Neutrino Physics in Taiwan – Overview

[Apologies - impossible to be unbiased and complete]

- **Global Landscape**
- **(Selected) Theory Mentions**
- **DayaBay & JUNO** *[credits: DB+JUNO team, c/o Hu Bai-Zhen]*
- **LEGEND** *[credits: Chiu Pin-Jung]*
- **TEXONO (+CDEX)**
- **Outlook**

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June 2024

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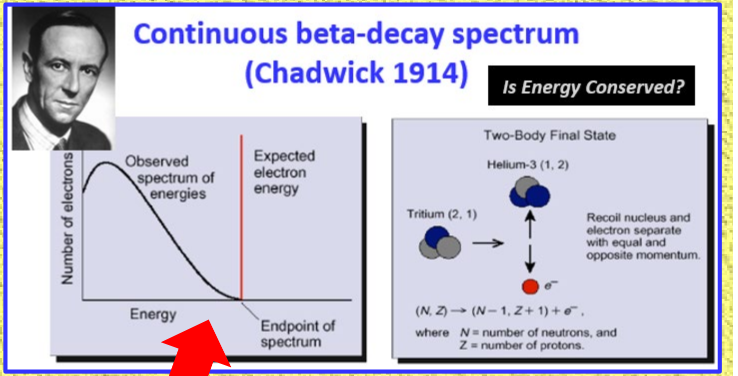
The Future is Flavourful

4–6 Jun 2024

NYCU
NATIONAL YANG MING CHIAO TUNG UNIVERSITY

Milestones of ν History



A Dark Matter/Missing Energy Problem !

1930 — Pauli: conceptual birth of ν to solve the β decay problem

1956 — Reines & Cowan: discovery of ν (from reactor) — Nobel 1995

1962 — Lederman et al.: discovery of muon neutrinos — Nobel 1988

1968 — Davis: observation of solar ν — Nobel 2002

1987 — Koshiba et al.: observation of Supernova neutrinos — Nobel 2002

1998 — Kajita et al. (Super-K): discovery of atmos. ν osc. (θ_{23}) — Nobel 2015

2000 — DONUT: discovery of tau neutrinos

2001 — McDonald et al. (SNO): discovery of solar ν osc. (θ_{12}) — Nobel 2015

2002 — KamLAND: confirmation of solar n osc. using reactor ν (θ_{12})

2012 — Daya Bay, RENO: measurement of the last mixing angle of ν (θ_{13})

……

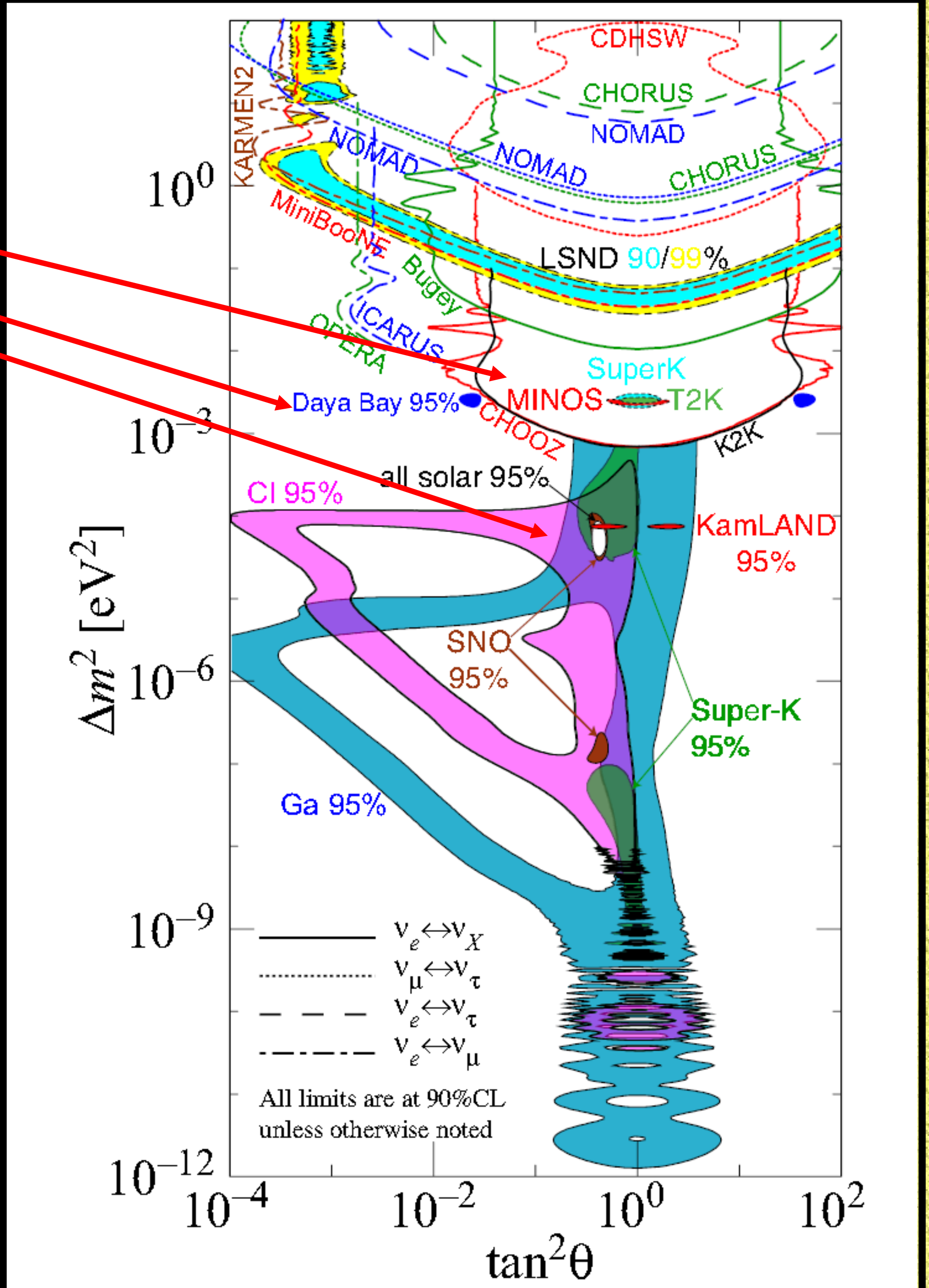
Slide credit: S. Seo

Neutrino Oscillation History & Status 2015

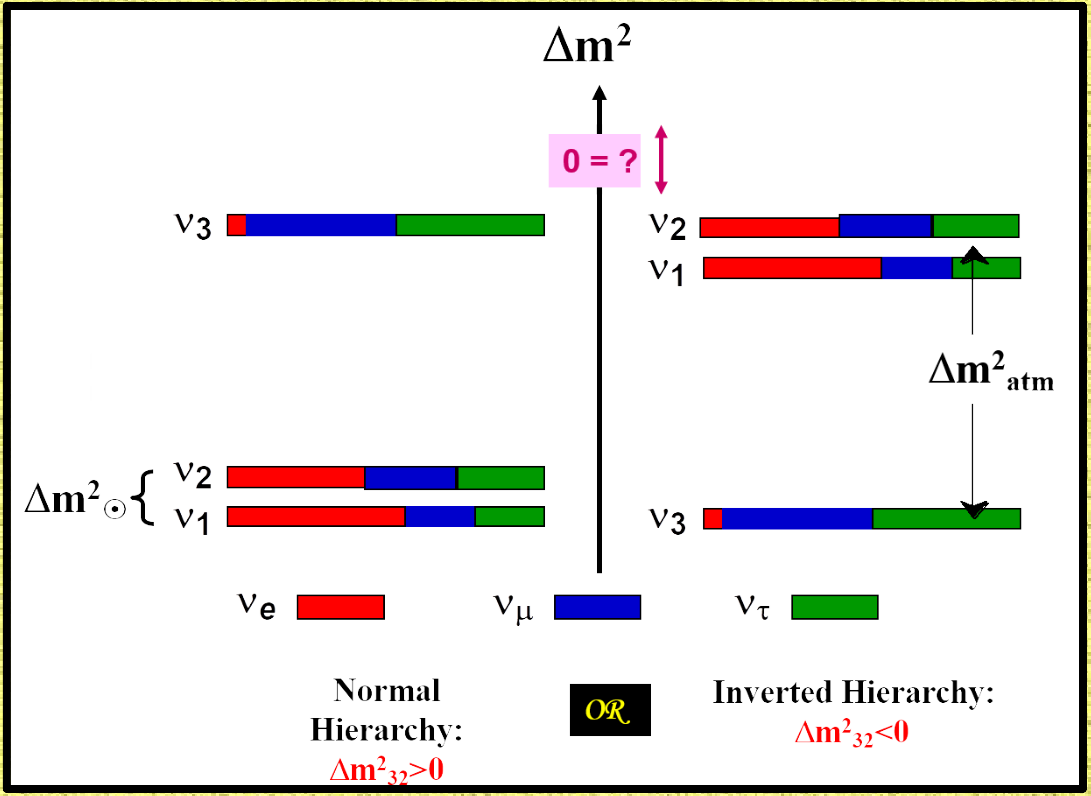
Positive Observation

A Lot of People Have Contributed !

Science Makes Progresses by Dispatching 1001 Competent Teams to Search, Knowing the Odds of Success is 0.1% in each.



Neutrino Masses are Finite !



$\theta_{23} \approx 45°$ $\theta_{13} = 9°$ $\theta_{12} \approx 34°$

$|\Delta m^2_{32}| \approx |\Delta m^2_{31}| \approx 2.4 \times 10^{-3}\ eV^2$ $\Delta m^2_{21} \approx 7.6 \times 10^{-5}\ eV^2$

Three Families of Neutrino "Flavor-Mass" Mixing

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{\alpha j} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

U : PMNS Matrix

Structure :

$$[U] \simeq \begin{bmatrix} \cos\theta_{solar} & \sin\theta_{solar} & \sin\theta_{13} \\ -\sin\theta_{solar}/\sqrt{2} & \cos\theta_{solar}/\sqrt{2} & 1/\sqrt{2} \\ \sin\theta_{solar}/\sqrt{2} & -\cos\theta_{solar}/\sqrt{2} & 1/\sqrt{2} \end{bmatrix}$$

Numerically:

$$U_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & s_{13}e^{i\delta} \\ -0.4 & 0.6 & 0.7 \\ 0.4 & -0.6 & 0.7 \end{pmatrix}$$

$S_{13} \sim 0.16$

$\delta = ?$

ν in the 2020's and beyond

- Neutrino oscillation: precision, MO, CPV
- # of neutrinos: sterile ν
- Abs. mass of ν: KATRIN, Ptolemy, etc.
- Dirac vs. Majorana: $0\nu\beta\beta$
- Neutrino interaction: CEνNS
- Astrophysical ν: solar, Supernova, extra galactic ν etc.

Slide credit: S. Seo

+ CNB Relic ν

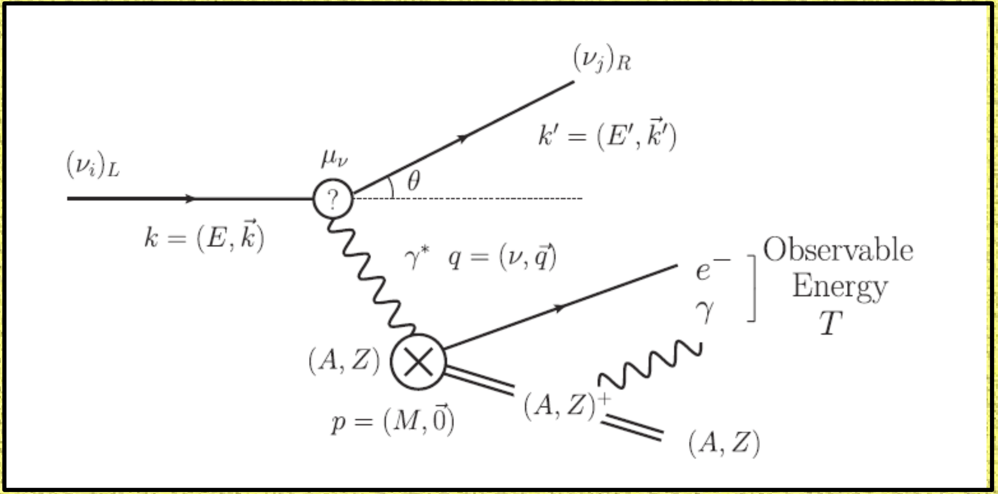
TW Theory Scenes on Neutrinos (Selected & Biased):

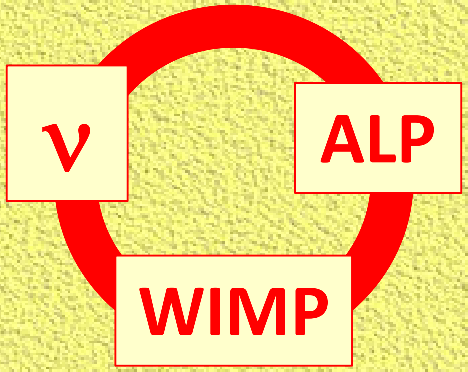
- Lin GL (NYCU) : neutrino and dark matter astroparticle physics phenomenology
- Wu MR (AS) : supernova neutrinos
- Anatolia F (AS) : cosmic-rays & astrophysical neutrinos interactions
  - 👍 Member of IceCube
- Martin S (NTHU) : relic neutrinos
- Cheung KM (NTHU) : BSM with LHC high energy neutrino “Forward Facility” beam
- Li HN (AS) : Origin of neutrino masses
- Chen JW (NTU) & Liu CP (NDHU) : low energy neutrino/dark matter/ALP interactions
- Almost ALL : phenomenology involving neutrino properties & data

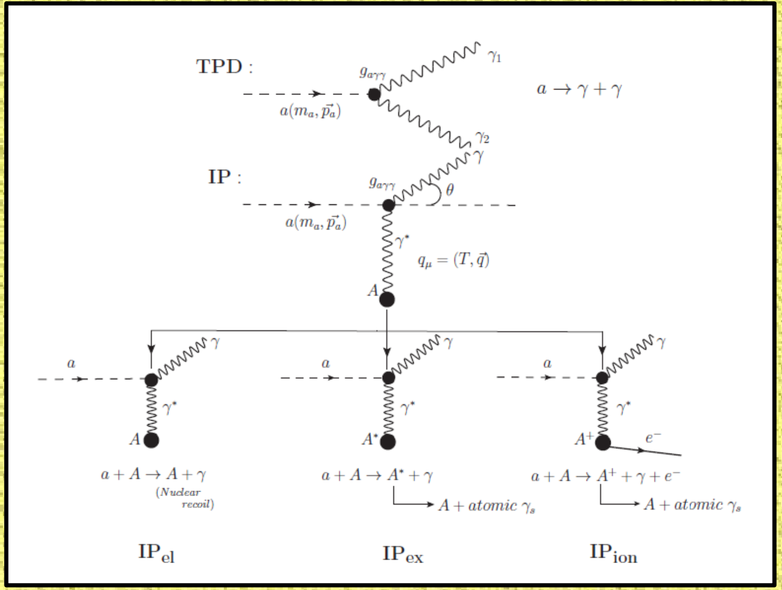
TEXONO Theory Program *[AS, NTU, NDHU, UCSB, DEU, SCU ……]*

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.* $\nu(\chi,\alpha)$ **A** instead of $\nu(\chi,\alpha)$ **N** or $\nu(\chi,\alpha)$ **e**



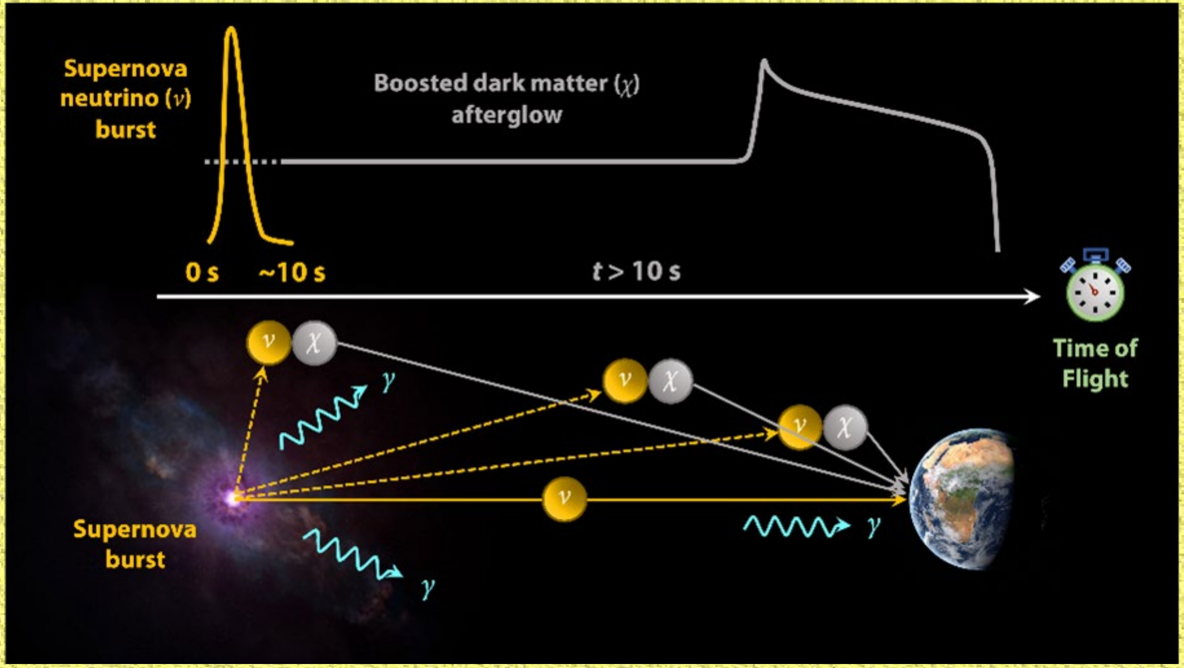




Selected Highlights:

- **Identified Pole structures, Cross-section enhancement, Smoking-gun signatures in *(CP Liu, JW Chen …)* :**
  - 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 *(MR Wu …)*** *[PRL23, PRD23]*
  - First case of using Time (other than interactions) as DM signature

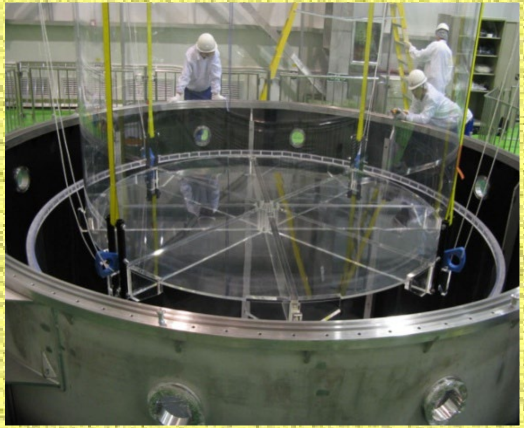


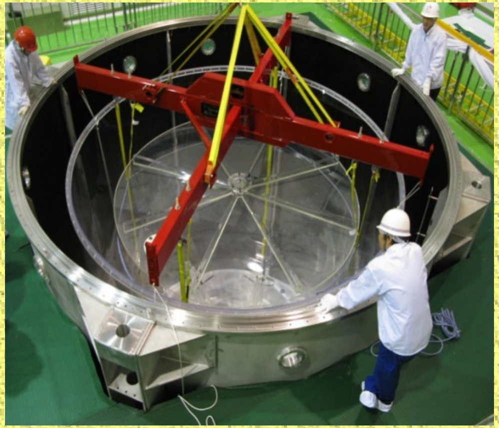
Taiwan Groups @ Daya Bay

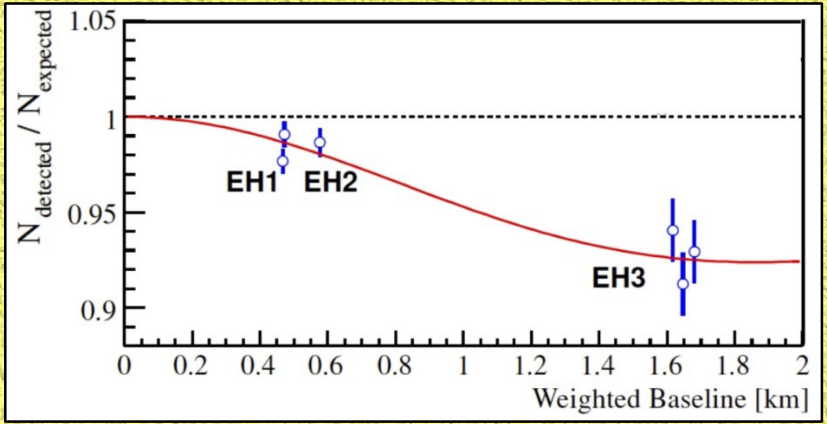
[B. Hsiung @ NTU, G.L. Lin @ NCTU, C.H Wang @ NUU]

Contributions:

- ※All 8 inner (3m) acrylic vessels to contain the "target", GdLS, are built in Taiwan.
- ※DAQ/Trigger and Control R&D
- ※PMT gain calibration and monitoring
- ※Calibration Database update and validation
- ※Data Quality Check







First Results from Daya Bay Final Dataset

The world's:

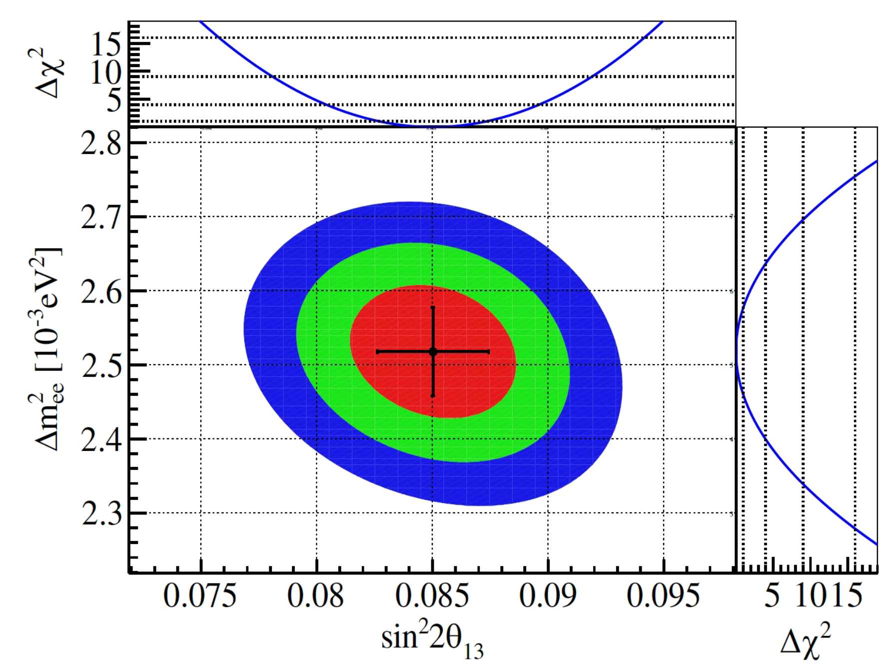
3158 days results: PRL 130, 161802 (2023)

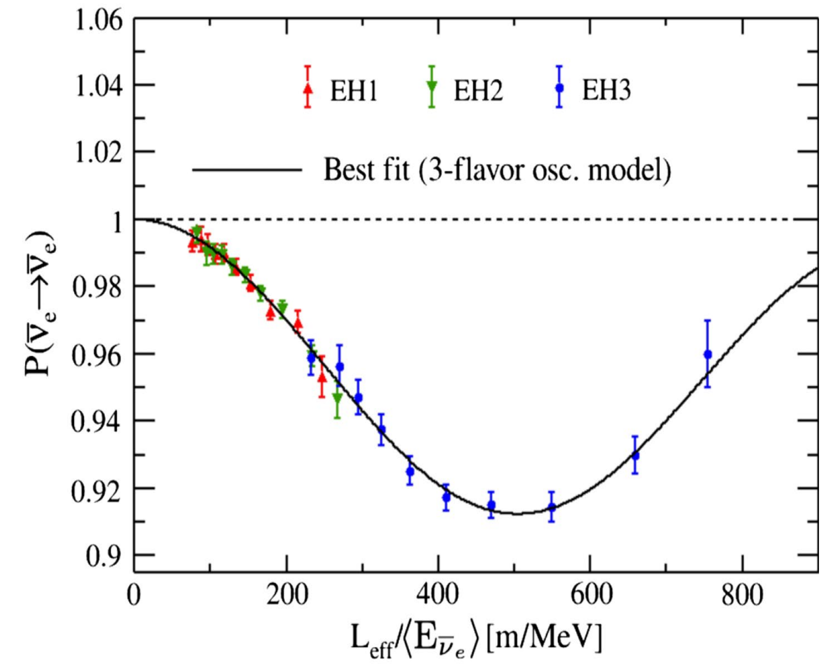
- **largest sample** of reactor antineutrinos to date 5.5 million IBD
- **most precise** determination of $sin^2 2\theta_{13}$ with > 5σ

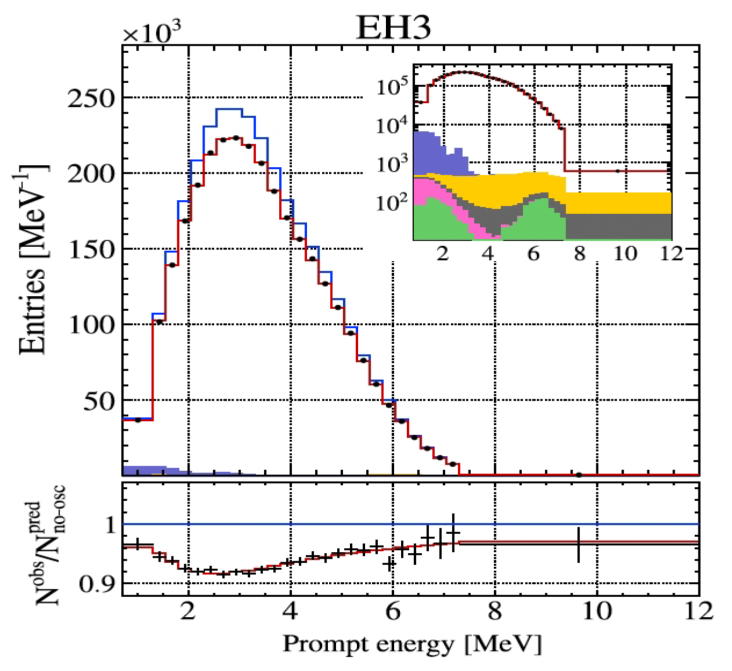
$$\sin^2 2\theta_{13} = 0.0851^{+0.0024}_{-0.0024}$$

Normal hierarchy: $\Delta m^2_{32} = +\left(2.466^{+0.060}_{-0.060}\right) \times 10^{-3} eV^2$

Inverted hierarchy: $\Delta m^2_{32} = -\left(2.571^{+0.060}_{-0.060}\right) \times 10^{-3} eV^2$

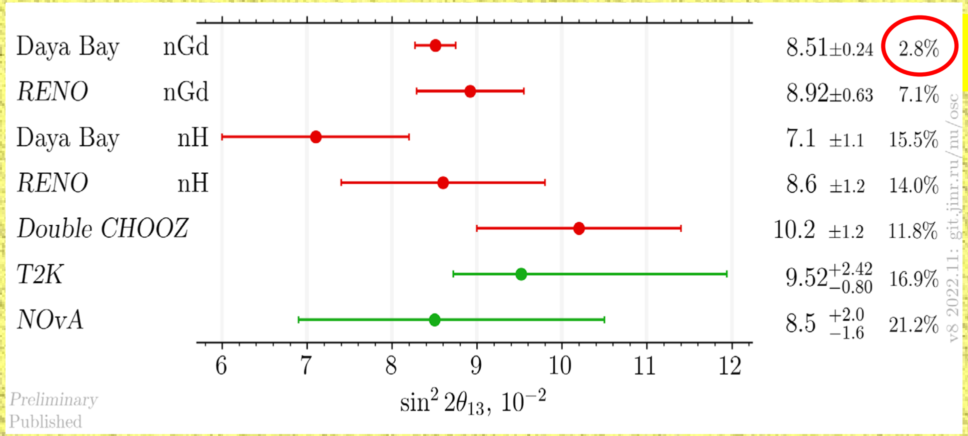






Global Landscape

◆ **Consistent results are obtained by all experiments:**

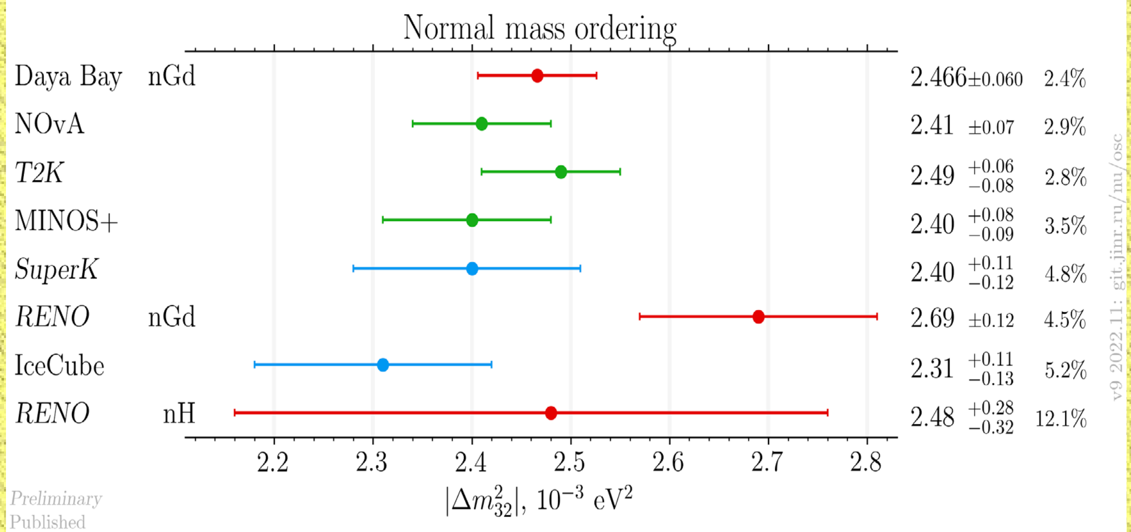


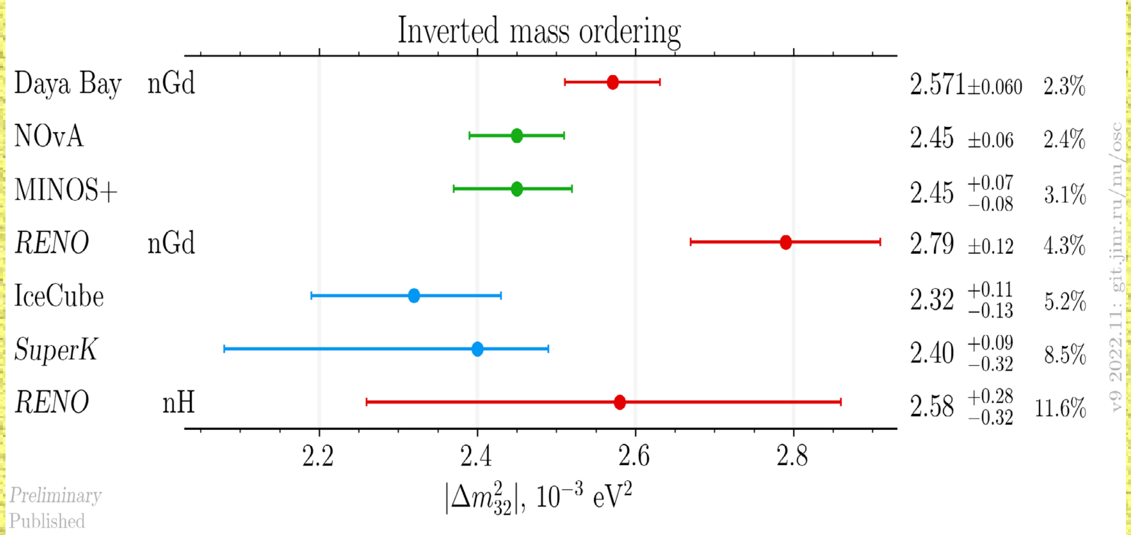
2.8% precision in $sin^2 2\theta_{13}$

The reactor measurement of θ_{13} will likely remain the most precise for a long time!

◆ **Reactor experiments also have excellent sensitivity to Δm^2_{32}:**

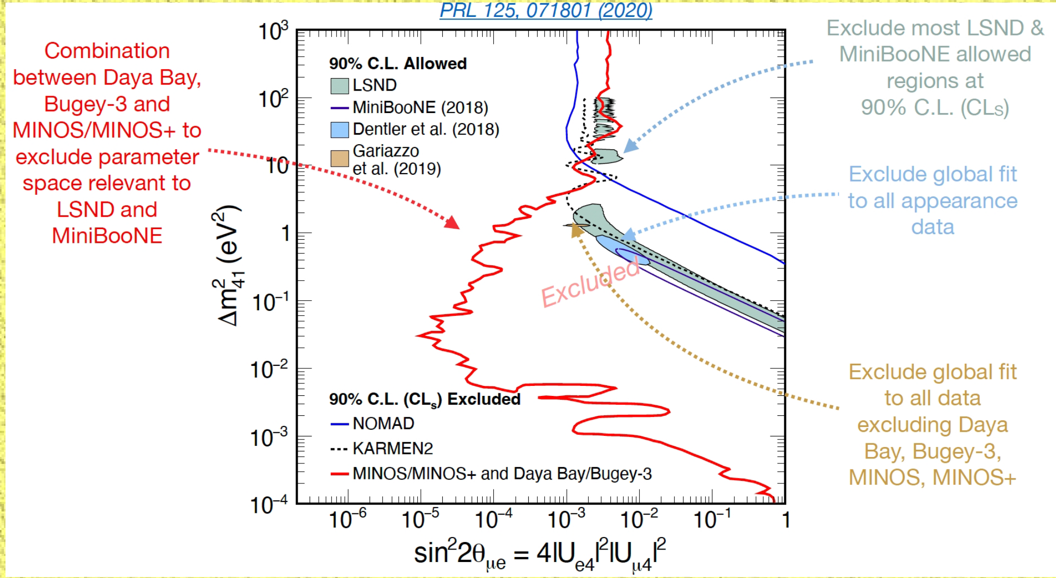
Great agreement with accelerator experiments!



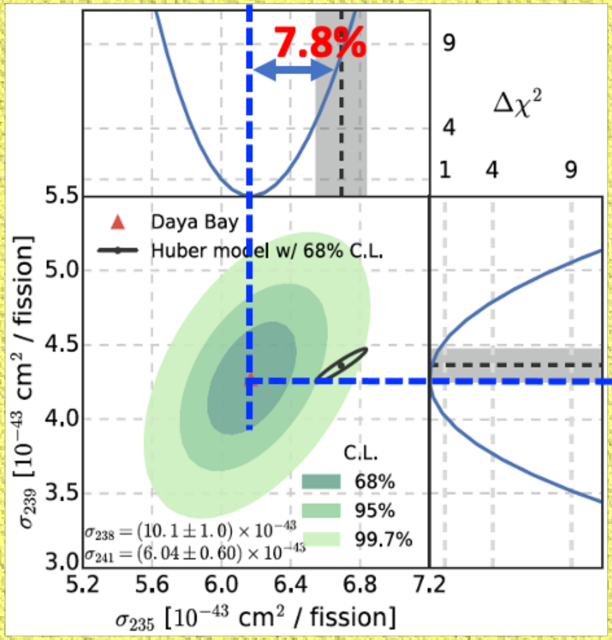


Others from DYB

❖ Sterile Neutrino Searches



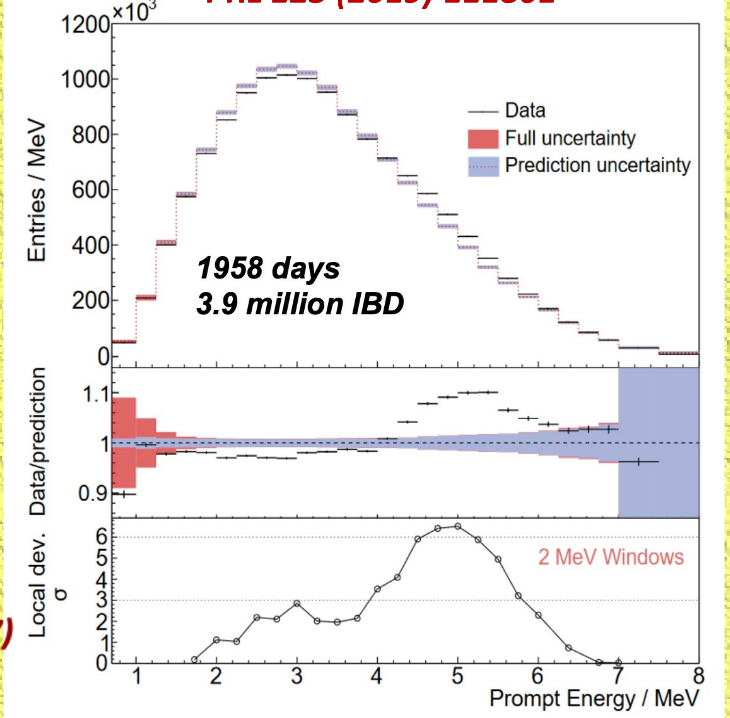
❖ Fuel Evolution



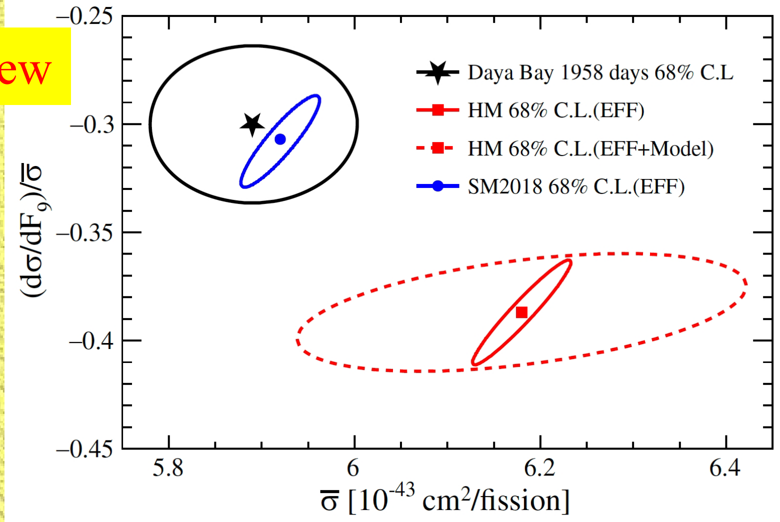
With 1230 days of data, PRL 118, 251801 (2017)

❖ Reactor antineutrino Spectrum

PRL 123 (2019) 111801



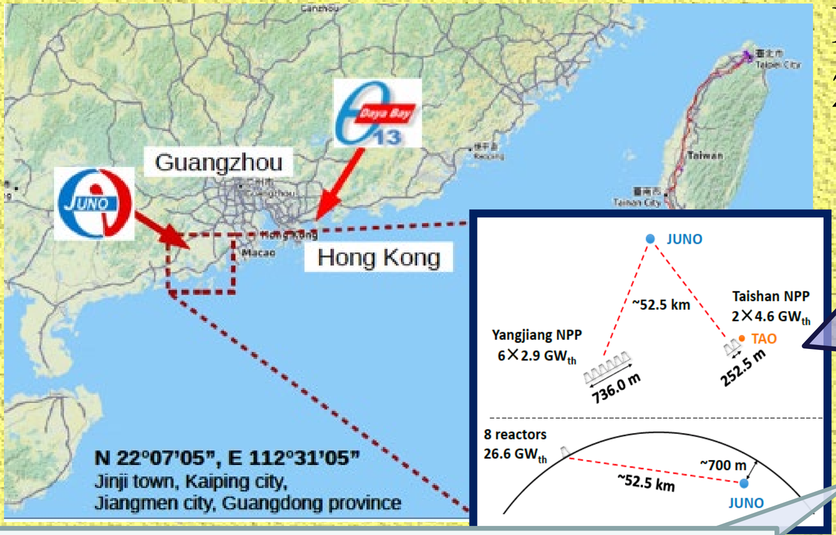
New



With 1958 days data, PRL 130 (2023) 211801

" … the SM2018 model is shown to agree with the average flux and its evolution but fails to describe the energy spectrum ….”

Jiangmen Underground Neutrino Observatory



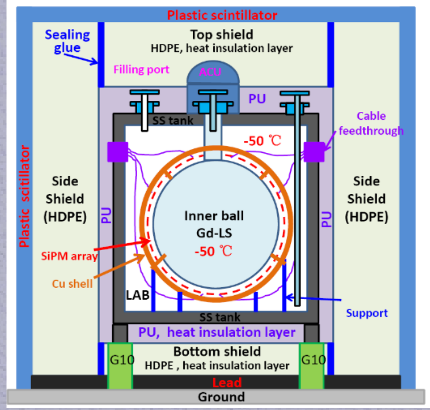
Main Goal: Determine neutrino mass hierarchy(MH)

2nd Goal: Precision measurement of mass and mixing

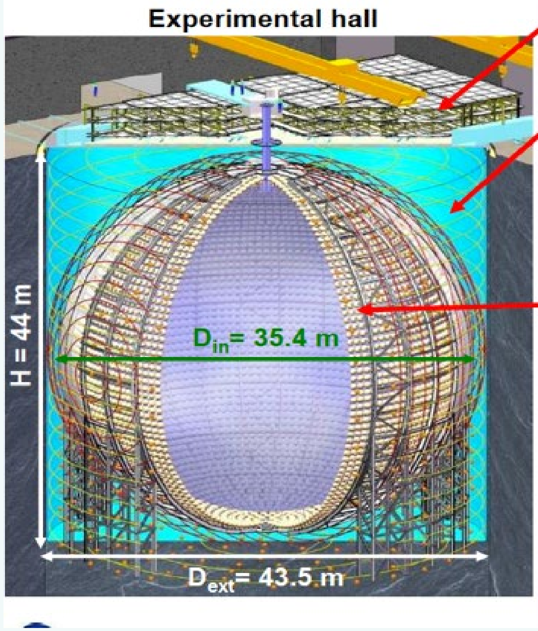
JUNO-Tao @40m from Taishan

(Taishan Antineutrino Observatory)

To measure the reactor neutrino spectrum to guarantee that MH measurement will not be affected by fine structures of the spectrum



Main Detector



Top Tracker for very precise muon tracking
- 3-layers of plastic scintillators
- Reuse of OPERA's Target Tracker

Water Cherenkov muon veto
- 35 ktons of ultrapure water
- 2,000 20-inch PMTs
- Muon detection efficiency > 95%
- Radon control → less than 0.2 Bq/m^3

Central detector :
- Acrylic sphere filled with 20 ktons of LS
- PMTs immerged in water buffer and fixed on a stainless steel truss:
  - 17,612 **20-inch PMTs**
  - 25,600 **3-inch PMTs** →**TW involved**
- 78% photocoverage

Compensation coils
- Earth's magnetic field <10%
- Necessary for 20"PMTs

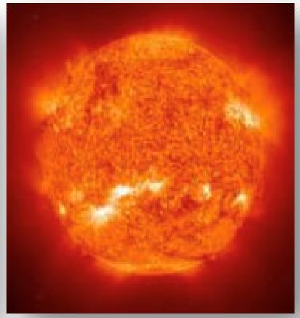
Taiwan's contributions:

- R&D on central detector design and supporting nodes, mechanical simulation
- HZC 3" PMTs testing and final acceptance tests
- Simulation of photon propagation with GPU, etc.

JUNO: a neutrino observatory

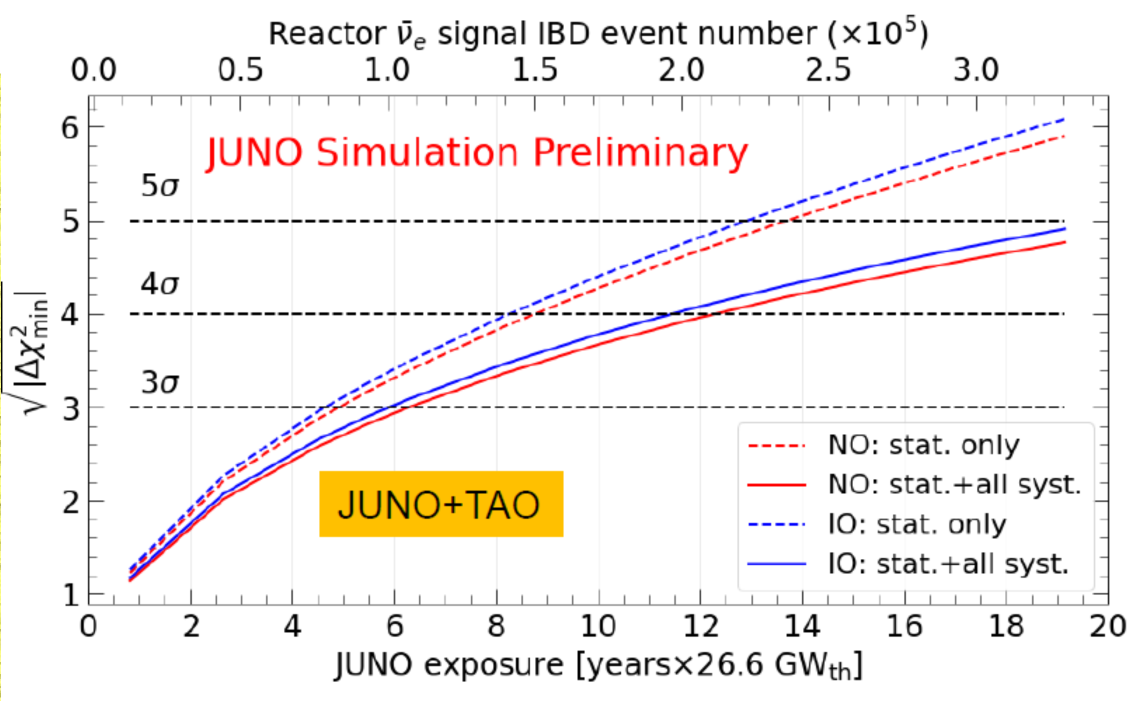
Reactor neutrino oscillation Chin.Phys.C 46 (2022) 12, 123001
Solar neutrino oscillation Chin.Phys.C 45 (2021) 2, 023004
Atmospheric neutrino flux Eur.Phys.J.C 81 (2021) 10
Diffuse supernova neutrinos JCAP 10 (2022) 033
Proton Decay arXiv: 2212.08502 and others

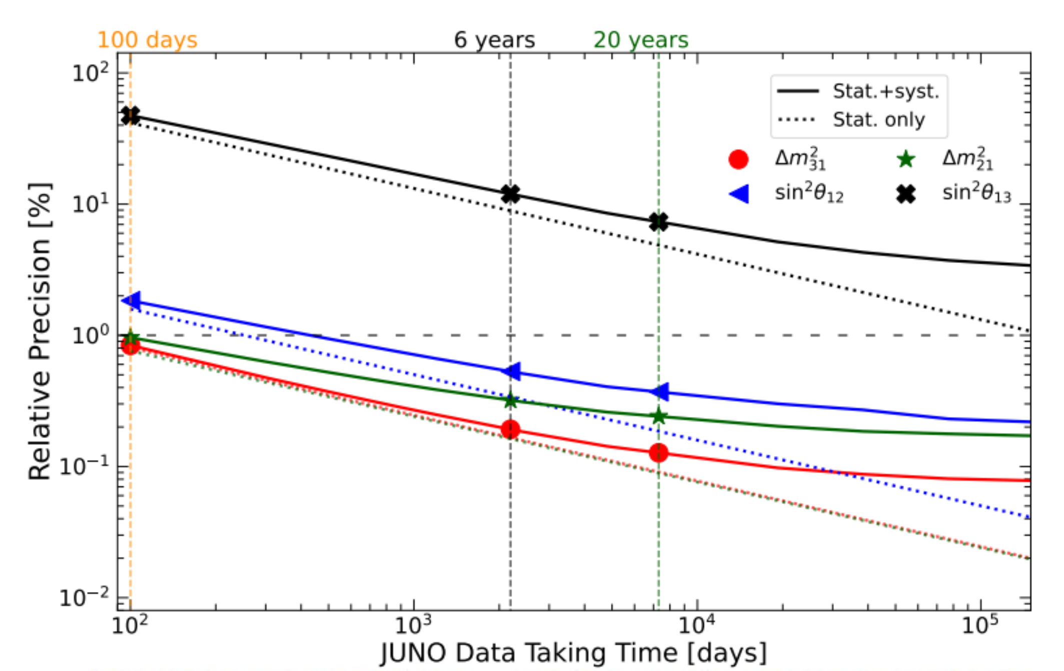
Reactor anti-ν | Atmospheric ν | Solar ν



~60 / day | Several / day | ^{8}B: ~50/day, CNO: ~1000/day, ^{7}Be: ~10000/day

- **In 6 years:**
  - **Determine neutrino mass ordering at 3σ**
  - **Precision of $\sin^2\vartheta_{12}$, Δm^2_{31}, Δm^2_{21} < 0.5%**



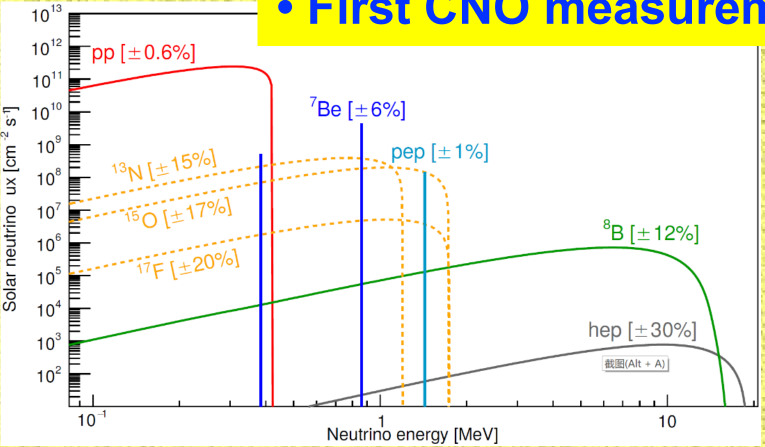


Precision of $\sin^2 2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{32}|$ < 0.5% in 6 yrs

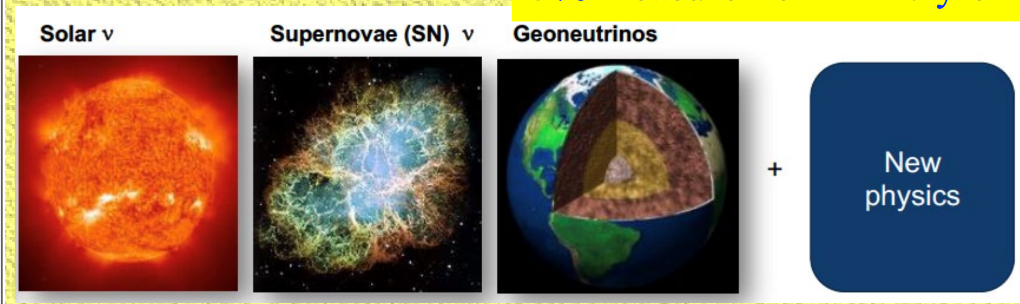
JUNO: neutrino as a probe

Core-collapse Supernova Neutrinos (CCSN)
Diffused Supernova Neutrino Background (DSNB)

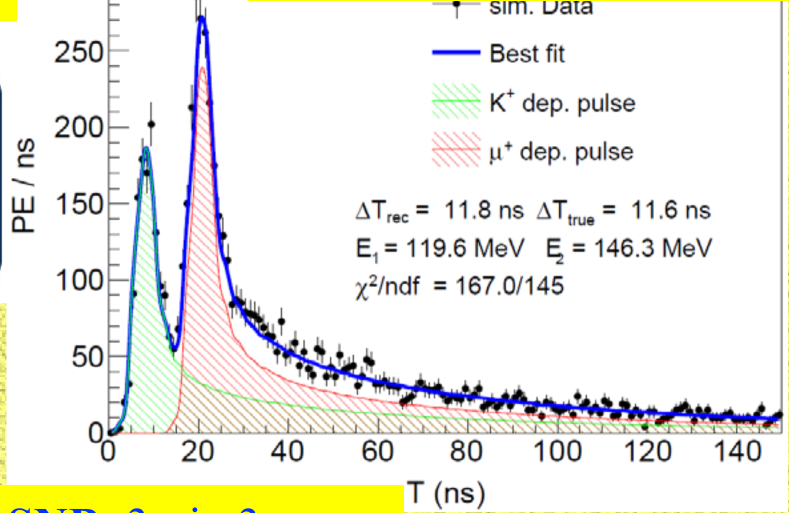
- **Better precision on ^{7}Be, pep**
- **First CNO measurement**



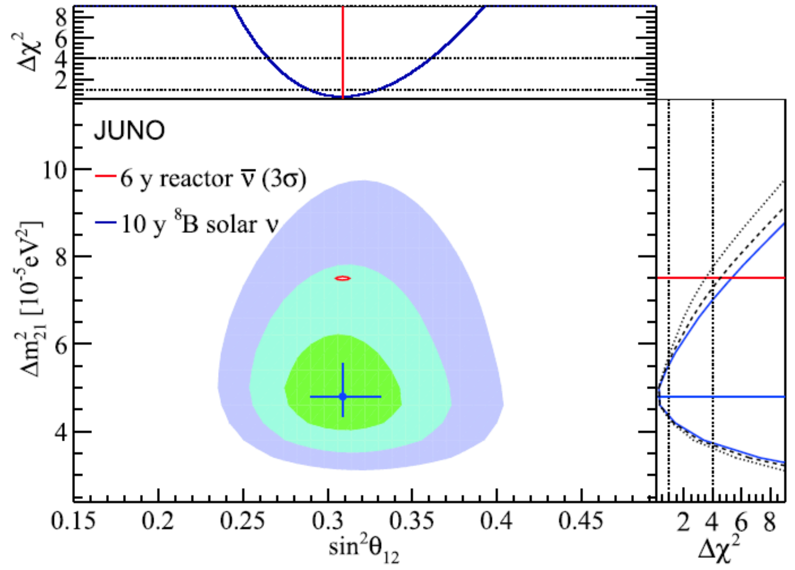
Geo-neutrino
~400 per year
5% measurement in 10 yrs



Proton decay search:
Expect sensitivity:
9.6×10^{33} years (90% C.L.) for 193 kton*yrs fiducial exposure

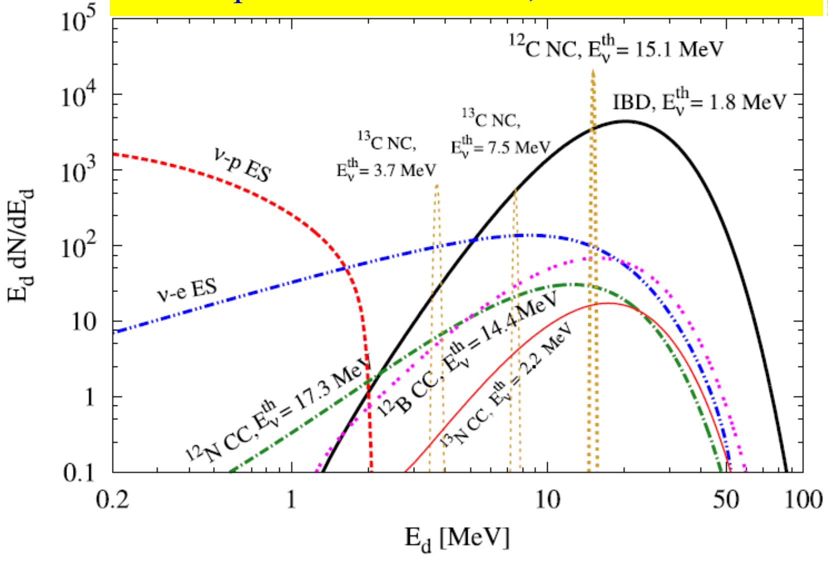


Solar & reactor measurement in Δm^2_{21} with one single detector

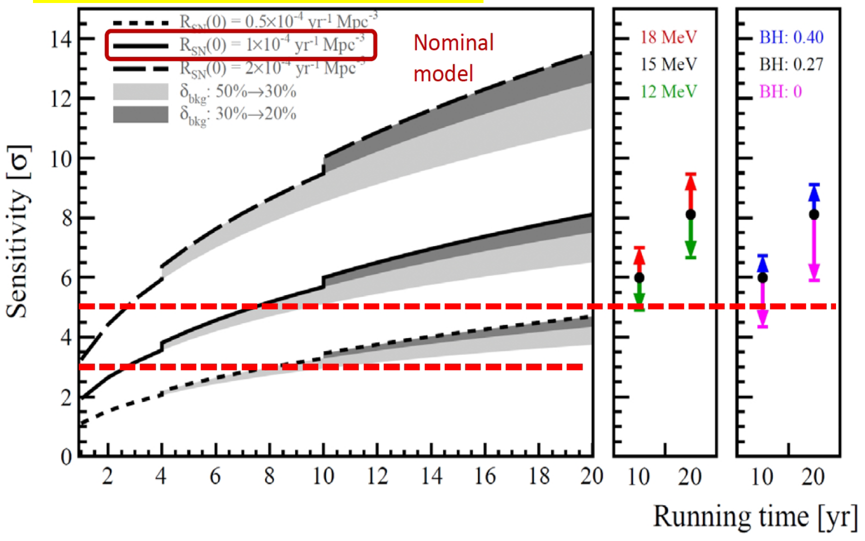


Multi-channel detection, all flavors of CCSN

10kpc Supernova: ~5000 IBD, ~300 eES, ~2000 pES，~200 ^{12}C CC, ~300 ^{12}C NC



DSNB: 3σ in 3 yrs

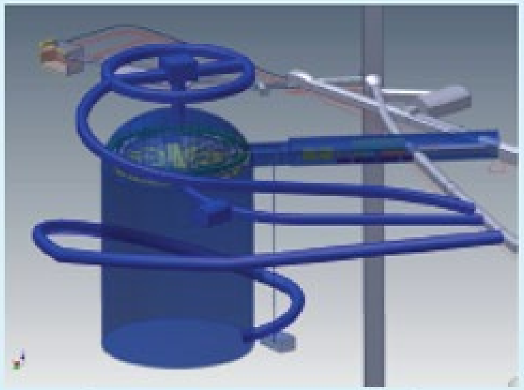


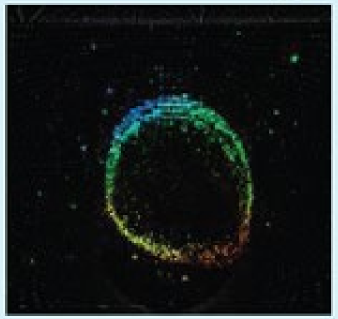
Current Status

- JUNO is motivated to measure the Neutrino Mass Ordering
- Rich physics program. World-leading studies on
  - Precision measurement of oscillation parameters, Supernova ν, DSNB, Geo-ν, solar ν, proton decay, …
  - Future JUNO-0νββ
- **JUNO construction has entered its final stage.**
- **Data taking is expected in 2024!**

Coming Generation of Big Neutrino Oscillation Experiments :

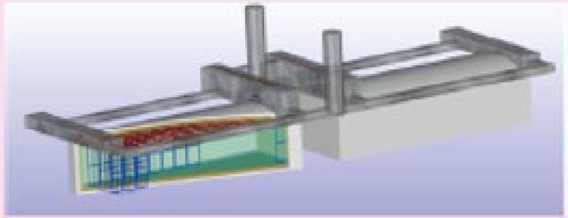
Water Cherenkov

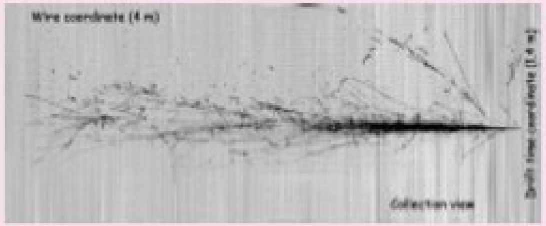




Cheap material, proven at very large scale

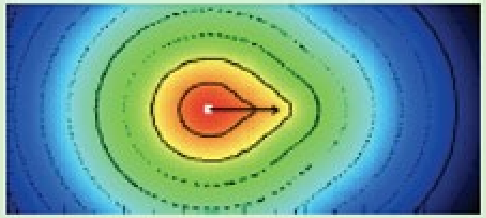
Liquid Argon





Excellent particle reconstruction

Liquid Scintillator



Low energy threshold

Physics Potentials with JUNO

JUNO has great potentials on the physics topics below, although except for CP phases, θ_{23} Octant

Exp.	Time	Mass ordering	CP phases	Precision Meas.	CCSN burst @ 10 kpc	DSNB	Geo-ν	Solar	Proton Decay (sensitivity@10 y)
JUNO (20 kt)	2024	3-4 σ 6 y	—	$\sin^2\theta_{12}$ (0.5%), Δm^2_{21} (0.3%), Δm^2_{31} (0.2%), 6 y	all-flavor ν (IBD, eES, pES)	3σ, 3 y	~400/y	^{7}Be, pep, CNO, ^{8}B	> 9.6x10^{33} y ($\bar{\nu}K^+$)
DUNE (17 kt*4)	2030	>5 σ 1-3 y	5σ (50%) 10 y	Δm^2_{32} ~0.4%, $\sin^2\theta_{23}$~1.1% *, 15 y	^{40}Ar CC & NC, eES	^{40}Ar CC	—	^{8}B, hep	>8.7x10^{33} y ($e^+\pi^0$) >1.3x10^{34} y ($\bar{\nu}K^+$)
HyperK (260 kt)	2027	3-5 σ 10 y	5σ (60%) 10 y	Δm^2_{32} ~0.6%, $\sin^2\theta_{23}$~1.6% *, 10 y	eES, IBD	3σ, 6 y	—	^{8}B, hep	>7.8x10^{34} y ($e^+\pi^0$) >3.2x10^{34} y ($\bar{\nu}K^+$)
ORCA (7 Mt)	Un-known	2-4 σ 3 y	—	Δm^2_{32} ~2% , 3 y	rate excess	—			
IceCube Upgrade	2026	2-4 σ 7 y	—	Δm^2_{32} ~1.3% , 3 y	rate excess	—			

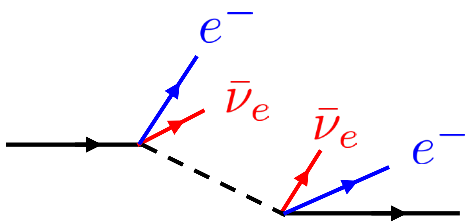
** Upper octant assumption*

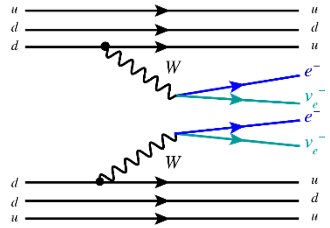
eES: ν-electron scattering, pES: ν-proton scattering, IBD: inverse beta decay

Double-beta decays

- Double-beta decays are observed in even-even nuclei when single-beta decays are energetically forbidden

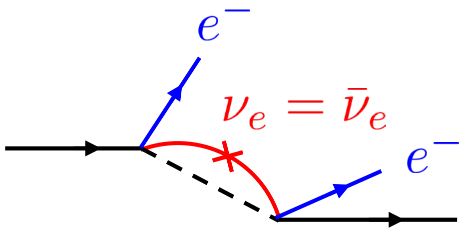
2νββ $2n \rightarrow 2p^{+} + 2e^{-} + 2\bar{\nu}_e$

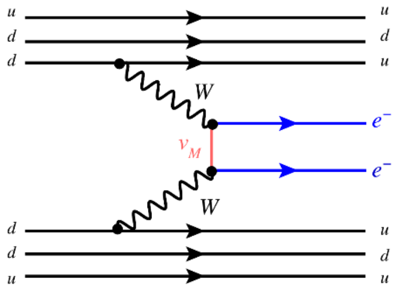




- Nature provides 35 double-beta-decay isotopes, e.g., ^{48}Ca, ^{70}Zn, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe
- A hypothetical process called "neutrinoless double-beta decay" was suggested

0νββ $2n \rightarrow 2p^{+} + 2e^{-}$

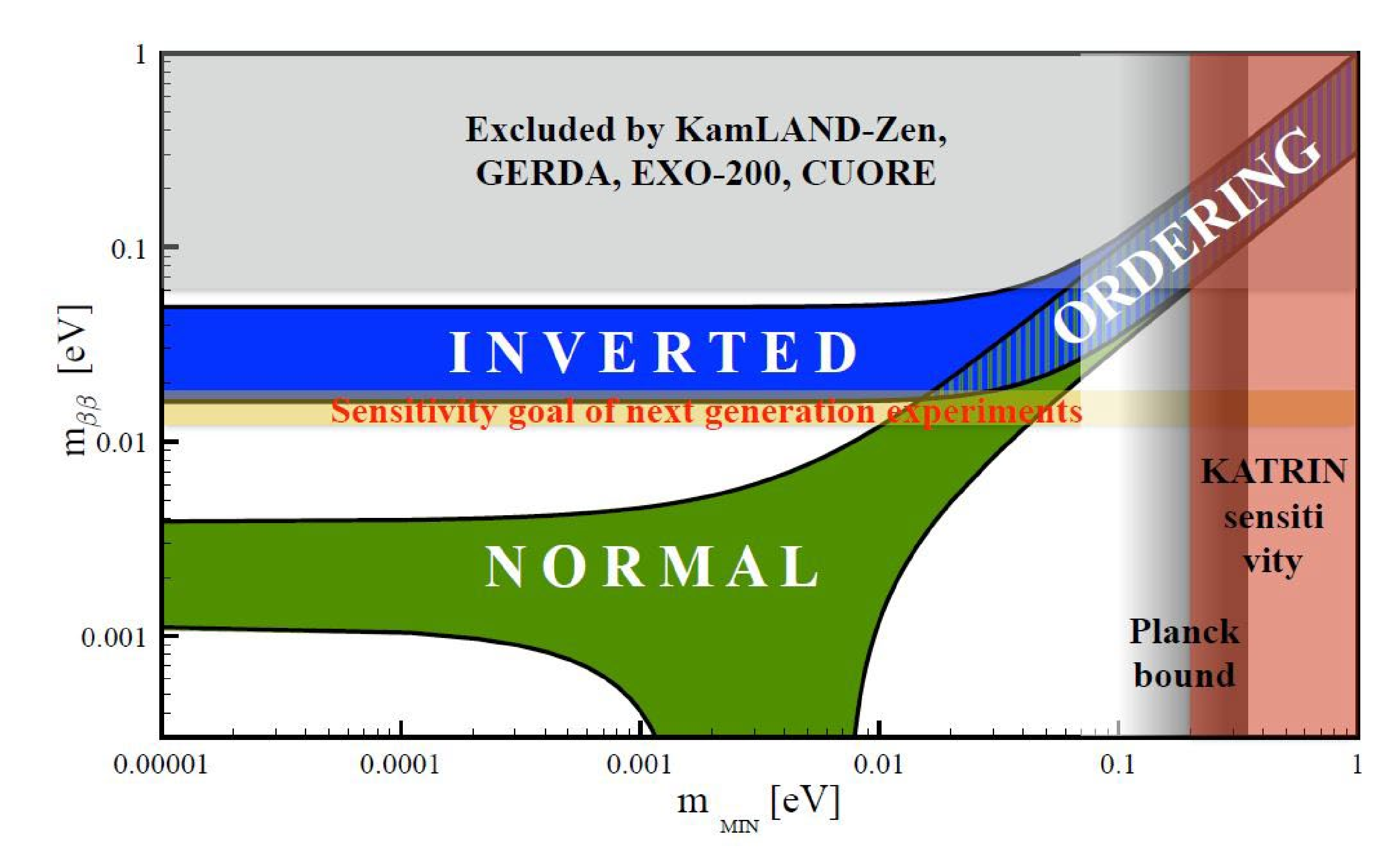




- If observed, this informs
  - ➡ Lepton number violation
  - ➡ Information about matter-antimatter imbalance of the Universe (leptogenesis)
  - ➡ Neutrinos have a Majorana mass
  - ➡ Hints on neutrino mass scale and mass ordering

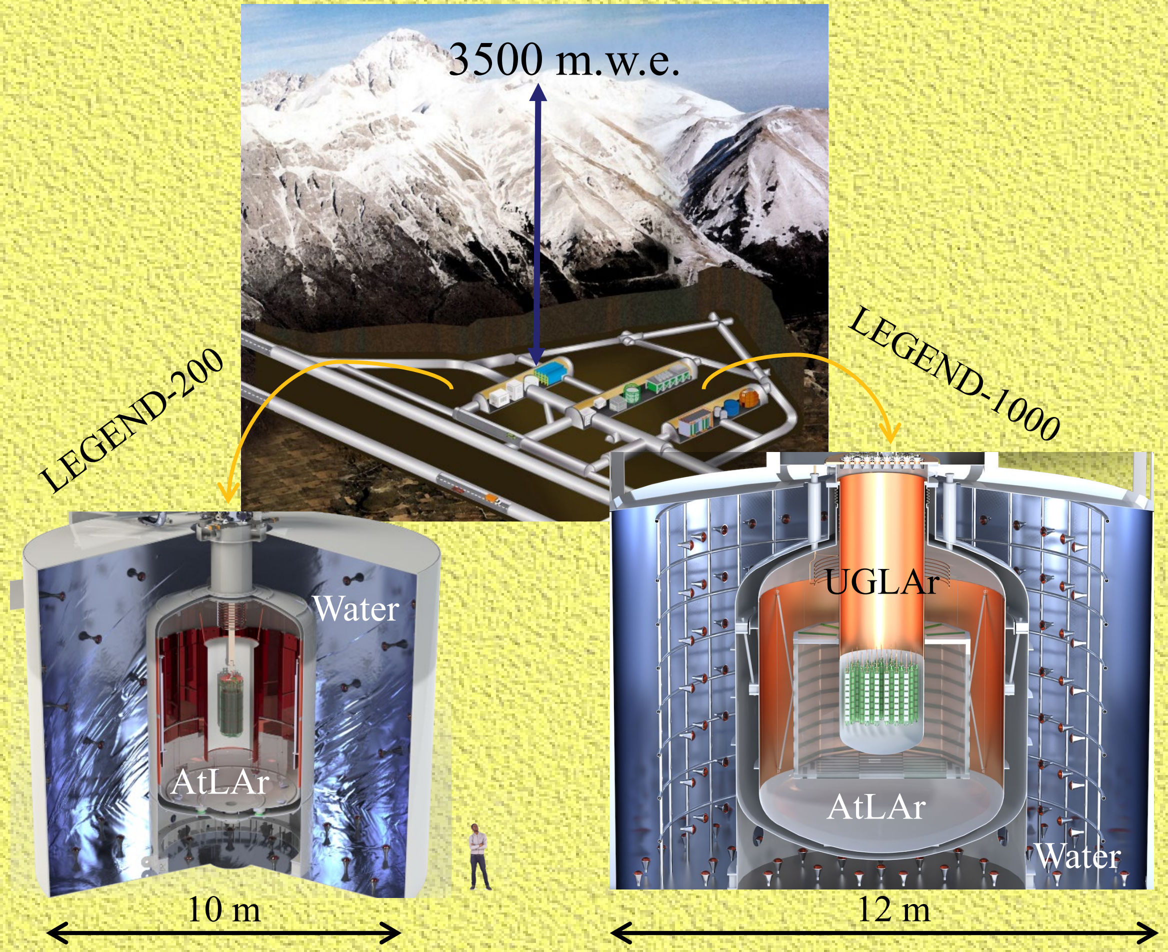
Searches of $0\nu\beta\beta$ (like m_ν) ….

- ✓ Definite BSM Predicted Scales are within Experimental Reach *(unlike proton decays, DM-searches …. etc)*
- ✓ Discovery Potentials !!



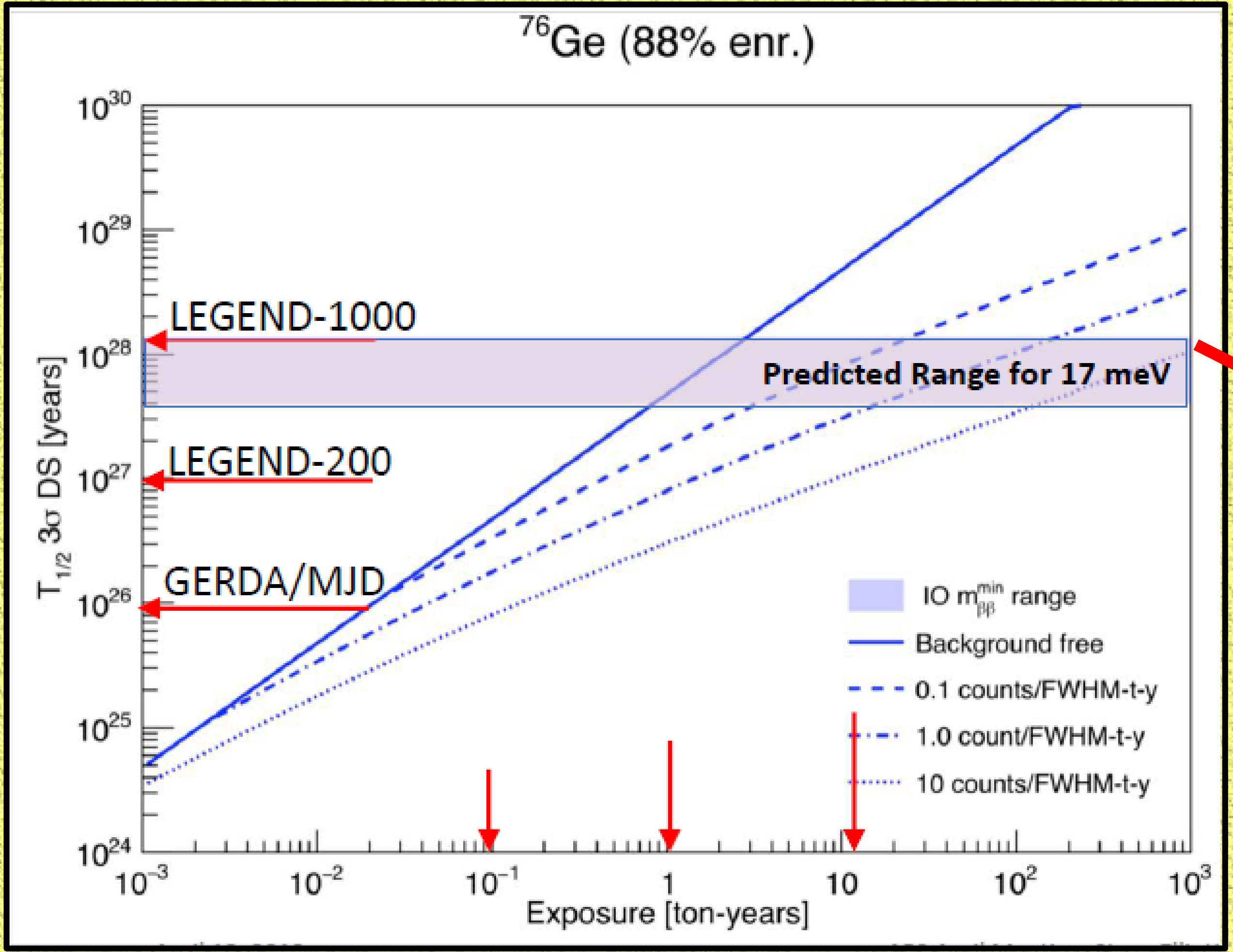
The LEGEND project

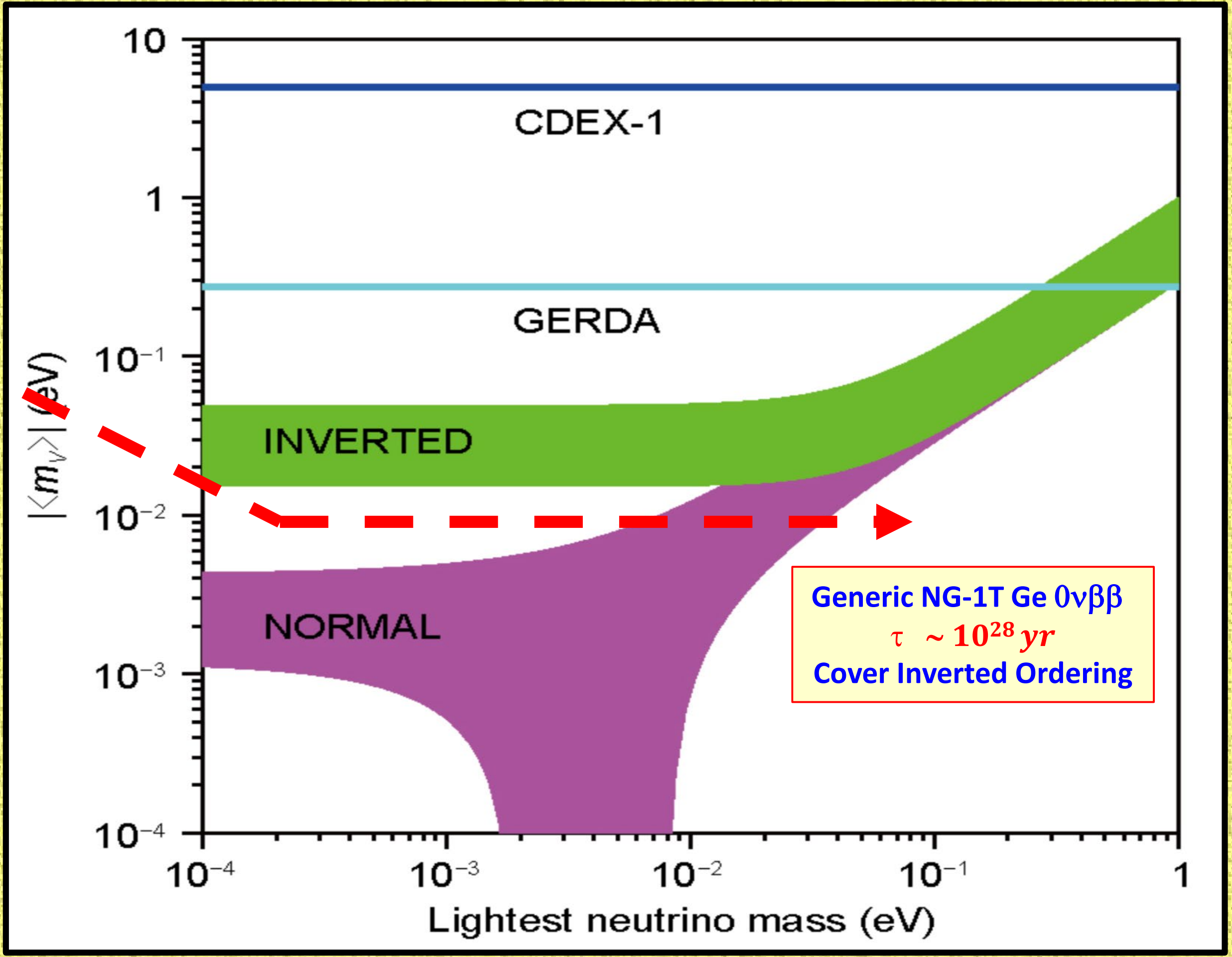
- Located 1.4 km (3500 m.w.e.) underground at the Gran Sasso National Laboratory (LNGS), Italy
- Two-phased experiment → Phase-I: LEGEND-200; Phase-II: LEGEND-1000
- Immerse ^{76}Ge-enriched high-purity germanium (HPGe) detectors in liquid argon (LAr)

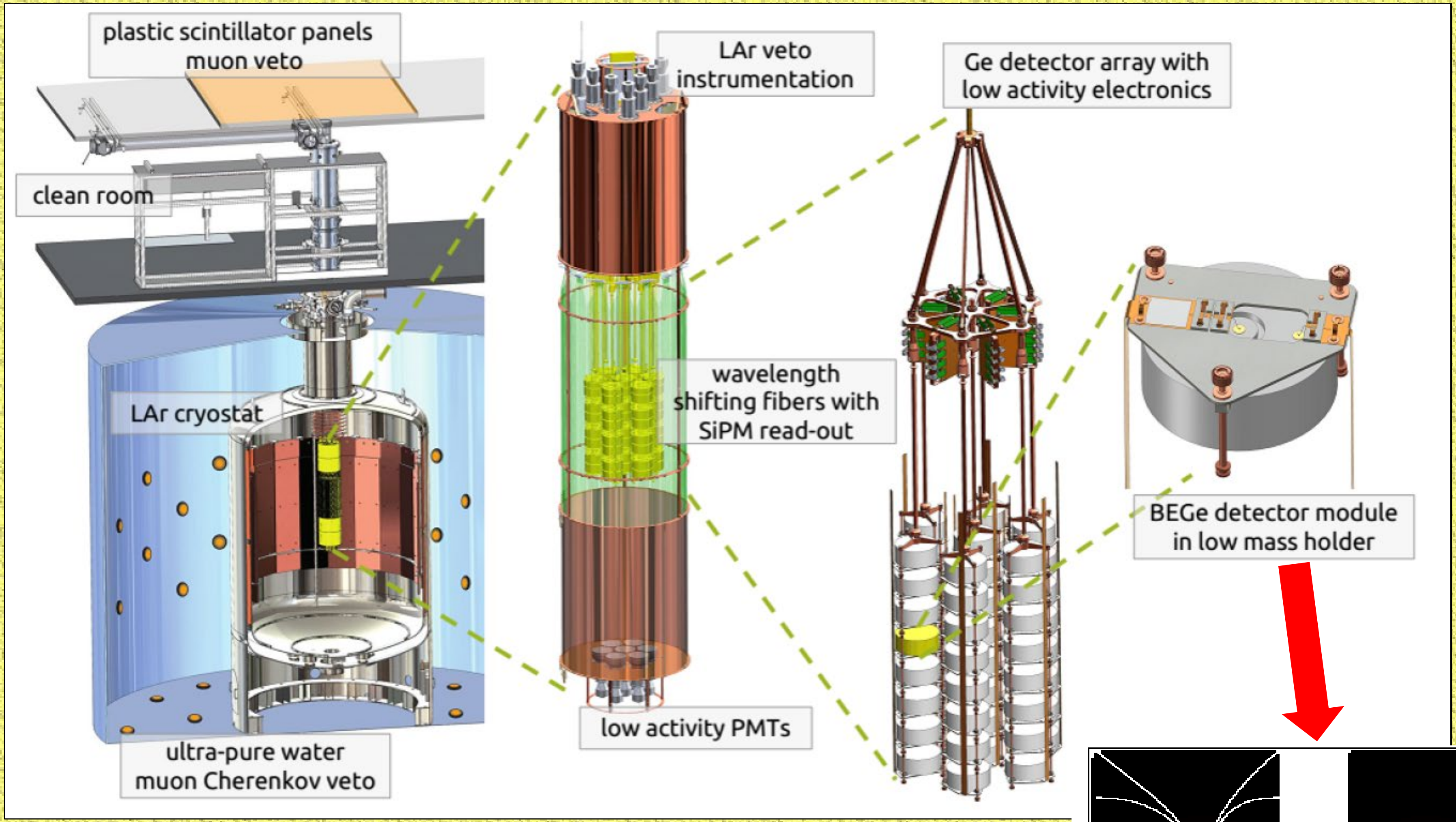


Phase	I (LEGEND-200)	II (LEGEND-1000)
HPGe detectors (kg)	200	1000
LAr (tonne)	90 (At*)	350 (At+**UG***)
Live time (yr)	5	10
Background requirement (counts/(keV·kg·yr))	$\sim 2 \times 10^{-4}$	$< 10^{-5}$
Discovery sensitivity of $T_{1/2}$ (yr)	$> 10^{27}$	$> 10^{28}$
$m_{\beta\beta}$ (meV)	33–71	Fully cover $m_{\beta\beta}$ inverted ordering regime
Status	Science run started in spring 2023	R&D ongoing; planned staged commissioning in 2030

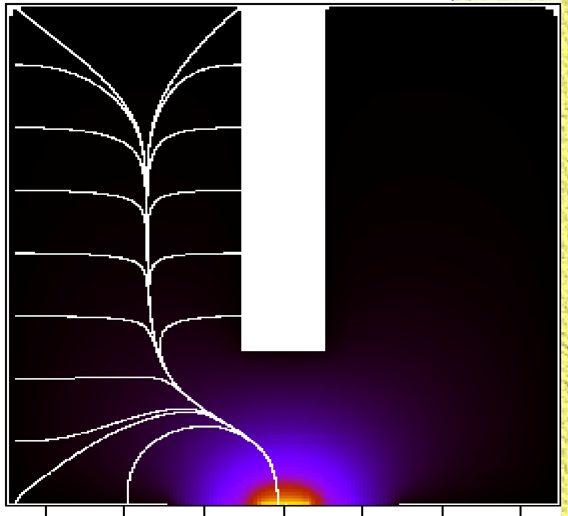
Projected Sensitivities







Mechanics following closely GERDA

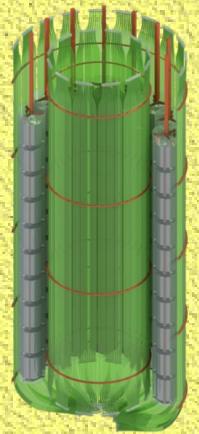


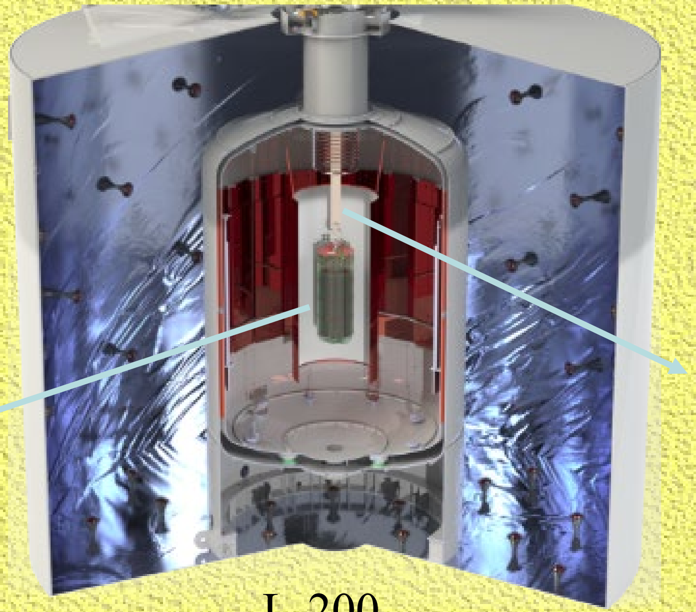
Inverted Coaxial Point-Contact Detector : > 2 kg

Liquid argon veto system

- Energy depositions in LAr induce VUV scintillation light (128 nm), which is used to veto background events
- Wavelength shifters (e.g., traphenyl butadiene; TPB) improve the light-detection efficiency of optical sensors
- TPB-coated fibers surround HPGe detectors, whose light is detected by silicon photomultipliers on both ends of the fibers
- TPB-coated Tetratex® (TTX) serves as a reflector, which encircles the detector array and further enhances the light-detection efficiency of the fibers

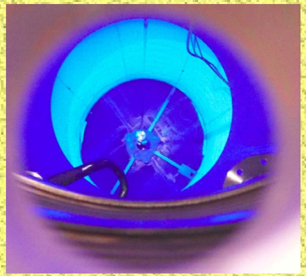
Wavelength-shifting (inner/outer) optical-fiber shrouds

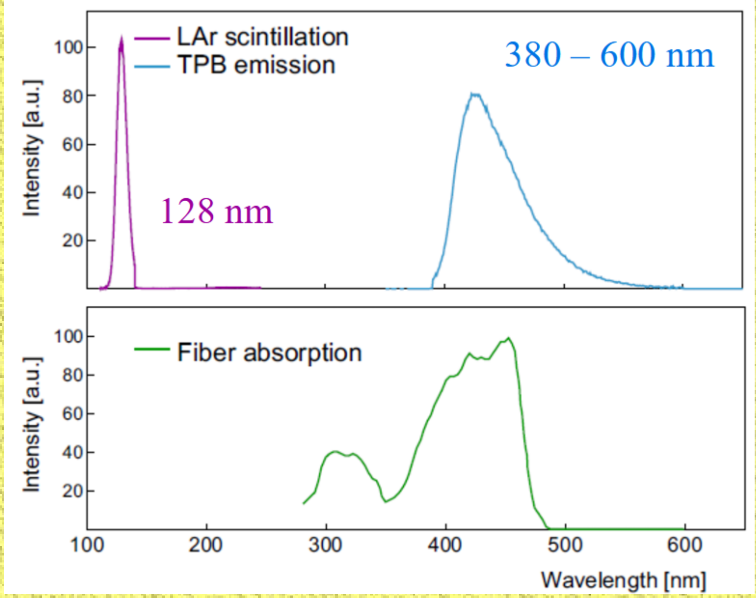




L-200

Wavelength-shifting reflector under VUV light





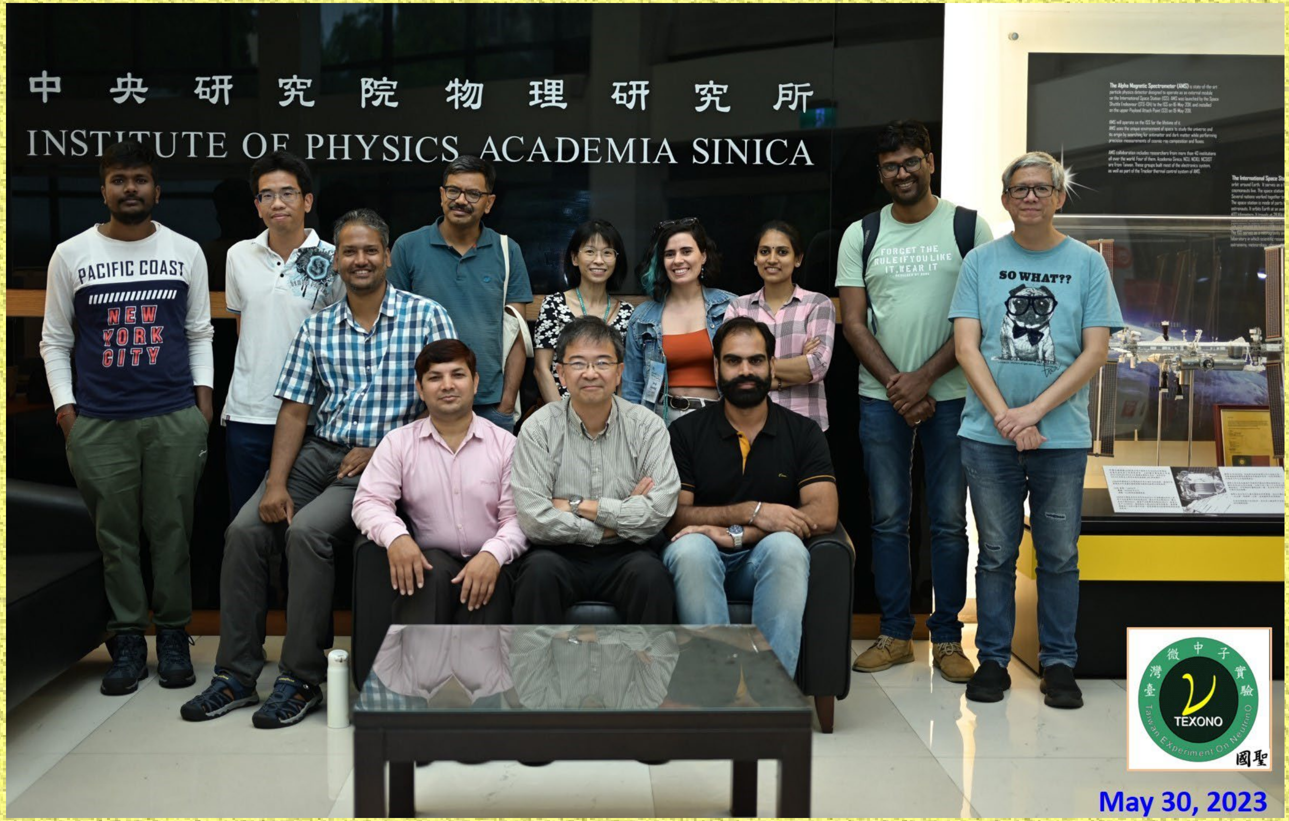
Ref.: G. R. Araujo et al., EPJC 82, 442 (2022)

LEGEND Large Enriched Germanium Experiment for Neutrinoless ββ Decay

Liquid argon facility at NTU for LEGEND-1000 and beyond

- Construct a LAr facility as a support for LEGEND-1000 to
  - ➡ Investigate next-generation large-scale wavelength-shifting materials
  - ➡ Test optical sensors for LAr light detections
  - ➡ Devise an independent LAr calibration mechanism
  - ➡ Serve as a test stand for future HPGe detector studies
- LAr is also used in other fields, e.g.,
  - ➡ Time projection chambers for neutrino-oscillation observations and dark-matter searches
  - ➡ Positron emission tomography with liquid argon in medical physics studies
- Other LAr-property studies, e.g.,
  - ➡ Scintillation light velocity, refractive index, and Rayleigh scattering length
  - ➡ Argon depletion techniques to remove unwanted background argon isotopes

Dr. Pin-Jung Chiu
邱品融

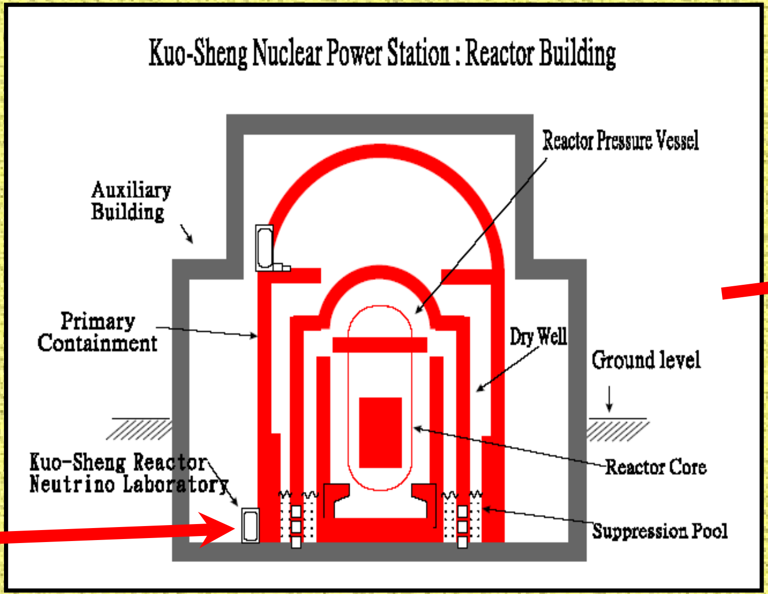


AS, KSNPS, NTU, NDHU,
IHEP, CIAE, THU, SCU,
BHU, CUSB, GLAU,
HNBGU, METU, DEU…..

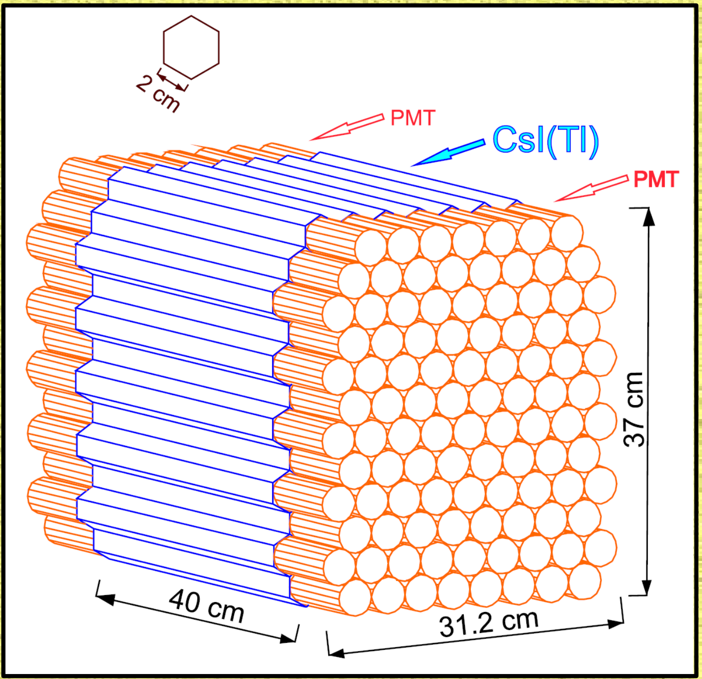
TEXONO Program *[since 1997]* **:**

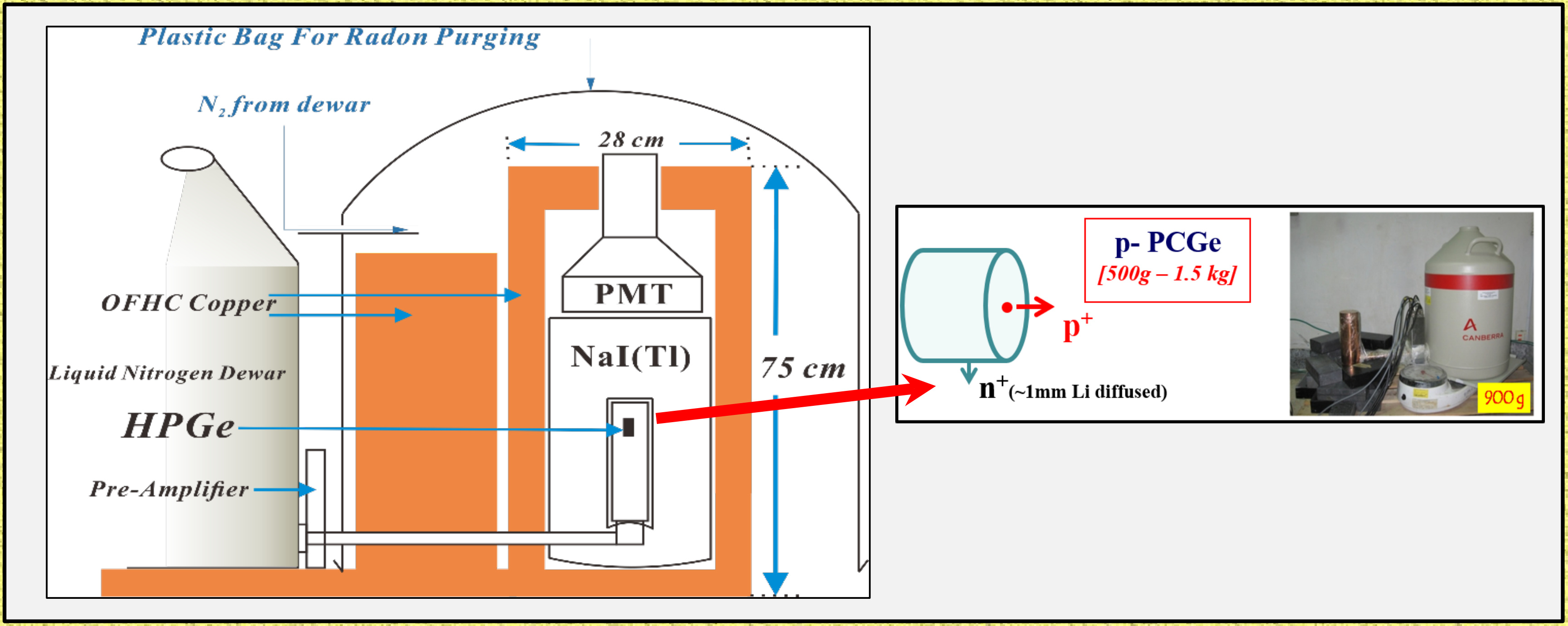
- ☐ Low Energy Neutrino (SM+EM) physics at Kuo-Sheng Neutrino Laboratory (KSNL), 28 m from 2.9 GW_{th} reactor core
- ☐ Founding partner of CDEX@CJPL Dark Matter Experiment *[since 2008]*
- ☐ Theory Program *[since 2010]*


TEXONO


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

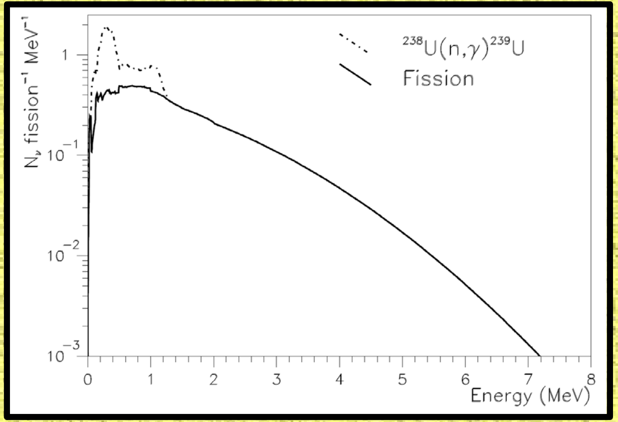

N
0
20mi
20km
NPS-I
NPS-II
Keelung
Taipei
ACADEMIA SINICA
NPS-IV
Hsinchu
Ilan


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)
75 cm
Liquid Nitrogen Dewar
HPGe
Pre-Amplifier
p- PCGe
[500g – 1.5 kg]
p+
n+(~1mm Li diffused)
CANBERRA
900g

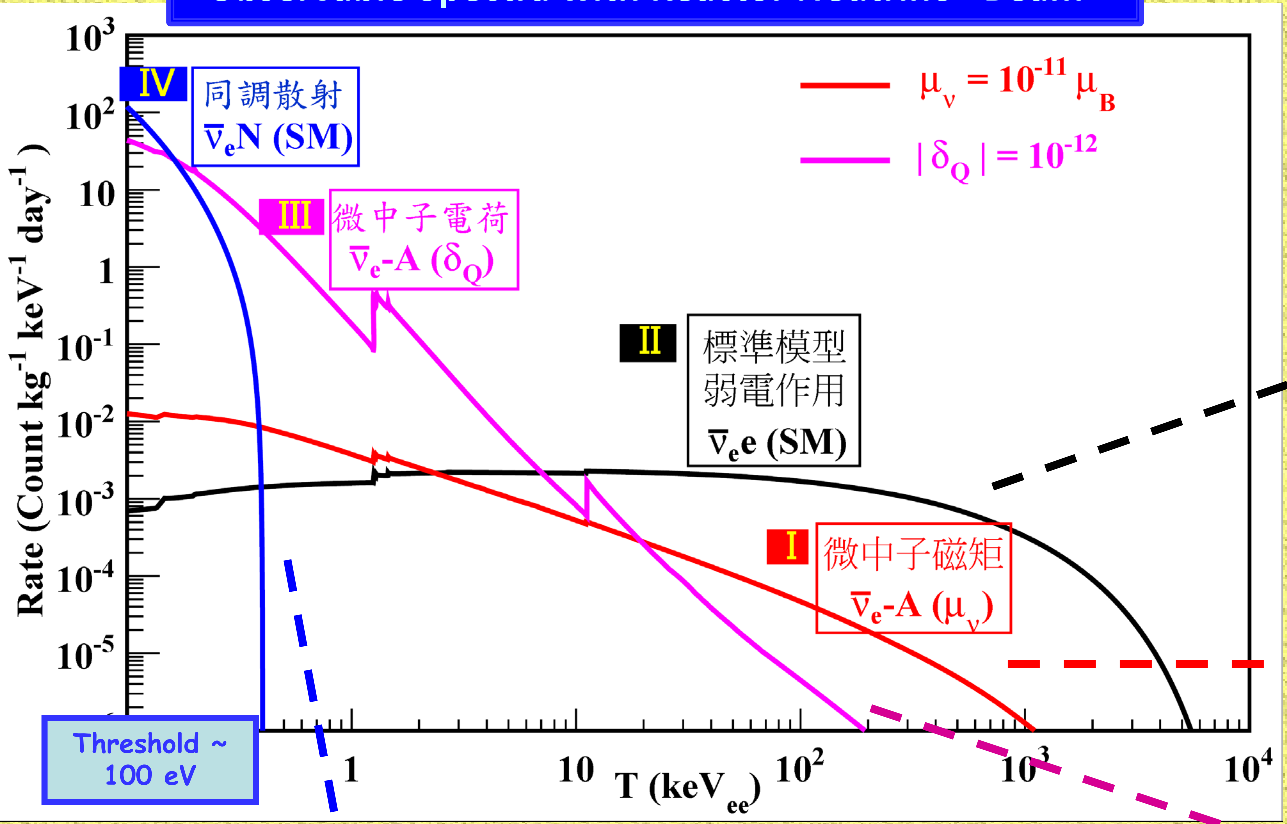
Neutrino Properties & Interactions at Reactor

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]*

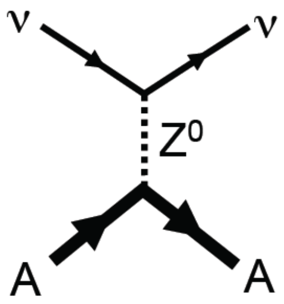
- Pioneered sub-keV O(kg) ULEGe / PCGe [MPLA08, NIMA16]
  - Light Dark Matter Searches @ KSNL *[PRD09,PRL13,AP14,PRD19]*
  - CDEX DM Program@CJPL *[PRD13………]*
  - Theory Program *[PLB14………]*

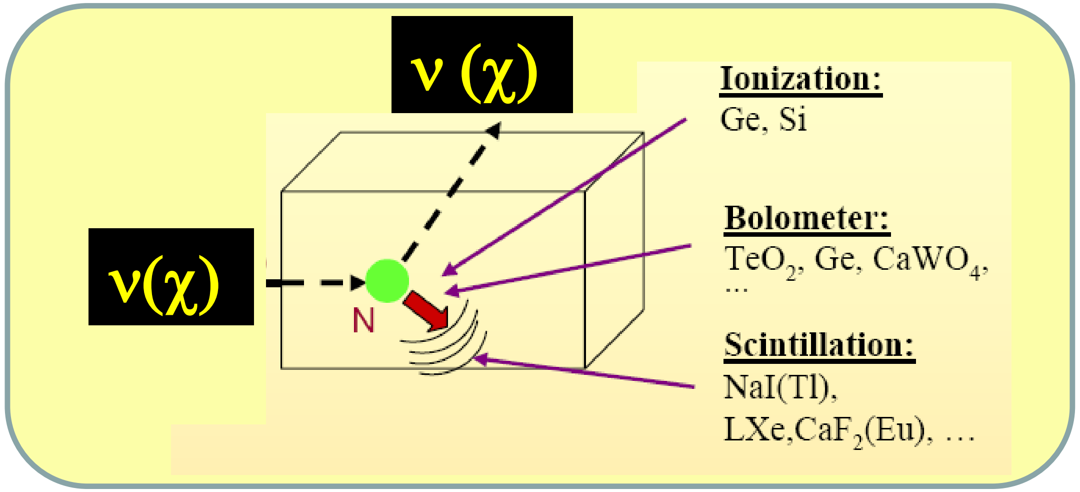
sub-keV PCGe

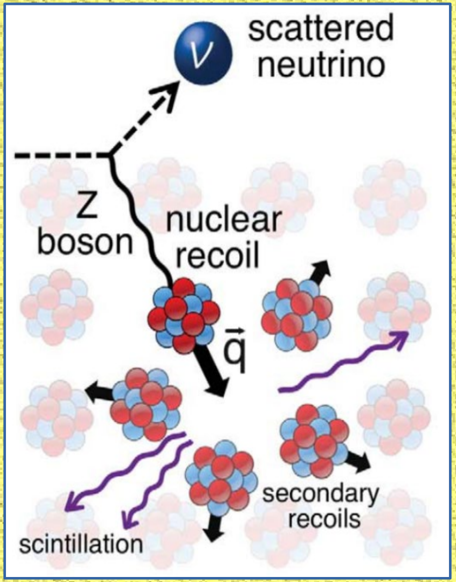
Neutrino-Nucleus Coherent Scattering :

Standard Model allowed and predicted processes :

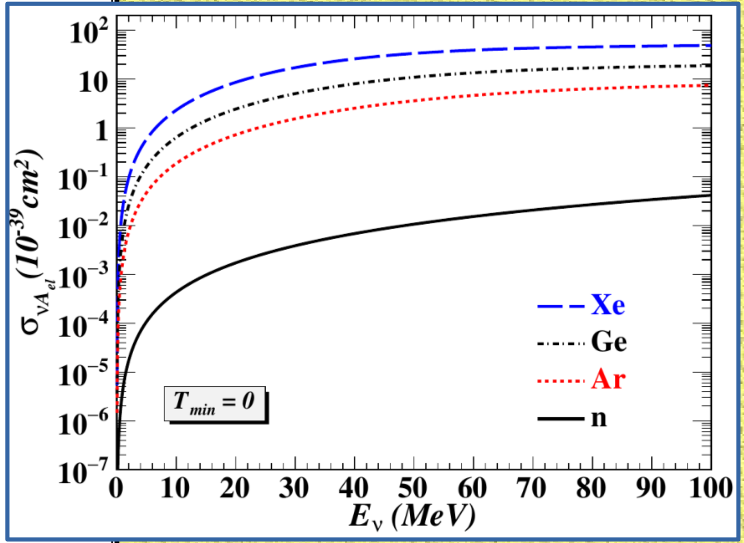
$\nu + A \rightarrow \nu + A$







- 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]

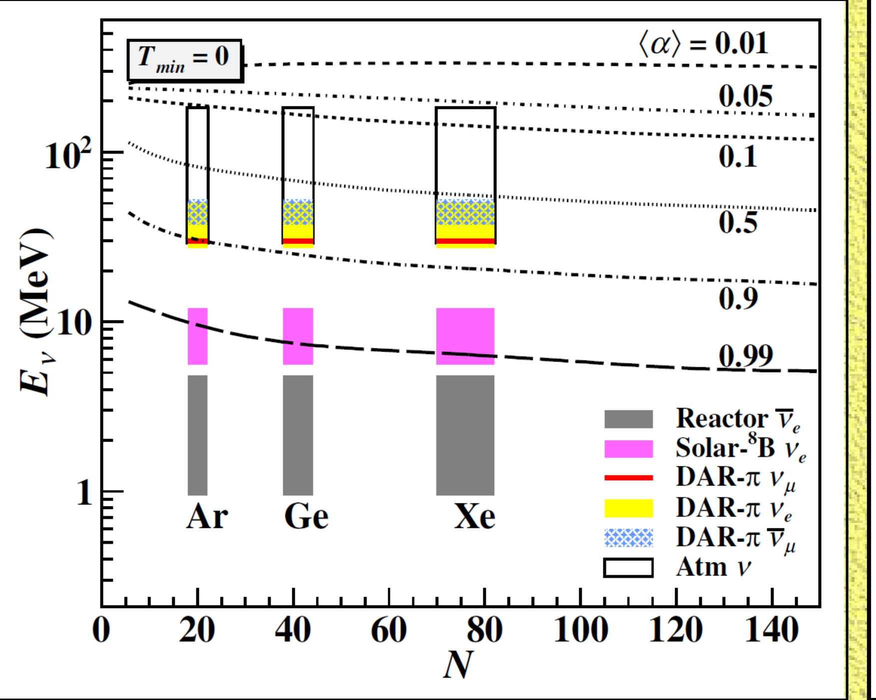
- Quantify transitions between QM Coherency & Decoherency
- Universal Characterization between different Sources & Target

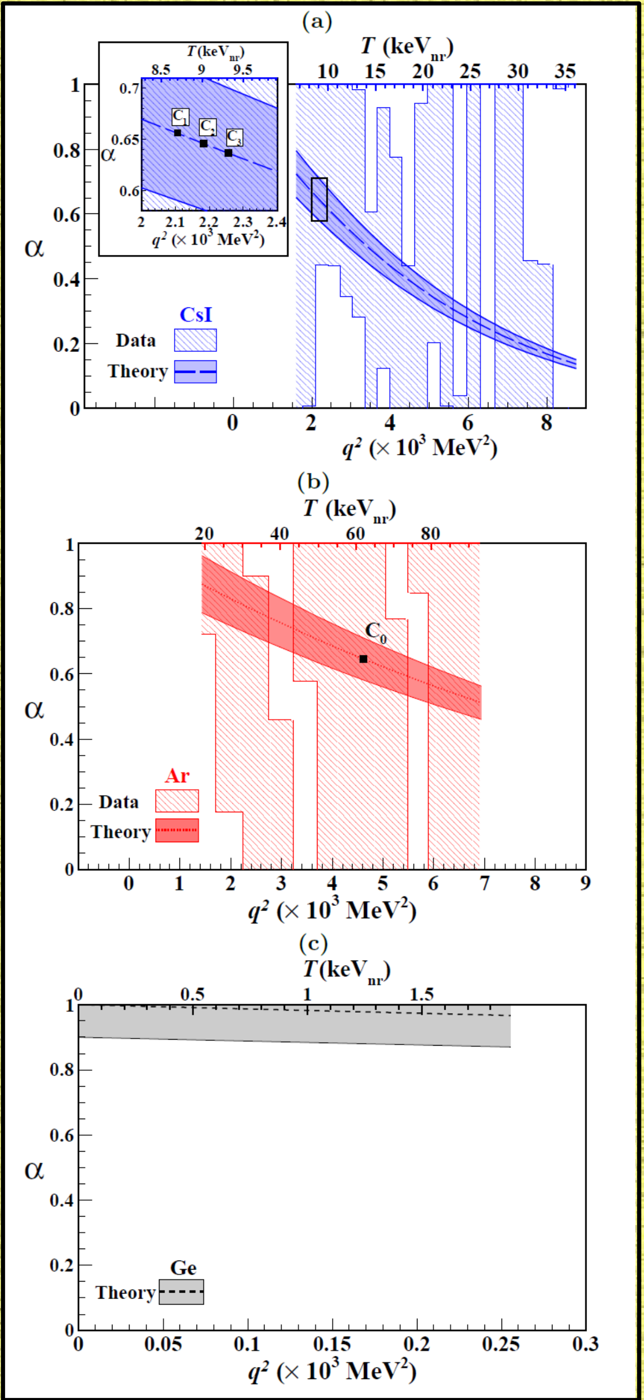
νA_{el} with Reactor Neutrinos:

- ☑ 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

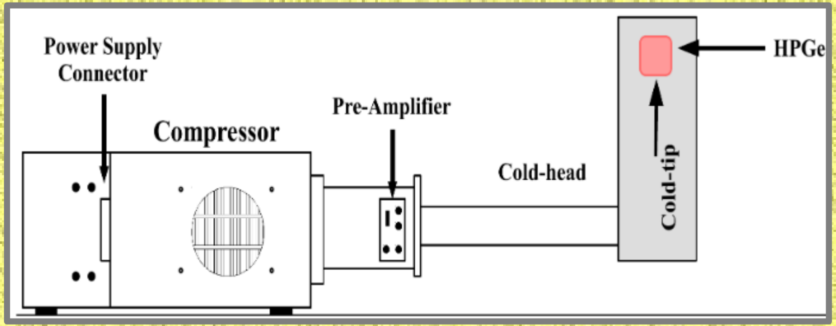




Seek Theorists' Input / Inspirations:

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

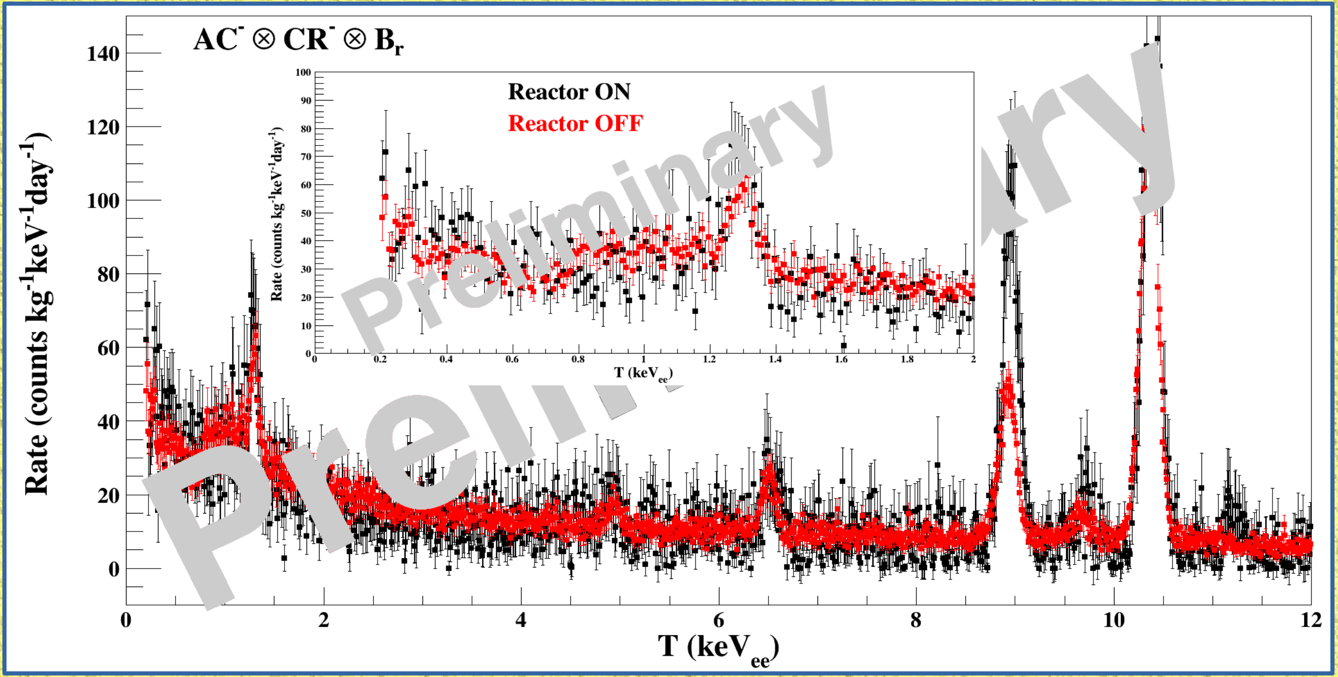
Electro-cooled PCGe



	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 (→ $G3^{++}$)

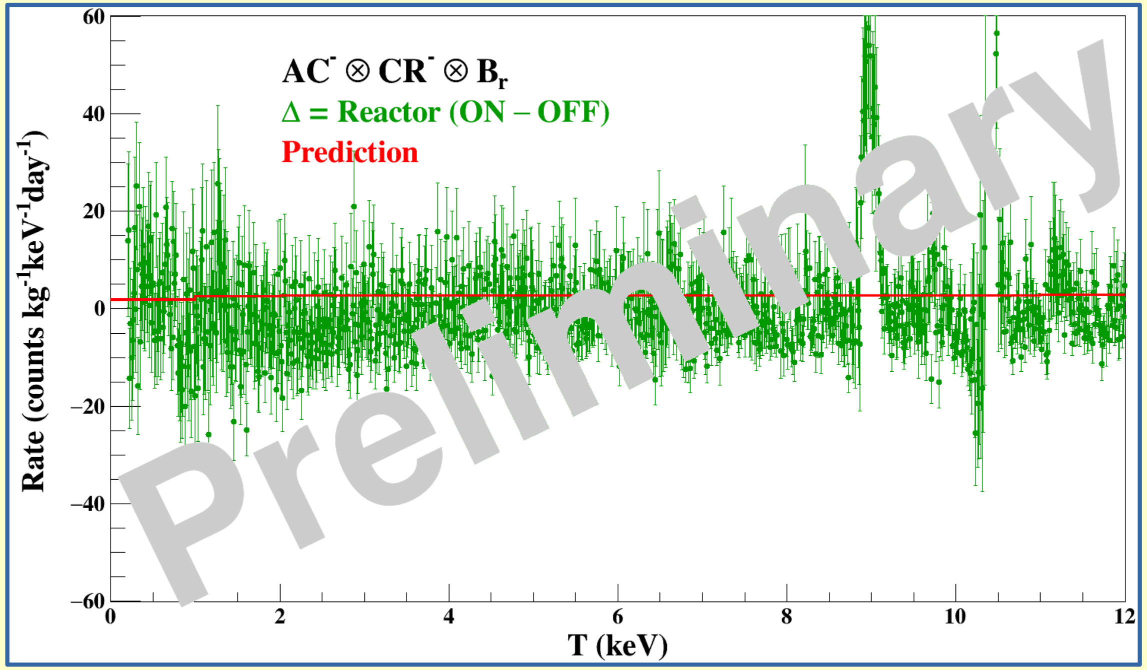
- ☑ Novel Technology with Negative Feedback Synchronized Pumping
- ☑ Typical G3 (500g) Spectrum ⇨
- ☑ With Anti-Compton & Cosmic-Ray & Surface Events Vetos
- ☑ Near Threshold Data Analysis In Progress.

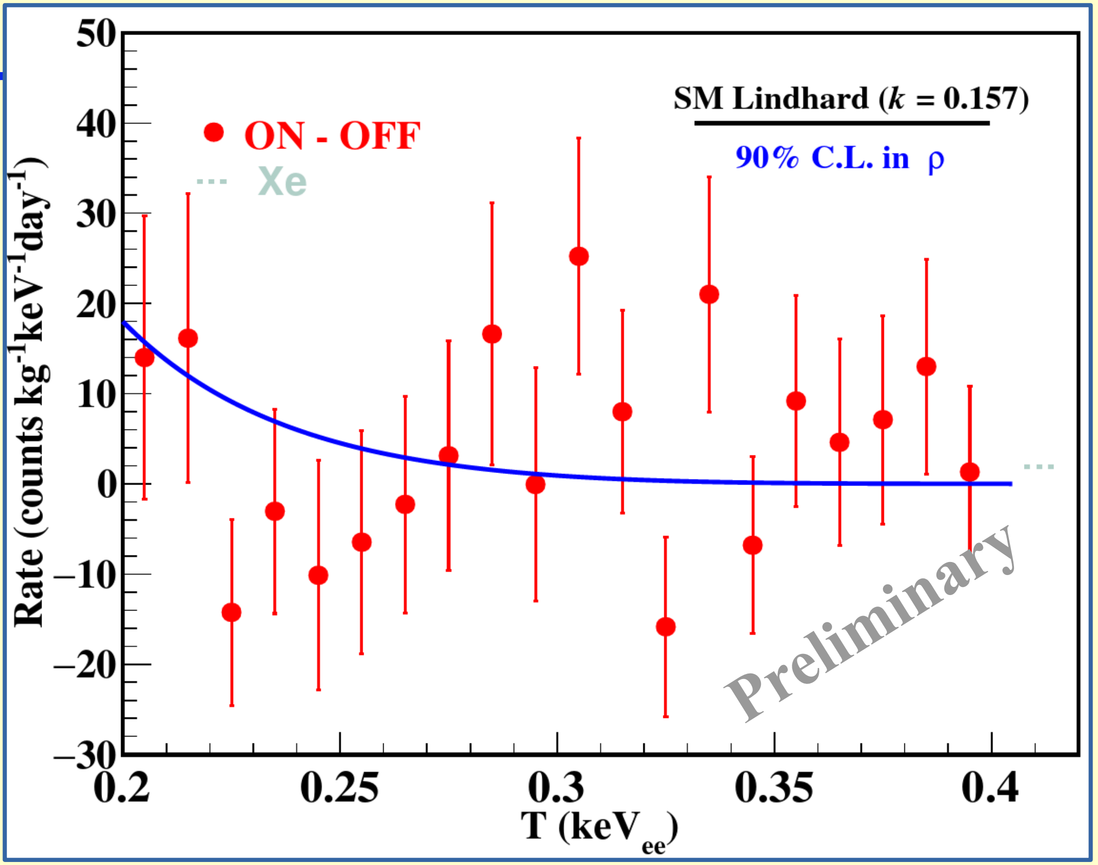


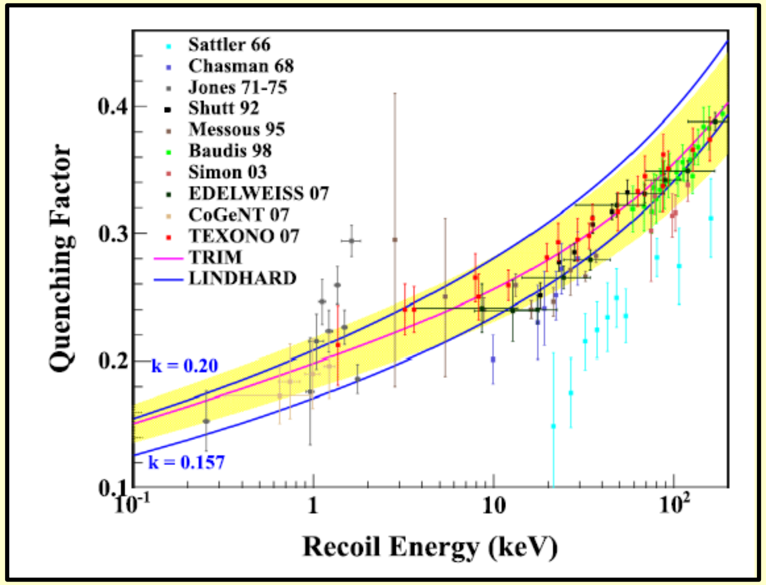
Sub-keV Ge Detector Techniques : Hardware/Software Development *[AP13, NIMA 16, NIMA18]*

- 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





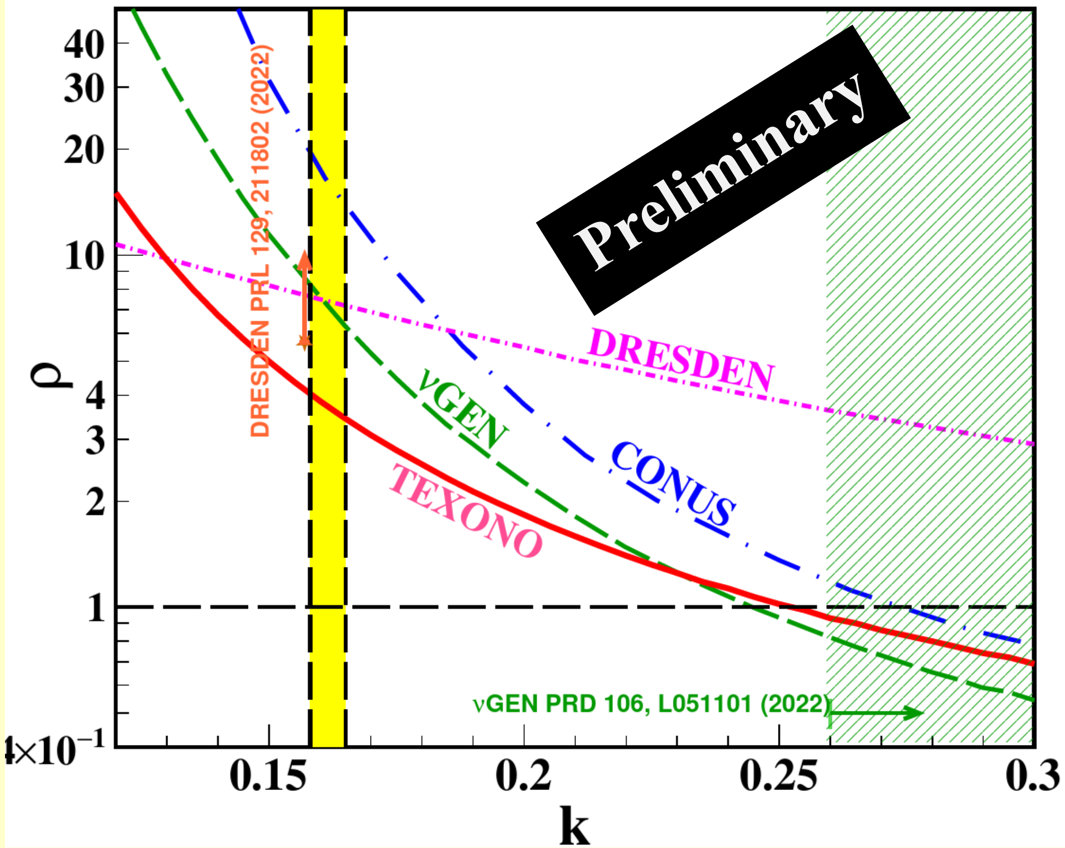


This Data *[TAUP2023]*

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

†AC⁻⊗CR⁻⊗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]

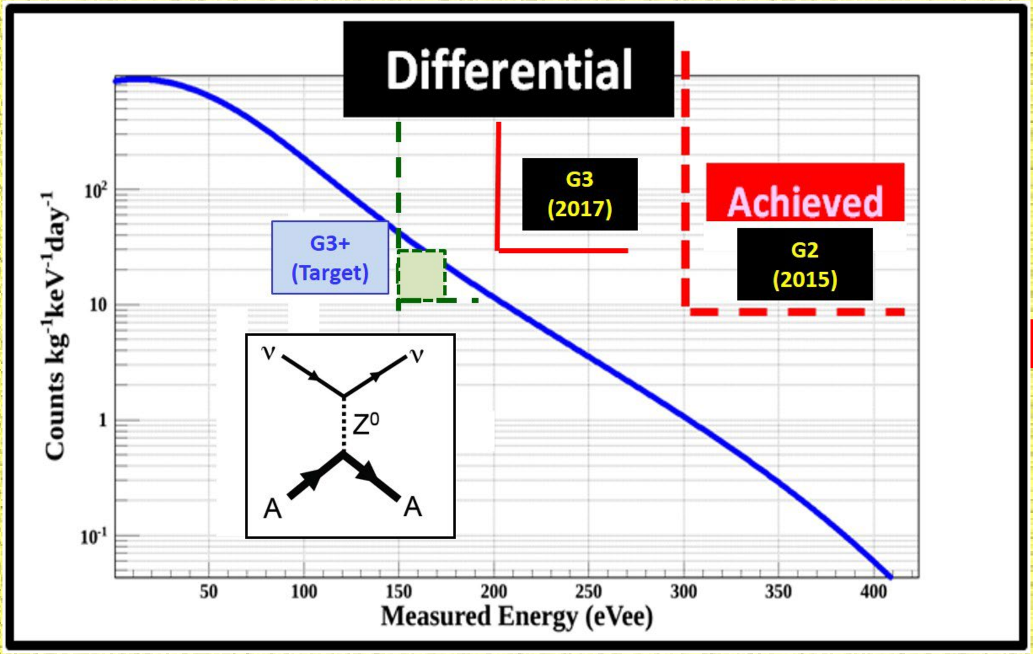
🛠 @90%CL Upper Limit :

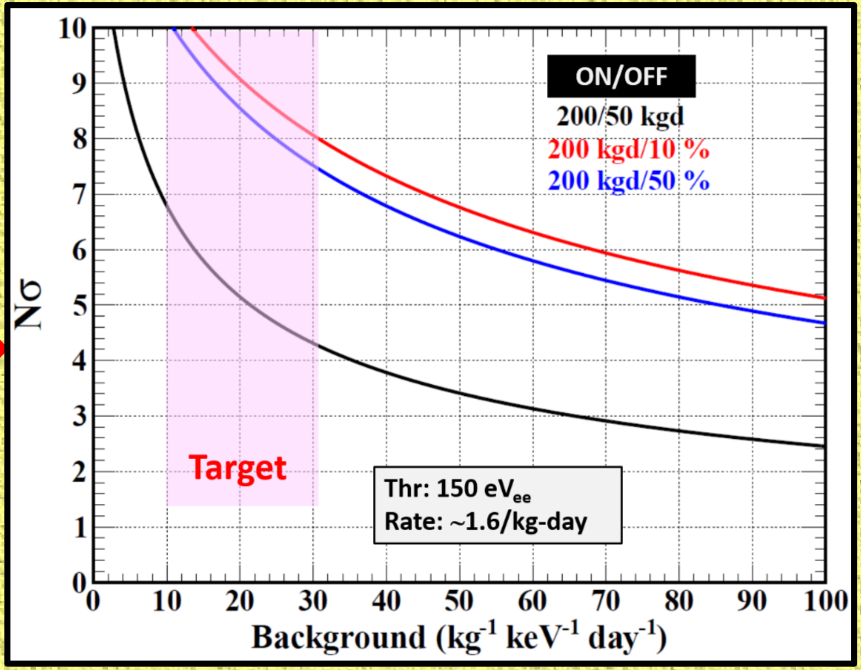
ρ < 4.2 @ Lindhard SM *k*=0.157

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)*]
- **νGEN:**[*ICPPA 2022, A. Lubashevskiy; PRD 106, L051101 (2022)*]
- **CONUS:**[*PRL 126, 041804 (2021); EPJC 81:267 (2021)*]

νA_{el} @ KSNL: Projected Sensitivities





Prospects:

☑ KSNL (2.9GW, 28m):

- G3 (200-eV) Data ON/OFF ~ >500 / >800 kg–days
- ν Decommissioned : 2023, Access till at least end of 2025

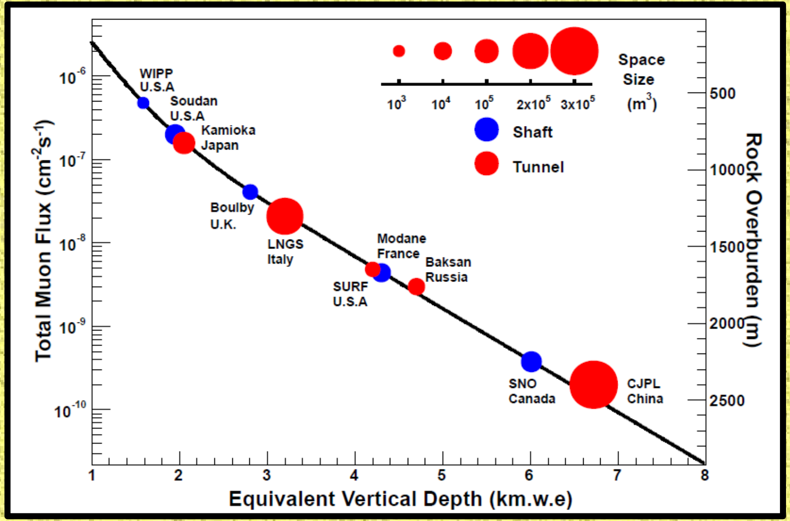
☑ R&D: G4 & PSD at threshold

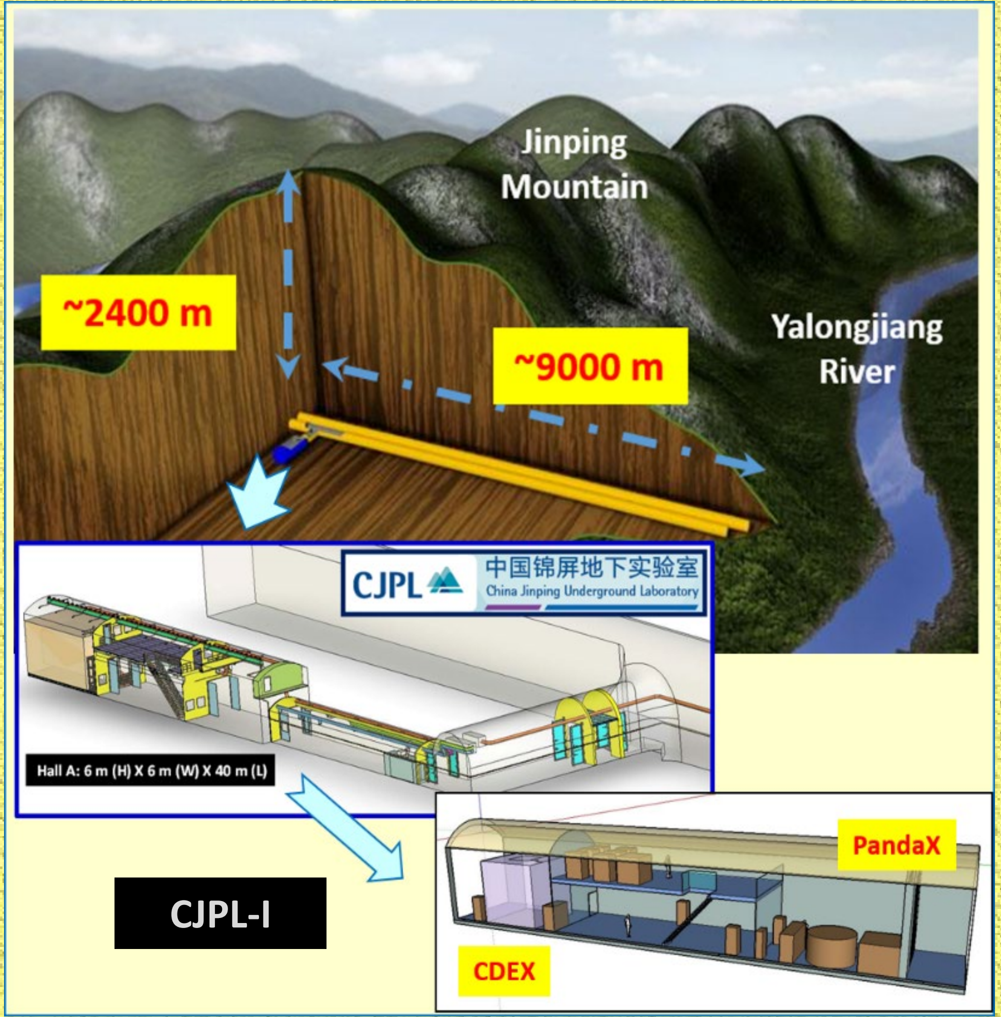
☑ Explore new site now that G4@150 eV secured at KSNL

- CDEX new development:

  Sanmen（三門）Reactor (3.4GW) @ Zhejiang（浙江）
- Exploring Site, possibility at 12-13m !

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

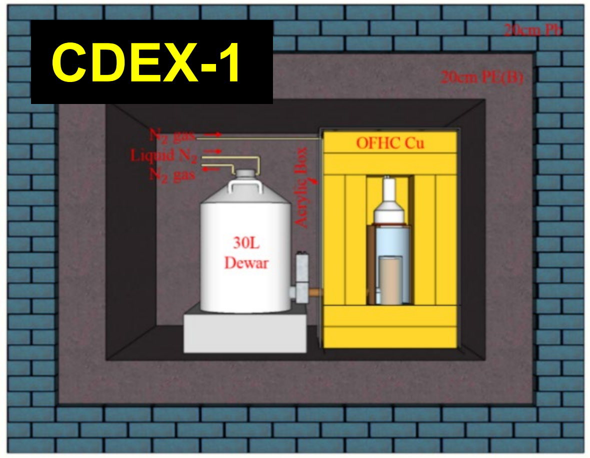


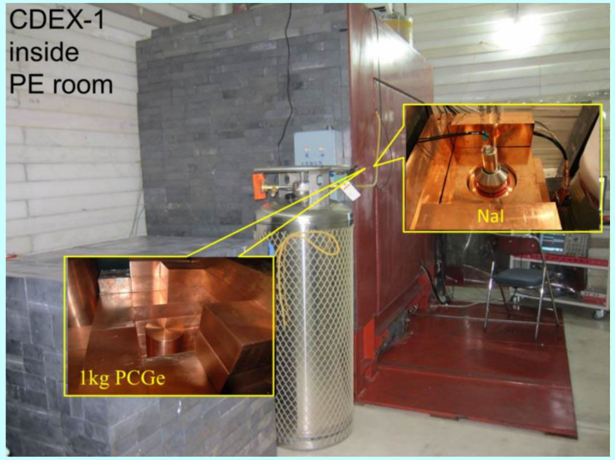


- **Merits:** 2400+ m rock overburden ; drive-in road tunnel access ; superb supporting infrastructures
- **CJPL-I (2010):** *6X6X40 m* cavern
- ***CJPL-II (2018+) : [4X(14X14X130 m) Halls] + Pits***

CDEX

CDEX-1

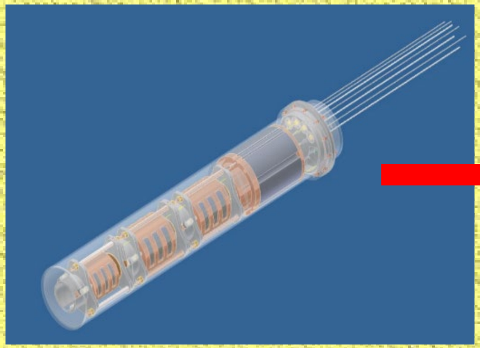


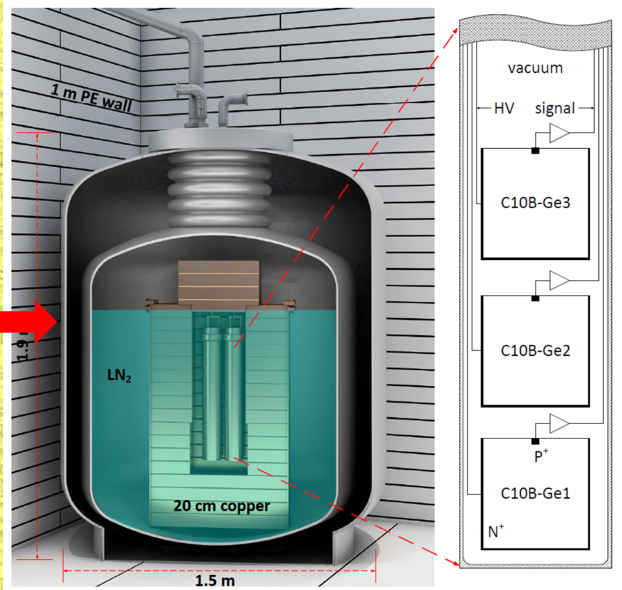


CDEX-I Dark Matter Program

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

CDEX-10



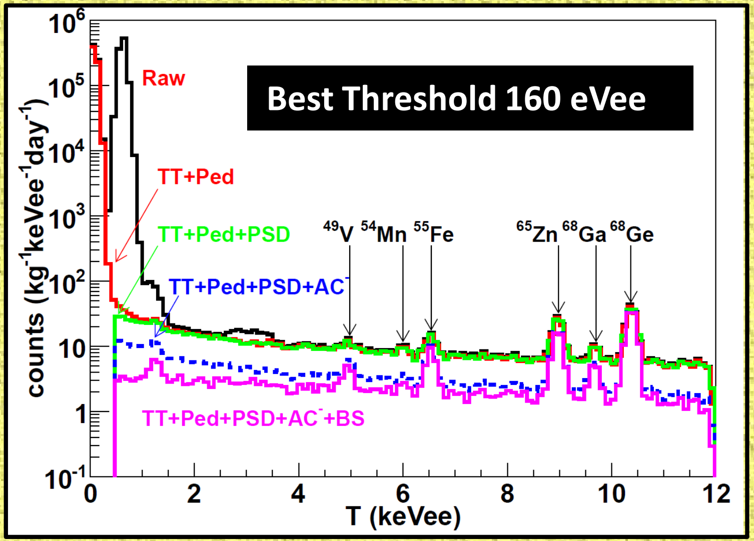


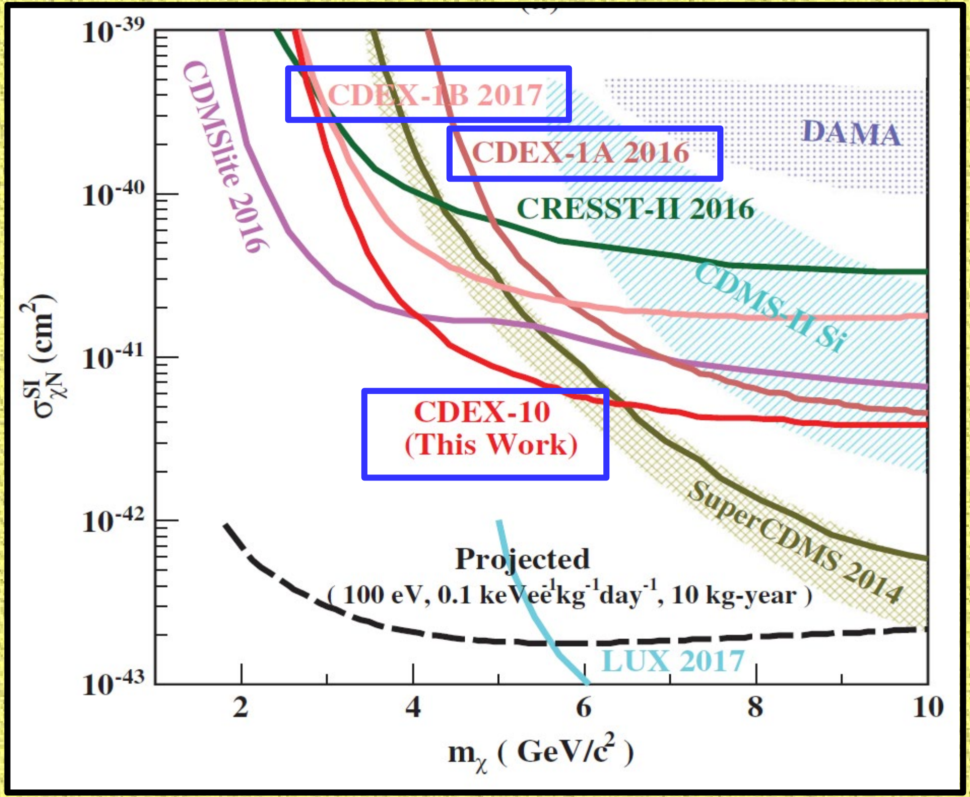
CDEX-10

- ☑ 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* ($0\nu\beta\beta$)

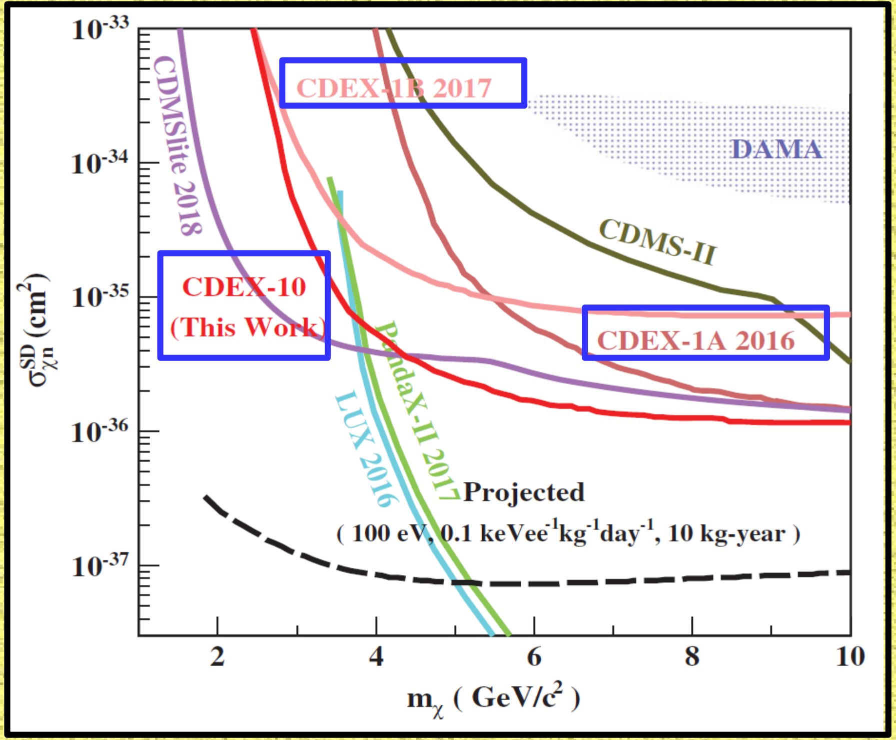
CDEX-1(10) Mainstream Results on $\sigma_{\chi N}$ SI/SD *[PRD14,PRD16,CPC18,PRL18]*

CDEX





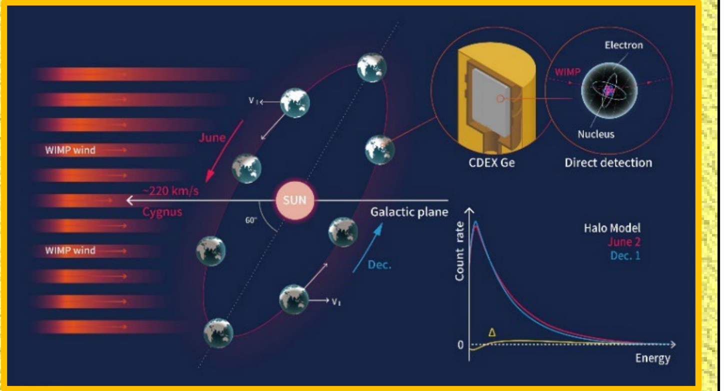
Spin-Independent χN



Spin-Dependent χN

CDEX

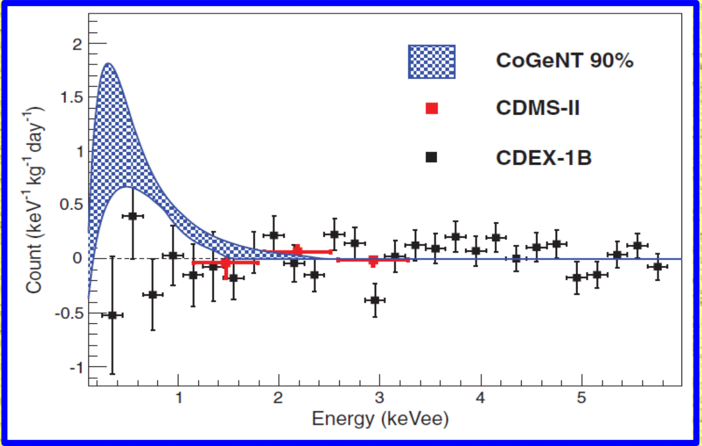
CDEX-1 Annual Modulation Analysis on SI $\sigma_{\chi N}$ SI *[PRL19]*



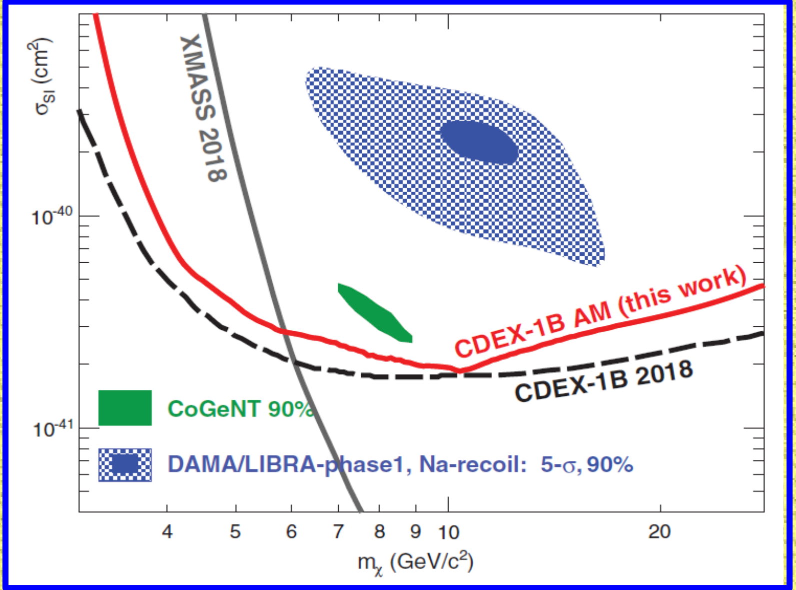
Schematic Diagram Illustrating the Physics Basis of WIMP Annual Modulation

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

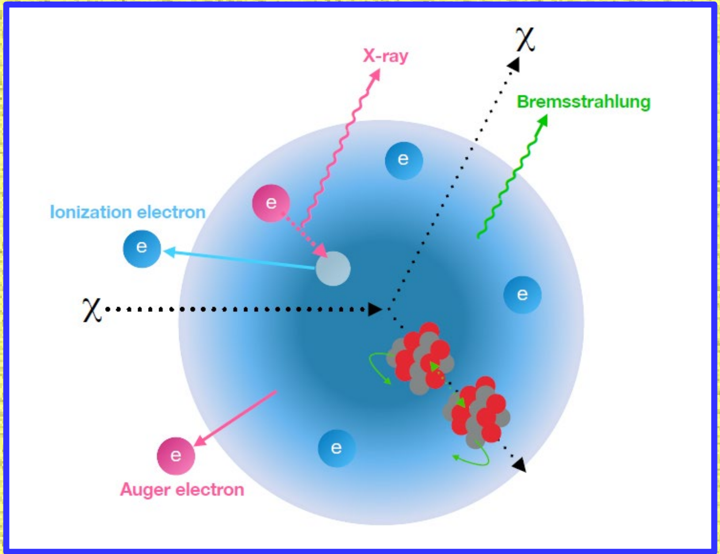


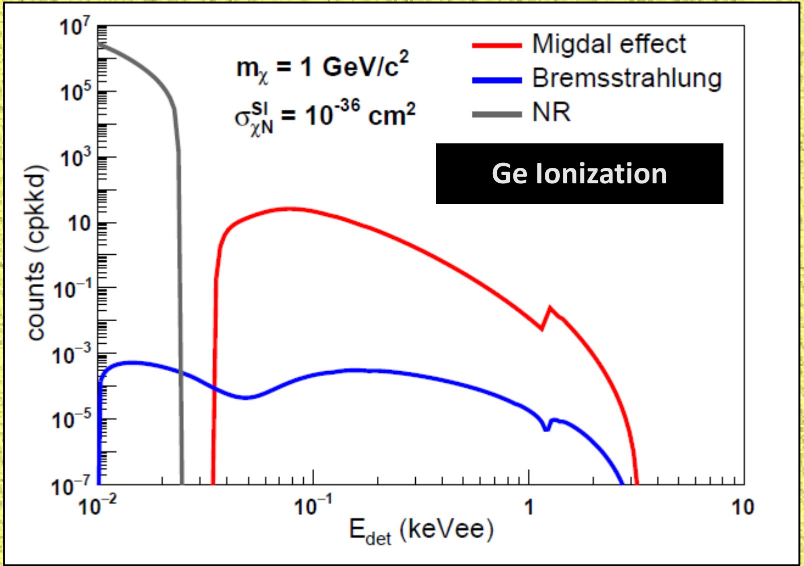
Modulation Data Inconsistent with Expectations from Earlier Positive Signatures from CoGENT Expeirment



Exclusion Plot from AM Analysis

Migdal (& Bremsstrahlung) Effects – Higher Order Inelastic Scattering *[PRL19]*





- ☑ Atomic electrons do not follow instantaneously the motion of recoiling nucleus in **DM+N scattering**
- ☑ Finite time necessary for electrons to "catch up", resulting in possible **ionization** and **excitation** in that atom ⇒ **inelastic processes**
- ☑ Energy loss E_{EM} with electromagnetic signatures, in addition to E_{NR} for nuclear recoil.
- ☑ Small probability but **enhance total energy loss** to above detector threshold for light DM
- ☑ Energy boost esp. significant for E_{ER} with quenched signals.

CDEX "Novel" Analysis Results:

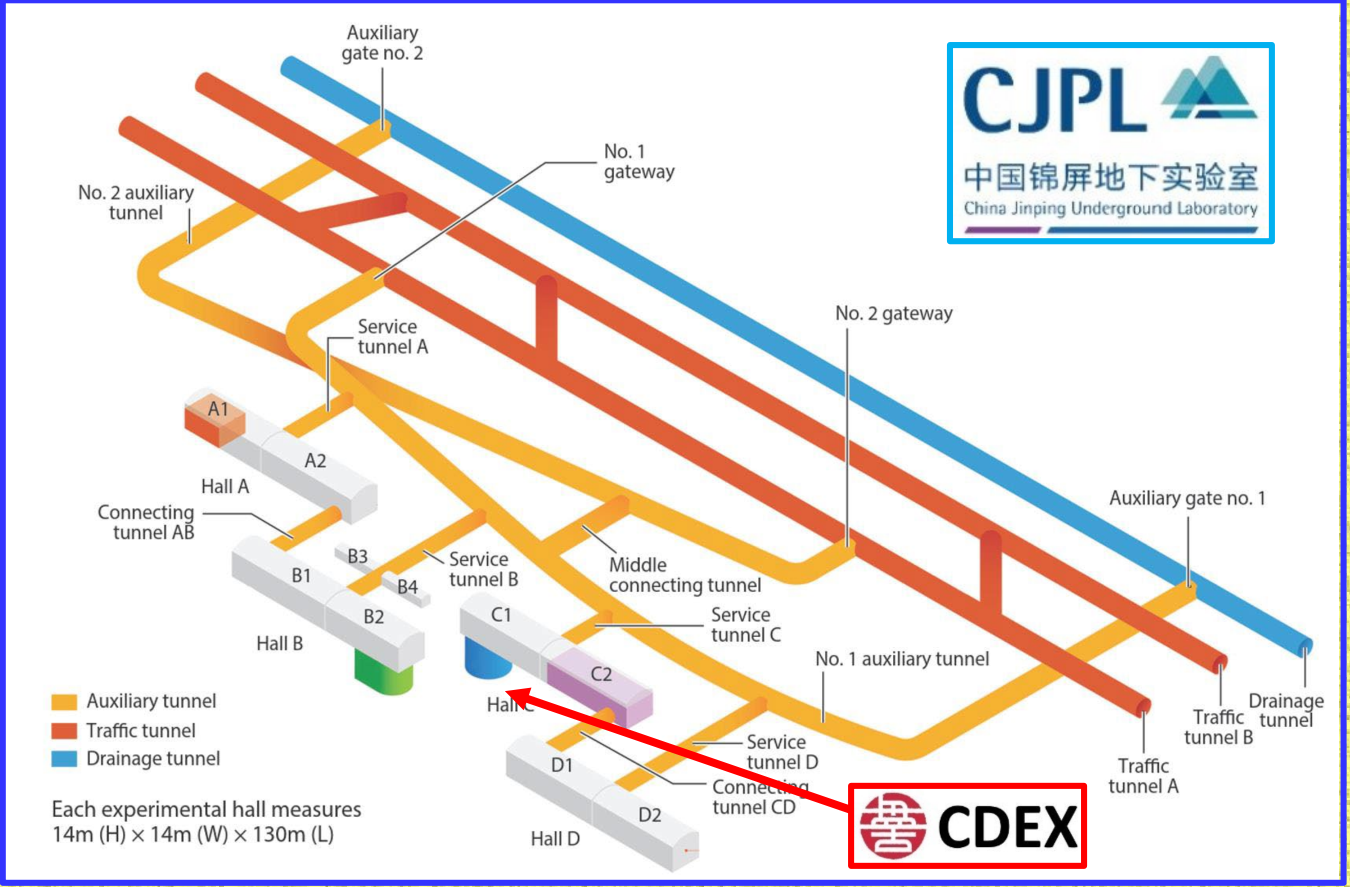
CDEX

- $\sigma_{\chi N}$ SI AM *[PRL19]*
- $\sigma_{\chi N}$ Migdal *[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]*
- BDM by Sun *[PRL24]*
- …………

Team (+knowhow, connections) are Matured Enough to "Compete" on Novel Theoretical Ideas …. !!

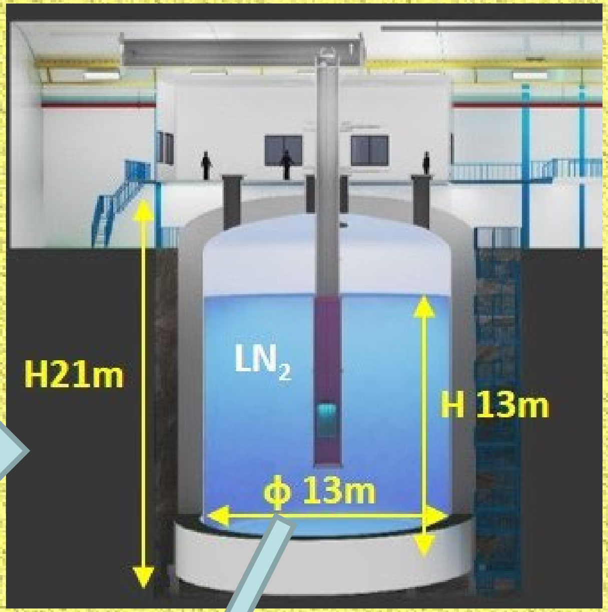
CJPL-II

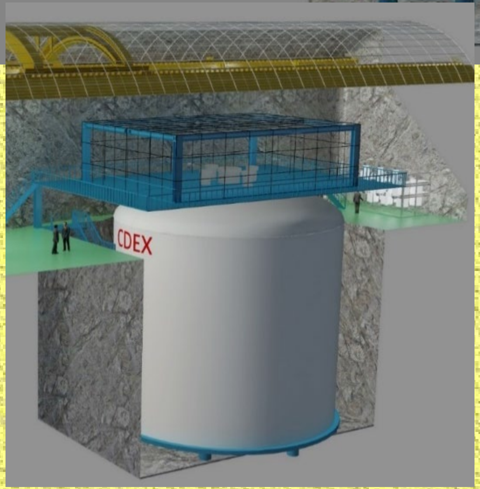
- ☑ ~500 m west to CJPL-I
- ☑ Four 14m*14m*130m Main Halls ; Total space: ~300K m³
- ☑ Two Pits: (1) *18(ϕ)X18(H)m* ; (2) *27(L)X16(w)X14(D)m*
- ☑ Commissioned for users Dec 2023

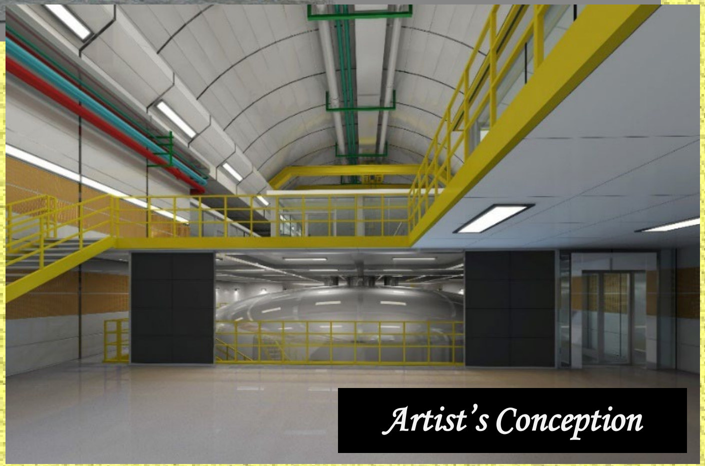


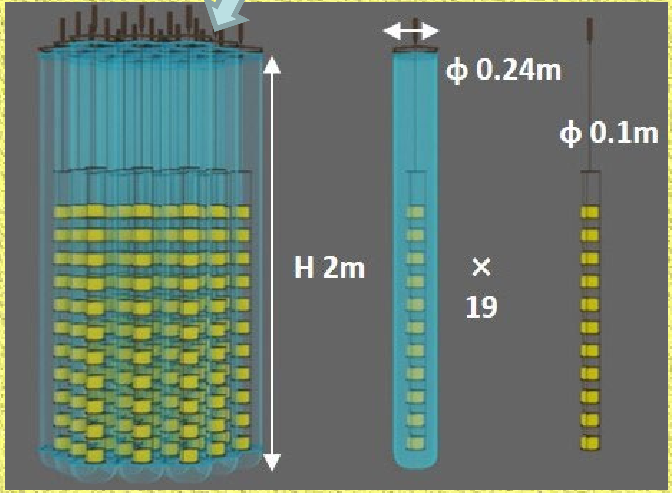
Future Prospects @ CJPL-II : Ge1T Project

- **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)

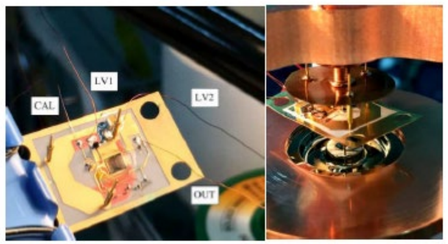




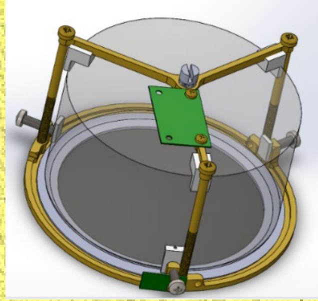


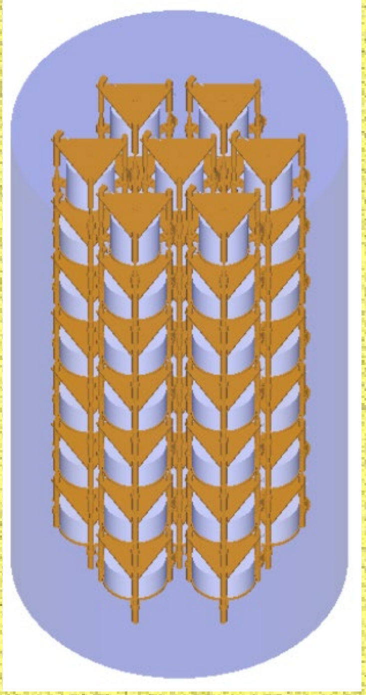


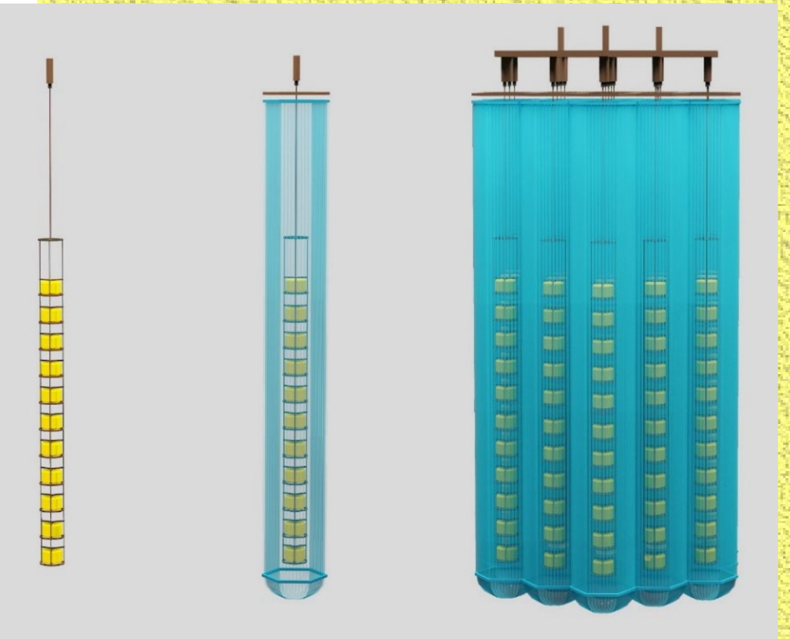
Mastering Key Technologies towards Ge-1T



ASIC前放







- ☑ **Enriched Ge Production** *(world leading now !)*
- ☑ **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"**

Summary & Outlook

- Neutrinos are strange – & "intellectually" rich -- objects

  history of ν physics full of surprises !

- Saga on the "Discovery of massive ν's & finite mixings", still continuing to complete PMNS matrix
  - *Taiwan's contributions via participation in DayaBay & JUNO*
- The Taiwan-based TEXONO program has contributed to LE-ν studies, opened sub-keV detection window, catalyzed realization of CJPL and CDEX-DM, with eye on NG-0νββ.
- Future: Explore Roles of Neutrinos in Dark Matter Problem, Astrophysics and Cosmology …..
  - *Young new members are bringing in fresh air and new skills/directions*