TEXONO's ν+DM : Status & Plans

- Highlights
  - ν @ KSNL
  - DM @ CJPL
  - Theory
- Lesson from History *(Thought Provoking/Provocative)*

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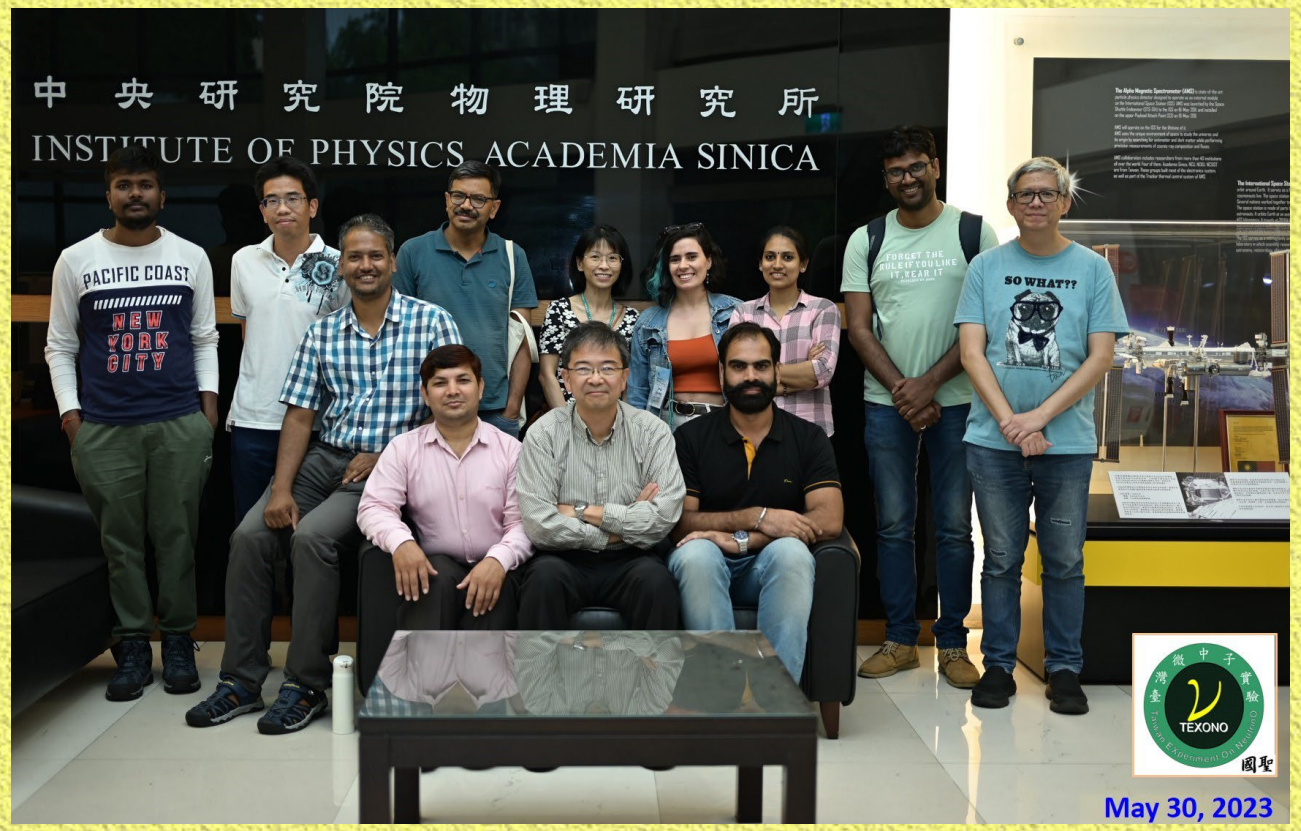
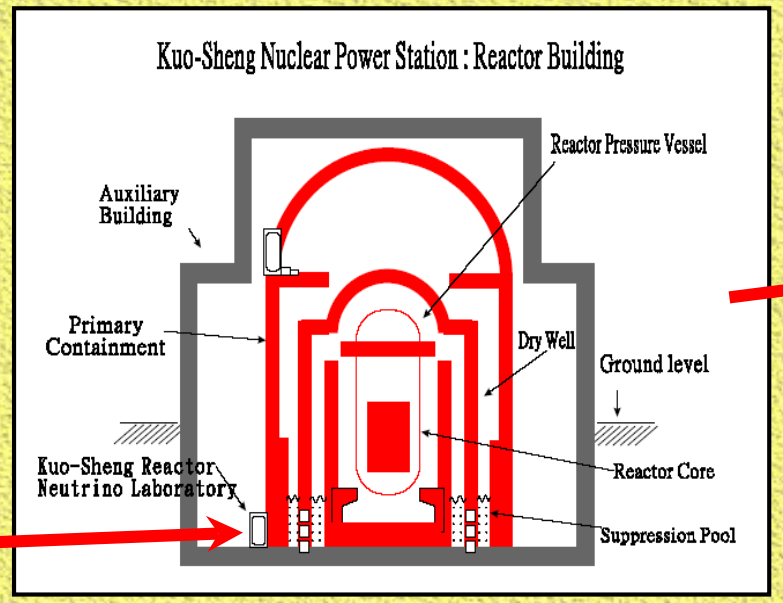


AS, KSNPS, NTU, NDHU,
IHEP, CIAE, THU, SCU,
BHU, CUSB, GLAU,
HNBGU, METU, DEU.....

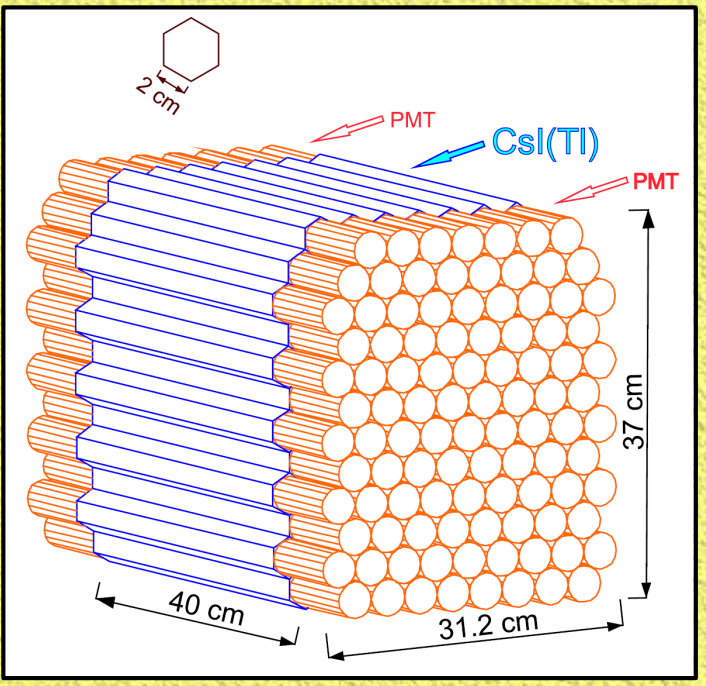
TEXONO Program ***[since 1997]*** **:**

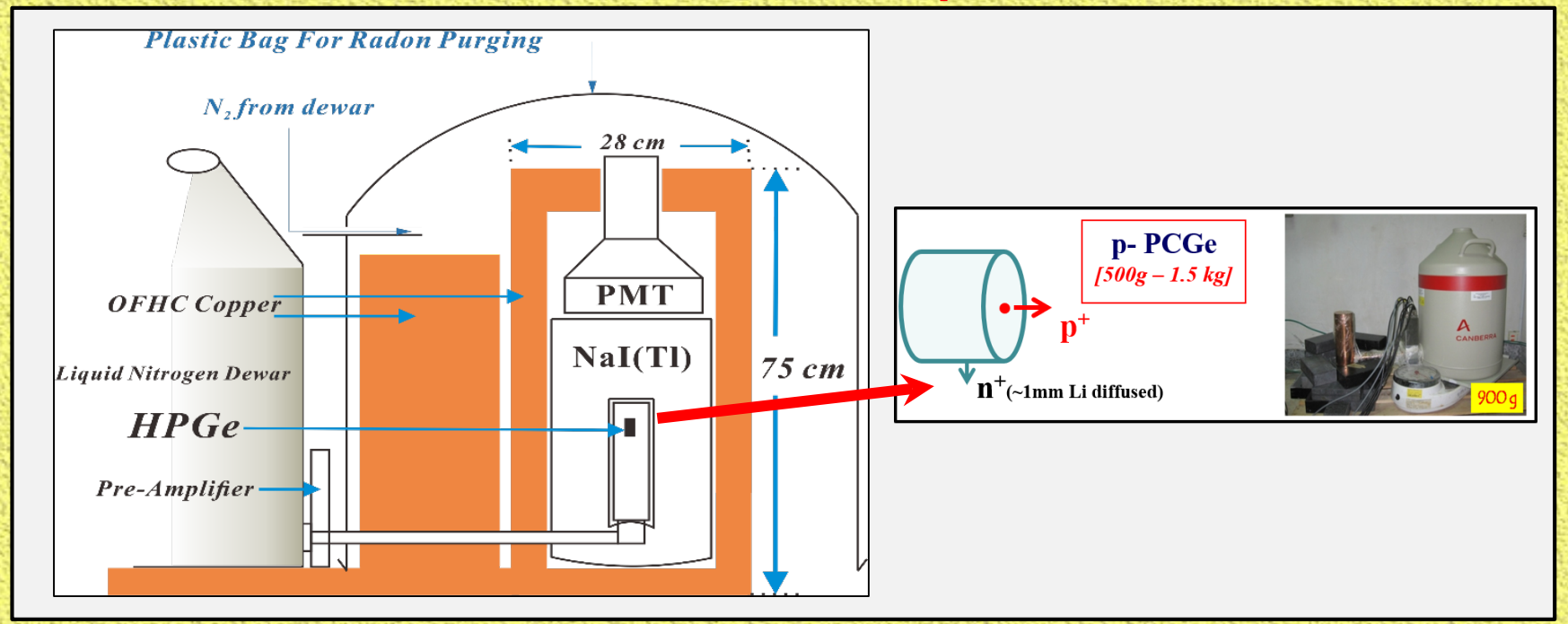
- ☐ Low Energy Neutrino (SM+EM) physics at Kuo-Sheng Neutrino Laboratory (KSNL), 28 m from 2.9 GW_{th} reactor core
- ☐ Founding partner of CDEX@CJPL Dark Matter Experiment *[since 2008]*
- ☐ Theory Program *[since 2010]*


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

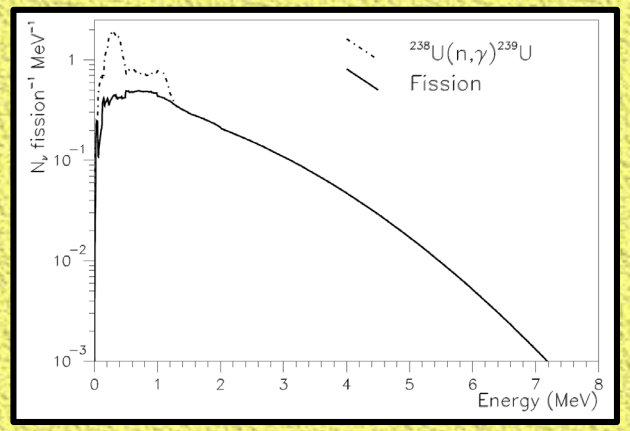

N
0
20mi
20km
NPS-I
NPS-II
Keelung
Taipei
ACADEMIA SINICA
NPS-IV
Hsinchu
Ilan


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

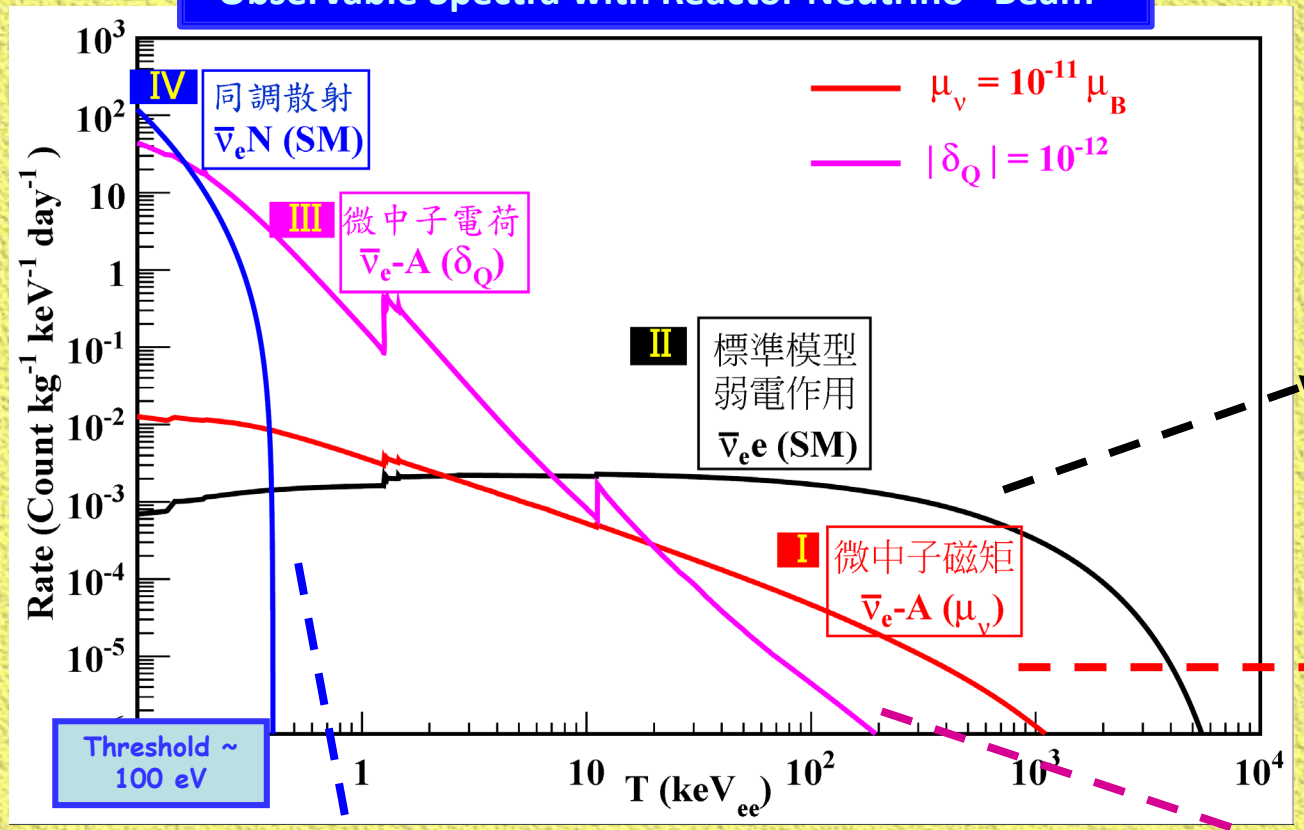
Neutrino Properties & Interactions at Reactor

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]*

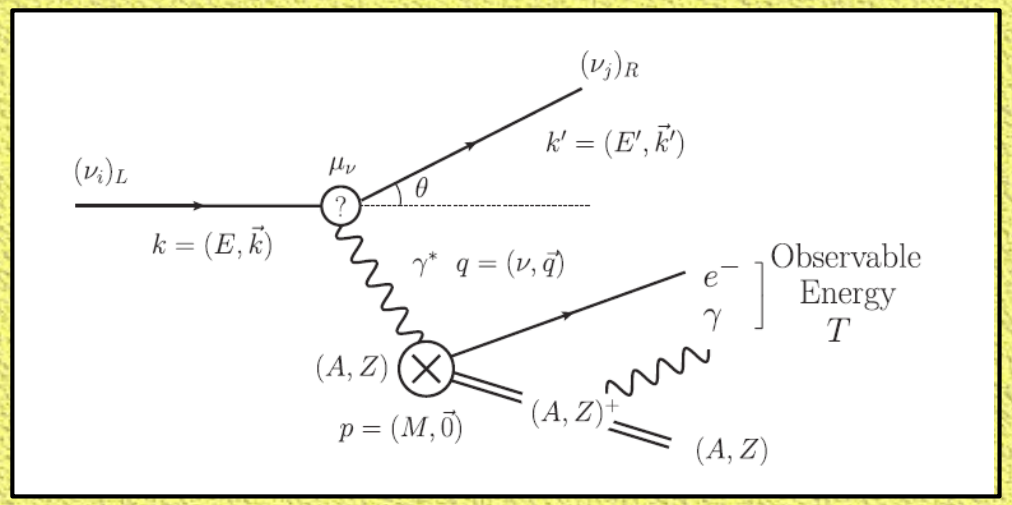
- Pioneered sub-keV O(kg) ULEGe / PCGe [MPLA08, NIMA16]
  - Light Dark Matter Searches @ KSNL *[PRD09,PRL13,AP14,PRD19]*
  - CDEX DM Program@CJPL *[PRD13……]*
  - Theory Program *[PLB14……]*

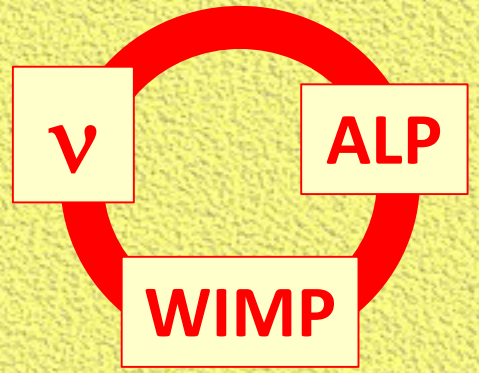
sub-keV PCGe

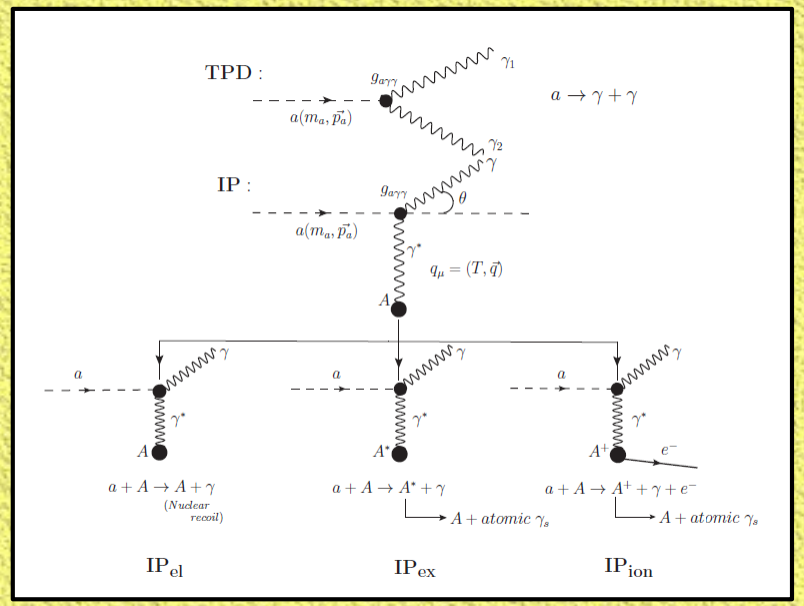
TEXONO Theory Program *[AS, NTU, NDHU, UCSB, DEU, SCU ……]*

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**



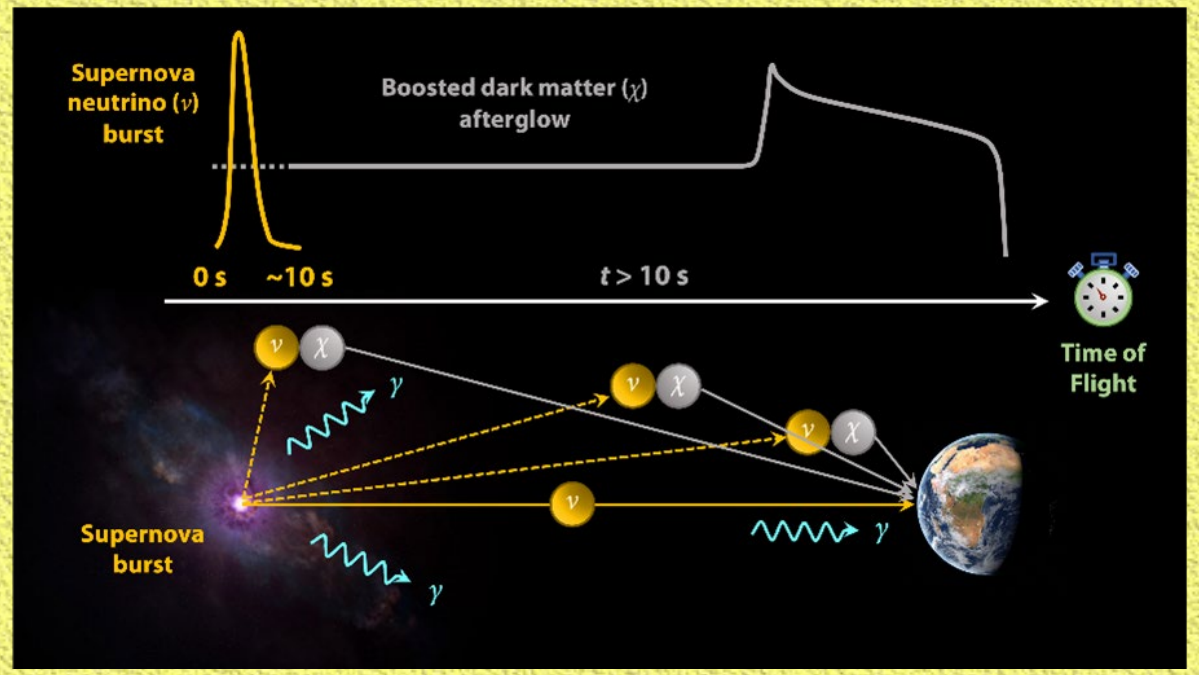




Selected Highlights:

- **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]*

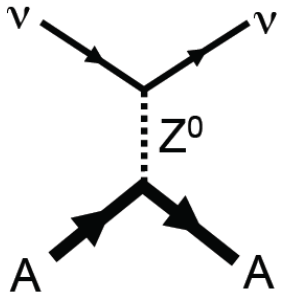
- **Time-of-Flight as Signature of Boosted Dark Matter by Supernova Neutrinos** *[PRL23, PRD23]*
  - First case of using Time (other than interactions) as DM signature

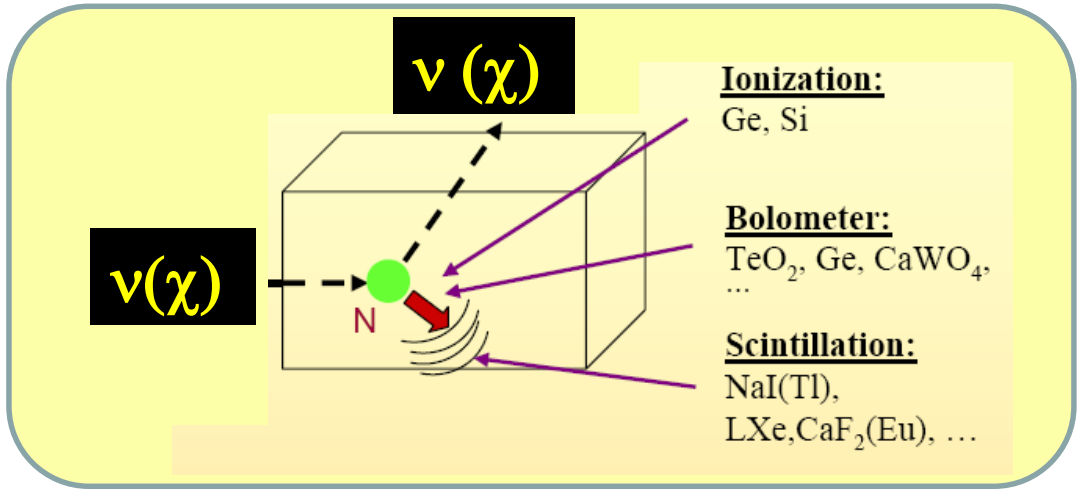


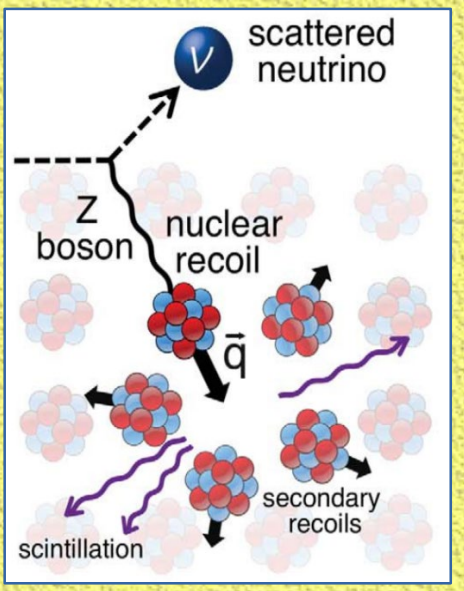
Neutrino-Nucleus Coherent Scattering :

Standard Model allowed and predicted processes :

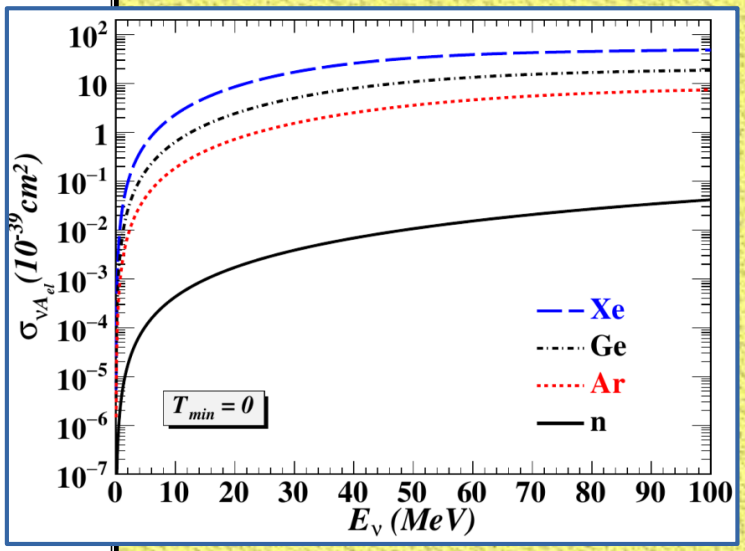
$$\nu + A \rightarrow \nu + A$$







- 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



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:

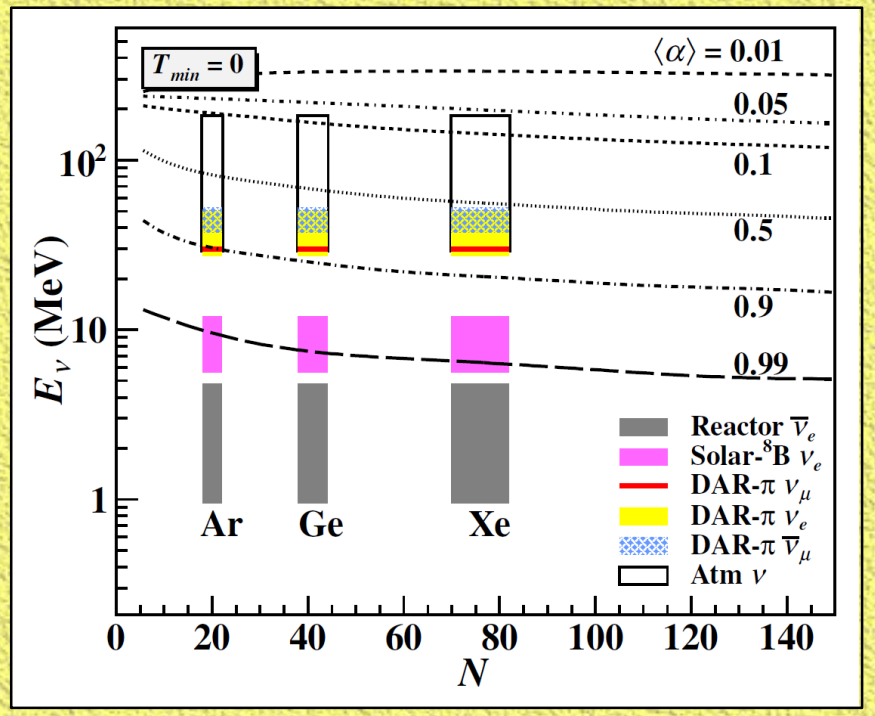
- ☑ Different kinematics regimes : $q^2 \rightarrow 0$; $FF(q^2)=1$
- ☑ Full QM Coherency *[DAR-νN @~0.6 - 0.7]*
- ☑ BSM/NSI Searches → no degeneracy with nuclear physics FF uncertainties

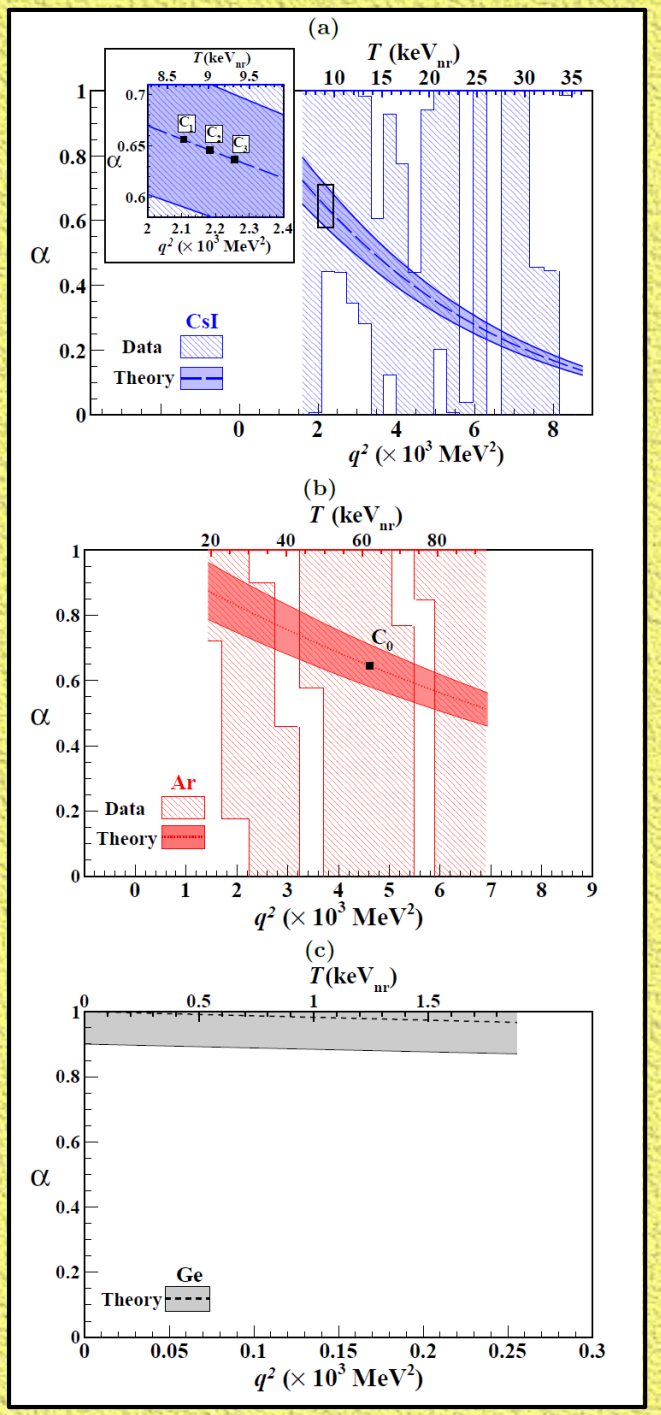
$$\alpha \equiv \cos\langle\phi\rangle \in [0,1]$$

<ϕ> : averaged decoherence angle

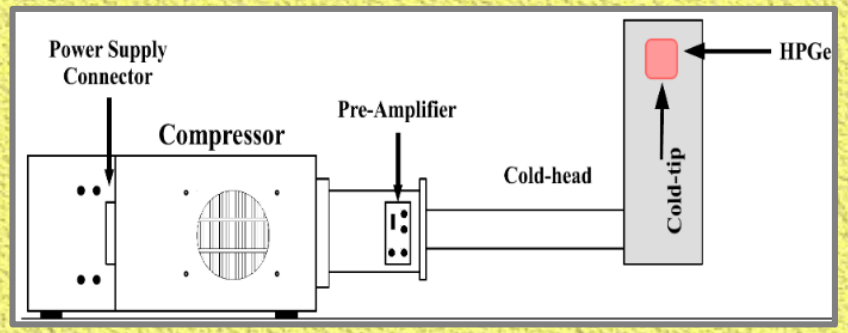
Seek Theorists' Input / Inspirations:

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



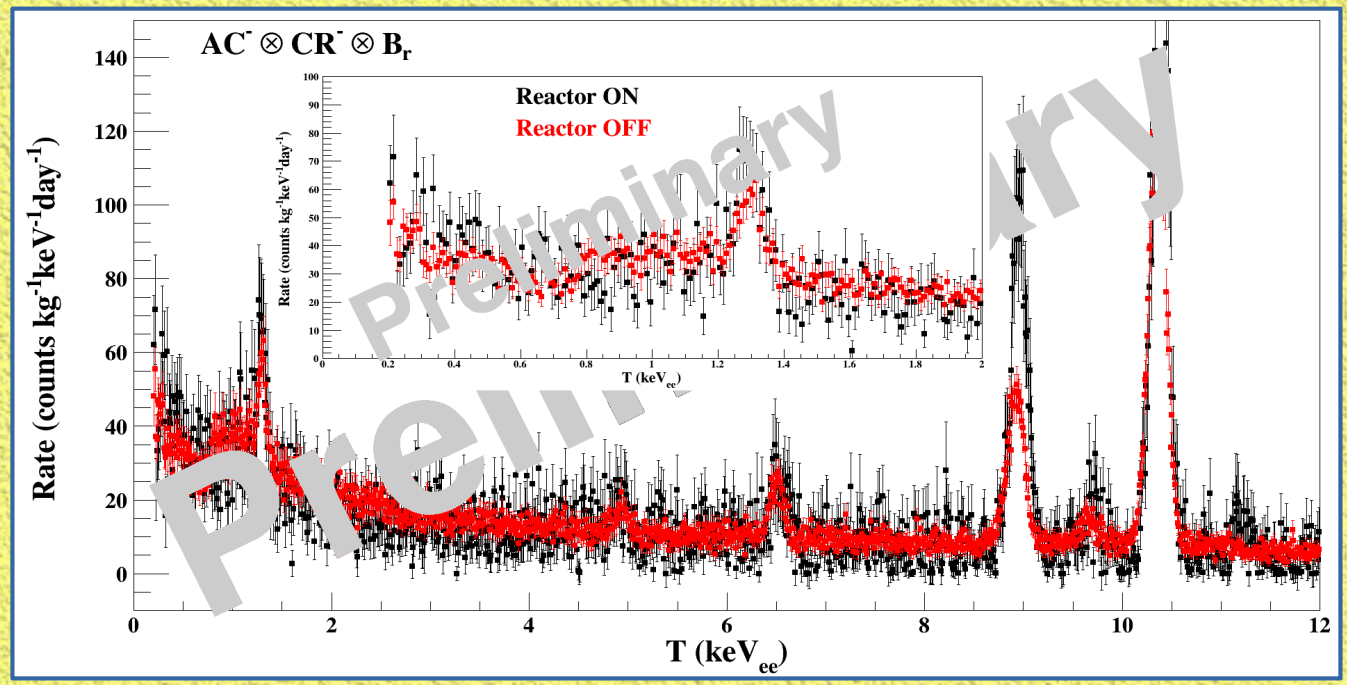


Electro-cooled PCGe



	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

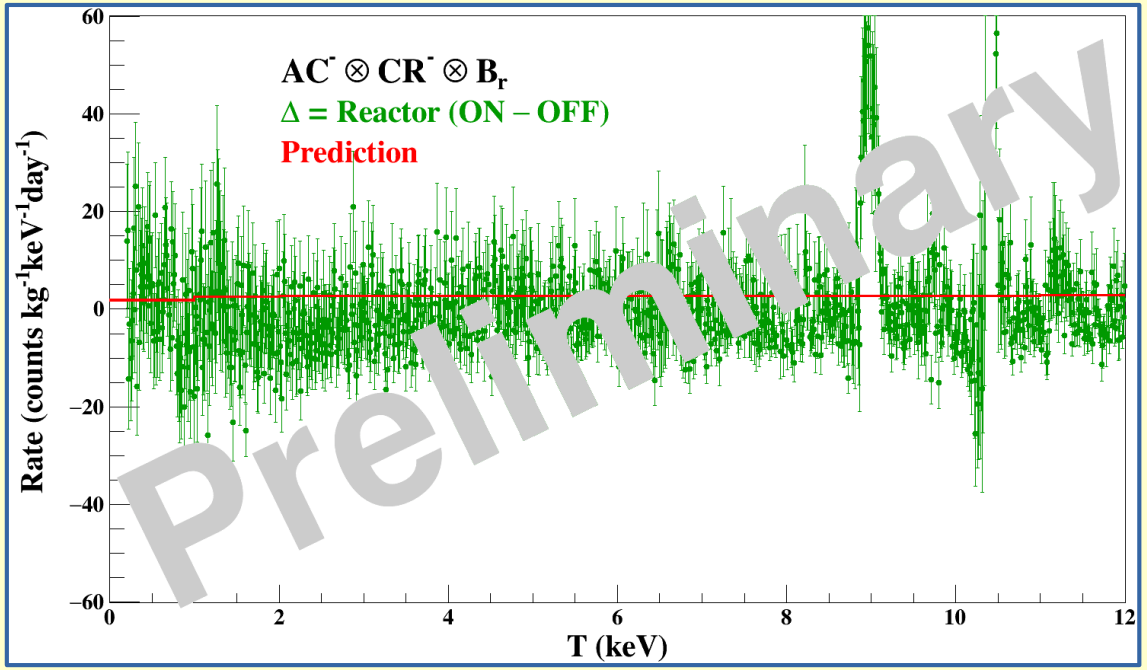


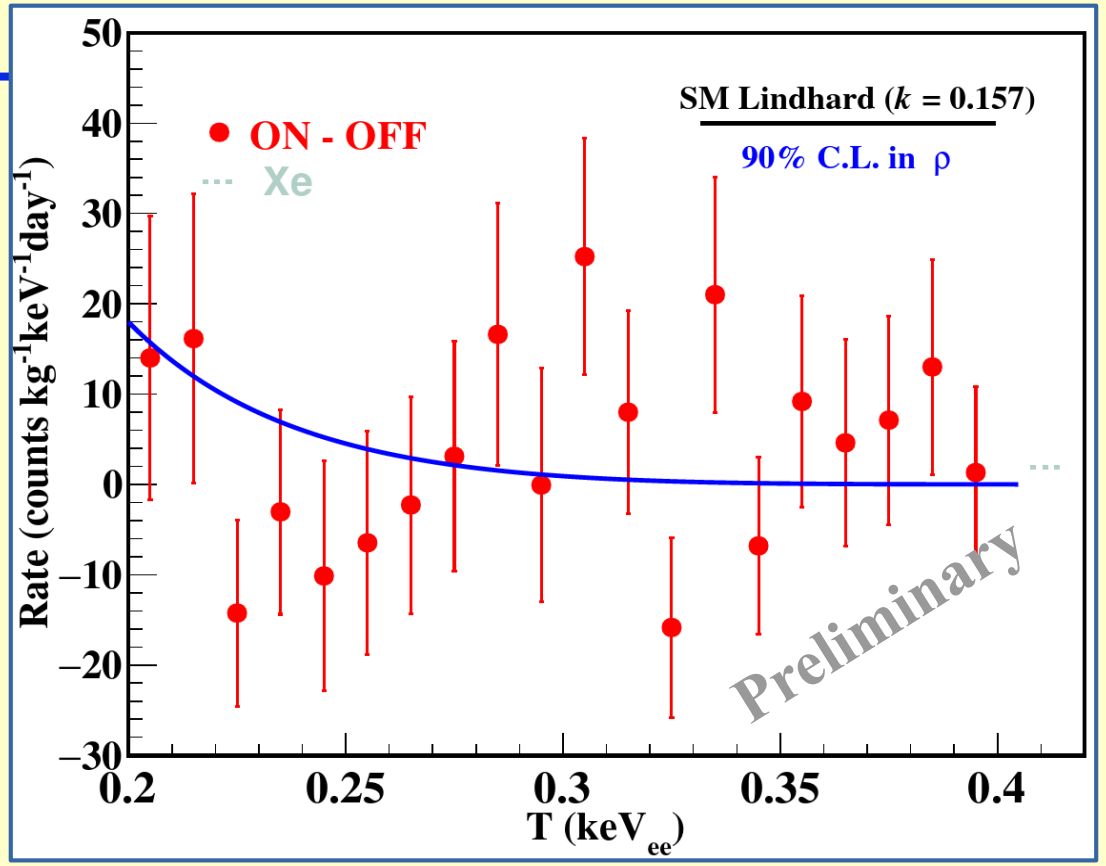
- ☑ Novel Technology with Negative Feedback Synchronized Pumping
- ☑ Typical G3 (500g) Spectrum ⇨
- ☑ With Anti-Compton & Cosmic-Ray & Surface Events Vetos
- ☑ Near Threshold Data Analysis In Progress.

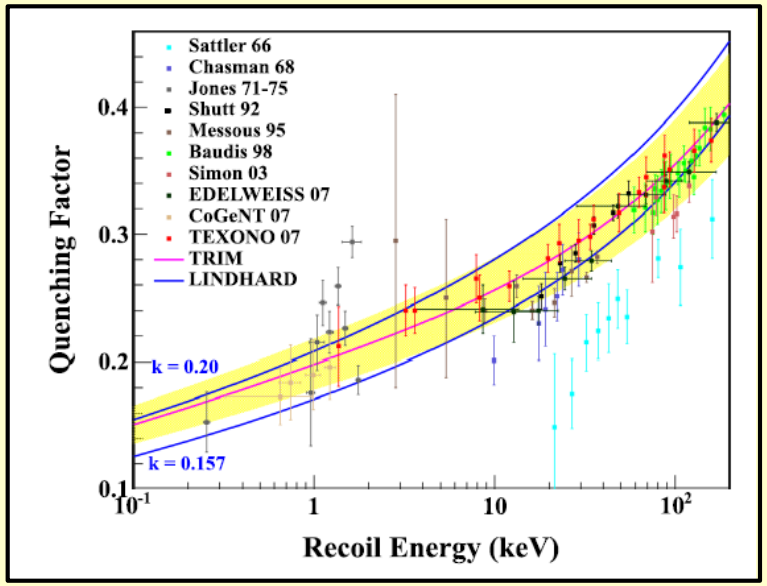
Sub-keV Ge Detector Techniques : Hardware/Software Development *[AP13, NIMA 16, NIMA18]*

- 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

Sensitivity Limits on TEXONO Data





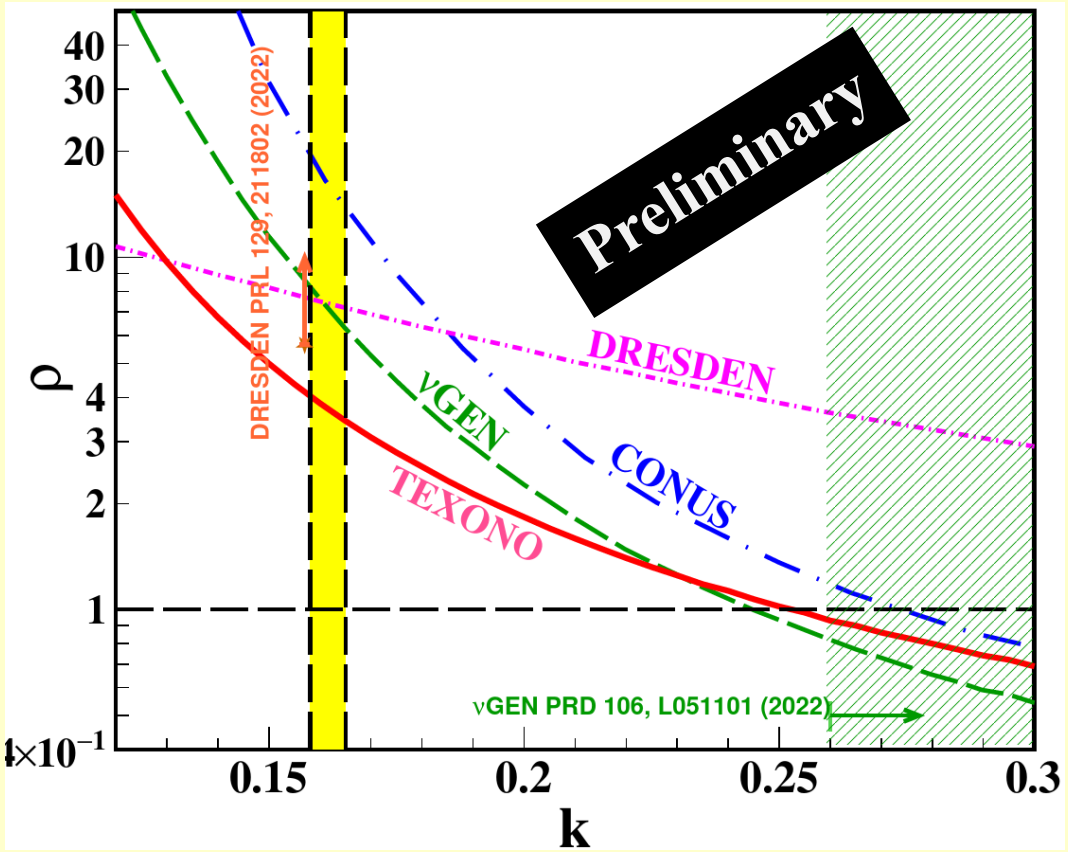


This Data *[TAUP2023]*

- **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]

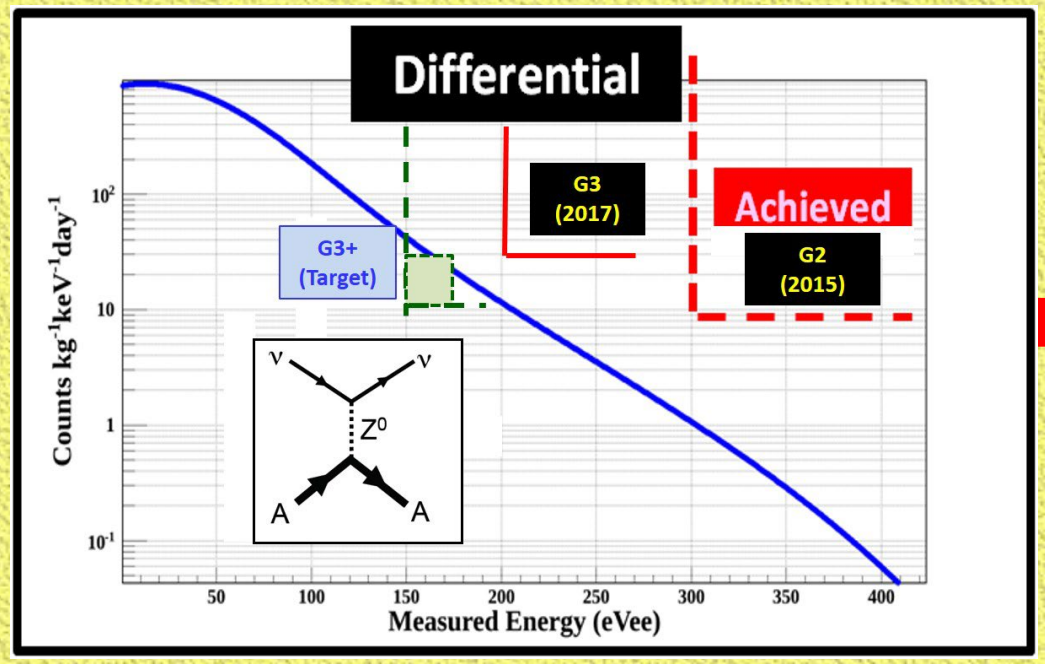
🛠 @90%CL Upper Limit :

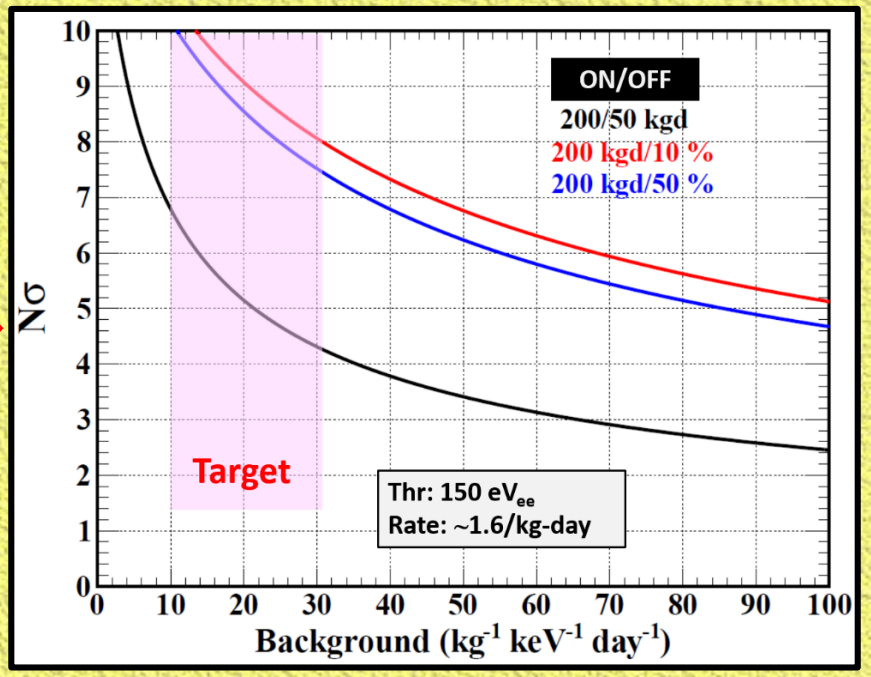
$\rho < 4.2$ @ Lindhard SM $k=0.157$

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} @ KSNL: Projected Sensitivities

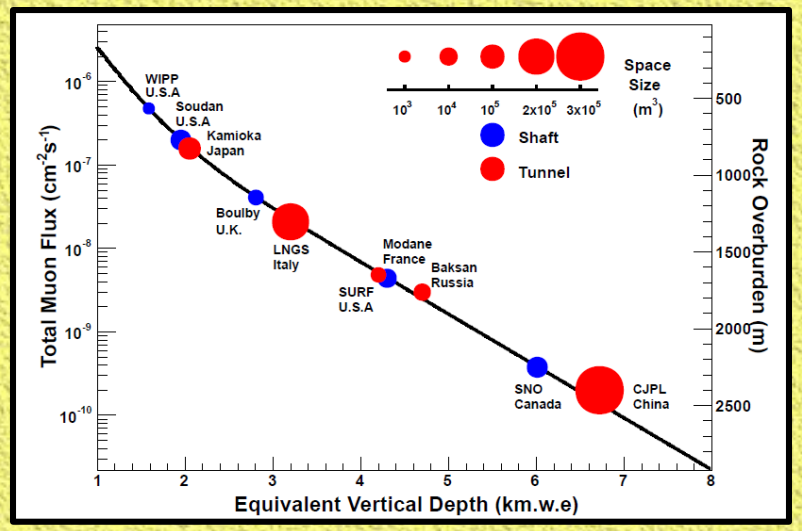


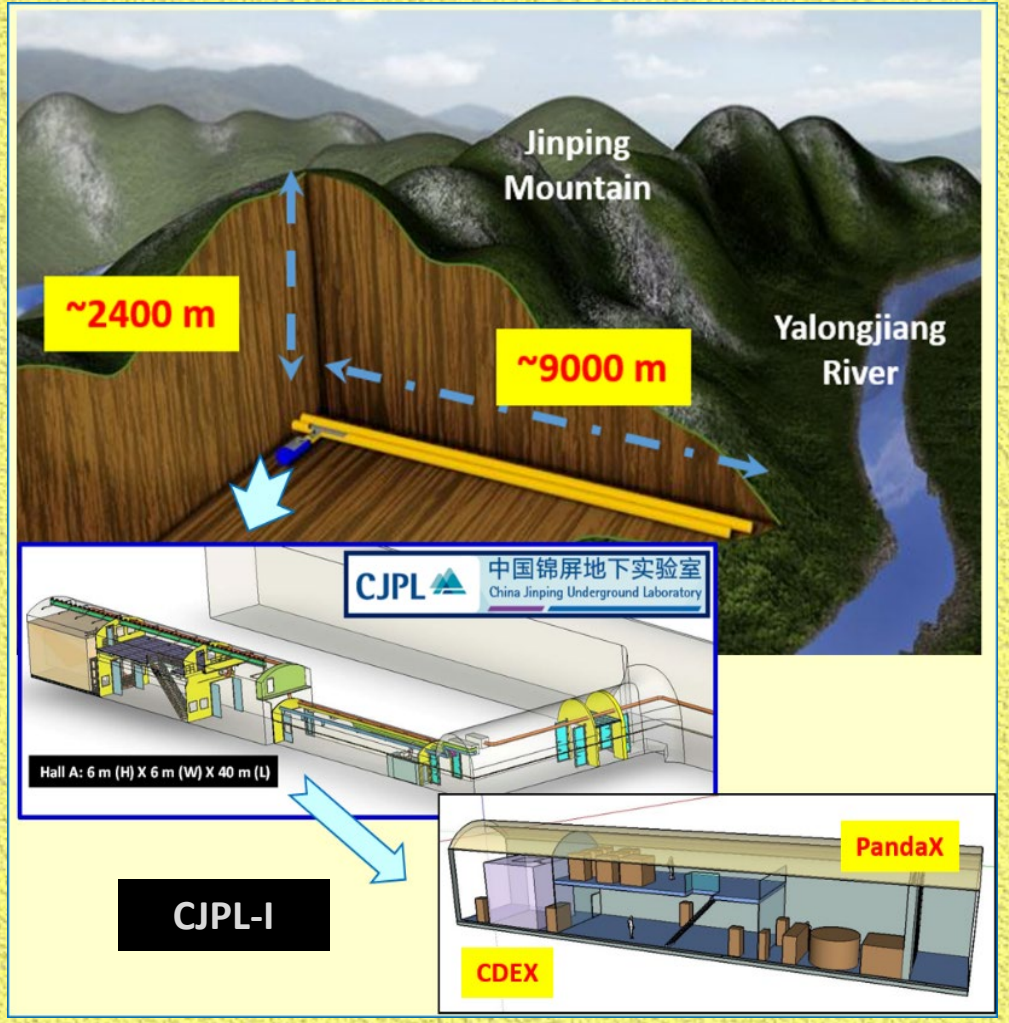


Prospects:

- ☑ G3 (200-eV) Data Collected
  - ON/OFF ~ >500 / >800 kg–days
- ☑ KS Power Plant Decommissioned : 2023 ;
  - ⇨ Access till end of 2025.
- ☑ R&D: G4 & PSD at threshold
- ☑ Explore new site if G4@150 eV *(achieved in lab!)* secured
- ☑ Candidate: Sanmen（三門）Reactor @ Zhejiang（浙江）

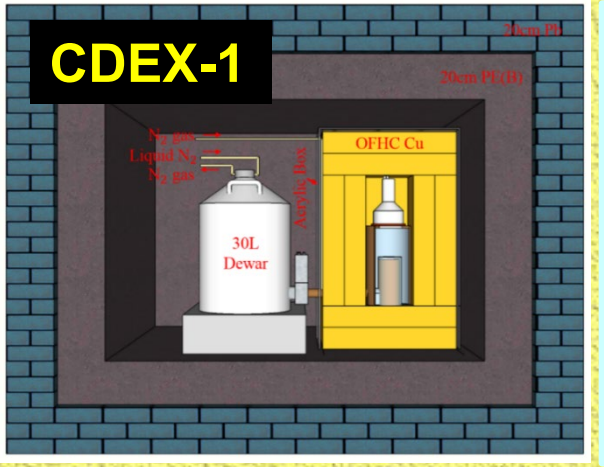
CJPL 中国锦屏地下实验室 China Jinping Underground Laboratory





- **Merits:** 2400+ m rock overburden ; drive-in road tunnel access ; superb supporting infrastructures
- CJPL-I (2010): *6X6X40 m* cavern
- *CJPL-II (2018+) : [4X(14X14X130 m) Halls] + Pits*

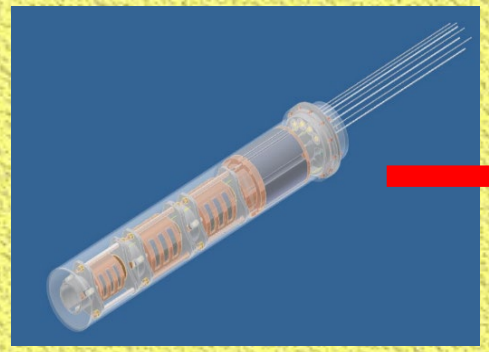
CDEX

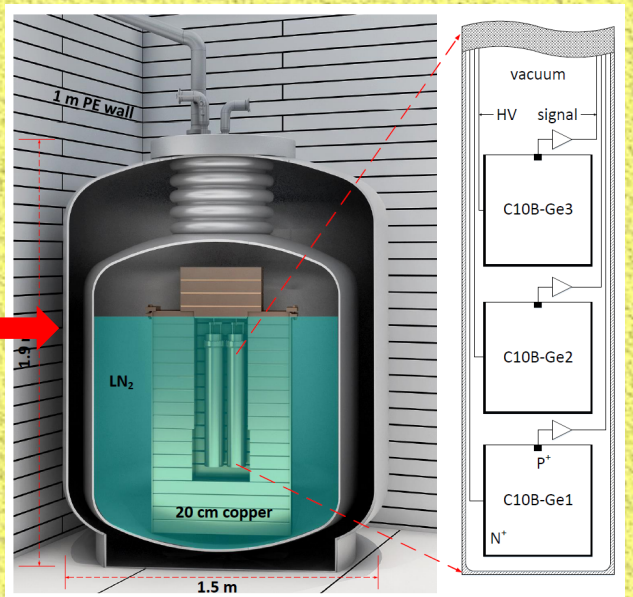


CDEX-I Dark Matter Program

- ☑ *Evolved from TEXONO Reactor Neutrinos Experiments @ KSNL*
- ☑ *Based on sub-keV Ge detectors*

CDEX-10

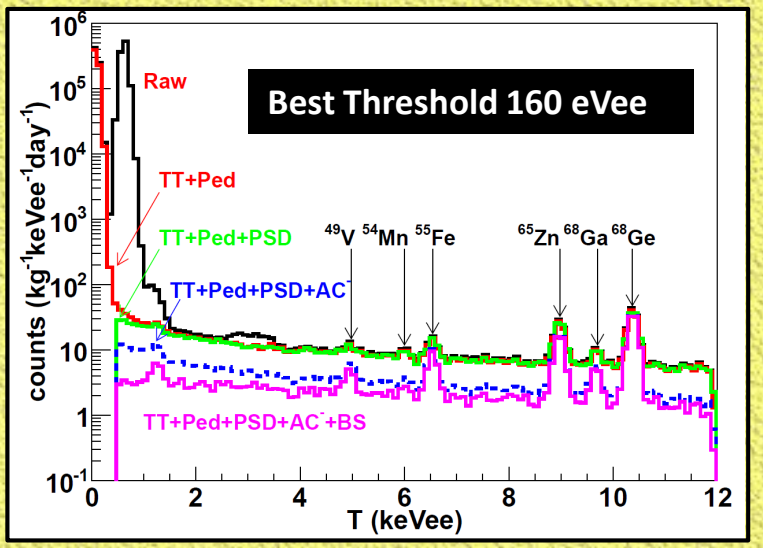


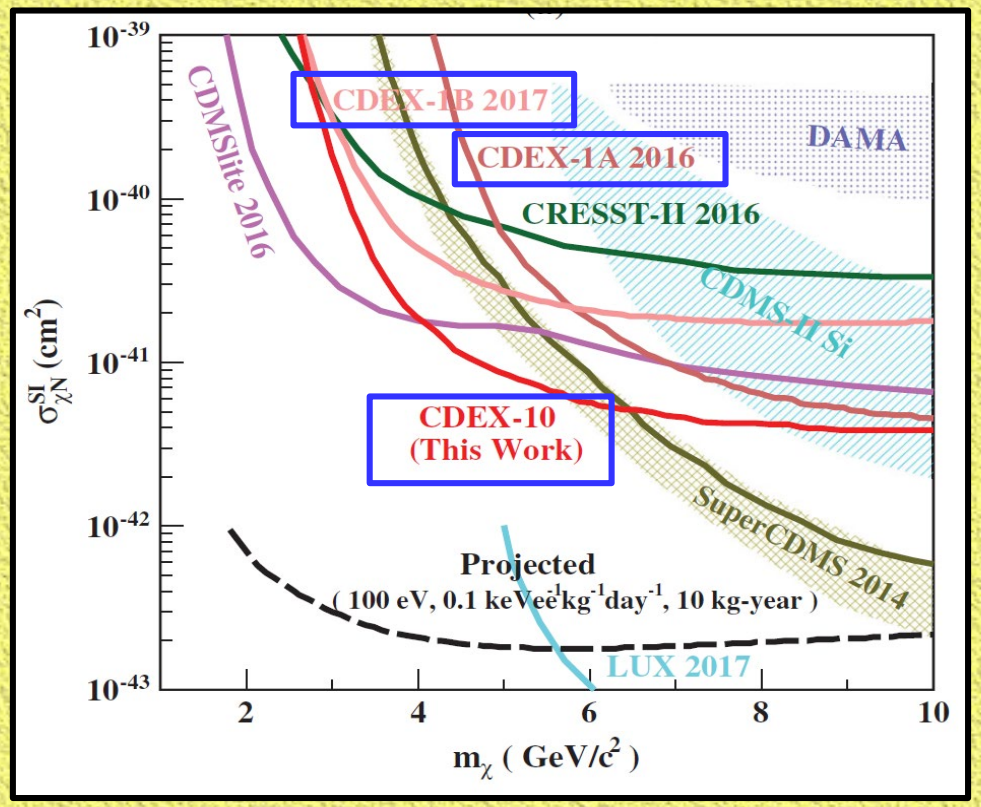


CDEX-10

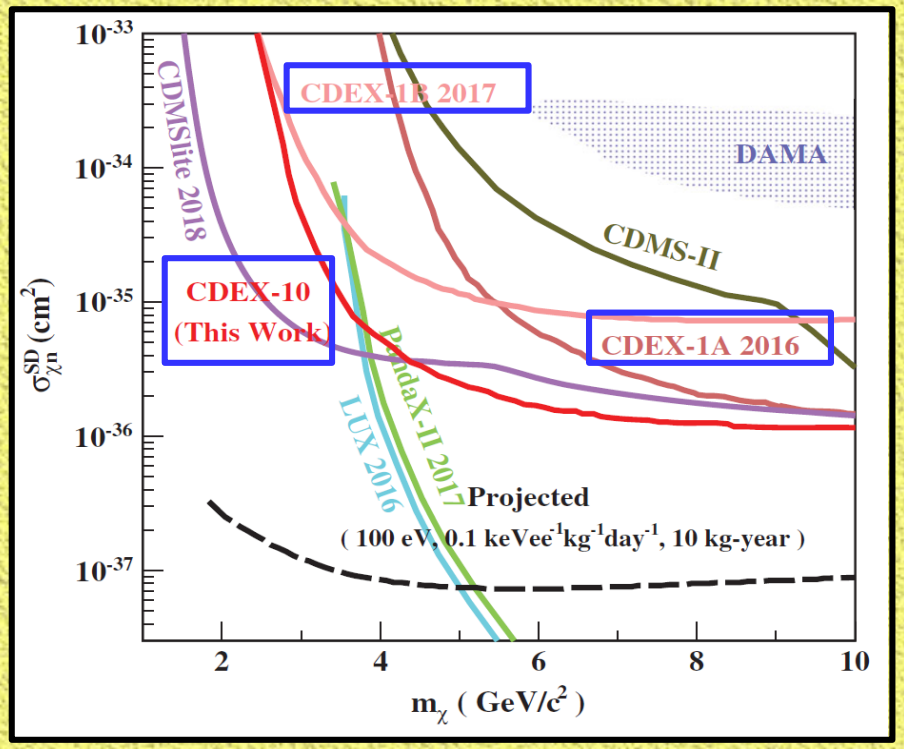
- ☑ As Ge-Array -- important stage towards large-scale Ge experiment
- ☑ Novel -- Directly immersed into liquid nitrogen for cooling
- ☑ May well evolve back to *neutrino physics* ($0\nu\beta\beta$)

CDEX-1(10) Mainstream Results on $\sigma_{\chi N}$ SI/SD *[PRD14,PRD16,CPC18,PRL18]*



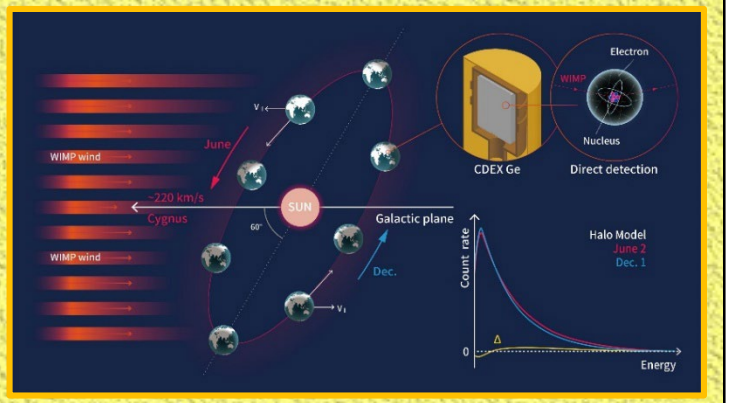


Spin-Independent χN



Spin-Dependent χN

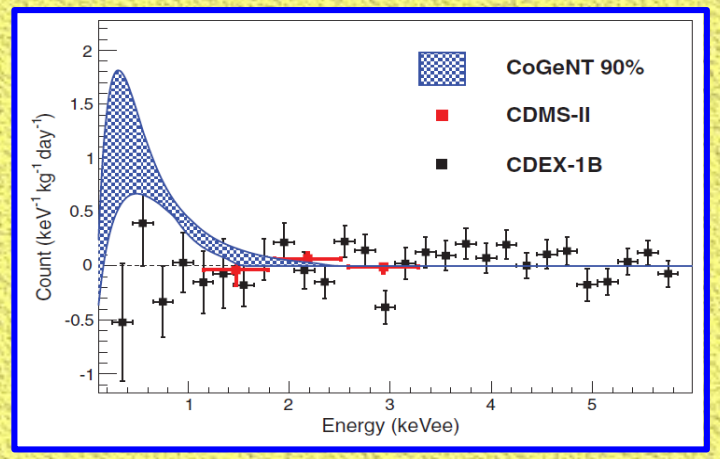
CDEX-1 Annual Modulation Analysis on SI $\sigma_{\chi N}$ SI *[PRL19]*



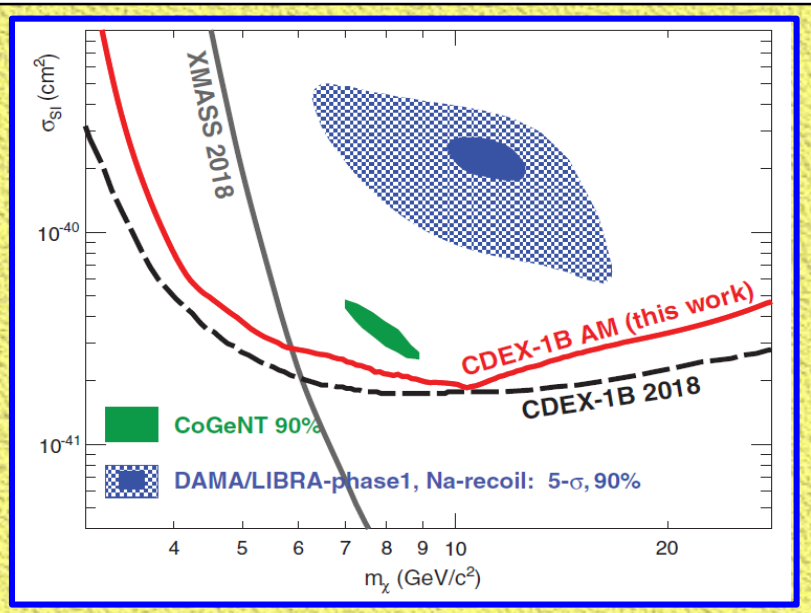
Schematic Diagram Illustrating the Physics Basis of WIMP Annual Modulation

Merits:

- ☑ All positive results in DM searches are from AM
- ☑ Long Time Level-Arm (4.2 yr)
- ☑ Low Threshold (250 eVee)
- ☑ Stable (Simple) Detector
- ☑ Decoupled from Residual Seasonal Cosmic Effects
- ☑ Less (or No) Astrophysical Model Dependences



Modulation Data Inconsistent with Expectations from Earlier Positive Signatures from CoGENT Expeirment



Exclusion Plot from AM Analysis

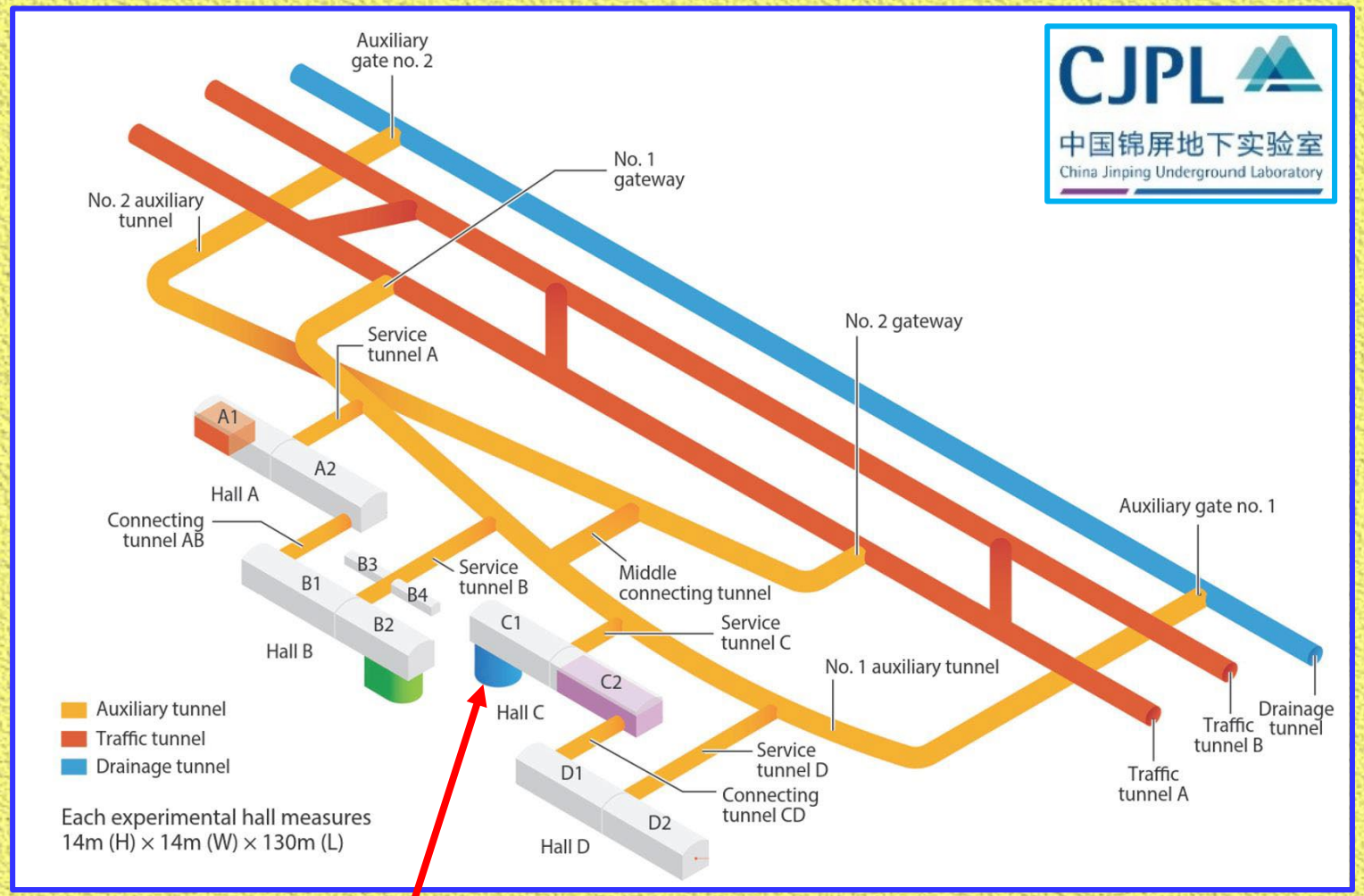
CDEX

CDEX "Novel" Analysis Results:

- $\sigma_{\chi N}$ SI [Migdal & AM] *[PRL19]*
- Dark Photon Searches *[PRL20]*
- Axion-Like-Particles (ALP) & Bosonic Vector DM *[PRD17,PRD20]*
- χ-N Effective Field Theory Constraints *[SCPMA21]*
- Earth Shielding Effects *[PRD22]*
- Boosted Dark Matter by Cosmic-Rays *[PRD22]*
- χ-e scattering *[PRL22]*
- Exotic BSM Models on DM *[PRL22]*
- BDM from Evaporating Black Holes *[PRD23]*
- .....

CJPL-II

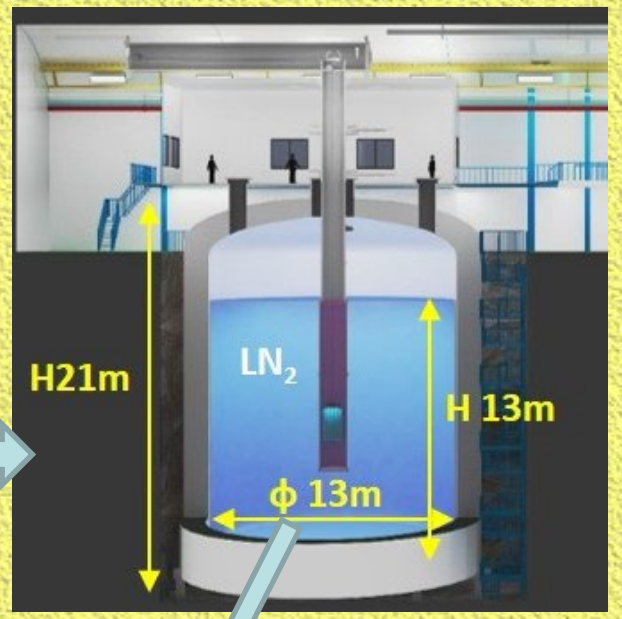
- ☑ ~500 m west to CJPL-I
- ☑ Four 14m*14m*130m Main Halls
- ☑ Two Pits:
  - (1) *18(ϕ)X18(H)m* ;
  - (2) *27(L)X16(w)X14(D)m*
- ☑ Total space: ~300K m³
- ☑ Under Construction, commissioning expected in 2024.

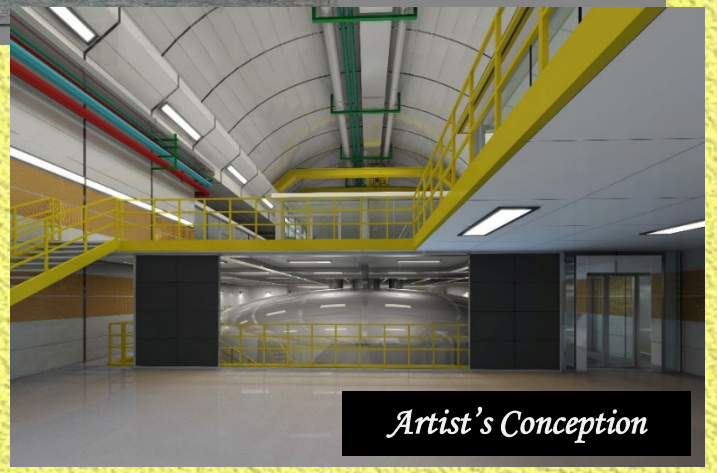


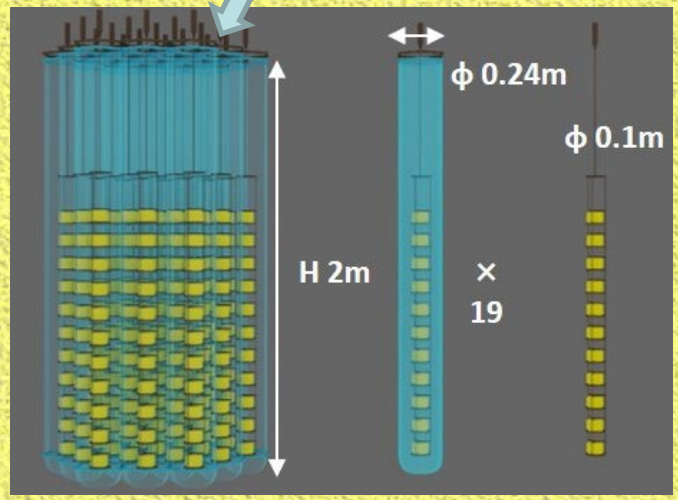
CDEX

Future Prospects @ CJPL-II : Ge1T Project

- **Next:** 300-kg $0\nu\beta\beta$ (towards IH) ; 50-kg DM (@ $0\nu\beta\beta$ bkg spec) (2028)
- **Visions:** Ge-1T (2033) → Ge-10T (2040) $0\nu\beta\beta$ (towards NH)

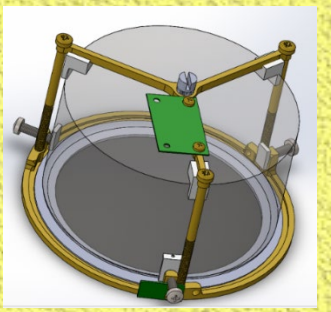


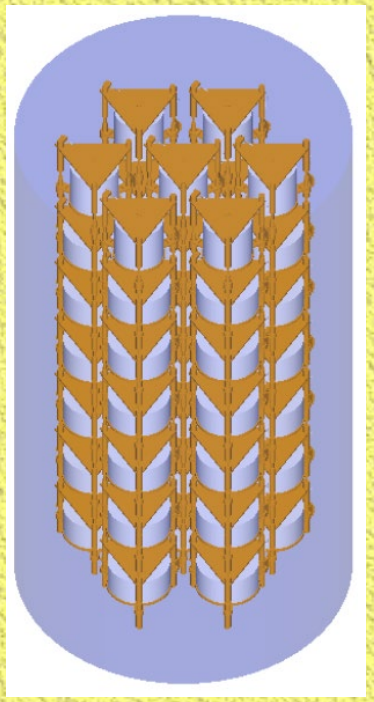




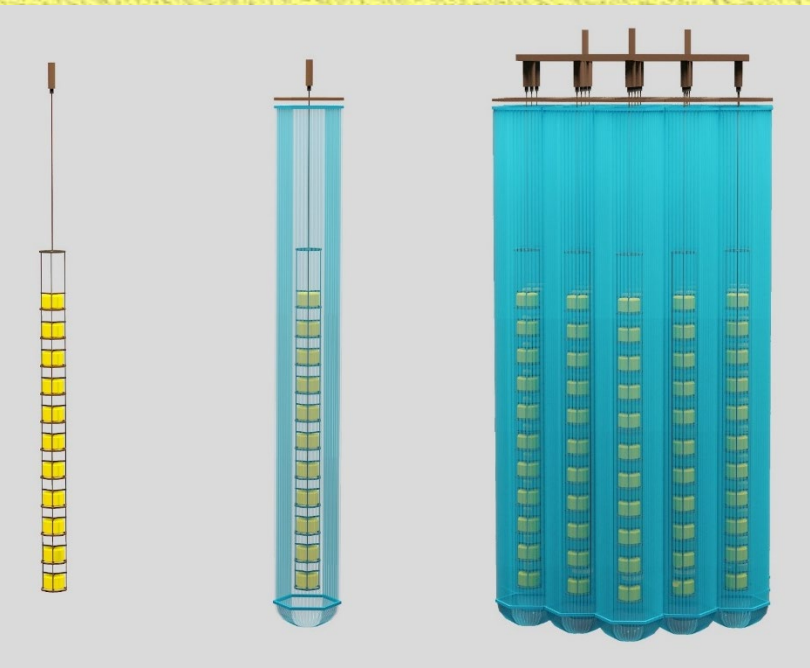
Mastering Key Technologies towards Ge-1T

ASIC前放





- ☑ Ge purification and crystal growth;
- ☑ HPGe detector fabrication;
- ☑ Ultra-low background VFE and FADC;
- ☑ Ultra-pure Cu for structure and cables;
- ☑ Large-volume cooling tank “cryostat”



TEXONO : Prospects & Outlook

- 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 & Have Fun ….
- Gravitational Physics Related research *(testing the waters)*

Wish/Expect/Trust:

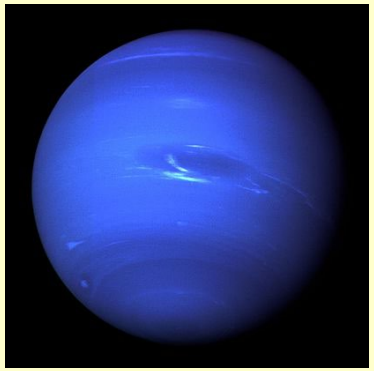
Both the Journeys & Destinations for the Evolving Story will be as Fascinating as in the past 2+ decades.

期待：依然精彩

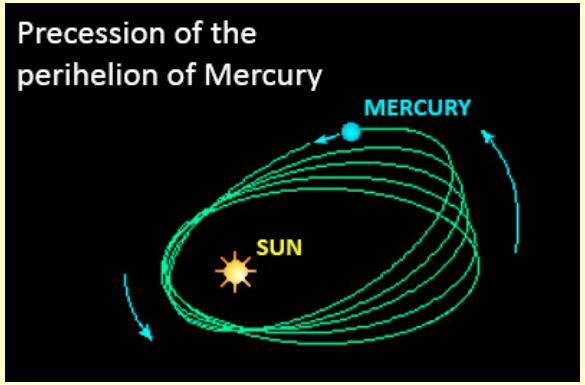
Step Back & Reflect: Recall Lessons from History

⚐ Anomalies in *"Precision Measurements"* in Planetary Orbits Vs
Newton's *"Standard Model"* Theory of Gravitation in the 19th Century

☑ **Irregularities of Uranus's Orbit** [天皇星軌跡]
Solution *[Alphabet]*
⇨ Prediction *[1845, Verrier, Adams] AND THEN*
Observation *[1846, Galle ….]* of Neptune [發現海皇星]



☑ **Anomalous Perihelion Precession of Mercury** [水星軌跡] *[1859, Verrier]*
Solution *[Grammar]*
⇨ General Relativity[廣義相對論] *[1915, Einstein]*
Vs ***"Vulcan (Hypothetical Inner Planet) Theory"*** *[~1860, Verrier]*
AND !! *…… World-Wide Searches … +*
Multi Observation Claims **&** *Refutations [1859-1908]*



[Natural & Human !!!]