The Hunt for the Axion

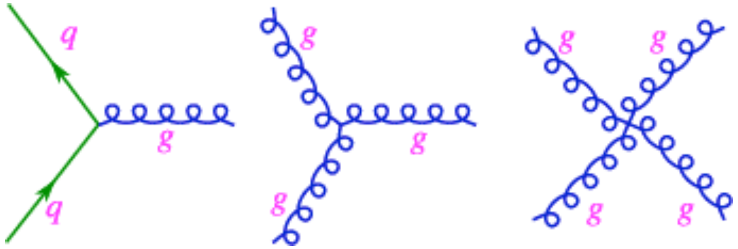
Andreas Ringwald
GGI Tea Break Web-Seminar
03 February 2021

Strong CP Puzzle

Theta term in Quantum Chromodynamics

- Quantum Chromodynamics (QCD): [Gross,Wilczek 73;Politzer 73; Fritzsch,Gell-Mann,Leutwyler 73]

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



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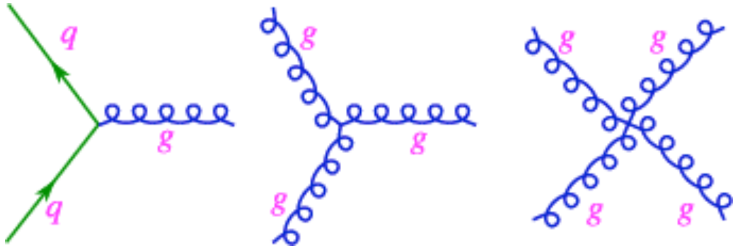

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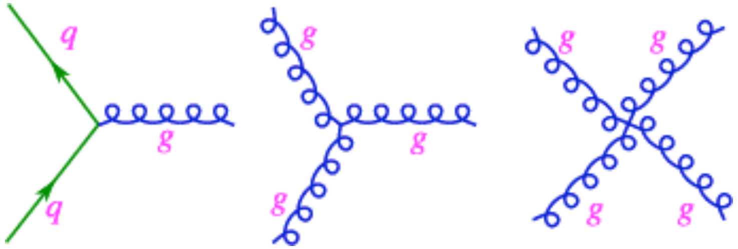

$$\int d^4x\,\partial_\mu J^\mu_{\rm CS} = 0, \pm 1, \pm 2, \ldots$$

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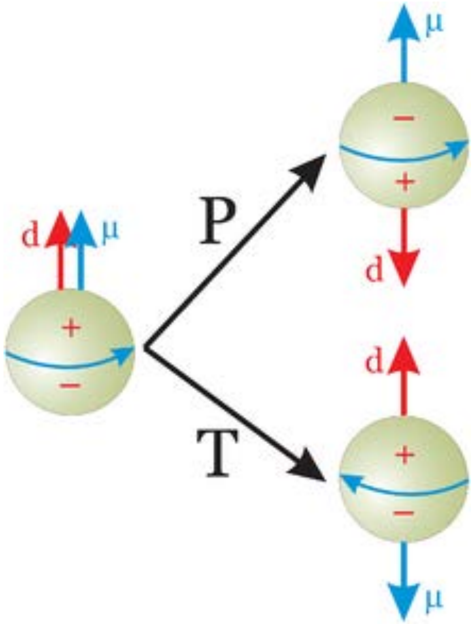
- Most sensitive probe of T and P violation in flavor conserving interactions: electric dipole moment of neutron



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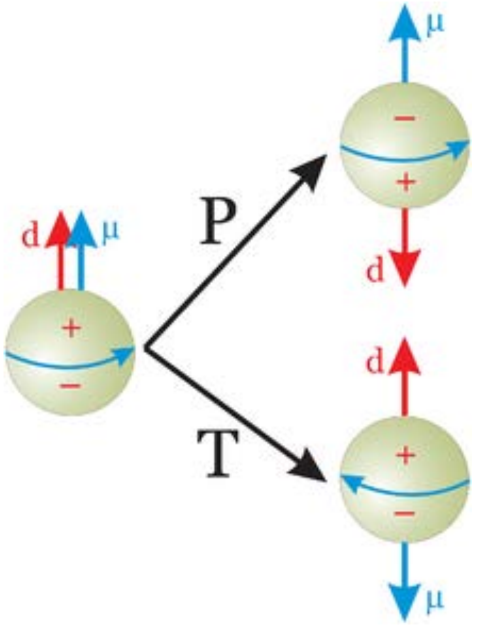
$$d_n(\overline{\theta}) = 2.4(1.0) \times 10^{-16}\,\overline{\theta}\,e\,{\rm cm}$$



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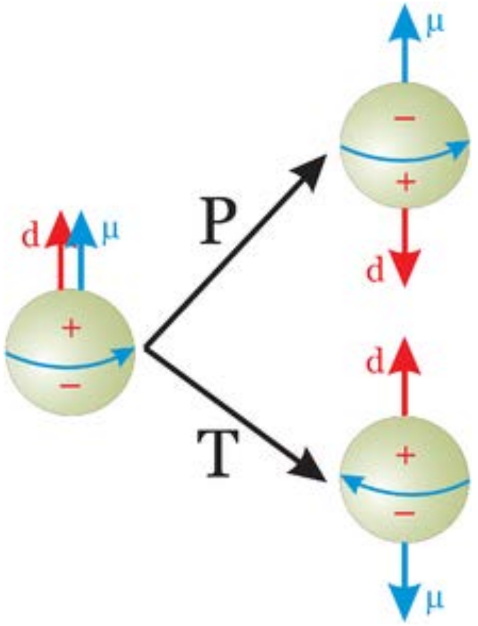
- Experiment: [Abel et al. 20]

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

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



Axionic Solution of Strong CP Puzzle

In a nutshell: replace theta parameter by dynamical theta field

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

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

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

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

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

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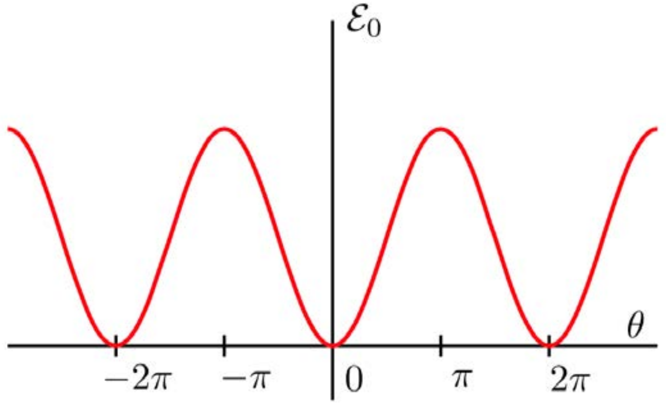
  - Effective potential at energies below $\Lambda_{\rm QCD}$ has absolute minimum at $\theta = 0$ and thus predicts vanishing vev, $\langle\theta(x)\rangle = 0$
    No strong CP violation in vacuum [Vafa,Witten 84]



$$V(\theta) = \Sigma\, (m_u + m_d)\left(1 - \frac{\sqrt{m_u^2 + m_d^2 + 2 m_u m_d \cos\theta}}{m_u + m_d}\right)$$

$$\Sigma \equiv -\langle\bar{u}u\rangle = -\langle \bar{d}d\rangle$$

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

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  - Particle excitation: pseudo Nambu-Goldstone boson "axion" [Weinberg 78; Wilczek 78]
  - Topological susceptibility in QCD, $\chi \equiv \int d^4x \langle q(x) q(0)\rangle$, determines mass in units of decay constant: $m_A = \sqrt{\chi}/f_A$
  - Recent precise determination (ChPT; lattice QCD):

$$m_A = 5.691(51)\left(\frac{10^9\ {\rm GeV}}{f_A}\right){\rm meV}$$

[Grilli di Cortona et al. `16; Borsanyi et al. `16; Gorghetto, Villadoro `19]

Peccei-Quinn Extension of Standard Model

Simple way to get dynamical theta field

- A singlet complex scalar field σ, featuring a spontaneously broken global $U(1)_{\rm PQ}$ symmetry
- Particle excitations:

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

  - Mass of particle excitation of modulus: $m_\rho \sim v_{\rm PQ}$
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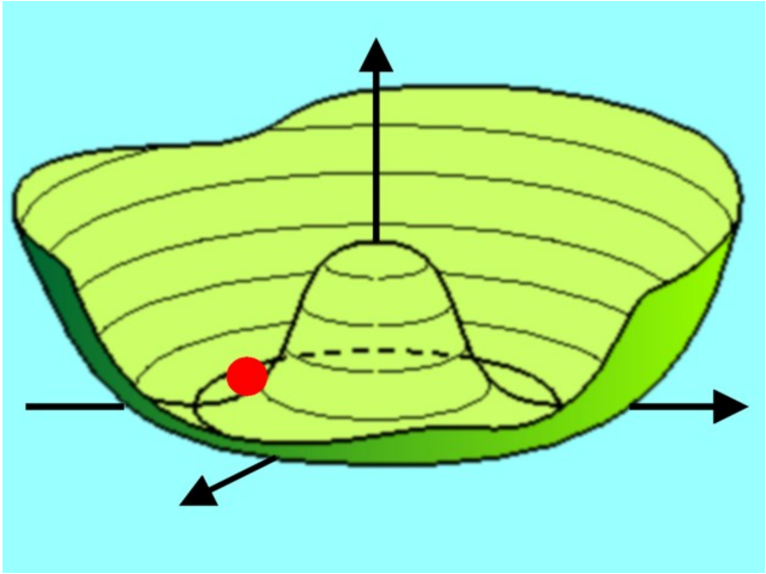

[Raffelt]

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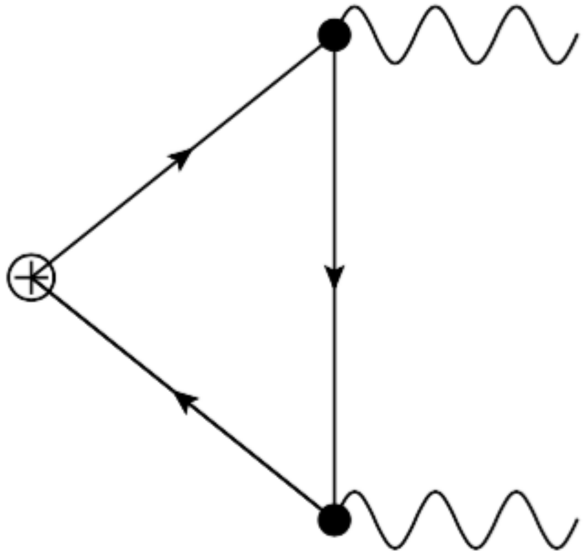
- Coloured fermions carry PQ charges such that $U(1)_{\rm PQ}$ is broken due to gluonic triangle anomaly:

$$\partial_\mu J^\mu_{U(1)_{\rm PQ}} \supset -\frac{\alpha_s}{8\pi} N\, G^b_{\mu\nu} \tilde{G}^{b,\mu\nu}$$



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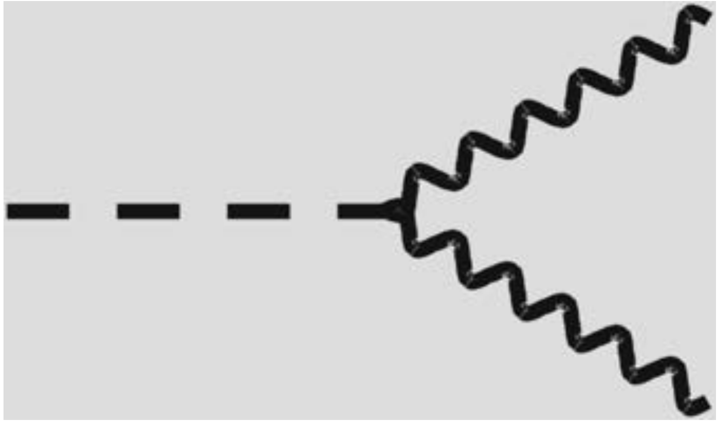
- Low energy effective field theory at energies above $\Lambda_{\rm QCD}$ but below v $(\ll v_{\rm PQ})$: [Peccei,Quinn 77; Weinberg 78; Wilczek 78]

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\,\theta(x)\, G^b_{\mu\nu}\tilde{G}^{b,\mu\nu}\,; \qquad \theta(x) = A(x)/f_A\,; \qquad f_A = v_{\rm PQ}/N$$

[Kim 79;Shifman,Vainshtein,Zakharov 80;Zhitnitsky 80;Dine,Fischler,Srednicki 81;...]



Peccei-Quinn Extension of Standard Model

Axion couplings to SM at energies below QCD scale

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

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

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

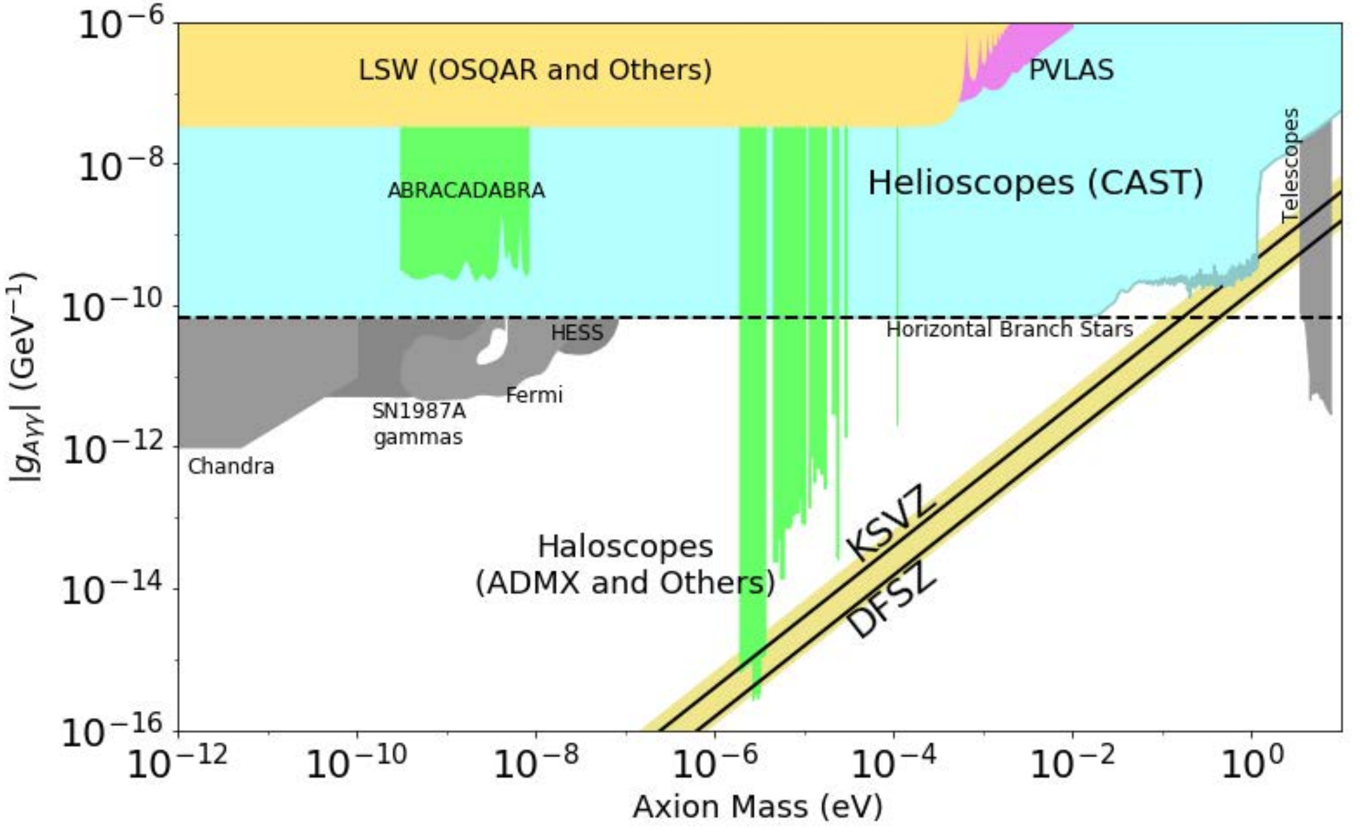
$$C_{An} = -0.02(3) + 0.88(3)C_{Ad} - 0.39(2)C_{Au} - 0.038(5)C_{As} - 0.012(5)C_{Ac} - 0.009(2)C_{Ab} - 0.0035(4)C_{At}$$

[Grilli di Cortona et al. `16]

Current Constraints on Axion Couplings

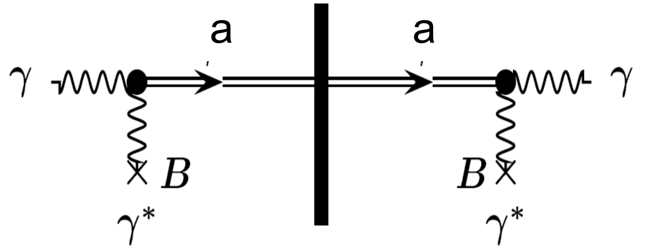
Coupling to the photon

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

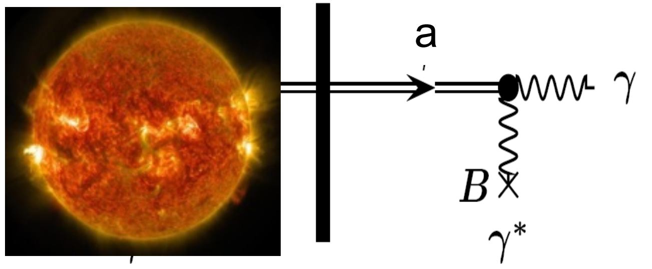


[AR,Rosenberg,Rybka in: Review of Particle Physics, PTEP 2020 (2020) 8, 083C01]

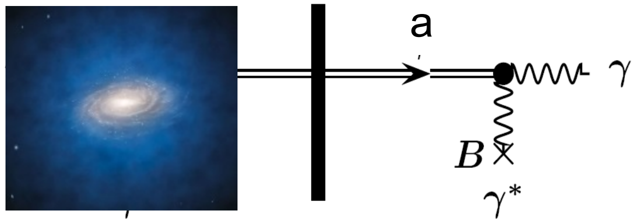
Laser shining through a wall (LSW)



Sun shining through a wall (Helioscope)



DM shining through a wall (Haloscope)

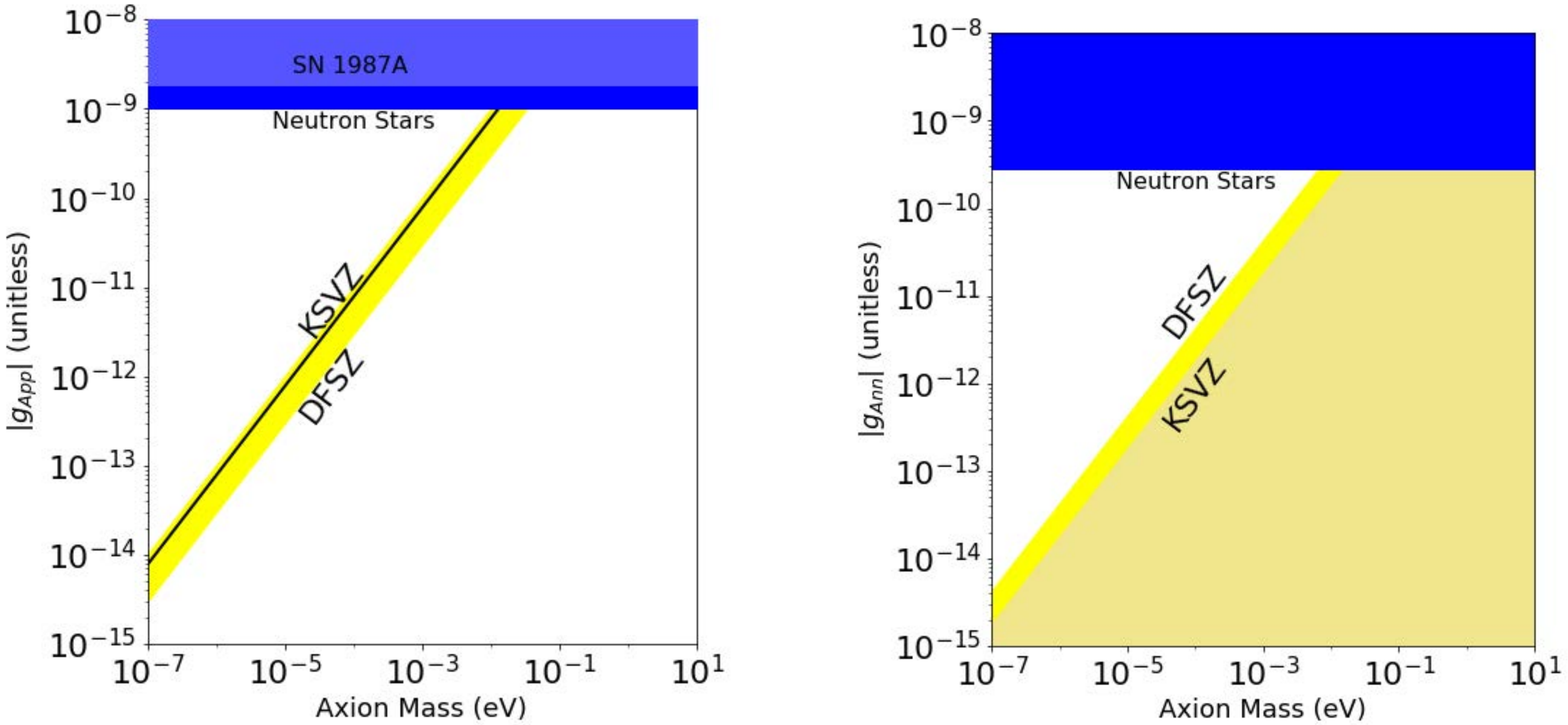


[Axel Lindner]

Current Constraints on Axion Couplings

Coupling to protons and neutrons

$$g_{ANN} \equiv \frac{m_N}{f_A} C_{AN}$$



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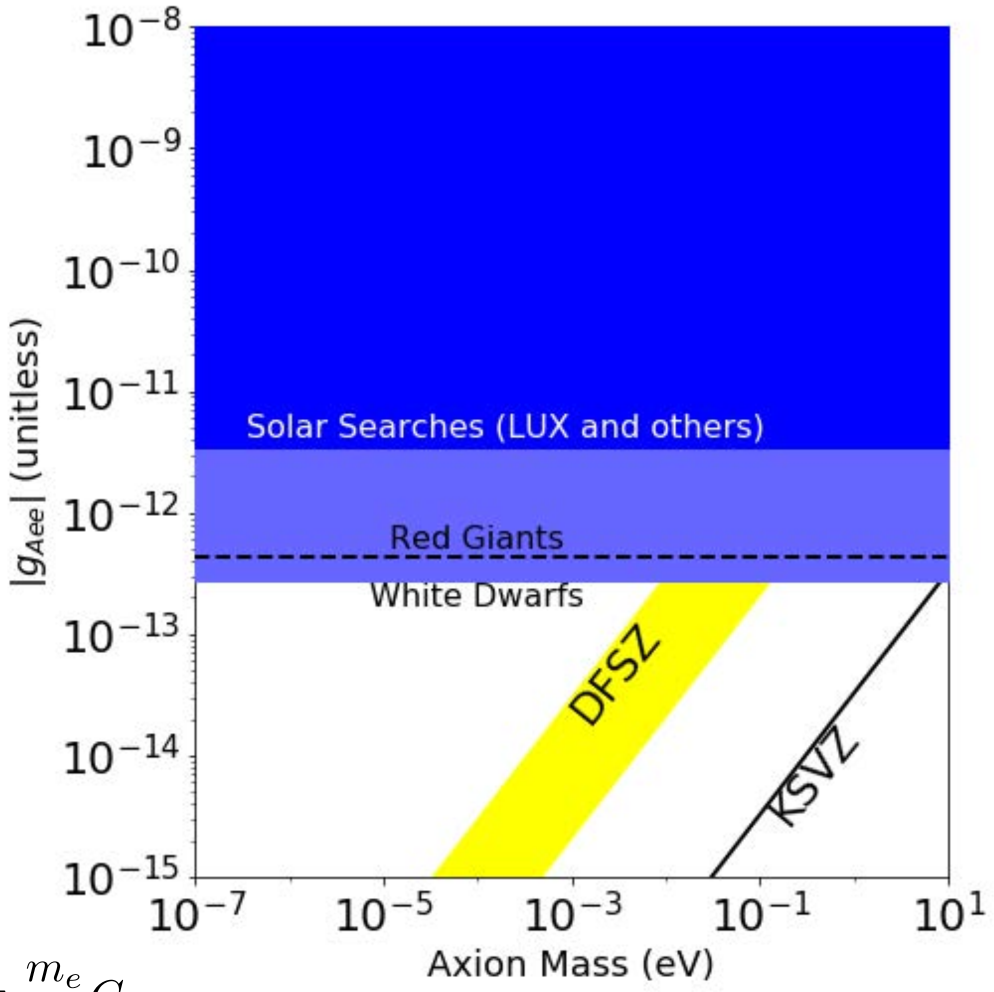
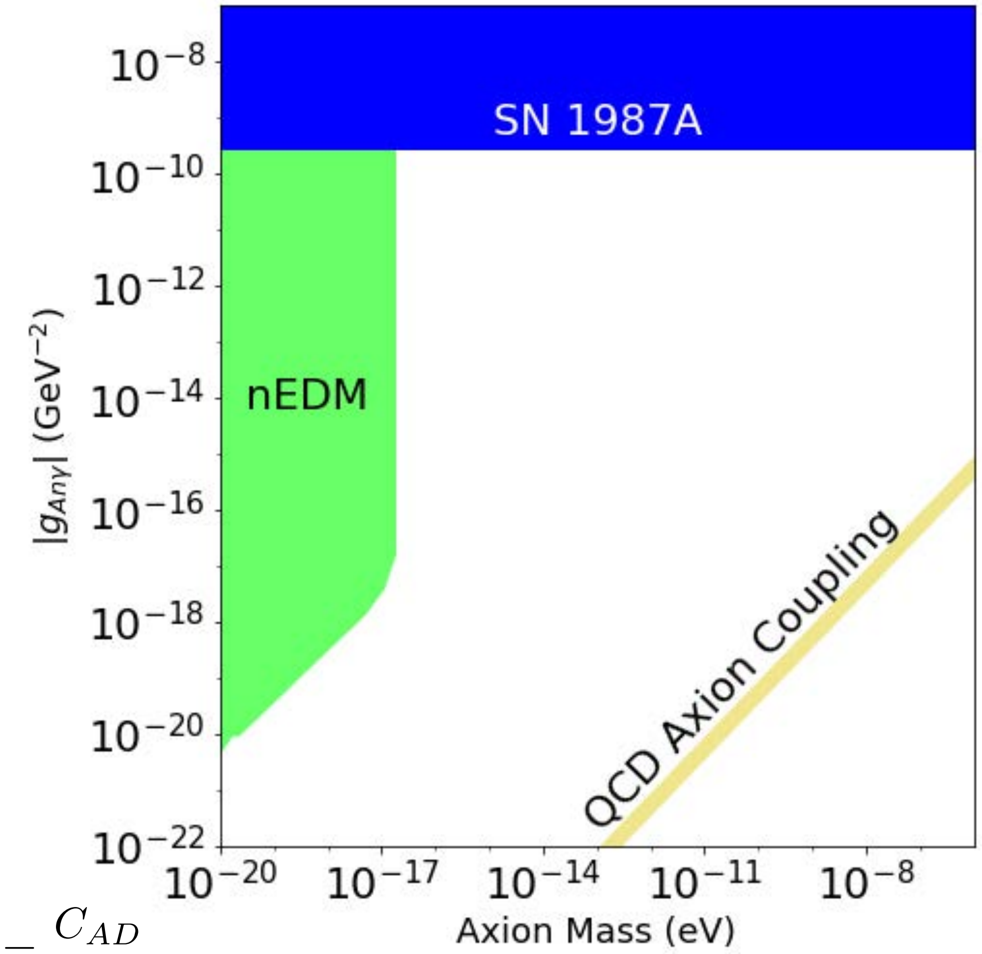
Constraints on Axion/ALP Couplings

Coupling to the electron and the neutron EDM



$$g_{Aee} \equiv \frac{m_e}{f_A} C_{Ae}$$



$$g_{An\gamma} \equiv \frac{C_{AD}}{f_A}$$

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

Light-Shining-through-a-Wall Searches

Searching for Home-Made Axions

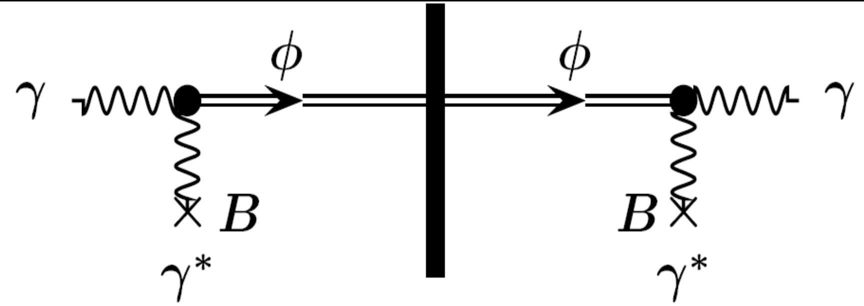
$$\mathcal{L} \supset -\frac{g_{a\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \equiv g_{a\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$$

- Axion experiences mixing with photon in an external electromagnetic field
- 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: $$P(\gamma \leftrightarrow a) \simeq \frac{1}{4}\left(g_{a\gamma} B L_B\right)^2$$

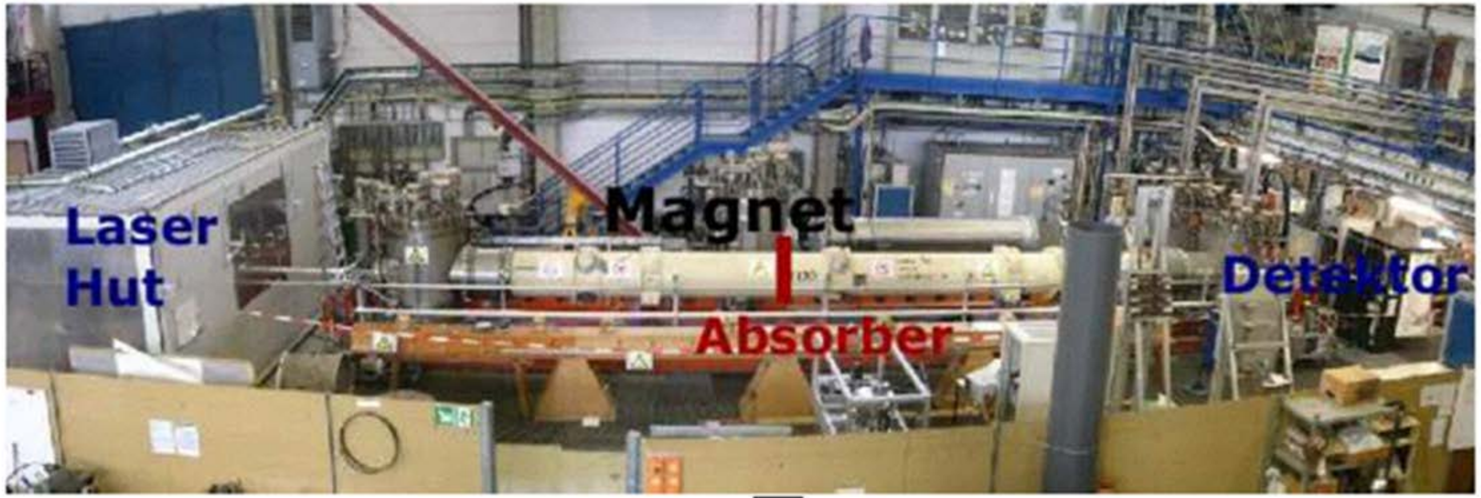
- Light-shining-through a wall:



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

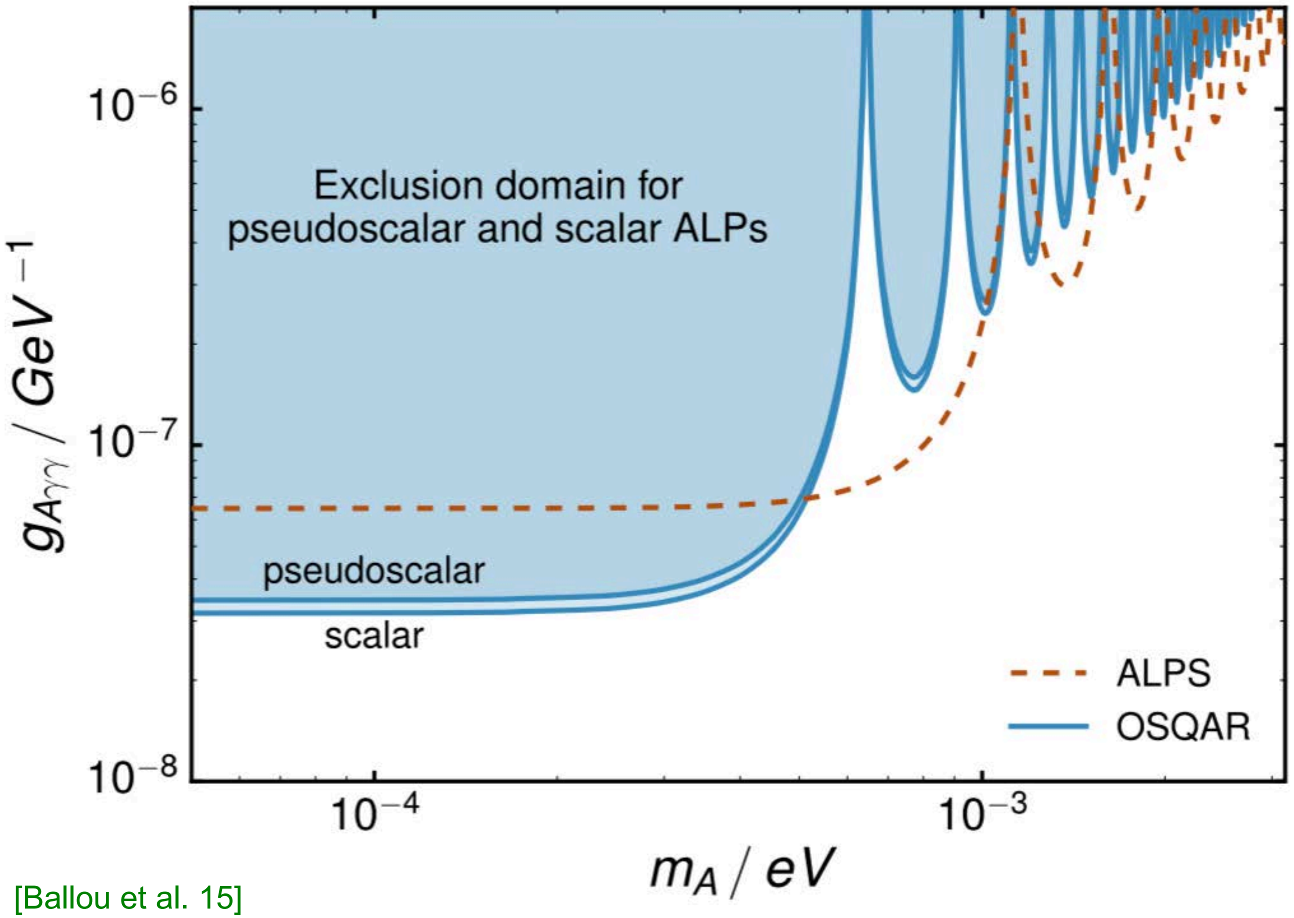
Light-Shining-through-a-Wall Searches

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



Light-Shining-through-a-Wall Searches

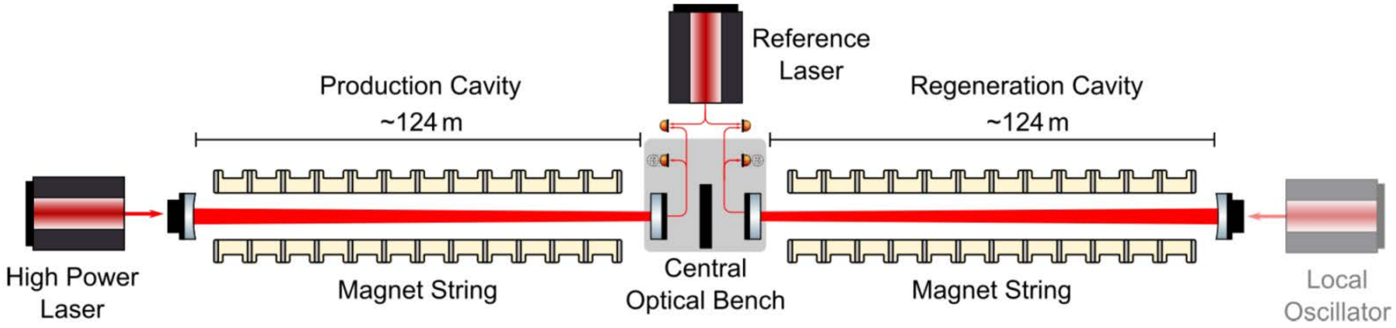
- ALPS I @ DESY (in collaboration with AEI Hannover and U Hamburg) [Ehret et al. 10]
  - LSW experiments ALPS I and OSQAR @ CERN give currently the best purely laboratory limit on low mass axions:

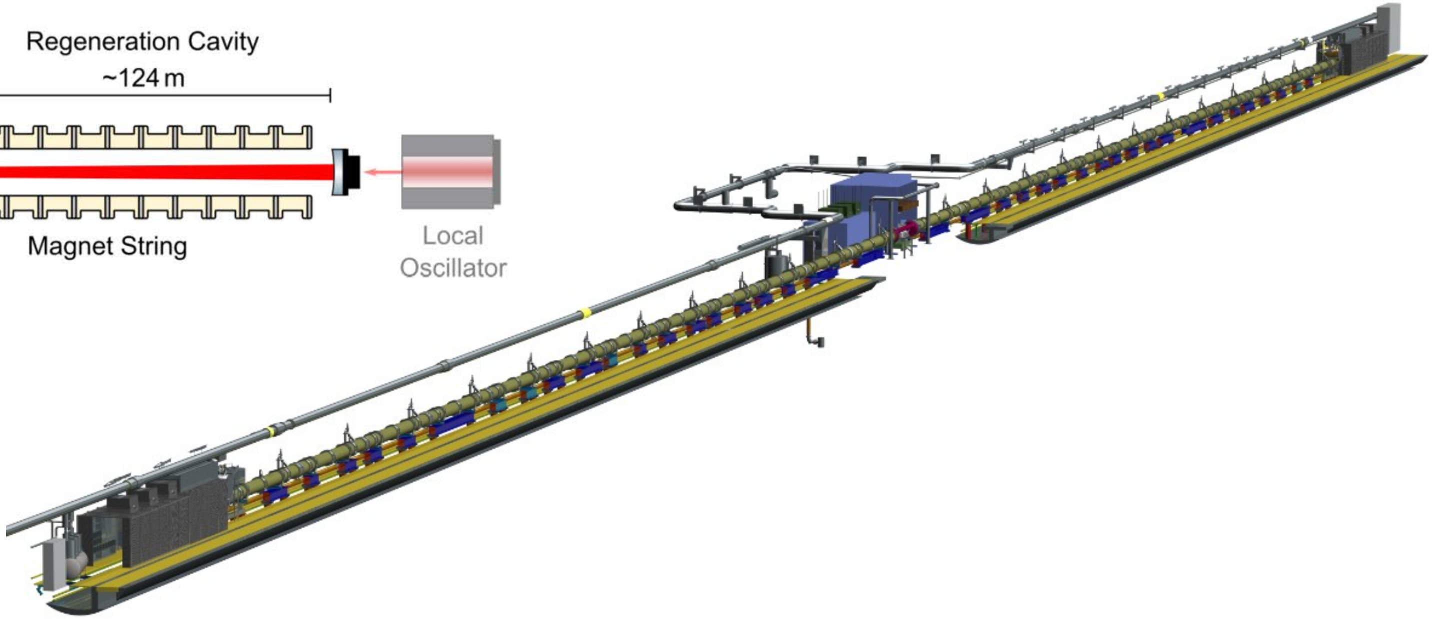


[Ballou et al. 15]

Light-Shining-through-a-Wall Searches

- 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

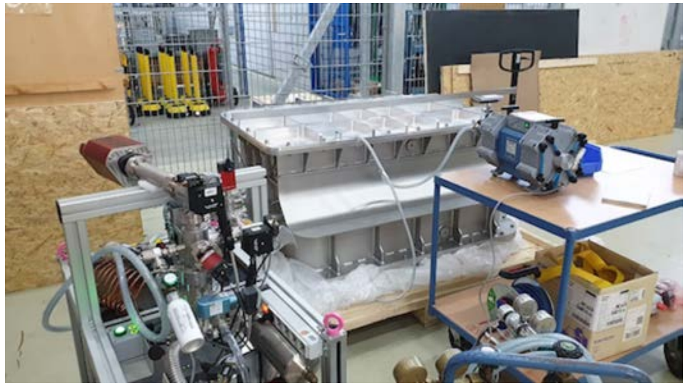
Light-Shining-through-a-Wall Searches

ALPS II at DESY

- HERA tunnel on about 300 m cleared

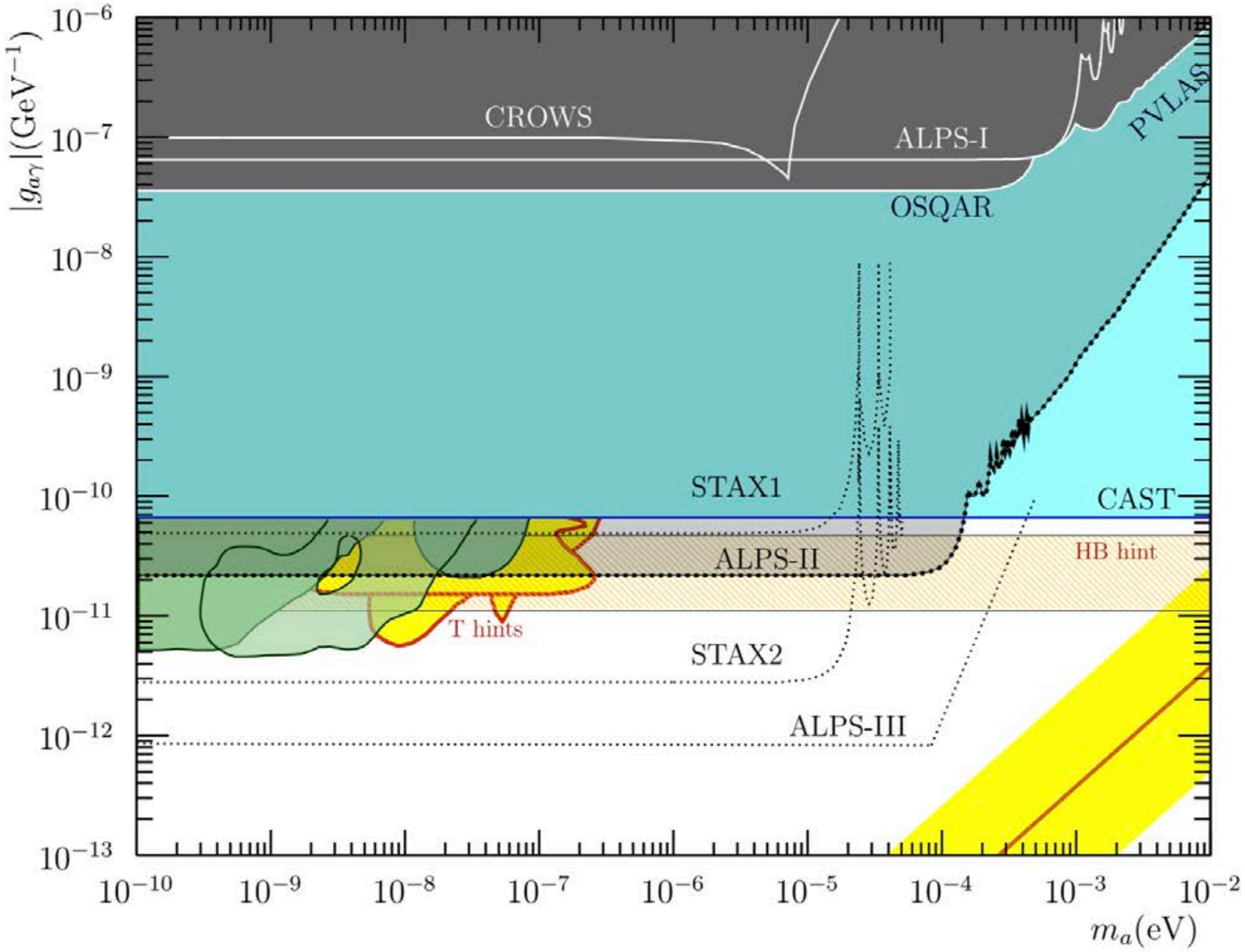
- 24 magnets straightened, tested and in-stalled

- Everything on track for data taking starting in fourth quarter of this year



Light-Shining-through-a-Wall Searches

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

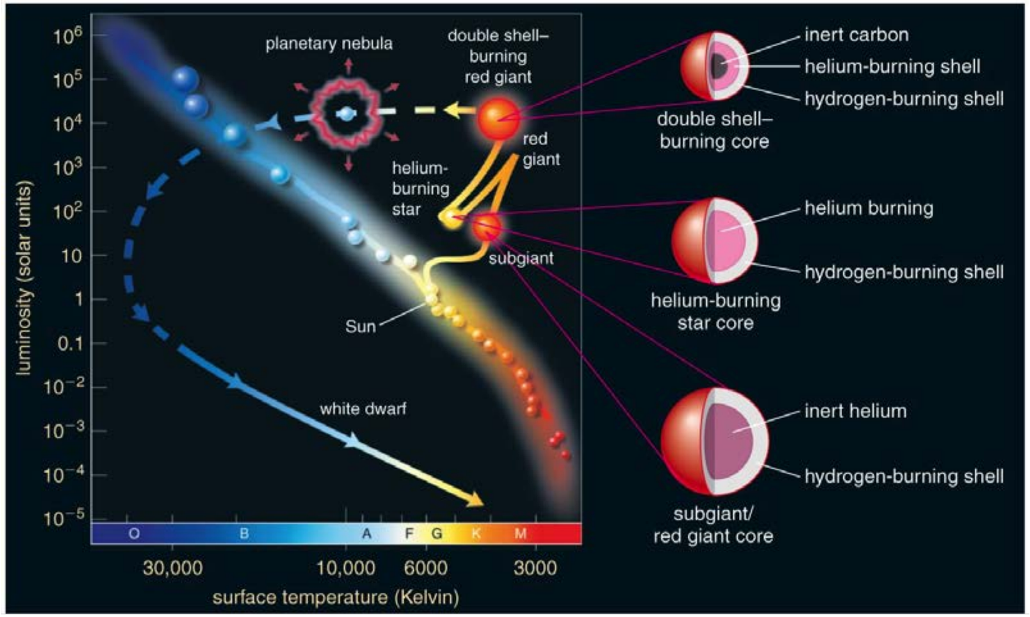


[Irastorza, Redondo, 18]

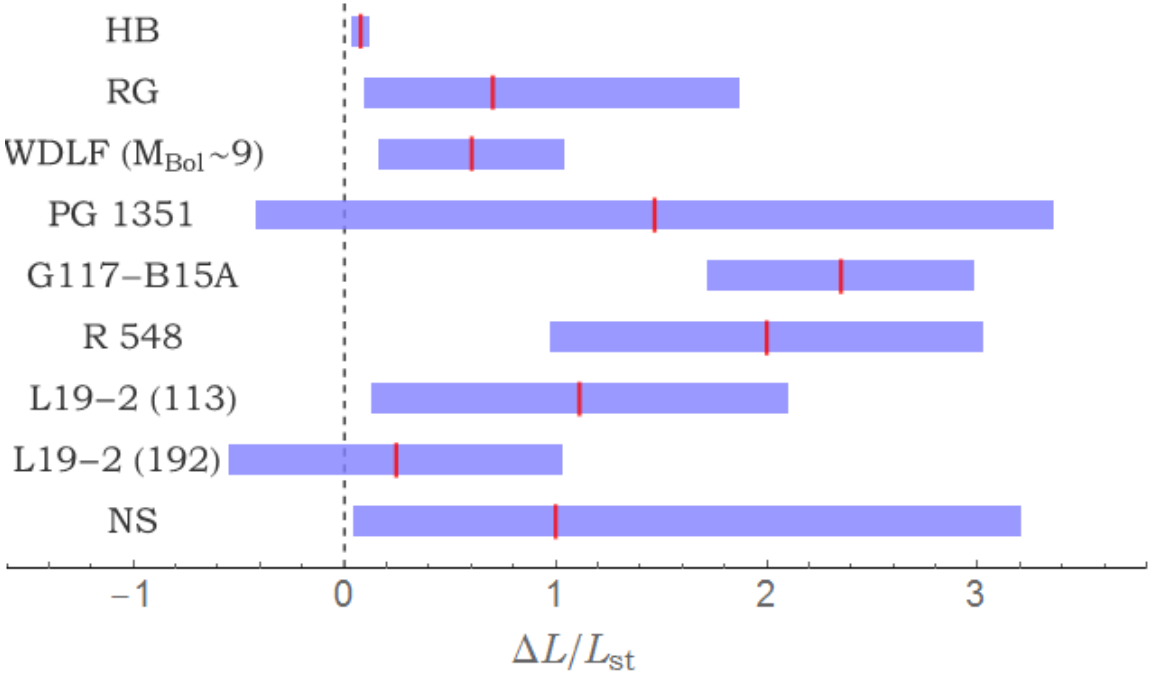
Light-Shining-through-a-Wall Searches

Astrophysical hints for axions

- 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]



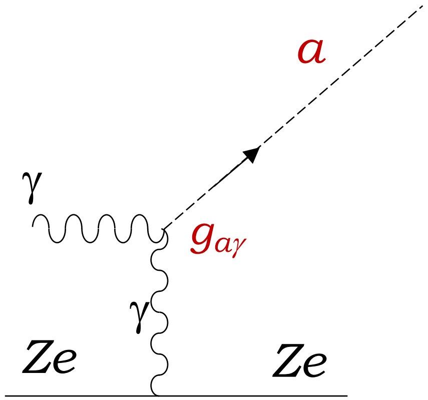
[Giannotti, Irastorza, Redondo, AR 15]

Light-Shining-through-a-Wall Searches

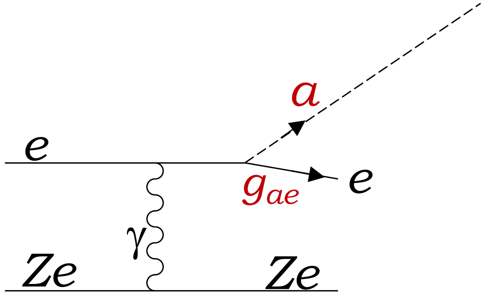
Astrophysical hints for axions

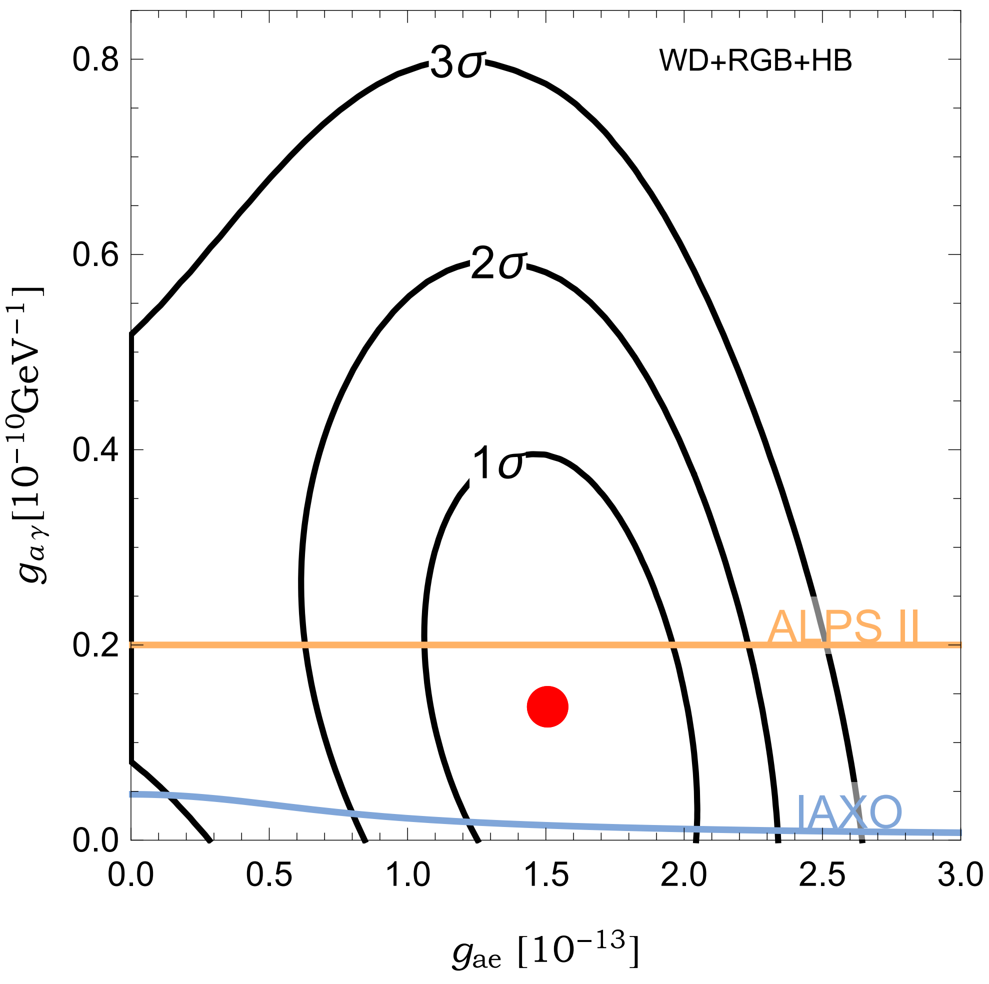
- Apart from dark matter, there are also other hints from astrophysics which may explained by axions:
  - Excessive energy losses of stars in various stages of their evolution: may be explained by axion production

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



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



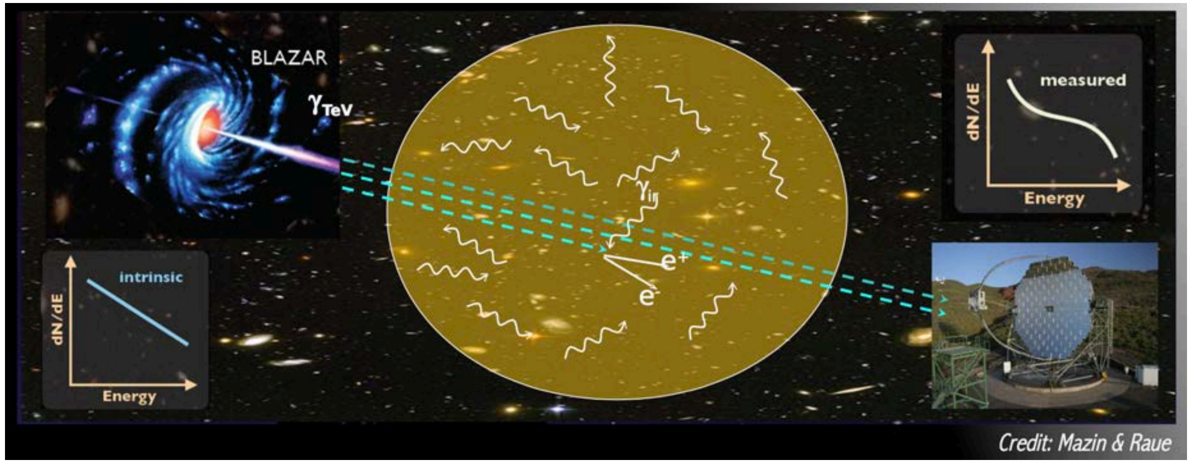


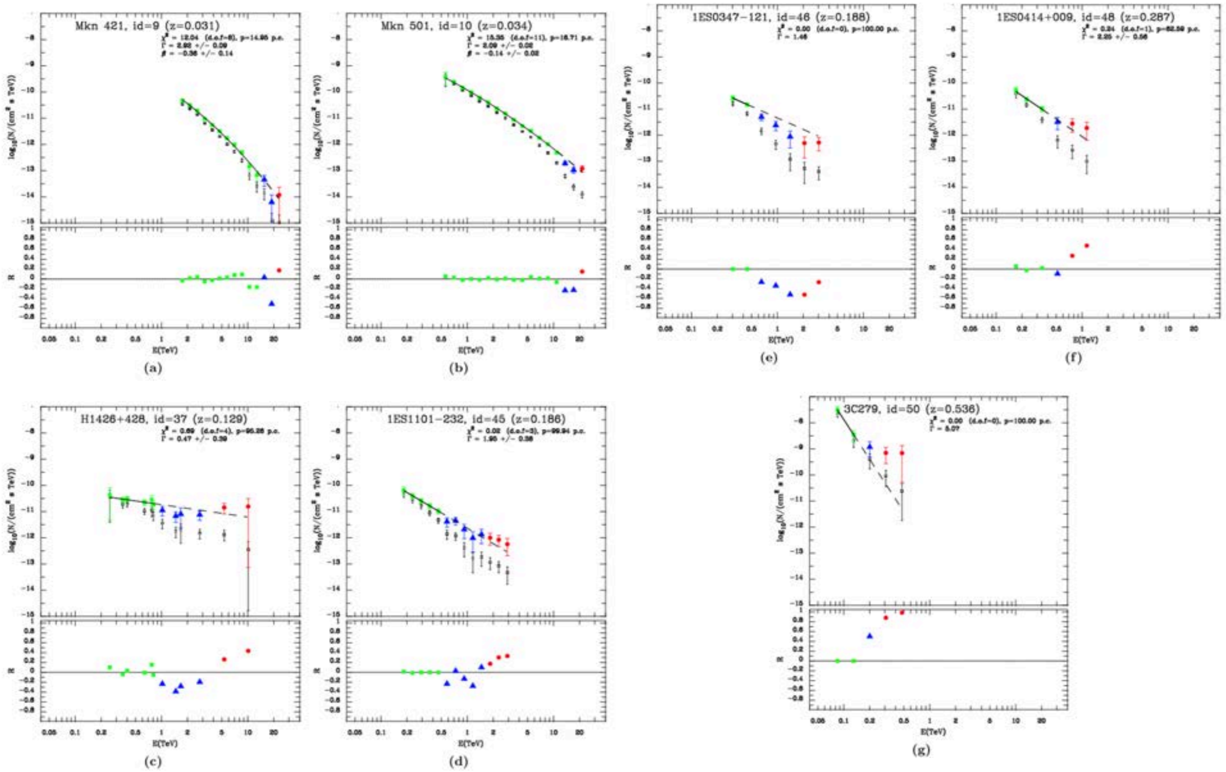
[Giannotti et al. 17]

Light-Shining-through-a-Wall Searches

Astrophysical hints for axions

- 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





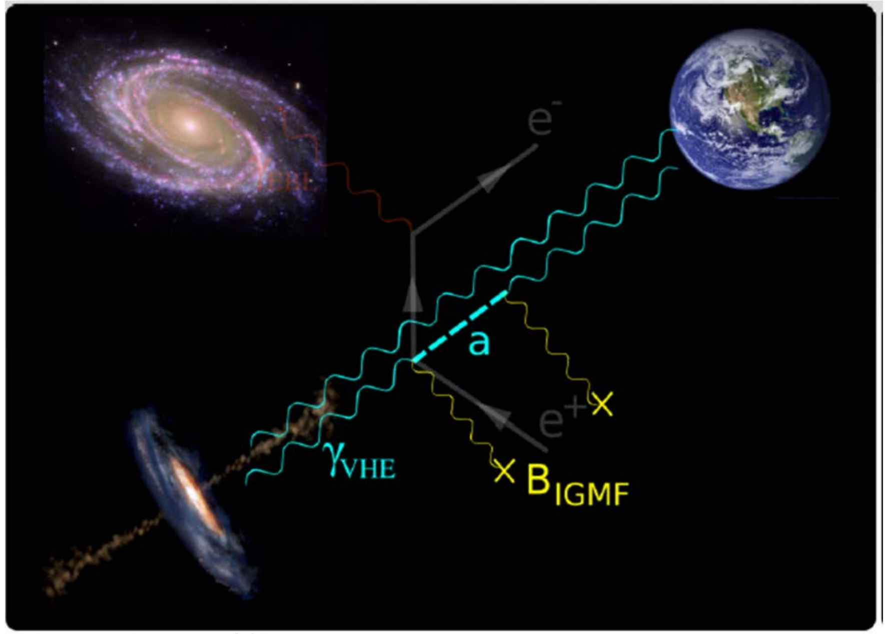
[Horns,Meyer 12]

Light-Shining-through-a-Wall Searches

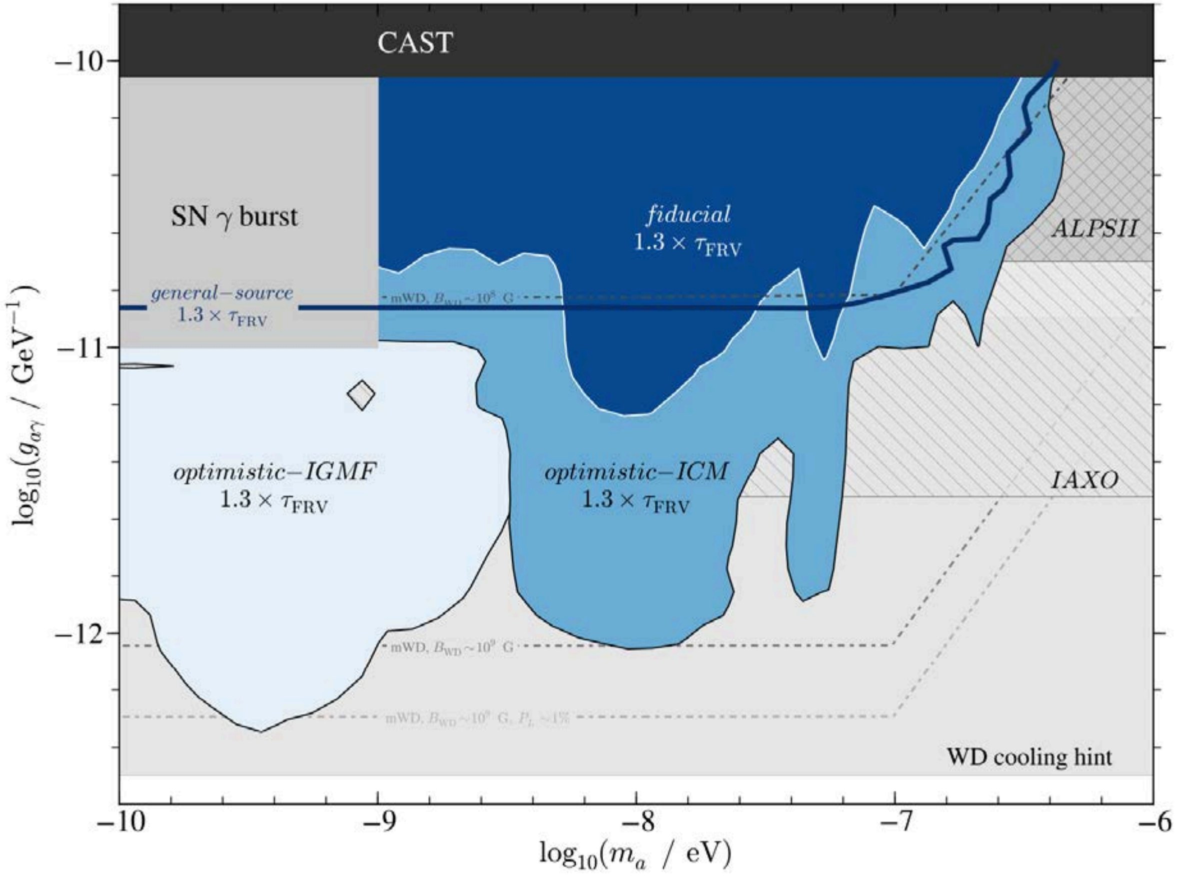
Astrophysical hints for axions

- 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 ↔ axion conversion

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



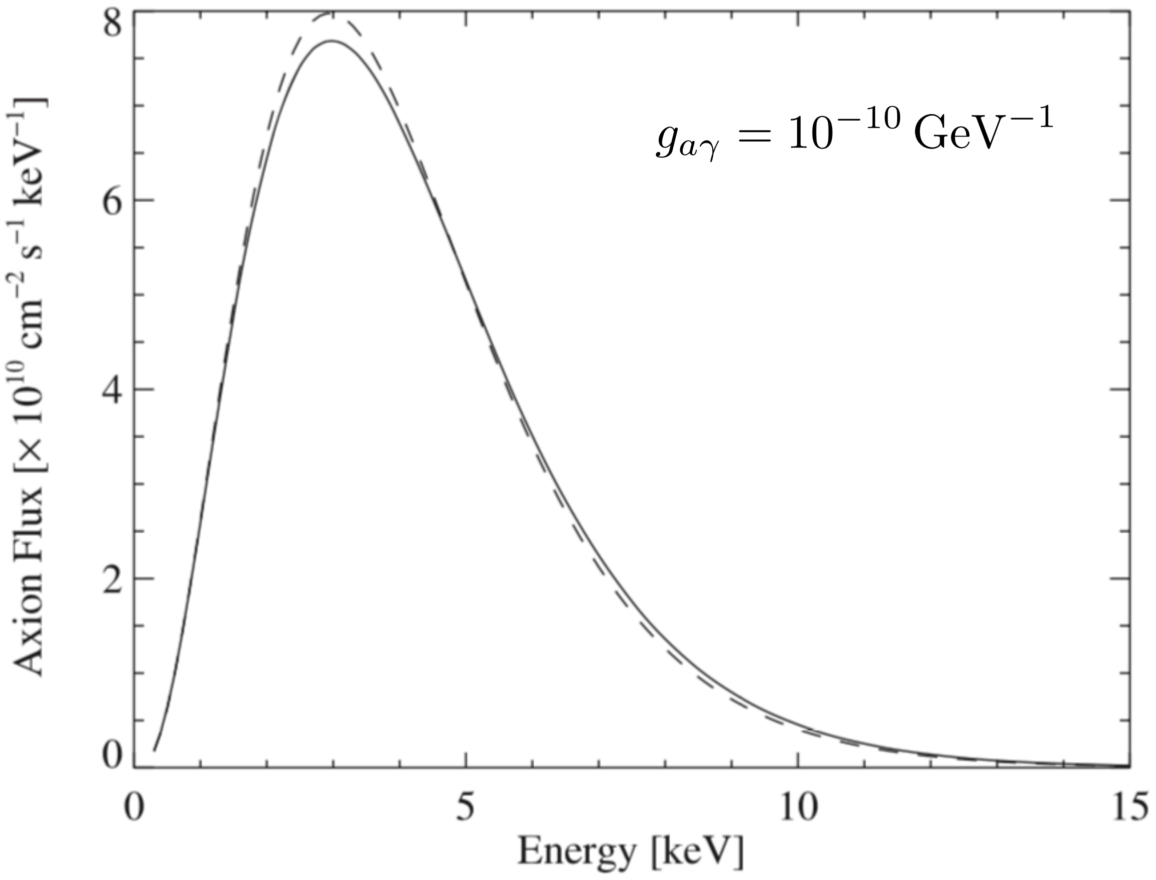
[Manuel Meyer 12]



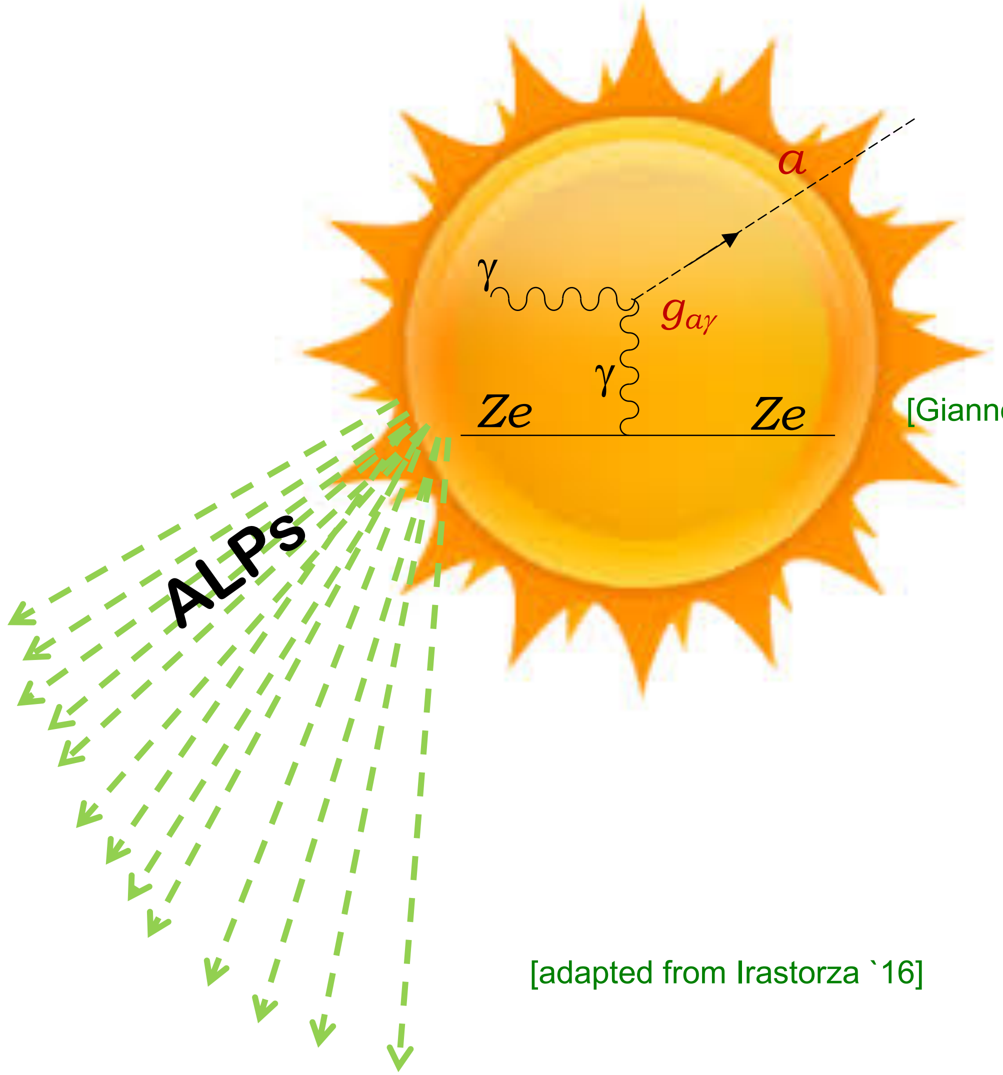
[Meyer,Horns,Raue 13]

Searches for Solar Axions

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



[Adriamonje et al. `07]

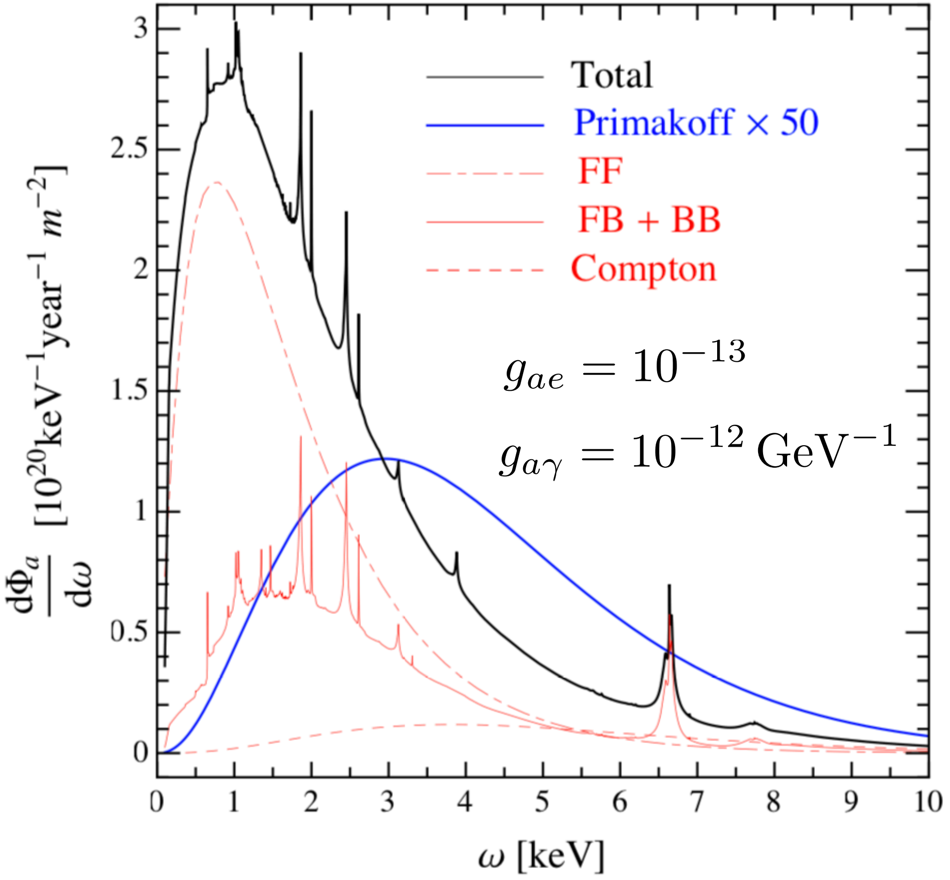


[Giannotti `16]

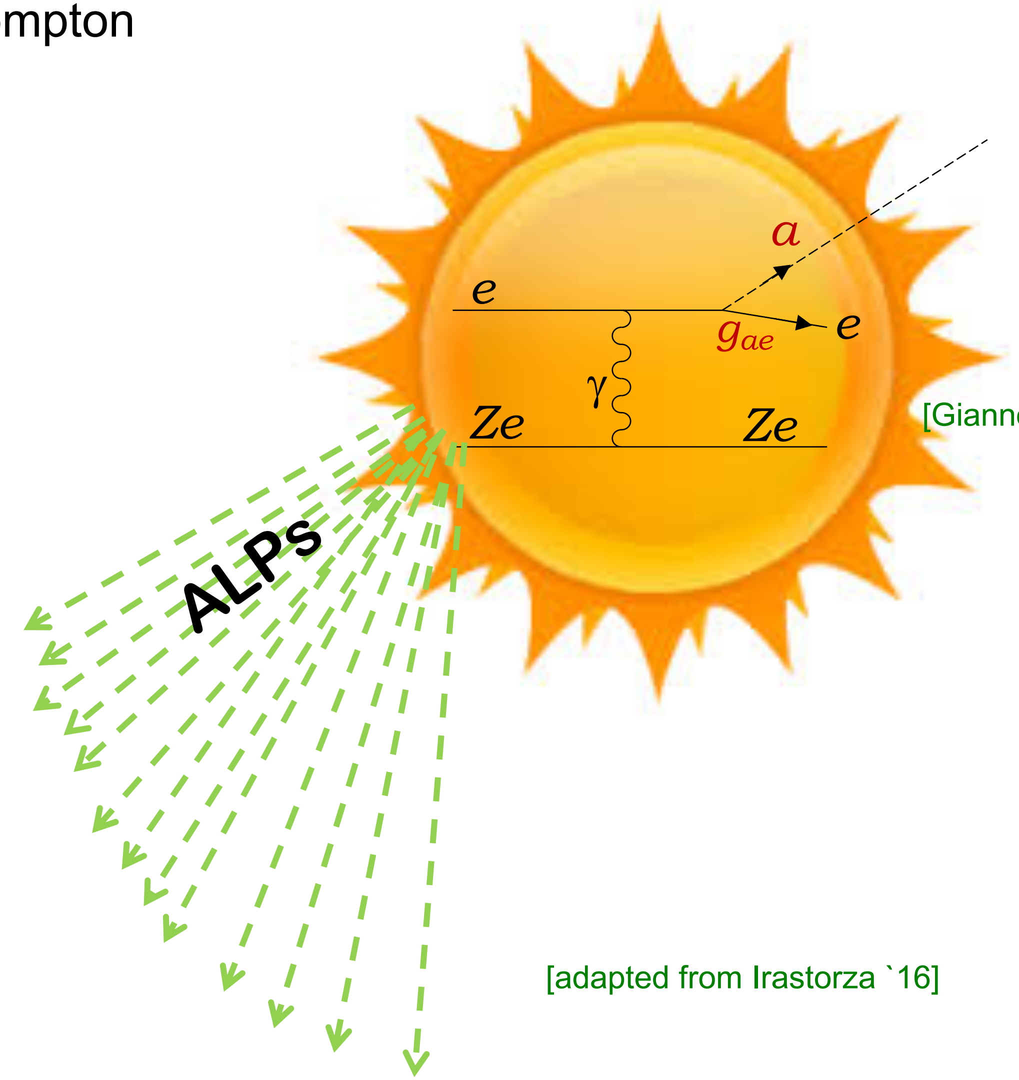
[adapted from Irastorza `16]

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]



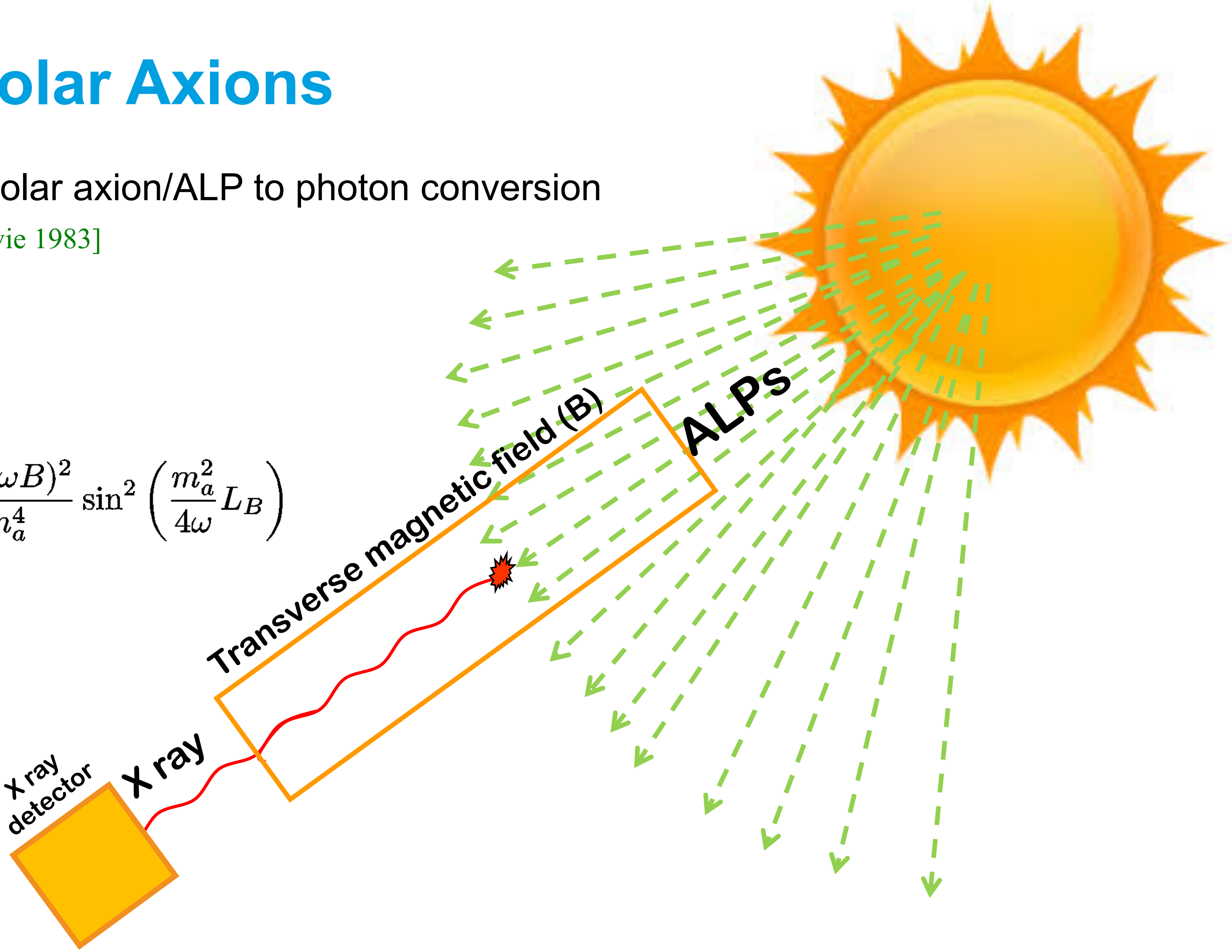
[Giannotti `16]

[adapted from Irastorza `16]

Searches for Solar Axions

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

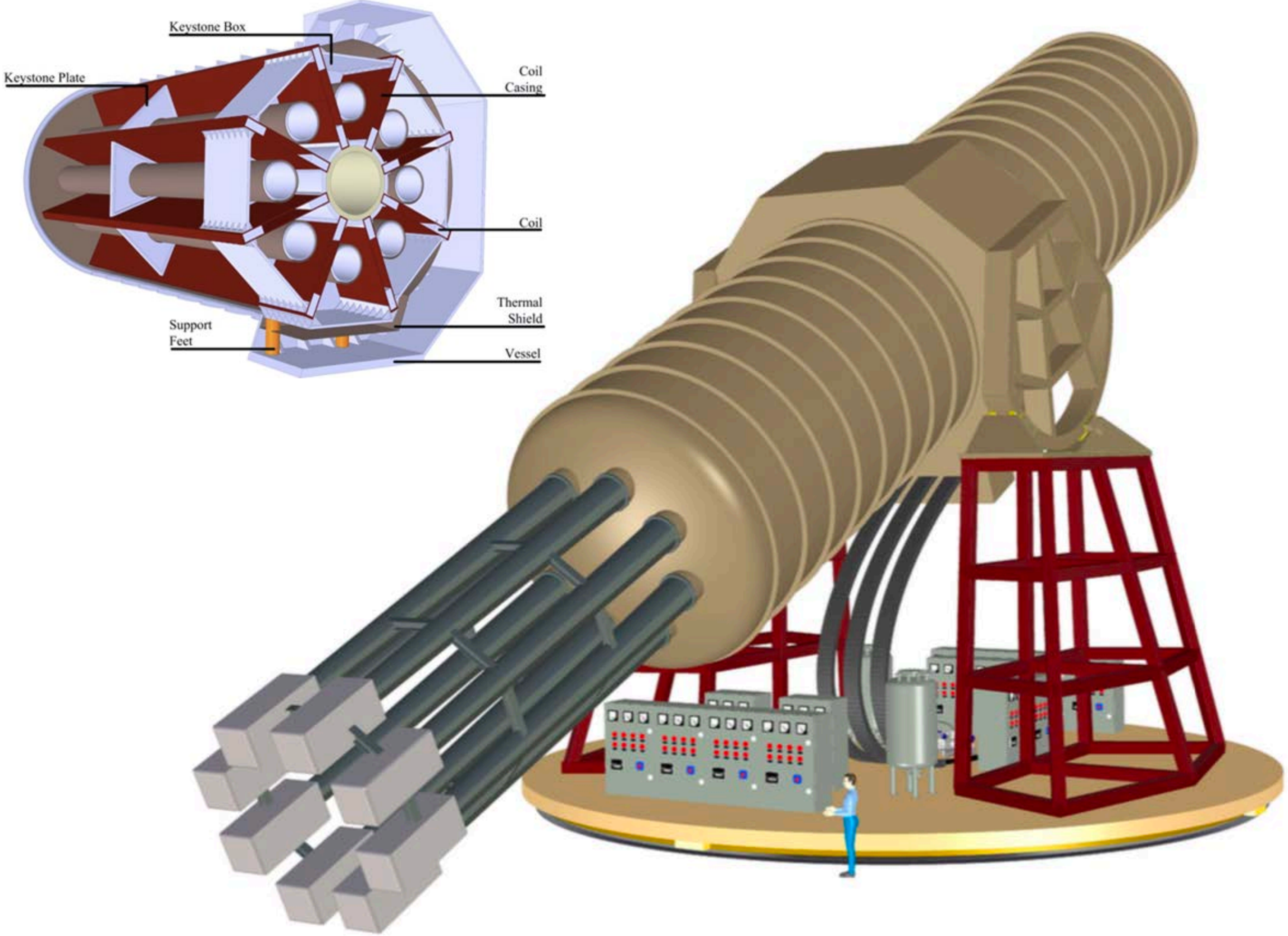
Searches for Solar Axions

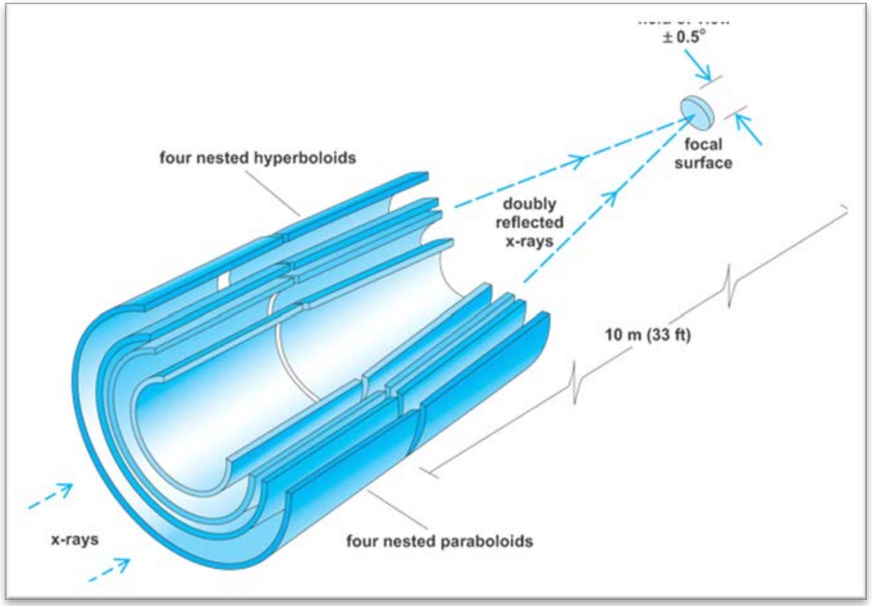
- Most sensitive until now: CERN Axion Solar Telescope (CAST)
  - Superconducting LHC dipole magnet
  - X-ray detectors
  - Use of buffer gas to extend sensitivity to higher masses (axion band)

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

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





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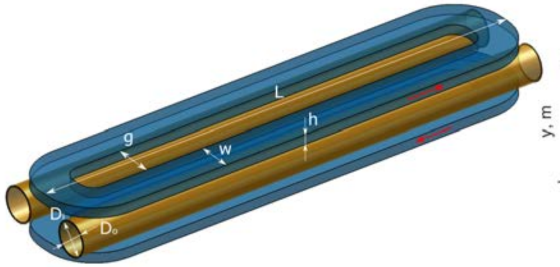
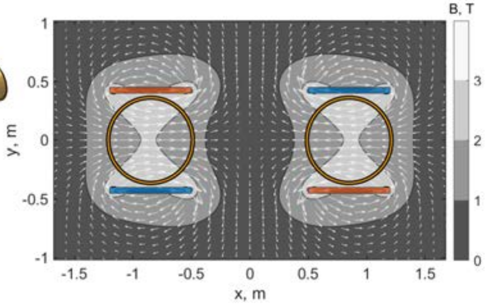
  - 8 X-ray telescopes + 8 detection systems
  - Rotating platform with services
- Proposed site: DESY

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

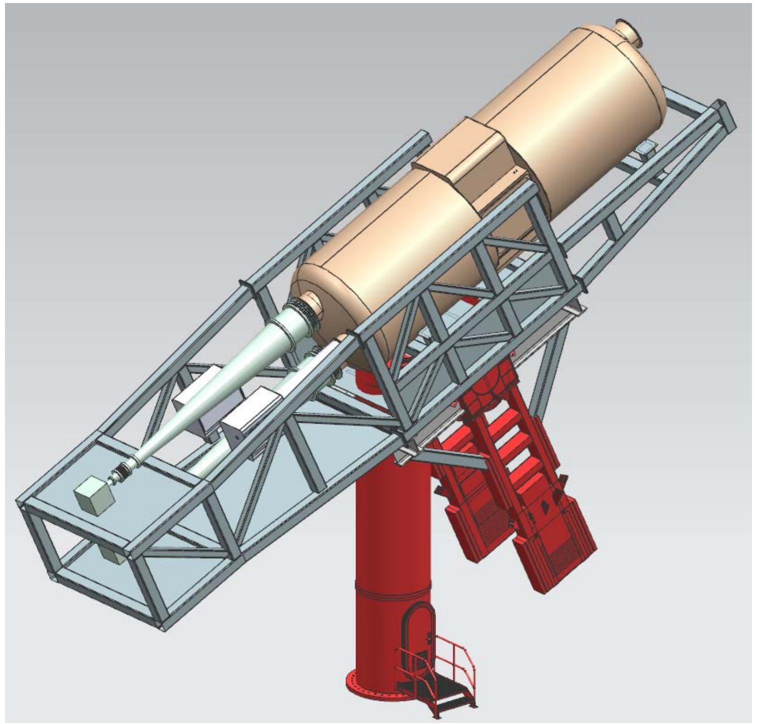
Searches for Solar Axions

- 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



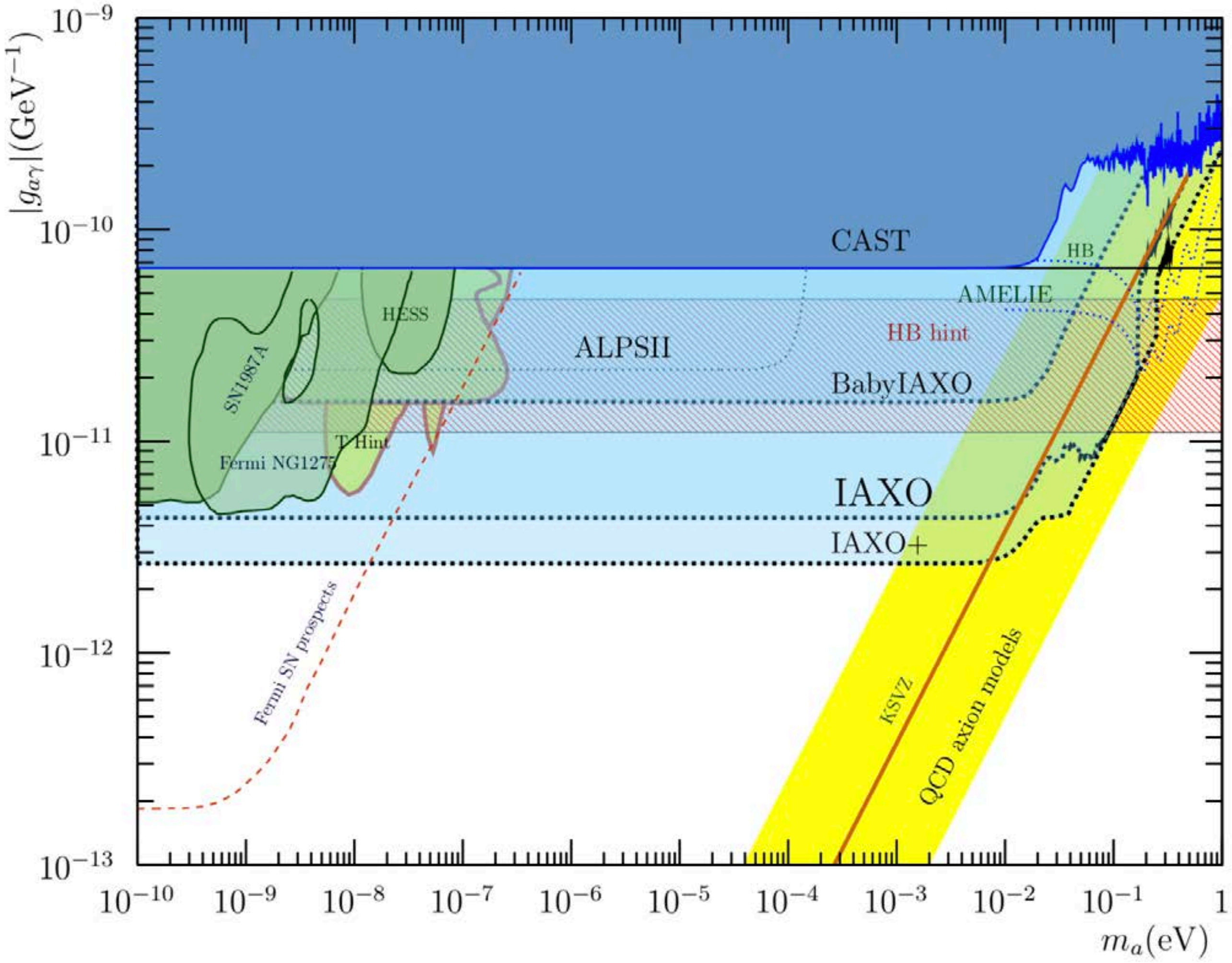


- Construction site: DESY
- Funded by DESY, CERN and Irastorza: ERC-AvG 2017 IAXO+
- Preparations have already started in 2020
- Data taking may start in 2024/25



Searches for Solar Axions

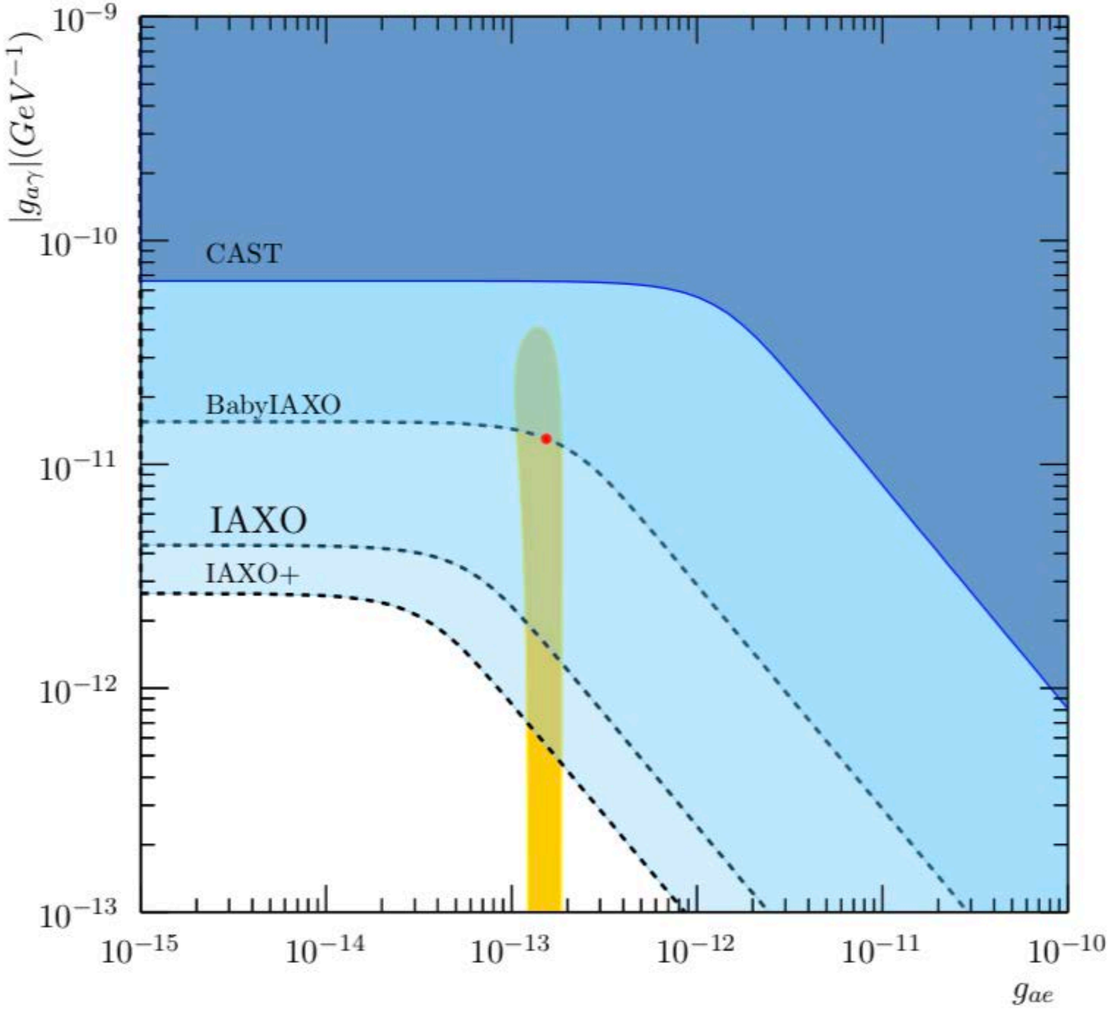
- (Baby)IAXO probes meV mass axion:



[Irastorza, Redondo, 18]

Searches for Solar Axions

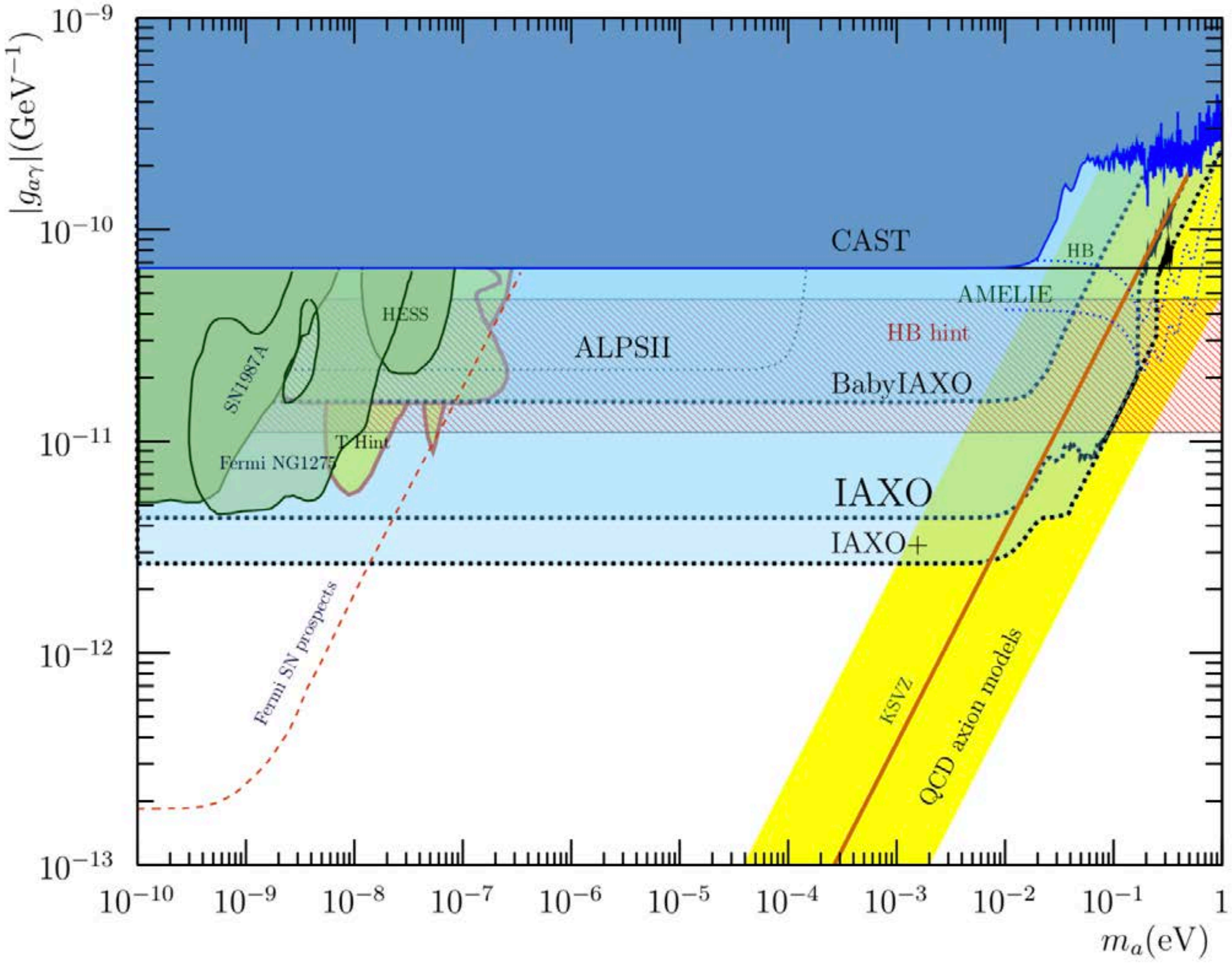
- (Baby)IAXO also sensitive to electron coupling hinted at by stellar energy losses:



[Armengaud et al. 19]

Axion or Axion-Like-Particle (ALP)?

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



[Irastorza, Redondo, 18]

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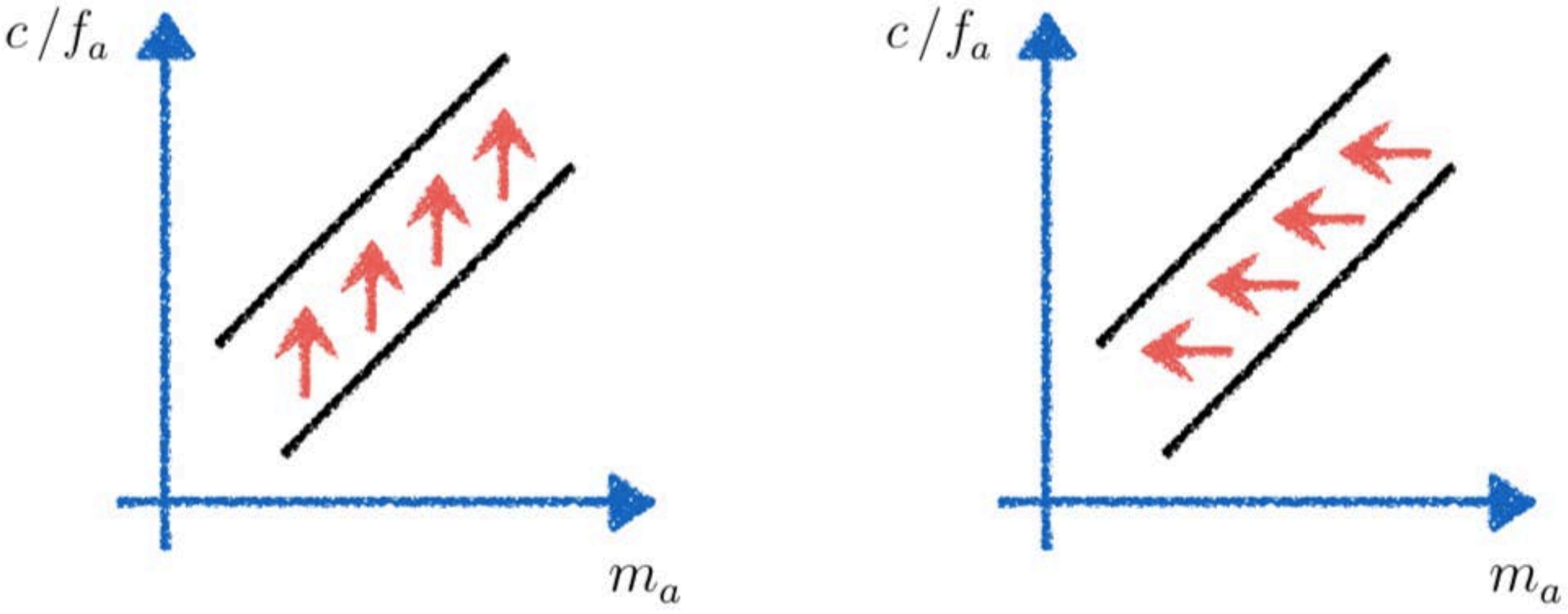
  - increased values of $C_{a\gamma}$, for fixed value of m_a [Di Luzio et al. 16, Farina et al. 16, Agrawal et al. 17]
  - smaller values of m_a, for fixed values of $C_{a\gamma}/f_a$ [Hook 18, Di Luzio et al. 21]



[Di Luzio, Gavela, Quilez, AR 2102.00012]

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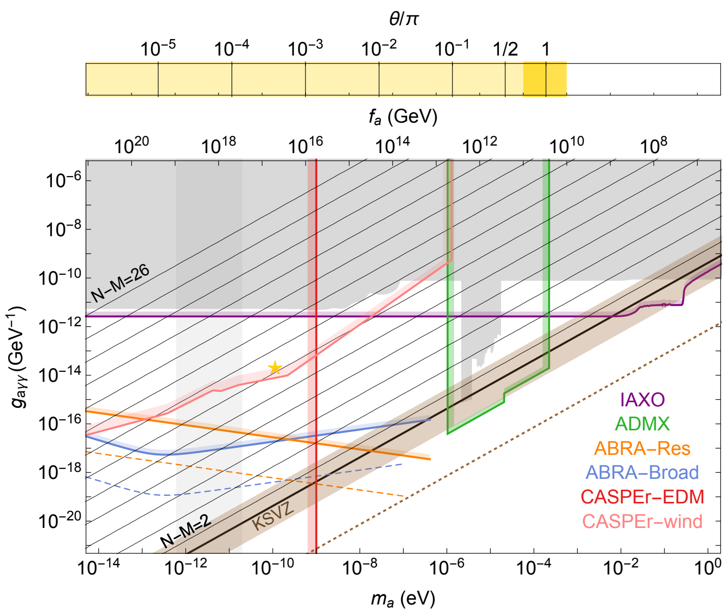
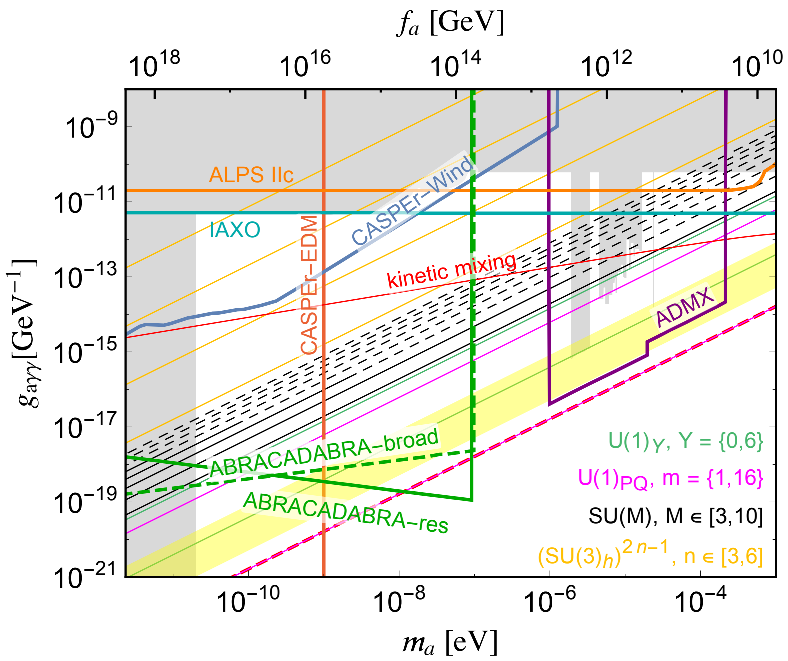
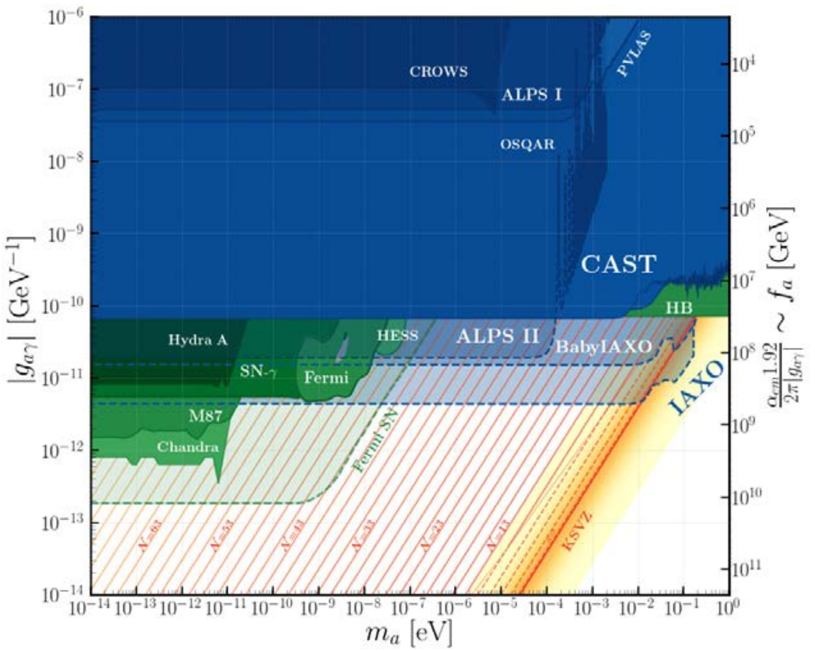


[Farina et al., 1611.09855]



[Agrawal et al., 1709.06085]



[Di Luzio et al., 2102.00012]

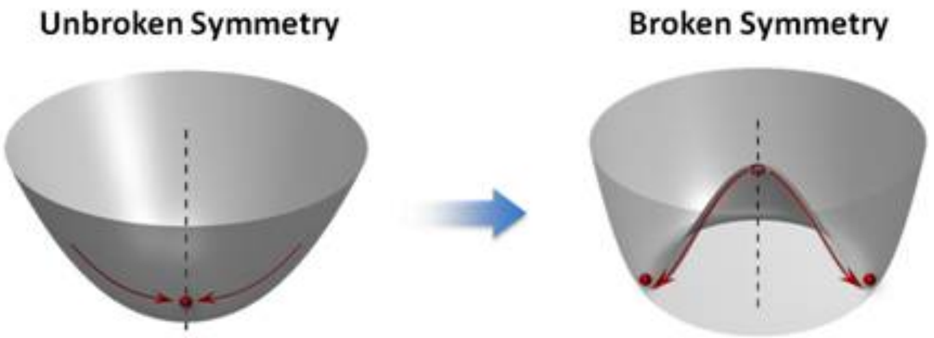
Axion Dark Matter

Production via misalignment mechanism

- PQ phase transition takes place at

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

- Axion takes random initial values in causally connected domains



[Peking University]

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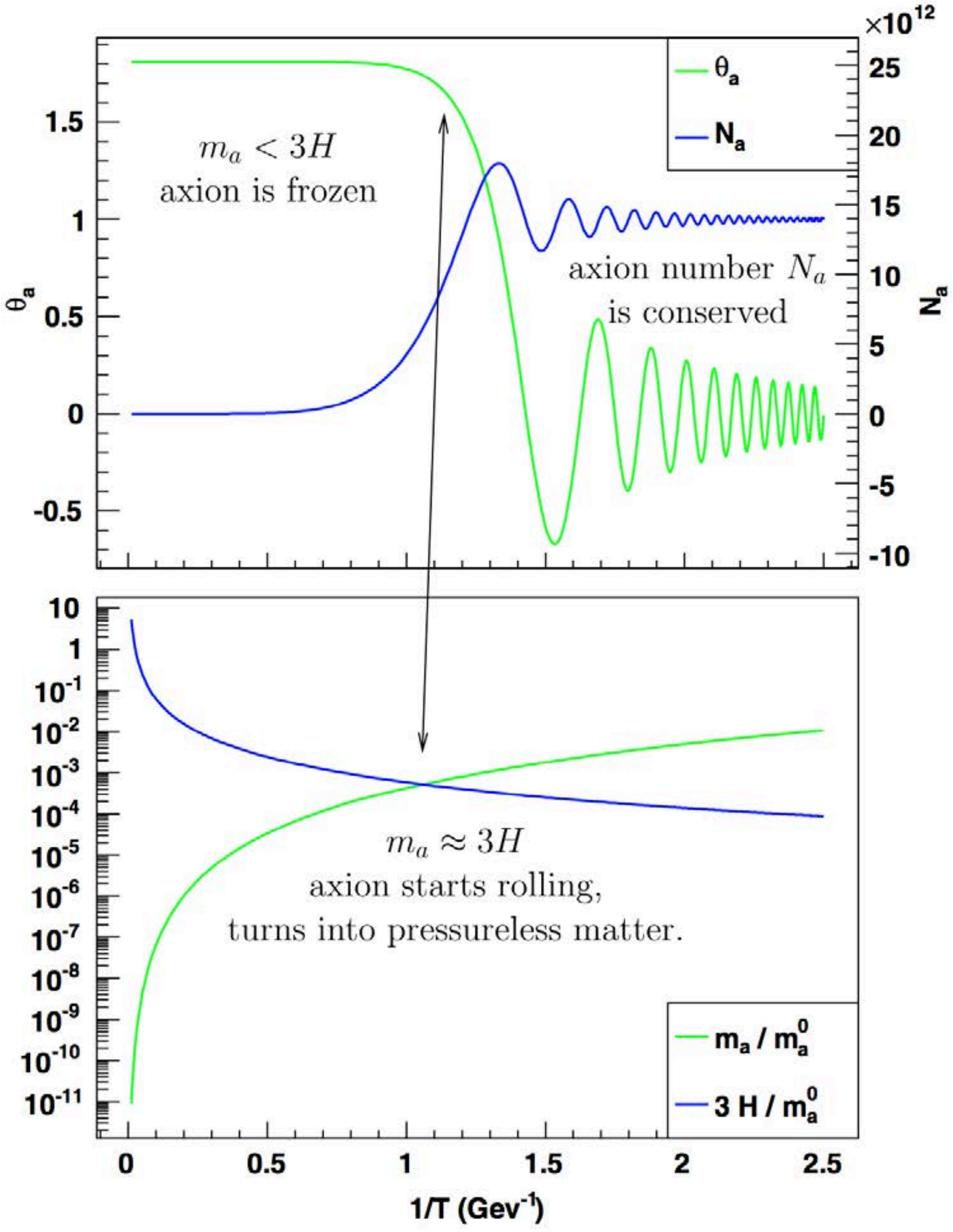
- When $H(T) \sim m_A(T)$, axion field starts to oscillate around minimum of potential; behaves like cold dark matter: $w_A = p_A/\rho_A \simeq 0$

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



[Wantz,Shellard `09]

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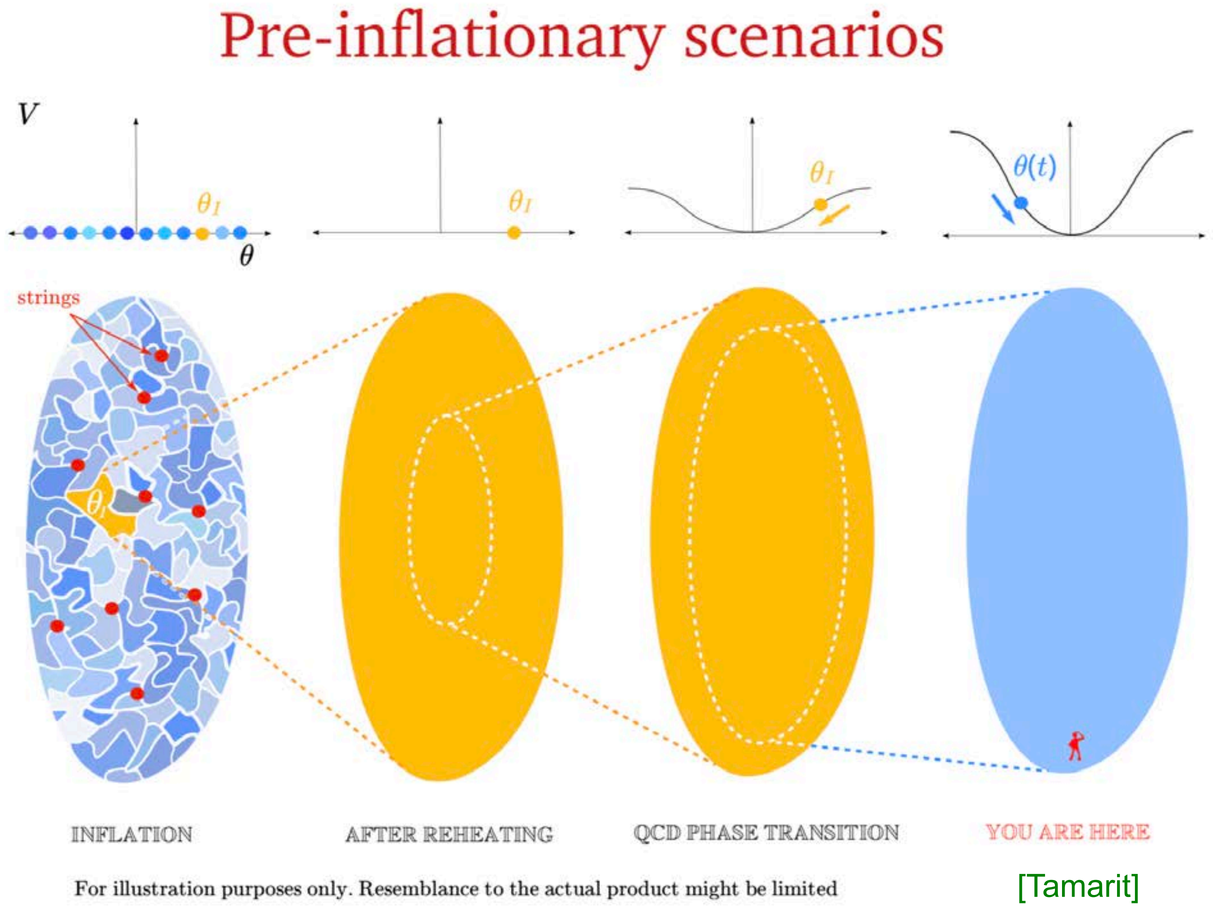
- If PQ symmetry broken before or during inflation and not restored afterwards:
  - Axion CDM density depends on single initial value in patch, which becomes observable universe, and decay constant



[Tamarit]

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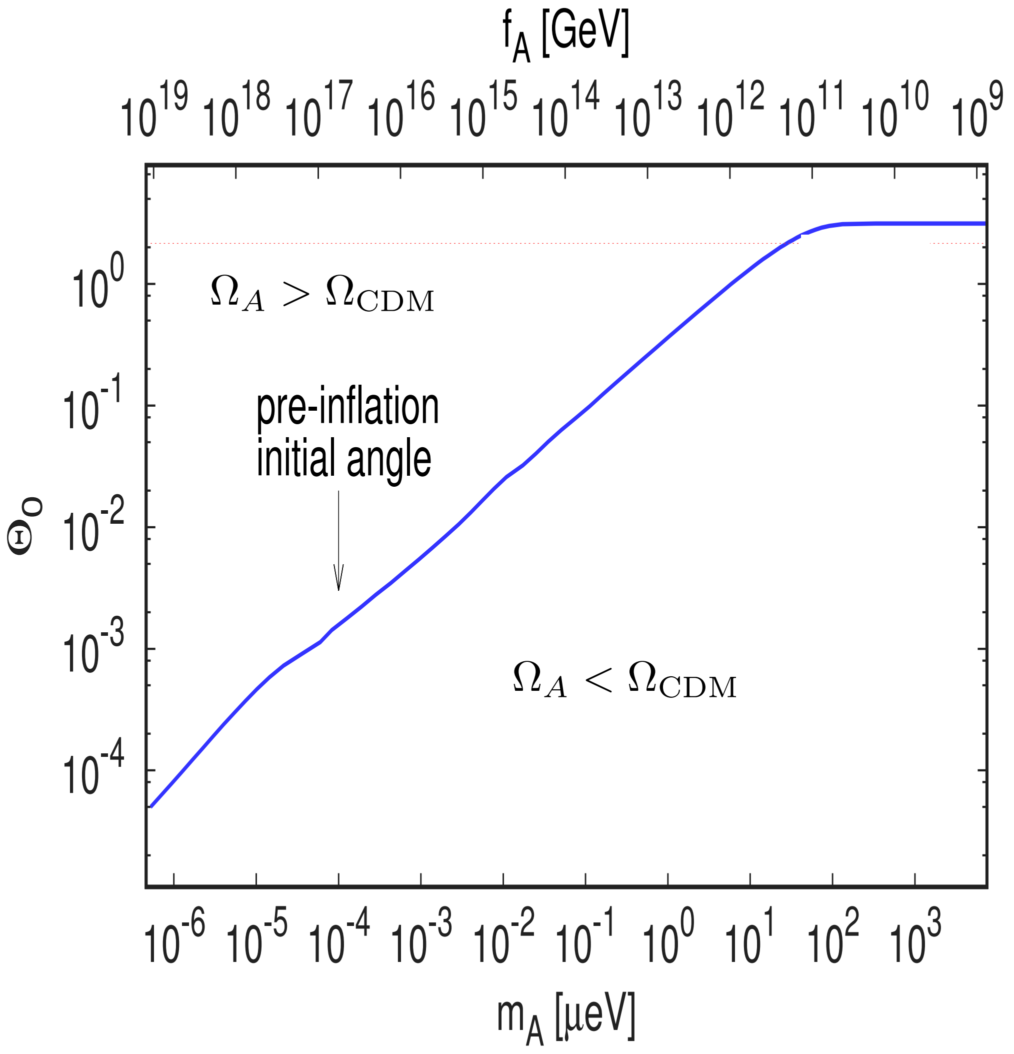


[Borsanyi et al., Nature `16]

Axion Dark Matter

Post-inflationary PQ SSB scenario

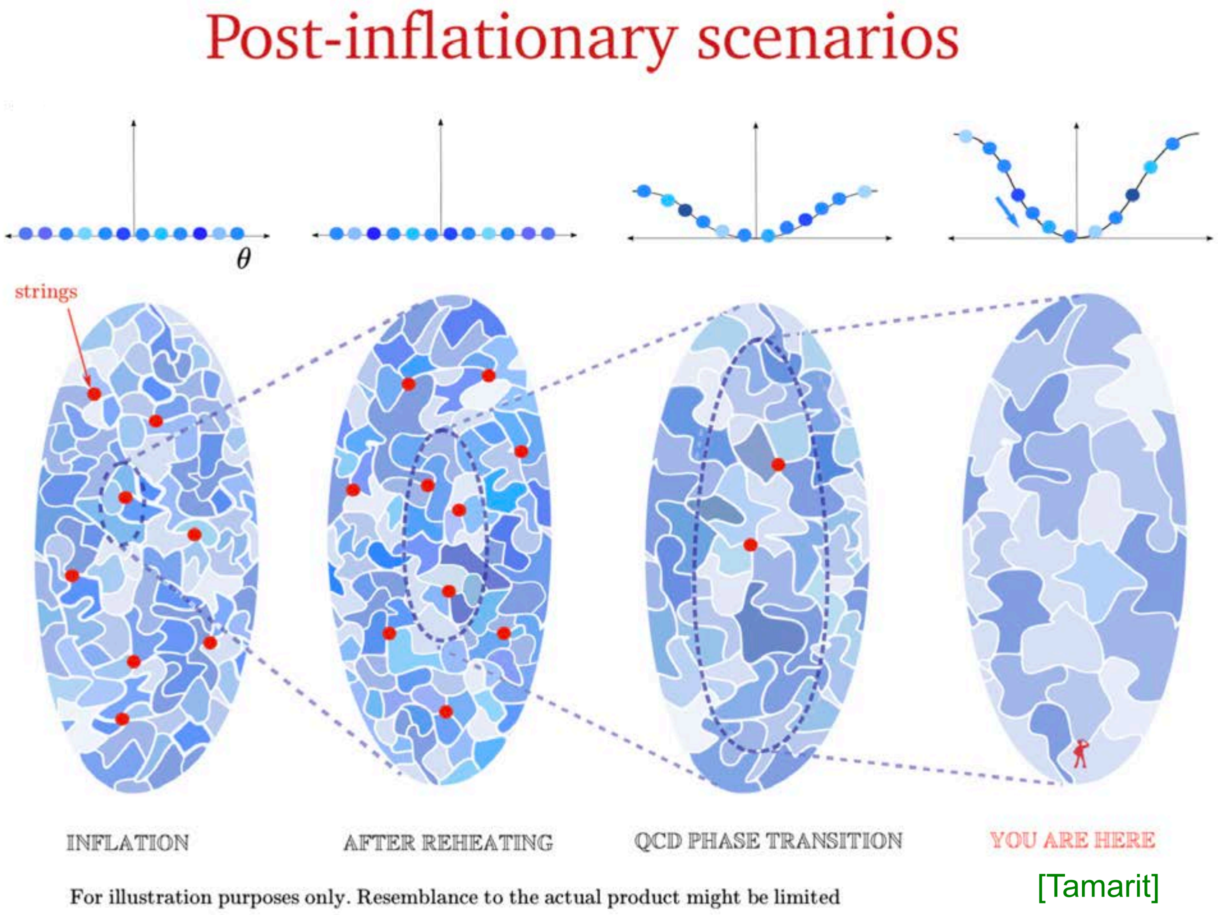
- If PQ symmetry broken after inflation, need to average over random initial axion field values:

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

- Observed CDM abundance puts lower bound on axion mass:

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

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



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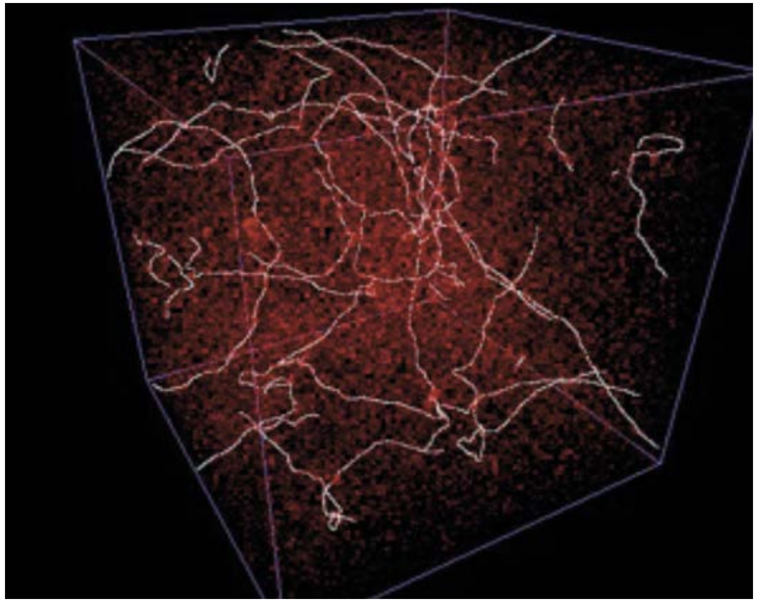
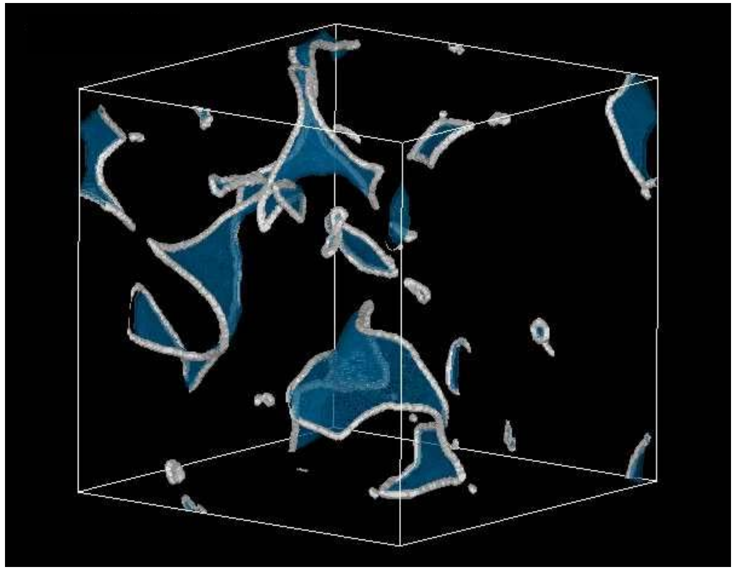
[Borsanyi et al., Nature `16 [1606.0794]]

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

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

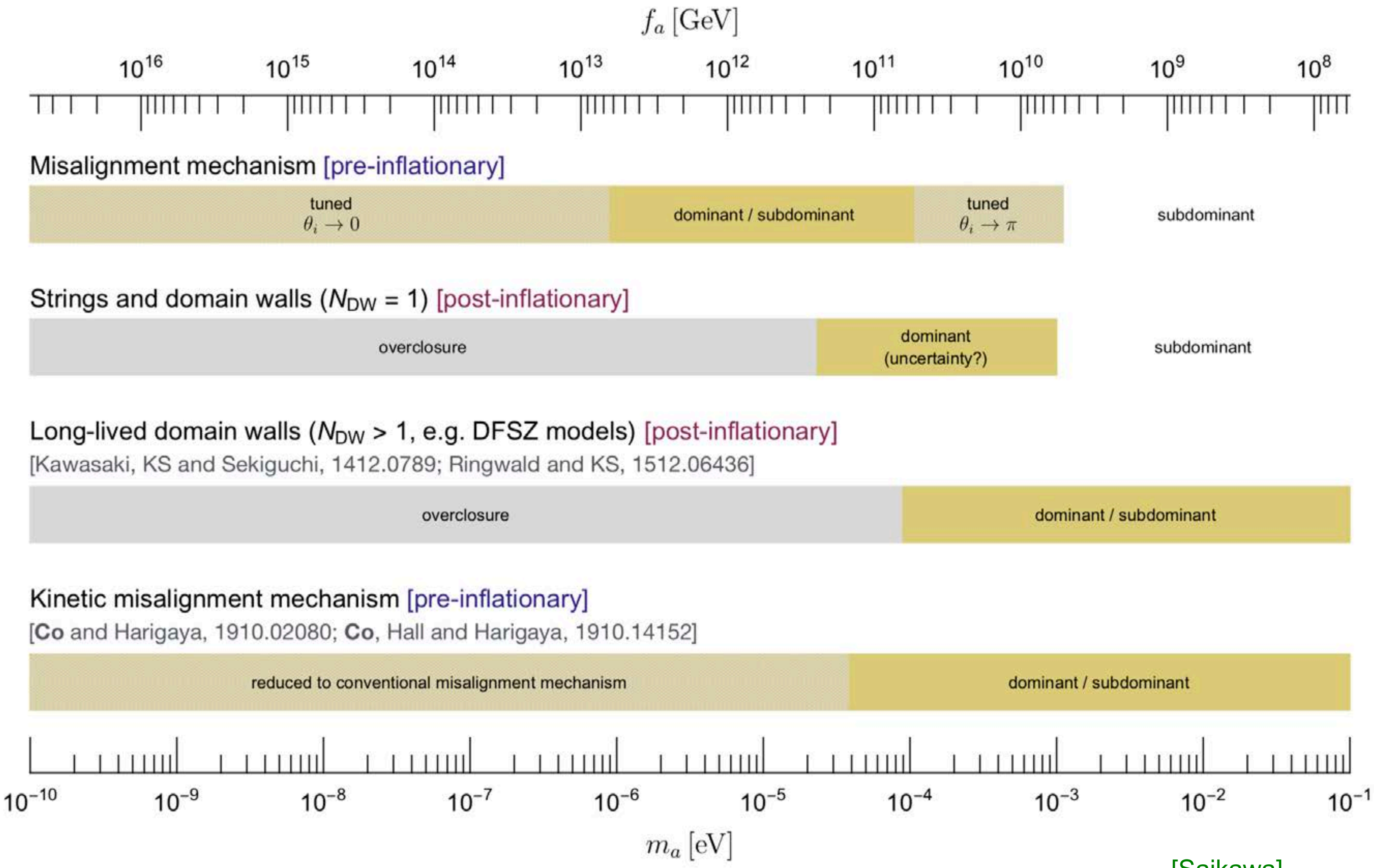


[Hiramatsu et al.]



Axion Dark Matter

Dark Matter axion mass spans a huge range



[Saikawa]

Searches for Dark Matter Axions

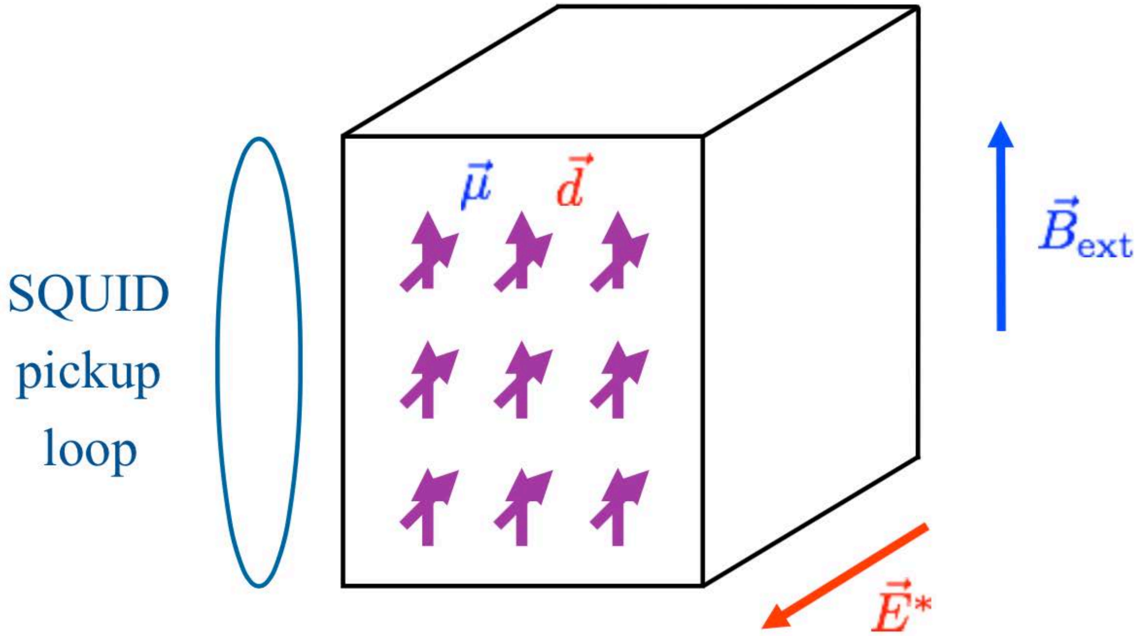
Magnetic Resonance Searches

- 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]

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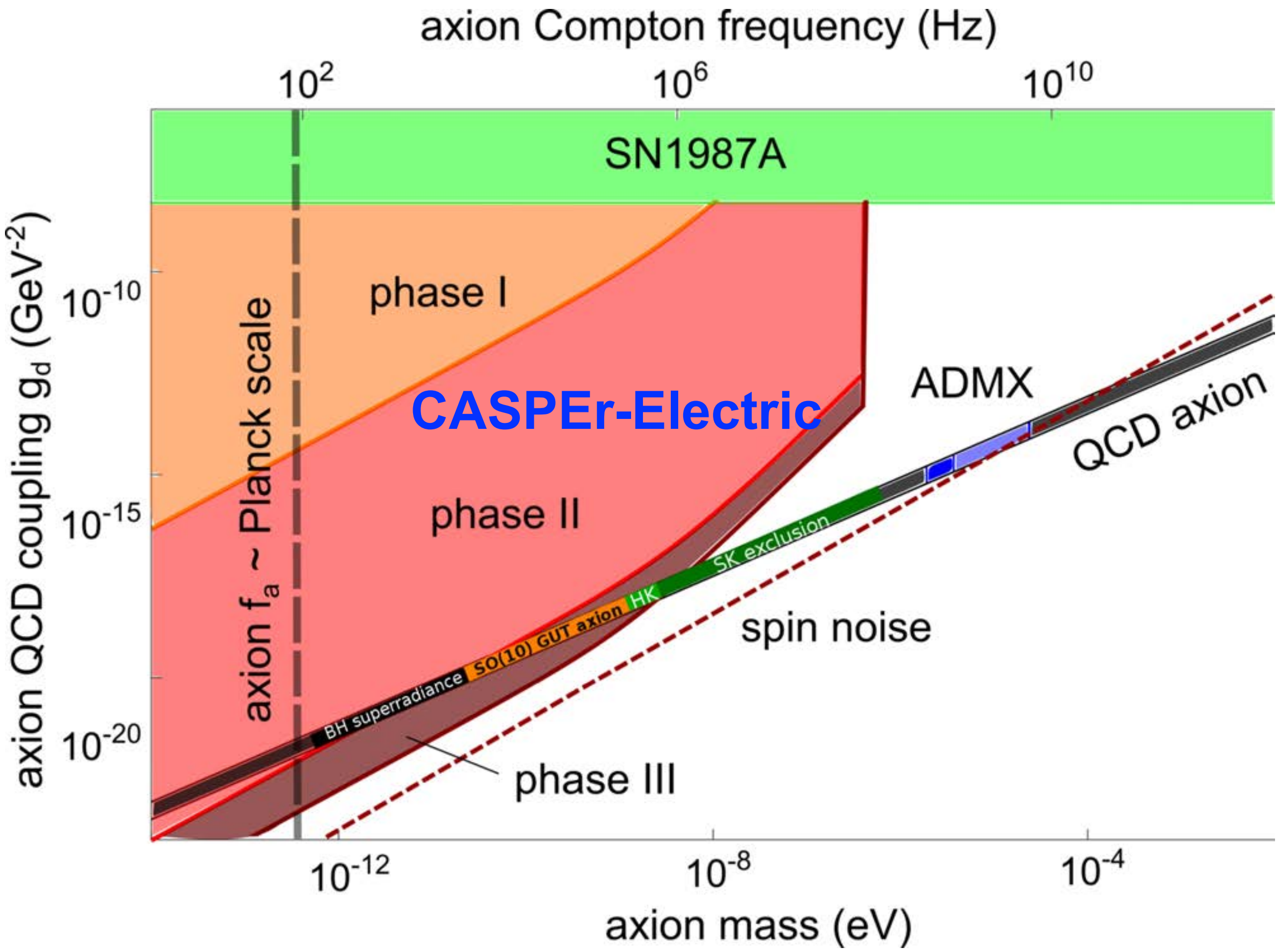
  - In phase III: probes axion dark matter in mass range predicted by GUTs [Ernst,AR,Tamarit 18; Di Luzio,AR,Tamarit 18]



[Ernst,Di Luzio,AR,Tamarit 18]

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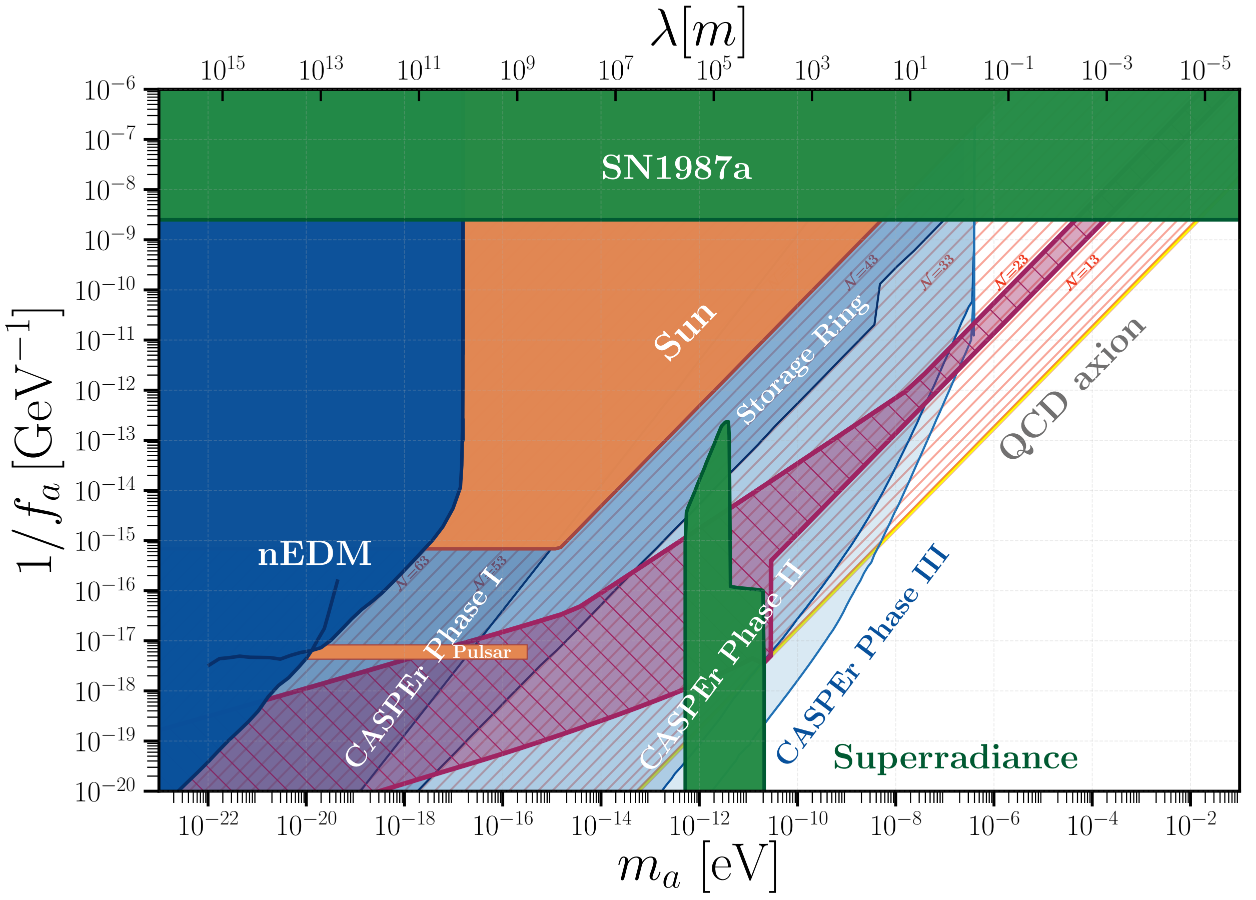
  - In phase I and II: probes Z_N axion dark matter

[Di Luzio, Gavela, Quilez, AR 2102.00012]



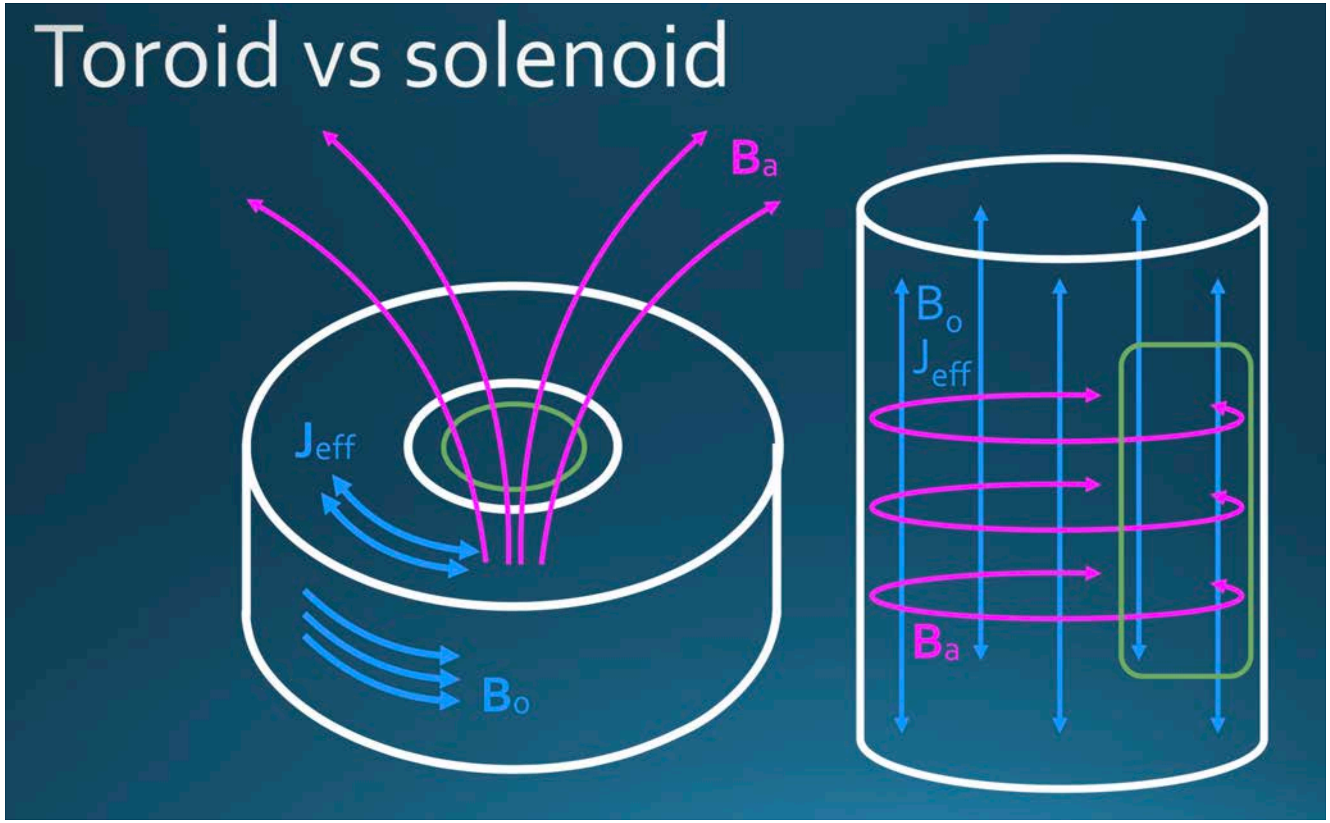
[Di Luzio, Gavela, Quilez, AR 2102.00012]

Searches for Dark Matter Axions

Searching for Axion-induced Magnetic Fields

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

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



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

[Salemi ‘21]

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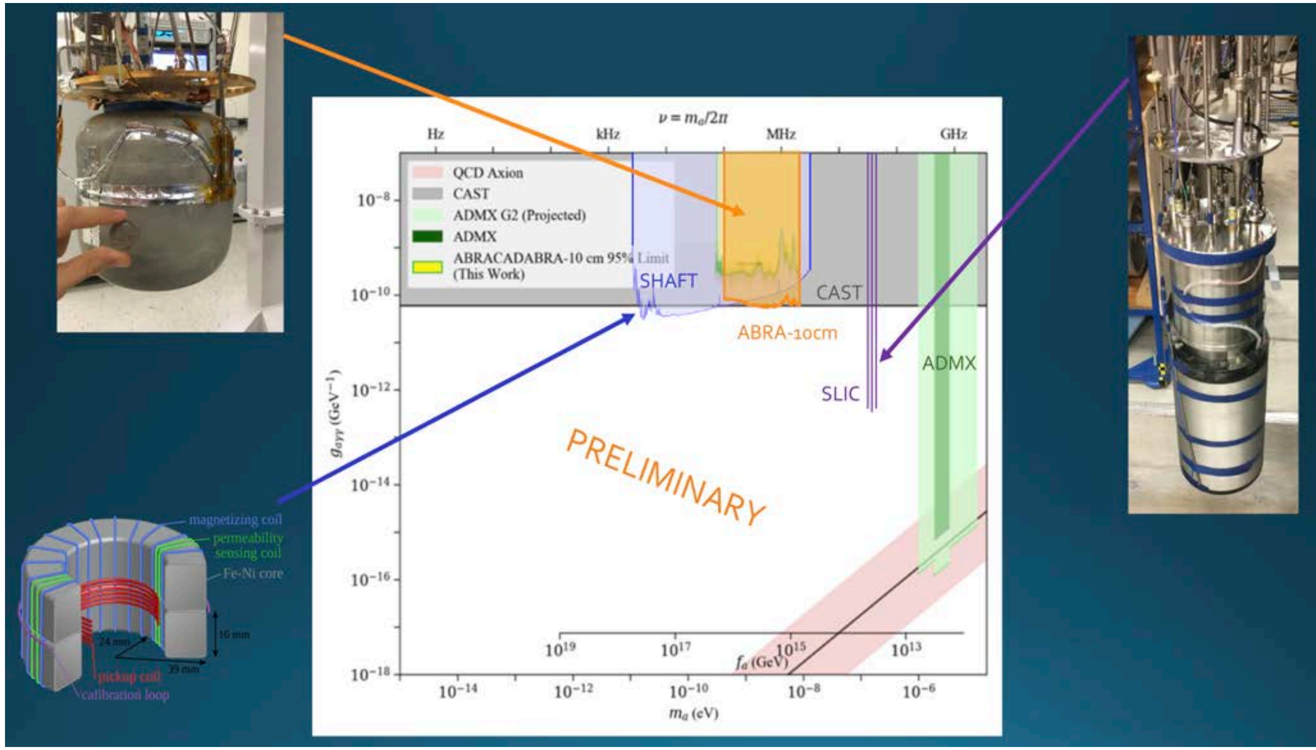
  - ... which can be read out by pickup structure
- Pathfinder experiments:
  - ABRACADABRA [Ouellet et al. 19]
  - ADMX SLIC [Crisosto et al. 20]
  - SHAFT [Gramolin et al. 21]



[Salemi '21]

Searches for Dark Matter Axions

Searching for Axion-induced Magnetic Fields

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

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

DM Radio Cubic Meter Consortium

Funded as part of DOE New Initiatives in Dark Matter program

R&D Phase Consortium Leadership:

Project manager for R&D phase: Dale Li

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

DARK MATTER RADIO

U.S. DEPARTMENT OF ENERGY Office of Science

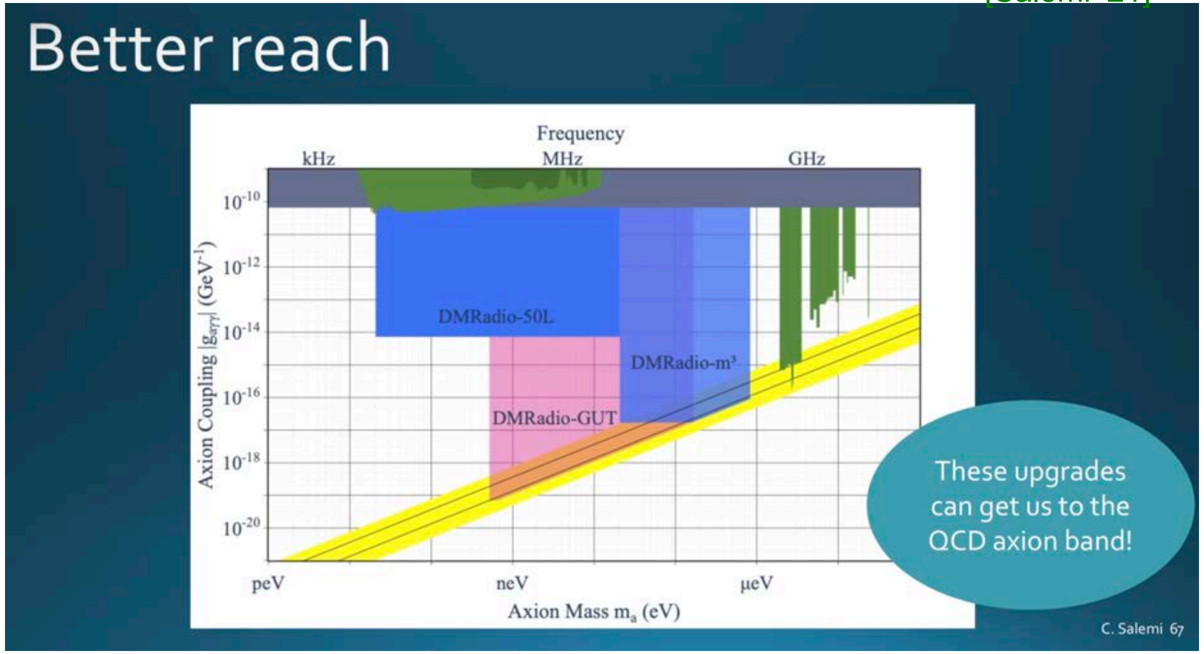
SLAC

PRINCETON UNIVERSITY

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

DMRm3consortium v1 20191104

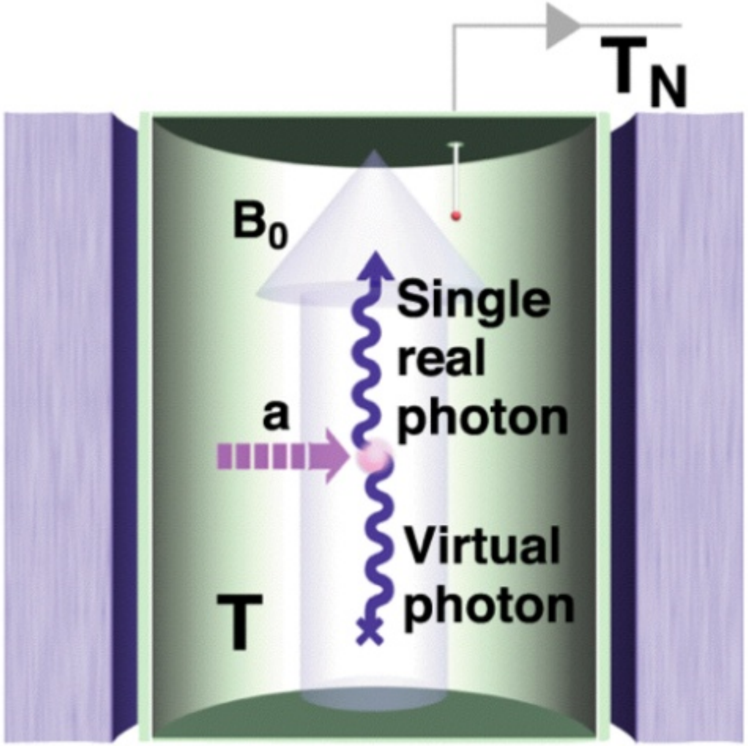
[Salemi '21]



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 $m_a = 2\pi\nu \sim 4\ \mu\text{eV} \left(\frac{\nu}{\text{GHz}}\right)$

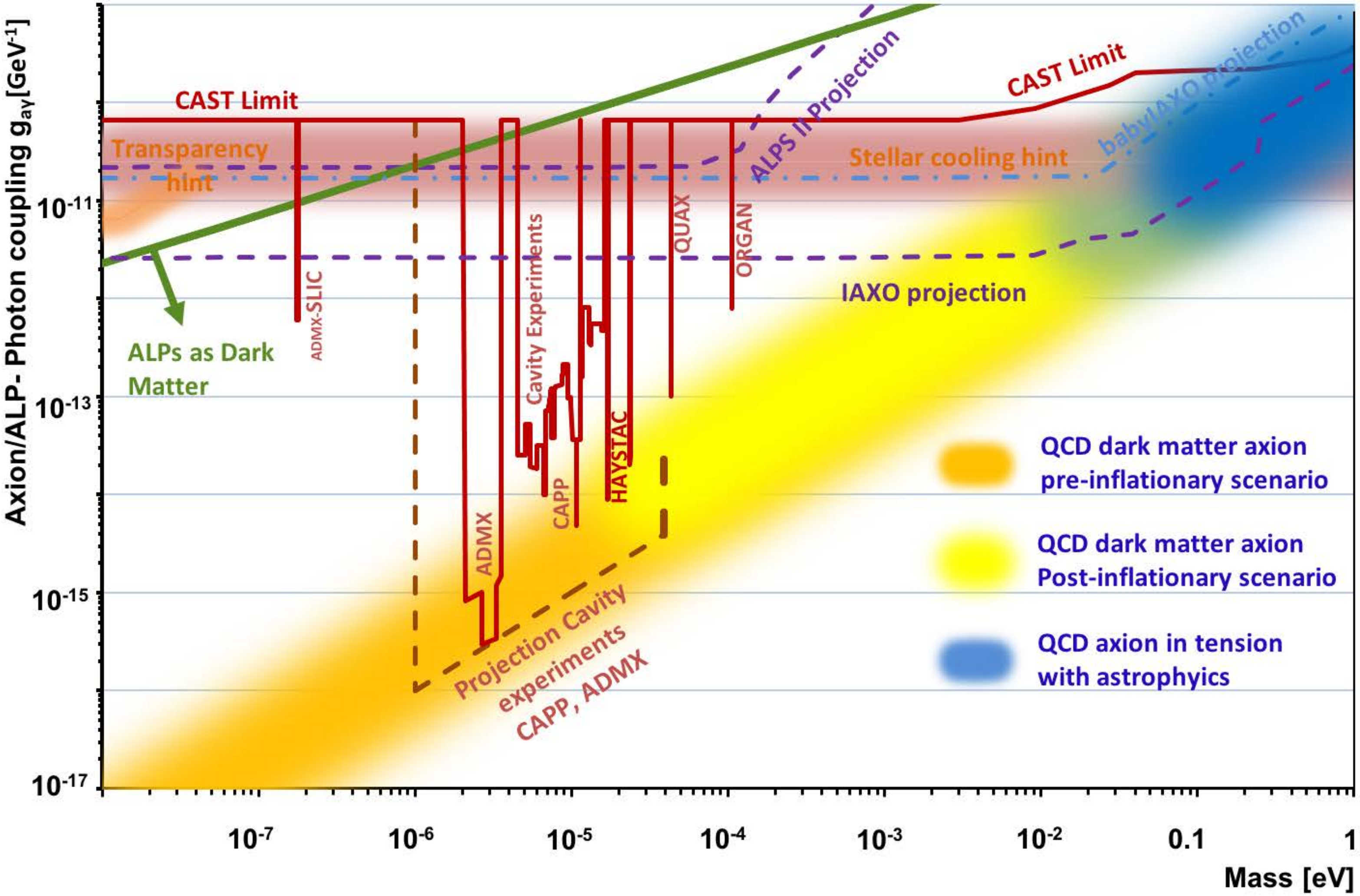


$$P_{\text{out}} \sim g^2 \mid \mathbf{B}_0 \mid^2 \rho_{\text{DM}} V Q / m_a$$

Searches for Dark Matter Axions

Microwave Cavities

- Currently running:
  - ADMX
  - CAPP
  - HAYSTACK
  - ORGAN
  - QUAX
- Projected to probe deep into the axion band in the mass range between 1 and 40 micro-eV

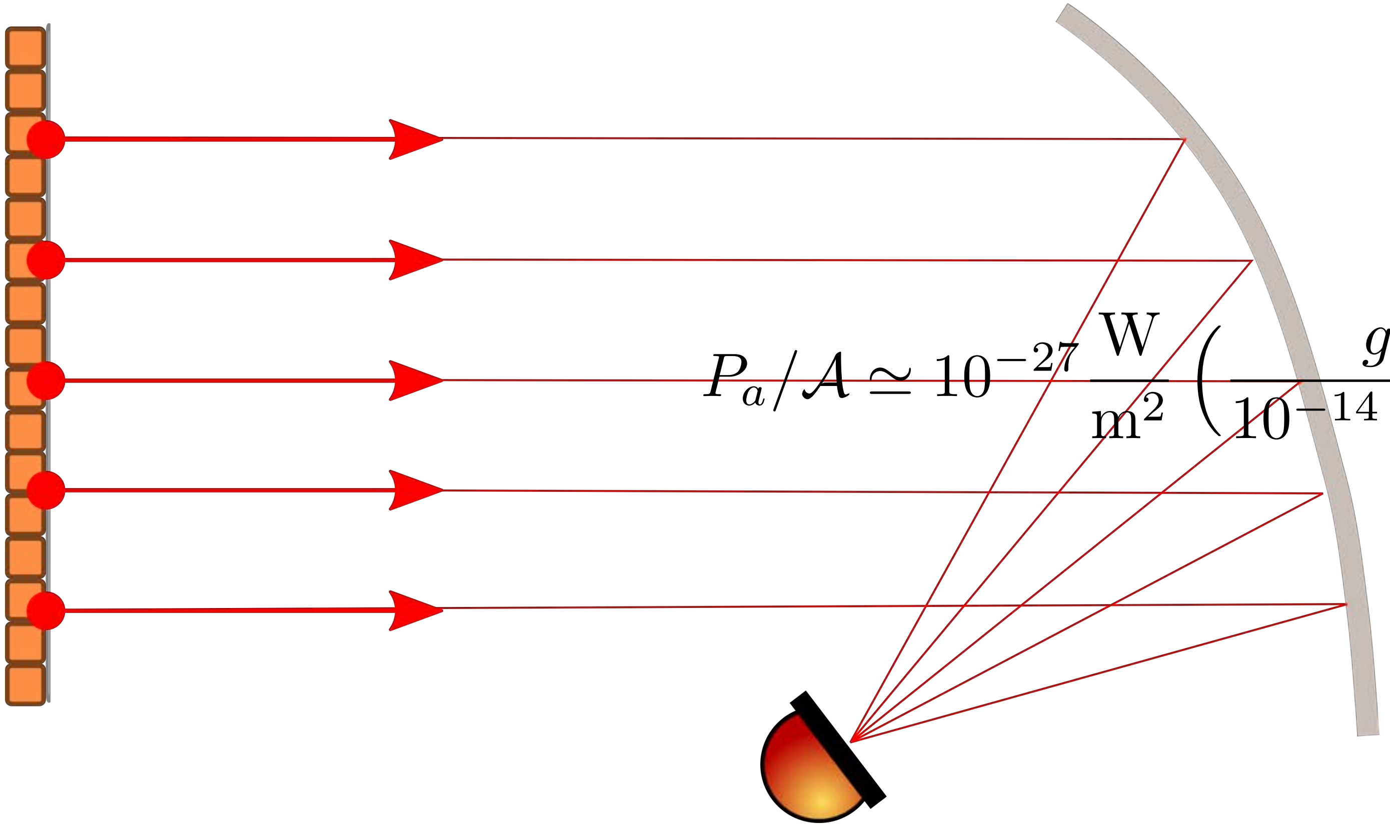


[adapted from Lindner,Majorovits,AR, to appear]

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

Dish Antennas

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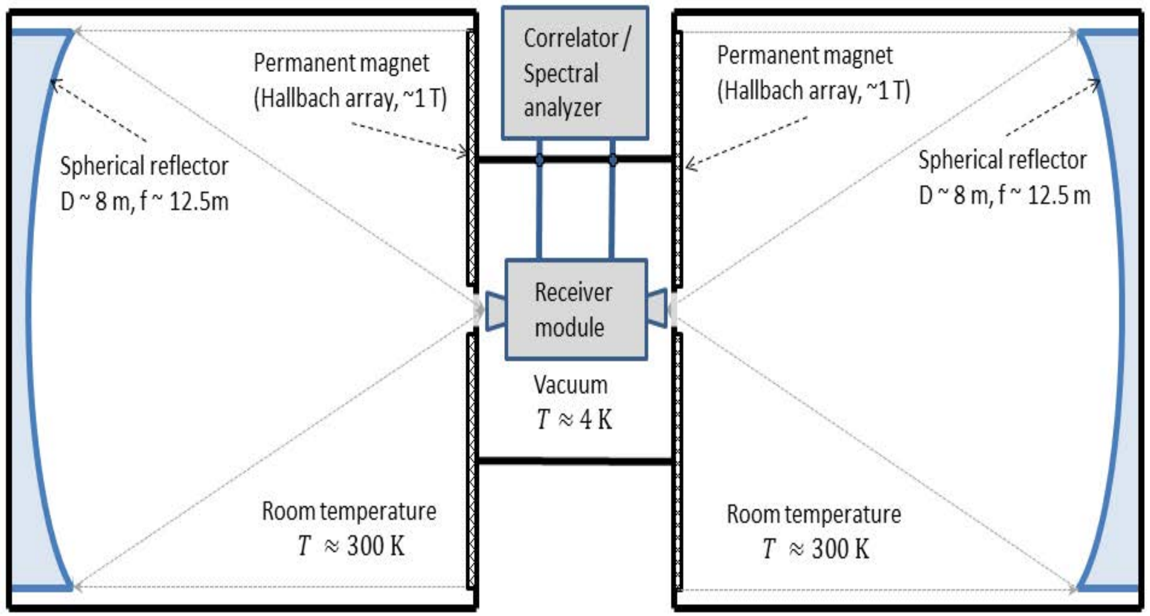
- Axion/ALP DM dish antenna experiment: BRASS (U Hamburg)



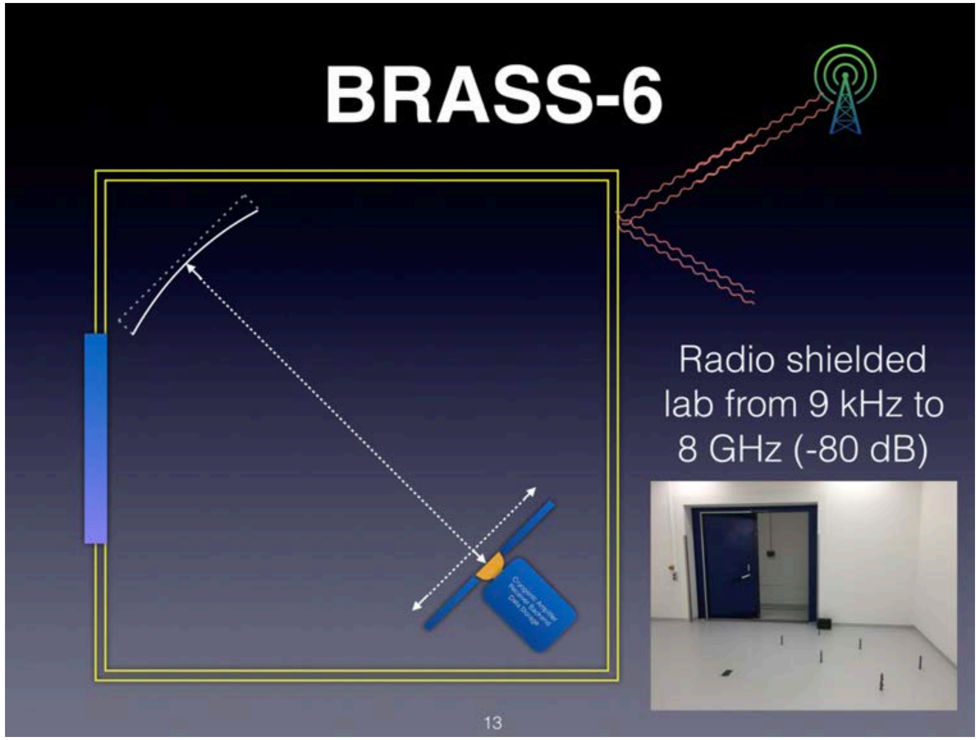
[Horns et al. (unpublished)]

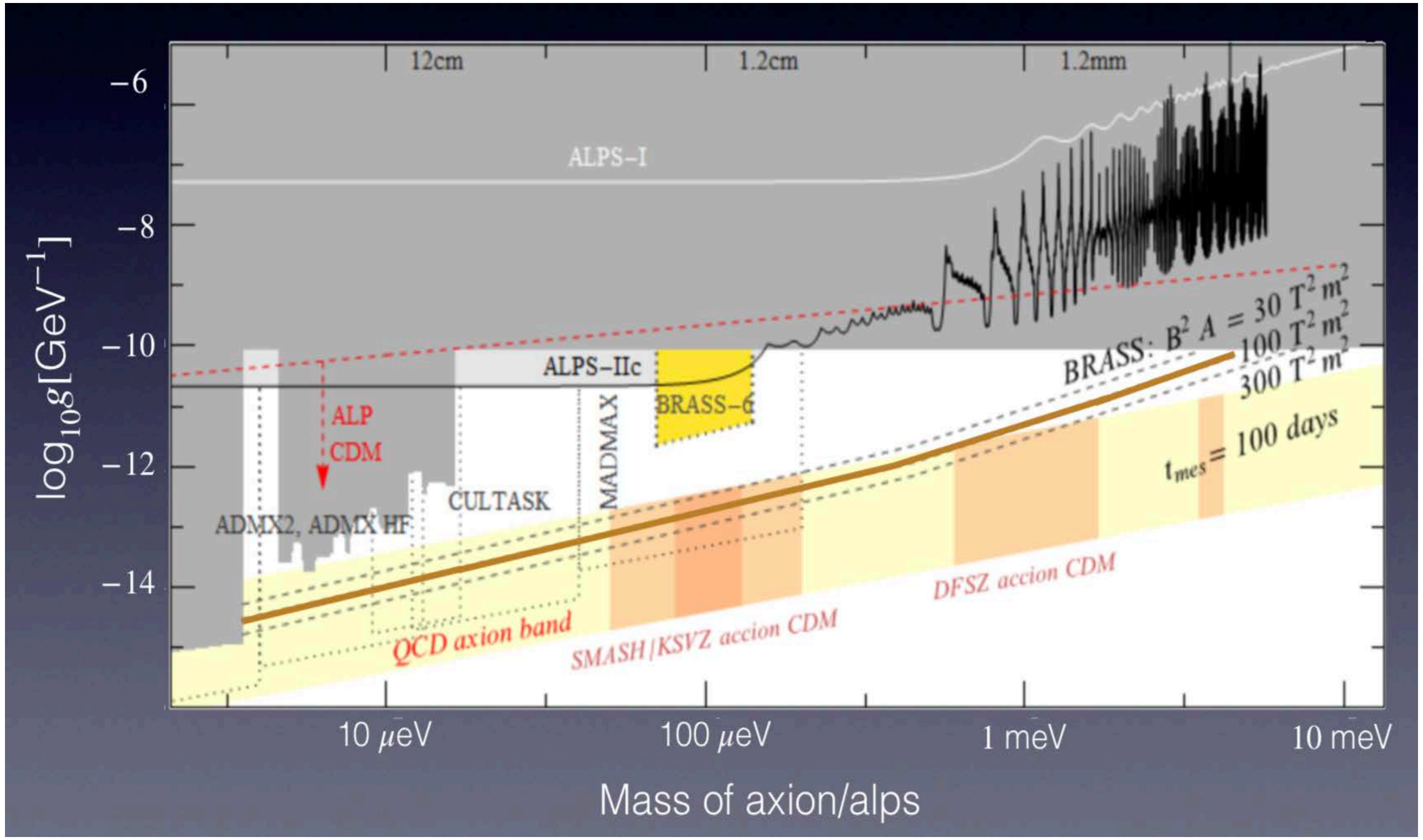
- Permanently magnetized surface for axion/ALP photon conversion
- Dish antenna for photon signal concentration
- Broadband acquisition (16 GHz bandwidth, 10^7 channels)

Searches for Dark Matter Axions

Dish Antennas

- Prototype BRASS-6 in construction, data taking starting 2021





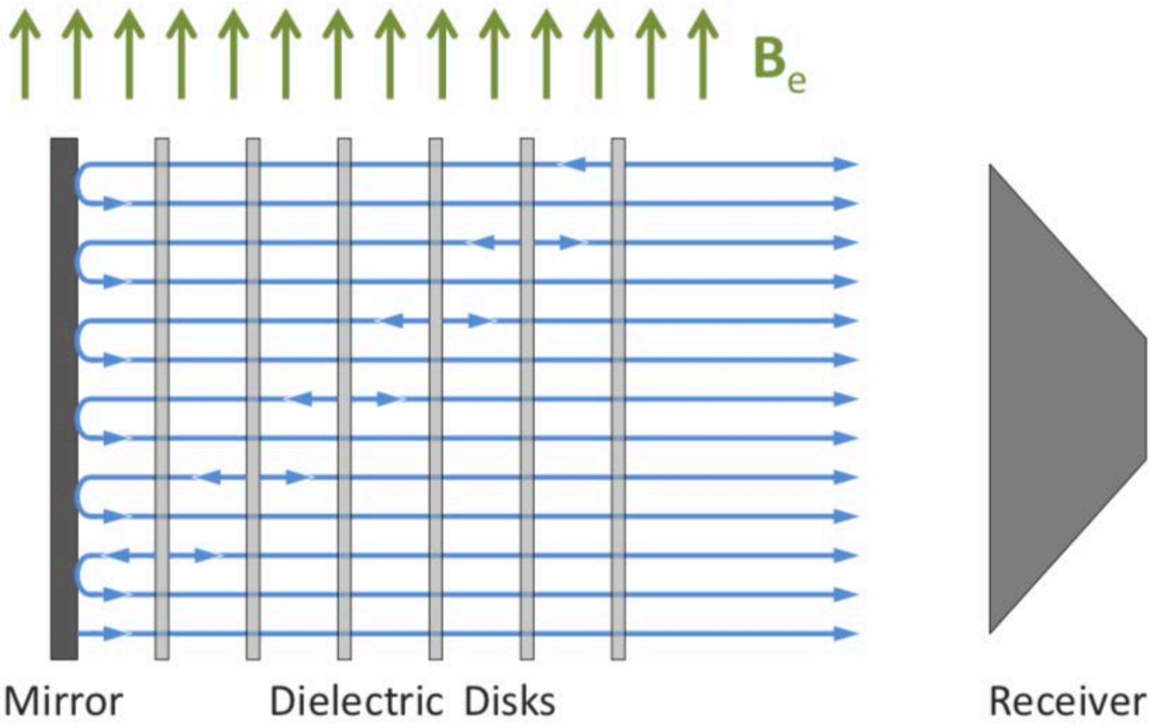
[Le Hoang Nguyen, Patras Workshop 2019]

Searches for Dark Matter Axions

Dish Antennas

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

[Baryakhtar,Huang,Lasenby18]



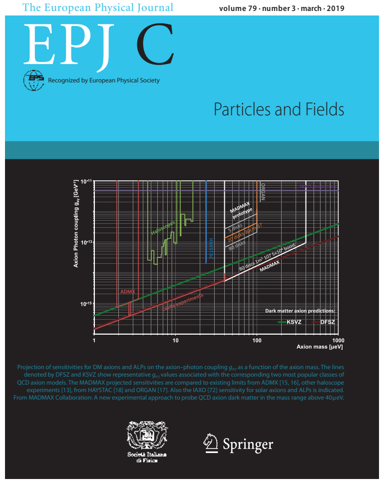
[Caldwell et al. `16]

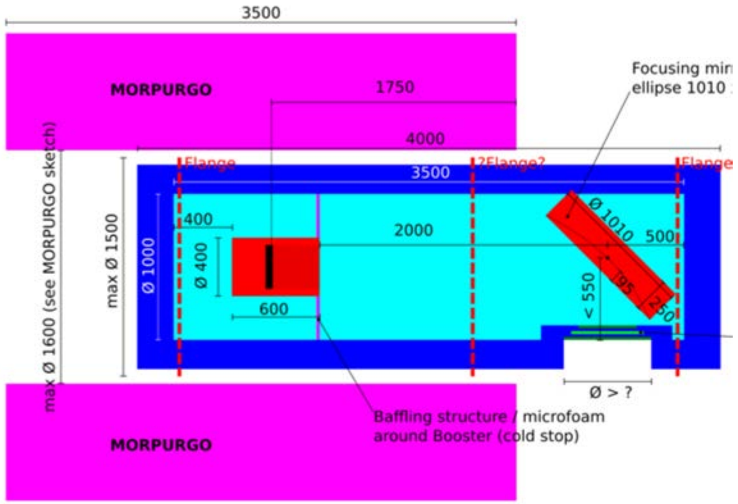
Searches for Dark Matter Axions

Dish Antennas

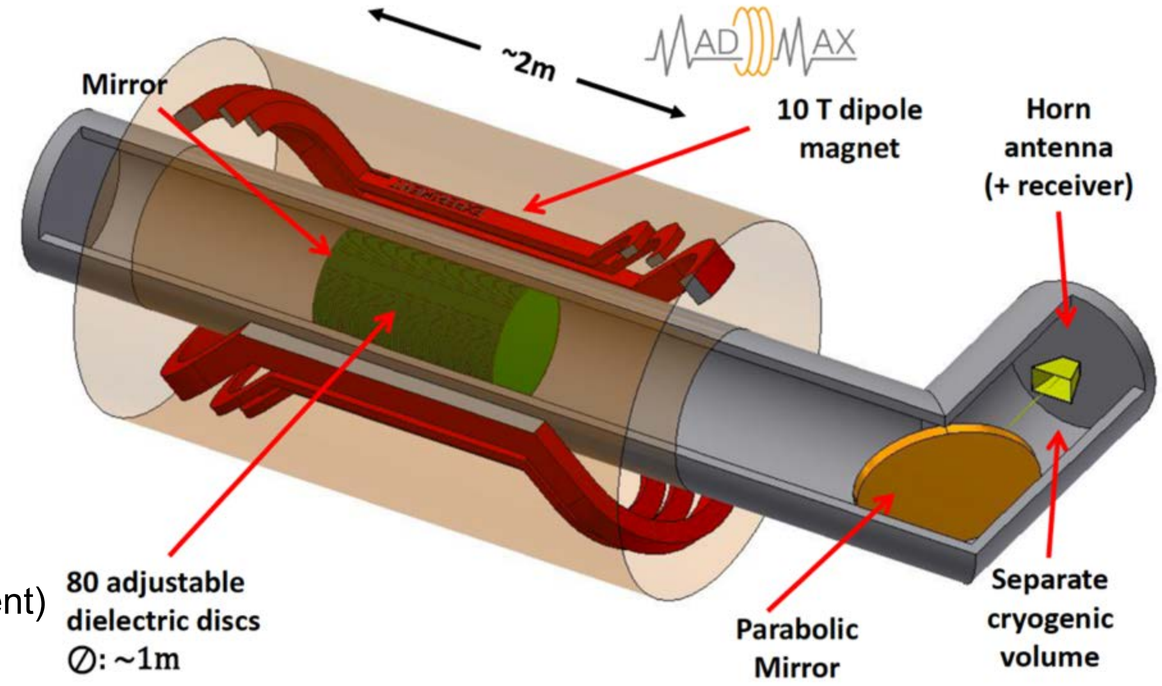
- Boosted dish antenna: Proposed MADMAX experiment [Caldwell et al. `16; Bruns et al. 19]

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





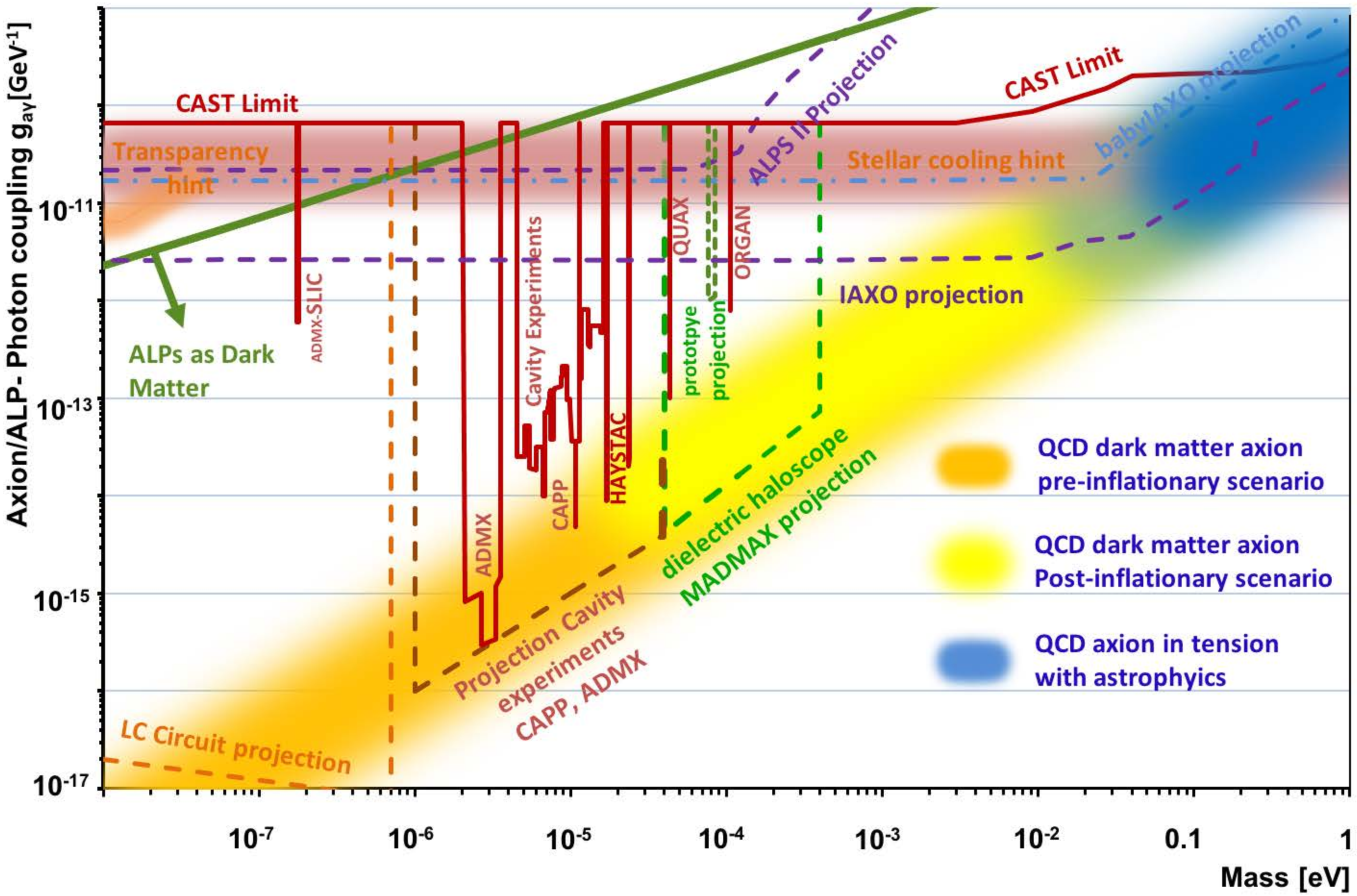
Scaling: Area 1/10 (of final experiment)
\# discs 1/4
B [T] 1/5



Searches for Dark Matter Axions

Dish Antennas

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

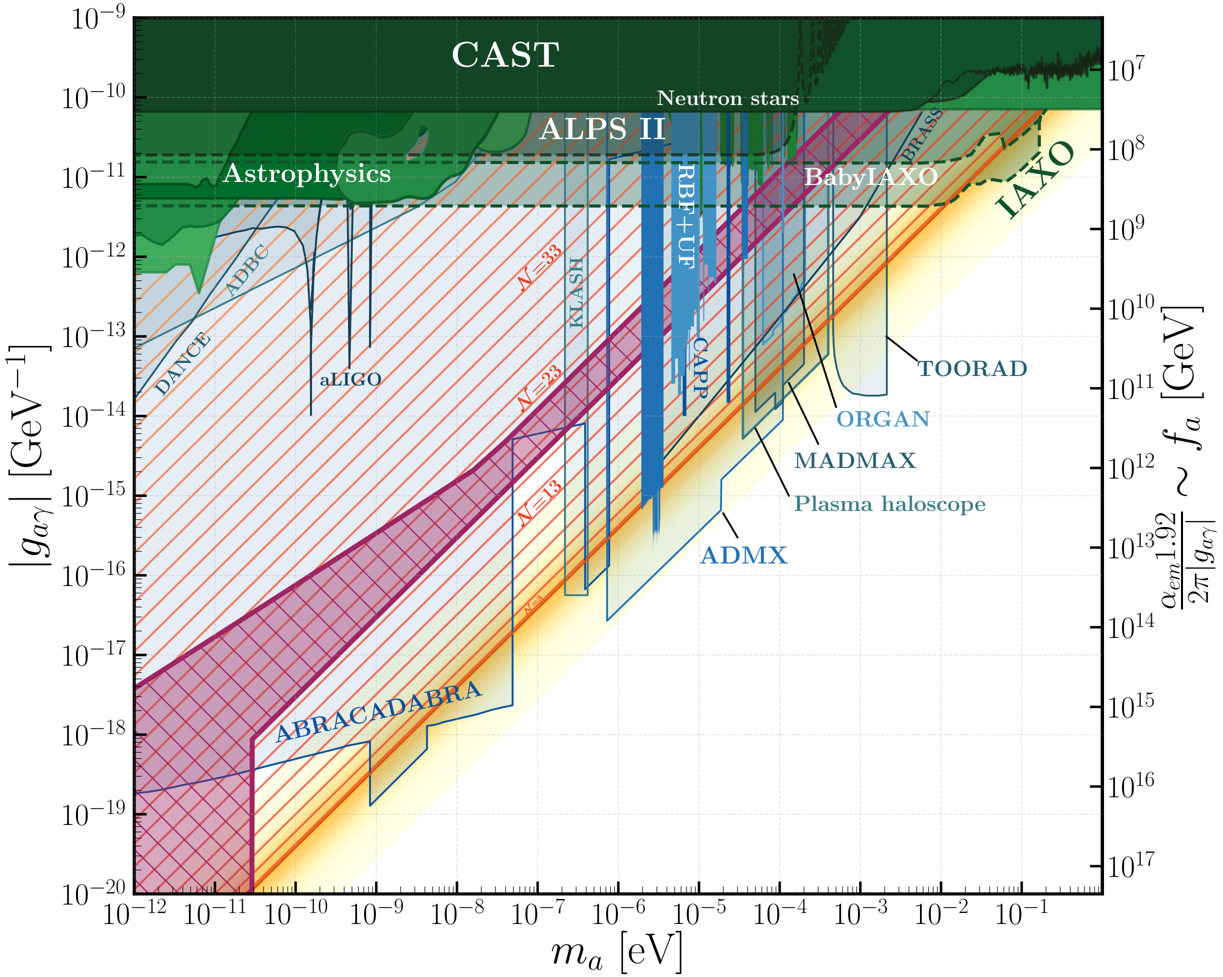


[Lindner,Majorovits,AR, to appear]

Searches for Dark Matter Axions

Dish Antennas

- MADMAX prototype can already probe Z_N axion:



[Di Luzio, Gavela, Quilez, AR 2102.00012]

Conclusions

- Axion extensions of SM very attractive:
  - Axion solves strong CP puzzle
  - Axion is dark matter candidate (for $f_A \gtrsim 10^8\,\mathrm{GeV} \;\Leftrightarrow m_A \lesssim 60\,\mathrm{meV}$)
- Boom in axion searches!
- Large parts in axion parameter space will be tackled in the upcoming decade by a number of terrestrial experiments:
  - Light-shining-through-a-wall experiments (ALPS II, ...)
  - Solar axion searches ((Baby)IAXO, ...)
  - Axion dark matter searches (ADMX, BRASS, CAPP, CASPEr, DM RADIO, HAYSTAC, MADMAX, ORGAN, QUAX, ...)
  - Searches for axion-mediated forces (ARIADNE, ...)
- If 100 % of DM consists of QCD axions, one of the dark matter axion experiments likely to see a signal in the upcoming decade!

STAY TUNED!

Searches for Axion Mediated Forces

Magnetic Resonance Searches

- Experiments searching for axion mediated forces particularly effective in meV mass range
- Monopole-dipole interaction between nucleon and fermion:

$$U_{\rm mon-dip}(r) = \frac{g_{\overline{aN\bar N}}\, g_{af\bar f}}{8\pi m_f}\left(\frac{m_a}{r}+\frac{1}{r^2}\right) e^{-m_a r}\,(\hat\sigma\cdot\hat r)$$

$$\mathcal{L}_{\rm int} = g_{\overline{aN\bar N}}\; a\bar N N - i\, g_{af\bar f}\, a\bar f\gamma_5 f$$

- Proposed ARIADNE experiment searches for forces between a rotating cylinder, made of unpolarized material, and a vessel containing hyper-polarized ^{3}He gas
  - Since ^{3}He magnetic moment dominated by neutron contribution: sensitive to monopole-dipole interaction between nucleus and neutrons, $|\, g_{\overline{aN\bar N}}\, g_{an\bar n}\,|$

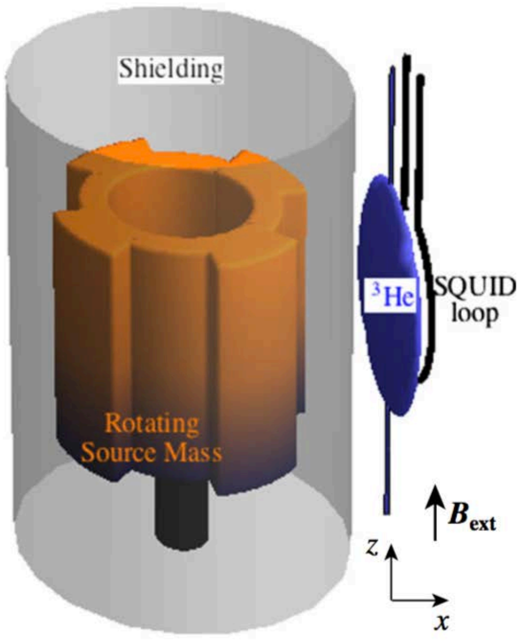


FIG. 1 (color online). A source mass consisting of a segmented cylinder with n sections is rotated around its axis of symmetry at frequency $\omega_{\rm rot}$, which results in a resonance between the frequency $\omega = n\omega_{\rm rot}$ at which the segments pass near the sample and the resonant frequency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

Searches for Axion Mediated Forces

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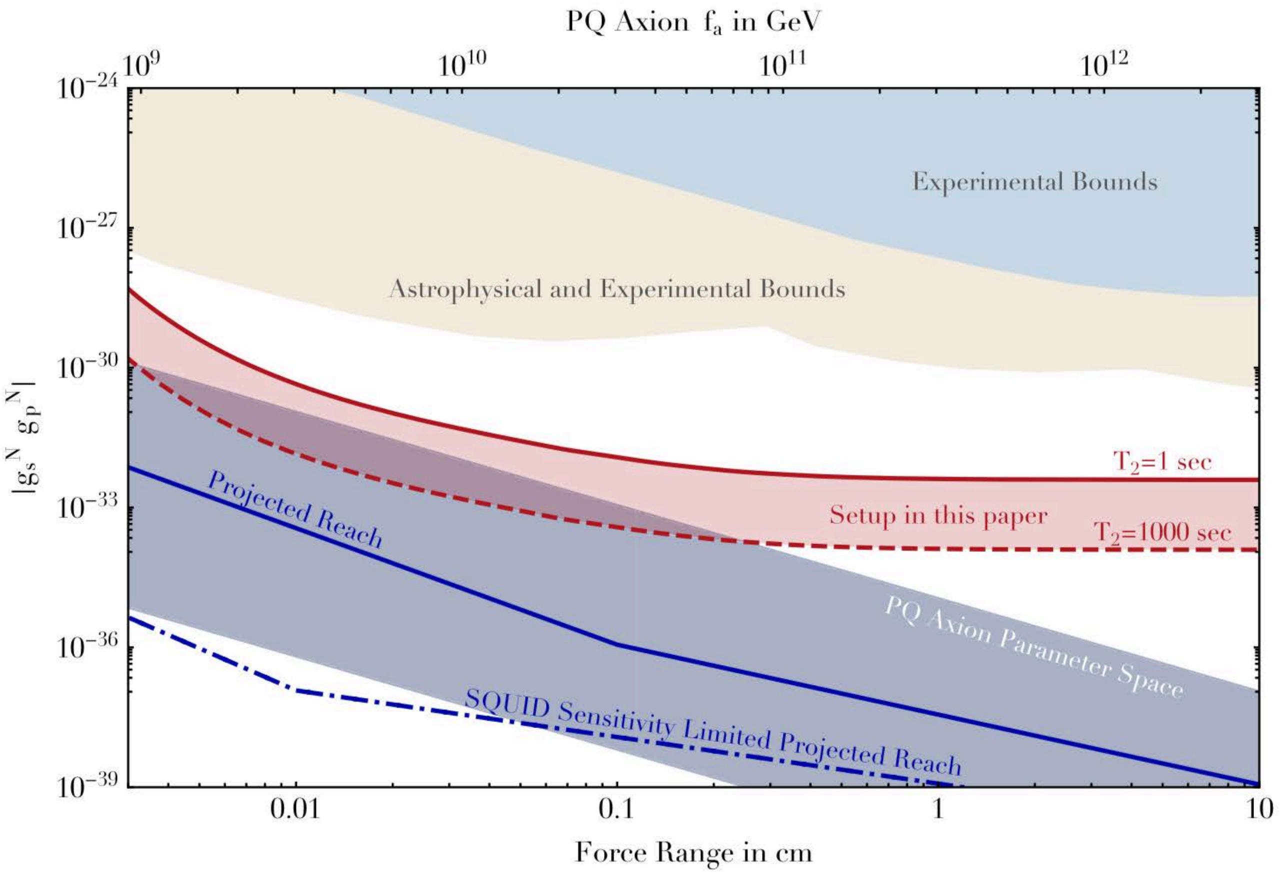


[Arvanitaki, Geraci 14]

Searches for FCNC Interactions

Minimal flavored SMASH

- Introduce right-handed singlet neutrinos N_α and complex scalar field σ with flavor-dependent spontaneously broken global chiral $U(1)_{\rm FN}$ Froggatt-Nielsen (FN) symmetry
  - Explains SM fermionic mass hierarchies and mixings by FN mechanism
  - Explains neutrino masses and mixing by seesaw
  - FN symmetry is at the same time a PQ symmetry
    - Nambu-Goldstone boson of FN breaking solves also strong CP problem ("axion"): "flaxion" or "axiflavon"
  - Flaxion has flavor changing neutral current (FCNC) interactions
    - Currently best bound from $\text{Br}\,(K^+ \to \pi^+ A) \lesssim 7.3 \times 10^{-11}$

$$\Rightarrow \quad f_A \gtrsim 2 \times 10^{10}\,\text{GeV} \left(\frac{26}{N_{\rm DW}}\right) \left|\frac{(\kappa^d_{\rm ah})_{12}}{m_s}\right|$$

[Ema et al., 1612.05492;1802.07739; Calibbi et al., 1612.08040]

- Flaxion properties:
  - Decay constant:

$$f_A = \frac{v_{\rm FN}}{N_{\rm DW}}, \qquad N_{\rm DW} = \text{Tr}\,(n^u + n^d)$$

  - Typically large domain wall number
    - Viable example:

$$\begin{pmatrix} q_{Q_1} & q_{Q_2} & q_{Q_3} \\ q_u & q_c & q_t \\ q_d & q_s & q_b \end{pmatrix} = \begin{pmatrix} 3 & 2 & 0 \\ -5 & -1 & 0 \\ -4 & -3 & -3 \end{pmatrix}$$

$$\begin{pmatrix} q_{L_1} & q_{L_2} & q_{L_3} \\ q_e & q_\mu & q_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ -8 & -5 & -3 \end{pmatrix}$$

$$\Rightarrow \quad n^u_{ij} = \begin{pmatrix} 8 & 4 & 3 \\ 7 & 3 & 2 \\ 5 & 1 & 0 \end{pmatrix}, \quad n^d_{ij} = \begin{pmatrix} 7 & 6 & 6 \\ 6 & 5 & 5 \\ 4 & 3 & 3 \end{pmatrix}, \quad n^l_{ij} = \begin{pmatrix} 9 & 6 & 4 \\ 8 & 5 & 3 \\ 8 & 5 & 3 \end{pmatrix}$$

$$\Rightarrow N_{\rm DW} = 26$$

  - Coupling to photon:

$$C_{A\gamma} = \frac{2}{N_{\rm DW}} \sum_{f=u,d,l} \left[N_f \text{Tr}\,(n^f) \left(q_f^{(\rm em)}\right)^2 \right] - 1.92(2)$$

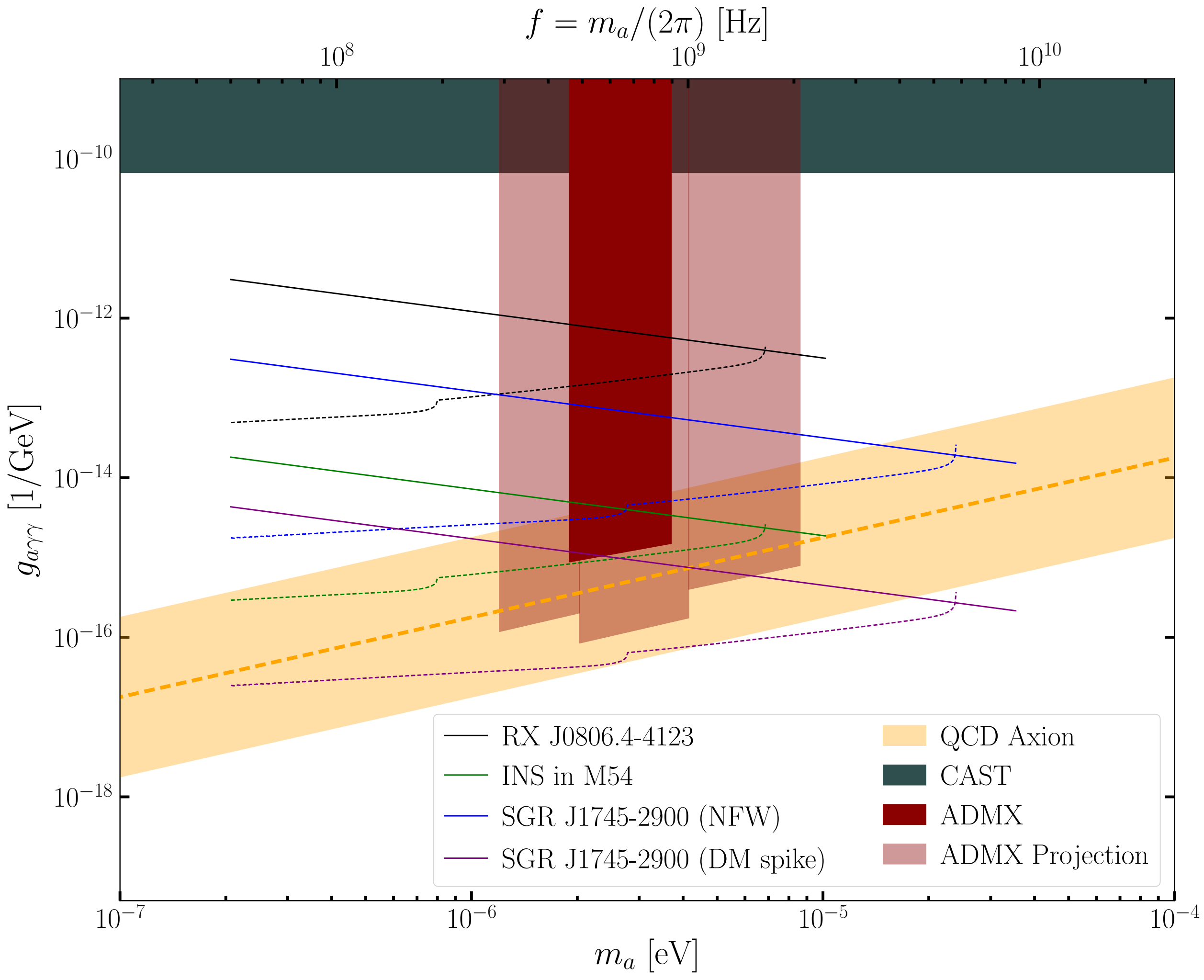
  - For example above: $C_{A\gamma} = 113/39 - 1.92 \simeq 0.97$

- NA62: reach in decay constant increased by order of magnitude!

Indirect Detection of Axion Dark Matter

Telescope searches

- In presence of axion DM, monochromatic radio signals are emitted from neutron stars (NSs) due to axion-photon conversion within high magnetic field regions in NS magnetosphere
  - Forthcoming radiotelescopes such as SKA can search for those [Huang et al. `18; Hook et al. `18]
- In dwarf spheroidal magnetic fields expected to be small enough that monochromatic radio line due to axion DM decay dominates over signal due to axion-photon conversion in magnetic field
  - SKA sensitivity not enough to probe QCD axion DM, but sufficient for ALP DM [Caputo et al. `18]



[Hook et al. `18]

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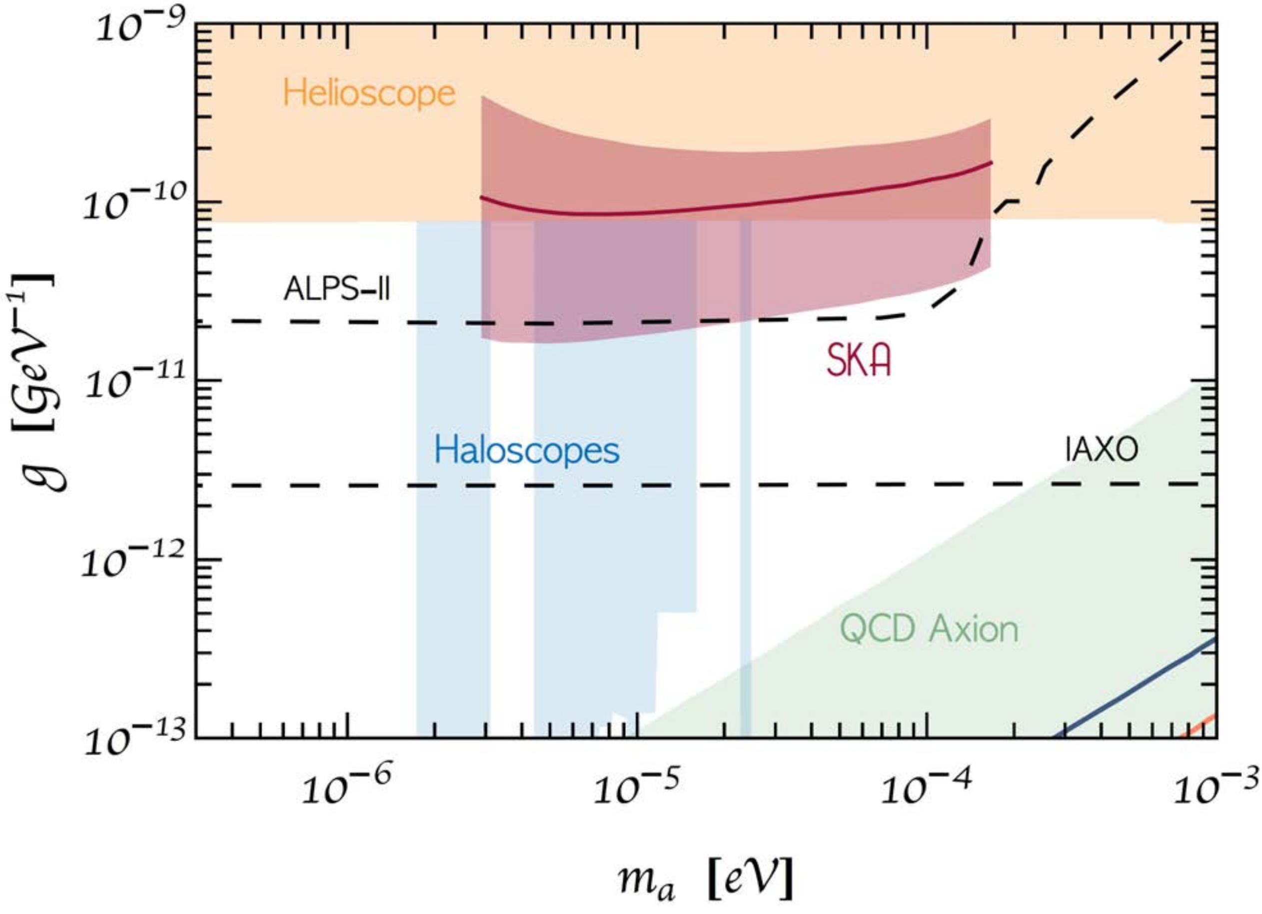

[Caputo et al. `18]