Coherency in Neutrino-Nucleus (νA_{el}) Scattering

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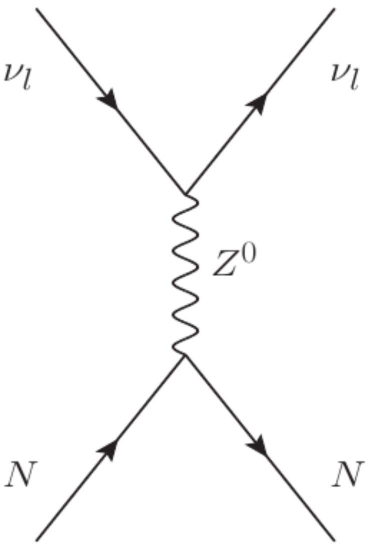
Outline of Talk ..

- **Introduction and Motivation.**
- **Global Status of νA_{el}.**
- **TEXONO Facilities.**
- **νA_{el} at KSNL.**
- **Background and Threshold.**
- **Sensitivity of Experiment.**
- **Coherency in νA_{el} scattering**
- **Summary.**

Coherent Neutrino-Nucleus Scattering

A neutrino interacts with a nucleus of neutron number "N" via exchange of Z - Boson.

$$\nu + N \longrightarrow \nu + N$$



Cross-Section of νA_{el} : $$\frac{d\sigma_{\nu A_{el}}}{dq^2}(q^2, E_\nu) = \frac{1}{2}\left[\frac{G_F^2}{4\pi}\right]\left[1 - \frac{q^2}{4E_\nu^2}\right][\varepsilon Z - N]^2 F(q^2)$$

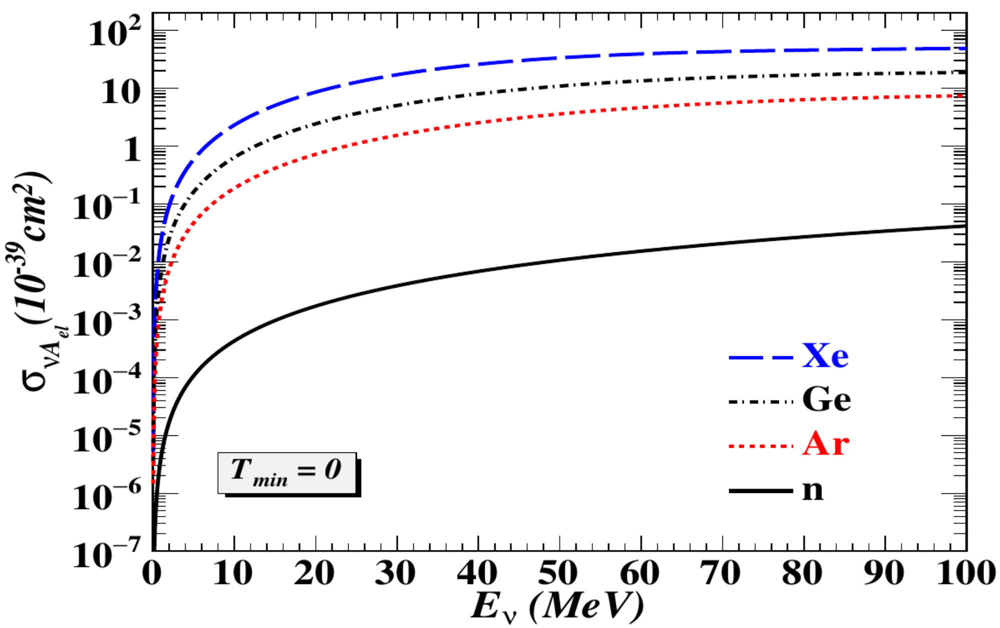
Where G_F is fermi constant, E_ν is incident neutrino energy, Z(N) is Atomic(Neutron) number of nuclei and q is three momentum transfer.

$F(q^2)$ is nuclear form factor approaches to ~1 at small momentum transfer.

$\varepsilon = 1 - 4\mathrm{Sin}^2\Theta_W = 0.045$

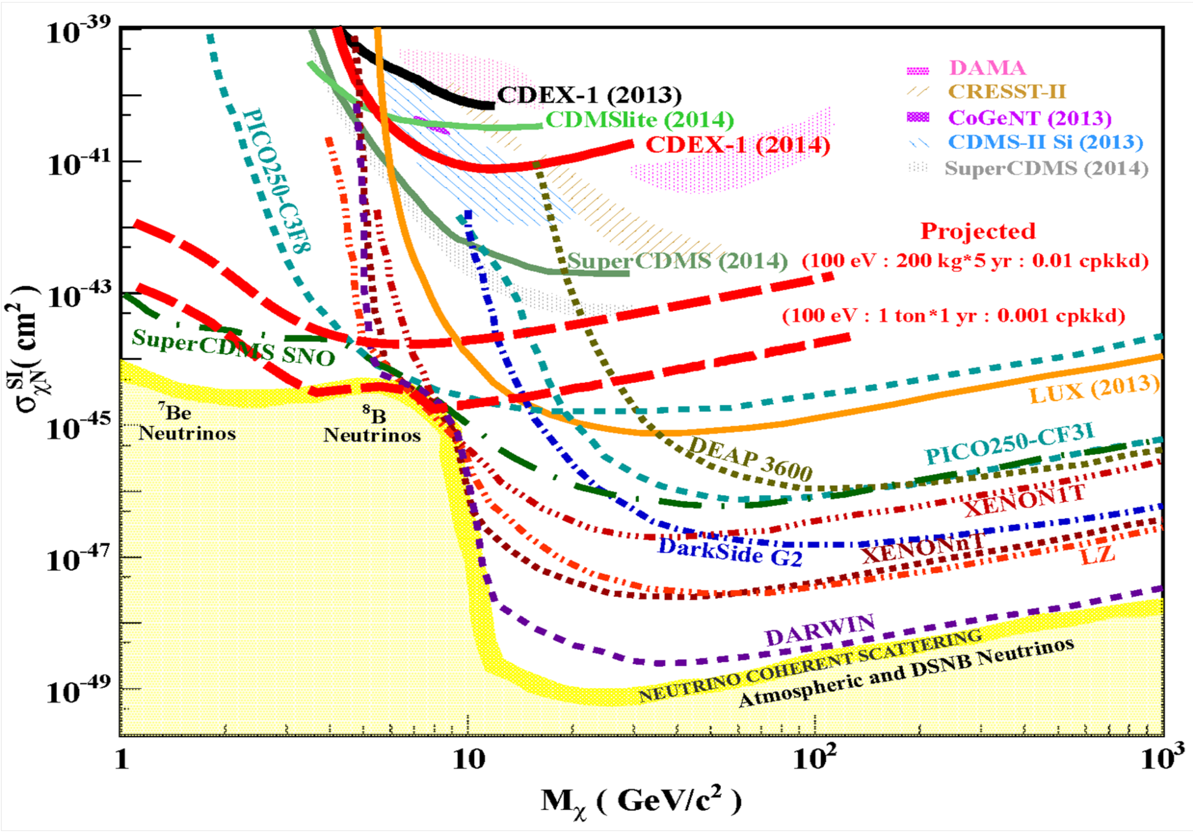
Heavier nuclei $\longrightarrow$ larger cross-section

- **This process is coherent upto ~<50 MeV neutrino**
- **Cross-section is well-defined in Standard Model.**
- **Observed for >10 MeV stopped pion neutrinos.**



Important to study for ...

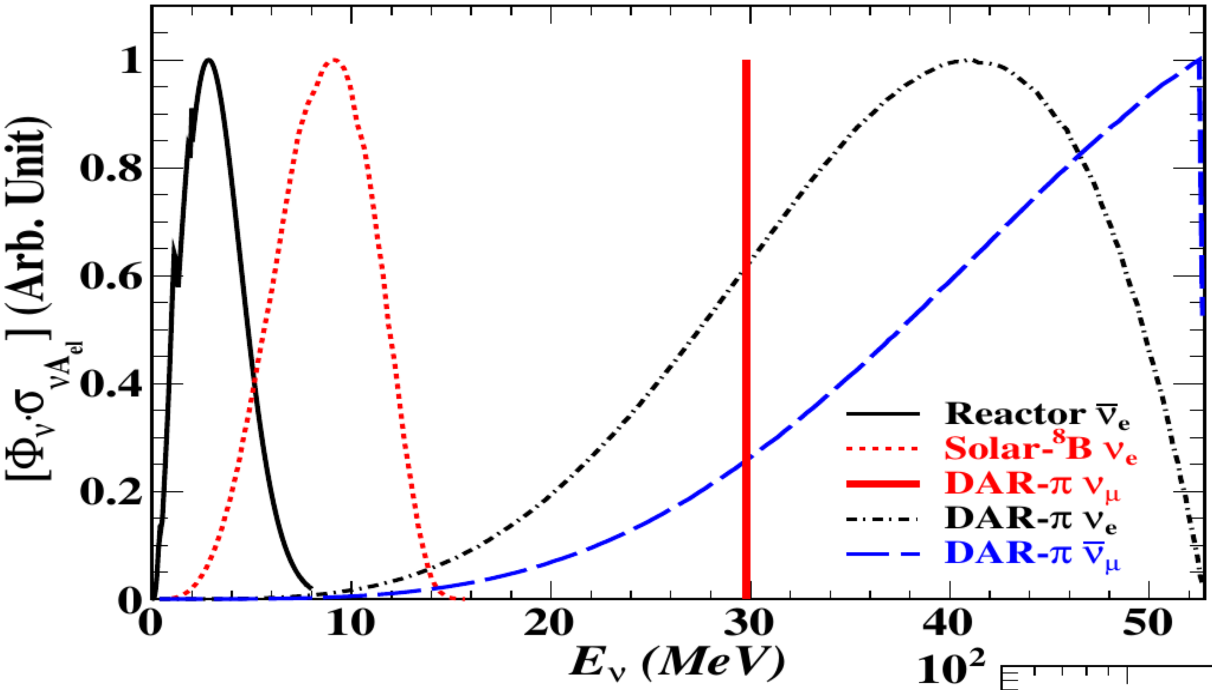
- Important role in Supernova Explosions.
- Test of fundamental SM-electroweak interaction.
- In study of Beyond Standard Model Physics.
- Probe transition of Quantum Mechanical Coherency in electro-weak process.
- Potential use in Reactor monitoring as a portable device.
- νA_{el} Scattering is important to study the irreducible background for Dark Matter search.



Requirements to observe νA_{el}

- High Neutrino Flux
- Lower Threshold
- Better Resolution
- Quenching Factor
- Understanding of Background
- Better Shielding from Gamma, Neutrons etc..
- Sufficient Source On/Off Statistics

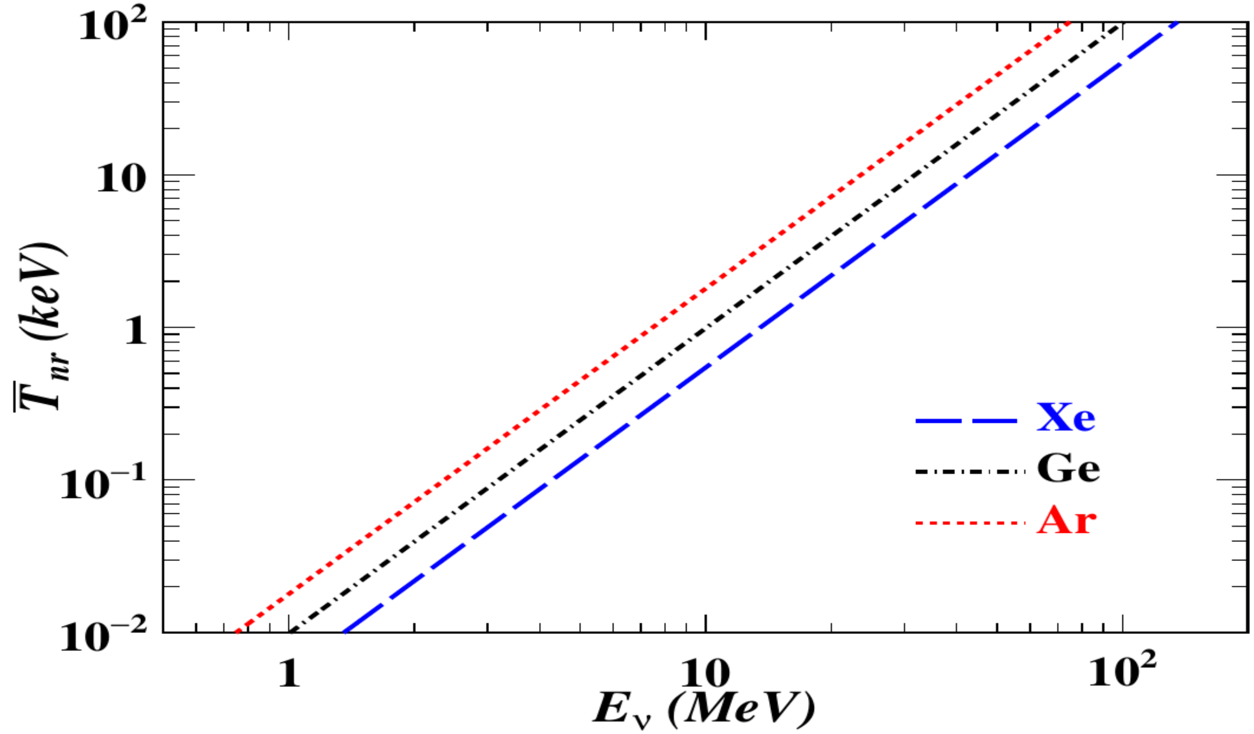
Measurable Cross-Section of νA_{el}



The weightage region to probe νA_{el} can be predicted by $[\Phi_\nu \cdot \sigma_{\nu Ael}]$ plot for various neutrino sources.

Averaged nuclear recoil for νA_{el} interaction:

$$\bar{T}_{nr} = \frac{2}{3} T_{max} \simeq \frac{2E_\nu^2}{3M}$$



COHERENT @ SNS, ORNL

Two independent analysis were done:

1. University of Chicago.

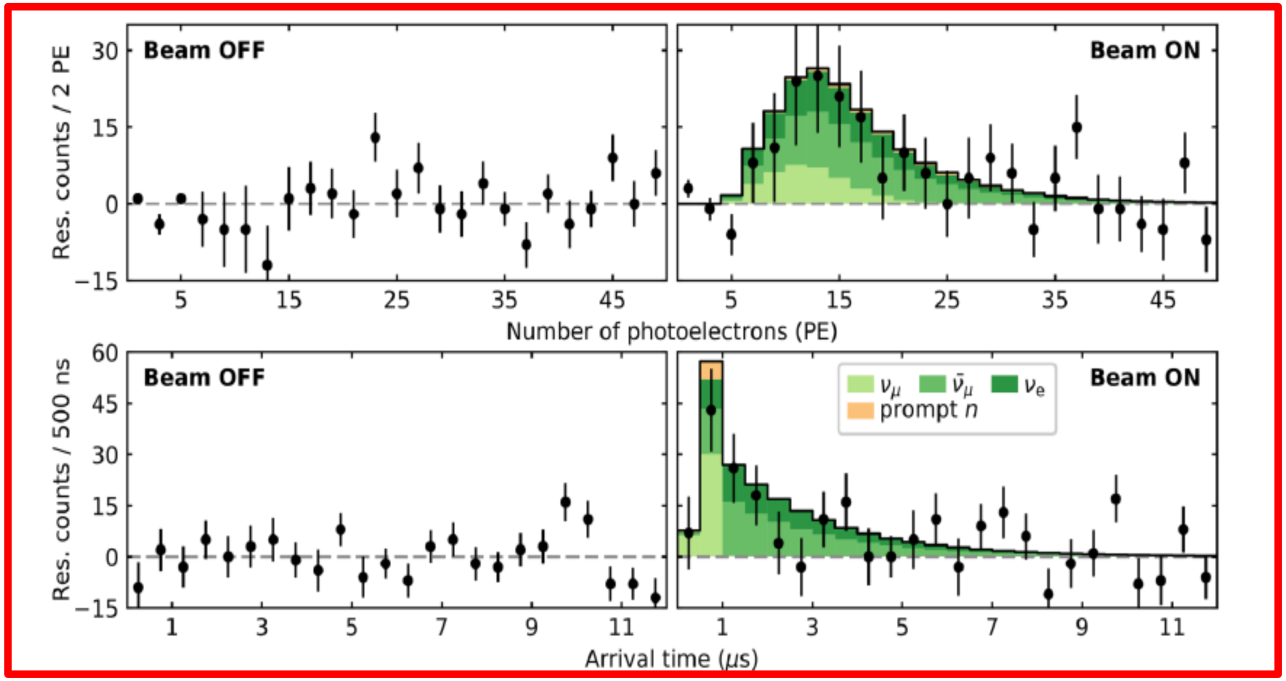
2. University of Tennessee and ITEP/MEPhI, Moscow.

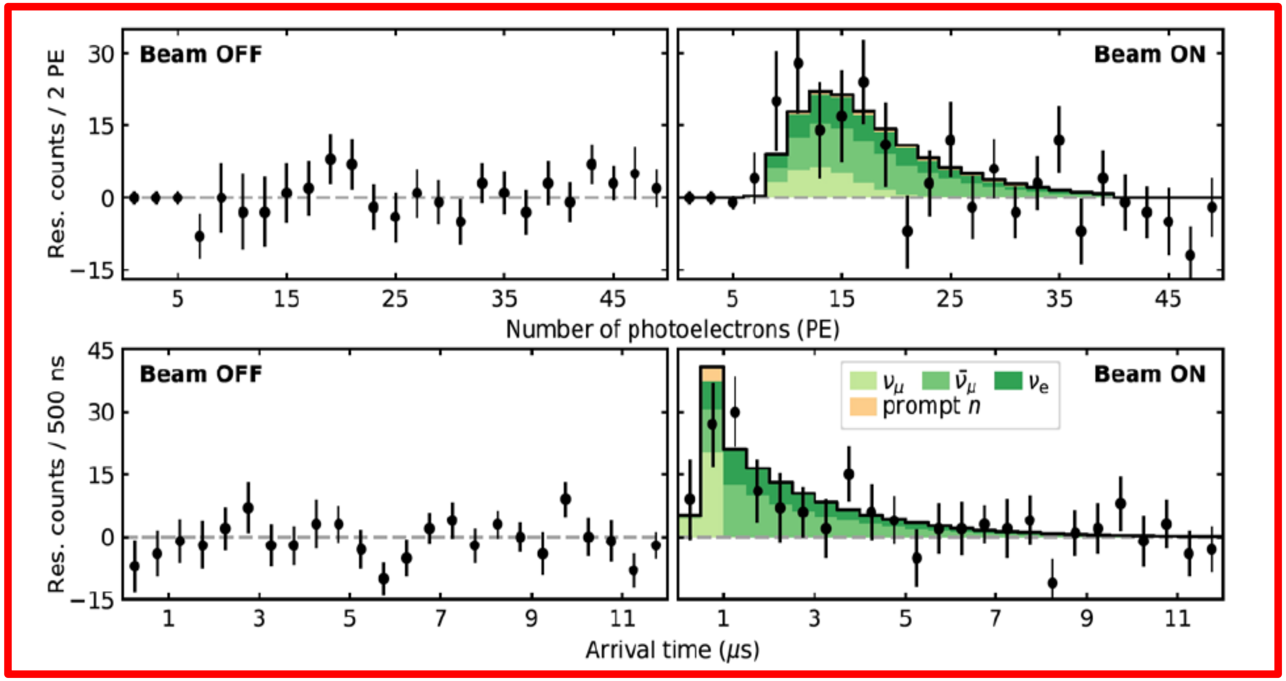
Results obtained at 6.7 sigma C.L. for nuclear recoil from ~6 keV to 45 keV.

However, with reactor neutrino, maximum nuclear recoil is <2 keV.

Neutrinos detected are >10 MeV.

Still far to go ….

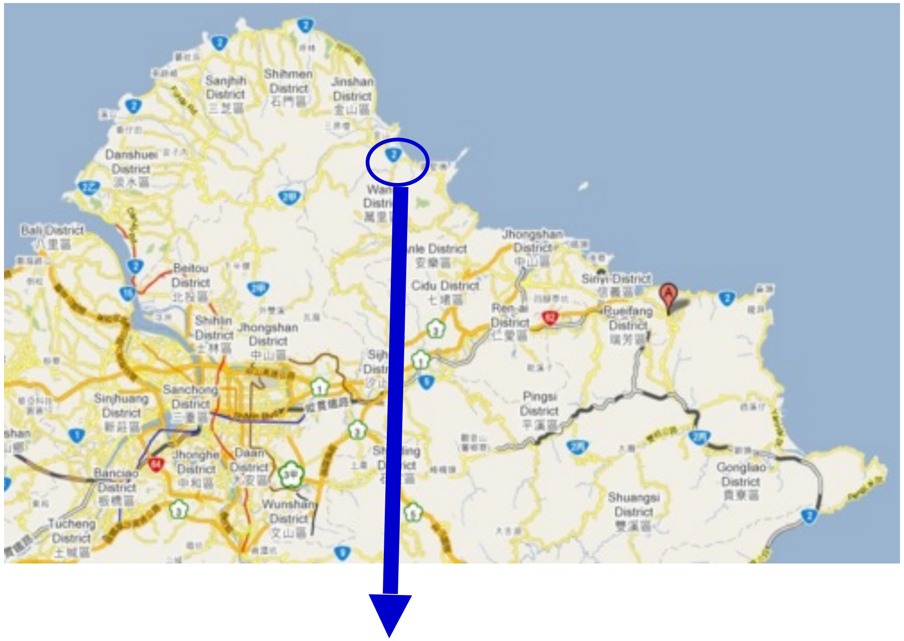




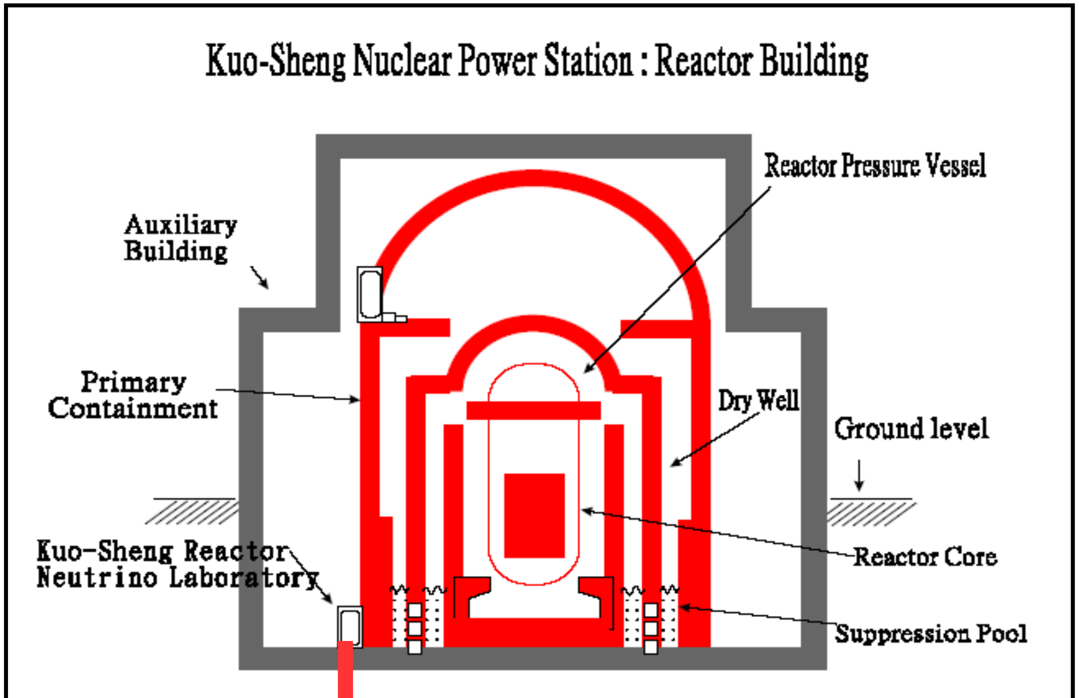
D. Akimov et al., Science 10.1126/science.aao0990 (2017)

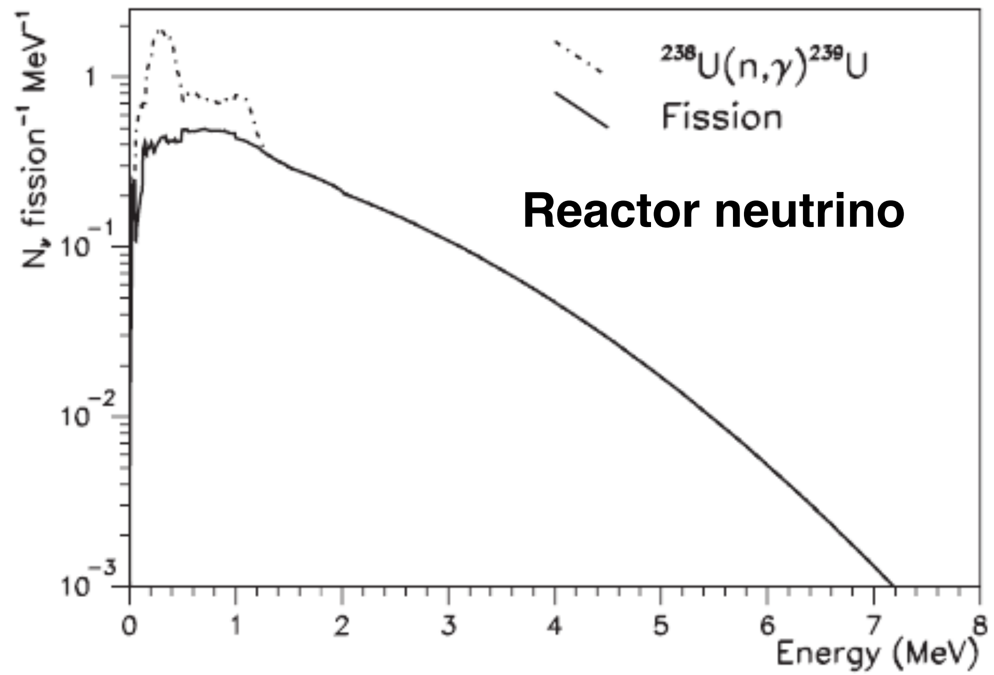
TEXONO Collaboration

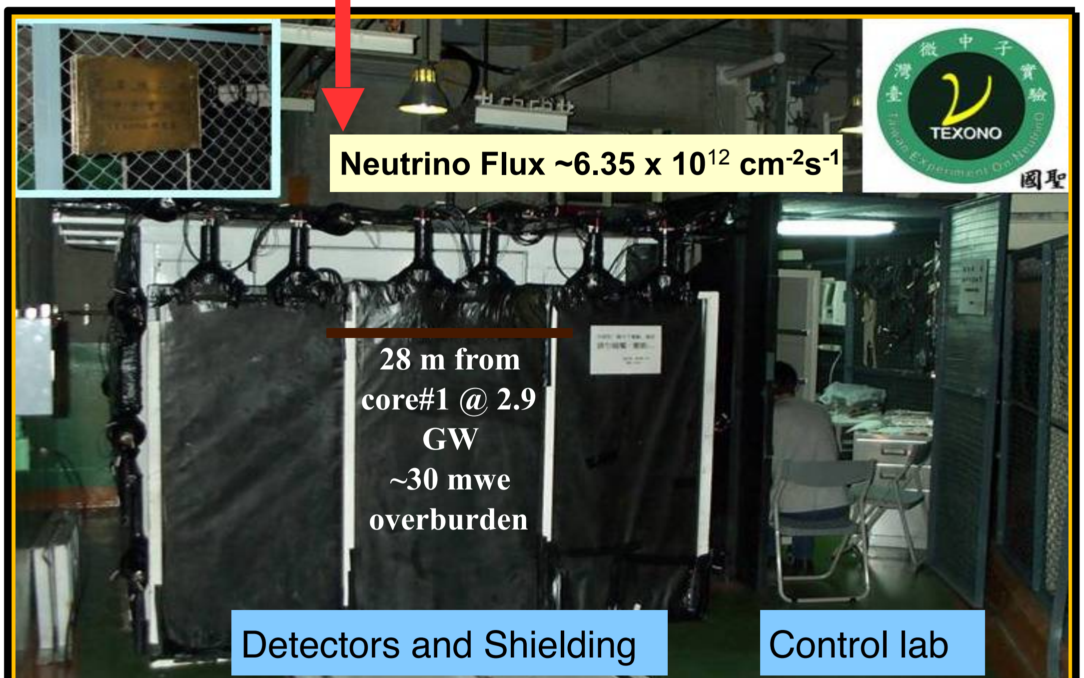
- **TEXONO (Taiwan EXperiment On NeutrinO)** Experiment is located at Kuo-Sheng Nuclear Power Plant -II on northern shore of Taiwan.
- **<u>Theme:</u>** Low Energy Neutrino Physics and Dark Matter Searches.
- Collaboration with Turkey, China and India.
- The reactor power of 2.9 GW gives 6.35×10^{12} cm^{-2} s^{-1} electron anti-neutrinos at a distance of 28 m.
- Collaboration with CDEX Underground Dark-Matter Experinemt, China.

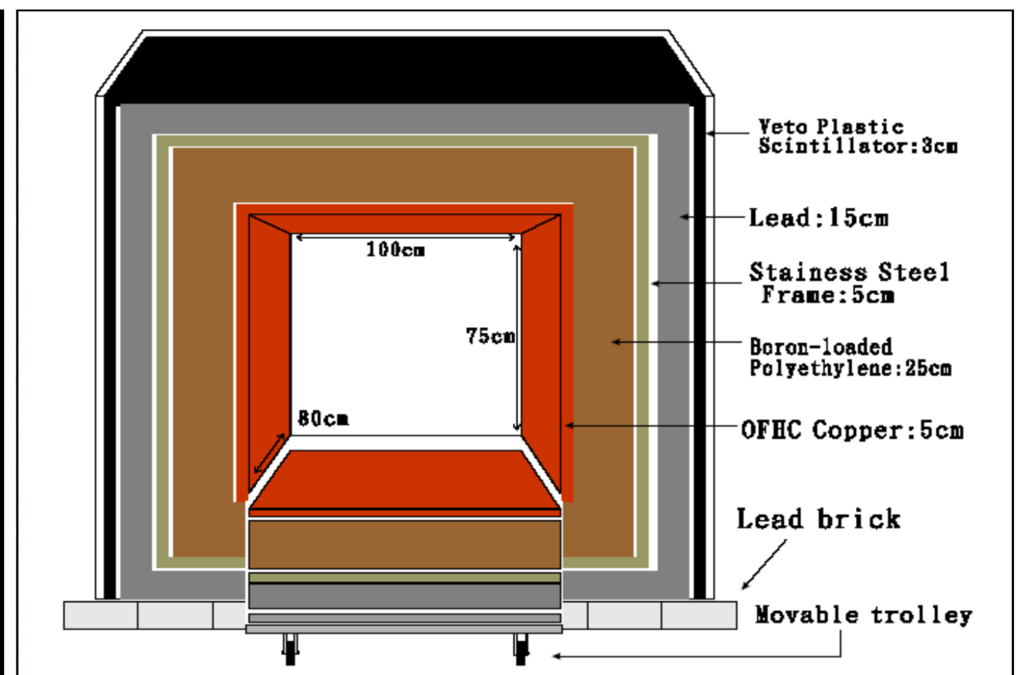


Kuo-Sheng Reactor Laboratory (KSNL)



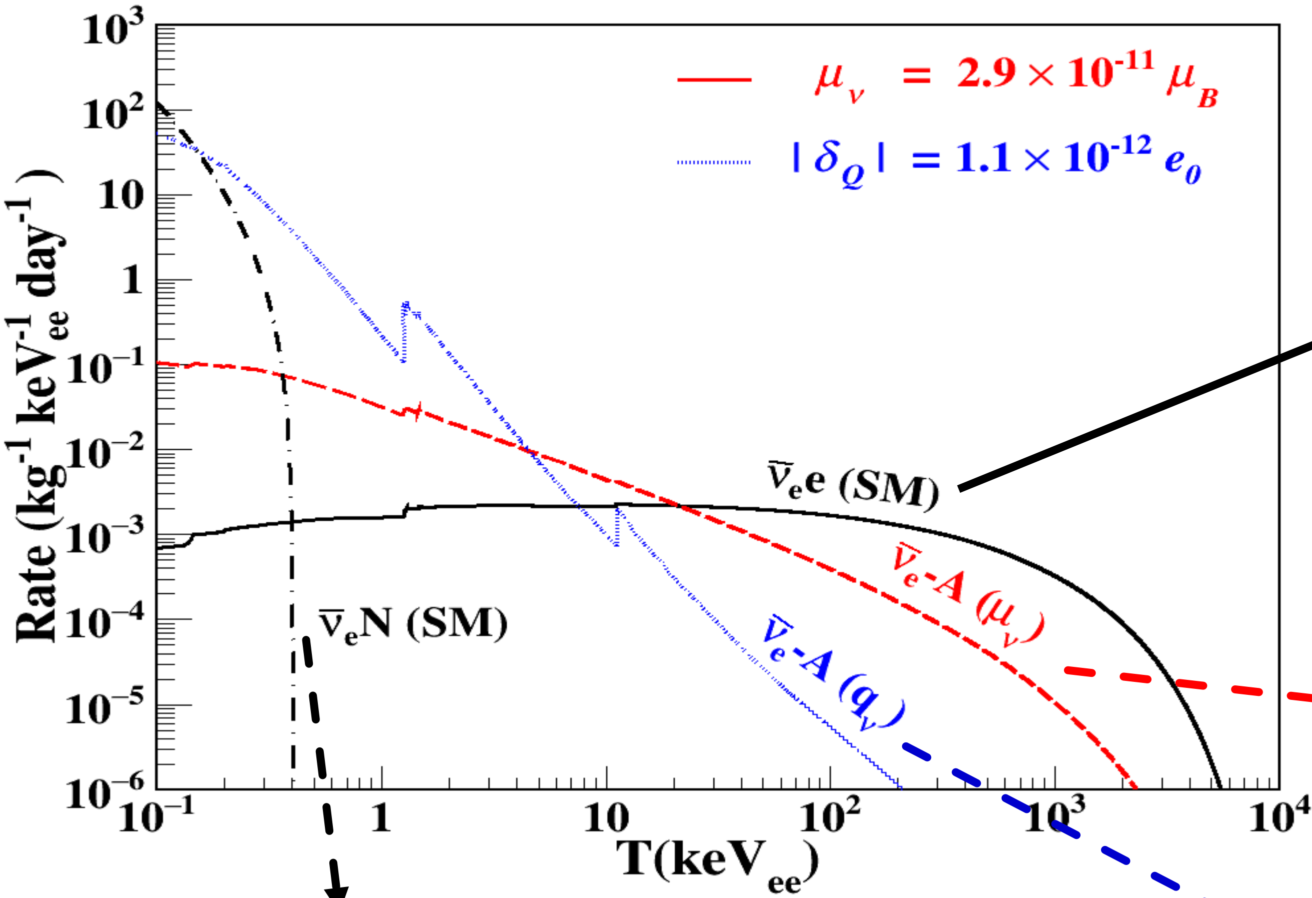






Neutrino Studies at KSNL

Quality ← **Detector Requirements** → **Mass**



ν-e Scattering SM *[PRD10] & NSI/BSM [PRD10,PRD12,PRD15,PRD17]*

➡ 200 kg CsI(Tl)

Magnetic Moment *[PRL03,PRD05,PRD07]*

➡ 1 kg HPGe

Neutrino Milli-charge*[PRD14]*

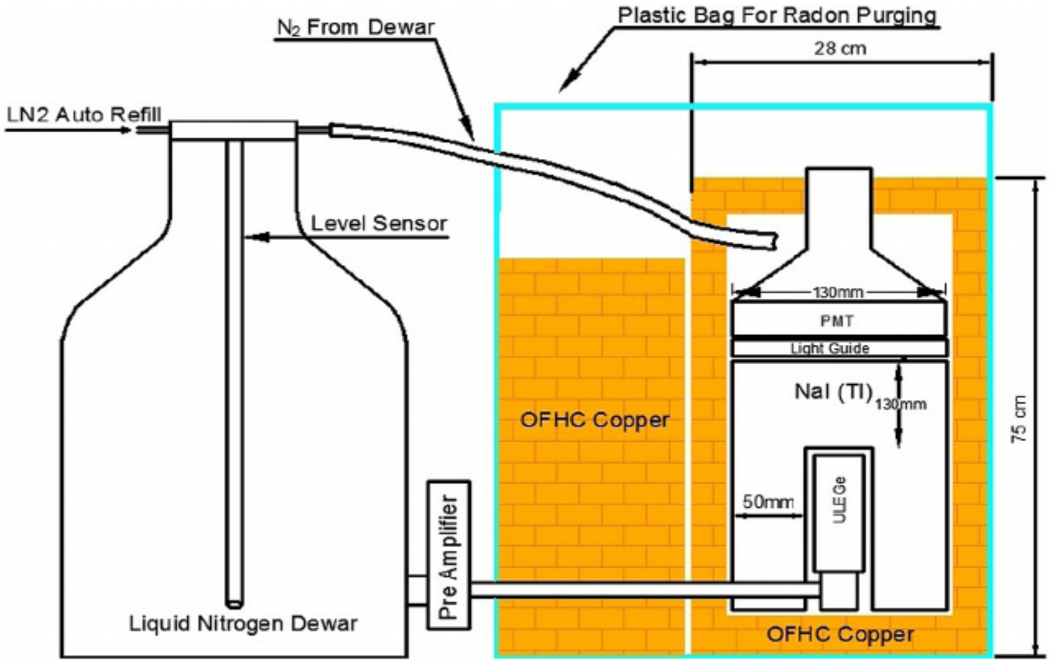
➡ sub-keV O(kg) ULEGe/PCGe

ν-N Coherent Scattering*[Current Theme; PRD16]*

➡ sub-keV O(kg) ULEGe/PCGe

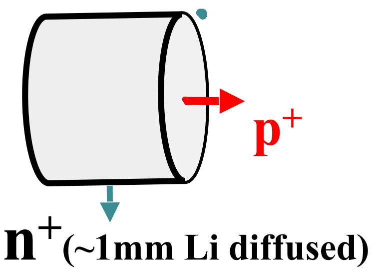
- Dark Matter Searches @ KSNL*[PRD09,PRL13,AP14]*
- CDEX Program @ CJPL*[PRD13,PRD14,PRD16,PRD17]*
- Theory Program

Pulsar FWHM and Threshold



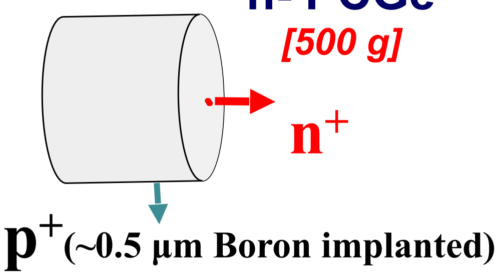
p- PCGe

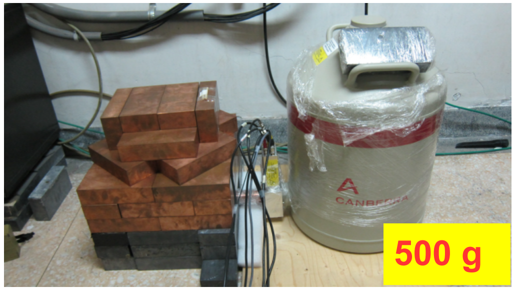
[500g – 1.5 kg]



n- PCGe

[500 g]



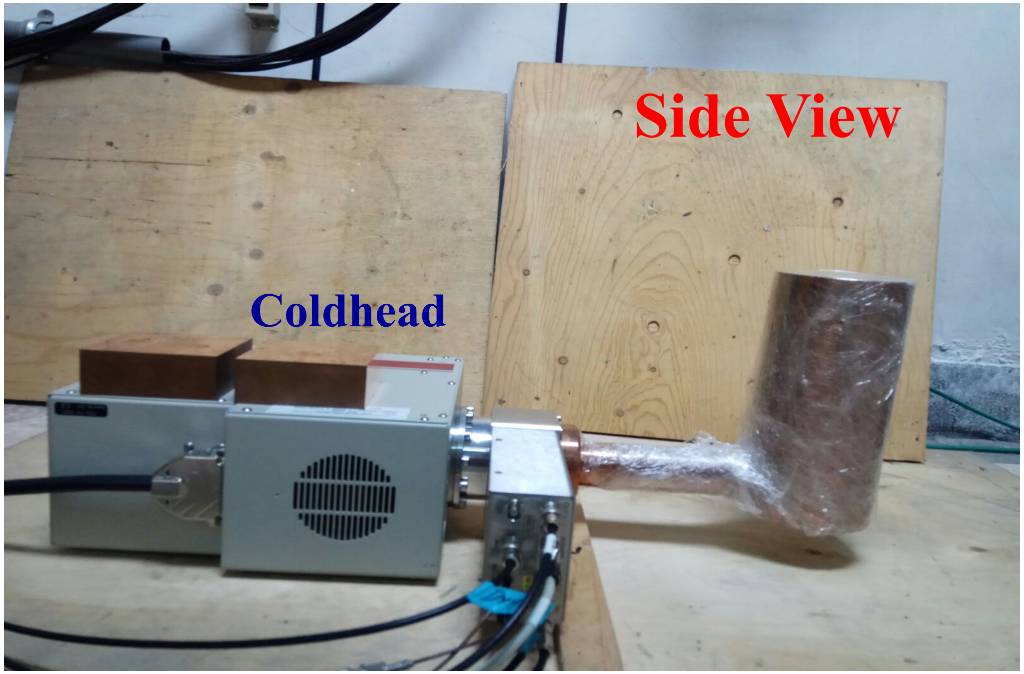


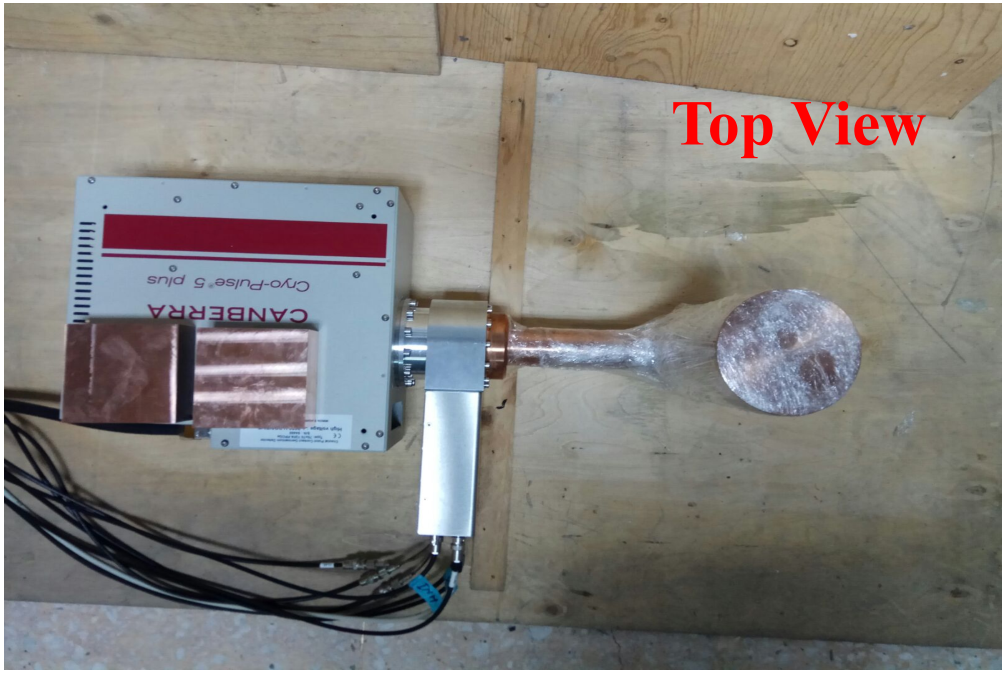
	Generation	Mass (g)	Pulsar FWHM (eV_{ee})	Threshold (eV_{ee})
Liquid Nitrogen	G1	500	130	500
	G2	900	100	300
Electro-cool	G3	900	70	200
	G3+	1430	~60	~160

G3 Detector

Advantages of G-3 Electro-cooled HPGe Detectors:

- ➢ No liquid Nitrogen required.
- ➢ Custom Cold-tip Temperature.
- ➢ Controlled microphonic noise.
- ➢ Synchronized negative feedback pumping.

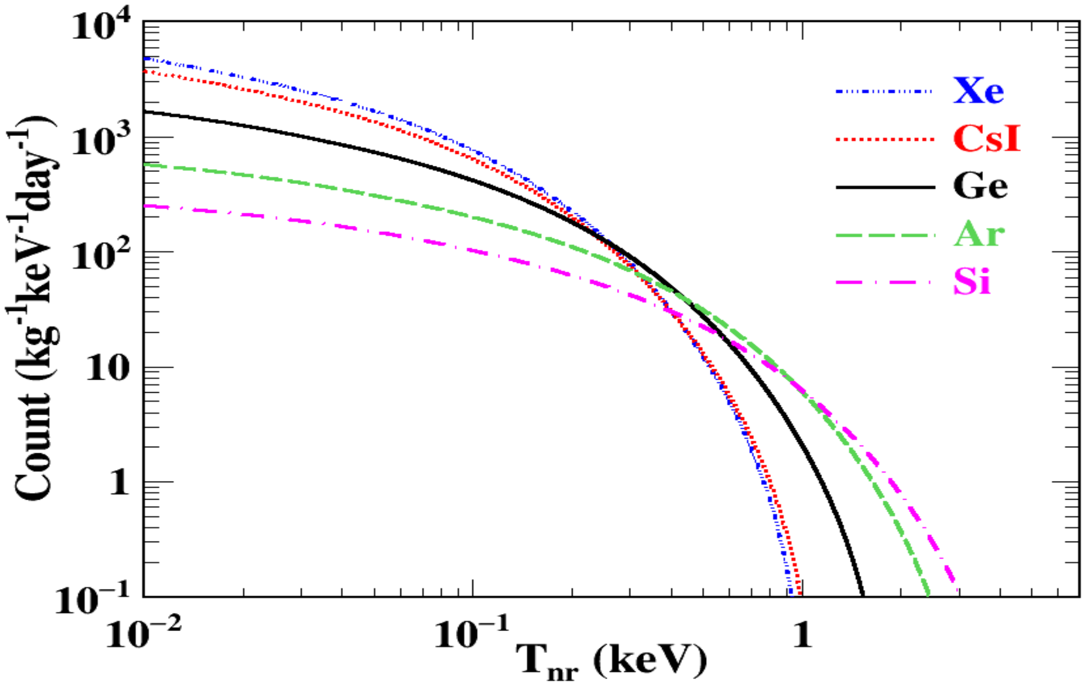


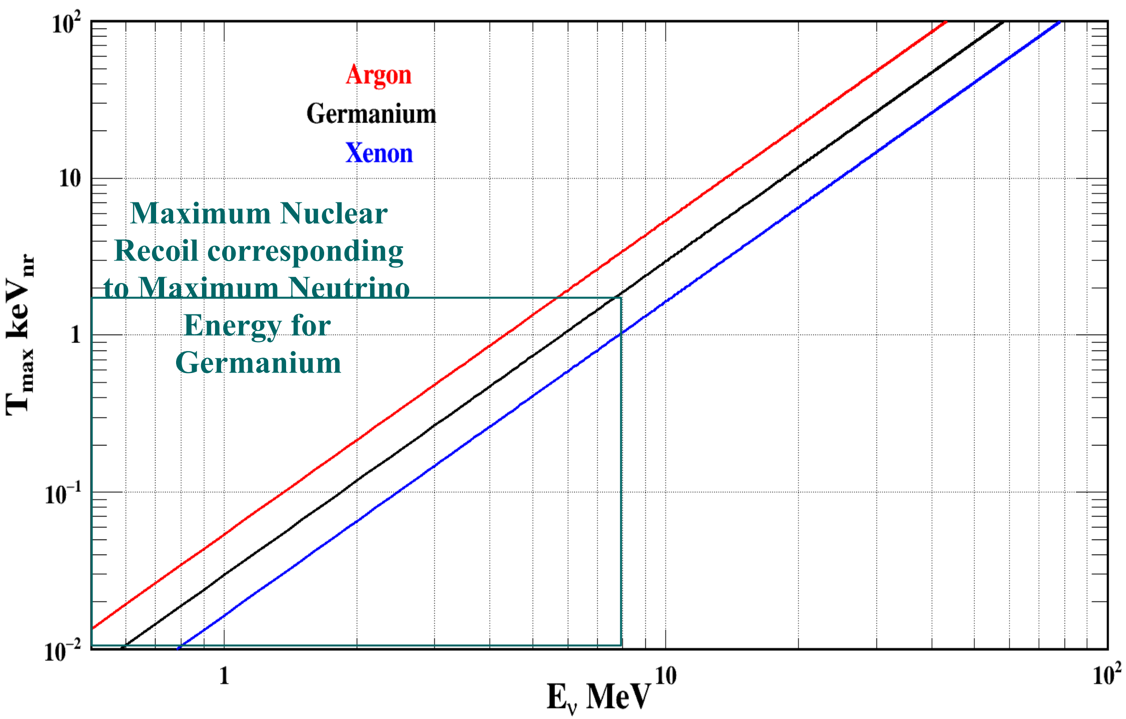


Electrically Refrigerated HPGe Detector

νA_{el} Scattering Rate at KSNL

Expected νA_{el} differential rate in various detectors at Kuo-Sheng Neutrino Laboratory

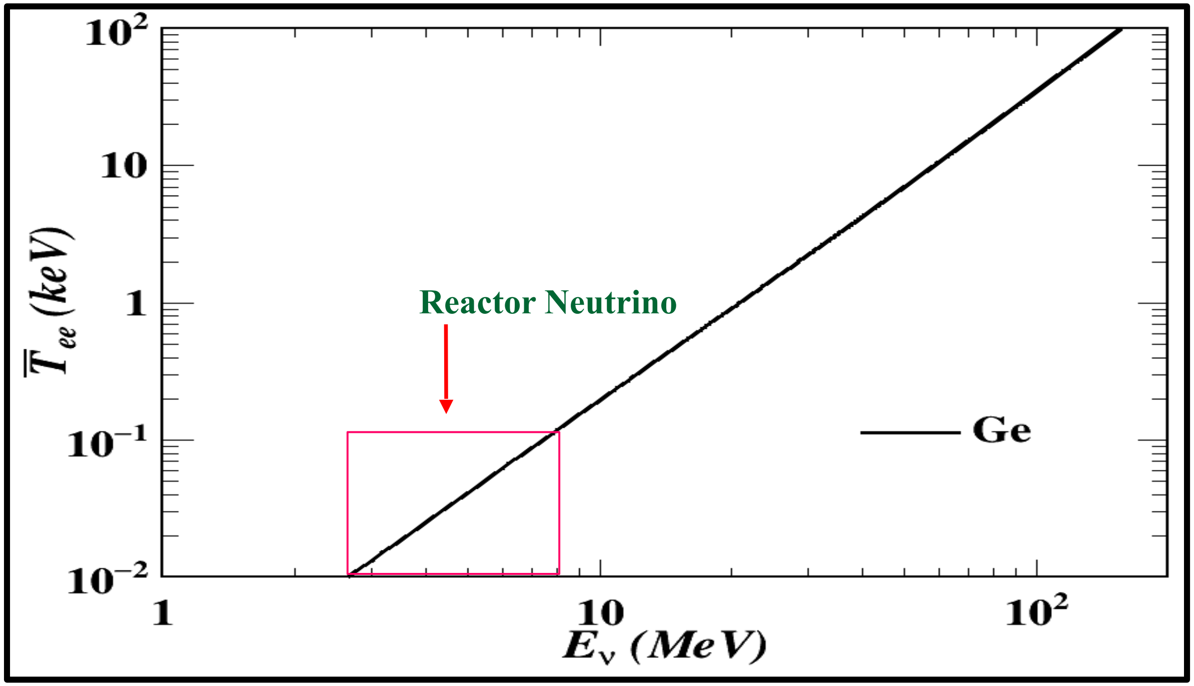




Maximum nuclear recoil depends on mass of target nuclei and incident neutrino energy

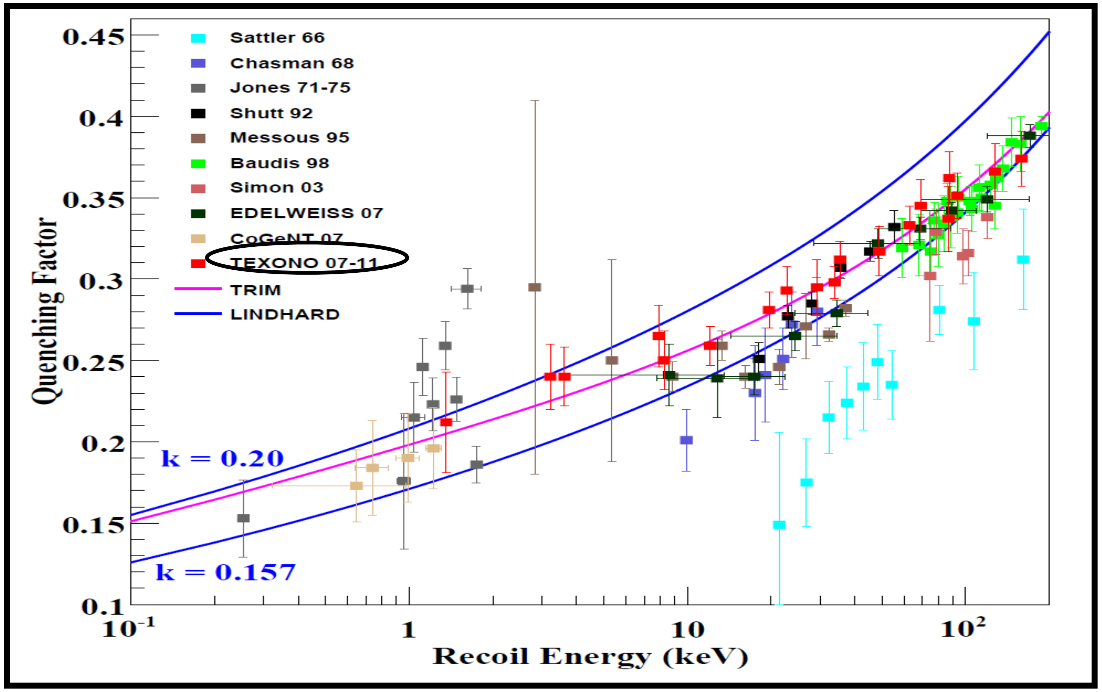
$$T_{max} = \frac{2E_\nu^2}{2E_\nu + M_N}$$

Quenching Factor and Recoil Energy



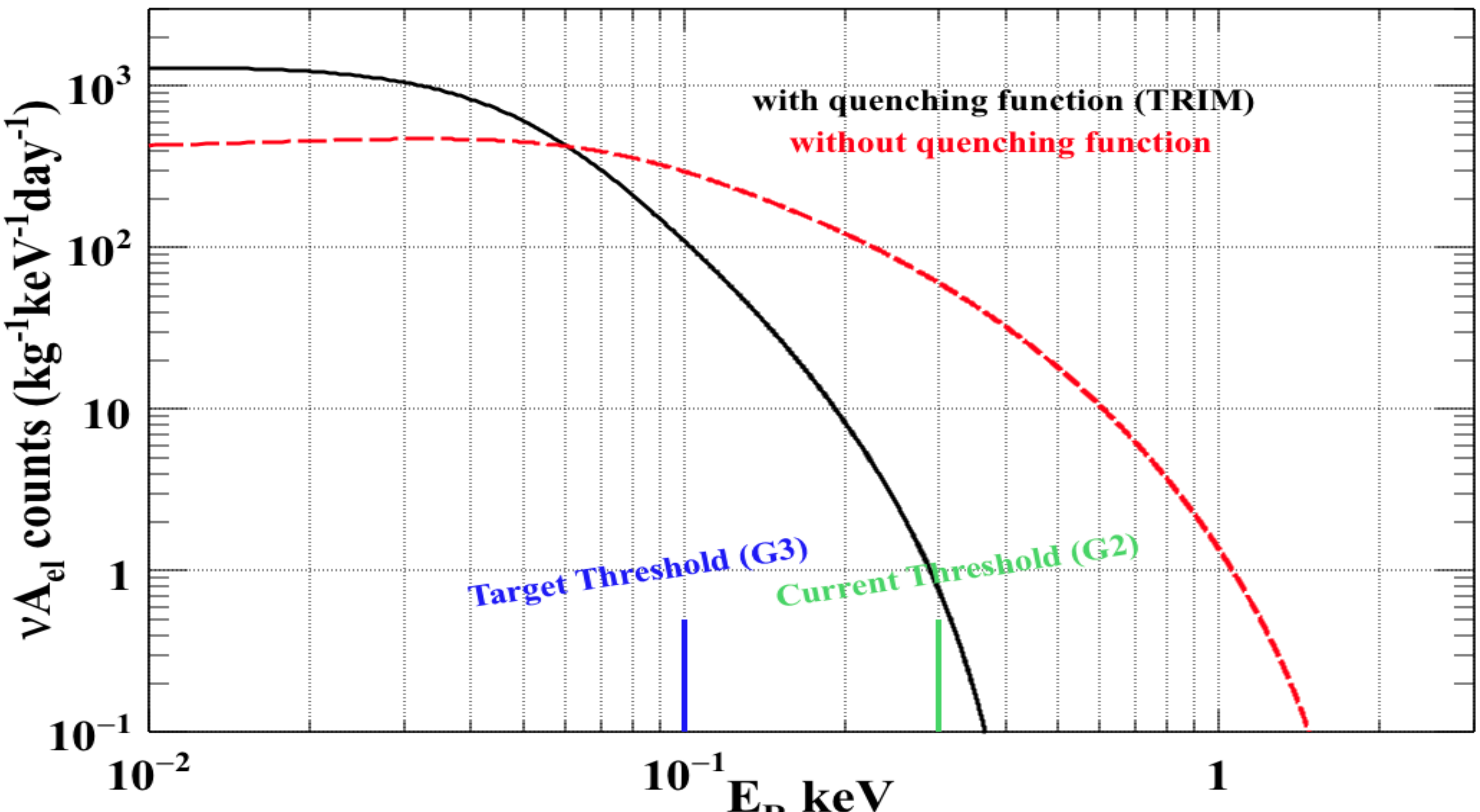
Averaged recoil energy for Germanium target in keV(electron equivalent)

TRIM is used for Quenching factor, obtained from fitting on various experimental data ...



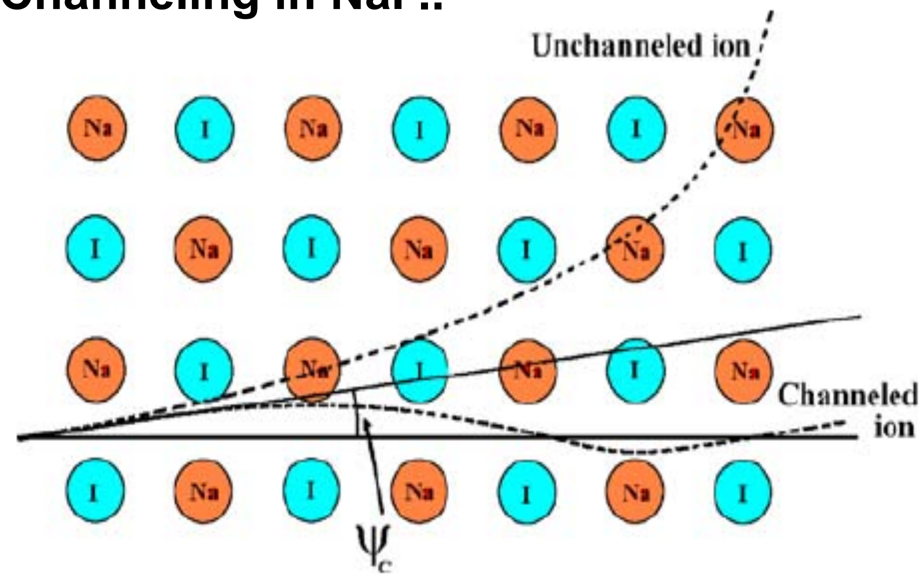
νA_{el} at KSNL with Reactor neutrino..

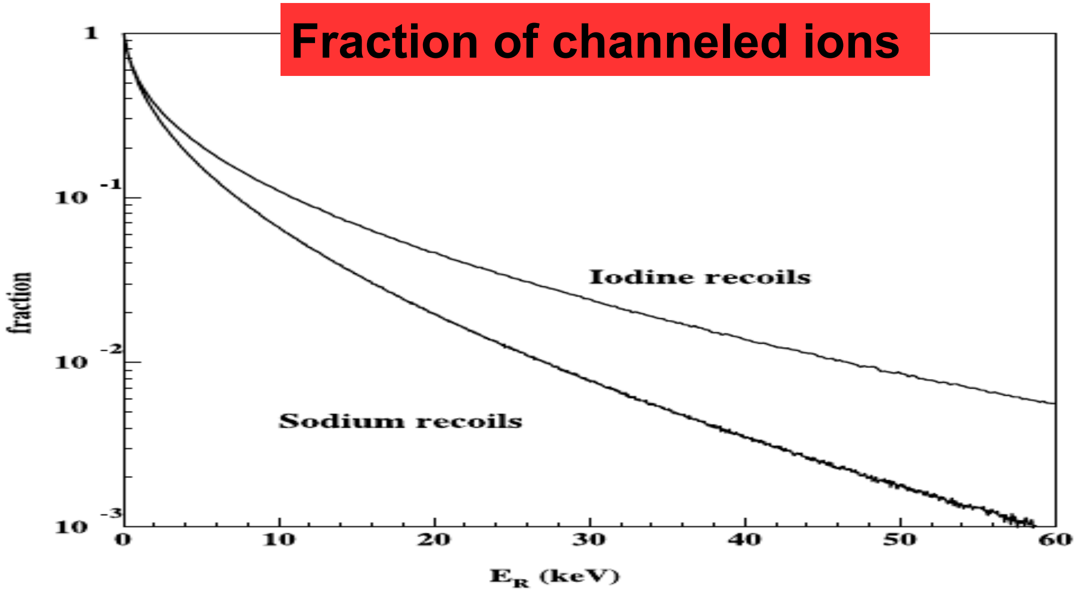
Threshold	300 eV	200 eV	150 eV	100 eV
Differential	0.8 cpkkd	8.3 cpkkd	27.3 cpkkd	109.5 cpkkd
Integral	0.04 cpkd	0.47 cpkd	1.6 cpkd	6.4 cpkd



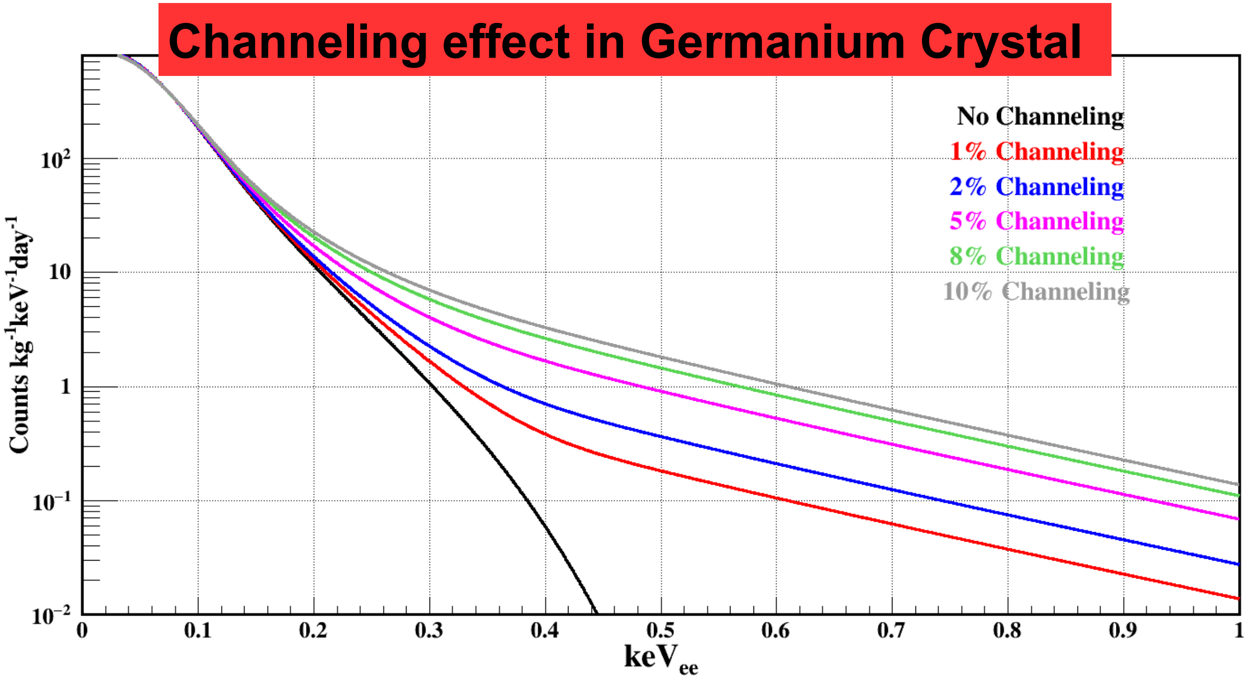
Channeling Fraction

Channeling in NaI ..





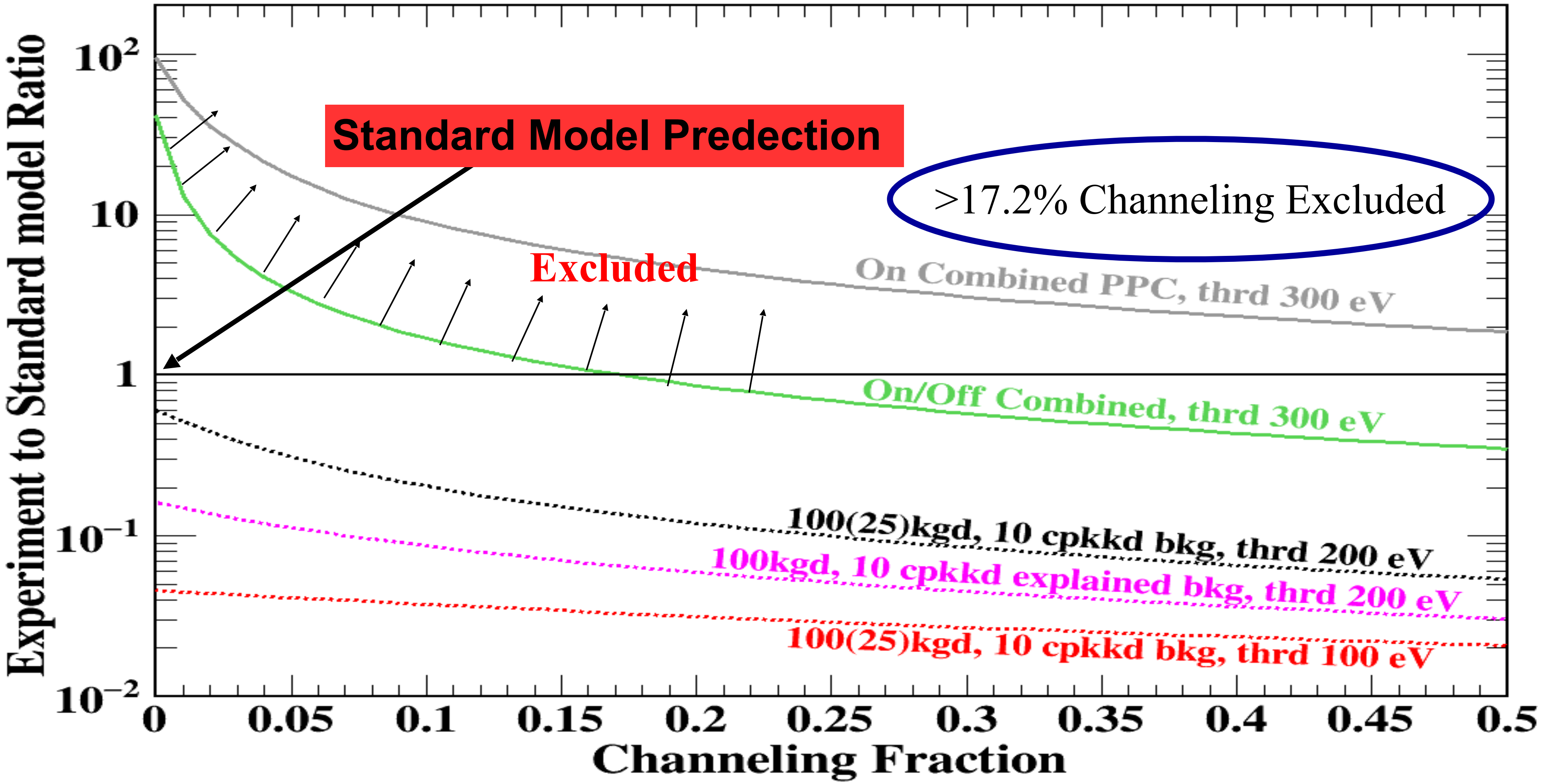
Bernabei et al. 2008, Eur. Phys. J. C53, 205



- Channeling increase counts at higher energy.
- Quenching factor is assumed to be ~1
- Estimated Channeling in NaI is ~3 %

Sensitivity Towards νA_{el} Scattering

- Better to have High On/Off Statistics
- Threshold required below ~200 eV

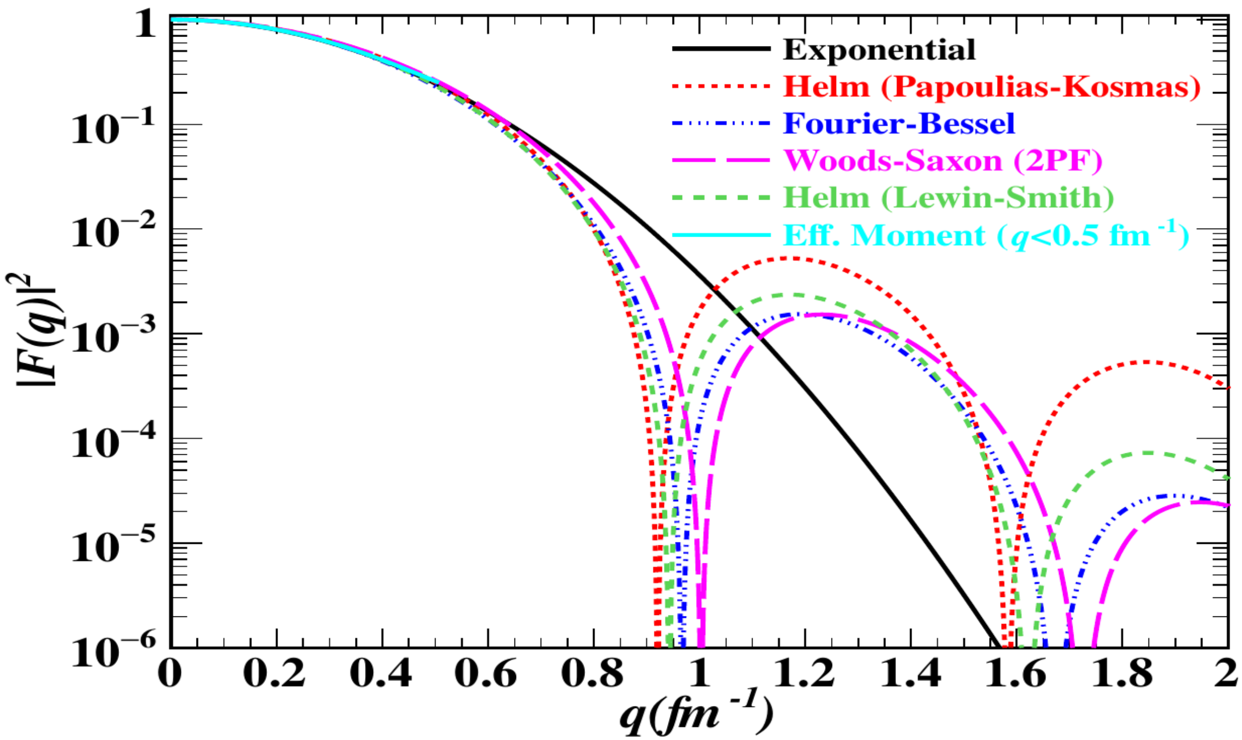


V. Sharma et al. I.J.P. (2018) 92: 1145. https://doi.org/10.1007/s12648-018-1202-8

Coherency in νA_{el} Scattering

Form-Factor:

- Gives an idea about coherency within the nucleons.
- Used for study of Nuclear Structure.
- Complete Coherence at low Energy.
- νA_{el} measures the neutron distribution



Form-Factor is fourier transformation of Charge distribution in the nucleus:

$$F(q) = \frac{1}{A}\int \rho(r) e^{-i\mathbf{q}.\mathbf{r}} d^3 r$$

Helm Model Form-Factor:

$$F(q) = \frac{3j_1(qR)}{qR} e^{-(qs)^2/2} = 3\frac{\sin(qR) - qR\cos(qR)}{(qR)^3} e^{-(qs)^2/2}$$

G.Duda et.al, JCAP04(2007)012

Coherency in νA_{el} Scattering

- The finite phase of net combined amplitude vector can define degree of coherency.
- Combined amplitude can be defined as:

$$\mathcal{A} = \sum_{j=1}^{Z} e^{i\theta_j} \mathcal{X}_j + \sum_{k=1}^{N} e^{i\theta_k} \mathcal{Y}_k \qquad \text{where} \quad (\mathcal{Y}_n, \mathcal{X}_m) = (1,\text{-}\varepsilon)$$

- The cross-section comprise $(N + Z)^2$ terms.
- In total cross-section $\sigma_{\nu A_{el}}(Z, N) \propto \mathcal{A}\mathcal{A}^\dagger$, average phase mis-alignment angle follows:

$$e^{i(\theta_j - \theta_k)} - e^{-i(\theta_j - \theta_k)} = 2cos(\theta_j - \theta_k) = 2cos\langle\phi\rangle$$

- Degree of coherency described as:

$$\alpha \equiv cos\langle\phi\rangle \in [0, 1]$$

$$\frac{\sigma_{\nu A_{el}}(Z, N)}{\sigma_{\nu A_{el}}(0, N)} = Z\varepsilon^2[1 + \alpha(Z - 1)] + N[1 + \alpha(N - 1)] - 2\alpha\varepsilon Z N$$

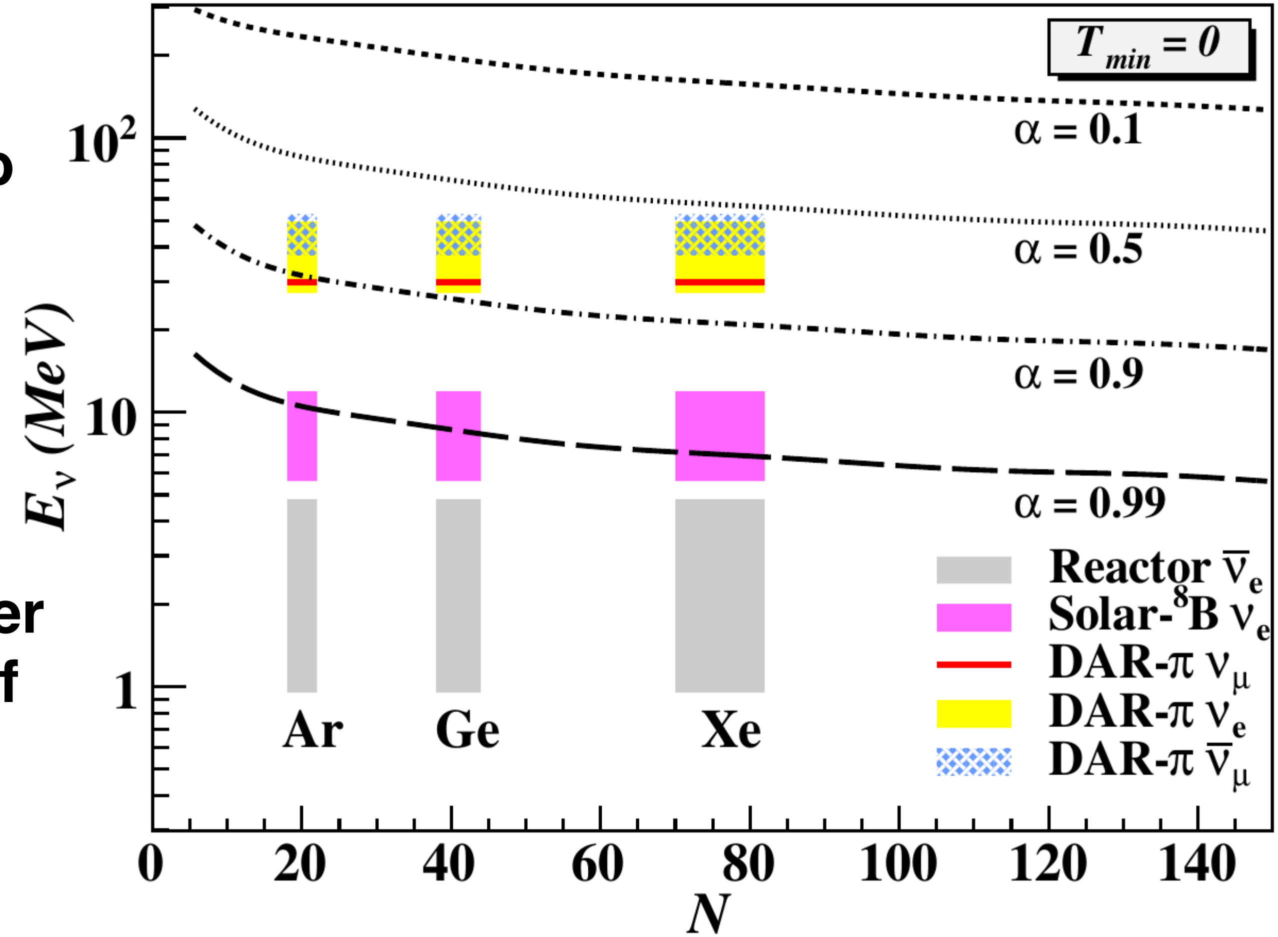
$$\sigma_{\nu A_{el}}(\alpha) = \frac{\sigma_{\nu \mathrm{A}_{el}}(Z, N)}{\sigma_{\nu \mathrm{A}_{el}}(0, 1)} \propto \begin{cases} [\varepsilon^2 Z + N], & \alpha = 0 \ (\text{incoherent}) \\ [\varepsilon Z - N]^2, & \alpha = 1 \ (\text{coherent}) \end{cases}$$

Phys. Rev. D 93, 113006 (2016)

Contour for Degree of coherency

Reactor and solar neutrino seems to probe νA_{el} in region with higher degree of coherency

Lower mass nuclei are better choice for higher degree of coherency



ν Source	Half-Maxima of $\sigma_{\nu A_{el}}\Phi_\nu$ in E_ν(MeV)	$\langle\alpha\rangle$ with Ar	Ge	Xe
Reactor $\bar{\nu}_e$	0.96−4.82	1.00	1.00	1.00
Solar ^{8}B-ν_e	5.6−11.9	0.99	0.99	0.98
DAR-π ν_μ	29.8	0.91	0.86	0.80
DAR-π ν_e	27.3−49.8	0.89	0.83	0.76
DAR-π $\bar{\nu}_\mu$	37.5−52.6	0.85	0.79	0.71

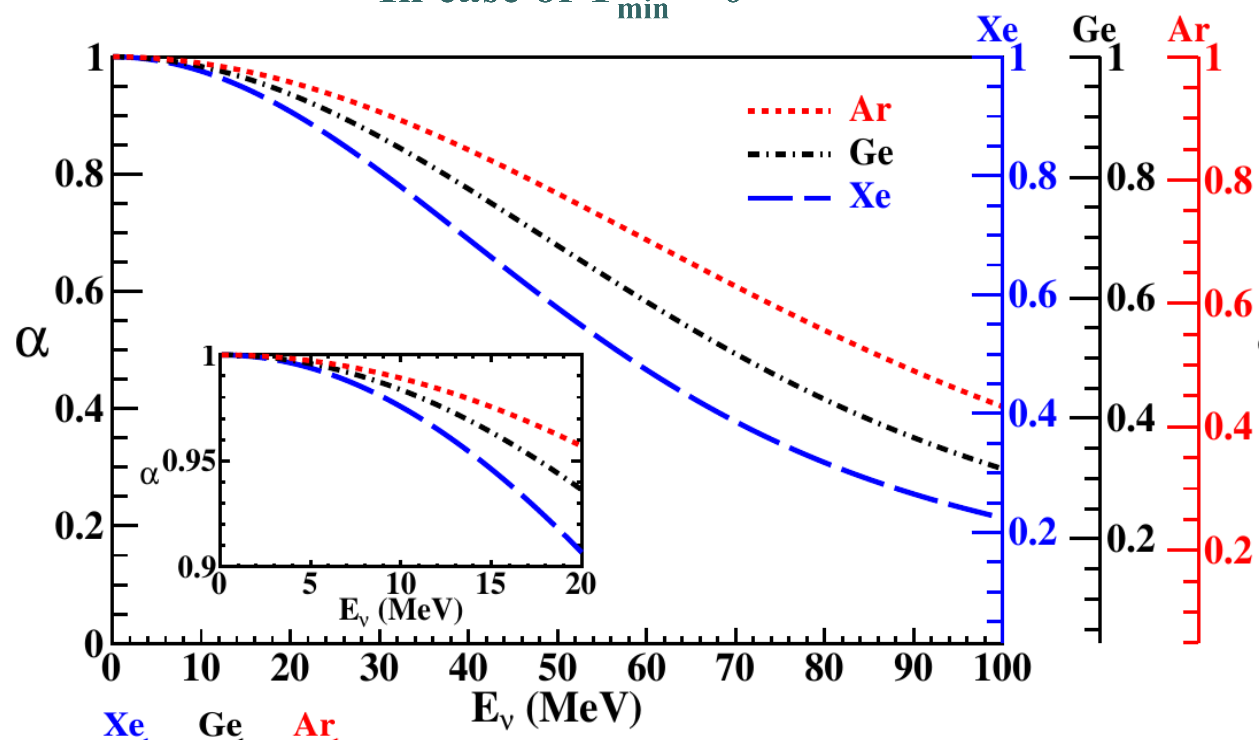
Provides minimal uncertainty region @T_{min} = 0

Coherency and Relative cross-section..

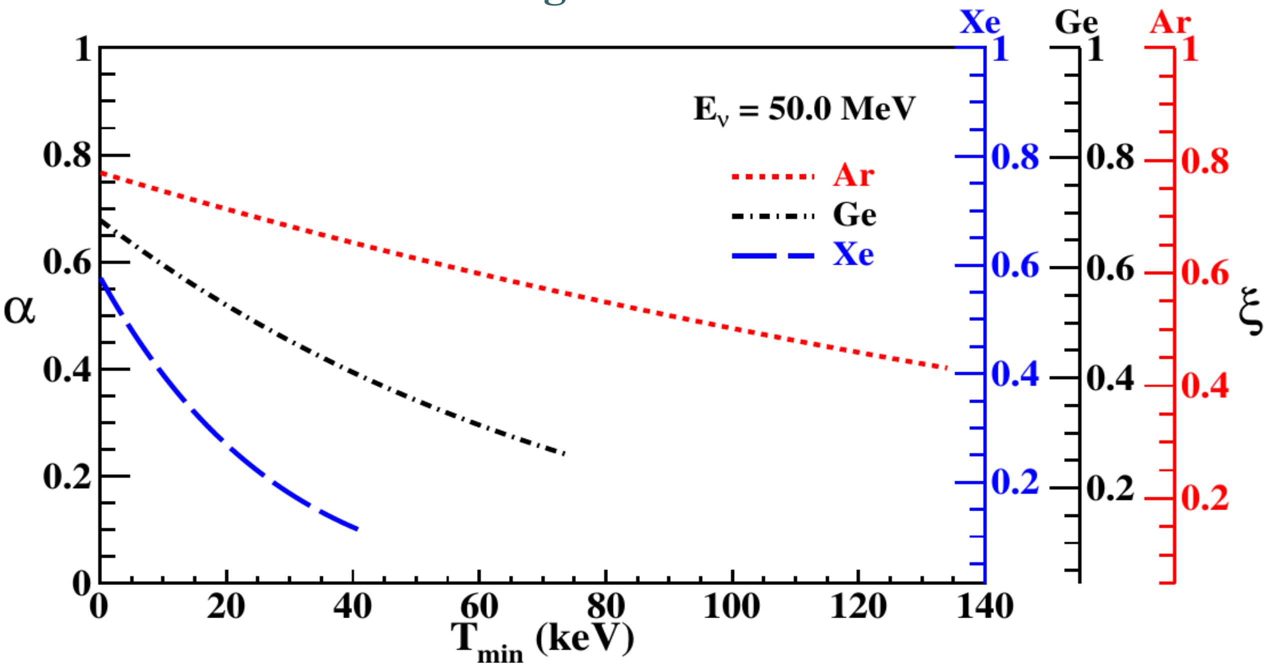
The relative change in cross-section can be given as:

$$\xi = \frac{\sigma_{\nu A_{el}}(\alpha)}{\sigma_{\nu A_{el}}(\alpha = 1)}$$

In case of $T_{min} = 0$



In case of Mono-energetic Source:



Lower Detector threshold

↓

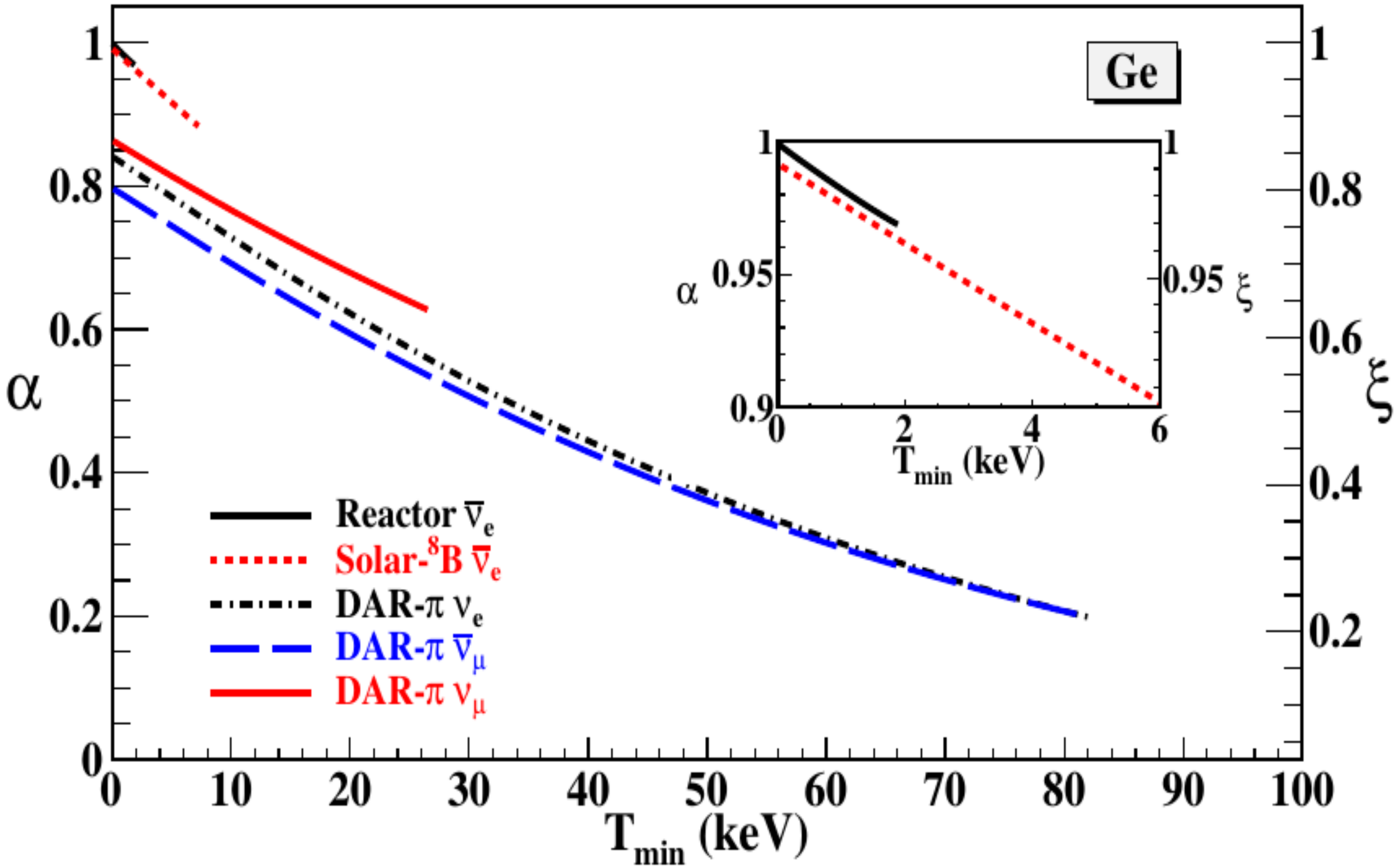
Higher Degree of coherency

Continued..

Expected averaged degree of coherency and relative cross-section for various neutrino source with Germanium target

Different neutrino sources are important in probing different coherency regions.

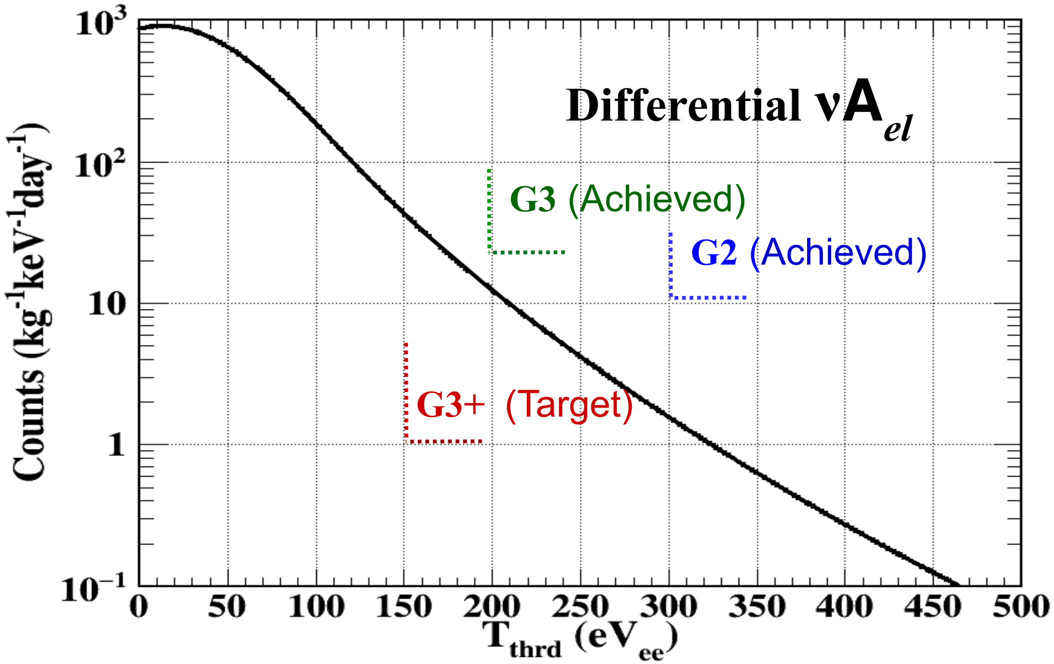
Averaged degree of coherency also depends on the detector threshold

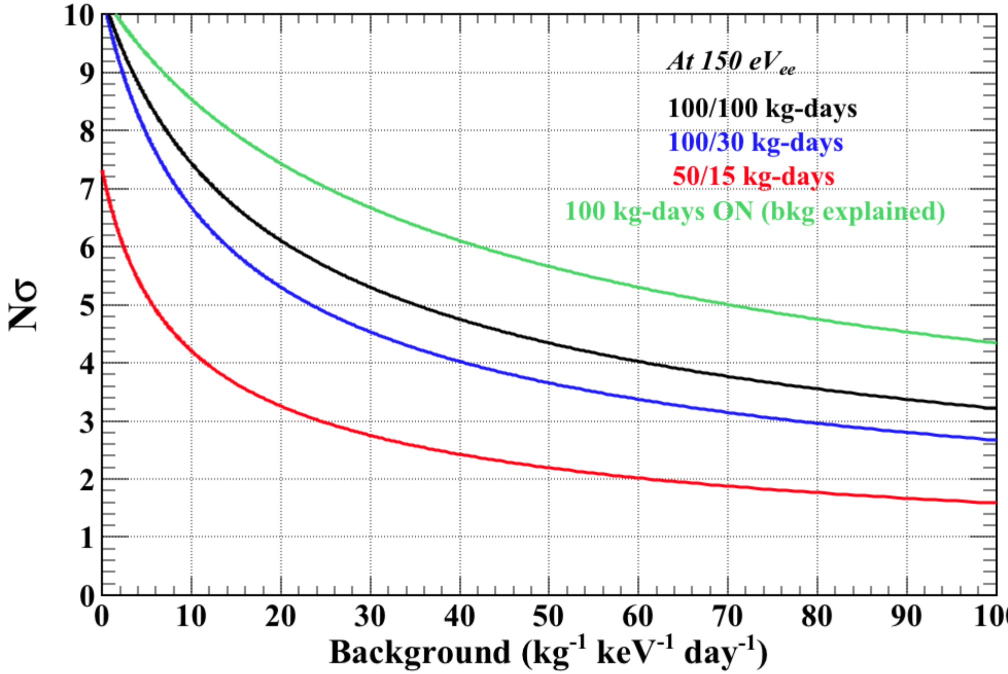


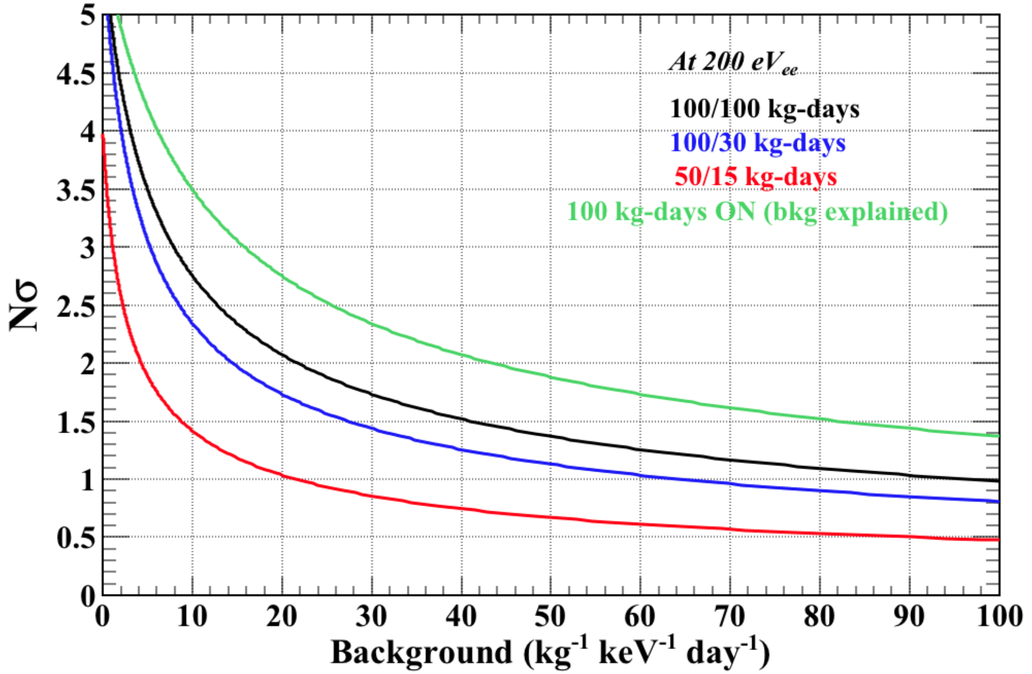
Status of νA_{el} Scattering @KSNL

$$\nu + A(Z,N) \rightarrow \nu + A(Z,N)$$

$$\frac{d\sigma_{\nu A_{el}}}{dq^2}(q^2, E_\nu) = \frac{1}{2}\left[\frac{G_F^2}{4\pi}\right]\left[1 - \frac{q^2}{4E_\nu{}^2}\right] \times [\varepsilon Z F_Z(q^2) - N F_N(q^2)]^2$$







Summary

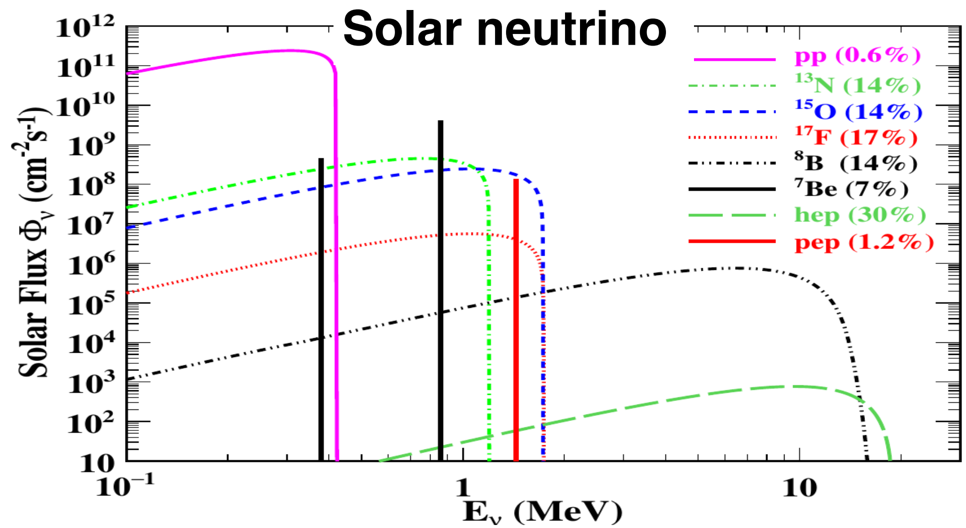
- Study of $\nu\mathbf{A}_{el}$ interaction has importance in order to study the electroweak interaction in SM, Astrophysics and Irreducible background in Dark Matter searches.
- Low energy $\nu\mathbf{A}_{el}$ can be probed by several experiments in the near future with different neutrino sources.
- Studies for $\nu\mathbf{A}_{el}$ from different neutrino sources probe transitions of QM Coherency in Electroweak process.
- Probe to BSM using $\nu\mathbf{A}_{el}$ interaction with low energy neutrinos is less vulnerable to uncertainties in coherency and Form-Factor.
- Ultra low energy threshold 200 eV is achieved and 150 eV is expected from future detector.
- Roadmap is ready to probe $\nu\mathbf{A}_{el}$ in near future.

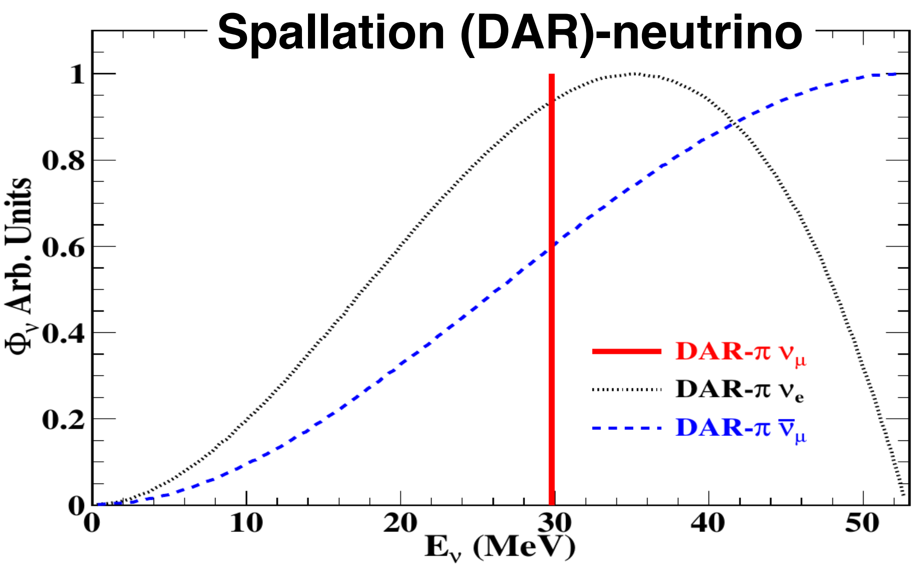
Thank You ..

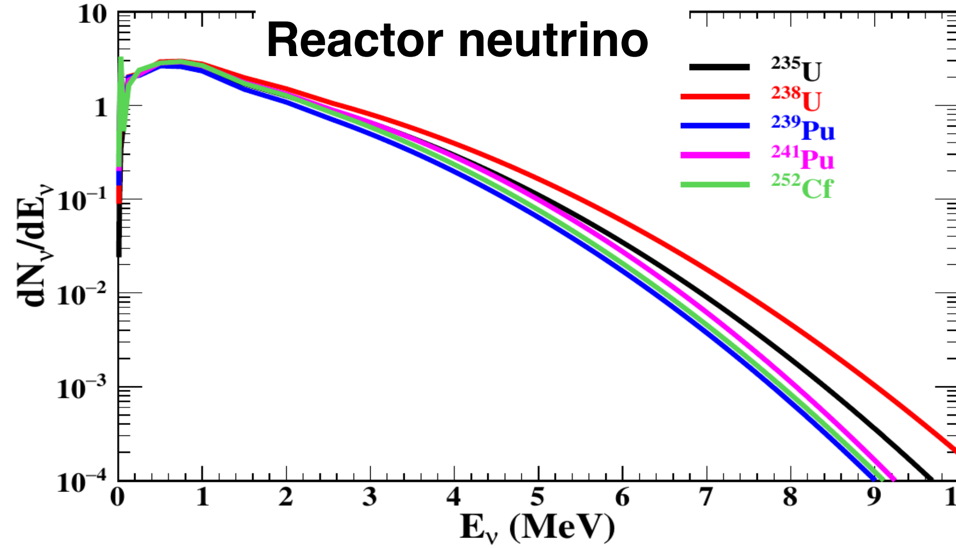
Neutrino Sources for νA_{el}

Promising Neutrino Sources:

- **Solar Neutrinos.**
- **Spallation Neutrinos.**
- **Reactor Neutrinos.**

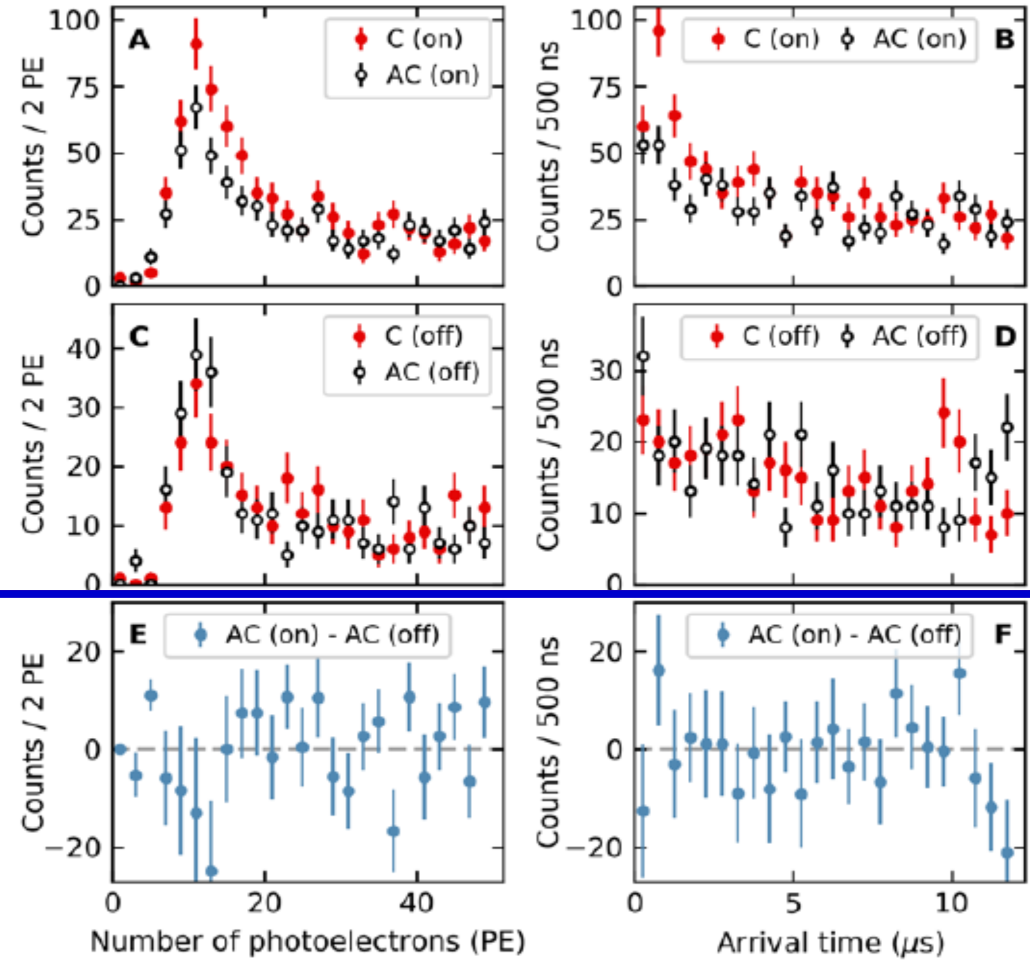






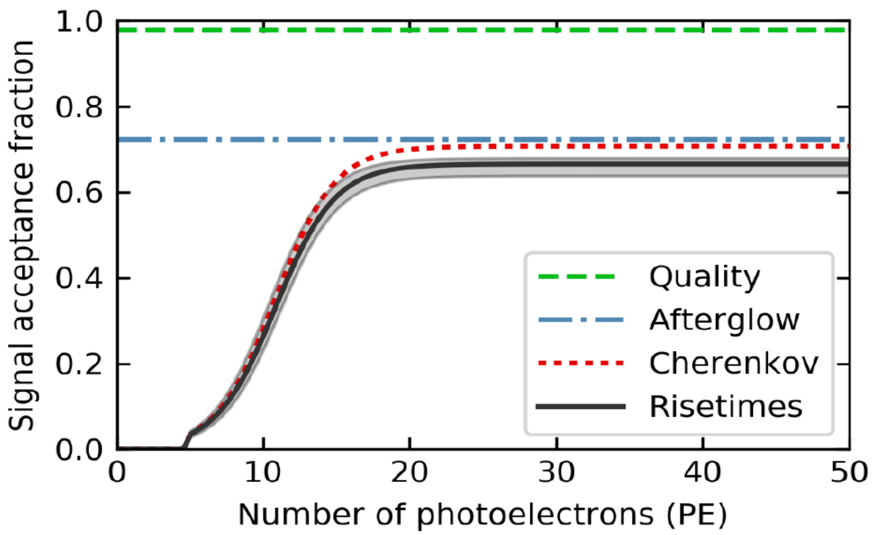
Neutrino Source	Reactor	DAR	Solar
Flux	~2×10^{17} s^{-1} per MW	~10^{15} s^{-1}	~2.7×10^{6} $cm^{-2}s^{-1}$ (^{8}B)
Pros. Cons.	Huge and Pure neutrino Flux, Few MeV	Various flavors, ν-like backgrounds	Small flux

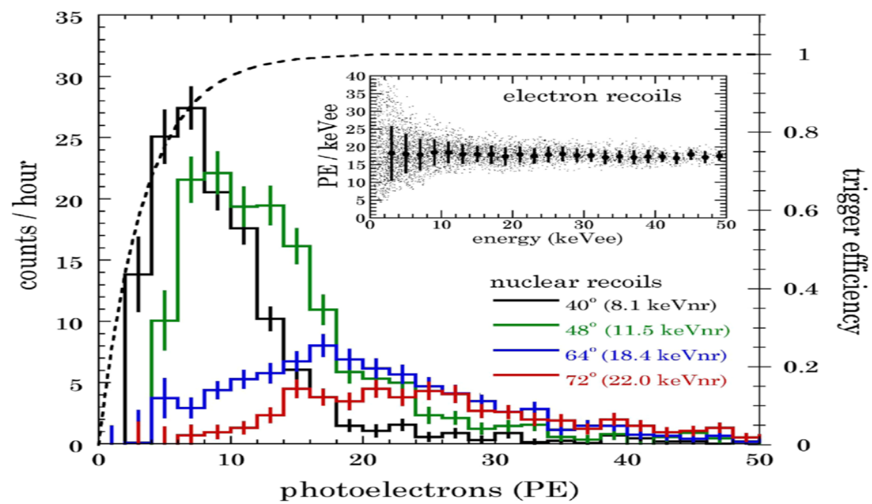
Residuals in result fig are generated from the C-AC differences in the corresponding panels in this figure

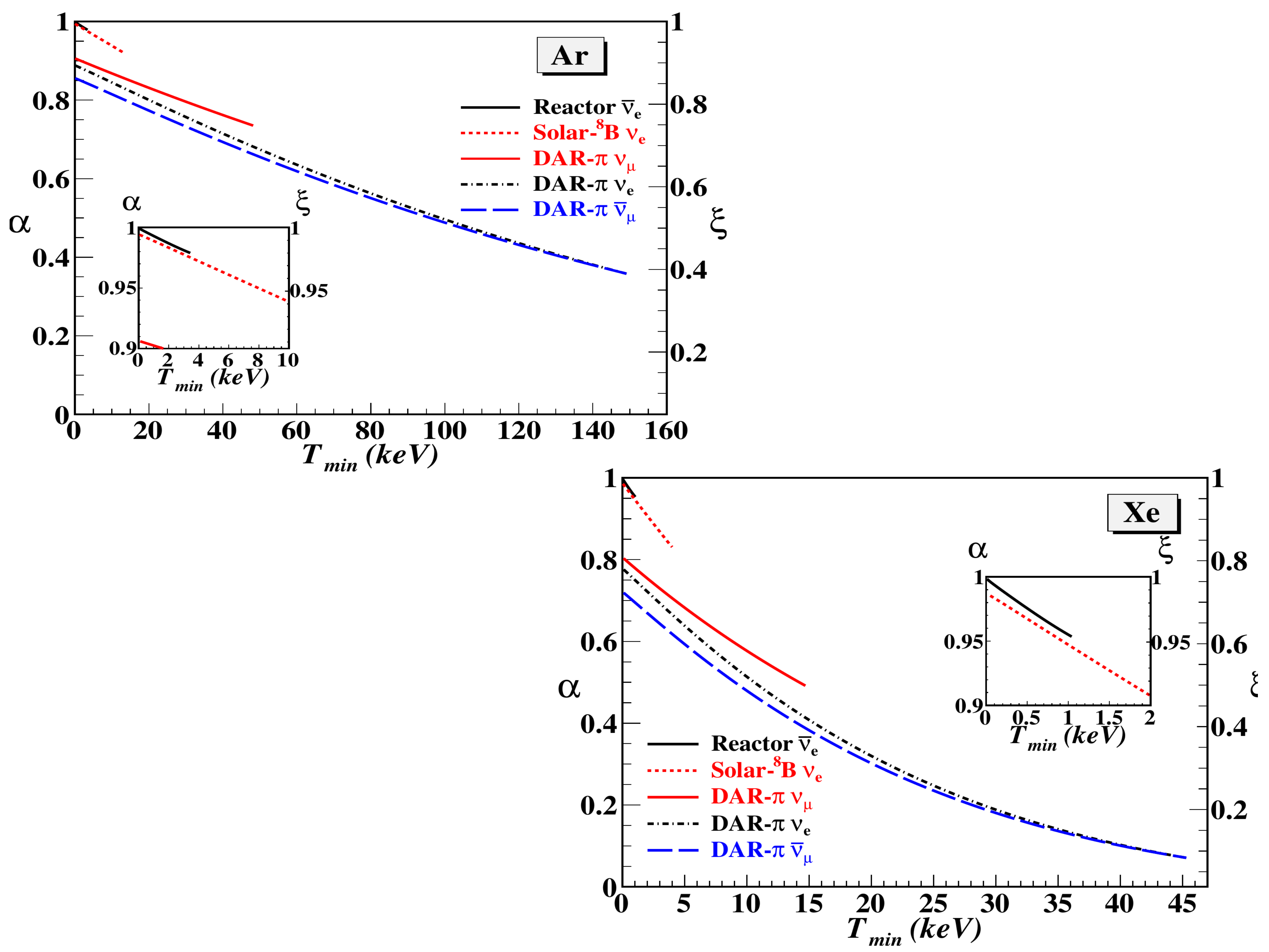


Exposure-corrected residuals between Beam ON and Beam OFF periods, for AC data (i.e., containing only steady-state environmental backgrounds)

- **Super Bialkali Hamamatsu Photo-multiplier R877-100.**
- **Quantum efficiency is ~38 %**
- **Basic pulse shape cuts can result 46% CENNS signal acceptance and 96% rejection of background. Bicron 501A liquid scintillator is used to distinguish neutron from gamma interaction via PSD cut.**
- **Muon veto efficiency is 99.6%**



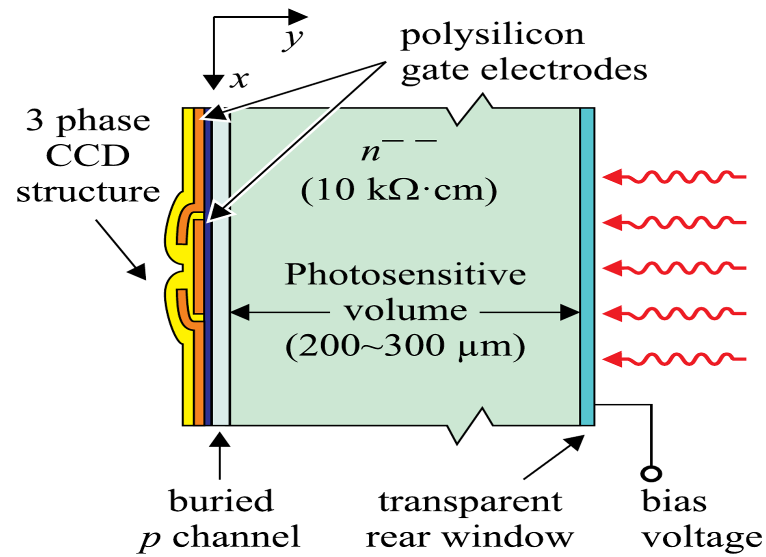



Ar
Reactor $\bar{\nu}_e$
Solar-^{8}B ν_e
DAR-π ν_μ
DAR-π ν_e
DAR-π $\bar{\nu}_\mu$
α
ξ
T_{min} (keV)
Xe
Reactor $\bar{\nu}_e$
Solar-^{8}B ν_e
DAR-π ν_μ
DAR-π ν_e
DAR-π $\bar{\nu}_\mu$
α
ξ
T_{min} (keV)

Other νA_{el} Experiments

CONNIE Experiment

- Angra II Reactor @ Brazil, Power = 3.95 GW
- Distance from core = 30 m
- Neutrino Flux ~ 7.8×10^{12} cm^{-2}s^{-1}
- At 0 keV threshold ~ 33 events kg^{-1}day^{-1} are expected.
- Detector mass = 5.2 g
- Net mass of prototype = 52 g



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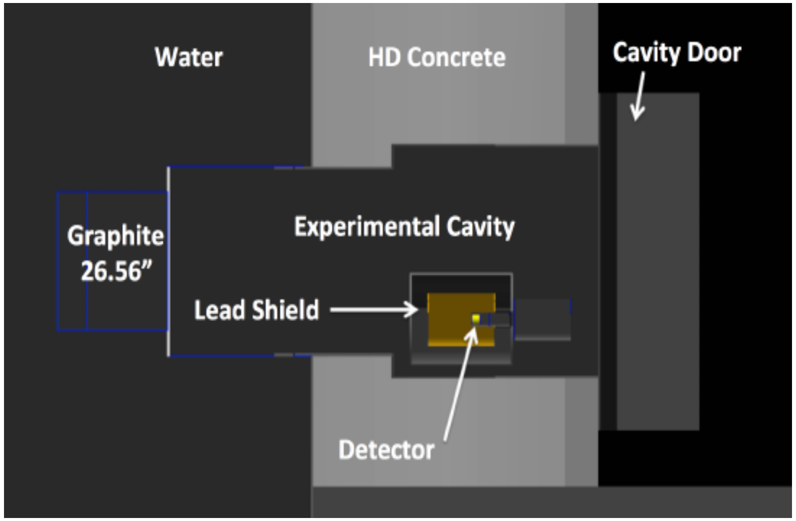
MINER Experiment

- A&M University Texas, Reactor Power = 1 MW
- Germanium and Silicon detectors.
- Distance from core = 2.3 m
- Neutrino Flux ~ 4×10^{11} cm^{-2}s^{-1}
- Huge thermal, fast neutron and gamma flux.
- Background of 100 per kg-day in 10-1000 eV$_{nr}$
- Expected count rate ~ 20 kg^{-1} day^{-1} recoil energy between 10 – 1000 keV$_{nr}$



arXiv: 1609.02066v1