Low Threshold Detectors for Neutrino-Nucleus Elastic Scattering and the Studies of its Quantum-Mechanical Coherency Effects

Vivek Sharma

On behalf of TEXONO Collaboration

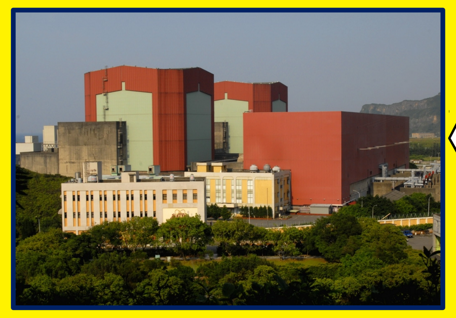
Home Base: Institute of Physics, Academia Sinica, Taiwan

Collaborating Partners: Taiwan, China, India, Turkey.

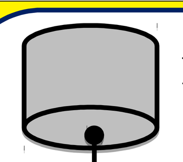
Based On:

- Studies of quantum-mechanical coherency effects in neutrino-nucleus elastic scattering, V. Sharma et al. Phys. Rev. D 103, 092002 (2021).
- Coherency in neutrino-nucleus elastic scattering, S. Kerman et al. Phys. Rev. D 93, 113006 (2016).
- Characterization and performance of germanium detectors with sub-keV sensitivities for neutrino and dark matter experiments, A.K. Soma et al. NIM in Phys. Res. A 836, 67-82 (2016).

TEXONO Program and Kuo-Sheng Nuclear Reactor Lab



Neutrino Physics
TEXONO @ KSNL



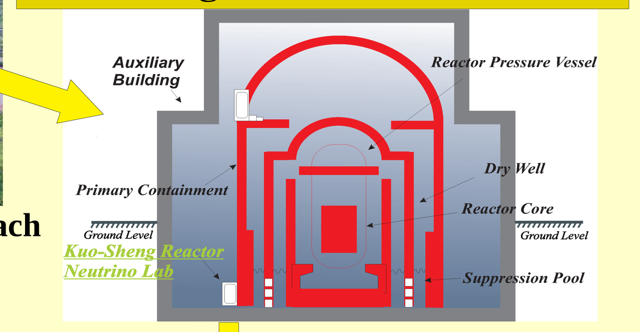
Point Contact Ge-Detector

TEXONO-CDEX Collaboration

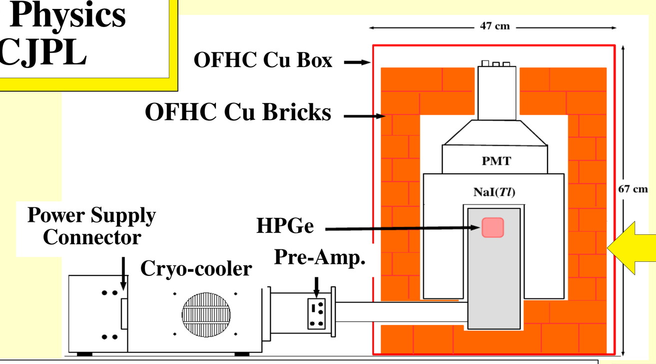
Taiwan (AS, INER, KSNPS), India (BHU,CUSB,GLAU), Turkey (METU,DEU), China (THU, CIAE, NKU, SCU,YLJHD)

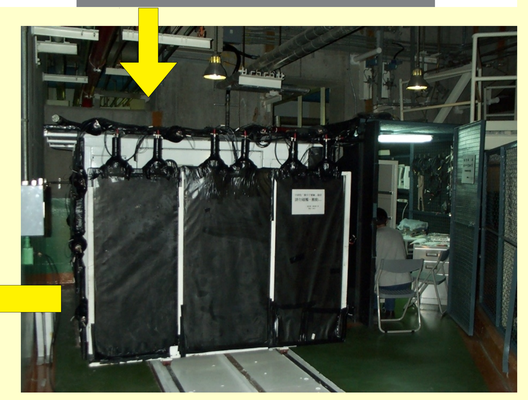
Dark Matter Physics
CDEX @ CJPL

Kuo-Sheng Nuclear Power Station

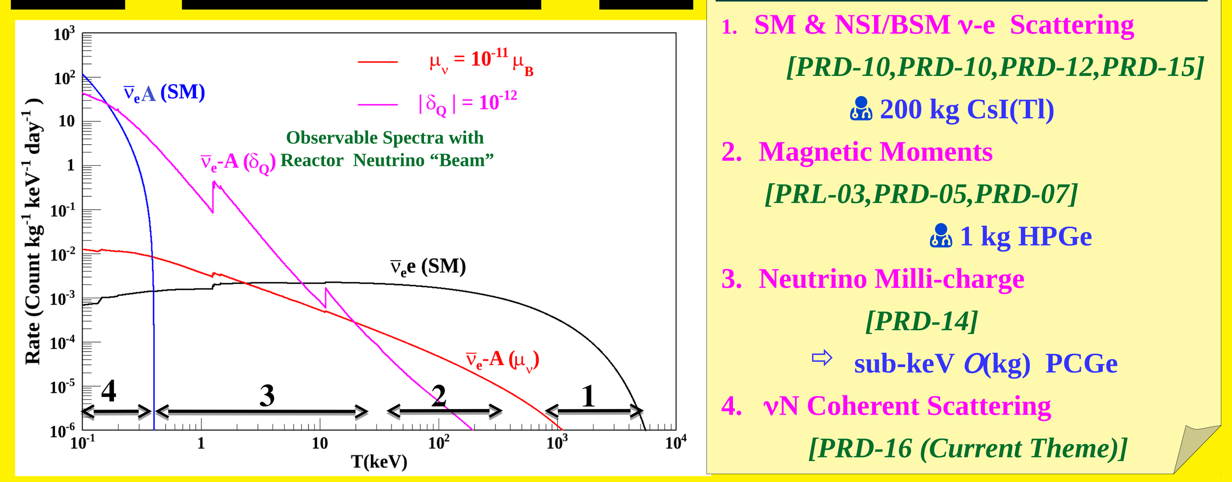


Total Capacity 2.9 GW each
$\Phi\nu$ = 6.4×10^{12} cm^{-2} s^{-1}
- *Lab: 28 m from core #1,*
- *30 MWE overburden concrete*



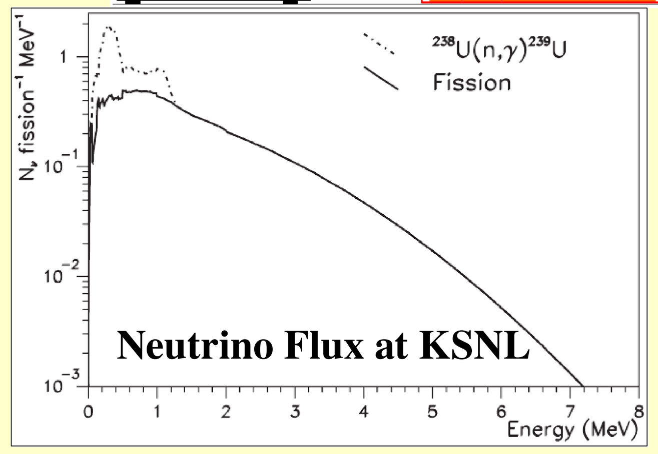


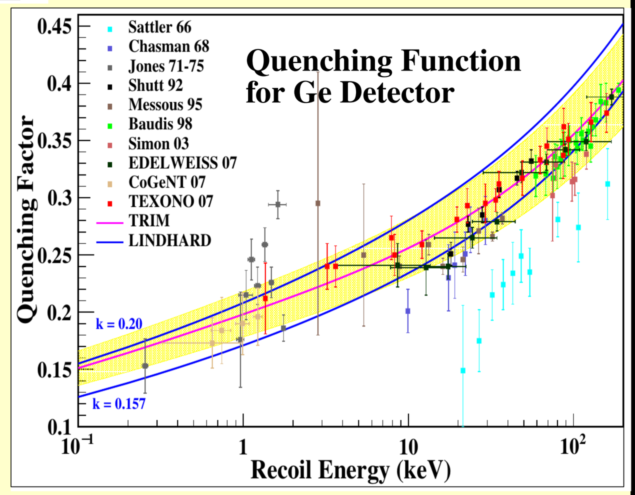
Quality → Detector Requirements ← Mass



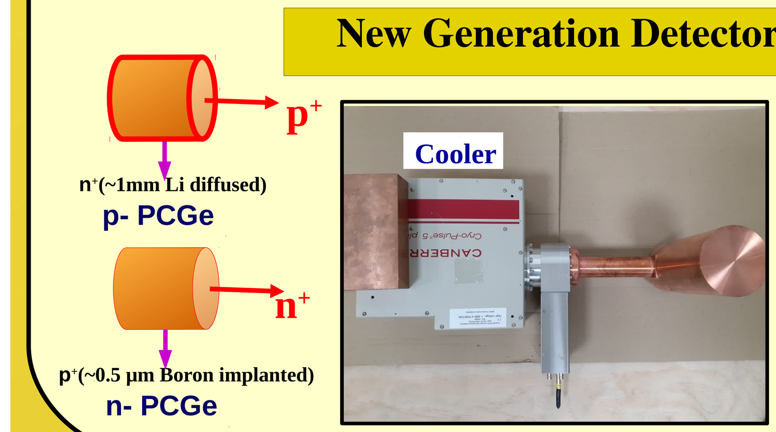
Neutrino Interactions at KSNL

1. SM & NSI/BSM ν-e Scattering [PRD-10,PRD-10,PRD-12,PRD-15] 200 kg CsI(Tl)
2. Magnetic Moments [PRL-03,PRD-05,PRD-07] 1 kg HPGe
3. Neutrino Milli-charge [PRD-14] ⇨ sub-keV O(kg) PCGe
4. νN Coherent Scattering [PRD-16 (Current Theme)]





New Generation Detectors at KSNL



Generation	Mass (g)	Pulser 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+ Germanium detectors

- ➢ Less microphonic noise.
- ➢ Customized achievable temperature.
- ➢ Upgraded point contact electronics.
- ➢ No Liquid Nitrogen needed.

Neutrino-Nucleus Elastic Scattering νA_{el}

A fundamental neutrino interaction: $\nu_l + A \rightarrow \nu_l + A$

Differential cross-section:
$$\left[\frac{d\sigma}{dq^2}(q^2,E_\nu)\right]_{\nu A_{el}} = \frac{1}{2}\left[\frac{G_F^2}{4\pi}\right]\cdot\left[1-\frac{q^2}{4E_\nu^2}\right]\cdot\Gamma(q^2)$$

The term $\Gamma(q^2)$ have different description based on particular physics:

A. Nuclear Physics: $\Gamma_{NP}(q^2) = [\varepsilon ZF_Z(q^2)-NF_N(q^2)]^2$.

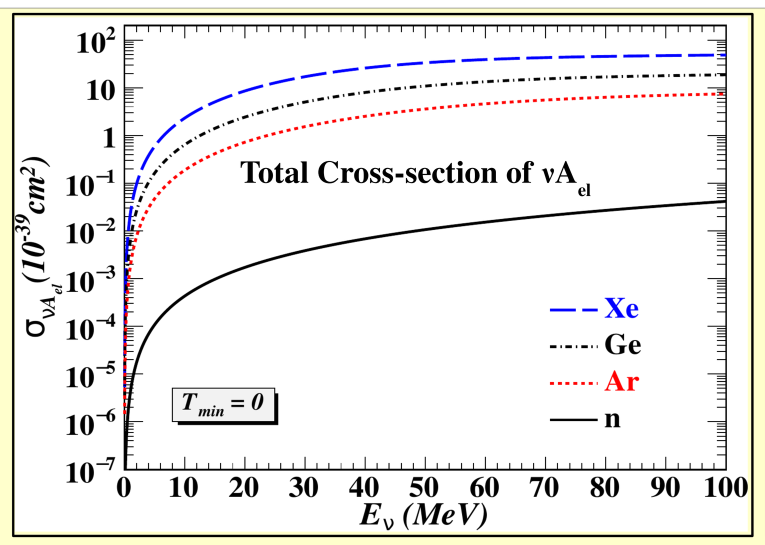
B. Quantum Mechanical Coherency: $\Gamma_{QM}(q^2) = [\varepsilon Z-N]^2\alpha(q^2) + (\varepsilon^2 Z+N)[1-\alpha(q^2)]$.

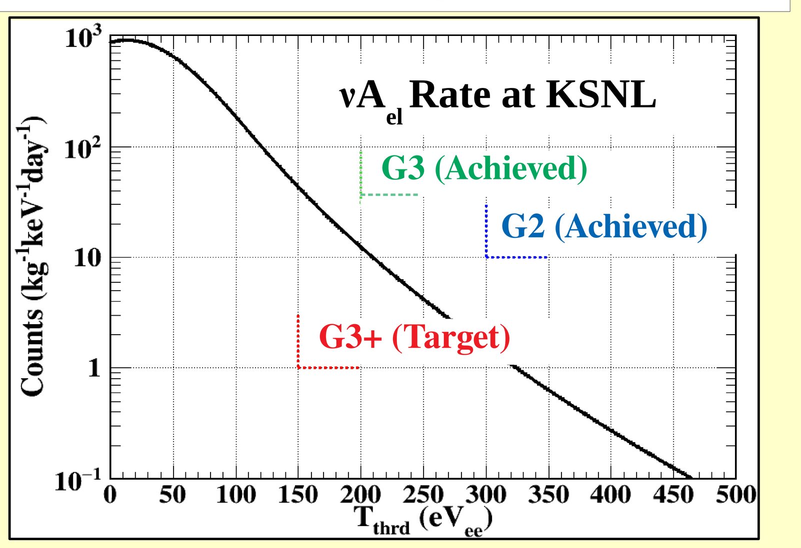
C. Data-driven Description: $\Gamma_{DATA}(q^2) = [\varepsilon Z-N]^2\xi(q^2)$.

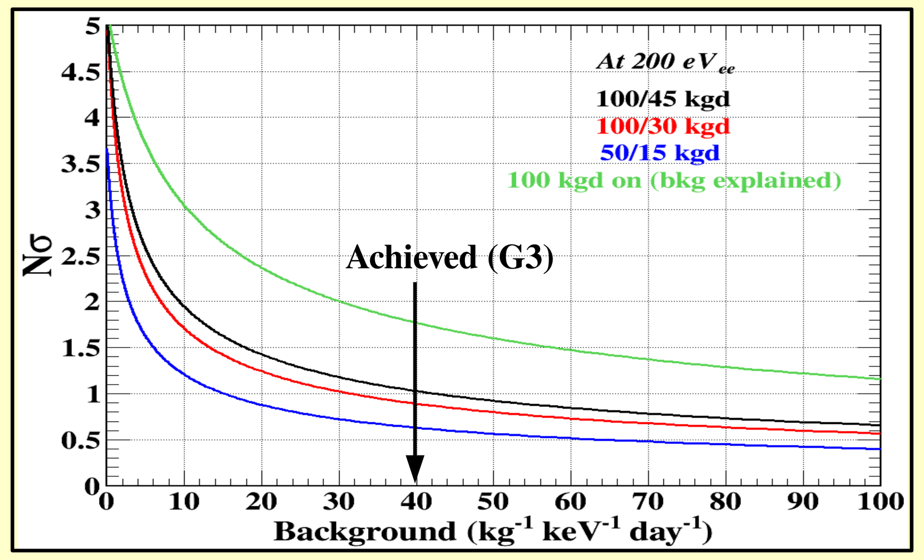
Total cross-section is given by:
$$\sigma_{\nu A_{el}} = \int_{T_{min}}^{T_{max}}\left[\frac{d\sigma_{\nu A_{el}}}{dT_{nr}}(T_{nr},E_\nu)\right]dT_{nr} = \int_{q^2_{min}}^{q^2_{max}}\left[\frac{d\sigma_{\nu A_{el}}}{dq^2}(q^2,E_\nu)\right]dq^2$$

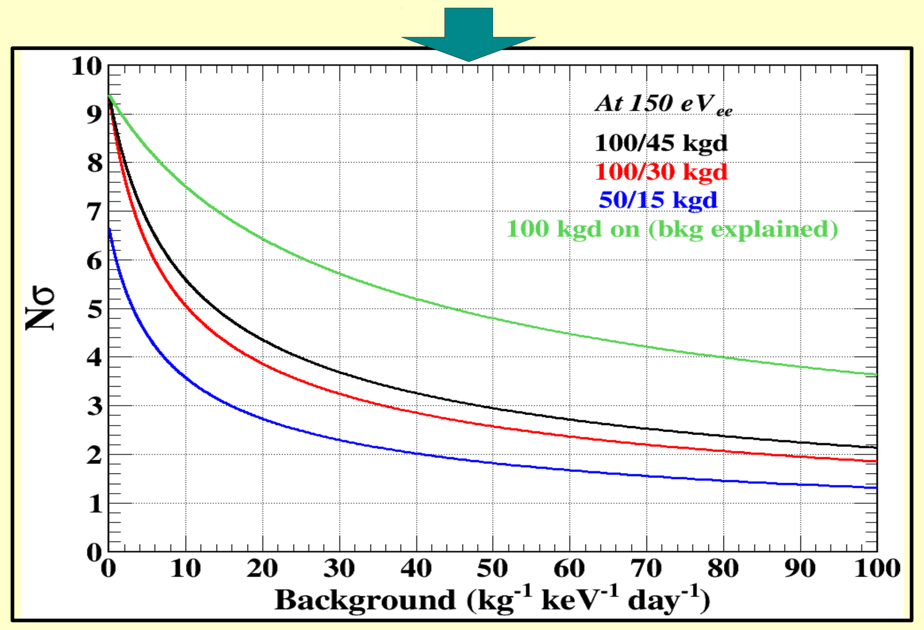
A. Nuclear Physics Description: $\Gamma(q^2) \equiv \Gamma_{NP}(q^2) = [\varepsilon ZF_Z(q^2) - NF_N(q^2)]^2$ where $F_Z(q^2)\in[0,1]$ and $F_N(q^2)\in[0,1]$

The Helm form-factor is given by: $F(q) = \frac{3j_1(qR)}{qR}e^{-(qs)^2/2} = 3\frac{\sin(qR)-qR\cos(qR)}{(qR)^3}e^{-(qs)^2/2}$ where R and s are the radius and surface thickness parameters of nucleus.









Coherency in Neutrino-Nucleus Elastic Scattering νA_{el}

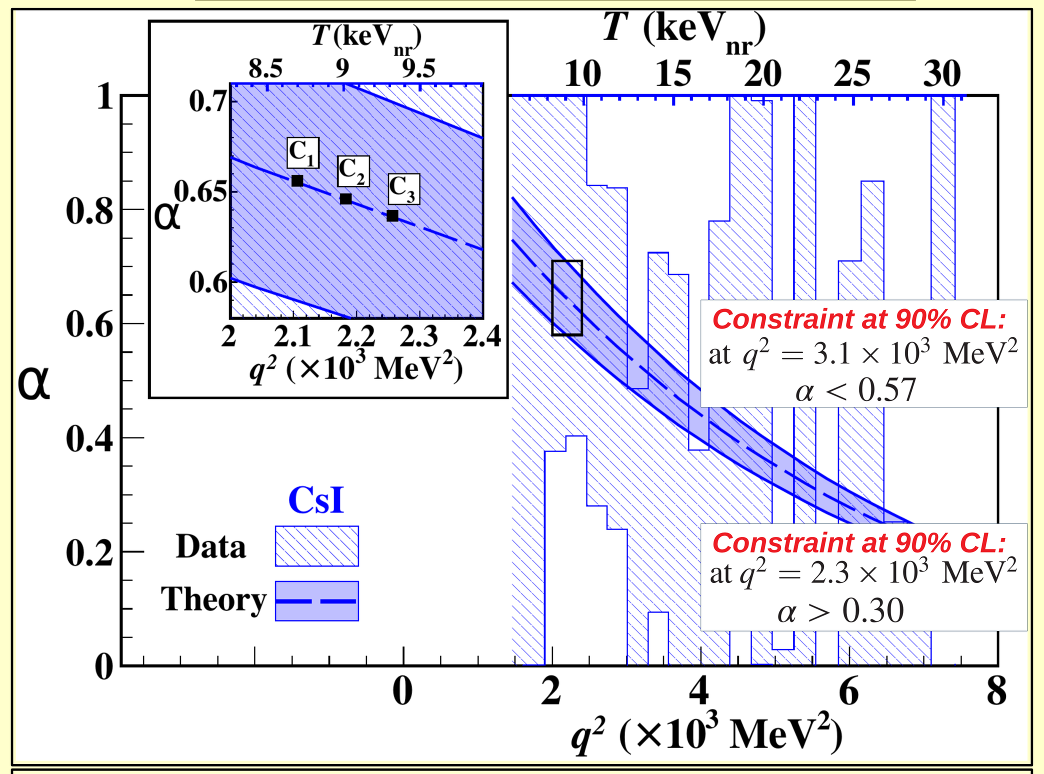
B. Quantum Mechanical Coherency:
$$\Gamma(q^2) \equiv \Gamma_{QM}(q^2) = (\varepsilon Z - N)^2\cdot\alpha(q^2) + (\varepsilon^2 Z + N)\cdot[1-\alpha(q^2)]$$
where α is Degree of Coherency in νA_{el}

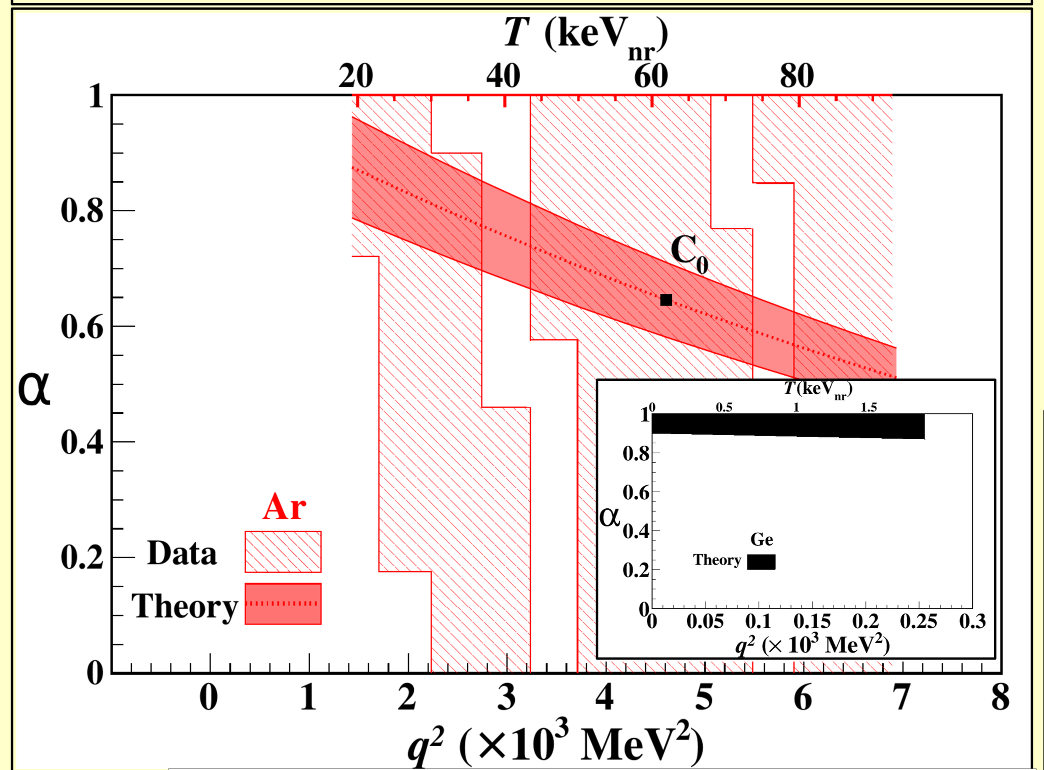
Condition for full coherence and incoherence:
$$\frac{d\sigma_{\nu A_{el}}}{dq^2}(q^2,E_\nu) \propto \begin{cases}[\varepsilon^2 Z+N], & \alpha=0 \text{ (incoherent)}\\ [\varepsilon Z-N]^2, & \alpha=1 \text{ (coherent)}\end{cases}$$

C. Data Driven Description:
$$\Gamma(q^2) \equiv \Gamma_{DATA}(q^2) = (\varepsilon Z - N)^2\cdot\xi(q^2)$$
The term $\xi(q^2)$ is the cross-section suppression relative to the complete coherency condition
$$\xi(q^2) \equiv \frac{(d\sigma/dq^2)_{\nu A_{el}}(\alpha)}{(d\sigma/dq^2)_{\nu A_{el}}(\alpha=1)}$$

The experimentally measurable cross-section reduction fraction (ξ) is related to QM coherency (α) and nuclear form factors via:
$$\xi(q^2) = \alpha(q^2) + [1-\alpha(q^2)]\left[\frac{(\varepsilon^2 Z+N)}{(\varepsilon Z-N)^2}\right] \quad \& \quad \xi(q^2) = \frac{[\varepsilon ZF_Z(q^2)-NF_N(q^2)]^2}{(\varepsilon Z-N)^2}$$

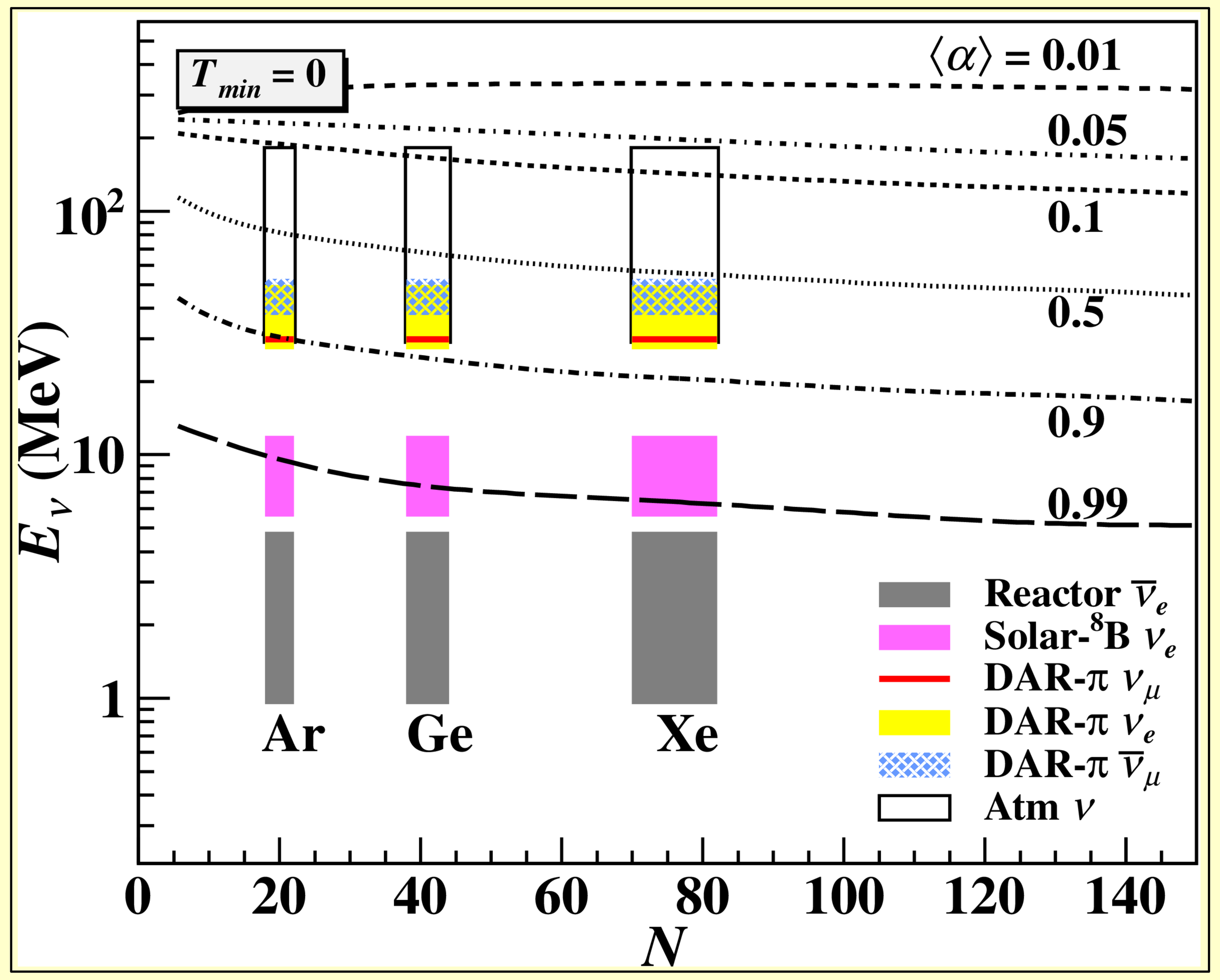
Constraints on COHERENT Data



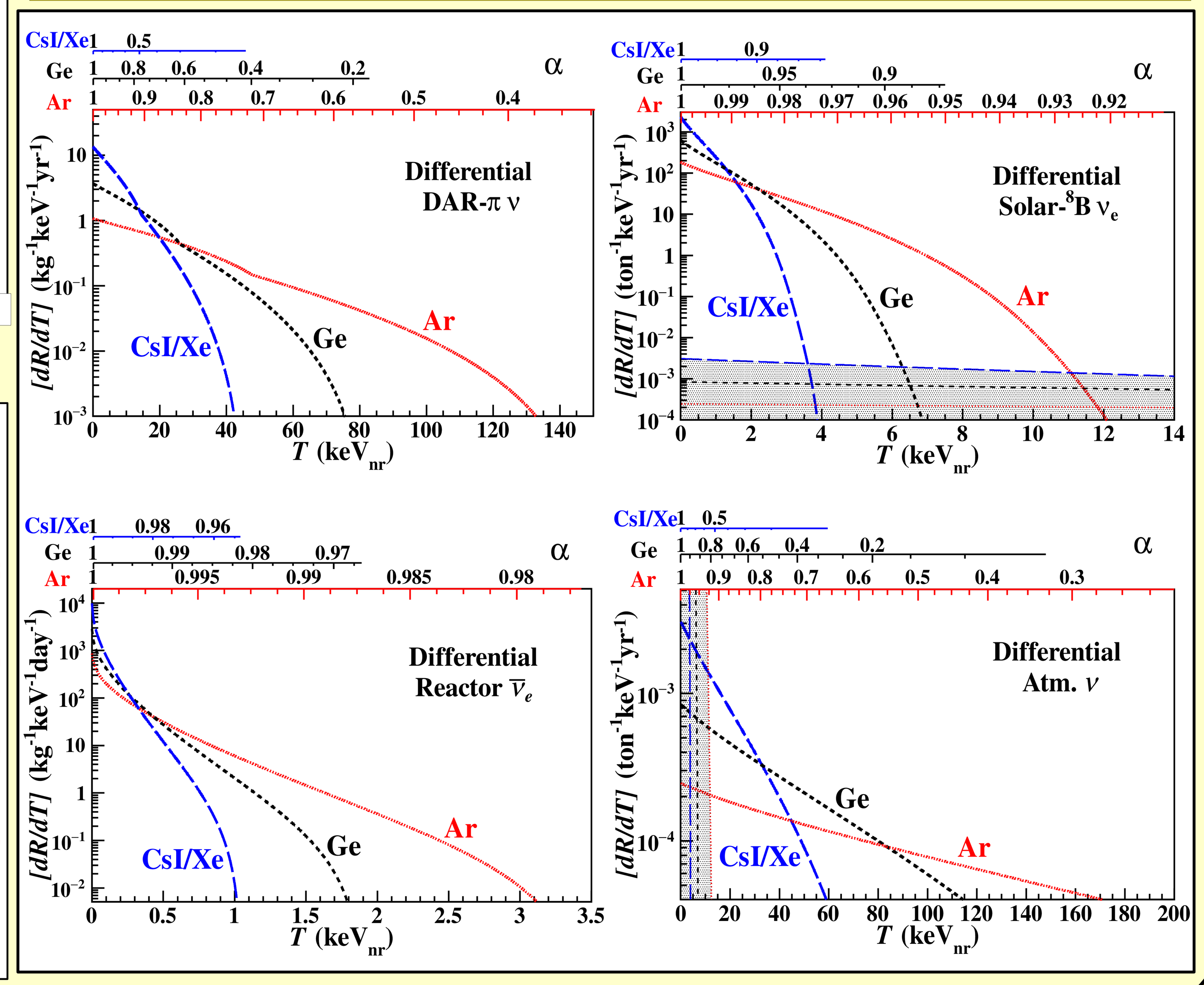


V. Sharma et al. Phys. Rev. D 103, 092002 2021; D. Akimov et al., Science 357, 1123 (2017).

Contour of Degree of Coherency in E_ν vs Neutron number(Target) plane



νA_{el} Event rates with expected coherency for different neutrino sources and targets



Degree of coherency w.r.t. square of three momentum transfer