Axion dark matter (theory and experiment)

Andreas Ringwald
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The Axion

Solving two problems in one go

[Peccei,Quinn `77; Weinberg `78; Wilczek `78]

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$$\mathcal{L}_{\rm QCD} \supset \overline{\theta}\,\frac{\alpha_s}{8\pi}G^b_{\mu\nu}\tilde{G}^{b,\mu\nu}$$

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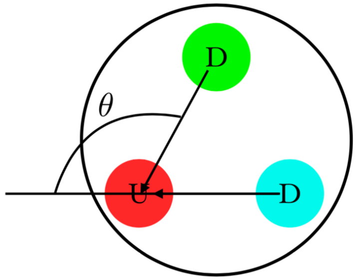
- leads to electric dipole moment of neutron (nEDM):

[Crewther,Di Vecchia,Veneziano,Witten 79;...; Pospelov,Ritz 00]

$$d_n \sim \frac{m_u m_d}{m_u+m_d}\frac{1}{m_n^2}\,\bar{\theta}\, e \sim 10^{-16}\,\bar{\theta}\,e\,{\rm cm}$$



[Hook 18]

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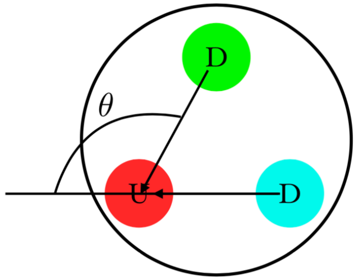
- Experiment: [Abel et al. 20]

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



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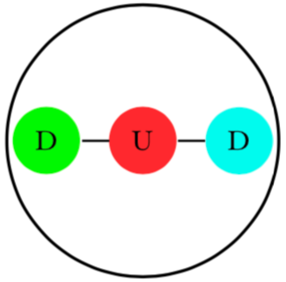
[Hook 18]



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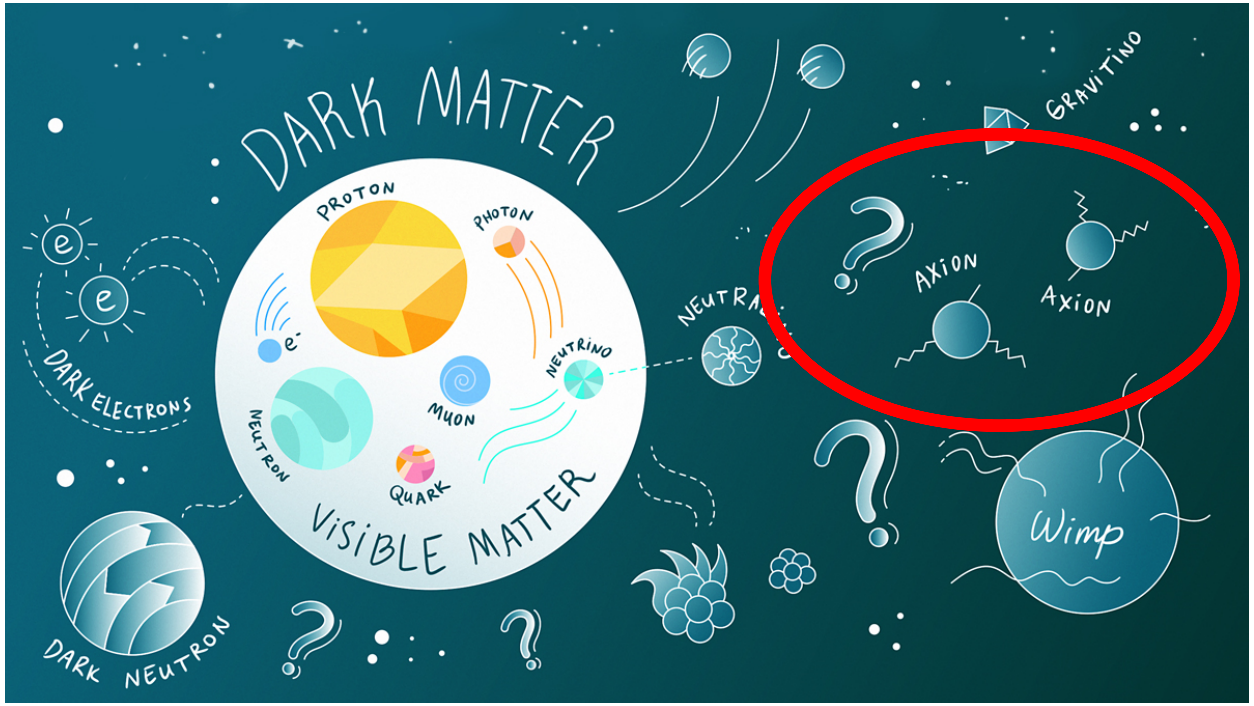
  1. Why do strong interactions conserve CP so accurately?
  2. **What is the nature of dark matter (DM)?**



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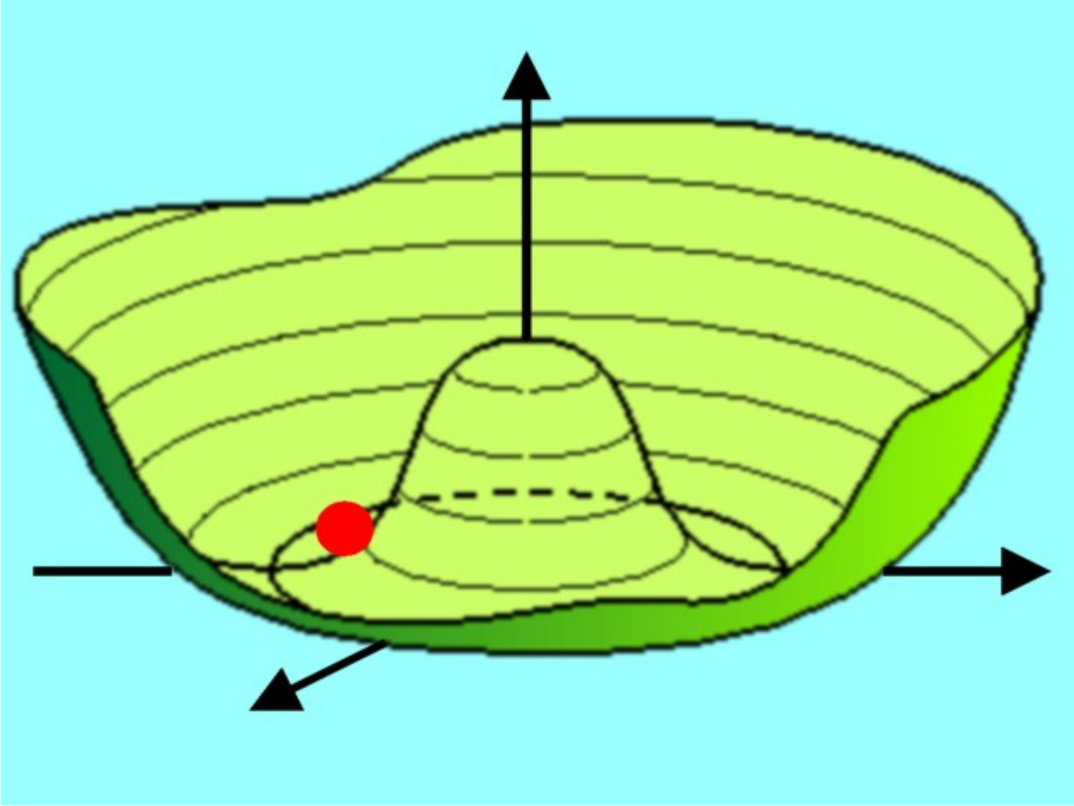
$$\mathcal{L} \supset -\lambda_\sigma \left(|\sigma|^2 - \frac{v_{\rm PQ}^2}{2} \right)^2 + y\,\sigma\,\bar{\mathcal{Q}}_L \mathcal{Q}_R$$



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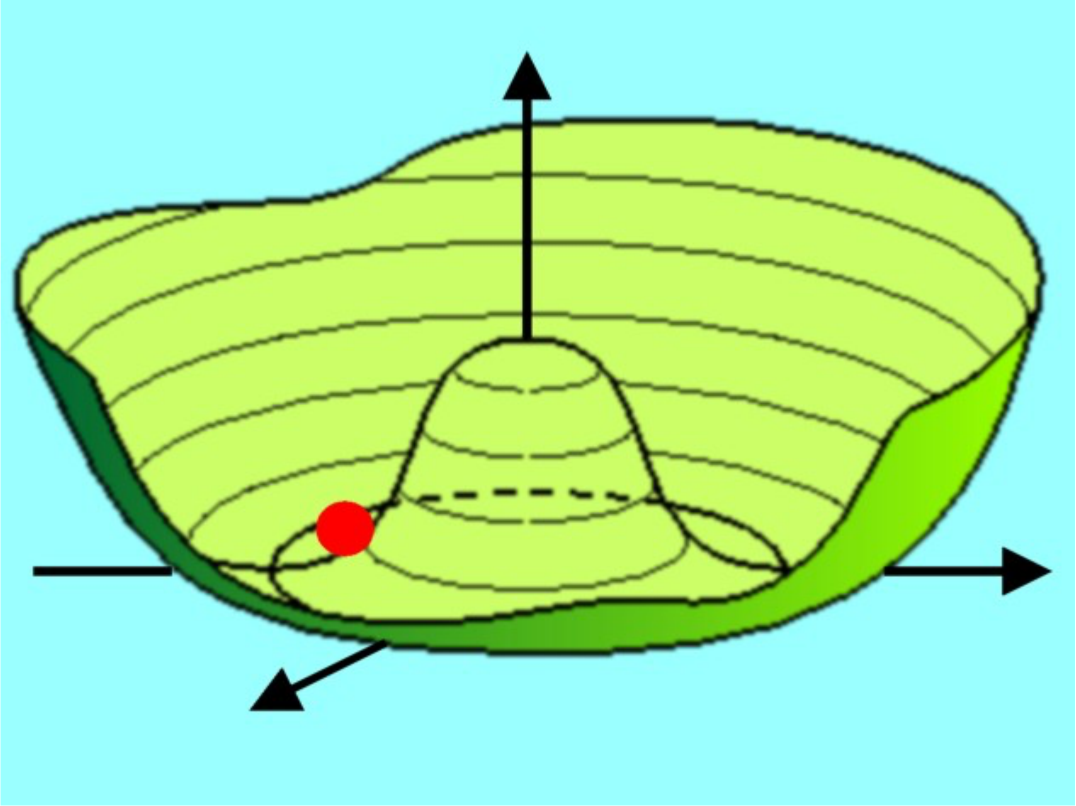
    1. Excitation of angular field a: axion (NG-boson)
    2. Excitation of modulus field ρ: $m_\rho = \sqrt{2\lambda_\sigma} v_{\rm PQ}$
    3. Exotic quark: $m_{\mathcal{Q}} = \frac{y}{\sqrt{2}} v_{\rm PQ}$

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



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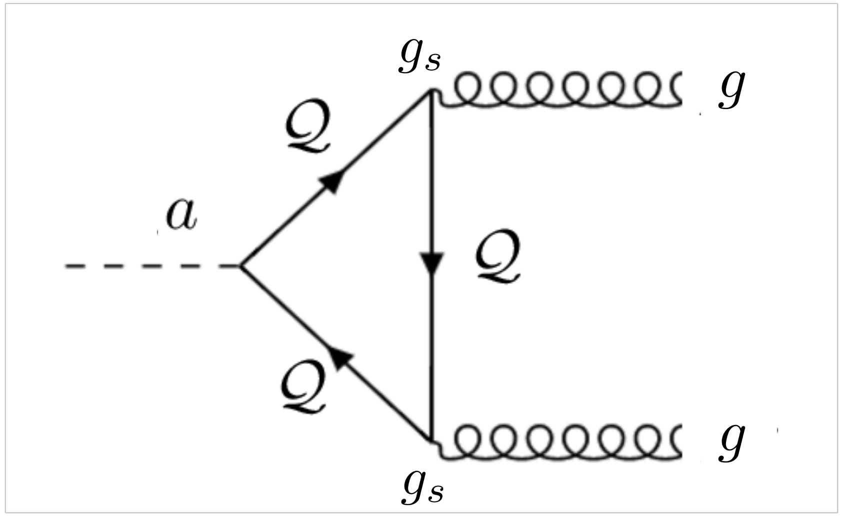

[Chadha-Day, Ellis, Marsh, Science Advances 22]

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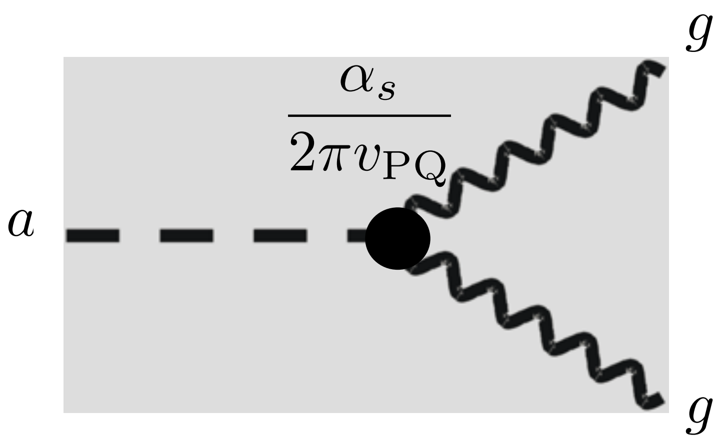
$$\mathcal{L}_{\rm eff} \supset \frac{1}{2}\partial^\mu a\, \partial_\mu a + \frac{\alpha_s}{8\pi} \frac{a}{v_{\rm PQ}} G^a_{\mu\nu} \tilde{G}^{a\,\mu\nu}$$



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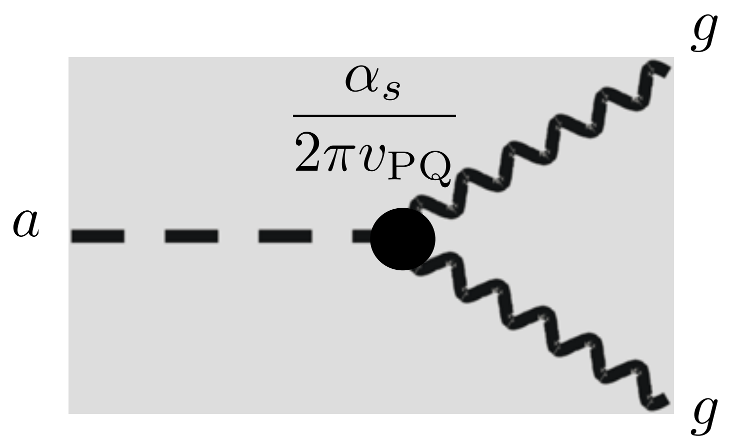

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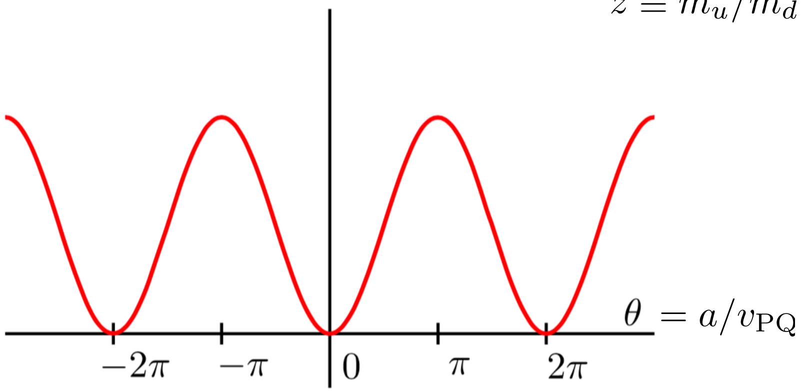
- Integrating out gluons (matching to chiral Lagrangian) results in non-trivial effective potential for axion field

- Effective axion potential at energies below confinement scale [Di Vecchia,Veneziano `80; Leutwyler,Smilga 92]

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

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



predicts

- $\langle\theta(x)\rangle = 0 \;\Rightarrow$ nEDM vanishes
- axion mass:

$$m_a = \frac{\sqrt{V''(0)}}{v_{\rm PQ}} = \frac{\sqrt{z}}{1+z}\frac{m_\pi f_\pi}{v_{\rm PQ}} \approx 6\ \mu{\rm eV}\left(\frac{10^{12}\ {\rm GeV}}{v_{\rm PQ}}\right)$$

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Effective field theory below QCD scale

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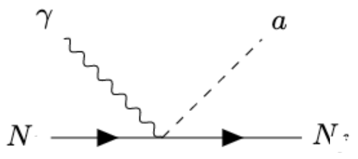

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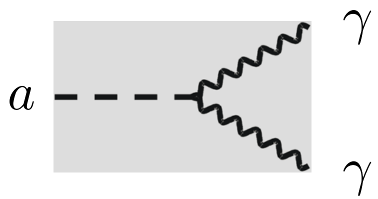

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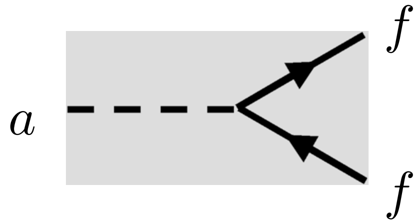

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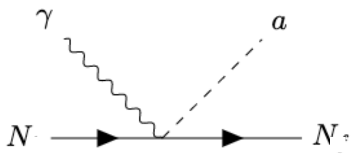

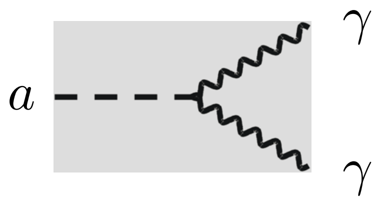

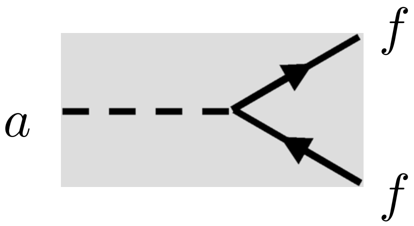

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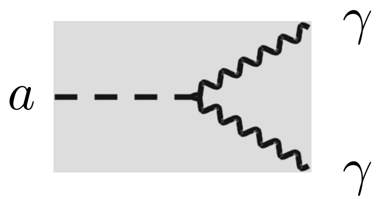

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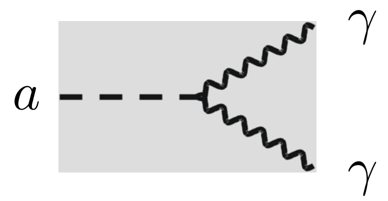

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[Kaplan 85;Srednicki `85]

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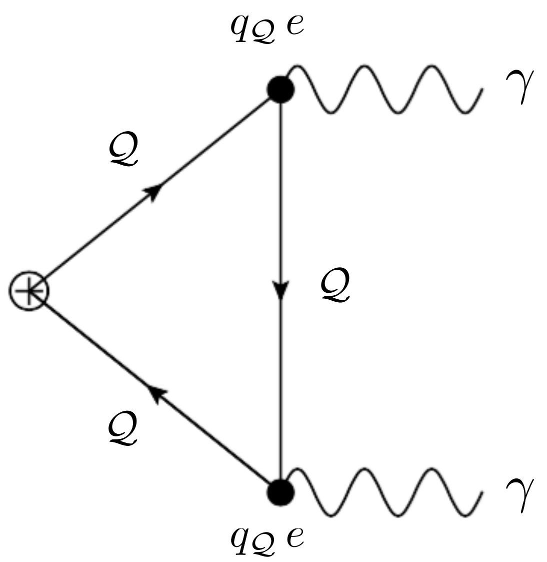

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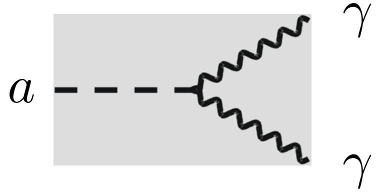

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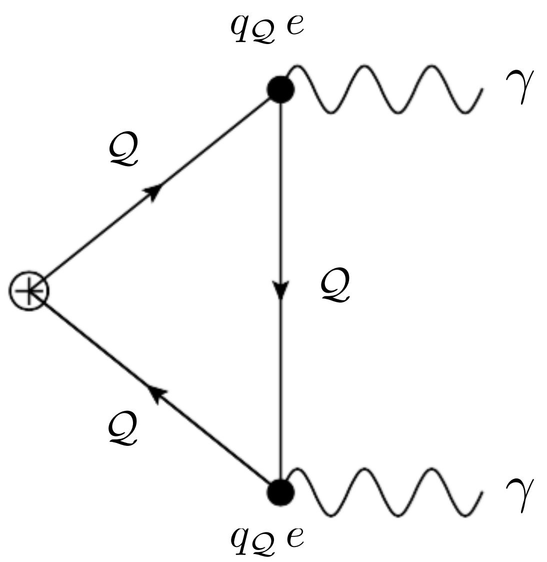
    - For exotic quark $\mathcal{Q}$ with electric charge $q_{\mathcal{Q}}$: $N_{\mathcal{Q}} = 1/2,\ E_{\mathcal{Q}} = 3\, q_{\mathcal{Q}}^2$



The Axion

Electromagnetic coupling

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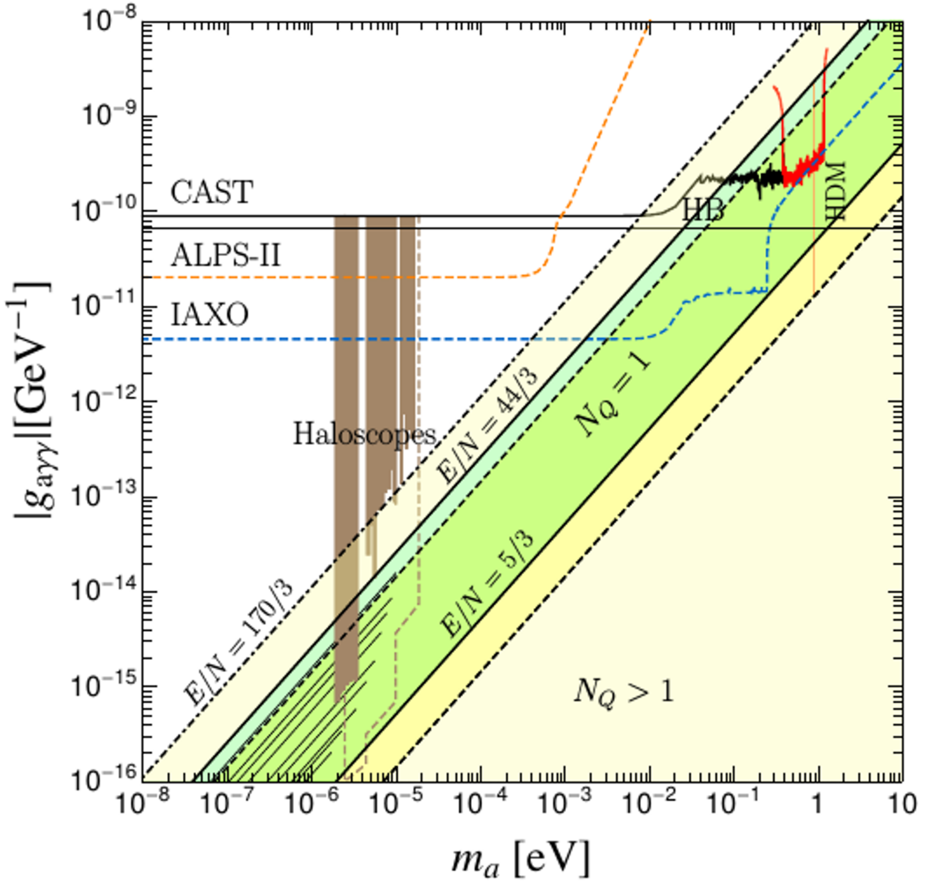

[Di Luzio,Mescia,Nardi 16, 18]

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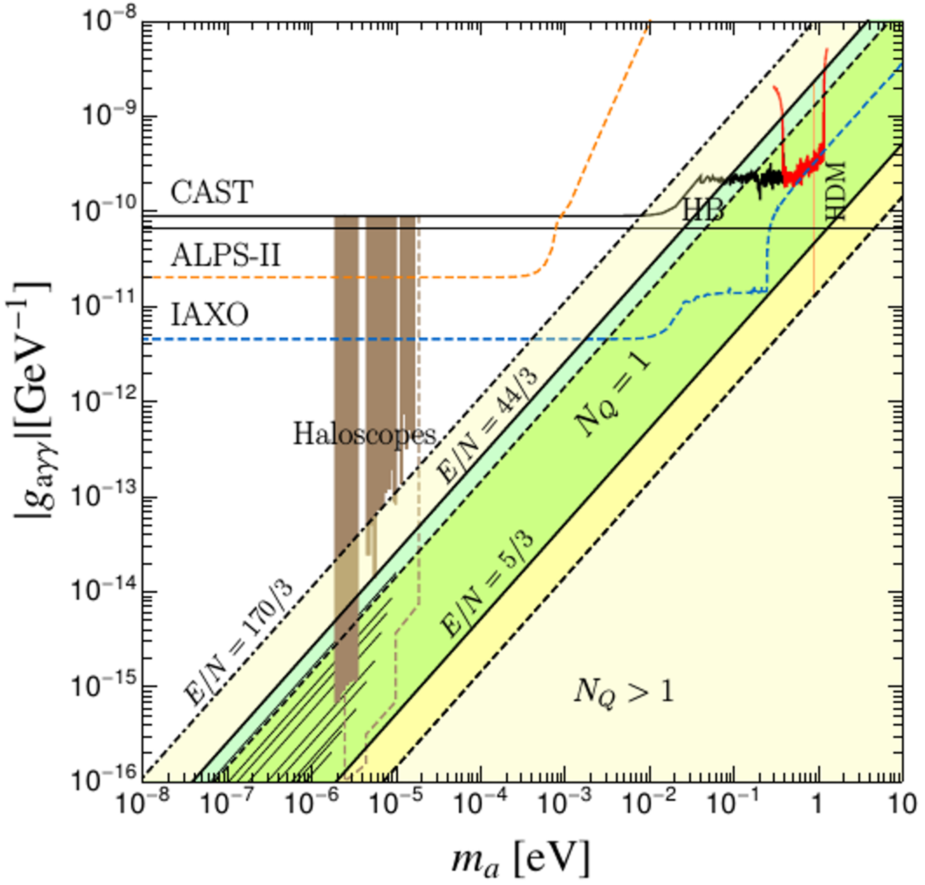
- What if exotic quark carries a magnetic charge? [Sokolov,AR 21, 22, 23]
  - Its existence would explain not only strong CP conservation, but also charge quantisation [Dirac 1931, Schwinger 1966, Zwanziger 1968]



[Di Luzio,Mescia,Nardi 16, 18]

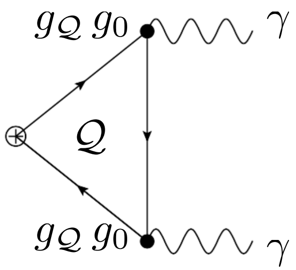
The Axion

Electromagnetic coupling

$$g_{a\gamma\gamma} \equiv \frac{\alpha}{2\pi f_a} C_{a\gamma} \simeq \frac{\alpha}{2\pi f_\pi} \frac{m_a}{m_\pi} \frac{1+z}{\sqrt{z}} \left(\frac{E_{\mathcal{Q}}}{N_{\mathcal{Q}}} - \frac{2}{3} \frac{4+z}{1+z} \right)$$

- Allowing for more general representations of exotic quark leads to “band” of predictions for photon coupling
- What if exotic quark carries a magnetic charge? [Sokolov,AR 21, 22, 23]
    - Its existence would explain not only strong CP conservation, but also charge quantisation [Dirac 1931, Schwinger 1966, Zwanziger 1968]
    - Induced photon coupling:

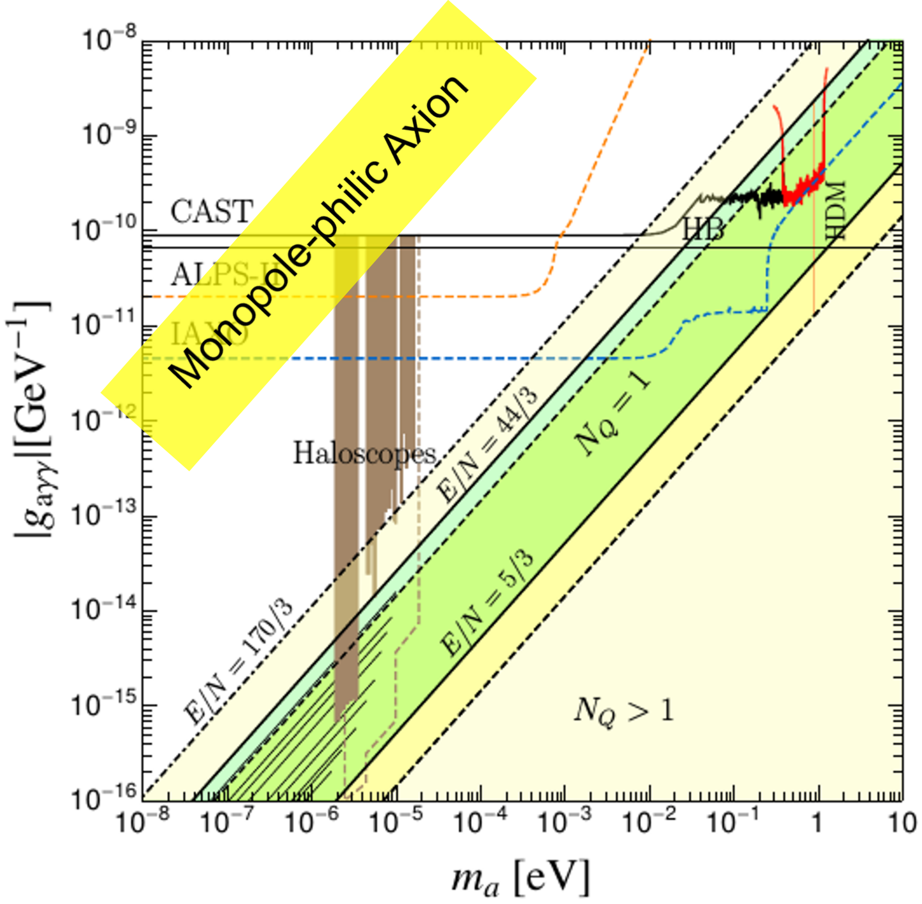
$$g_{a\mathrm{MM}} \simeq \frac{\alpha_{\mathrm{M}}}{2\pi f_\pi} \frac{m_a}{m_\pi} \frac{1+z}{\sqrt{z}} \frac{M_{\mathcal{Q}}}{N_{\mathcal{Q}}}$$



$$M_{\mathcal{Q}} = 3\, g_{\mathcal{Q}}^2$$

strongly enhanced due to charge quantisation ($e\, g_0 = 6\pi\, n$):

$$\alpha_{\mathrm{M}} \equiv \frac{g_0^2}{4\pi} = \frac{9\pi}{e^2} = \frac{9}{4}\alpha^{-1} \quad \Rightarrow \quad \frac{g_{a\mathrm{MM}}}{g_{a\gamma\gamma}} = \left(\frac{3\, g_{\mathcal{Q}}}{2\, q_{\mathcal{Q}}} \right)^2 \alpha^{-2} \sim 10^5$$



[Di Luzio,Mescia,Nardi 16, 18]

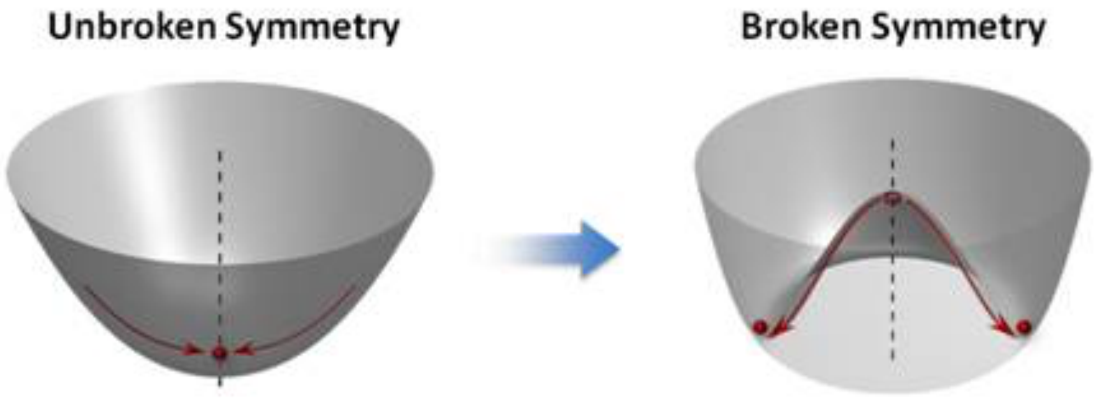
Axion Dark Matter

Standard production mechanisms

Axion Dark Matter

Standard production mechanisms

- Axion comes to existence as soon as Peccei-Quinn (PQ) symmetry is spontaneously broken



[Peking University]

Axion Dark Matter

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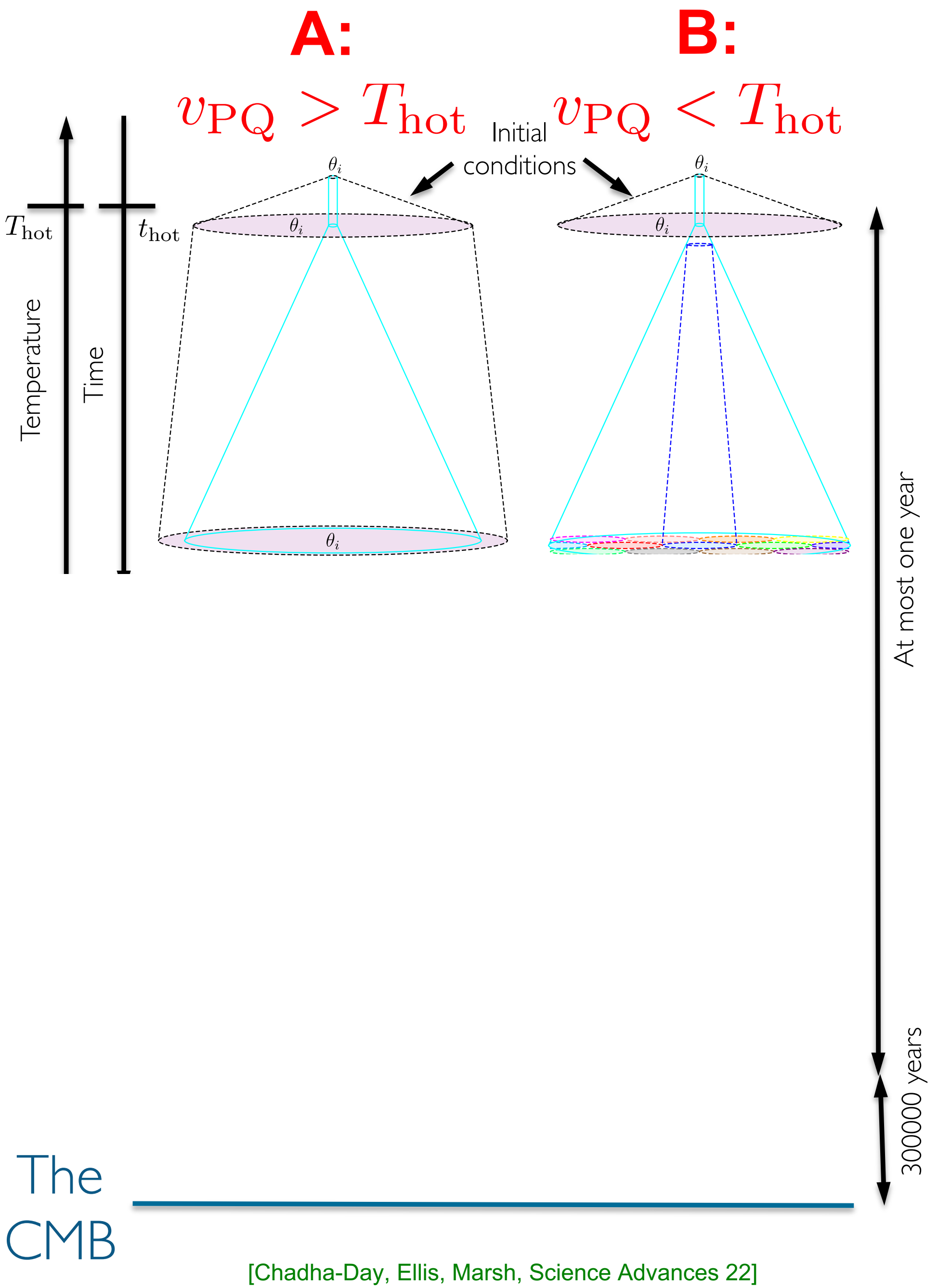
- Axion comes to existence as soon as Peccei-Quinn (PQ) symmetry is spontaneously broken
- Dynamics and resulting DM density depends on whether PQ breaking scale $v_{\rm PQ}$ is larger or smaller than the temperature of the universe at the onset of the hot phase, $T_{\rm hot}$



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

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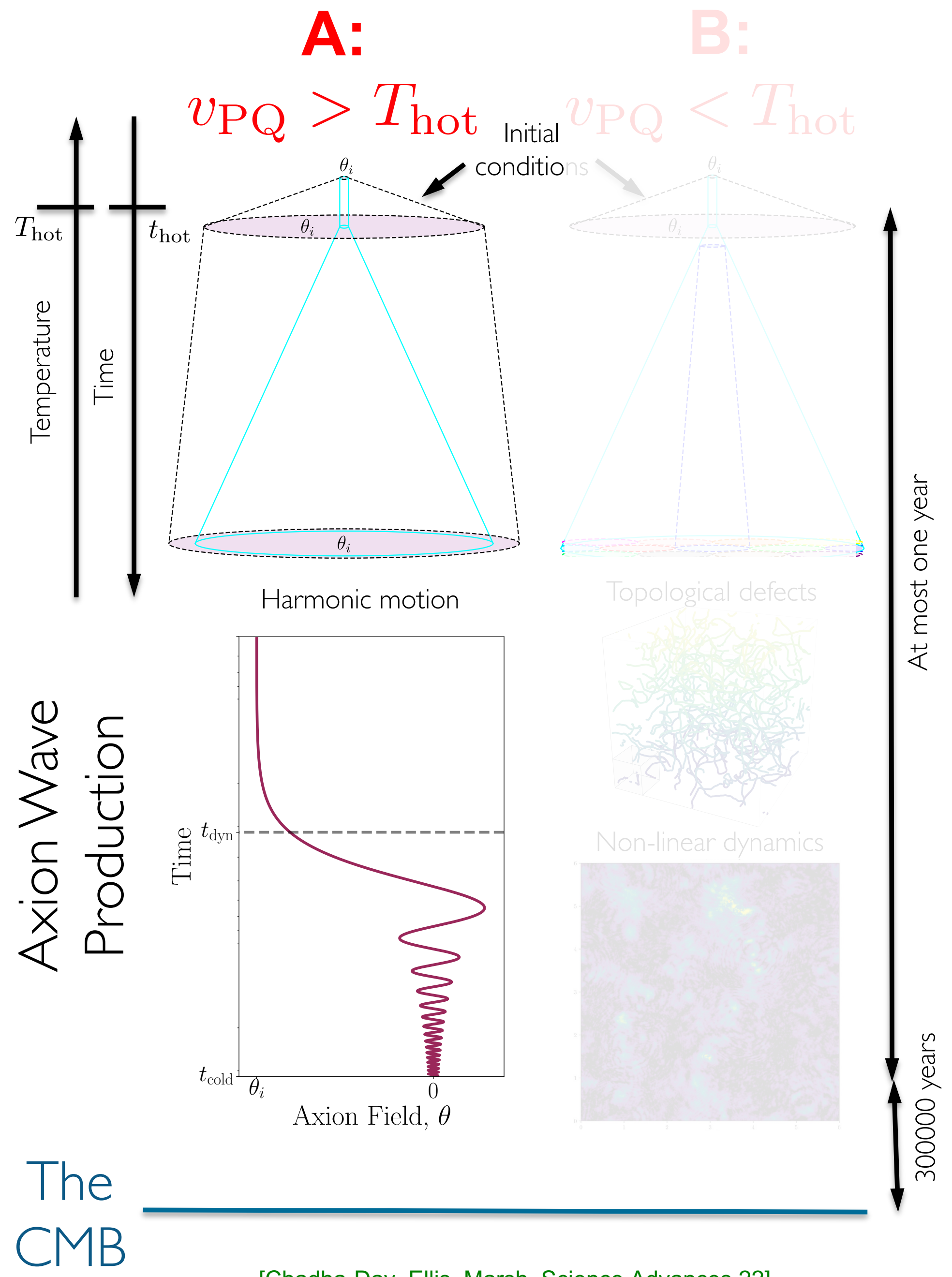
    - axion DM production by realignment mechanism

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



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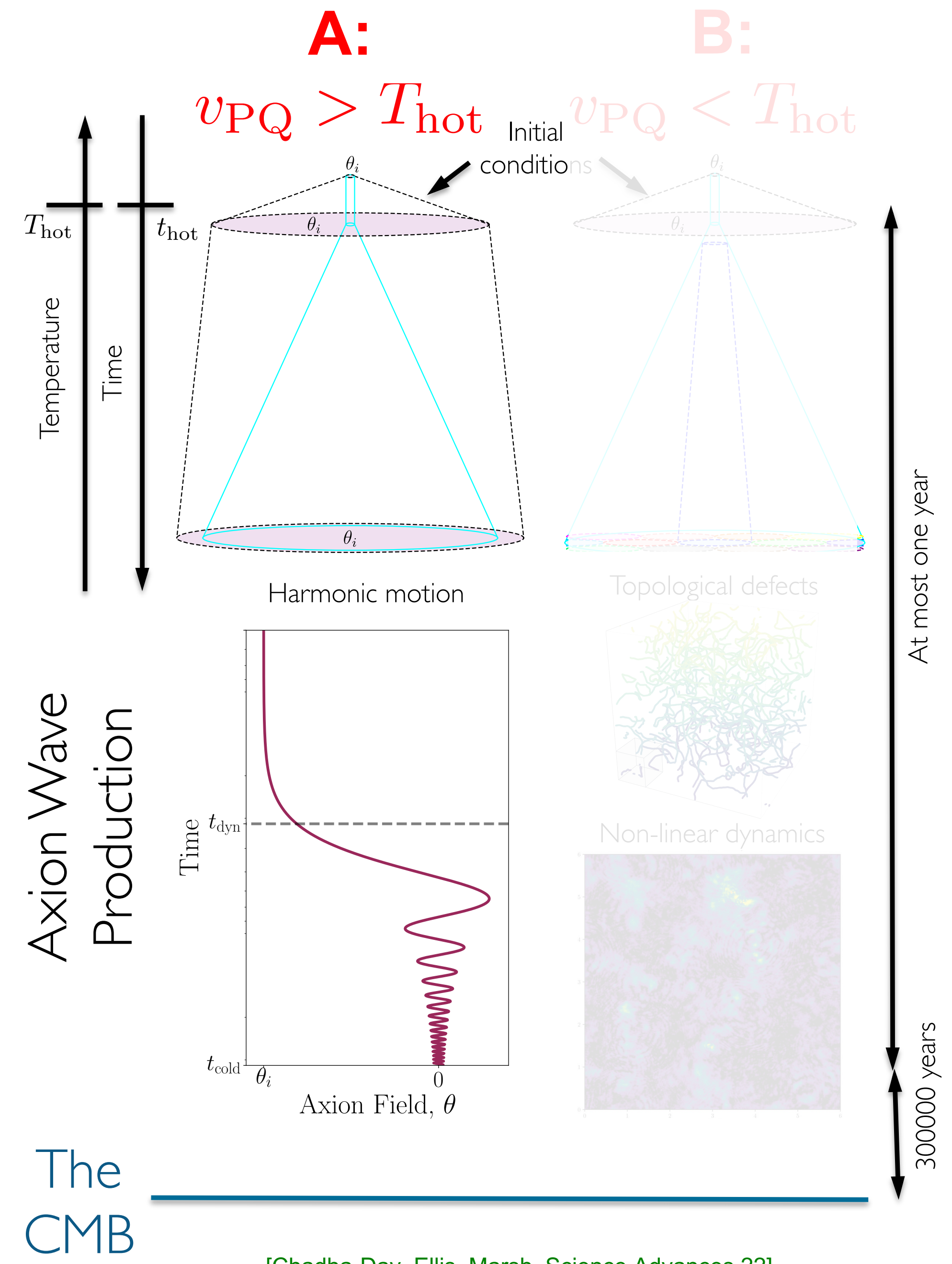
$$\Omega_a h^2 \approx 0.12 \left(\frac{6\ \mu\text{eV}}{m_a}\right)^{1.165} \theta_i^2\,, \qquad \theta_i \equiv a(t_{\rm hot})/f_a$$

[Borsanyi et al. `16]



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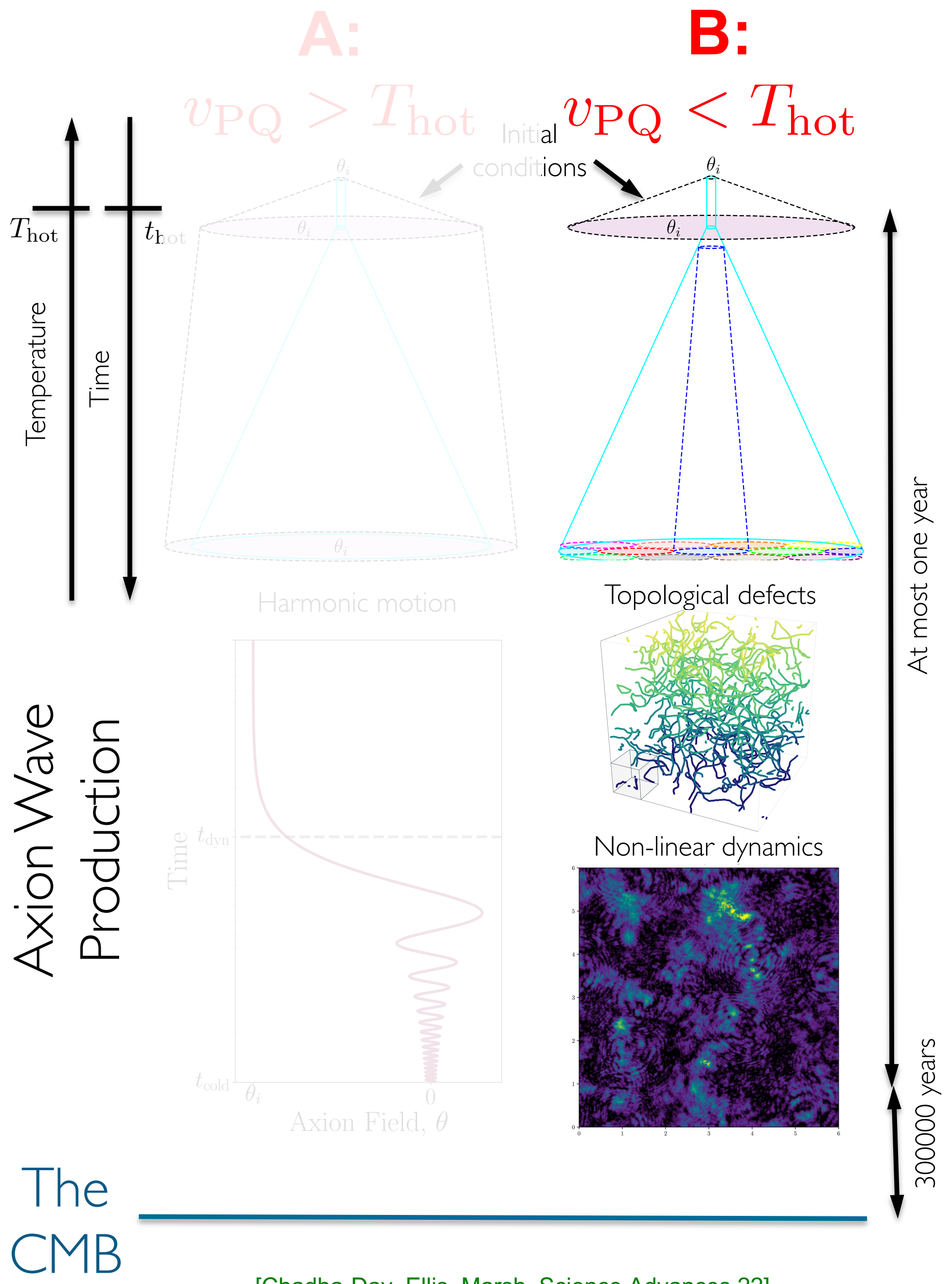
  - Scenario B ("post-inflationary PQ breaking"):
    - axion DM production by realignment mechanism and decay of topological defects (strings and domain walls)



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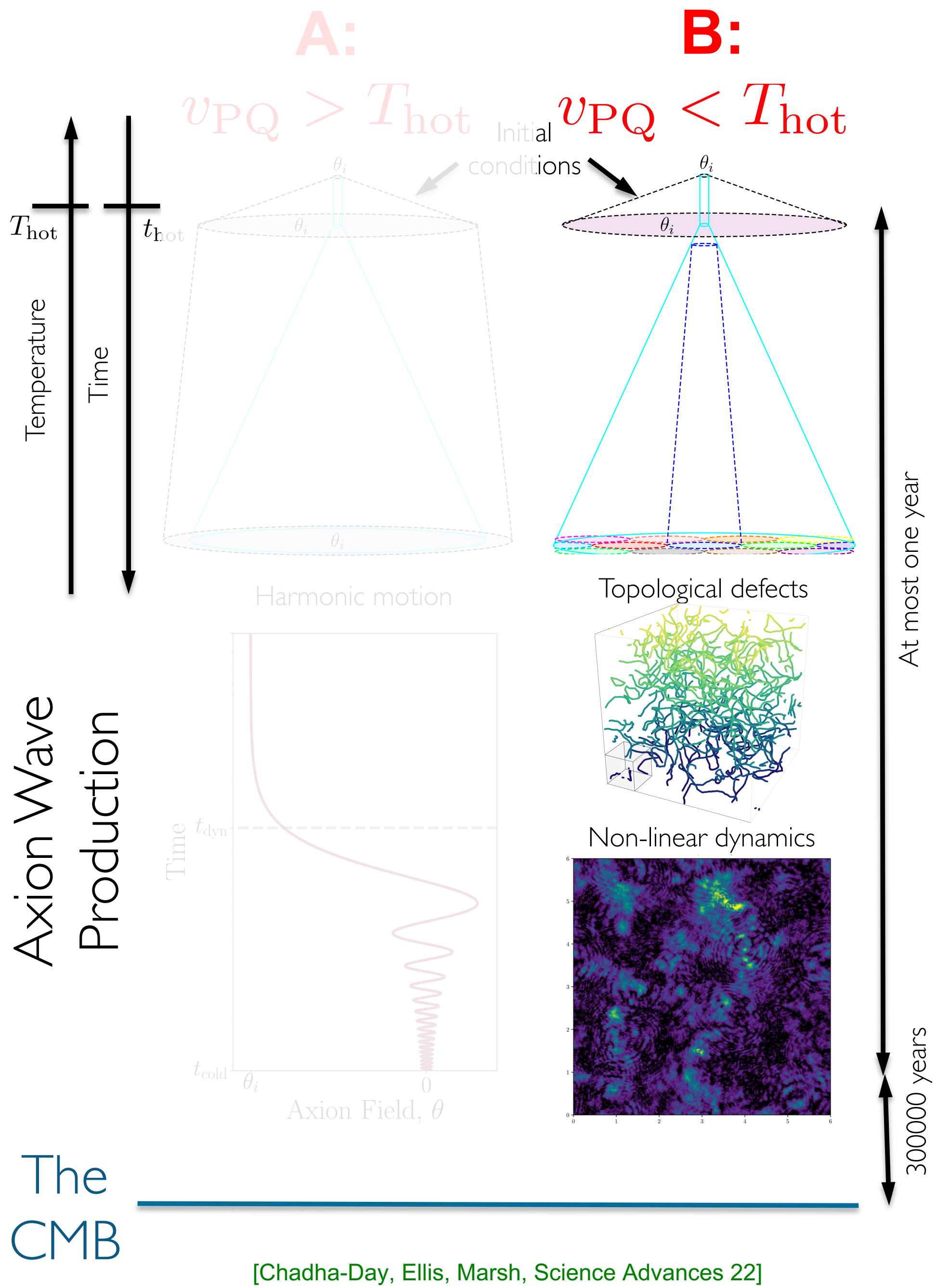
  - Scenario B ("post-inflationary PQ breaking"):
    - axion DM production by realignment mechanism and decay of topological defects (strings and domain walls)
      - required axion mass to explain 100% of DM abundance:

[Hiramatsu et al. 11,12,13; Kawasaki,Saikawa,Segikuchi 15; AR,Saikawa `16; Borsanyi et al. `16; Klaer,Moore `17; Gorghetto,Hardy,Villadoro `18; Buschmann et al. 19; Hindmarsh 19; Gorghetto,Hardy,Villadoro '20; Buschmann et al. 21;Beyer,Sarkar 23;...]

$$m_a \approx 26\ \mu{\rm eV} - 0.5\ {\rm meV},\ \ {\rm for}\ N_{\rm DW} = 2N_Q = 1$$
$$m_a \gtrsim {\rm meV},\ \ {\rm for}\ N_{\rm DW} = 2N_Q > 1$$



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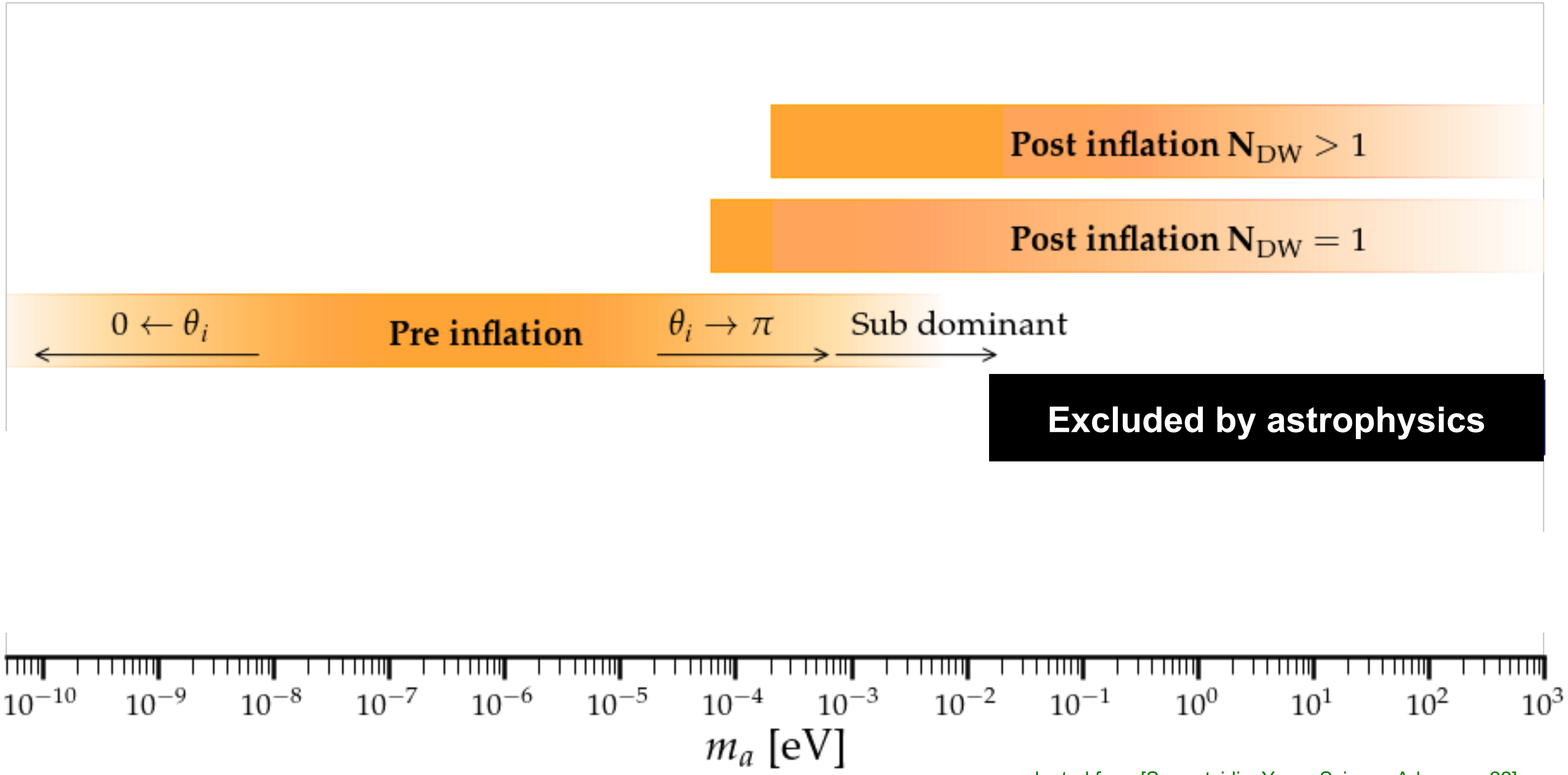
Axion Dark Matter Experiments

Variety of experimental techniques

- Huge possible mass range:



adapted from [Semertzidis, Youn, Science Advances 22]

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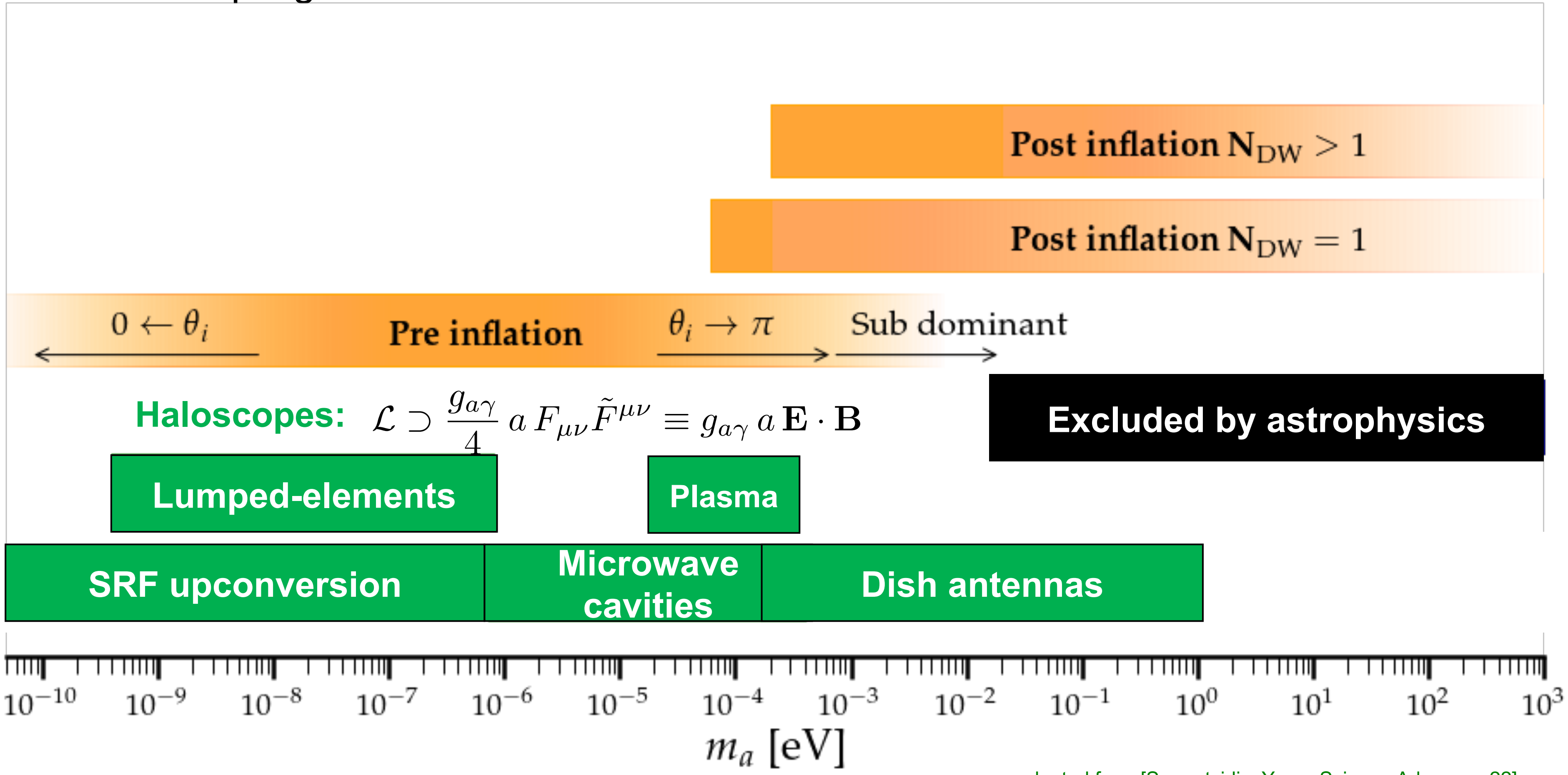
- Huge possible mass range requires various experimental techniques to search for axion dark matter via different axion couplings:



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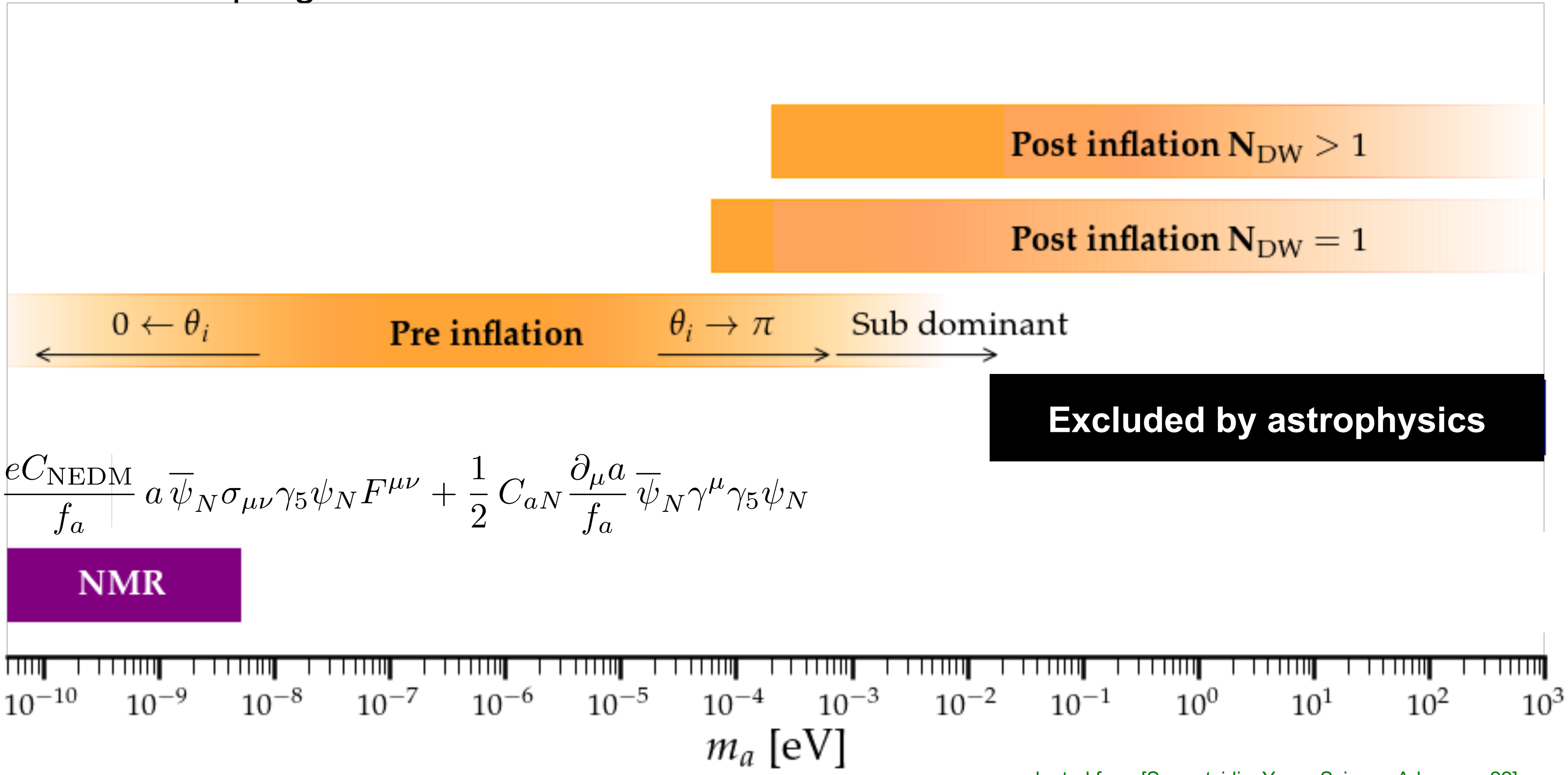
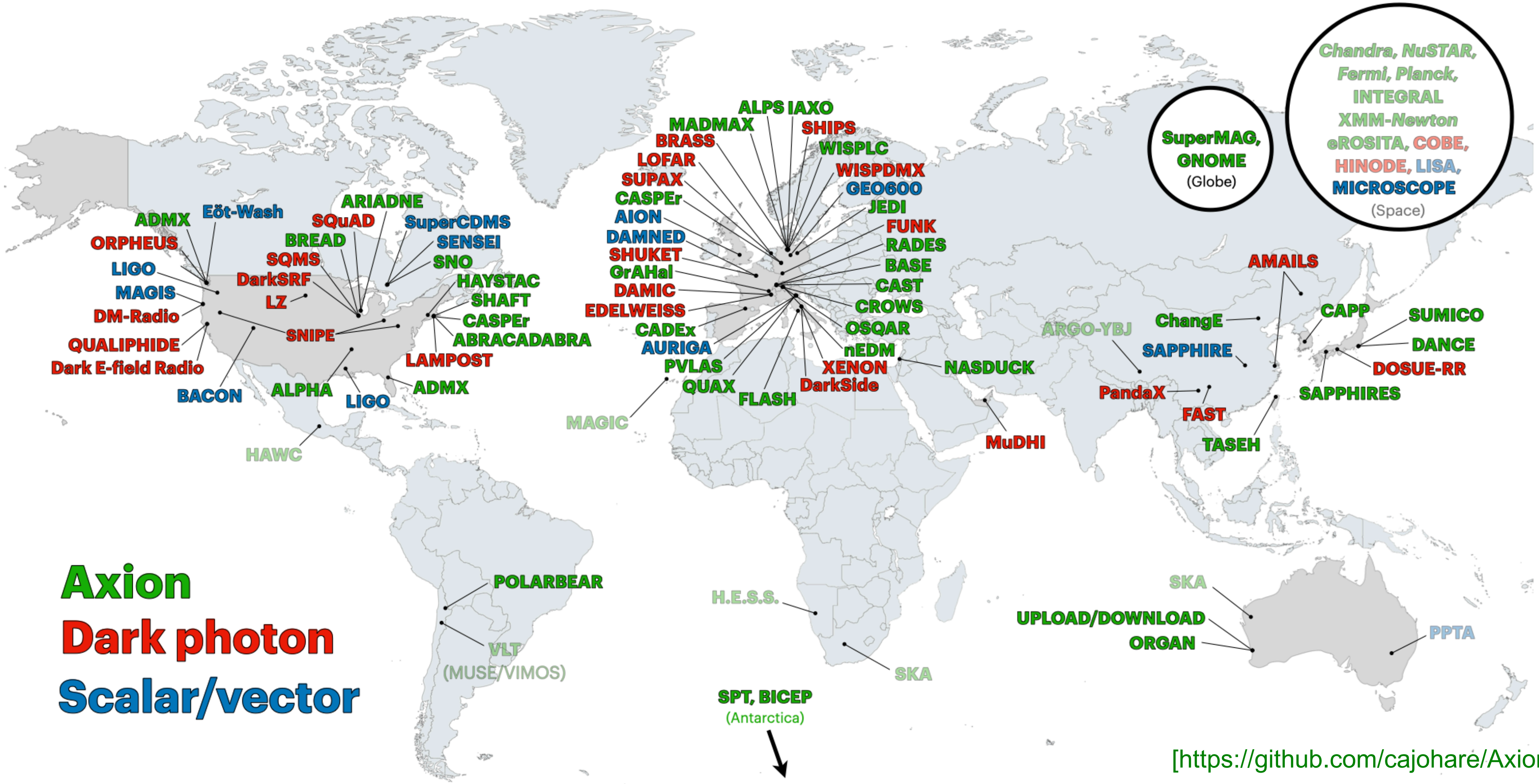


$$\mathcal{L} \supset -\frac{i}{2}\frac{eC_{\rm NEDM}}{f_a}\, a\,\overline{\psi}_N \sigma_{\mu\nu}\gamma_5\psi_N F^{\mu\nu} + \frac{1}{2} C_{aN}\frac{\partial_\mu a}{f_a}\,\overline{\psi}_N\gamma^\mu\gamma_5\psi_N$$

adapted from [Semertzidis, Youn, Science Advances 22]

Axion Dark Matter Experiments

Enormous number of axion experiments worldwide

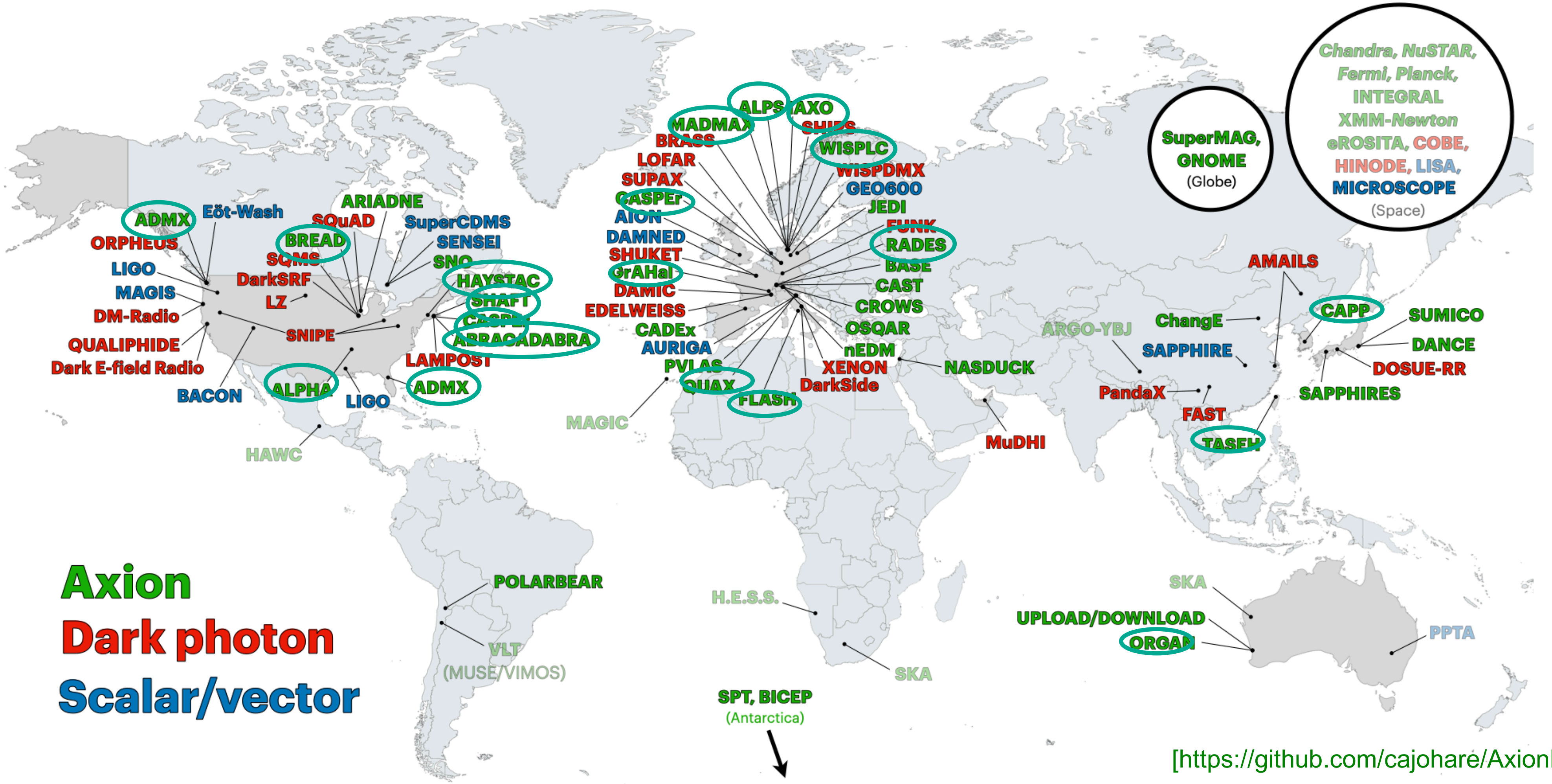


[https://github.com/cajohare/AxionLimits]

Axion Dark Matter Experiments

Enormous number of axion experiments worldwide

Can only talk about a subset of them …



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Axion Dark Matter Experiments

Wavy dark matter

- Axion DM experiments rely on the assumption that the dark matter halo of the Milky Way is comprised by axions
- The velocity dispersion of halo dark-matter axions is given by the galactic virial velocity, implying a macroscopic de Broglie wave length,

$$\lambda_{\rm dB} = 2\pi/(m_a v_a) \simeq {\rm km}\,(\mu{\rm eV}/m_a)(10^{-3}\,c/v_a)$$

- Correspondingly, halo dark-matter axions behave as an approximately spatially homogeneous and monochromatic classical oscillating field,

$$a(t) \simeq \sqrt{2\rho_a}\cos(m_a t)/m_a$$

- When presenting (projected) limits on halo dark-matter axion couplings it is assumed that

$$\rho_a = \rho_{\rm DM}^{\rm halo} \approx 0.45\,{\rm GeV\,cm^{-3}}$$

Haloscopes

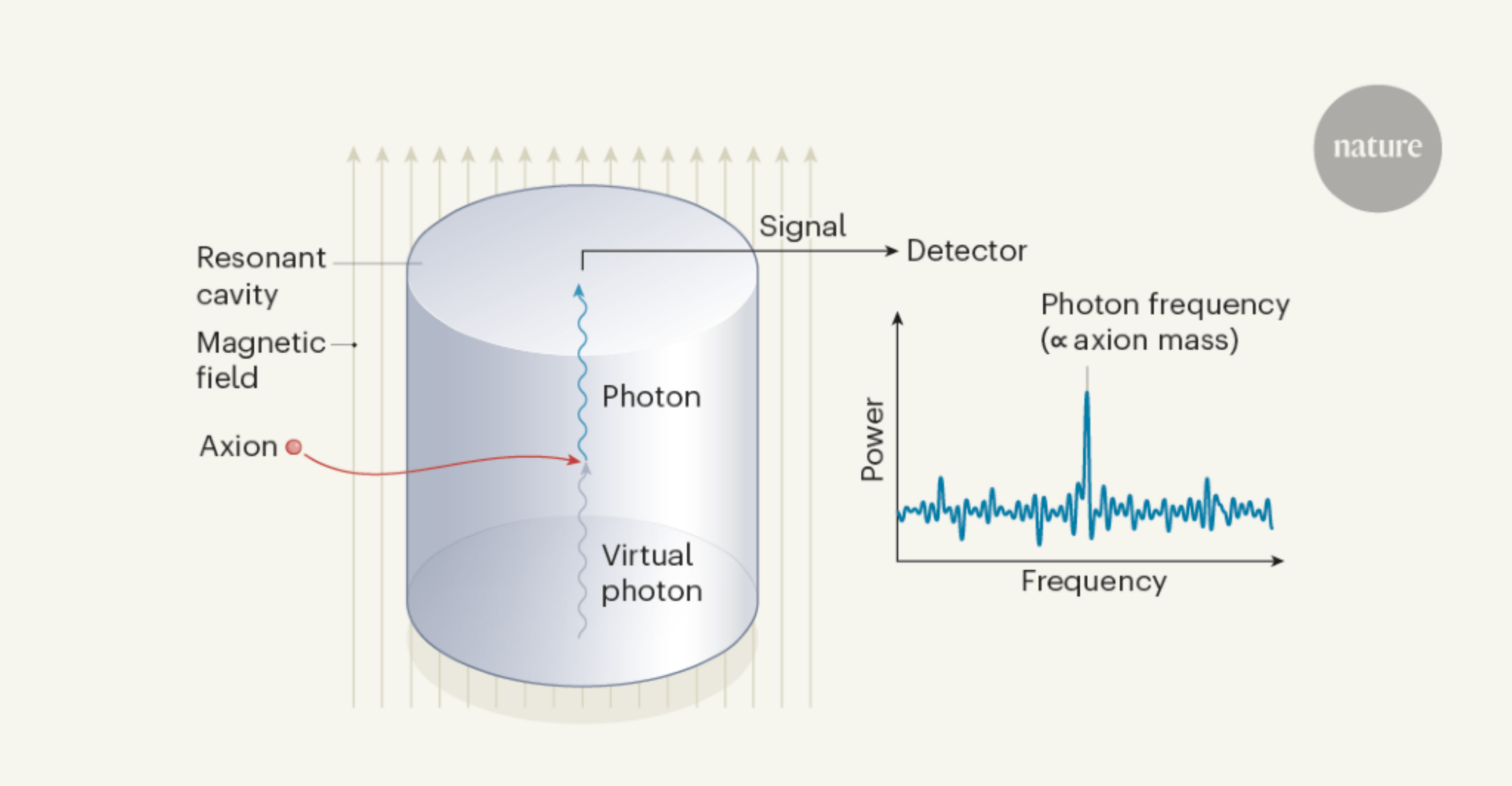
$$\mathcal{L} \supset \frac{g_{a\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \equiv g_{a\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$$

Haloscopes

Microwave cavities

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

- **Concept:** In microwave cavity placed in magnetic field, DM axion converts into photon [Sikivie 83]



[Irastorza, Nature '21]

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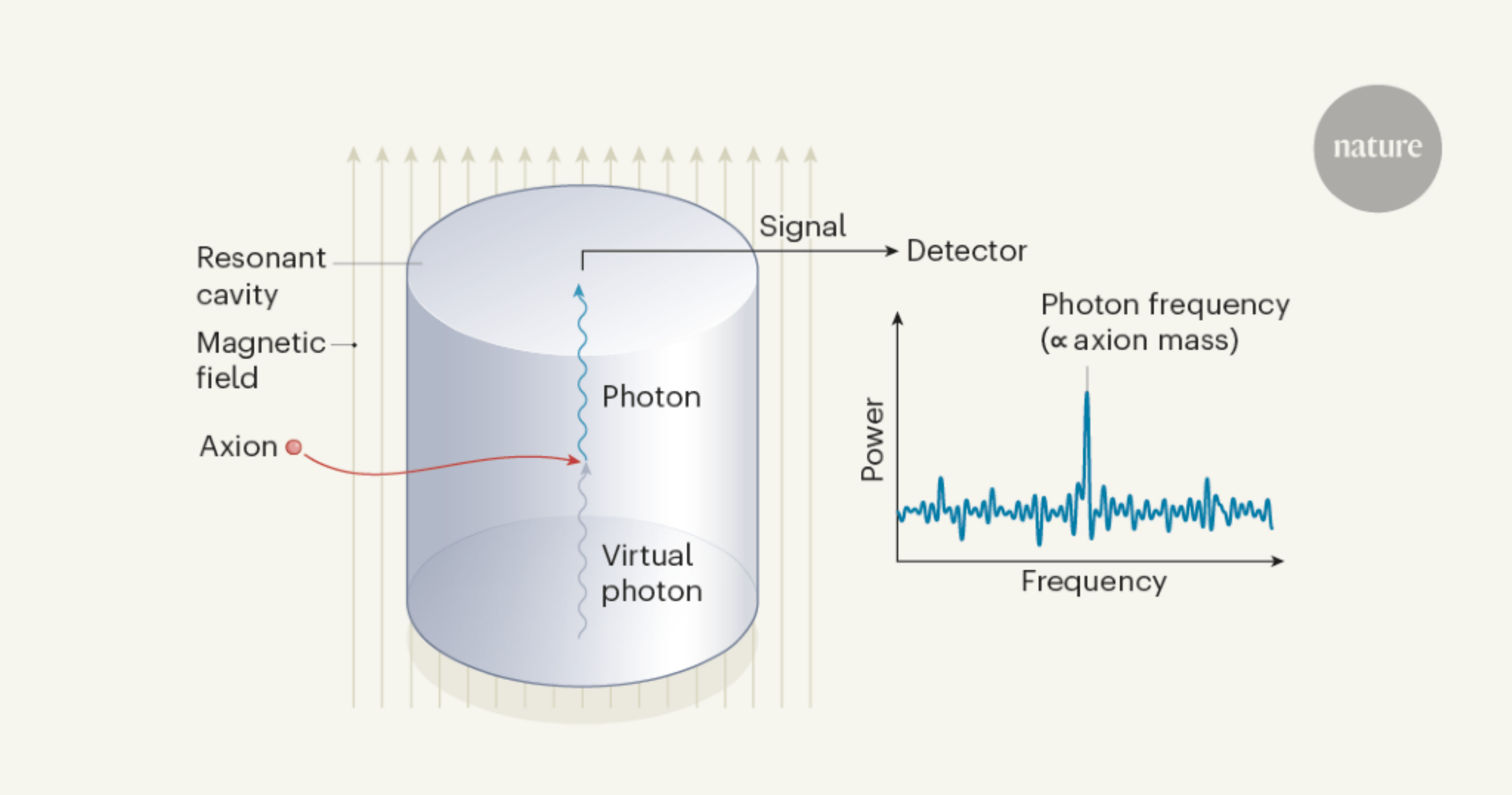

[Irastorza, Nature '21]

- If axion mass matches resonance frequency of cavity,

$$m_a = 2\pi\nu_{\rm res} \sim 4\,\mu{\rm eV}\left(\frac{\nu_{\rm res}}{\rm GHz}\right)$$

power output

$$P_{\rm out} \sim g_{a\gamma}^2\, \rho_{\rm a}\, B_0^2\, V\, Q$$

enhanced by quality factor

$$Q \sim 10^5$$

- Need to scan by tuning resonance frequency

Haloscopes

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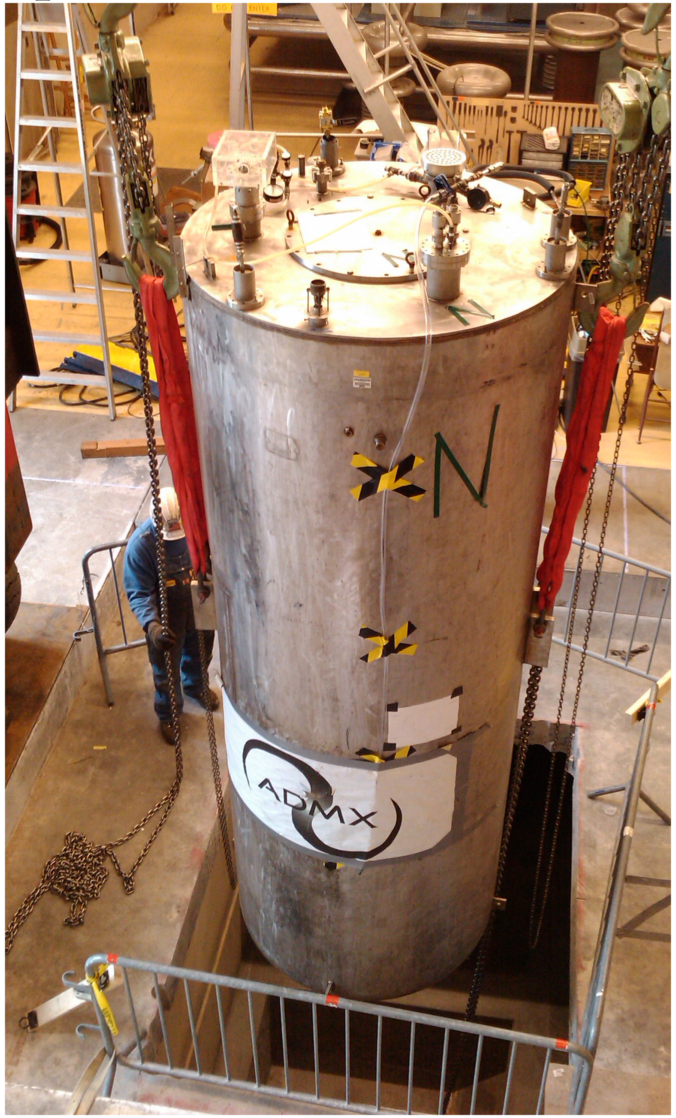
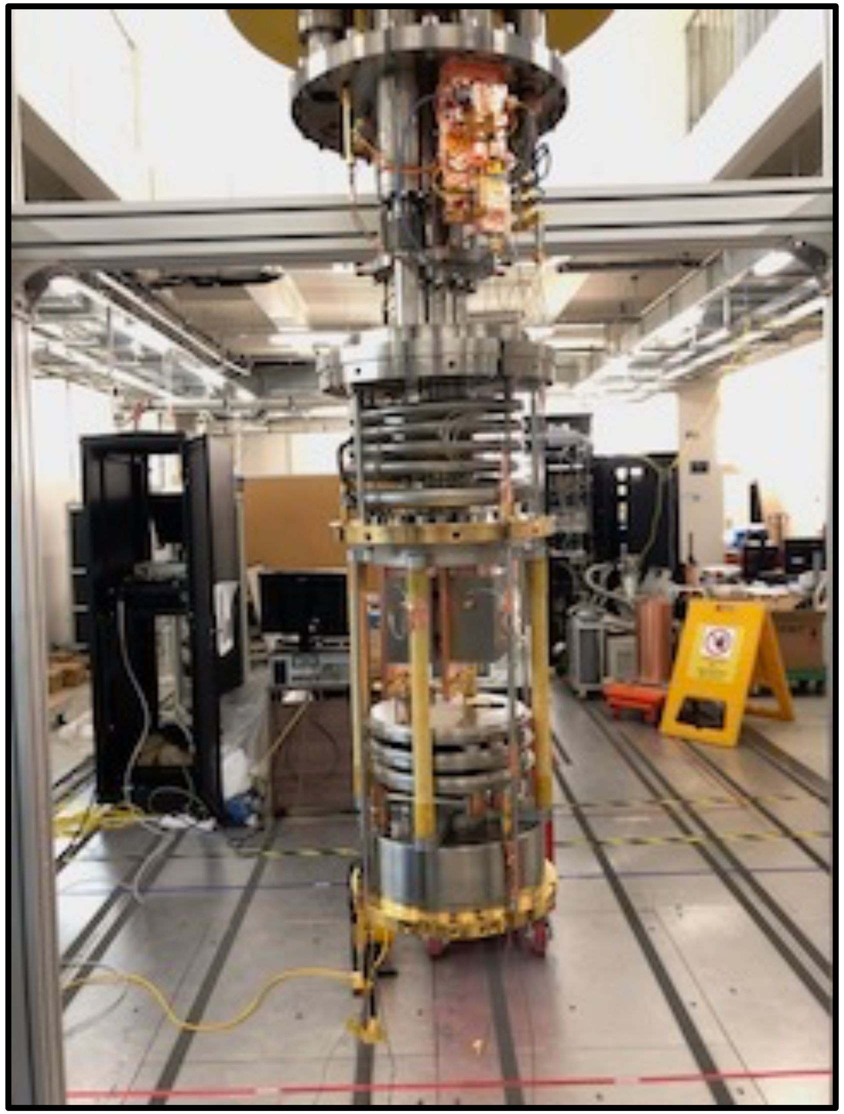
Microwave cavities

- **Currently running:**
  - ADMX
  - CAPP [Sung Woo Youn, DM par. session 2A]
  - CAST-CAPP
  - GrAHal
  - HAYSTAC
  - ORGAN
  - QUAX
  - RADES
  - TASEH



ADMX



CAPP

Haloscopes

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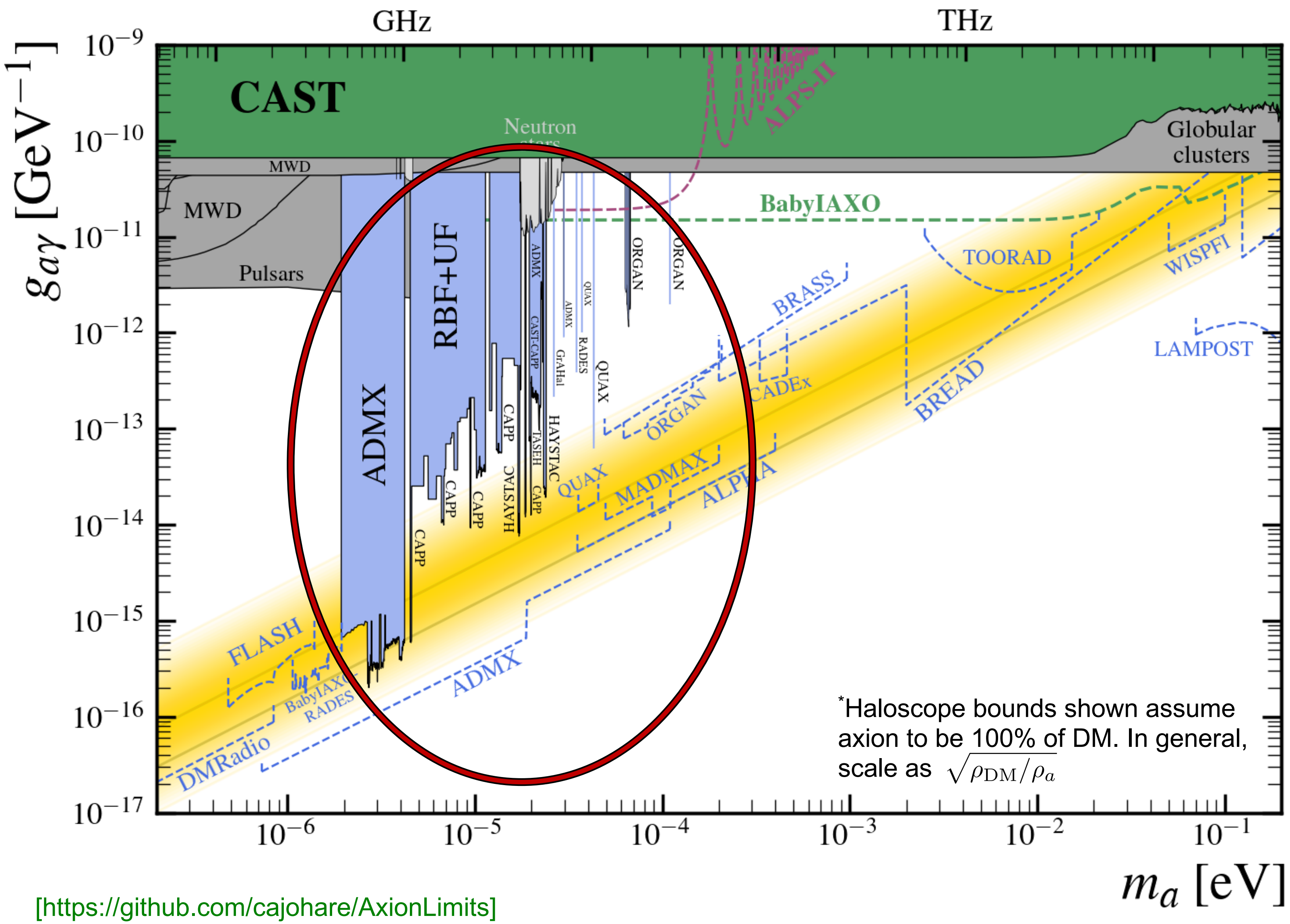

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  - QUAX
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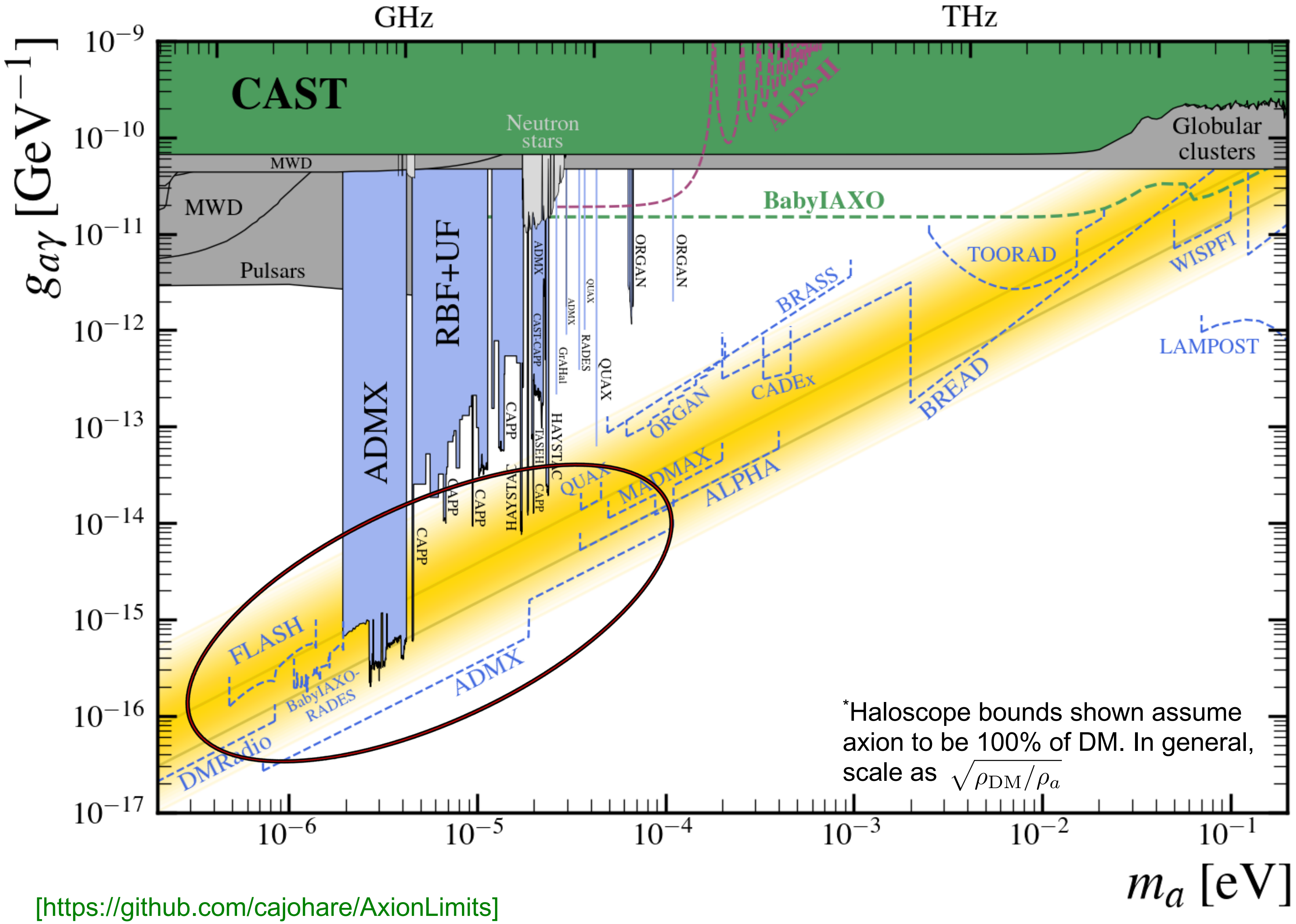
  - TASEH
- More experiments proposed
- Within next decade, microwave cavities will dig deep into vanilla axion band in mass range

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



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Dish antennas

- **Dish antenna concept**:

  [Horns,Jaeckel,Lindner,Lobanov,Redondo,AR 13]

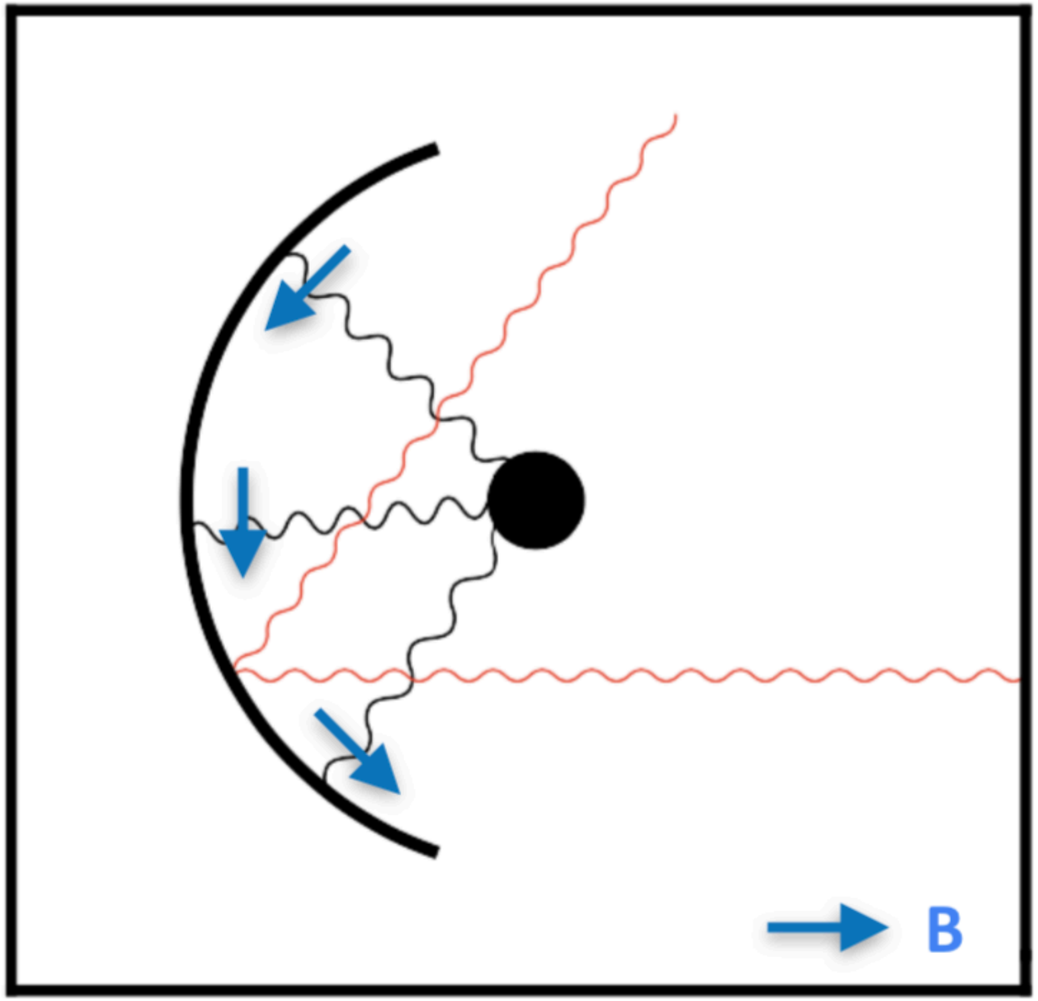
  - Oscillating axion DM in a background magnetic field carries a small electric field component,

    $$\vec{E}_a(t) = -g_{a\gamma}\vec{B}a(t)$$

  - Metallic mirror placed in a magnet field pointing parallel to the mirror surface will emit a nearly monochromatic EM wave perpendicular to the mirror surface with a frequency $\nu = m_a/(2\pi)$ and a cycle-averaged power per unit area:

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

  - Broadband! No tuning necessary!



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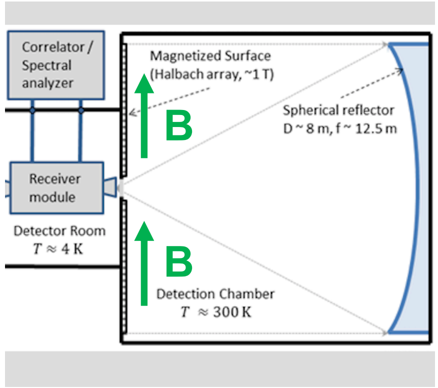
- **BRASS** @ U Hamburg

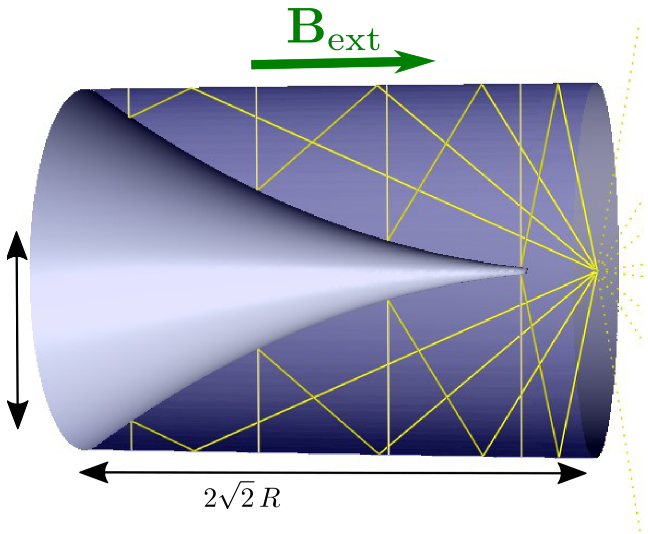


- Plane permanently magnetized conversion panel
  $B = 0.8\,\mathrm{T}$
  $\mathcal{A} = 4.7\,\mathrm{m}^2$
- Spherical reflector

[Bajjali et al., `23]

BRASS

- **BREAD** @ Fermilab



- Cylindric parabolic conversion panel allows use of solenoidal magnetic field
  $B \sim 10\,\mathrm{T}$
  $\mathcal{A} \sim 10\,\mathrm{m}^2$

[Liu et al., 22]

BREAD

Haloscopes

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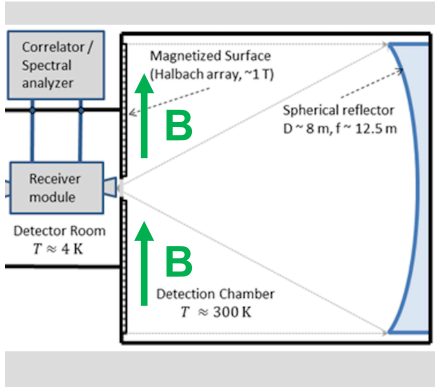

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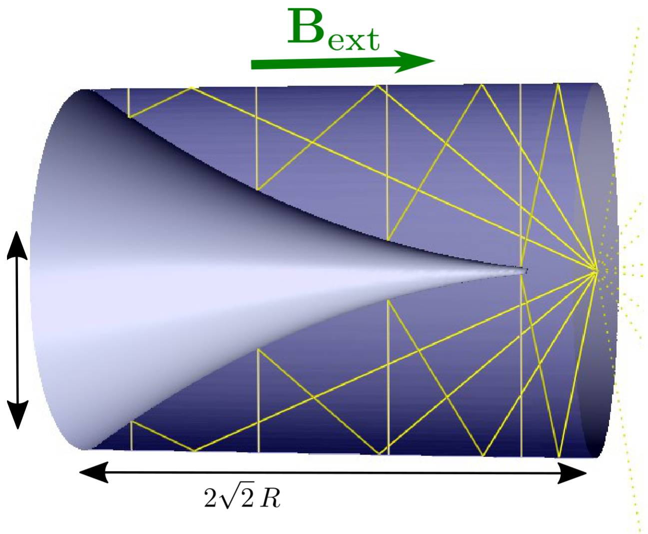

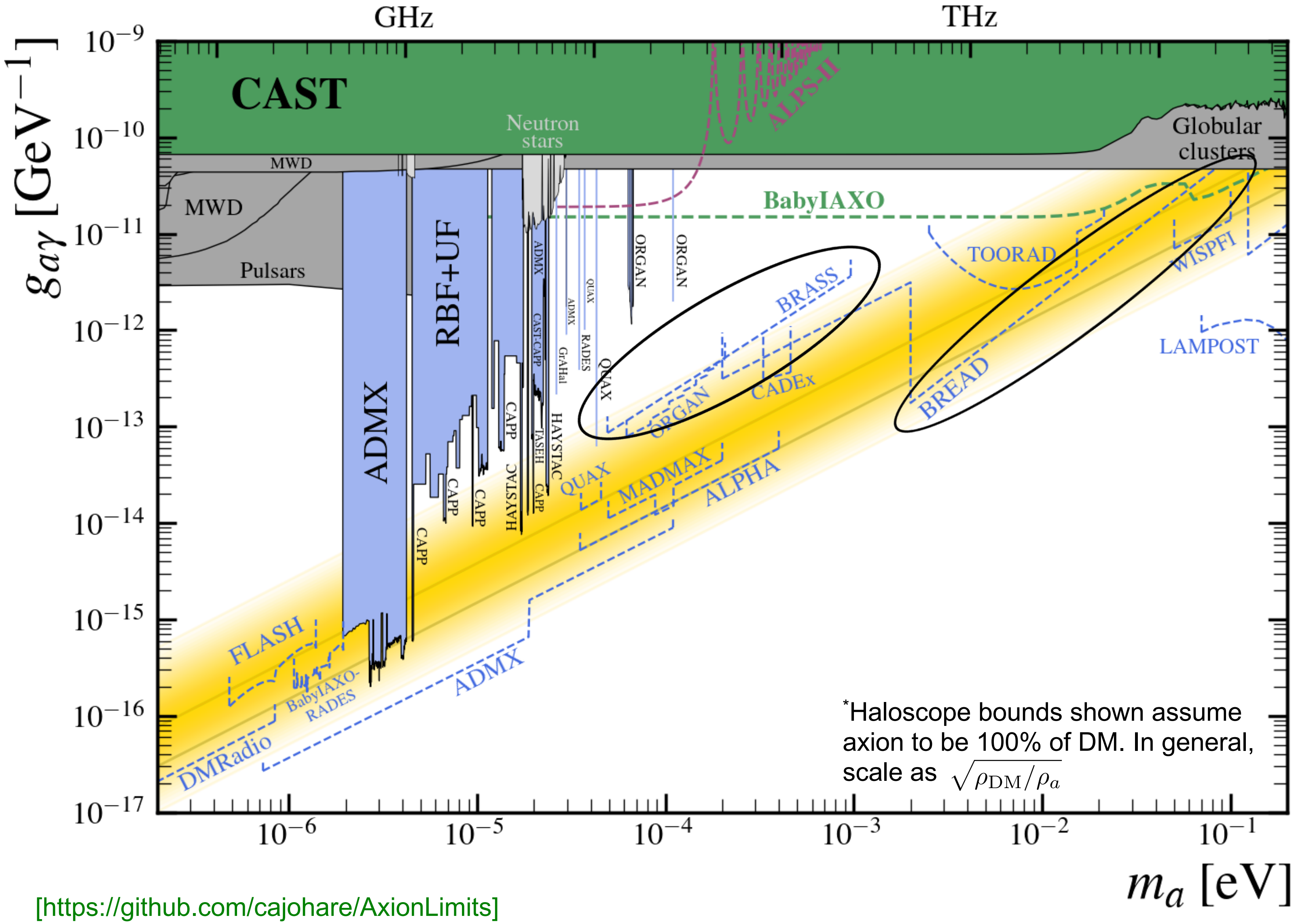

*Haloscope bounds shown assume axion to be 100% of DM. In general, scale as $\sqrt{\rho_{DM}/\rho_a}$

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Haloscopes

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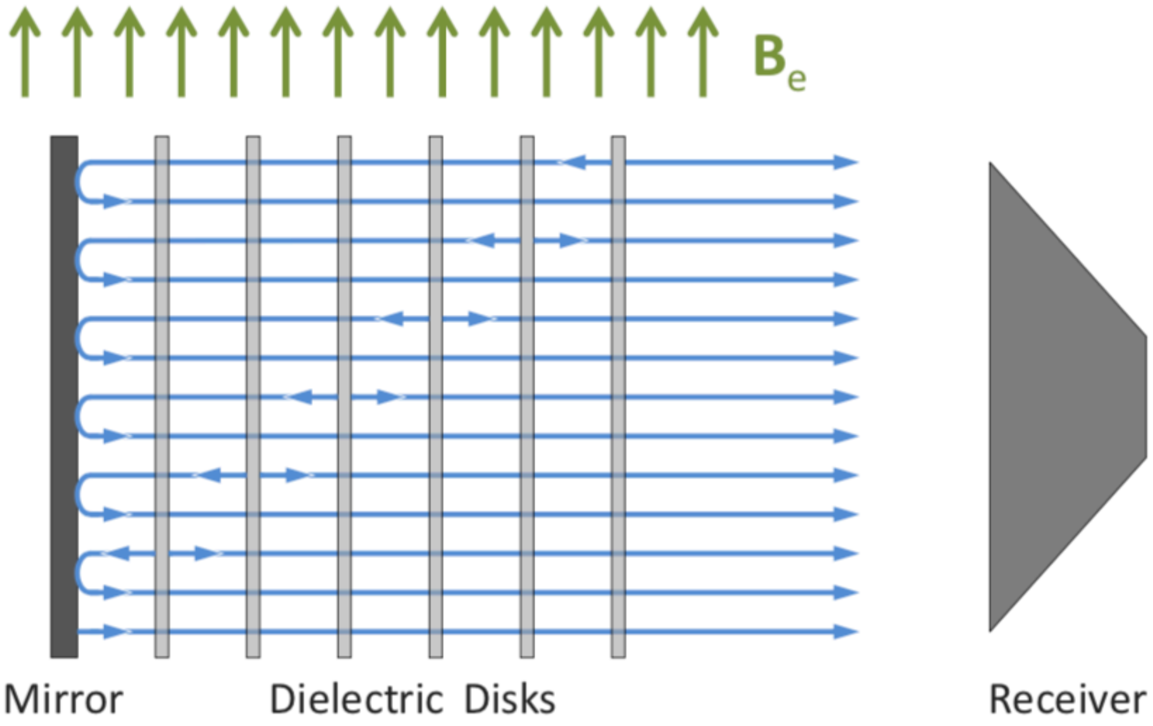
Dish antennas

- **Boosted dish antenna** aka **open dielectric resonator concept:**
  - 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]

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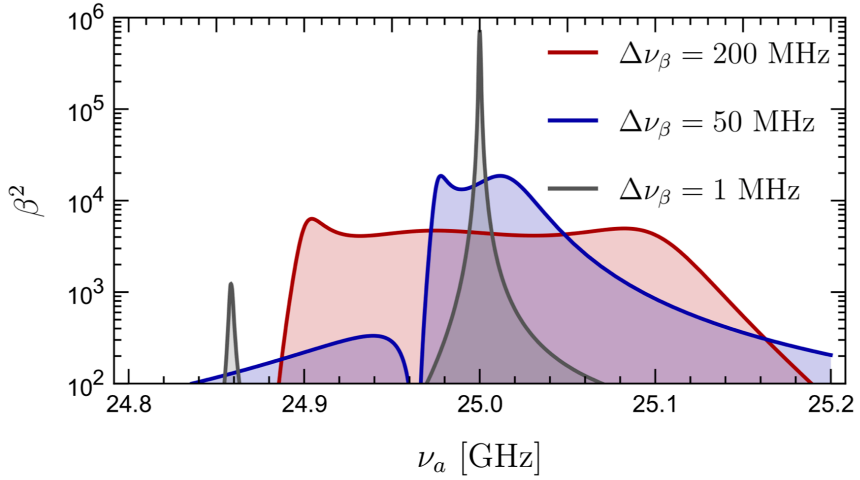
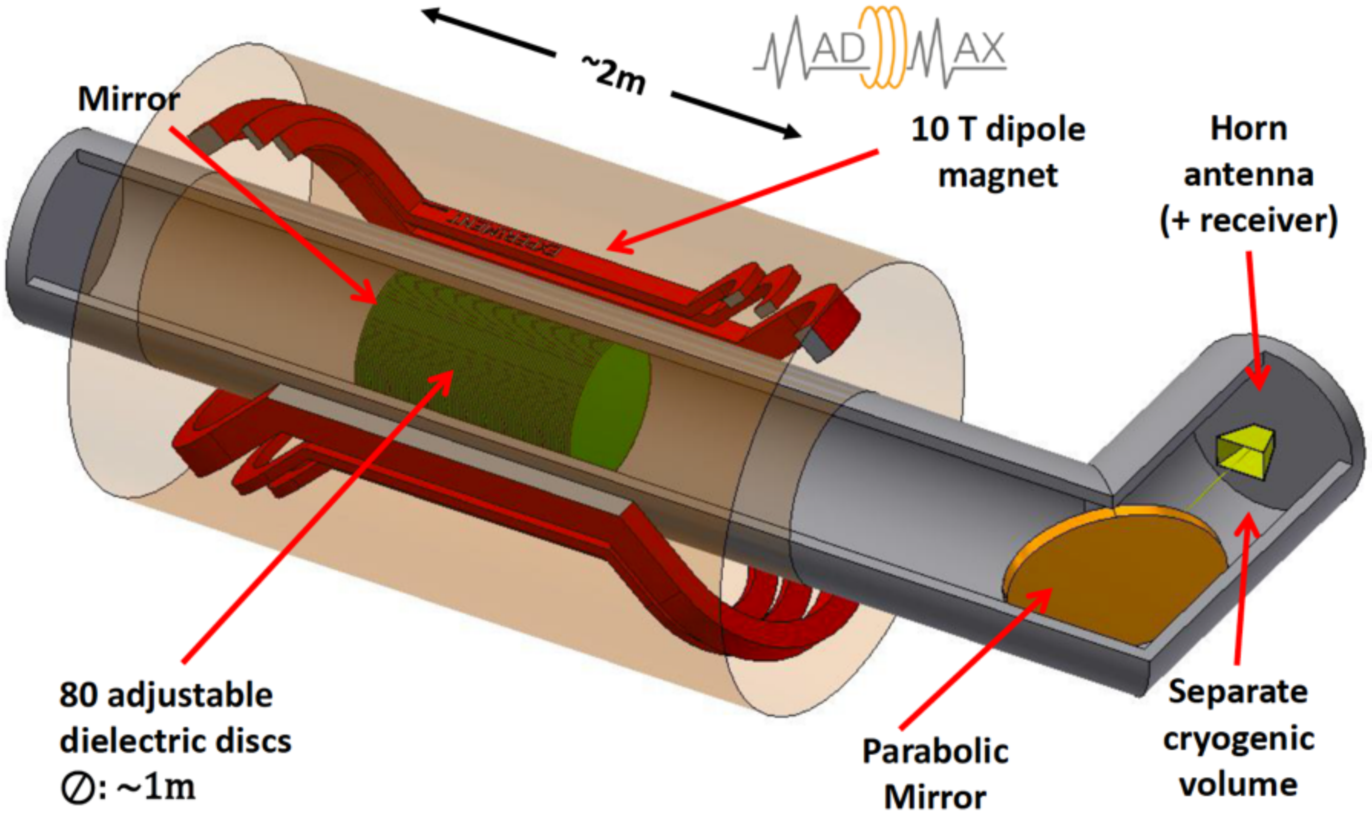
Dish antennas

MADMAX @ DESY

[Juan Maldonado, poster session A]
[Juan Maldonado, DM parallel session 8B]

- Conceptional design [Bruns et al. 19]
  - 10 T magnet
  - Large number of adjustable dielectric disks
    - Tunable frequency and bandwidth





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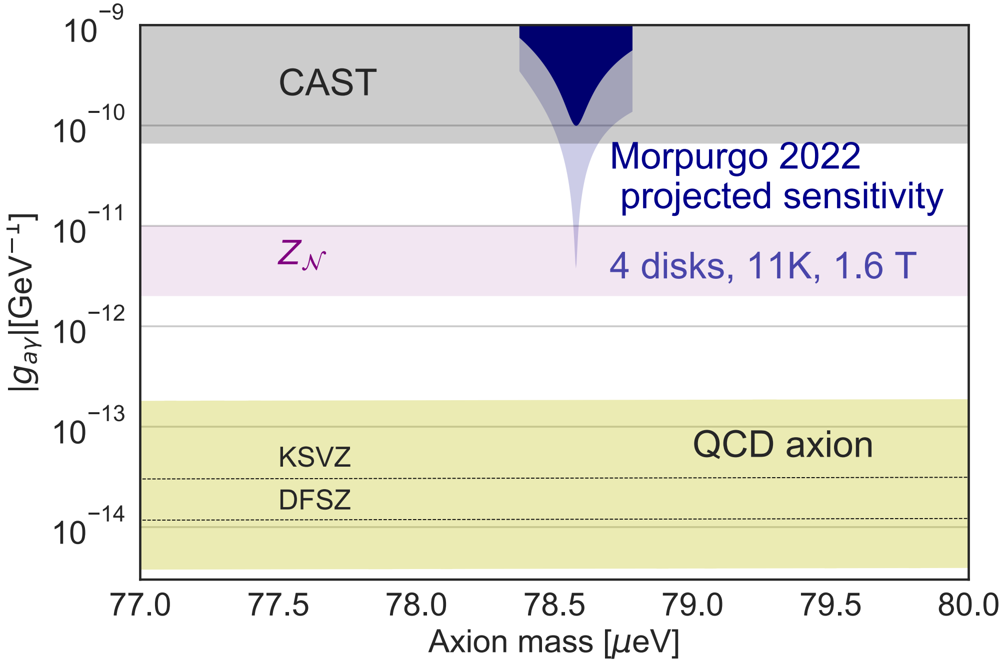
- New prototype magnet could allow further exploration of so far unexplored parameter range



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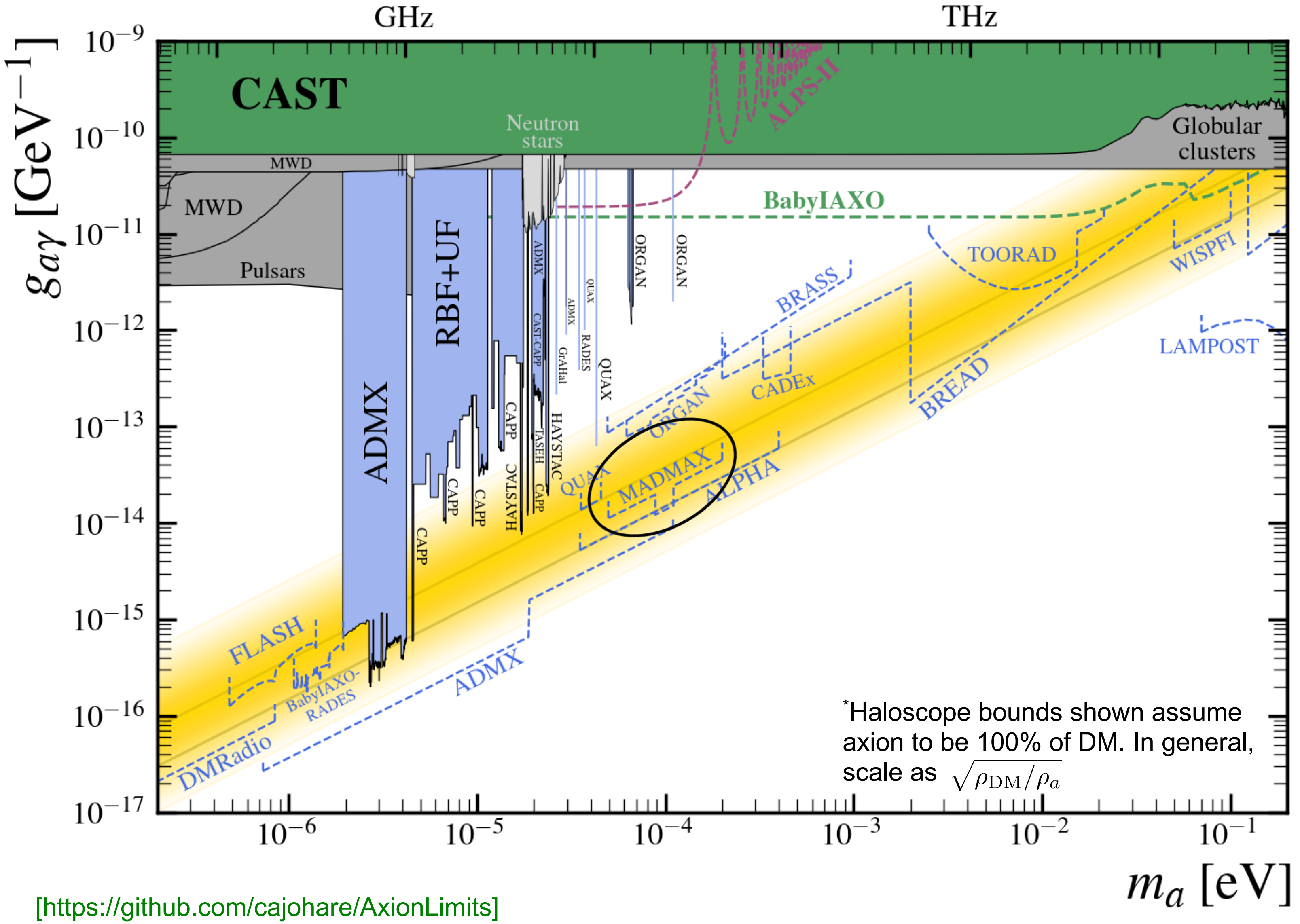
- **Full MADMAX expected to start data taking in 2030**



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Plasma haloscope

- **Plasma haloscope concept**:

  [Lawson, Millar, Pancaldi, Vitagliano, Wilczek, 19]

  - In a magnetized plasma, oscillating axion DM induces plasmon excitations,

    $$\mathbf{E} = -g_{a\gamma}\mathbf{B}_{\rm e} a \left(1 - \frac{\omega_p^2}{\omega_a^2 - i\omega_a\Gamma}\right)^{-1}$$

    - resonant enhancement, when plasma frequency matches axion mass,

      $$\omega_p = \omega_a \approx m_a$$

    - limited by losses (Γ)

Haloscopes

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

Plasma haloscope

- **Plasma haloscope concept**:

  [Lawson, Millar, Pancaldi, Vitagliano, Wilczek, 19]

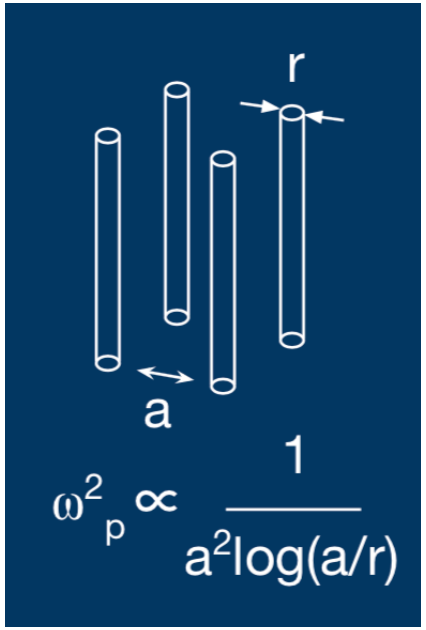
  - In a magnetized plasma, oscillating axion DM induces plasmon excitations,

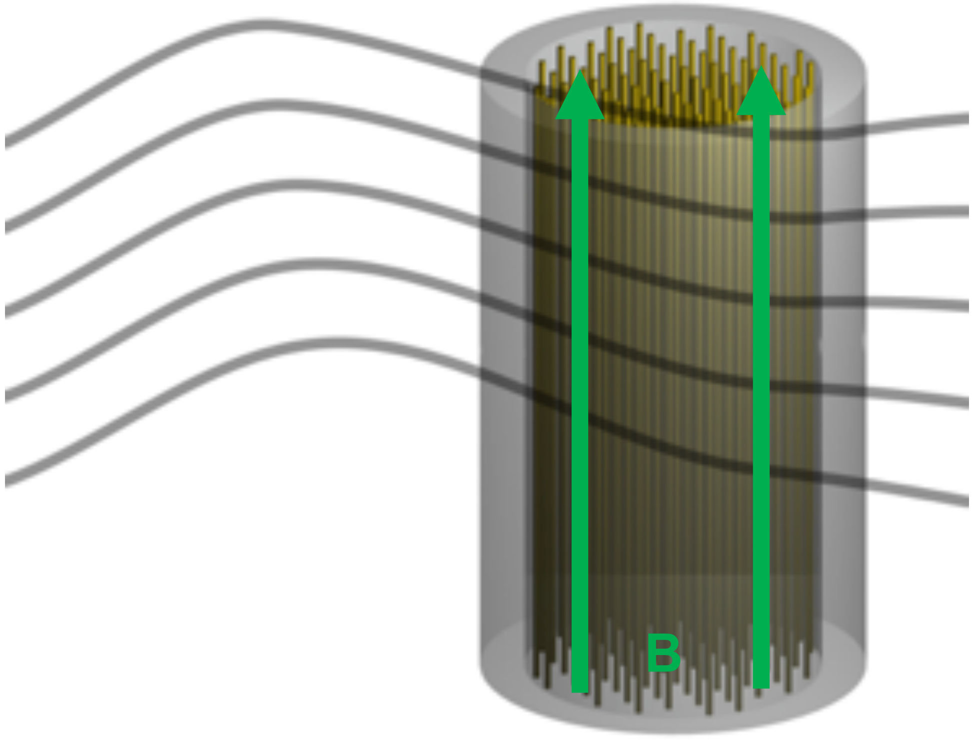
    $$\mathbf{E} = -g_{a\gamma}\mathbf{B}_{\rm e}a\left(1-\frac{\omega_p^2}{\omega_a^2 - i\omega_a\Gamma}\right)^{-1}$$

    - resonant enhancement, when plasma frequency matches axion mass,

      $$\omega_p = \omega_a \approx m_a$$

    - limited by losses (Γ)
  - A plasma with tunable plasma frequency in the GHz range can be realised by a wire array with variable interwire spacing ("wire metamaterial")





adapted from [Dunne, LBNL Instr. Sem. Feb 22]

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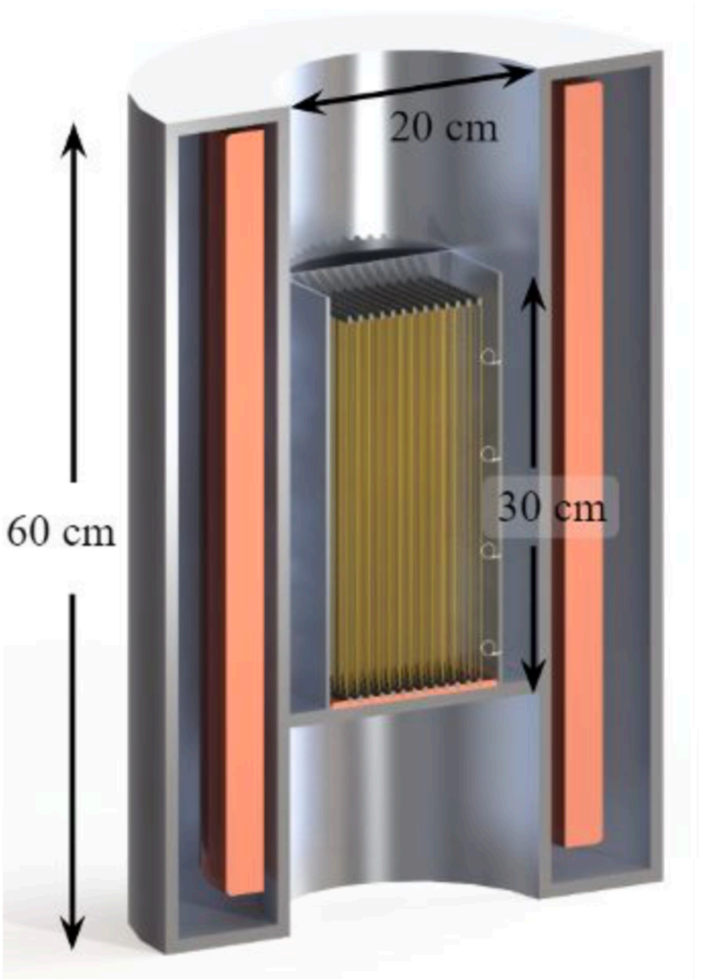
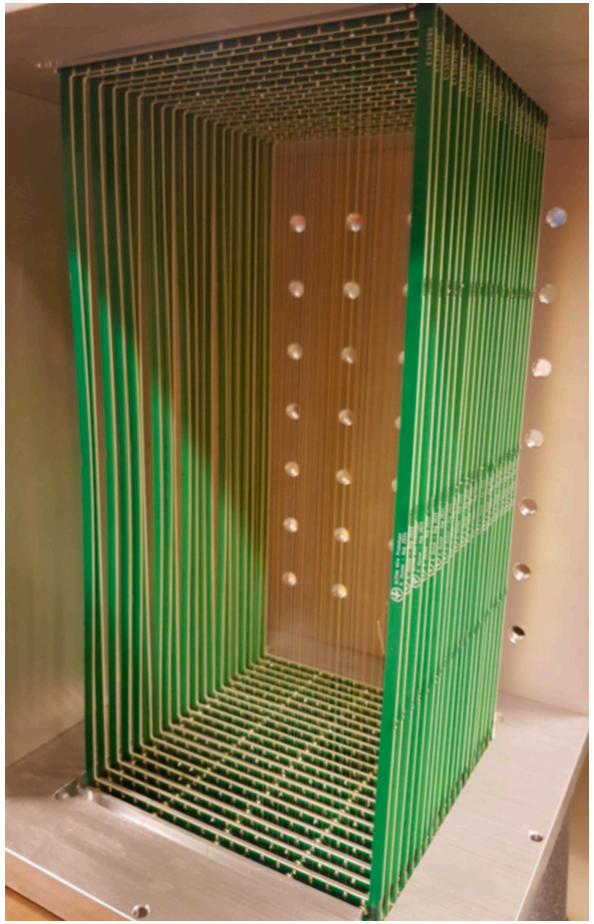
Plasma haloscope

ALPHA @ Oakridge

- Goal: building tunable, cryogenic plasma haloscope
- ALPHA Pathfinder
  - 20 cm bore 8T solenoid
  - several wire material prototy-pes constructed
  - tuning with low power piezo-electric translation
  - sensitive to mass range around 10–20 GHz
  - data run expected ~2026

ALPHA Pathfinder





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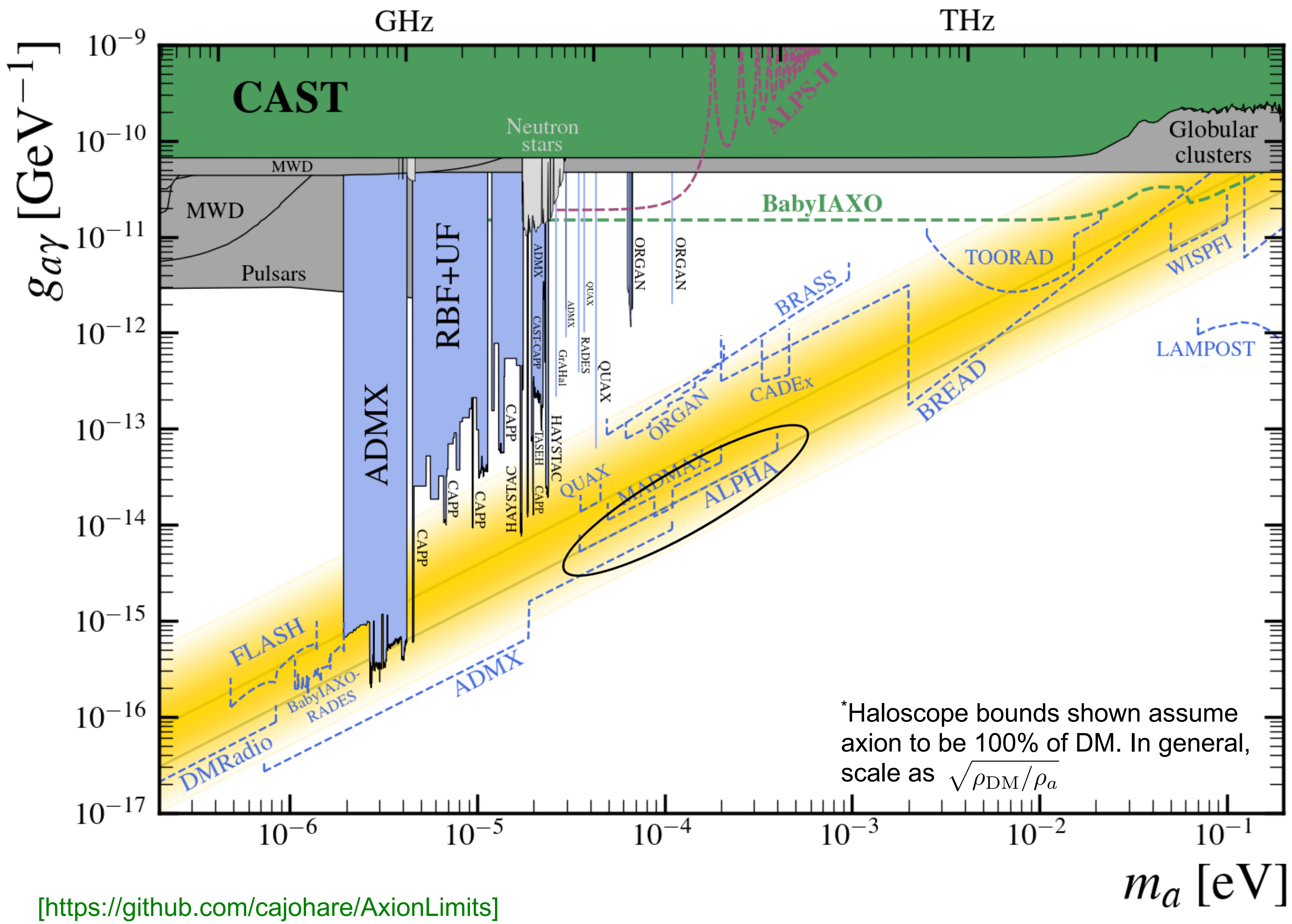
- **Full ALPHA designed to dig deep into axion band**



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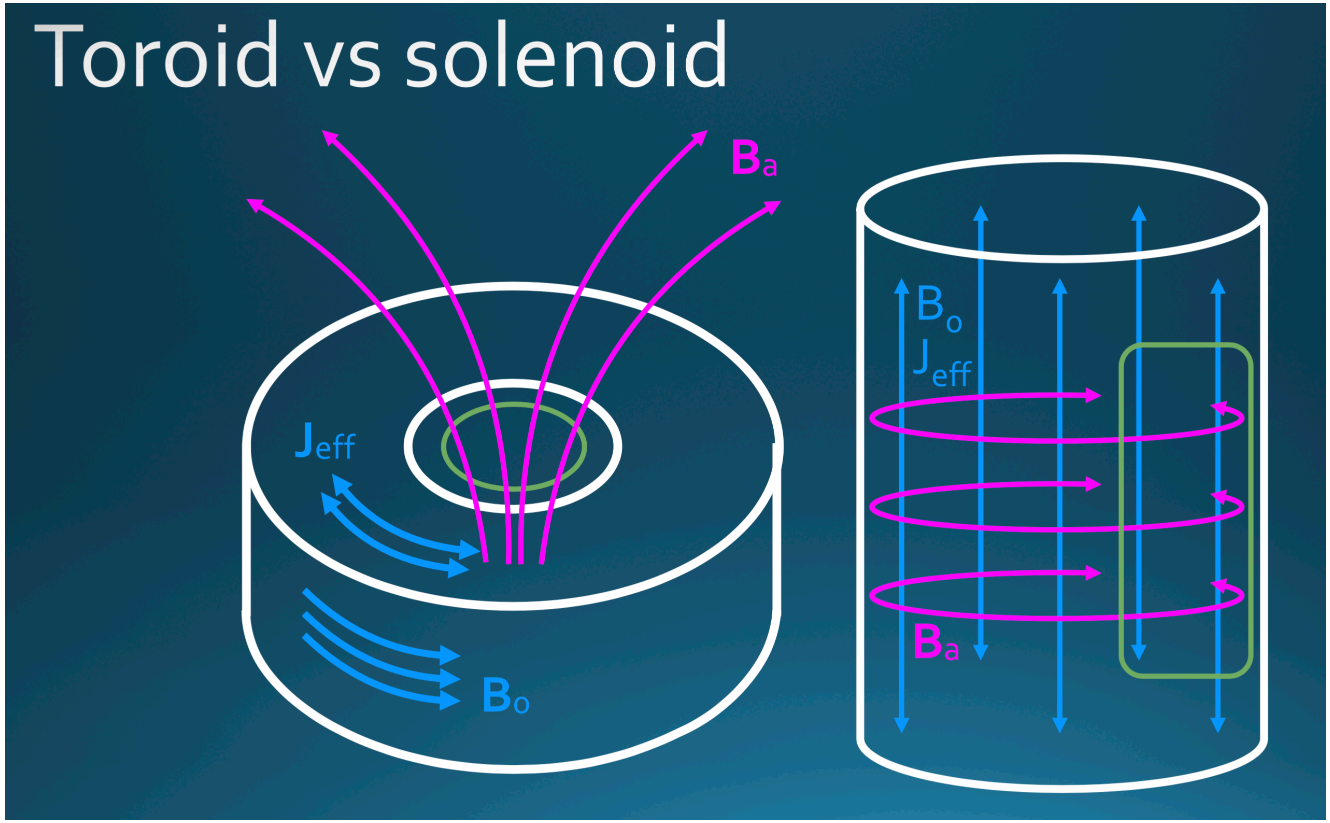
Lumped-element detectors

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

- **Concept:**
  - 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]

Haloscopes

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Lumped-element detectors

- **Pilot experiments:**
  - ABRACADABRA [Ouellet et al. 19]
  - ADMX SLIC [Crisosto et al. 20]
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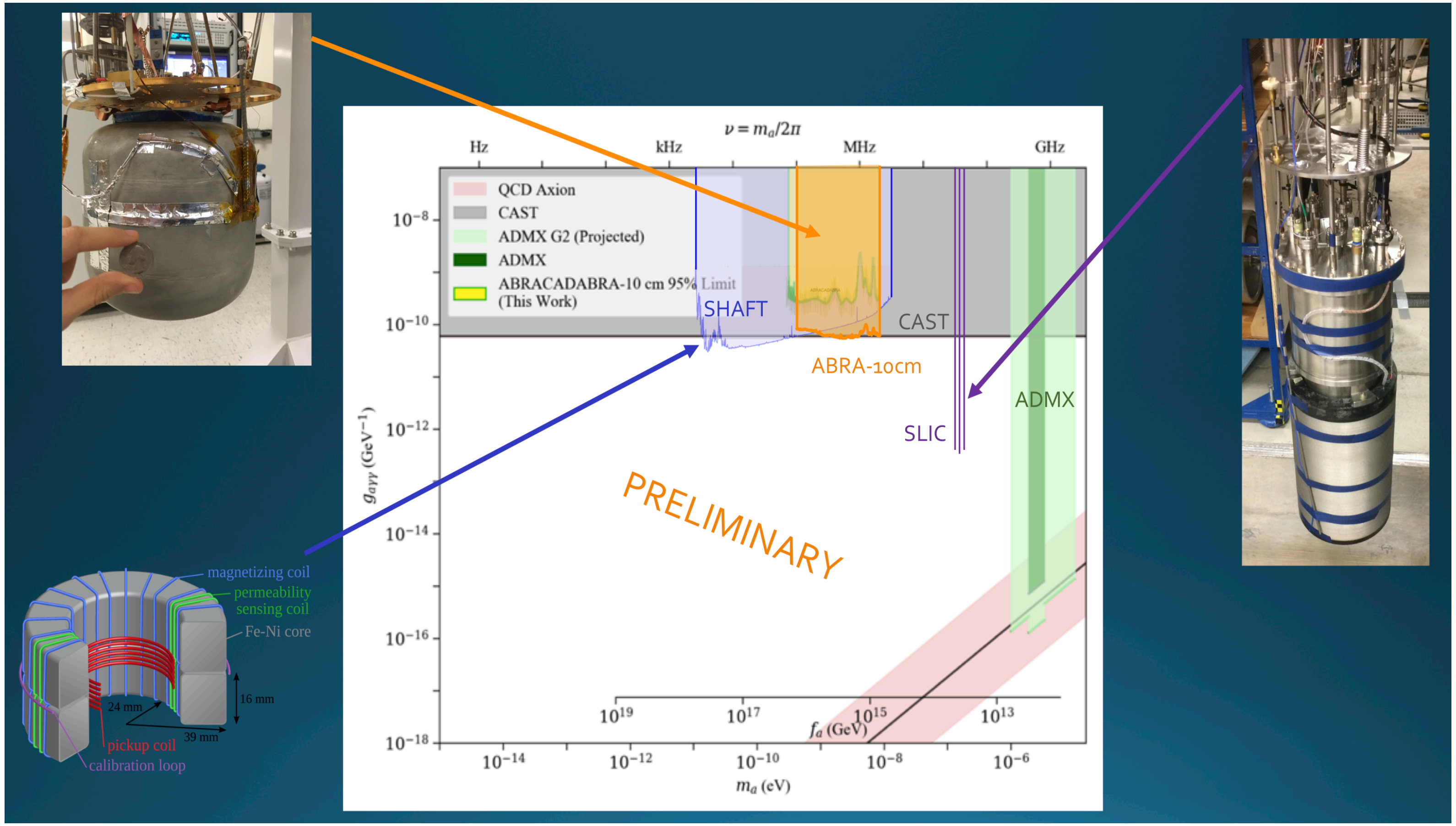

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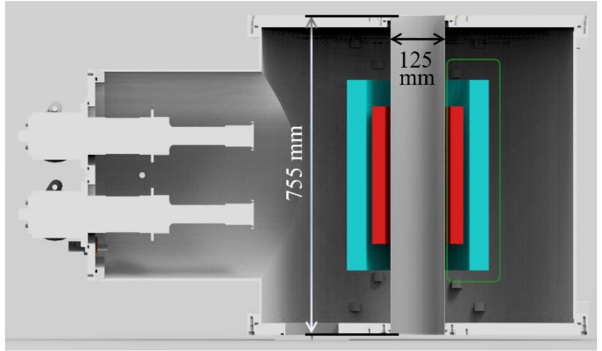
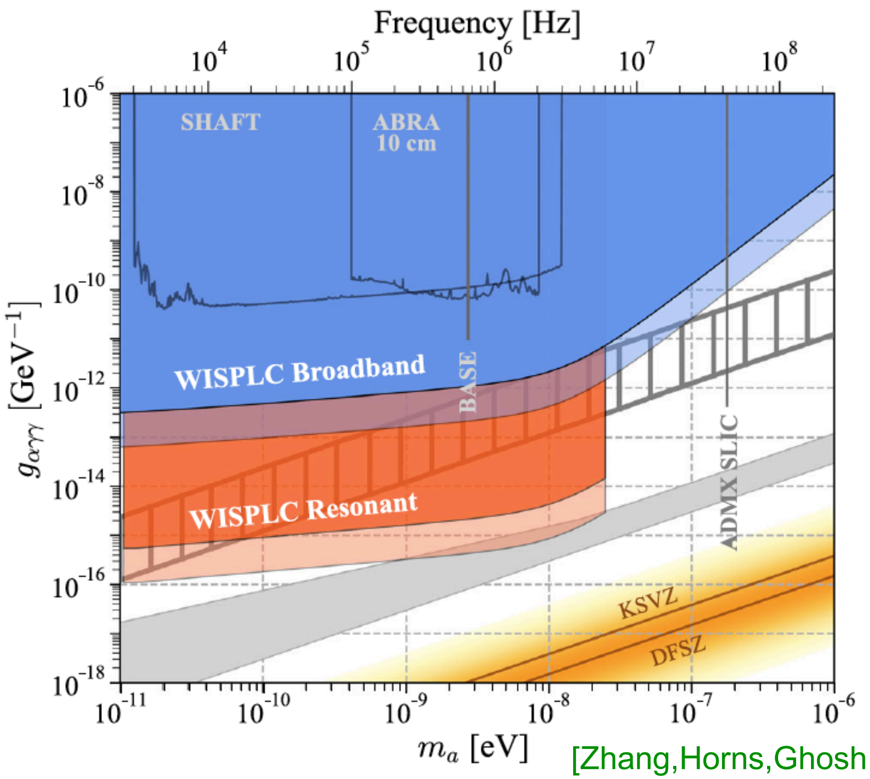


WISPLC



[Zhang,Horns,Ghosh 22]

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    [Chiara Salemi, DM par. session 2A]
    [Jessica Fry, DM par. session 2A]
    [Nicholas Rapidis, DM par. session 2A]
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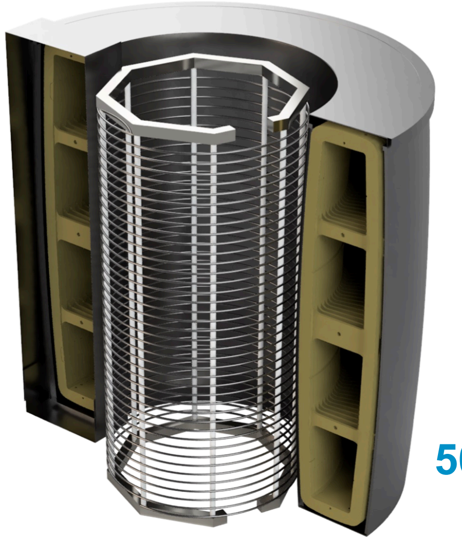
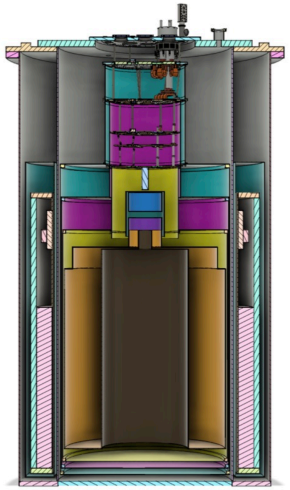
    - DMRadio-m^3
    - DMRadio-GUT

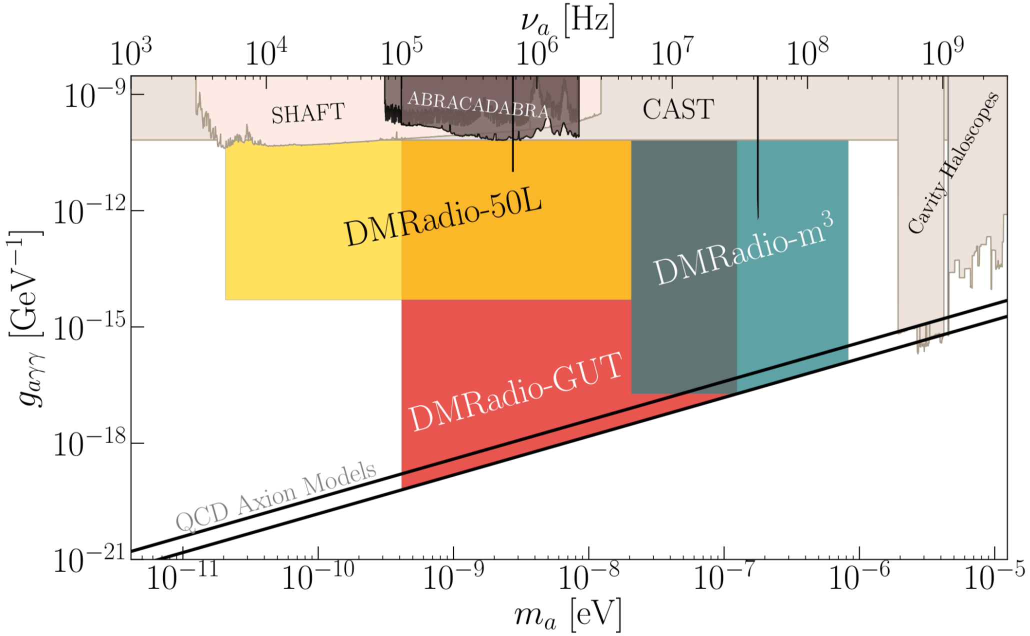
DMRadio



50L



m^3



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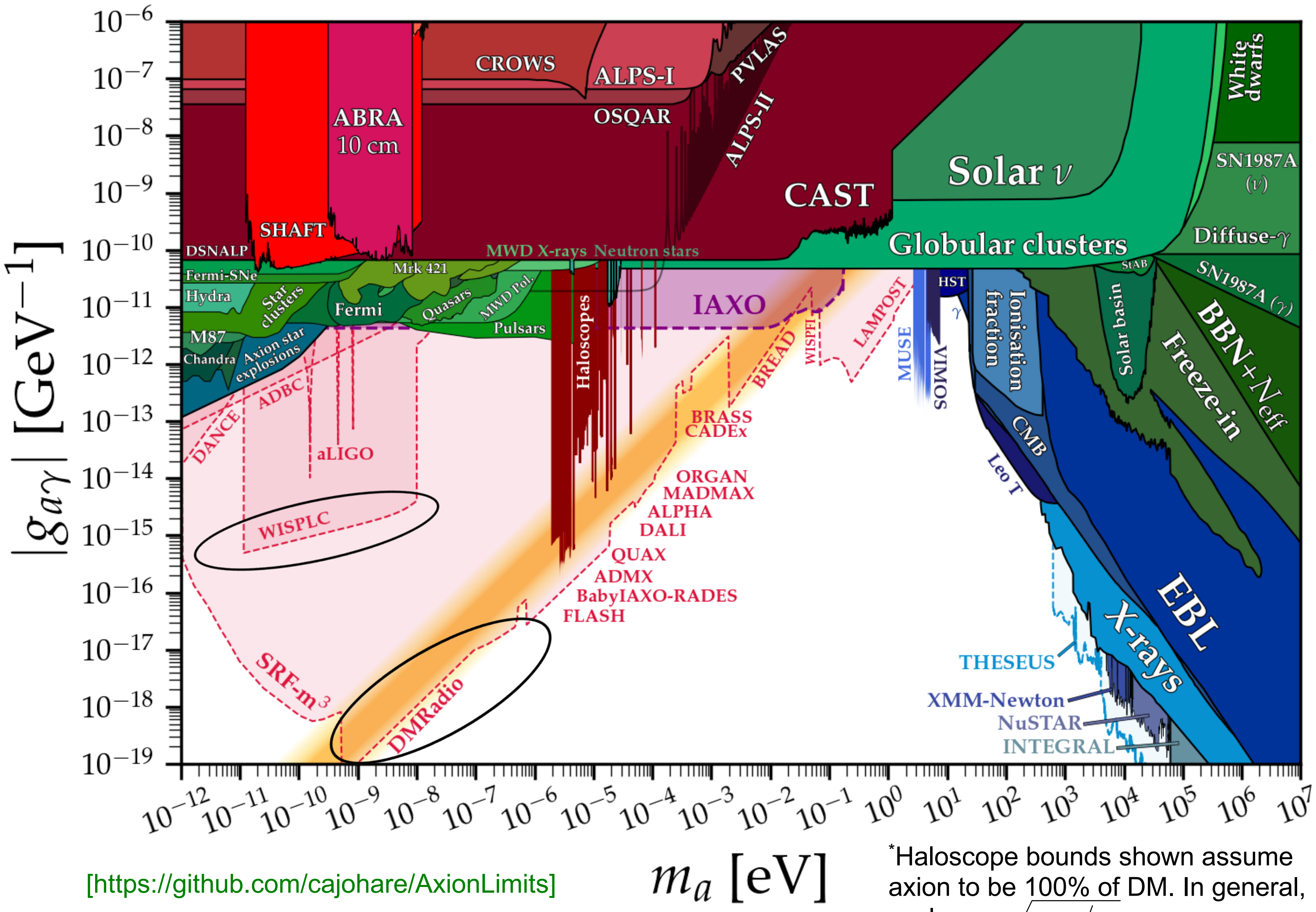
- **Digging deep into unexplored territory at low mass**



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*Haloscope bounds shown assume axion to be 100% of DM. In general, scale as $\sqrt{\rho_{\rm DM}/\rho_a}$

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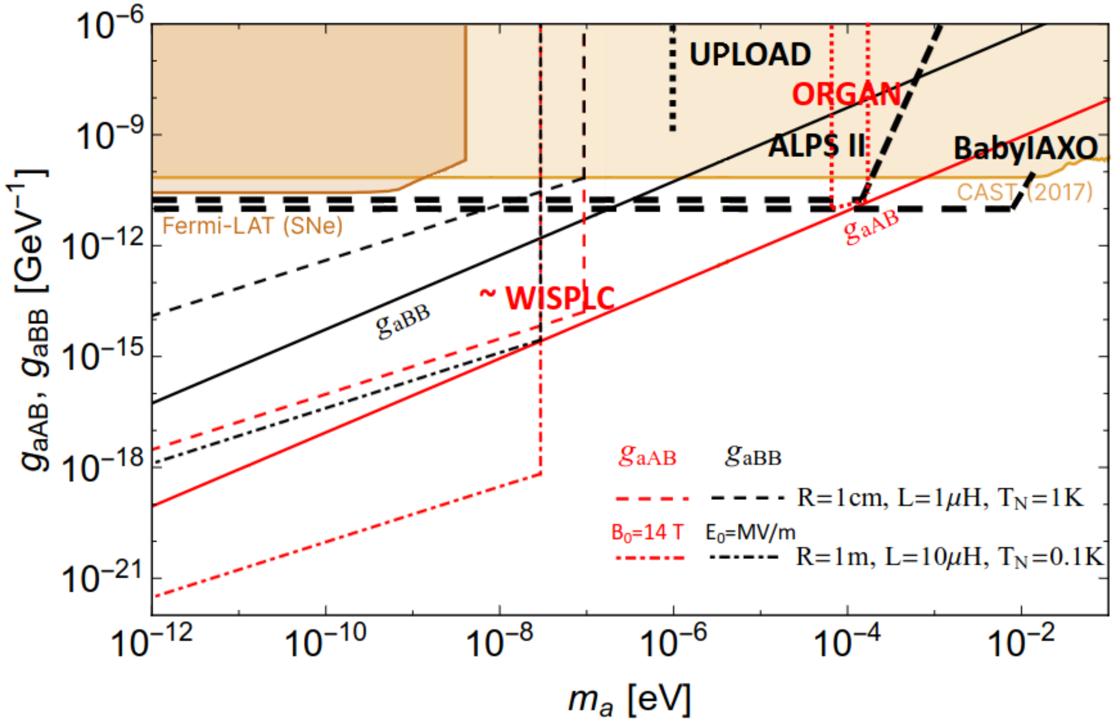
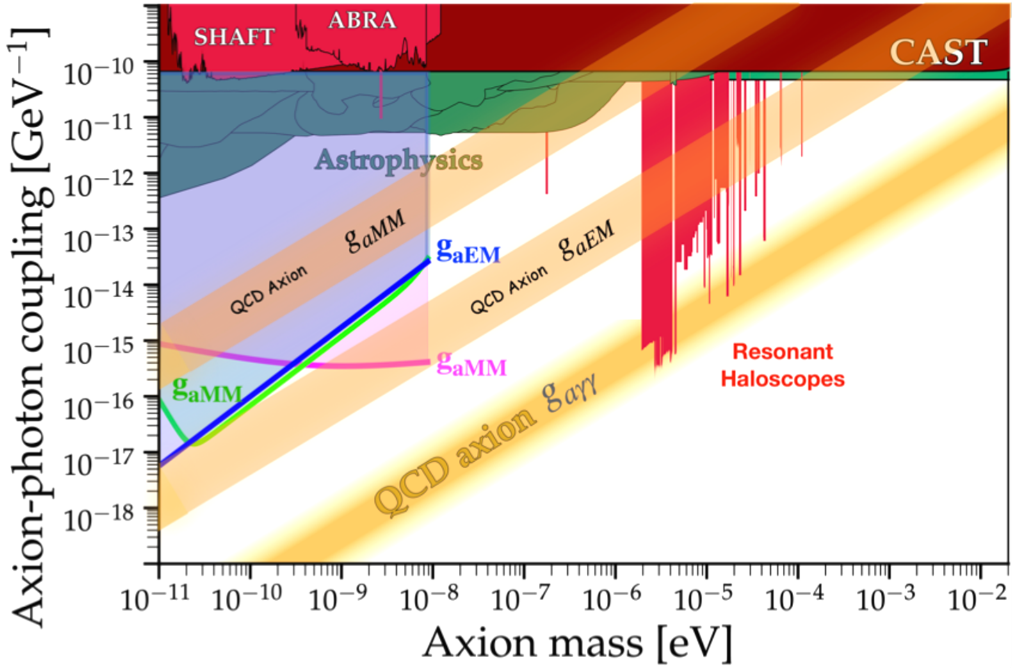
Lumped-element detectors

- Lumped-element detectors can also probe the new couplings of the monopole-philic axion:





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adapted from [Li,Zhang,Dai, 2211.06847]

[Tobar,Sokolov,AR,Goryaev, 2306.13320]

NMR Experiments

Searches for oscillating NEDMs

$$\mathcal{L} \supset -\frac{i}{2}\frac{eC_{\rm NEDM}}{f_a}\, a\,\overline{\psi}_N \sigma_{\mu\nu}\gamma_5\psi_N F^{\mu\nu} \equiv -\frac{i}{2} g_{aN\gamma}\, a\,\overline{\psi}_N \sigma_{\mu\nu}\gamma_5\psi_N F^{\mu\nu}$$

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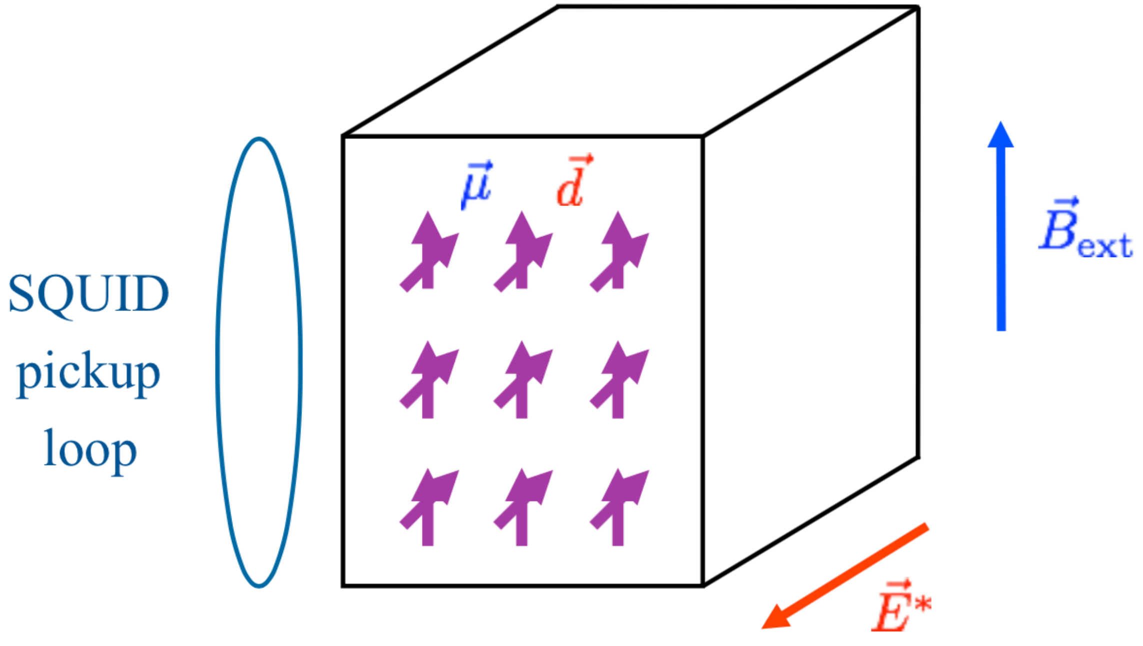
Searches for oscillating NEDMs

- **Concept:**
  - Axion DM field induces oscillating NEDMs:

    $$d_N(t) = g_{aN\gamma}\sqrt{2\rho_a}\cos(m_a t)/m_a$$

  - Place a ferroelectric crystal (permanent electric polarisation fields $\vec{E}^*$) in external $\vec{B}_{\rm ext} \perp E^*$
  - Nuclear spins are polarised along $\vec{B}_{\rm ext}$ and precess at Larmor frequency $\omega_L = 2\mu_N B_{\rm ext}$
  - Interaction $\epsilon_S \vec{d}_N(t)\cdot\vec{E}^*$ of DM induced NEDM with the $\vec{E}^*$-field leads to resonant increase of transverse magnetisation of sample when $\omega_L = m_a$

[Graham,Rajendran 13; Budker et al. 14]



[Budker et al. 14]

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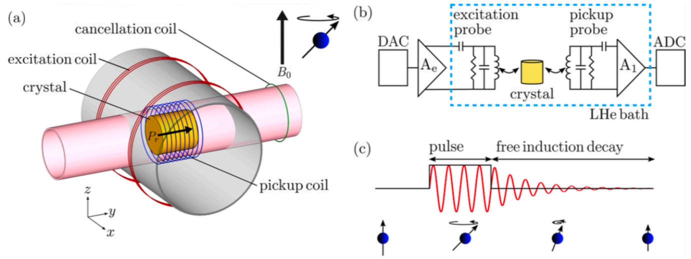
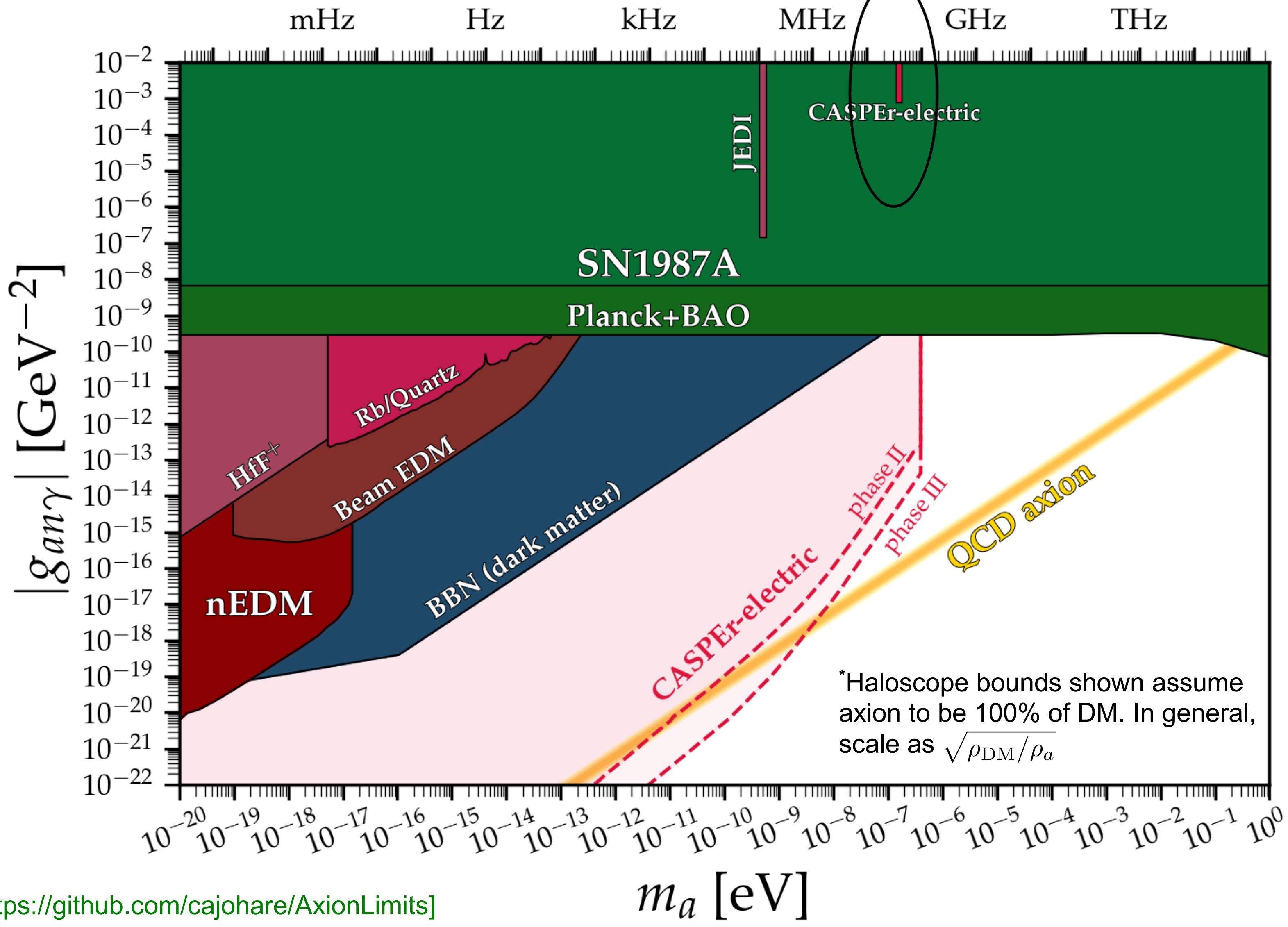
- CASPEr-Electric in Boston
  - **Initial pathfinder experiment deep in the excluded region**



[Aybas et al., 2101.01241]



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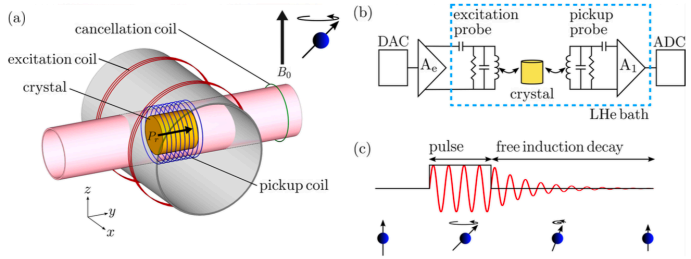
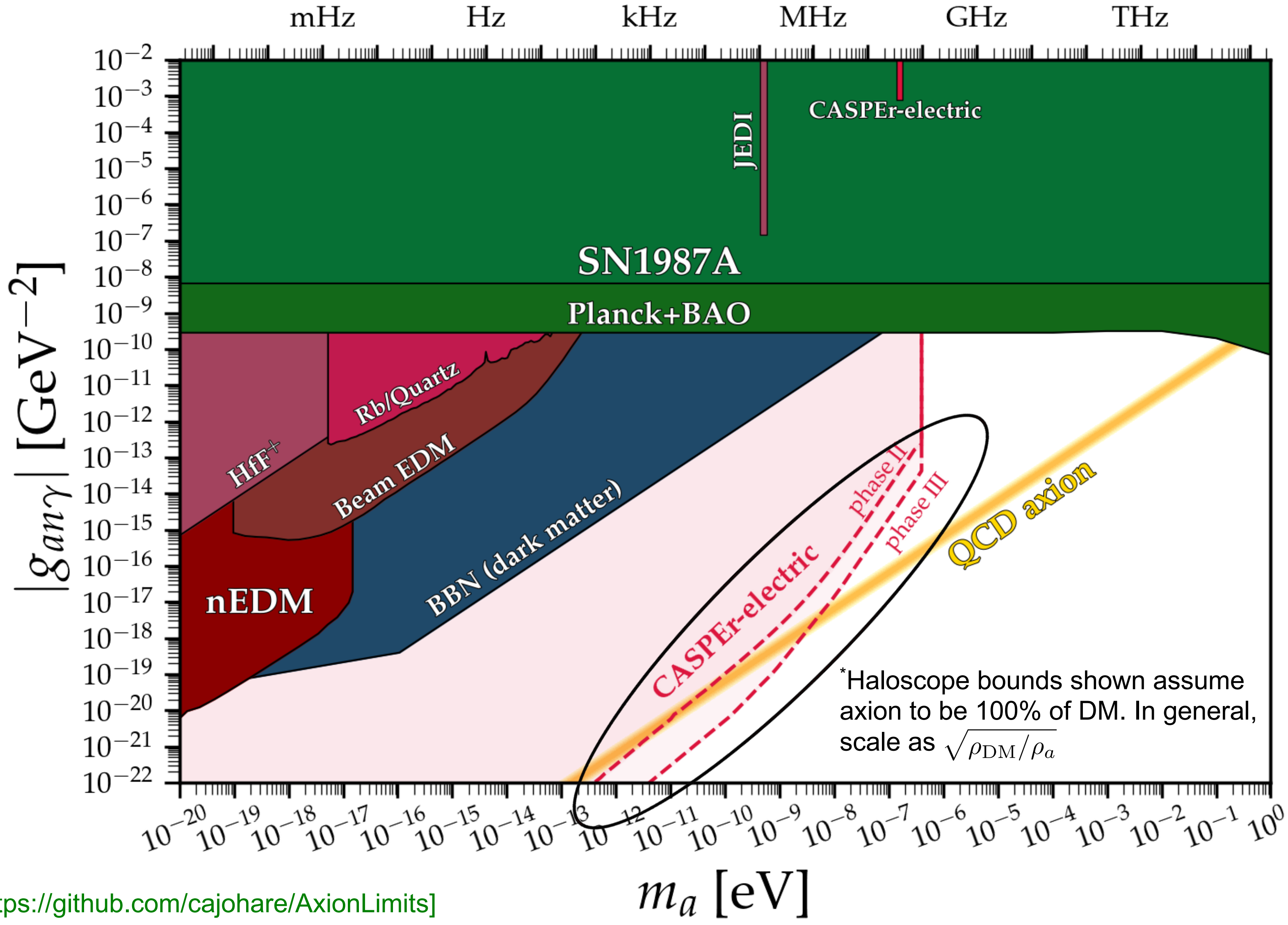


[Aybas et al., 2101.01241]

  - **Full experiment probes axion dark matter in mass range predicted by GUTs**

- For nEDM bounds see poster session

  [Jacek Zejma, poster session A]



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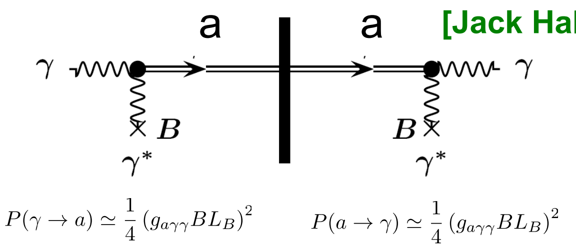
Searches for Home-Made or Solar Axions

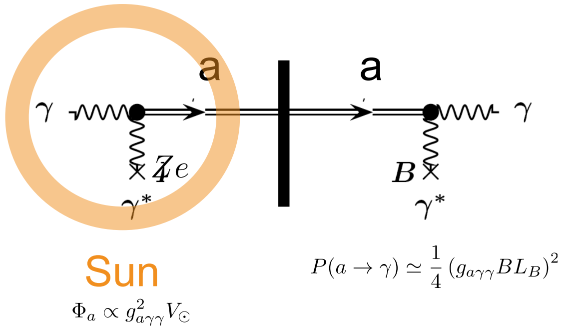
Further axion experiments

- So far only discussed experiments searching for halo DM axions
- Further experiments not relying on galactic halo being the source of axions:
  - Light-shining through walls: [Anselm 85; van Bibber 87]



[Jack Halliday, poster session 2A]

  - Helioscopes: [Sikivie 83]



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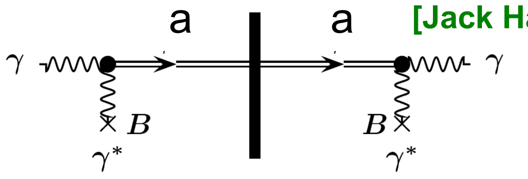

$P(\gamma \to a) \simeq \frac{1}{4}(g_{a\gamma\gamma} B L_B)^2$ $\quad P(a \to \gamma) \simeq \frac{1}{4}(g_{a\gamma\gamma} B L_B)^2$

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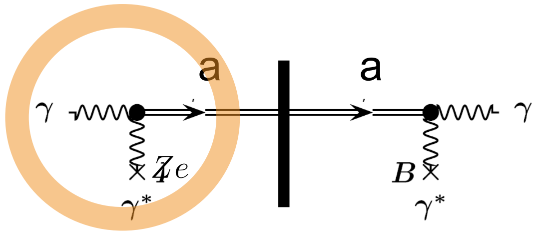

Sun

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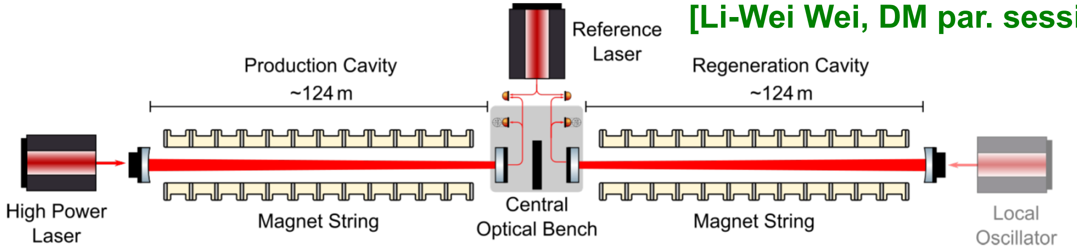
- **ALPS II** @ DESY: data taking started in May 2023

[Li-Wei Wei, DM par. session 4B]



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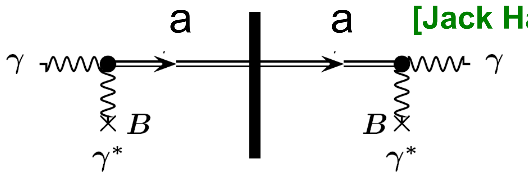

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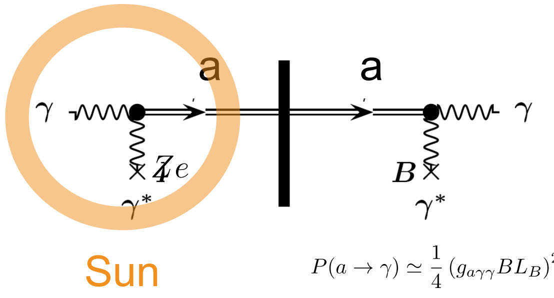

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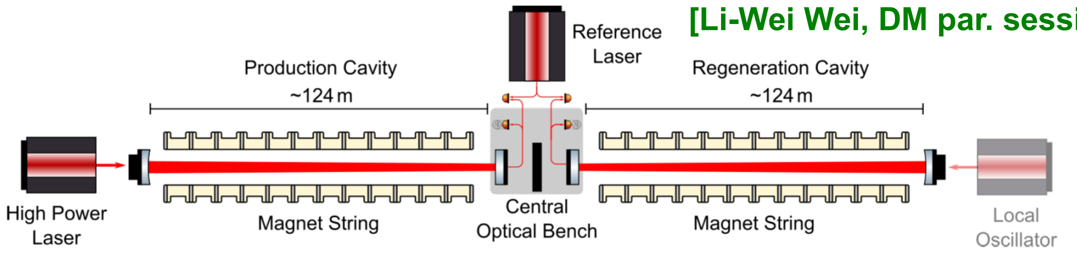
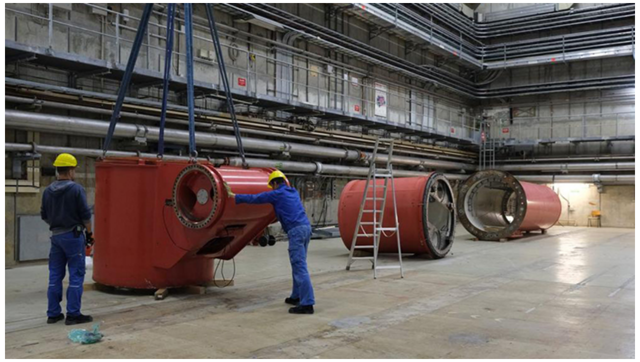
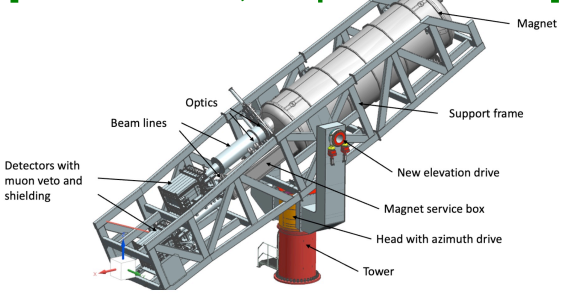


- **BabyIAXO** @ DESY: start data taking in 2028



[Juanan Garcia, DM par. session 2A]



[Christoph Wiesinger, poster session A]

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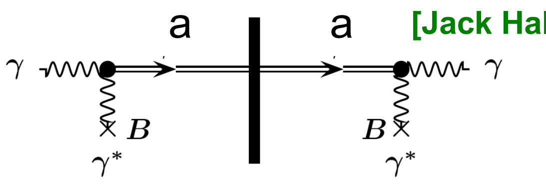

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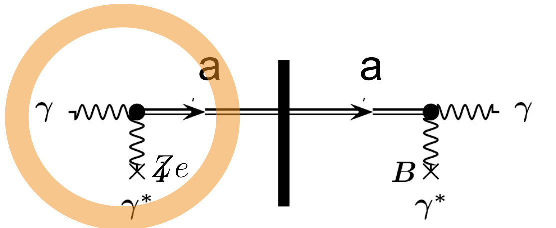

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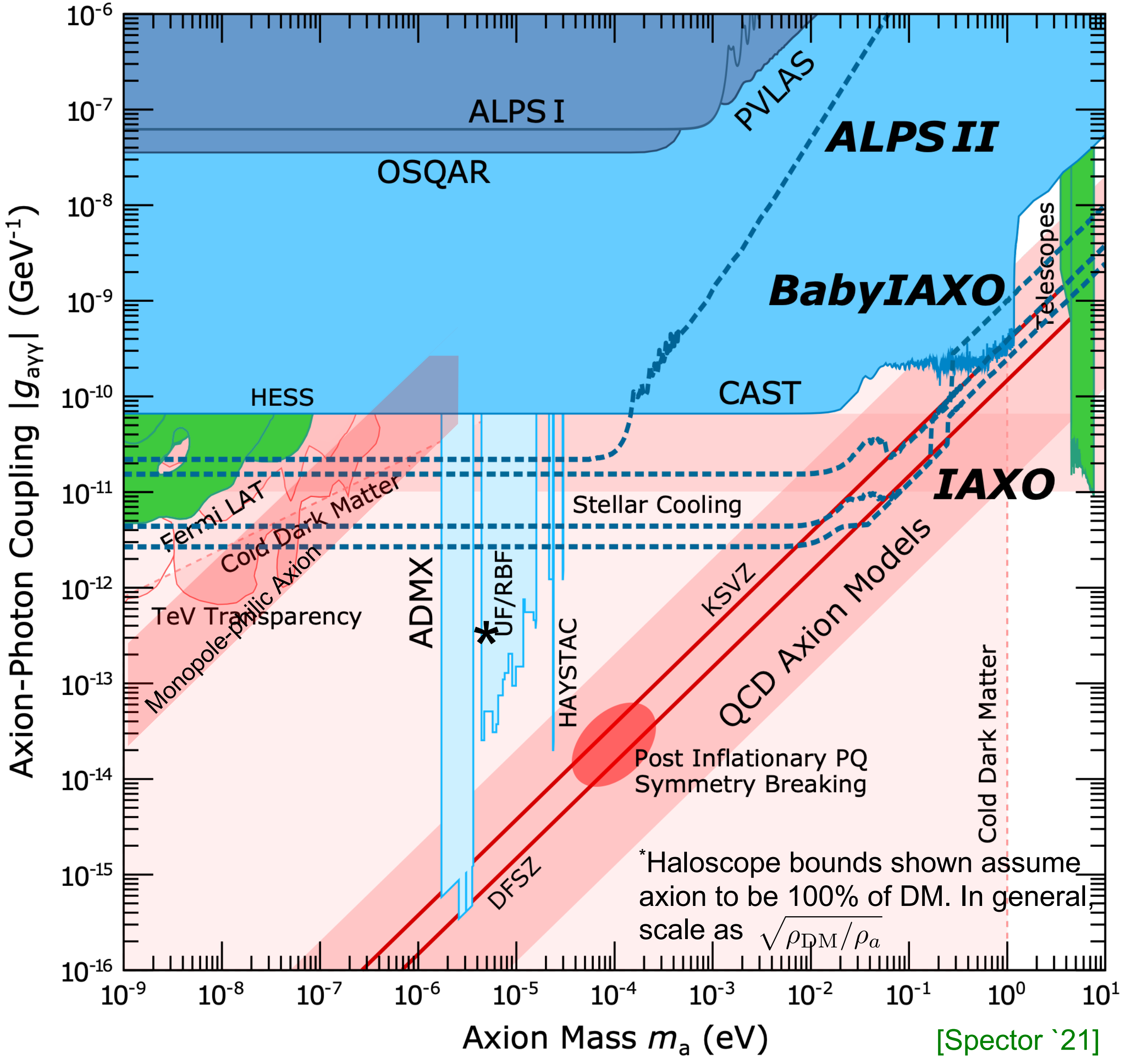


[Spector `21]

Searches for High-Frequency Gravitational Waves

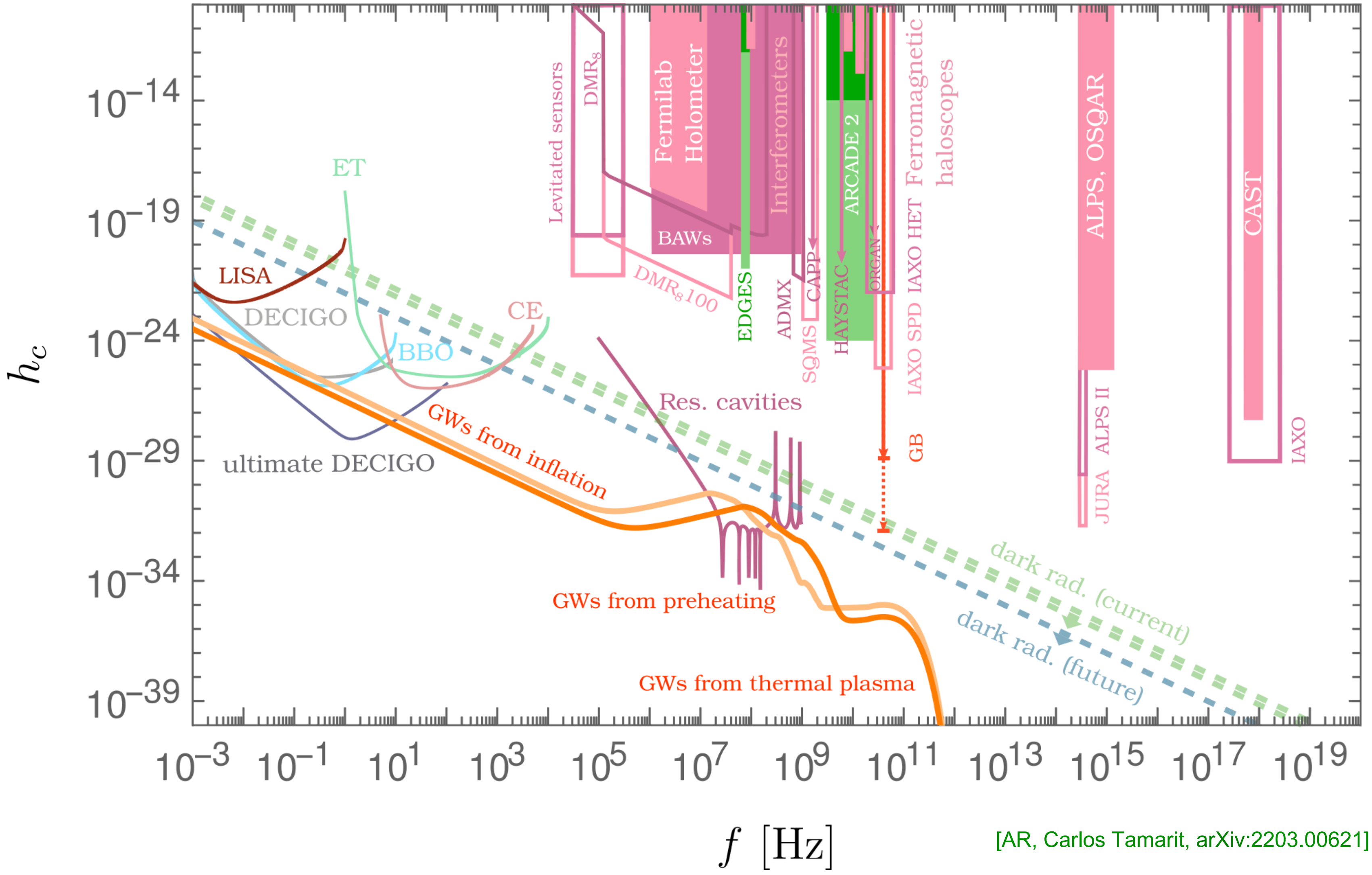
Axion haloscopes, LSW experiments, and helioscopes as HF-GW detectors

[Ejlli et al., 1908.00232]

[AR et al., 2011.04731]

[Berlin et al., 2112.11465]

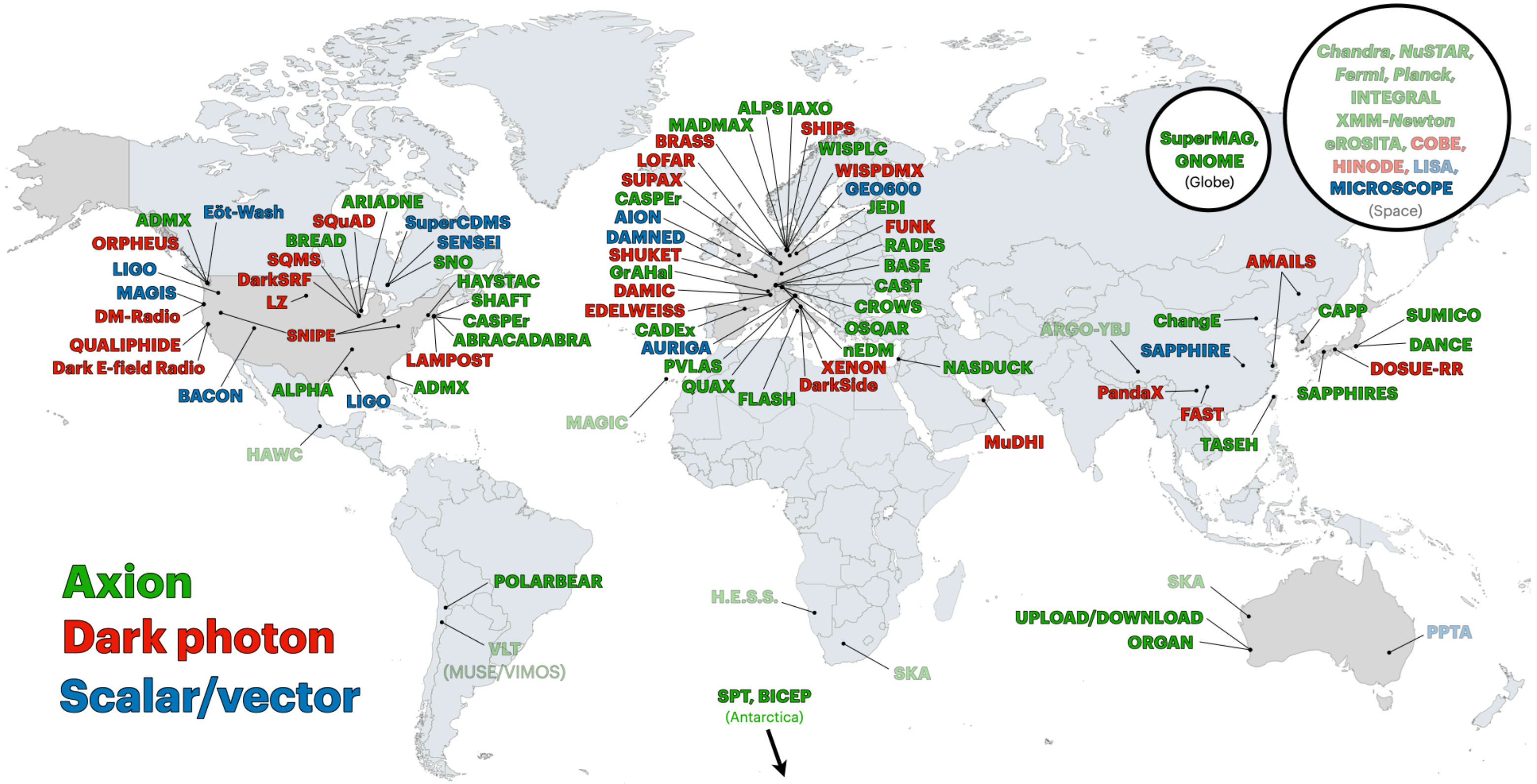
[Domcke et al., 2202.00695]



[AR, Carlos Tamarit, arXiv:2203.00621]

Summary

- World-wide big experimental activity on axion searches exploiting different techniques and couplings:



- Many new experimental techniques developed ... often in very tight collaborations between phenomenologically oriented theorists and theoretically interested experimentalists

Stay tuned!