From TEXONO to CDEX and Beyond – Connecting the Dots

- TEXONO-ν @ KSNL
- TEXONO-DM(pre-CDEX) → CDEX@CJPL, *via Y2L* ♥♥♥
- CDEX-DM @ CJPL
- Beyond: CDEX-ν @ CJPL
- Outlook & Prospects

⚐ *Predecessor of Yemilab IS an Important Connection to the Dots . . .*

Henry T. Wong / 王子敬
Academia Sinica / 中央研究院
October 2022

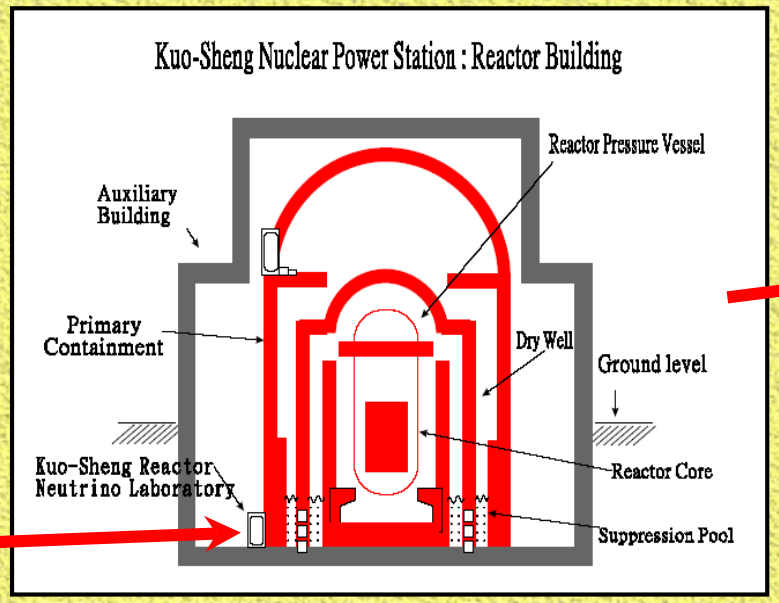
@ The 1st Yemilab Workshop
15–18 Oct 2022

- Taiwan
- India
- Turkey

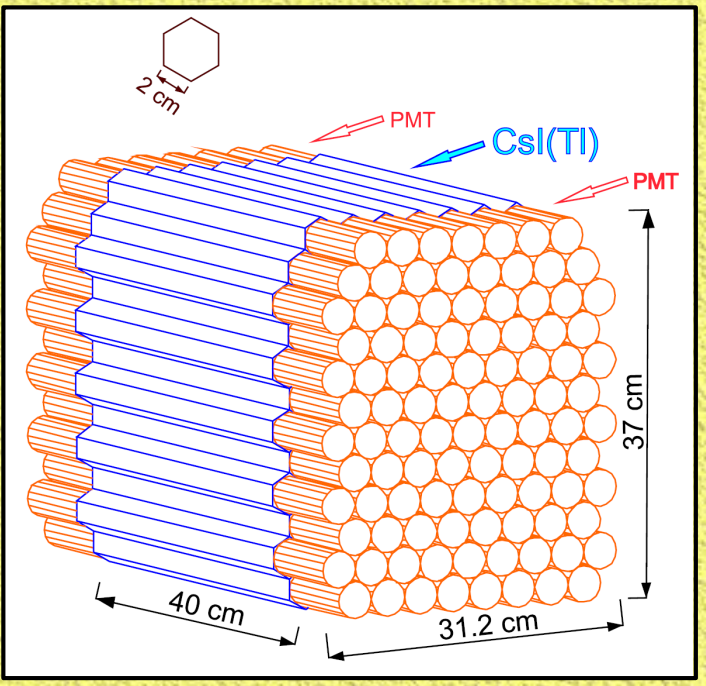
TEXONO Program *[since 1997]* :

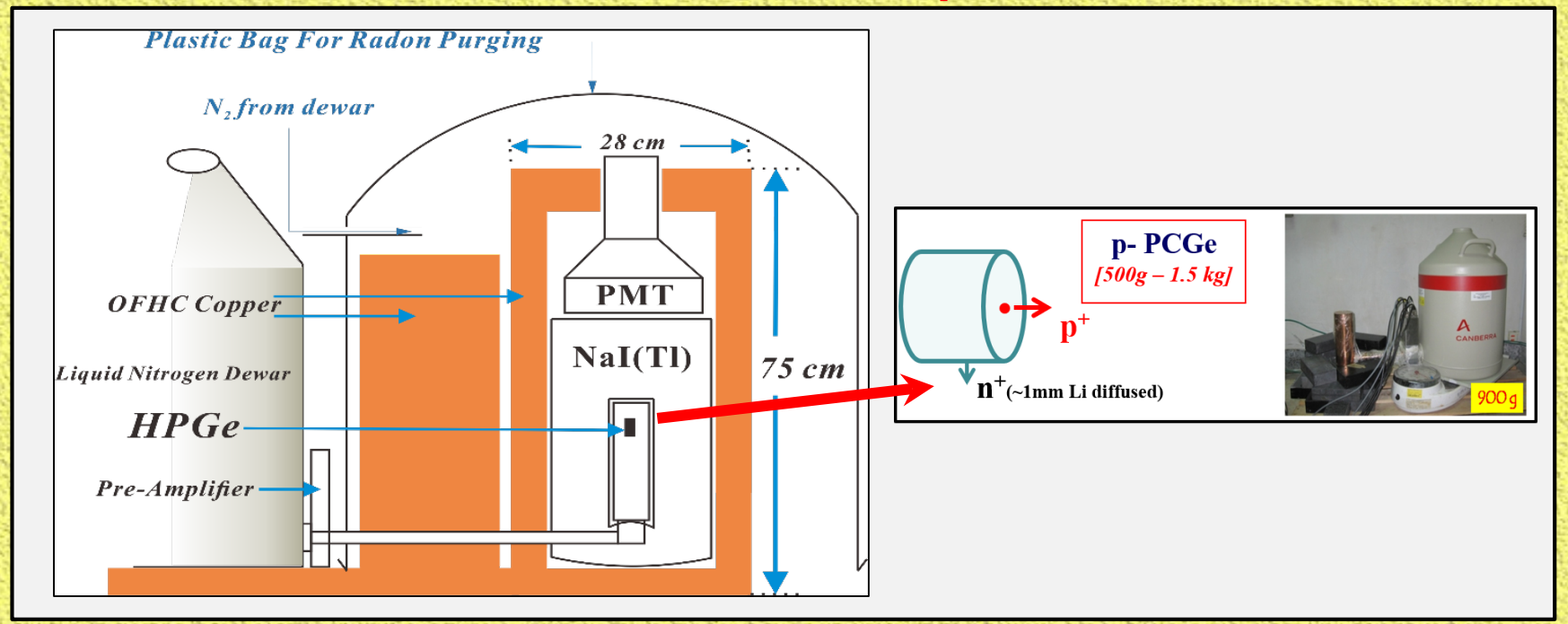
- Low Energy Neutrino (SM+EM) physics at Kuo-Sheng Neutrino Laboratory (KSNL), 28 m from 2.9 GW_{th} reactor core
- Founding partner of CDEX Dark Matter Experiment *[since 2008]*
- Theory Program *[since 2010]*


TEXONO

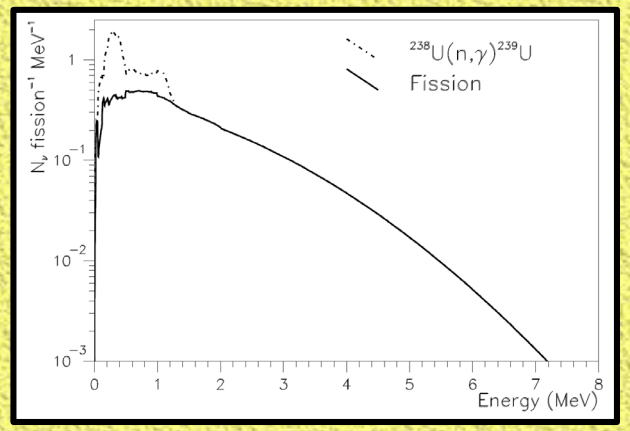

Kuo-Sheng Nuclear Power Station : Reactor Building
Reactor Pressure Vessel
Auxiliary Building
Primary Containment
Dry Well
Ground level
Reactor Core
Kuo-Sheng Reactor Neutrino Laboratory
Suppression Pool


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
N_2 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

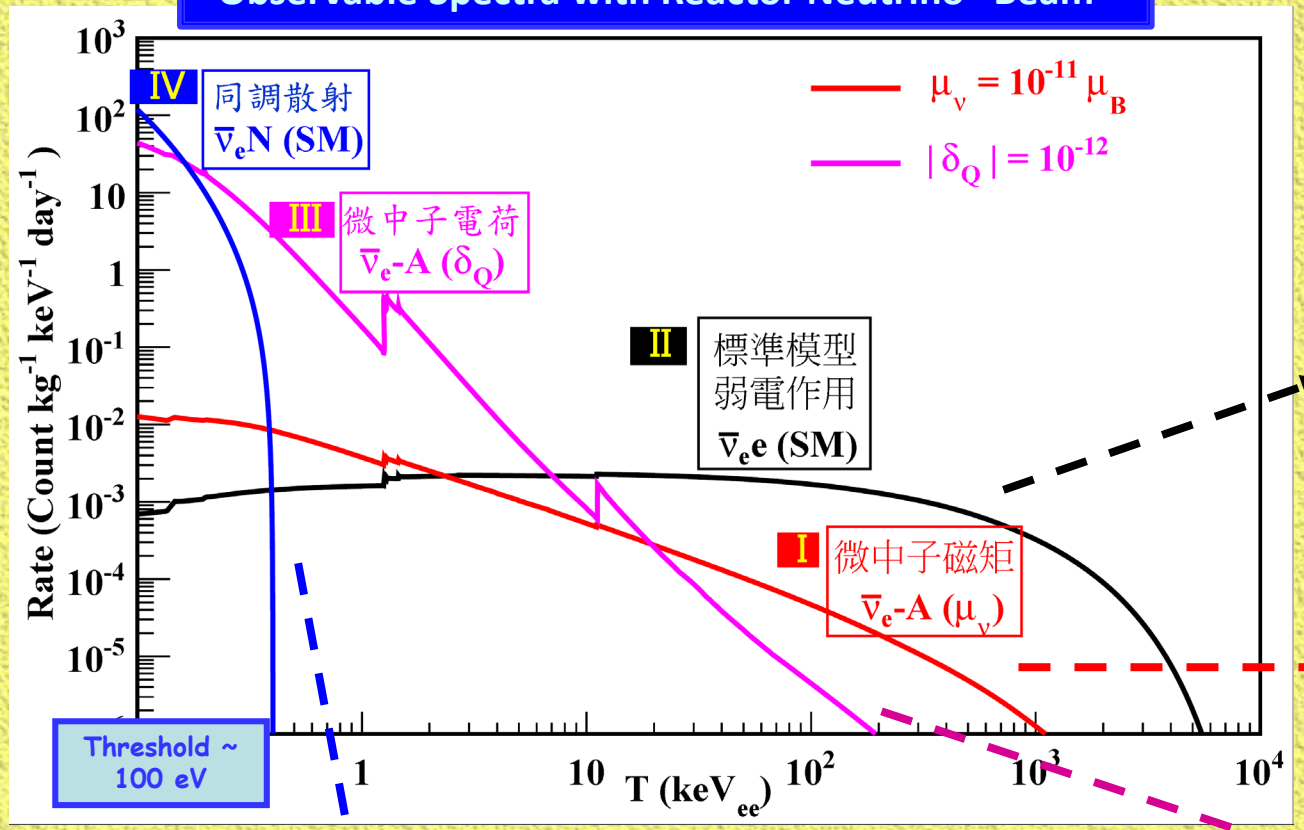
Neutrino Properties & Interactions at Reactor



Reactor Neutrino Spectrum

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

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]*

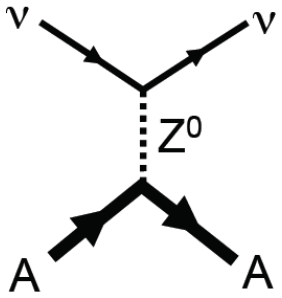
- Pioneered sub-keV O(kg) ULEGe / PCGe [MPLA08, NIMA16]
  - Light Dark Matter Searches @ KSNL *[PRD09,PRL13,AP14,PRD19]*
  - CDEX DM Program@CJPL *[PRD13……]*
  - Theory Program *[PLB14……]*

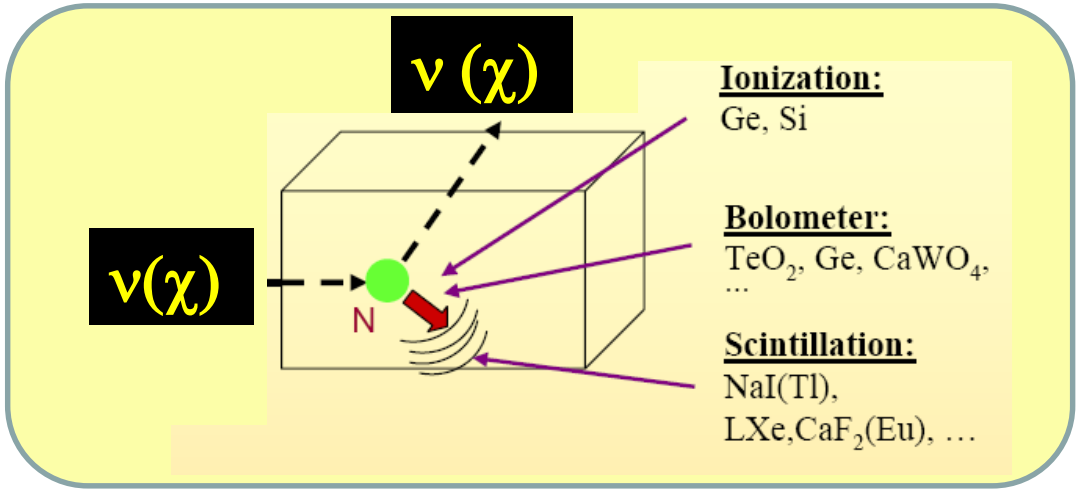
sub-keV PCGe

Neutrino-Nucleus Coherent Scattering :

Standard Model allowed and predicted processes :

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

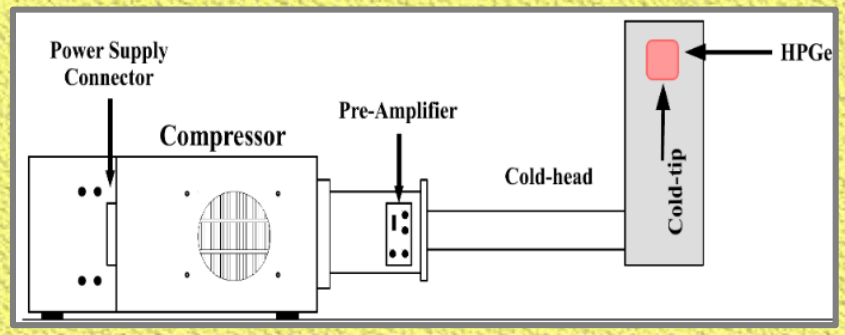




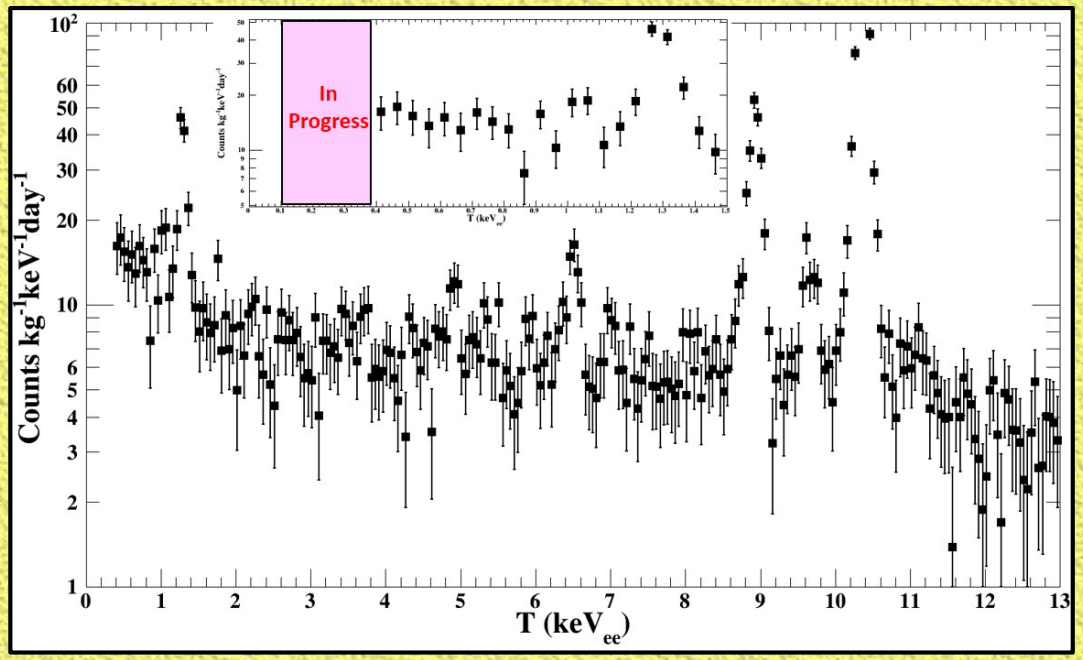
- Neutral current process (same for all ν-flavor)
- $\sigma \propto N^2$ @ $E_\nu < 50$ MeV
  - ⇒ *"Complete Coherency" for Reactor Neutrinos*
  - *[probe "sees" the whole nucleus]*
- sensitive probe for BSM ; interest in reactor monitoring
- important process in stellar collapse & supernova explosion
- 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

Electro-cooled PCGe

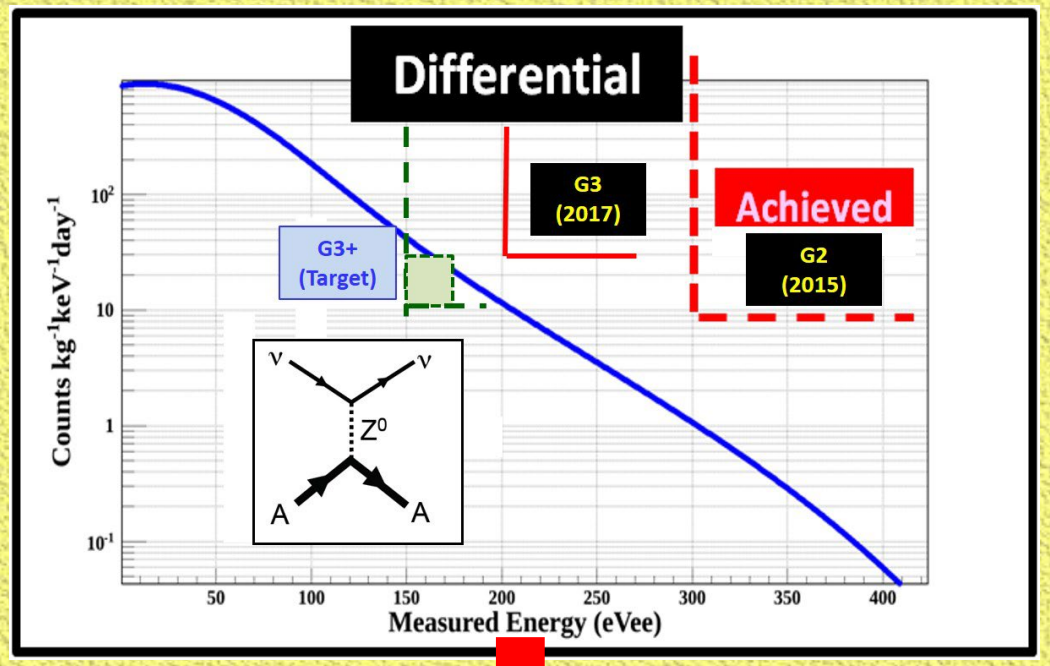
PC-Ge	Generation	Detector Mass (g)	Pulser FWHM (eV_{ee})	Threshold (eV_{ee})
Liquid Nitrogen Cryostat	G1	500	130	500
	G2	500, 900	100	300
Electro-cooled	G3	500, 1430	70	200
	G4 (NG)	900	50 (target)	150 (target)



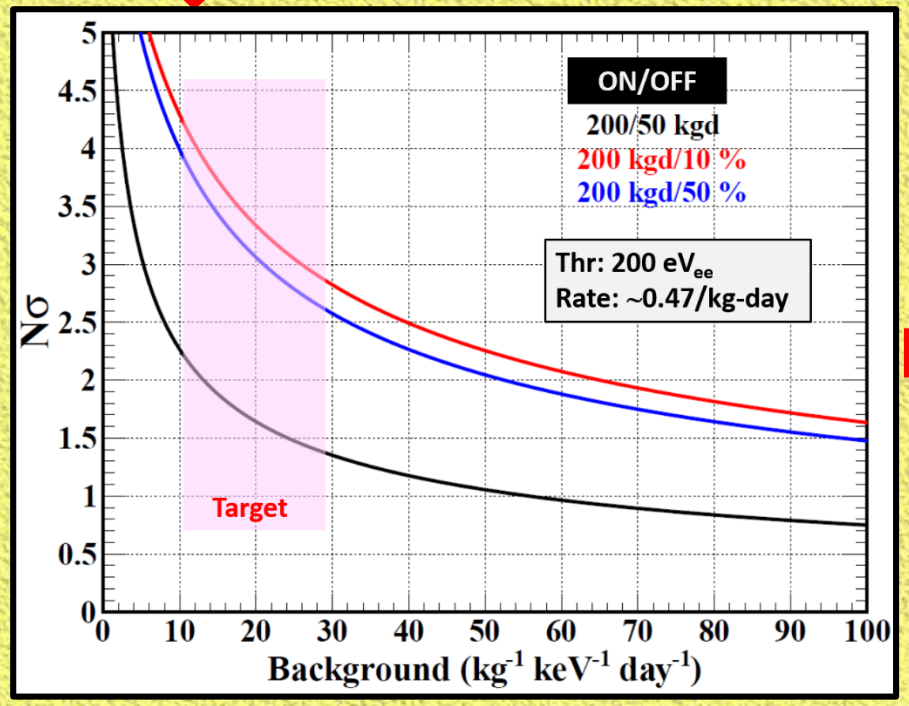
- ☑ Novel Technology with Negative Feedback Synchronized Pumping
- ☑ Typical G3 Spectrum ⇨
  - ➢ 200 eV_{ee} threshold
  - ➢ + Anti-Compton & Cosmic-Ray & Surface Vetos
- ☑ Near Threshold Data Analysis In Progress
- ☑ G4(NG) expected in early 2023

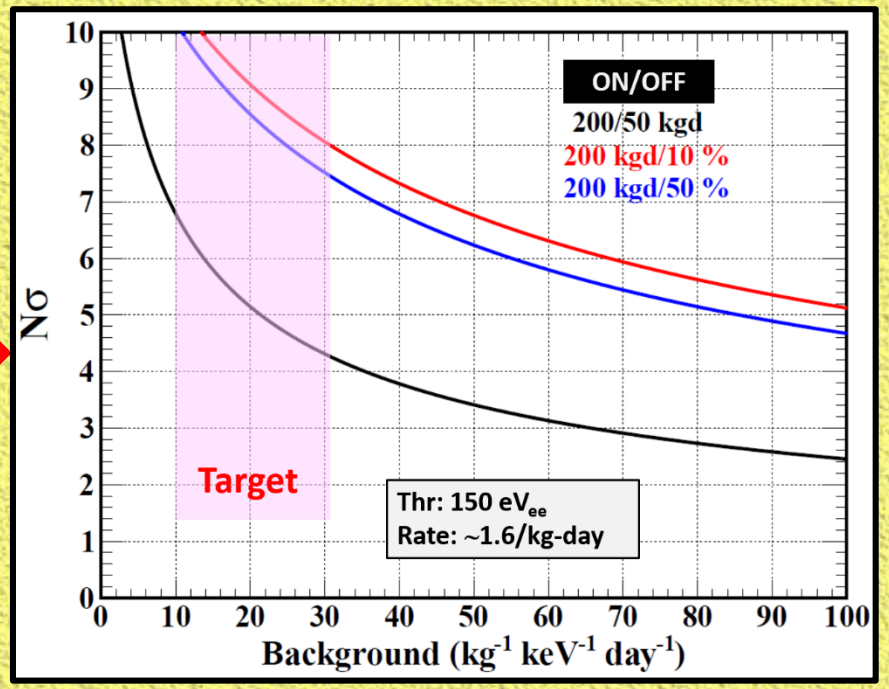


νA_{el} at KSNL : Projected Sensitivities



- ☑ G3 (200-eV) Data Taking
  ON/OFF ~ >600 / >400 kg–days
- ☑ Power Plant Decommissioned : 2023 ;
  Access till end of 2025.
- ☑ May look for new site when G4
  (threshold 150 eV) secured.





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:
  - milli-charged ν interactions: $\nu\ (\delta_Q) + A$ *[PRD 14]*
  - DM-$_n$ (NR) transitive-μ_ν interactions: $\nu_{DM} + A \rightarrow \nu_{SM} + A^+ + e^-$ *[PRD15]*
  - DM-ALP (NR) Inverse Primikoff scattering: $a_{DM} + A \rightarrow \gamma + A^+ + e^-$ *[arXiv:2206.07878]*
- Identified universal parameter to quantify QM-coherency in νN_{el} *[PRD16,PRD21]*

TEXONO-DM (pre-CDEX) & Yangyang Laboratory

Talk by Sunkee Kim 2006:

History

- 2000.12.16 Mini-workshop on WIMP search with crystals, Seoul (Henry Wong, Jin Li)
- 2001.3.21 Beijing Mini-workshop, Beijing
- 2001.9.13 Cold Dark Matter Mini-workshop, Taipei
- 2003.9.23 TEXONO-KIMS joint meeting, Beijing
- 2003.9.28 Vasily Kornoukhov visited KIMS
- 2004.1.29 TEXONO-KIMS Joint workshop, Yongpyung
- 2004.4.21 KIMS visited Moscow
- 2004.7.5 ITEP group visited KIMS
- 2004.10.27 Chinese Funding agency visited KIMS
- 2005.10.9 Fedor Danevich visited KIMS
- 2005.12.18 Takayuki Matsui visited KIMS
- 2006.2.6 Workshop on the underground experiments at Yangyang

- Good news in 2005
  - Tsinghua Univ. group got funding support ***[approved 2006]***
  - ITEP group got ISTC project funded

- **More Joint Meetings:**
  - 2006/10 Beijing; 2007/11 Seoul; 2008/12 Haikou; 2010/11 Chengdu; 2011/9 Yangyang

2000: Low background CsI(Tl) applications and techniques brought the teams together. TEXONO-DM joined KIMS and got into DM.

2001: Agenda started 9/12 ! All were overwhelmed by events 12 hours before in New York.

2004: TEXONO-DM proposed to bring a 5g ULEGe to Y2L as a new setup. KIMS readily agreed. Start of *"Light Dark Matter Searches"*.

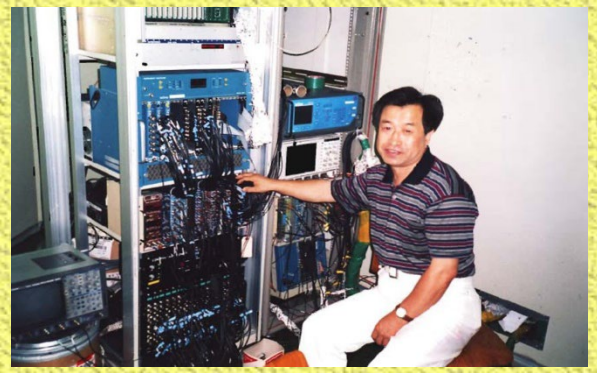
Set the Stage of "Beyond".

First investment in Underground Basic Science Experiments by China.

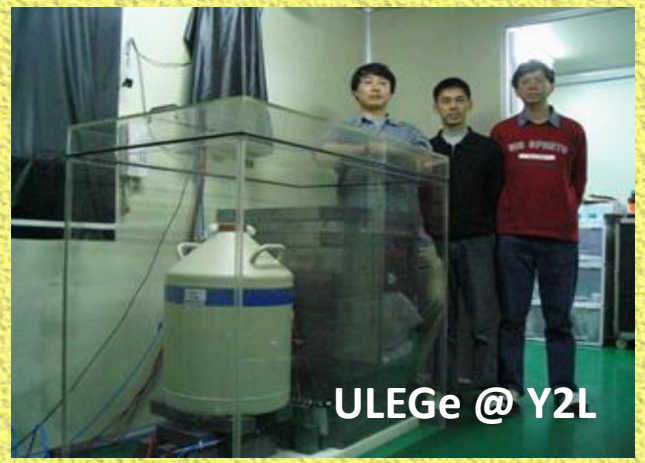
2008 August: Possibility of Jinping Tunnel for Underground Laboratory identified (from TV ….)

2000: First Meeting in Seoul. Visited *Cheong Pyung Lab (350m Underground)*

2001 September: Visit KSNL. Last Lab Tour with easy access.



Jin LI @ Y2L
Leadership in all Activities.



That is:

Many of the key researchers, investors and stake-holders of CJPL and CDEX got their first experience on the diverse aspects of "Underground Experiments" at Y2L.

Joint Meeting @ Chengdu , Nov 2010.

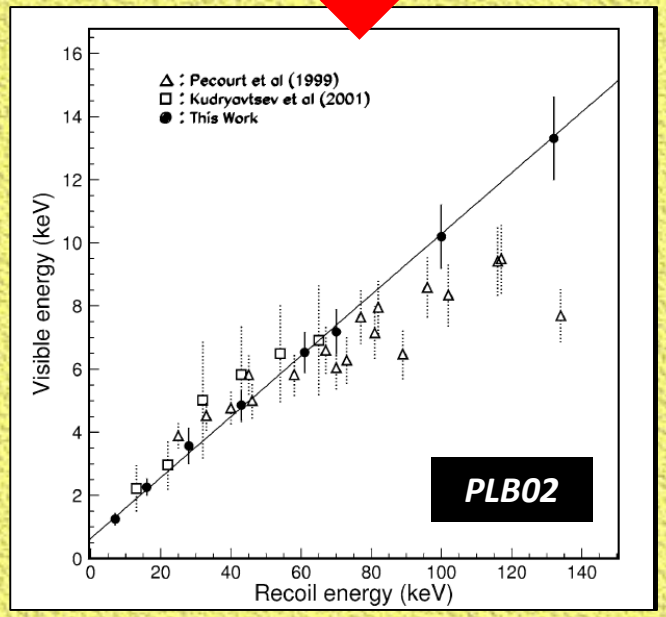
Then .. Overnight Train to Xichang for CJPL site visit.

CJPL Inauguration

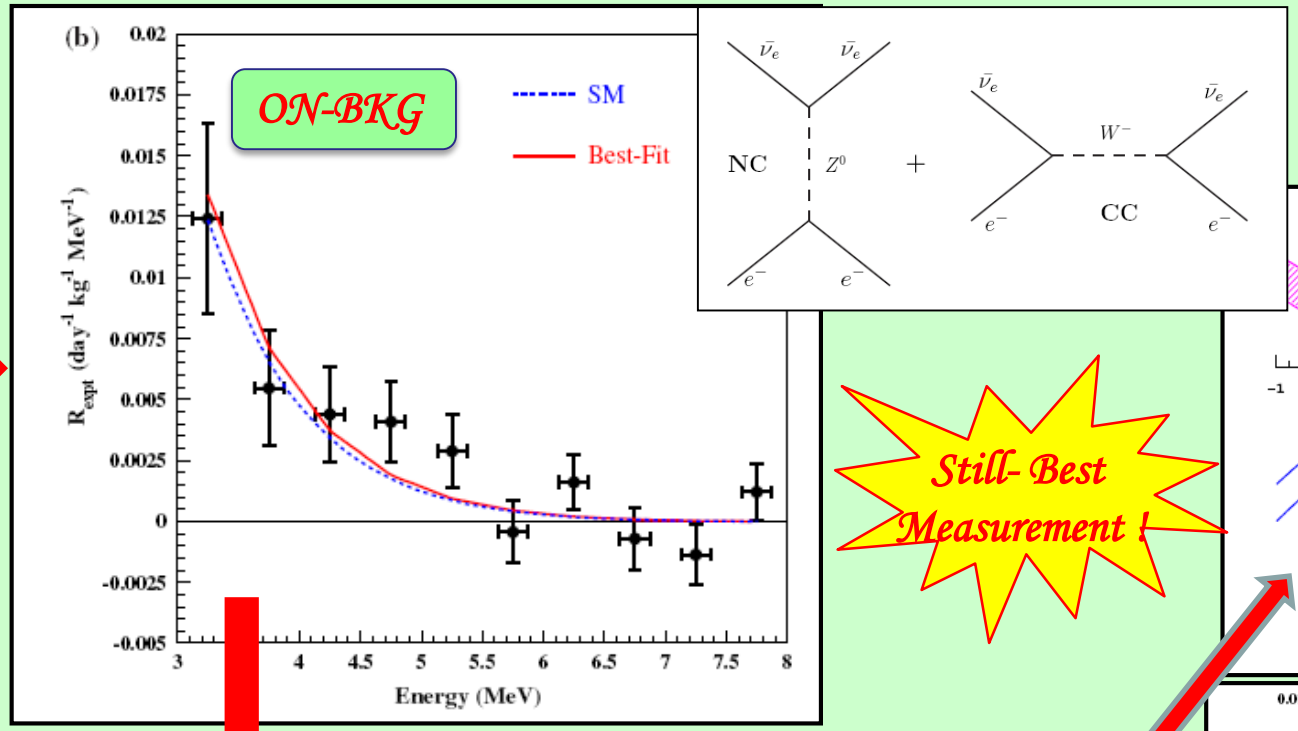
December 10, 2010

Another Interesting Twist:

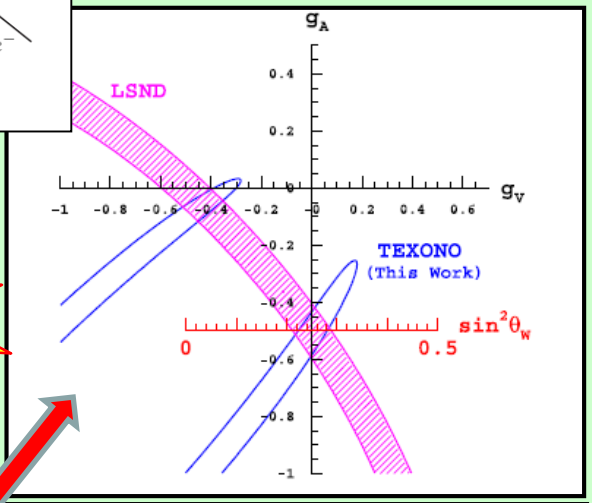
- CsI(Tl) connected the two groups together in 2000 & brought TEXONO to Y2L
- TEXONO-CsI Science:
  - ν: $\bar{\nu}_e$-e scattering cross-section
  - DM: QF measurements



$\bar{\nu}_e$-e: Probe Electroweak Physics *[PRD10]*



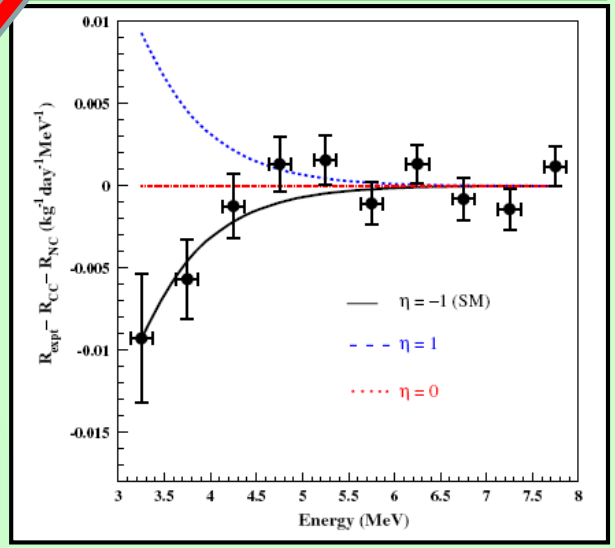
Still- Best Measurement !



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

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

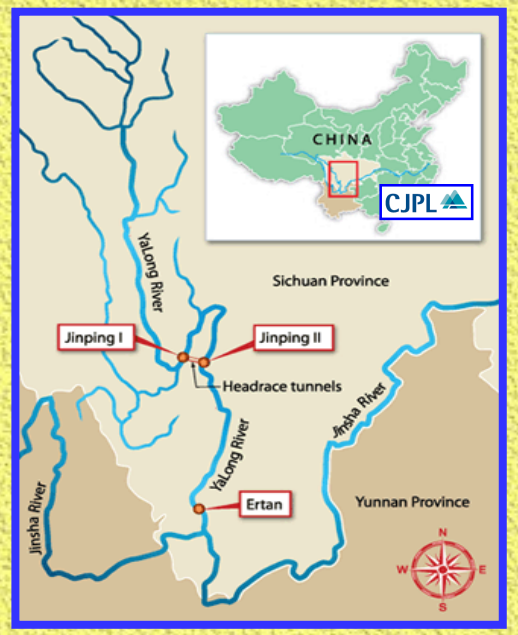
Verify SM Destructive Interference

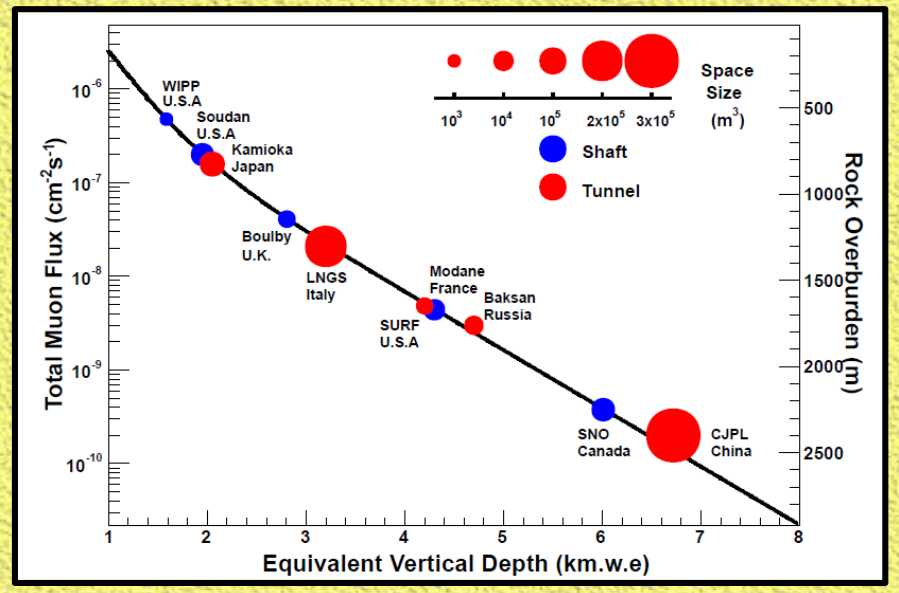


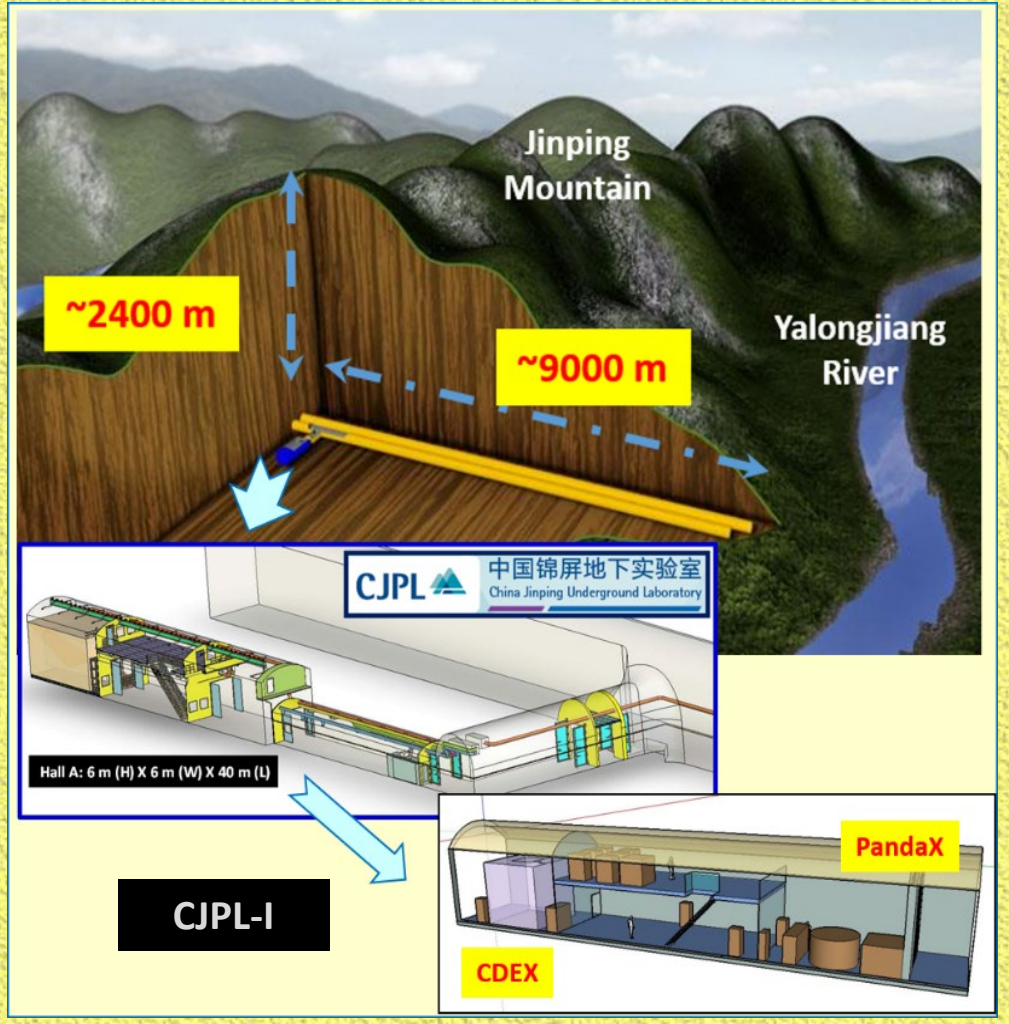
⊕ Constraints on Beyond SM Effects *[PRD10;PRD12;PRD15]*

↳ **… further advances on $\bar{\nu}_e$-e will be pursued by IsoDAR @ Yemilab, as its flagship program.** ***[next two talks]***

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

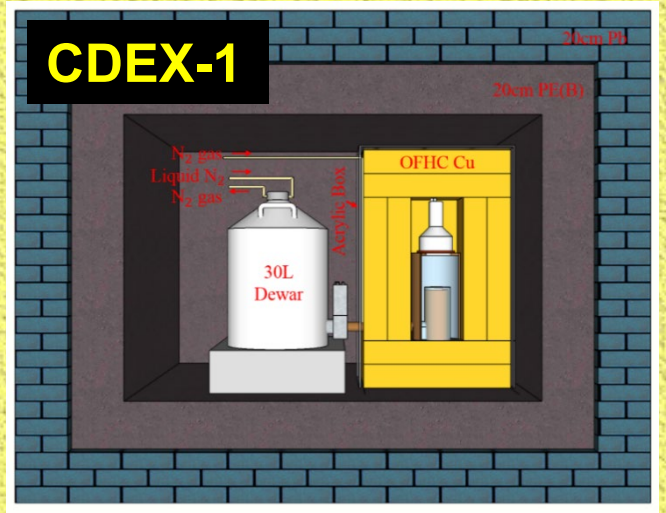


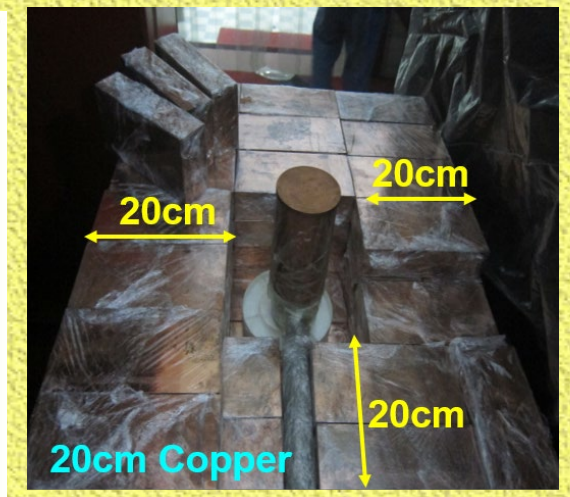


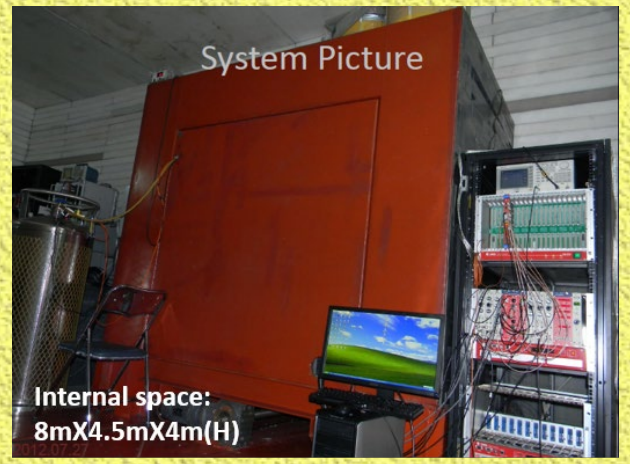


- **Merits:** 2400+ m rock overburden ; drive-in road tunnel access ; superb supporting infrastructures
- **CJPL-I (2010):** *6X6X40 m* cavern
- ***CJPL-II (2018+) : [4X(14X14X130 m) Halls] + Pits***
- **CDEX Dark Matter Program**
  - ☑ *Based on sub-keV Ge detectors*
  - ☑ *May well evolve back into neutrino physics*

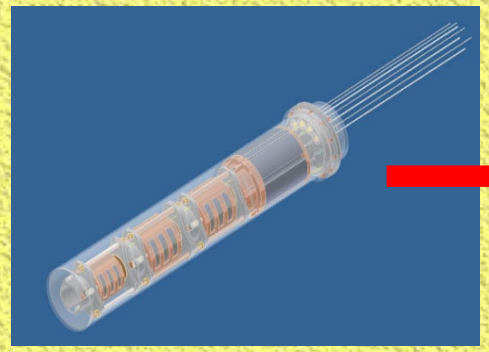
CDEX

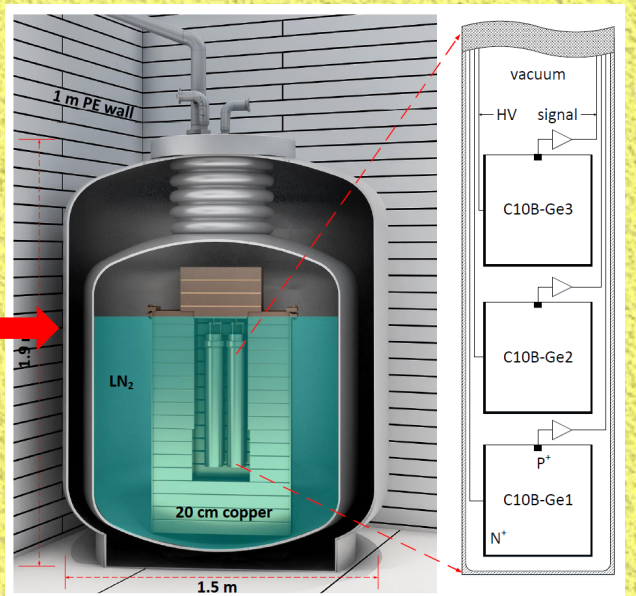






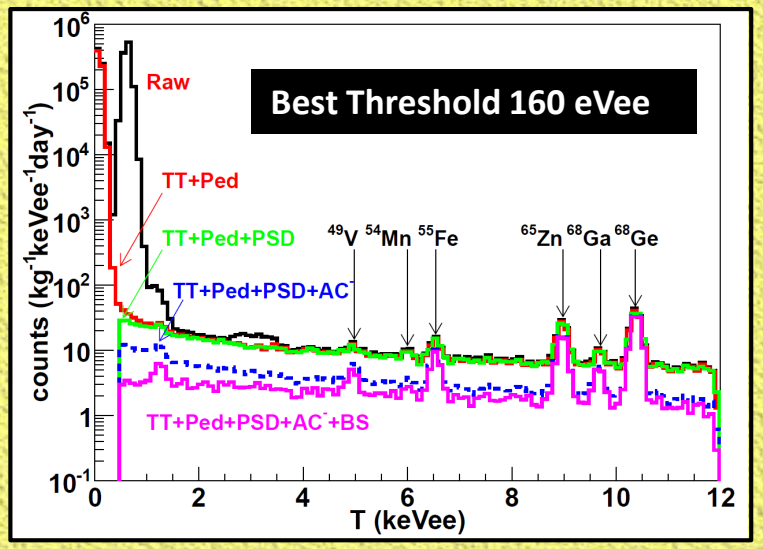
CDEX-10

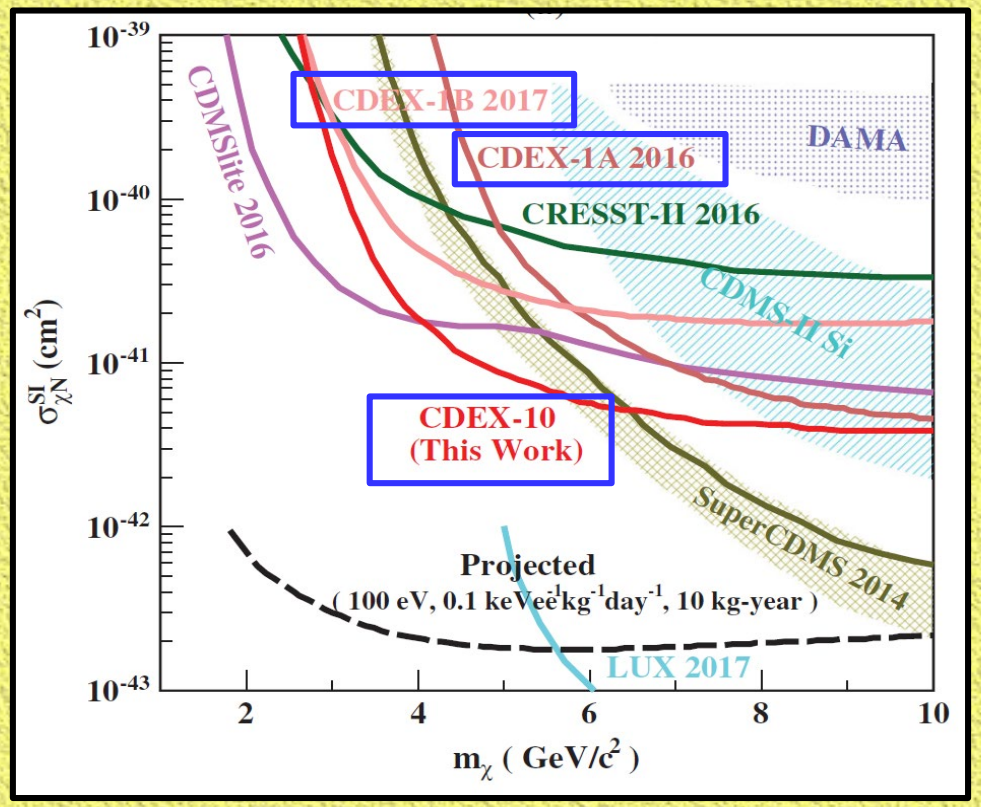




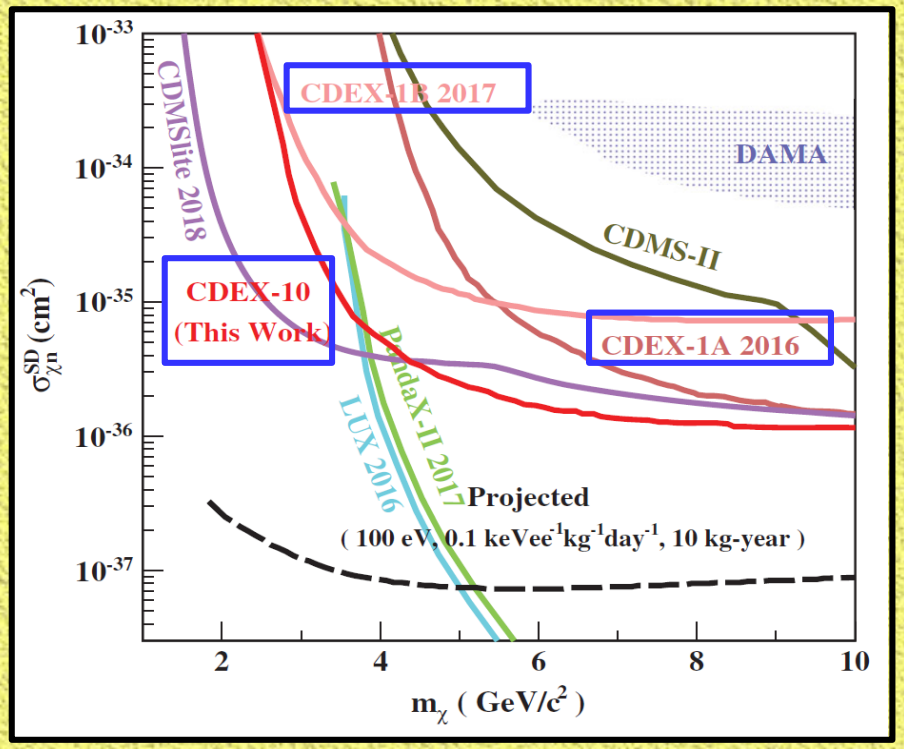
- ☑ As Ge-Array -- important stage towards large-scale Ge experiment
- ☑ Novel -- Directly immersed into liquid nitrogen for cooling;

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



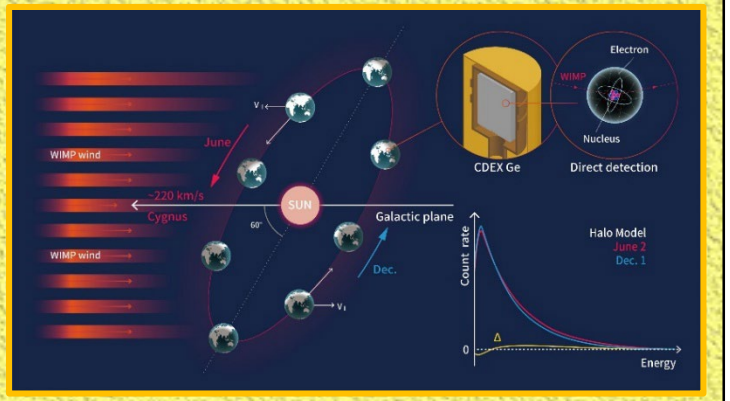


Spin-Independent χN



Spin-Dependent χN

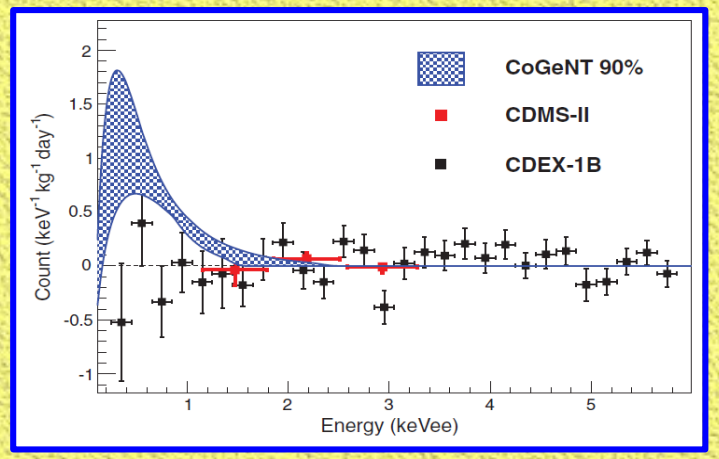
CDEX-1 Annual Modulation Analysis on SI $\sigma_{\chi N}$ SI *[PRL19]*



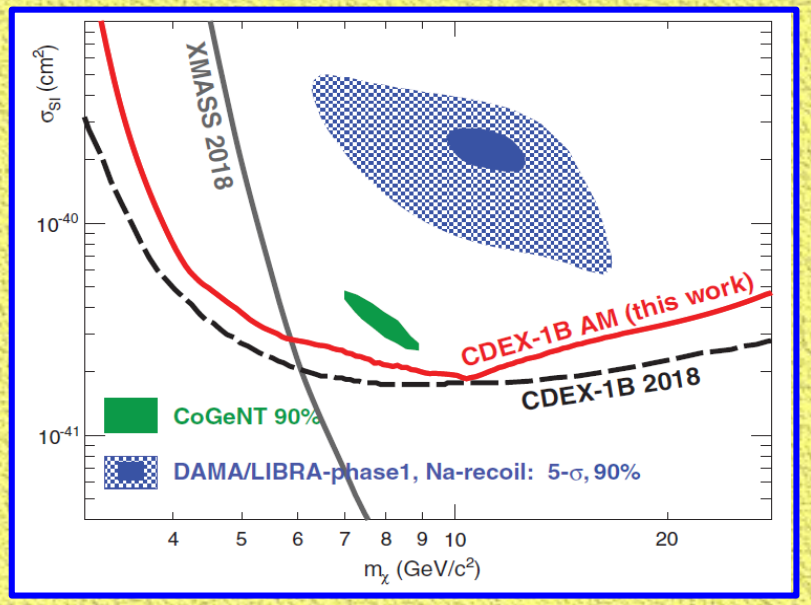
Schematic Diagram Illustrating the Physics Basis of WIMP Annual Modulation

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 Exotic BSM 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 *[arXiv:2206]*

CJPL-Phase II

- ☑ ~500m west to CJPL-1
- ☑ Construction started 2014
- ☑ Rock Excavation completed May 2016
- ☑ JUNA, PandaX … running

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

PHYSICS

Science V346, Nov 2014

China supersizes its underground physics lab

Planned expansion could pave way for "ultimate dark matter experiment"

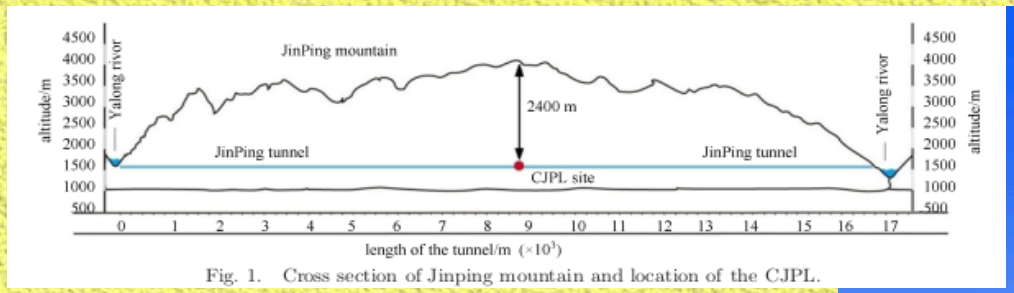
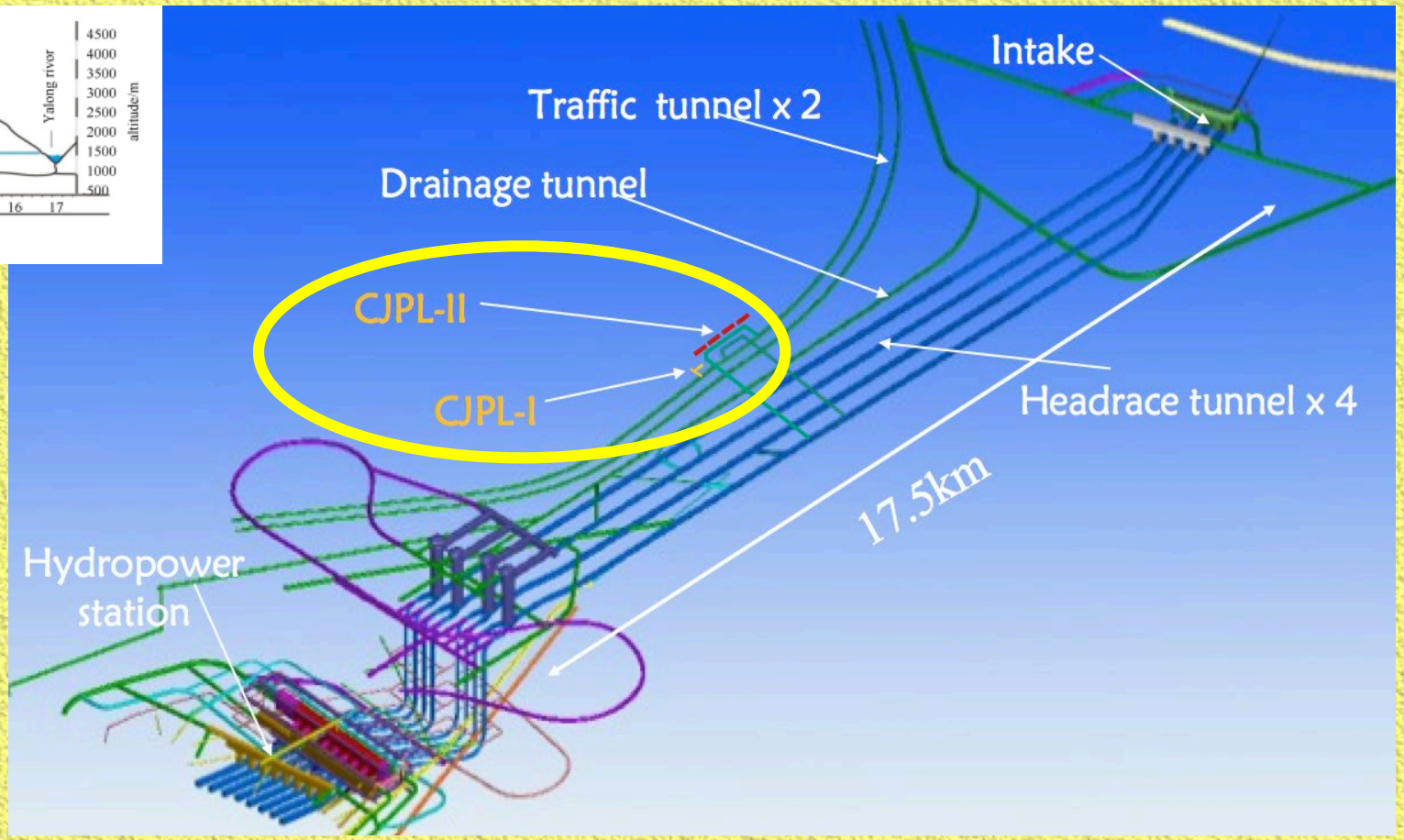
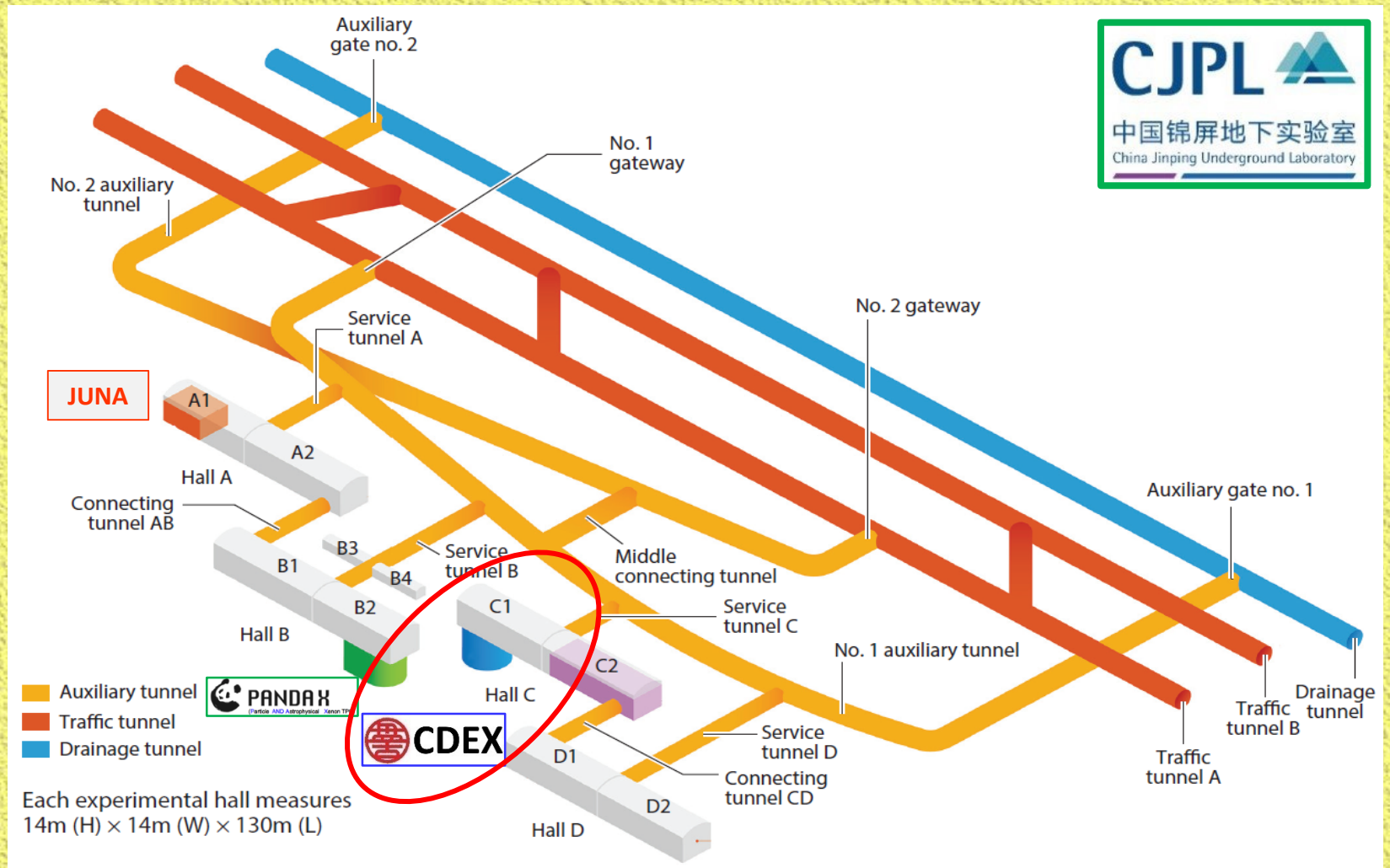


Fig. 1. Cross section of Jinping mountain and location of the CJPL.



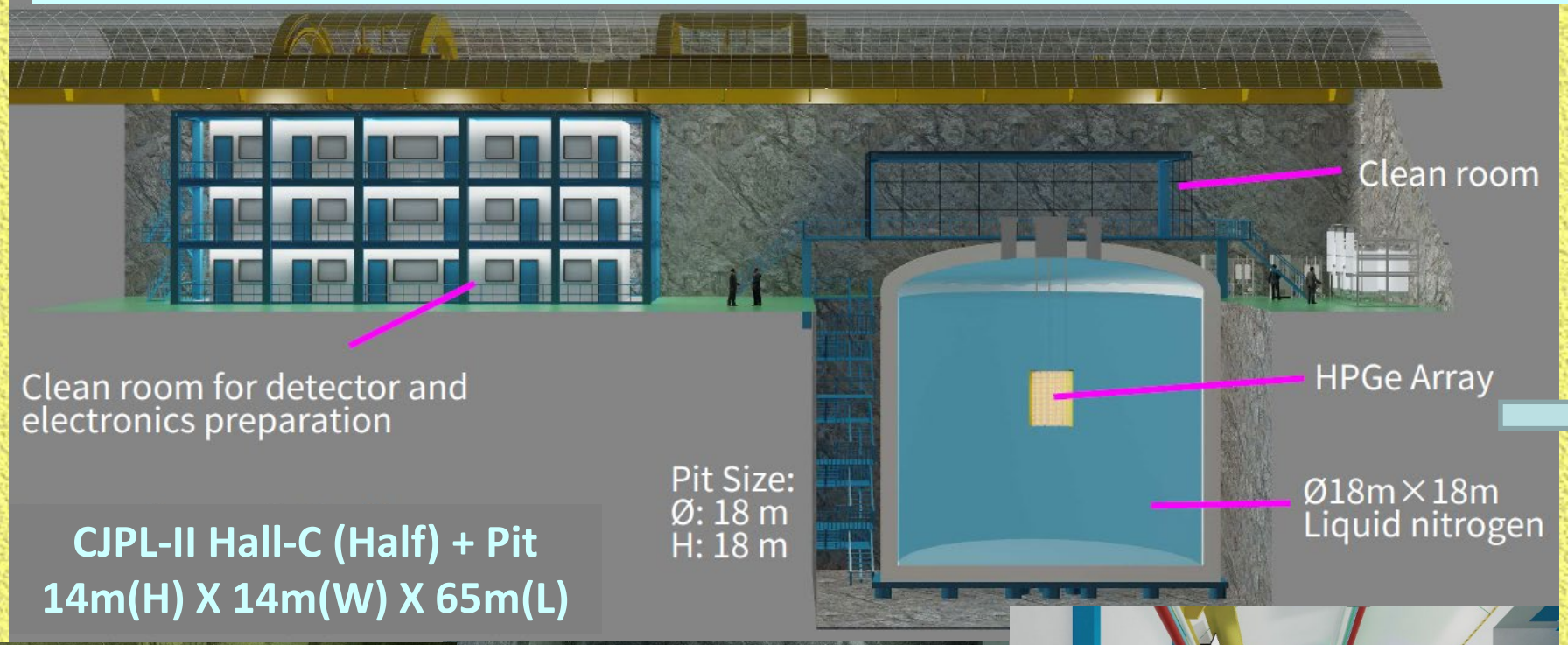
CJPL-II Layout

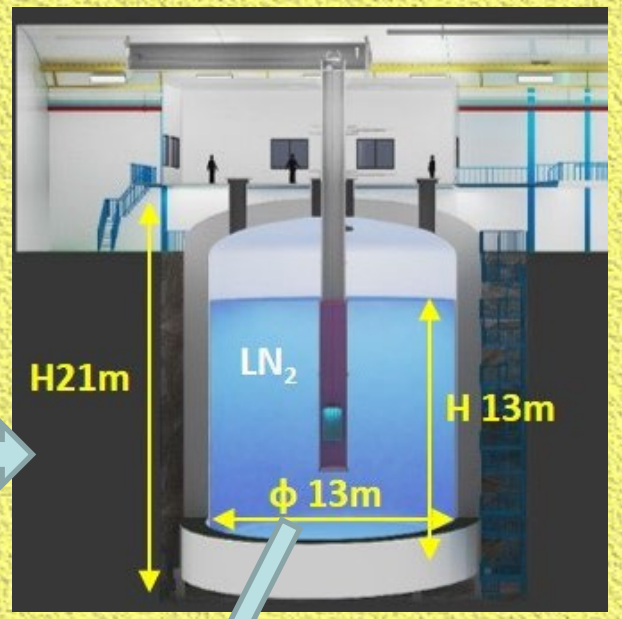
- ☑ Four 14m*14m*130m Main Halls
- ☑ Two Pits: (1) *18(ϕ)X18(H)m* (CDEX) ;
  (2) *27(L)X16(w)X14(D)m* (PandaX)
- ☑ Total space: ~300K m³

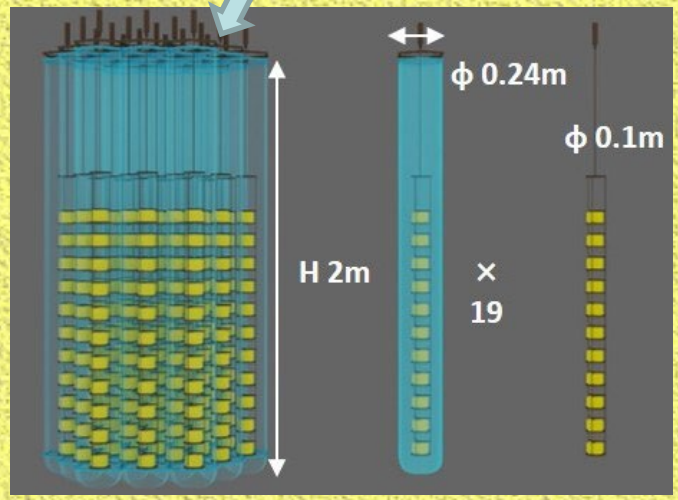


Prospects of CDEX @ CJPL-II : Ge1T Project

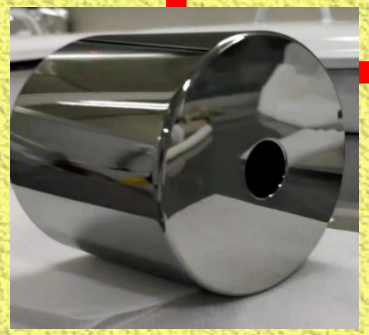
- **Next:** 300-kg $0\nu\beta\beta$ (towards IH) ; 50-kg DM (@ $0\nu\beta\beta$ bkg spec) (2028)
- **Visions:** Ge-1T (2033) → Ge-10T (2040) $0\nu\beta\beta$ (towards NH)

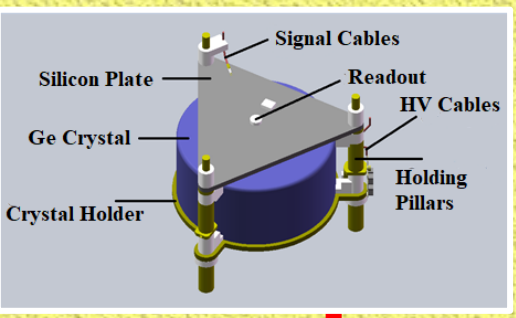






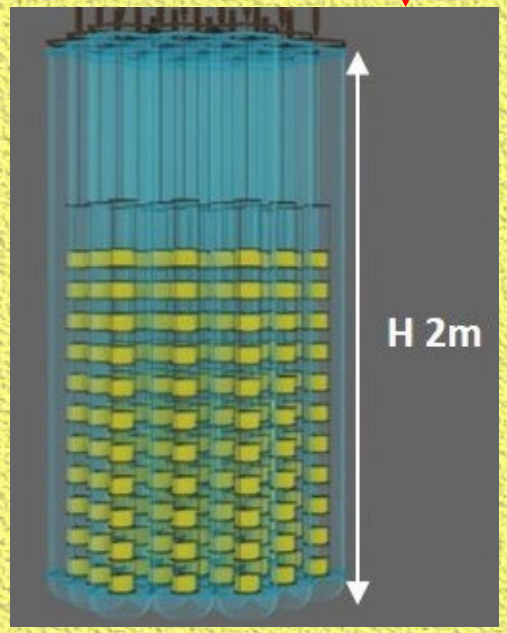
Mastering Key Technologies towards Ge-1T



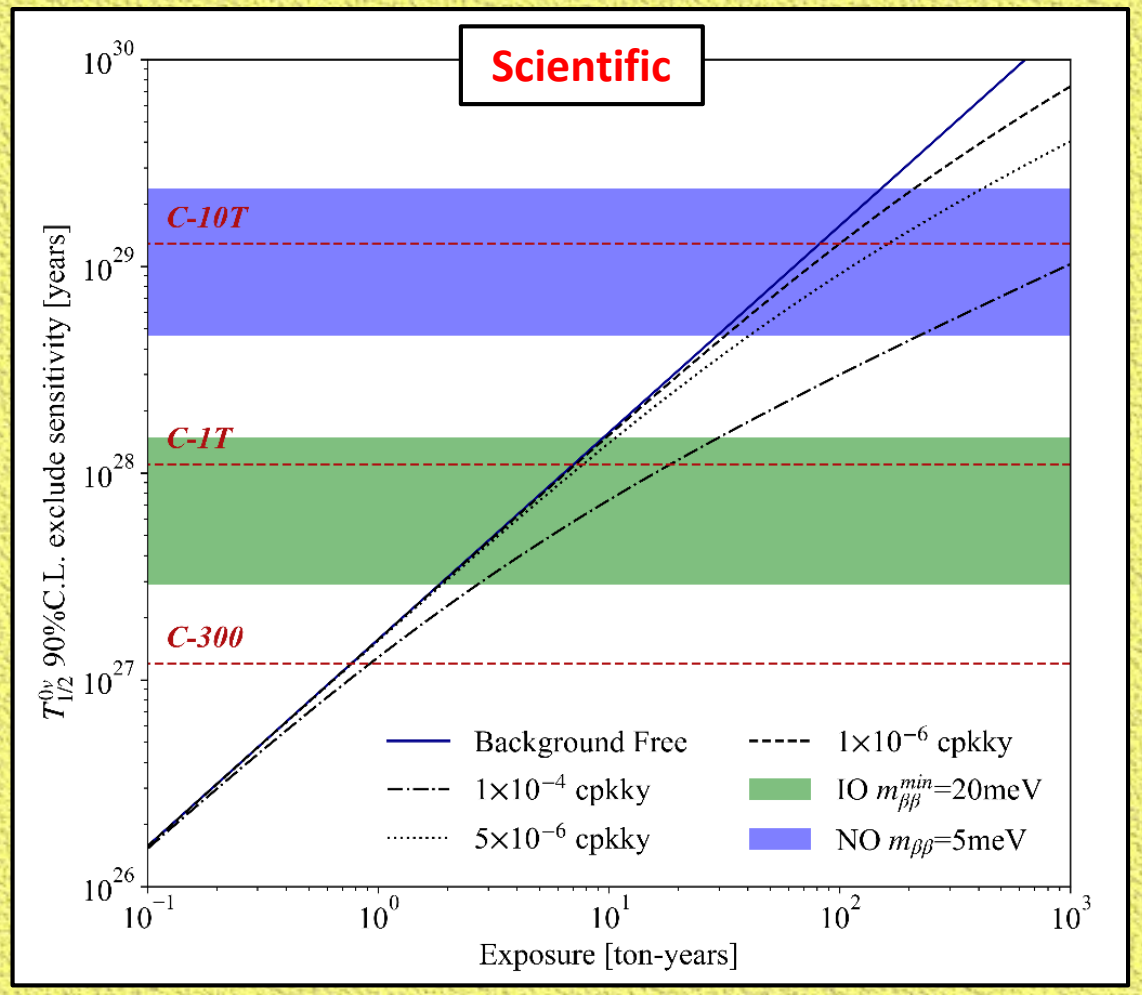


ASIC前放

- ☑ ^{76}Ge enrichment *(acquired: 200 kg @ CJPL)*
- ☑ Ge purification and crystal growth;
- ☑ HPGe detector fabrication;
- ☑ Ultra-low background VFE-ASIC and FADC;
- ☑ Ultra-pure Cu for structure and cables;
- ☑ Large-volume cooling tank “cryostat”



Goals: Ge 0νββ



Technical/Industrial

- **Strong Industry Connection**
  - ☑ NucTech is a major partner *IN* CDEX
- **Targets for 1T-10T Projects (relative to current world capability)**
  - Enriched Ge production power increase by factor ~3-10
  - Ge detector production power increase by factors ~3-5
  - Cost Reduction factor ~4
  - Underground Ge crystal growth and detector fabrication → Background Reduction >20

Future: Concerted *multi-experiments , multi-sites* desirable (necessary ?) to *probe Normal Ordering* with *beyond-ton-scale projects*.

Meanwhile, TEXONO Program in Taiwan:

- In addition to continuation of sub-keV Ge, νN_{el} @ KSNL, Theory projects …..
- Working with local LIGO-GW groups (NCU, NTHU) to develop a *gravitational experiment research program*, incl. exploring GW detection principles at low frequency
- **Future:** if successful & thriving, potentials for multi-location deployment in *underground sites* …..

Prospects & Outlook

- *Congratulations* to our Korean Colleagues & Friends for Commissioning Yemilab, based on admirable solid efforts for 2+ decades.
- The collaboration between TEXONO, pre-CDEX & KIMS in 2000-2010 set the stage & define the landscape in the realization of CJPL. We are *grateful to the Y2L Host*.
- CDEX@CJPL2: Gathering momentum towards multi-T Ge-$0\nu\beta\beta$ program; multi-experiments necessary to probe NO.
- CJPL & Yemilab *[+ the expanding communities & expertise]* add to the world's arsenal of low-background science. Room to collaborate again.
- Wish/Expect/Trust: *Both the Journeys & Destinations for the New Lab will be as Fascinating in the next 2+ decades*.