Searches for Axions and Axion-Like Particles

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International Symposium on
Revealing the History of the Universe With Underground Particle and Nuclear Research 2019
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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

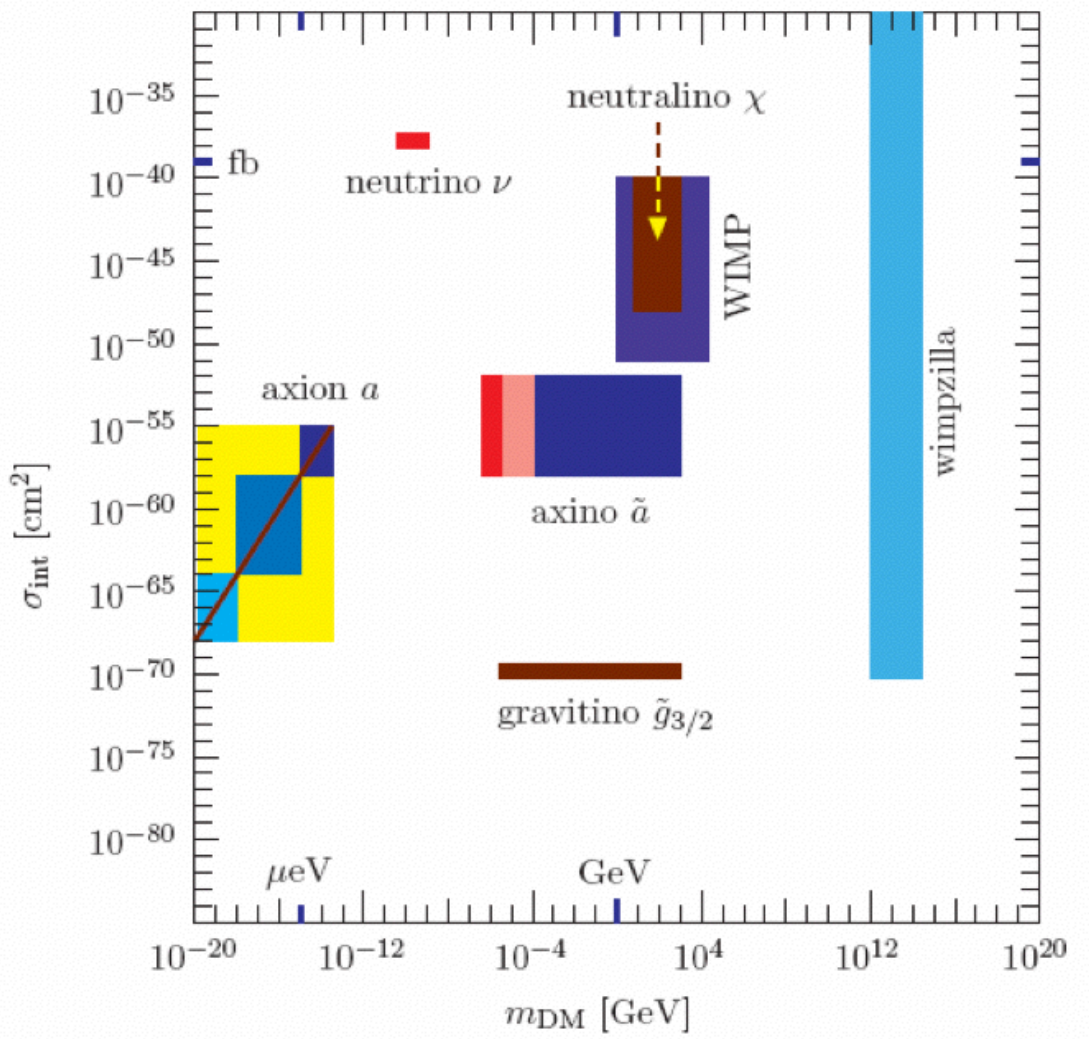
DESY.

Motivation

- Unraveling nature of dark matter (DM) most urgent problem of particle physics and cosmology
- Non-observation of Weakly Interacting massive Particles (WIMPs) at LHC and in direct detection DM experiments strong motivation to focus more attention to alternative candidates, in particular to very Weakly Interacting Slim Particles dubbed WISPs

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

- Particularly well motivated WISPs: Nambu-Goldstone bosons arising from the breaking of global symmetries introduced to solve other problems, e.g.
  - Axion – breaking of Peccei-Quinn symmetry – solves strong CP problem [Peccei,Quinn 77; Weinberg 78; Wilczek 78]
  - Majoron – breaking of lepton symmetry – solves neutrino mass problem
  - Flavon – breaking of flavor symmetry – solves flavor puzzles

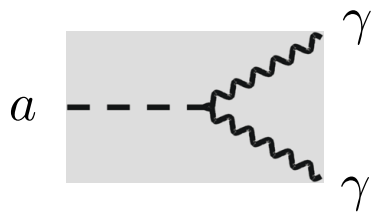


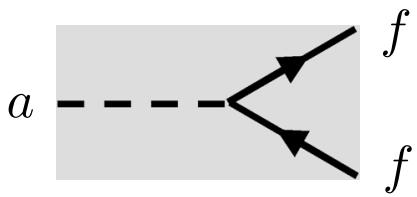
[Kim,Carosi 10]

Motivation

- NG bosons are natural WISP candidates:
  - Very weakly interacting:
    - Couplings to SM suppressed by powers of symmetry breaking scale $f_a \gg v \simeq 246\,\mathrm{GeV}$:

$$\mathcal{L} = \frac{1}{2}\,\partial_\mu a\,\partial^\mu - \frac{1}{2}m_a^2 a^2 - \frac{\alpha}{8\pi}C_{a\gamma}\frac{a}{f_a}\;F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\,C_{af}\frac{\partial_\mu a}{f_a}\,\overline{\psi}_f\gamma^\mu\gamma_5\psi_f$$





  - Small mass:
    - Massless if global symmetry exact
    - Small mass from explicit breaking of global symmetry
- Axion:

$$m_A = 57.0(7)\,\left(\frac{10^{11}\,\mathrm{GeV}}{f_A}\right)\mu\mathrm{eV}$$

[Weinberg ´78; ... Borsanyi et al. `16]

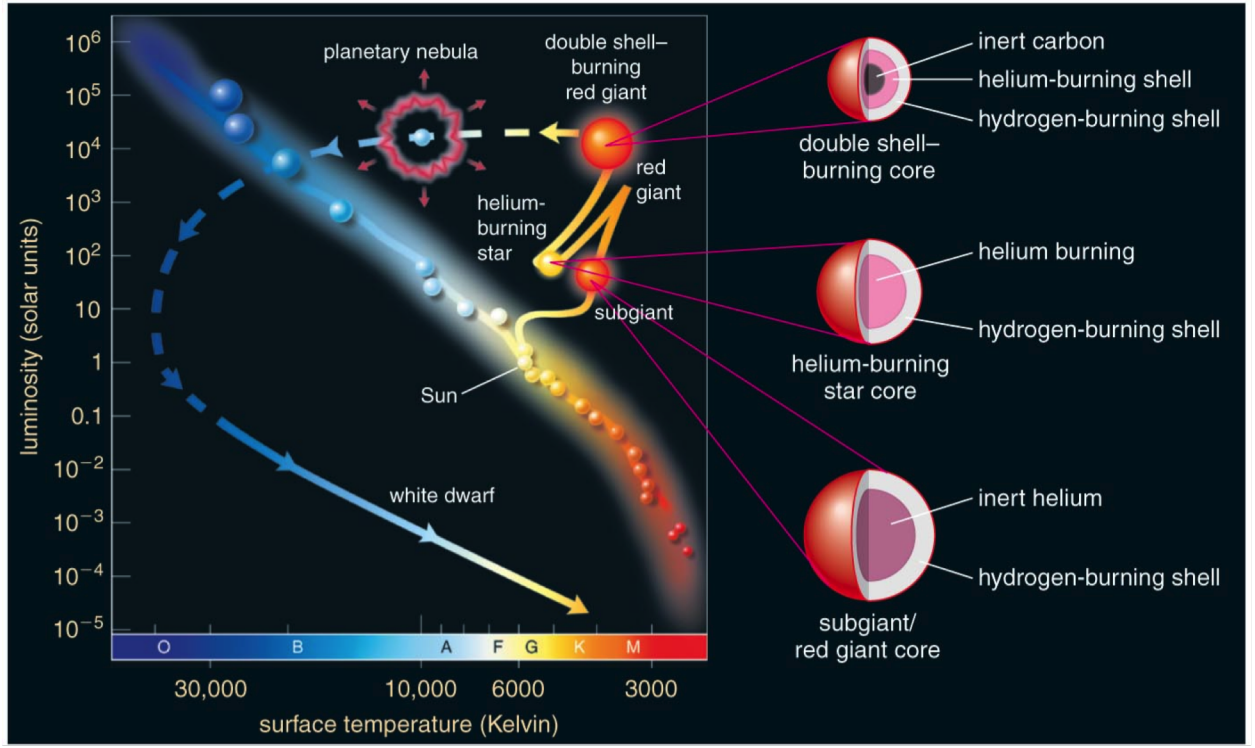
$$C_{A\gamma} = \frac{E}{N} - 1.92(4)$$

[Kaplan 85;Srednicki `85; Grilli di Cortona et al. `16]

Motivation

Astrophysical Hints for Axions and ALPs

- Apart from dark matter, there are also other hints from astrophysics which may explained by axions:
  - Excessive energy losses of stars in various stages of their evolution



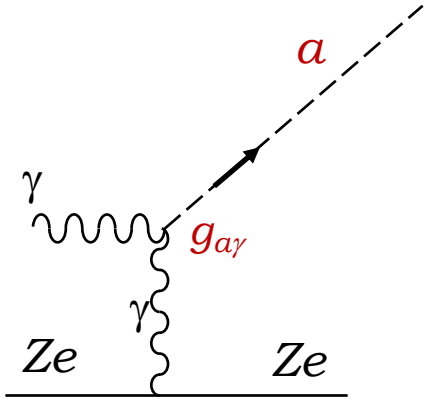
[Copyright Addison Wesley]

Motivation

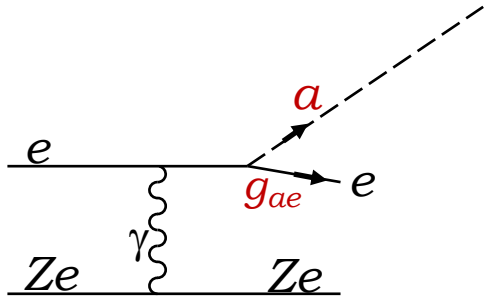
Astrophysical Hints for Axions and ALPs

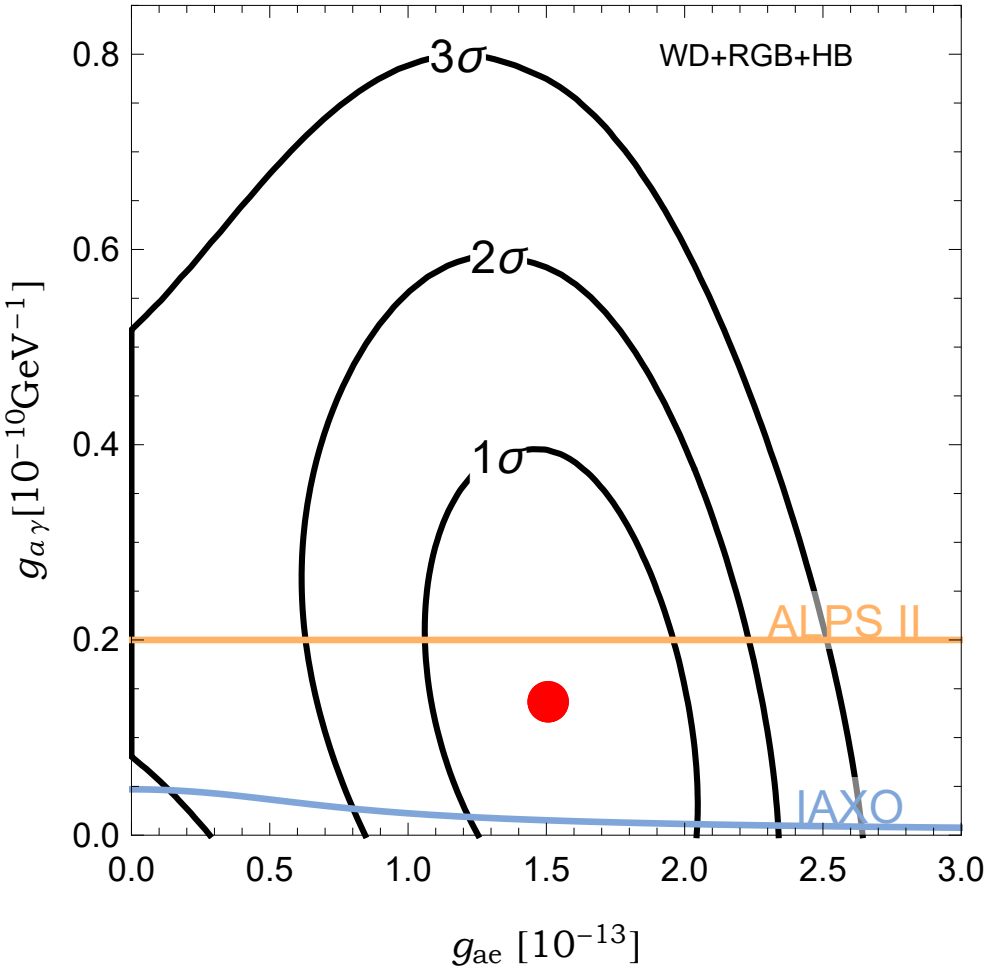
- Apart from dark matter, there are also other hints from astrophysics which may explained by axions:
  - Excessive energy losses of stars in various stages of their evolution: may be explained by axion production

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



$$\mathcal{L} \supset -i g_{ae}\, a\, \overline{\psi}_e \gamma_5 \psi_e$$



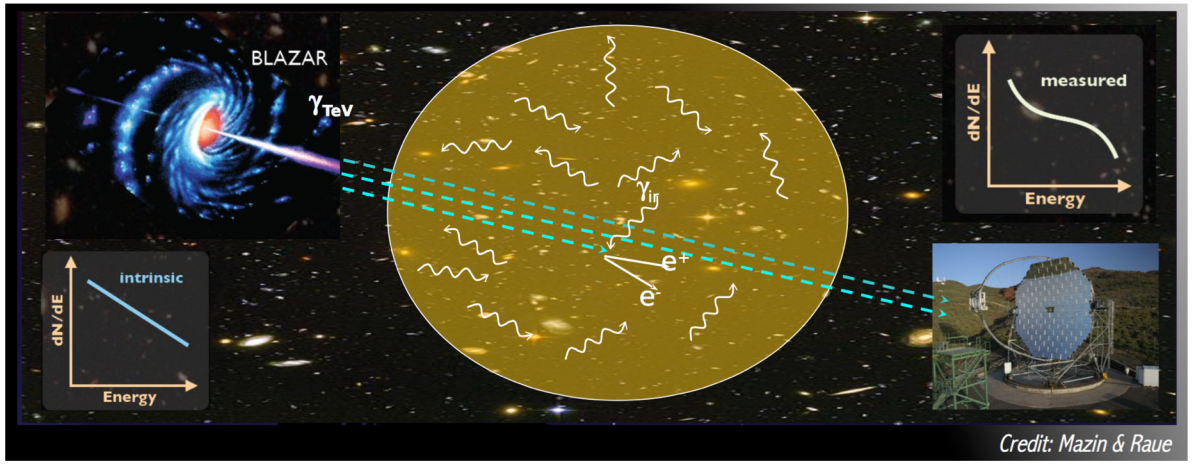


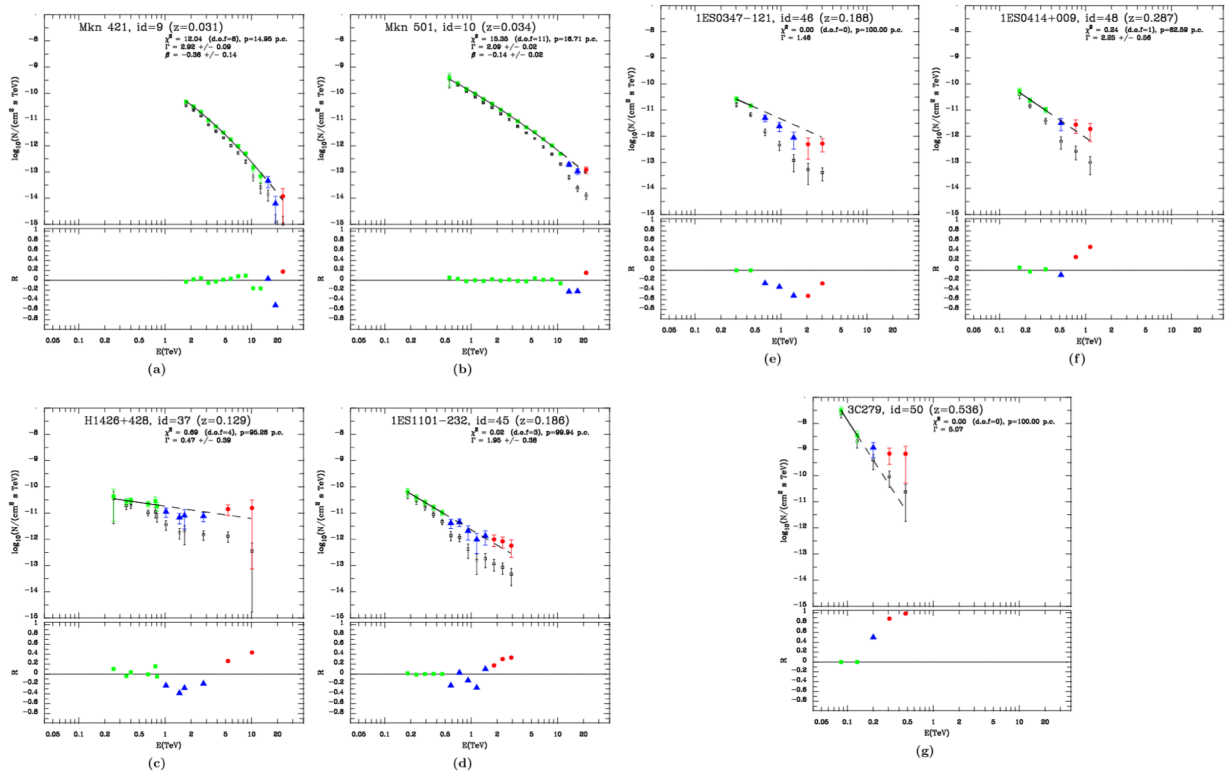
[Giannotti et al. 17]

Motivation

Astrophysical Hints for Axions and ALPs

- Apart from dark matter, there are also other hints from astrophysics which may explained by axions:
  - Excessive energy losses of stars in various stages of their evolution
  - Excessive transparency of the universe for TeV gamma rays



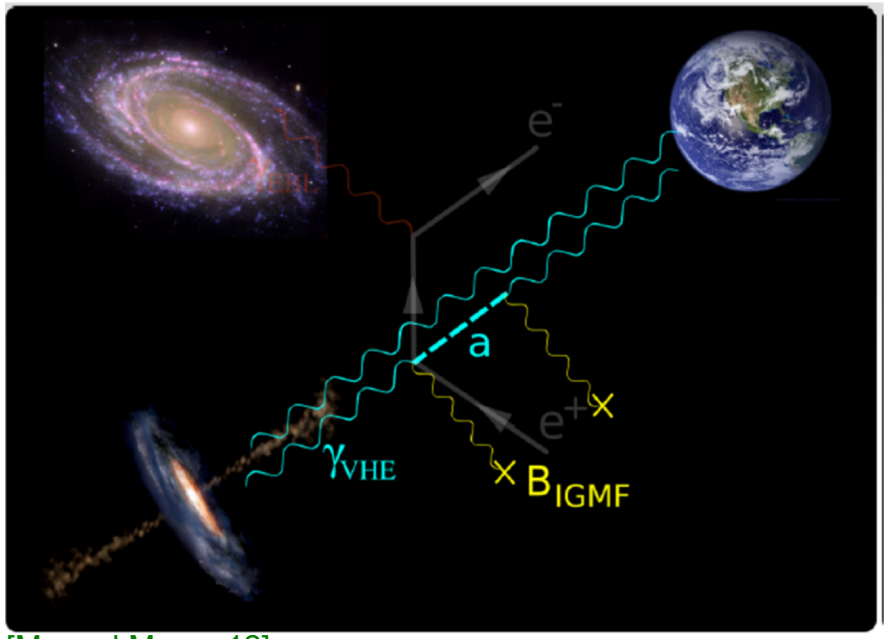


[Horns,Meyer 12]

Motivation

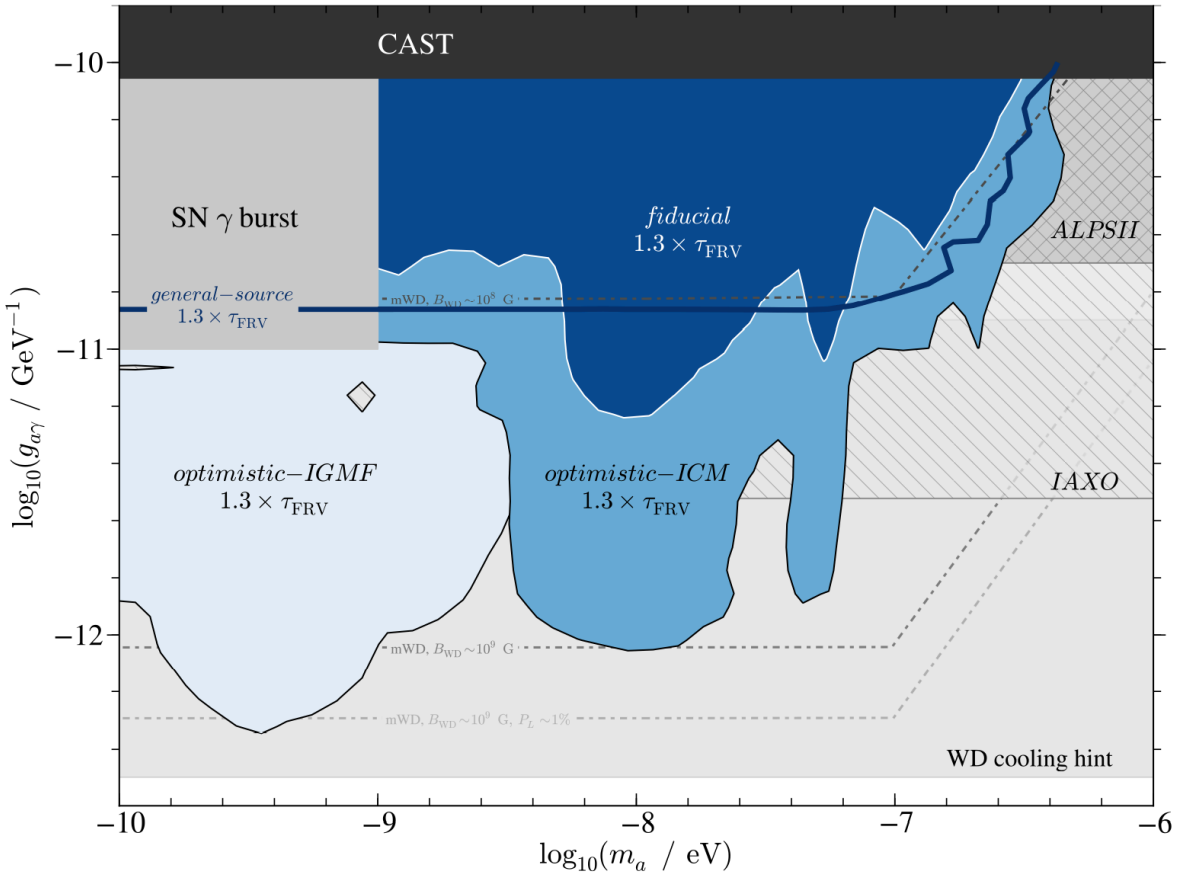
Astrophysical Hints for Axions and ALPs

- Apart from dark matter, there are also other hints from astrophysics which may explained by axions
  - Excessive energy losses of stars in various stages of their evolution
  - Excessive transparency of the universe for TeV gamma rays: may be explained by photon $\leftrightarrow$ axion conversion



[Manuel Meyer 12]

Name	IGMF $B^0_{\rm IGMF}$ (nG)	IGMF $\lambda^c_{\rm IGMF}$ (Mpc)	IGMF $n^0_{\rm el,IGM}$ ($\times 10^{-7}$ cm^{-3})	ICM $B^0_{\rm ICMF}$ (μG)	ICM $\lambda^c_{\rm ICMF}$ (kpc)	ICM $r_{\rm cluster}$ (Mpc)	ICM $n^0_{\rm el,ICM}$ ($\times 10^{-3}$ cm^{-3})	ICM $r_{\rm core}$ (kpc)	ICM η
General source	Only conversion in GMF, but $\rho_{\rm init} = 1/3{\rm diag}(e^{-\tau}, e^{-\tau}, 1)$								
Optimistic IGMF	5	50	1	···	···	···	···	···	···
Optimistic ICM	···	···	···	10	10	2	10	200	0.5
Fiducial	0.01	10	1	1	10	2/3	1	···	···

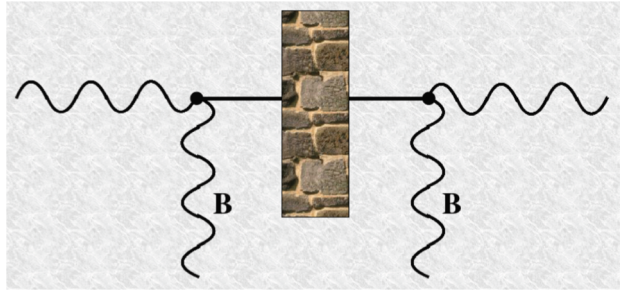


[Meyer,Horns,Raue 13]

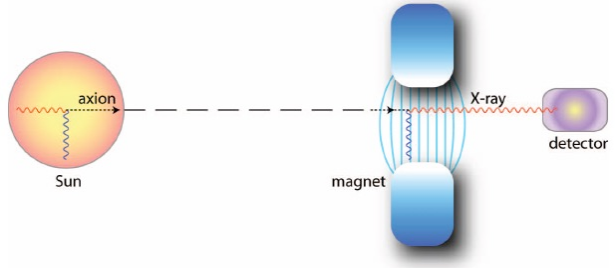
Experimental Axion/ALP Search Methods

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

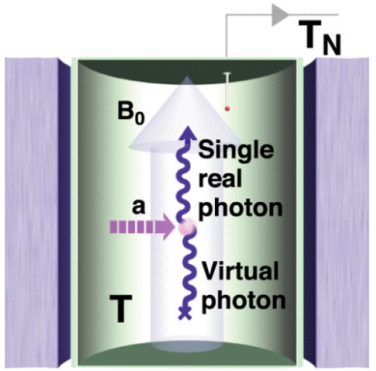
- **Light-shining-through-a-wall (LSW) Searches**
  - Production and detection of axions in laboratory



- **Searches for Solar Axions**
  - Axion production in Sun, detection in laboratory



- **Searches for Dark Matter Axions**
  - Axion dark matter production in early universe, detection in lab



Light-Shining-through-a-Wall Searches

Searching for Home-Made Axions

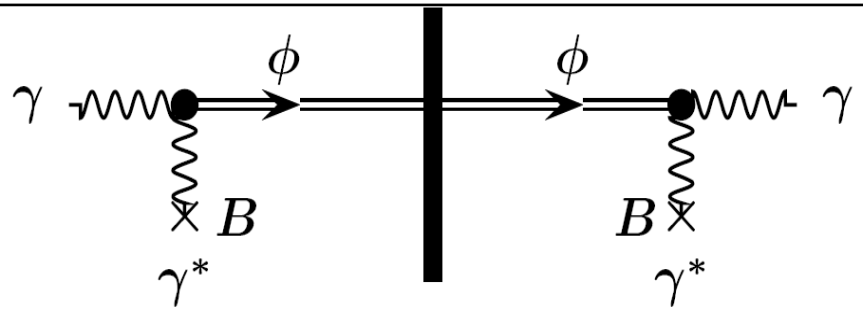
- Axion experiences mixing with photon in an external electromagnetic field
- Probability, that photon converted in axion/ALP after having traversed a distance L_B in magnetic field:

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

- For very light axion:

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

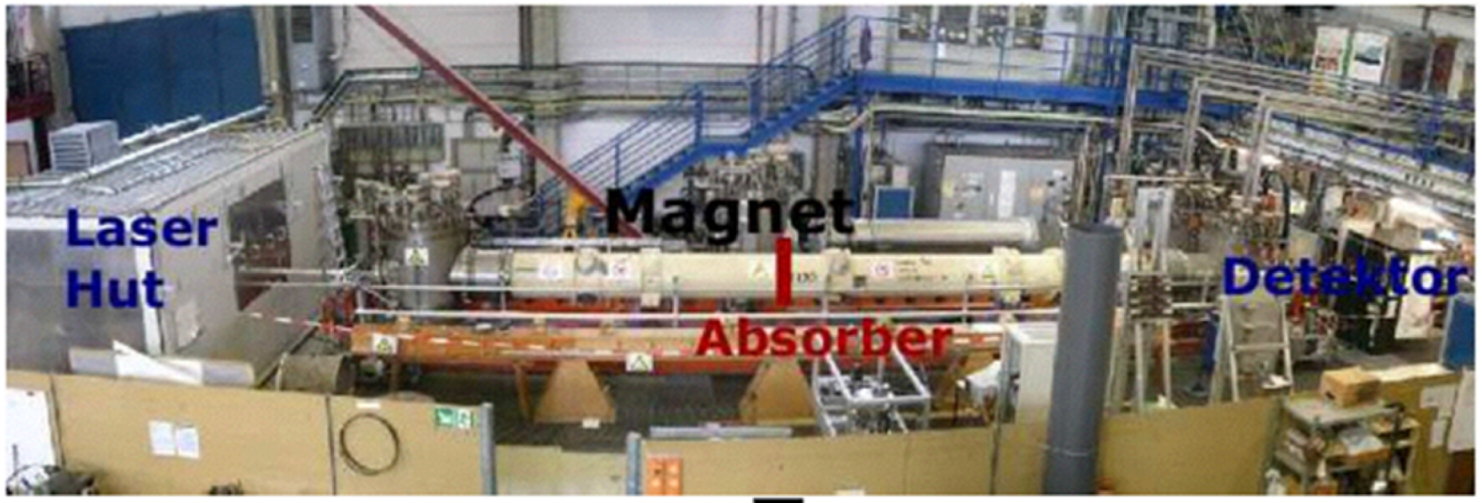
- Light-shining-through a wall:



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

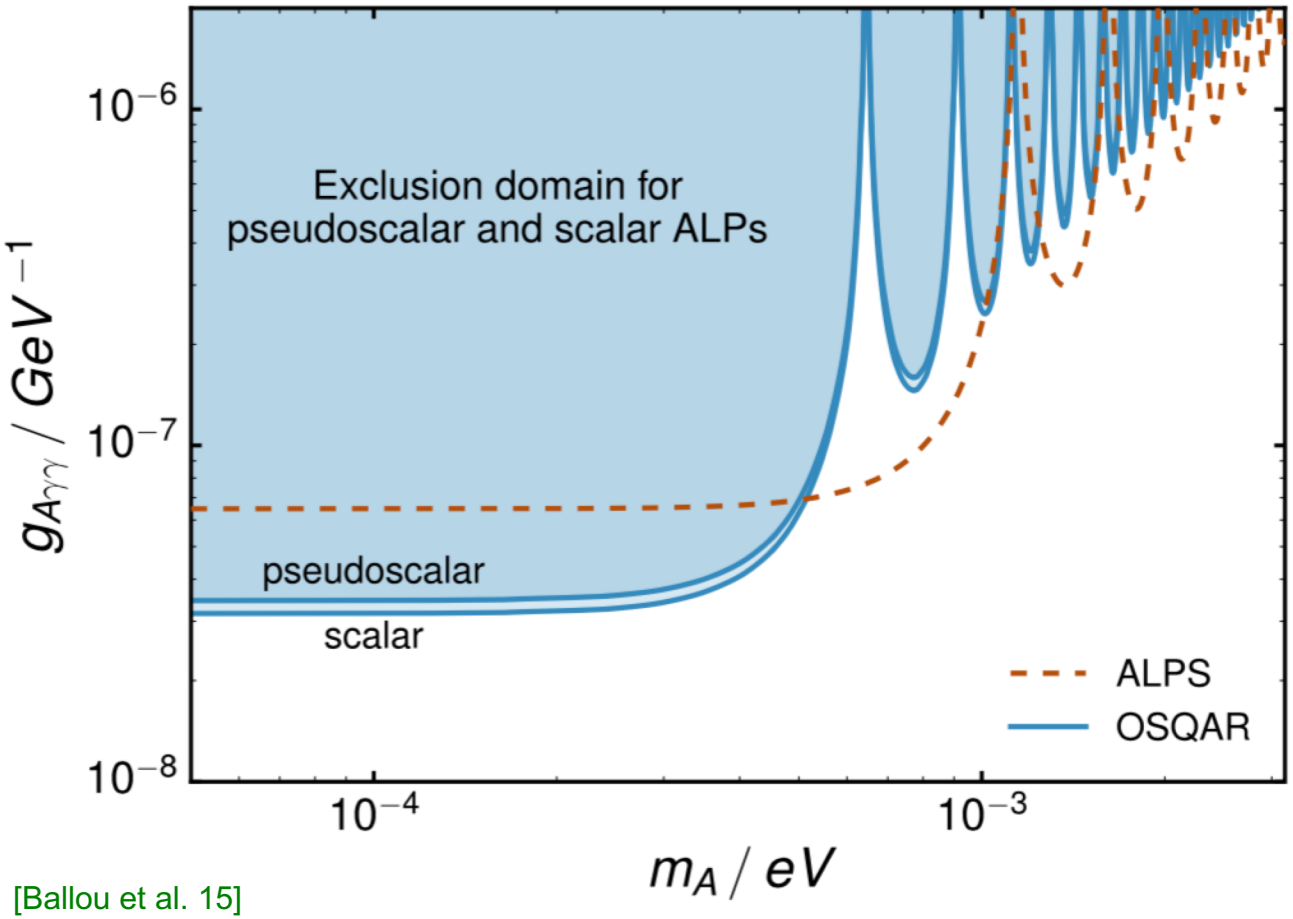
Light-Shining-through-a-Wall Searches

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



Light-Shining-through-a-Wall Searches

- ALPS I @ DESY (in collaboration with AEI Hannover and U Hamburg) [Ehret et al. 10]
  - LSW experiments ALPS I and OSQAR @ CERN give currently the best purely laboratory limit on low mass axions:



[Ballou et al. 15]

Light-Shining-through-a-Wall Searches

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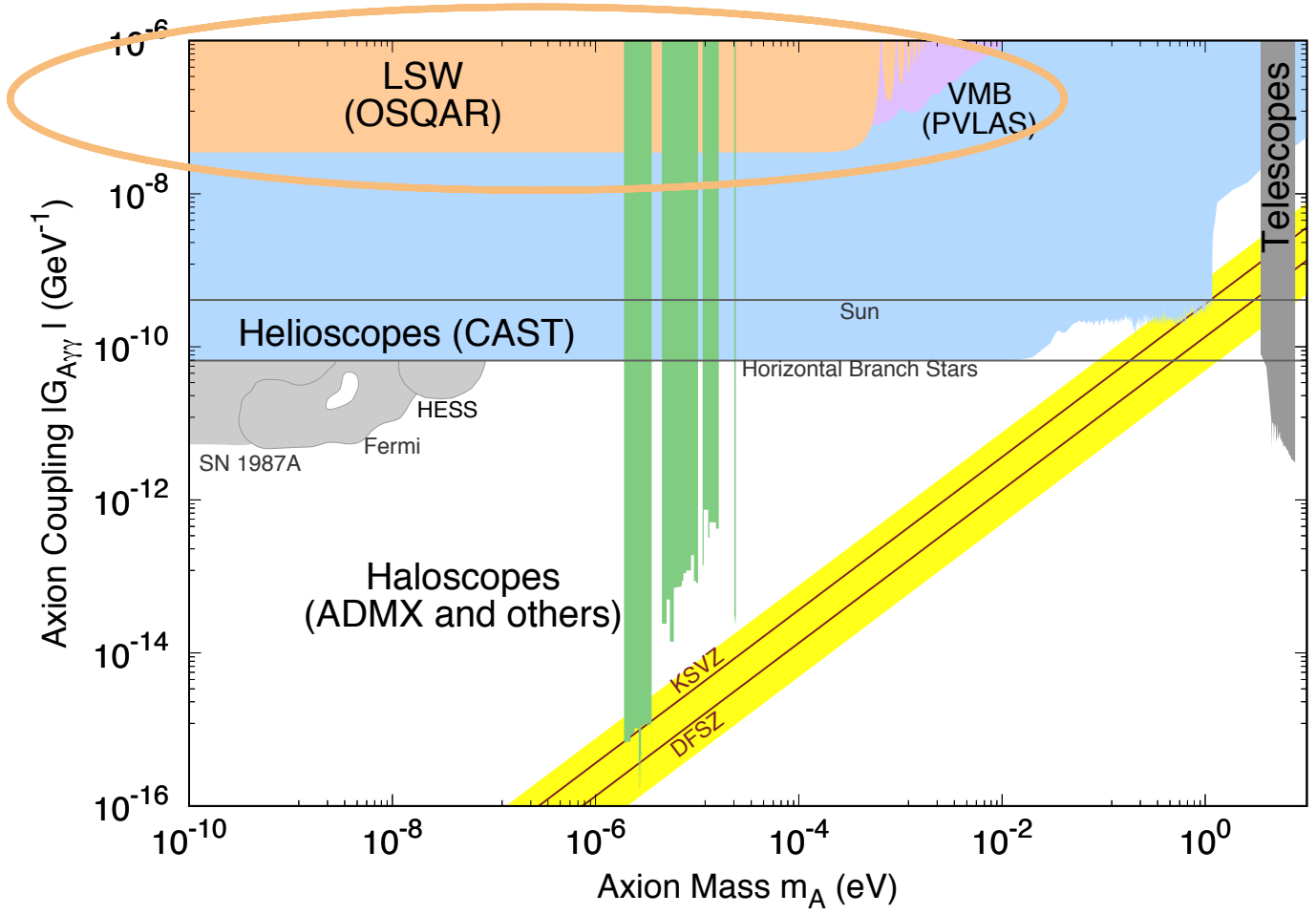
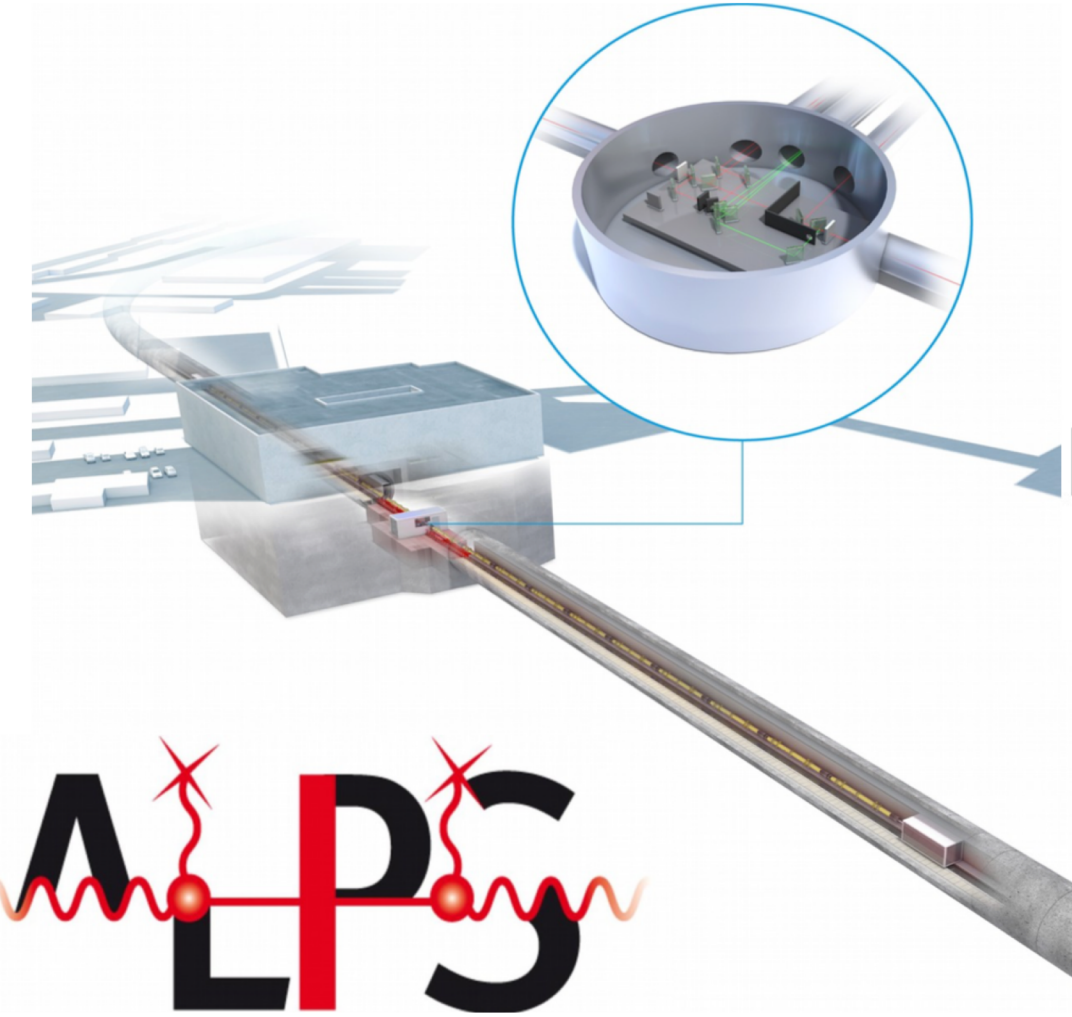
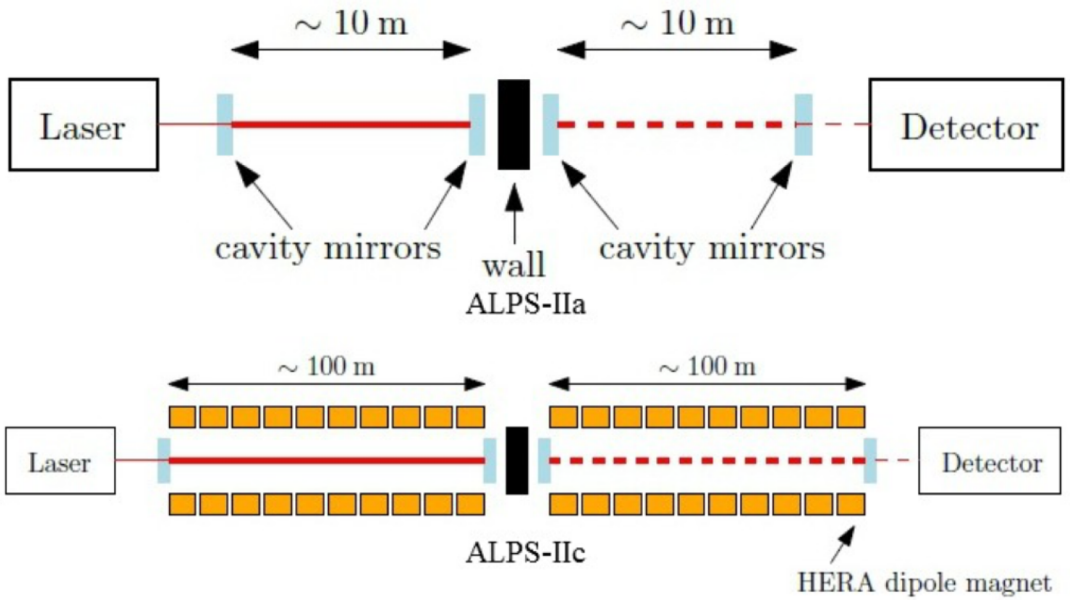


Light-Shining-through-a-Wall Searches

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

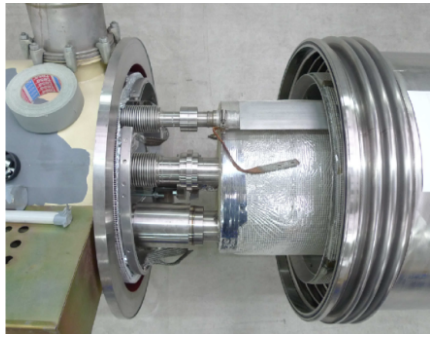


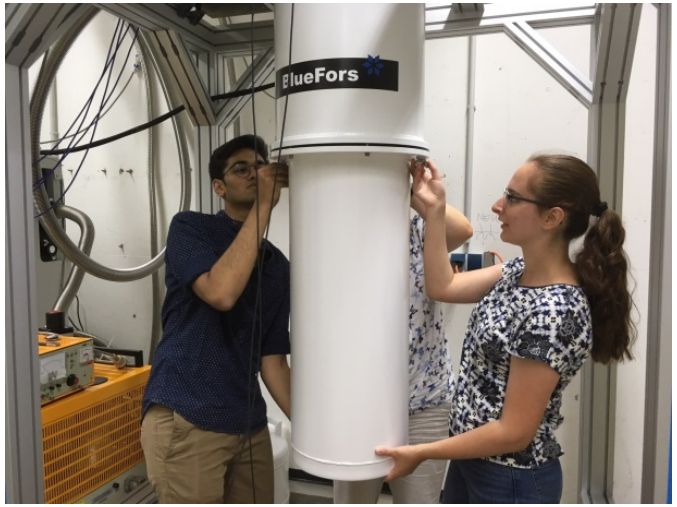


Parameter	Scaling	ALPS I	ALPS IIc	Sens. gain
Effective laser power P_{laser}	$g_{a\gamma} \propto P_{\text{laser}}^{-1/4}$	1 kW	150 kW	3.5
Rel. photon number flux n_γ	$g_{a\gamma} \propto n_\gamma^{-1/4}$	1 (532 nm)	2 (1064 nm)	1.2
Power built up in RC P_{RC}	$g_{a\gamma} \propto P_{reg}^{-1/4}$	1	40,000	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 construction in full swing:

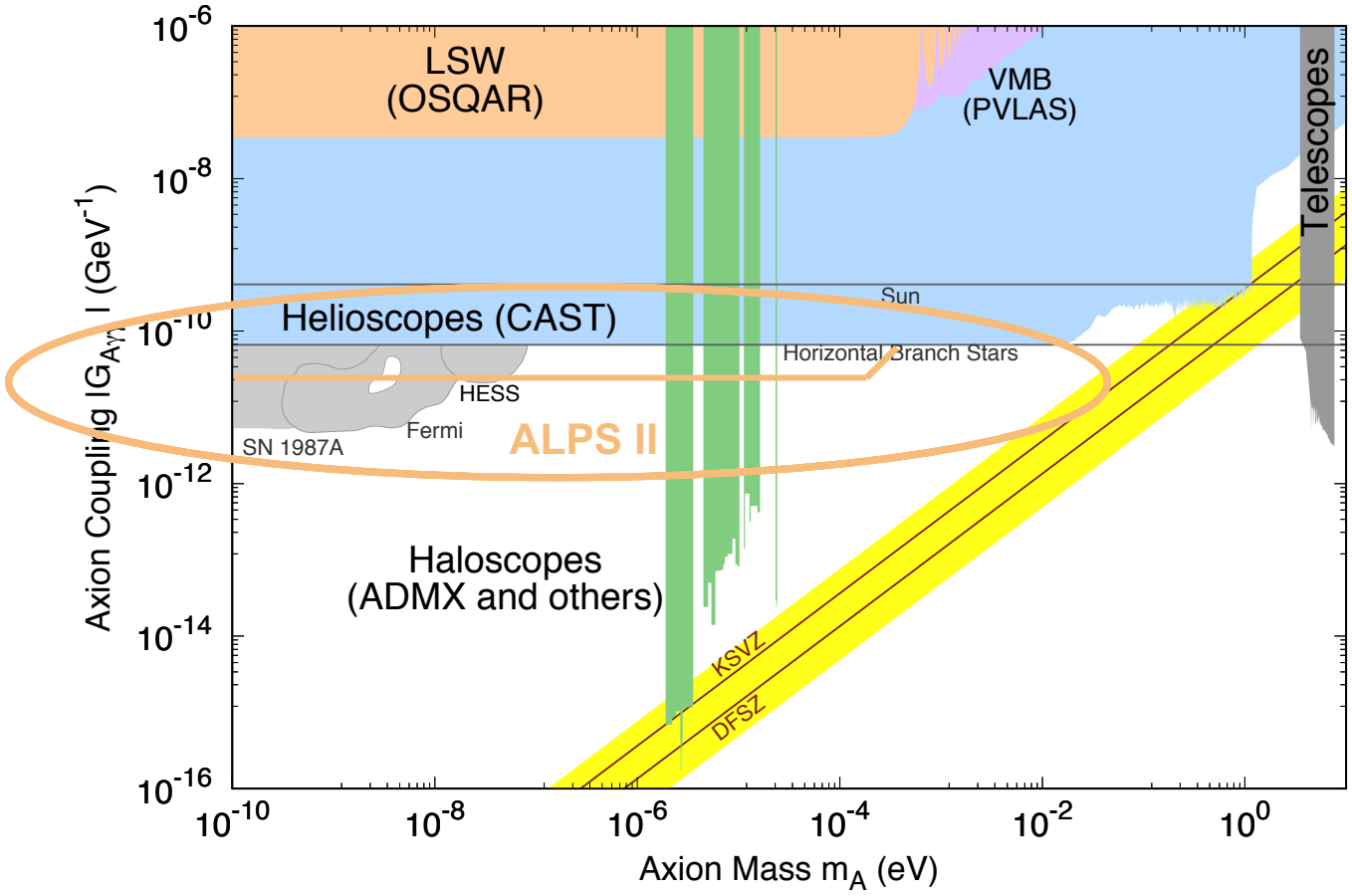




- Ready for data taking end of 2020

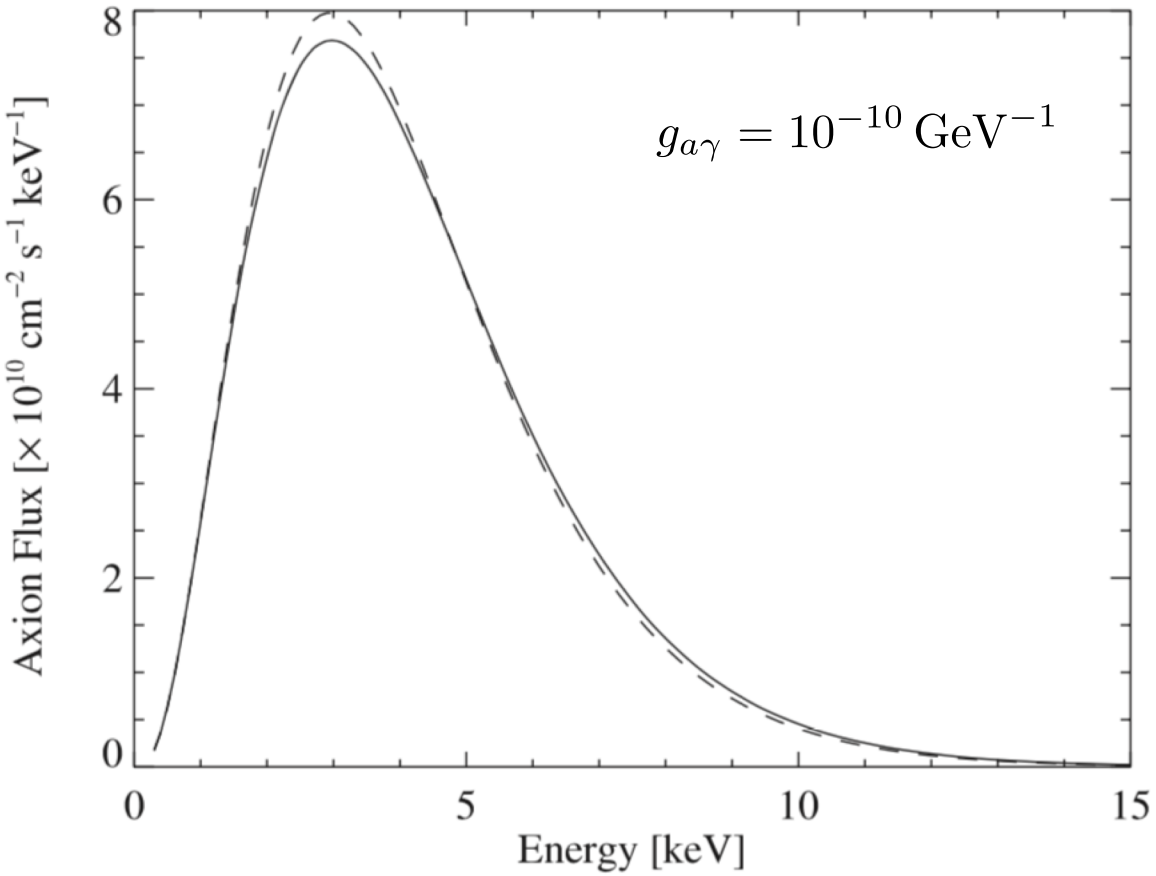
Light-Shining-through-a-Wall Searches

- ALPS II will probe previously uncharted territory, in particular part of parameter space relevant for dark matter and astro hints (excessive energy losses of Horizontal Branch stars in globular clusters, TeV transparency anomaly)

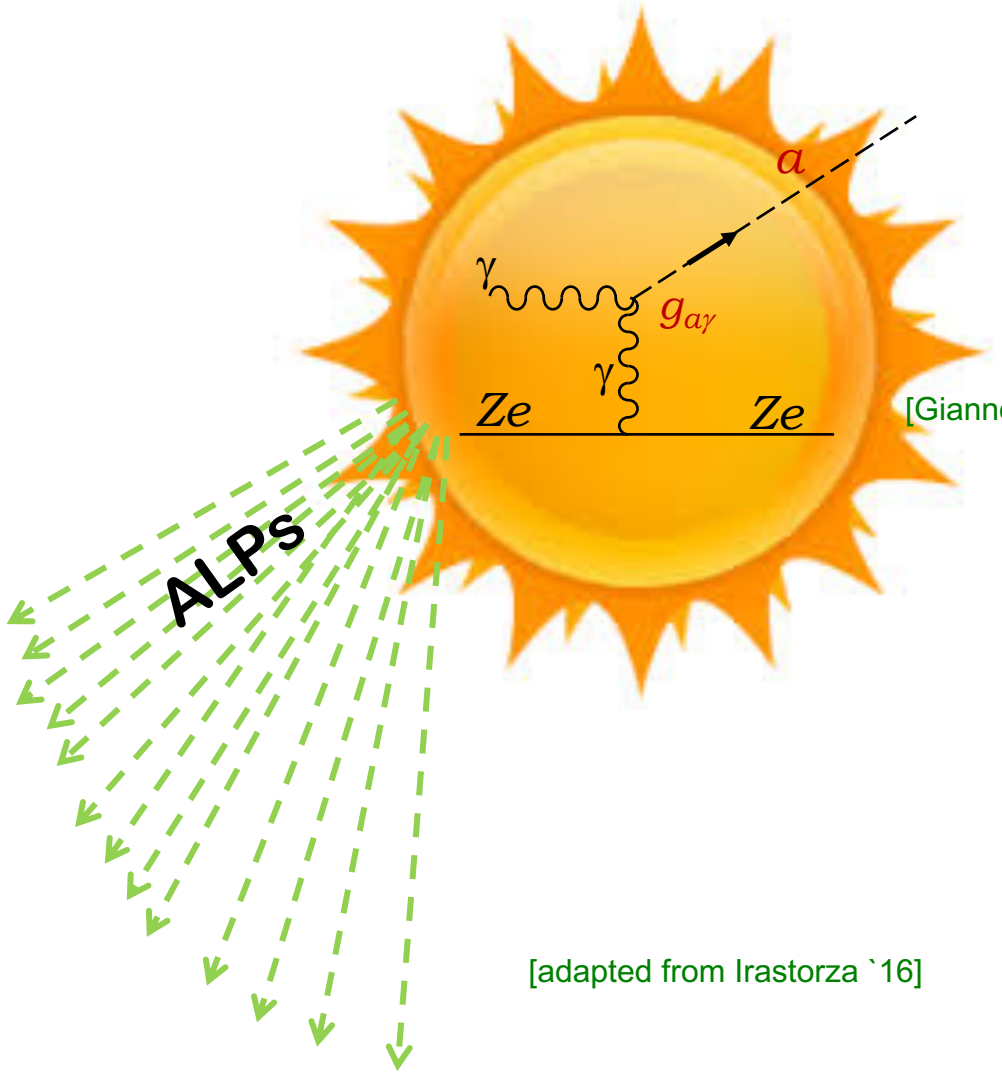


Searches for Solar Axions

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



[Adriamonje et al. `07]

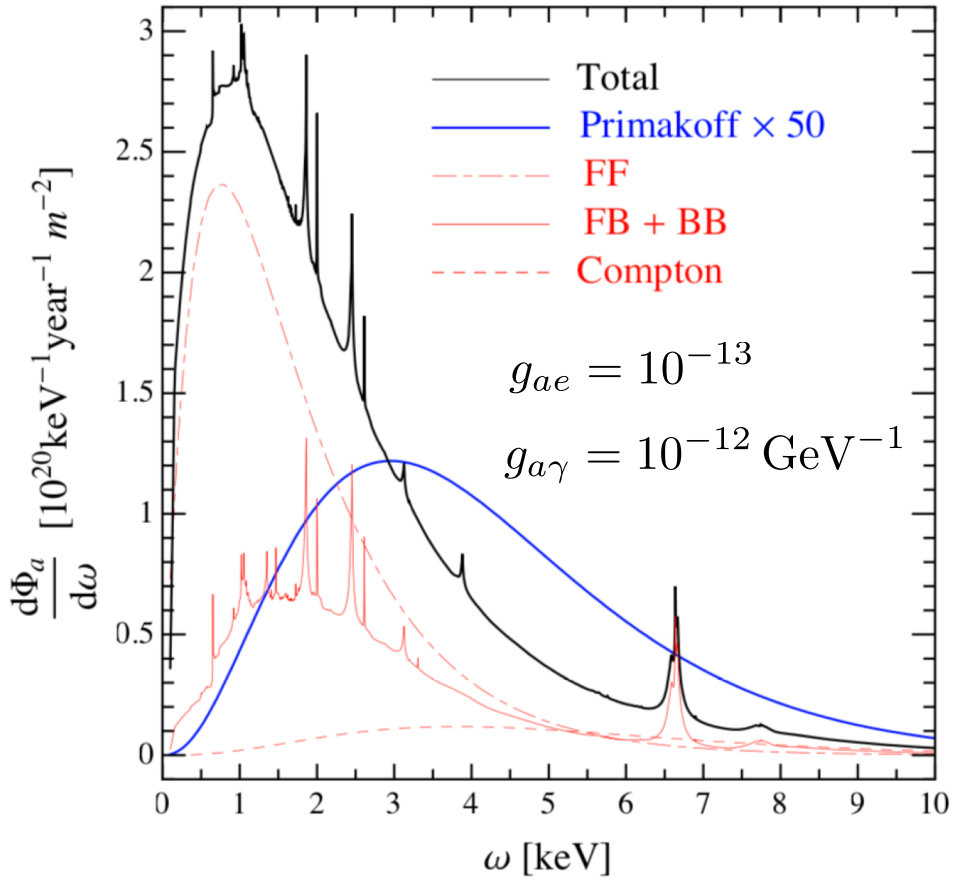


[Giannotti `16]

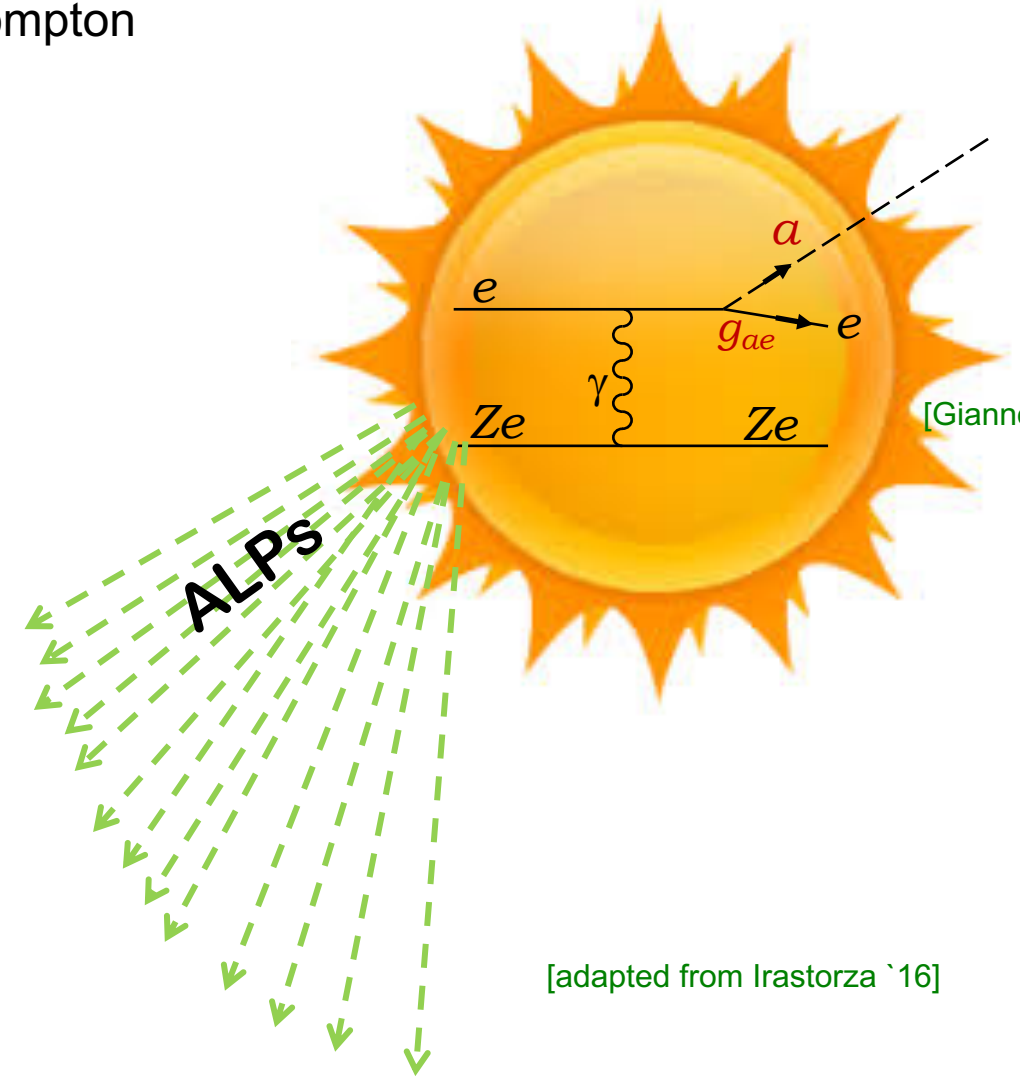
[adapted from Irastorza `16]

Searches for Solar Axions

- 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]



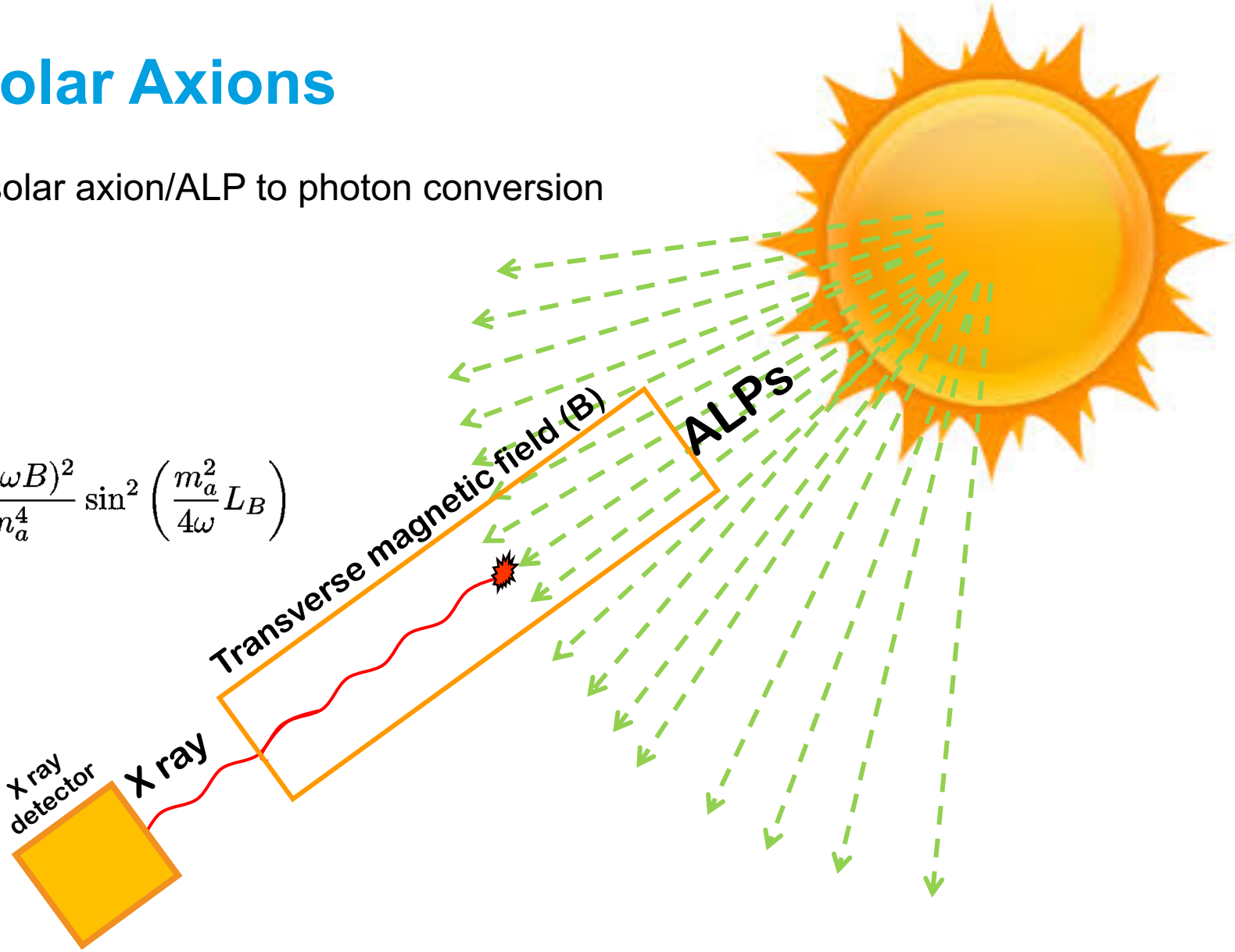
[Giannotti `16]

[adapted from Irastorza `16]

Searches for Solar Axions

- 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]

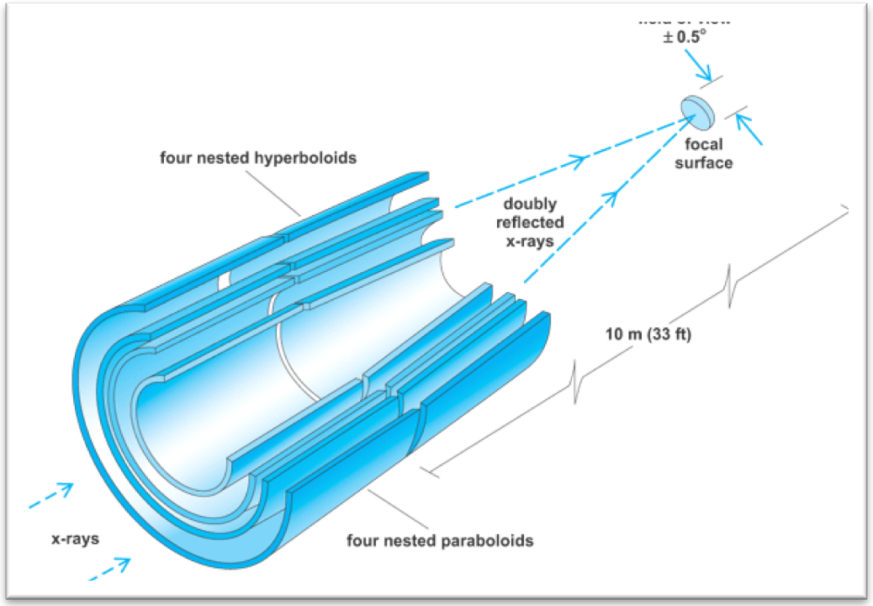
Searches for Solar Axions

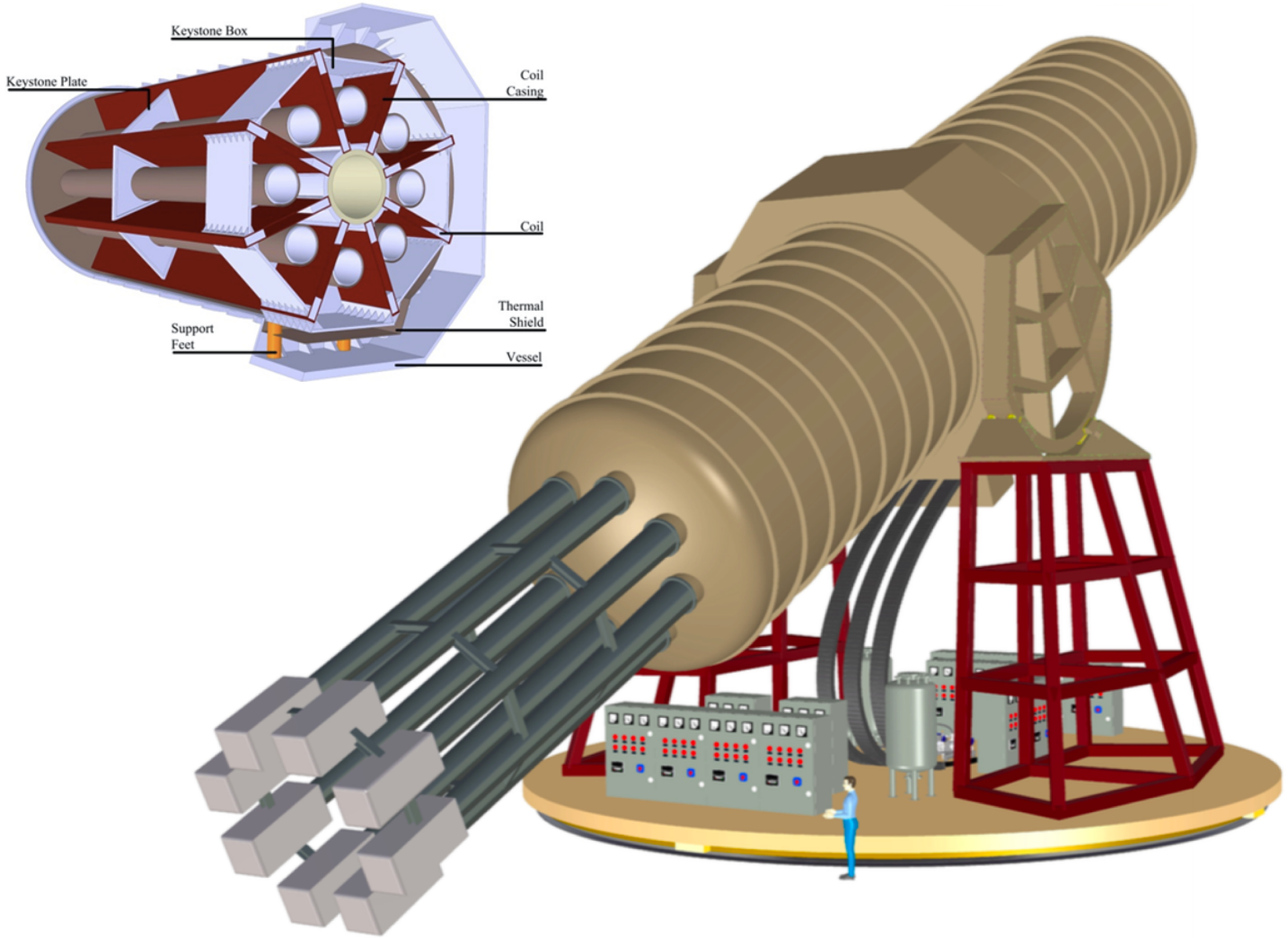
- Most sensitive until now: CERN Axion Solar Telescope (CAST)
  - Superconducting LHC dipole magnet
  - X-ray detectors
  - Use of buffer gas to extend sensitivity to higher masses (axion band)

Searches for Solar Axions

- 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

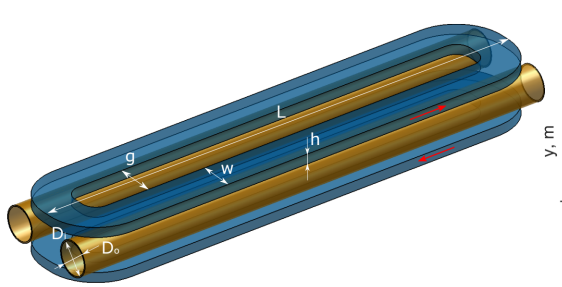
[IAXO CDR: JINST 9 (2014) T05002 (arXiv:1401.3233)]

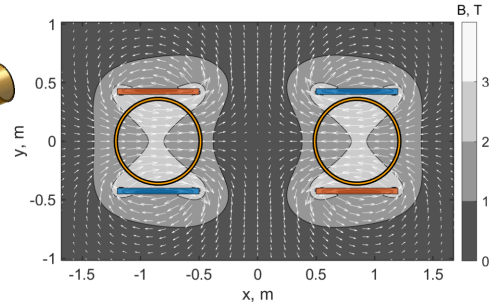




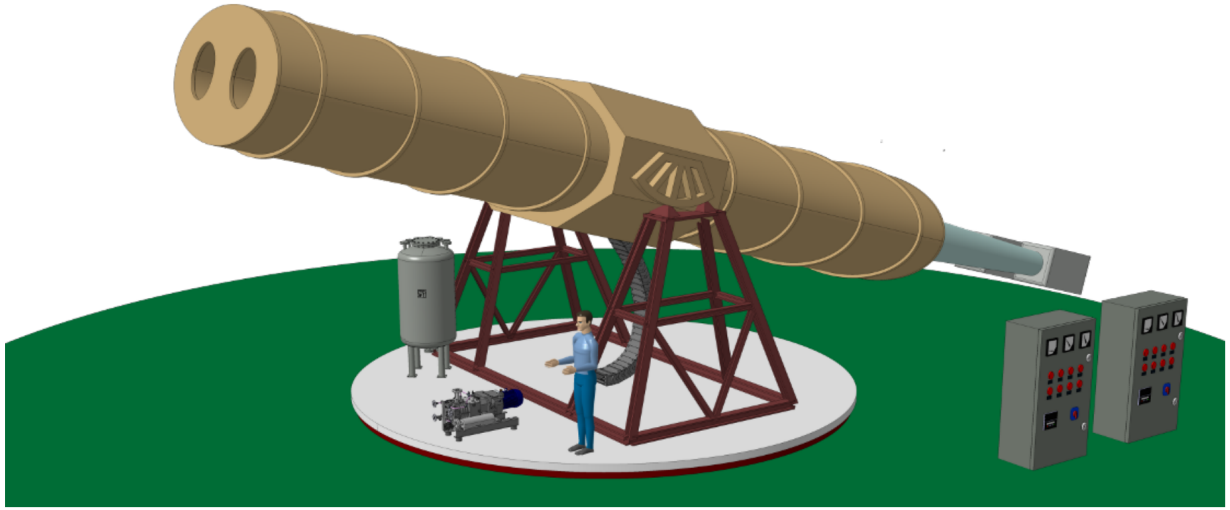
Searches for Solar Axions

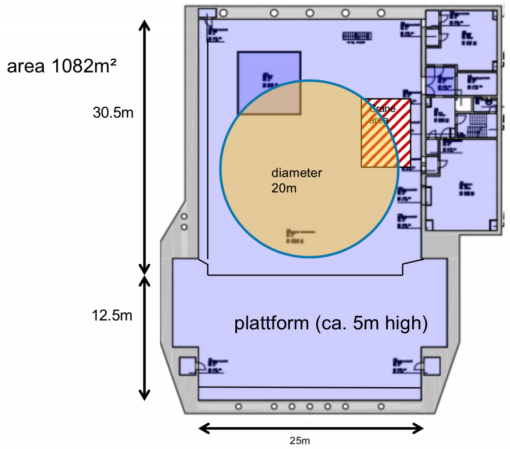
- Prototype for IAXO: BabyIAXO
  - Two bores of dimensions similar to final IAXO bores
  - Detection lines representative of final ones
  - Test & improve all systems
- Magnet technical design ongoing at CERN

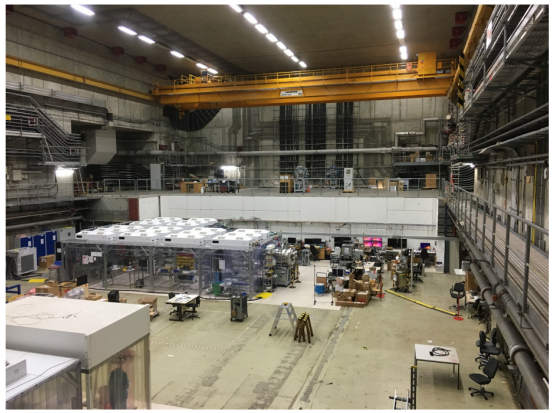




- Funded mainly via Irastorza: ERC-AvG 2017 IAXO+
- Preferred site: HERA South Hall at DESY
- Construction may start in 2020
- Data taking may start in 2024

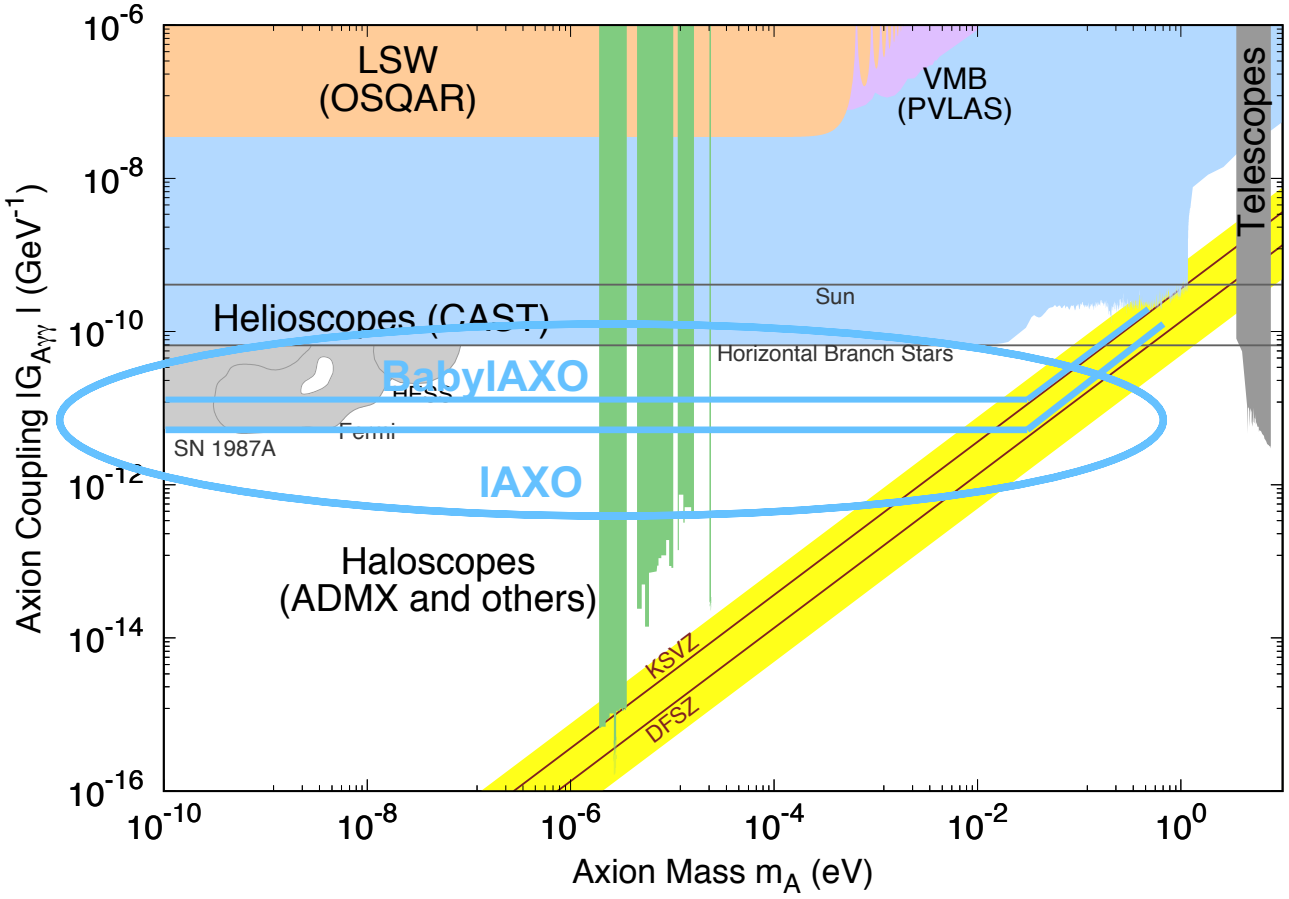






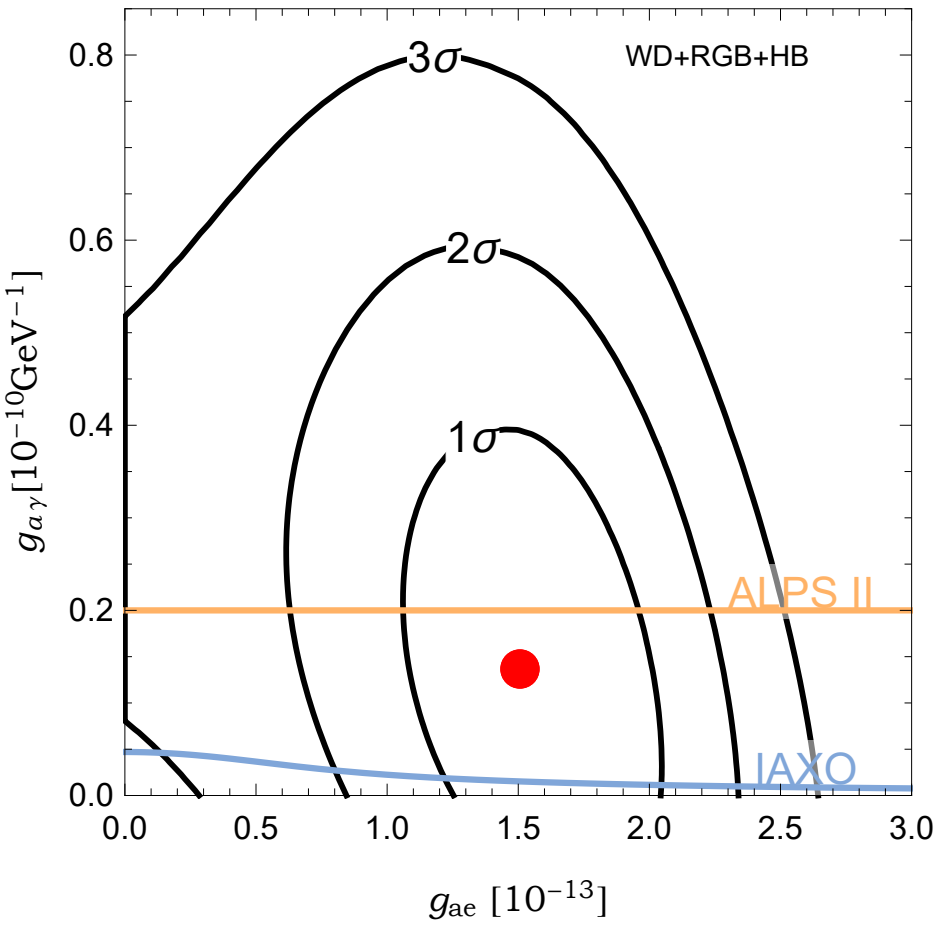
Searches for Solar Axions

- (Baby)IAXO probes meV mass QCD axion and covers most of parameter space relevant for astro hints

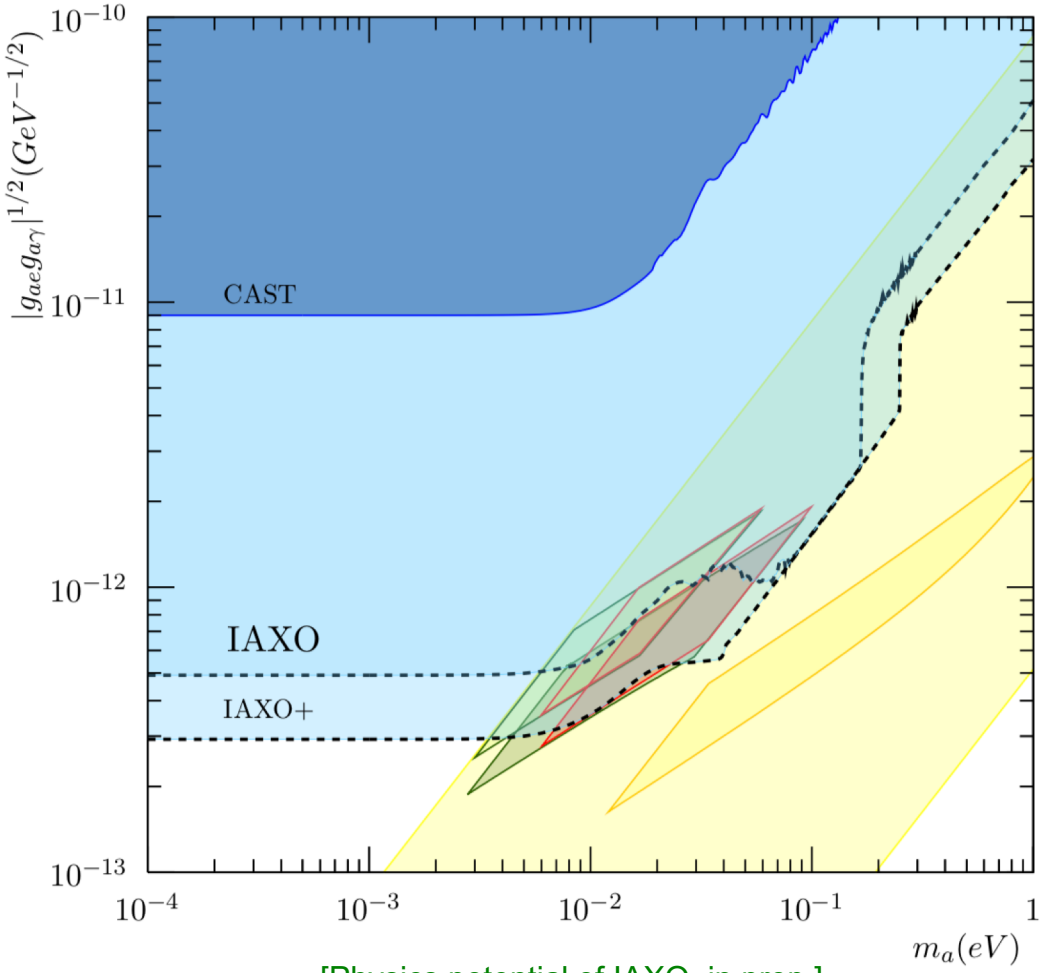


Searches for Solar Axions

- IAXO also sensitive to electron coupling hinted at by stellar energy losses



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

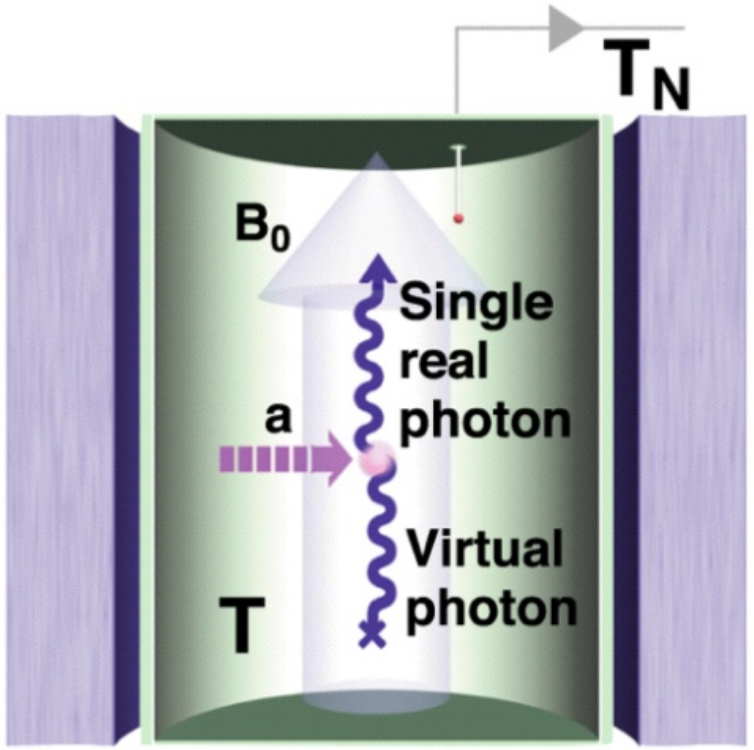


[Physics potential of IAXO, in prep.]

Searches for Dark Matter Axions

Microwave Cavities

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

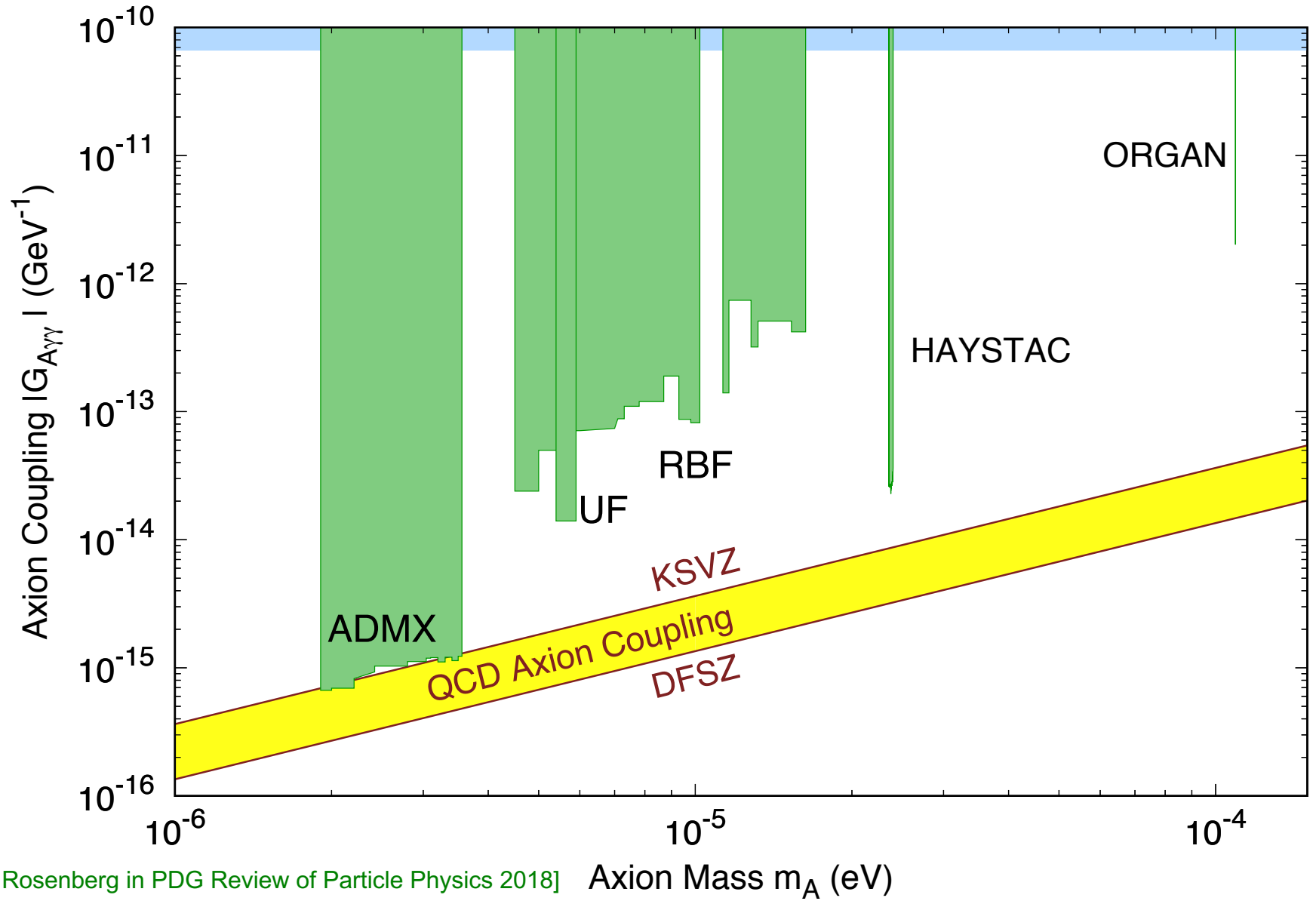


$$P_{\mathrm{out}} \sim g^2 \mid \mathbf{B}_0 \mid^2 \rho_{\mathrm{DM}} V Q / m_a$$

Searches for Dark Matter Axions

Microwave Cavities

- Currently running:
  - ADMX
  - HAYSTAC
  - ORGAN

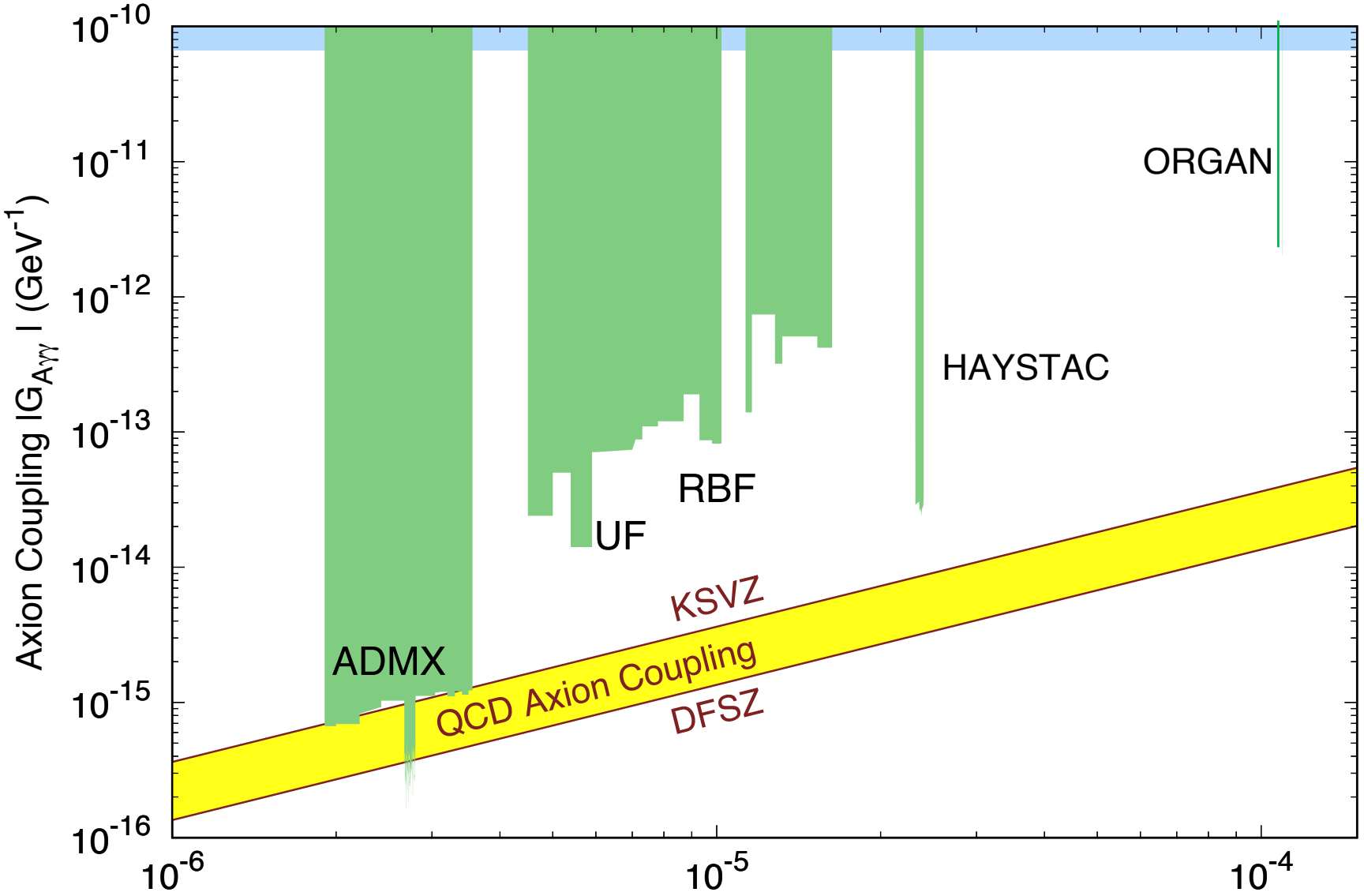


[AR,Rybka,Rosenberg in PDG Review of Particle Physics 2018]

Searches for Dark Matter Axions

Microwave Cavities

- Currently running:
  - ADMX
  - HAYSTAC
  - ORGAN

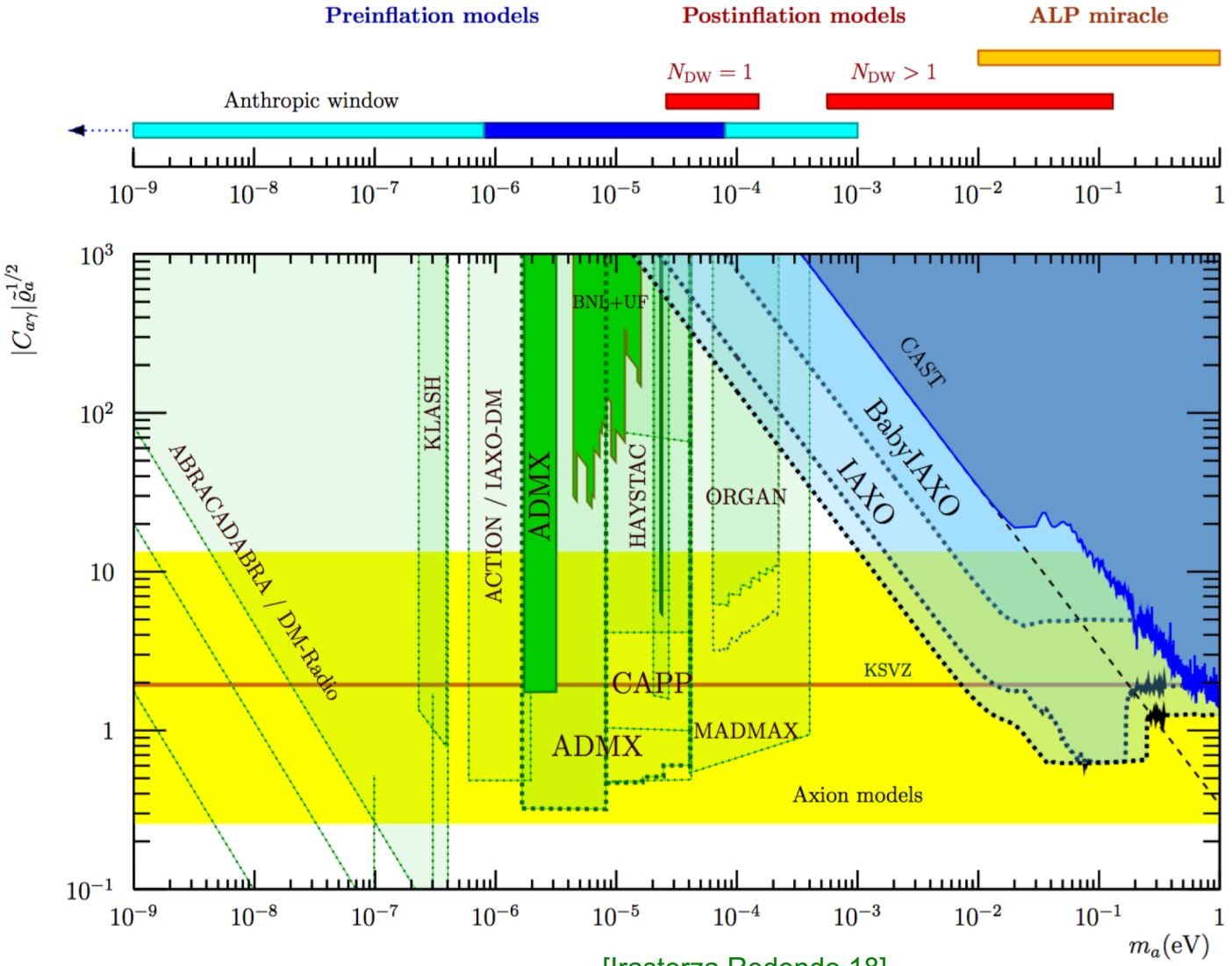


[AR,Rybka,Rosenberg in prep. for update PDG RPP 2019]

Searches for Dark Matter Axions

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 $0.3\,\mu\text{eV} \lesssim m_a \lesssim 30\,\mu\text{eV}$
- Need other techniques in remaining mass range

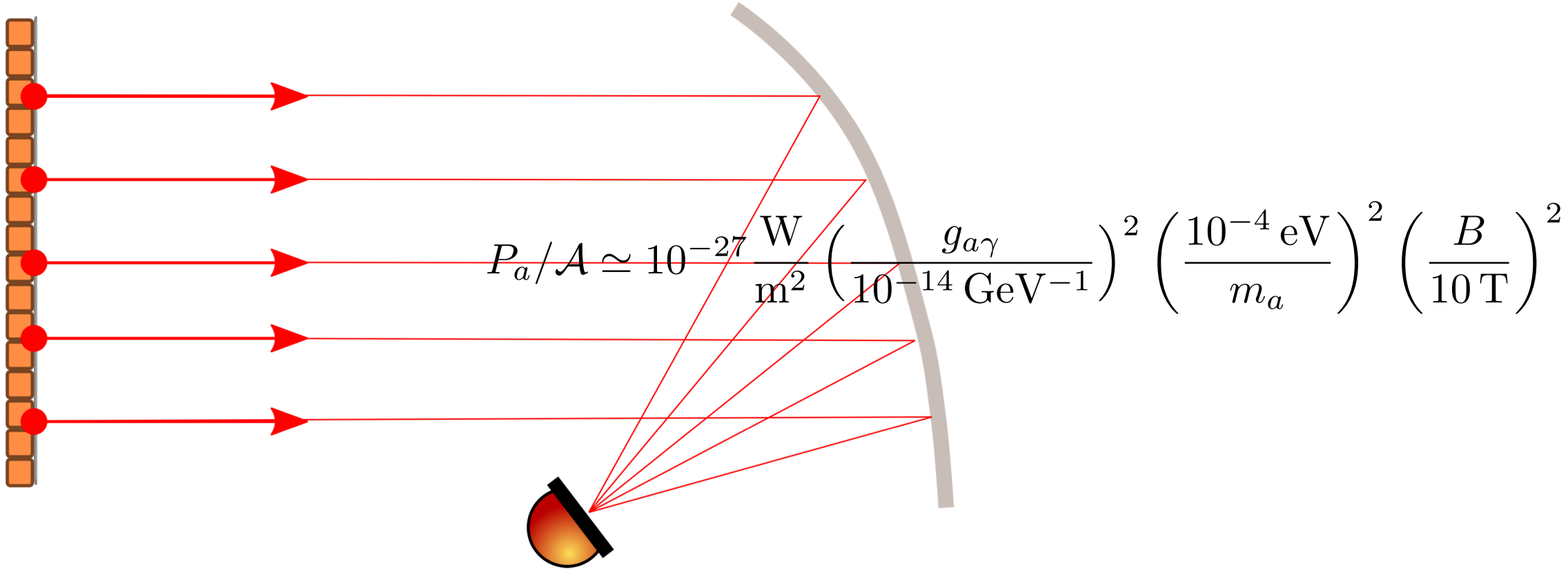


[Irastorza,Redondo 18]

Searches for Dark Matter Axions

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]



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

Searches for Dark Matter Axions

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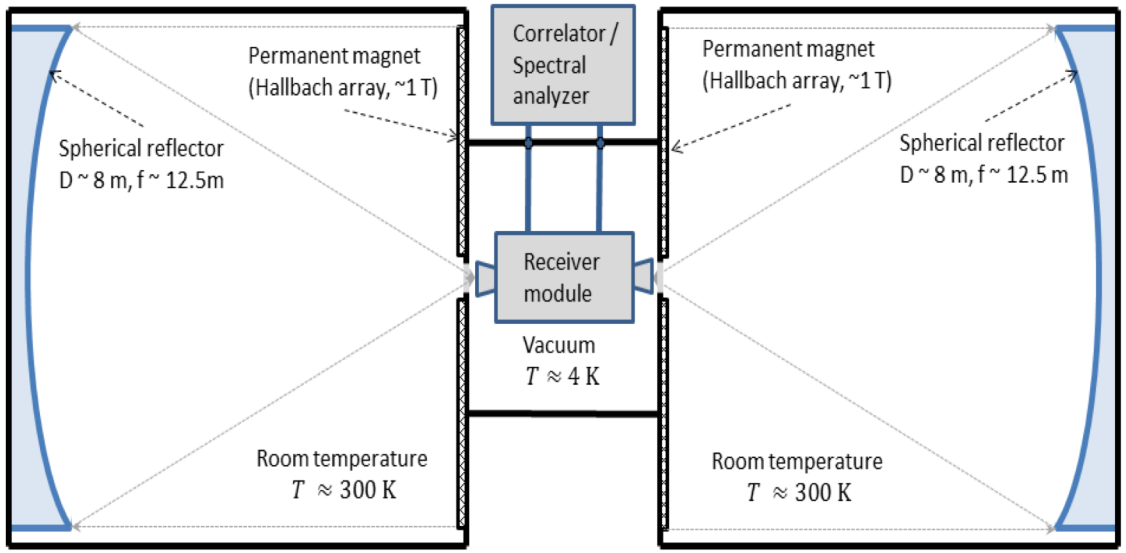
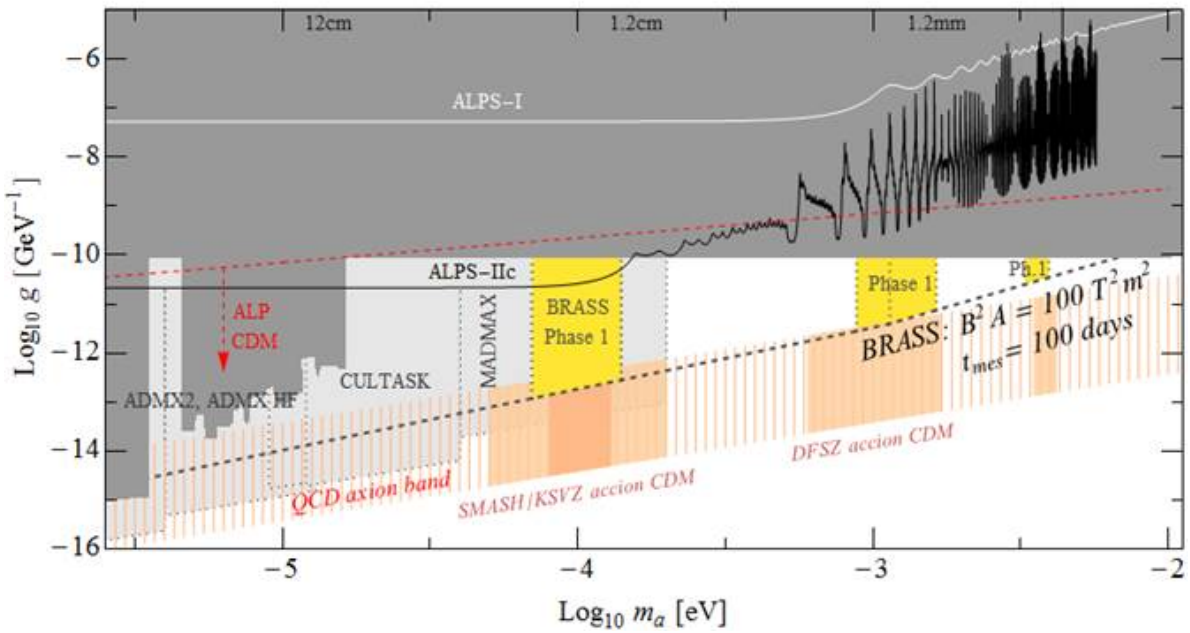
- Proposed axion/ALP DM dish antenna experiment: BRASS (U Hamburg) [Hidden photon DM: FUNK (KIT)] [Engel et al.]





[Horns et al. (unpublished)]

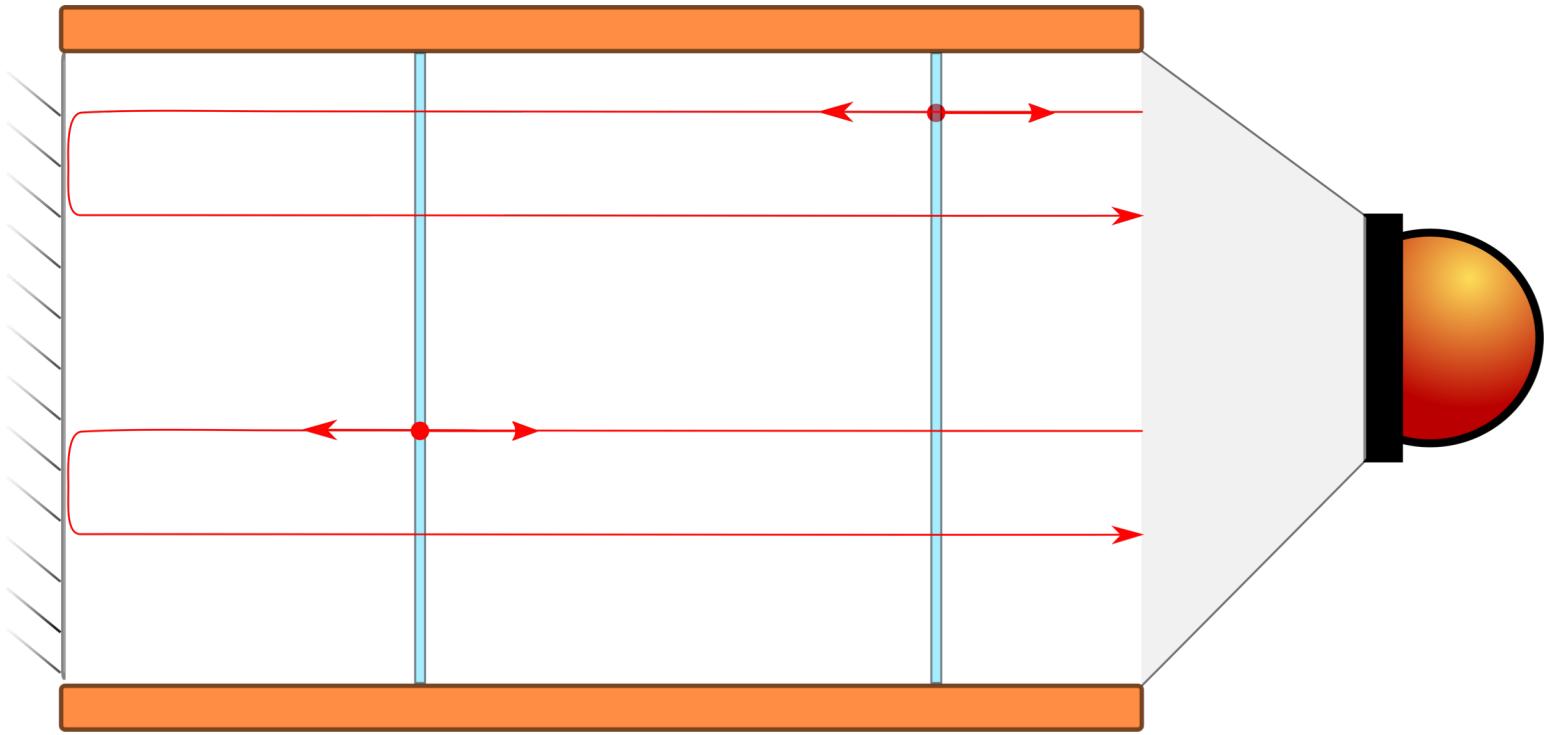
Searches for Dark Matter Axions

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]

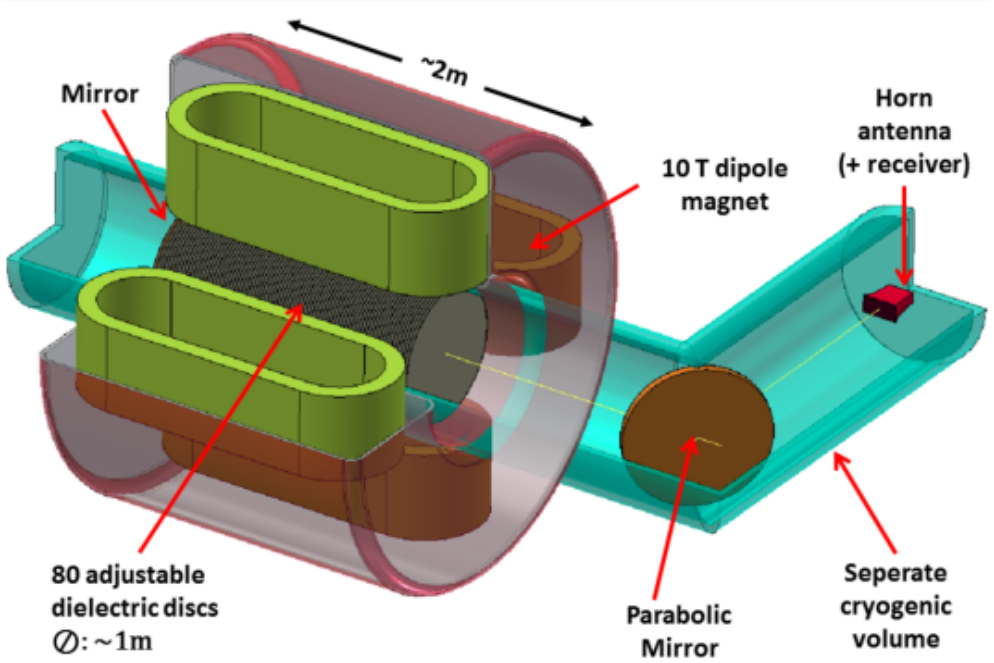


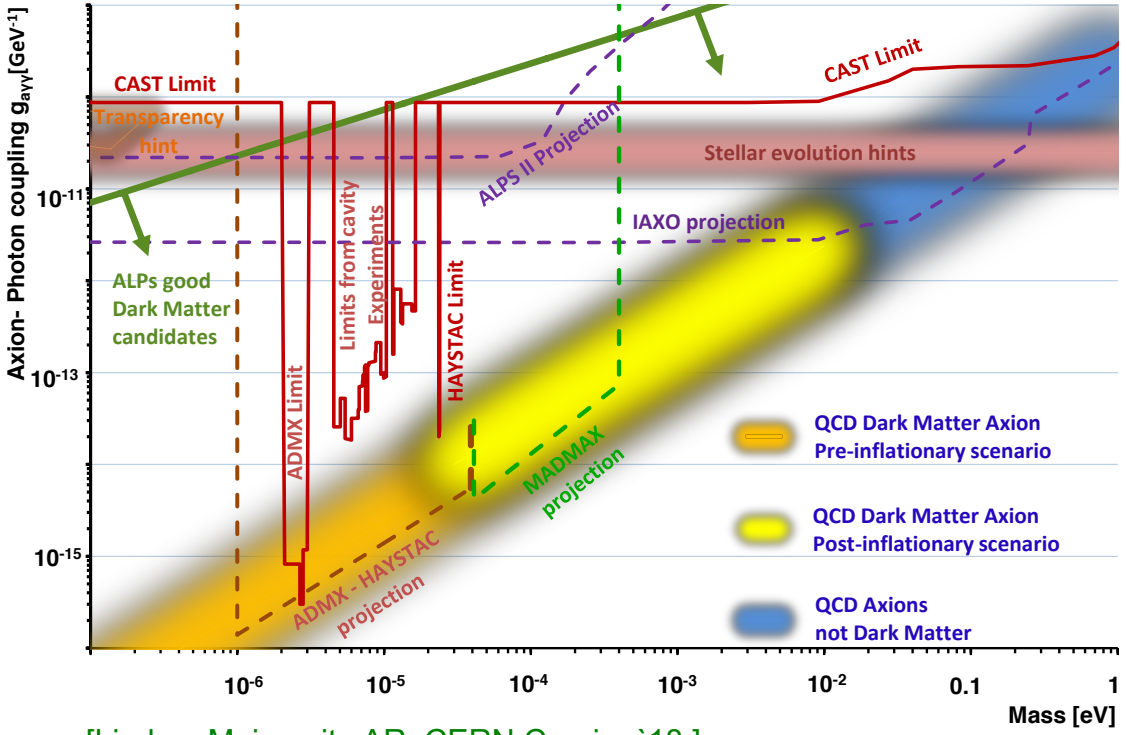
Searches for Dark Matter Axions

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; data taking may start in 2026

Searches for Dark Matter Axions

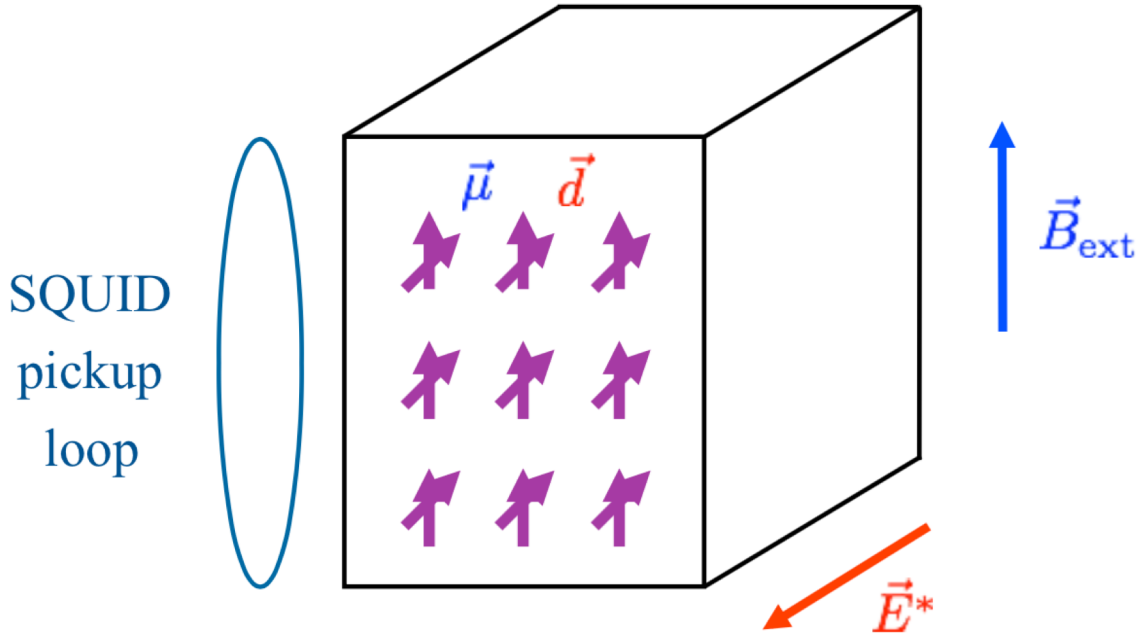
Magnetic Resonance Searches

- Axion DM field induces oscillating NEDMs:

$$d_N(t) = g_d \sqrt{2\rho_{\rm DM}}\cos(m_A t)/m_A$$

  - 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]

- CASPEr-Electric currently being set-up in Boston
- Probe QCD axion dark matter in mass range predicted by GUTs [Ernst,AR,Tamarit 18; Di Luzio,AR,Tamarit 18]

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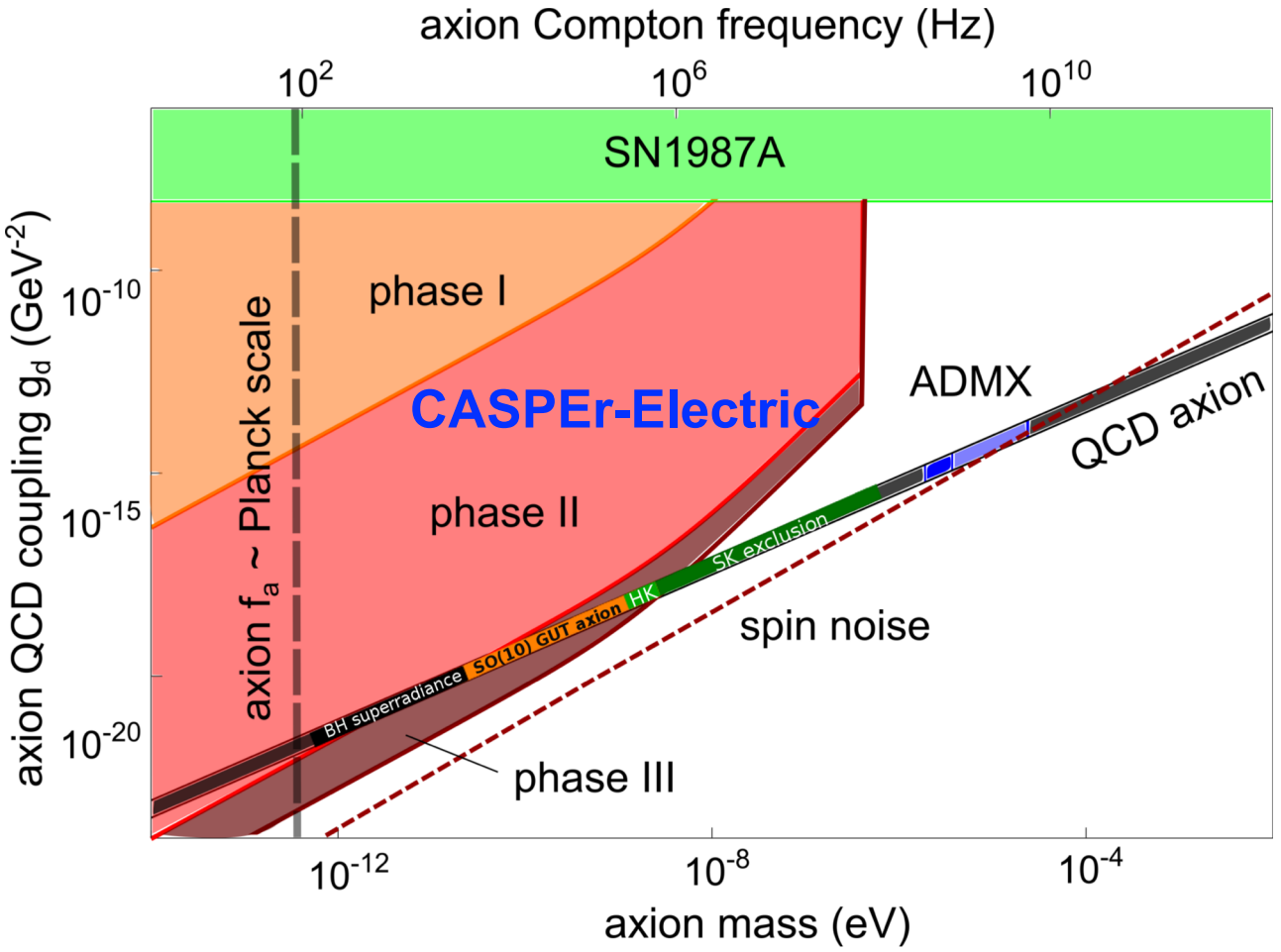

[Ernst,Di Luzio,AR,Tamarit 18]

Searches for Dark Matter Axions

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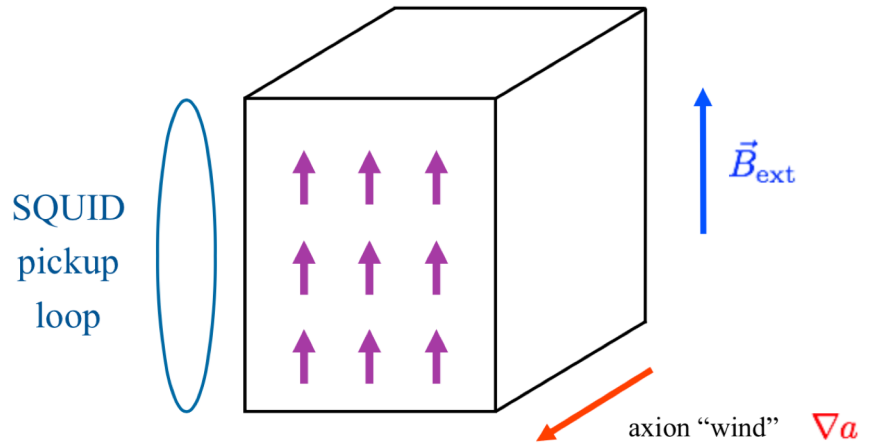
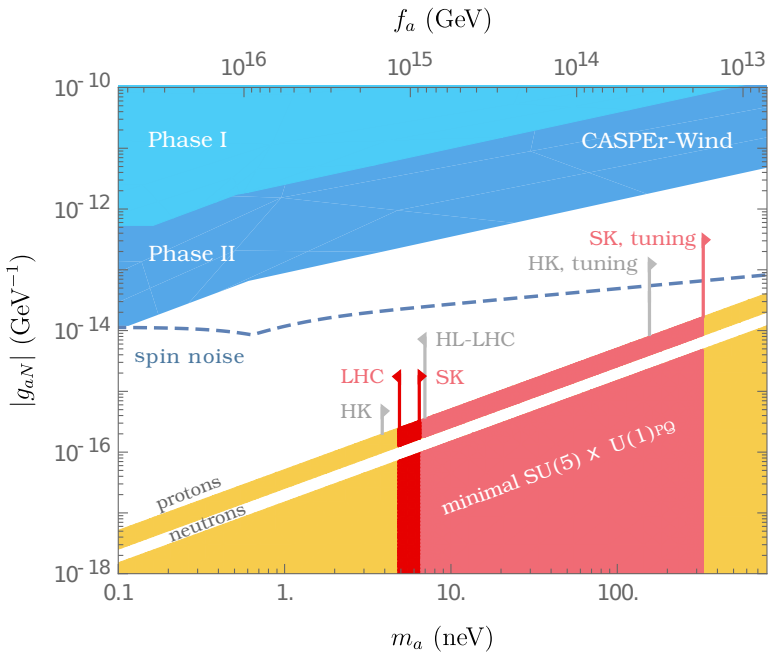
- CASPEr-Wind (Mainz) and QUAX (Legnaro) search for spin precession about axion wind



[Budker et al. 14]



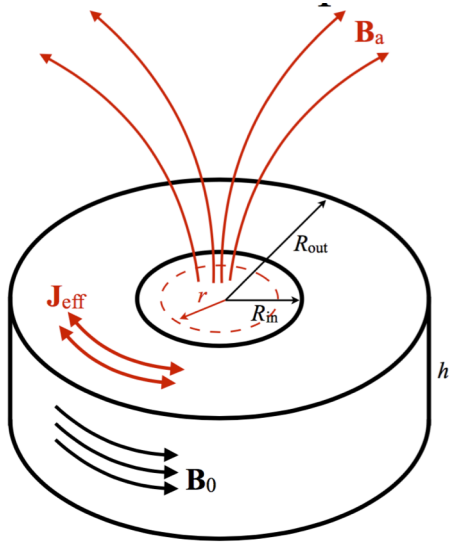
[Di Luzio,AR,Tamarit 18]

Searches for Dark Matter Axions

Searching for Axion-Induced Magnetic Fields

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

- ABRACADABRA (MIT) currently being set-up



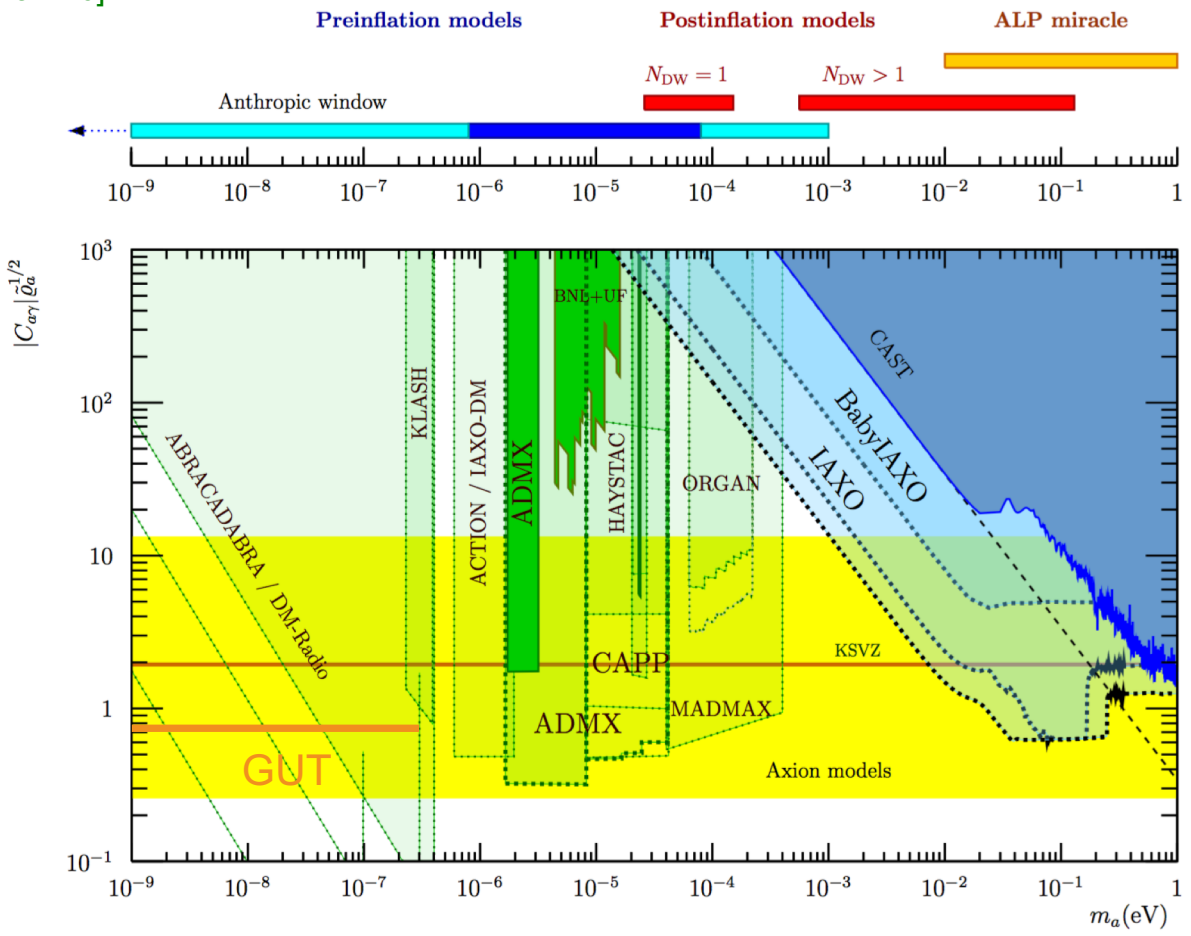
$$g_{A\gamma} = \frac{\alpha}{2\pi f_A} C_{A\gamma}$$

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

- DM-Radio (Stanford): similar experiment in path-finder status [Silva-Feaver et al. 16]

- Probe QCD axion dark matter in mass range predicted by Grand Unified Theories (GUTs)

[Ernst,AR,Tamarit 18; Di Luzio,AR,Tamarit 18]



[Irastorza,Redondo 18]

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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  - Helioscopes (IAXO, ...)
  - Haloscopes (ABRACADABRA, BRASS, ADMX, CASPEr, CULTASK, HAYSTAC, MADMAX, ORGAN, QUAX, ...)
- 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]

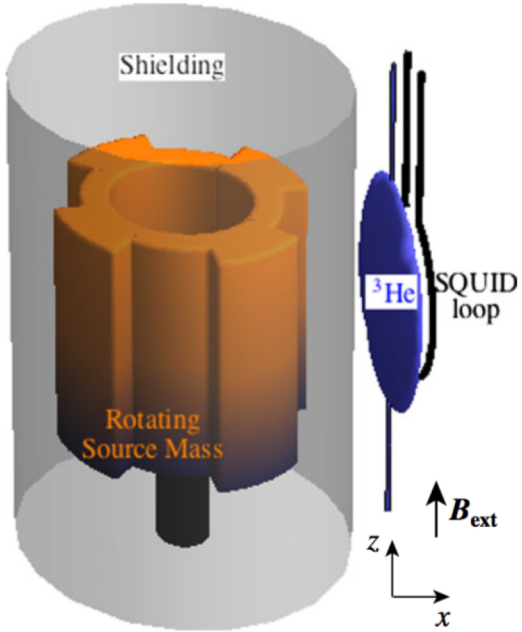

FIG. 1 (color online). A source mass consisting of a segmented cylinder with n sections is rotated around its axis of symmetry at frequency ω_{rot}, which results in a resonance between the frequency $\omega = n\omega_{rot}$ at which the segments pass near the sample and the resonant frequency $2\vec{\mu}_N \cdot \vec{B}_{ext}/\hbar$ 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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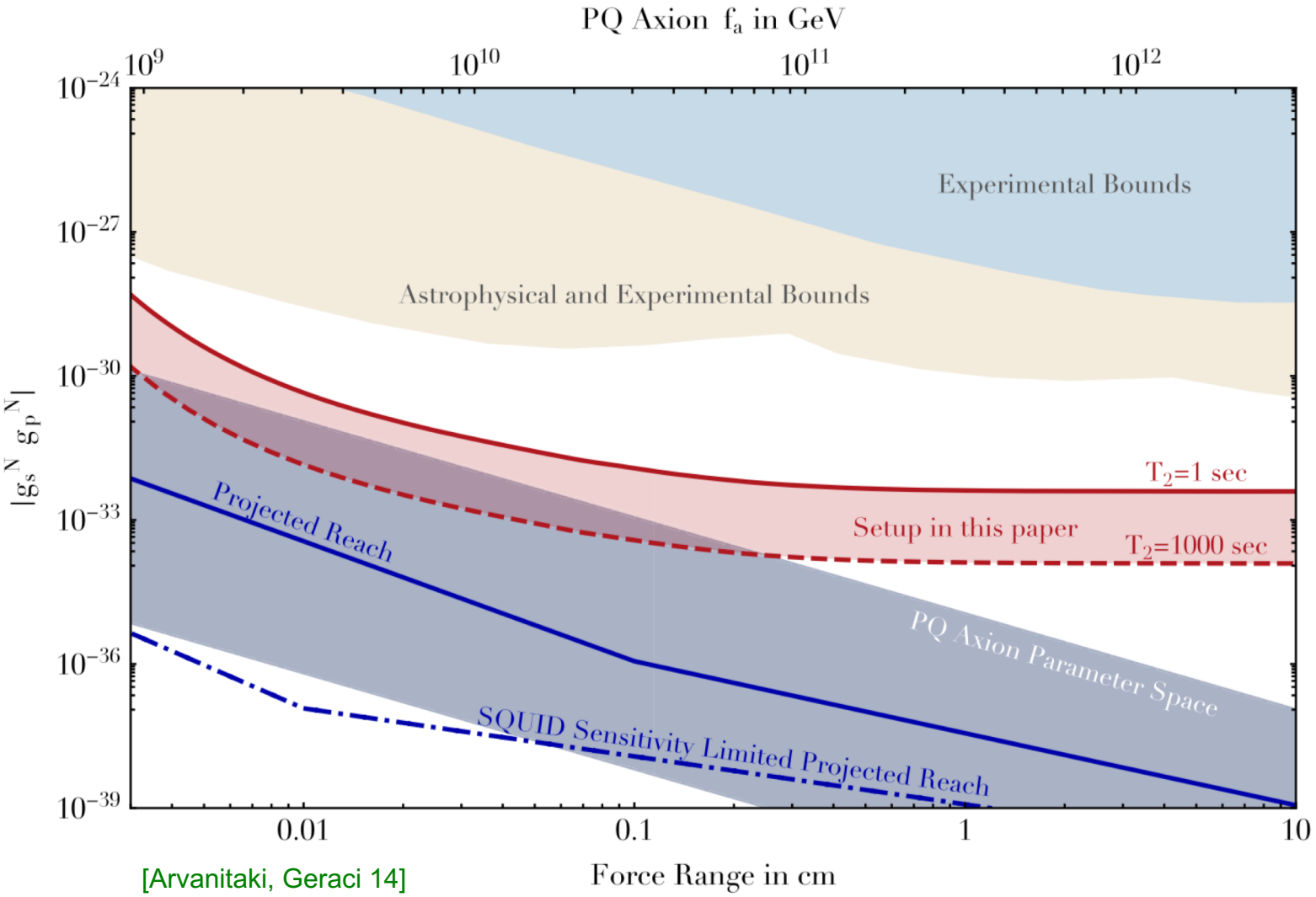

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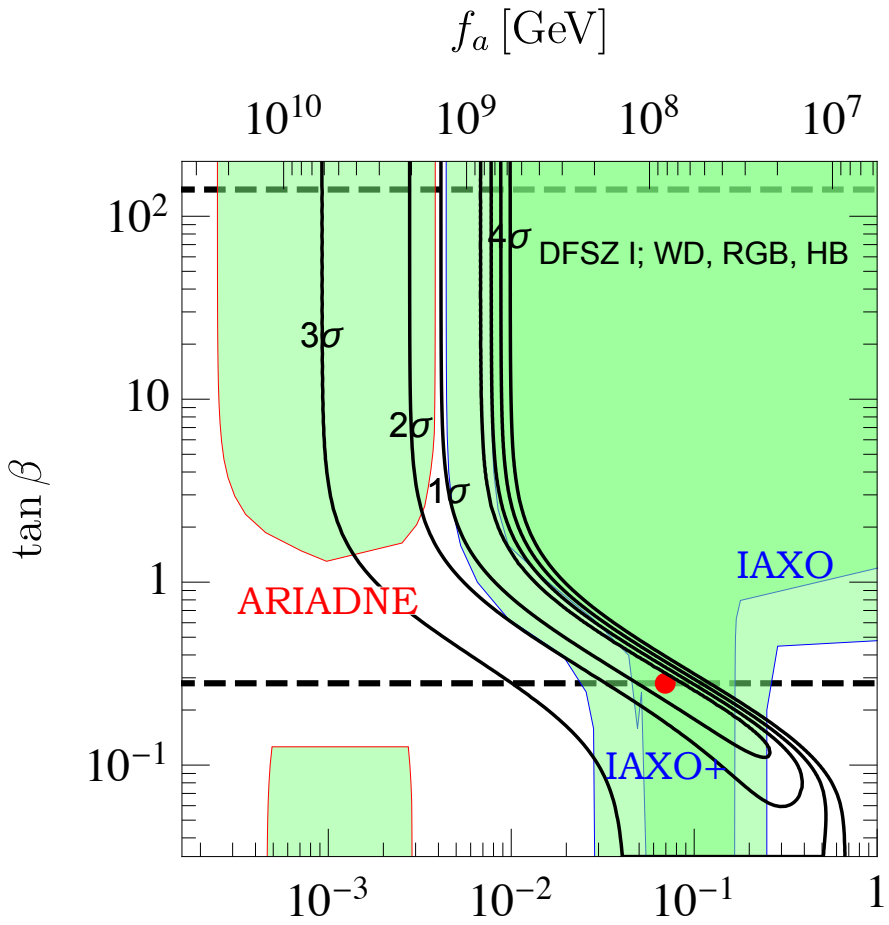
- Can probe QCD axion interpretation of cooling anomaly of WDs, RGB and HB stars complementary to IAXO

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



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