TEXONO Research Program : History & Legacies

[A Pre-Dinner Banquet E-Talk]

- Foundation
- Evolution Highlights
  - ν @ KSNL → Sanmen
    - In particular, coherent neutrino-nucleus elastic scattering
  - DM+0νββ @ CJPL
  - Theory
  - Gravitational Science *[Appeal to IoP Colleagues]*
- Random Thoughts: Prospects, Regrets, Hopes

Henry T. Wong / 王子敬
Academia Sinica / 中央研究院
June 2025

@

2025 IOP Mini workshop and AAC Meeting
25 Jun 2025, 08:30 → 27 Jun 2025, 17:10 Asia/Taipei
Institute of Physics, Academia Sinica

Founding Fathers (Pre-1997)

Defining (Confining) Frames:

- ***IN Taiwan***, as First Particle Physics Experiment (Lee, Chang)
  - ☛ almost dictate **Reactor Neutrinos**
- ***WITH China***, as First Institute-wise Collaboration (Chang, Wang, Li)

Theory (Why?)

兩岸透過學術合作 共創雙贏

許傳雲

兩岸學術社群 恰可互補

廿一世紀 知識決定國力

最關台灣 爭雄唯賴合作

東亞學圈 足與歐美鼎立

中國時報 (China Times)
1998/10/9

Experimental Results (What,How?)

Researchers make headway in neutrino study

By Myra Lu

After six years of painstaking work, researchers on the TEXONO project, or Taiwan Experiment on Neutrinos, have results of what being done at the Chinese stists involved

of the more particles that se. Scientists ve conducted nts to learn rticle, which least under-stood. Neutrinos are produced in the Earth's atmosphere, the sun, particle accelerators and nuclear power reactors.

Physicists believe that neutrino studies will help shed light on questions about the particle's mass and what roles they play in particle physics and cosmology.

The Kuo-Sheng Nuclear Power Station, which produces electricity used by millions of households in northern Taiwan, also houses the research facilities of the TEXONO project.

significant amount of neutrinos. This makes a reactor an ideal place for neu-

was quoted in the U.S.-based *Science* magazine as saying that even though

Wong said. The results of international collaborations such as the Super-Kamiokande in Japan and Sudbury Neutrino Observatory in Canada gave the Taiwan project what Wong described as a "positive impact."

This is because these earlier experiments have confirmed that the neutrino does have mass and that neutrino oscillation does take place. The latter refers to a phenomenon where neutrinos change from one type to another while traveling great distances. Such oscillation would not occur if neutrinos were entirely without mass, which scientists used to believe to be the case.

"These experiments use much larger instruments to explore different aspects of the neutrino properties from those pursued by the TEXONO experiment. However, given their findings, we know there is a grander picture behind and which direction to go," Wong noted.

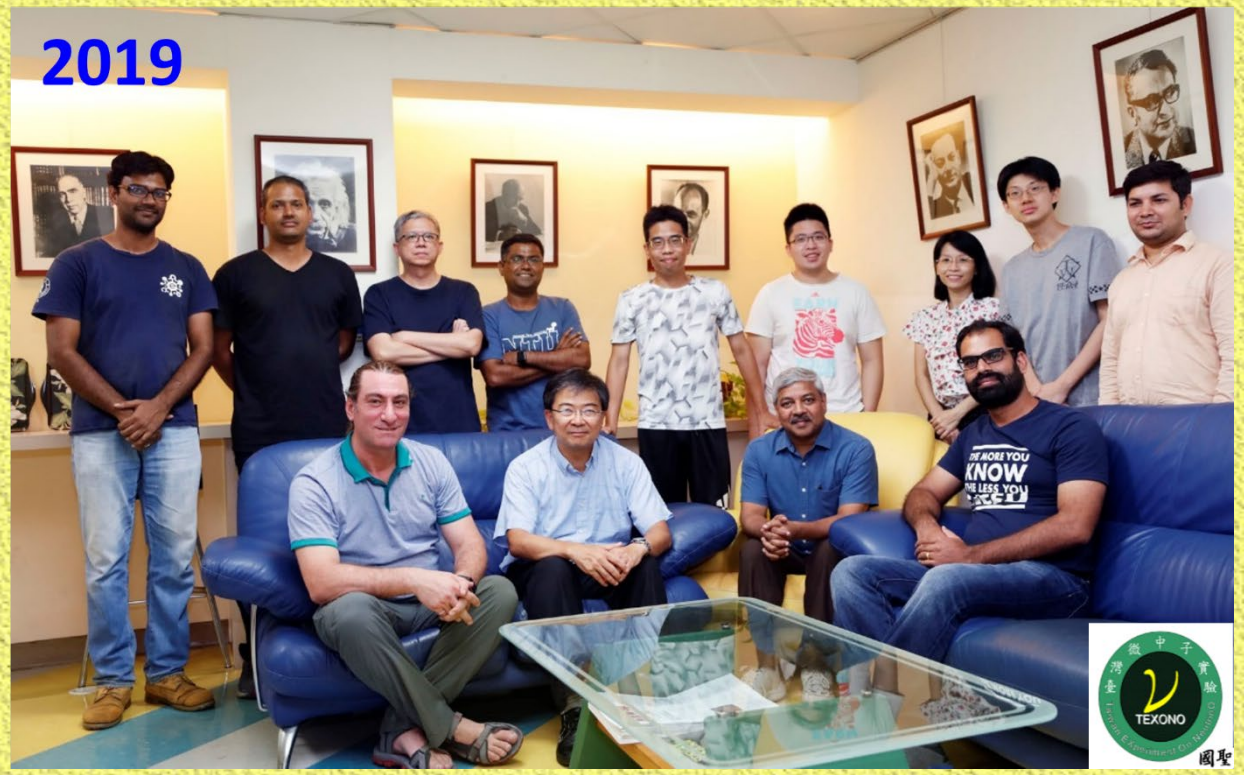
In the West, a country's technological development has often been

Taiwan Journal, Government Information Office
- Vol. XIX, No. 23, Pg. 8, June 13, 2003

A Bridge Over Troubled Waters

Researchers from Taiwan and the mainland have hit scientific pay dirt with the first—and so far the only—collaboration between two institutions across the Taiwan Strait

.... Their Aspirations Become Ours !!

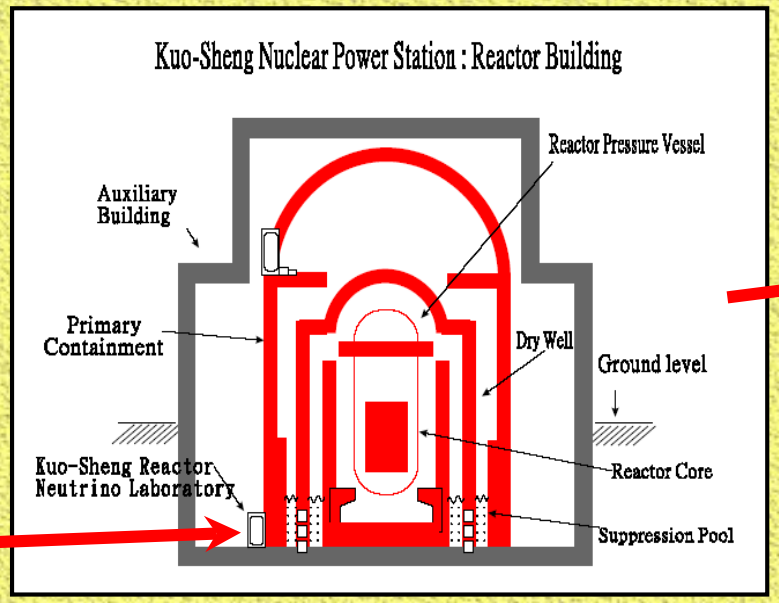


AS, KSNPS, NTU, NDHU,
IHEP, CIAE, THU, SCU,
BHU, CUSB, GLAU,
HNBGU, METU, DEU.....

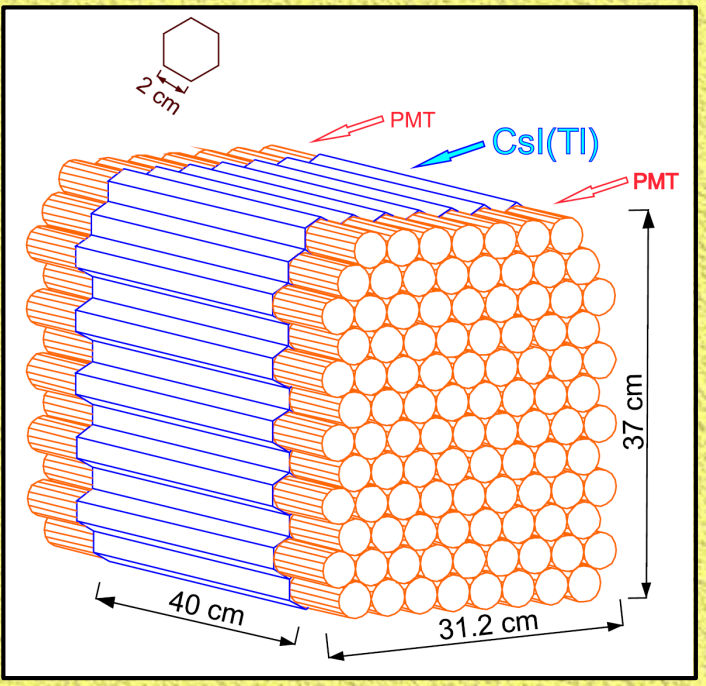
TEXONO Program *[since 1997]* **:**

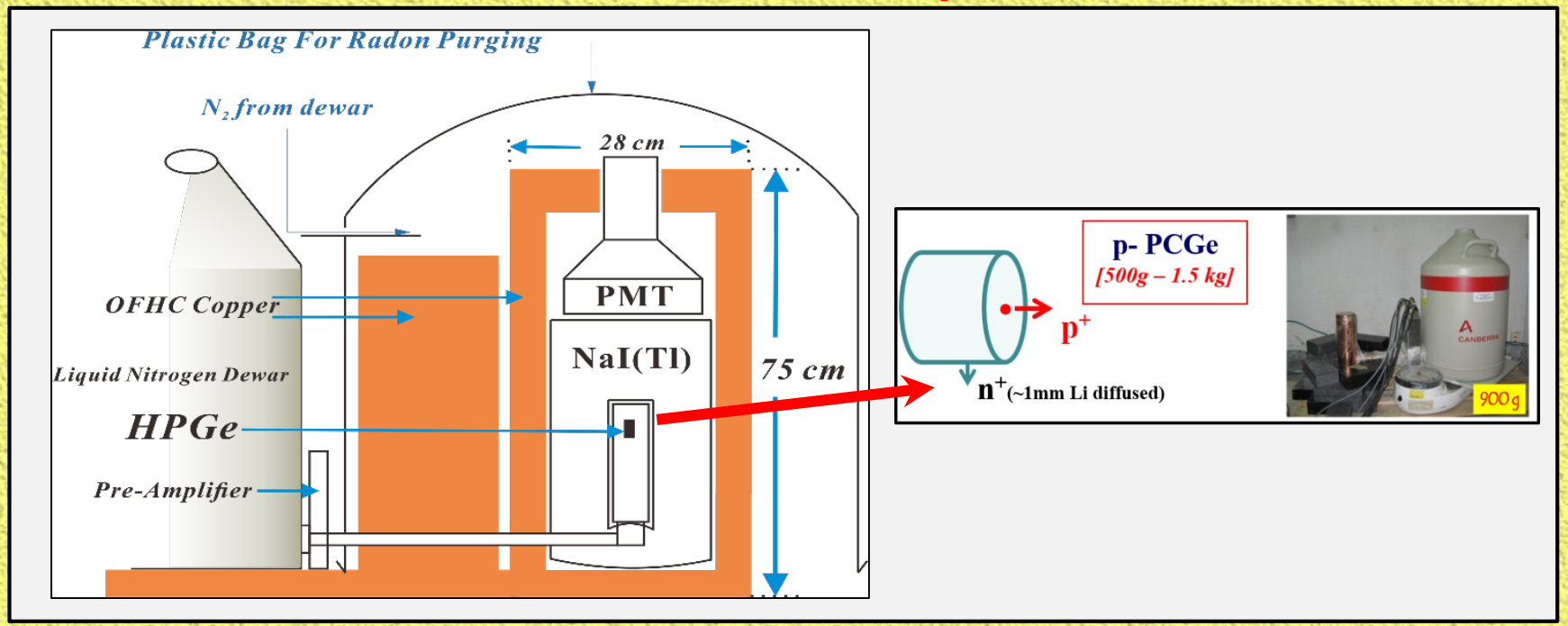
- Low Energy Neutrino (SM+EM) physics at Kuo-Sheng Neutrino Laboratory (KSNL), 28 m from 2.9 GW_{th} reactor core
- Founding partner of CDEX@CJPL Dark Matter Experiment *[since 2008]*
- Theory Program *[since 2010]*


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

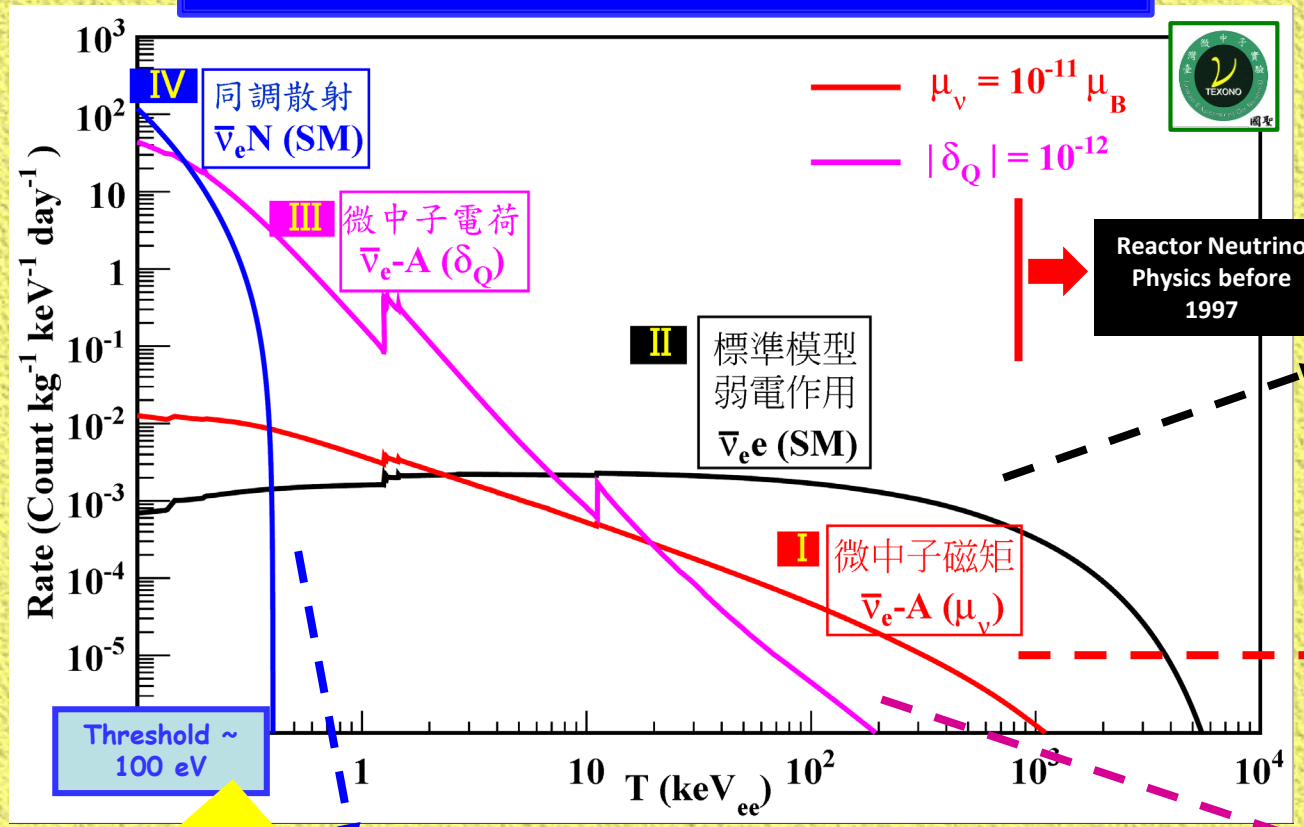

2 cm
PMT
CsI(Tl)
PMT
37 cm
40 cm
31.2 cm


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

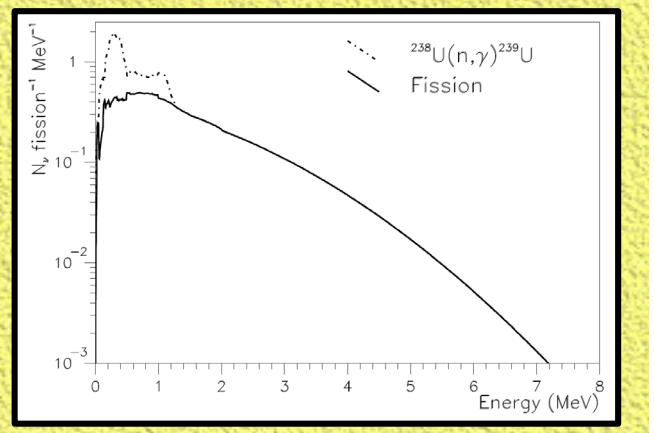
quality ← Detector requirements → mass

Observable Spectra with Reactor Neutrino "Beam"



Reactor Neutrino Physics before 1997

Reactor Neutrino Spectrum

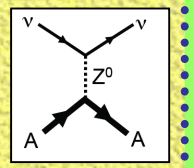


KSNL: $\phi_\nu \sim 6 \times 10^{12}$ cm^{-2} s^{-1}

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 Scatteri… *Theme;PRD16,PRD21]*

- Pioneered sub-keV …ge / PCGe [MPLA08, NIMA16]
  - Light Dark M… …ches @ KSNL *[PRD09,PRL13,AP14,PRD19]*
  - CDEX DM… …@CJPL *[PRD13……]*
  - Theo… … *[PLB14……]*

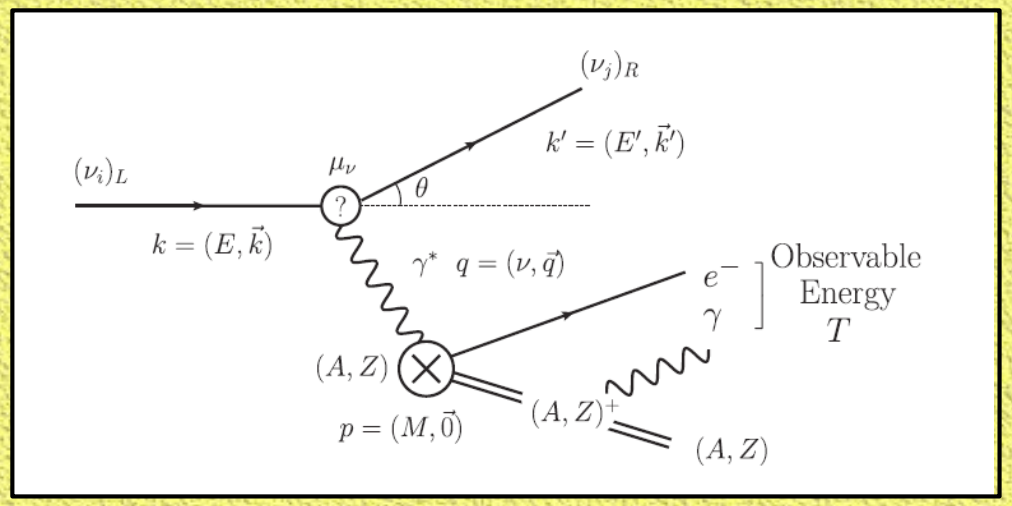
Convoluted Evolution ! Following Pages

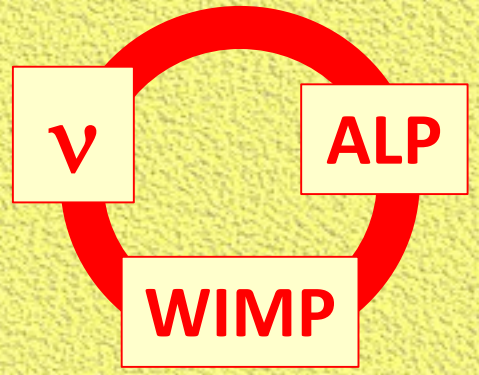
sub-keV PCGe

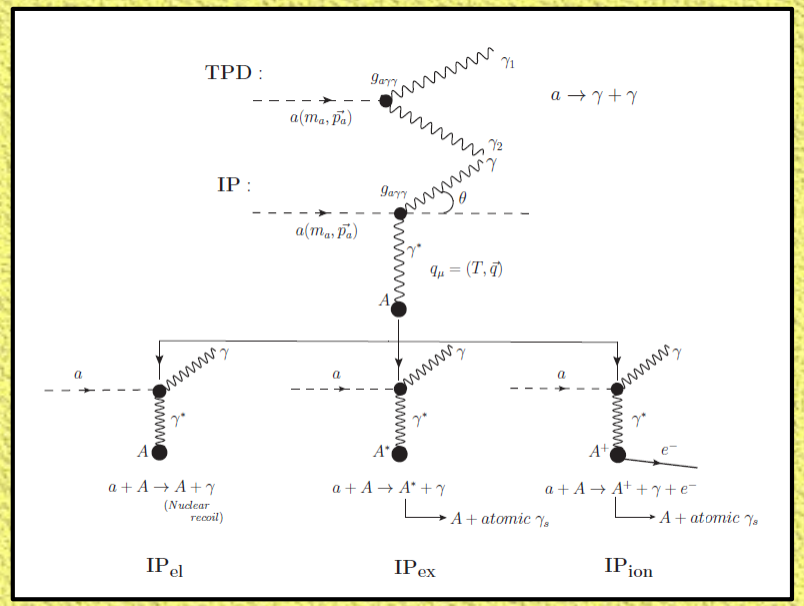
TEXONO Theory Program *[AS, NTU, NDHU, UCSB, DEU, SCU ……]*

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**



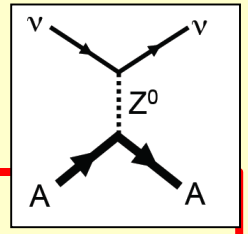




Selected Highlights:

- **Identified Pole structures, Cross-section enhancement, Smoking-gun signatures in:**
  - milli-charged ν interactions: $\nu\,(\delta_Q) + A$ *[PRD14]*
  - 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]*
- **Early Dark Photon Constraints from neutrino-electron scattering** *[PRD15]*
- **First Exploration of Time-of-Flight as Signature for Dark Matter Searches (Boosted DM by Supernova ν)** *[PRL23,PRD23]*

Coherent νA_{el} (CEvNS) Scattering [Our/World's Evolution with Twists]



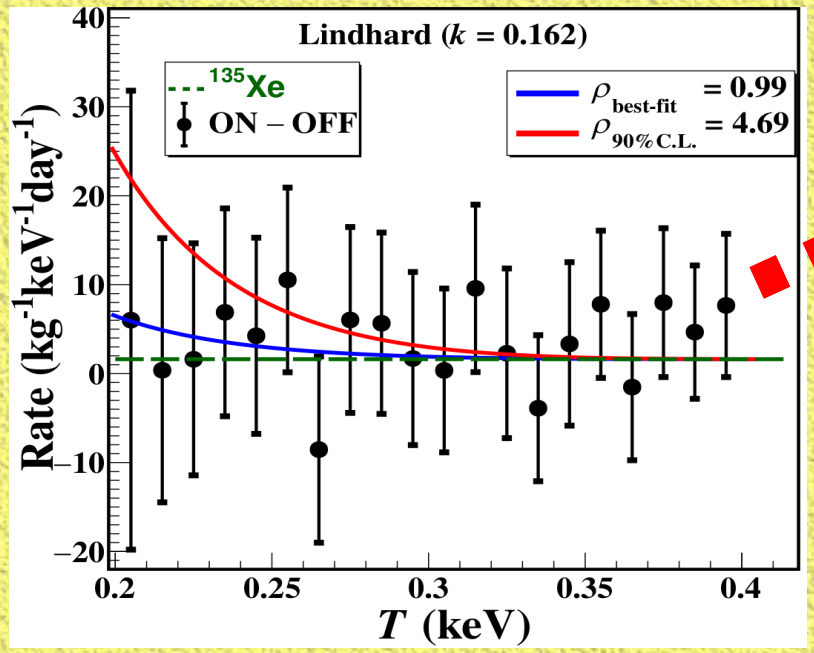
- *"CEvNS"* theoretically considered, Freedman 1974 *[known but not pursued]* ♥♥♥
- **TEXONO @ KSNL:**
  - ☑ Idea (sub-keV Ge for reactor νA_{el}) first raised in *TAUP2003* etc., after μ_ν results with threshold MeV→ 10 keV ⇨ *"Inaugural"* CEvNS talk at *Neutrino 2006 Santa Fe [by now session →schools, workshops!]*
  - ☑ Spin-off to *"Light Dark Matter"* searches, first results (20 g ULEGe @ 220 eV) 2007 *[also a non-subject then]*
  - ☑ Inspire theory R&D: $(\nu/\chi/\alpha)$-Atom cross-sections *[2010+]* & quantify universal QM-coherency *[2016+]*
- 2006 Scholberg: partial CEvNS proposed with Accelerator ν@π-DAR 👍👍👍
  - ☑ Experimental ObservationS since 2017, and BEYOND.
- 2007: CoGeNT 👍👍👍 :
  - ☑ Demonstration of *"Point-Contact Ge"*
  - ☑ large modular mass detectors → νA_{el} + LDM + $0\nu\beta\beta$
- **CDEX @ CJPL:**
  - ☑ Ge for νA_{el} : catalyzed *foundation of CJPL* in China & CDEX program
  - ☑ Dedicated LDM experiment with Ge, starts 2010
  - ☑ ~2015: explore future $0\nu\beta\beta$ with Ge
  - ☑ ~2023: return to NG Reactor νA_{el} at Sanmen Reactor Laboratory [2025+]
- 2024: ("Indications" of) Solar νA_{el} *positive observation*, XENON & PandaX 👍👍👍
- 2025: CONUS+ Reports Reactor νA_{el} *with 160-eV Ge, 3.7σ positive observation !!!* 👍👍♥♥

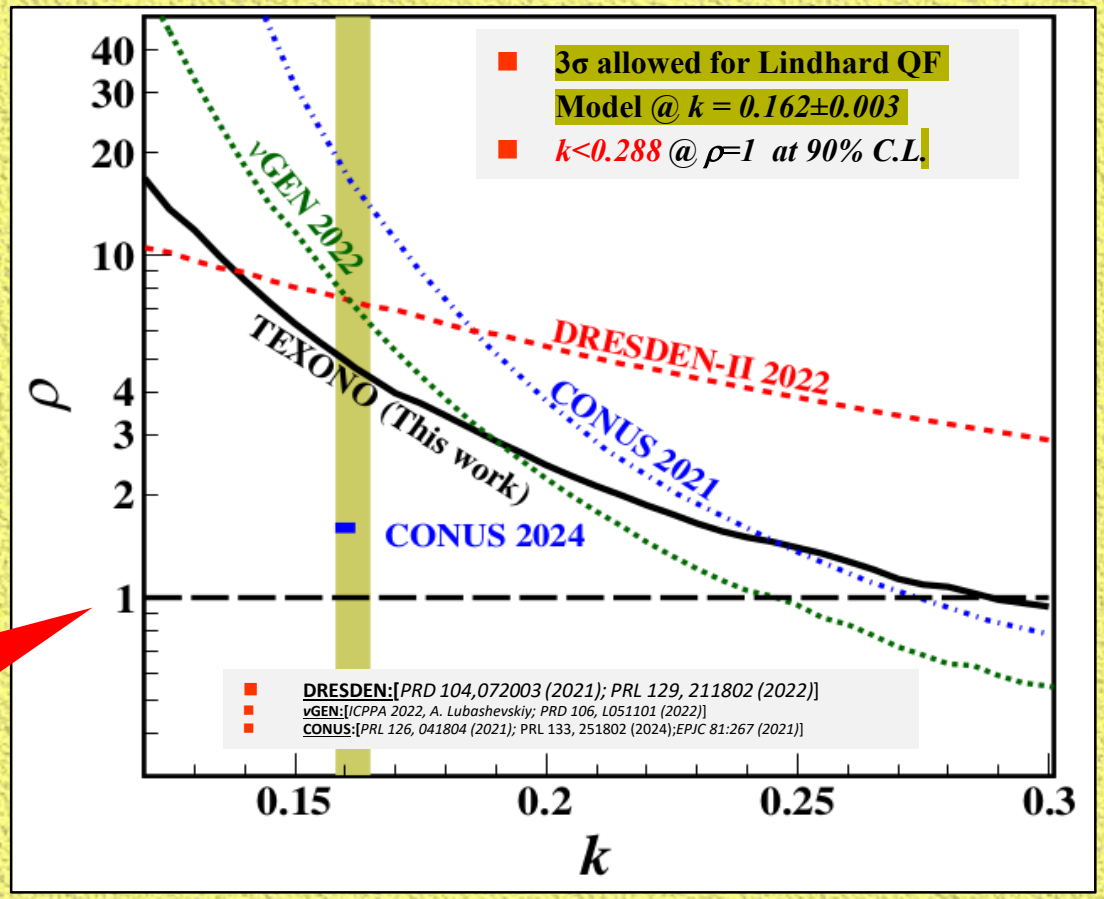
Fully CEvNS candidates *[after MUCH efforts]* at Reactor ON—OFF *[PRL2025]*

♥♥♥ TEXONO pioneers and pursues several generations of sub-keV Ge Detectors

	Generation	Mass (g)	Pulsar FWHM (eV_{ee})	Threshold (eV_{ee})
LN_2	G1	500	130	500
	G2	900	100	300
Electro-cool	G3	500	70	200
		900	70	~230
	$G3^{+}$	1430	~60	~160
	$G3^{++}$	1430	70	200
	G4	900	~50	~150

KSNPS Decommissioned



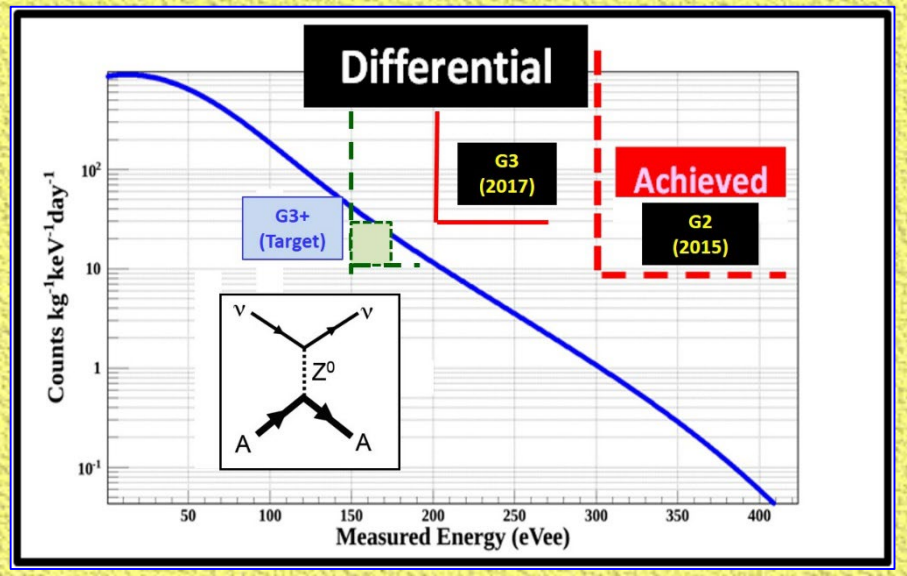


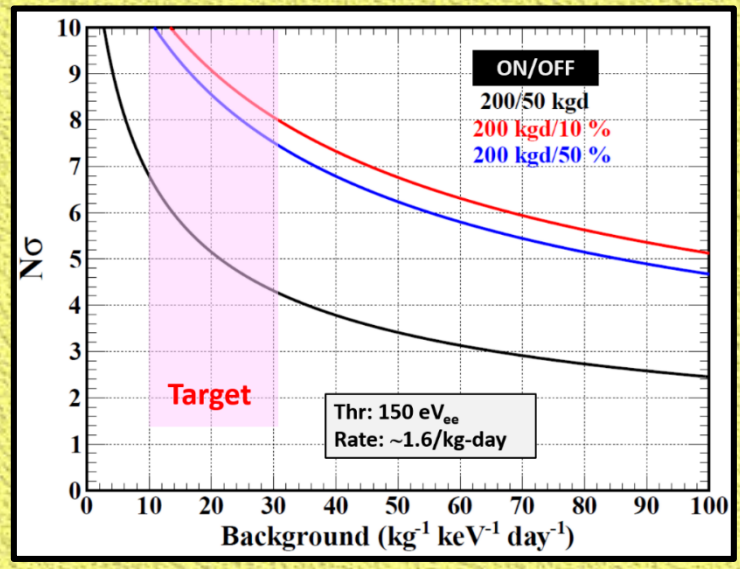
- ρ estimate the excess over SM prediction @ Lindhard Model k=0.162:
  - ρ=0.99+-0.23(stat)+-0.05(sys)
    - ρ < 4.7 @ 90% C.L.

νA_{el} @ KSNL Prospects

Projected Sensitivites

- KSNL (Hypothetical) →
- Sanmen (Underway)





☑ **KSNL (2.9GW, 28m):**

- G3 (200-eV) Data ON/OFF 242/357 *[PRL2025]* → 420 / 820 kg–days
- ν Decommissioned 2023 → Access till at least end of 2028
- Continue Operation → A good low-background surface lab

☑ **R&D:**

- G4 *(@150 eV noise edge demonstrated)*
- BS Cut optimization → suppress surface events
- PSD at threshold → reduce threshold via software
- Background Modeling → mitigate limited OFF-stat. error.

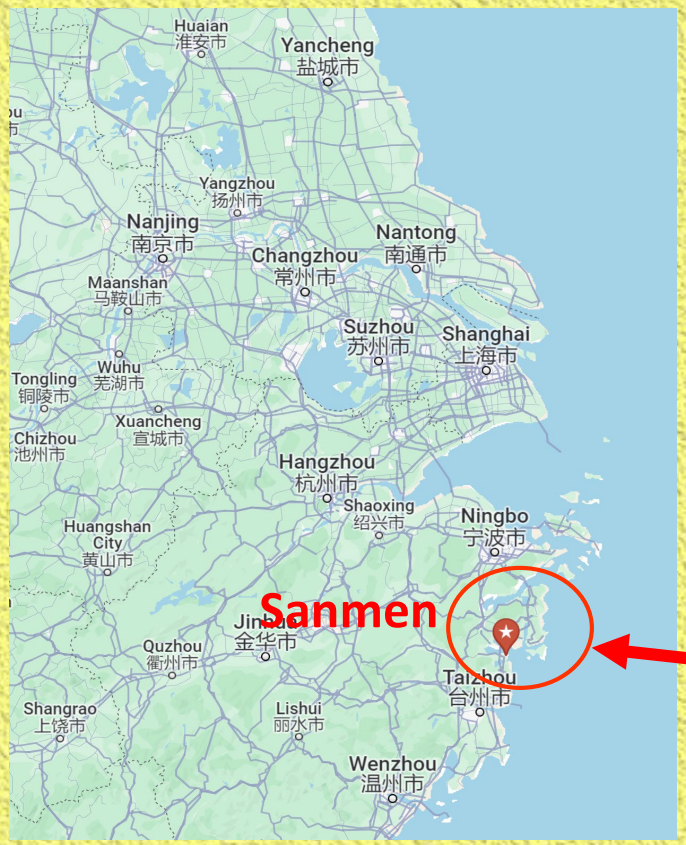
☑ **New reactor laboratory under construction (under CDEX):**

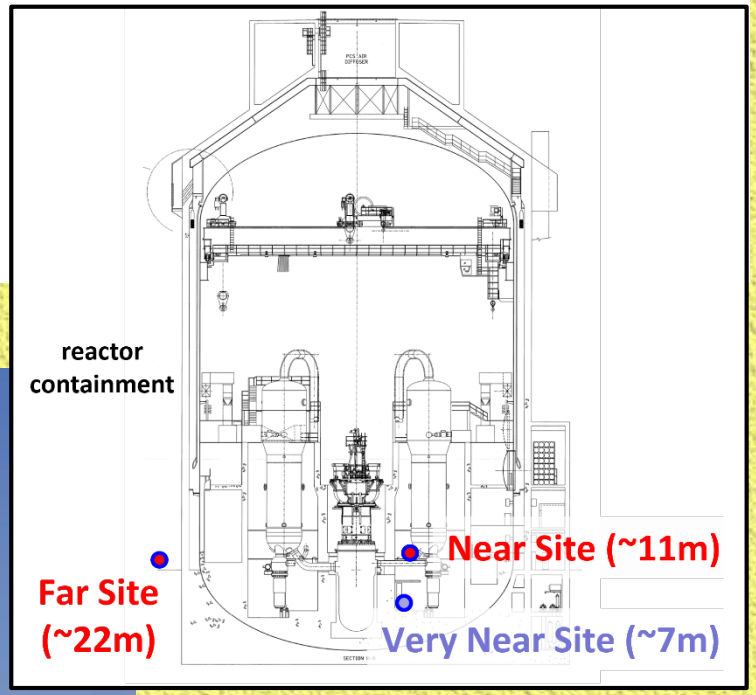
Sanmen（三門） Reactor (3.4GW, 11m) with RECODE program

Sanmen（三門）Reactor Laboratory & RECODE

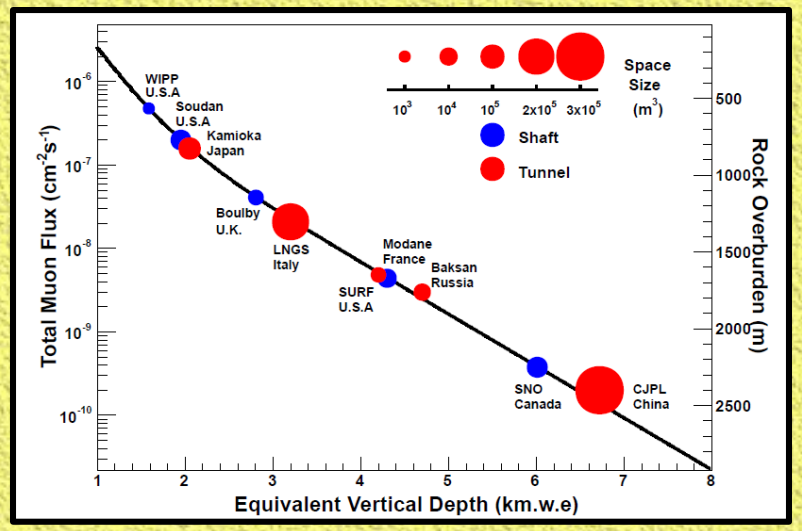
Sanmen Nuclear Power Plant @ Taizhou, Zhejiang, China *[~200 km south of Shanghai]*

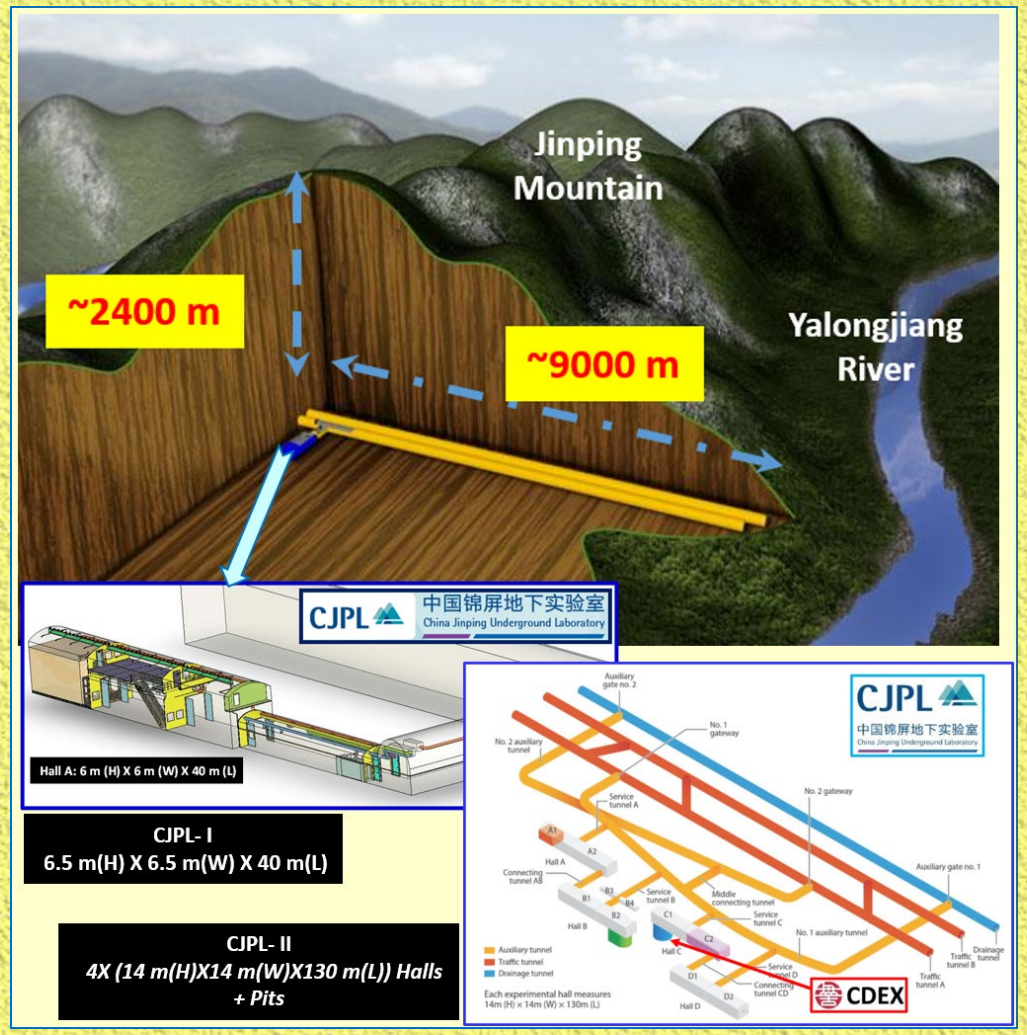
- Thermal power 3.4 GWth, ~22m /11m /7m from the core
- Neutrino flux at 11m> 5.6 × 10^{13} $cm^{-2}s^{-1}$ *(~10 X KSNL)*
- 22m & 11m sites to be completed second half of 2026
- **RECODE (Ge)** & **RELIC (LXe)** programs on NG-CEvNS





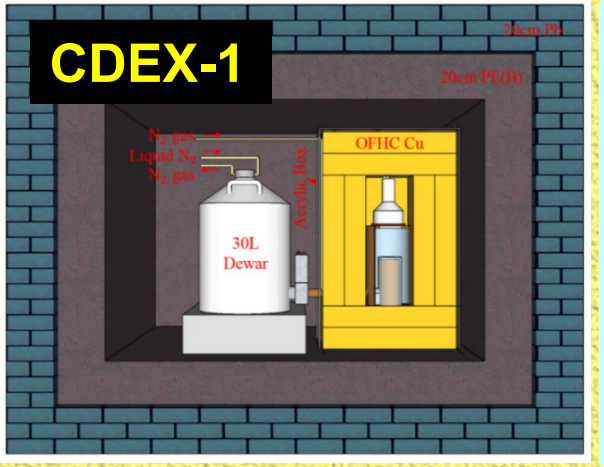
CJPL 中国锦屏地下实验室 China Jinping Underground Laboratory





- **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***

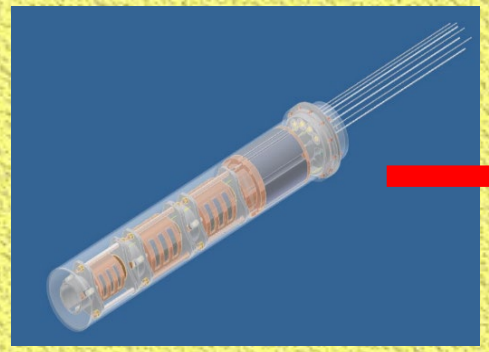
CDEX

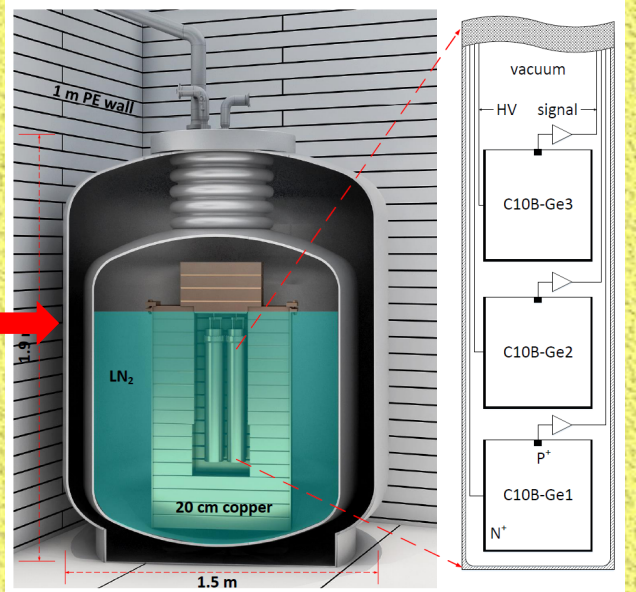


CDEX-I Dark Matter Program

- ☑ *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 Dark Matter Results:

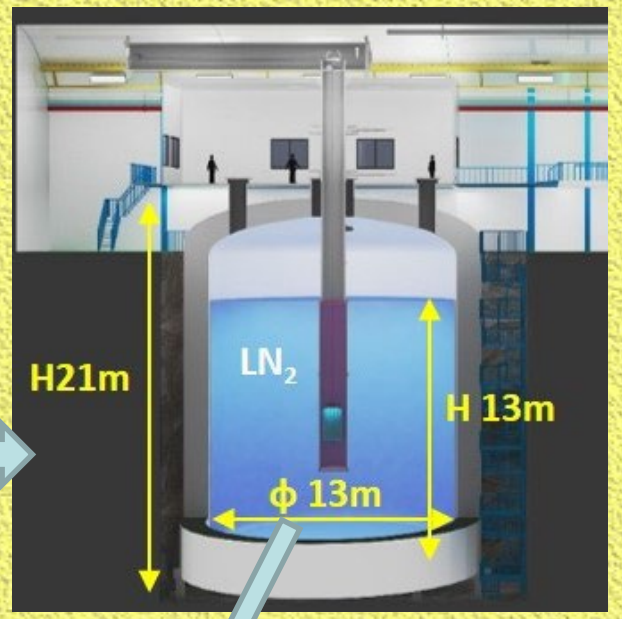
- Mainstream $\sigma_{\chi N}$ SI & SD TI *[PRD14,PRD16,CPC18,PRL18]*
- $\sigma_{\chi N}$ SI AM *[PRL19]*
- $\sigma_{\chi N}$ Migdal Inelastic Effects *[PRL19]*
- Dark Photon Searches *[PRL20]*
- Axion-Like-Particles (ALP) & Bosonic Vector DM *[PRD17,PRD20]*
- χ-N Effective Field Theory Constraints *[SCPMA21]*
- 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,SCPMA24]*
- Exotic NSI on solar ν *[PRD23]*
- BDM by Sun *[PRL24]*
- Light Mediator Constraints *[CPC25]*

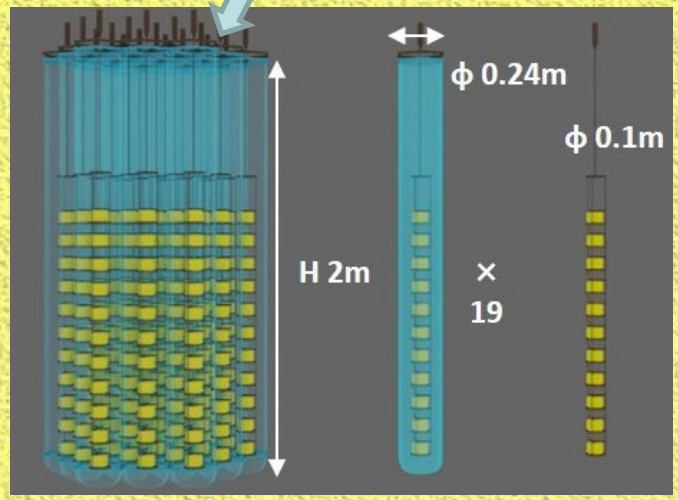
Legacies:

- A whole generation of junior scientists trained
- Team (+knowhow) Matured Enough to "Compete" on Novel Theoretical Ideas …. !!
- Backbone of the growing research scenes in China

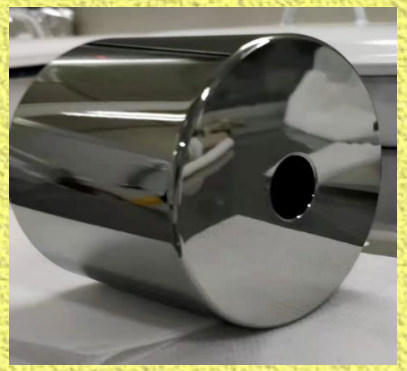
Future Prospects @ CJPL-II : Ge1T Project

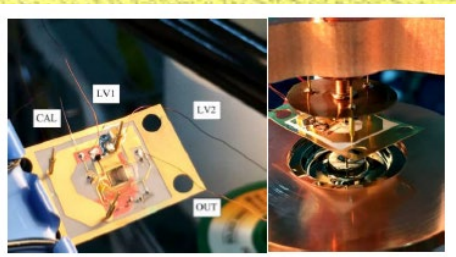
- **Next:** 300-kg $0\nu\beta\beta$ (towards IH) ; 50-kg DM (@ $0\nu\beta\beta$ bkg spec) (2028)
- **Visions:** Ge-1T (2033) → Ge-10T (2040) $0\nu\beta\beta$ (towards NH)



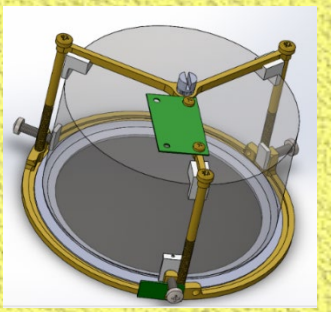


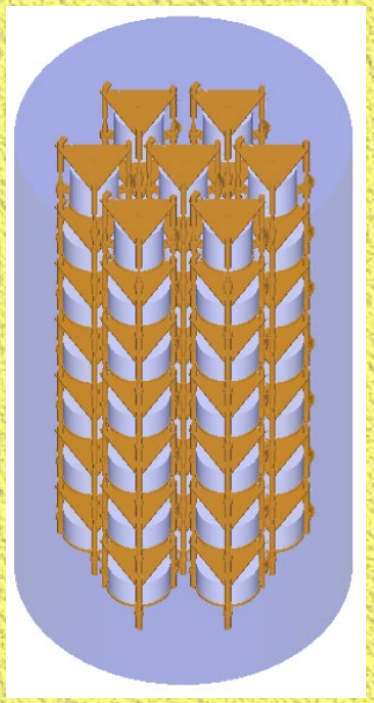
Mastering Key Technologies towards Ge-1T



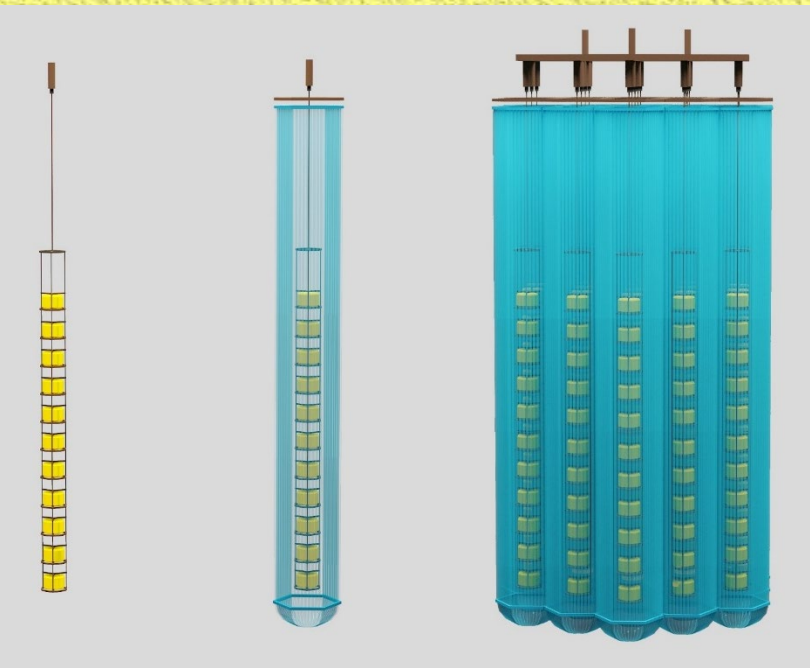


ASIC前放

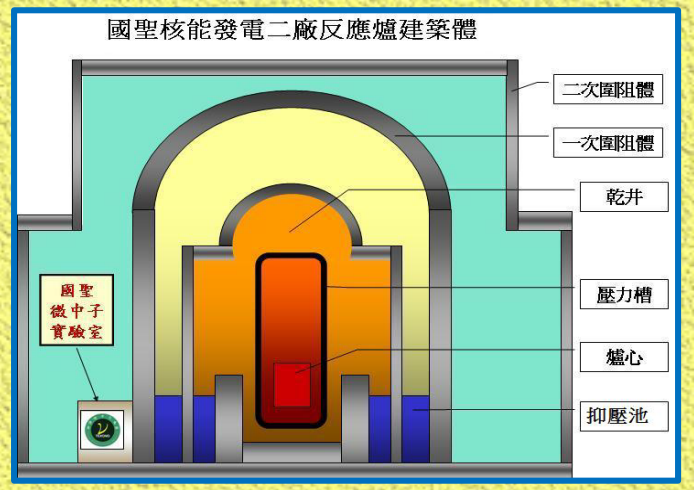


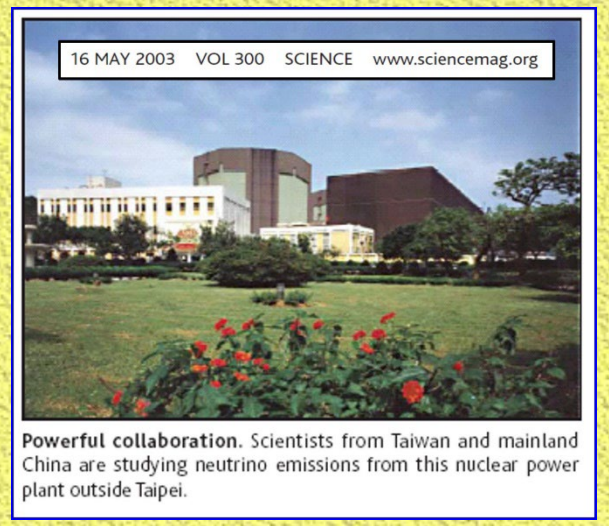


- ☑ Enriched Ge Production *(world leading now !)*
- ☑ Ge purification and crystal growth;
- ☑ HPGe detector fabrication;
- ☑ Ultra-low background VFE and FADC;
- ☑ Ultra-pure Cu for structure and cables;
- ☑ Large-volume cooling tank “cryostat”



From My Comfort Zone .....





Taiwan EXperiment On NeutrinO — History and Prospects

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CDEX

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Annu. Rev. Nucl. Part. Sci. 2017. 67:231–51

The China Jinping Underground Laboratory and Its Early Science

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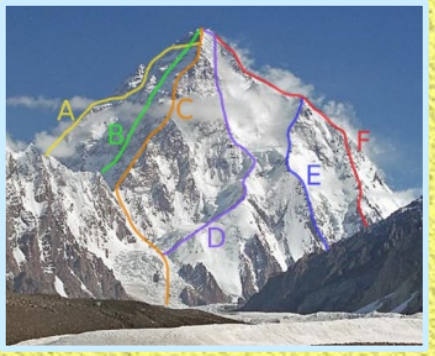
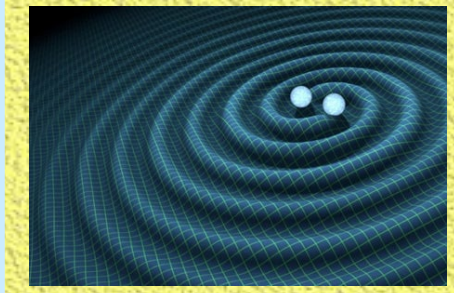




Facing Our Next Mountain .....

TEXONO @ Gravitational Physics

ASGRAF
ACADEMIA SINICA
GRAVITATIONAL PHYSICS
RESEARCH FACILITY

WHY:

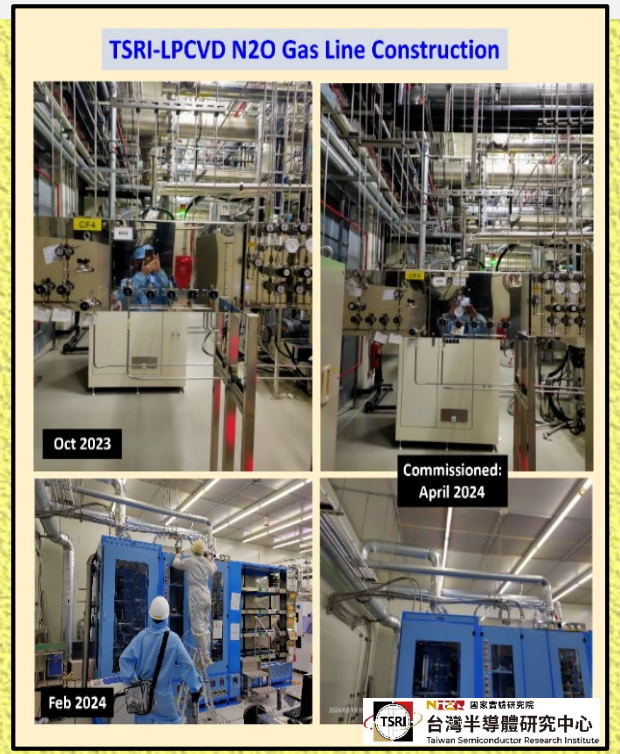
- ☑ Gravity is the least understood/tested interactions.
- ☑ Gravity may hold the keys to the Missing Energy Problem
- ☑ Inevitable that a (proper) physics department research program should include (get connected) to studies of Gravity.

WHAT:

- **Joined LIGO 2021** ***(with NTHU,NCU ➔ Natural Scale: Taiwan, not ASIoP)***
- ***Strategies (Goals)*:**
  - A ***Physics*** Program – **multi & diverse/balanced projects**
    - ⇨ Instrumentation (Domestic) – Mirror Coating Fabrication @ TSRI, Characterization @ IoP-B1-ASGRAF
    - ⇨ Operation -- Calibration, on-site shifts posting
    - ⇨ Physics/Science – BSM particle physics, Stochastic Background …..
  - **Connect multi-institute, multi-disciplinary teams -- beyond GW, beyond LIGO**
    - ⇨ TW HEP resources & expertise – both experiment & theory
    - ⇨ Resources from TEXONO & CDEX (ν & DM) teams
    - ⇨ TW semiconductors & lasers expertise
- **Expect new faculty** ***[Kuan HJ – neutron star with GW expertise]*** **joining IoP 2026/27**

Appeal to IoP Colleagues:

- We have access to **TSRI Facility** & built **B1-ASGRAF**
  - 🛠 to research on essentially a *semiconductor problem* !!
- We invite *(need!)* expertise help to use & run them – *properly!*
  - ☑ Semiconductor coating fabrication & characterization facilities & know-hows
  - ☑ Semiconductor chemistry processing
  - ☑ Precision laser techniques
  - ☑ ab initio solid-state theory on coating materials thermal and optical losses
- Either Bottom-Up *(introduce students, RAs)* or Top-Down *(Join and Run the Program)*



TEXONO – CDEX Family Tree

G1

G2

G3

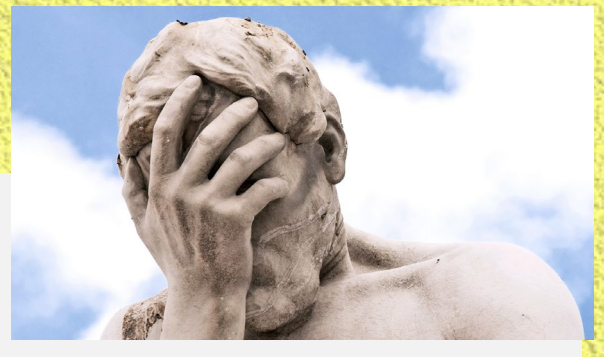
G4

As Proud Parent Bragging on His Children …..

TEXONO Chinese team catalyzed construction of Jinping Underground Laboratory (CJPL) [Budget 200M USD] and headed the CDEX Program (PI: G2-Yue Qian)

TEXONO G2-Venktesh Singh (BHU,CUSB) got Visitor's Award, presented in-person by India's President (Lady Murmu) at Presidential Palace, New Delhi.

Regrets *["The Unexamined Life is Not Worth Living", Socrates]*



- Evolution of international relations make the dreamed "World Experiment" at CJPL unrealistic
- We gave birth to the subject of CEvNS, proposed the correct experimental strategies and pursued several generations of development, but did ***NOT*** in the *"strict and restricted sense"* cross the finish line. *[COVID, National De-Nuclearization…]*

- High on my *Bucket List*: Someone(s) somewhere solve the Missing Energy Density Problem 『朝聞道．．．』
- CJPL World Experiment would still make advances despite …….
- Contribute to setting up gravitational science research in Taiwan.

TEXONO : Prospects & Outlook

- νA_{el}@KSNL → "Final" results underway
  - → G4 PCGe@150 eV threshold ; New Reactor Site @ Sanmen
- Partner of CDEX DM @ CJPL
  - → Goal/Dream: $0\nu\beta\beta$ ton-scale "World Experiment" *[passing the baton]*
- Theory: Continue Following our nose & Having Fun ….
- Gravitational Physics & Multi-Messenger Astrophysics:
  - → Inevitable → *towards a domestic multi-institute + disciplinary program*

⚐ Legacies: *(Positive?)* Differences *WERE* Made, Despite ……..

⚐ Prospects: 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