9th Patras Workshop on Axions, WIMPs and WISPs

Schloß Waldthausen

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A search for solar-axions from the bremsstrahlung process with point-contact Ge detectors

Frank T. Avignone III and Richard J Creswick

University of South Carolina

For the MAJORANA Collaboration

The data used in these analyses came from the PhD dissertation research of Dr. Padraic Finnerty of the MAJORANA Collaboration under the direction of Professor Reyco Henning at the University of North Carolina.

QCD is a very attractive theory, but only if terms of the following form are neglected:

$$\mathcal{L}_{int} = \left(\theta / 32\pi^2\right) trG^{\mu\nu}\tilde{G}_{\mu\nu}$$

In 1975 Polyakov showed that such terms cannot simply be neglected.

Terms of this form lead to a significant neutron dipole moment unless theta < 10^{-10}.

This is unnatural for a strong interaction parameter.

Roberto Peccei and Helen Quinn proposed an additional U(1) symmetry in the Lagrangian which is spontaneously broken at a high energy scale.

This results in the cancellation of the offending CP-Violating term.

The resulting Goldstone boson is our friend the axion. Many of us have been chasing it for years.

Weinberg and Wilczek independently pointed out the measurable physical properties of the axion within the standard model.

However, in a very short time the Standard Model axion was experimentally eliminated and two models for invisible axions were introduced.

Invisible Axions

The Kim, Shifman, Vainstein, Zakharov: KSVZ model. KSVZ axions couple to hadrons and photons at the tree level, but to electrons only via a one loop radiative correction

The Dine, Fischler, Srednicki, Zhitnitskii: DFSZ model. These axions couple to hadrons, photons and electrons at the tree level.

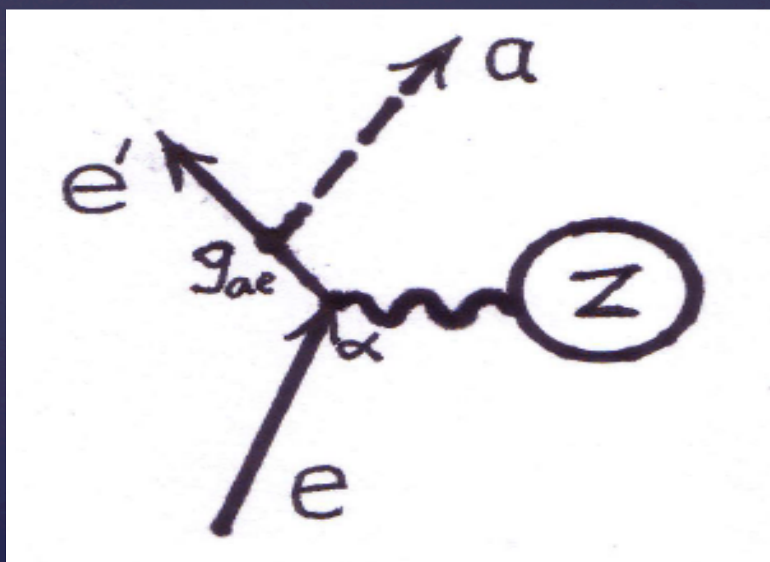
The relation between the axion mass and the Peccei-Quinn symmetry-breaking scale is given by:

$$m_a = \frac{f_\pi m_\pi}{f_a}\left(\frac{z}{(1+z+w)(1+z)}\right)^{1/2} \approx \frac{6.0\times 10^6}{f_a(GeV)}(eV),$$

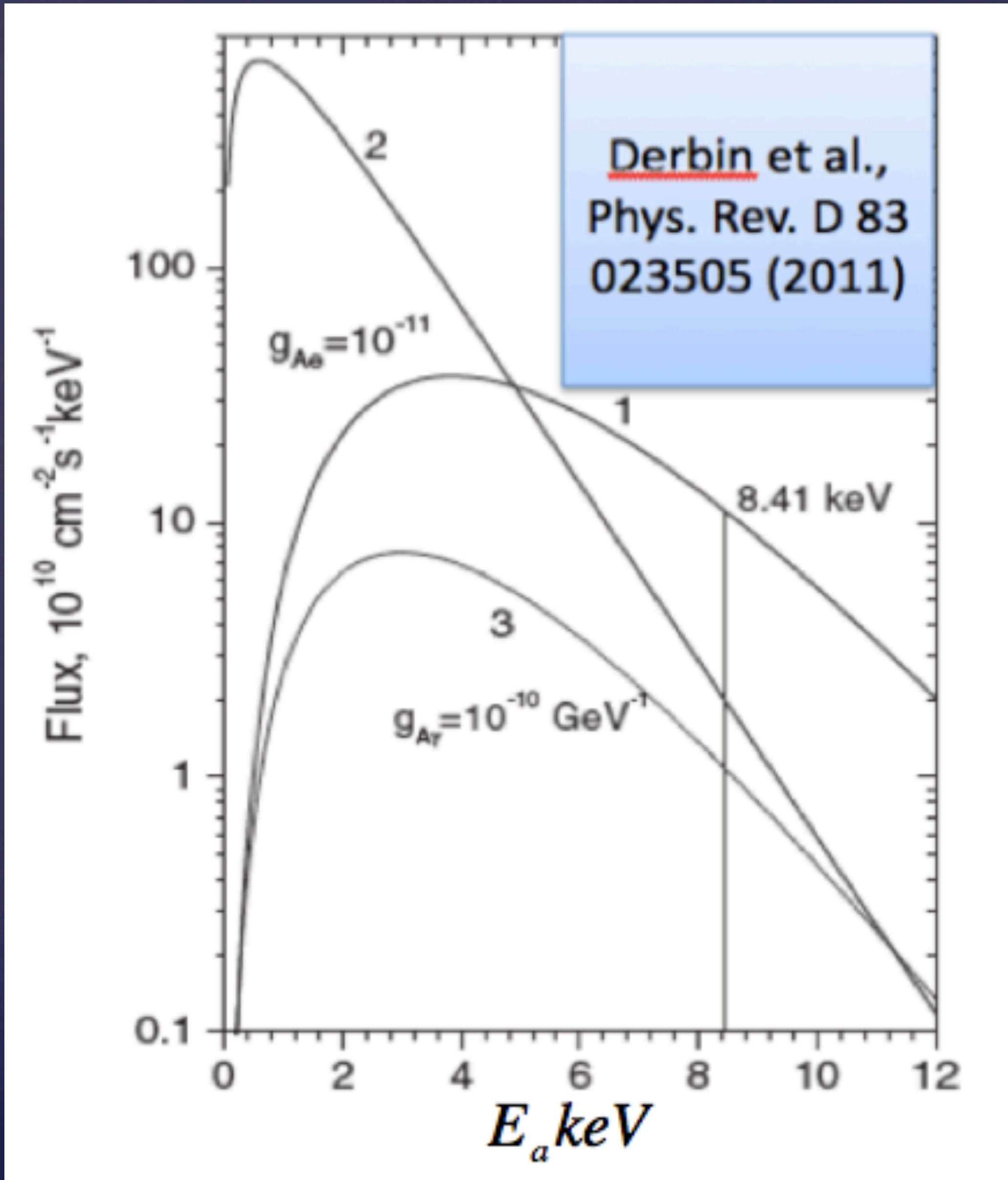
$$f_\pi \cong 92 MeV \; ; \; z \equiv m_u / m_d \approx 0.56 \; ; \; w \equiv m_u / m_s \approx 0.026$$

Axion Generation in the Sun

Compton Process



Bremsstrahlung *Primakoff*



1. *Compton mechanism for the generation of axions.*
2. *Bremsstrahlung mechanism for generating axions.*
3. *Primakoff mechanism for generating axions.*

The expression for the solar flux used is that given by Derbin et al., Phys. Rev. D, 83, 023505 (2011).

$$\frac{d\Phi}{dE_a} = g_{ae}^2 \times 4.14 \cdot 10^{35} E_a^{0.89} e^{-0.7E_a - 1.26\sqrt{E_a}} cm^{-2} s^{-1} keV^{-1}$$

The axioelectric cross section, derived by Dimopoulis et al., was used to analyze an early solar axion search by Avignone et al; it was corrected by a factor of 2 later by Maxim Pospelov. For DFSZ model:

$$\sigma_{ae} = \frac{\omega_a^2}{2\pi\alpha f_a^2} \times \sigma_{pe}$$

$$g_{ae} \equiv \cos^2\beta / 3 f_a$$

$$\cos^2\beta \approx 1$$

$$\sigma_{ae} = g_{ae}^2 E_a^2 (7.72 \times 10^{-4}) \sigma_{pe}$$

Physical Review D, Vol. 35 No.9 1. May 1987

Laboratory limits on solar axions from an ultralow-background germanium spectrometer

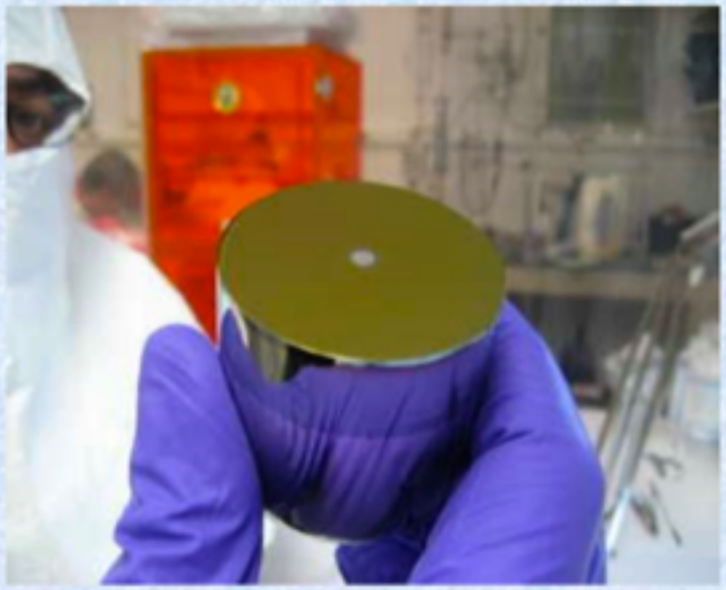
F.T. Avignone III, R.L. Brodzinski, S. Dimopoulos
G.D. Srarkman, A.K. Drukier, D.N. Spergel
G. Gelmimi and B.W. Lynn

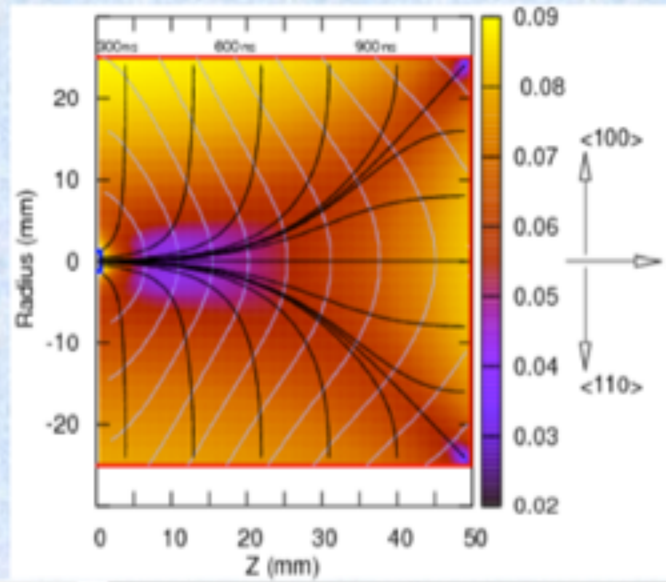
So what is new in the experimental tool box?

The Ultra-Low-Energy-Threshold
Point-Contact Germanium Detector

Originally conceived by Paul Luke of LBNL and recently developed by Juan Collar's group at the University of Chicago.

Point Contact Germanium Detectors





The point contact results in very low capacitance and very low energy thresholds

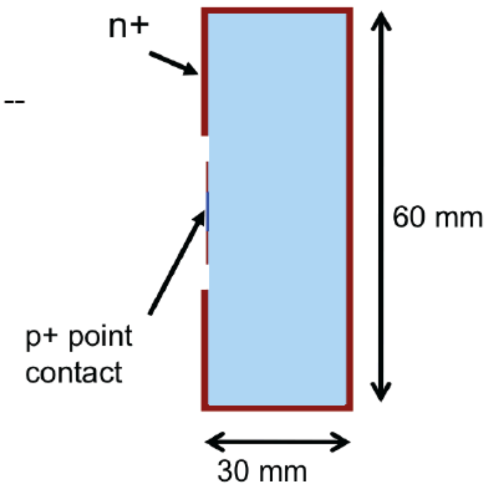
MALBEK

The Majorana Low-background Broad-Energy germanium detector at KURF

KURF- Kimballton Underground Research Facility

MALBEK: R&D for the DEMONSTRATOR

- 455g ^{nat}Ge
- Customized CANBERRA **B**road **E**nergy **Ge**rmanium Detector
  - Crystal geometry optimized for charge collection and noise performance.
  - Low-background Cu cryostat (J.I. Collar -- UC)
- Located at the Kimballton Underground Research Facility (KURF) – 1450 mwe
- Goals
  - Aspect ratio study
  - Test MJD-like DAQ
  - Backgrounds over broad energy range (surface events, noise, validate MJD background model)
  - Low-E sensitivity of MJD (Dark Matter)



P. Finnerty et al., Nucl. Instr. and Meth. A 652, (2011) 692-695.
P. Finnerty et al. IEEE NSS-MIC, (2010) 671-673.

MALBEK: R&D for the DEMONSTRATOR

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

- 455g ^{nat}Ge
- Customized CANBERRA **B**road **E**nergy **Ge**rmanium Detector
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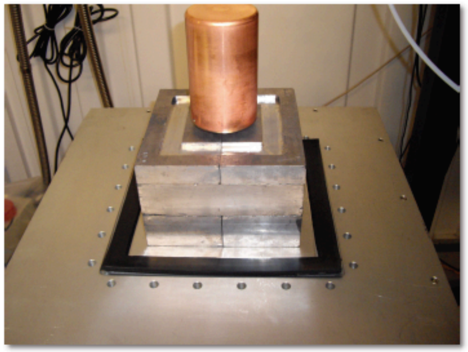
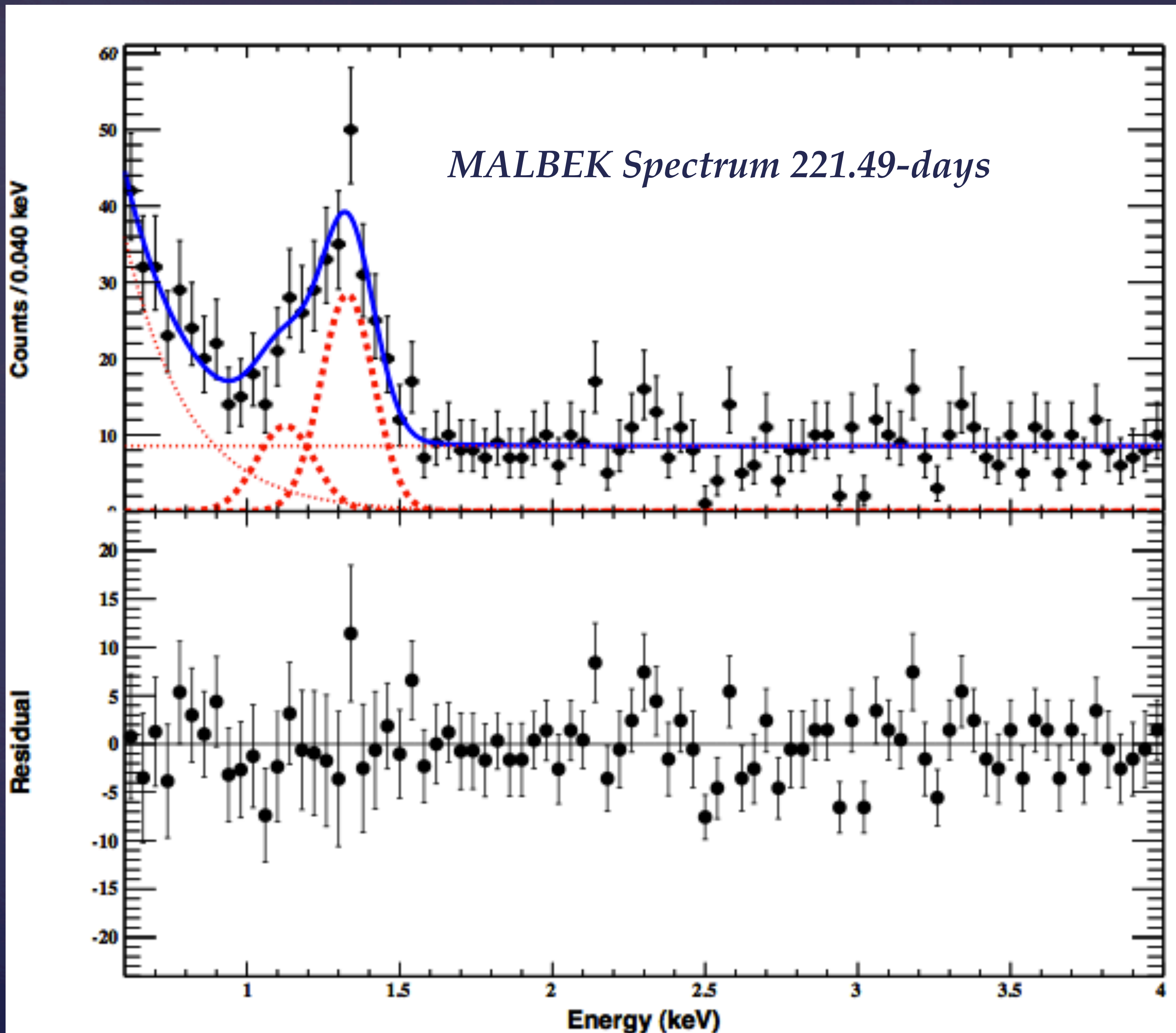


P. Finnerty et al., Nucl. Instr. and Meth. A 652, (2011) 692-695.
P. Finnerty et al. IEEE NSS-MIC, (2010) 671-673.

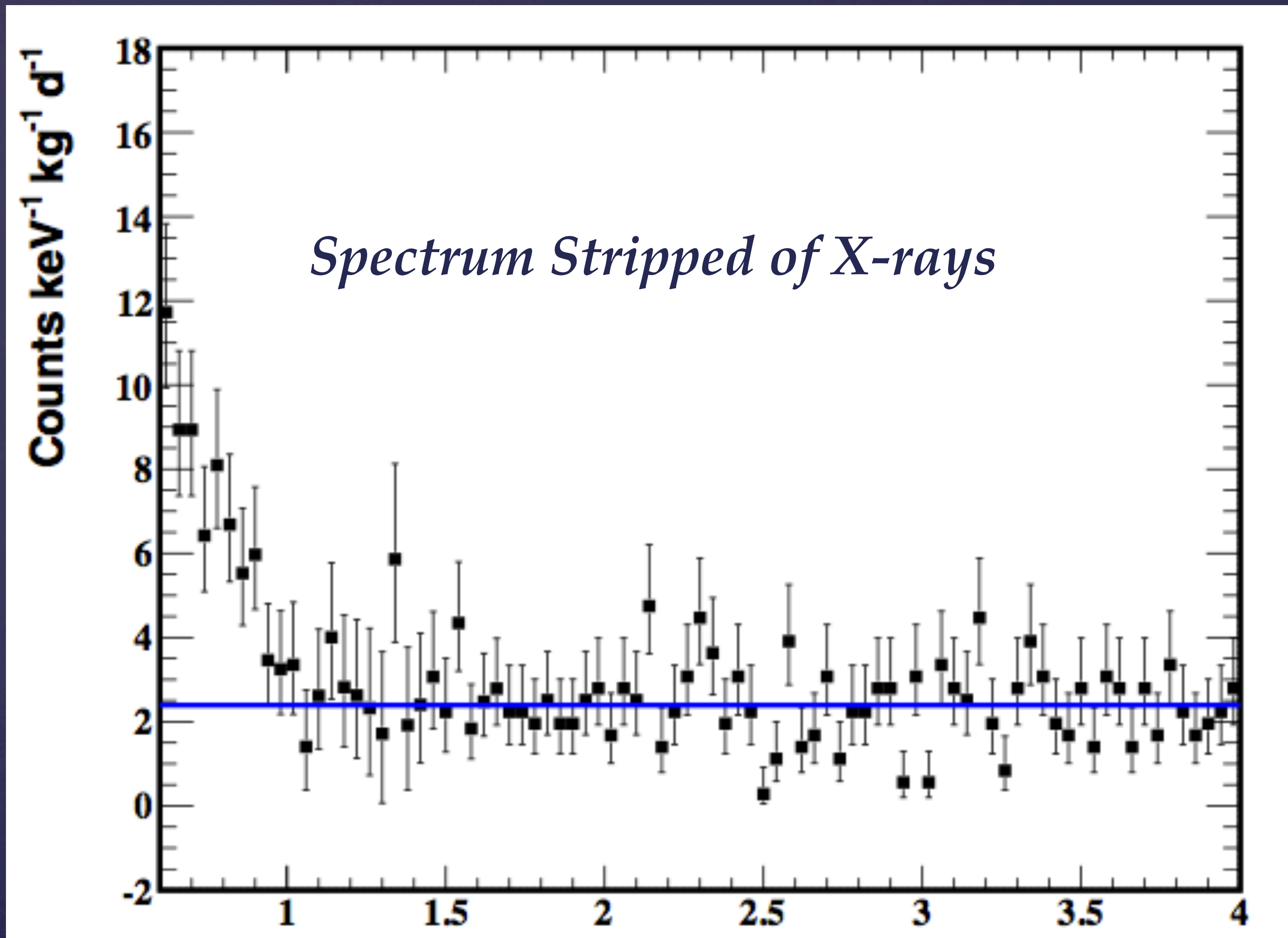
MALBEK operated for 221.4939 days = 1.9137 x 10^7 sec.

MALBEK's fiducial mass = 0.4042-kg
corresponds to 3.352 x 10^{24} Atoms.

N t = 6.414 x 10^{31} atom sec.



MALBEK Spectrum 221.49-days
Counts / 0.040 keV
Residual
Energy (keV)



Spectrum Stripped of X-rays
Counts keV^{-1} kg^{-1} d^{-1}
18
16
14
12
10
8
6
4
2
0
-2
1
1.5
2
2.5
3
3.5
4

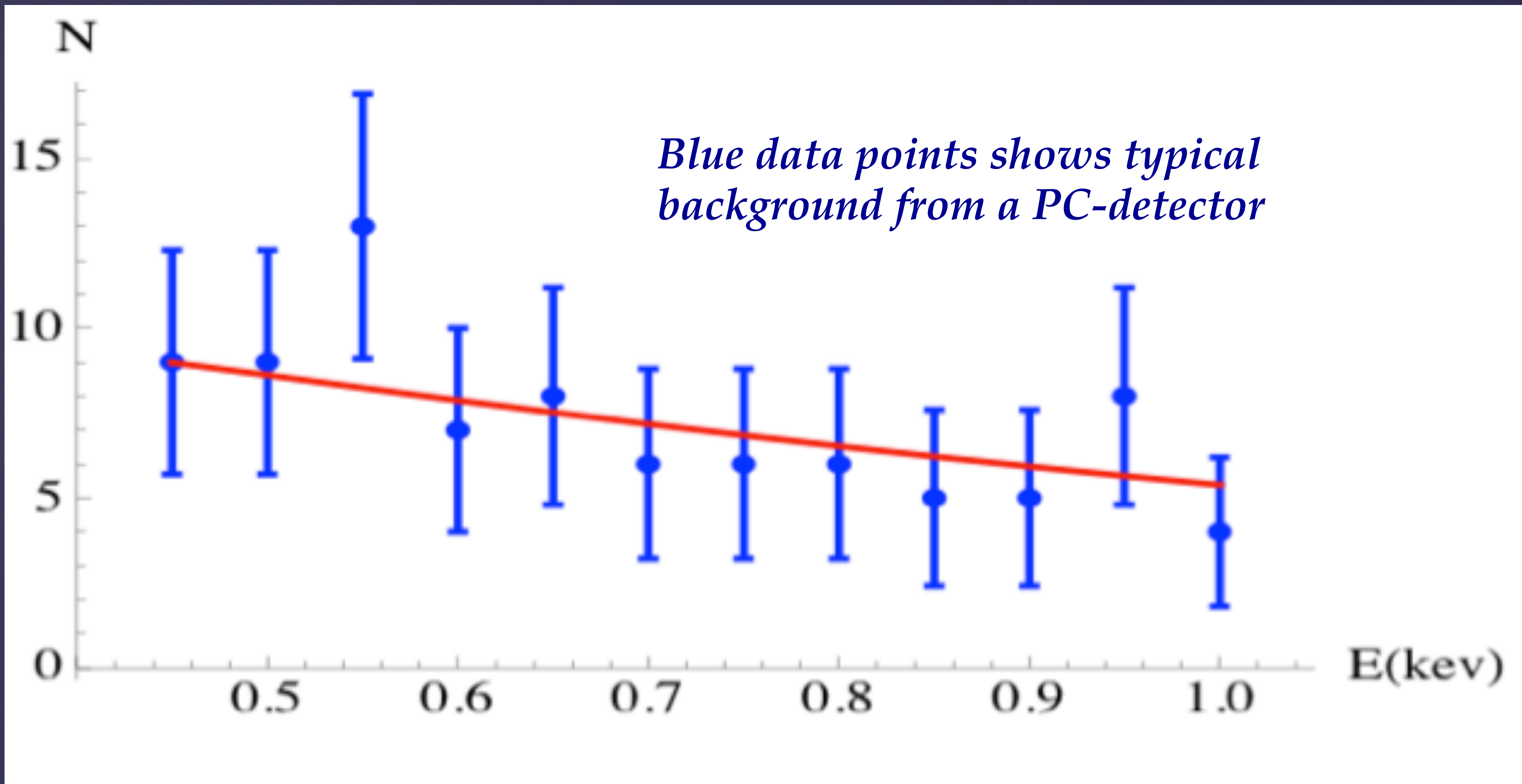
$$\int_{E_i}^{E_f} \frac{d\Phi}{dE_a}\sigma_a(E_a)dE_a =$$

$$3.18\cdot 10^{32} g_{ae}^4 \int_{E_i}^{E_f} E^{2.89} e^{-0.7E_a - 1.26\sqrt{E_a}} \sigma_{pe}(E_a)dE_a$$

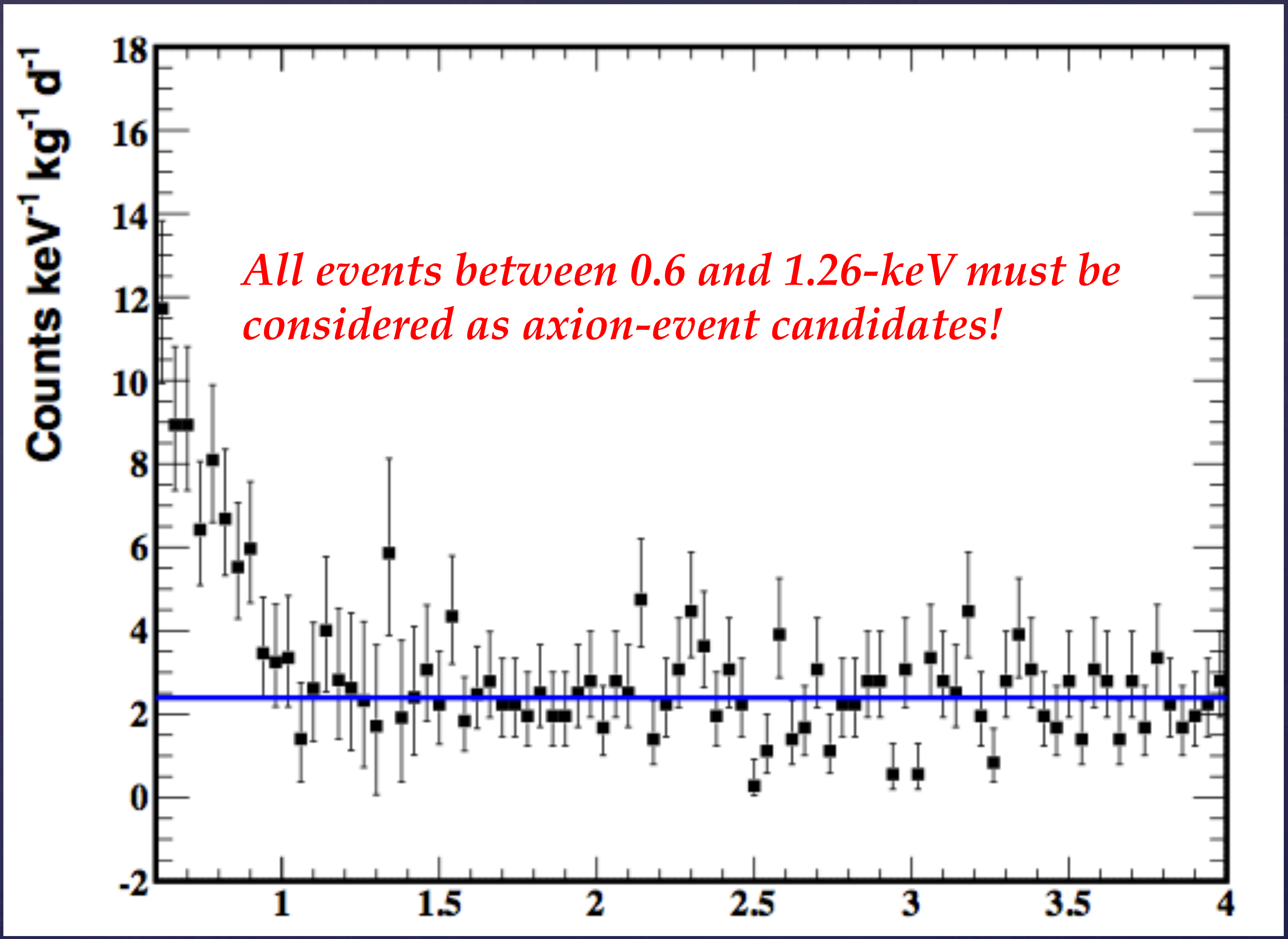
$$\int_{E_i}^{E_f} E_a^{2.89} e^{-0.7E_a - 1.26\sqrt{E_a}} \sigma_{pe}(E_a)dE_a$$

$$= 2.505 \times 10^{-20}\, atom^{-1}\,\sec^{-1}$$

$$E_i = 0.6 - keV; E_f = 1.26 - keV$$



The red line is the theoretical shape of the expected shape of spectrum the solar bremsstrahlung interactions in a PC-Germanium detector



Counts keV^{-1} kg^{-1} d^{-1}
18
16
14
12
10
8
6
4
2
0
-2
1
1.5
2
2.5
3
3.5
4
All events between 0.6 and 1.26-keV must be considered as axion-event candidates!

Calculate the rate for a value of the dimensionless coupling constant of 10^{-10}

$$R = 3.18 \times 10^{32} \times (g_{ae}^{4} = 10^{-40}) \times$$

$$2.505 \times 10^{-20} = 7.97^{-28}\, atom^{-1}\, \sec^{-1}$$

N t =3.352 x 10^{24} atoms x 1.914 x 10^{7} sec

N t *R= 47,913 predicted events*

The total number of events above the 2.1 count line, from 0.62 < 1.26-keV, is less than 211 to a 95% C.L.

Using a value of 10^{-10} for the dimensionless coupling of axions to electrons, we predict 47,913 axion interactions in the MALBEK experiment.

$$g_{ae}^{\exp} / g_{ae}^{calc} = \sqrt[4]{211/47{,}913} = 0.2576 \Rightarrow$$

$$g_{ae}^{\exp} \leq 2.58 \times 10^{-11} (95\% C.L.)$$

There would be some improvement by running the MAJORANA DEMONSTRATOR ; however, since the rate goes as the 4th power of the coupling constant, the bound will not improve very much.

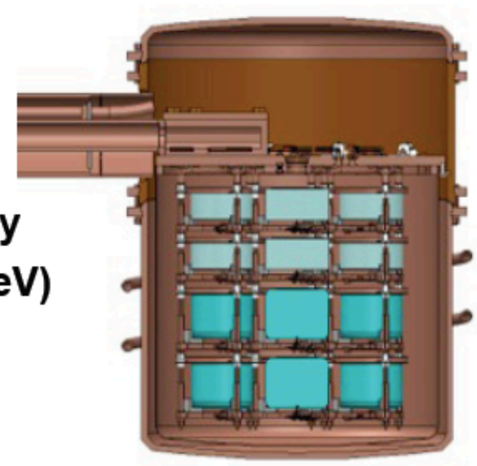
The ratio of rate measured and that predicted at 2.58 x 10^{-11} would have to improve by a factor of ~ 45 to reduce the bound to 1 x $10^{-11.}$

The real exciting possibility is with the entire MJD, searching for the ~ 6.68 % peak-to-peak annual modulation due to the seasonal change in the earth-sun-distance.

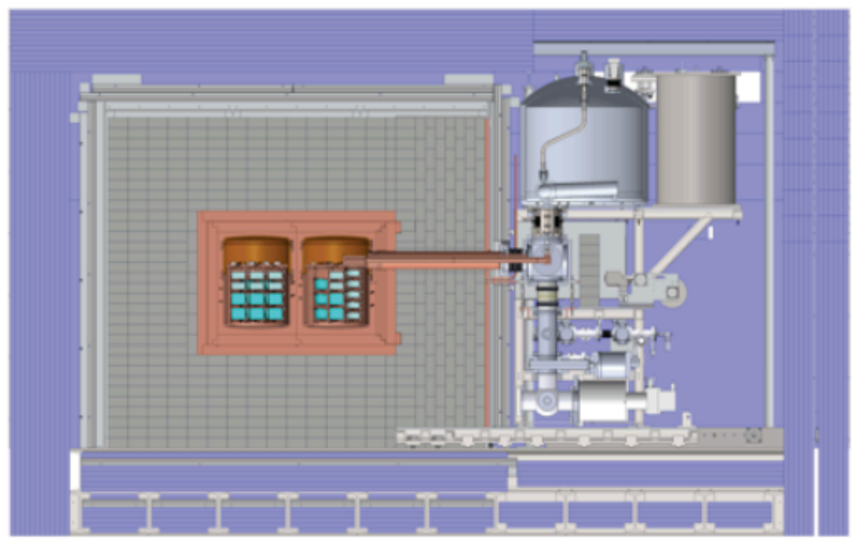
The MAJORANA DEMONSTRATOR

Funded by DOE Office of Nuclear Physics and NSF Particle Astrophysics,
with additional contributions from international collaborators.

Goals: - Demonstrate backgrounds low enough to justify building a tonne scale experiment.
- Establish feasibility to construct & field modular arrays of Ge detectors.
- Test Klapdor-Kleingrothaus claim.
- Searches for additional physics beyond the standard model.

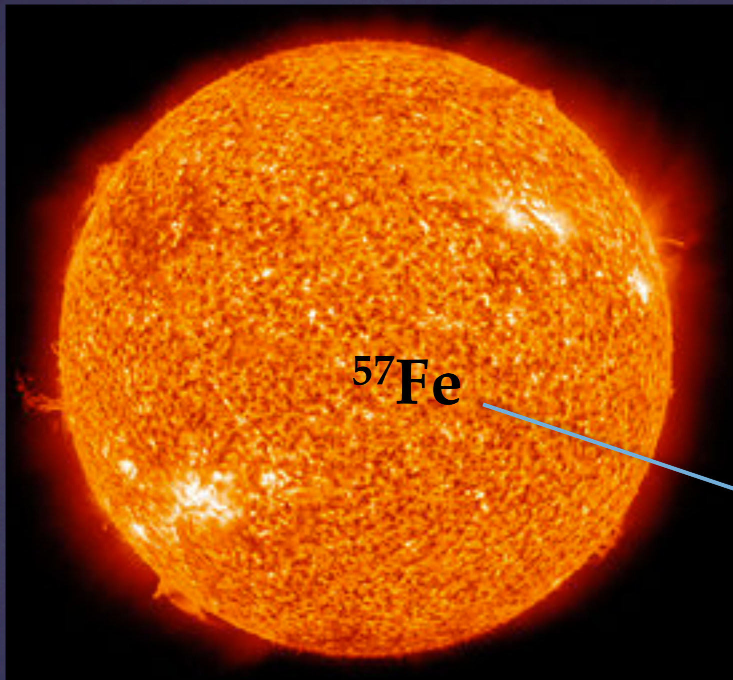


- **Located underground at 4850' Sanford Underground Research Facility**
- **Background Goal in the 0νββ peak region of interest (4 keV at 2039 keV)**
  3 counts/ROI/t/y (after analysis cuts)
  scales to 1 count/ROI/t/y for a tonne experiment
- **40-kg of Ge detectors**
  - 30 kg of 86% enriched ^{76}Ge crystals
  - 10 kg of ^{nat}Ge
  - Detector Technology: P-type, point-contact.
- **2 independent cryostats**
  - ultra-clean, electroformed Cu
  - 20 kg of detectors per cryostat
  - naturally scalable
- **Compact Shield**
  - low-background passive Cu and Pb shield with active muon veto



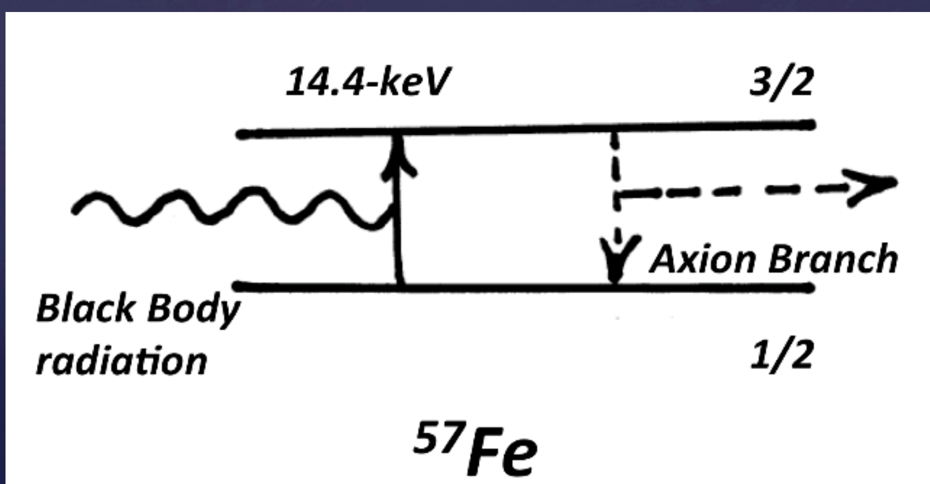
Another axion-search opportunity is for Hadronic axions from the M1 ground-state transition in ^{57}Fe in the solar core

14.4-keV hadronic axions from the solar core



14.4-keV

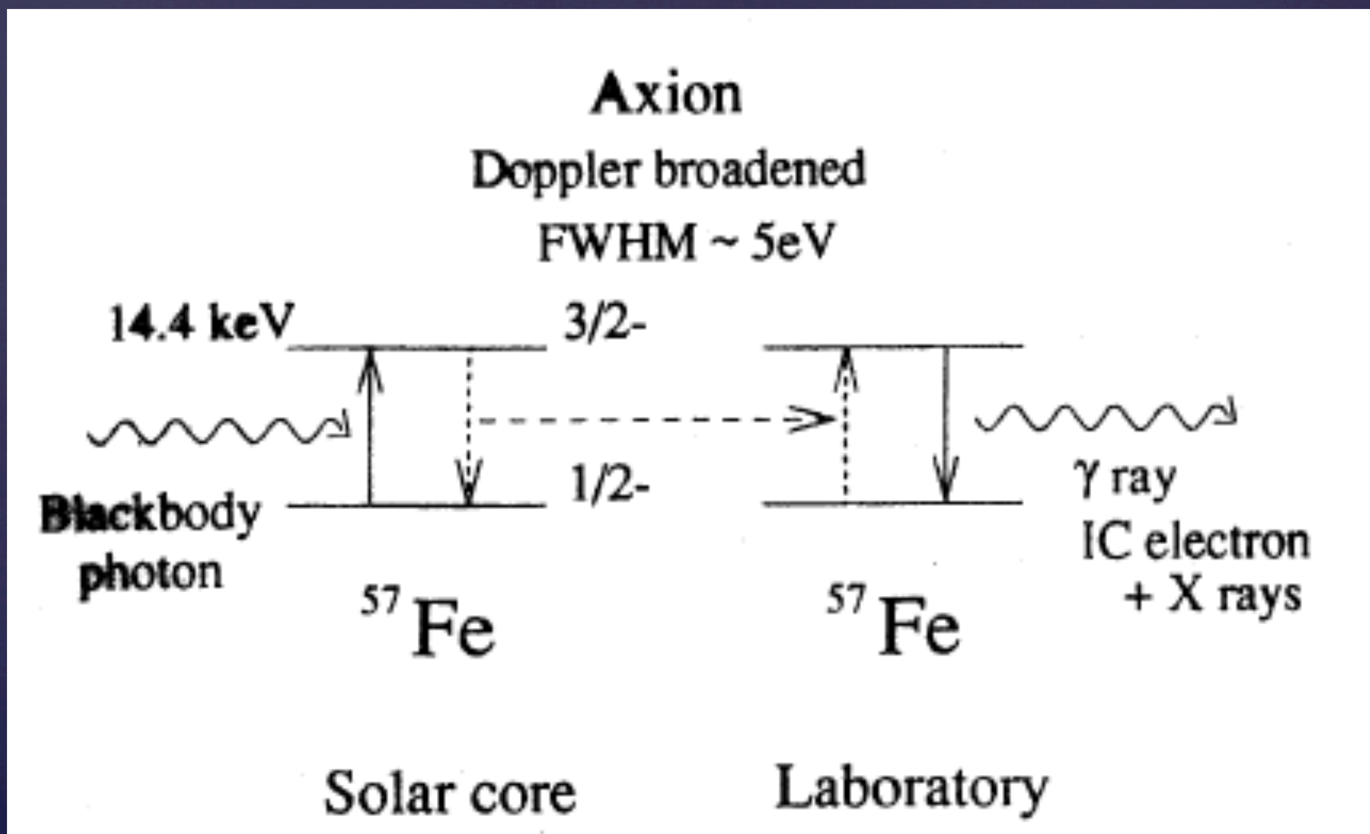
a



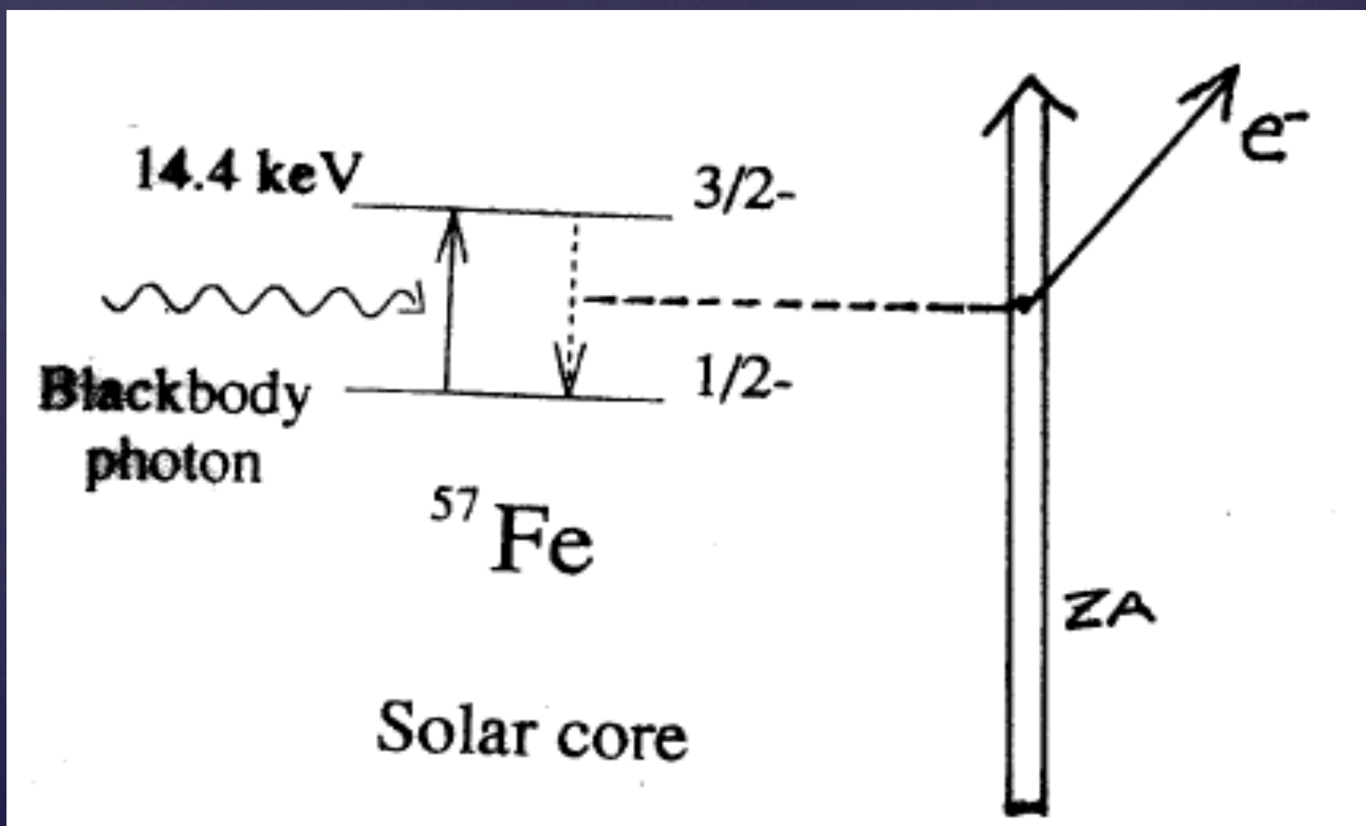
Shigetaka Moriyama 1999

^{57}Fe in the solar core is thermally excited and the M1 ground state transition has a small axion branch.

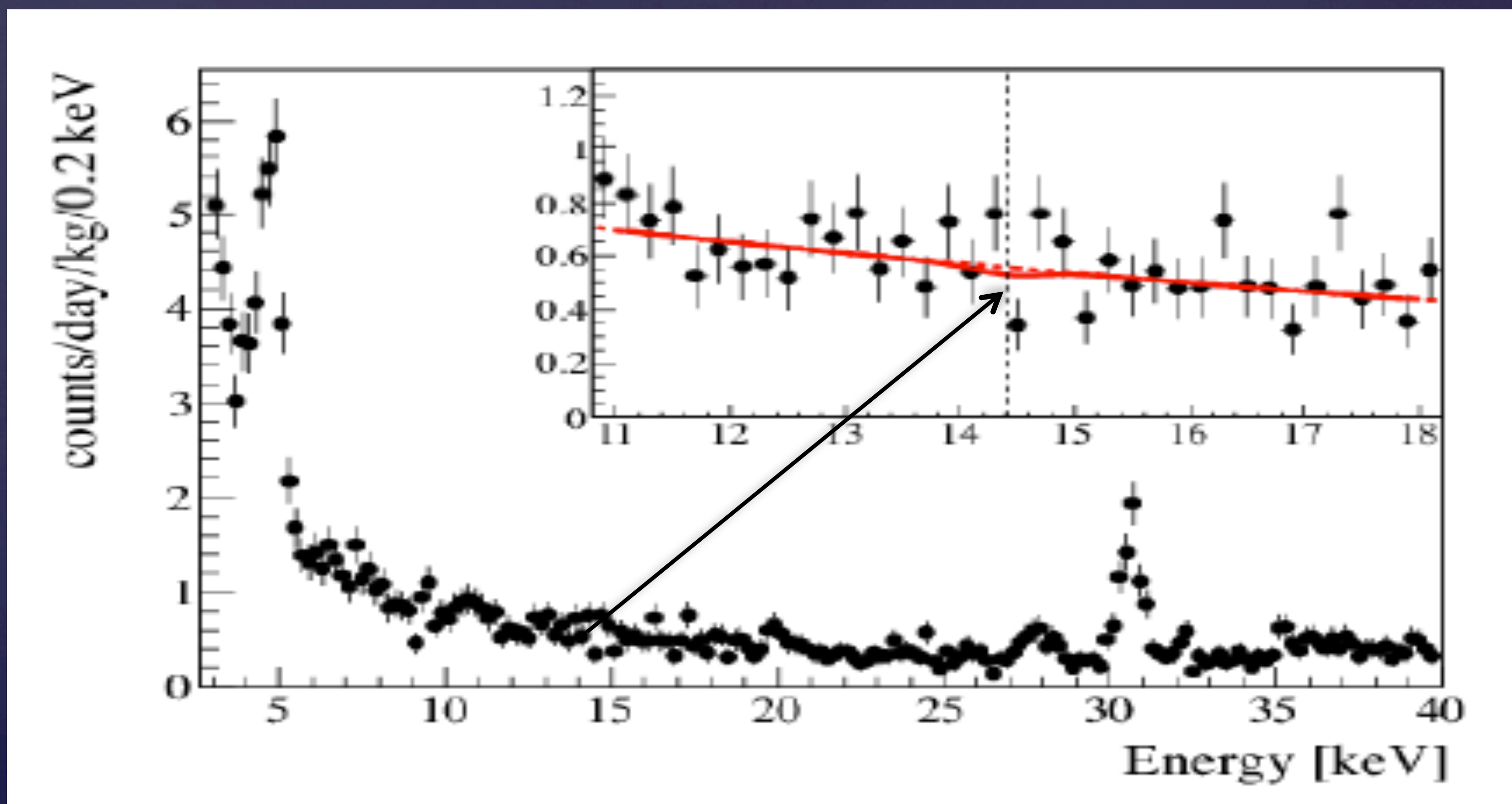
Shigetaka Moriyama 1999



Search for a monochromatic peak at 14.4-keV in the MAJORANA DEMONSTRATOR Array, and search for the annual modulation as well.



An example: 46.65-kg-days of data with 3 CUORE TeO_2 bolometers in a test facility. These data were used to search for 14.4-keV solar axions from ^{57}Fe in the sun.



Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Search for 14.4 keV solar axions from M1 transition of ^{57}Fe with CUORE crystals

The CUORE collaboration
E-mail: cuore-spokesperson@lngs.infn.it

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Abstract. We report the results of a search for axions from the 14.4 keV M1 transition from ^{57}Fe in the core of the sun using the axio-electric effect in TeO_2 bolometers. The detectors are $5\times5\times5$ cm^3 crystals operated at about 10 mK in a facility used to test bolometers for the CUORE experiment at the Laboratori Nazionali del Gran Sasso in Italy. An analysis of 43.65 kg·d of data was made using a newly developed low energy trigger which was optimized to reduce the energy threshold of the detector. An upper limit of 0.58 c·kg^{-1}·d^{-1} is established at 95% C.L., which translates into lower bounds $f_A \geq 3.12\times10^5$ GeV 95% C.L. (DFSZ model) and $f_A \geq 2.41 \times 10^4$ GeV 95% C.L. (KSVZ model) on the Peccei-Quinn symmetry-breaking scale, for a value of $S = 0.5$ of the flavor-singlet axial vector matrix element. These bounds can be expressed in terms of axion masses as $m_A \leq 19.2$ eV and $m_A \leq 250$ eV at 95% C.L. in the DFSZ and KSVZ models respectively. Bounds are given also for the interval $0.35 \leq S \leq 0.55$.

JCAP05(2013)007

All the formalism was developed earlier by Haxton in Avignone et al., Phys. Rev. D 37, 618 (1988); Haxton and Lee, Phys. Rev. Lett. 66, 2557 (1991). Andriamonje et al., (CAST) JCAP 12, 002 (2009)

$$\frac{\Gamma_a}{\Gamma_\gamma} = \left(\frac{k_a}{k_\gamma}\right)^3 \frac{1}{2\pi\alpha}\frac{1}{1+\delta^2}\left[\frac{g_{aN}^0\beta + g_{aN}^3}{(\mu_0 - 1/2)\beta + \mu_3 - \eta}\right]^2$$

$$\mathcal{L} = a\bar{\psi}_i\gamma_5(g_{aN}^0\beta + g_{aN}^3\tau_3)\psi$$

$$\frac{\Gamma_a}{\Gamma_\gamma} = \left(\frac{k_a}{k_\gamma}\right)^3 1.82(-1.19g_{aN}^0 + g_{aN}^3)$$

$$g_{\mathrm{aN}}^{\mathrm{eff}} \equiv (-1.19g_{\mathrm{aN}}^0 + g_{\mathrm{aN}}^3)$$

$$\Phi_a = \left(\frac{k_a}{k_\gamma}\right)^3 \times 4.56 \times 10^{23}(g_{aN}^{\mathrm{eff}})^2 \quad \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

CONCLUSIONS

There are several exciting axion searches that can be done with PC-detectors. The search for solar axions generated by Bremsstrahlung, with annual modulation using the MAJORANA DEMONSTRATOR, would have excellent discovery potential

Much better discovery potential would be with the one-ton Ge experiment and annual modulation.


IL LAVORO MI PERSEGUITA;
MA IO SONO PIU' VELOCE!