

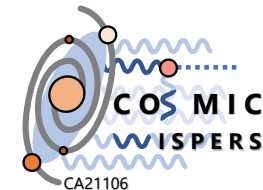
Axions and Other Wave-Like Dark Matter Candidates

Andreas Ringwald
Astroparticle Symposium 2025
Institut Pascal, Orsay, France
3-21 November 2025

HELMHOLTZ RESEARCH FOR
GRAND CHALLENGES

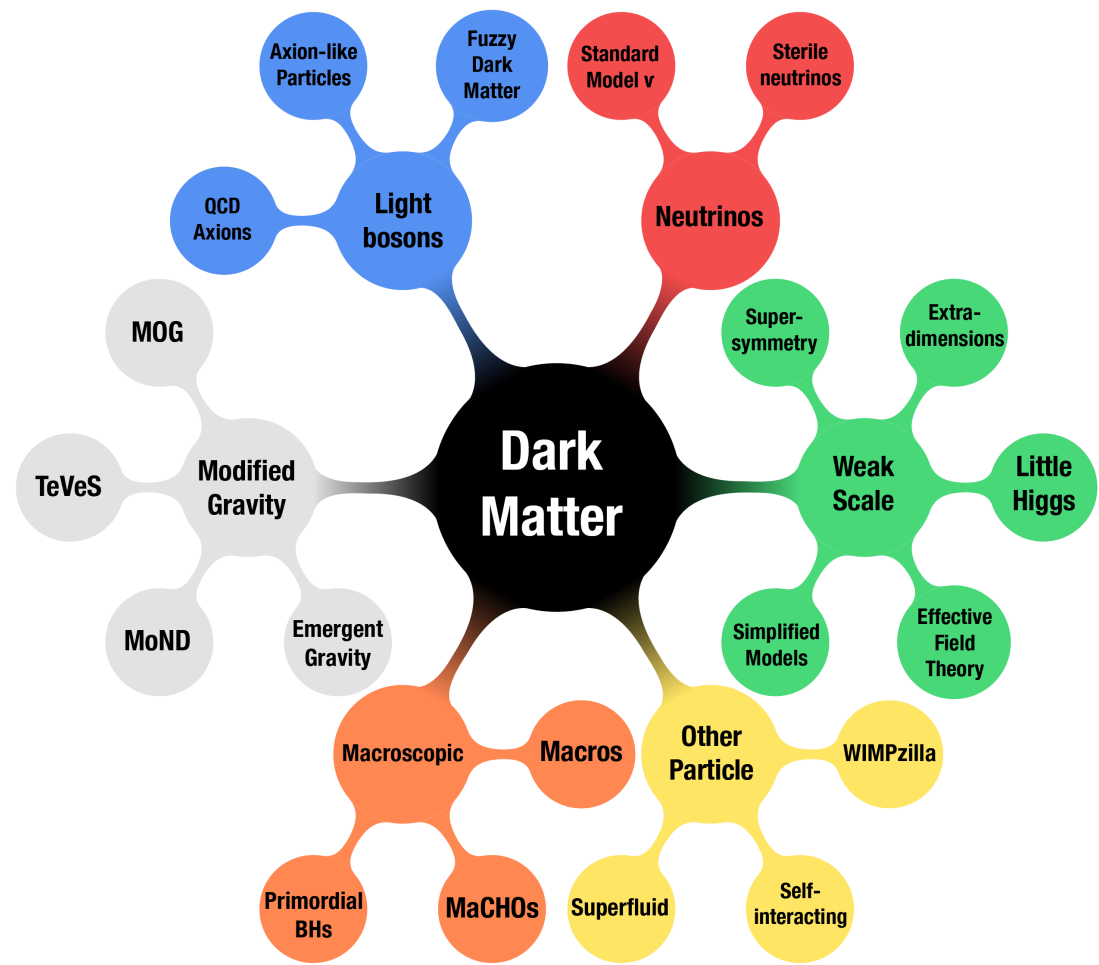
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

 **cost**
EUROPEAN COOPERATION
IN SCIENCE & TECHNOLOGY



Dark Matter Puzzle

Plenty of proposed solutions

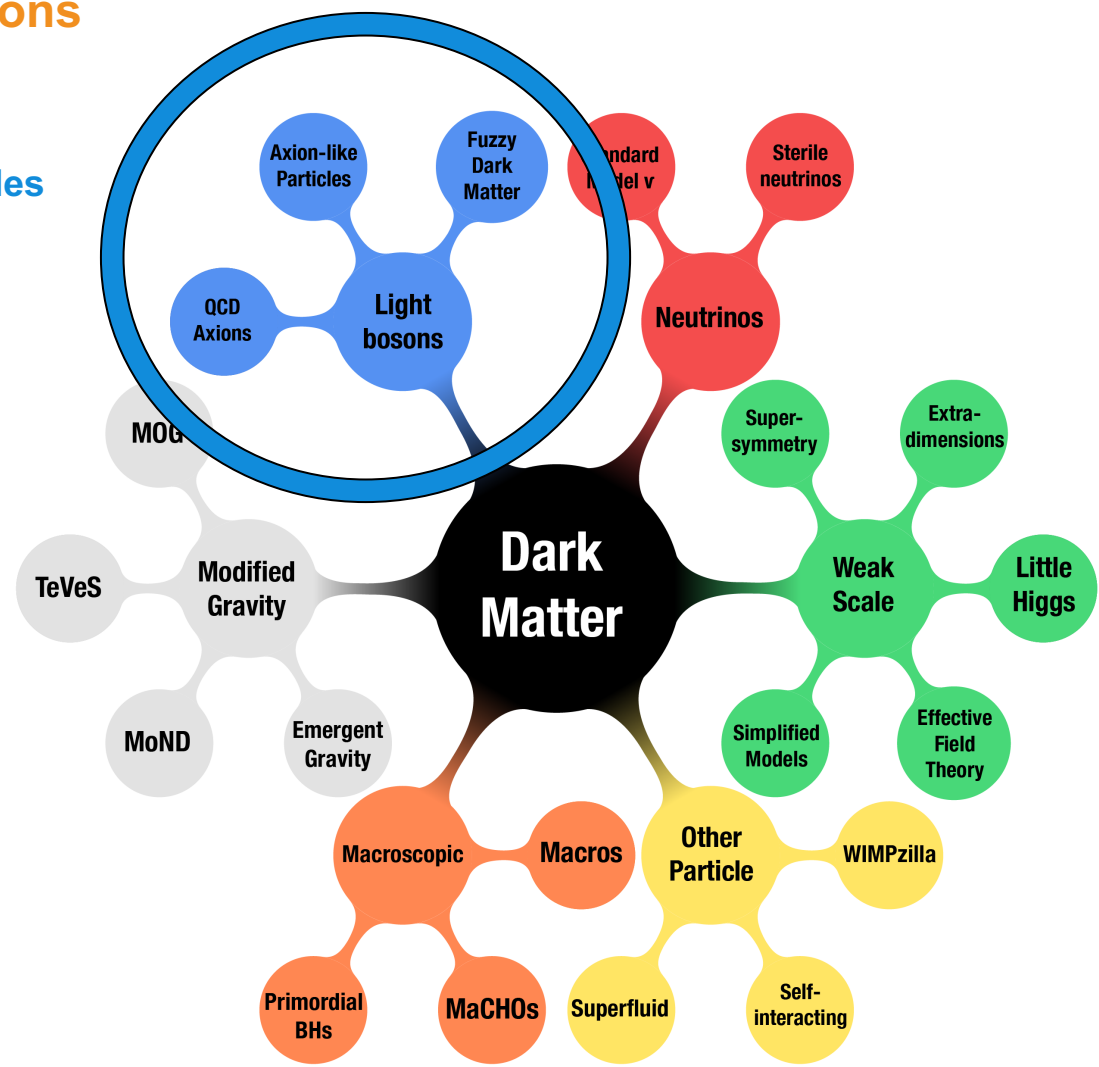


[Bertone,Tait, Nature 562 (2018) 7725, 51-56]

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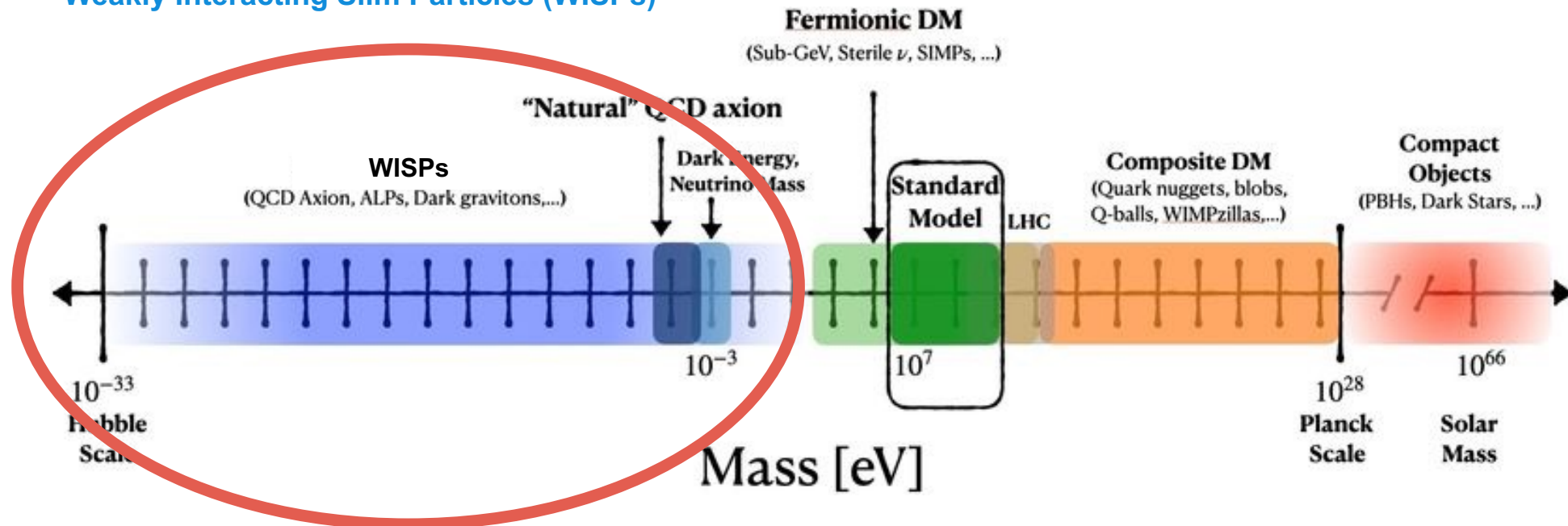
Weakly Interacting Sub-eV Particles
(WISPs)



[Bertone,Tait, Nature 562 (2018) 7725, 51-56]

Why Are We Interested in Bosonic WISPs?

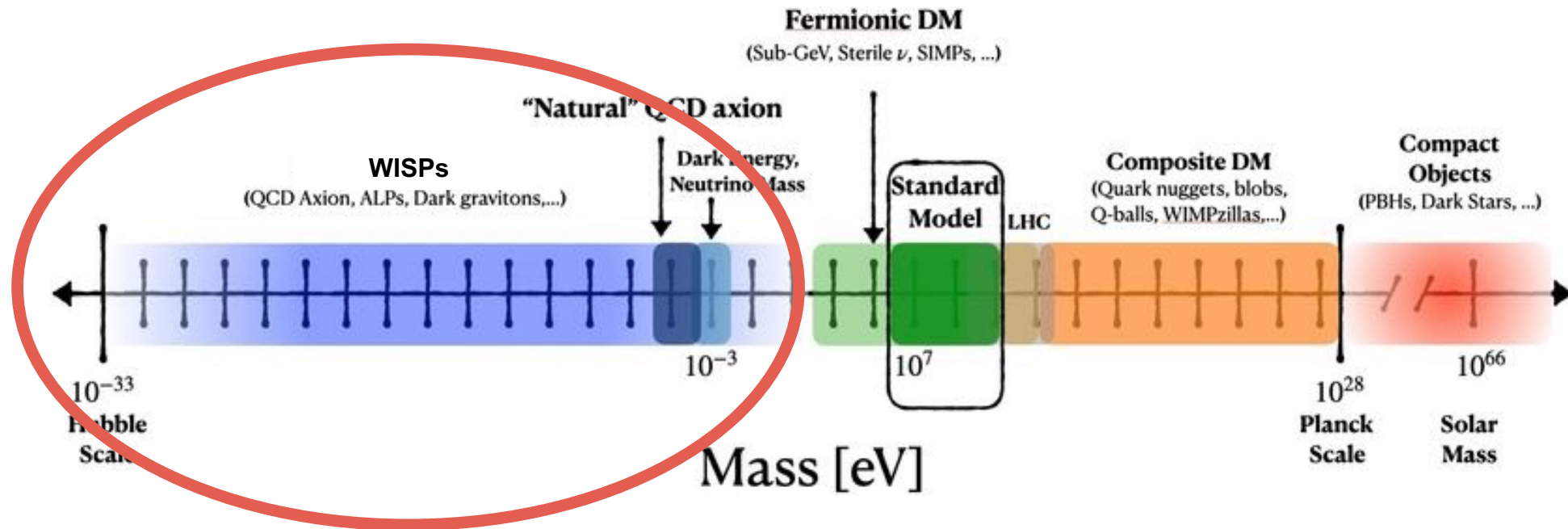
Weakly Interacting Slim Particles (WISPs)



adapted from [Prabhu, <https://aniprabhu.com>]

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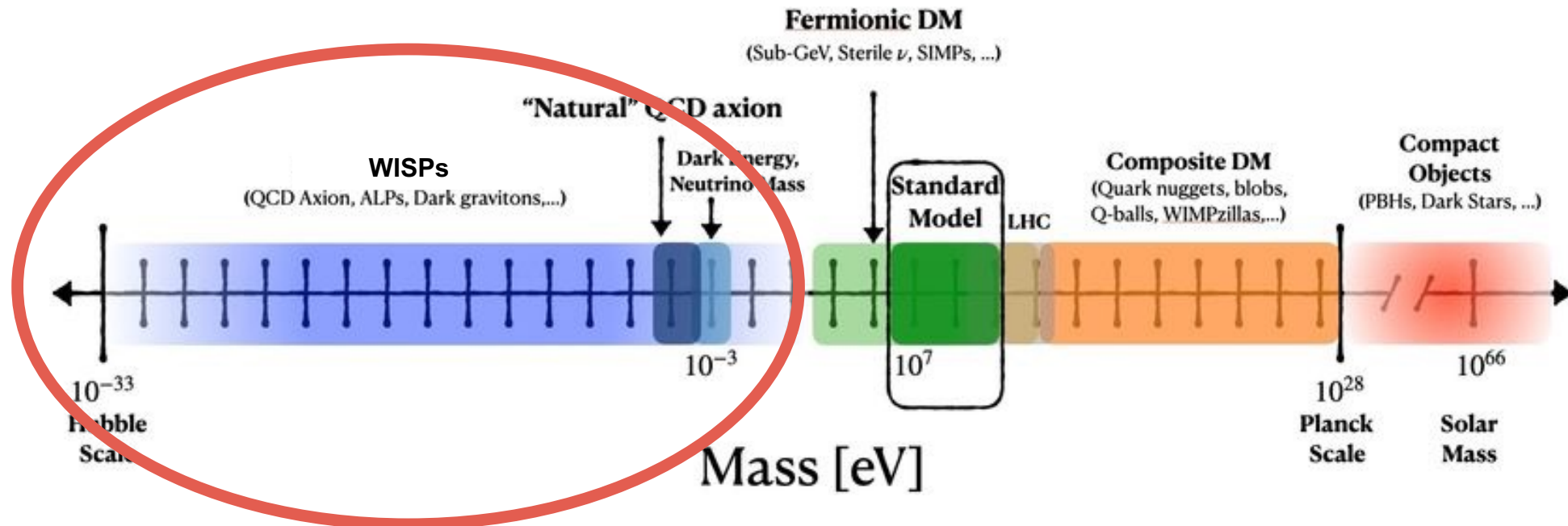
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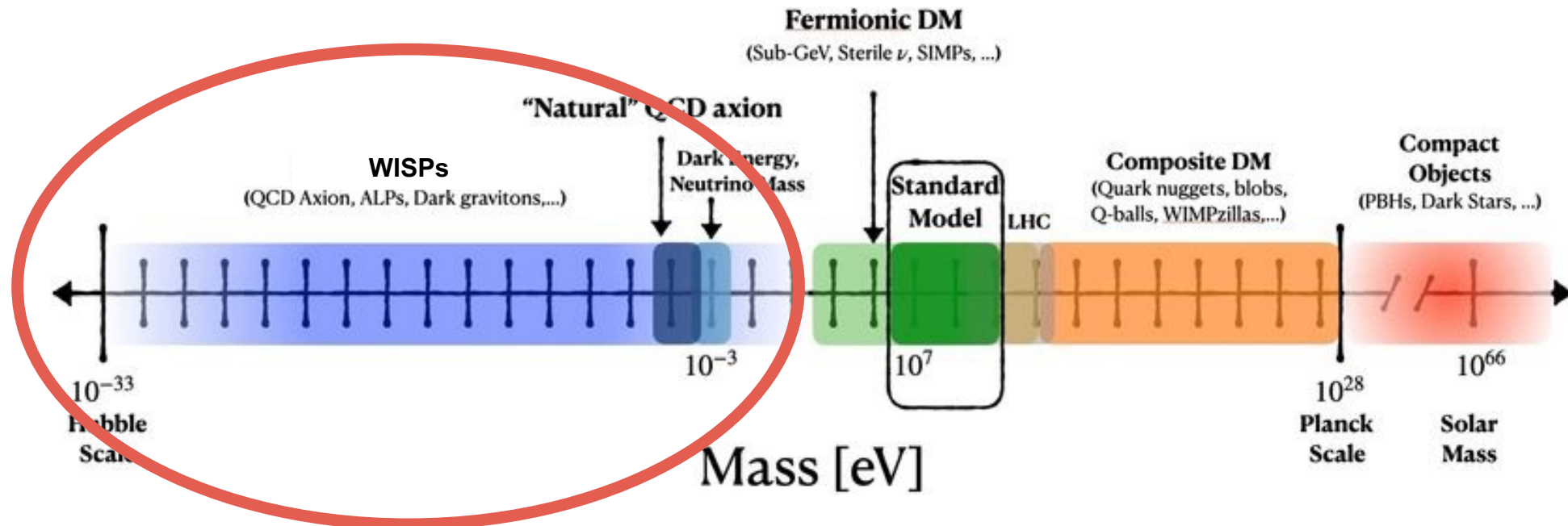
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1. Because they are well motivated BSM (Beyond the Standard Model) particles!
2. Because they are well motivated Dark Matter (DM) candidates!
3. Because they can be hunted in astrophysics and experiment!



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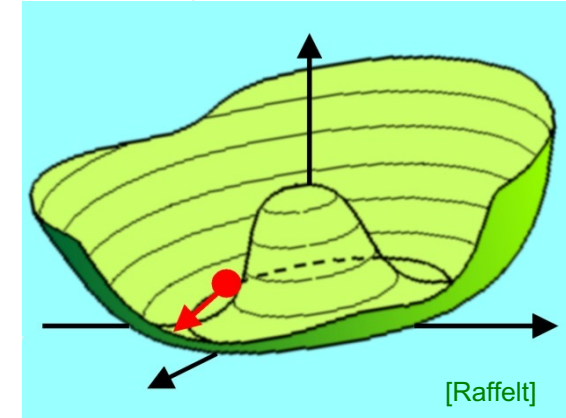
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Spin-0 WISPs

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Pseudo Nambu-Goldstone bosons arising from the breaking of **well-motivated symmetries** beyond the Standard Model (SM) at a scale much larger than the electroweak scale

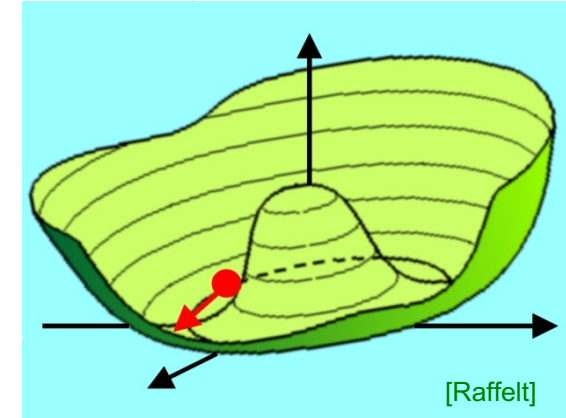


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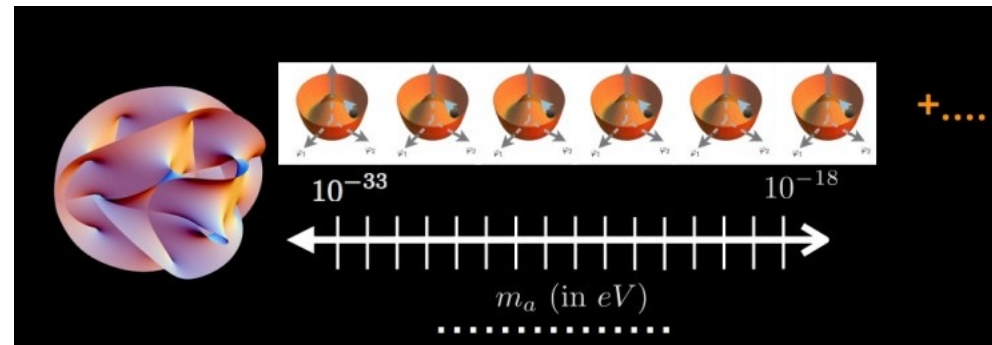
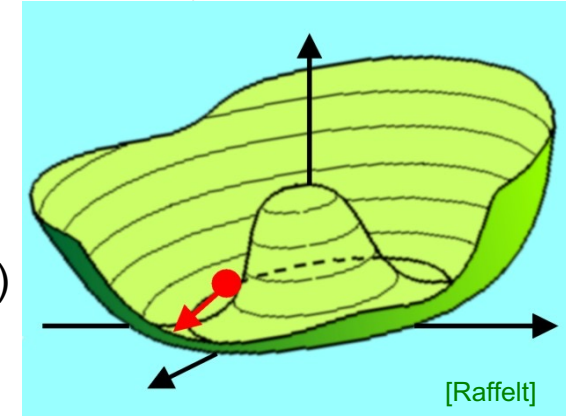
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[<http://danielgrin.net/2015/11/23/>]

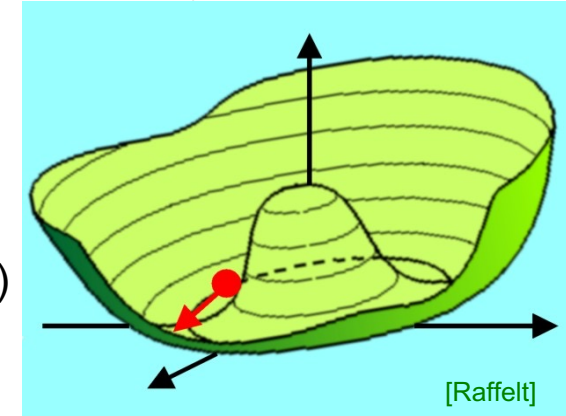
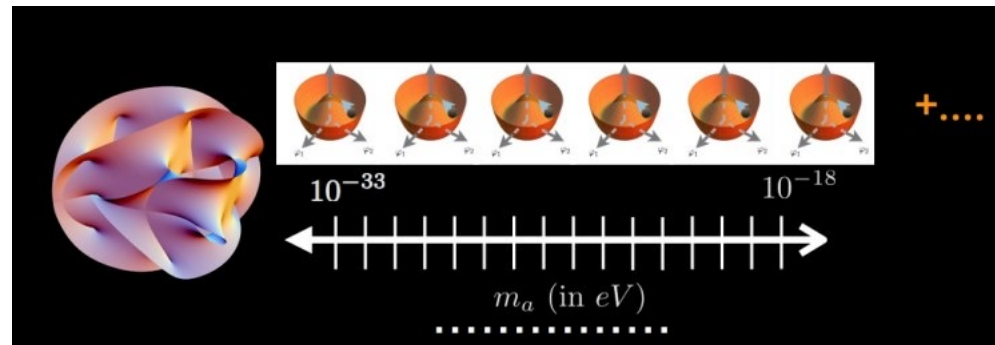
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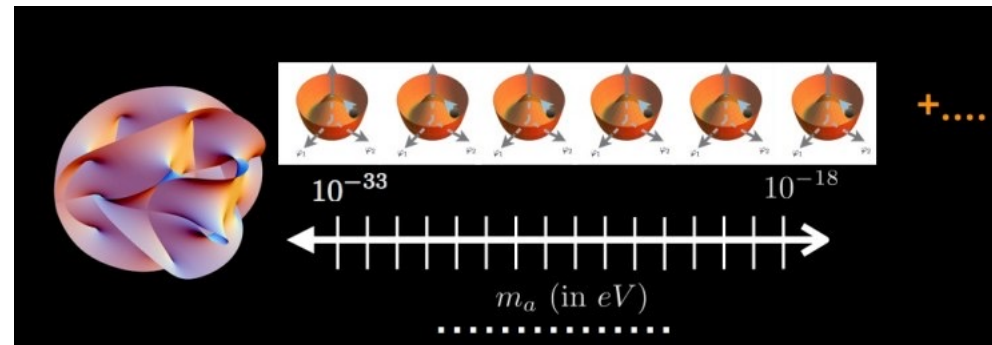
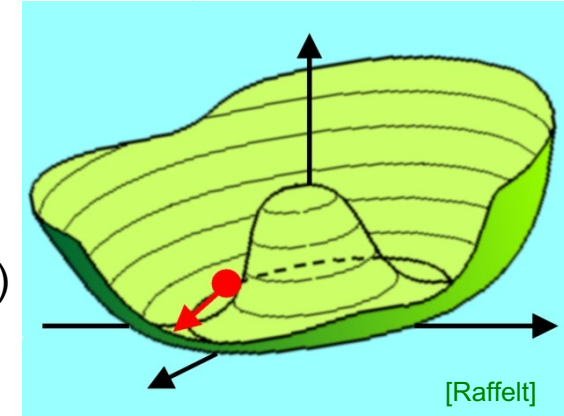
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can be **naturally slim:**

Massless as long as symmetry exact; **small mass** from tiny (non-perturbative) explicit symmetry breaking

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[Holdom 86]

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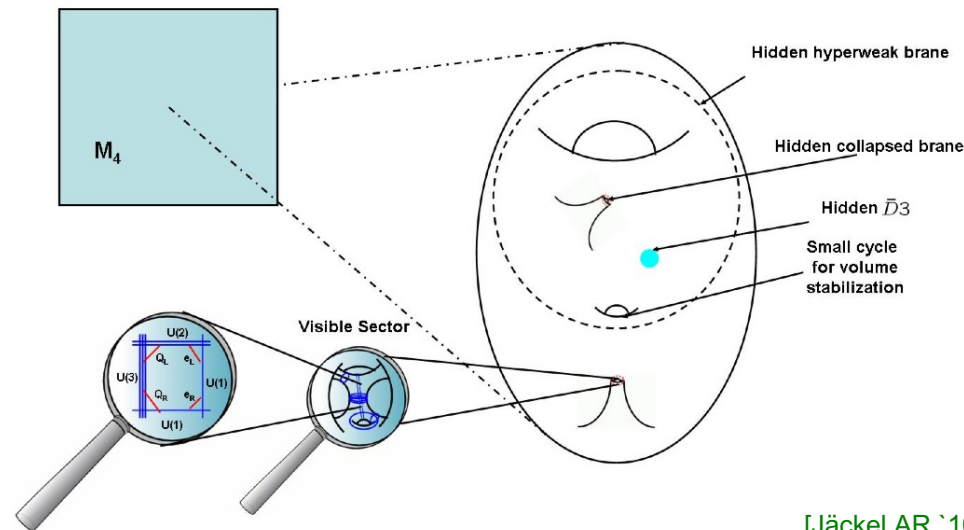
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[Hebecker, Jaeckel, Kuespert, 2311.10817]



[Jäckel,AR `10]

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can be **naturally slim**:

Gauge symmetry forbids explicit mass terms; small mass generated via hidden Higgs or Stückelberg mechanism

Bosonic WISPs are Well Motivated BSM Particles!

Spin-2 WISPs

“Hidden” or “dark” graviton – an extra massive spin-2 particle beyond the graviton -

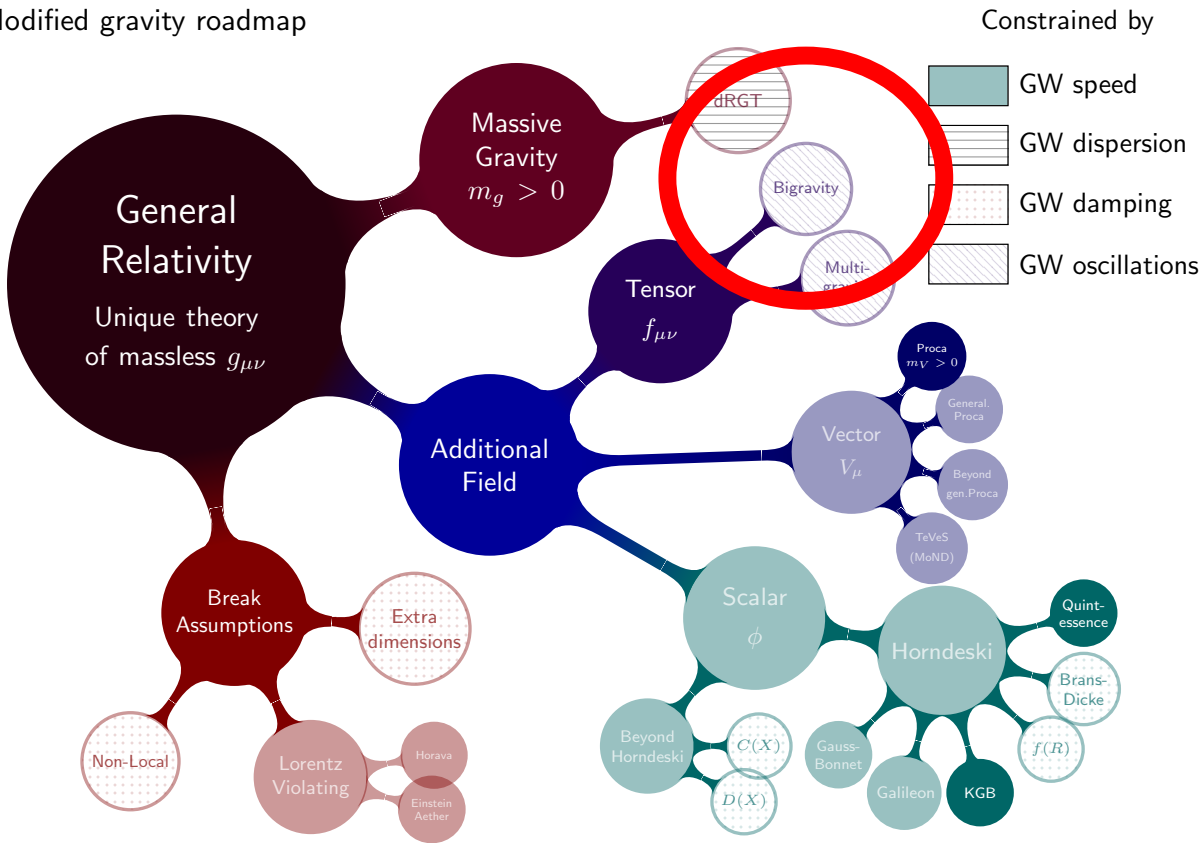
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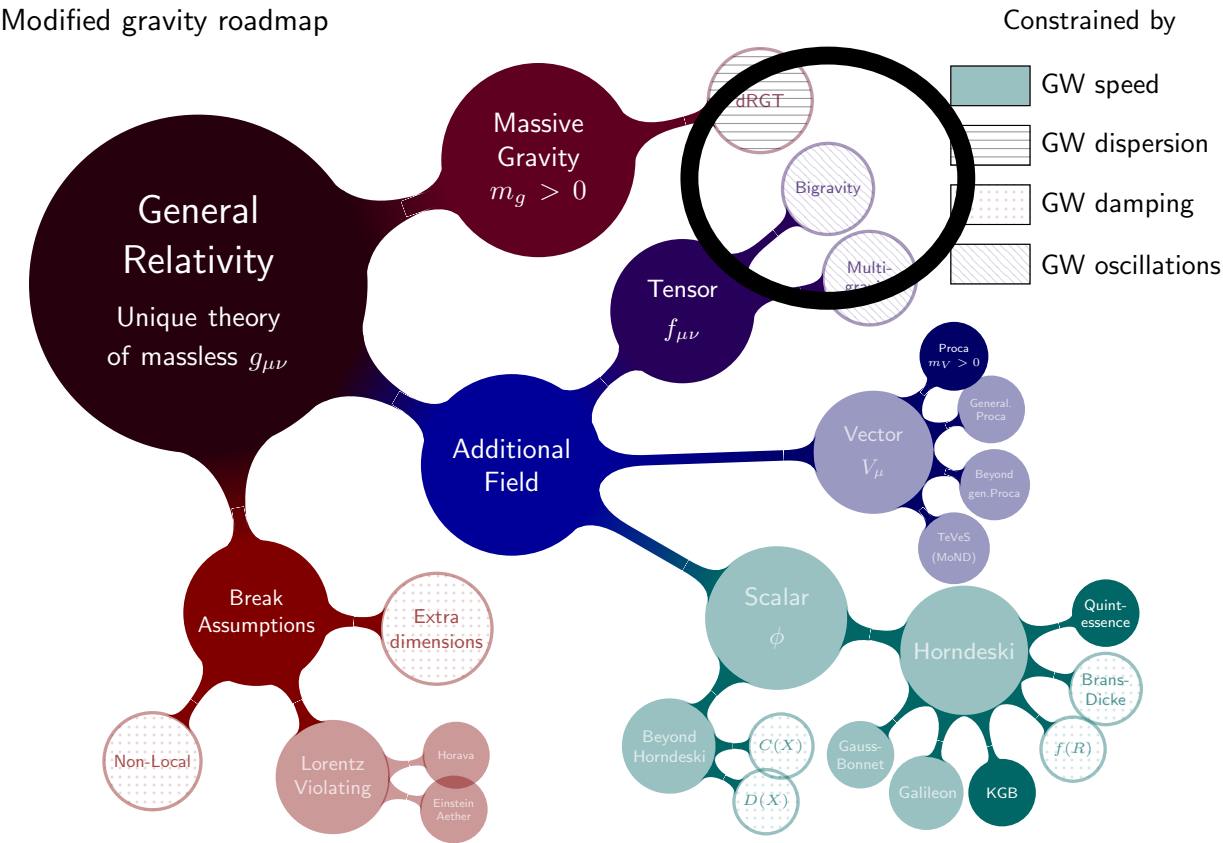
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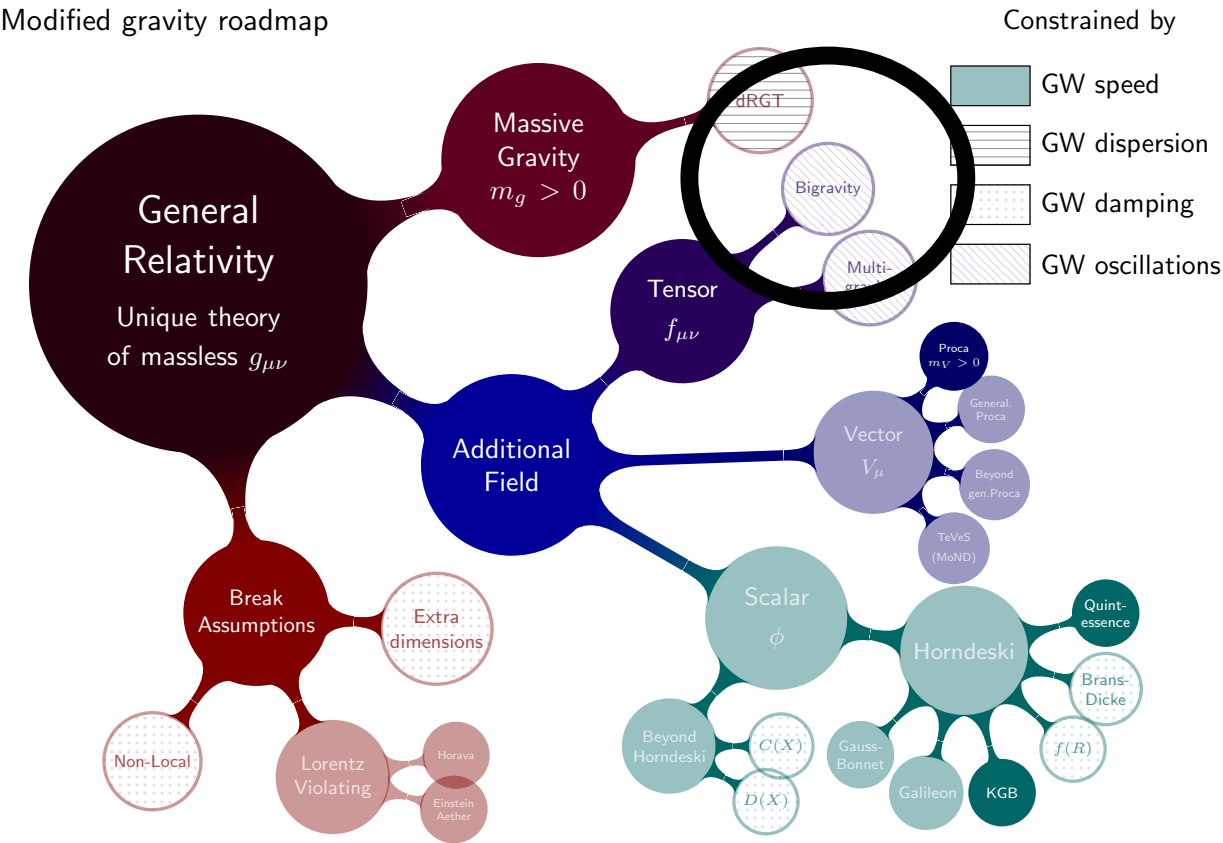
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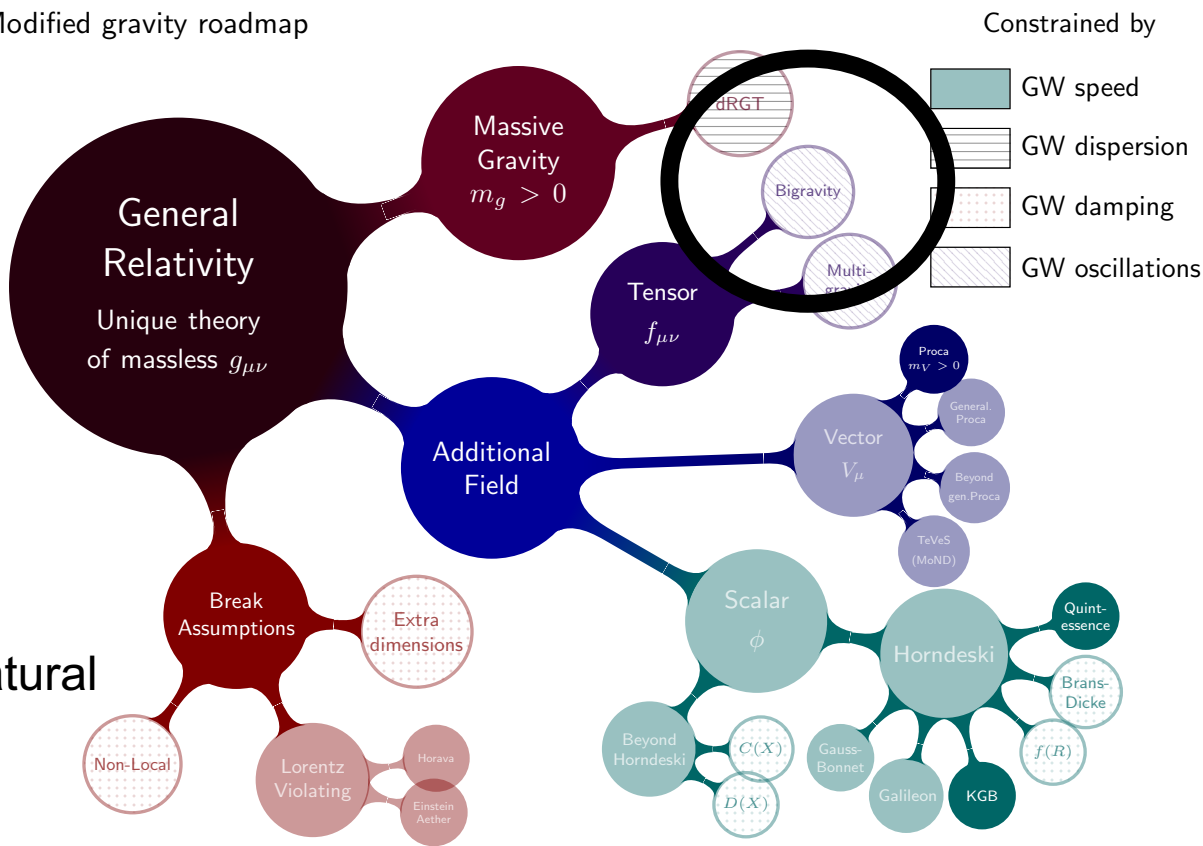
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can be **naturally slim**:

Arbitrarily small mass for massive spin-2 technically natural

[de Rham,Gabadadze,Heisenberg,Pirtskhalava , 1212.4128]

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Bosonic WISPs are Well Motivated DM Candidates!

Generic properties of WISPy dark matter

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WISPs constituting the Galactic Dark Halo have a macroscopic de Broglie wavelength,

$$\lambda_{\text{dB}} = \frac{2\pi}{m_{\text{WISP}} v_{\text{d}}} = 1.5 \text{ mm} \left(\frac{\text{eV}}{m_{\text{WISP}}} \right) \left(\frac{250 \text{ km/s}}{v_{\text{d}}} \right)$$

and therefore a huge occupation number per de Broglie volume:

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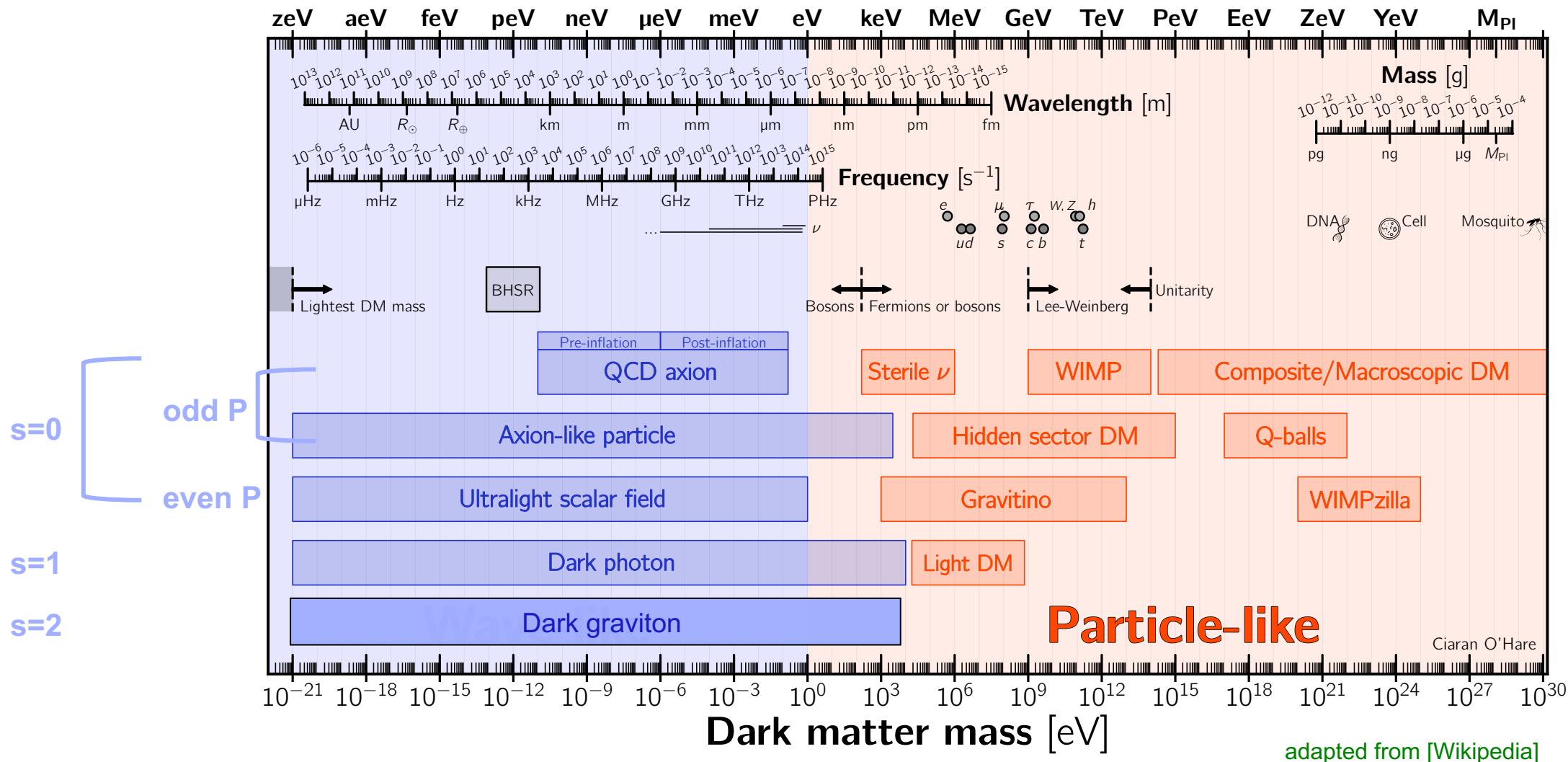
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- **WISPy Dark Matter** is most conveniently described by classical waves. Therefore also known as

Wave-Like Dark Matter

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Several candidates for different spin and parity

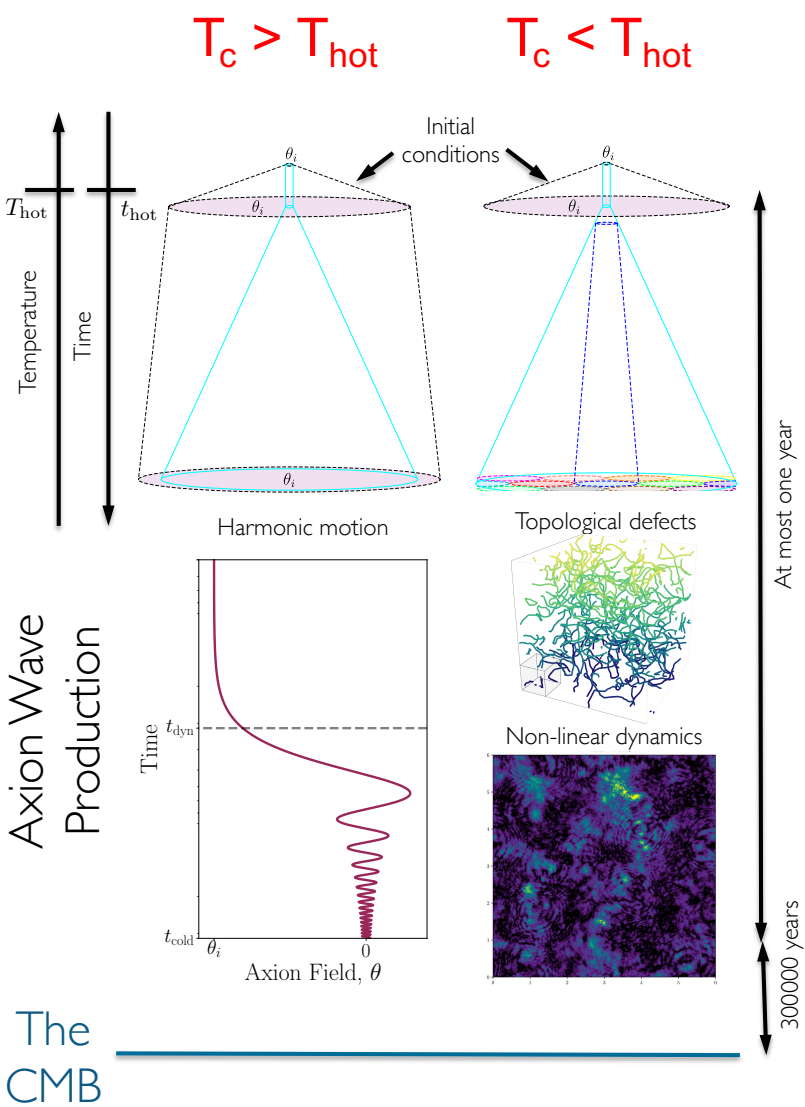


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DM production mechanisms support entire possible mass range

- Axion, ALPs, Dilaton, DILPs:
 - Preinflationary symmetry breaking: misalignment mechanism (conventional, kinetic, trapped, ...)
 - Postinflationary symmetry breaking: decay of topological defects

[Preskill,Wise,Wilczek `83; Abbott,Sikivie `83; Dine,Fischler `83; ... Co,Hall,Harigaya `20; ... Di Luzio et al. `21; ... Davis `86; ...]



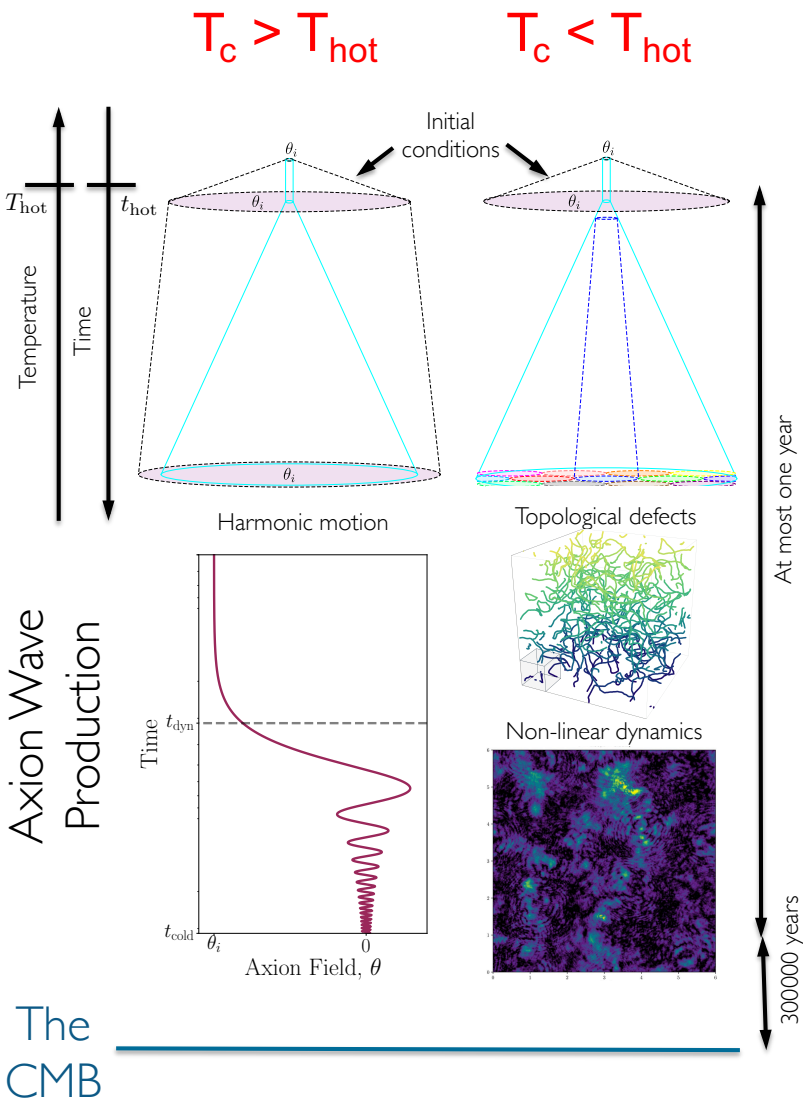
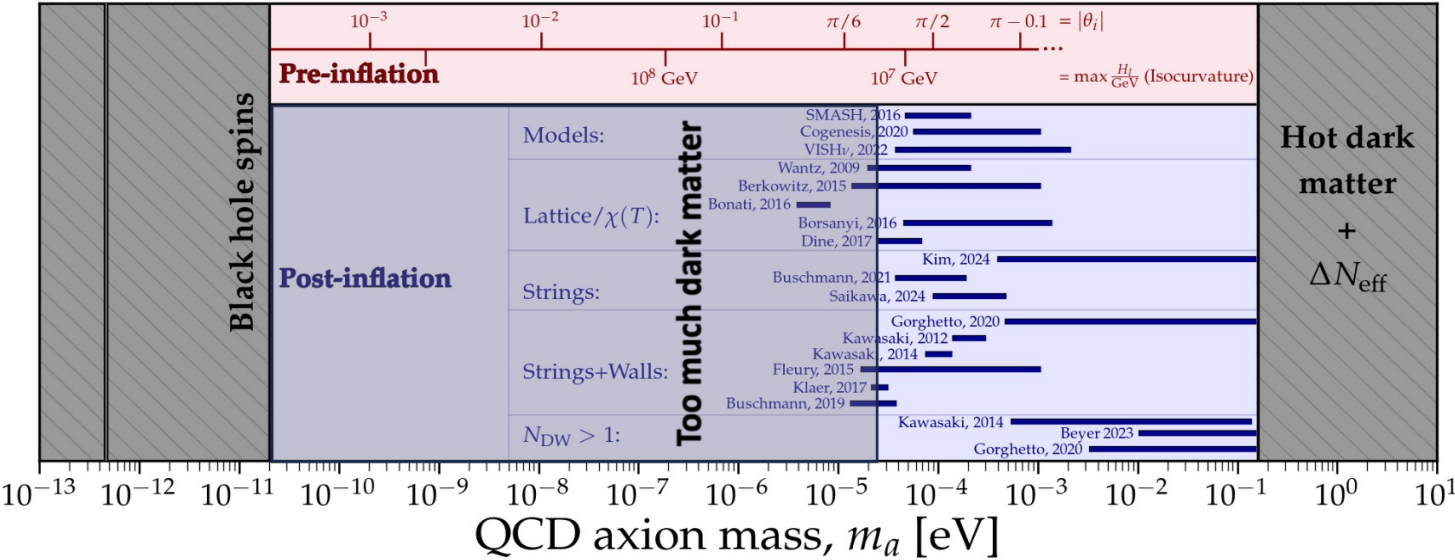
[Chadha-Day,Ellis,Marsh, Science Advances `22]

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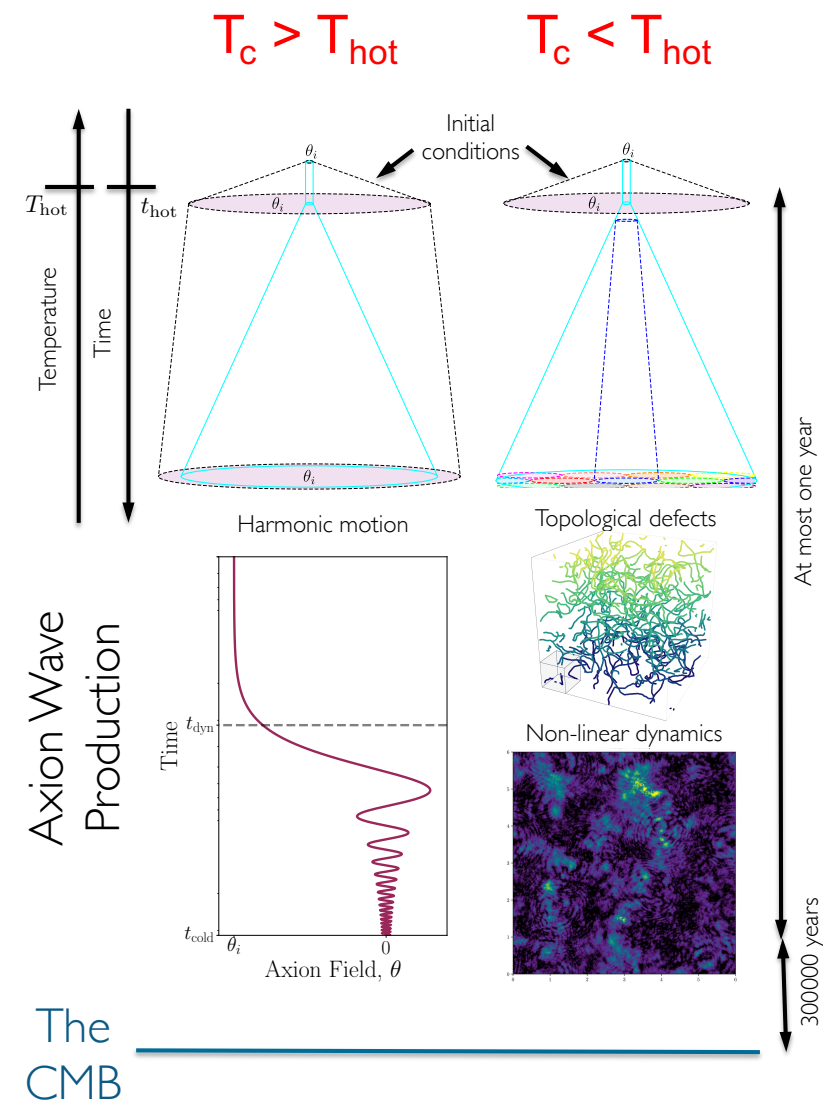
[adapted from https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/AxionMass.png

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- **Dark photons:**
 - Vector misalignment (requires finetuning of initial value or non-minimal coupling to gravity)
[Nelson,Scholtz, 1105.2812;
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 - Inflationary production
[Graham,Mardon,Rajendran, 1504.02102]
 - Production via an oscillating ALP
[Agrawal,Kitajima,Reece,Sekiguchi,Takahashi, 1810.07188]



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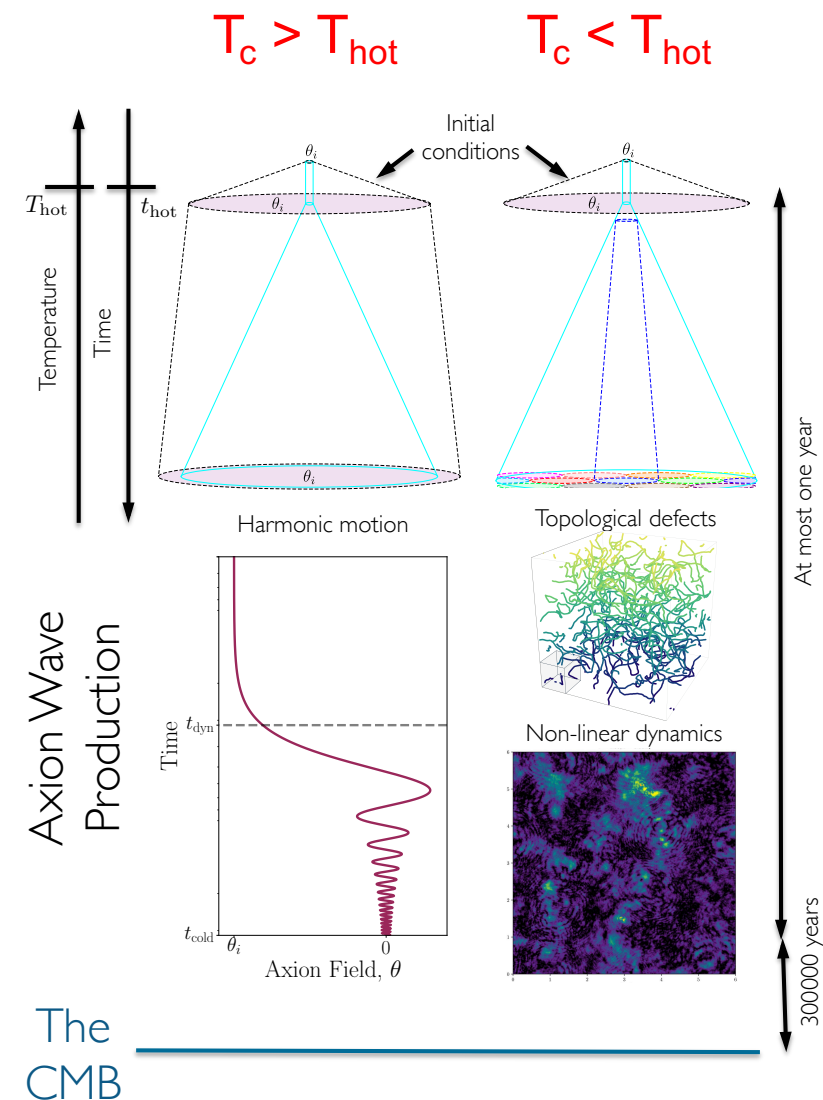
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- **Dark gravitons:**

- Tensor misalignment

[Marzola,Raidal,Urban, 1708.04253]



Bosonic WISPs Can Be Hunted in Astro and Exp!

Bosonic WISPs have tiny but non-zero interactions with SM

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Spin-0 WISP:

- Parity odd (Axion, ALP):

$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{1}{2} \sum_f \frac{g_{af}}{m_f} \partial_\mu a \bar{\psi}_f \gamma^\mu \gamma_5 \psi_f$$

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Spin-1 WISP (Dark Photon):

- Kinetic mixing, $\mathcal{L} \supset -\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$, for hidden U(1), or gauge coupling, for U(1)_B or U(1)_{B-L}

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Spin-0 WISP:

- Parity odd (Axion, ALP):

$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{1}{2} \sum_f \frac{g_{af}}{m_f} \partial_\mu a \bar{\psi}_f \gamma^\mu \gamma_5 \psi_f$$

- Parity even (Dilaton, DILP):

$$\mathcal{L} \supset \frac{1}{4} g_{\phi\gamma} \phi F_{\mu\nu} F^{\mu\nu} - \sum_f g_{\phi f} \phi \bar{\psi}_f \psi_f$$

Spin-1 WISP (Dark Photon):

- Kinetic mixing, $\mathcal{L} \supset -\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$, for hidden U(1), or gauge coupling, for U(1)_B or U(1)_{B-L}

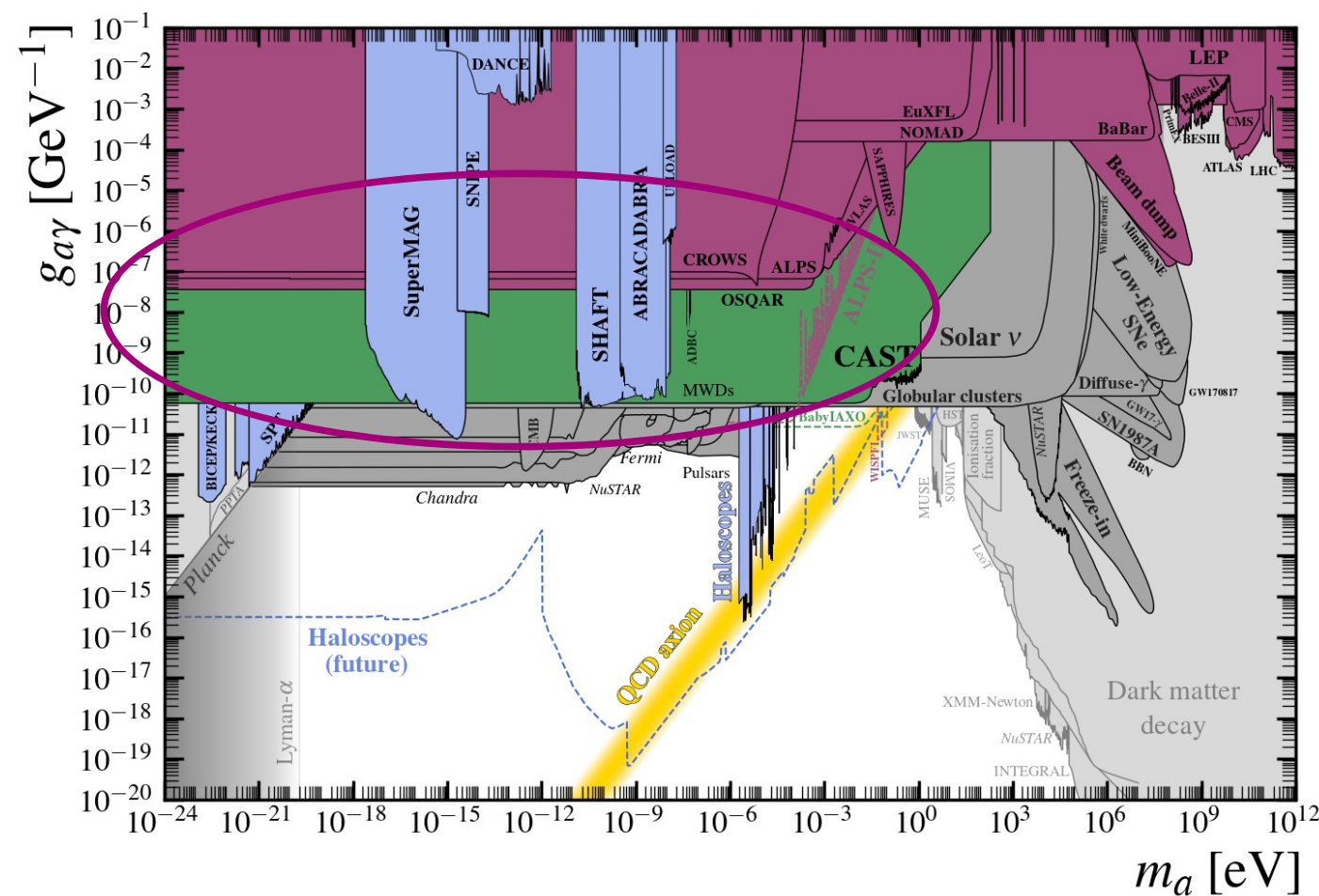
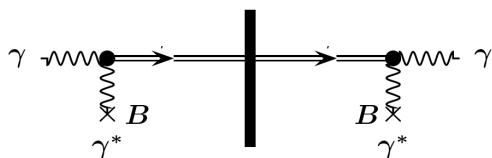
Spin-2 WISP (Dark Graviton)

- Interacts at the linearized level with SM like the graviton with a Fierz-Pauli mass term and an effective gravitational constant G'

Bosonic WISPs Can Be Hunted in Astro and Exp!

Experimental techniques to search for lab-produced or solar WISPs

- **Light-Shining-Through-Walls:**
 - Photon \leftrightarrow **ALP**/dark graviton conversion in magnetic field



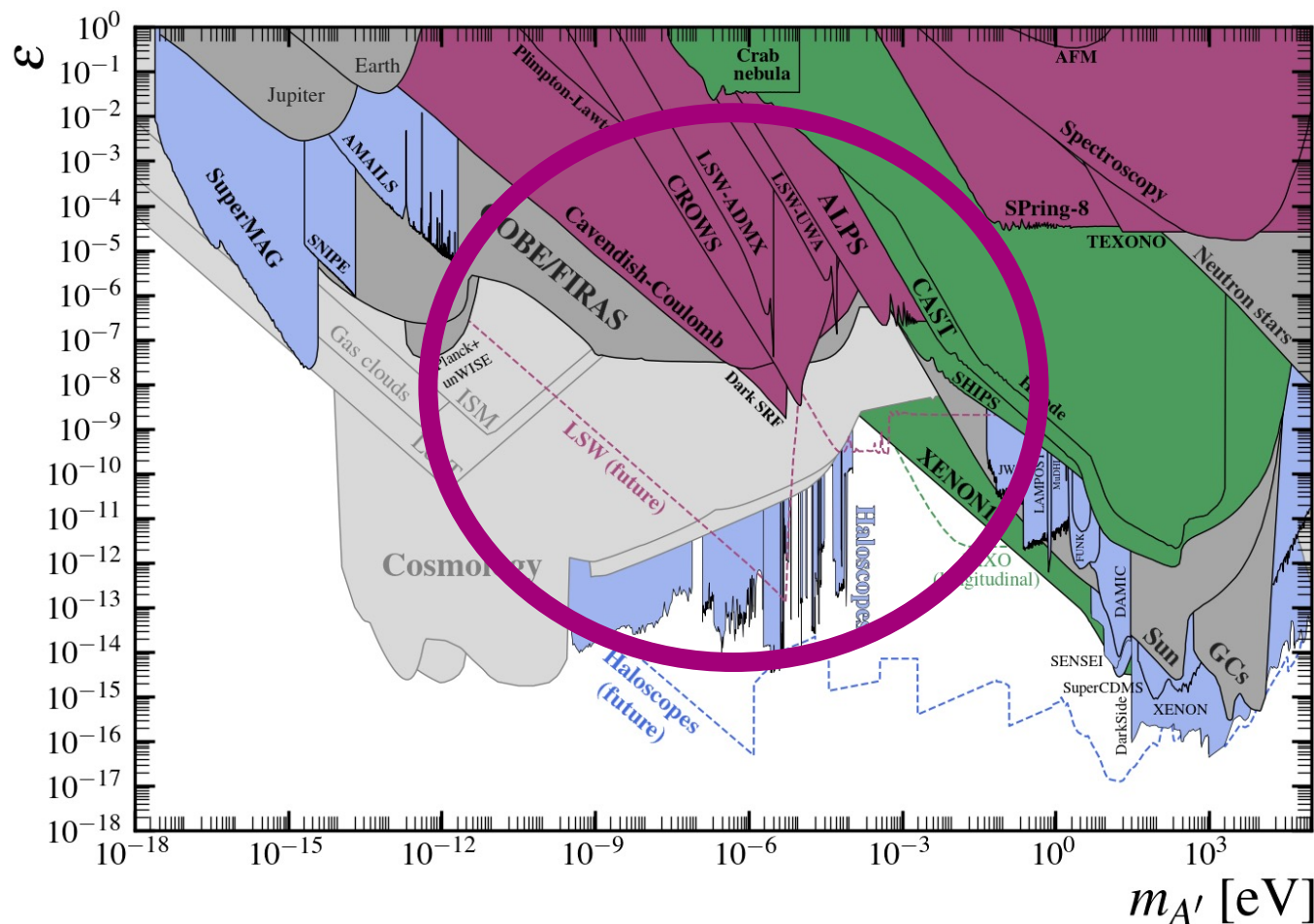
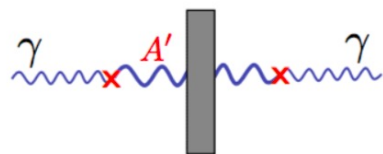
[https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/AxionPhoton_FIPS.png]

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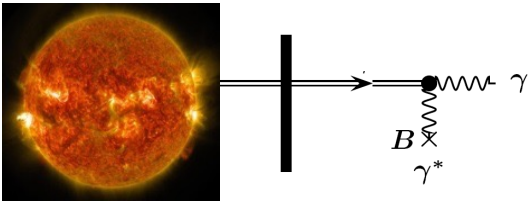
[https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/DarkPhoton_FIPS.png]

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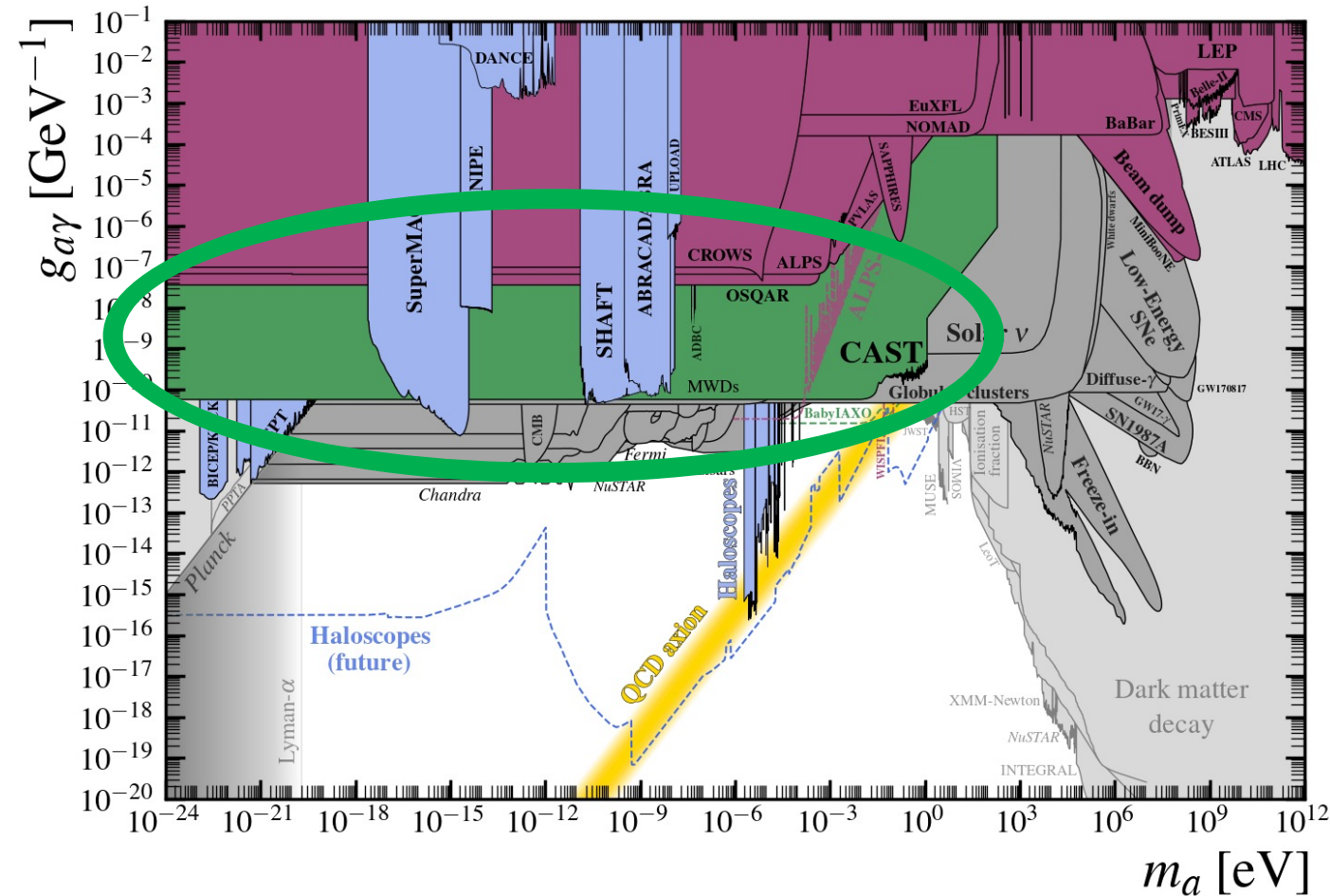
- Photon \leftrightarrow ALP/dark graviton conversion in magnetic field
- Photon \leftrightarrow dark photon conversion in vacuum



- **Helioscopes:**

- Solar **ALP**/dark graviton \rightarrow photon conversion in magnetic field

Talk by Esther Ferrer Ribas



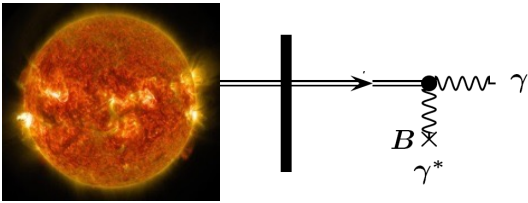
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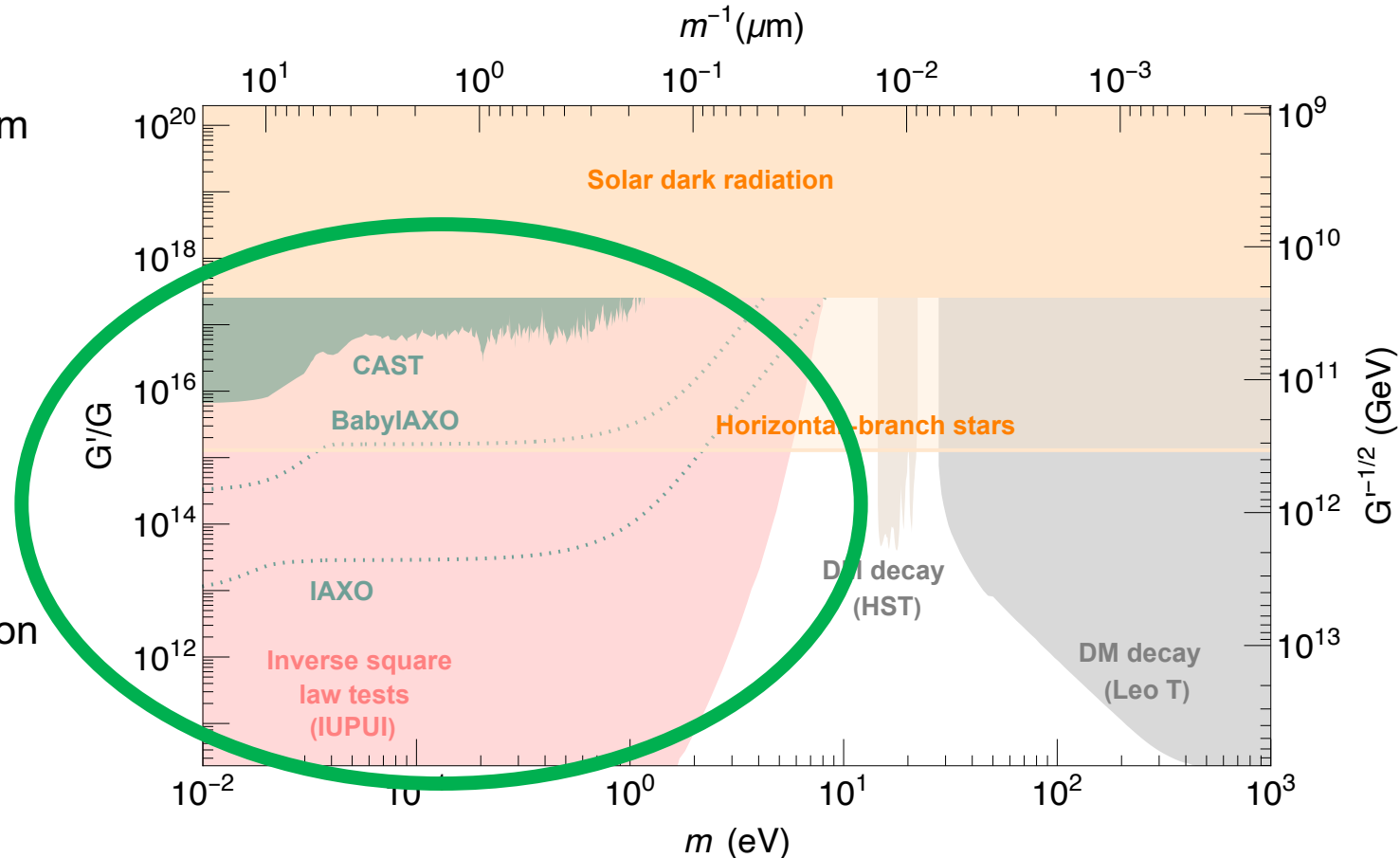
- **Light-Shining-Through-Walls:**

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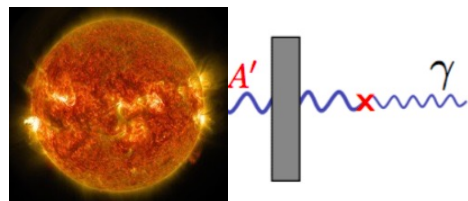
[Galan,Garcia-Cely,AR , 2511.03707]

Bosonic WISPs Can Be Hunted in Astro and Exp!

Experimental techniques to search for lab-produced or solar WISPs

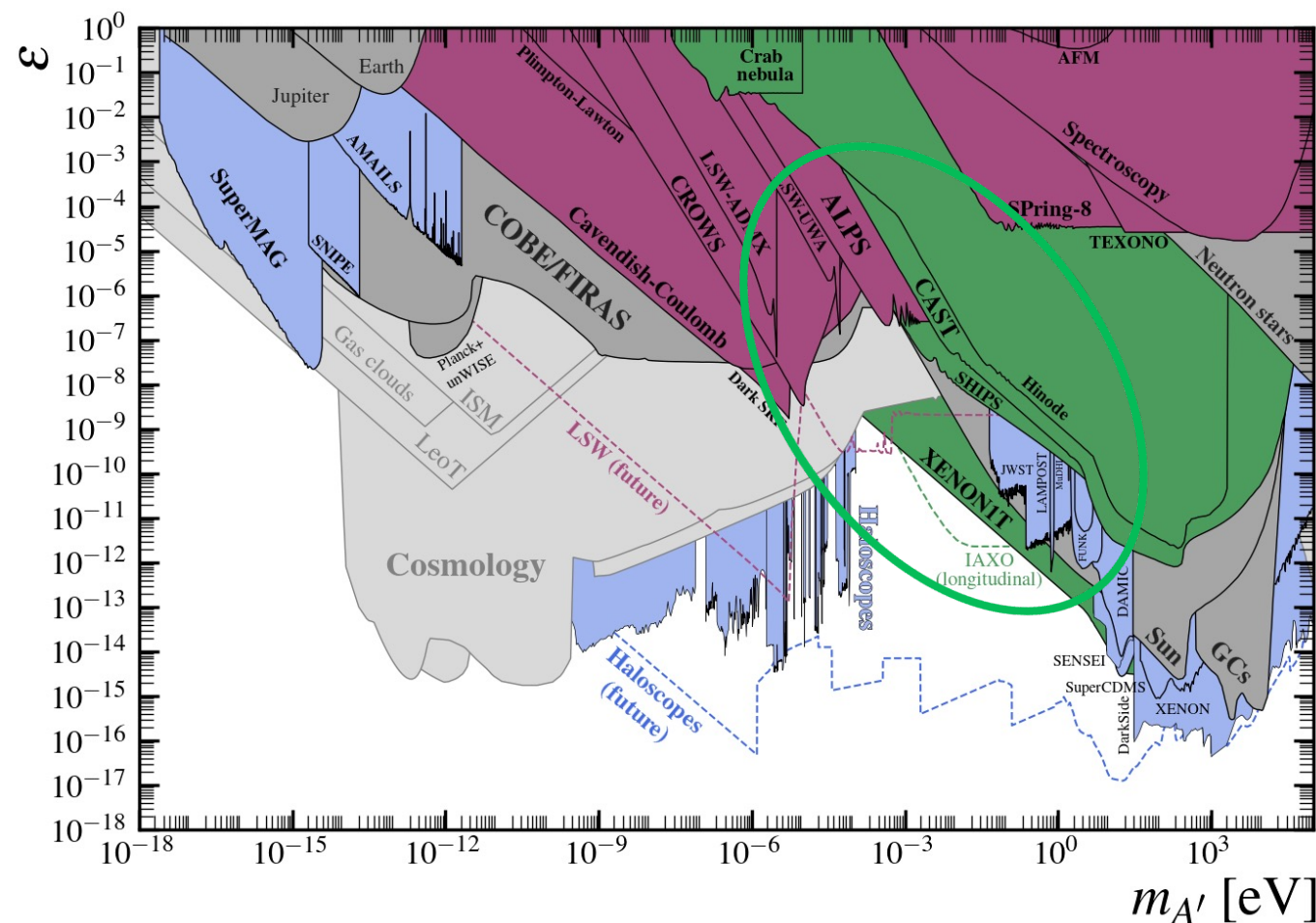
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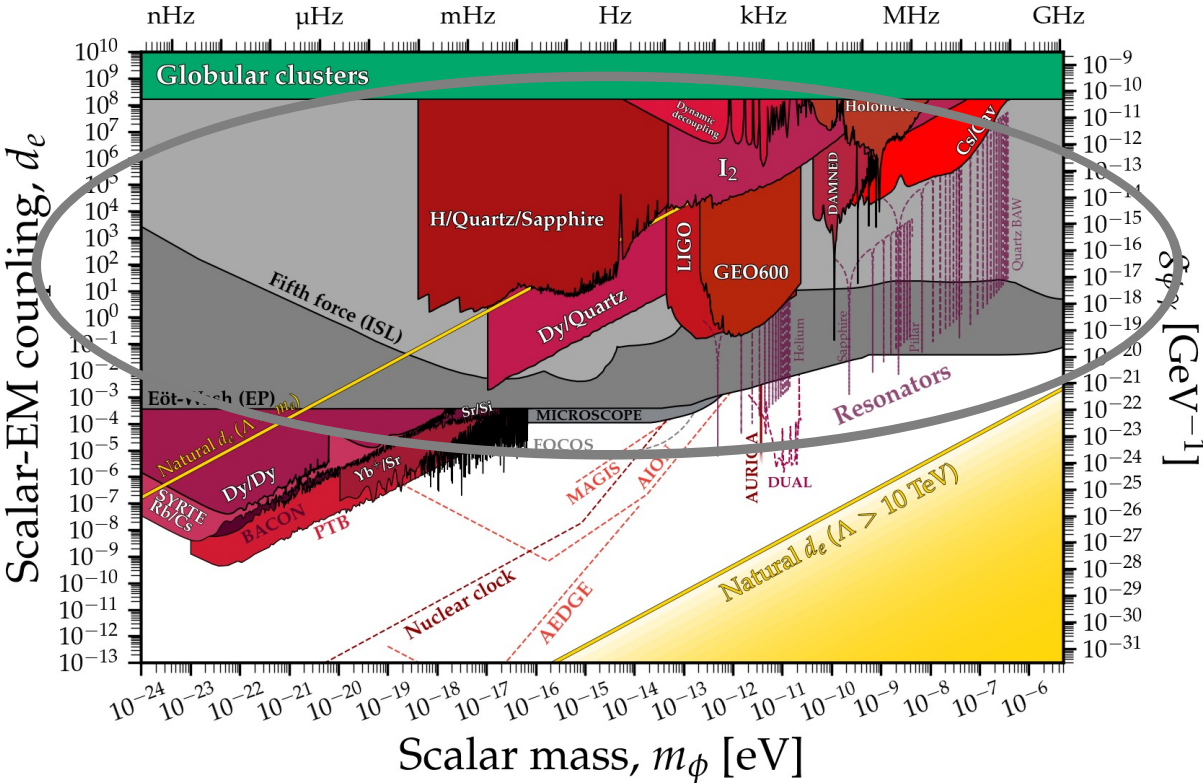


[https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/DarkPhoton_FIPS.png]

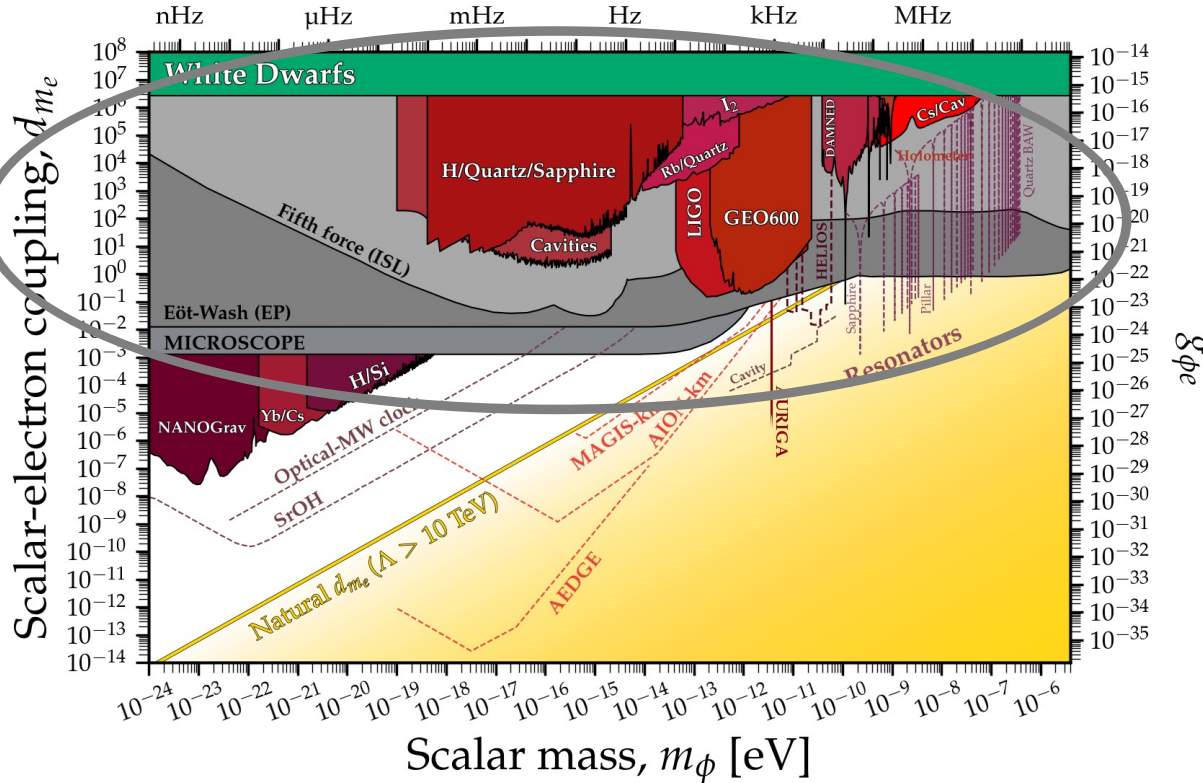
Bosonic WISPs Can Be Hunted in Astro and Exp!

Experimental techniques to search for lab-produced or solar WISPs

Inverse Square Law (ISL) and Equivalence Principle (EP) tests for P even scalars:



[https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/ScalarPhoton.png]

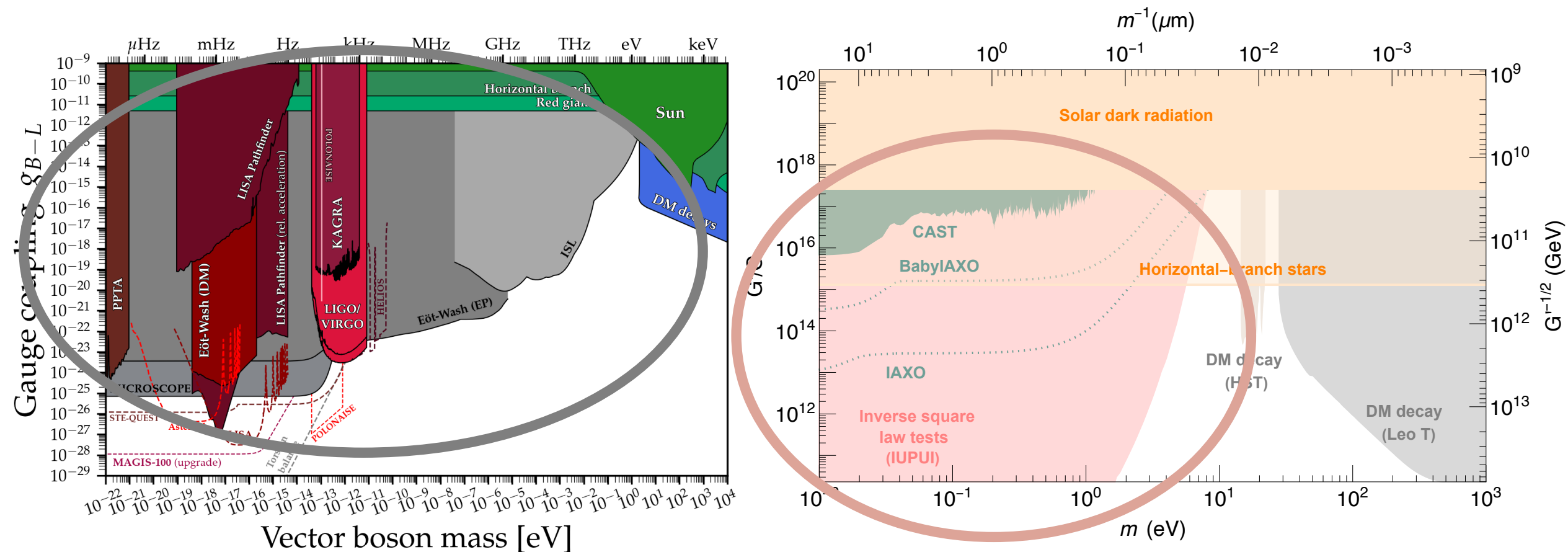


[https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/ScalarElectron.png]

Bosonic WISPs Can Be Hunted in Astro and Exp!

Experimental techniques to search for lab-produced or solar WISPs

Inverse Square Law (ISL) and Equivalence Principle (EP) tests for dark photons and dark gravitons:

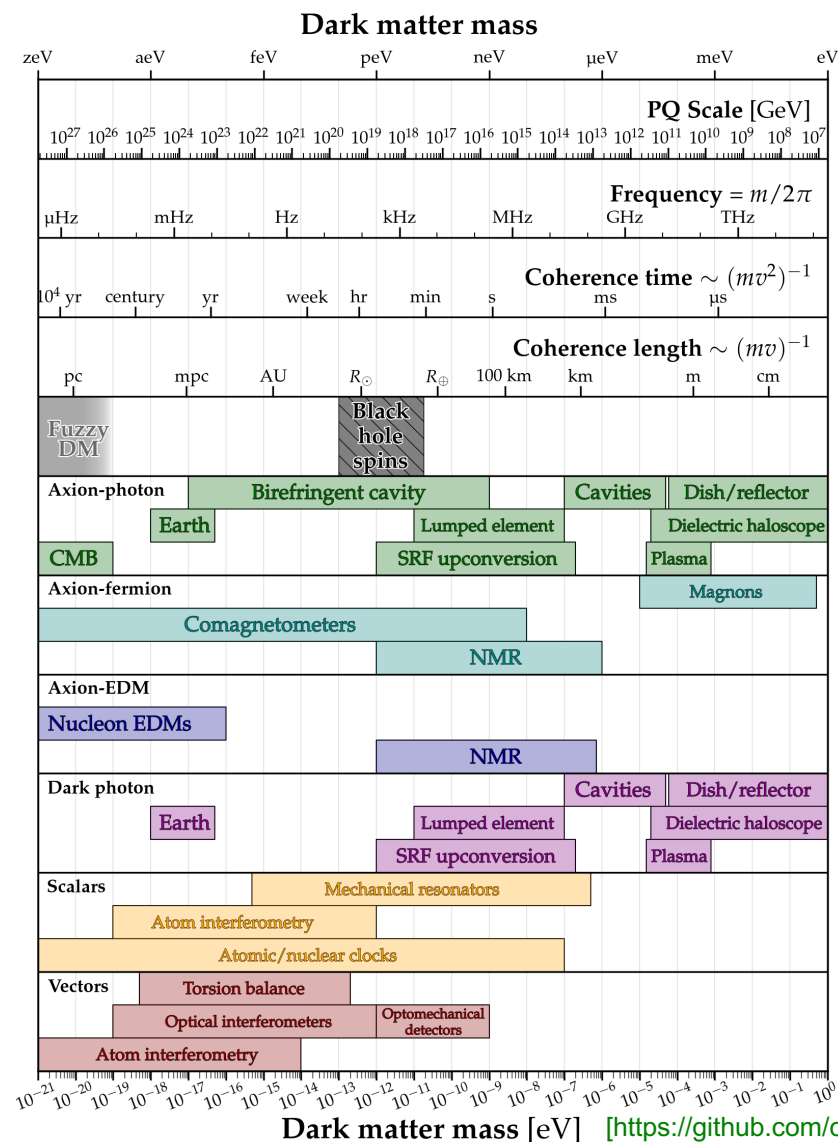


[Galan,Garcia-Cely,AR , 2511.03707]

[https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/VectorB-L.png]

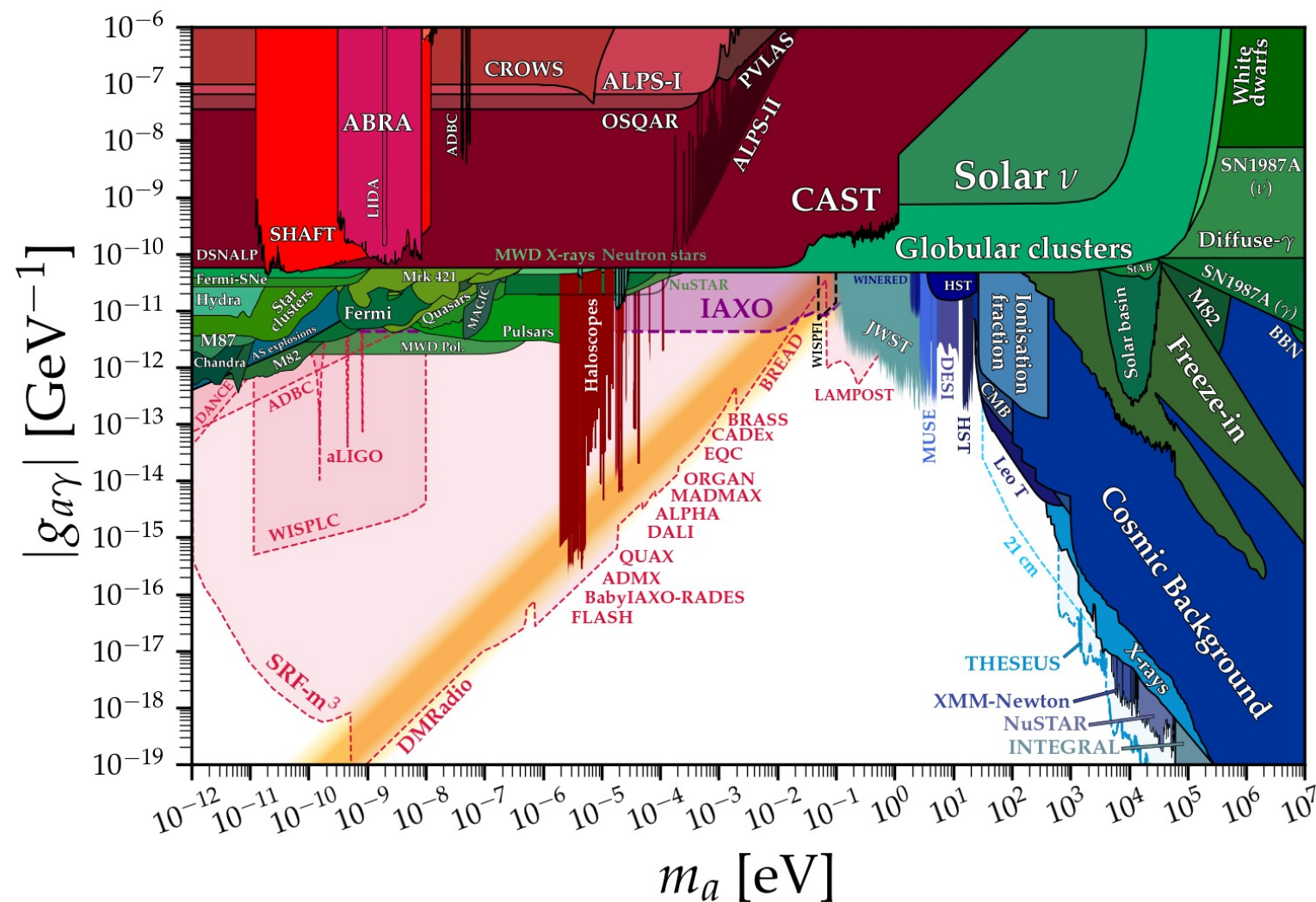
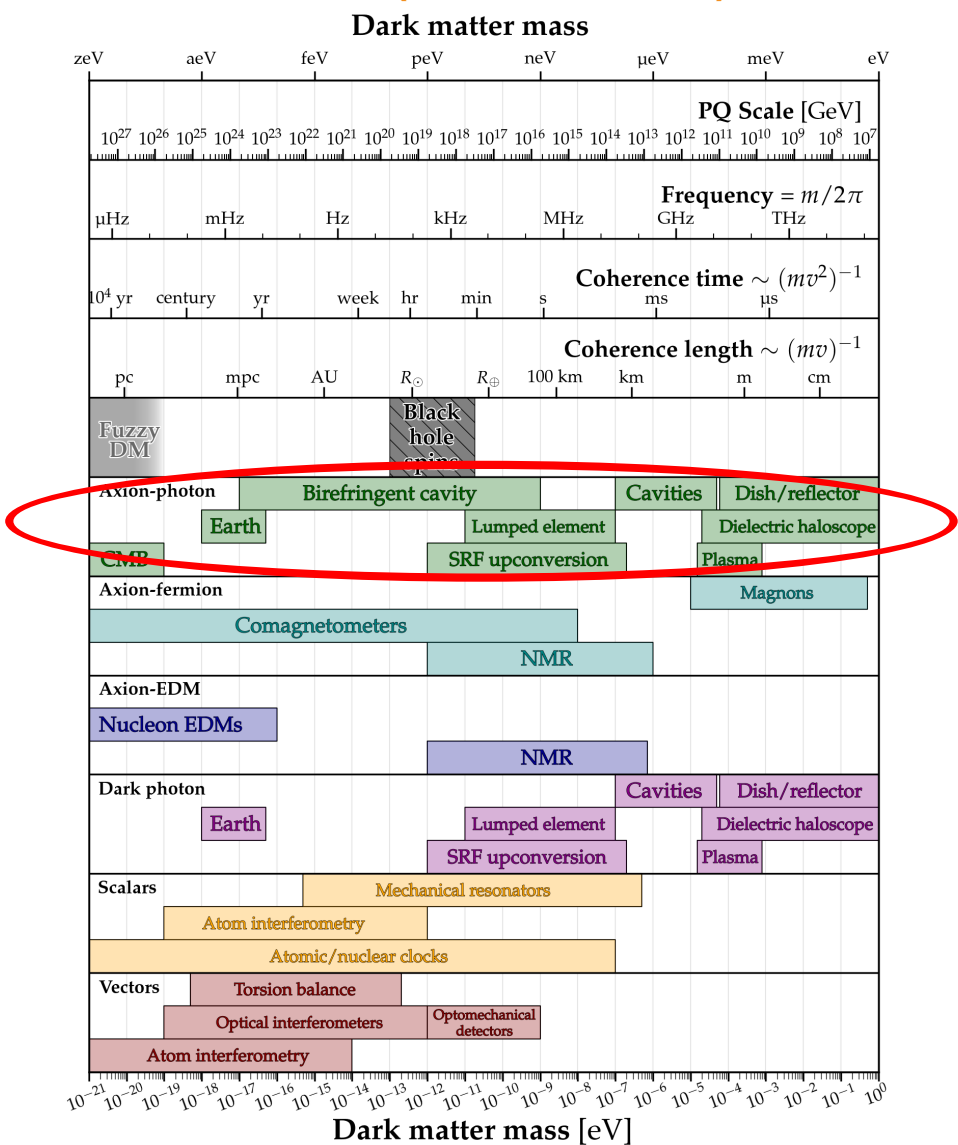
Bosonic WISPs Can Be Hunted in Astro and Exp!

Various experimental techniques to search for WISPy dark matter



Bosonic WISPs Can Be Hunted in Astro and Exp!

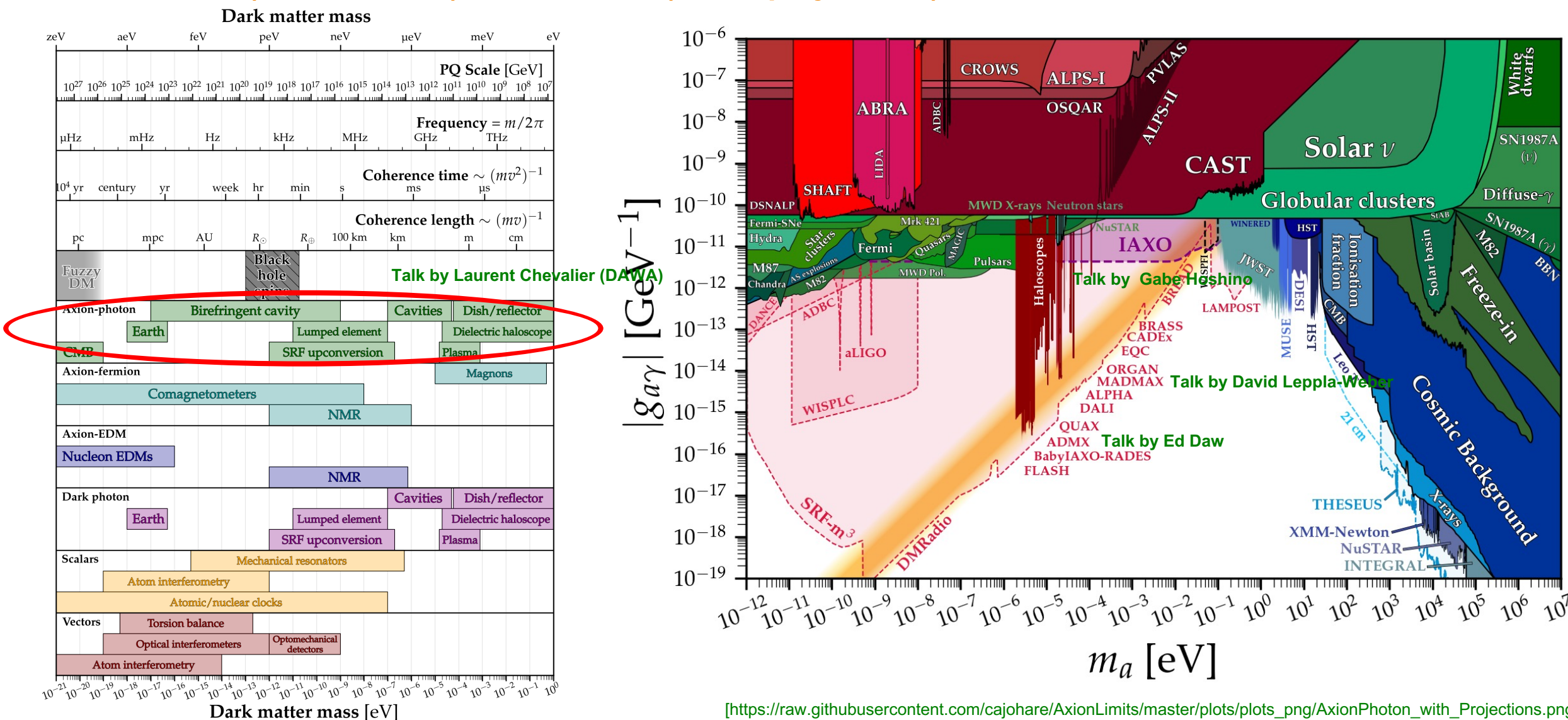
Pseudo-scalar (axion, ALP, ...) DM searches (future projections)



https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/AxionPhoton_with_Projections.png

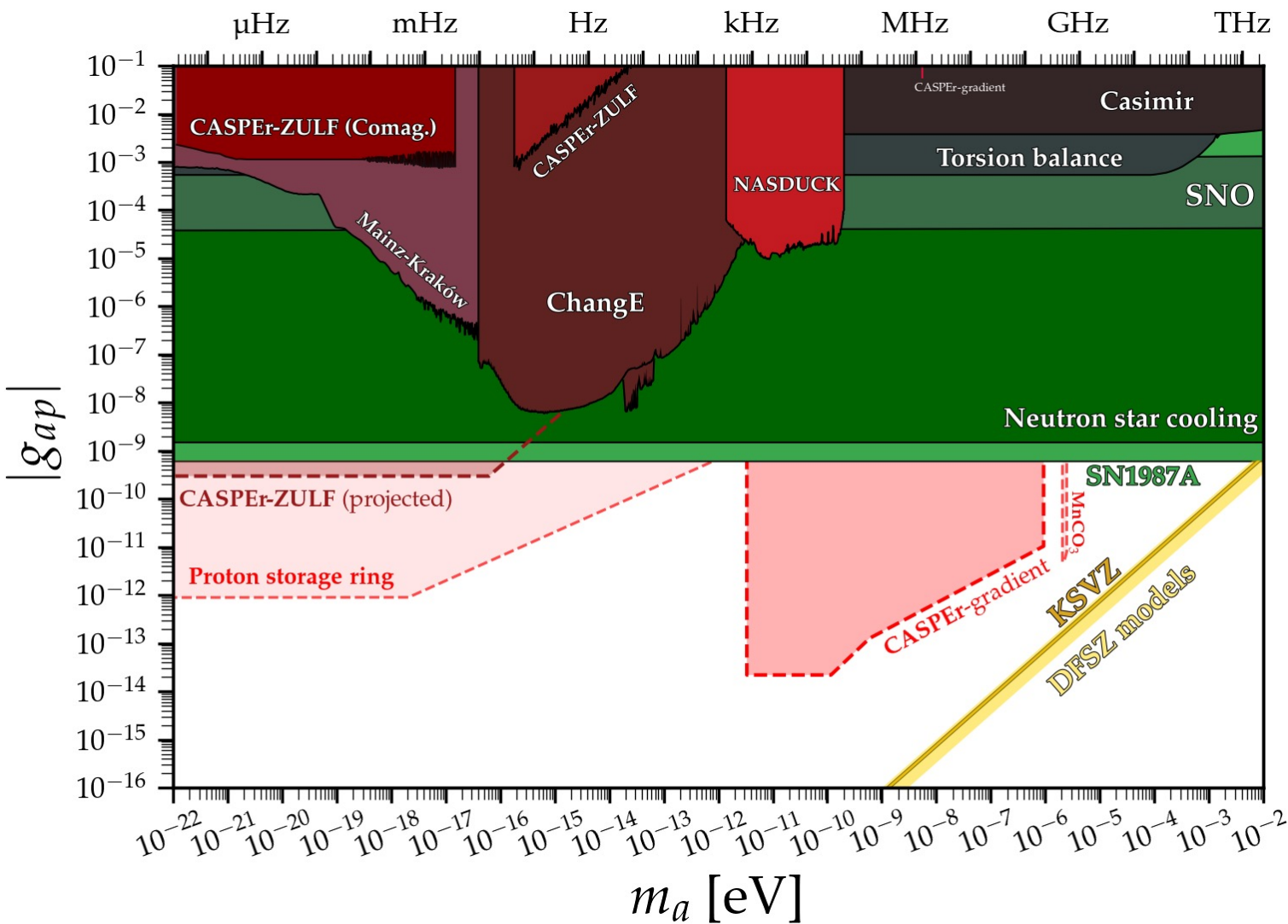
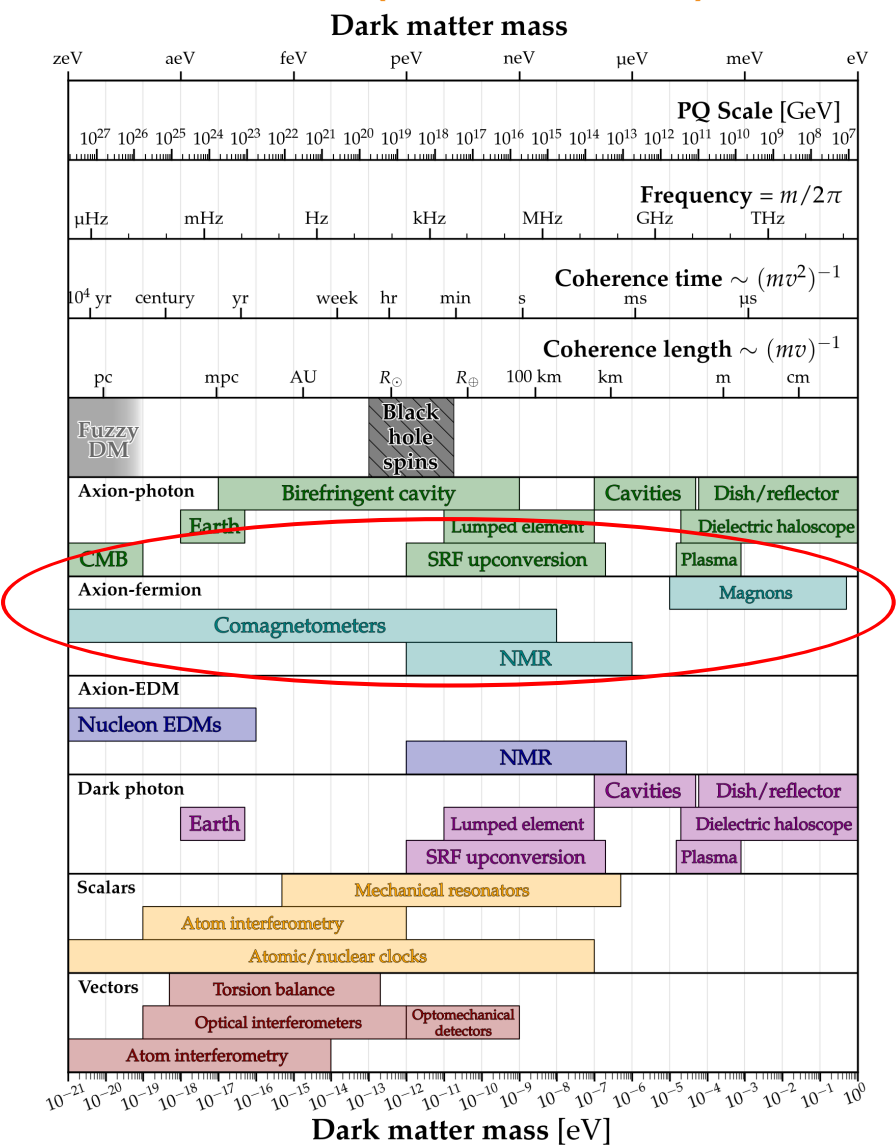
Bosonic WISPs Can Be Hunted in Astro and Exp!

Pseudo-scalar (axion, ALP, ...) DM searches (future projections)



Bosonic WISPs Can Be Hunted in Astro and Exp!

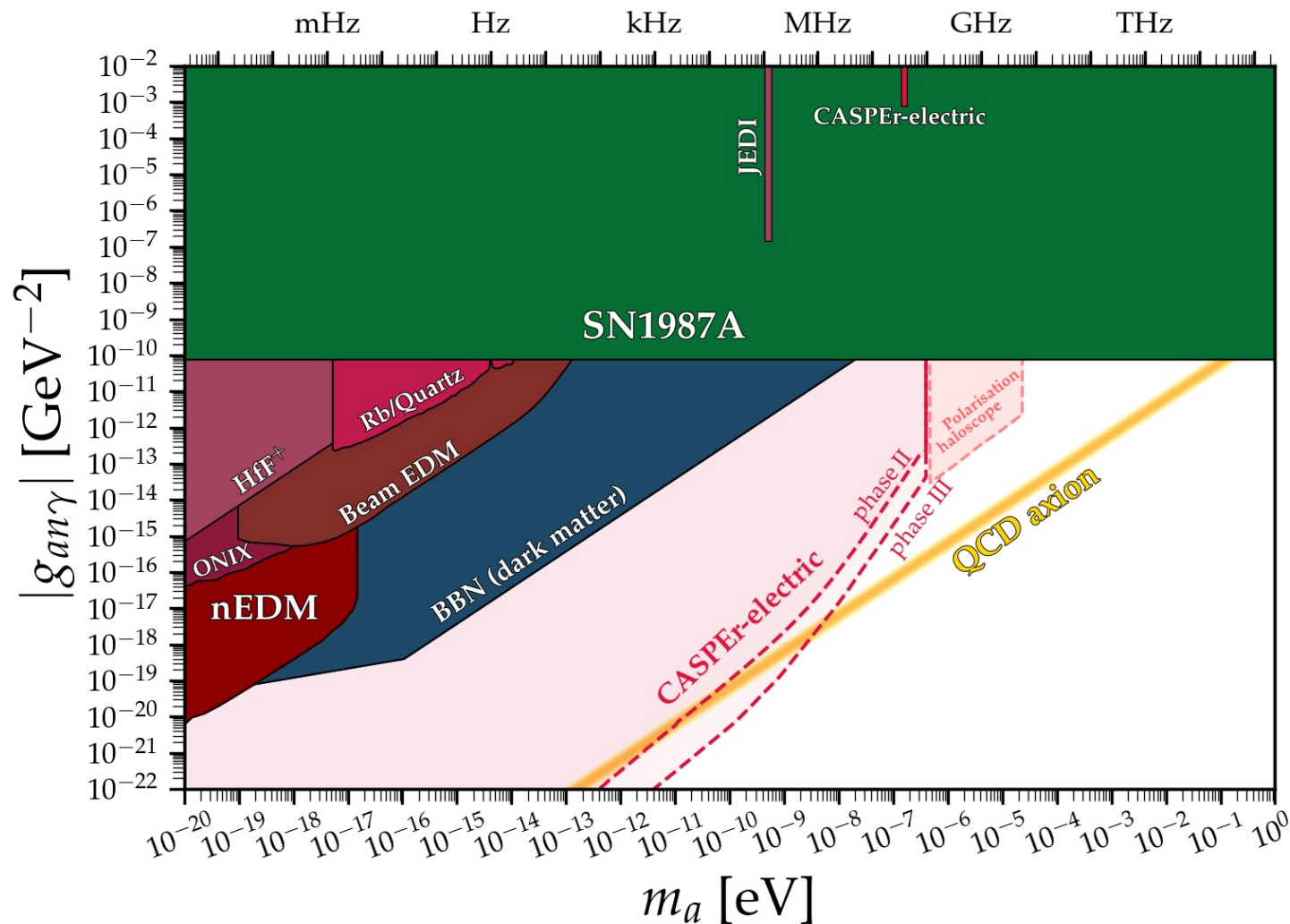
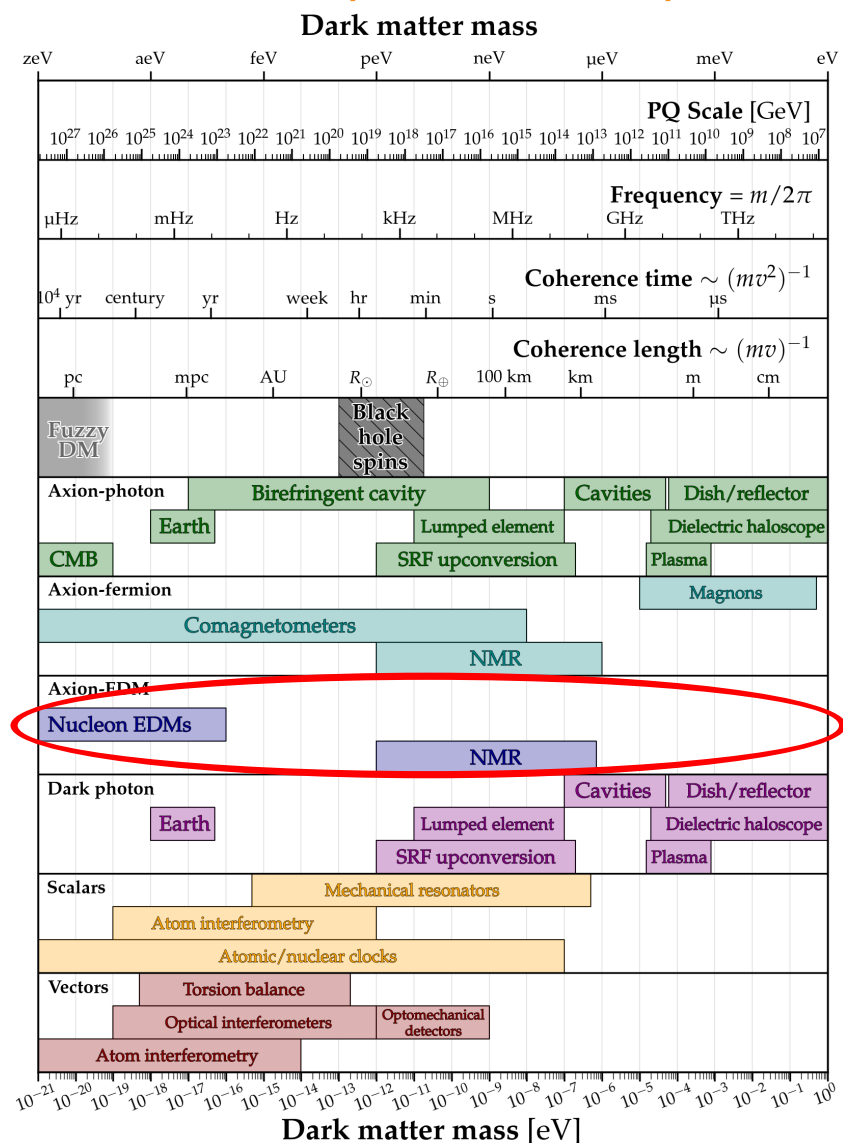
Pseudo-scalar (axion, ALP, ...) DM searches (future projections)



https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/AxionProton_with_Projections.png

Bosonic WISPs Can Be Hunted in Astro and Exp!

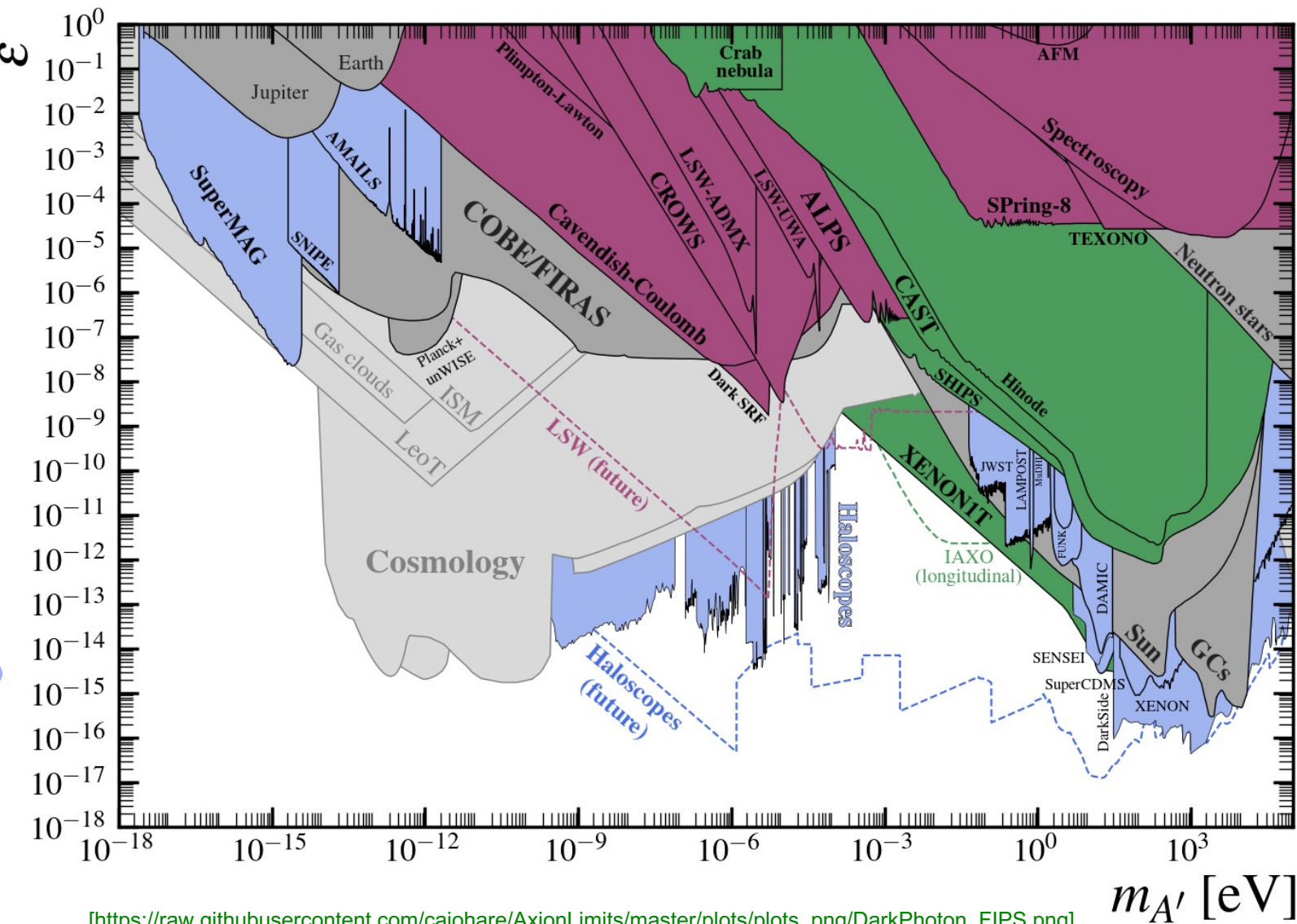
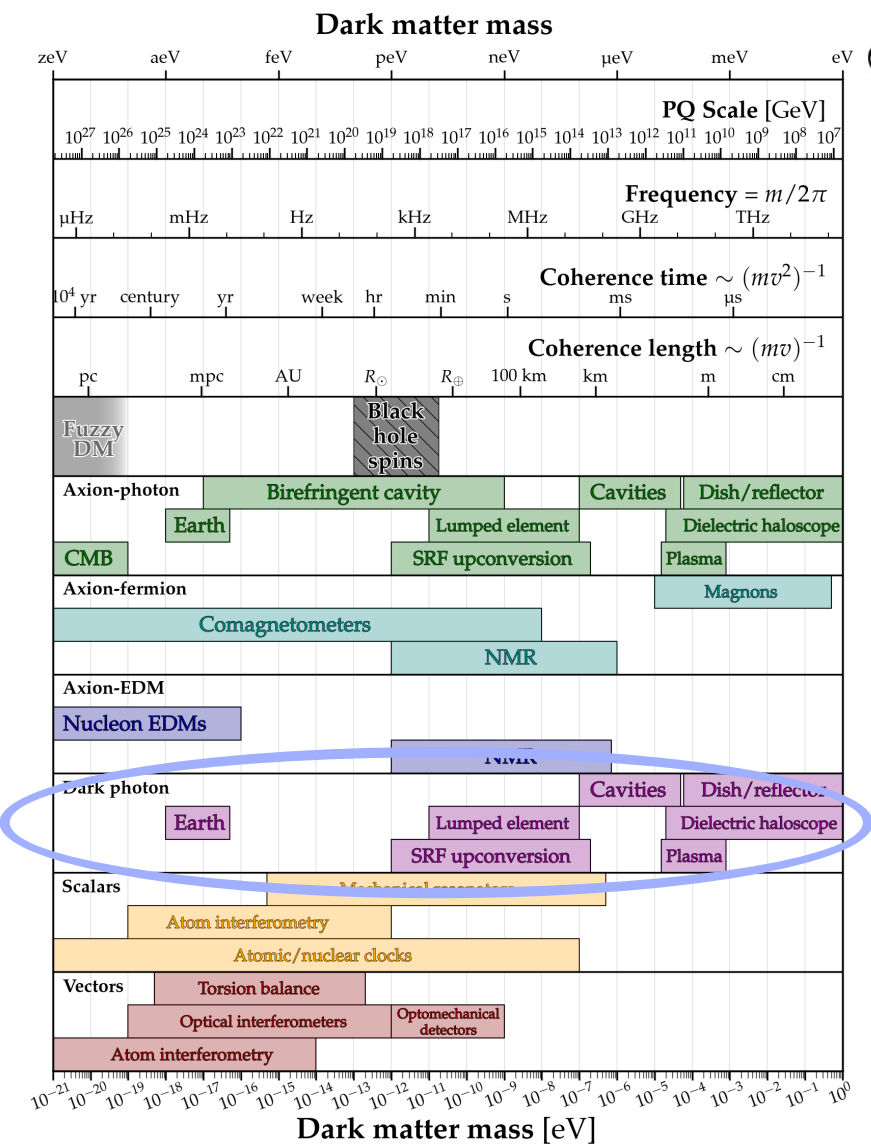
Pseudo-scalar (axion, ALP, ...) DM searches (future projections)



[https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/AxionEDM_with_Projections.png]

Bosonic WISPs Can Be Hunted in Astro and Exp!

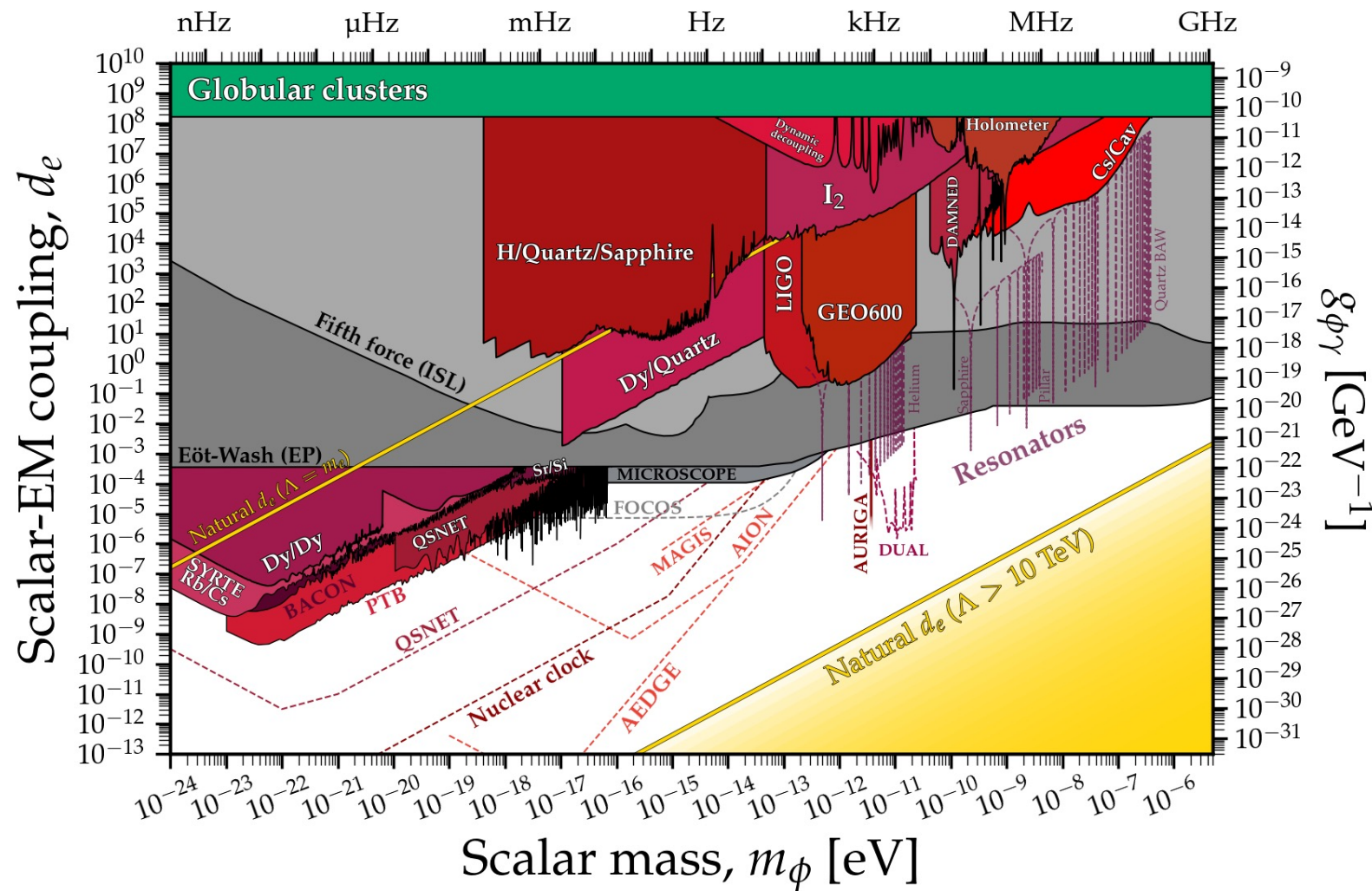
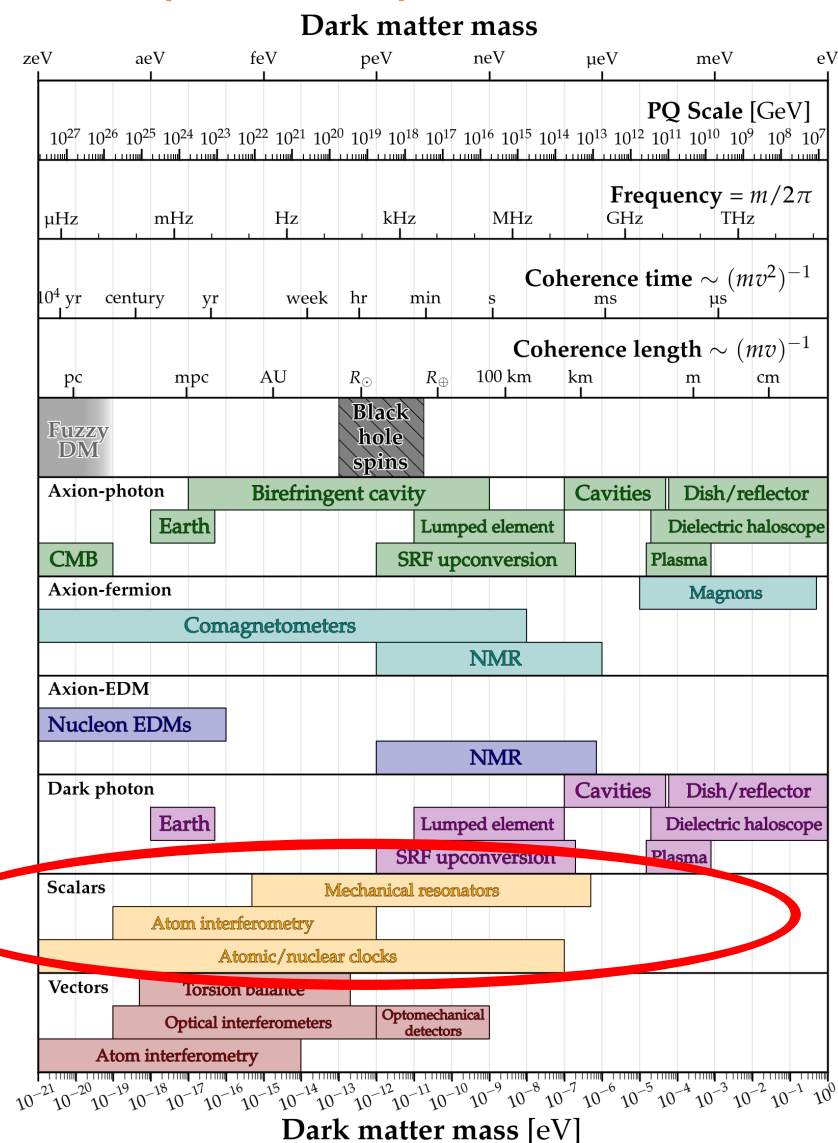
Dark photon DM searches



[https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/DarkPhoton_FIPS.png]

Bosonic WISPs Can Be Hunted in Astro and Exp!

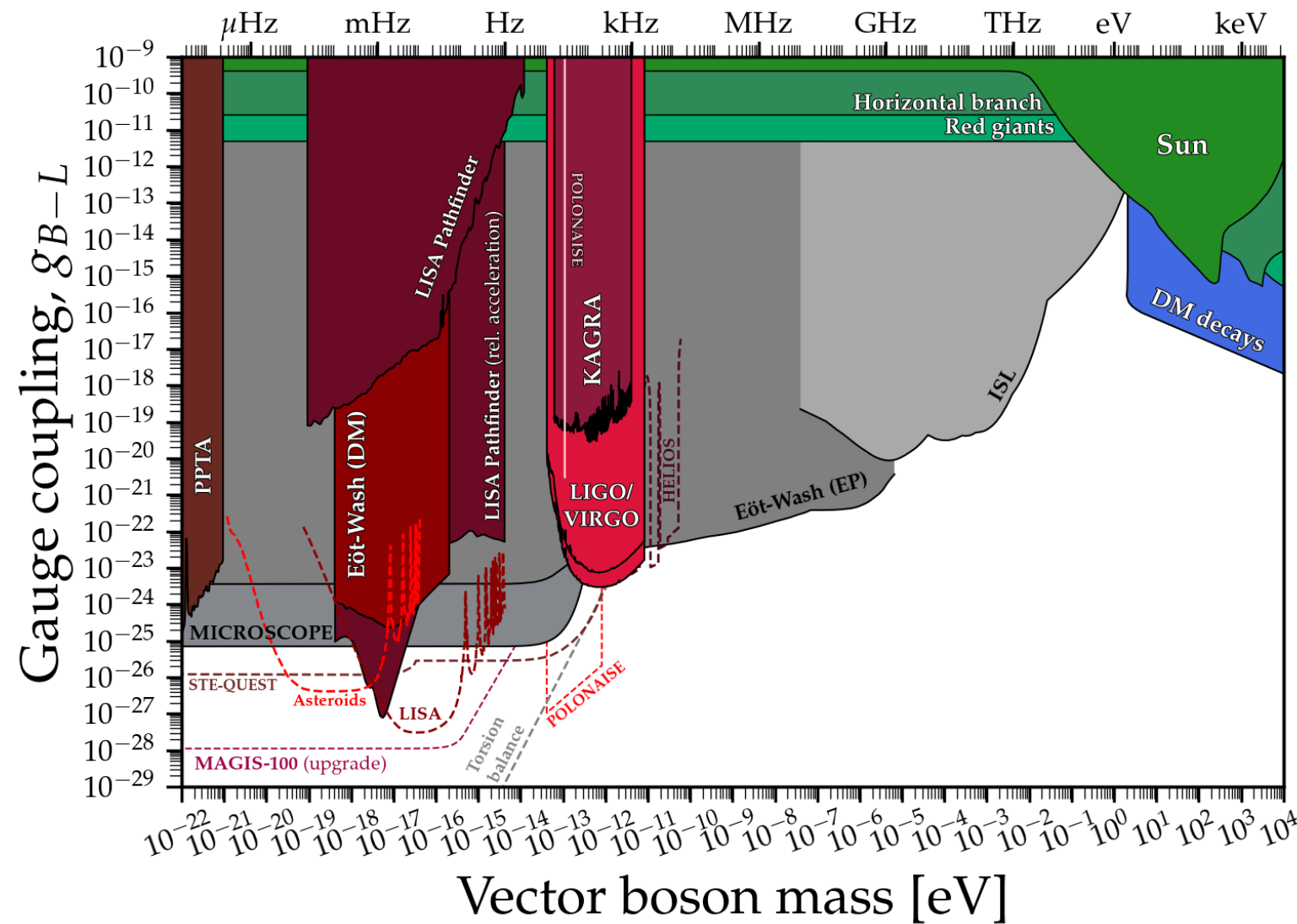
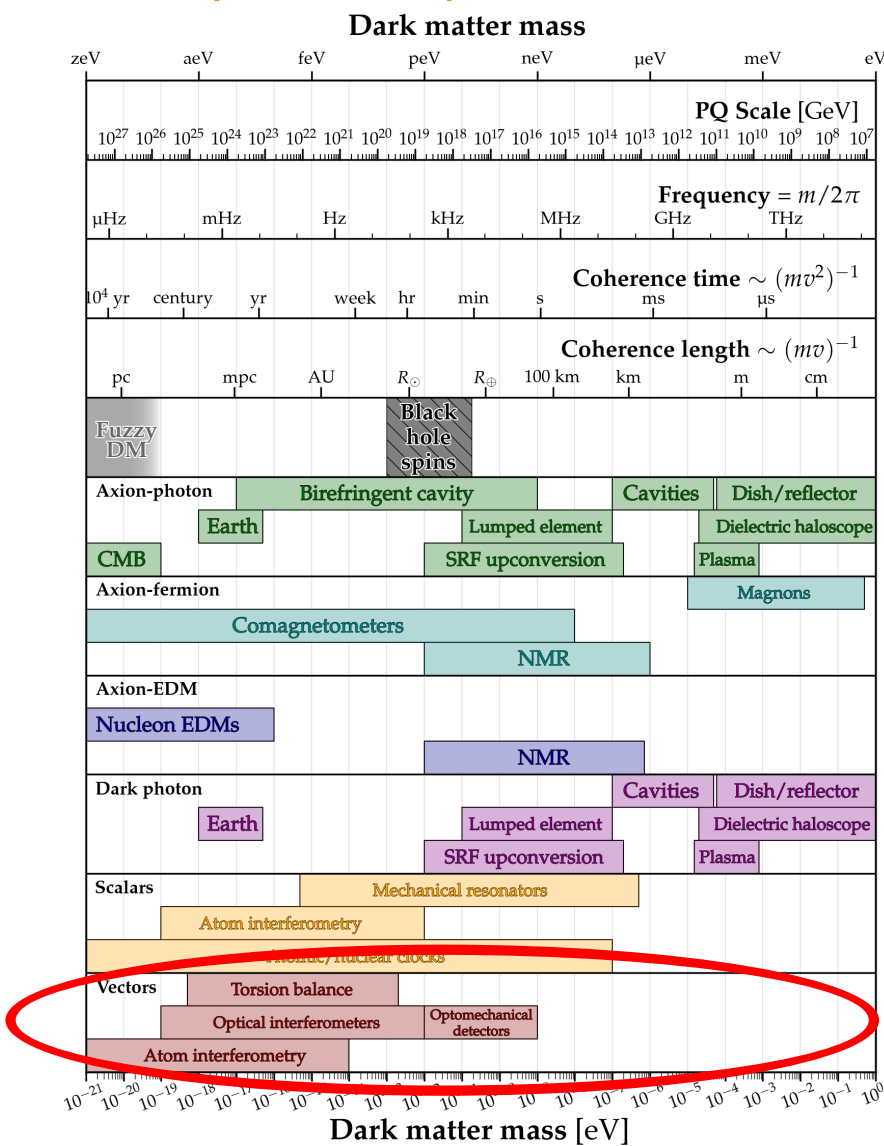
Scalar (dilaton, ...) DM searches



https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/ScalarPhoton_with_Projections.png

Bosonic WISPs Can Be Hunted in Astro and Exp!

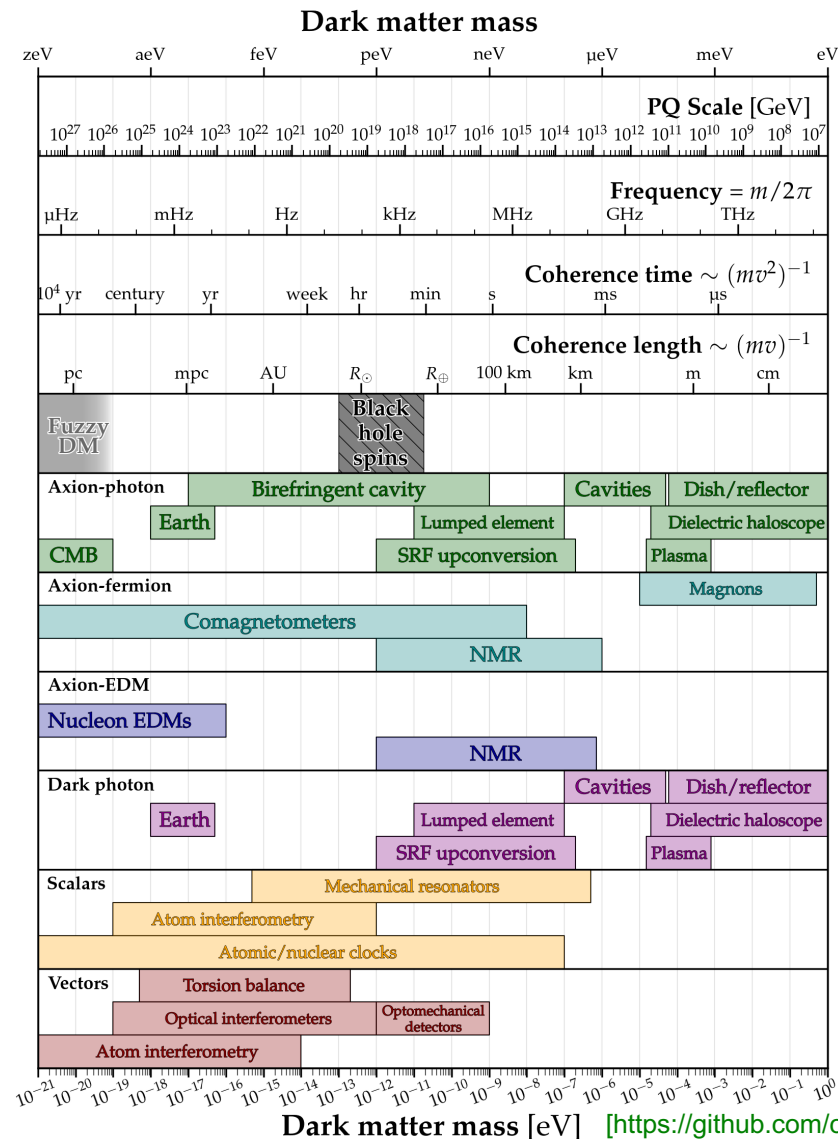
Scalar (dilaton, ...) DM searches



https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/VectorB-L_with_Projections.png

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Dark graviton DM searches



Searching for spin-2 ULDM with gravitational waves interferometers

Juan Manuel Armaleo,^a Diana López Nacir^a and Federico R. Urban^b

^aDepartamento de Física Juan José Giambiagi, FCEyN UBA and IFIBA CONICET-UBA, Facultad de Ciencias Exactas y Naturales, Ciudad Universitaria, Pabellon I, Buenos Aires 1428, Argentina
^bCEICO, FZU, Institute of Physics of the Czech Academy of Sciences, Na Slovance 2, Praha 8 182 21, Czech Republic

[<https://arxiv.org/abs/2012.13997>]

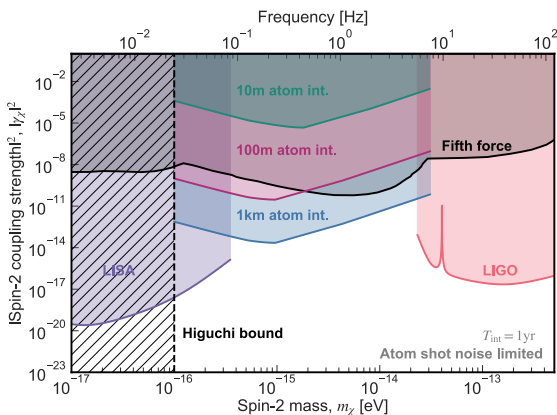
KCL-PH-TH/2024-69, AION-REPORT/2024-08

Massive graviton dark matter searches with long-baseline atom interferometers

Diego Blas,^{1,2} John Carlton,^{3, a} and Christopher McCabe³

¹*Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, 08193 Bellaterra (Barcelona), Spain*
²*Institució Catalana de Recerca i Estudis Avançats (ICREA), Passeig Lluís Companys 23, 08010 Barcelona, Spain*
³*Theoretical Particle Physics and Cosmology Group, Department of Physics, K*

[<https://arxiv.org/abs/2412.14282>]



Conclusions

- The dark sector may be richer — and more structured — than we ever imagined.
- Bosonic WISPs offer a unifying framework linking astrophysics, cosmology and particle physics.
- Rapid experimental progress is transforming WISP dark matter searches from speculation to precision science.
- Whether axions, dilatons, dark photons, or even dark gravitons — the hunt for wave-like dark matter is entering its decisive phase.