[Dark Matter and] Reactor Neutrino Physics with sub-keV Germanium Detectors

- Physics & Experiments & Requirements
- Users' Characterization & Operation Highlights
- Wishes & Challenges & Potential R&Ds

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@

Sino-German Germanium Workshop
Ringberg, October 2015

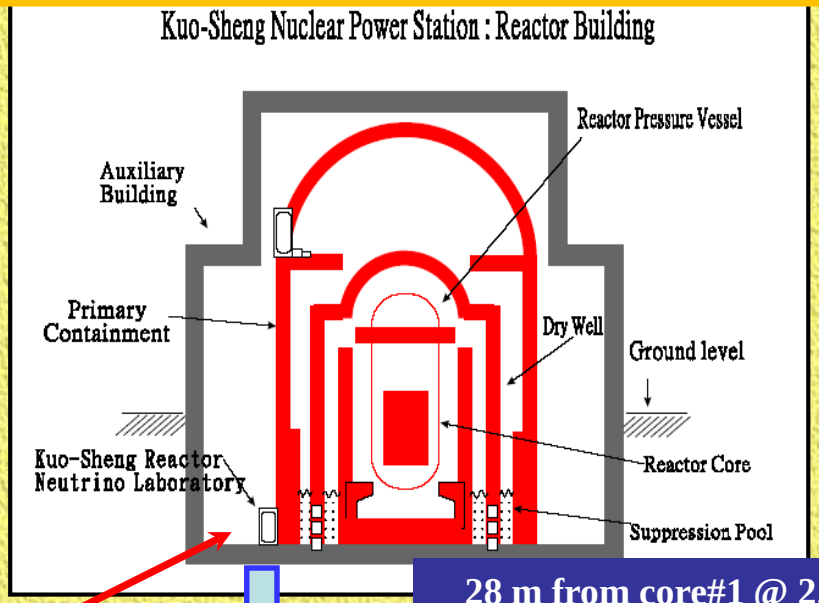
TEXONO 臺灣微中子實驗 Taiwan Experiment On NeutrinO 國聖

CJPL 中国锦屏地下实验室 China Jinping Underground Laboratory

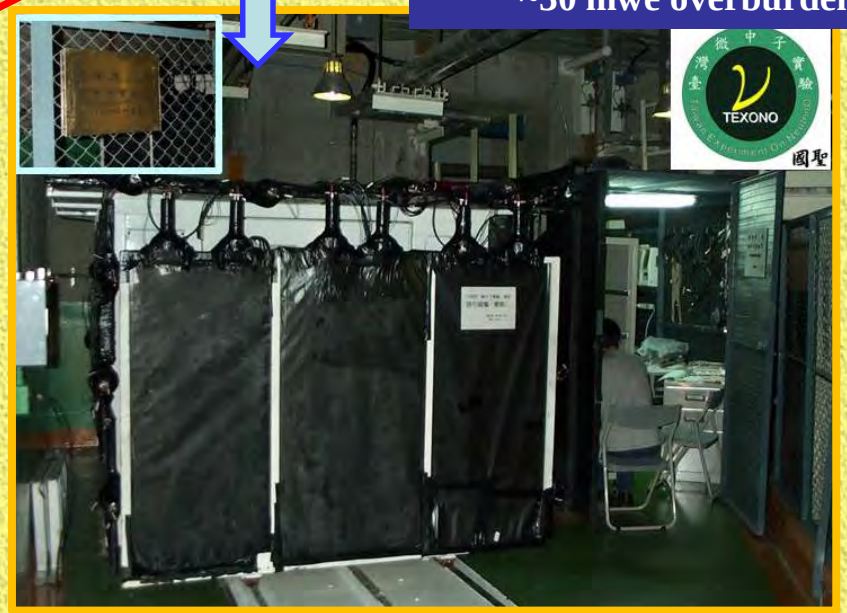
UNIVERSITÄT TÜBINGEN

Kuo Sheng Reactor Neutrino Laboratory (KSNL)

TEXONO Collaboration (since 1997) *[Taiwan, China, India, Turkey]*

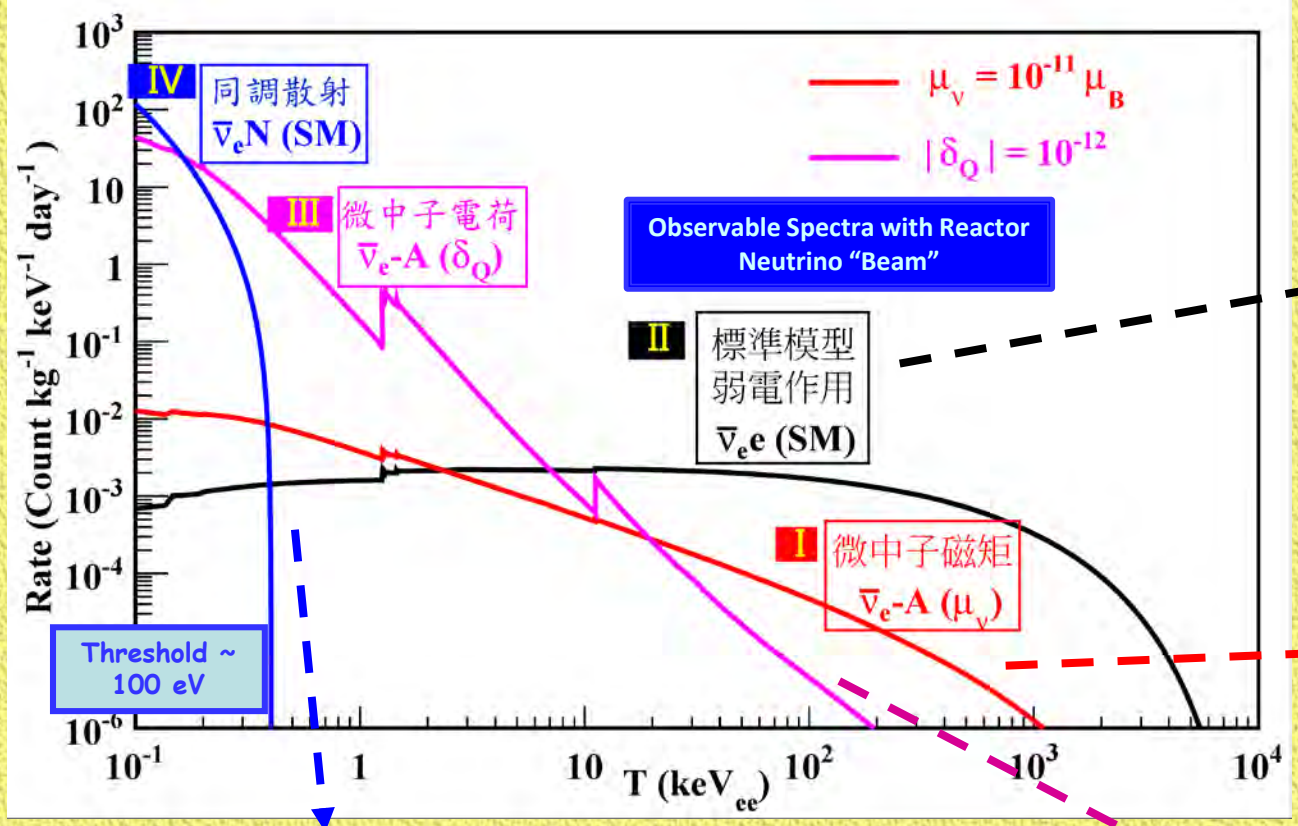


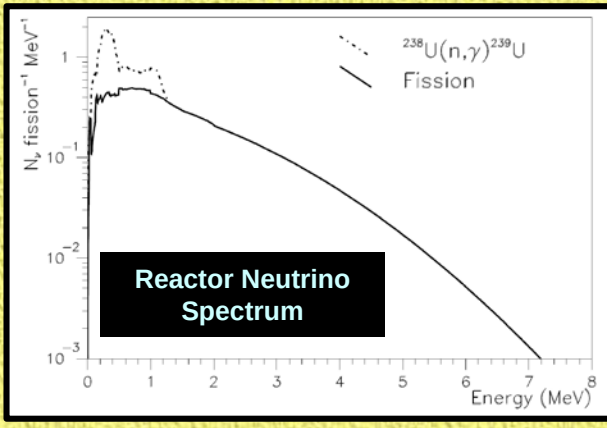
28 m from core#1 @ 2.9 GW
~30 mwe overburden



Neutrino Properties & Interactions at Reactor

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





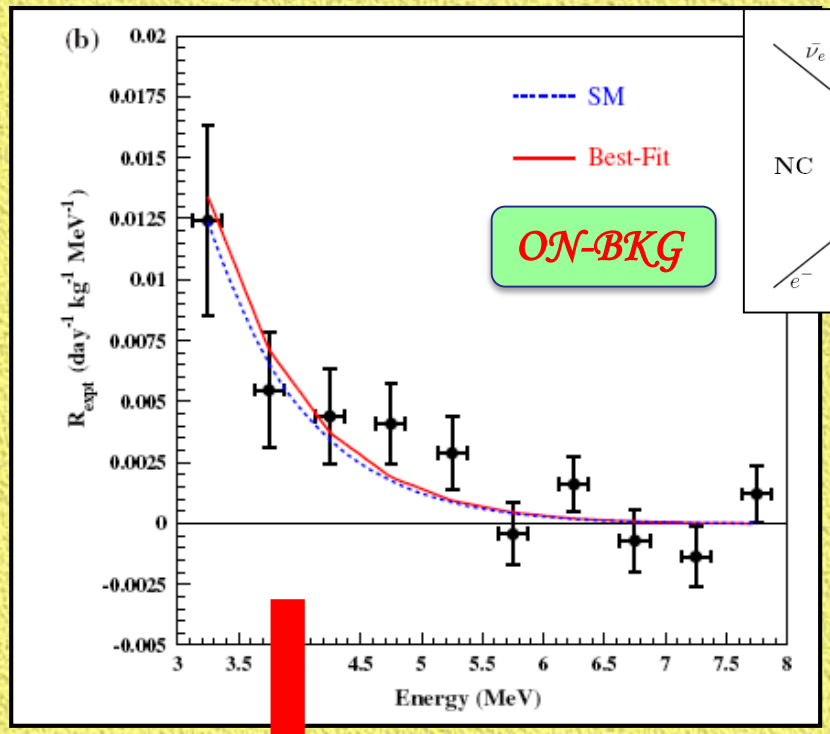
SM & NSI/BSM
ν-e Scattering
[PRD10,PRD10,PRD12,PRD15]
⇨ **200 kg CsI(Tl)**

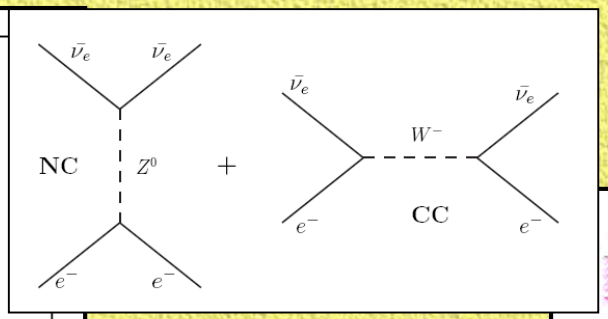
Magnetic Moments
[PRL03,PRD05,PRD07]
⇨ **1 kg HPGe**

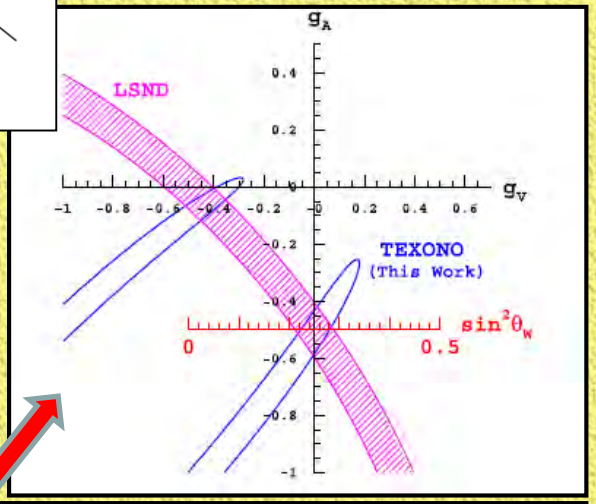
νN Coherent Scattering *[Current Theme]*
⇨ **sub-keV O(kg) ULEGe / PCGe**
- **Dark Matter Searches @ KSNL** *[PRD09,PRL13,AP14]*
- **CDEX Program@CJPL** *[PRD13,PRD14,PRD14]*

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

CsI(Tl) 200 kg : Probe Electroweak Physics *[PRD10]*



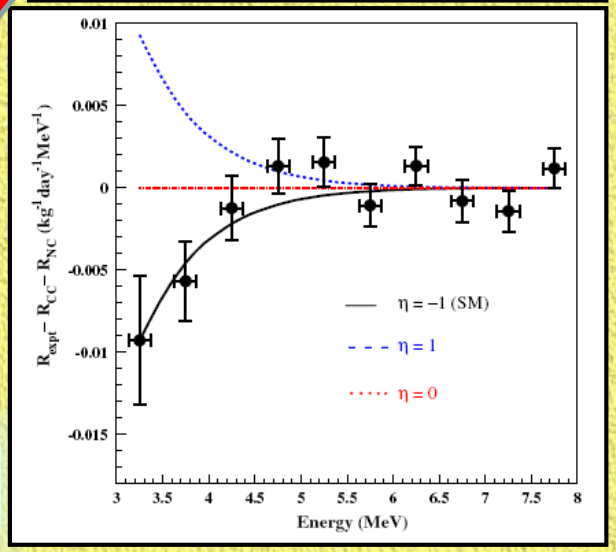




$$R = [1.08 \pm 0.21(stat) \pm 0.16(sys)] \times R_{SM}$$

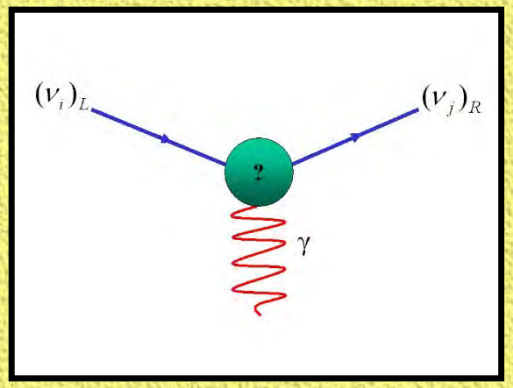
$$\sin^2\theta_W = 0.251 \pm 0.031(stat) \pm 0.024(sys)$$

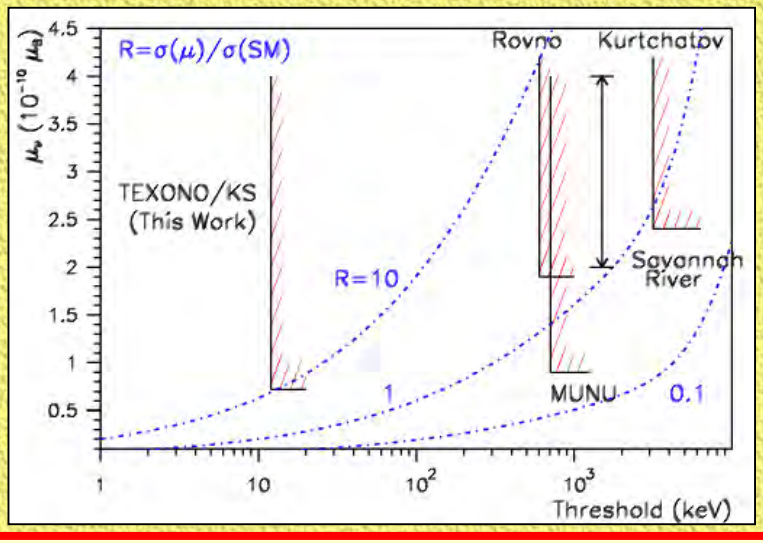
Verify SM Destructive Interference



⊕ Constraints on Various Beyond SM Effects *[PRD10;PRD12]*

Neutrino Electromagnetic Properties : Magnetic Moments





$$\frac{d\sigma}{dT}(\nu e)_\mu = \frac{\pi\alpha^2}{m_e^2}\left[\frac{1}{T} - \frac{1}{E_\nu}\right]\mu_\nu^{\ 2}$$

$\mu_\nu(\nu_e) < 7.2 \text{ X } 10^{-11}\ \mu_B$ [PRL03,PRL07]

Search of μ_ν at low enery with Reactor νe scattering

⇒ **high signal rate & robustness:**

- μ_ν>>SM [decouple irreducible bkg ⊕ unknown sources]
- T << E_ν ⇒ $d\sigma/dT$ depends on total ϕ_ν flux but *NOT* spectral shape [flux well known : ~6 fission-ν ⊕ ~1.2 ^{238}U capture-ν per fission]

……. Same approach continuing in GEMMA (Kalinin, Russia)

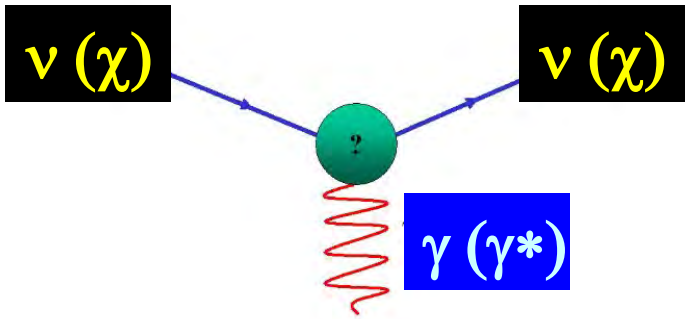
$\mu_\nu(\nu_e) < 2.9 \text{ X } 10^{-11}\ \mu_B$ *[2013]*

Current Research Theme:

"sub-keV" Ge Detectors

- **Physics Goals for *O[100 eV threhold⊕1 kg mass⊕1 cpkkd] detector* :**
  - **νN coherent scattering , potential applications to reactor monitoring**
  - **Low-mass WIMP searches ➡ *[CDEX Program @CJPL]***
  - **Explore ν/WIMP electromagnetic properties & interactions**
  - ***Open & Explore* new detector window & detection channel & physics parameter space**

Explore Exotic Electromagnetic Properties/Interactions



- Detectors with good resolution & sub-keV sensitivities
  - Excellent to detect peaks and spectral structures e.g. atomic transitions ⇨ X-rays lines
  - Atomic Physics ⇨ Electromagnetic Physics
    - Smoking Gun Signatures for Searching Exotica with Electromagnetic Interactions.

An example: Neutrino "Milli-charge" *[PRD14]*

Neutrino Electromagnetic Form Factors

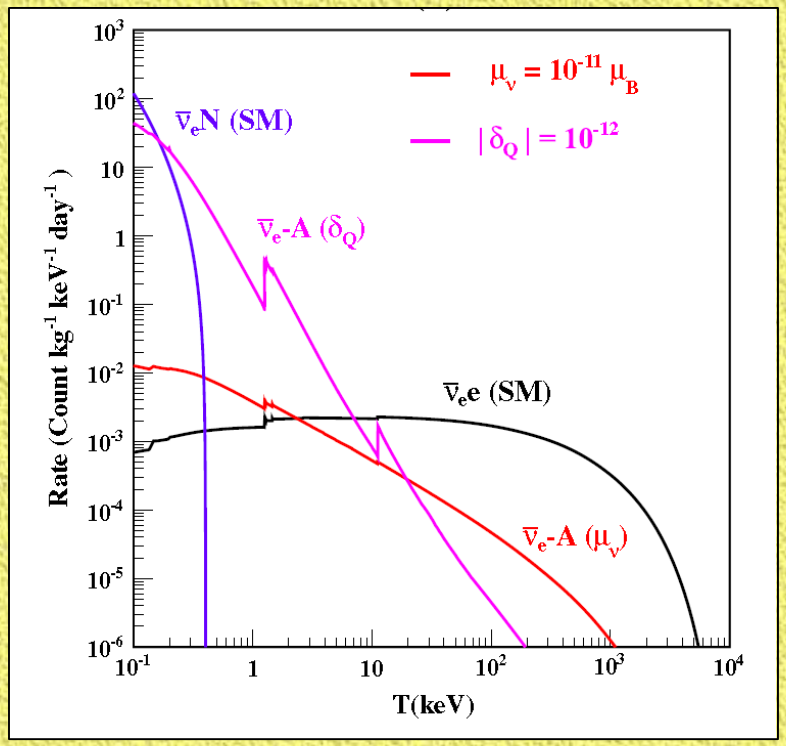
$$\Gamma^{\mu}_{\mathrm{em}} \equiv F_1 \cdot \gamma^{\mu} + F_2 \cdot \sigma^{\mu\nu} \cdot q_{\nu}$$

$$F_1 = \delta_Q \cdot e_0 + \frac{1}{6} \cdot q^2 \cdot \langle r_\nu^2 \rangle,$$

$$F_2 = (-i) \cdot \frac{\mu_\nu}{2 \cdot m_e},$$

Atomic Ionization Differential Cross-Section with full atomic physics many-body "MCRRPA" calculation [PL13]

$$\overline{\nu_e} + \mathrm{A} \rightarrow \overline{\nu_e} + \mathrm{A}^+ + e^-,$$



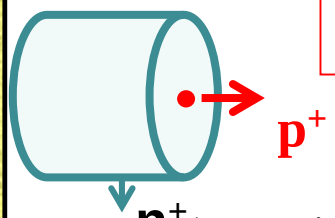
- ☑ **Cross-section enhanced** at low energy transfer ("minimum ionizing")
- ☑ **Smoking-gun signatures** for positive signals: peaks at known K/L binding energy at known ratios *[different from cosmic-activation electron-capture background]*
- ☑ Present Bound : $\delta_Q < 10^{-12}$
- ☑ Future Sensitivity Goal (100 eVee threshold): $\delta_Q \sim 10^{-14}$

Baseline Hardware Design

[Both TEXONO@KSNL & CDEX-1@CJPL]

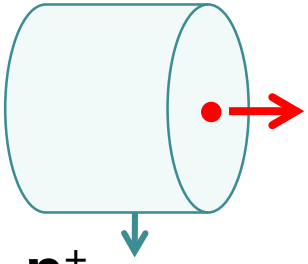
p- PCGe

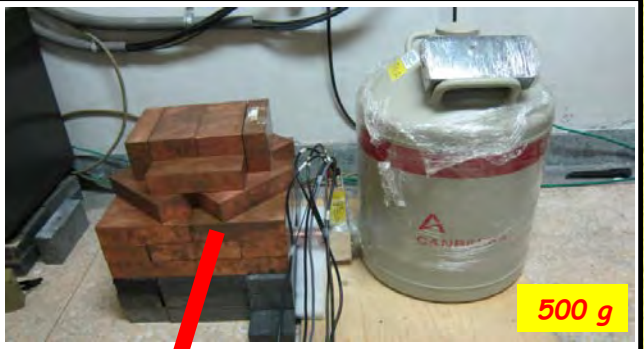
[500g – 1 kg]



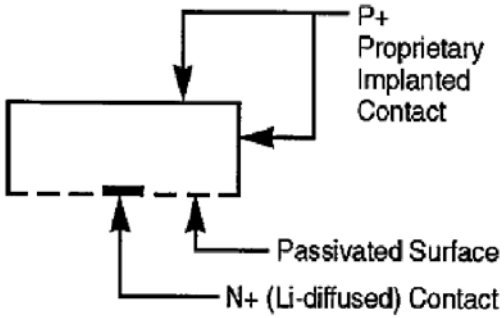
n- PCGe

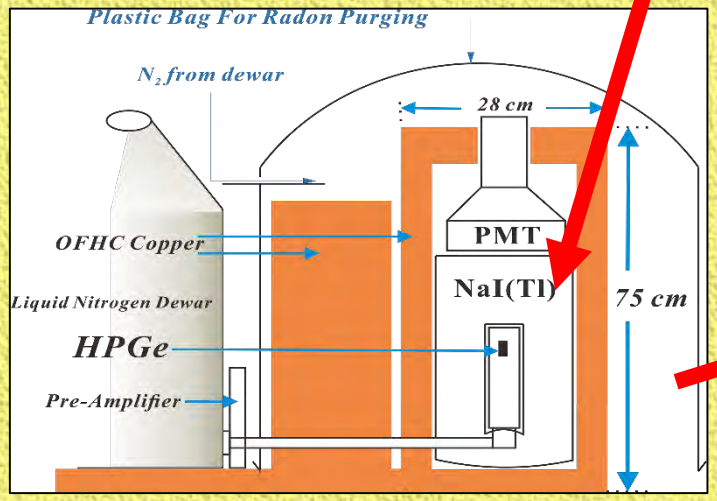
[500 g]

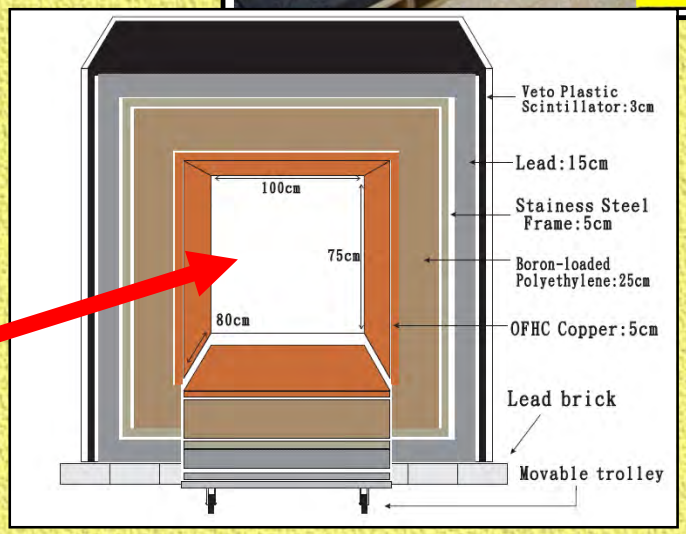




4x5g ULEGe



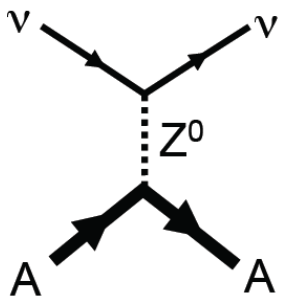


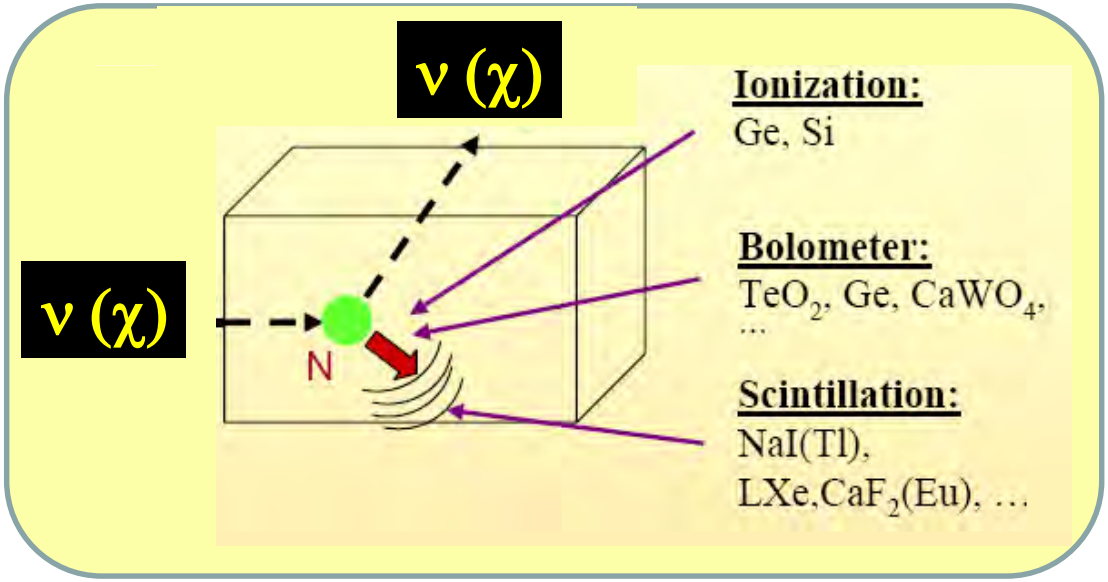


Neutrino-Nucleus Coherent Scattering :

Standard Model allowed and predicted processes :

$$\nu + A \rightarrow \nu + A$$





- **Neutral current process (same for all ν-flavor)**
- **$\sigma \propto N^2$ @ E_ν < 50 MeV**

  ⇒ ***"Coherent"*** *[probe "sees" the whole nucleus]*
- **sensitive probe for BSM ; interest in reactor monitoring**
- **important process in stellar collapse & supernova explosion**
- **analogous interaction used in dark matter detection**
- **Ge at KSNL @ QF~0.2 : cut-off ~ 300 eV ;**

  Rate ~10 kg^{-1} day^{-1} @ threshold~100 eV

Neutrino-Nucleus Coherent Scattering :

$$\nu + N \rightarrow \nu + N$$

Standard Model Cross-Sections:

$$\left(\frac{d\sigma}{dT}\right)^{coh}_{SM} = \frac{G_F^2}{4\pi} m_N [Z(1-4\sin^2\theta_W) - N]^2 [1 - \frac{m_N T_N}{2E_\nu^2}]$$

$$\sigma_{tot} = \frac{G_F^2 E_\nu^2}{4\pi} [Z(1-4\sin^2\theta_W) - N]^2$$

- a *fundamental neutrino interaction* never been experimentally-observed ; probe quantum mechanics coherence of pure weak interactions
- $\sigma \propto \sim N^2$ applicable at $E_\nu < 50$ MeV where $q^2 r^2 < 1$
- a sensitive *test to Stardard Model*
- important interaction/energy loss channel in *astrophysics* media
- a promising new detection channel for neutrinos; relative compact detectors possible (implications to *reactor monitoring*); & *the* channel for *WIMP direct detection* !
- Typical Rates for Ge at KSNL :

  ~10 kg^{-1} day^{-1} @ threshold~100 eV & QF~0.2

$$\nu + N \rightarrow \nu + N$$

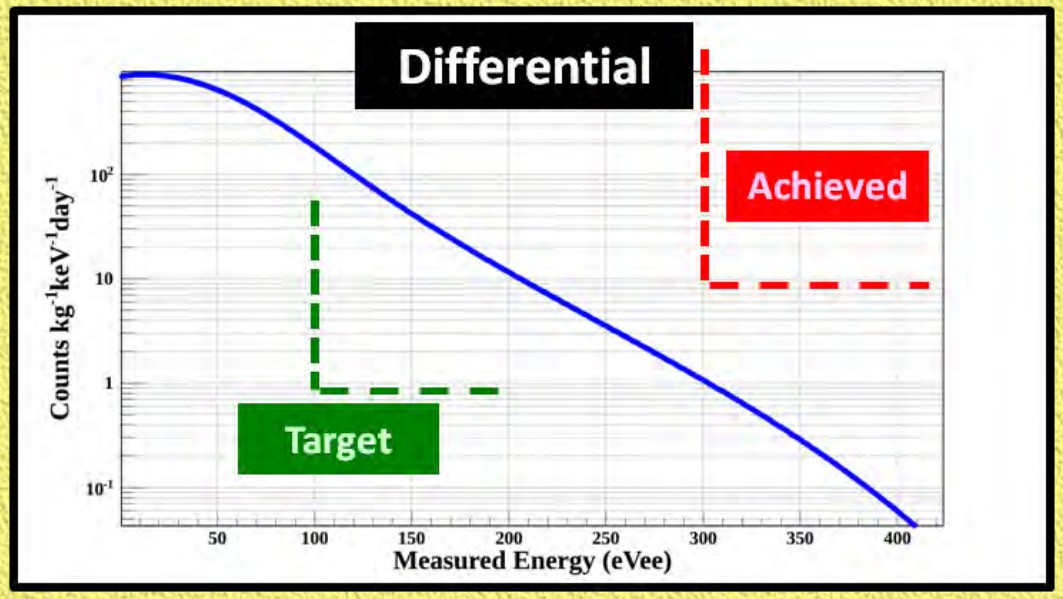
Standard Model Cross-Sections at KSNL

[with Quenching Function for Ge for nuclear recoils]

$$\left(\frac{d\sigma}{dT}\right)^{coh}_{SM} = \frac{G_F^2}{4\pi} m_N [Z(1-4\sin^2\theta_W) - N]^2 [1 - \frac{m_N T_N}{2E_\nu^2}]$$

- **Needs Background < 10 cpkkd, Target → 1 cpkkd**

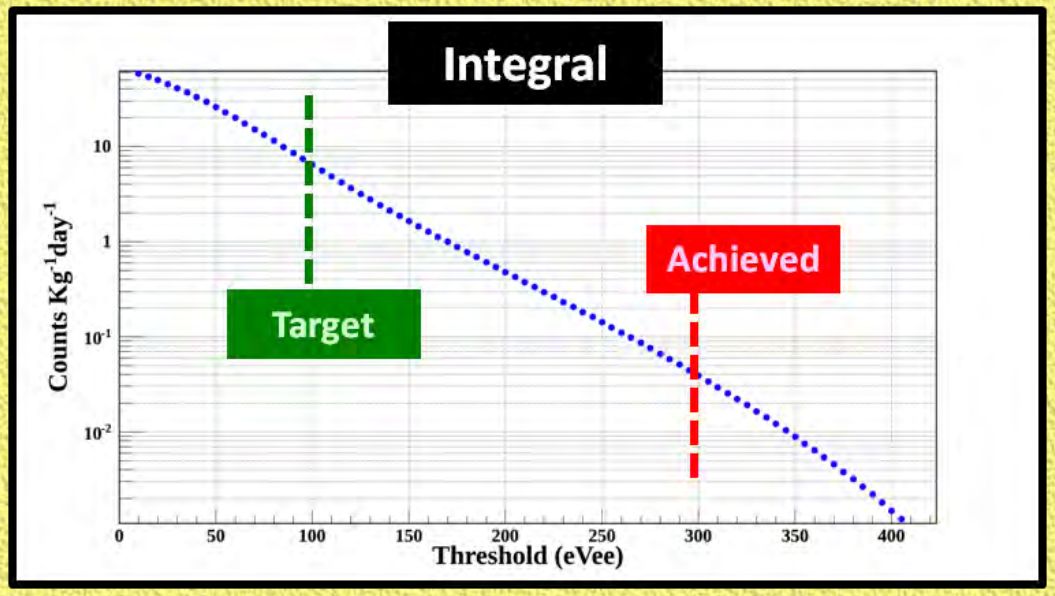
[Reactor ON/OFF typically gain 10+ factors]



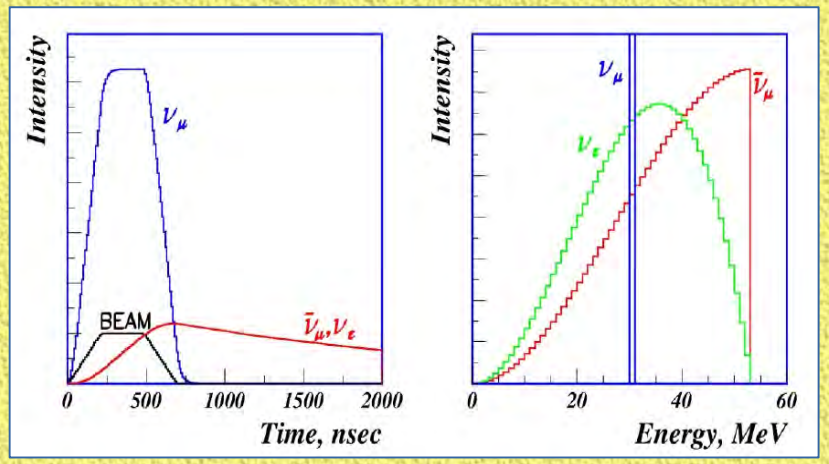
Current Focus !!

- **Needs Threshold < 200 eV_{ee}, Target → 100 eV_{ee}**

$$\sigma_{tot} = \frac{G_F^2 E_\nu^2}{4\pi} [Z(1-4\sin^2\theta_W) - N]^2$$



Ge in ORNL-SNS-COHERENT Program



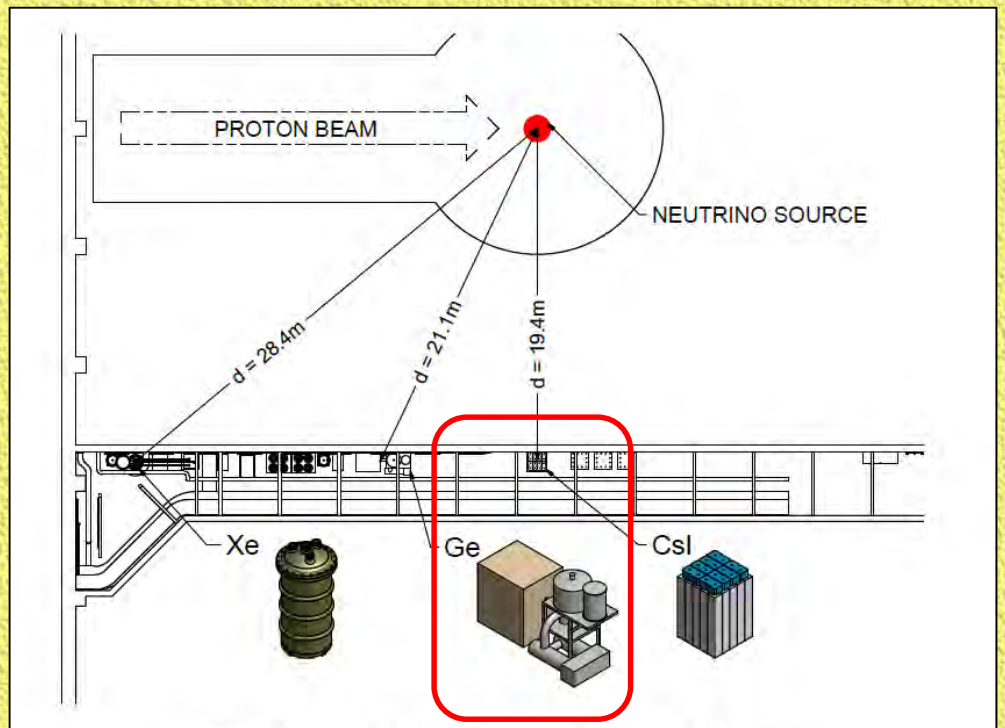
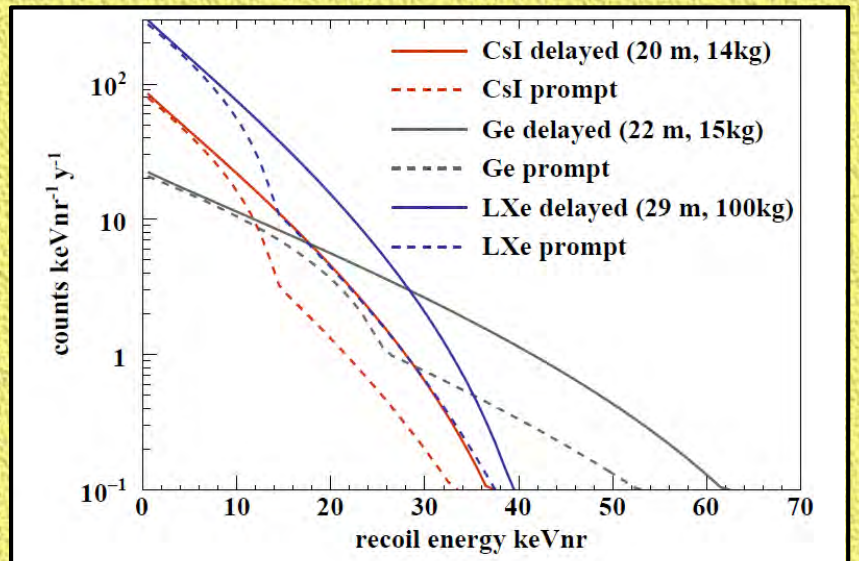


FIG. 6: Proposed siting in the SNS basement hallway.



(a)Recoil Spectra

pPCGe at

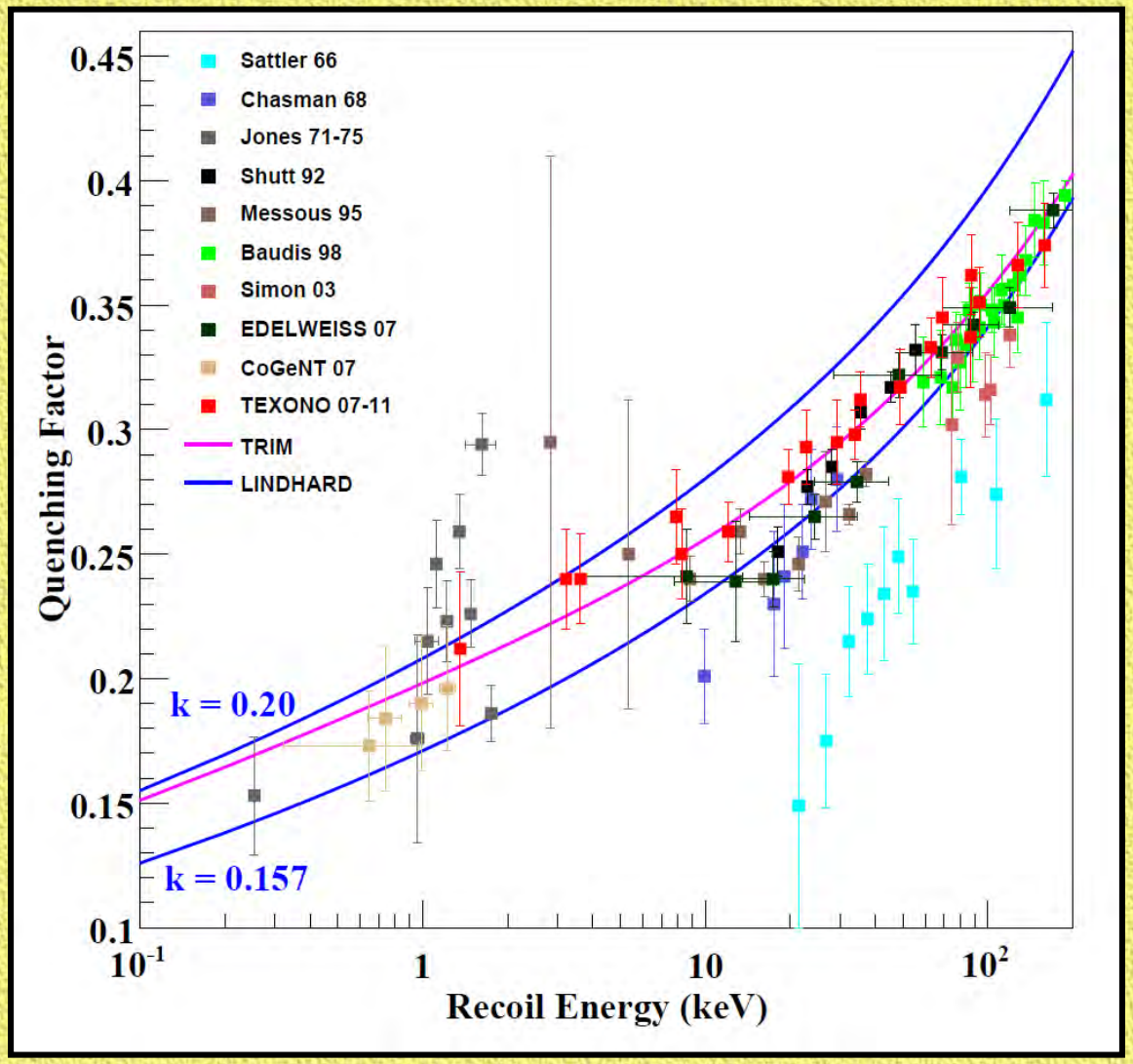
- ☑ **~1 keVee threshold**
- ☑ **~15 kg target**
- ☑ **~ 220 νN / year**

Sub-keV Ge Detector Techniques : Users' R&D Items

- Quenching Factors -- nuclear recoils' Ionization Yields
- Energy Definition & Calibration
- Trigger Efficiencies near threshold
- Bulk Vs Surface Events Selection – algorithms & efficiencies
- Physics Vs Noise Pulse-Shape Selection -- algorithms & efficiencies

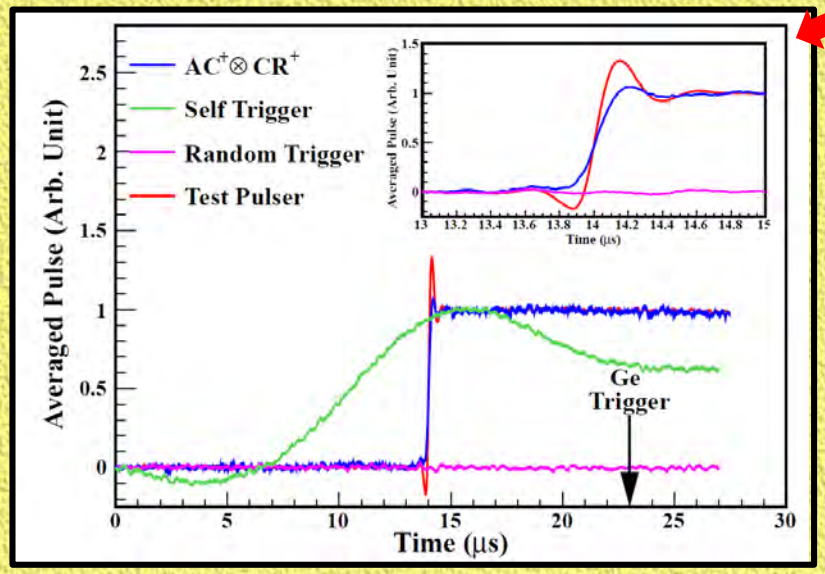
QF in Ge :

- ☑ Data available down to sub-keV measure-able energy
- ☑ TRIM Software : better match to data over extended energy

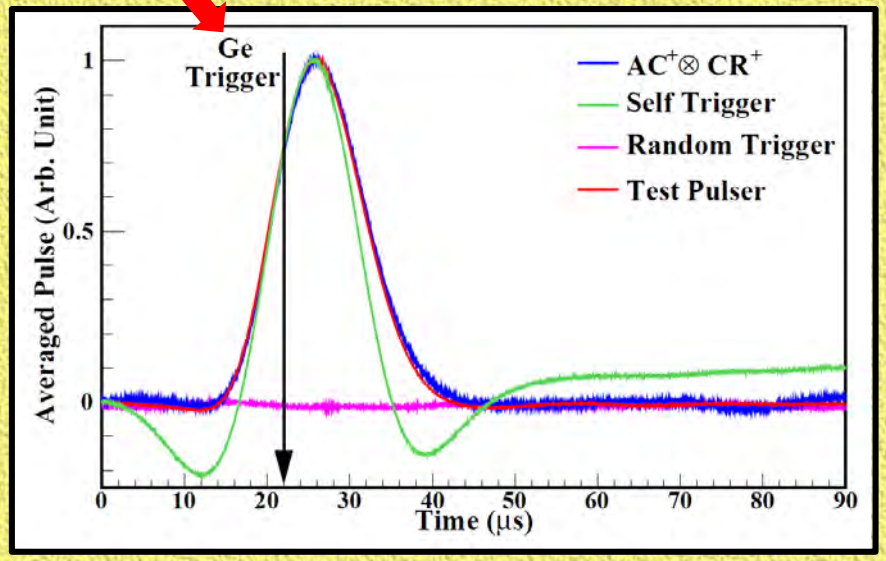


PCGe ⇨ Reset Preamp

Timing Amp



Shaping Amp @ ~6 μs shaping



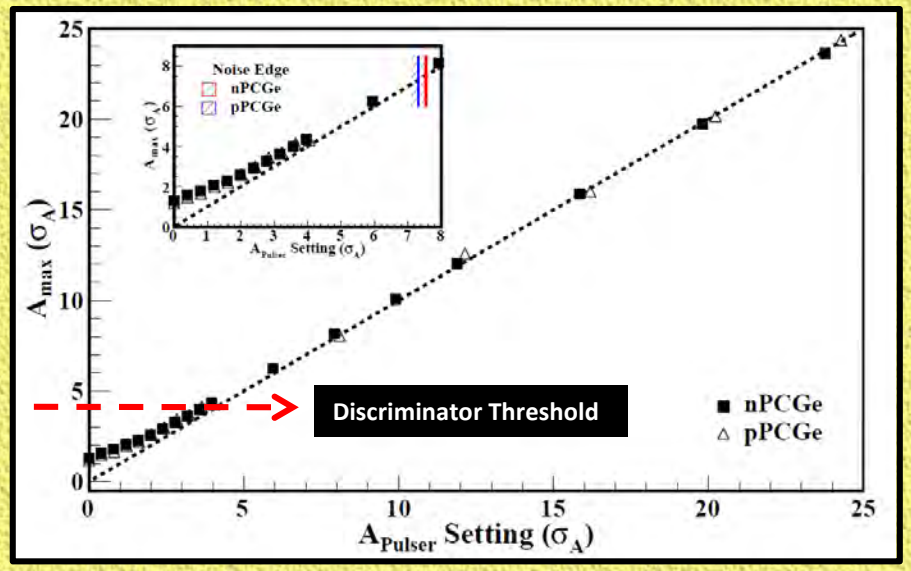
- ☑ **Test Pulser :** faster than TA , identical output to SA
  - ↳ valid for studying trigger, energy calibration ; not Bulk/Surface effects
- ☑ **Self-trigger electronic noise** events different from **Physics** events ***[AC+XCR+]*** in both TA & SA ***[AC==NaI Anti-Compton ; CR==Cosmic-Ray Panel]***
  - ↳ use pulse shape analysis to select physics events near/below threshold
- ☑ TA & SA pulse identical all over "Bulk" fiducial volume
  - ↳ ***[AC+XCR+XBulk]*** background events used for efficiency studies for ν/χ signals

Energy Definition:

- Both Amplitude or Area of Shaping Amplifier Output
- Linear & Well-Behaved above Electronics Threshold.

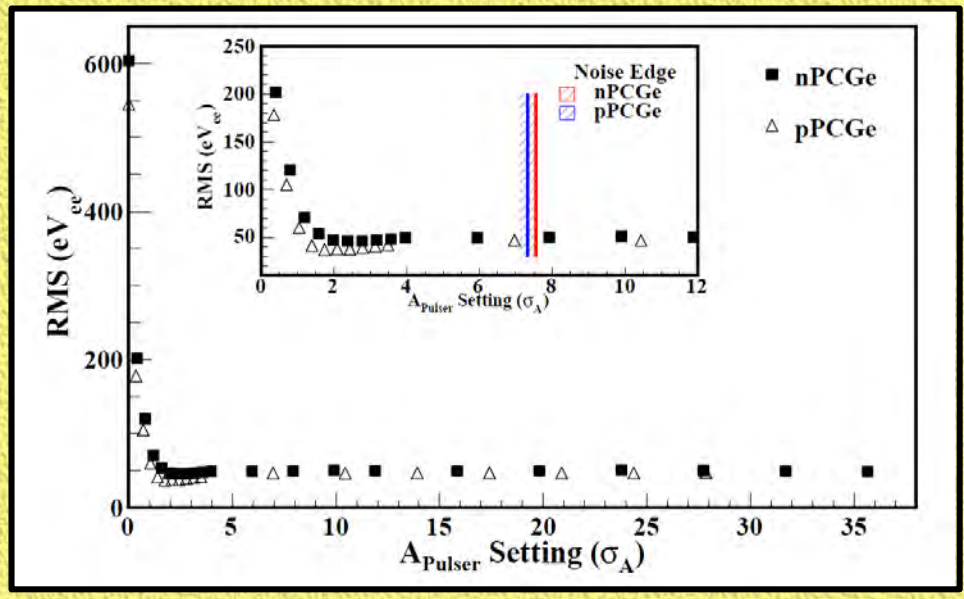
Energy Calibration:

- Random Trigger to define Pedestals
- X-ray Sources up to 60 keV
- Internal Lines (1-12 keV) from in situ data
- Precision Pulser for low energy interpolation



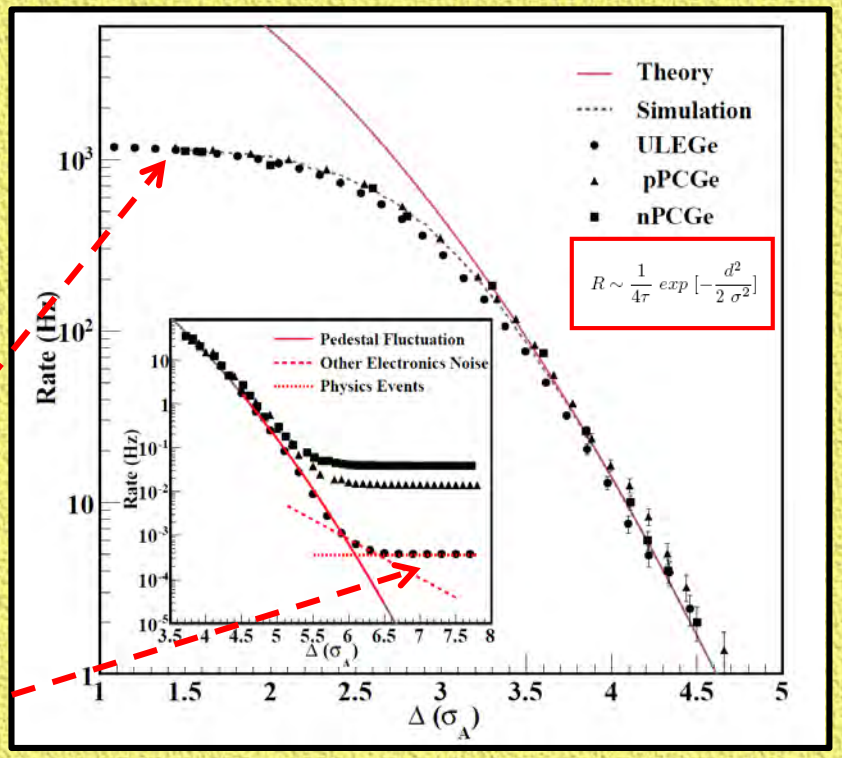
Pulser SA Amplitude Vs Input

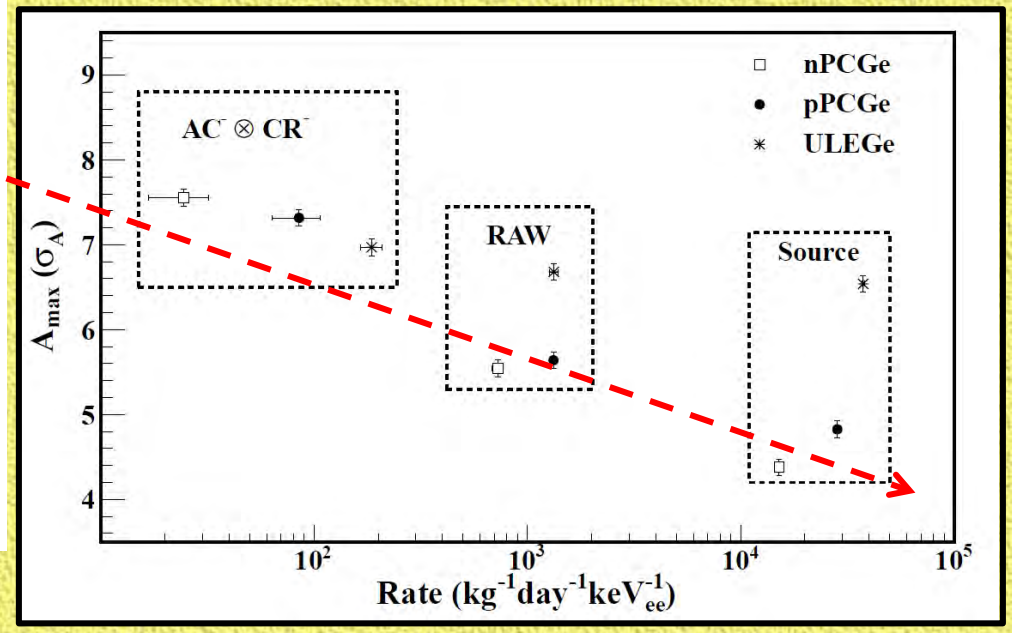
Pulser SA FWMH Vs Input



Trigger Rates :

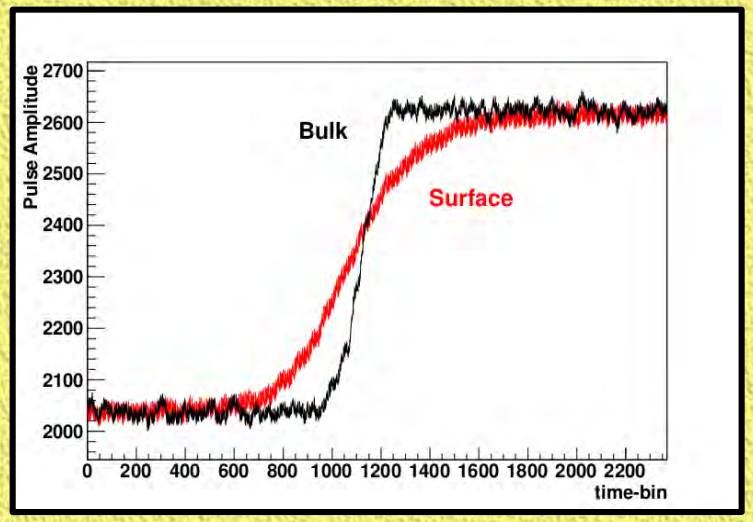
- ☑ Agreed with expectations
- ☑ A universal curve valid to all detectors with discriminator threshold in "Pedestal RMS" unit.
- ☑ Saturation at low threshold due to "Gate Width"
- ☑ Excess in high threshold due to dominating physics events
- ☑ Electronics "threshold" depends on physics background level for the same detector (lower background implies higher threshold)

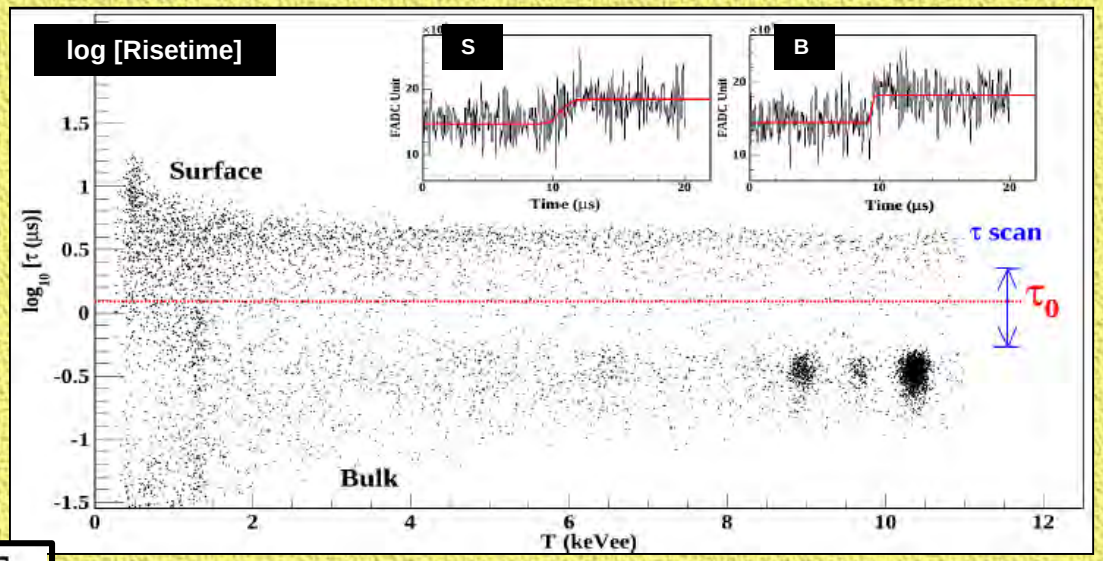


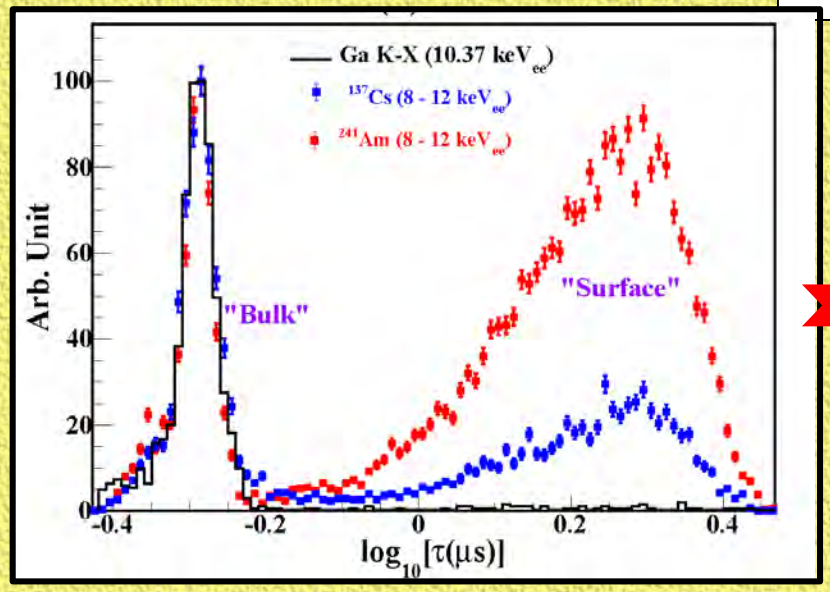


PSD for Surface Vs Bulk Events @ PCGe *[AstroPart.Phys. 2014]*

- n+ "inactive layer" is not totally dead; signals finite but slower rise time
- AC-XCR+ events (neutron rich) samples do not show strong surface band
- Understand/Measure Efficiencies and Suppression Factors

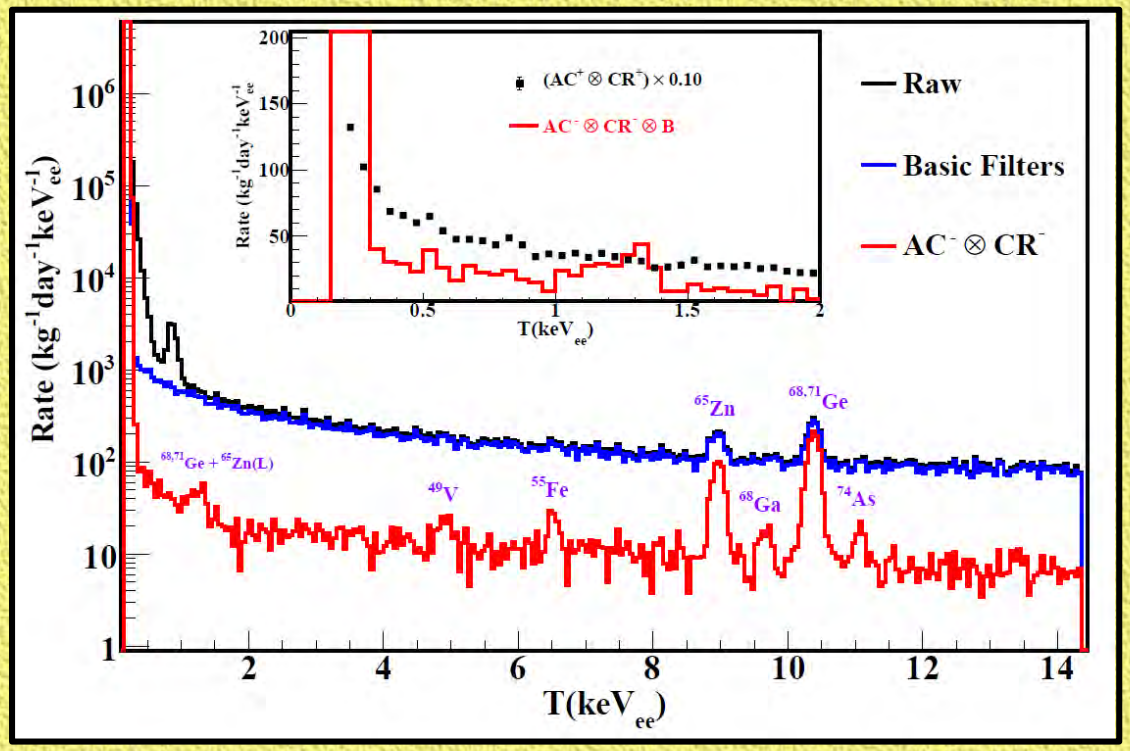






Different Background Sources give Identical TA-risetime in Bulk but Varying in Surface

- *[AC+XCR+XBulk]* background events valid for efficiency studies for ν/χ signals
- Surface TA-risetime distributions provide understanding of background



Typical Analysis Sequence:

RAW → Basic → ACXCR → B/S …..

… [→ sub-noise-edge PSD]

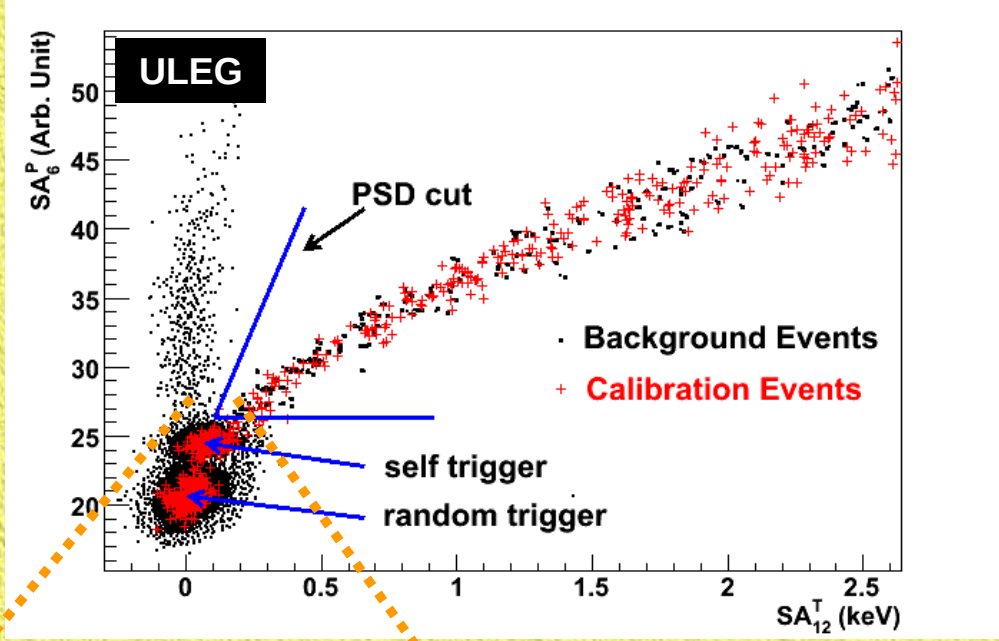
e.g. 500g pPCGe

- ☑ **RMS-pedestal ~41 eV ; Pulser FWHM ~110 eV**
- ☑ **AC- X CR- X B threshold at ~311 eV** *[no external tags]*
- ☑ **AC+ X CR+ X B threshold at ~197 eV** *[doubly external tags]*

PSD Selection to Suppress Electronic Noise

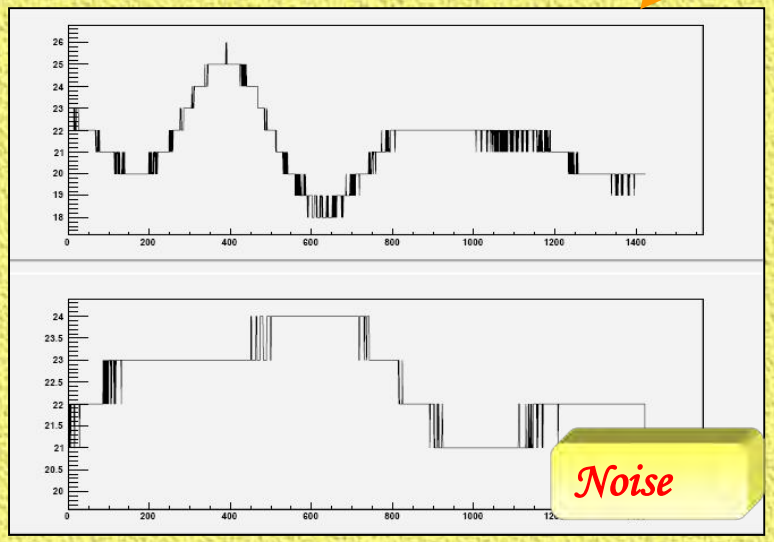
E.g. ⇨ correlations in two readout of different gains & shaping times

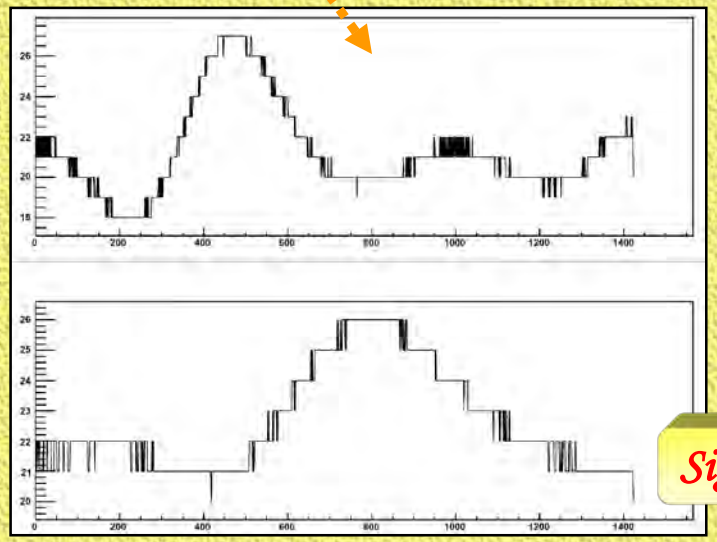
◎ **look for specific +ve pulse fluctuations at specific & known timing**



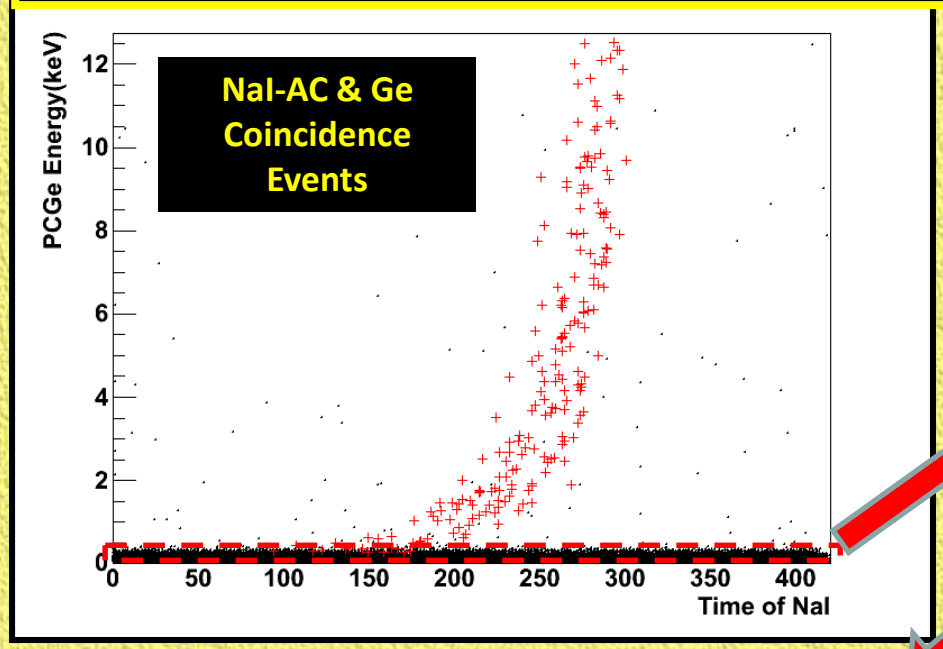
6 μs

12 μs

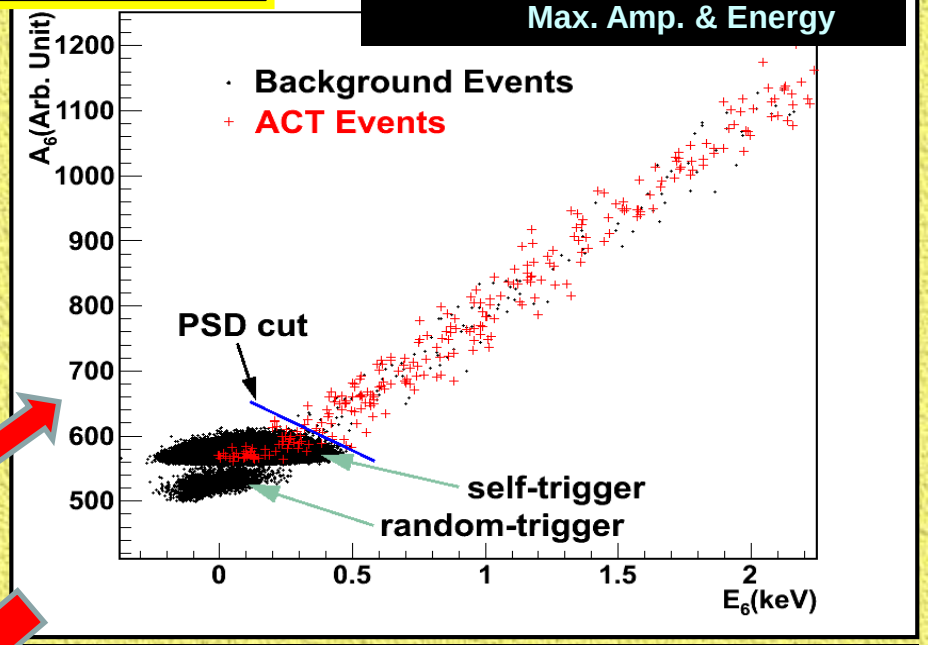


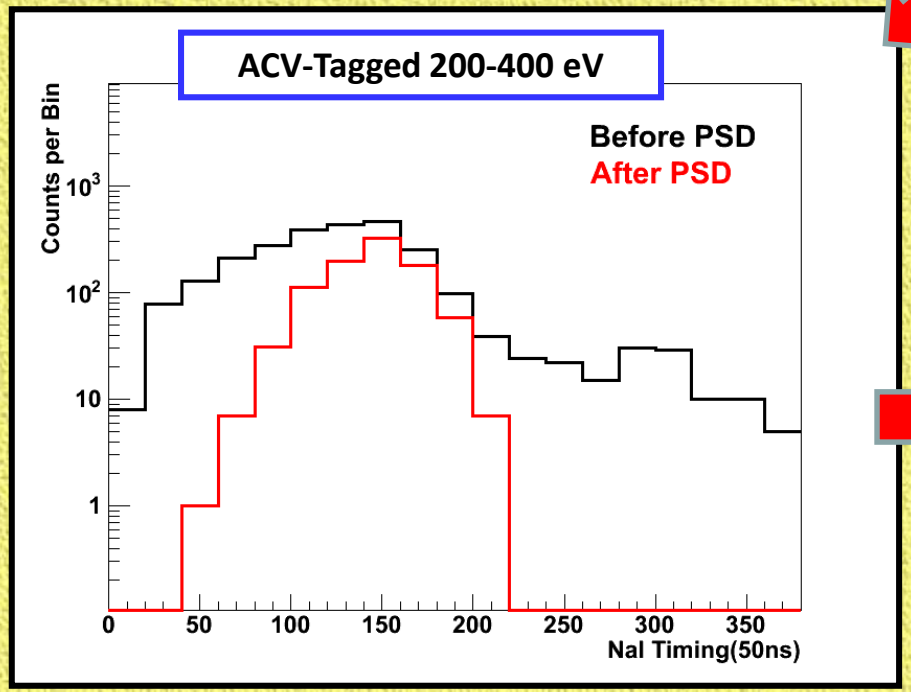


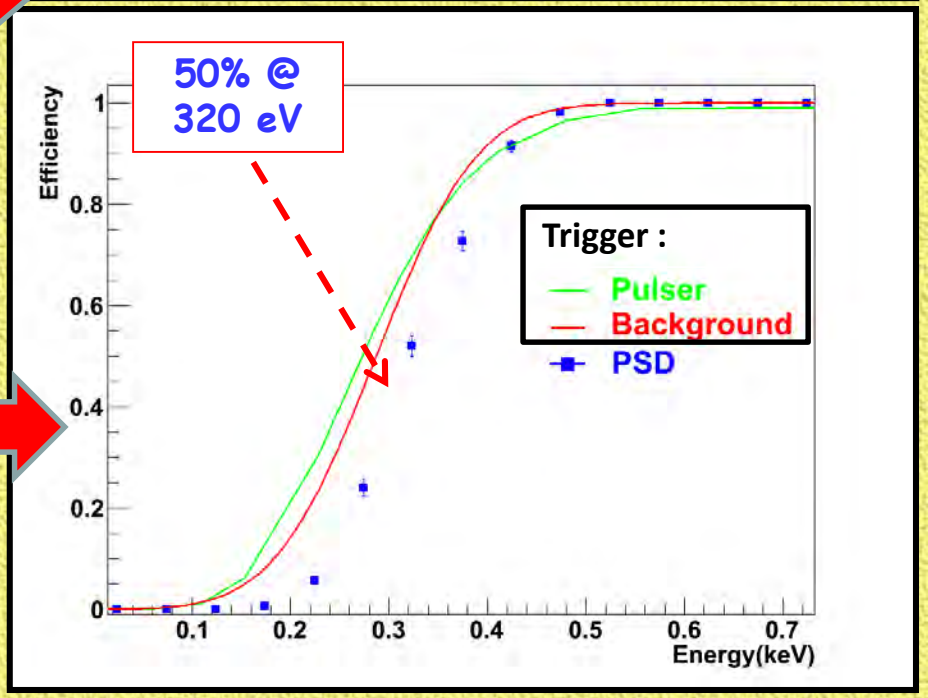
Phys-Vs-Noise Selection Efficiency



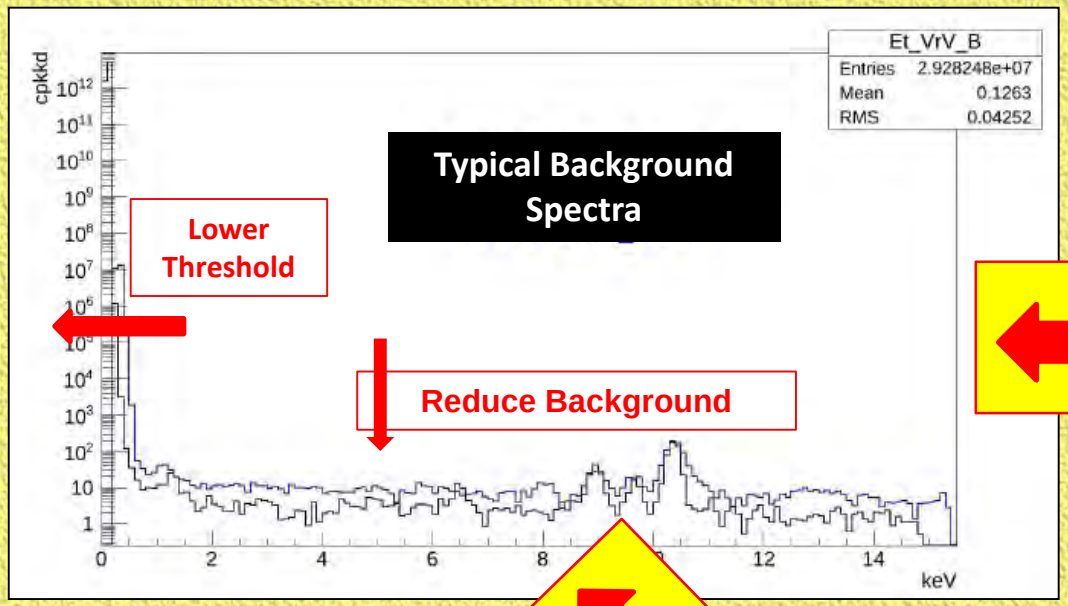
E.g. 2 ⇨ correlations between Max. Amp. & Energy

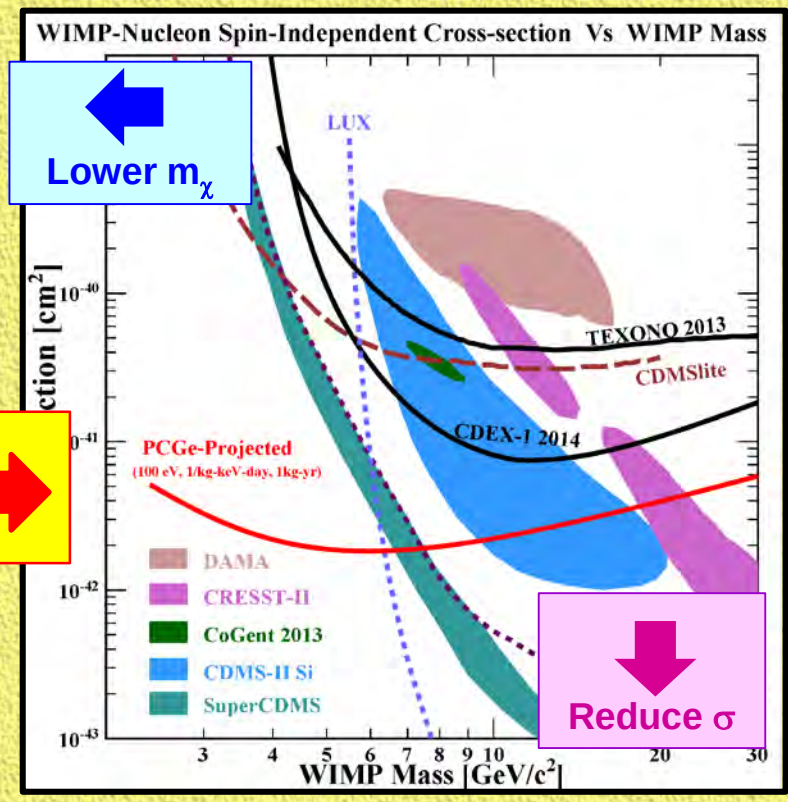


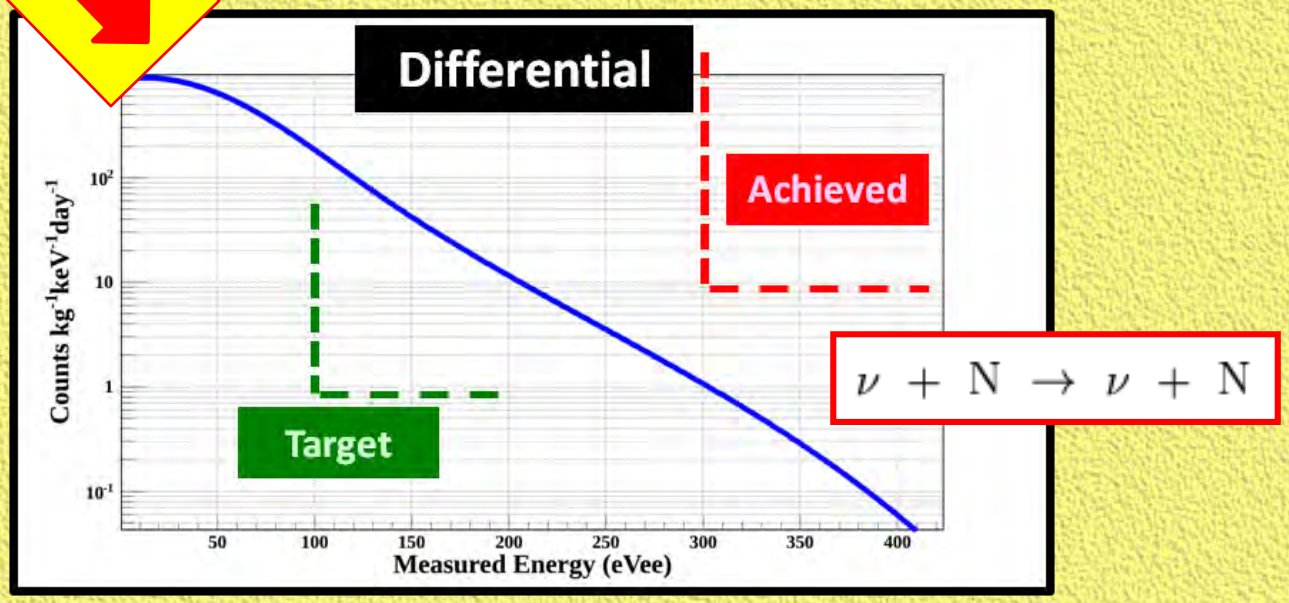




Experimental Challenges







Reduce Bkg

- ☑ > keV : O(1 cpkkd) achieved
- ☑ Sub-keV Bkg goal : O(10 cpkkd)→O(1 cpkkd)
- ☑ How? Understand background and detector response ; radiopure materials
  ⇨ *[$0\nu\beta\beta$ grade background control]*
- ☑ *Novel Ideas ?? Nuclear Vs Electron recoil differentiation ??*

Lower Threshold

- ☑ ~200-eV electronics threshold achieved *(pPCGe@CDEX)*
- ☑ kg-target Threshold goal → < 100 eV
- ☑ How? Sub noise-edge PSD (multi-cuts / Neural Network) ; electronics JFET R&D
- ☑ *Novel Ideas ?? Signal Amplification ?? Internal Gain ??*

Prospects & Outlook

- Interesting windows on neutrino and dark matter experiments are opened up with detectors having sub-keV sensitivities.
- Ge as ionization detectors has been and is a leading technology ; competitive results achieved.
- Formidable (potentially game-changing) challenges from bolometric Ge and liquid xenon techniques.
- Users are *Working Hard* to Extract All Available from the Device !
- In addition to incremental improvements, the users would *love (need)* to have quantum leaps through innovative techniques to maintain competitive edges

  [That is ..... 🛠 .... for brainstorming in this meeting]