TEXONO's νA_{el} @ KSNL : Before & Beyond

- TEXONO-ν @ KSNL
- TEXONO-Theory Highlights
- νA_{el} @ KSNL : status
- Outlook & Prospects

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Academia Sinica / 中央研究院
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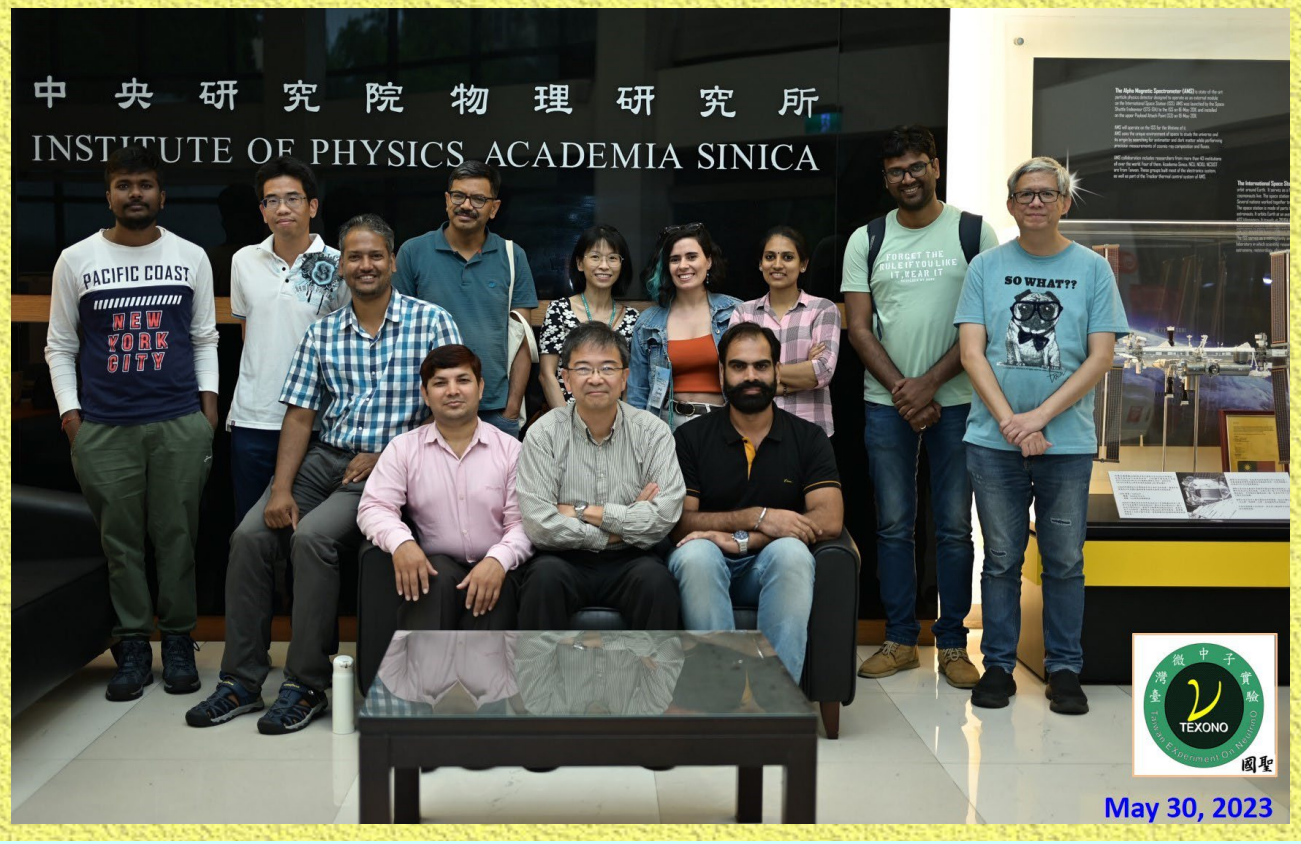
@

Symposium on Frontiers of Underground Physics

29 October 2023 to 2 November 2023

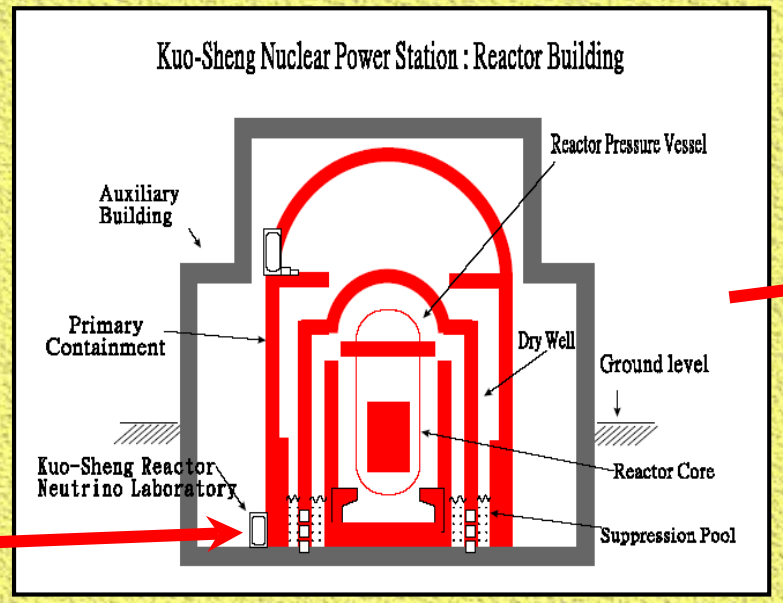


AS, KSNPS, NTU, NDHU, IHEP, CIAE, THU, SCU, BHU, CUSB, GLAU, HNBGU, METU, DEU.....

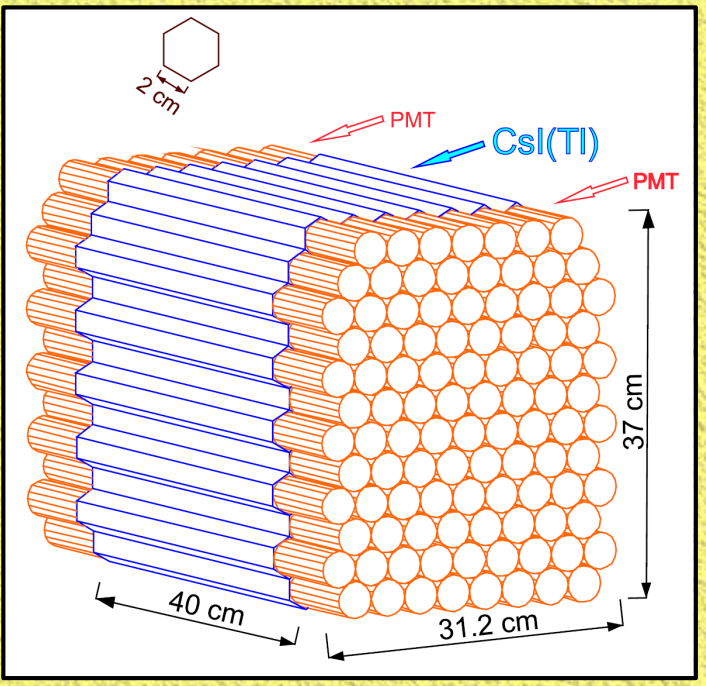
TEXONO Program *[since 1997]* :

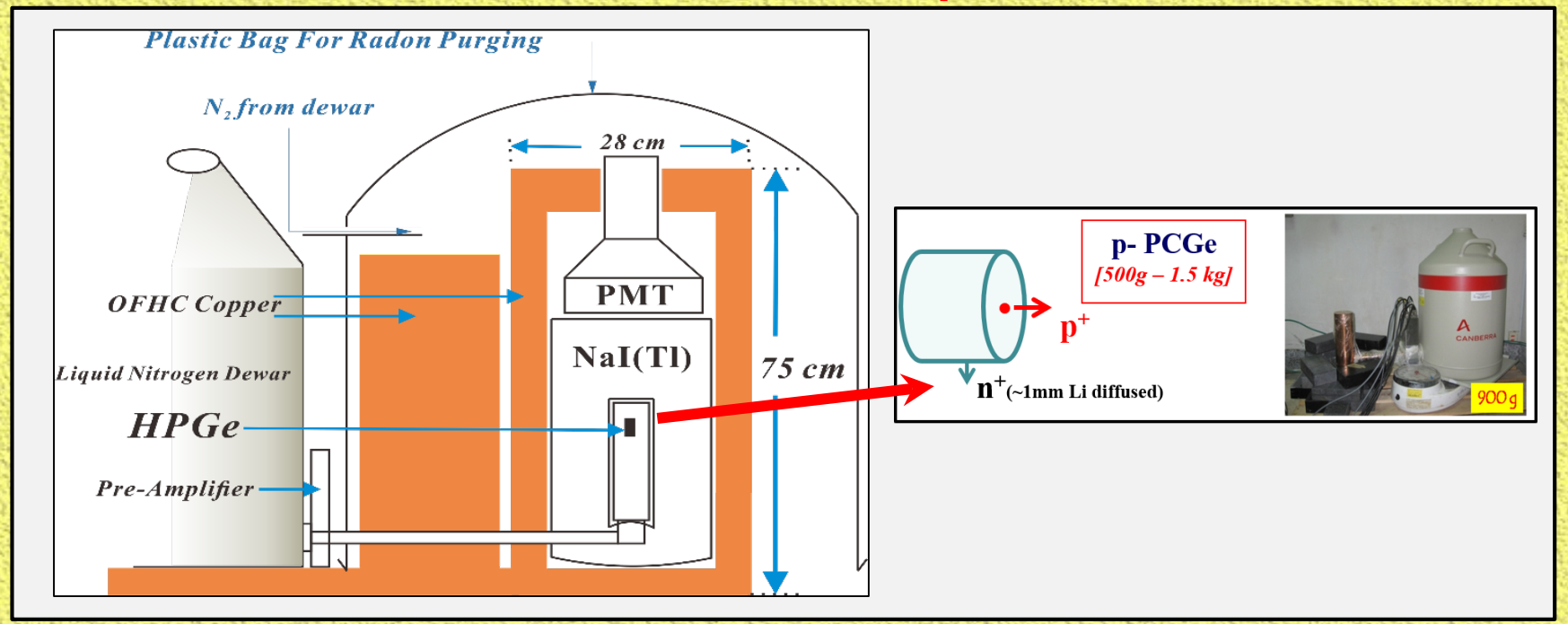
- Low Energy Neutrino (SM+EM) physics at Kuo-Sheng Neutrino Laboratory (KSNL), 28 m from 2.9 GW_{th} reactor core
- Founding partner of CDEX@CJPL Dark Matter Experiment *[since 2008], via DM KIMS@Y2L, Korea [2002-2008] { CDEX & KIMS : DM → Reactor ν's }*
- Theory Program *[since 2010]*


TEXONO


Kuo-Sheng Nuclear Power Station : Reactor Building
Reactor Pressure Vessel
Auxiliary Building
Primary Containment
Dry Well
Ground level
Kuo-Sheng Reactor Neutrino Laboratory
Reactor Core
Suppression Pool

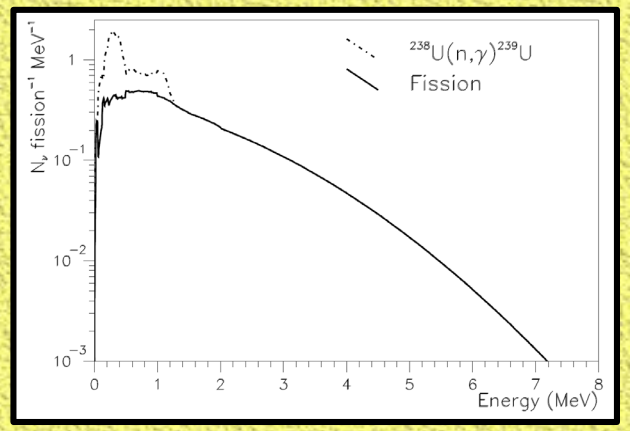

N
0
20mi
20km
NPS-I
NPS-II
Keelung
Taipei
ACADEMIA SINICA
NPS-IV
Hsinchu
Ilan


2 cm
PMT
CsI(Tl)
PMT
37 cm
40 cm
31.2 cm


Plastic Bag For Radon Purging
N2 from dewar
28 cm
OFHC Copper
PMT
NaI(Tl)
Liquid Nitrogen Dewar
75 cm
HPGe
Pre-Amplifier
p- PCGe
[500g – 1.5 kg]
p+
n+(~1mm Li diffused)
900g

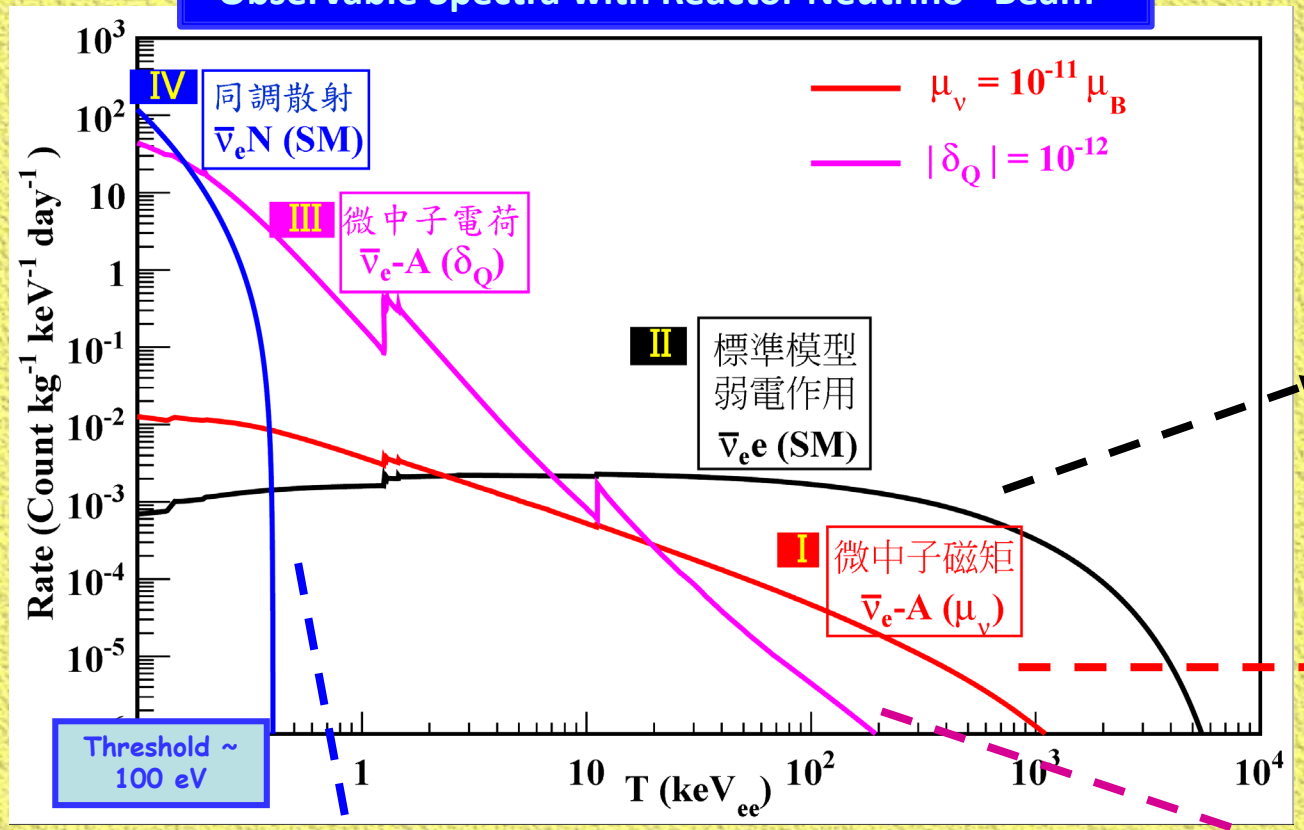
Neutrino Properties & Interactions at Reactor

quality ← Detector requirements → mass



Reactor Neutrino Spectrum

Observable Spectra with Reactor Neutrino "Beam"



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

νN Coherent Scattering *[Current Theme;PRD16,PRD21]*

- Pioneered sub-keV O(kg) ULEGe / PCGe [MPLA08, NIMA16]
  - Light Dark Matter Searches @ KSNL *[PRD09,PRL13,AP14,PRD19]*
  - CDEX DM Program@CJPL *[PRD13……]*
  - Theory Program *[PLB14……]*

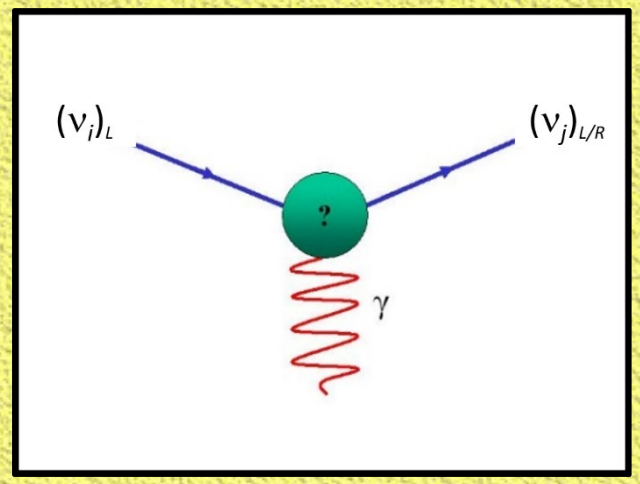
sub-keV PCGe

Neutrino Electromagnetic Interactions

Neutrino Electromagnetic Form Factors

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

$$F_1 = \delta_{\mathrm{Q}} \cdot e_0 + \frac{1}{6} \cdot q^2 \cdot \langle r^2_{\nu} \rangle, \qquad F_2 = (-i) \cdot \frac{\mu_{\nu}}{2 \cdot m_e},$$



$$\left(\frac{d\sigma}{dT}\right)_{\mathrm{FEA}} = \delta^2_{\mathrm{Q}} \left[\frac{2\pi\alpha^2_{\mathrm{em}}}{m_e}\right] \left[\frac{1}{T^2}\right],$$

Helicity Conserved : milli-charge

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

Helicity Flipped : Magnetic Moments

$$\sin^2\theta_{\mathrm{W}} \rightarrow \sin^2\theta_{\mathrm{W}} + \left(\frac{\sqrt{2}\pi\alpha_{em}}{3G_F}\right)\langle r^2_{\bar{\nu}_e}\rangle,$$

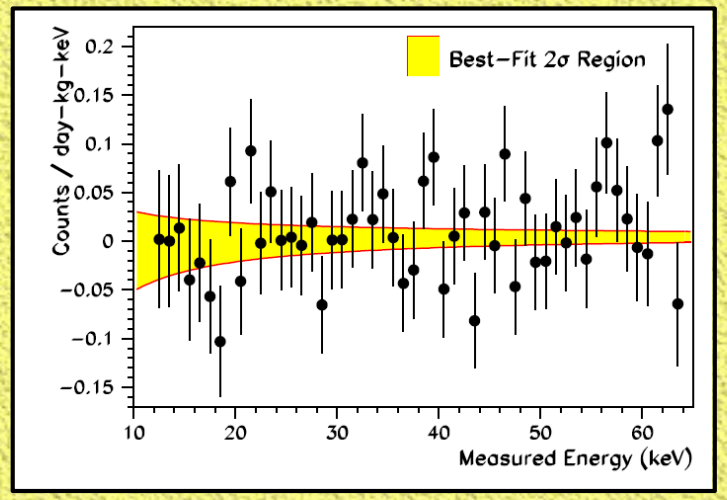
Helicity Conserved : charge radius

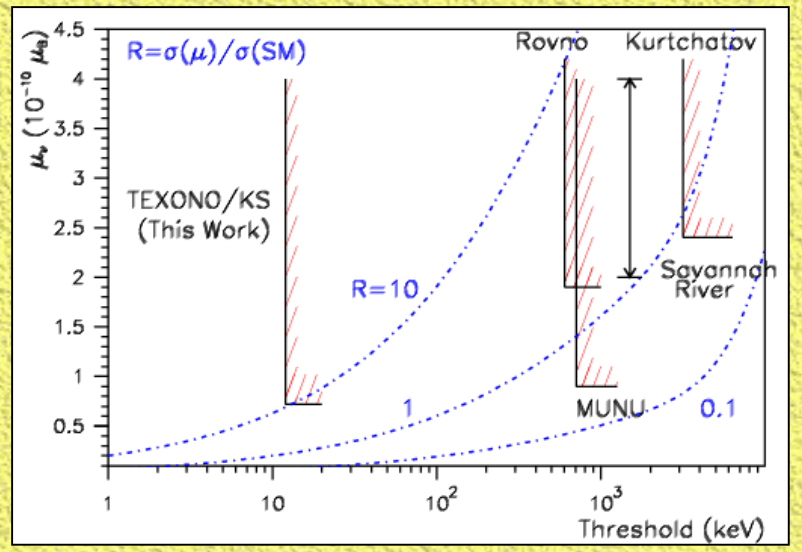
Neutrino "Magnetic Moments"

Search of μ_ν at low energy 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]





$\mu_\nu(\nu_e) < 7.2 \times 10^{-11}\ \mu_B$ [PRL03,PRD07]

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

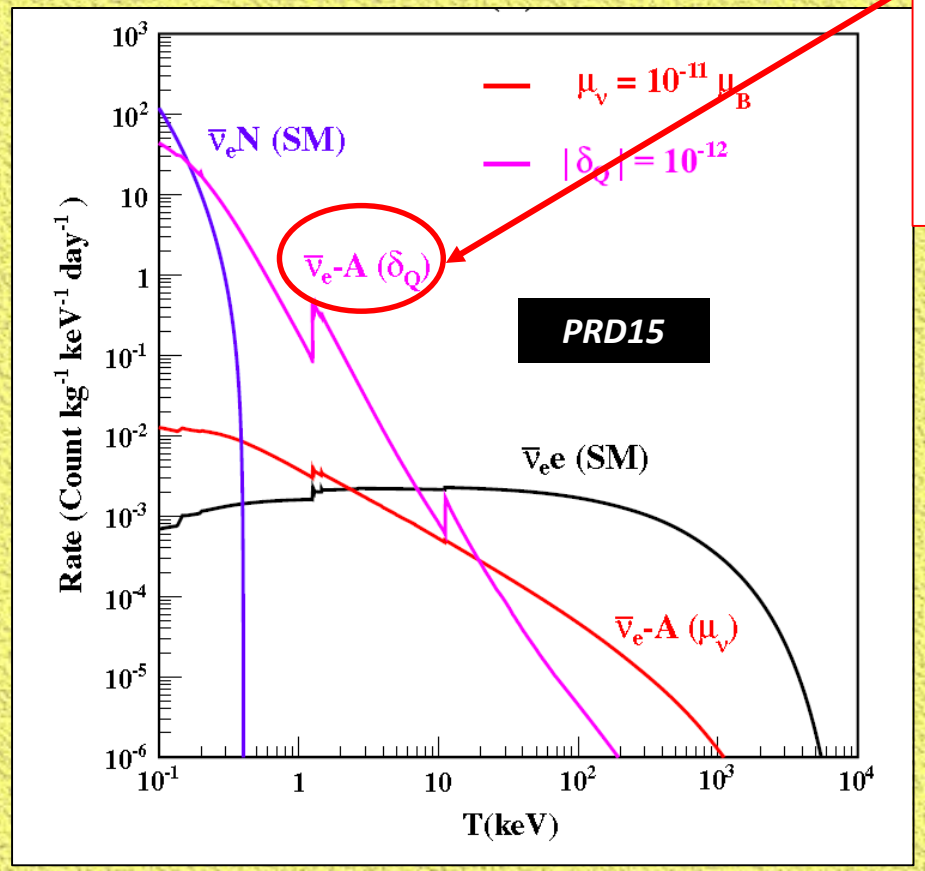
$\mu_\nu(\nu_e) < 2.9 \times 10^{-11}\ \mu_B$ *[2013]*

Neutrino "Milli-charge"

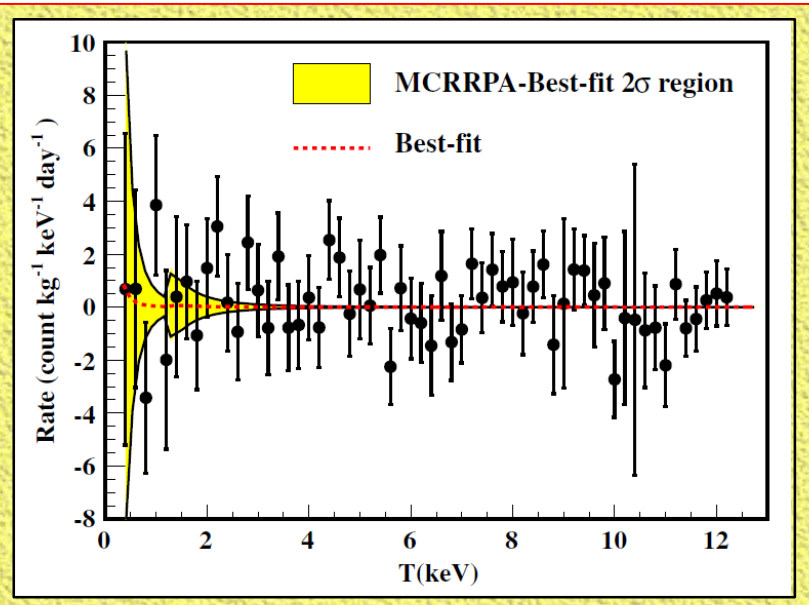
[PRD14]

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

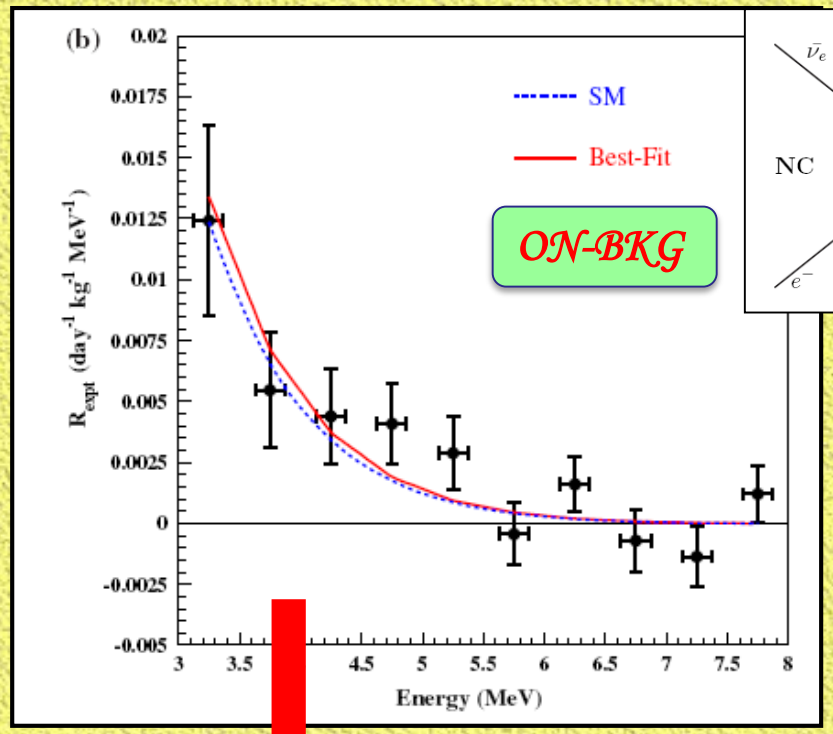
Atomic Ionization Differential Cross-Section with full atomic physics many-body "MCRRPA" calculation [PL13]

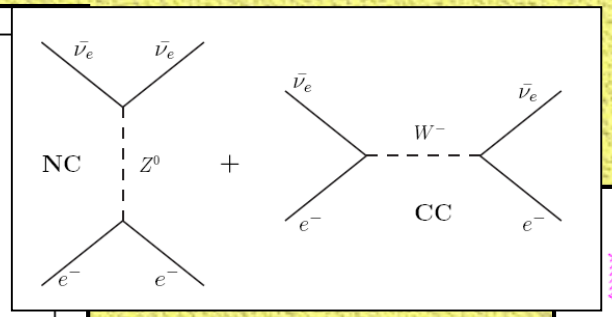


- ☑ **Identify New Twist - Cross-section enhanced at low energy transfer ("minimum ionizing")**
- ☑ **Smoking-gun signatures for positive signals: peaks at known K/L binding energy at known ratios *[different from cosmic-activation electron-capture background]***
- ☑ **Present Bound : $\delta_Q < 10^{-12}$**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

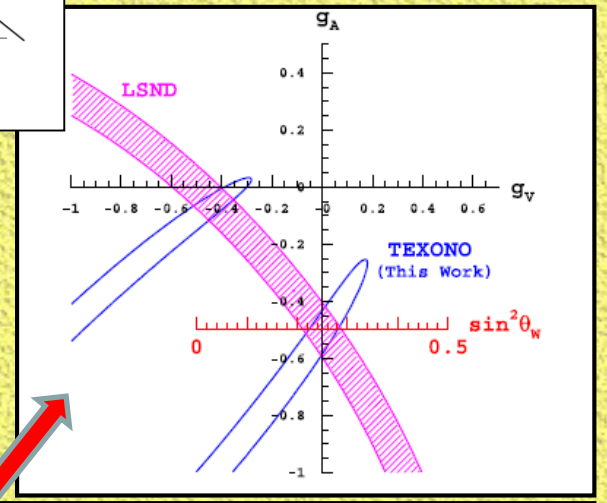


CsI(Tl) 200 kg : Probe Electroweak Physics *[PRD10]*





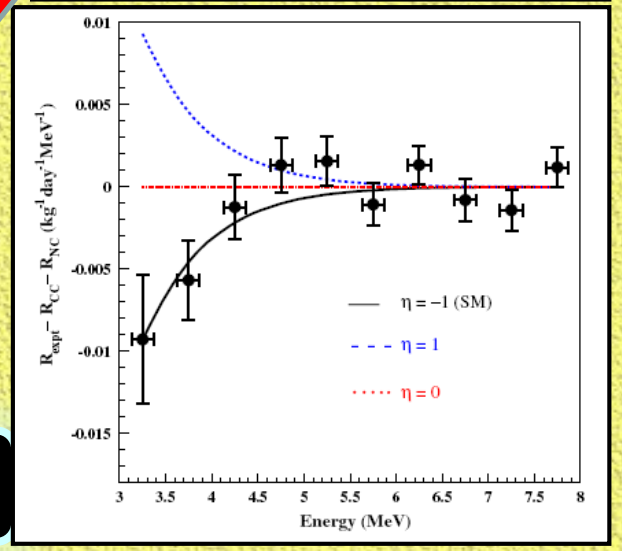
Still- Best Measurement !



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

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

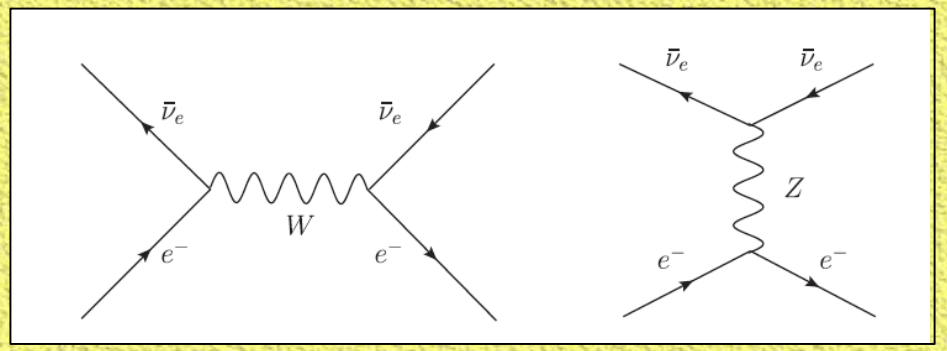
Verify SM Destructive Interference



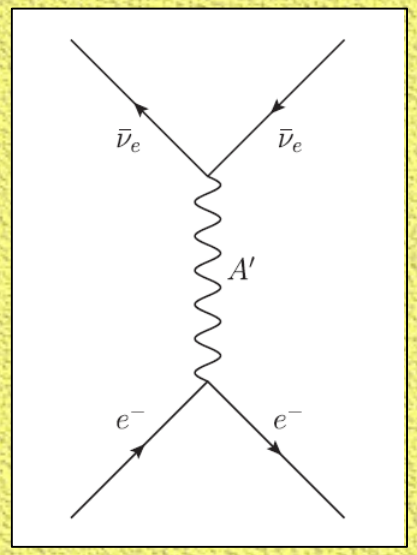
⊕ Constraints on Various Beyond SM Effects *[PRD10;PRD12;PRD15] 0*

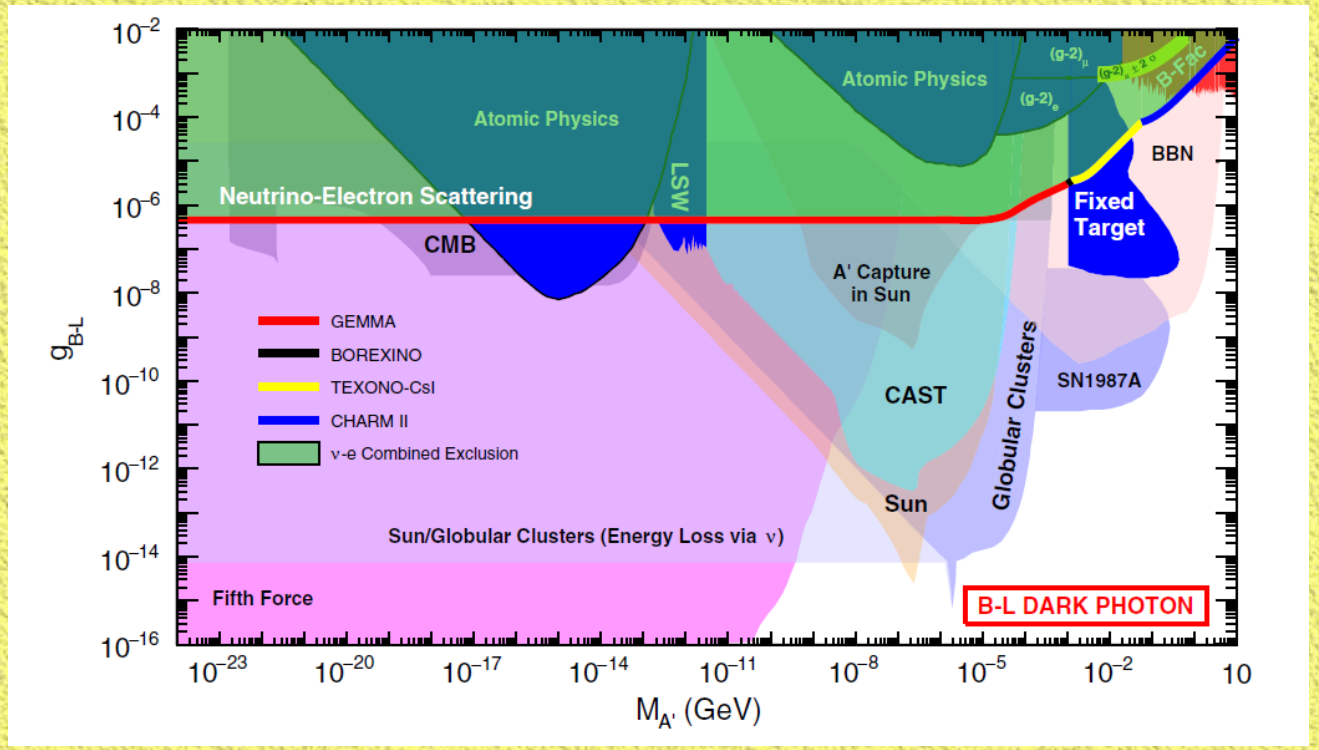
Constraints on Dark-Photon with ν-electron Scattering *[PRD15]*

Early constraints on Dark Photons → high citation



⊕

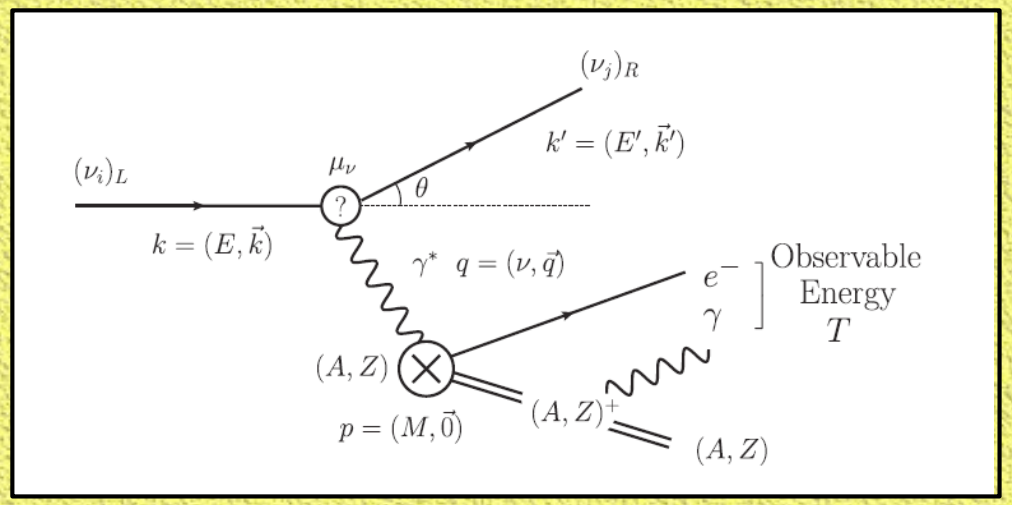


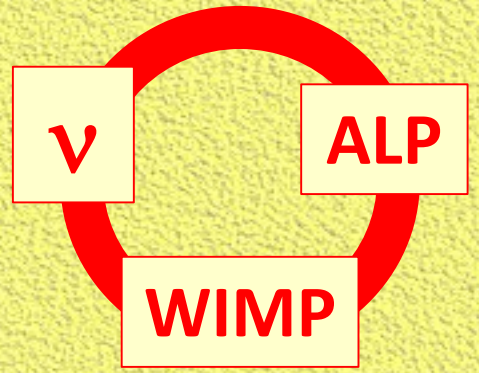


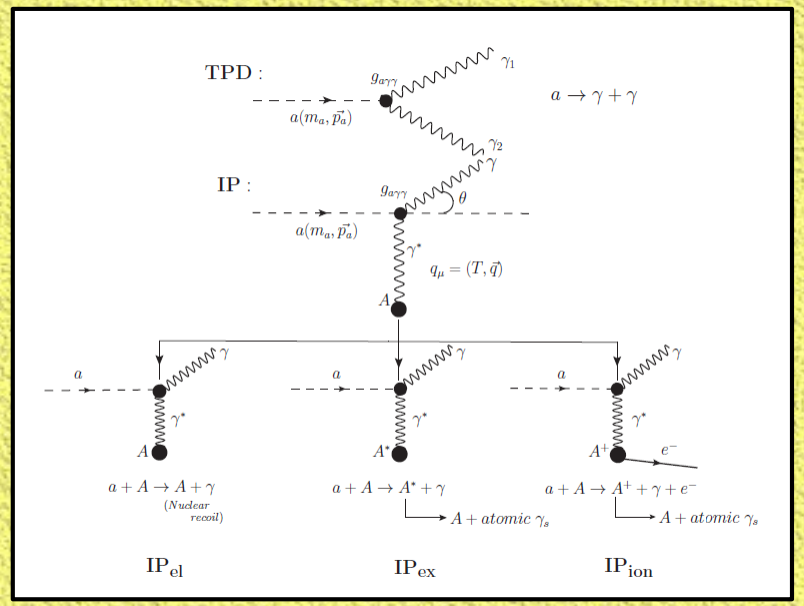
TEXONO Theory Program *[AS, NTU, NDHU, UCSB, DEU, SCU ……]*

Connecting the Dots:

- TEXONO & CDEX detector frontiers in low (sub-keV) energy
  - → atomic physics range
- Studies of EW/BSM physics
  - understanding of the detection many-body physics
  - state-of-the-art techniques in atomic, nuclear & QCD physics.
- *i.e.* **ν(χ,α) A** instead of **ν(χ,α) N** or **ν(χ,α) e**



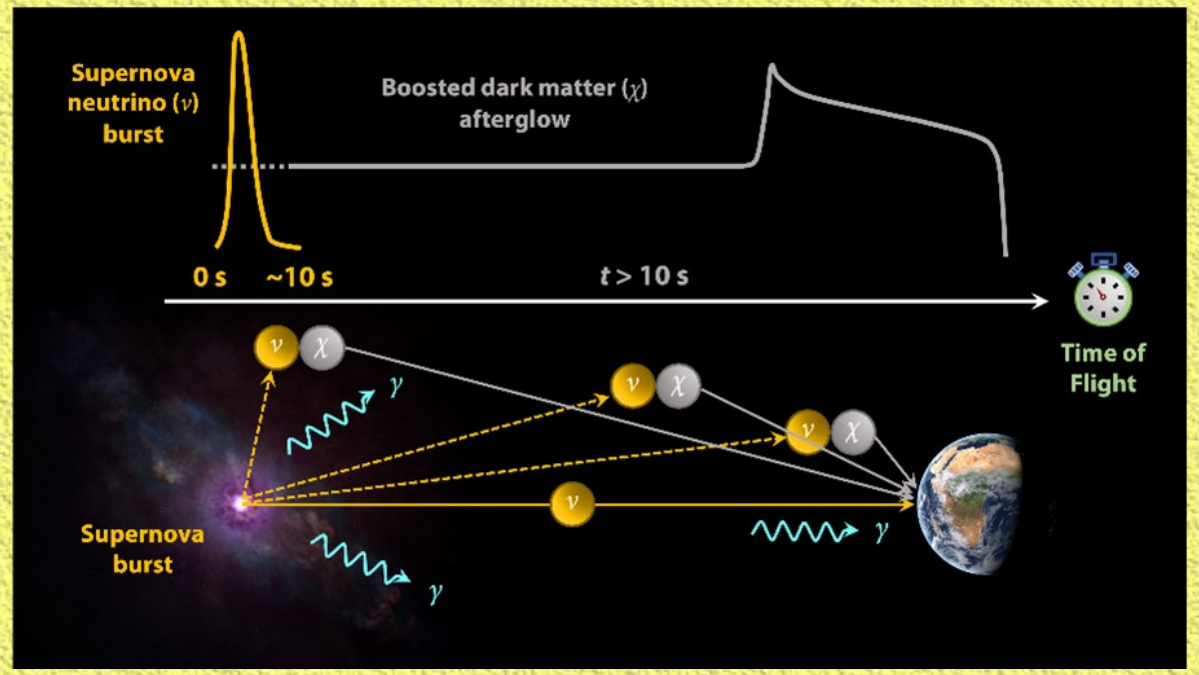




Selected Highlights:

- **Identified Pole structures, Cross-section enhancement, Smoking-gun signatures in:**
  - milli-charged ν interactions: $\nu\ (\delta_Q) + A$ *[PRD 14]*
  - DM-ν (NR) transition-μ_ν interactions: $\nu_{DM} + A \rightarrow \nu_{SM} + A^+ + e^-$ *[PRD15]*
  - DM-ALP (NR) Inverse Primikoff scattering: $a_{DM} + A \rightarrow \gamma + A^+ + e^-$ *[PRD23]*

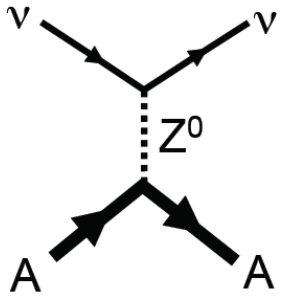
- **Time-of-Flight as Signature of Boosted Dark Matter by Supernova Neutrinos** *[PRL23, PRD23]*
  - First case of using Time (other than interactions) as DM signature

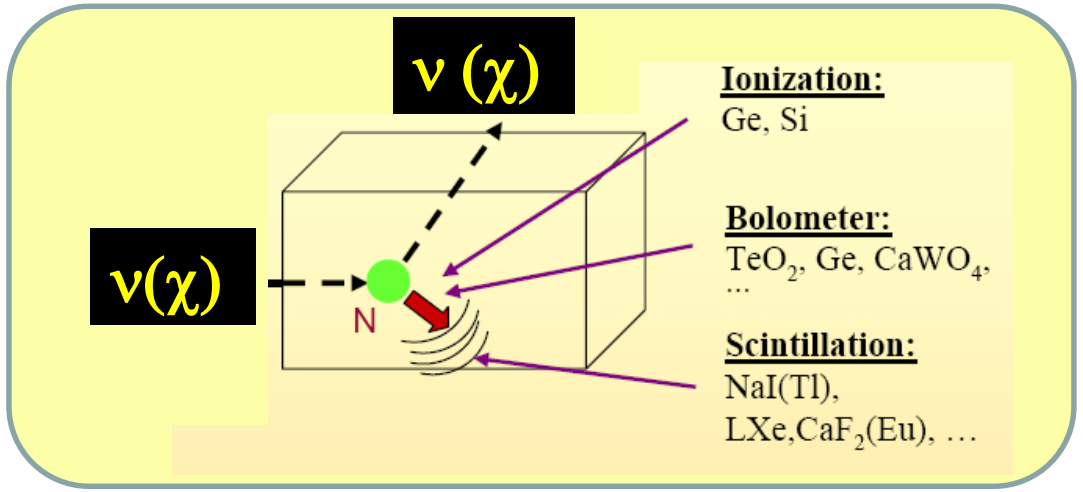


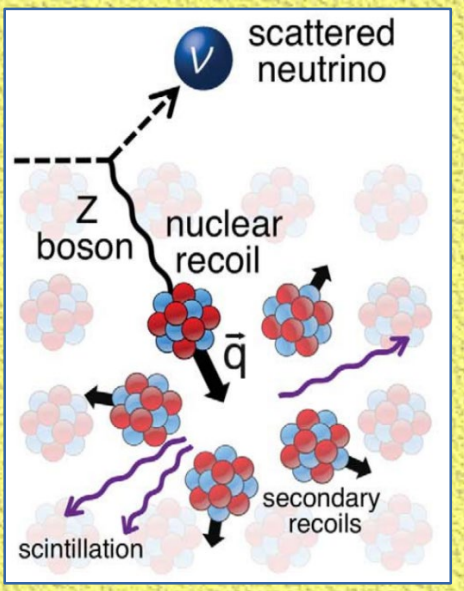
Neutrino-Nucleus Coherent Scattering :

Standard Model allowed and predicted processes :

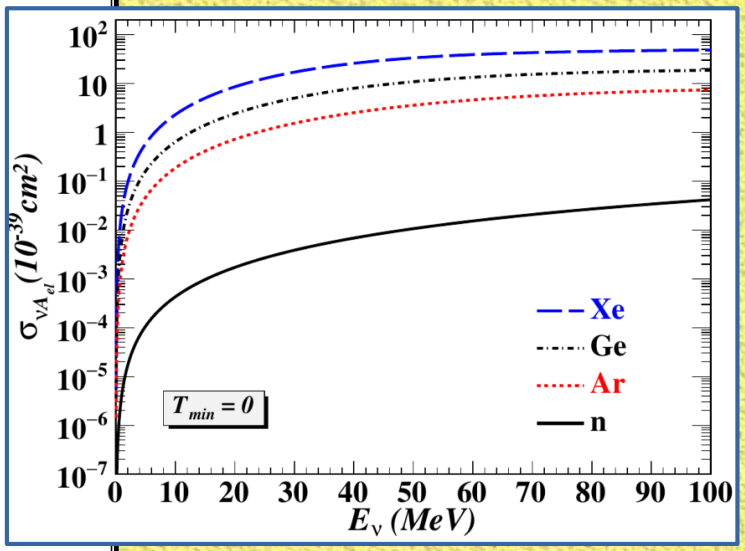
$$\nu + A \rightarrow \nu + A$$



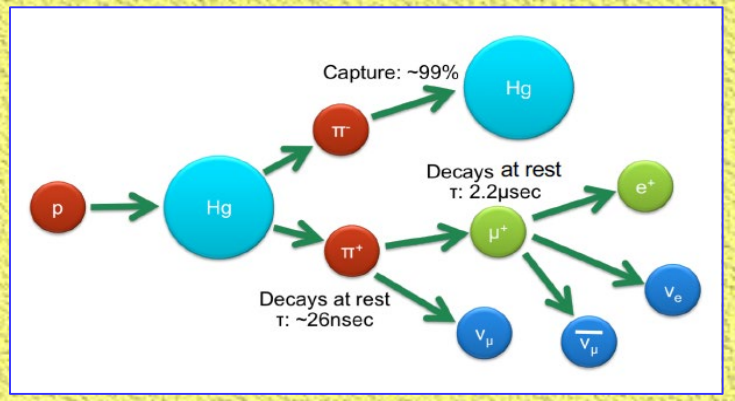




- Neutral current process (same for all ν-flavor)
- $\sigma \propto N^2$ @ $E_\nu < 50$ MeV
  - ⇒ *"Complete Coherency" for Reactor Neutrinos*
  - *[probe "sees" the whole nucleus]*
- sensitive probe for BSM ; interest in reactor monitoring
- important process in stellar collapse & supernova explosion
- analogous interaction used in dark matter detection
- Ge at KSNL @ QF~0.16 : cut-off ~ 200 eV ;
  - Rate ~10 kg⁻¹ day⁻¹ @ threshold~100 eVee

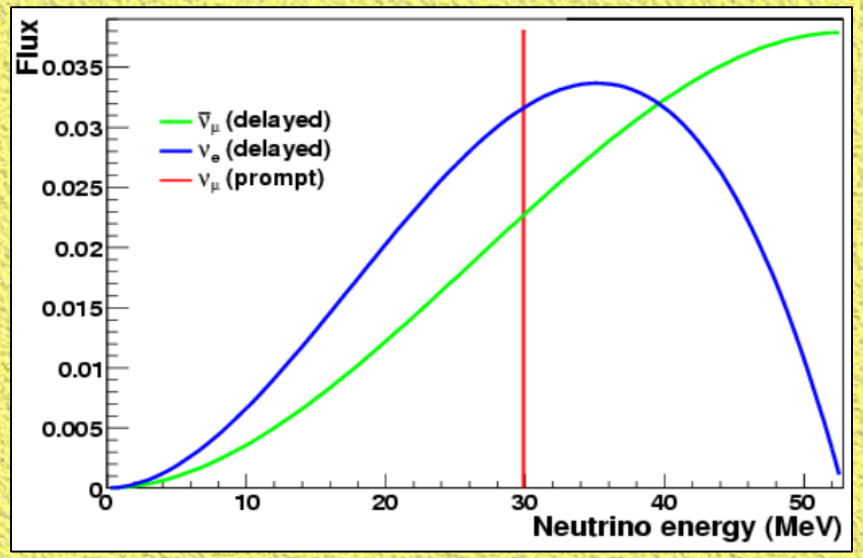


Stopped-Pion (πDAR) Neutrinos

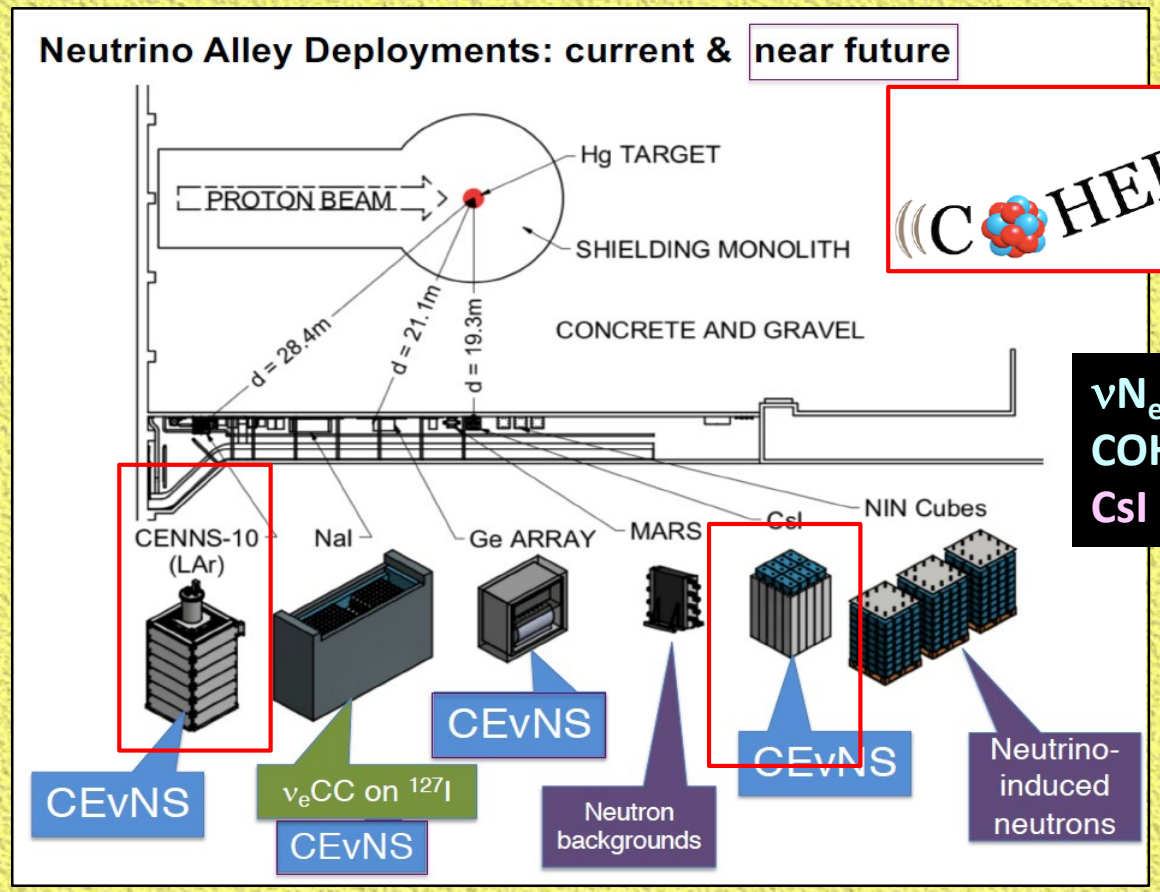


$\pi^+ \rightarrow \mu^+ + \nu_\mu$ 2-body decay: monochromatic 29.9 MeV ν_μ PROMPT

$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$ 3-body decay: range of energies between 0 and $m_\mu/2$ DELAYED (2.2 μs)



Neutrino Alley Deployments: current & near future



νN_{el} observed in COHERENT@ORNL in CsI (2017) & LAr (2019)

Coherency in Neutrino-Nucleus Elastic Scattering [PRD16,PRD21]

- Quantify transitions between QM Coherency & Decoherency
- Universal Characterization between different Sources & Target

νA_{el} with Reactor Neutrinos:

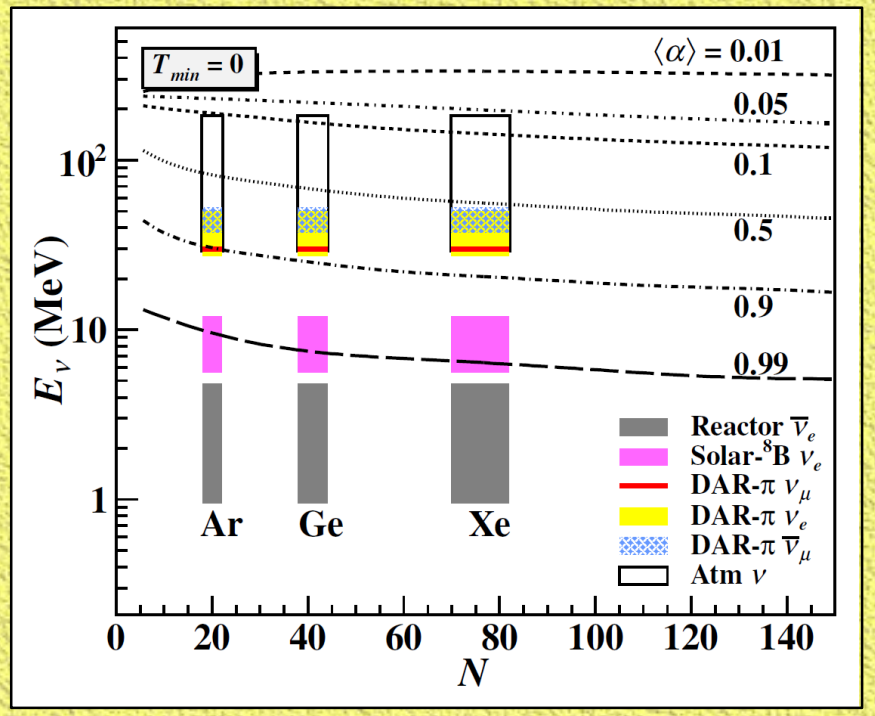
- ☑ Different kinematics regimes : $q^2 \rightarrow 0$; $FF(q^2)=1$
- ☑ Full QM Coherency *[DAR-νN @~0.6 - 0.7]*
- ☑ BSM/NSI Searches → no degeneracy with nuclear physics FF uncertainties

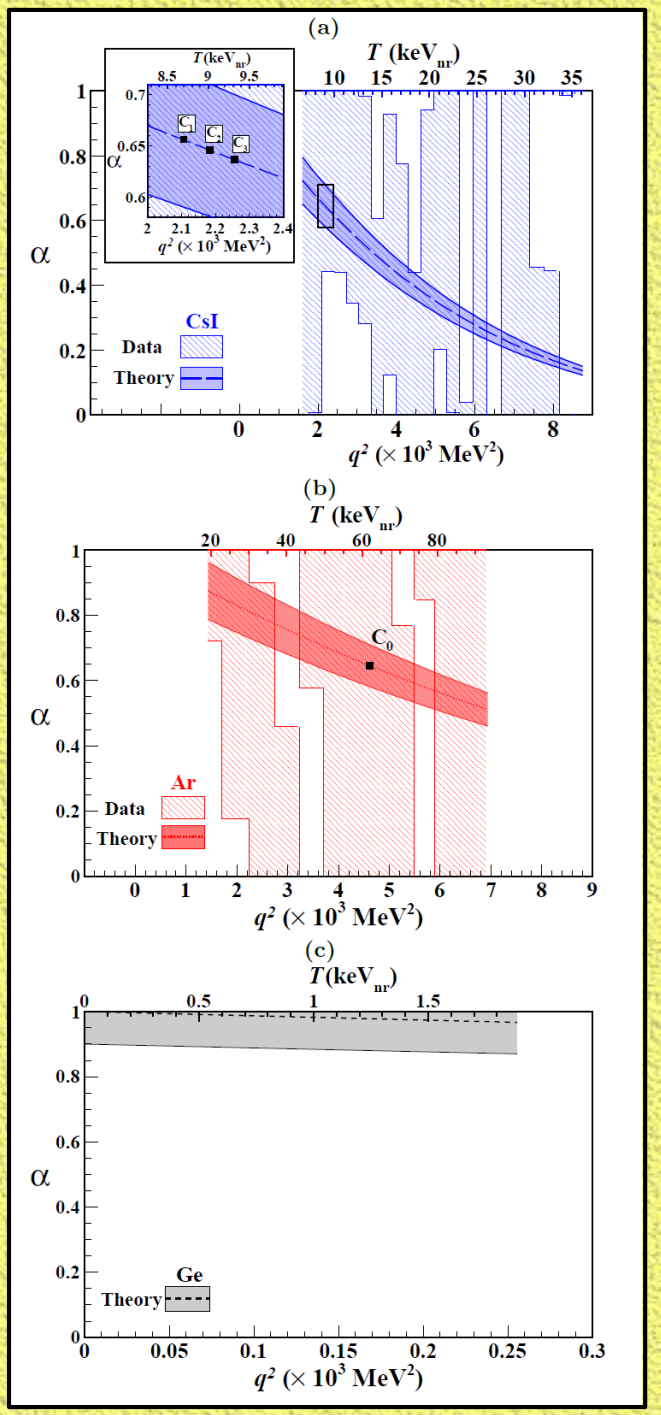
$$\alpha \equiv \cos\langle\phi\rangle \in [0,1]$$

<ϕ> : averaged decoherence angle

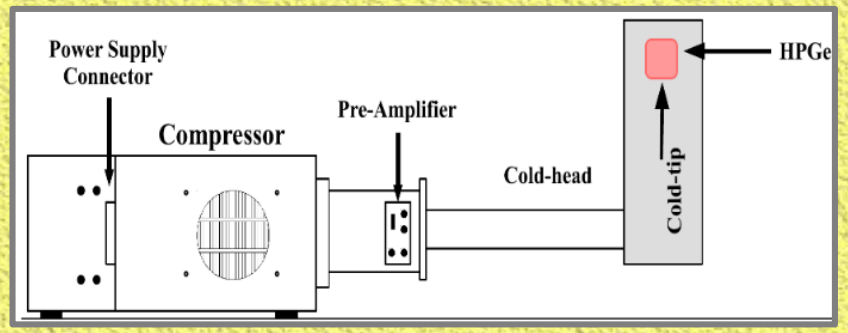
Seek Theorists' Input / Inspirations:

- ☑ Derive α from basics QM & Relate to nuclear physics



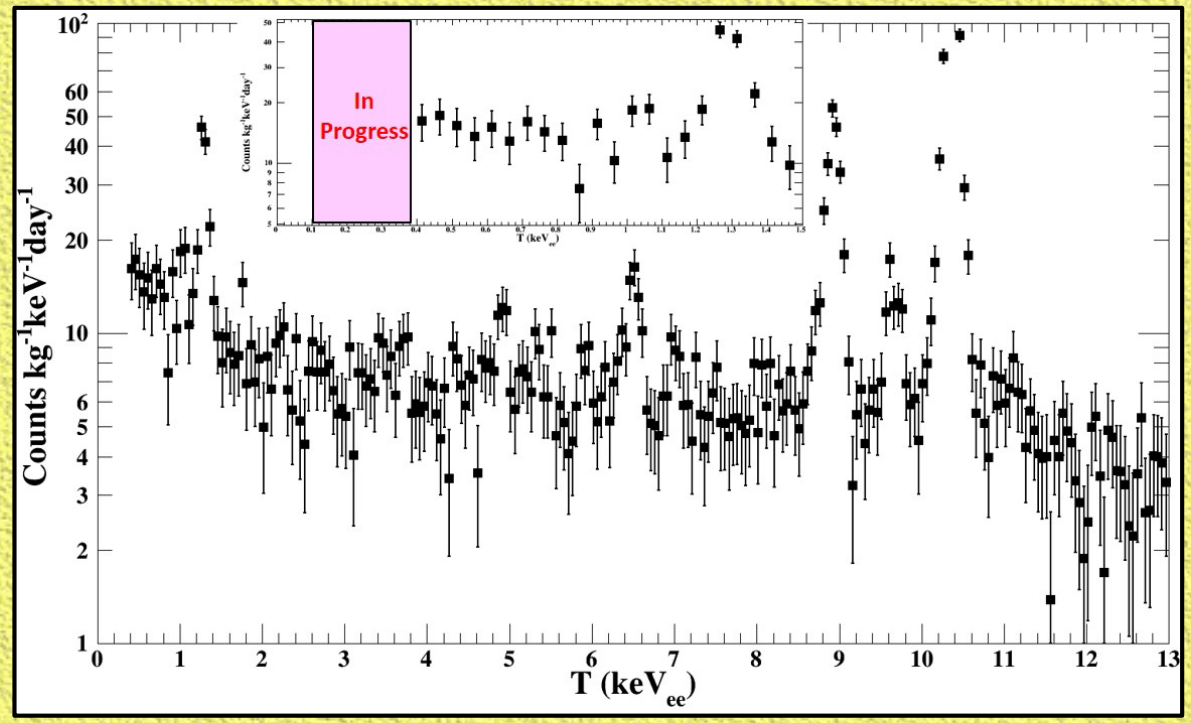


Electro-cooled PCGe



	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	900	70	~230
Electro-cool	$G3^{+}$	1430	~60	~160
Electro-cool	$G3^{++}$	1430	70	200
Electro-cool	G4	900	<70	<200

This Analysis

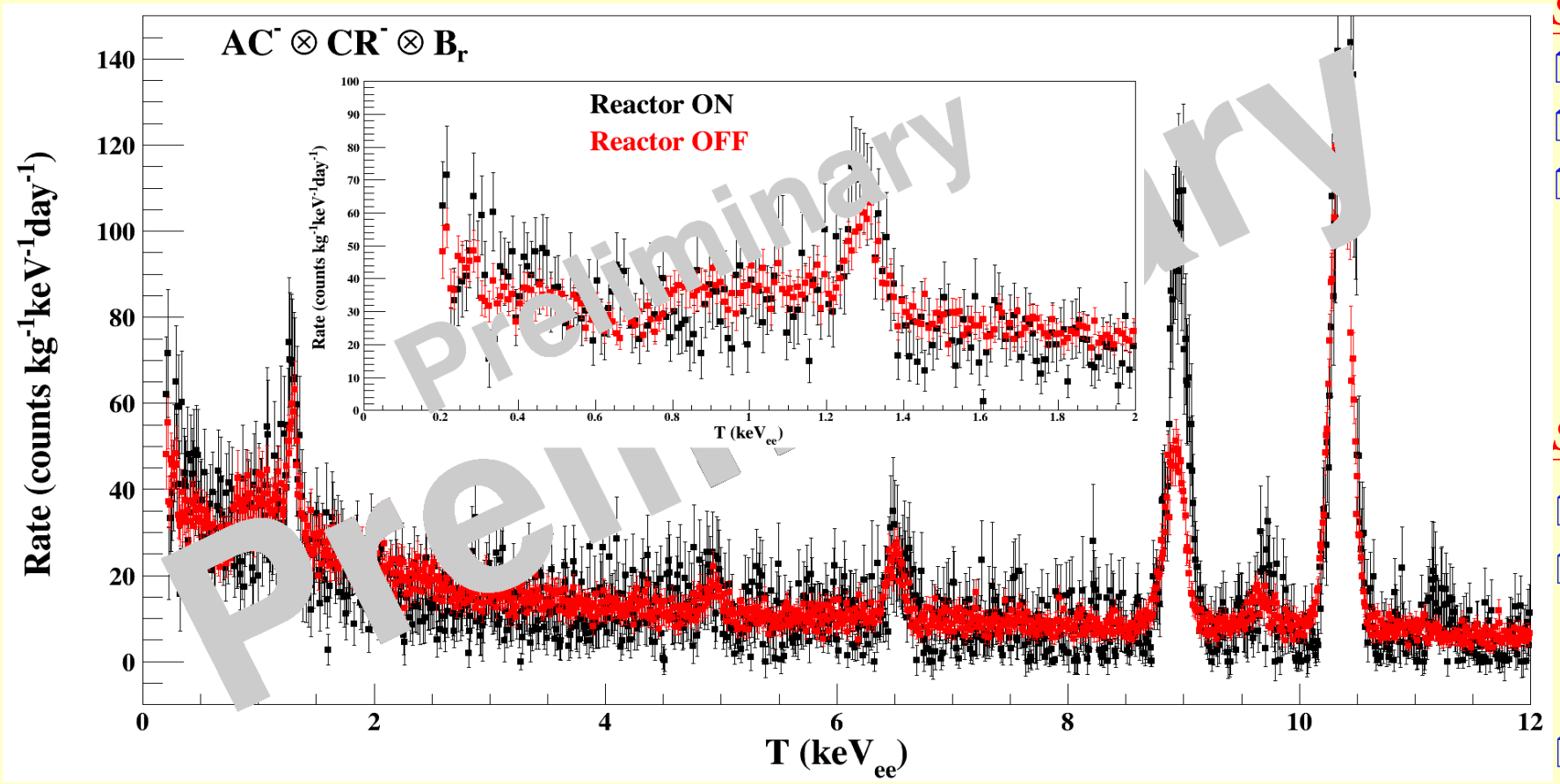


- ☑ Novel Technology with Negative Feedback Synchronized Pumping
- ☑ Typical G3 (500g) Spectrum ⇨
- ☑ With Anti-Compton & Cosmic-Ray & Surface Events Vetos
- ☑ Near Threshold Data Analysis In Progress.

Sub-keV Ge Detector Techniques : Hardware/Software Development *[AP13, NIMA 16, NIMA18]*

- 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

νA_{el} @ KSNL



***Secured Key Parameters*:**

- ❒ 200 eV Threshold
- ❒ Pulsar FWHM 70 eV
- ❒ Controlled Background
  - Stable Running for >3.5 years

***Sensitivity Achieved*:**

- ❒ G^{3++} (1.43 kg) [*p*PCGe]
- ❒ Data [Statistics - partial]
  - Reactor ON – 65 kg-days
  - Reactor OFF – 438 kg-days
- ❒ Background
  - In sub-keV region:

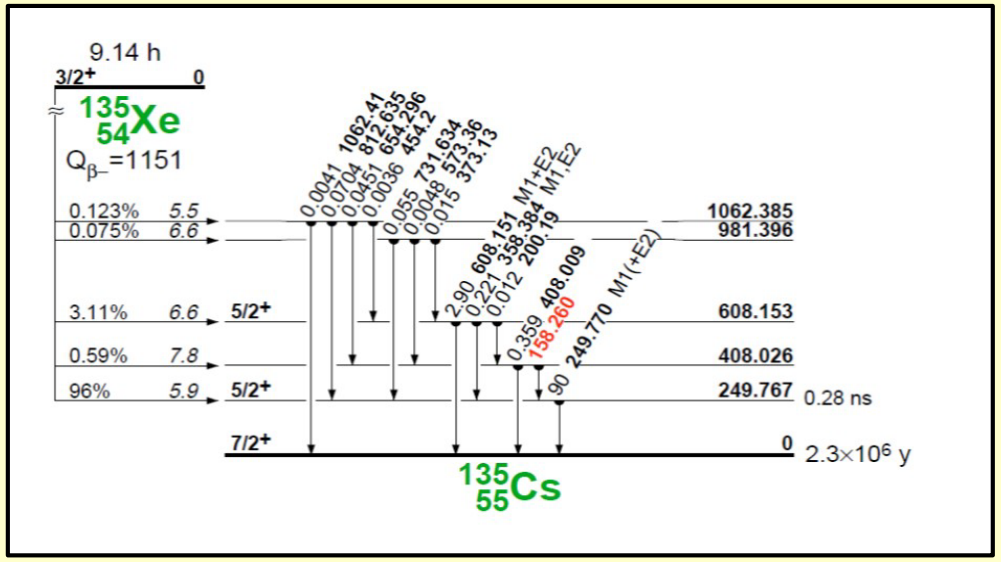
  ~ 50 counts (kg^{-1} keV^{-1} day^{-1})
  - Residual Reactor ON related Background: ^{135}Xe [2-3%@ Threshold]

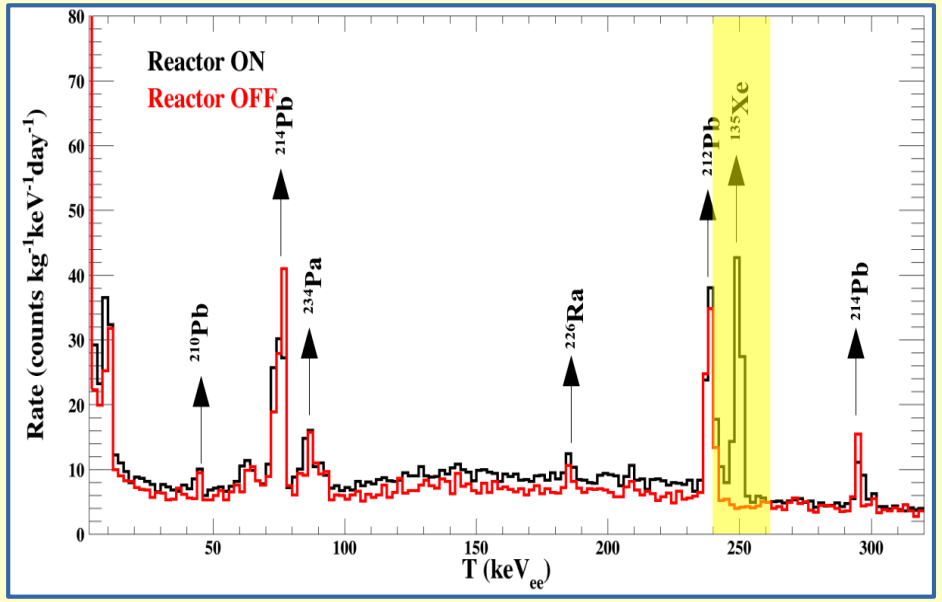
***To Achieve Better Sensitivity*:**

- ❒ More data to be analysed
- ❒R&D to achieve Low Energy Threshold & Less Background

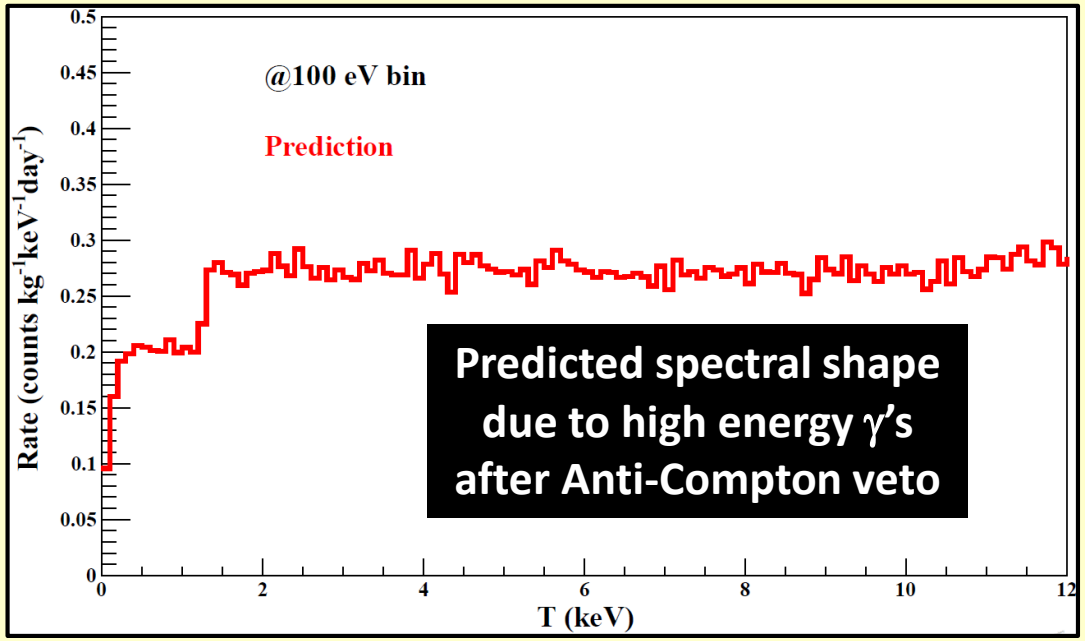
†$AC^{-}\otimes CR^{-}\otimes B_r$ → Anti-Compton veto ⊗ Cosmic Ray veto ⊗ Bulk Events Corrected

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



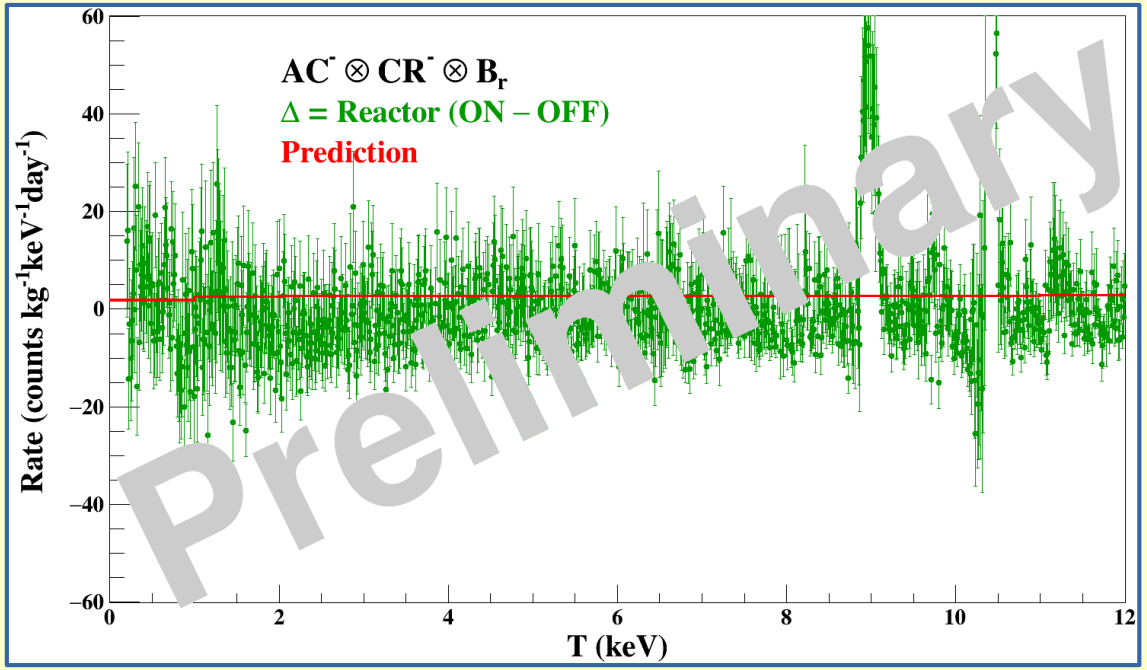


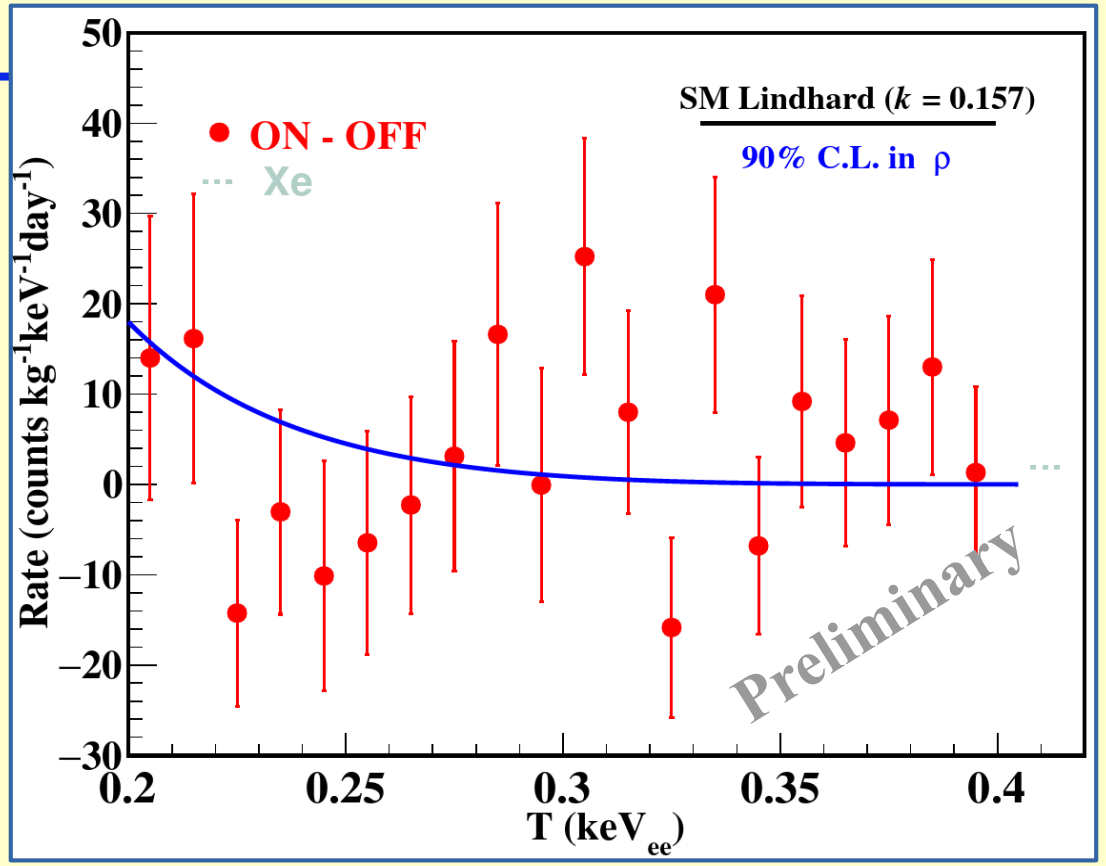
- A Decay Product of ^{235}U- β
  - $^{135}Xe \rightarrow {}^{135}Cs^{*} + \bar{\nu}_e + e^-$
  - $^{135}Cs^{*} \rightarrow {}^{135}Cs + \gamma$ (249.8 keV)
- Very Good Neutron Absorber
  - Poison For Reactor
- Half-life = 9.14 h
- Contributes ~1.89 ± 0.02 counts.kg^{-1}.keV^{-1}.day^{-1} @ sub-keV energy region

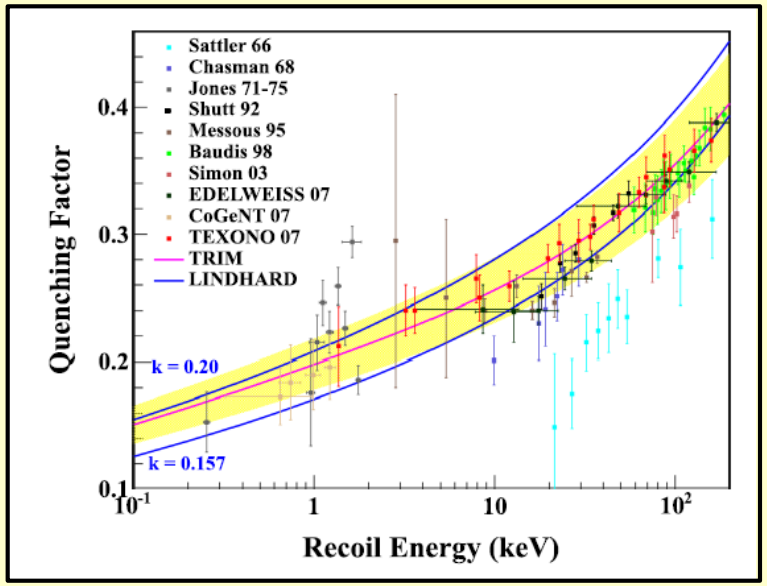


†AC$^-$⊗CR$^-$⊗B$_r$ → Anti-Compton veto ⊗ Cosmic Ray veto ⊗ Bulk Events Corrected

Sensitivity Limits on TEXONO Data





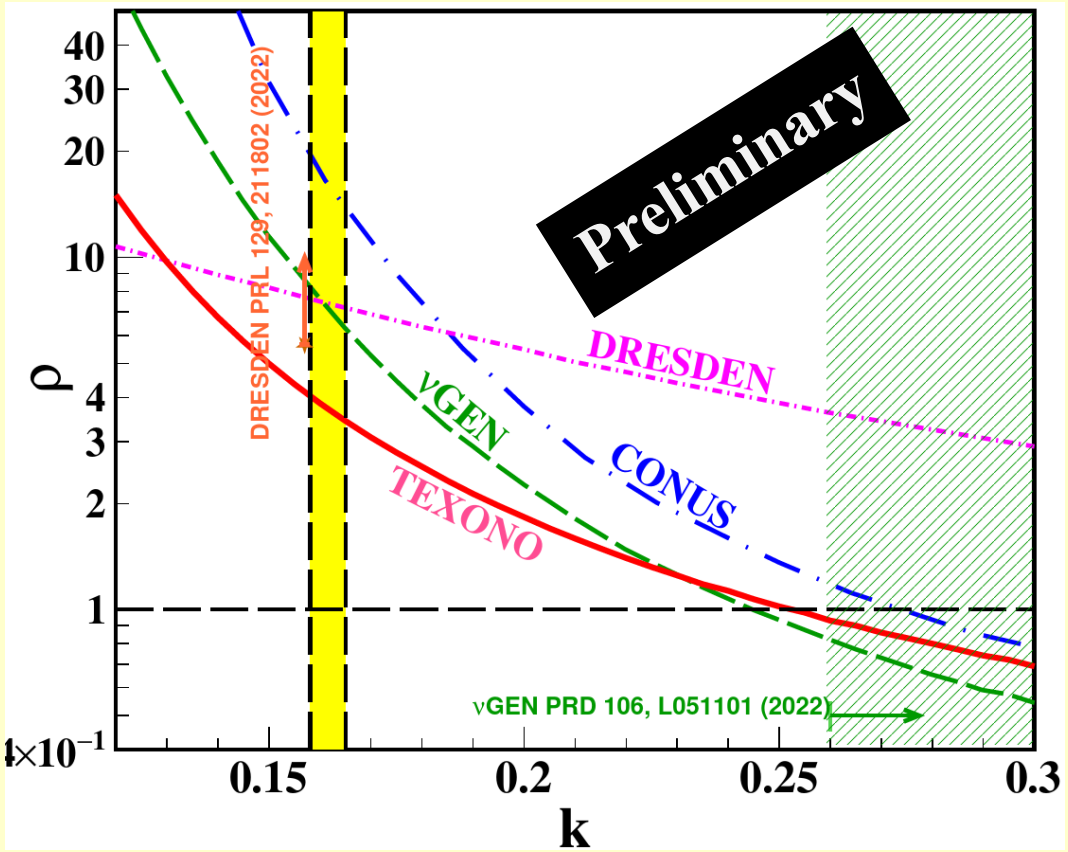


This Data *[TAUP2023]*

- **Reactor ON – 65 kg-days**
- **Reactor OFF – 438 kg-days**

†$AC^{-}\otimes CR^{-}\otimes B_r$ → Anti-Compton veto ⊗ Cosmic Ray veto ⊗ Bulk Events

Sensitivity Limits on TEXONO Data



☑ ρ : ratio of measured to SM cross-sections

☑ 3σ allowed for *k* from QF measurement data

☑TEXONO [with 200 eV threshold]

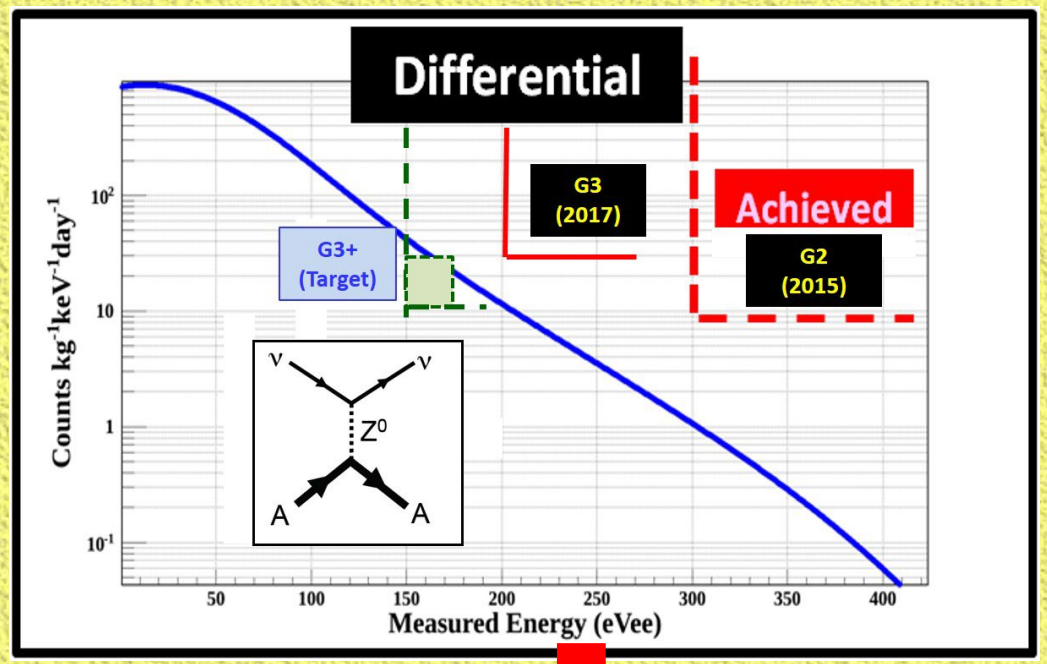
🛠 @90%CL Upper Limit :

$\rho < 4.2$ @ Lindhard SM $k=0.157$

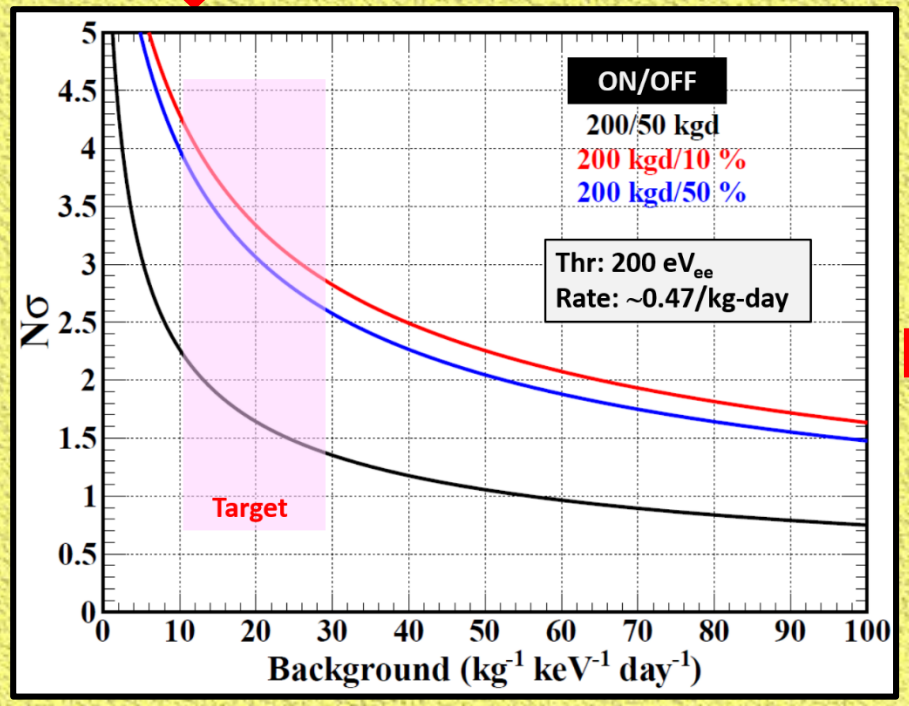
Reactor Ge Experiment	TEXONO	DRESDEN	ν-GEN	CONUS
Flux (10^{12} $cm^{-2}s^{-1}$)	6.36	48	39	23
Distance (m)	28	10.39	11.83	17.1
Power (GW)	2.9	2.96	3.1	3.9
Overburden (m.w.e)	30	6	50	24
Exposure (kg-days) ON[OFF]	65[438]	282[73]	133[66]	248.7[58.8]
Pulsar FWHM (eV)	70	161	101.6	69 (C1)
Threshold (eV)	200	200	300	~300
Background ON @ Threshold (counts.kg^{-1}keV^{-1}day^{-1})	62	3095	134	100
$\sigma_{Residual}$ @ Threshold (counts.kg^{-1}keV^{-1}day^{-1})	15.8	510	17.3	27.9

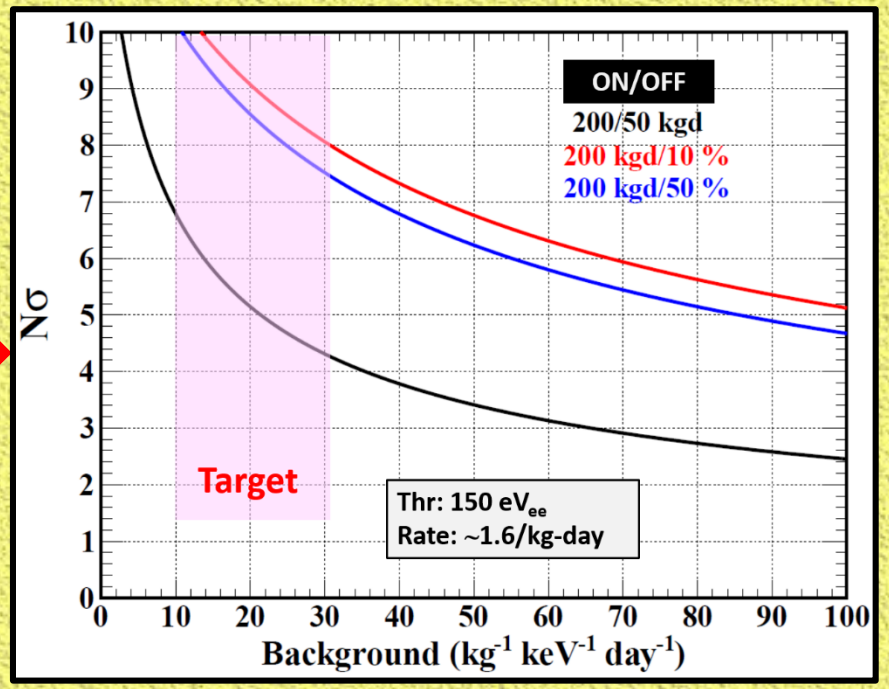
- **DRESDEN:**[*PRD 104,072003 (2021); PRL 129, 211802 (2022)*]
- ***ν*GEN:**[*ICPPA 2022, A. Lubashevskiy; PRD 106, L051101 (2022)*]
- **CONUS:**[*PRL 126, 041804 (2021); EPJC 81:267 (2021)*]

νA_{el} at KSNL : Projected Sensitivities



- ☑ G3 (200-eV) Data Collected
  ON/OFF ~ >500 / >800 kg–days
- ☑ R&D: G4 & PSD at threshold
- ☑ KS Power Plant Decommissioned : 2023 ;
  Access till end of 2025.
- ☑ Explore new site if G4@150 eV threshold secured.





Meanwhile, TEXONO Program in Taiwan:

- In addition to continuation of sub-keV Ge, νN_{el} @ KSNL, Theory projects, CDEX@CJPL ..... *(all in good hands of our collaborators)*
- Working with local LIGO-GW groups (NCU, NTHU) to develop a *gravitational experiment research program,* incl.
  - ☑ Mirror coating R&D
  - ☑ Cryogenics techniques, active vibration suppression
  - ☑ Calibration analysis and theoretical modelling
  - ☑ Physics (BSM, DM, SB) Analysis
  - ☑ exploring GW detection principles at low frequency
  - ☑ .....

Prospects & Outlook

TEXONO Program

- νA_{el} @ KSNL → G4 PCGe@150 eV threshold → New Reactor Site
- Partner of CDEX DM @ CJPL → $0\nu\beta\beta$ Project
- Theory: LE ν/χ cross-sections, BSM searches, QM coherency, Follow our nose ….
- Gravitational Physics Related research *(testing the waters)*

Wish/Expect/Trust:

Both the Journeys & Destinations for the Evolving Story will be as Fascinating as in the past 2+ decades.