

Status and Prospects of Axion Experiments at DESY

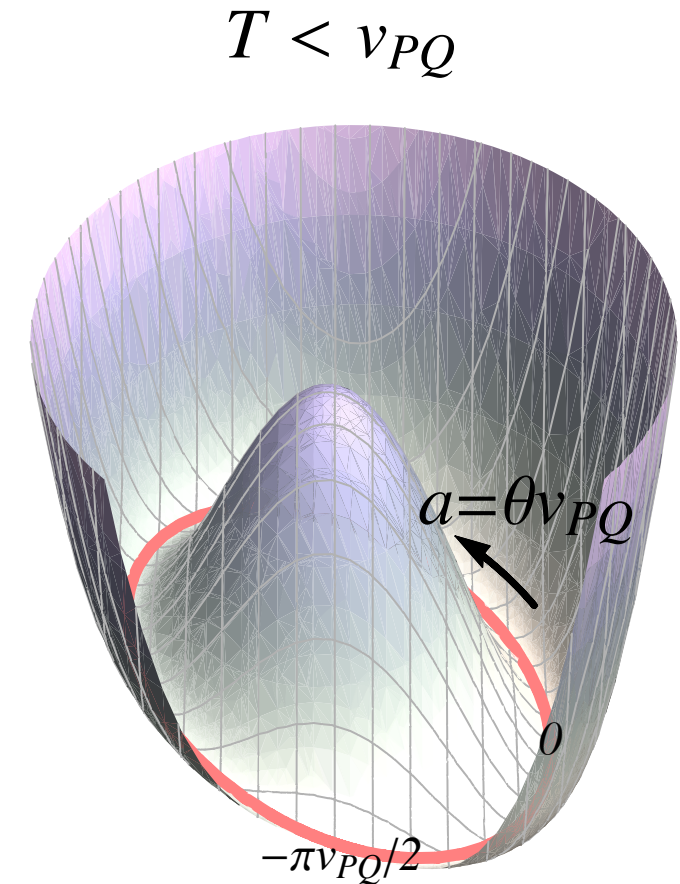
Andreas Ringwald
Quarks Online Workshop
Dark Matter
22-24 June 2021



The Quest for Axions and Axion-Like Particles

Motivations from Particle Physics and Cosmology

- Axions, or more generally Axion-Like Particles (ALPs)
 - arise as pseudo-scalar pseudo-Nambu-Goldstone bosons from approximate Abelian global symmetries beyond the SM which are broken at a scale f_a much greater than the electroweak scale
 - Peccei-Quinn symmetry: Axion
[Peccei,Quinn '77; Weinberg '78; Wilczek '78]
 - Lepton symmetry: Majoron
[Chikashige,Mohapatra,Peccei '81, Gelmini,Roncadelli '81]
 - Family symmetry: Familon
[Wilczek '82; Berezhiani,Khlopov '90]

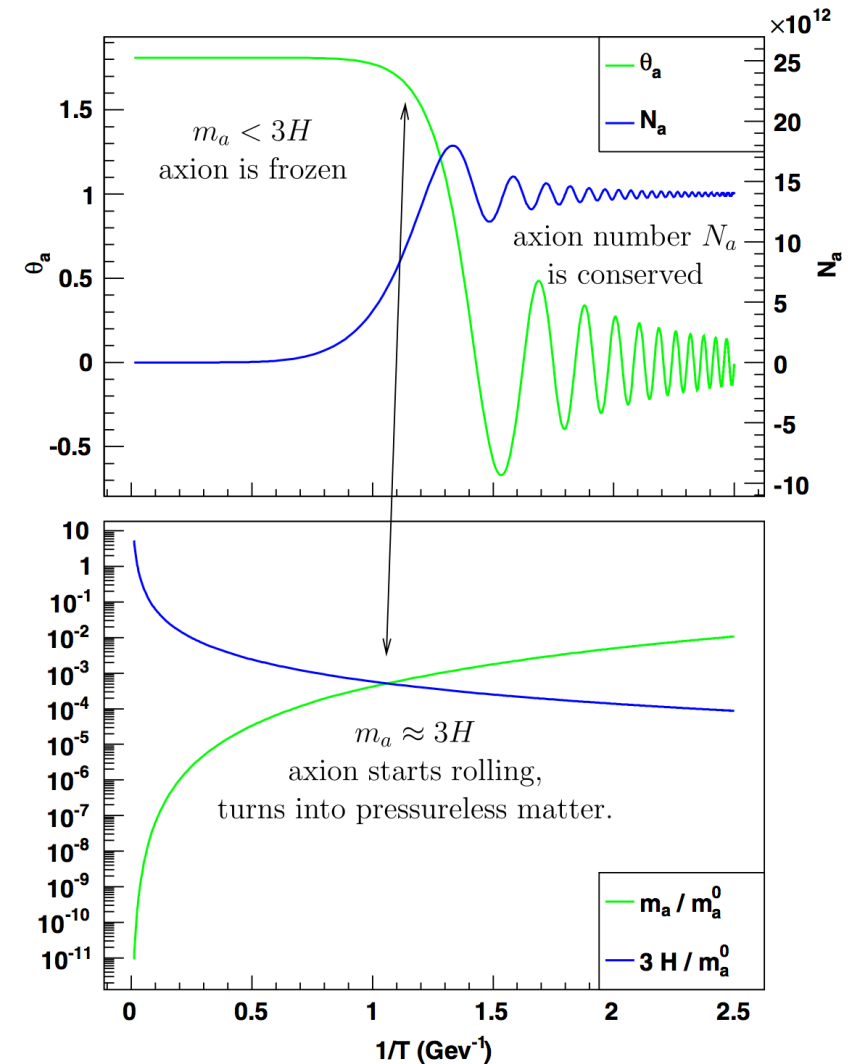


[Majorovits,Desch,AR '18]

The Quest for Axions and Axion-Like Particles

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 - Family symmetry: Familon
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 - are well-motivated dark matter candidates
[Preskill,Wise,Wilczek '83; Abbott,Sikivie '83; Dine,Fischler '83]
 - generated via vacuum re-alignment mechanism (and variants) and, in the case of post-inflationary symmetry breaking, by decay of topological defects



[Wantz,Shellard '09]

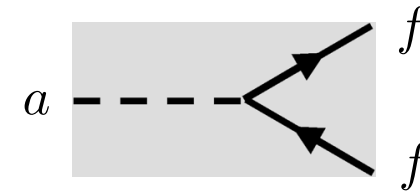
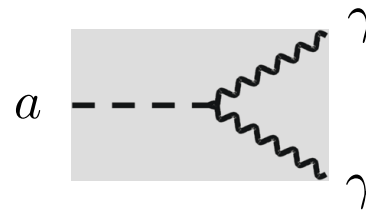
Axion and ALPs

WISPs: very Weakly Interacting Slim Particles

- Very weakly interacting:

- Couplings to SM suppressed by powers of symmetry breaking scale $f_a \gg v \simeq 246 \text{ GeV}$:

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



- Slim:

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

- Axion:

$$m_A \approx \frac{m_\pi f_\pi}{f_A} \frac{\sqrt{z}}{1+z}$$

[Weinberg '78]

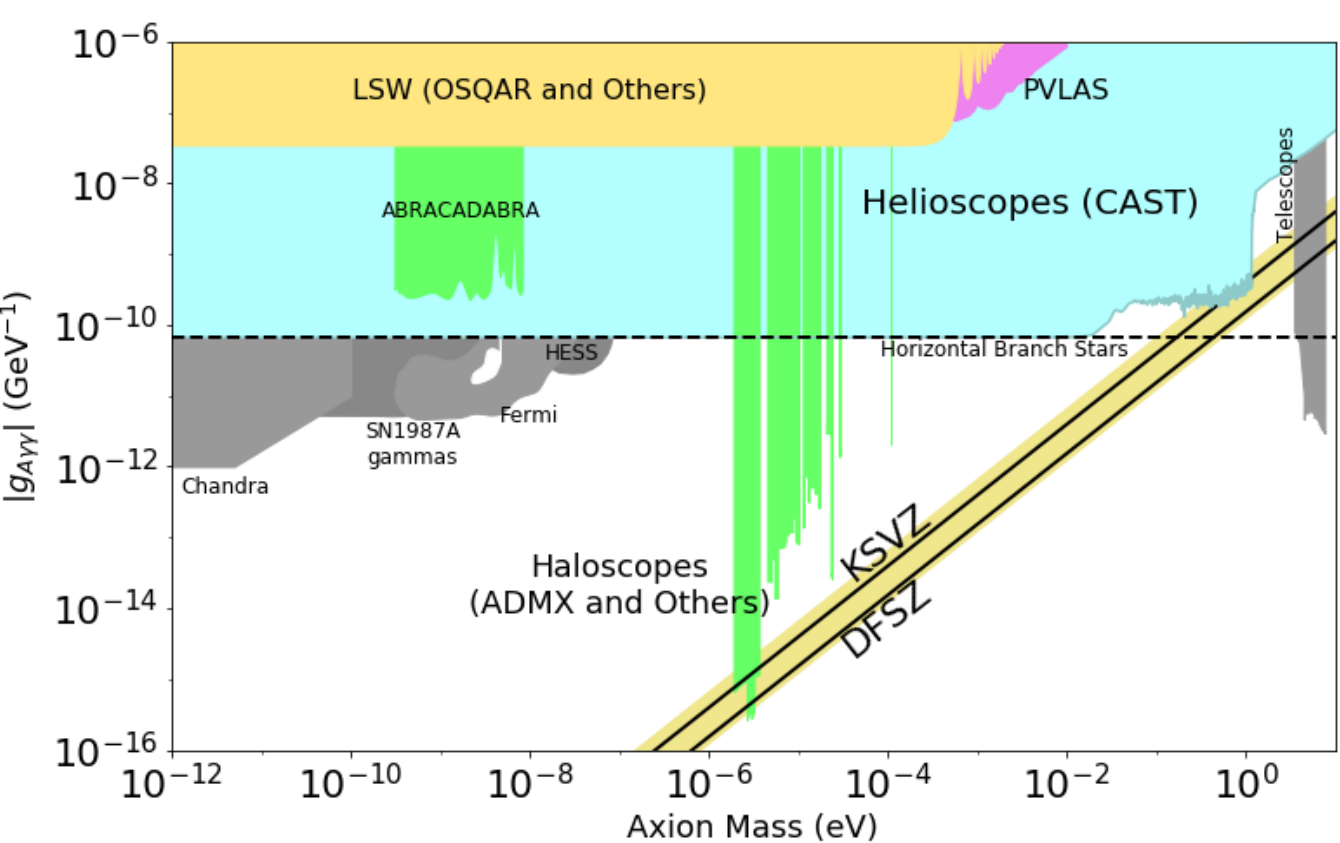
$$z = m_u/m_d$$

$$C_{A\gamma} = \frac{E}{N} - \frac{2}{3} \frac{4+z}{1+z}$$

[Kaplan 85; Srednicki '85]

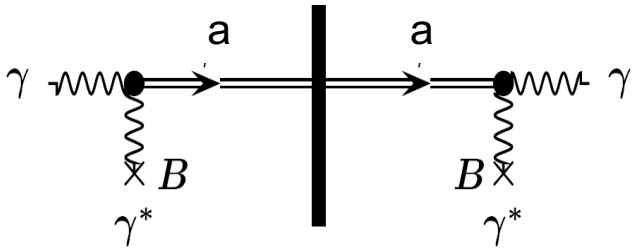
Current Constraints on Photon Coupling

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

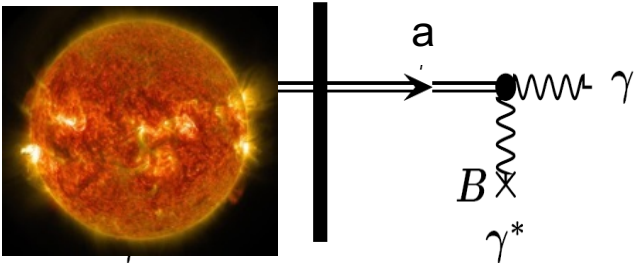


[AR,Rosenberg,Rybka in: Review of Particle Physics, PTEP 2020 (2020) 8, 083C01]

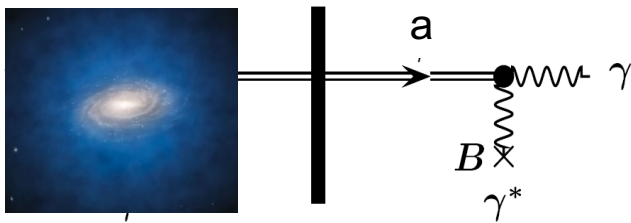
Laser shining through a wall (LSW)



Sun shining through a wall (Helioscope)



DM shining through a wall (Haloscope)



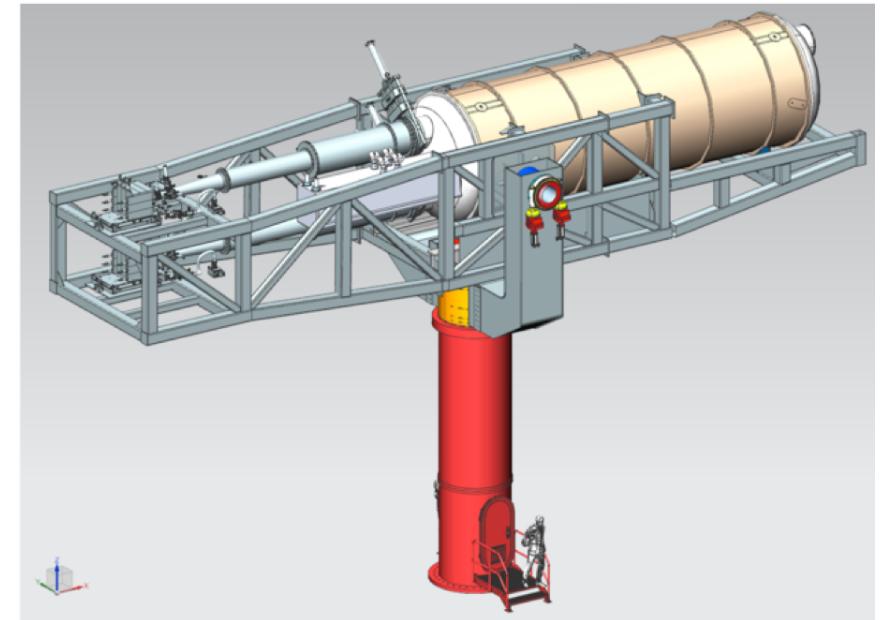
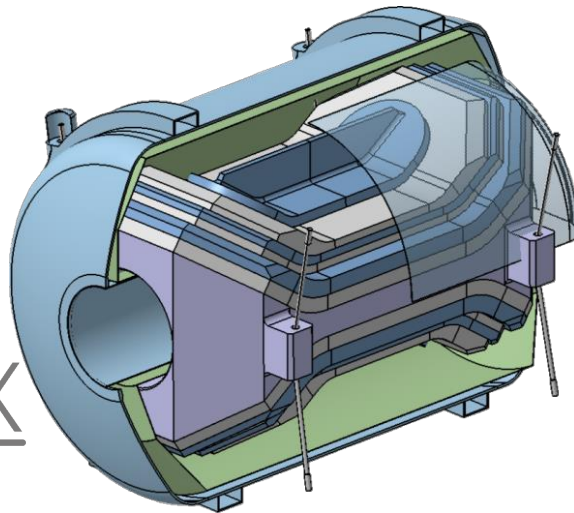
[Axel Lindner]

Upcoming Axion Searches at DESY

ALPS II

Baby IAXO

AD MAX



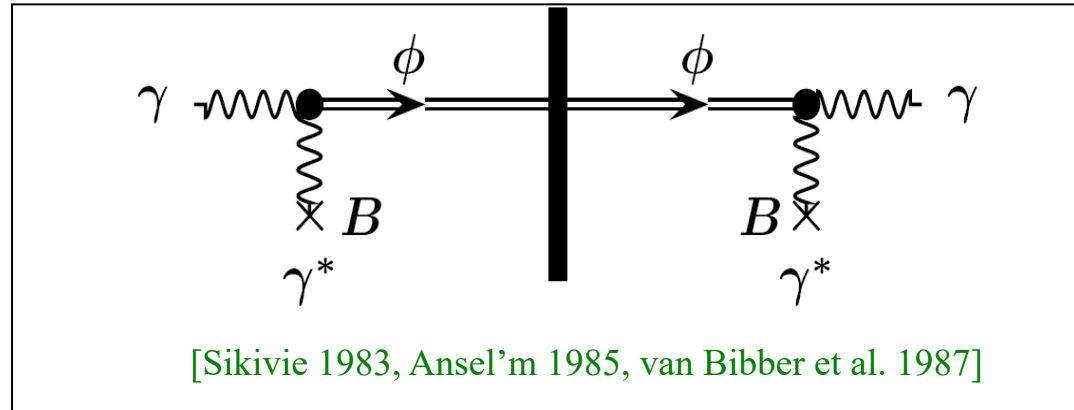
Light Shining through a Wall

Searching for Home-Made Axions

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

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

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



- Probability, that photon converted in axion 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:
- $$P(\gamma \leftrightarrow a) \simeq \frac{1}{4} (g_{a\gamma} B L_B)^2$$

Light Shining through a Wall

- Proposal to recycle HERA dipoles for a light shining through a wall experiment:

[AR 03]



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Physics Letters B 569 (2003) 51–56

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Production and detection of very light bosons in the HERA tunnel

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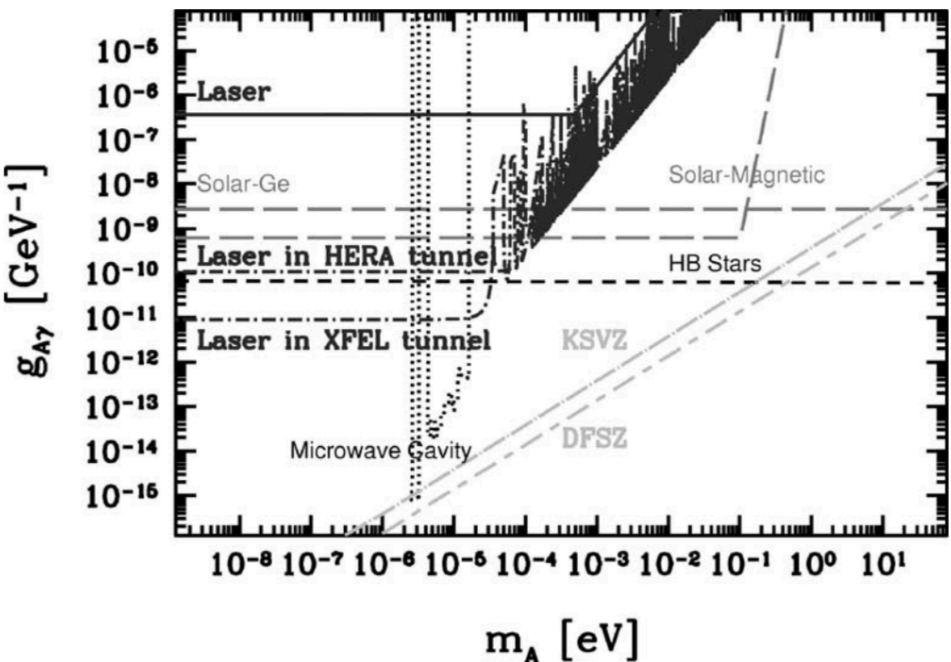
Editor: P.V. Landshoff

Abstract

There are strong theoretical arguments in favour of the existence of very light scalar or pseudoscalar particles beyond the Standard Model which have, so far, remained undetected, due to their very weak coupling to ordinary matter. We point out that after HERA has been decommissioned, there arises a unique opportunity for searches for such particles: a number of HERA's four hundred superconducting dipole magnets might be recycled and used for laboratory experiments to produce and detect light neutral bosons that couple to two photons, such as the axion. We show that, in this way, laser experiments searching for photon regeneration or polarization effects in strong magnetic fields can reach a sensitivity which is unprecedented in pure laboratory experiments and exceeds astrophysical limits from stellar evolution considerations.

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A. Ringwald / Physics Letters B 569 (2003) 51–56



Light Shining through a Wall

[Ehret et al.. 07]

- Letter of Intent for ALPS experiment:

DESY 07-014

Public version — 8.12.2006

Production and Detection of Axion-Like Particles in a HERA Dipole Magnet – Letter-of-Intent for the ALPS experiment –

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Niels Meyer,¹ Dieter Notz,¹ Andreas Ringwald,^{1,†} and Günter Wiedemann³

¹*Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, D-22607 Hamburg, Germany*

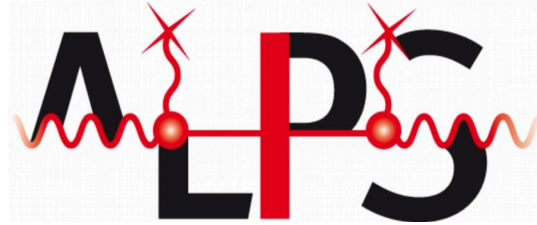
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³*Sternwarte Bergedorf, Gojenbergsweg 112, D-21029 Hamburg, Germany*

Recently, the PVLAS collaboration has reported evidence for an anomalous rotation of the polarization of light in vacuum in the presence of a transverse magnetic field. This may be explained through the production of a new light spin-zero (axion-like) neutral particle coupled to two photons. In this letter-of-intent, we propose to test this hypothesis by setting up a photon regeneration experiment which exploits the photon beam of a high-power infrared laser, sent along the transverse magnetic field of a superconducting HERA dipole magnet. The proposed¹ ALPS (Axion-Like Particle Search) experiment offers a window of opportunity for a rapid firm establishment or exclusion of the axion-like particle interpretation of the anomaly published by PVALS. It will also allow for the measurement of mass, parity, and coupling strength of this particle.

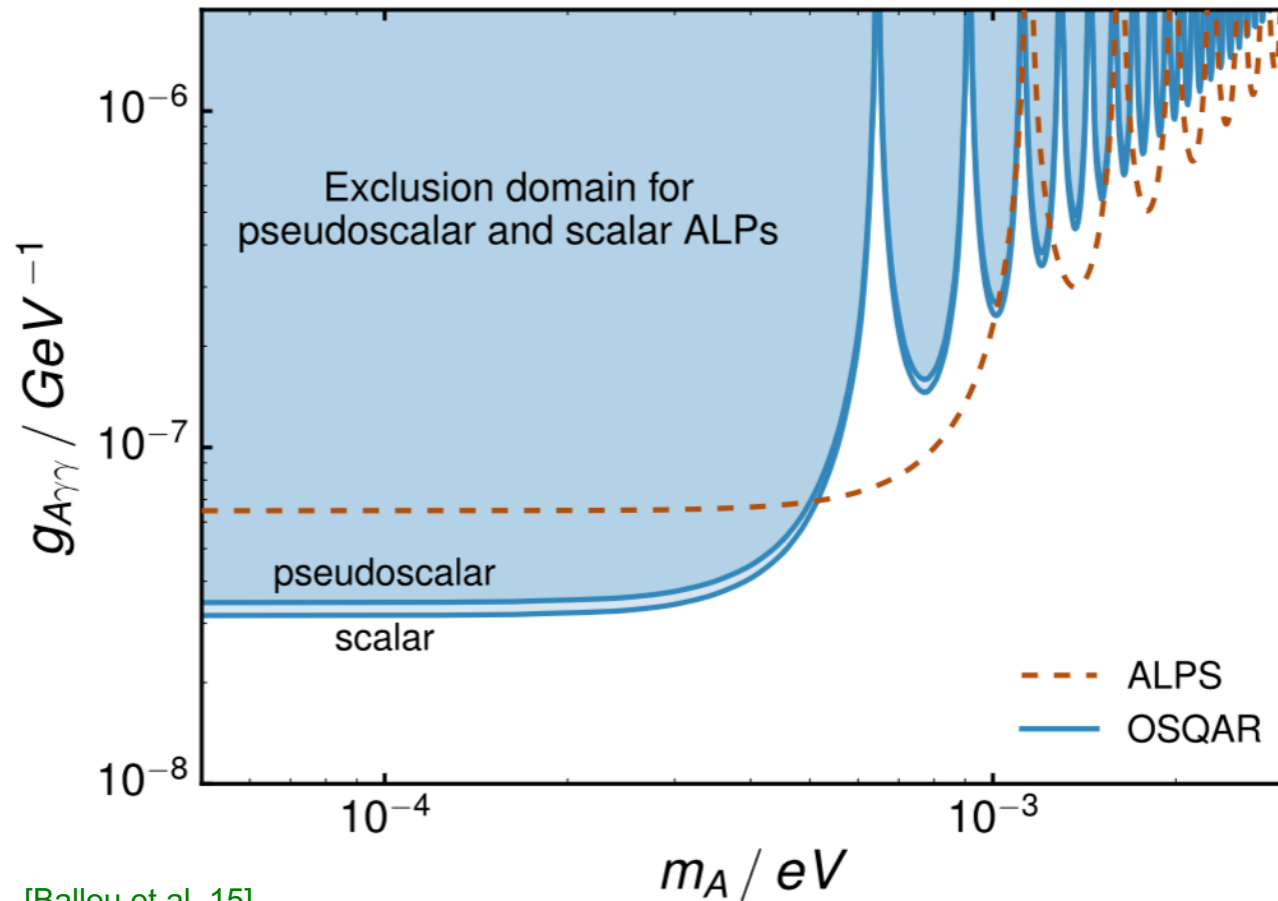
Light Shining through a Wall

- ALPS I @ DESY (in collaboration with AEI Hannover and U Hamburg)



Light Shining through a Wall

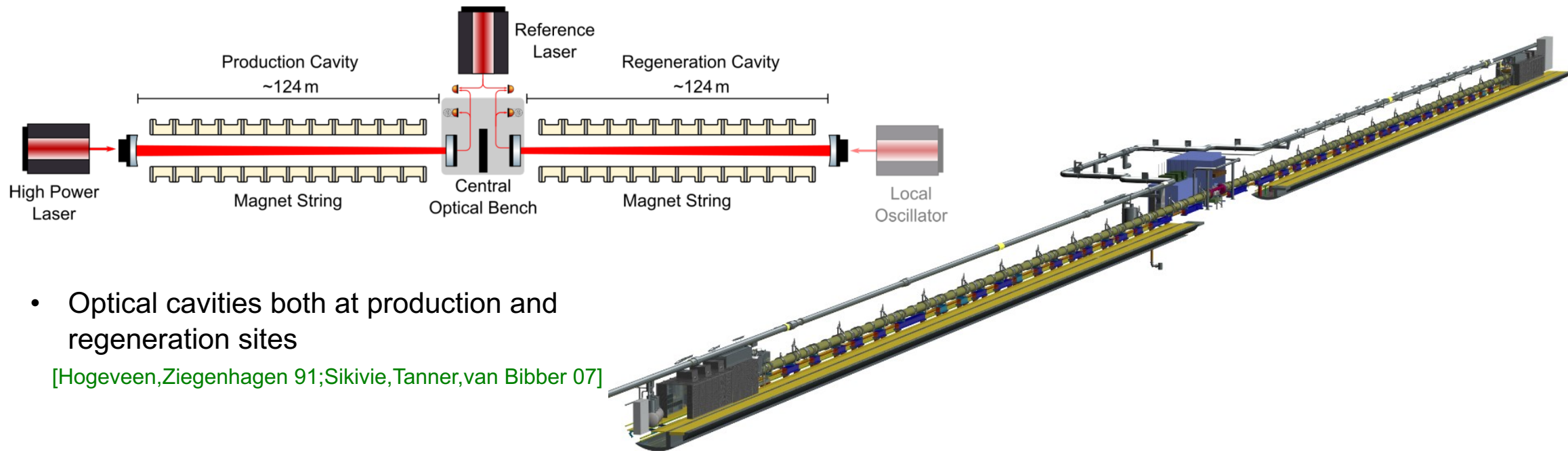
- **ALPS I** @ DESY (in collaboration with AEI Hannover and U Hamburg) [Ehret et al. 10]
- LSW experiments **ALPS I** and **OSQAR** @ CERN give currently the best purely laboratory limit on low mass axions:



[Ballou et al. 15]

Light Shining through a Wall

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

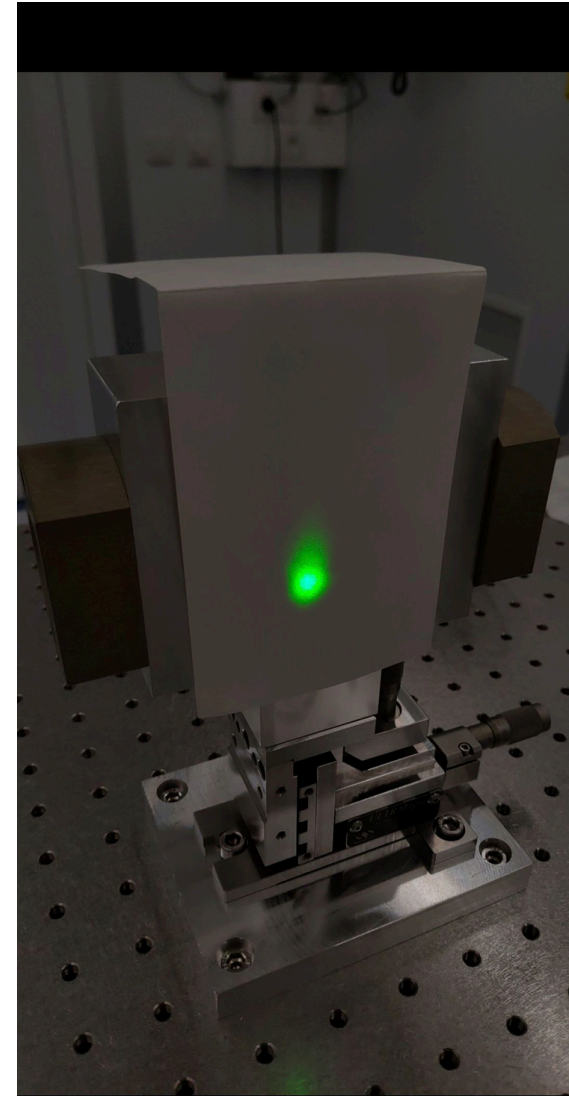
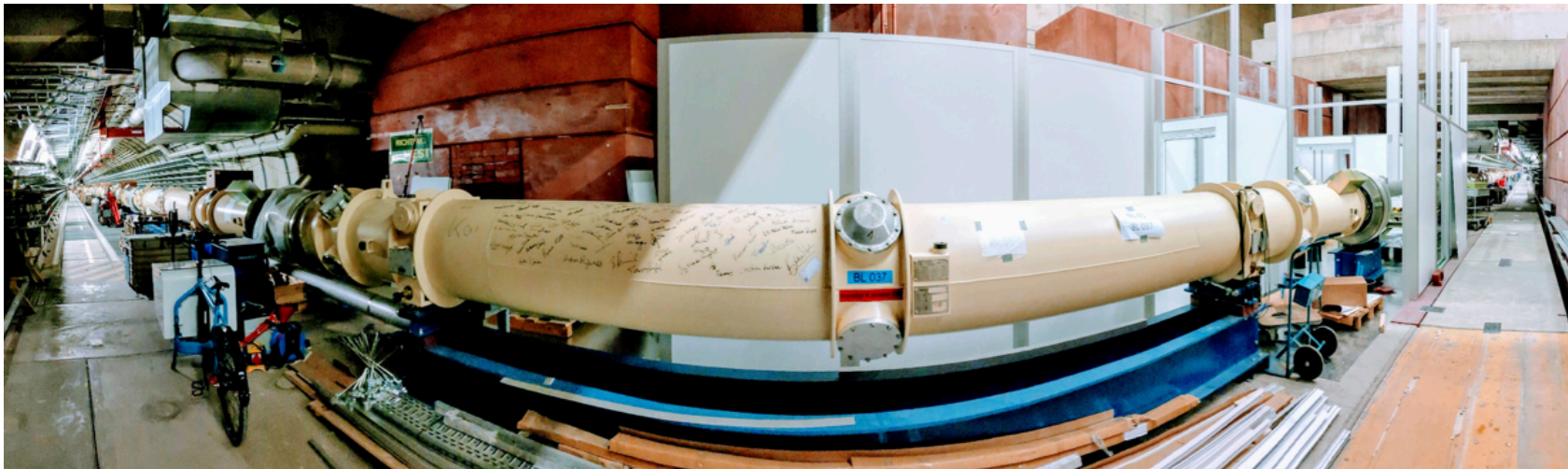


- Optical cavities both at production and regeneration sites
[Hogeveen,Ziegenhagen 91; Sikivie, Tanner, van Bibber 07]

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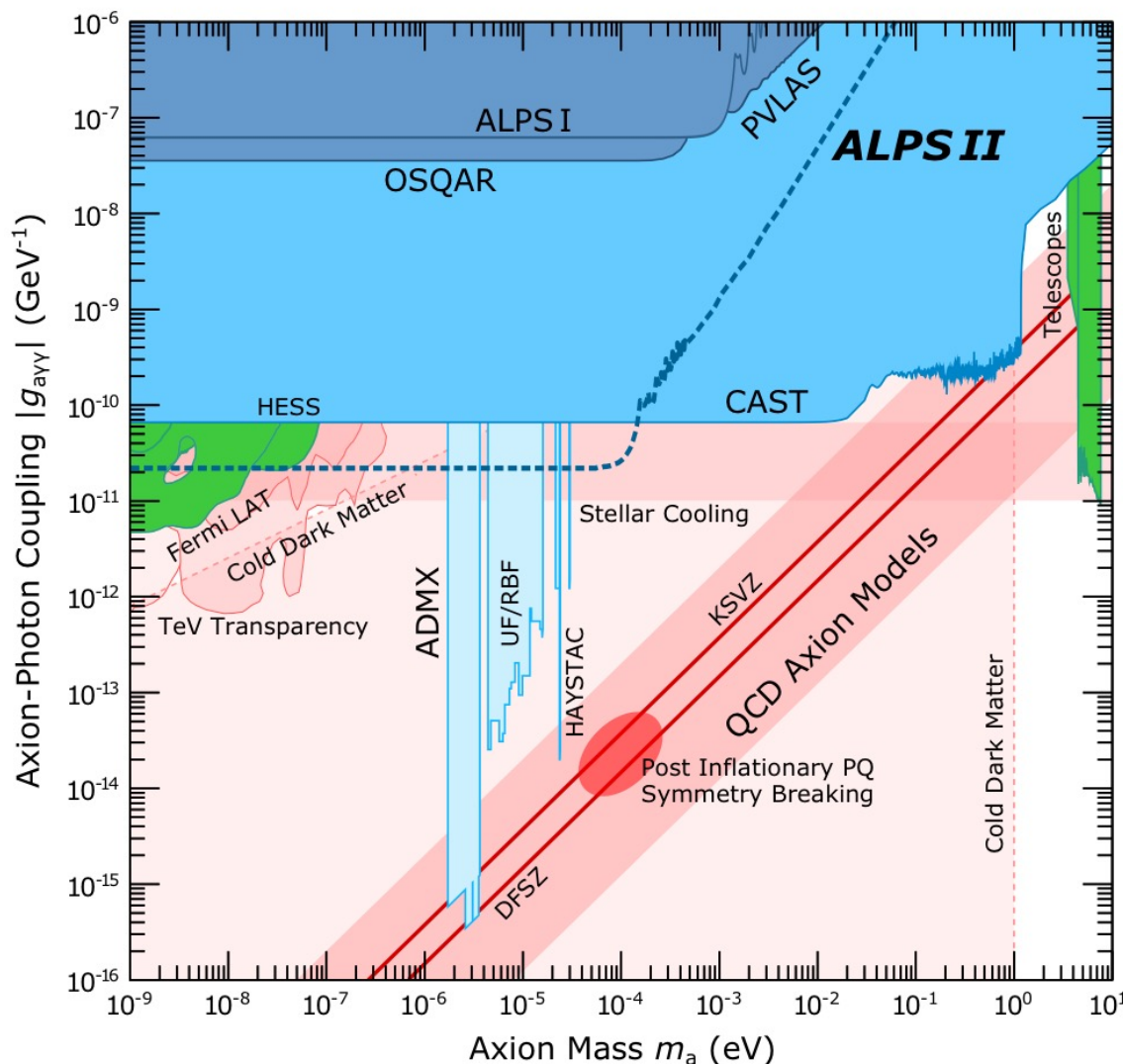
- **ALPS II** @ DESY (in collaboration with AEI Hannover, U Cardiff, U Florida, U Mainz)
- Construction progressing:
 - All 24 magnets are now installed and aligned
 - Cleanrooms at end stations are now operational
 - Commissioning of the optical system has begun
 - Alignment laser through the beam tube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

[Bähre et al (ALPS II TDR) 13]



Light Shining through a Wall

- **ALPS II** will probe previously uncharted territory, in particular part of parameter space relevant for astro hints:

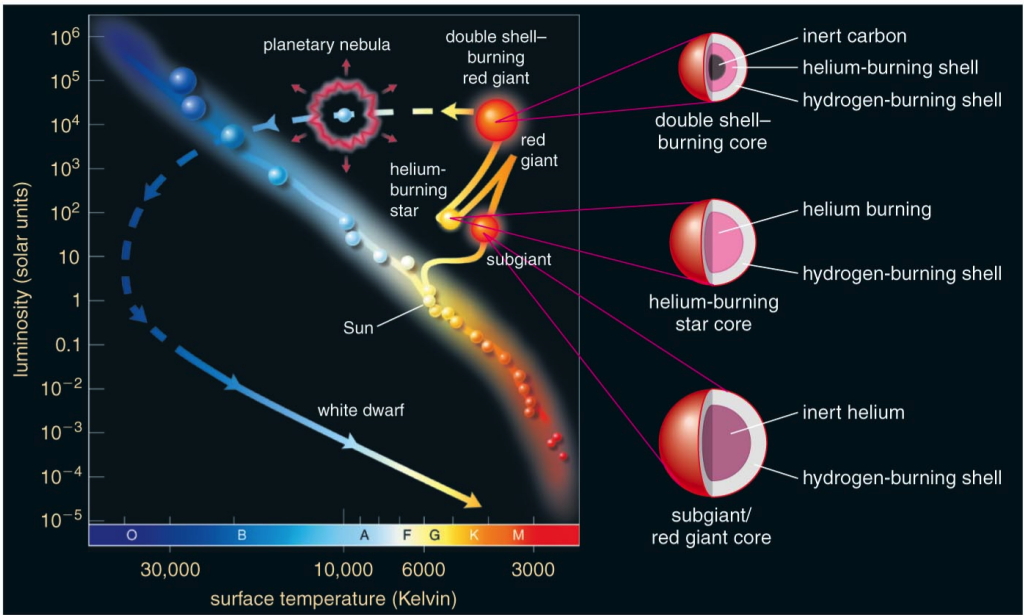


[Spector '21]

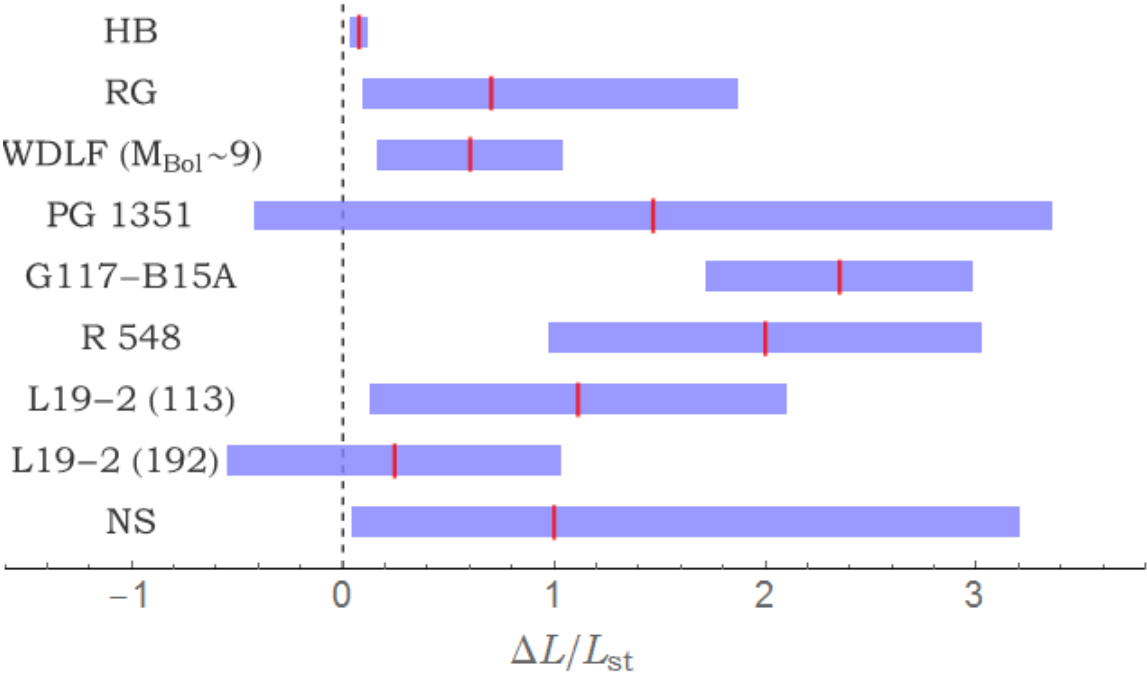
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Astrophysical hints for axions

- There are hints from astrophysics which may explained by axions:
 - Excessive energy losses of stars in various stages of their evolution



[Copyright Addison Wesley]



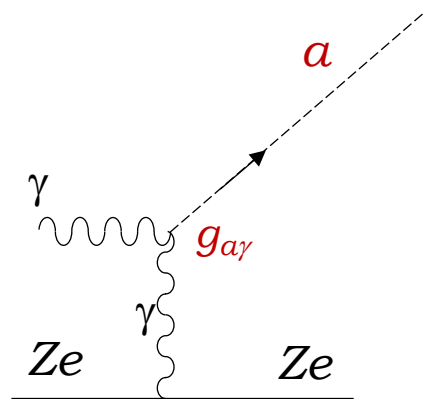
[Giannotti, Irastorza, Redondo, AR 15]

Light Shining through a Wall

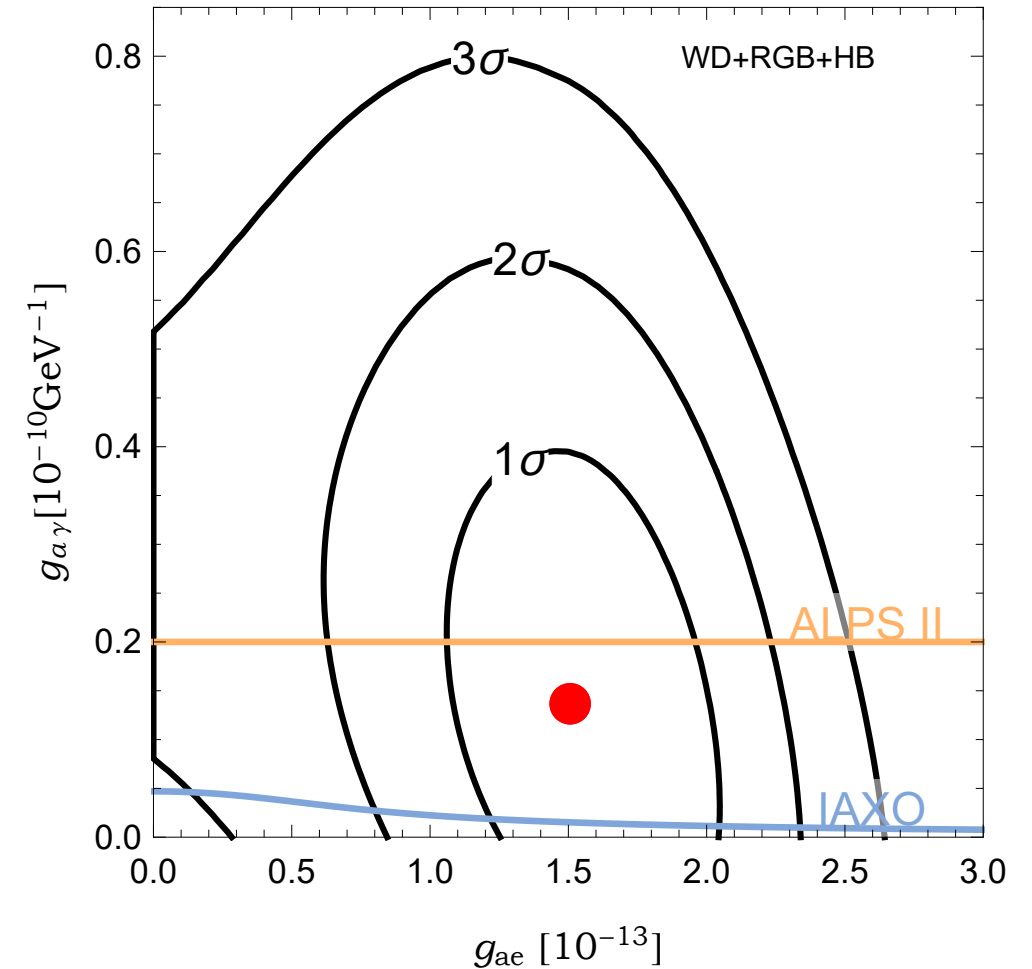
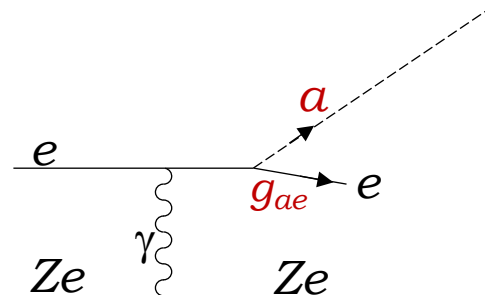
Astrophysical hints for axions

- There are hints from astrophysics which may be explained by axions:
 - Excessive energy losses of stars in various stages of their evolution: may be explained by axion production

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



$$\mathcal{L} \supset -ig_{ae} a \bar{\psi}_e \gamma_5 \psi_e$$

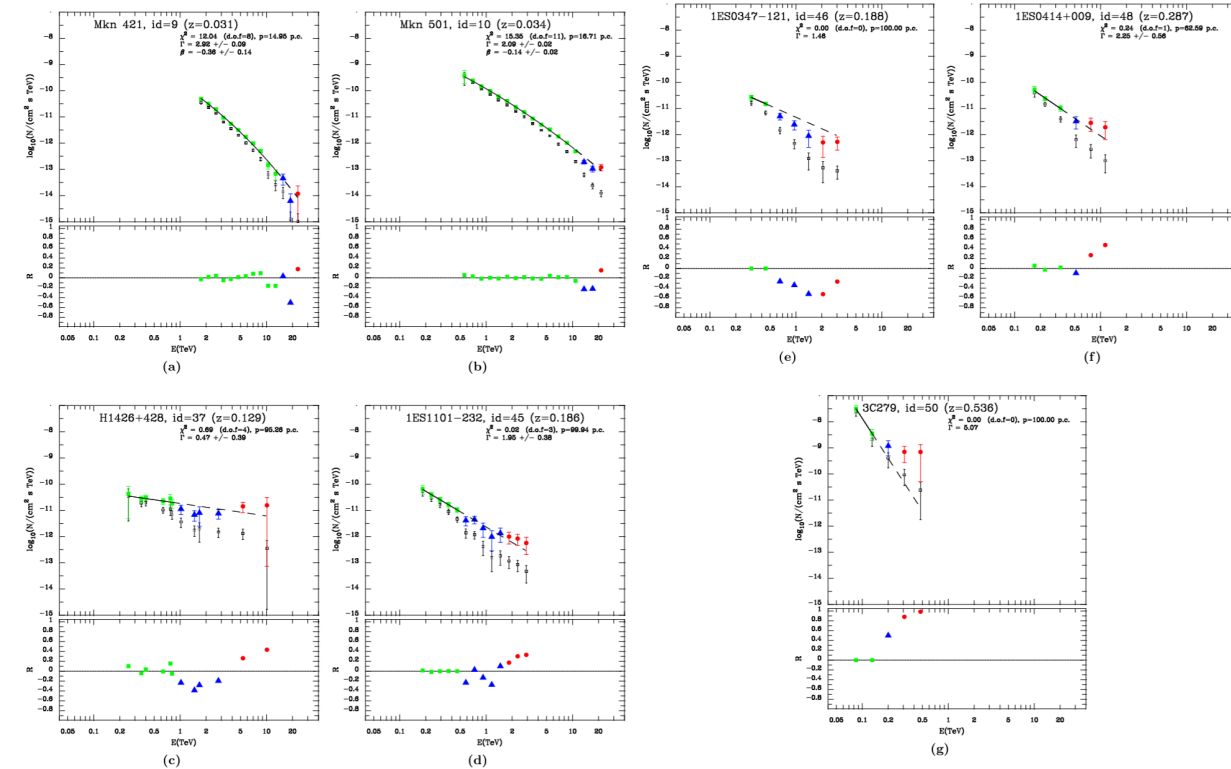
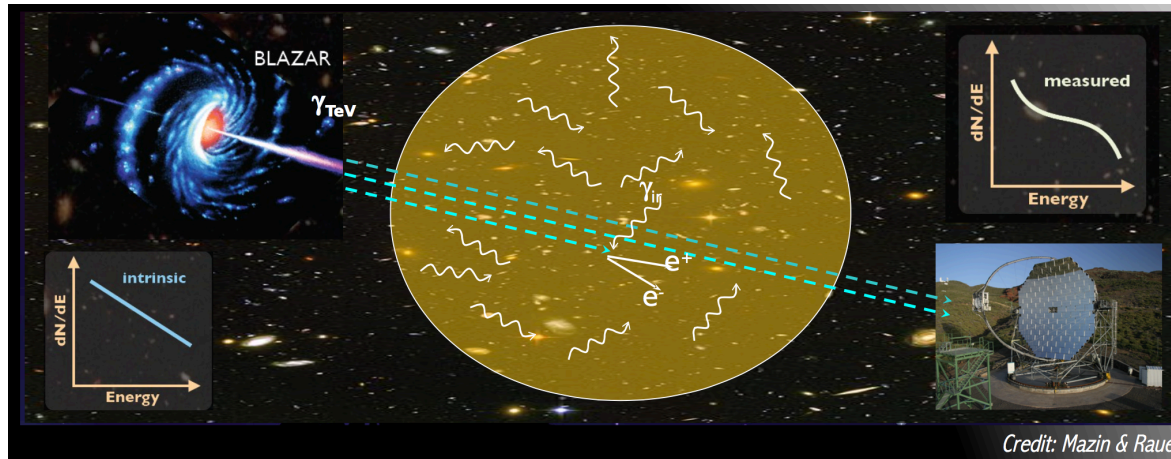


[Giannotti et al. 17]

Light Shining through a Wall

Astrophysical hints for axions

- There are 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; Rubtsov,Troitsky 14,...,Troitsky 21]



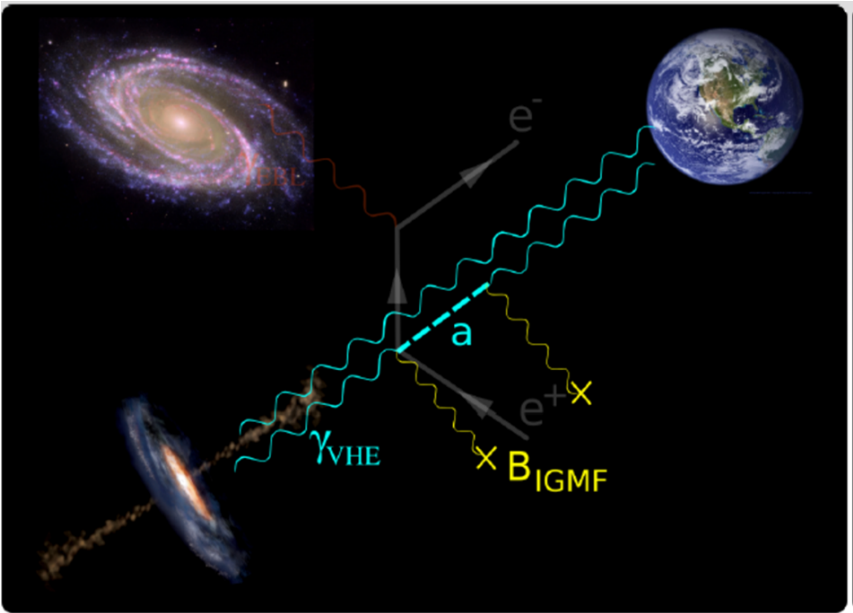
[Horns,Meyer 12]

Light Shining through a Wall

Astrophysical hints for axions

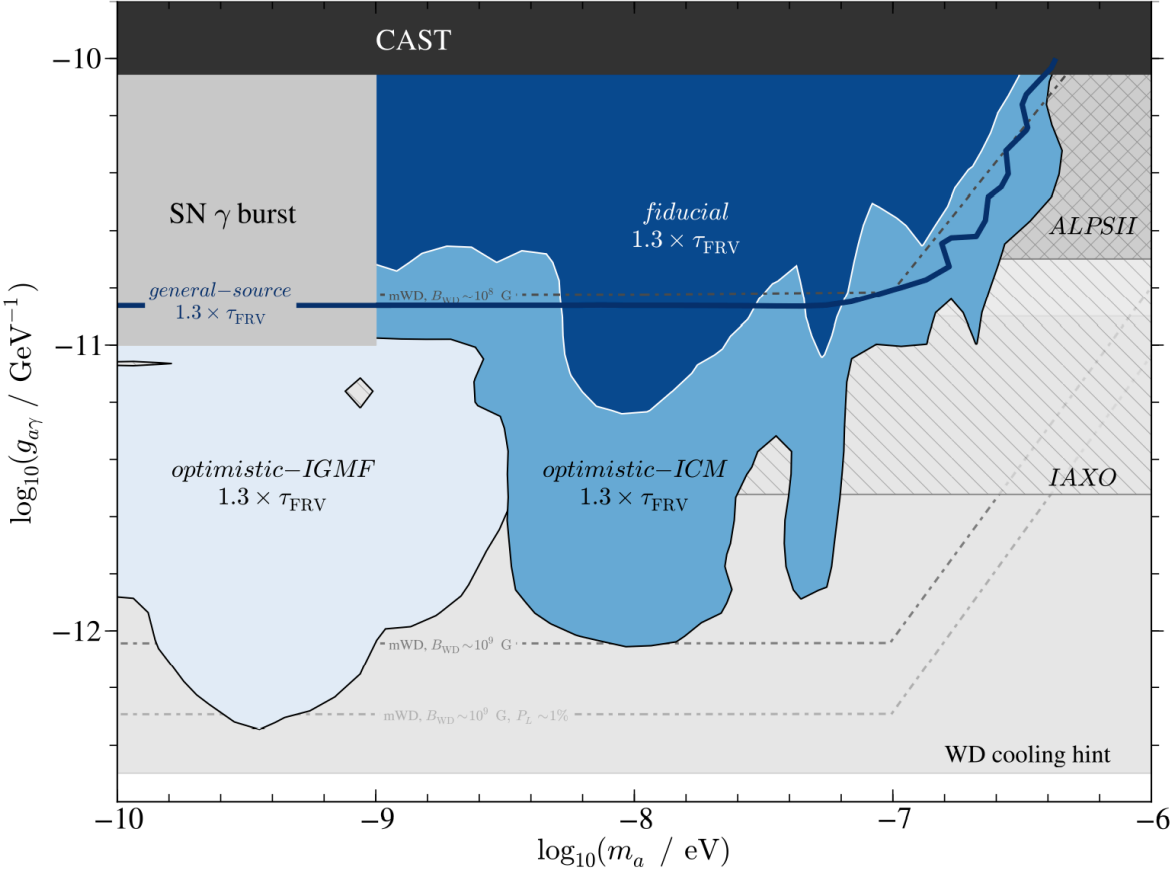
- There are hints from astrophysics which may be explained by axions:
 - Excessive energy losses of stars in various stages of their evolution
 - Excessive transparency of the universe for TeV gamma rays: may be explained by photon \leftrightarrow axion conversion

[Simet et al. 08; Sanchez-Conde et al. 09; De Angelis et al. 11]



[Manuel Meyer 12]

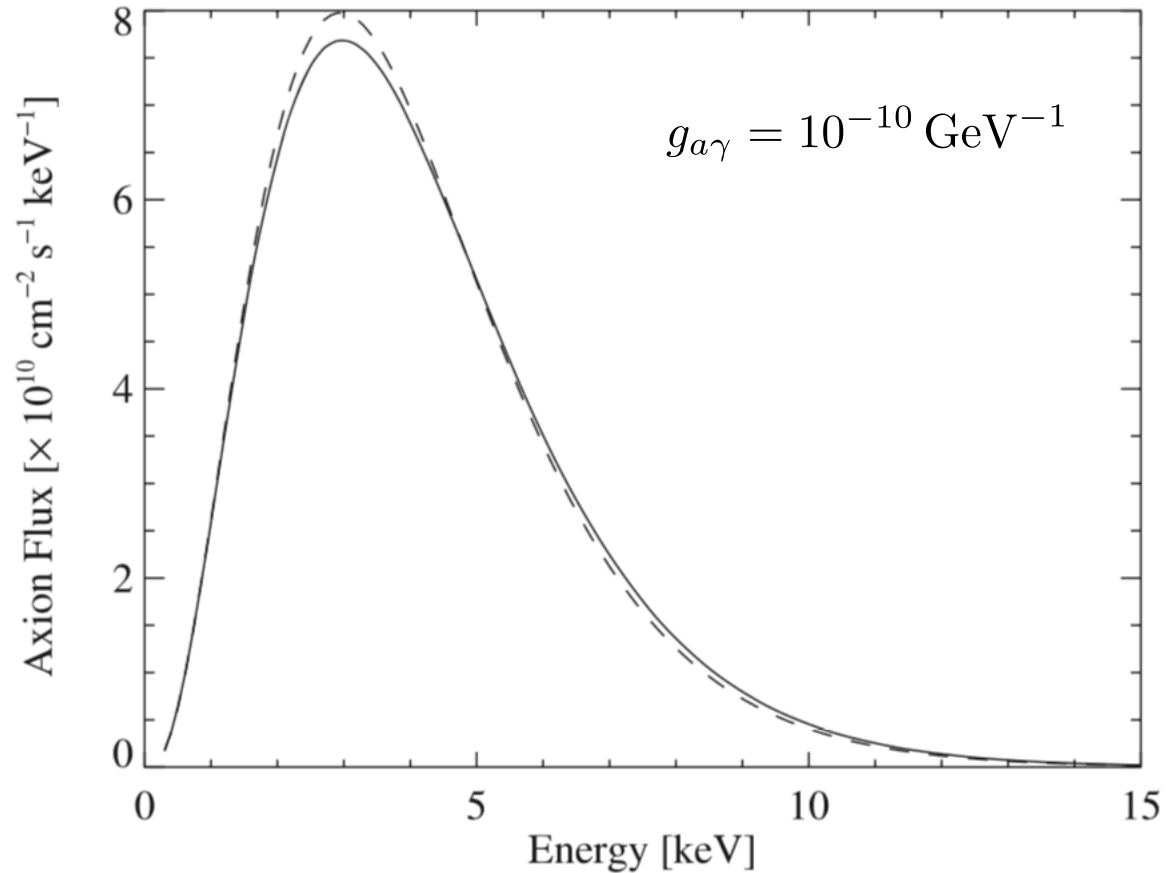
	IGMF			ICM					
Name	B_{IGMF}^0 (nG)	λ_{IGMF}^c (Mpc)	$n_{\text{el,IGM}}^0$ ($\times 10^{-7} \text{ cm}^{-3}$)	B_{ICMF}^0 (μG)	λ_{ICMF}^c (kpc)	r_{cluster} (Mpc)	$n_{\text{el,ICM}}^0$ ($\times 10^{-3} \text{ cm}^{-3}$)	r_{core} (kpc)	η
General source			Only conversion in GMF, but $\rho_{\text{init}}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



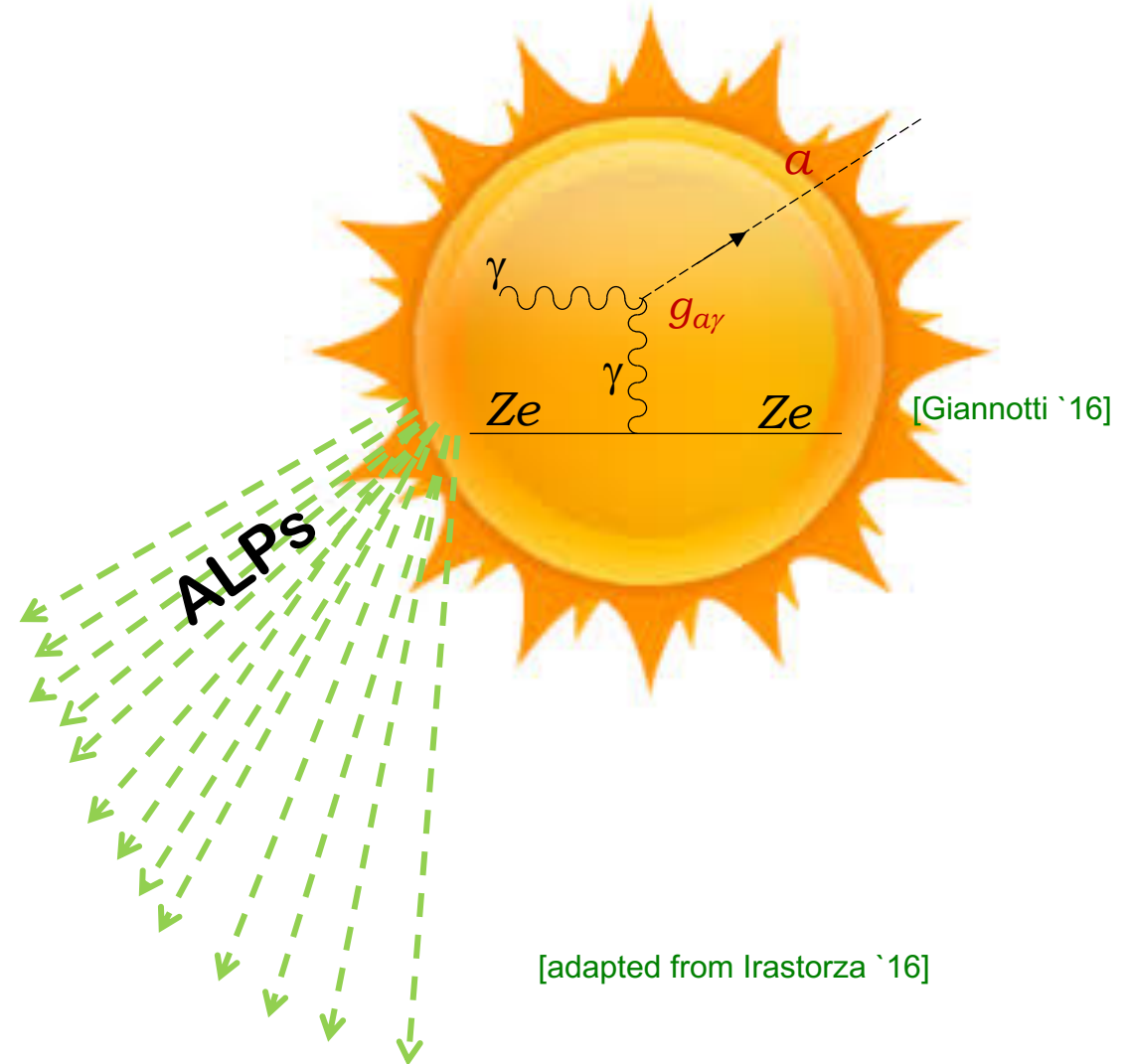
[Meyer,Horns,Raue 13]

Sun Shining through a Wall

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

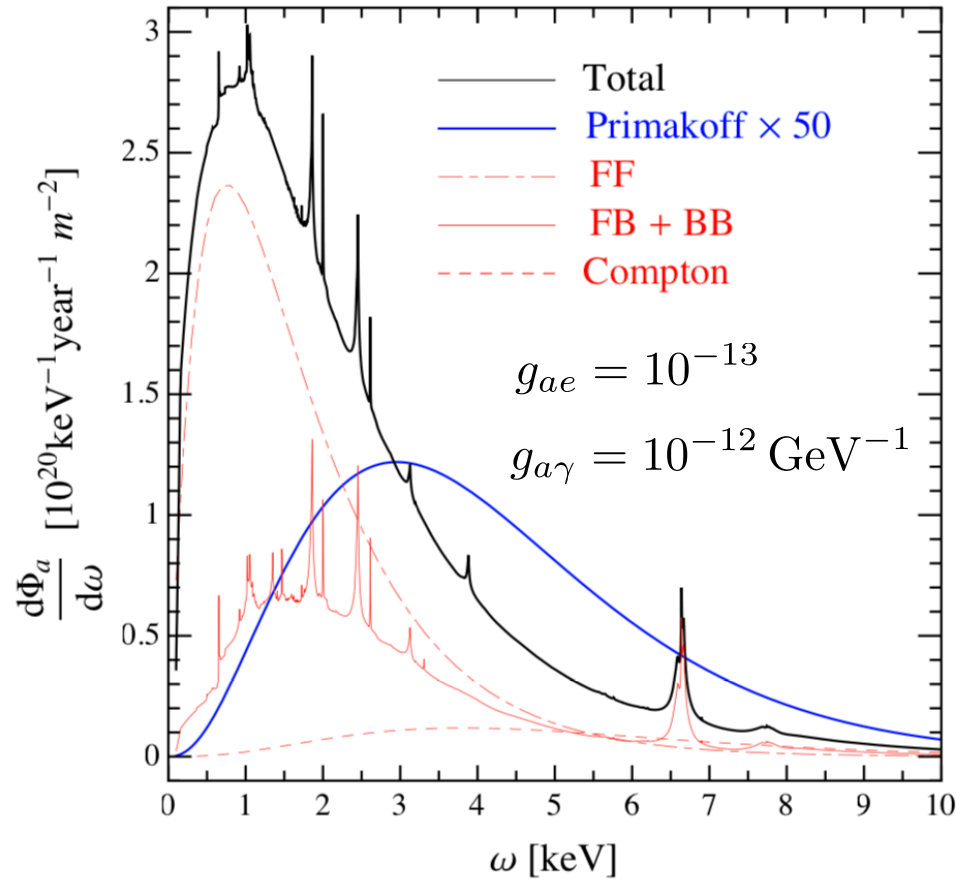


[Adriamonje et al. '07]

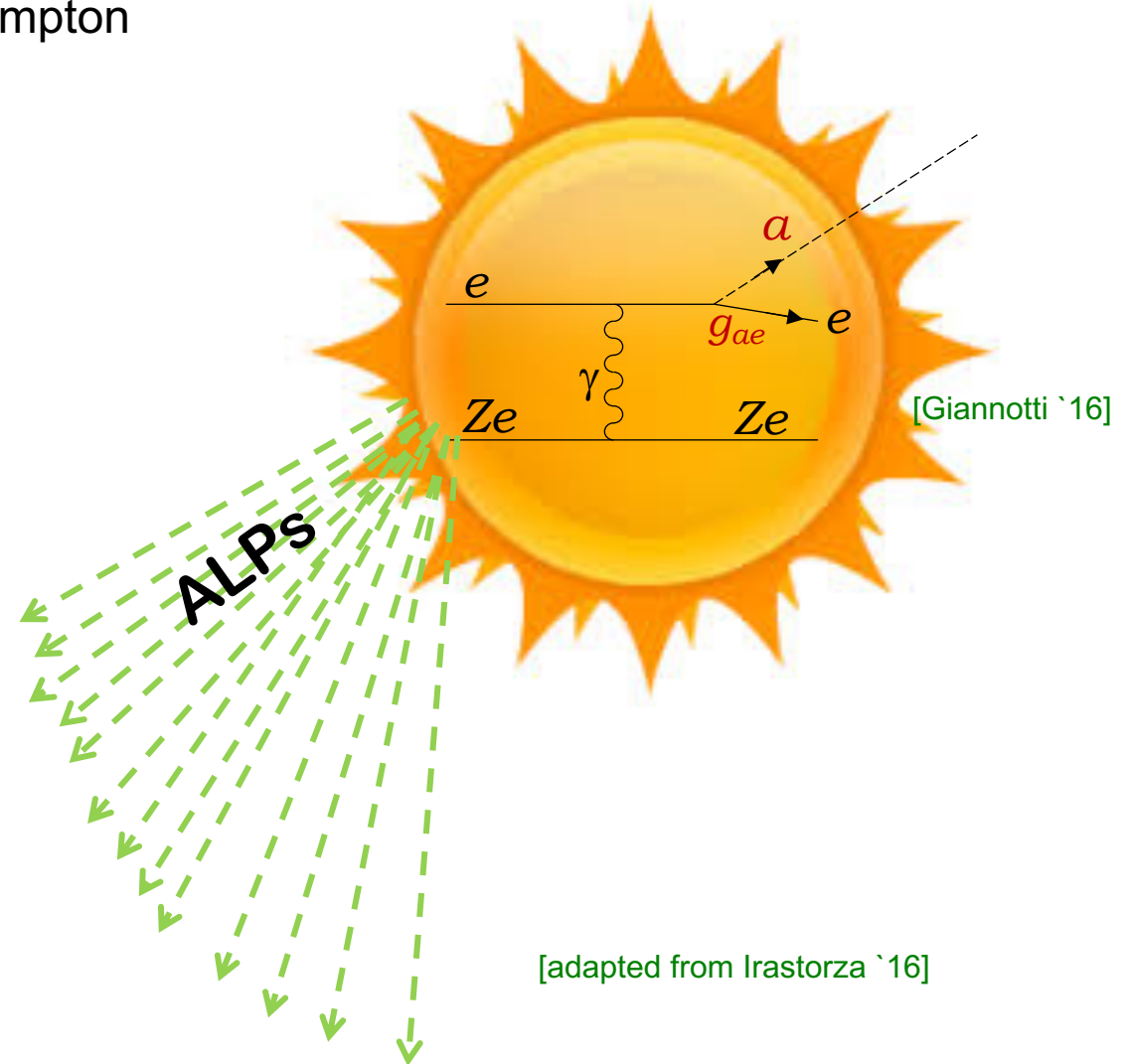


Sun Shining through a Wall

- 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



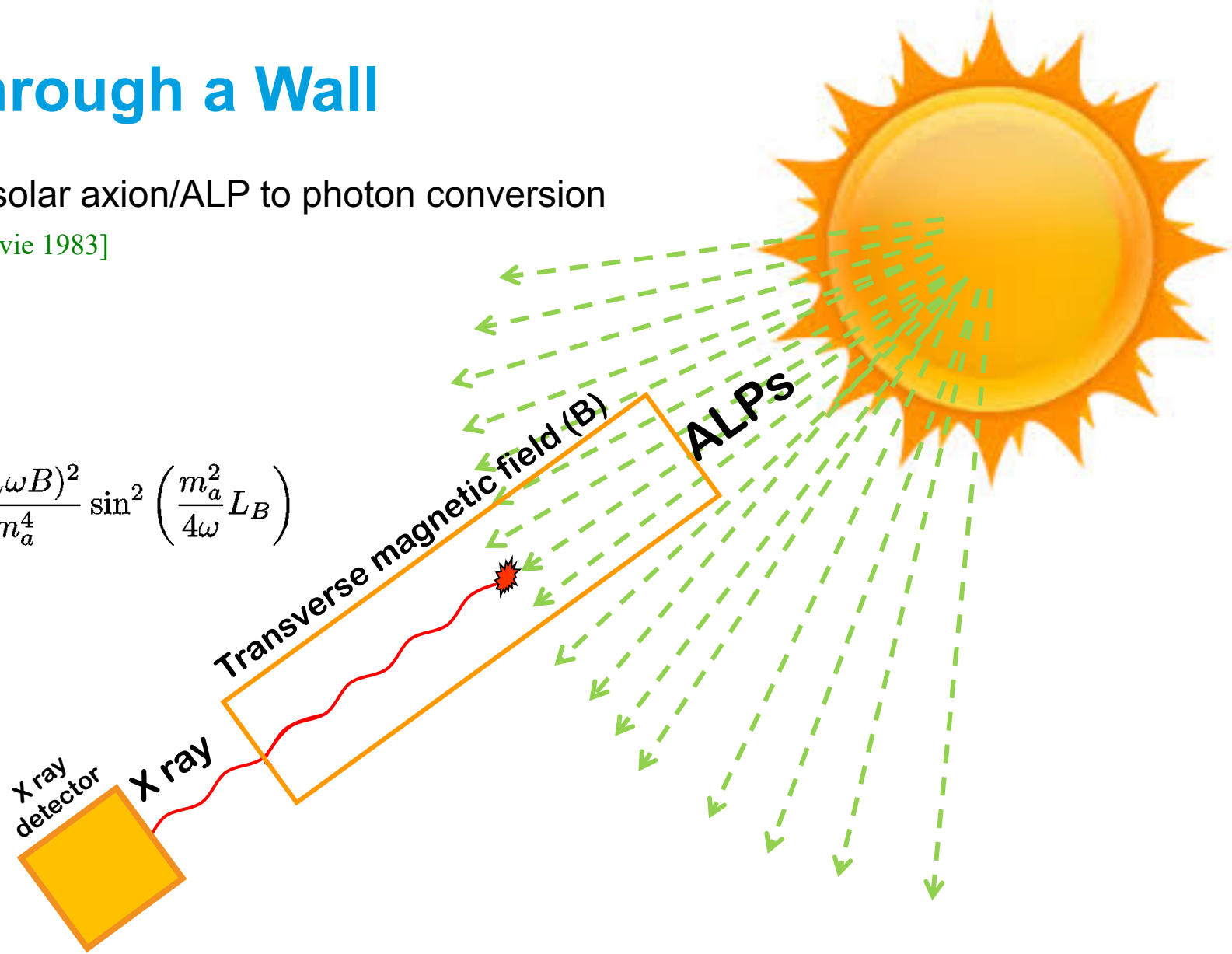
[Redondo '13]



Sun Shining through a Wall

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

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



[adapted from Irastorza '16]

Sun Shining through a Wall

- 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)

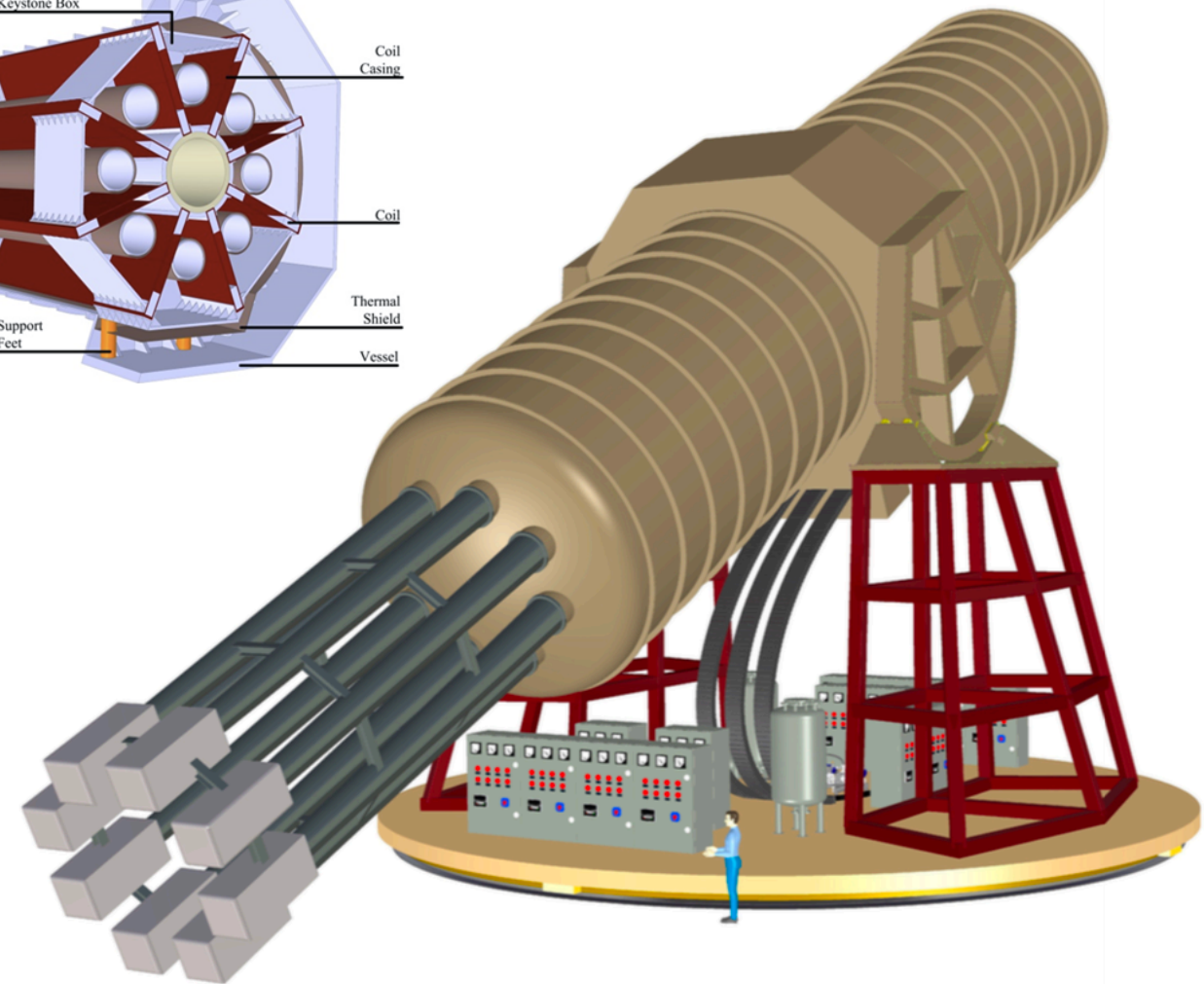
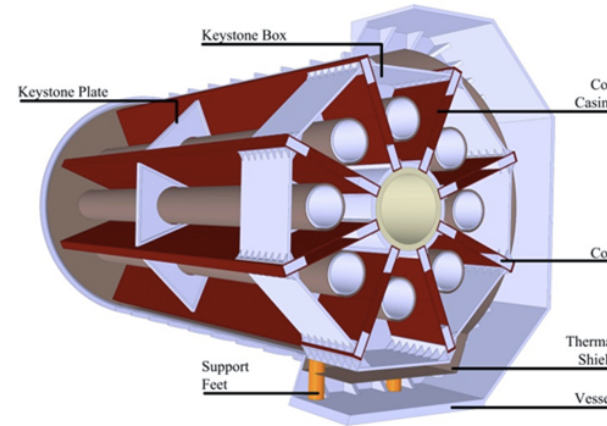
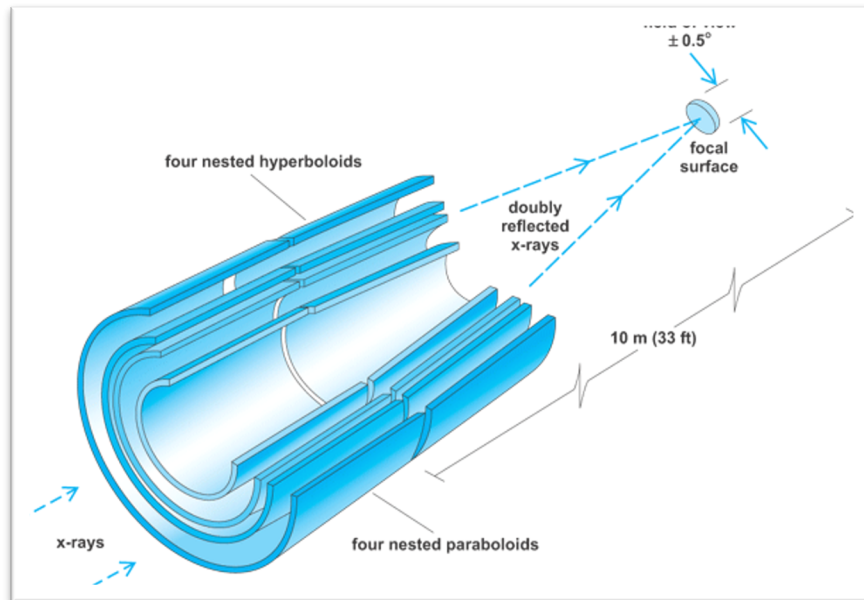


Sun Shining through a Wall

- International Axion Observatory (IAXO)

- Large toroidal 8-coil magnet $L = \sim 20$ m
- 8 bores: 600 mm diameter each
- 8 X-ray telescopes + 8 detection systems
- Rotating platform with services

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



Sun Shining through a Wall

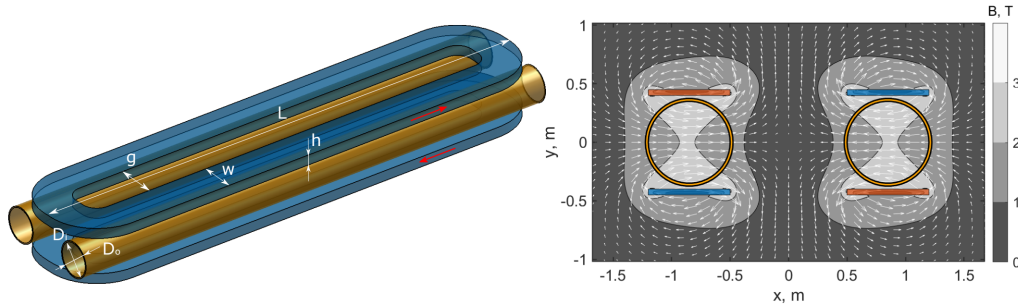
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 - 8 X-ray telescopes + 8 detection systems
 - Rotating platform with services
- Proposed site: [DESY](#)

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

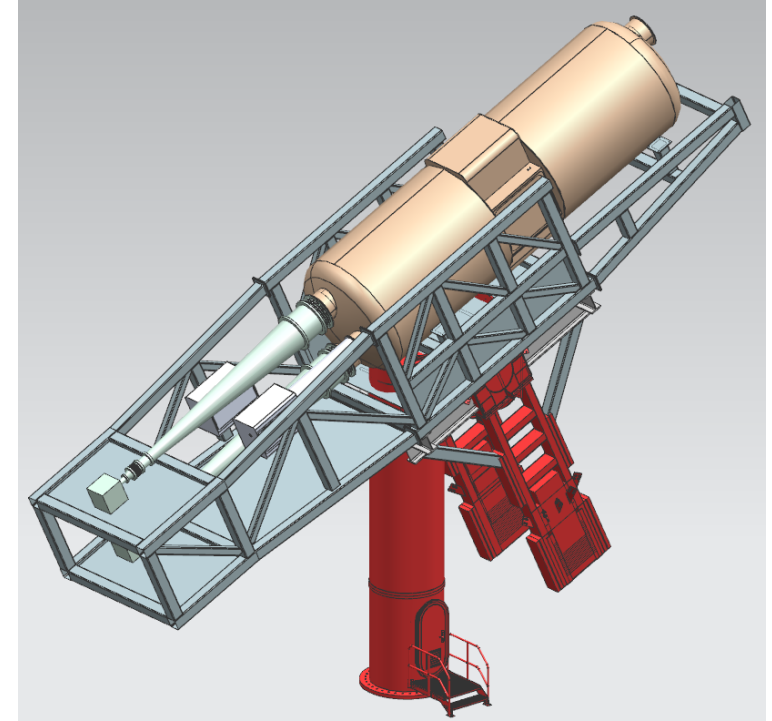


Sun Shining through a Wall

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

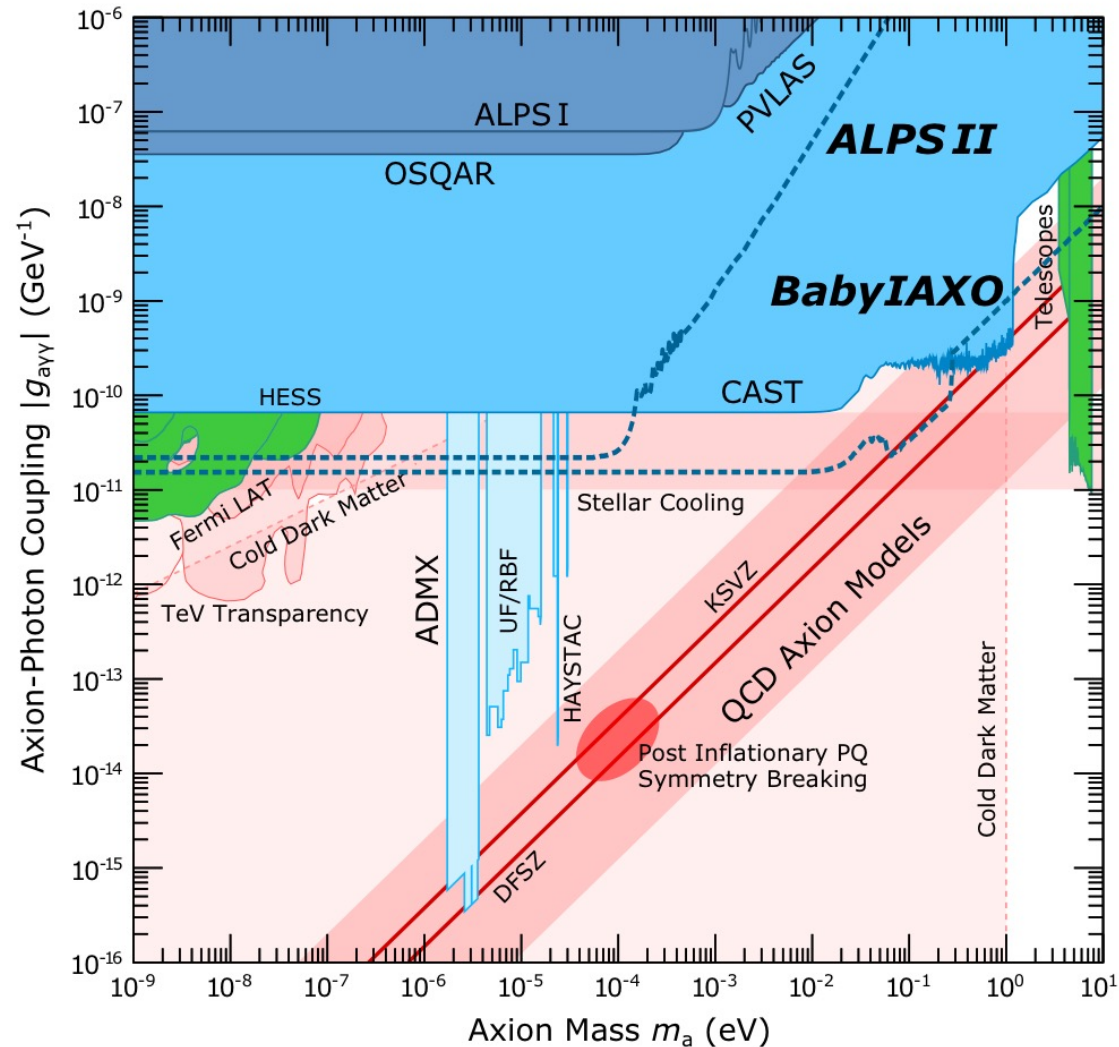


- Construction site: [DESY](#)
- Funded by [DESY](#), [CERN](#) and [Iraistorza](#): [ERC-AvG 2017 IAXO+](#)
- Preparations have already started in 2020
- Data taking may start in 2025



Sun Shining through a Wall

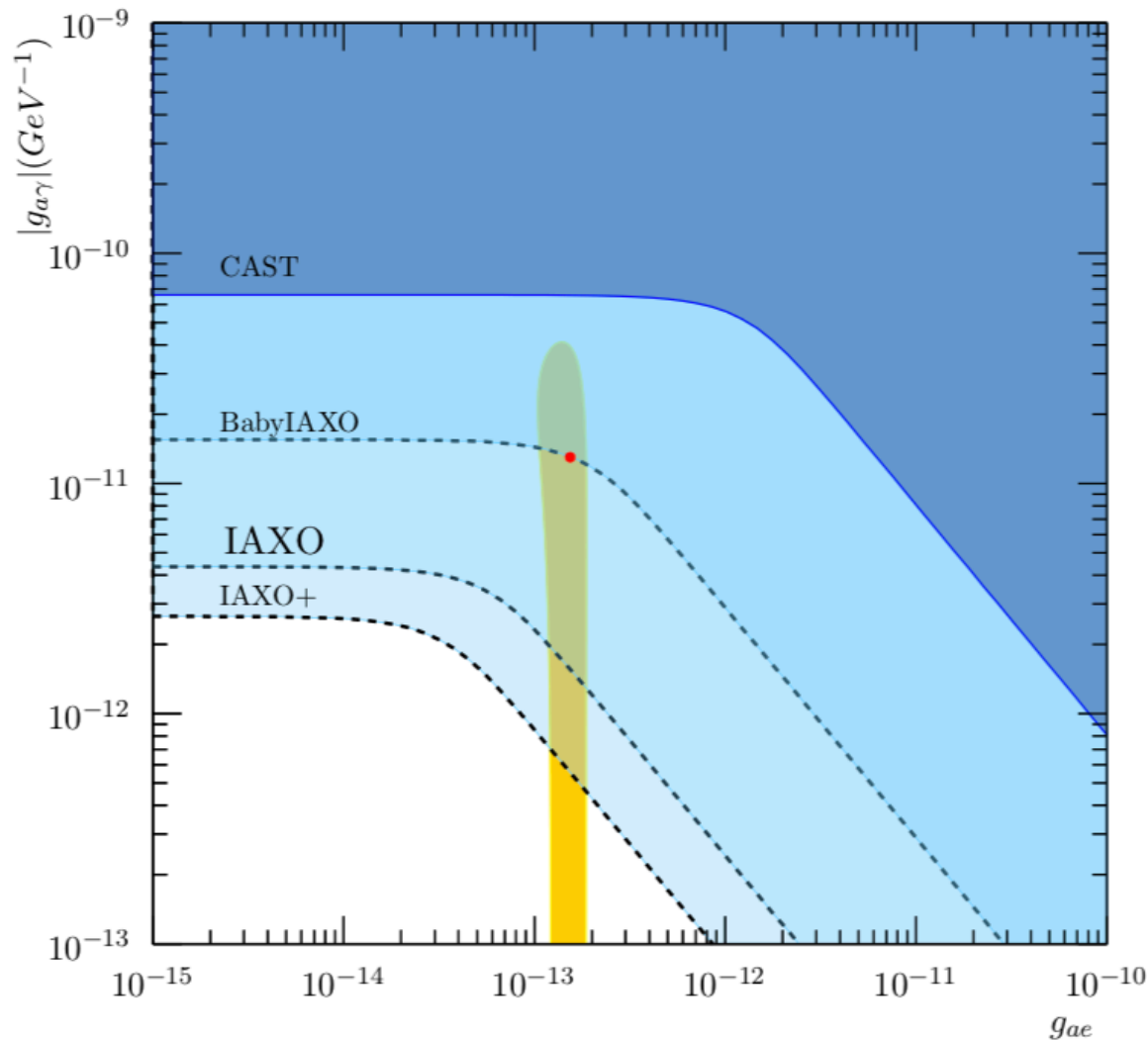
- **BabyIAXO**: at low masses sensitivity similar to ALPS II, but probes also meV mass QCD axion:



[Spector '21]

Sun Shining through a Wall

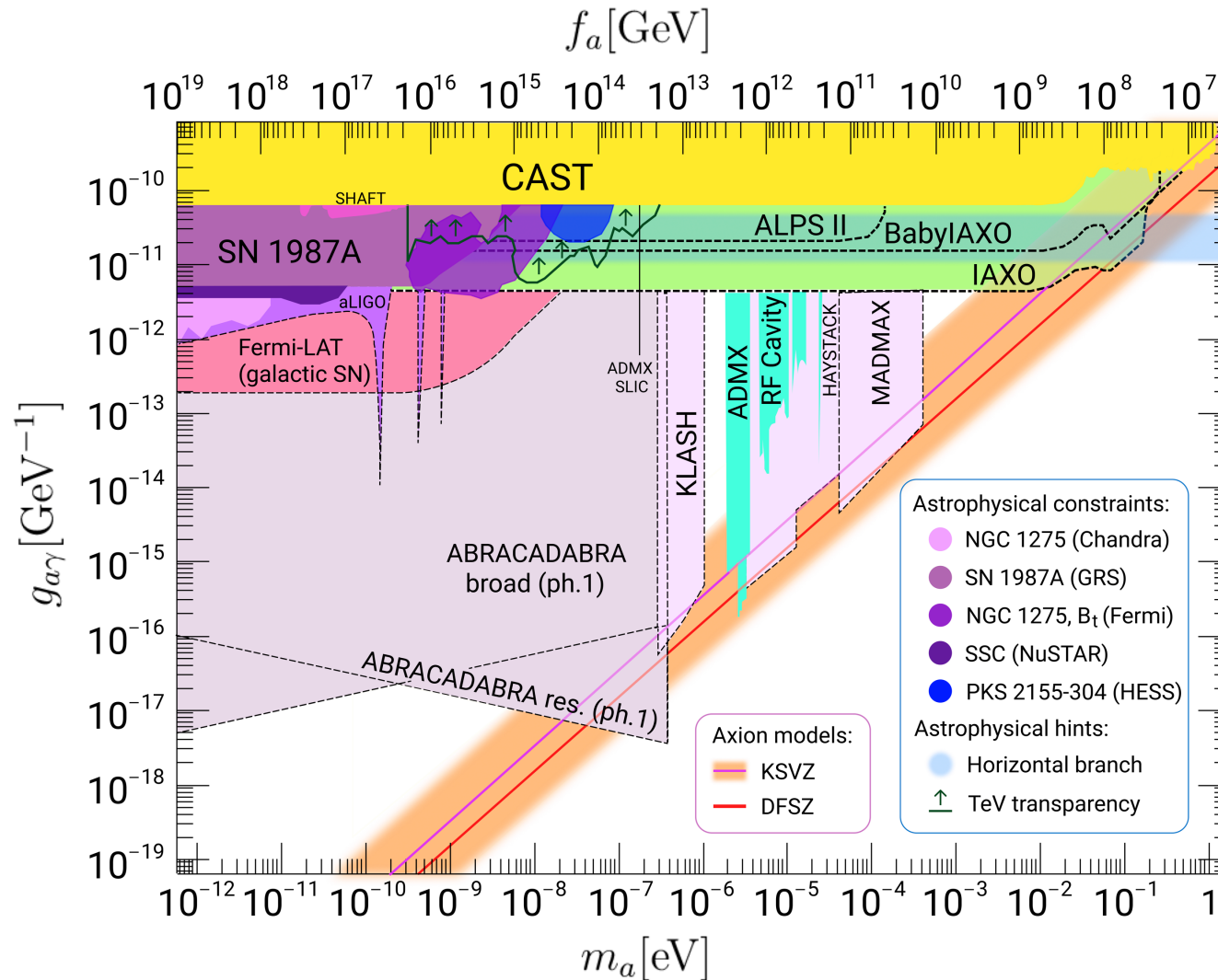
- **BabyIAXO** also sensitive to electron coupling hinted at by stellar energy losses:



[Armengaud et al. 19]

ALP or Axion?

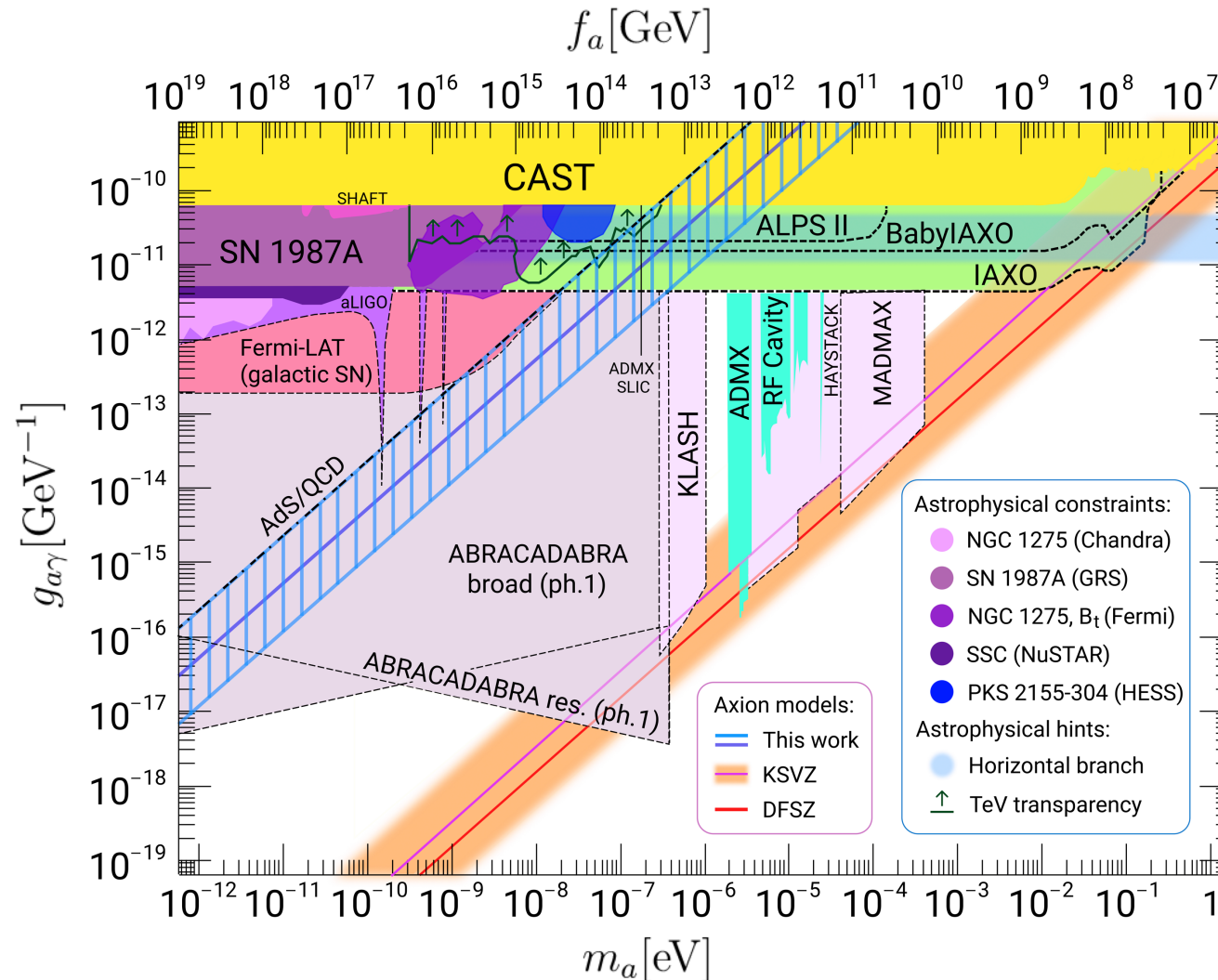
- (Most of) Parameter range accessible by **ALPS II** & **BabylAXO** seems far away from expectation for axion:



adapted from [Sokolov,AR '21]

ALP or Axion?

- Anton Sokolov will talk about a variant of the KSVZ axion model which is testable at **ALPS II & BabyIAXO**:

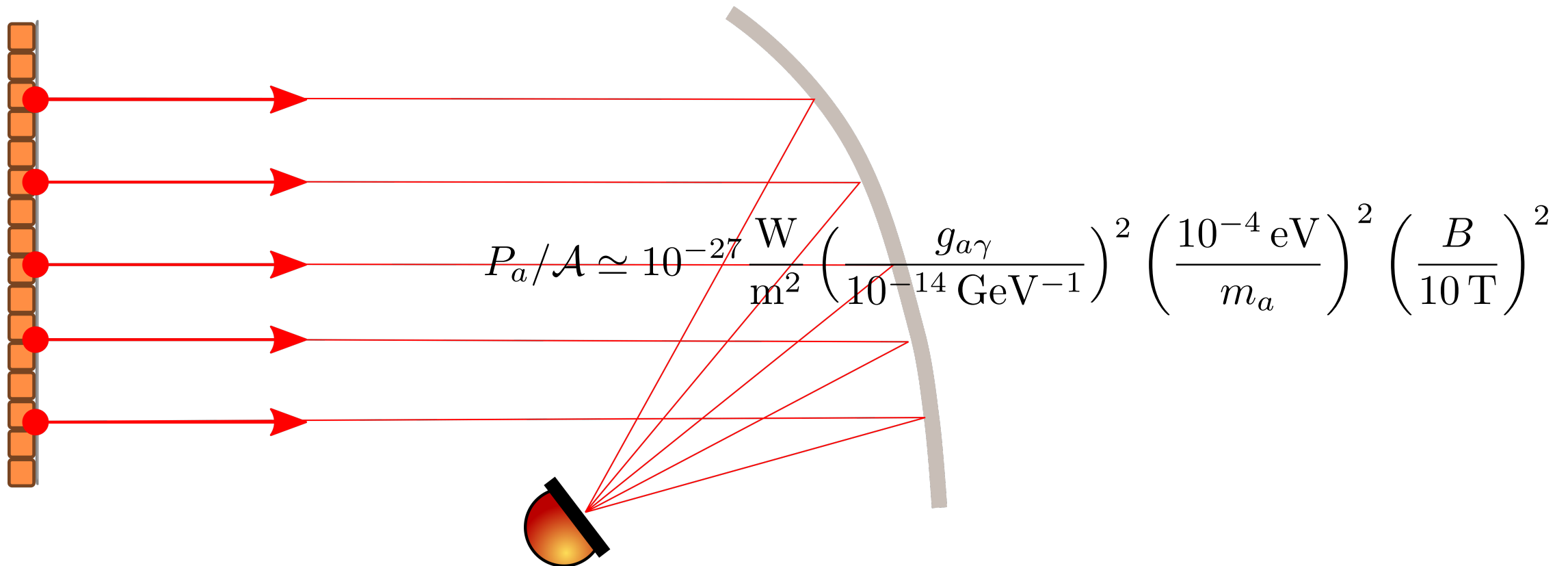


[Sokolov,AR '21]

Dark Matter Shining through a Wall

Dish Antennas

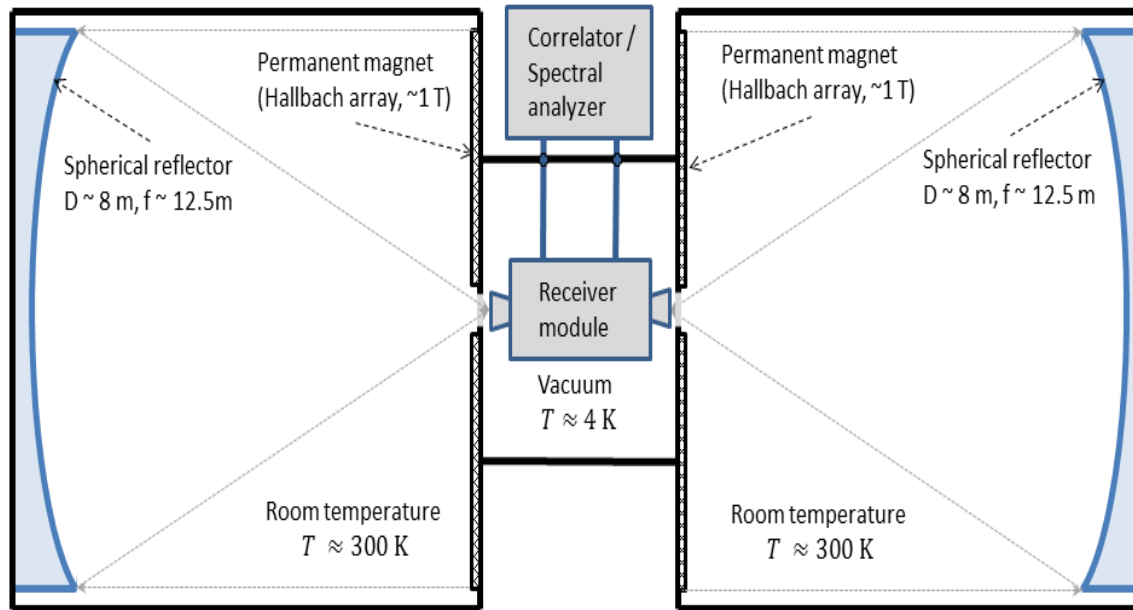
- Oscillating axion/ALP DM in a background magnetic field carries a small electric field component
- A magnetised mirror in axion/ALP DM background radiates photons [Horns, Jaeckel, Lindner, Lobanov, Redondo, AR 13]



Dark Matter Shining through a Wall

Dish Antennas

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



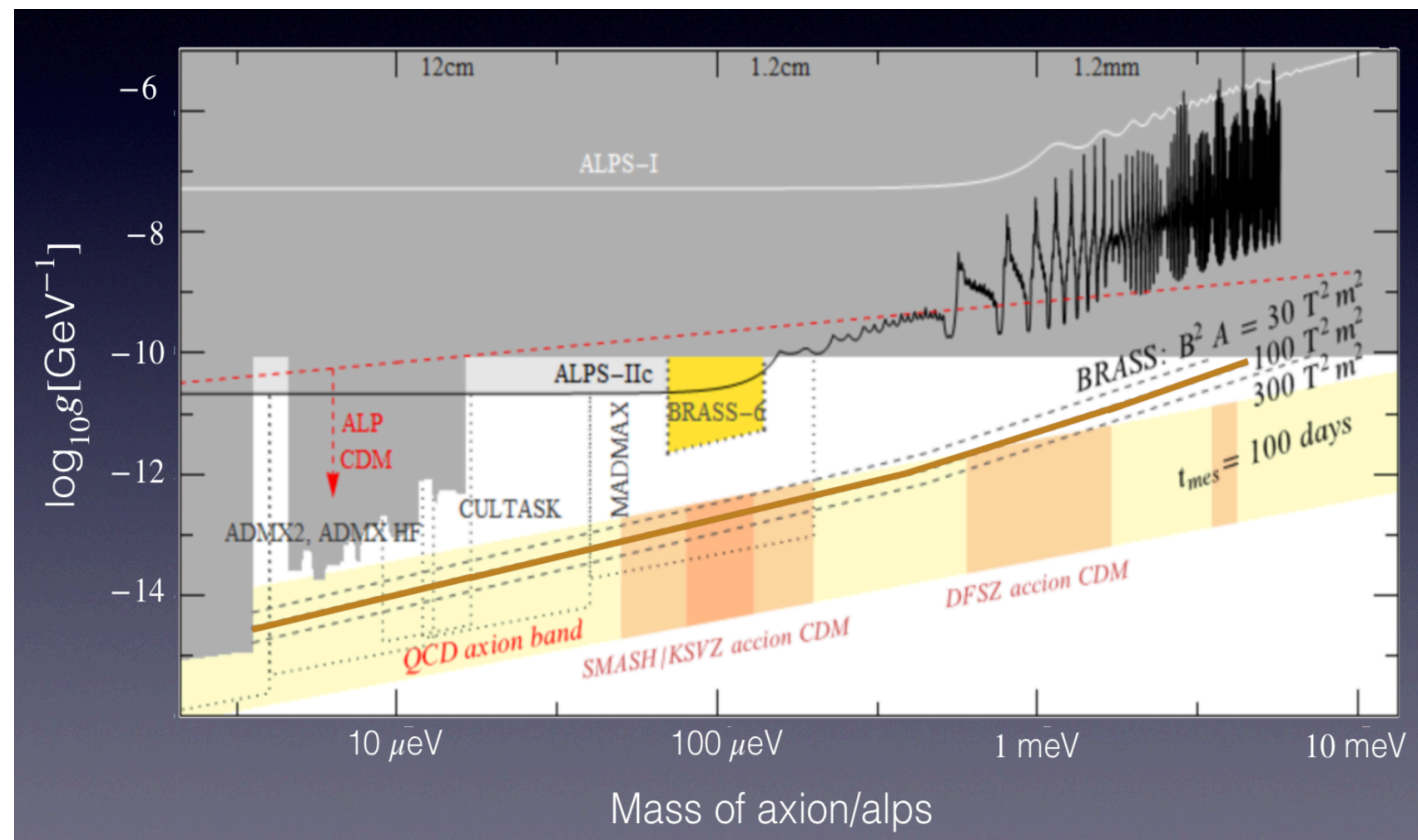
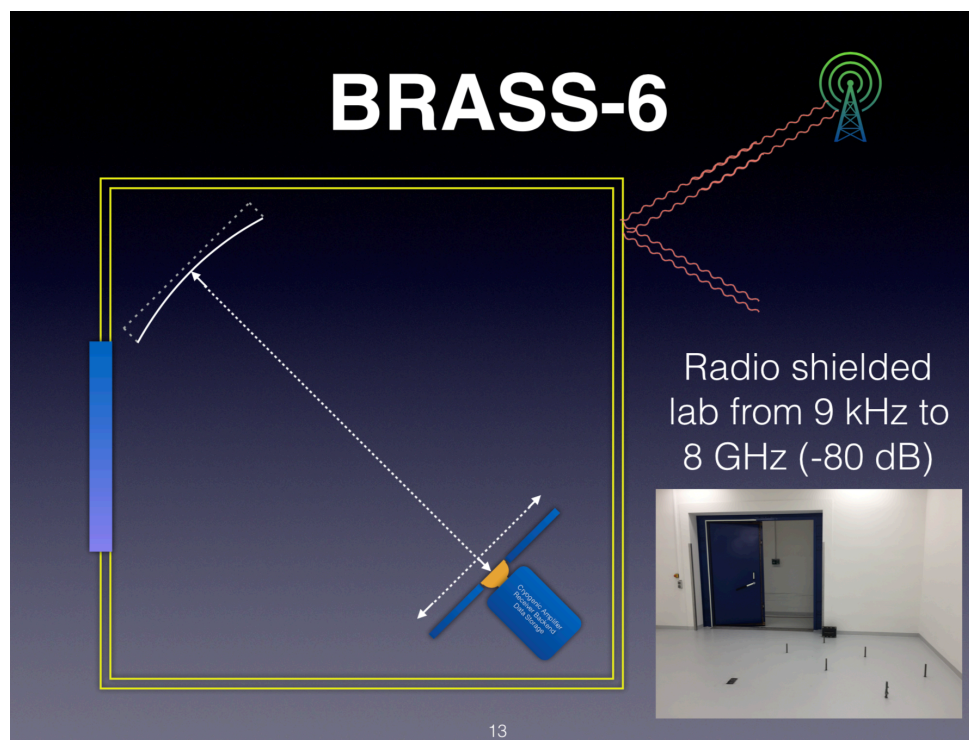
[Horns et al. (unpublished)]

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

Dark Matter Shining through a Wall

Dish Antennas

- Prototype **BRASS-6** in construction, data taking starting 2022



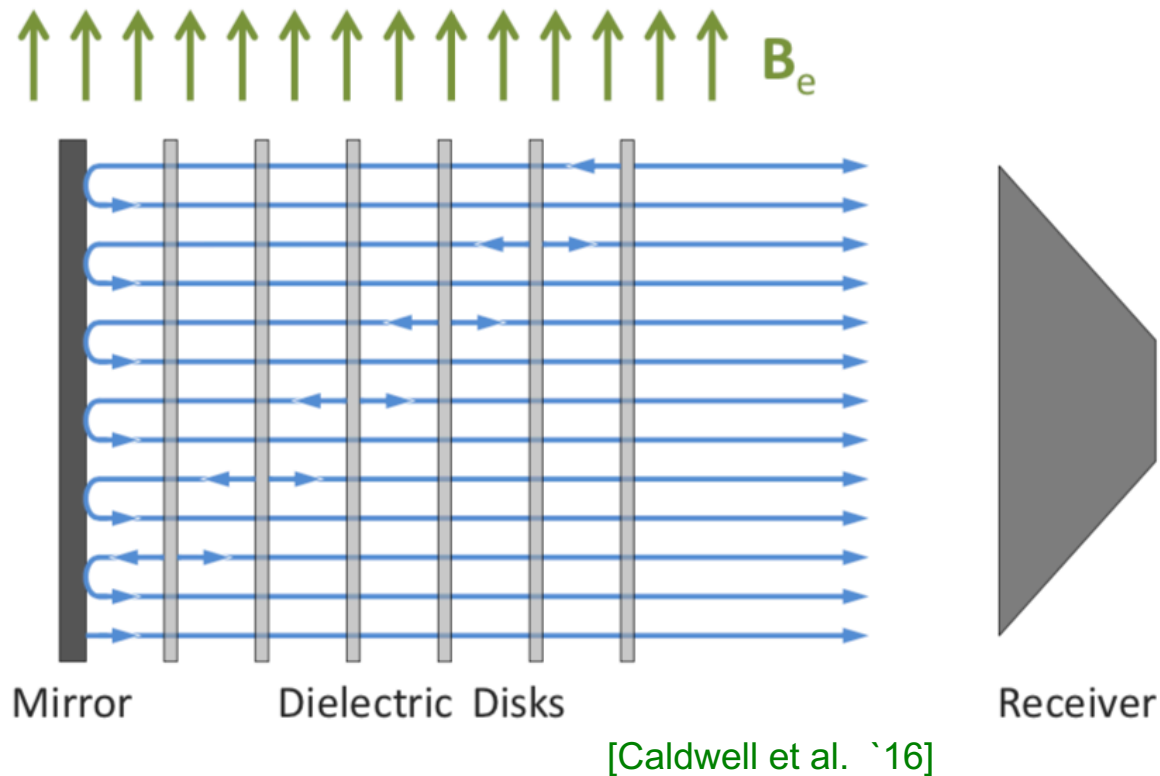
[Le Hoang Nguyen, Patras Workshop 2019]

Dark Matter Shining through a Wall

Dish Antennas

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

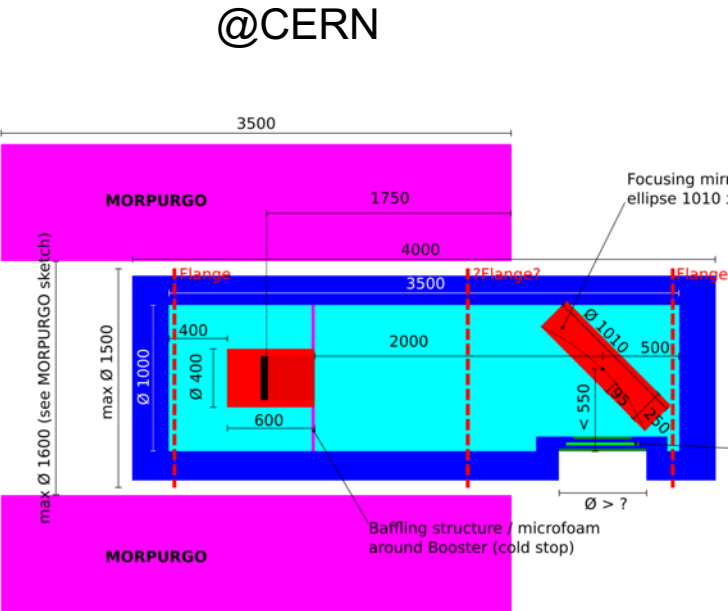
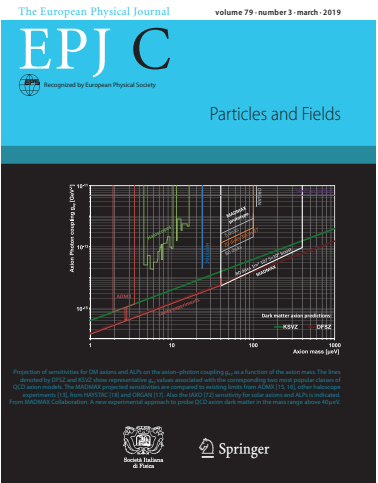
[Baryakhtar, Huang, Lasenby 18]



Dark Matter Shining through a Wall

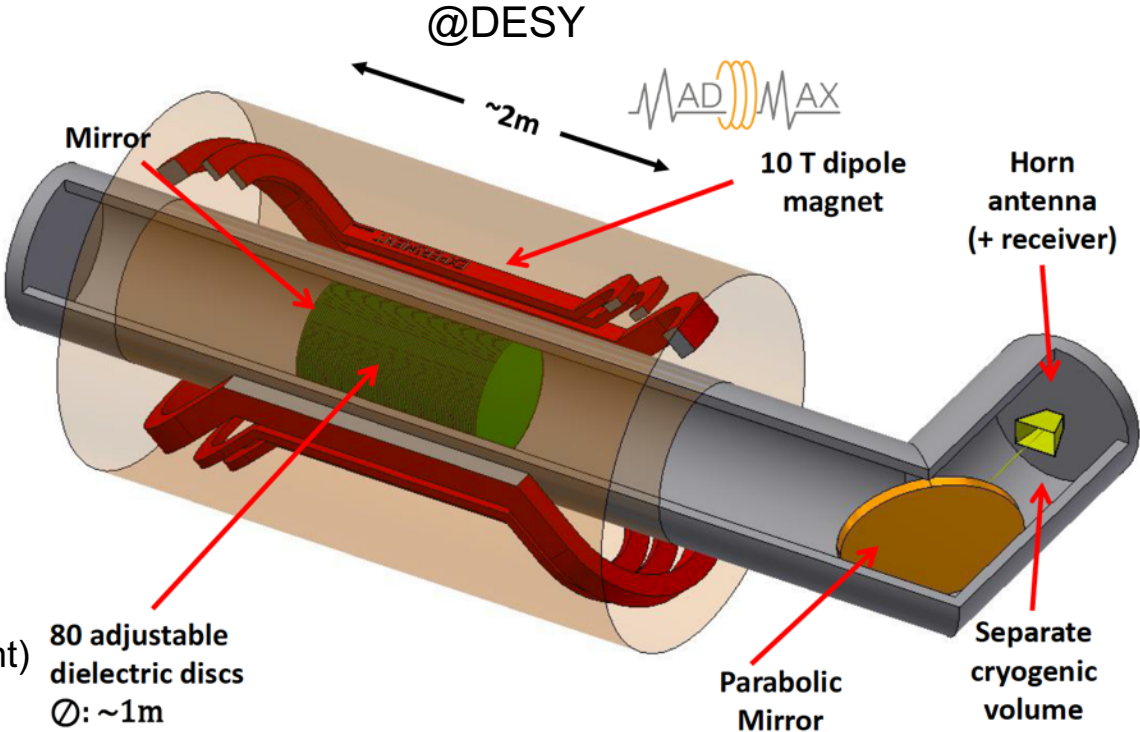
Dish Antennas

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



Scaling: (of final experiment)

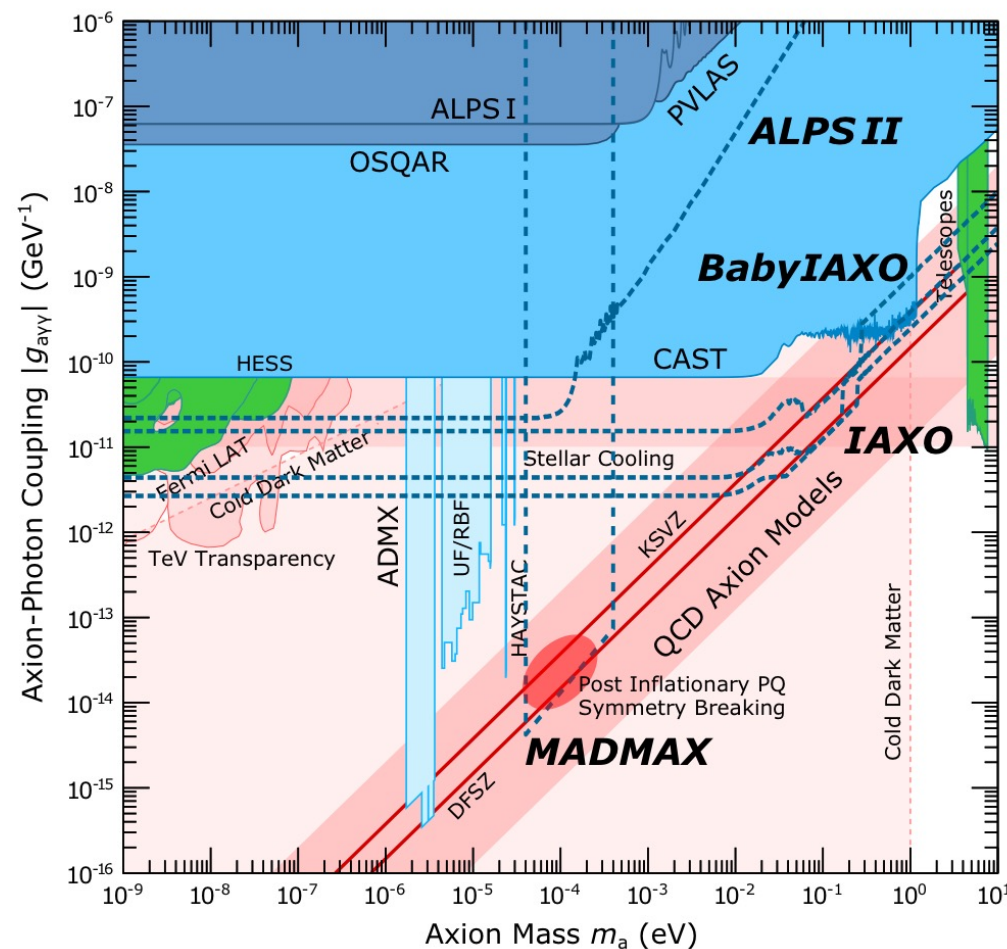
Area	1/10
# discs	1/4
B [T]	1/5



Dark Matter Shining through a Wall

Dish Antennas

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

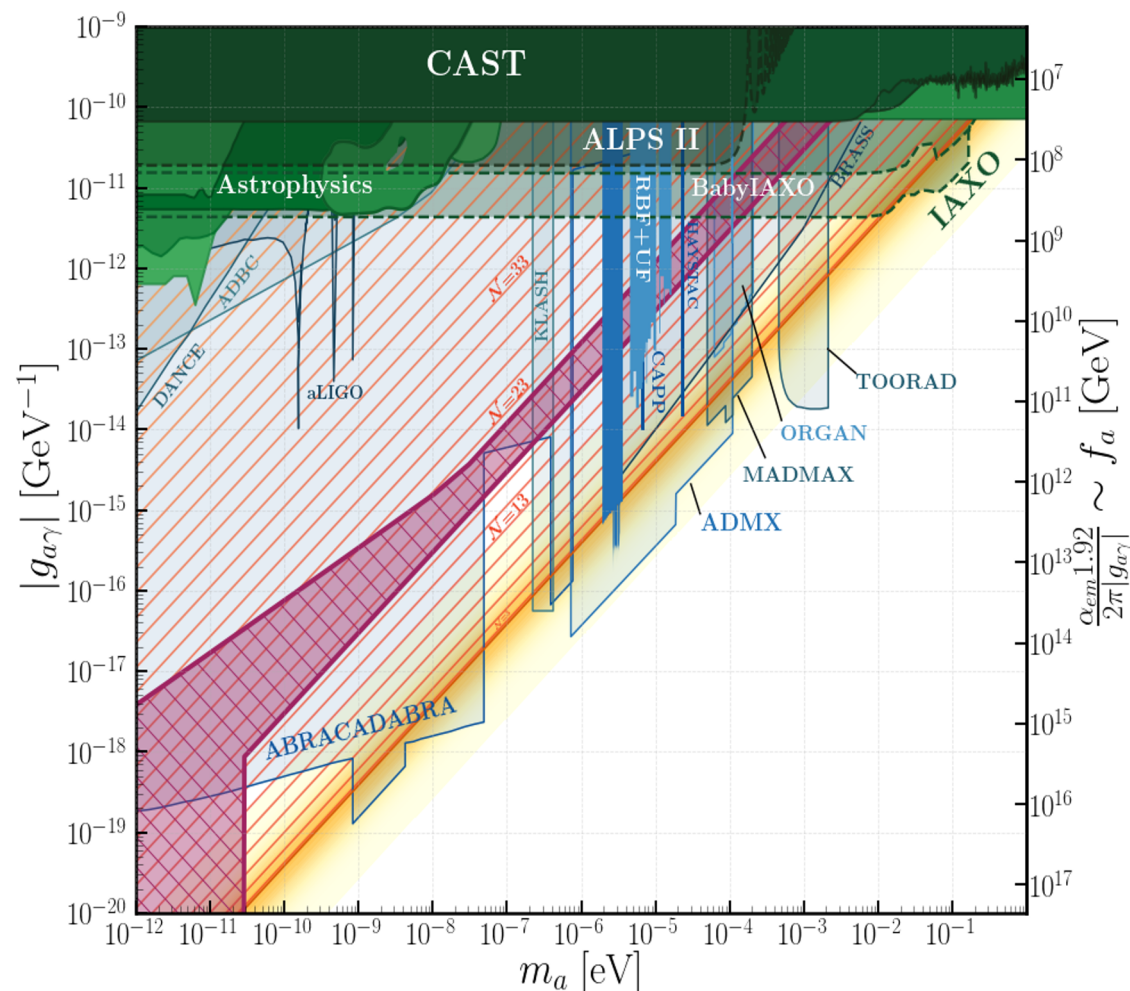


[Spector '21]

Dark Matter Shining through a Wall

Dish Antennas

- MADMAX** prototype can probe Z_N axion mediating between N mirror copies of the SM:



[Di Luzio, Gavela, Quilez, AR '21]

Conclusion

Stay Tuned!

- **DESY** has a robust on-site axion experimental programme that will produce results as early as next year:

