Coherent-Field Dark Matter: Candidates and Search Methods

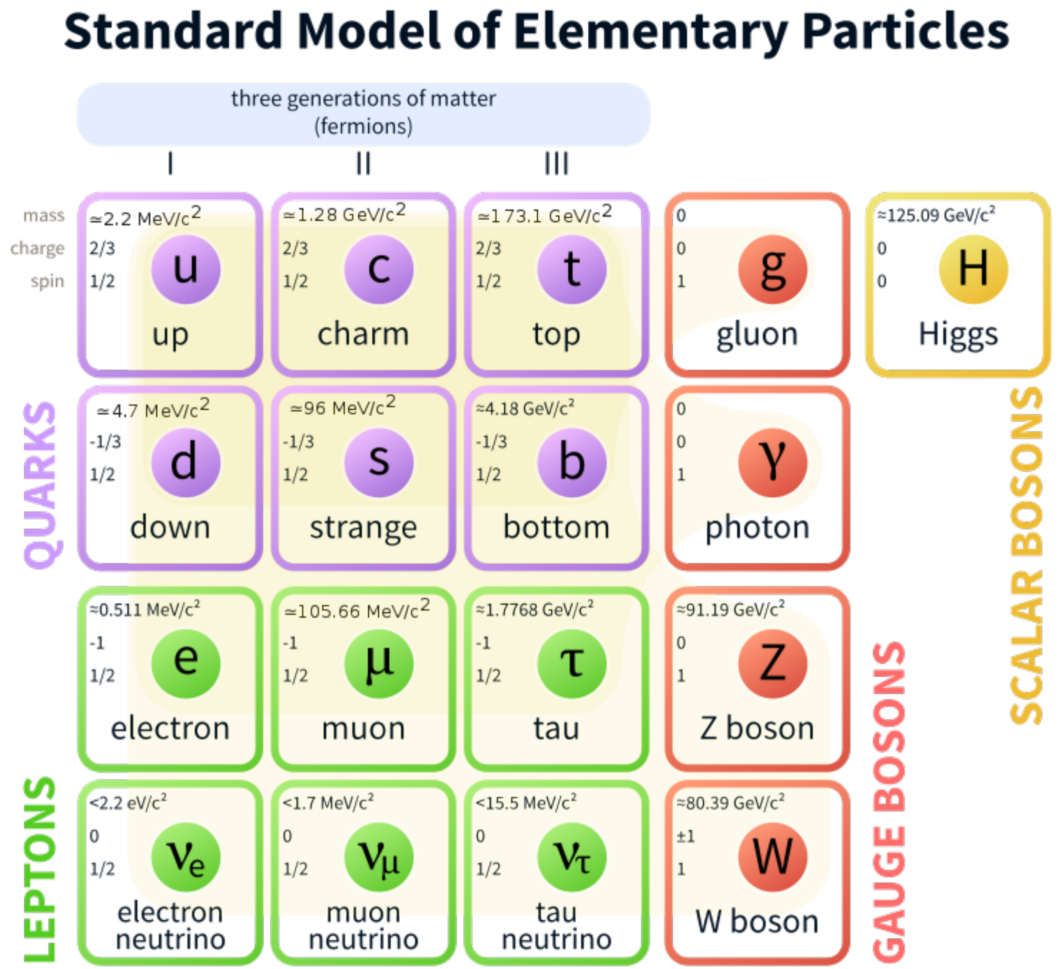
Andreas Ringwald
Perspectives on Quantum Sensing and Computation for Particle Physics
CERN TH Institute
5-16 July 2021

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
CLUSTER OF EXCELLENCE QUANTUM UNIVERSE
DESY.

Introduction

Big Success: Standard Model of Particle Physics

- Standard Model of elementary particle physics (SM) describes interactions of all known particles



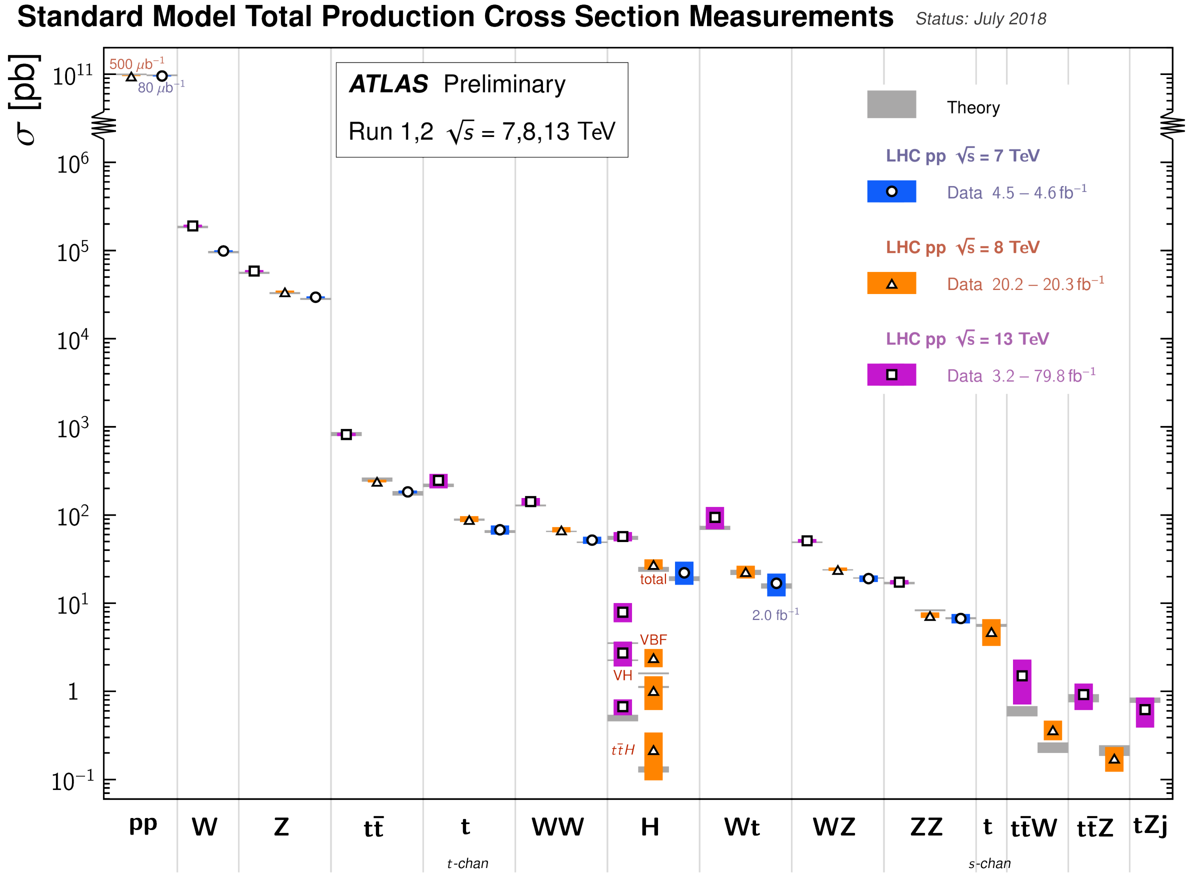
[Wikipedia]

Introduction

Big Success: Standard Model of Particle Physics

- Standard Model of elementary particle physics (SM) describes interactions of all known particles with remarkable accuracy

[cern.ch]

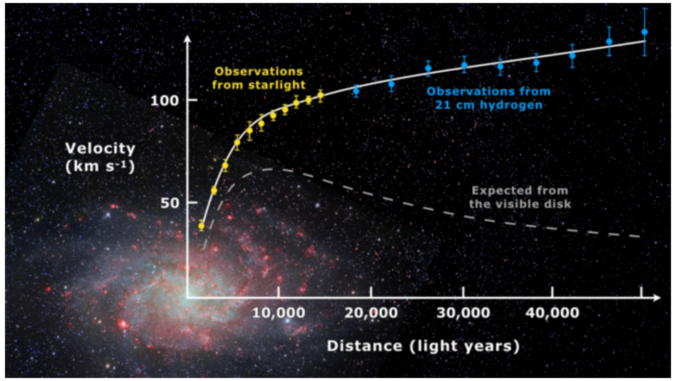


[atlas.web.cern.ch]

Introduction

Big Flaw: SM accounts only for few percent of total energy of Universe

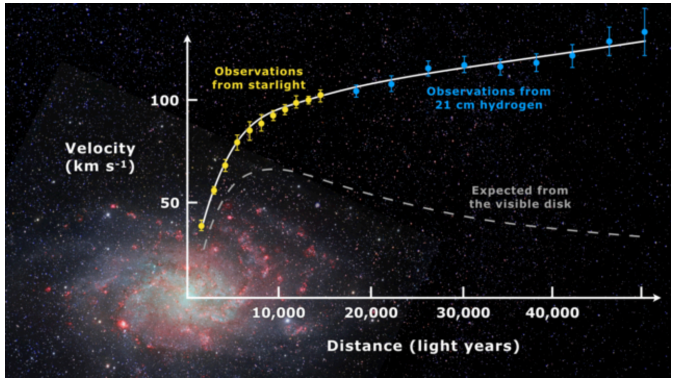
- Astronomical observations on galactic

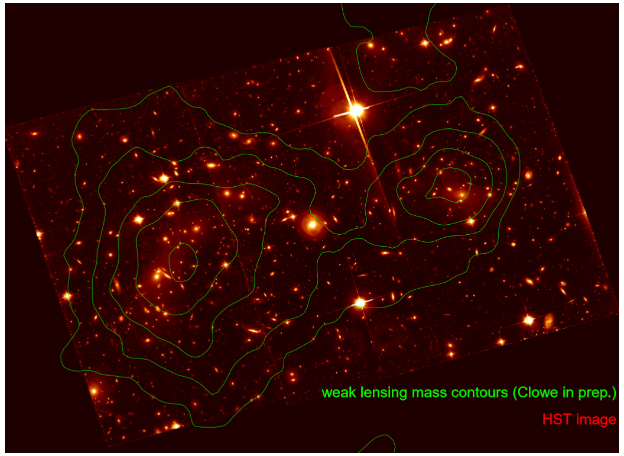


Introduction

Big Flaw: SM accounts only for few percent of total energy of Universe

- Astronomical observations on galactic, galaxy cluster



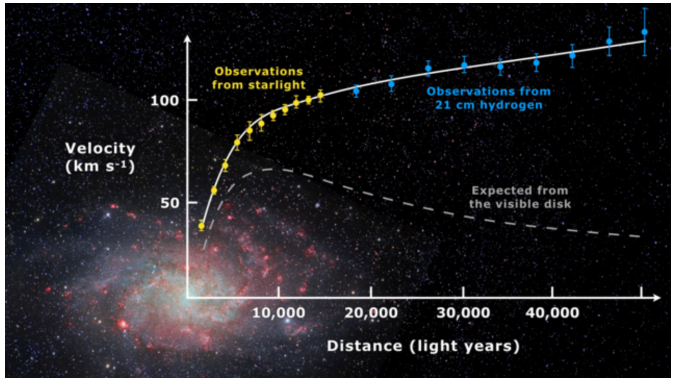


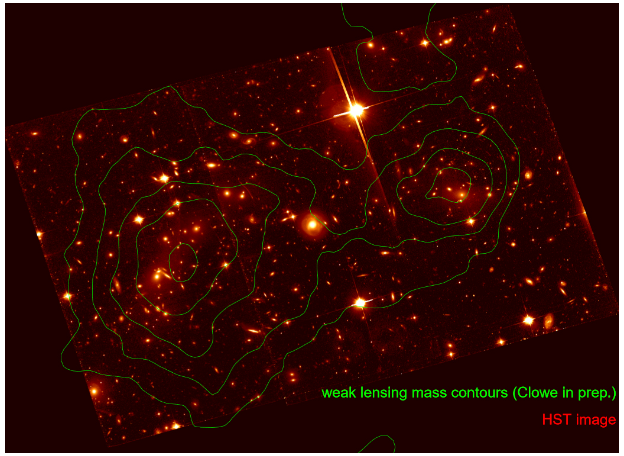
[Wikipedia]

Introduction

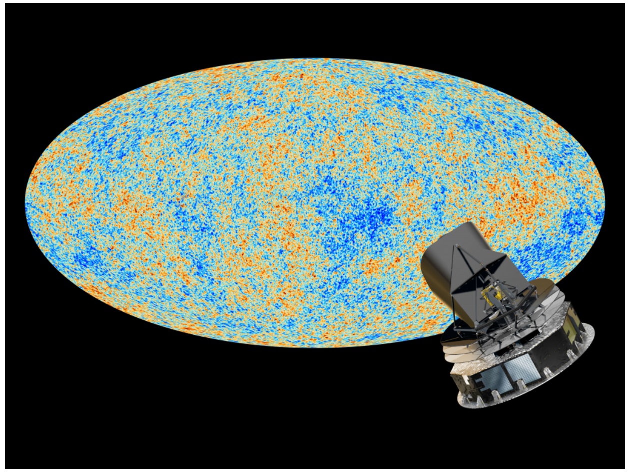
Big Flaw: SM accounts only for few percent of total energy of Universe

- Astronomical observations on galactic, galaxy cluster and cosmological scales:





[Wikipedia]

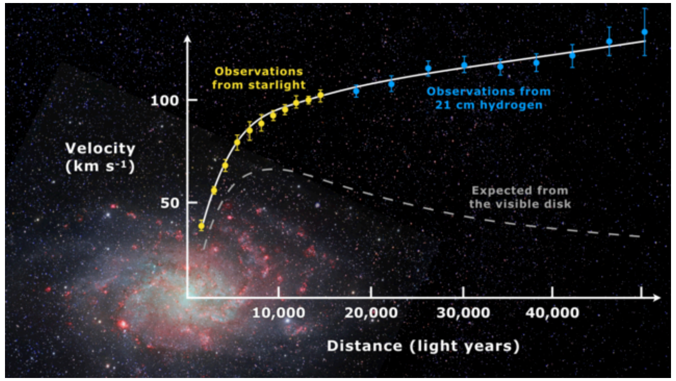


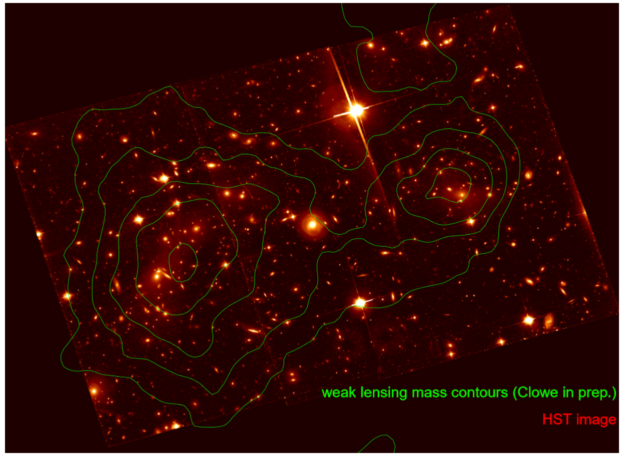
[NASA]

Introduction

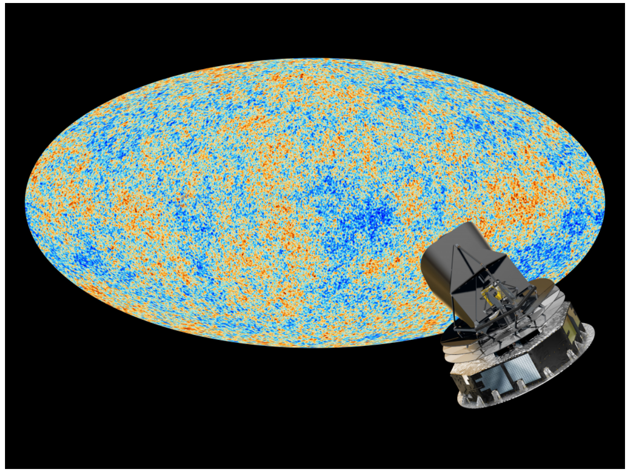
Big Flaw: SM accounts only for few percent of total energy of Universe

- Astronomical observations on galactic, galaxy cluster and cosmological scales show that about 85 % of the matter in Universe not comprised of ordinary matter

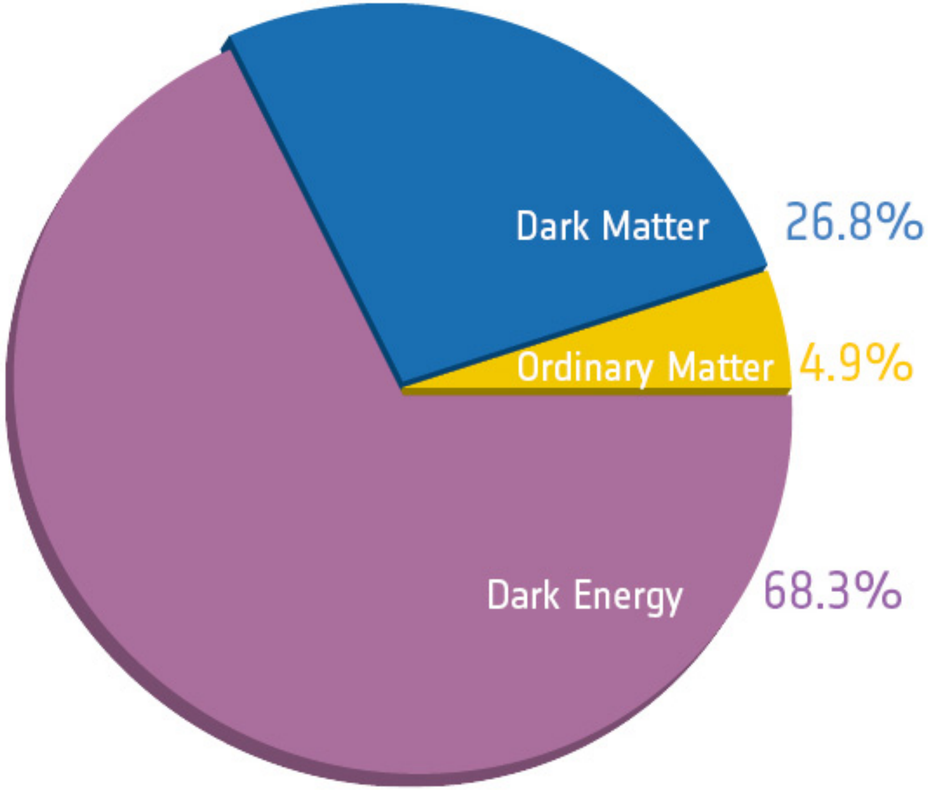




[Wikipedia]



[NASA]

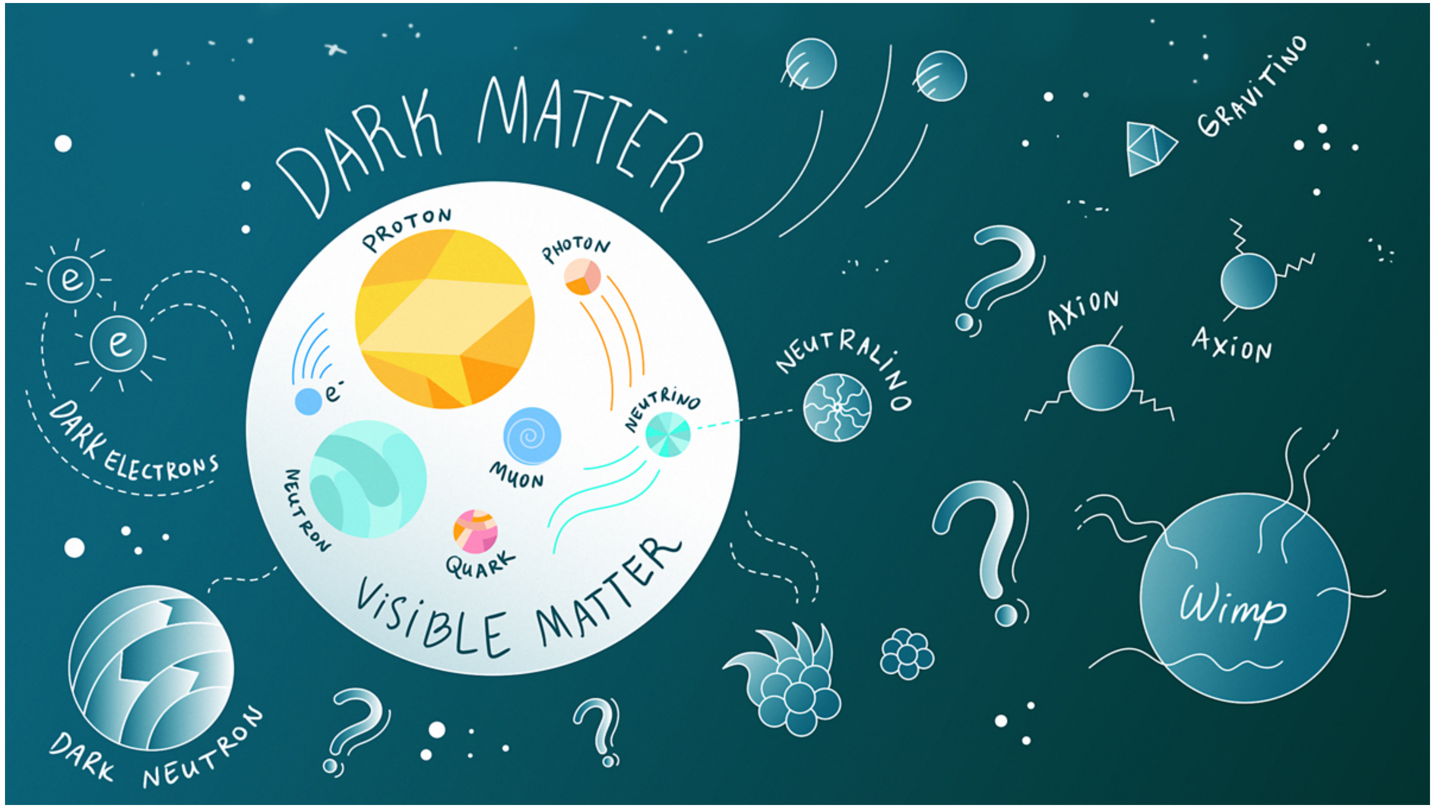


[PLANCK]

Introduction

Big Variety: Zoo of Dark Matter candidates

- Theoretical particle physicists have proposed a plenitude of Dark Matter (DM) candidates:

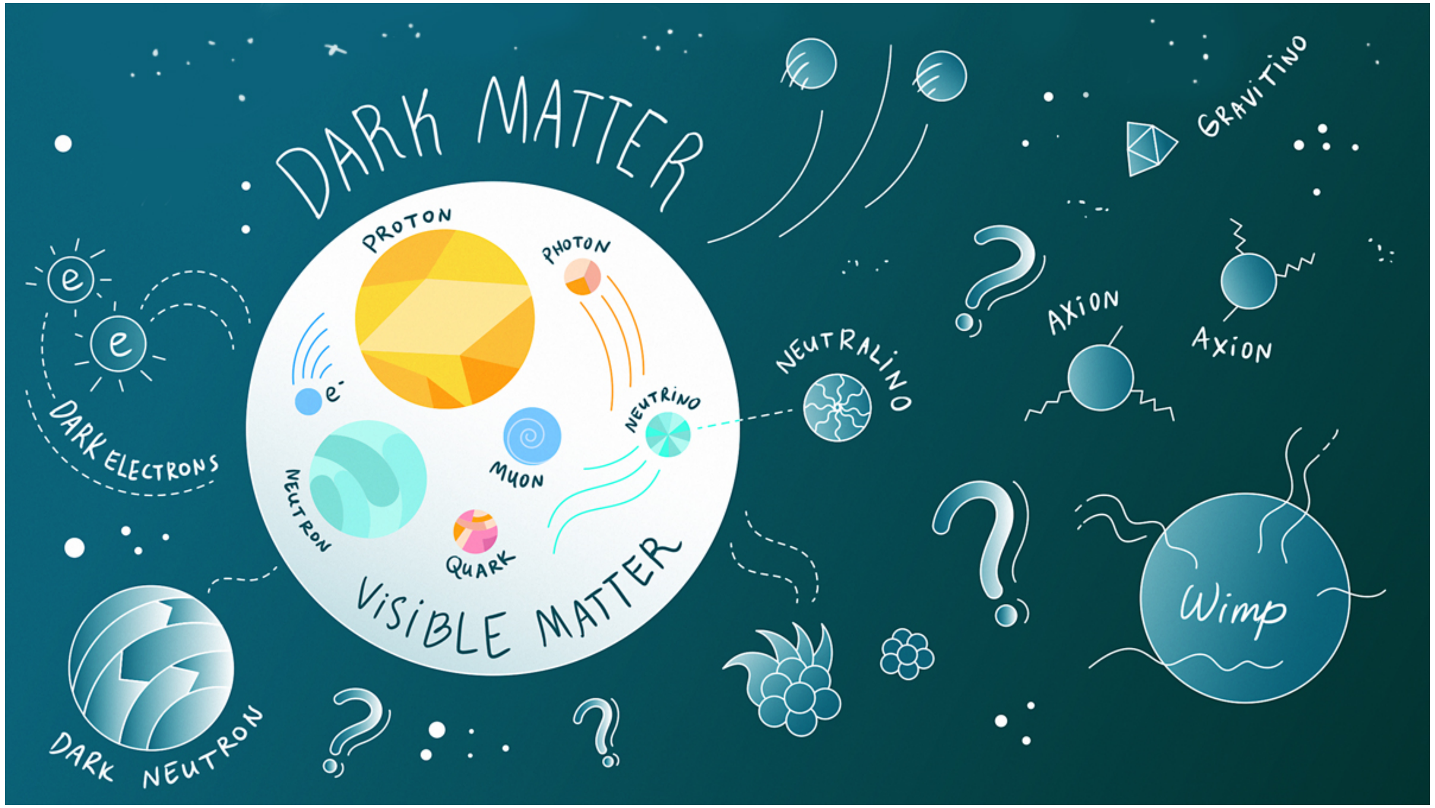


[Symmetry Magazine]

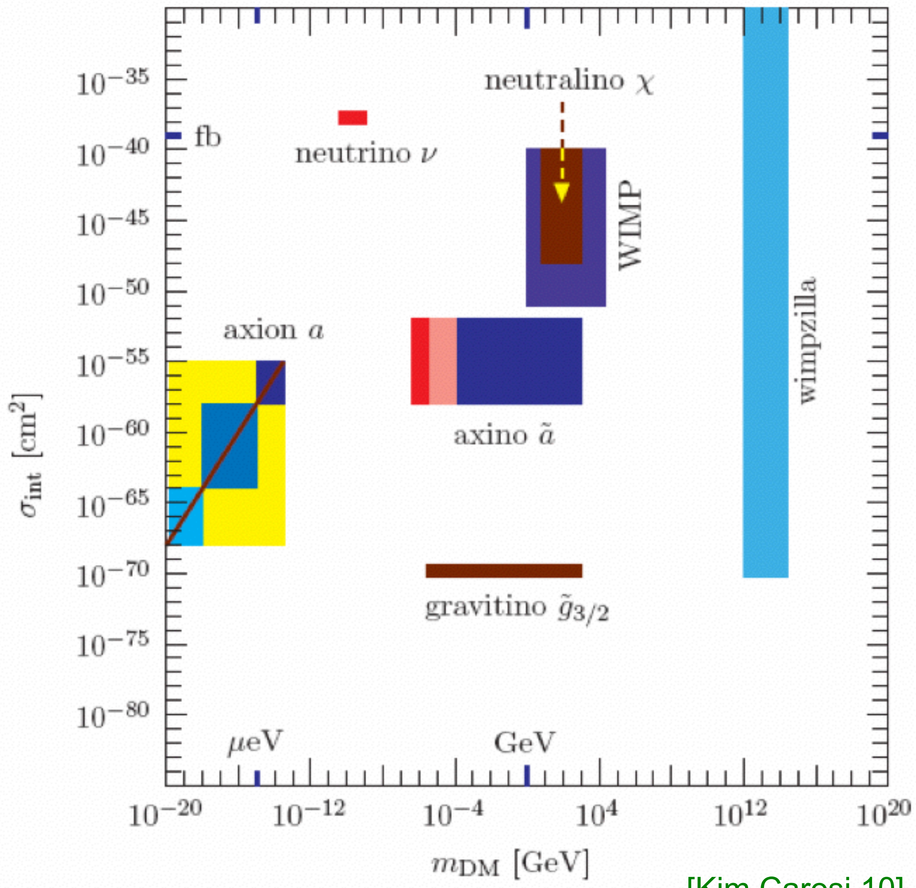
Introduction

Big Variety: Zoo of Dark Matter candidates

- Theoretical particle physicists have proposed a plenitude of Dark Matter (DM) candidates, spanning a huge range in masses and interaction strength:



[Symmetry Magazine]



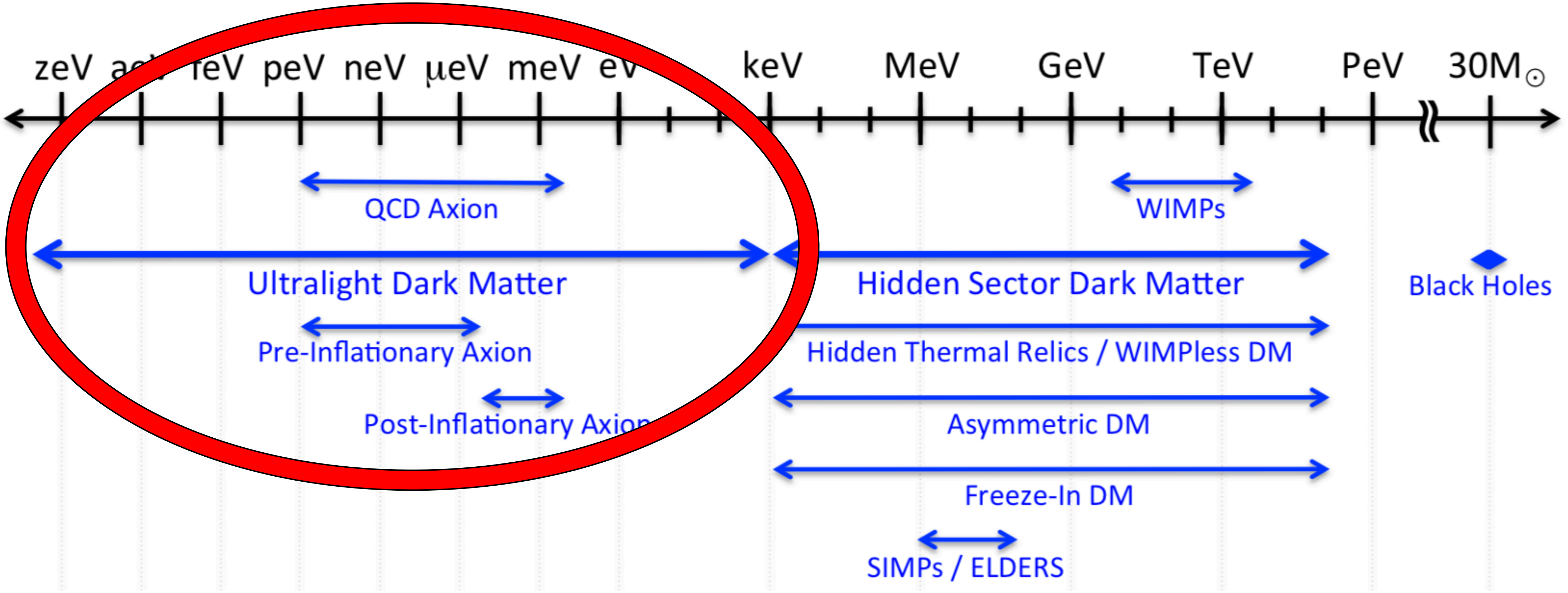
[Kim,Carosi 10]

Introduction

Big Variety: Zoo of Dark Matter candidates

- Concentrate here on generic class of **Ultralight Dark Matter**, also dubbed **WISPy Dark Matter**:

[March-Russell private comm. `07]



[US Cosmic Visions: New Ideas in Dark Matter 2017]

Ultralight Dark Matter

Generic properties

- For $m_{\rm DM} \lesssim 30\,{\rm eV}$, large occupation number per de Broglie volume in our neighborhood in Milky Way:

$$N_{\rm DM}\,|_{\rm dB} = n_{\rm DM}\,\lambda_{\rm dB}^3 = \frac{\rho_{\rm DM}}{m_{\rm DM}}\left(\frac{2\pi}{m_{\rm DM}\,v_{\rm d}}\right)^3 = 1.3\times 10^6\left(\frac{\rm eV}{m_{\rm DM}}\right)^4\left(\frac{250\,{\rm km/s}}{v_{\rm d}}\right)^3\left(\frac{\rho_{\rm DM}}{0.4\,{\rm GeV/cm^3}}\right)$$

Ultralight Dark Matter

Generic properties

- For $m_{\rm DM} \lesssim 30\,{\rm eV}$, large occupation number per de Broglie volume in our neighborhood in Milky Way:

$$N_{\rm DM}\,|_{\rm dB} = n_{\rm DM}\,\lambda_{\rm dB}^3 = \frac{\rho_{\rm DM}}{m_{\rm DM}} \left(\frac{2\pi}{m_{\rm DM}\,v_{\rm d}}\right)^3 = 1.3\times 10^6 \left(\frac{\rm eV}{m_{\rm DM}}\right)^4 \left(\frac{250\,{\rm km/s}}{v_{\rm d}}\right)^3 \left(\frac{\rho_{\rm DM}}{0.4\,{\rm GeV/cm^3}}\right)$$

  - Pauli exclusion principle excludes fermions as Ultralight Dark Matter Candidates:

Ultralight Dark Matter Candidates are necessarily bosons

Ultralight Dark Matter

Generic properties

- For $m_{\rm DM} \lesssim 30\,{\rm eV}$, large occupation number per de Broglie volume in our neighborhood in Milky Way:

$$N_{\rm DM}\,|_{\rm dB} = n_{\rm DM}\,\lambda_{\rm dB}^3 = \frac{\rho_{\rm DM}}{m_{\rm DM}}\left(\frac{2\pi}{m_{\rm DM}\,v_{\rm d}}\right)^3 = 1.3\times 10^6 \left(\frac{\rm eV}{m_{\rm DM}}\right)^4 \left(\frac{250\,{\rm km/s}}{v_{\rm d}}\right)^3 \left(\frac{\rho_{\rm DM}}{0.4\,{\rm GeV/cm^3}}\right)$$

  - Pauli exclusion principle excludes fermions as Ultralight Dark Matter Candidates:

    Ultralight Dark Matter Candidates are necessarily bosons

  - Ultralight Dark Matter best described by classical waves. Therefore also known as

    Coherent-Field Dark Matter or **Wave Dark Matter**

Ultralight Dark Matter

Generic properties

- For $m_{\rm DM} \lesssim 30\,{\rm eV}$, large occupation number per de Broglie volume in our neighborhood in Milky Way:

$$N_{\rm DM}\,|_{\rm dB} = n_{\rm DM}\,\lambda_{\rm dB}^3 = \frac{\rho_{\rm DM}}{m_{\rm DM}} \left(\frac{2\pi}{m_{\rm DM}\,v_{\rm d}}\right)^3 = 1.3\times 10^6 \left(\frac{\rm eV}{m_{\rm DM}}\right)^4 \left(\frac{250\,{\rm km/s}}{v_{\rm d}}\right)^3 \left(\frac{\rho_{\rm DM}}{0.4\,{\rm GeV/cm^3}}\right)$$

  - Pauli exclusion principle excludes fermions as Ultralight Dark Matter Candidates:

    Ultralight Dark Matter Candidates are necessarily bosons

  - Ultralight Dark Matter best described by classical waves. Therefore also known as

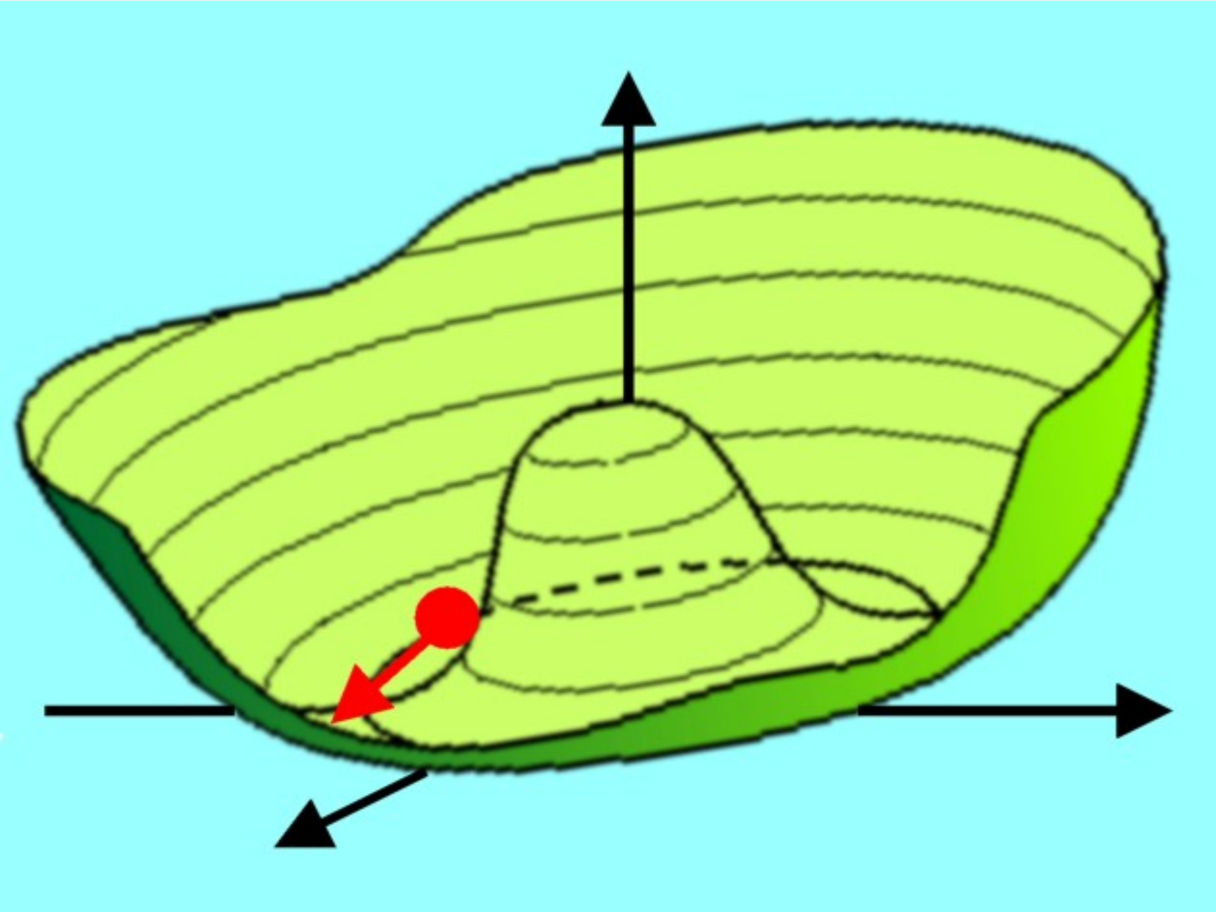
    Coherent-Field Dark Matter or **Wave Dark Matter**

- For $m_{\rm DM} \lesssim 10^{-22}\,{\rm eV}$, the de Broglie wave length exceeds the size of dwarf galaxies. Therefore,

  Ultralight Dark Matter Candidates must have a mass $\gtrsim 10^{-22}\,{\rm eV}$

Ultralight Dark Matter Candidates

- Spin 0: Pseudo Nambu-Goldstone bosons with small mass and large decay constant



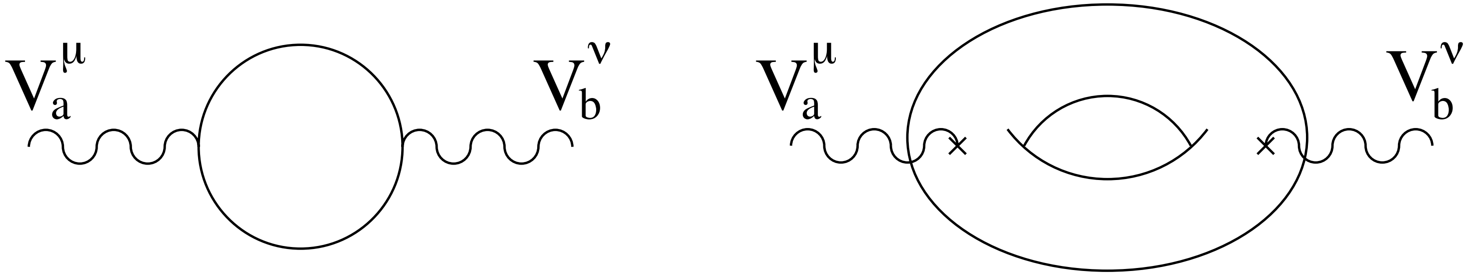
[Raffelt]

Ultralight Dark Matter Candidates

- Spin 0: Pseudo Nambu-Goldstone bosons with small mass and large decay constant
- Spin 1: Hidden sector U(1) gauge bosons with small mass and small kinetic mixing with photon

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

[Holdom `86]



[Dienes,Kolda,March-Russell `96]

(a) (b)

Ultralight Dark Matter Candidates

Spin 0: Pseudo Nambu-Goldstone Bosons

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

are natural **Ultralight Dark Matter Candidates**

Ultralight Dark Matter Candidates

Spin 0: Pseudo Nambu-Goldstone Bosons

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

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

Ultralight Dark Matter Candidates

Spin 0: Pseudo Nambu-Goldstone Bosons

Pseudo Nambu-Goldstone bosons arising from the breaking of approximate global 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]

Ultralight Dark Matter Candidates

Spin 0: Pseudo Nambu-Goldstone Bosons

Pseudo Nambu-Goldstone bosons arising from the breaking of approximate global 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]

Ultralight Dark Matter Candidates

Spin 0: Pseudo Nambu-Goldstone Bosons

Pseudo Nambu-Goldstone bosons arising from the breaking of approximate global 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]

Ultralight Dark Matter Candidates

Spin 0: Pseudo Nambu-Goldstone Bosons

Pseudo Nambu-Goldstone bosons arising from the breaking of approximate global 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**)
  [Witten `84; Arvanitaki et al. `10; Acharya et al. `10; Cicoli et al. `12; Halverson et al. `17]

Ultralight Dark Matter Candidates

Spin 0: Pseudo Nambu-Goldstone Bosons

Pseudo Nambu-Goldstone bosons arising from the breaking of approximate global 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**) [Witten `84; Arvanitaki et al. `10; Acharya et al. `10; Cicoli et al. `12; Halverson et al. `17]

are natural **Ultralight Dark Matter Candidates**

Ultralight Dark Matter Candidates

Spin 0: Pseudo Nambu-Goldstone Bosons

Pseudo Nambu-Goldstone bosons arising from the breaking of approximate global 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**)
  [Witten `84; Arvanitaki et al. `10; Acharya et al. `10; Cicoli et al. `12; Halverson et al. `17]

are natural **Ultralight Dark Matter Candidates**:

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

Ultralight Dark Matter Candidates

Spin 0: Pseudo Nambu-Goldstone Bosons

Pseudo Nambu-Goldstone bosons arising from the breaking of approximate global 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**) [Witten `84; Arvanitaki et al. `10; Acharya et al. `10; Cicoli et al. `12; Halverson et al. `17]

are natural **Ultralight Dark Matter Candidates**:

1. Massless as long as global symmetry exact; small mass from tiny (non-perturbative) explicit symmetry breaking
2. Interactions with SM suppressed by large symmetry breaking scale

Ultralight Dark Matter Candidates

Spin 0: Pseudo Nambu-Goldstone Bosons

Pseudo Nambu-Goldstone bosons arising from the breaking of approximate global 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**)
  [Witten `84; Arvanitaki et al. `10; Acharya et al. `10; Cicoli et al. `12; Halverson et al. `17]

are natural **Ultralight Dark Matter Candidates**:

1. Massless as long as global 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 re-alignment

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

The Axion

Strong CP Puzzle

- Theta-term in Quantum Chromodynamics (QCD):

$$S_{\rm QCD} = \int d^4x \left\{ \overline{q}\,(i\gamma_\mu D^\mu - \mathcal{M}_q)\, q - \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} - \frac{\alpha_s}{8\pi}\,\overline{\theta}\, G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} \right\}$$

The Axion

Strong CP Puzzle

- Theta-term in Quantum Chromodynamics (QCD): [Belavin et al. `75;´t Hooft 76;Callan et al. `76;Jackiw,Rebbi `76]

$$S_{\rm QCD} = \int d^4x \left\{ \overline{q}\,(i\gamma_\mu D^\mu - \mathcal{M}_q)\,q - \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} - \frac{\alpha_s}{8\pi}\,\overline{\theta}\, G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} \right\}$$

The Axion

Strong CP Puzzle

- Theta-term in Quantum Chromodynamics (QCD): [Belavin et al. `75;´t Hooft 76;Callan et al. `76;Jackiw,Rebbi `76]

$$S_{\rm QCD} = \int d^4x \left\{ \overline{q}\,(i\gamma_\mu D^\mu - \mathcal{M}_q)\,q - \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} - \frac{\alpha_s}{8\pi}\,\overline{\theta}\, G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} \right\}$$

  - Theta angle $\overline{\theta} \in [-\pi, +\pi]$ fundamental parameter in addition to α_s and quark masses $\mathcal{M}_q = {\rm diag}(m_u, m_d, \ldots)$

The Axion

Strong CP Puzzle

- Theta-term in Quantum Chromodynamics (QCD): [Belavin et al. `75;´t Hooft 76;Callan et al. `76;Jackiw,Rebbi `76]

$$S_{\rm QCD} = \int d^4x \left\{ \overline{q}\,(i\gamma_\mu D^\mu - \mathcal{M}_q)\,q - \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} - \frac{\alpha_s}{8\pi}\,\overline{\theta}\,G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} \right\}$$

  - Theta angle $\overline{\theta} \in [-\pi, +\pi]$ fundamental parameter in addition to α_s and quark masses $\mathcal{M}_q = {\rm diag}(m_u, m_d, \ldots)$

- Topological theta term $\propto G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} \propto \mathbf{E}^a \cdot \mathbf{B}^a$
violates T and P, and thus CP

The Axion

Strong CP Puzzle

- Theta-term in Quantum Chromodynamics (QCD): [Belavin et al. `75;´t Hooft 76;Callan et al. `76;Jackiw,Rebbi `76]

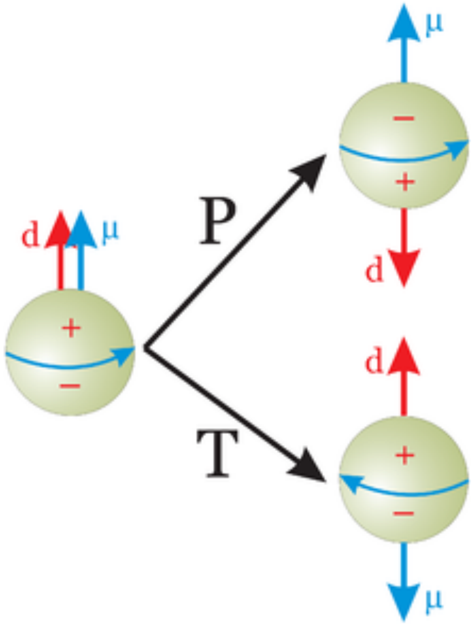
$$S_{\rm QCD} = \int d^4x \left\{ \overline{q}\,(i\gamma_\mu D^\mu - \mathcal{M}_q)\, q - \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} - \frac{\alpha_s}{8\pi}\, \overline{\theta}\, G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} \right\}$$

  - Theta angle $\overline{\theta} \in [-\pi, +\pi]$ fundamental parameter in addition to α_s and quark masses $\mathcal{M}_q = {\rm diag}(m_u, m_d, \ldots)$

- Topological theta term $\propto G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} \propto \mathbf{E}^a \cdot \mathbf{B}^a$ violates T and P, and thus CP

- Most sensitive probe of T and P violation in flavor conserving interactions: electric dipole moment of neutron; prediction: [Crewther,Di Vecchia,Veneziano,Witten 79;...; Pospelov,Ritz 00]

$$d_n \sim e\, \frac{m_*}{m_n^2}\, \overline{\theta} \sim 10^{-16}\, \overline{\theta}\; e\,{\rm cm}; \qquad m_* = \frac{m_u m_d}{m_u + m_d}$$



The Axion

Strong CP Puzzle

- Theta-term in Quantum Chromodynamics (QCD): [Belavin et al. `75;´t Hooft 76;Callan et al. `76;Jackiw,Rebbi `76]

$$S_{\rm QCD} = \int d^4x \left\{ \overline{q}\,(i\gamma_\mu D^\mu - \mathcal{M}_q)\,q - \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} - \frac{\alpha_s}{8\pi}\,\overline{\theta}\,G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} \right\}$$

  - Theta angle $\overline{\theta} \in [-\pi, +\pi]$ fundamental parameter in addition to α_s and quark masses $\mathcal{M}_q = {\rm diag}(m_u, m_d, \ldots)$

- Topological theta term $\propto G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} \propto \mathbf{E}^a \cdot \mathbf{B}^a$ violates T and P, and thus CP

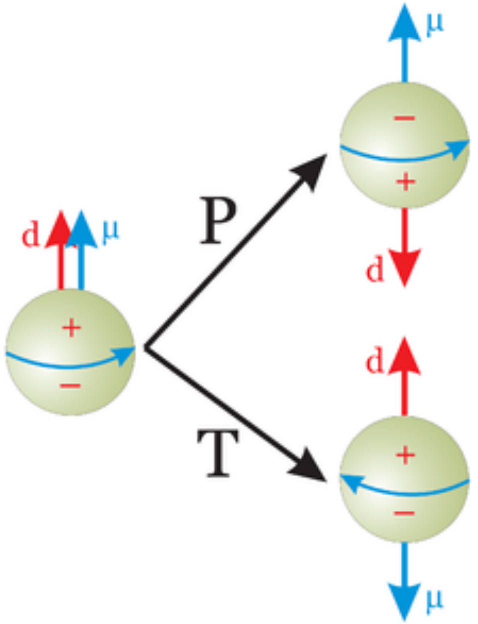
- Most sensitive probe of T and P violation in flavor conserving interactions: electric dipole moment of neutron; prediction: [Crewther,Di Vecchia,Veneziano,Witten 79;...; Pospelov,Ritz 00]

$$d_n \sim e\,\frac{m_*}{m_n^2}\,\overline{\theta} \sim 10^{-16}\;\overline{\theta}\;e\,{\rm cm}; \qquad m_* = \frac{m_u m_d}{m_u + m_d}$$

- Experiment: [Abel et al. 20]

$$|d_n| < 1.8 \times 10^{-26}\,e\,{\rm cm}$$

$$\Rightarrow |\overline{\theta}| \lesssim 10^{-10}$$



The Axion

Axionic Solution of Strong CP Puzzle

- Add to SM Nambu-Goldstone field, $\theta(x) \equiv A(x)/f_A \in [-\pi, \pi]$, respecting a non-linearly realized $U(1)_{\rm PQ}$ symmetry ($\theta(x) \to \theta(x) + \rm const.$), broken by coupling to gluonic topological charge density: [Peccei,Quinn 77]

$$\mathcal{L} \supset -\theta(x)\, q(x)\,; \qquad q(x) \equiv \frac{\alpha_s}{8\pi}\, G^b_{\mu\nu}(x)\tilde{G}^{b,\mu\nu}(x)$$

The Axion

Axionic Solution of Strong CP Puzzle

- Add to SM Nambu-Goldstone field, $\theta(x) \equiv A(x)/f_A \in [-\pi, \pi]$, respecting a non-linearly realized $U(1)_{\rm PQ}$ symmetry ($\theta(x) \to \theta(x) + \rm const.$), broken by coupling to gluonic topological charge density: [Peccei,Quinn 77]

$$\mathcal{L} \supset -\theta(x)\, q(x)\,; \qquad q(x) \equiv \frac{\alpha_s}{8\pi}\, G^b_{\mu\nu}(x)\tilde{G}^{b,\mu\nu}(x)$$

  - Can eliminate QCD $\overline{\theta}$-parameter

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\left[\overline{\theta} + \theta(x)\right] G^b_{\mu\nu}\tilde{G}^{b,\mu\nu}$$

    by shift $\theta(x) \to \theta(x) - \overline{\theta}$

The Axion

Axionic Solution of Strong CP Puzzle

- Add to SM Nambu-Goldstone field, $\theta(x) \equiv A(x)/f_A \in [-\pi, \pi]$, respecting a non-linearly realized $U(1)_{\rm PQ}$ symmetry ($\theta(x) \to \theta(x) + {\rm const.}$), broken by coupling to gluonic topological charge density: [Peccei,Quinn 77]

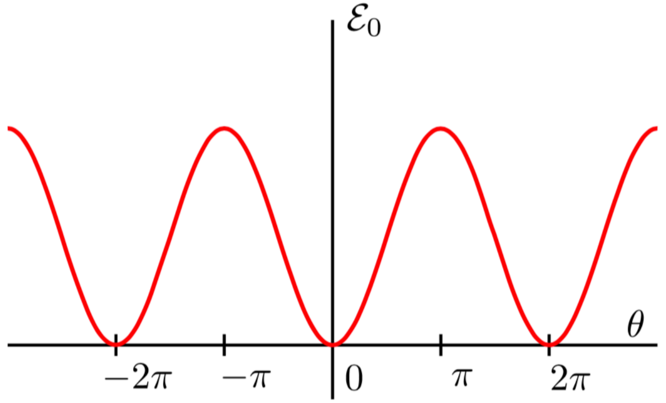
$$\mathcal{L} \supset -\theta(x)\, q(x)\,; \qquad q(x) \equiv \frac{\alpha_s}{8\pi}\, G^b_{\mu\nu}(x)\tilde{G}^{b,\mu\nu}(x)$$

  - Can eliminate QCD $\overline{\theta}$-parameter

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\left[\overline{\theta} + \theta(x)\right] G^b_{\mu\nu}\tilde{G}^{b,\mu\nu}$$

    by shift $\theta(x) \to \theta(x) - \overline{\theta}$

  - Effective potential $V(\theta)$ at energies below $\Lambda_{\rm QCD}$ has absolute minimum at $\theta = 0$ and thus predicts $\langle\theta(x)\rangle = 0$ [Vafa,Witten 84]
    No strong CP violation in vacuum



$$V(\theta) = m_\pi^2 f_\pi^2 \left(1 - \frac{\sqrt{1 + z^2 + 2z\cos\theta}}{1+z}\right)$$

[Di Vecchia,Veneziano `80; Leutwyler,Smilga 92]

$$z \equiv m_u/m_d \approx 1/2$$

The Axion

Axionic Solution of Strong CP Puzzle

- Add to SM Nambu-Goldstone field, $\theta(x) \equiv A(x)/f_A \in [-\pi, \pi]$, respecting a non-linearly realized $U(1)_{\rm PQ}$ symmetry ($\theta(x) \to \theta(x) + {\rm const.}$), broken by coupling to gluonic topological charge density: [Peccei,Quinn 77]

$$\mathcal{L} \supset -\theta(x)\, q(x)\,; \qquad q(x) \equiv \frac{\alpha_s}{8\pi}\, G^b_{\mu\nu}(x)\tilde{G}^{b,\mu\nu}(x)$$

  - Can eliminate QCD $\overline{\theta}$-parameter

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\left[\overline{\theta} + \theta(x)\right] G^b_{\mu\nu}\tilde{G}^{b,\mu\nu}$$

    by shift $\theta(x) \to \theta(x) - \overline{\theta}$

  - Effective potential $V(\theta)$ at energies below $\Lambda_{\rm QCD}$ has absolute minimum at $\theta = 0$ and thus predicts $\langle\theta(x)\rangle = 0$ [Vafa,Witten 84]
    No strong CP violation in vacuum
  - Particle excitation: **"axion"** [Weinberg 78; Wilczek 78]
  - It is a pseudo Nambu-Goldstone boson with mass parametrically suppressed by decay constant:

$$m_A \simeq \frac{\sqrt{z}}{1+z}\,\frac{m_\pi f_\pi}{f_A} \approx 6\ {\rm meV}\left(\frac{10^9\,{\rm GeV}}{f_A}\right)$$

$$z \equiv m_u/m_d \approx 1/2$$

The Axion

Minimal UV completion to get dynamical theta field

[Kim 79;Shifman,Vainshtein,Zakharov 80]

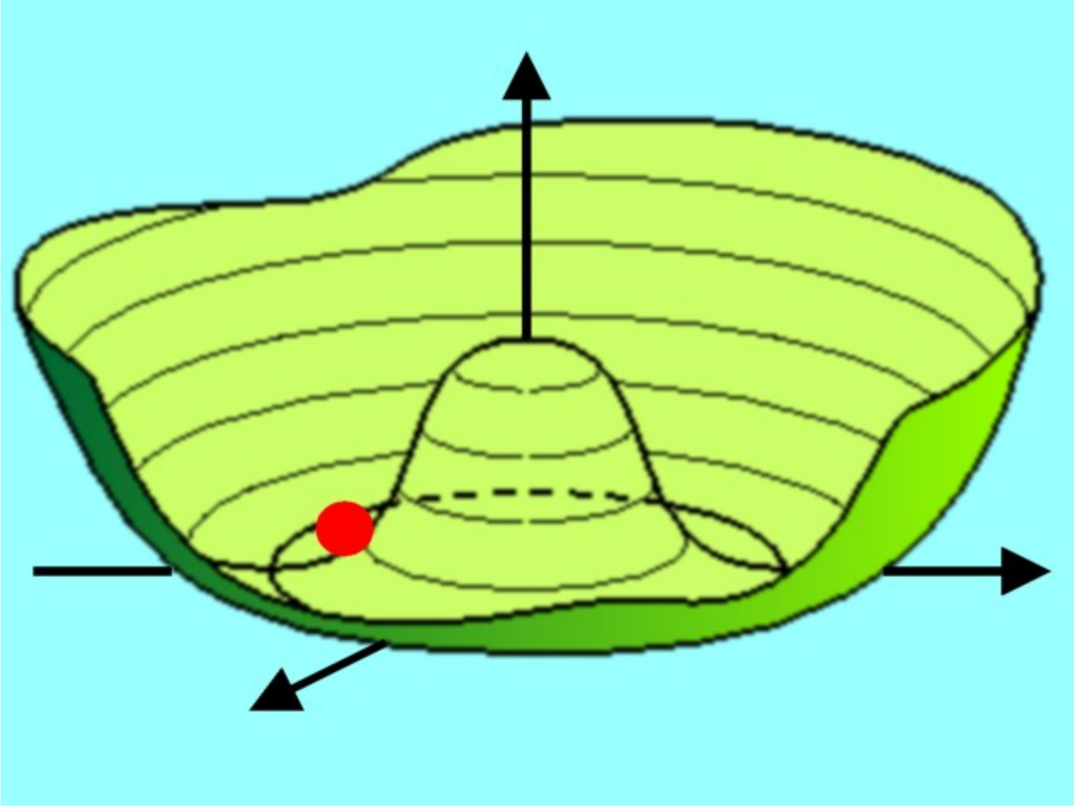
- Add to SM a singlet complex scalar field σ, featuring a spontaneously broken global $U(1)_{\rm PQ}$ symmetry and a vector-like coloured fermion charged under $U(1)_{\rm PQ}$:

$$\mathcal{L} \supset -\lambda_\sigma \left(|\sigma|^2 - \frac{v_{\rm PQ}^2}{2} \right)^2 + y\, \sigma\, \bar{\psi}_L \psi_R$$

  - Features three particles beyond SM:

$$\left[\sigma(x) = \frac{1}{\sqrt{2}} \left(v_{\rm PQ} + \rho(x) \right) {\rm e}^{iA(x)/v_{\rm PQ}} \right]$$

1. Excitation of angular field A: NG-boson
2. Excitation of modulus field ρ: $m_\rho = \sqrt{2\lambda_\sigma} v_{\rm PQ}$
3. Coloured fermion: $m_\psi = \frac{y}{\sqrt{2}} v_{\rm PQ}$



[Raffelt]

The Axion

Minimal UV completion to get dynamical theta field

[Kim 79;Shifman,Vainshtein,Zakharov 80]

- Add to SM a singlet complex scalar field σ, featuring a spontaneously broken global $U(1)_{\rm PQ}$ symmetry and a vector-like coloured fermion charged under $U(1)_{\rm PQ}$

$$\mathcal{L} \supset -\lambda_\sigma \left(|\sigma|^2 - \frac{v_{\rm PQ}^2}{2} \right)^2 + y\, \sigma\, \bar\psi_L \psi_R$$

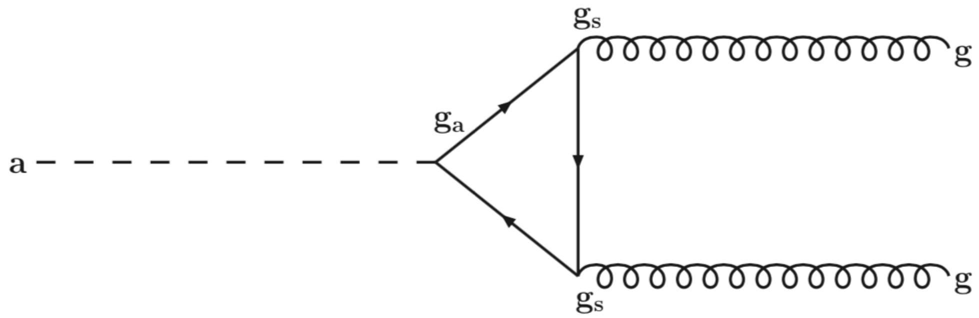
  - Features three particles beyond SM

$$\left[\sigma(x) = \frac{1}{\sqrt{2}} \left(v_{\rm PQ} + \rho(x) \right) {\rm e}^{iA(x)/v_{\rm PQ}} \right]$$

  1. Excitation of angular field A: NG-boson:
  2. Excitation of modulus field ρ: $m_\rho = \sqrt{2\lambda_\sigma} v_{\rm PQ}$
  3. Coloured fermion: $m_\psi = \frac{y}{\sqrt{2}} v_{\rm PQ}$

- Integrating out the modulus and the heavy fermion, the dynamics of the NG-boson is described by

$$\mathcal{L}_{\rm eff} \supset \frac{1}{2} \partial^\mu A\, \partial_\mu A - \frac{\alpha_s}{8\pi} \frac{A}{v_{\rm PQ}} G^a_{\mu\nu} \tilde G^{a\,\mu\nu}$$



[Vogel `09]

The Axion

Minimal UV completion to get dynamical theta field

[Kim 79;Shifman,Vainshtein,Zakharov 80]

- Add to SM a singlet complex scalar field σ, featuring a spontaneously broken global $U(1)_{\rm PQ}$ symmetry and a vector-like coloured fermion charged under $U(1)_{\rm PQ}$

$$\mathcal{L} \supset -\lambda_\sigma \left(|\sigma|^2 - \frac{v_{\rm PQ}^2}{2} \right)^2 + y\,\sigma\,\bar\psi_L \psi_R$$

  - Features three particles beyond SM

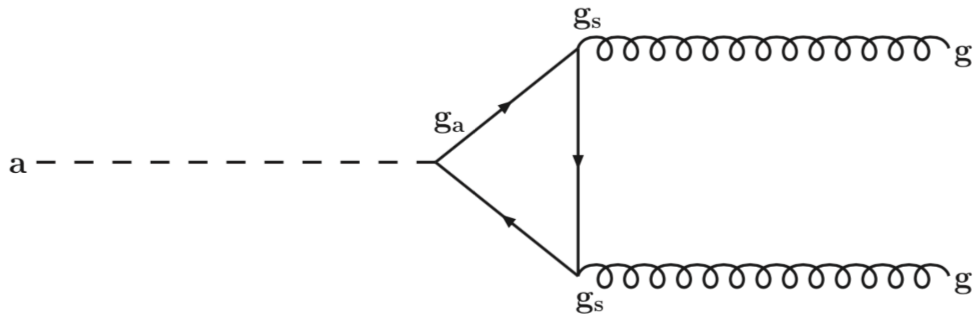
$$\left[\sigma(x) = \frac{1}{\sqrt{2}} \left(v_{\rm PQ} + \rho(x) \right) {\rm e}^{iA(x)/v_{\rm PQ}} \right]$$

    1. Excitation of angular field A: NG-boson:
    2. Excitation of modulus field ρ: $m_\rho = \sqrt{2\lambda_\sigma} v_{\rm PQ}$
    3. Coloured fermion: $m_\psi = \frac{y}{\sqrt{2}} v_{\rm PQ}$

- Integrating out the modulus and the heavy fermion, the dynamics of the NG-boson is described by

$$\mathcal{L}_{\rm eff} \supset \frac{1}{2}\partial^\mu A\, \partial_\mu A - \frac{\alpha_s}{8\pi} \frac{A}{v_{\rm PQ}} G^a_{\mu\nu} \tilde{G}^{a\,\mu\nu}$$

- QCD theta-parameter can be replaced by dynamical field $\theta(x) = A(x)/v_{\rm PQ}$



[Vogel `09]

The Axion

Axion couplings to SM at energies below QCD scale

- UV model-independent parametrisation of axion couplings to SM below QCD scale:

$$\mathcal{L}_A \supset -\frac{i}{2}\frac{C_{Ad_N}}{f_A}\,A\,\overline{\Psi}_N\sigma_{\mu\nu}\gamma_5\Psi_N F^{\mu\nu} - \frac{\alpha}{8\pi}\frac{C_{A\gamma}}{f_A}\,A\,F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{2}\frac{C_{Af}}{f_A}\,\partial_\mu A\,\overline{\Psi}_f\gamma^\mu\gamma_5\Psi_f$$

The Axion

Axion couplings to SM at energies below QCD scale

- UV model-independent parametrisation of axion couplings to SM below QCD scale:

$$\mathcal{L}_A \supset -\frac{i}{2}\frac{C_{Ad_N}}{f_A}\,A\,\overline{\Psi}_N\sigma_{\mu\nu}\gamma_5\Psi_N F^{\mu\nu} - \frac{\alpha}{8\pi}\frac{C_{A\gamma}}{f_A}\,A\,F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{2}\frac{C_{Af}}{f_A}\,\partial_\mu A\,\overline{\Psi}_f\gamma^\mu\gamma_5\Psi_f$$

- „Invisible axion“: [Kim 79;Shifman,Vainshtein,Zakharov 80;Zhitnitsky 80;Dine,Fischler,Srednicki 81;...]
  - Couplings to SM suppressed by inverse power of $f_A = v_{\rm PQ}/N \gg v = 246\,{\rm GeV}$
  - Since mass inversely proportional to decay constant: couplings proportional to mass

The Axion

Axion couplings to SM at energies below QCD scale

- UV model-independent parametrisation of axion couplings to SM below QCD scale:

$$\mathcal{L}_A \supset -\frac{i}{2}\frac{C_{Ad_N}}{f_A}\, A\, \overline{\Psi}_N \sigma_{\mu\nu}\gamma_5 \Psi_N F^{\mu\nu} - \frac{\alpha}{8\pi}\frac{C_{A\gamma}}{f_A}\, A\, F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{2}\frac{C_{Af}}{f_A}\, \partial_\mu A\, \overline{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

- „Invisible axion“: [Kim 79;Shifman,Vainshtein,Zakharov 80;Zhitnitsky 80;Dine,Fischler,Srednicki 81;...]
  - Couplings to SM suppressed by inverse power of $f_A = v_{\rm PQ}/N \gg v = 246\,{\rm GeV}$
  - Since mass inversely proportional to decay constant: couplings proportional to mass
- Least model-dependent couplings:
  - EDM coupling: $C_{Ad_N} = 2.4(1.0) \times 10^{-16}\, e\,{\rm cm}$ [Pospelov,Ritz `00]

The Axion

Axion couplings to SM at energies below QCD scale

- UV model-independent parametrisation of axion couplings to SM below QCD scale:

$$\mathcal{L}_A \supset -\frac{i}{2}\frac{C_{Ad_N}}{f_A}\,A\,\overline{\Psi}_N\sigma_{\mu\nu}\gamma_5\Psi_N F^{\mu\nu} - \frac{\alpha}{8\pi}\frac{C_{A\gamma}}{f_A}\,A\,F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{2}\frac{C_{Af}}{f_A}\,\partial_\mu A\,\overline{\Psi}_f\gamma^\mu\gamma_5\Psi_f$$

- „Invisible axion“: [Kim 79;Shifman,Vainshtein,Zakharov 80;Zhitnitsky 80;Dine,Fischler,Srednicki 81;...]
  - Couplings to SM suppressed by inverse power of $f_A = v_{\rm PQ}/N \gg v = 246\,{\rm GeV}$
  - Since mass inversely proportional to decay constant: couplings proportional to mass
- Least model-dependent couplings:
  - EDM coupling: $C_{Ad_N} = 2.4(1.0)\times 10^{-16}\,e\,{\rm cm}$ [Pospelov,Ritz `00]
  - Photon coupling: $C_{A\gamma} = \frac{E}{N} - 1.92(4)$ [Kaplan 85;Srednicki `85; Grilli di Cortona et al. `16]

The Axion

Axion couplings to SM at energies below QCD scale

- UV model-independent parametrisation of axion couplings to SM below QCD scale:

$$\mathcal{L}_A \supset -\frac{i}{2}\frac{C_{Ad_N}}{f_A}\, A\,\overline{\Psi}_N \sigma_{\mu\nu}\gamma_5 \Psi_N F^{\mu\nu} - \frac{\alpha}{8\pi}\frac{C_{A\gamma}}{f_A}\, A\, F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{2}\frac{C_{Af}}{f_A}\,\partial_\mu A\;\overline{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

- „Invisible axion“: [Kim 79;Shifman,Vainshtein,Zakharov 80;Zhitnitsky 80;Dine,Fischler,Srednicki 81;...]
  - Couplings to SM suppressed by inverse power of $f_A = v_{\rm PQ}/N \gg v = 246\,{\rm GeV}$
  - Since mass inversely proportional to decay constant: couplings proportional to mass
- Least model-dependent couplings:
  - EDM coupling: $C_{Ad_N} = 2.4(1.0)\times 10^{-16}\, e\,{\rm cm}$ [Pospelov,Ritz `00]
  - Photon coupling: $C_{A\gamma} = \frac{E}{N} - 1.92(4)$ [Kaplan 85;Srednicki `85; Grilli di Cortona et al. `16]
  - Nucleon couplings: [Grilli di Cortona et al. `16]

$$\begin{aligned} C_{Ap} &= -0.47(3) + 0.88(3)C_{Au} - 0.39(2)C_{Ad} - 0.038(5)C_{As} \\ &\quad - 0.012(5)C_{Ac} - 0.009(2)C_{Ab} - 0.0035(4)C_{At}\,, \\ C_{An} &= -0.02(3) + 0.88(3)C_{Ad} - 0.39(2)C_{Au} - 0.038(5)C_{As} \\ &\quad - 0.012(5)C_{Ac} - 0.009(2)C_{Ab} - 0.0035(4)C_{At} \end{aligned}$$

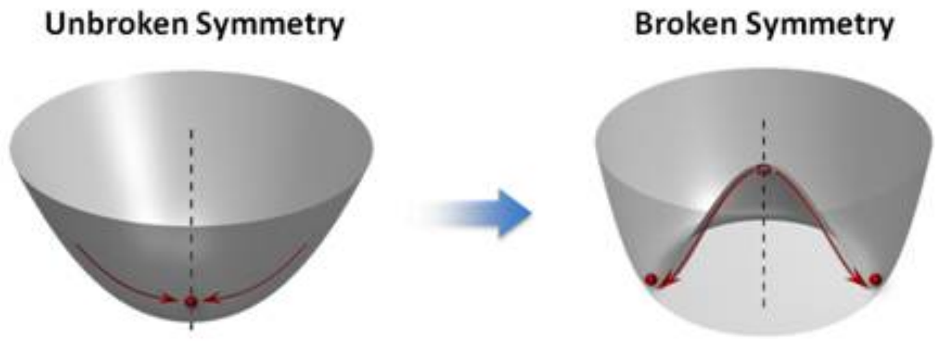
Axion Dark Matter

Production via vacuum re-alignment

- PQ phase transition takes place at

$$T \lesssim T_c^{\rm PQ} \sim v_{\rm PQ} = N f_A$$

- Axion takes random initial values in causally connected domains



[Peking University]

Axion Dark Matter

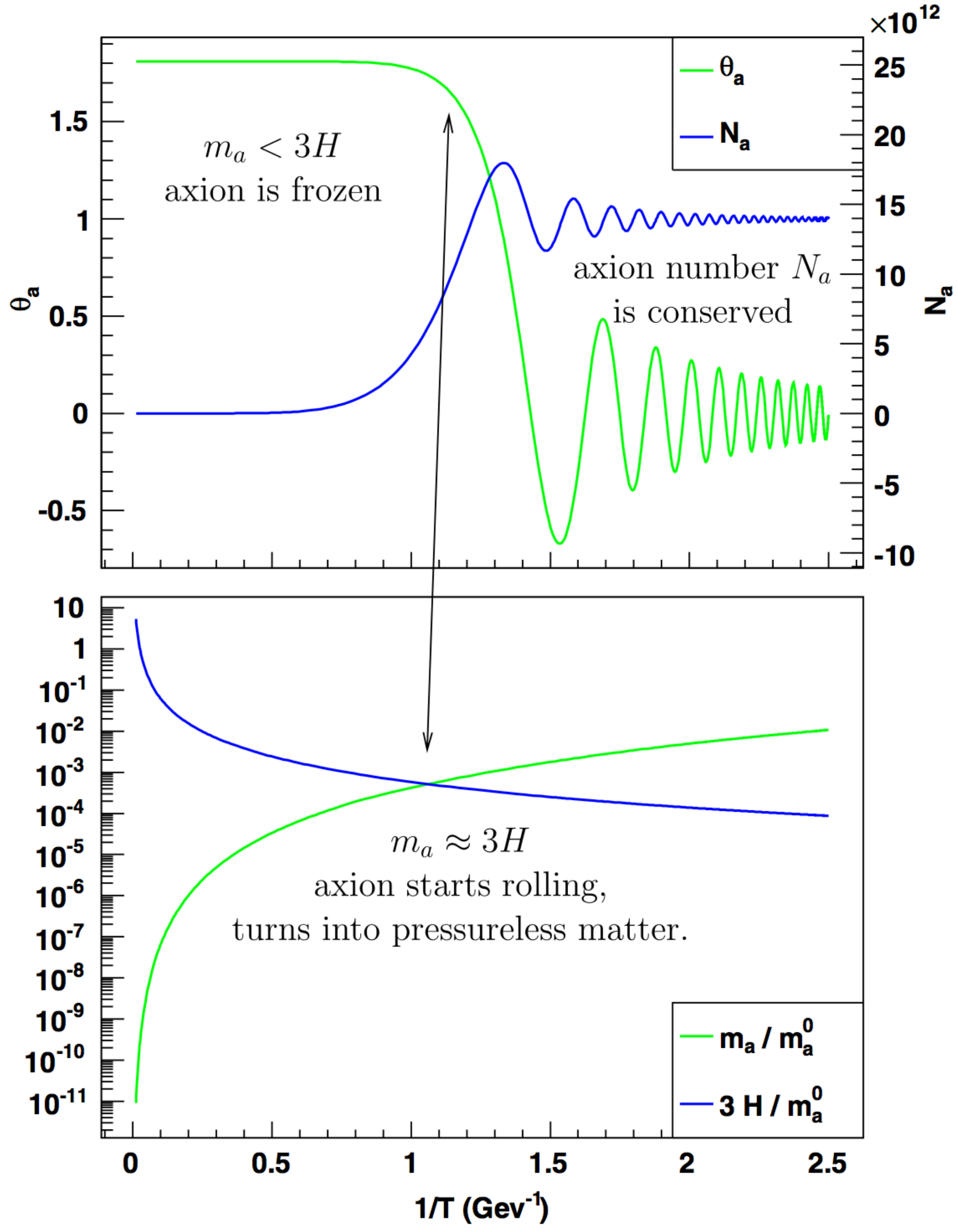
Production via vacuum re-alignment

- PQ phase transition takes place at

$$T \lesssim T_c^{\rm PQ} \sim v_{\rm PQ} = N f_A$$

- Axion takes random initial values in causally connected domains
- When $H(T) \sim m_A(T)$, axion field starts to oscillate around minimum of potential; behaves like cold dark matter: $w_A = p_A/\rho_A \simeq 0$

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



[Wantz,Shellard `09]

Axion Dark Matter

Production via vacuum re-alignment

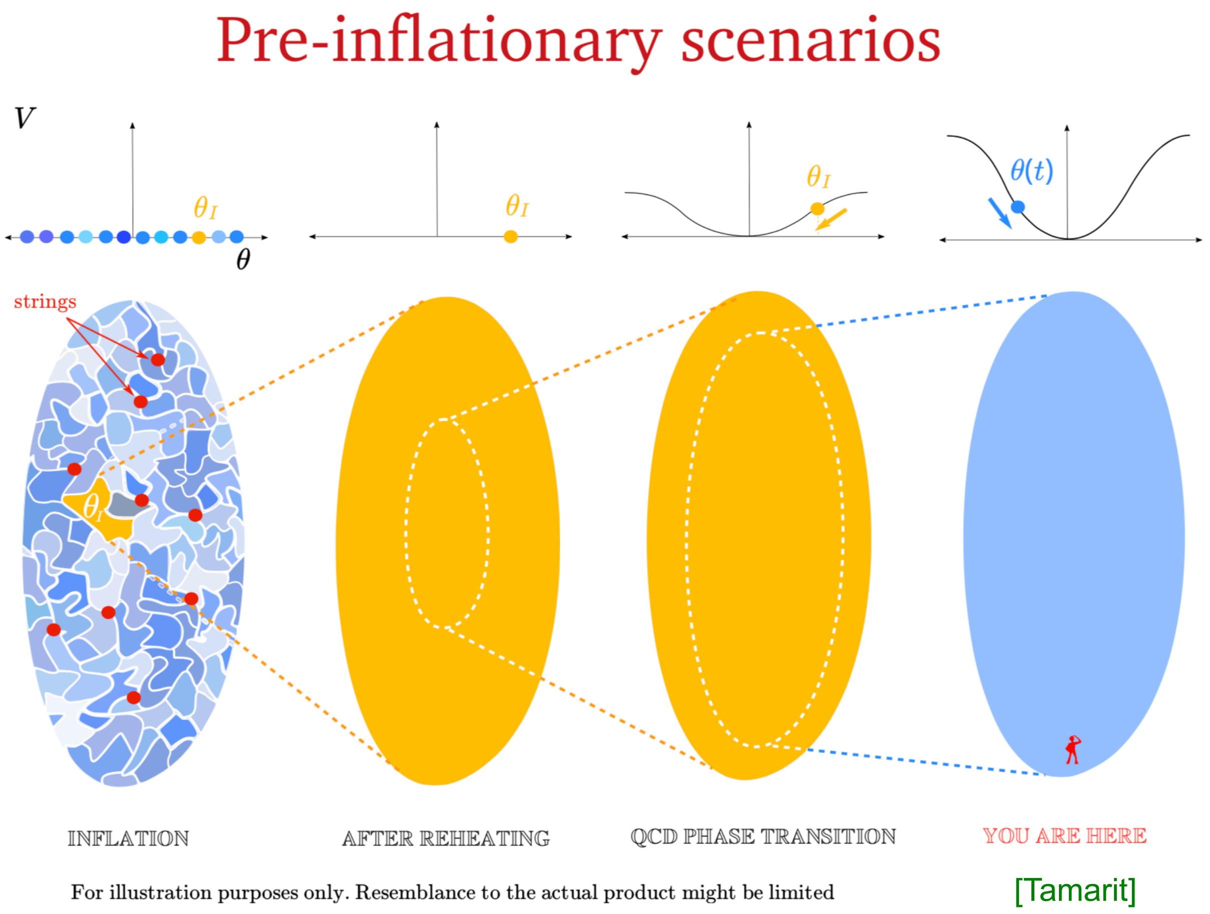
- PQ phase transition takes place at

$$T \lesssim T_c^{\rm PQ} \sim v_{\rm PQ} = N f_A$$

- Axion takes random initial values in causally connected domains

- When $H(T) \sim m_A(T)$, axion field starts to oscillate around minimum of potential; behaves like cold dark matter: $w_A = p_A/\rho_A \simeq 0$
  [Preskill,Wise,Wilczek 83; Abbott,Sikivie 83; Dine,Fischler 83,....]

- If PQ symmetry broken before or during inflation and not restored afterwards:
  - Axion CDM density depends on single initial value in patch, which becomes observable universe, and decay constant



[Tamarit]

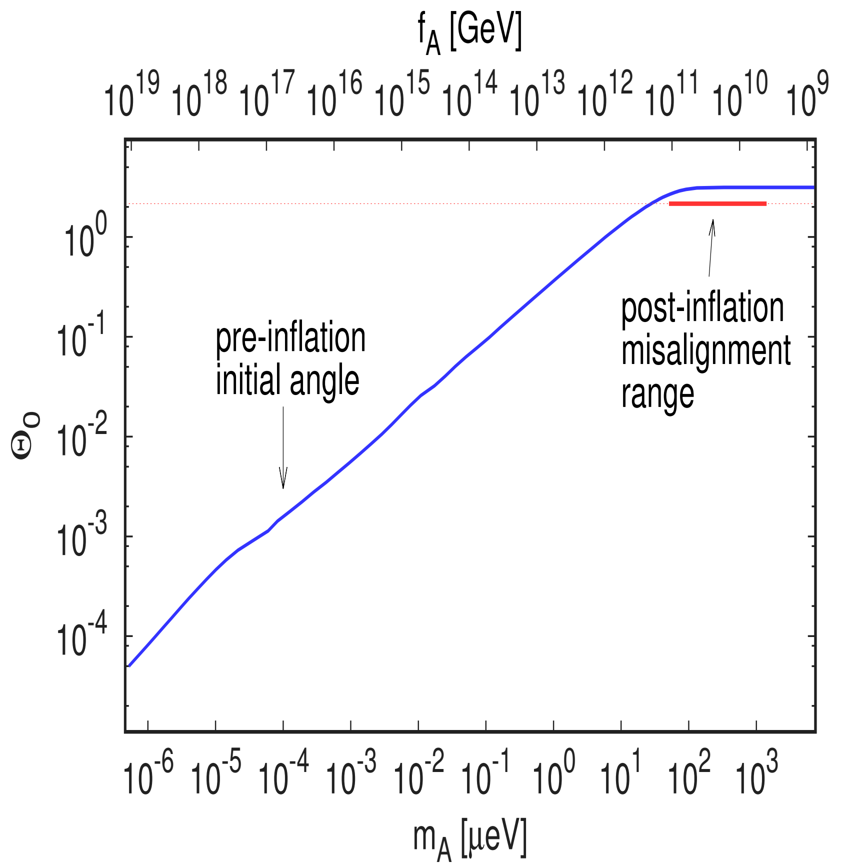
Axion Dark Matter

Production via vacuum re-alignment

- PQ phase transition takes place at

$$T \lesssim T_c^{\rm PQ} \sim v_{\rm PQ} = N f_A$$

- Axion takes random initial values in causally connected domains
- When $H(T) \sim m_A(T)$, axion field starts to oscillate around minimum of potential; behaves like cold dark matter: $w_A = p_A/\rho_A \simeq 0$
  [Preskill,Wise,Wilczek 83; Abbott,Sikivie 83; Dine,Fischler 83,....]
- If PQ symmetry broken before or during inflation and not restored afterwards:
  - Axion CDM density depends on single initial value in patch, which becomes observable universe, and decay constant



[Borsanyi et al., Nature `16]

$$\Omega_A^{\rm vr} h^2 \approx 0.12 \left(\frac{f_A}{9\times 10^{11}\ {\rm GeV}}\right)^{1.165} \Theta_0^2$$

$$\approx 0.12 \left(\frac{6\ \mu{\rm eV}}{m_A}\right)^{1.165} \Theta_0^2 ,$$

Axion Dark Matter

Axion/ALP DM parameter range huge

- In pre-inflationary PQ symmetry breaking scenario, wide range of decay constant and mass yields observed DM abundance:
  - Axion: $\Omega_A^{\rm vr} h^2 \approx 0.12 \left(\frac{f_A}{9 \times 10^{11}\ \rm GeV} \right)^{1.165} \Theta_0^2$
  - ALP: $\Omega_{\rm ALP}^{\rm vr} h^2 = 0.12 \left(\frac{f_A}{10^{16}\,\rm GeV} \right)^2 \left(\frac{m_A}{4.7 \times 10^{-19}\,\rm eV} \right)^{1/2} \Theta_0^2$

Axion Dark Matter

Axion/ALP DM parameter range huge

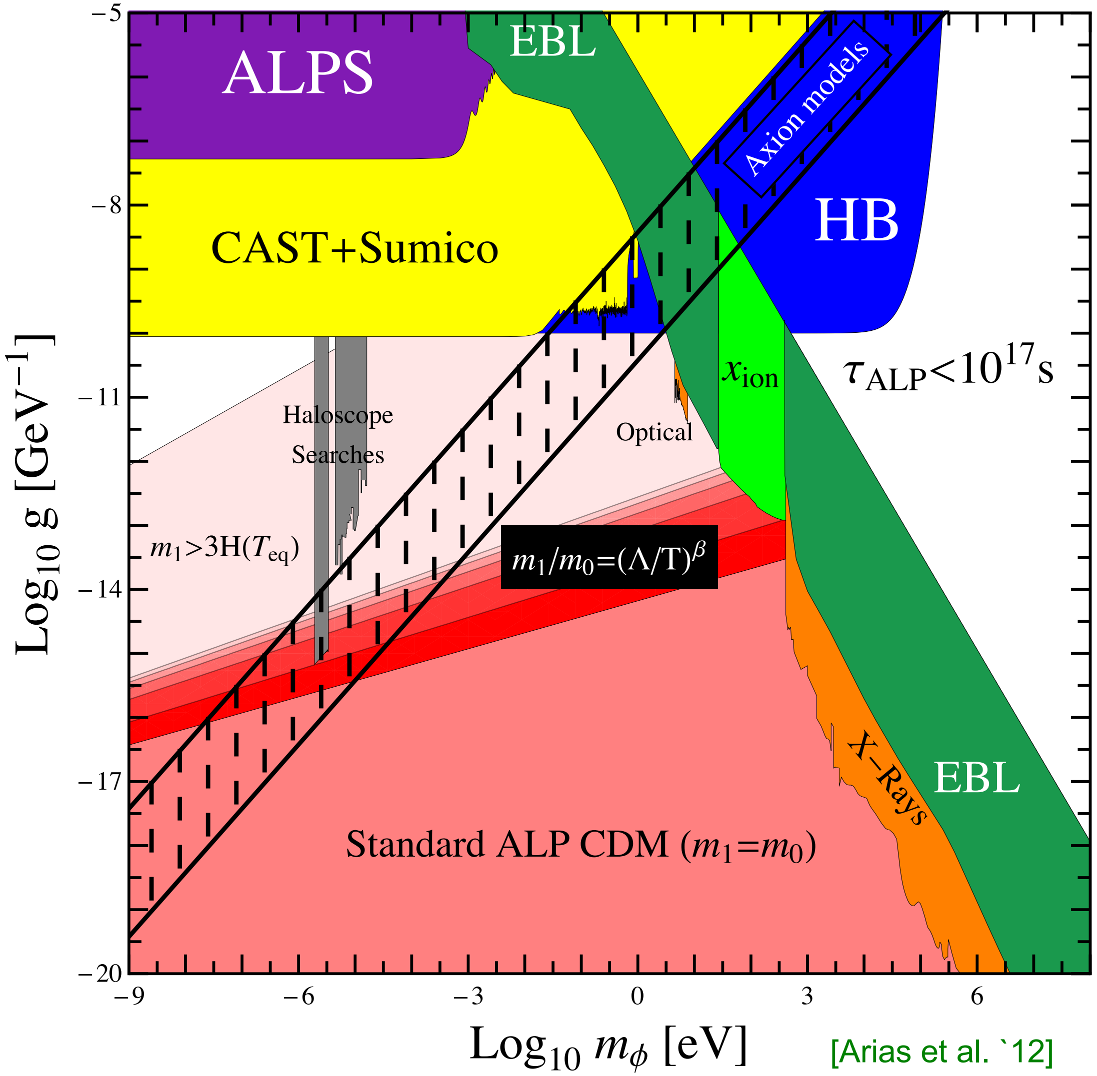
- In pre-inflationary PQ symmetry breaking scenario, wide range of decay constant and mass yields observed DM abundance:
  - Axion: $\Omega_A^{\rm vr} h^2 \approx 0.12 \left(\frac{f_A}{9\times 10^{11}\ {\rm GeV}}\right)^{1.165} \Theta_0^2$
  - ALP: $\Omega_{\rm ALP}^{\rm vr} h^2 = 0.12 \left(\frac{f_A}{10^{16}\ {\rm GeV}}\right)^2 \left(\frac{m_A}{4.7\times 10^{-19}\ {\rm eV}}\right)^{1/2} \Theta_0^2$
- Parameter space in SM couplings vs. mass of interest for DM even wider because of model dependent Wilson coefficients, e.g.:

$$g_{A\gamma} \equiv \frac{\alpha}{2\pi f_A} C_{A\gamma}$$

  - There are models with $C_{A\gamma} \gg 1$

[Di Luzio,Mescia,Nardi 16, 18;Farina et al. `16;Agrawal et al. `17;Sokolov,AR `21]

$$C_{A\gamma} = 1:$$



[Arias et al. `12]

Axion Dark Matter

Axion/ALP DM parameter range huge

- In pre-inflationary PQ symmetry breaking scenario, wide range of decay constant and mass yields observed DM abundance:
  - Axion: $\Omega_A^{\rm vr} h^2 \approx 0.12 \left(\frac{f_A}{9\times 10^{11}\ {\rm GeV}}\right)^{1.165} \Theta_0^2$
  - ALP: $\Omega_{\rm ALP}^{\rm vr} h^2 = 0.12 \left(\frac{f_A}{10^{16}\ {\rm GeV}}\right)^2 \left(\frac{m_A}{4.7\times 10^{-19}\ {\rm eV}}\right)^{1/2} \Theta_0^2$
- Parameter space in SM couplings vs. mass of interest for DM even wider because of model dependent Wilson coefficients, e.g.:

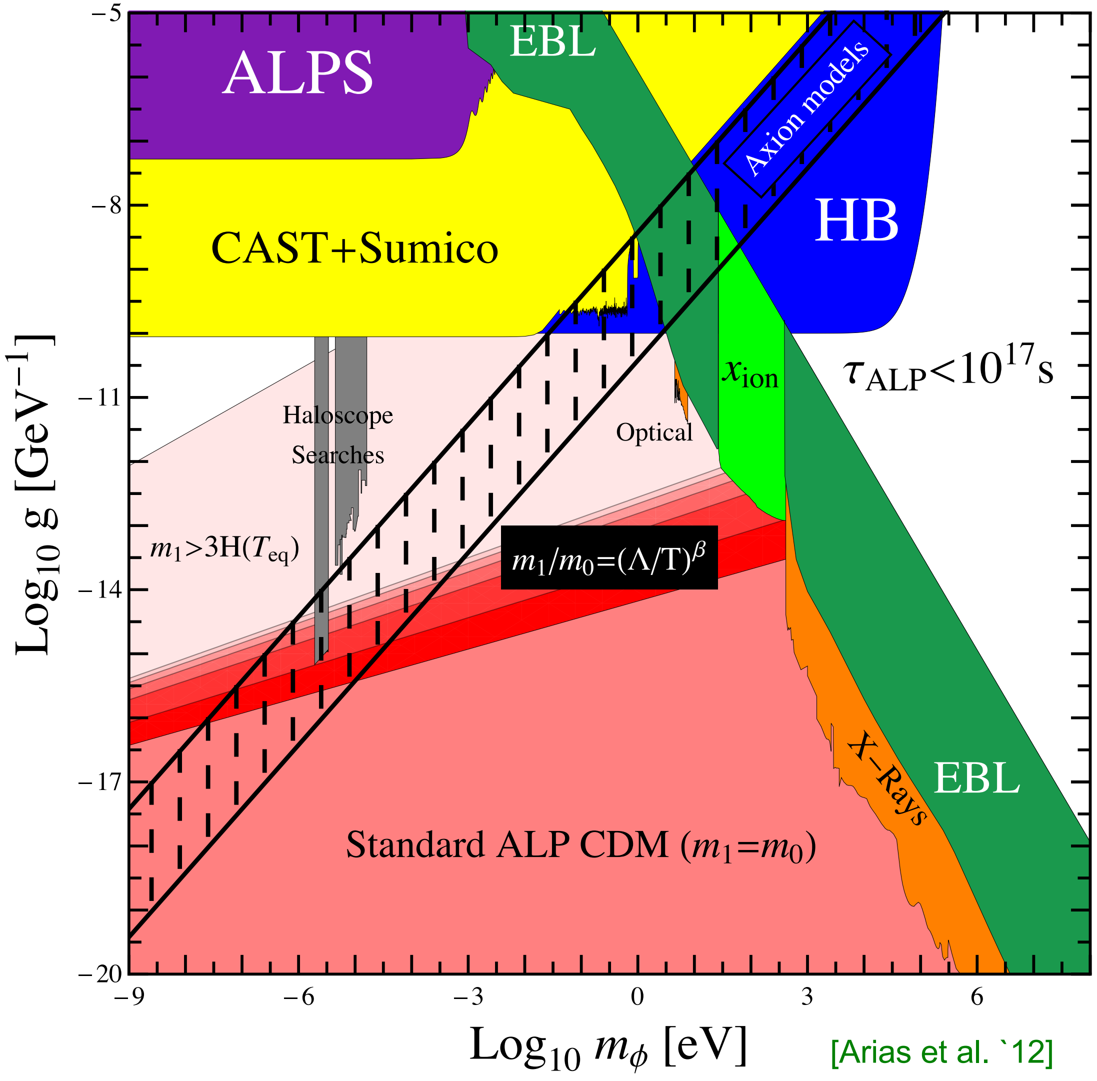
$$g_{A\gamma} \equiv \frac{\alpha}{2\pi f_A} C_{A\gamma}$$

  - There are models with $C_{A\gamma} \gg 1$

    [Di Luzio,Mescia,Nardi 16, 18;Farina et al. `16;Agrawal et al. `17;Sokolov,AR `21]

- Modified initial conditions: Kinetic/trapped misalignment enhance abundance, leading to preference of lower decay constant (higher SM couplings) [Co,Harigaya `19;Co,Hall,Harigaya `19;Di Luzio et al. `21]

$C_{A\gamma} = 1:$



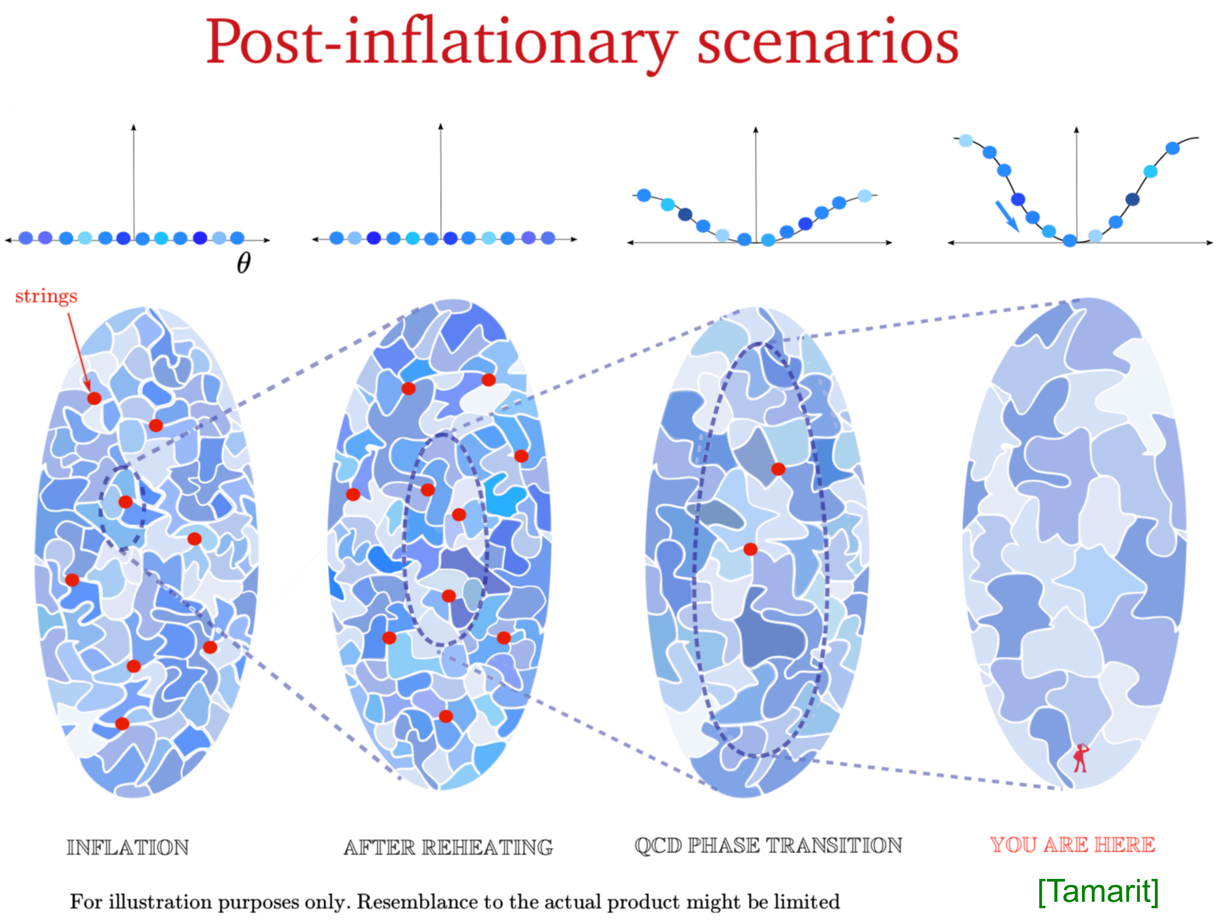
[Arias et al. `12]

Axion Dark Matter

Production via decay of topological defects

- If PQ symmetry broken after inflation, need to average over random initial axion field values:

$$\Omega_A^{\rm vr} h^2 \approx 0.12 \left(\frac{30\ \mu\text{eV}}{m_A}\right)^{1.165}$$



[Tamarit]

Axion Dark Matter

Production via decay of topological defects

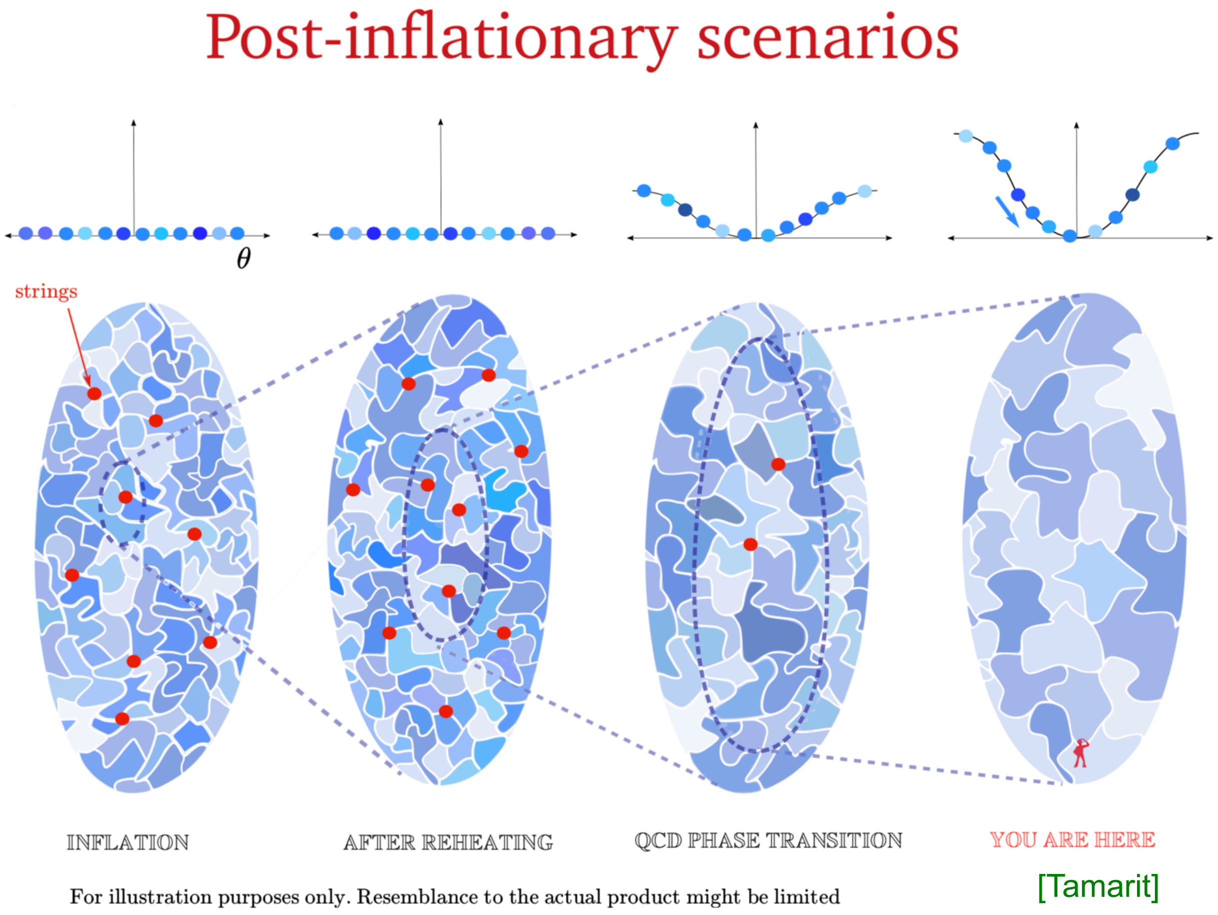
- If PQ symmetry broken after inflation, need to average over random initial axion field values:

$$\Omega_A^{\rm vr} h^2 \approx 0.12 \left(\frac{30\ \mu\text{eV}}{m_A}\right)^{1.165}$$

- Observed CDM abundance puts lower bound on axion mass:

$$m_A > 28(2)\ \mu\text{eV}$$

[Borsanyi et al., Nature `16 [1606.0794]]



[Tamarit]

Axion Dark Matter

Production via decay of topological defects

- If PQ symmetry broken after inflation, need to average over random initial axion field values:

$$\Omega_A^{\rm vr} h^2 \approx 0.12 \left(\frac{30\ \mu\text{eV}}{m_A}\right)^{1.165}$$

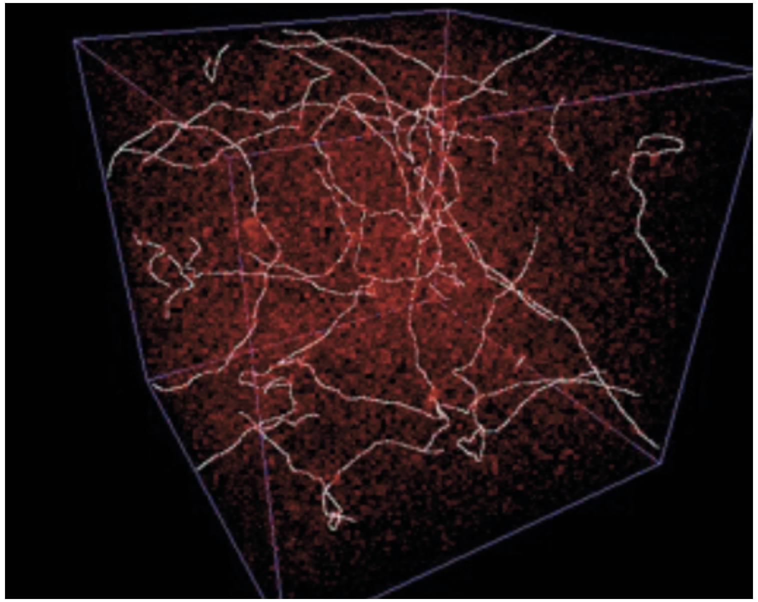
- Observed CDM abundance puts lower bound on axion mass:

$$m_A > 28(2)\ \mu\text{eV}$$

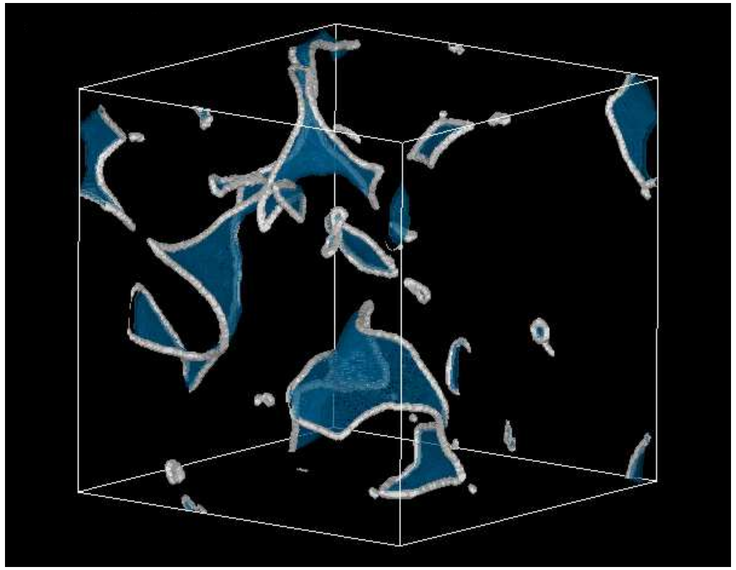
[Borsanyi et al., Nature `16 [1606.0794]]

- Axions also produced by collapse of network of topological defects – strings and domain-walls –
  - Very active research field:

[Hiramatsu et al. 11,12,13; Kawasaki,Saikawa,Segikuchi 15; AR,Saikawa `16; Klaer,Moore `17; Gorghetto,Hardy,Villadoro `18; Buschmann et al. 19; Hindmarsh 19; Gorghetto,Hardy,Villadoro ‘20]

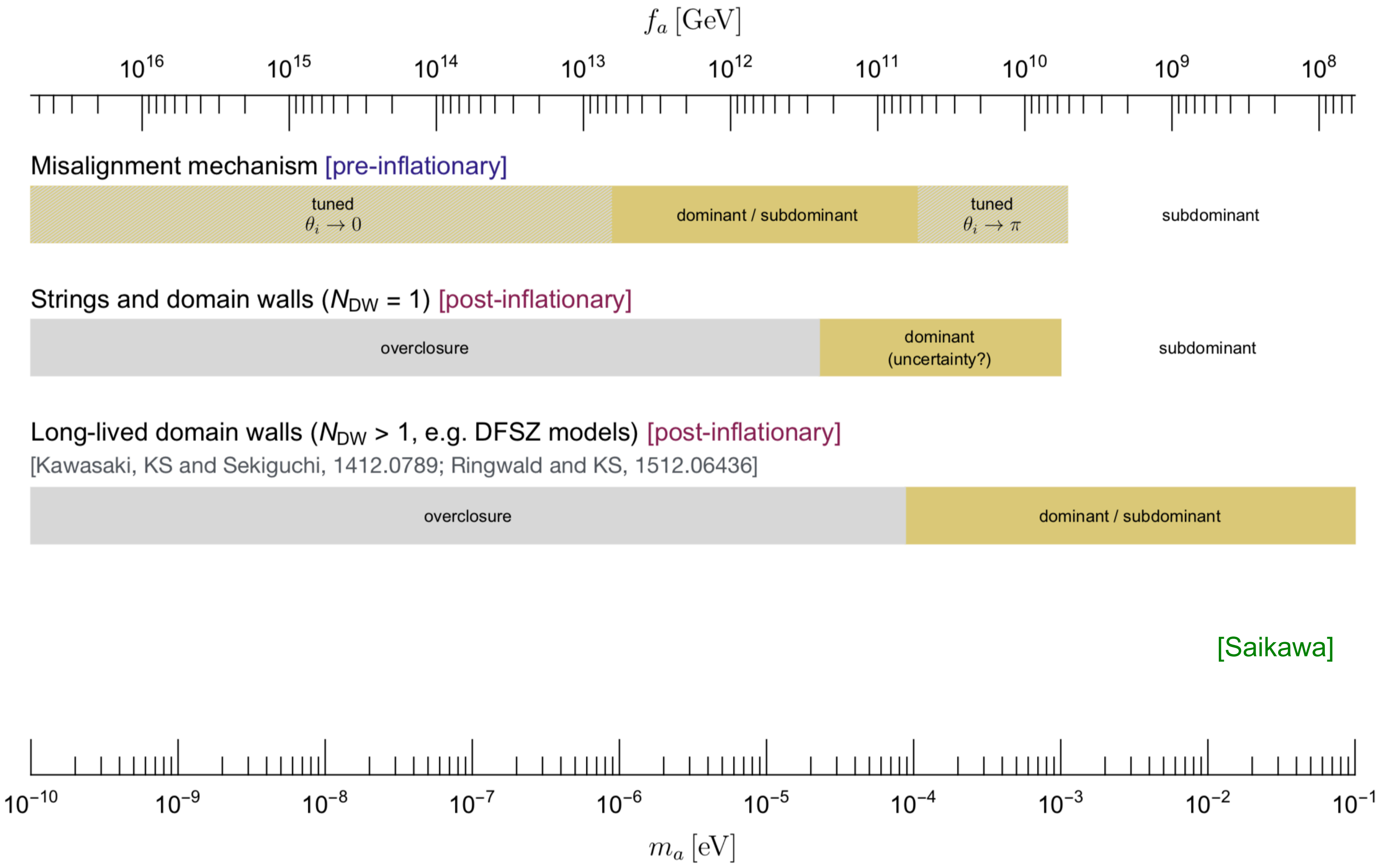


[Hiramatsu et al.]



Axion Dark Matter

Dark Matter axion mass spans a huge range



Ultralight Dark Matter Candidates

Spin 1: Ultralight U(1) gauge bosons

“Hidden” or “dark” photons (DPs) - gauge bosons of a local U(1) gauge theory under which SM particles are uncharged –

are **Ultralight Dark Matter Candidates**

Ultralight Dark Matter Candidates

Spin 1: Ultralight U(1) gauge bosons

“Hidden” or “dark” photons (DPs) - gauge bosons of a local U(1) gauge theory under which SM particles are uncharged – such as

- U(1) factors from breaking of grand unified gauge group

Ultralight Dark Matter Candidates

Spin 1: Ultralight U(1) gauge bosons

“Hidden” or “dark” photons (DPs) - gauge bosons of a local U(1) gauge theory under which SM particles are uncharged – such as

- U(1) factors from breaking of grand unified gauge group
- Occuring in low energy effective field theories from string theory: [Goodsell,AR 10]

Ultralight Dark Matter Candidates

Spin 1: Ultralight U(1) gauge bosons

“Hidden” or “dark” photons (DPs) - gauge bosons of a local U(1) gauge theory under which SM particles are uncharged – such as

- U(1) factors from breaking of grand unified gauge group
- Occuring in low energy effective field theories from string theory: [Goodsell,AR 10]
    - Type II string (brane world scenarios):
        - RR U(1)s: KK zero modes arising in 4D decomposition of 10D form fields

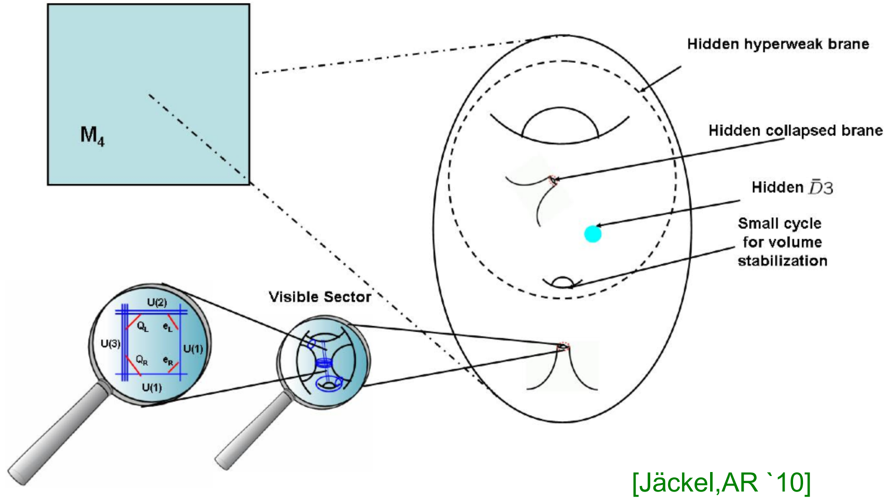
Ultralight Dark Matter Candidates

Spin 1: Ultralight U(1) gauge bosons

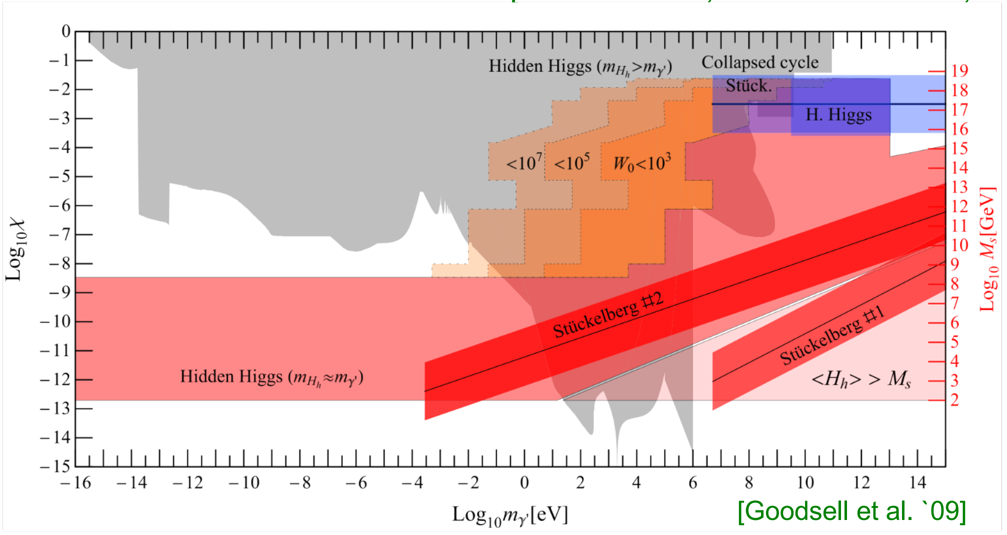
“Hidden” or “dark” photons (DPs) - gauge bosons of a local U(1) gauge theory under which SM particles are uncharged – such as

- U(1) factors from breaking of grand unified gauge group
- Occuring in low energy effective field theories from string theory: [Goodsell,AR 10]
  - Type II string (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]



[Jäckel,AR `10]



[Goodsell et al. `09]

Ultralight Dark Matter Candidates

Spin 1: Ultralight U(1) gauge bosons

“Hidden” or “dark” photons (DPs) - gauge bosons of a local U(1) gauge theory under which SM particles are uncharged – such as

- U(1) factors from breaking of grand unified gauge group
- Occuring in low energy effective field theories from string theory: [Goodsell,AR 10]
  - Type II string (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]

are **Ultralight Dark Matter Candidates**

Ultralight Dark Matter Candidates

Spin 1: Ultralight U(1) gauge bosons

“Hidden” or “dark” photons (DPs) - gauge bosons of a local U(1) gauge theory under which SM particles are uncharged – such as

- U(1) factors from breaking of grand unified gauge group
- Occuring in low energy effective field theories from string theory: [Goodsell,AR 10]
  - Type II string (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]

are **Ultralight Dark Matter Candidates**:

1. Gauge symmetry forbids explicit mass terms; small mass may be generated via
   - Higgs mechanism $m_{\gamma'} \sim g_h v_h$
   - Stückelberg mechanism: topological mass

Ultralight Dark Matter Candidates

Spin 1: Ultralight U(1) gauge bosons

"Hidden" or "dark" photons (DPs) - gauge bosons of a local U(1) gauge theory under which SM particles are uncharged – such as

- U(1) factors from breaking of grand unified gauge group
- Occuring in low energy effective field theories from string theory: [Goodsell,AR 10]
    - Type II string (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]

are **Ultralight Dark Matter Candidates**:

1. Gauge symmetry forbids explicit mass terms; small mass may be generated via
    - Higgs mechanism $m_{\gamma'} \sim g_h v_h$
    - Stückelberg mechanism: topological mass
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]

Ultralight Dark Matter Candidates

Spin 1: Ultralight U(1) gauge bosons

“Hidden” or “dark” photons (DPs) - gauge bosons of a local U(1) gauge theory under which SM particles are uncharged – such as

- U(1) factors from breaking of grand unified gauge group
- Occuring in low energy effective field theories from string theory: [Goodsell,AR 10]
  - Type II string (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]

are **Ultralight Dark Matter Candidates**:

1. Gauge symmetry forbids explicit mass terms; small mass may be generated via
   - Higgs mechanism $m_{\gamma'} \sim g_h v_h$
   - Stückelberg mechanism: topological mass
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 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]

Coherent-Field Dark Matter Search Methods

Many possibilities and challenges

1. Axion, ALP, DP searches based on coupling to electromagnetism
   - Light-Shining-Through-a-Wall (LSW) experiments
   - Searches for solar axions (Helioscopes)
   - Direct detection of axion, ALP, DP DM via coupling to EM (Haloscopes)
2. Axion/ALP searches based on matter couplings
   - Fifth-force experiments
   - Direct detection of axion/ALP DM wind via EMR and NMR techniques
3. Axion Searches based on EDM coupling
   - Direct detection of axion DM via NMR search for oscillating nuclear EDMs

Coherent-Field Dark Matter Search Methods

Many possibilities and challenges

1. **Axion, ALP, DP searches based on coupling to electromagnetism**
   - **Light-Shining-Through-a-Wall (LSW) experiments**
   - **Searches for solar axions (Helioscopes)**
   - **Direct detection of axion, ALP, DP DM via coupling to EM (Haloscopes)**
2. Axion/ALP searches based on matter couplings
   - Fifth-force experiments
   - Direct detection of axion/ALP DM wind via EMR and NMR techniques
3. Axion Searches based on EDM coupling
   - Direct detection of axion DM via NMR search for oscillating nuclear EDMs

Will concentrate on 1.

Axion/ALP, DP searches based on EM coupling

Photon regeneration experiments

Axion/ALP coupling

$$\mathcal{L} \supset -\frac{g_{a\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \equiv g_{a\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$$

Dark Photon coupling

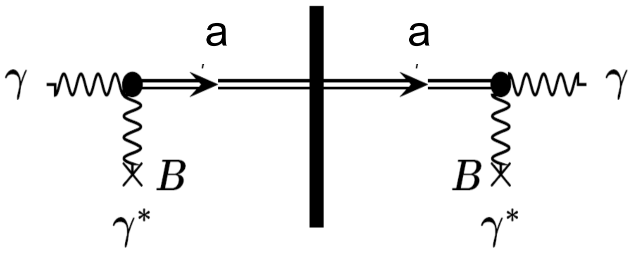
$$\mathcal{L} \supset -\frac{\chi}{2} F'_{\mu\nu}F^{\mu\nu}$$

Axion/ALP, DP searches based on EM coupling

Photon regeneration experiments

Axion/ALP coupling

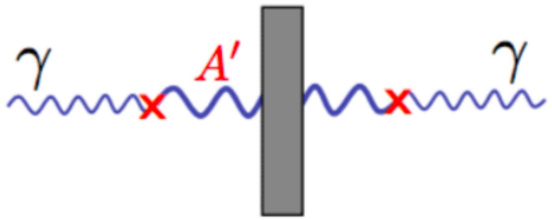
$$\mathcal{L} \supset -\frac{g_{a\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \equiv g_{a\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$$



Laser shining through a wall (LSW)

Dark Photon coupling

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



[Sikivie `83]

Axion/ALP, DP searches based on EM coupling

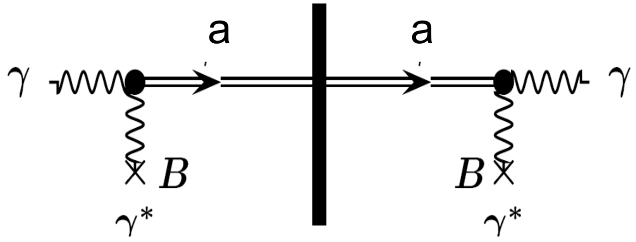
Photon regeneration experiments

Axion/ALP coupling

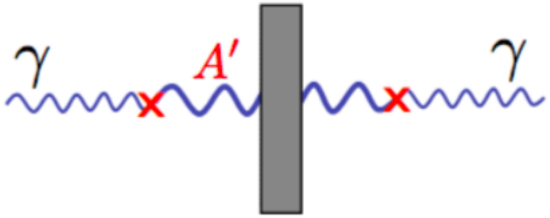
$$\mathcal{L} \supset -\frac{g_{a\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \equiv g_{a\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$$

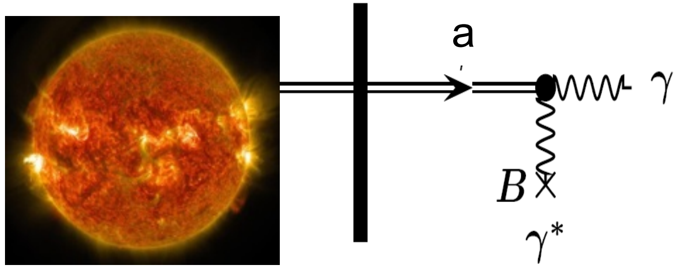
Dark Photon coupling

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



Laser shining through a wall (LSW)





Sun shining through a wall (Helioscope)

[Sikivie `83]

Axion/ALP, DP searches based on EM coupling

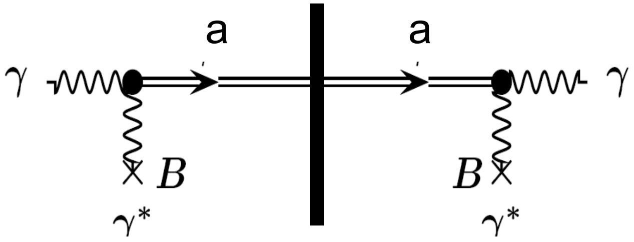
Photon regeneration experiments

Axion/ALP coupling

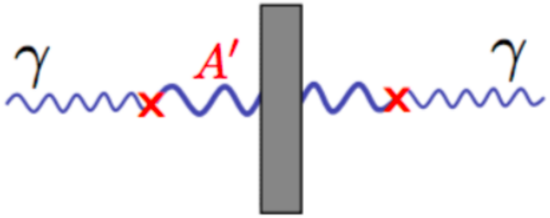
$$\mathcal{L} \supset -\frac{g_{a\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \equiv g_{a\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$$

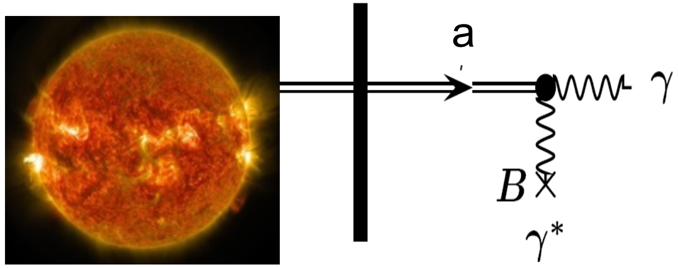
Dark Photon coupling

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

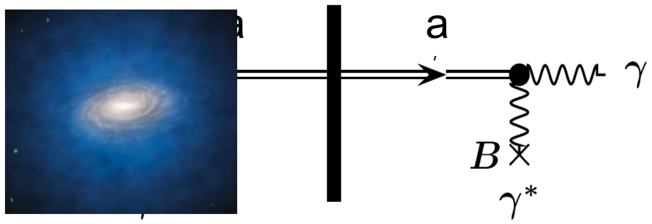


Laser shining through a wall (LSW)





Sun shining through a wall (Helioscope)



DM shining through a wall (Haloscope)

[Sikivie `83]

Light-Shining-through-a-Wall Searches

Searching for Home-Made Axions and ALPs

$$\mathcal{L} \supset -\frac{g_{a\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \equiv g_{a\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$$

$$\left(g_{A\gamma} \equiv \frac{\alpha}{2\pi f_A} C_{A\gamma}\right)$$

- Axion or ALP experiences mixing with photon in an external magnetic field

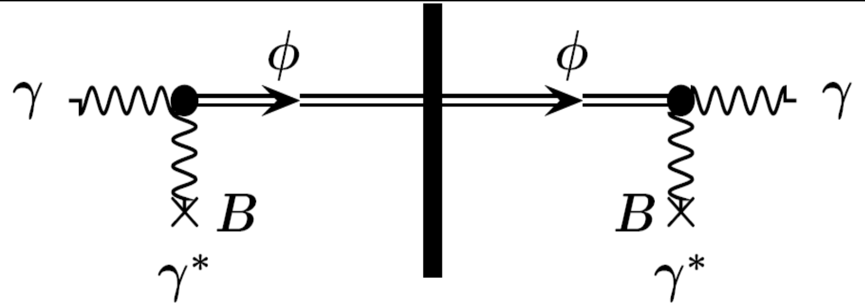
Light-Shining-through-a-Wall Searches

Searching for Home-Made Axions and ALPs

$$\mathcal{L} \supset -\frac{g_{a\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \equiv g_{a\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$$

$$\left(g_{A\gamma} \equiv \frac{\alpha}{2\pi f_A} C_{A\gamma}\right)$$

- Axion or ALP experiences mixing with photon in an external magnetic field
- Light-shining-through a wall:



[Sikivie 1983, Ansel'm 1985, van Bibber et al. 1987]

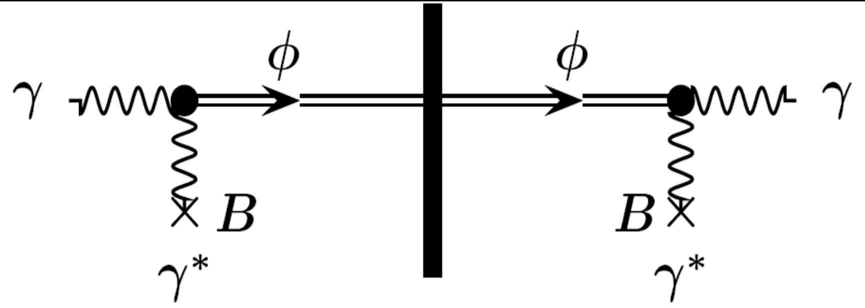
Light-Shining-through-a-Wall Searches

Searching for Home-Made Axions and ALPs

$$\mathcal{L} \supset -\frac{g_{a\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \equiv g_{a\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$$

$$\left(g_{A\gamma} \equiv \frac{\alpha}{2\pi f_A} C_{A\gamma}\right)$$

- Axion or ALP experiences mixing with photon in an external magnetic field
- Light-shining-through a wall:



[Sikivie 1983, Ansel'm 1985, van Bibber et al. 1987]

- Probability, that photon ($\omega \gg m_a$) converted in axion after having traversed a distance L_B in magnetic field:

$$P(\gamma \leftrightarrow a) \simeq 4\frac{(g_{a\gamma}\omega B)^2}{m_a^4}\, \sin^2\left(\frac{m_a^2 L_B}{4\omega}\right)$$

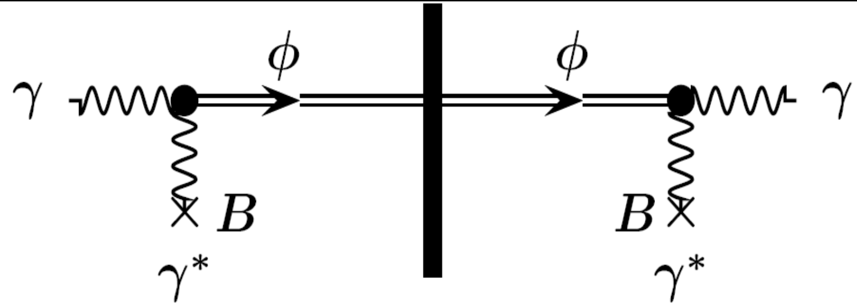
Light-Shining-through-a-Wall Searches

Searching for Home-Made Axions and ALPs

$$\mathcal{L} \supset -\frac{g_{a\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \equiv g_{a\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$$

$$\left(g_{A\gamma} \equiv \frac{\alpha}{2\pi f_A} C_{A\gamma}\right)$$

- Axion or ALP experiences mixing with photon in an external magnetic field
- Light-shining-through a wall:



[Sikivie 1983, Ansel'm 1985, van Bibber et al. 1987]

- Probability, that photon ($\omega \gg m_a$) converted in axion after having traversed a distance L_B in magnetic field:

$$P(\gamma \leftrightarrow a) \simeq 4\frac{(g_{a\gamma}\omega B)^2}{m_a^4}\,\sin^2\left(\frac{m_a^2 L_B}{4\omega}\right)$$

- Best sensitivity for $m_a \ll \left(\frac{4\pi\omega}{L_B}\right)^{1/2}$: $\quad P(\gamma \leftrightarrow a) \simeq \frac{1}{4}\,(g_{a\gamma} B L_B)^2$

Light-Shining-through-a-Wall Searches

Searching for Home-Made Dark Photons

- Dark photon experiences mixing with photon in vacuum

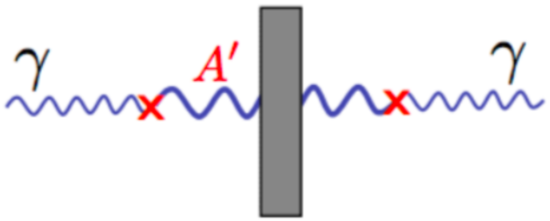
$$\mathcal{L} \supset -\frac{\chi}{2} F'_{\mu\nu} F^{\mu\nu}$$

Light-Shining-through-a-Wall Searches

Searching for Home-Made Dark Photons

- Dark photon experiences mixing with photon in vacuum
- Light-shining-through a wall:

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



[Okun `82]

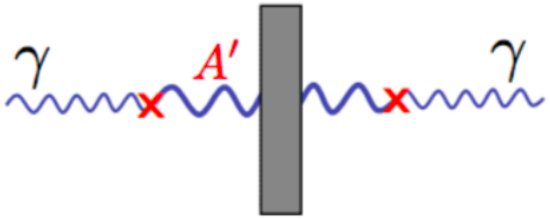
Light-Shining-through-a-Wall Searches

Searching for Home-Made Dark Photons

- Dark photon experiences mixing with photon in vacuum

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

- Light-shining-through a wall:



[Okun `82]

- Probability, that photon ($\omega \gg m_{\gamma'}$) converted in dark photon after having traversed a distance L :

$$P(\gamma \leftrightarrow \gamma') \simeq 4\chi^2 \sin^2\left(\frac{m_{\gamma'}^2 L}{4\omega}\right)$$

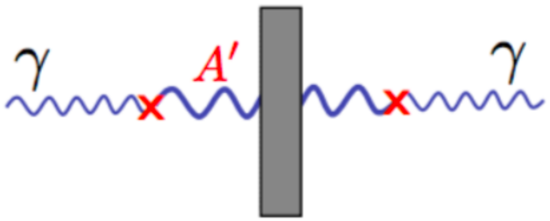
Light-Shining-through-a-Wall Searches

Searching for Home-Made Dark Photons

- Dark photon experiences mixing with photon in vacuum

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

- Light-shining-through a wall:



[Okun `82]

- Probability, that photon ($\omega \gg m_{\gamma'}$) converted in dark photon after having traversed a distance L :

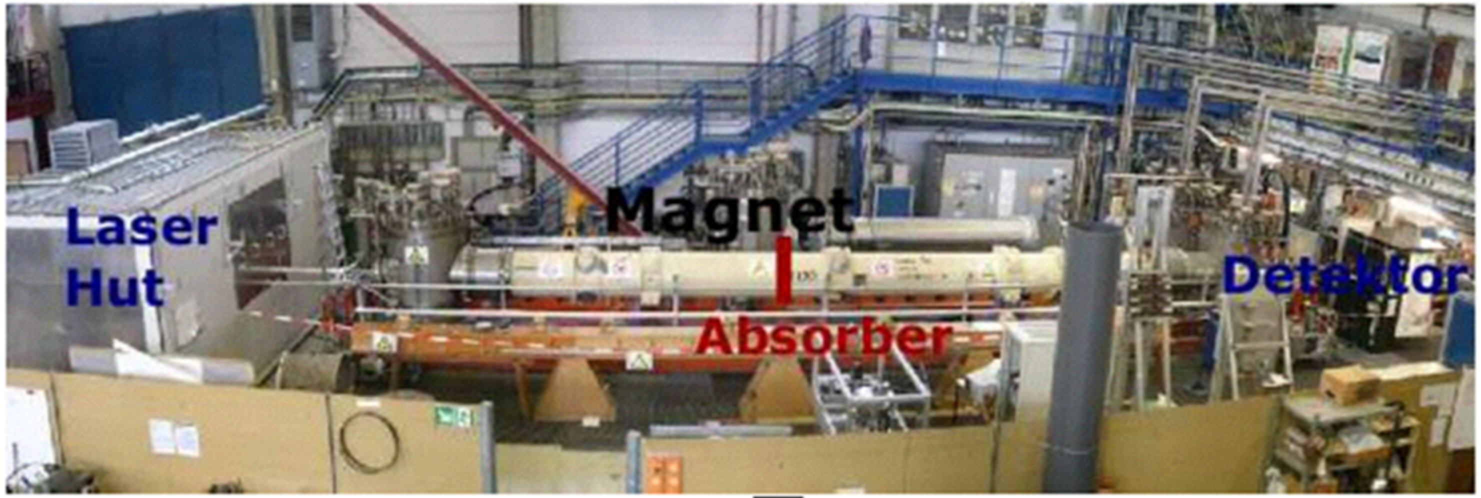
$$P(\gamma \leftrightarrow \gamma') \simeq 4\chi^2 \sin^2\left(\frac{m_{\gamma'}^2 L}{4\omega}\right)$$

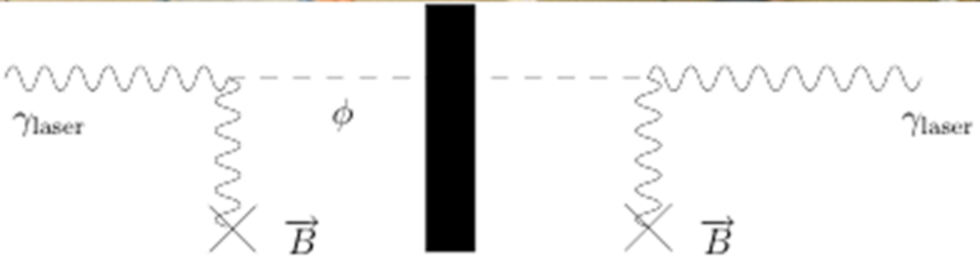
- Best sensitivity around

$$\left(\frac{4\pi\omega}{L}\right)^{1/2} \lesssim m_{\gamma'} \ll \omega$$

Light-Shining-through-a-Wall Searches

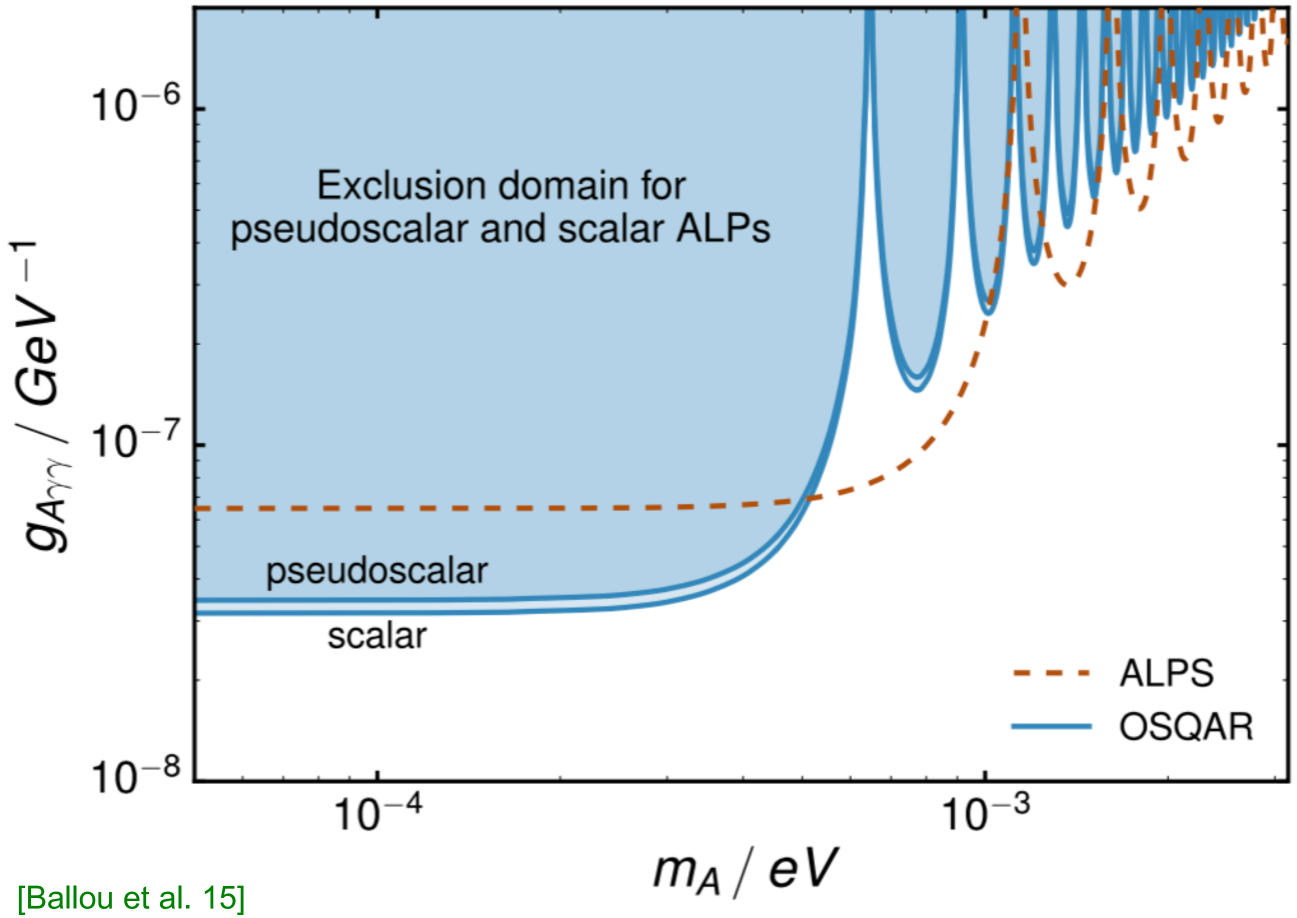
- ALPS I @ DESY (in collaboration with AEI Hannover and U Hamburg) [AR 03;....;Ehret et al. 10]





Light-Shining-through-a-Wall Searches

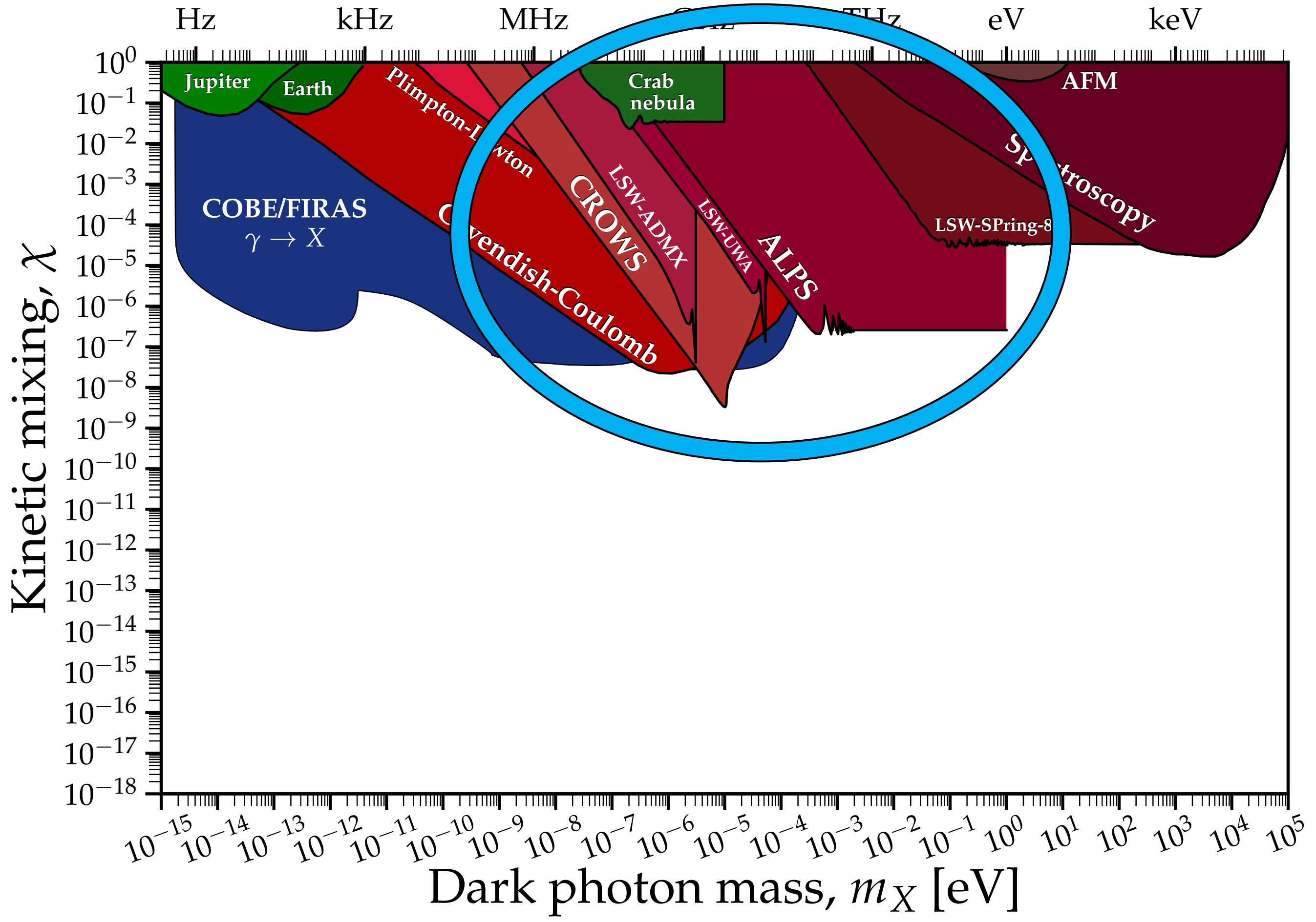
- ALPS I and OSQAR @ CERN give currently the best purely laboratory limit on low mass ALPs:



[Ballou et al. 15]

Light-Shining-through-a-Wall Searches

- LSW constraints for Dark Photon:



[https://github.com/cajohare/AxionLimits/tree/master/plots]

Light-Shining-through-a-Wall Searches

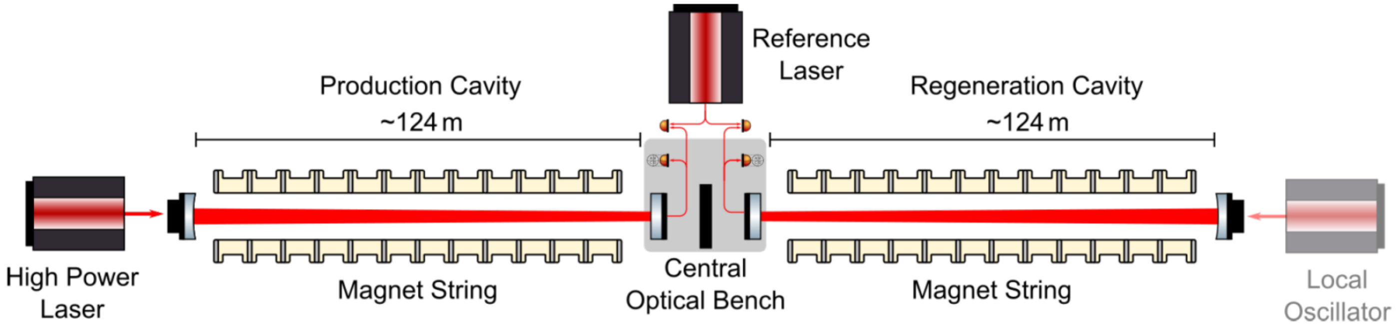
- ALPS II @ DESY (in collaboration with AEI Hannover, U Cardiff, U Florida, U Mainz) [Bähre et al (ALPS II TDR) 13]

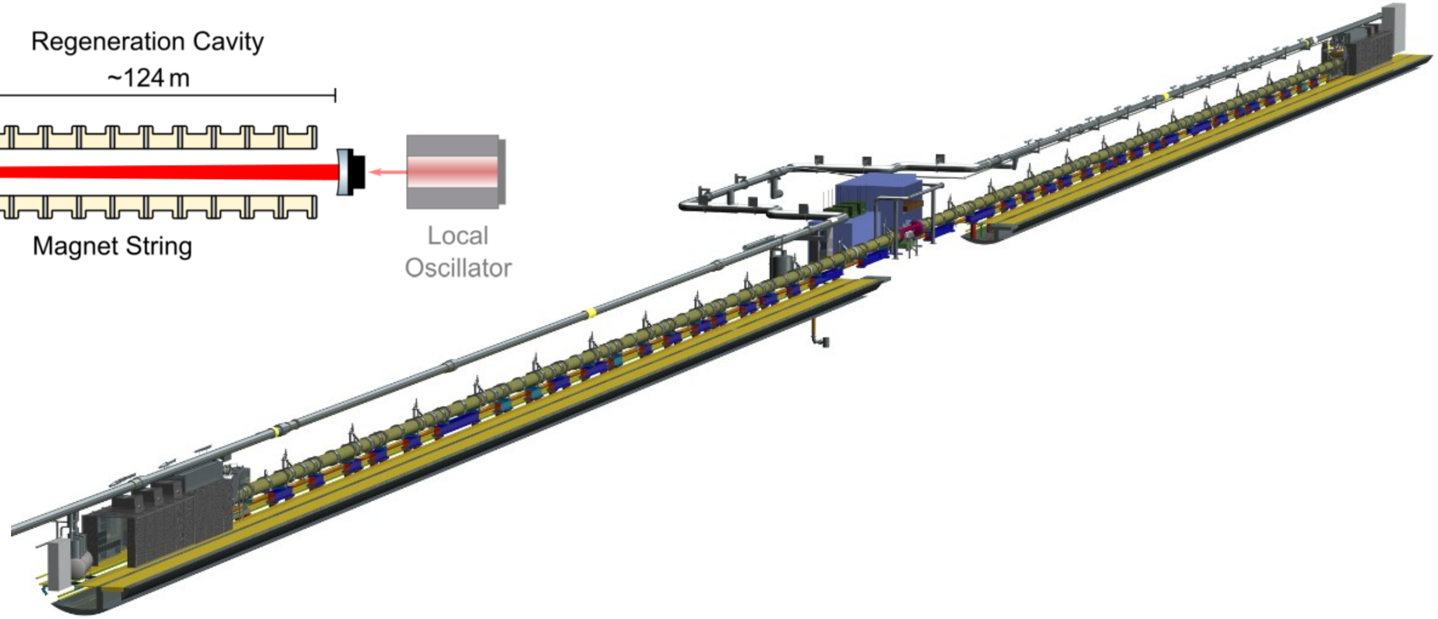
Light-Shining-through-a-Wall Searches

- ALPS II @ DESY (in collaboration with AEI Hannover, U Cardiff, U Florida, U Mainz) [Bähre et al (ALPS II TDR) 13]
  - Increase sensitivity in photon coupling by a factor of more than 10^3

Light-Shining-through-a-Wall Searches

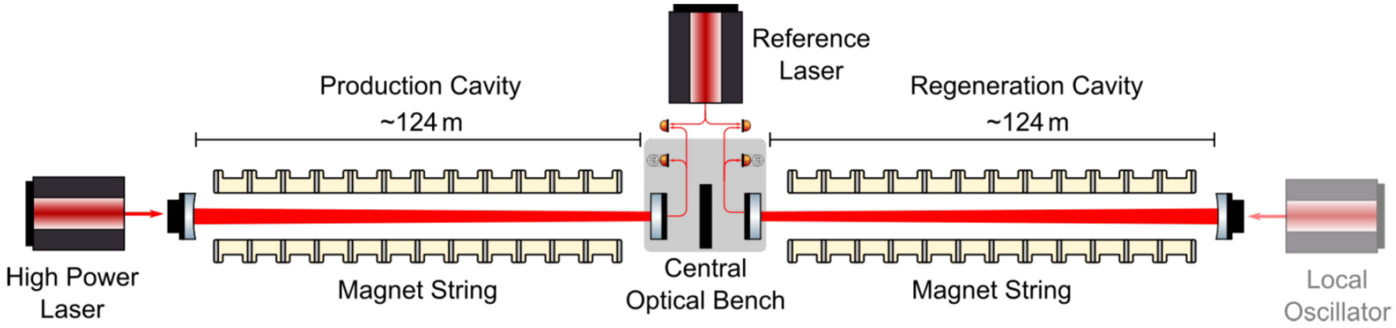
- ALPS II @ DESY (in collaboration with AEI Hannover, U Cardiff, U Florida, U Mainz) [Bähre et al (ALPS II TDR) 13]
  - Increase sensitivity in photon coupling by a factor of more than 10^3 by exploiting
    - 12 + 12 straightened HERA magnets

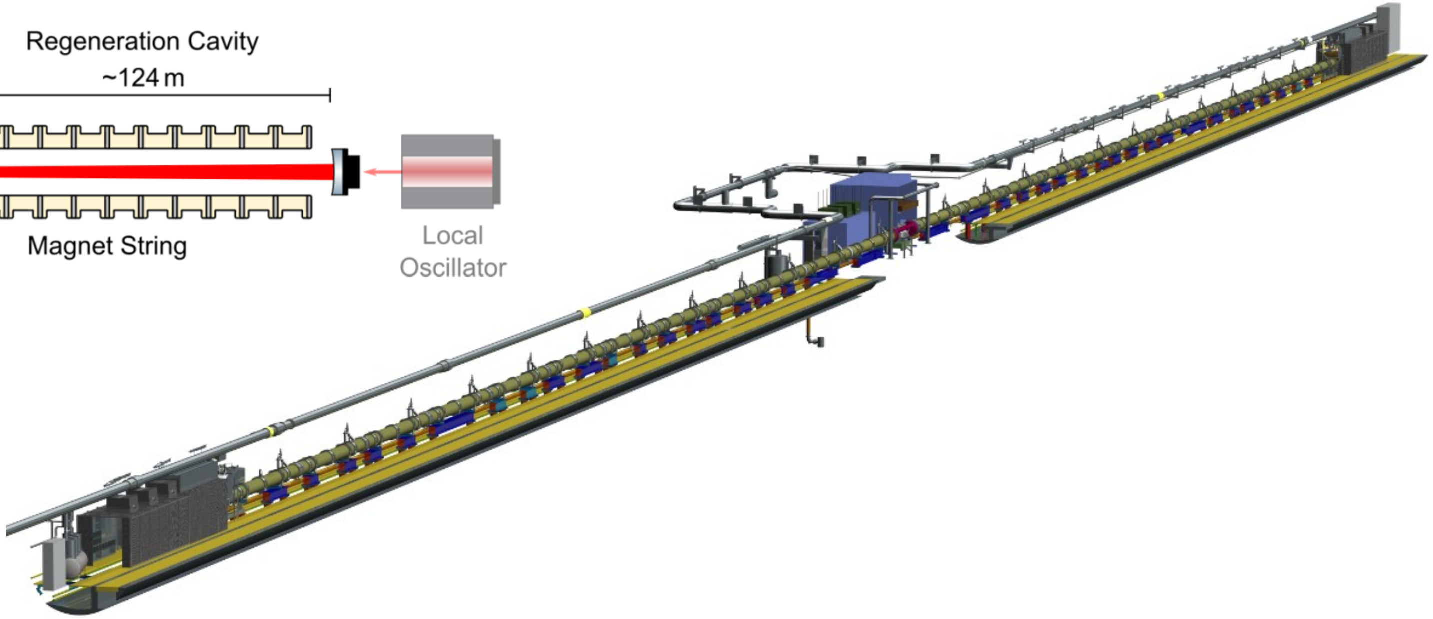




Light-Shining-through-a-Wall Searches

- ALPS II @ DESY (in collaboration with AEI Hannover, U Cardiff, U Florida, U Mainz) [Bähre et al (ALPS II TDR) 13]
  - Increase sensitivity in photon coupling by a factor of more than 10^3 by exploiting
    - 12 + 12 straightened HERA magnets

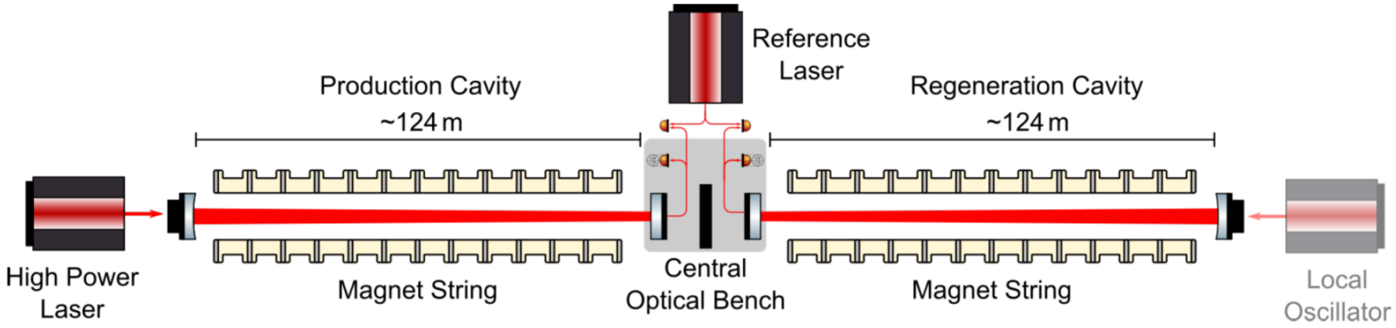


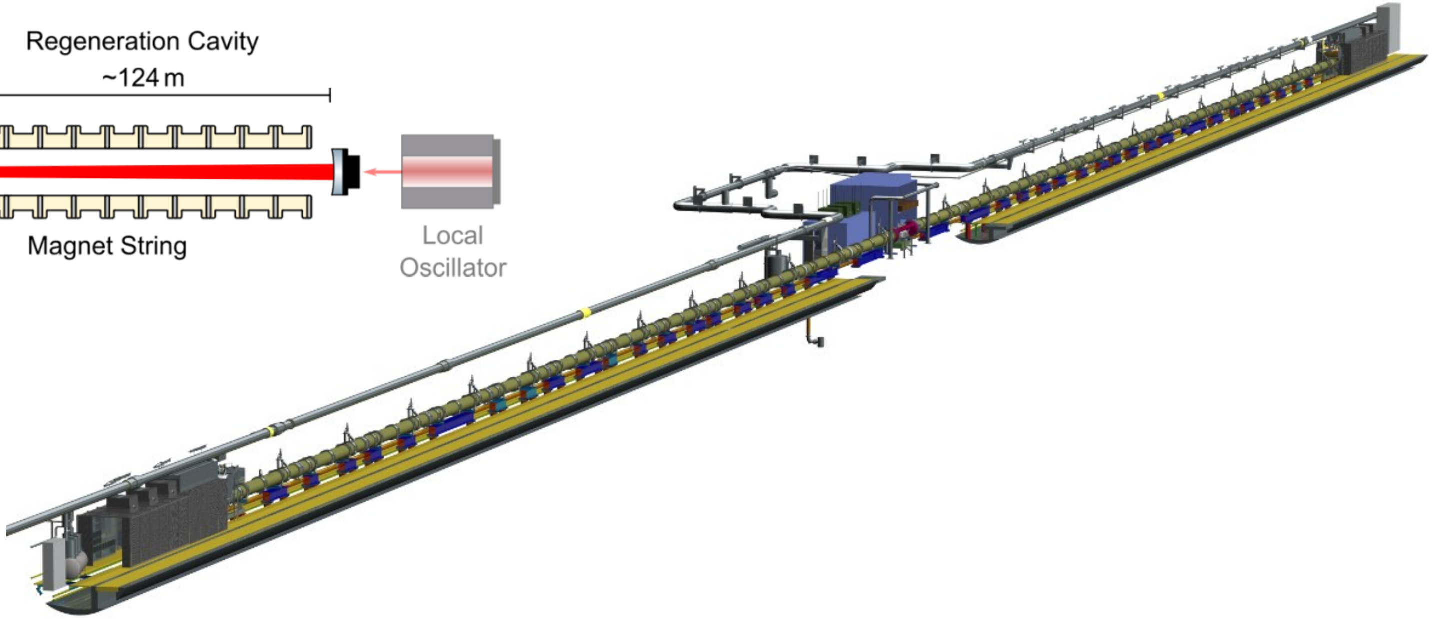


    - Optical cavities both at production and regeneration sites
      [Hogeveen,Ziegenhagen 91;Sikivie,Tanner,van Bibber 07]

Light-Shining-through-a-Wall Searches

- ALPS II @ DESY (in collaboration with AEI Hannover, U Cardiff, U Florida, U Mainz) [Bähre et al (ALPS II TDR) 13]
  - Increase sensitivity in photon coupling by a factor of more than 10^3 by exploiting
    - 12 + 12 straightened HERA magnets

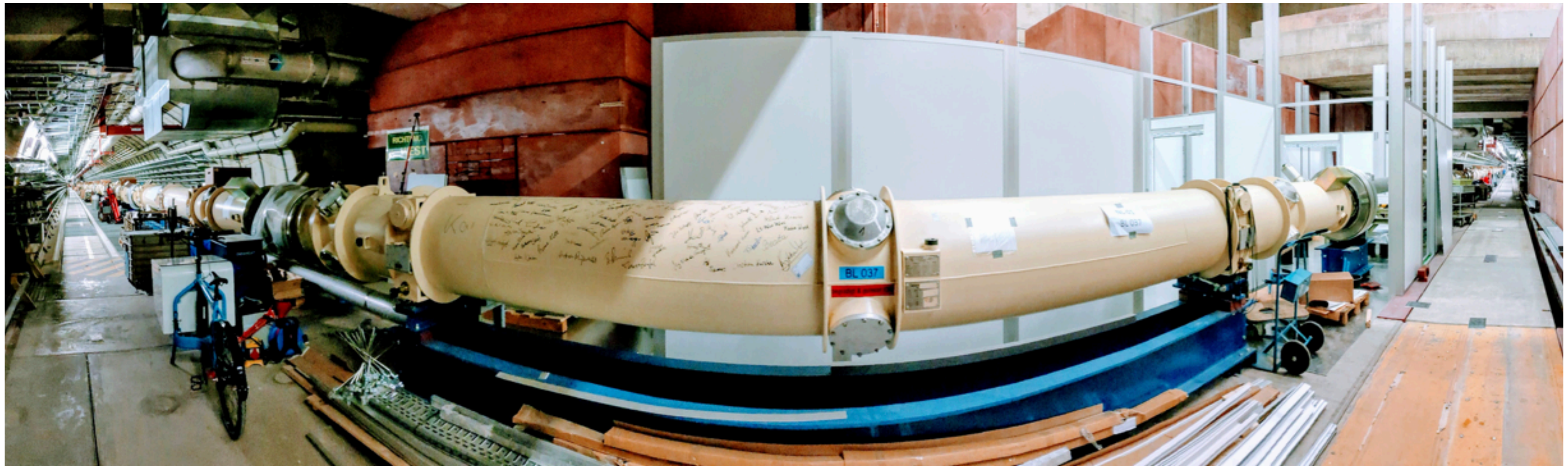


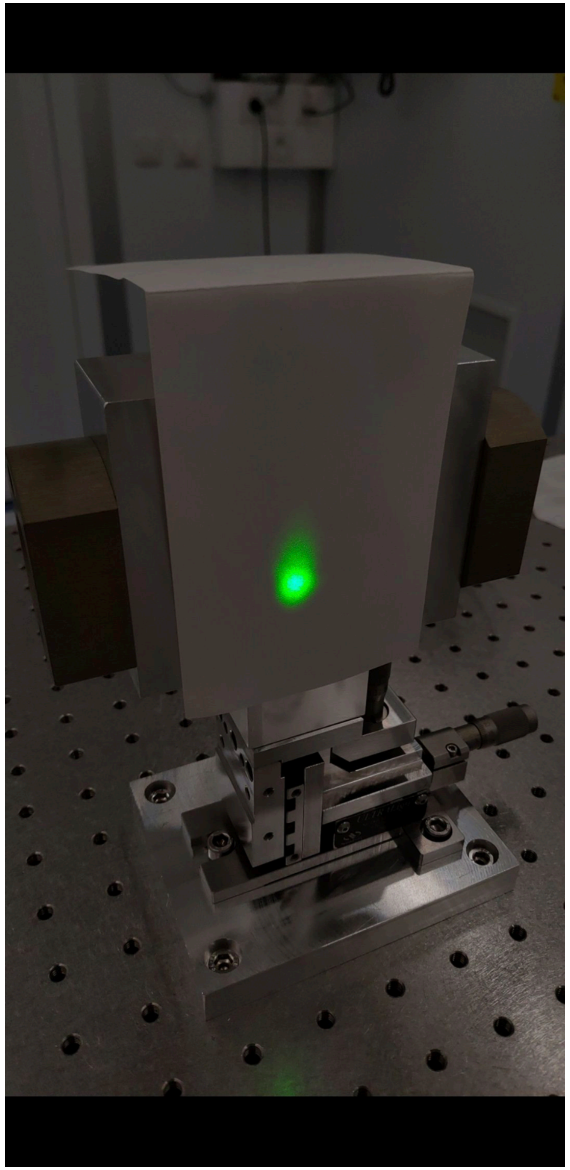


- Optical cavities both at production and regeneration sites [Hogeveen,Ziegenhagen 91;Sikivie,Tanner,van Bibber 07]
- Two detection techniques:
  - Heterodyne
  - Transition edge sensor (TES)

Light-Shining-through-a-Wall Searches

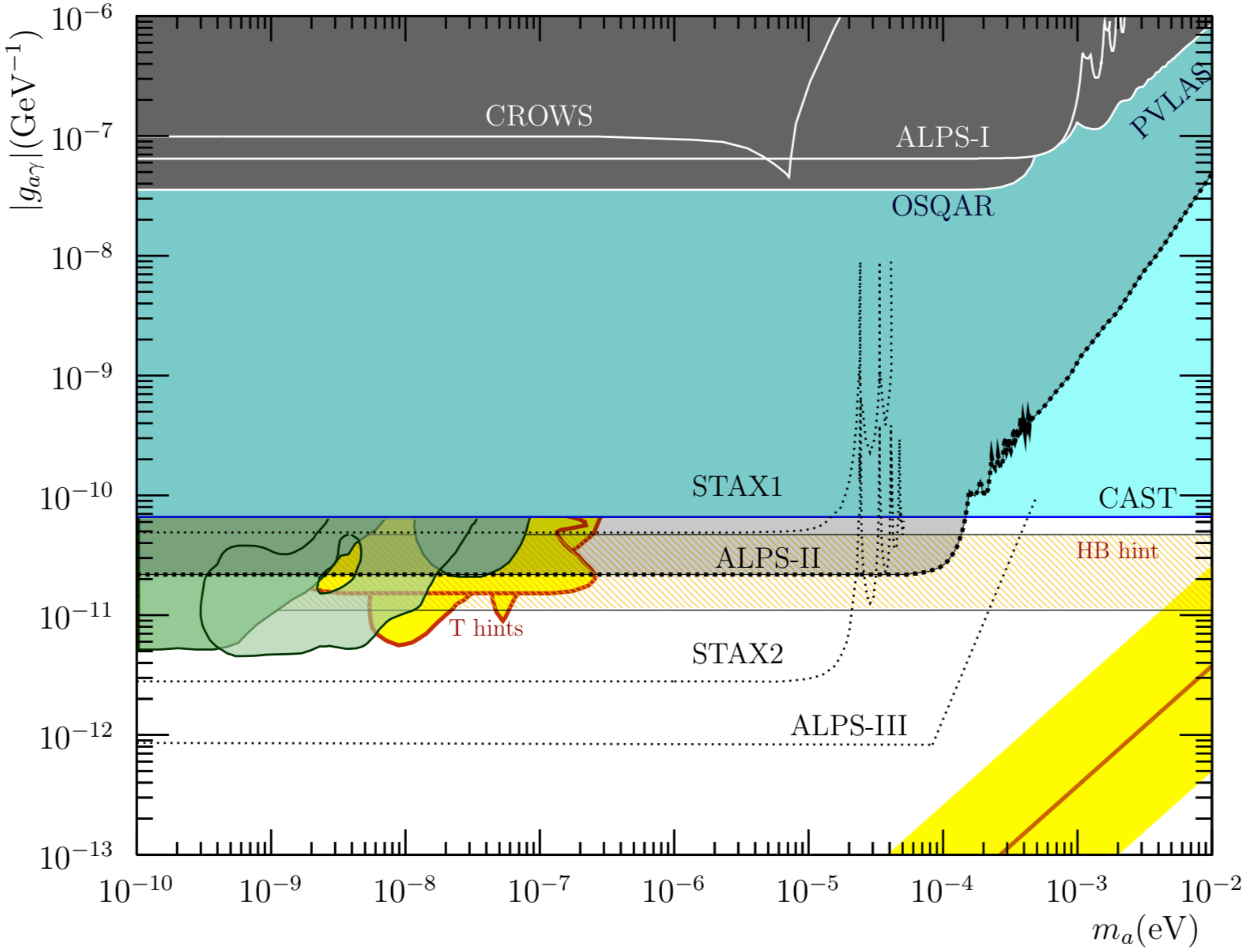
- ALPS II @ DESY (in collaboration with AEI Hannover, U Cardiff, U Florida, U Mainz)
  - Construction progressing:
    - All 24 magnets are installed and aligned
    - Cleanrooms at end stations are operational
    - Commissioning of the optical system has begun
      - Alignment laser through the beam tube accomplished
    - Cryogenic test operation of magnets July 2021
  - First science run scheduled for Fall 2021





Light-Shining-through-a-Wall Searches

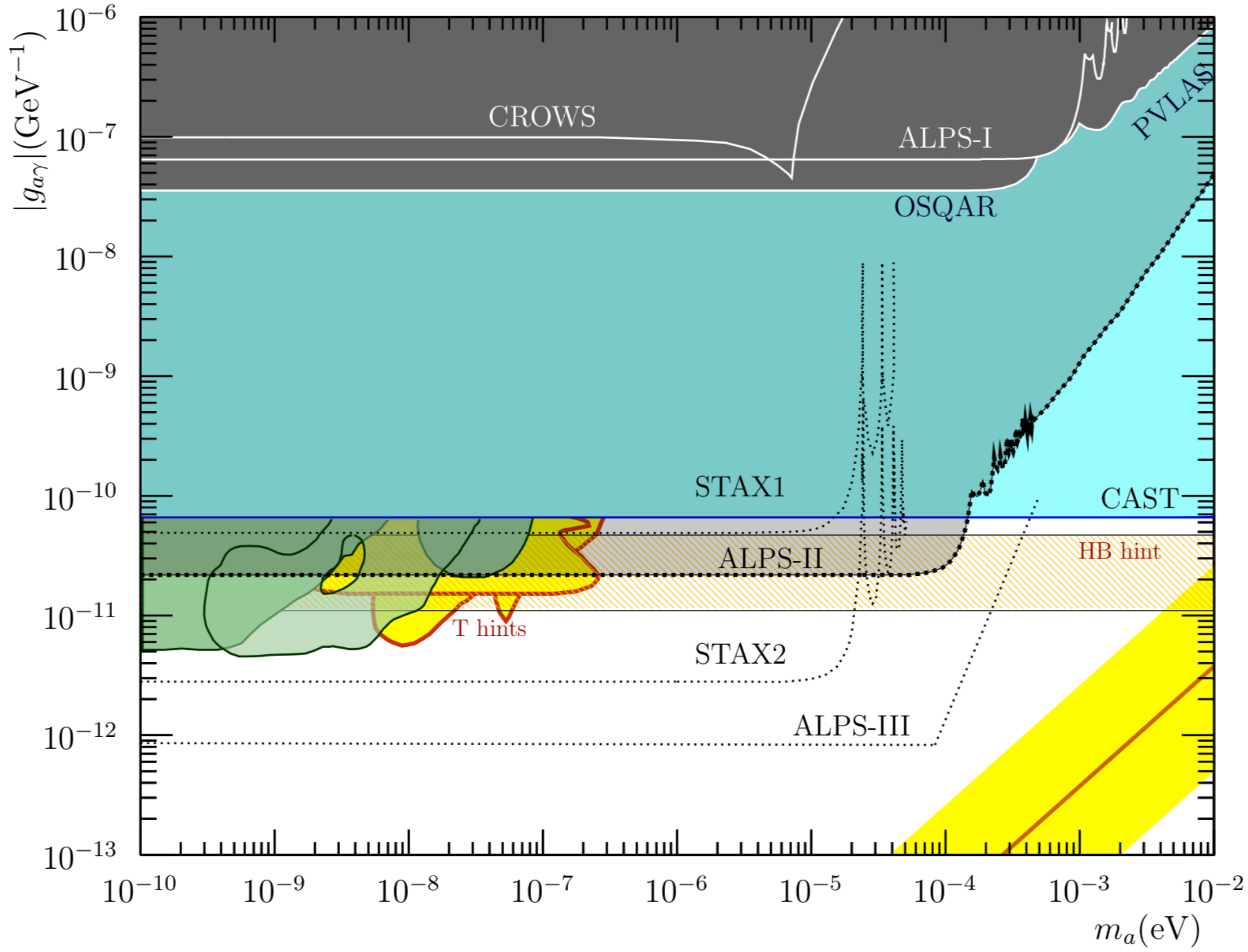
- ALPS II designed to beat astrophysical constraints and check astrophysical hints of axions and ALPs:



[Irastorza, Redondo `18]

Light-Shining-through-a-Wall Searches

- **ALPS II** designed to beat astrophysical constraints and check astrophysical hints of axions and ALPs:



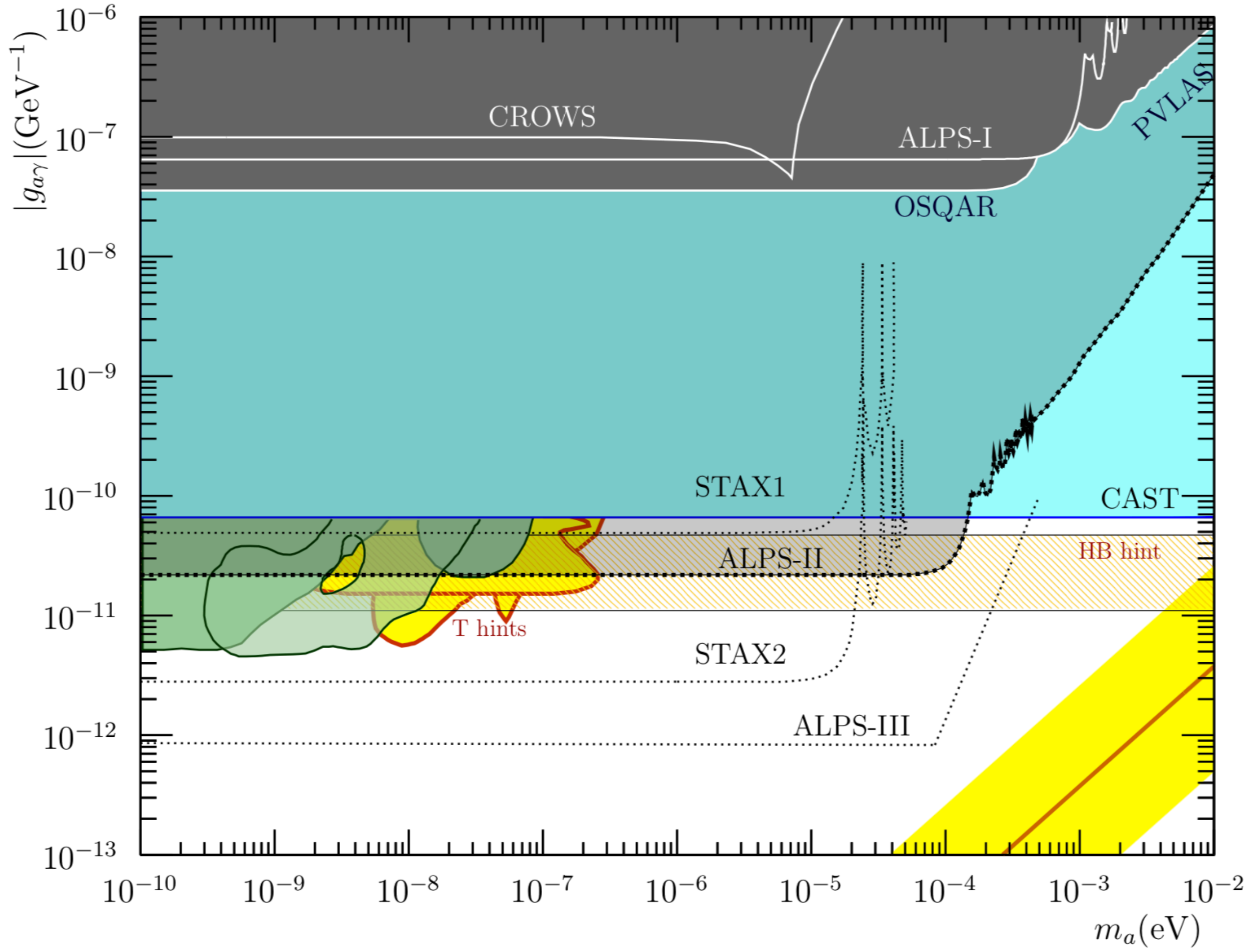
[Irastorza, Redondo `18]

- Proposed next generation LSW experiments
  - **STAX**: [Capparelli et al. `15]
    - Photon source: GHz gyrotron
    - Challenges of microwave range:
      - Resonant photon regeneration
      - Single photon detection (TES?)

        [Miyazaki,Spagnolo `20]

Light-Shining-through-a-Wall Searches

- ALPS II designed to beat astrophysical constraints and check astrophysical hints of axions and ALPs:



[Irastorza, Redondo `18]

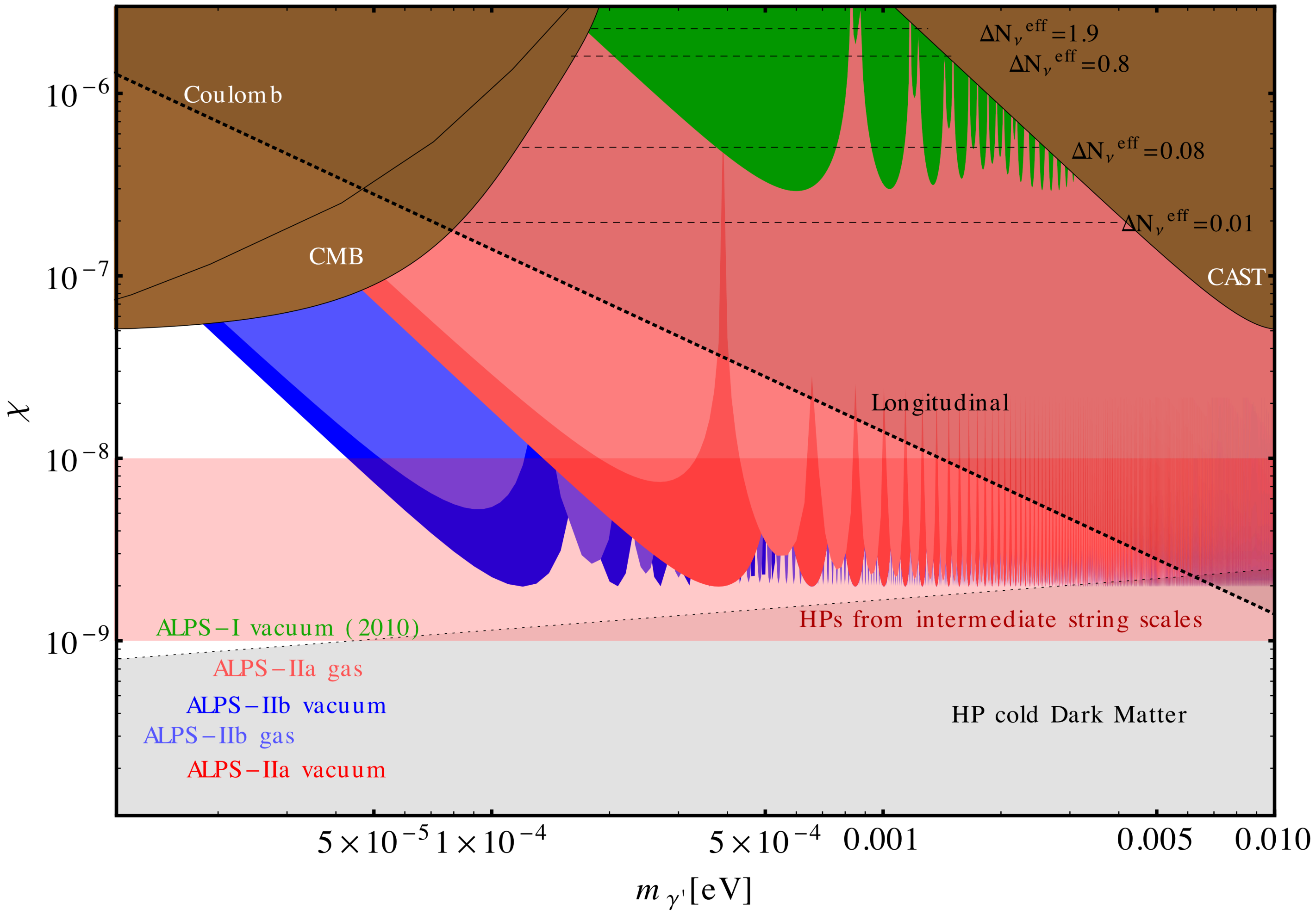
- Proposed next generation LSW experiments
  - **STAX**: [Capparelli et al. `15]
    - Photon source: GHz gyrotron
    - Challenges of microwave range:
      - Resonant photon regeneration
      - Single photon detection (TES?)

      [Miyazaki,Spagnolo `20]
  - **ALPS III** (aka JURA)

    [Lindner,Willke,Ten Kate `16]
    - 2 x 426 m long string of FCC-hh magnets (13 T)
    - MW scale optical resonator

Light-Shining-through-a-Wall Searches

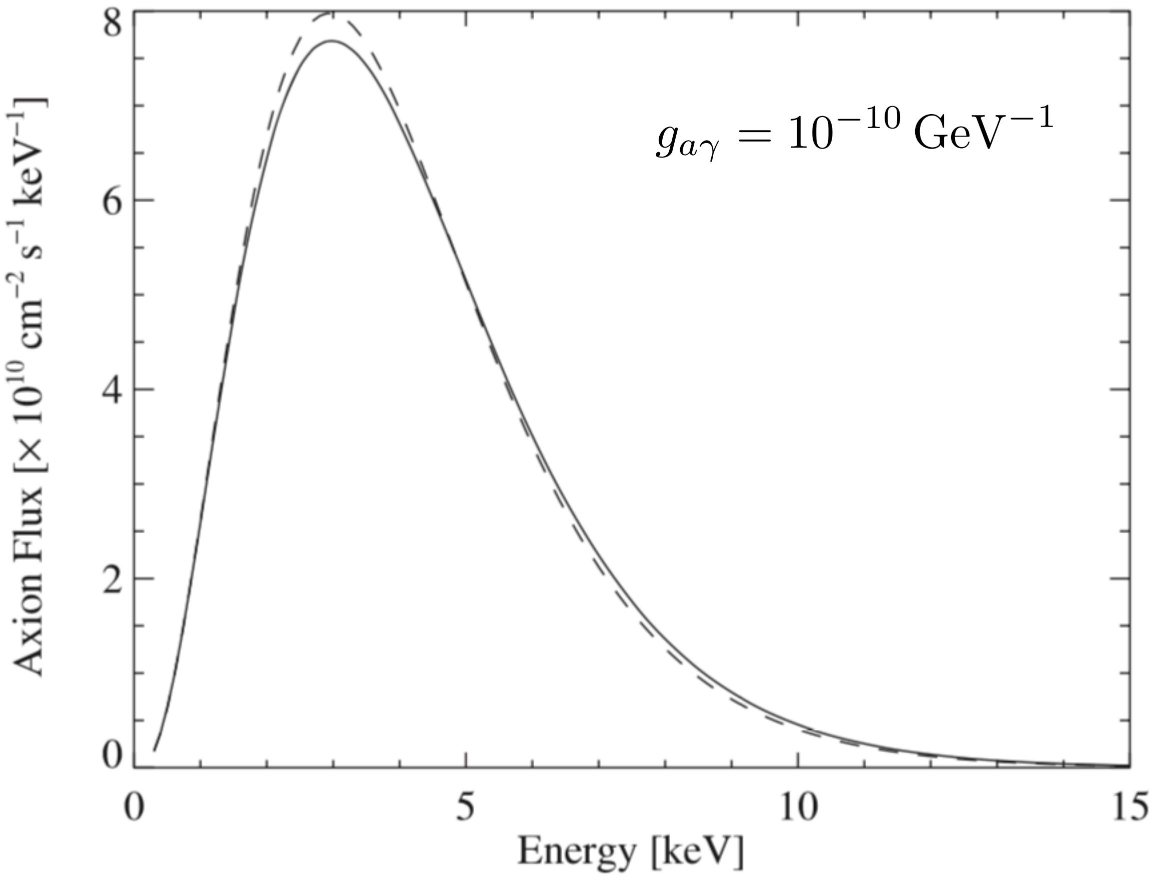
- ALPS II also designed to improve constraints on DPs by two orders of magnitude:



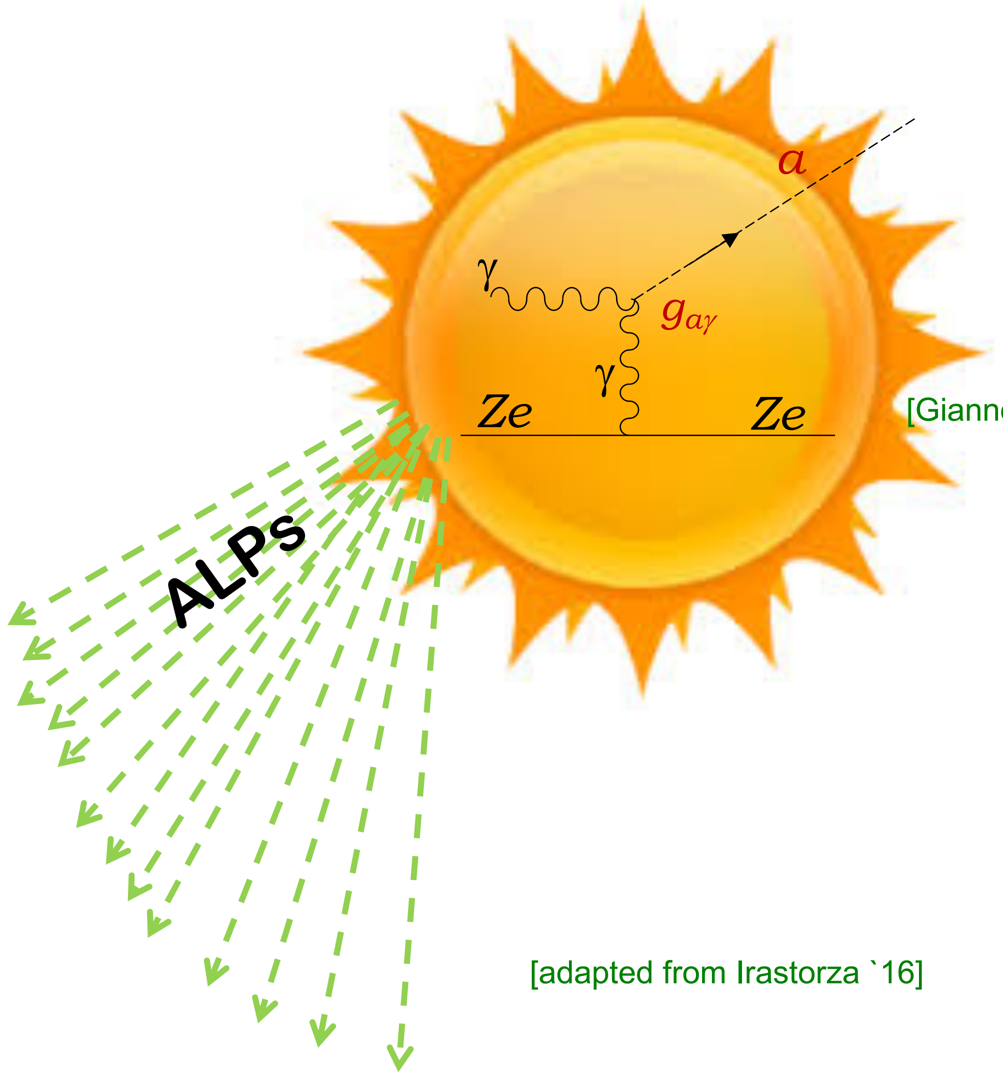
[Bähre et al. `13]

Helioscope Searches

- Flux of solar axions/ALPs produced by two photon process in core:



[Adriamonje et al. `07]



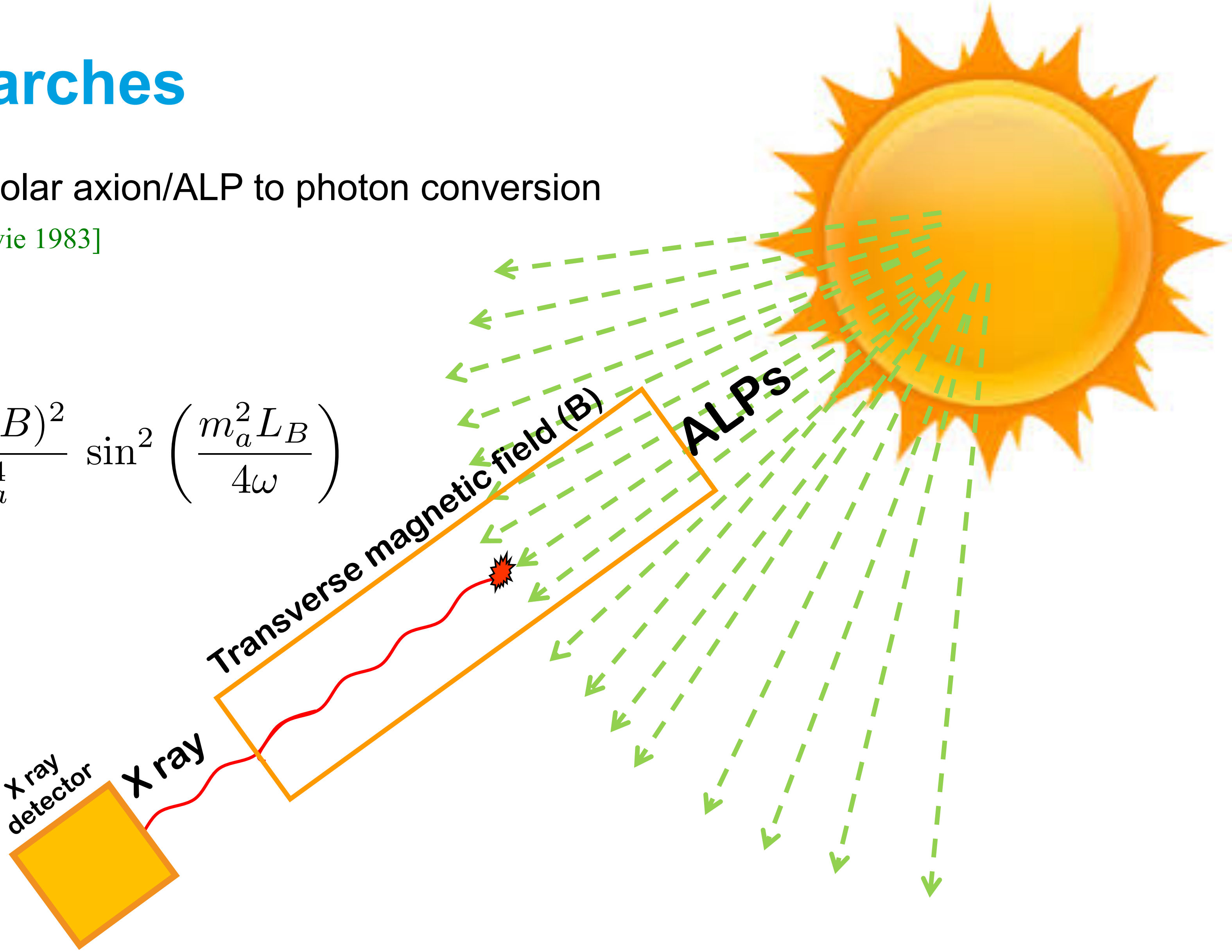
[Giannotti `16]

[adapted from Irastorza `16]

Helioscope Searches

- Helioscope concept: solar axion/ALP to photon conversion in magnetic field [Sikivie 1983]

$$P(a \to \gamma) \simeq 4 \frac{(g_{a\gamma}\omega B)^2}{m_a^4} \sin^2\left(\frac{m_a^2 L_B}{4\omega}\right)$$



[adapted from Irastorza `16]

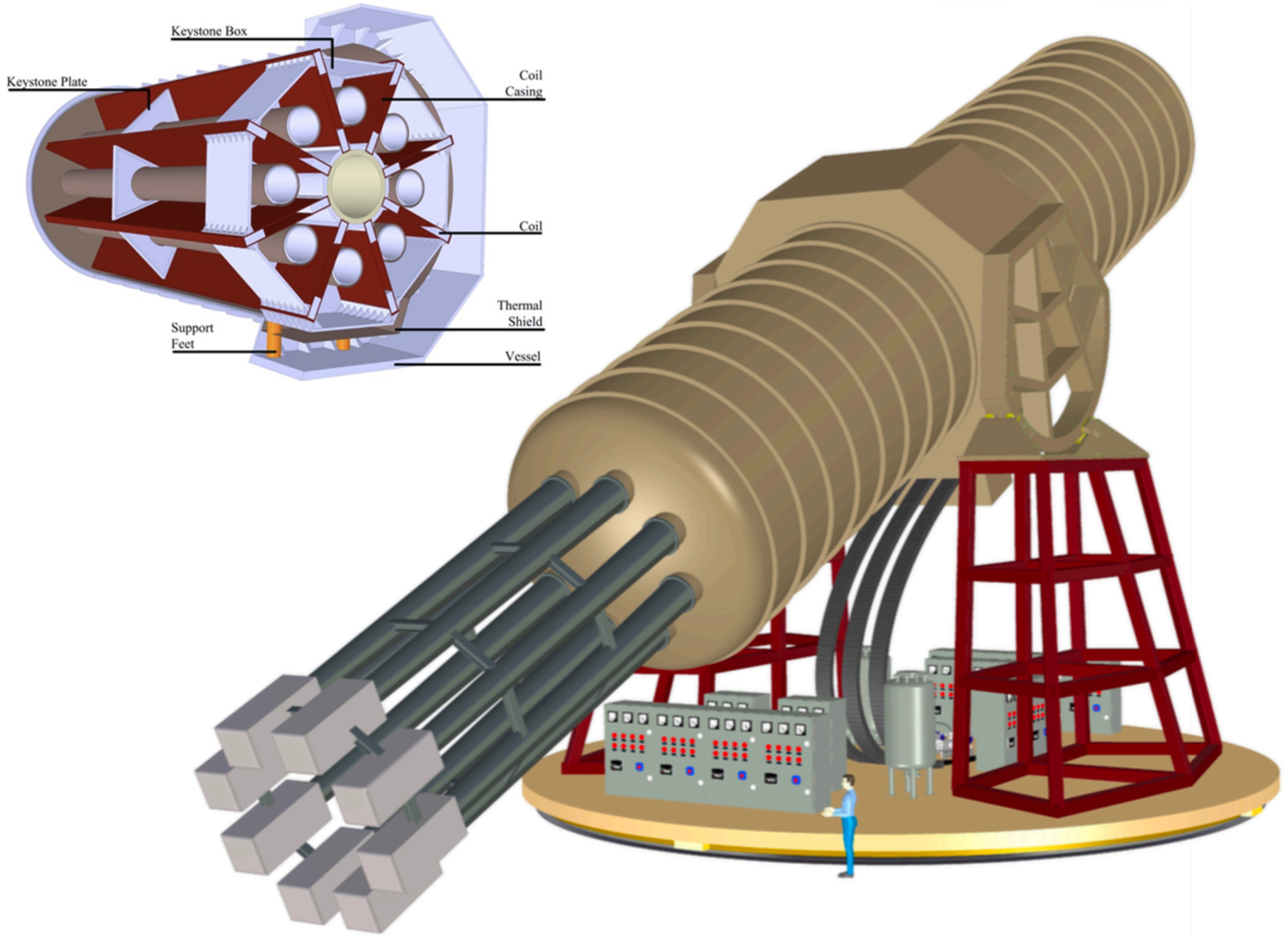
Helioscope Searches

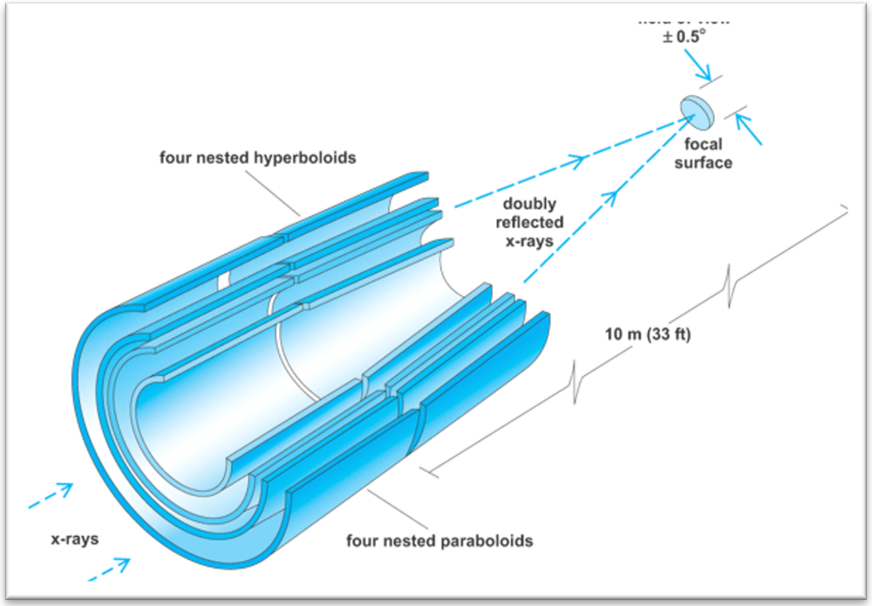
- Most sensitive until now: CERN Axion Solar Telescope (CAST)
  - Superconducting LHC dipole magnet
  - X-ray detectors
  - Use of buffer gas to extend sensitivity to higher masses (axion band)

Helioscope Searches

- International Axion Observatory (IAXO)
  - Large toroidal 8-coil magnet L = ~20 m
  - 8 bores: 600 mm diameter each
  - 8 X-ray telescopes + 8 detection systems
  - Rotating platform with services

[IAXO CDR: JINST 9 (2014) T05002 (arXiv:1401.3233)]





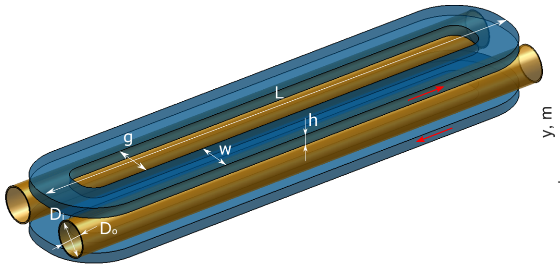
Helioscope Searches

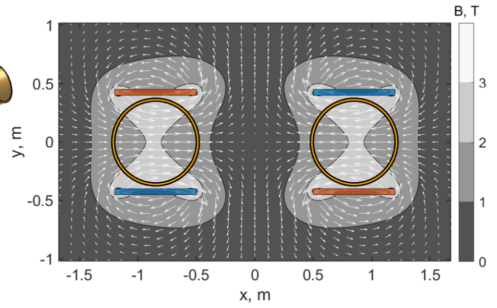
- International Axion Observatory (IAXO)
  - Large toroidal 8-coil magnet L = ~20 m
  - 8 bores: 600 mm diameter each
  - 8 X-ray telescopes + 8 detection systems
  - Rotating platform with services
- Proposed site: DESY

[IAXO CDR: JINST 9 (2014) T05002 (arXiv:1401.3233)]

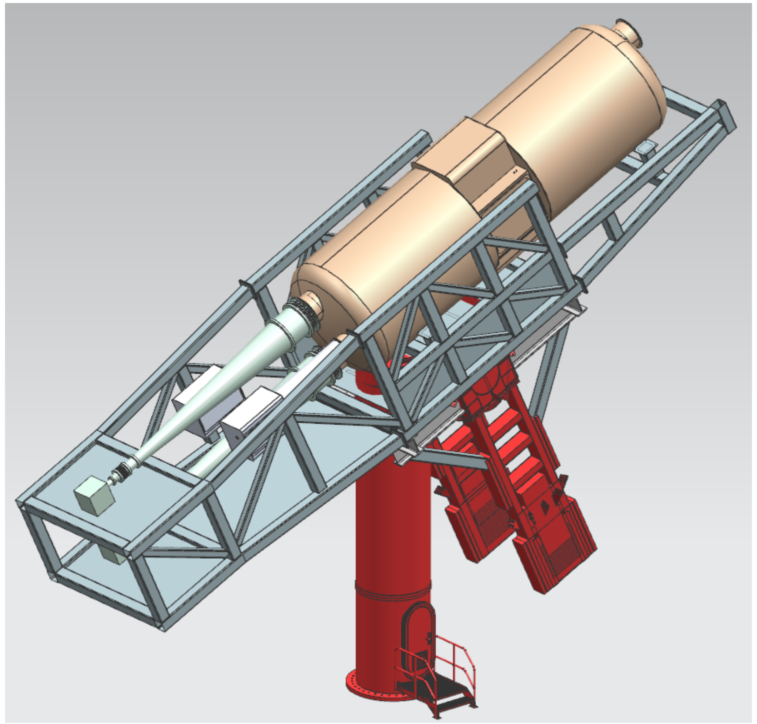
Helioscope Searches

- Prototype for IAXO: BabyIAXO
  - Two bores of dimensions similar to final IAXO bores
  - Detection lines representative of final ones
  - Test & improve all systems
- Magnet technical design ongoing at CERN



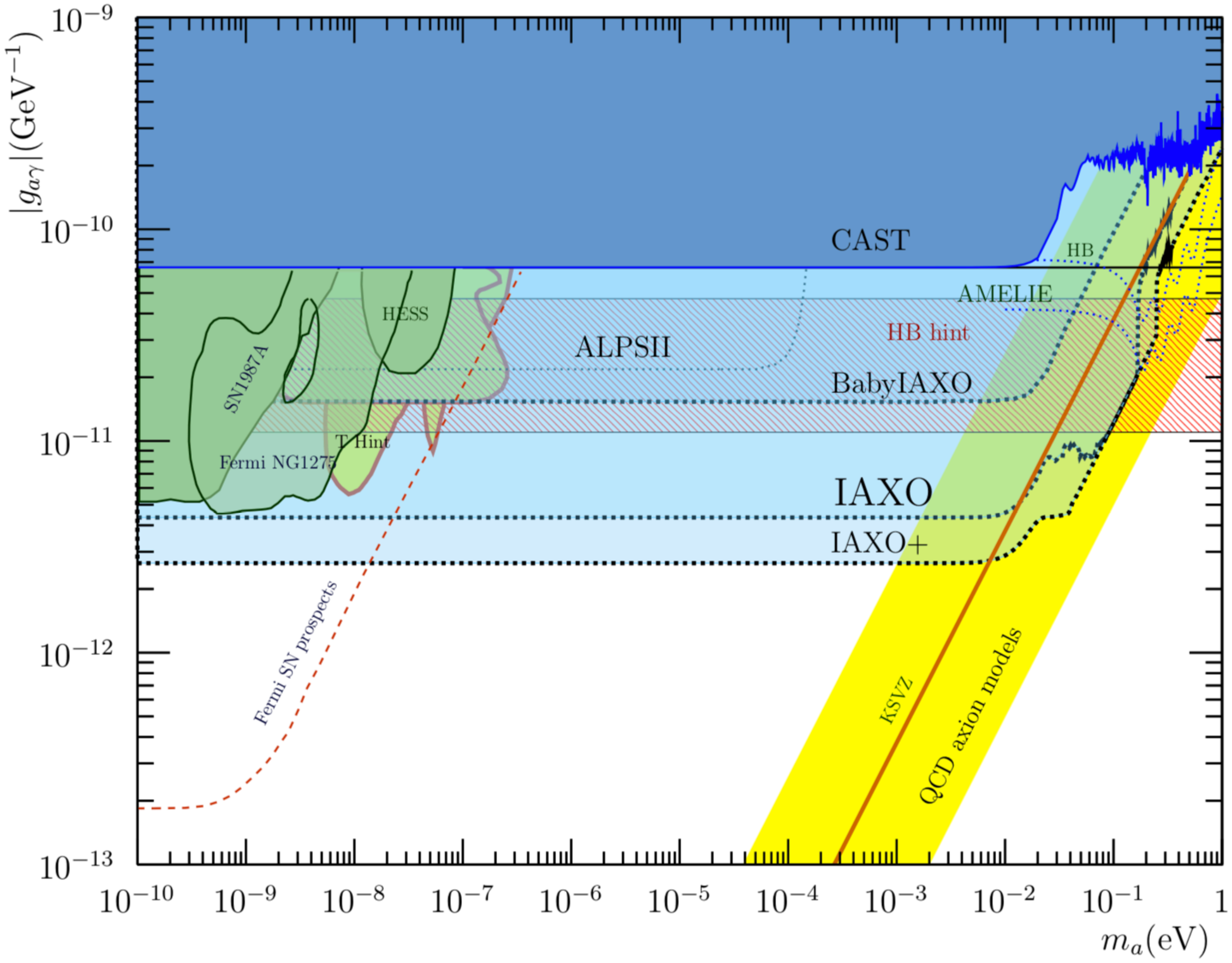


- Construction site: DESY
- Funded by DESY, CERN and Irastorza: ERC-AvG 2017 IAXO+
- Preparations have already started in 2020
- Data taking may start in 2024/25



Helioscope Searches

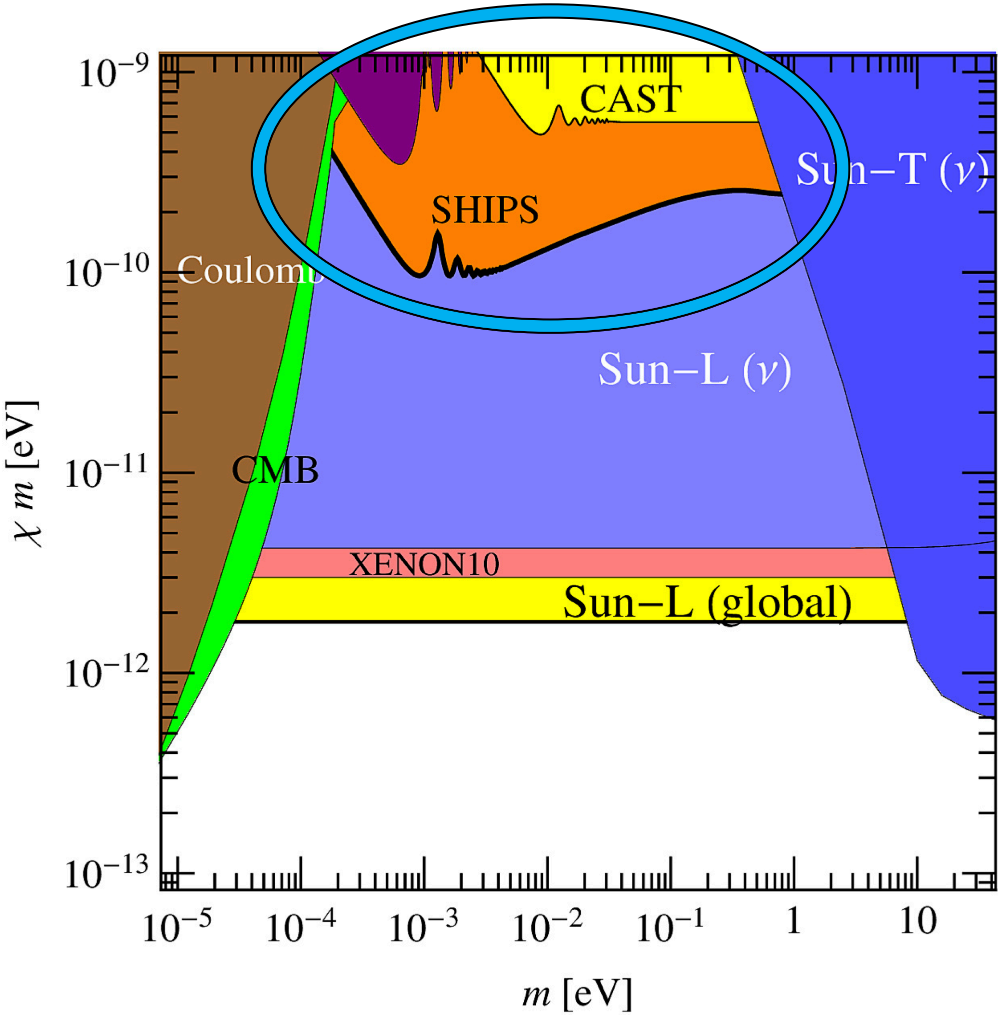
- (Baby)IAXO probes meV mass axion:



[Irastorza, Redondo, 18]

Helioscope Searches

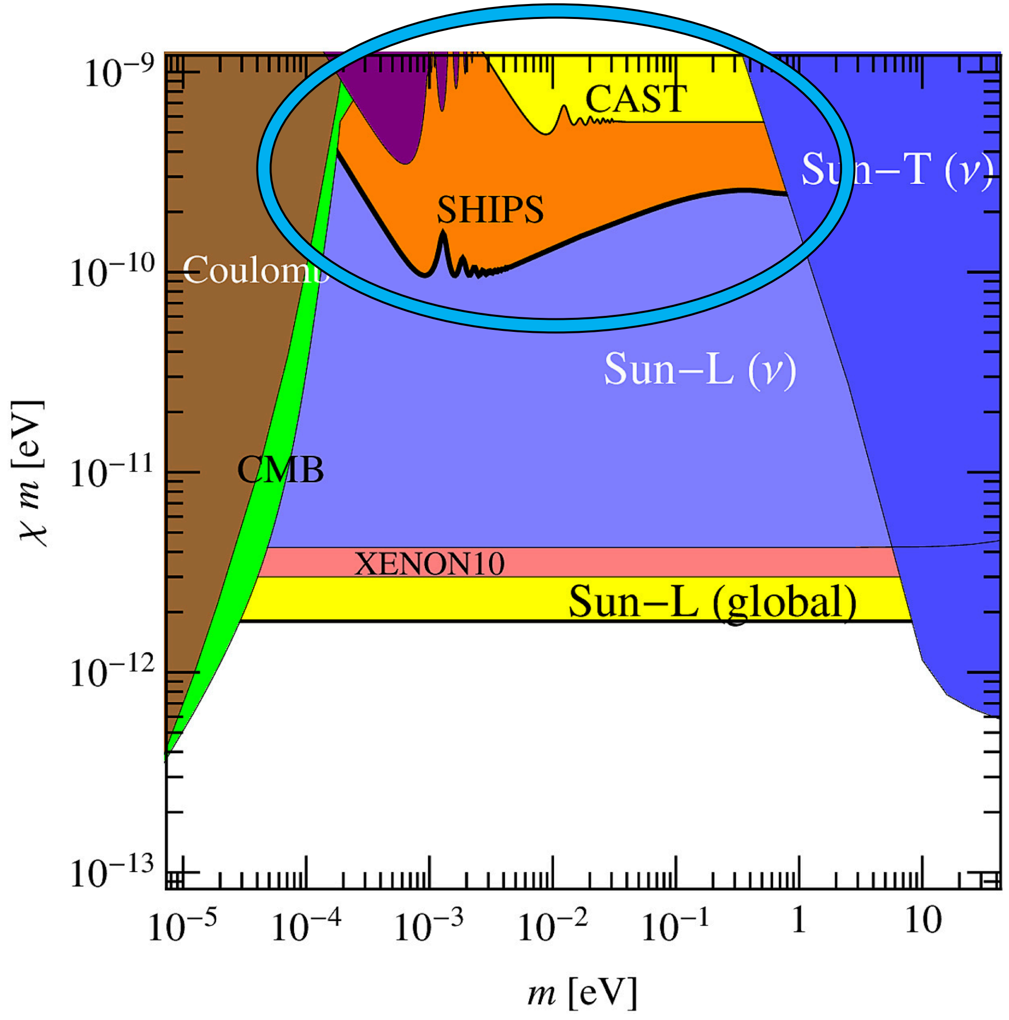
- **Helioscope DP searches** not competitive with astrophysical bound from solar global fit:



[Vinyoles et al. `15]

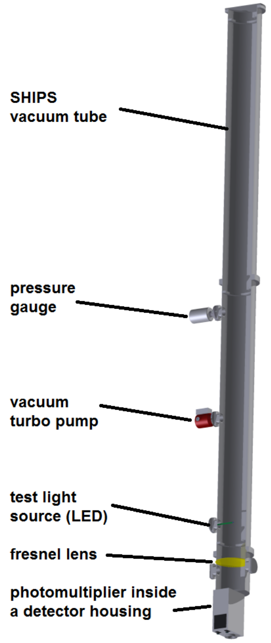
Helioscope Searches

- **Helioscope DP searches** not competitive with astrophysical bound from solar global fit:



[Vinyoles et al. `15]

- Dedicated dark photon helioscope:
  - **SHIPS** (Solar Hidden Photon Search)
    - Location: Hamburg Observatory

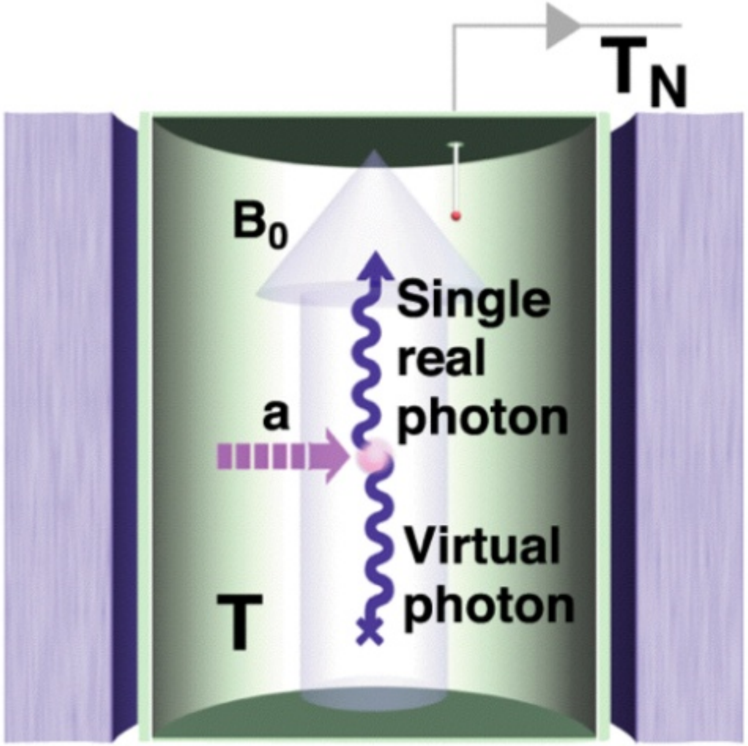


- Should increase aperture to 10 m^2 to beat astrophysics [Schwarz et al. `14]

Haloscope Searches

Microwave Cavities

- Axion or ALP DM – photon conversion in microwave cavity placed in magnetic field [Sikivie 83]
- Best sensitivity: mass = resonance frequency $m_a = 2\pi\nu \sim 4\ \mu\mathrm{eV}\left(\frac{\nu}{\mathrm{GHz}}\right)$

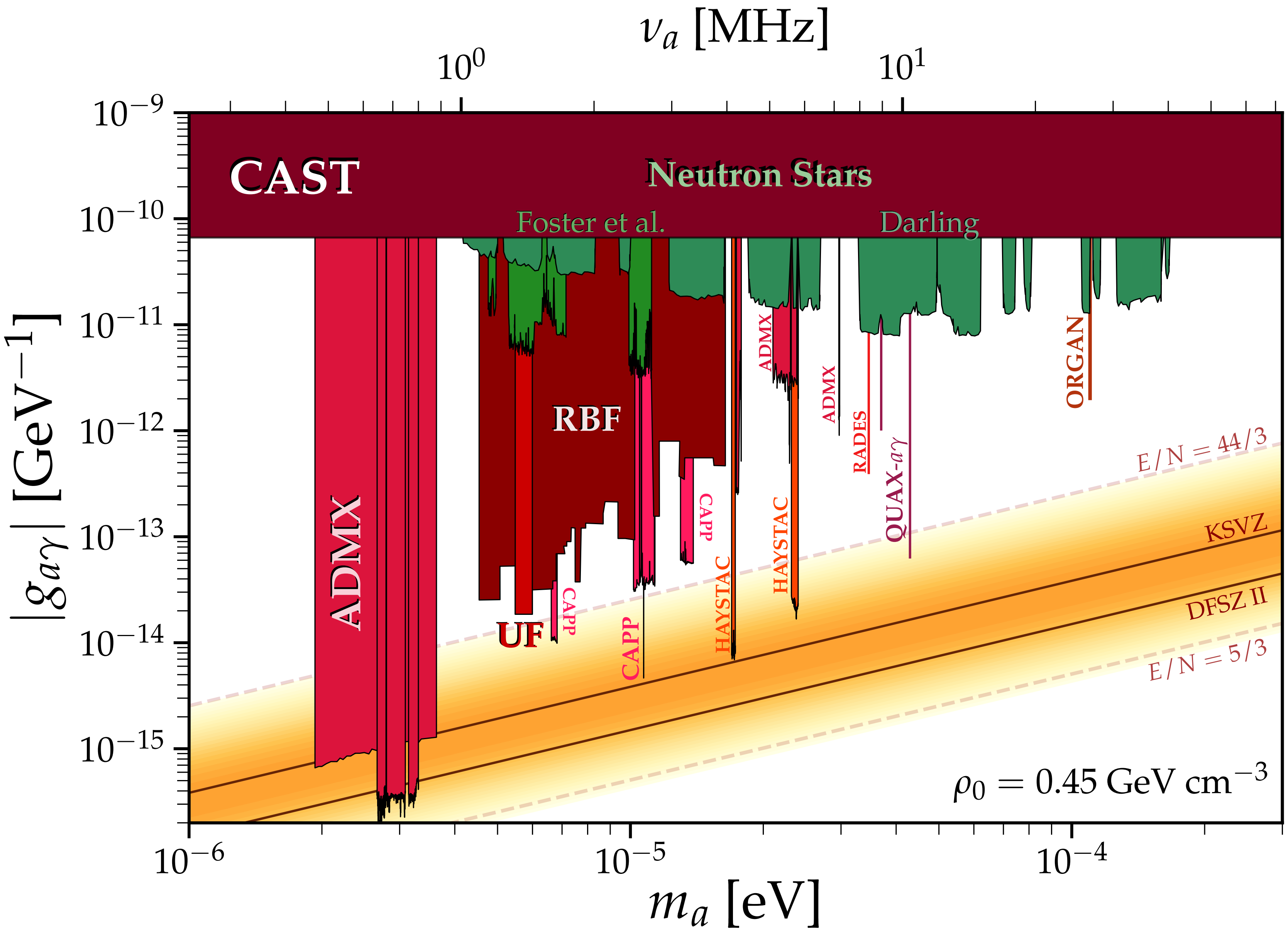


$$P_{\rm out} \sim g^2 \mid \mathbf{B}_0 \mid^2 \rho_{\rm DM} V Q / m_a$$

Haloscope Searches

Microwave Cavities

- Currently running:
  - ADMX
  - CAPP
  - HAYSTAC
  - ORGAN
  - QUAX a gamma
  - RADES

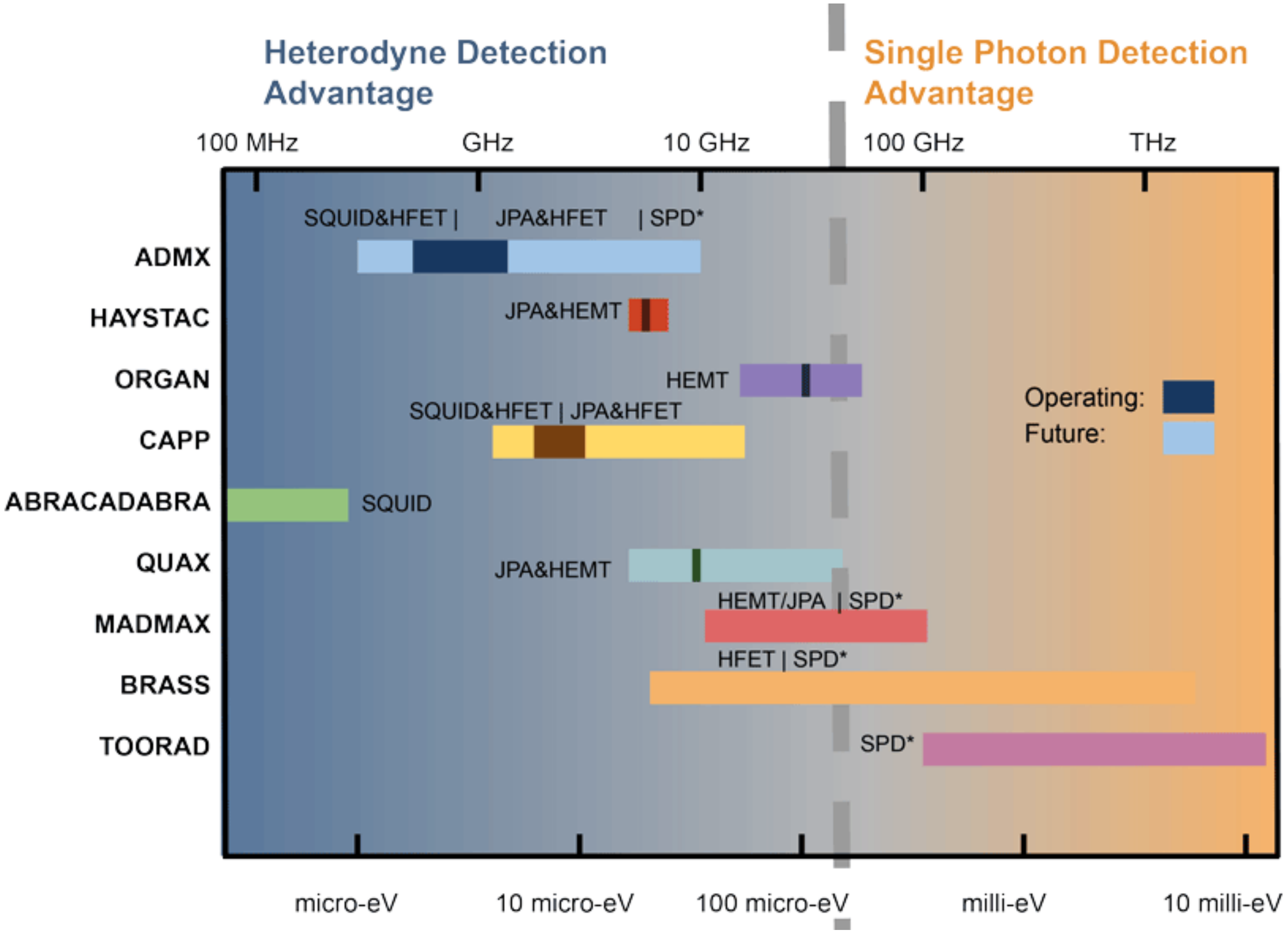


[https://github.com/cajohare/AxionLimits/blob/master/plots/AxionPhoton_RadioFreqCloseup.pdf]

Haloscope Searches

Microwave Cavities

- Currently running:
  - ADMX
  - CAPP
  - HAYSTAC
  - ORGAN
  - QUAX a gamma
  - RADES
- Use quantum sensors



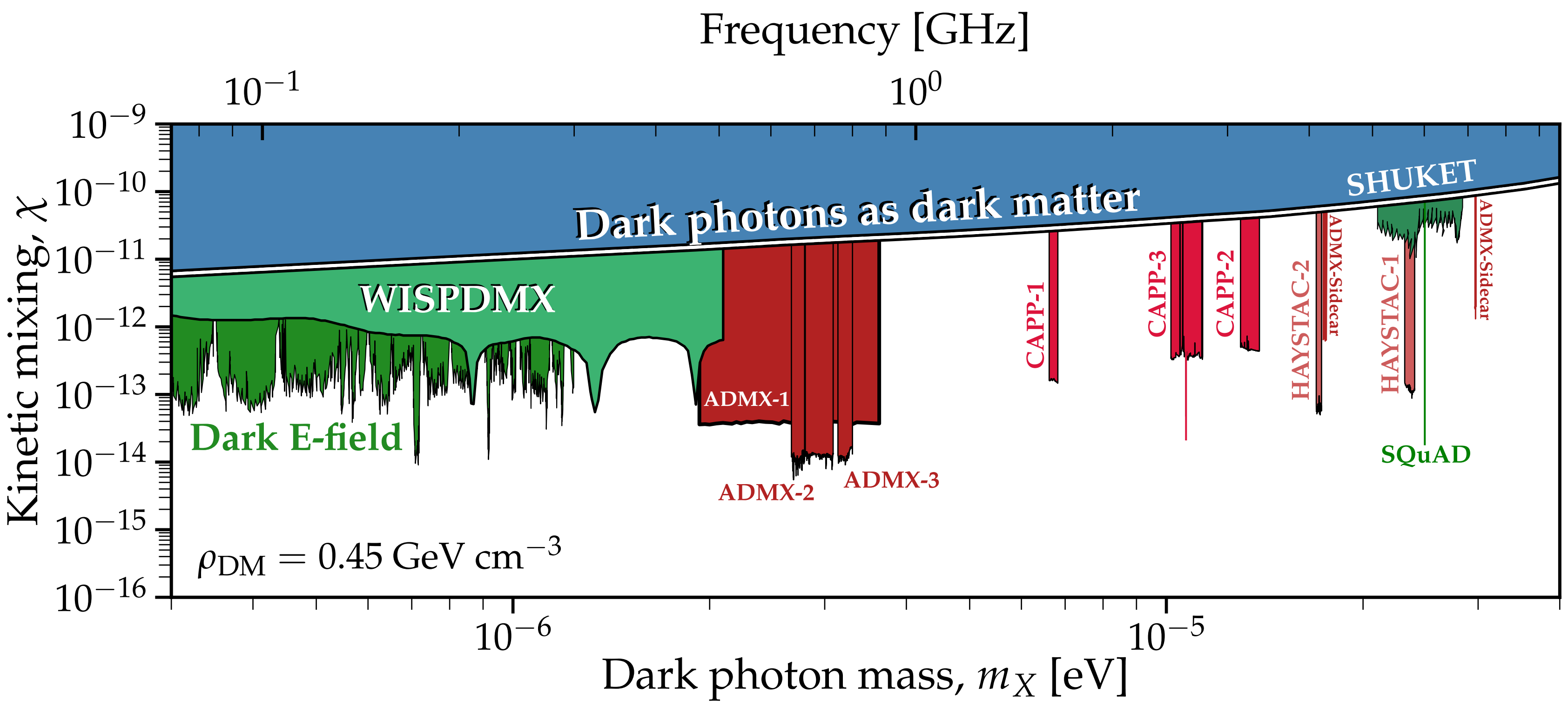
[https://researchoutreach.org/wp-content/uploads/2020/07/David-Marsh.pdf]

Haloscope Searches

Microwave Cavities

- Currently running:
  - ADMX
  - CAPP
  - HAYSTAC
  - ORGAN
  - QUAX a gamma
  - RADES
- Use quantum sensors
- Also sensitive for DP DM

[Arias et al. `12; Caputo et al. `21]



[https://github.com/cajohare/AxionLimits/blob/master/plots/DarkPhoton_Haloscopes_Closeup.pdf]

Haloscope Searches

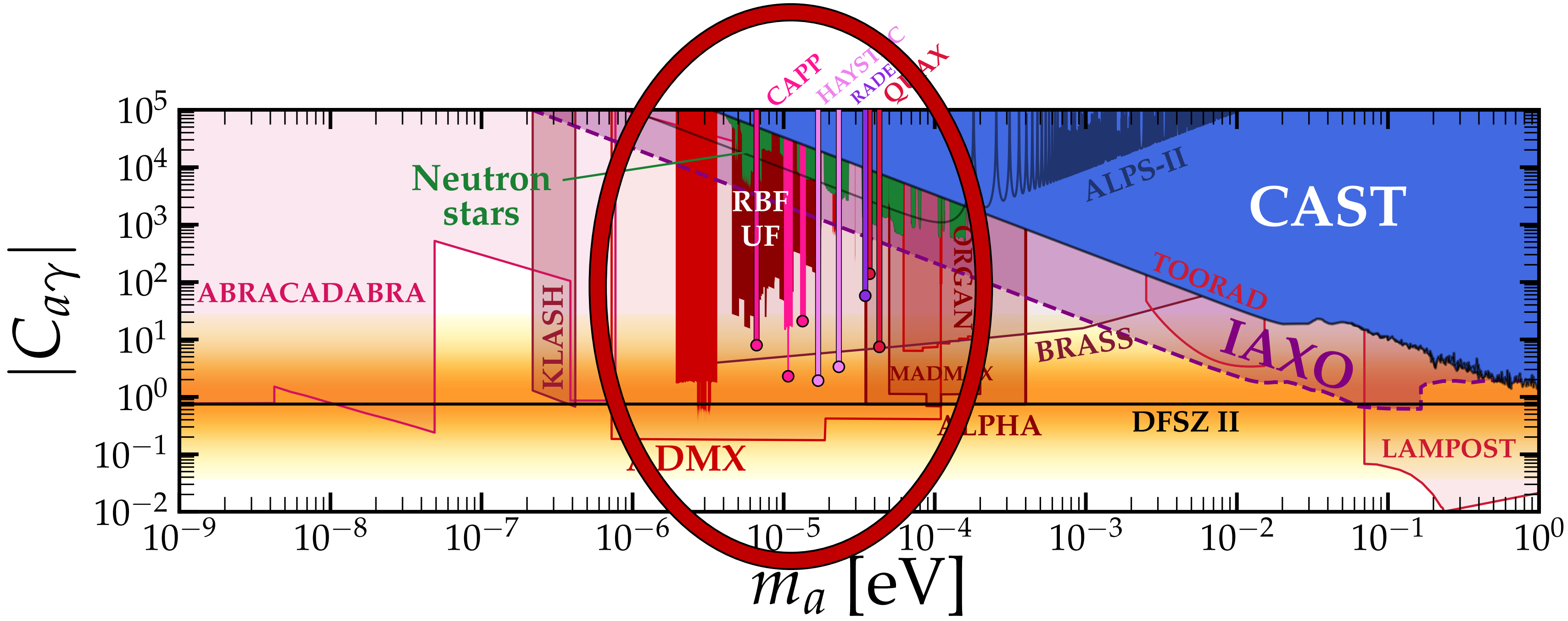
Microwave Cavities

- Currently running:
  - ADMX
  - CAPP
  - HAYSTAC
  - ORGAN
  - QUAX a gamma
  - RADES
- Use quantum sensors
- Also sensitive for DP DM

  [Arias et al. `12; Caputo et al. `21]

- Axion/ALP reach deep into axion band for

  $\mu\mathrm{eV} \lesssim m_a \lesssim 100\,\mu\mathrm{eV}$

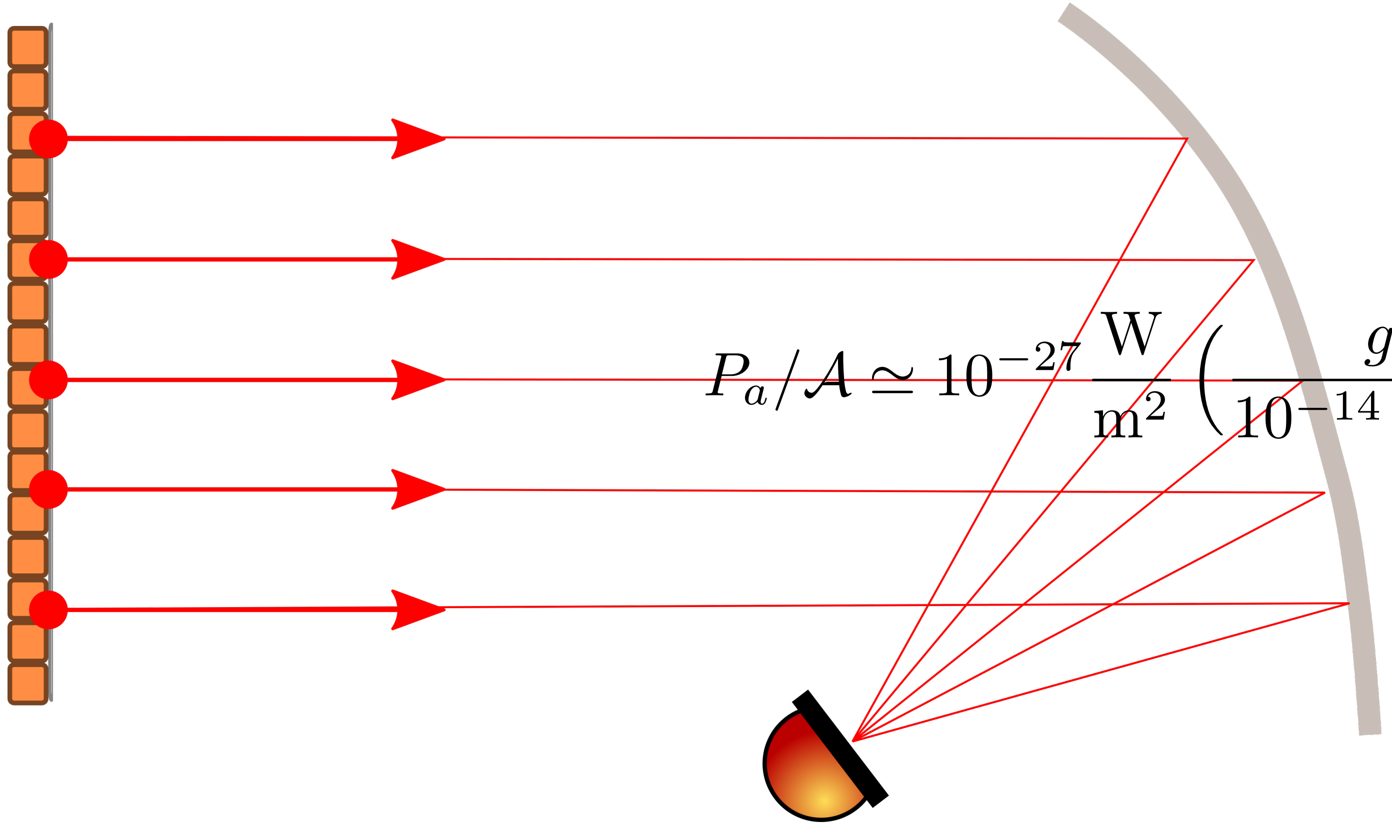


[Caputo et al. `21]

Haloscope Searches

Dish Antennas

- Oscillating axion/ALP DM in a background magnetic field carries a small electric field component
- A magnetised mirror in axion/ALP DM background radiates photons [Horns,Jaeckel,Lindner,Lobanov,Redondo,AR 13]

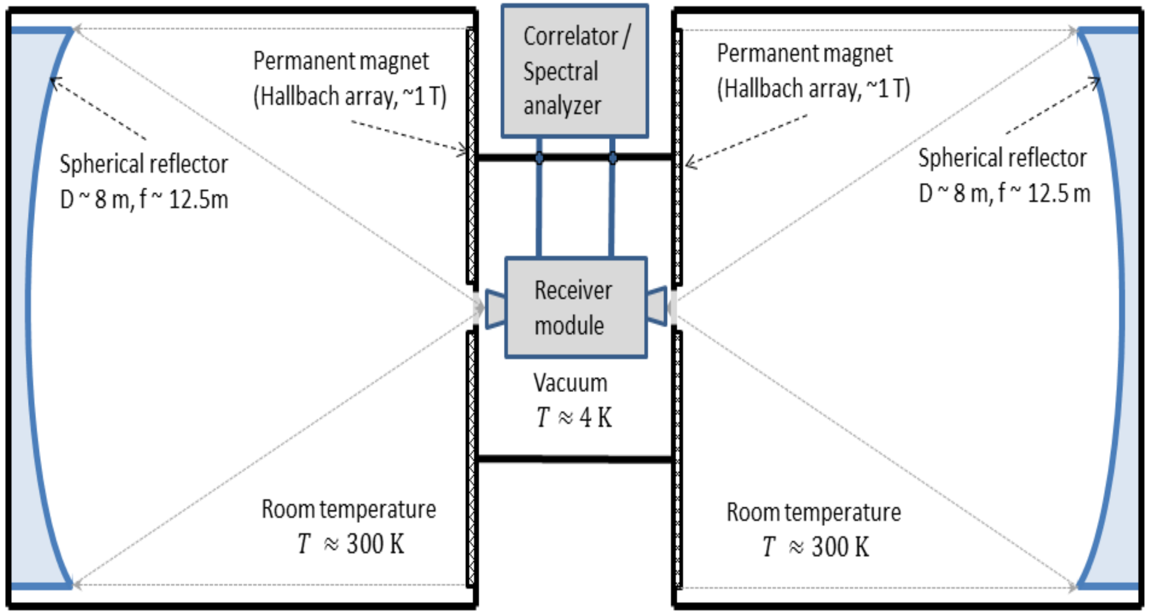


$$P_a/\mathcal{A} \simeq 10^{-27}\,\frac{\mathrm{W}}{\mathrm{m}^2}\left(\frac{g_{a\gamma}}{10^{-14}\,\mathrm{GeV}^{-1}}\right)^2\left(\frac{10^{-4}\,\mathrm{eV}}{m_a}\right)^2\left(\frac{B}{10\,\mathrm{T}}\right)^2$$

Haloscope Searches

Dish Antennas

- Oscillating axion/ALP DM in a background magnetic field carries a small electric field component
- A magnetised mirror in axion/ALP DM background radiates photons [Horns,Jaeckel,Lindner,Lobanov,Redondo,AR 13]
- Axion/ALP DM dish antenna experiment: BRASS (U Hamburg)



[Horns et al. (unpublished)]

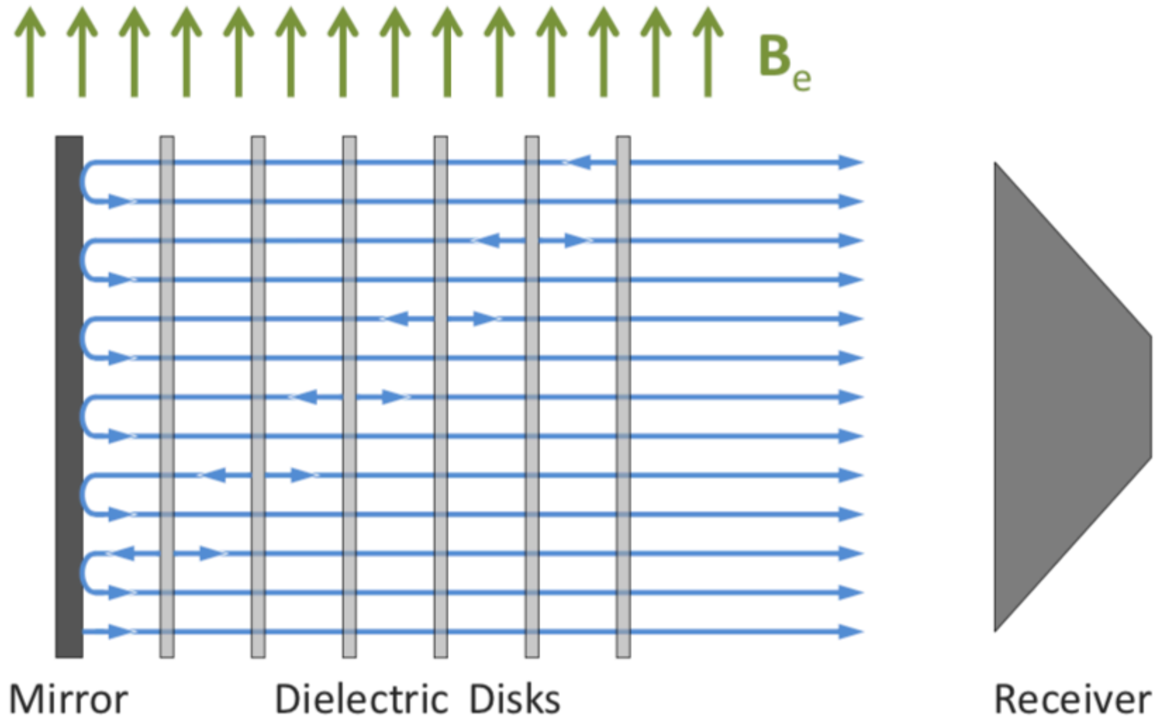
- Permanently magnetized surface for axion/ALP photon conversion
- Dish antenna for photon signal concentration
- Broadband acquisition (16 GHz bandwidth, 10^7 channels)

Haloscope Searches

Dish Antennas

- **Boosted dish antenna:** Open dielectric resonator
  - Add stack of dielectric disks with $\sim \lambda/2$ spacing in front of mirror (all immersed in magnetic field) [Jaeckel,Redondo 13]
  - Constructive interference of photon part of wave function [Millar,Raffelt,Redondo,Steffen 16]

[Baryakhtar,Huang,Lasenby18]



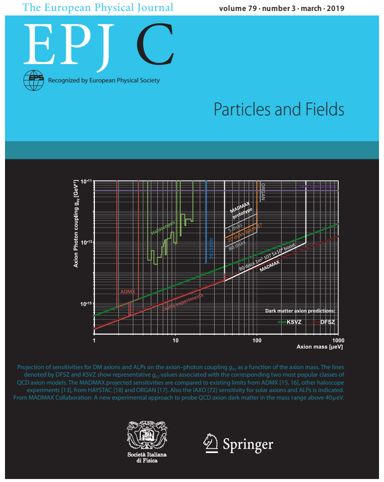
[Caldwell et al. `16]

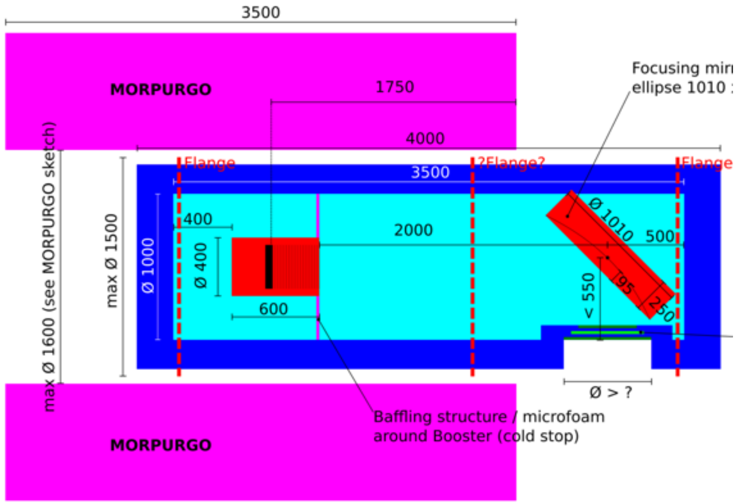
Haloscope Searches

Dish Antennas

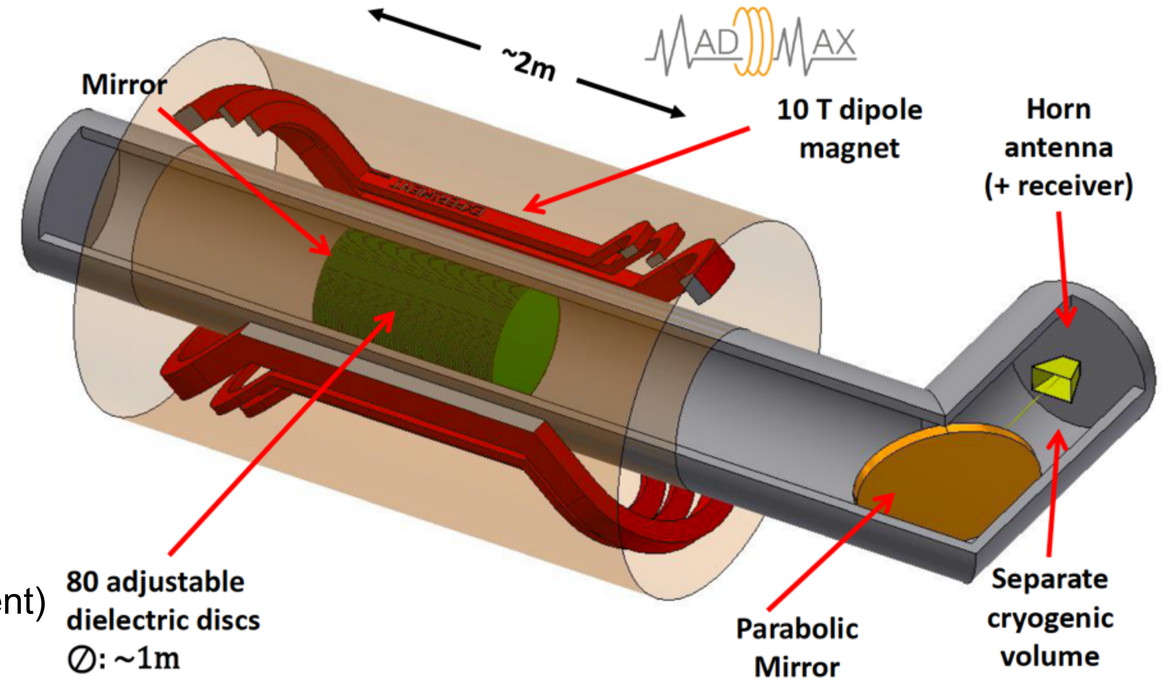
- **Boosted dish antenna:** Proposed MADMAX experiment [Caldwell et al. `16; Bruns et al. 19]

2017 -2019 Design	2020 -2028 Prototype	2028 -2038 Experiment
	@CERN	@DESY





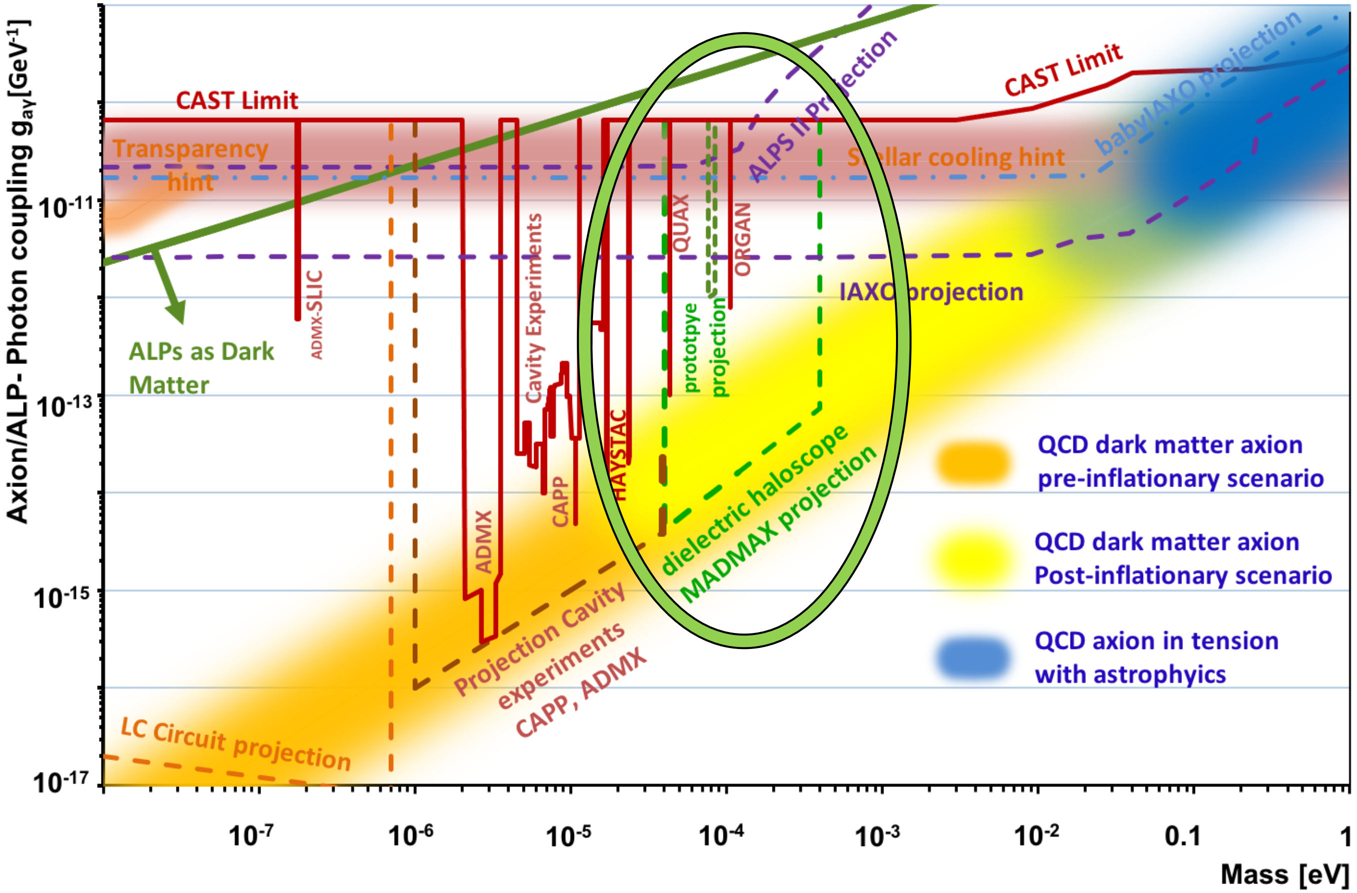
Scaling: Area 1/10 (of final experiment)
discs 1/4
B [T] 1/5



Haloscope Searches

Dish Antennas

- MADMAX projected to probe deep into axion band in the mass range prefered by the post-inflationary PQ symmetry breaking scenario:

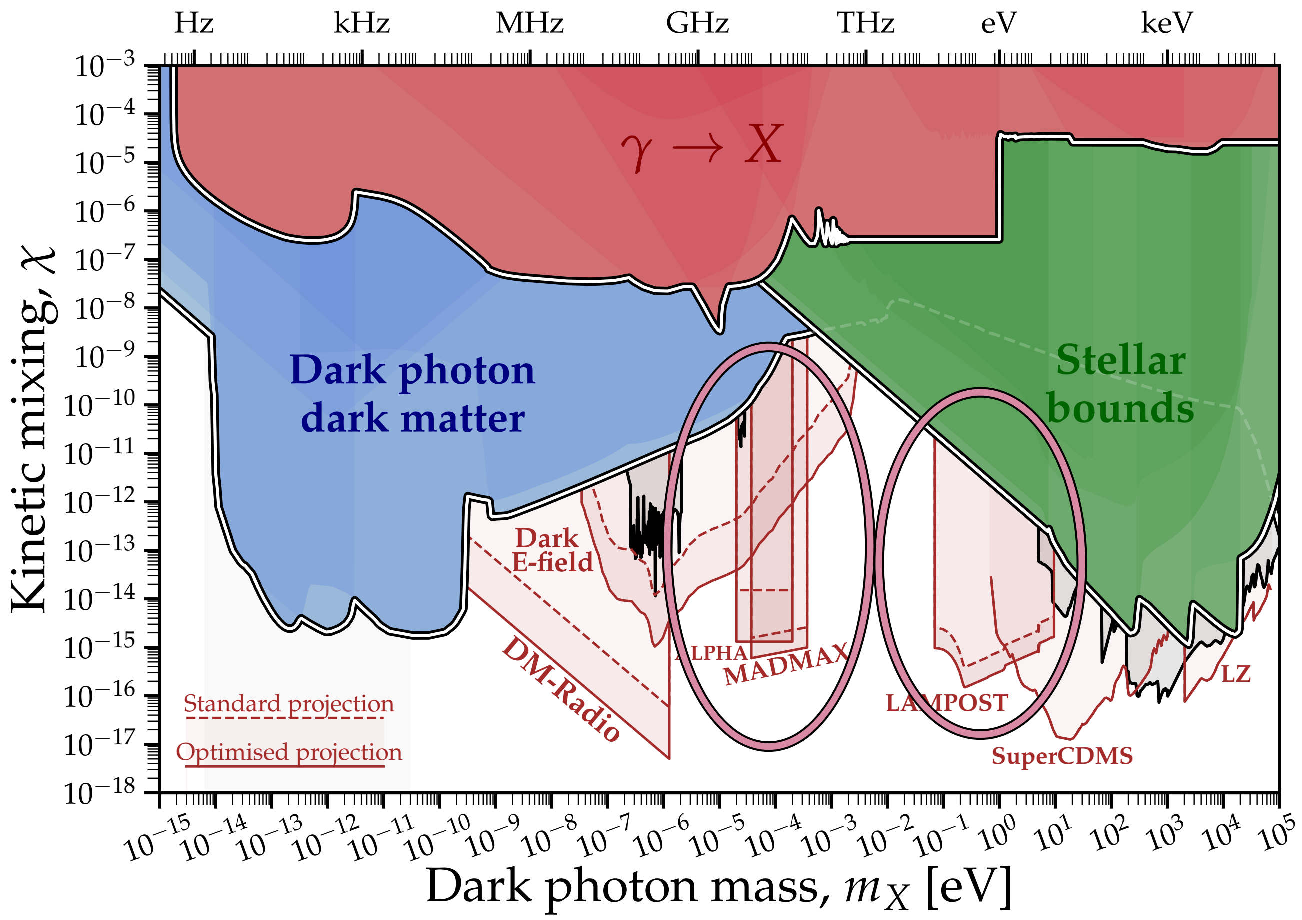


[Lindner,Majorovits,AR `21]

Haloscope Searches

Dish Antennas

- Dielectric haloscopes probe also deep into DP parameter space:



[https://github.com/cajohare/AxionLimits/blob/master/plots/DarkPhoton_with_Projections.pdf]

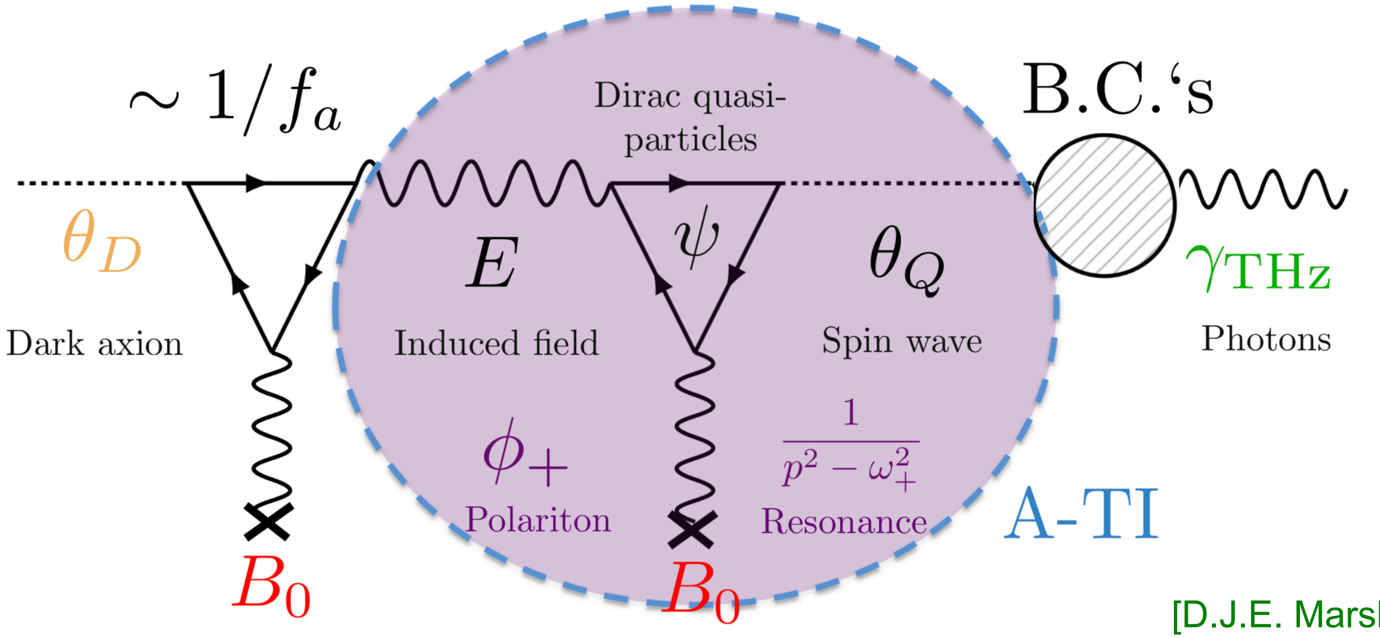
Haloscope Searches

Dish Antennas

- **Boosted dish antenna:** Replace magnetised dish by antiferromagnetic topological insulator (A-TI)

[Marsh et al. 19; Schütte-Engel et al. `21]

  - Some AF-TIs predicted to feature axionic quasiparticles (AQ) - longitudinal A spin fluctuations coupled to E.B [Li et al. `10]
  - In presence of magnetic field, the induced oscillating electric field associated with the DM axion field, mixes with the AQ, leading to a resonant conversion into photons



[D.J.E. Marsh `21]

Haloscope Searches

Dish Antennas

- **TOORAD:** Projected sensitivity reaches axion band in meV region

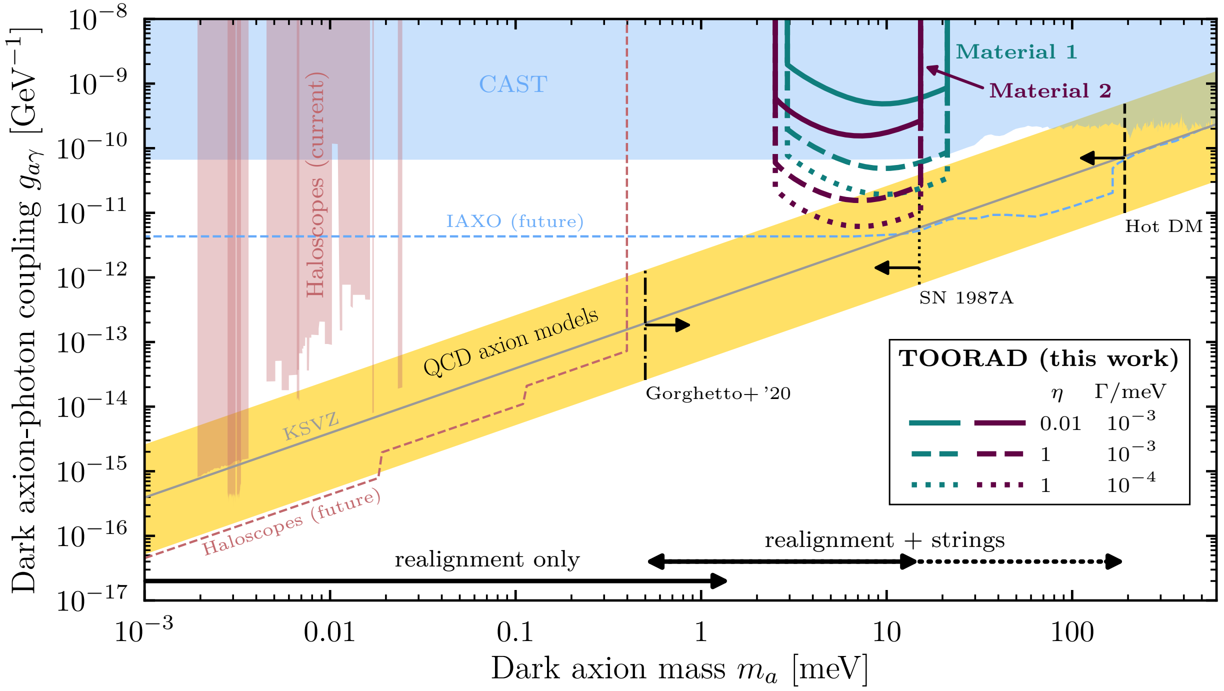


Table 8: Parameter reference values and ranges. Our benchmark material is "Material 2", based on $Mn_2Bi_2Te_5$.

Parameter name & symbol		Range	Benchmark
TMI parameters			
Decay constant	f_Θ	[50, 200] eV	70 eV
AQ mass	m_Θ	$\sim \mathcal{O}$(meV)	1.8 meV
Permittivity	ϵ	[9,49]	25
Magnetic permeability	μ	$\sim \mathcal{O}(1)$	1
Magnon losses	Γ_m	$[10^{-5}, 10^{-3}]$ meV	
Specific conductance	Γ_ρ	$[10^{-5}, 10^{-3}]$ meV	
Area of crystal face	A	$(0.2\,\mathrm{m})^2$	
Thickness	d	d_{opt}, cf. Eq. (4.51)	
Experimental parameters			
External *B*-field	B_e	[1, 10] T	2 T
Detection effciency	η	[0.01, 1]	0.01
Dark count rate	λ_d	$\gtrsim 1$ mHz	1 mHz

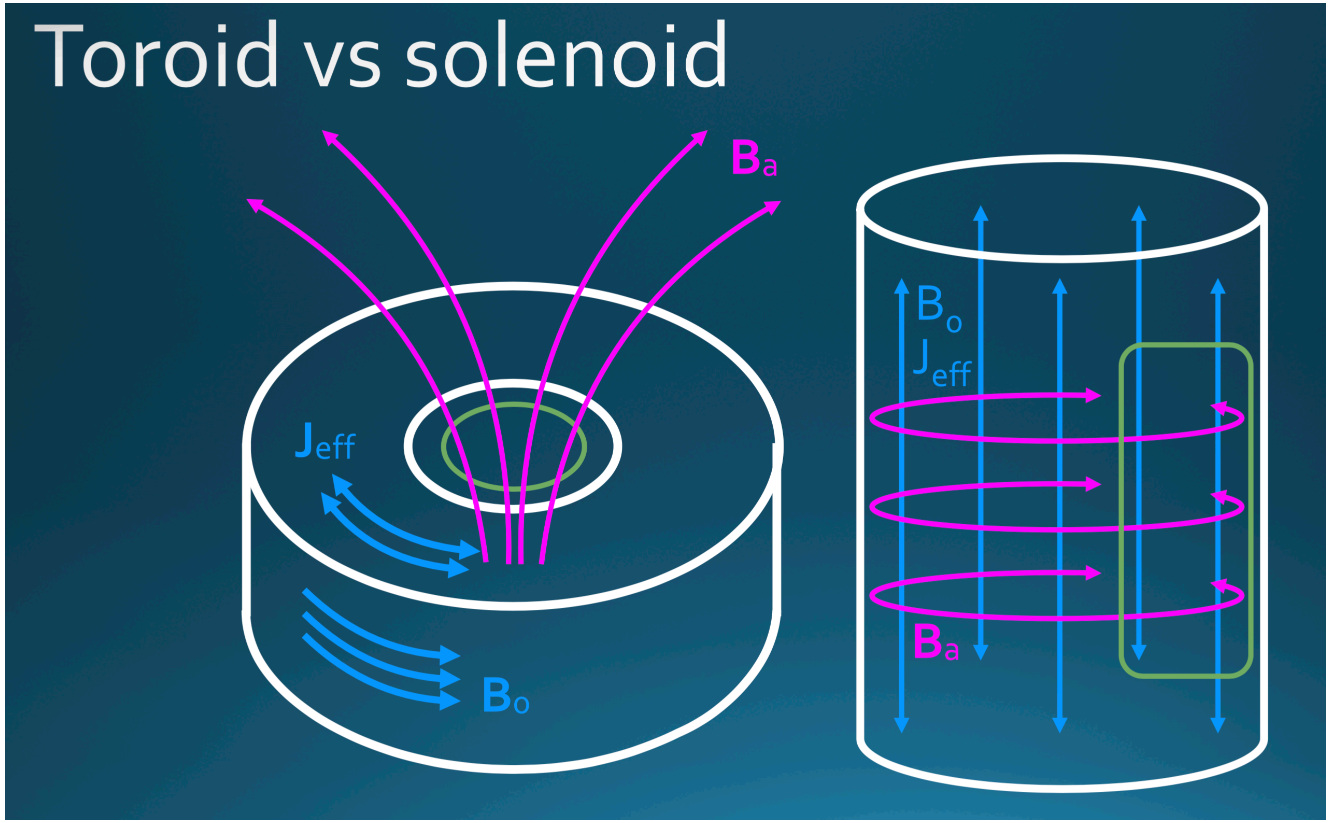
[Schütte-Engel et al. `21]

Haloscope Searches

Searching for Axion-induced Magnetic Fields

[Sikivie,Sullivan,Tanner 14; Kahn,Safdi,Thaler `16]

- Toroidal (solenoidal) magnet with fixed field B_0:
  - Axion DM generates oscillating effective current J_{eff} parallel to B_0
  - ... generating oscillating magnetic flux B_a through center (azimuthal magnetic flux)
  - ... which can be read out by pickup structure



$$\mathbf{J}_{eff} = g_{a\gamma\gamma}\sqrt{2\rho_{DM}}\cos(m_a t)\mathbf{B}$$

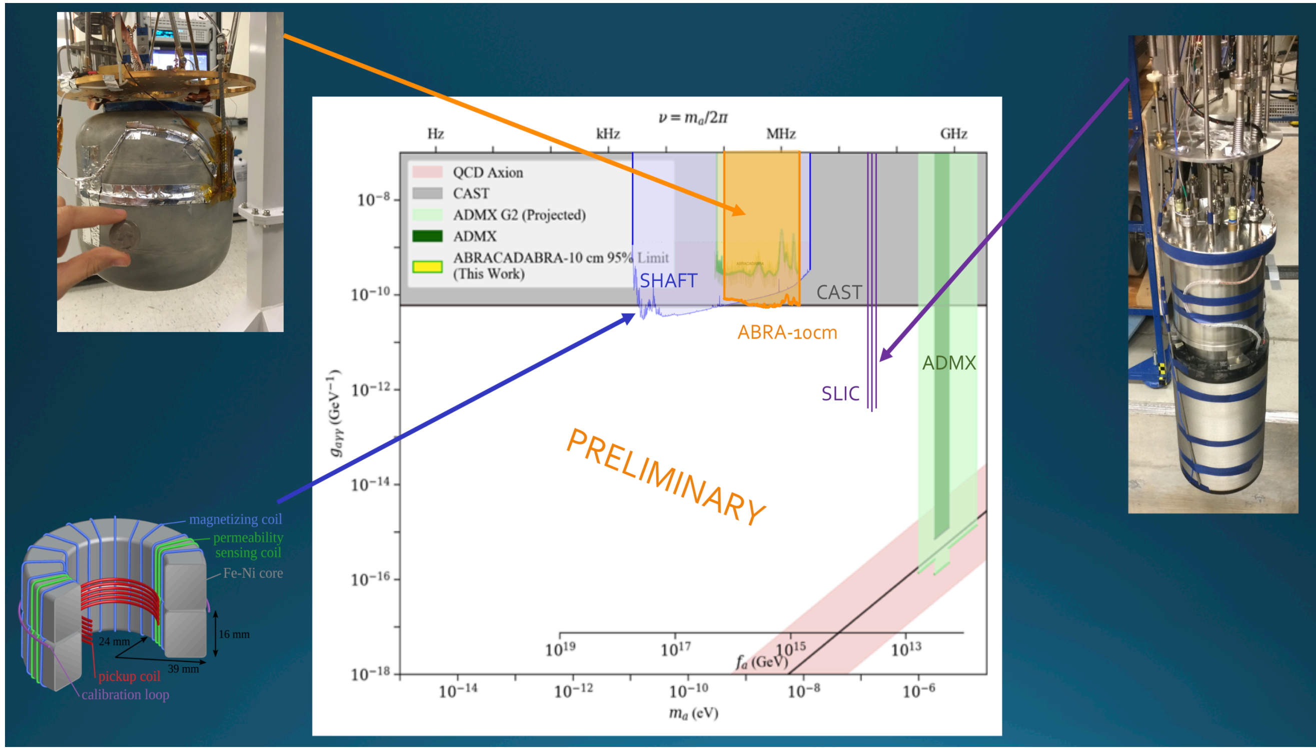
[Salemi '21]

Haloscope Searches

Searching for Axion-induced Magnetic Fields

[Sikivie,Sullivan,Tanner 14; Kahn,Safdi,Thaler `16]

- Toroidal (solenoidal) magnet with fixed field B_0:
  - Axion DM generates oscillating effective current J_{eff} parallel to B_0
  - ... generating oscillating magnetic flux B_a through center (azimuthal magnetic flux)
  - ... which can be read out by pickup structure
- Pathfinder experiments:
  - ABRACADABRA [Ouellet et al. 19]
  - ADMX SLIC [Crisosto et al. 20]
  - SHAFT [Gramolin et al. 21]



[Salemi '21]

Haloscope Searches

Searching for Axion-induced Magnetic Fields

[Sikivie,Sullivan,Tanner 14; Kahn,Safdi,Thaler `16]

- Toroidal (solenoidal) magnet with fixed field B_0:
  - Axion DM generates oscillating effective current J_{eff} parallel to B_0
  - ... generating oscillating magnetic flux B_a through center (azimuthal magnetic flux)
  - ... which can be read out by pickup structure
- Pathfinder experiments:
  - ABRACADABRA [Ouellet et al. 19]
  - ADMX SLIC [Crisosto et al. 20]
  - SHAFT [Gramolin et al. 21]
  - DM-Radio Cubic Meter Consortium: aims to reach the canonical axion band, even reaching predictions from GUTs [Ernst,AR,Tamarit 18; Di Luzio,AR,Tamarit 18]

DM Radio Cubic Meter Consortium

Funded as part of DOE New Initiatives in Dark Matter program

R&D Phase Consortium Leadership:

Project manager for R&D phase: Dale Li

Name	Institution	Role / Team Lead
Kent Irwin	SLAC and Stanford	Consortium PI
Karl van Bibber	UC Berkeley	Magnet
Lindley Winslow	MIT	Magnetic shielding, vibration
Saptarshi Chaudhuri	Princeton	Control system, scan
Peter Graham	Stanford	Theory
Reyco Henning	UNC Chapel Hill	Calibration and DAQ
Dale Li	SLAC	Cryomechanical
Hsiao-Mei Cho	SLAC	SQUID
Wes Craddock	SLAC	Lead Engineer
Nadine Kurita	SLAC	Project Management Plan

DARK MATTER RADIO

U.S. DEPARTMENT OF ENERGY | Office of Science

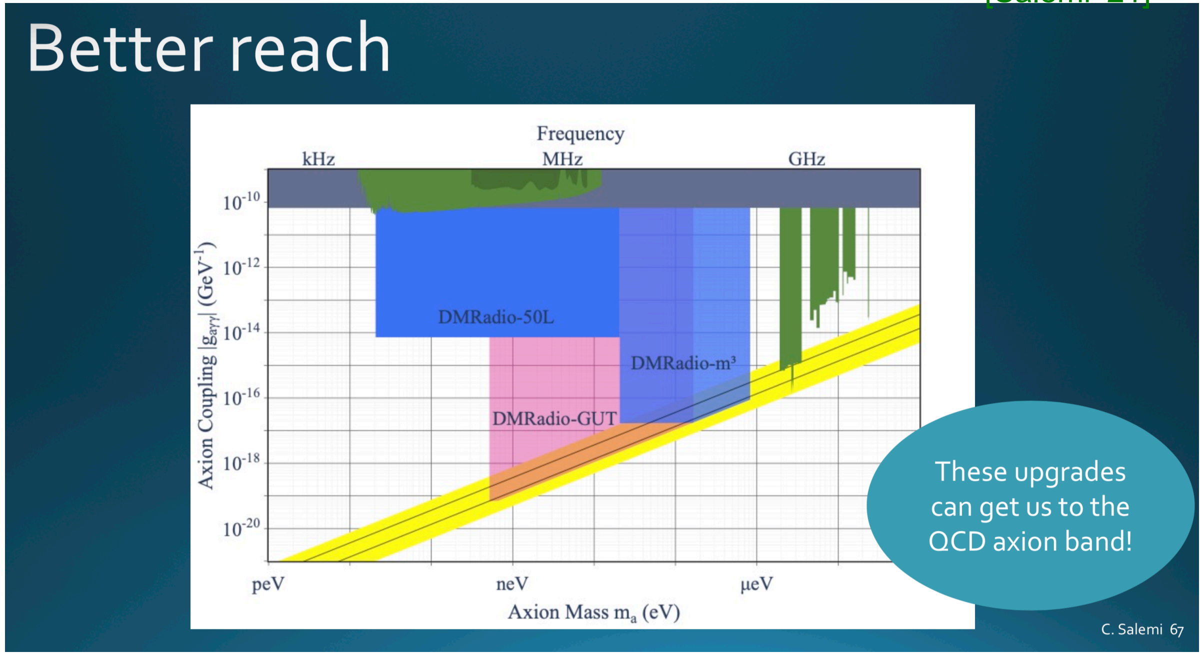
SLAC

PRINCETON UNIVERSITY

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

DMRm3consortium v1 20191104

[Salemi ‘21]

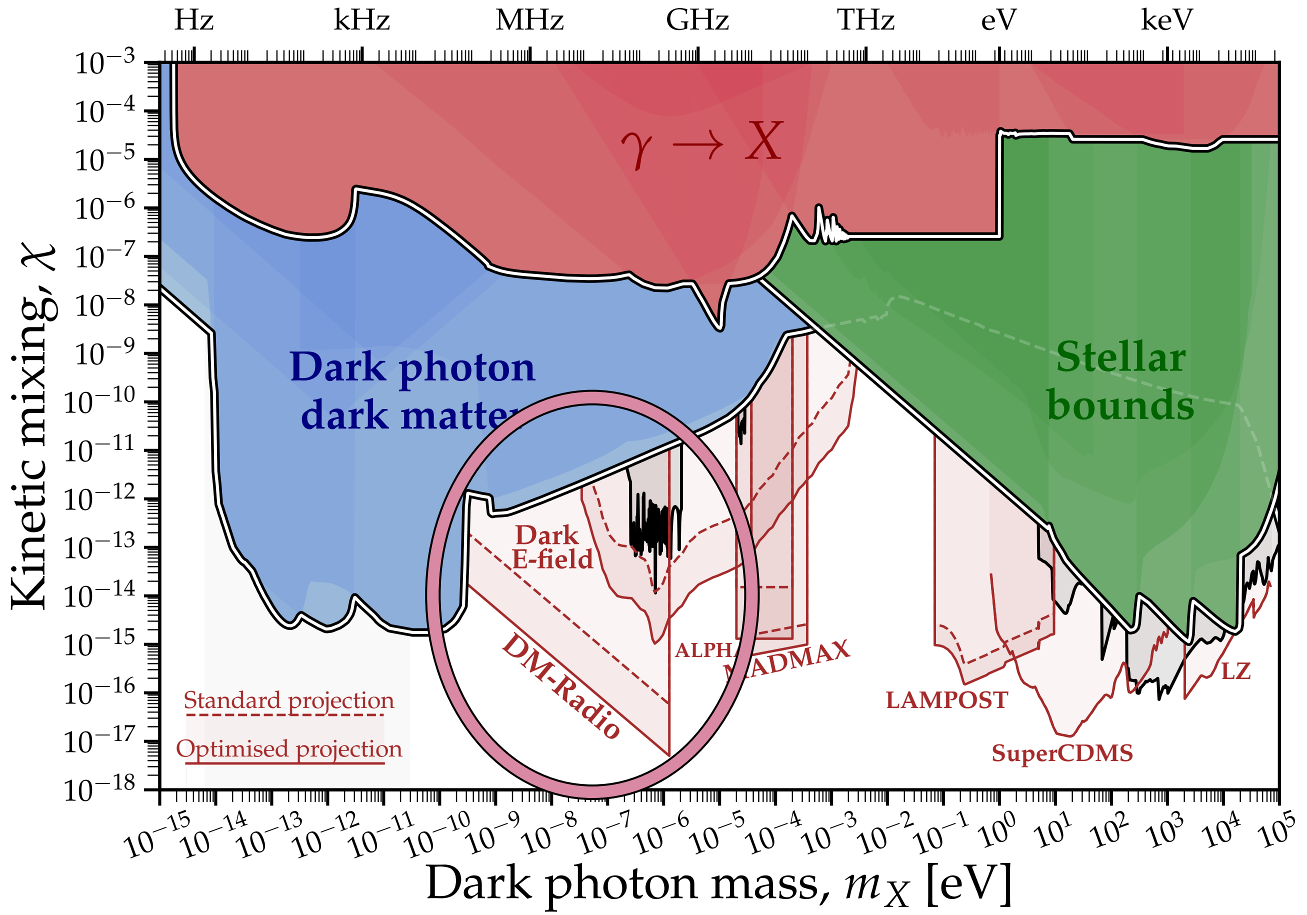


Haloscope Searches

Searching for Axion-induced Magnetic Fields

[Sikivie,Sullivan,Tanner 14; Kahn,Safdi,Thaler `16]

- Toroidal (solenoidal) magnet with fixed field B_0:
  - Axion DM generates oscillating effective current J_{eff} parallel to B_0
  - ... generating oscillating magnetic flux B_a through center (azimuthal magnetic flux)
  - ... which can be read out by pickup structure
- Pathfinder experiments:
  - ABRACADABRA [Ouellet et al. 19]
  - ADMX SLIC [Crisosto et al. 20]
  - SHAFT [Gramolin et al. 21]
  - DM-Radio Cubic Meter Consortium: aims to reach the canonical axion band, even reaching predictions from GUTs [Ernst,AR,Tamarit 18; Di Luzio,AR,Tamarit 18]
- Can also probe DP DM

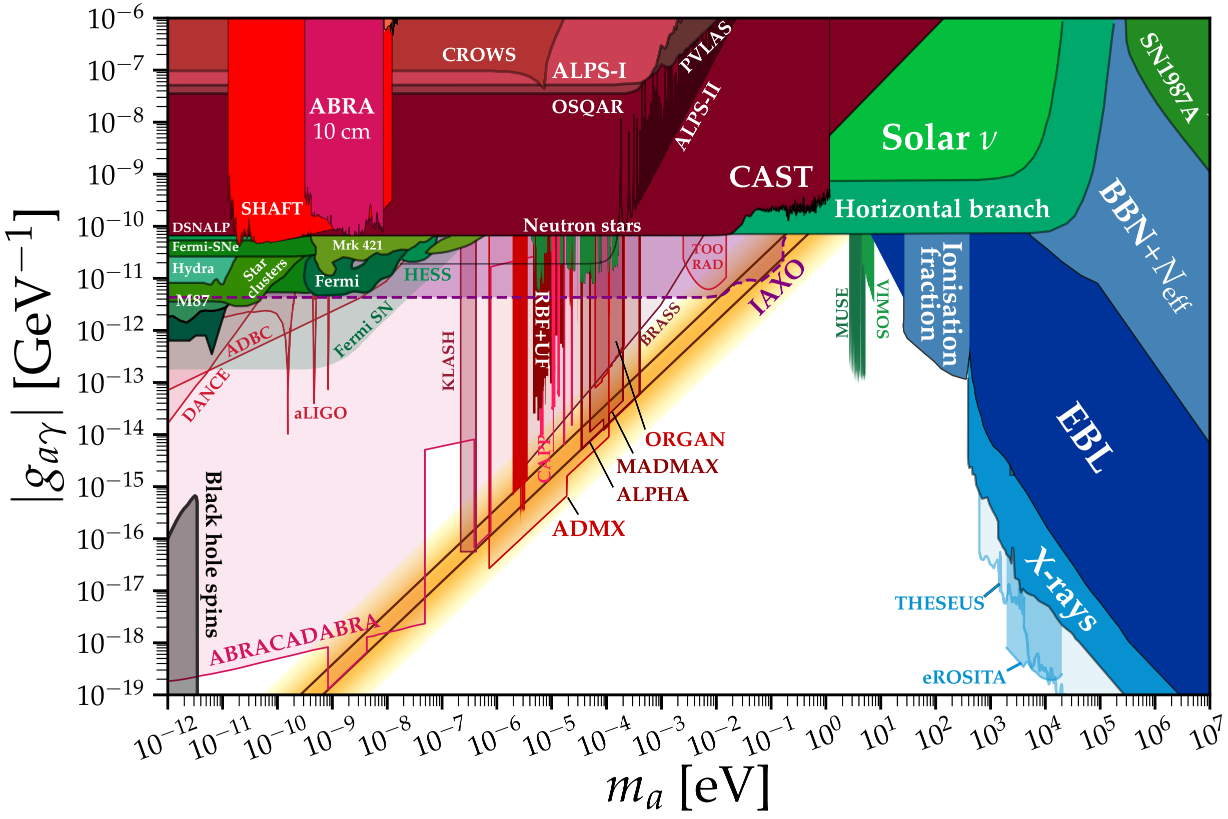


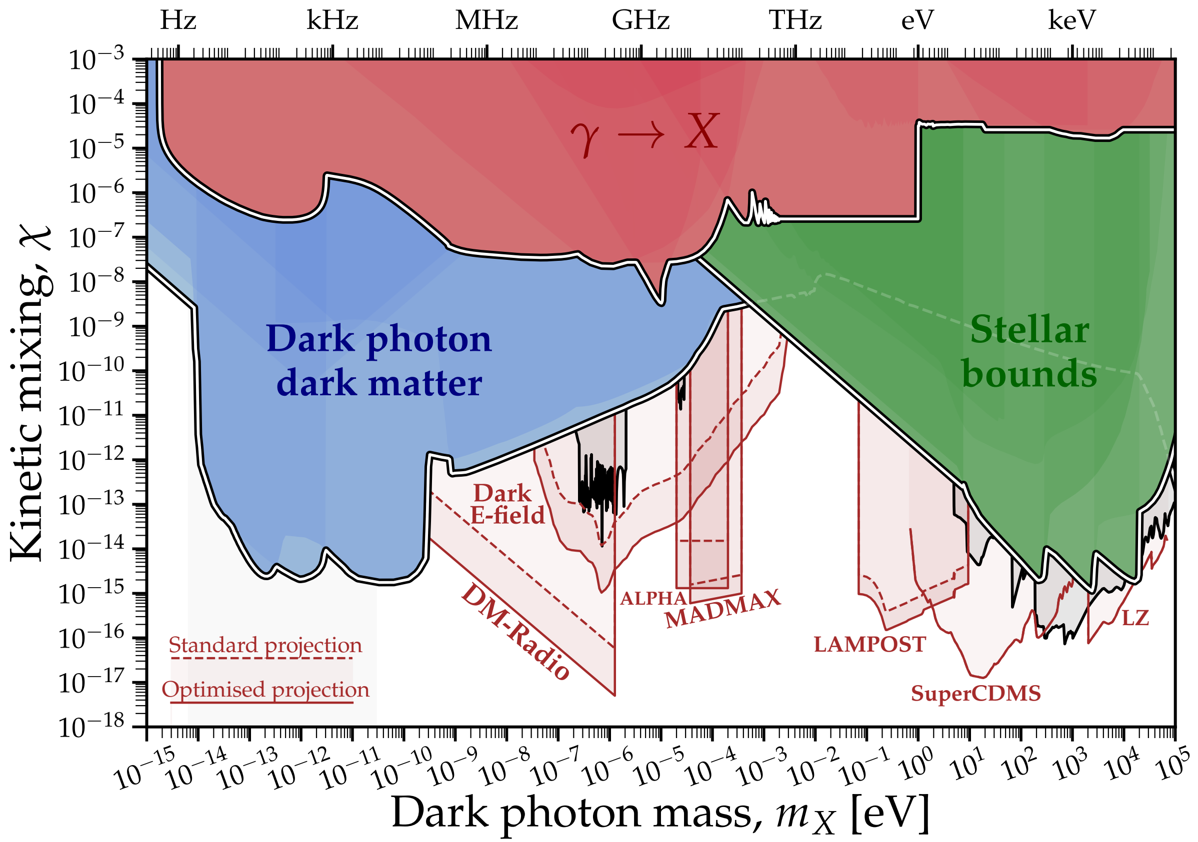
[https://github.com/cajohare/AxionLimits/blob/master/plots/DarkPhoton_with_Projections.pdf]

Summary

Ultra-Light Dark Matter = WISPy Dark Matter = Coherent-Field Dark Matter

- Solid physics case
- Large parts in associated parameter space will be tackled in the upcoming decade by many experiments:





- Field profits/depends from/on progress in quantum sensing