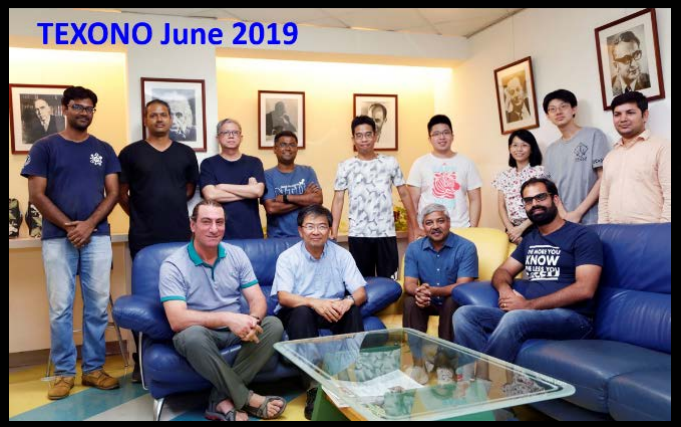
Studies of Coherent Neutrino-Nucleus Elastic Scattering in the TEXONO Program

- Programs with sub-keV Ge at Kuo-Sheng Reactor Neutrino Laboratory
- Formulation & Studies of QM Coherency in νA_{el}



Henry T. Wong / 王子敬
Academia Sinica / 中央研究院
November 2020

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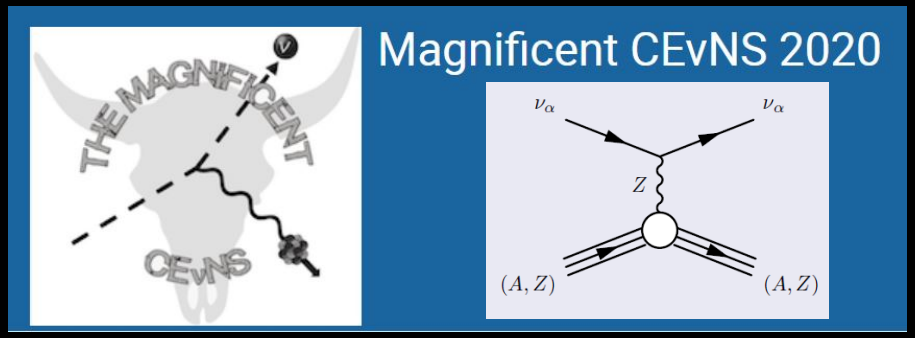
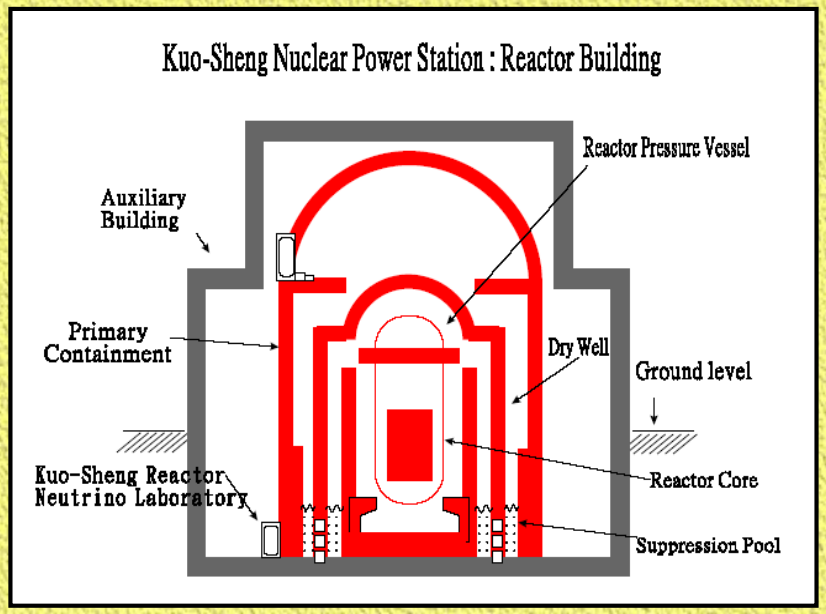
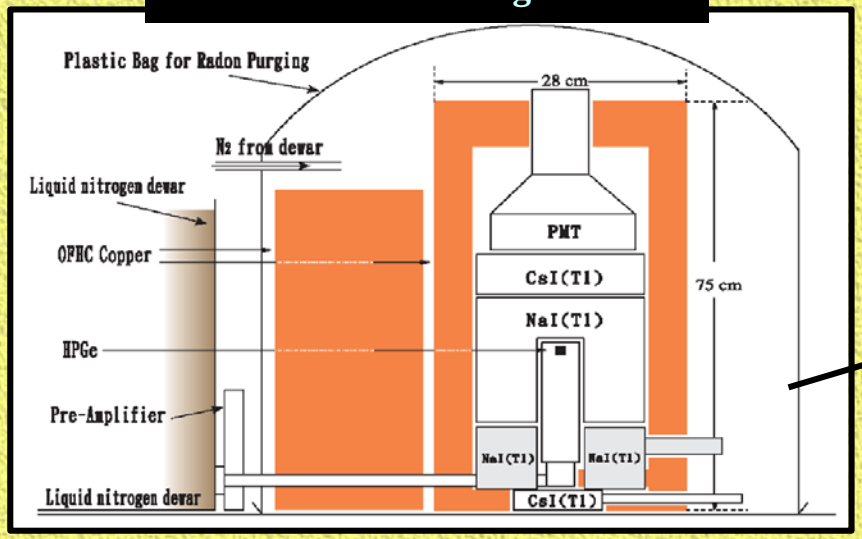
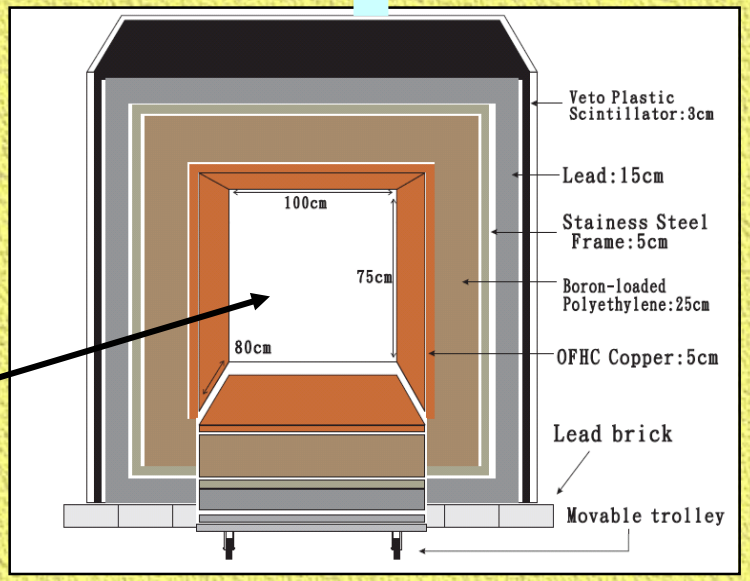


TEXONO at Kuo-Sheng Reactor Neutrino Laboratory (KSNL) in Taiwan



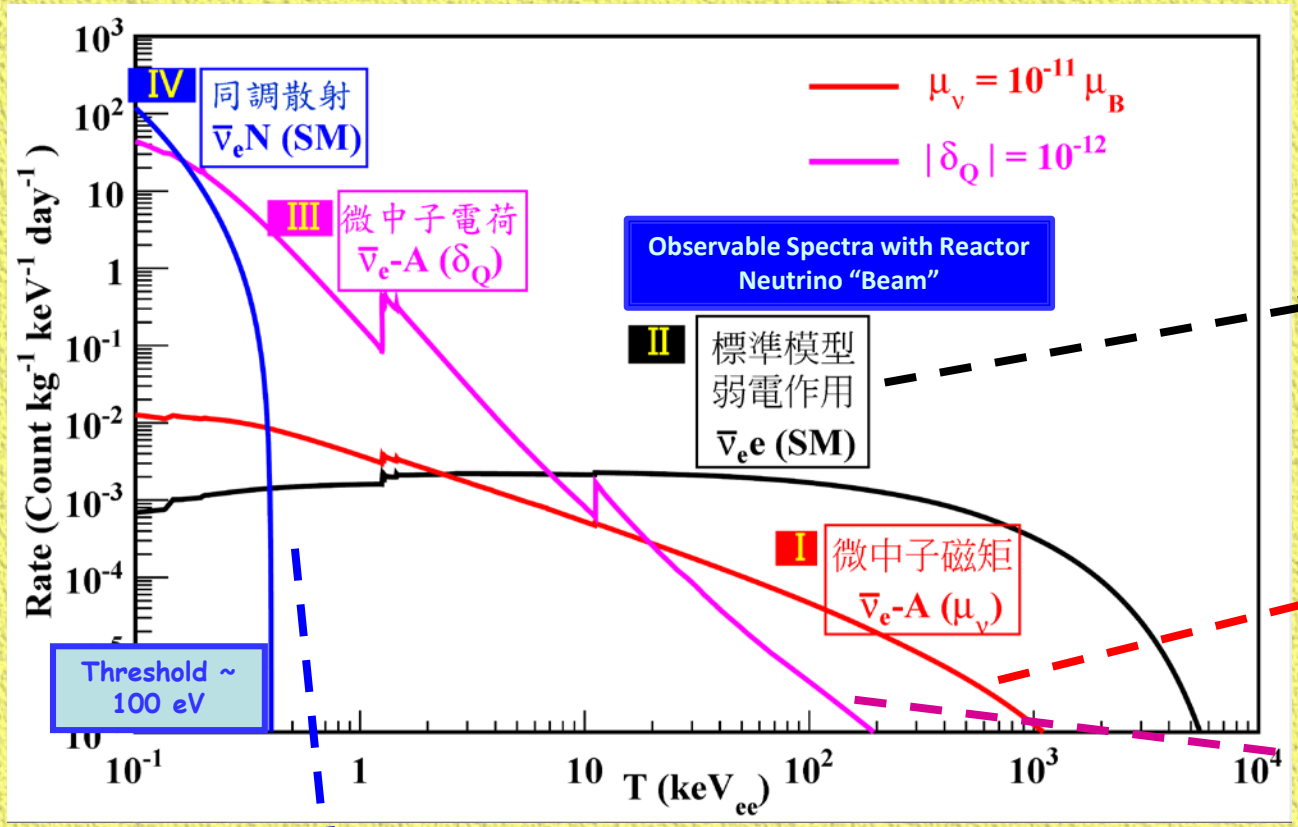
Baseline Design

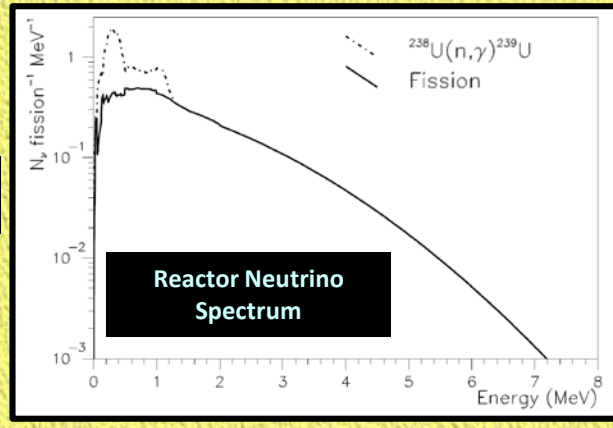




Neutrino Properties & Interactions at Reactor

quality ← **Detector requirements** → **mass**





ν-e Scattering SM *[PRD10]*
& NSI/BSM
[PRD10,PRD12,PRD15,PRD17]
⇨ 200 kg CsI(Tl)

Magnetic Moments
[PRL03,PRD05,PRD07]
⇨ 1 kg HPGe

Neutrino Milli-charge
[PRD14]
⇨ sub-keV O(kg) PCGe

Current Theme: νN Scattering *[hep-ex05,MLPA08,PRD16]*

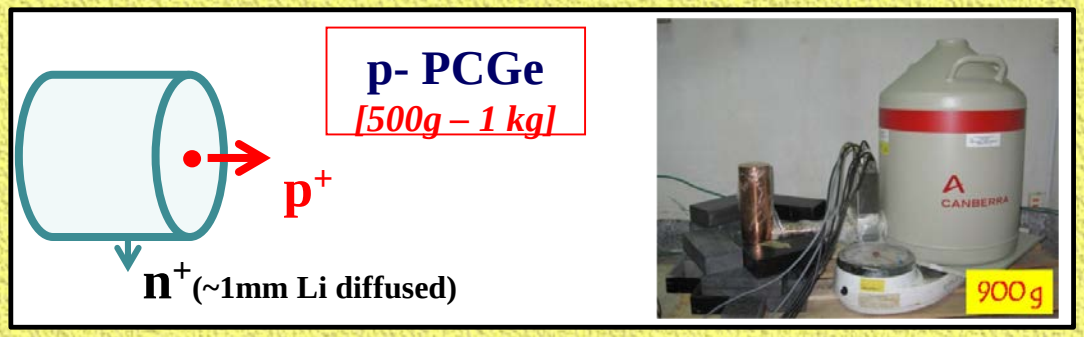
⇨ **sub-keV O(kg) ULEGe / PCGe** *[NIMA16]*

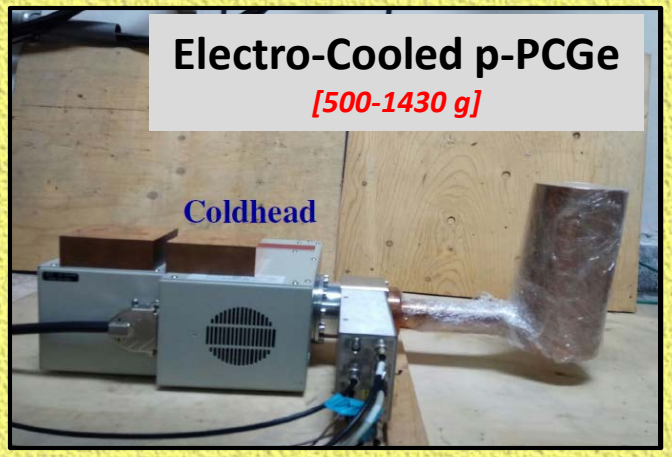
- Theory Program (Atomic effects in ν(χ)–N
- Light Dark Matter @ KSNL *[PRD09,PRL13,AP14]*
- CDEX Dark Matter @ CJPL *[PRD13 ..etc]*

Future Ge-based Projects at CJPL :

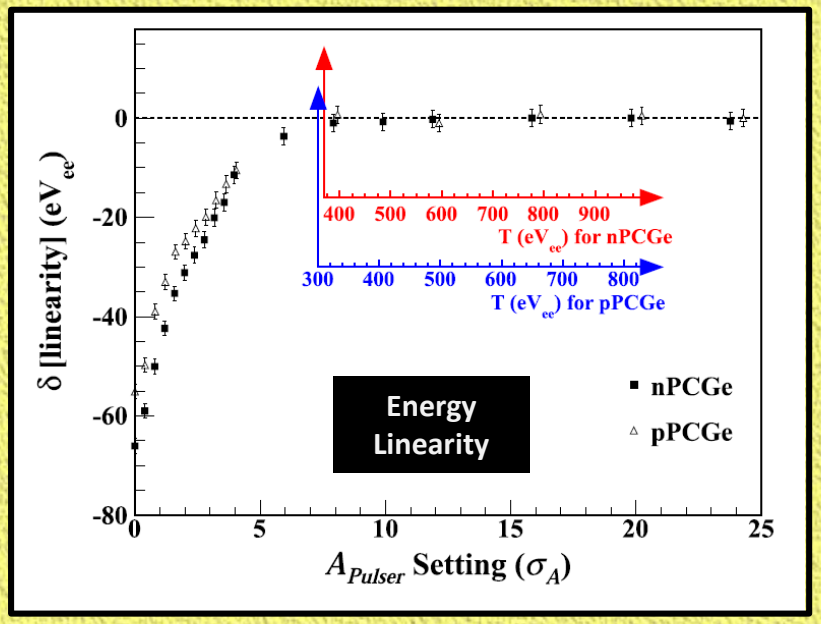
DM & $0\nu\beta\beta$

Sub-keV Ge Detector Techniques : Hardware/Software Development *[NIMA16]*





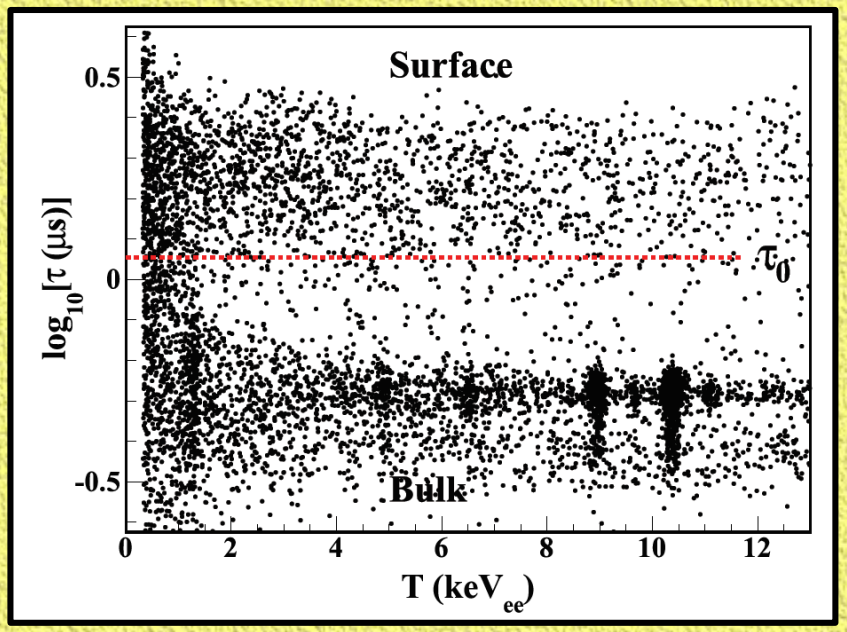
- Cooling & Temperature Control within Shielding
- Adopt Lindhard Quenching Factors
- Near Threholds Energy Definition & Calibration & Linearity
- Trigger Efficiencies near threshold
- Bulk Vs Surface Event Selection – algorithms & efficiencies
- Physics Vs Noise Pulse Shape Differentiation -- algorithms & efficiencies

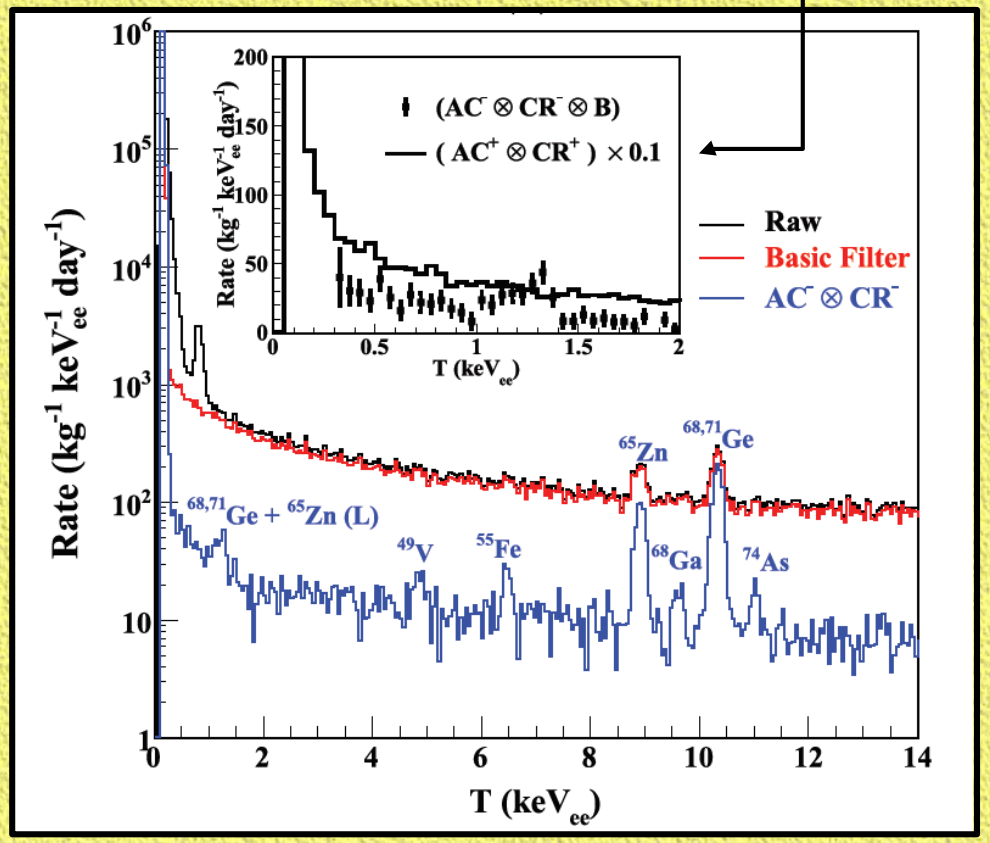


	Generation	Mass (g)	Pulsar FWHM (eV_{ee})	Threshold (eV_{ee})
LN_2	G1	500	130	500
LN_2	G2	900	100	300
Electro-cool	G3	500	70	200
Electro-cool	$G3^+$	1430	*In Progress*	*In Progress*

AC- (Anti-Compton), CR-(Cosmic Veto) & B (Bulk) Events Selection

Cosmic-Induced HE Neutron Events





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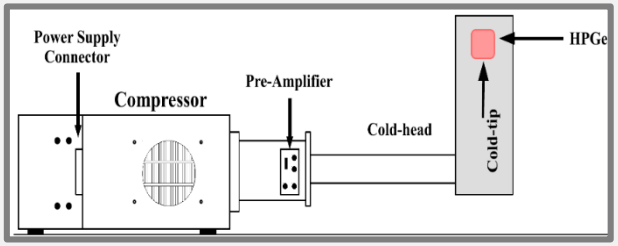
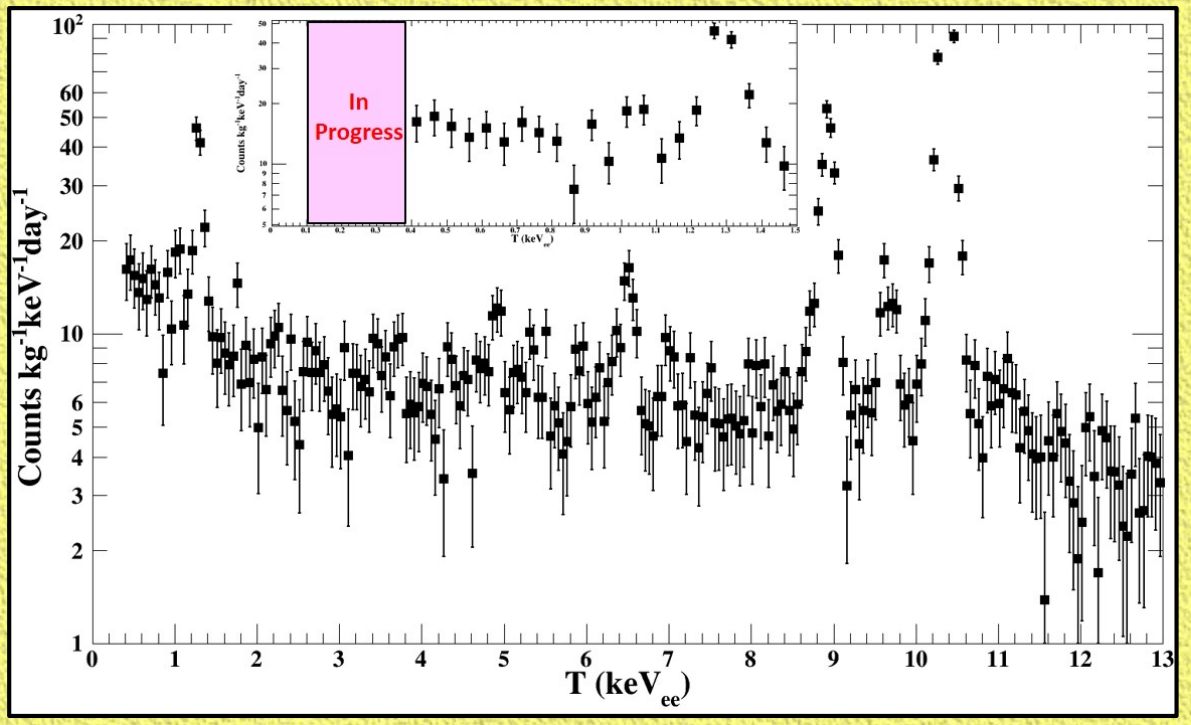
Electro-cool	G3	500	70	200
Electro-cool	G3+	1430	*In Progress*	*In Progress*

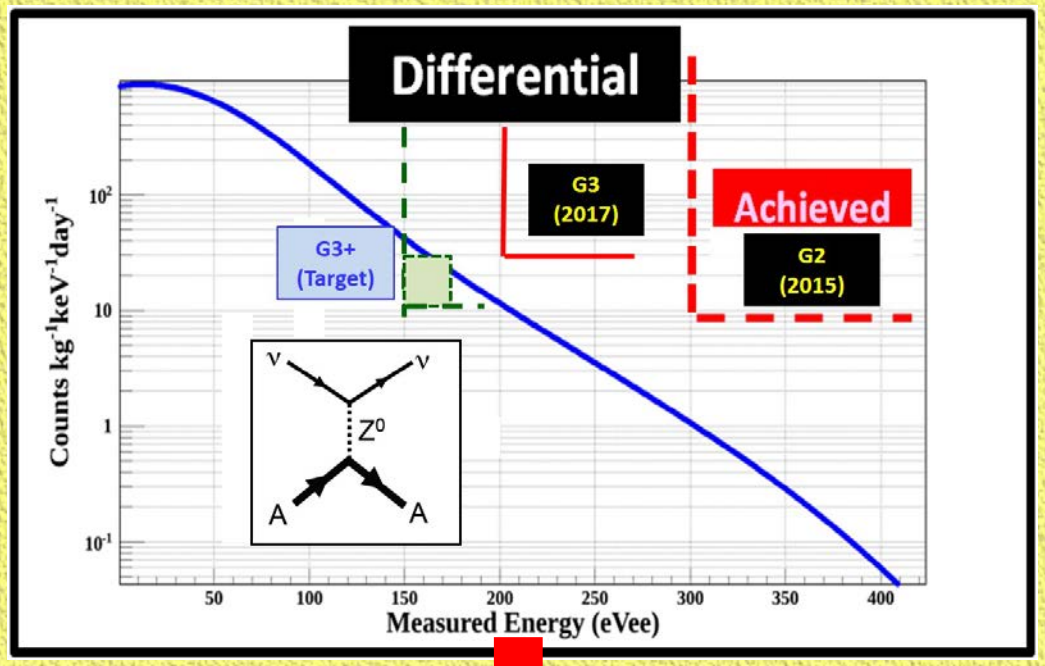
Electro-cooled PCGe



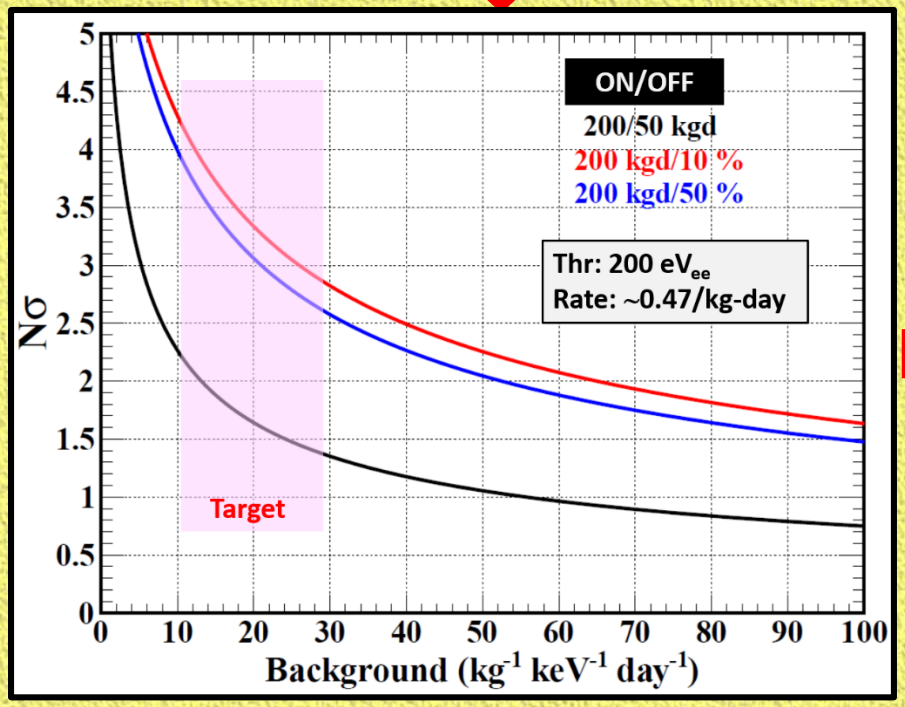
- ☑ Typical G3 (500g) Spectrum ⇨
- ☑ With Anti-Compton & Cosmic-Ray & Surface Events Vetos
- ☑ Near Threshold Data Analysis In Progress.

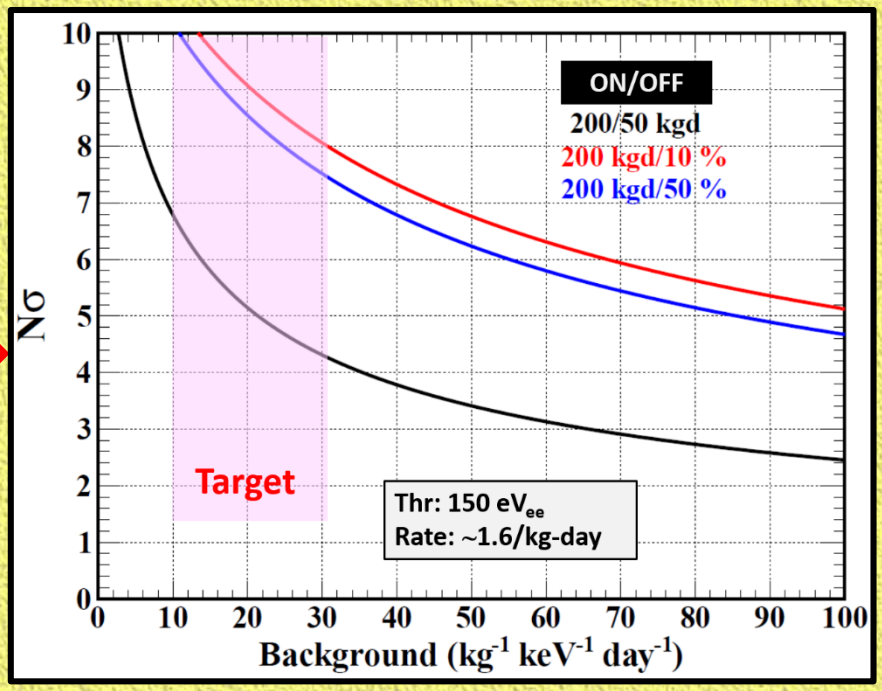


Projected Sensitivities: νA_{el} at KSNL



- ☑ G3 (500g, 200-eV) Data Taken ON/OFF ~ >200 / >30 kg–days
- ☑ Current DAQ: G3+ (1430g)
- ☑ Power Plant Decommissioned : 2022-23





QM Coherency as a Qualifier for νA_{el}

[PRD 93, 113006 (2016) ; arXiv: 2010.06810]

- ☑ **QM Coherency is central**
- ☑ **Coherency is a *continuous* variable dependent on q^2 via E_ν & Target A(Z,N) in νA_{el}**
- ☑ **Define a *quantifiable* parameter beyond qualitative descriptions**
- ☑ **Parametrize: $\alpha(q^2) \equiv \cos\langle\phi\rangle \in [0,1]$, where $\langle\phi\rangle(q^2)$ is the QM *phase mis-alignment angle* between two non-identical nucleons in A(Z,N)**
- ☑ **Unified Description for all A(Z,N) ; consistent comparison possible.**

νA_{el} differential cross-section

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

$\Gamma(q^2)$ describes many-body physics of A(Z,N)

Application-Dependent Complementary formulations

1. **Data-Driven:**

$$\Gamma_{DATA}(q^2) = [\,\varepsilon Z - N\,]^2\,\xi(q^2)$$

$\xi(q^2)$=measurable σ-suppression relative to full coherency

$\varepsilon=(1-4\sin^2\theta_W)=0.045$

2. **Nuclear (Microscopic) Physics * :**

$$\Gamma_{NP}(q^2) = [\,\varepsilon Z\,F_Z(q^2) - N\,F_N(q^2)\,]^2$$

3. **Quantum-Mechanical Coherency:**

$$\Gamma_{QM}(q^2) = [\varepsilon Z - N]^2\,\alpha(q^2) + (\varepsilon^2 Z + N)\,[1-\alpha(q^2)]$$

Data-Driven

$$\xi(q^2) = \alpha(q^2) + \left[1 - \alpha(q^2)\right]\left[\frac{(\varepsilon^2 Z + N)}{(\varepsilon Z - N)^2}\right]$$

$\xi(q^2)$

$$\xi(q^2) = \frac{\left[\varepsilon Z F_Z(q^2) - N F_N(q^2)\right]^2}{(\varepsilon Z - N)^2}$$

Quantum Mechanics Coherency

Microscopic Nuclear Physics

$$\left[\frac{d\sigma}{dq^2}\right]_{\nu A_{el}} \propto \begin{cases} [\varepsilon^2 Z + N], \\ [\varepsilon Z - N]^2, \end{cases}$$

Total Decoherency: $\alpha=0$; $\langle\phi\rangle=\pi/2$

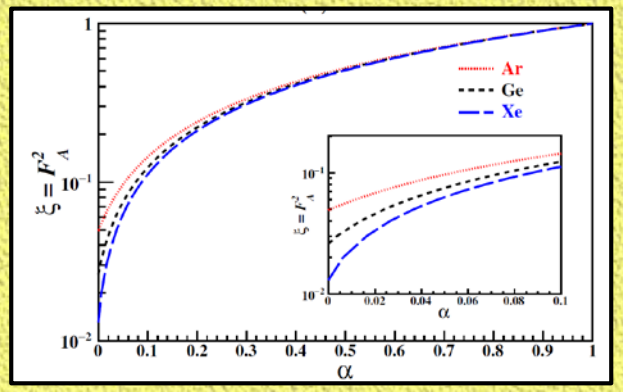
Complete Coherency: $\alpha=1$; $\langle\phi\rangle=0$

* **NP Model** ***(to define ranges & get approximate numbers for q^2-dependence)*:**

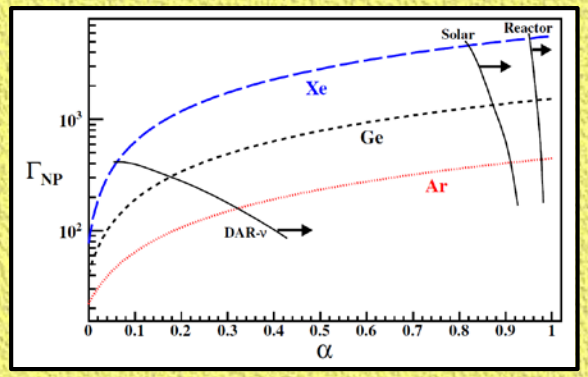
$$F_N(q^2) = F_Z(q^2) \equiv F_A(q^2) \Rightarrow \xi(q^2) = F_A^2(q^2)$$

$$\oplus \quad F_A(q^2) = \left[\frac{3}{qR_0}\right] j_1(qR_0)\, \exp\left[-\frac{1}{2}q^2 s^2\right]$$

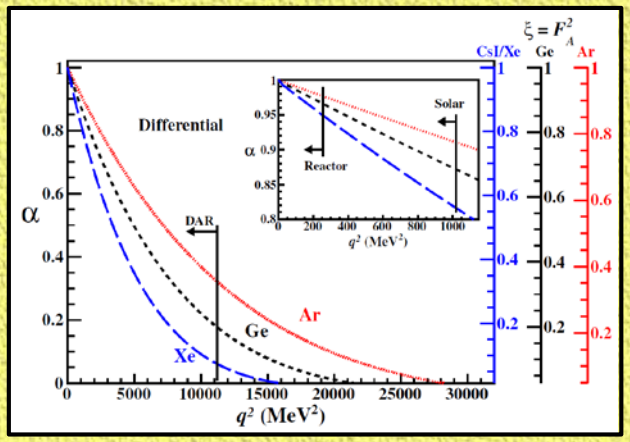
Helm Form Factor



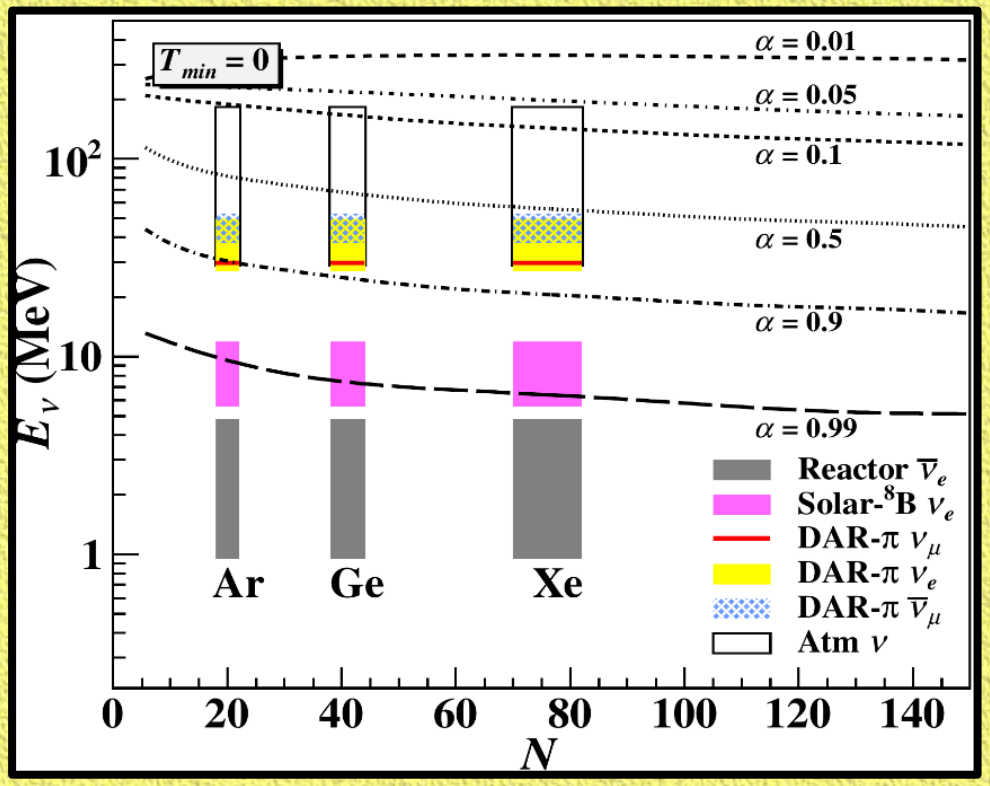
$\xi=f(\alpha)$



$\Gamma_{NP}=f(\alpha)$



$\xi(q^2)$ & $\alpha(q^2)$



CsI/Xe @ DAR-π :

$\alpha \in [0.72, 0.32]$ for $T \in [6, 23]$

Ar @ DAR-π :

$\alpha \in [0.88, 0.51]$ for $T \in [19, 93]$

Ge @ Reactor :

$\alpha \in [1.00, 0.97]$ for $T \in [0, 1.9]$

TABLE II: The half-maxima in the distributions of $[\Phi_\nu \cdot \sigma_{\nu A_{el}}]$ at T_{min}=0 for the different neutrino sources, and the values of $\langle\alpha\rangle$ probed by the selected target nuclei. The ν_μ from DAR-π is mono-energetic.

ν Source	Half-Maxima of $[\Phi_\nu \cdot \sigma_{\nu A_{el}}]$ 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

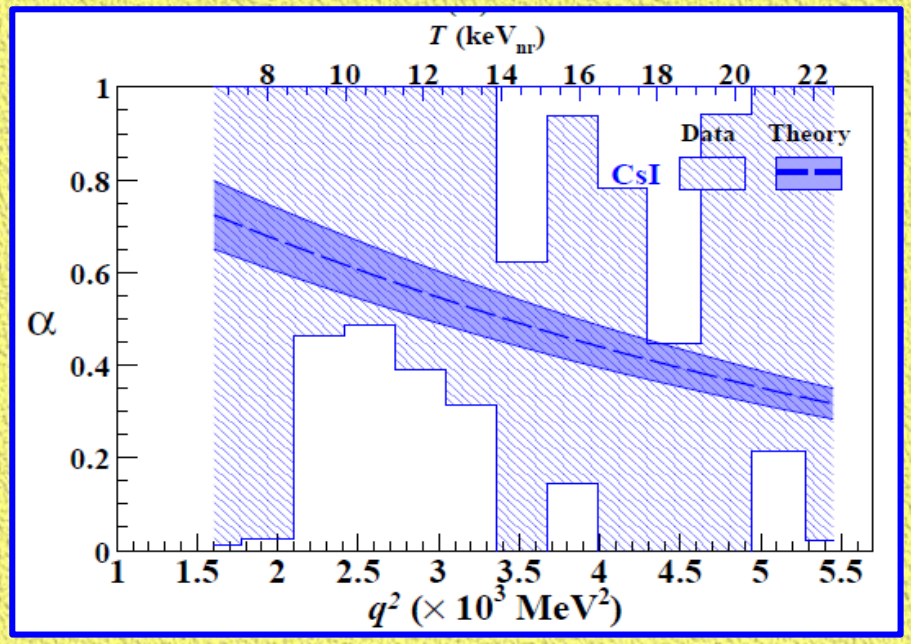
TABLE III. Maximum neutrino energy (E_ν) with which coherency is maintained among the constituents, as characterized by the parameters $F(q^2_{\rm max})$, α and ξ being > 0.95.

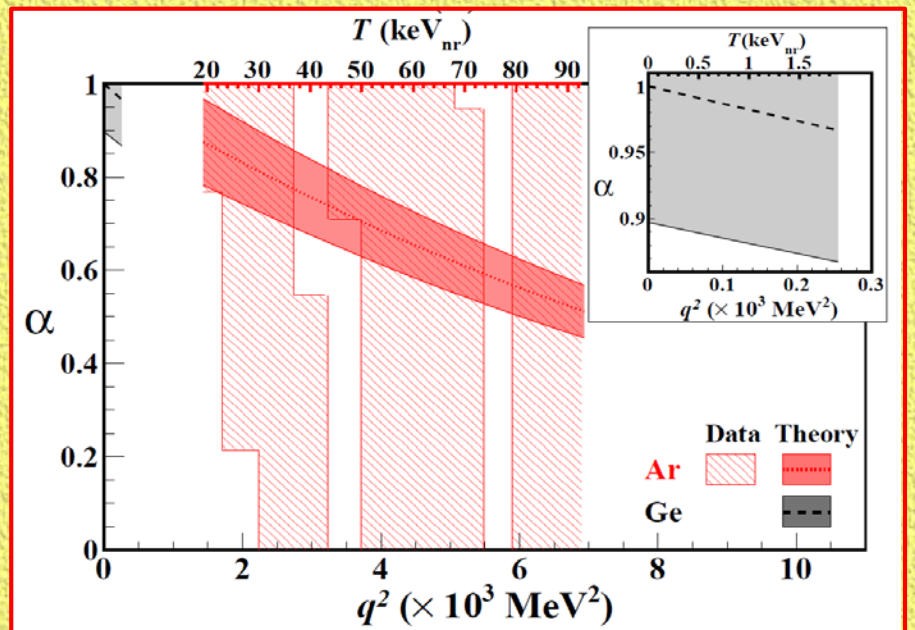
Parameter	Maximum E_ν (MeV) for		
> 0.95	Ar	Ge	Xe
$F(q^2_{\rm max})$	17.2	14.1	11.6
α at $T_{\rm min} = 0$	21.1	17.4	14.3
ξ at $T_{\rm min} = 0$	21.6	17.6	14.4

$\langle\alpha\rangle$ @ different ν-Sources

E_ν(max) @ Full Coherency

e.g. "Applications" to COHERENT Data:





Data:

- COHERENT CsI *[PRD 100, 033003, (2019)]*
- COHERENT Ar *[arXiv:2003.106302 (2020)]*

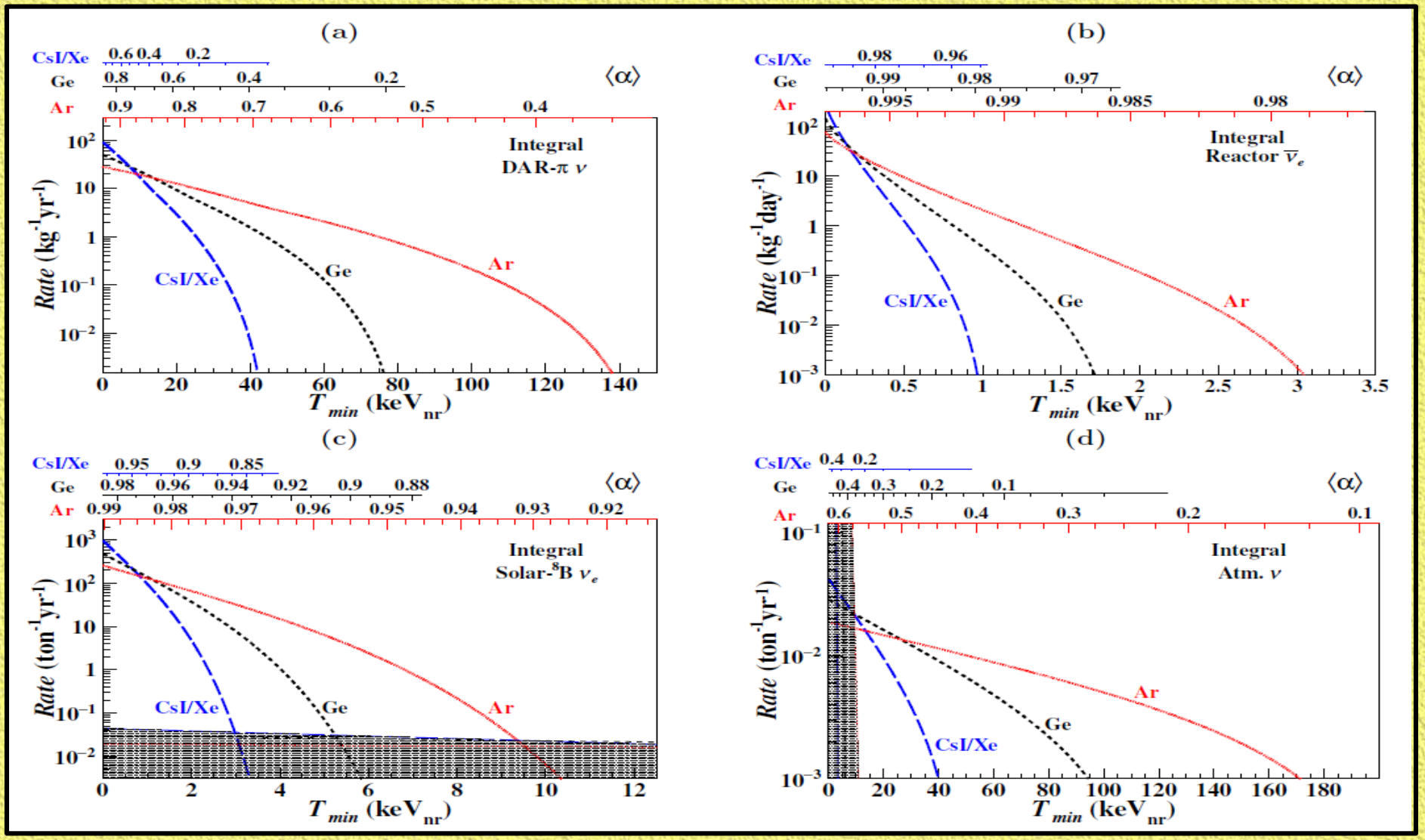
Theory:

- Helm Form Factor with 10% bin-wise accuracy

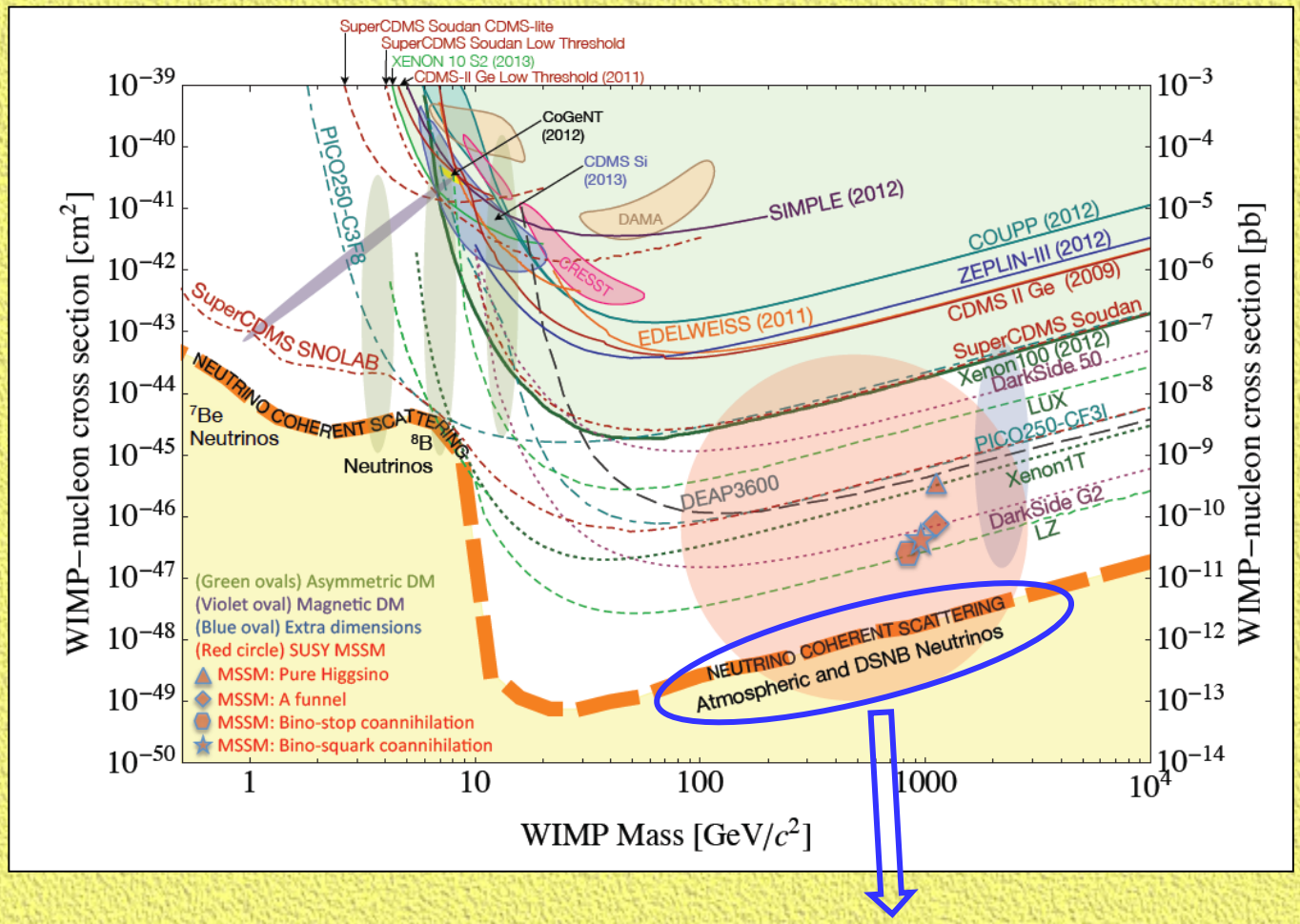
CsI (Data Only)

- **Exclude Complete Coherency** *($\alpha = 1$) [⇒QM+MBP] @*
  - $q^2 = 3.5\text{x}10^3$ MeV²
  - $\alpha < 0.73$ (90%CL)
  - $\langle\phi\rangle < 0.24\pi$ (90%CL)
  - p=0.025
- **Exclude Complete Incoherent Sum** *(α=0) [⇒QM] @*
  - $q^2 = 2.6\text{x}10^3$ MeV²
  - $\alpha > 0.38$ (90%CL)
  - $\langle\phi\rangle > 0.38\pi$ (90%CL)
  - p=0.012

Rates & <α> to Integral Cross-sections: Different Sources & Targets



$$\nu(\chi) + A \rightarrow \nu(\chi) + A$$



- ☑ α<0.2 for Xe
- ☑ Describing Neutrino Floor at large WIMP-mass as due to [atm νA_{el}] "Coherent" scattering is Marginal !!
- ☑ EvNS rather than C-EvNS !

Prospects & Outlook

- νA_{el} observed in experiment with ν from ORNL-SNS DAR-π : 🏆🏆 *"Taming of the Beam Background"*
- Probe *finer questions* after 1st generation, both theory & experiments: precision-SM, BSM, Nuclear Form Factors, QM Coherency, Applications ……
- Reactor νA_{el} – Probe Complete Coherency *(i.e. less theoretical uncertainties for BSM)* ; testbed for novel low threshold detectors
- TEXONO@KSNL: 200 eVee threshold with 1.5 kg EC-Ge ; data taking and analysis continues to scale νA_{el} -summit
- *A natural Portal for Synergy* between Neutrino and Dark Matter programs – both Physics & Techniques, Both Directions