The Road Ahead for Axion Physics

Andreas Ringwald

Axions in the Sky!

Barolo Astroparticle Meeting 2024

Barolo, Italy

12-15 June 2024

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

COSMIC WISPERS CA21106

DESY.

The Road Ahead for Axion Physics

As seen about 22 years ago ...

AXIONS: PAST, PRESENT, AND FUTURE

MARK SREDNICKI

Department of Physics
University of California
Santa Barbara, CA 93106, USA

I give a pedagogical and historical introduction to axion physics, and briefly review the present status of axions in our understanding of particle physics and cosmology. This is a contribution to *Continuous Advances in QCD 2002/Arkadyfest*, held in honor of Arkady Vainshtein's 60th birthday.

[arXiv:hep-th/0210172]

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Over twenty years have passed since the invention of the invisible axion, and we still do not know whether or not this is the correct solution to the strong CP problem. It is vitally important that the current searches continue until they have covered at least the most plausible mass and coupling ranges; it would be a great shame if such important physics surrounded us, and we left it undiscovered. Of course, even if these searches do not find dark matter axions, this means only that the dark matter is not axions, and not that axions do not exist. There are many cosmological scenarios for this possibility.

Also, it should be noted that axions arise rather naturally in superstring models, and it may be that any ground state of string/M theory that resembles the Standard Model always includes an axion with, say, $f_a \sim (v_{\rm EW} M_{\rm Planck})^{1/2} \sim 10^{11}$ GeV. However at present we seem a long way from being to reach this sort of conclusion.

The road ahead for axion physics is thus likely to be a hard one, both theoretically and experimentally. But the reward for a successful traversal will make the journey worthwhile.

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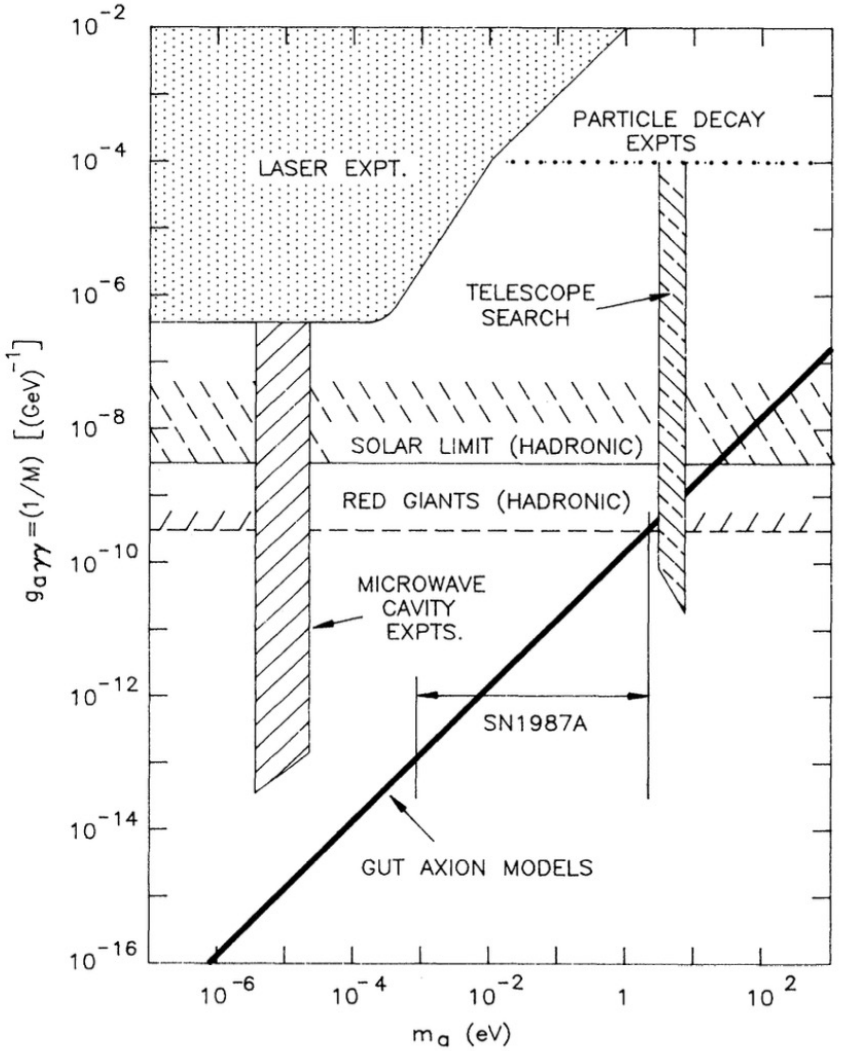
The Road Behind Us

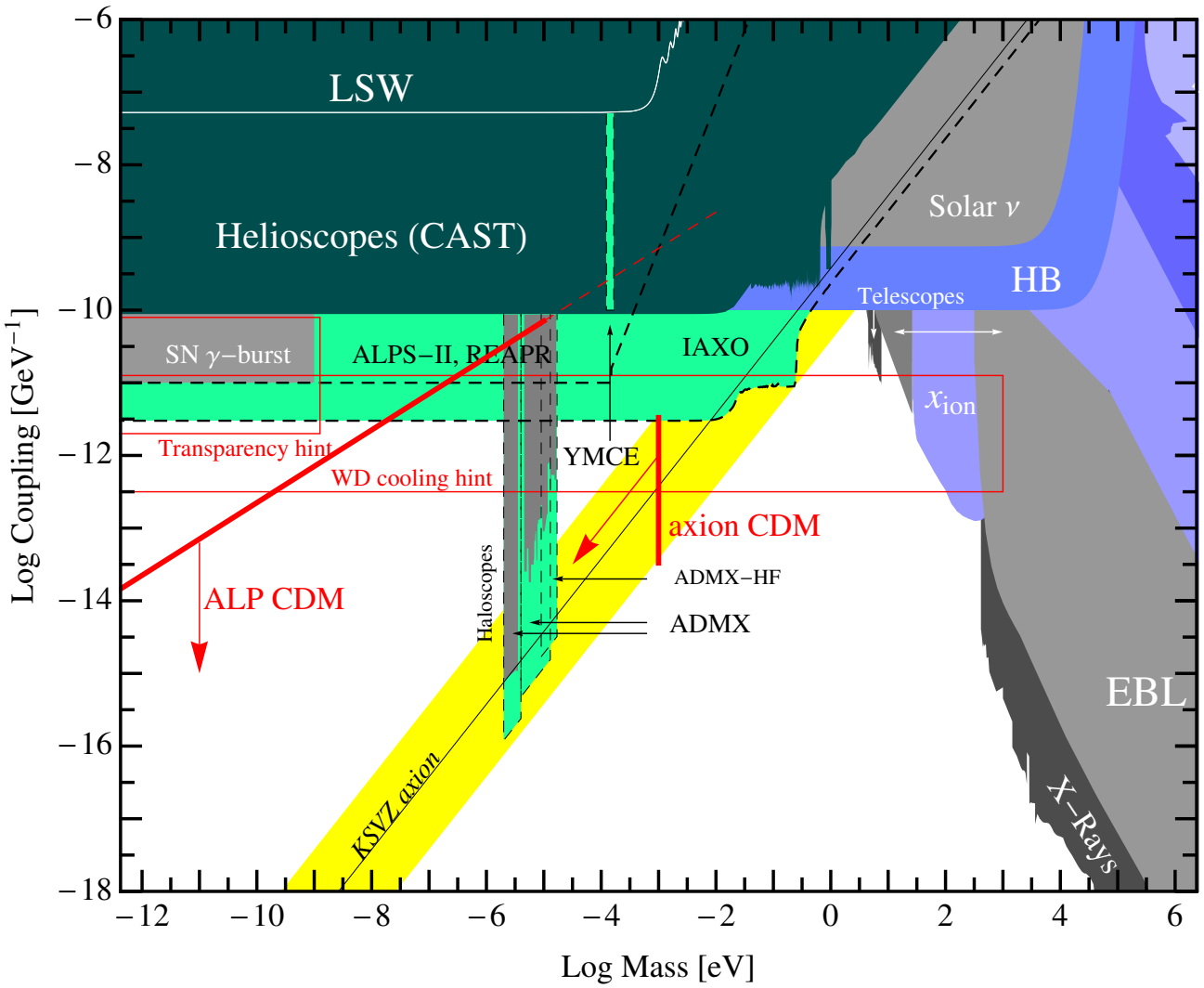
31 years ago ...



[Cameron et al., Phys. Rev. D 47 (1993) 3707]

The Road Behind Us

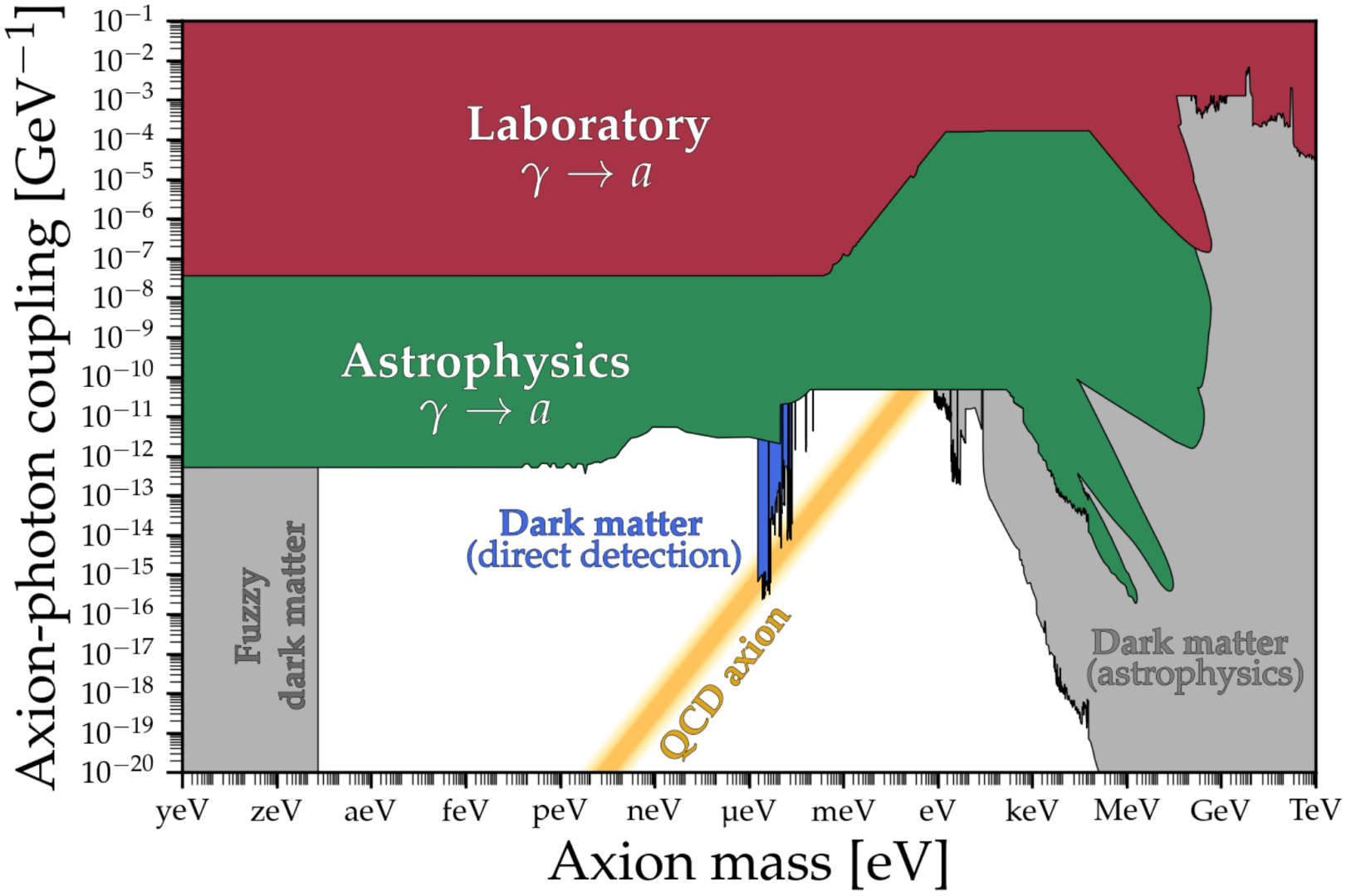
12 years ago ...



[AR, 1210.5081]

Here and Now

Still most of the most plausible mass and coupling range uncharted ...

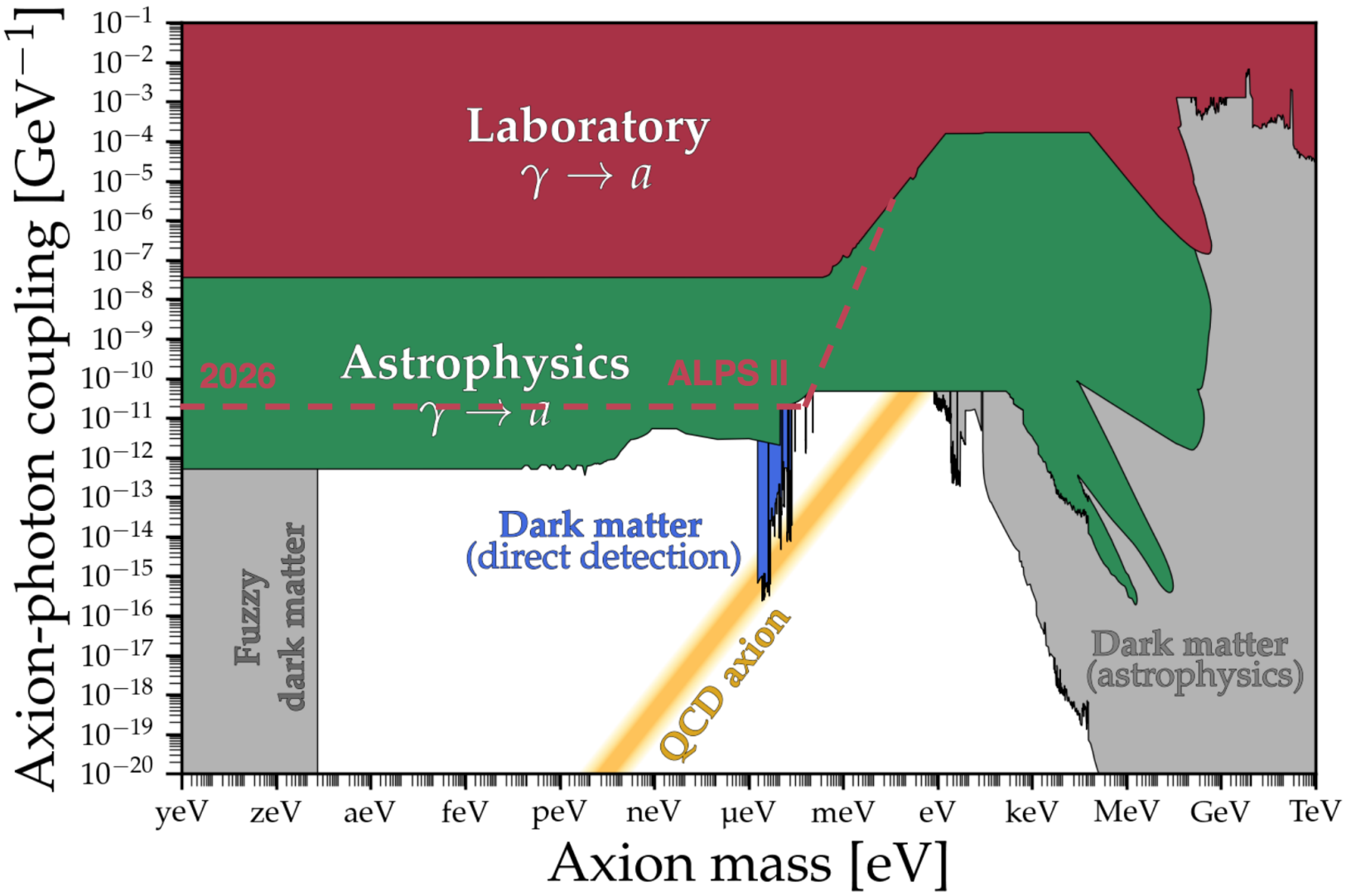


- **Laboratory** ($\gamma \to a$)
  - Light-Shining-through Walls
  - Beam dump
  - Collider
- **Astrophysics** ($\gamma \to a$)
  - Helioscopes
  - Stellar bounds
  - Axion-photon oscillation bounds
  - Supernova bounds
- **Dark matter** (astrophysics)
  - Indirect detection,
  - Birefringence, ...
- **Dark matter** (direct detection)
  - Haloscopes

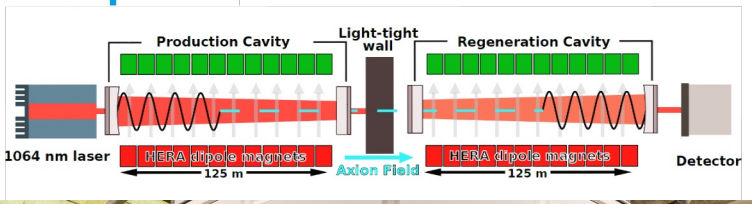
[https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/AxionPhoton_UltraSimple_FullParameterSpace.png]

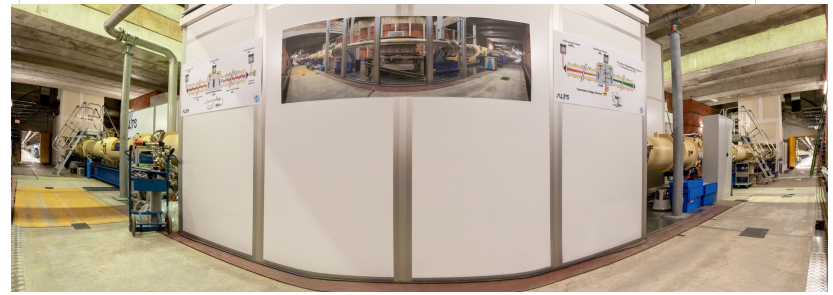
The Road Ahead in the Laboratory

Expect remarkable progress in Light-Shining-through-Walls (LSW)



ALPS II [Döbrich et al., ALPS II TDR, 1302.5647]





- First runs finished 6 May 2024
- Writing papers at present
- Next steps:
  - Full optics in 2025
  - Design sensitivity in 2026

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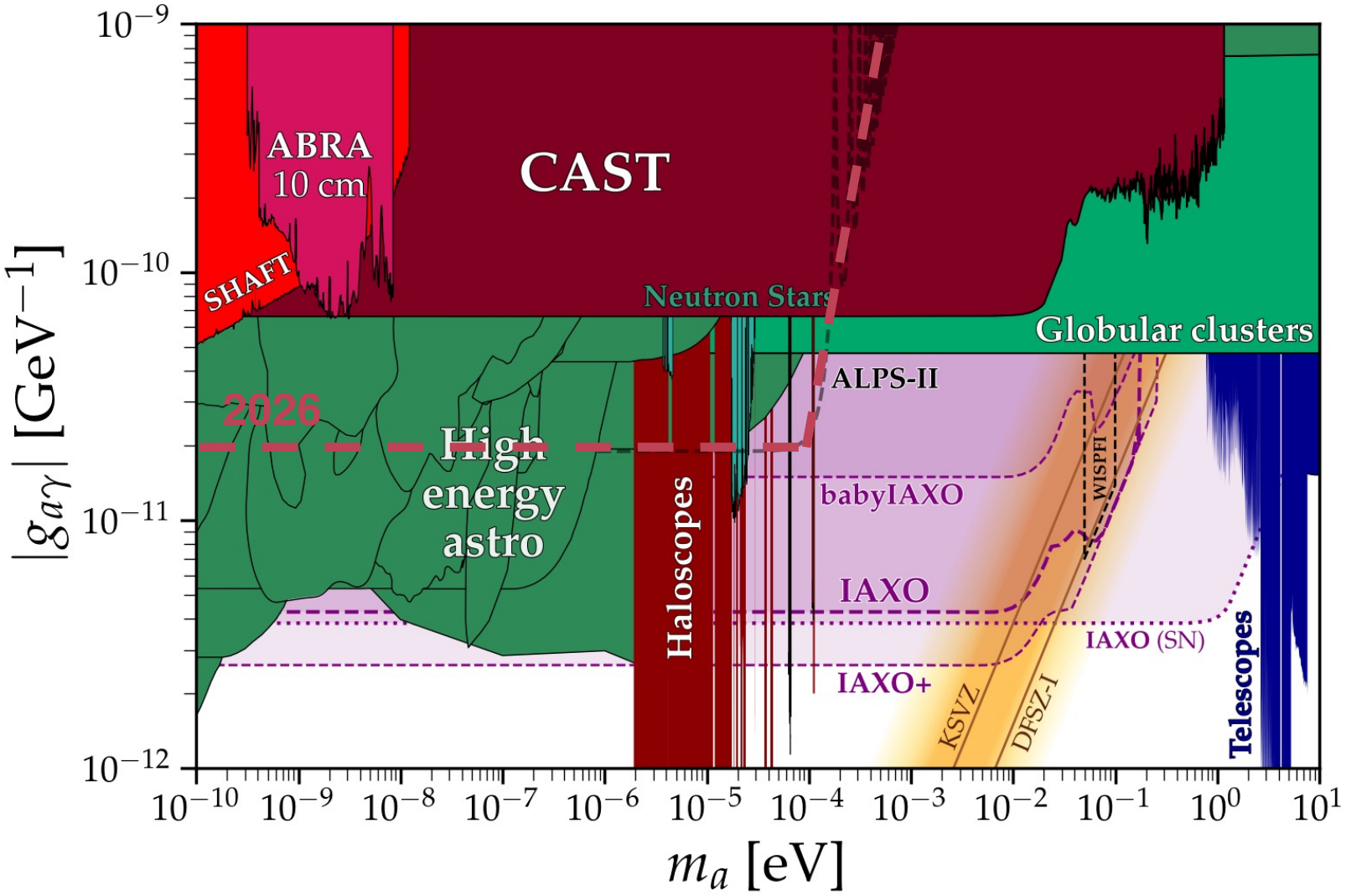

[https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/AxionPhoton_IAXOCloseup.png]

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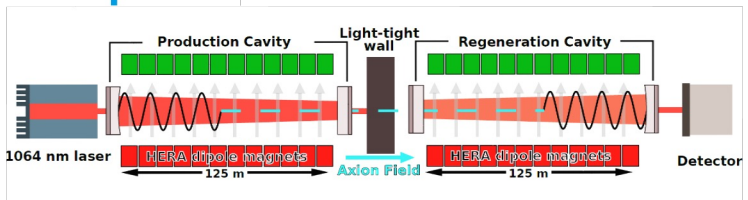

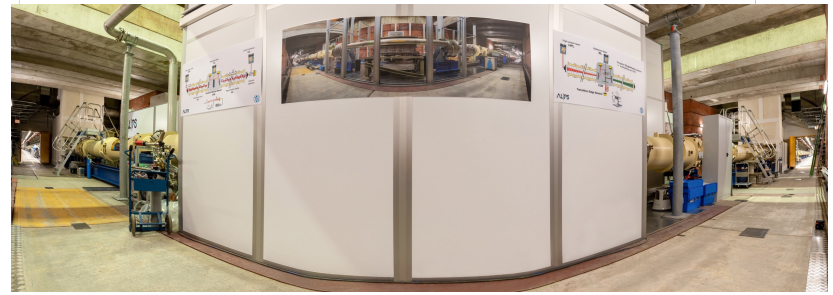

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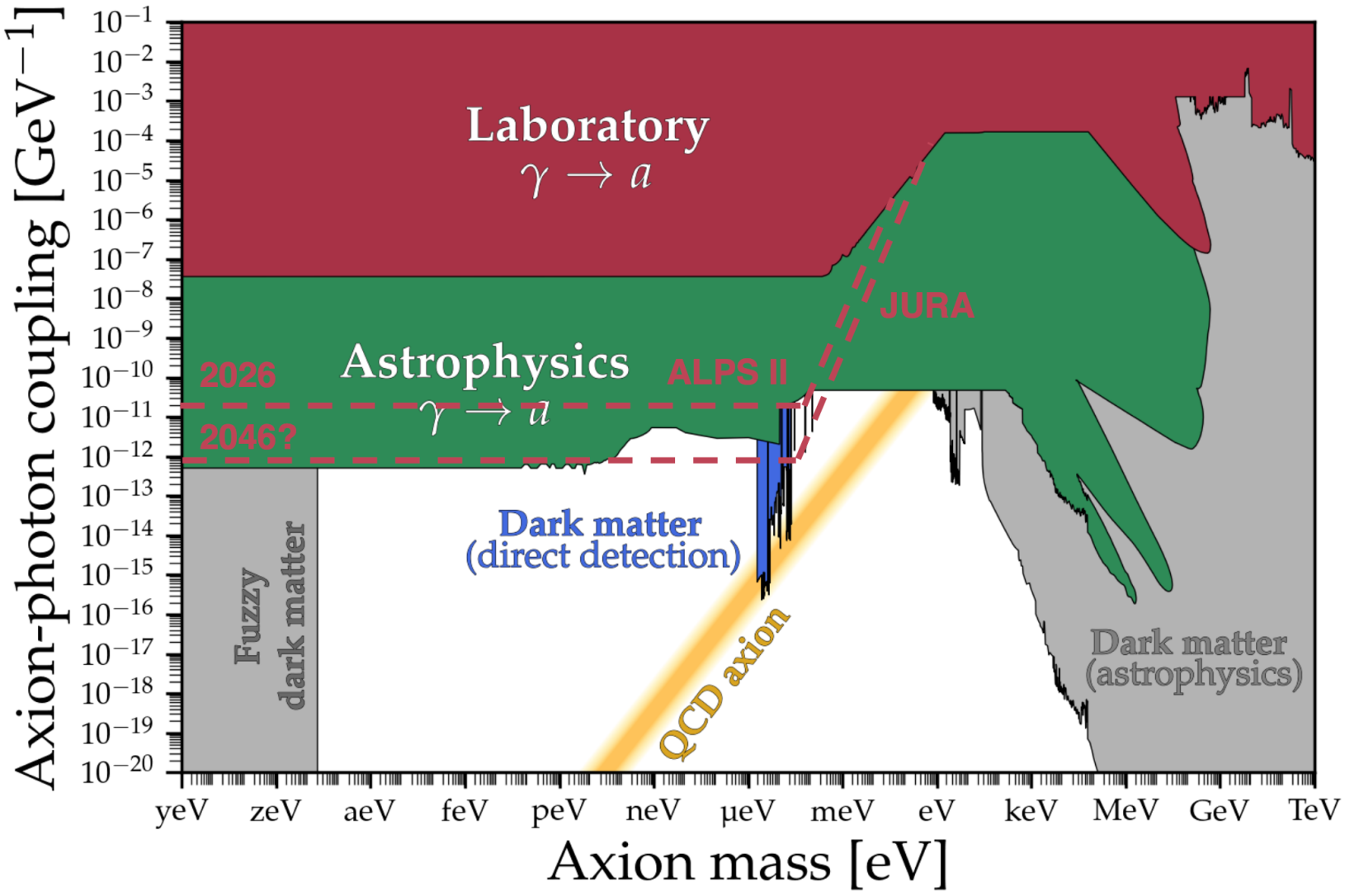

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JURA [Beacham et al., PBC Report, 1901.09966]

- Exploit magnets developed for FCC-hh

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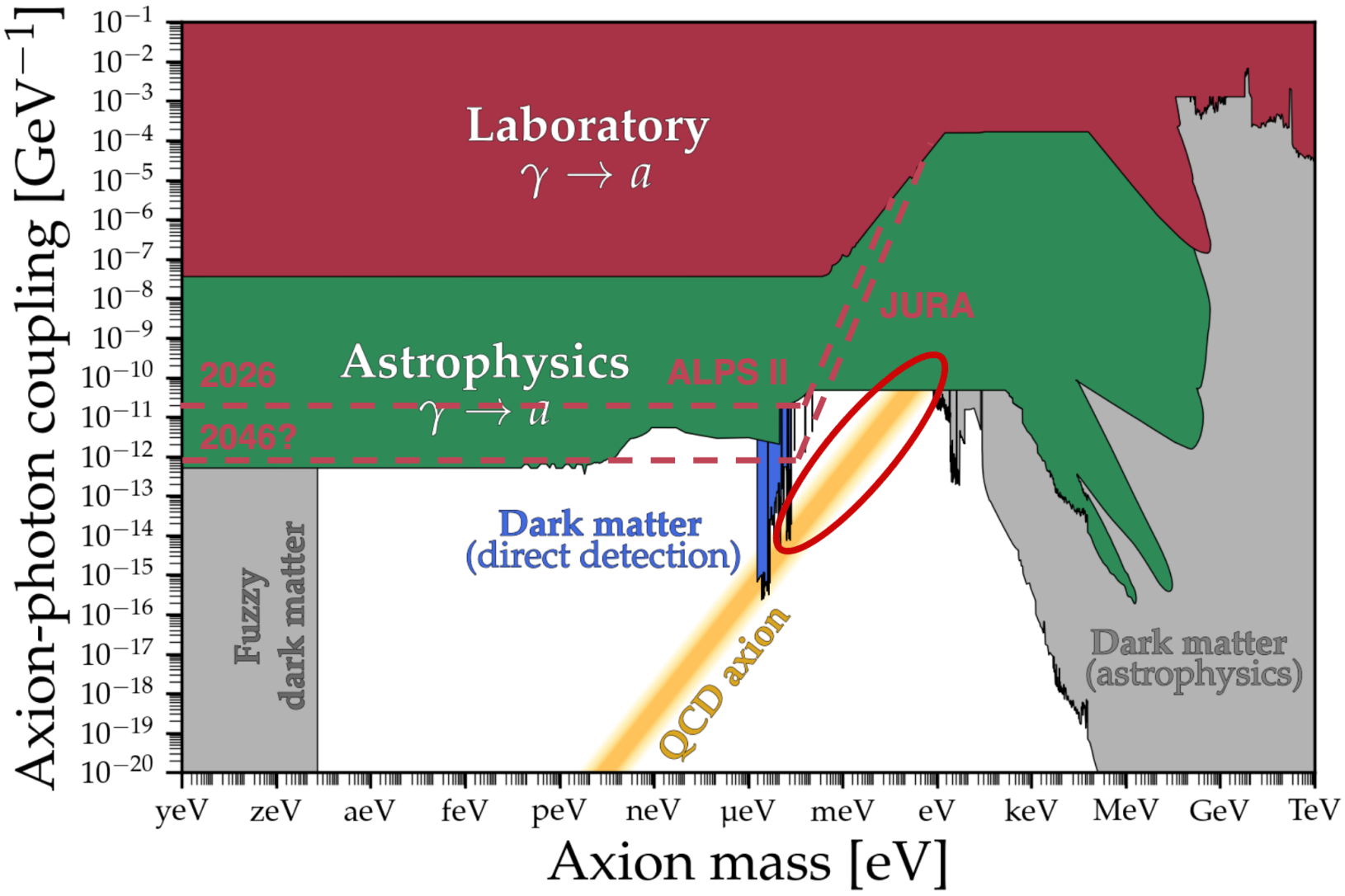

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Do not reach vanilla axion band

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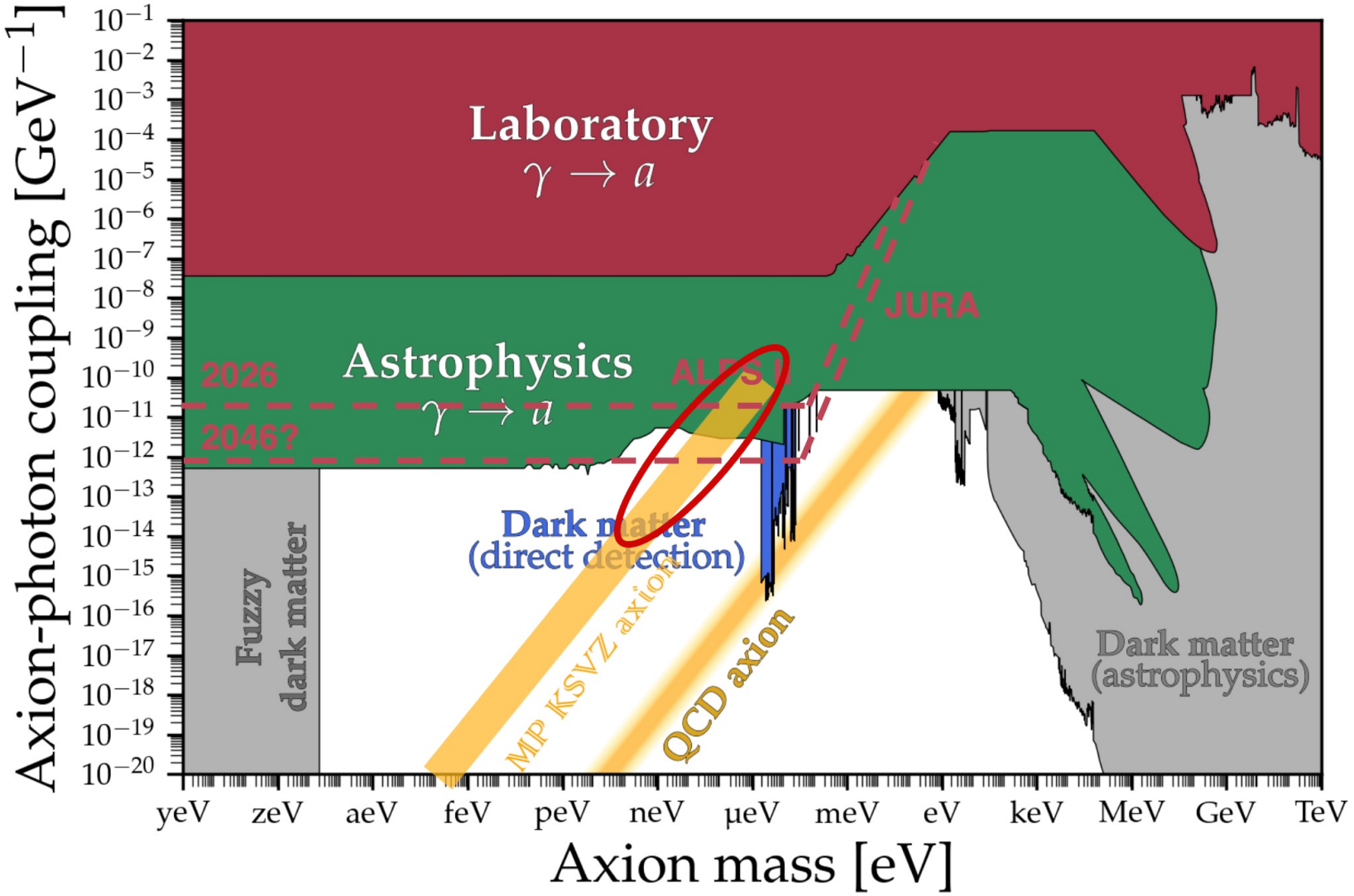

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Do not reach vanilla axion band

However, there is a variant of the KSVZ axion which is as plausible as the original KSVZ axion

Monopole-philic (MP) KSVZ axion

which can be probed

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

Monopole-Philic KSVZ Axion

[Anton Sokolov, AR, 2104.02574; 2109.08503; 2205.02605; 2303.10170]

Generalized axion-Maxwell equations

- Assume, that PQ-charged heavy quark $\mathcal{Q}$ in KSVZ model carries a magnetic charge $g_{\mathcal{Q}}\, g_0$, where the fundamental magnetic charge g_0 and the fundamental electric charge e satisfy the charge quantization condition: $eg_0 = 6\pi,\ n \in \mathbb{Z}$

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- Integrating out $\mathcal{Q}$ non-perturbatively,
  - Schwinger proper time method [2104.02574]
  - Anomaly of axial current from monopole ([1003.0448]) [2109.08503]
  - Fujikawa method [2205.02605]
  - World-line path integral method [2303.10170]

  results in additional EM coupling

$$g_{am} = \frac{\alpha_m}{2\pi f_a}\left(6g_{\mathcal{Q}}^2\right)$$

$$\alpha_m \equiv \frac{g_0^2}{4\pi}$$

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  results in additional EM coupling in axion-Maxwell equations

$$g_{am} = \frac{\alpha_m}{2\pi f_a}\left(6g_{\mathcal{Q}}^2\right) \qquad g_{a\gamma} = \frac{\alpha}{2\pi f_a}(-1.92) = g_{a\gamma}^{\rm KSVZ}$$

$$\alpha_m \equiv \frac{g_0^2}{4\pi} \qquad \alpha \equiv \frac{e^2}{4\pi} \approx \frac{1}{137}$$

$$\left(\partial^2 + m_a^2\right) a = -\left(g_{a\gamma} - g_{am}\right) \mathbf{E}_0 \cdot \mathbf{B}_0\,,$$

$$\boldsymbol{\nabla} \times \mathbf{B}_a - \dot{\mathbf{E}}_a = g_{a\gamma}\left(\mathbf{E}_0 \times \boldsymbol{\nabla} a - \dot{a}\mathbf{B}_0\right)\,,$$

$$\boldsymbol{\nabla} \times \mathbf{E}_a + \dot{\mathbf{B}}_a = -g_{am}\left(\mathbf{B}_0 \times \boldsymbol{\nabla} a + \dot{a}\mathbf{E}_0\right)\,,$$

$$\boldsymbol{\nabla} \cdot \mathbf{B}_a = -g_{am}\, \mathbf{E}_0 \cdot \boldsymbol{\nabla} a\,,$$

$$\boldsymbol{\nabla} \cdot \mathbf{E}_a = g_{a\gamma}\, \mathbf{B}_0 \cdot \boldsymbol{\nabla} a$$

- $\mathbf{E}_0$, $\mathbf{B}_0$: background fields created in experiments or astrophysical environments
- $\mathbf{E}_a$, $\mathbf{B}_a$: axion-induced fields

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  results in additional EM coupling in axion-Maxwell equations

$$g_{am} = \frac{\alpha_m}{2\pi f_a}\left(6g_{\mathcal{Q}}^2\right) \quad \gg \quad g_{a\gamma} = \frac{\alpha}{2\pi f_a}(-1.92) = g_{a\gamma}^{\rm KSVZ}$$

- Charge quantization implies huge hierarchy between couplings

$$\alpha_m \equiv \frac{g_0^2}{4\pi} = \frac{9\pi}{\alpha} \approx 3.87\times 10^3 \gg \alpha \equiv \frac{e^2}{4\pi} \approx \frac{1}{137}$$

$$\left(\partial^2 + m_a^2\right) a \;=\; -\left(g_{a\gamma} - g_{am}\right)\mathbf{E}_0\cdot\mathbf{B}_0\,,$$

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The Road Ahead in the Laboratory

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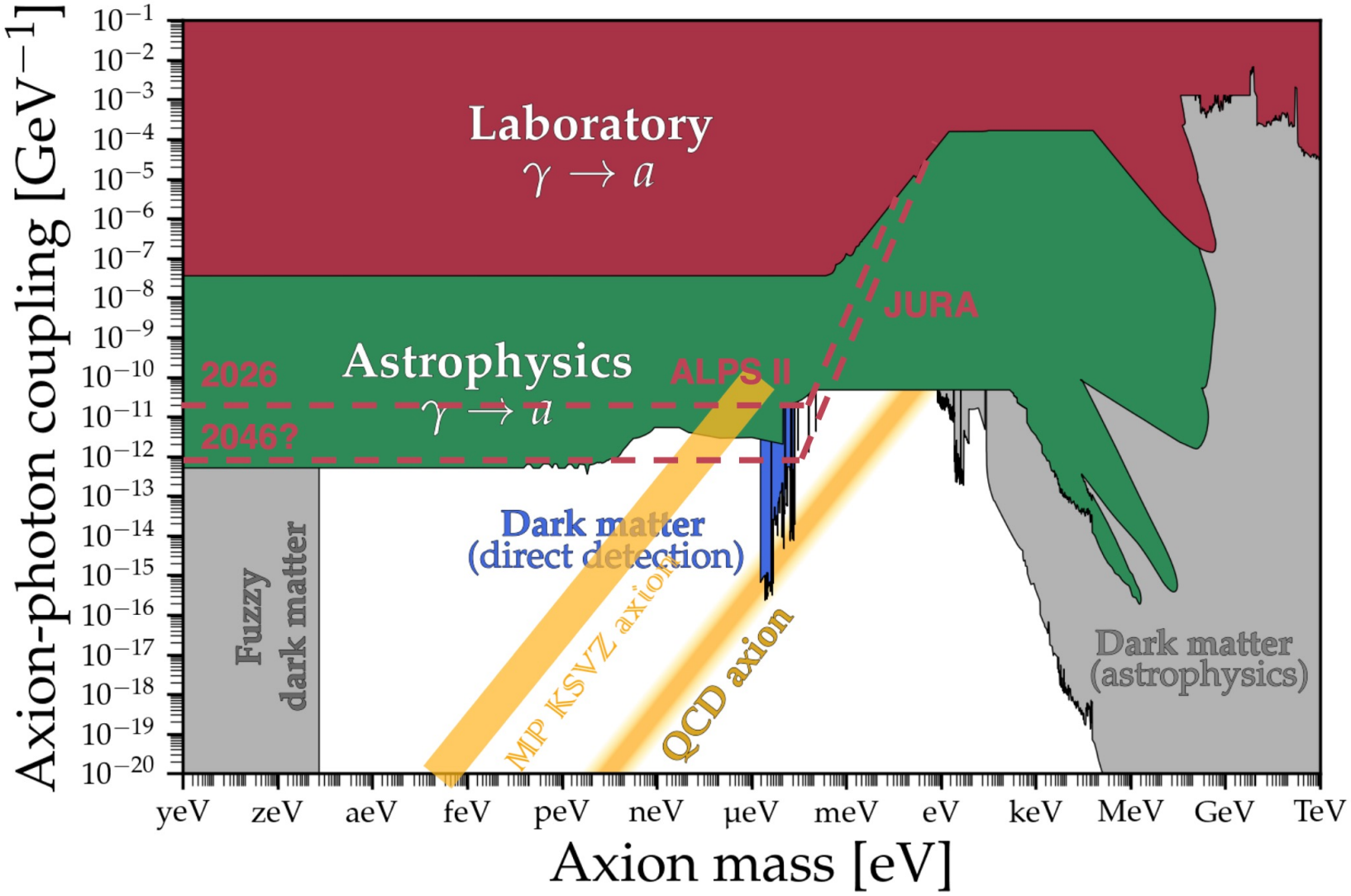

Monopole-philic (MP) KSVZ axion can be probed by LSW experiments

- Axion-photon conversion in external field described by

$$\left(\partial^2 + m_a^2\right) a = -\left(g_{a\gamma} - g_{am}\right) \mathbf{E}_0 \cdot \mathbf{B}_0$$

- Constraints from axion-photon conversion in magnetic background field stay approximately the same, with the identification

$$|g_{a\gamma}| \to |g_{am}|$$

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

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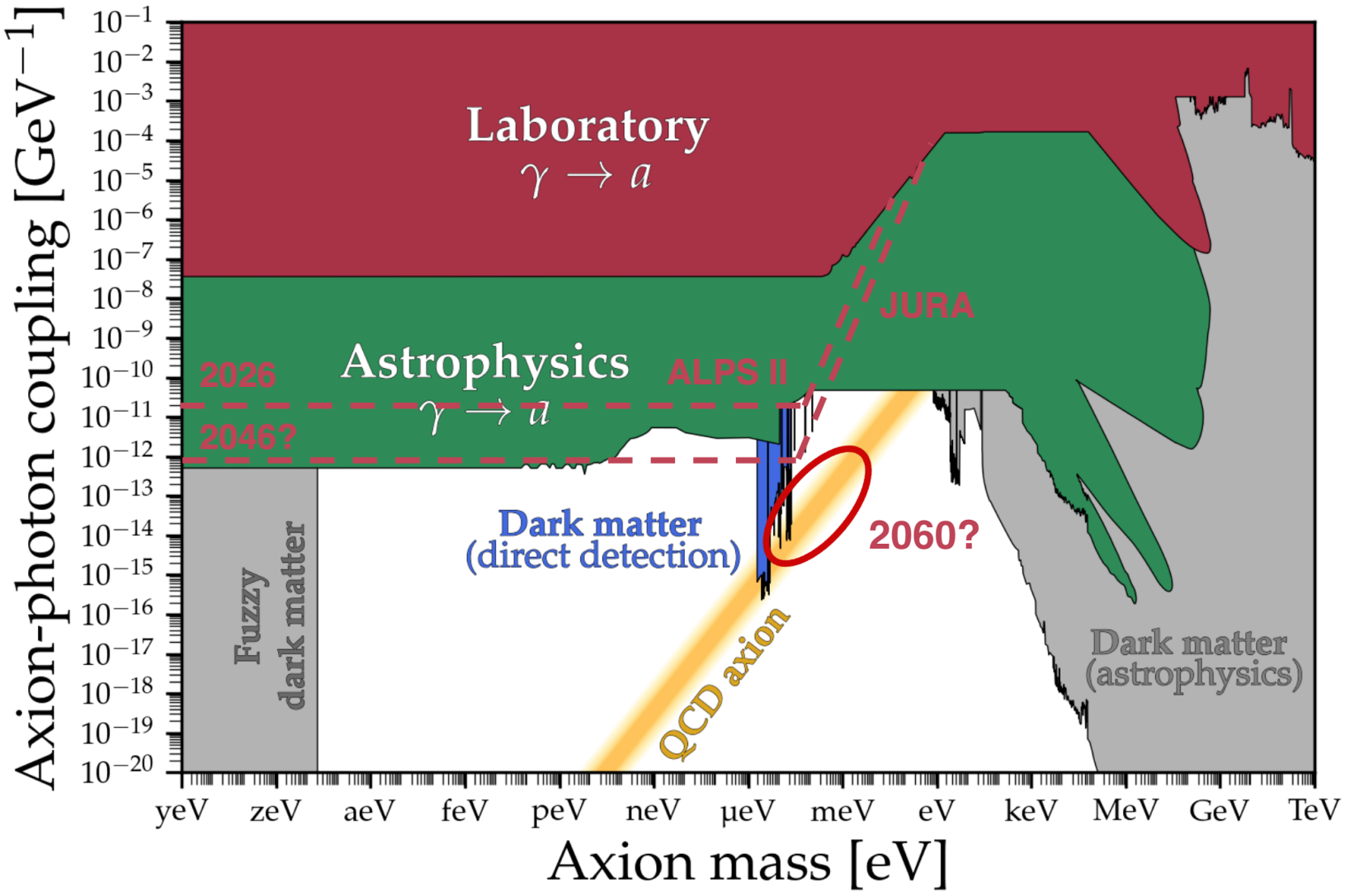
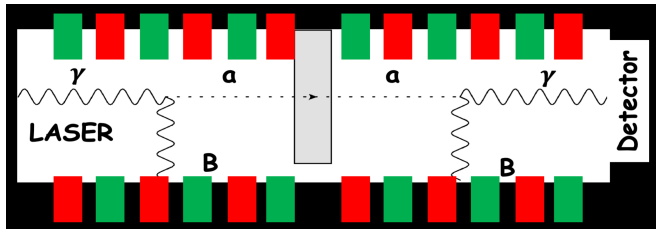


Can tackle vanilla axion band by exploiting alternating magnetic field directions

[van Bibber et al., PRL 59 (1987) 759.; Arias et al., 1009.4875]



HyperLSW Talk by Joerg Jaeckel

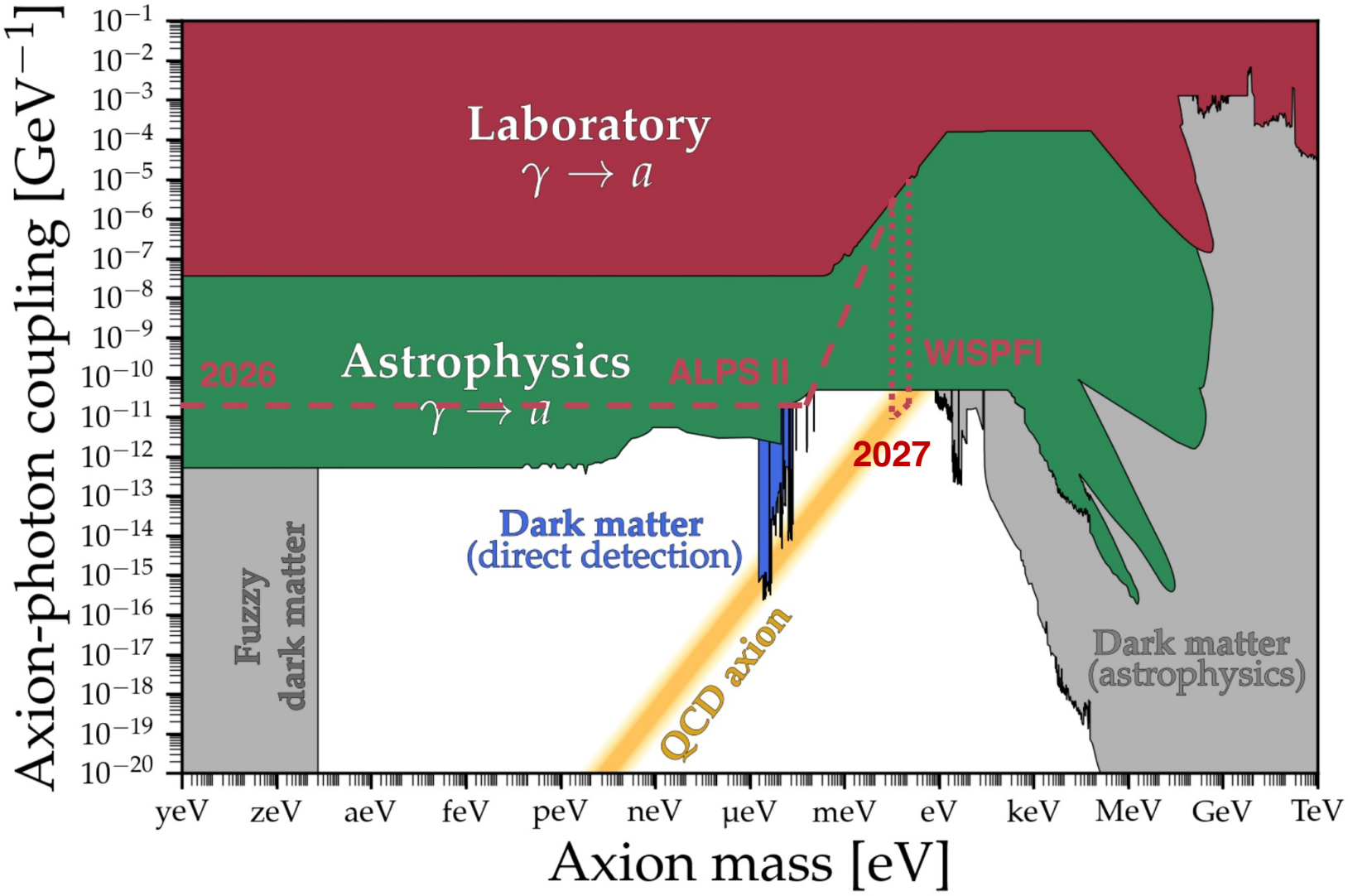
[Hoof,Lucente,Jaeckel, in prep.]

- Long tunnel (~200-400 km)
- Many big aperture 10 T dipoles
- ~100s G€

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

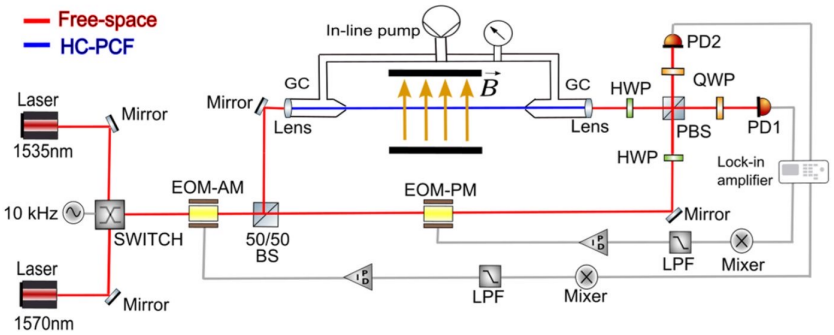
The Road Ahead in the Laboratory

Fiber interferometer experiment can dig in vanilla axion band



WISPFI

[Batllori et al., 2305.12969]



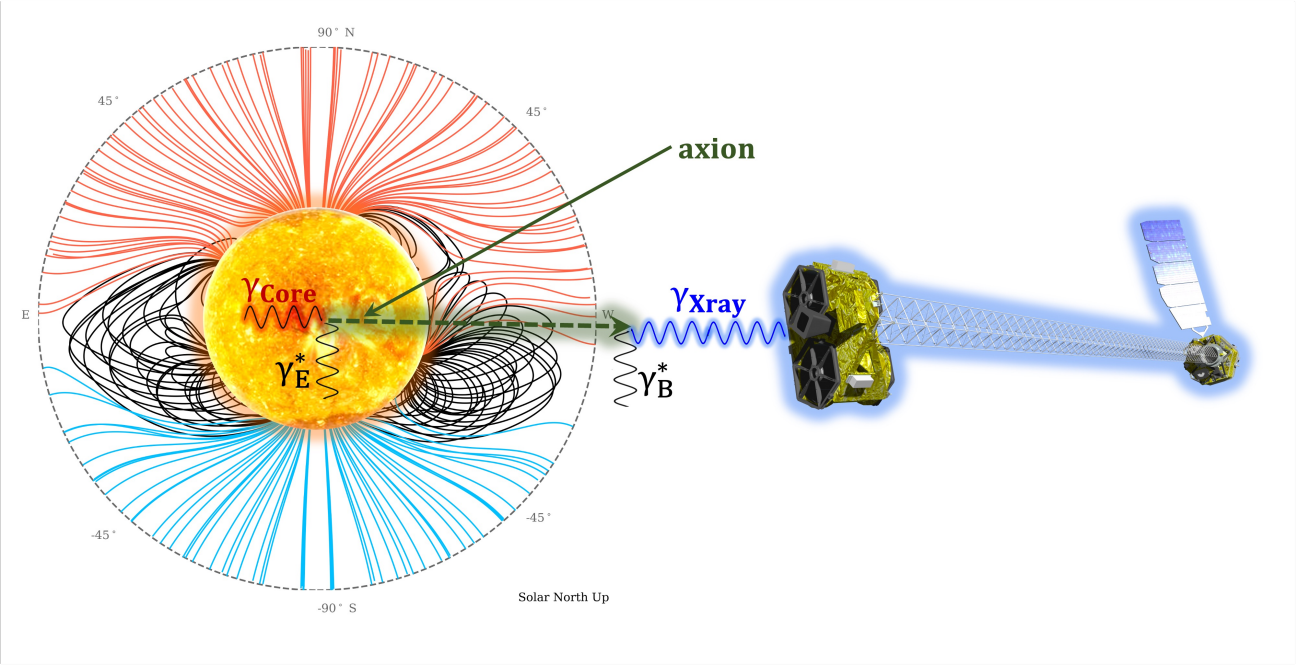
- Mach-Zehnder-type interfero-meter with a hollow-core photonic crystal fiber (refractive index <1) placed inside an external magnetic field searches for photon disappearance
- Changing the gas pressure in the fiber allows to achieve resonant mixing for a mass range between 28 and 100 meV

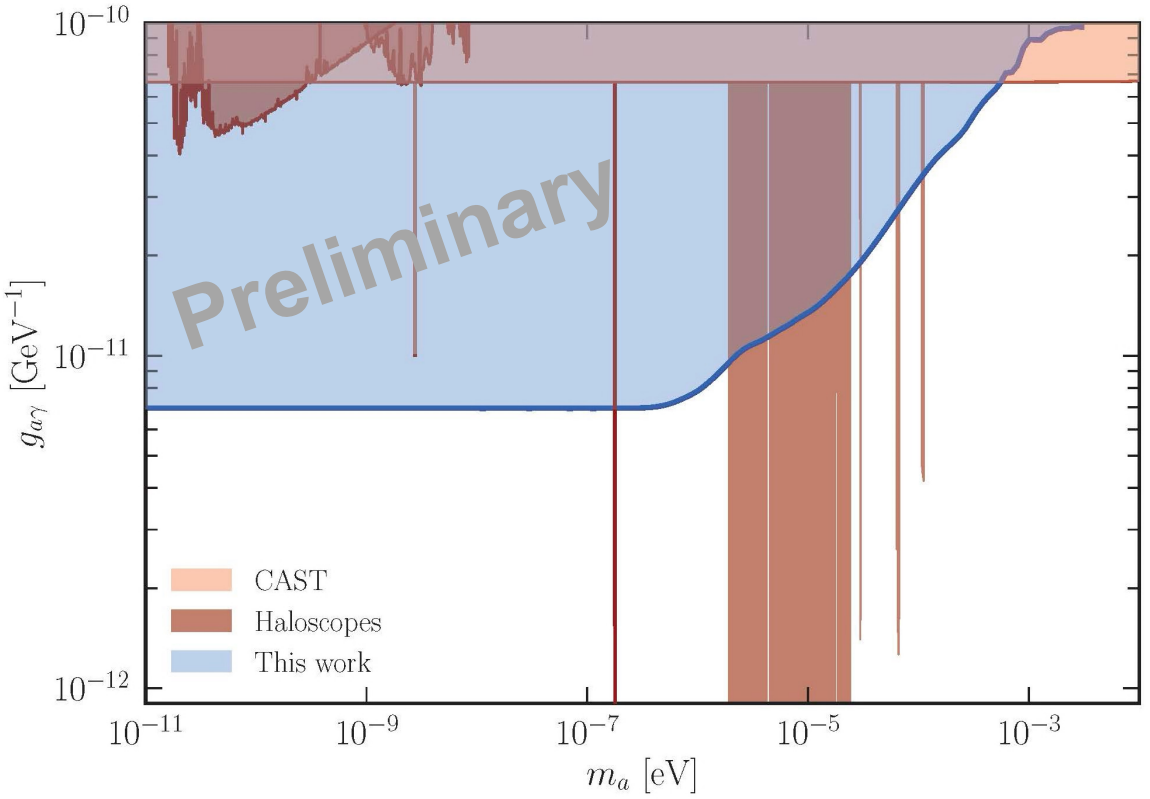
[https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/AxionPhoton_UltraSimple_FullParameterSpace.png]

The Road Ahead in Astrophysics

NuSTAR as Helioscope

Talks by Jaime Ruz and Elisa Todarello





- Capable to look directly into the Sun
- Dedicated campaign observation

[Ruz, Todarello, Giannotti, Regis, Taoso, Voge, in prep.]

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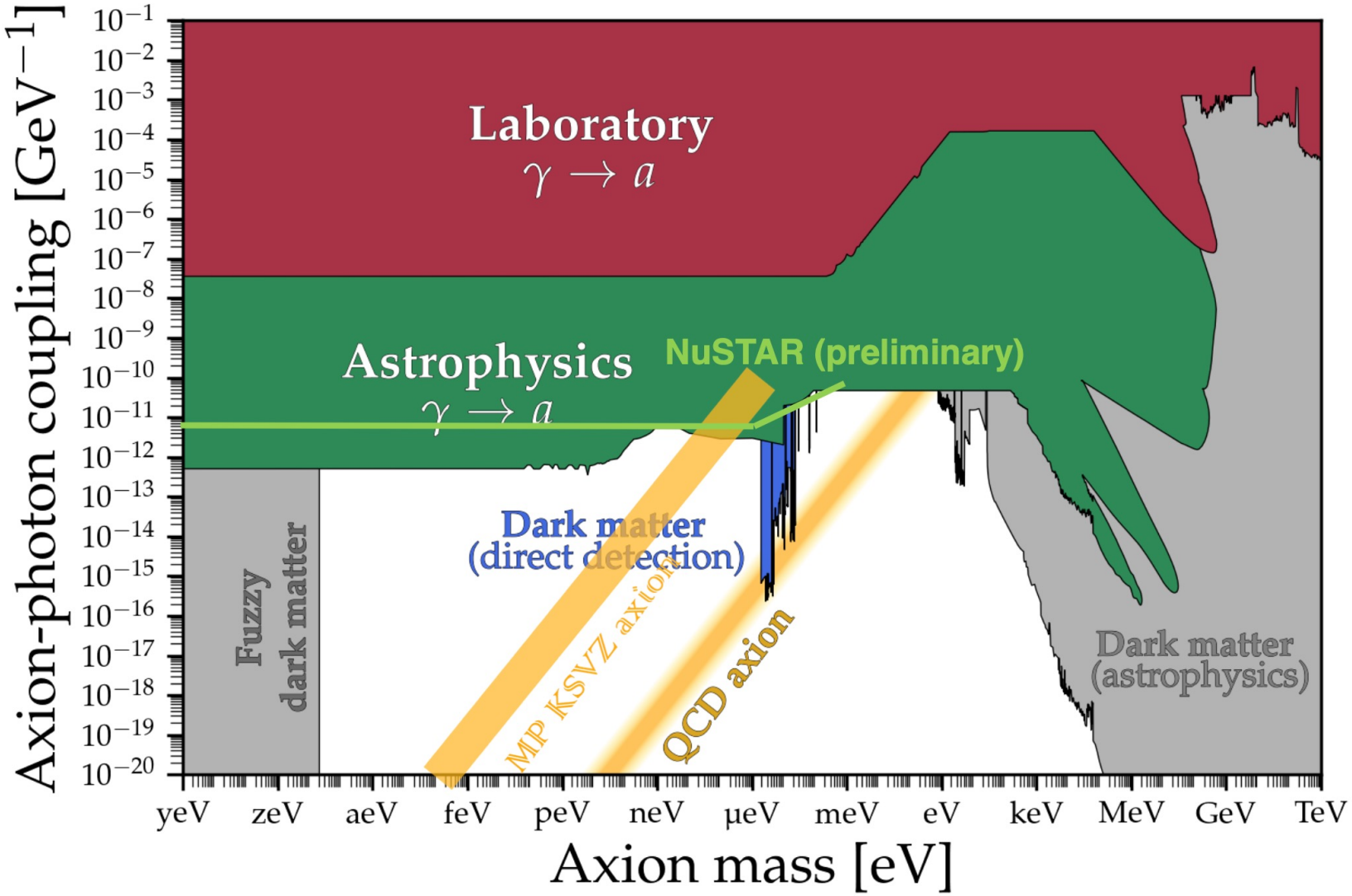
NuSTAR as Helioscope

Talks by Jaime Ruz and Elisa Todarello



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The Road Ahead in Astrophysics

Expect remarkable progress in helioscopes

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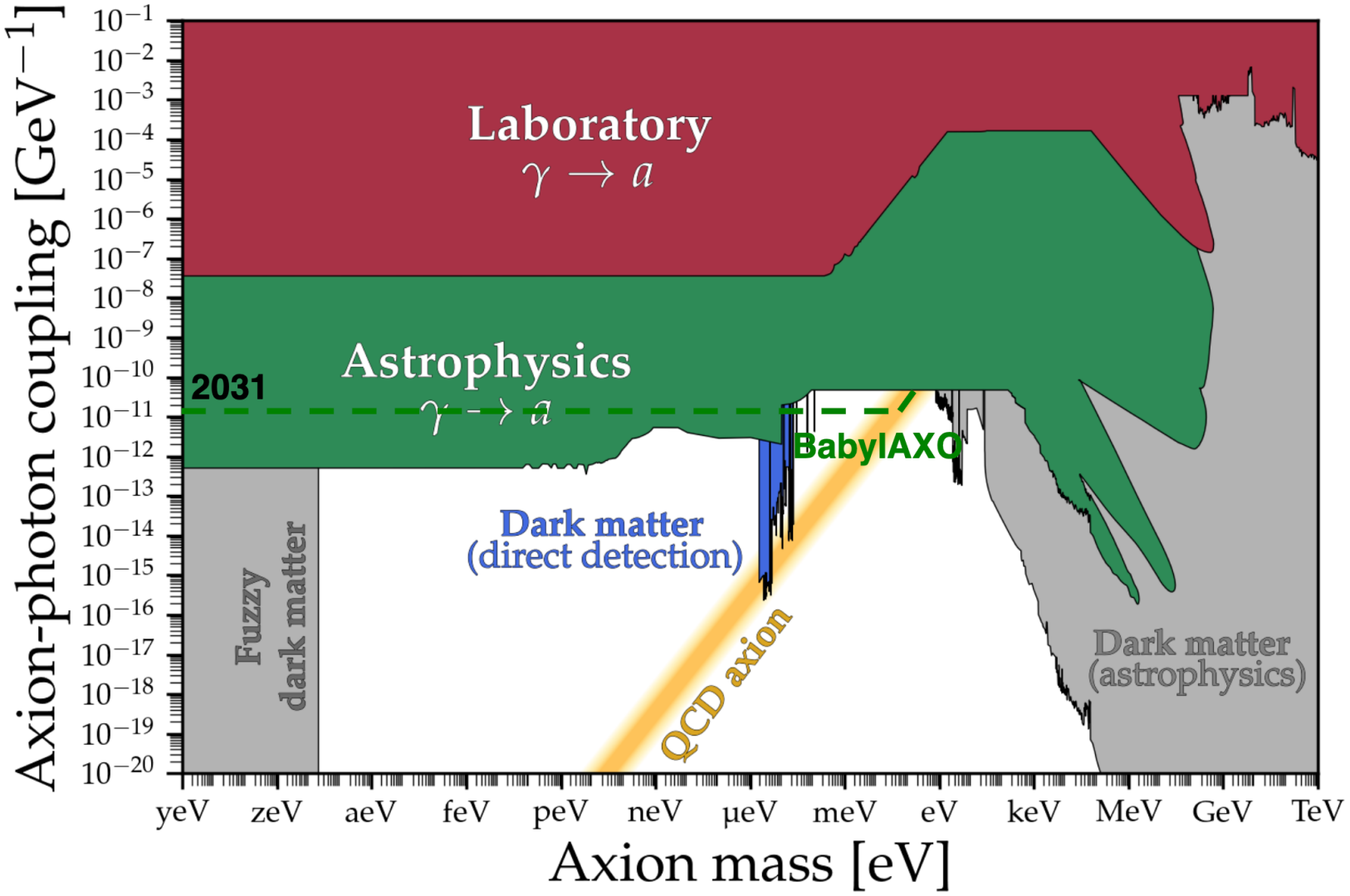
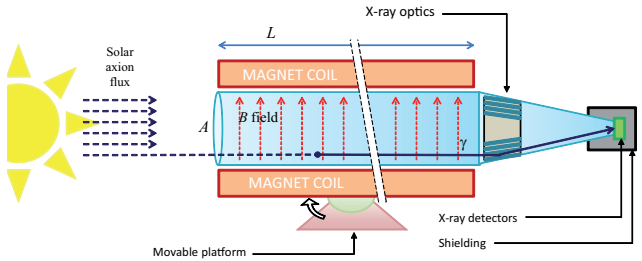
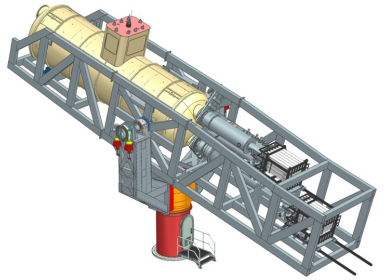




IAXO [Armengaud et al., 1904.09155]

- **BabyIAXO**



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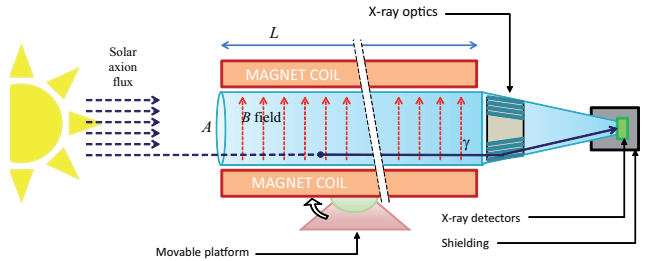

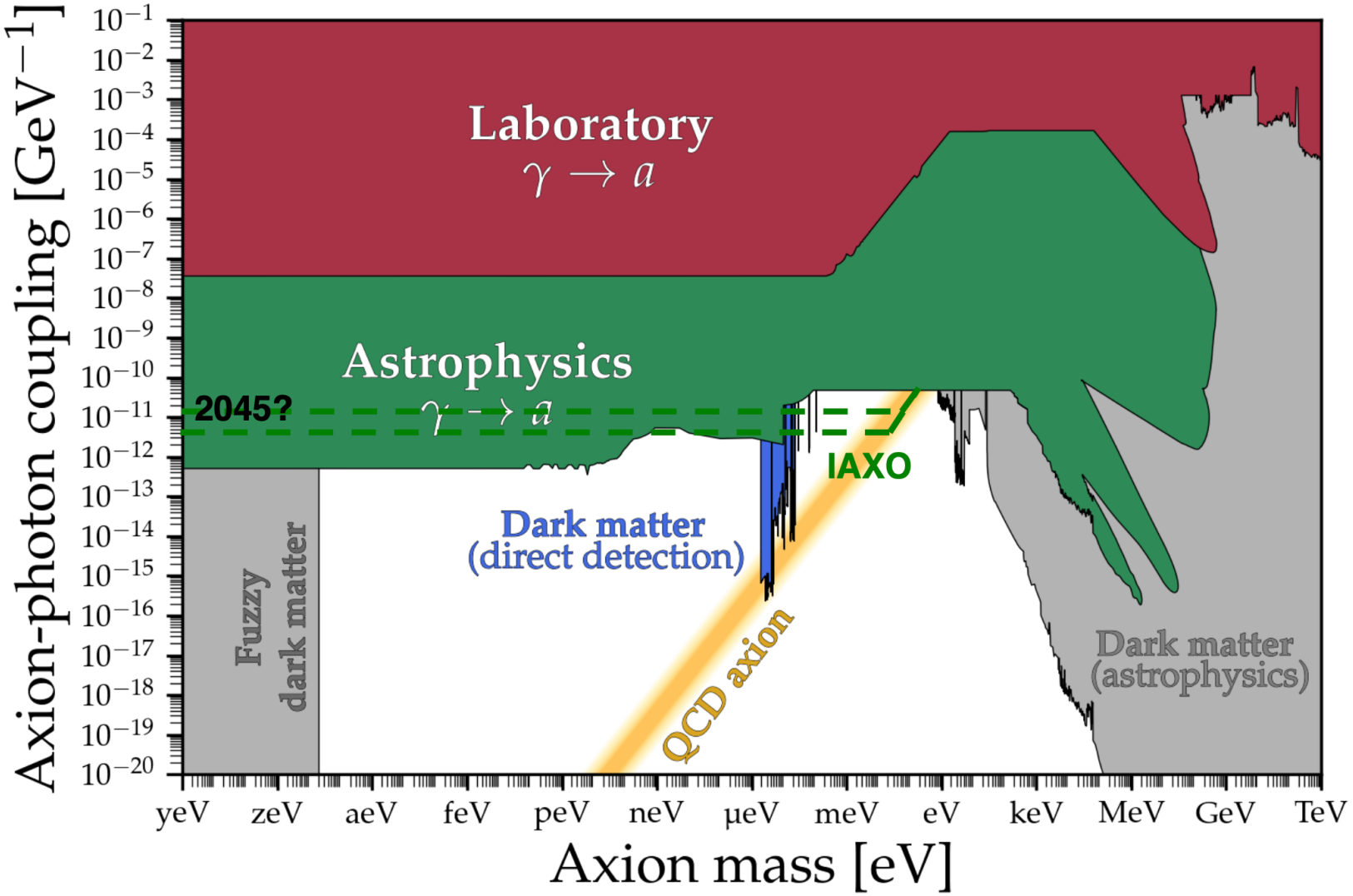

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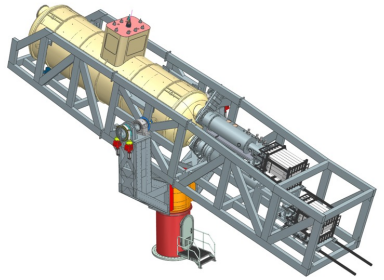

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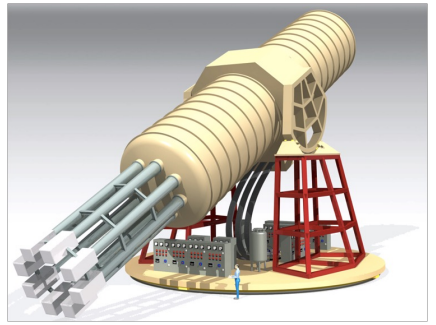

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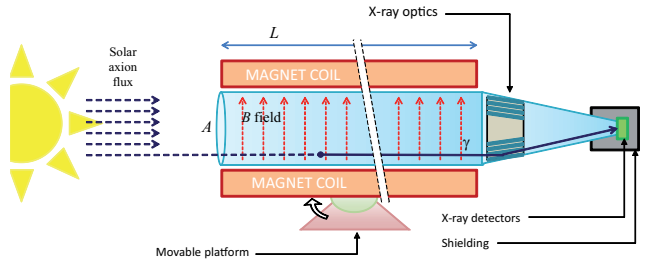

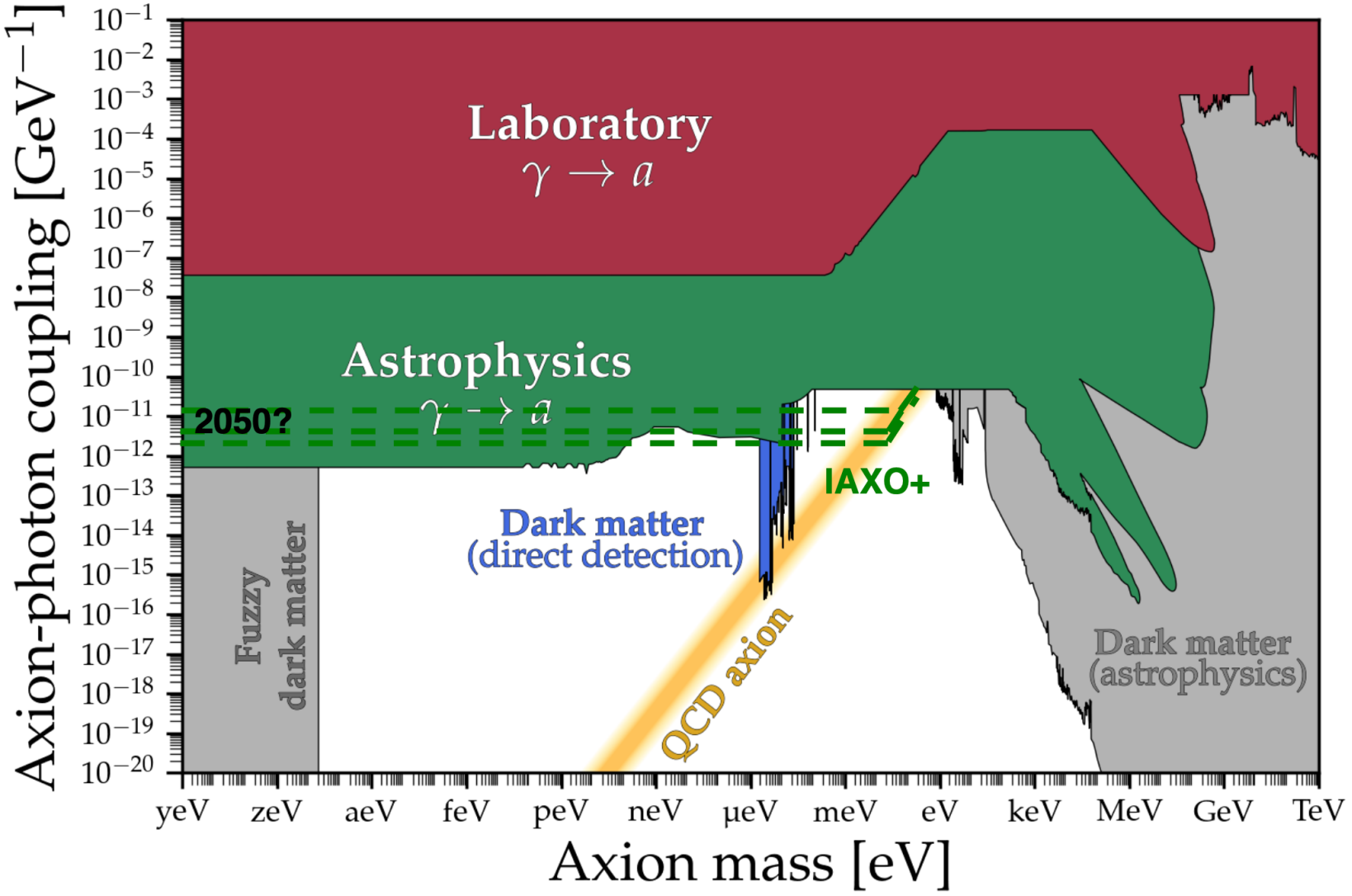

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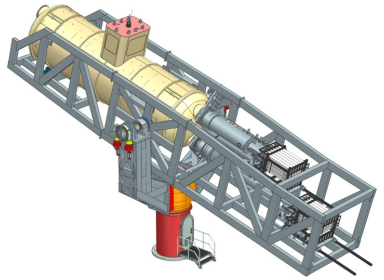

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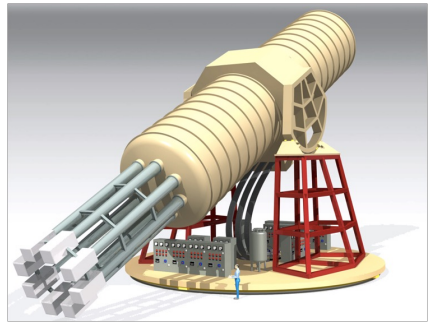

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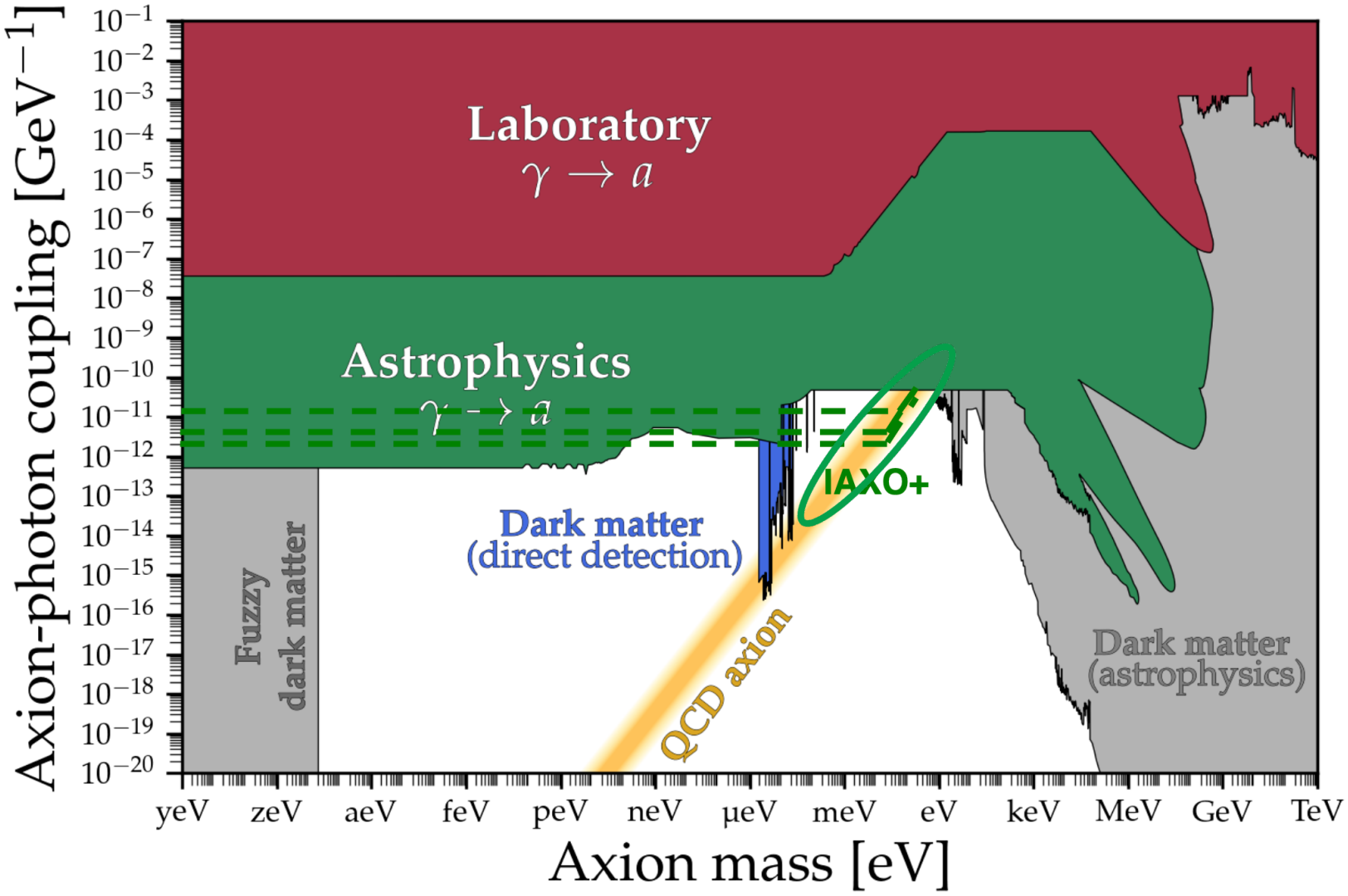

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Helioscopes probe

- **probe vanilla axions in meV mass region**
  - Complementary to haloscope searches and astrophysical and cosmological probes of other couplings

Talks by Francesco D'Eramo and Georg Raffelt

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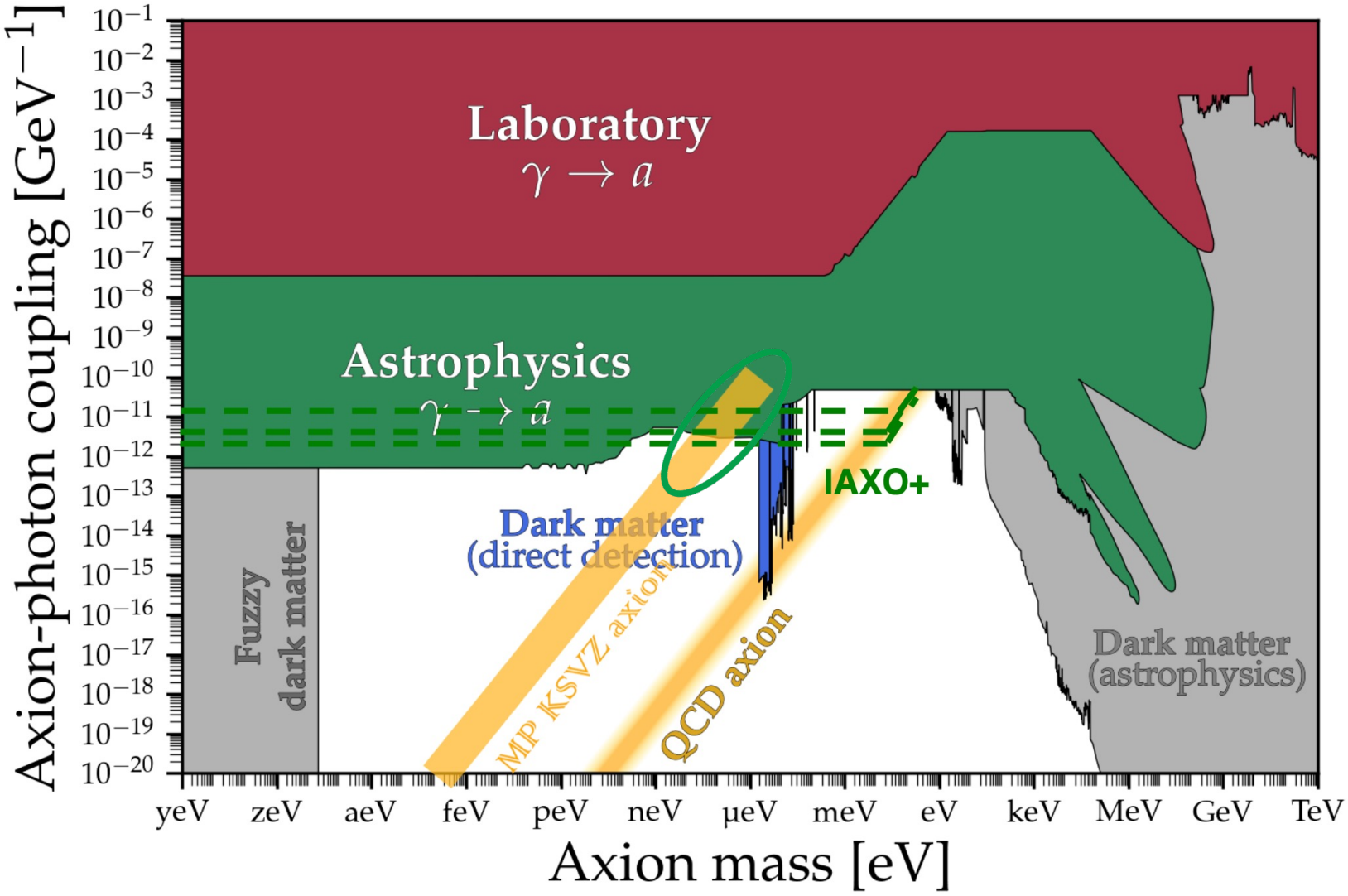

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- **MP KSVZ axion in neV mass region**

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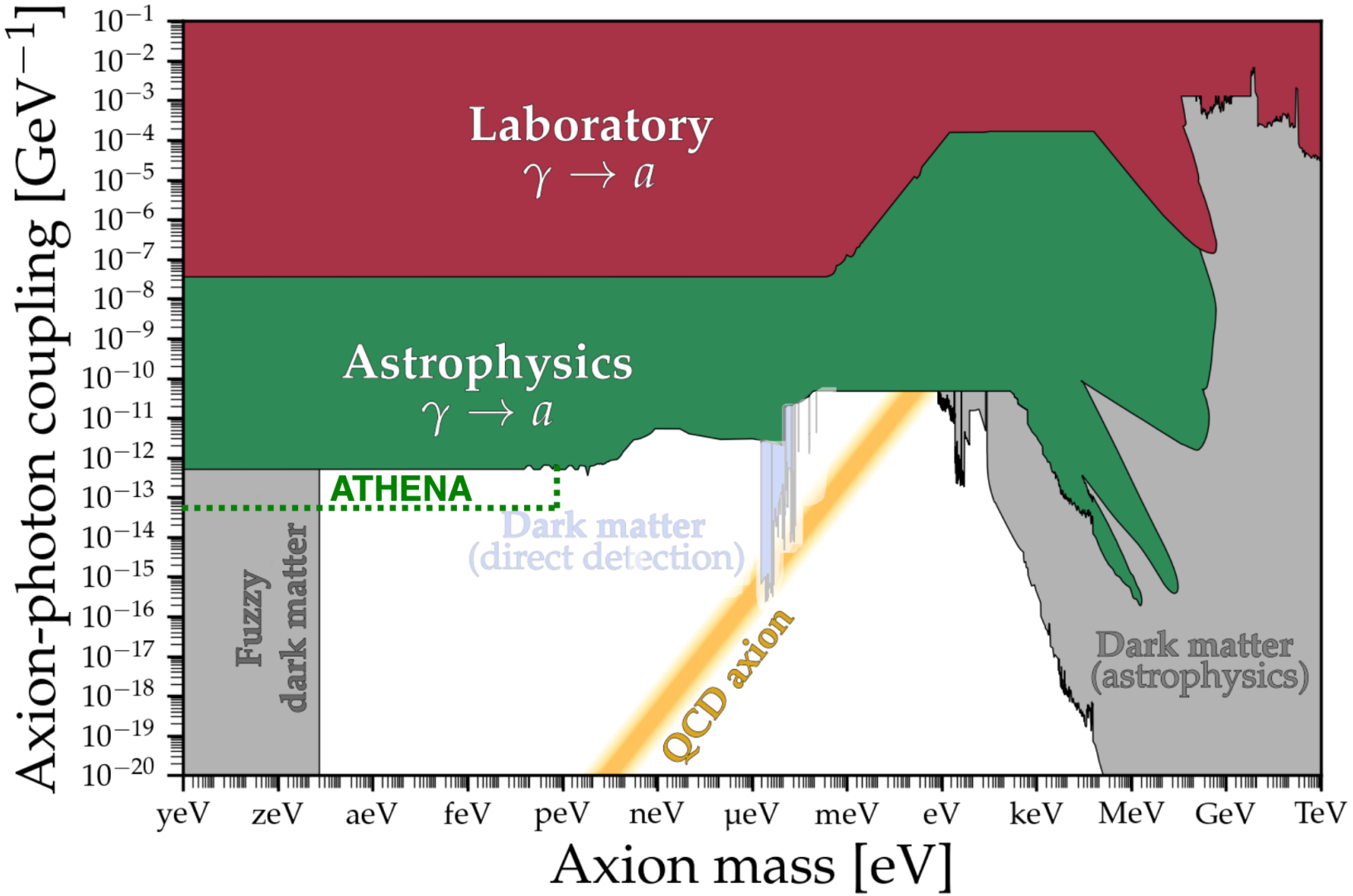

- X-ray observations of bright active galactic nuclei (AGNs) hosted by rich clusters of galaxies are excellent probes of ALPs with sub-peV masses

  Talk by Francesca Chada-Day

- Future X-ray observatory **Athena** may improve current constraints by an order of magnitude

  [Sisk-Reynés et al., 2211.05136]

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

The Road Ahead in Astrophysics

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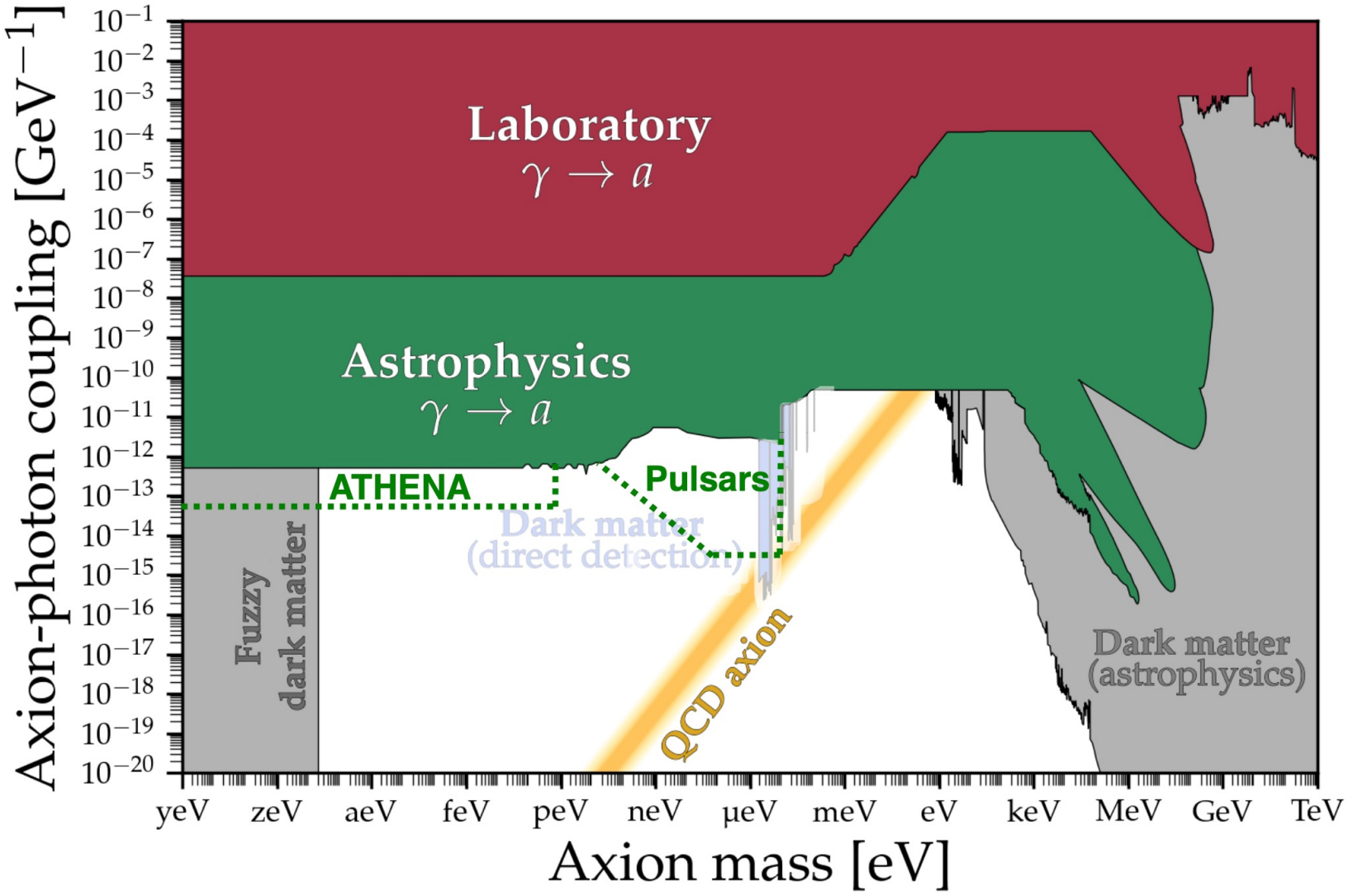
Talk by Samuel Witte



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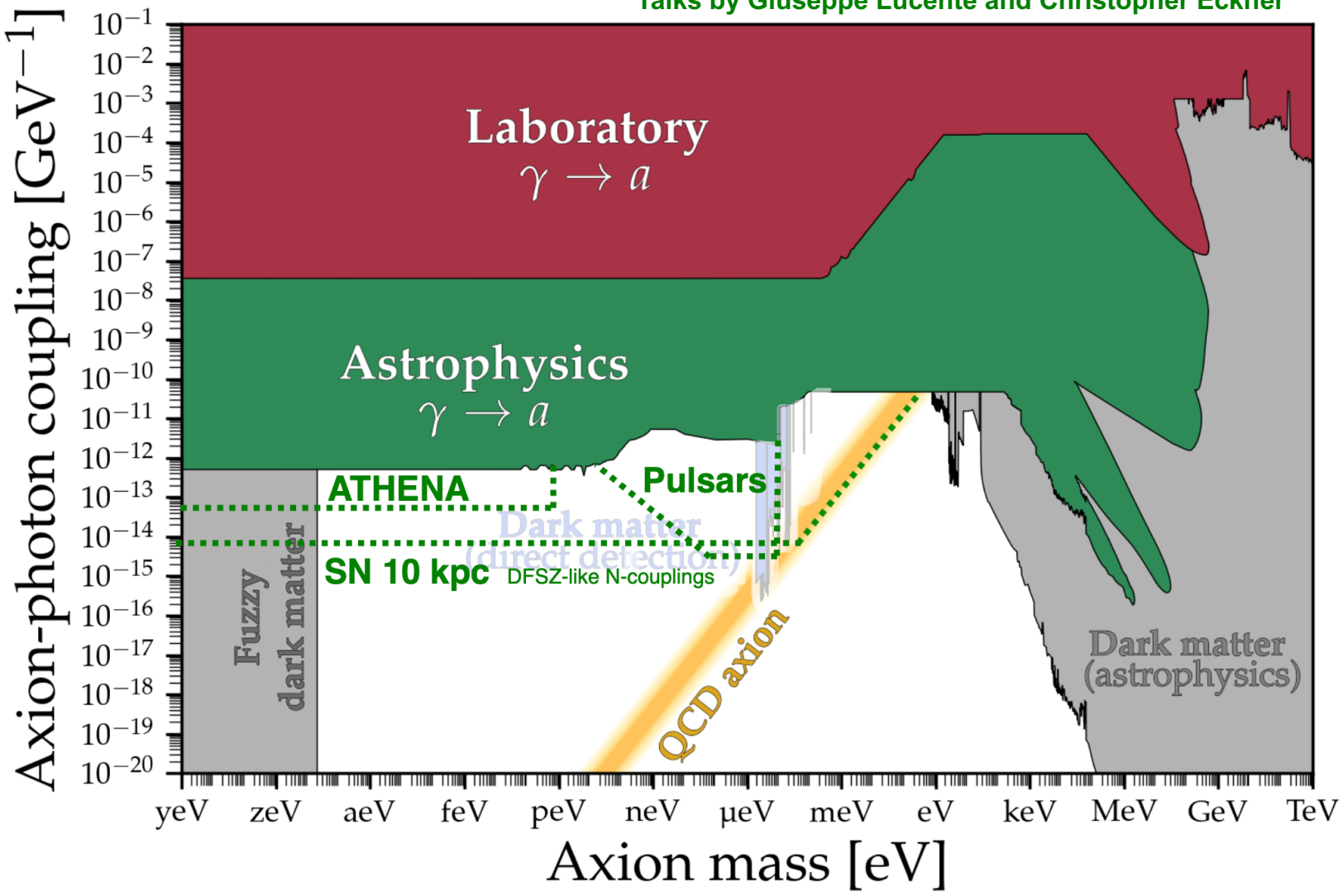
- Axions efficiently produced in polar cap region of pulsars
- For neV – 0.1 meV masses a sizable fraction of the sourced axion population gravitationally confined to the neutron star, accumulating over astrophysical timescales, forming a dense ‘axion cloud’ around the star
- For axion masses above 0.1 micro-eV, energy primarily radiated from the axion cloud via resonant axion-photon mixing, generating a number of distinctive signatures:

  [Nordhuis et al., 2307.11811]
  - sharp line in radio spectrum of each pulsar located axion mass
  - transient events arising from the reconfiguration of charge densities in the magnetosphere

The Road Ahead in Astrophysics

Expect remarkable progress in astrophysics

Talks by Giuseppe Lucente and Christopher Eckner



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- Axion-photon conversion on the still-intact magnetic fields of the progenitor star of SN1987A constrains ALPs all the way to 0.1 meV
- Gamma-ray observations of the next Galactic supernova, leveraging the magnetic fields of the progenitor star, could probe the vanilla axion band above roughly 50 μeV
- A new full-sky gamma-ray satellite constellation dubbed GALactic AXion Instrument for Supernova (GALAXIS) has been proposed to search for such future signals along with related signals from extragalactic neutron star mergers

[Manzari et al., 2405.19393]

The Road Ahead in Astrophysics

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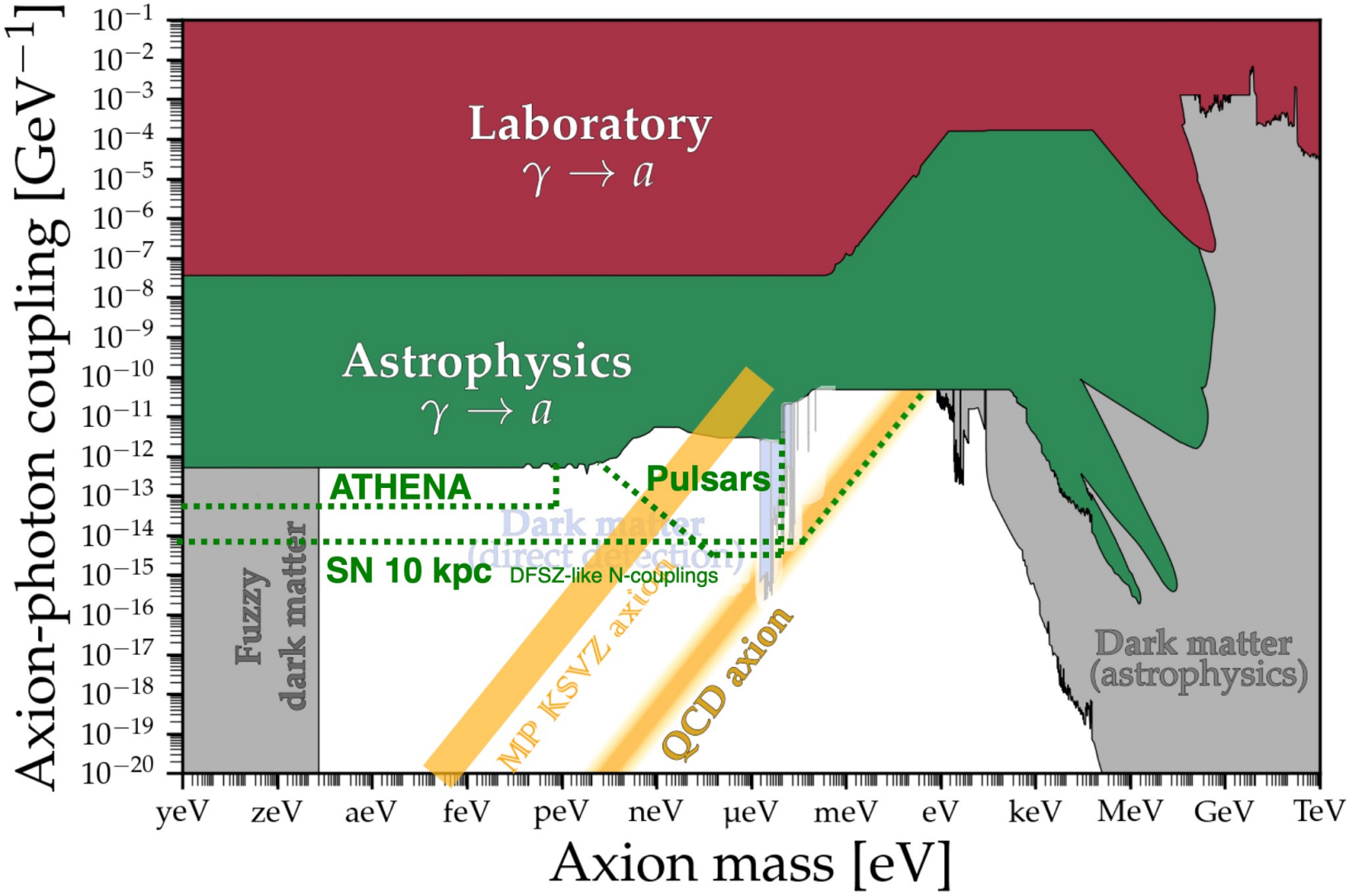

Future astrophysics may probe

- **MP KSVZ axion in the neV mass region, corresponding to a PQ breaking scale $f_a \sim M_Q$ (monopole mass) of order GUT scale**
- **Vanilla axion in meV region**
  - Complementary to haloscope searches and astrophysical and cosmological probes of other couplings

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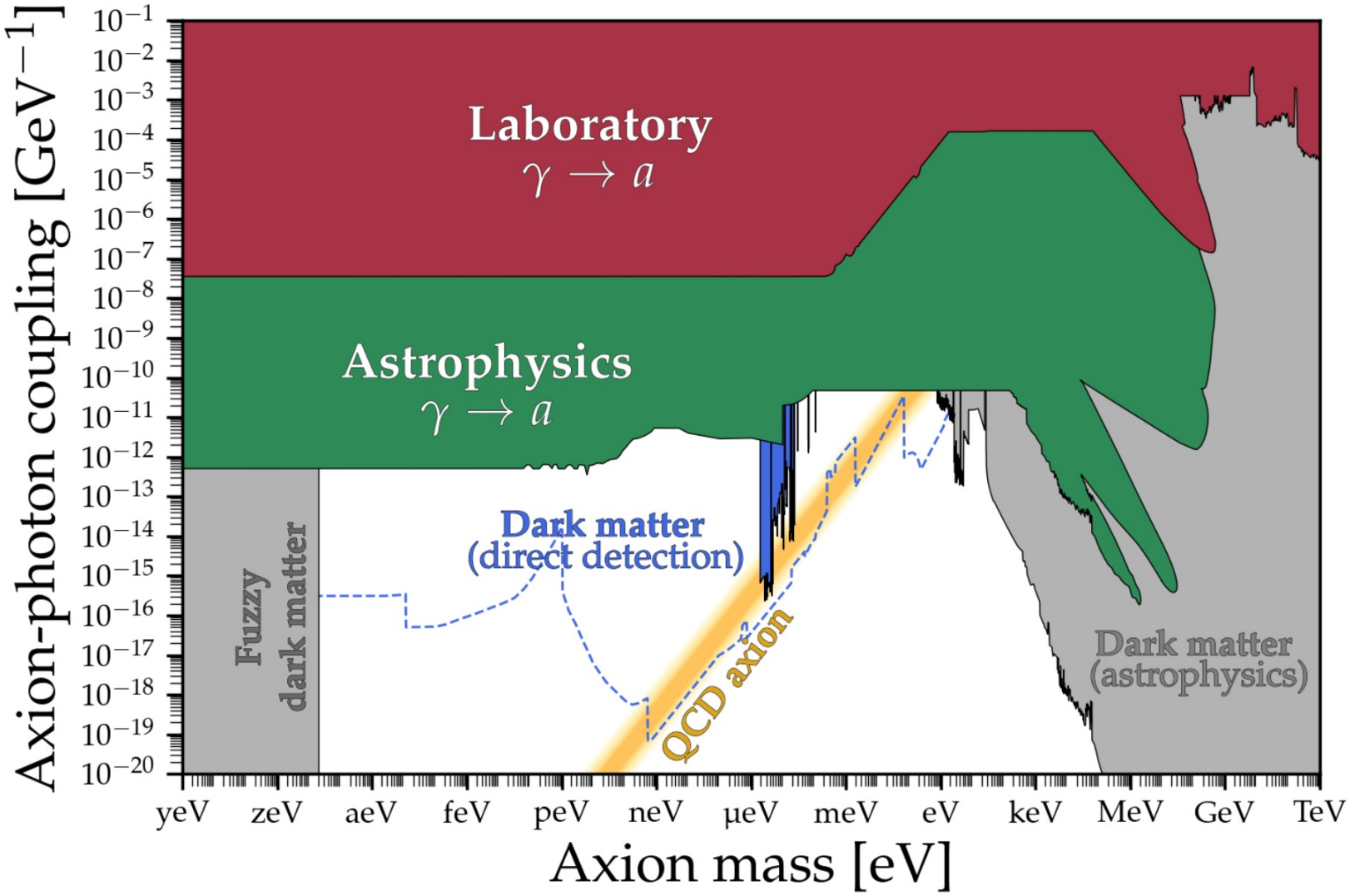
The Road Ahead in Dark Matter

Expect huge progress in axion DM searches

Talks by Joerg Jaeckel, Jamie McDonald, Elisa Todarello



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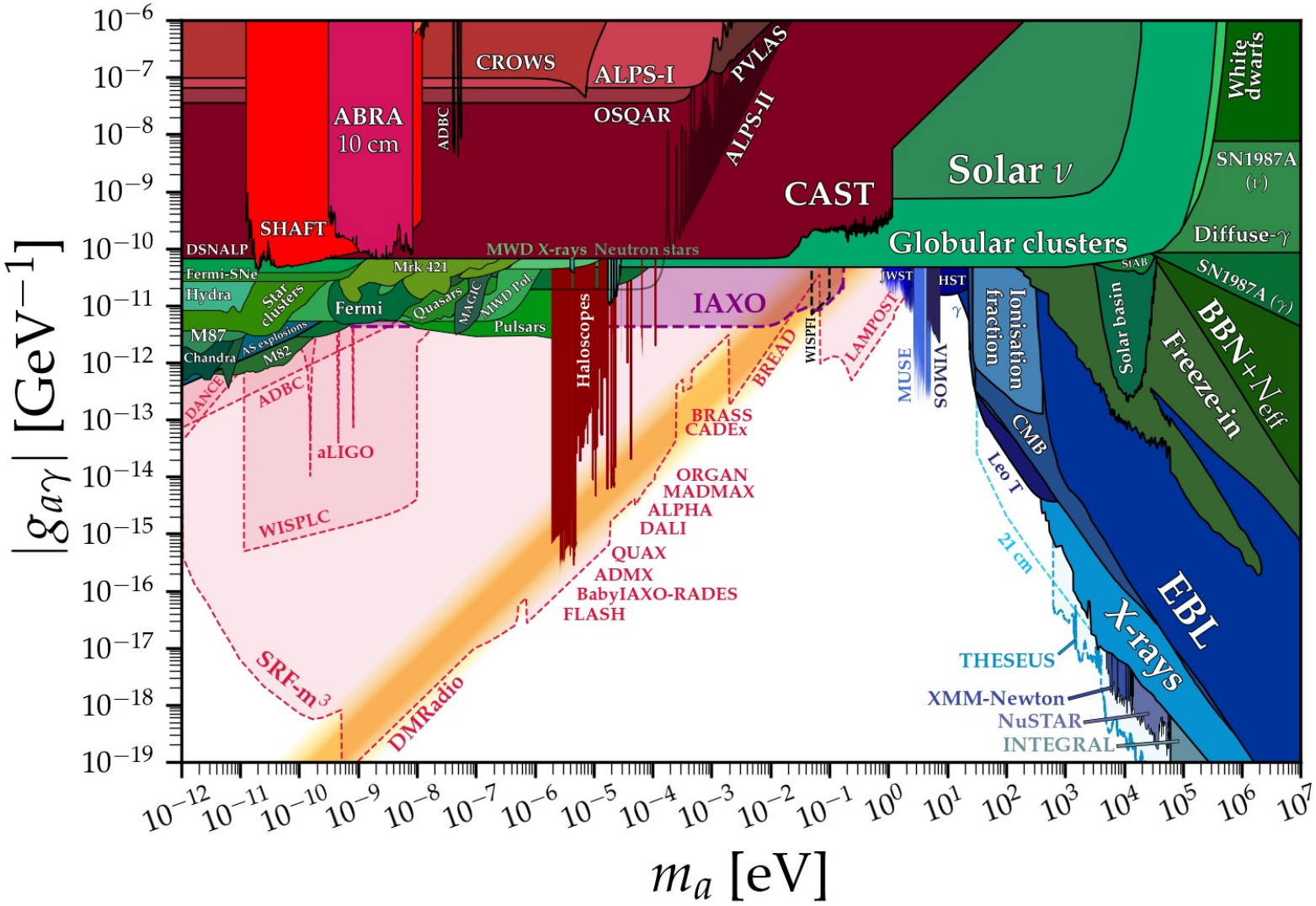

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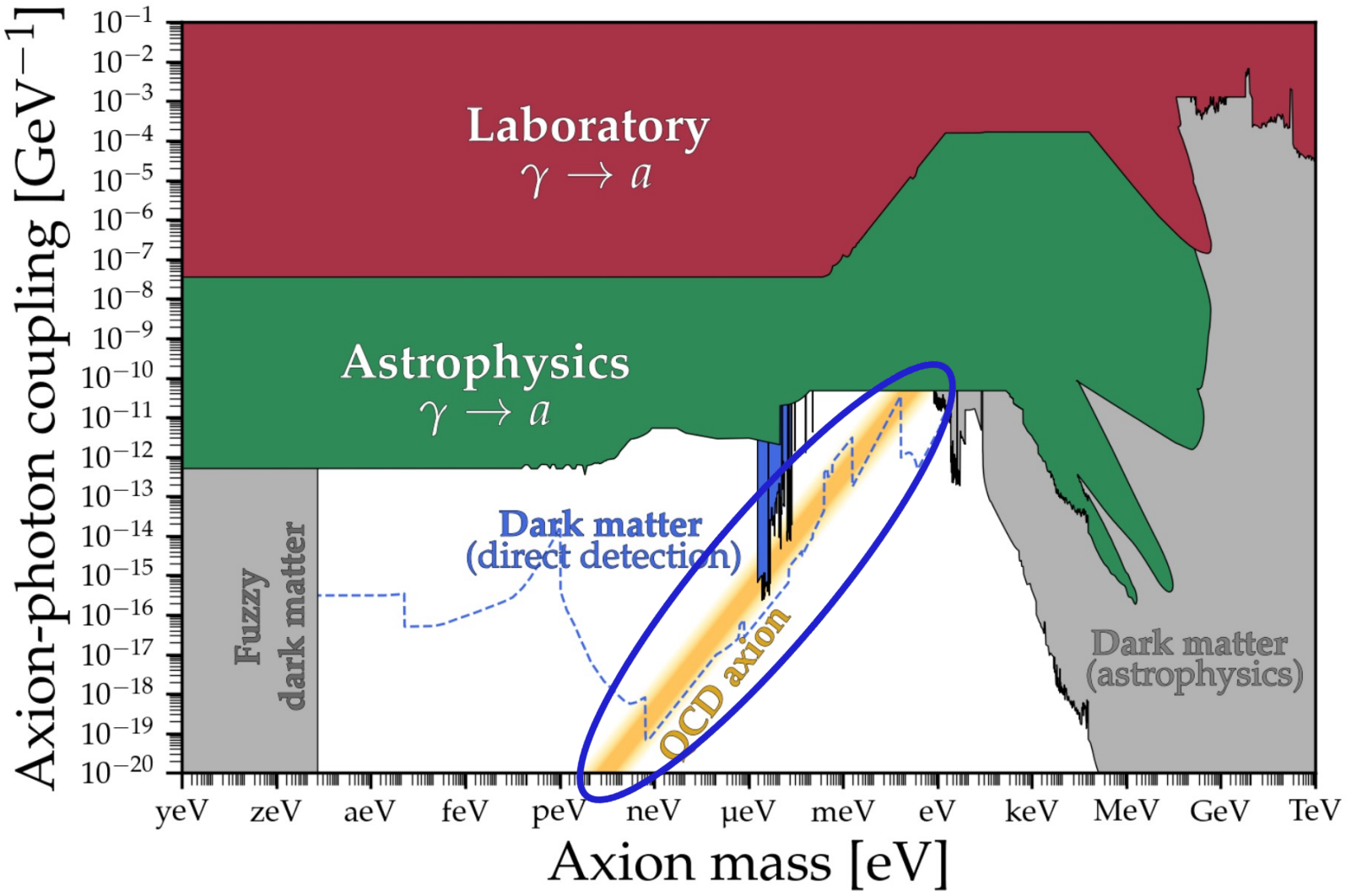

Haloscopes appear to cover most of the plausible parameter range for the axion

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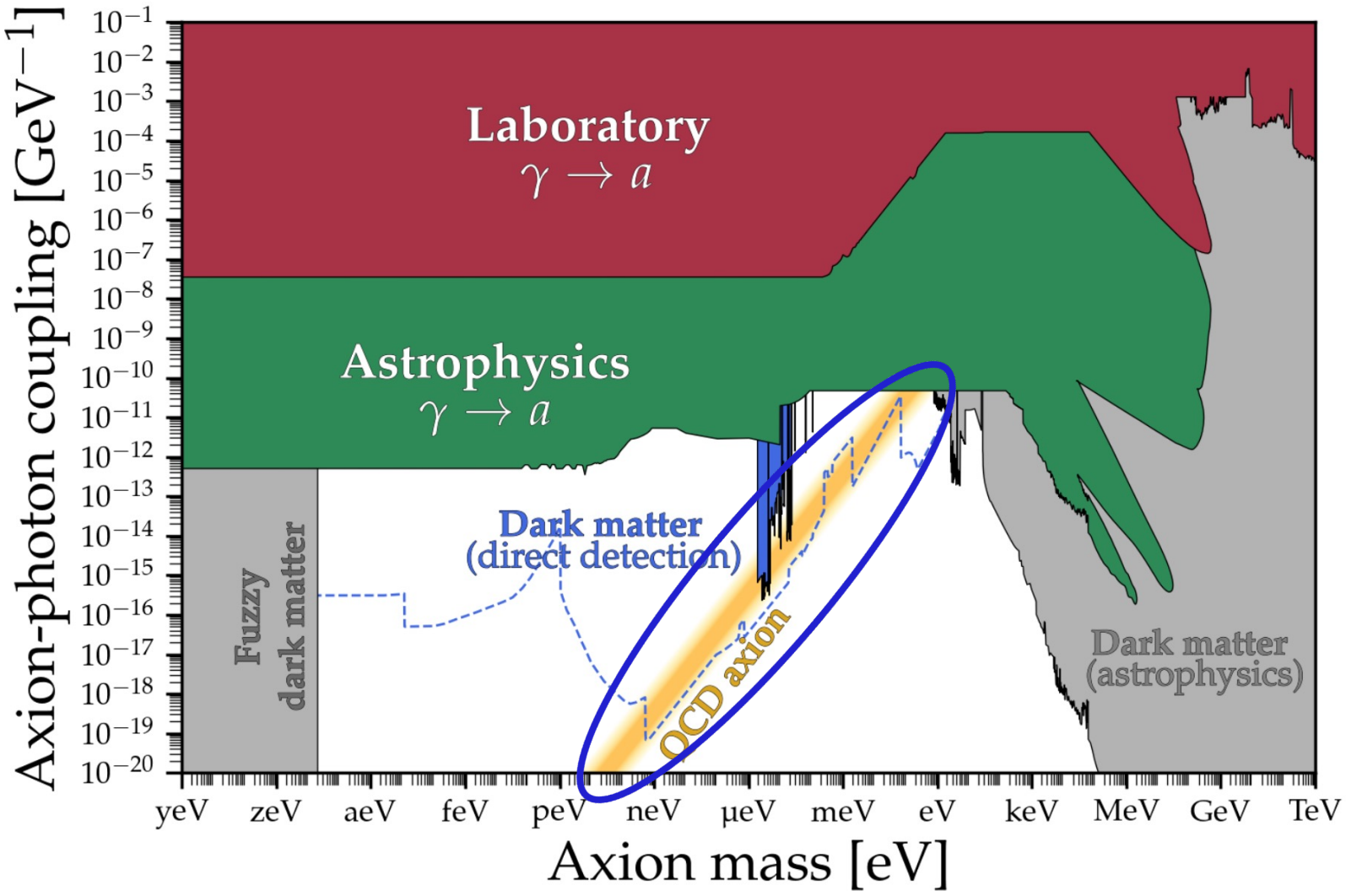

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Caveats:

- Local axion DM energy density may be much less than assumed 0.45 GeV/cm^3

Talk by Joshua Eby

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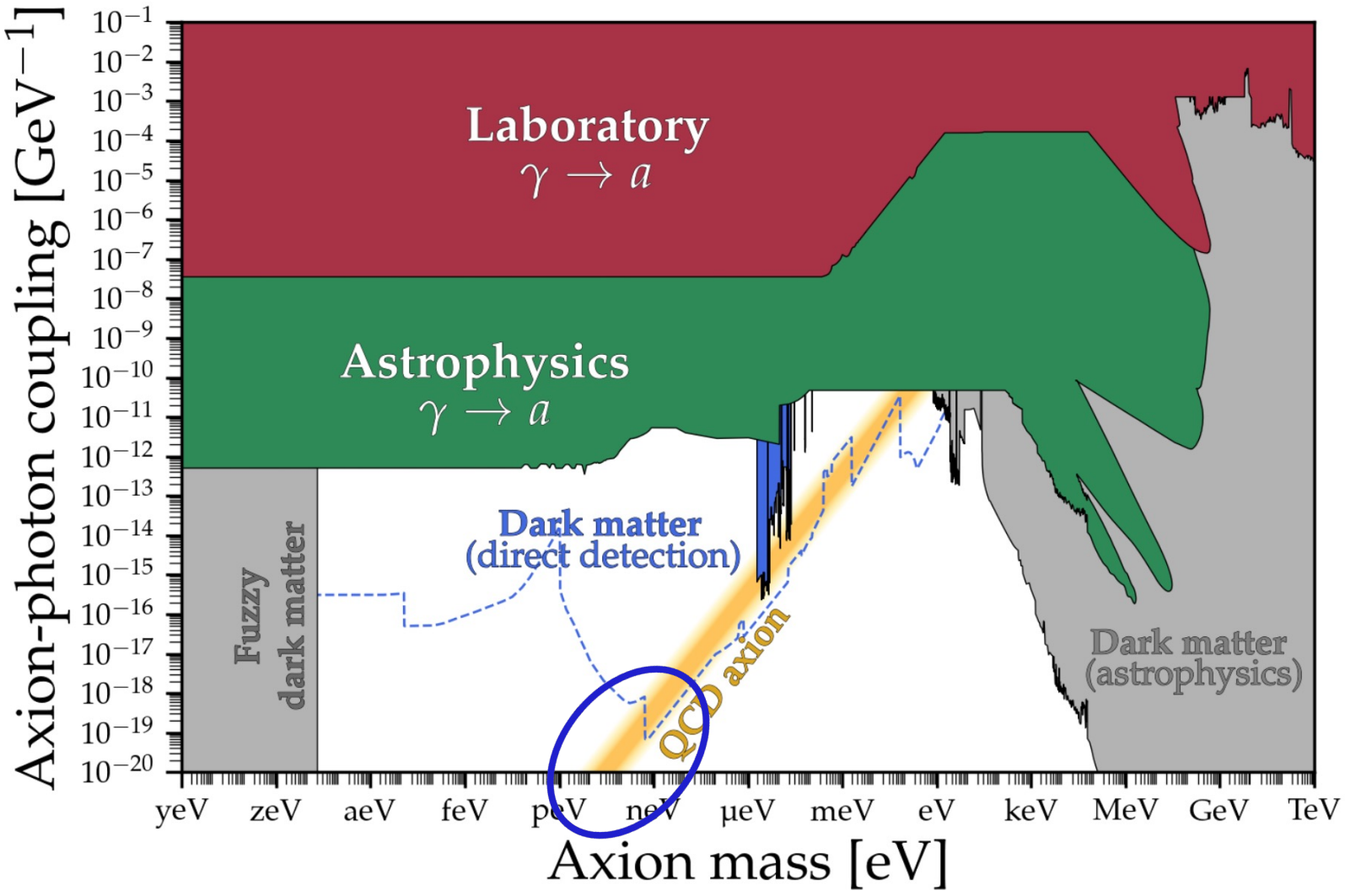
The Road Ahead in Dark Matter

Sensitivity hole of haloscopes at peV to neV mass



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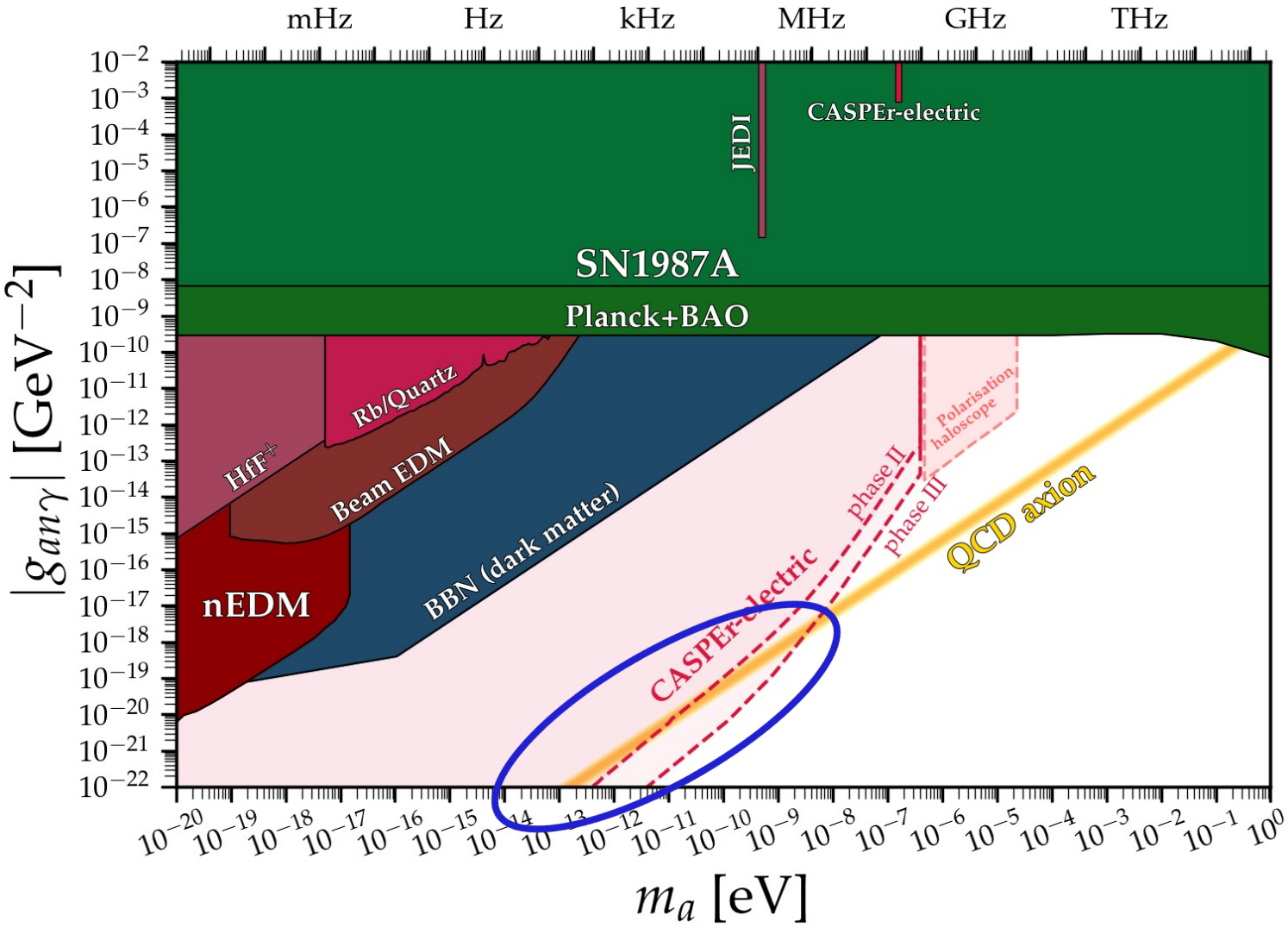
- Sensitivity holes around
  - peV to neV mass ($M_P > f_a > M_{GUT}$)

[https://github.com/cajohare/AxionLimits/blob/master/UltraSimplifiedPlots.ipynb]

The Road Ahead in Dark Matter

peV to neV mass can be probed by NMR experiment



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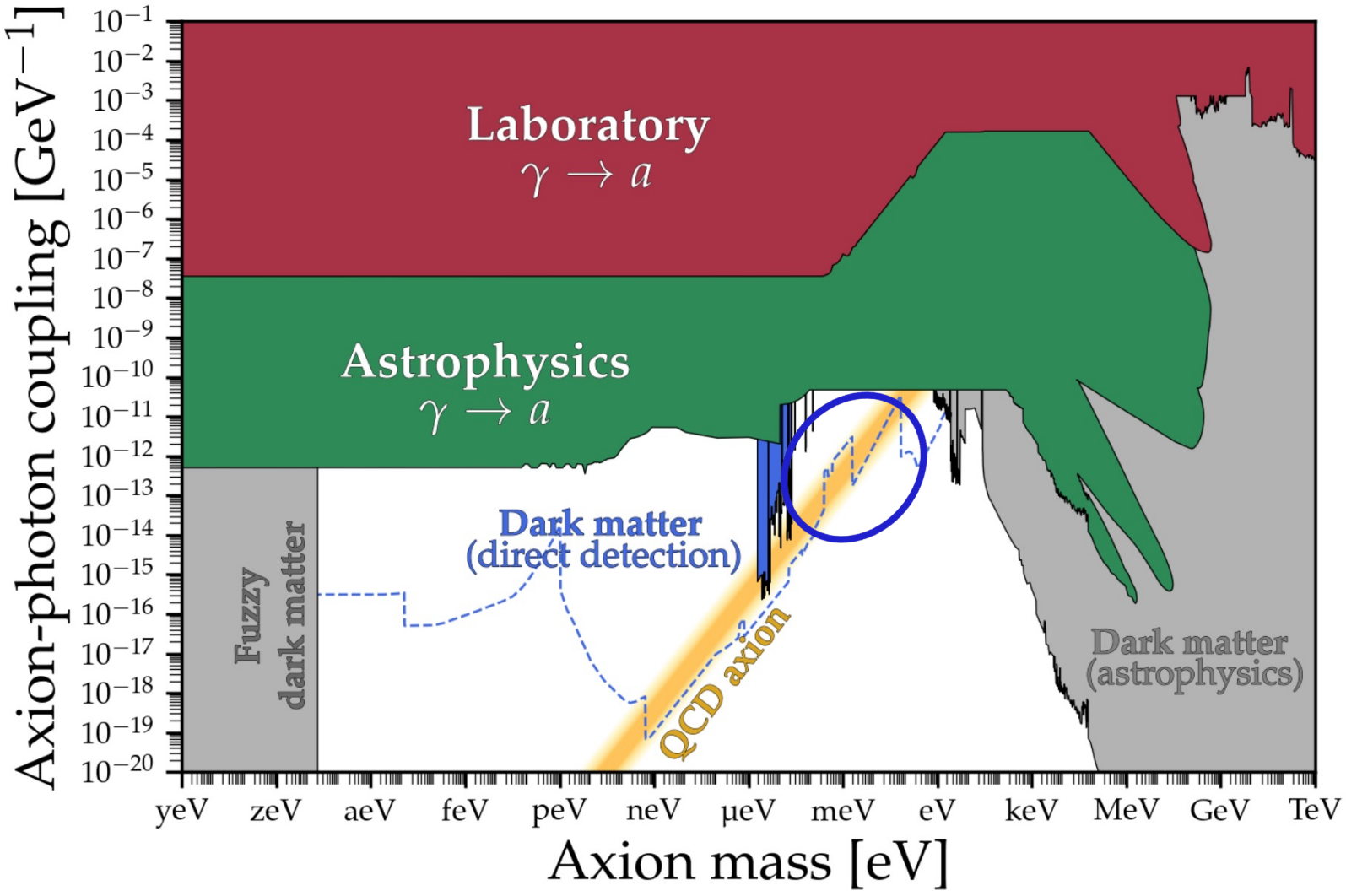
    - Search for oscillating NEDMs

Talk by Joerg Jaeckel

The Road Ahead in Dark Matter

Sensitivity hole of haloscopes at meV to eV mass?



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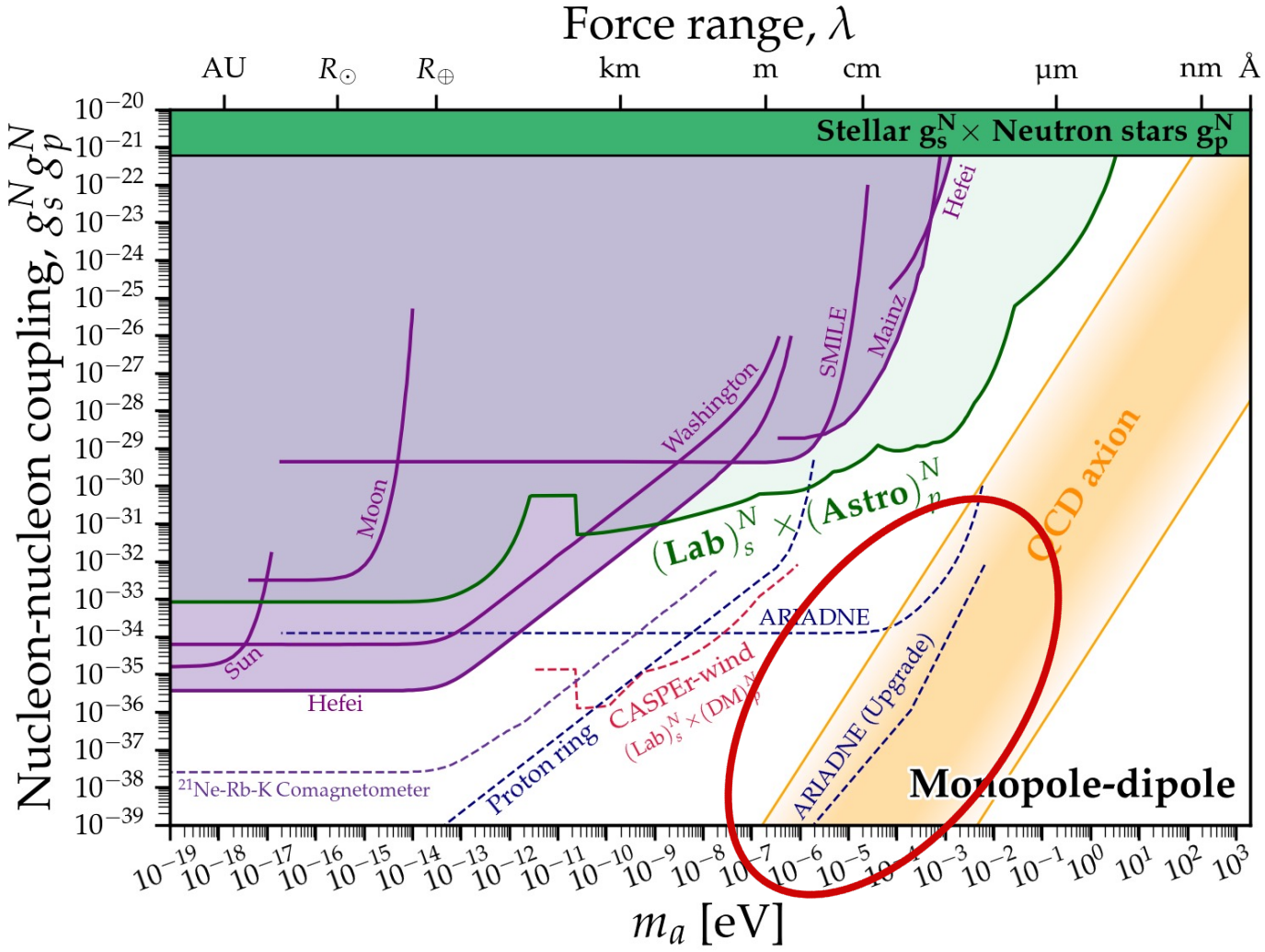
  - meV mass

[https://github.com/cajohare/AxionLimits/blob/master/UltraSimplifiedPlots.ipynb]

The Road Ahead in Dark Matter

meV mass can be probed by search for CP violating Yukawa interactions



[O'Hare, Vitagliano, 2010.03889]

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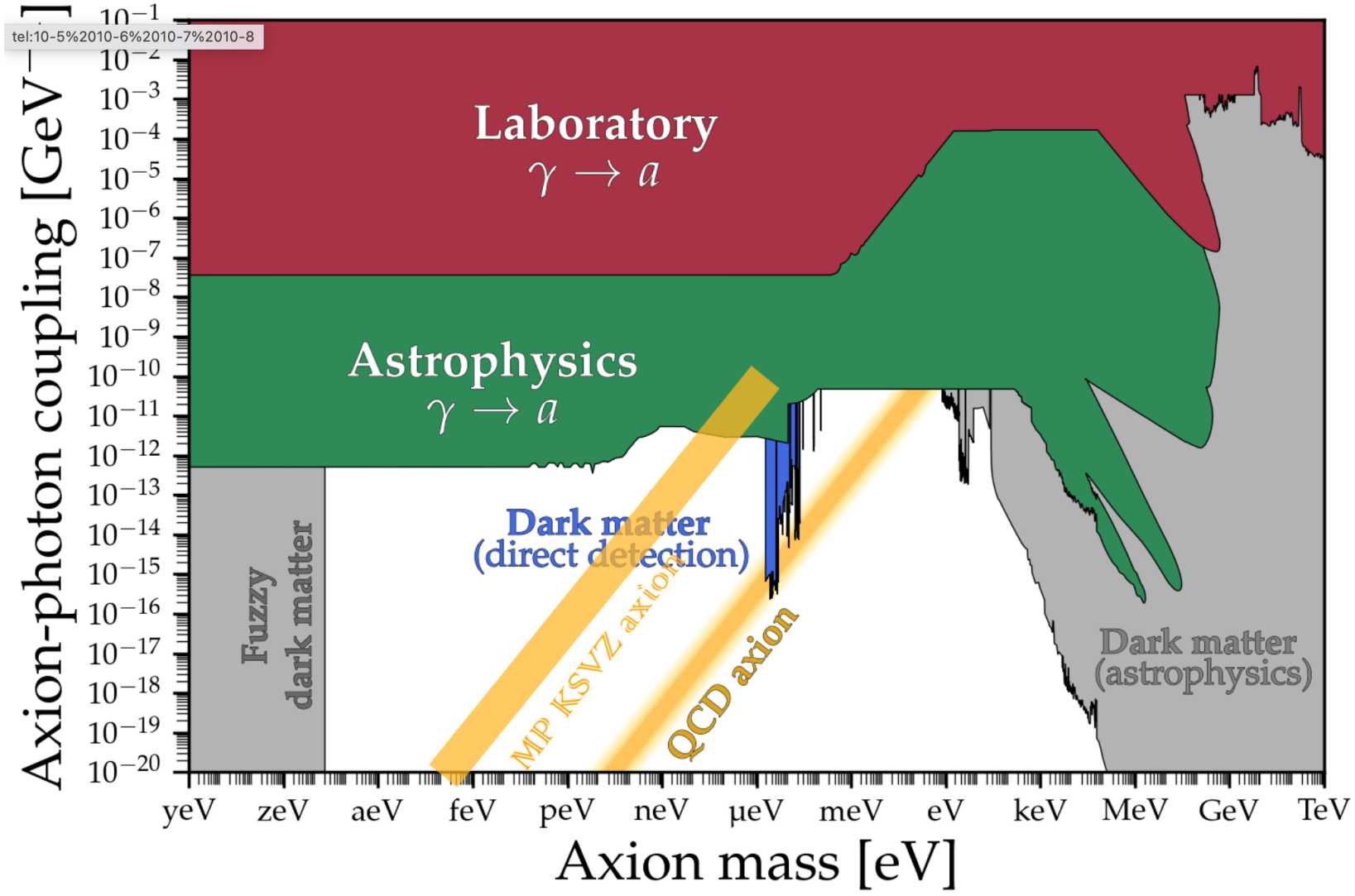
  - meV mass
    - Search for axion-induced monopole-dipole forces

Monopole-Philic KSVZ Axion

[Anton Sokolov, AR, 2104.02574; 2109.08503; 2205.02605; 2303.10170]

Axion dark matter implications

- Astrophysics implies an upper bound on axion mass ~ 3×10^{-7} eV



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$$\left(\partial^2 + m_a^2\right) a = -\left(g_{a\gamma} - g_{am}\right) \mathbf{E}_0 \cdot \mathbf{B}_0 \,,$$

$$\boldsymbol{\nabla} \times \mathbf{B}_a - \dot{\mathbf{E}}_a = g_{a\gamma} \left(\mathbf{E}_0 \times \boldsymbol{\nabla} a - \dot{a} \mathbf{B}_0\right) \,,$$

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[Tobar et al., 2306.13320]

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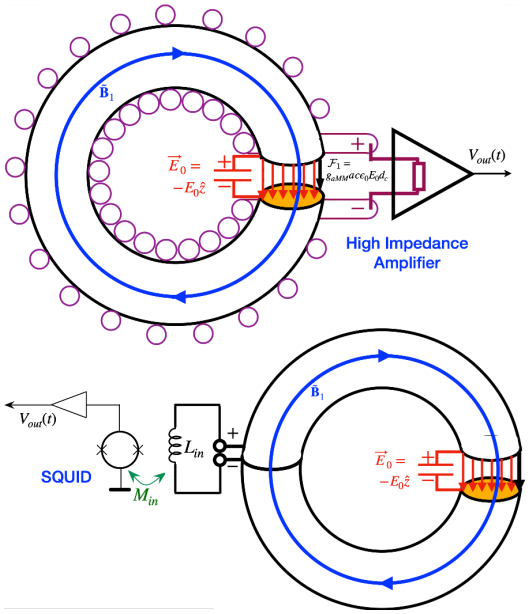

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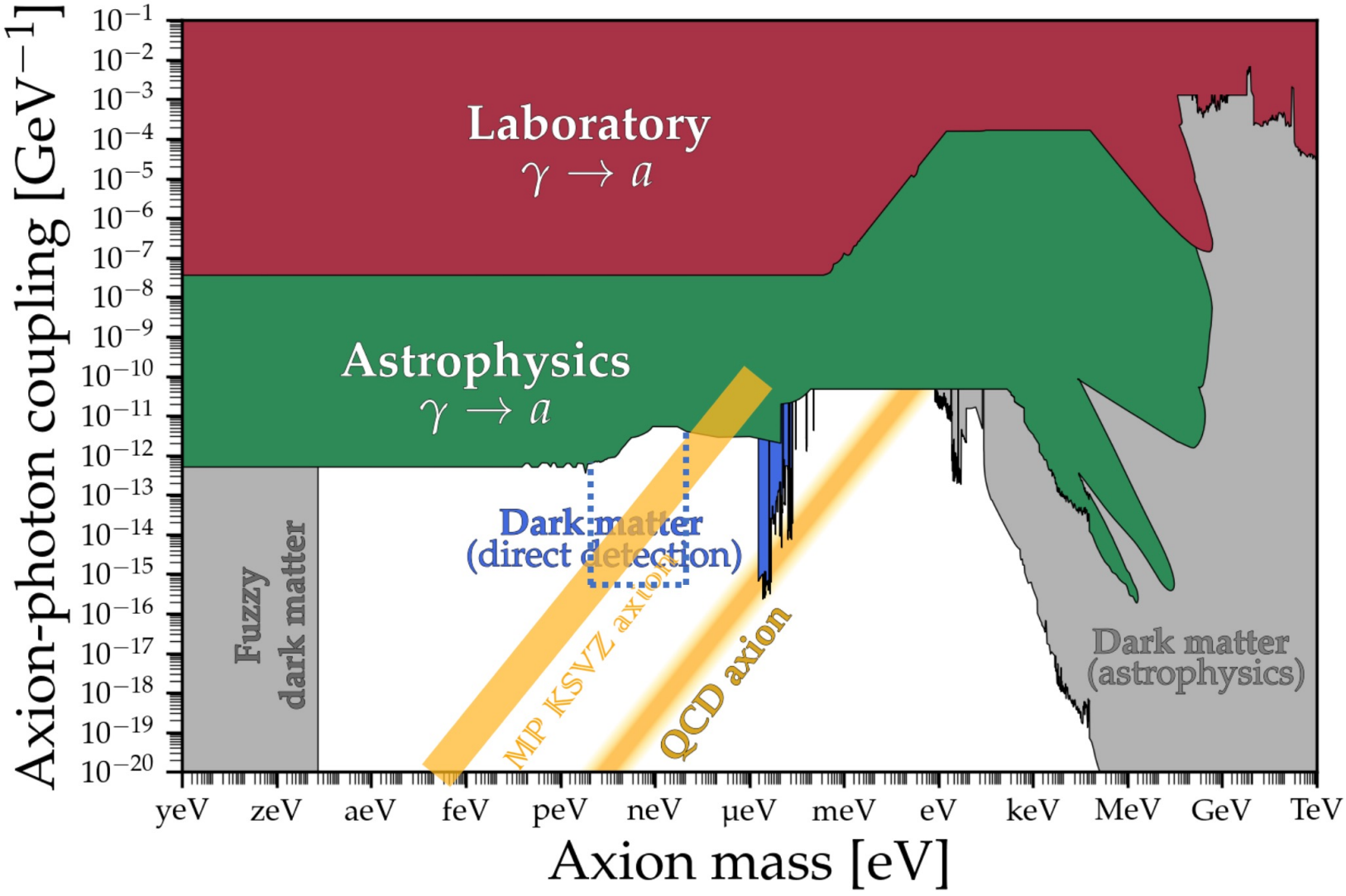
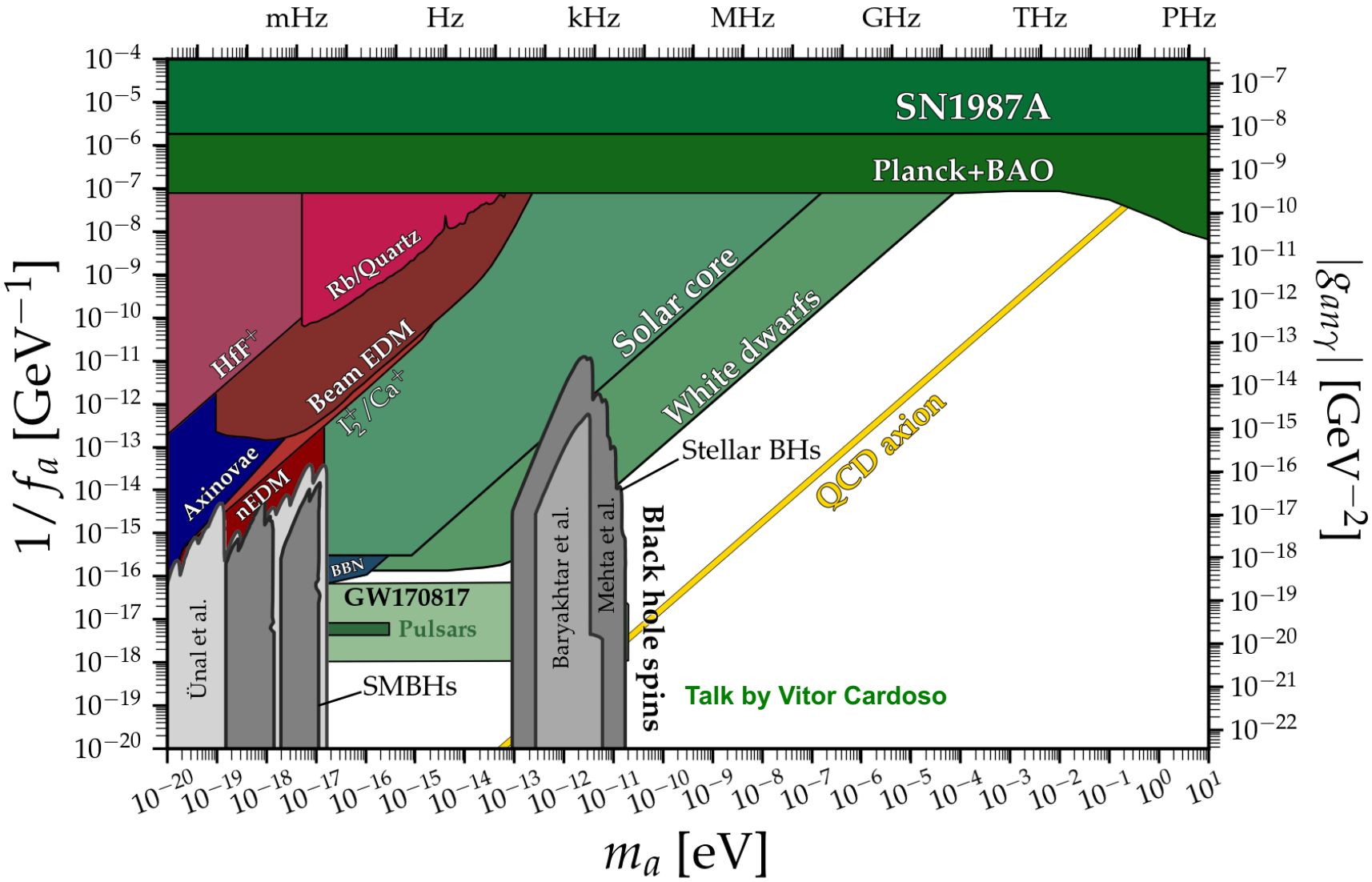


The Road Ahead in Distinguishing ALP from Axion

Ultimate goal: to measure the coupling to the gluon resp. the NEDM



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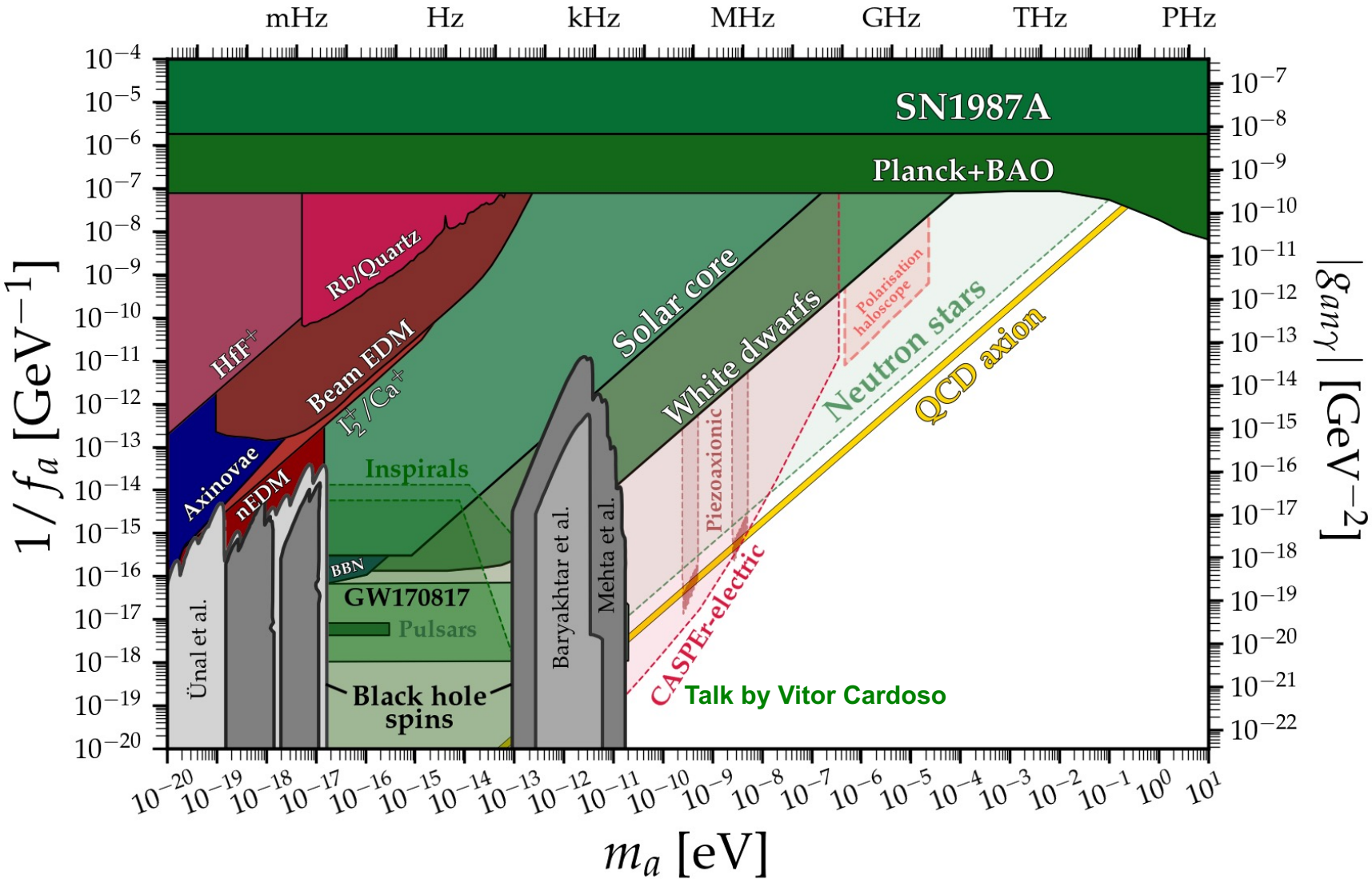

Conclusions

We are on a good way to cover the most plausible mass and coupling ranges of the axion

We need the complementarity of laboratory, astrophysics, and dark matter direct detection