Search of axions from a nuclear power reactor with a high-purity germanium detector

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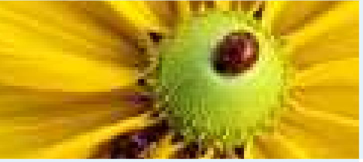
Outline

- Introduction to Axions
- Axion Production & Detection
- Data analysis
- Physics Results

This work is published in PRD 75, 052004 (2007), a by-product of Taiwan EXperiment On NeutrinO.

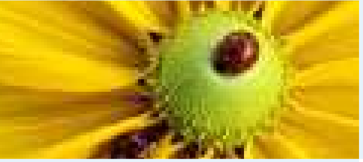


Introduction to Axion

- Strong CP Problem:
  Neutron EDM $< 10^{-25}$ e cm,
  Why QCD does not seem to break the CP-symmetry?

- PQWW Axion ($m_a \gtrsim 100$ keV):
  - A hypothetical particle to solve stong CP problem.
  - Excluded after extensive searches.

- Invisible Axion:
  - Evade previous experimental searches.
  - Mass window $10^{-6} \lesssim m_a \lesssim 10^{-2}$ (eV),
    from cosmological and astrophysical arguments.
  - Popular models: DFSZ, KSVZ.



Reactor as Source

- Axions could be emitted via magnetic transition.
- Inspired by F. T. Avignone III *et al.*, PRD37, 618 (1988).
  $\Rightarrow$ Radioactive ^{65}Zn source & HPGe detector.
- Reactor is the most powerful radioactive source we can control!
  - Slow neuton capture: $n + (Z, A) \to (Z, A+1) + \gamma$ (or $axion$).
  - Nuclear de-excitation: $(Z, A)^* \to (Z, A) + \gamma$ (or $axion$).
- The photon fluxes ϕ_γ at detector:

	Energy (keV)	Mode	ϕ_γ (10^{10} cm^{-1}s^{-1})
np$\to$dγ	2230	Isovector M1	22.1
^{7}Li*	478	M1	24.7
^{91}Y*	555	M4	2.10
^{97}Nb*	743	M4	4.81
^{135}Xe*	526	M4	0.85
^{137}Ba*	662	M4	0.37

- Axion flux is $\phi_a = \phi_\gamma \frac{\Gamma_a}{\Gamma_\gamma}$.
- Solar axion flux $\sim 10^{12}(\frac{m_a}{\text{eV}})^2$ cm^{-2}sec^{-1}, with average energy $\sim$4 keV.

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Kinematics Constraint!

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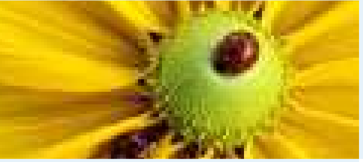


Branching Ratio Γ_a/Γ_γ Complications

The axion-to-photon branching ratio for M1 transition is:

$$\frac{\Gamma_a}{\Gamma_\gamma} = \frac{1}{2\pi\alpha}\frac{1}{1+\delta^2}\left(\frac{p_a}{\epsilon_a}\right)^3\left(\frac{g^0_{aNN}\beta + g^1_{aNN}}{(\mu_0 - \frac{1}{2})\beta + (\mu_1 - \eta)}\right)^2 .$$

δ: E2/M1 mixing ratio ≈ 0.
μ_0 (μ_1): Isoscalar (isovector) magnetic moment $= 0.88$ (4.71).
η, β: Matrix elements from nuclear physics.

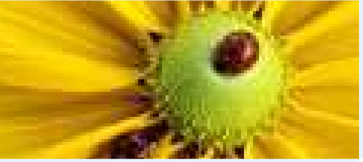
- Numerical calculations of η and β are needed.
- Even if η and β are known, two free parameters g^0_{aNN} and g^1_{aNN} still remain.

How to circumvent the complications?

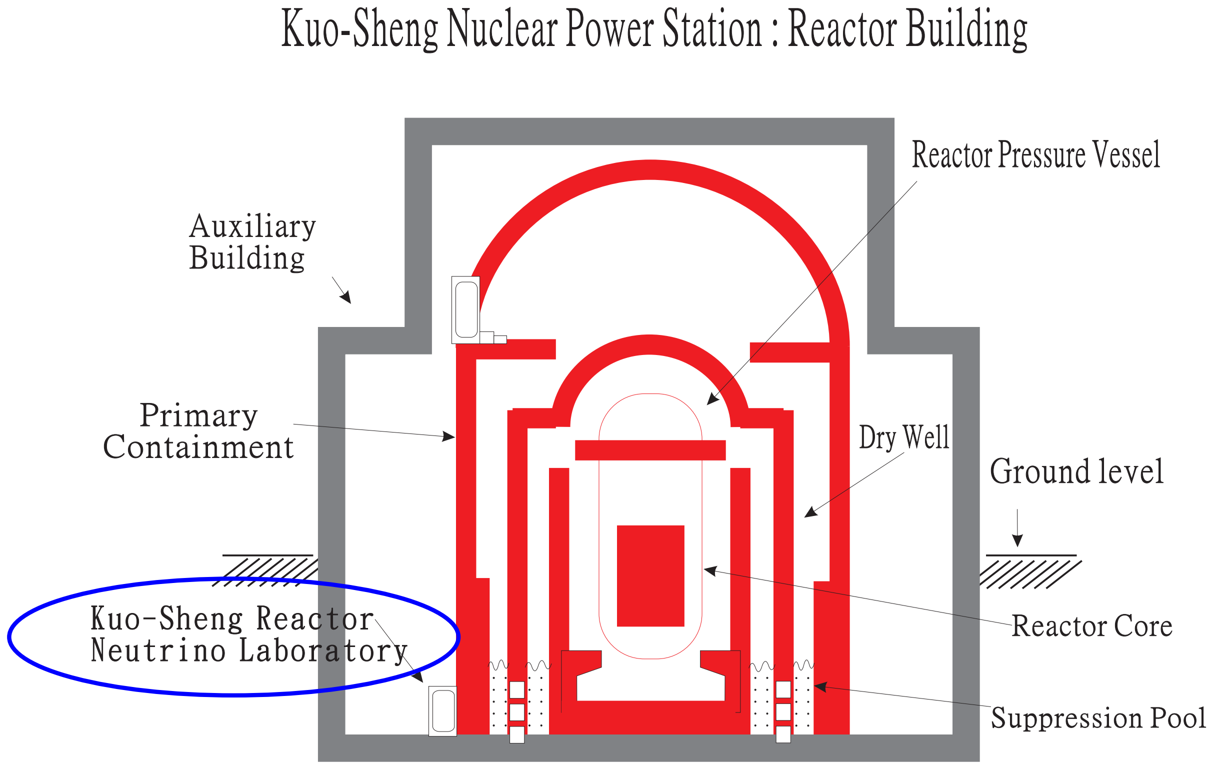
- It happens that np$\rightarrow$dγ is an isovetor M1 transition:

$$\left(\frac{\Gamma_a}{\Gamma_\gamma}\right)_{np} \equiv \frac{\Gamma_a}{\Gamma_\gamma}(np \rightarrow d\gamma) \approx \frac{1}{2\pi\alpha}\left(\frac{p_a}{\epsilon_a}\right)^3\left(\frac{g^1_{aNN}}{\mu_1}\right)^2 \propto (g^1_{aNN})^2 .$$

- In analysis, g_{aNN} can be parametrized as a function of m_a with axion models.



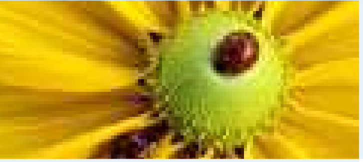
Reactor Building



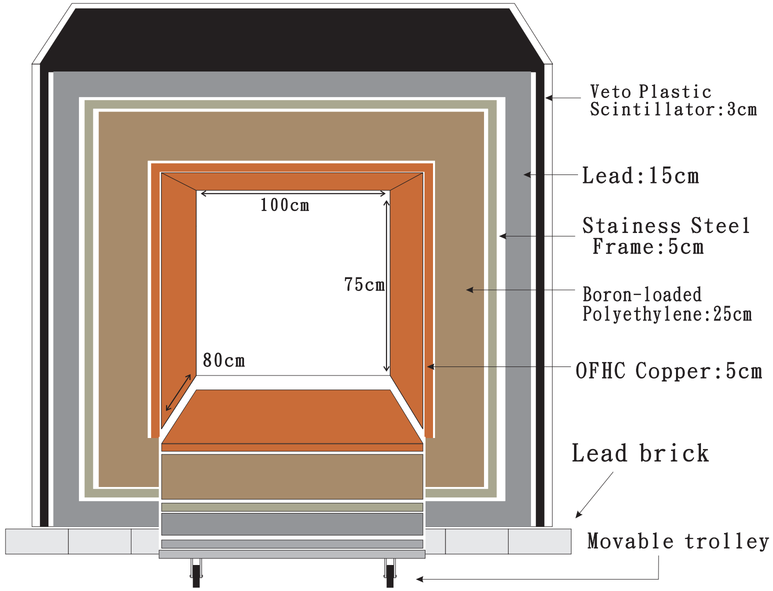
- Power: 2.9 GW.
- $\overline{\nu}_e$ flux: 6×10^{12} cm^{-2}·s^{-1} .
- 30 mwe overburden.

- Data Size:
  - ON: 459.0 days.
  - OFF: 96.3 days.

  in two ON/OFF periods.



Detector & Shielding

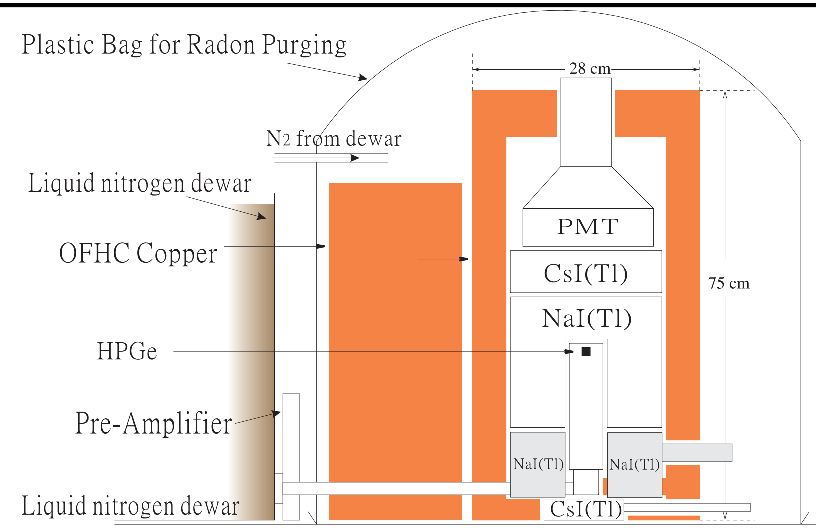


Outer Shielding:

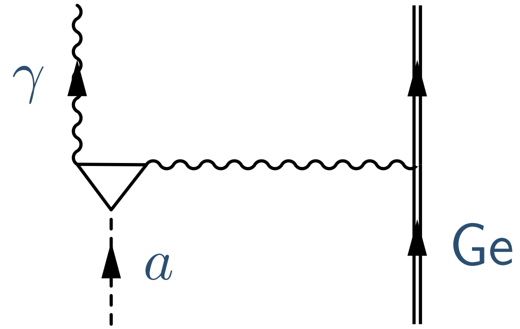
1. Plastic scintillator: cosmic-ray veto.
2. Lead: block γ's from outside.
3. Stainless steel: support the structure.
4. B-loaded polyethylene: neutron capturer.
5. OFHC copper: reduce the γ's from lead or polyethylene.

HPGe detector:

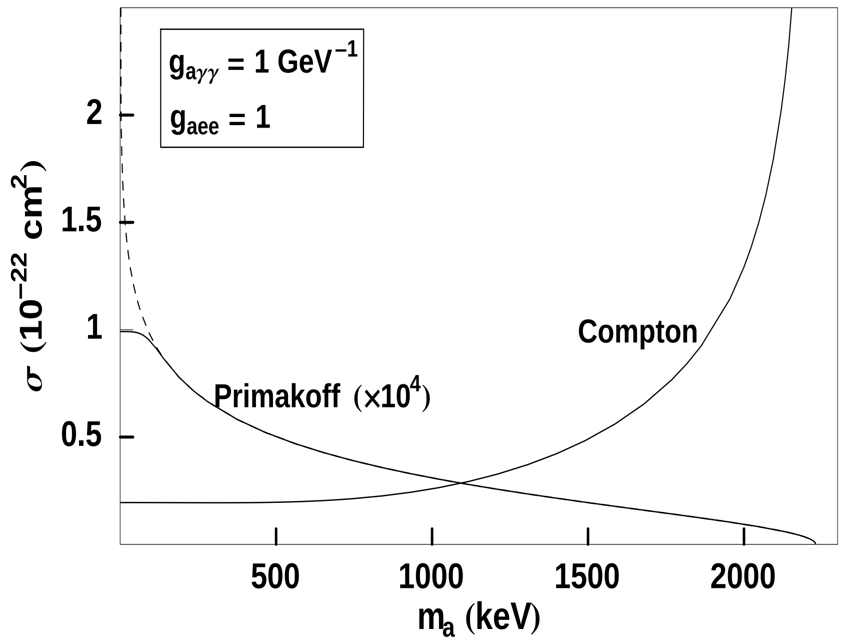
- Mass: 1 kg.
- Threshold: 5 keV.
- CsI and NaI: anti-Compton system.
- 28m from reactor core.

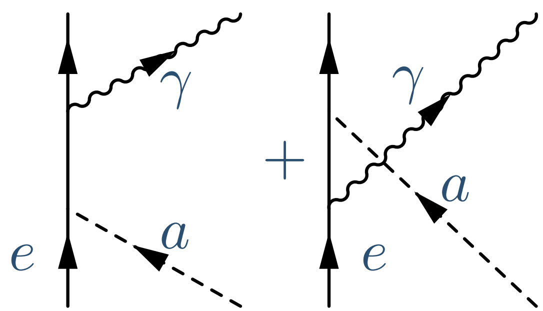


Axion Detection



Primakoff conversion ($g_{a\gamma\gamma}$)

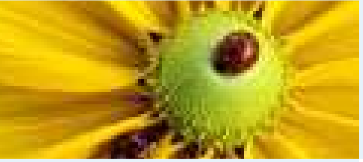




Compton conversion (g_{aee})

- $\sigma_{Pri} = g^2_{a\gamma\gamma} \cdot f(m_a, \epsilon_a)$
  $\Rightarrow$ sensitive at low m_a
- $\sigma_{Com} = g^2_{aee} \cdot f(m_a, \epsilon_a)$
  $\Rightarrow$ sensitive at high m_a

(Here $\epsilon_a = 2230$ keV)



Event Rate Formula

The event rate in unit of day^{-1}kg^{-1} is

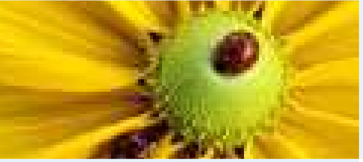
$$R = \sigma \Big(\phi_\gamma \frac{\Gamma_a}{\Gamma_\gamma} \cdot P_{decay} \cdot P_{matter} \Big) N\epsilon \ ,$$

P_{decay}: Survival probability without decay.
P_{matter}: Survival probability without interaction.
N: # of Ge atoms in kilogram target.
ϵ: Efficiency of full-energy deposition at detector.

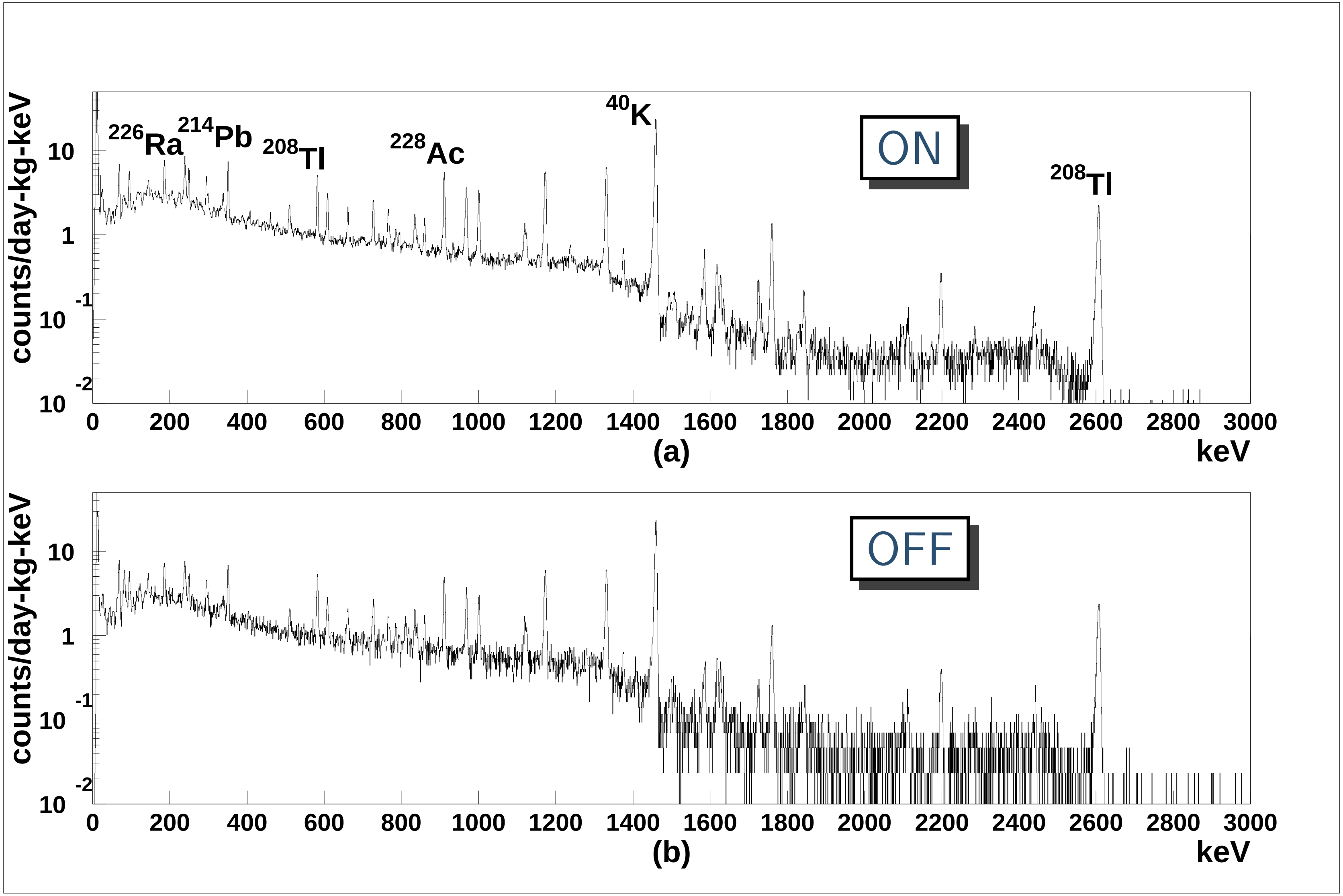
$$R = R(m_a \ , \ g_{a\gamma\gamma/aee} \ , \ g_{aNN}) \ .$$

Invoking the widely-used DFSZ model ($g_{aNN} \propto m_a$) to reduce free parameter:

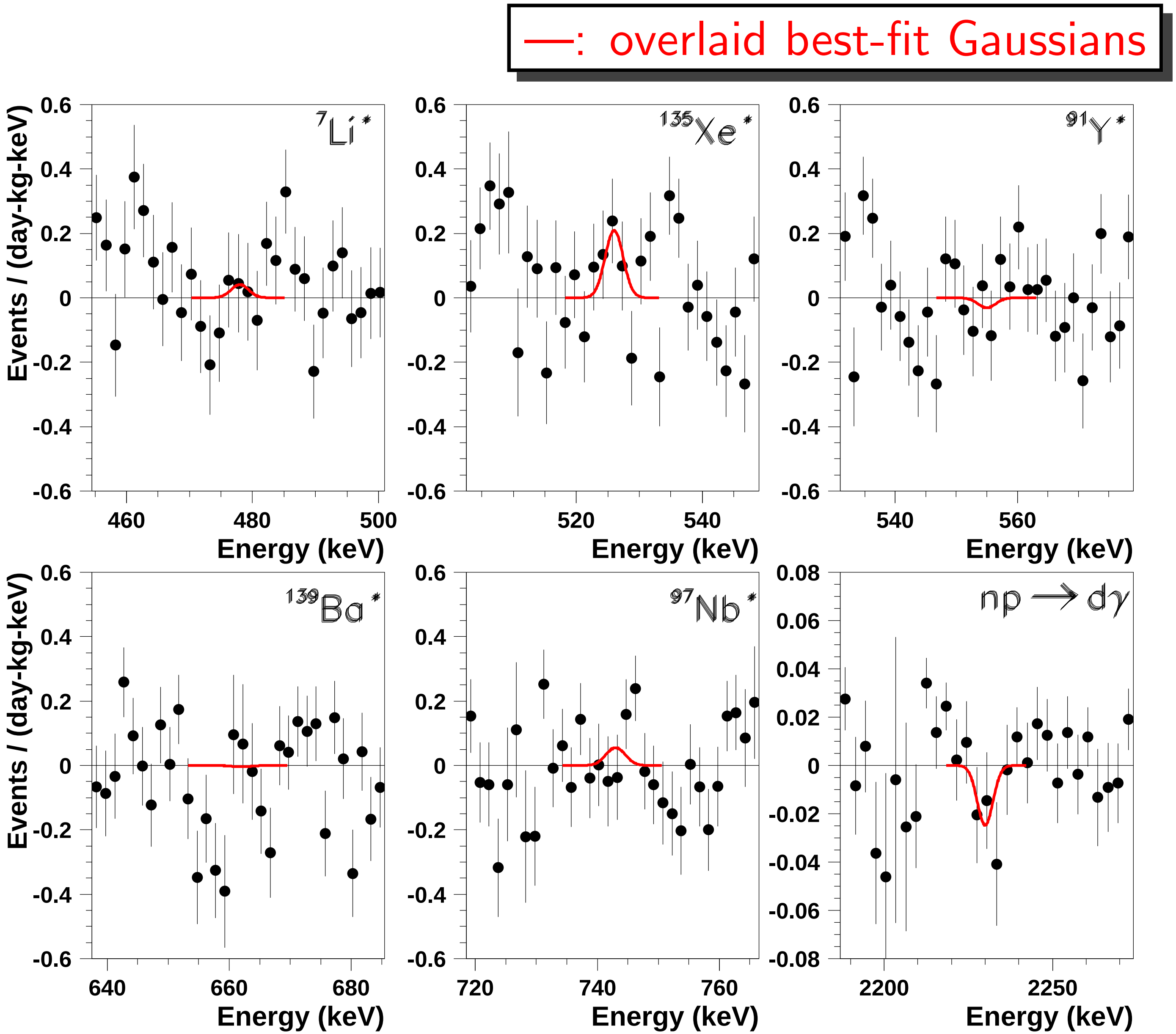
$$R \propto g^2_{a\gamma\gamma/aee} m_a^2 \ .$$



Energy Spectra



ON-OFF Residual

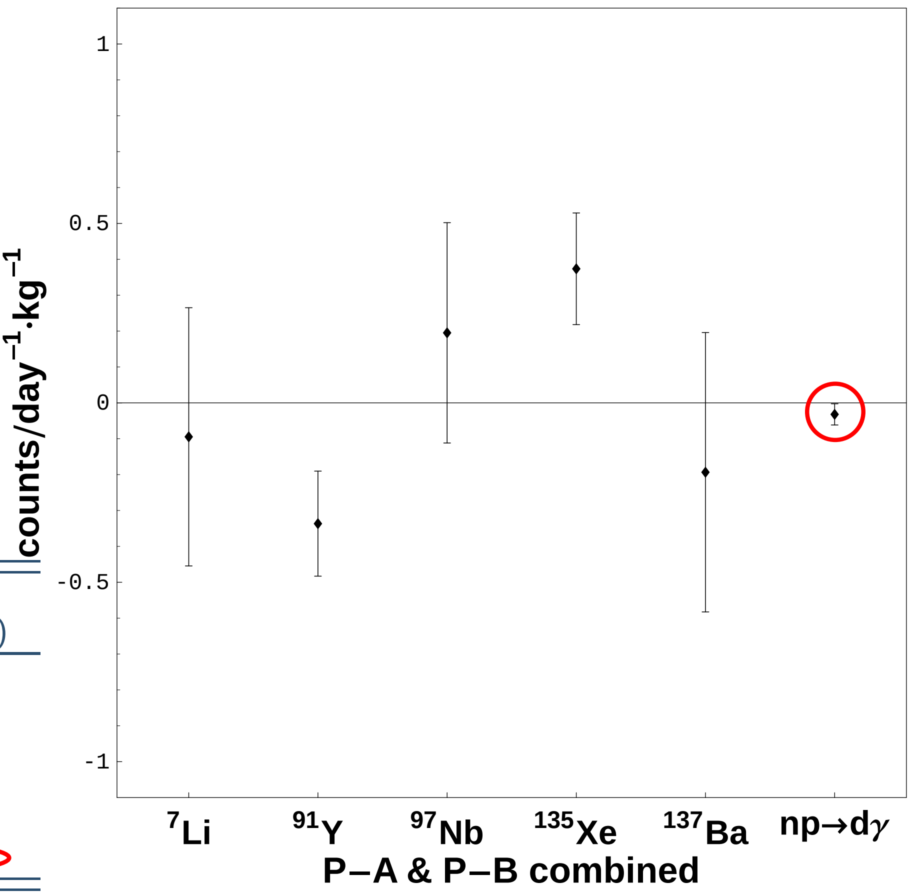


Results

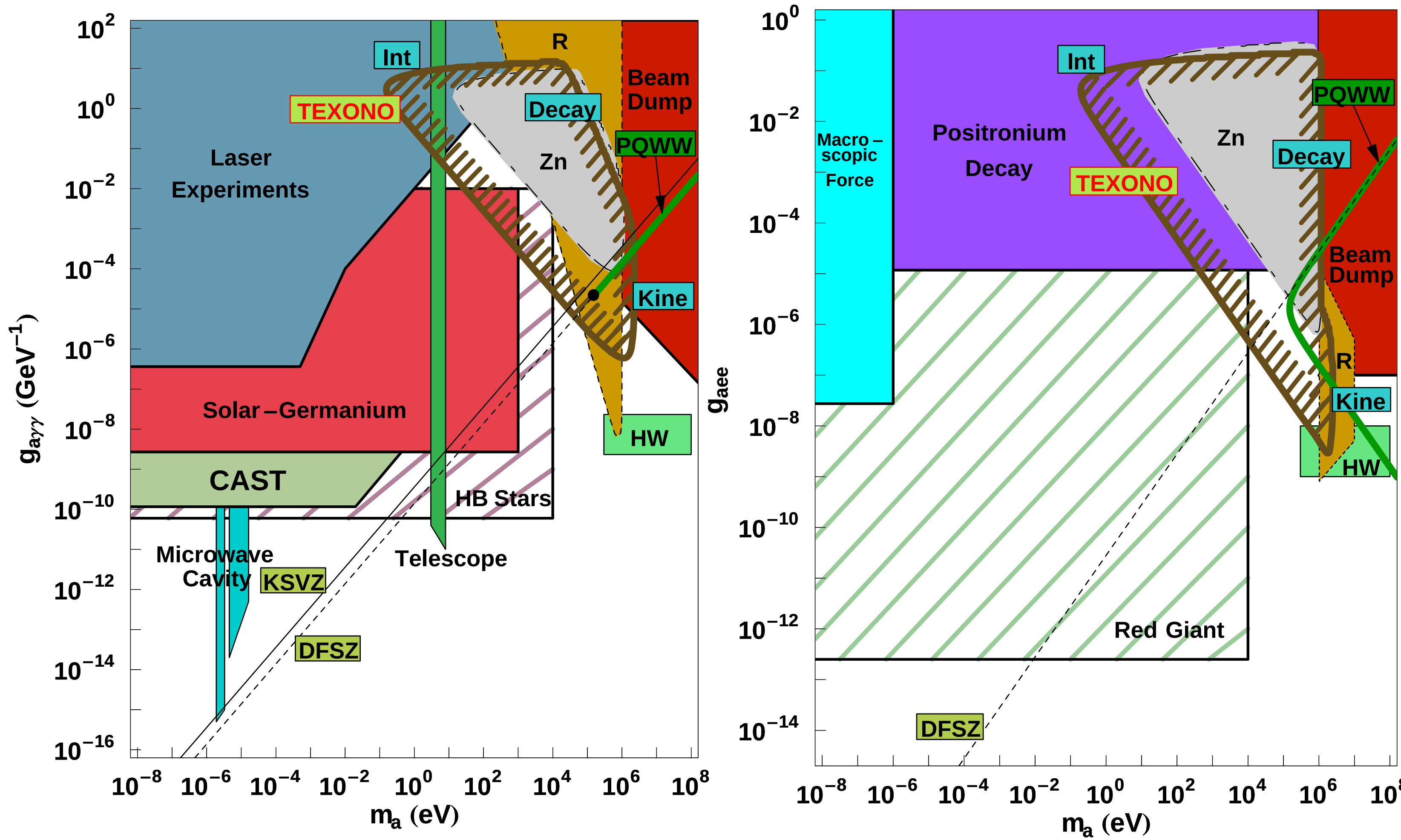
Statistical results:

Energy (keV)	Period A ($day^{-1}kg^{-1}$)	Period B ($day^{-1}kg^{-1}$)
478	-0.88±0.75	0.14±0.41
526	0.26±0.67	0.38±0.16
555	-0.47±0.67	-0.33±0.15
662	-0.46±0.62	-0.02±0.50
743	0.14±0.55	0.22±0.37
2230	-0.10±0.17	-0.03±0.03

Energy (keV)	P-A&P-B Combined ($day^{-1}kg^{-1}$)	Upper Bound ($day^{-1}kg^{-1}$)
478	-0.09±0.36	0.49
526	0.37±0.15	0.62
555	-0.34±0.15	0.05
662	-0.19±0.39	0.46
743	0.19±0.31	0.69
2230	-0.04±0.03	0.02



Systematics Uncertainty: $< 20\%$, dominated by evaluation of ϕ_γ from np→dγ.



10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
$g_{a\gamma\gamma}$ (GeV^{-1})
Int
TEXONO
R
Beam Dump
Decay
Zn
PQWW
Laser Experiments
Kine
Solar – Germanium
HW
CAST
HB Stars
Microwave Cavity
KSVZ
Telescope
DFSZ
10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4} 10^{6} 10^{8}
m_a (eV)
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
g_{aee}
Int
PQWW
Macro – scopic Force
Positronium Decay
Zn
Decay
TEXONO
Beam Dump
R
Kine
HW
Red Giant
DFSZ
10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4} 10^{6} 10^{8}
m_a (eV)

Summary

- There are 9 reactor axion papers among literature, and the latest one was in 1995. They all focused on standard (PQWW) axion.
- We have new and more stringent results for general axions. PQWW, DFSZ and KSVZ models are excluded for $m_a \approx 10^4$eV - 10^6eV.
- This approach defines exclusion boundary for $m_a \approx 10^3$ - 10^6eV among direct experiments.
- The model-independent (not invoking the DFSZ $g_{aNN} - m_a$ relation) upper bounds:

$$\begin{cases} g^2_{a\gamma\gamma} \cdot \left(\dfrac{\Gamma_a}{\Gamma_\gamma}\right)_{np} < 5.9 \times 10^{-17}\ \text{GeV}^{-2} \\ g_{a\gamma\gamma} \cdot g^1_{aNN} < 7.7 \times 10^{-9}\ \text{GeV}^{-1} \end{cases}, \qquad \begin{cases} g^2_{aee} \cdot \left(\dfrac{\Gamma_a}{\Gamma_\gamma}\right)_{np} < 1.7 \times 10^{-20} \\ g_{aee} \cdot g^1_{aNN} < 1.3 \times 10^{-10} \end{cases}.$$