Experimental Searches of Solar Axions and ALPs

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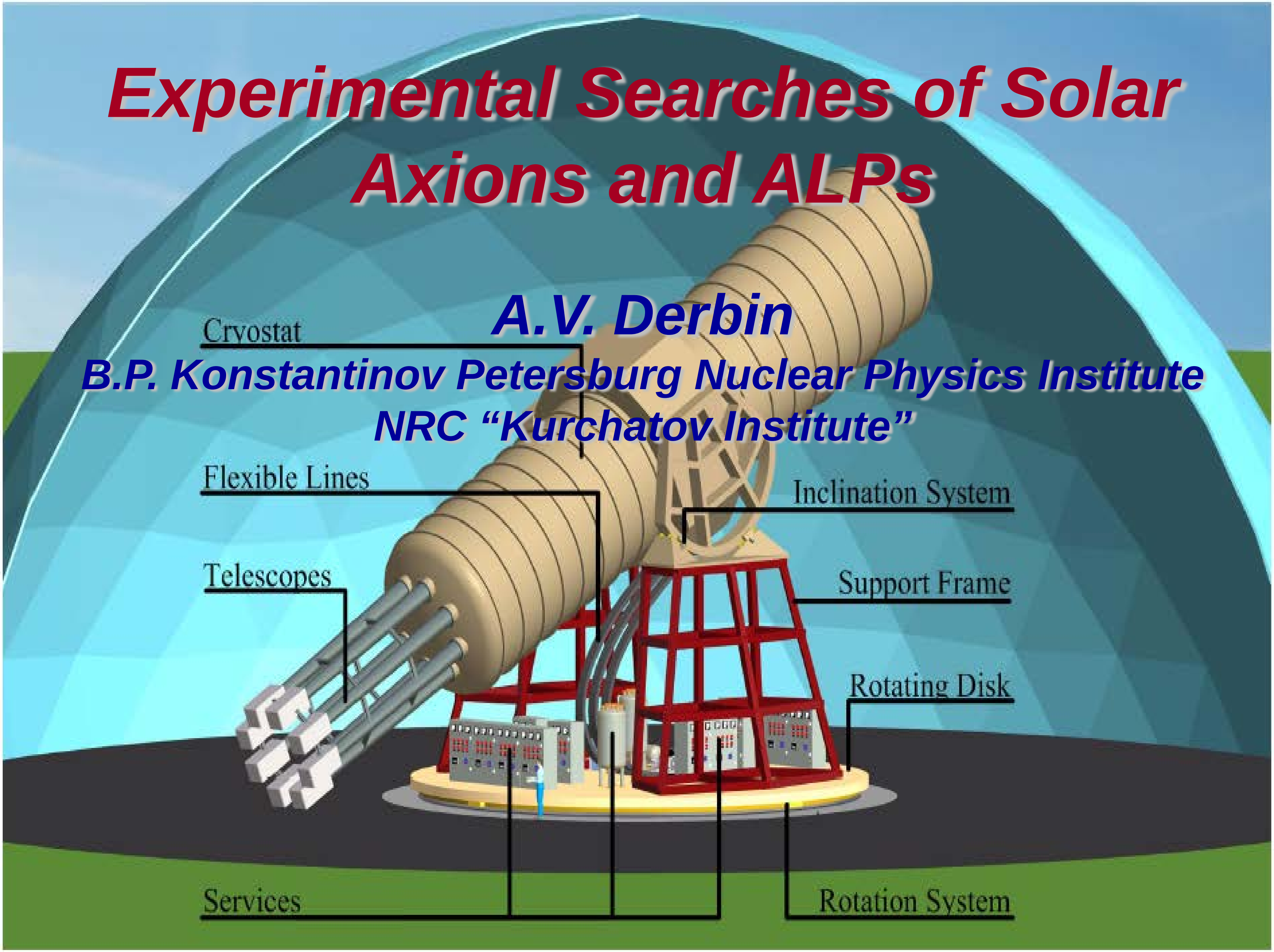


Content

1) Appearance of axions

Strong CP-problem, WWPQ-standard axion, KSVZ- u DFSZ-invisible axion, axion mass and coupling constants $g_{A\gamma}$, g_{Ae}, *u* g_{AN}. *ALPs*

2) Limits and hints from astrophysics and cosmology

Abnormal transparency of the Universe for γ-quanta, cooling of white dwarfs.

3) Solar axions and helioscopes.

Primakoff, Compton and bremstruhlung axions

Monochromatic 14.4 keV, 478 keV, 5.5 MeV axions,

$g_{Ae\gamma}$, *Conversion A* $\rightarrow\gamma$, *experiments CAST, IAXO, TASTE,..*

4) Axioelectrical effect

g_{Ae}, *Si-detector, Cuore, XMASS, Edelweiss, Xenon 100, LUX*

5.5 MeV axions, Borexino, BGO-scintillator, BGO-bolometr

5) Resonant excitation of nuclear levels

g_{AN}, *7Li, 57Fe, 83Kr, to search for monochromatic axions*

169Tm to search for axions with continues spectrum,

6) Axions as dark matter particles, relic axions and haloscopes.

Conversion A $\rightarrow\gamma$, *ADMX. Axioelectric effect, LUX.*

7) Laboratory axions

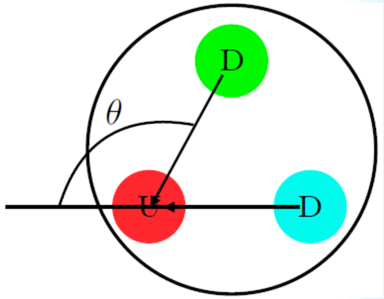
Reactors, accelerators, radioactive sources, lasers "Light shining through walls"

Strong CP-problem

(non-observation of CP violation in strong interactions

***The** appearance of an axion in theory is connected with the problem of CP-violation in strong interactions. The fact that QCD **L**agrangian can be supplemented by term representing the interaction of the gluon fields. ϴ-term is P and T odd, i.e. in strong interactions should be observed CP violation.*

$$\boxed{L_{\Theta} = \Theta \frac{g_s^2}{32\pi^2} G_a^{\mu\nu} \tilde{G}_{a\mu\nu}}$$



***E.G.** EDM of neutron is:*

$$\boxed{d_n \sim \Theta \times 10^{-16}\, e \text{ cm}}$$

$$d_n = 32.7 \times 10^{-3} e \frac{3 m_u m_d m_s}{m_u m_d + m_u m_s + m_d m_s} R^2 \bar{\theta}.$$

Present experimental limit on nEDM:

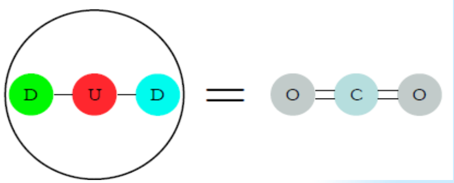
$$\boxed{| d_n | < 1.8 \times 10^{-26}\, e \text{ cm (90\% c.l.)} \Rightarrow \mathbf{\Theta < 10^{-10}}}$$

As it follows from the experimental limit on neutron's dipole moment the upper limit on the CP-violating parameter is $\theta \leq 10^{-10}$. This term is very small in comparison with all the other parameters of the QCD Lagrangian, and this fact still remains a mystery over a few decades. Θ is one from 19-th free parameters of SM.

Emergence of axion

***In** order to solve this puzzle R. D. Peccei and H. R. Quinn in 1977 proposed the concept of the new chiral symmetry U(1)$_{PQ}$. The spontaneous breaking of this symmetry at the energy f$_A$ allows one to compensate CP-violating term of the QCD Lagrangian completely. S. Weinberg and F. Wilczek showed (1978) that the introduced PQ-model should lead to the existence of a new neutral pseudoscalar particle.*

$$\boxed{L_\Theta = \left(\Theta - \frac{A}{f_A}\right)\frac{g_s^2}{32\pi^2}G_a^{\mu\nu}\tilde{G}_{a\mu\nu}}$$



The axion mass (m$_A$) and the strengths of an effective axion's coupling to an electron (g$_{Ae}$), a photon (g$_{A\gamma}$) and nucleons (g$_{AN}$) are proportional to the inverse of f$_A$.

$$\boxed{m_A \approx \left(f_\pi m_\pi / f_A\right)\left(\sqrt{z}/(1+z)\right)}$$

$$\boxed{g_{af} = \frac{C_f m_f}{f_a}}$$

$$\boxed{g_{Ae} = C_e m / f_A}$$

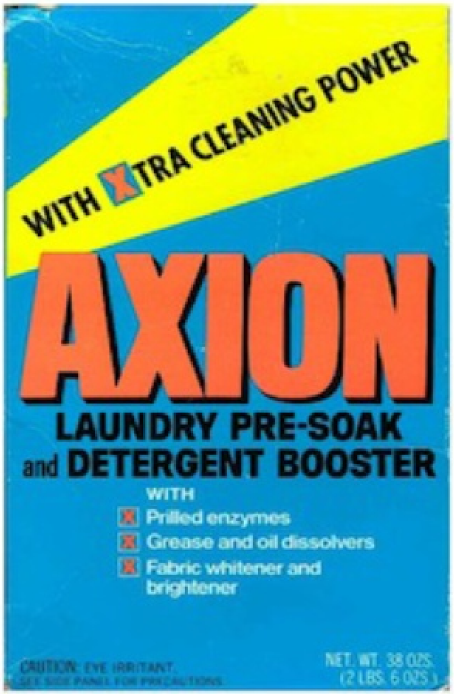
$$\boxed{g_{A\gamma} = \frac{\alpha}{2\pi f_A}\left(\frac{E}{N} - \frac{2(4+z+w)}{3(1+z+w)}\right) \equiv \frac{\alpha}{2\pi f_A}C_{A\gamma\gamma}}$$

$$\frac{g_{a\gamma\gamma}}{10^{-10}\ \text{ГэВ}^{-1}} = C\frac{m}{1\ \text{эВ}}$$

$$\boxed{g_{ap} = C_{ap}m_p / f_a}$$

The name the "axion" is given by F. Wilczek on the brand of washing powder, since the axion must to "clear" QCD from the problem of a strong CP-violation, and because of the connection with the axial current.

Peccei-Quinn-Weinberg-Wilczek (PQWW) аксион



The axion is a pseudoscalar; has the same quantum numbers as the π^0, and the same interactions, but with coupling strengths scaled by the axion mass

“I named them after a laundry detergent, since they clean up a problem with an axial current.” (Nobel lecture 2004)

PQWW or "standard axion"

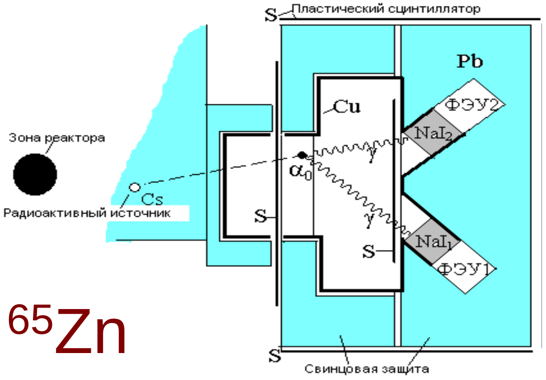
***The** original PQWW axion model contained certain strict predictions for the coupling constants between an axion and photons ($g_{A\gamma}$), electrons (g_{Ae}), and nucleons (g_{AN}) because assumed that f_A is equal to electroweak scale:*

$$f_A = (\sqrt{2}G_F)^{-1/2} \approx 250\mathrm{GeV}$$

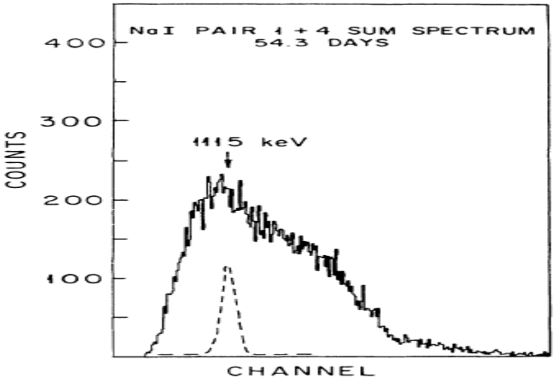
The standard axion mass depends on the number of quark doublets N and unknown parameter X, which is the ratio of two Higgs vacuum expectation values and it should be more:

$$m_A(\mathrm{keV}) \approx 25N(X + 1/X) \geq 150\ \mathrm{keV}$$

Existence of the WWPQ axion had been *disproved* by experiments performed on reactors and accelerators, and by experiments with artificial radioactive sources (decay channel *A* → *γ* + *γ was searched for)*



^{65}Zn



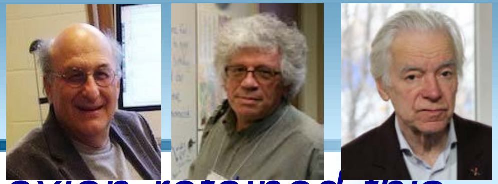
$$K^+ \to a + \pi^+$$

$$J/\psi \to a + \gamma,$$

$$\Upsilon \to a + \gamma$$

$$\Gamma_{A\to\gamma\gamma} = \frac{G^2_{A\gamma\gamma} m^3_A}{64\pi} = 1.1 \times 10^{-24}\ \mathrm{s}^{-1} \left(\frac{m_A}{\mathrm{eV}}\right)^5$$

“Invisible” axion



Two classes of new theoretical models of an ”invisible” axion retained this particle in the form required for solving the CP problem of strong interactions and at the same time suppressed it’s interaction with matter:

1) **“hadronic”, or *KSVZ* (Kim, Shifman, Vainshtein, Zakharov) axion model that postulates existence of the additional heavy quark;**

2) **“GUT”, or *DFSZ* (Dine, Fischer, Srednicki, Zhitnycki) axion model that requires additional Higgs field.**

DSFZ

$$\boxed{g_{Ae} = C_e m / f_A}$$

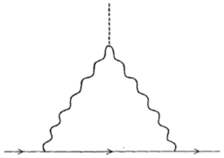
$$\boxed{C_e = 1/3\cos^2\beta_{\rm dfsz}}$$

$$g_{Ae} \approx 2\times 10^{-6}$$

$$\boxed{g_{A\gamma} = \frac{\alpha}{2\pi f_A}\left(\frac{E}{N} - \frac{2(4+z+w)}{3(1+z+w)}\right) \equiv \frac{\alpha}{2\pi f_A} C_{A\gamma\gamma}}$$

E/N = 3/8

$$(C_{A\gamma\gamma} = 0.74)$$



KSVZ

$$\boxed{m_A[eV] = \frac{f_\pi m_\pi}{f_A}\sqrt{\frac{z}{(1+z+w)(1+z)}} \approx \frac{6.0\times 10^6}{f_A[GeV]}}$$

$$\boxed{g_{Ae} = \frac{3n\alpha^2 m}{2\pi f_a}\left(\frac{E}{N}\ln\frac{f_A}{m} - \frac{2}{3}\frac{4+z+w}{1+z+w}\ln\frac{\Lambda}{m}\right)}$$

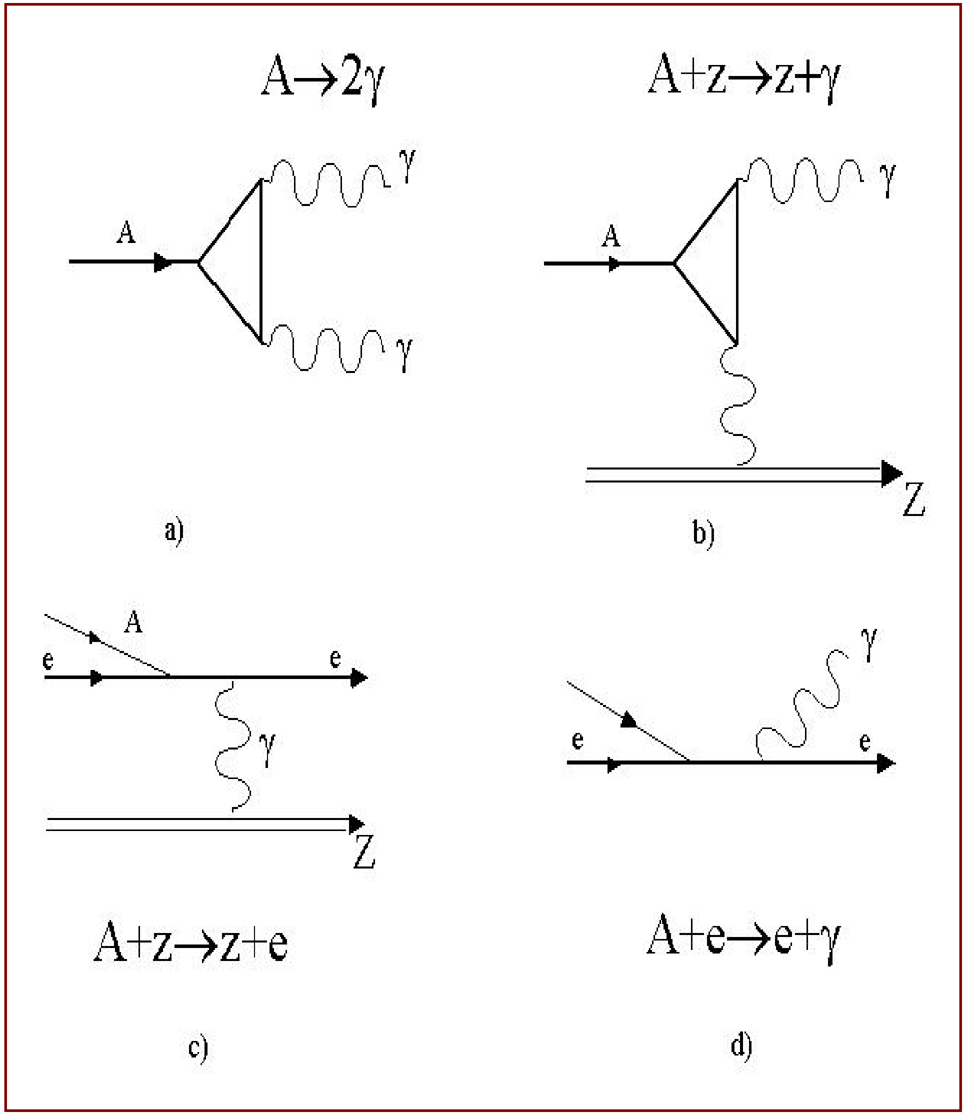
$$\boxed{g_{A\gamma} = \frac{\alpha}{2\pi f_A}\left(\frac{E}{N} - \frac{2(4+z+w)}{3(1+z+w)}\right) \equiv \frac{\alpha}{2\pi f_A} C_{A\gamma\gamma}}$$

E/N = 0

$$(C_{A\gamma\gamma} = -1.92)$$

The scale of Peccei-Quinn symmetry violation (f_A) in both models is arbitrary and can be extended up to the Plank mass ≈ 10^{19} GeV. **T**he interaction strength scales as $(f_A)^{-1}$, and the *interaction between an axion and matter is suppressed.* **In** contrast to the DFSZ axions, the KSVZ axions have no coupling to leptons and ordinary quarks at the tree level, which results in the strong suppression of the interaction of the KSVZ axion with electrons through radiatively induced coupling. Moreover, in some variants of these models axion–photon coupling may differ from the original DFSZ or KSVZ $g_{A\gamma}$ couplings by a factor < 10^{-2}.

Axion interactions with ɣ,e, N



Interactions of axion with matter depends on coupling constants of the axion to the photons, electrons and nucleons:

$g_{A\gamma}$

•*A* → 2*γ* ***decay*** (***a***) and inverse ***Primakoff*** (***b***) effect (axion-2-photon conversion in the electromagnetic field)

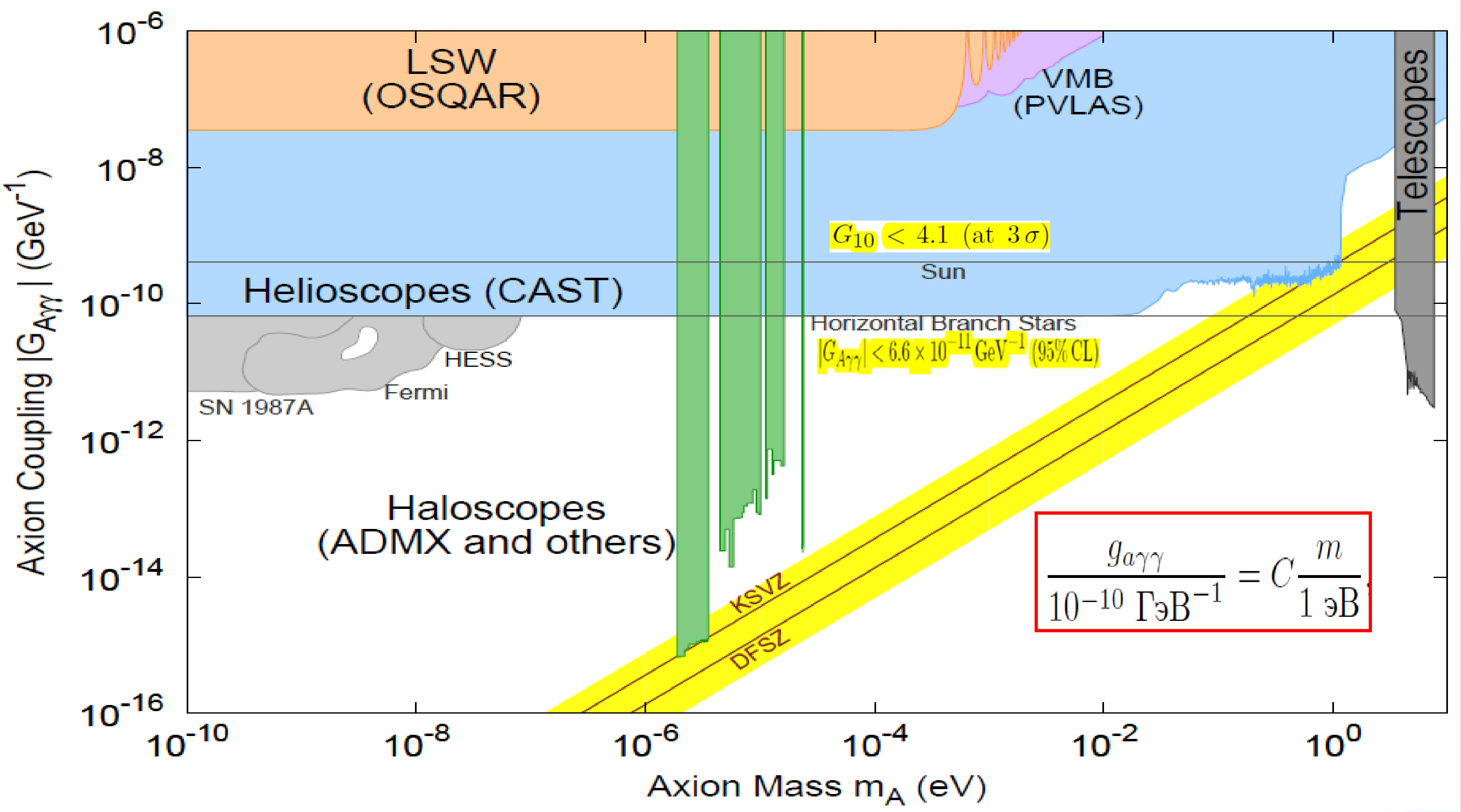
g_{Ae}

• ***axio-electric*** (*c*) and ***compton-like*** (*d*) processes;

g_{AN}

• as a pseudoscalar particle axion can be absorbed and emitted in ***magnetic-type transitions***

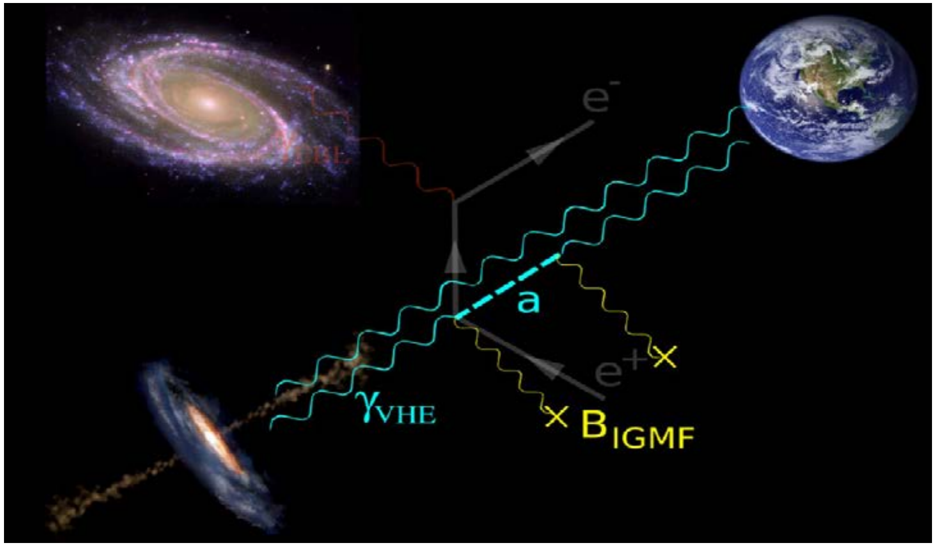
Limits on axion-photon coupling constant $g_{A\gamma}$



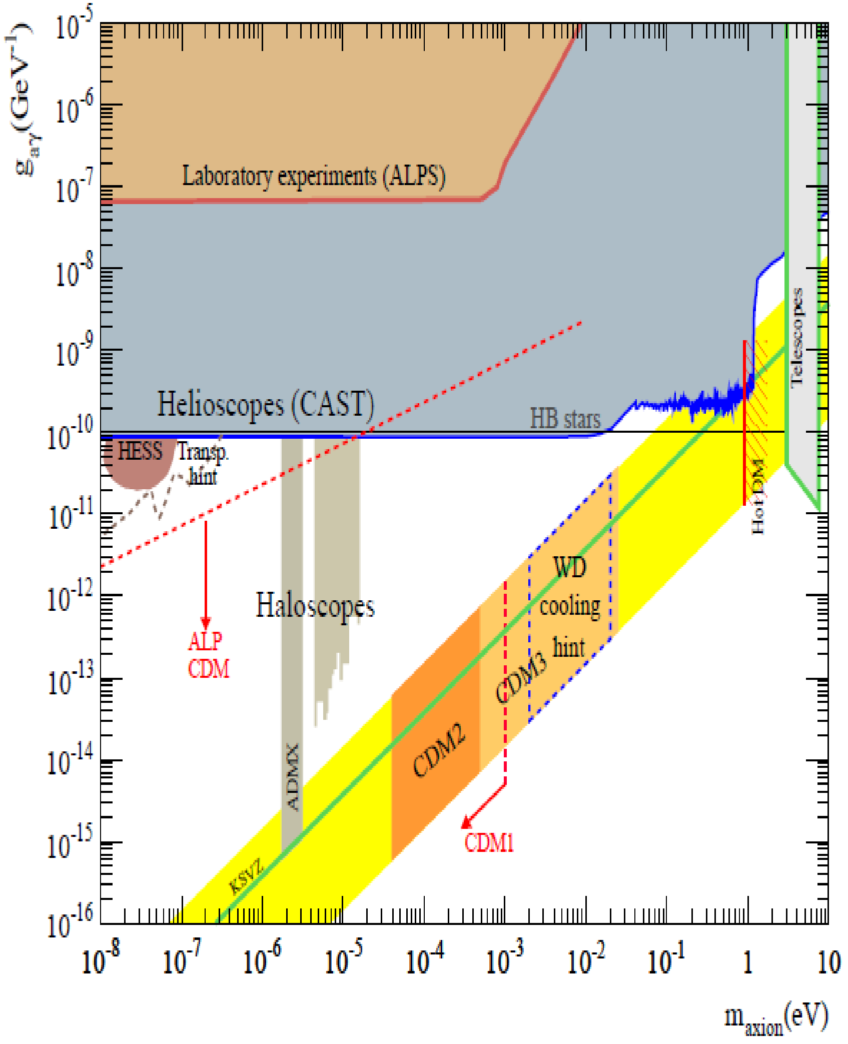
The region of predicted by KSVZ and DFSZ axion model $g_{A\gamma}$ and g_{Ae} values are free from constraints obtained in direct laboratory experiments if $m_A < 1$ eV.

Astrophysical hints

1. The excessive transparency of the intergalactic medium to very high energy (VHE) photons. HESS, Fermi, Magic. Estimates give small ALP mass m_A 10^{-10} – 10^{-7} eV (to maintain coherence over sufficiently large magnetic lengths) and $g_{A\gamma}$ coupling in the range 10^{-12} – 10^{-10} GeV^{-1}.

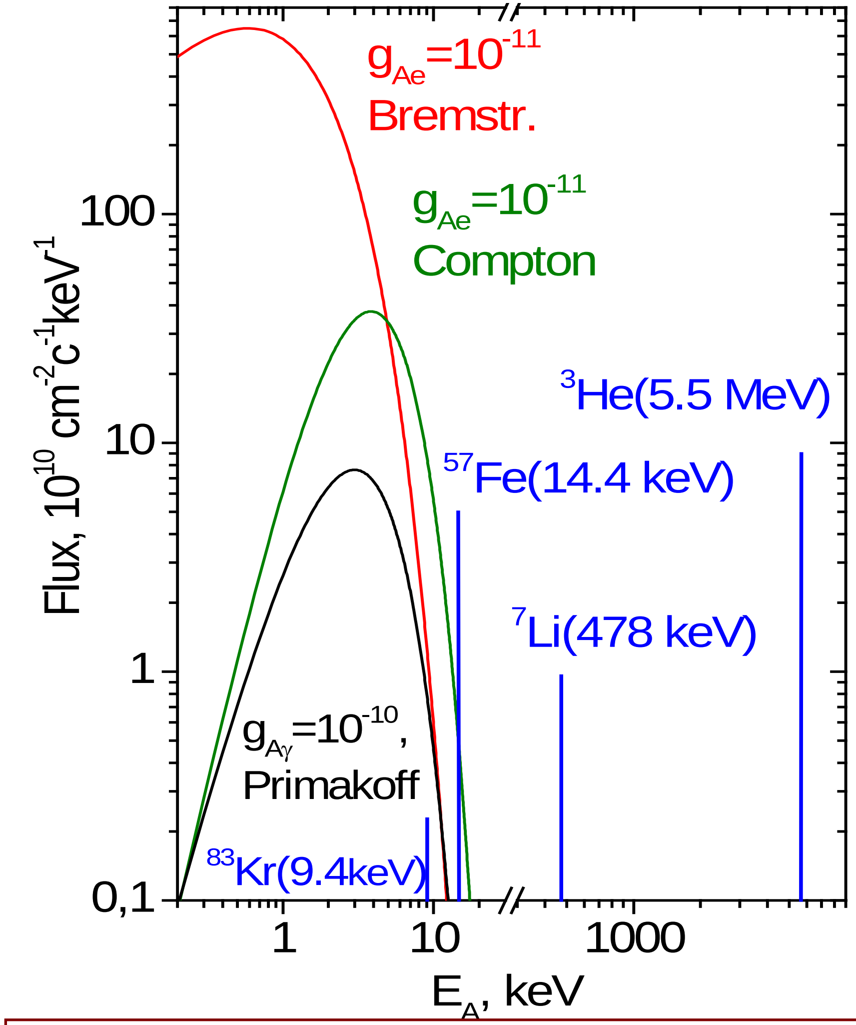


2. The anomalous cooling rate of white dwarfs. These arguments were used long ago to constrain gae and they have been cross-checked and improved over the years. Nowadays, there is common agreement on an upper limit g_{Ae} < 3 x10^{-13}. Recently, it has been pointed out that excessive cooling of WDs, RGs and HB stars can be explained at one stroke by an ALP coupling to electrons and photons, with couplings |gAee| 1.5 × 10−13 and gAg 1.4 × 10−11 GeV−1, respectively. Good fits to the data can be obtained employing the DFSZ axion with a mass in the range 4 meV - 250 meV



ALPs - particles with zero spin and two-photon vertex, like the axion and there is no connection between the coupling constants and mass.

Solar axion spectra vs $g_{A\gamma}$, g_{Ae} и g_{AN}



The main sources of solar axions:

1. Reactions of main solar chain. *The most intensive fluxes are expected from M1-transitions in ^{7}Li and ^{3}He nuclei* (g_{AN}):

^{7}Be + e^{-} → ^{7}Li*+ γ; ^{7}Li* → ^{7}Li+A (478 кэВ)

***p* + *d* → ^{3}He + A (5.5 MэВ).**

2. Magnetic type transitions *in nuclei whose low-lying levels are excited due to high temperature in the Sun* (**^{57}Fe,^{83}Kr**) (g_{AN})
3. Primakoff conversion *of photons in the electric field of solar plasma* ($g_{A\gamma}$).
4. Bremsstrahlung: **e + Z(e) → Z + A.** (g_{Ae})
5. Compton process: **γ + e → e + A.** (g_{Ae})
6. axio-recombination: **e + I → I^{-} + A** and axio-deexcitation: **I* → I + A.** *PRD 83 023505 (2011) CAST 1302.6283, 1310.0823*
7. *Plasmon-axion conversion. E<200 eV.*

If axion does exist, the Sun should be an intense source of axions. The expected energy spectrum of solar axions, like the spectrum of solar neutrinos, contains both continuous spectra and monochromatic lines.There are 6(7) main ***axion formation processes*** inside the stars:

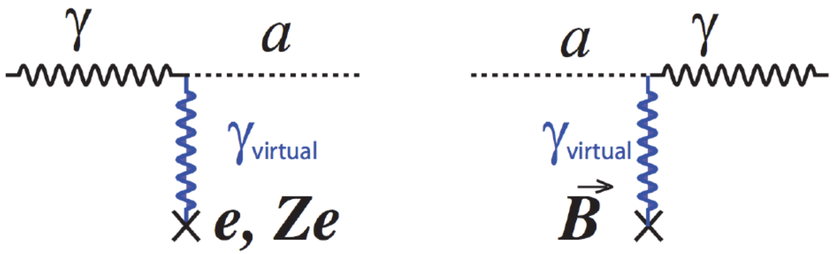
Classification of experiments

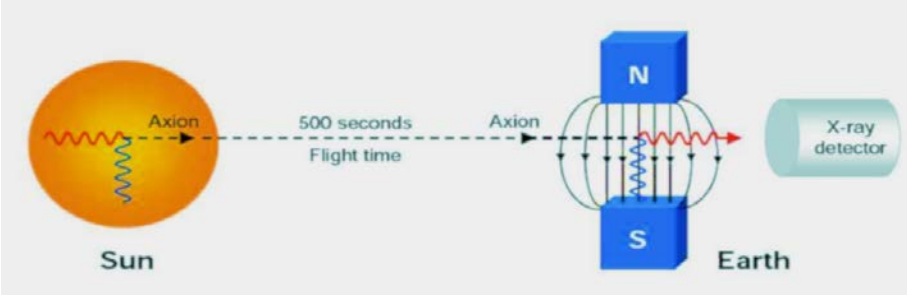
Detection

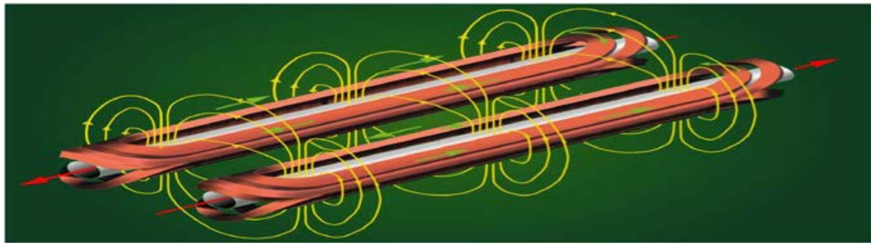
Creation

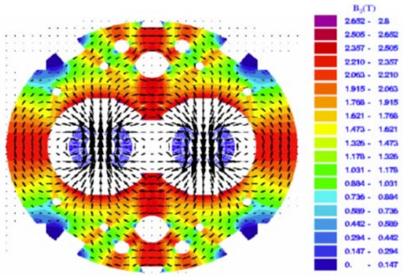
	$g_{A\gamma}$	g_{AN}	g_{Ae}
$g_{A\gamma}$	Axion-photon conversion in magnetic field **CAST,** **IAXO, TASTE**,	Resonant absorption by nuclei **^{169}Tm, ^{83}Kr** **PNPI, BAKSAN,** **LNGS**	Axioelectric effect in Si-, Ge-, Xe-atoms **PNPI(SAXS), CUORE, EDELWEISS, XMASS, XENON100**
g_{AN}	Primakoff conversion **7Li-axions,** **3He-axions** **BOREXINO**	Resonant absorption by nuclei **^{57}Fe, ^{6}Li, ^{83}Kr** **Krcmar et al, PNPI, BAKSAN**	Axioelectric effect in Si-, Ge-, Xe Bi-atoms **BOREXINO, CUORE, LUCIFER**
g_{Ae}	Axion-photon conversion in magnetic field **IAXO, CAST,** **Tokyo Helioscope**,	Resonant absorption by nuclei **^{169}Tm, ^{83}Kr** **PNPI, BAKSAN,** **LNGS**	Axioelectric effect in Si-, Ge-, Xe-atoms **PNPI(SAXS), CUORE, EDELWEISS, XMASS, XENON100**

CAST - CERN Axion Solar Telescope





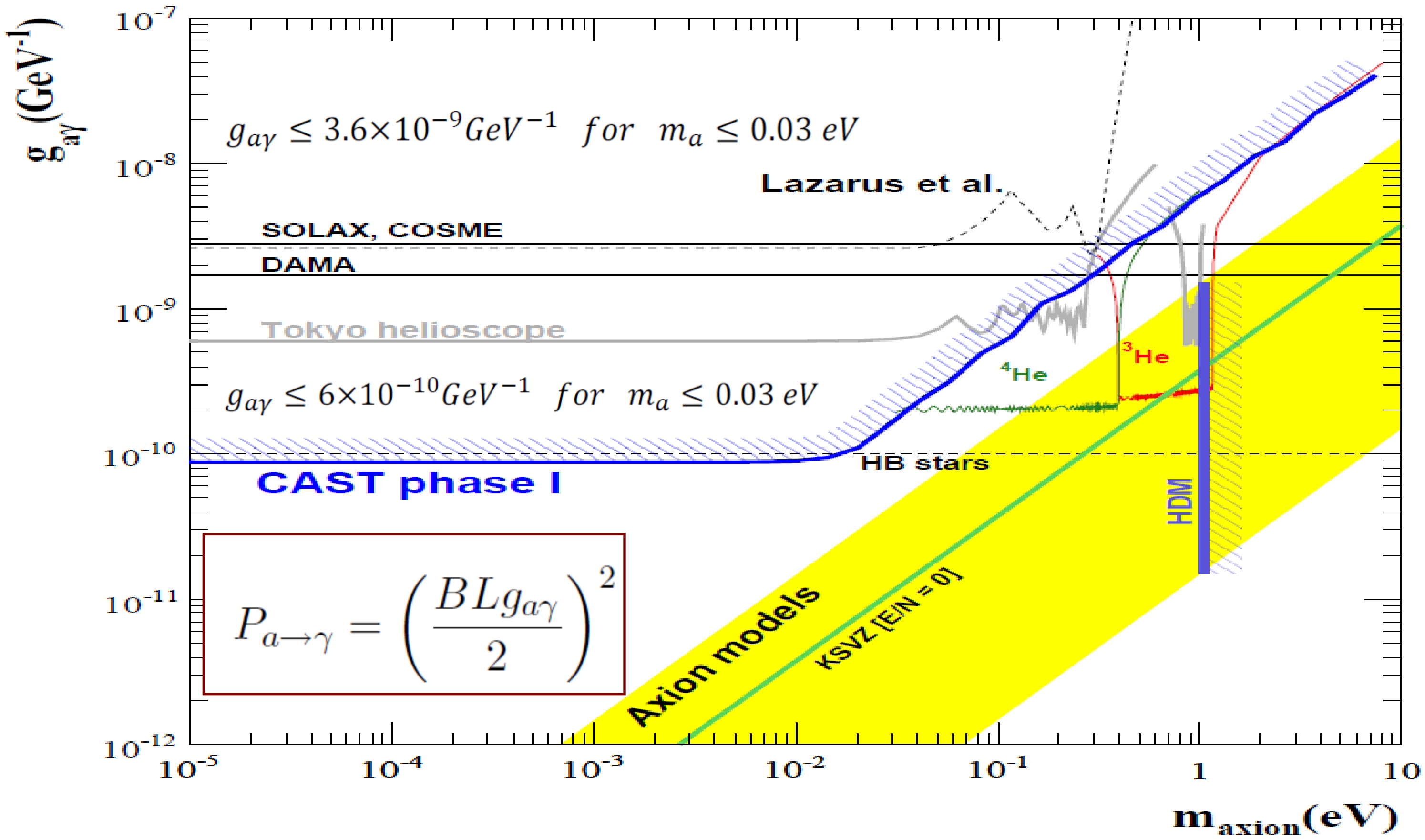




Pipe 9260 mm long with a diameter of 43 mm, area 14 cm^2

The axis of the magnet is directed to the Sun 6 hours day (3 at sunrise and 3 at sunset)

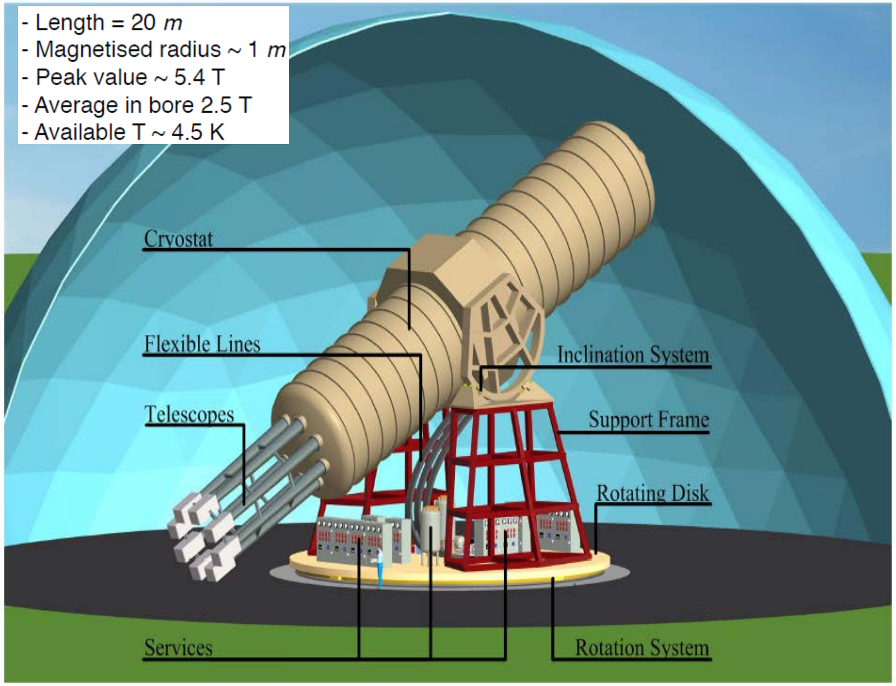
CAST Results



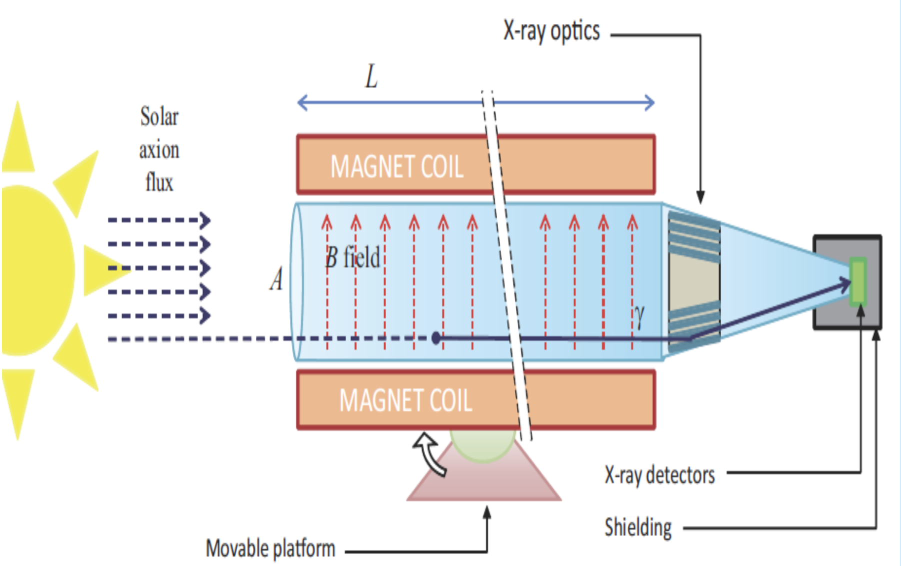
Year	Phase	Sensitivity Range
2000 – 2003	Commissioning	–
2003 – 2004	Phase I (Vacuum)	< 0.02 eV
2006 – 2007	Phase II (He^4)	0.02 eV – 0.4 eV
2008 – 2011	Phase II (He^3)	0.4 eV – 1.15 eV
2012	Phase II (He^4 - revisit)	0.02 eV – 0.4 eV

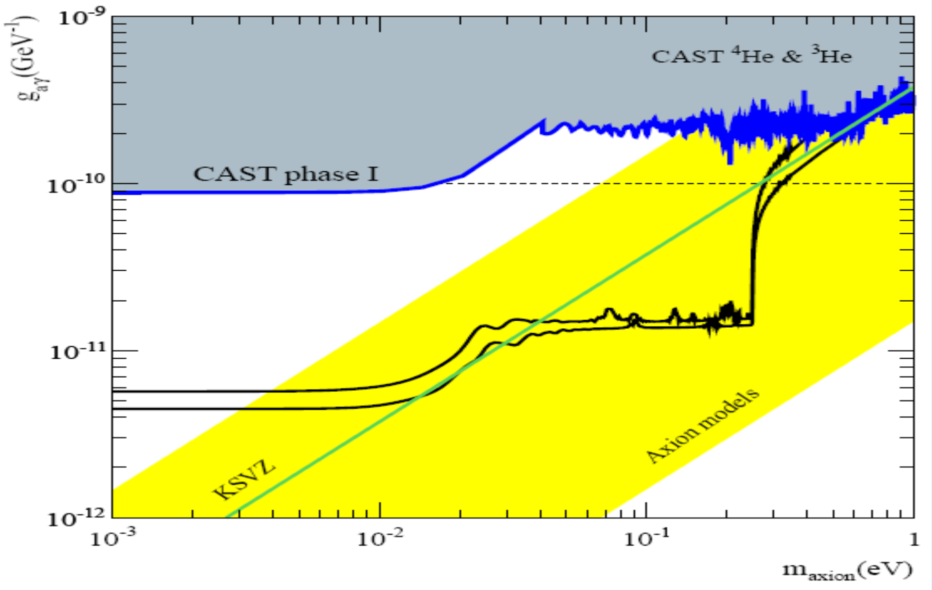
The limit on gAg constant of an axion with a photon turned out to be the most stringent among laboratory experiments. The CAST sensitivity turned out to be sufficient to test only a small range of possible values of axion parameters in the KSVZ and DFSZ axion models.

IAXO – International Axion Observatory



- Length = 20 *m*
- Magnetised radius ~ 1 *m*
- Peak value ~ 5.4 T
- Average in bore 2.5 T
- Available T ~ 4.5 K

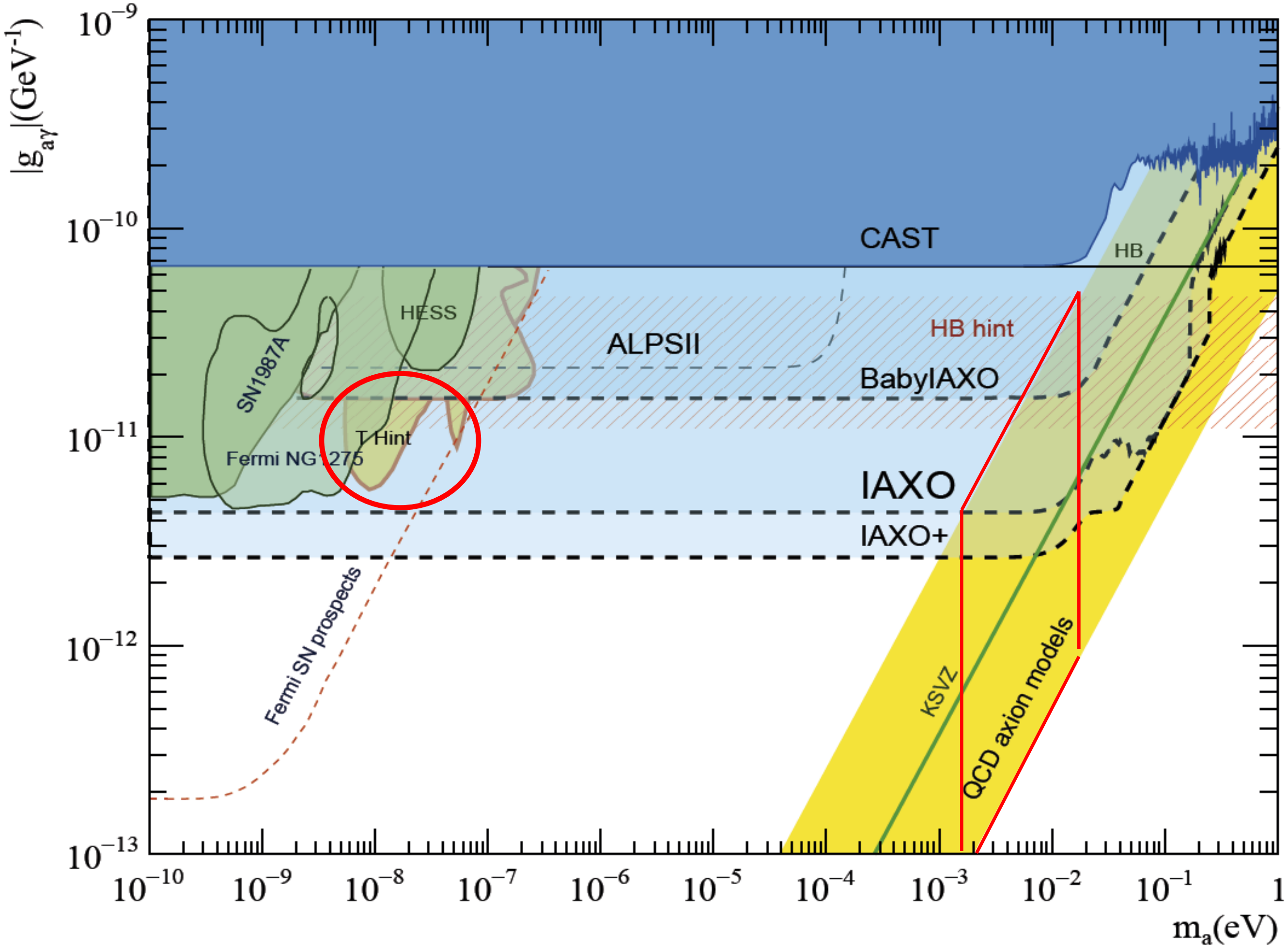




4-th generation of axion helioscopes after CAST with large-scale magnet which is >300 times larger B^2L^2A than CAST magnet. Toroid geometry with 8 conversion bores of 60 cm diameter and 20 m long. Detection systems is (XRT+detectors) scaled-up versions based on experience in CAST. Low-background techniques for detectors. Optics based on slumped-glass technique used in NuStar. 50% Sun-tracking time. Large magnetic volume available for DM searches.

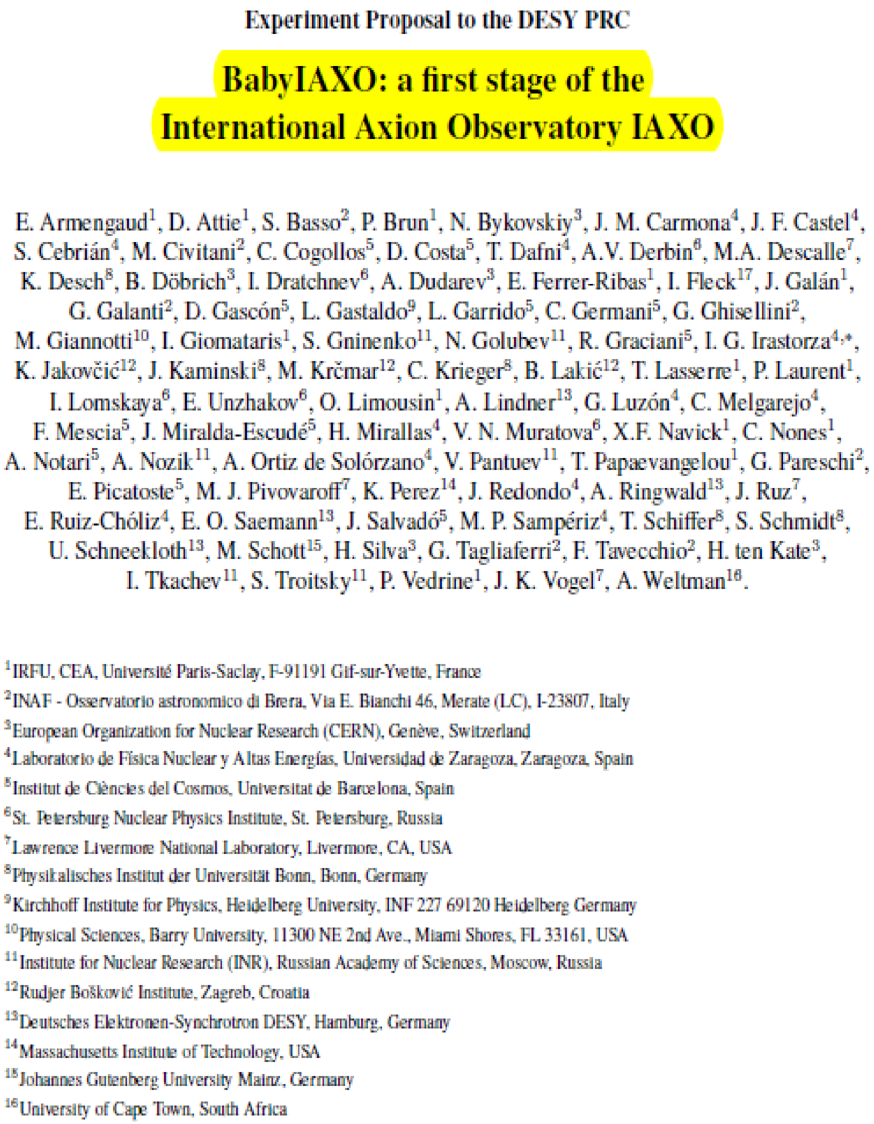
Physical program of IAXO

1904.09155v3



IAXO will improve the experimental “helioscope frontier” by more than 1 order of magnitude in sensitivity to $g_{a\gamma}$. More than 10^4 in terms of signal to noise ratio. IAXO will probe a large fraction of QCD axion models in the meV to eV mass band. IAXO will fully or largelrly probe the ALP region invoked to solve the transparency anomaly and stellar cooling anomaly. IAXO will partially explore viable QCD axion DM models.

Prototype - BabyIAXO



Experiment Proposal to the DESY PRC

BabyIAXO: a first stage of the International Axion Observatory IAXO

E. Armengaud[1], D. Attie[1], S. Basso[2], P. Brun[1], N. Bykovskiy[3], J. M. Carmona[4], J. F. Castel[4], S. Cebrián[4], M. Civitani[2], C. Cogollos[5], D. Costa[5], T. Dafni[4], A.V. Derbin[6], M.A. Descalle[7], K. Desch[8], B. Döbrich[3], I. Dratchnev[6], A. Dudarev[3], E. Ferrer-Ribas[1], I. Fleck[17], J. Galán[1], G. Galanti[2], D. Gascón[5], L. Gastaldo[9], L. Garrido[5], C. Germani[5], G. Ghisellini[2], M. Giannotti[10], I. Giomataris[1], S. Gninenko[11], N. Golubev[11], R. Graciani[5], I. G. Irastorza[4,*], K. Jakovčić[12], J. Kaminski[8], M. Krčmar[12], C. Krieger[8], B. Lakić[12], T. Lasserre[1], P. Laurent[1], I. Lomskaya[6], E. Unzhakov[6], O. Limousin[1], A. Lindner[13], G. Luzón[4], C. Melgarejo[4], F. Mescia[5], J. Miralda-Escudé[5], H. Mirallas[4], V. N. Muratova[6], X.F. Navick[1], C. Nones[1], A. Notari[5], A. Nozik[11], A. Ortiz de Solórzano[4], V. Pantuev[11], T. Papaevangelou[1], G. Pareschi[2], E. Picatoste[5], M. J. Pivovaroff[7], K. Perez[14], J. Redondo[4], A. Ringwald[13], J. Ruz[7], E. Ruiz-Chóliz[4], E. O. Saemann[13], J. Salvadó[5], M. P. Sampériz[4], T. Schiffer[8], S. Schmidt[8], U. Schneekloth[13], M. Schott[15], H. Silva[3], G. Tagliaferri[2], F. Tavecchio[2], H. ten Kate[3], I. Tkachev[11], S. Troitsky[11], P. Vedrine[1], J. K. Vogel[7], A. Weltman[16].

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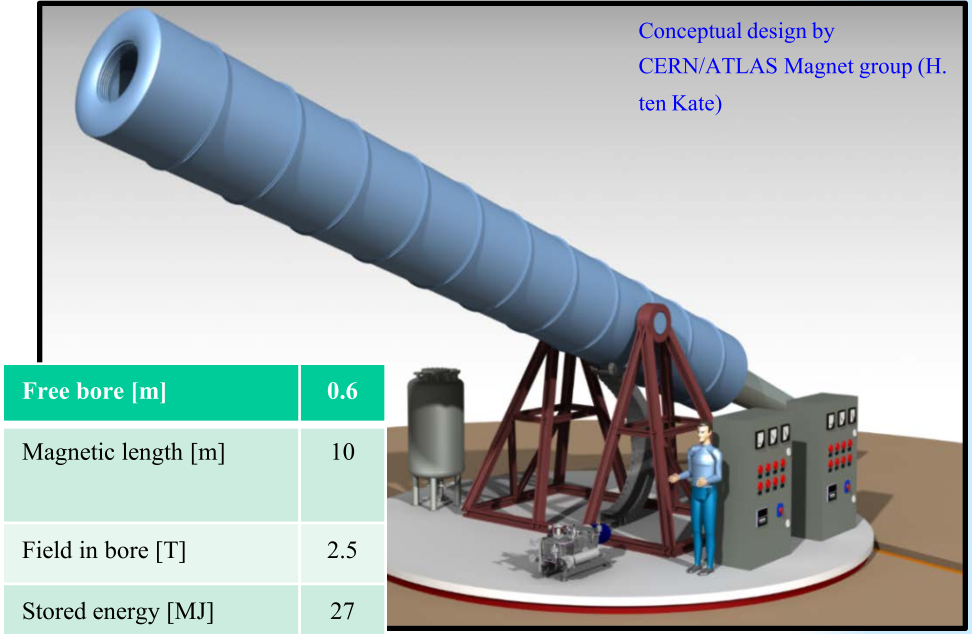
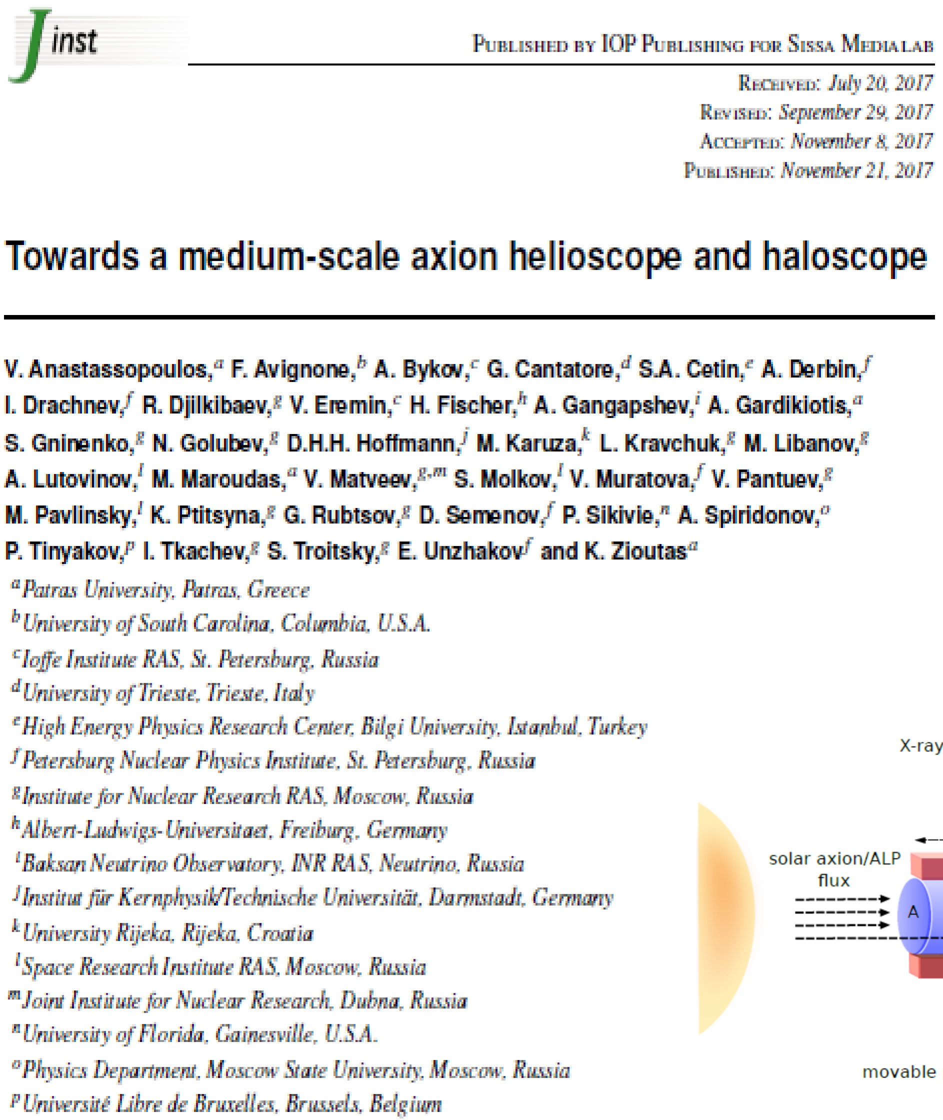


Conceptual design by CERN/ATLAS Magnet group (H. ten Kate)

Free bore [m]	0.6
Magnetic length [m]	10
Field in bore [T]	2.5
Stored energy [MJ]	27
Peak field [T]	4.1

- Bore dimensions similar to full IAXO bores → detection line representative of final ones.
- New magnet configuration (saddle dipole). Potential to go to higher B.
- Test & improve all systems. Risk mitigation for full IAXO
- Produce relevant physics
- More staged access to funds
- Mover earlier to “experiment mode”
- Baby IAXO CDR finished. Moving to Technical Design

TASTE - Troitsk Axion Solar Telescope Experiment



JINST

Published by IOP Publishing for Sissa Medialab

Received: July 20, 2017
Revised: September 29, 2017
Accepted: November 8, 2017
Published: November 21, 2017

Towards a medium-scale axion helioscope and haloscope

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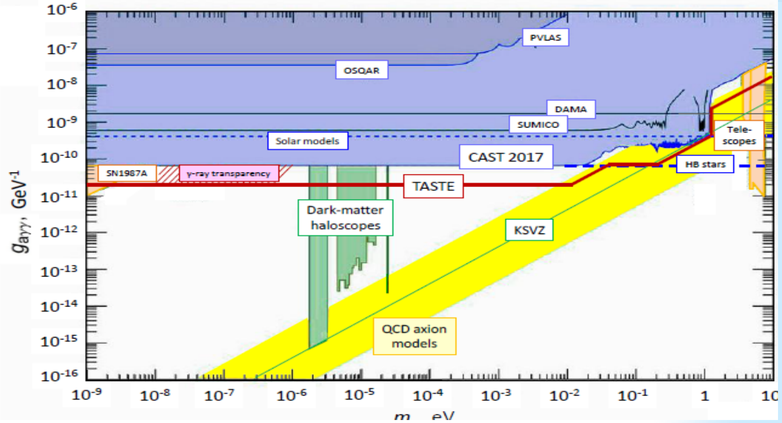
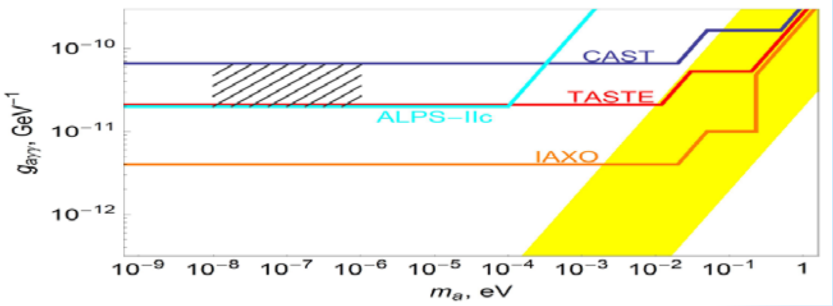
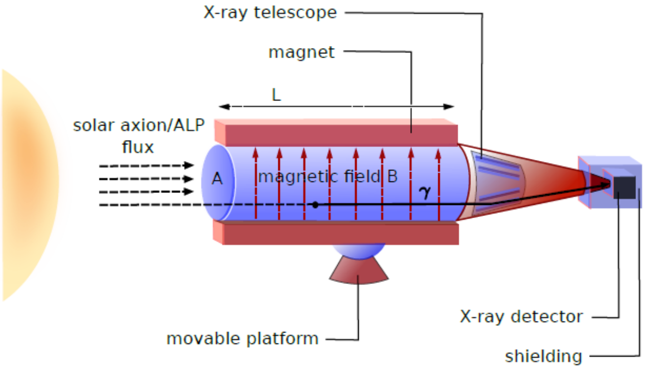
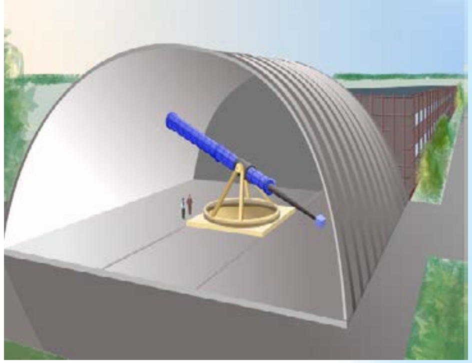








Axioelectric effect in atoms and resonant absorption by nuclei

Two special reactions with high cross sections:

The axioelectric absorption of axions by atoms is an analog of the photoelectric effect. ***The*** *reaction cross section is proportional to* g_{Ae}^2 *and* σ_{pe}*:*

$$\sigma_{Ae}(E_A) = \sigma_{pe}(E_A)\frac{g_{Ae}^2}{\beta}\frac{3E_A^2}{16\pi\alpha m_e^2}\left(1-\frac{\beta^{2/3}}{3}\right)$$

Photo effect crosssections are 4×10^{-23} cm^2 (C) - 4×10^{-20} cm^2 (Pb) at 10 keV

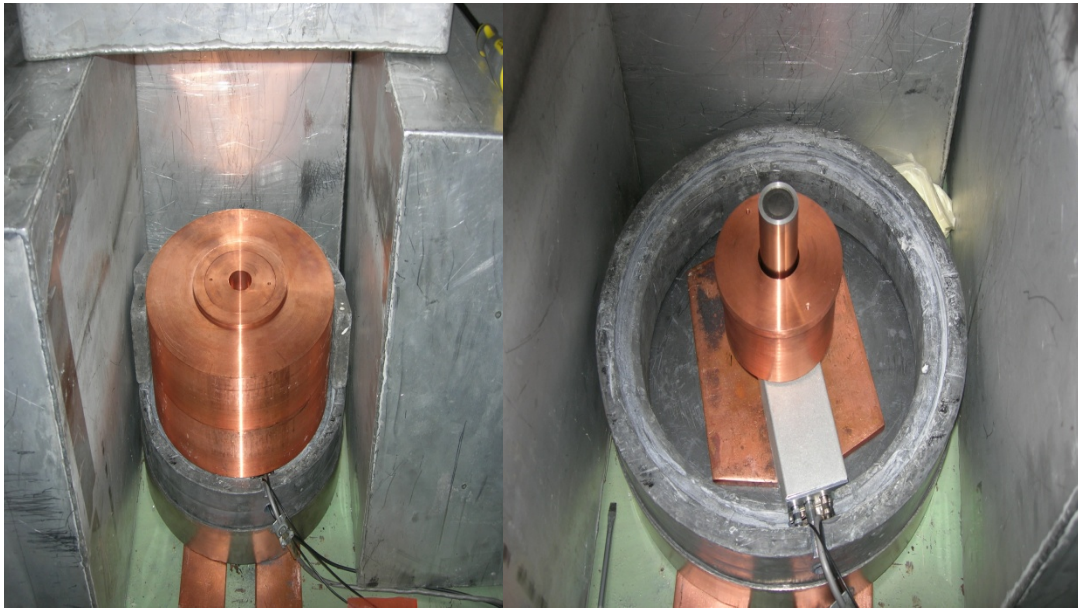
The cross section of the resonant absorption of the axions is given by an expression similar to the one for the γ *–ray absorption and corrected by the* ω_A/ω_γ *ratio*

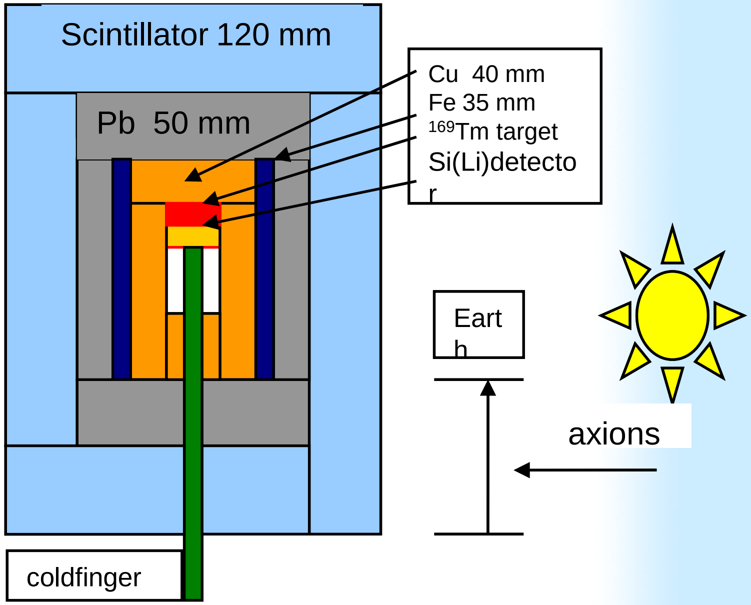
$$\sigma(E_A) = 2\sqrt{\pi}\sigma_{0\gamma}\exp\left[-\frac{4(E_A-E_M)^2}{\Gamma^2}\right]\left(\frac{\omega_A}{\omega_\gamma}\right)$$

where $\sigma_{0\gamma}$ is the maximum cross section of the γ -ray resonant absorption and $\Gamma = 1/\tau$. The experimentally obtained value of $\sigma_{0\gamma}$ **for** the ^{57}Fe nucleus is equal **to 2.56 $\times10^{-18}$ cm^2**. Due to huge c.s.

High sensitivity for g_{Ae} and g_{AN} can be reached with a relatively small detector

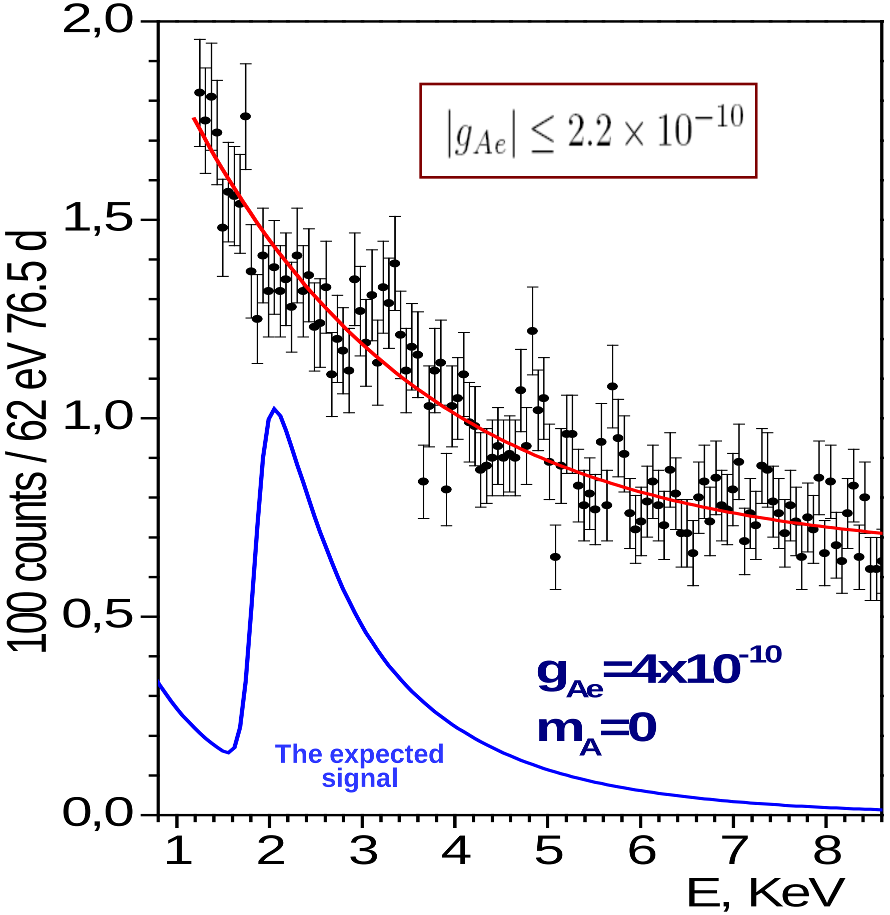
Si(Li)-detector inside low-background setup

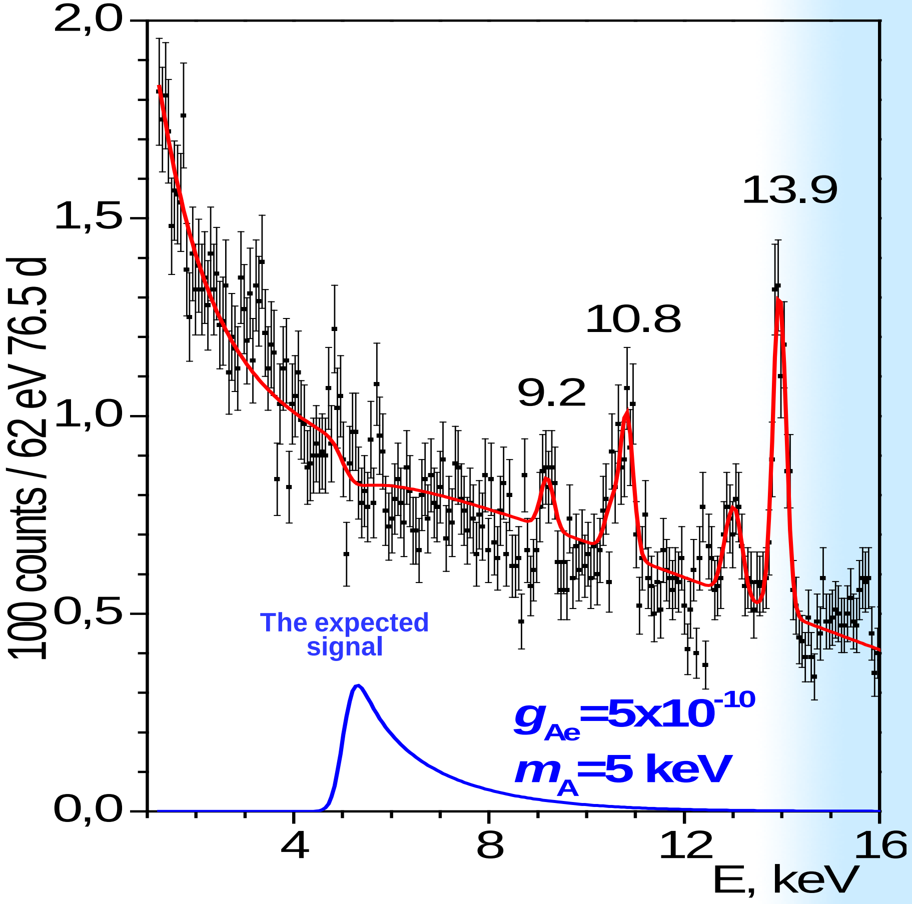




__In__ our experiment, we used a Si(Li) detector with a sensitive region diameter of 17 mm and a thickness of 2.5 mm (1.4 g). __The__ detector was placed in a vacuum cryostat was surrounded by 12.5 cm of copper and 2.5 cm of lead, which reduced the background of the detector at an energy of 14 keV by a factor of 110. __In__ order to suppress the background from cosmic rays and fast neutrons, we used five scintillators, which closed the detector almost completely except for the bottom side, where a Dewar vessel with liquid nitrogen was placed. Measurements continued for 76.5 days of live time in the form of two hour runs in order to control the stability of the Si(Li) detector and active shielding scintillation detectors.

Search for axioelectric effect in Si-atoms





The spectrum measured by Si(Li) detector. Optimal fit and ***the*** *expected spectrum in the case of axions with* $m_A \approx 0$ *and* $g_{Ae} = 4 \times 10^{-10}$*. The upper limit on* g_{Ae}*:* $g_{Ae} < 2.2x10^{-10}$ *(90% c.l.)*

The spectrum in (1-16) keV range. Optimal fit for $m_A = 5$ *keV.* ***The*** *expected "axion" spectrum is shown for* $m_A = 5$ *keV and* $g_{Ae} = 5 \times 10^{-10}$*.*

Results of dark matter detectors

Si(Li), XMASS, EDELWEISS, XENON, LUX, COSINE, CDEX, PANDA

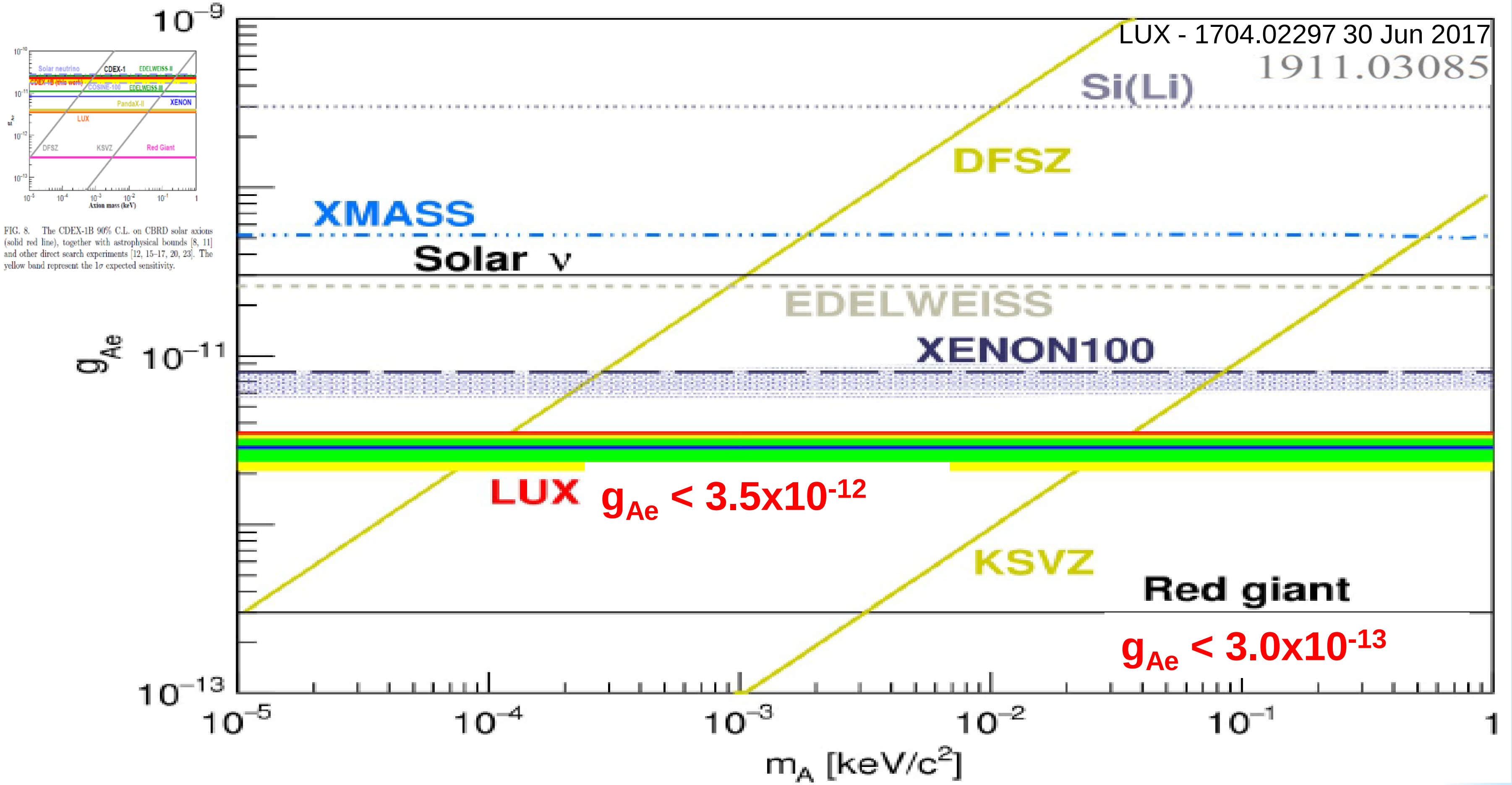


FIG. 8. The CDEX-1B 90% C.L. on CBRD solar axions (solid red line), together with astrophysical bounds [8, 11] and other direct search experiments [12, 15–17, 20, 23]. The yellow band represent the 1σ expected sensitivity.

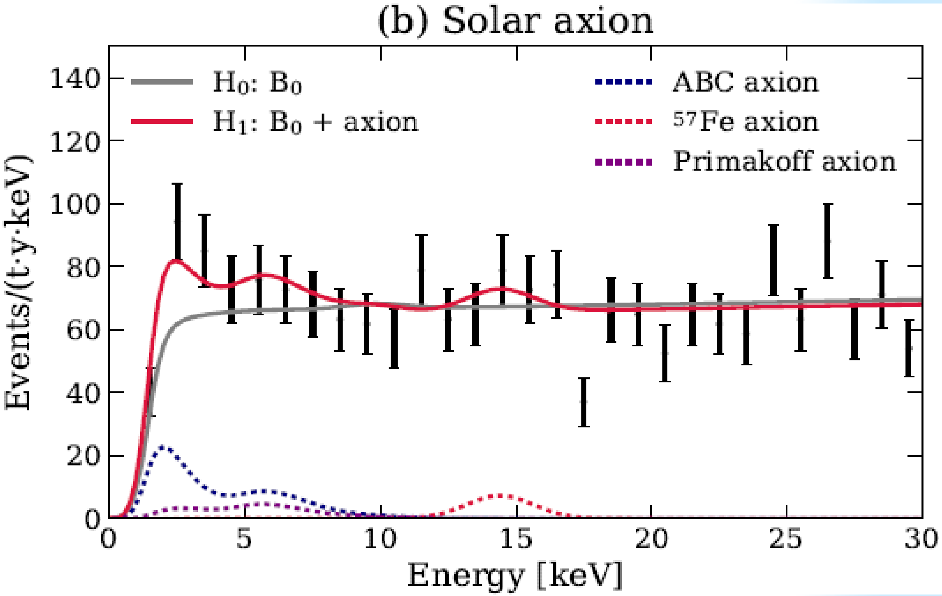
$g_{Ae} < 3.5\text{x}10^{-12}$

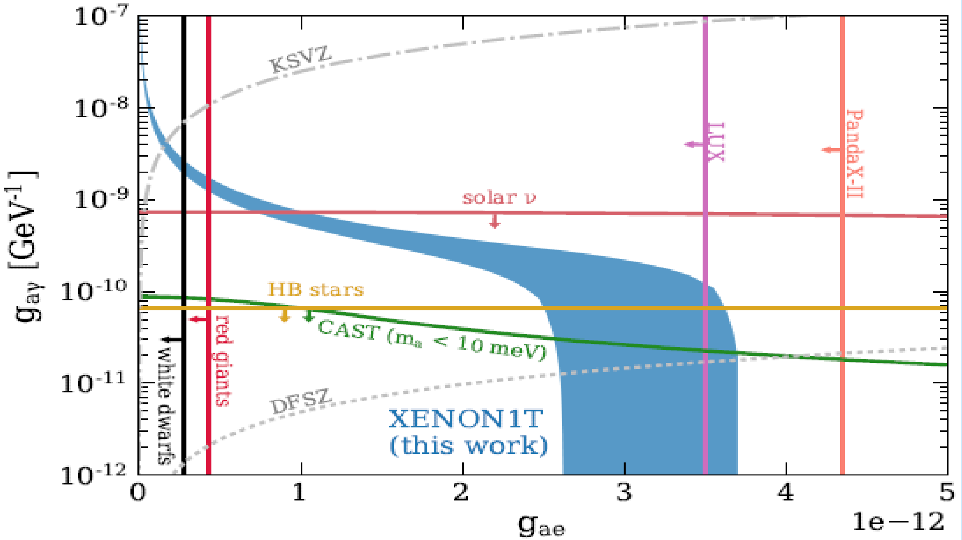
$g_{Ae} < 3.0\text{x}10^{-13}$

Upper limits on axion-electron coupling obtained with different detectors for DM particles (WIMPs) searches. Solar neutrino limit (<10% energy carried way by neutrinos) and RG limits are shown. Stars in the red giant (RG) branch are particularly sensitive to axion-electron processes due to gAe. In fact, it leads to an extension of the RG stars brightness in comparison state-of-the-art stellar evolution theory.

Observation of Excess Electronic Recoil Events in XENON1T

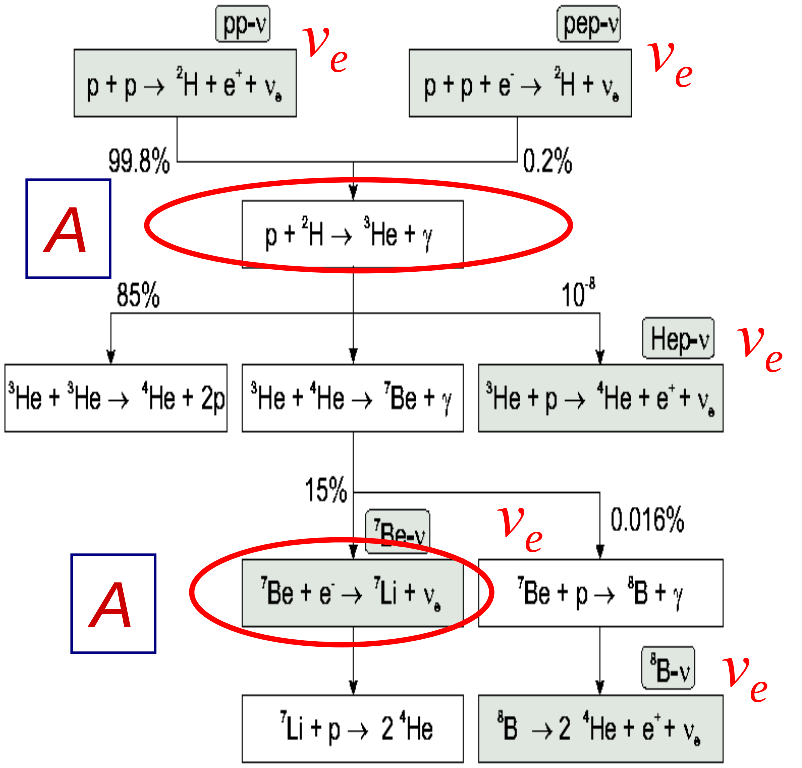
arXiv:2006.09721v2 [hep-ex] 30 Jun 2020





Xenon coll. report results from searches for new physics with low-energy electronic recoil data recorded with the XENON1T detector. With an exposure of 0.65 t.y. and an low background rate, the data enables searches for solar axions, an enhanced neutrino magnetic moment using solar neutrinos. The solar axion model has a 3.5 sigma significance, and a three-dimensional 90% confidence surface is reported for axion couplings to electrons, photons, and nucleons. This surface is inscribed in the cuboid defined by $g_{Ae} < 3.7\text{x}10^{-12}$ and excludes $g_{Ae} = 0$.

Solar axions from pp-chain



$p + d \to {}^3He + Axion\ (5.49\ MeV)$

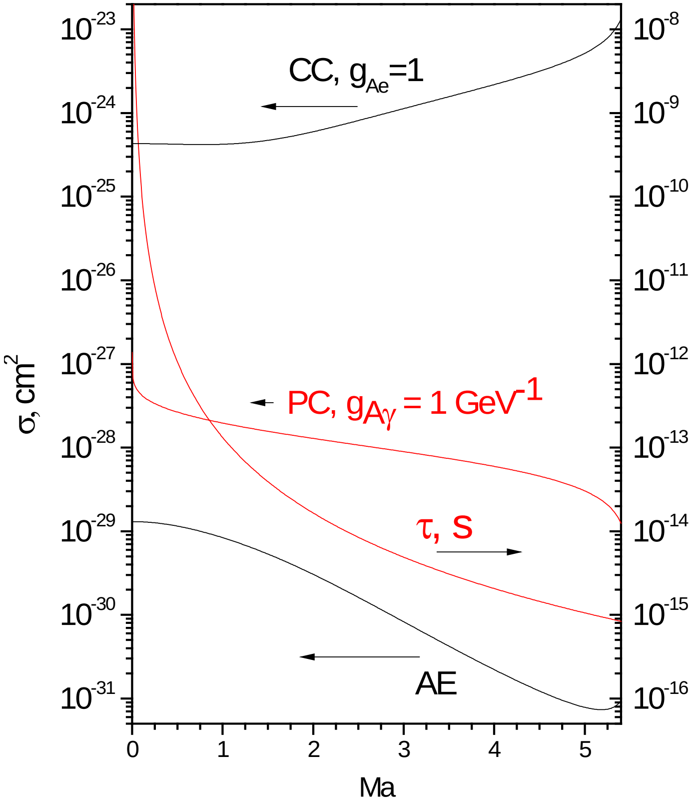
$$\Phi_{A0}(pd) \cong 0.54 \times \Phi_{\nu pp} (g^3_{AN})^2 (p_A / p_\gamma)^3$$
$$\cong 3.3 \times 10^{10} (g^3_{AN})^2$$

$e + {}^7Be \to {}^7Li^* \to {}^7Li + A\ (478\ keV)$

$$\Phi_{A0}(7Be) \cong 0.1 \times \Phi_{\nu 7Be} (g^0_{AN} + g^3_{AN})^2 (p_A / p_\gamma)^3$$
$$\cong 5 \times 10^8 (g^0_{AN} + g^3_{AN})^2$$

The expected solar axion flux can thus be expressed in terms of the ^{7}Be- and pp-neutrino fluxes, which are 4.9×10^9 and 6.0×10^{10} cm^{-2} s^{-1}. The fluxes depends on gAN. The flux of 5.5 MeV axions is in 60 times more then 478 keV axions. The additional advantage to look for 5.5 MeV axions is that a background level is lower usually for higher energy. In Borexino 4 reactions were selected to detect axions. The signature of all these reactions is a 5.5 MeV peak in the energy spectrum.

Axion detection via $g_{A\gamma}$ and g_{Ae} coupling constants



1. **Primakoff conversion**:

$A + Z \to \gamma + Z$.

on nuclei, $E_\gamma \approx E_A$ γ is detected.

C.S. has a complex form,

CS for 5.5 MeV axions

$\sigma_{CC} \approx g_{A\gamma}^2 \text{ x } 4.7\text{x}10^{-28}$ cm^2

at $m_A < 1$ MeV

2. **Axion decay:**

$A \to \gamma + \gamma$.

the axion lifetime is

$\Gamma\,[s^{-1}] = 1/\tau = g_{A\gamma}^2 m_A^3/64\pi =$

$0.8\text{x}10^{-5}(g_{A\gamma}[GeV^{-1}])^2\,(m_A\,[eV])^3$

and τ have to be < 500 s

1. **Compton conversion**:

$A + e \to \gamma + e$.

both e and γ are detected.

C.S. has a complex form,

the total CS for 5.5 MeV axions

$\sigma_{CC} \approx g_{Ae}^2 \text{ x } 4.3\text{x}10^{-25}$ cm^2

at $m_A < 1$ MeV

2. **Axioelectric effect**:

$A + e + Z \to Z + e$.

is analog of photo effect

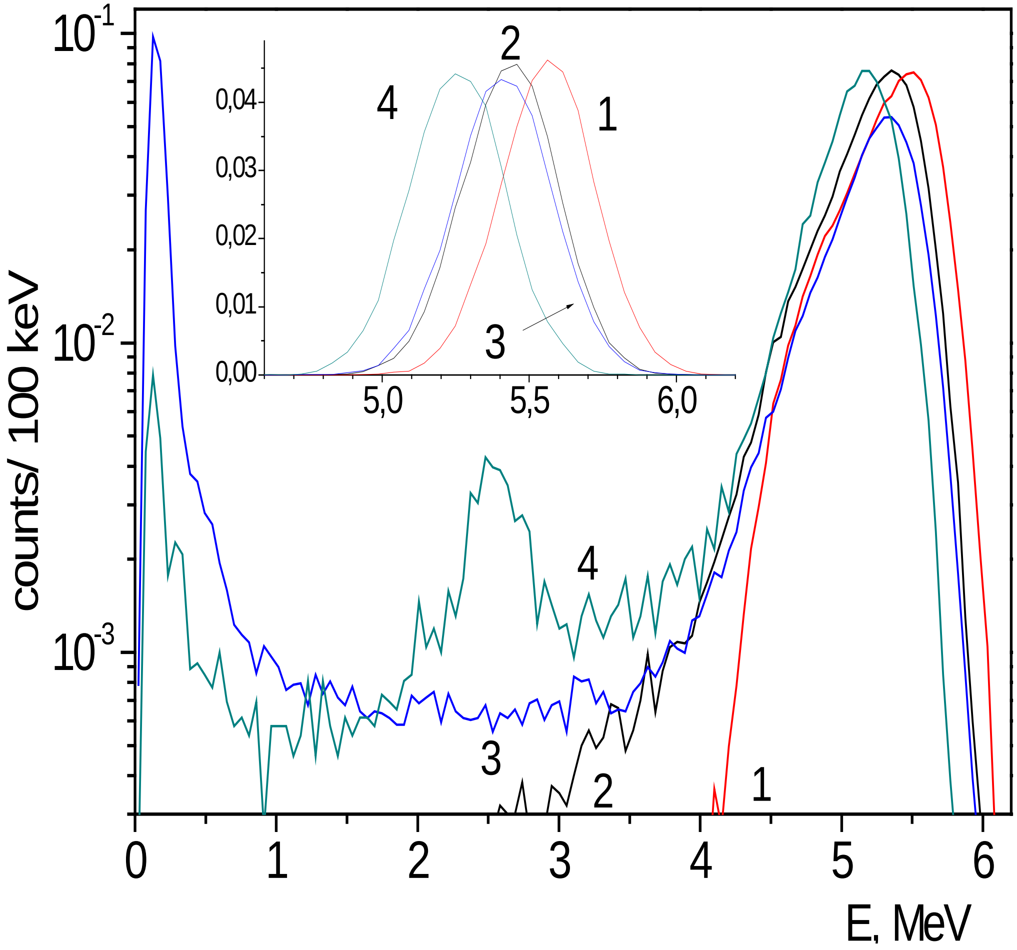
CS is proportional Z^5, for C atom

and $E_A = 5.5$ MeV

$\sigma_{AE} \approx g_{Ae}^2 \text{ x } 1.3\text{x}10^{-29}$ cm^2

For PC the AE CS is more than 4 orders of magnitude lower than for Compton process, so the AE effect can not be taken into account. However, using the different energy dependence $\sigma_{cc} \sim E_A$, $\sigma_{Ae} \sim E_A^{-3/2}$ and Z^5 dependence, the AE effect is more effective to search for low energy axions with detectors having high Z. We also consider the possible signals from the decay of axion into two γ-quanta and from Primakoff conversion on nuclei. The amplitudes of the reactions depend on $g_{A\gamma}$. No statistically significant indications of axion interactions were found.

Response function of Borexino detector



1 – axioelectric effect

2 – Compton conversion

3 – Primakoff conversion

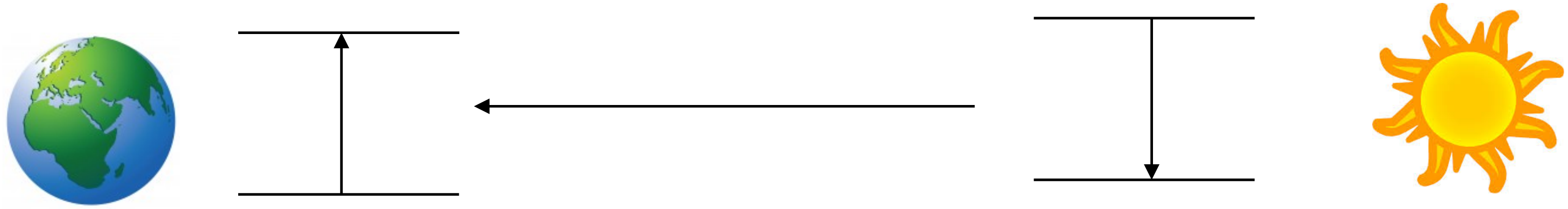
4 – Axion decay A→2γ

The Monte Carlo method has been used to simulate the Borexino response to electrons and γ-quanta appearing in axion interactions. The response function of the Borexino to the axion's was found by MC simulations based on ***GEANT4 code****, taking into account the effect of ionization quenching and the dependence of the registered charge on the distance from the detector's center.*

The uniformly distributed γ's and e's were simulated inside the inner vessel, but the response functions were obtained for events restored inside the FV. The MC candidate events are selected by the same cuts that was applied for real data selection. The signature of all reactions is peak at 5.5 MeV energy.

Resonant excitation of nuclear levels

The axions can be produced when thermally excited nuclei (or excited due to nuclear reactions) in the Sun relaxes to its ground state and could be detected via resonant excitation of the same nuclide in a laboratory.



^{7}Li, ^{57}Fe, ^{83}Kr, ^{169}Tm

^{7}Li, ^{57}Fe, ^{83}Kr, ^{169}Tm

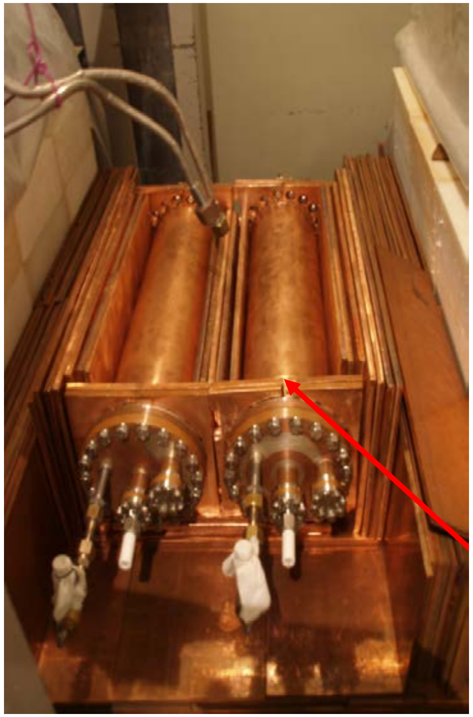
The monochromatic axions can excite the same nuclide in a laboratory, because the axions are Doppler broadened due to thermal motion of the axion emitter in the Sun, and thus some axions have suitable energy to excite the nuclide.

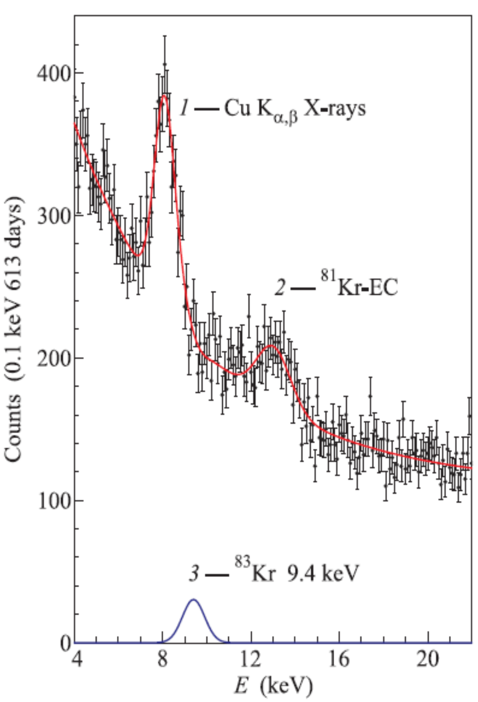
The axions from Primakoff, Compton and Bremsstrahlung processes with wide continues energy spectra can also excite low-lying levels of some nuclei.

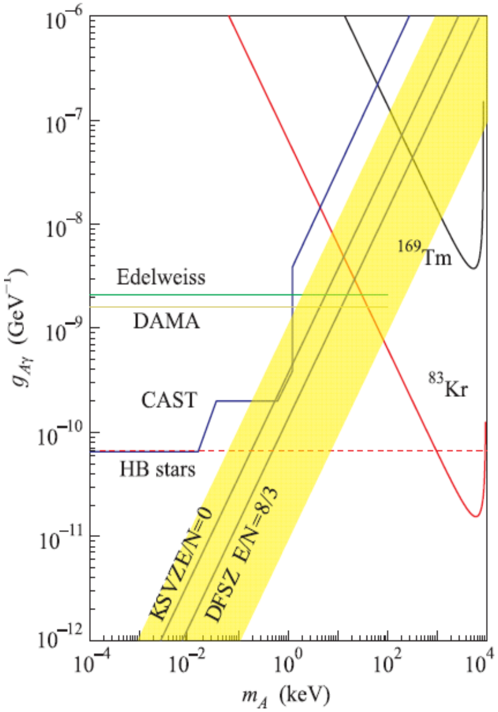
^{169}Tm

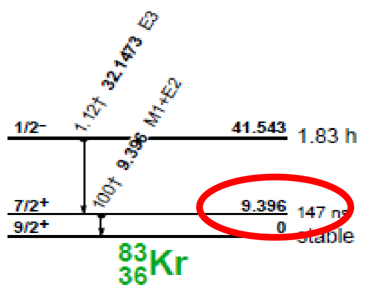
Search for solar axions emitted in M1-transition of ^{83}Kr nuclei (INR BNO + PNPI)

A search was carried out for 9.4 keV axions emitted in the M1 transition of 83Kr nuclei on the Sun, using the resonance absorption reaction : **$A + {}^{83}Kr \rightarrow {}^{83}Kr^* \rightarrow {}^{83}Kr + \gamma$ (9.4 keV).** To register γ-quanta and electrons arising from the discharge of the nuclear level, a proportional gas chamber filled with 99.9% enriched krypton-83 and located in a low-background installation in the underground laboratory of the **Baksan Neutrino Observatory** was used**.**



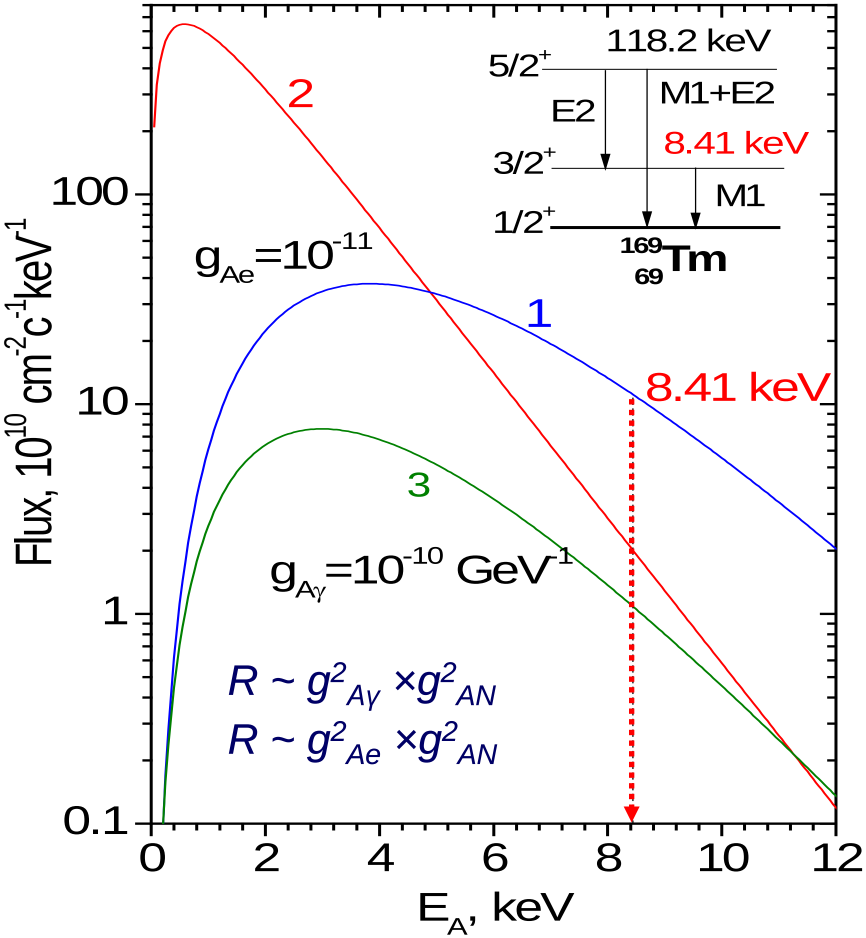


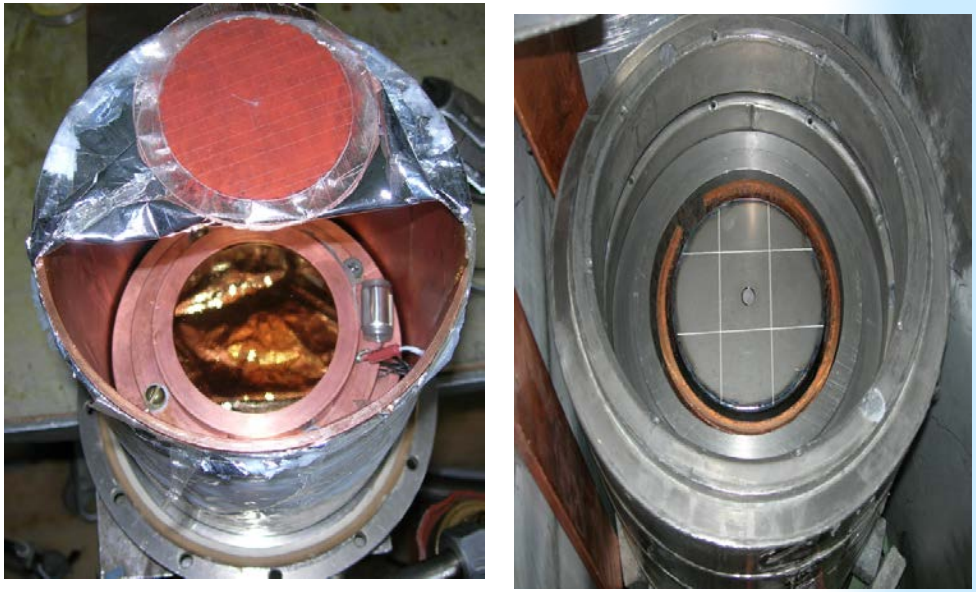




Two proportional Kr-chambers with the first layer of passive protection. Spectrum of the Kr camera measured over 613 days. Limits on gAγ. Decay scheme and the Andyrchi mountain, under which the BNO INR is located at a depth of 4800 m.

Resonant absorption by ^{169}Tm nuclei





To search for 8.41 keV γ's the planar Si(Li) detector with a sensitive area diameter of 66 mm and a thickness of 5 mm was used.

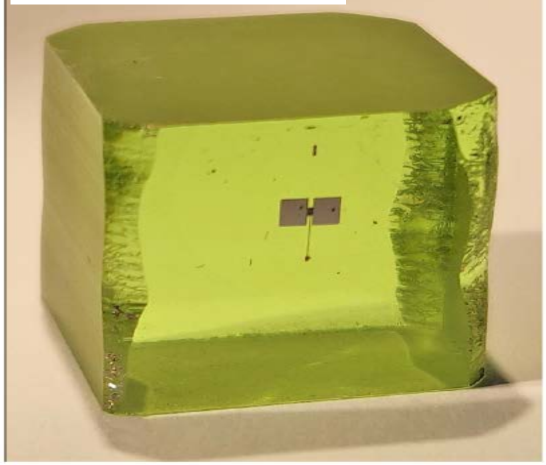
The detection probability of the axions is determined by the product $g^2_{A\gamma} \times g^2_{AN}$ and $g^2_{Ae} \times g^2_{AN}$ which is preferable for small $g_{A\gamma e}$ values.

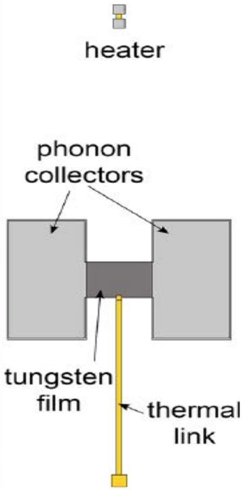
The search for resonant absorption of Primakoff, Compton and Bremsstrahlung solar axions by 169Tm nuclei have been performed using Si(Li) detector and Tm target. The expected axion count rate is proportional $R \sim g^2_{A\gamma} \times g^2_{AN}$ for Primakoff axions and $R \sim g^2_{Ae} \times g^2_{AN}$ for Bremsstrahlung and Compton axions.

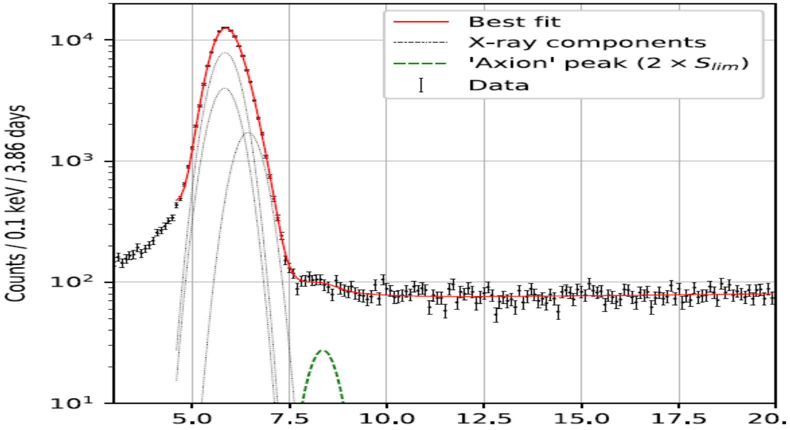
PL B 678 181 (2009) PRD83, 023505 (2011)

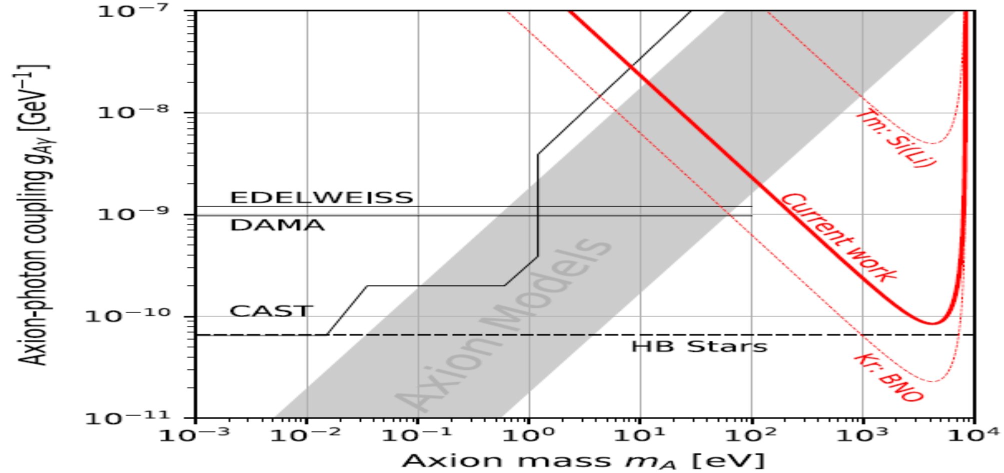
$Tm_3Al_5O_{12}$ cryogenic bolometer at 10 mK

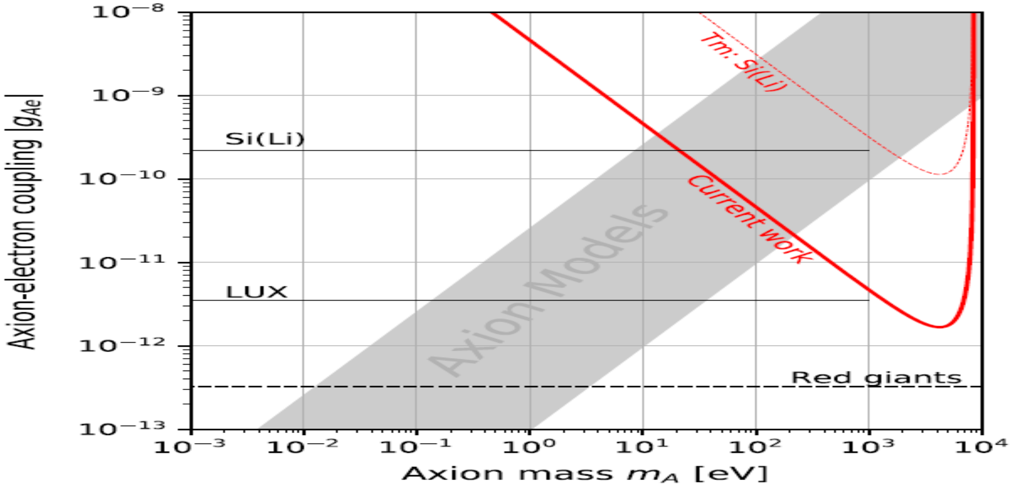
Eur. Phys. J. C (2020) 80:376





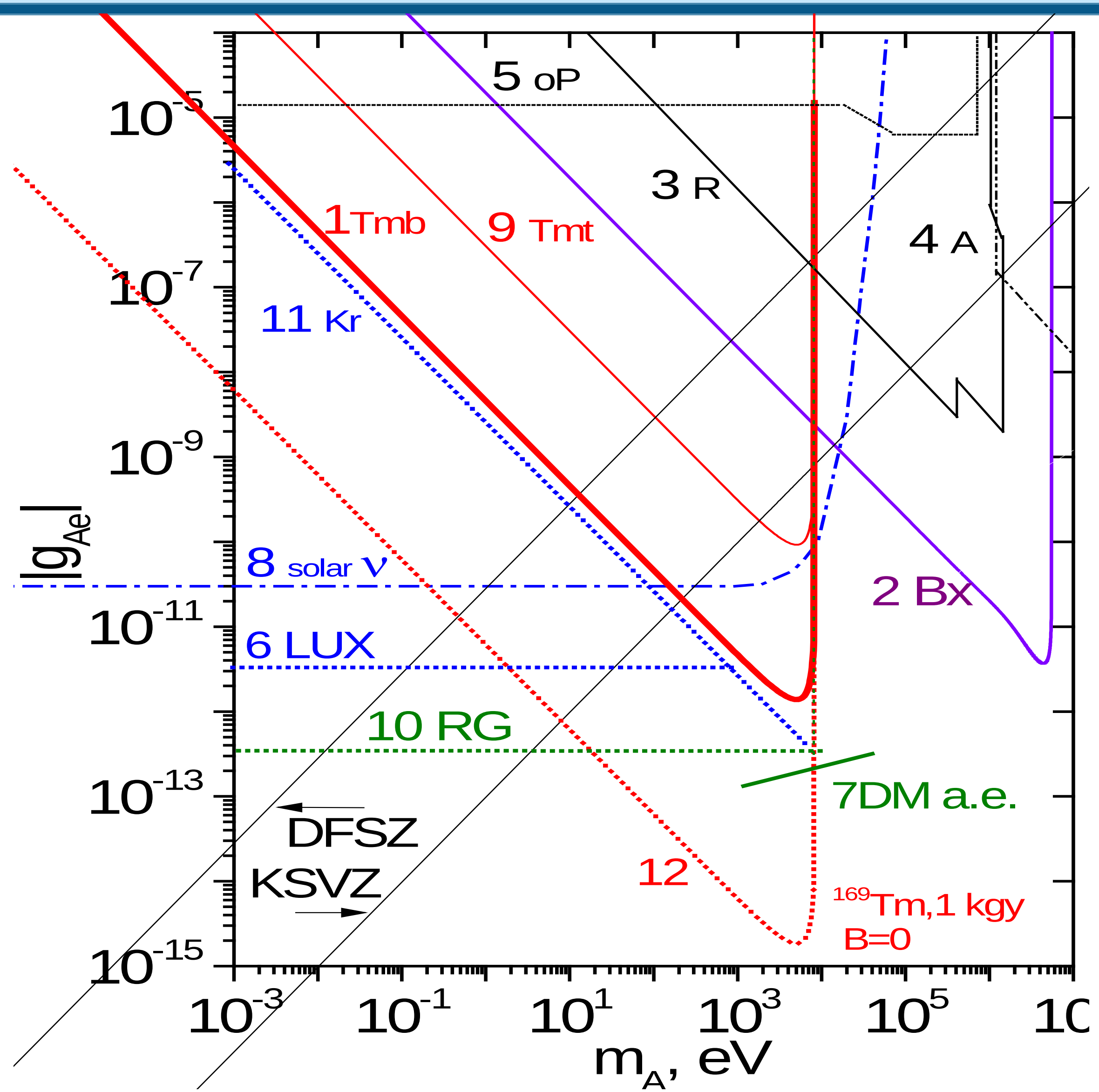






A search for resonant absorption of solar axions by ^{169}Tm nuclei was carried out. A newly developed approach involving low-background cryogenic bolometer based on $Tm_3Al_5O_{12}$ crystal was used that allowed for significant improvement of sensitivity in comparison with previous ^{169}Tm based experiments. The measurements performed with 8.18 g crystal during 6.6 days exposure yielded the following limits on axion couplings: $|g_{A\gamma}m_A| \leq 2.31\times10^{-7}$ and : $|g_{Ae}m_A| \leq 4.59\times10^{-9}$ eV.

Limits on axion-electron coupling g_{Ae} and m_A



The existing upper limits on g_{Ae} (90% c.l.).

1 – $Tm_3Al_5O_{12}$ bolometer;

2 - Borexino;

3 - reactor;

4 - accelerator;

5 - orthopositronium;

6 - LUX (solar);

7 - PANDA II (DM);

8 - 0.1 from neutrinos;

9 - ^{169}Tm + Si (Li) “target-detector”;

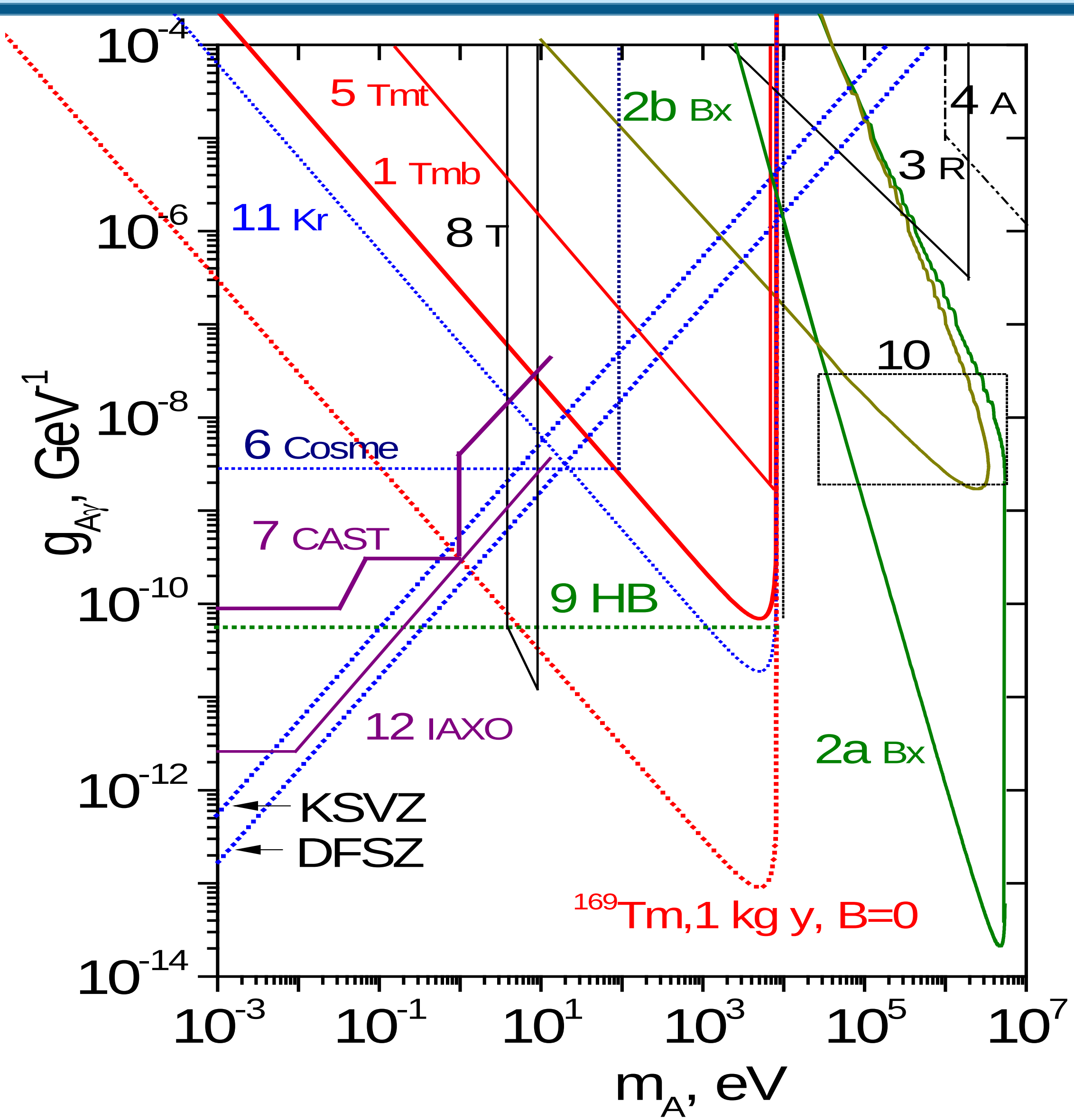
10 - red giants;

11 - 83Kr, Baksan (preliminary);

12 - Tm bolometer with an exposure of 1 kg per year in backgroundfree experiment.

13 - g_{Ae} values in DFSZ and KSVZ axion models.

Limits on axion-photo coupling $g_{A\gamma}$ and m_A



The existing upper limits on $g_{A\gamma}$ (90% c.l.).

1 – $Tm_3Al_5O_{12}$ bolometer;

2 a,b - Borexino;

3 - reactor;

4 - accelerator;

5 - ^{169}Tm + Si (Li) “target-detector”;

6 – Cosme, Solax, Dama;

7 - CAST;

8 - telescopes;

9 - HB stars;

10 - red giants;

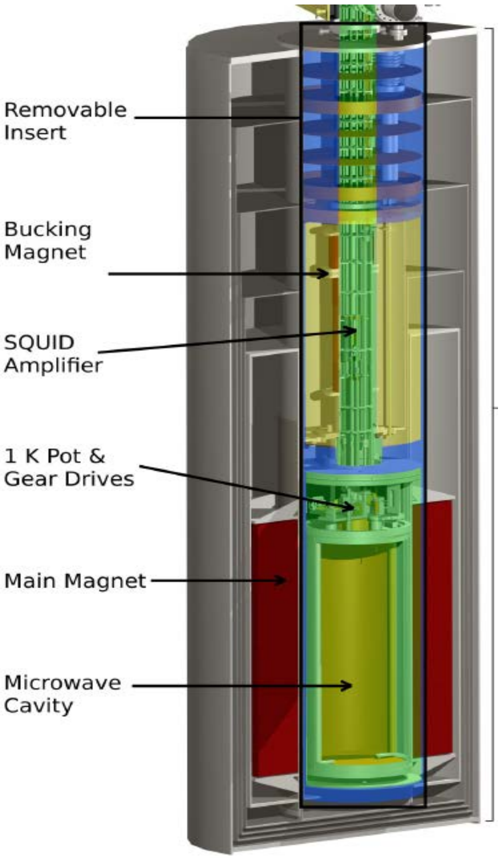
11 – SUSY and mirror models;

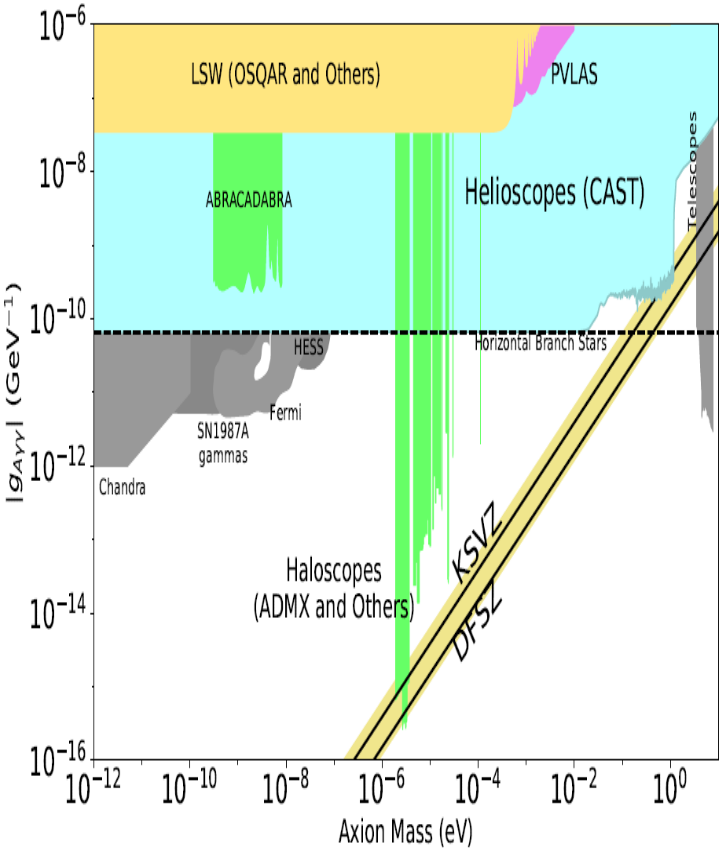
12 - IAXO (project)

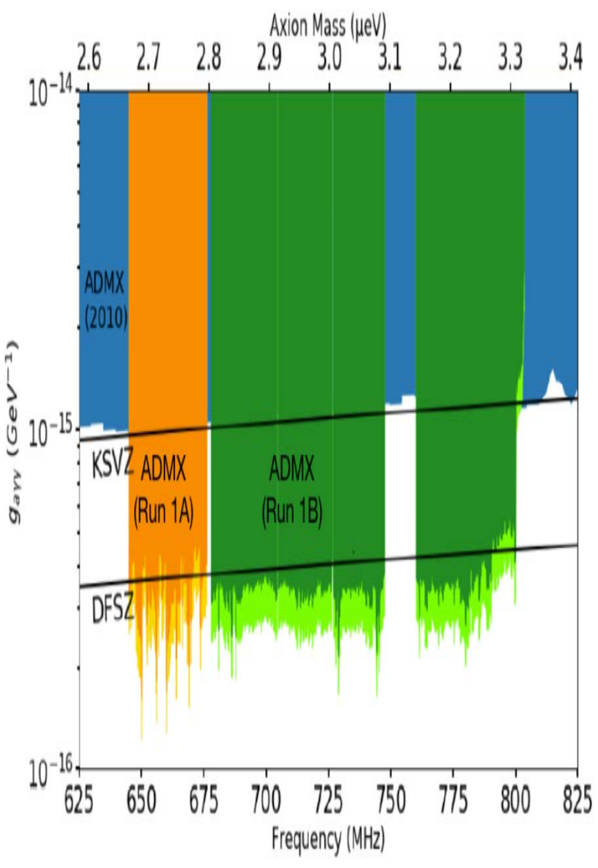
13 – Tm-bolometer with an exposure of 1 kg per year in background free experiment.

14- $g_{A\gamma}$ values in DFSZ and KSVZ axion models.

Search for relic axions A→γ : ADMX



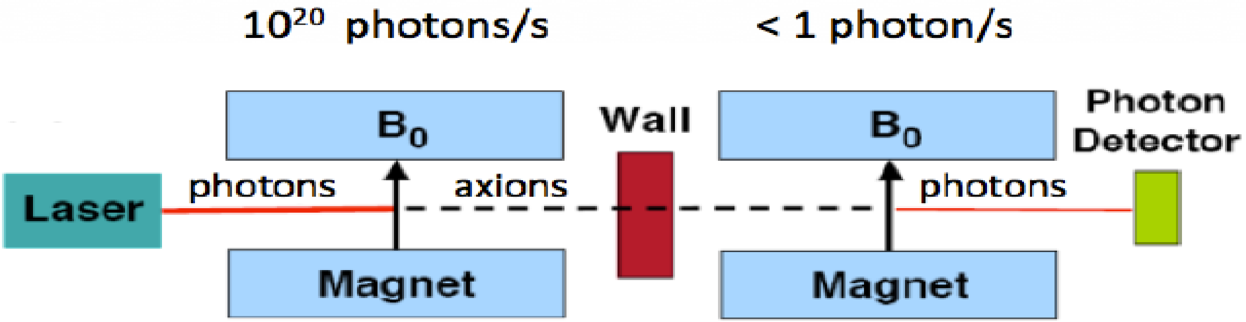




ADMX - microwave chamber 1 m in length and a diameter of 0.5 m with a strong magnetic field. To search for relic axions ADMX experiment uses microwave chamber with a strong magnetic field. Signal occurs when the resonant frequency coincides with the mass of the axion. Search for axions is carried out by changing the resonant frequency of the camera. Exclusion regions reported from the microwave cavity experiments in comparison with other limits are shown.

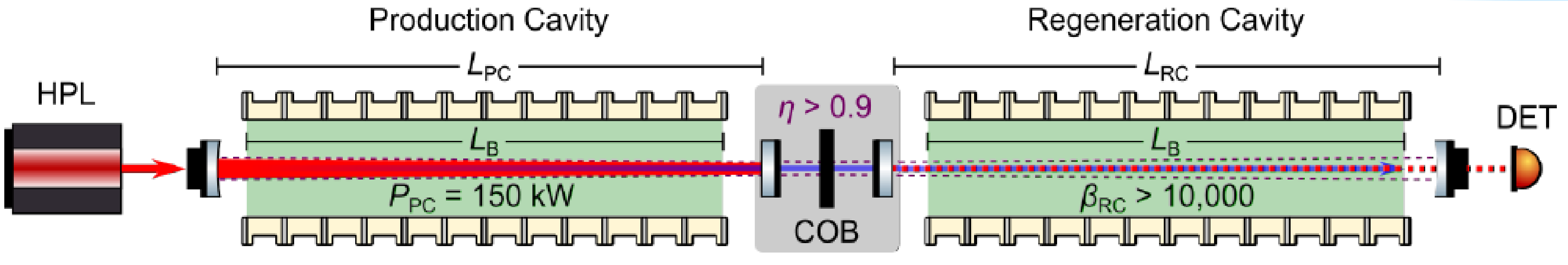
Laboratory axions

"Shining light through the wall" or "Photon regeneration"



Any Light Particle Search II (ALPS II)

2009.1429429 Sep 2020



ALPs-II at DESY using a HERA dipole magnet, Gammev at Fermilab using a Tevatron Magnet, and OSQAR experiment at CERN using a LHC superconductive dipole magnet. The length of magnets is planned to increase up to 100 m. **T**he ALPS II is an experiment currently being built at DESY that will use a light-shining-through-a-wall approach to search for axion-like particles**.** **A**LPS II will use 24 superconducting dipole magnets,122m long optical cavities. The experiment to achieve a sensitivity to the coupling between axion-like particles and photons down to $g_{A\gamma} = 2\times10^{-11}\,\mathrm{GeV}^{-1}$, more than three orders of magnitude beyond the sensitivity of previous laboratory experiments. ALPSII will not achieve the IAXO sensitivity and it is model-free experiment.

Conclusion

Axion (and ALPs) *simultaneously solve the CP problem of strong interactions and are well-motivated candidates for dark matter. Perhaps the anomalous transparency of the Universe for high-energy quanta and the rapid cooling of stars are the first indications of their existence.*

Currently, the ***IAXO*** *(and babyIAXO, TASTe) projects offer the most sensitive laboratory experiment with solar neutrinos to the axion-photon* $g_{A\gamma}$ *coupling constant for a wide range of axion masses.*

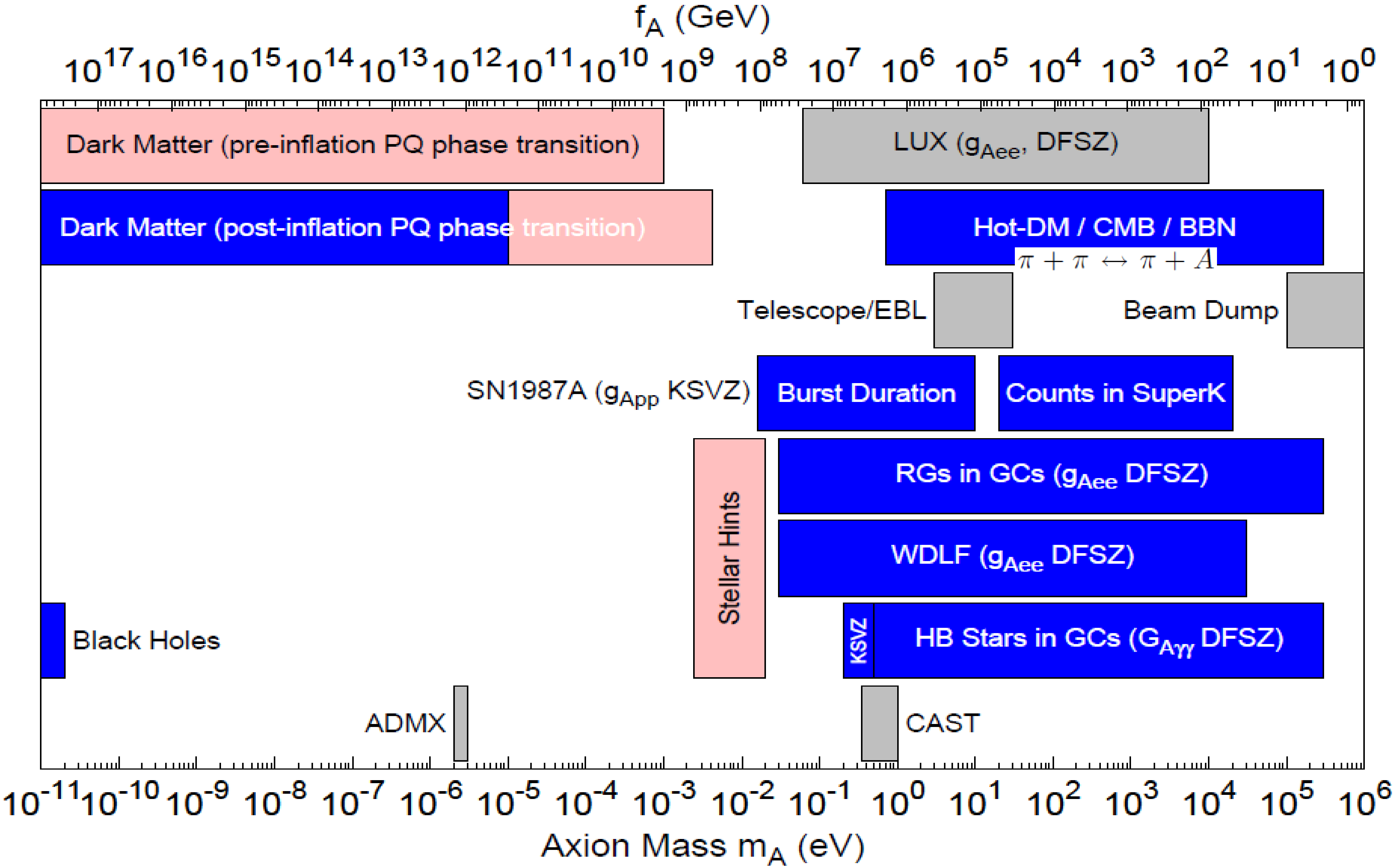
Searches for the axioelectric effect and resonant absorption for solar and relict axions using neutrino and dark matter detectors have ruled out a new large region of possible masses and coupling constants of the axion and ALPs. Searches for resonant excitation of the 8.4 keV nuclear level of the ^{169}**Tm** *nucleus in a Tm-containing bolometer can significantly improve the sensitivity (up to two orders of magnitude) to the axion coupling constants.*

Thank you for your attention!

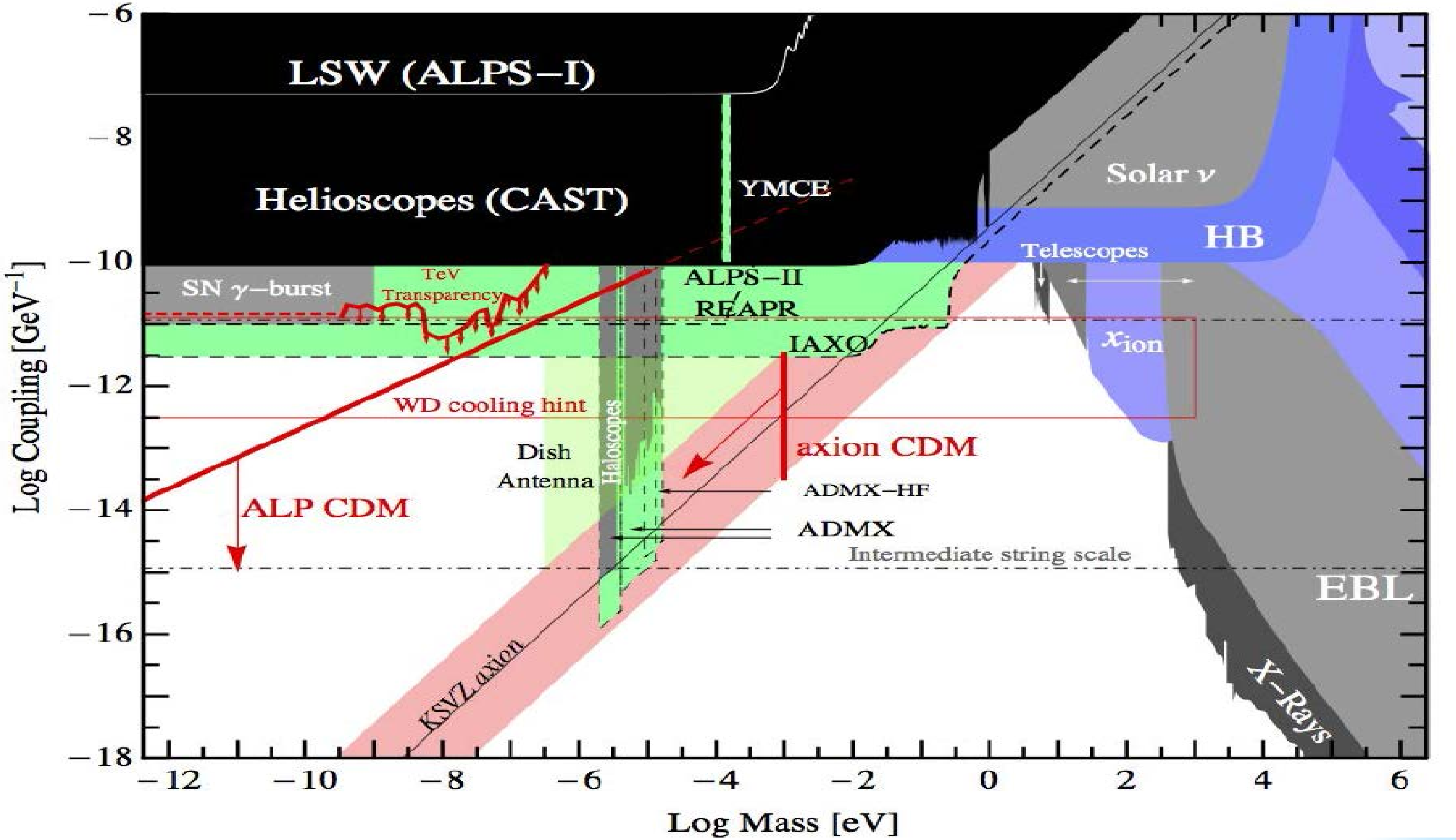
Number of words neutrino and axion in a title of papers in arXiv.org during last 5 years:

	2016 г.	2017 г.	2018 г.	2019 г.	2020 г.
Neutrino	830	782	760	953	820
Axion	148	200	232	264	333
A / N	0.18	0.26	0.31	0.28	0.41

Allowed and forbidden regions of m_A (PDG2018)



Axions + ALPs



Аксионы: CP-проблема + темная материя. ALPs – Axion like particles: Аномальная прозрачность + динамика звезд различных типов. Слово axion в названии статей, выложенных в arXive в 2017 г, встречается всего в 3 (760/232) раз реже чем слово neutrino