Search for axions and axion-like particles

Andreas Ringwald

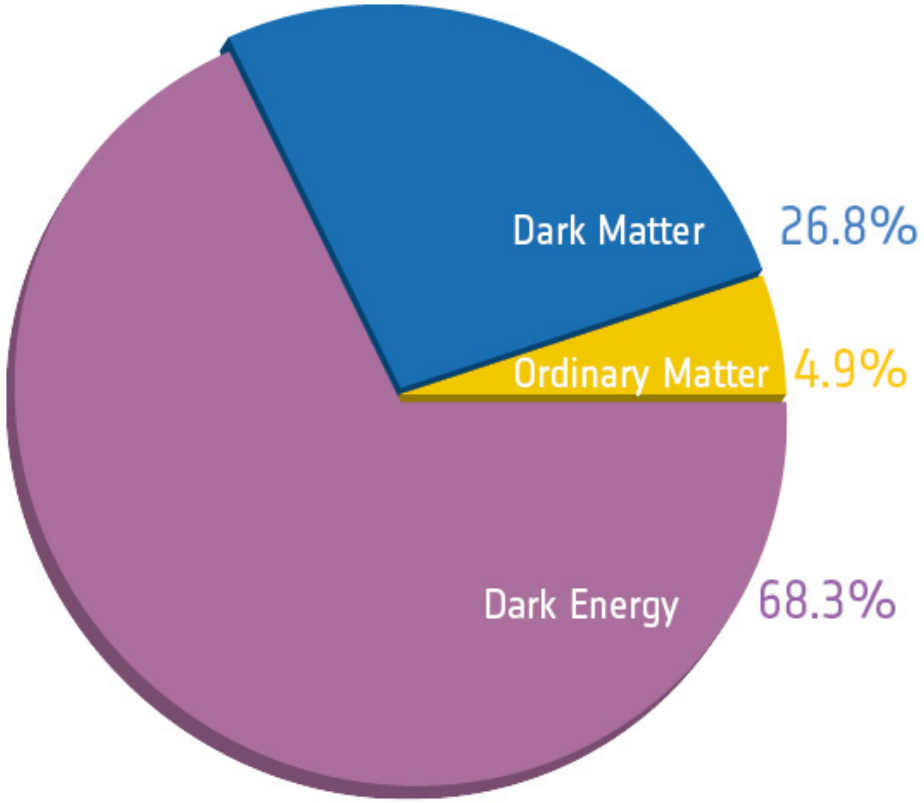
Astroparticle Physics in Germany
Mainz, 17-19 September 2018

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Motivation

- Unraveling nature of dark matter (DM) most urgent problem of particle physics and cosmology



[PLANCK]

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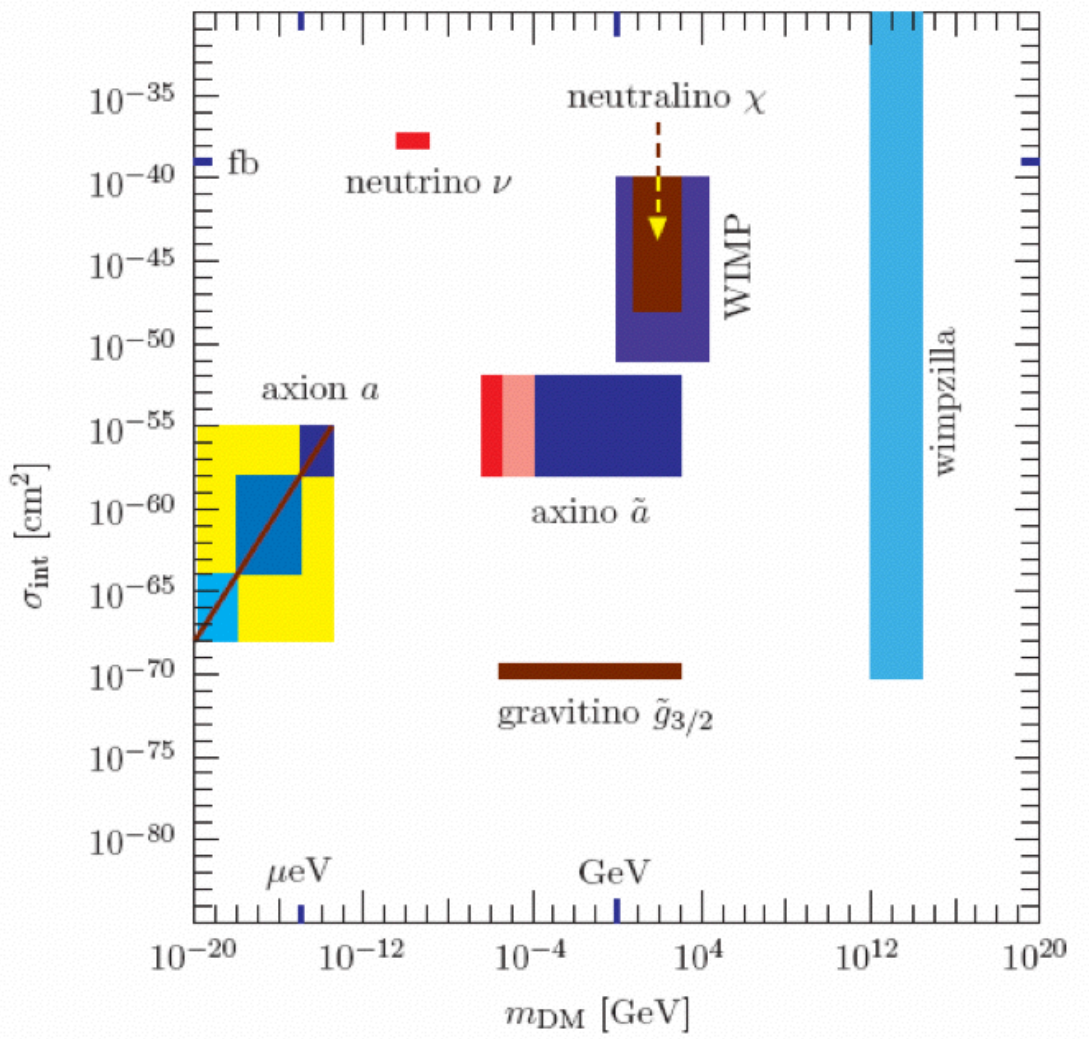
- Non-observation of WIMPs at LHC and in direct detection dark matter (DM) experiments strong motivation to focus more attention to non-WIMPy DM candidates



[Kim,Carosi 10]

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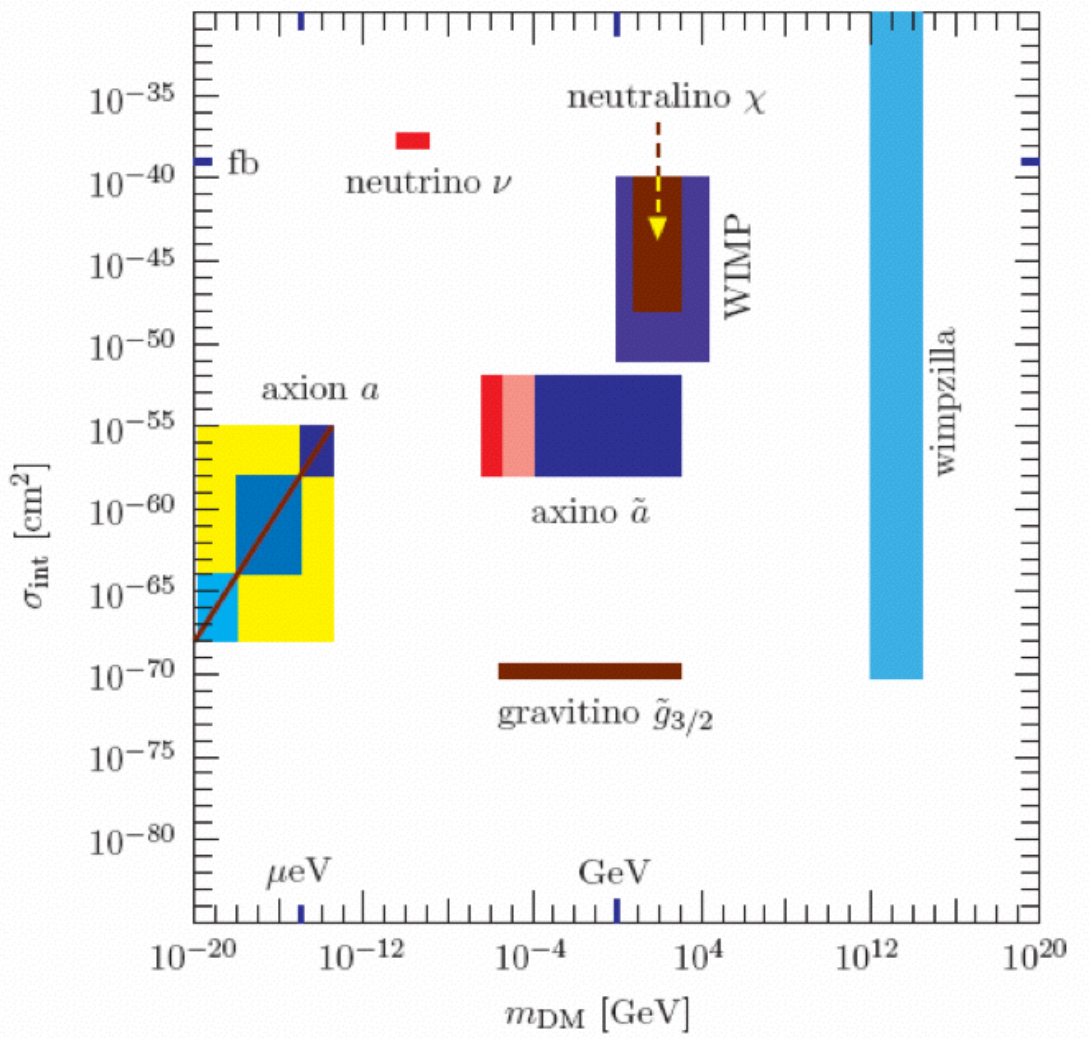
- Axion - the Nambu-Goldstone boson (NGB) from breaking of a color anomalous global chiral U(1) symmetry which is spontaneously broken in the vacuum - strongly motivated since it solves also strong CP problem [Peccei,Quinn 77; Weinberg 78; Wilczek 78]



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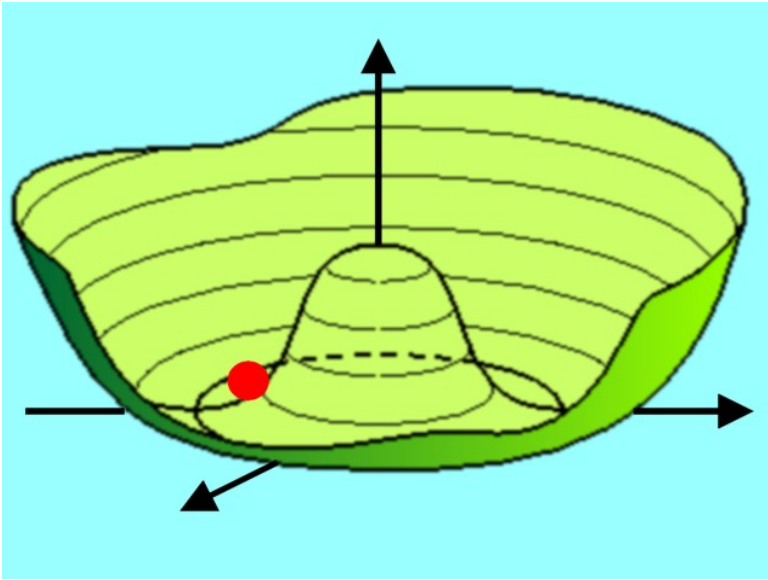

[Raffelt]

$$\Sigma(x) = \frac{1}{2}\left[f_A + \rho(x)\right] \mathrm{e}^{iA(x)/f_A}$$

$$f_A \gg v_h = 246\,\mathrm{GeV}$$

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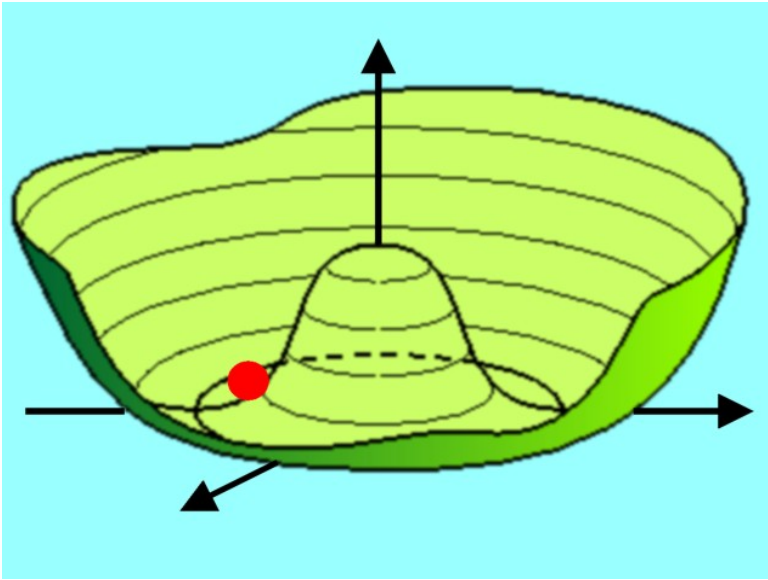
- Axion-like particles (ALPs) - further NGBs from breaking of other global symmetries – also DM candidates [Arias et al. 12]
  - Lepton symmetry: Majoron
  - Family symmetry: Familon
  - Flavor symmetry: Flavon



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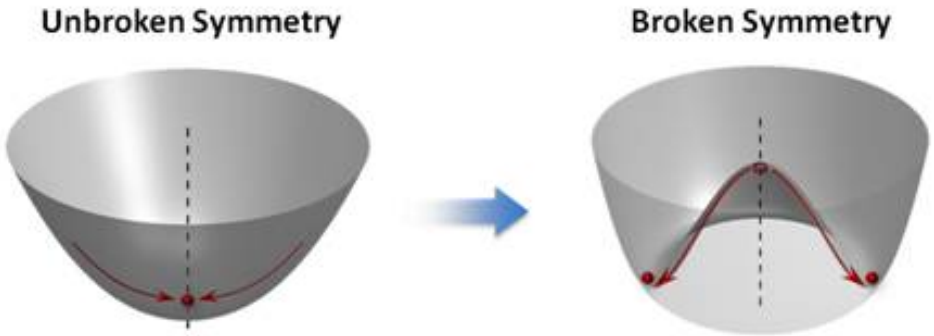
Axion/ALP DM

- Axion/ALP field born after breaking of global symmetry: $T \lesssim f_a$



[Peking University]

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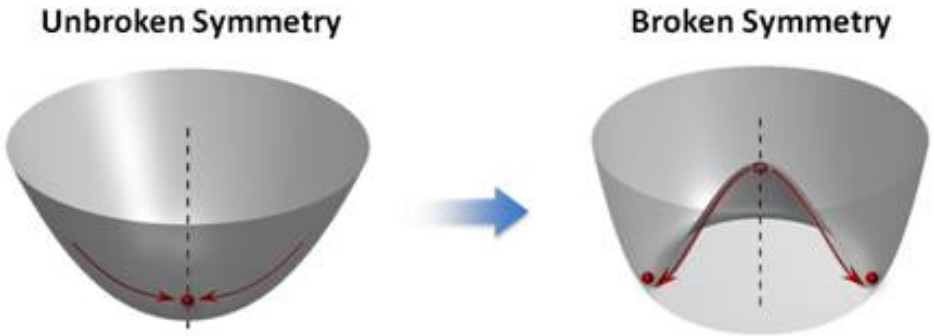
- Frozen as long as Hubble expansion rate exceeds mass, $H \gtrsim m_a$



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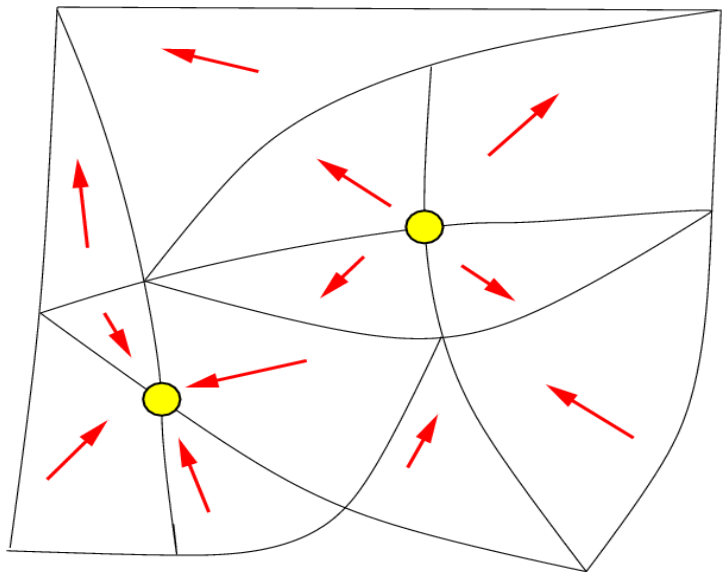
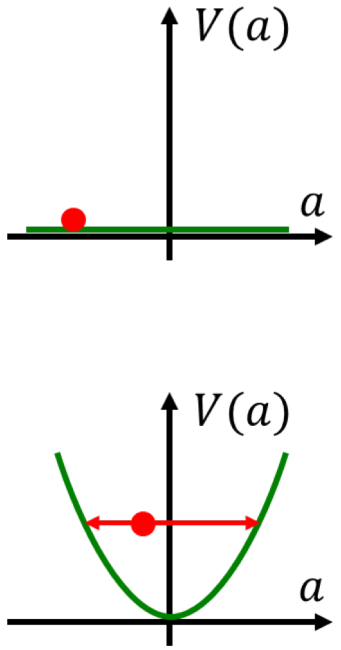


[Uhlmann et al. `10]



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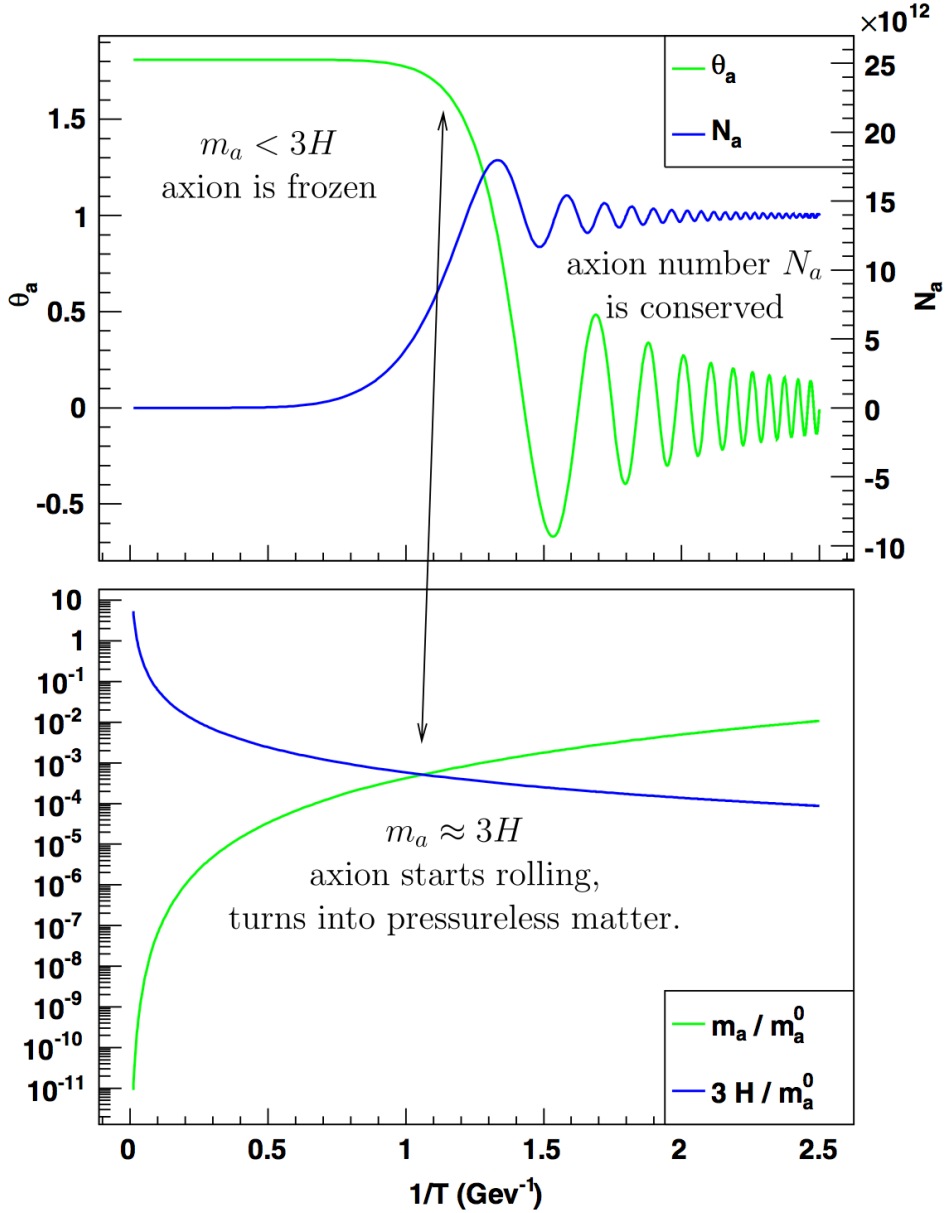
- Later, when $H \sim m_a$, field starts to oscillate around zero; behaves like cold dark matter:

$$w_a = p_a/\rho_a \simeq 0$$

[Preskill,Wise,Wilczek 83; Abbott,Sikivie 83; Dine,Fischler 83,...; Arias et al. 12]



[Wantz,Shellard `09]

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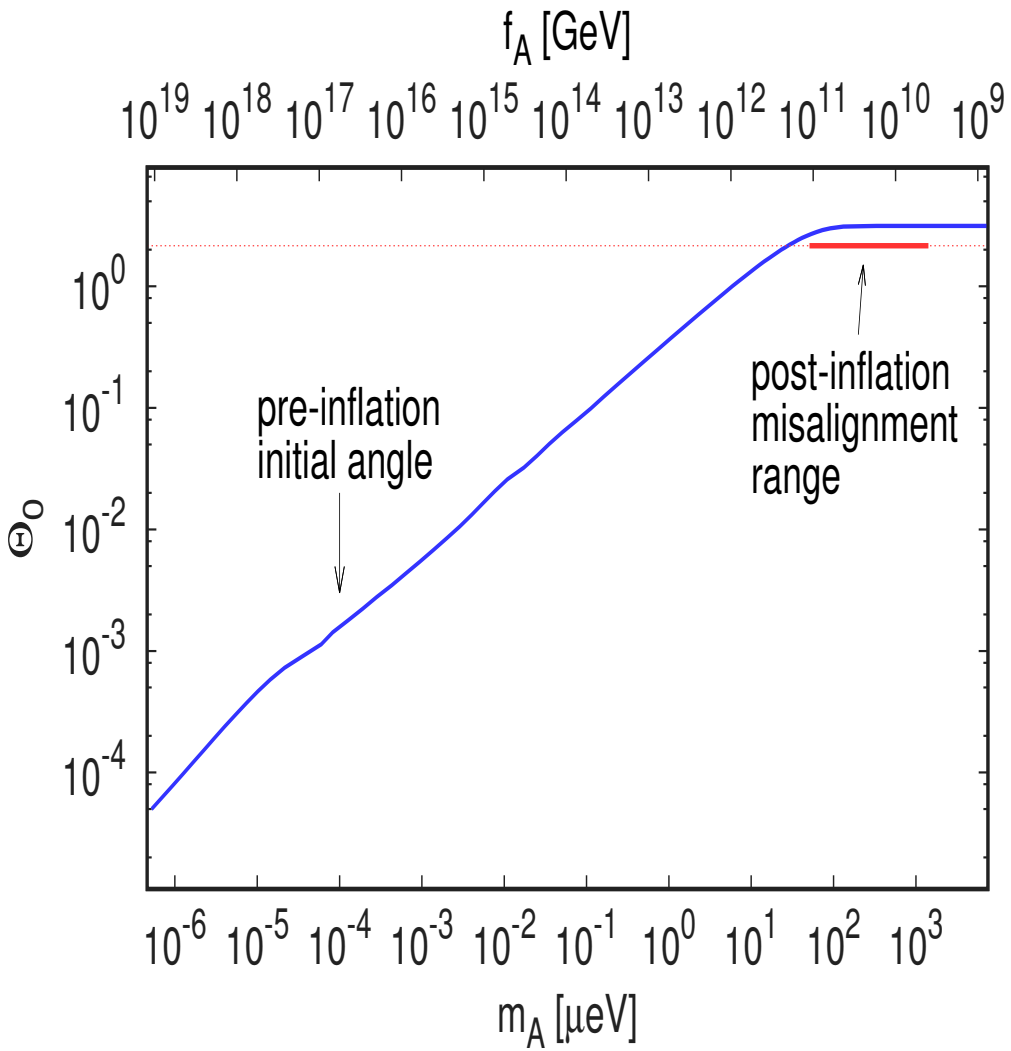
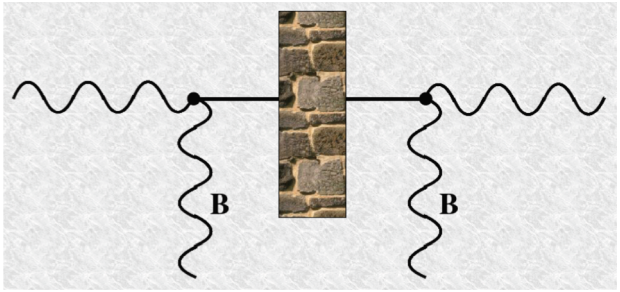
- DM prediction:
  - Axion can be 100% of DM for $f_A \gtrsim 10^9\,\mathrm{GeV}$
  - ALP can be 100% of DM for $f_a \gtrsim 10^9\,\mathrm{GeV}\left(\frac{\mathrm{neV}}{m_a}\right)^{1/2}$



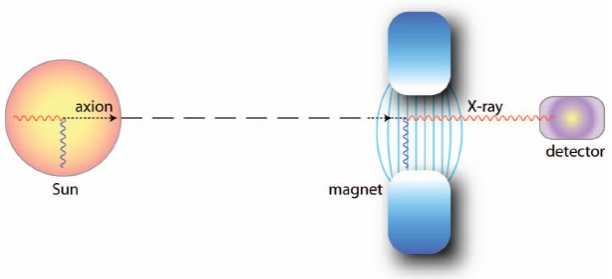
[Borsanyi et al., Nature `16]

Axion/ALP searches

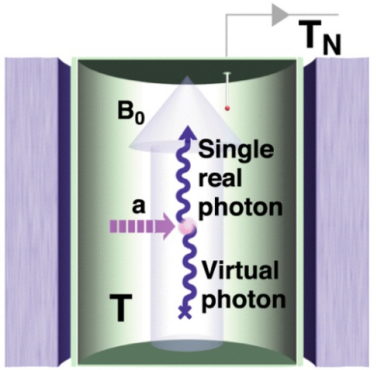
- Light-shining-through-a-wall
  - Production and detection of axions/ALPs in laboratory



- Helioscopes
  - Axion/ALP production in Sun, detection in laboratory



- Haloscopes
  - DM Axion/ALP production in early universe, detection in lab



Light-shining-through-a-wall searches

$$\mathcal{L} \supset \frac{1}{2}\left(\partial_\mu a\right)^2 - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}g_{a\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad g_{a\gamma} \equiv \frac{\alpha}{2\pi f_a} C_{a\gamma}$$

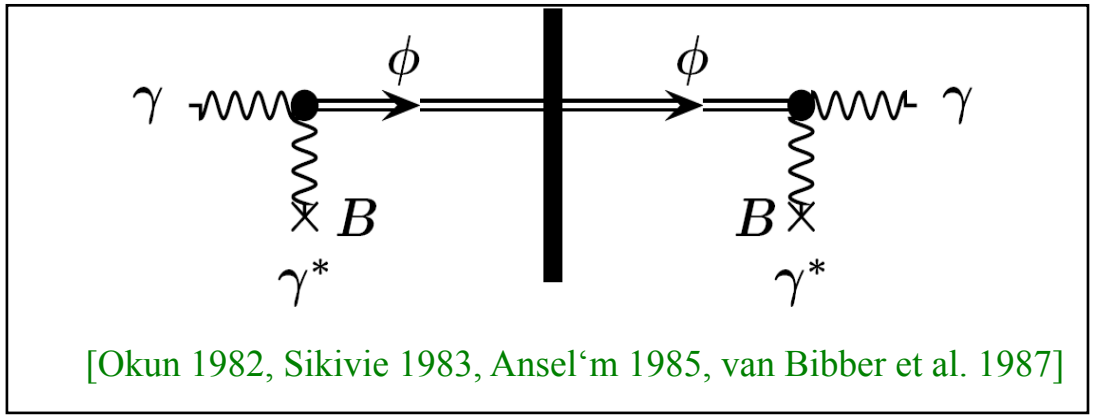
- Due to two-photon vertex, axion/ALPs experiences mixing with photon in an external field
- Probability, that photon converted in axion/ALP after having traversed a distance L_B in magnetic field:

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

- For very light axion/ALP:

$$P(\gamma \leftrightarrow a) \simeq \frac{1}{4}\left(g_{a\gamma} B L_B\right)^2$$

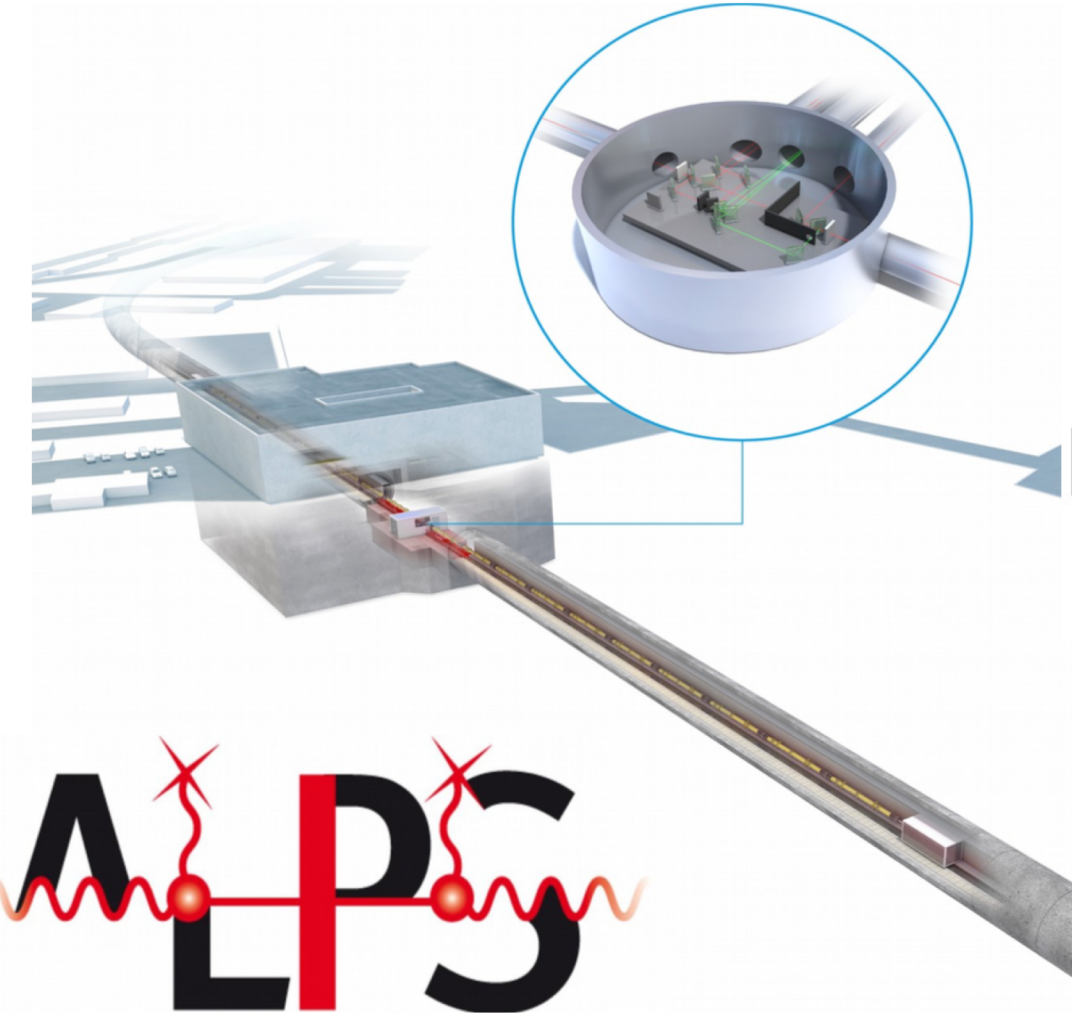
- Light-shining-through a wall:

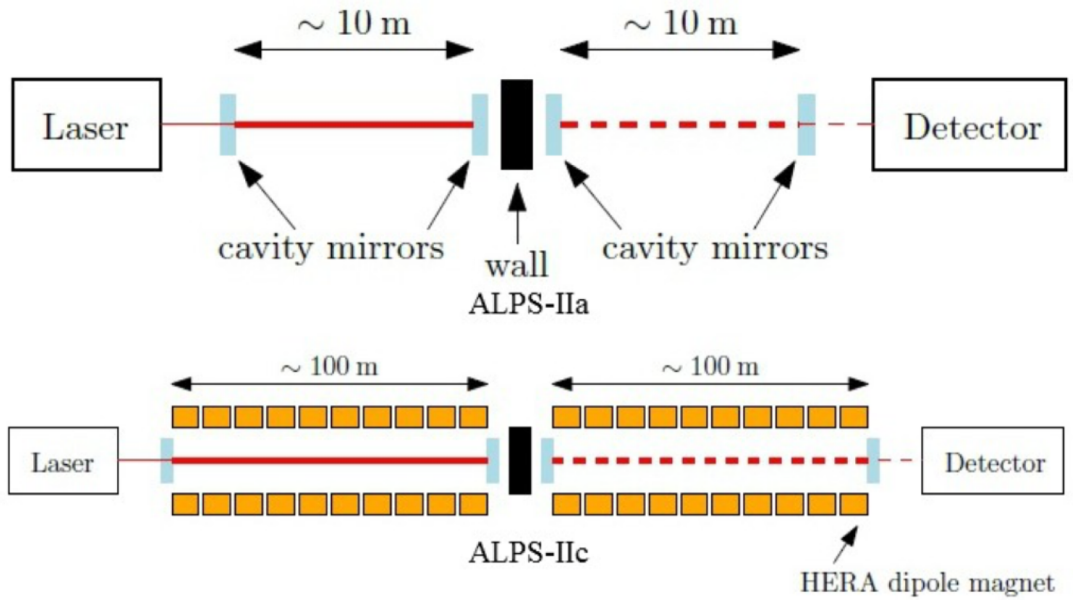


[Okun 1982, Sikivie 1983, Ansel'm 1985, van Bibber et al. 1987]

Light-shining-through-a-wall searches

- ALPS II at DESY (in coll. with AEI, UFL, U Mainz): Data taking planned in 2020 [Bähre et al (ALPS II TDR) 13]

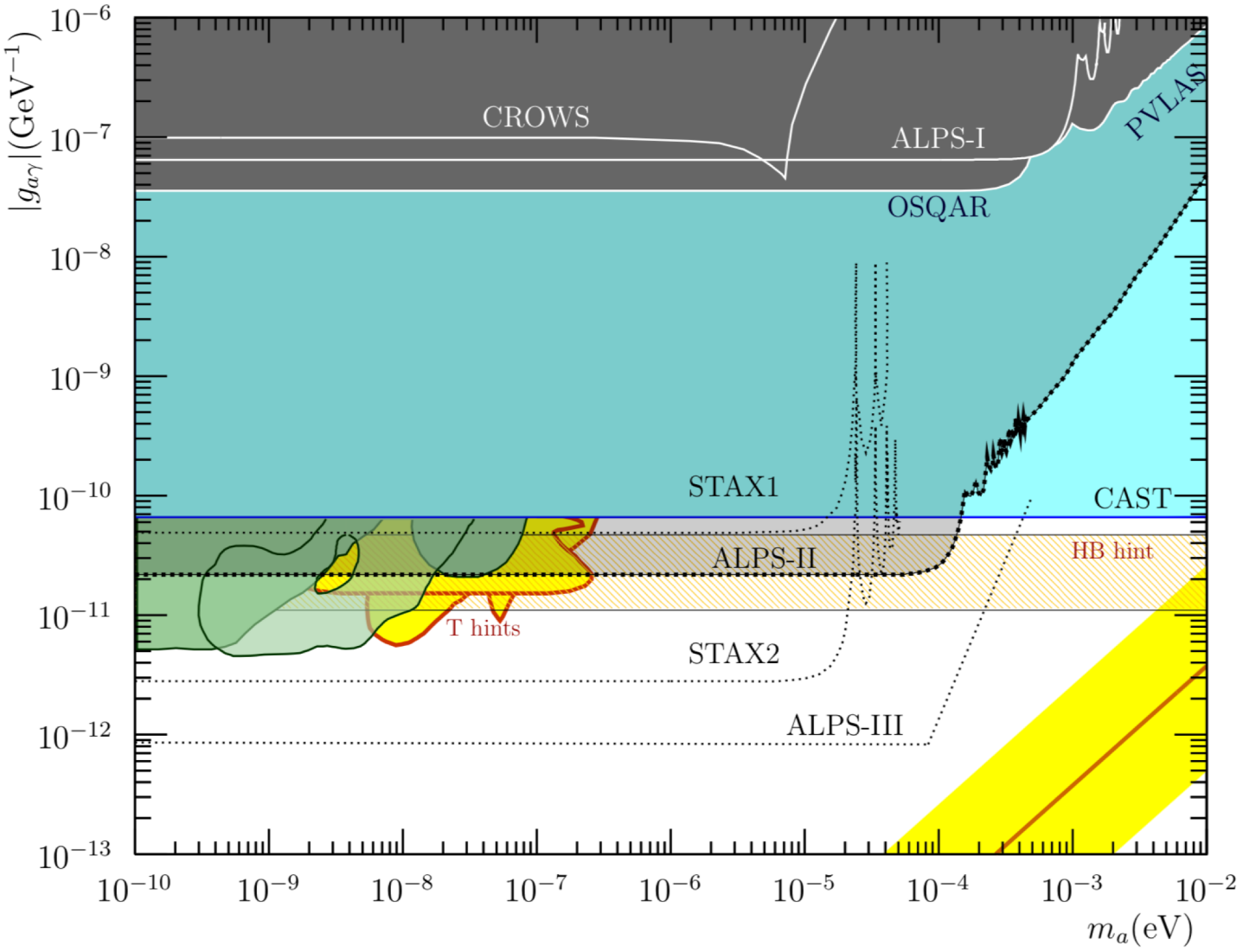




Parameter	Scaling	ALPS I	ALPS IIc	Sens. gain
Effective laser power P_{laser}	$g_{a\gamma} \propto P_{\text{laser}}^{-1/4}$	1 kW	150 kW	3.5
Rel. photon number flux n_γ	$g_{a\gamma} \propto n_\gamma^{-1/4}$	1 (532 nm)	2 (1064 nm)	1.2
Power built up in RC P_{RC}	$g_{a\gamma} \propto P_{reg}^{-1/4}$	1	40,000	14
BL (before& after the wall)	$g_{a\gamma} \propto (BL)^{-1}$	22 Tm	468 Tm	21
Detector efficiency QE	$g_{a\gamma} \propto QE^{-1/4}$	0.9	0.75	0.96
Detector noise DC	$g_{a\gamma} \propto DC^{1/8}$	0.0018 s^{-1}	0.000001 s^{-1}	2.6
Combined improvements				3082

Light-shining-through-a-wall searches

- ALPS II prospects:
  - Improves current pure laboratory bounds by three orders of magnitude



[Irastorza,Redondo 18]

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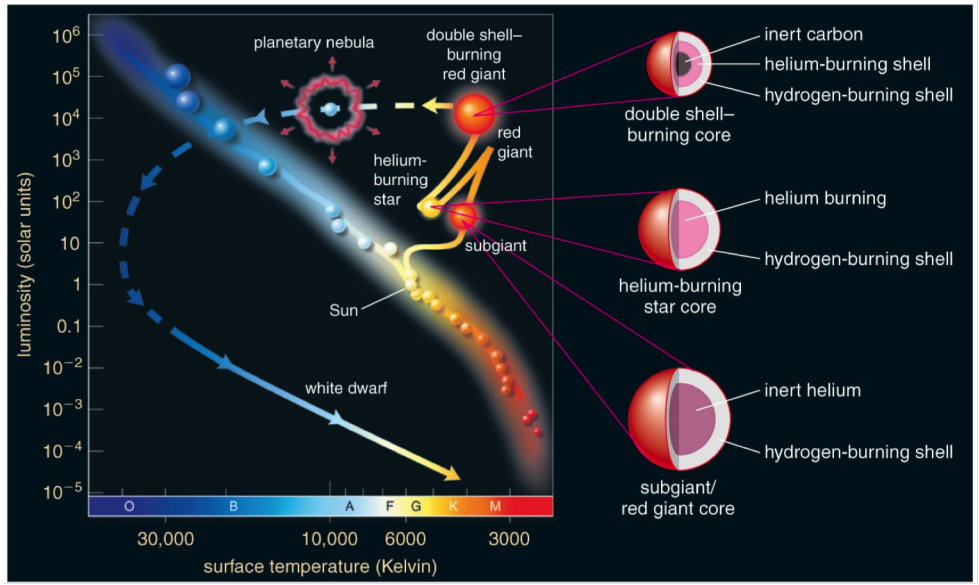
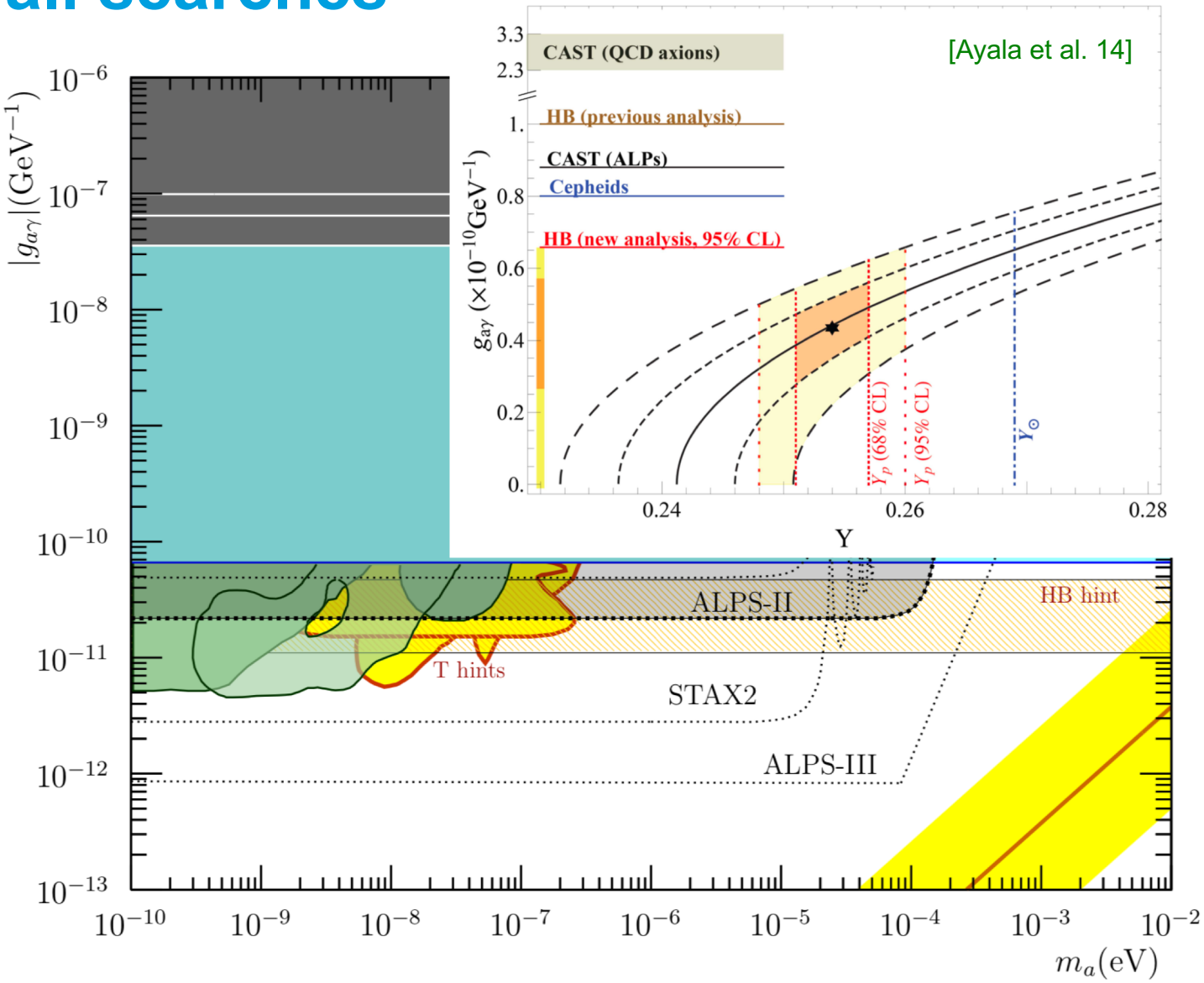


[Copyright Addison Wesley]



[Ayala et al. 14]

[Irastorza,Redondo 18]

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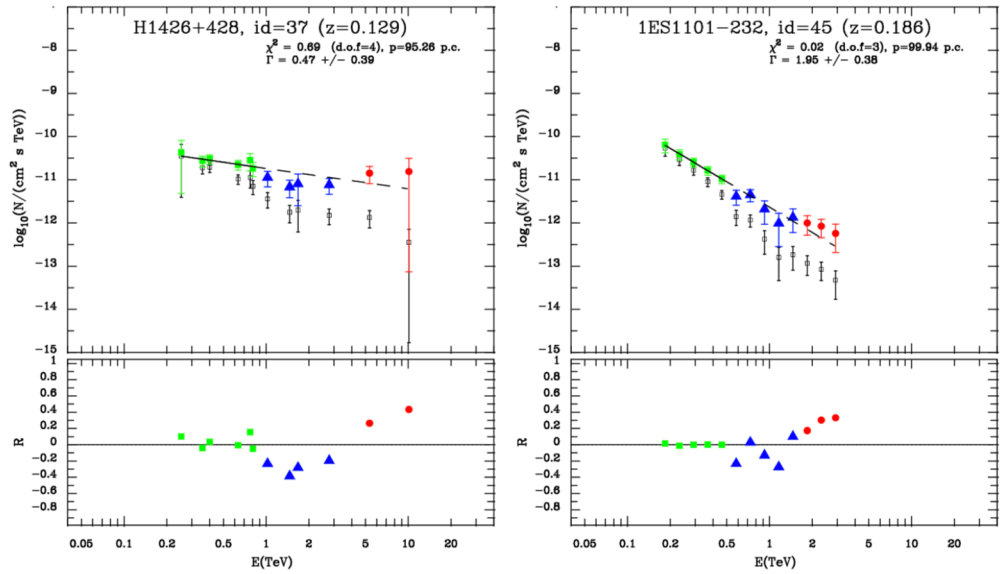
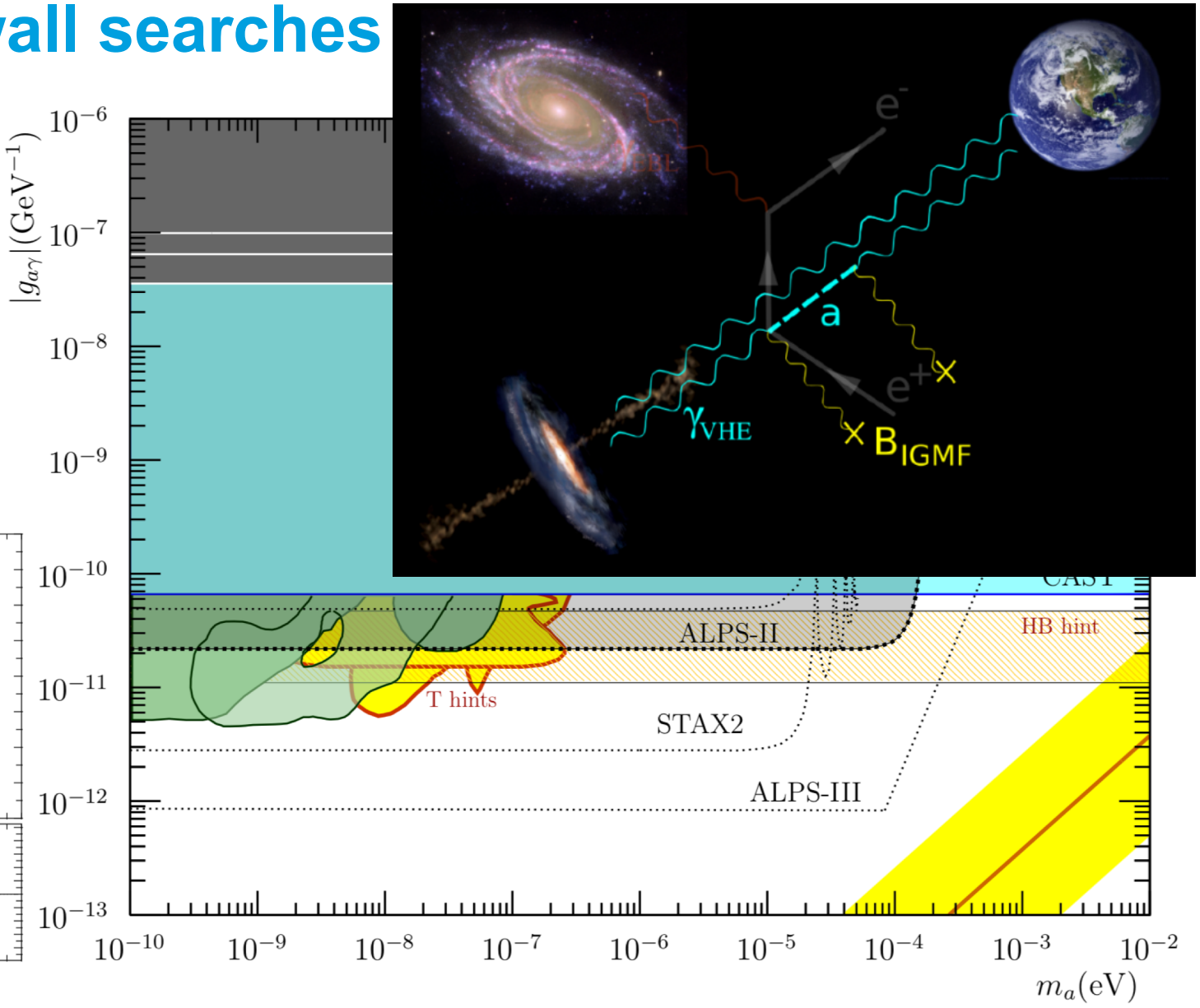


[Horns,Meyer 12]



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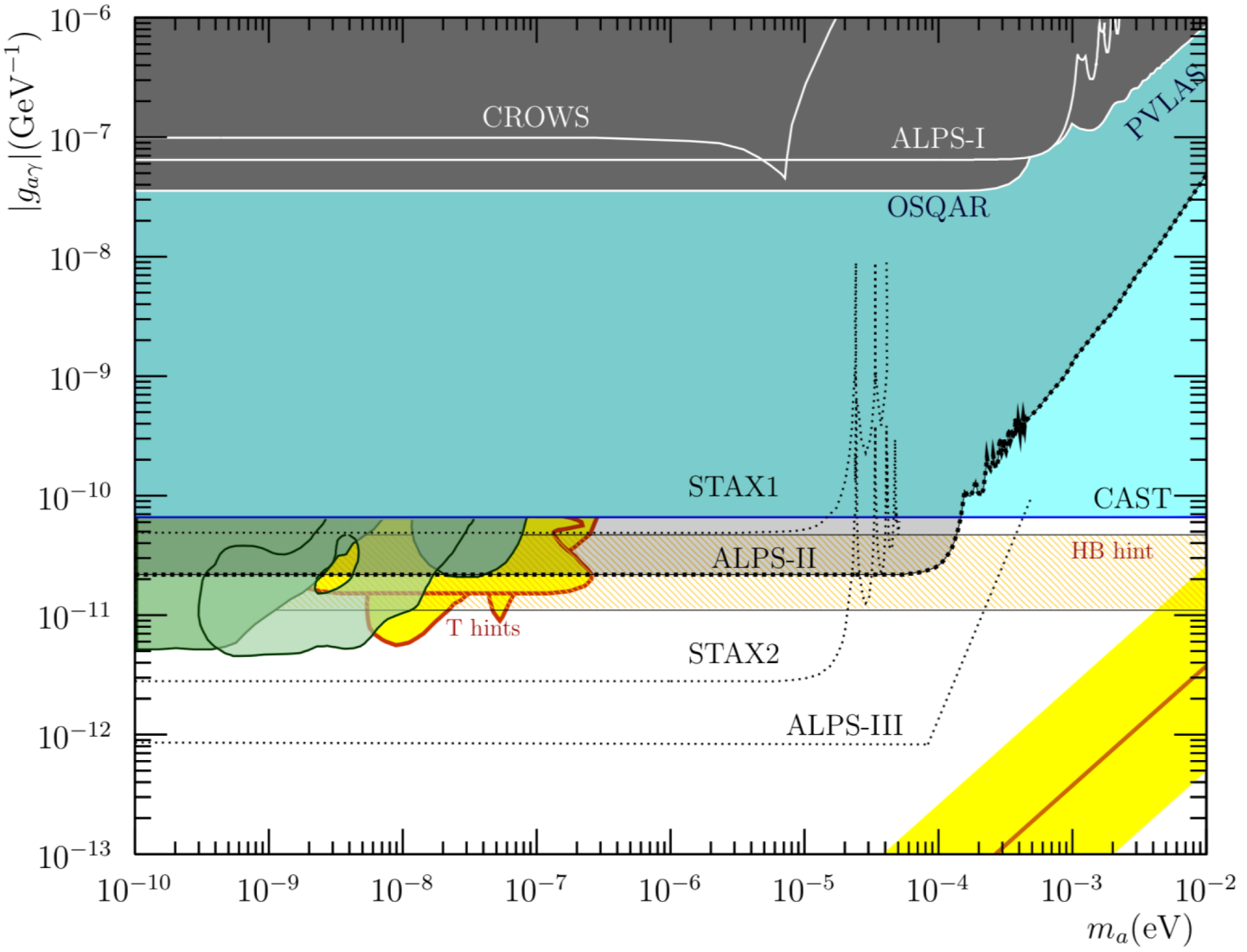

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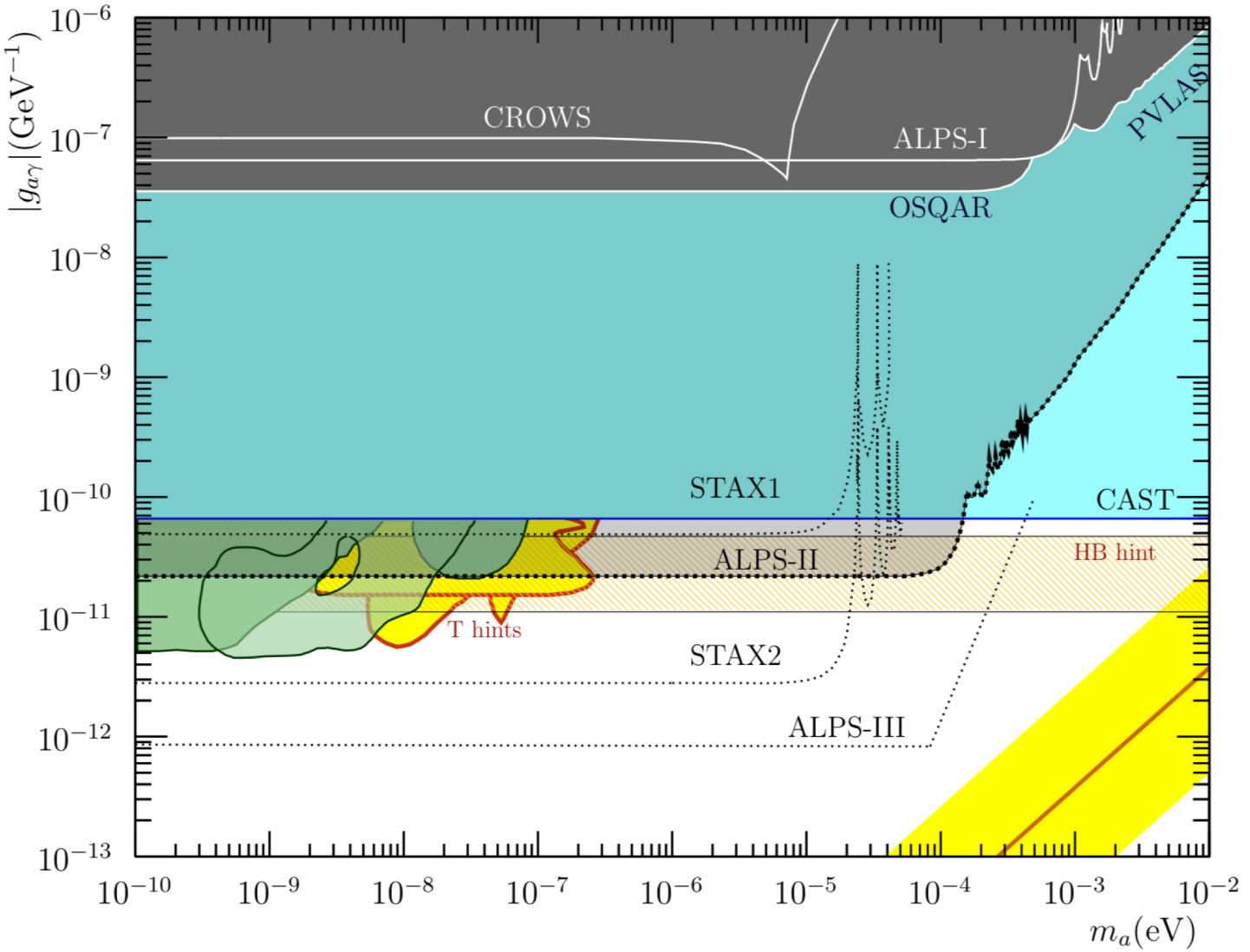
- ALPS III a.k.a. JURA proposes to exploit 13 T magnets presently being developped for LHC energy upgrade or FCC-hh and a generation cavity with 2.5 MW circulating power [Lindner 14 (unp.)]
  - Could even touch axion band if one exploits “wiggler” type of magnet string

[Arias et al. 10]



[Irastorza,Redondo 18]

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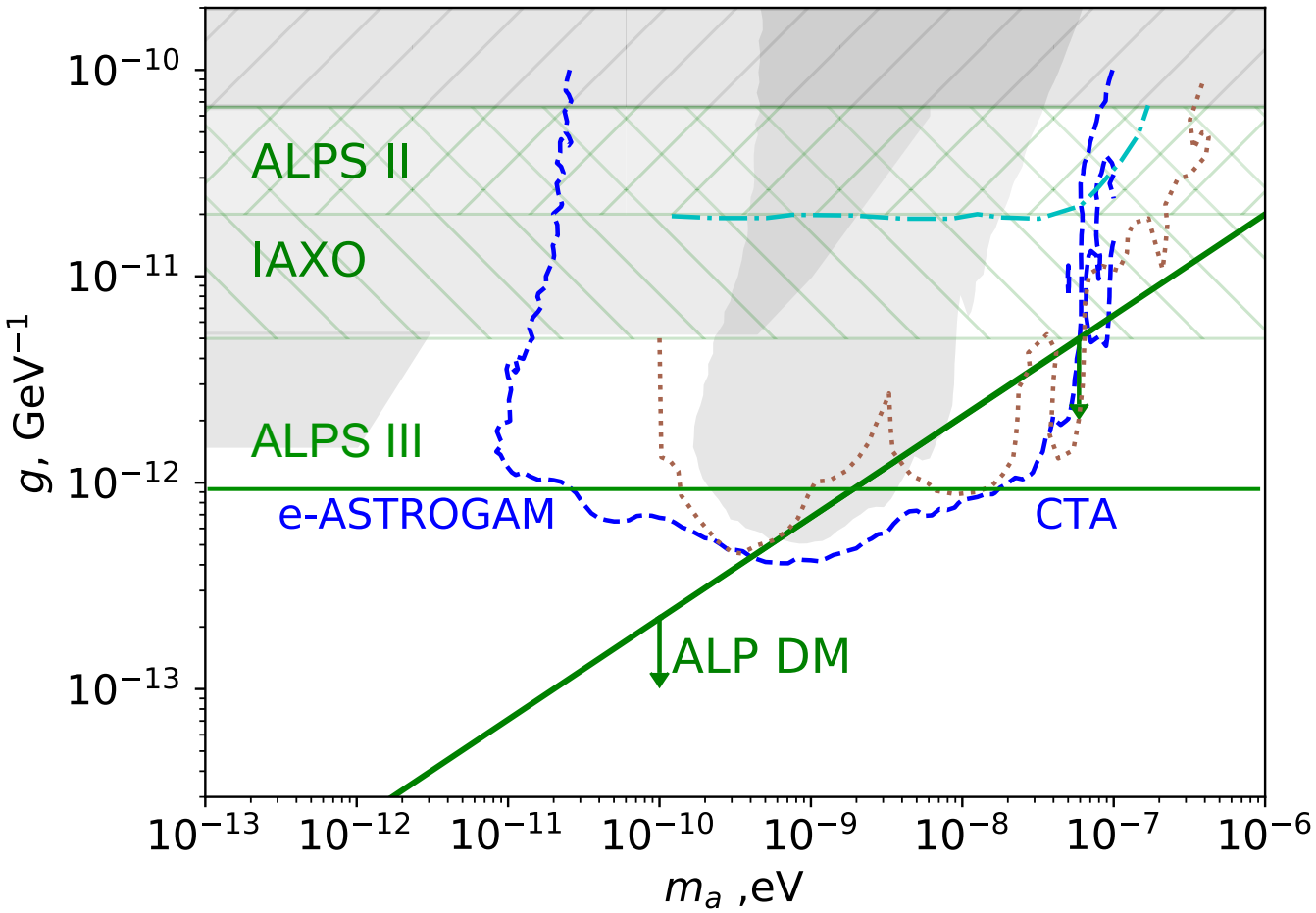
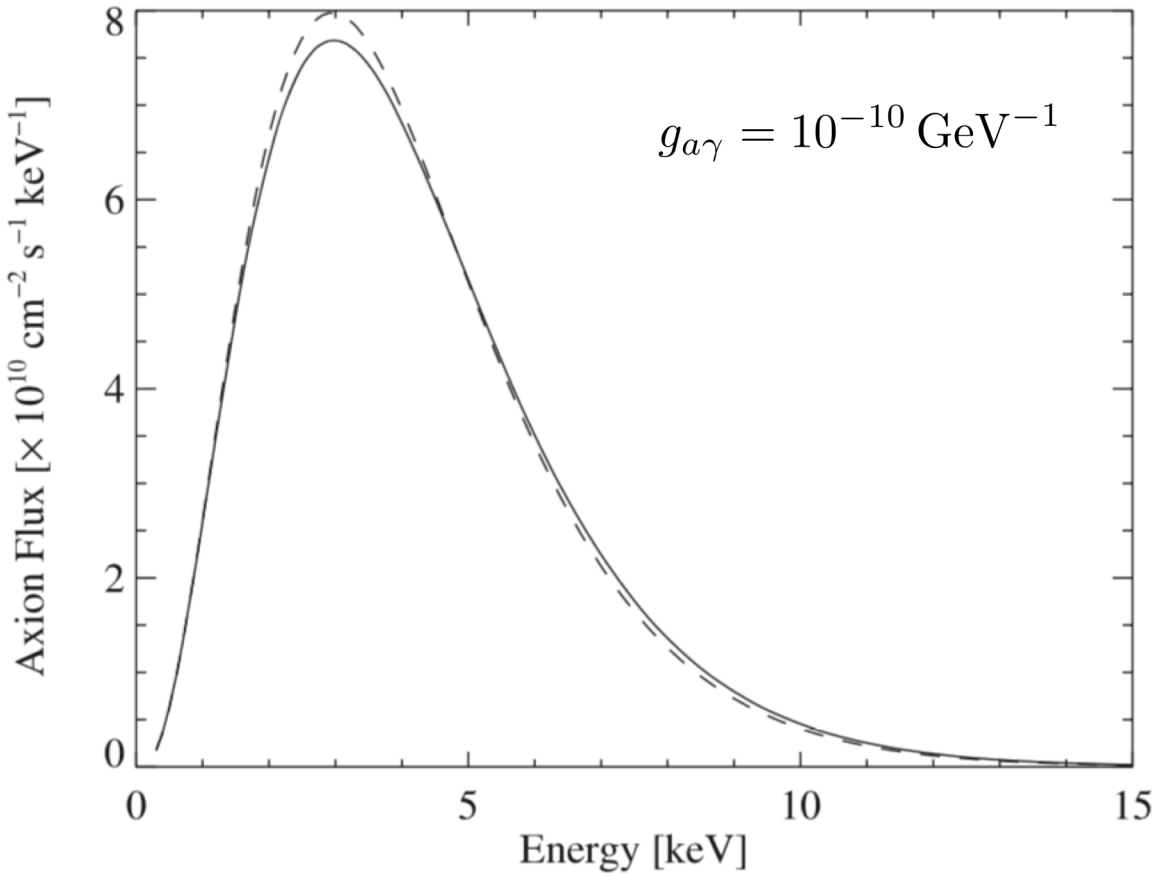
  - Competitive with future searches for ALP induced spectral features in γ-ray spectra



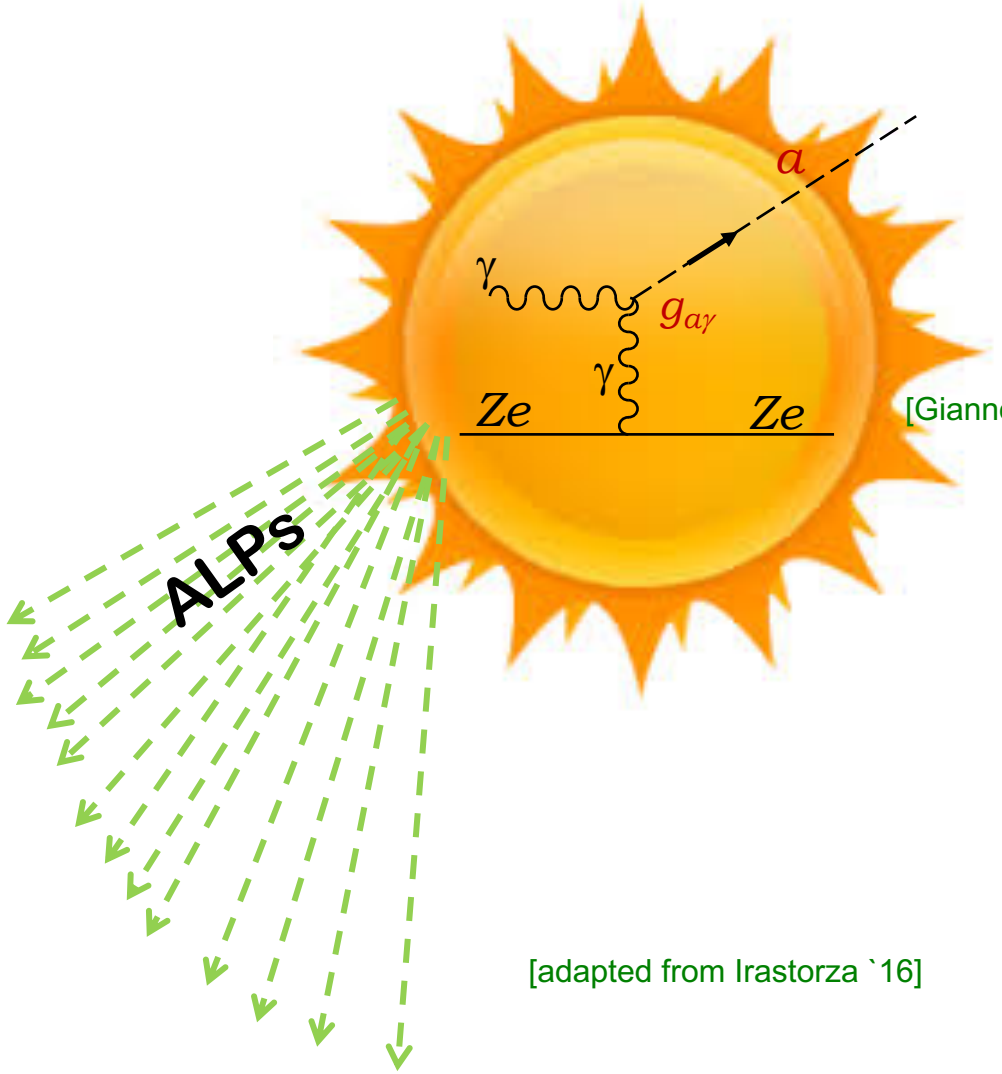
[adapted from Malyshev,Neronov,Semikoz,Santangelo,Jochum 18]

Helioscope searches

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



[Adriamonje et al. `07]

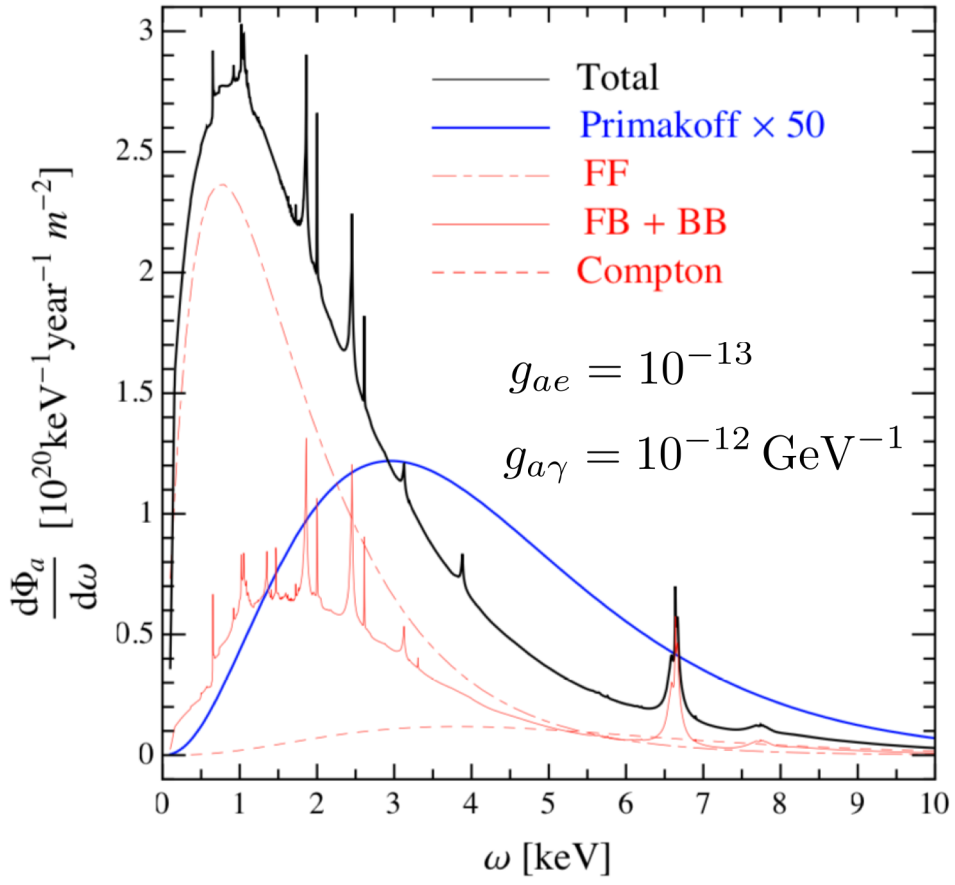


[Giannotti `16]

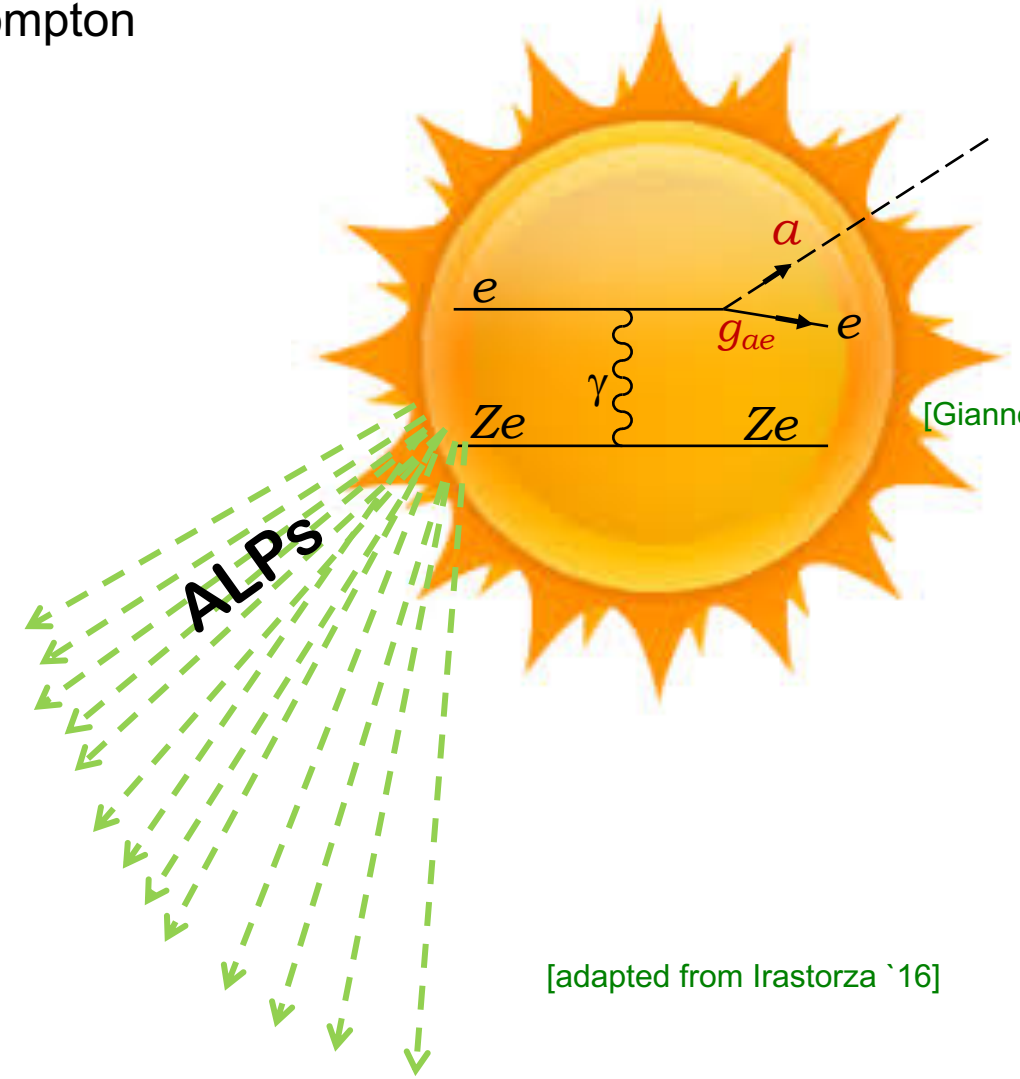
[adapted from Irastorza `16]

Helioscope searches

- If axion/ALP couples to electron, even higher flux of solar axion/ALPs produced by atomic recombination and deexcitation (FB+BB), Bremsstrahlung (FF) and Compton



[Redondo `13]



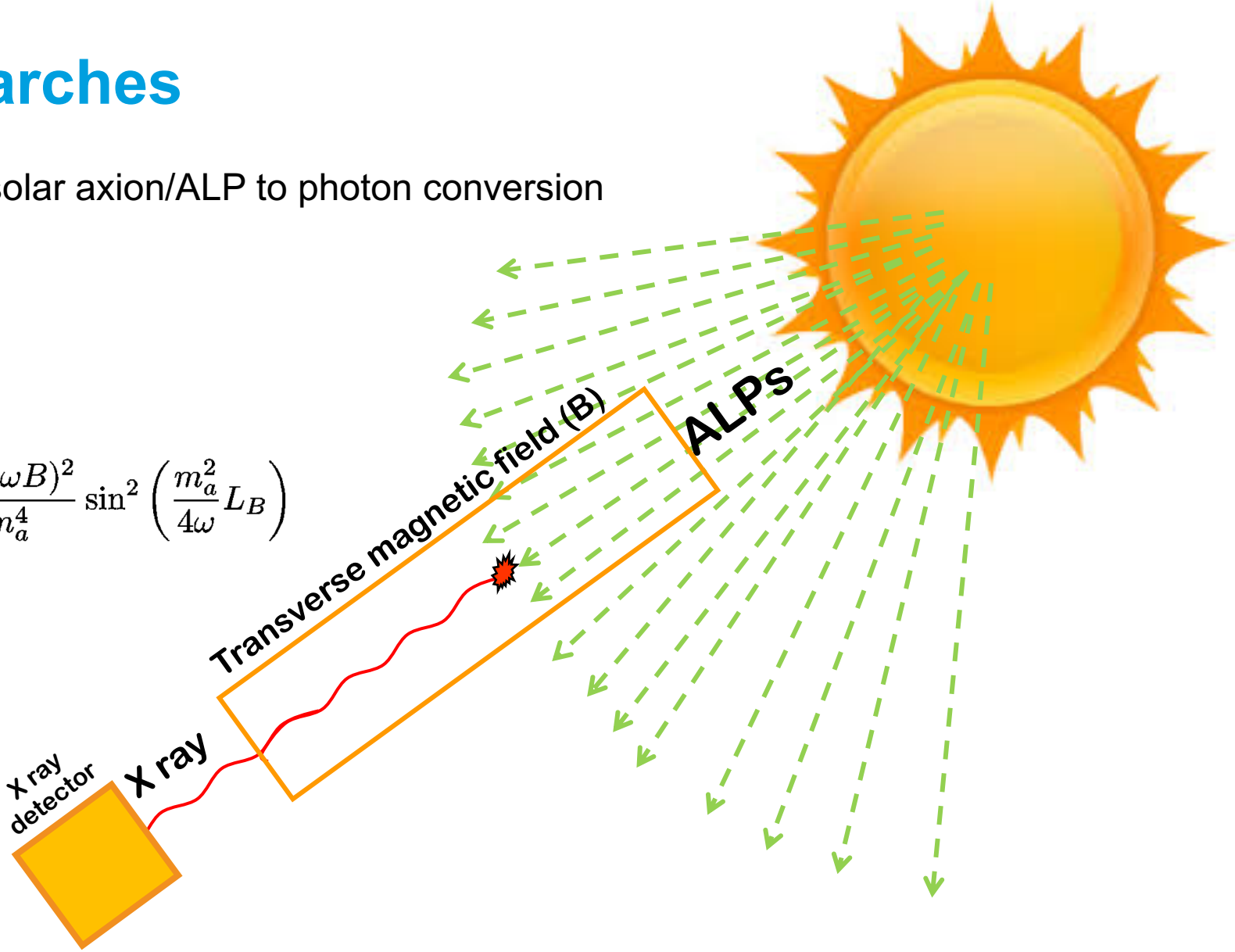
[Giannotti `16]

[adapted from Irastorza `16]

Helioscope searches

- Helioscope concept: solar axion/ALP to photon conversion in magnetic field

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



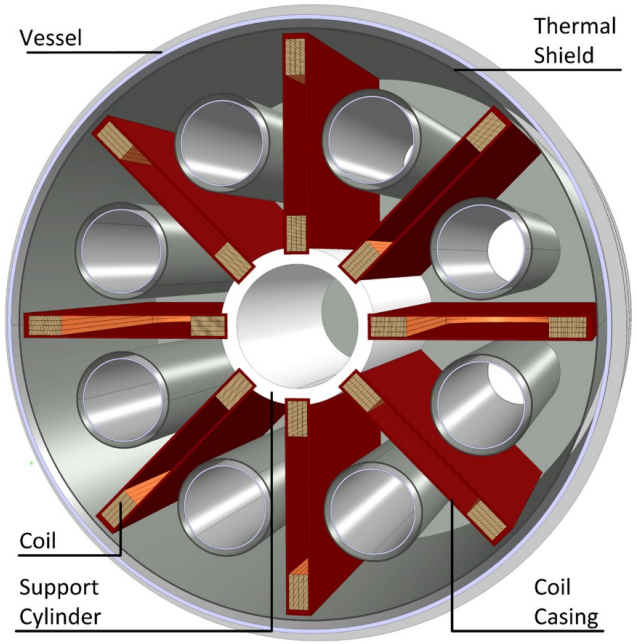
[adapted from Irastorza `16]

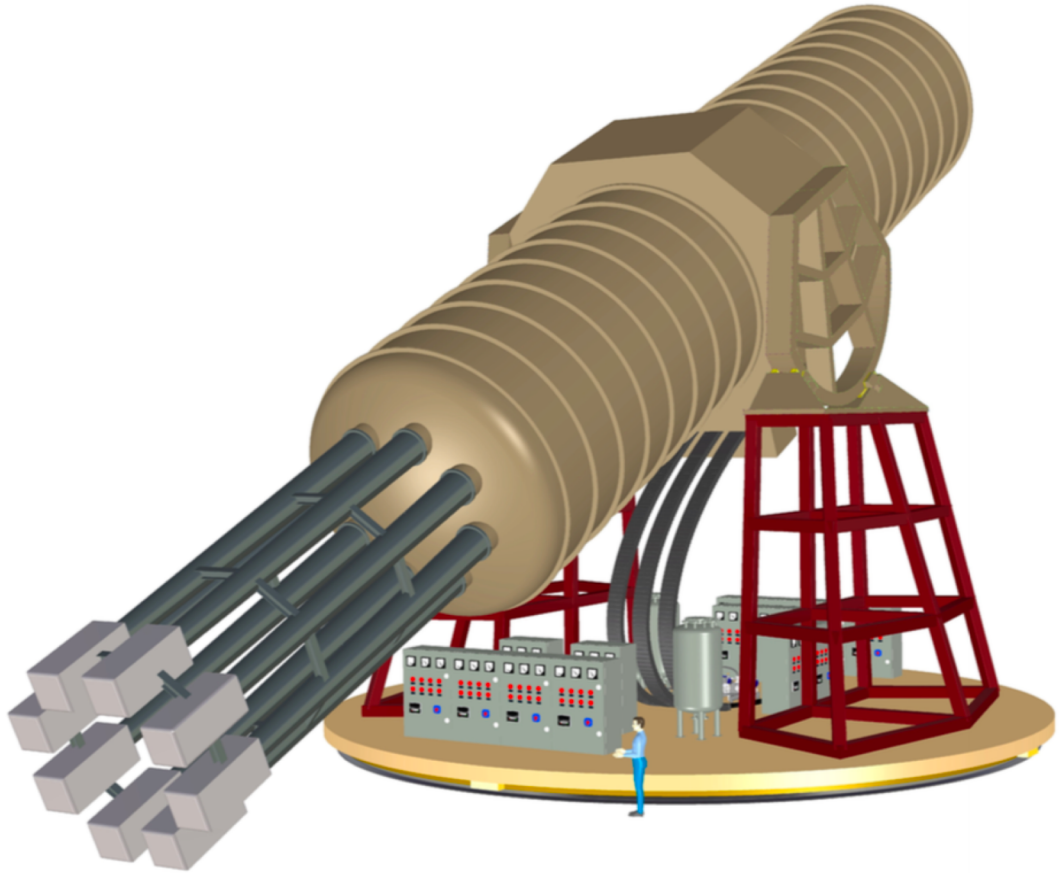
Helioscope searches

- 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

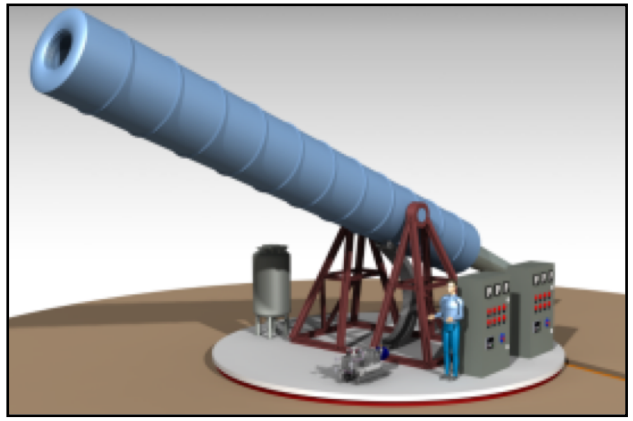
- Proposed successor: International Axion Observatory (IAXO)
  - Dedicated superconducting toroidal magnet with much bigger aperture than CAST
  - Extensive use of X-ray optics
  - Low background X-ray detectors





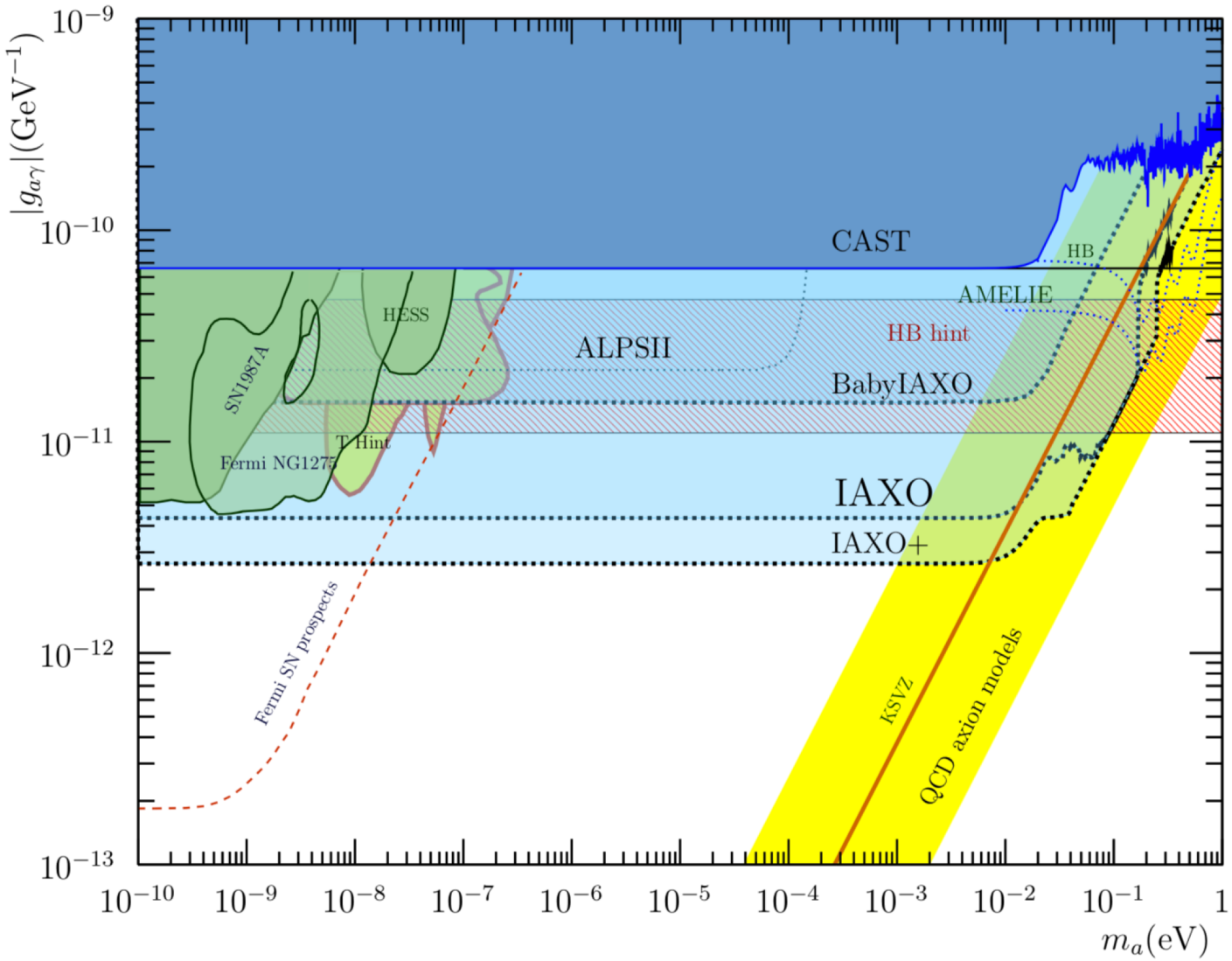
Helioscope searches

- Proposed successor: International Axion Observatory (IAXO)
  - Dedicated superconducting toroidal magnet with much bigger aperture than CAST
  - Extensive use of X-ray optics
  - Low background X-ray detectors
- Proposed site: DESY
- Timeline:
  - Prototype BabyIAXO ready in 2021
  - Several options for locations at DESY



Helioscope searches

- IAXO prospects:
  - Probes the elusive meV mass QCD axion
  - Covers most of parameter space relevant for astro hints



[Irastorza,Redondo 18]

Helioscope searches

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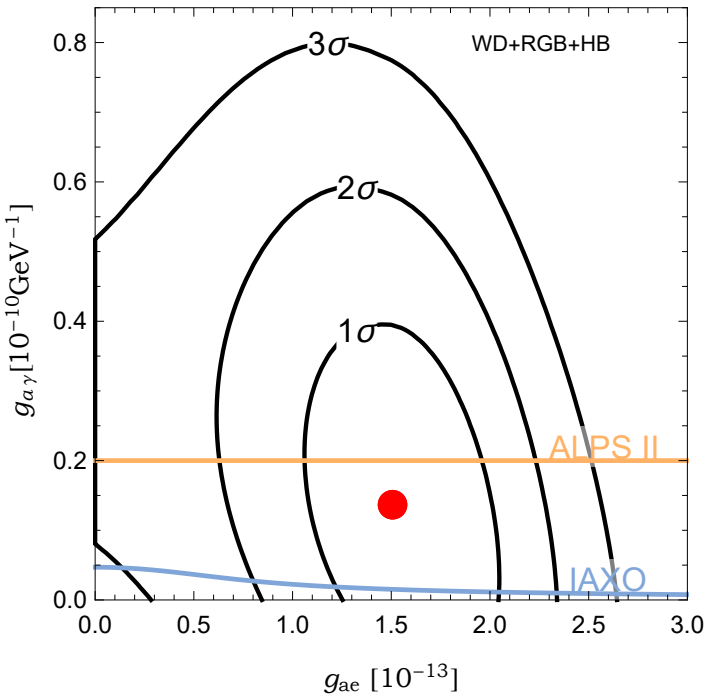
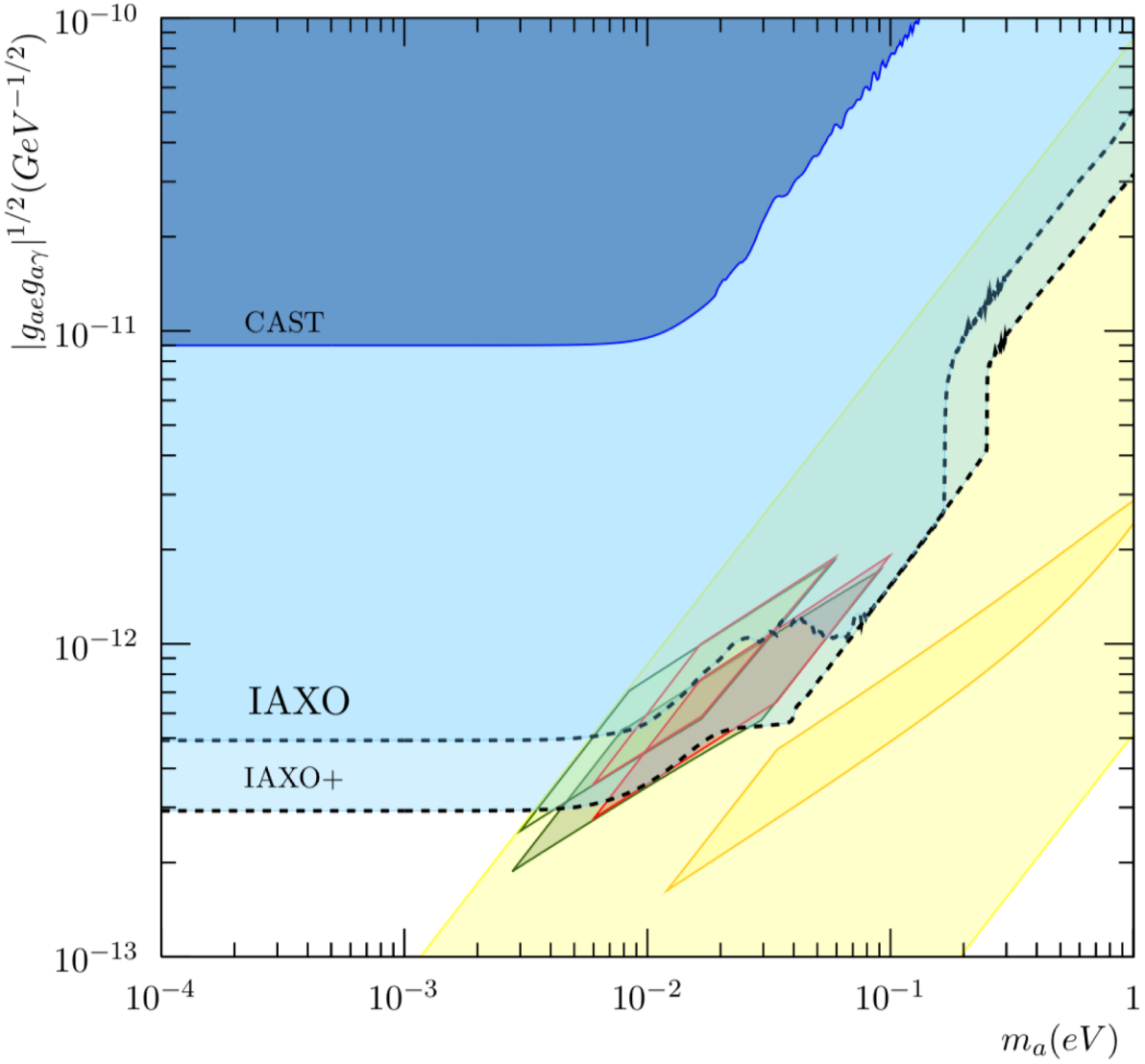
  - Also sensitive to electron coupling hinted at by stellar energy losses



[Giannotti,Irastorza,Redondo,AR,Saikawa 17]

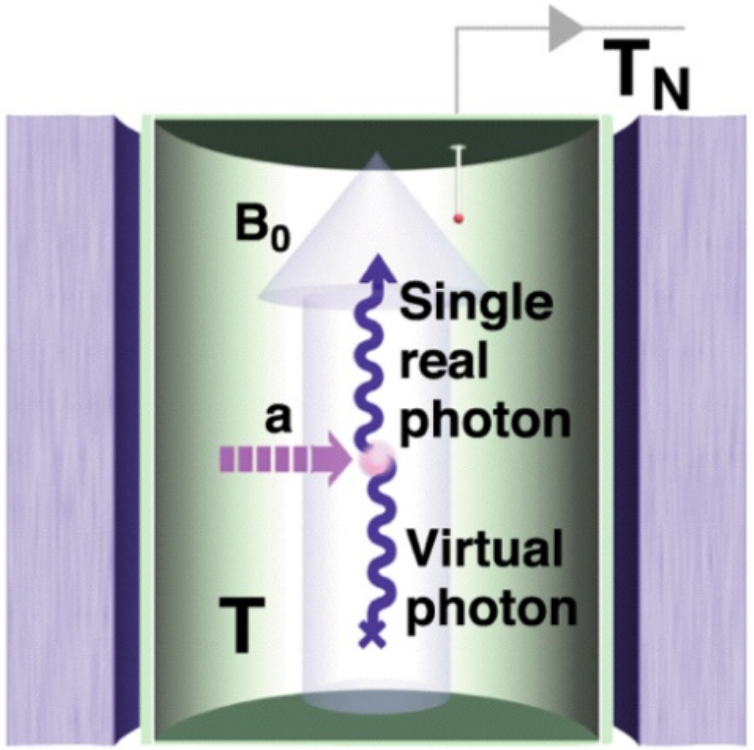


[Physics potential of IAXO, in prep.]

Haloscope searches

Microwave cavities

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

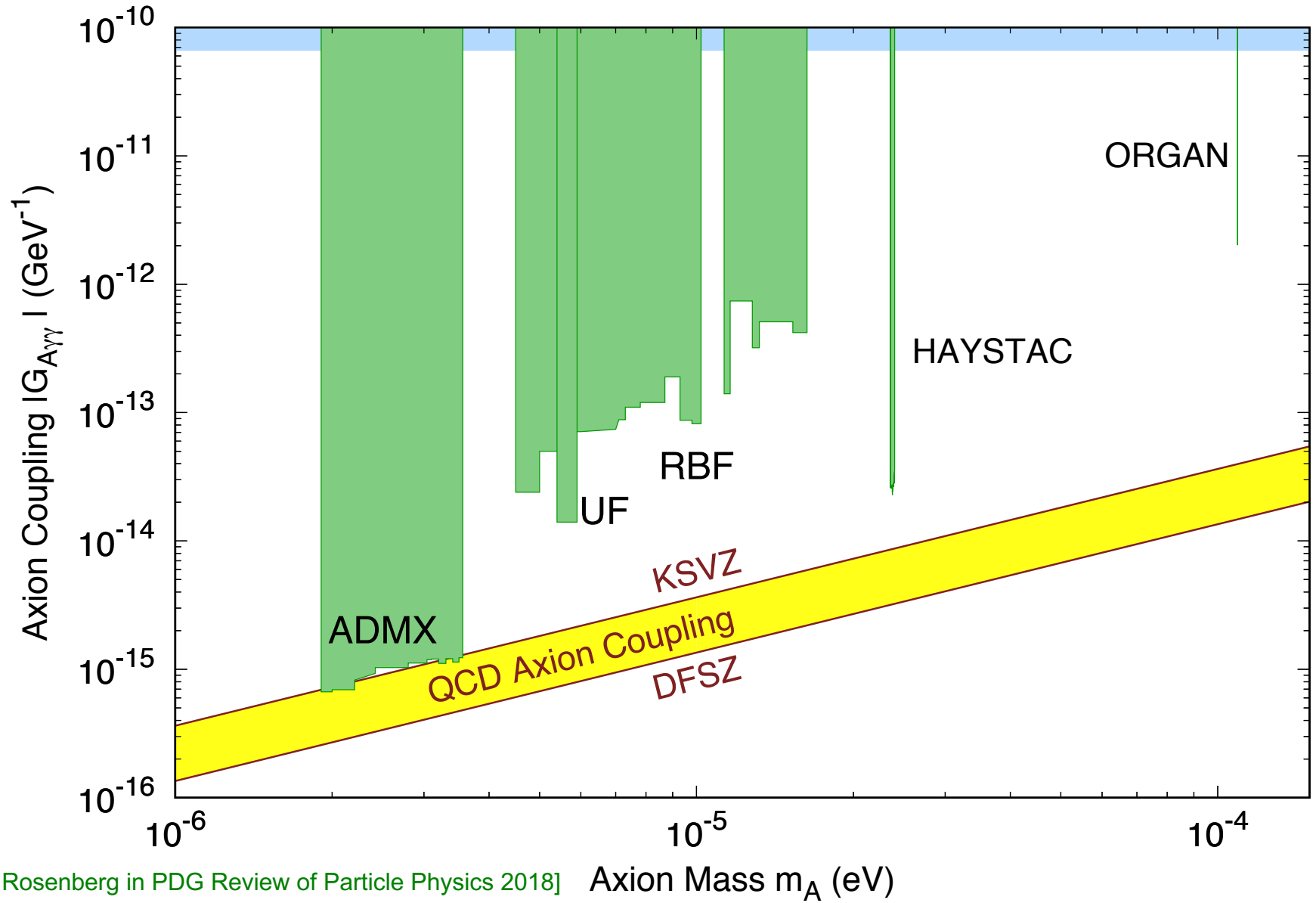


$$P_{\mathrm{out}} \sim g^2 \mid \mathbf{B}_0 \mid^2 \rho_{\mathrm{DM}} V Q / m_a$$

Haloscope searches

Microwave cavities

- Currently running:
  - ADMX
  - HAYSTAC
  - ORGAN



[AR,Rybka,Rosenberg in PDG Review of Particle Physics 2018]

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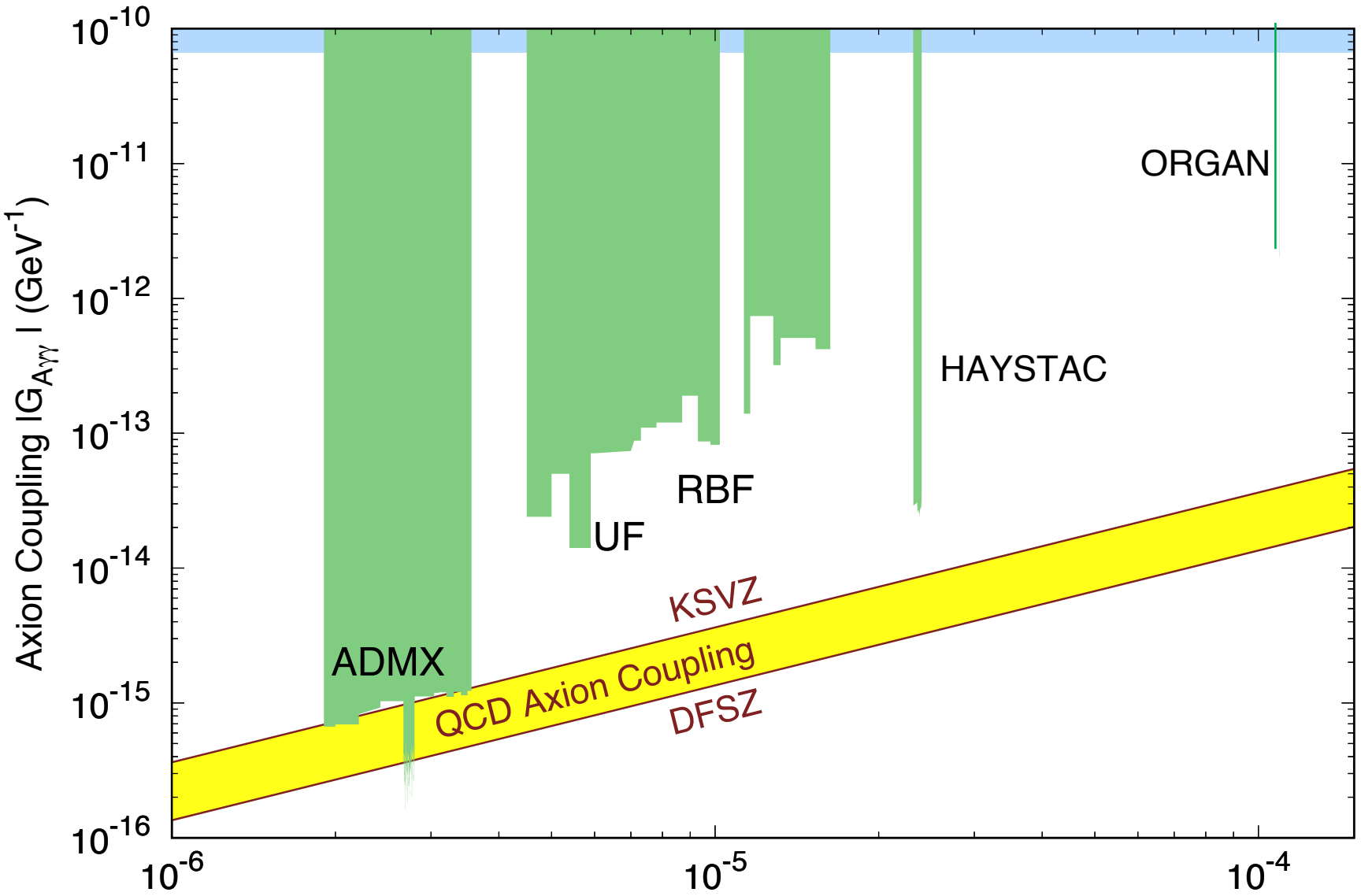
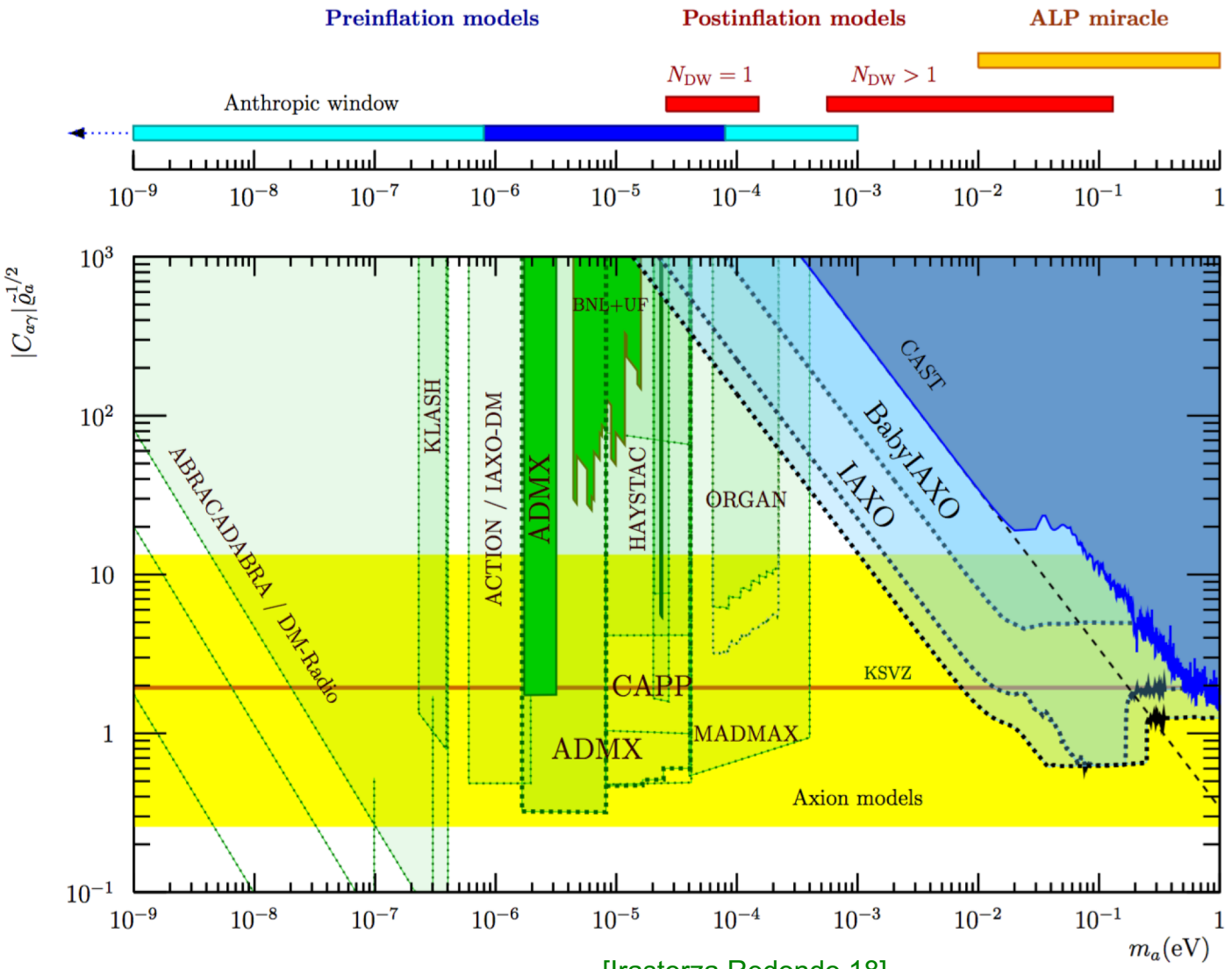


[AR,Rybka,Rosenberg in prep. for update PDG RPP 2019]

Haloscope searches

Microwave cavities

- Currently running:
  - ADMX
  - HAYSTAC
  - ORGAN
- Currently in construction:
  - CULTASK (at CAPP in South Korea)
- Proposed:
  - KLASH (Frascati)
  - ACTION (at CAPP in South Korea)
  - IAXO-DM
- Axion DM searches with microwave cavities may cover $0.3\,\mu\mathrm{eV} \lesssim m_a \lesssim 30\,\mu\mathrm{eV}$
- Need other techniques in remaining mass range

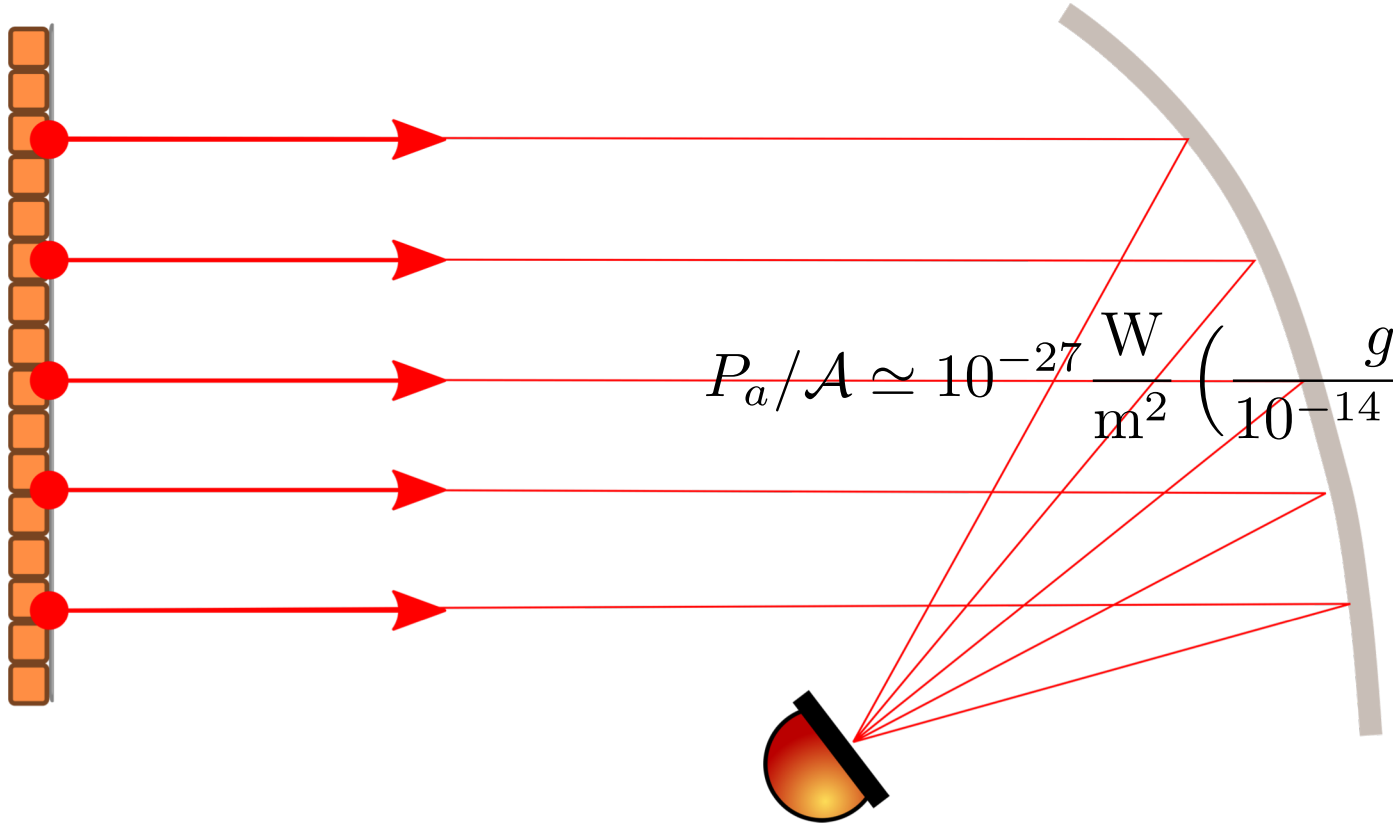


[Irastorza,Redondo 18]

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

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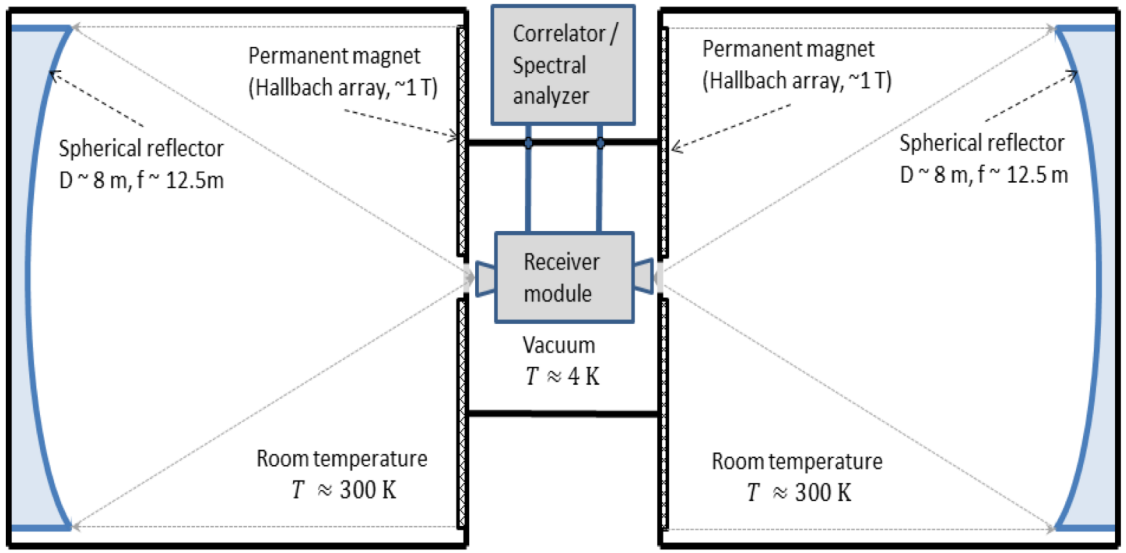
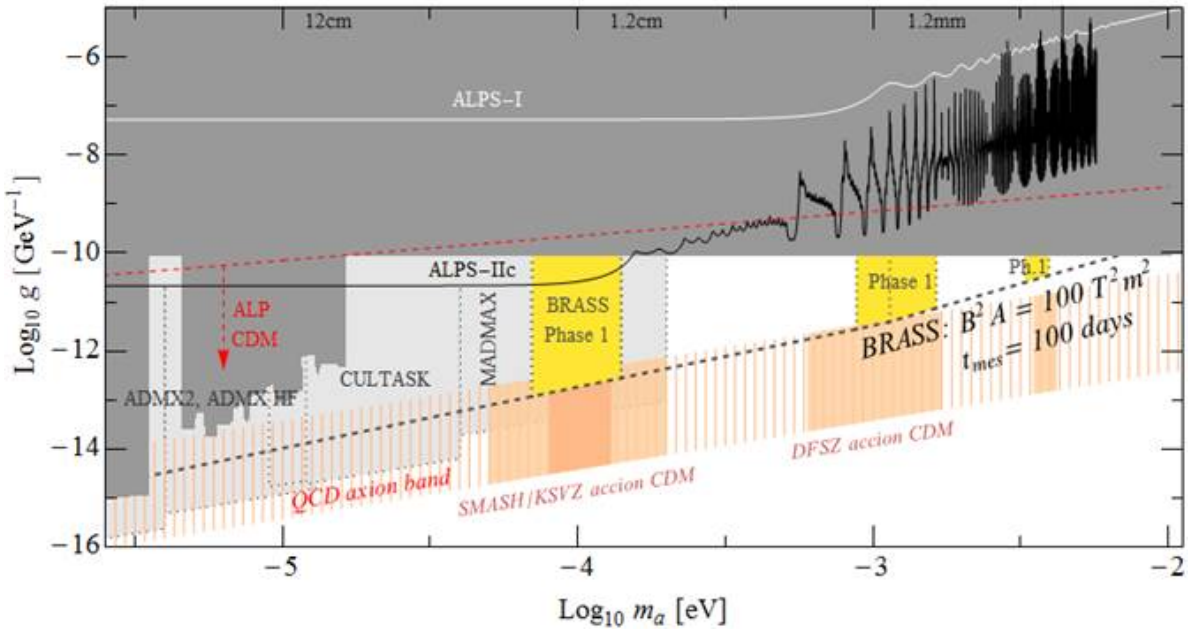
- A magnetised mirror in axion/ALP DM background radiates photons [Horns,Jaeckel,Lindner,Lobanov,Redondo,AR 13]
- Proposed axion/ALP DM dish antenna experiment: BRASS (U Hamburg) [Hidden photon DM: FUNK (KIT)] [Engel et al.]





[Horns et al. (unpublished)]

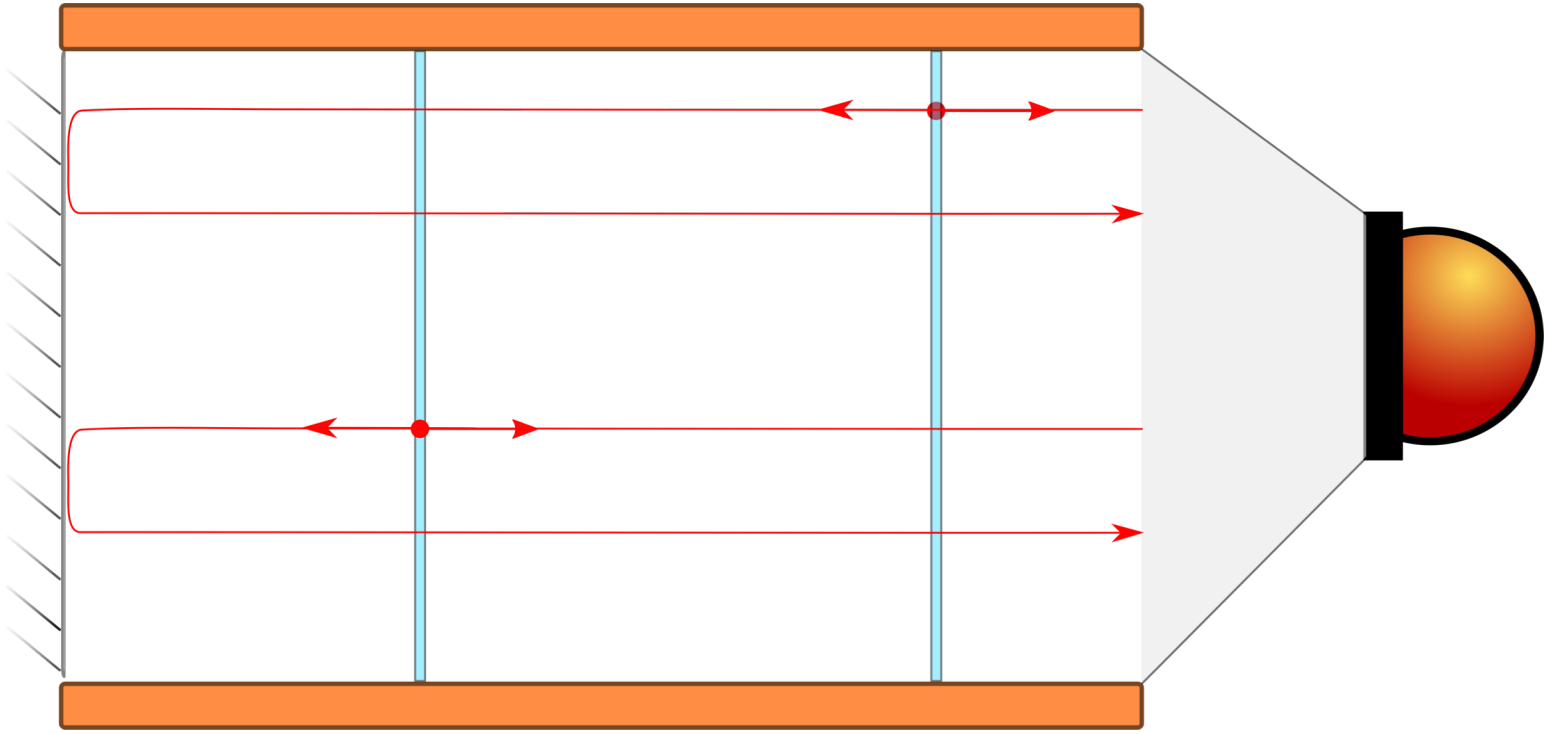
Haloscope searches

Dish antennas

- Boosted dish antenna: Open dielectric resonator
  - Add stack of dielectric disks in front of mirror (all immersed in magnetic field)
  - May achieve constructive interference of photon part of wave function

[Jaeckel,Redondo 13]

[Millar,Raffelt,Redondo,Steffen 16]

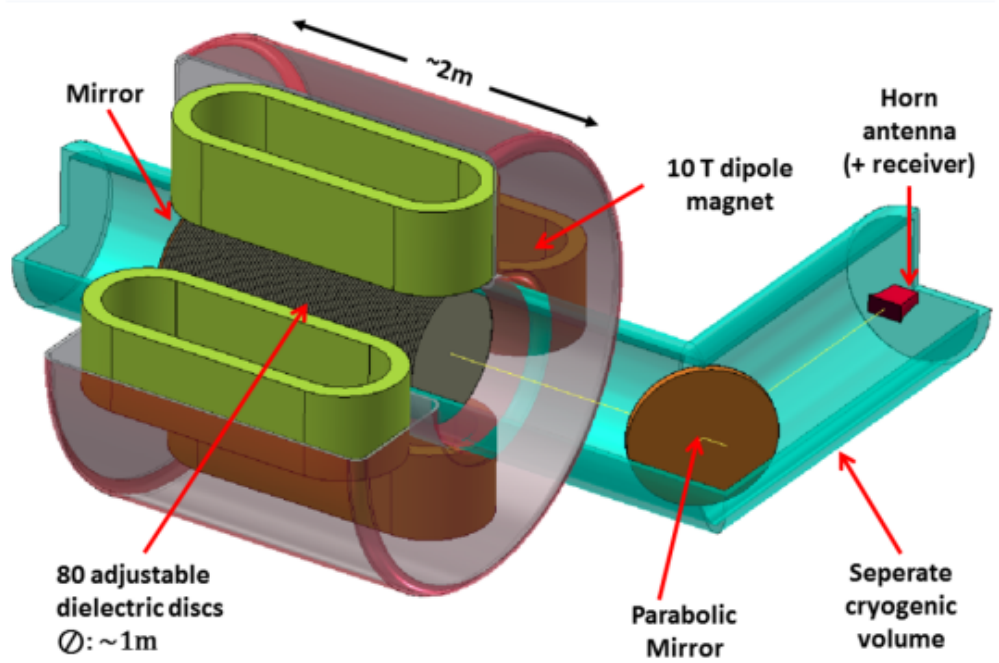


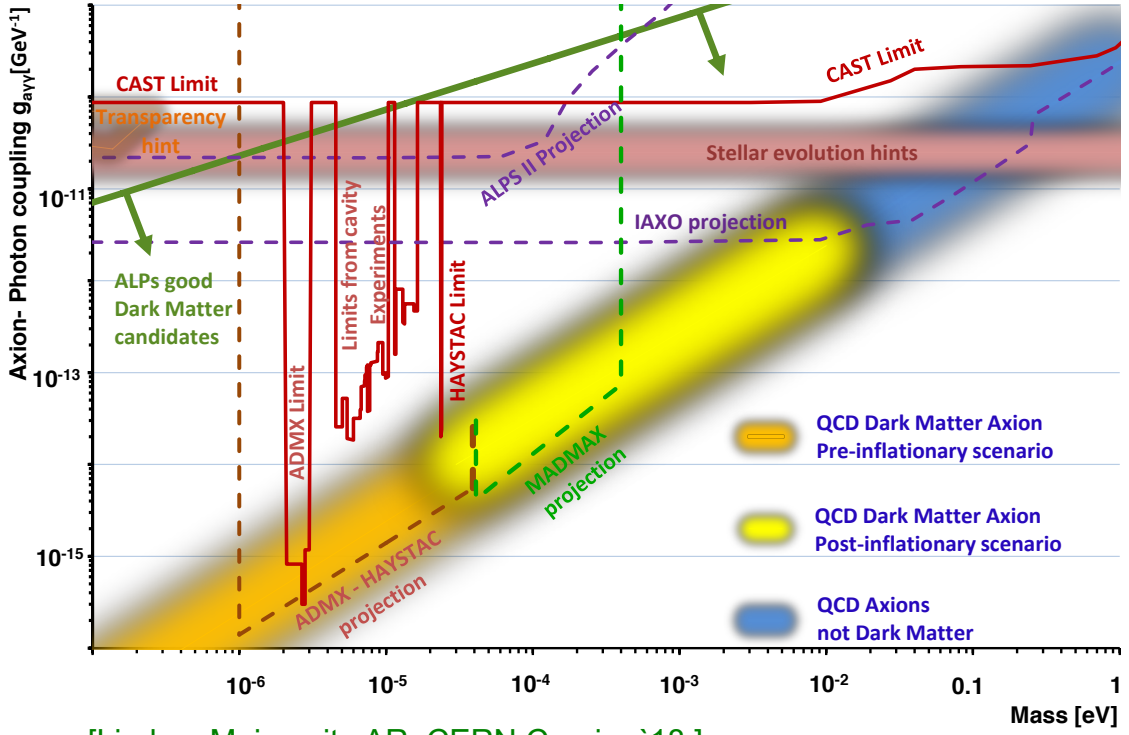
Haloscope searches

Dish antennas

- Boosted dish antenna: Proposed MADMAX experiment

[Caldwell et al. `16]





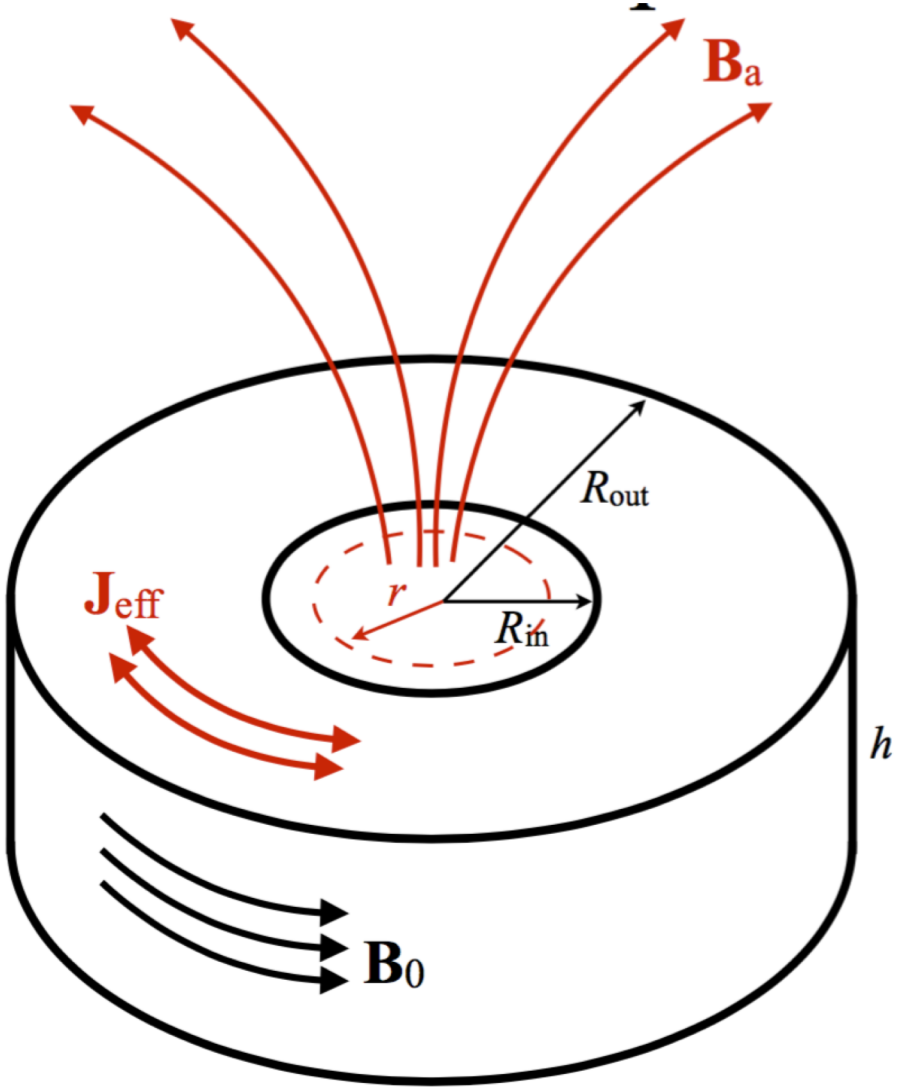
[Lindner,Majorovits,AR CERN Courier `18]

- Sensitive for axion DM in post-inflationary PQ symmetry breaking scenario
- Site: HERA Hall North next to ALPS II at DESY; prototype ready in 2021

Haloscope searches

Low frequency resonators with LC circuits

- Exploit toroidal magnet with fixed magnetic field:
  - Axion/ALP DM generates oscillating effective current around ring
  - ... this generates oscillating magnetic field through center
  - ... this can be detected by pickup loop



[Ouellet `16; adapted from Kahn,Safdi,Thaler `16]

Haloscope searches

Low frequency resonators with LC circuits

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  - Axion/ALP DM generates oscillating effective current around ring
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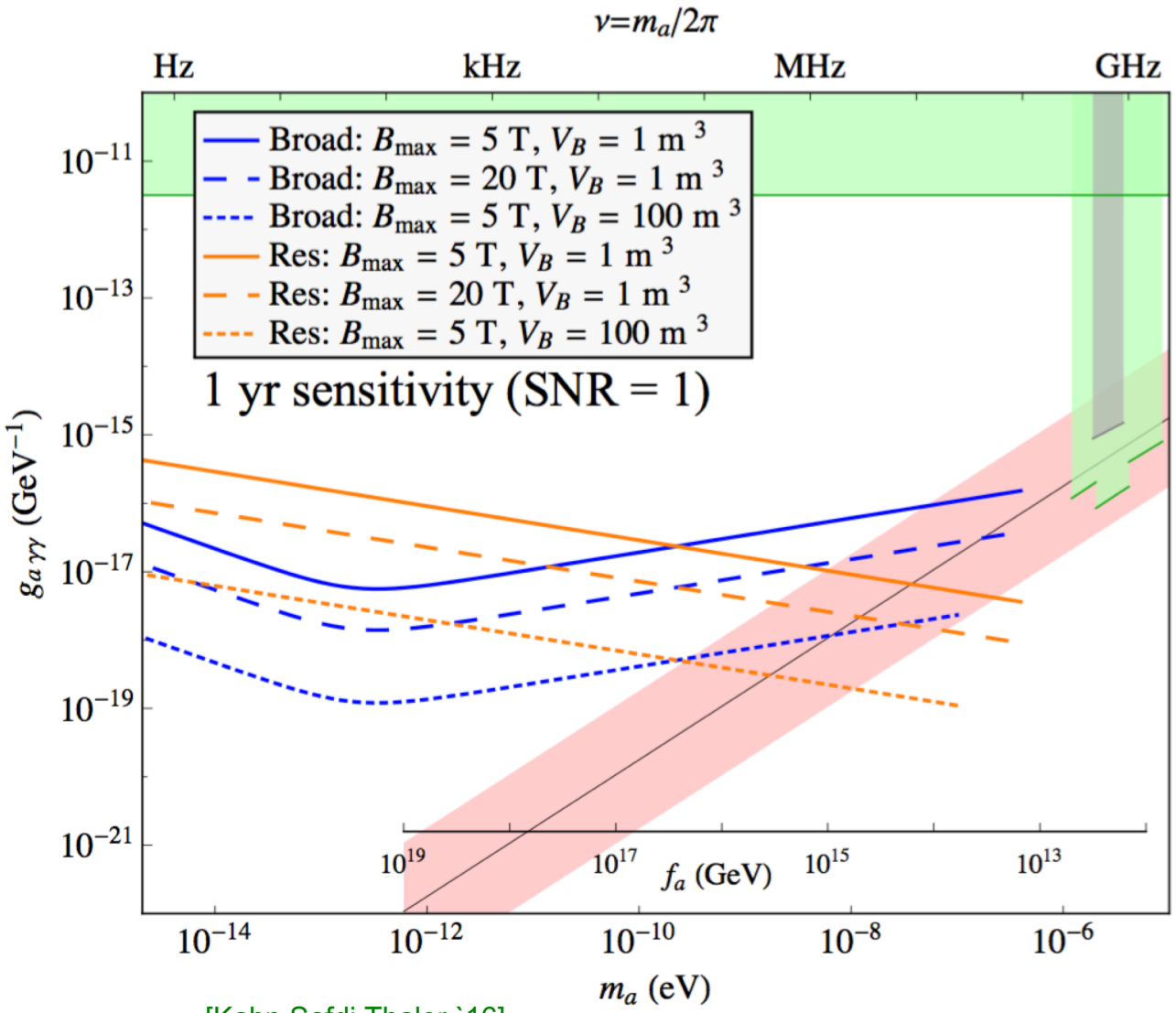
- ABRACADABRA (MIT) currently being set-up
  - Projected sensitivity:
    - Probe QCD axion dark matter in mass range

$$0.1\,\mathrm{neV} \lesssim m_a \lesssim \mu\mathrm{eV}$$



[Kahn,Safdi,Thaler `16]

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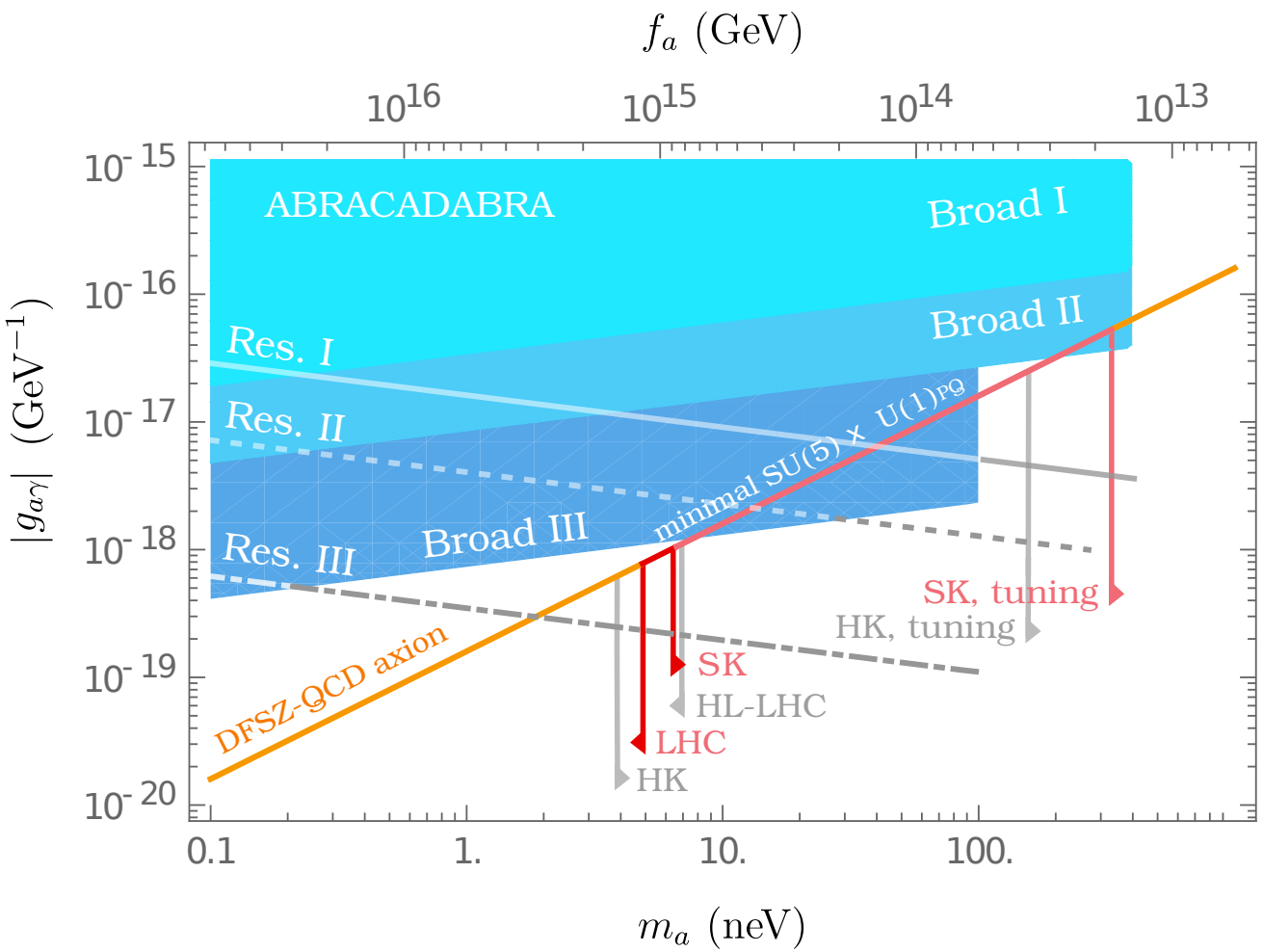
    - Probe of axion predictions in
      - $SO(10) \times U(1)_{\mathrm{PQ}}$ GUT [Ernst,AR,Tamarit 18]
      - $SU(5) \times U(1)_{\mathrm{PQ}}$ GUT [Di Luzio,AR,Tamarit 18]
- DM-Radio (Stanford): similar experiment in path-finder status [Silva-Feaver et al. 16]



[Di Luzio,AR,Tamarit 18]

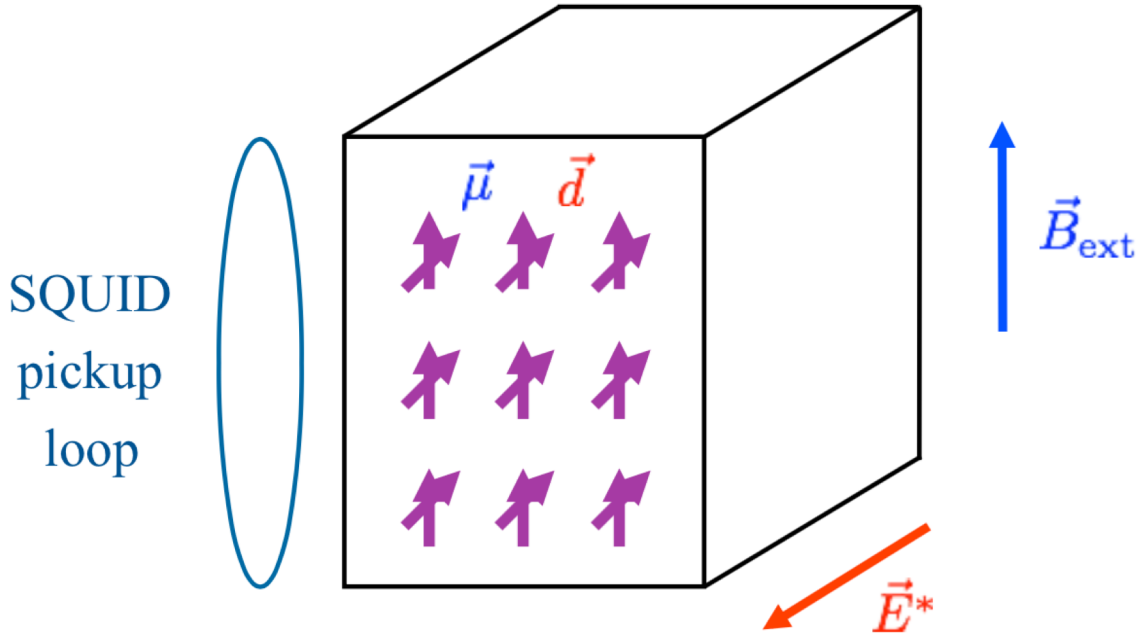
Haloscope searches

Magnetic resonance searches

- Axion/ALP DM field induces oscillating NEDMs:

$$d_N(t) = g_{aD}\, a_{\rm DM}(t) \approx g_{aD}\sqrt{2\rho_{\rm DM}}\cos(m_a t)/m_a$$

- Place a ferroelectric crystal (permanent electric polarisation fields $\vec{E}^*$) in an 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 the transverse magnetisation of the sample when the Larmor frequency equals equals the axion mass,



[Budker et al. 14]

$$M_\perp(t) \approx \frac{g_{aD}\sqrt{2\rho_{\rm DM}}}{m_a} p\, n_N \mu_N E^* \epsilon_S \frac{\sin\left[(2\mu_N B_{\rm ext} - m_a)\, t\right]}{2\mu_N B_{\rm ext} - m_a} \sin\left(2\mu_N B_{\rm ext} t\right)$$

- p spin polarisation fraction,
- n_N spin density

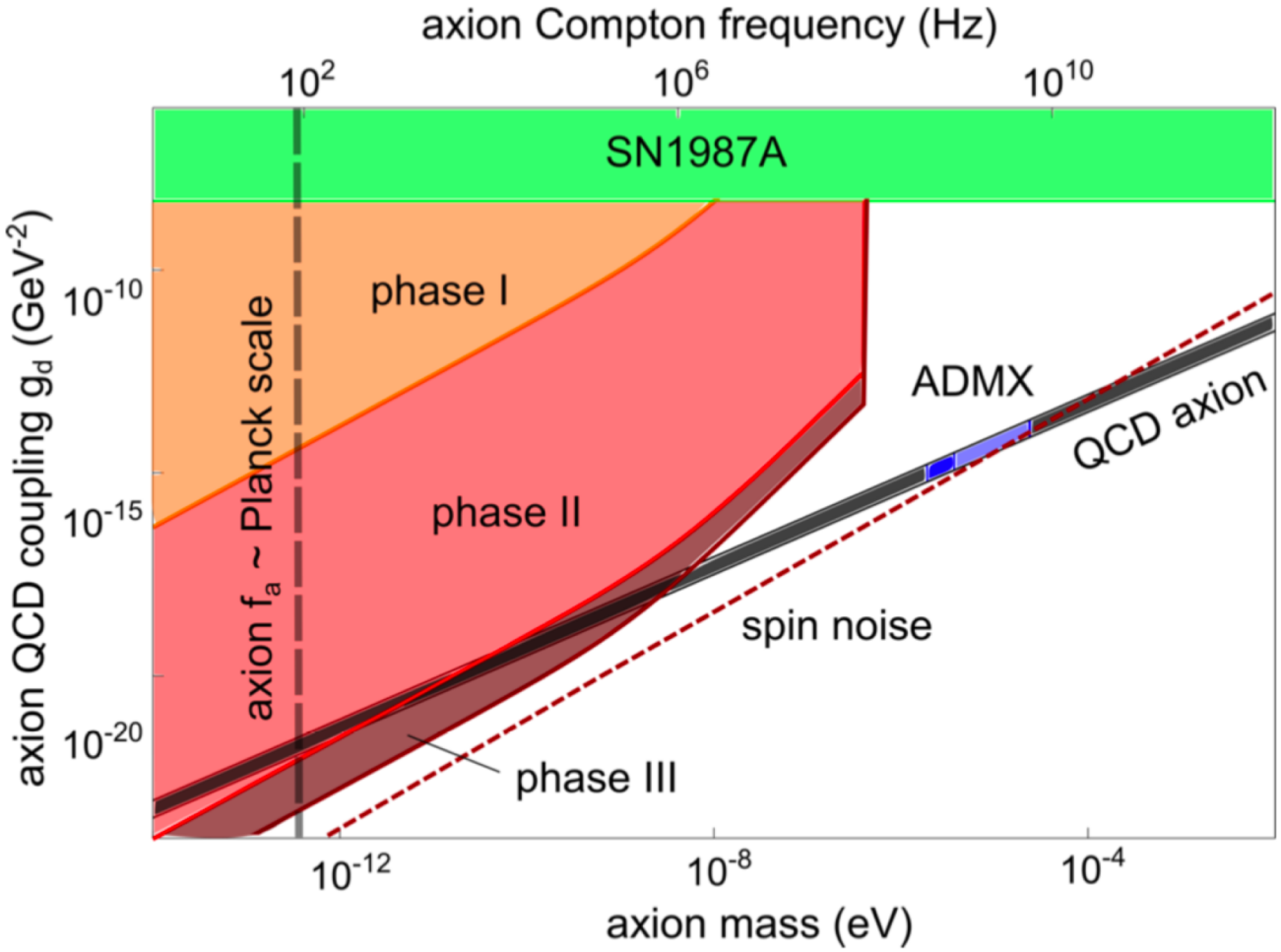
[Graham,Rajendran 13; Budker et al. 14]

Haloscope searches

Magnetic resonance searches

- CASPEr-Electric currently being set-up in Boston
  - A signal corresponding to the NEDM coupling strength of the QCD axion would establish that the detected DM particle is not only axion-like, but that it solves the strong CP problem (since it couples like the theta parameter of QCD to the NEDM)
  - Aims to probe QCD axion dark matter in mass range

$$m_A \lesssim 10^{-8}\,\mu\mathrm{eV}$$



[Jackson Kimball et al. 17]

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  - Allows to probe predictions of GUTs:
    - $SO(10) \times U(1)_{\mathrm{PQ}}$ GUT [Ernst,AR,Tamarit 18]
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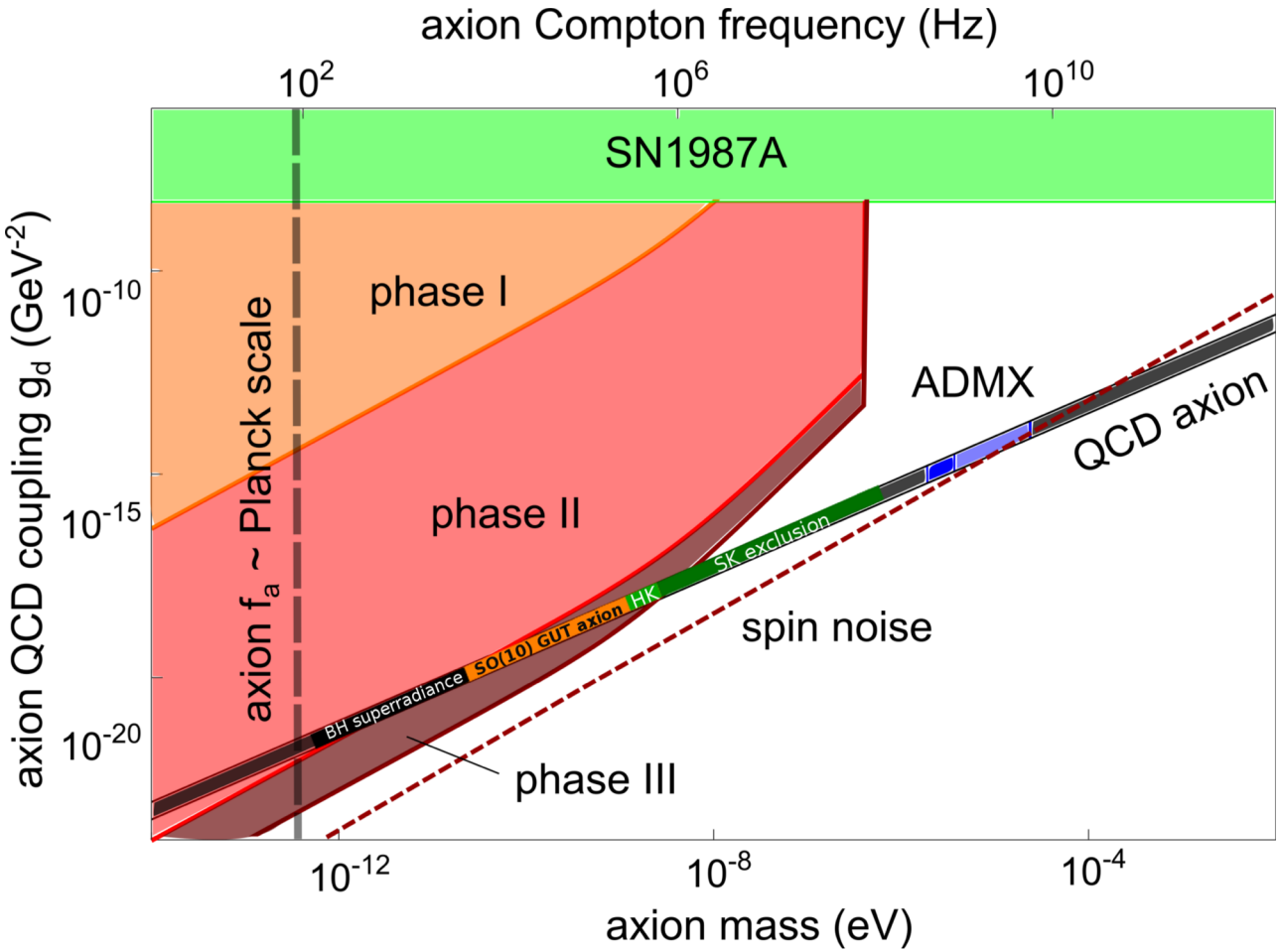


[Ernst 18; adapted from Kimball et al. 17]

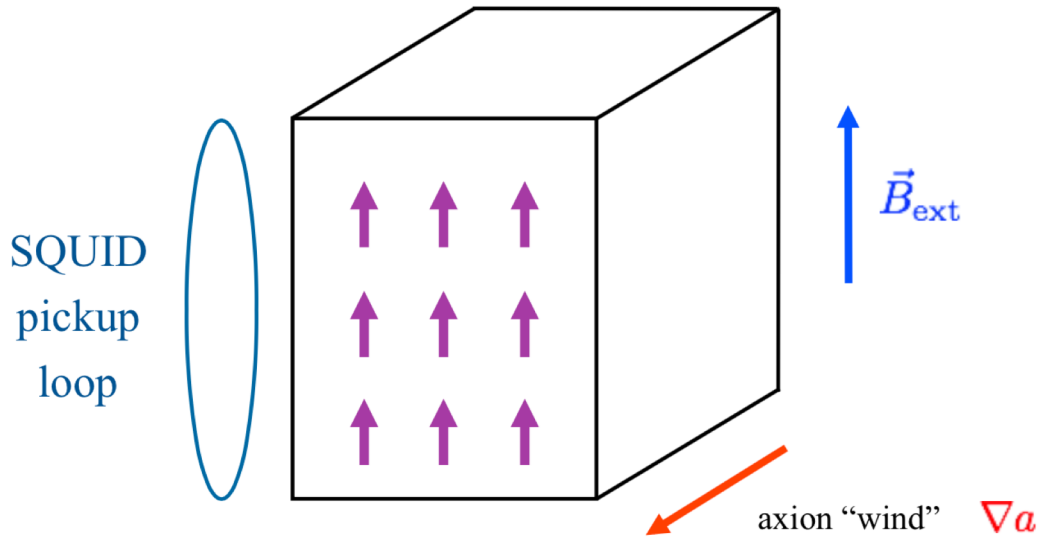
Haloscope searches

Magnetic resonance searches

- Axion/ALP nucleon (electron coupling) leads to nucleon (electron) spin precession about galactic axion/ALP DM wind
- MRT search for transverse magnetization due to precession of nuclear (electron spins) in polarized sample in DM wind

$$M_\perp(t) \approx g_{aNN}\sqrt{2\rho_{\rm DM}}\, v\, p\, n_N \mu_N \frac{\sin\left[\left(2\mu_N B_{\rm ext} - m_a\right) t\right]}{2\mu_N B_{\rm ext} - m_a} \sin\left(2\mu_N B_{\rm ext} t\right)$$

[Graham,Rajendran 13]



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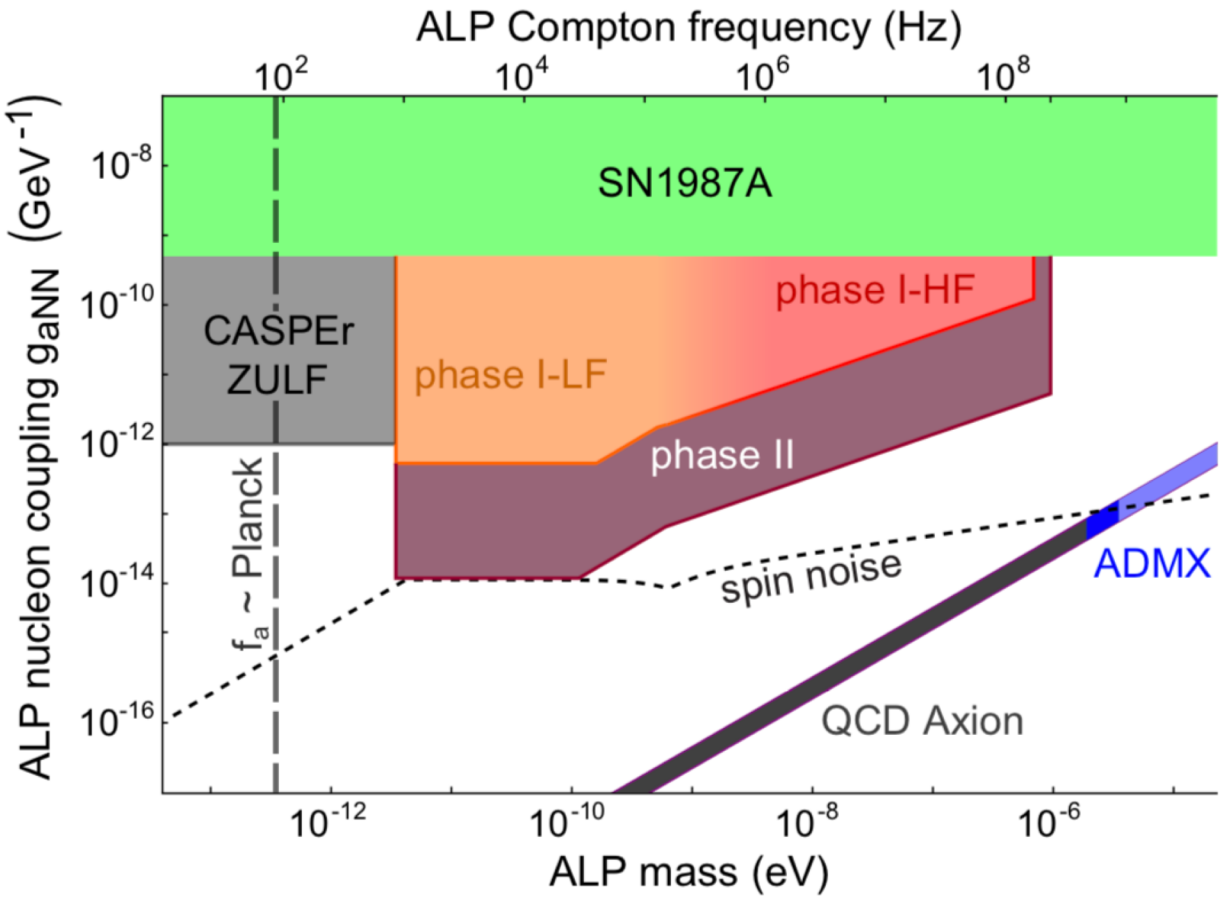
[Graham,Rajendran 13]

- CASPEr-Wind currently set-up at HMI Mainz [Budker et al.]
  - Projected sensitivity:
    - Probe ALP dark matter in mass range

$$\text{peV} \lesssim m_a \lesssim \text{neV}$$



[Jackson Kimball et al. 17]

- QUAX (Legnaro): electron spin precession $(\mu_e/\mu_N \sim m_N/m_e \sim 2000)$ [Barbieri et al. 17]

Conclusions

- Boom in axion/ALP searches!
- Large parts in axion/ALP parameter space will be tackled in the upcoming decade by a number of terrestrial experiments:
  - Light-shining-through-a-wall experiments (ALPS II, ...)
  - Helioscopes (IAXO, ...)
  - Haloscopes (ABRACADABRA, BRASS, ADMX, CASPEr, CULTASK, HAYSTAC, MADMAX, ORGAN, QUAX, ...)

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- If 100 % of DM consists of QCD axions, one of the haloscopes will see a signal in the upcoming decade!

STAY TUNED!

Back-up: Search for axion/ALP-mediated forces

- ARIADNE: Experiment based on precision magnetometry to search for axion/ALP-mediated spin-dependent forces; set-up in Reno
- Combining techniques used in NMR and short-distance tests of gravity [Arvanitaki, Geraci 14]

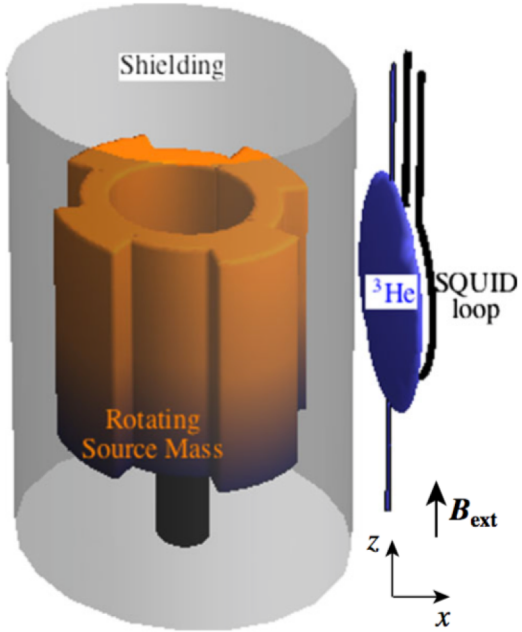

FIG. 1 (color online). A source mass consisting of a segmented cylinder with n sections is rotated around its axis of symmetry at frequency ω_{rot}, which results in a resonance between the frequency $\omega = n\omega_{rot}$ at which the segments pass near the sample and the resonant frequency $2\vec{\mu}_N \cdot \vec{B}_{ext}/\hbar$ of the NMR sample. Superconducting cylinders screen the NMR sample from the source mass and (not shown) the setup from the environment.

[Arvanitaki, Geraci 14]

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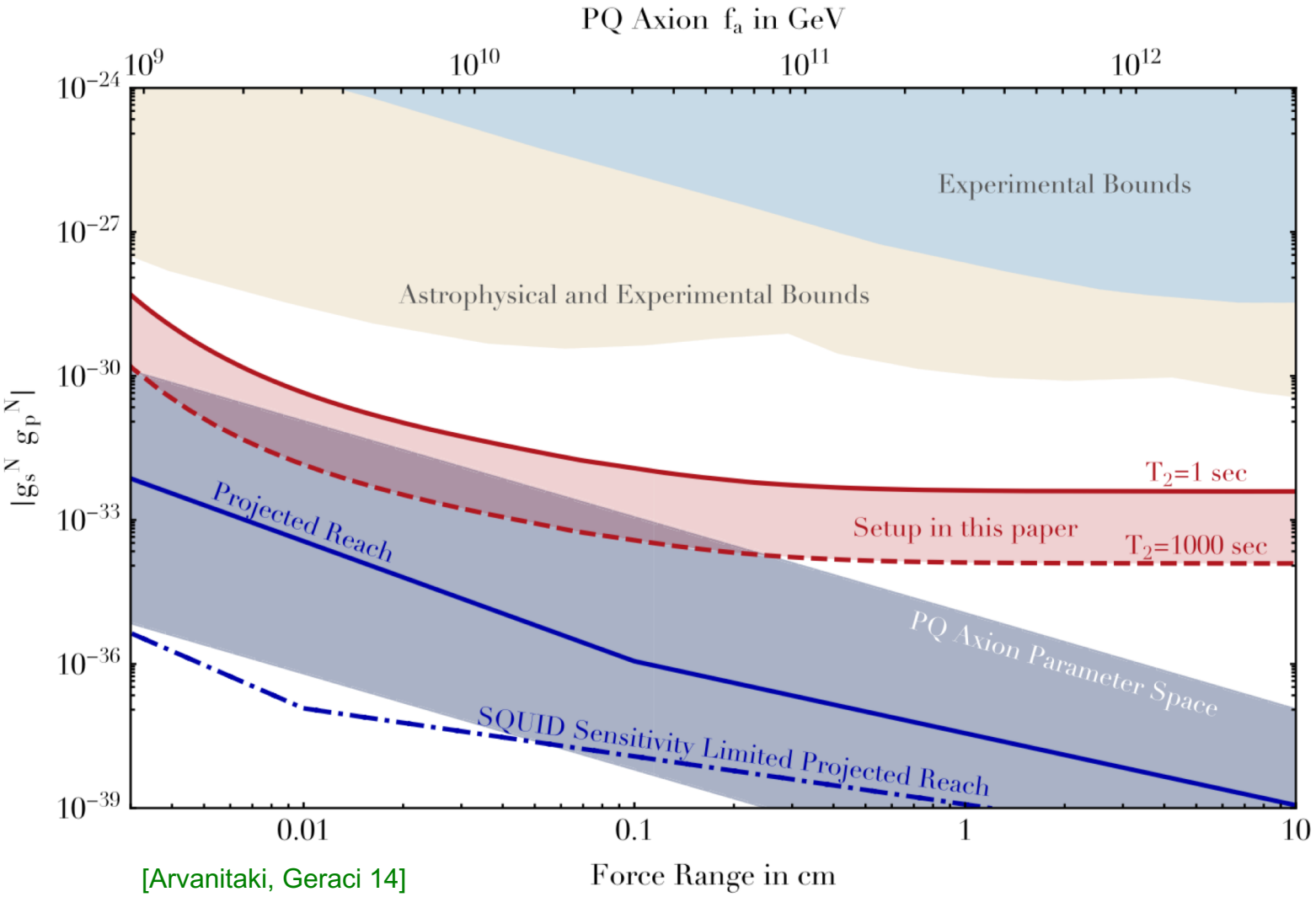

[Arvanitaki, Geraci 14]

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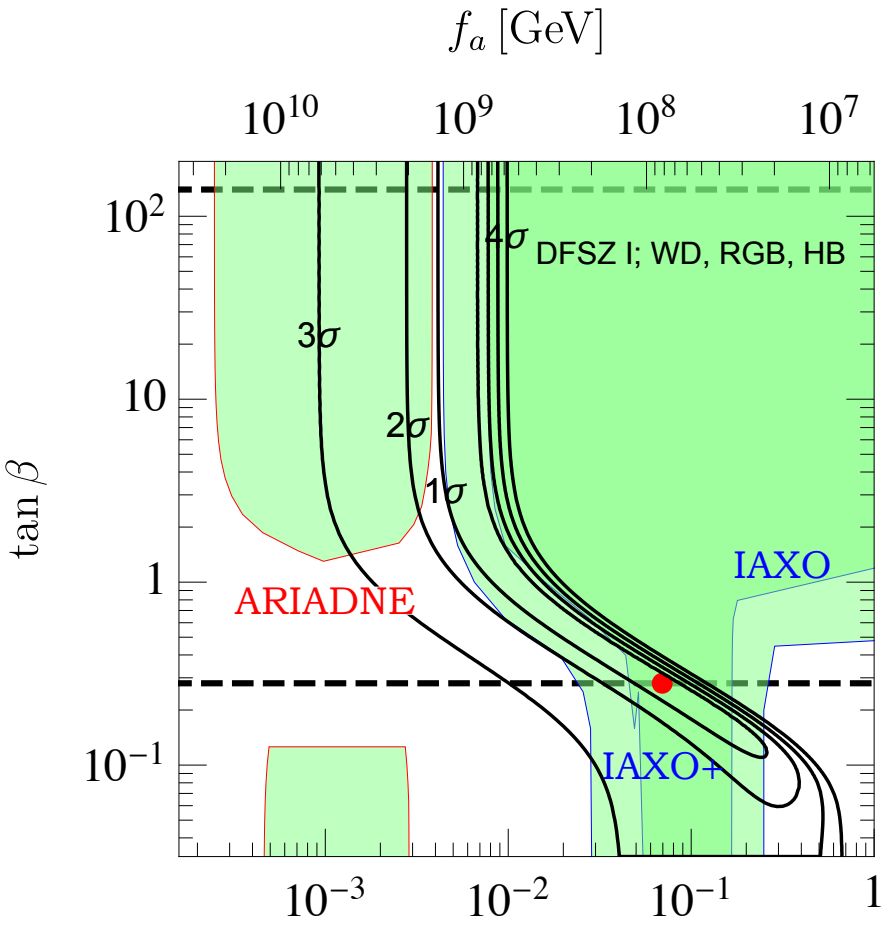
- Can probe QCD axion interpretation of cooling anomaly of WDs, RGB and HB stars complementary to IAXO

[Giannotti,Irastorza,Redondo,AR,Saikawa 17]



[Giannotti,Irastorza,Redondo,AR,Saikawa 17]