Studies of Quantum Mechanical Coherency Effects in Neutrino-Nucleus Elastic Scattering

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Outline

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

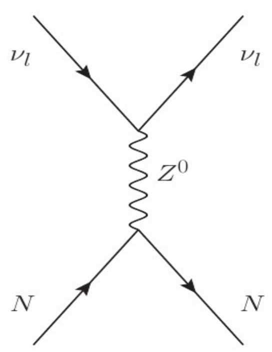
ICHEP 2020 | PRAGUE

Saturday, 31 July. 2020

Neutrino-Nucleus Elastic Scattering

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

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

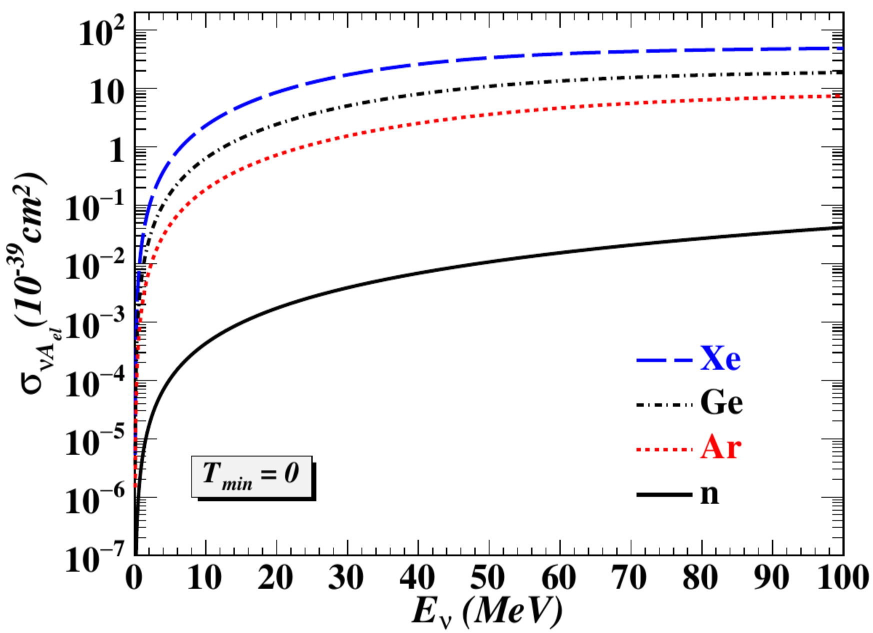


Cross-Section of νA_{el} :

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

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.

$\varepsilon = 1 - 4\mathrm{Sin}^2\Theta_W = 0.045$, gives $\mathbf{N^2}$ dependence

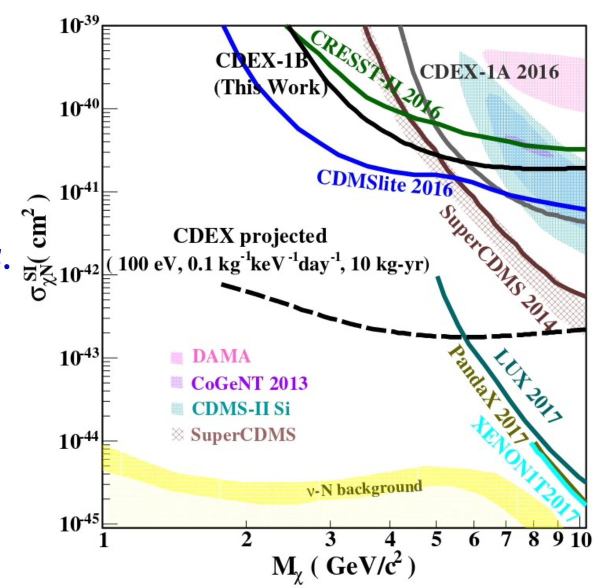


Requirements:

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

Importance:

- *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.*



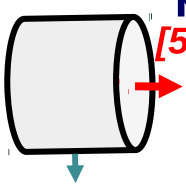
Li-Tao Yang et al, Chinese Phys. C42 023002 (2018)

TEXONO Collaboration

- **TEXONO (Taiwan EXperiment On NeutrinO)** Experiment is located at Kuo-Sheng Nuclear Power Plant -II on northern shore of Taiwan.
- **Theme:** 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.

p- PCGe

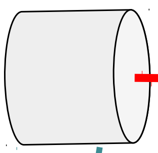
[500g – 1 kg]



n+(~1mm Li diffused)

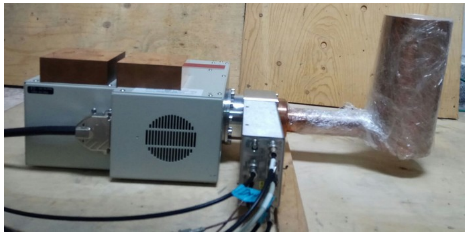
n- PCGe

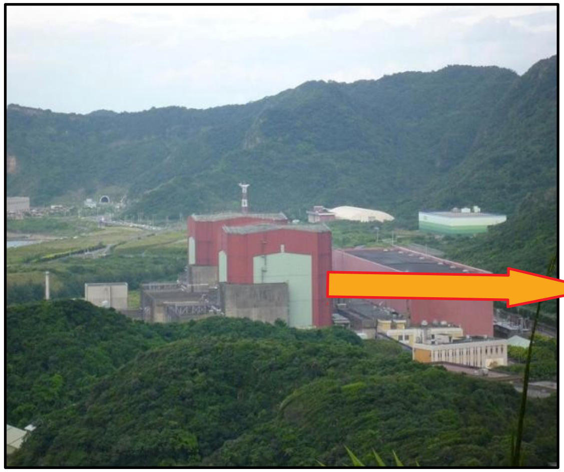
[500 g]

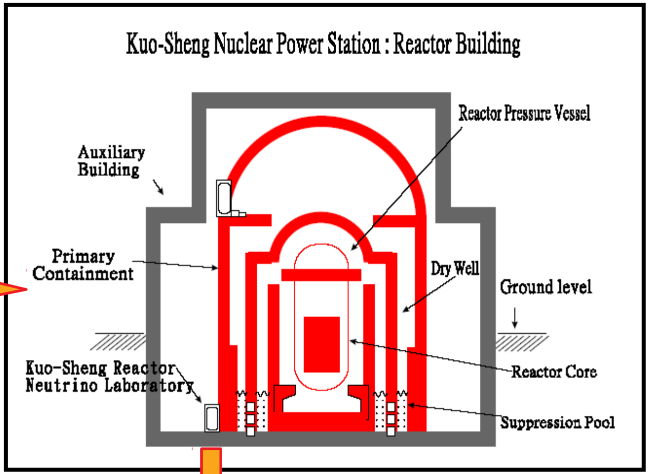


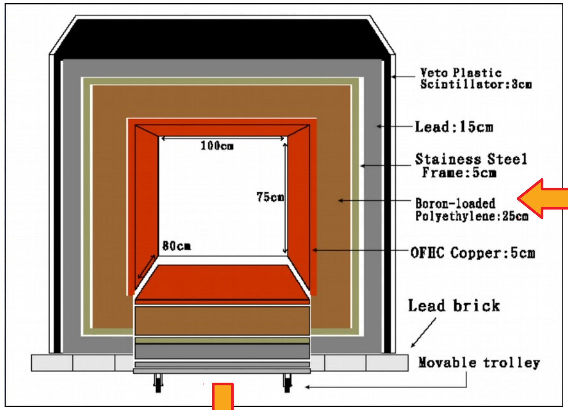
p+(~0.5 µm Boron implanted)

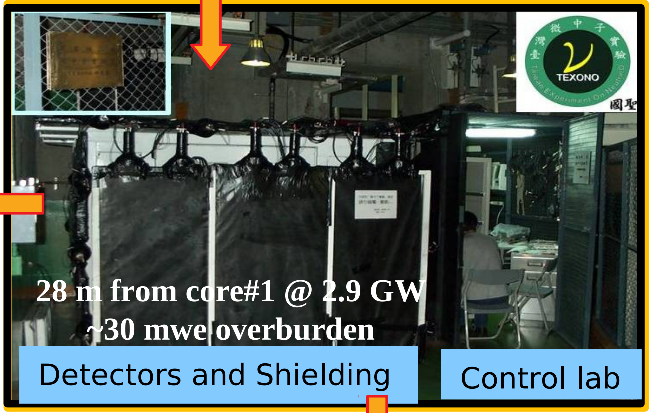
Electro-cooled Germanium Detector

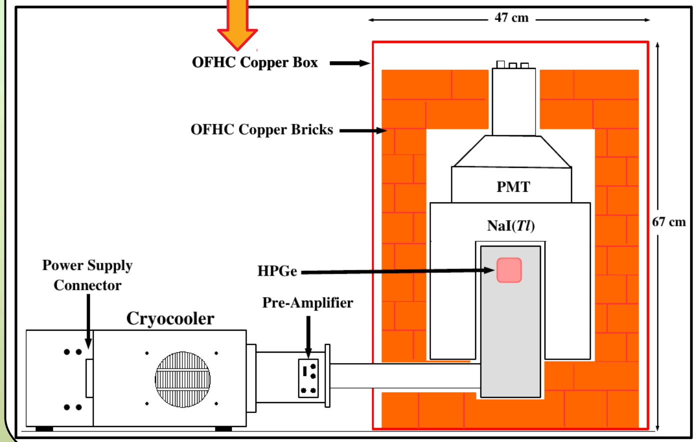


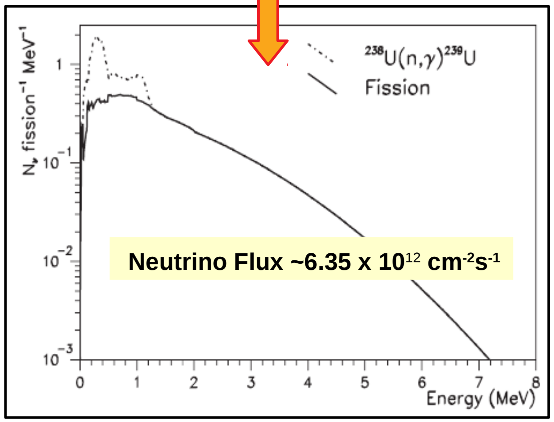












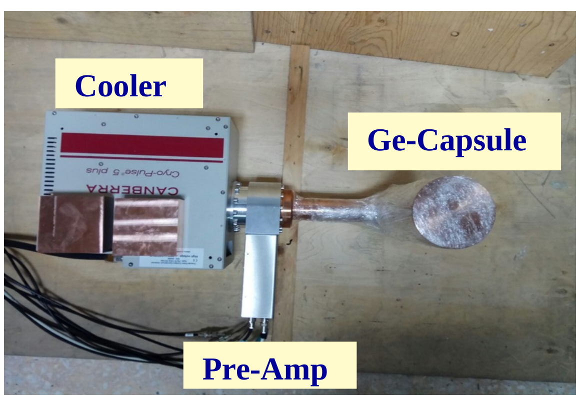
Detector Generation and Neutrino Physics at KSNL

Quality ← *Detector Requirements* → *Mass*

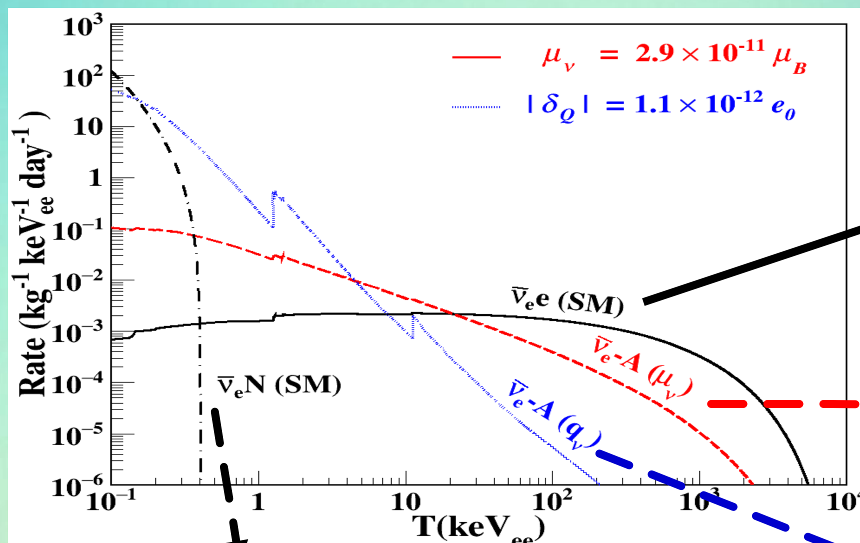
Generation	Mass (g)	Pulsar FWHM (eV_{ee})	Threshold (eV_{ee})
G1	500	130	500
G2	900	100	300
G3	500	70	200
G3+	1430	*Soon*	*Soon*

Advantages of G3(+) Electro-cooled HPGe Detectors:

- Controlled micro-phonic noise.
- Customized achievable temperature.
- Improved near contact electronics.
- No liquid Nitrogen required.



Electrically Refrigerated HPGe Detector



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

⇨ 200 kg CsI(Tl)

Magnetic Moments *[PRL03,PRD05,PRD07]*

⇨ 1 kg HPGe

νN Coherent Scattering *[Current Theme;PRD16]*

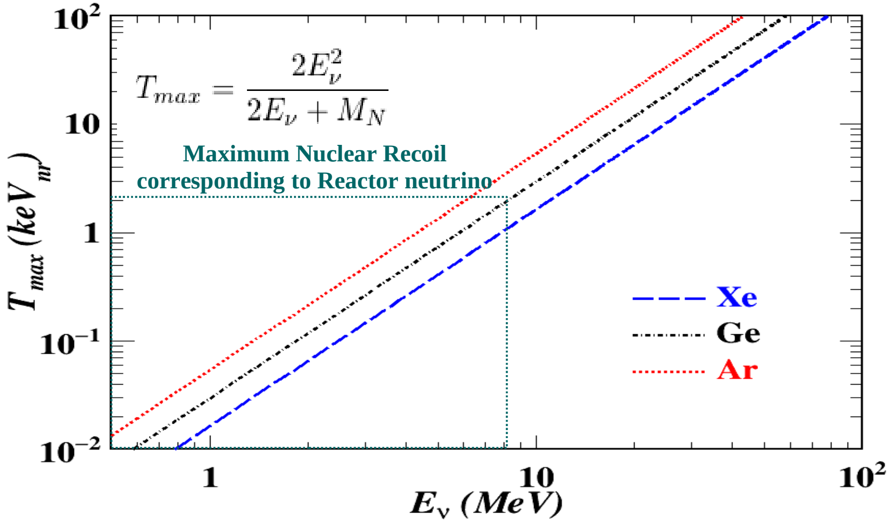
⇨ sub-keV O(kg) ULEGe / PCGe

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

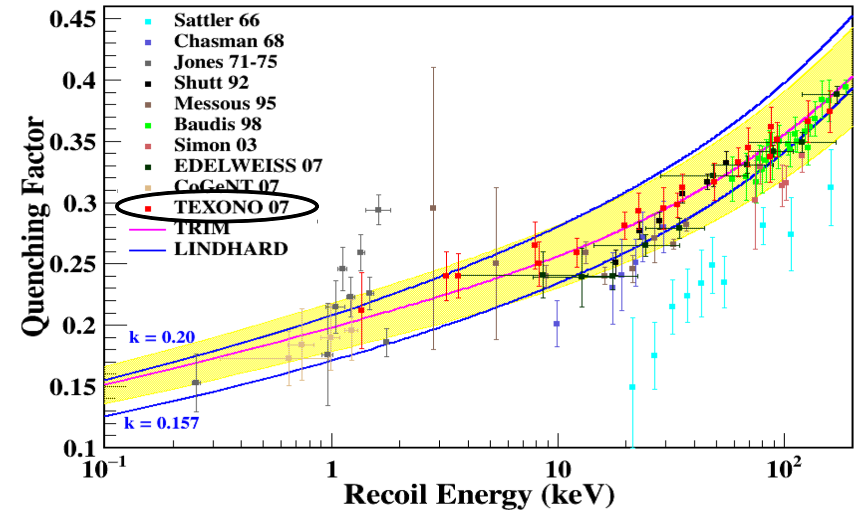
Neutrino Milli-charge *[PRD14]*

⇨ sub-keV O(kg) ULEGe / PCGe

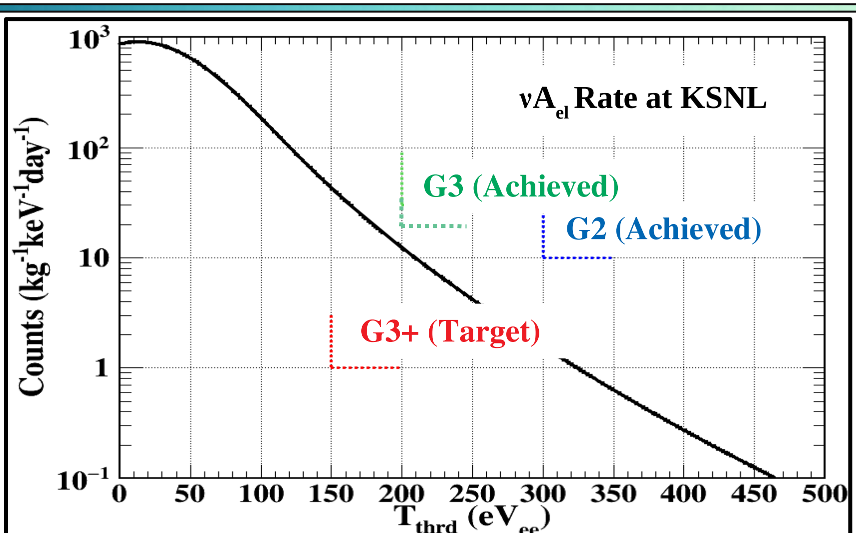
νA_{el} at KSNL with Reactor Neutrino..



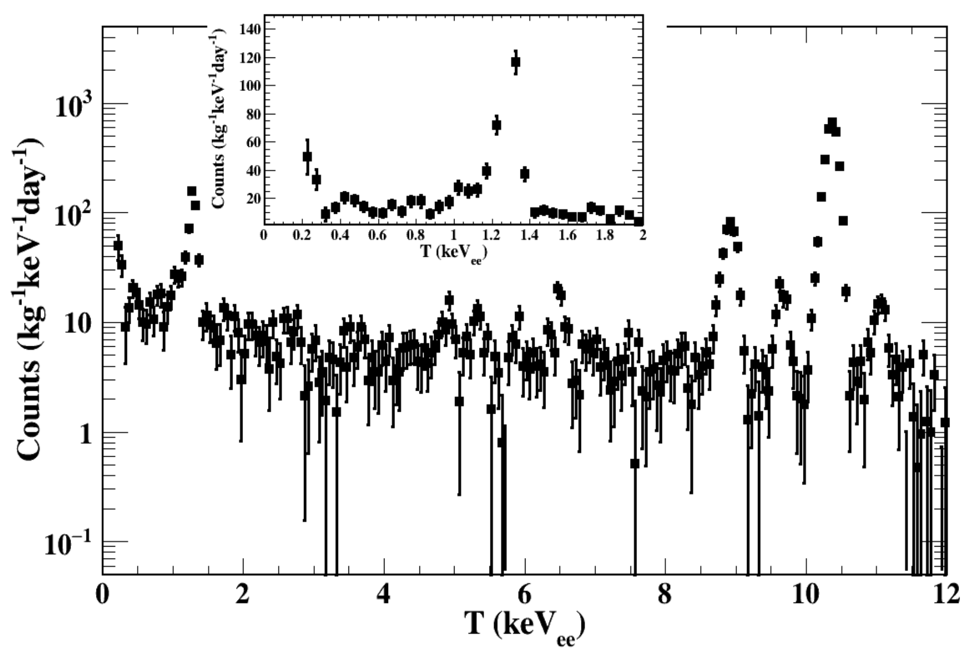
Max. Nuclear Recoil vs Incident Neutrino Energy



TRIM is used for Quenching factor for Germanium



Threshold	300 eV	200 eV	150 eV	100 eV
Differential (Cpkkd)	0.8	8.3	27.3	109.5
Integral (Cpkd)	0.04	0.47	1.6	6.4



Coherency in νA_{el} Scattering

Form-Factor:

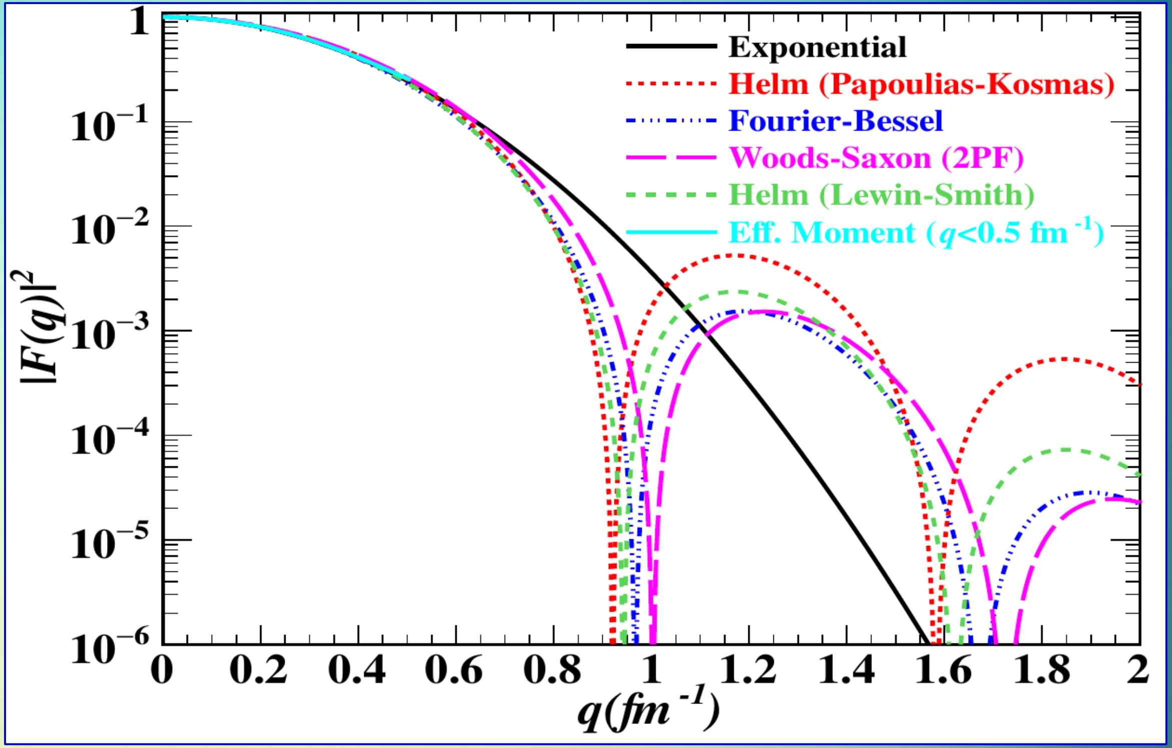
- Gives an idea about coherency within the nucleons.
- Used for study of Nuclear Structure.
- Complete Coherence at low Energy.
- νA_{el} measures the neutron distribution

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

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

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:

$$\mathcal{A} = \sum_{j=1}^{Z} e^{i\theta_j} \mathcal{X}_j + \sum_{k=1}^{N} e^{i\theta_k} \mathcal{Y}_k$$

where $(\mathcal{Y}_n, \mathcal{X}_m) = (1, -\varepsilon)$

- The cross-section comprise $(N + Z)^2$ terms.
- In total cross-secti $\sigma_{\nu A_{el}}(Z, N) \propto \mathcal{A}\mathcal{A}^{\dagger}$, 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)

Degree of Coherency and Relative Cross-section

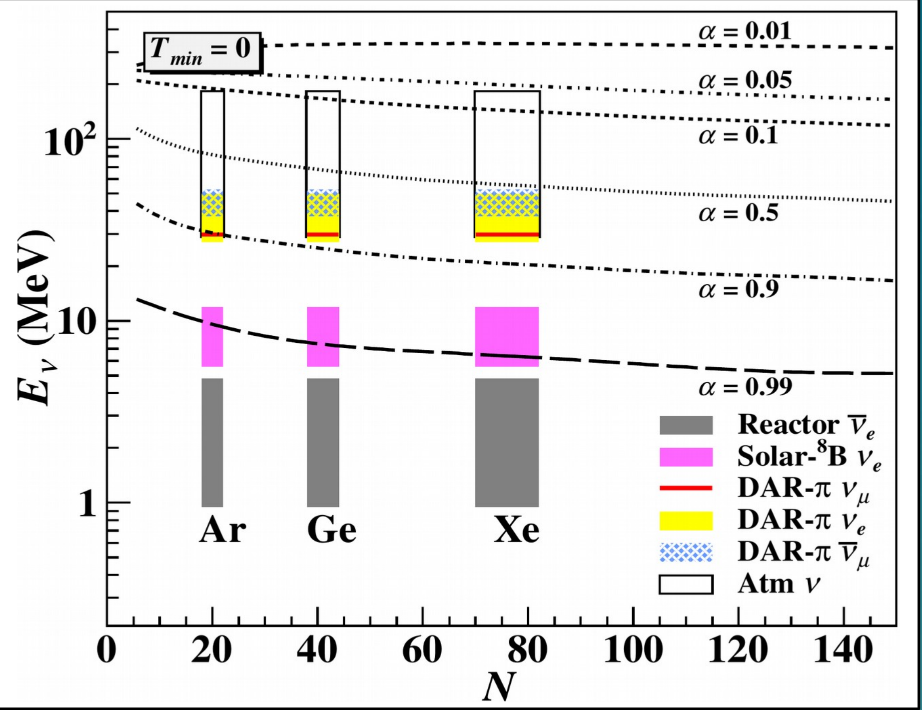
Reactor and solar neutrino probe νA_{el} in region with higher degree of coherency

Lower mass nuclei are better choice for higher degree of coherency

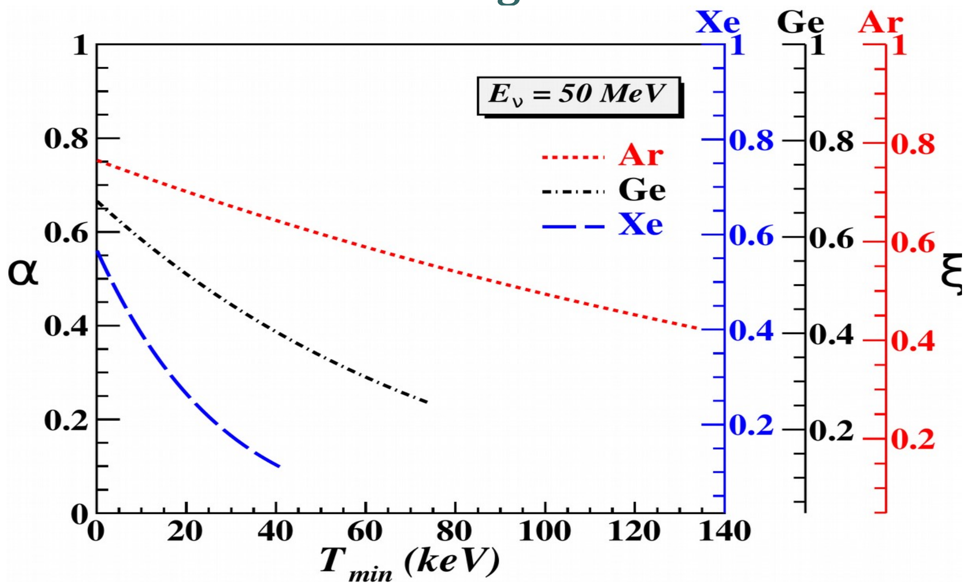
ν Source	Half-Maxima of $\sigma_{\nu A_{el}} \Phi_\nu$ in E_ν(MeV)	$\langle\alpha\rangle$ with Ar	Ge	Xe
Reactor $\bar{\nu}_e$	0.96−4.82	1.00	1.00	1.00
Solar ^{8}B-ν_e	5.6−11.9	0.99	0.99	0.98
DAR-π ν_μ	29.8	0.91	0.86	0.80
DAR-π ν_e	27.3−49.8	0.89	0.83	0.76
DAR-π $\bar{\nu}_\mu$	37.5−52.6	0.85	0.79	0.71

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

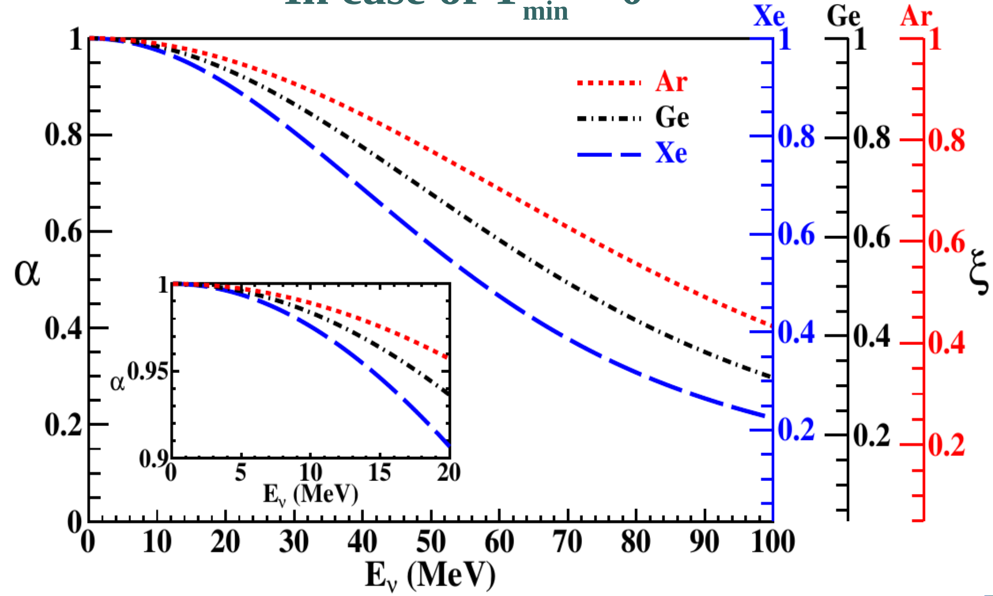
$$\xi = \frac{\sigma_{\nu A_{el}}(\alpha)}{\sigma_{\nu A_{el}}(\alpha = 1)}$$



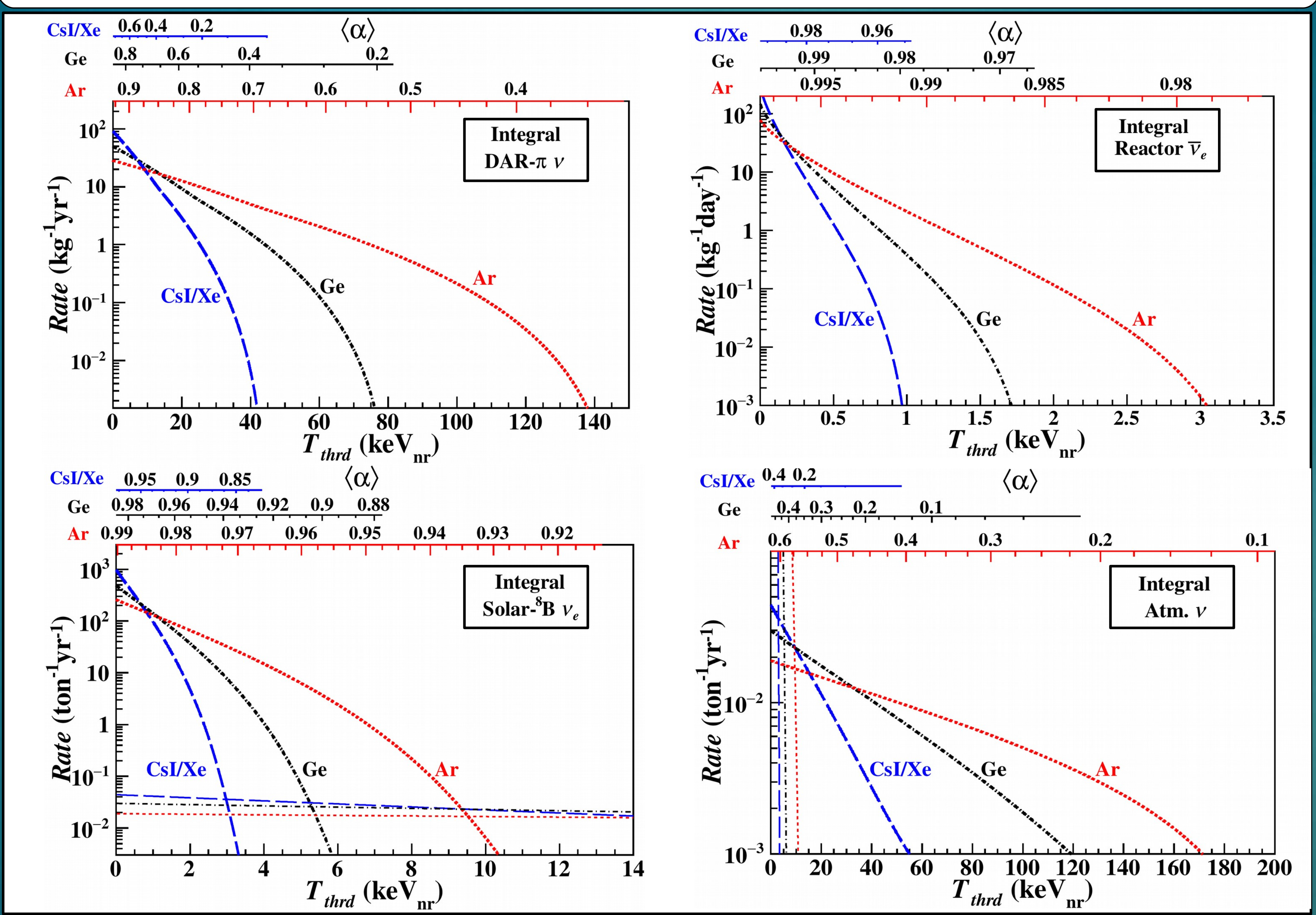
In case of Monoenergetic Source:



In case of $T_{min} = 0$



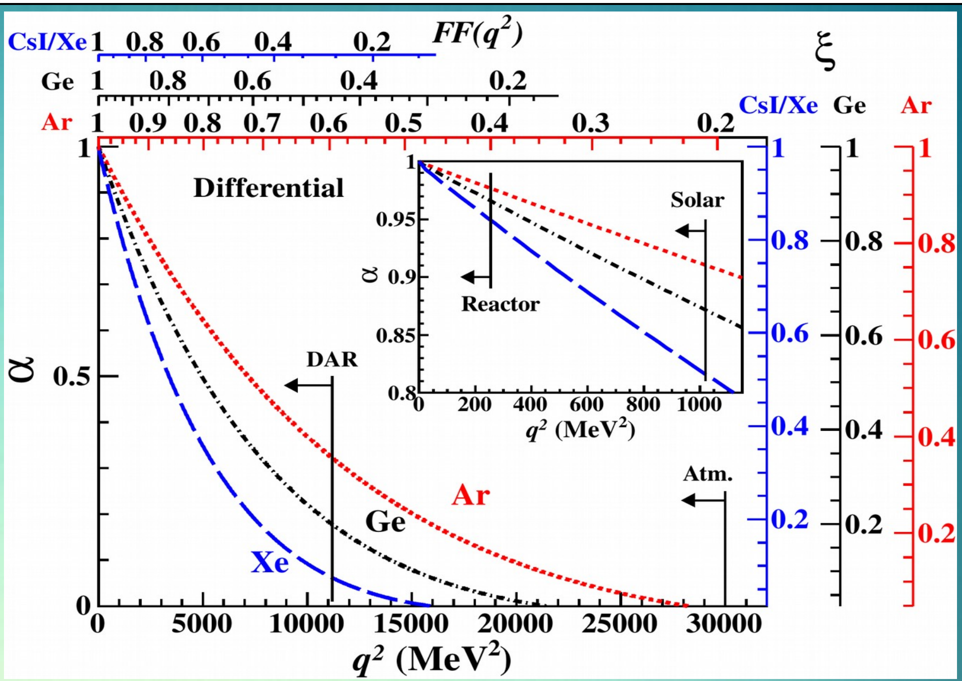
Integral Rate and Degree of Coherency for different Sources

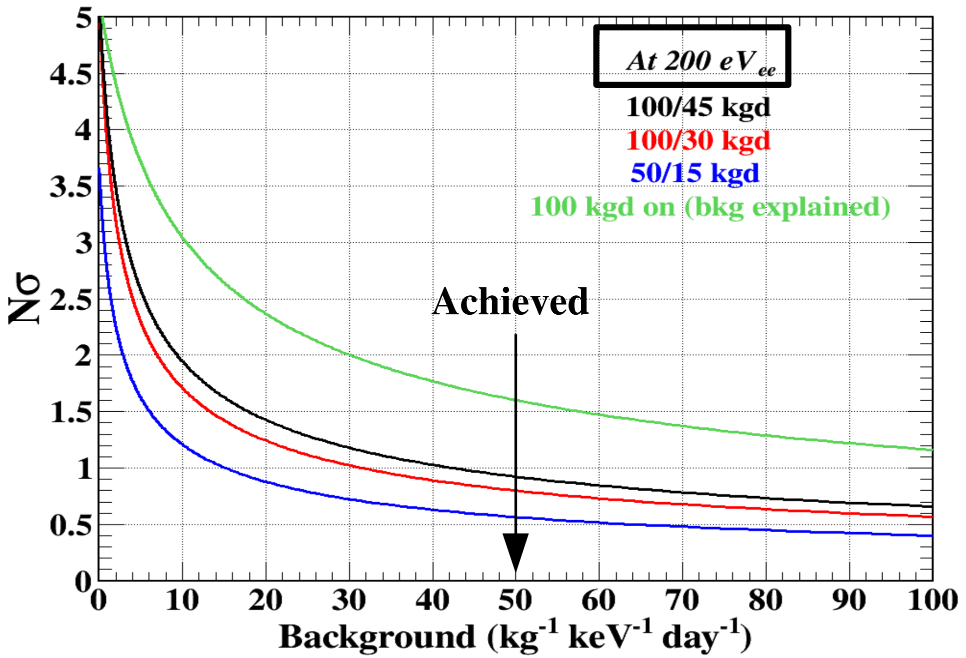


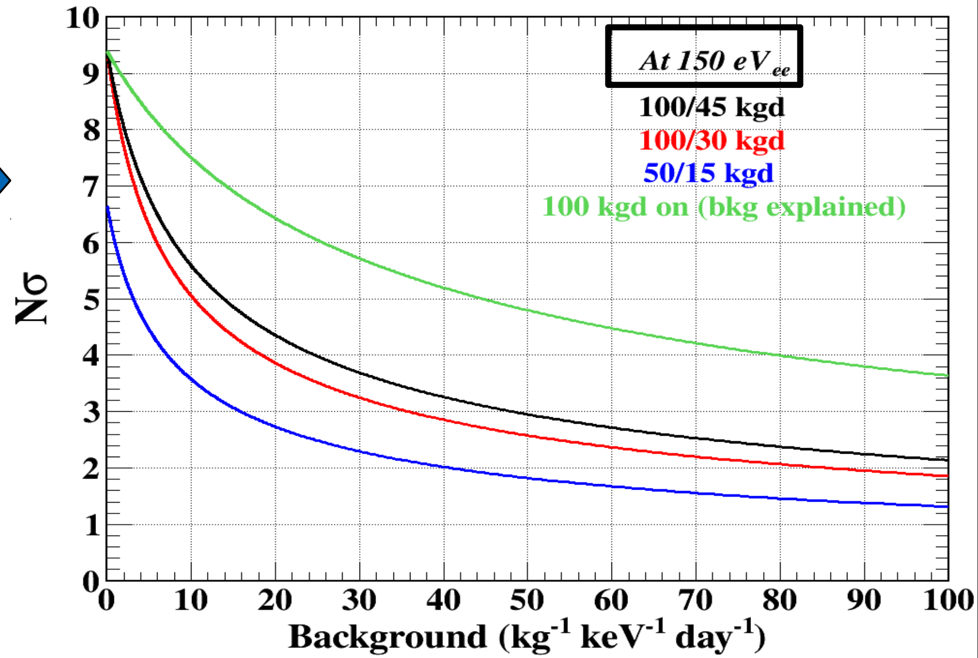
Status of νA_{el} Scattering @KSNL

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

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







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.
- 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 Reactor and Solar $\nu\mathbf{A}_{el}$ in near future.

Thank You