Visions and Whispers of WISPs

Andreas Ringwald
2nd General Meeting of COST Action Cosmic Whispers
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2-6 September 2024

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
CLUSTER OF EXCELLENCE QUANTUM UNIVERSE
cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY
COSMIC WISPERS CA21106
DESY.

Well-motivated WISP Candidates

Spin 0: Ultralight pseudo Nambu-Goldstone bosons

Pseudo Nambu-Goldstone bosons arising from the breaking of symmetries beyond the SM at a scale much larger than the electroweak scale, such as

- Scale invariance: **Dilaton** [Kaluza `1921;Klein `1926;...]
- Peccei-Quinn symmetry: **Axion** [Peccei,Quinn `77; Weinberg `78; Wilczek `78]
- Lepton symmetry: **Majoron** [Chikashige,Mohapatra,Peccei `81, Gelmini,Roncadelli `81]
- Family symmetry: **Familon** [Wilczek `82; Berezhiani,Khlopov `90]
- Gauge symmetries in ten dimensions: Type II closed string **axion-like particles** (**ALPs**)

  [Arvanitaki et al. `10; Cicoli,Goodsell,AR `12; ...]

  Talks by Alexander Westphal, Jacob Leedom, Andreas Schachner

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are natural **WISPs and even DM candidates**:

1. Massless as long as symmetry exact; small mass from tiny (non-perturbative) explicit symmetry breaking
2. Interactions with SM suppressed by large symmetry breaking scale
3. Produced automatically in the early universe by vacuum misalignment
   [Preskill,Wise,Wilczek `83; Abbott,Sikivie `83; Dine,Fischler `83]
   Talk by Cem Eroncel

Well-motivated WISP Candidates

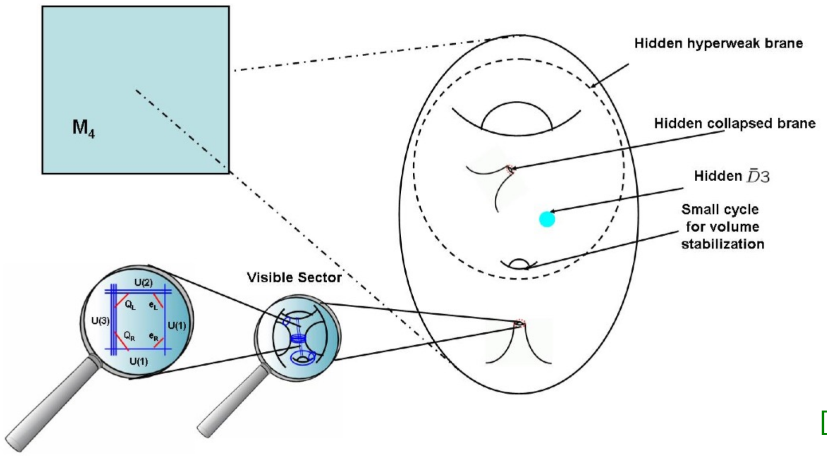
Spin 1: Ultralight U(1) gauge bosons

“Hidden” or “dark” photons from a local U(1) gauge theory under which SM particles are uncharged, for example from U(1)s occurring

- from the breaking of a grand unified gauge group
- in low energy effective field theories from string theory: [Goodsell,AR 10]
  - hidden U(1)s of the heterotic string
  - compactifications of type II string theory (brane world scenarios):
    - RR U(1)s: KK zero modes arising in 4D decomposition of 10D form fields
    - Brane localized U(1)s: massless excitations of space-time filling D-branes wrapping cycles in extra dimensions

[Abel et al. 08;Goodsell et al. 09;Cicoli et al. 11]

[Hebecker, Jaeckel, Kuespert, 2311.10817]



[Jäckel,AR `10]

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are **natural WISPs and even DM candidates**:

1. Gauge symmetry forbids explicit mass terms; small mass generated via hidden Higgs or Stückelberg
2. Interactions with SM suppressed for small kinetic mixing $\mathcal{L} \supset -\frac{\chi}{2} F'_{\mu\nu} F^{\mu\nu}$; $\chi \sim \frac{e\, g_h}{16\pi^2}$ [Holdom `86]
3. Produced automatically by
   - vacuum misalignment (requires non-minimal coupling to gravity) [Nelson,Scholtz `11; Arias et al., `12]
   - by quantum fluctuations during inflation $m_{\gamma'} \sim 10^{-5}\,\mathrm{eV}\,\left(10^{14}\,\mathrm{GeV}/H_{\mathrm{inf}}\right)^4$ [Graham,Mardon,Rajendran `16]

Coverage of Parameter Range in the Past

In 2012:

$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

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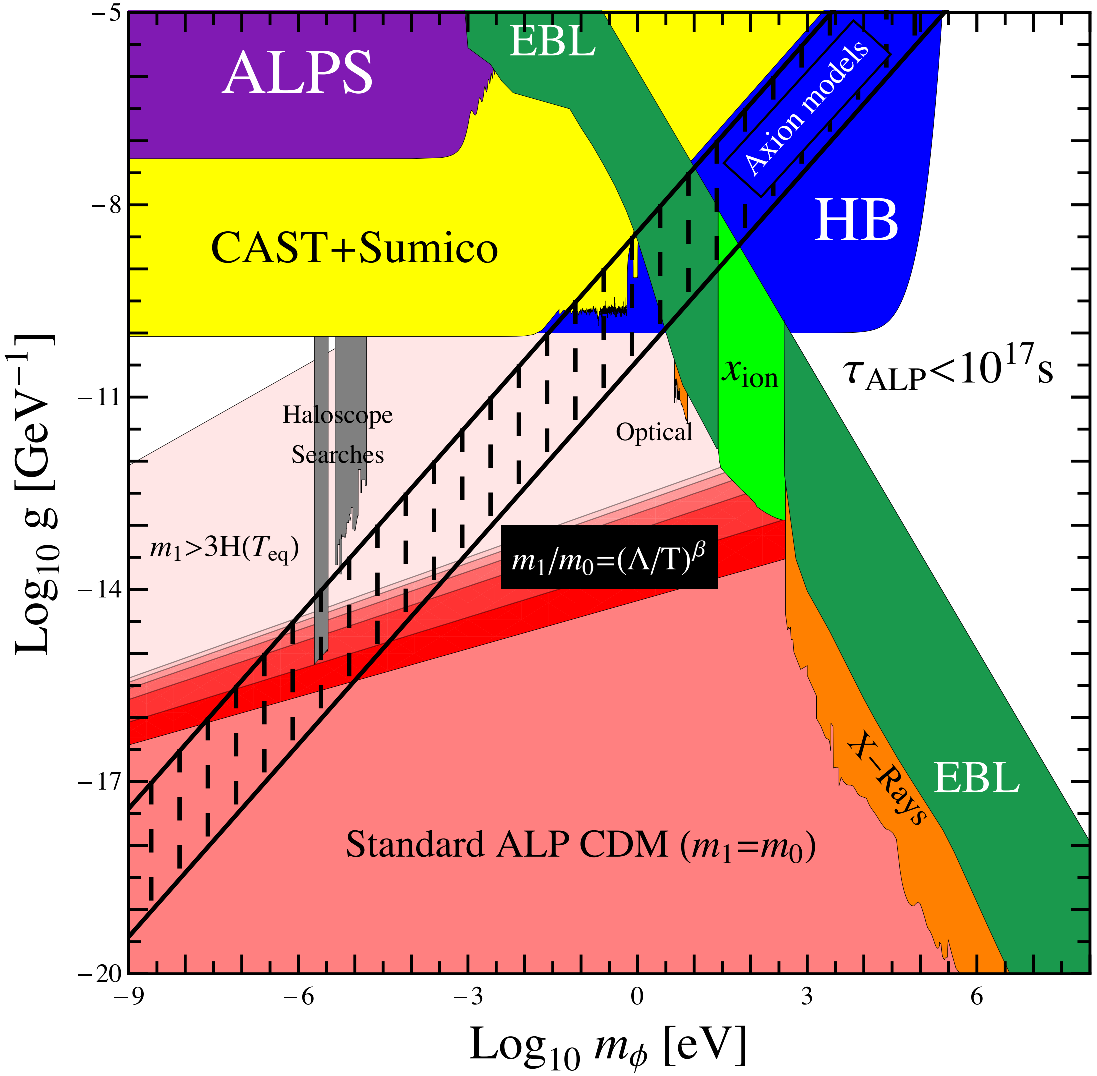

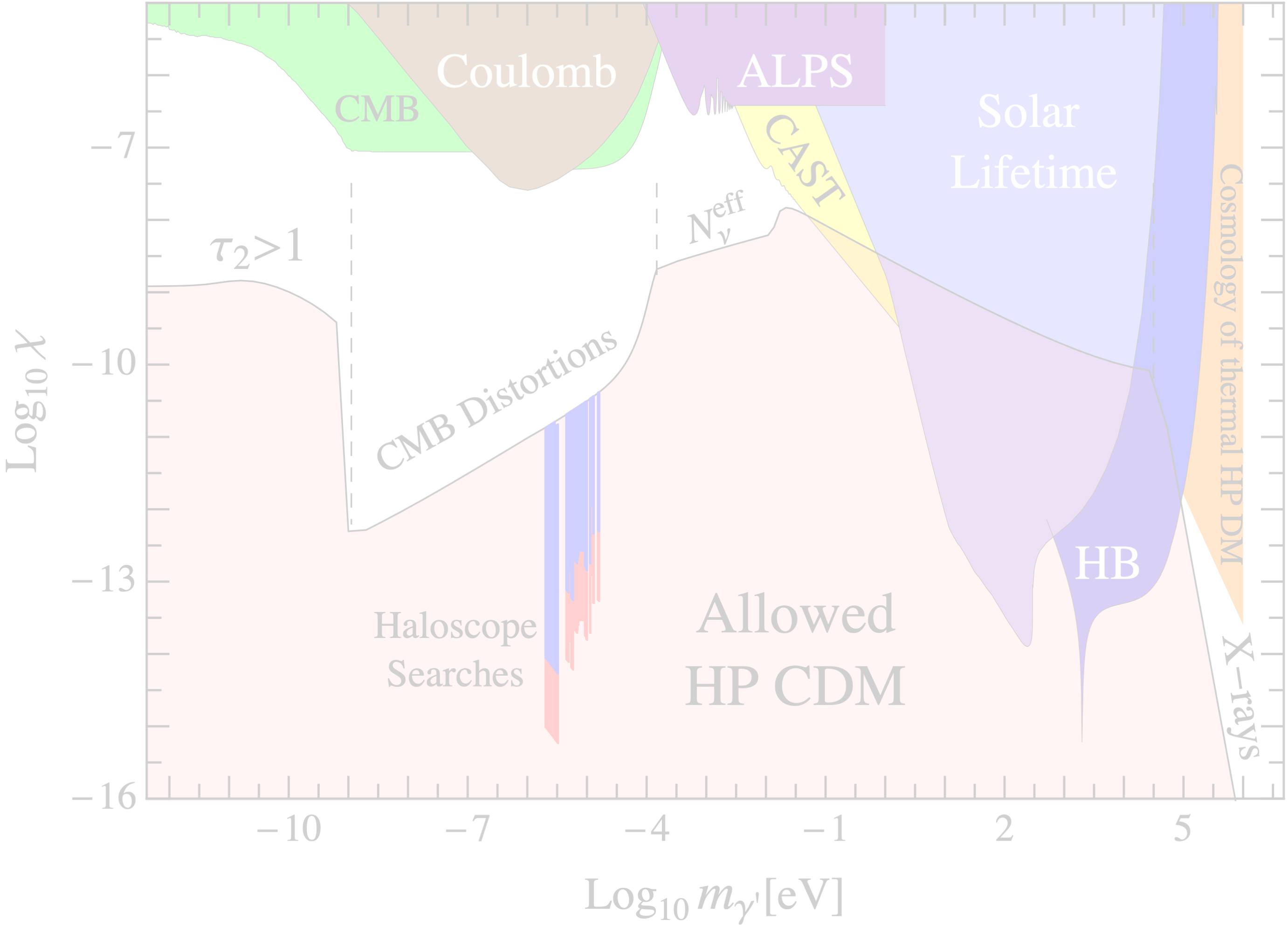

[Arias, Cadamuro, Goodsell, Jaeckel, Redondo, AR, 1201.5902]

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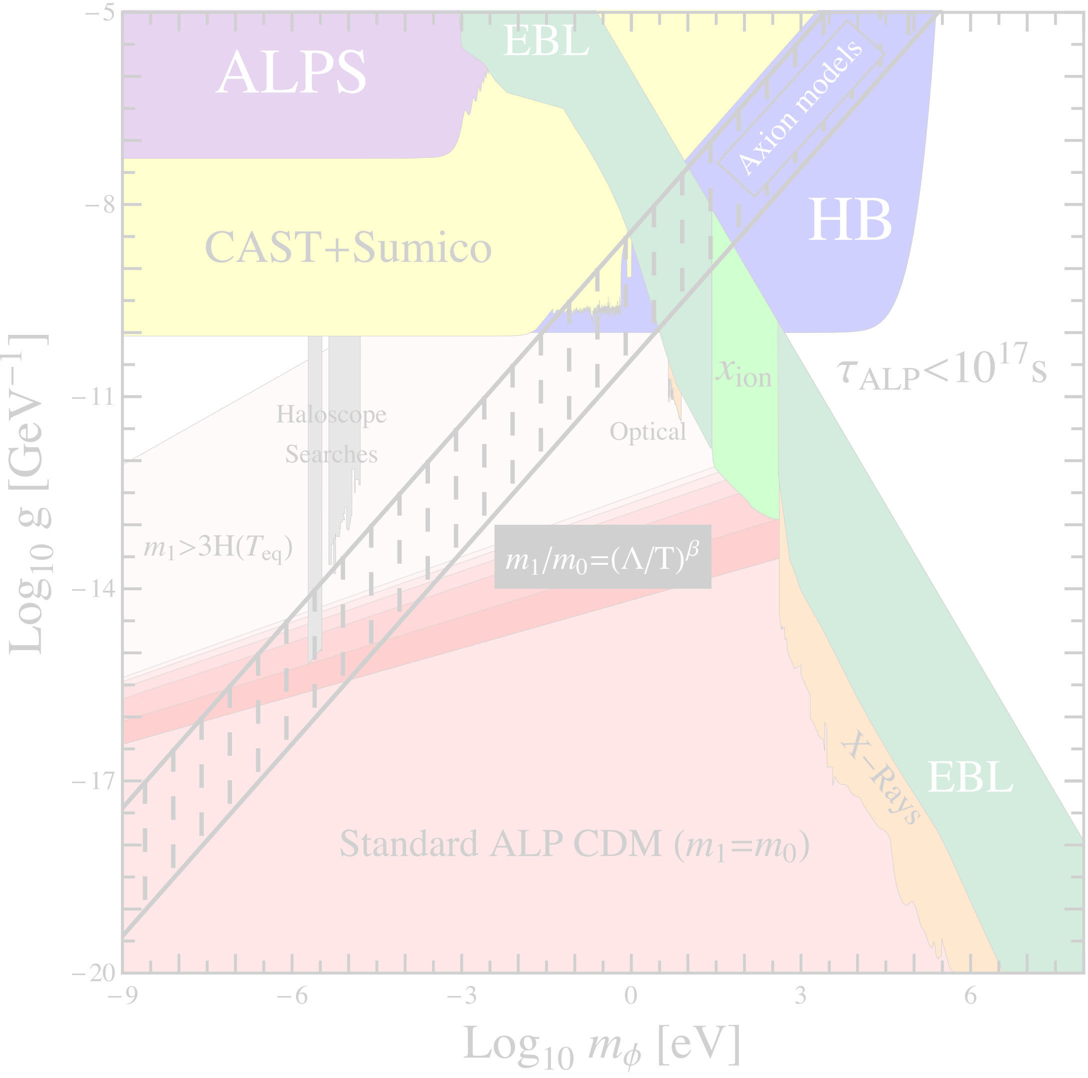

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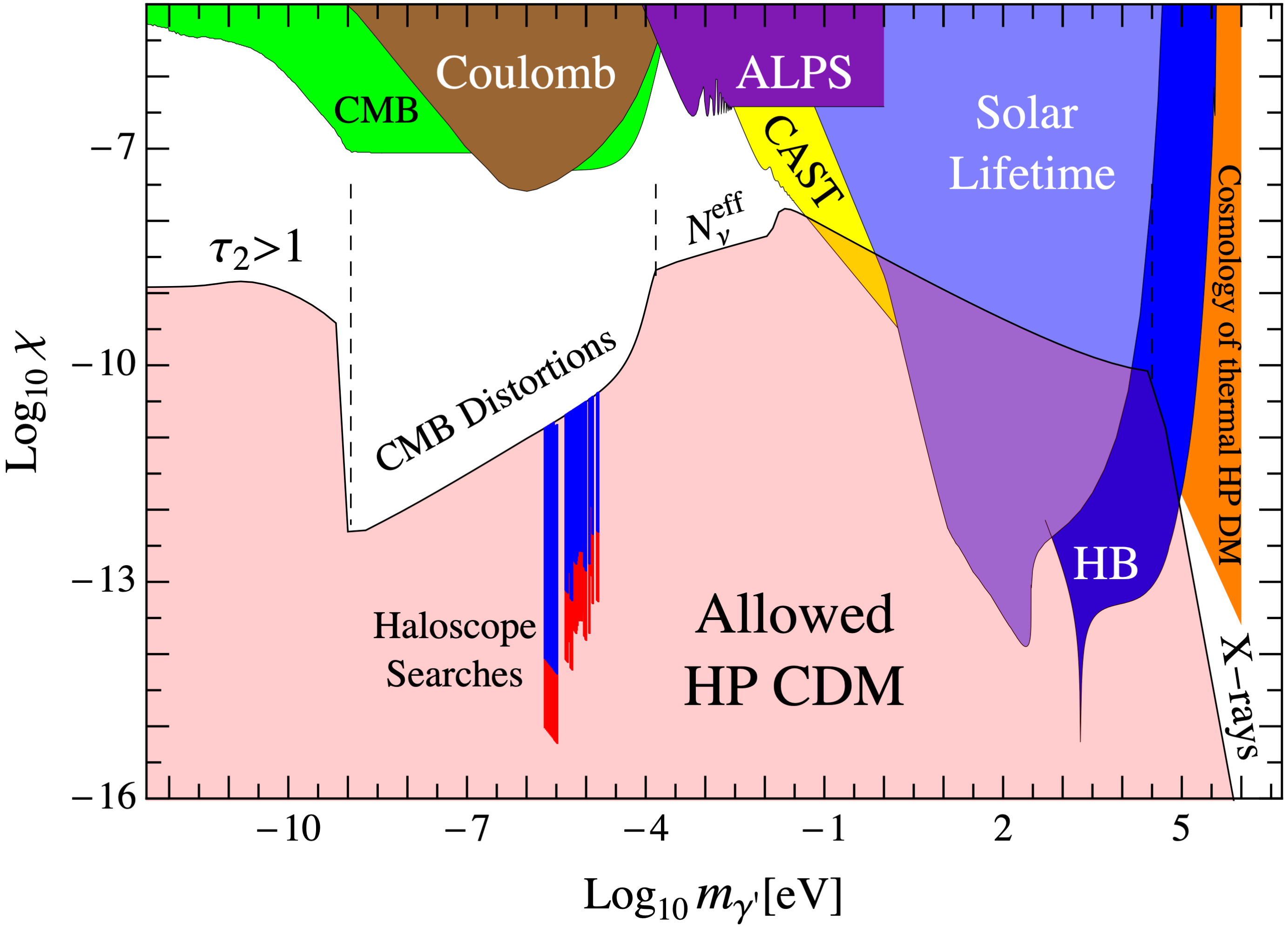

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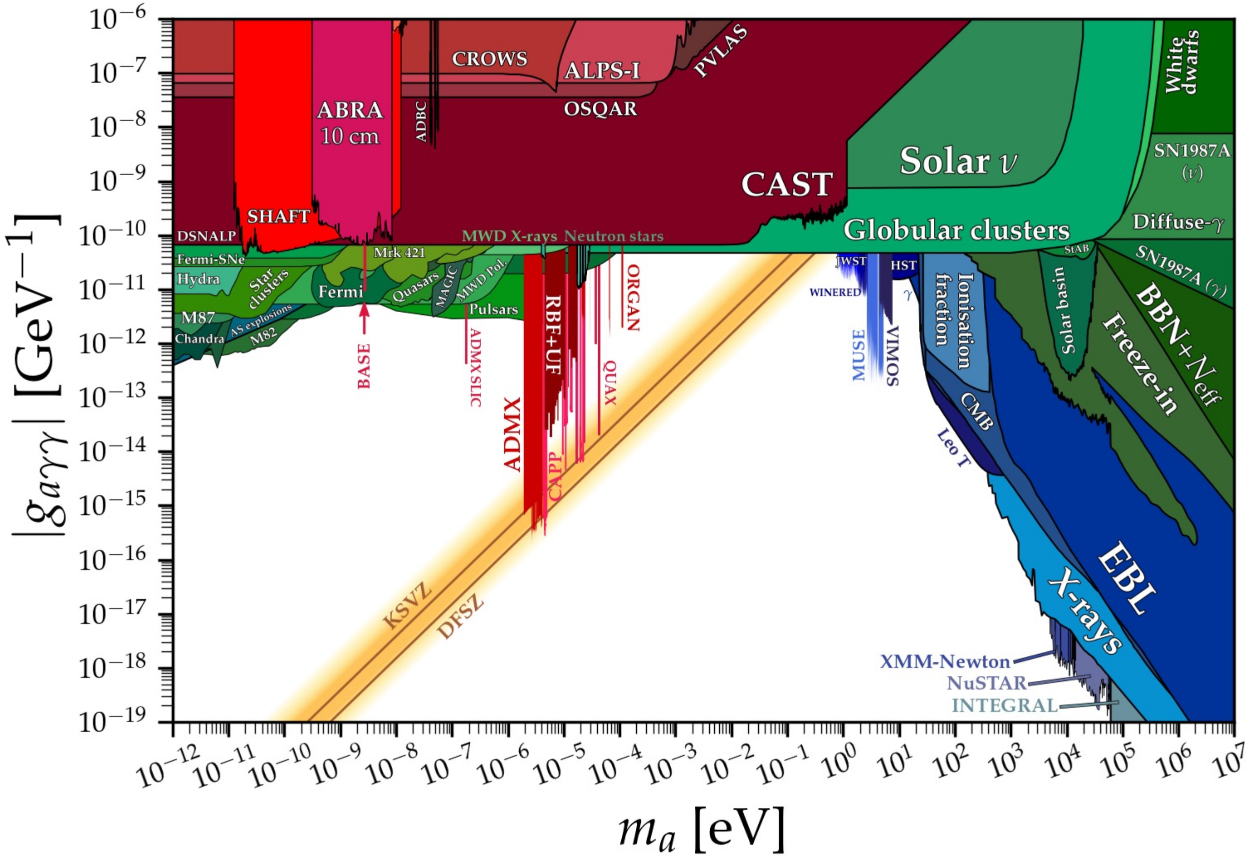
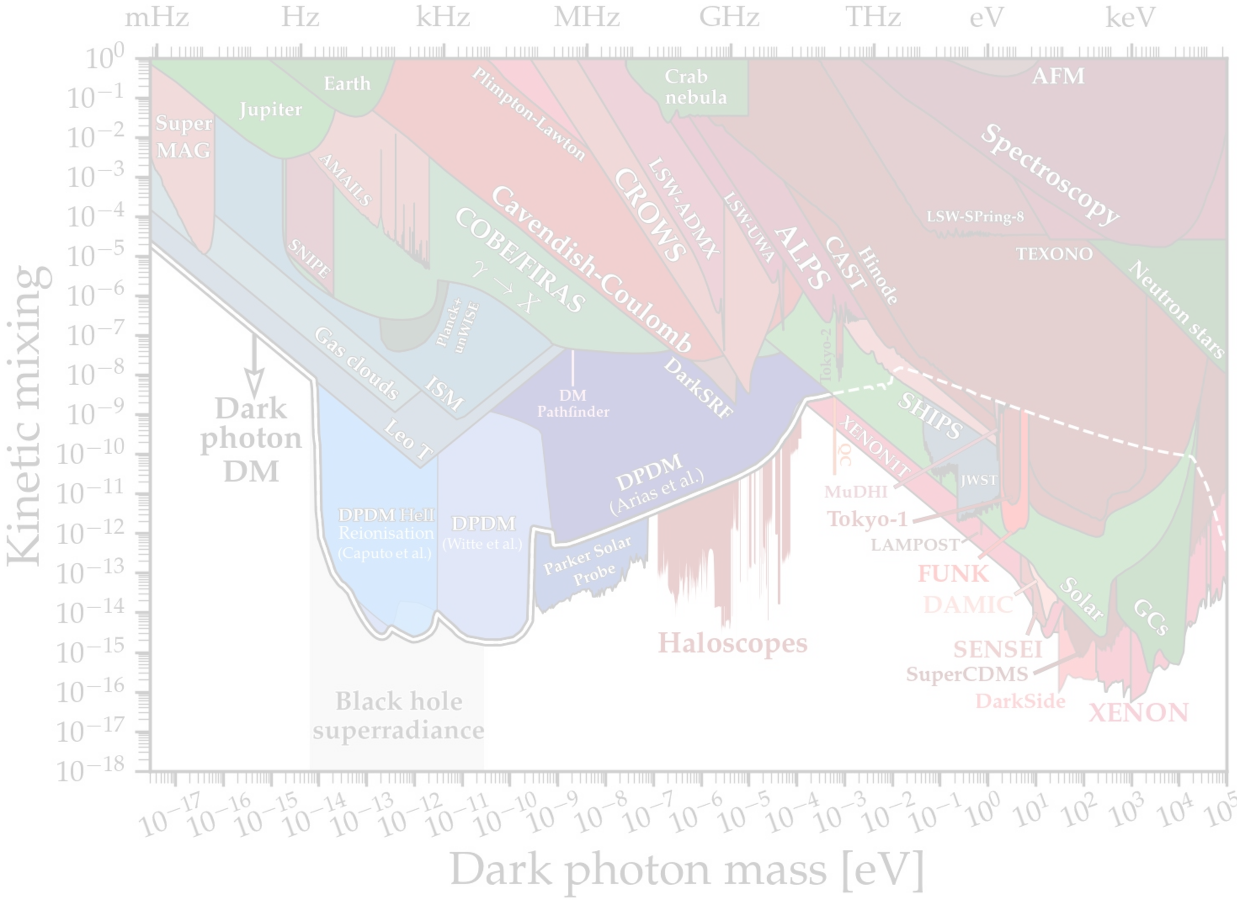


https://cajohare.github.io/AxionLimits/



adapted by O'Hare from [Caputo et al. 2021]

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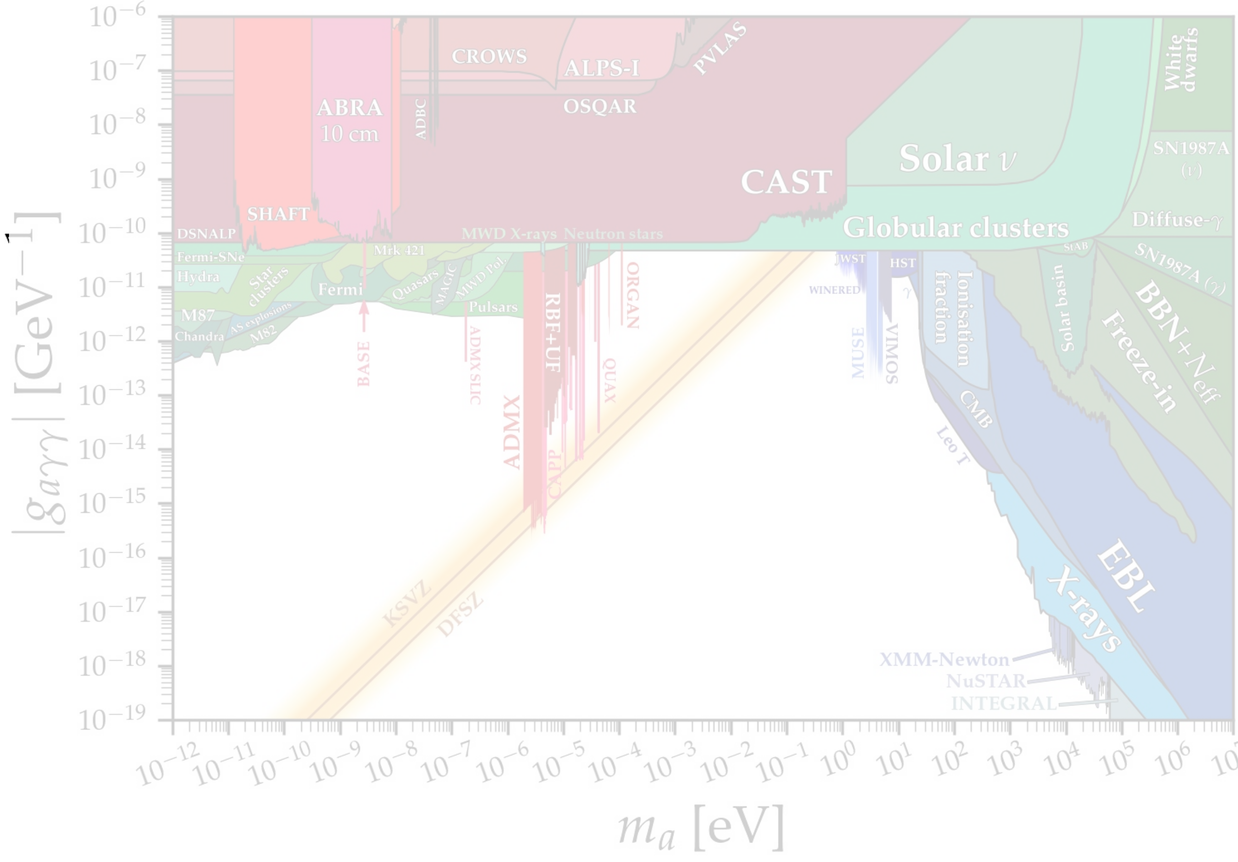

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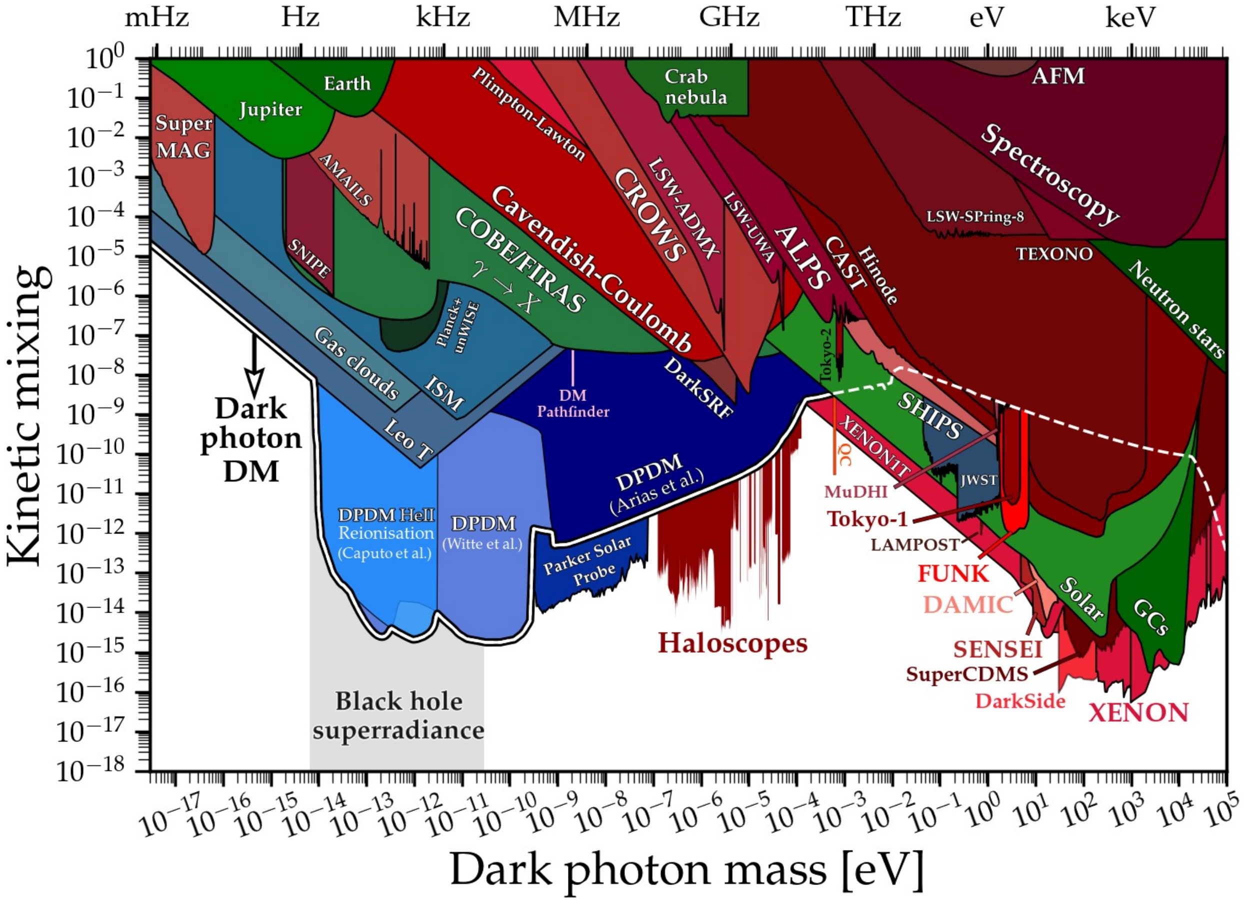

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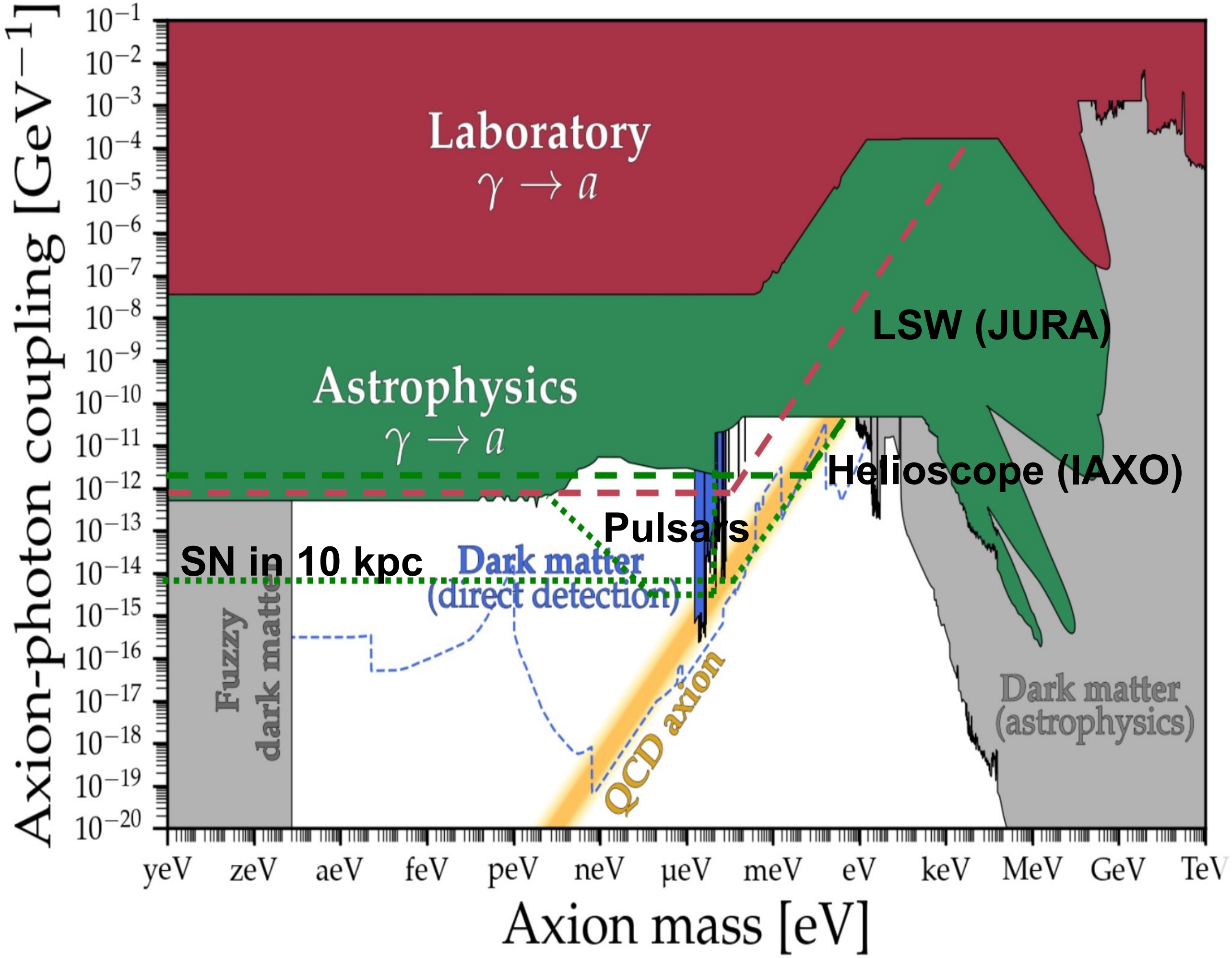

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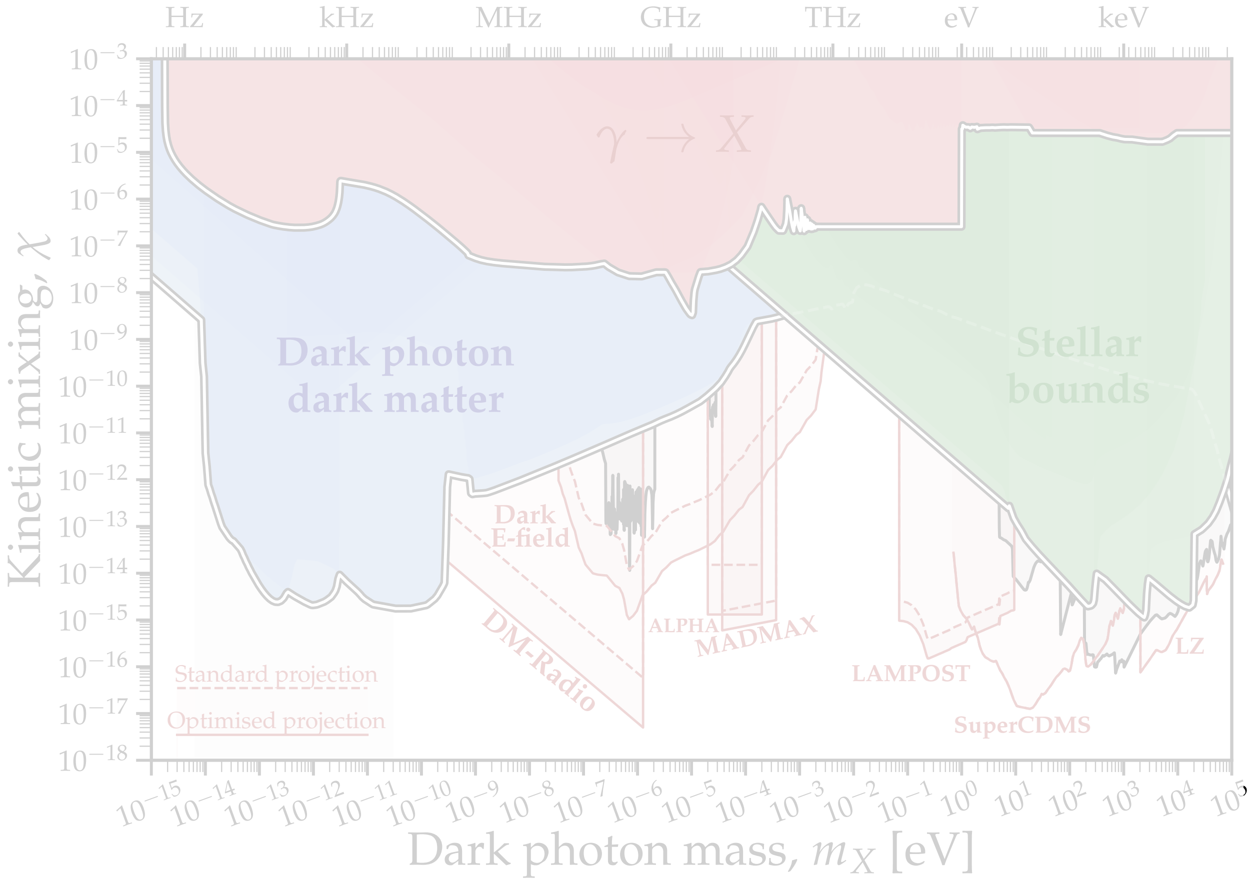

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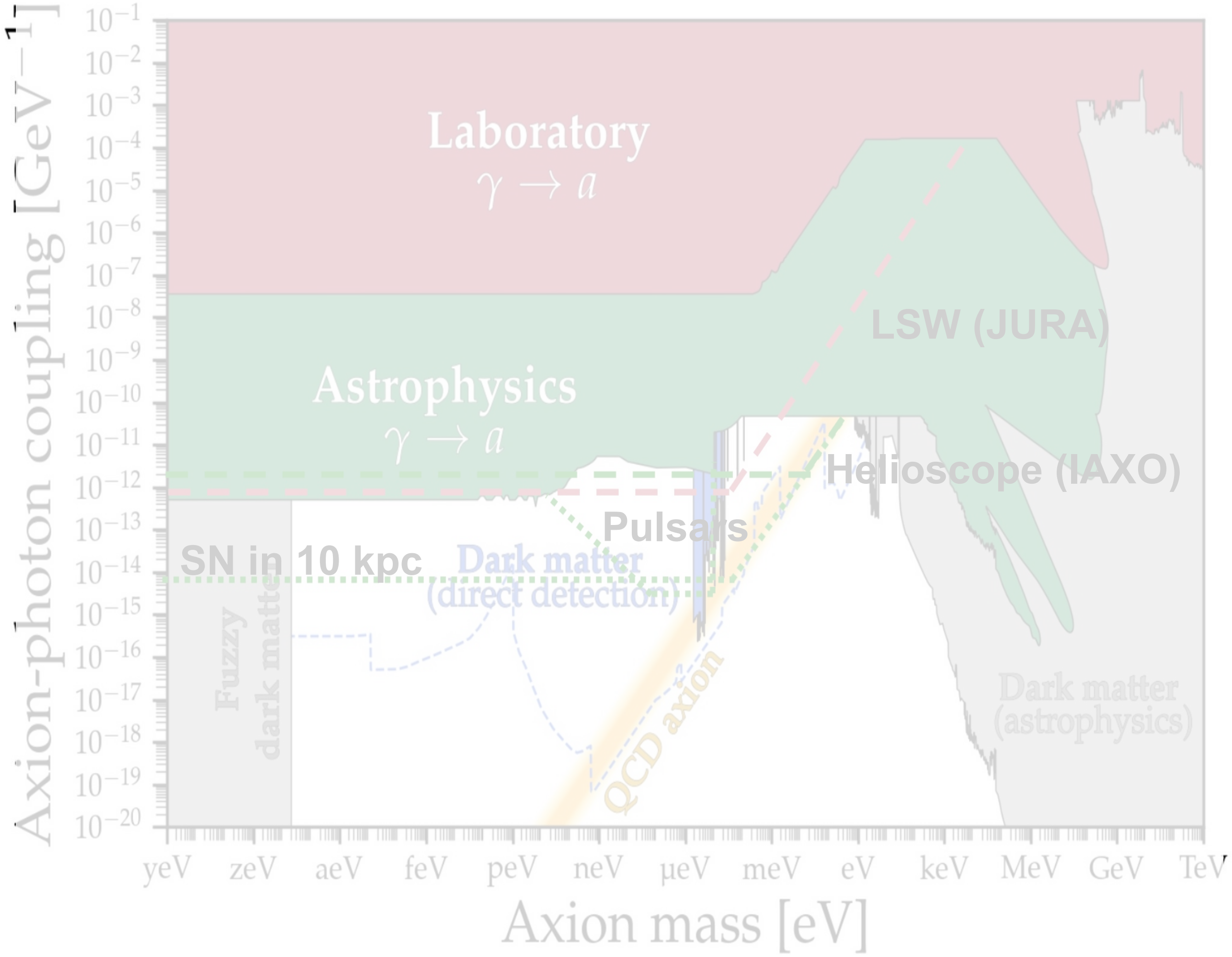

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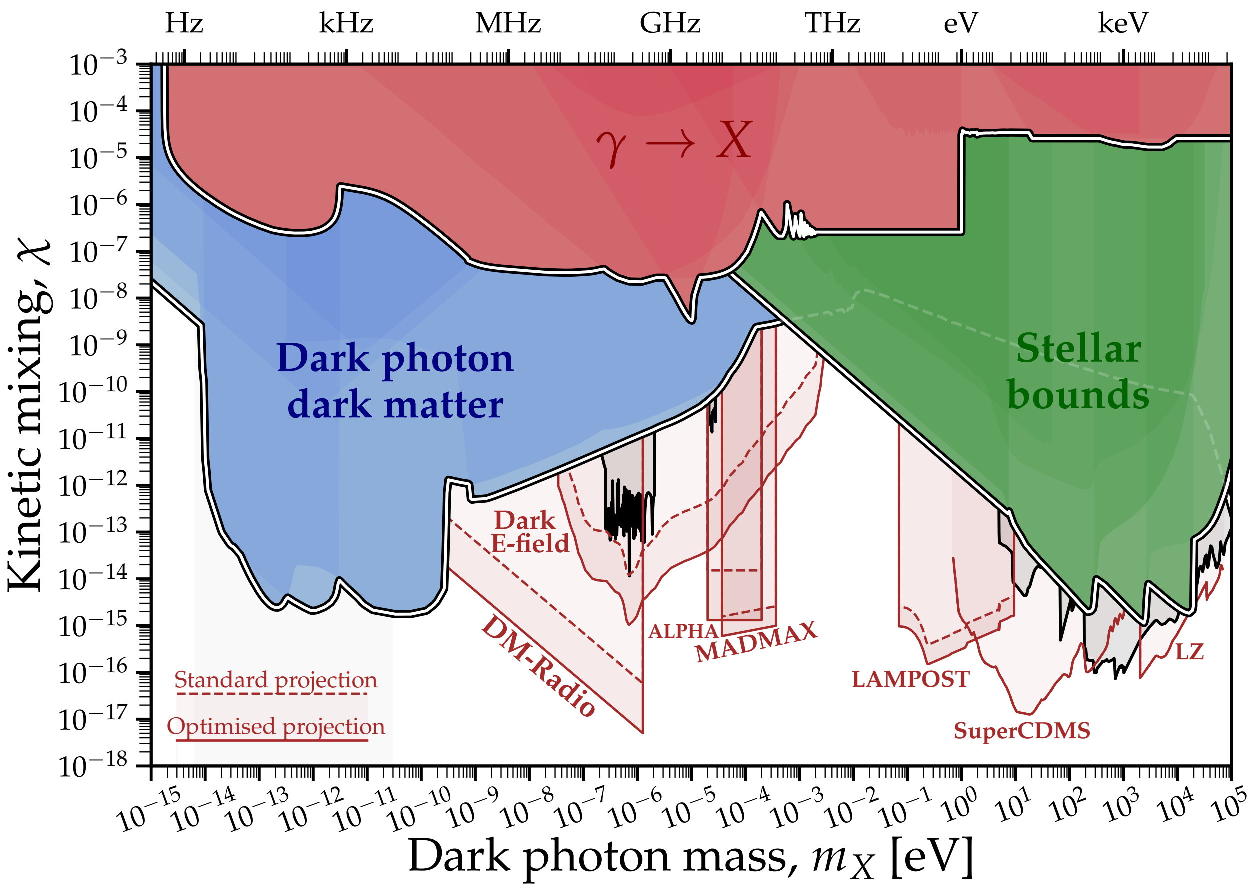

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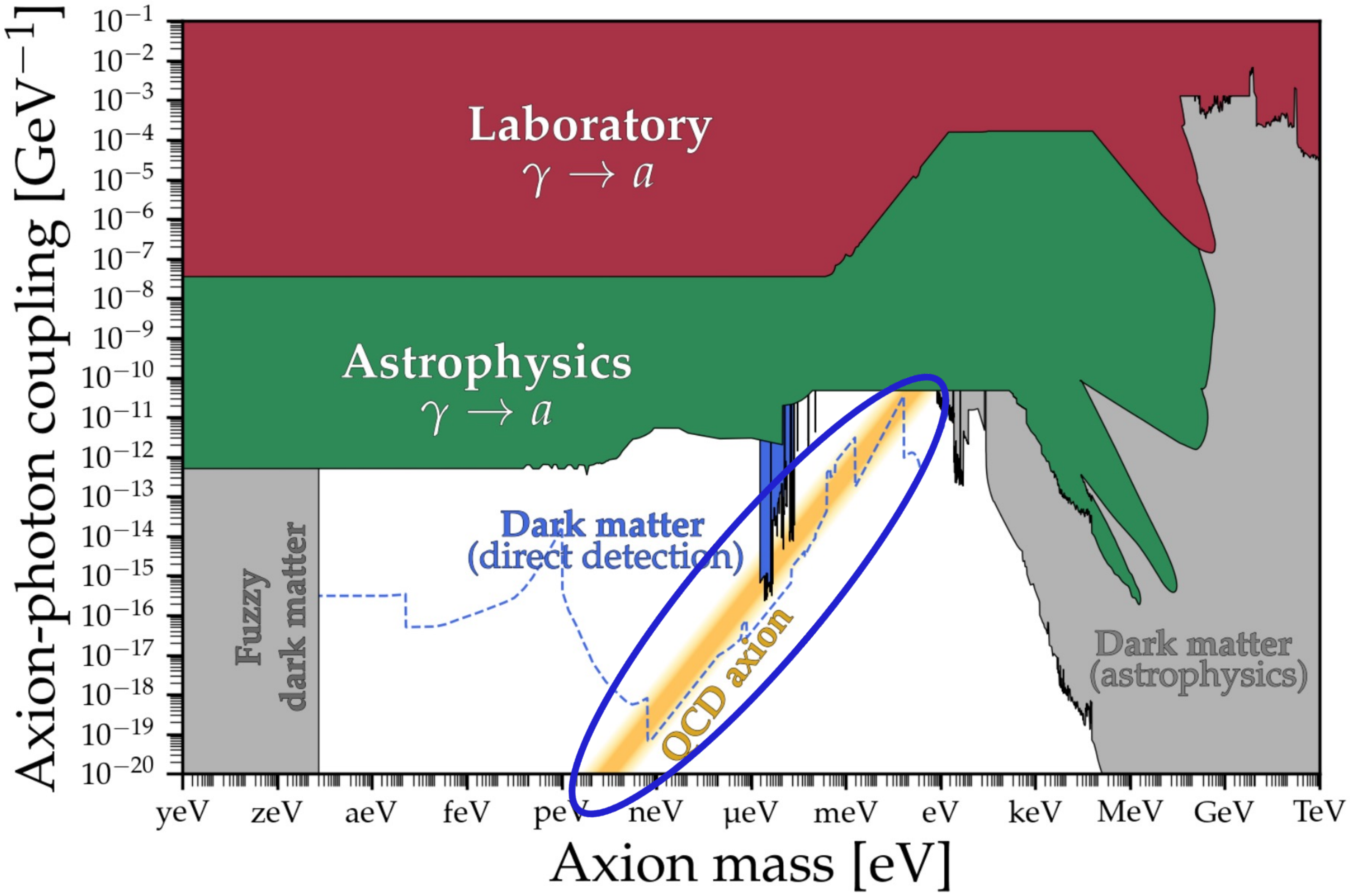
In 2036:

- Seems that we are in a good way to cover the most plausible mass and coupling ranges of the axion by DM direct detection
- Caveats:
  - Local axion DM density could be much less than average 0.4 GeV/cm^3

Talks by Edward Hardy, Yannis Semertzidis, Luca Visinelli



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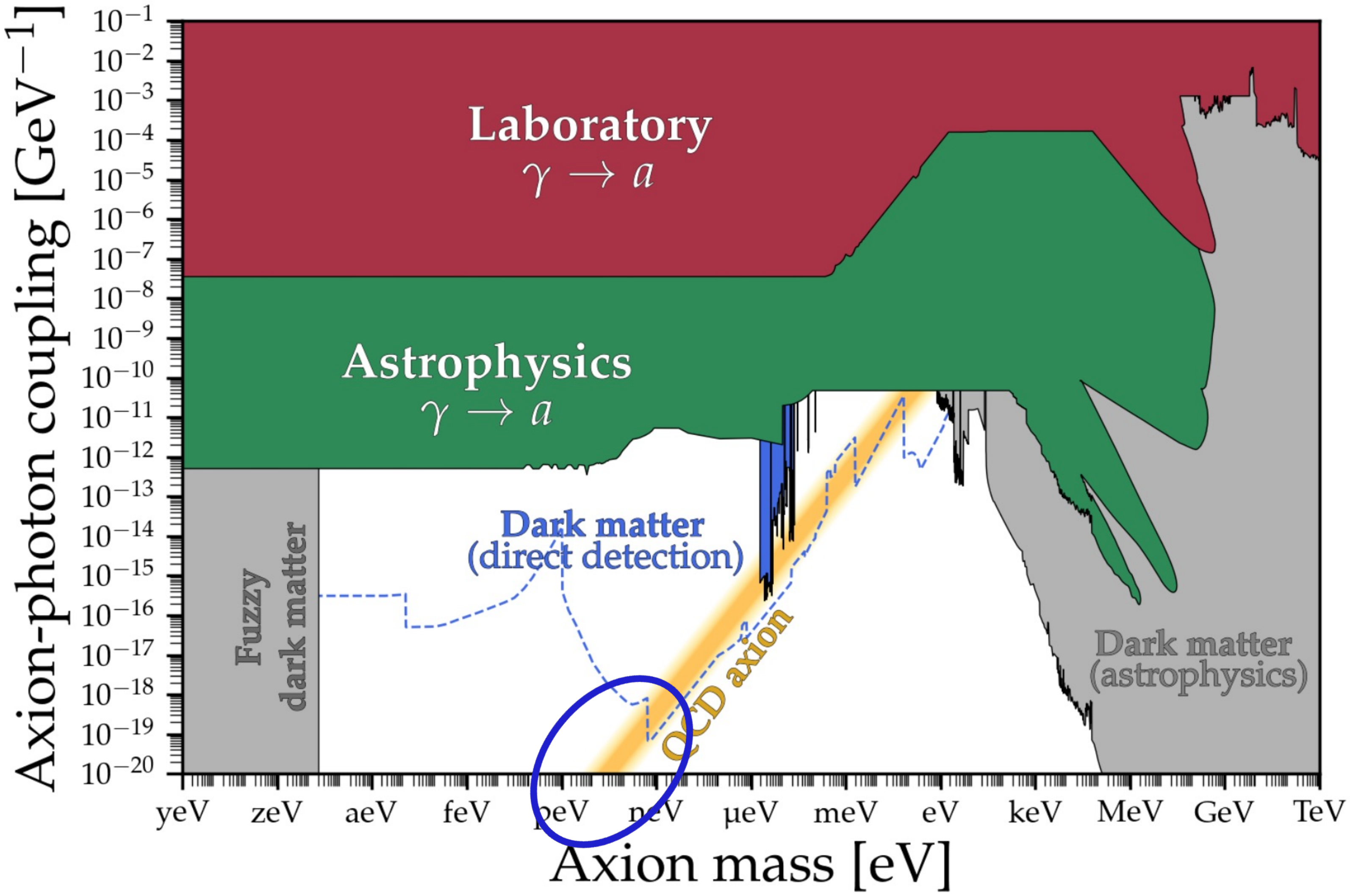

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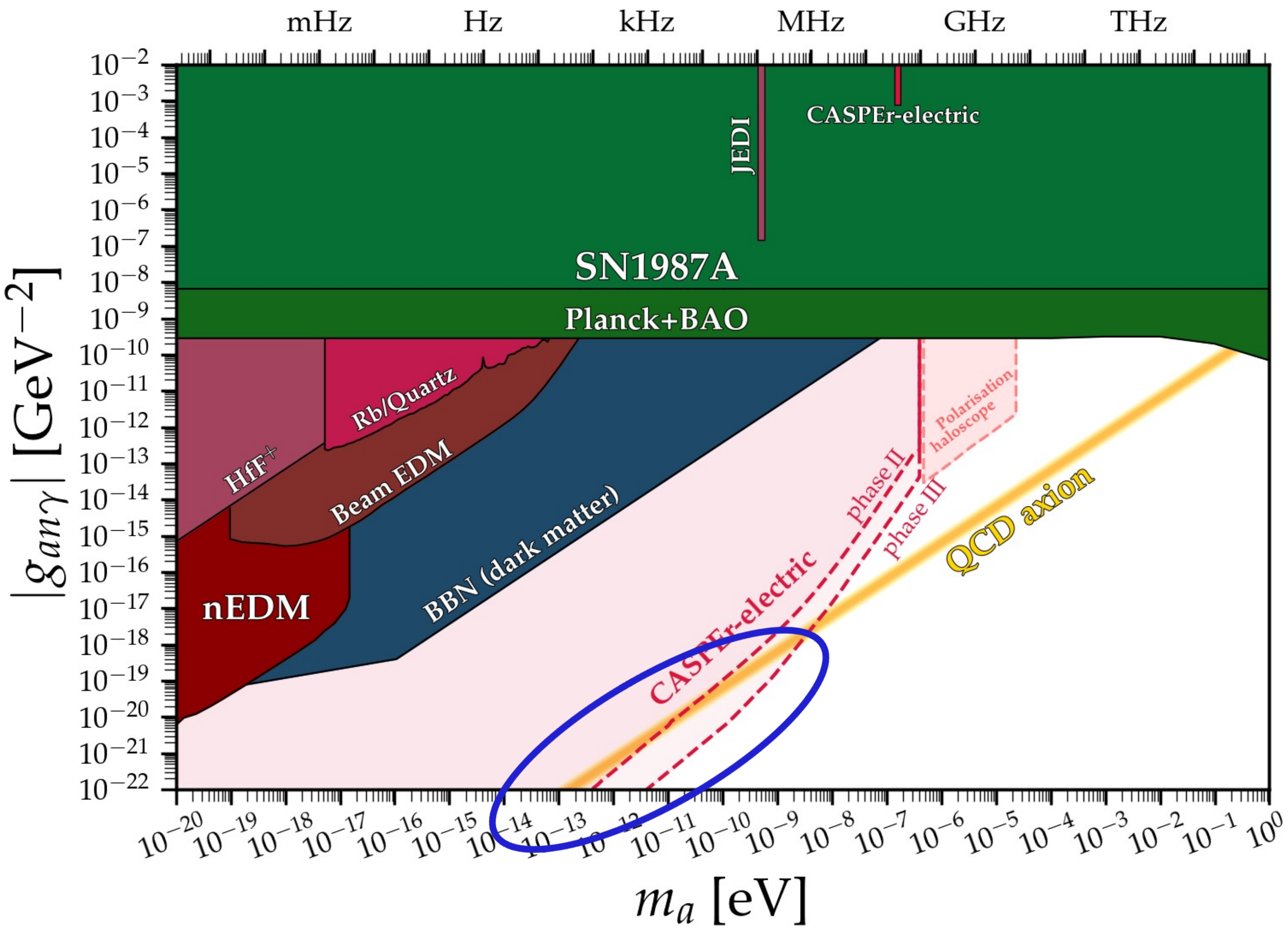

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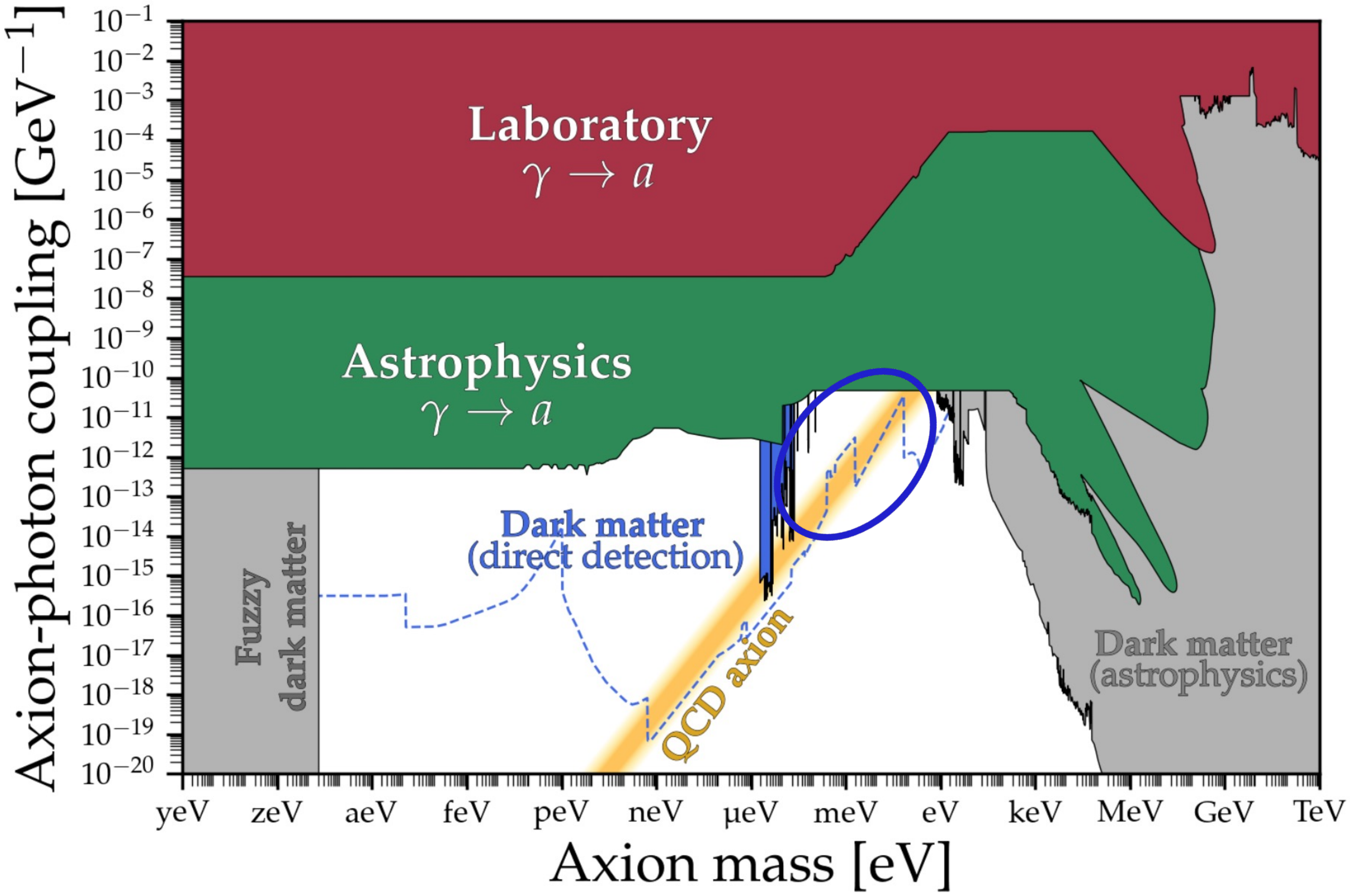

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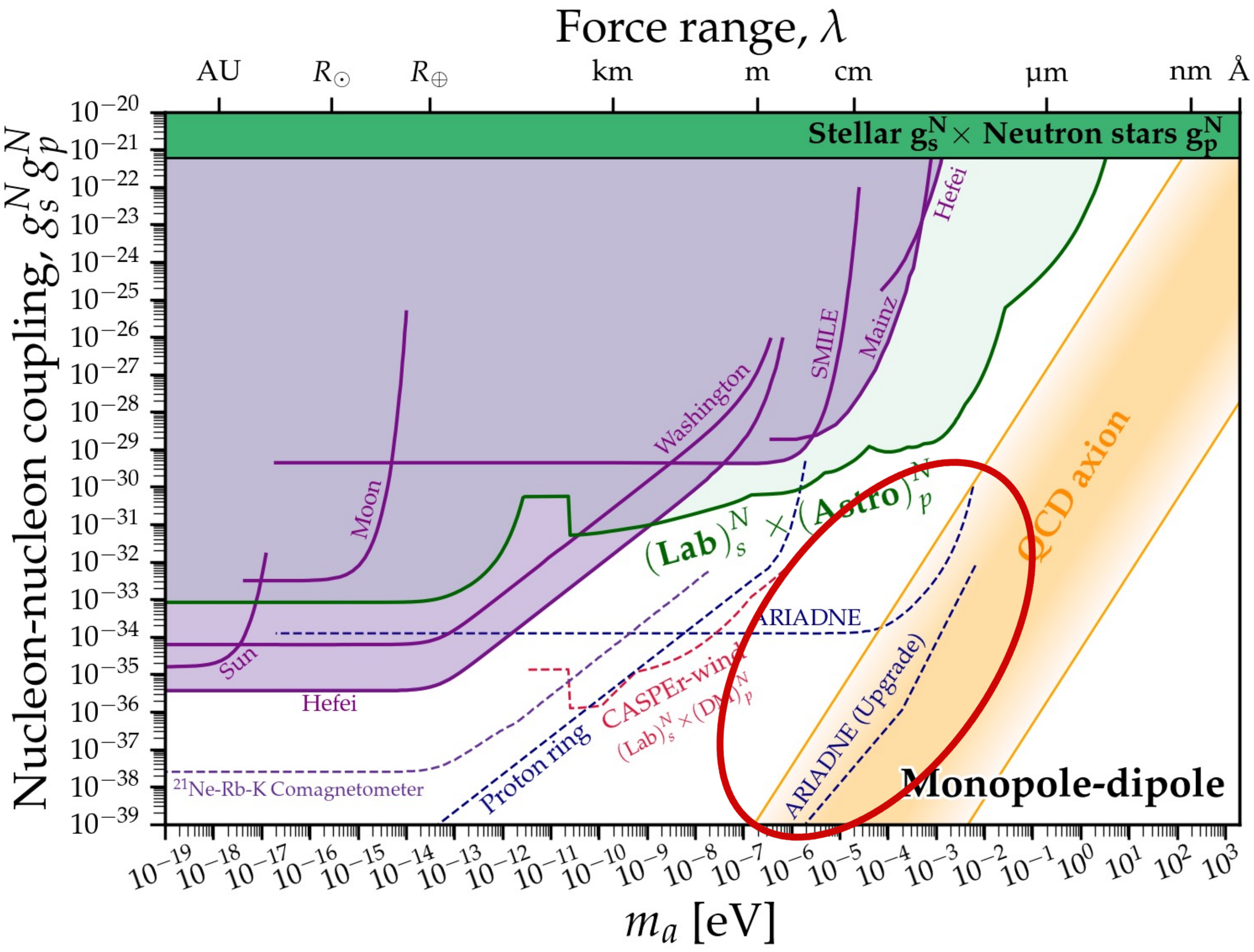

[O'Hare, Vitagliano, 2010.03889]

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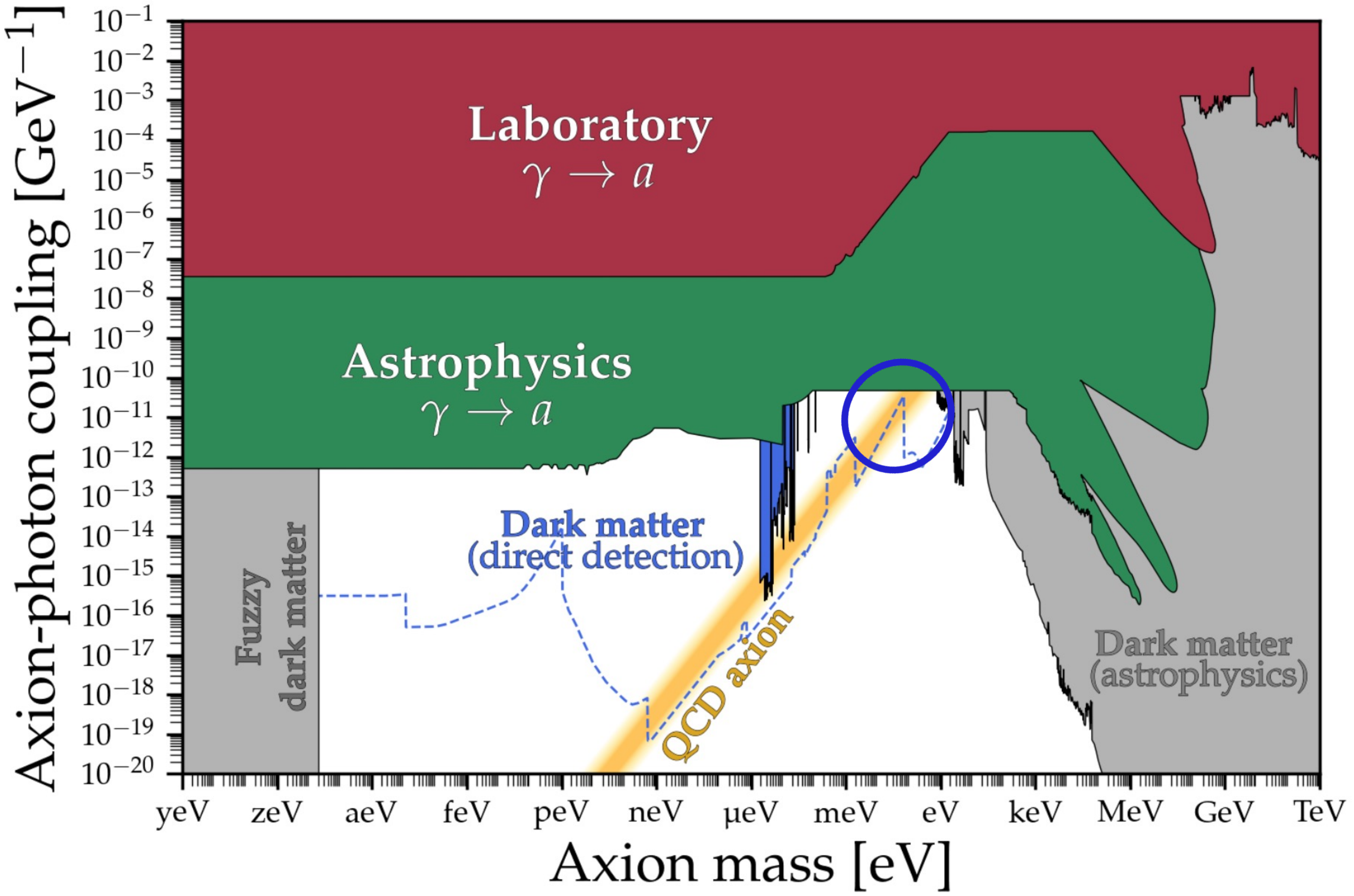
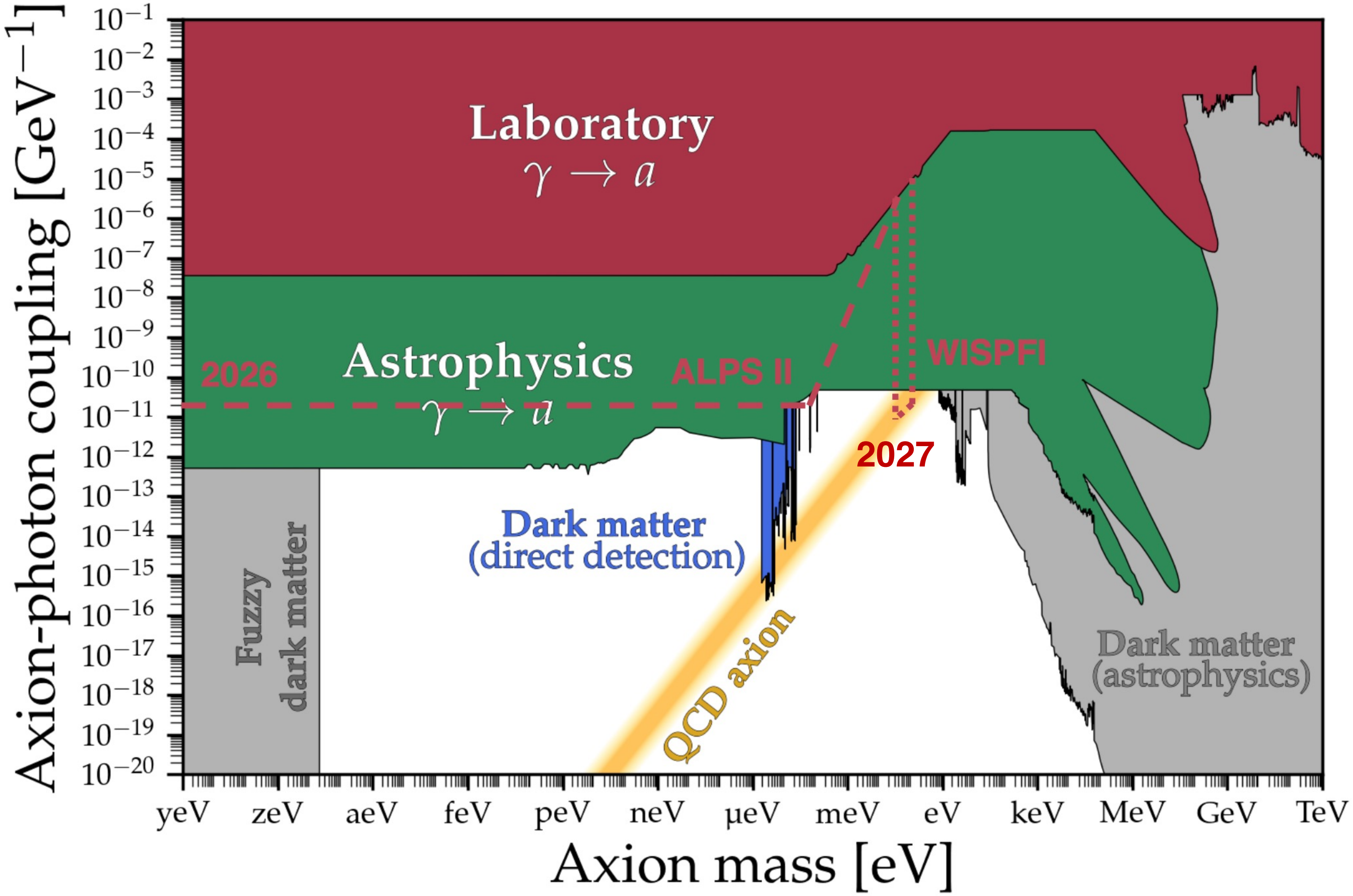
    - eV mass
      - Fiberinterferometer search!



Coverage of Parameter Range in Future

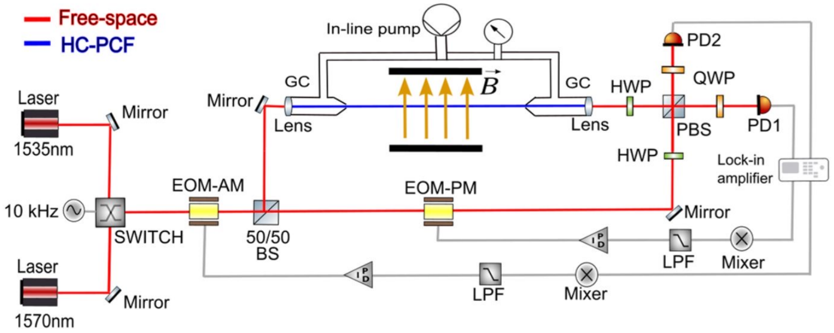
Fiber interferometer experiment can dig in vanilla axion band



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

WISPFI

[Batllori et al., 2305.12969]



- Mach-Zehnder-type interferometer 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

Coverage of Parameter Range in Future

Monopole-philic KSVZ axion

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

- Low-mass haloscopes exploiting DC magnetic field, e.g. DMRadio, are insensitive to dominant effects (zeroth order in velocity) of the new, but dominant coupling g_{am} in the generalized axion-Maxwell equations

Talk by Anton Sokolov

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

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

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- New experiments proposed to probe MP KSVZ axion dark matter
  - Measure axion-DM induced effective polarization and magnetization

[Tobar et al., 2306.13320]

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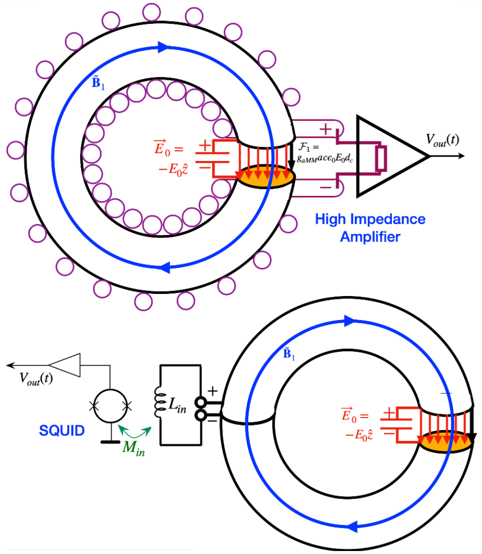

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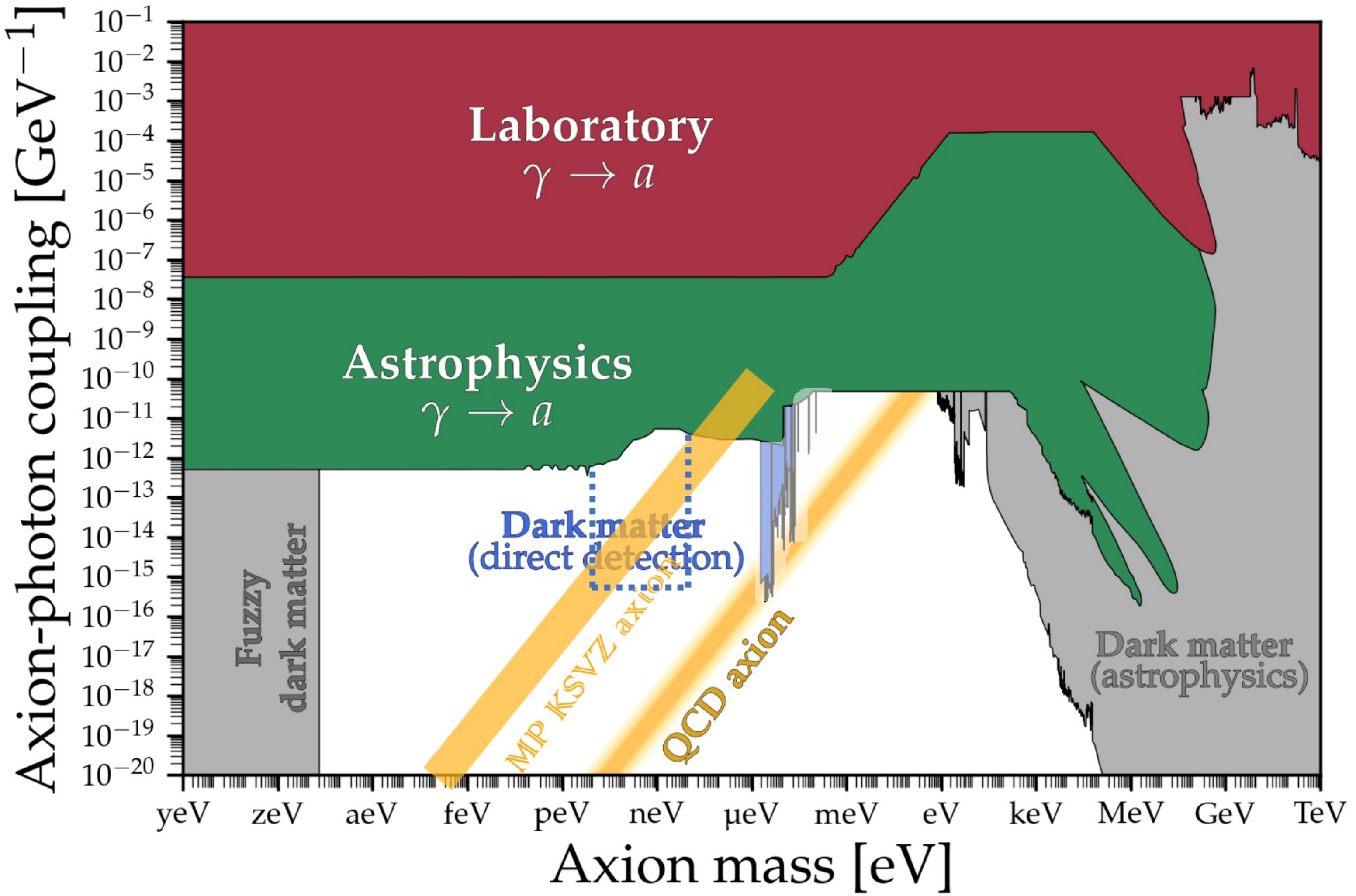
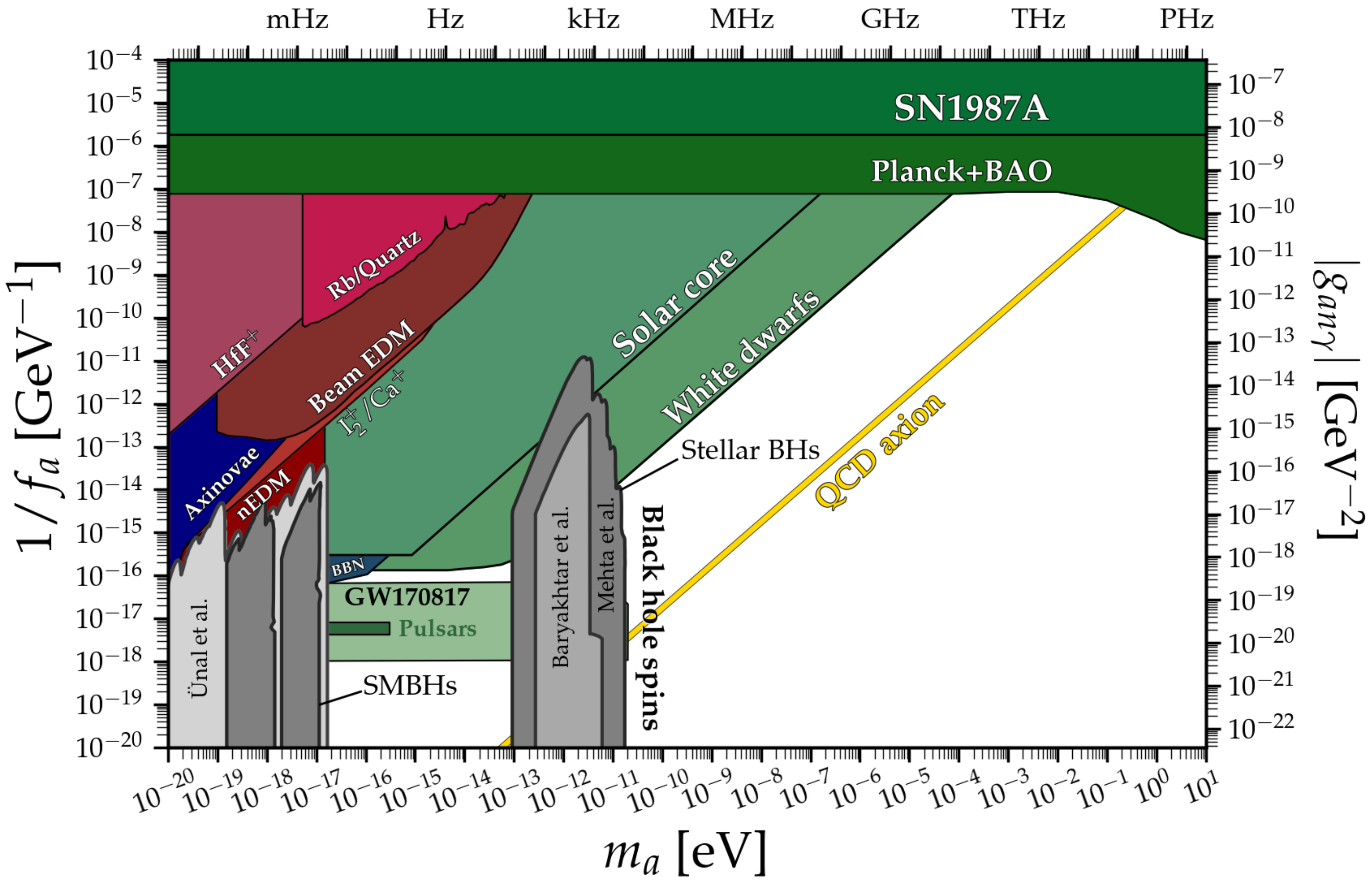
  - Probes neV mass axion, that is $f_a \sim M_Q$ of order GUT scale



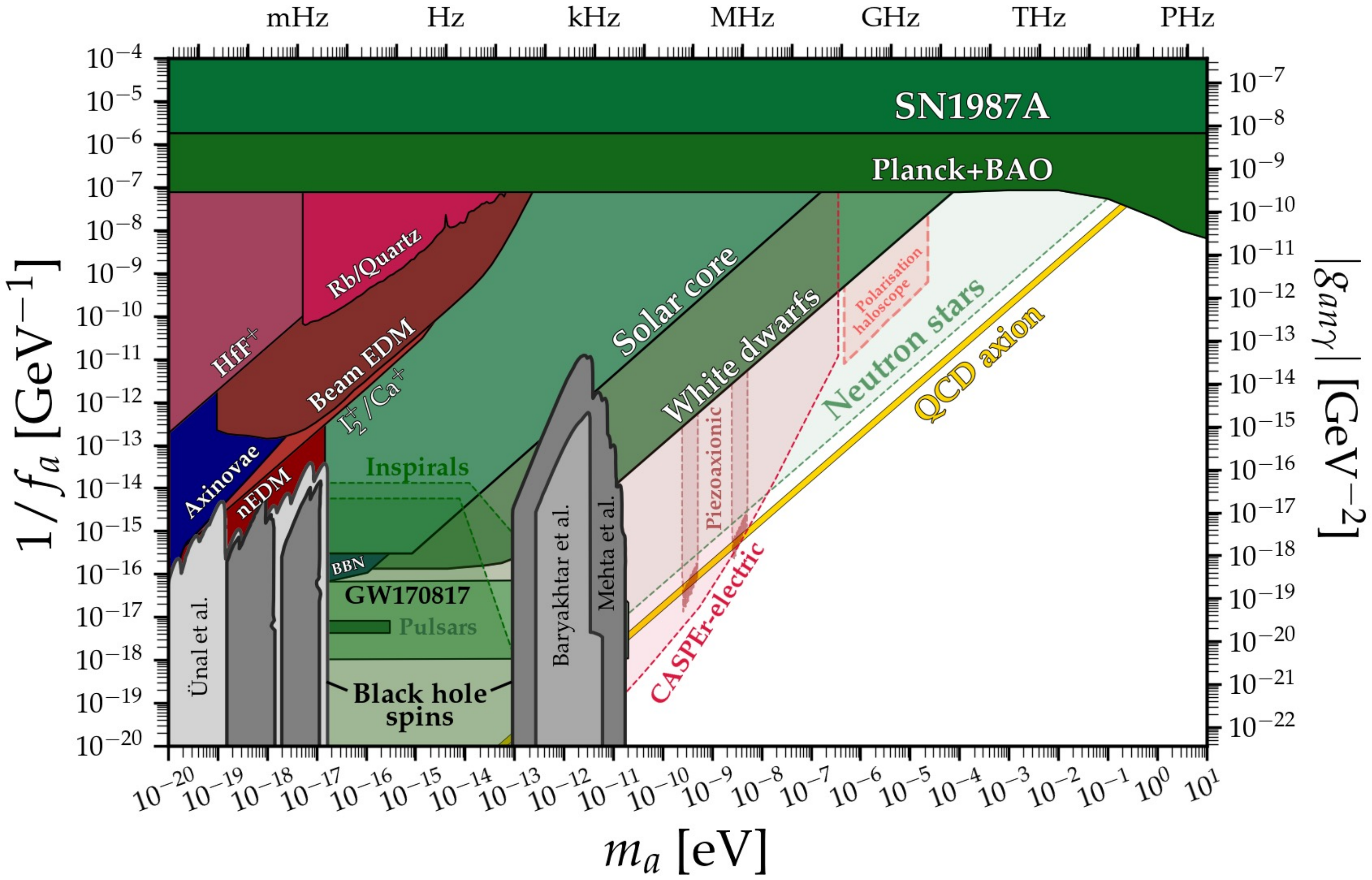
Distinguishing between axion and ALP

Current bounds on the coupling to the gluon resp. the NEDM



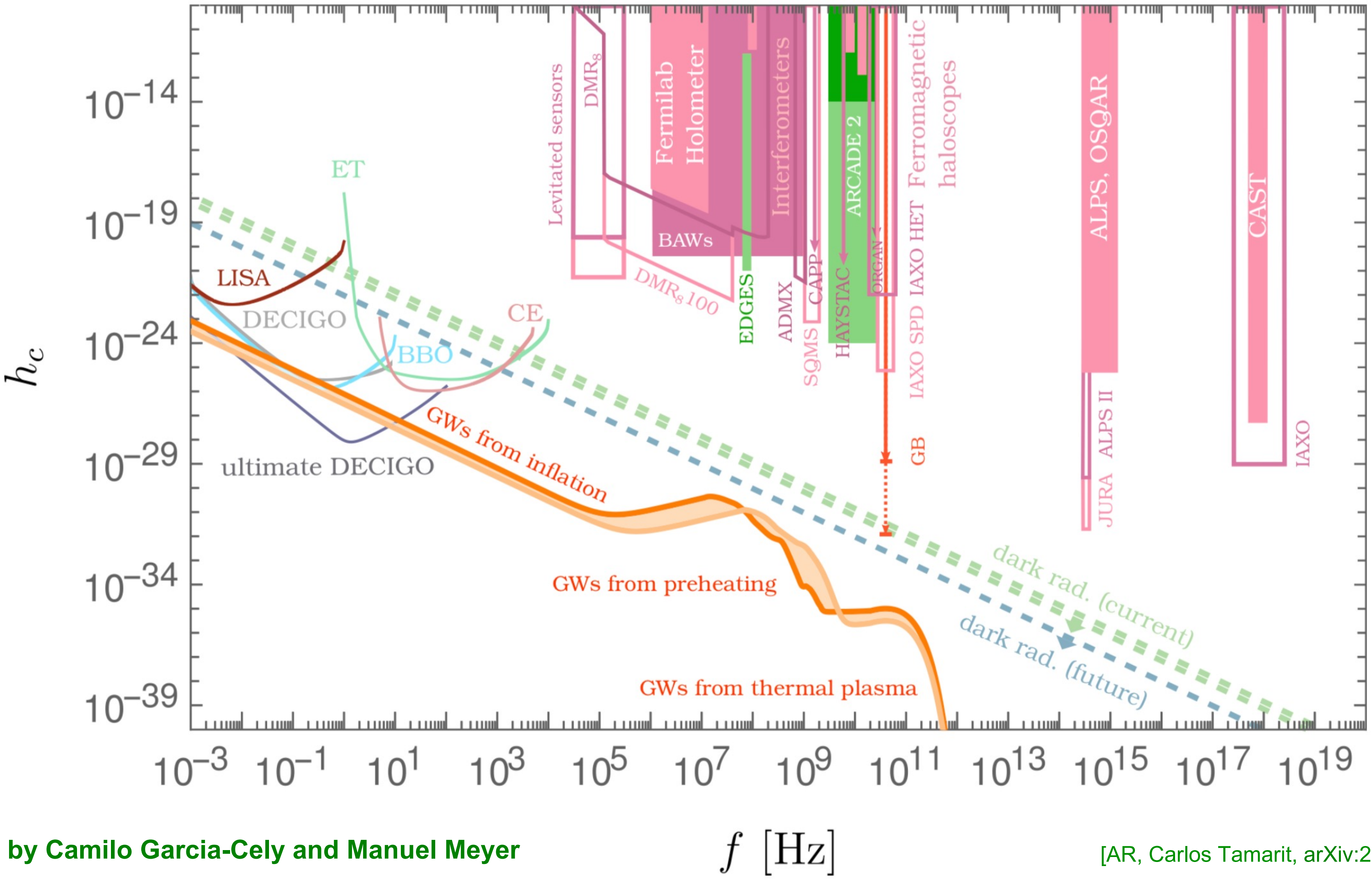
Distinguishing between axion and ALP

Prospected sensitivity on the coupling to the gluon resp. the NEDM



Searches for High-Frequency Gravitational Waves

Axion haloscopes, LSW experiments, and helioscopes as HF-GW detectors



Talks by Camilo Garcia-Cely and Manuel Meyer

[AR, Carlos Tamarit, arXiv:2203.00621]

[Ejlli et al., 1908.00232]

[AR et al., 2011.04731]

[Berlin et al., 2112.11465]

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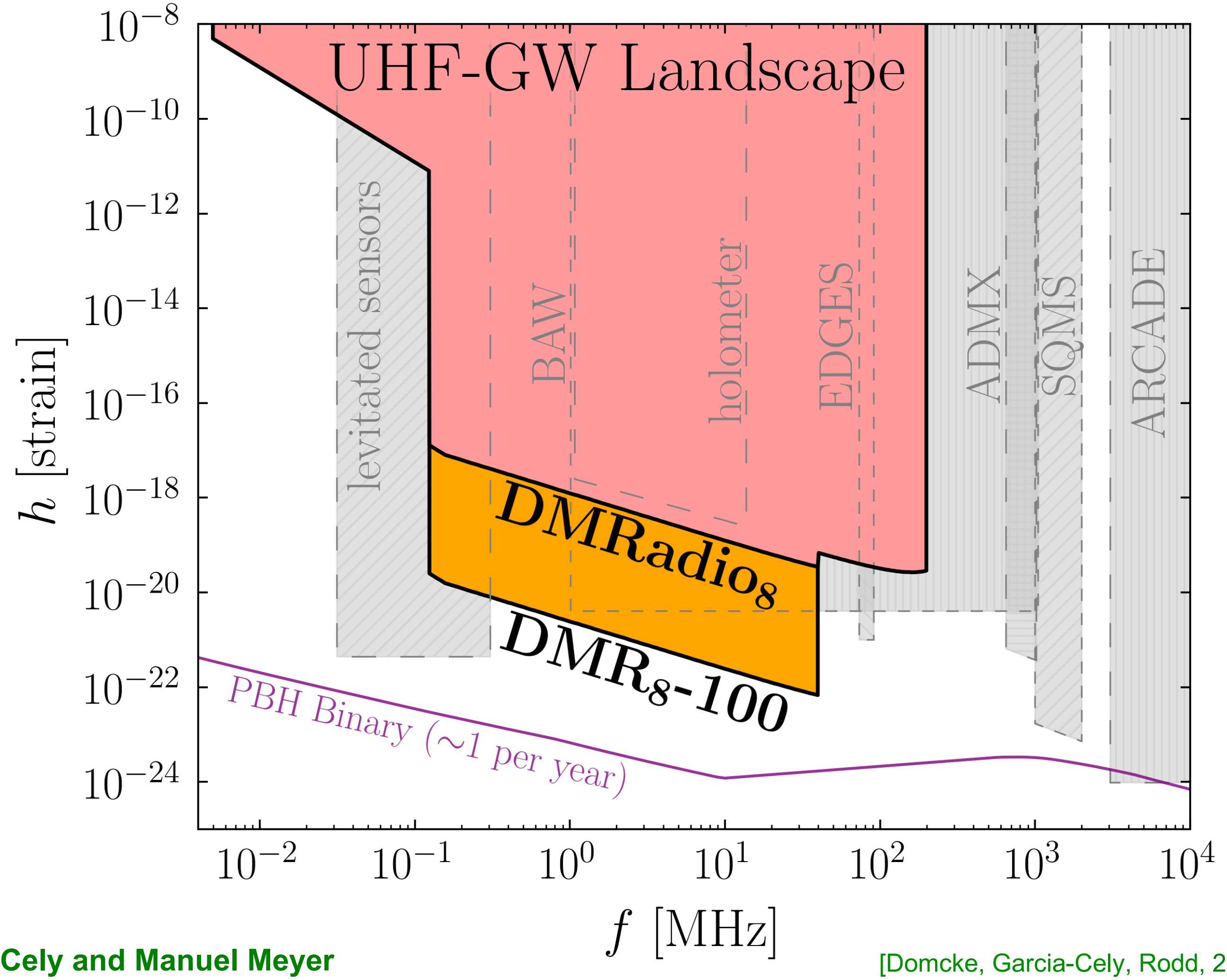


Talks by Camilo Garcia-Cely and Manuel Meyer

[Domcke, Garcia-Cely, Rodd, 2202.00695]

Guaranteed High Frequency Gravitational Wave Sources

Primordial plasma and solar plasma

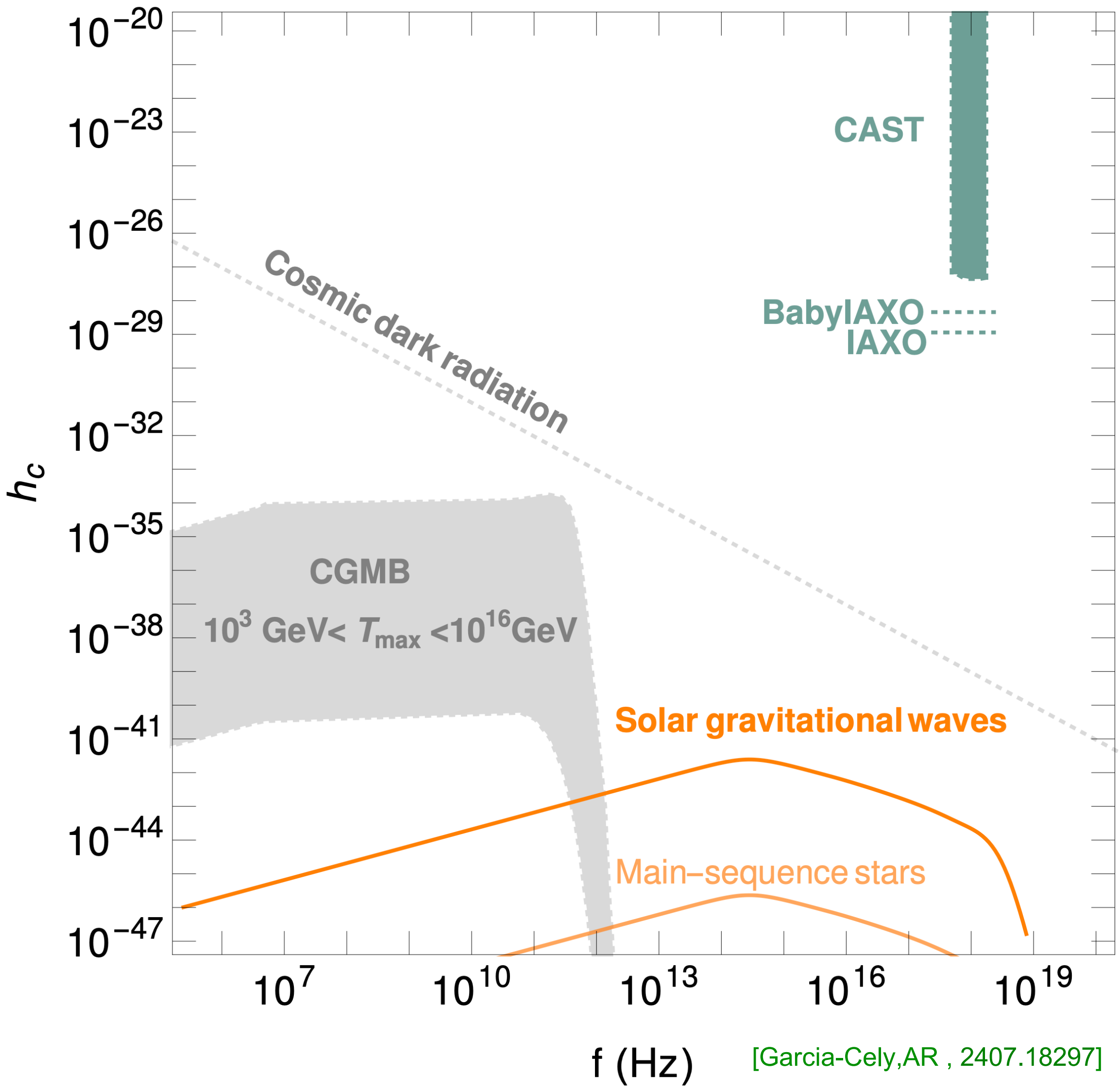
- Cosmic Gravitational Microwave Background (CGMB) can act as Big Bang thermometer

[Ghiglieri,Laine ’15; Ghiglieri,Jackson,Laine,Zhu ’20; AR,Schütte-Engel,Tamarit ‘20]

See also related talk by Anshuman Maharana

- Solar gravitational wave spectrum has no free parameter, but strain sensitivity of current helioscopes about fifteen orders of magnitude above prediction [Garcia-Cely,AR , 2407.18297]

Talk by Camilo Garcia-Cely



[Garcia-Cely,AR , 2407.18297]

A Further WISP Candidate

Spin-2 WISP

- Massive spin-2 field emerging from bimetric gravity can be
  - wavy dark matter [Marzola,Raidal,Urban `18]
  - produced in the sun [Cembranos et al. `17]
  - searched for by photon regeneration experiments, in particular LSW and helioscopes [Biggio,Masso,Redondo `09]

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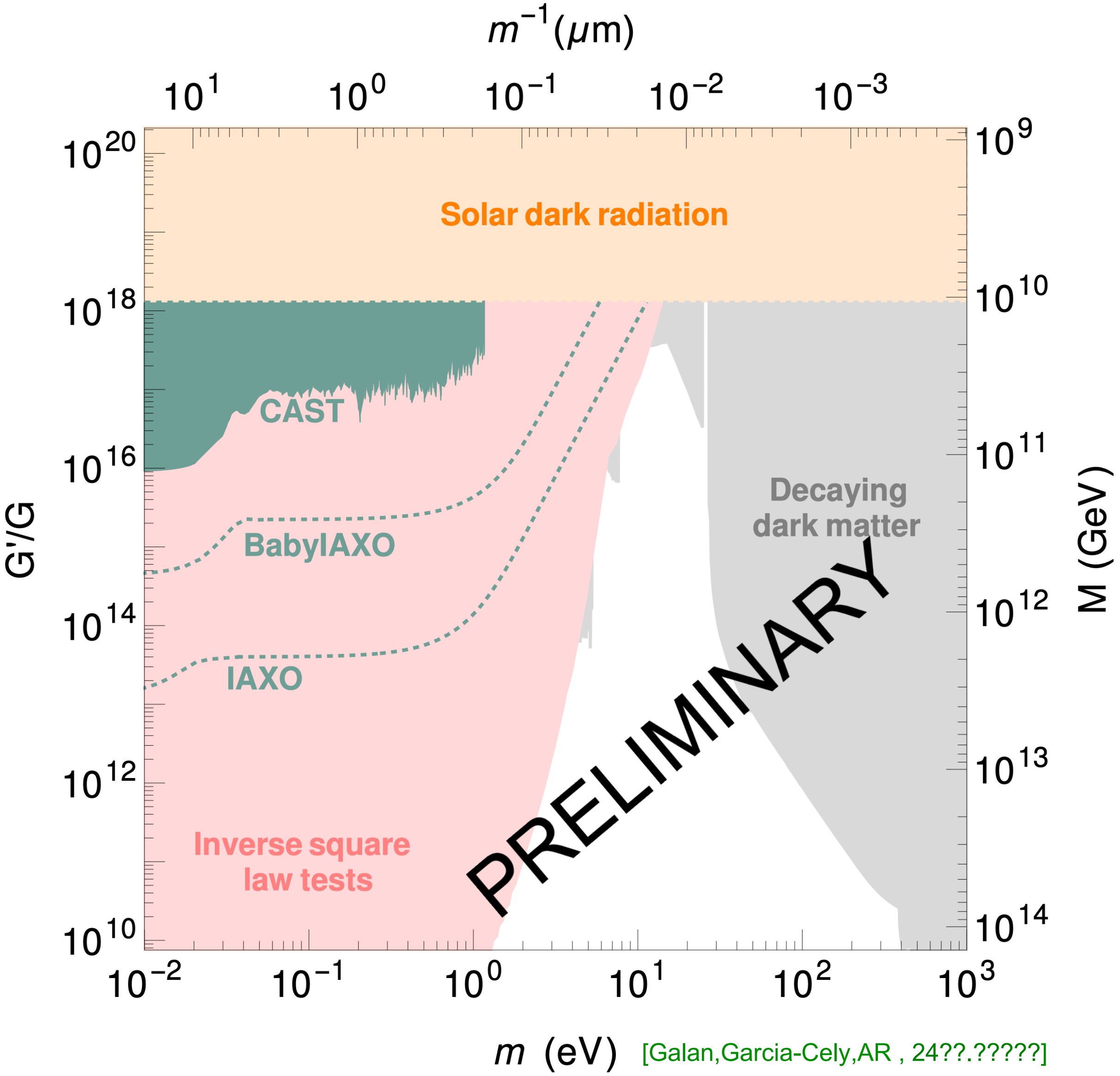
- Upper bound on energy loss of sun gives a bound on its coupling $G' = (8\pi M^2)^{-1}$
- Current and future helioscope bounds better than solar dark radiation bound, but less stringent than inverse square law tests
- Window of opportunity around 10 eV?

[Galan,Garcia-Cely,AR , 24??.?????]



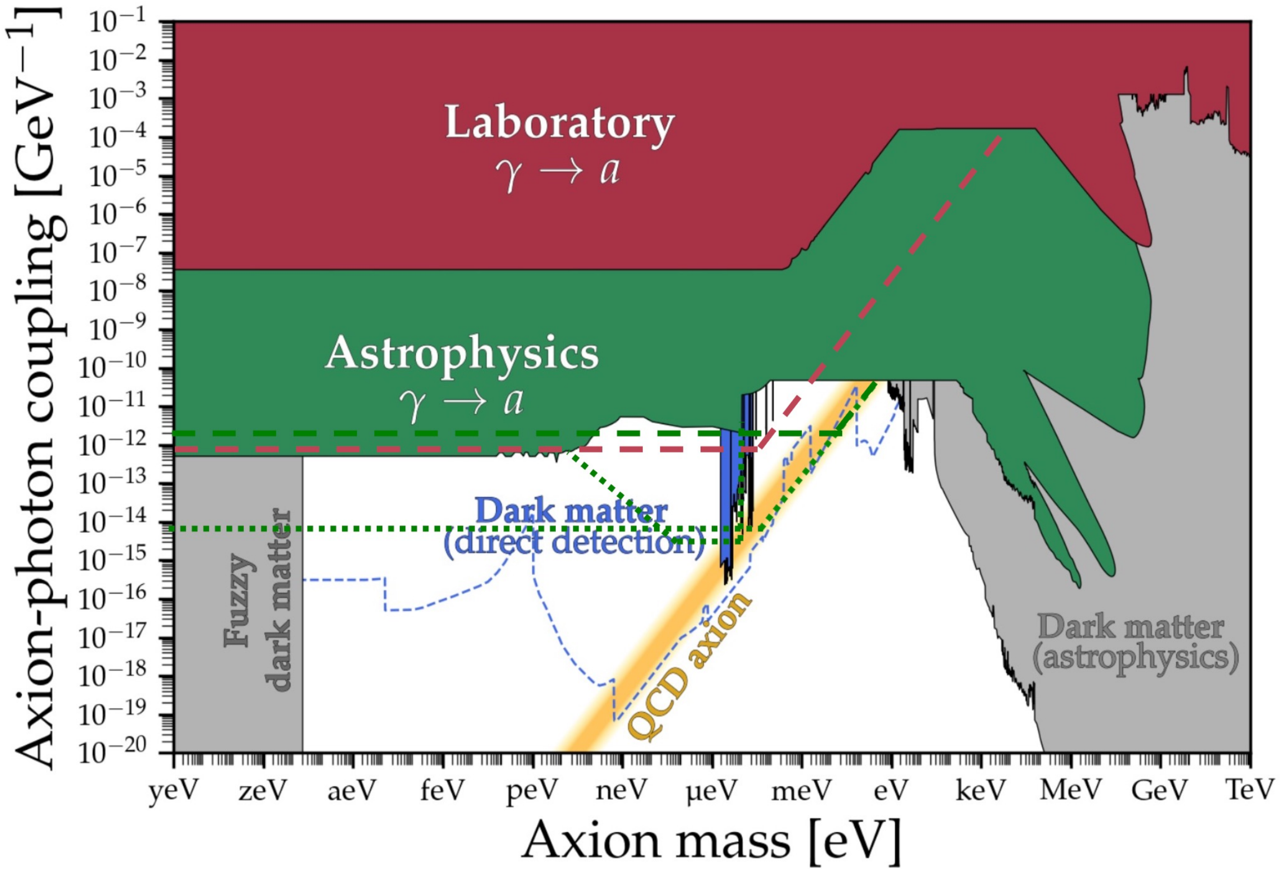
[Galan,Garcia-Cely,AR , 24??.?????]

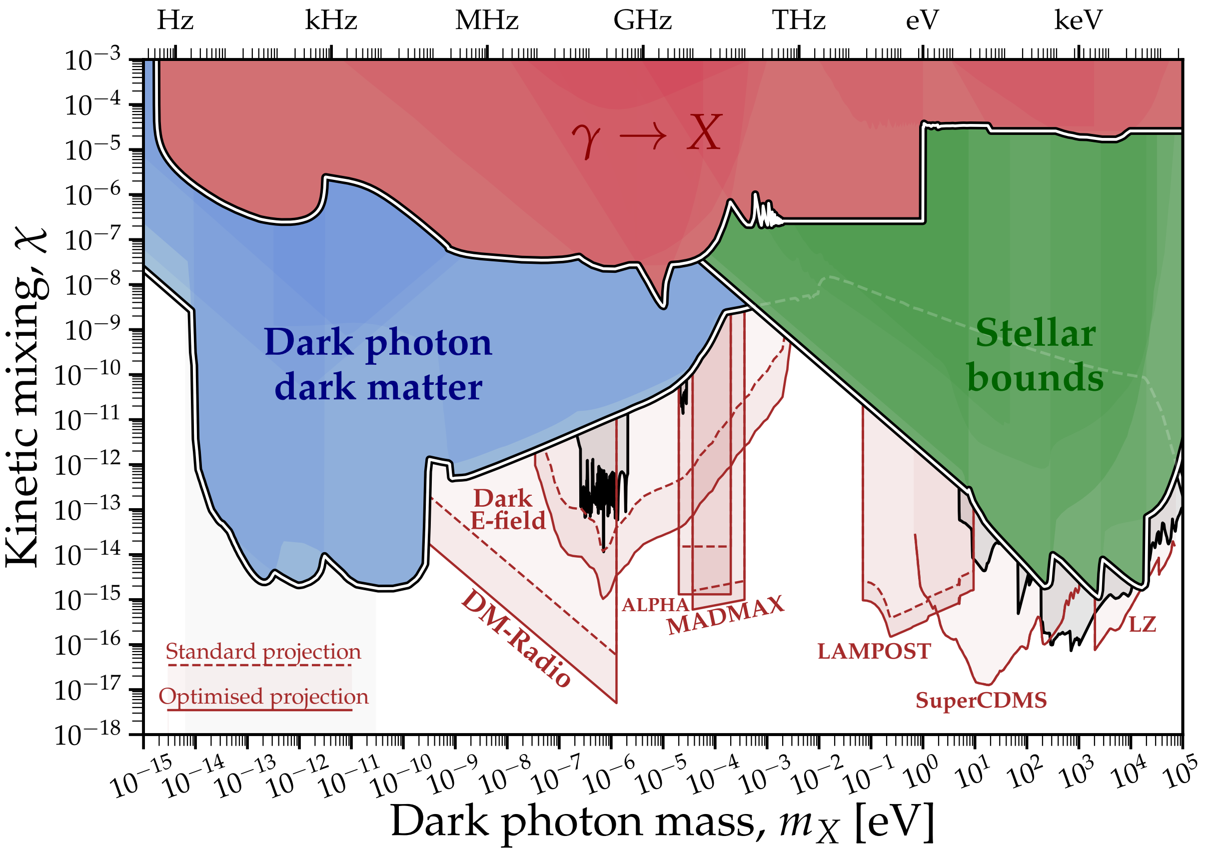
Conclusions

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

For the dark photon, we are missing a sense for the most plausible mass and coupling

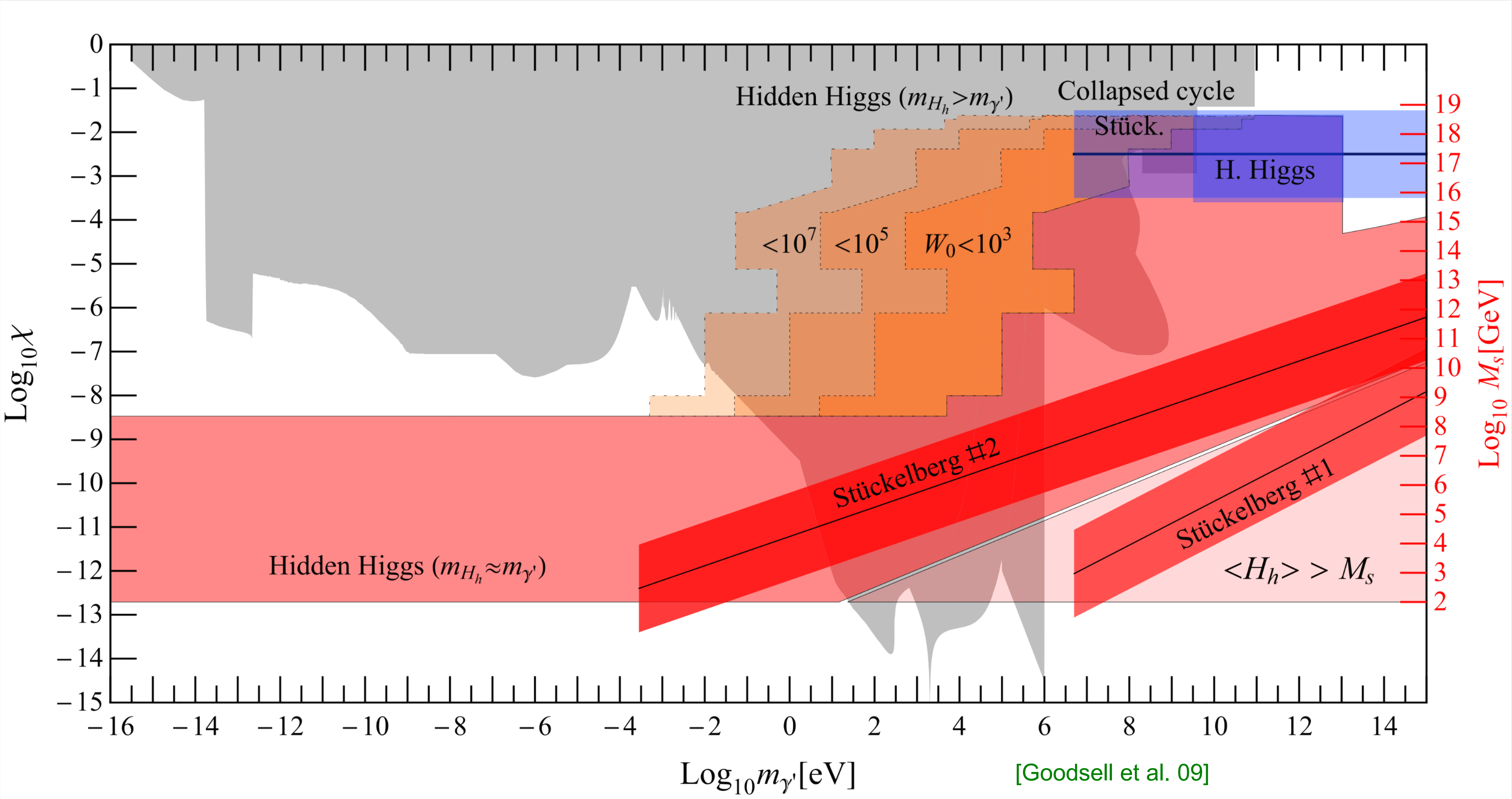
We need the complementarity of laboratory, astrophysics, and dark matter direct detection





Popular WISP Candidates

Spin 1: Ultralight U(1) gauge bosons



[Goodsell et al. 09]

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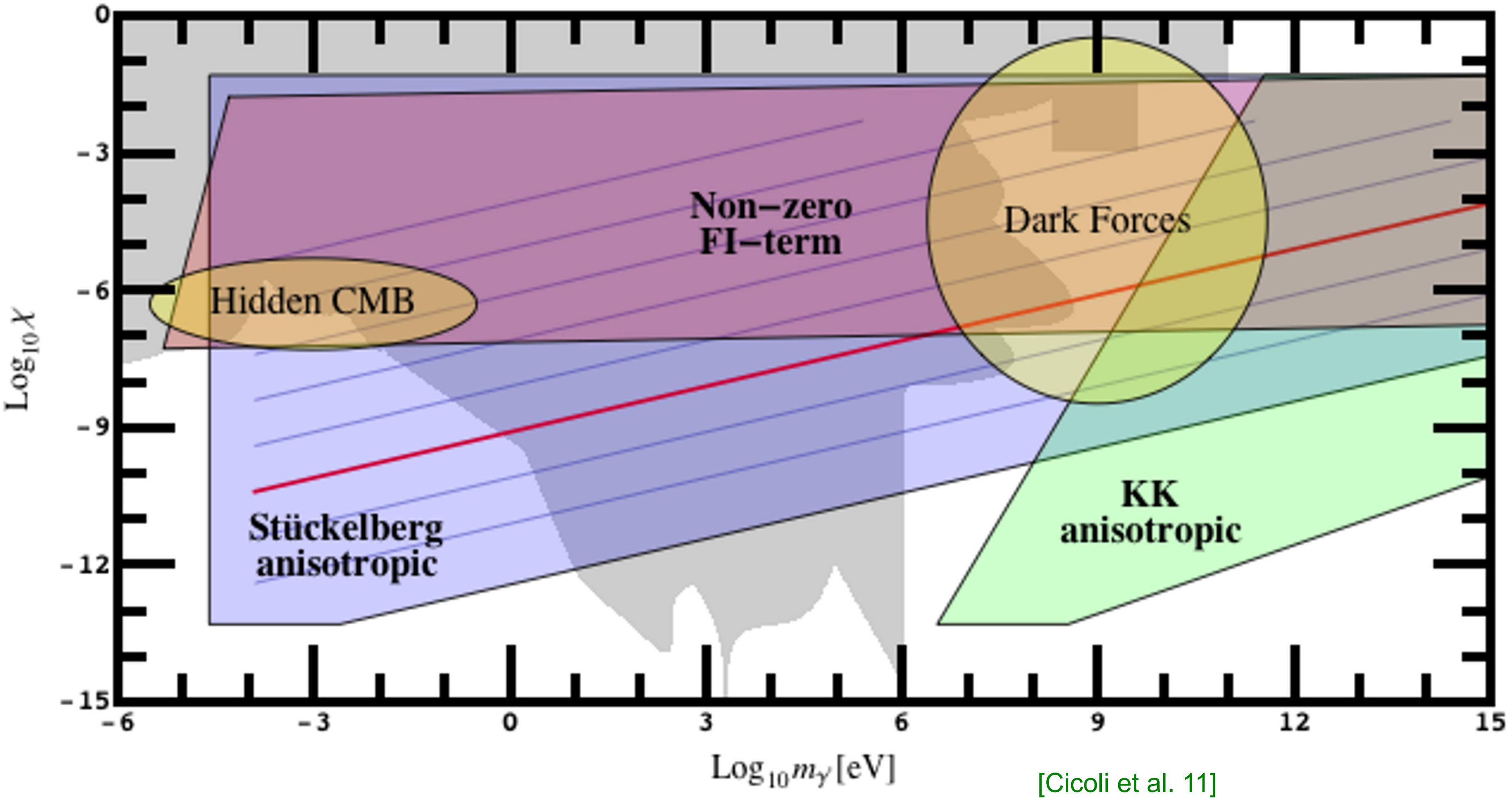

[Cicoli et al. 11]

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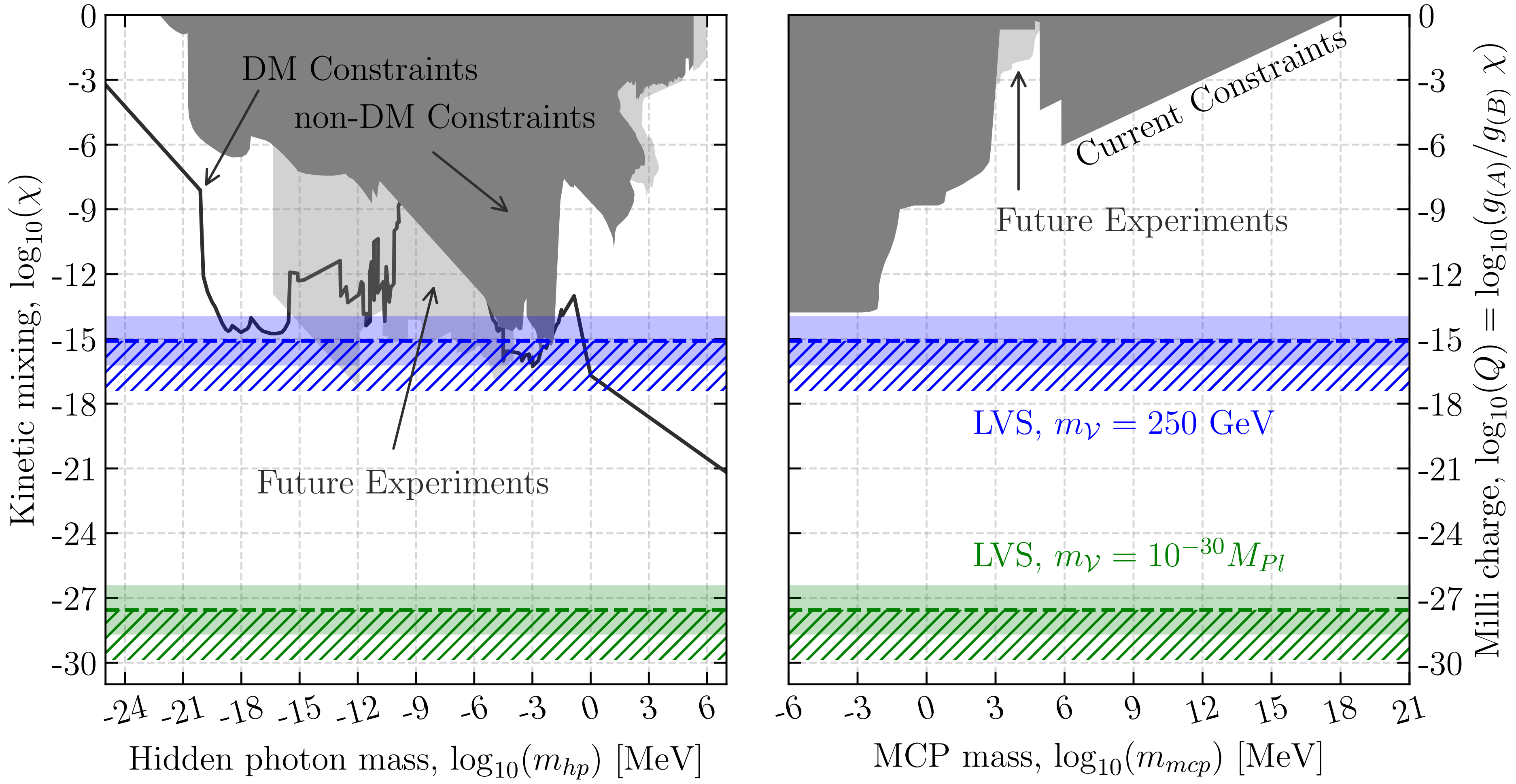
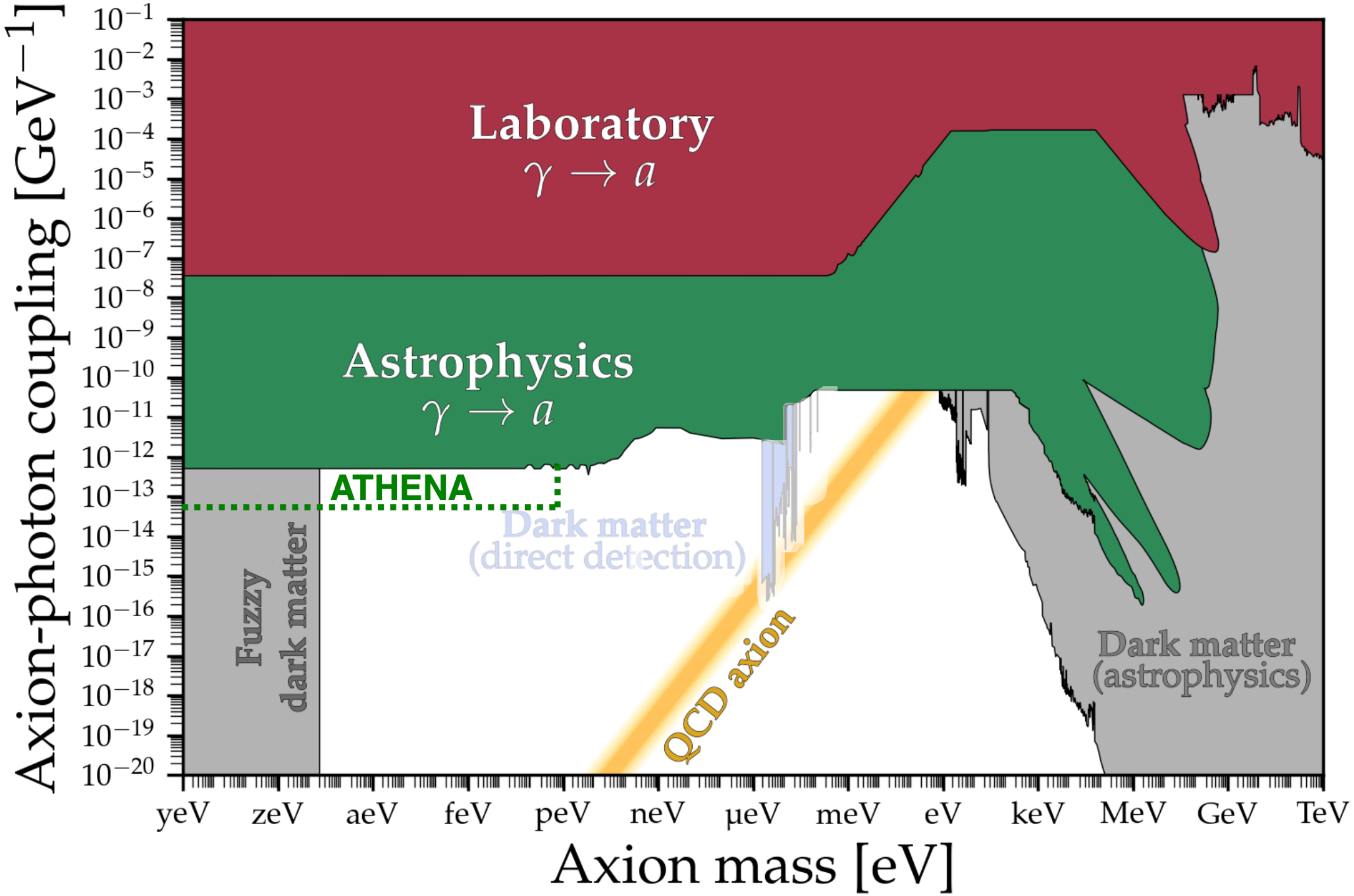


[Hebecker, Jaeckel, Kuespert, 2311.10817]

The Road Ahead in Astrophysics

Expect remarkable progress in astrophysics



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

- 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]

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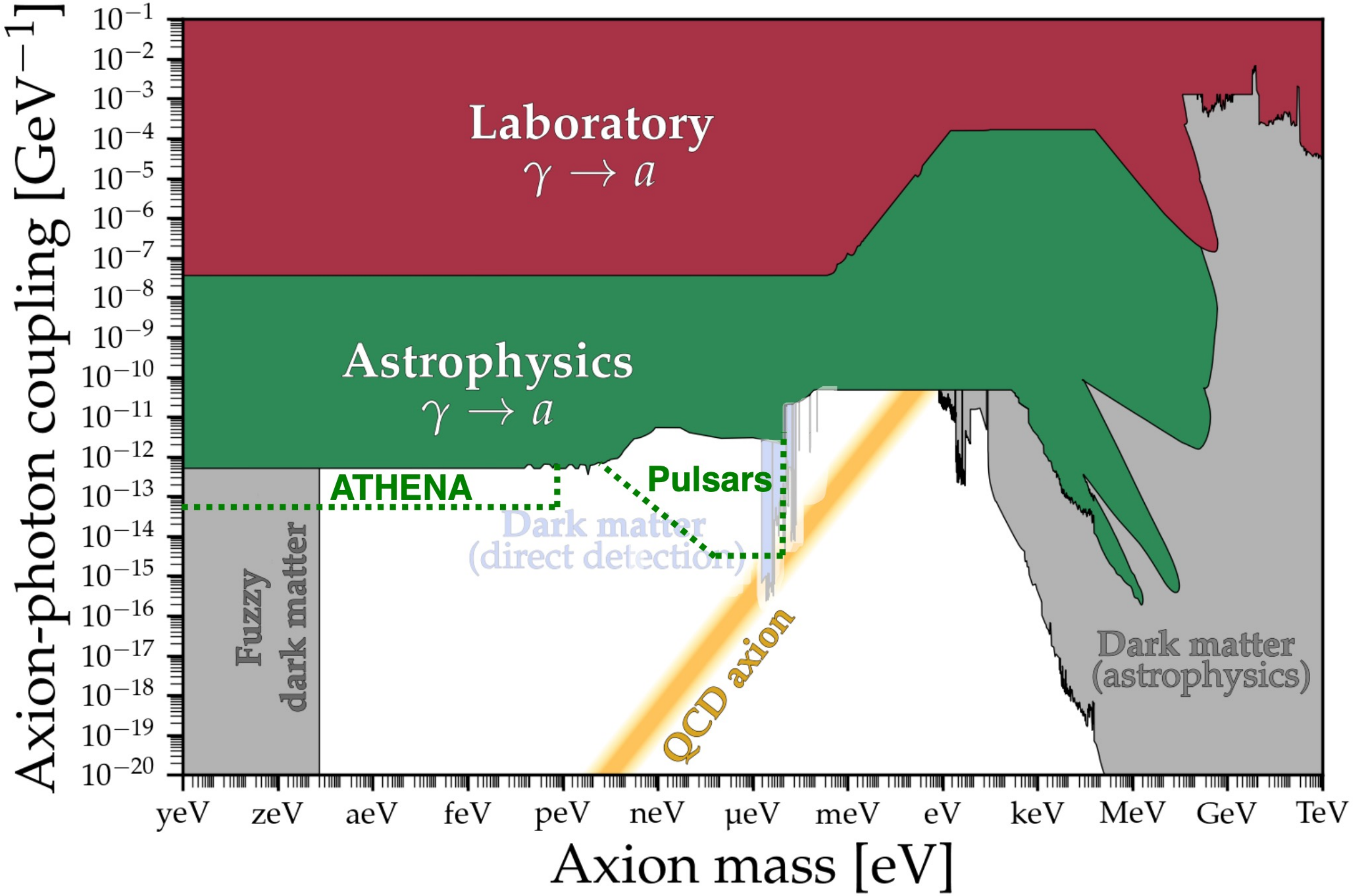

[https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/AxionPhoton_UltraSimple_FullParameterSpace.png]

- 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

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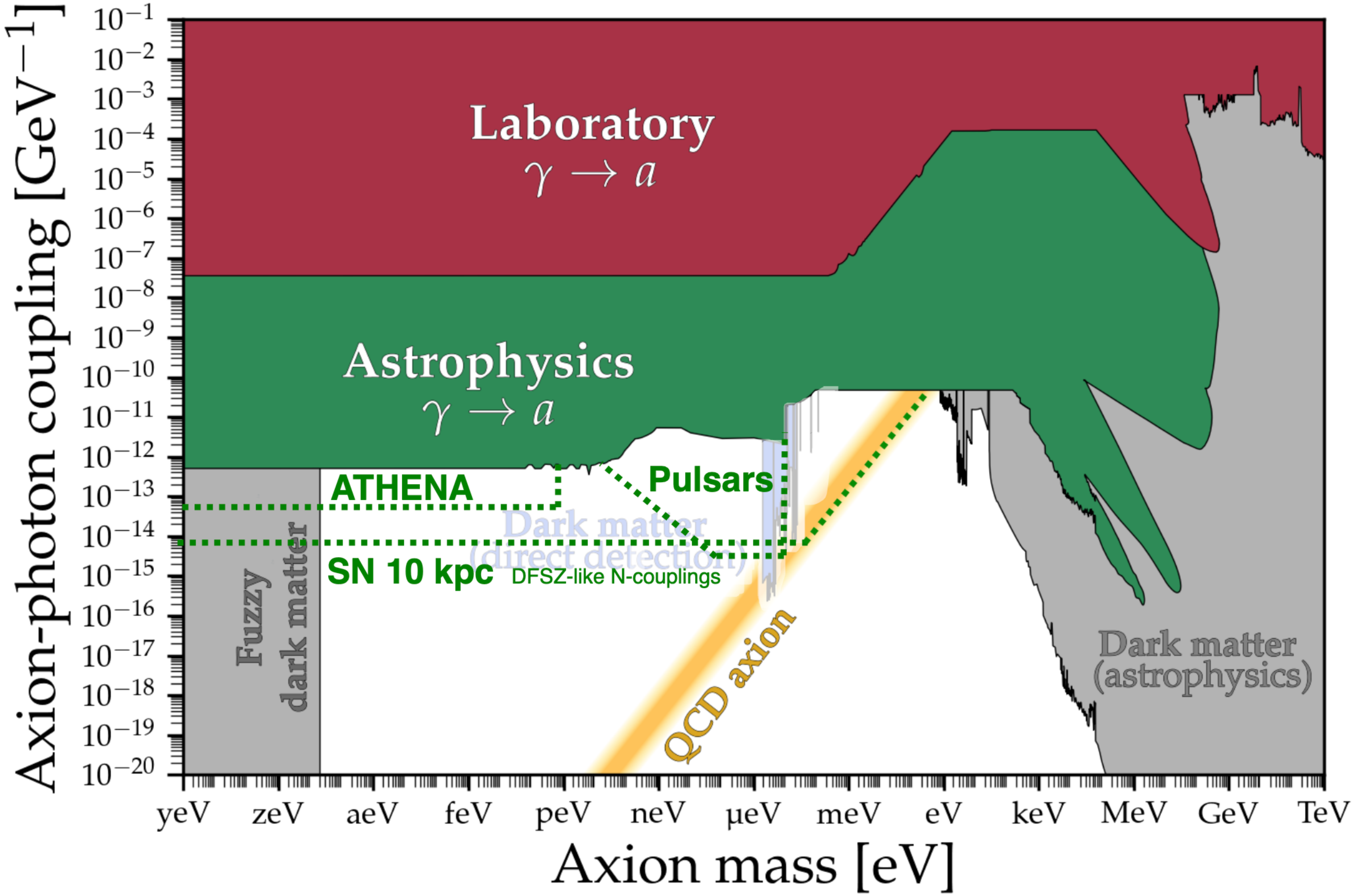

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- Axion-photon conversion on the still-intact magnetic fields of the progenitor star of SN1987A constrains ALPs all the way to 0.1 meV
- Gamma-ray observations of the next Galactic supernova, leveraging the magnetic fields of the progenitor star, could 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]