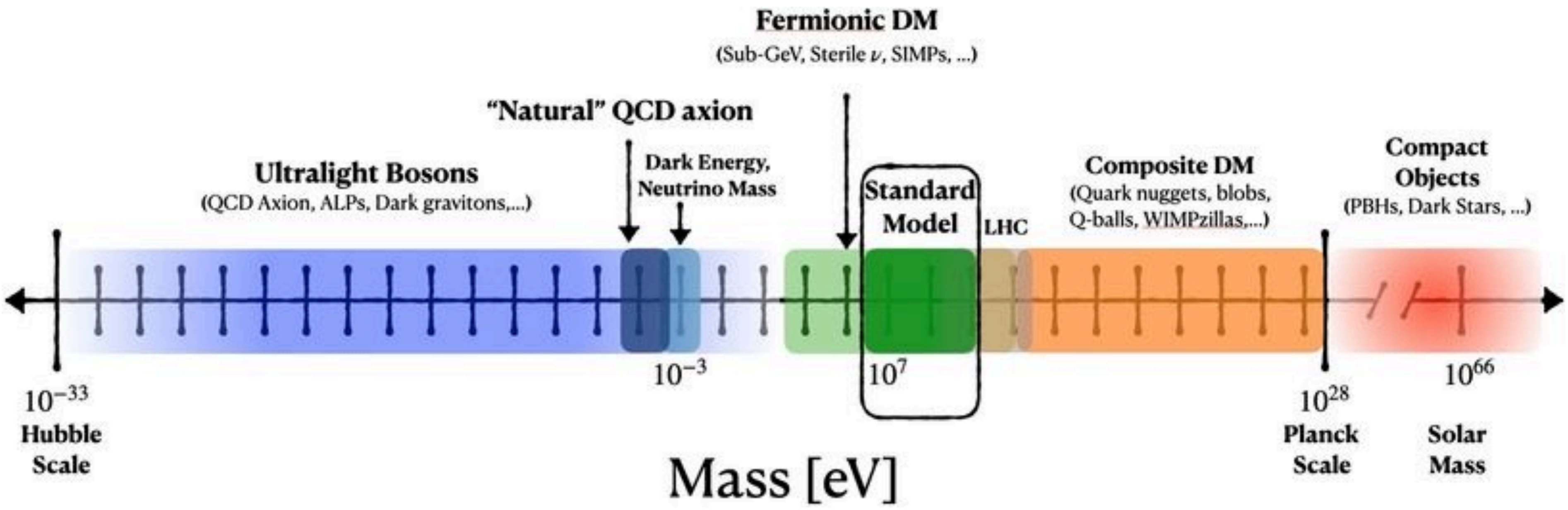
Ultralight Bosonic Dark Matter

Andreas Ringwald

Quantum Technologies for Fundamental Physics (QTFP) Meeting
Mazumdar-Shaw Advanced Research Centre (ARC)
University of Glasgow
21-22 January 2025

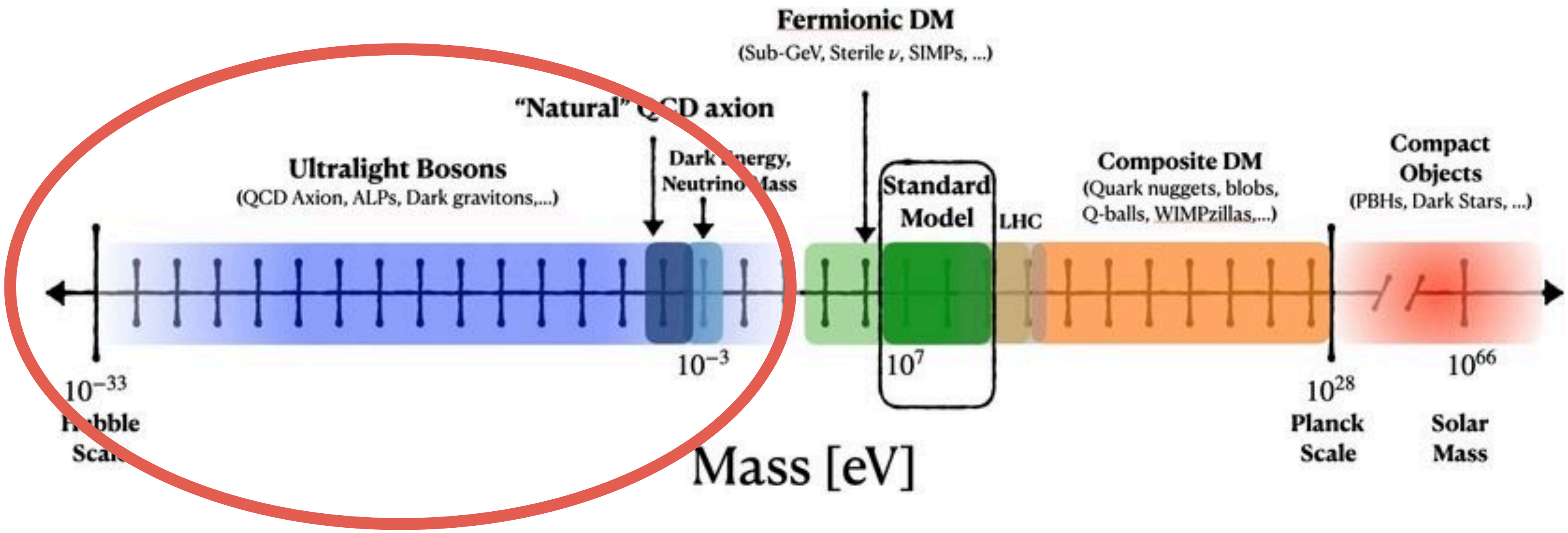
Why We Should Search for Ultralight Bosons?

Why We Should Search for Ultralight Bosons?



[Prabhu, https://aniprabhu.com]

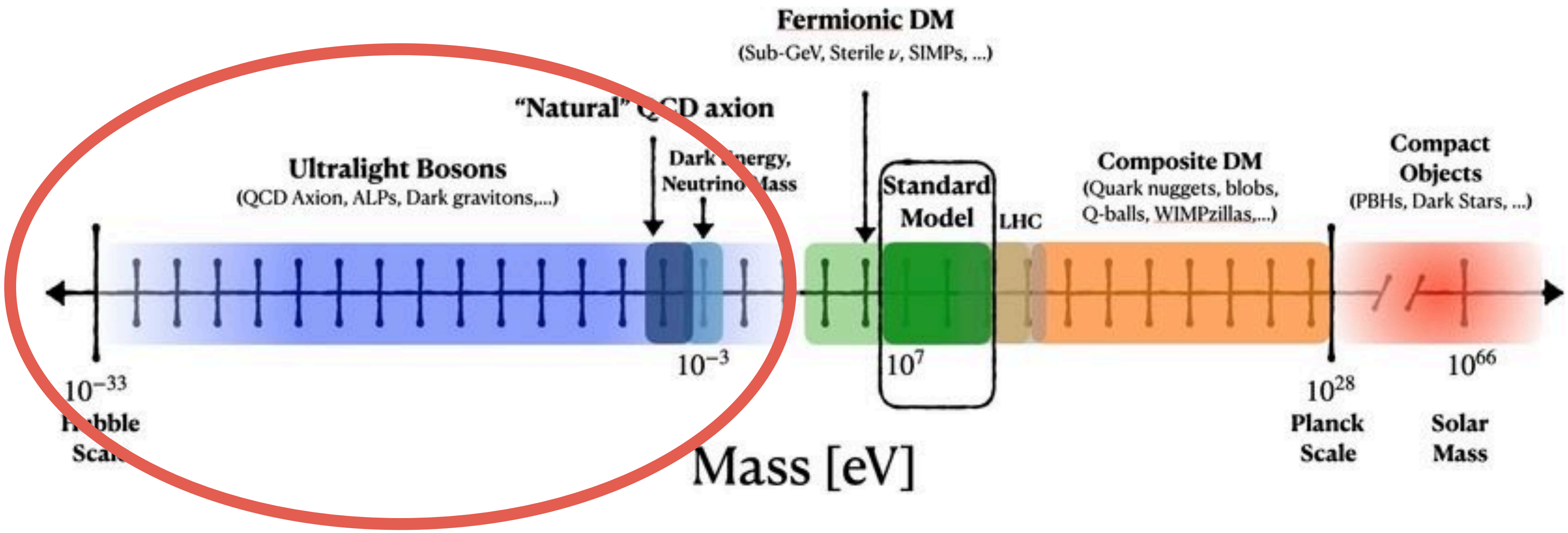
Why We Should Search for Ultralight Bosons?



[Prabhu, https://aniprabhu.com]

Why We Should Search for Ultralight Bosons?

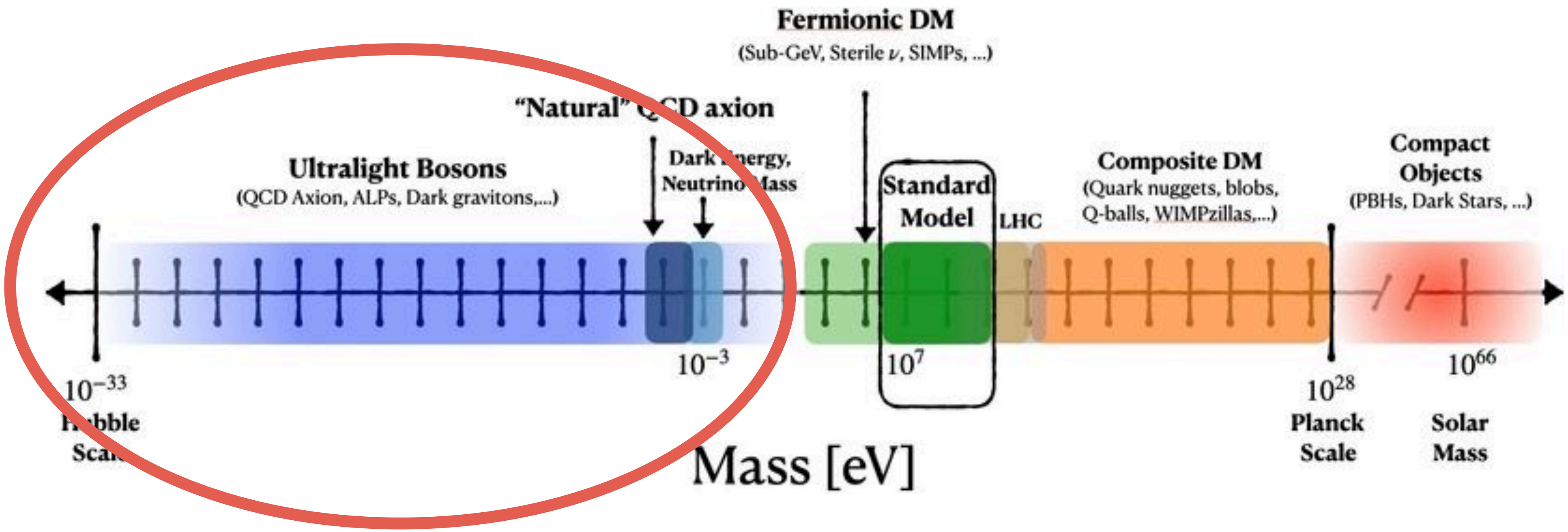
1. **Because they are well motivated BSM (Beyond the Standard Model) particles!**



[Prabhu, https://aniprabhu.com]

Why We Should Search for Ultralight Bosons?

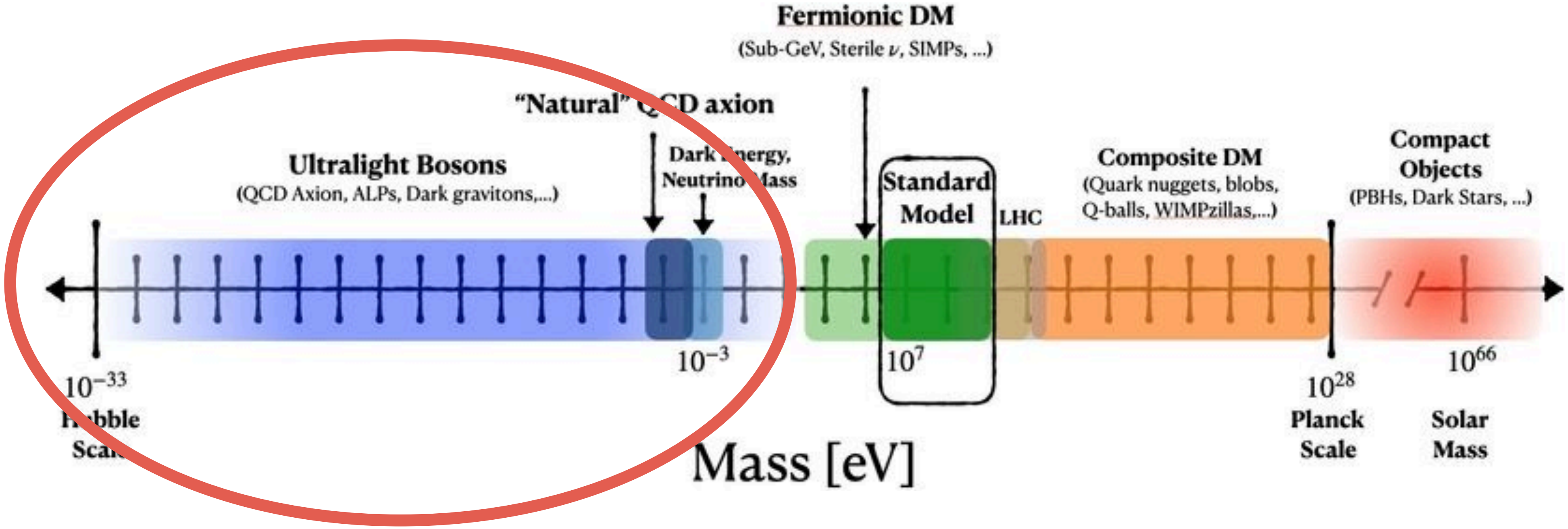
1. **Because they are well motivated BSM (Beyond the Standard Model) particles!**
2. **Because they are well motivated cold Dark Matter (DM) candidates!**



[Prabhu, https://aniprabhu.com]

Why We Should Search for Ultralight Bosons?

1. **Because they are well motivated BSM (Beyond the Standard Model) particles!**
2. **Because they are well motivated cold Dark Matter (DM) candidates!**
3. **Because we can!**



[Prabhu, https://aniprabhu.com]

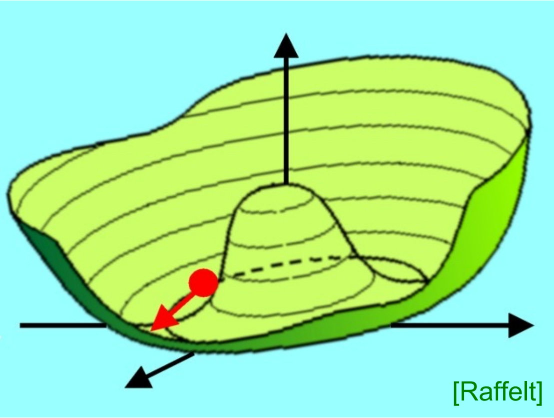
Ultralight Bosons are Well Motivated BSM Particles!

Spin 0: Pseudo Nambu-Goldstone bosons

Ultralight Bosons are Well Motivated BSM Particles!

Spin 0: Pseudo Nambu-Goldstone bosons

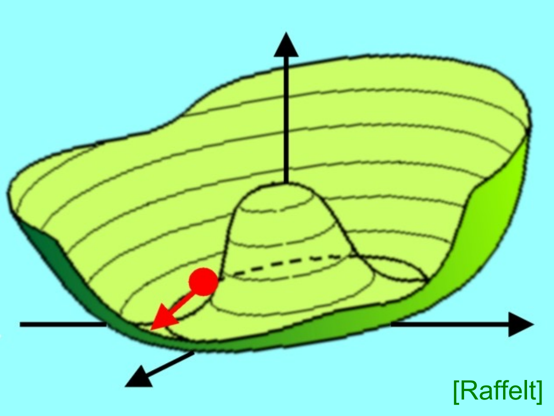
Pseudo Nambu-Goldstone bosons arising from the breaking of symmetries beyond the Standard Model (SM) at a scale much larger than the electroweak scale



Ultralight Bosons are Well Motivated BSM Particles!

Spin 0: Pseudo Nambu-Goldstone bosons

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



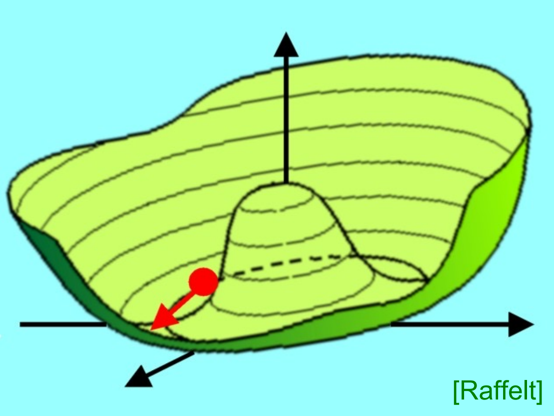
- Peccei-Quinn symmetry: **Axion** [Peccei,Quinn `77; Weinberg `78; Wilczek `78]

Ultralight Bosons are Well Motivated BSM Particles!

Spin 0: Pseudo Nambu-Goldstone bosons

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

- Peccei-Quinn symmetry: **Axion** [Peccei,Quinn `77; Weinberg `78; Wilczek `78]
- Lepton symmetry: **Majoron** [Chikashige,Mohapatra,Peccei `81, Gelmini,Roncadelli `81]

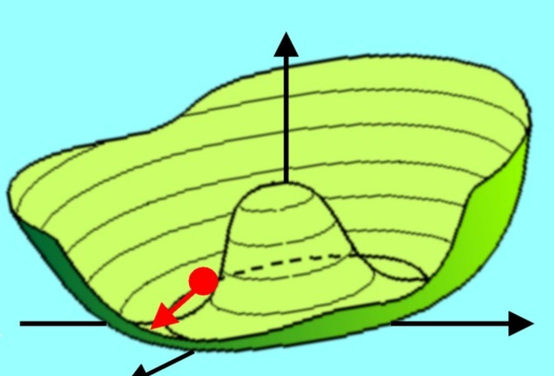


Ultralight Bosons are Well Motivated BSM Particles!

Spin 0: Pseudo Nambu-Goldstone bosons

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

- 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]

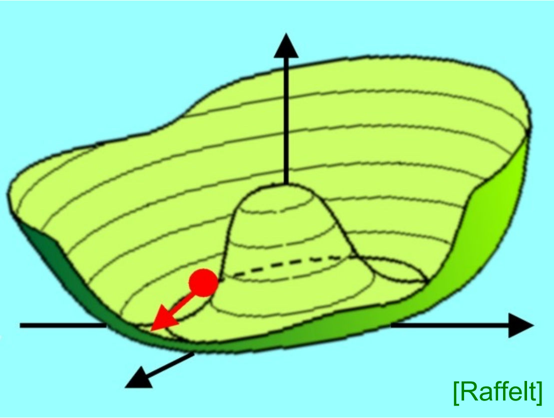

[Raffelt]

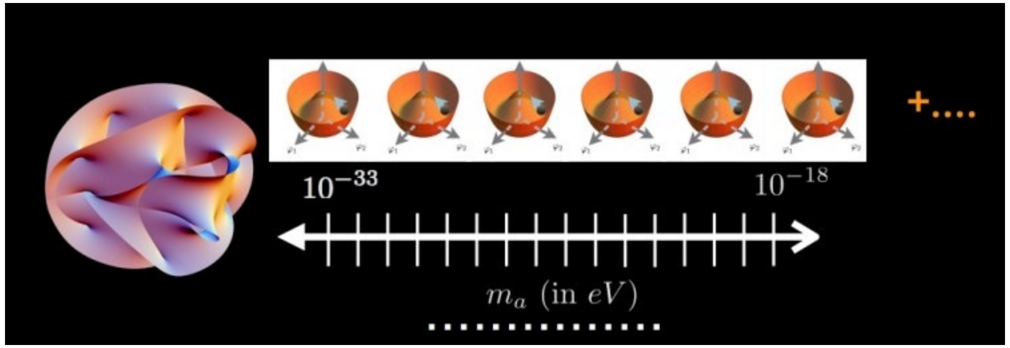
Ultralight Bosons are Well Motivated BSM Particles!

Spin 0: Pseudo Nambu-Goldstone bosons

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

- 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; ...]


[Raffelt]

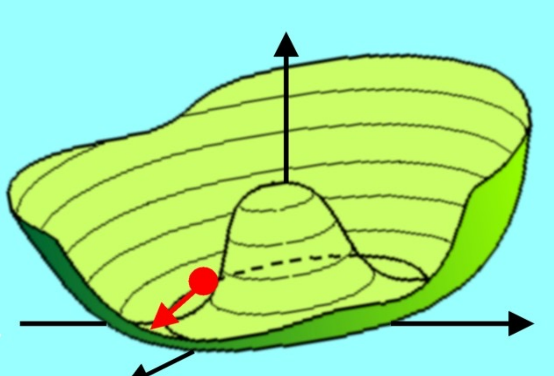


[http://danielgrin.net/2015/11/23/]

Ultralight Bosons are Well Motivated BSM Particles!

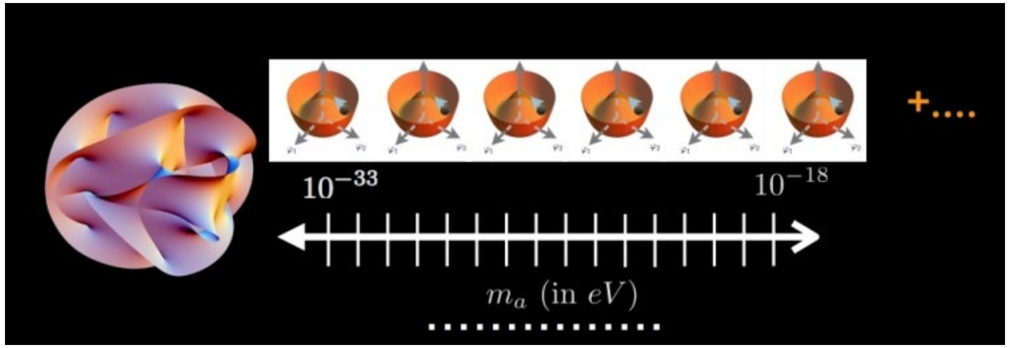
Spin 0: Pseudo Nambu-Goldstone bosons

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



[Raffelt]

- 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; ...]



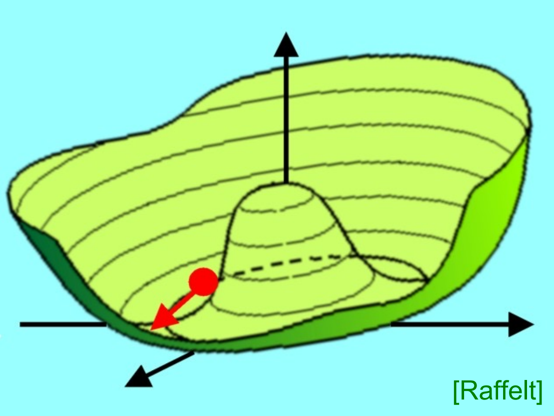
[http://danielgrin.net/2015/11/23/]

- Scale invariance: **Dilaton** [Kaluza `1921;Klein `1926;...]

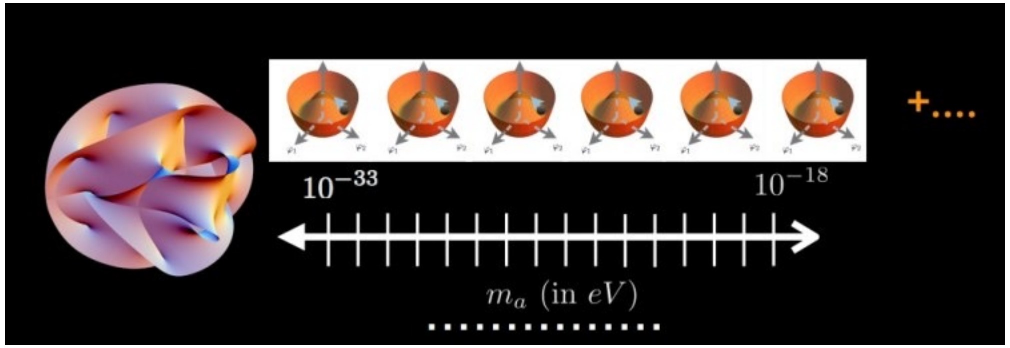
Ultralight Bosons are Well Motivated BSM Particles!

Spin 0: Pseudo Nambu-Goldstone bosons

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



- 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; ...]



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

- Scale invariance: **Dilaton** [Kaluza `1921;Klein `1926;...]

are **naturally ultralight**:

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

Ultralight Bosons are Well Motivated BSM Particles!

Spin 1: Ultralight U(1) gauge bosons

Ultralight Bosons are Well Motivated BSM Particles!

Spin 1: Ultralight U(1) gauge bosons

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

Ultralight Bosons are Well Motivated BSM Particles!

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

Ultralight Bosons are Well Motivated BSM Particles!

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]

Ultralight Bosons are Well Motivated BSM Particles!

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

Ultralight Bosons are Well Motivated BSM Particles!

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)

Ultralight Bosons are Well Motivated BSM Particles!

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

Ultralight Bosons are Well Motivated BSM Particles!

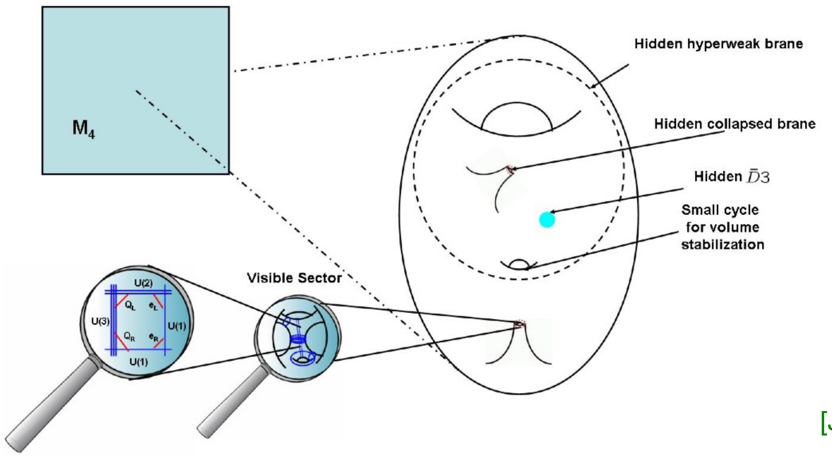
Spin 1: Ultralight U(1) gauge bosons

“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]

Ultralight Bosons are Well Motivated BSM Particles!

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

are **naturally ultralight**:

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

Ultralight Bosons are Well Motivated DM Candidates!

Generic properties of ultralight dark matter

Ultralight Bosons are Well Motivated DM Candidates!

Generic properties of ultralight dark matter

Ultralight particles constituting the Galactic Dark Halo have a macroscopic De Broglie wavelength,

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

Ultralight Bosons are Well Motivated DM Candidates!

Generic properties of ultralight dark matter

Ultralight particles constituting the Galactic Dark Halo have a macroscopic De Broglie wavelength,

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

and therefore a huge occupation number per de Broglie volume:

$$N_{\rm ULP}\,|_{\rm dB} = n_{\rm ULP}\,\lambda_{\rm dB}^3 = 1.3\times 10^6 \left(\frac{\rm eV}{m_{\rm ULP}}\right)^4 \left(\frac{250\,{\rm km/s}}{v_{\rm d}}\right)^3 \left(\frac{\rho_{\rm ULP}}{0.4\,{\rm GeV/cm^3}}\right)$$

Ultralight Bosons are Well Motivated DM Candidates!

Generic properties of ultralight dark matter

Ultralight particles constituting the Galactic Dark Halo have a macroscopic De Broglie wavelength,

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

and therefore a huge occupation number per de Broglie volume:

$$N_{\rm ULP}\,|_{\rm dB} = n_{\rm ULP}\,\lambda_{\rm dB}^3 = 1.3\times 10^6 \left(\frac{\rm eV}{m_{\rm ULP}}\right)^4 \left(\frac{250\,{\rm km/s}}{v_{\rm d}}\right)^3 \left(\frac{\rho_{\rm ULP}}{0.4\,{\rm GeV/cm^3}}\right)$$

➢ **Ultralight Dark Matter** is necessarily constituted by bosons (to avoid Pauli exclusion principle)

Ultralight Bosons are Well Motivated DM Candidates!

Generic properties of ultralight dark matter

Ultralight particles constituting the Galactic Dark Halo have a macroscopic De Broglie wavelength,

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

and therefore a huge occupation number per de Broglie volume:

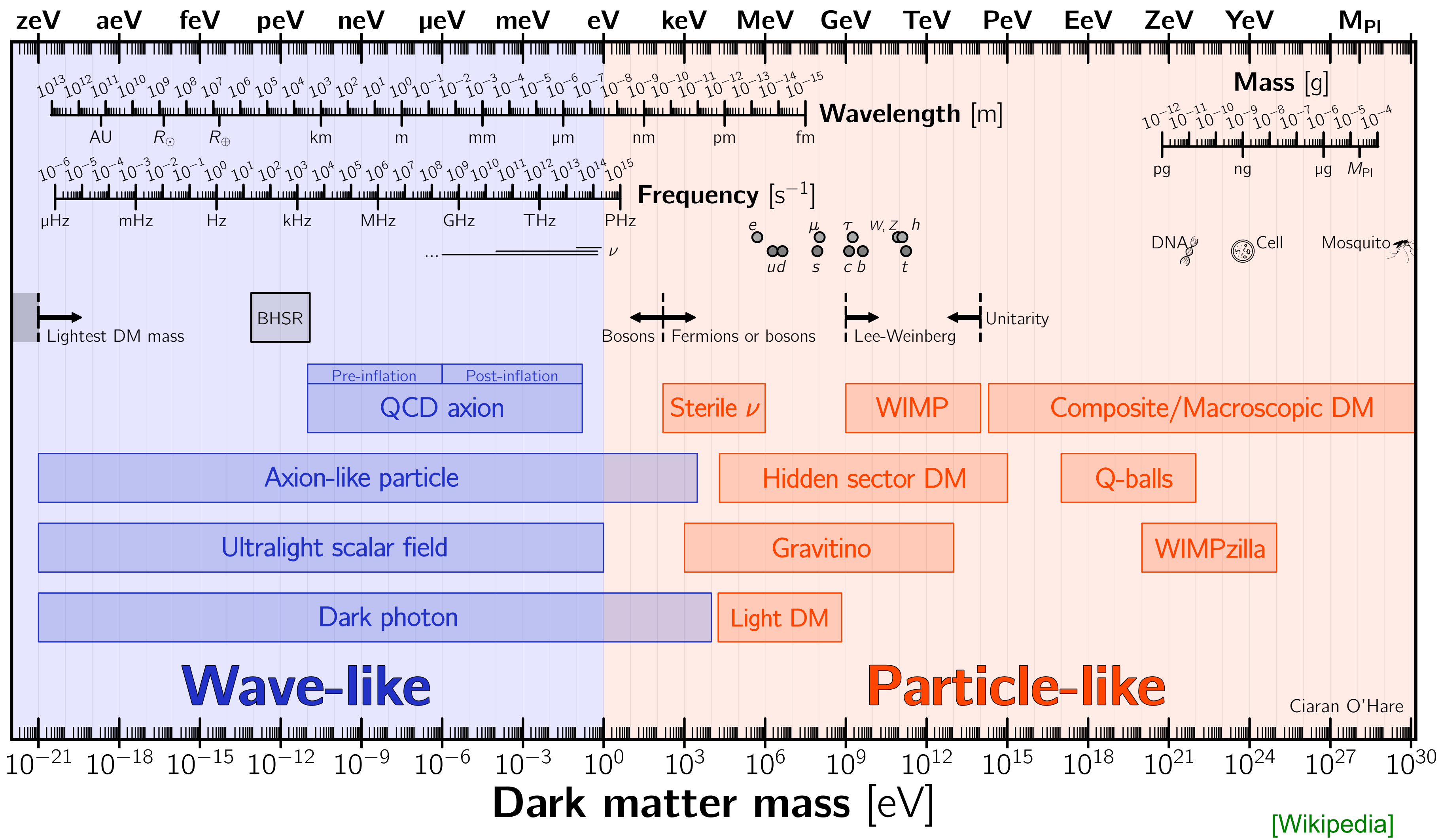
$$N_{\rm ULP}\, |_{\rm dB} = n_{\rm ULP}\, \lambda_{\rm dB}^3 = 1.3\times 10^6 \left(\frac{\rm eV}{m_{\rm ULP}}\right)^4 \left(\frac{250\,{\rm km/s}}{v_{\rm d}}\right)^3 \left(\frac{\rho_{\rm ULP}}{0.4\,{\rm GeV/cm^3}}\right)$$

- **Ultralight Dark Matter** is necessarily constituted by bosons (to avoid Pauli exclusion principle)
- **Ultralight Dark Matter** is most conveniently described by classical waves. Therefore also known as

Wave-Like Dark Matter

Ultralight Bosons are Well Motivated DM Candidates!

Several candidates



[Wikipedia]

Ultralight Bosons are Well Motivated DM Candidates!

Appear to be dark because of tiny interactions with SM, in particular with photons

Spin-0 Pseudo Goldstone Boson:

Ultralight Bosons are Well Motivated DM Candidates!

Appear to be dark because of tiny interactions with SM, in particular with photons

Spin-0 Pseudo Goldstone Boson:

- **Tiny couplings to photons** since they are suppressed by inverse power of symmetry breaking scale

Ultralight Bosons are Well Motivated DM Candidates!

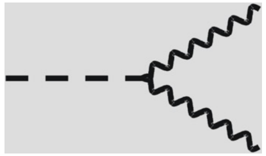
Appear to be dark because of tiny interactions with SM, in particular with photons

Spin-0 Pseudo Goldstone Boson:

- **Tiny couplings to photons** since they are suppressed by inverse power of symmetry breaking scale:

  For a pseudo-scalar (axion or axion-like particle):

$$\mathcal{L} \supset C_{a\gamma} \frac{\alpha}{8\pi} \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} \equiv g_{a\gamma}\, a\, \mathbf{E} \cdot \mathbf{B}$$



Ultralight Bosons are Well Motivated DM Candidates!

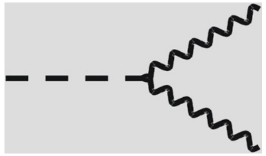
Appear to be dark because of tiny interactions with SM, in particular with photons

Spin-0 Pseudo Goldstone Boson:

- **Tiny couplings to photons** since they are suppressed by inverse power of symmetry breaking scale:

For a pseudo-scalar (axion or axion-like particle):

$$\mathcal{L} \supset C_{a\gamma} \frac{\alpha}{8\pi} \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} \equiv g_{a\gamma}\, a\, \mathbf{E} \cdot \mathbf{B}$$



For a scalar (dilaton or dilaton-like particle):

$$\mathcal{L} \supset \frac{d_e}{4\sqrt{2}} \frac{\phi}{M_{\rm P}} F_{\mu\nu} F^{\mu\nu} \equiv g_{\phi\gamma}\, \phi\, \left(\mathbf{E}^2 - \mathbf{B}^2\right)$$

Ultralight Bosons are Well Motivated DM Candidates!

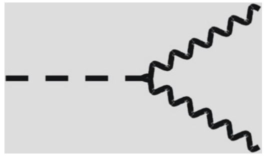
Appear to be dark because of tiny interactions with SM, in particular with photons

Spin-0 Pseudo Goldstone Boson:

- **Tiny couplings to photons** since they are suppressed by inverse power of symmetry breaking scale:

  For a pseudo-scalar (axion or axion-like particle):

$$\mathcal{L} \supset C_{a\gamma} \frac{\alpha}{8\pi} \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} \equiv g_{a\gamma}\, a\, \mathbf{E} \cdot \mathbf{B}$$



  For a scalar (dilaton or dilaton-like particle):

$$\mathcal{L} \supset \frac{d_e}{4\sqrt{2}} \frac{\phi}{M_{\rm P}} F_{\mu\nu} F^{\mu\nu} \equiv g_{\phi\gamma}\, \phi\, \left(\mathbf{E}^2 - \mathbf{B}^2\right)$$

Spin-1 Boson (Dark Photon):

Ultralight Bosons are Well Motivated DM Candidates!

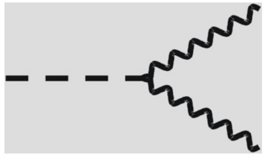
Appear to be dark because of tiny interactions with SM, in particular with photons

Spin-0 Pseudo Goldstone Boson:

- **Tiny couplings to photons** since they are suppressed by inverse power of symmetry breaking scale:

  For a pseudo-scalar (axion or axion-like particle):

$$\mathcal{L} \supset C_{a\gamma} \frac{\alpha}{8\pi} \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} \equiv g_{a\gamma}\, a\, \mathbf{E} \cdot \mathbf{B}$$



  For a scalar (dilaton or dilaton-like particle):

$$\mathcal{L} \supset \frac{d_e}{4\sqrt{2}} \frac{\phi}{M_{\rm P}} F_{\mu\nu} F^{\mu\nu} \equiv g_{\phi\gamma}\, \phi\, \left(\mathbf{E}^2 - \mathbf{B}^2\right)$$

Spin-1 Boson (Dark Photon):

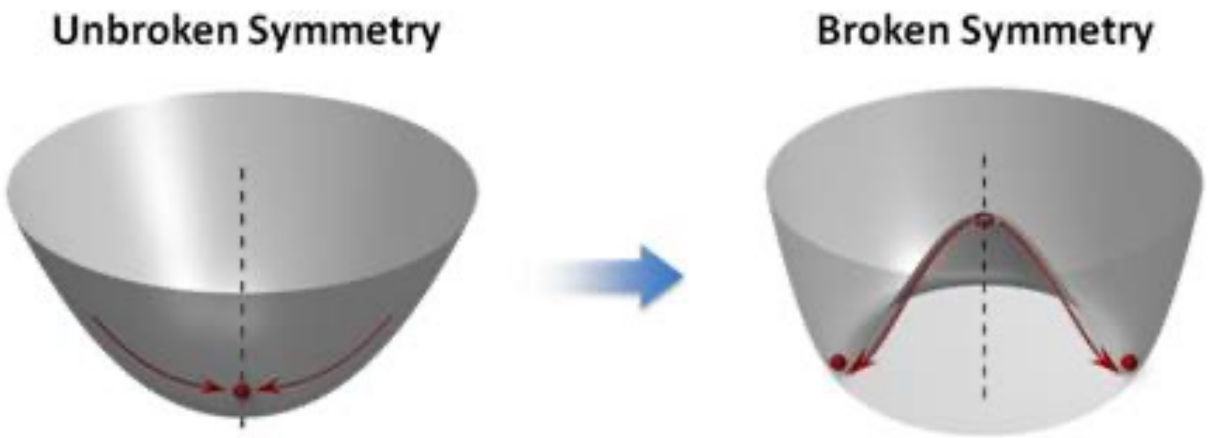
- **Tiny couplings to photons** if the gauge coupling in the dark sector is tiny, such that kinetic mixing tiny:

$$\mathcal{L} \supset -\frac{\chi}{2} F'_{\mu\nu} F^{\mu\nu} \qquad \chi \sim \frac{e\, g_{\rm dark}}{16\pi^2} \ll 1$$

Ultralight Bosons are Well Motivated DM Candidates!

Expectations for axion dark matter

Axion appears as soon as $U(1)_{PQ}$ symmetry is broken. DM density depends on whether PQ symmetry broken before or after inflation



Ultralight Bosons are Well Motivated DM Candidates!

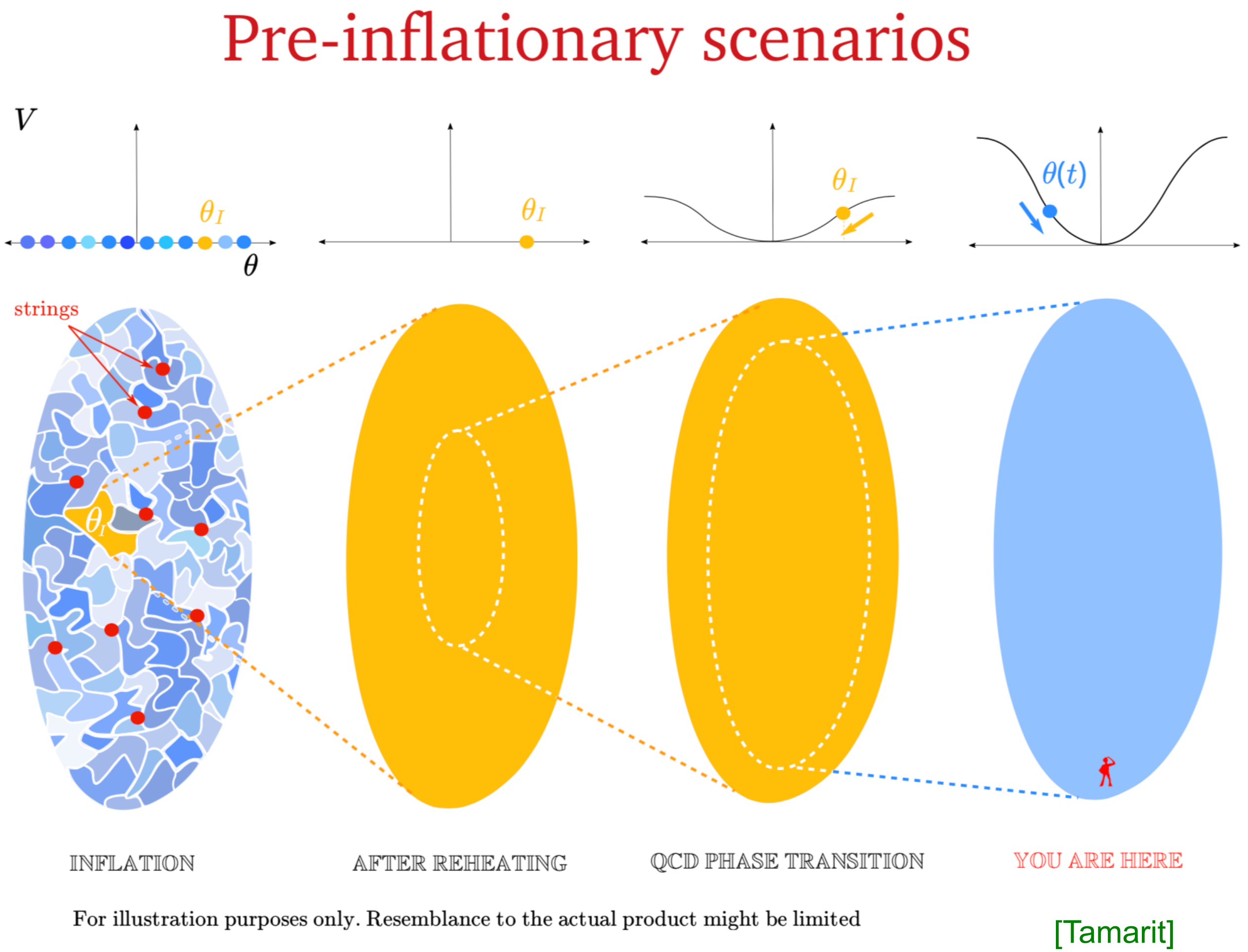
Expectations for axion dark matter

Axion appears as soon as $U(1)_{PQ}$ symmetry is broken. DM density depends on whether PQ symmetry broken before or after inflation

- **Pre-inflationary PQ breaking:** $(f_a > T_{\rm hot})$

  [Preskill,Wise,Wilczek 83; Abbott,Sikivie 83; Dine,Fischler 83,....]

  - Axion DM produced by misalignment mechanism



[Tamarit]

Ultralight Bosons are Well Motivated DM Candidates!

Expectations for axion dark matter

Axion appears as soon as U(1)$_{PQ}$ symmetry is broken. DM density depends on whether PQ symmetry broken before or after inflation

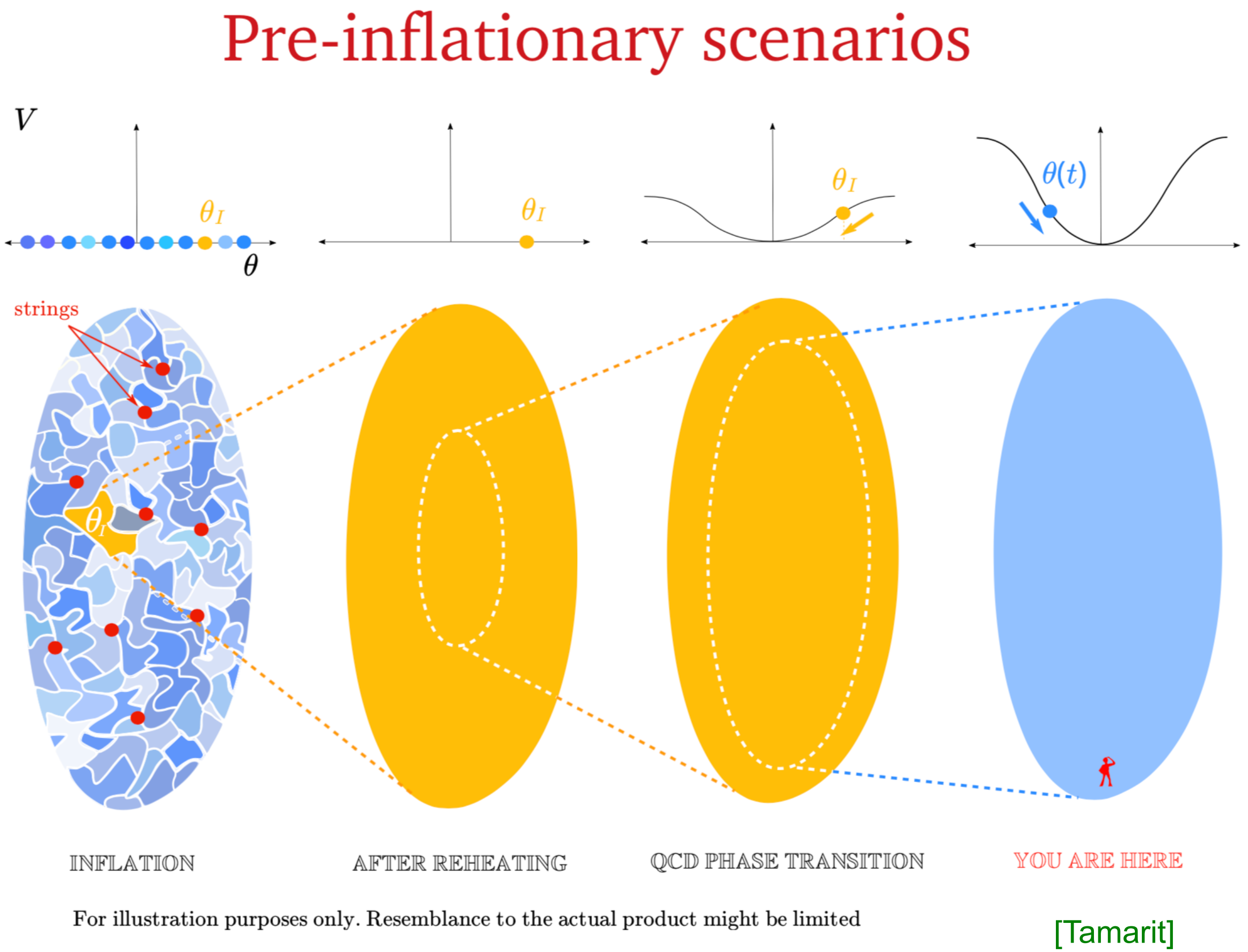
- **Pre-inflationary PQ breaking:** $(f_a > T_{\rm hot})$

  [Preskill,Wise,Wilczek 83; Abbott,Sikivie 83; Dine,Fischler 83,....]

  - Axion DM produced by misalignment mechanism
  - Relic abundance depends both on f_a (resp. m_a) and on initial value of axion field, $\theta_i \equiv a(t_{\rm hot})/f_a$:

$$\Omega_a h^2 \approx 0.12 \left(\frac{f_a}{9\times 10^{11}\ {\rm GeV}}\right)^{1.165} \theta_{\rm i}^2 \simeq 0.12 \left(\frac{6\ \mu{\rm eV}}{m_a}\right)^{1.165} \theta_i^2$$

[Borsanyi et al., Nature 539 (2016) 7627, 69-71]



[Tamarit]

Ultralight Bosons are Well Motivated DM Candidates

Expectations for axion dark matter

Axion appears as soon as $U(1)_{PQ}$ symmetry is broken. DM density depends on whether PQ symmetry broken before or after inflation

- **Pre-inflationary PQ breaking:** $(f_a > T_{\rm hot})$

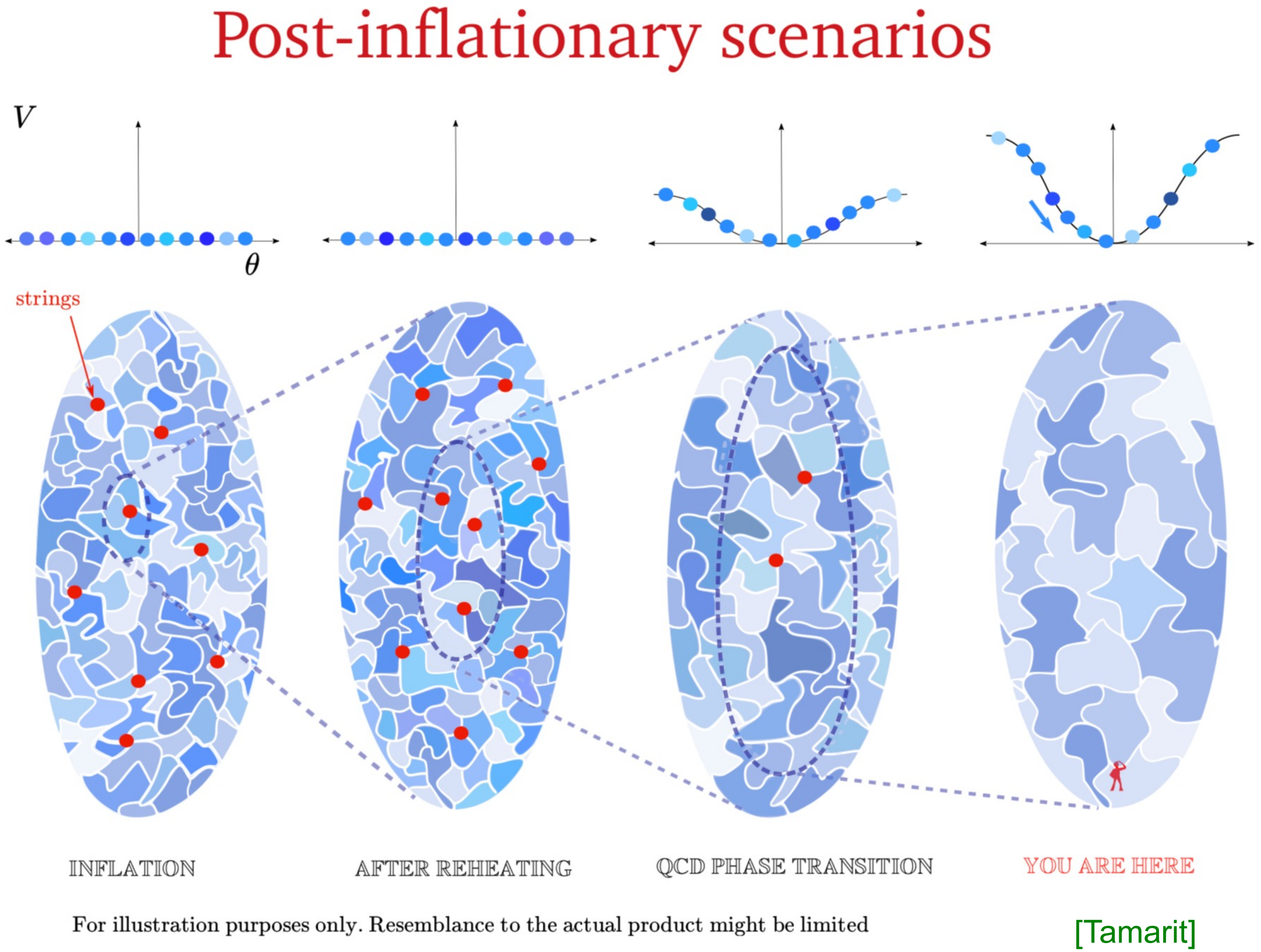
  [Preskill,Wise,Wilczek 83; Abbott,Sikivie 83; Dine,Fischler 83,....]

  - Axion DM produced by misalignment mechanism
  - Relic abundance depends both on f_a (resp. m_a) and on initial value of axion field, $\theta_i \equiv a(t_{\rm hot})/f_a$:

$$\Omega_a h^2 \approx 0.12 \left(\frac{f_a}{9\times 10^{11}\ {\rm GeV}}\right)^{1.165} \theta_{\rm i}^2 \simeq 0.12 \left(\frac{6\ \mu{\rm eV}}{m_a}\right)^{1.165} \theta_i^2$$

[Borsanyi et al., Nature 539 (2016) 7627, 69-71]

- **Post-inflationary PQ breaking:** $(f_a < T_{\rm hot})$
  - Axion DM produced also by string and domain wall decay



[Tamarit]

Ultralight Bosons are Well Motivated DM Candidates!

Expectations for axion dark matter

Axion appears as soon as $U(1)_{PQ}$ symmetry is broken. DM density depends on whether PQ symmetry broken before or after inflation

- **Pre-inflationary PQ breaking:** $(f_a > T_{\rm hot})$

  [Preskill,Wise,Wilczek 83; Abbott,Sikivie 83; Dine,Fischler 83,....]

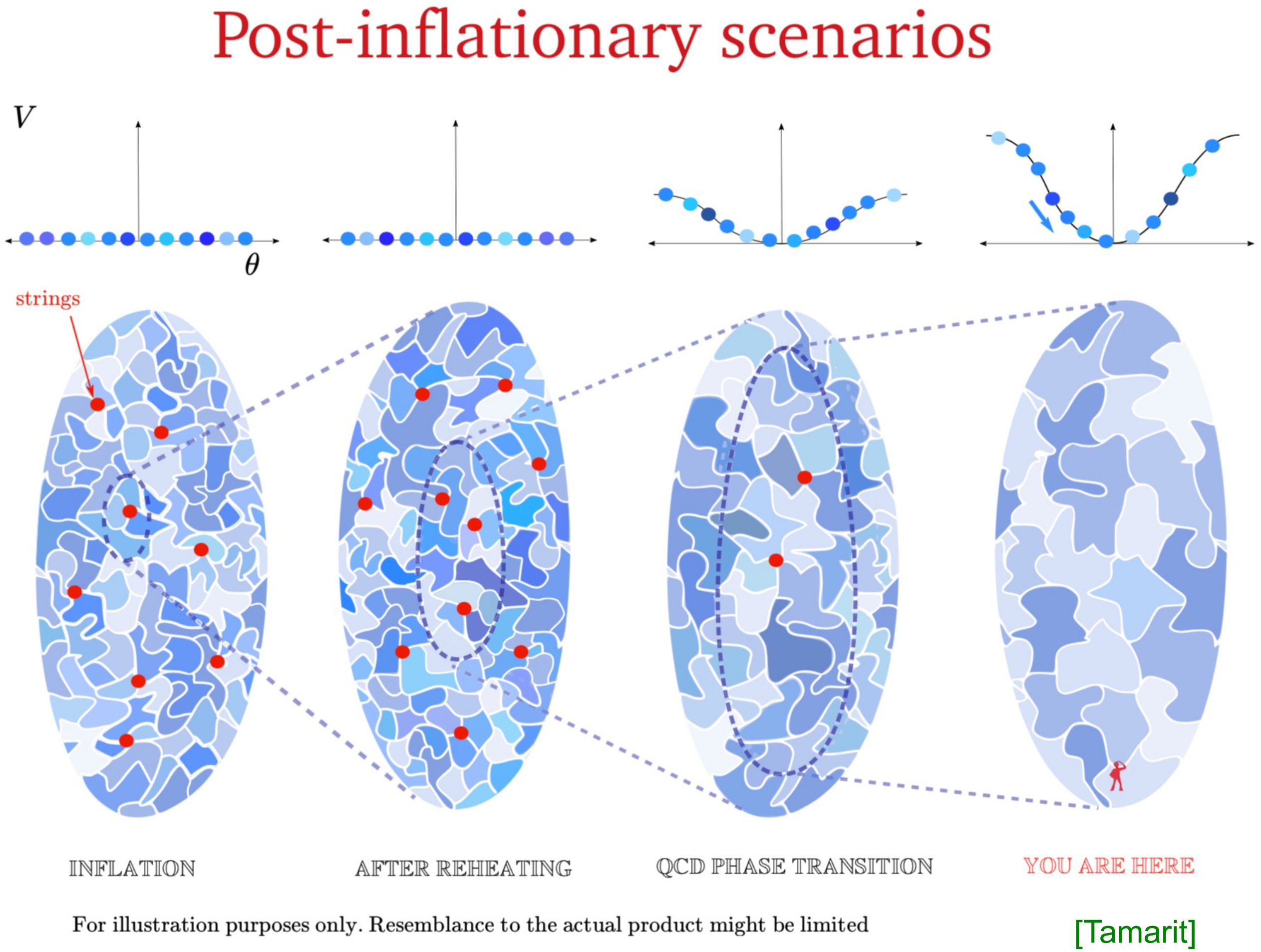
  - Axion DM produced by misalignment mechanism
  - Relic abundance depends both on f_a (resp. m_a) and on initial value of axion field, $\theta_i \equiv a(t_{\rm hot})/f_a$:

$$\Omega_a h^2 \approx 0.12 \left(\frac{f_a}{9\times 10^{11}\ {\rm GeV}}\right)^{1.165} \theta_{\rm i}^2 \simeq 0.12 \left(\frac{6\ \mu{\rm eV}}{m_a}\right)^{1.165} \theta_i^2$$

[Borsanyi et al., Nature 539 (2016) 7627, 69-71]

- **Post-inflationary PQ breaking:** $(f_a < T_{\rm hot})$
  - Axion DM produced also by string and domain wall decay
    - ➢ Strict lower bound (too much DM): $m_a > 28(2)\ \mu{\rm eV}$

      [Borsanyi et al., Nature 539 (2016) 7627, 69-71]
    - ➢ Axion DM mass range model-dependent and computational challenging
    - ➢ Formation of compact DM objects ("miniclusters") leads to increased theoretical uncertainty in axion DM density in our location in the Milky Way

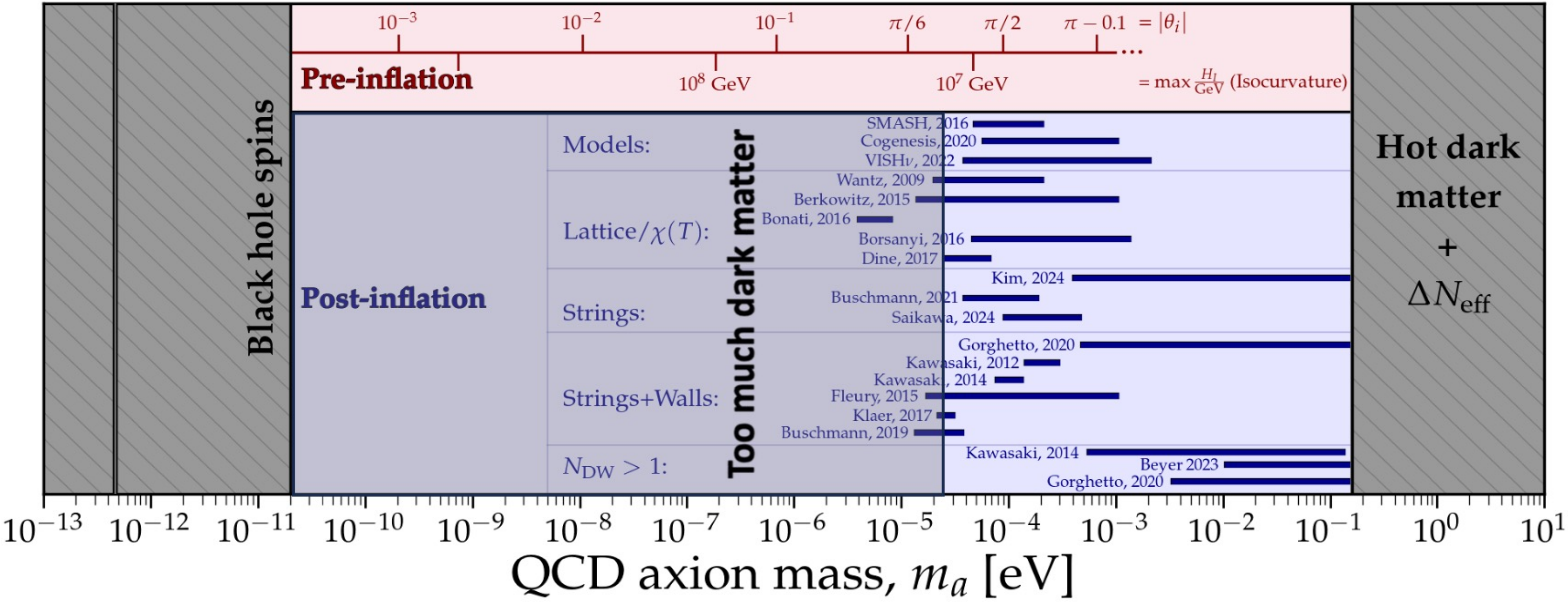


[Tamarit]

Ultralight Bosons are Well Motivated DM Candidates!

Expectations for axion dark matter

Axion dark matter mass predictions:



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

Ultralight Bosons are Well Motivated DM Candidates!

Expectations for dark photon dark matter

Ultralight Bosons are Well Motivated DM Candidates!

Expectations for dark photon dark matter

Various dark photon dark matter production mechanisms:

Ultralight Bosons are Well Motivated DM Candidates!

Expectations for dark photon dark matter

Various dark photon dark matter production mechanisms:

- Vector misalignment (requires finetuning of initial value or non-minimal coupling to gravity)
  [Nelson,Scholtz, 1105.2812;
  Arias,Cadamuro,Goodsell,Jaeckel,Redondo,AR, 1201.5902]

Ultralight Bosons are Well Motivated DM Candidates!

Expectations for dark photon dark matter

Various dark photon dark matter production mechanisms:

- Vector misalignment (requires finetuning of initial value or non-minimal coupling to gravity)
  [Nelson,Scholtz, 1105.2812;
  Arias,Cadamuro,Goodsell,Jaeckel,Redondo,AR, 1201.5902]
- Inflationary production
  [Graham,Mardon,Rajendran, 1504.02102]

Ultralight Bosons are Well Motivated DM Candidates!

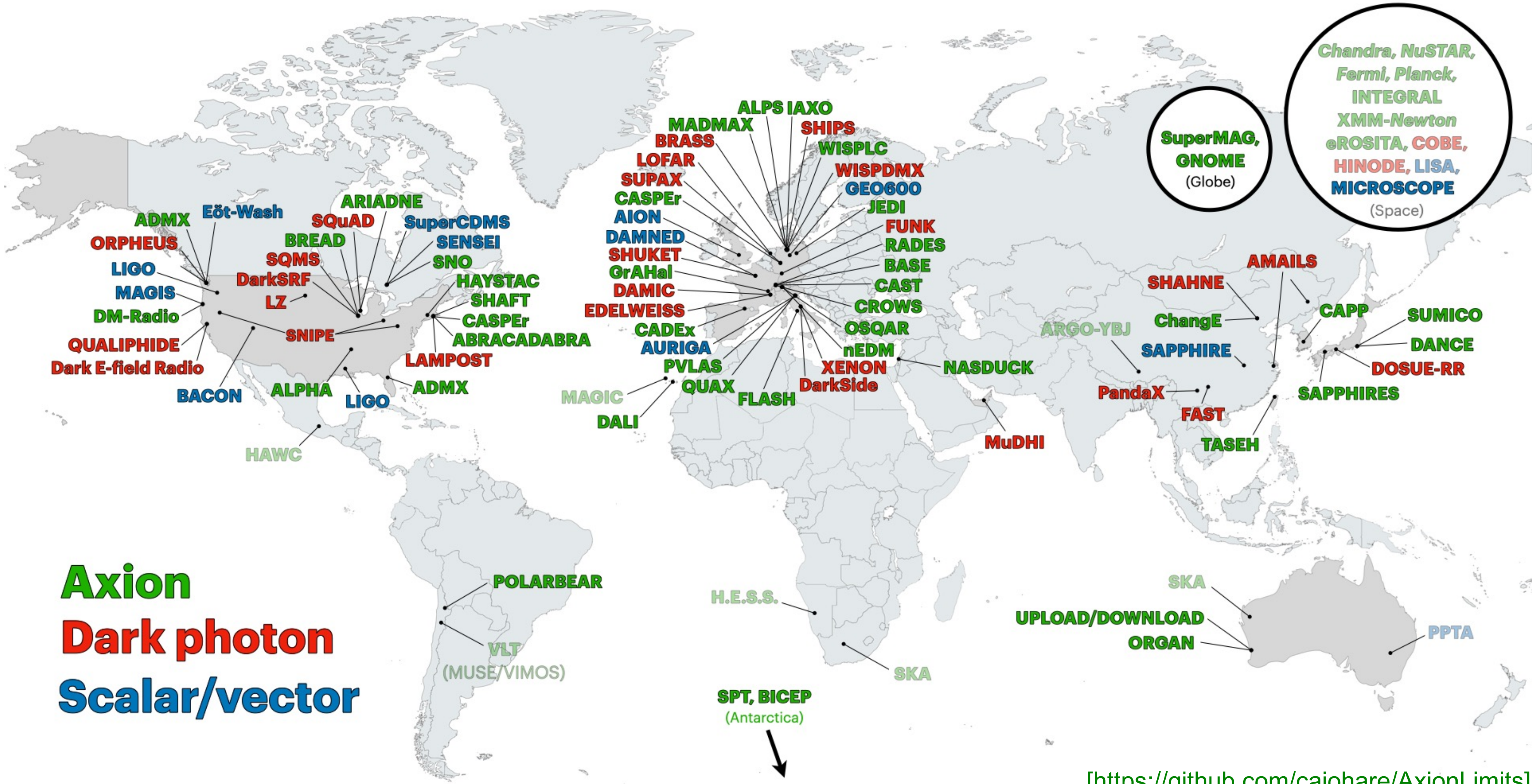
Expectations for dark photon dark matter

Various dark photon dark matter production mechanisms:

- Vector misalignment (requires finetuning of initial value or non-minimal coupling to gravity)
  [Nelson,Scholtz, 1105.2812;
  Arias,Cadamuro,Goodsell,Jaeckel,Redondo,AR, 1201.5902]
- Inflationary production
  [Graham,Mardon,Rajendran, 1504.02102]
- Production via an oscillating ALP
  [Agrawal,Kitajima,Reece,Sekiguchi,Takahashi, 1810.07188]

Ultralight Bosons Can Be Searched For in the Laboratory!

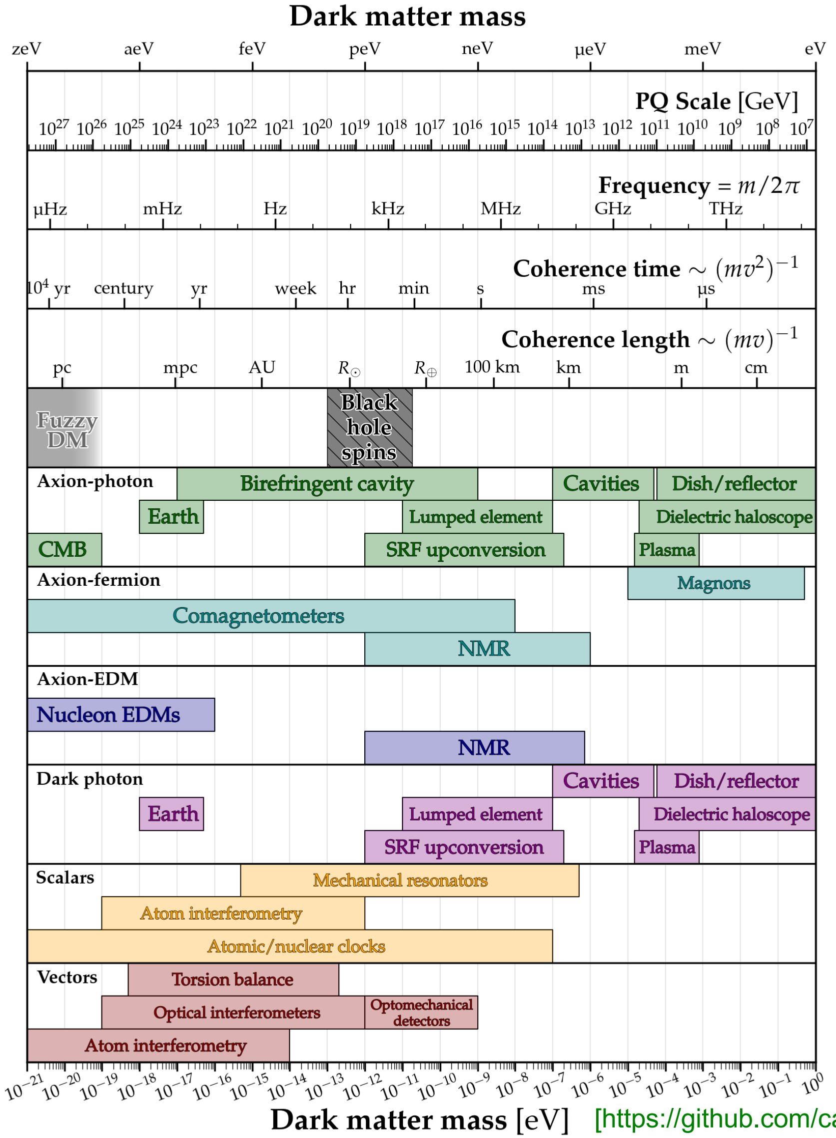
Enormous number of ultralight boson experiments worldwide



[https://github.com/cajohare/AxionLimits]

Ultralight Bosons Can Be Searched For in the Laboratory!

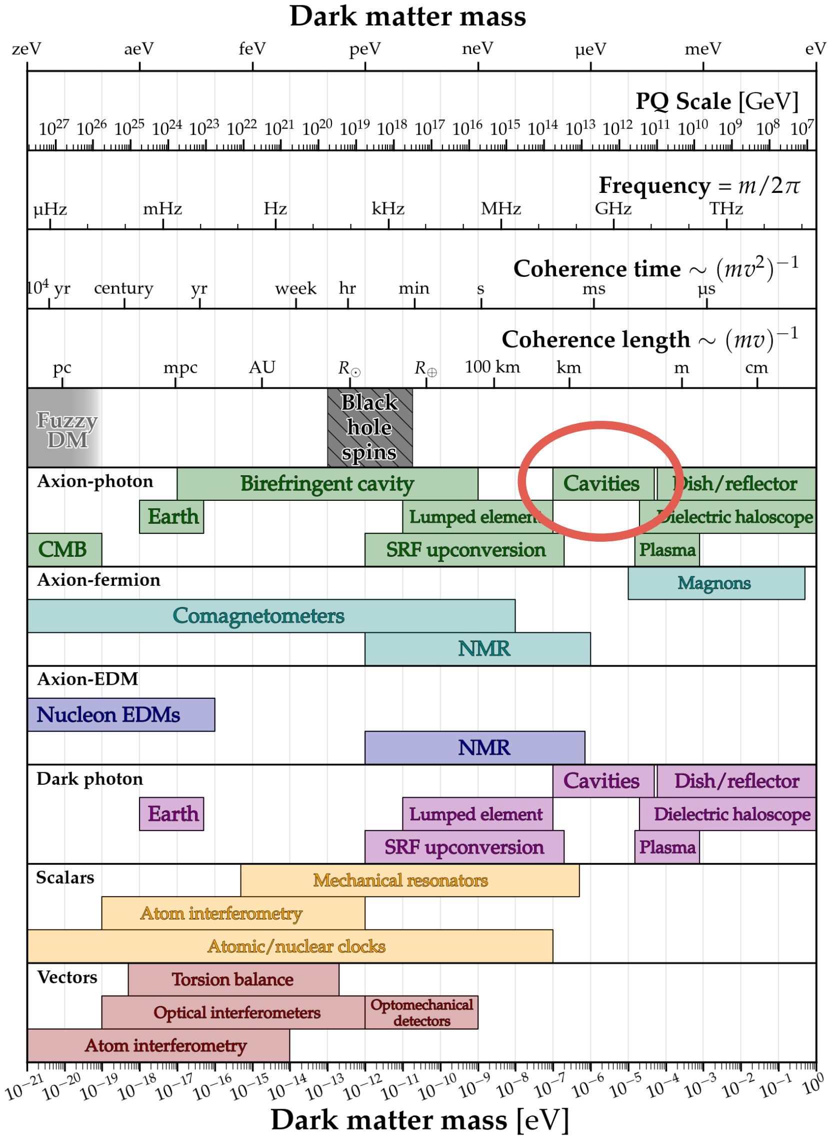
Various experimental techniques to search for ultralight bosonic dark matter

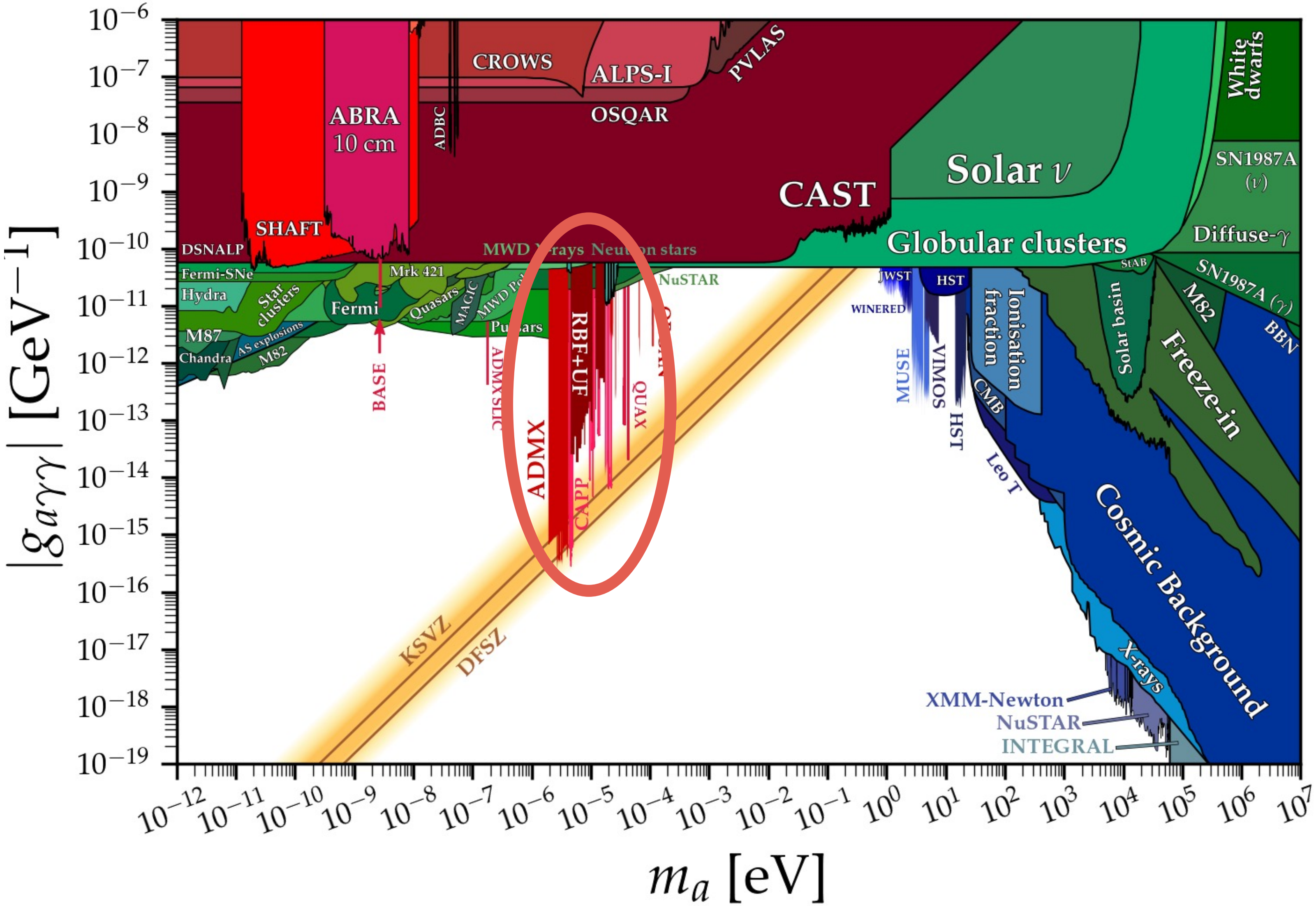


[https://github.com/cajohare/AxionLimits]

Ultralight Bosons Can Be Searched For in the Laboratory!

Pseudo-scalar (axion, ALP, ...) DM searches (current status)

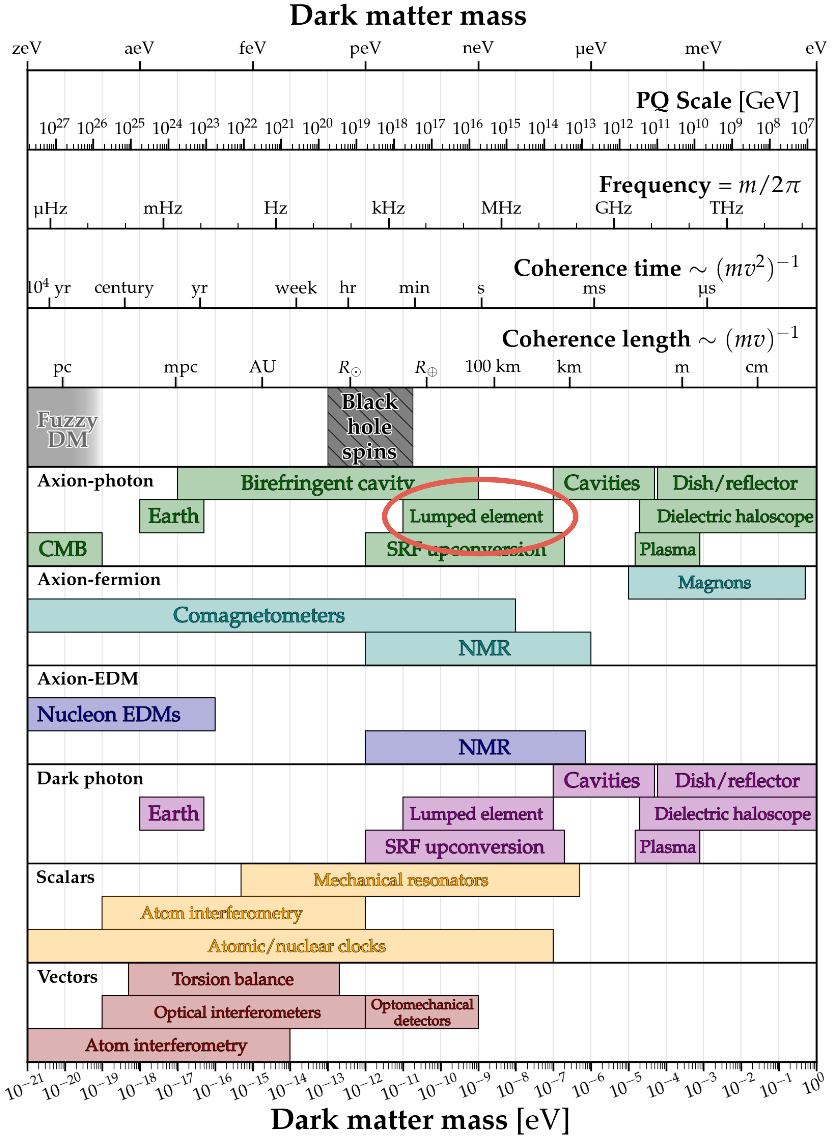


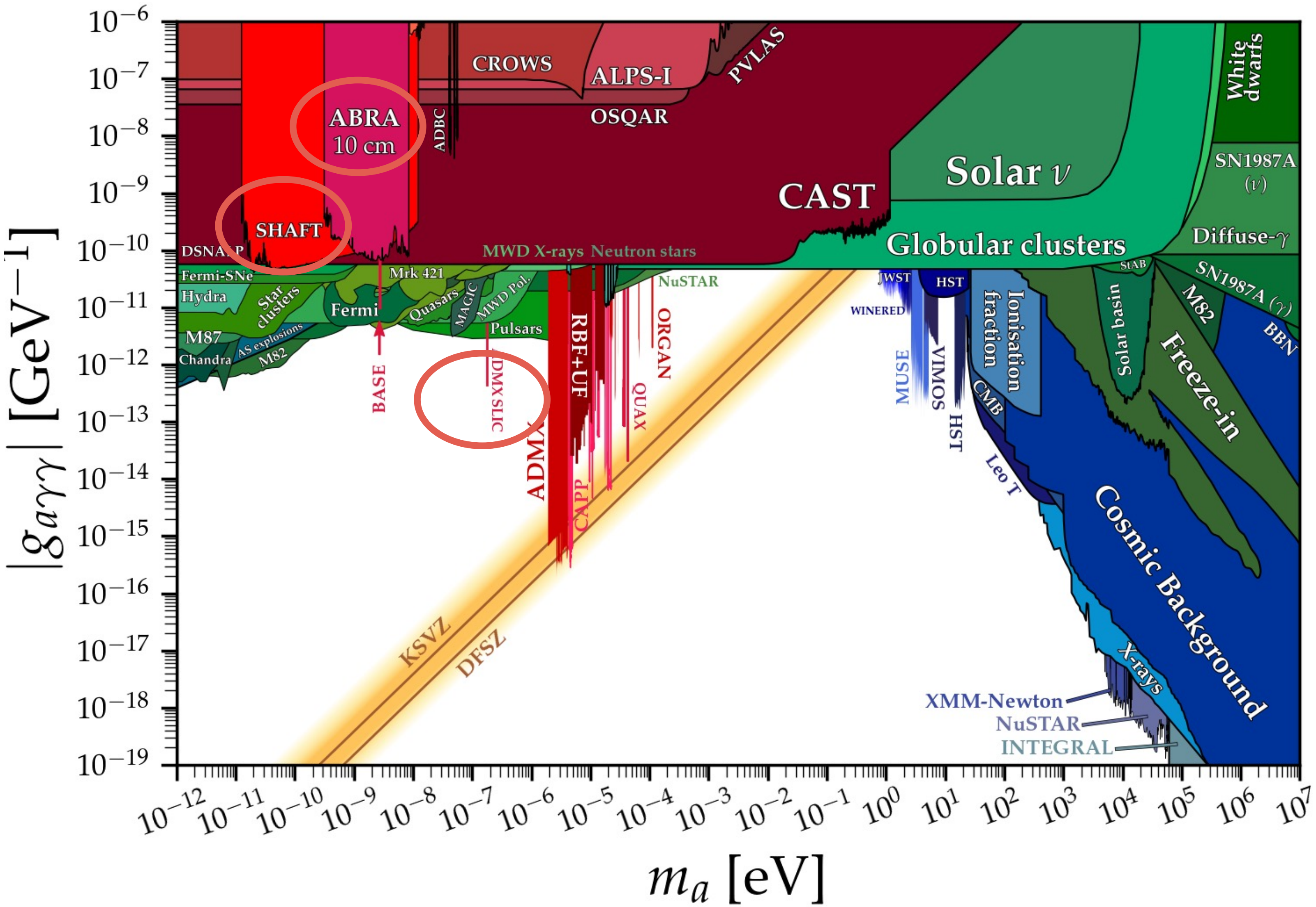


[https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/AxionPhoton.png]

Ultralight Bosons Can Be Searched For in the Laboratory!

Pseudo-scalar (axion, ALP, ...) DM searches (current status)

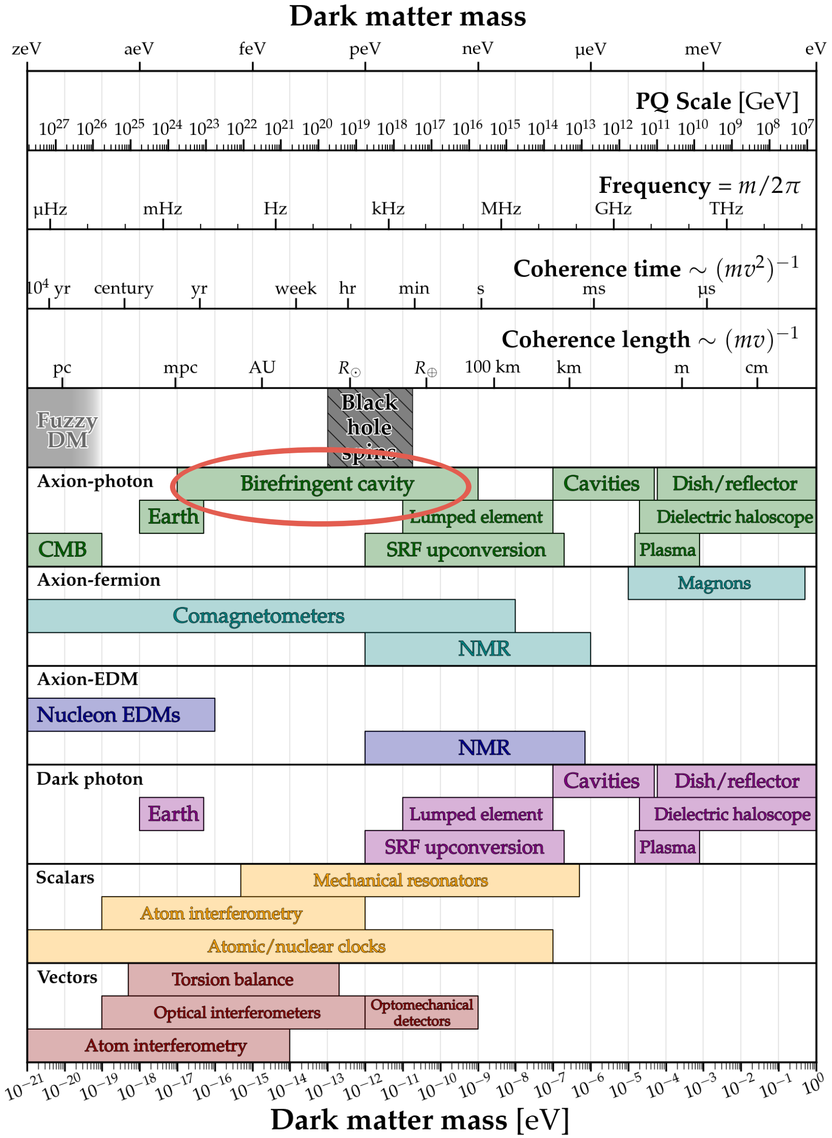


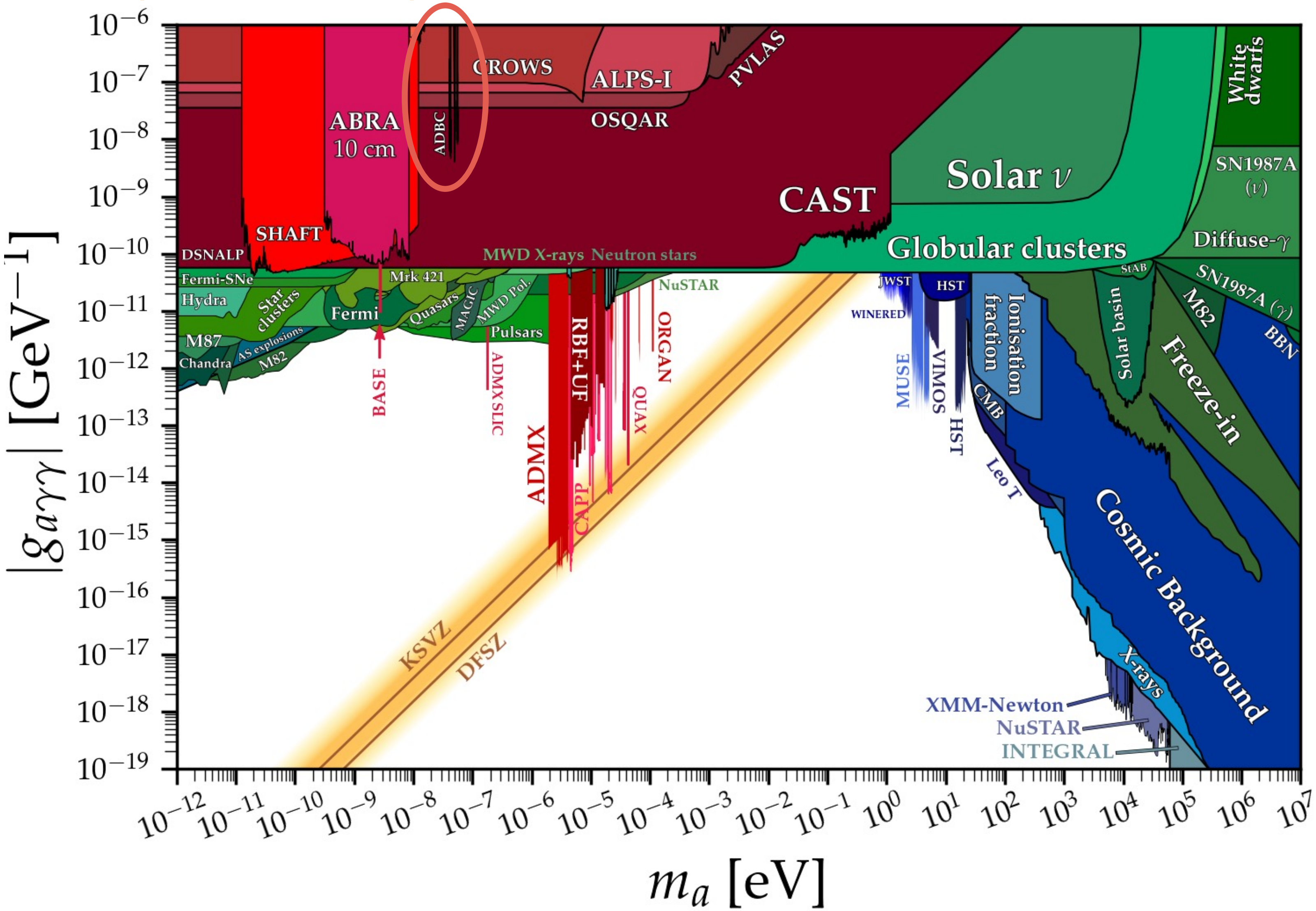


[https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/AxionPhoton.png]

Ultralight Bosons Can Be Searched For in the Laboratory!

Pseudo-scalar (axion, ALP, ...) DM searches (current status)

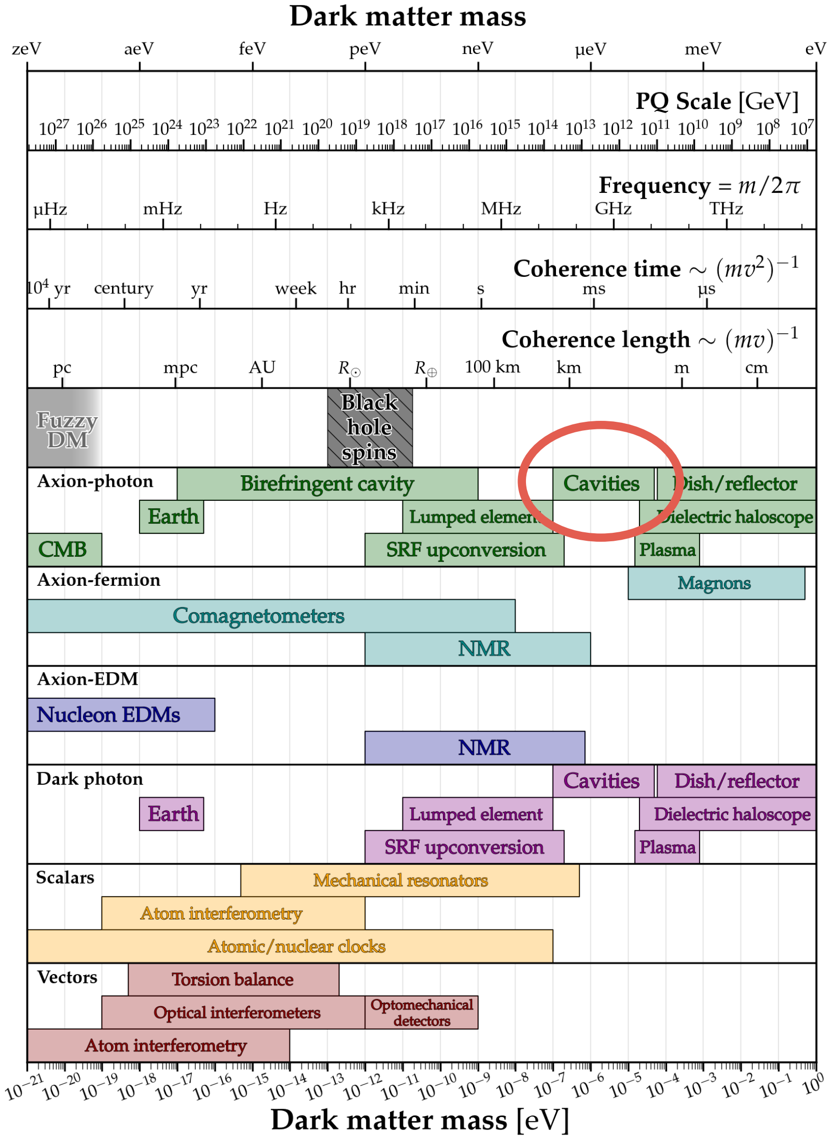


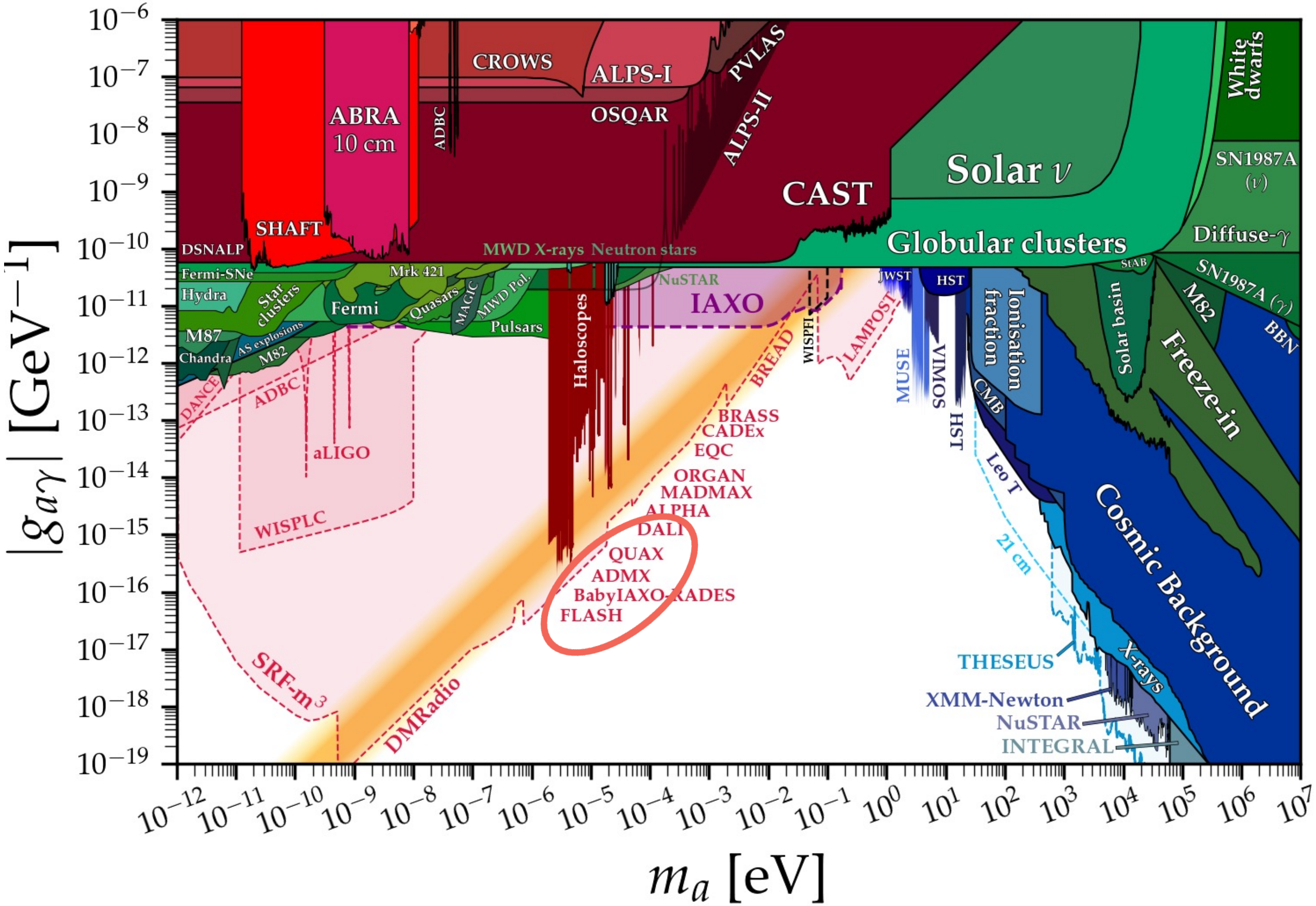


[https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/AxionPhoton.png]

Ultralight Bosons Can Be Searched For in the Laboratory!

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

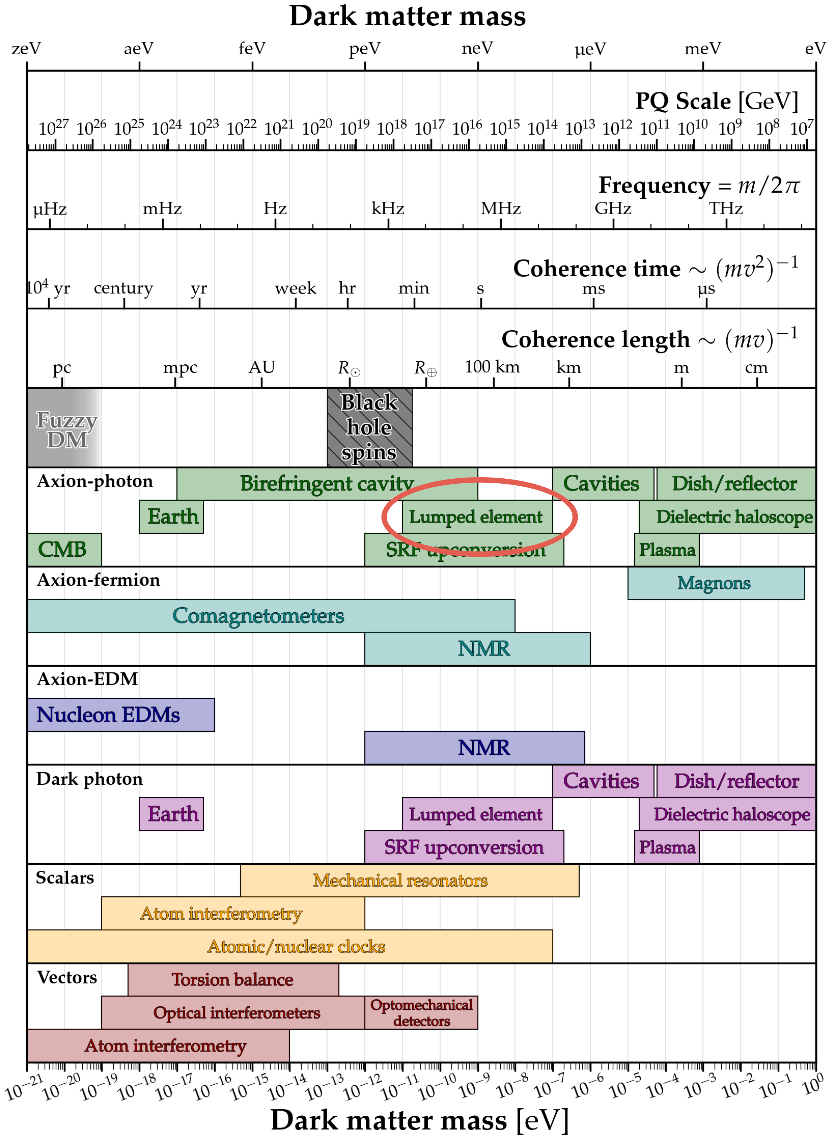


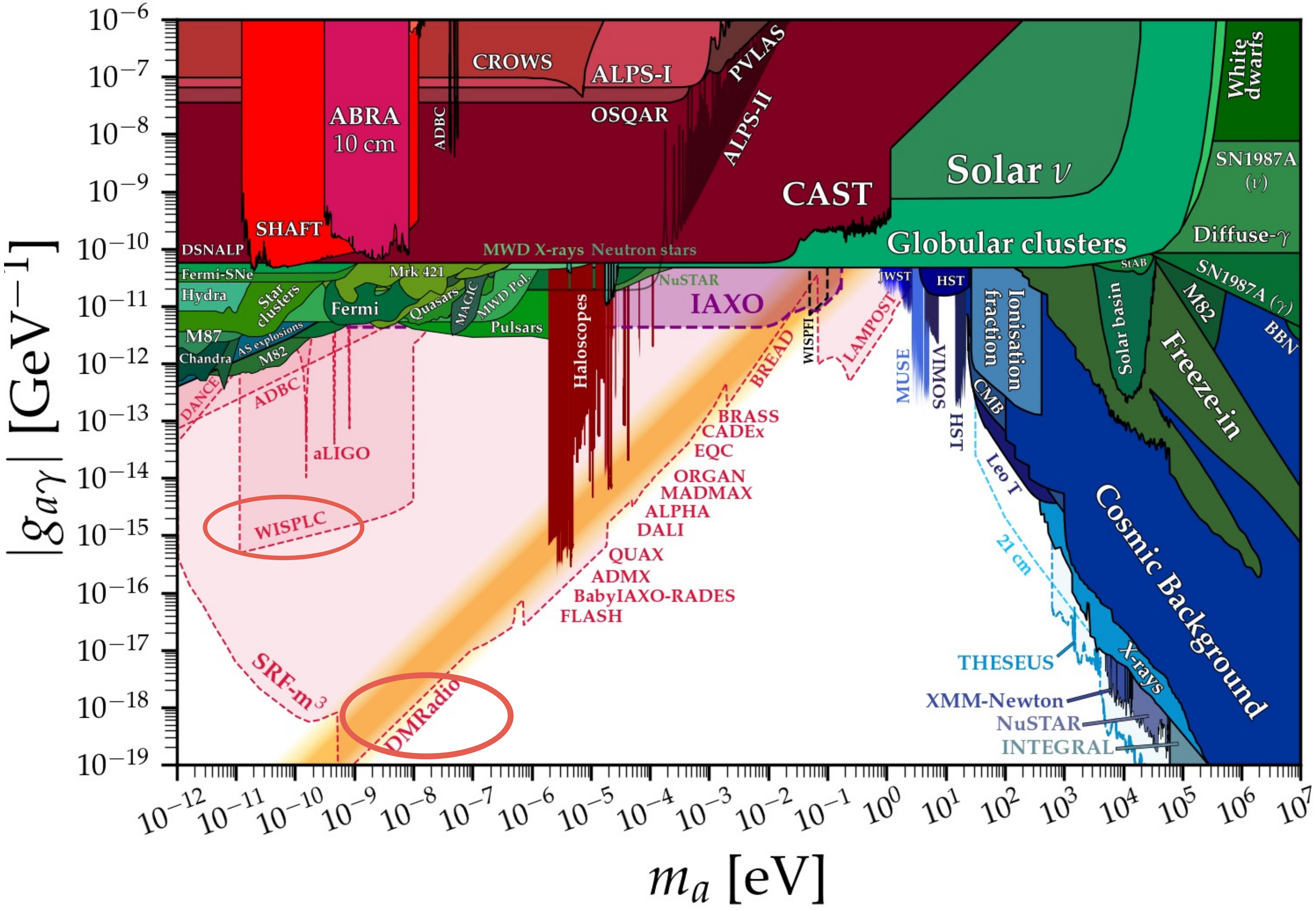


[https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/AxionPhoton_with_Projections.png]

Ultralight Bosons Can Be Searched For in the Laboratory!

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

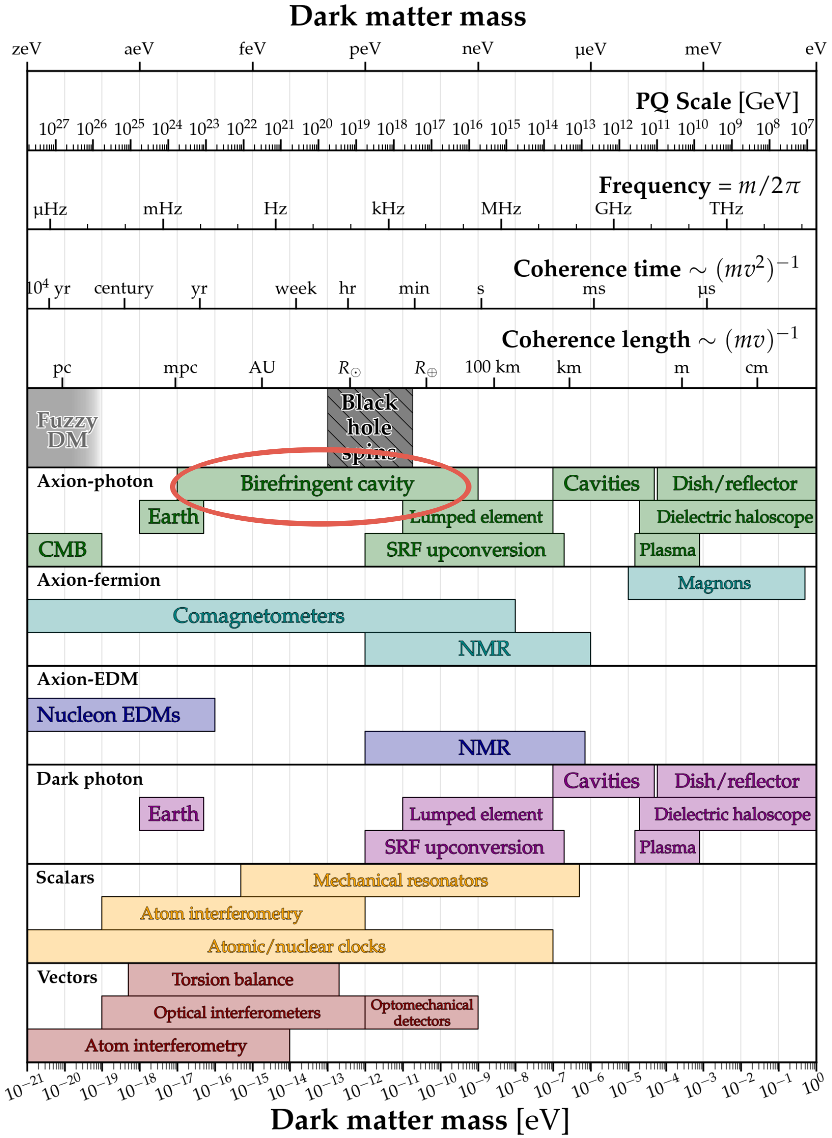


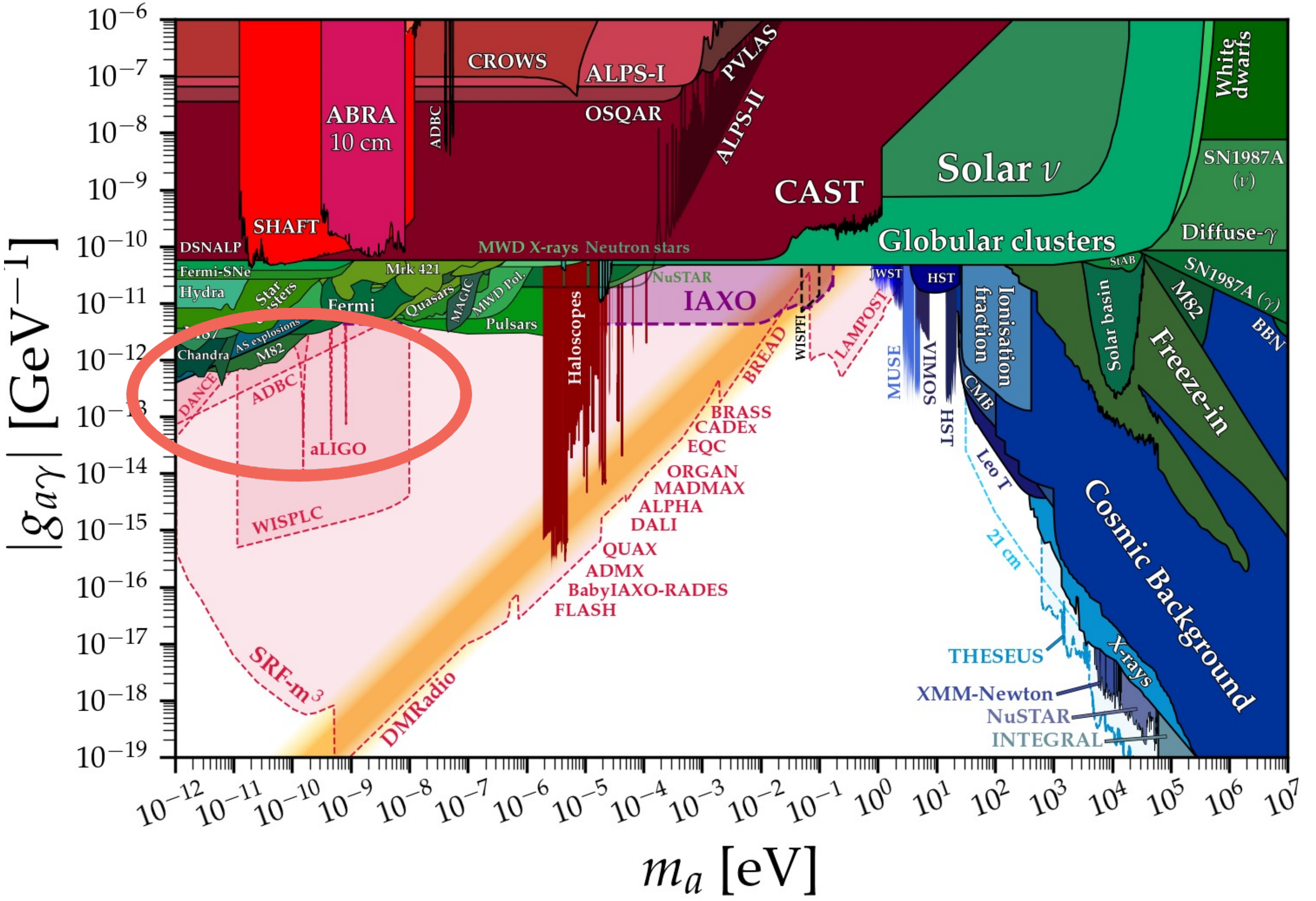


[https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/AxionPhoton_with_Projections.png]

Ultralight Bosons Can Be Searched For in the Laboratory!

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

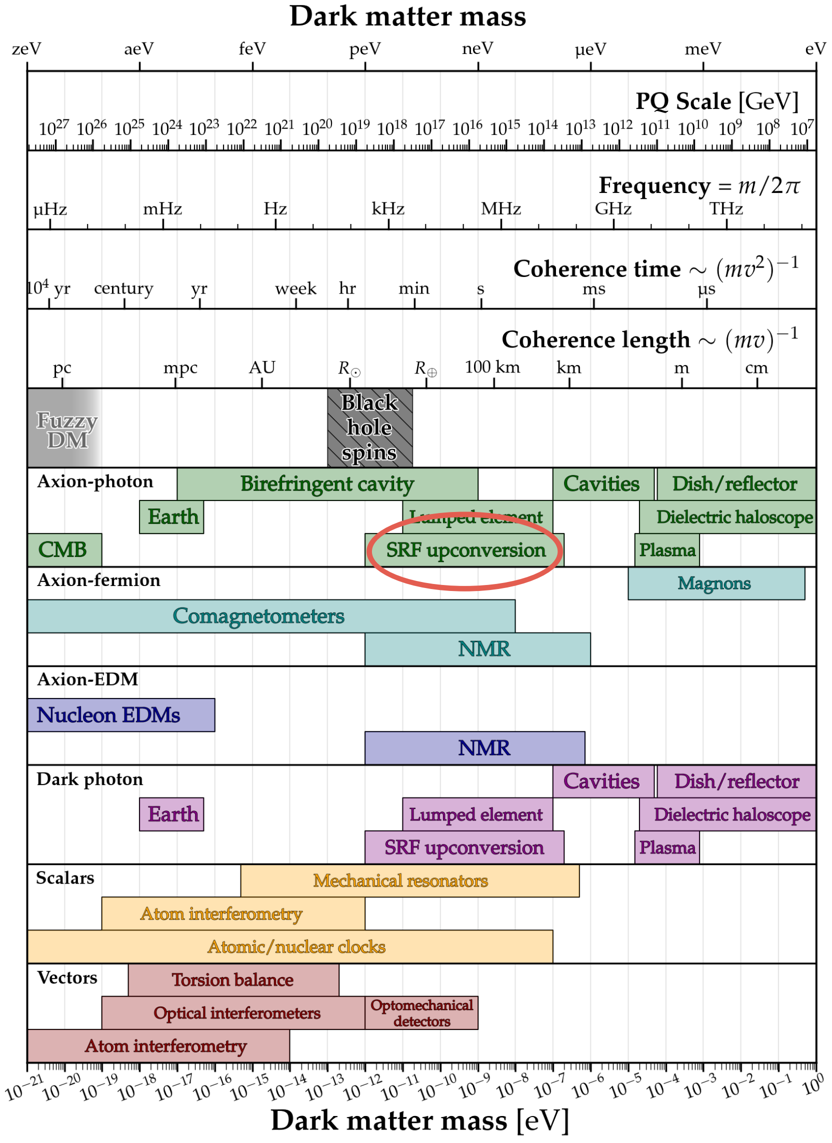


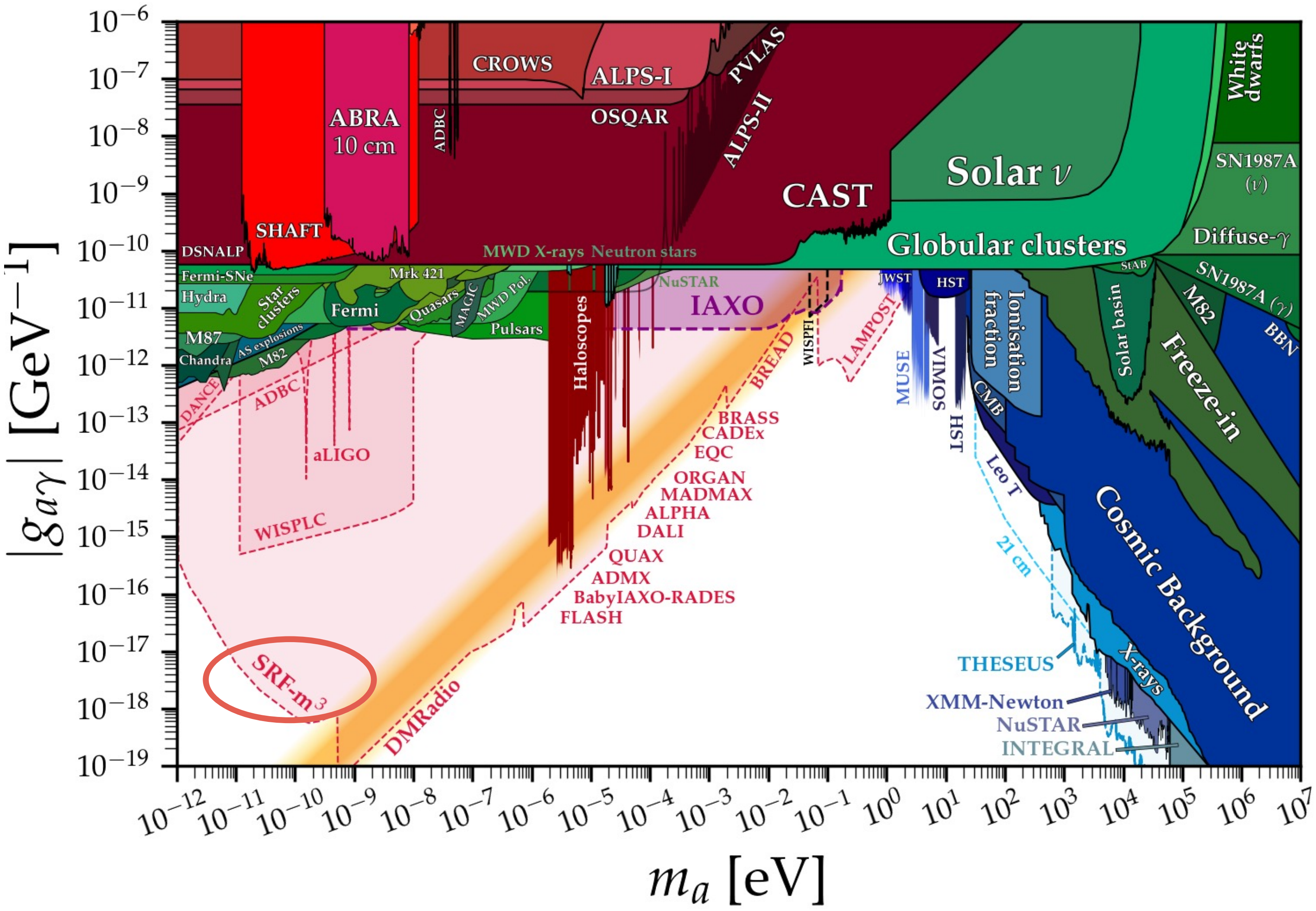


[https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/AxionPhoton_with_Projections.png]

Ultralight Bosons Can Be Searched For in the Laboratory!

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

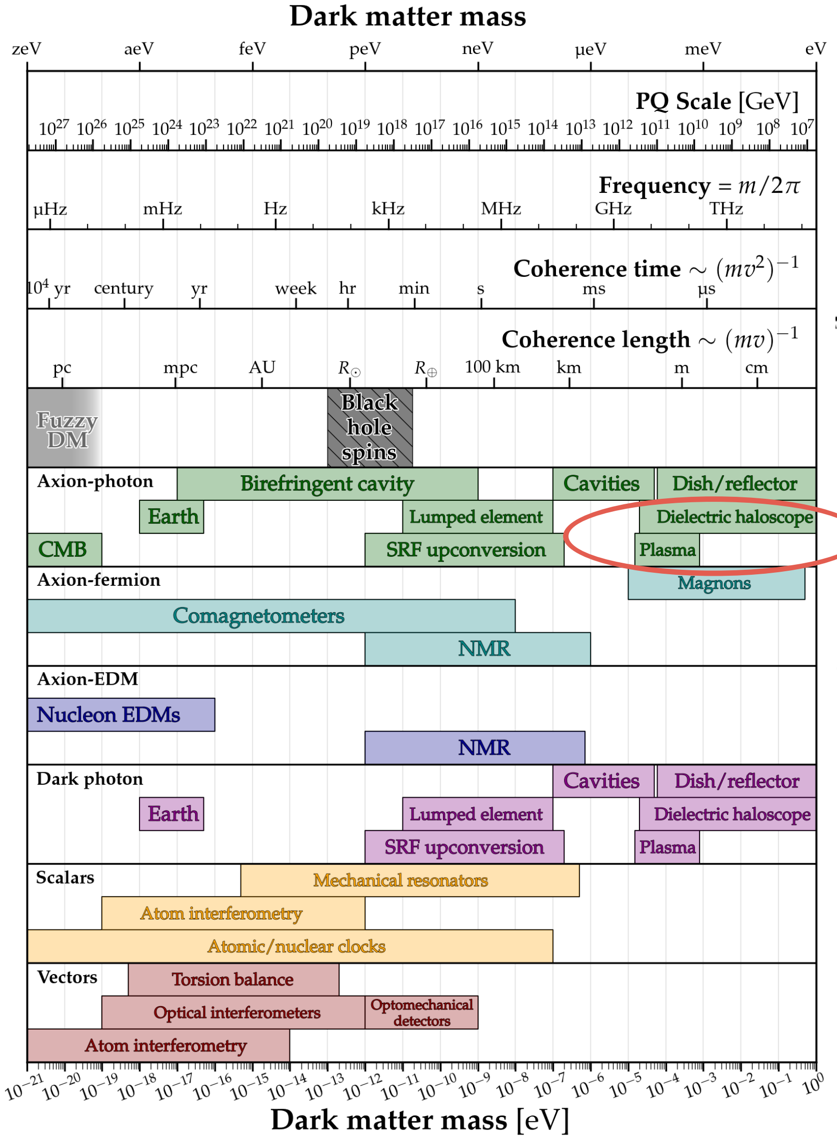


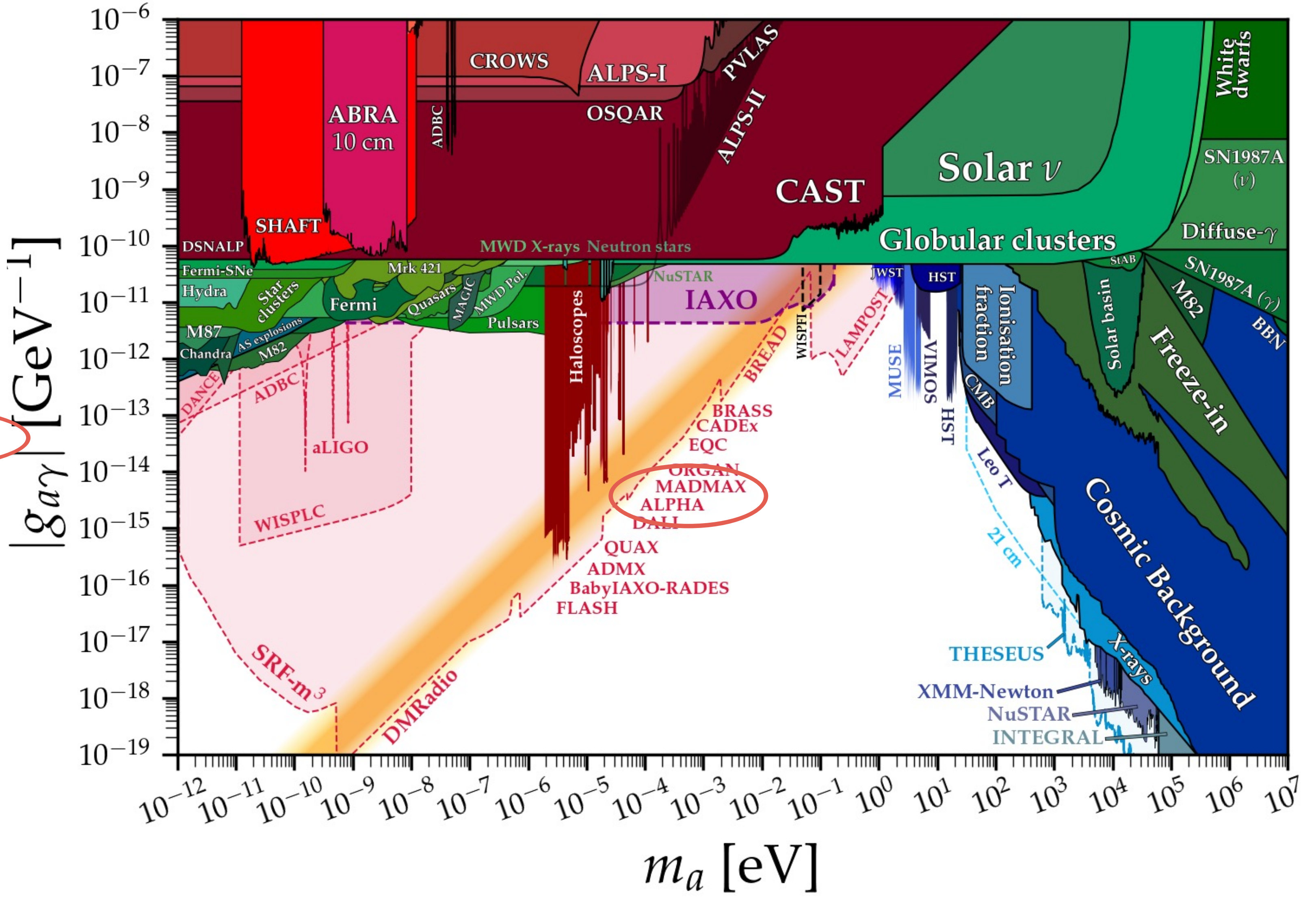


[https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/AxionPhoton_with_Projections.png]

Ultralight Bosons Can Be Searched For in the Laboratory!

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

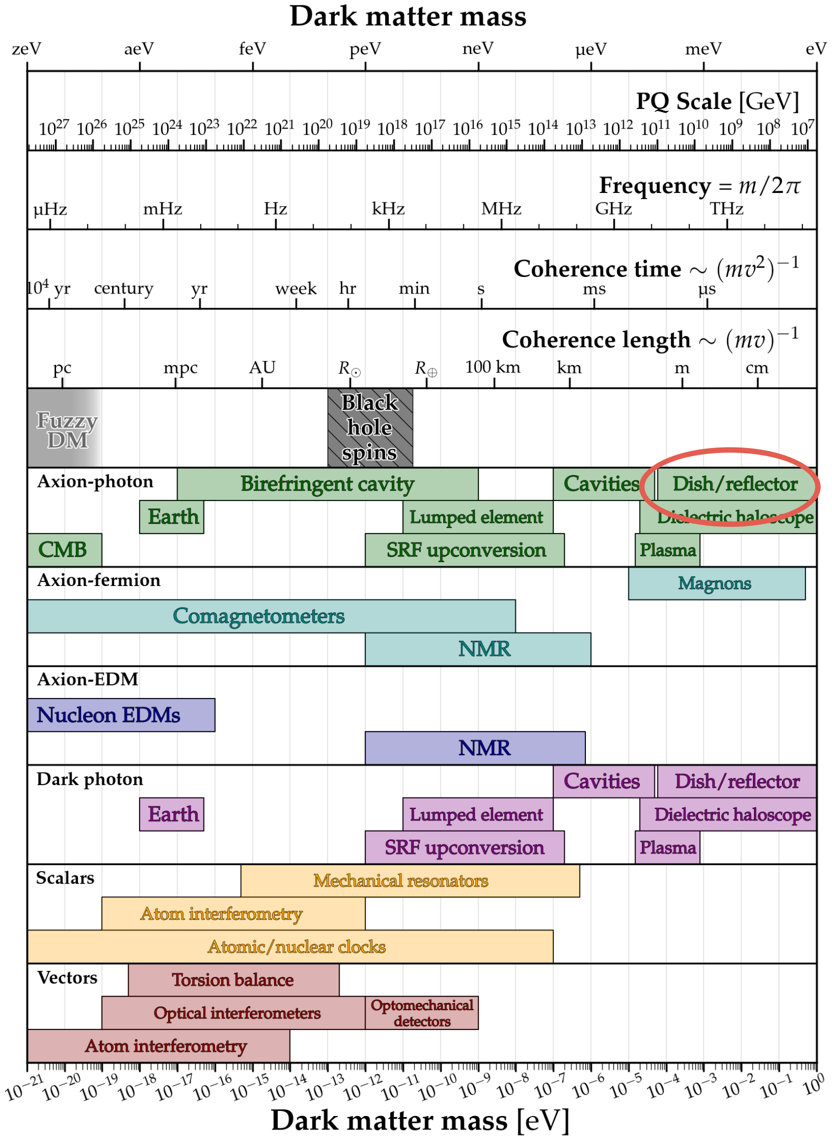


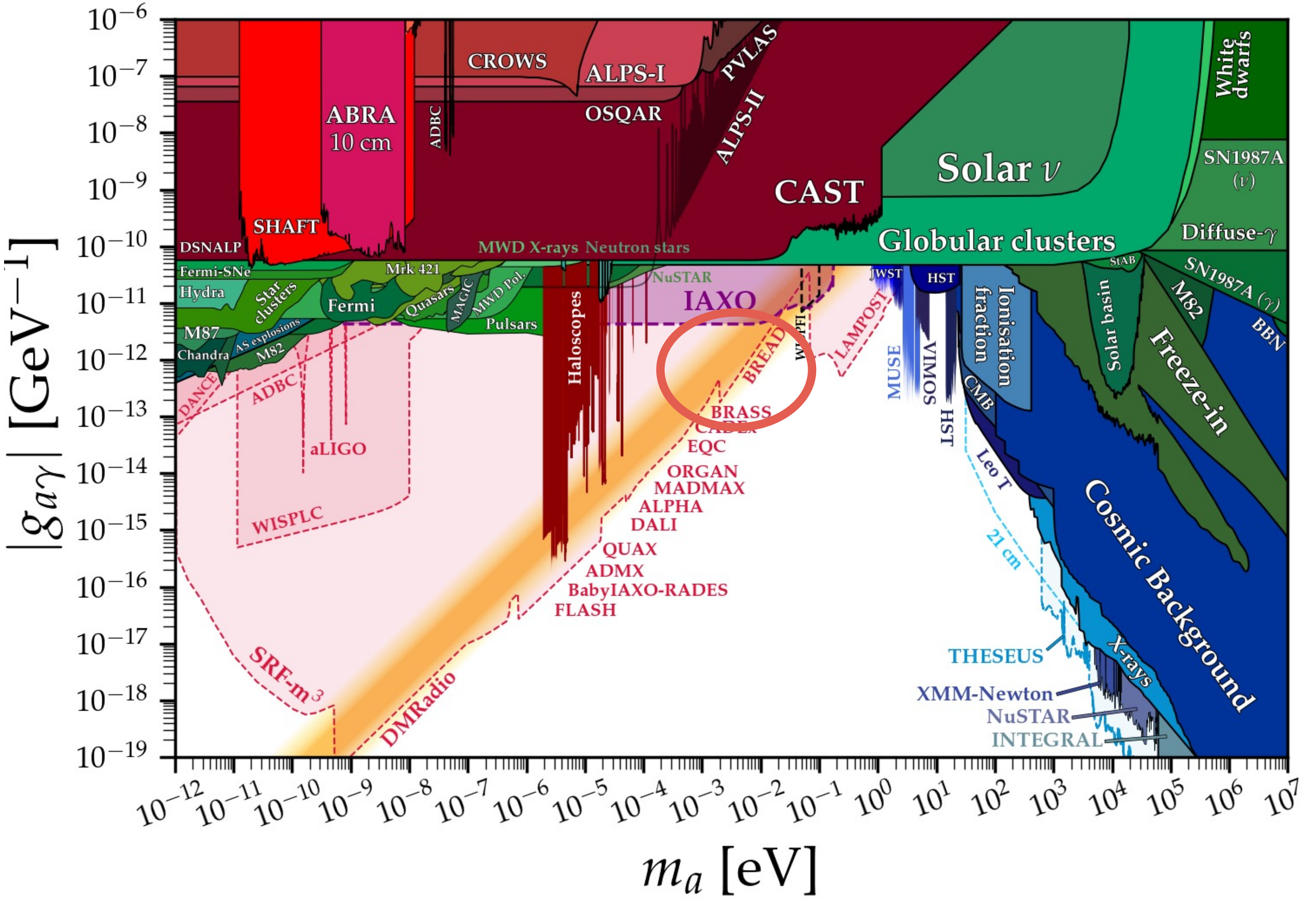


[https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/AxionPhoton_with_Projections.png]

Ultralight Bosons Can Be Searched For in the Laboratory!

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

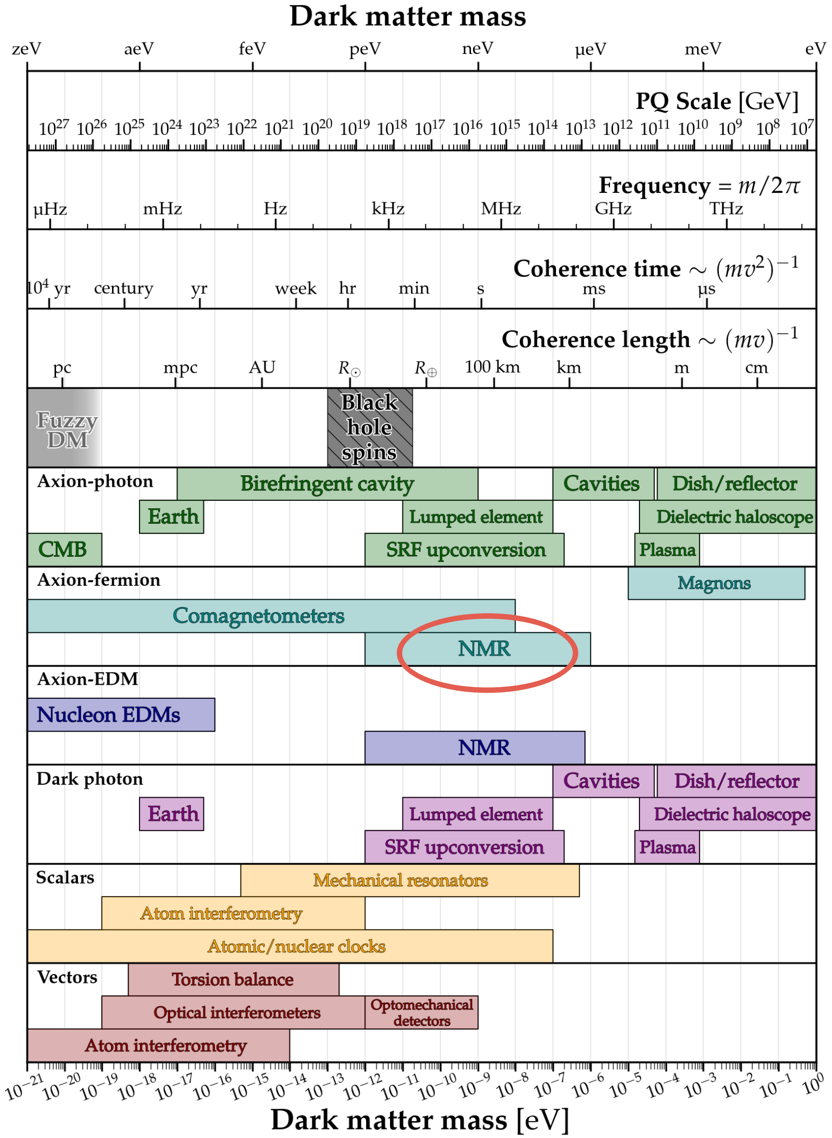


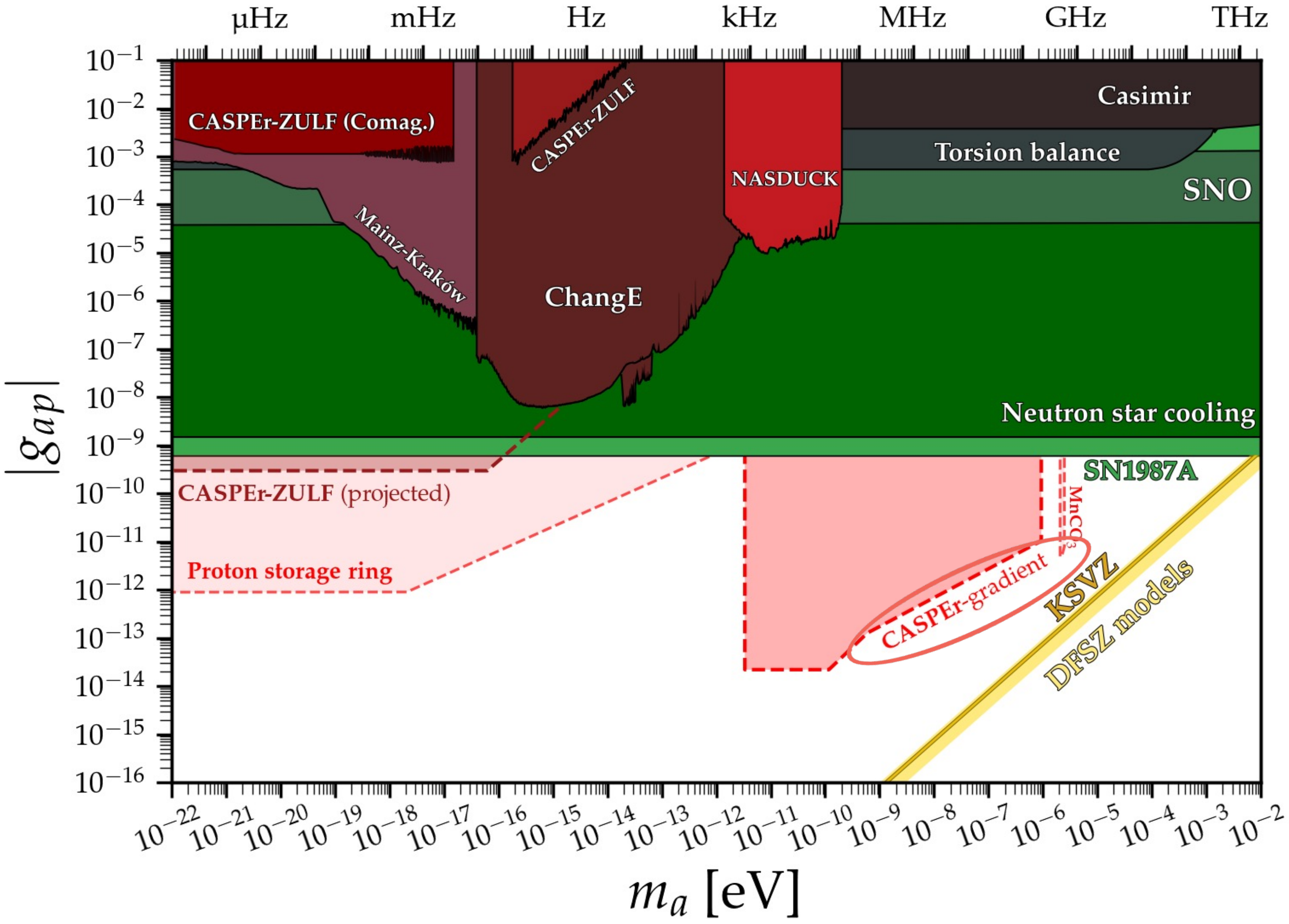


[https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/AxionPhoton_with_Projections.png]

Ultralight Bosons Can Be Searched For in the Laboratory!

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

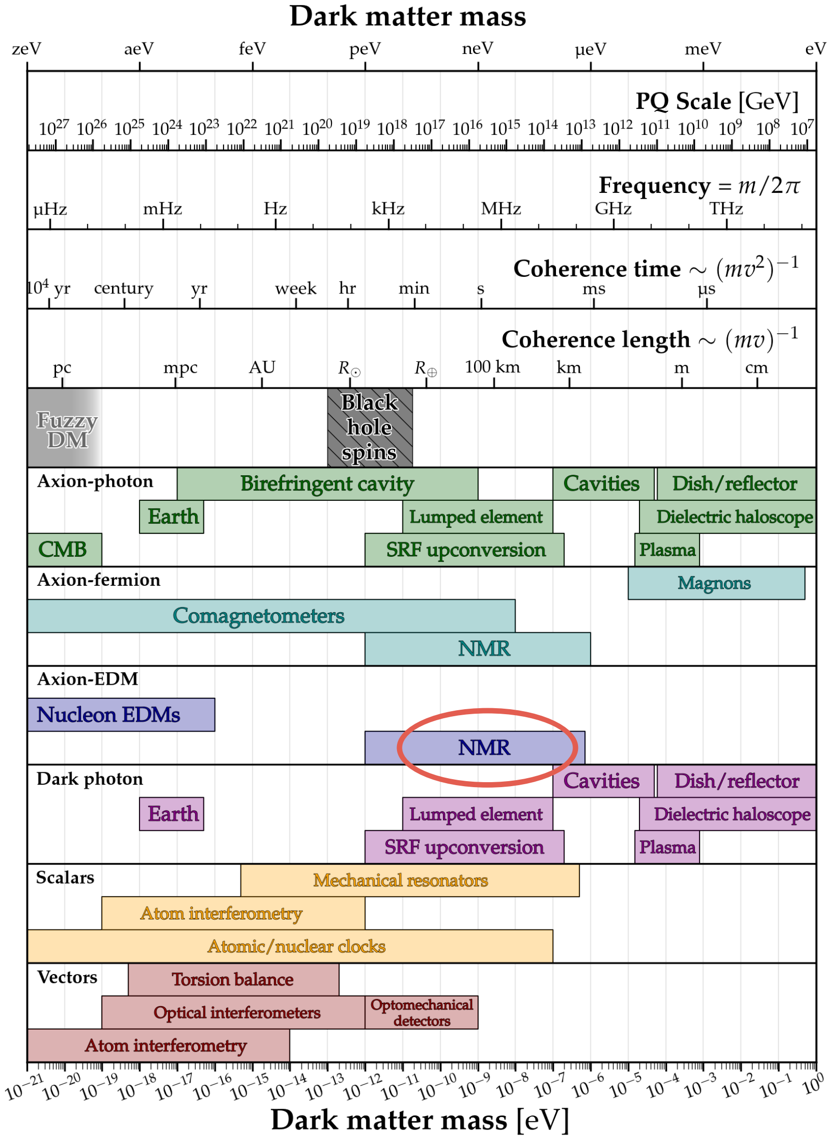


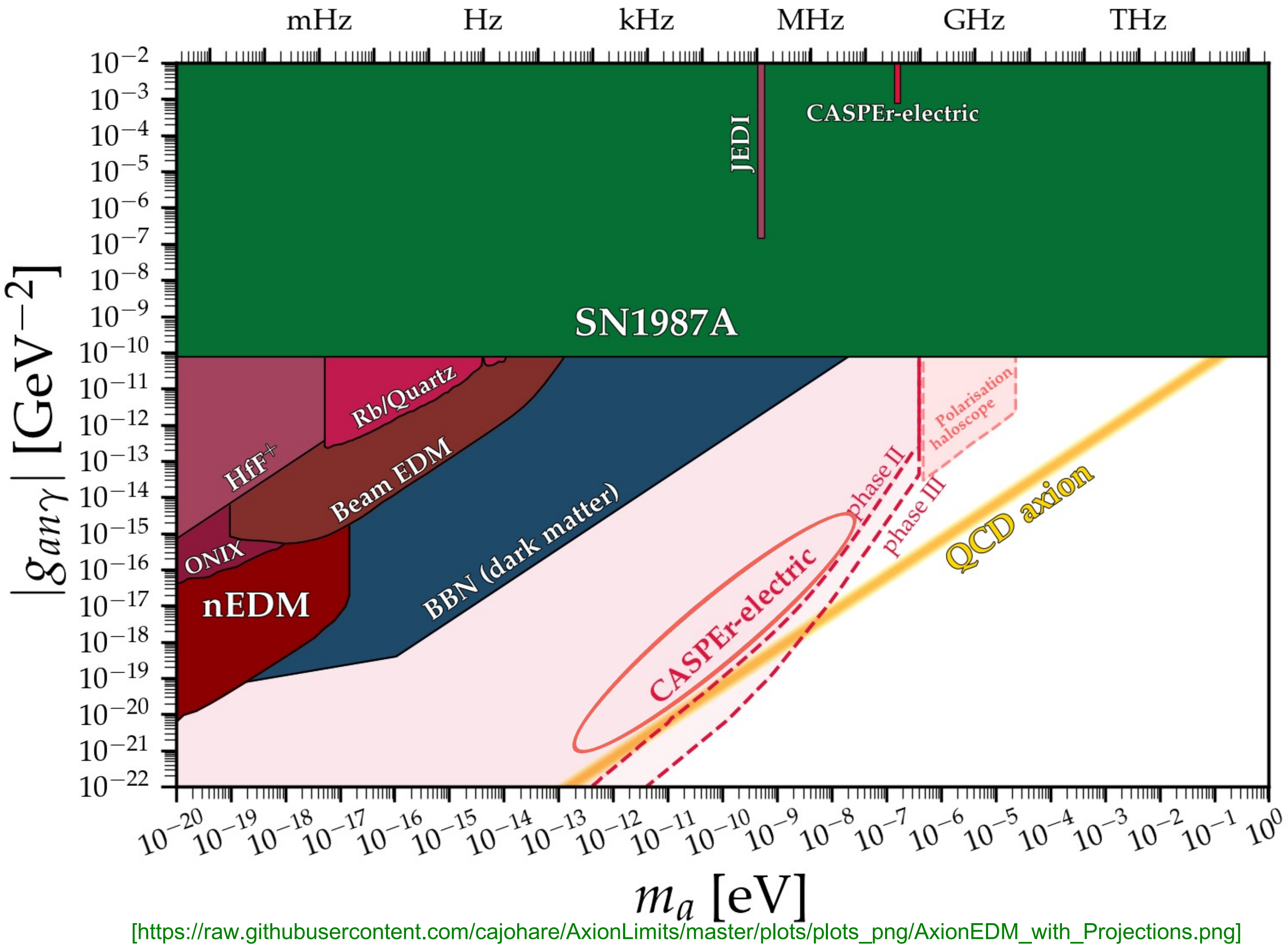


[https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/AxionProton_with_Projections.png]

Ultralight Bosons Can Be Searched For in the Laboratory!

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

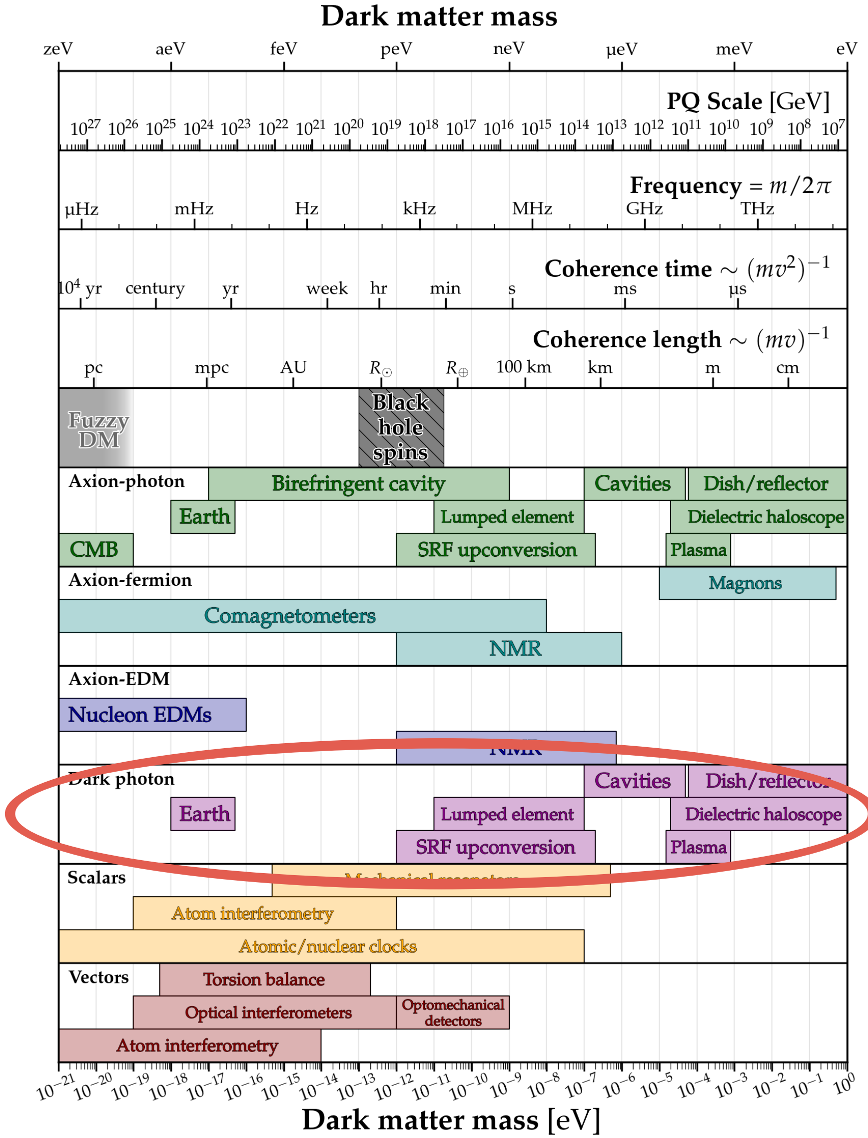


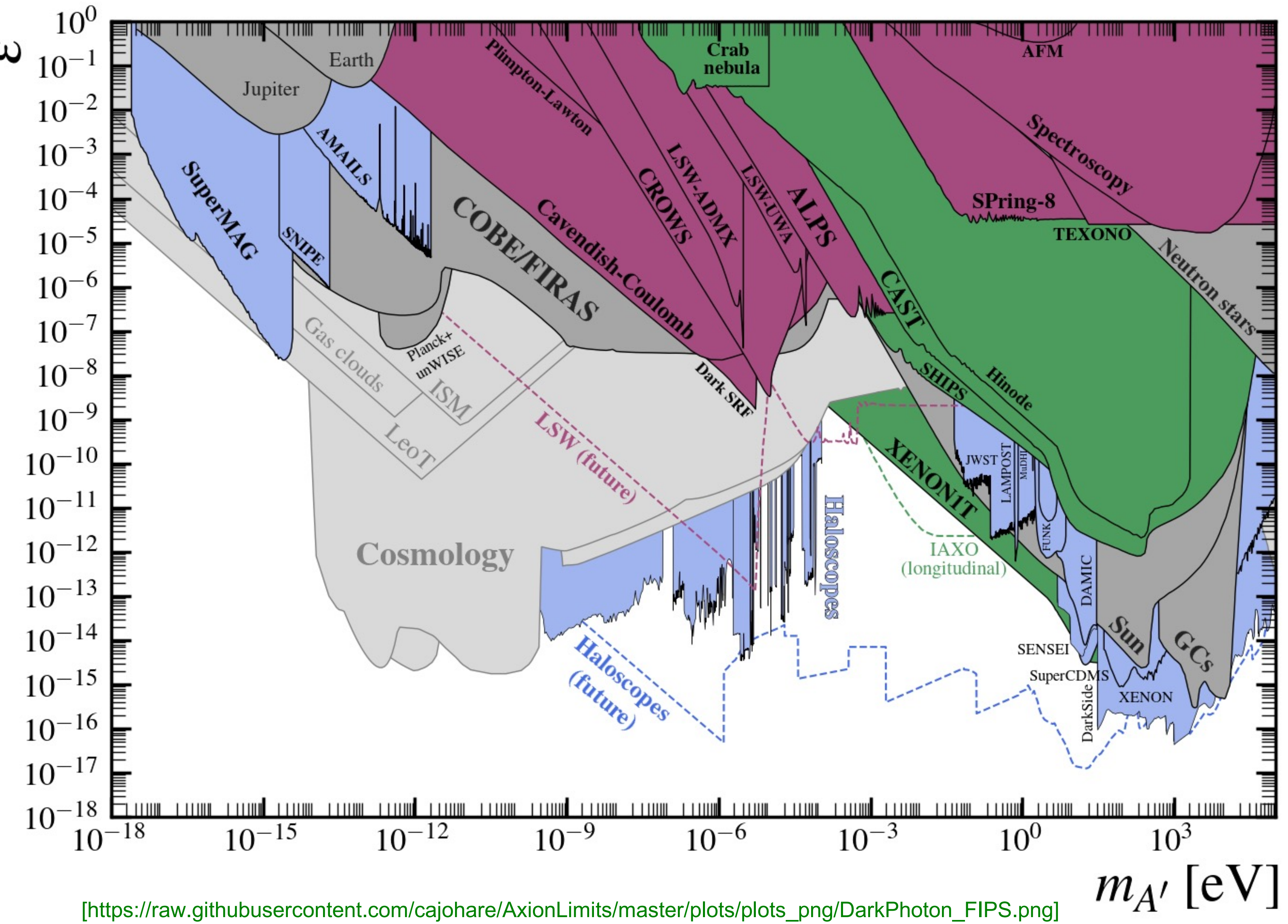


[https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/AxionEDM_with_Projections.png]

Ultralight Boson Can Be Searched For in the Laboratory!

Dark photon DM searches

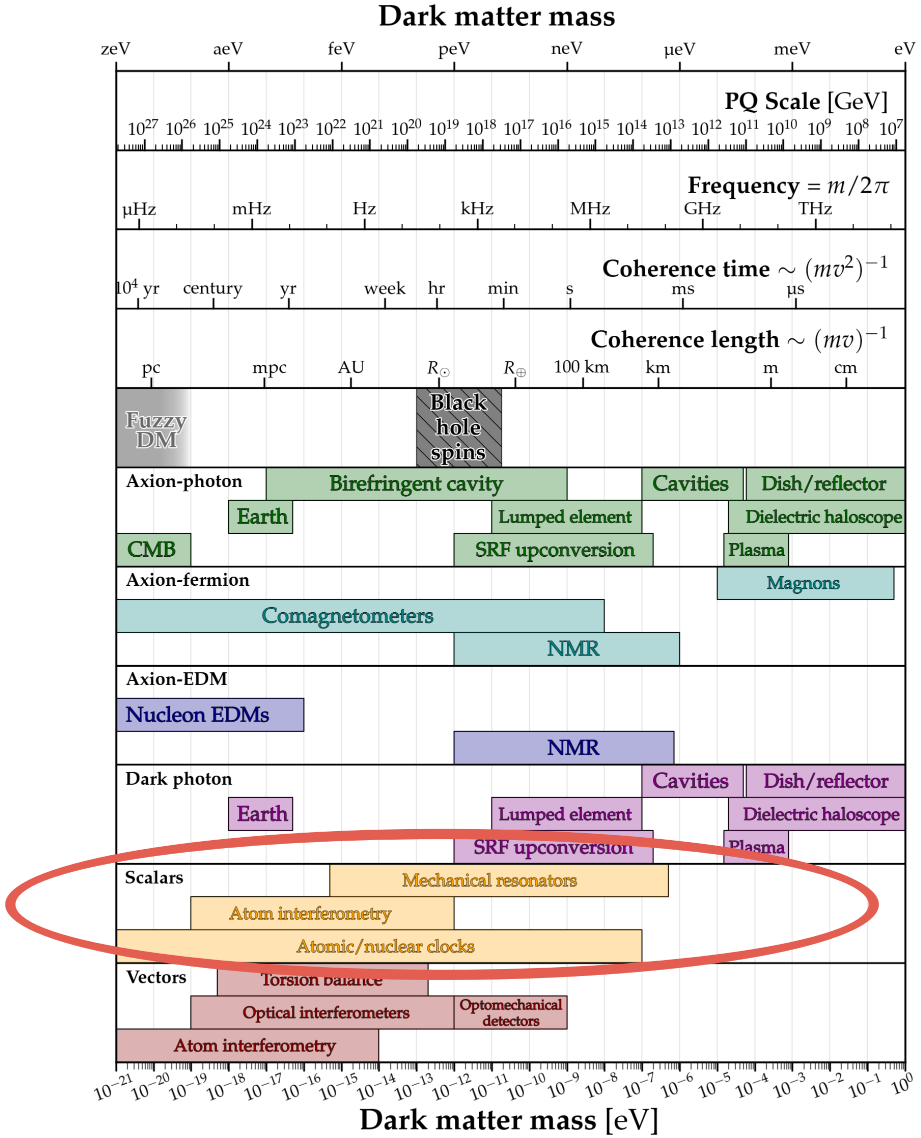


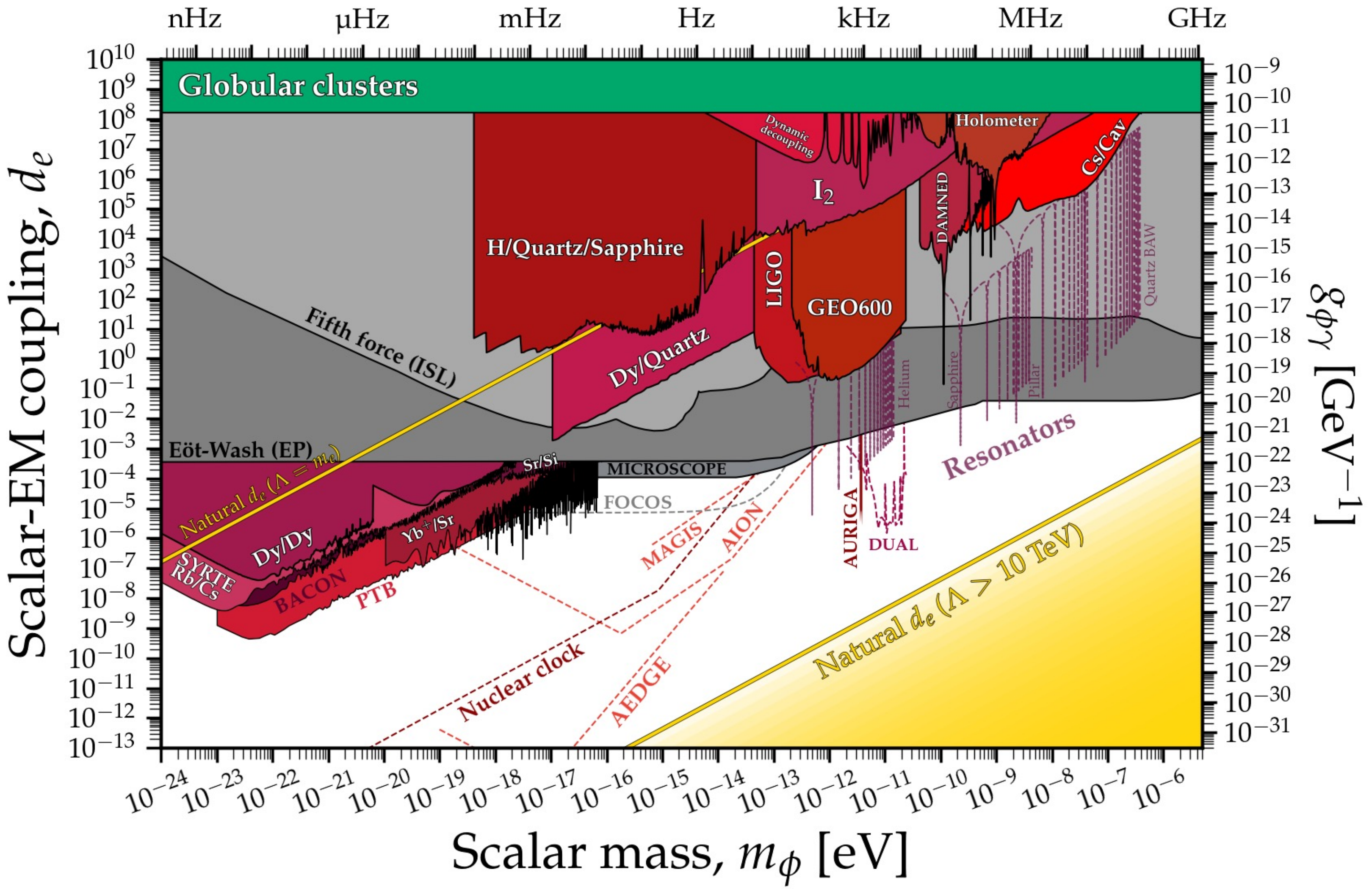


[https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/DarkPhoton_FIPS.png]

Ultralight Boson Can Be Searched For in the Laboratory!

Scalar (dilaton, ...) DM searches





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

Conclusions

We are on a good way to cover the most plausible mass and coupling ranges of ultralight bosonic dark matter.

However, should bear in mind that the sensitivity projections depend on the assumption that the DM energy density is 0.45 GeV/cm^3, as inferred from a simple DM halo model.

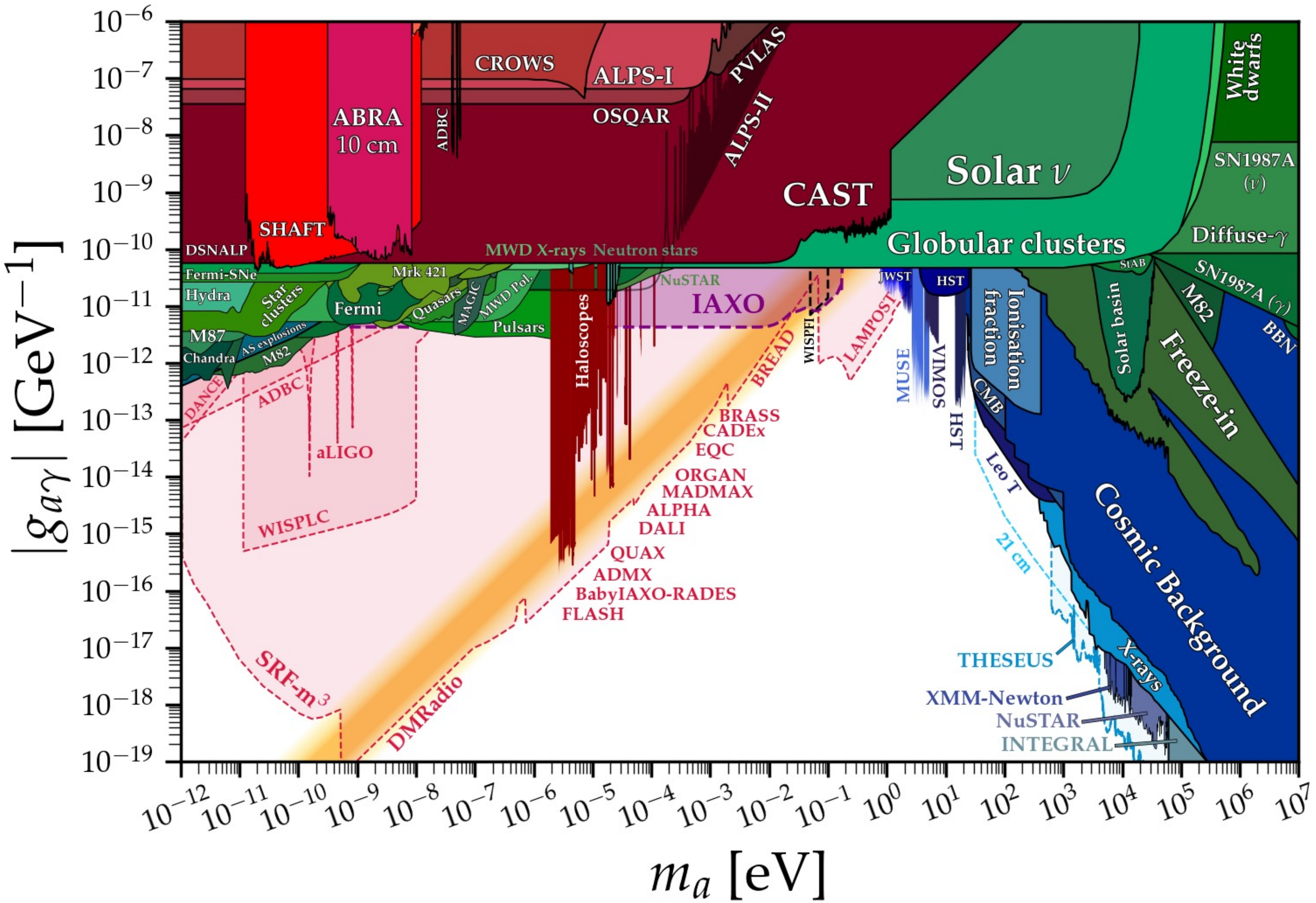
Need also experiments which do not depend on this assumption, such as

- **ALPS II:** searches light-shining-through-the-wall via photon-ULB-photon conversion in the laboratory
- **WISPFI:** searches for photon disappearance via photon-ULB conversion exploiting a Mach-Zehnder-type interferometer with a hollow-core photonic crystal fiber (refractive index <1)
- **(Baby)IAXO:** searches for ULBs from the sun via their conversion into photons
- **ARIADNE:** searches for ULB-induced forces via NMR techniques

Backup Slides

Ultralight Bosons Can Be Searched For in the Laboratory!

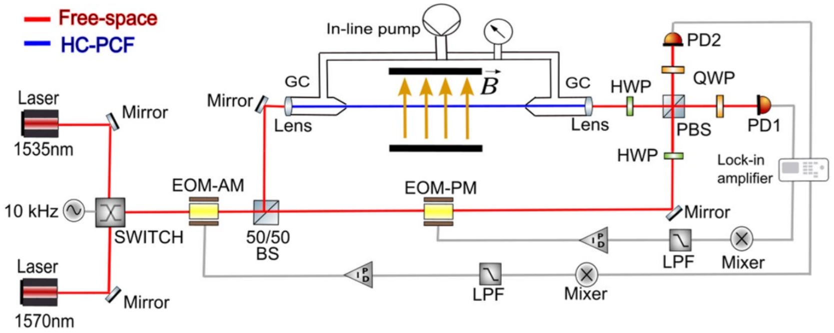
Pseudo-scalar (axion, ALP, ...) searches (future projections)



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

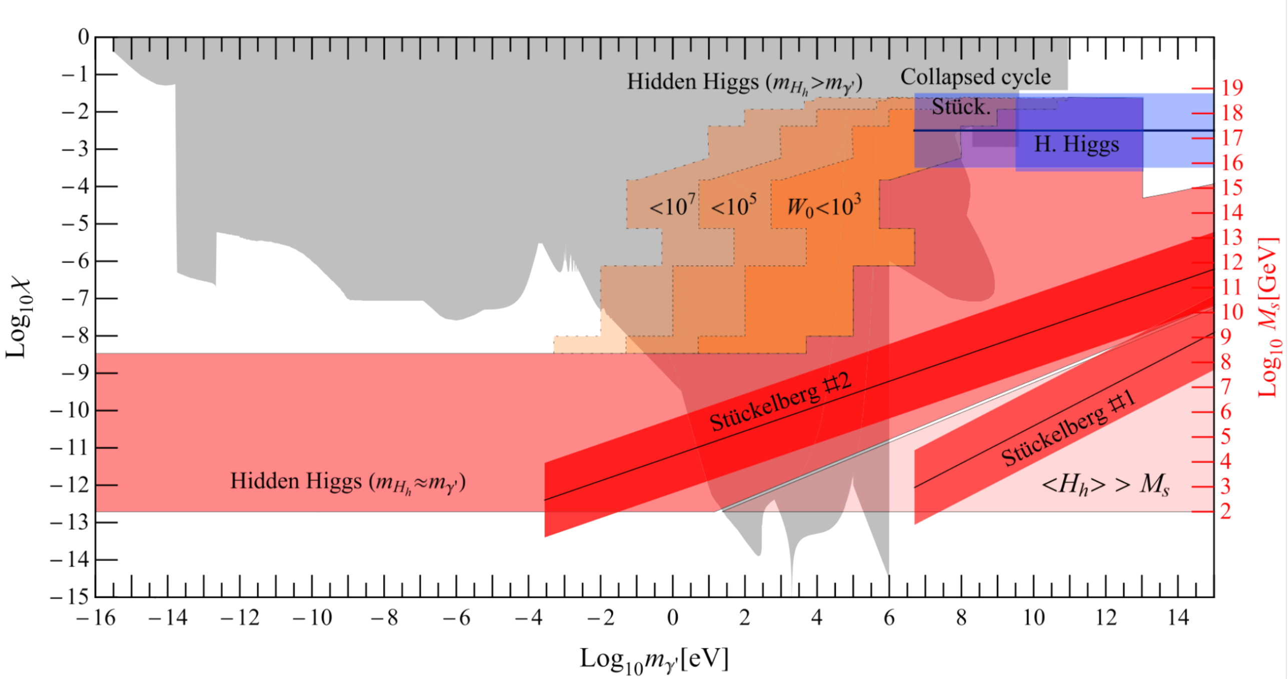
Dark Photon

Generic properties

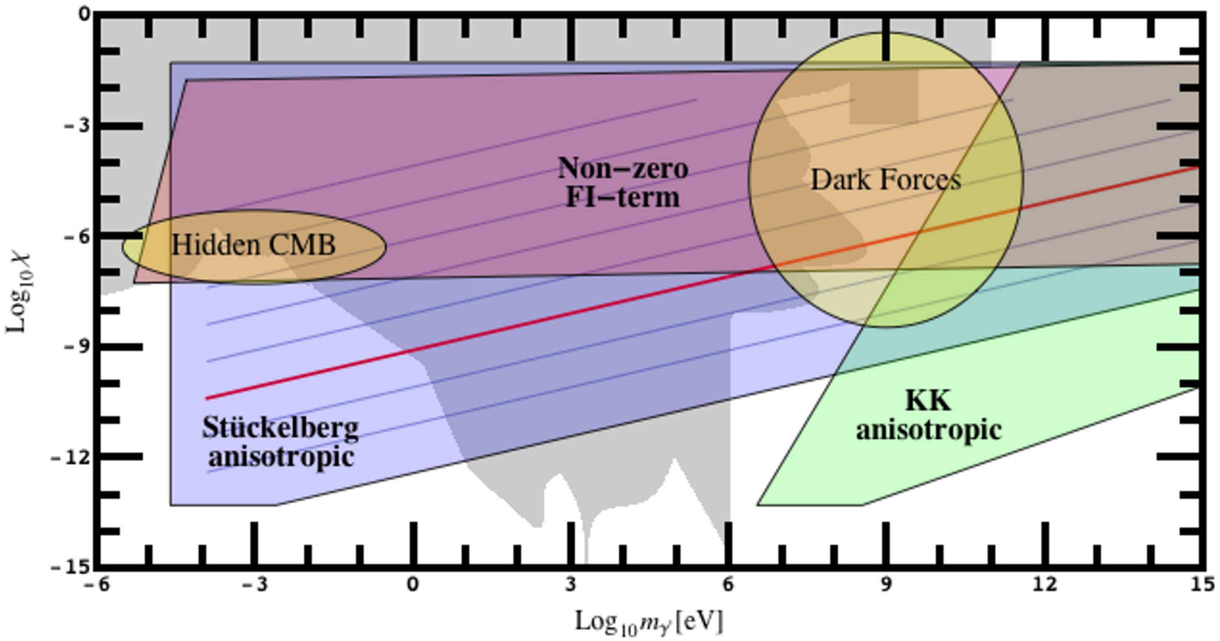
Low-energy effective interactions:

$$\mathcal{L} \supset \frac{1}{2} F'_{\mu\nu} F'^{\mu\nu} - \frac{1}{2} m_{\gamma'}^2 A'^2 - \frac{\chi}{2} F'_{\mu\nu} F^{\mu\nu}$$

- Mass generated via hidden Higgs or Stückelberg mechanism
- Kinetic mixing typically loop-induced $\chi \sim \frac{e\, g_h}{16\pi^2}$
- Predictions from compactifications of type II string theory:



[Goodsell,Jaeckel,Redondo,AR, 0909.0515]



[Cicoli,Goodsell,Jaeckel,AR, 1103.3705]

Dark Photon

Expectations for dark photon dark matter

Various dark photon dark matter production mechanisms:

- Vector misalignment (requires finetuning of initial value or non-minimal coupling to gravity)

[Nelson,Scholtz, 1105.2812; Arias,Cadamuro,Goodsell,Jaeckel,Redondo,AR, 1201.5902]

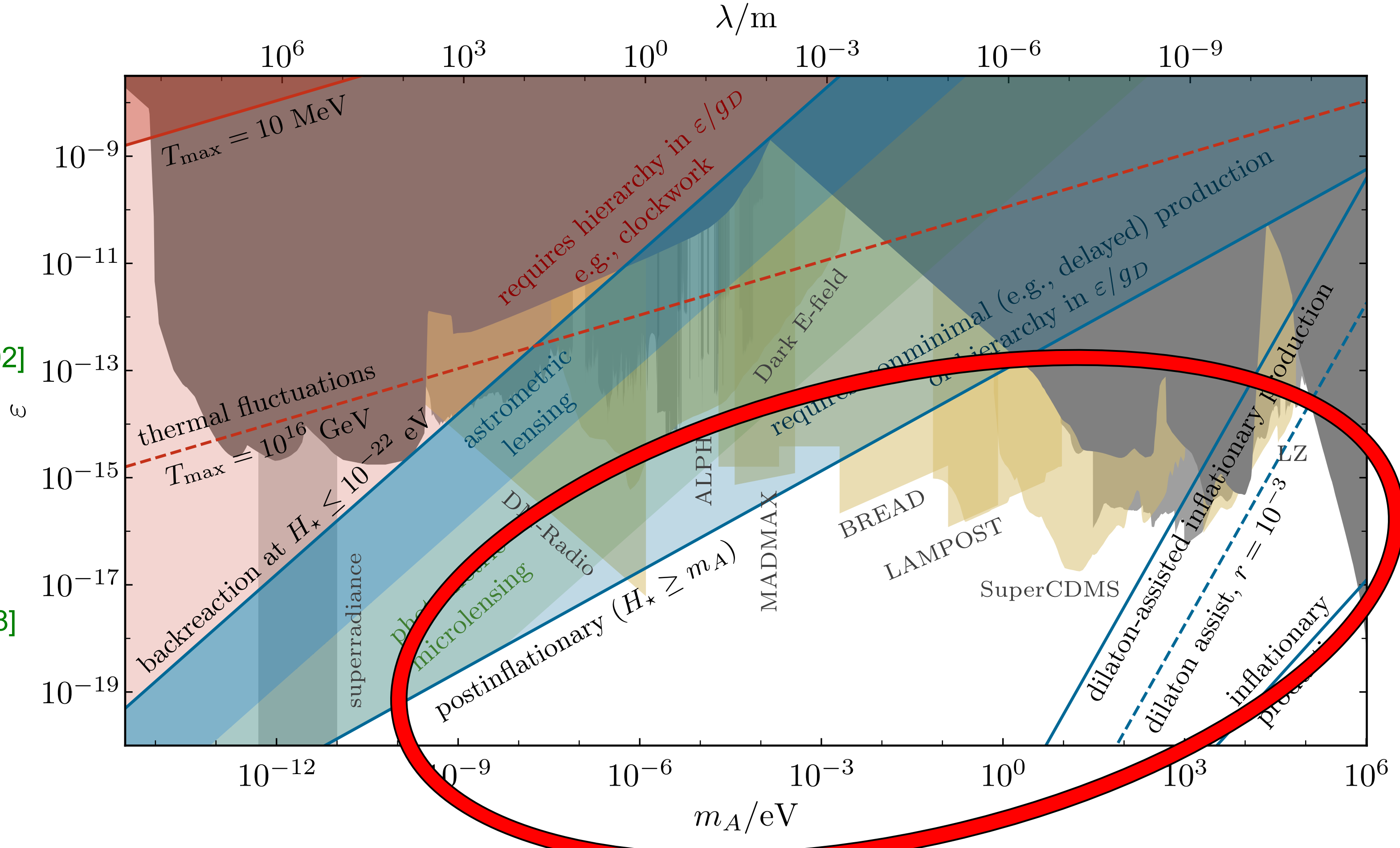
- Inflationary production

[Graham,Mardon,Rajendran, 1504.02102]

- Production via an oscillating ALP

[Agrawal,Kitajima,Reece,Sekiguchi,Takahashi, 1810.07188]

Lots of uncharted parameter space for dark photon dark matter direct detection

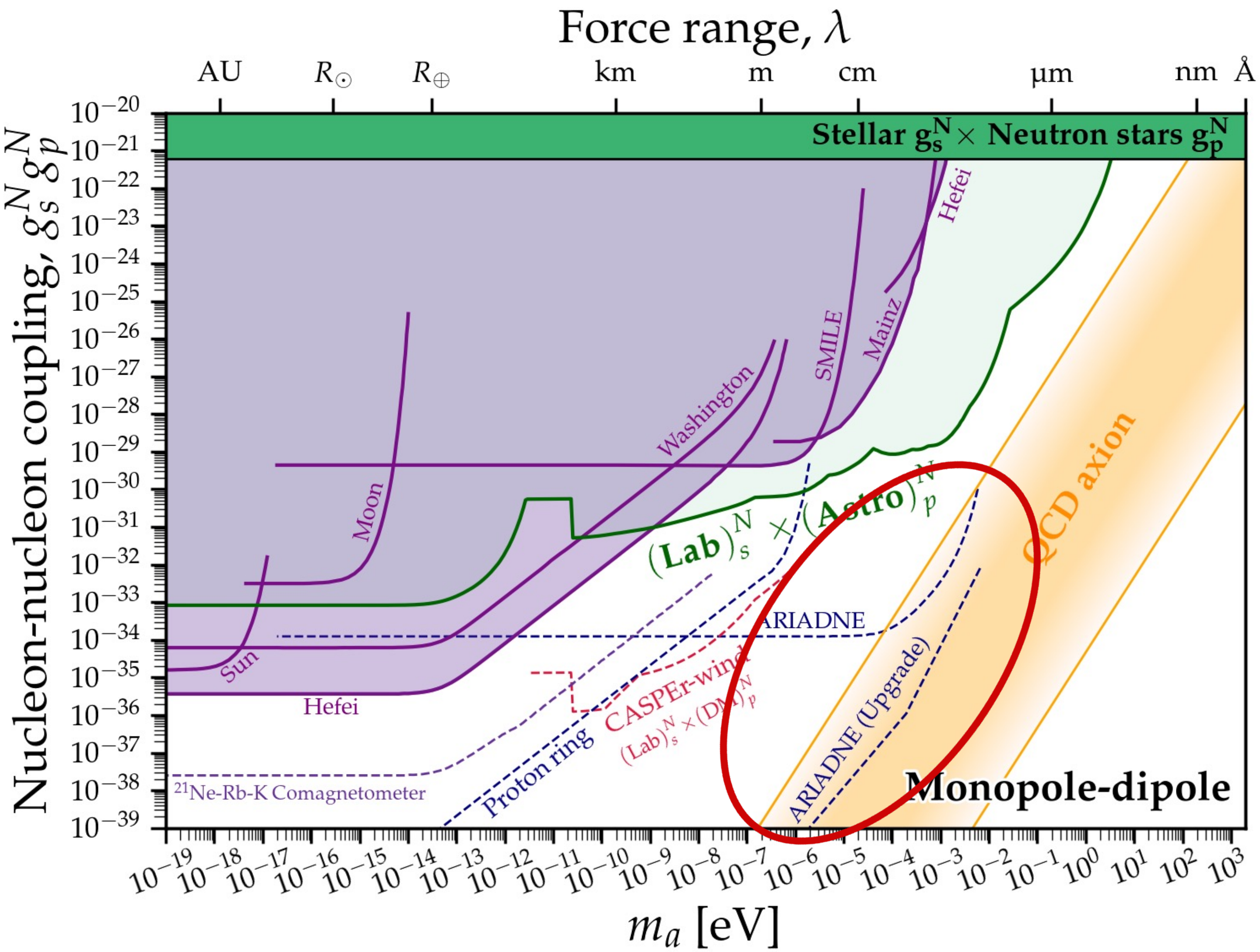


[Cyncynates,Weiner, 2410.14774]

Coverage of Parameter Range in Future

In 2035:

- Seems that most plausible mass and coupling range of axion will be covered by direct detection, exploiting axion-photon conversion in a magnetic field
- Caveats:
  - Local axion DM density could be much less than average 0.4 GeV/cm^3
  - Sensitivity holes around
    - eV mass
      - Closed by search for solar axions or photon disappearance with a fiber-interferometer in a magnetic field
    - meV mass
      - Closed by search for axion-induced monopole-dipole forces

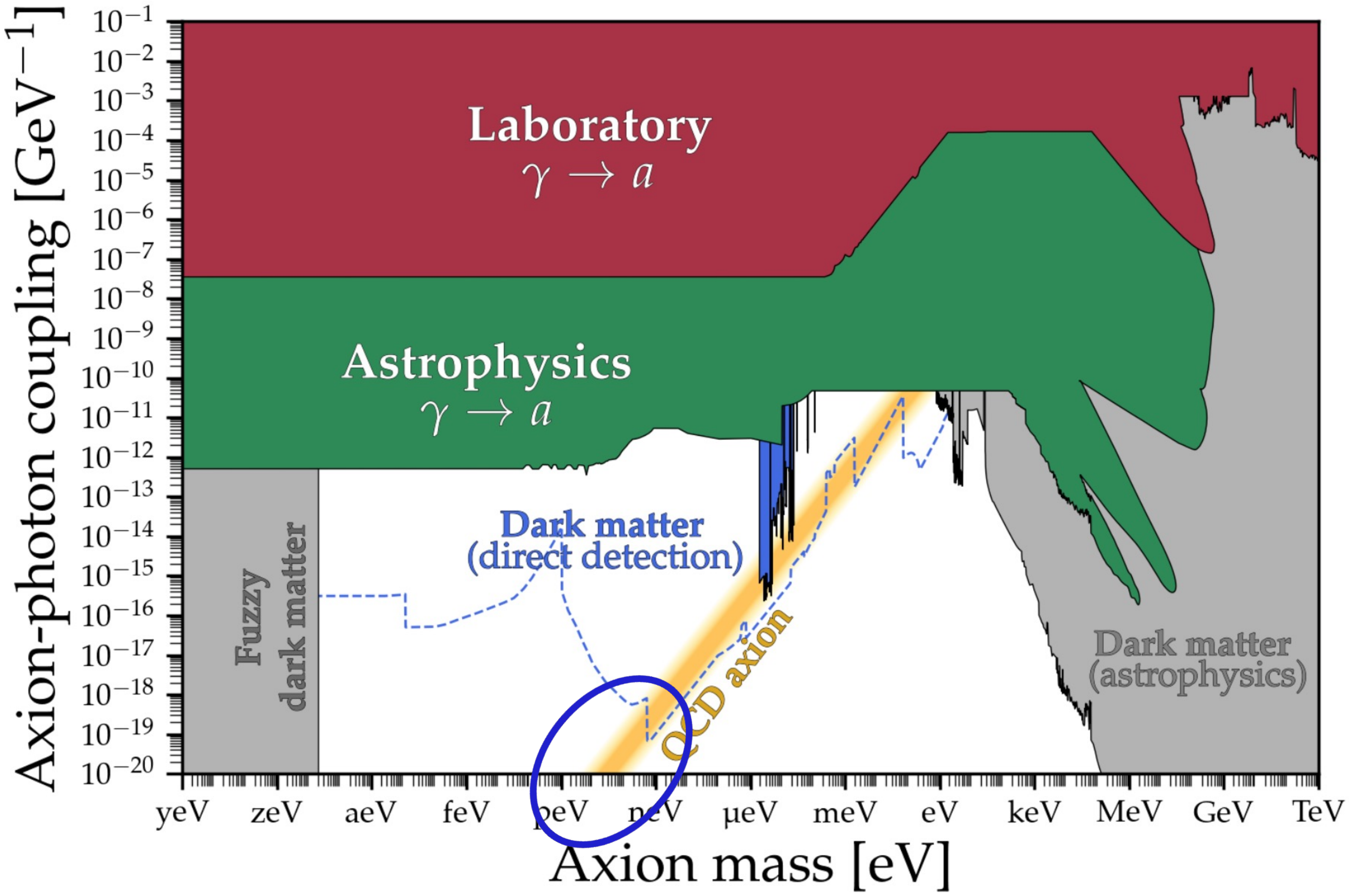


[O'Hare, Vitagliano, 2010.03889]

Coverage of Parameter Range in Future

In 2035:

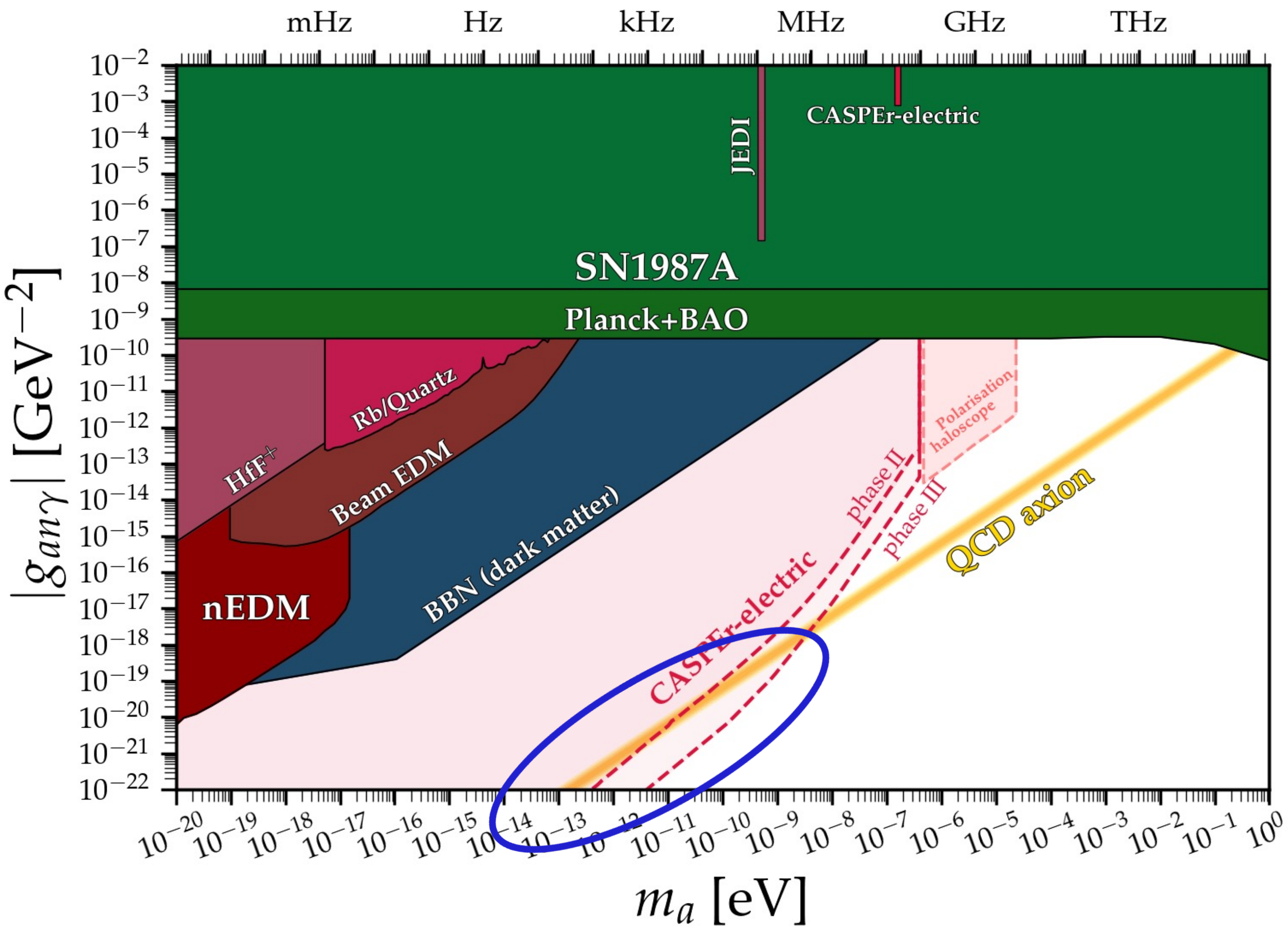
- Seems that most plausible mass and coupling range of axion will be covered by direct detection, exploiting axion-photon conversion in a magnetic field
- Caveats:
  - Local axion DM density could be much less than average 0.4 GeV/cm^3
  - Sensitivity holes around
    - eV mass
      - Closed by search for solar axions or photon disappearance with a fiber-interferometer in a magnetic field
    - meV mass
      - Closed by search for axion-induced monopole-dipole forces
    - peV to neV mass ($M_P > f_a > M_{GUT}$)



Coverage of Parameter Range in Future

In 2035:

- Seems that most plausible mass and coupling range of axion will be covered by direct detection, exploiting axion-photon conversion in a magnetic field
- Caveats:
  - Local axion DM density could be much less than average 0.4 GeV/cm^3
  - Sensitivity holes around
    - eV mass
      - Closed by search for solar axions or photon disappearance with a fiber-interferometer in a magnetic field
    - meV mass
      - Closed by search for axion-induced monopole-dipole forces
    - peV to neV mass ($M_P > f_a > M_{GUT}$)
      - Closed by search for oscillating NEDMs



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

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

    [Tobar et al., 2306.13320]
  - Probes neV mass axion, that is $f_a \sim M_Q$ of order GUT scale