Search for solar axions and sterile neutrino from the CUP (Center for Undergroud Physics), IBS

HyangKyu Park
Center for Underground Physics, ibs

Light Dark World 2016, Jul 13th, 2016

Contents

- Introduction
- Experiment
- Data Analysis
- Prospects

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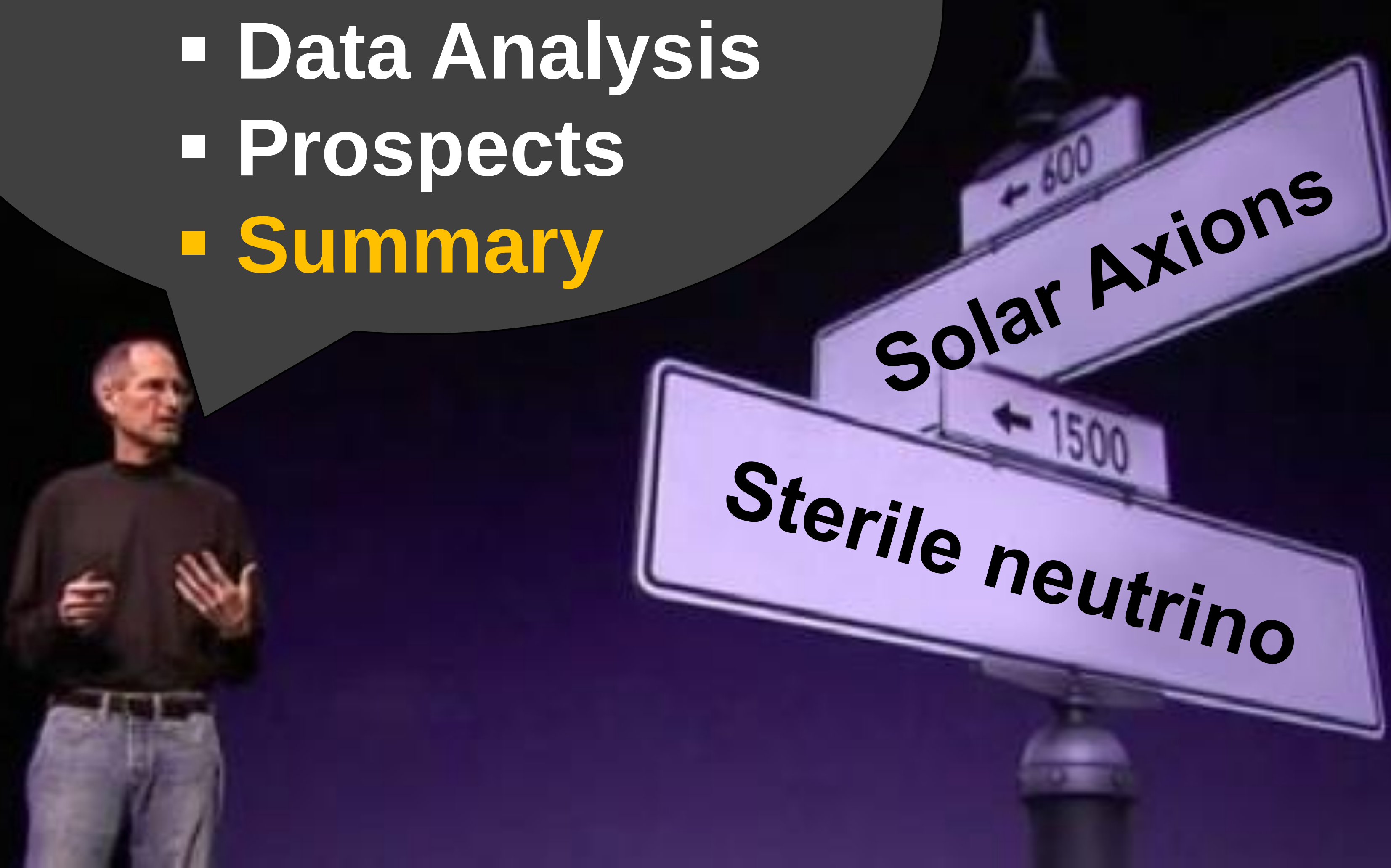
- Introduction
- Experiment
- Data Analysis
- Prospects
- Summary



Search
for
Solar Axions

(JHEP 06 (2016) 011 [arXiv:1604.01825])

Axion: Strong CP problem

- **Most general gauge invariant the Lagrangian of QCD:**

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} + \bar{q}\,(i\gamma_\mu D^\mu - \mathcal{M}_q)\, q - \underline{\frac{\alpha_s}{8\pi}\,\theta\, G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}}$$

Non-zero & CP-violation

- **Electric-dipole moment of neutron:**
  d < ~10^{-26} e cm → $\theta < 10^{-10}$

- **Introduce the axion field ϕ_a:**

$$\mathcal{L} = (\bar{\theta} - \frac{\phi_a}{f_a}) \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}$$

Note: f_a is the only parameter in the model.

Choose the minimum $\phi_a = \bar{\theta} f_a$,
then CP is conserved.

Interaction of Axion with Matter

- **Effective Lagrangian:**

$$\mathcal{L}_{int} = g_{a\gamma}\phi_a \vec{E}\cdot\vec{B} + i g_{ae}\phi_a \bar{\psi}_e \gamma_5 \psi_e + i\phi_a \bar{\psi}_N \gamma_5 (g^0_{aN} + g^1_{aN}\tau_3)\psi_N, \ \psi_N = \begin{pmatrix} p \\ n \end{pmatrix}$$

$$\mathcal{L}_{int} = -\frac{1}{4} g_{a\gamma}\phi_a F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma}\phi_a \vec{E}\cdot\vec{B}$$

- **Axion Model**

Axion Model (m_a/eV)	$g_{a\gamma}$ (GeV^{-1})	g_{ae}	g_{aN}
Hadronic axion (KSVZ axion)	4.9×10^{-10}	9.6×10^{-13}	-3.5×10^{-8} -2.8×10^{-8}
GUT axion (DFSZ axion)	1.4×10^{-10}	2.84×10^{-11}	-2.6×10^{-8} -2.8×10^{-8}

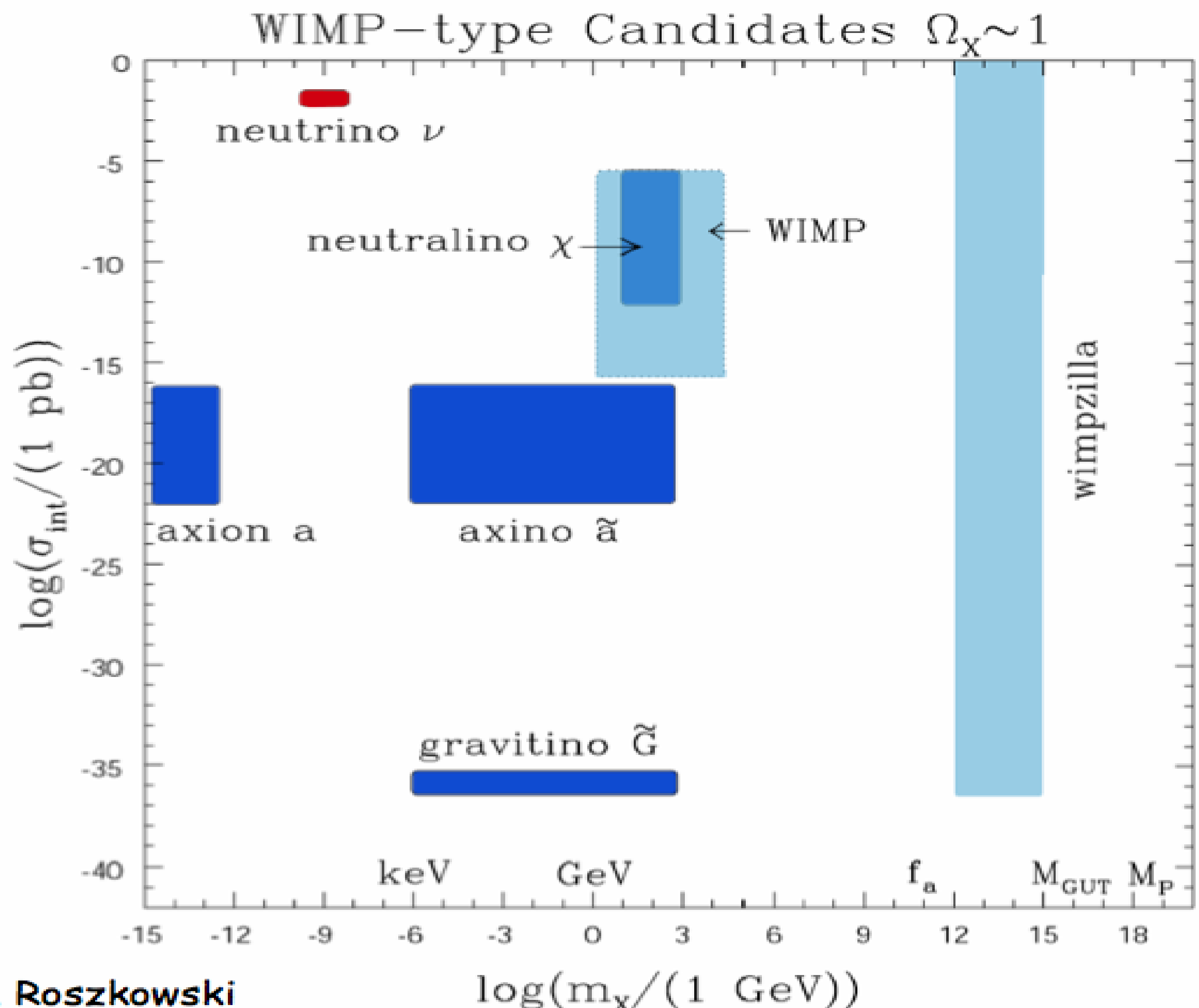
$$m_a = \frac{0.62 \times 10^7}{f_a(GeV)} eV$$

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

E/N=8/3 (DFSG)

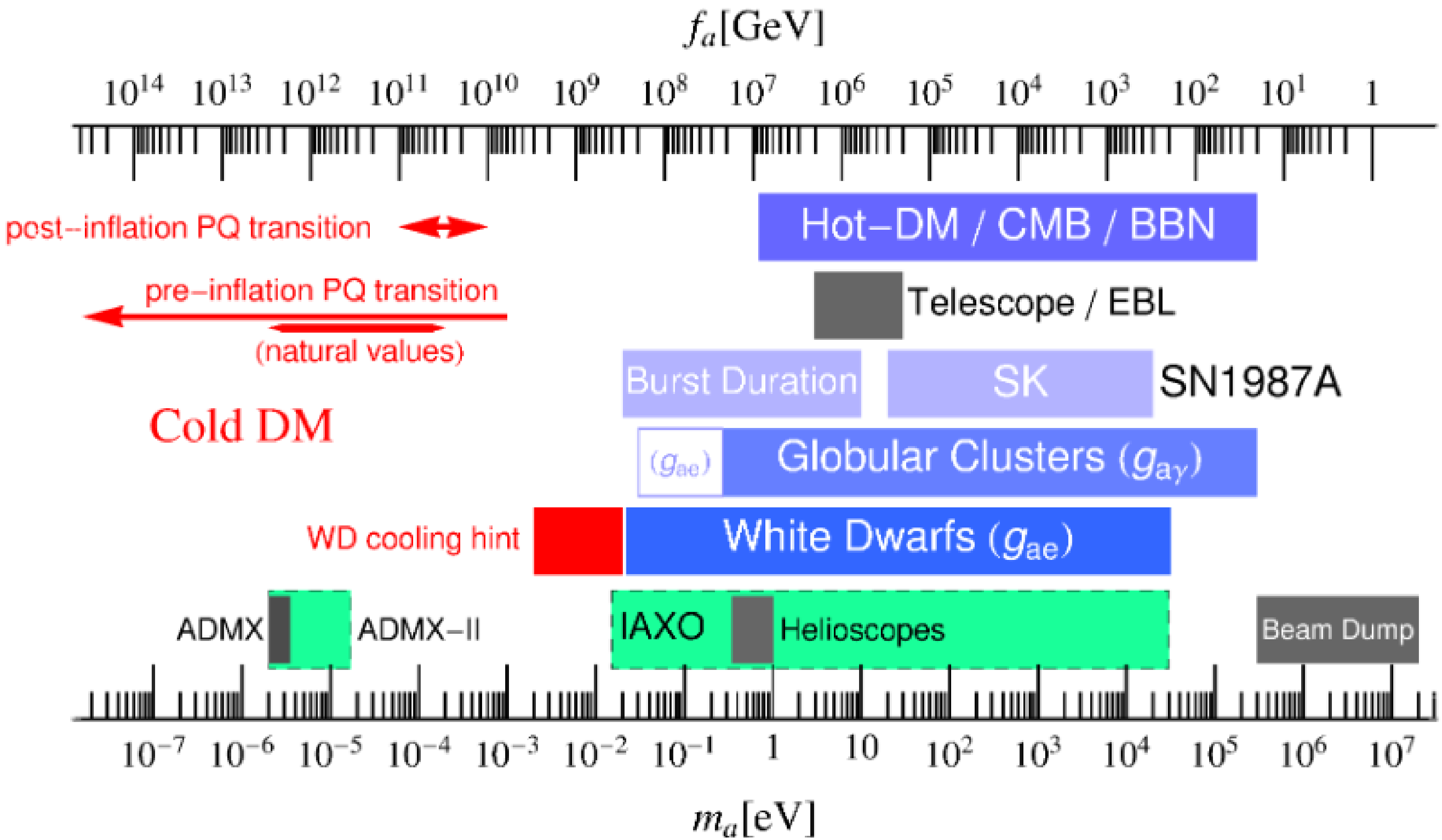
E/N=0 (KSVZ)

Dark Matter Candidates



L. Roszkowski

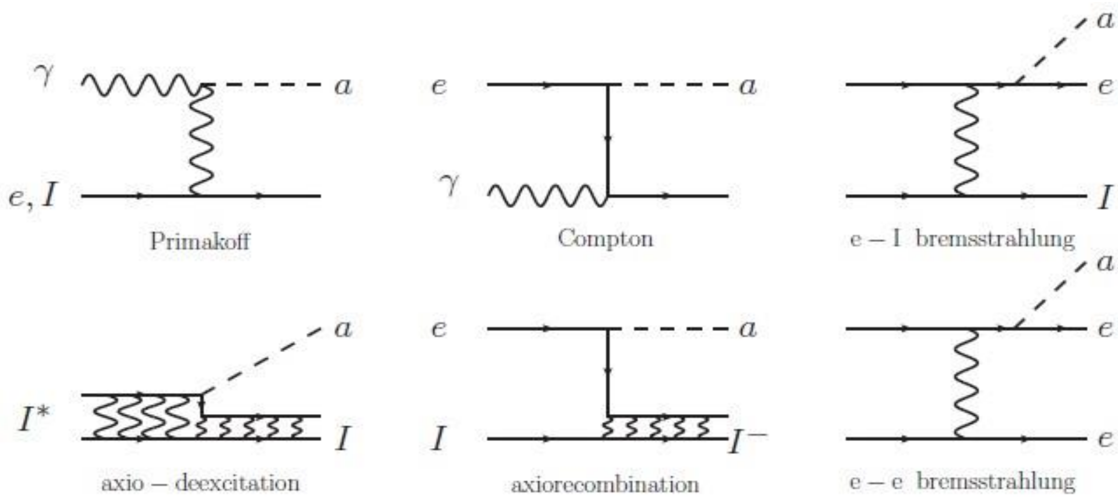
Exclusion Regions in PDG

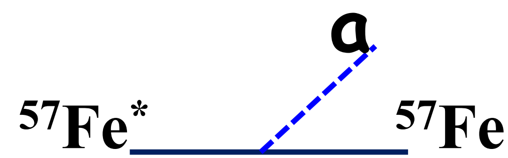


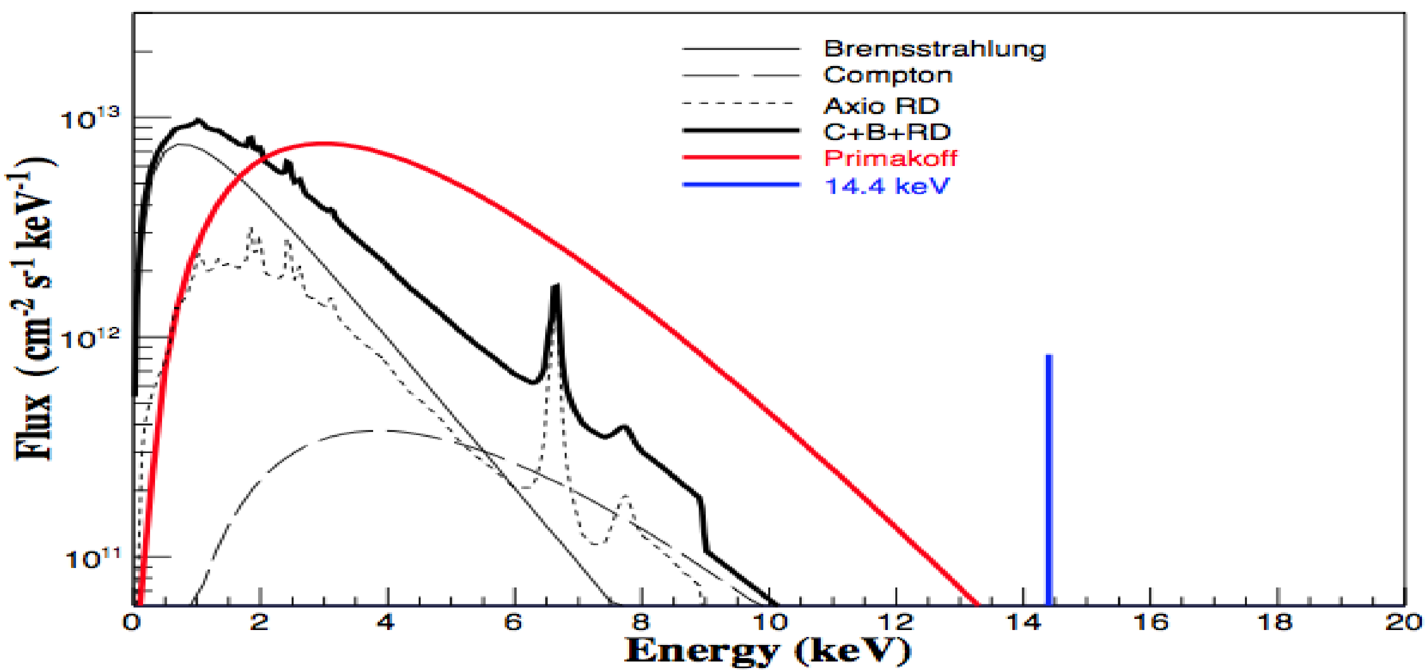
Future Plan

ADMX, CAST

Axion Production in Sun







$g_{a\gamma}=10^{-9}$ GeV^{-1}

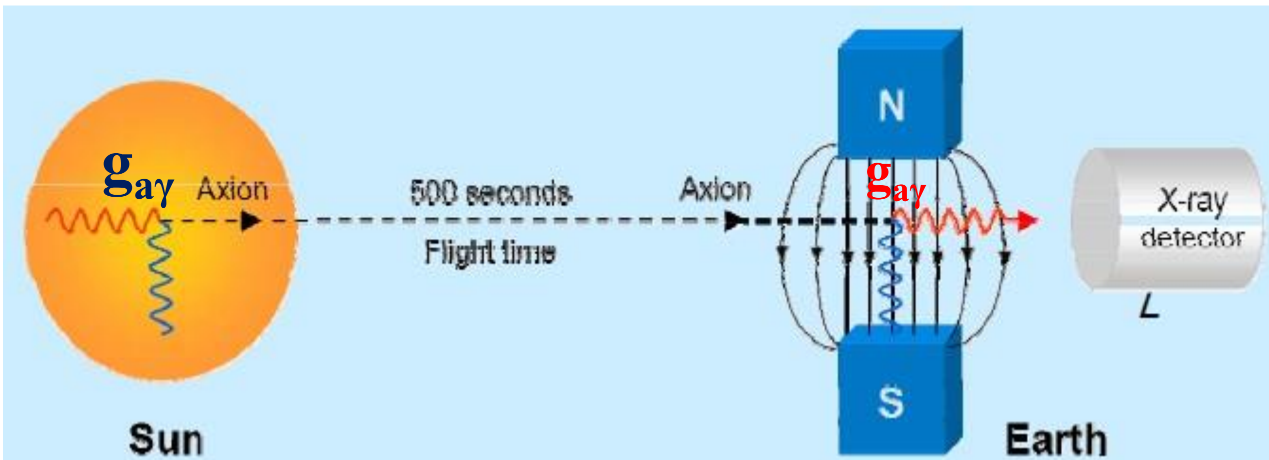
$g_{ae}=10^{-11}$

$g_{aN}=10^{-7}$

Basic idea for Solar Axion Detection

- **Detection for solar axion:**

$$\mathcal{L} = g_{a\gamma} a E \cdot B_{ext} \quad or \quad g_{a\gamma} a E_{ext} \cdot B$$

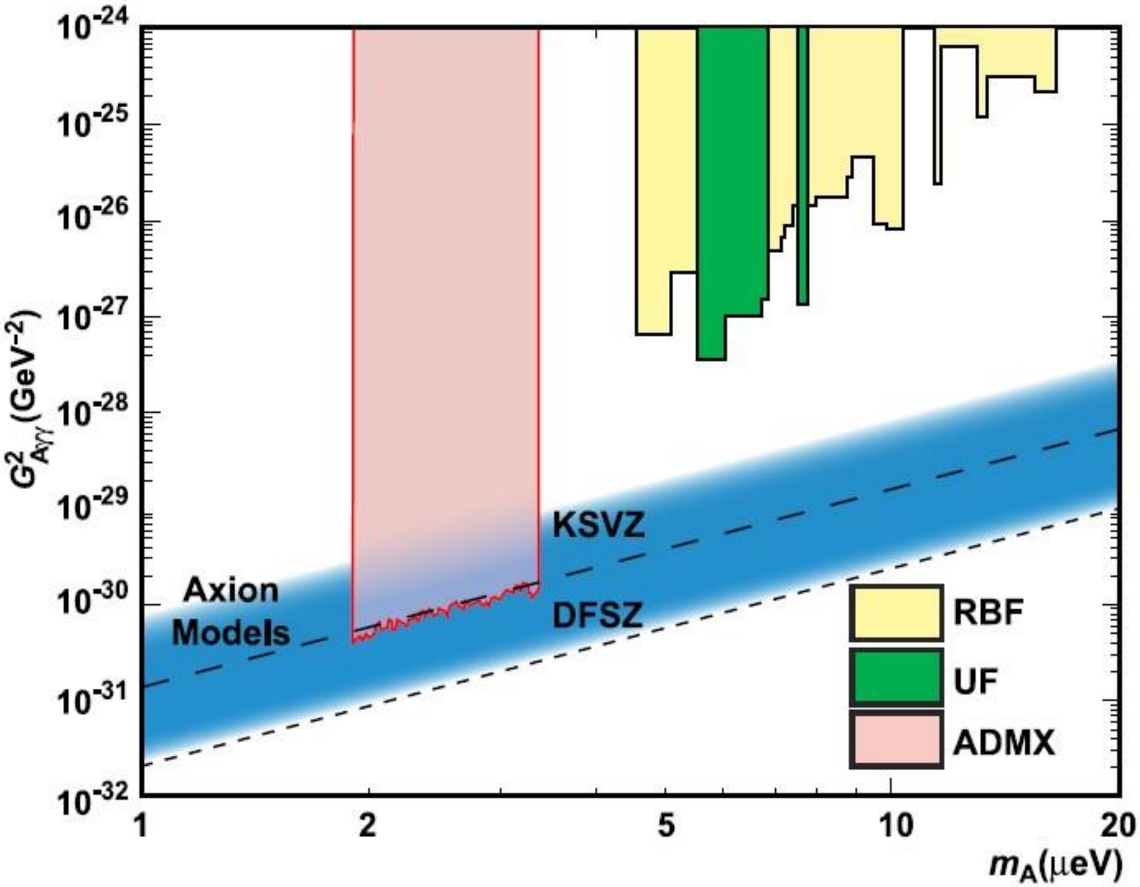


Event Rate: $R = P(\gamma \to a) P(a \to \gamma) \propto g_{a\gamma}^2 \times g_{a\gamma}^2 = g_{a\gamma}^4$

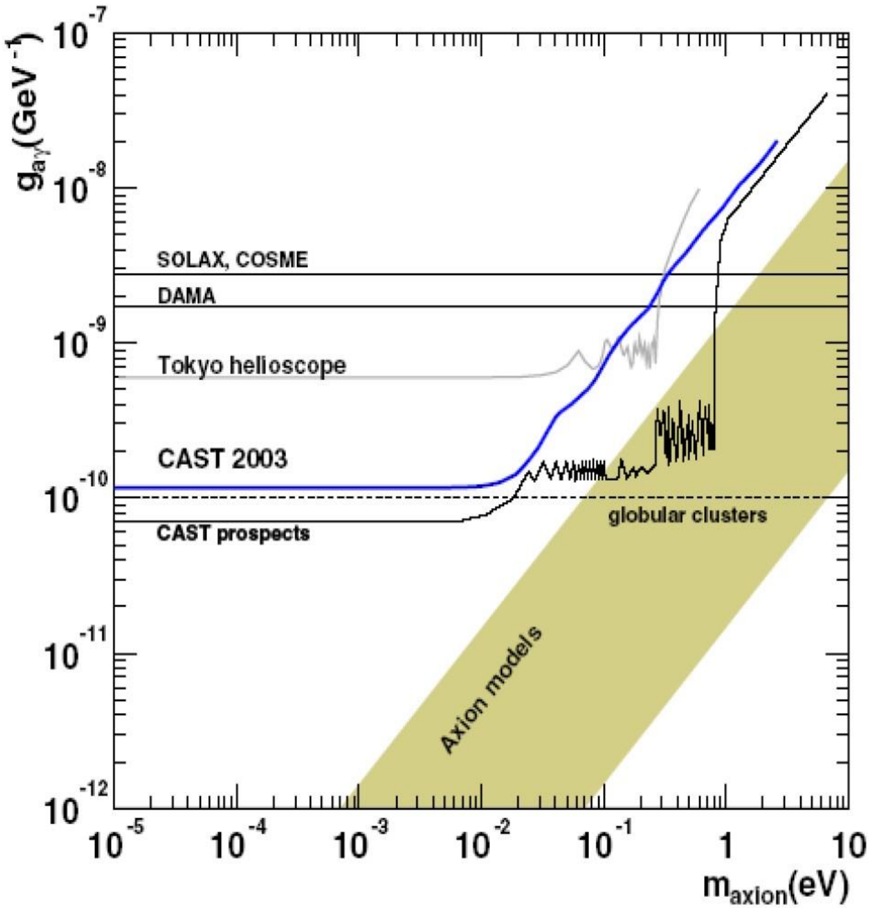
Sensitivity of $g_{a\gamma}$: $\delta g_{a\gamma} \propto R^{\frac{1}{4}}$

Axion Search Experiments

Dark-Matter Axion Searches



Solar Axion Searches



Axion searches with D.M. detector: 4 channels

Production	Detection	Signature
Solar Primakov $g_{a\gamma}$	Primakov (Bragg scattering) $g_{a\gamma}$	Time correlated energy dependence $g^4_{a\gamma}$
Solar Compton Bremsstrahlung g_{ae}	Axio electric effect g_{ae}	Energy bump g^4_{ae}
Solar ^{57}Fe deexcitation g_{aN}	Axio electric effect g_{ae}	Energy bump @ 14.4 keV $g^2_{aN} x g^2_{ae}$
Assume axion makes up all of galactic D.M. (m_a ~ keV)	Axio electric effect g_{ae}	Energy bump g^2_{ae}

KIMS (Korea Invisible Mass Search)

- Dark matter search at Yangyang underground laboratory

- Funded by National Research Foundation of Korea (2000)
  - Dark matter search with CsI(Tl) crystals (KIMS-CsI)

- Establishing the Center for Underground Physics (CUP) in the Institute for Basic Science (2013)
  - AMoRE (Advanced ^{100}Mo Rare Event): Neutrinoless double beta decay
  - KIMS-NaI: Dark matter searche with NaI(Tl) crystals

Yangyang Underground Laboratory (Y2L)

Korea Middleland Power Co.
Yangyang Pumped Storage Power Plant

Minimum depth : 700 m
Access to the lab by car (~2km)

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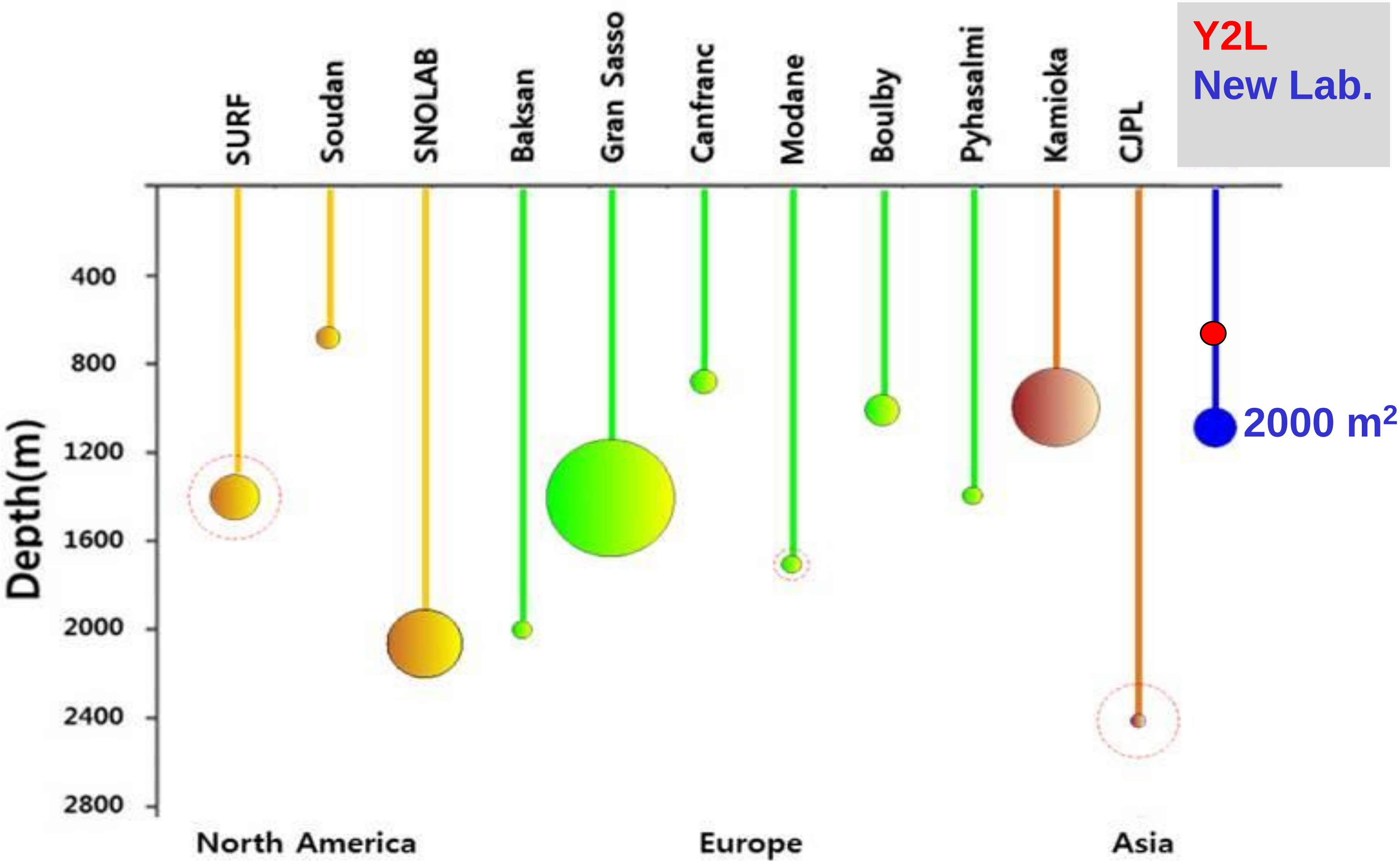
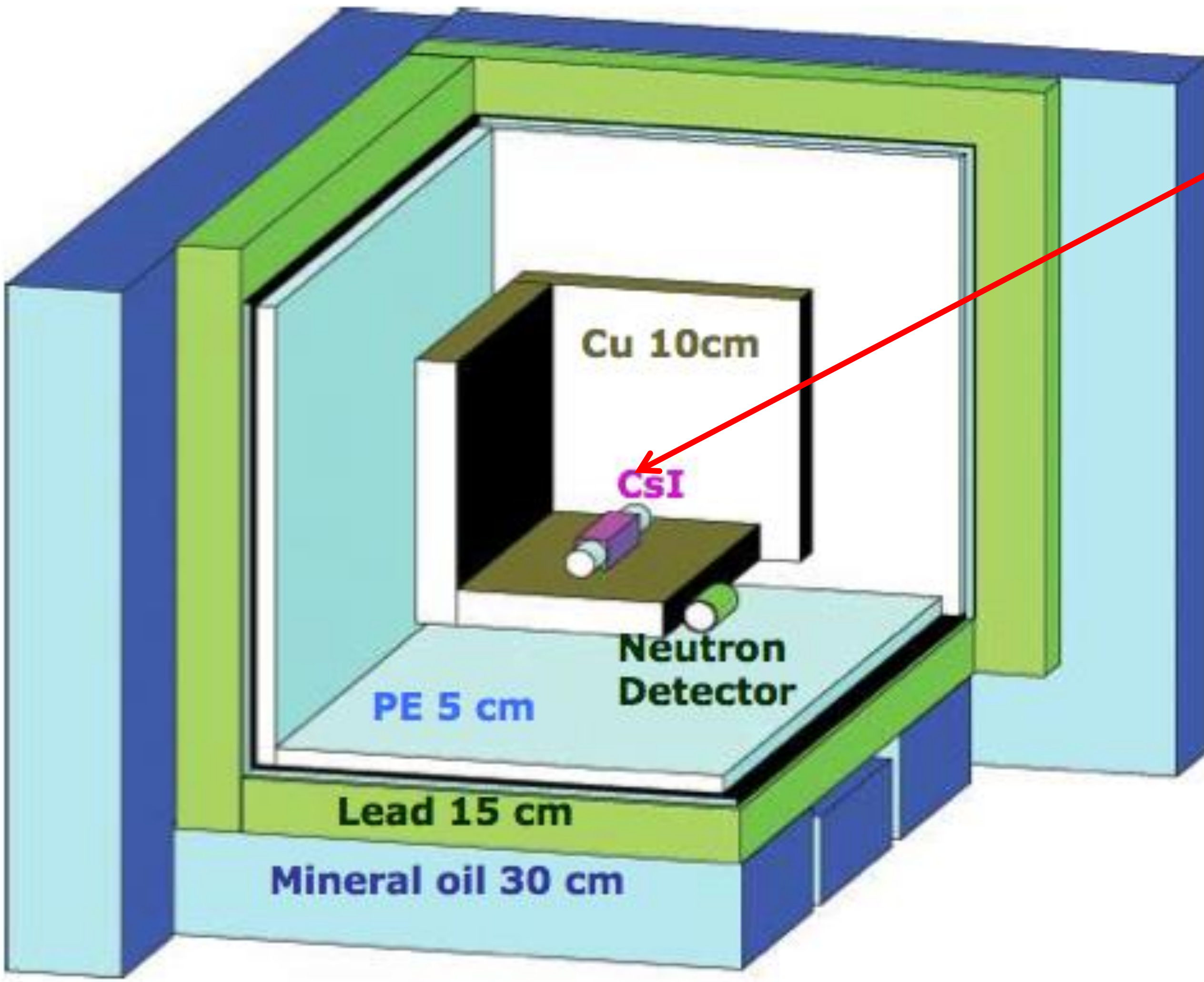
Worldwide Underground Lab.



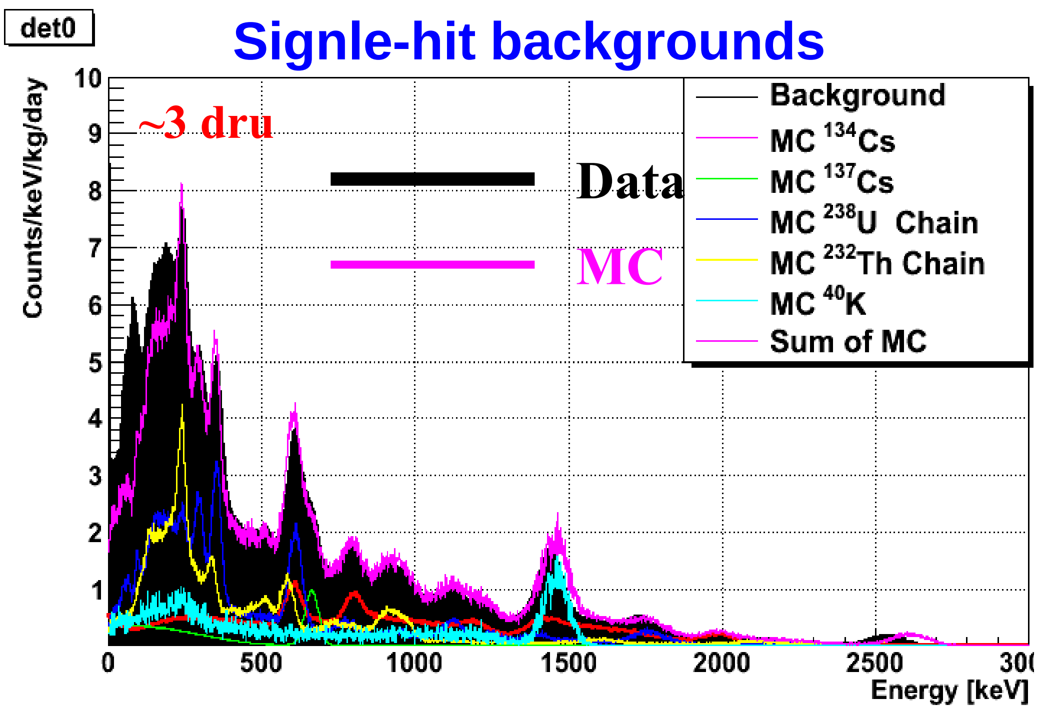
KIMS Detector

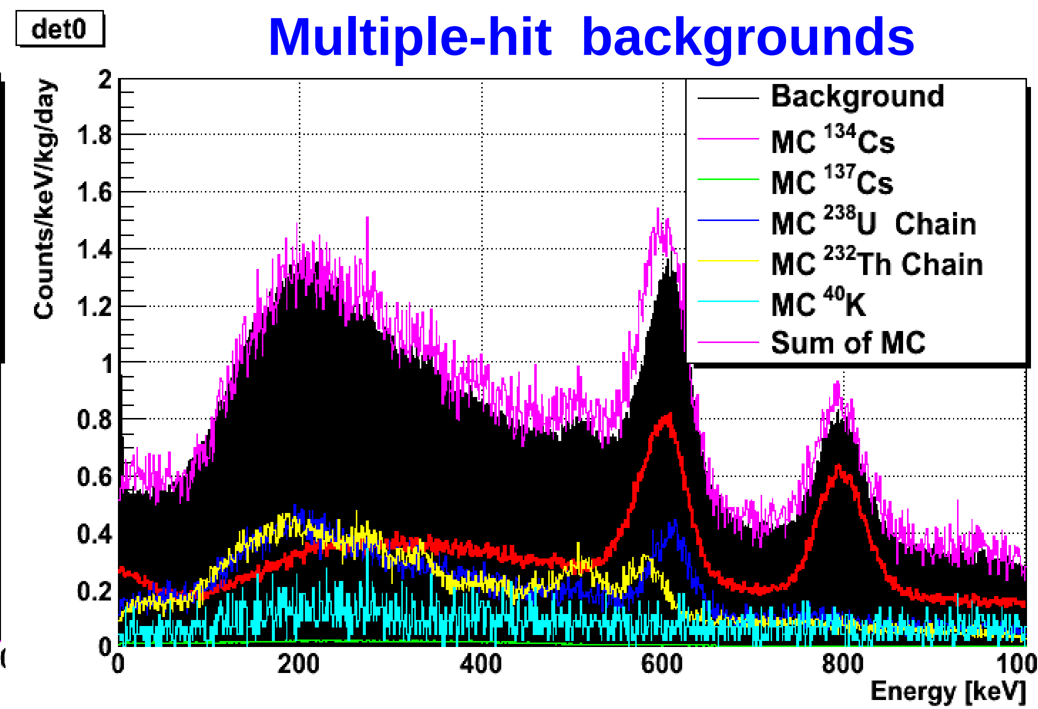
- Total 12 CsI(Tl) crystals



KIMS Detector (II)

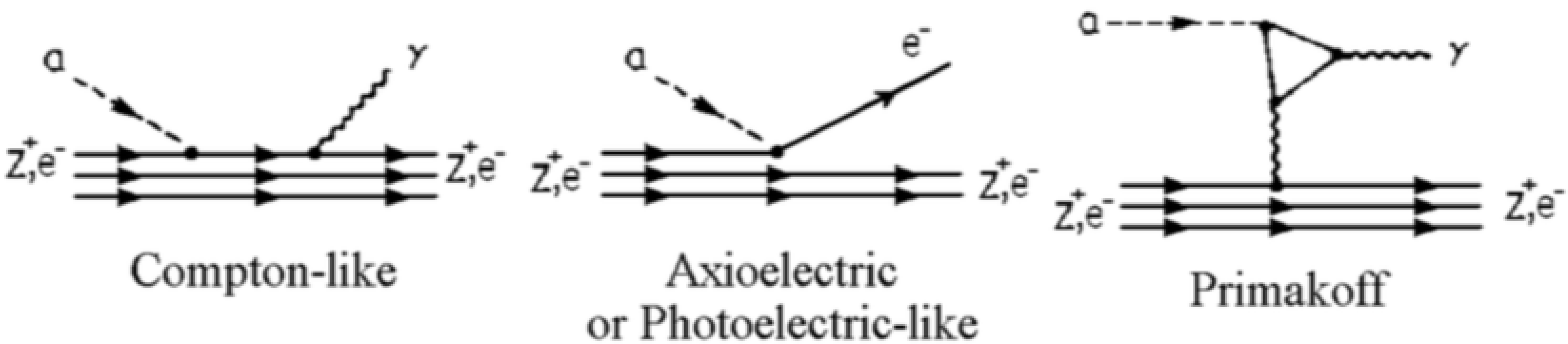
- Three years stable operation: 2009-2012
- Major backgrounds are internal radioactive sources: ^{40}K, ^{134}Cs, ^{137}Cs, ^{232}Th & ^{238}U





Axion detection

- **Axion can be detected by three process:**



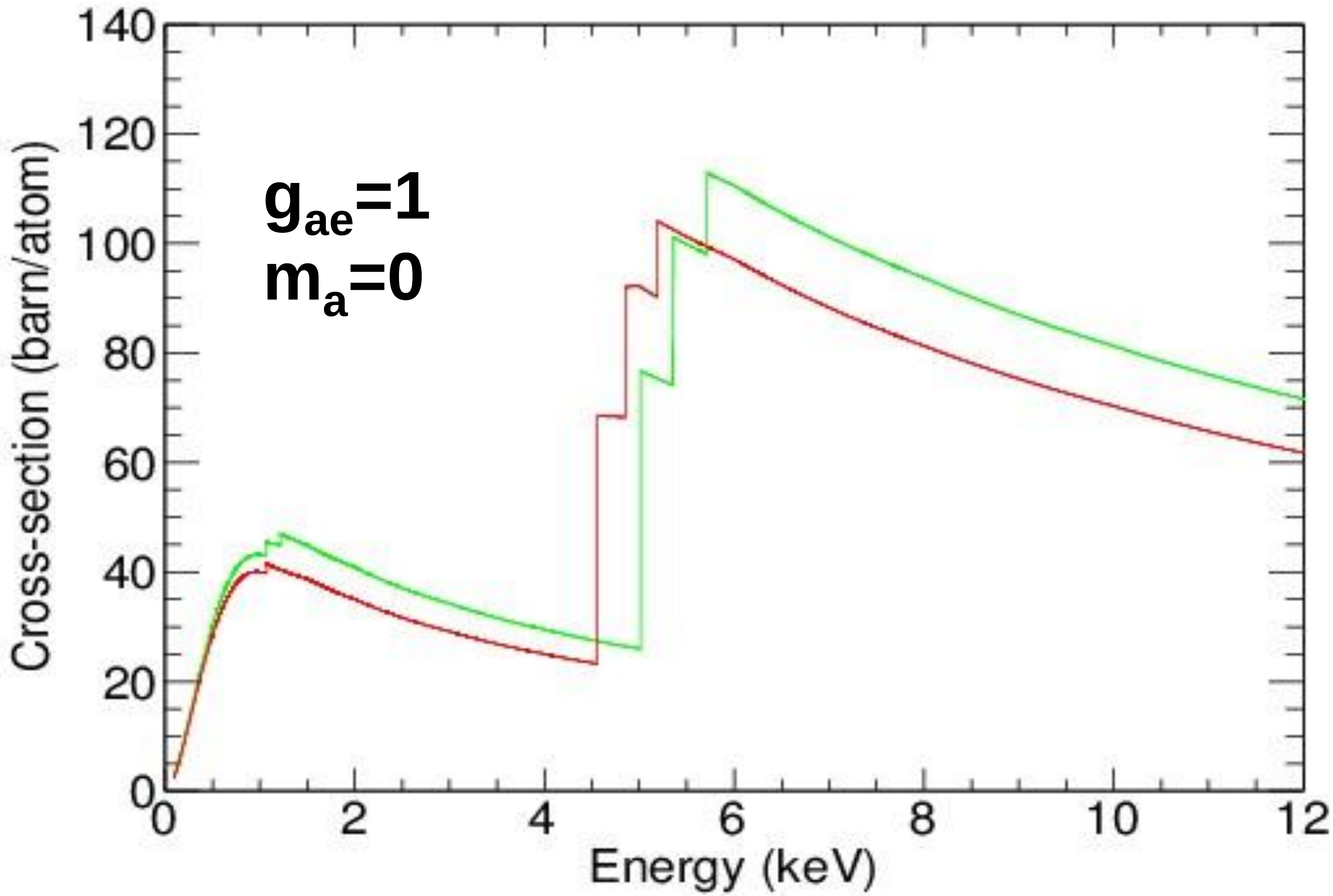
$$\sigma_{ae}(E_a) = \sigma_{pe}(E_a)\frac{g_{ae}^2}{\beta_a}\frac{3E_a^2}{16\pi\alpha m_e^2}(1 - \frac{\beta_a^{\frac{2}{3}}}{3})$$

Photo-electric efect: http://physics.nist.gov/PhysRefData/Xcom/html/xcom1.html

Note: Axion energy, E_a, is the same as electron recoil energy.

-> Axion events induce e/gamma energy below 12 keV.

Axio-electric X-sections for Cs and I atoms



Signal and Backgrounds

- **Axion signals:**
  electron recoil with energy below 12 keV

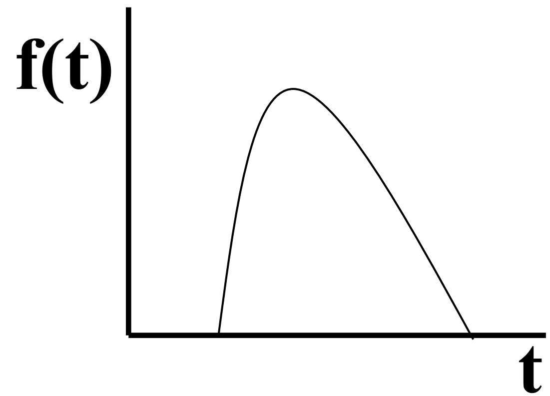
- **Backgrounds:**
  - **Alpha decays from the crystal surface**
  - **β-decays:**
    ^{137}Cs (Q=1175.6 keV), ^{134}Cs (Q=2058.7 keV), ^{87}Rb (Q=282 keV)
  - **Compton scattering**

Discrimination of e/γ and surface-alpha events

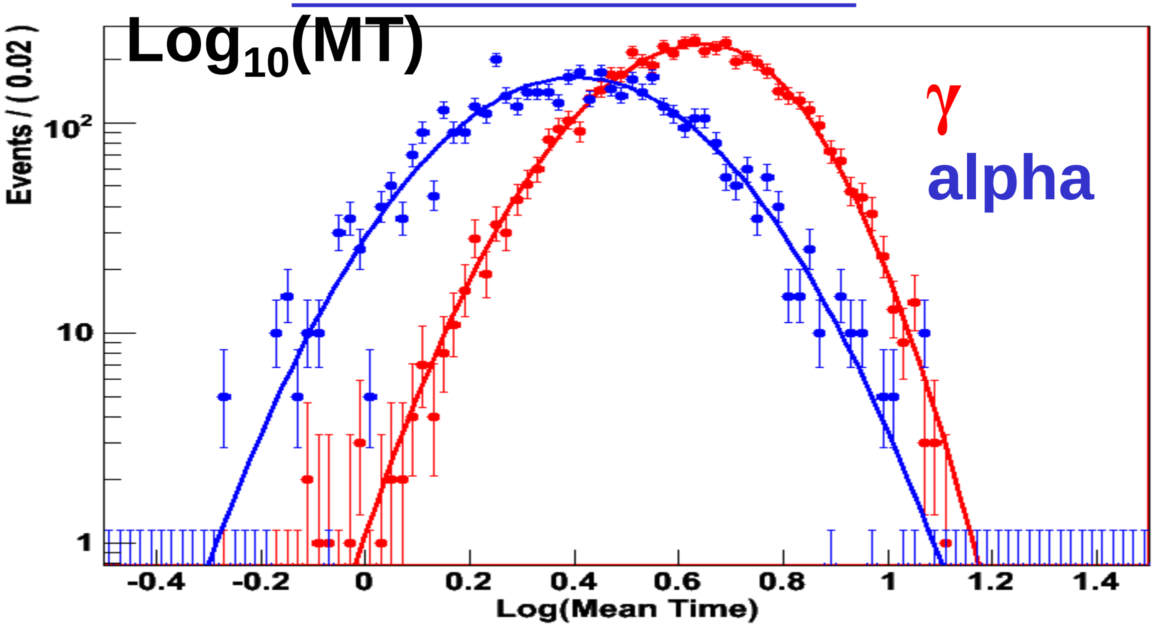
- **Pulse Shape Discrimination (PSD)**

Mean decay time

$$MT = \int t f(t) dt / \int f(t) dt$$



Calibration data

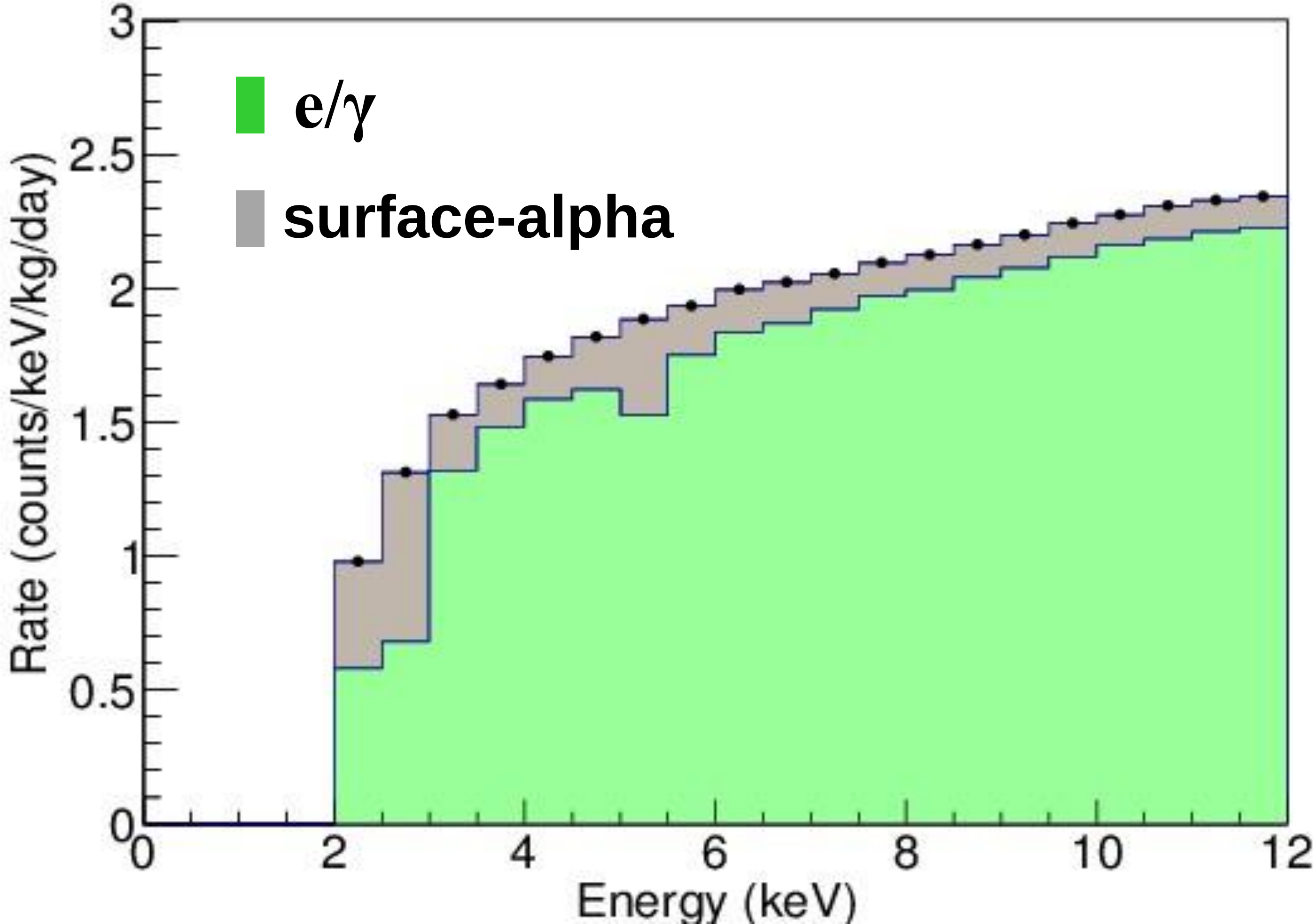


Fitting function:

$$g(t) = \begin{cases} \dfrac{A}{1/2(\sigma_L + \sigma_R)} e^{-\frac{1}{2}\left(\frac{t-\mu}{\sigma_L}\right)^2}, & t < \mu, \\ \dfrac{A}{1/2(\sigma_L + \sigma_R)} e^{-\frac{1}{2}\left(\frac{t-\mu}{\sigma_R}\right)^2}, & t \geq \mu, \end{cases}$$

Energy Spectrum for e/γ and surface-alpha Events

- **Estimate e/γ and surface-alpha in each energy bin**
- **We use e/γ events for axion candidate events.**



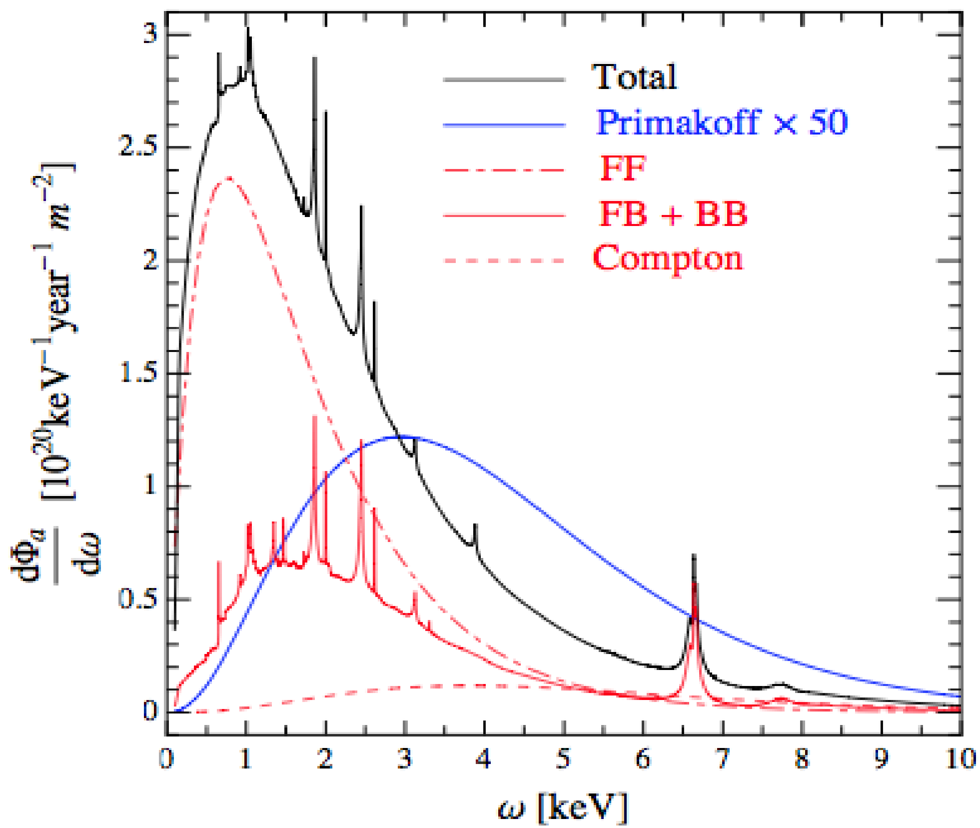
Energy Spectrum for signal and background (I)

- **Expected axion events rate:**

$$R(E) = \int dE_a \frac{d\Phi_a}{dE_a} \epsilon(E)(\sigma_{ae}^{Cs}(E_a)N_{Cs} + \sigma_{ae}^{I}(E_a)N_I)T\underline{R_{det}(E, E_a)}$$

Detector Resolution

$$\propto \; g_{ae}^4$$



g_{ae}=10^{-13}

$g_{a\gamma}$=10^{-12} GeV^{-1}

FF: Bremsstrahlung

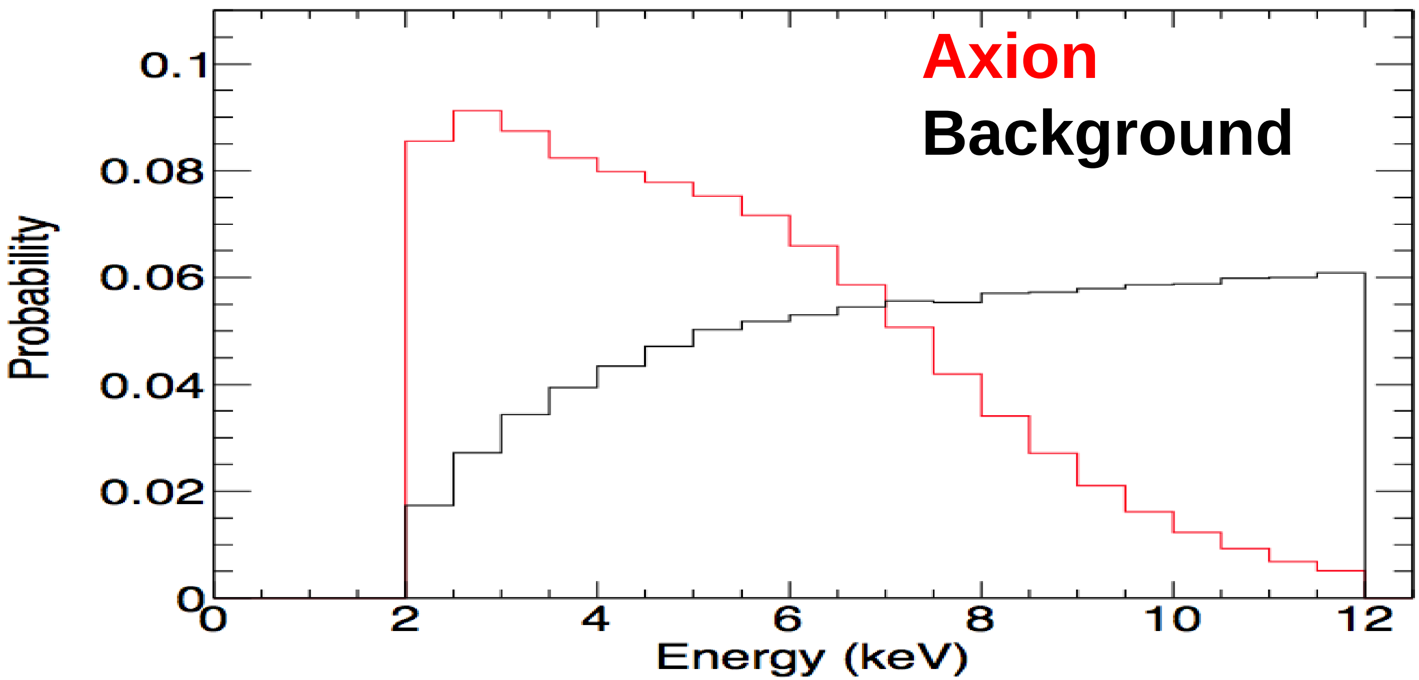
FB+BB:

Atomic recombination & deexcitation

Energy Spectrum for signal and background (II)

- **Background shape:**
  - **β-decays from internal background:**
    ^{137}Cs (Q=1175.6 keV), ^{134}Cs (Q=2058.7 keV), ^{87}Rb (Q=282 keV)
  - **Compton scattering**

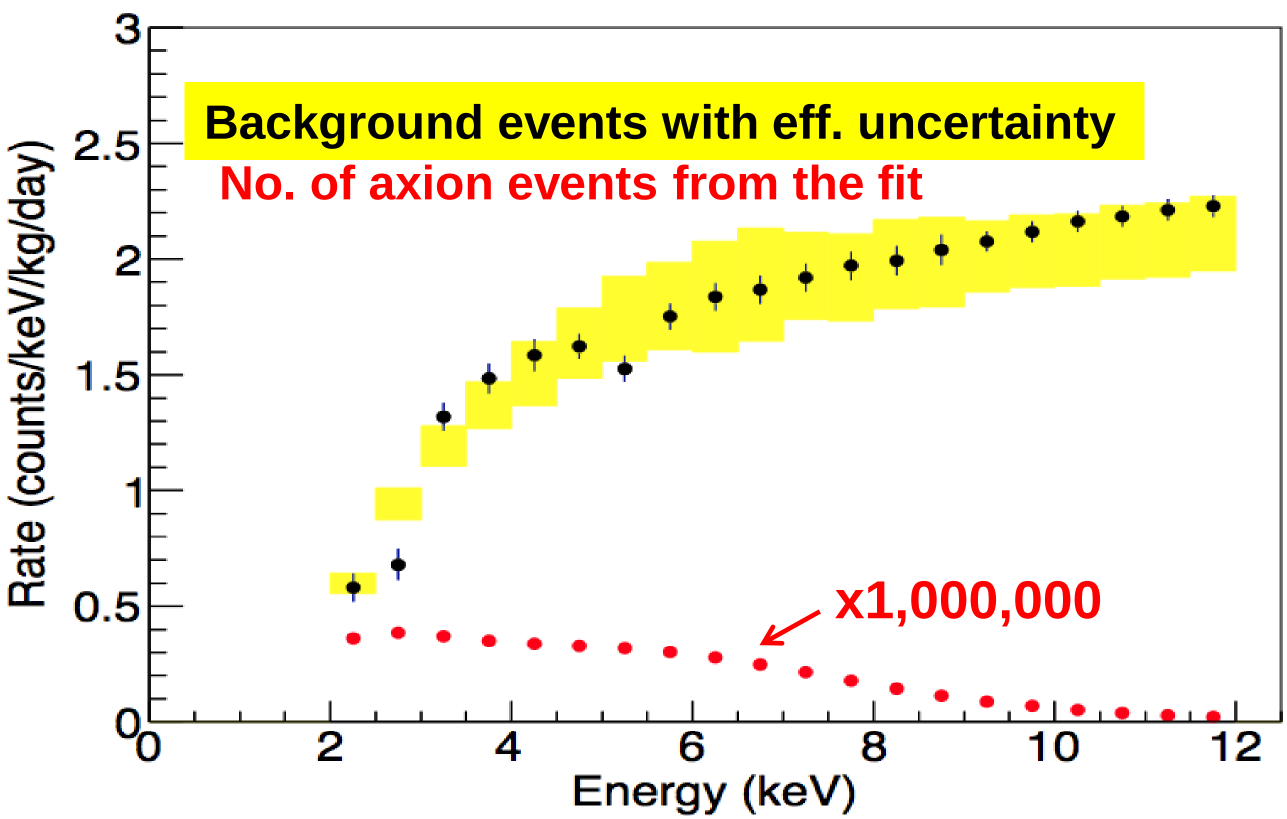
-> Expected to be flat distribution but efficiency depends on energy.



Extraction of No. of Axion events

- **Maximizing binned maximum likelihood function**

$$\mathcal{L} = \prod_{i=1}^{N_{bin}} e^{-(n_s P_s(E_i)+n_b P_b(E_i))} \frac{(n_s P_s(E_i) + n_b P_b(E_i))^{N_i}}{N_i!}$$



No. of expected events for 1 year in KIMS exp.:

$$n_s = 0.077^{+36.59}_{-127.64} \quad \text{for } m_a = 0 \text{ keV}/c^2$$

$$n_s = 0.077^{+40.22}_{-132.12} \quad \text{for } m_a = 1 \text{ keV}/c^2$$

->Consistent with 0 event

Estimation of 90 % confidence limit

- **Find out n_s^{up} with the following formula:**

$$\frac{\int_0^{n_s^{up}} \mathcal{L}(n_s)dn_s}{\int_0^{\infty} \mathcal{L}(n_s)dn_s} = 0.9$$

- **The limit for g_{ae} is obtained with n_s^{up}:**

$$N = \int R(E)dE = \int\int dEdE_a \frac{d\Phi_a}{dE_a}\epsilon(E)\sigma_{ae}(E_a)N_{Cs,I} + \sigma_{ae}^{I}(E_a)N_I)TR_{det}(E, E_a)$$
$$= constant \times g_{ae}^4 < n_s^{up}$$

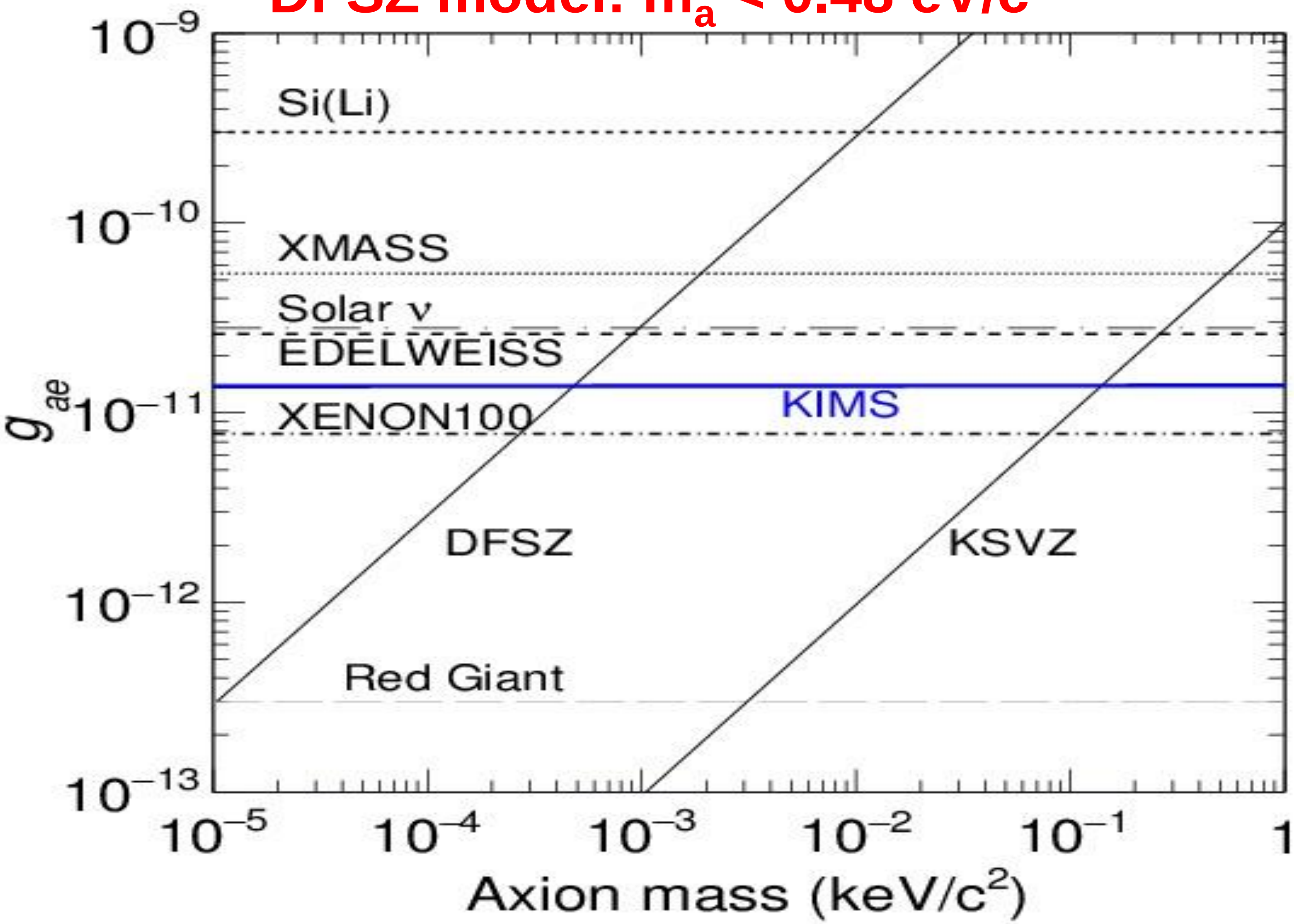
$$g_{ae} < 1.37 \times 10^{-11} \text{ for } \mathrm{m_a} = 0 \text{ keV/c}^2$$

$$g_{ae} < 1.39 \times 10^{-11} \text{ for } \mathrm{m_a} = 1 \text{ keV/c}^2$$

Summary of Axion Search by KIMS

KSVZ model: $m_a < 140.9$ eV/c^2

DFSZ model: $m_a < 0.48$ eV/c^2

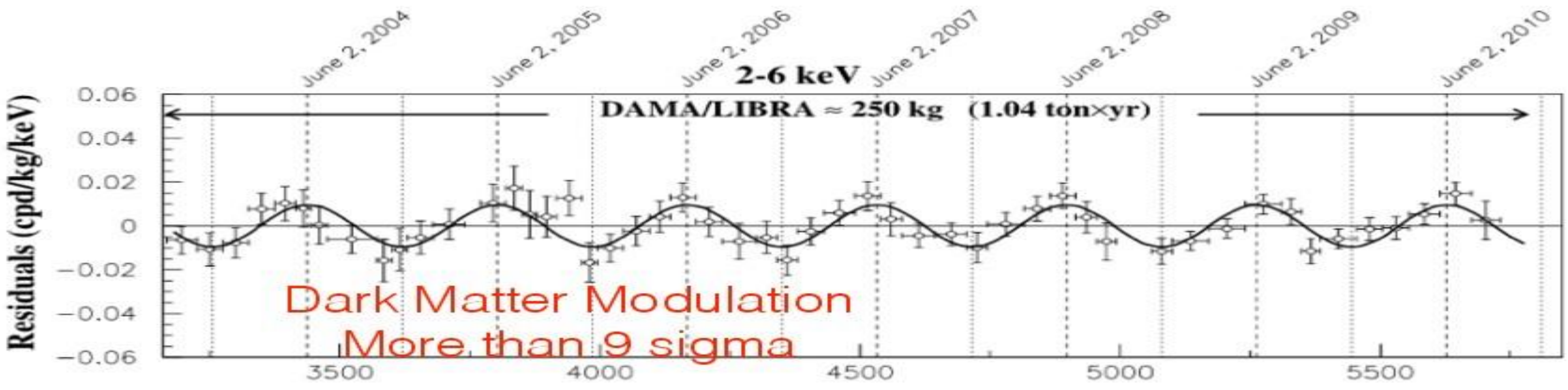


Prospect for Axion search in KIMS

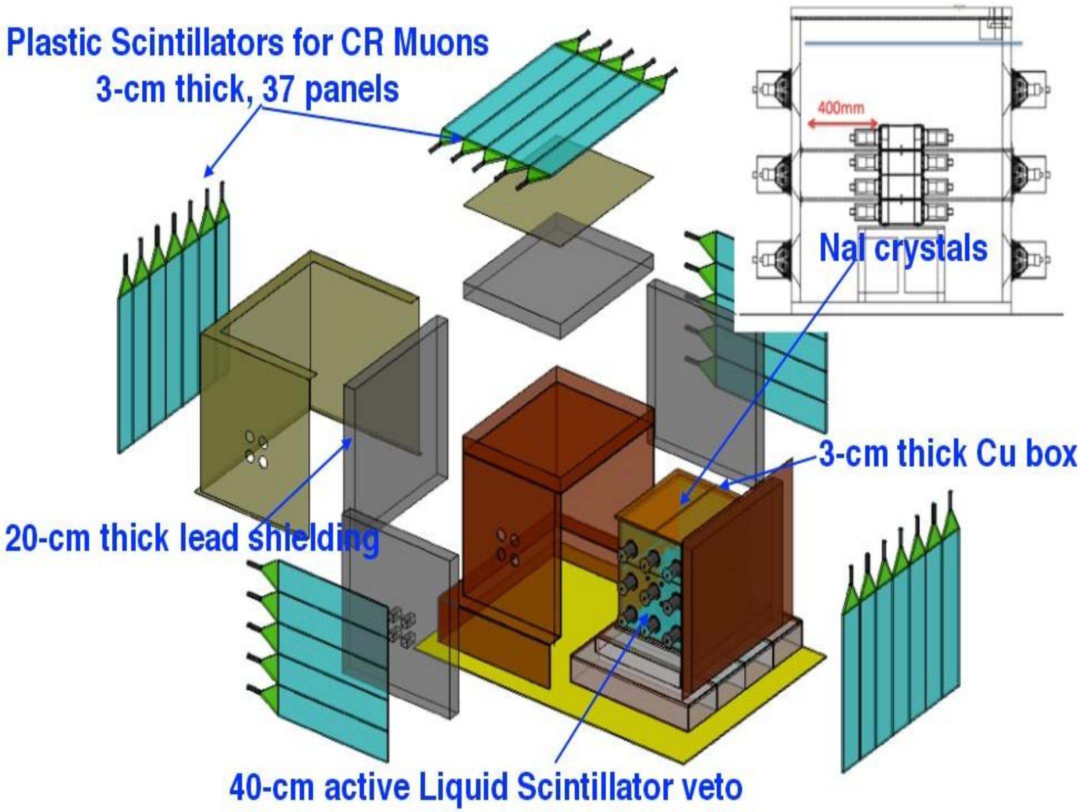
- Search for Solar axions from M1-transition of ^{57}Fe: 14.4 keV

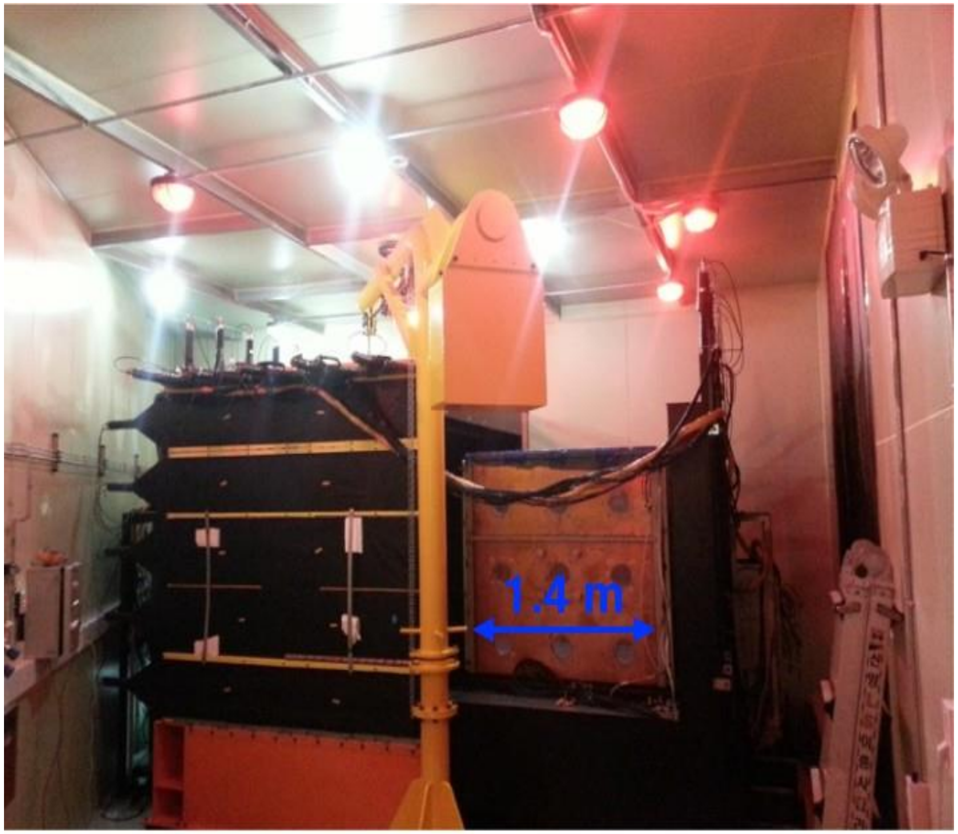
- Search for keV scale Pseudoscalar D.M. and Vector D.M.:
  Maxim Pospelov, Adam Ritz, and Mikhail Voloshin,
  "Bosonic super-WIMPS as keV-scale dark matter", PRD 78, 115012 (2008)

- We will start a new experiment, KIMS-NaI, to check on the DAMA signal.



KIMS-NaI

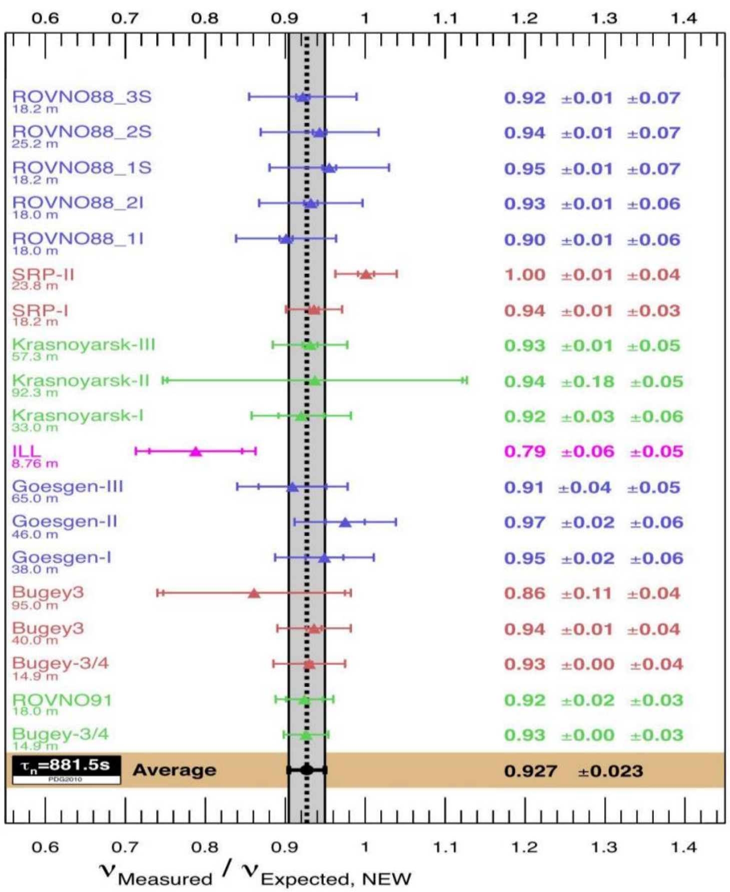

Plastic Scintillators for CR Muons
3-cm thick, 37 panels
400mm
NaI crystals
3-cm thick Cu box
20-cm thick lead shielding
40-cm active Liquid Scintillator veto

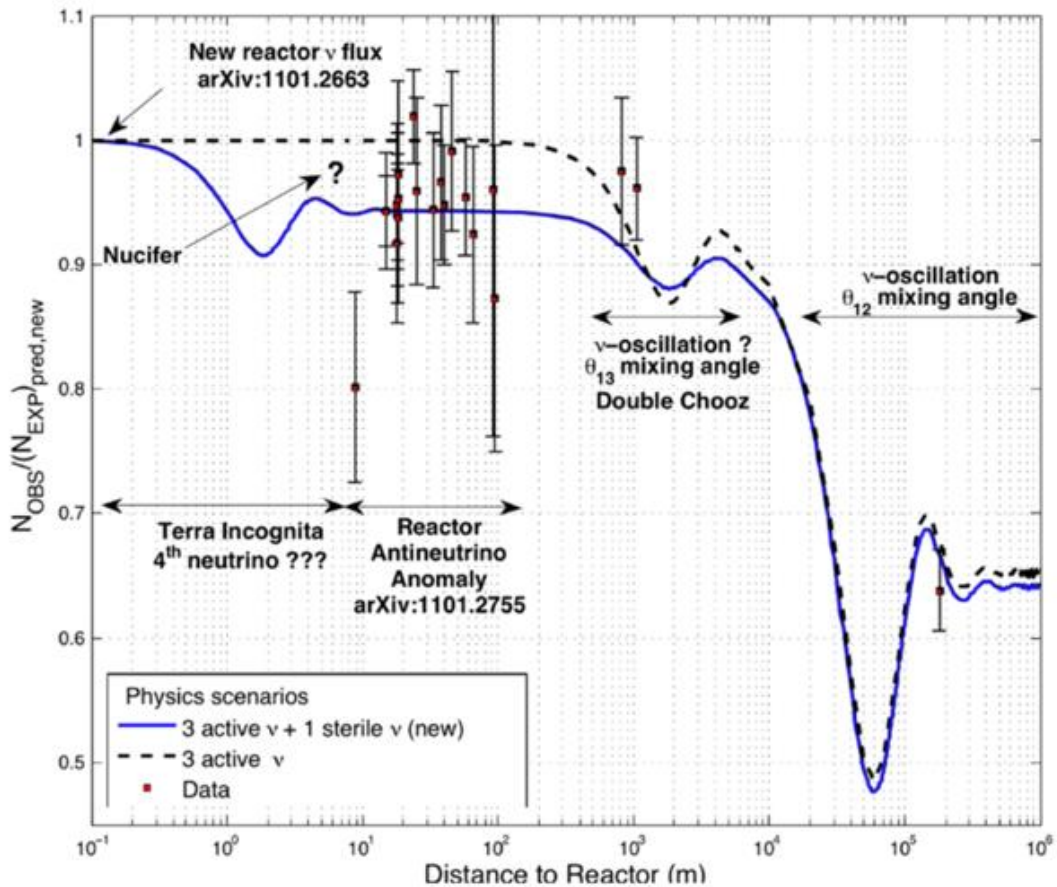

1.4 m

Search for sterile neutrino
by
NEOS
(Neutrino Experiment for Oscillation at Short baseline)

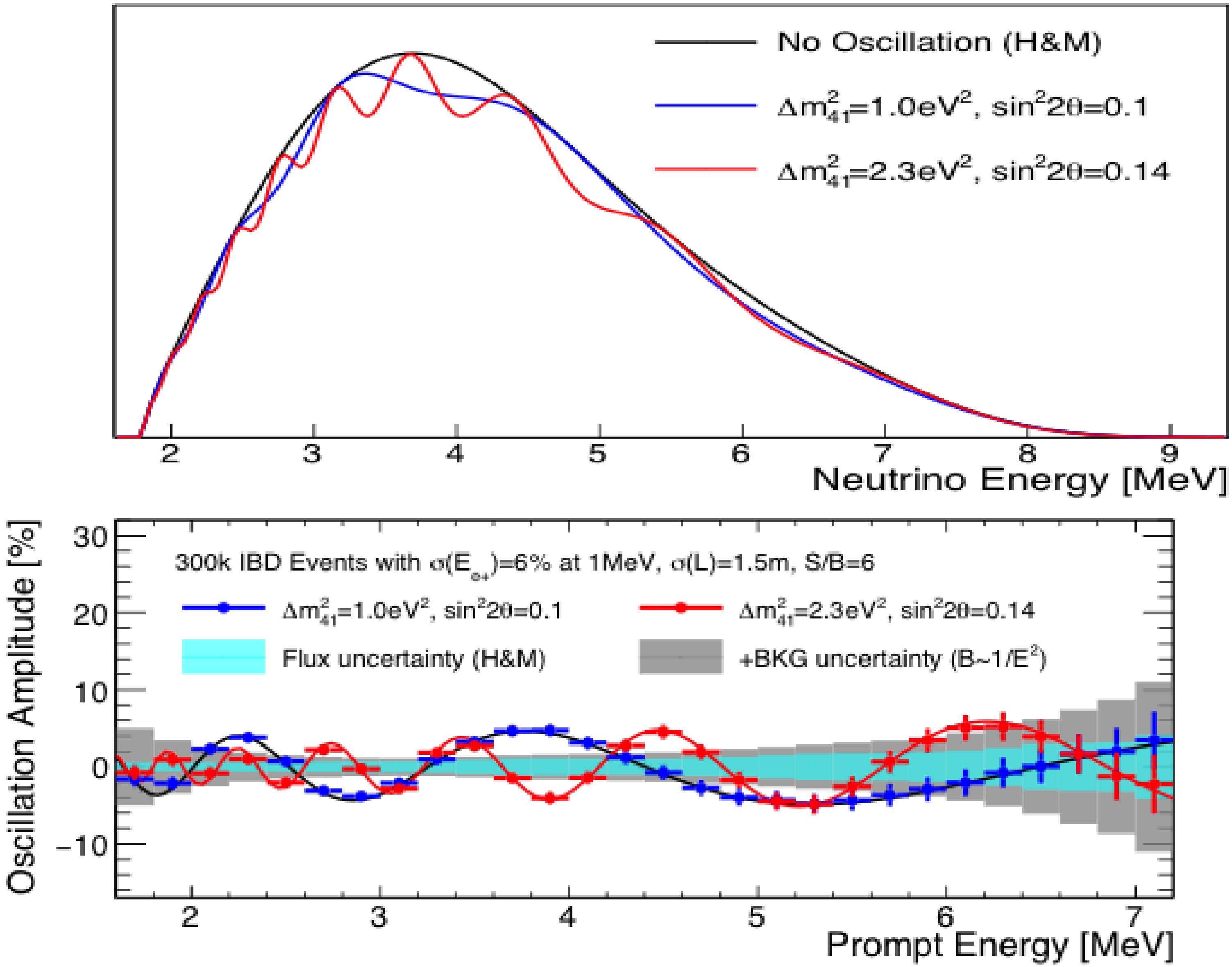
Motivation for short-baseline neutrino

- **Reactor $\bar{\nu}_e$ anomaly:**
  - Possible oscillation of $\bar{\nu}_e \rightarrow \nu_s$



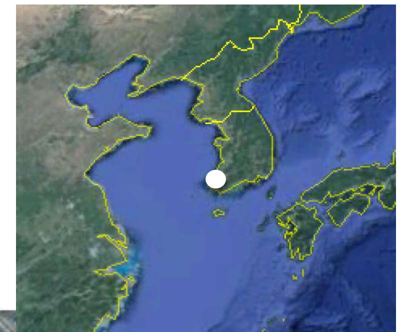


Distortions in spectral shape by the 4th ν

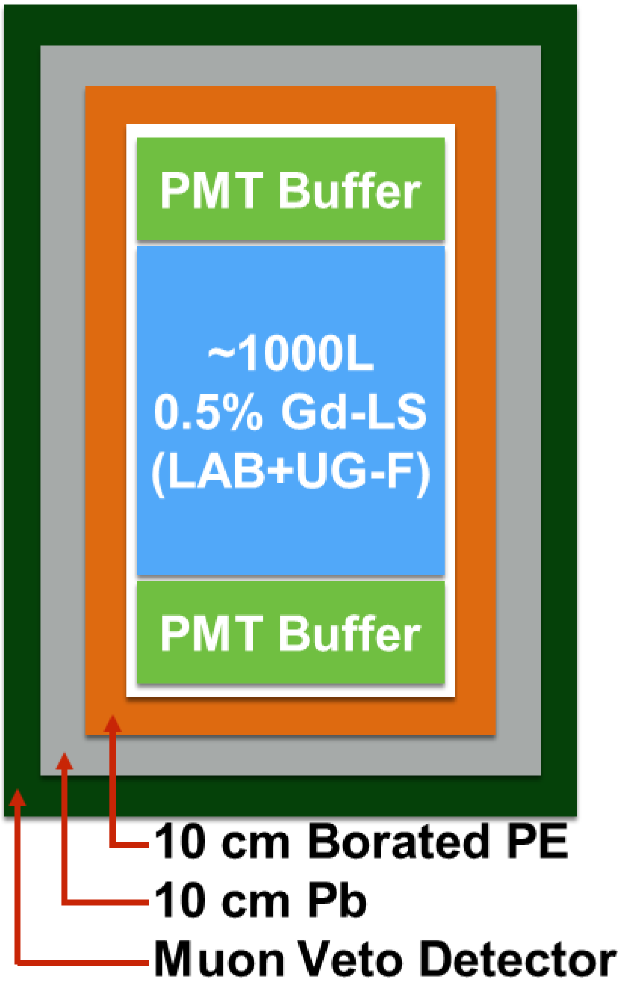


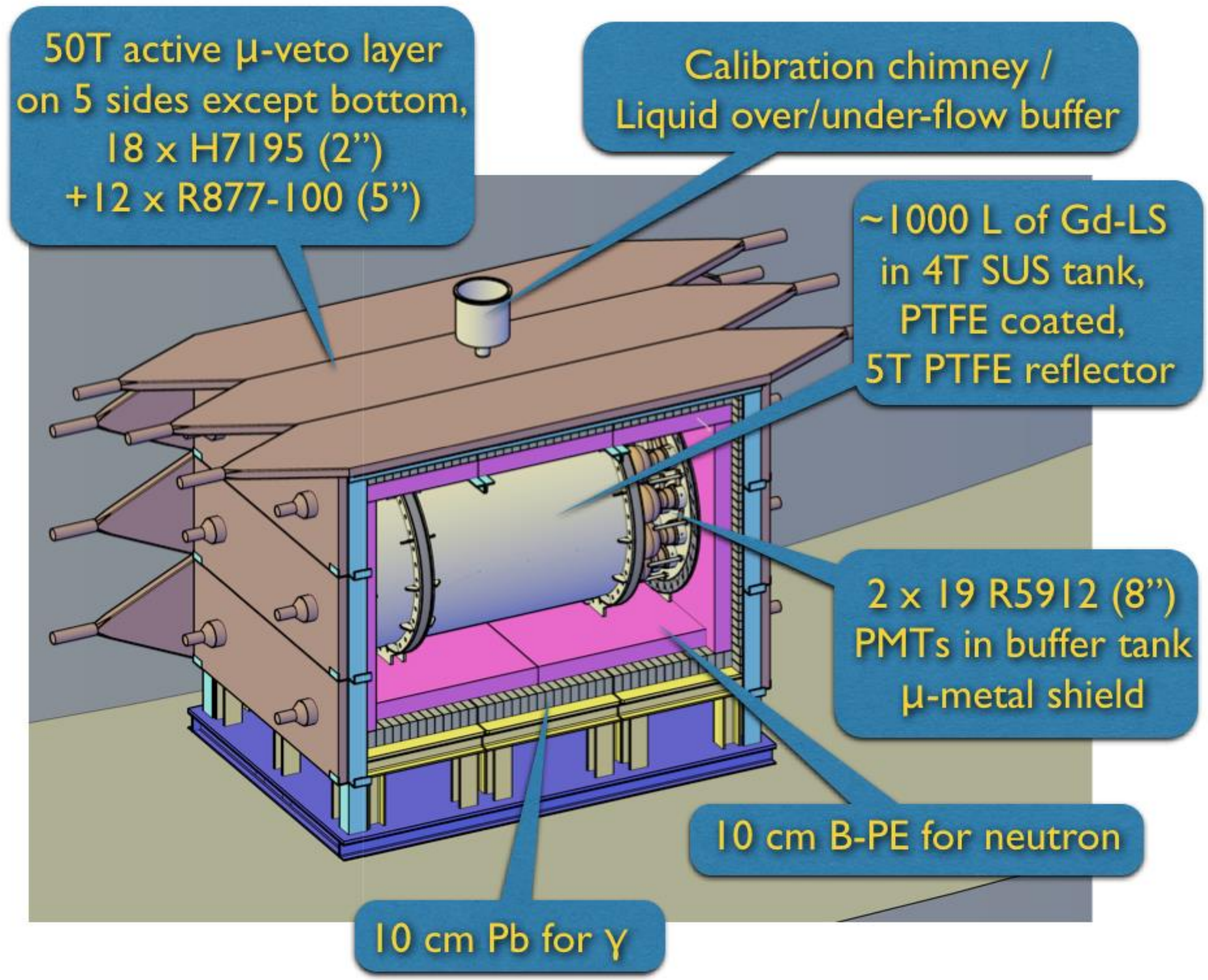
Experimental Site: Tendon Gallery of Reactor 5

- **2.815 $GW_{th,}$ commertial reactor with Φ3.1 m, H3.7m**
- **Tendon gallery**
  - **Baseline: 23.7m**
  - **overburden ~30 m.w.e. of concrete**
- **Distance to nearest cores: 256 m**
  - **1% contribution from it**

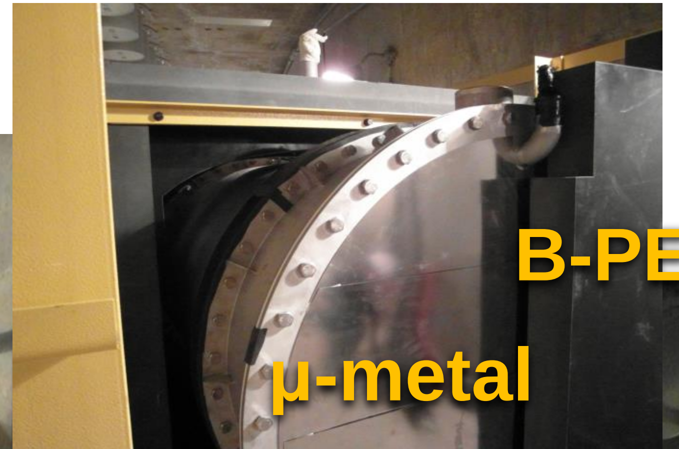


The NEOS detector





Installation in the Tendon Gallery (I)

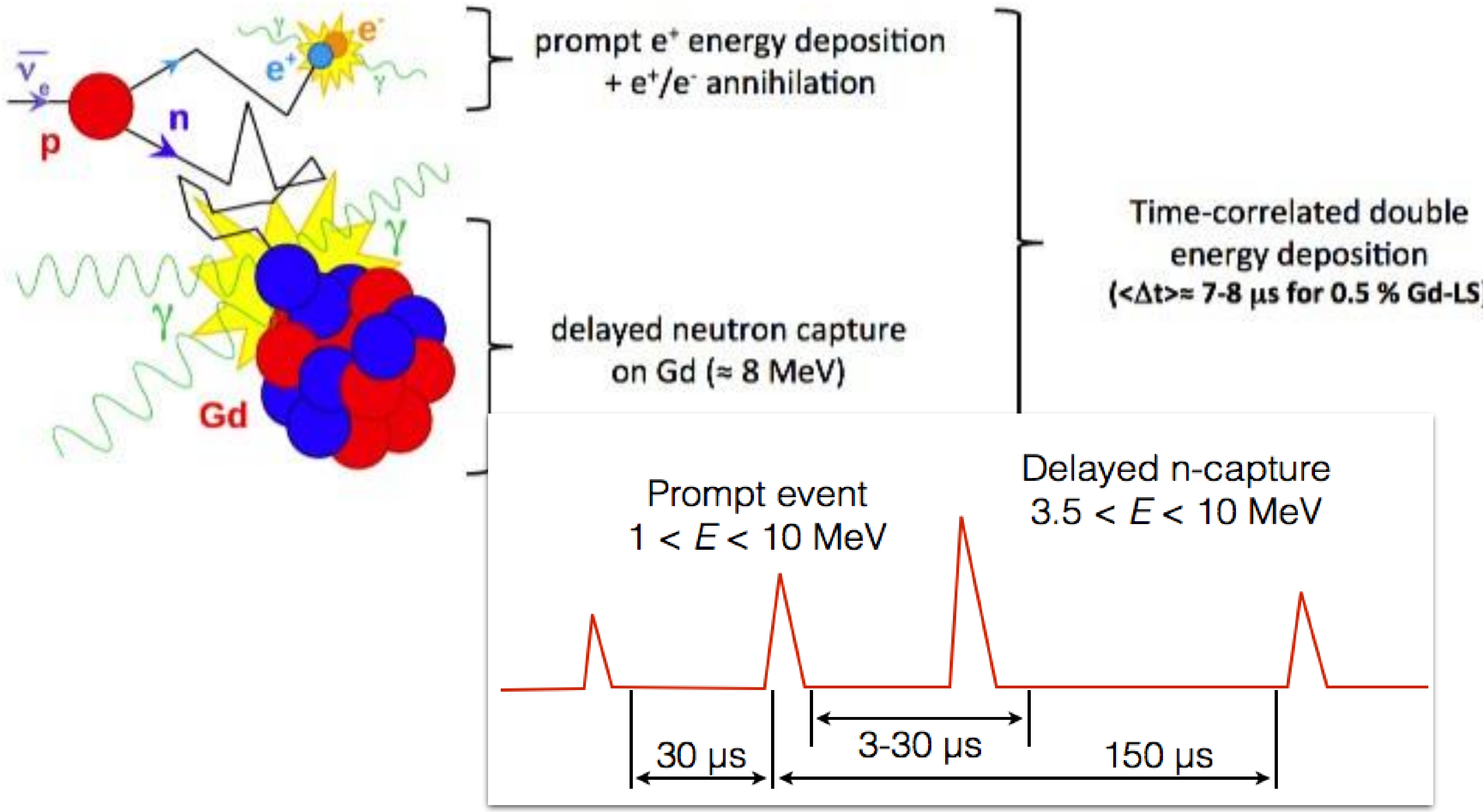


Installation in the Tendon Gallery (II)

Neutrino event detection

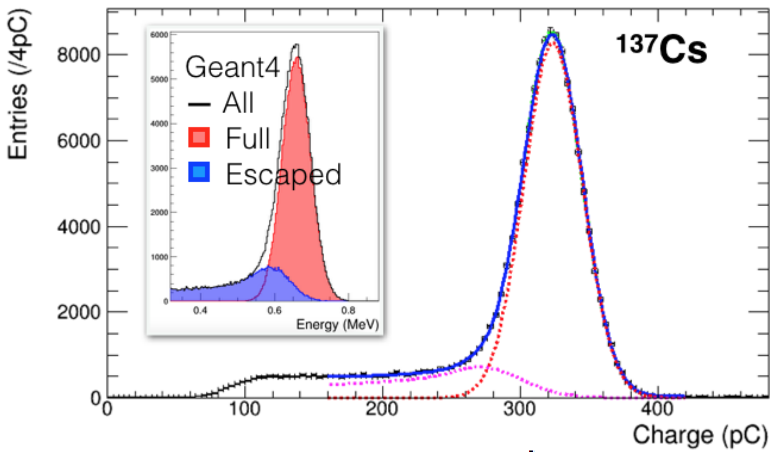
- **Use inverse beta decay (IBD) process:**

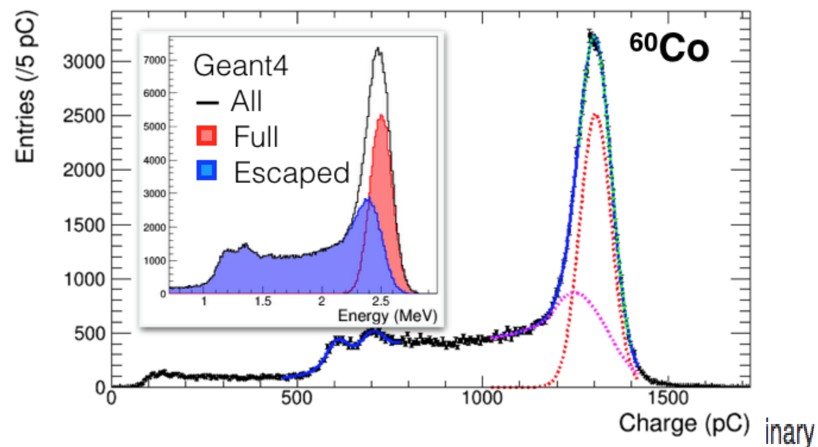
  $\bar{\nu}\, p \rightarrow e^{+}\, n$

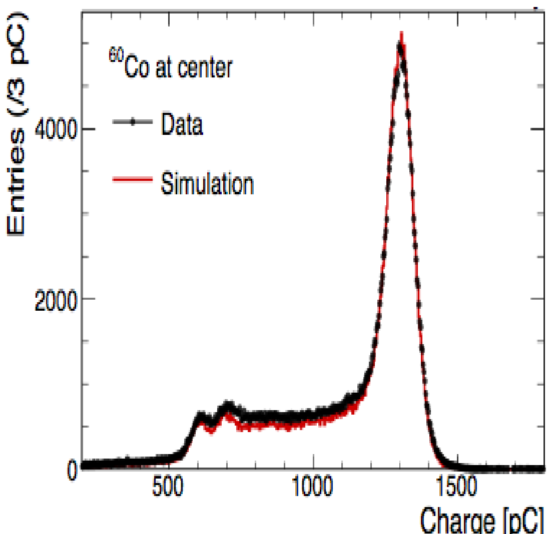


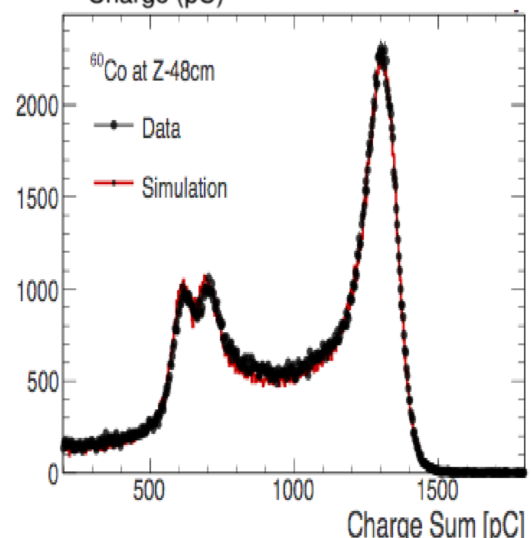
Detector Performance: Calibration

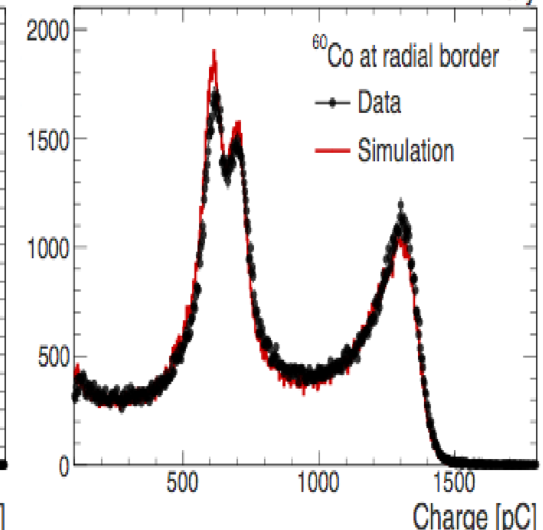
- We typically use ^{60}Co, ^{137}Cs and ^{252}Cf.
- Calibration energy is not fully deposited to the detector.





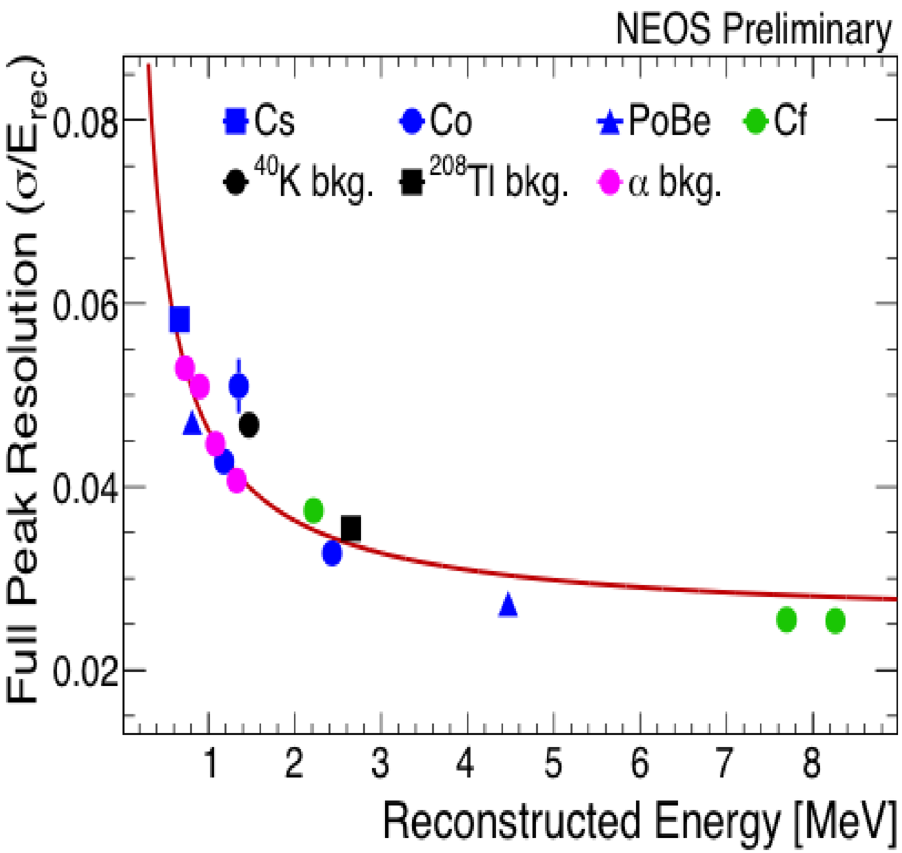




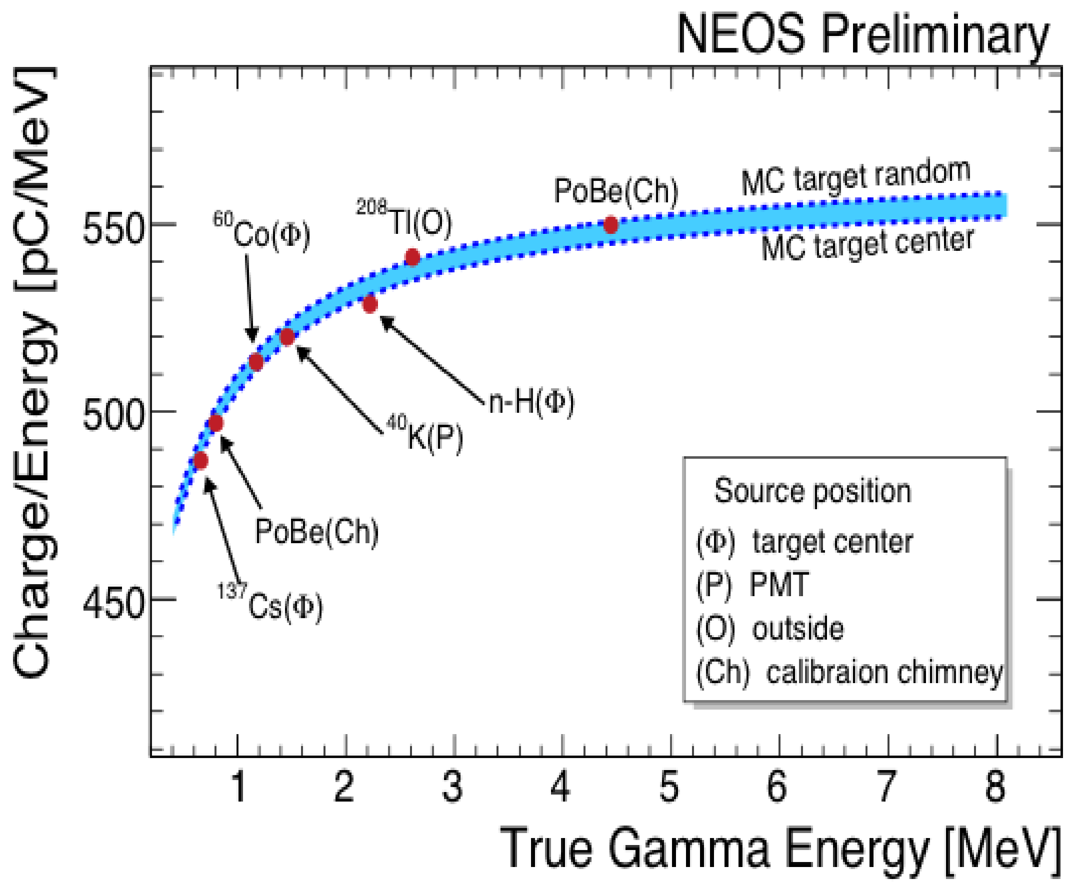


Detector Performance: Energy Resolution and Reponse

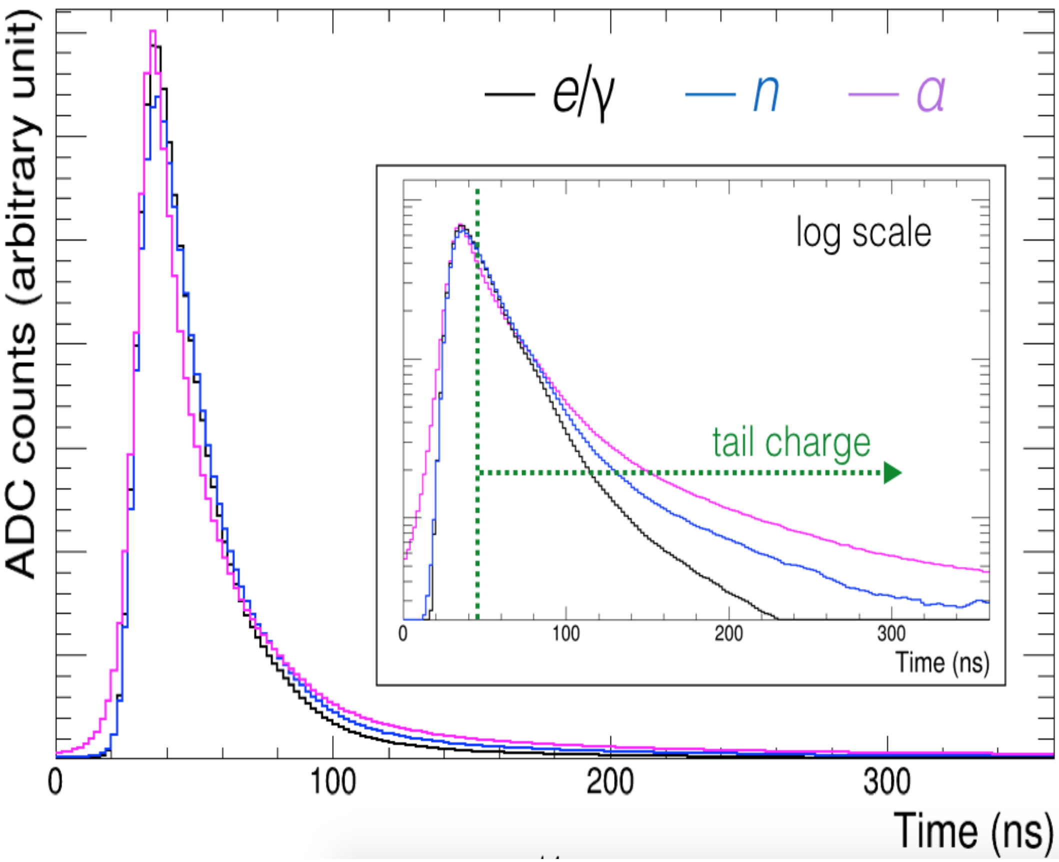
- ~5% at 1 MeV

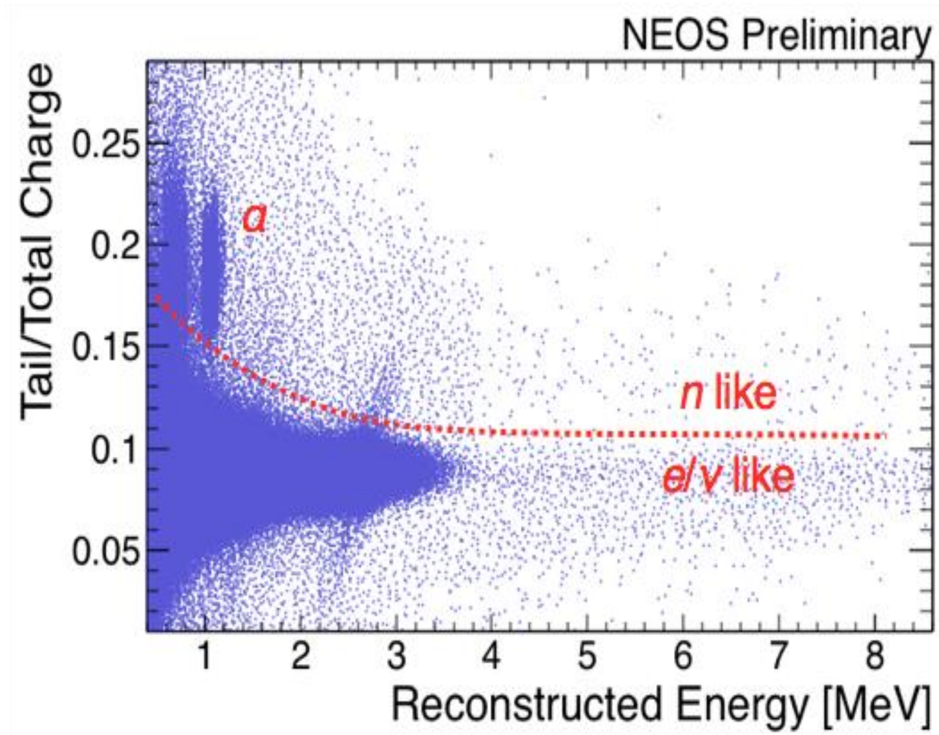


- Non-linear response to energy



Detector Performance: Pulse Shape Discrimination

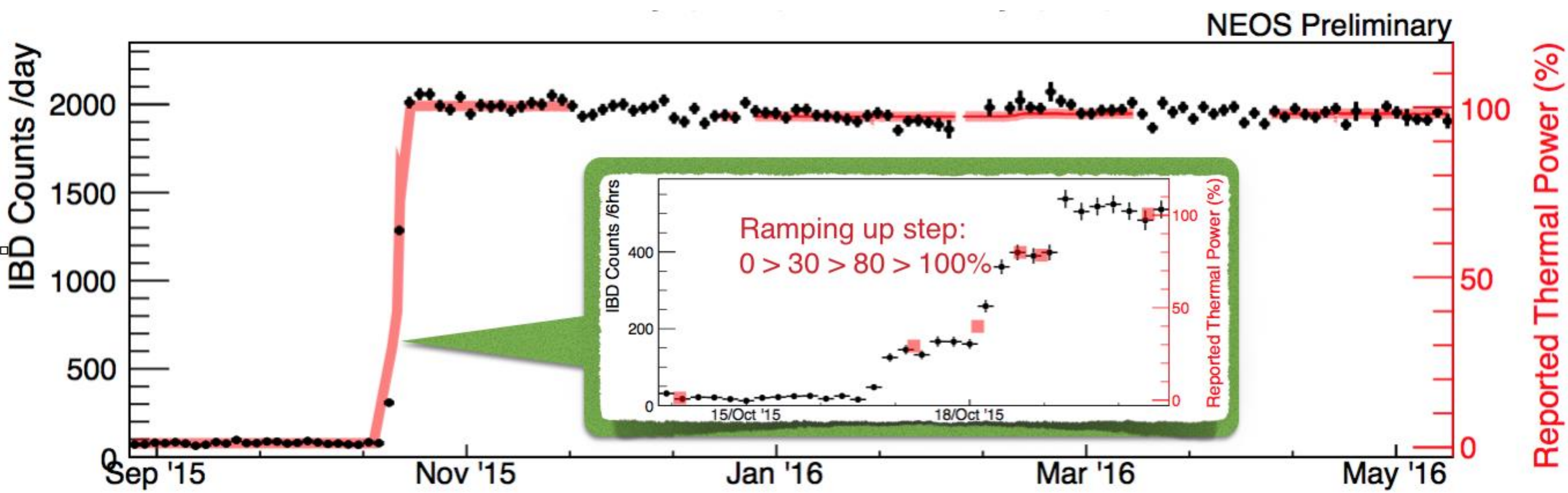




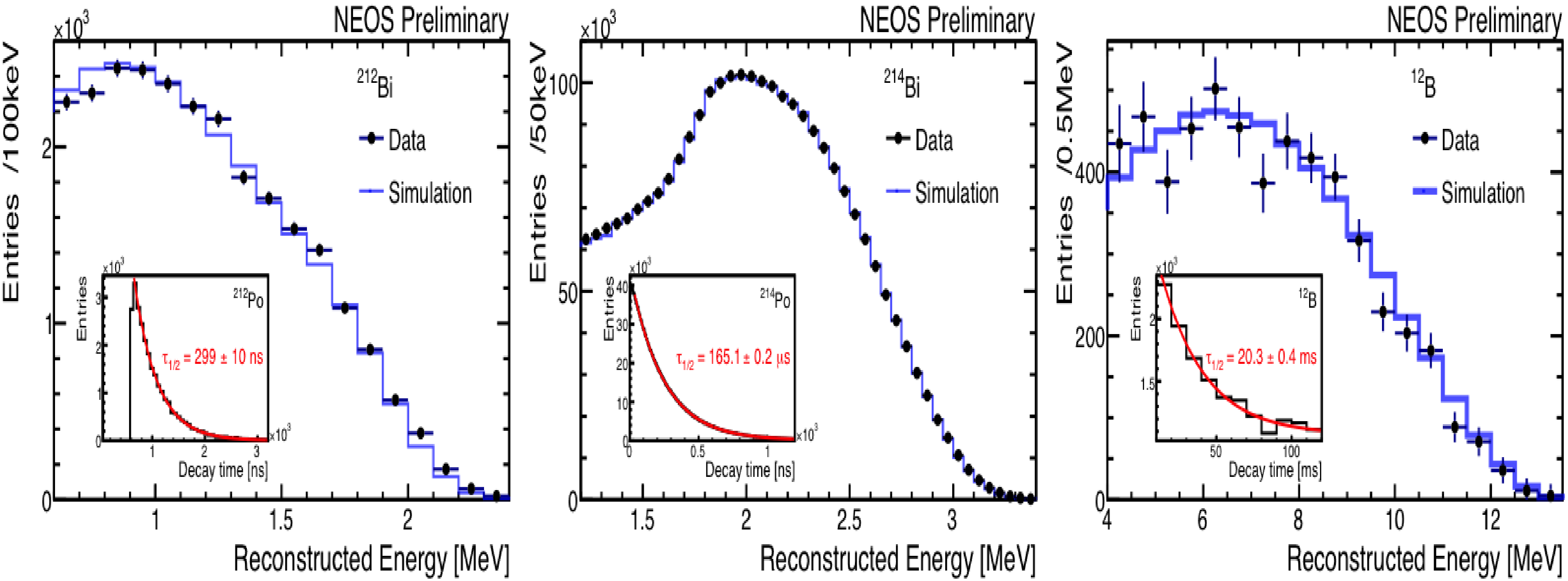
Reactor Neutrino Event Rate

- **Data taking from Aug. '15 to May '16**
  - Reactor off for 49 days : 85 events/day
  - Reactor on for 205 days: ~ 2,000 events/day

S/N=23

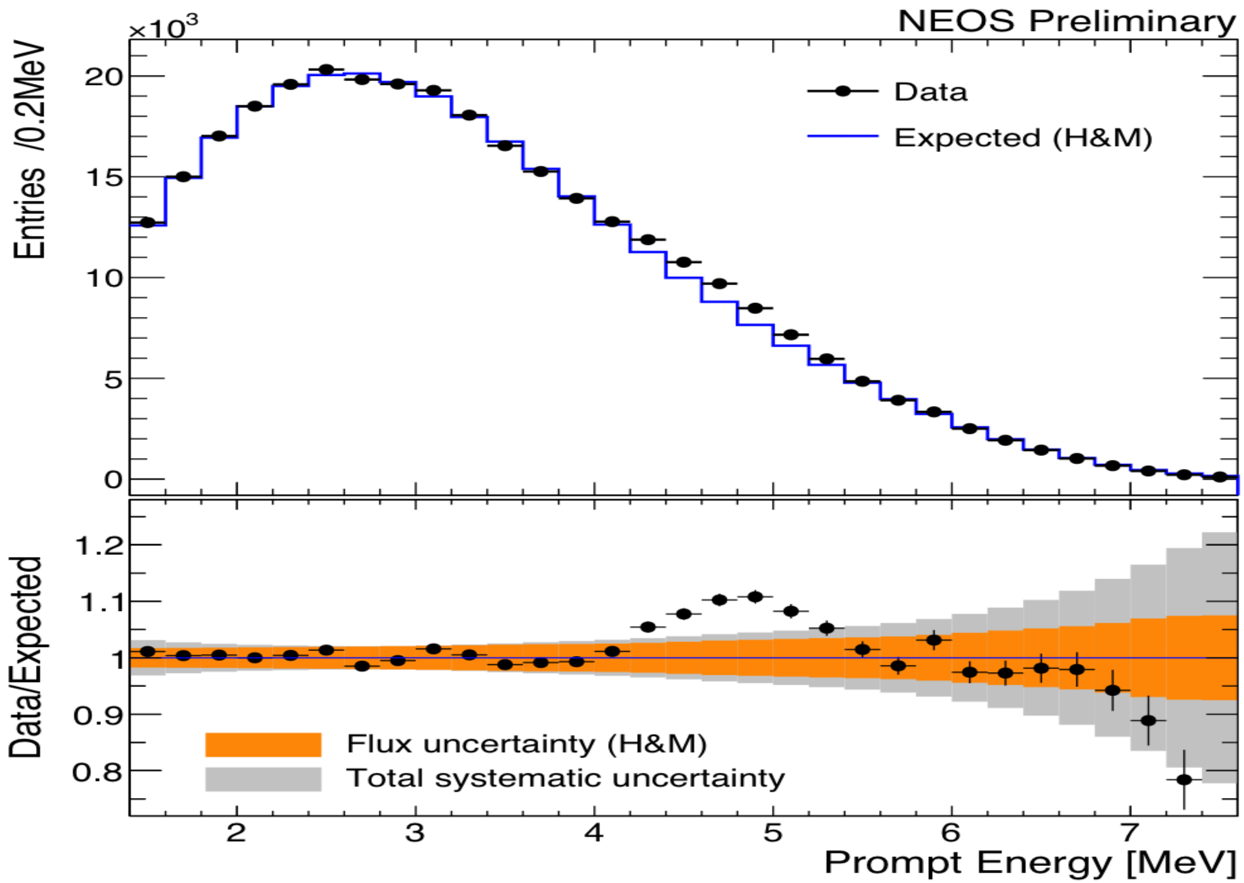


Comparision of data with simulation



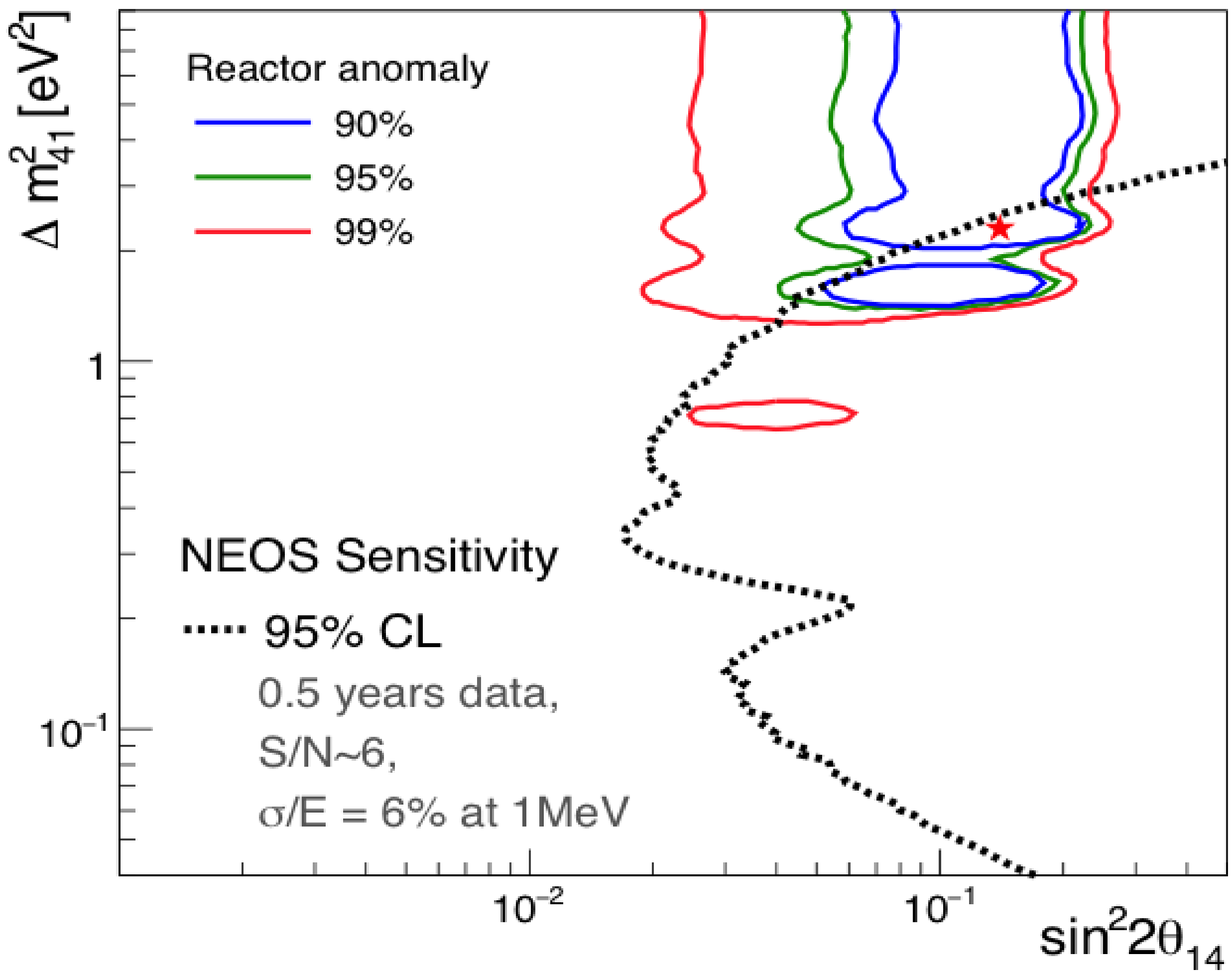
Energy Spectrum for Neutrino Events

- We used P. Huber and Th. A. Mueller for ν energy spectrum.
- Bump around 5 MeV as seen by RENO and DayBay



The Expected Sensitivity of NEOS

- **Some of the allowed region is ruled out.**



Summary

- The KIMS has obtained more stringent limit than most of previous experiments for solar axion search:

$$g_{ae} < 1.37 \times 10^{-11} \text{ for } \mathrm{m_a} = 0 \text{ keV/c}^2$$

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KSVZ model: m_a < 140.9 eV/c^2

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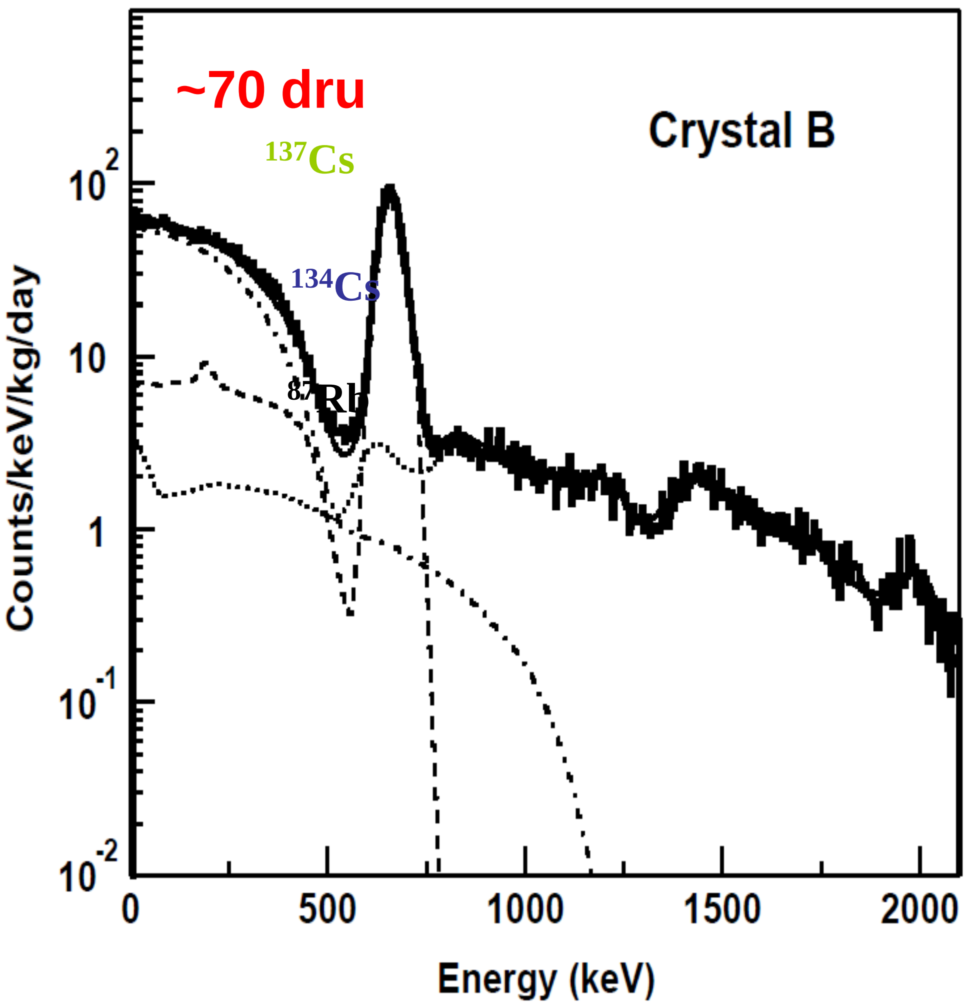
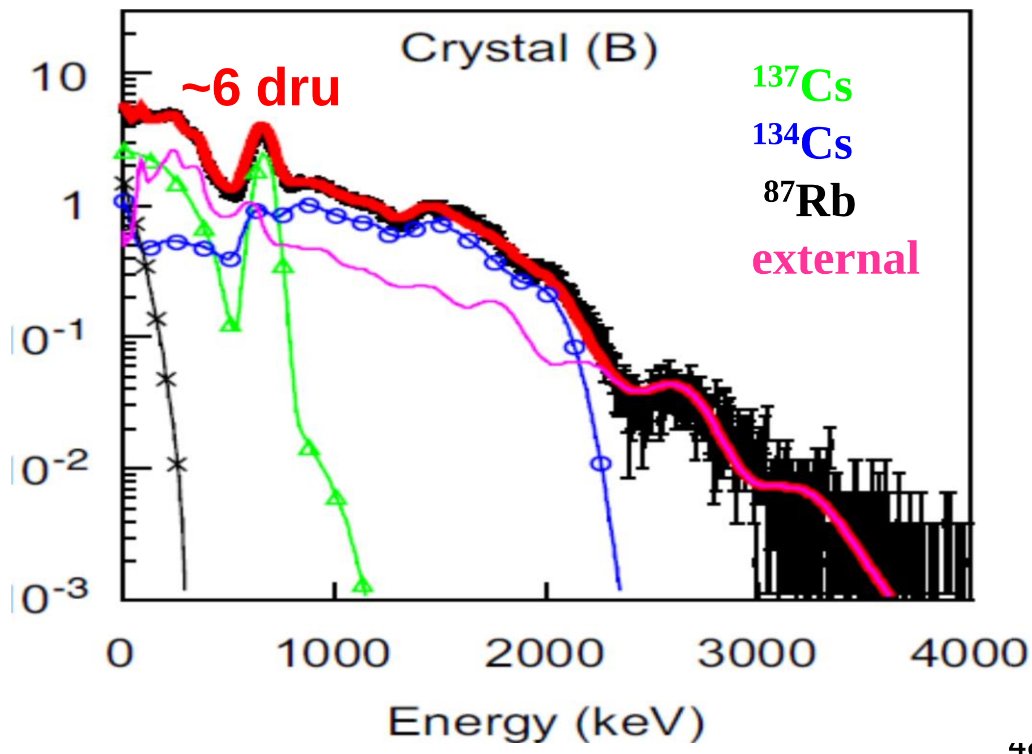
Stay Tuned !

Develpopment of CsI(Tl) crystals

The best CsI(Tl) crystal in the market



The developed CsI(Tl) crystal

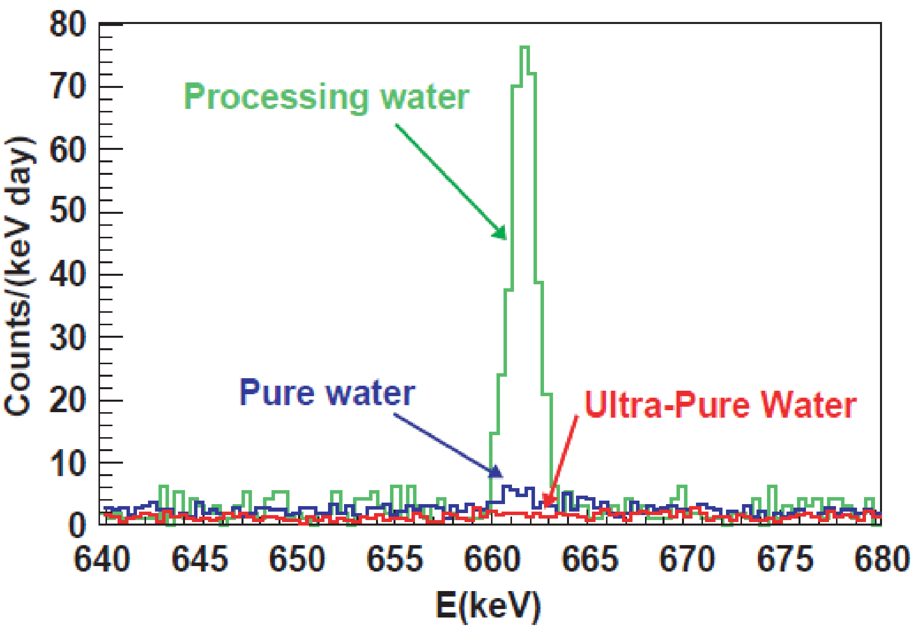


Event Selection

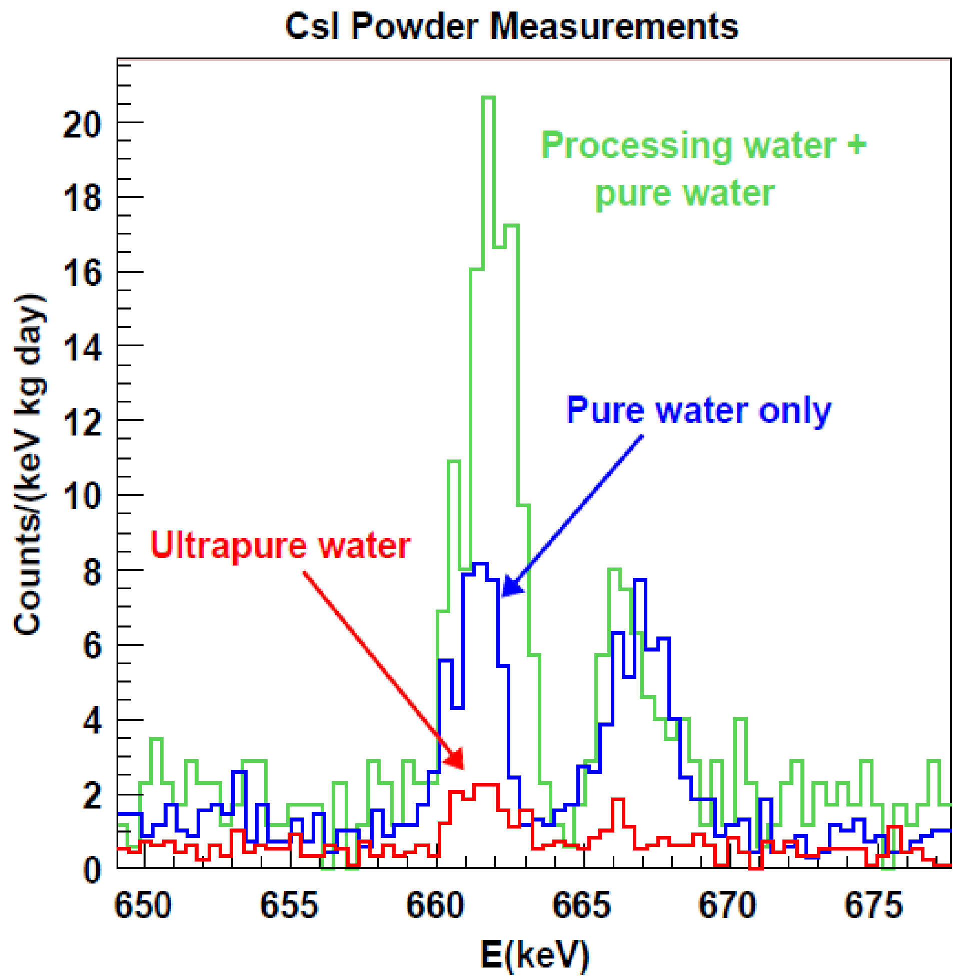
- Split two data sets for 1 year data (2012)
  - Single hit: Axion event selection
  - Multiple hits: Detector efficient study
- Axion signals: electron recoil with energy below 12 keV
  -> single hit among 12 crystals with EM events, < 12 keV.
- Backgrounds:
  - Alpha decays from the crystal surface
  - β-decays:
    ^{137}Cs (Q=1175.6 keV), ^{134}Cs (Q=2058.7 keV), ^{87}Rb (Q=282 keV)
  - Compton scattering

^{137}Cs reduction

- Water is main source



Nucl. Instrum. Meth. A 552 (2005) 456



- With **purified water**, we can reduce the internal background

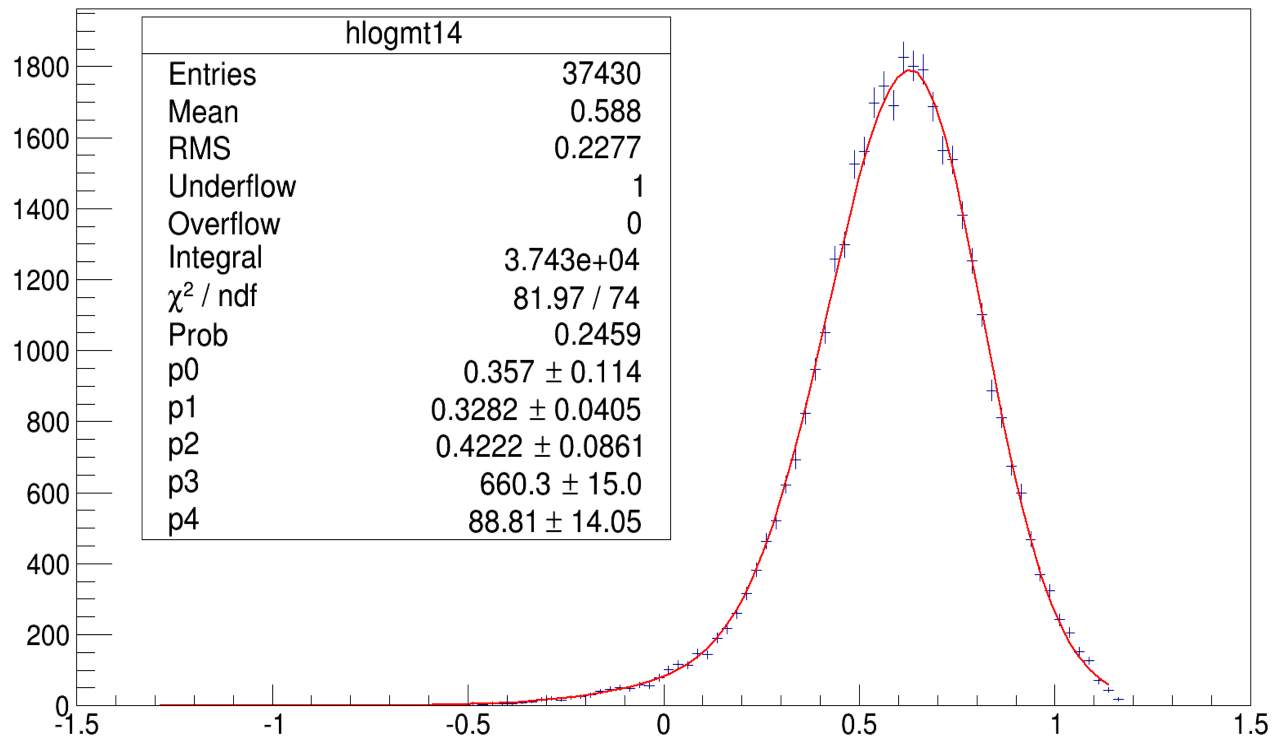
Estimation of No. of e/γ and surface-alpha events (II)

- **Fitting Log_{10}(MT) distribution for each energy bin for single hit events with the following function:**

$G(t) = A_e\, g(t;\mu_e,\sigma_{L1},\sigma_{R1}) + A_a\, g(t;\mu_a,\sigma_{L2},\sigma_{R2})$

-> Extract A_e and A_a

Log_{10}(MT) (8.5-9.0keV)



Estimation of 90 % confidence limit

- **Find out n_s^{up} with the following formula:**

$$\frac{\int_0^{n_s^{up}} \mathcal{L}(n_s)dn_s}{\int_0^{\infty} \mathcal{L}(n_s)dn_s} = 0.9$$

- **The limit for g_{ae} is obtained from the event rate:**

$$N = \int R(E)dE = \int\int dEdE_a \frac{d\Phi_a}{dE_a}\epsilon(E)\sigma_{ae}(E_a)N_{Cs,I}+\sigma_{ae}^{I}(E_a)N_I)TR_{det}(E,E_a)$$

$$= \ constant \ \times g_{ae}^4 \ < \ n_s^{up}$$

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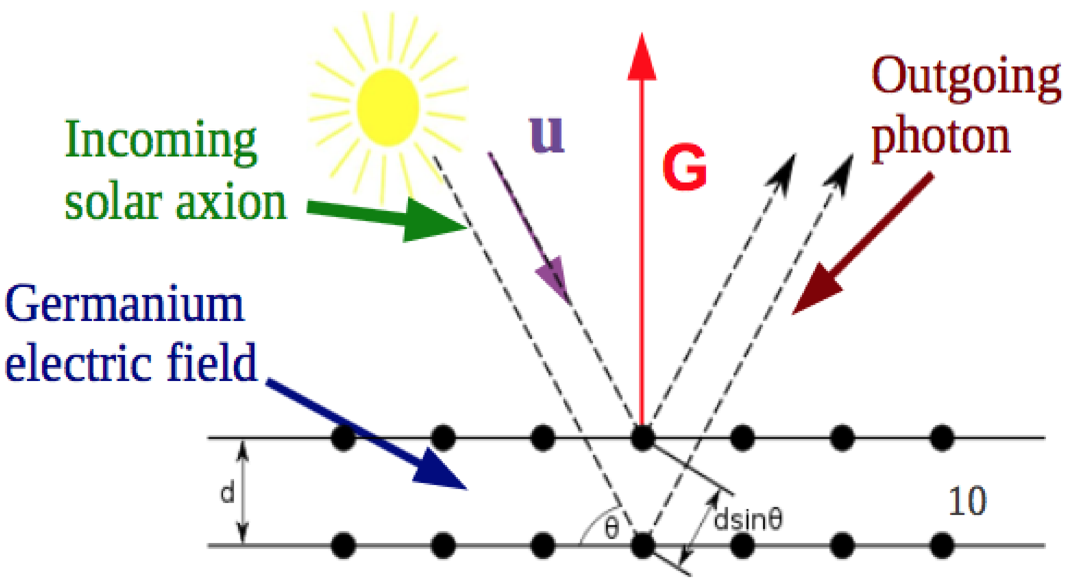
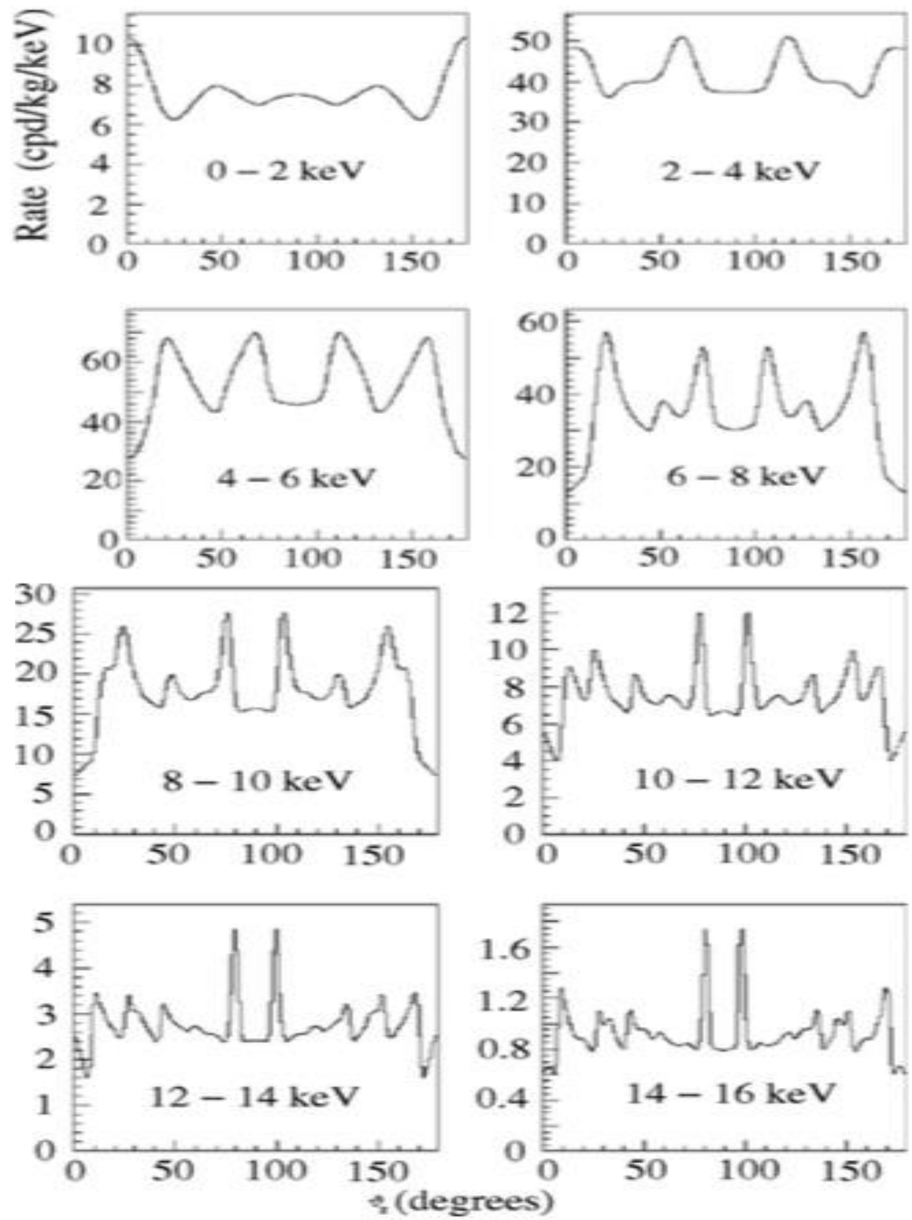
Solar Axion Search: Primakov effect

Bragg: $E_{axion} = \frac{\vec{G}^2}{2\vec{u}\cdot\vec{G}}$





Axion search with Bragg scattering

- **Solar axion conversion rate:**

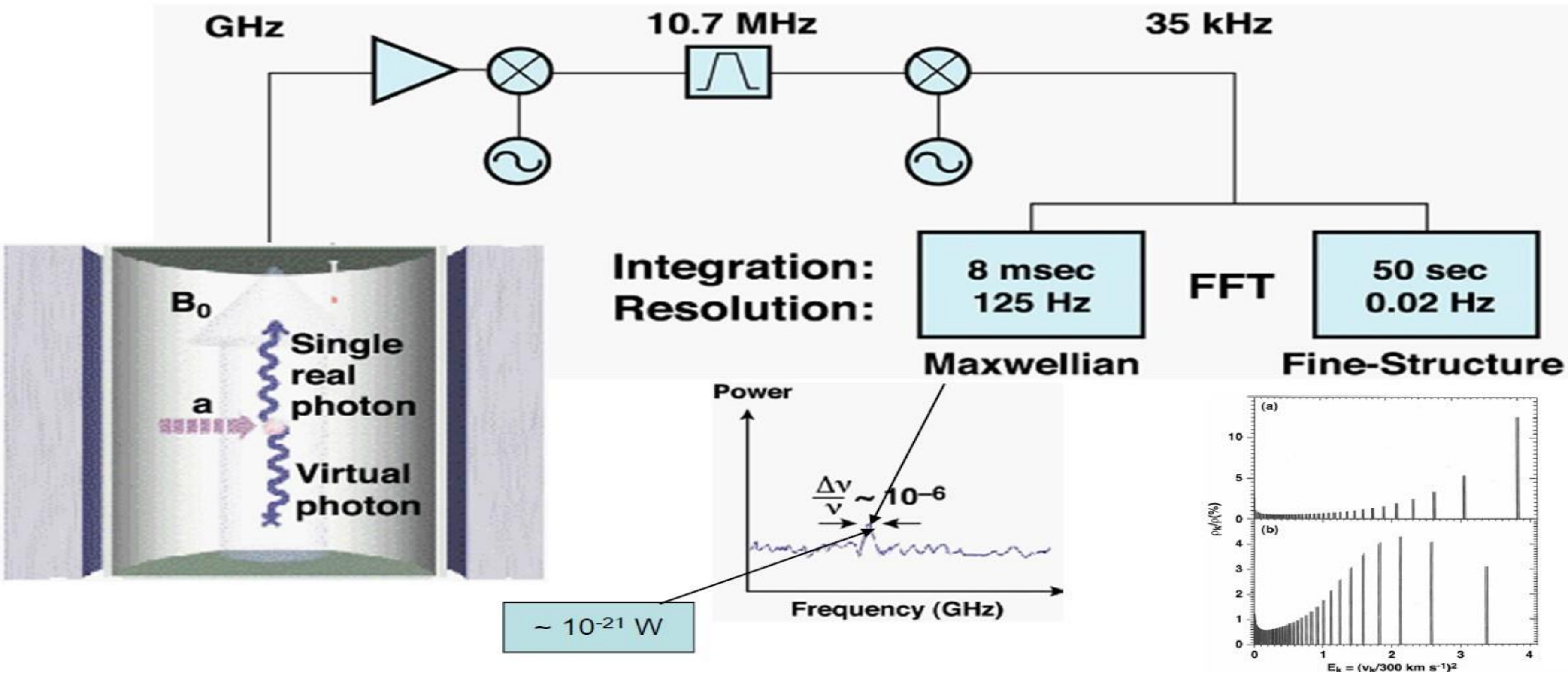
$$\frac{d\dot{N}}{dE} = 2\frac{V}{{v_c}^2}\sum_G |S(G)|^2 \frac{d\sigma}{d\Omega}\frac{1}{|\mathbf{G}|^2}\frac{d\Phi}{dE}\delta(E_a - \frac{|\mathbf{G}|^2}{2\mathbf{u}\cdot\mathbf{G}})$$

$$\mathbf{G} = \frac{2\pi}{a}(h\ k\ l) \quad S(G) = [1 + e^{i\pi(h+k+l)/2}] \times [1 + e^{i\pi(h+k)} + e^{i\pi(h+l)} + e^{i\pi(k+l)}].$$

(h,k,l)	E_0 (keV)	mult	(h,k,l)	E_0 (keV)	mult
(1,1,1)	1.89	8	(5,5,1)	7.78	24
(2,2,0)	3.08	12	(7,1,1)	7.78	24
(3,1,1)	3.62	24	(6,4,2)	8.16	48
(4,0,0)	4.36	6	(5,5,3)	8.37	24
(3,3,1)	4.75	24	(7,3,1)	8.37	48
(4,2,2)	5.34	24	(8,0,0)	8.72	6
(3,3,3)	5.66	8	(7,3,3)	8.92	24
(5,1,1)	5.66	24	(8,2,0)	8.99	24
(4,4,0)	6.17	12	(6,6,0)	9.25	12
(5,3,1)	6.45	48	(5,5,5)	9.44	8
(5,3,3)	6.45	24	(7,5,1)	9.44	48
(4,4,4)	7.55	8	(7,5,3)	9.93	48

Dark Matter Axion Search (II)

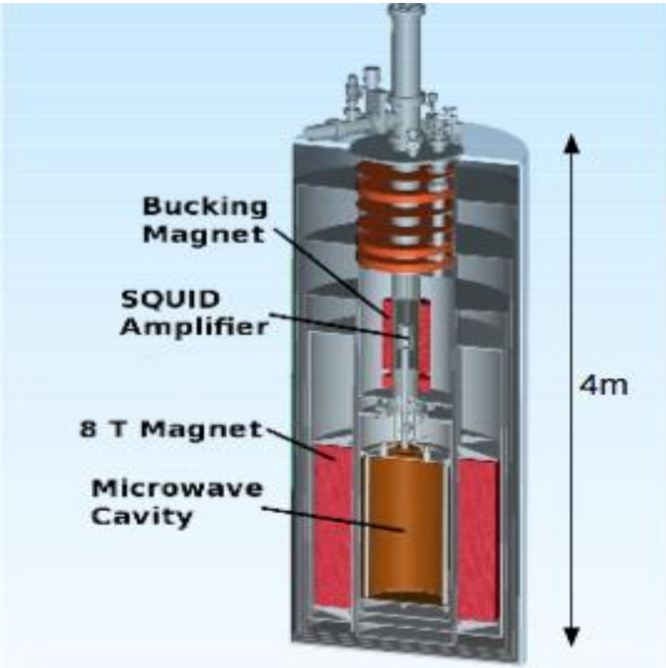
- **Experimental details of the RF-cavity technique**



- **The conversion is resonant: frequency=mass+K.E.**
- **The total noise temperature ($T+T_{amp}$) is critical factor.**

Dark Matter Axion Search (III)

- **ADMX exp.: Axion Dark-Matter eXperiment**



Technology	Squid Amp.
Noise (T)	150 mK(=50mK+100mK)
B	8 T
V	200,000 cm^3
C	0.69
Quality factor	$5x10^5$
b (Band Width)	12.5 Hz

- Conversion power for 1 μeV of axion: $P_a=g^2_{a\gamma}VB^2\rho_aCQ = 2.1x10^{-23}$ W
- Noise power: $P_N=k_bTb = 2.6 \times 10^{-23}$ W

-SNR = $(P_a / P_N)(b\ t)^{1/2} > 3$ -> scanning time t > 0.5 s
- It takes about 1 yr to scan from 1 μeV to 4.2 μeV

Solar Axion Search:
CAST (CERN Axion Solar Telescope) Exp. (I)

- **Use S.C. dipole magnet for LHC:**
  -B=9 T, L=9.26 m, Area=14.5 cm^2
  - Solar tracking: ~ 3h/day

$$P_{a\to\gamma} \sim g^2_{a\gamma} B^2 L^2$$

Solar Axion Search:
IAXO (International AXion Observatory) Exp. (II)

Parameter	CAST	Scenario 1	Scenario 2	Scenario 3	Scenario 4
B (T)	9	3	3	4	5
L (m)	9.26	12	15	15	20
A (m^2)	2x0.0015	1.7	2.6	2.6	4