The search for solar hadronic axions

by nuclear resonant method

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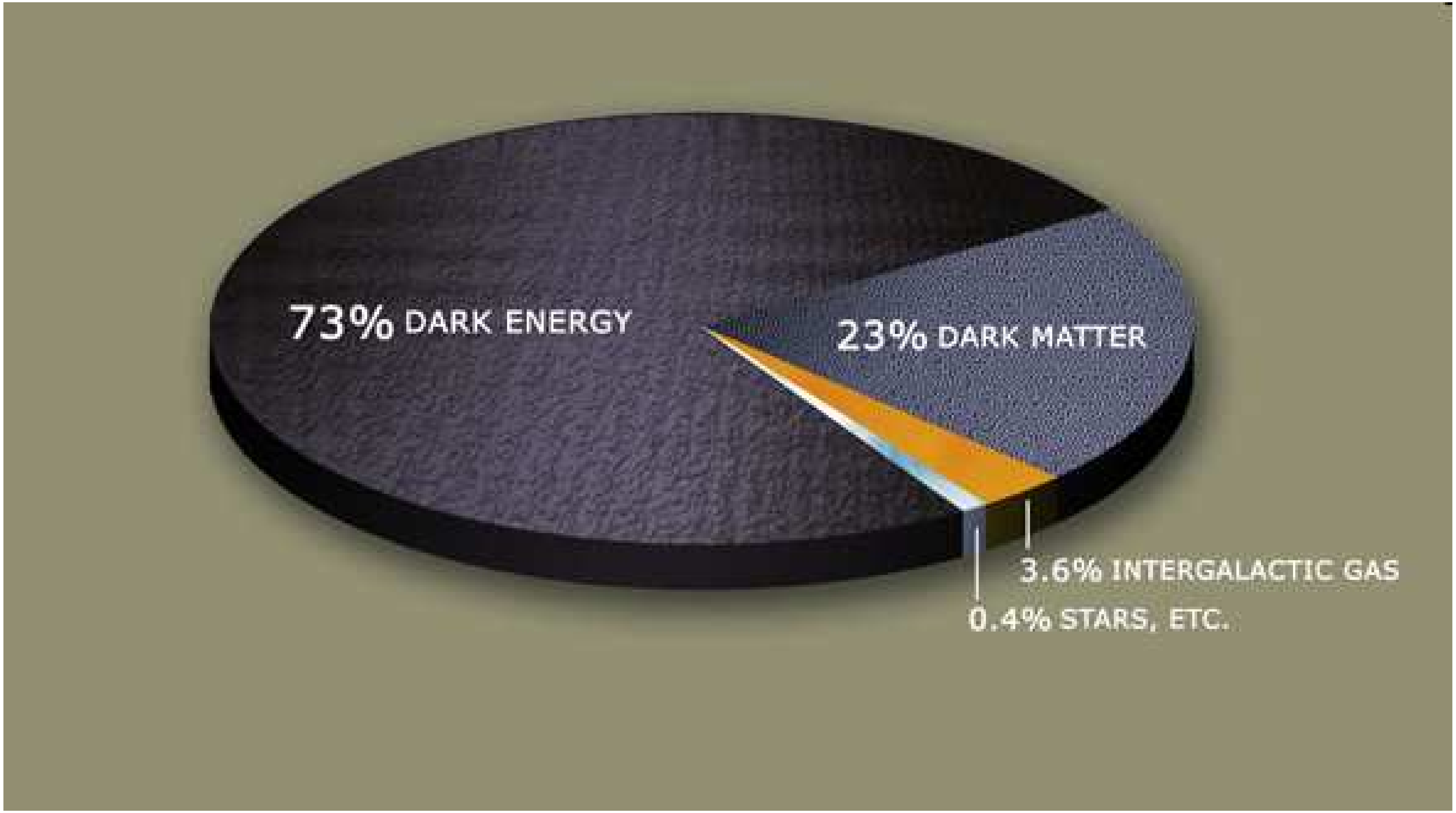
1. Axions: theor. motivations
2. Experimental methods of search
3. Nuclear resonant absorption of solar hadronic axions
4. Conclusions and prospects

Dark matter



Among the best candidates for the dark matter particles:

Axions

A slide from presentation of C. Rubbia (Venice, 2008):

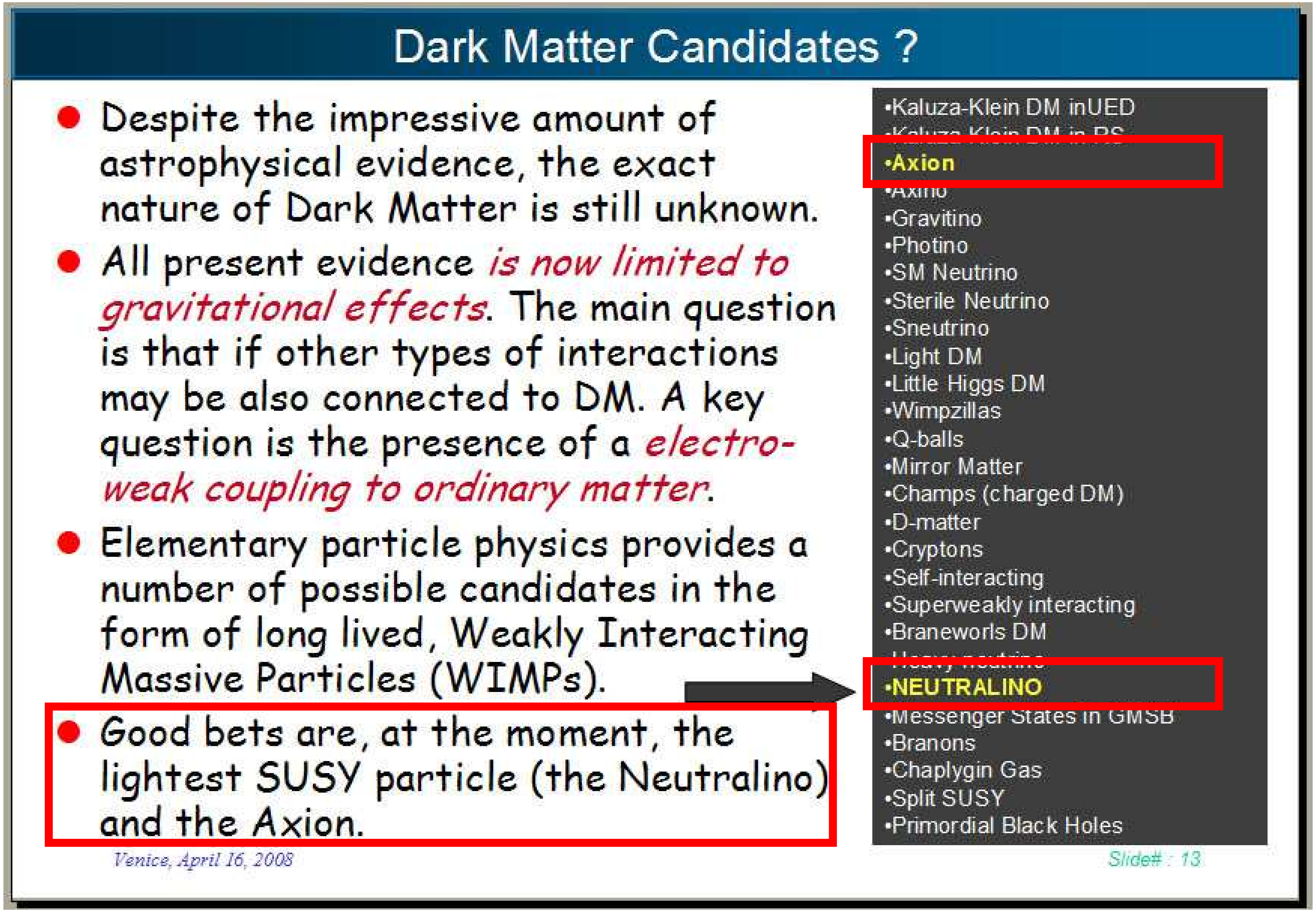
Dark Matter Candidates ?

- Despite the impressive amount of astrophysical evidence, the exact nature of Dark Matter is still unknown.
- All present evidence *is now limited to gravitational effects*. The main question is that if other types of interactions may be also connected to DM. A key question is the presence of a *electro-weak coupling to ordinary matter*.
- Elementary particle physics provides a number of possible candidates in the form of long lived, Weakly Interacting Massive Particles (WIMPs).
- Good bets are, at the moment, the lightest SUSY particle (the Neutralino) and the Axion.

•Kaluza-Klein DM inUED
•Kaluza-Klein DM in RS
•**Axion**
•Axino
•Gravitino
•Photino
•SM Neutrino
•Sterile Neutrino
•Sneutrino
•Light DM
•Little Higgs DM
•Wimpzillas
•Q-balls
•Mirror Matter
•Champs (charged DM)
•D-matter
•Cryptons
•Self-interacting
•Superweakly interacting
•Braneworls DM
•Heavy neutrino
•**NEUTRALINO**
•Messenger States in GMSB
•Branons
•Chaplygin Gas
•Split SUSY
•Primordial Black Holes

Venice, April 16, 2008 Slide# : 13

A slide from presentation of C. Rubbia (Venice, 2008):



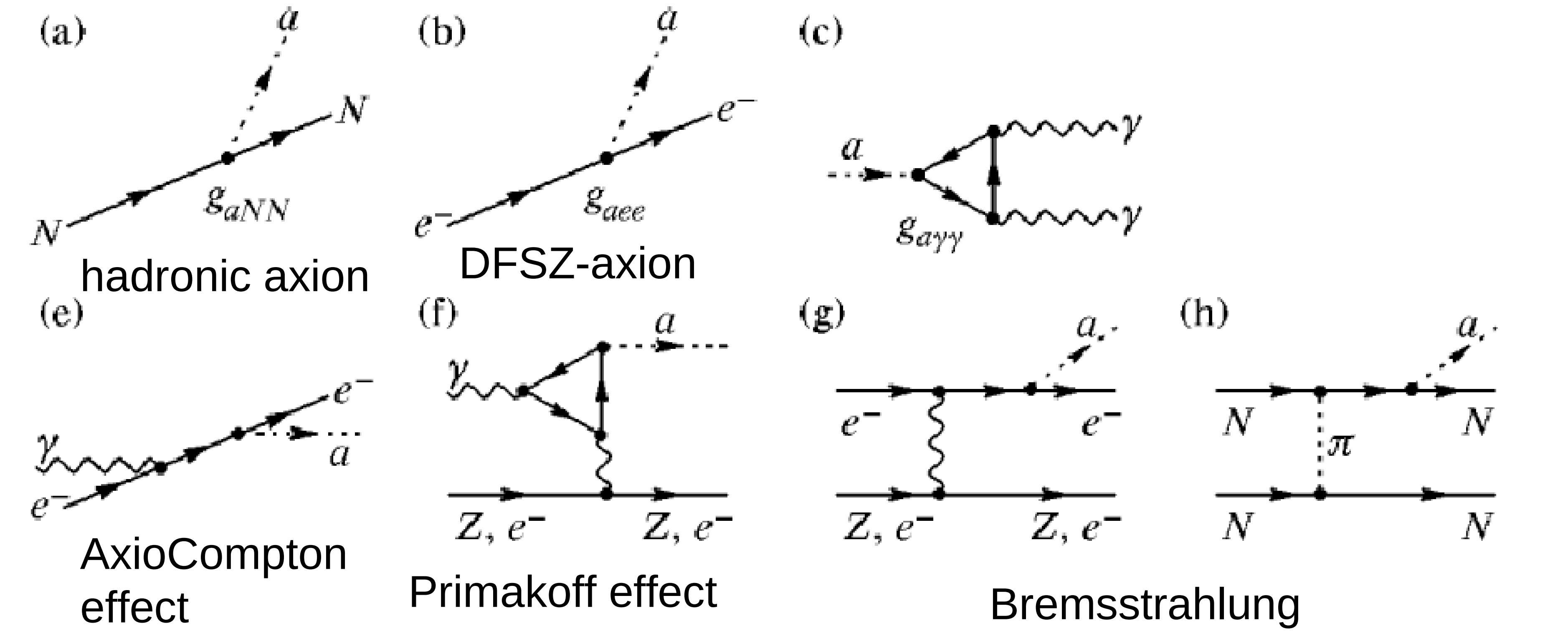
Prediction of axions

Axion is a hypothetical neutral massive particle, introduced to theory in connection with the problem of strong CP-violation. The QCD includes the so-called θ-phase, which is experimentally very small (0 or, at least, $<10^{-10}$ – from the upper limit on EDM of neutron), but its smallness is not required by the theory (θ-phase can take any value between 0 and 2π) – the strong CP problem.

Peccei and Quinn (1977) proposed a mechanism to make $\theta = 0$ by introducing a new symmetry, with θ being a dynamical variable, of zero value at the minimal energy state. The spontaneous violation of the PQ symmetry creates the (pseudo-)Goldstone boson, which was named *axion* by Frank Wilczek. The first model, PQWW (Peccei, Quinn, Weinberg, Wilczek), was not confirmed, but other models of *invisible* axion were built. Usually, $m_a \sim 1/f_a$ (m_a – mass and f_a – coupling constant).

Axion is considered as one of the best candidates for the Dark Matter particles, because it is massive and its interaction with normal matter should be extremely small.

Axion: interactions and models



Mass of axion varies from 10^{-18} to 1 MeV in different variants of theory. Spin/parity is 0^- (pseudoscalar particle).

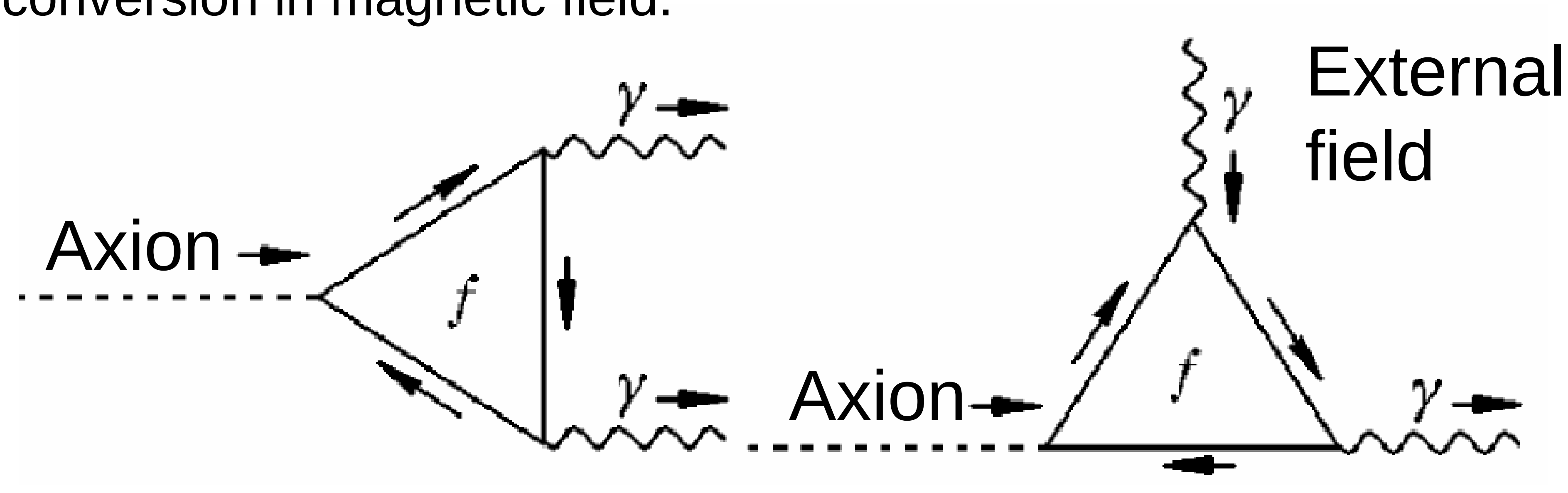
The DFSZ-axion (Dine-Fischler-Srednicki-Zhitnitsky) interacts with usual quarks and leptons directly and requires two Higgs doublets; the hadronic axion (prototype: Kim-Shifman-Vainshtein-Zakharov, KSZV-axion) – requires a new heavy quark.

Axion-like particles (ALPs) are also considered (familons, majorons, dark photons etc.), with some common properties, like coupling with 2 photons.

Laboratory searches for axions

(I will not discuss here astrophysical and cosmological restrictions, see http://pdg.lbl.gov/2016/reviews/rpp2016-rev-axions.pdf)

In many cases, the searches are based on axion-photon conversion in magnetic field.



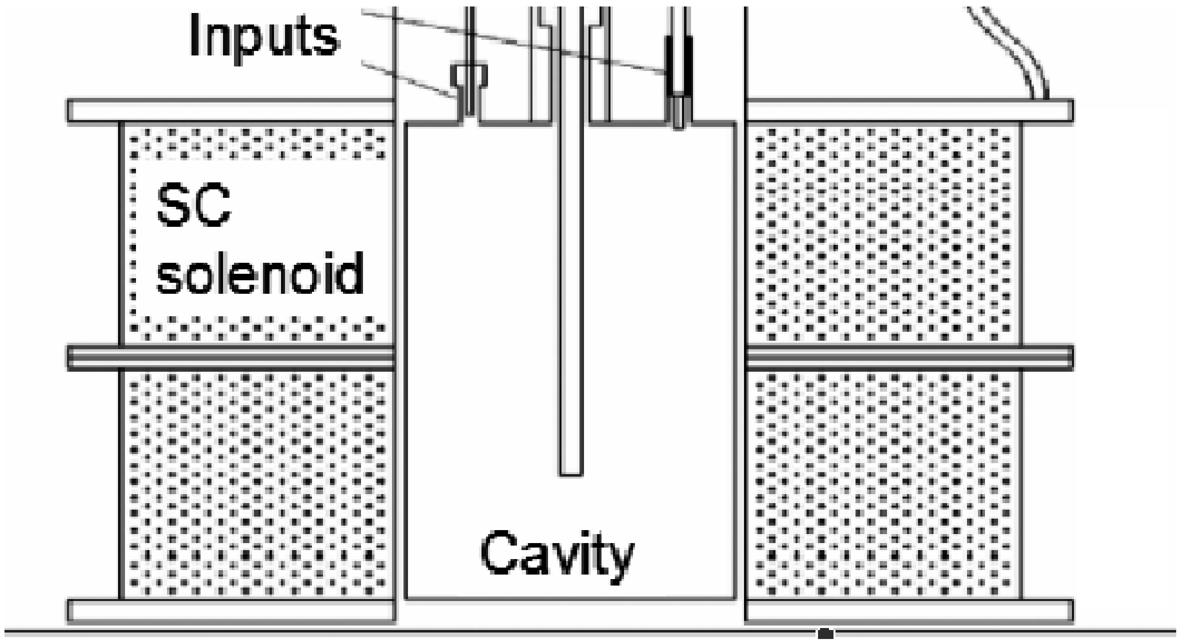
$$\Gamma_{a\gamma\gamma} = \frac{G_{a\gamma\gamma}^2 m_a^3}{64\pi} = 1.1\times 10^{-24}\,\mathrm{s}^{-1}\left(\frac{m_a}{\mathrm{eV}}\right)^5$$

Haloscope: Resonant conversion of relic axions to microwave photons in a tunable resonant cavity (with high quality factor) in magnetic field.

Resonant enhancement factor of $10^{(10\text{-}12)}$.

Mass range $\sim 10^{-6}$ eV

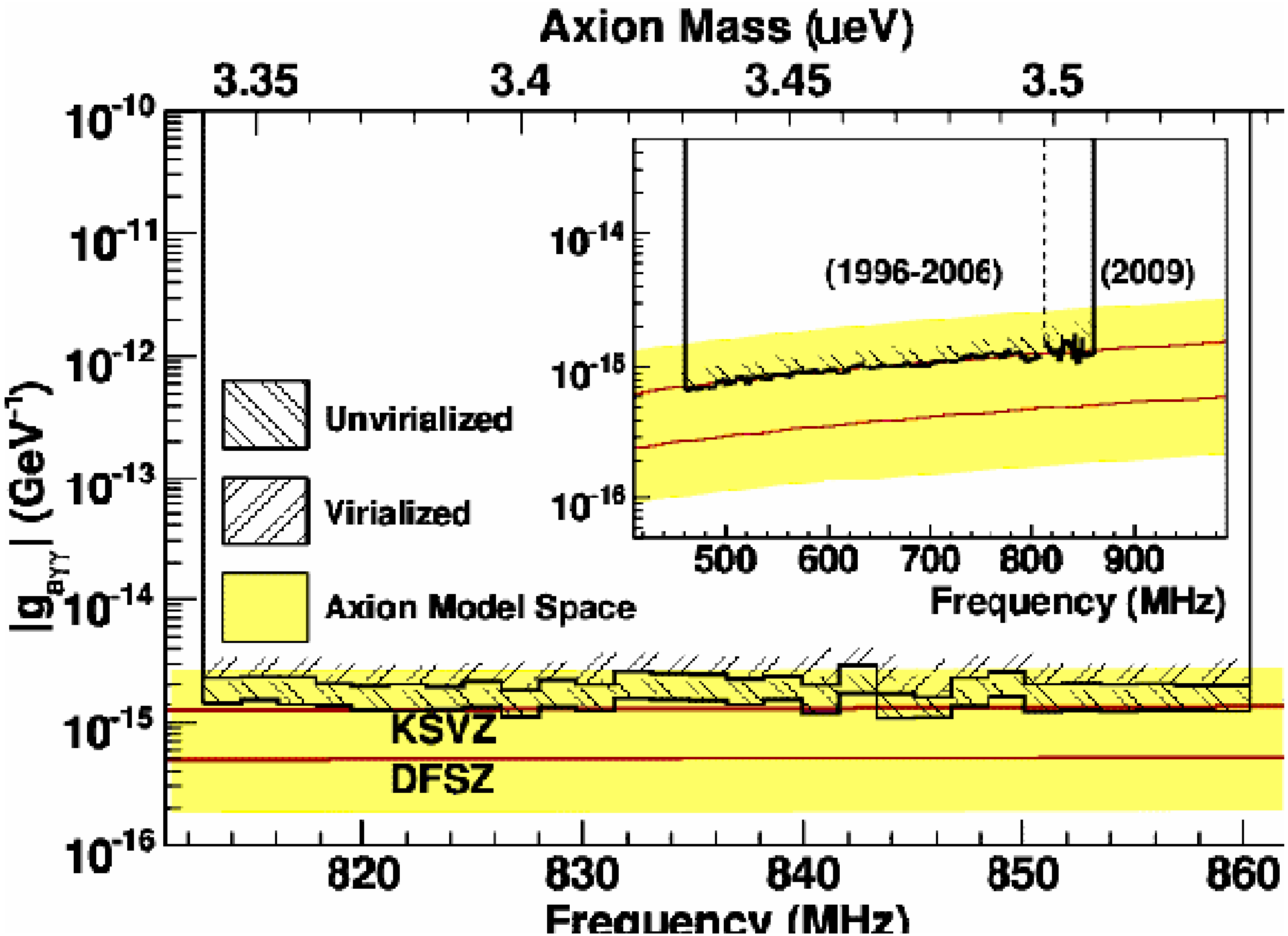
Currently, the most sensitive experiment: **ADMX**



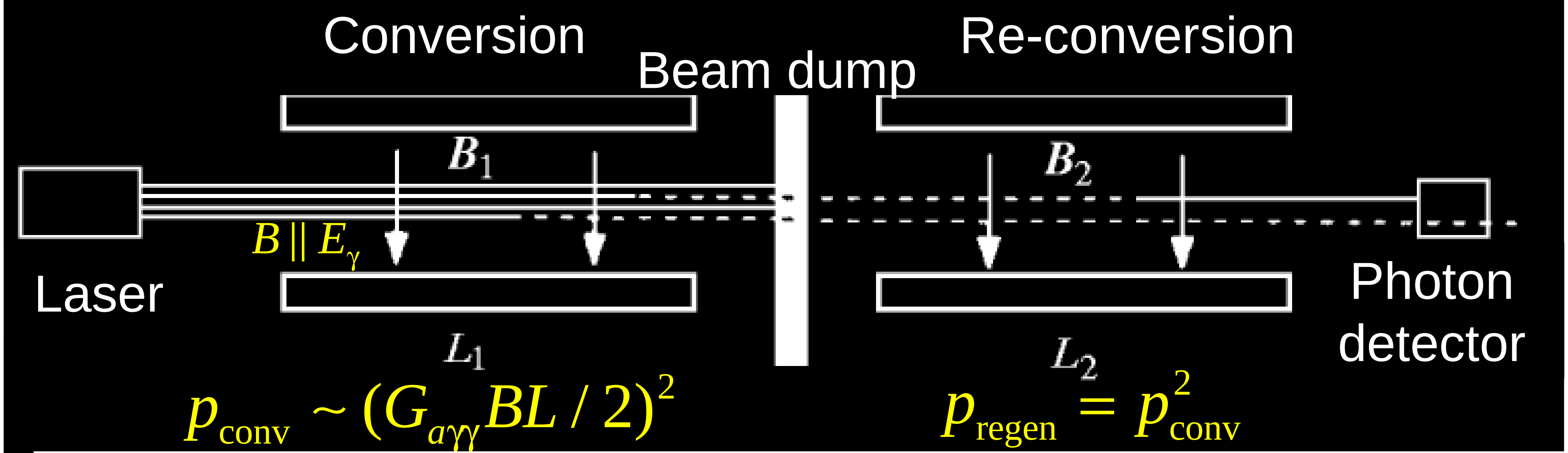
Typical design of a haloscope

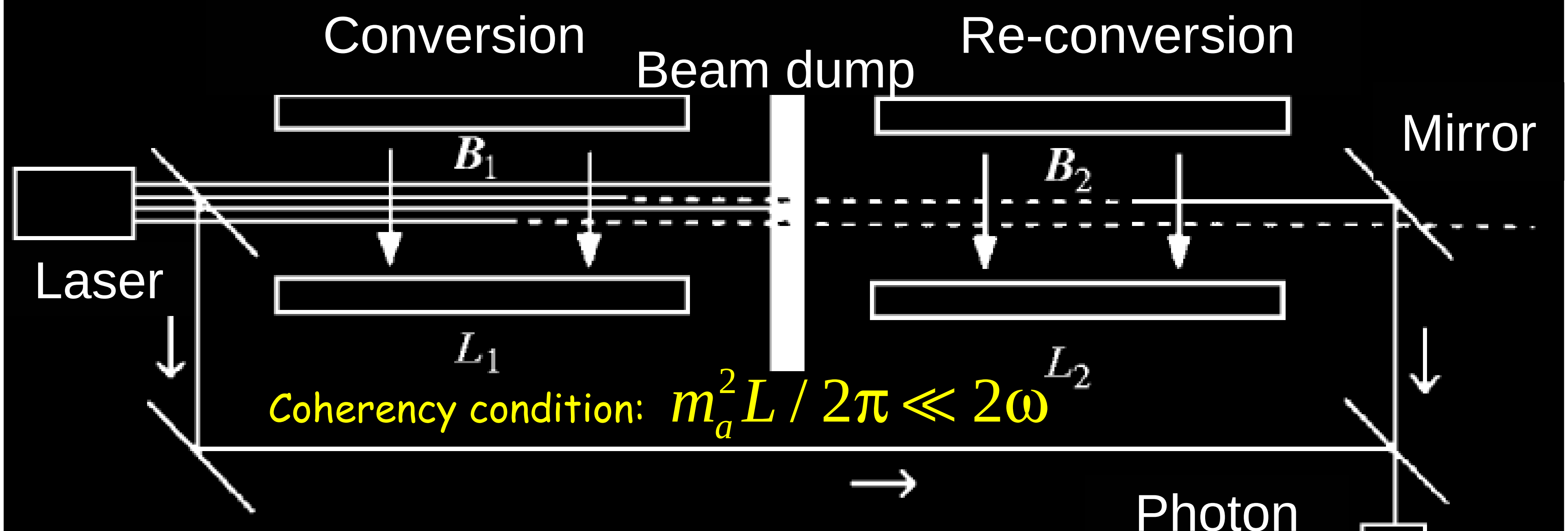
Restrictions from ADMX

[S. J. Asztalos et al., Phys. Rev. Lett. 104 (2010) 041301]



Optical experiments: scheme "Light Shining through Wall"





Example: ALPS (Any Light Particles Search) experiment.

Optical experiments: scheme "Light Shining through Wall"

The probabilities of conversion can be resonantly enhanced in Fabry-Perot resonators ("axionic laser"): P.Sikivie *et al.*, Phys. Rev. Lett. **98** (2007) 172002;

Best limits:

$$G_{a\gamma\gamma} < 0.7 \times 10^{-7}\,\mathrm{GeV}^{-1}$$

$$\text{for } m_a < 0.5\ \mathrm{meV}$$

A. Afanasev *et al.* (LIPSS coll.), Phys. Rev. Lett. **101** (2008) 120401;
K. Ehret *et al.* (ALPS coll.), Phys.Lett. B **689** (2010) 149.

Also the experiments QSQAR, BMV,…

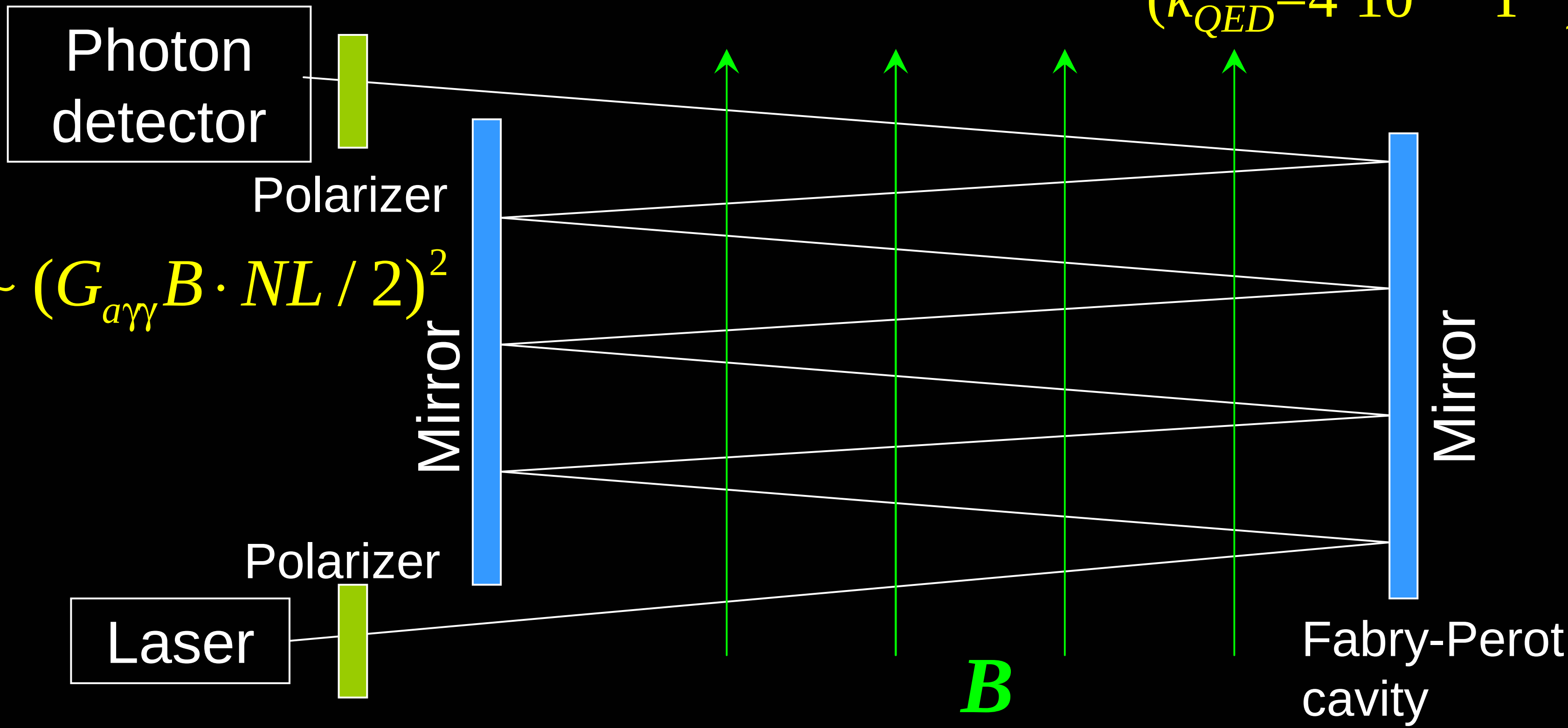
Optical experiments: vacuum refraction index

Admixture of axion to photon in magnetic field has to produce two observable effects: vacuum birefringence ($\mathrm{Re}\, n > 1$) and vacuum dichroism ($\mathrm{Im}\, n > 0$).

$$\Delta n_{QED} = n_{\parallel} - n_{\perp} = k_{QED} B^2$$

$$(k_{QED} = 4 \cdot 10^{-24}\ \mathrm{T}^{-2})$$

$$p_{\mathrm{conv}} \sim (G_{a\gamma\gamma} B \cdot NL / 2)^2$$



Experiments: PVLAS (P. Berceau *et al.*, Appl. Phys. B 100 (2010) 803), BMV (A.Cadene *et al.*, arXiv 1302.5389), QSQAR

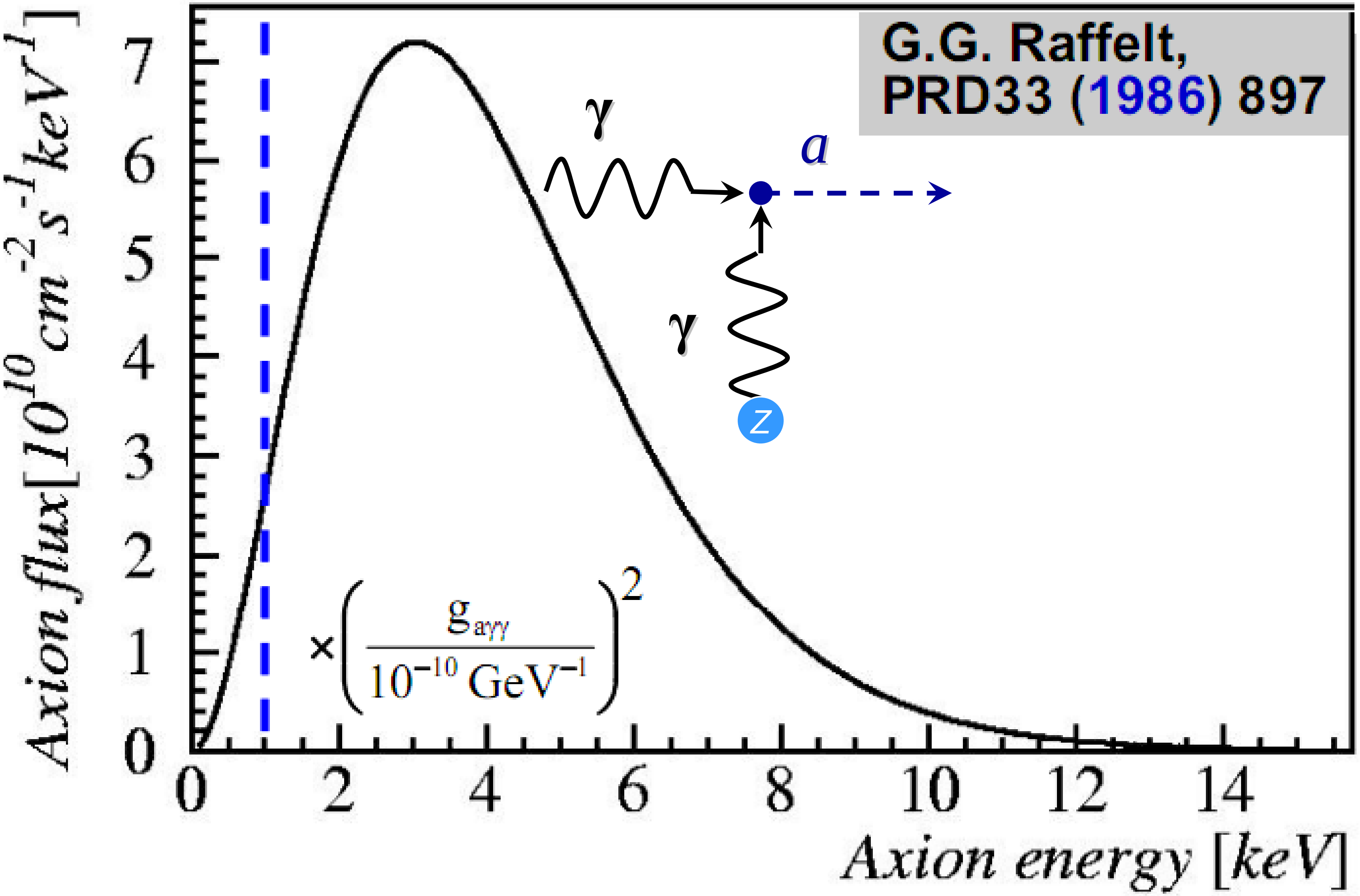
Laboratory search for solar axions

The predicted solar axion luminosity for DFSZ-axions:

$$L_a = 3.6 \times 10^{-3} L_{\Theta} \left(\frac{m_a}{1\,\mathrm{eV}} \right)^2$$

Their mean energy is predicted to be 4.2 keV, the maximum of their spectrum is at 3.0 keV. The flux at Earth is $(G_{a\gamma\gamma} \cdot 10^{10}\ \mathrm{GeV})^{-2} \cdot 3.75 \cdot 10^{11}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$.

In order to detect the axions, they are converted to X-ray quanta with strong transversal magnetic field. X-rays are then detected by an appropriate detector. The most sensitive experiment of this kind is the axio-helioscope CAST (CERN), using a huge de-commissioned accelerator magnet.



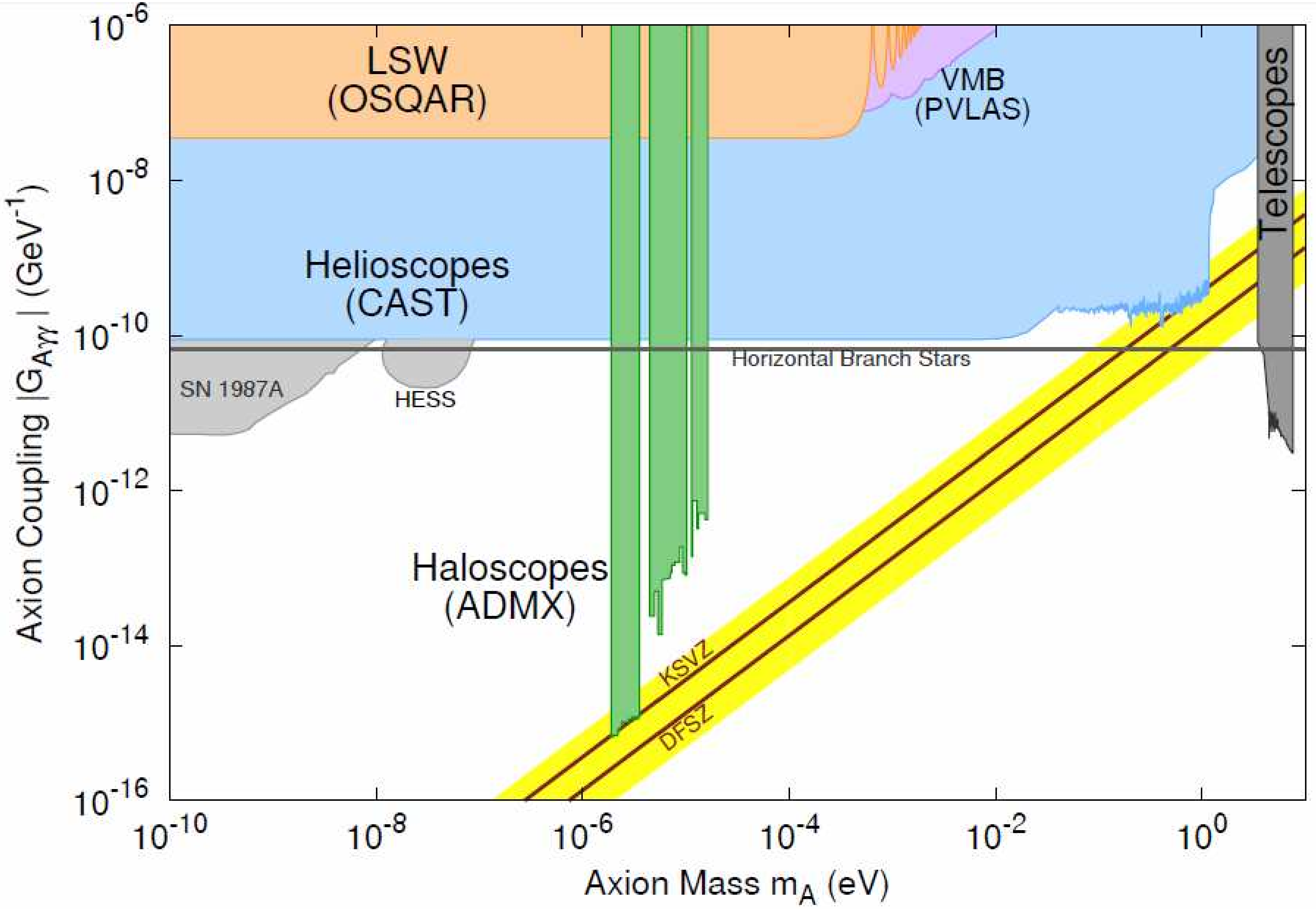
Solar axions: continuous spectrum (Primakoff effect: photon-to-axion conversion in the electric field of a nucleus). Other contributions to the continuous axion spectrum are from axio-Compton ($\gamma+e\rightarrow a+e$) and from axio-bremsstrahlung ($Z+e\rightarrow a+Z+e$).

Laboratory search for solar axions (helioscopes and other detectors)

CAST helioscope

Restrictions in the range of
m_a = 0.39–0.64 eV and
$f_a = 0.98–1.6 \times 10^7$ GeV

The next generation of helioscopes, based on the same principle – IAXO (project)



The plot from: http://pdg.lbl.gov/2016/reviews/rpp2016-rev-axions.pdf

Laboratory search for solar axions

Other searches for solar axions have been carried out using crystal detectors, exploiting the coherent conversion of axions into photons when the axion angle of incidence satisfies a Bragg condition with a crystal plane:

F.T. Avignone *et al.*, (SOLAX) Phys.Rev.Lett. 81 (1998) 5068

A. Morales *et al*. (COSME Collab.), Astropart.Phys.16 (2002) 325

R. Bernabei *et al*. (DAMA), Phys. Lett. B515(2001)6

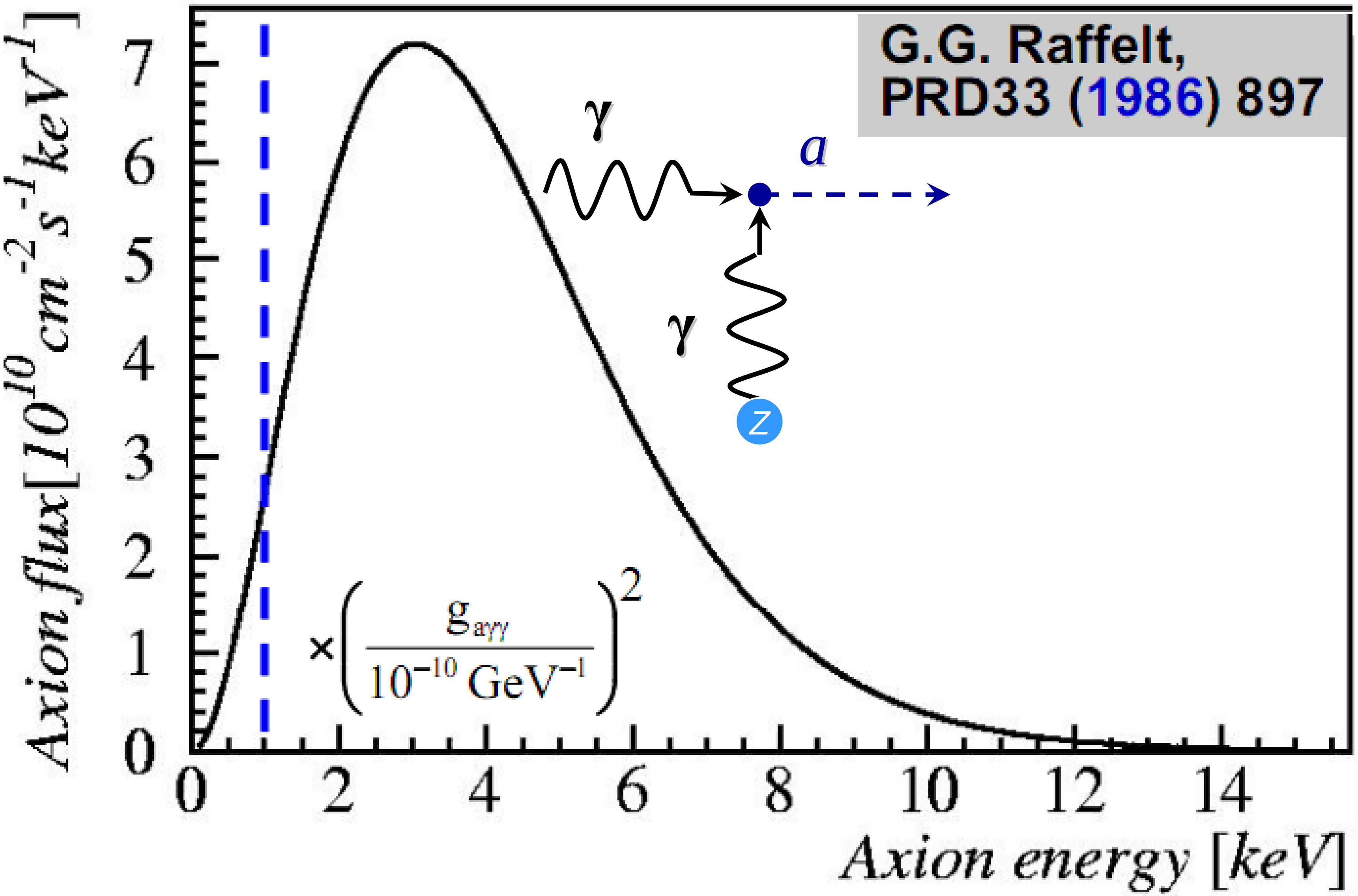
Z. Ahmed *et al.* (CDMS). Phys.Rev.Lett. 103(2009)141802

Laboratory search for solar axions

Resonant absorption of solar axions.

The thermal excitation of low-energy nuclear levels (of few keV, f.i., ^{57}Fe) can be excited in the solar core (T = 1.3 keV). These levels can (in some conditions) deexcite via emission of an axion which escapes from the Sun almost freely. In Earth, the axion can resonantly excite a nucleus of the same kind which then de-excites by emission of a detectable gamma quantum. Many experiments are based on this scheme.

Modification: the level of the nucleus-emitter is populated not by thermal excitation, but in a nuclear reaction (for example, the 478 keV excited level of ^{7}Li is populated by the electron capture of ^{7}Be in the *pp*-chain with ~10% branching ratio)



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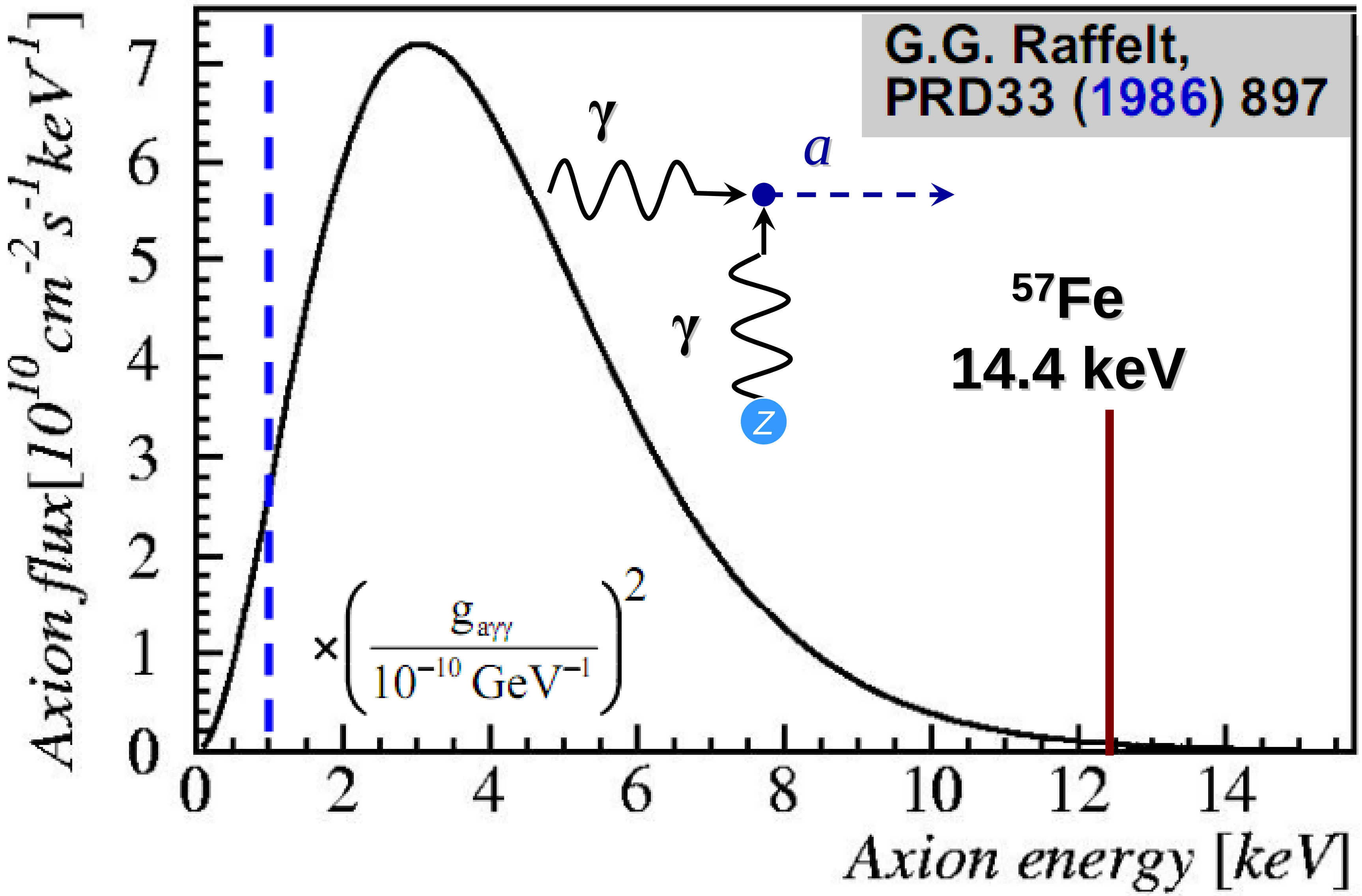


The monoenergetic lines can also be present in the solar axion spectrum.

Solar Core

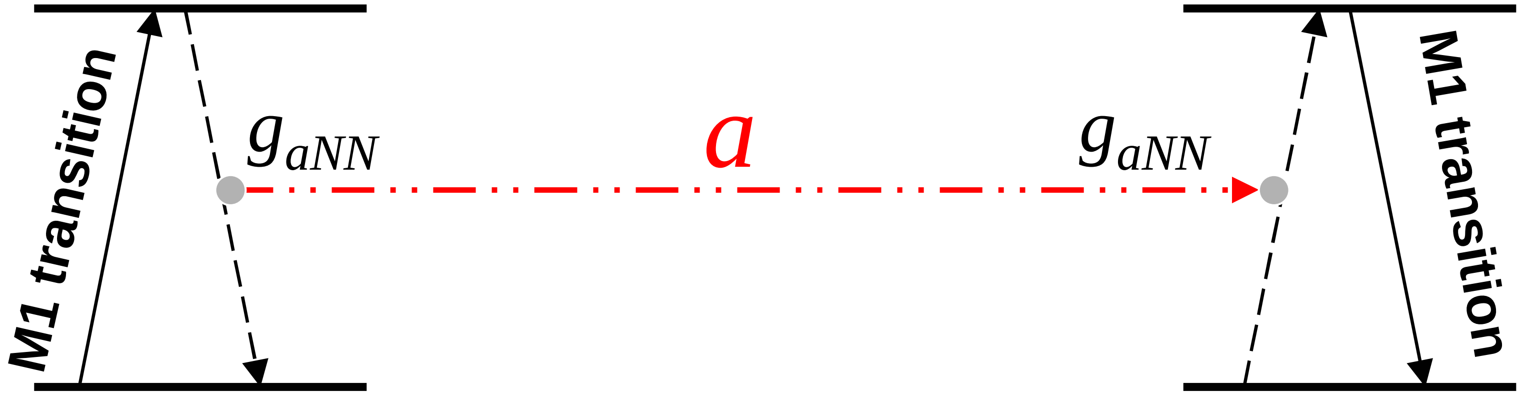
^{57}Fe

14.4 keV

Laboratory

^{57}Fe

14.4 keV



1. Thermal excitation
2. Emission of a monoenergetic axion.

3. Resonant excitation of a target ^{57}Fe nucleus by the axion.
4. Emission of gamma/IC.
5. Detection.

The method was proposed by S.Moriyama [PRL 75(1995)3222].

Other natural isotopes with low-lying levels, de-excitated via M1-transitions, can be (and are) also used; for example, ^{83}Kr (9.4 keV).

Solar Core

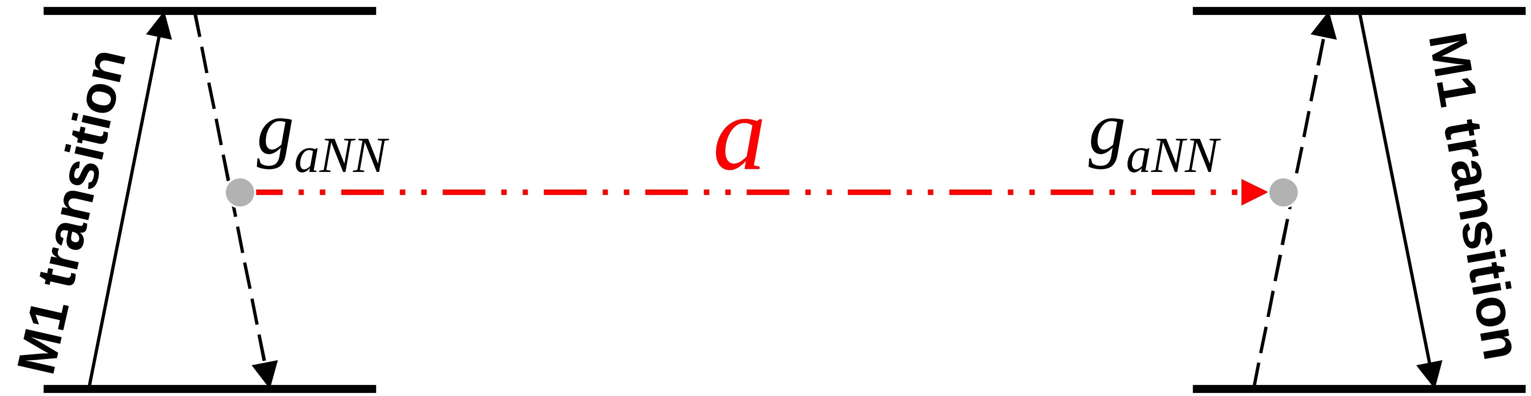
^{57}Fe

14.4 keV

Laboratory

^{57}Fe

14.4 keV



1. Thermal excitation
2. Emission of a monoenergetic axion.

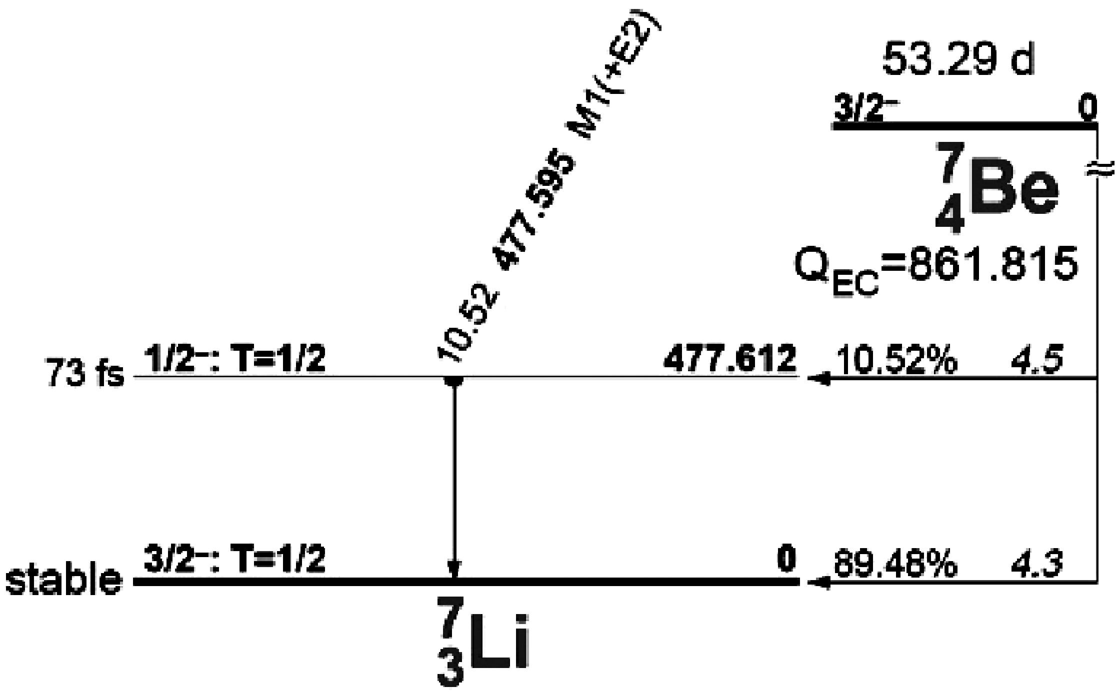
3. Resonant excitation of a target ^{57}Fe nucleus by the axion.
4. Emission of gamma/IC.
5. Detection.

Thermal width (1.3 keV): 2.2 eV
Recoil shift: 0.0018 eV
Natural width: 4.7×10^{-9} eV

Thermal width (300 K): 0.01 eV
Recoil shift: 0.0018 eV
Natural width: 4.7×10^{-9} eV

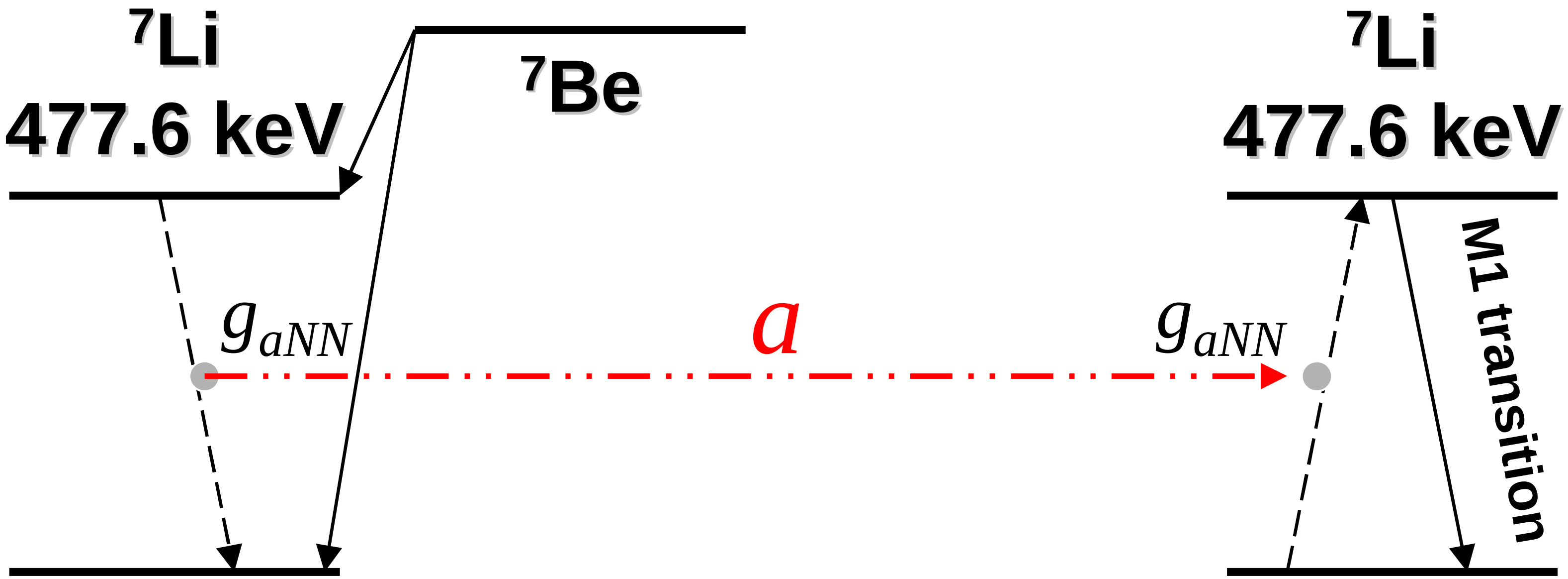
^{57}Fe ('iron') solar axions allow to exclude axion mass values between ~7 keV (E<<14.4 keV) and (on today) 0.145 keV [A.V.Derbin et al., PAN 74 (2011) 596].

Other possible origin of lines in the solar axion spectrum: non-thermal excitation of source nuclei



^{7}Li is created in the *pp*-chain (the main energy source of the Sun).

Solar Core Laboratory



1. Level population via electron capture of ^{7}Be
2. Emission of a monoenergetic axion.
3. Resonant excitation of a target ^{7}Li nucleus by the axion.
4. Emission of gamma/IC.
5. Detection.

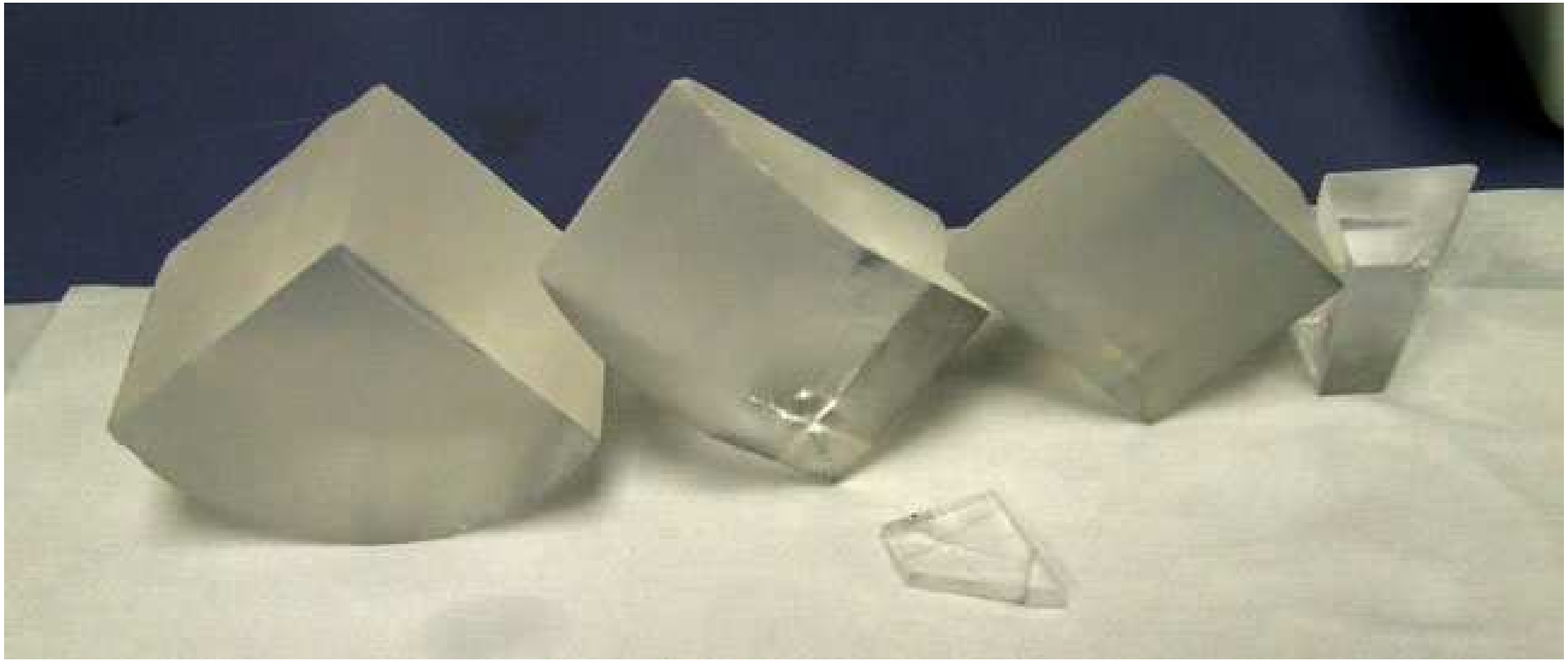
First experiment: M.Krcmar *et al.* [PRD 64(2001) 115016]
(m_a < 32 keV)

Best limit: P.Belli *et al.* (DAMA+KINR) [Phys.Lett.B711(2012) 41]
(m_a < 8.6 keV)

Our experiment (DAMA+KINR):

1. Lithium fluoride (LiF) was chosen as a target due to:
   a) its high density of Li nuclei in comparison to other Li compounds;
   b) chemical passivity;
   c) non-hygroscopicity.
2. Few samples of LiF (powder of 99.99% purity, a single crystal) were placed on two HPGe detectors in Laboratori Nazionali del Gran Sasso (3800 m w.e.).

LiF(W) single crystals

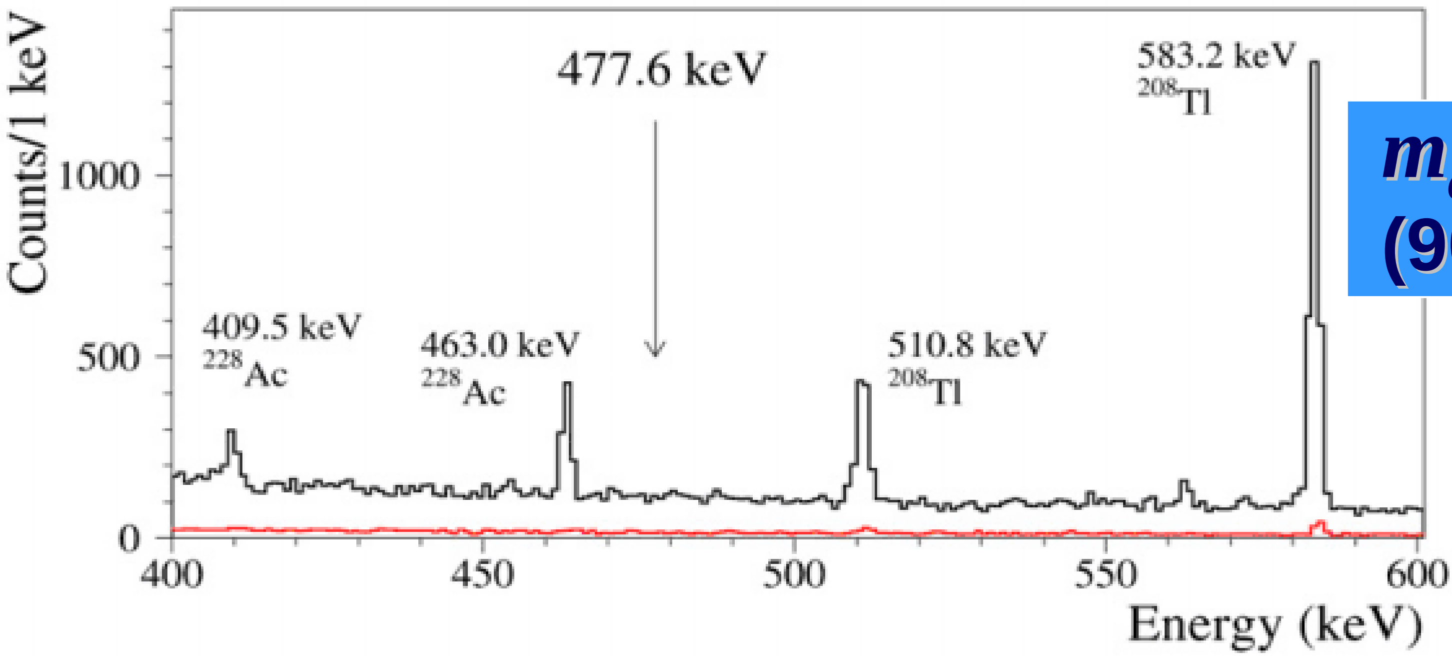


Total mass is ~550 g.

If we would observe a gamma peak at 478 keV with area S, mass of axion would be:

$m_a = 1.55\times10^{11} \times (S / \varepsilon\, t\, N_7)^{1/4}$ eV

ε – efficiency of the detector,
t – time of measurement,
N_7 – number of ^{7}Li nuclei in the sample.



m_a < 8.6 keV (90% C.L.)

The problem with this experiment is that the detection efficiency is small, ~2.3 %. The LiF crystals are used only as a target, the emitted gammas are registered by an external HPGe SCD.

But there was the same problem with all the experiments of such scheme: if the target mass was high, the efficiency was small, and *vice versa.*

For example, the mean range of 14.4 keV photon in Fe is only 20 μm, so the passive target should be a thin foil.

^{7}Li lines in the solar axion spectrum: non-thermal excitation of source nuclei

^{7}Li is created in the *pp*-chain (the main energy source of the Sun).

Another possible reaction from the *pp*-chain with emission of monoenergetic axions:

$$p + d \rightarrow {}^3He + a + 5.5\ MeV$$

This line was searched for by BOREXINO (using a non-resonant method, see PRD 85(2012)092003). There was a proposition to search for resonant absorption in ^{3}He target (S.Nagorny, I.Drachnev, private comm.), but the registered signal should be only proton + deuteron with $E = O(1\ eV)$.

Experiments on search for nuclear resonant absorption of solar axions.

Experiment, nuclide	*M* of nuclide, substance	*N* of nuclei	*T*, days	Efficiency, %	FWHM (%, keV)
Krcmar 1998, ^{57}Fe	0.03153 g (33 mg ^{57}Fe foil, 95%)	3.16e20	61.343	1.6(1)%	1.6%, 0.235 keV @14.4 keV
Krcmar 2001, ^{7}Li	56.72 g (61.4 g nat. metal Li)	4.88e24	111.11	0.83%	0.3%,1.4 keV @478 keV
Jacovcic 2004, ^{83}Kr	0.193 g (1.7 g nat.Kr gas)	1.40e21	23.5	99%	50%,4.7 keV @9.4 keV
Derbin 2005, ^{7}Li	1048 g (3900 g nat. LiOH)	9.02e25	126.5	0.92(10)%	0.6%, 3 keV @478 keV
Derbin 2007, ^{57}Fe	0.0128 g (16 mg ^{57}Fe foil, 80%)	1.35e20	29.7	0.41%	10.3%, 1.48 keV @14.4keV
Namba 2007, ^{57}Fe	0.206 g (0.215 g ^{57}Fe foil, 96%)	2.8e21	13.92	14.8%	16.3%, 2.35 keV @14.4 keV
Belli 2008, ^{7}Li	61 g (243 g nat. LiF powder)	0.30e25	30.08	2.27%	0.4%, 2keV @478 keV
Derbin 2011, ^{169}Tm	1.75 g (2 g Tm_2O_3)	6.23e21	76.5	6.16(30)%	~20%, 1.6 keV @8.41 keV
Derbin 2011a, ^{57}Fe	1.15 g (1.26 g ^{57}Fe foil, 91%)	1.21e22	44.8	8.91%	10.3%, 1.48 keV @14.4 keV
Belli 2012, ^{7}Li	138.3 g (552.6 g nat. LiF(W) crystal)	1.19e25	168.5	2.27%	3%, 14 keV @478 keV
Our unpublished work, 2014, ^{83}Kr	347 g of Kr (Enr) (82 g of ^{83}Kr)	5.14e23	260.12	91.7 %	10%, 0.93 keV @9.4 keV

Experiments on search for nuclear resonant absorption of solar axions
(only low energies)

Experiment, nuclide	*M* of nuclide, substance	Number of nuclei x days x efficiency	FWHM (%, keV)
Krcmar 1998, ^{57}Fe	0.03153 g (33 mg ^{57}Fe foil, 95%)	3.1e20	1.6%, 0.235 keV @14.4 keV
Jacovcic 2004, ^{83}Kr	0.193 g (1.7 g nat.Kr gas)	3.3e22	50%,4.7 keV @9.4 keV
Derbin 2007, ^{57}Fe	0.0128 g (16 mg ^{57}Fe foil, 80%)	1.6e19	10.3%, 1.48 keV @14.4keV
Namba 2007, ^{57}Fe	0.206 g (0.215 g ^{57}Fe foil, 96%)	5.8e21	16.3%, 2.35 keV @14.4 keV
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Candidate nuclides

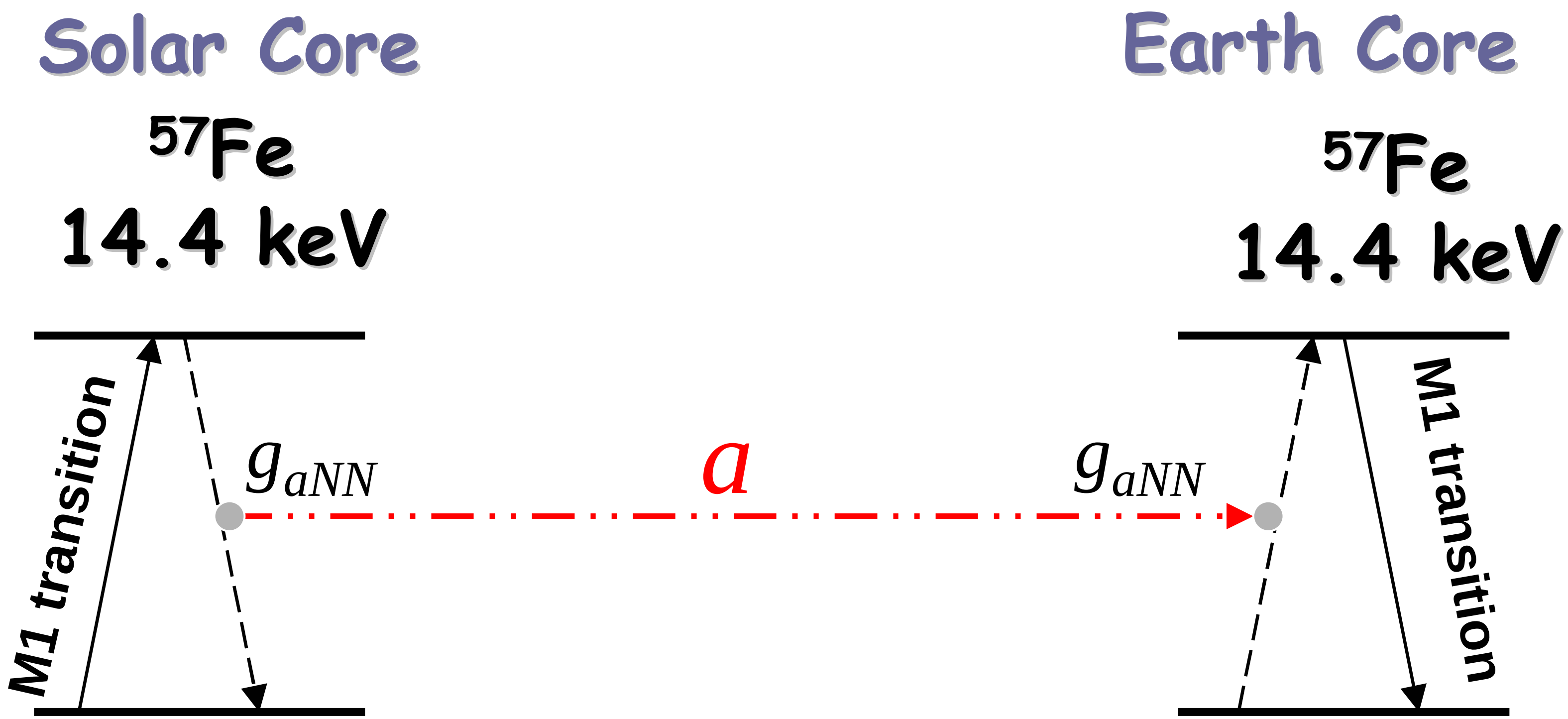
Nuclide	$E_{exc.}$, keV	$\tau_{exc.}$	$\Gamma_{exc.}$	η, %	$\log_{10} bs\eta$	J^{π} (exc.) / J^{π} (g.s.)	Transition
^{169}Tm	8.4103	5.9 ns	0.11 μeV	100.0	–2.7	3/2+ / 1/2+	M1+E2
^{83}Kr	**9.396**	**212 ns**	**3.10 neV**	**11.55**	**–0.80**	**7/2+ / 9/2+**	**M1+E2**
^{187}Os	9.746	3.4 ns	0.19 μeV	1.6	–3.6	3/2− / 1/2−	M1(+E2)
^{45}Sc	12.40	458 ms	1.4 feV	100.0	–1.0	3/2+ / 7/2−	(M2)
^{57}Fe	14.4125	141 ns	4.66 neV	2.14	+0.97	3/2− / 1/2−	M1+E2

$E_{exc.}$, $\tau_{exc.}$ and $\Gamma_{exc.}$ – energy, mean time and width of the level,
η – Solar isotopic abundance of the nuclide,
$\log_{10} s$ – photosphere elemental abundance normalized to $\log_{10} s(\mathrm{H})=12.00$,
J^{π} (g.s.) and J^{π} (exc.) – spin and parity of the ground state and the excited level,
b – Boltzmann factor of $b=\exp(-E_{exc.}/kT)$.

The search for mono-energetic axions from the Sun can be performed also without resonant nucleus as a target (the resonant target only allows to decrease its mass by increasing the cross-section). Such the searches were carried out by Borexino and CAST collaborations (both are mentioned above) for ^{7}Li solar axions, and by CUORE – for ^{57}Fe solar axions. In these cases, not the g_{aNN} itself, but the product of coupling constants ($g_{aNN}g_{aee}$ or $g_{aNN}g_{a\gamma\gamma}$) is tested.

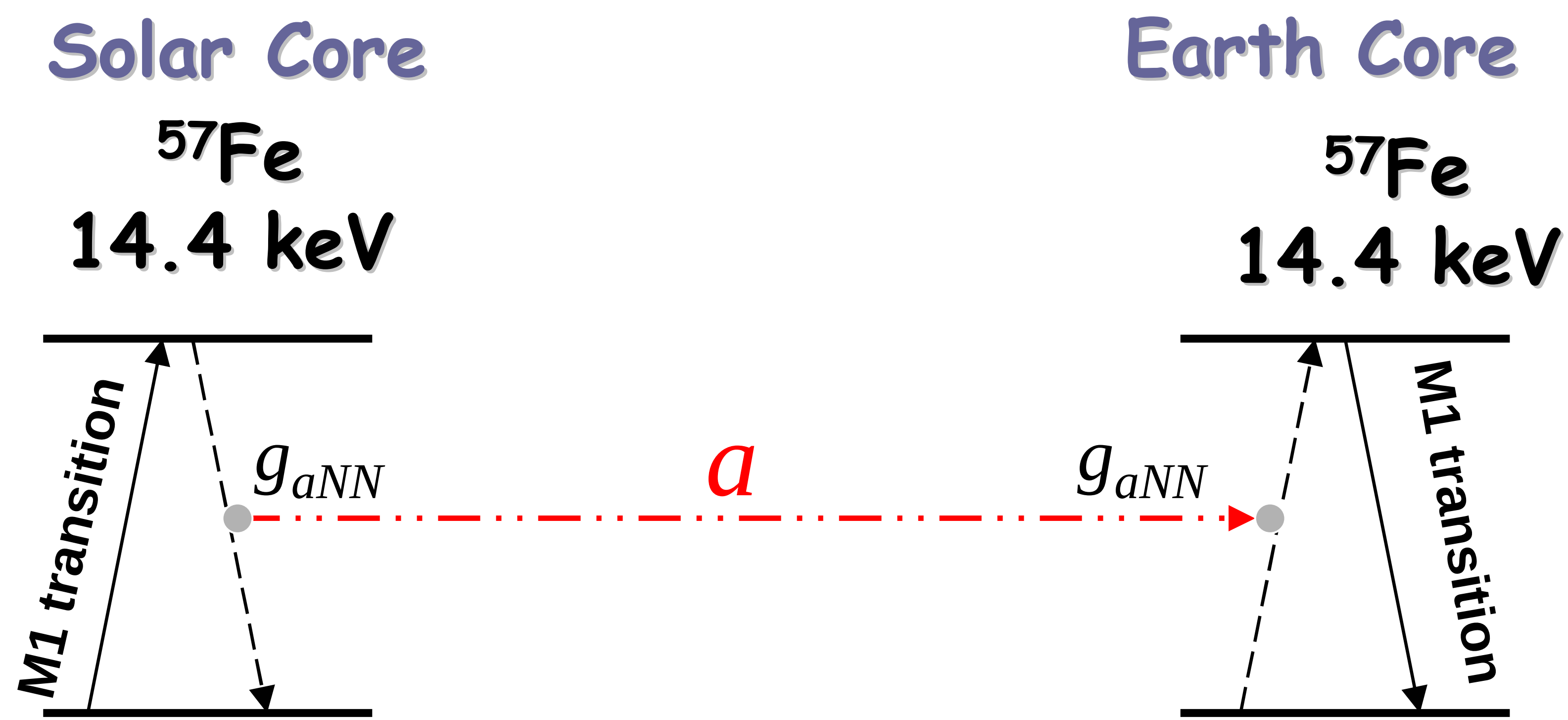
F. Alessandria et al. (Cuore Coll.), *Search for 14.4 keV solar axions from M1 transition of Fe-57 with CUORE crystals*. JCAP 05 (2013) 007 [arXiv:1209.2800]:
$m_a \le 19.2$ eV and $m_a \le 250$ eV at 95% C.L. in the DFSZ and KSVZ models, respectively.

"Geophysical" search for solar hadronic axions



The "geophysical" modification of this approach: we have a lot of iron within the Earth core; let us consider it as a target for "iron" solar axions. The resonant absorption of 14.4 keV axions by ^{57}Fe nuclei would heat the Earth core, and the thermal flow through the Earth surface outwards (measured: ~42 TW) would give us the upper limit on probability of such the process.

“Geophysical” search for solar hadronic axions



Taking into account that the part of this heat flow is produced by radioactive transitions (U, Th, K) in the Earth crust, we have set the upper limit on the hadronic axion mass of m_a<1.6 keV.

F.Danevich et al., *Kinematics and Physics of Celestial Bodies*, 25(2009)102 (arXiv:0811.3836).

Candidate nuclides

Nuclide	$E_{exc.}$, keV	$\tau_{exc.}$	$\Gamma_{exc.}$	η, %	$\log_{10} bs\eta$	J^π (exc.) / J^π (g.s.)	Transition
^{169}Tm	8.4103	5.9 ns	0.11 μeV	100.0	**–2.7**	3/2+ / 1/2+	M1+E2
^{83}Kr	**9.396**	**212 ns**	**3.10 neV**	**11.55**	**–0.80**	**7/2+ / 9/2+**	**M1+E2**
^{187}Os	9.746	3.4 ns	0.19 μeV	1.6	**–3.6**	3/2− / 1/2−	M1(+E2)
^{45}Sc	12.40	458 ms	1.4 feV	100.0	**–1.0**	3/2+ / 7/2−	(M2)
^{57}Fe	14.4125	141 ns	4.66 neV	2.14	**+0.97**	3/2− / 1/2−	M1+E2

One can see that Kr-83 is the second nuclide after Fe-57 in number of thermally excited nuclei.
The total amount of Kr-83 in the Sun is 0.57 M_{Earth}.
Inside the layer with T > 1 keV, M(Kr-83) = 0.09 M_{Earth}.

New search is performed with the setup created for a DBD experiment with ^{78}Kr (a proportional chamber, Baksan Neutrino Observatory): Both the efficiency and the target mass are high.

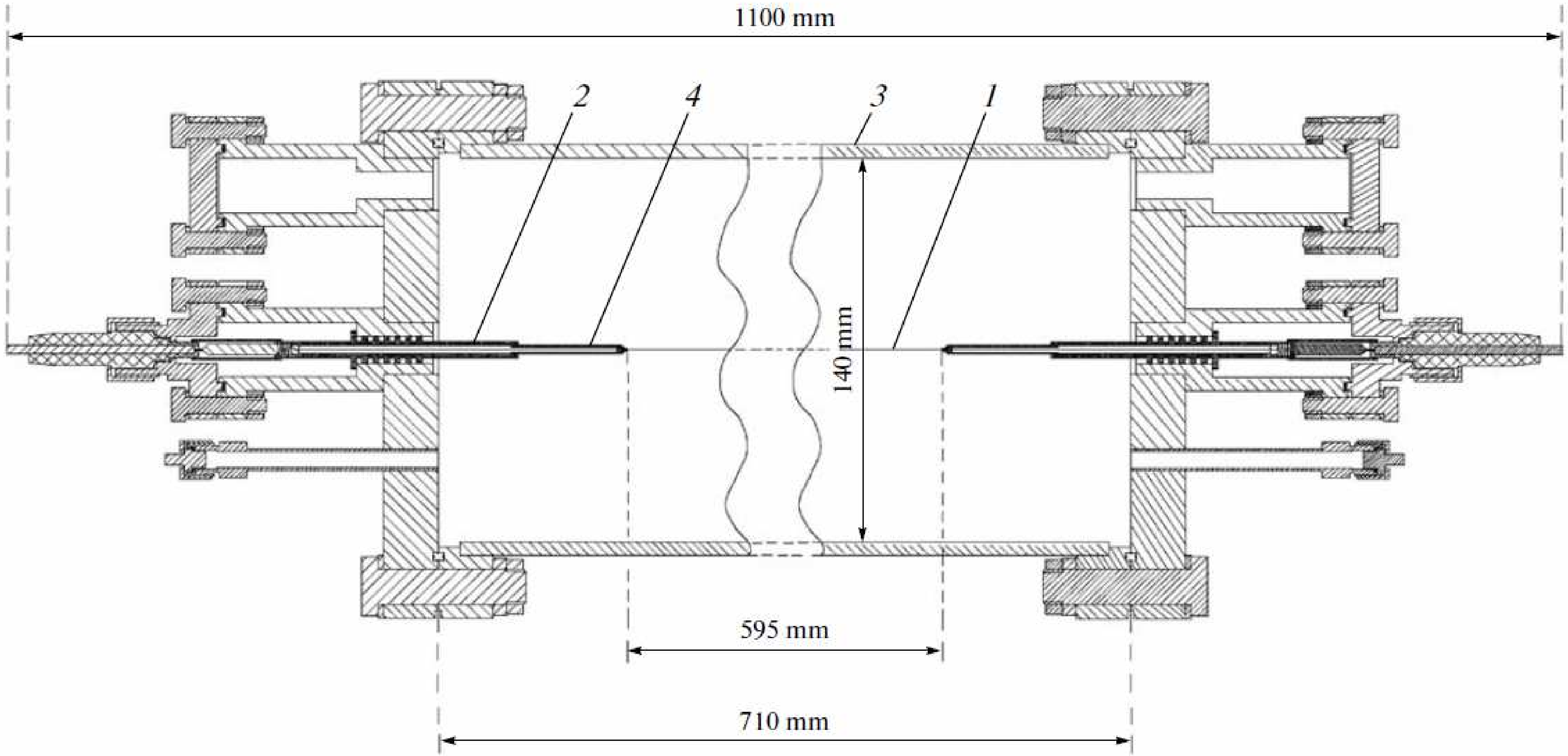


Fig. 1. Schematic view of the LPC in section along the anode wire: (*1*) wire (collecting electrode), (*2*) load-carrying insulator, (*3*) cathode, (*4*) tubular bulge of the anode, (XX) insulator, (\\\\\\) copper, and (///) steel.

Yu. M. Gavrilyuk *et al*. Phys. Rev. C 87 (2013) 035501

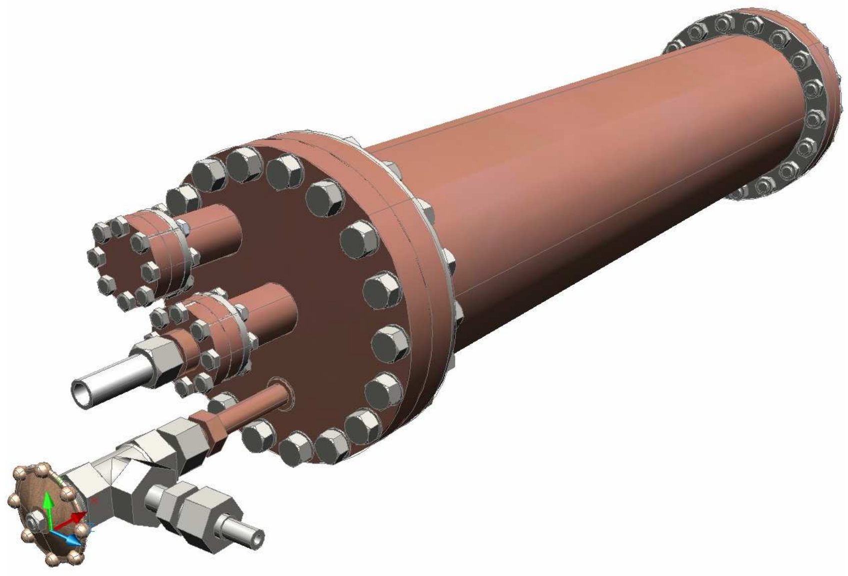
Shield:

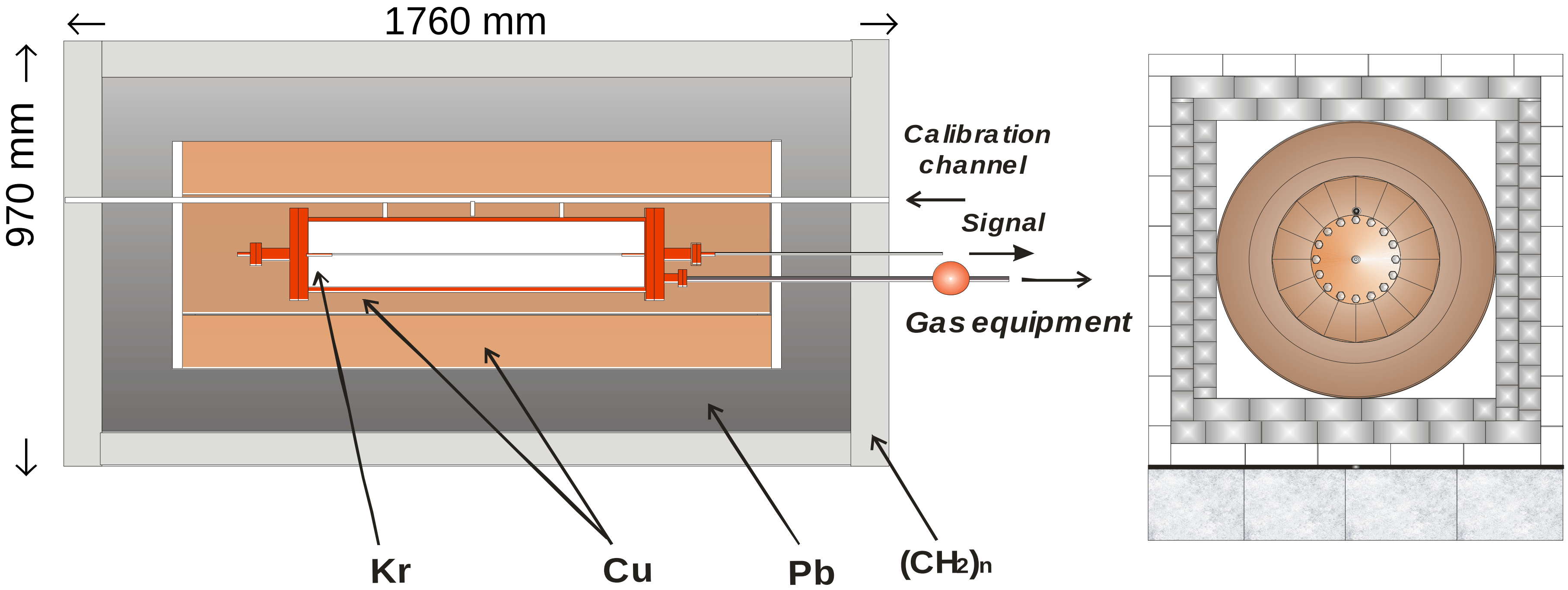
8 cm borated polyethylene

20 cm lead

20 cm copper

Depth: 4900 m w.e.





P = 5.6 bar, $M_{Kr\text{-}83}$ = 101 g (7.3x10^{23} nuclei), V = 8.77 dm^3

Isotopic abundances of the samples.

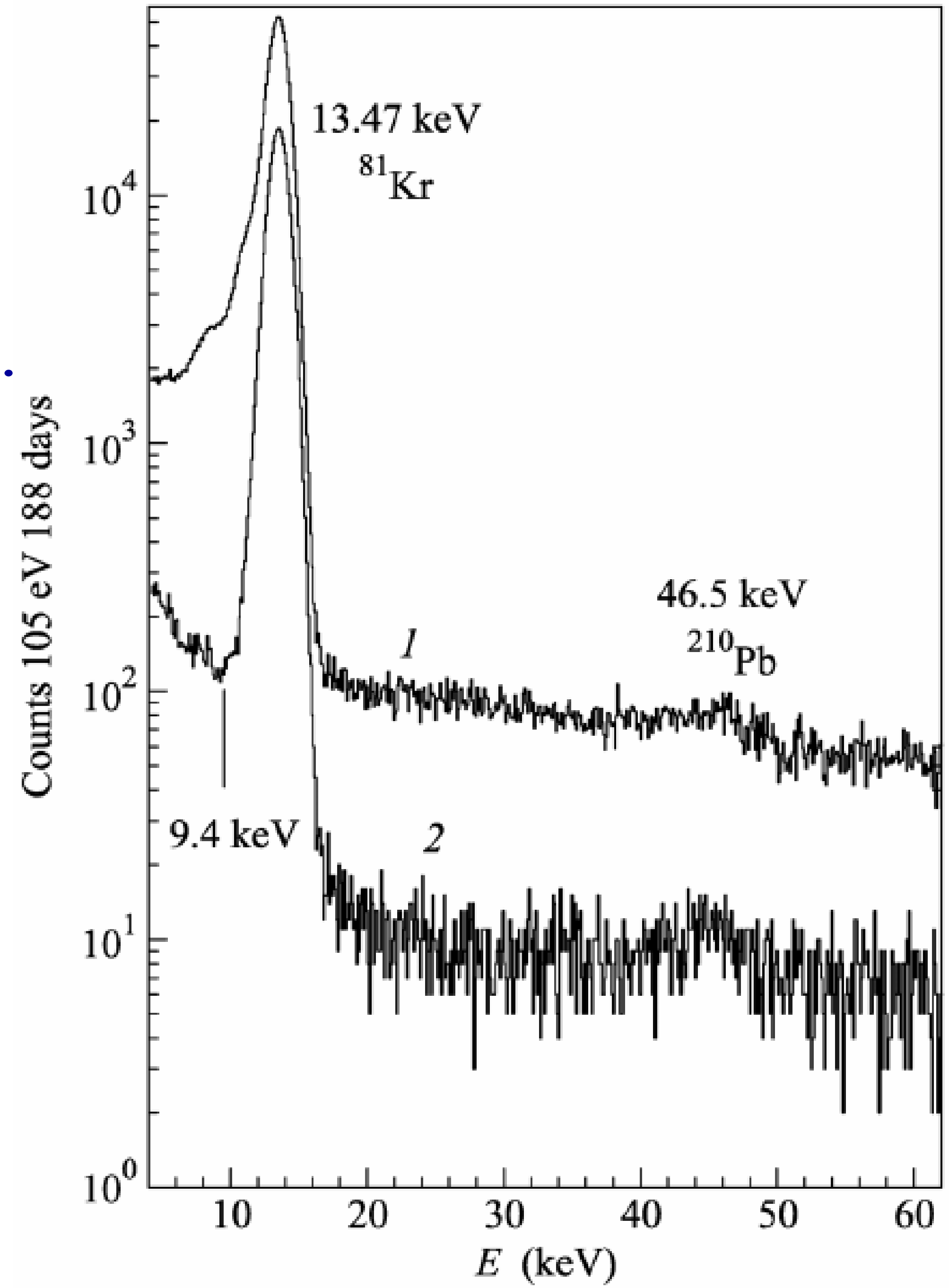
Kr (enriched)		Kr (depleted)	
Isotope	Abundance(%)	Isotope	Abundance (%)
Kr78	99.810	Kr78	0.002
Kr80	0.170	Kr80	0.411
Kr82	0.005	Kr82	41.355
Kr83	0.005	Kr83	58.229
Kr84	0.005	Kr84	0.003
Kr86	0.005	Kr86	0.00

The current restriction: $m_a < 130$ eV (95% CL) for 26.5 days data collection with 101 g of ^{83}Kr [Yu.M.Gavrilyuk *et al*., arXiv:1405.1271].
It is the best limit obtained by this method (the second best is $m_a < 145$ eV by A.V.Derbin et al., 2011, for ^{57}Fe).

Background spectrum of Kr-83

(T = 188.3 days)

Published in
Yu.M.Gavrilyuk et al., JETP Lett. 101 (2015) 664



Background spectrum of Kr-83

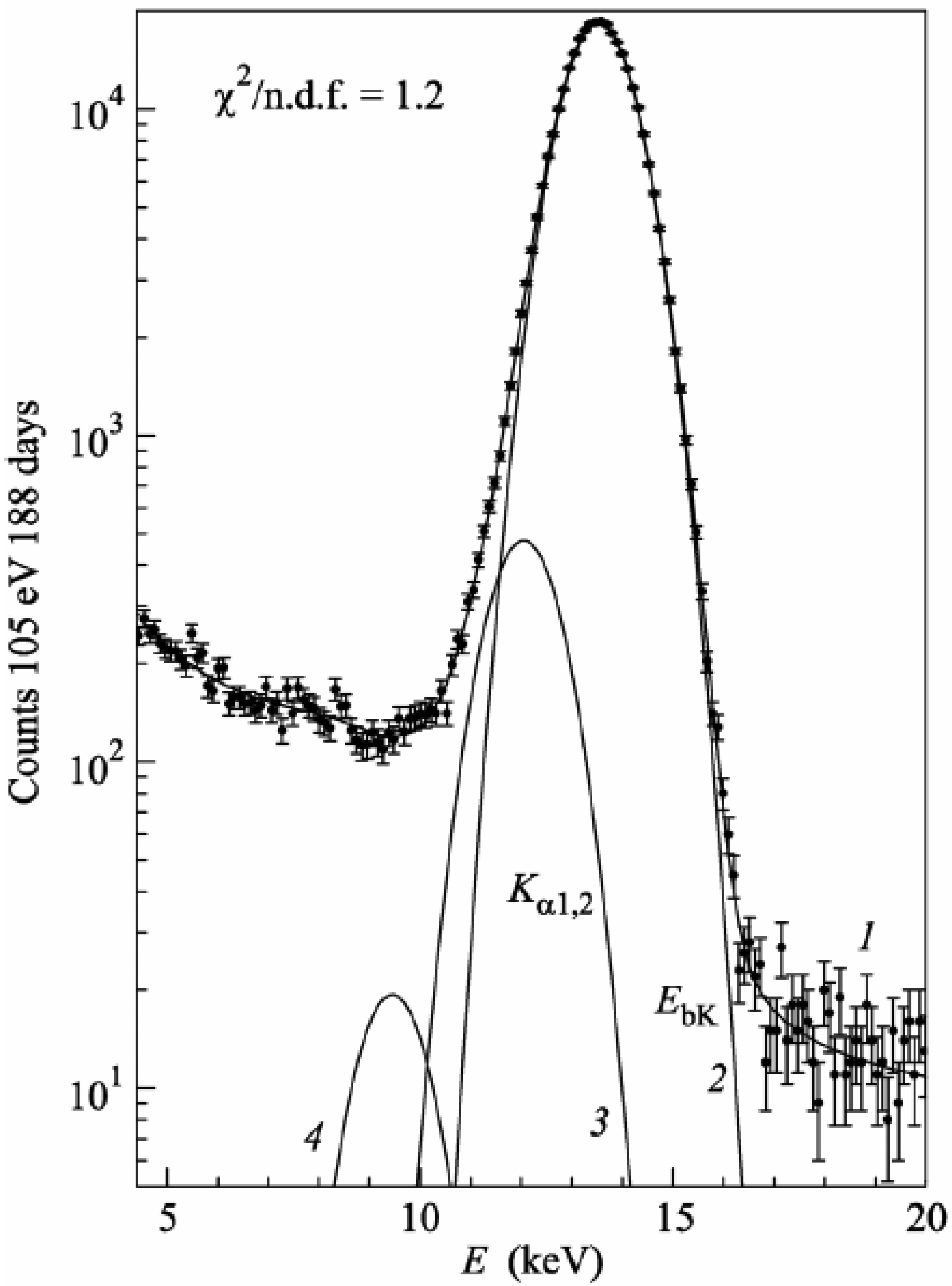
Fit by background and effect response functions.

The Kr-81 background is: 13.47 keV peak (tot.abs.) and 11.91 keV peak ($K_{\alpha 1,2}$ of Br).

Expected effect: Peak at 9.405 keV.

Lim S = –(259±153) events

Limit: m_a < 100 eV (95% C.L.)



Obtained restrictions (95% CL)

Live time of measurements: 188,3 days
Mass of Kr-83: 101 g

Model independent (for m_a < 2 keV):

$$\omega_a/\omega_\gamma < 2.4\times10^{-12}$$

$$|g^{(3)} - g^{(0)}|_{aN} < 1.3\times10^{-6}$$

Model dependent:

$$m_a < 100 \text{ эВ}$$

Current live time of measurements: ~3 years (not published yet)

Preliminary estimated limit: $m_a < 70\ldots75$ эВ

Prospects

The “detector=target” geometry demonstrates its good performance in search for solar hadronic axions by nuclear resonant absorption. Next possible steps: to use much bigger detectors containing nuclei of interest. Fe-57 and Li-7 are still preferred (for example, the flux of “iron” axions should be $10^{1.8} \approx 63$ times more than that of “krypton” axions). There is an idea (by A.Gangapshev) to use FeS_2 single crystals (pyrite) as a semiconductor detector, possibly with enriched Fe-57. Pyrite is used as semiconductor in photovoltaic applications.

Natural iron pyrite

Prospects

Another possibility is to use Li containing single crystals as bolometric cryogenic detectors. For example, lithium molybdate crystals are already tested as such detectors for search of DBD of ^{100}Mo (they also have scintillation properties which are used for suppression of background)

Crystals for bolometric search for solar ^{7}Li axion

Cylindrical crystals with *D* = *H*, *M* = 1 kg

Crystal	Dopant content (at. %)	Density (g/cm3)	Diameter and height (mm)	Full absorp. efficiency (%)	*N* (kg $^{-1}$)
LiF(Pure)	0	2.635	78.47	1.0	2.13×10^{24}
LiF(Ca)	3	2.635	78.47	1.7	2.06×10^{24}
LiF(W)	**1**	**2.635**	**78.47**	**19.5**	**2.10×10^{24}**
LiF(Tl)	0.8	2.635	78.47	14.2	2.11×10^{24}
LiF(Pb)	0.3	2.635	78.47	7.8	2.12×10^{24}
Li_2WO_4	**0**	**4.560**	**65.35**	**55**	**4.25×10^{24}**
Li_2MoO_4	**0**	**2.660**	**78.20**	**19.1**	**6.38×10^{24}**
$Li_6Eu(BO_3)_3$	**0**	**3.188**	**73.64**	**32**	**9.03×10^{24}**
$Li_3Sc(BO_3)_2$	0	2.631	78.51	4	9.06×10^{24}
$Li_6Gd(BO_3)_3$	**0**	**3.246**	**73.20**	**33.6**	**8.91×10^{24}**
$Li_6Y(BO_3)_3$	0	2.760	77.26	16.9	1.61×10^{25}

(Geant4 simulations by Ali Luqman)

Conclusions

1. Axions are the second best candidate for DM particles (after neutralinos).
2. Resonant conditions in many cases enhance the sensitivity of experiments to search for axions.
3. In the experiment with ^{83}Kr in a proportional chamber, the nuclear resonant absorption of solar hadronic axions has been searched (in the first time – with large target and good detection efficiency). The best upper limit on the mass of hadronic axion had been set.

Thank you for attention