Studies of Reactor νA_{el} & Neutrino Electromagnetic Interactions @ KSNL with TEXONO

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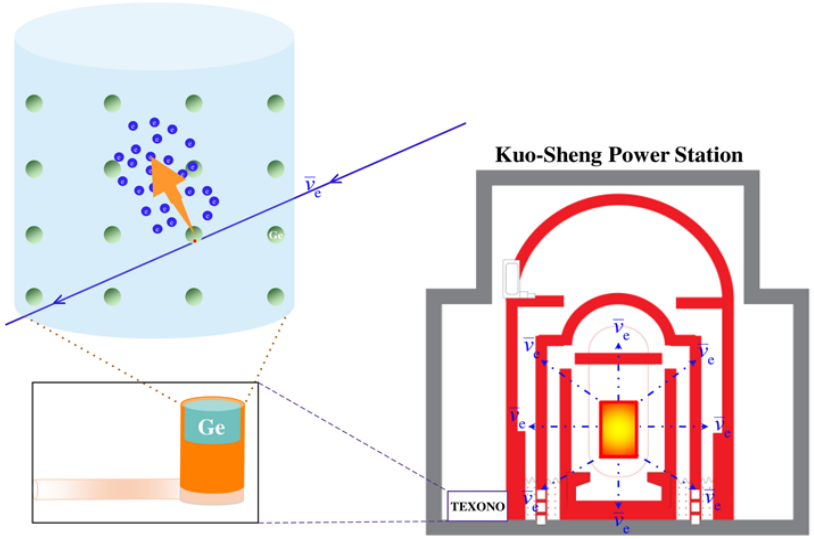
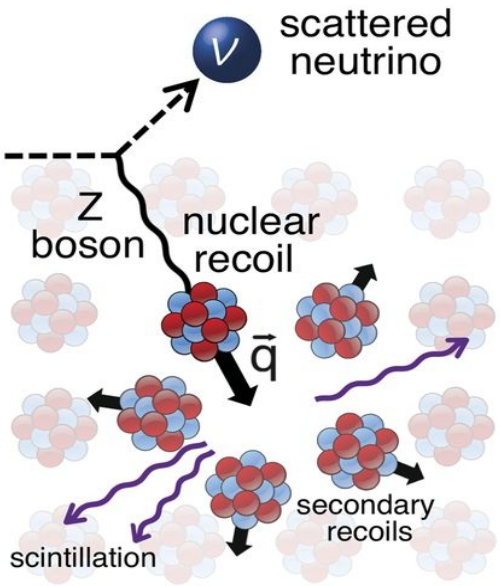
Based on – arXiv:2606.16864 (2026)



Introduction



☆ **Coherent Elastic Neutrino-Nucleus Scattering (νA_{el})**

- ❑ Electroweak NC Process
- ❑ Allowed in Standard Model

☆ **Exchange of Z^0 – Boson**

☆ **Signature:** sub-keV Nuclear Recoils

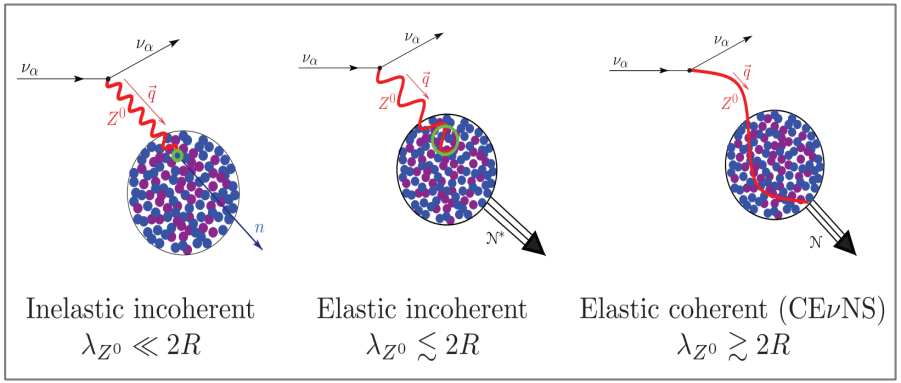
☆ **Coherent:** Outgoing nucleon wave-functions remain in-phase [$E_\nu < \mathcal{O}(10)$MeV]

☆ **Elastic:** Target remains in the same energy state

✍ **Proposed right after discovery of Neutral Current**

D. Z. Freedman [1974]

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



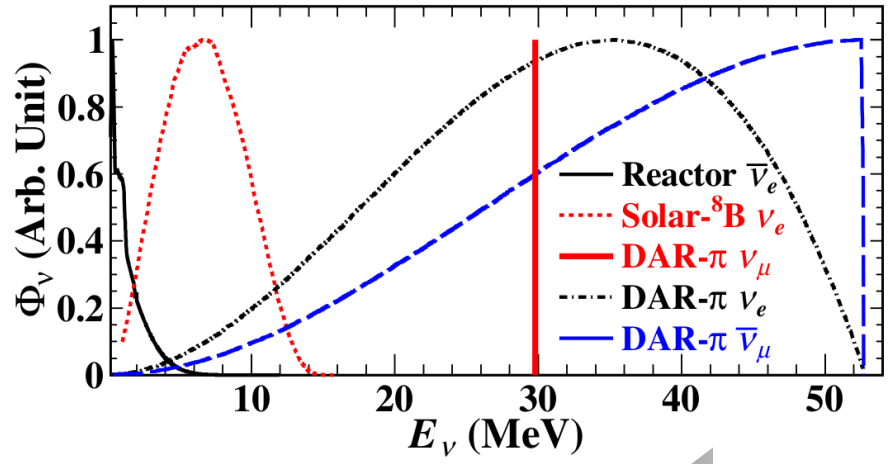
Why νA_{el} Matters ?

- ❑ **Blind** to flavor
- ❑ **Precision test** of SM & Neutrino Properties
- ❑ **Neutrino floor** for Dark Matter
- ❑ **Extensions of SM, & NSI's** test
  - Beyond Standard Model (BSM) Searches
- ❑ Reactor monitoring …….

Observation

1. SNS – COHERENT CsI – [2017]
2. Solar ν – PandaX & Xenon LXe – [2024]
3. Reactor ν – CONUS+ Ge – [2025]

Reactor and Ge for νA_{el} study



COHERENCY

PRD 93, 113006 (2016)

Sources:

Solar, Accelerator, Reactor

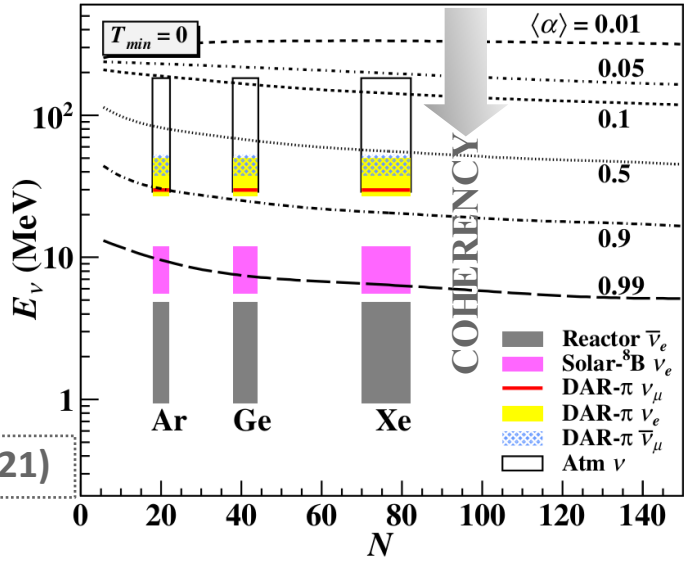
➢ **Reactor:**

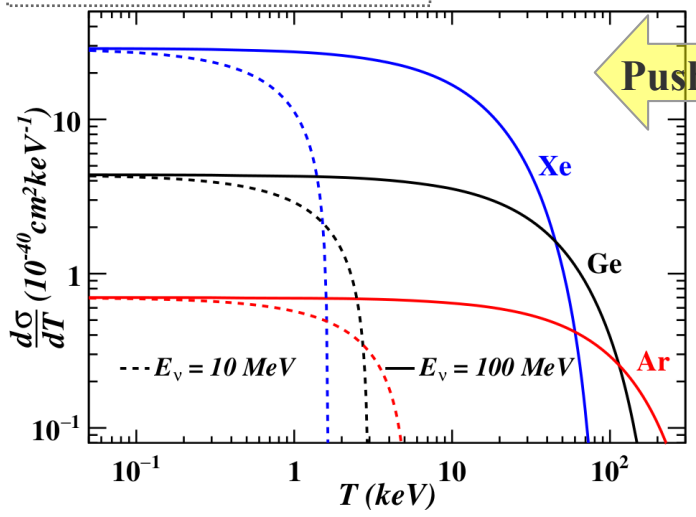
Intense ⊕ Pure ν_e-flux

~ 10^{12} cm^{-2}s^{-1}

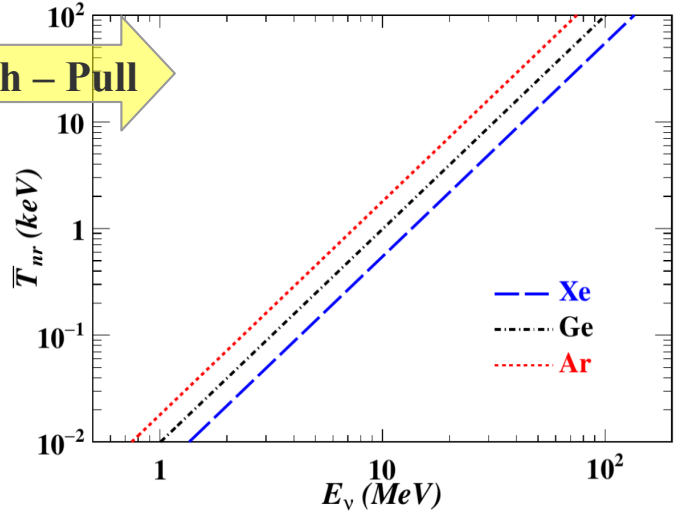
● > 99% Coherent process (anti-ν_e < 10 MeV)

PRD 103, 092002 (2021)





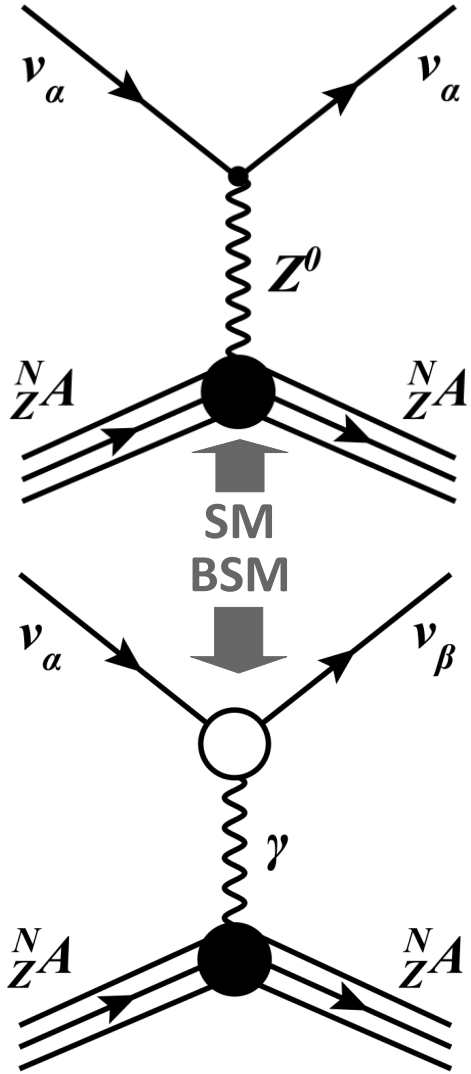
Push – Pull



Ge: A well-suited Target

- νA_{el} Largest Cross Section @ low-energy ν
- Favors heavy nuclei → N^2 Enhancement
- Ge:
  - ☑ Low Energy Threshold Potential *(key advantage)*
  - ☑ Excellent Energy Resolution
  - ☑ Push-Pull scenario

BSM (Neutrino Magnetic Moment μ_ν) – via νA_{el}



- Neutrino-γ Couplings → Consequence of Neutrino Mass
- Constitute Intrinsic **Neutrino Properties BSM**
- Among these:
  - NMM (μ_ν): Sensitive probe in LE Experiments including νA_{el}
  - νA_{el} Process: Induced by μ_ν is Coherent ($F_{em}(q^2 \to 0) \approx 1$)
  - Cross Section Scales as Z^2

Phys. Rev. D 39, 3378 (1989)

$$\left[\frac{d\sigma_{\nu A_{el}}}{dT_{nr}}\right]_{\text{odd-}A} = \frac{\pi\alpha_{em}^2\mu_\nu^2}{m_e^2}\left[\frac{1-T_{nr}/E_\nu}{T_{nr}}Z^2 - \frac{T_{nr}}{2E_\nu^2}\mu_N Z + \frac{(2-T_{nr}/E_\nu)^2 - 2MT_{nr}/E_\nu^2}{8M}\mu_N^2\right]$$

Odd-A Nuclei

@ Low Recoil Energy regime ($T_{nr}/E_\nu << 1$)

$$\left[\frac{d\sigma_{\nu A_{el}}}{dT_{nr}}\right]_{\text{spin-zero}} = \frac{\pi\alpha_{em}^2\mu_\nu^2}{m_e^2}\left[\frac{1-T_{nr}/E_\nu}{T_{nr}} + \frac{T_{nr}}{4E_\nu^2}\right]Z^2$$

Even-A Nuclei

$$\frac{d\sigma_{\nu A_{el}}}{dT_{nr}} \simeq \frac{\pi\alpha_{em}^2\mu_\nu^2}{m_e^2}\frac{Z^2}{T_{nr}}$$

- **Further:** Millicharge, Charge Radius,…. via ν-N

Quenching Factor (Ge)

Quantifies
Ionization Efficiency of Nuclear Recoils

Recoil Spectrum → Convoluted *with Quenching Factor*

$$\frac{dR}{dE_I} = \frac{dR}{dE_R}\left(\frac{1}{Q} - \frac{E_I}{Q^2}\frac{dQ}{dE_I}\right)$$

We follow:
Standard Lindhard Quenching Function

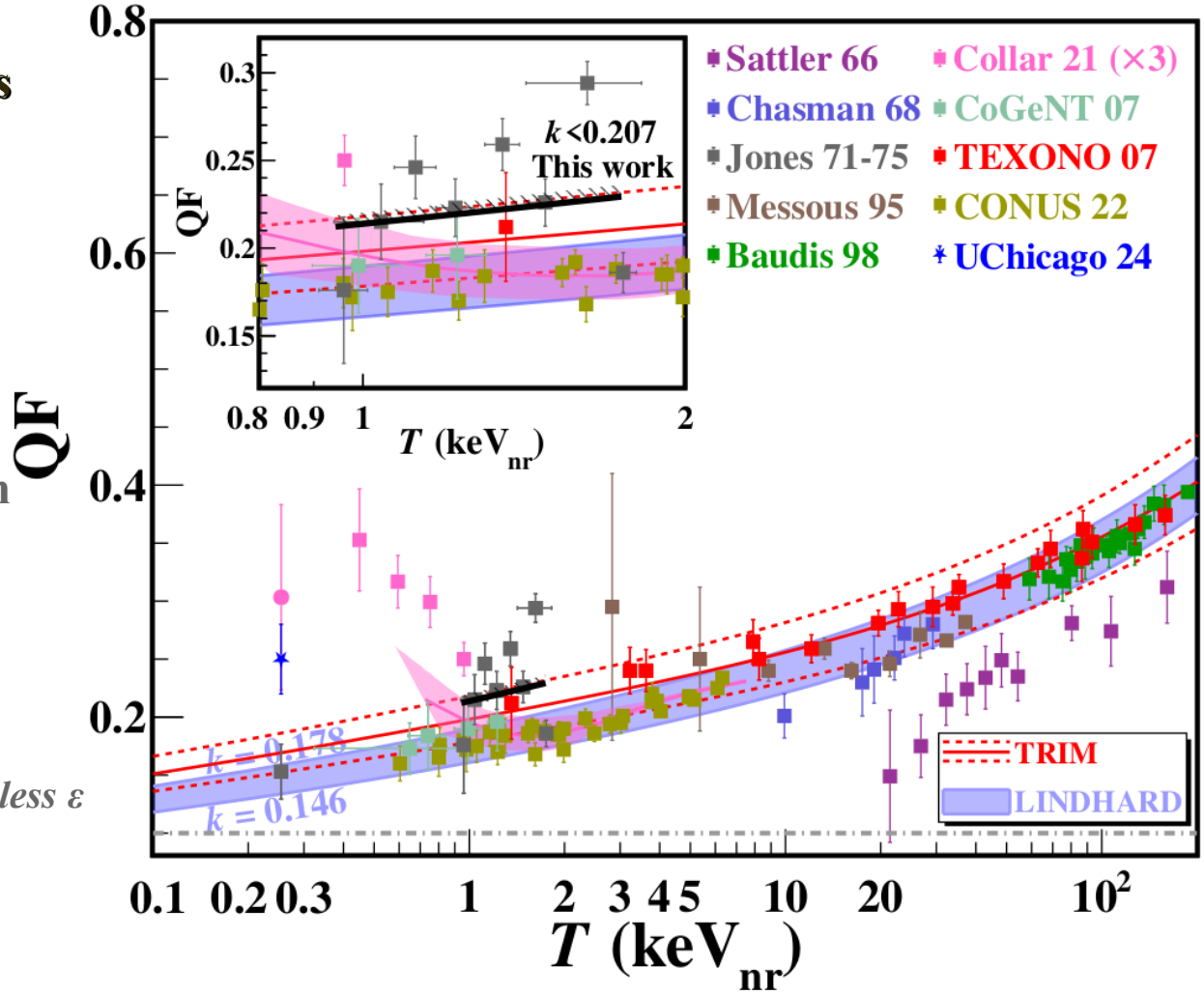
$$Q(E_R) = \frac{kg(\epsilon)}{1 + kg(\epsilon)}$$

- ☑ *k*: A Measure of Electronic Energy Loss
- ☑ Lindhard *k = 0.157* (Ge)
- ☑ *g(ε): Empirical fitting function of dimensionless ε*

Further Research:

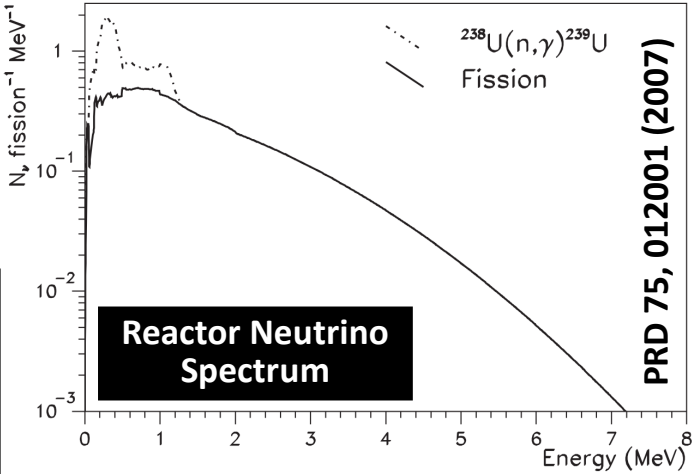
Accurate knowledge of QF is Essential

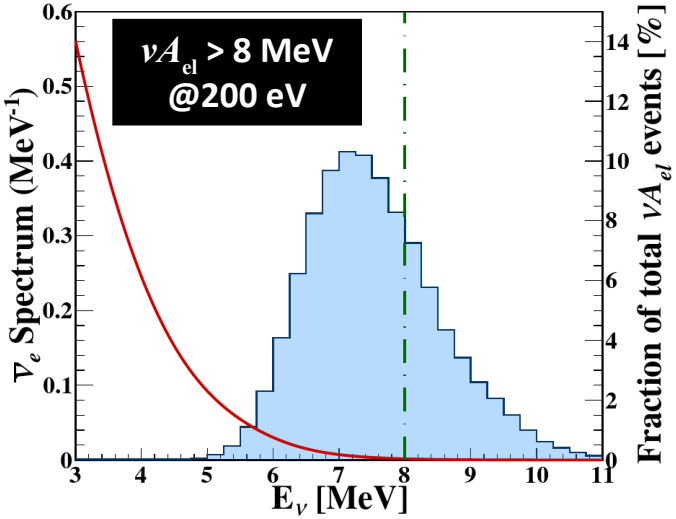
1. **Precisely interpreting νA_{el} data**
2. **Low energy responses in Ge**



TEXONO [Taiwan EXperiment On NeutrinO]

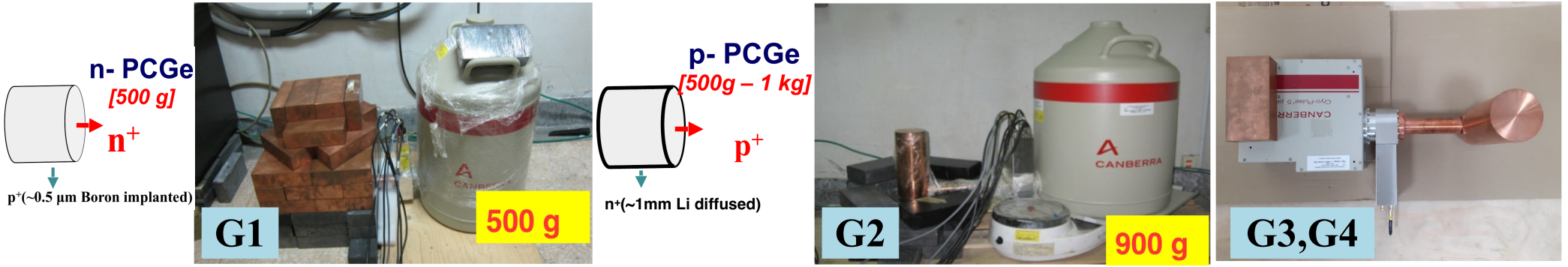
- **Location**: @ Kuo-Sheng Nuclear Power Plant -II [Northern shore of Taiwan]
- **Theme:** Low Energy Neutrino Physics & Dark Matter Searches
- **Collaboration:** India, China [CDEX] & Turkey
- **Flux:** Reactor Power of 2.9 GW → 6.35×10^{12} cm^{-2}s^{-1} @ distance of 28 m
- **Shielding:** 30 m.w.e. Overburden





- Reactor-ν analyses ➡ Traditionally restricted E_ν < 8 MeV
- Recent measurements [Daya Bay & JUNO] ➡ HE Tail 8-11 MeV
- Total cross section $\nu A_{el} \propto E_\nu^2$
- HE Tail ➡ Contribute 30% of total νA_{el} events [@ 200 eV Thrs.]

Point-Contact HPGe Detector @ TEXONO



	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	70	200
Electro-cool	G4	900	~50	~150

- *Custom Cold-tip temp.*
- *Compact Design*
- *Real-time monitoring*
- *No LN_2 required*
- *Less micro-phonic noise*

Electro-cooled
***p*PCGe**
(0.5,0.9,1.43 kg)
***n*PCGe**
(0.5 kg)

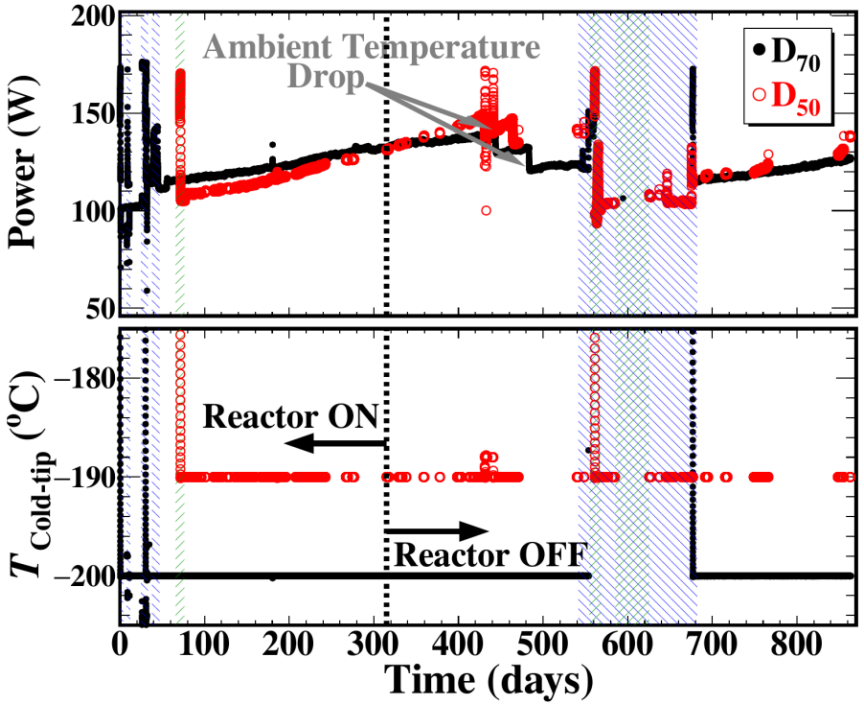
This Analysis

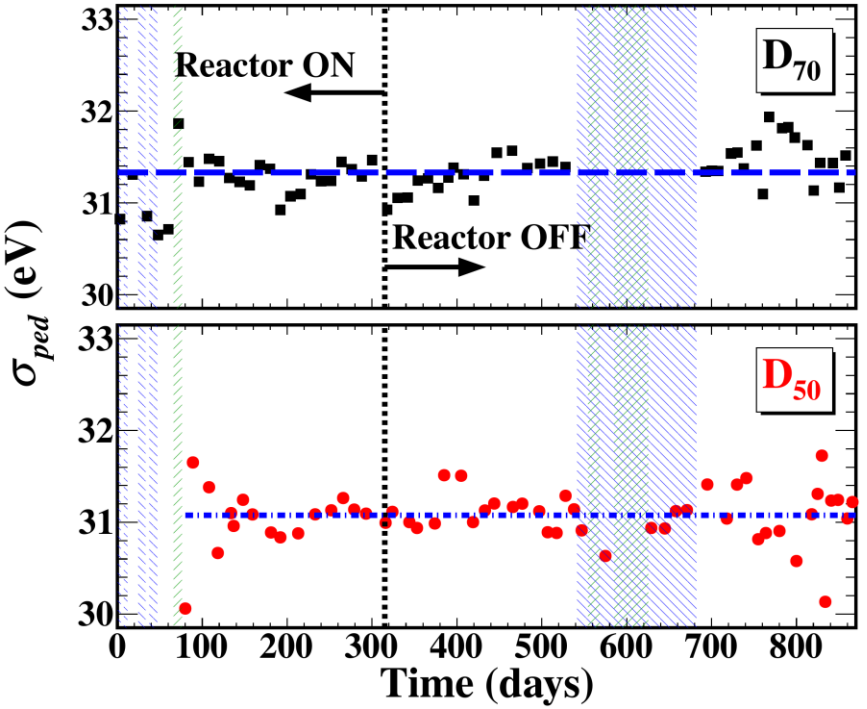
νA_{el} Data Analysis Strategies:

- **Events identified in 8 categories**
  - **$CR^{\pm} \otimes AC^{\pm} \otimes B/S$ [Cosmic-Ray / Anti-Compton / Bulk or Surface]**
  - **$CR^{-} \otimes AC^{-} \otimes B$ are PHYS candidate (ν/χ) events, uncorrelated with other signals**
  - **Others are "background/benchmark" samples, in situ with PHYS data**

- **Benchmark samples for optimizing analysis parameters & procedures, monitor stability & performance, measuring efficiencies, & reducing systematic uncertainties**
- **Optimized procedures & parameters applied to analysis of PHYS Samples**

Stability [>3.5 Years ⊕ COVID-19 Period]





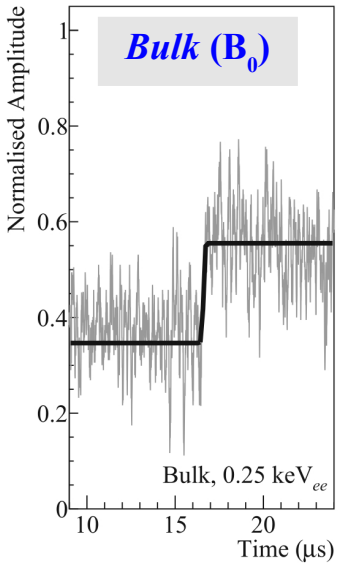
Secured key Parameters for D70 & D50:

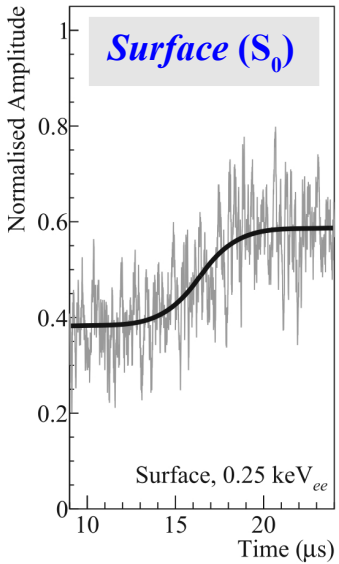
- ❒ 200 eV Threshold
- ❒ Pulsar FWHM 70 eV
- ❒ Controlled Background

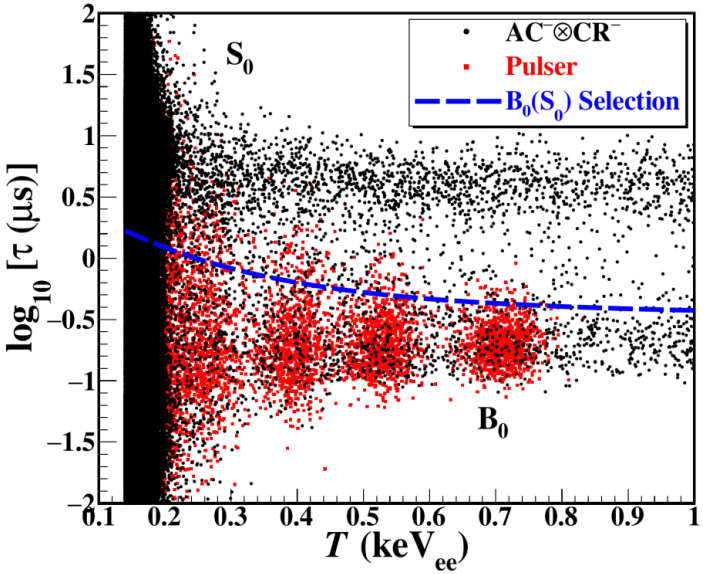
- Cold-tip temp. Offset = ± 0.05°C
- ~15 hrs. => Room Temp. → Set Temp.
  ~12 hrs. => Set Temp. → Room Temp.
- σ_{RMS} = 31.3(31.2) eV for D70(D50)
- σ_{RMS} Fluctuations ≈ 3.5(2.8) eV for D70(D50)

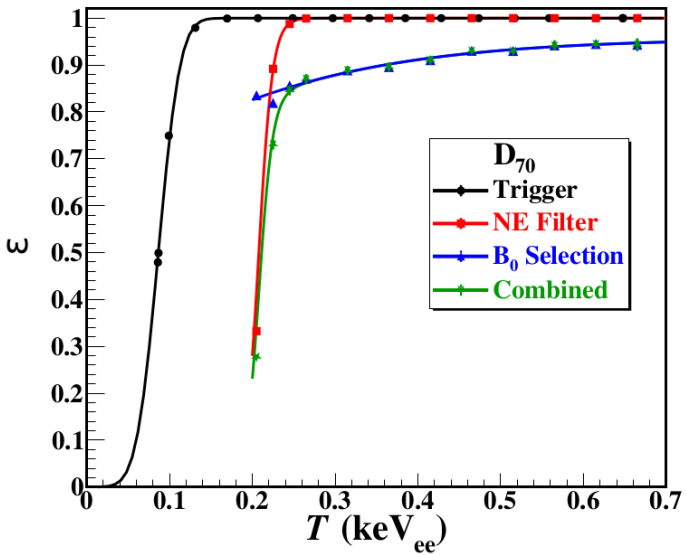
† D70 [70×70 – 1430 g] & D50 [50×50 – 500 g] *p*PCGe Detectors

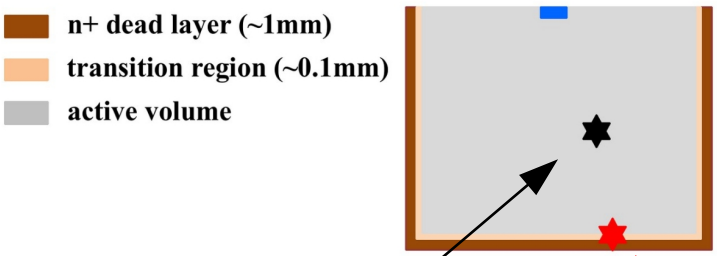
Signal Selection & Efficiency











Bulk Event
- Full Energy Deposit
- Drift → Fast

Surface Event
- Partial Energy Deposit
- Diffuse & Drift → Slow

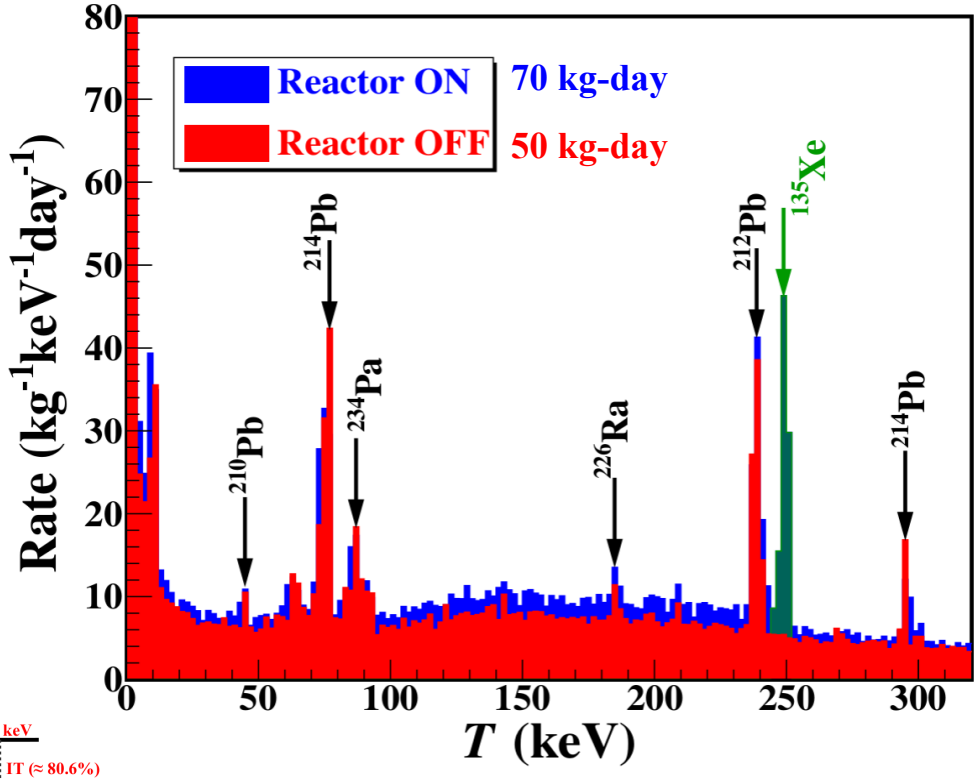
Pulse Rise-Time (τ)

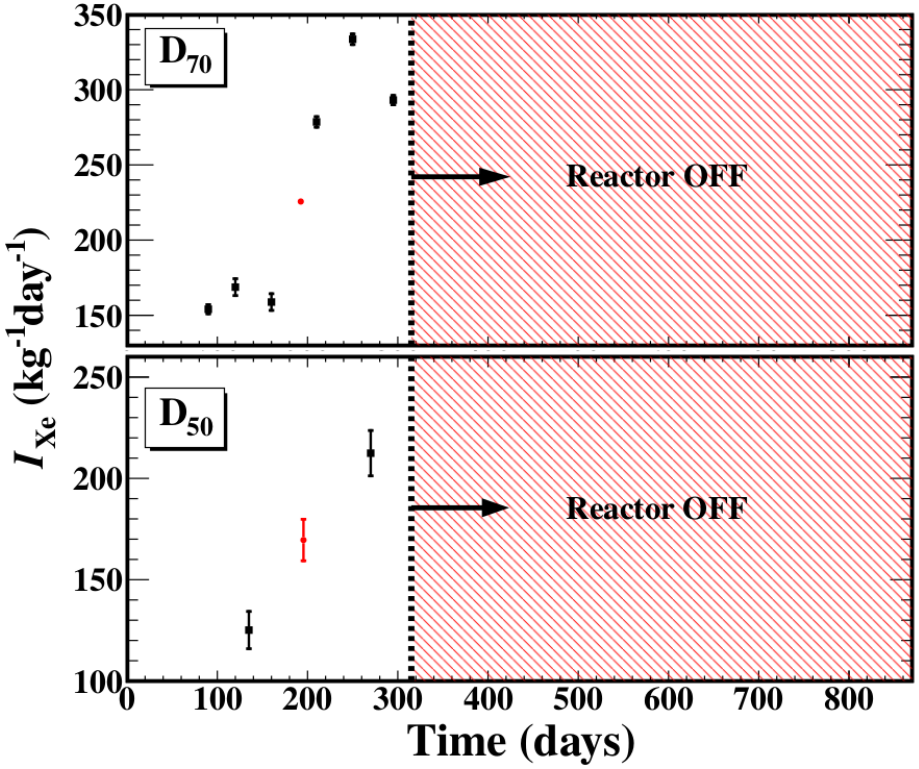
$$\frac{1}{2}A_0 \times \tanh\left(\frac{t-t_0}{\tau}\right) + P_0$$

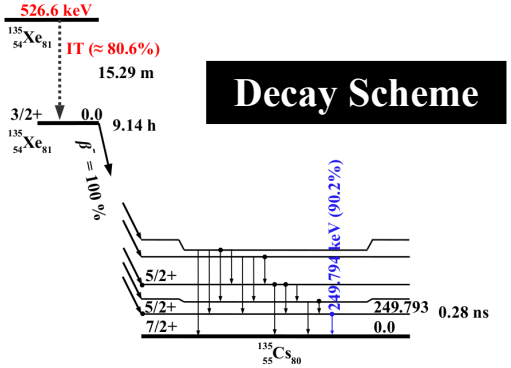
B_0/S_0 Selection

- ☑ Largest source of systematic uncertainty
- ☑ Multiple approaches for corrections [sub-keV region]
- ☑ Current Analysis: ***Optimized Pulsar* Reference as Bulk events**
- ☑ Efficiency >80%

Reactor ON-Related ^{135}Xe Background – [250-keV γ]







Decay Scheme

Anomalous Background

↓

Reactor ON Periods

✍ A Decay Product of ^{235}U

^{135}Xe → ^{135}Cs* + anti-ν_e + e$^-$

^{135}Cs* → ^{135}Cs + γ (249.8 keV)

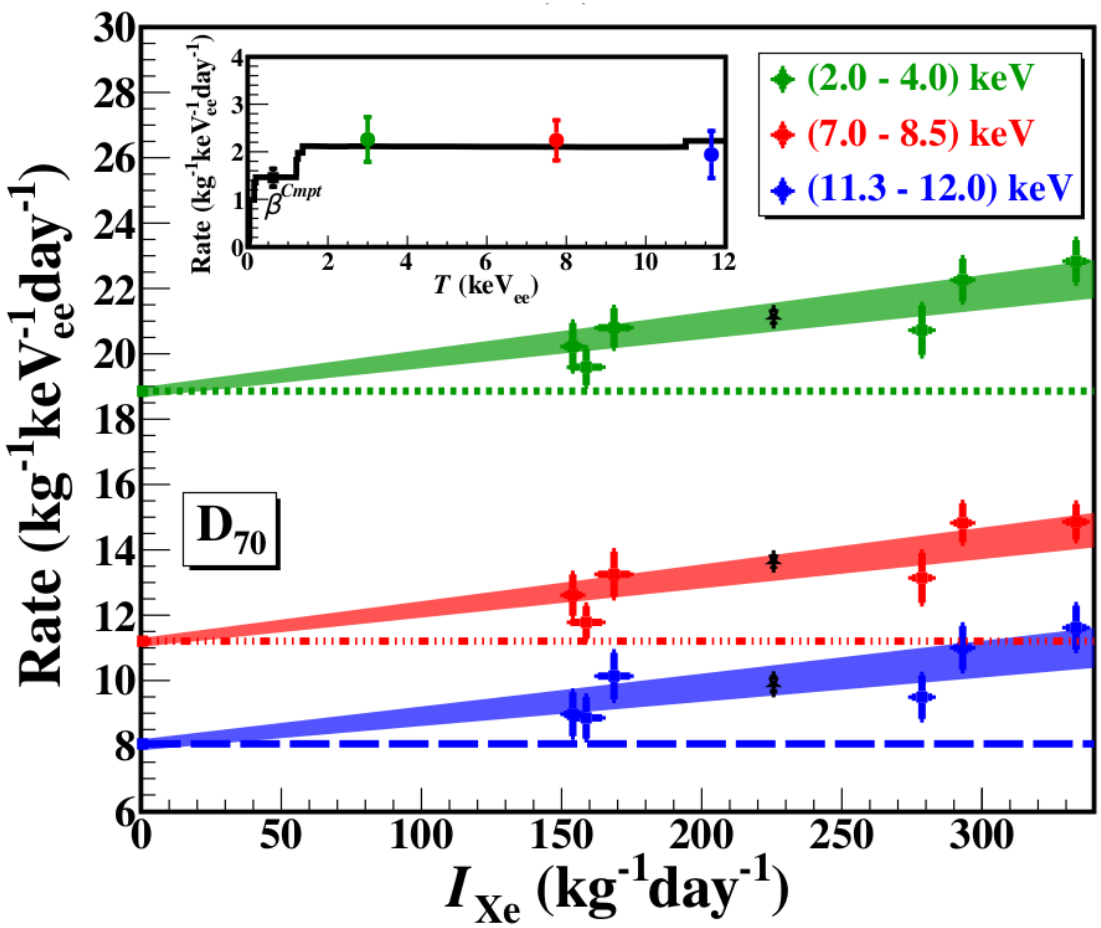
✍ Half-life = 9.14 h

✍ Good Neutron Absorber

Poison For Reactor

NIM A 705, 117 (2013)

TEXONO: ^{135}Xe Subtraction [250-keV γ]



Correlation & Calibration

- ❑ Evaluated for:

[2-4] keV, [7-8.5] keV, and [11.3-12] keV Energy Regions

- ❑ Free from Cosmogenic X-ray Peaks

Contribution: Sub-keV Region

- ❑ **On-Average Contributes:**

~1.72 ± 0.02 kg^{-1}.keV^{-1}.day^{-1}

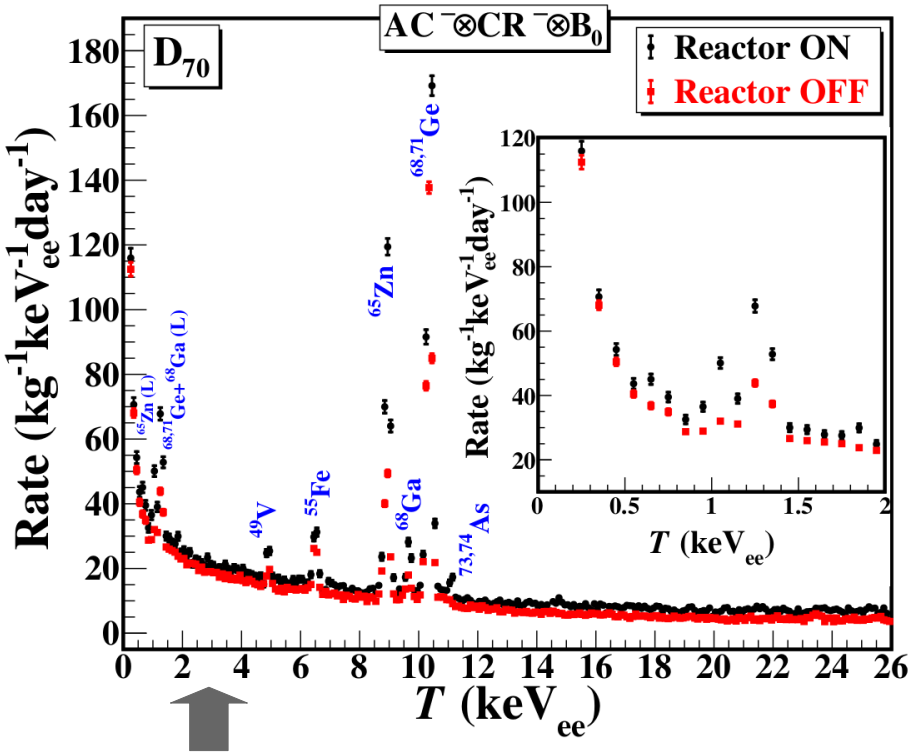
- ❑ **Reactor ON PHYS background:**

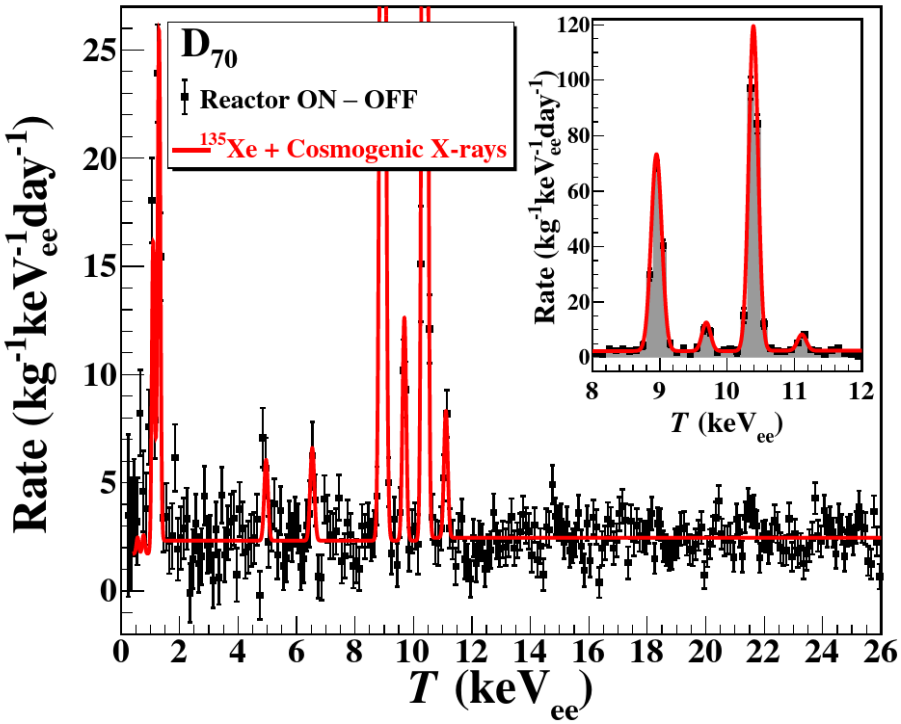
~116 counts.kg^{-1}.keV^{-1}.day^{-1}

- ❑ **Minor (~ 0.9% of PHYS – Reactor ON counts) & known background source**

J. Phys. G: Nucl. Part. Phys. 47, 045202 (2020)

νA_{el} Candidate Spectra [PHYS Samples]

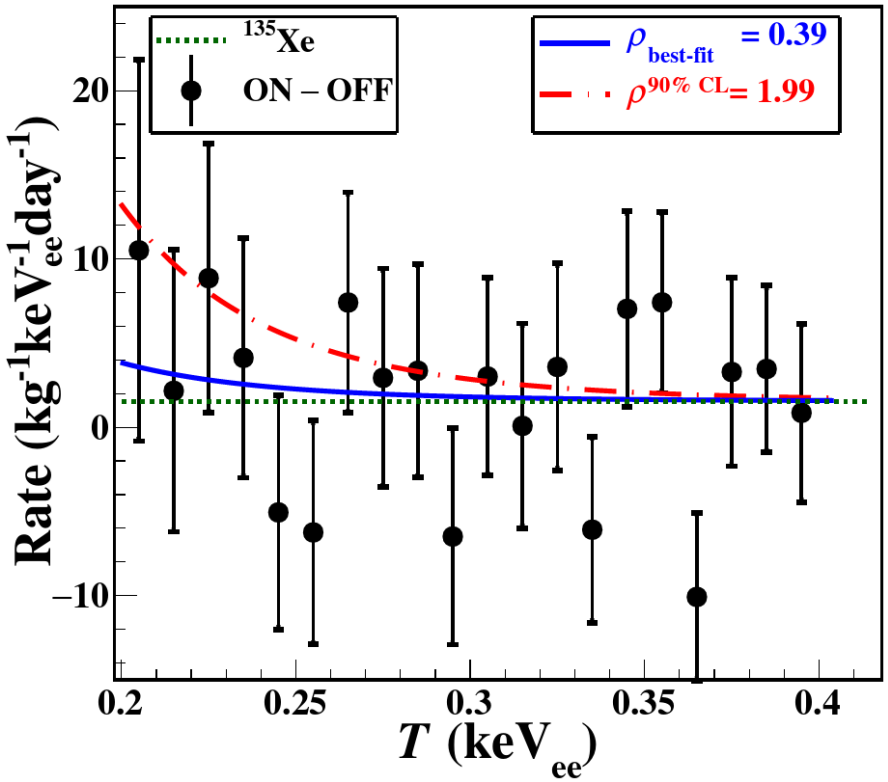




- **Exposure: D70 – 242(559.3) & *Total* – 404(813.7) kg.days ON(OFF)**
- **Residual [ON-OFF] → Finite ^{135}Xe Compton excess**
- **Region < 12 keV → Populated by Cosmogenic peaks → Valuable for Calibration**

†AC⁻⊗CR⁻⊗B_0 → Anti-Compton veto ⊗ Cosmic Ray veto ⊗ Bulk Events

Limits: SM



Residual Spectrum (Dominant ROI)

Total Exposure

Reactor ON: 404 kg.days

Reactor OFF: 813.7 kg.days

➢ **ρ Estimate Excess over SM Prediction**

$$\chi^2(\rho,\beta,\mu_\nu;k) = \sum_i \left[\frac{N_i - (\rho\ \nu_i^{\rm SM}(k) + \nu_i^{\rm BSM}(\mu_\nu)) - \beta}{\Delta_i}\right]^2 + \left[\frac{\beta - \beta^{\rm Cmpt}}{\Delta^{\rm Cmpt}}\right]^2$$

TEXONO [with 200 eV threshold]

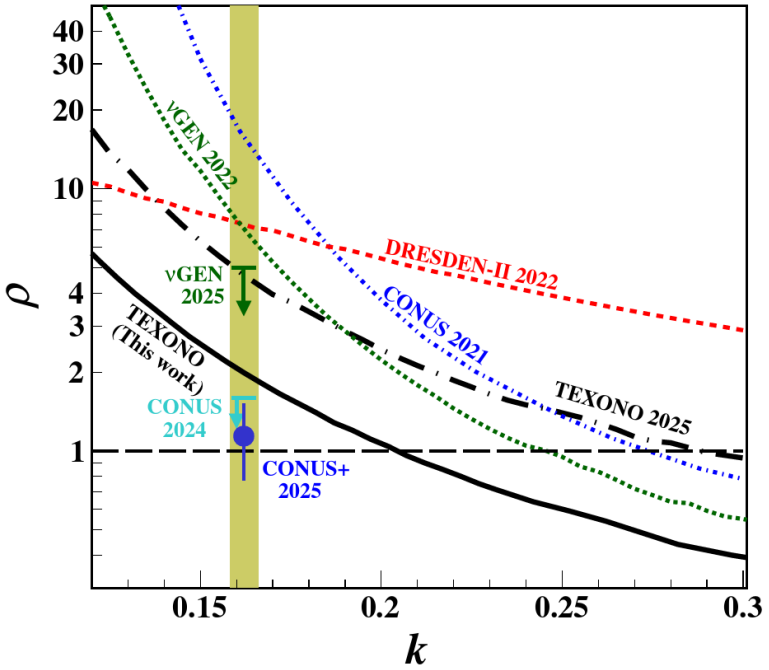
ρ < 2.0 @ SM [Lindhard k = 0.157] @ 90%CL

@ SM value ρ =1

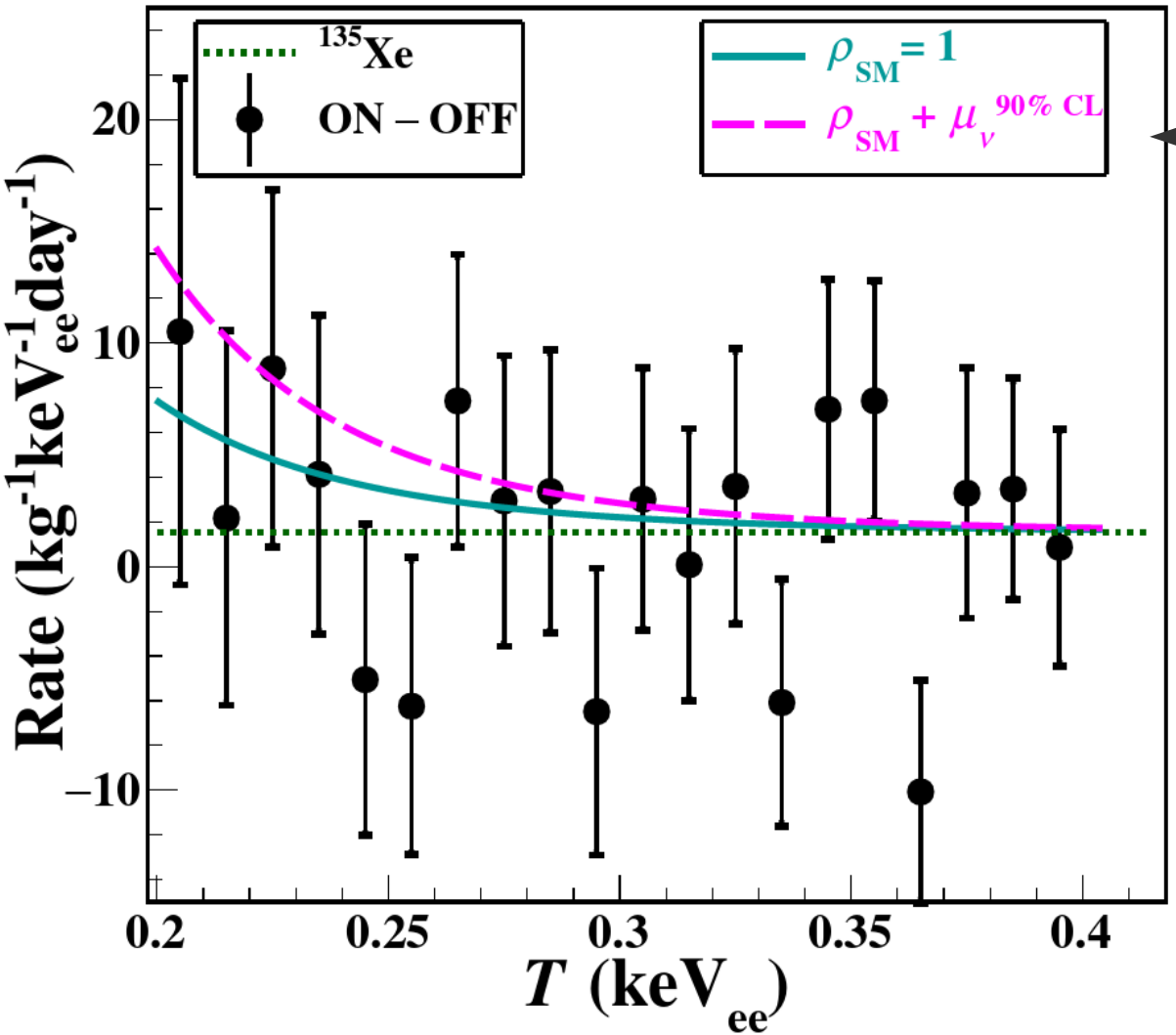
Upper limit of

k < 0.205

at 90% CL



Limits: BSM [$\mu_\nu - \nu A_{el}$]



Residual Spectrum (Dominant ROI)

Total Exposure

Reactor ON: 404 kg.days

Reactor OFF: 813.7 kg.days

@ SM Configuration [ρ=1; k=0.162]

☑ No statistically significant μ_ν signal observed

☑ Upper limit on μ_ν derived:

$$\mu_\nu < 5.9\times10^{-10}\mu_B$$

@ 90% CL

Competitive νA_{el} Constraint [Reactor anti-ν_e]

☑ TEXONO [PRL-2025]: $< 11\times10^{-10}\mu_B$

☑ CONUS+ [Nature-2025]: $< 5.6\times10^{-10}\mu_B$

Phys. Rev. D 112, 015007 (2025)

Summary

- ☑ **Exposure: 404[813.7] kg.days ON[OFF]**
- ☑ **Challenge:** Most data taken during COVID-19
- ☑ **Achieved Threshold: 200 eV**
- ☑ **No deviation from SM prediction observed**
  - SM (ρ) → $\rho < 2.0$ [@ Standard Lindhard $k = 0.162$]
  - @ SM value $\rho = 1$, Upper limit of $k < 0.205$
  - BSM (μ_ν) → $\mu_\nu < 5.9\times10^{-10}\mu_B$ [@ SM $\rho = 1$ & $k = 0.162$]

@ 90% CL

- ☑ **Benchmark for precision SM & BSM tests**

Future Prospects

- ❒ **KSNL: ν Decommissioned: 2023, Access till 2028**
- ❒ **R&D Ongoing: Aim ~ 150 eV Threshold**

  Cross-correlation ⊕ Pulse Analysis ⊕ Optimized Pulsar….
- ❒ **New [G4] Detector: Data taking for DM studies**

RECODE

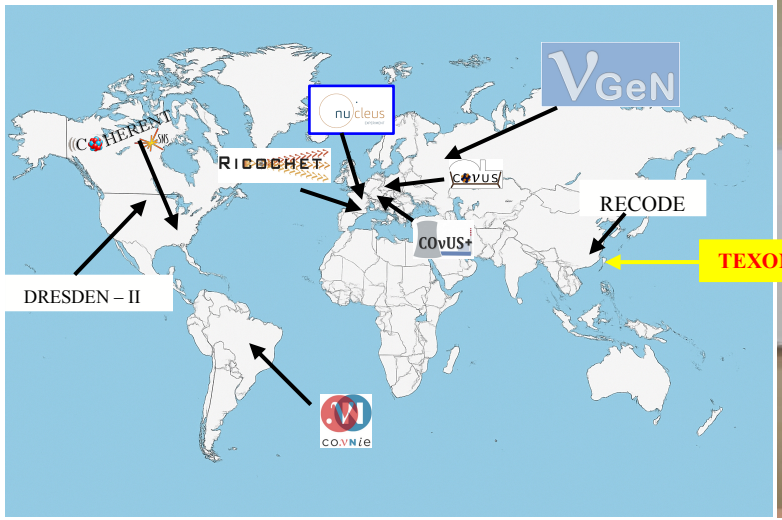
[Sanmen Reactor @ Zhejiang]

New Reactor Site

RECODE
[Sanmen Reactor @ Zhejiang]
with CDEX

Complementing to/Enhancing CDEX [DM & $0\nu\beta\beta$] @ CJPL with Ge

Global Efforts & TEXONO



Thank You !