particle physicist

Thank you!

Figure 1 – Program and Timeline in Baseline Scenario

Index: Operation, Construction, R&D, Research; P: Primary; S: Secondary

§ Possible acceleration/expansion in more favorable budget situations

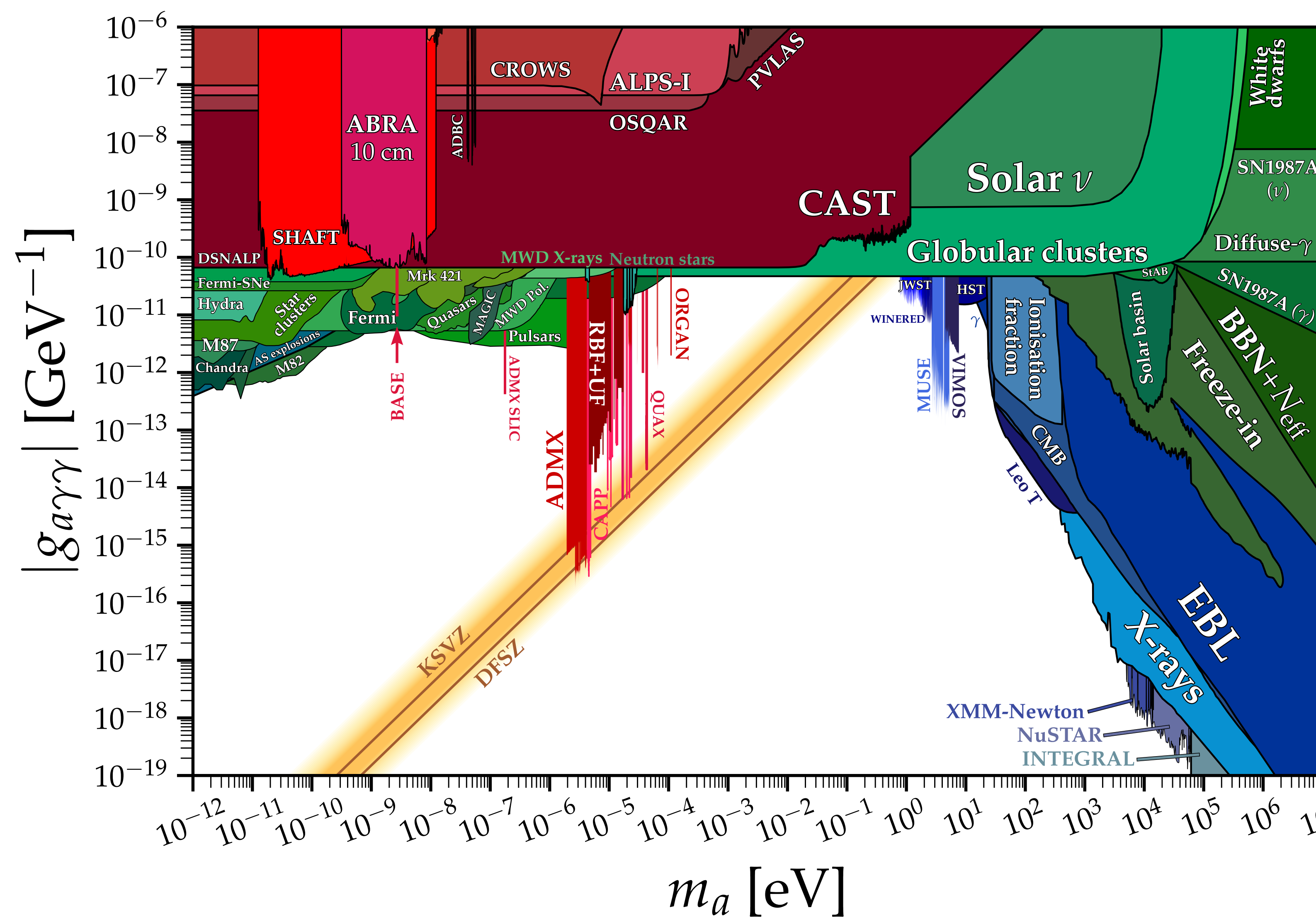
Science Experiments

Science Experiments	Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
LHC		P	P		P	P	
LZ, XENONnT			P				
NOvA/T2K	P				S		
SBN	P				S		
DESI/DESI-II	S		S	P			P
Belle II			S		S	P	
IceCube	P		S				P
SuperCDMS			P				
Rubin/LSST & DESC	S		S	P			P
Mu2e						P	
DarkSide-20k			P				
HL-LHC		P	P		P	P	
DUNE Phase I	P				S	S	S
CMB-S4	S		S	P			P
CTA			S				P
G3 Dark Matter §	S		P				
IceCube-Gen2	P		S				P
DUNE FD3	P				S	S	S
DUNE MCND	P				S	S	
Higgs factory §		P	S		P	P	
DUNE FD4 §	P				S	S	S
Spec-S5 §	S		S	P			P
Mu2e-II						P	
Multi-TeV §		P	P		P	S	
LIM	S		P	P			P

Science Drivers: Neutrinos, Higgs Boson, Dark Matter, Cosmic Evolution, Direct Evidence, Quantum Imprints

Small-Scale Experiments

Proliferation of many small-scale experiments over the last decade, many focused on detection of light bosons particles and dark matter



Recommendation to implement a new small-project portfolio:
"Advancing Science and Technology through Agile Experiments" (ASTAE)