Поиски аксионов и аксионо-подобных частиц (ALPs)

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Частицы темной материи не содержатся в Стандартной модели (небарионная материя и не легкие нейтрино)

WIMPs: weakly interacting massive particles
Если реализуется суперсимметрия,
легчайшая стабильная суперсимметричная частица
(нейтралино) кандидат на роль частиц ТМ

χ

ρ=0.3 ГэВ/см^3
$\Phi=\rho/m_\chi$ 3×10^7см$^{-2}$с$^{-1}$

WISPs: Axion. Для решения проблемы CP-сохранения в сильных взаимодействиях, КХД СМ должна быть дополнена аксионом, который может составлять ТМ

A, a

Отрицательные результаты LHC и экспериментов по поиску рассеяния частиц темной материи на ядрах смещают интерес от SUSY в сторону моделей с более легкими частицами

Strong CP-problem
(ненаблюдение CP-нарушения в сильных взаимодействиях)

***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.*

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

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

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

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

Present experimental limit on nEDM:

$$|\, d_n \,| < 2.9 \times 10^{-26}\ \boldsymbol{e}\ \text{cm (90\% c.l.)} \Rightarrow \boldsymbol{\Theta < 10^{-10}}$$

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.

Появление аксиона

***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.*

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

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.

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

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

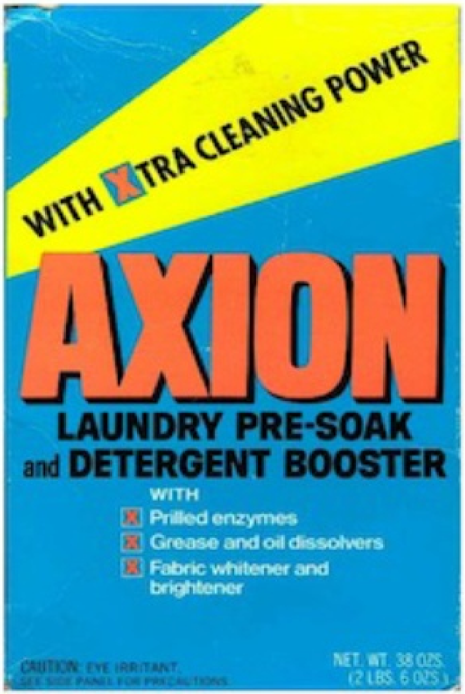
$$g_{Ae} = C_e m / f_A$$

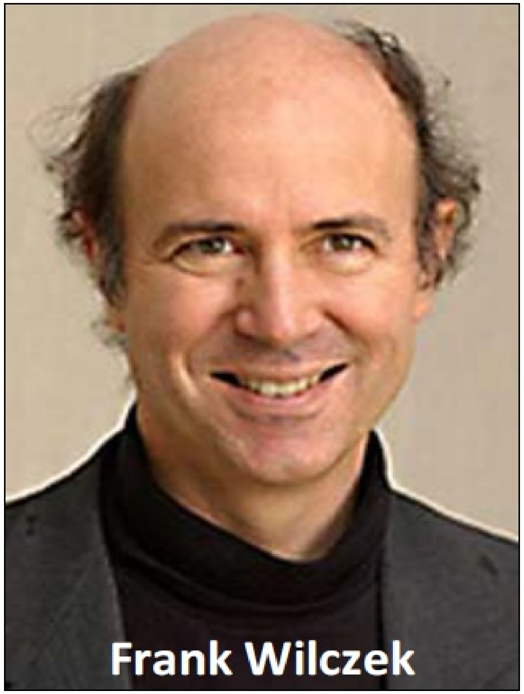
$$g_{A\gamma} = \frac{\alpha}{2\pi f_A}\left(\frac{E}{N} - \frac{2(4+z+w)}{3(1+z+w)}\right) \equiv \frac{\alpha}{2\pi f_A} C_{A\gamma\gamma}$$

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

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 аксион





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

Константы связи

$$m_a = \frac{m_{\pi^0} f_\pi}{f_a}\left(\frac{z}{(1+z+w)(1+z)}\right)^{1/2} \simeq 0.60 \text{ eV}\frac{10^7 \text{ GeV}}{f_a}$$

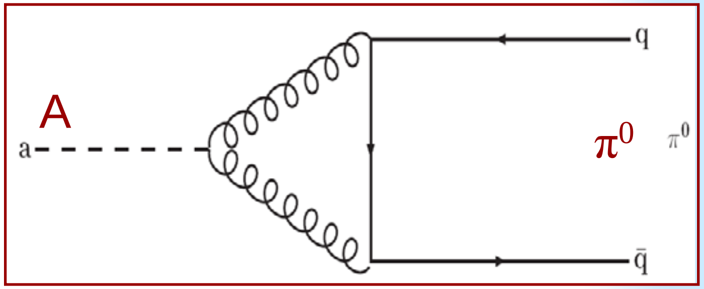
$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu} a$$

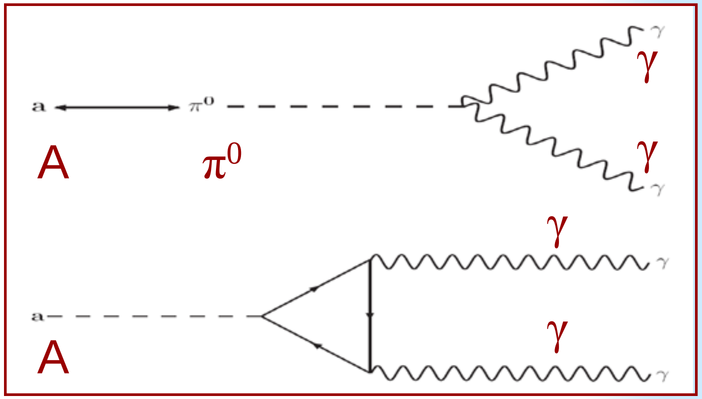
$$g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - \frac{2\,(4+z+w)}{3\,(1+z+w)}\right)$$

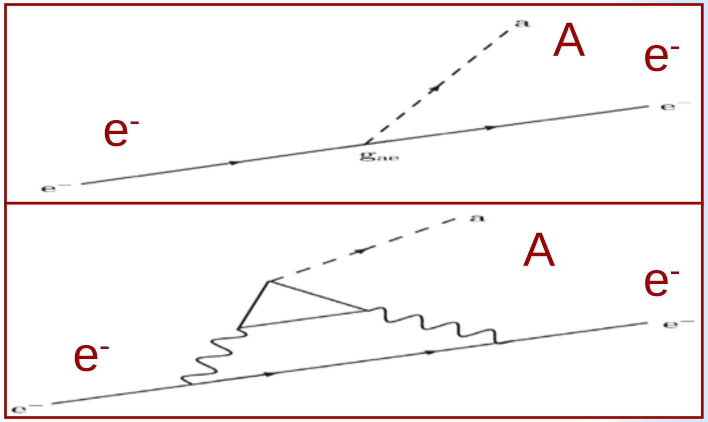
$$g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92 \pm 0.08\right) = \frac{\alpha}{2\pi f_a} C_\gamma$$

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

$$\mathcal{L}_{af} = \frac{g_{af}}{2m_f}\left(\bar{\psi}_f \gamma^\mu \gamma_5 \psi_f\right)\partial_\mu a,$$







PQWW- или стандартный аксион

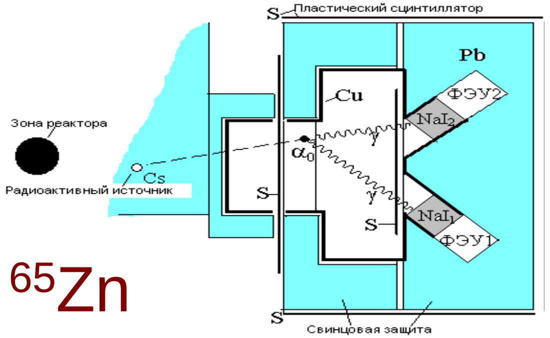
The *original WWPQ axion model contained certain strict predictions for the coupling constants between an axion and photons ($g_{A\gamma}$), electrons (g_{Ae}), and nucleons (g_{AN}) because assumed that f_A is equal to electroweak scale:*

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

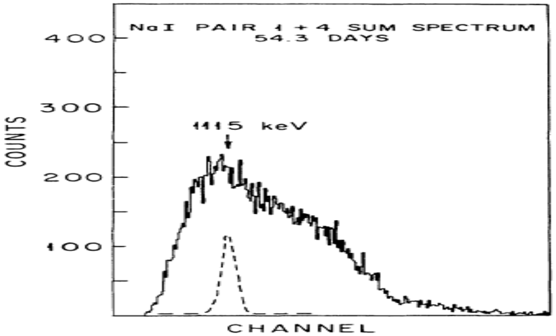
The standard axion mass depends on the number of quark doublets N and unknown parameter X, which is the ratio of two Higgs vacuum expectation values and it should be more:

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

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



$$K^+ \rightarrow a + \pi^+$$
$$J/\psi \rightarrow a + \gamma,$$
$$\Upsilon \rightarrow a + \gamma$$

«Невидимый" аксион

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

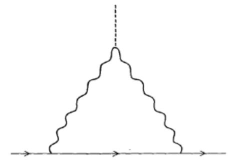
$$g_{Ae} = C_e m / f_A$$

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

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

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

E/N = 3/8 $(C_{A\gamma\gamma} = 0.74)$



KSVZ

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

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

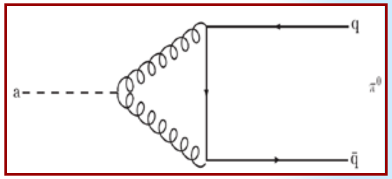
E/N = 0 $(C_{A\gamma\gamma} = -1.92)$

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. The 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}.

Масса невидимого аксиона

The axion mass in both models is given in terms of neutral pion properties and depends on the axion decay constant f_A:

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



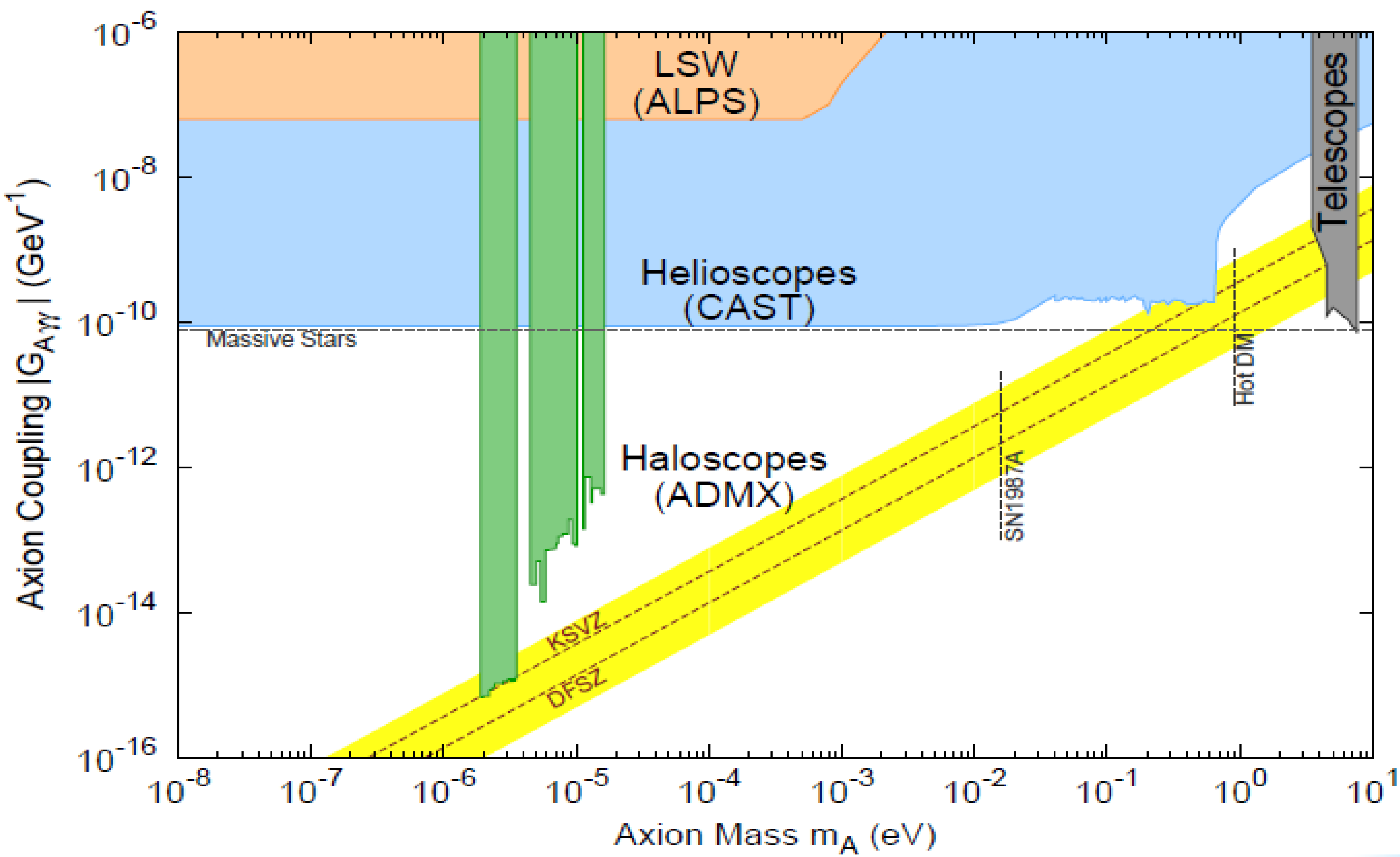
where z and w – mass ratios for light quarks ($z = m_u/m_d \approx 0.56$, $w = m_u/m_s \approx 0.029$), m_π and f_π – mass and decay constant of π-meson.

***The** restrictions on the axion mass appear as a result of the restrictions on the coupling constants $g_{A\gamma}$, g_{Ae} and g_{AN}, which are **significantly model dependent**.*

***The** results from present-day experiments are interpreted within these two most popular axion models. The main experimental efforts are focused on searching for an axion with a mass in the range of **10^{-6} to 10^{-2} eV**. This range is free of astrophysical and cosmological constraints, and relic axions with such mass are considered to be the **most likely candidates for the particles that form dark matter**.*

***D**irect laboratory searches for solar axions with CAST and IAXO helioscopes and relic axions with ADMX haloscope rely on the axion-two-photon vertex, allowing for axion–photon conversion in external electric or magnetic fields. Reactions of a.e. effect in atoms and r.a. by nuclei are induced by g_{Ae} and g_{AN} coupling constants.*

Ограничения на константу связи аксиона с фотоном $g_{A\gamma}$



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.

Астрофизические ограничения

Emission of axions from the Sun

$g_{a\gamma} \lesssim 0.7 \times 10^{-9}\,\mathrm{GeV}^{-1}$ $\qquad g_{ae} < 2.5 \times 10^{-11}$

Helium-Burning Lifetime of stars on the H-branch

$|G_{A\gamma\gamma}| < 6.6 \times 10^{-11}\,\mathrm{GeV}^{-1}$

m_A<0.5 eV (DFSZ)

$|G_{A\gamma\gamma}| = 4.5^{+1.2}_{-1.6} \times 10^{-11}\ \mathrm{GeV}^{-1}$

Helium Ignition in stars on the red-giant branch

$g_{aee} < 3 \times 10^{-13}$

m_A<0.02 eV (DFSZ) b.f. 7 meV

White-Dwarf Cooling

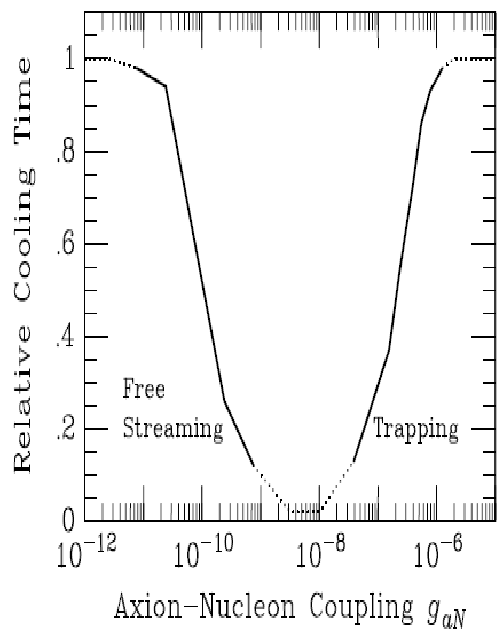
$g_{aee} < 1.3 \times 10^{-13}$

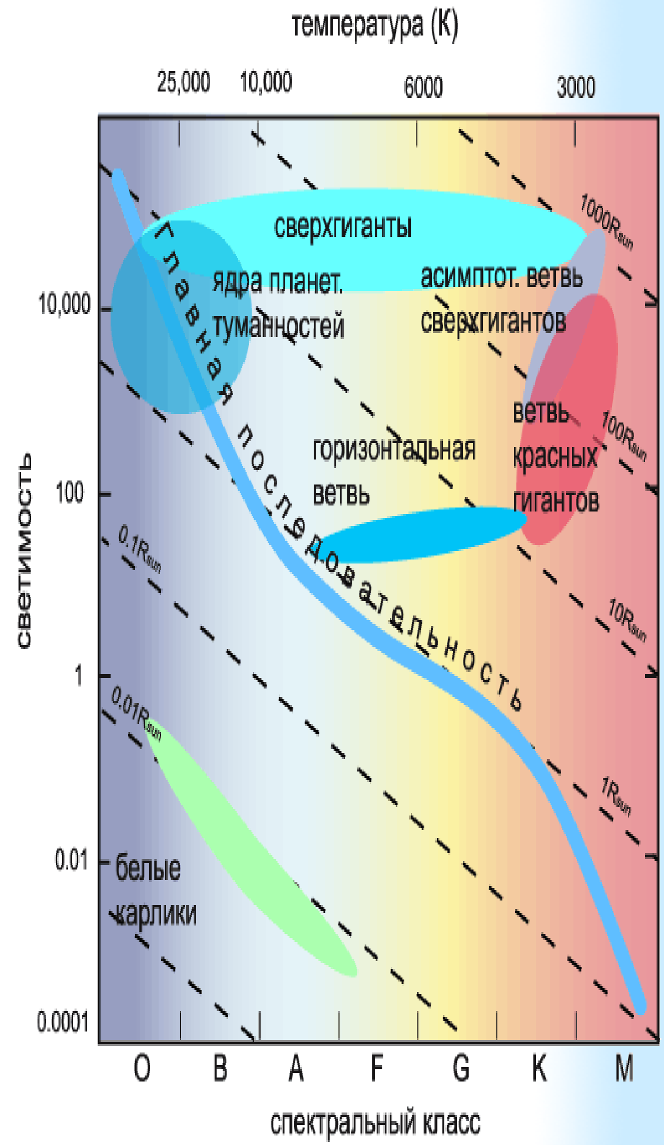
$2.5\ \mathrm{meV} \lesssim m_A \cos^2\beta' \lesssim 7.5\ \mathrm{meV}$

Supernova 1987A

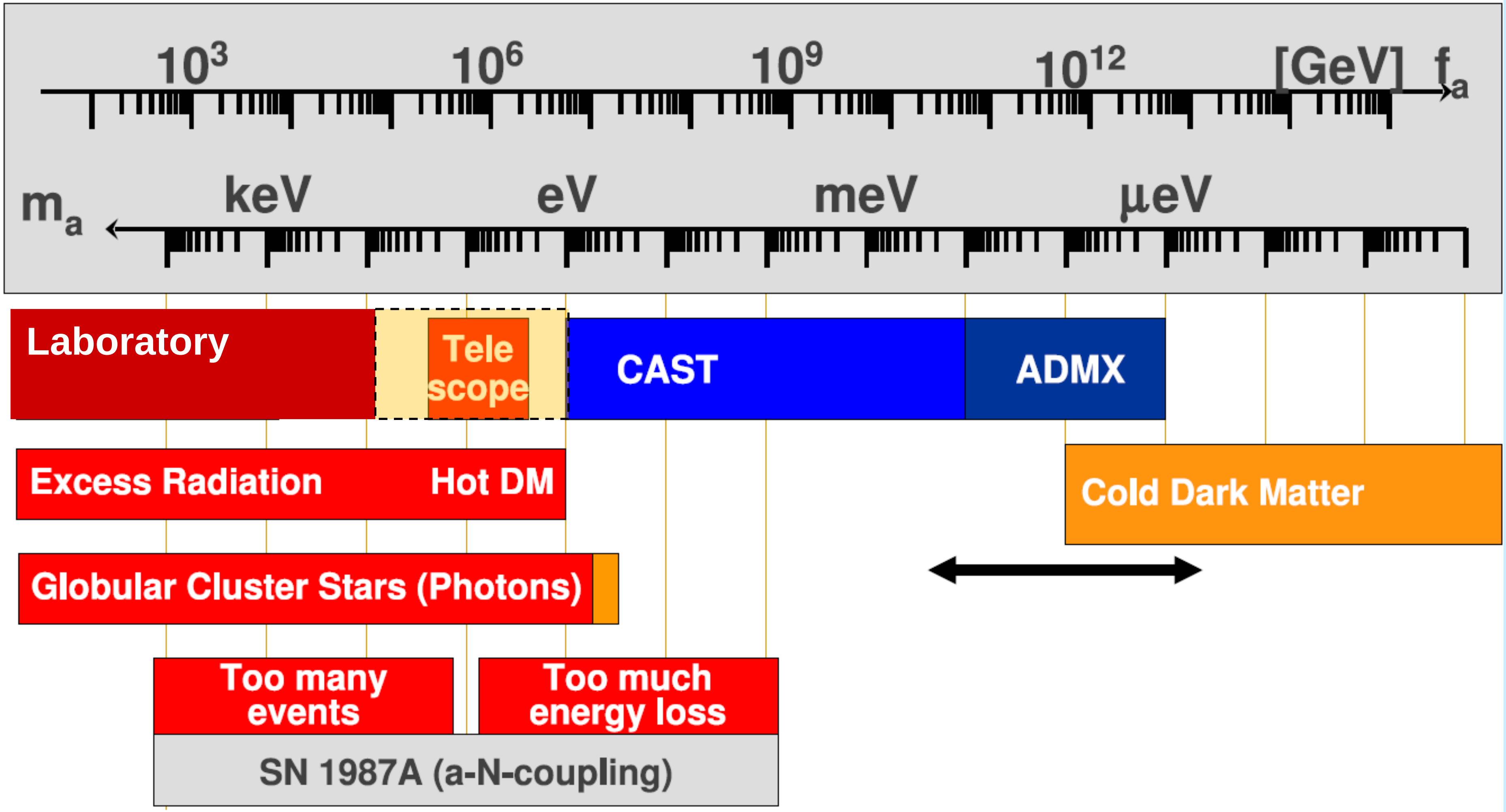
$f_a \gtrsim 4 \times 10^8\ \mathrm{GeV}$

$m_A \lesssim 16\ \mathrm{meV}$



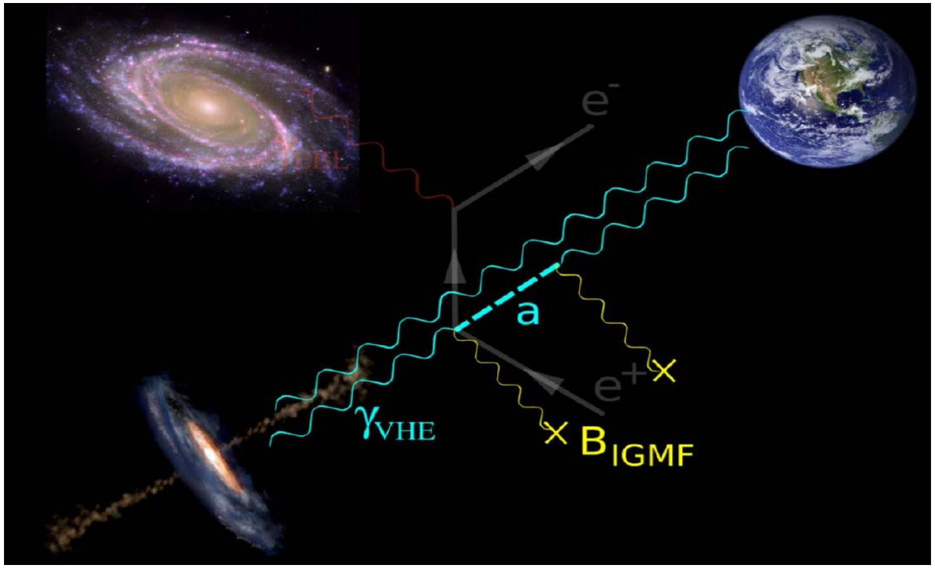


Разрешенные и запрещенные области масс аксиона

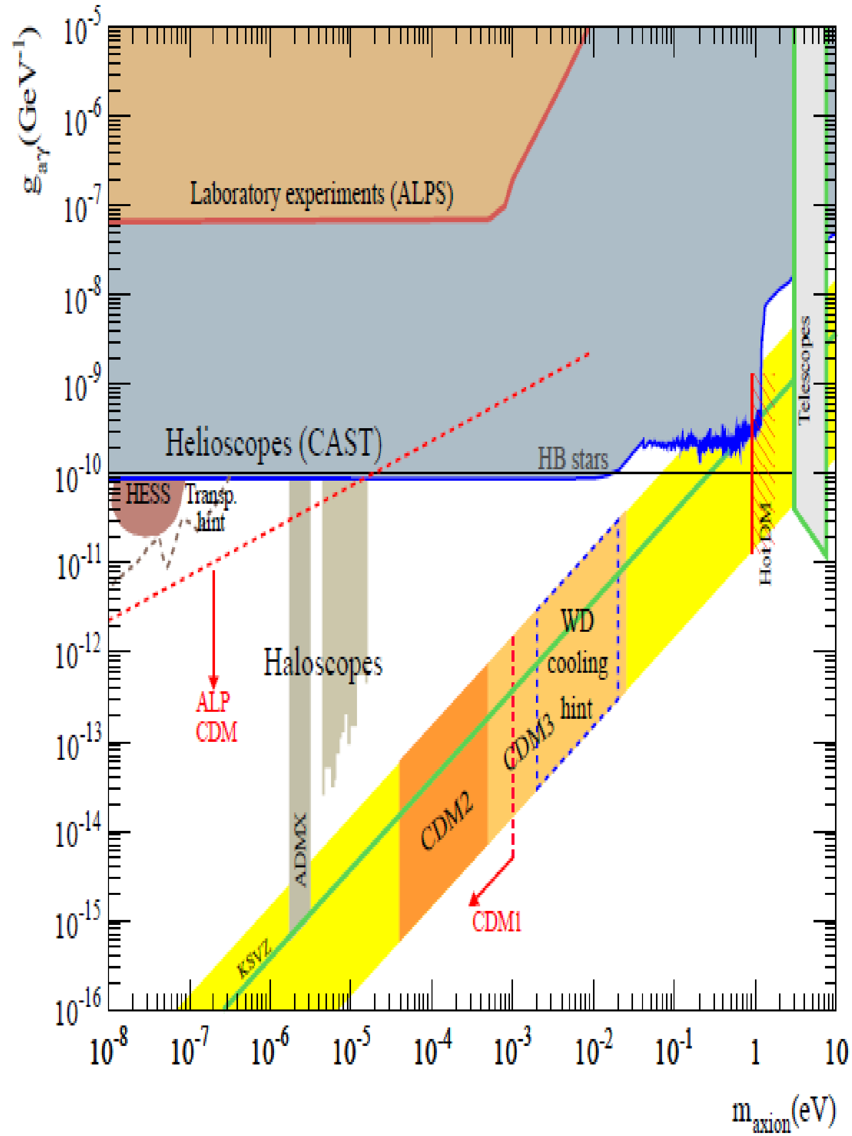


Астрофизические указания на аксионы и ALPs

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}.

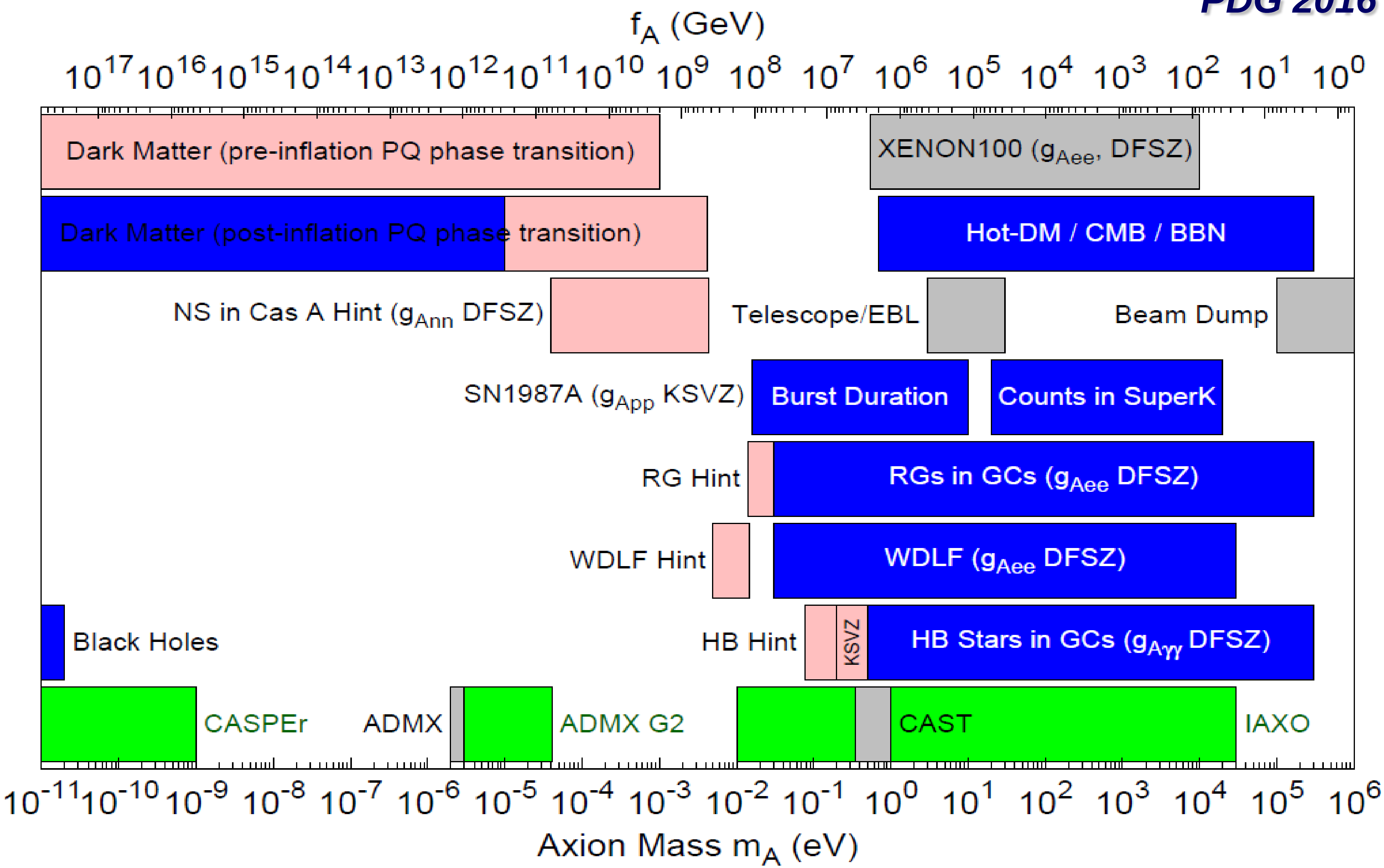


2. The anomalous cooling rate of white dwarfs. These arguments were used long ago to constrain gae and they have been cross-checked and improved over the years. Nowadays, there is common agreement on an upper limit $g_{Ae} < 3 \times 10^{-13}$. However, recent works are based on such a well populated luminosity function and well studied WD cooling models that are able to claim that a small amount of axion energy loss is actually favored by data . This claim corresponds to $g_{Ae} = (1\text{-}2)10^{-13}$.



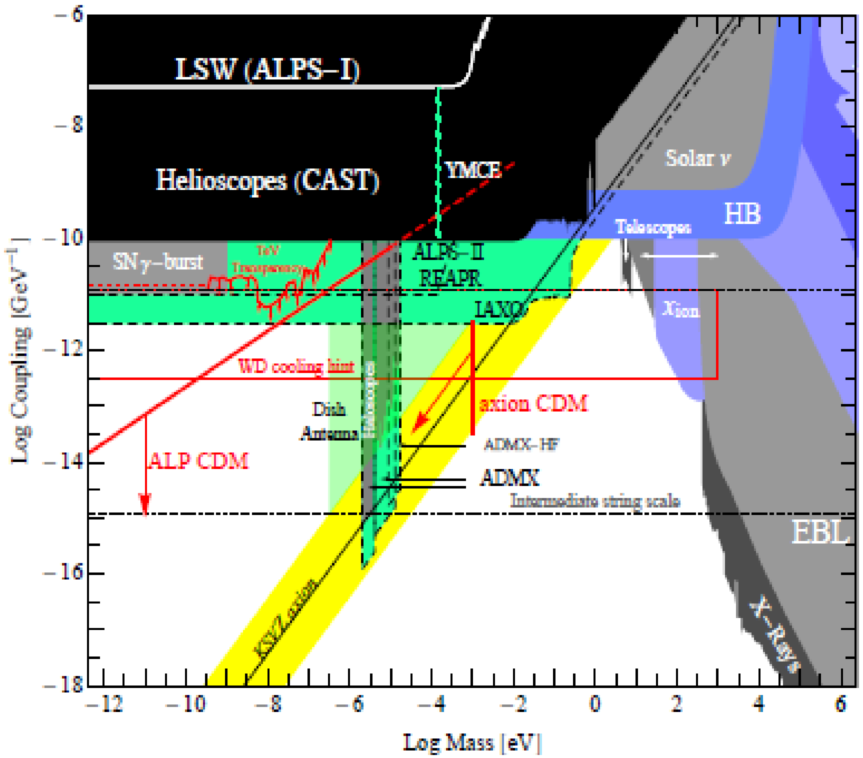
Исключенные области и указания для m_A и f_A

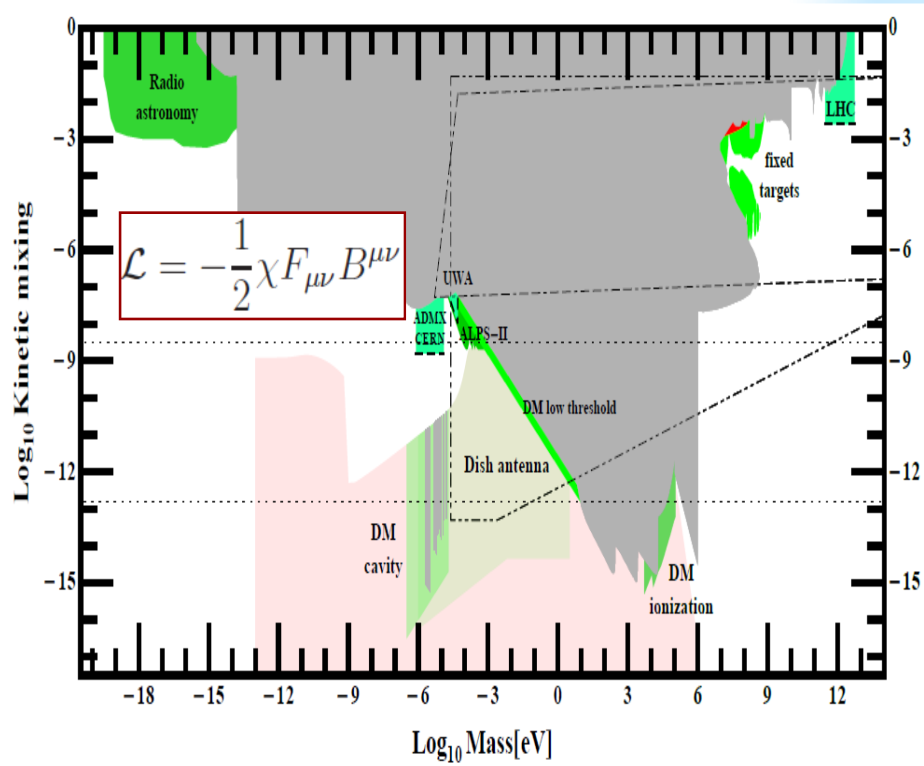
PDG 2016



WISPs = ALPs + Hidden sector

D. Hooper, T.M.P. Tait, PRD80, 055028 (2009); S. Andreas et al., JHEP 1008:003, (2010). K. Baker et al., arXiv:1306.2841; J. Jaeckel, Frascati Phys. Ser. 56, 172 (2013).





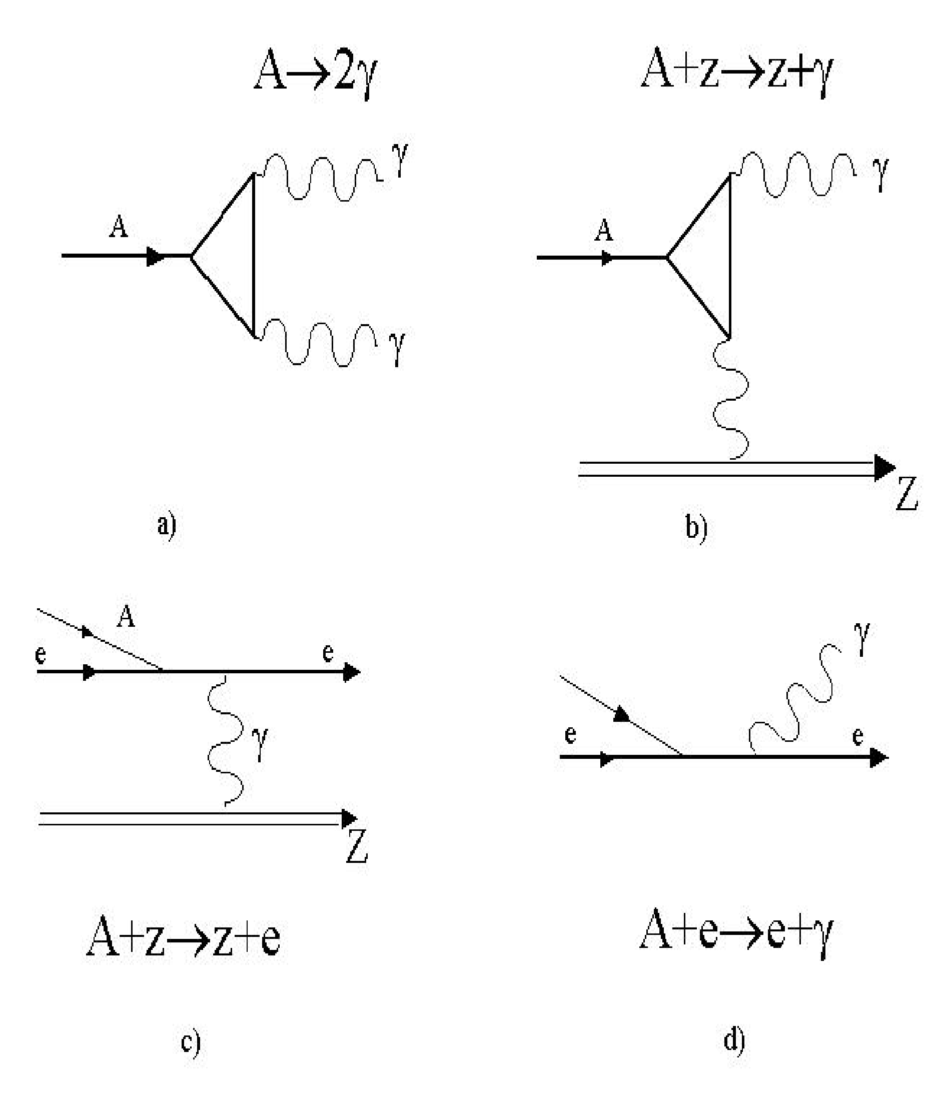
Помимо WIMPs есть целый класс кандидатов на ТМ = WISP (Slim, Sub-eV), куда входит и аксион.

*1. **ALPs** – частицы с нулевым спином и двухфотонной вершиной, как у аксиона (но не с кварками).и отсутствует связь констант связи и массы.*

*2. **Hidden (dark) photons**, смешаны с фотонами $(\chi/2)F_{\mu\nu}X^{\mu\nu}$, и минизаряженные частицы, взаимодействуют с частицами СМ через обмен очень тяжелой частицей. Аксионные эксперименты чувствительны к темным фотона*

3. Существуют модели аксиона с массой около 1 МэВ, основанные на концепции зеркального мира и SUSY, решающие проблему и незапрещенные лабораторными экспериментами и астрофизическими данными.

Взаимодействия аксиона



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***

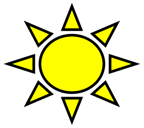
Источники и детекторы аксионов

Источники аксионов:

1. Солнце 2. Реактор 3. Искусственные р.а. источники (SOX) 4. Реликтовые

Эксперименты с искусственным образованием аксионов:

Реакторы, ускорители, р/а источники, лазеры "Light shining through walls"



Поиск солнечных аксионов

Конверсия в фотон: Солнечные **гелиоскопы**: CAST, IAXO:

в поле кристалла:Solax, Cosme и DAMA

Резонансное поглощение атомными ядрами: 57Fe, 169Tm, 7Li, 83Kr

Аксиоэлектрический эффект: Si, Ge, Xe, Bi

С.С. BOREXINO, BGO

Поиск реликтовых аксионов

Конверсия в фотон: **галоскопы**: ADMX, WISPDMX, Carrack (RAs),

А.Е. в *Si-, Ge-, Xe-, Bi-* (Xenon, XMASS, Edelweiss)

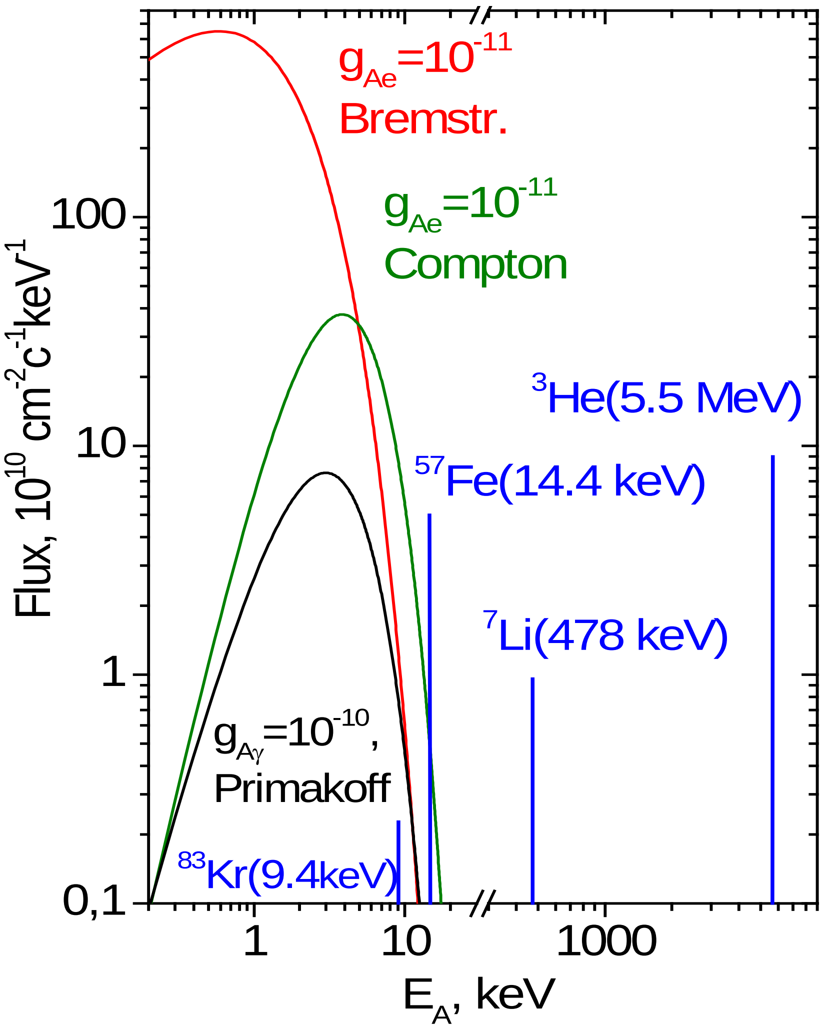
Классификация экспериментов

Detection

Creation

	$g_{A\gamma}$	g_{AN}	g_{Ae}
$g_{A\gamma}$	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**
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 **PNPI(SAXS), 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**

Спектры солнечных аксионов vs $g_{A\gamma}$, g_{Ae} и g_{AN}

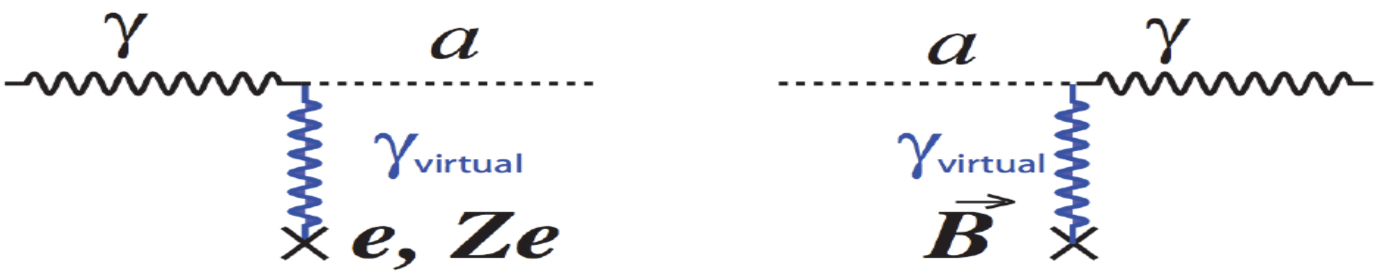


The main sources of solar axions:

1. Reactions of main solar chain. *The most intensive fluxes are expected from M1-transitions in ^{7}Li and ^{3}He nuclei* (**g_{AN}**):
$^{7}Be + e^{-} \rightarrow {}^{7}Li^{*} + \gamma$; $^{7}Li^{*} \rightarrow {}^{7}Li + A$ (478 кэВ)
***p* + *d* → ^{3}He + A (5.5 МэВ).**
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*

If axion does exist, the Sun should be an intense source of axions. There are 6 main ***axion formation processes*** inside the stars:

Конверсия в лабораторном магнитном поле



$$P(a \to \gamma) \simeq \frac{(2 g_{a\gamma} B \omega)^2}{m_a^4} \sin^2\left(\frac{m_a^2 L}{4\omega}\right)$$

$$m_a < \sqrt{\frac{4\pi E_a}{L}}$$

$$= \left(\frac{B g_{a\gamma}}{2}\right)^2 \frac{1}{q^2 + \Gamma^2/4}\left[1 + e^{-\Gamma L} - 2e^{-\Gamma L/2}\cos(qL)\right]$$

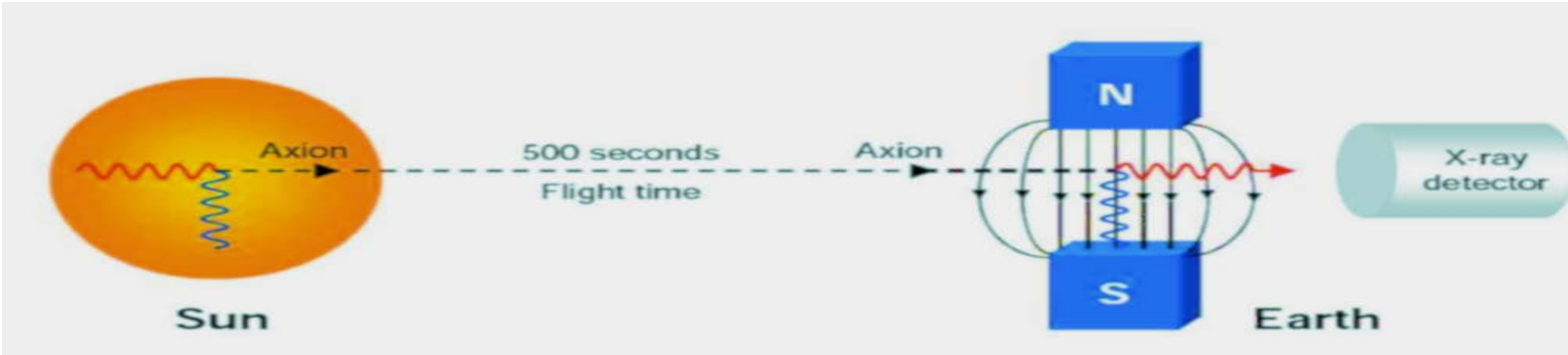
$$L_c = \frac{\lambda}{2(1-\beta_a)} \cong \frac{2\pi\hbar c \cdot \hbar\omega}{m_a^2 c^4}$$

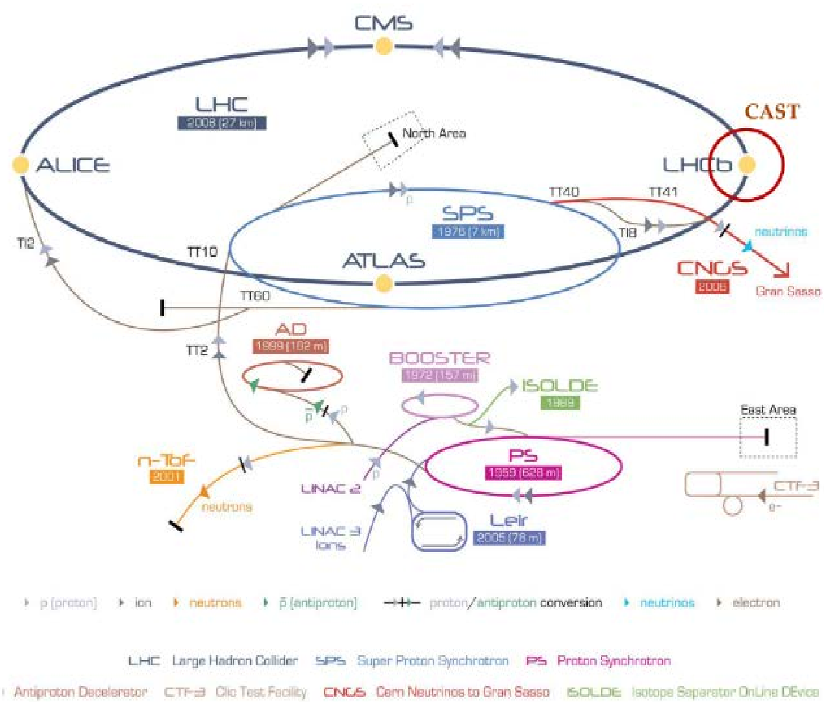
$$\Psi_a(\vec{r},t) \Rightarrow \left\{c_a \Psi_a(\vec{r},t) + c_\gamma \Psi_\gamma(\vec{r},t)\right\}$$

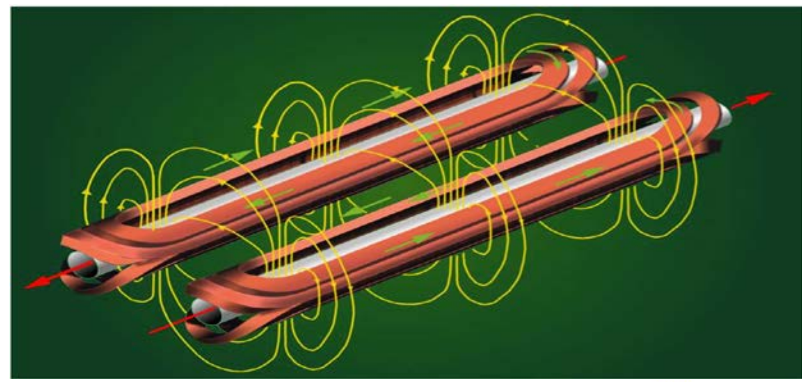
$$(c - v_a)t \equiv \lambda/2 = (1-\beta_a)ct$$

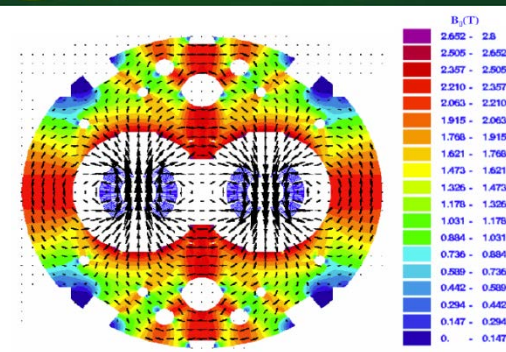
In a laboratory magnetic field, solar axions can be converted into real photons via the inverse Primakoff effect. The virtual photon is hereby provided by the magnetic field. The conversion process can be treated in a similar way as neutrino oscillations. Although the photon has spin 1 and the axion is a spin-zero particle, they can mix provided that the mixing agent, which can be an external magnetic or electric field, matches the missing quantum numbers. The conversion from a free photon into a spin-zero axion requires a change in the azimuthal quantum number of angular momentum (Jz). For the photon Jz = ±1, while for the axion Jz = 0 holds. A longitudinal field, i.e. a field providing an azimuthal symmetry, cannot allow for these transitions since it cannot change Jz. A transverse field however allows for mixing of a photon with an axion.

CAST - CERN Axion Solar Telescope

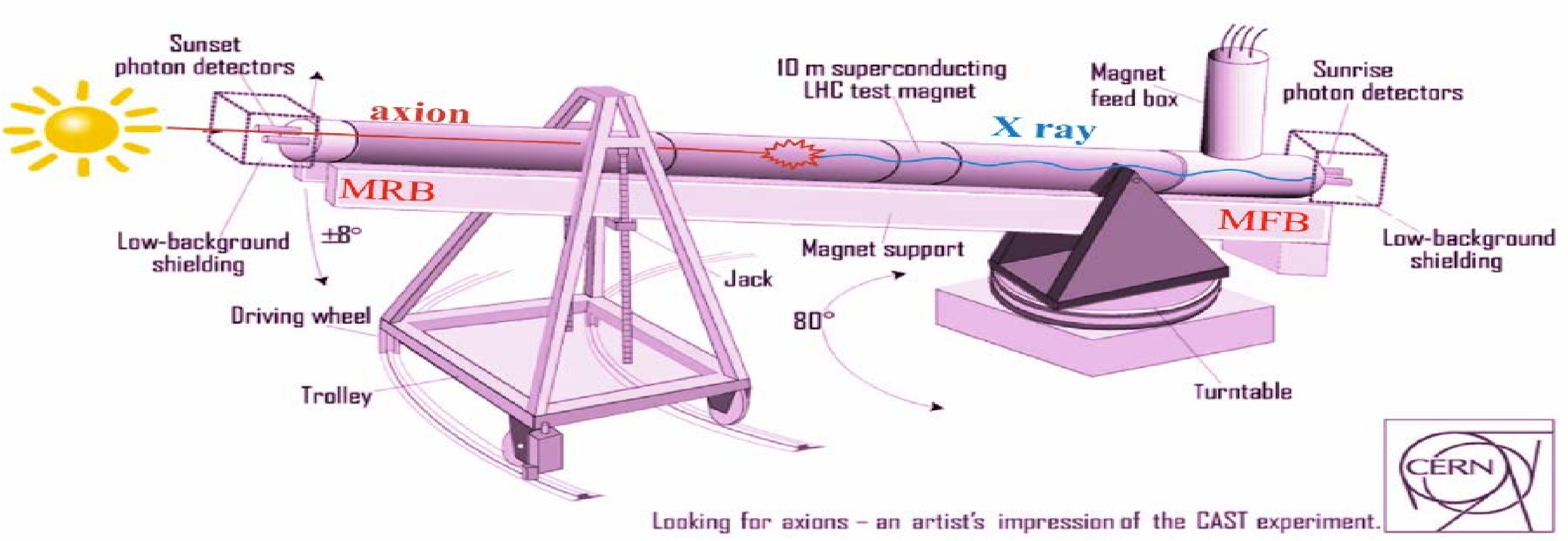




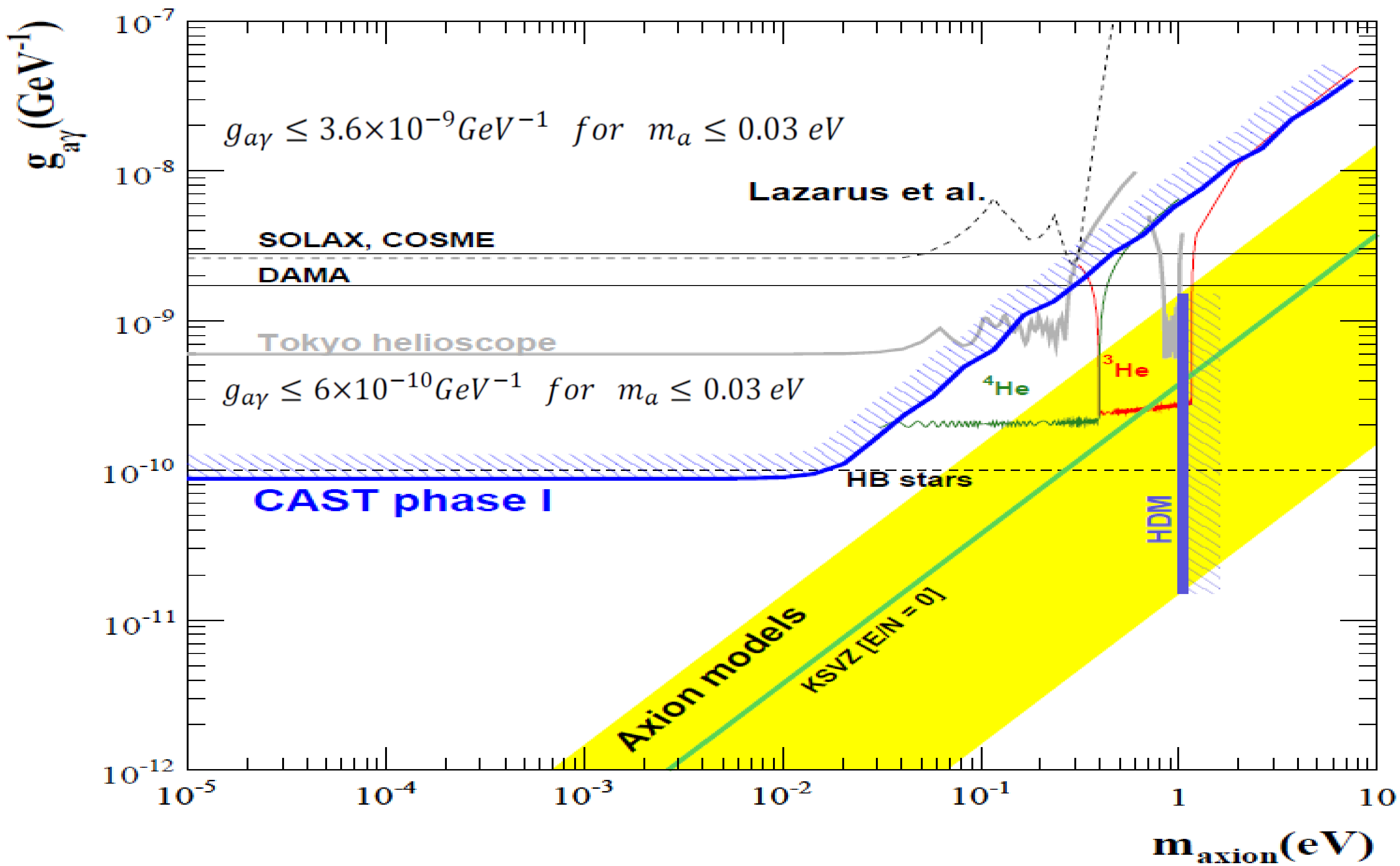




CAST - CERN Axion Solar Telescope

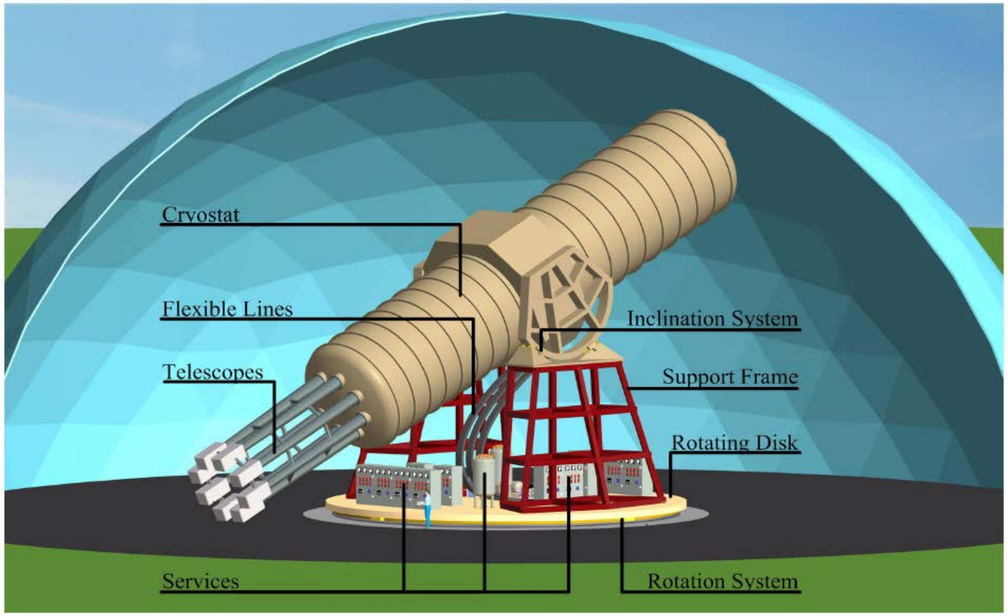


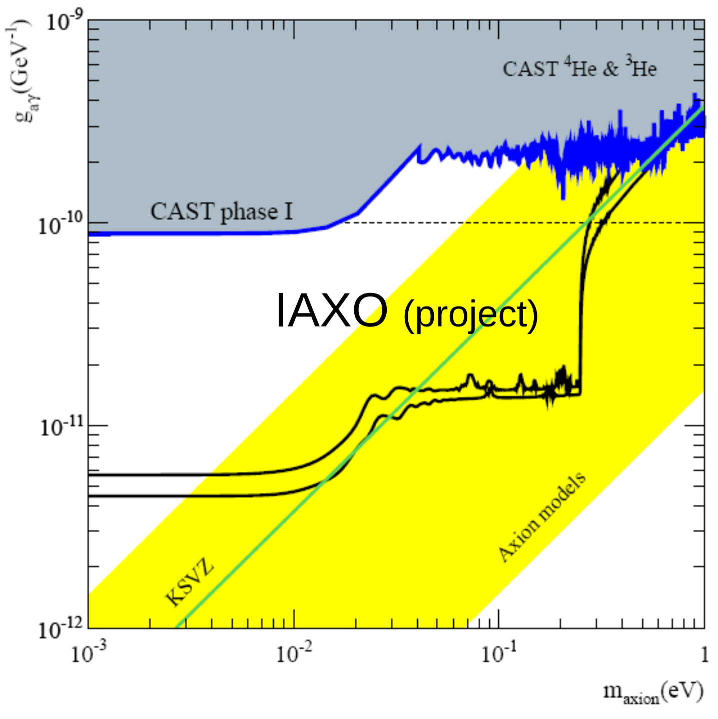
Результаты CAST

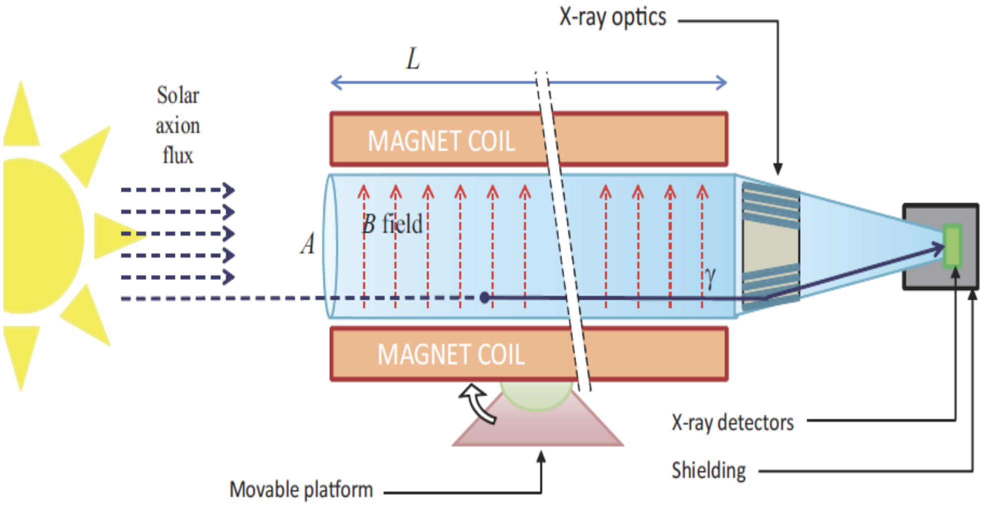


Year	Phase	Sensitivity Range
2000 – 2003	Commissioning	–
2003 – 2004	Phase I (Vacuum)	< 0.02 eV
2006 – 2007	Phase II (He^4)	0.02 eV – 0.4 eV
2008 – 2011	Phase II (He^3)	0.4 eV – 1.15 eV
2012	Phase II (He^4 - revisit)	0.02 eV – 0.4 eV

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

ПИЯФ в коллаборации IAXO

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ScienceDirect
Physics Procedia 61 (2015) 193 – 200
Physics Procedia

The next generation of axion helioscopes: The International Axion Observatory (IAXO)

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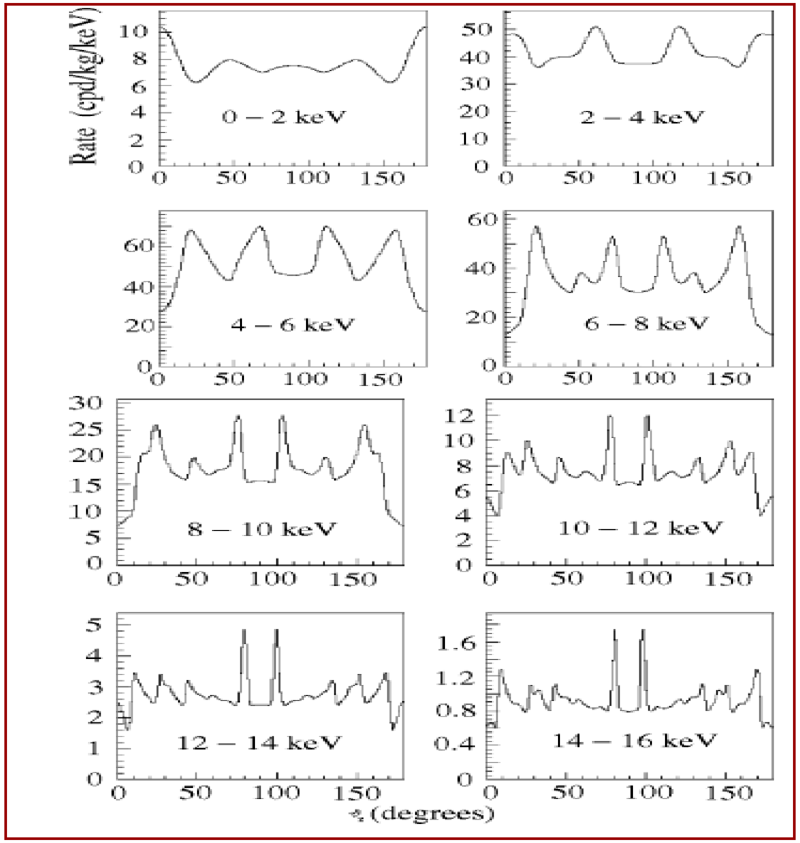
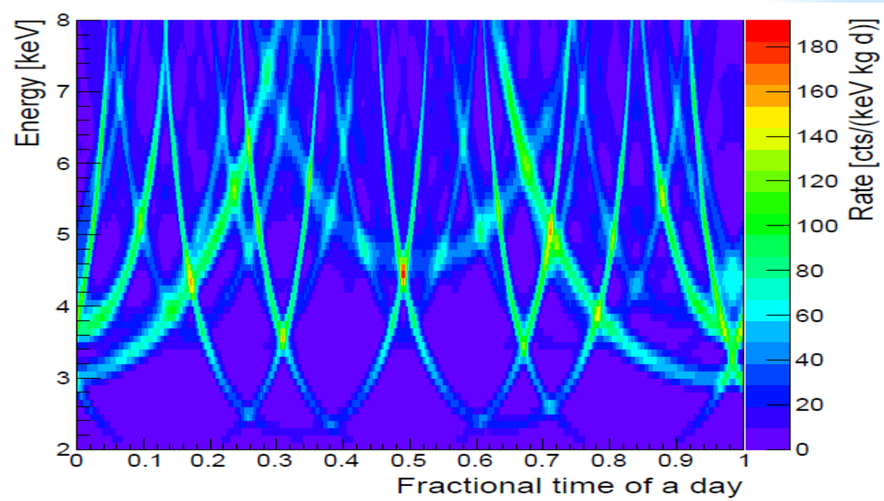
2016 –
40 институтов

ПИЯФ

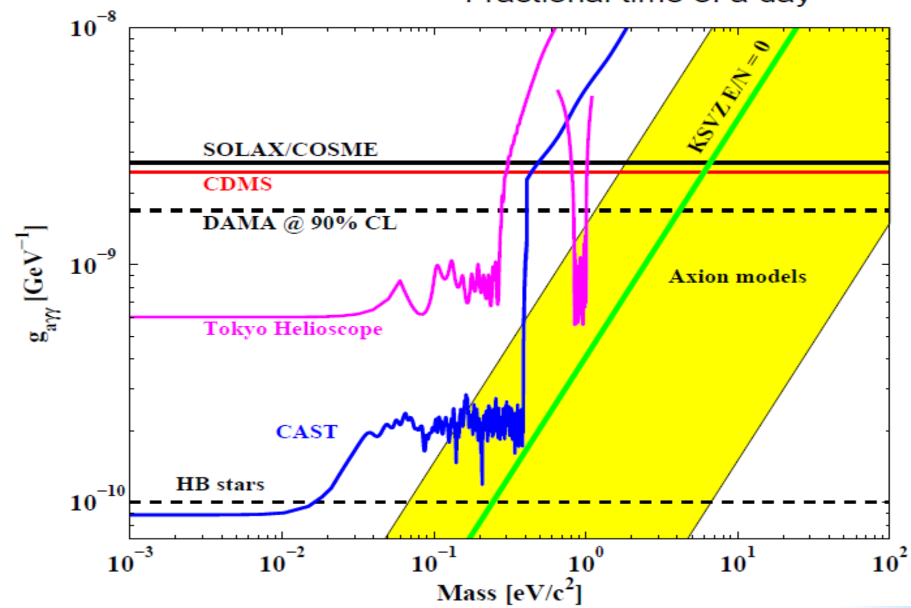
ИЯИ

Bragg diffraction experiments



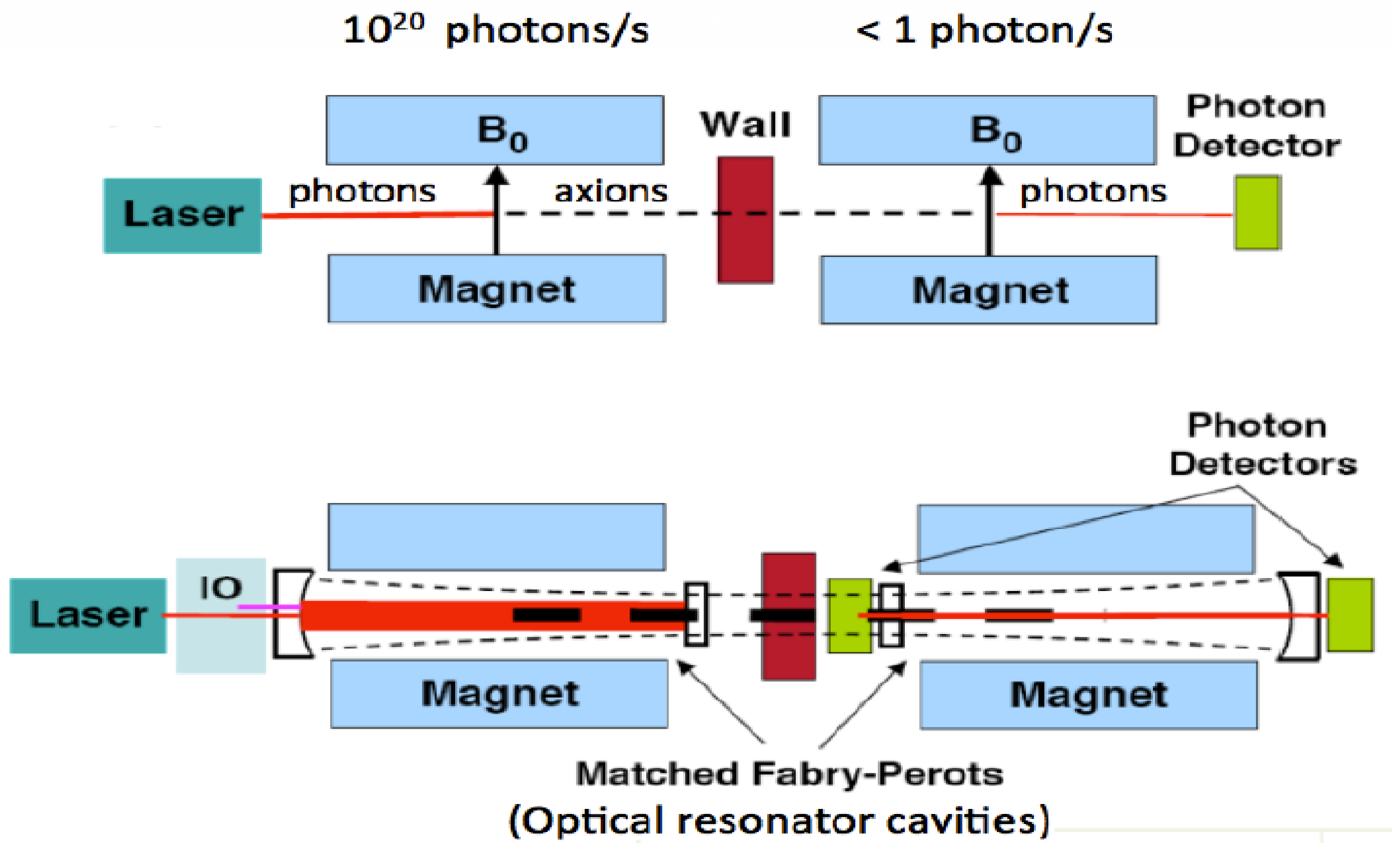


Experiment	Exposure kg d	$g_{a\gamma\gamma}$ upper limit $\times 10^{-9}$ GeV^{-1}
SOLAX [23]	708	2.7 (95% CL)
DAMA [27]	53437	1.7 (90% CL)
COSME [24]	72.7	2.78 (95% CL)
CDMS [25]	443.2	2.4 (95% CL)
EDELWEISS [26]	448	2.15 (95% CL)



Solax $g_{A\gamma} \leq 2.7\times10^{-9}$ GeV^{-1} , Cosme $g_{A\gamma} \leq 2.8\times10^{-9}$ GeV^{-1}, DAMA (NaI) $g_{A\gamma} \leq 1.7\times10^{-9}$ GeV^{-1}

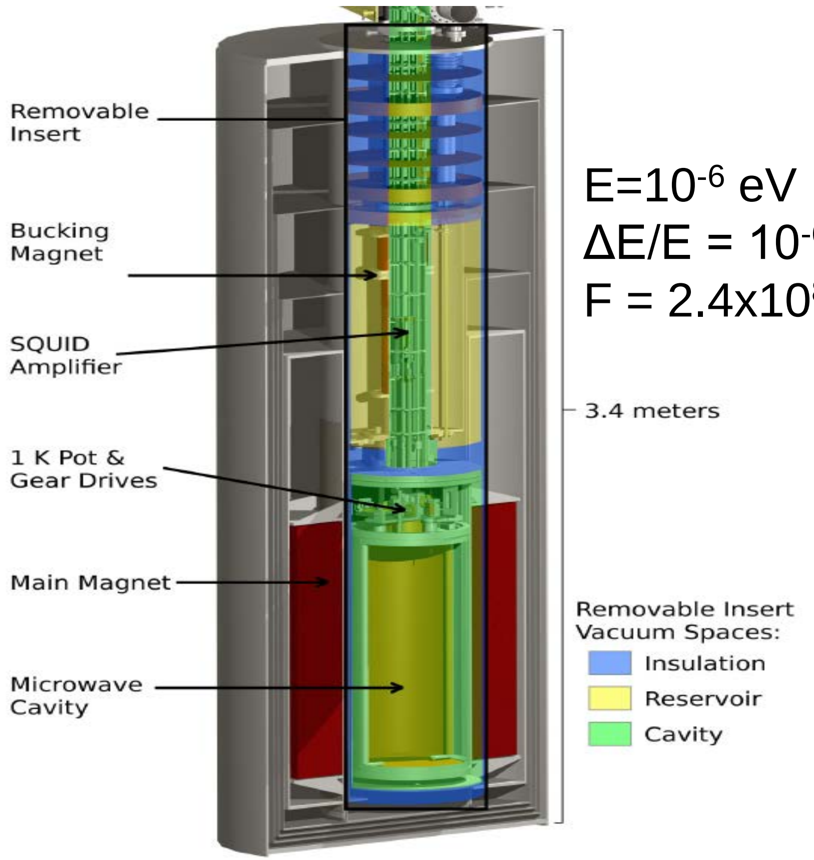
"Shining light through the wall" or "Photon regeneration"



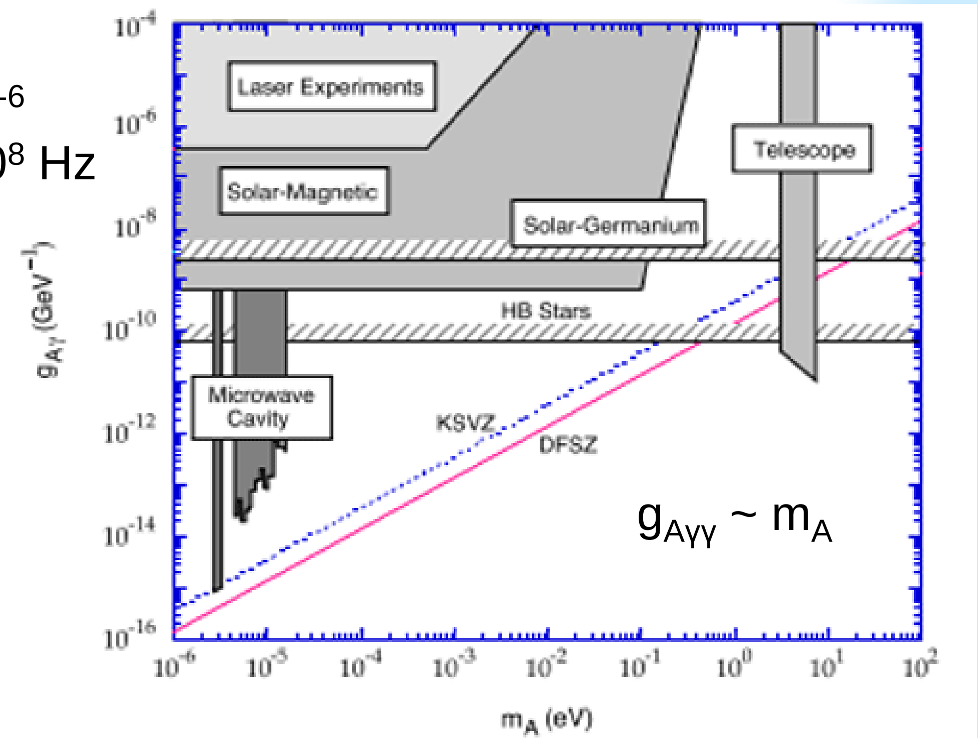
ALPs at DESY using a HERA dipole magnet, Gammev at Fermilab using a Tevatron Magnet, and OSQAR experiment at CERN using a LHC superconductive dipole magnet. The length of magnets is planned to increase up to 100 m. + Polarisation experiments,

Поиск реликтовых аксионов A→γ : ADMX

$$P_{\rm out} \propto G\,Q\,V\,|\mathbf{B}|^2$$



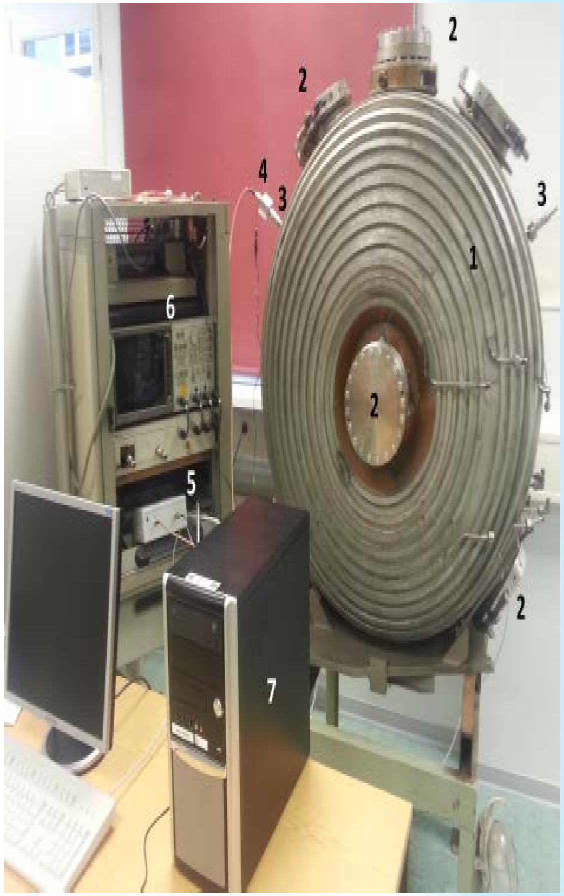
E=10^{-6} eV
ΔE/E = 10^{-6}
F = 2.4×10^{8} Hz



*ADMX - microwave chamber 1 m in length and a diameter of 0.5 m 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. **Un**til 2017 ADMX will test region (3-40) x10^{-6} eV at the level predicted by KSVZ-DFSZ models. It is a small part of wide 10^{-6}-10^{-2} region. Reactions of a.e. effect in atoms and r. a. by nuclei can be induced by the gAe and gAN couplings.*

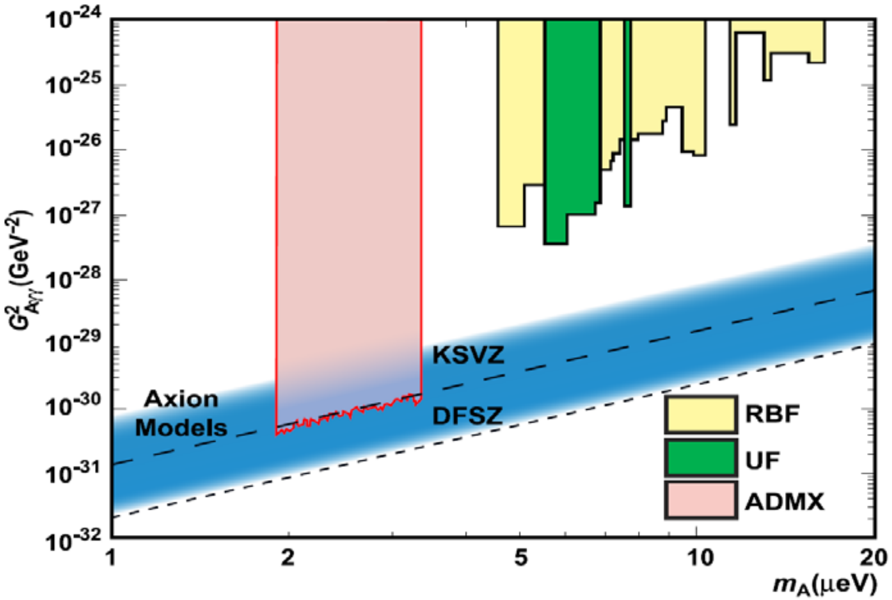
$$P = 3.17\times10^{-21}\ \text{Watts}\left(\frac{V}{200\ \text{l}}\right)\left(\frac{B}{8\ \text{T}}\right)^2\left(\frac{f_{nlm}}{.5}\right)\left(\frac{\rho_a}{0.3\frac{\text{GeV}}{\text{cc}}}\right)\left(\frac{g_\gamma}{0.97}\right)^2\left(\frac{Q}{100000}\right)\left(\frac{\nu_a}{750\ \text{MHz}}\right)$$

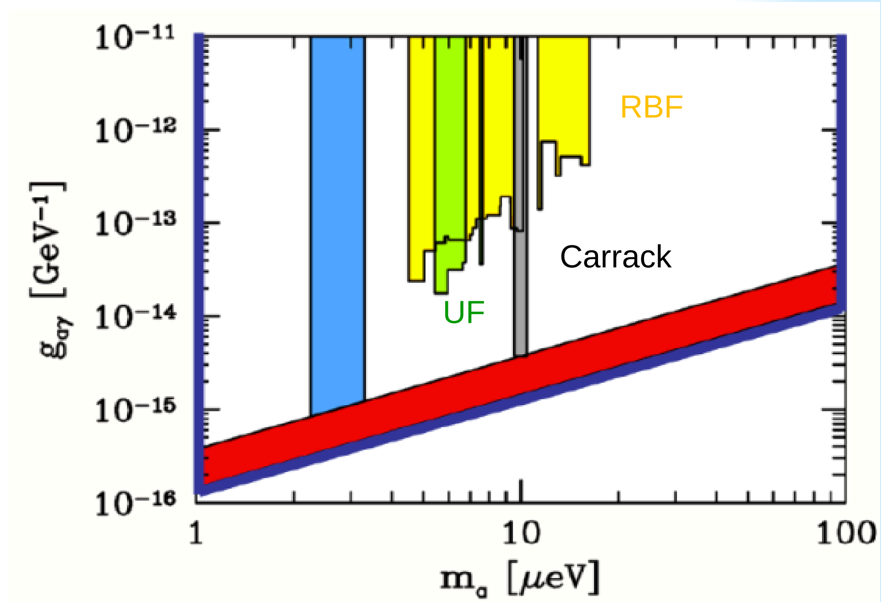
Резонансные камеры ADMX, ADMXHF и WISPDMX

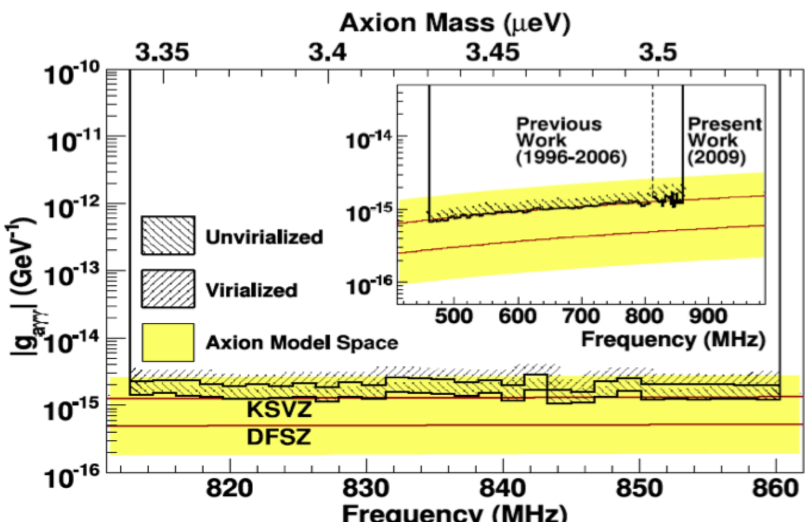


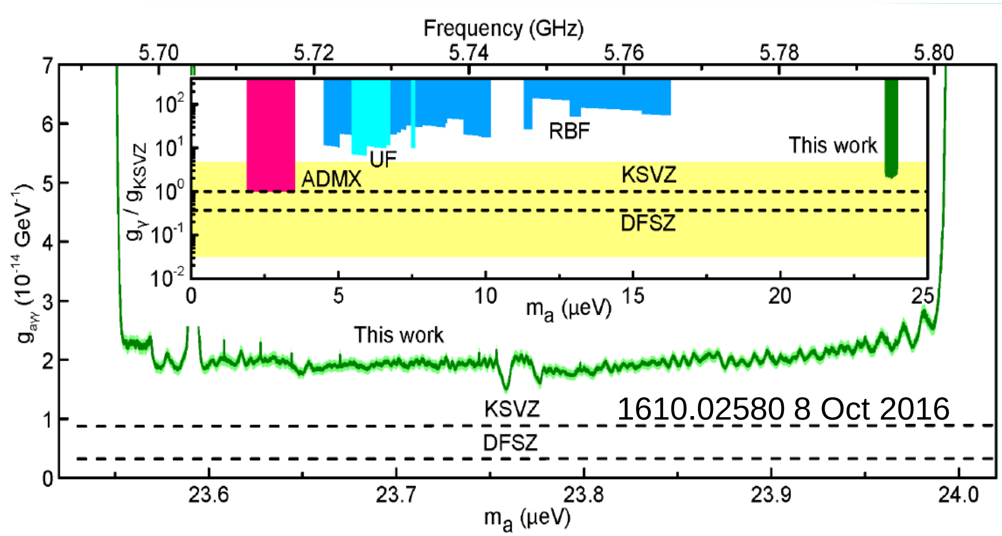
*At frequencies below 1 GHz the ADMX experiment employed the haloscope approach to probe the axion/(ALP, HP) dark matter in the 460-860 MHz **(1.9-3.6) µeV** range. The high frequency extension ADMX-HF is planned for the 4-40 GHz **(16-160) µeV** range. The WISP Dark Matter eXperiment extends the haloscope searches to particles masses below1.9 µeV, aiming to cover the range 200-600 MHz (**0.8- 2.5) µeV.***

Результаты ADMX, ADMXHF и WISPDMX

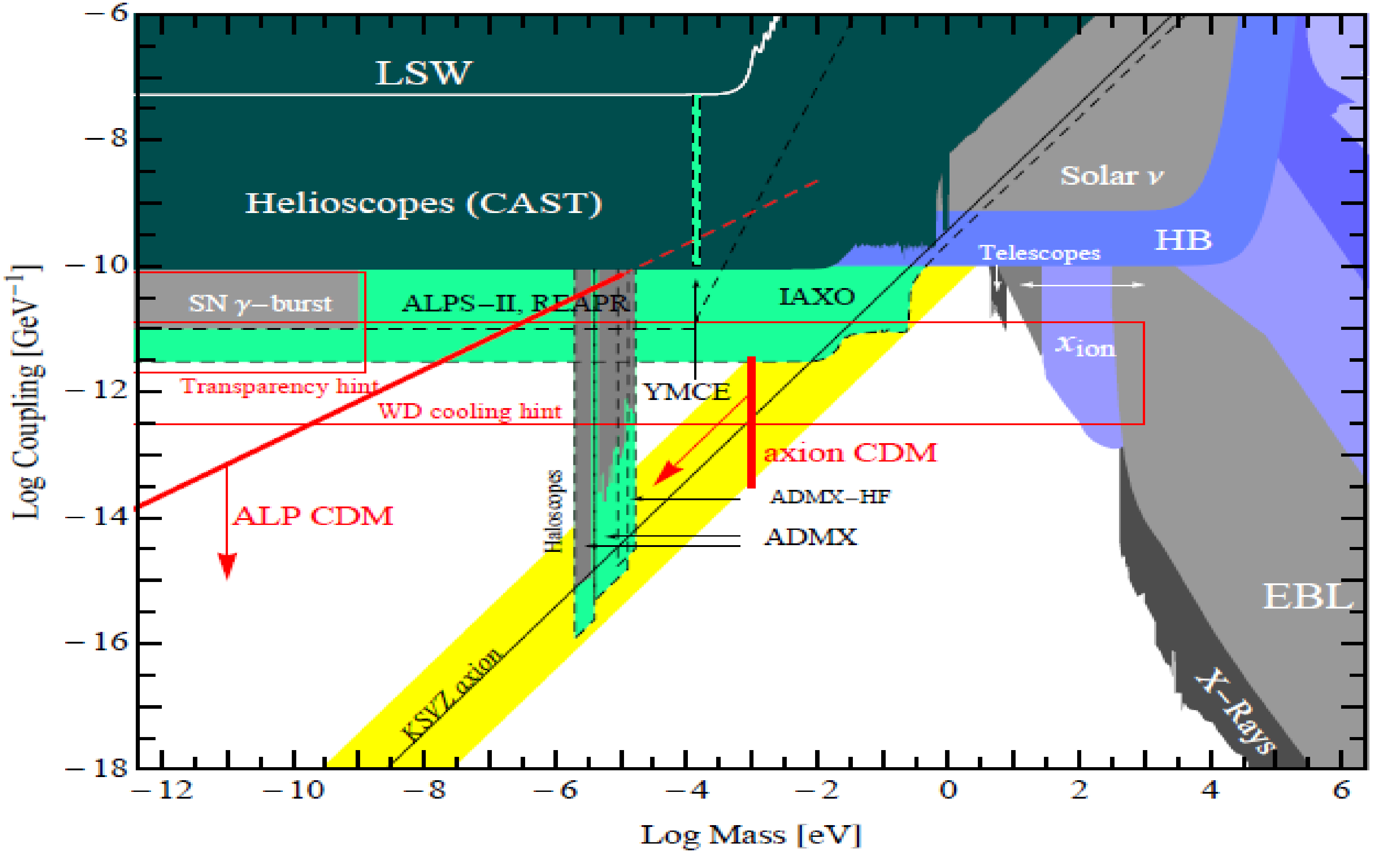






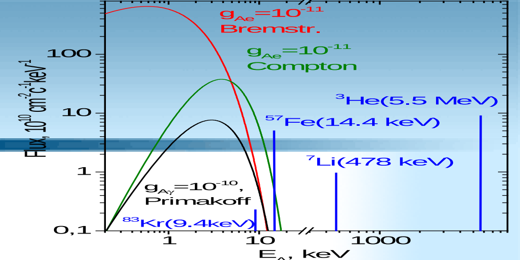


Ограничения, указания и неоцененные области



Constrains from astronomical observations (gray) or from astrophysical or cosmological arguments (blue), hints for axions and axion-like particles from astrophysics (red)and sensitivity of planned experiments (light green). The large region of mA and gAɣ is free from estimates.

Работы ПИЯФ+Borexino



Detection

Creation

	$g_{A\gamma}$	g_{AN}	g_{Ae}
$g_{A\gamma}$	Axion-photon conversion in magnetic field **IAXO, CAST,** ,	Resonant absorption by nuclei **^{169}Tm, ≤ 190 eV** **^{83}Kr,**	Axioelectric effect in atoms
g_{AN}	Primakoff conversion axion decays **7Li-axions,** **3He-axions** **BOREXINO**	Resonant absorption by nuclei **^{6}Li, ≤ 16 keV (478)** **^{57}Fe, ≤ 145 eV (14.4)** **^{83}Kr ≤ 100 eV (9.4)**	Axioelectric effect in atoms, axion-compton conversion **BGO, Bi, ≤** **BOREXINO**
g_{Ae}	Axion-photon conversion in magnetic field **IAXO, CAST,**	Resonant absorption by nuclei **^{169}Tm, ≤ 105 eV DFSZ** **^{169}Tm, ≤ 1.3 keV KSVZ** **^{83}Kr,**	Axioelectric effect in atoms **Si, ≤ 7.9 eV DFSZ** **Si, ≤ 1.4 keV KSVZ** **^{83}Kr,**

Аксиоэлектрический эффект в атомах и резонансное поглощение ядрами

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}:

$$\sigma_{abs}(E_A) = \sigma_{pe}(E_A)\frac{g_{Ae}^2}{\beta}\frac{3E_A^2}{4\pi\alpha}\left(1-\frac{\beta}{3}\right)$$

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

Сечение аксиоэлектрического эффекта: 2 случая

$$\sigma_{Ae} = 2(Z\alpha m)^5 \frac{g_{Ae}^2}{m^2}\frac{p_e}{p_A}\left\{\frac{4E_A(E_A^2+m_A^2)}{(p_A^2-p_e^2)^4} - \frac{2E_A}{(p_A^2-p_e^2)^3} - \frac{64}{3}p_e^2 p_A^2 m \frac{m_A^2}{(p_A^2-p_e^2)^6} - \frac{16m_A^2 p_A^2 E_e}{(p_A^2-p_e^2)^5} - \frac{E_A}{p_e p_A}\frac{1}{(p_A^2-p_e^2)^2}\ln\frac{p_e+p_A}{p_e-p_A}\right\}.$$

High energy axions. *The axioelectric effect cross section for K-shell electrons was calculated (on the assumption that Z<<137 and **E_A>> E_b** in A.R. Zhitnitskii and Yu.I.Skovpen, Yad. Fiz., 29b, 995 (1979). and has complex form ~ Z^5*

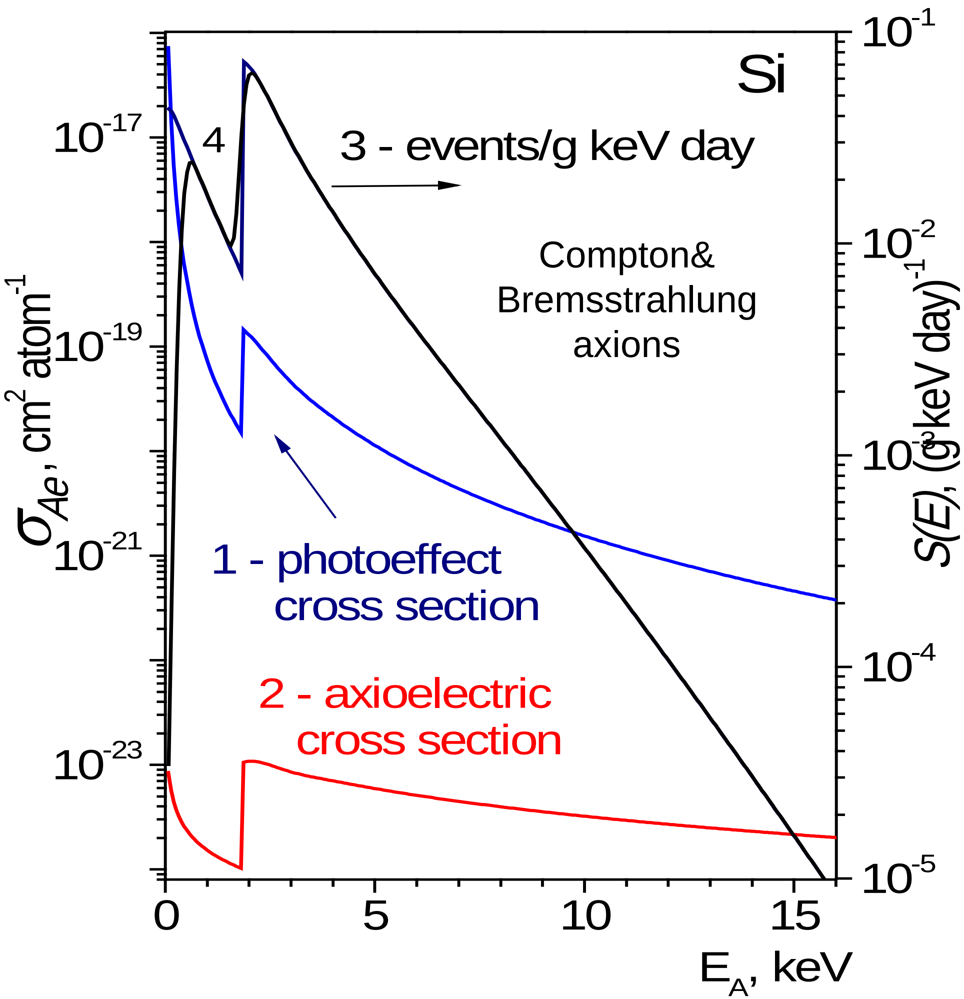
$$\sigma_{ae}(E_A) = \sigma_{pe}(E_A)\times g_{Ae}^2\left(\frac{E_A^2}{8\pi\alpha m_e^2}\right)$$

$$\sigma_{ae}(E_A) = \sigma_{pe}(E_\gamma = m_A)\times g_{Ae}^2\frac{1}{\beta}\left(\frac{3m_A^2}{16\pi\alpha m_e^2}\right)$$

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

***Low energy axion** E_A, m_A< 511 keV The cross section for the axio-electric effect for nonrelativistic axions is proportional to the cross section for the photoelectric effect for photons with the energy equal to the mass of the axion [Pospelov, A. Ritz, and M. B. Voloshin, Phys. Rev. D78, 115012 (2008). A. Derevianko, V. A. Dzuba, V. V. Flambaum, and M.Pospelov, Phys. Rev. D 82,065006 (2010)]. For relativistic axions in the case $E_A < m_e$ and $m_A \to 0$, the cross section differs by a factor of about 2/3 and by a change of m_A to E_A. In the intermediate case, one can use the simple approximation.*

Сечение а.э. эффекта для Si-атома



Axioelectric effect is analogue of photoeffect. The cross sections for relativistic and non-relativistic axions were obtained in:

M. Pospelov, A. Ritz, and M.B. Voloshin, Phys. Rev. D **78**, 115012 (2008).
A. Derevianko, V. A. Dzuba, V. V. Flambaum, and M. Pospelov, Phys. Rev. D **82**, 065006 (2010).

$$\sigma_{Ae}\Big|_{\beta\to 0} \simeq \sigma_{pe}(m_A)\frac{3m_A^2}{4\pi\alpha f_A^2\beta}$$

$$\sigma_{Ae}\Big|_{\beta\to 1} \simeq \sigma_{pe}(E)\frac{E^2}{2\pi\alpha f_A^2},$$

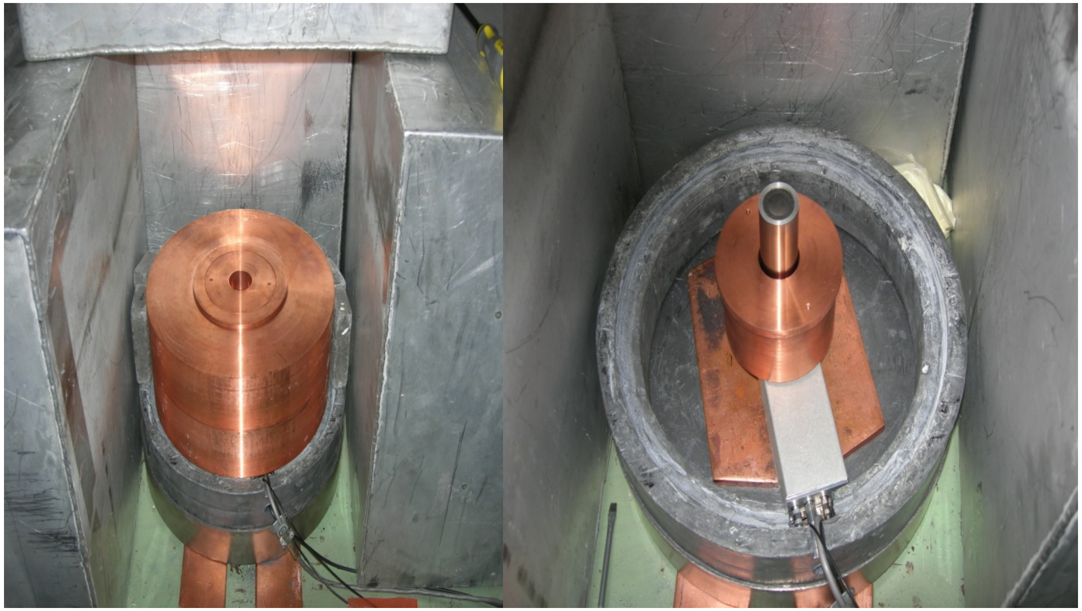
We proposed the approximation for all β values and $g_{Ae}=2m_e/f_A$:

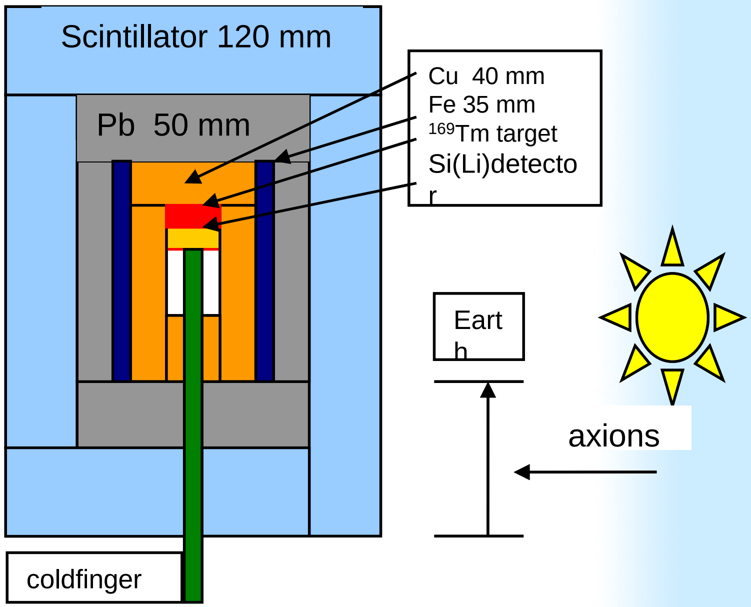
$$\sigma_{abs} = \frac{g_{Ae}^2}{\beta}\frac{3}{16}\frac{E_A^2}{\pi\alpha m_e^2}\sigma_{ph}(E_A)(1-\frac{\beta^{2/3}}{3})$$

JETP Lett., 95, 379 (2012) arXiv:1206.4142

Cross sections for the (1) photoelectric effect for Si atom and (2) axioelectric effect for g_{Ae} = 1 and m_A = 0, (3) the expected spectrum of events detected per day in 1 g of Si in 1 keV for CC and Br axions, (4) the resolution of Si-detector taken into account(right scale).

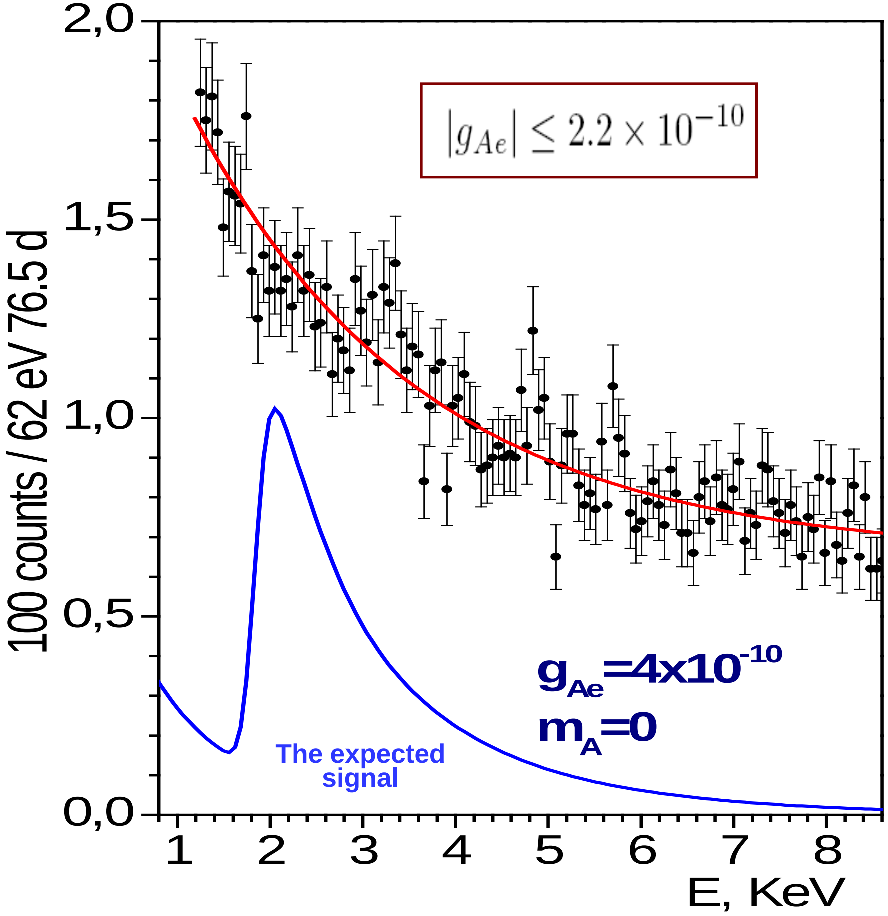
Si(Li)-детектор внутри низкофоновой установки

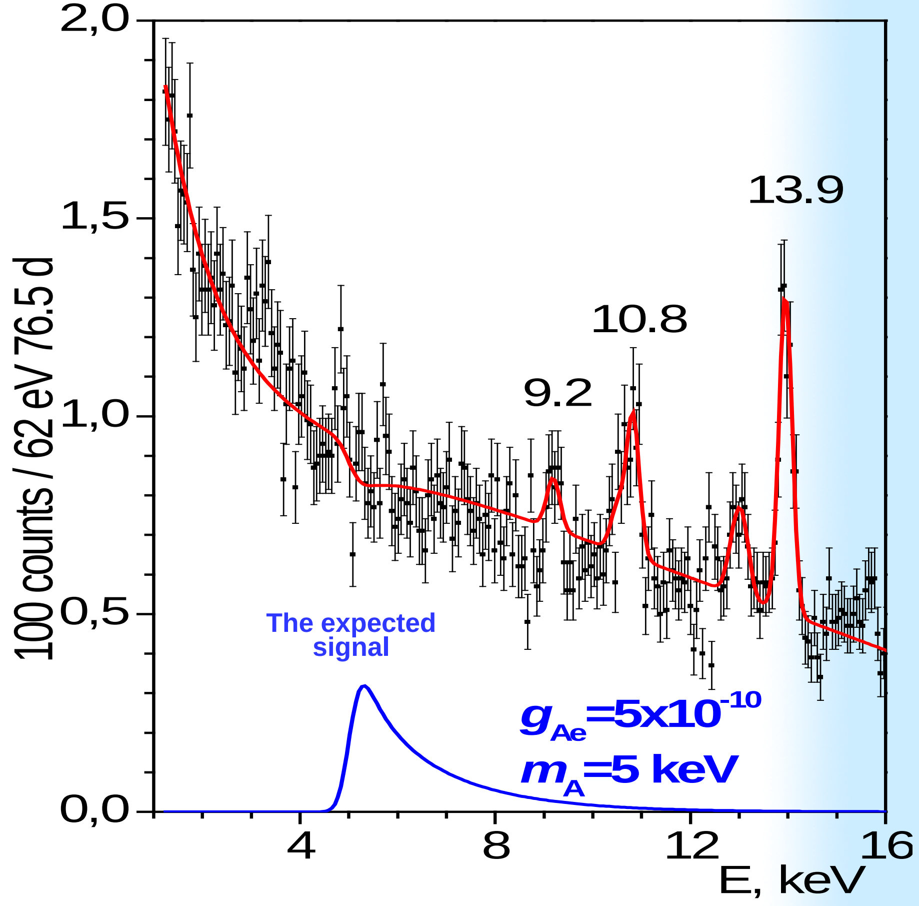




***In** our experiment, we used a Si(Li) detector with a sensitive region diameter of 17 mm and a thickness of 2.5 mm (1.4 g). **The** detector was placed in a vacuum cryostat was surrounded by 12.5 cm of copper and 2.5 cm of lead, which reduced the background of the detector at an energy of 14 keV by 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.*

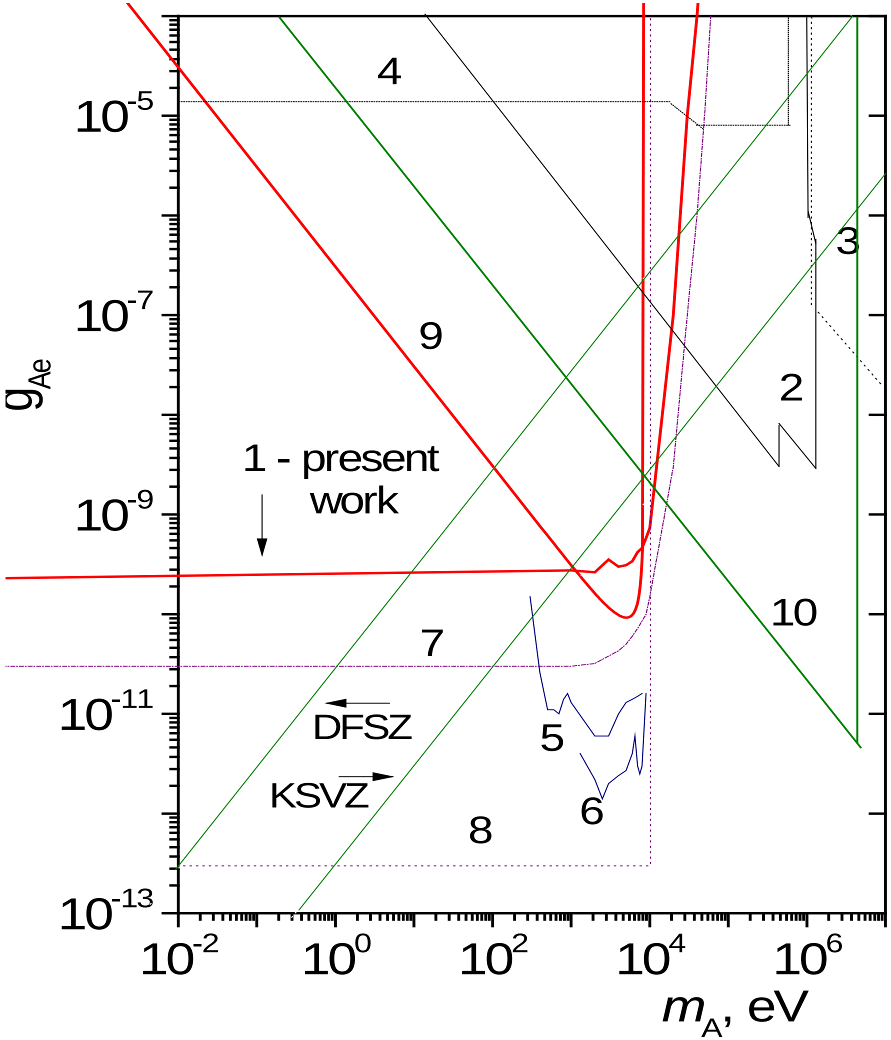
Результаты поиска а.э. эффекта в Si-атомах





*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 $g_{Ae} = 5 \times 10^{-10}$.*

Ограничение на константу g_{Ae}



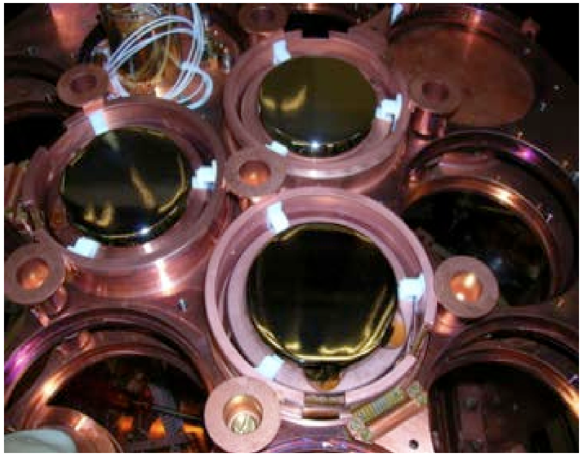
$N_{events} \sim Flux(g_{Ae}^2)\times\sigma_{Ae}(g_{Ae}^2) \sim g_{Ae}^4$

1- *Axioelectric effect (Si)*
2- *reactor experiments and 478 keV solar axions*
3- *beam dump experiments*
4- *decay of orthopositronium*
5- *CoGeNT*
6- *CDMS*
7- *axion luminosity of the Sun less than 10% of ν-luminosity*
8- *red giants He ignition*
9- *^{169}Tm resonant absorption*
10- *Borexino 5.5 MeV axions*

The number of axion events ~ g_{Ae}^4. The regions of excluded values lie above the corresponding lines. 7,8 – more stronger limits. Two lines show the g_{Ae} values in the DFSZ and KSVZ models.

CUORE, XMASS, EDELWEISS, XENON100

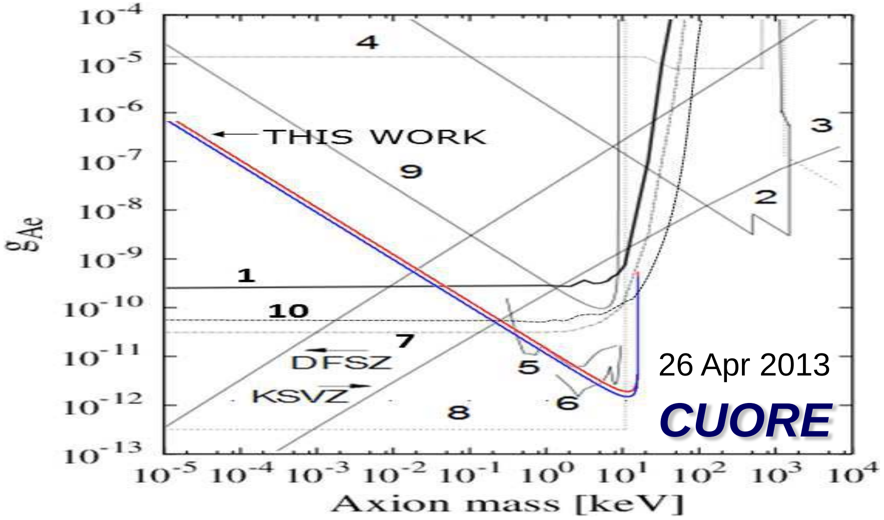
In water Cherenkov shield at Kamioka
835 kg LXe **(100 kg** fiducial), 1-phase, 642 PMTs

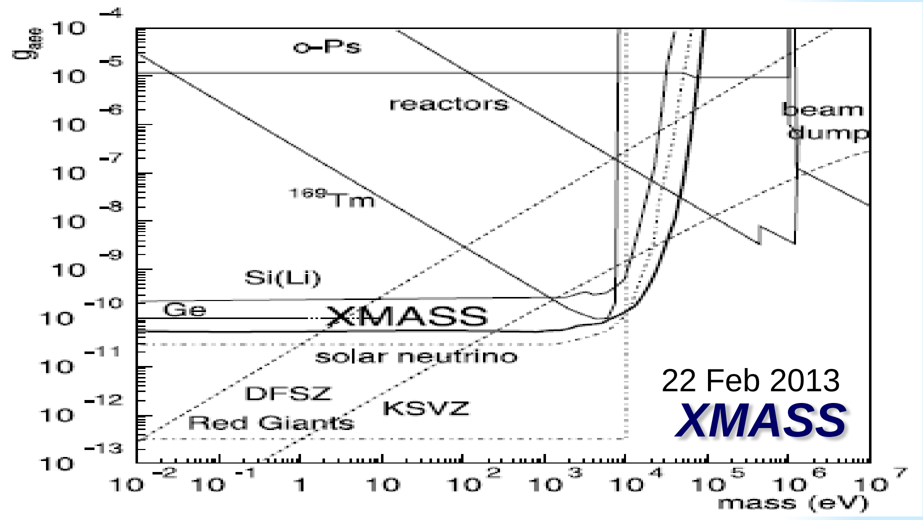


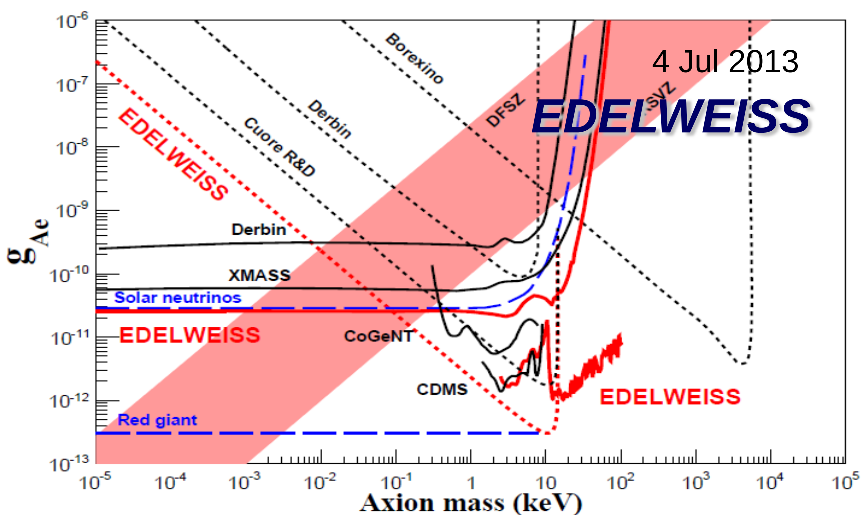
Ge *детекторы при 18 mK*
5 событий за 427 кг сут. 3 соб. ожидаются как фоновые. Новые 10 x 800 г кристаллы с лучшим фоном.

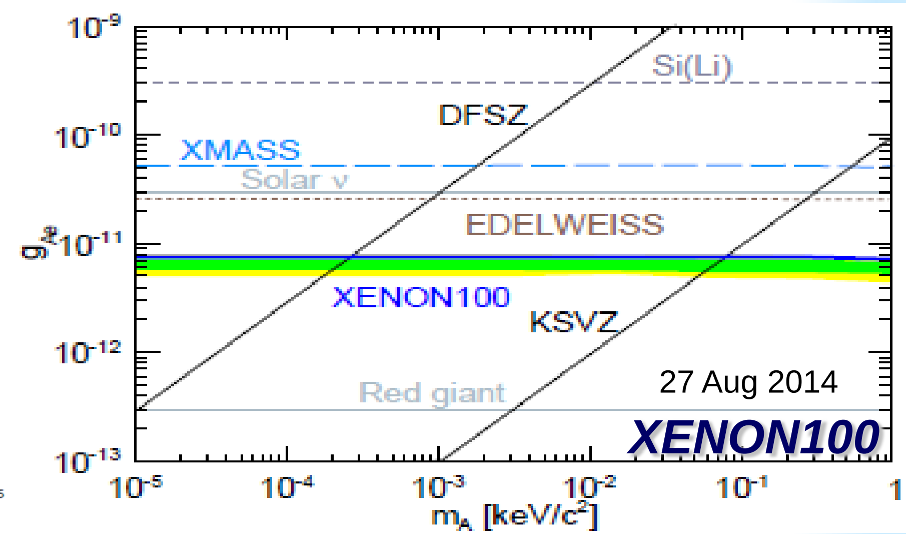
In passive shield at LNGS
161 kg LXe (**50 kg** fiducial), 2-phase, 242 PMTs

CUORE, XMASS, EDELWEISS, XENON100



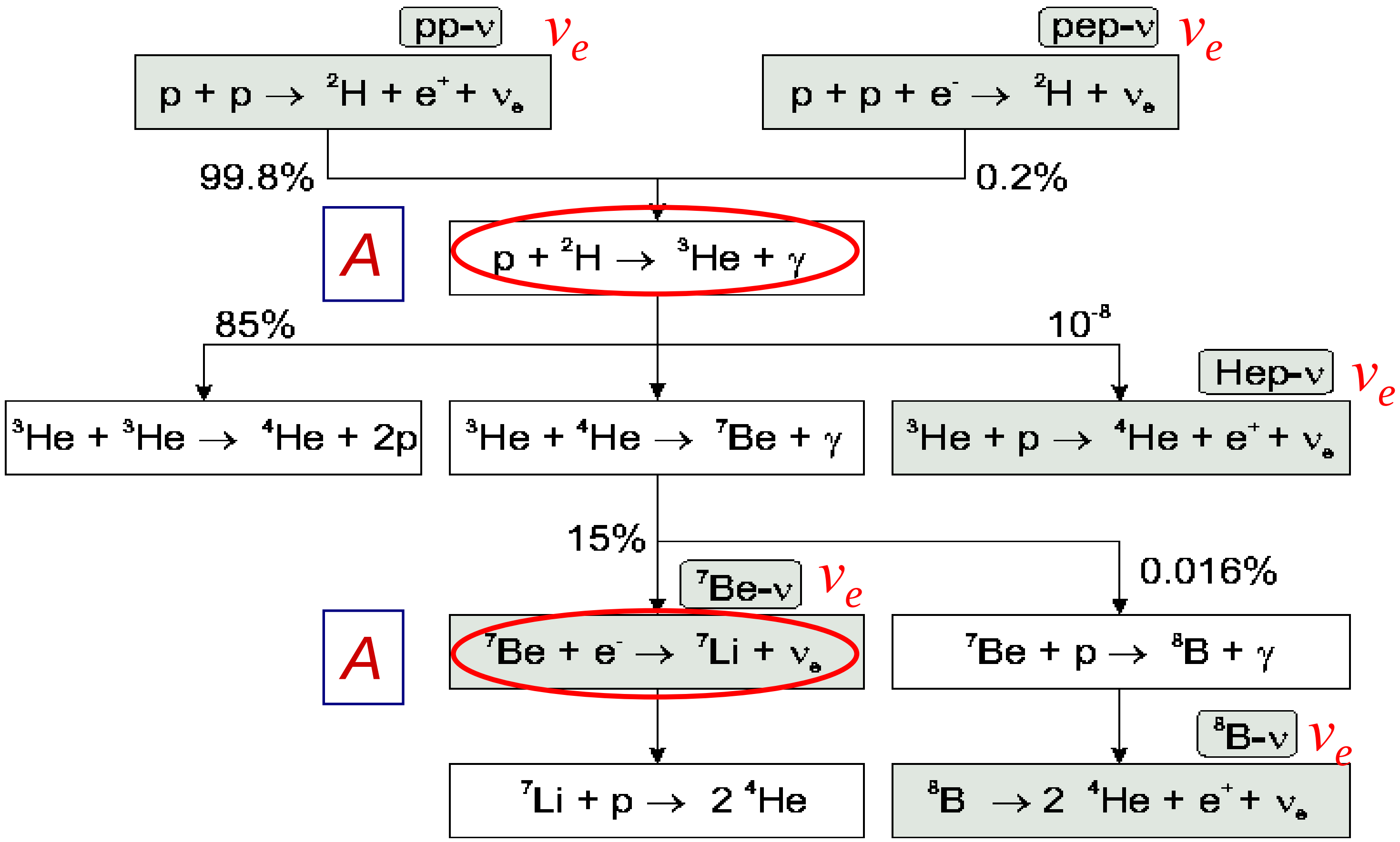






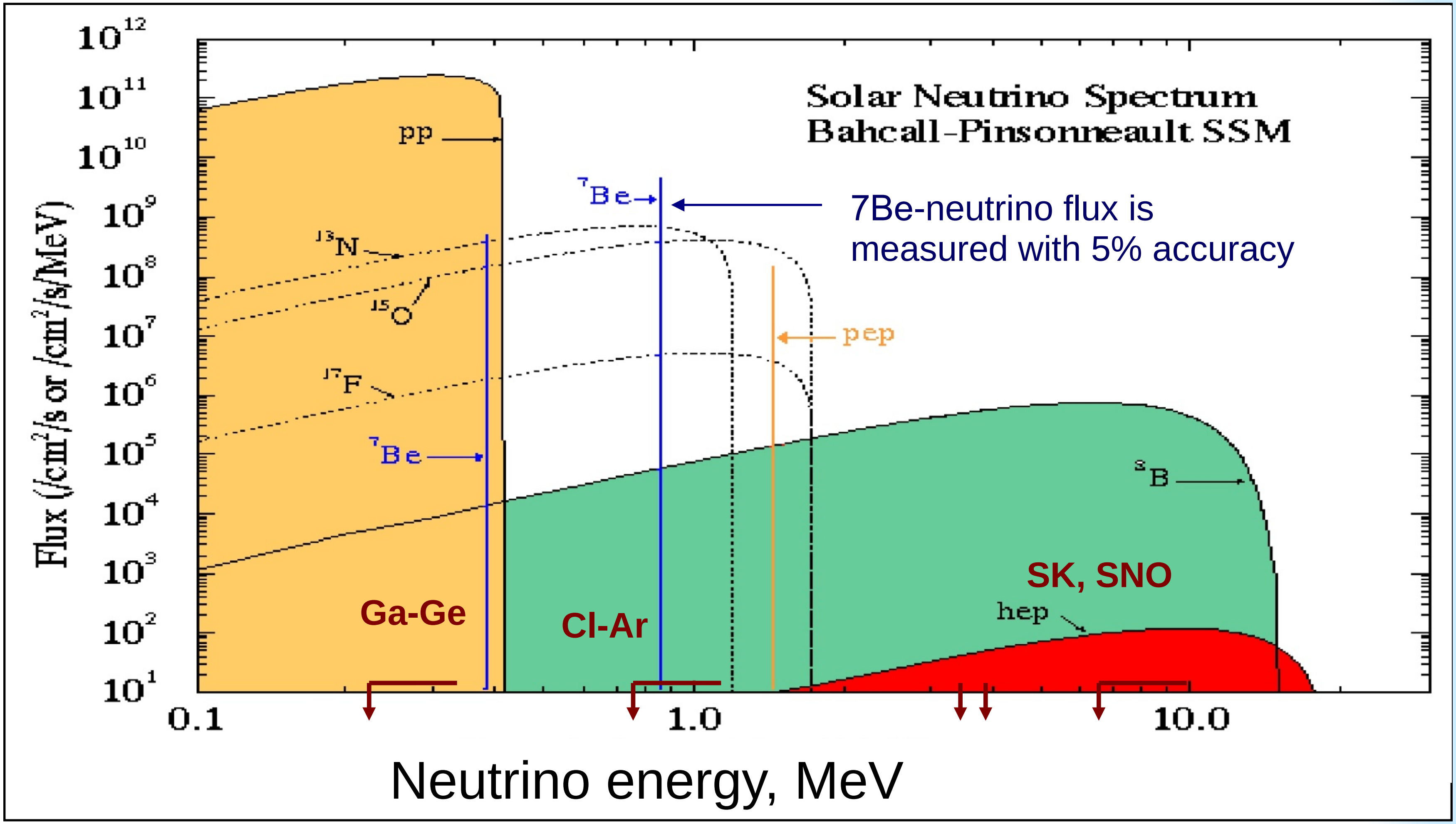
***Si**(Li) limits on $g_{Ae}{}^2$ were significantly improved soon by. The most stringent limit* **$g_{Ae} < 7.7\times10^{-12}$ ($m_A Cos^2\beta < 0.27$ eV)** *was obtained by XENON100. Limits on g_{Ae} from RG is in 25 times stronger*

А.Э. эффект для НЕ солнечных аксионов



The Sun produces energy by conversion of hydrogen into helium. The total energy release of is about 26.7 MeV of which about 0.6 MeV is carried away by neutrinos. We searched for axions emitted in 2 reactions which are directly connected with reactions producing 2 most intensive neutrino fluxes - pp- and ^{7}Be- neutrinos.

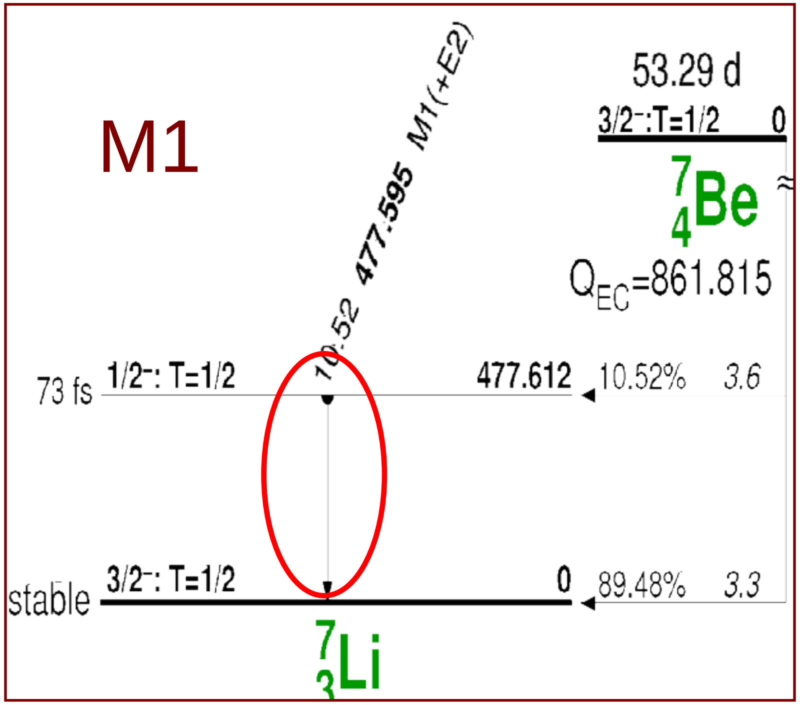
Спектр солнечных нейтрино



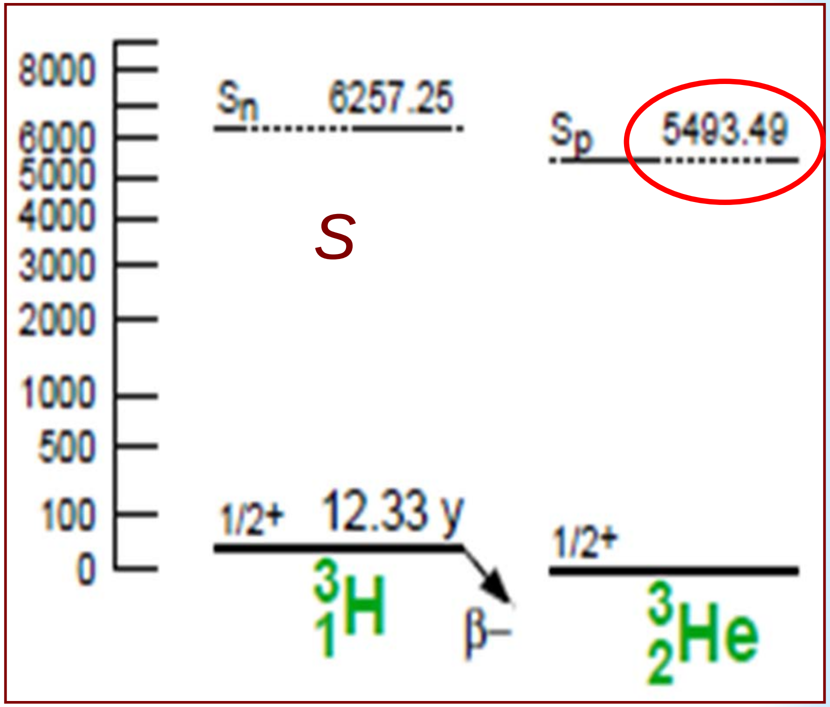
Borexino has been measured low energy solar neutrinos via (ν,e)-scattering. The most intensive flux of pp-neutrino is **6.0×10^{10} ν / cm² s**, then ^{7}Be – neutrino – **4.5×10^9**, high energy ^{8}B-neutrino - **6×10^6**. Reactor gives – **10^{13} ν/cm²s** at 15 m.

Аксионы с энергией 478 кэВ и 5.5 МэВ

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



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



Axions can be emitted in reactions of electron capture and proton capture. Because energy of transitions is high, the range of axion masses under study can be expanded up to 5 MeV. Some models based on the concept of MW [Berezhiani, et al., 2001] and SUSY [Hall and Watari, 2004] allow for the existence of axions with a m_A~1 MeV. The additional possible reactions producing high energy solar axions were considered by [Raffelt, Stodolsky, 1982].

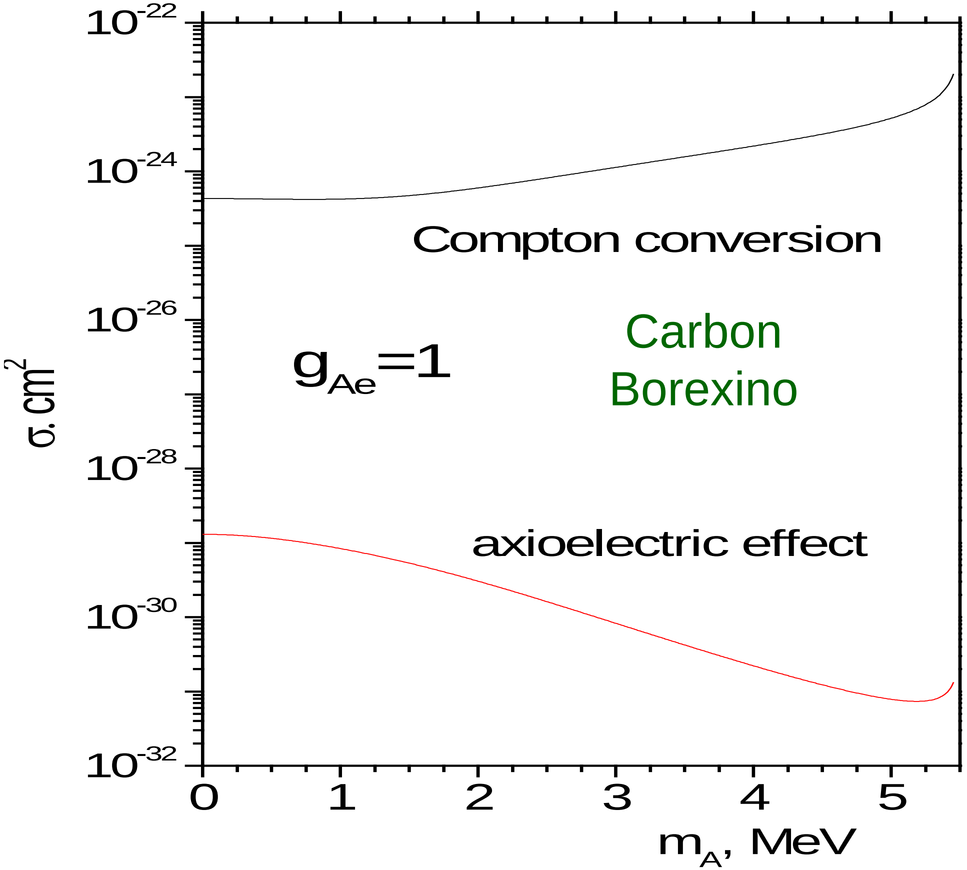
Поток аксионов на Земле в см$^{-2}$ с$^{-1}$

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

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

The expected solar axion flux can thus be expressed in terms of the ^{7}Be- and pp-neutrino fluxes, which are 4.9x10^9 and 6.0x10^{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.

Регистрация через константу g_{Ae}



1. Compton conversion:

$A + e \rightarrow \gamma + e.$

both e and γ are detected.

C.S. has a complex form,

the total CS for 5.5 MeV axions

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

at $m_A < 1$ MeV

2. Axioelectric effect:

$A + e + Z \rightarrow Z + e.$

is analog of photo effect

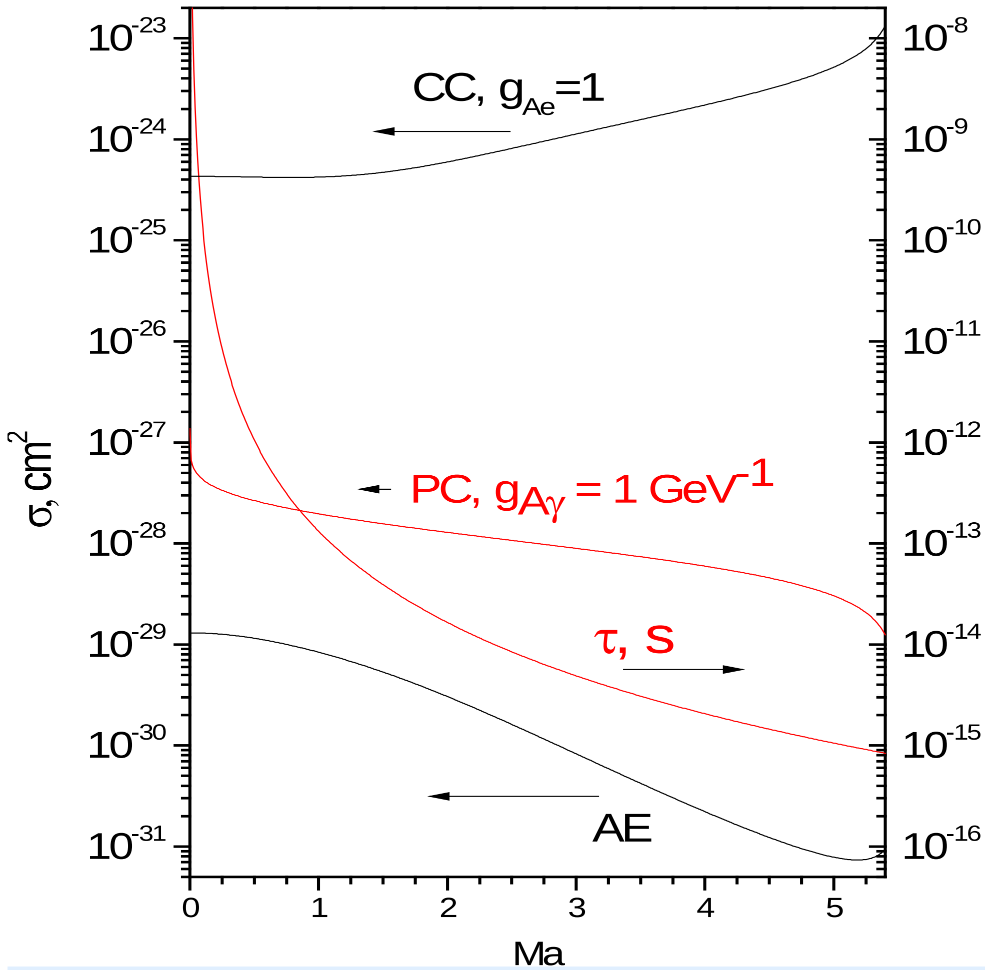
CS is proportional Z^5, for C atom

and E_A=5.5 MeV

$\sigma_{AE} \approx g_{Ae}^2 \times 1.3 \times 10^{-29}$ 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.

Регистрация через константу $g_{A\gamma}$



1. *inv. Primakoff conversion:*

$$A + Z \rightarrow \gamma + Z.$$

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

C.S. has a complex form,

the total CS for 5.5 MeV axions

$$\sigma_{CC} \approx g_{A\gamma}^2 \times 4.7\times10^{-28}\ cm^2$$

at m_A< 1 MeV

2. *Axion decay:*

$$A \rightarrow \gamma + \gamma.$$

the axion lifetime is

$$\Gamma\ [s^{-1}] = 1/\tau = g_{A\gamma}^2 m_A^3/64\pi =$$
$$0.8\times10^{-5}(g_{A\gamma}[GeV^{-1}])^2\ (m_A[eV])^3$$

and lifetime have to be < 500 s

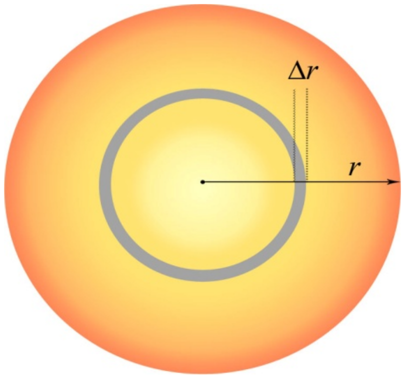
We also consider the possible signals from the decay of axion into two γ-quanta and from Primakoff conversion on nuclei. The amplitudes of the reactions depend on $g_{A\gamma}$. No statistically significant indications of axion interactions were found.

Условия вылеты аксионов из Солнца

There are 2 main disadvantages of experiments with solar axions: the Sun can not been switched off and axions must to escape from the Sun and reach the Earth

particle	e	p	^4He	^{12}C	^{14}N	^{16}O	Fe	Pb
in 10^{35} cm^{-2}	6.8	5	0.9	$6x10^{-4}$	$7x10^{-4}$	$2.3x10^{-3}$	$1.5x10^{-4}$	$5x10^{-10}$

Constant	g_{Ae}	$g_{A\gamma}$ GeV^{-1}	g_{AN}
Limit	**$<10^{-6}$**	**$<10^{-4}$**	**$<10^{-3}$**
Process	CC	PC	PD

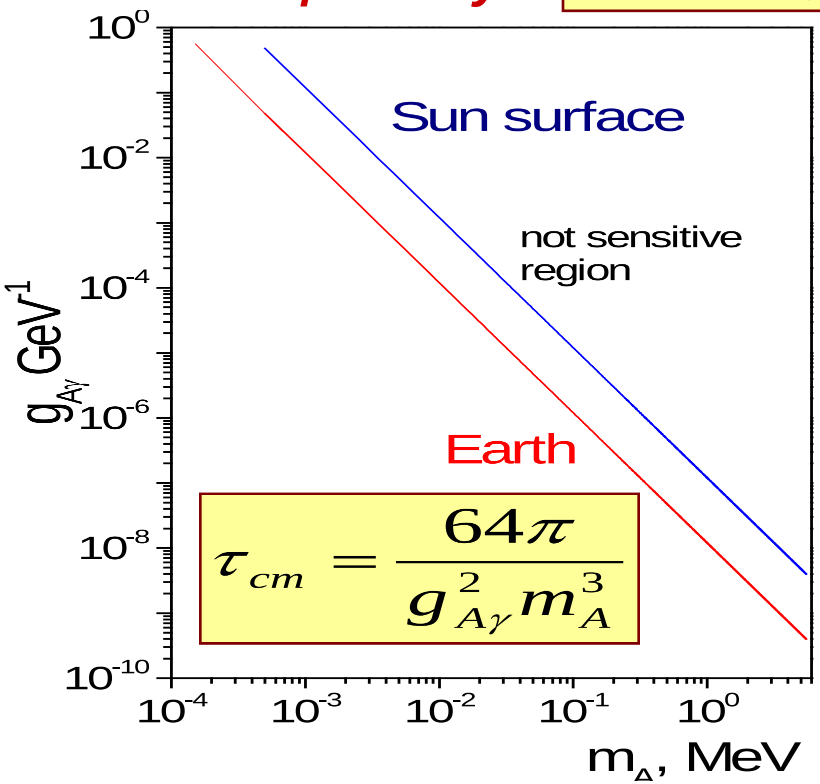


The axions produced inside the Sun must pass through a layer of $6.8x10^{35}$ e's/cm^2 $5x10^{35}$ p's and $1x10^{35}$ α's in order to reach the Sun's surface. The Compton conversion of an axion into a photon imposes an upper limit on the sensitivity of Earth surface experiments to the constant g_{Ae}. **For** g_{Ae} values below 10^{-6}, the axion flux is not substantially suppressed. The similar limitations are for axion-photon (Primakoff conversion) and axion-nucleon couplings (photodisintegration).

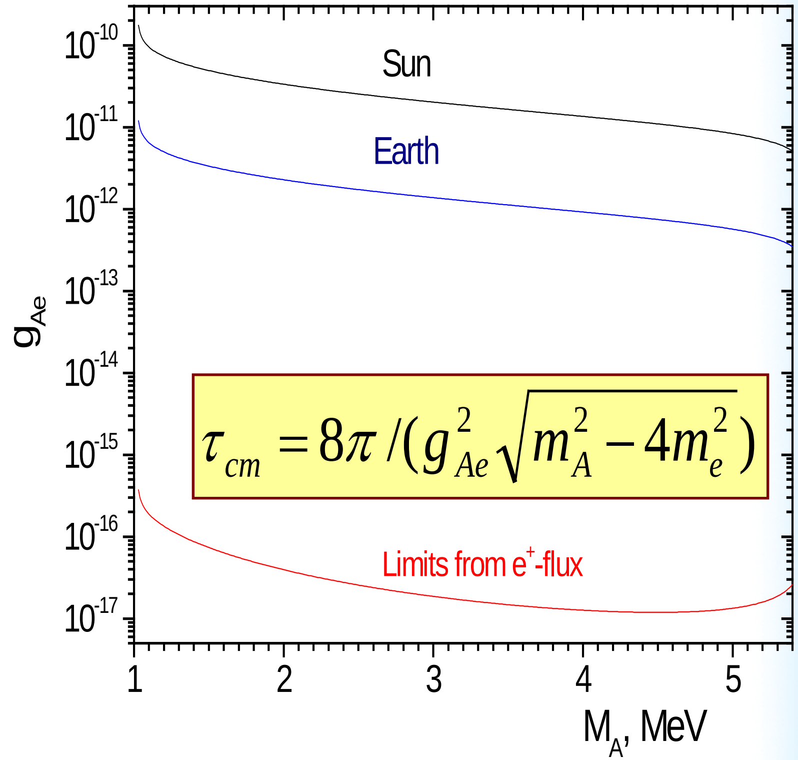
Распад аксионов в полете

$$\Phi_A = \exp\left(-\frac{\tau_f}{\tau_{cm}}\right)\Phi_{A0}$$

A →2γ decay

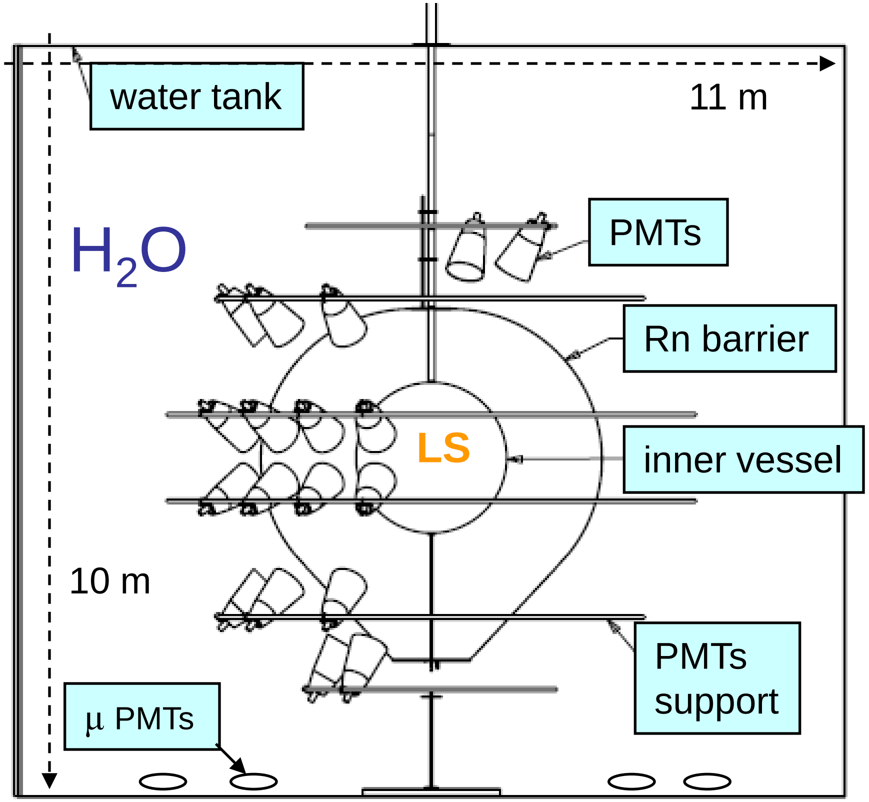


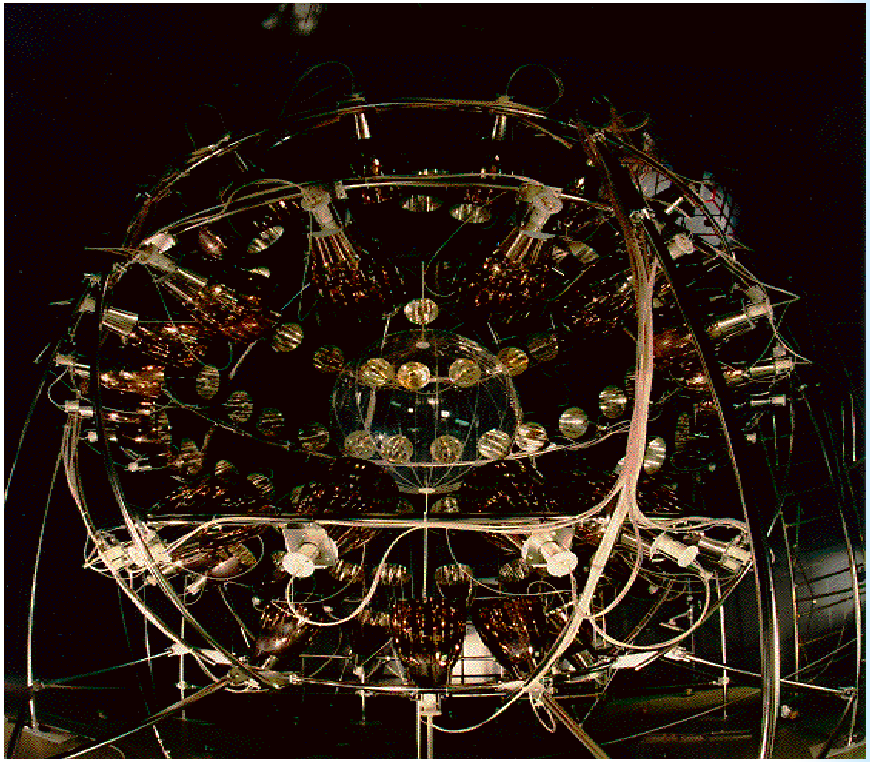
A → e⁺ e⁻ decay (m_A>2m_e)



For axions with a mass above 2m_e, the main decay mode is into an e^+e^- pair. If m_A< 2m_e the axion can decay into 2 γ's. The condition τ_f <0.1x τ_{cm} (in this case 90% of all axions reach Earth) yields the sensitivity limits for the constants g_{Ae} and $g_{A\gamma}$ vs m_A.

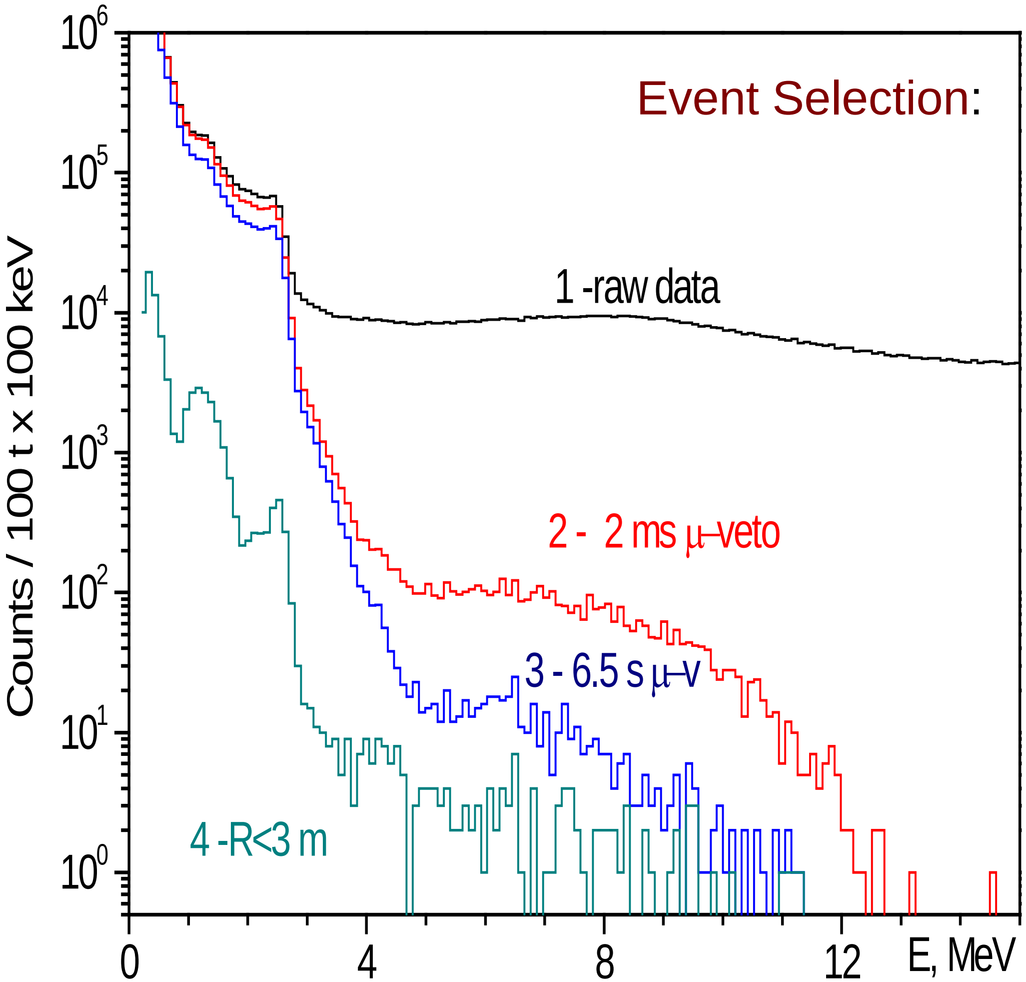
Первые результаты для 478 кэВ аксионов с прототипом Борексино (EPJ, C54, 2008)





***C**TF was a prototype of the Borexino detector. The CTF consisted of an external cylindrical water tank with **1000 t of water** serving as passive shielding for **4.2 m^3 of LS** contained in a nylon vessel of **Ø2.0 m**. The additional nylon screen between the scintillator vessel and PMTs takes the part of barrier against penetration of external radon. **T**he scintillation light was collected with **100 PMTs** placed inside the water tank. The PMTs with light concentrators provide a total optical coverage of **21%.** The water volume is instrumented with a **Cherenkov muon veto system**.*

Спектры Борексино за 738 суток



Extremely low background level – at least in 10^2 times lower then in previous works

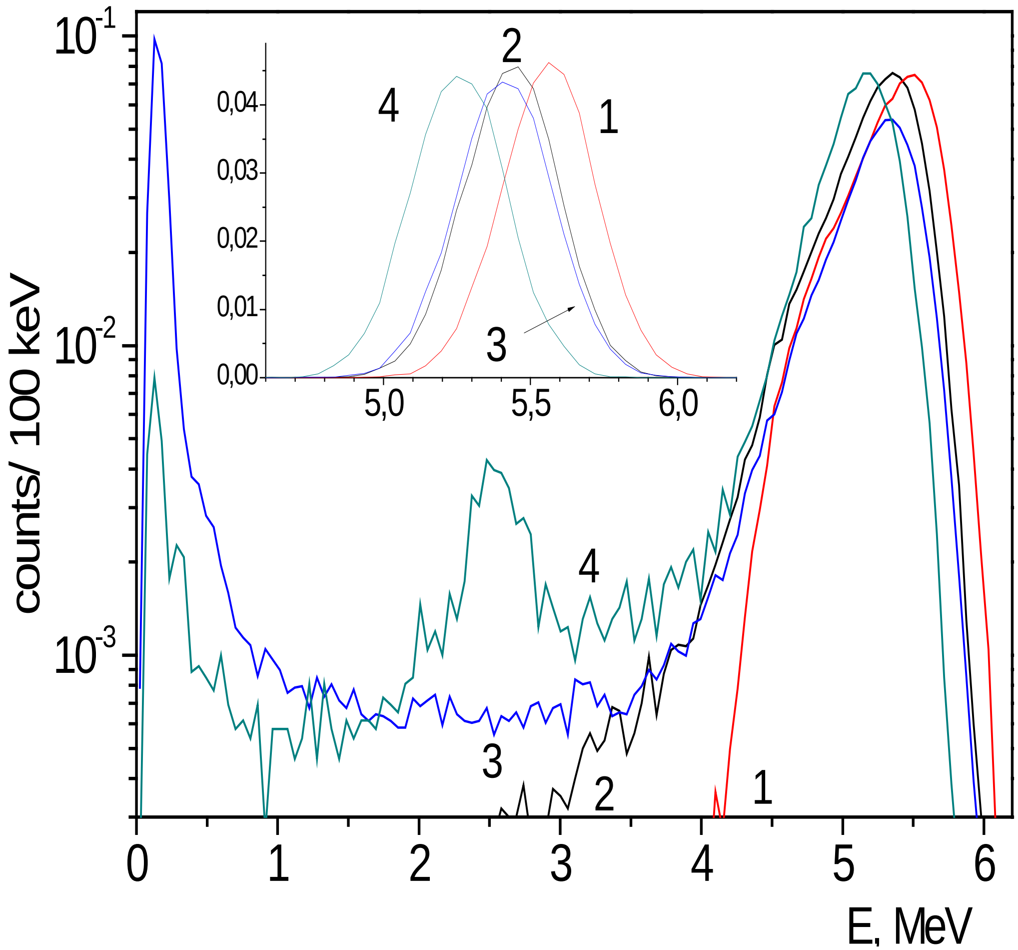
1. The raw spectrum. At energies below 3 MeV, the spectrum is dominated by 2.6 MeV γ's from the β-decay of 208Tl due to radioactive contaminations in the PMTs and in the SSS.

2.The second spectrum is obtained by vetoing all events within 2 ms after muon.

3. To reduce the background due to the short-lived isotopes (8B, 1.1s; 8Li, 1.2 s etc) induced by muons, an additional 6.5 s veto is applied after each muon crossing the SSS

4. In order to remove the external background, only signals reconstructed within a spherical 100 t fiducial volume are accepted.

Функция отклика Борексино для аксионных процессов

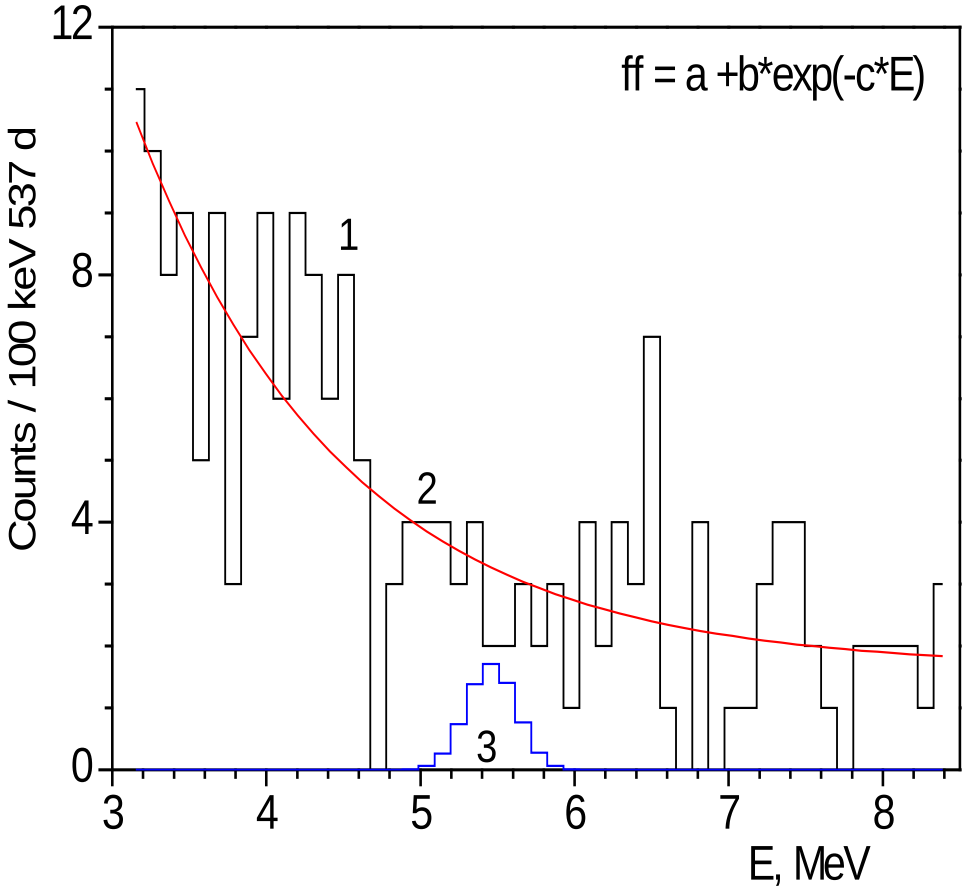


1 – axioelectric effect
2 – Compton conversion
3 – Primakoff conversion
4 – Axion decay A→2γ

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.

Подгонка



The spectrum was fitted by a sum of exp and Gaussian functions, the position and dispersion of the later was found from the MC response:

$$N_{th}(E) = a + b\exp(-cE) + \frac{S}{\sqrt{2\pi}\sigma}\exp\left[-\frac{(E_0 - E)^2}{2\sigma^2}\right]$$

The number of counts in the axion peak S was calculated using the maximum likelihood method for Poisson distribution.

$$L = \prod_i \exp(-N_i^{th})(N_i^{th})^{N_i^{\exp}} / N_i^{\exp}!$$

The upper limit on the number of counts in the peak was found using the profile of maximal values of L for different fixed S when all others parameters were free. The obtained values of Lmax(S) were normalized to unit for S < 0 that allows to select the given confidence level. The goodness-of-fit was found by MC (p = 52%)

Верхние пределы для числа событий от 5.5 МэВ аксионов

reaction	CC	AE	A→2γ	PC
$S_{lim,}$68(90)%	3.8(6.9)	3.4(6.5)	4.8(8.4)	3.8(6.9)

$(100\ t\ 536\ d)^{-1}$

CC - Compton axion to photon conversion A+e →e+γ, AE -axio-electric effect A+e+Z→ e+Z, PC - Primakoff conversion on nuclei A +^{12}C →γ+^{12}C. The limits are given at 68(90)% c.l.

The obtained limits are close to limit given by simple 3.3σ method:

$$S_{\lim}(1\sigma) = 1.1\sqrt{3.3\sigma[keV]B[KeV^{-1}]} = 3.7$$

*where **σ (E)** is the energy resolution and **B(E)** is background level of the detector.*

The obtained upper limits on number of 5.5 MeV axion's events for different reactions are shown in the table.

*The 5.5 MeV axion count rate is very low - **< 0.013 events / (100 t 1 d)***

For comparison the expected number of

***pp**-neutrino events is – **135** events / (100 t 1 d) (LMAMSW)*

*^{7}**Be** neutrino events – **45** events / (100 t 1 d)*

*^{8}**B** neutrino events – **0.25** events / (100 t 1 d)*

5.5** MeV neutrino having pp-neutrino flux would give **2100 events / (100 t 1 d)

Пределы на потоки и сечения 5.5 МэВ аксионов

The upper limit on product of flux and cross sections can be obtained from relation:

$$N_{events} = \varepsilon \cdot N_{e,12C} \cdot T \cdot \Phi_A \cdot \sigma_{CC,Ae,PC} \le S_{\lim}$$

ε - the efficiency of registering an event (in 100 t inner volume),
$N_{e,12C}$ - the number of electrons or nuclei under consideration,
T - the time of measurements,
Φ_A - the axion flux,
$\sigma_{CC,Ae,PC}$ - the cross sections, and
S_{lim} is the upper limit on the number of candidate events.

$$\Phi_A \times \sigma_{axion-electron} \le 4.5 \times 10^{-39} s^{-1}$$

$$\Phi_A \times \sigma_{axion-proton} \le 2.5 \times 10^{-38} s^{-1}$$

$$\Phi_A \times \sigma_{axion-carbon} \le 3.3 \times 10^{-38} s^{-1}$$

4.5×10^{-3} SNU
SNU = 1 c/ s10^{36} at

The next model independent limits on the flux and cross section for any particle giving 5.5 MeV peak were found. These limits show very high sensitivity to a model independent value ΦAσA. For comparison the standard solar neutrino capture rate is SNU 10^{-36} s^{-1} atom^{-1}.A capture rate of solar neutrinos measured by Ga-Ge radiochemical detectors is about 70 SNU.

Пределы на g_{AN}, g_{Ae} и $g_{A\gamma}$ и m_A для 5.5 МэВ аксионов

$$\Phi_{A0}(pd) \cong 3.3\times10^{10}(g_{AN}^{3})^{2}$$

$$\sigma_{CC} \cong g_{Ae}^{2} \times 4.3\times10^{-25}\ cm^{2}$$

***B**ecause axion flux depends on axion-nucleon coupling and cross section of compton-like process depends on axion-electron coupling the obtained limit leads to the model-independent limit on g_{AN} x g_{Ae} for general pseudoscalar (90% C.L.):*

$$|g_{Ae}\times g_{AN}| \le 5.5\times10^{-13} \qquad (m_A \le 1\,MeV)$$

$$g_{AN}^{3} = -2.75\times10^{-8}(m_A/1\,eV)$$

***Ta**king the dependency g_{AN}^{0} on m_A given by KSVZ one can exclude g_{Ae} vs m_A region:*

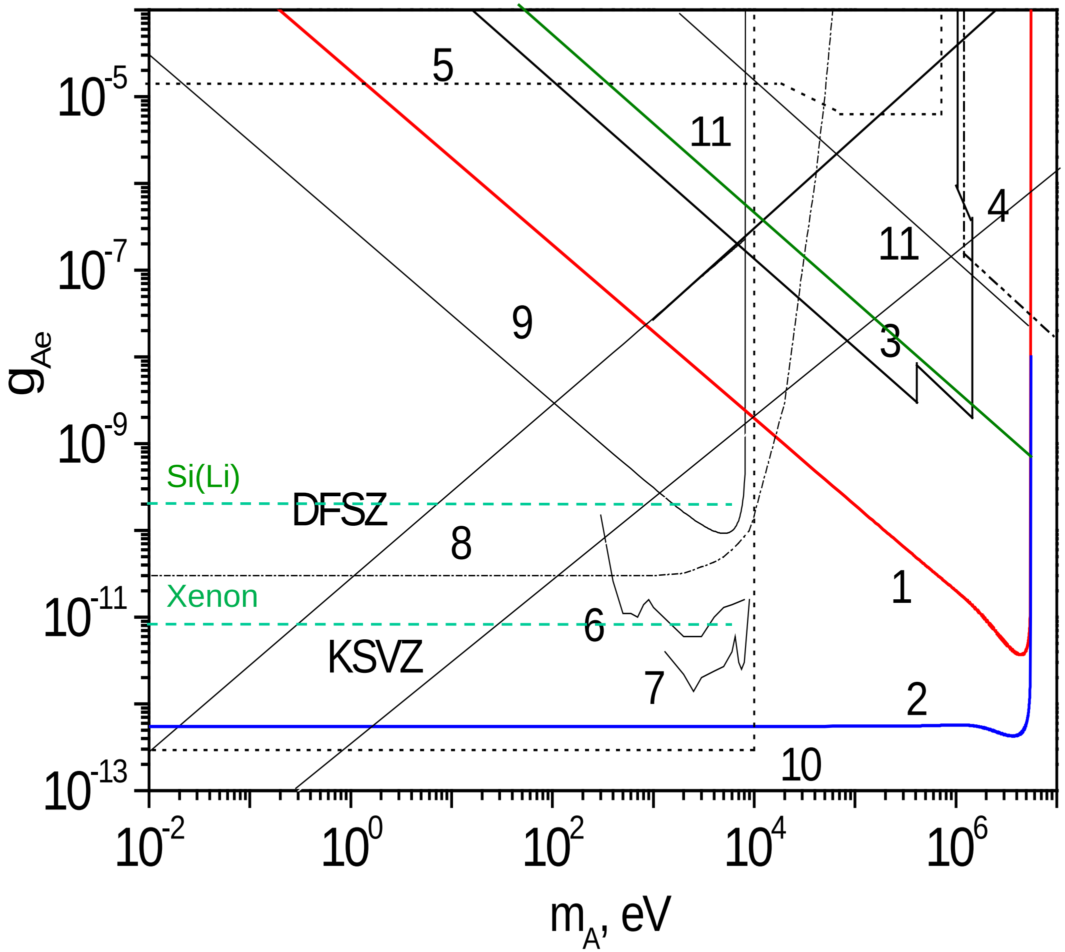
$$|g_{Ae}\times m_A| \le 2.0\times10^{-5}\,eV$$

At least, one can obtain limit on axion mass:

$$g_{Ae}^{DFSZ} = 2.8\times10^{-11} m_A \quad (\cos^2\beta = 1) \quad \Rightarrow \quad m_A \le 845\,eV$$

$$g_{Ae}^{KSVZ} = \frac{3\alpha^2 N m_e}{2\pi f_A}\left(\frac{E}{N}\ln\frac{f_A}{m_e} - \frac{2}{3}\frac{4+z+w}{1+z+w}\ln\frac{\Lambda}{m_e}\right) \Rightarrow m_A \le 12\,keV$$

Пределы на (g_{Ae} x g_{AN} и m_A) и (g_{Ae} и m_A)



1- Borexino limits on g_{Ae}

2-Borexino limits on g_{Ae}xg_{AN}

3 – Reactor experiments and ^{64}Cu source

4 – beam-dump experiments

5 – ortopositronium decay

6 – CoGeNT coll.

7 – CDMS coll.

8 – Solar axion luminosity

9 – Resonant absorption by ^{169}Tm nuclei

10 – Red giant

11 – Axioelectric effect in BGO

Borexino results exclude the new large regions of axion masses (0.01-1) MeV and coupling constants g_{Ae}~(10^{-11}-10^{-9}). For hadronic axion with m_A=1 MeV, g_{Ae} <2x10^{-11}. Figure also shows the constraints on g_{Ae} that were obtained in the experiments with reactor, accelerator and solar axions as well from astrophysical arguments.

Пределы на g_{AN} и $g_{A\gamma}$ и m_A

If the axion mass is less than $2m_e$, $A \to e^+e^-$ decay is impossible, but the axion can decay into 2 γ's. The flux of axions reaching the detector:

$$\Phi_A = \exp\left(-\frac{\tau_f}{\tau_{cm}}\right)\Phi_{A0}$$

Where τ_{cm} is lifetime in the axion reference system

$$\tau_{cm} = \frac{64\pi}{g_{A\gamma}^2 m_A^3} = \frac{1.3\times 10^5}{g_{A\gamma}^2 m_A^3} s \quad (g_{A\gamma}\ in\ GeV^{-1}\ m_A\ in\ eV)$$

and is τ_f time of flight in the axion reference system

$$\tau_f = \frac{m_A L}{E_A \beta c} \cong 9.1\times 10^{-5}(m_A/1eV)[s] \quad (\beta = 1)$$

$$\Phi_A = \exp(-7.0\times 10^{-10} g_{A\gamma}^2 m_A^4)\Phi_{A0}$$

The analysis of $A \to 2\gamma$ decay and Primakoff photo production is more complicated because axions can decay during their flight from the Sun. The exponential dependence of axion flux versus $g_{A\gamma}$ and m_A have to be taken into account.

Пределы на g_{AN} и $g_{A\gamma}$ и m_A из конверсии Примакова

The number of Primakof conversion on N_{12C} nuclei during time T is proportional the product of axion-nucleon and axion-photon coupling constants.

$$N_{PC} = \sigma_{PC} \exp(\sim g^2_{A\gamma} m^4_A) \Phi_{A0} N_{12C} T \varepsilon$$
$$\sim (g^2_{AN} g^2_{A\gamma}) \exp(\sim g^2_{A\gamma} m^4_A)$$
$$\sim (g^2_{\gamma} m^2_A) \exp(\sim g^2_{A\gamma} m^4_A)$$
$$\sim m^4_A \exp(\sim m^6_A)$$

If exp( )≈1 then

$|g_{AN} \times g_{A\gamma}| < 4.6 \times 10^{-11}$ GeV^{-1}

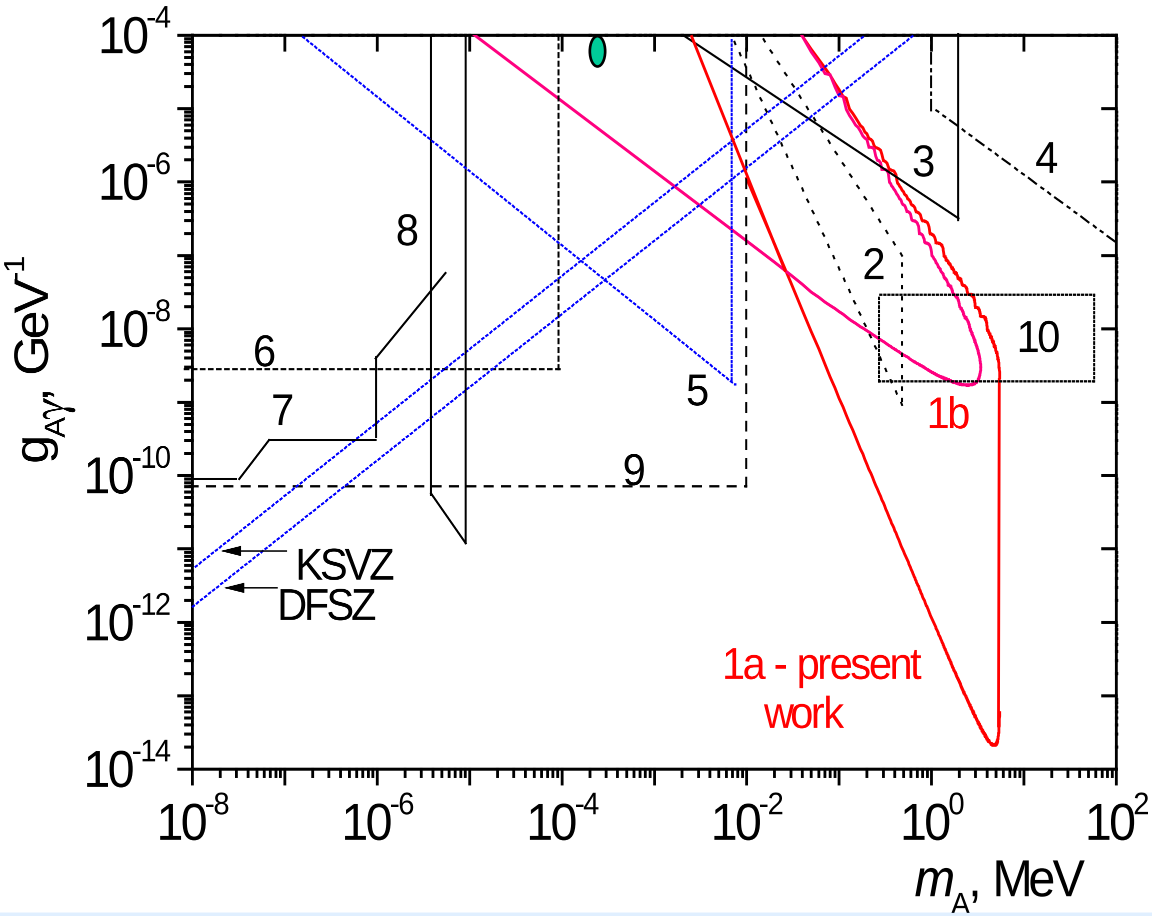
$|g_{A\gamma} \times m_A| < 1.7 \times 10^{-12}$

if m_A=1 MeV

$g_{A\gamma} < 1.7 \times 10^{-9}$ GeV^{-1}

*The obtained model independent limit on the product of axion-nucleon and axion-photon coupling is **4.6×10^{-11} GeV^{-1} (90% C.L.).** This limit is 25 times stronger than the one obtained by CAST [J. Cosmol. Astropart. Phys. 03 (2010) 032.], which searches for conversion of 5.5 MeV axions in a laboratory magnetic field **$|g_{A\gamma} \times g_{3AN}| < 1.1 \times 10^{-9}$ at mA < 1 eV.** In the KSVZ model , the constraint on gAγ and mA is 1.7x10^{-12} under the assumption that gAγ depends on mA as in the hadronic axion (KSVZ) model we exclude axions with masses between (1.5—73) keV.*

Пределы на $g_{A\gamma}$ и m_A для $g_{AN}^3 = 2.8\times10^{-8}\, m_A$ (KSVZ)



1a – Borexino A→2γ decay

1b – Borexino PC

2 – CTF results

3 – Reactor experiments

4 - beam-dump experiments

5 – Resonant absorption

6 – Cosme, Solax, DAMA

7, 11 – CAST

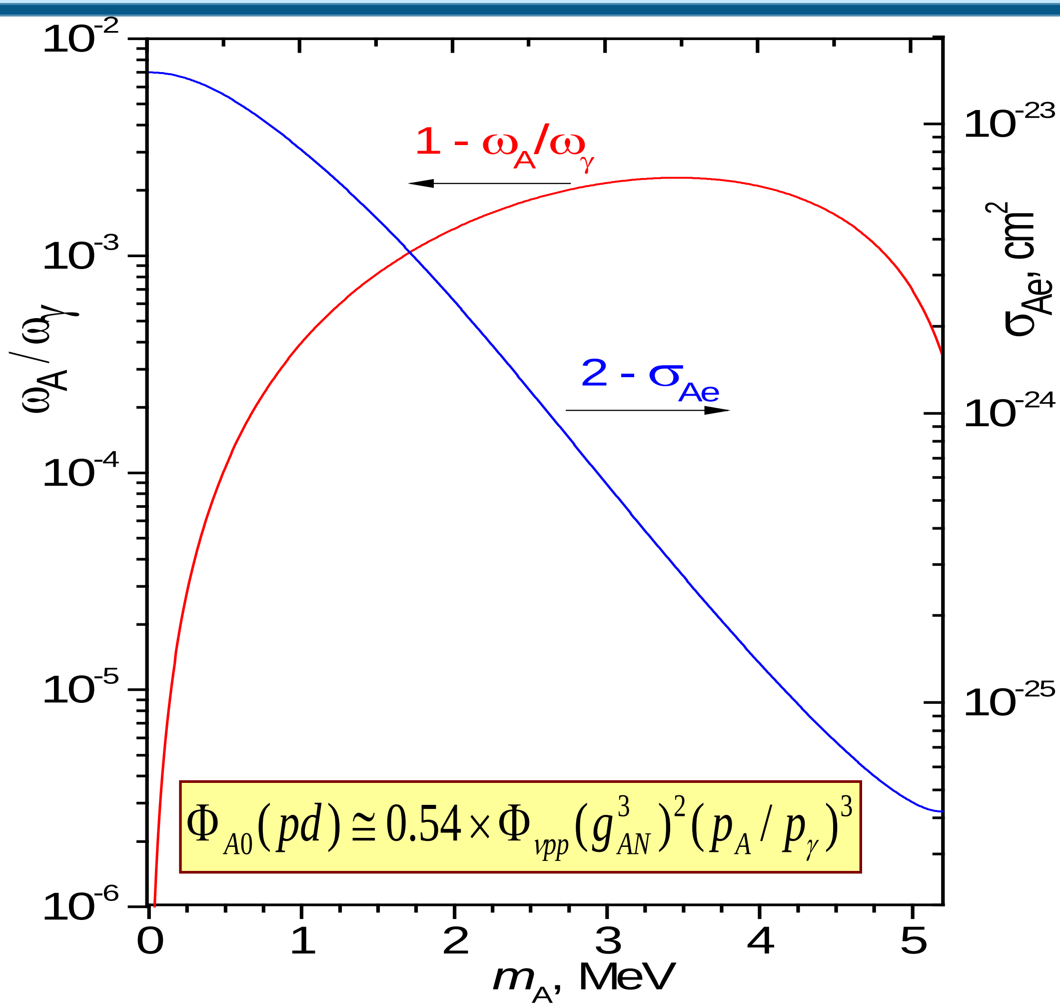
8 – Telescopes (A→2γ)

9 – HB stars He-burning LT

10 – SUSY and mirror axions allowed region

The Borexino results exclude the new large regions of axion masses 10 keV - 5 MeV and coupling constants $g_{A\gamma}$ (2×10^{-14}-10^{-7}) GeV^{-1}. For higher values g^2m^3 axions decay before they reach the detector, for lower one the probability of axion decay inside Borexino is too low. Borexino limits are more then 2-4 orders magnitude stronger than obtained by laboratory-based experiments using nuclear reactors.

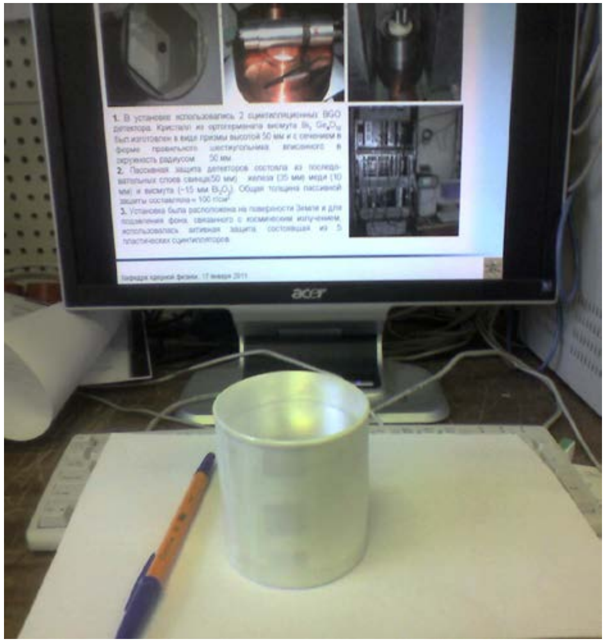
$Bi_4Ge_3O_{12}$ детектор для поиска АЕ эффекта для 5.5 МэВ аксионов



The ratio (ω_A/ω_γ) in the p+d→^{3}He +γ reaction (1, left scale); the cross section σ_{Ae} for 5.5-MeV axions on Bi-atoms for g_{Ae}=1 (2, right-h. scale)

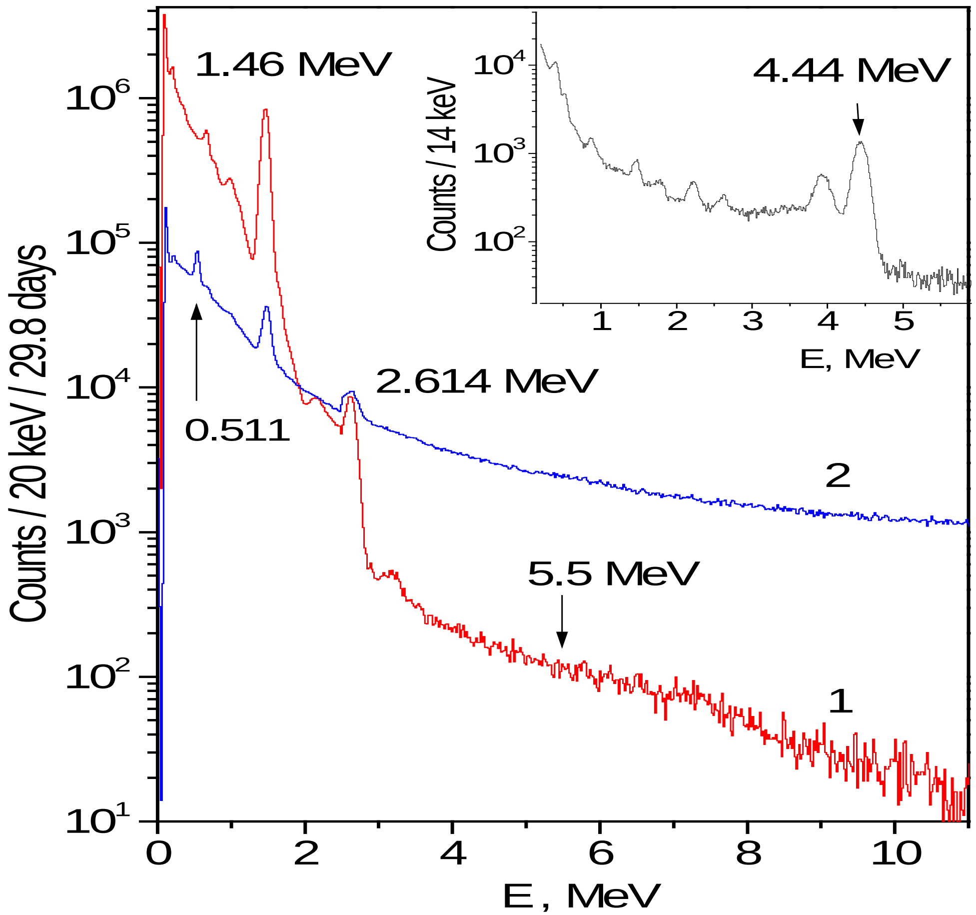
In order to detect 5.5 MeV solar axions, we considered the reaction of axioelectric effect A + Z + e → Z + e in Bi-atoms, which is governed by the axion–electron coupling constant gAe. The cross section of this process depends on the charge of the nucleus as Z^5, thus making materials with high Z values favorable for use in such experiments. For bismuth atoms, the cross section of axioelectric effect exceeds the one for Compton conversion by almost two orders of magnitude. The axioelectric effect c.s. for Bi-atom in 5×10^5 times more than for carbon atoms.

Установка с BGO сцинтилляционными детекторами



We used a 2.46 kg BGO crystal, manufactured from bismuth orthogermanate $Bi_4Ge_3O_{12}$ (1.65 kg of Bi) to search for the 5.5 MeV axions. The BGO crystal was shaped as a cylinder, 76 mm in diameter and 76 mm in height. Passive shield of the detector consisted of lead layers (100 mm), bismuth (~ 20 mm Bi_2O_3) and copper (10 mm). The total thickness of the passive shielding was ≈ 130 g/cm^2. The setup was located on the Earth's surface. In order to suppress the cosmic–ray background we used an active veto, which consisted of five 50x50x12 cm plastic scintillators.

Спектр BGO за 29.8 суток

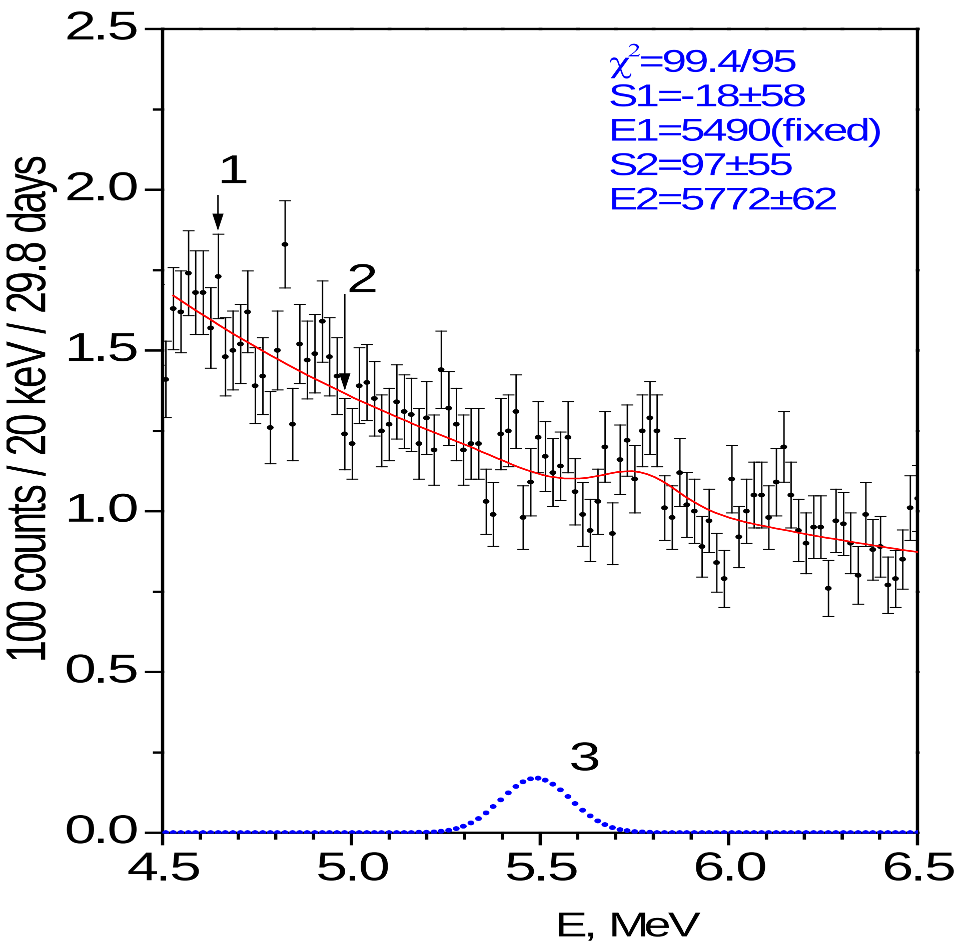


The energy spectrum of the BGO detector measured (1) in anticoincidence and (2) in coincidence with the muon veto. The position of the expected 5.5 MeV axion peak is denoted by an arrow. In inset the spectrum measured with Pu-Be neutron source is shown.

Two intense peaks with the energies 1.46 MeV and 2.614 MeV are induced by ^{40}K and ^{208}Tl decays. The peaks were used for energy calibration and stability.
The dependence of energy resolution of BGO detector vs energy σ(E) = C · √E . *The parameter* C *was found to be 0.04 MeV$^{1/2}$. The values of* σ(E) *determined from the background spectrum are in good agreement with the measurements performed with 60Co and 207Bi standard calibration souses. The expected deviation of the 5.5 MeV peak due to the axion absorption is* σ(5.5 MeV)=93 keV.

Eur. Phys. J. C (2013) 73:2490

Результаты подгонки



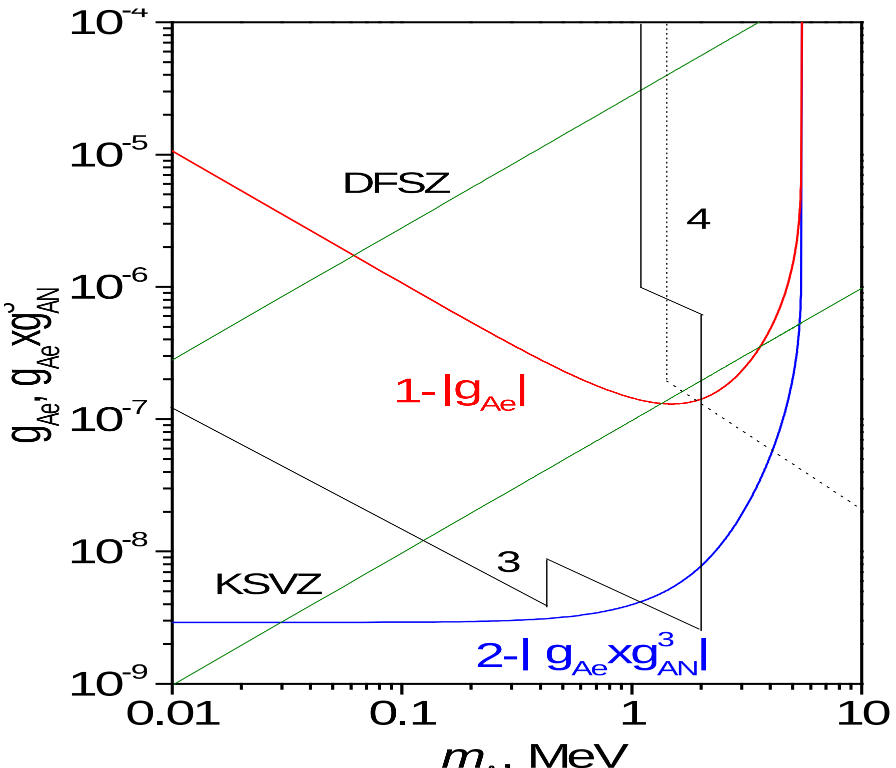
Energy spectrum measured by BGO detector in 4.5 -6.5 MeV interval. The response function of BGO for 5.5 MeV electrons is shown (line 3).

The spectrum measured in the range of (4.5-6.5) MeV was fitted by a sum of exponential and two Gaussian functions:

$$N(E) = a + b \times \exp(cE) + \sum_{i=1}^{2} \frac{S_i}{\sqrt{2\pi\sigma_i}} \exp[-\frac{(E_i - E)^2}{2\sigma_i^2}]$$

Here a, b and c are parameters of the function describing the smooth background. The position and dispersion of the first Gaussian peak corresponded to the desired-peak parameters: E1 = 5.49 MeV is the axion peak position, σ1 = 0.093 MeV. Because a small unknown peak can be seen at ~ 5.8 MeV, the second Gaussian was added to the fitting function. We attribute this peak to the intense 5.824 MeV γ-line resulting in the capture of thermal neutrons by 113Cd. The intensity of the 5.49 MeV peak was found to be S1 = 18±58, this corresponds to the upper limit on the number of counts in the peak, S_{lim} = 85 at a 90% confidence level

Пределы на константы g_{Ae} и g_{Ae} x g_{AN}



The limits on the g_{Ae} coupling constant obtained by 1- present work, 2 - present work for $|g_{Ae}xg^3_{AN}|$, 3- solar and reactor experiments (Borexino, Texono), 4- beam dump experiments.

The expected number of events S due to axio-electric absorption is:

$$S = \varepsilon \cdot N_{Bi} \cdot T \cdot \Phi_A \cdot \sigma_{Ae}$$

where ε=0.67-registration efficiency, $N_{Bi}=4.76\cdot10^{24}$- number of Bi atoms, $T=2.57\cdot10^6$ – time of measurement. The axion flux Φ_A is proportional to the constant $(g^3_{AN})^2$ and cross section σ_{Ae} is proportional g_{Ae}^2 . As a result, the value S depends on the product of the axion coupling with the electron and nucleons – $(g_{Ae})^2 \times (g^3_{AN})^2$. The relation $S \leq S_{lim}$ obtained in the experiment, limits the possible values $|g_{Ae} \times g^3_{AN}|$ and m_A as it is shown in figure.

As a result, the new upper limit on $|g_{Ae}\times g^3_{AN}| < 2.9\cdot10^{-9}$ (90% c.l.) at m_A=1 MeV is obtained. In model of the hadronic axion this restriction corresponds to the limit on the hadronic axion-electron coupling $|g_{Ae}| \leq (1.4\text{-}9.7) \times 10^{-7}$ for axions with masses $0.1< m_A <1$ MeV.

Сцинтиллятор vs Болометр (+Сцинтиллятор)

Eur. Phys. J. C (2014) 74:3035
DOI 10.1140/epjc/s10052-014-3035-8

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Search for axioelectric effect of solar axions using BGO scintillating bolometer

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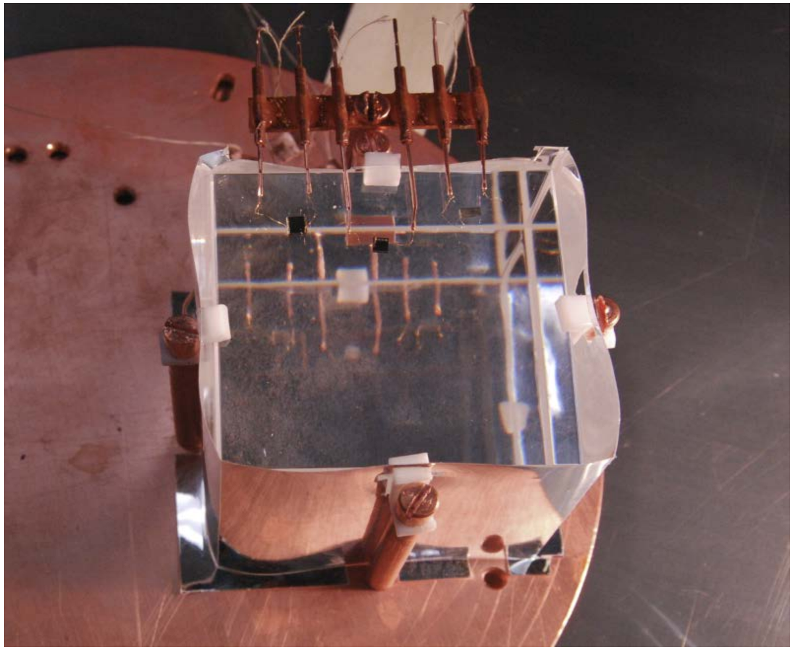
Detector	σ(keV) at 5.5 MeV	S_lim c / d	mass, g
Scintillator	93	85 / 30	2460
Bolometer	16	2.44 / 152	4x890

BGO-bolometer [L. Cardani S.Di Domizio, L.Gironi,JINST 7,(2012)] has some advantages (energy resolution and background level) compared with BGO- scintillator detector.

BGO сцинтилляционный болометр

arXiv:1405.3782v1 [hep-ex] 15 May 2014

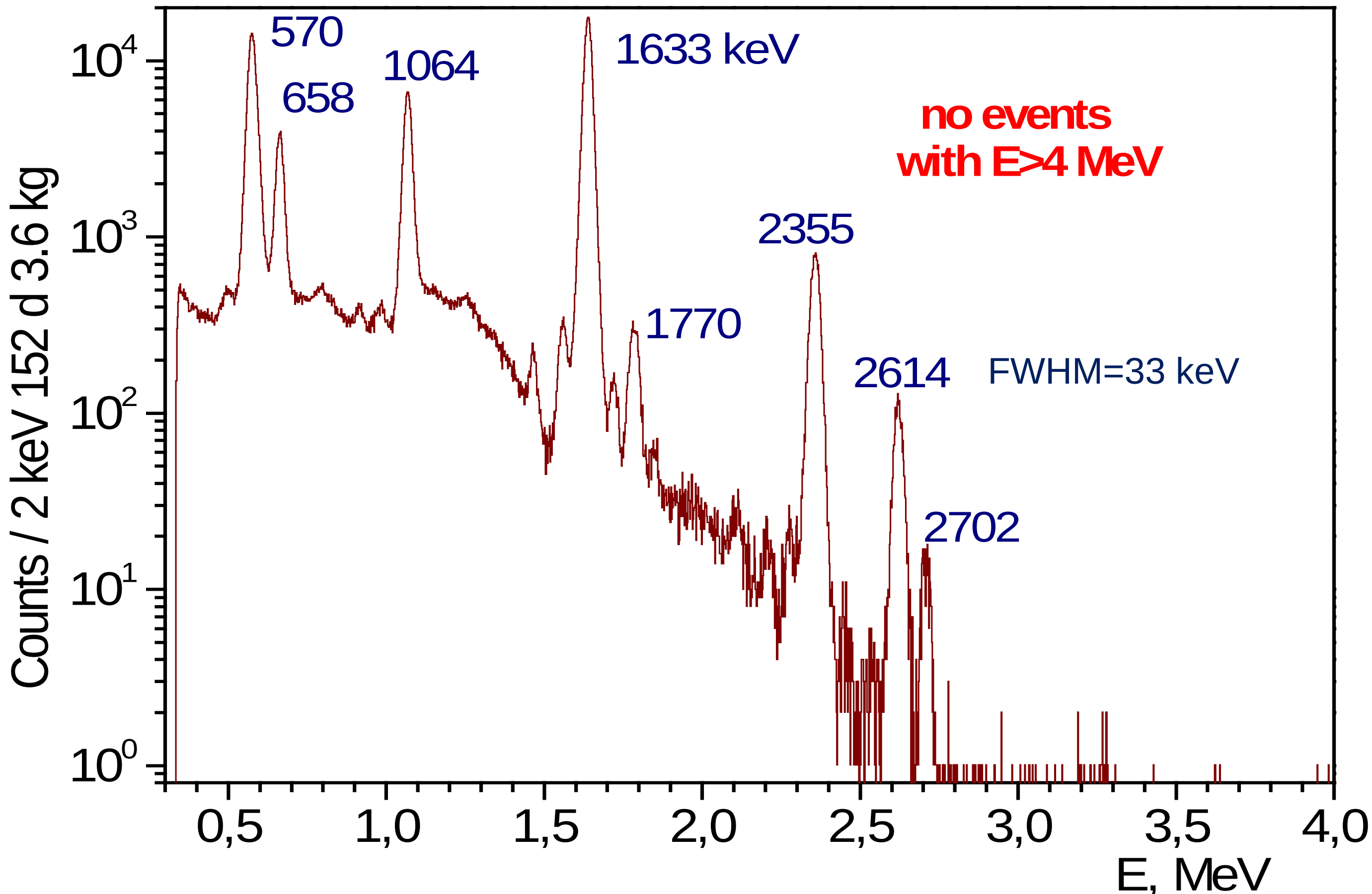
The detector used for this study is an array of BGO scinitillating bolometers containing 1.65 kg of Bi. Four cubic (5x5x5 cm^3) BGO crystals,with all optical faces were arranged in a four-plex module, one single plane set-up. The scintillation light produce by particle interaction in the BGO absorbers was monitored with an auxiliary bolometer made of high-purity germanium, operated as a light detector (LD).The detector was operated for a total live time of 151.7 days.



BGO bolometer
[L. Cardani S.Di Domizio, L.Gironi,JINST 7,(2012)]

The detector was installed in the $^3He/^4He$ dilution refrigerator in the Hall C and operated at a temperature of few mK. The four crystals were housed in a highly pure copper structure, described in [F. Alessandria et al., Astropart. Phys. 35, 839849 (2012)]. Coupled to each bolometer there is a Neutron Transmutation Doped (NTD) Ge-thermistor that acts as a thermometer: recording the temperature rises produced by particle interaction in the absorbers and producing voltage pulses proportional to the energy deposition. These pulses then are amplified and fed into an 18-bit analog-to-digital converter. Details on electronics and on the cryogenic set-up can be found [S. Pirro et al., NIM A 444, 331 (2000) C. Arnaboldi et al., NIM A 559, 826 (2006)]

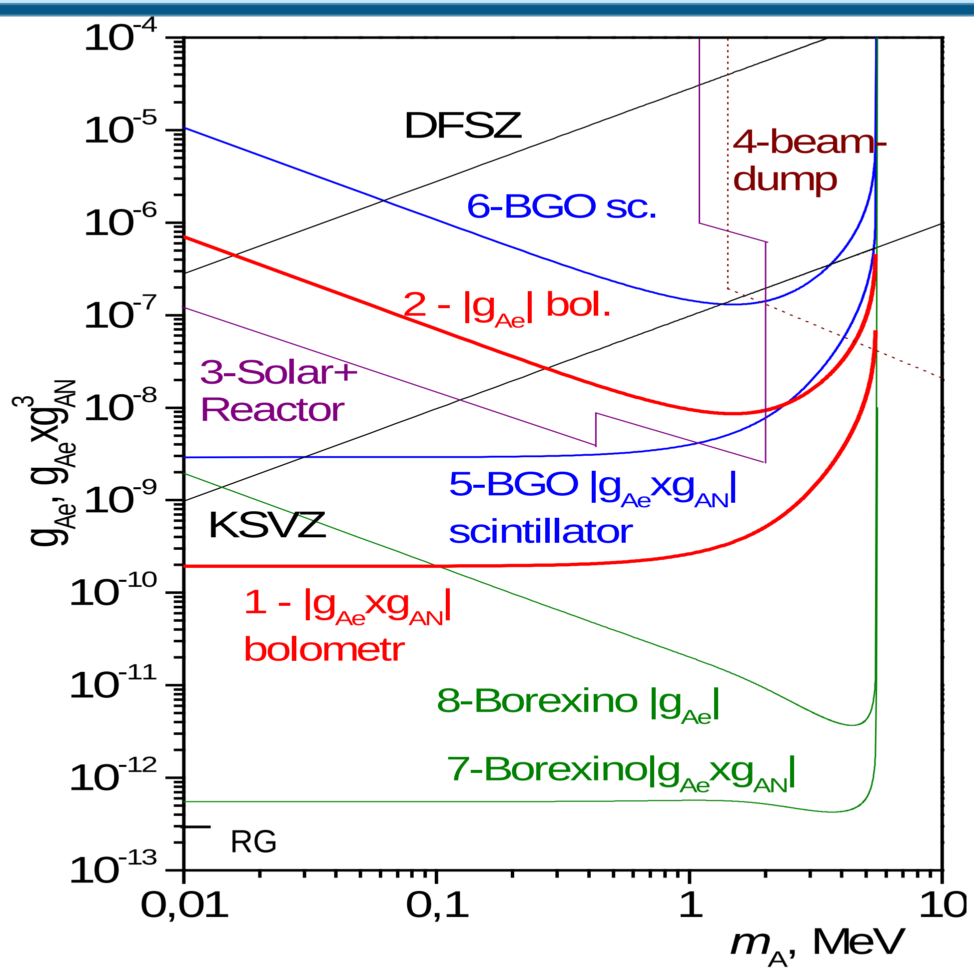
Спектр BGO-болометра за 152 суток



Eur. Phys. J. C (2014) 7:3035

The energy spectrum of the four BGO detectors (β and γ events) measured for 152 days. The most prominent gamma lines are produced by 207Bi decay. The limits on the 5.5 MeV axion flux and cross-section are based on the experimental fact that no events above 4 MeV were observed. The upper limit on the number of axioelectric effects is Slim = 2.44 with 90 % c.l. in accordance with the F–C procedure.

Пределы на $|g_{Ae}\times g_{AN}|$ и $|g_{Ae}|$ для m_A в интервале (0.01-10) МэВ



1,2–BGO bolometer limits $|g_{Ae}\times g^3_{AN}|$ and $|g_{Ae}|$, correspondingly;

3 – solar and reactor experiments;

4 – beam dump experiments;

5,6–BGO scintillator limits $|g_{Ae}\times g^3_{AN}|$ and $|g_{Ae}|$;

7,8–Borexino results for $|g_{Ae}\times g^3_{AN}|$ and $|g_{Ae}|$;

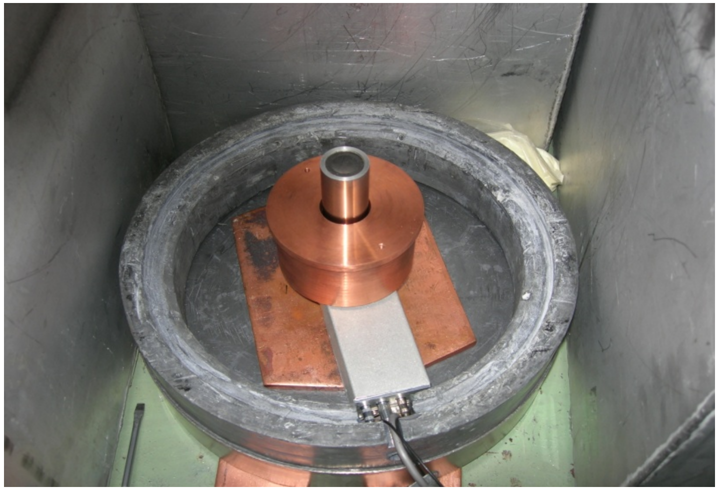
The relation between g_{Ae} and m_A for DFSZ and KSVZ-models are also shown.

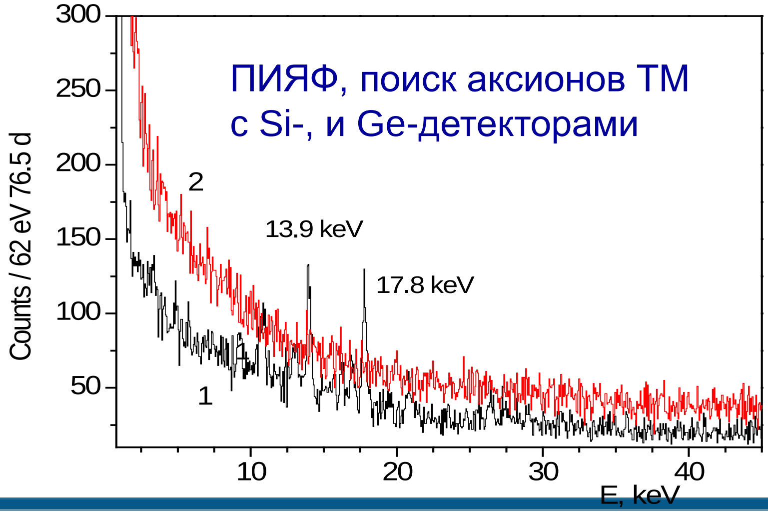
As a result, a model-independent limit has been obtained: $|g_{Ae}\times g^3_{AN}|<1.9\times10^{-10}$ (90% c.l.). These limits are more then one order of magnitude stronger than ones obtained with the 2.5 kg BGO scintillation detector. Unlike our work, Borexino limits were obtained in assumption that the axion interacts through the C.C. process.

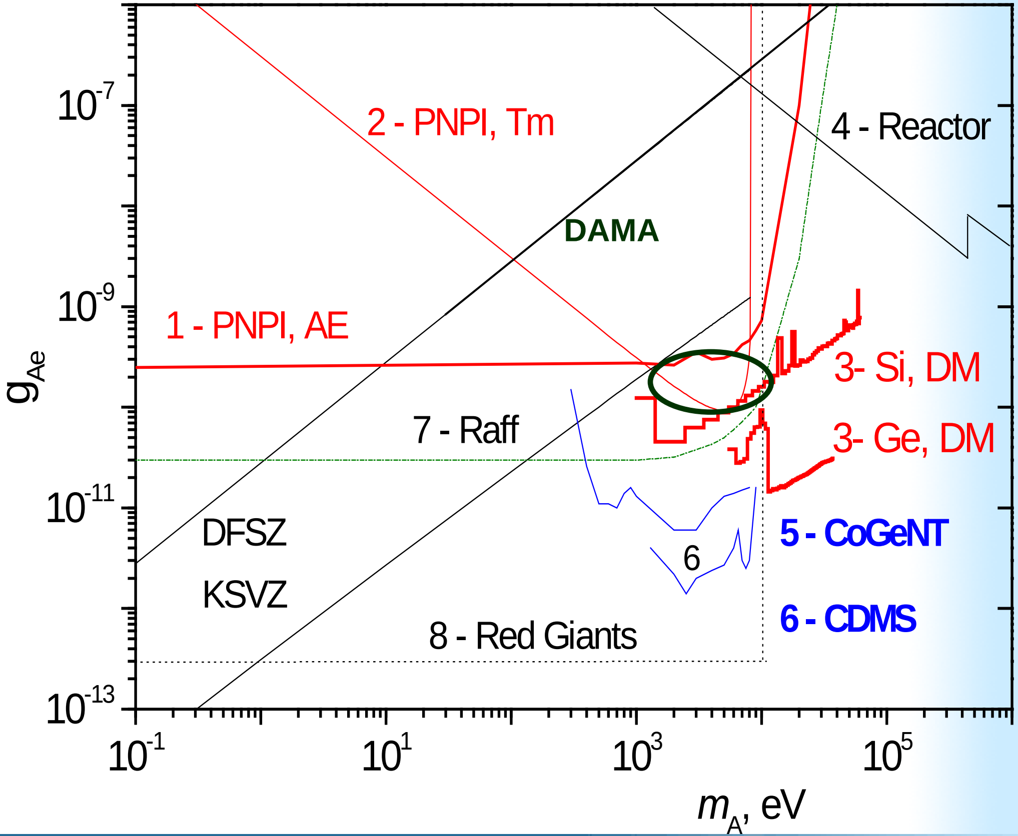
Поиски а.э. эффекта для реликтовых аксионов

Для нерелятивистских аксионов сечение аксио-электрического эффекта пропорционально сечению фотоэффекта для фотонов с энергией равной массе аксиона (Pospelov et al.)

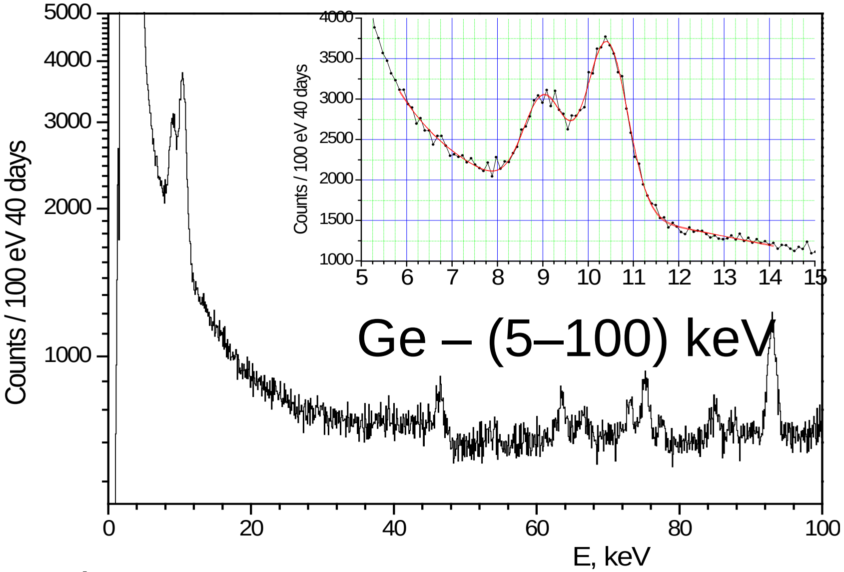
$$\sigma_{ae}(E_A) = \sigma_{pe}(E_\gamma = m_A) \times g_{Ae}^2 \frac{1}{\beta}\left(\frac{3m_A^2}{16\pi\alpha m_e^2}\right)$$



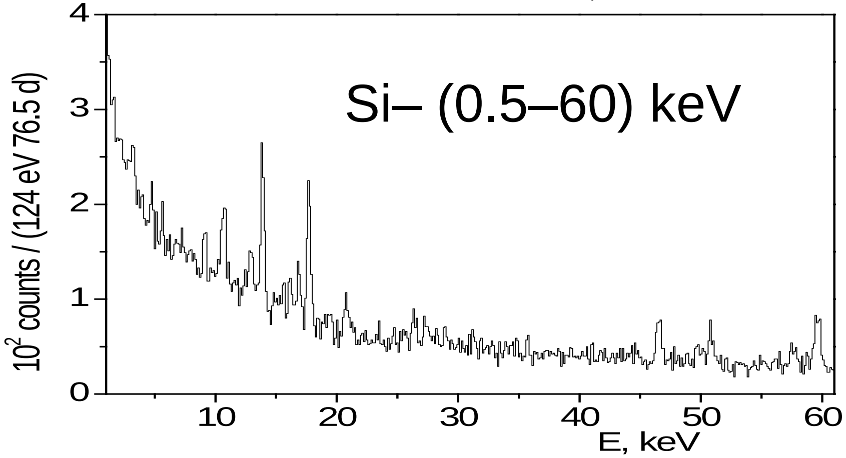


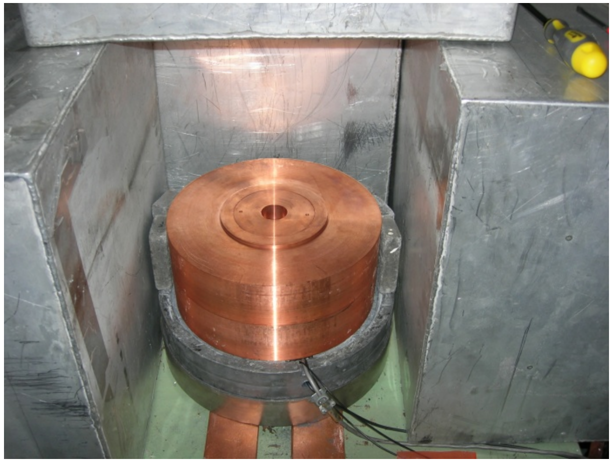


Аксиоэлектрический эффект в Ge и Si



160 см³
40 сут.





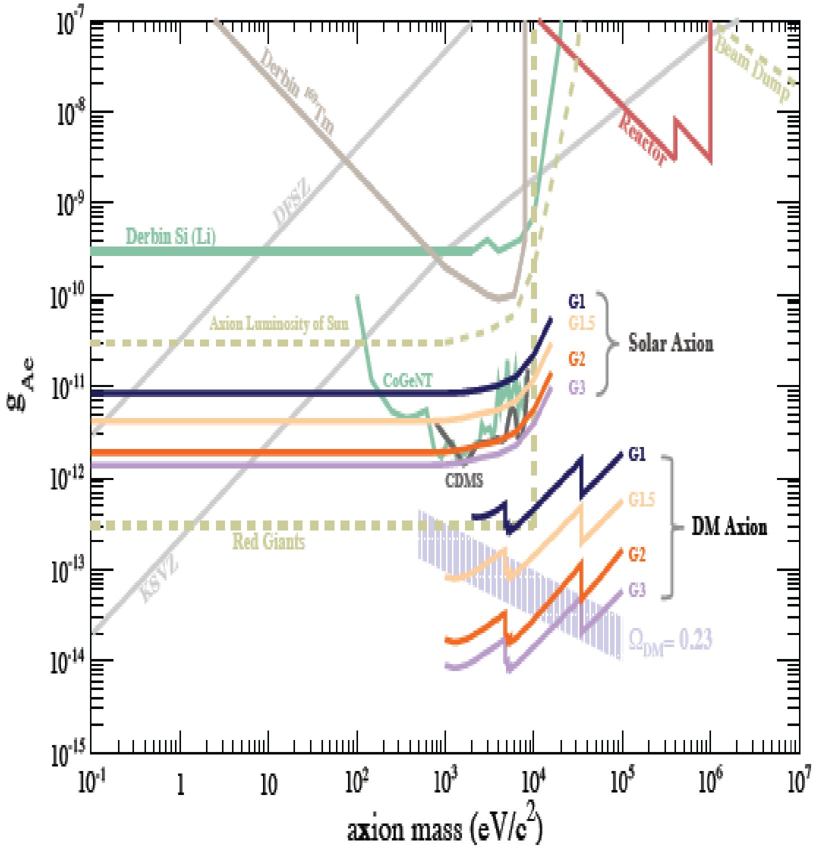
2 см³
77 сут.

Ожидаемый сигнал – монохроматический пик с положением $E = m_A$ и шириной σ, определяемой разрешением детектора.

Пределы на константу связи аксиона с e⁻

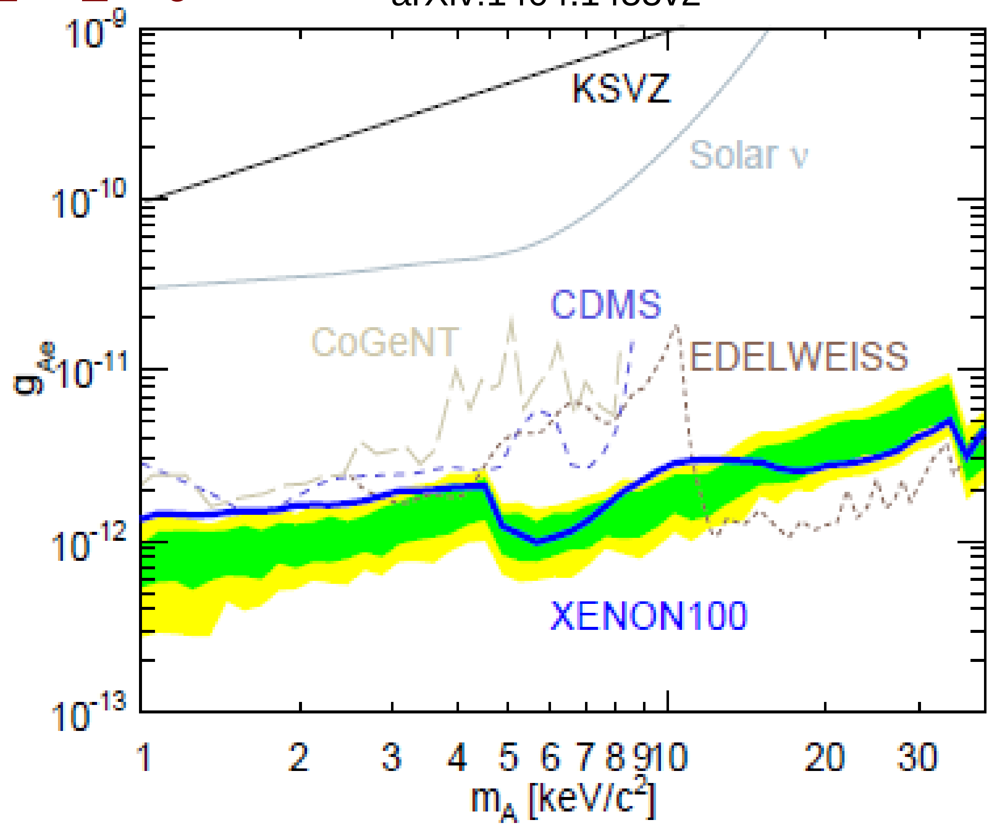
$A + e + Z \rightarrow Z + e$

arXiv:1209.3810v4



Expected Sensitivity to Galactic / Solar Axions based on the Axio-electric Effect in LXenon Dark Matter Detectors g_{Ae}~10^{-14}

arXiv:1404.1455v2



Limits on axion coupling to electrons as a function of the axion mass, under the assumption that axions constitute all the dark matter in our galaxy. gAe ~ 10^{-12}

a.e. effect can be used to look for non relativistic relic axions with mass > 1 keV. In this case, electron with energy = mA-Eb appears that can be detected.

Резонансное возбуждение ядерных уровней

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.

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

Резонансное возбуждение: $A+(Z,N) \to (Z,N)^* \to (Z,N) + \gamma$

$$\sigma(E_A) = 2\sqrt{\pi}\sigma_{0\gamma}\exp\left[-\frac{4(E_A - E_{M1})^2}{\Gamma^2}\right]\left(\frac{\omega_A}{\omega_\gamma}\right)$$

18. W. C. Haxton and K. Y. Lee, Phys. Rev. Lett. **66**, 2557 (1991).
19. S. Mariyama, Phys. Rev. Lett. **75**, 3222 (1995).
20. M. Krçmar, Z. Kreçak, A. Ljubiçic, et al., Phys. Rev. D **64**, 115016 (2001).

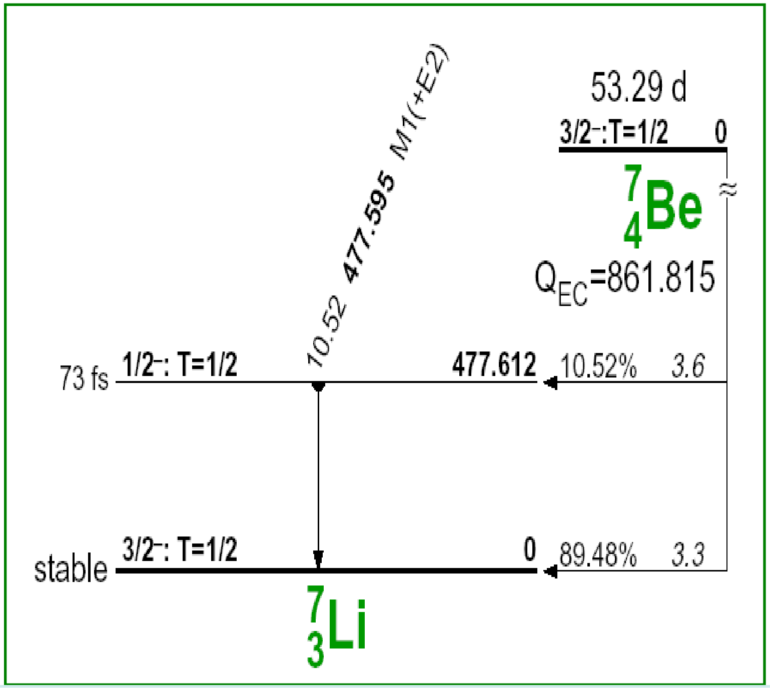
Axions on the Earth can be observed in the resonant absorption reaction by detecting γ rays (or conversion e's) emitted in the process of the deexcitation of the excited nuclear level. The cross section for the resonant absorption of axions is given by the expression similar to the resonant absorption of γ rays that is corrected by the ratio ωA/ωγ where σ0γ is the maximum cross section of the resonant absorption of γ rays. E.G. the experimentally determined $\sigma_{0\gamma}$ value for the ^{57}Fe nucleus is equal to 2.56×10^{-18} cm^2.

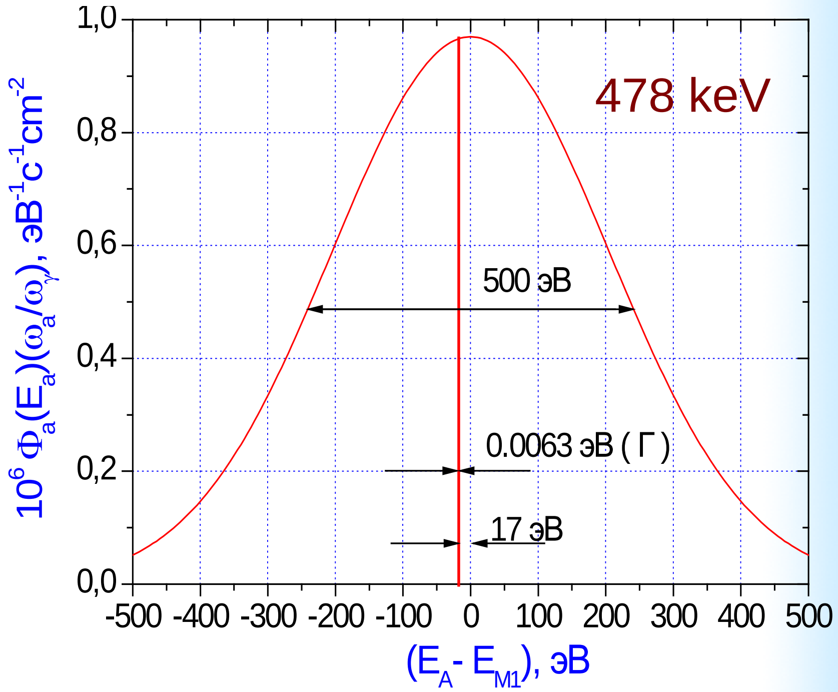
$$\frac{\omega_A}{\omega_\gamma} = \frac{1}{2\pi\alpha}\frac{1}{1+\delta^2}\left[\frac{g_{AN}^0\beta + g_{AN}^3}{(\mu_0 - 0.5)\beta + \mu_3 - \eta}\right]^2\left(\frac{p_A}{p_\gamma}\right)^3$$

The probability of emitting an axion (ω_A/ω_γ) is given by the above expression and depends on g^0_{AN} and g^3_{AN}. Here, p_γ and p_A are the momenta of the photon and axion, respectively; δ is the ratio of the probabilities of the E2 and M1 transitions; μ0 and μ3 are the isoscalar and isovector nuclear magnetic moments, respectively; and β and η are the parameters depending on concrete nuclear matrix elements.

Резонансное возбуждение ядер ^{7}Li

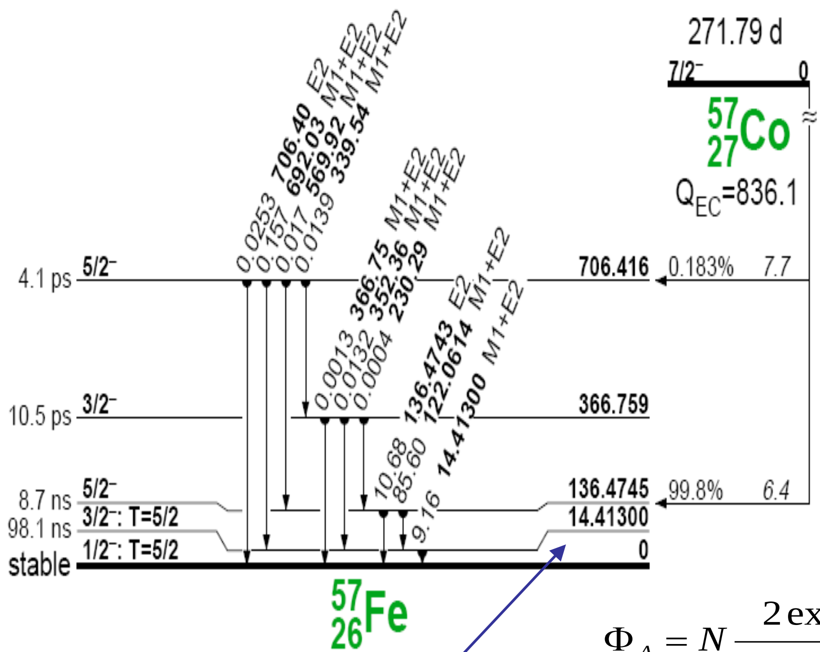
O**ne possible source of axions are the reactions of the main solar cycle. **E**lectron capture reaction* ^{7}Be + e*** $\rightarrow$ ^{7}***Li (***^{7}***Li*) +*** ν_e *with probability ≈10% goes to the first excited state of the nucleus* ^{7}*Li, which is discharged in the γ-quantum transition magnetic type M1. The expected flux of axions, is directly related to the flux of 7Be-neutrinos which on the surface of the Earth is* $4.8 \times 10^9\ \nu / cm^2c$

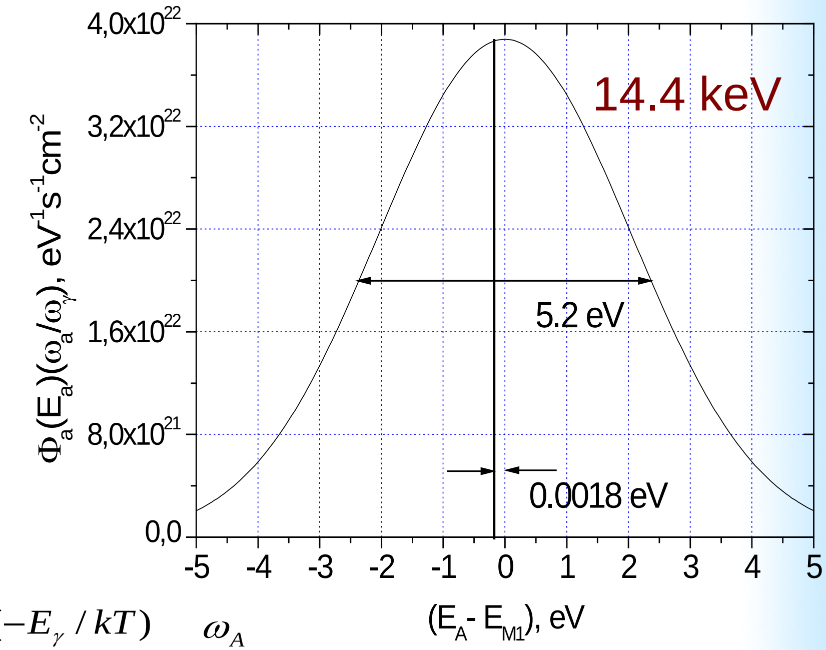




Quasi-monochromatic axions in the laboratory may excite Li-nuclei, γ-quanta with energies of 478 keV can be registered: $A + {}^7Li \rightarrow {}^7Li^* \rightarrow {}^7Li + \gamma$. *Doppler broadening* σ_S *=210* eV, recoil energy 17 eV, own width $\Gamma = 6.3\times10^{-3}$ eV. $\Gamma/\sigma_S \sim 10^{-5}$

Резонансное возбуждение ядер ^{57}Fe



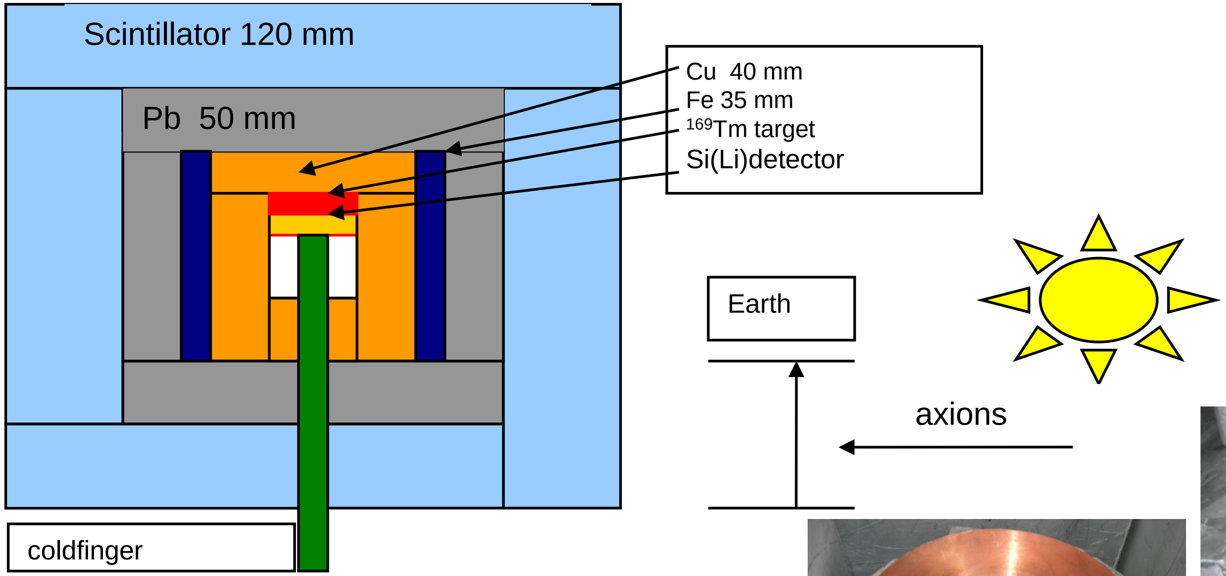


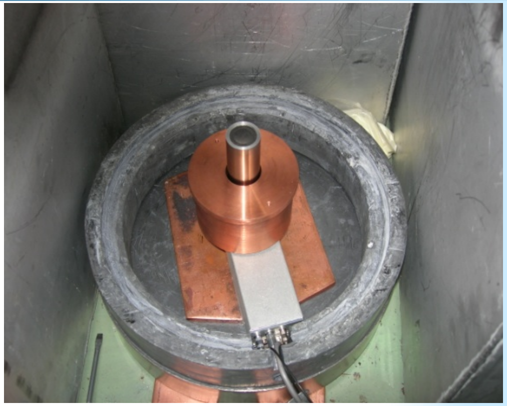
$$\Phi_A = N\frac{2\exp(-E_\gamma/kT)}{1+2\exp(-E_\gamma/kT)}\frac{\omega_A}{\tau_\gamma\omega_\gamma}$$

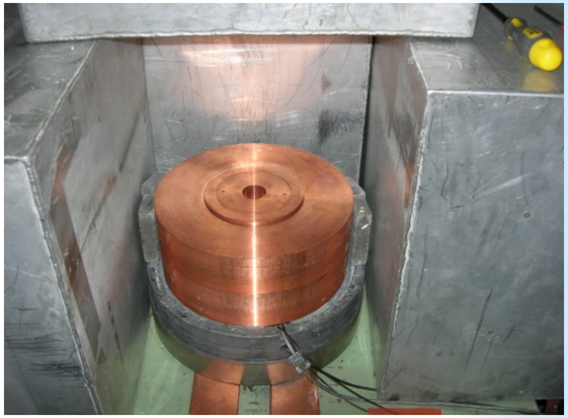
$$\Phi_A(E_{M1}) = 4.15\times 10^{25}\left(\frac{\omega_A}{\omega_\gamma}\right)\ \mathrm{cm^{-2}\,s^{-1}\,keV^{-1}}$$

The most intense flux of solar axions is attributed to the M1 transition in ^{57}Fe nuclei whose level scheme is shown in Figure. The energy of the first excited nuclear level is equal to 14.413 keV, and the electron conversion coefficient is equal to α = 8.5. Owing to the Doppler broadening, the axion spectrum is a Gaussian curve $\Phi_A(E_A)$ with the width $\sigma_S(T) = E_\gamma(kT/M)^{1/2}$, = 2.2 eV. This value is significantly higher than the recoil-nucleus energy (1.8 meV), Doppler broadening of the line at temperature *T*= 300 K of the target nuclei (10 meV), and the own width of the level Γ= 4.7×10^{-9} eV. Thus, the fraction of axions satisfying the resonant-absorption condition is equal to $\sim\Gamma/\sigma_S \sim 10^{-9}$.

Si(Li)- и Ge-детекторы и 57Fe- 7Li-мишени

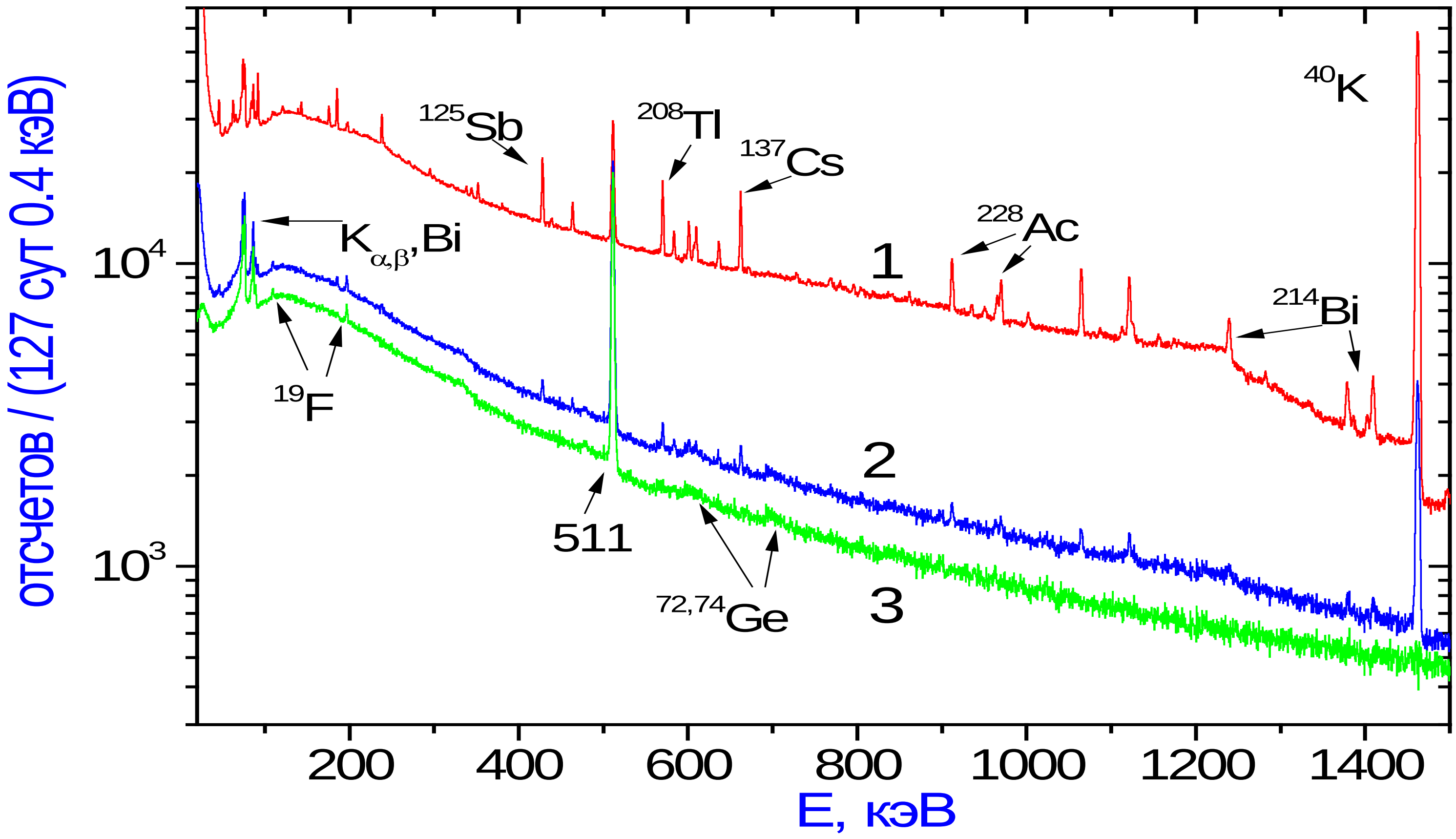






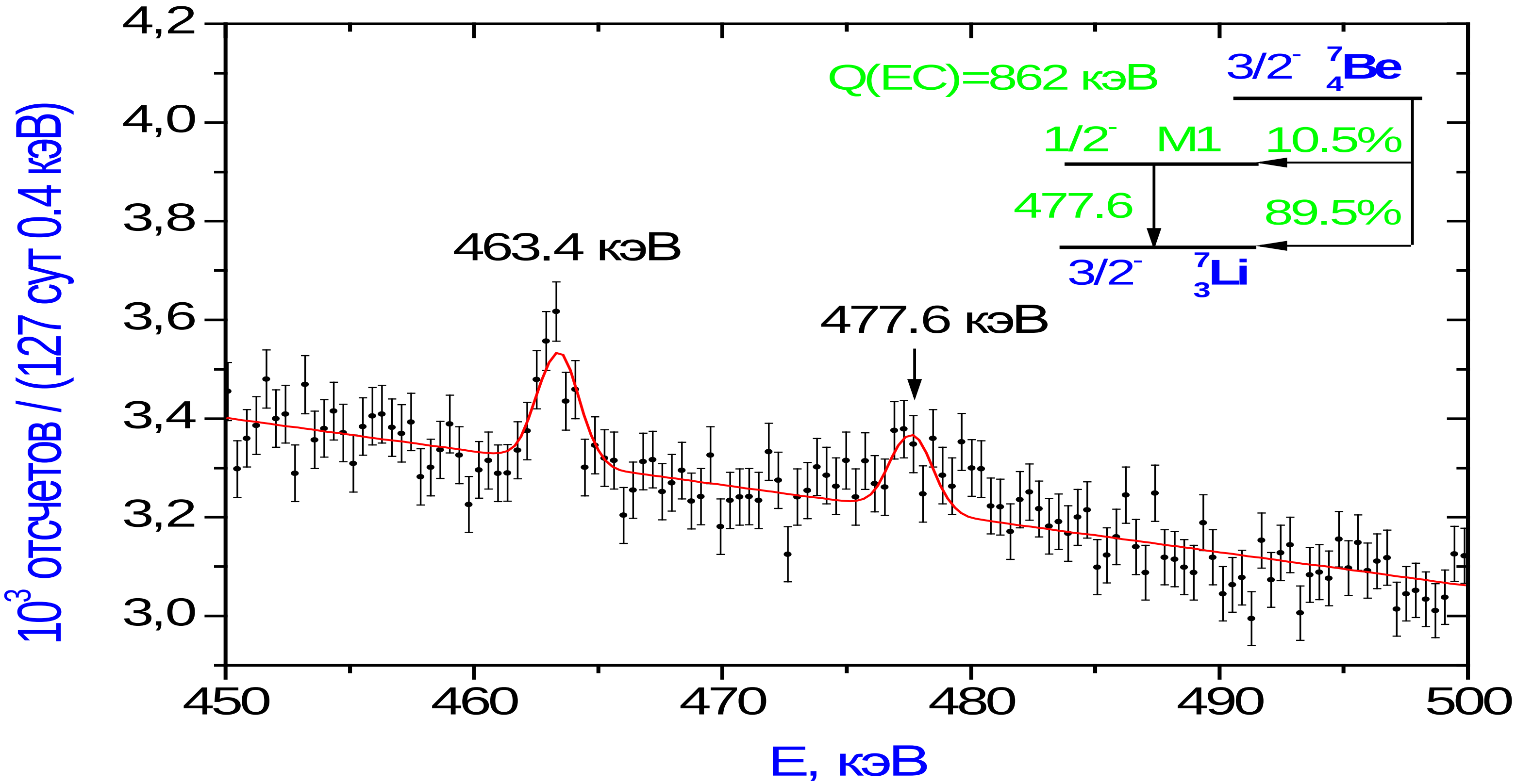
The Si(Li) and Ge detectors and 57Fe and 7Li targets placed inside the low-background setups were used to search for the resonant absorption of monochromatic solar axions.

Спектр Ge детектора, измеренный за 126 .5 суток



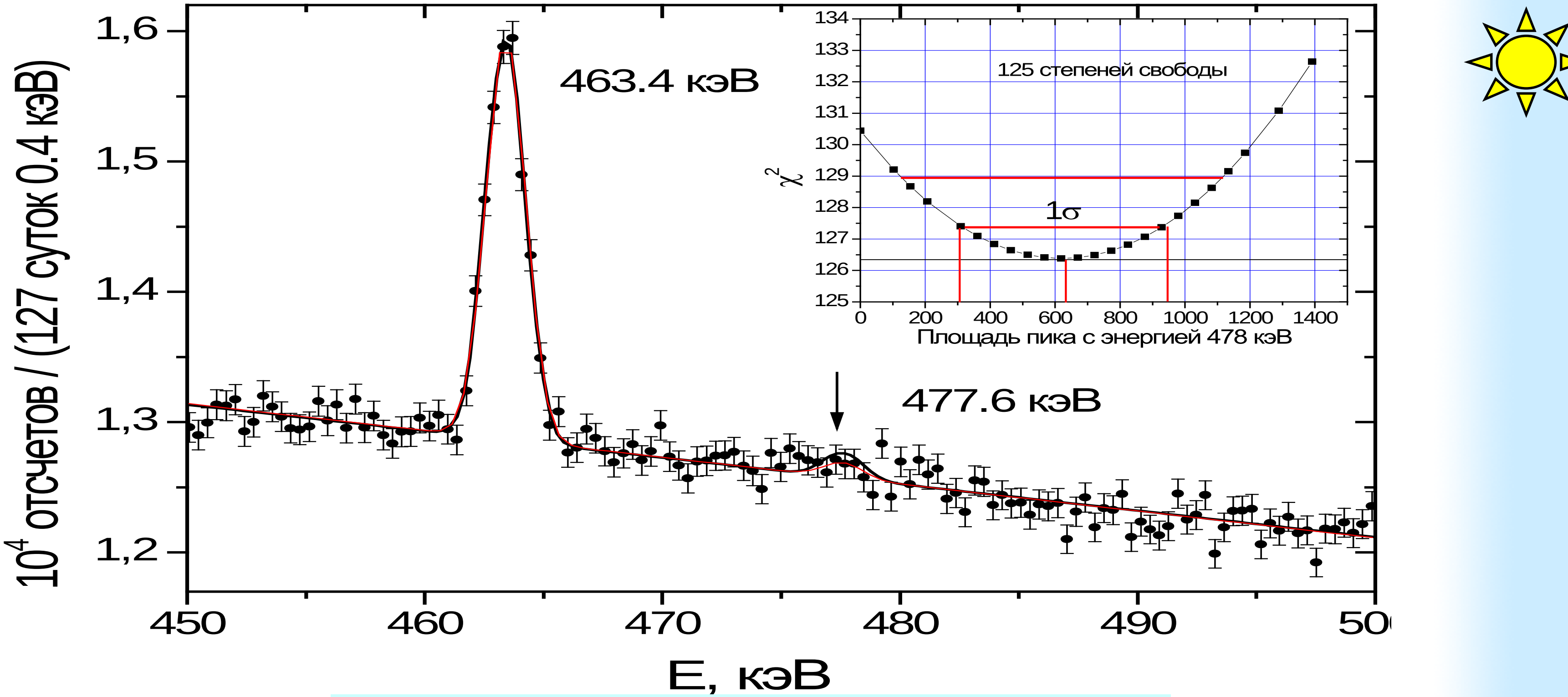
В спектре (1) сигналов Ge-детектора, несовпадающих с сигналом активной защиты, идентифицируется 40 выраженных пиков, связанных с активностью уранового и ториевого семейств, ^{40}К, ^{137}Cs и ^{125}Sb. В спектре (2) сигналов в совпадении с активной защитой наиболее интенсивным является пик 511 кэВ ; Спектр (3) – сигналы в совпадении с активной защитой за вычетом случайных совпадений, количество которых определено из интенсивности пика ^{40}К в спектре 2. Присутствуют пики, соответствующие возбуждению уровней F, из которого была изготовлена оправка мишени и Ge.

Интервал 450-500 кэВ спектра сигналов, зарегистрированных в совпадении с сигналом активной защиты



Измерение спектра Ge-детектора в совпадении с активной защитой позволяет определить вероятность возбуждения первого уровня ^{7}Li космическим излучением. Площадь пика с энергией 463.4 кэВ составила (1200 ± 180) событий, что согласуется с 7% вероятностью случайных совпадений сигналов Ge-детектора и активной защиты. Интенсивность пика с энергией 477.6 кэВ оказывается равной (840 ± 170), что свидетельствует о том, что мы действительно наблюдаем возбуждение данного уровня ^{7}Li ядерно-активной компонентой и мюонами космического излучения.

Интервал 450-500 кэВ спектра сигналов, зарегистрированных в антисовпадении с сигналом активной защиты



$$R = NT\varepsilon\sigma_0\xi\Phi_\nu({}^7Be)\left(\frac{\Gamma}{\sigma_S}\right)\left(\frac{\omega_a}{\omega_\gamma}\right)^2 < S_{\lim}$$

Определенное значение S= 630±320 событий, что соответствует верхнему пределу на массу аксиона ***m_A ≤ 16 кэВ****. Данный результат является вдвое более строгим, чем полученный в предыдущих работах и практически закрывает окно возможных масс аксиона до значения энергии* ***М1-перехода ядра ^{57}Fe (14.4 кэВ),*** *следующего возможного наиболее интенсивного источника монохроматических солнечных аксионов.*

Скорость поглощения аксионов ~ $\Phi_A\sigma$

$$\Phi_A(E_{M1}) = 4.15 \times 10^{25} \left(\frac{\omega_A}{\omega_\gamma}\right) \quad [\mathrm{cm^{-2}\ s^{-1}\ keV^{-1}}].$$

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

$$\frac{\omega_A}{\omega_\gamma} = \frac{1}{2\pi\alpha}\frac{1}{1+\delta^2} \times \left[\frac{g^0_{AN}\beta + g^3_{AN}}{(\mu_0 - 0.5)\beta + \mu_3 - \eta}\right]^2 \left(\frac{p_A}{p_\gamma}\right)$$

$$g^0_{AN} = -\frac{m_N}{6 f_A}\left[2S + (3F - D)\frac{1+z-2w}{1+z+w}\right]$$

$$g^3_{AN} = -\frac{m_N}{2 f_A}\left[(D+F)\frac{1-z}{1+z+w}\right].$$

$$g^0_{AN} = -4.03 \times 10^{-8}(m_A/1\ \mathrm{eV})$$

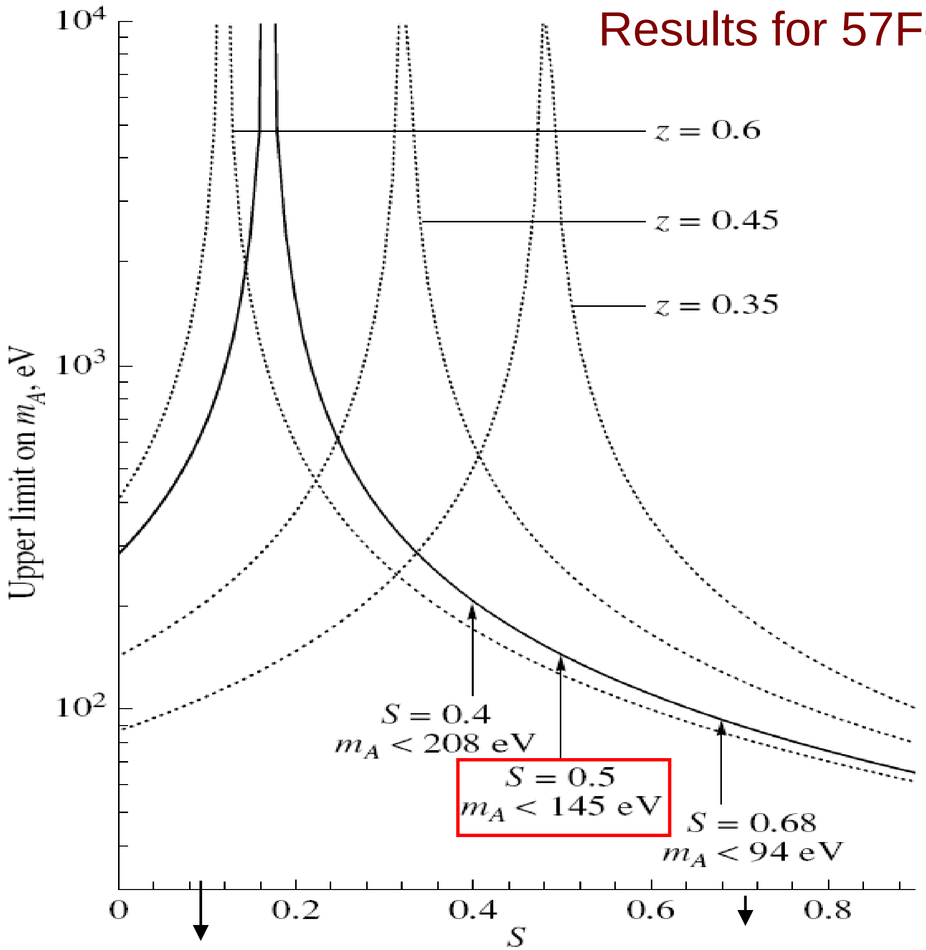
$$g^3_{AN} = -2.75 \times 10^{-8}(m_A/1\ \mathrm{eV})$$

β = -1.19 η =0.8
Haxton, Lee, PRL 66, (1991)
S = 0.5 (0.15-0.53)
z = 0.56 (0.35–0.6)

$$R_A\ [\mathrm{s^{-1}}] = \begin{cases} 1.56 \times 10^{-3}(\omega_A/\omega_\gamma)^2, \\ 5.16 \times 10^{-3}(g^0_{AN}\beta + g^3_{AN})^4 (p_A/p_\gamma)^6 \\ 9.29 \times 10^{-34}(m_A)^4 (p_A/p_\gamma)^6. \end{cases}$$

The expected rate of resonance axion absorption by the ^{57}Fe nucleus depends on the probability for axion emission ωA/ωγ -> the axion–nucleon coupling constants $(g^0_{AN}\beta + g^3_{AN})^4$ -> and the axion mass. The numerical relations are obtained for KSVZ model with concrete values of parameters S, z, β, η.

Верхний предел на m_A для KSVZ аксиона (от S и z)



Results for 57Fe:

$$\omega_A/\omega_\gamma \leqslant 1.63 \times 10^{-11},$$

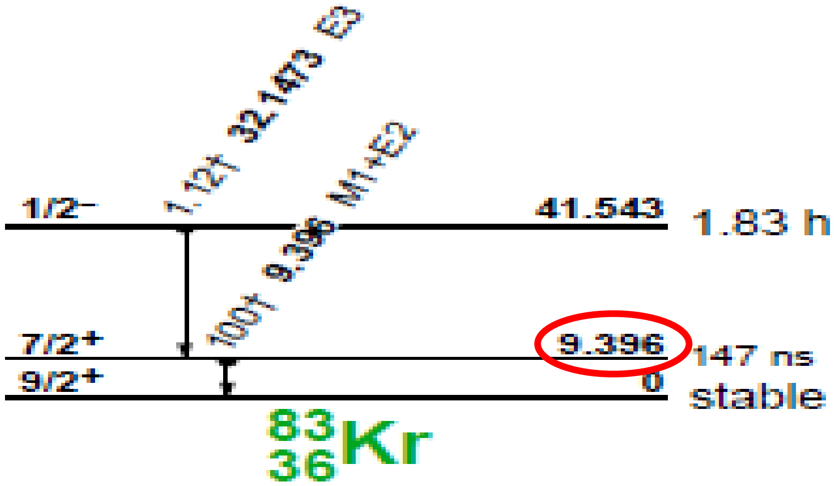
$$\left|-1.19 g_{AN}^0 + g_{AN}^3\right| \leqslant 3.0 \times 10^{-6}$$

$$m_A \leqslant 145 \text{ eV},$$

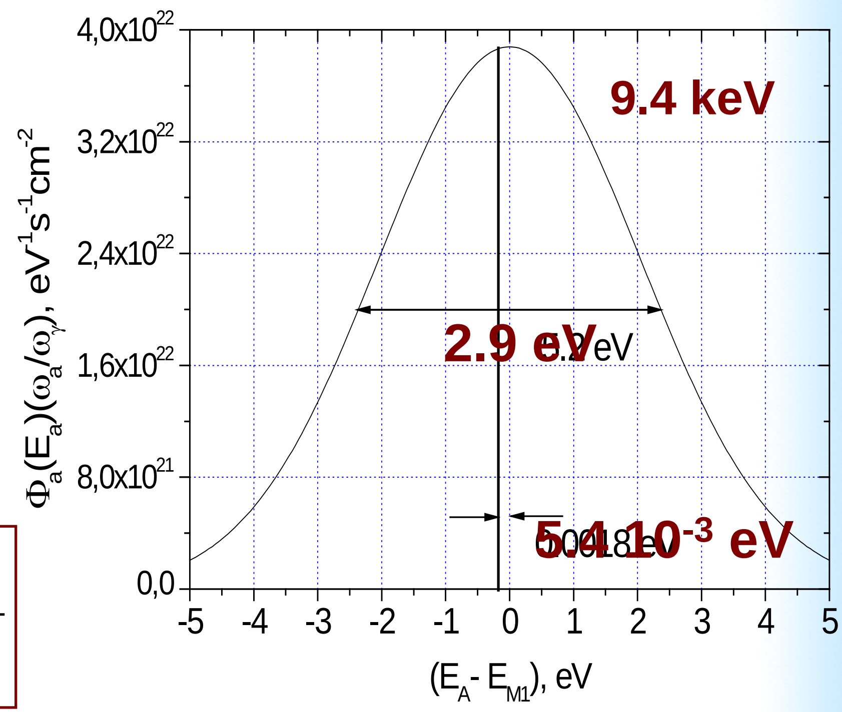
One can show that, if the values of S and z satisfy the relation S = 1–1.5(z ± 0.01), the axion emission probability ωA/ωγ is close to zero. A negative value of the parameter β, together with broad intervals of possible values of S and z, leads to a large uncertainty in the expected probability for axion emission in the 14.4-keV M1 transition in the 57Fe nucleus, and this is a serious flaw in the present searches for such axions.

The upper limit on the hadronic-axion mass depends strongly on specific values of the parameters β, η,S and z. The uncertainty in the value of the parameter S changes substantially the mass limit: mA< 208 eV at S = 0.4 and mA< 94 eV at S = 0.68. Moreover, no limit on the hadronic-axion mass can be obtained at S ≈ 0.17 since $|g^0_{AN}\beta + g^3_{AN}|$ then vanishes.

Резонансное возбуждение ядер ^{83}Kr



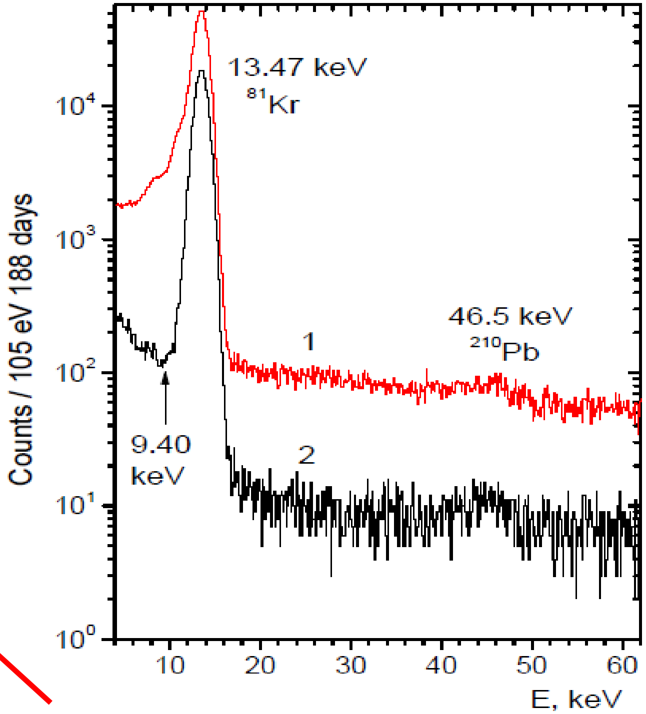
$$\Phi_A = N\frac{2\exp(-E_\gamma/kT)}{1+2\exp(-E_\gamma/kT)}\frac{\omega_A}{\tau_\gamma\omega_\gamma}$$



The flux of solar axions is attributed to the M1 transition in ^{83}Kr nuclei whose level scheme is shown in Figure. The energy of the first excited nuclear level is equal to 9.4 keV, and the electron conversion coefficient is equal to α = 17.1. ***Owing*** *to the Doppler broadening, the axion spectrum is a Gaussian curve $\Phi_A(E_A)$ with the width $\sigma_S(T) = E_\gamma(kT/M)^{1/2}$,* = 1.23 eV. **T**his value is significantly higher than the recoil-nucleus energy (0.5 meV), Doppler broadening of the line at temperature *T*= 300 K of the target nuclei (5.4 meV), and **the** own width of the level $\Gamma = 3.0\times10^{-9}$ eV. Thus, the fraction of axions satisfying the resonant-absorption condition is equal to $\sim\Gamma/\sigma_S \sim 10^{-9}$.

Поиск солнечных аксионов, излучаемых в M1-переходе ядра ^{83}Kr (ИЯИ + ПИЯФ)

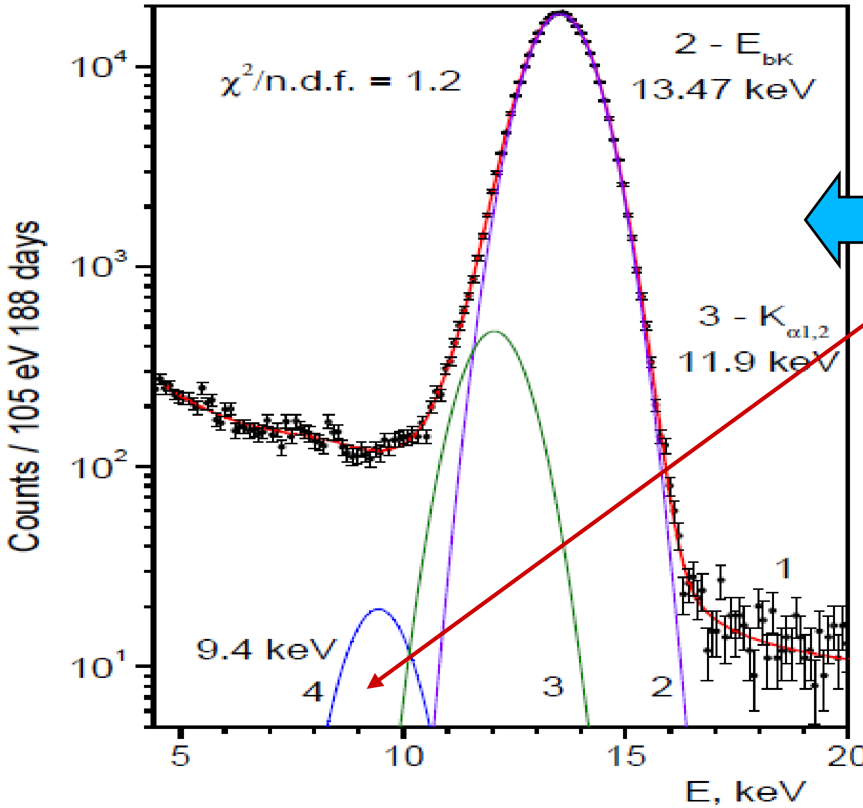
Проведен поиск аксионов с энергией 9.4 кэВ, излучаемых в M1-переходе ядер ^{83}Kr на Солнце, с помощью реакции резонансного поглощения: **A + ^{83}Kr → ^{83}Kr* → ^{83}Kr + γ (9.4 кэВ).** Для регистрации γ-квантов и электронов, возникающих в результате разрядки ядерного уровня, использовалась пропорциональная газовая камера, заполненная криптоном и размещенная в низкофоновой установке в подземной лаборатории **Баксанской нейтринной обсерватории.**



***Слева** – две пропорциональные Kr-камеры с первым слоем пассивной защиты. **В центре** - спектр Kr-камеры, измеренный за 188 сут. **Справа** – гора Андырчи, под которой расположена **БНО ИЯИ** на глубине 4800 м.в.э..*

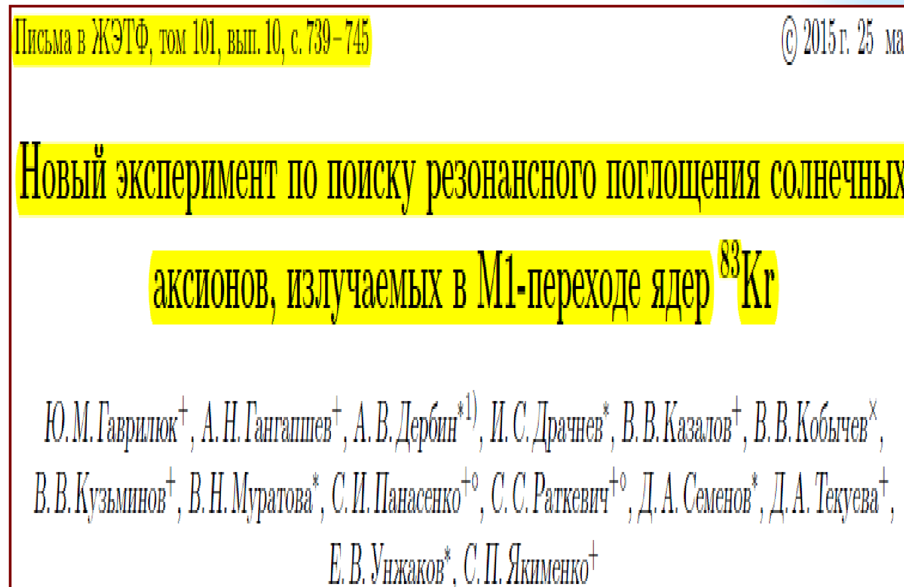
Поиск солнечных аксионов: ^{83}Kr – новое ограничение на массу адронного аксиона

В результате установлено новое ограничение на изоскалярную и изовекторную константы связи аксиона с нуклонами **$|g_{AN}^3 - g_{AN}^0| \leq 1.29\times10^{-6}$**, которое в модели адронного аксиона приводит к **новому** верхнему пределу на массу аксиона **$m_A \leq 100$ эВ (95% у.д.).** Предыдущий предел улучшен в 1.5 раза.



Результаты подгонки спектра Kr-камеры в области «аксионного» пика.

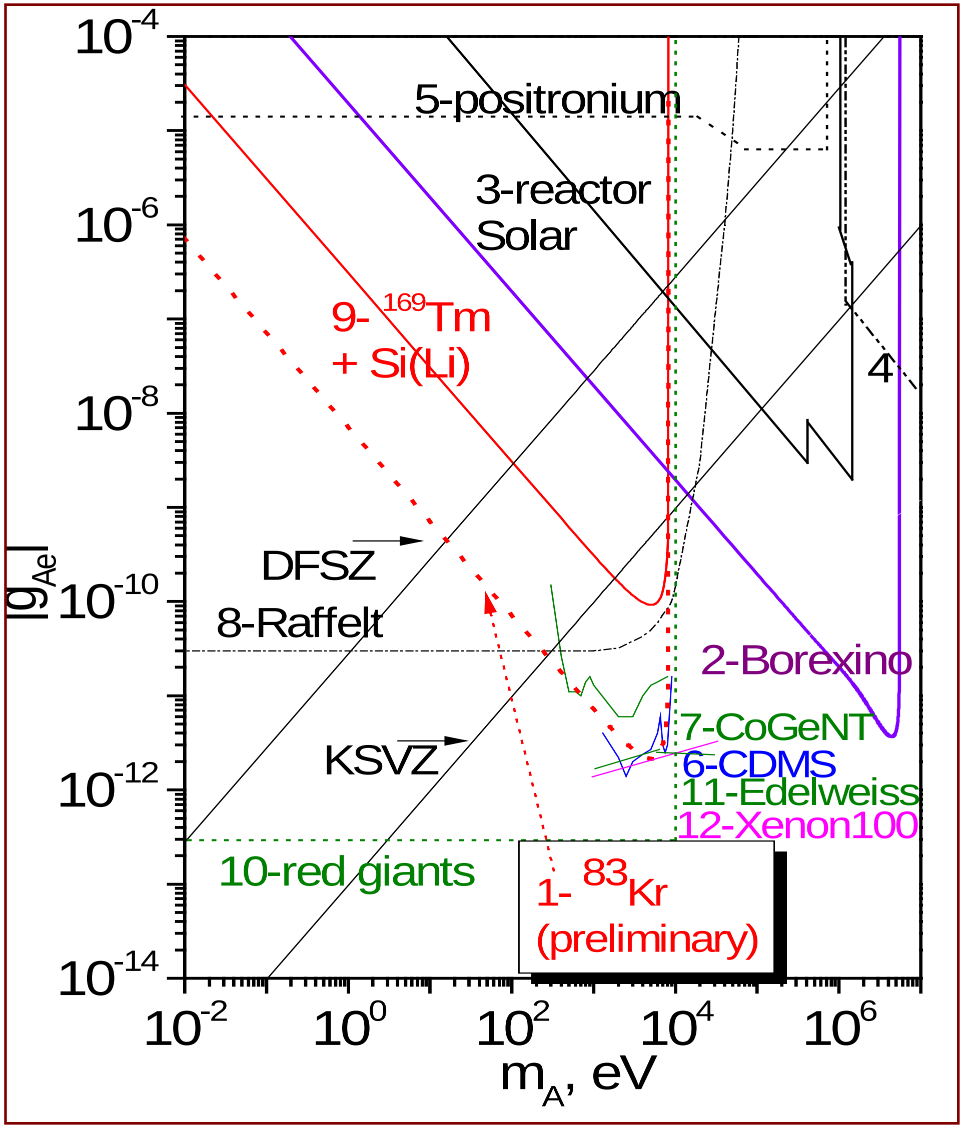
Энергетический спектр в интервале 5-20 кэВ, измеренный Kr-детектором, и его основные компоненты. Ожидаемый вклад от взаимодействия аксионов показан синей сплошной линией 4. Работа выполнена совместно с ИЯИ РАН


Письма в ЖЭТФ, том 101, вып. 10, с. 739–745 © 2015 г. 25 мая

Новый эксперимент по поиску резонансного поглощения солнечных аксионов, излучаемых в M1-переходе ядер ^{83}Kr

Ю. М. Гаврилюк+, А. Н. Гангапшев+, А. В. Дербин*1), И. С. Драчнев*, В. В. Казалов+, В. В. Кобычев×, В. В. Кузьминов+, В. Н. Муратова*, С. И. Панасенко+○, С. С. Раткевич+○, Д. А. Семенов*, Д. А. Текуева+, Е. В. Унжаков*, С. П. Якименко+

^{83}Kr: пределы на g_{Ae} и m_A



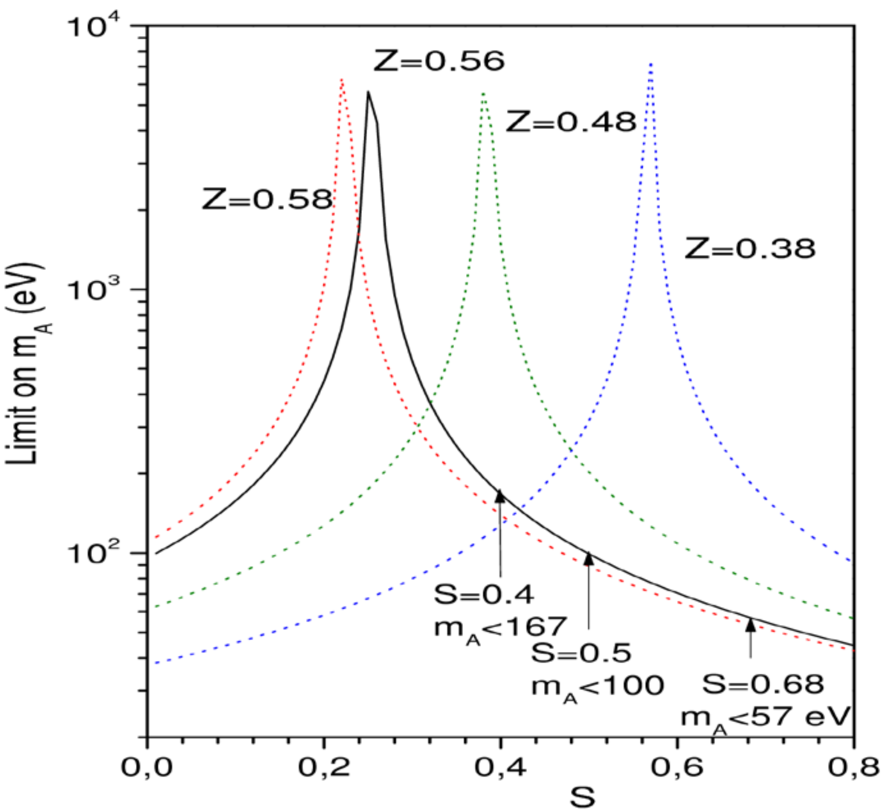
A search for resonant absorption of the solar axion by ^{83}Kr nuclei was performed using the proportional counter installed inside the low-background setup at the Baksan Neutrino Observatory. ***The*** *obtained model independent upper limit on axion-nucleon couplings allowed us to set the new upper limit on the hadronic axion mass with the generally accepted values S=0.5 and z=0.56.*

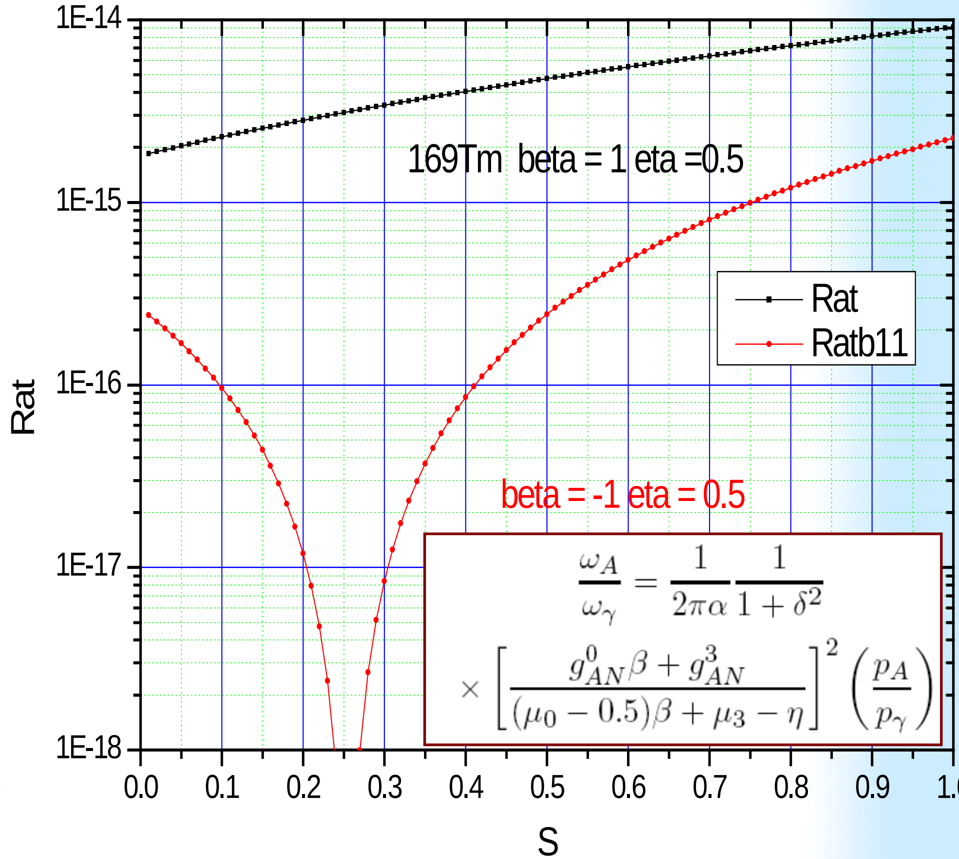
$$|g^3_{AN} - g^0_{AN}| \le 1.29 \times 10^{-6},$$

$$m_A \le 100 \text{ eV at } 95\% \text{ C.L.}$$

The obtained limit on axion mass strongly depends on the exact values of the parameters S and z.

^{83}Kr: пределы на mA в зависимости от S и z

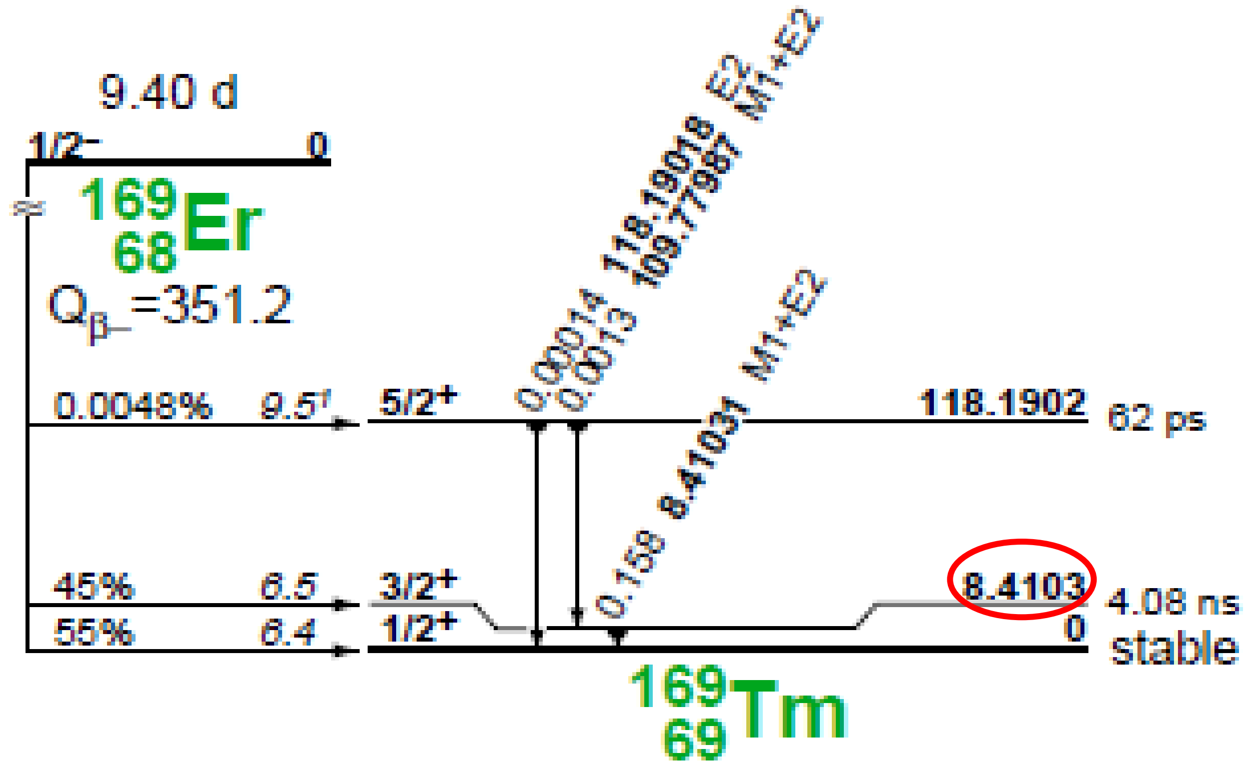




$$\frac{\omega_A}{\omega_\gamma} = \frac{1}{2\pi\alpha}\frac{1}{1+\delta^2} \times \left[\frac{g^0_{AN}\beta + g^3_{AN}}{(\mu_0 - 0.5)\beta + \mu_3 - \eta}\right]^2 \left(\frac{p_A}{p_\gamma}\right)$$

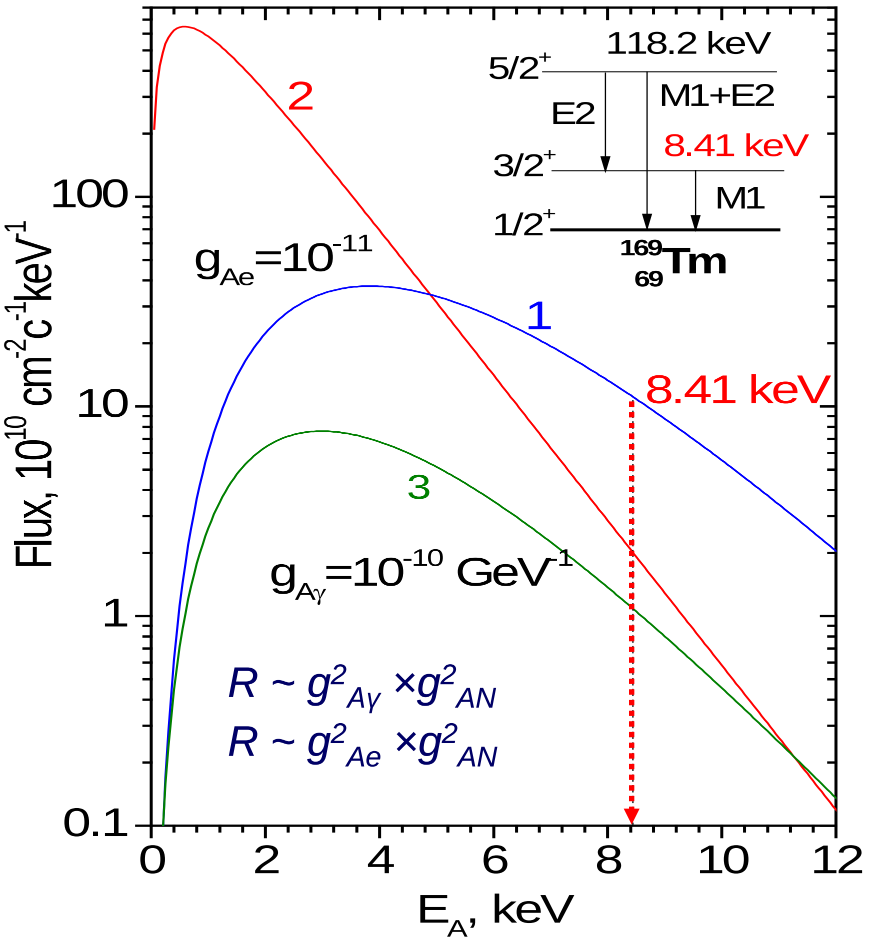
A negative value of the parameter β, together with broad intervals of possible values of S and z, leads to a ***la****rge uncertainty in the expected probability for axion emission in the 9.4-keV M1 transition in the 83Kr nucleus, and this is a serious flaw in the present searches for such axions. The obtained limit on axion mass strongly depends on the exact values of the parameters S and z.* ***But*** *this is not the case for the other nucleus - 169Tm.*

Схема уровней ядра 169Tm



For our experiment we have chosen the 169Tm nucleus as a target. Tm has one stable isitipe. Axion absorption should lead to the excitation of low-lying nuclear energy level: A+$_{169}$Tm→ $_{169}$Tm→$_{169}$Tm+γ(8.41 keV). The energy of the first nuclear level (3/2+) is equal to 8.41 keV, the axion flux at this energy is only 7 times less than at the maximum. The 8.41 keV nuclear level discharges through M1-type transition with E2-transition admixture value of δ2 = 0.11%. The electron conversion ratio e/γ = 263, maximum cross section of γ-ray absorption is 2.6×10^{-19} cm^2.*

Резонансное поглощение ядрами ^{169}Tm



1,2—the spectra of the axions produced by the Compton process and the bremsstrahlung ($g_{Ae}=10^{-11}$). 3—spectrum of the axions produced by the Primakoff effect ($g_{A\gamma}=10^{-10}$ GeV^{-1}). The level scheme of the ^{169}Tm nucleus is shown in the inset.

The rate of solar axion absorption by the 169Tm:

$$R_A = \pi\sigma_{0\gamma}\Gamma\frac{d\Phi_A}{dE_A}(E_A = 8.4)\left(\frac{\omega_A}{\omega_\gamma}\right),$$

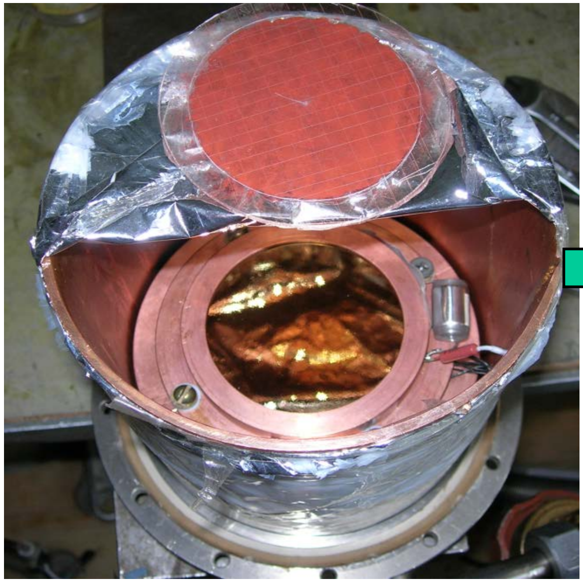
where $\sigma_{0\gamma}$ is a maximum cross section of γ-ray absorption. The experimentally derived value of $\sigma_{0\gamma}$ for ^{169}Tm nucleus is 2.6×10^{-19} cm^2. Width of energy level $\Gamma = 1.13\times10^{-10}$ keV.

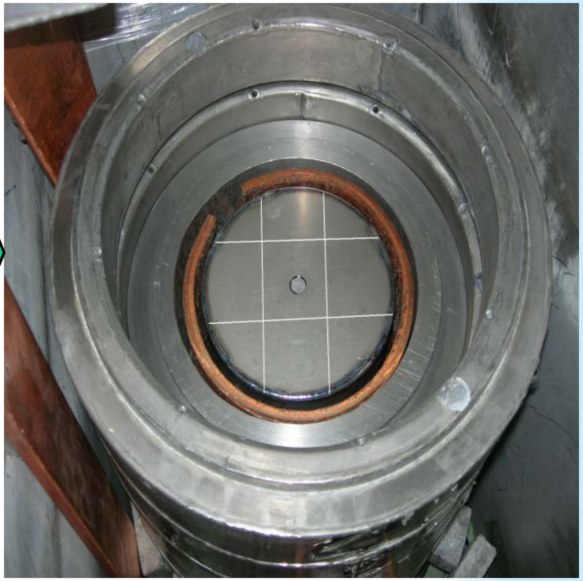
The detection probability of the axions is determined by the product $g^2_{A\gamma}\times g^2_{AN}$ and $g^2_{Ae}\times g^2_{AN}$ which is preferable for small $g_{A\gamma e}$ values.

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)

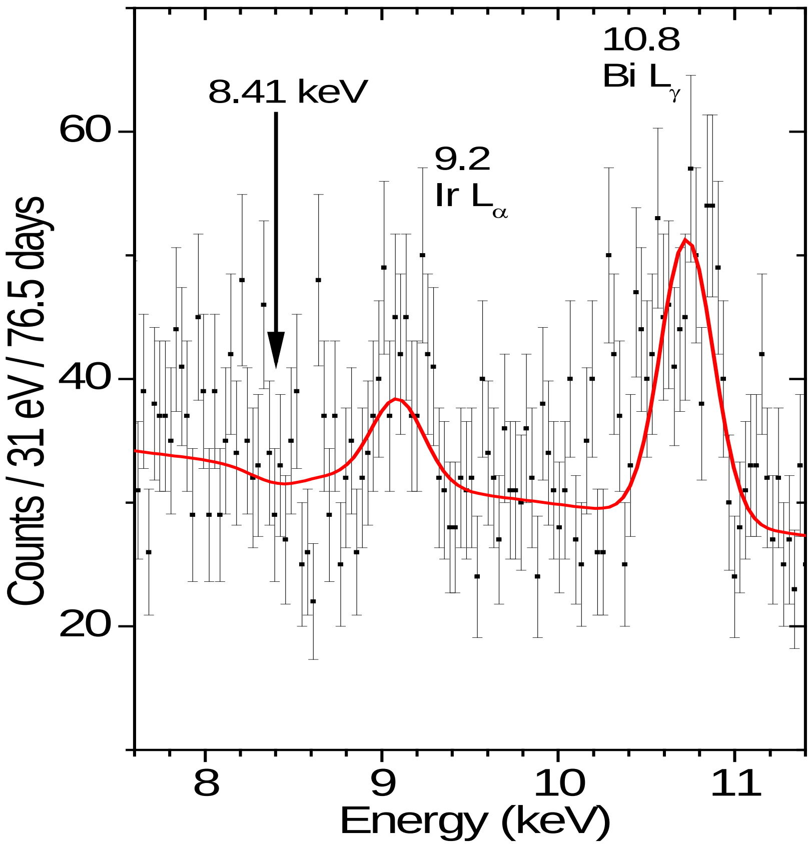
Si(Li)-детектор и Tm-мишень внутри низкофоновой установки

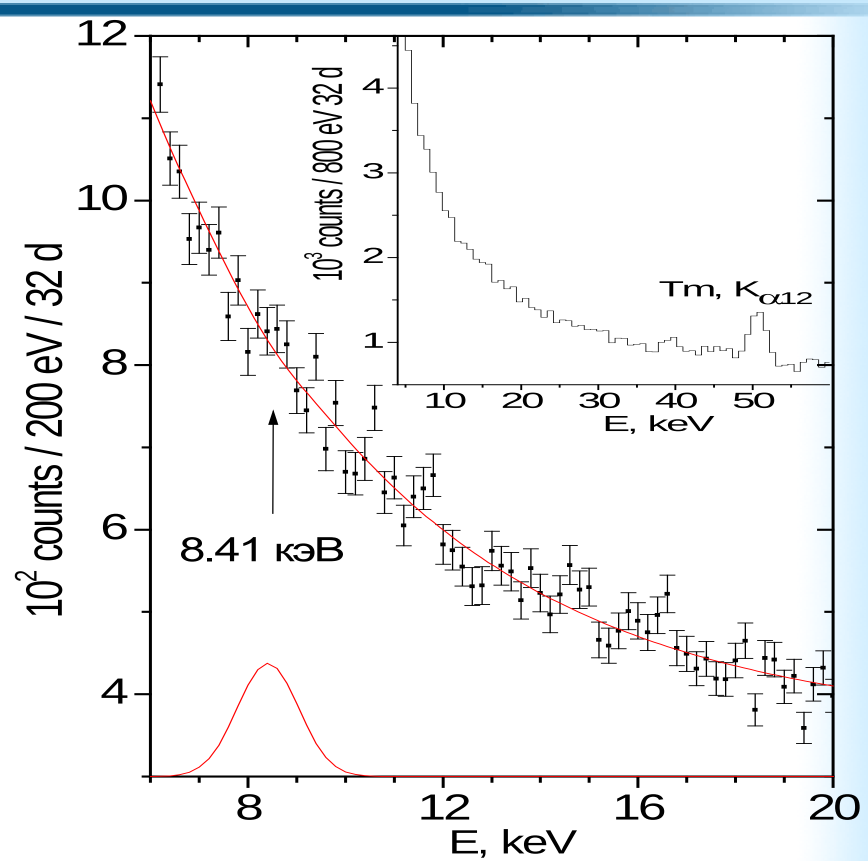




To search for quanta with an energy of 8.41 keV, the planar Si(Li) detector with a sensitive area diameter of 66 mm and a thickness of 5 mm was used. The detector was mounted on 5 cm thick copper plate that protected the detector from the external radioactivity. The detector and the holder were placed in a vacuum cryostat and cooled to liquid nitrogen temperatures. A Tm_2O_3 target of 2 g mass was uniformly deposited on a Plexiglas substrate 70 mm in diameter at a distance of 1.5 mm from the detector surface. External passive shielding composed of copper, iron, and lead layers was adjusted to the cryostat and eliminated external radioactivity background by a factor of about 500. The setup was located on the ground surface and was assembled of five 50×50×12 cm^3 plastic scintillators against the cosmic rays and fast neutrons.

169Tm: Результаты поиска резонансного поглощения





Spectrum measured with 2 cm² Si(Li)-detector in the region 7.6-11.4 keV.The limits on axion-photon (GeV⁻¹) and axion-nucleon couplings:

Spectrum of 34 cm² Si(Li)-detector measured with 169Tm target. The limits on axion-electron and axion-nucleon couplings:

$g_{A\gamma} \cdot |(g^0_{AN} + g^3_{AN})| \leqslant 9.2 \times 10^{-13}$ | $g_{A\gamma} m_A \leqslant 1.36 \times 10^{-14}$ | $m_A \leqslant 191\ \mathrm{eV}$ | $g_{Ae} \times |(g^0_{AN} + g^3_{AN})| \leq 2.1 \times 10^{-14}$,

Tm-содержащий детектор (болометр)

Since the coefficient of electron conversion for 8.4 keV transition in the nucleus ^{169}Tm is very large (e / γ = 260), the sensitivity of the experiment can be further increased in 260 / ε = 5E3 times (ε = 0.05 - detection efficiency of gamma rays emitted from the target by Si(Li) detector) for the case of registration of all particles (conversion and Auger electrons and γ- and X-rays) that accompany this transition. This can be done in the implementation of thulium in the volume of the detector (scintillator or bolometer). For 1 kg detector the enhancement factor can be:

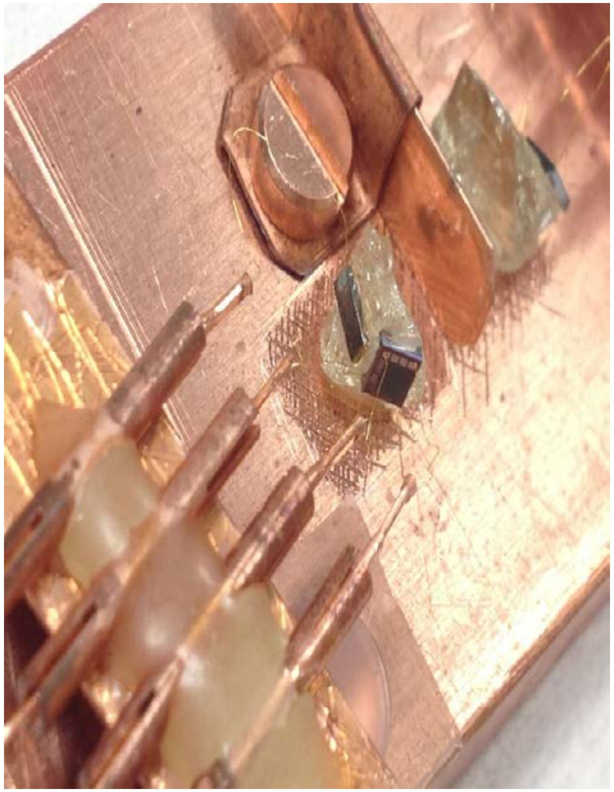
$$(e / \gamma = 260) \times (1/ \varepsilon = 20) \times (M / m = 500) \times (B\sigma_s / B\sigma_b = 1)^{0.5} = 2.5\times10^6$$

Creating a detector (scintillator or bolometer) containing 1 kg 169Tm increases the sensitivity of the experiment in 10^6 times, compared to measurements with 169Tm targets and Si (Li) detectors. We have used a liquid scintillation detector based on dioxane, in which dissolved salts of thulium.

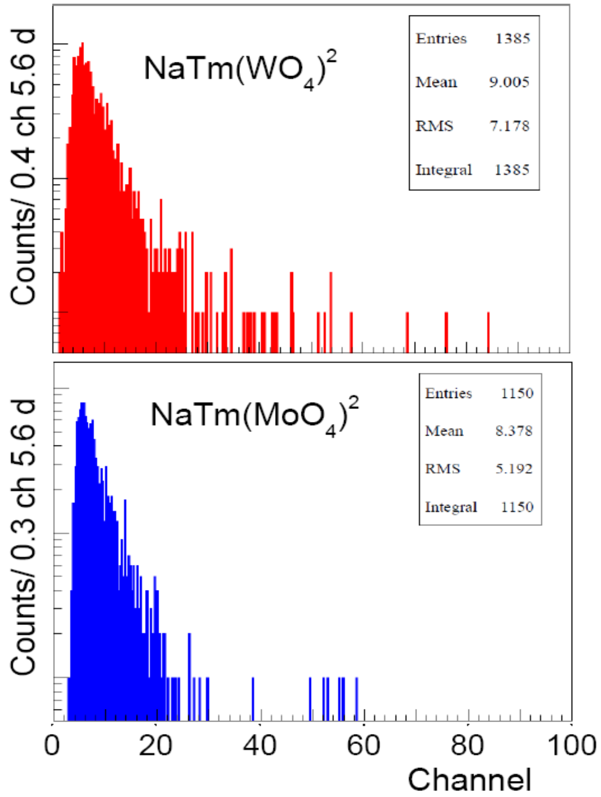
$$\frac{\omega_A}{\omega_\gamma} = \frac{1}{2\pi\alpha}\frac{1}{1+\delta^2}\left[\frac{g_{AN}^0\beta + g_{AN}^3}{(\mu_0 - 0.5)\beta + \mu_3 - \eta}\right]^2\left(\frac{p_A}{p_\gamma}\right)^3$$

In case of the 169Tm nucleus, which has the odd number of nucleons and an unpaired proton, in the one-particle approximation the values of β and η can be estimated as β ≈ 1.0 and η ≈ 0.5. In contrast with the 14.4 keV 57Fe and 9.4 83Kr solar axions, the uncertainty of the flavor-singlet axial-vector matrix element S and parameter z does not change the obtained constraints significantly

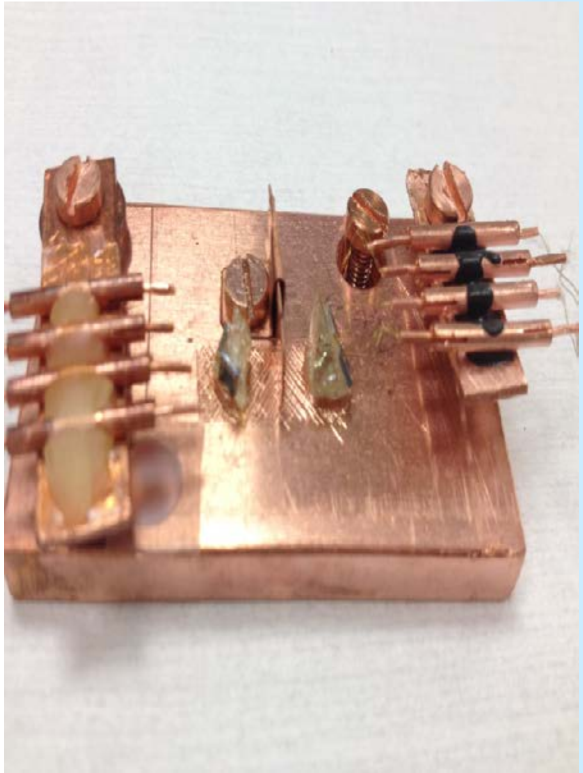
Кристаллы $NaTm(Mo0_4)^2$ и $NaTm(W0_4)^2$ как болометры



Кристаллы внутри криогенной установки



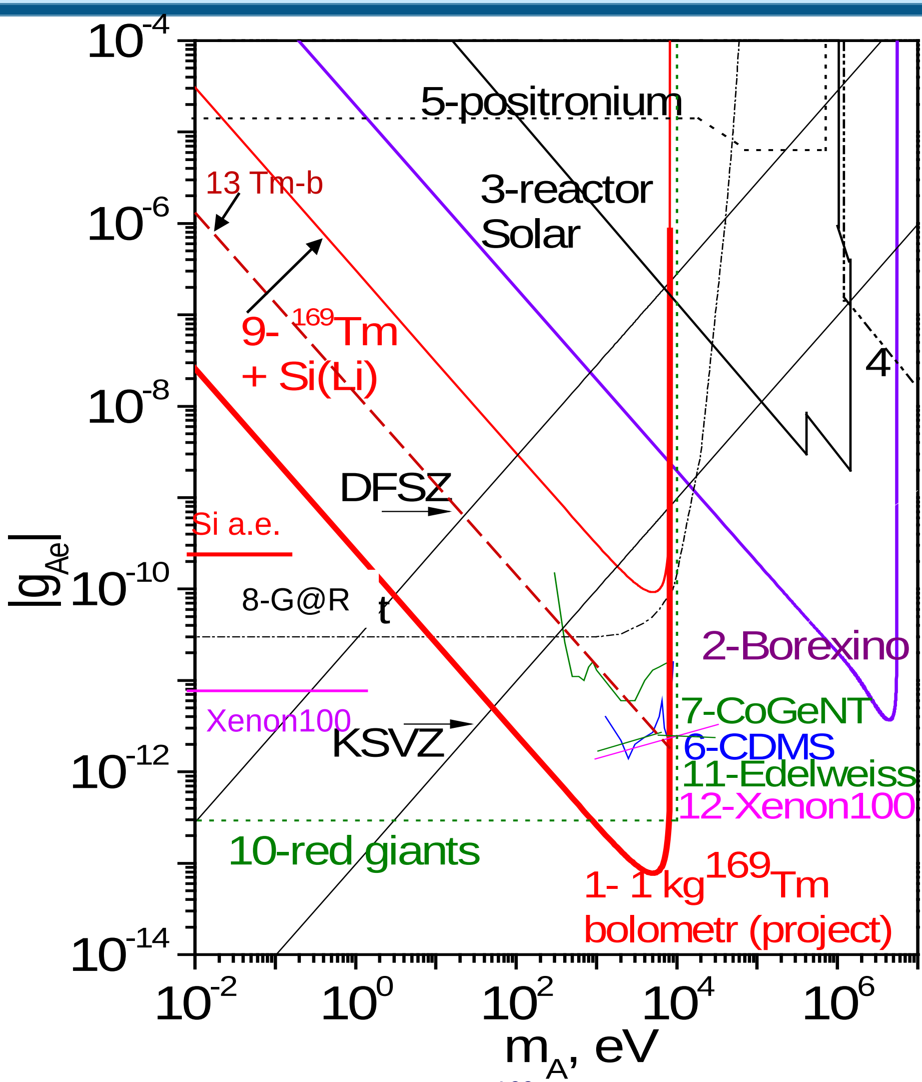
Спектры фононных сигналов за 135 ч.



Кристаллы внутри криогенной установки

Кристаллы были испытаны как болометрические детекторы для поиска резонансного поглощения солнечных аксионов, имеющих непрерывный спектр. Кристаллы были доставлены из ПИЯФ в лабораторию Гран Сассо, смонтированы в криогенной установке вместе с германиевыми термисторами и охлаждены до температуры около 10 мК. Измерены спектры фононных сигналов с 2-х детекторов.

Ограничения на g_{Ae} и m_A



9 – limit on g_{Ae} obtained with ^{169}Tm target; 13 – 0.2 g NaTm(MoO4)2 bolometer;1– expected sensitivity for 1 kg Tm bolometer.

For Primakoff's axions:

$$g_{A\gamma} \cdot |(g^0_{AN} + g^3_{AN})| \leqslant 9.2 \times 10^{-13}$$

$$g_{A\gamma} m_A \leqslant 1.36 \times 10^{-14}$$

$$m_A \leqslant 191 \text{ eV}$$

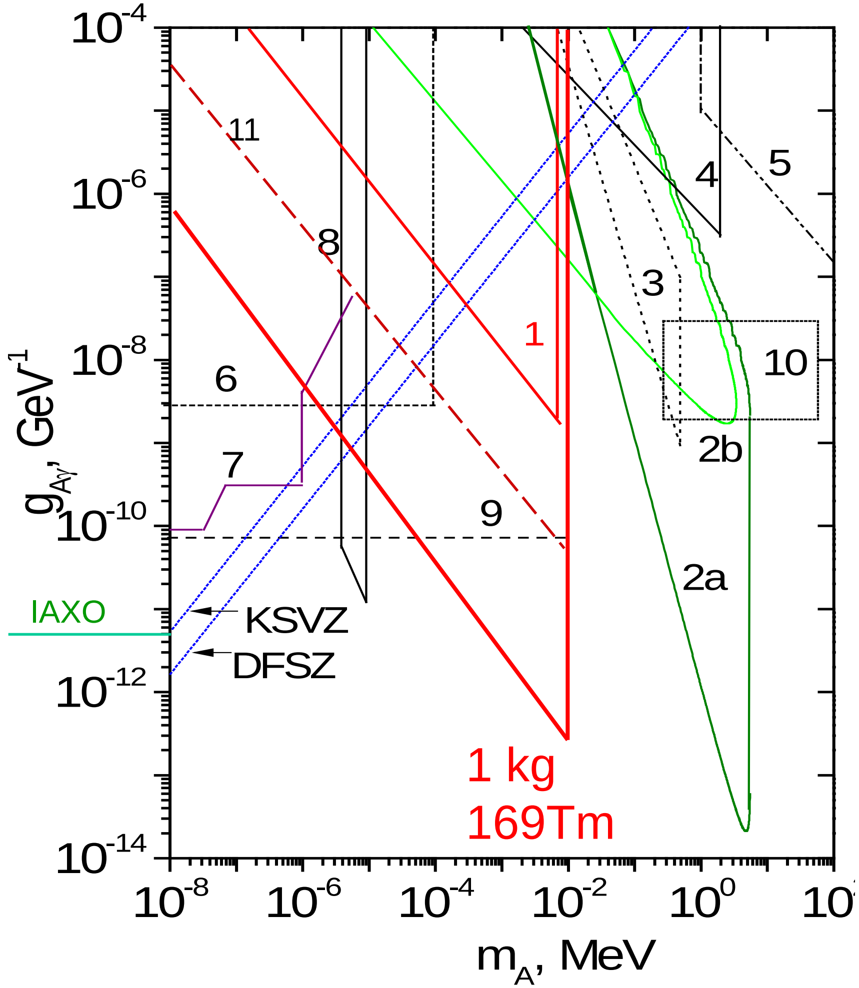
For bremsstrahlung and Compton's axions:

$$g_{Ae} \times |(g^0_{AN} + g^3_{AN})| \leq 2.1 \times 10^{-14},$$

$$g_{Ae} \times m_A \leq 3.1 \times 10^{-7} \text{ eV}.$$

IF the scheme of experiment –[Si(Li)-detectors + Tm target] will be replaced by scintillation bolometer containing thulium, the sensitivity to axion flux can be increased in 10^6 times in comparison with the present results.

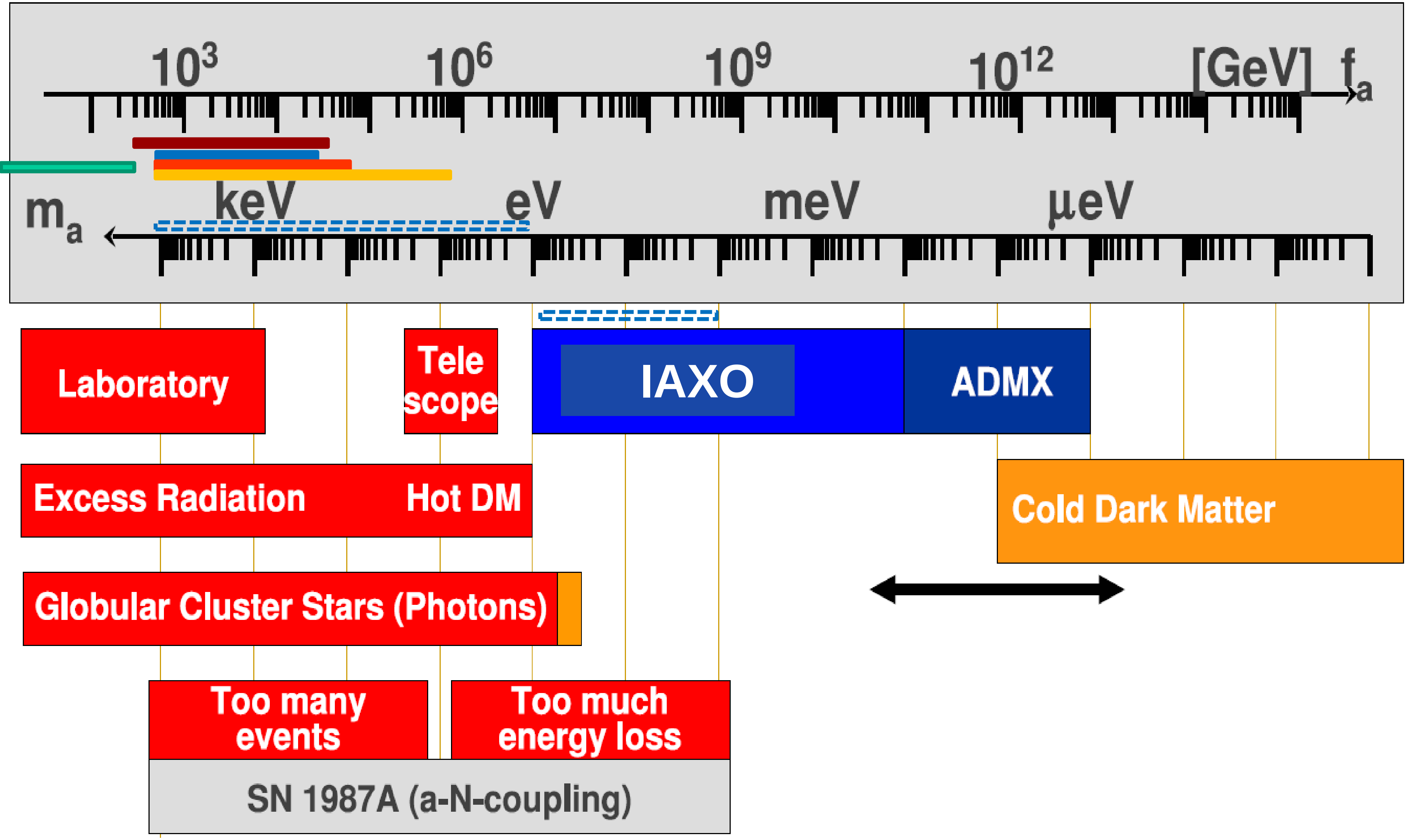
Ограничения на $g_{A\gamma}$ и m_A



1 – 169Tm resonant absorption of Primakoff axions
2 – Borexino, 5.5 MeV axions
3 – CTF, 478 keV axions
4 – Reactor experiments
5 – beam-dump experiments
6 – Cosme, Solax, DAMA
7 – CAST
8 – Tokyo telescope
9 – HB-stars He burning LT
10 – predictions of SUSY and mirror heavy axion models

1- The limit on gAγ obtained with 169Tm target. Two lines show the $g_{A\gamma}$ values in the DFSZ and KSVZ models. The expected sensitivity of 1 kg Tm bolometer is more than astrophysical limits.

Результаты и планы



ПИЯФ аксион в Particle Data Group (2015)

A^0 (Axion) and Other Light Boson (X^0) Searches in Nuclear Transitions

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< 8.5 \times 10^{-6}$	90	90 DERBIN	02	CNTR	^{125m}Te decay
		91 DEBOER	97C	RVUE	M1 transitions
$< 5.5 \times 10^{-10}$	95	92 TSUNODA	95	CNTR	^{252}Cf fission, $A^0 \rightarrow ee$
$< 1.2 \times 10^{-6}$	95	93 MINOWA	93	CNTR	$^{139}\text{La}^* \rightarrow {}^{139}\text{La}\,A^0$
$< 2 \times 10^{-4}$	90	94 HICKS	92	CNTR	^{35}S decay, $A^0 \rightarrow \gamma\gamma$
$< 1.5 \times 10^{-9}$	95	95 ASANUMA	90	CNTR	^{241}Am decay
$<(0.4\text{–}10) \times 10^{-3}$	95	96 DEBOER	90	CNTR	$^{8}\text{Be}^* \rightarrow {}^{8}\text{Be}\,A^0$, $A^0 \rightarrow e^+e^-$
$<(0.2\text{–}1) \times 10^{-3}$	90	97 BINI	89	CNTR	$^{16}\text{O}^* \rightarrow {}^{16}\text{O}\,X^0$,

Invisible A^0 (Axion) MASS LIMITS from Astrophysics and Cosmology

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none $0.7\text{–}3 \times 10^5$		166 CADAMURO	11	COSM	D abundance
<105	90	167 DERBIN	11A	CNTR	D, solar axion
		168 ANDRIAMON...	10	CAST	K, solar axions
< 0.72	95	169 HANNESTAD	10	COSM	K, hot dark matter
		170 ANDRIAMON...	09	CAST	K, solar axions
<191	90	171 DERBIN	09A	CNTR	K, solar axions
<334	95	172 KEKEZ	09	HPGE	K, solar axions
< 1.02	95	173 HANNESTAD	08	COSM	K, hot dark matter

ПИЯФ аксион в Particle Data Group (2015)

Limit on Invisible A^0 (Axion) Electron Coupling

The limit is for $G_{Aee}\partial_\mu \phi_A \bar{e}\gamma^\mu\gamma_5 e$ in GeV^{-1}, or equivalently, the dipole-dipole potential $\frac{G_{Aee}^2}{4\pi}((\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) - 3(\boldsymbol{\sigma}_1 \cdot \boldsymbol{n})(\boldsymbol{\sigma}_2 \cdot \boldsymbol{n}))/r^3$ where $\boldsymbol{n}=\boldsymbol{r}/r$.

VALUE (GeV^{-1})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<7.8 \times 10^{-10}$	90	[1] ABE	14F	XMAS	$m_{A^0} = 60$ keV
$<7.5 \times 10^{-9}$	90	[2] APRILE	14B	X100	Solar axions
$<1 \times 10^{-9}$	90	[3] APRILE	14B	X100	$m_{A^0} = 5$–7 keV
$<$ 0.94–8.0 $\times 10^{-5}$	90	[4] DERBIN	14	CNTR	$m_{A^0} = 0.1$–1 MeV
$<3 \times 10^{-10}$	99	[5] MILLER-BER...	14	ASTR	White dwarf cooling
$<5.3 \times 10^{-8}$	90	[6] ABE	13D	XMAS	Solar axions
$<1.05 \times 10^{-9}$	90	[7] ARMENGAUD	13	EDEL	$m_{A^0} = 12.5$ keV
$<2.53 \times 10^{-8}$	90	[8] ARMENGAUD	13	EDEL	Solar axions
		[9] BARTH	13	CAST	Solar axions
$<$ 1.4–9.5 $\times 10^{-4}$	90	[10] DERBIN	13	CNTR	$m_{A^0} = 0.1$–1 MeV
$<2.9 \times 10^{-5}$	68	[11] HECKEL	13		$m_{A^0} \leq 0.1\ \mu$eV
$<4.2 \times 10^{-10}$	95	[12] VIAUX	13A	ASTR	Low-mass red giants
$<7 \times 10^{-10}$	95	[13] CORSICO	12	ASTR	White dwarf cooling
$<2.2 \times 10^{-7}$	90	[14] DERBIN	12	CNTR	Solar axions
$<$ 0.02–1 $\times 10^{-7}$	90	[15] AALSETH	11	CNTR	$m_{A^0} = 0.3$–8 keV

Invisible A^0 (Axion) Limits from Nucleon Coupling

Limits are for the axion mass in eV.

VALUE (eV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<8.6 \times 10^3$	90	[1] BELLI	12	CNTR	Solar axion
$<1.41 \times 10^2$	90	[2] BELLINI	12B	BORX	Solar axion
$<1.45 \times 10^2$	95	[3] DERBIN	11	CNTR	Solar axion
		[4] BELLINI	08	CNTR	Solar axion
		[5] ADELBERGER	07		Test of Newton's law

Заключение

Авторы аксионных работ из ПИЯФ:

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Аксион и ALPs *весьма востребованы поскольку одновременно решают CP-проблему сильных взаимодействий и являются хорошо мотивированными кандидатами на ТМ. Поиски аксиоэлектрического эффекта и резонансного поглощения для солнечных и реликтовых аксионов с помощью детекторов нейтрино и темной материи исключили новую большую область возможных масс и констант связи аксиона или ALPs.*

Поиски резонансного возбуждения ядерного уровня 8.4 кэВ ядра ***169Tm*** *в составе Tm-содержащего* ***болометра*** *могут существенно улучшить чувствительность (до 3-х порядков) к константам связи аксиона.*

В настоящее время проект ***IAXO*** *предлагает наиболее чувствительный эксперимент к константе связи* $g_{A\gamma}$ *для широкого диапазона масс аксиона.*

Спасибо за внимание!

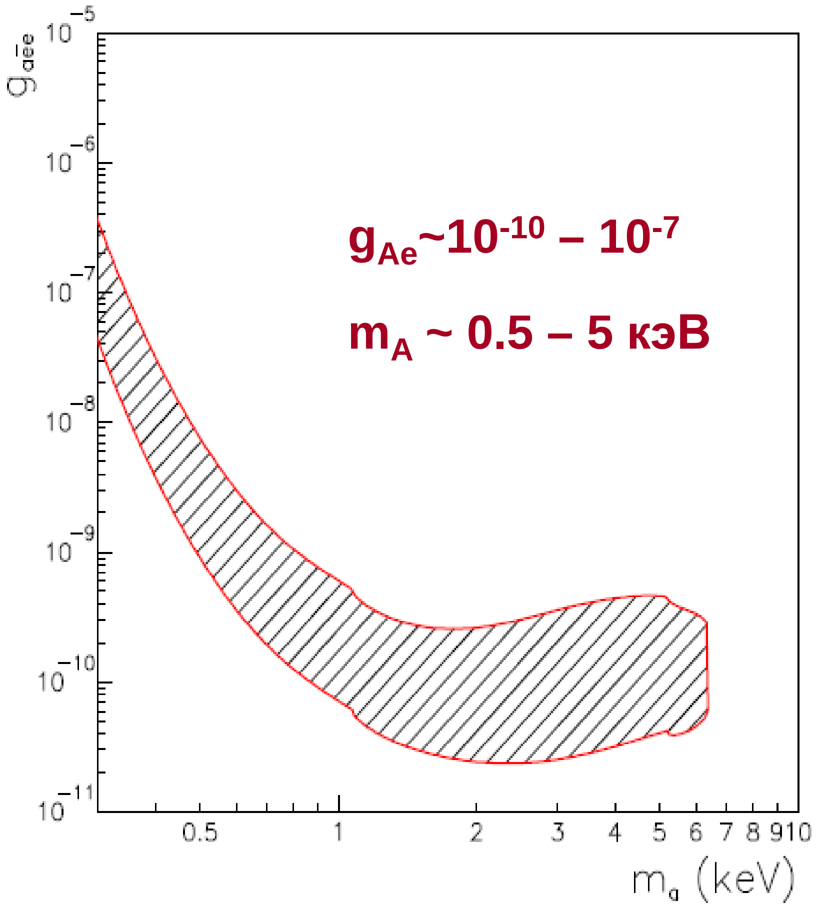
Слово axion в названии статей, выложенных в arXive в 2016 году, встречается всего в 6 (648/113) раз реже чем слово neutrino.

Не опоздай!

EXTRA slides

Аксиоэлектрический эффект и DAMA

arXiv:astro-ph/0511262v1

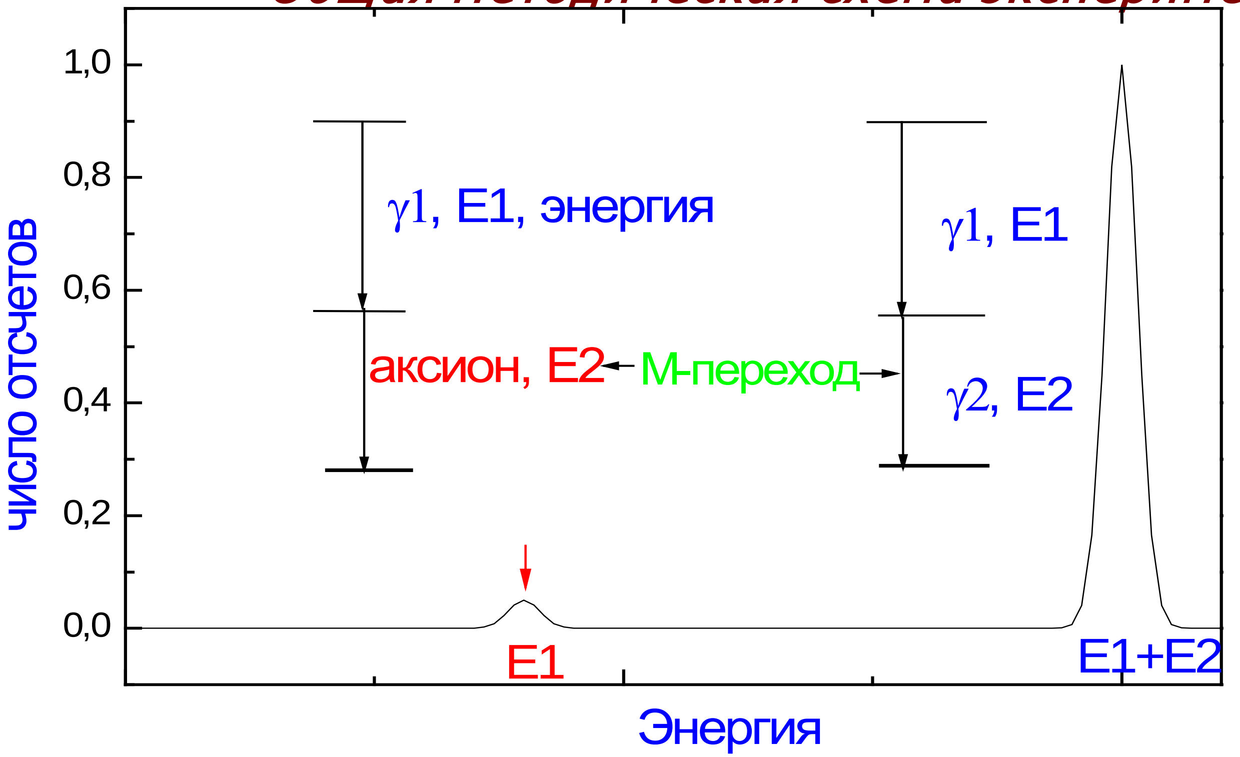


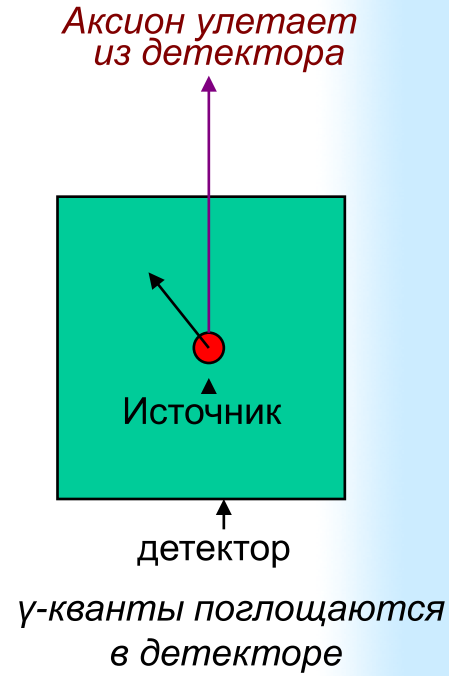
$$\frac{\sigma_{\rm abs} v}{\sigma_{\rm photo}(\omega = m_a)c} \simeq \frac{3m_a^2}{4\pi\alpha f_a^2}$$

Интригующее объяснение результатов DAMA аксиоэлектрическим эффектом для реликтовых аксионов массой 2-3 кэВ. Вариация скорости счета связана с изменением потока аксионов. К сожалению, неправильное вычисление сечения а.э. эффекта. Правильное вычисление (M. Pospelov, A. Ritz and M. B. Voloshin) приводит к независимости скорости счета от скорости аксиона.

Эксперимент с ^{125m}Te

Общая методическая схема эксперимента





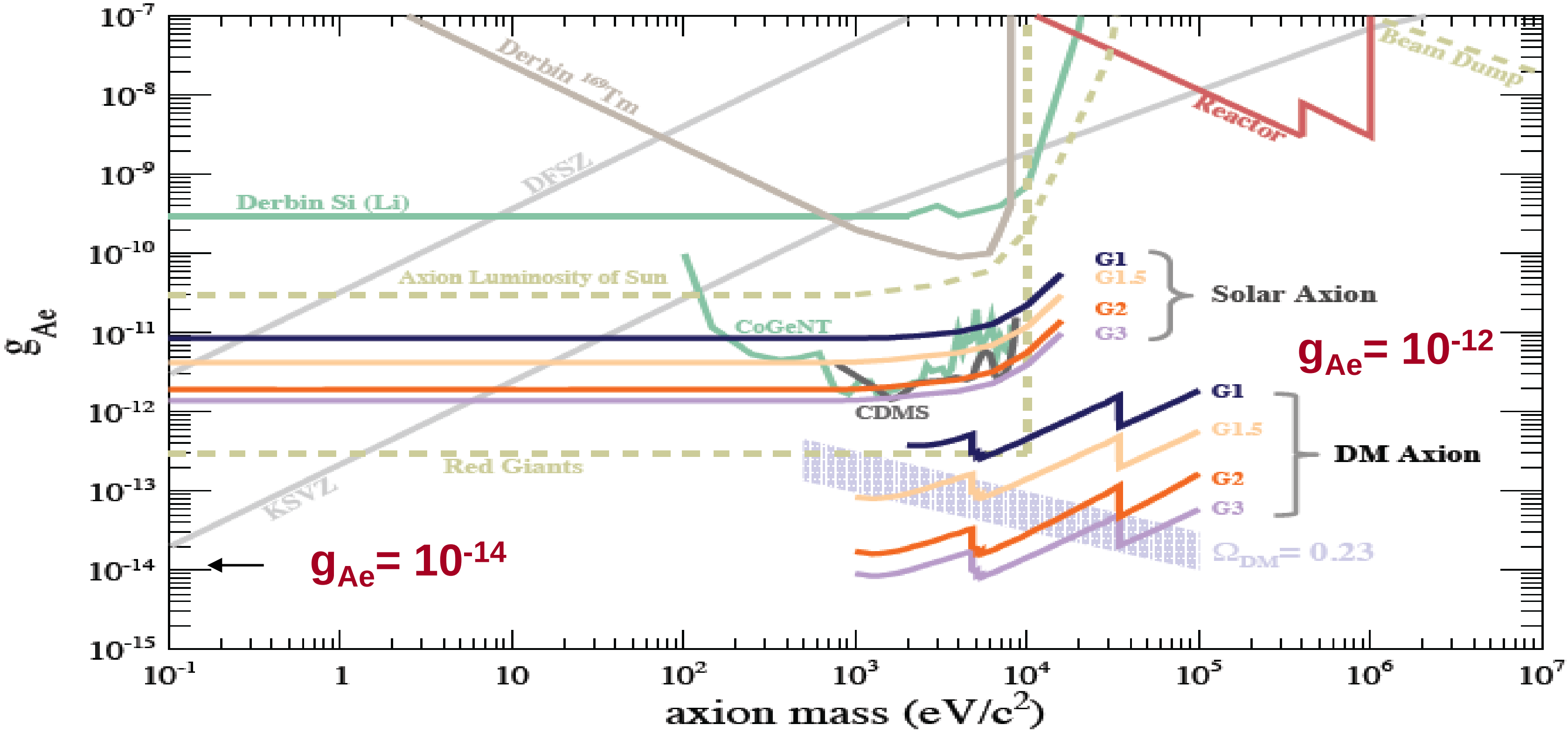
Изомерное ядро ^{125m}Te распадается на основное состояние, излучая при этом два γ-кванта с энергиями E1=109 кэВ и E2=35 кэВ. «Идеальный» детектор полного поглощения, обладающий 4π-геометрией, регистрирует оба γ-кванта с вероятностью 100%, в измеренном энергетическом спектре будет присутствовать только один монохроматический пик с энергией E1+E2 и с шириной определяемой разрешением детектора. Излучение "невидимого" аксиона в переходе с энергией E2, покидающего детектор без взаимодействия, приведет к появлению пика с энергией E1.

Планы поиска а.э. эффекта для аксионов ТМ

Table 2: Experiment Input Parameters

		Weight W (kg)	Live Time T (years)	Resolution b ($\sqrt{\text{keV}}$)	Energy Threshold (keV)	Background dN/dE (dru)
G1	XENON100	34	$\frac{1}{2}$	0.6	2	0.01
G1.5	LUX/XMASS	100	1	0.4	1	5×10^{-4}
G2	XENON1T	1000	2	0.4	1	$(1.4+.07E)\times10^{-5*}$
G3	XAX	10000	2	0.4	1	$1.4\times10^{-5\dagger}$

*pp ν chain+ 2νDBD of ^{136}Xe † pp ν chain only, ^{136}Xe depleted



Поиск а.э. эффекта будет проведен на установках для поиска WIMPs ТМ.