Neutrino and Dark Matter Physics with Low Threshold Germanium Detectors

- Overview : TEXONO Program/Facilities
- Neutrino Physics at KSNL
- New Facility CJPL & CDEX Dark Matter
- Prospects & Perspectives

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Academia Sinica / 中央研究院

November 2017

@

Workshop of Recent Developments in QCD and Quantum Field Theories

November 9-12, 2017

National Taiwan university, Taipei, Taiwan

臺灣大學

National Taiwan University

TEXONO-CDEX Collaboration

TEXONO *Taiwan EXperiment On NeutrinO* *[since 1997]*:

- **Neutrino Physics at Kuo-Sheng Reactor Neutrino Laboratory (KSNL)**
  - **Taiwan (AS, INER, KSNPS,NTU,NDHU)**
  - **India (BHU)**
  - **Turkey (METU,DEU)**

CDEX *China Dark Matter EXperiment* *[birth 2009]*:

CJPL

- **Dark Matter Searches at China Jin-Ping Underground Laboratory (CJPL)**
  - **China (THU, CIAE, NKU, SCU,YLJHD)**

Research Program: Low Energy Neutrino and Dark Matter Physics

TEXONO Theory Program *[AS, NTU, NDHU, DEU(Turkey), SCU(China) ……]*

NCTS ECP (2015+)

C.P. Liu (NDHU)

J.W. Chen (NTU)

Experimental/Interdisciplinary program Group Proposal

Title of the Experimental collaboration (or Interdisciplinary research) group

English: Light Dark Matter and Neutrinos
Chinese: 輕暗物質與微中子

1. Coordinators and core members. Name also young participants (postdocs, students etc).

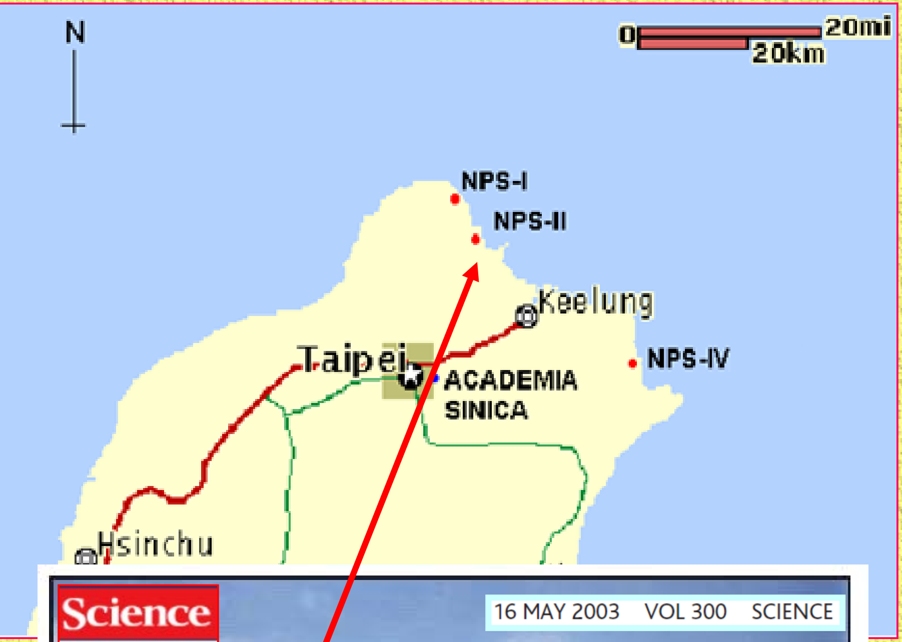
Coordinators: 劉承邦 Cheng-Pang Liu (NDHU, th.), 王子敬 Henry T. Wong (AS, exp.)
Core members: 陳俊瑋 Jiunn-Wei Chen (NTU, th.), 紀信昌 Hsin-Chang Chi (NDHU, th.), 劉承邦 Cheng-Pang Liu (NDHU, th.), Mukesh Kr Pandey (NTU, Postdoc, th.), Lakhwinder Singh (AS, Postdoc, exp.), 王子敬 Henry T. Wong (AS, exp.), 吳峙磐 Chih-Pan Wu (NTU, Ph.D. student, th.)

[*] Note that our group has established strong collaboration (e.g., publish papers together that acknowledge NCTS's support) with the following foreign researchers whom we would list as our adjunct members: 黃克寧 Keh-Ning Huang (四川大學, th.), Saime Kerman (AS & Dokuz Eylül University, Turkey, th.), 林興德 Shin-Ted Lin (四川大學, exp.), 岳騫 Qian Yue (北京清華大學, exp., Chief Scientist of the China Dark Matter Experiment)

- ☑ **ν-NSI ; BSM ν-e & ν-N ;**
- ☑ **Atomic/nuclear effects in ν/χ interactions ;**
- ☑ **ν/χ – em effects ;**
- ☑ **ν-N QM coherency effects ;**
- ☑ **Sterile-ν DM ; dark photons ;**
- ☑ **……**

Connections: Studies of EW/BSM physics involves exquisite understanding of the detection physics mechanisms which require state-of-the-art command of atomic, nuclear & QCD physics.

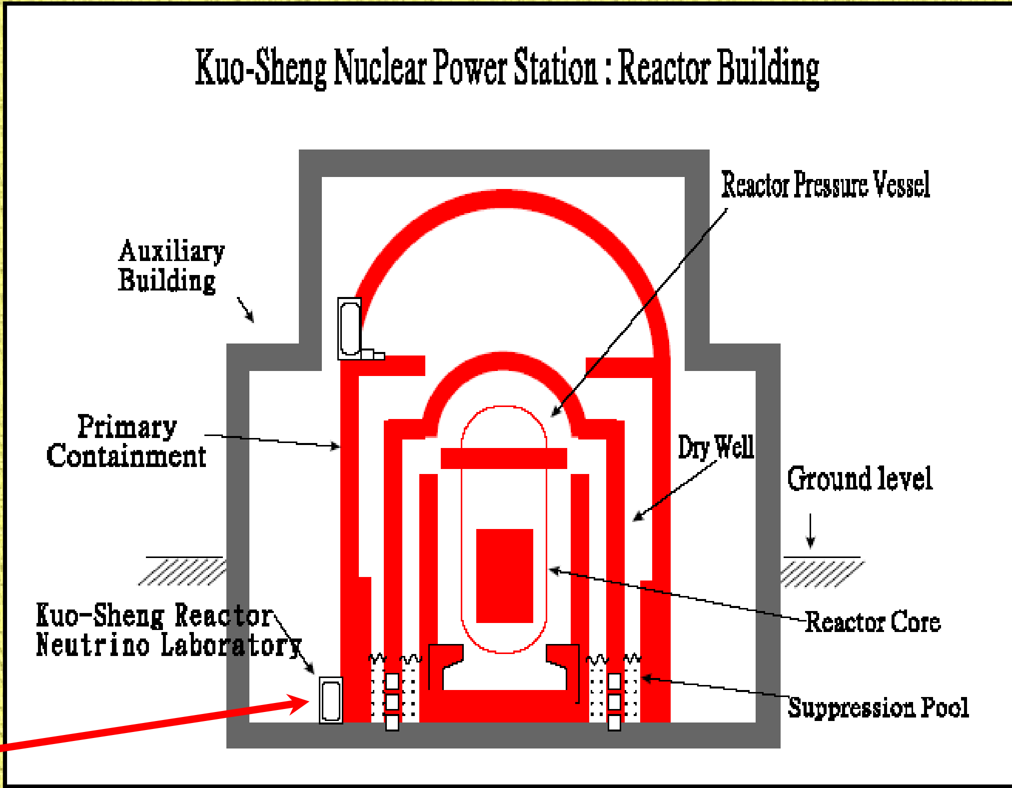
Kuo Sheng Reactor Neutrino Laboratory [KSNL]



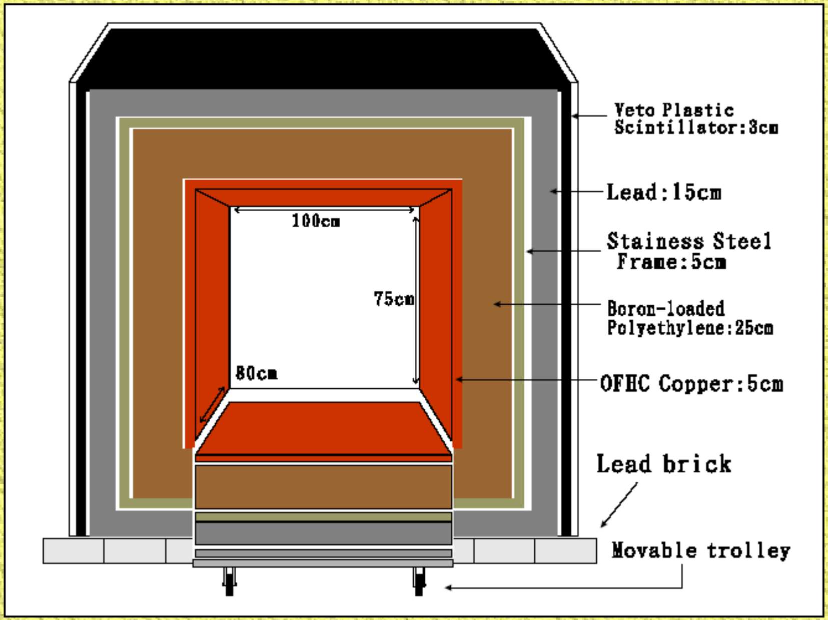

Science
AAAS
16 MAY 2003 VOL 300 SCIENCE
Taiwan-China Collaboration

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



- 28 m from core#1 @ 2.9 GW
- Shallow site : ~30 *mwe* overburden
- ~10 m below ground level



Front View *(cosmic vetos, shieldings, control room …..)*

Inner Target Volume

Configuration: **Modest yet Unique**

Flexible Design: **Allows different detectors conf. for different physics**

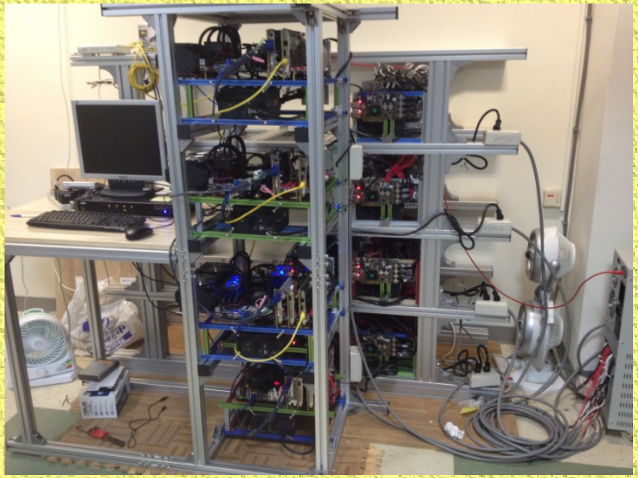
KSNL : Detectors Schematics

ULB-HPGe [1 kg]

CsI(Tl) [200 kg]

Sub-keV Ge Detectors
(20-900 g)

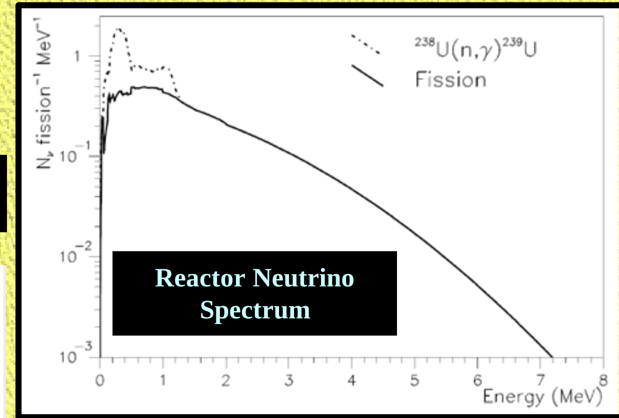
Data Acquisition with FADC
Readout & FPGA Capabilities

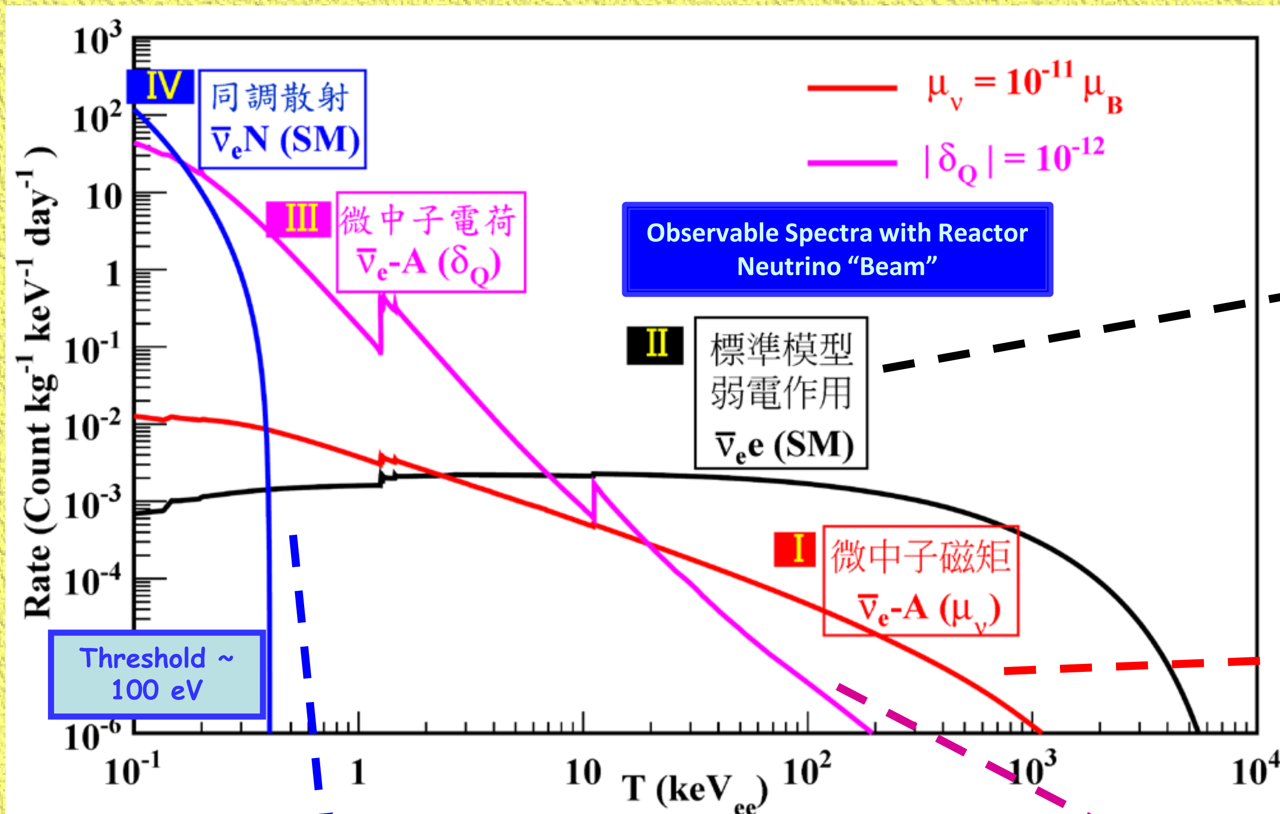


Multi-Disks Array [~300 Tb]

Neutrino Properties & Interactions at Reactor

quality ← Detector requirements → mass





ν-e Scattering SM *[PRD10]*

& NSI/BSM

[PRD10,PRD12,PRD15,PRD17]

⇨ 200 kg CsI(Tl)

Magnetic Moments

[PRL03,PRD05,PRD07]

⇨ 1 kg HPGe

νN Coherent Scattering *[Current Theme;PRD16]*

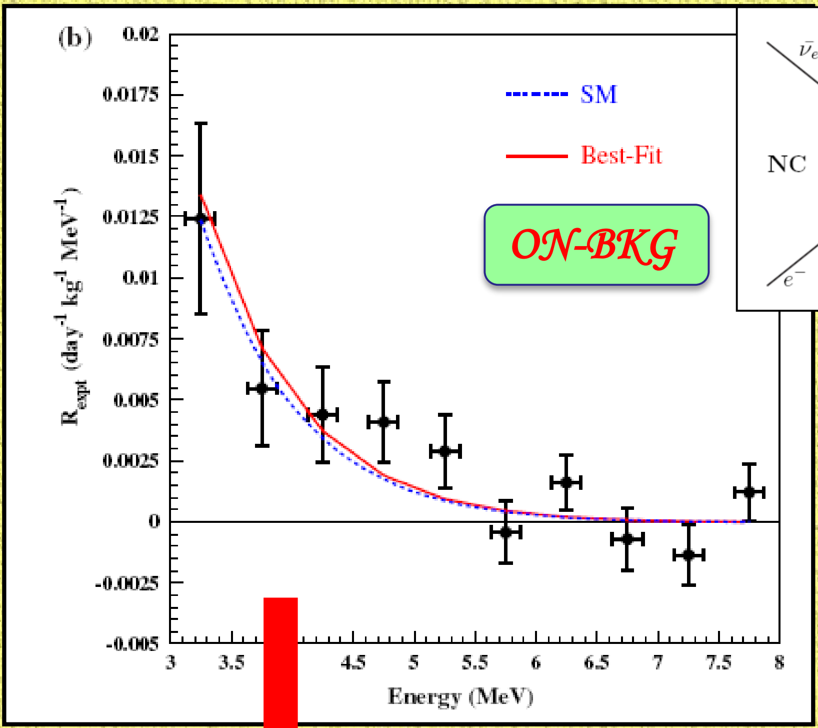
⇨ sub-keV O(kg) ULEGe / PCGe

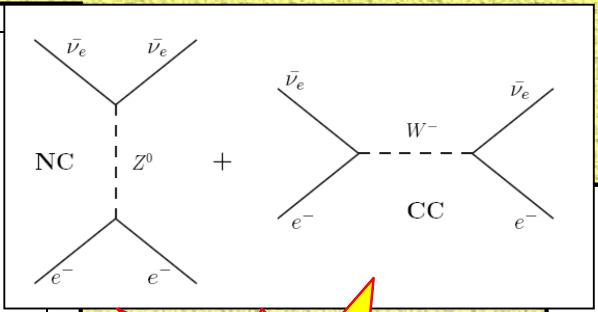
- Dark Matter Searches @ KSNL *[PRD09,PRL13,AP14]*
- CDEX Program@CJPL *[PRD13,PRD14,PRD14;PRD16,PRD17]*
- Theory Program

Neutrino Milli-charge *[PRD14]*

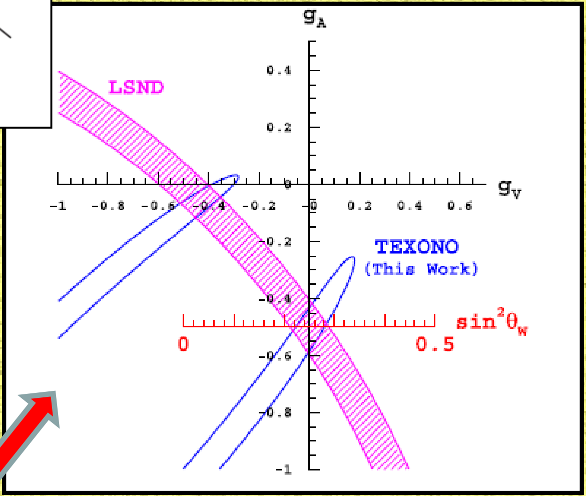
⇨ sub-keV O(kg) ULEGe / PCGe

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





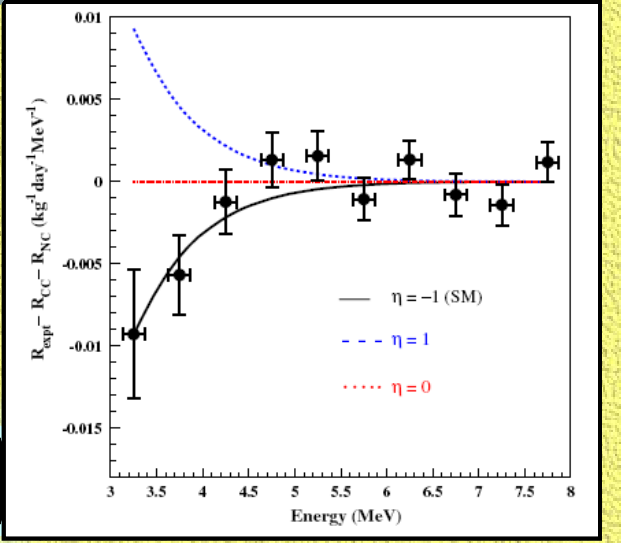
Best Measurement !



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

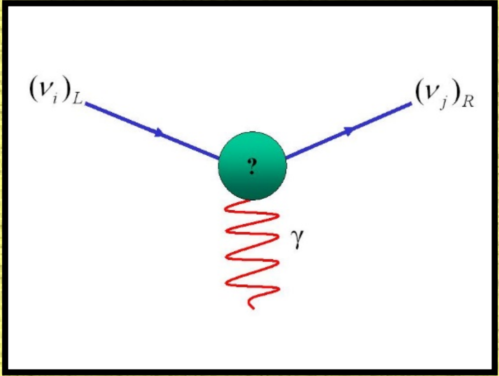
$$\sin^2\theta_W = 0.251 \pm 0.031(stat) \pm 0.024(sys)$$

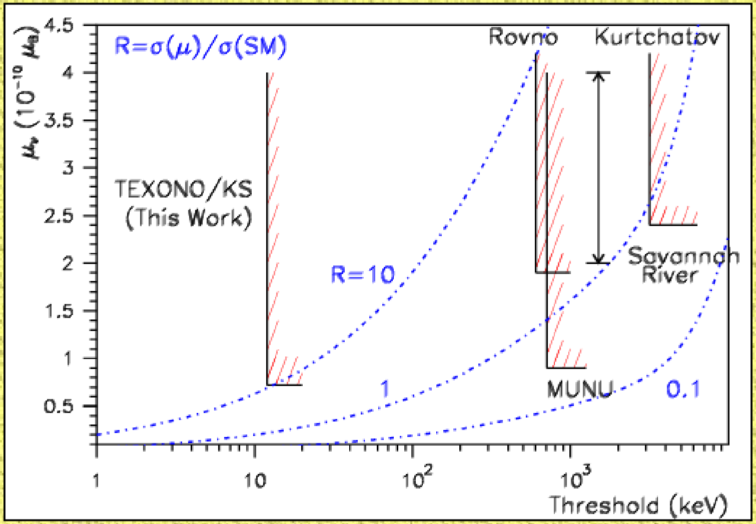
Verify SM Destructive Interference



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

Neutrino Electromagnetic Properties : Magnetic Moments





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

$\mu_\nu(\nu_e) < 7.2 \times 10^{-11}\ \mu_B$ [PRL03,PRL07]

Search of μ_ν at low enery with Reactor νe scattering

⇒ high signal rate & robustness:

- μ_ν>>SM [decouple irreducible bkg ⊕ unknown sources]
- T << E_ν ⇒ $d\sigma/dT$ depends on total ϕ_ν flux but ***NOT*** spectral shape [flux well known : ~6 fission-ν ⊕ ~1.2 ^{238}U capture-ν per fission]

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

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

Neutrino "Milli-charge" *[+ Theorists: Chen, Liu, Chi; PRD14]*

Neutrino Electromagnetic Form Factors

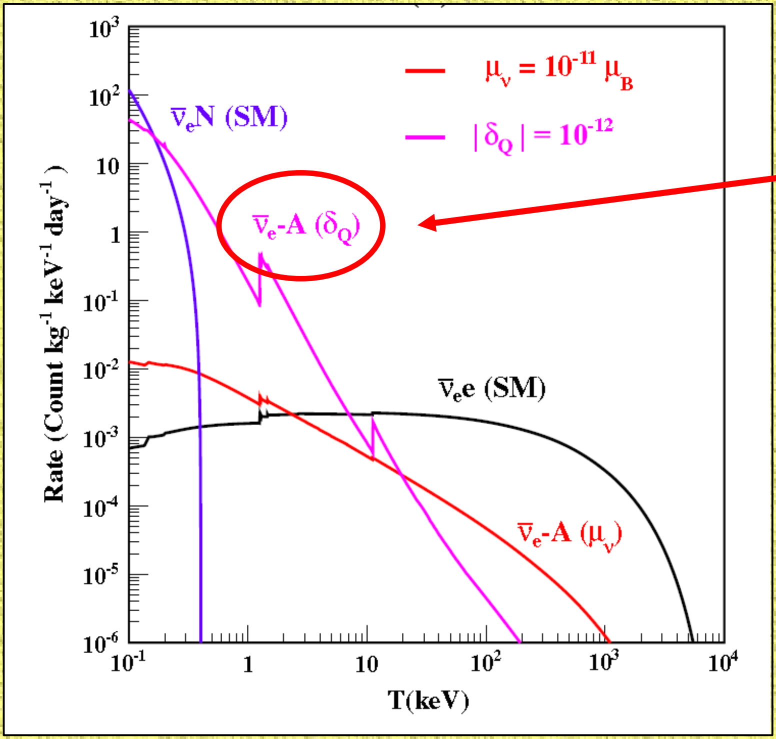
$$\Gamma^{\mu}_{\rm em} \equiv F_1 \cdot \gamma^{\mu} + F_2 \cdot \sigma^{\mu\nu} \cdot q_{\nu}$$

$$F_1 = \delta_{\rm Q} \cdot e_0 + \frac{1}{6} \cdot q^2 \cdot \langle r_{\nu}^2 \rangle,$$

$$F_2 = (-i) \cdot \frac{\mu_{\nu}}{2 \cdot m_e},$$

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

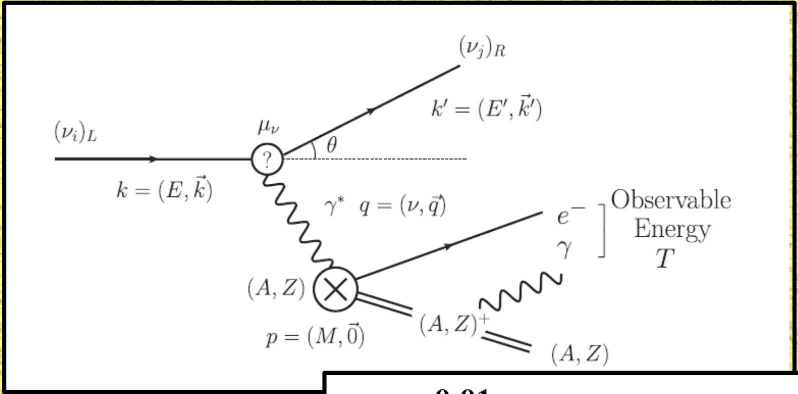
$$\overline{\nu_{\rm e}} + {\rm A} \rightarrow \overline{\nu_{\rm e}} + {\rm A}^+ + e^-,$$

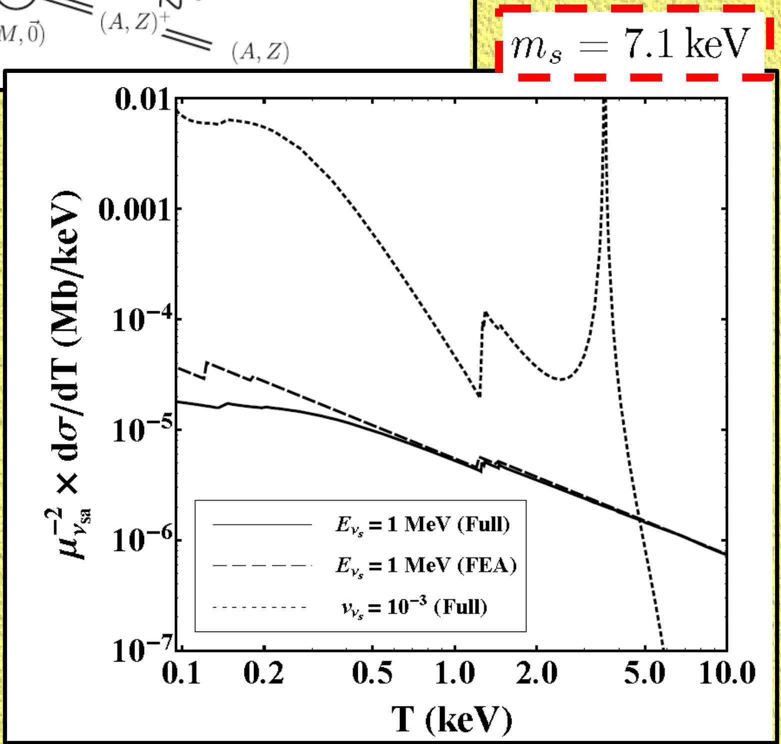


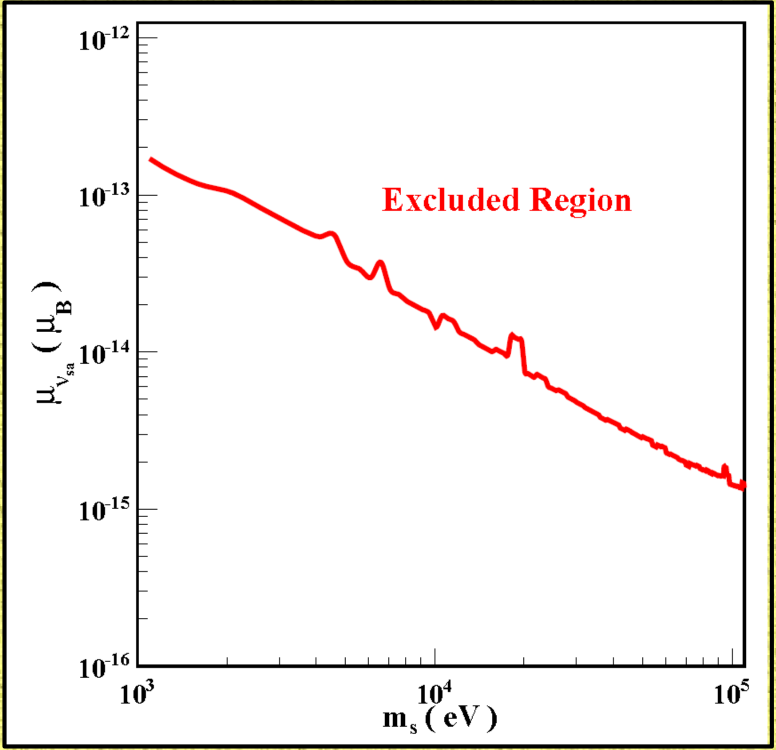
- ☑ **Identify New Twist - Cross-section enhanced at low energy transfer ("minimum ionizing")**
- ☑ **Smoking-gun signatures for positive signals: peaks at known K/L binding energy at known ratios *[different from cosmic-activation electron-capture background]***
- ☑ **Present Bound : $\delta_Q < 10^{-12}$**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

Non-Relativistic Massive Sterile Neutrino to Light SM Neutrinos Via Transition Magnetic Moment Atomic Ionization *[PRD16]*

- Pole structure at differential cross-section at $m_\nu/2$ ($q^2 \sim 0$)







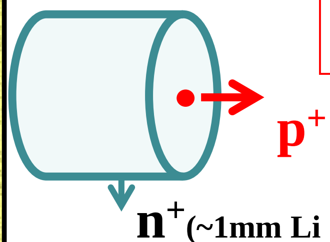
Direct Search of Sterile Neutrinos as Dark Matter

Current Research Theme:
"sub-keV" Ge Detectors

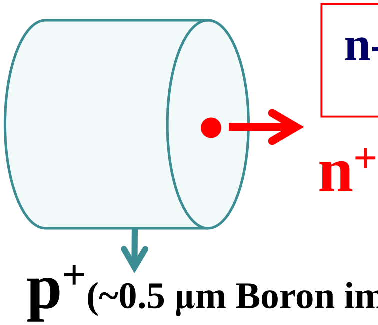
- **Physics Goals for *O[100 eV threhold⊕1 kg mass⊕1 cpkkd] detector* :**
  - **νN coherent scattering , potential applications to reactor monitoring**
  - **Low-mass WIMP searches** ➡ ***[CDEX Program @CJPL]***
  - **Explore ν/WIMP electromagnetic properties & interactions**
  - ***Open & Explore* new detector window & detection channel & physics parameter space**

Baseline Hardware Design
[Both TEXONO@KSNL & CDEX-1@CJPL]

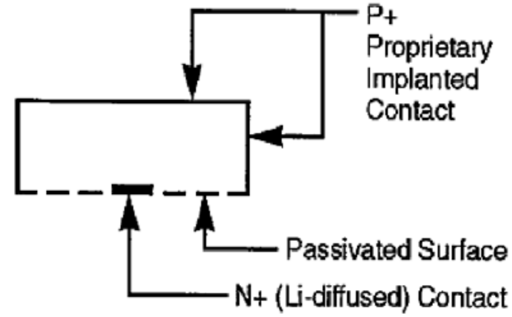
p- PCGe
[500g – 1 kg]



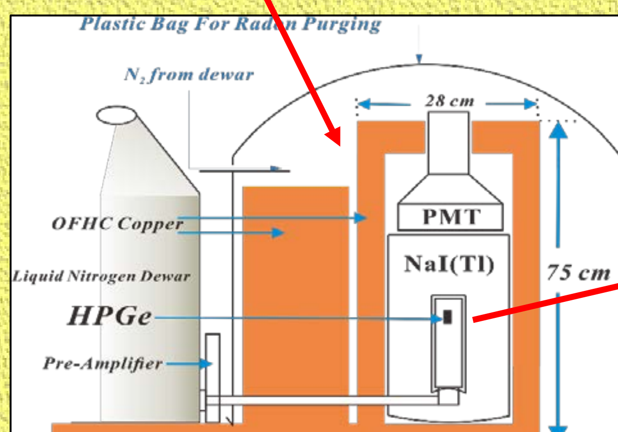
n- PCGe
[500 g]

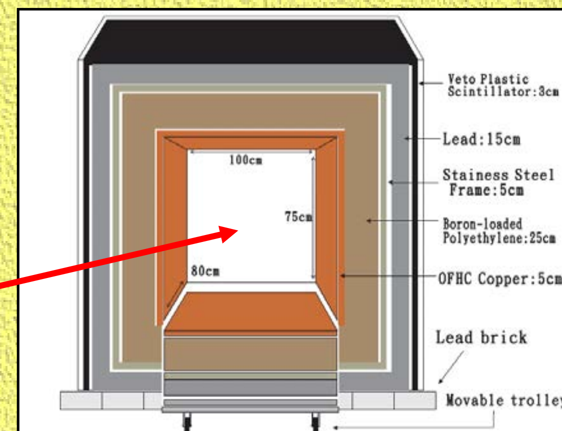


4x5g ULEGe



Electro-Cooled p-PCGe *[1430 g]*

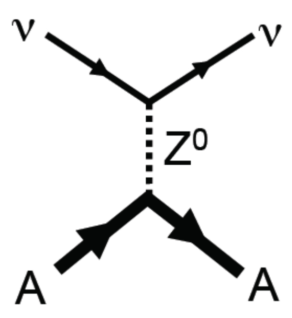


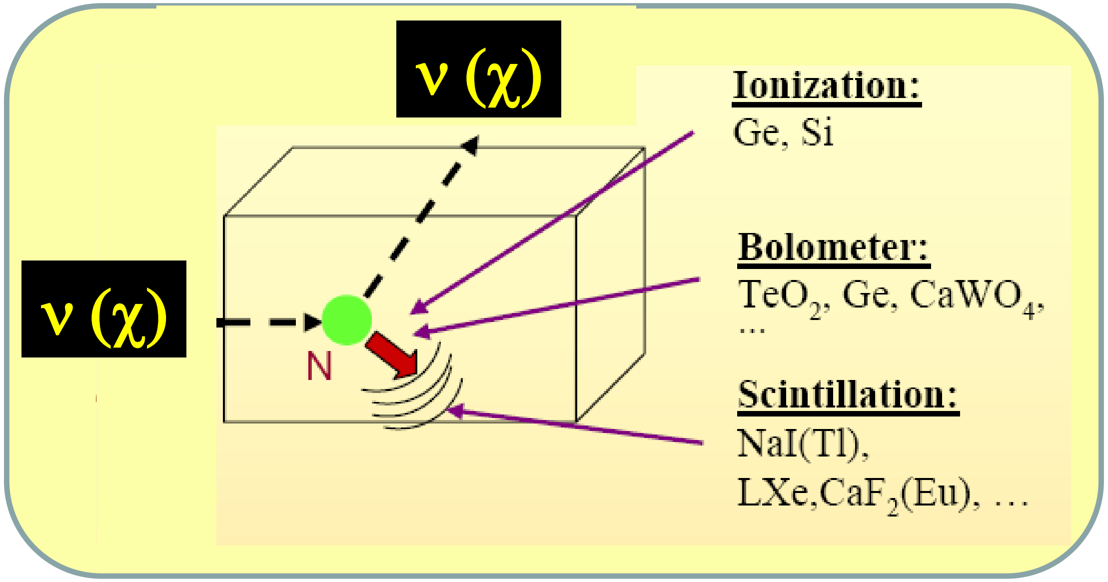


Neutrino-Nucleus Coherent Scattering :

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**
  - $\Rightarrow$ ***"Coherent"** [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~0.2 : cut-off ~ 300 eV ;**
  - **Rate** ~10 kg^{-1} day^{-1} @ threshold~100 eVee

Partial Coherent νN Elastic Scattering Observed by COHERENT@ORNL, ν @ π-DAR *(Science-2017)* !

Complementarity (Extensions) of Reactor Neutrinos:

- ☑ Different kinematics regimes : $q^2 \rightarrow 0$; $FF(q^2)=1$
- ☑ Full QM Coherency *[DAR-νN @ ~0.6 - 0.7 for CsI , threshold 4 keVnr]*
- ☑ Sensitive to different BSM/NSI *(e.g. photon-like massless mediator)*
- ☑ Interest in Potential Applications to reactor monitoring

Coherency in Neutrino-Nucleus Elastic Scattering [PRD16]

- Quantify transitions between Coherency & Decoherency
- Complementarity between different Sources & Target

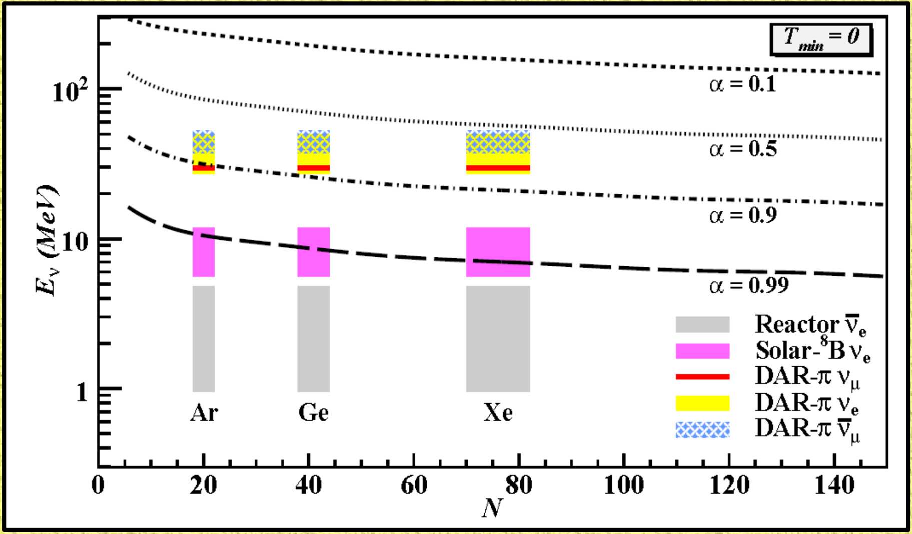


TABLE II: The half-maxima in the distributions of $[\Phi_\nu \cdot \sigma_{\nu A_{el}}]$ at $T_{min}=0$ for the different neutrino sources, and the values of $\langle\alpha\rangle$ probed by the selected target nuclei. The ν_μ from DAR-π is mono-energetic.

ν Source	Half-Maxima of $[\Phi_\nu \cdot \sigma_{\nu A_{el}}]$ in E_ν(MeV)	$\langle\alpha\rangle$ with Ar	Ge	Xe
Reactor $\bar{\nu}_e$	0.96−4.82	1.00	1.00	1.00
Solar-^{8}B ν_e	5.6−11.9	0.99	0.99	0.98
DAR-π ν_μ	29.8	0.91	0.86	0.80
DAR-π ν_e	27.3−49.8	0.89	0.83	0.76
DAR-π $\bar{\nu}_\mu$	37.5−52.6	0.85	0.79	0.71

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

<φ> : averaged decoherence angle

$$\nu + \mathrm{N} \rightarrow \nu + \mathrm{N}$$

Standard Model Cross-Sections at KSNL

[with Quenching Function for Ge for nuclear recoils]

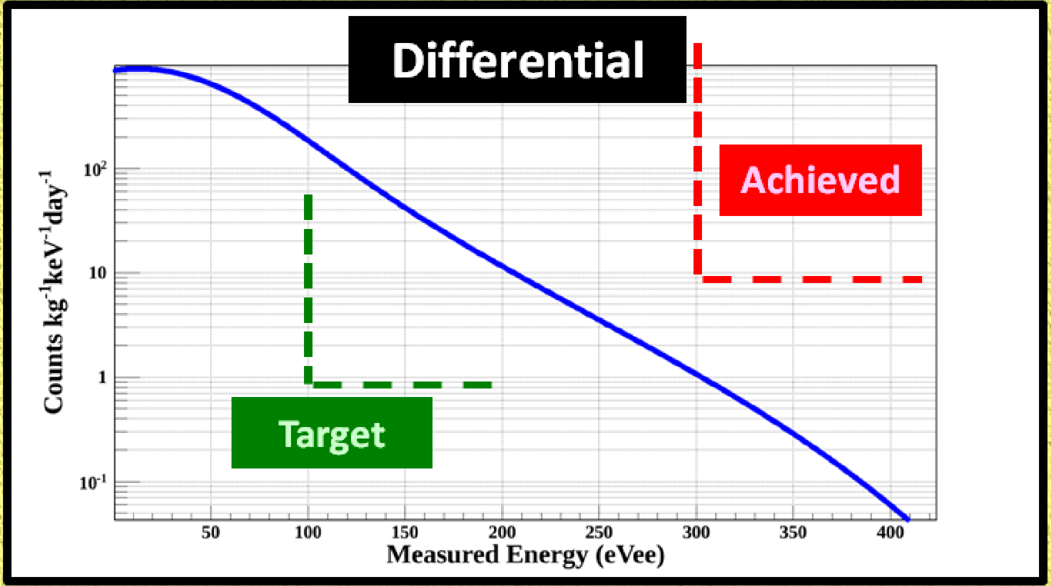
$$\left(\frac{d\sigma}{dT}\right)^{coh}_{SM} = \frac{G_F^2}{4\pi} m_N [Z(1-4\sin^2\theta_W) - N]^2 [1 - \frac{m_N T_N}{2E_\nu^2}]$$

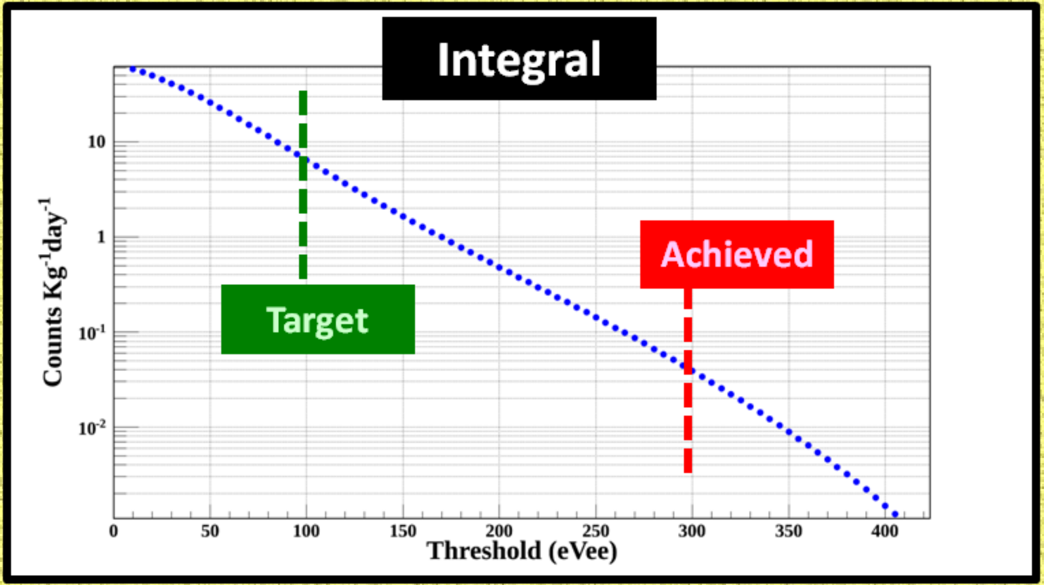
- **Needs Background < 10 cpkkd, Target → 1 cpkkd**

Current Focus !!

- **Needs Threshold < 200 eV_{ee}, Target → 100 eV_{ee}**

$$\sigma_{tot} = \frac{G_F^2 E_\nu^2}{4\pi} [Z(1-4\sin^2\theta_W) - N]^2$$

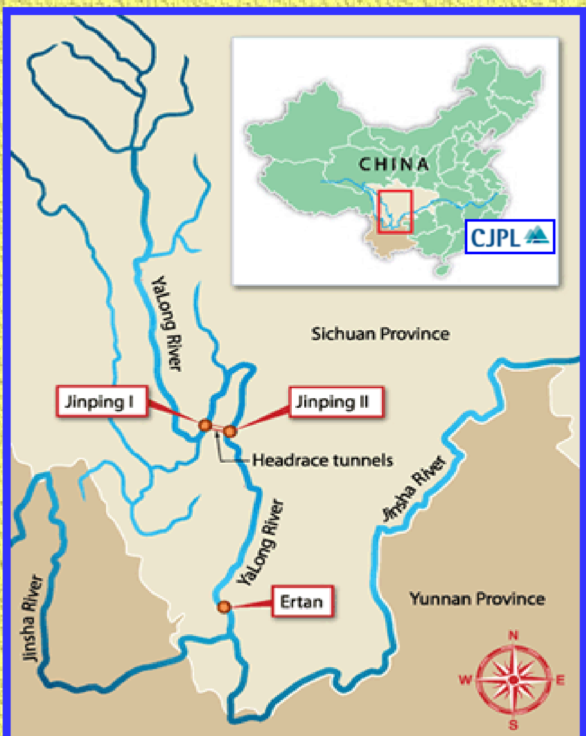


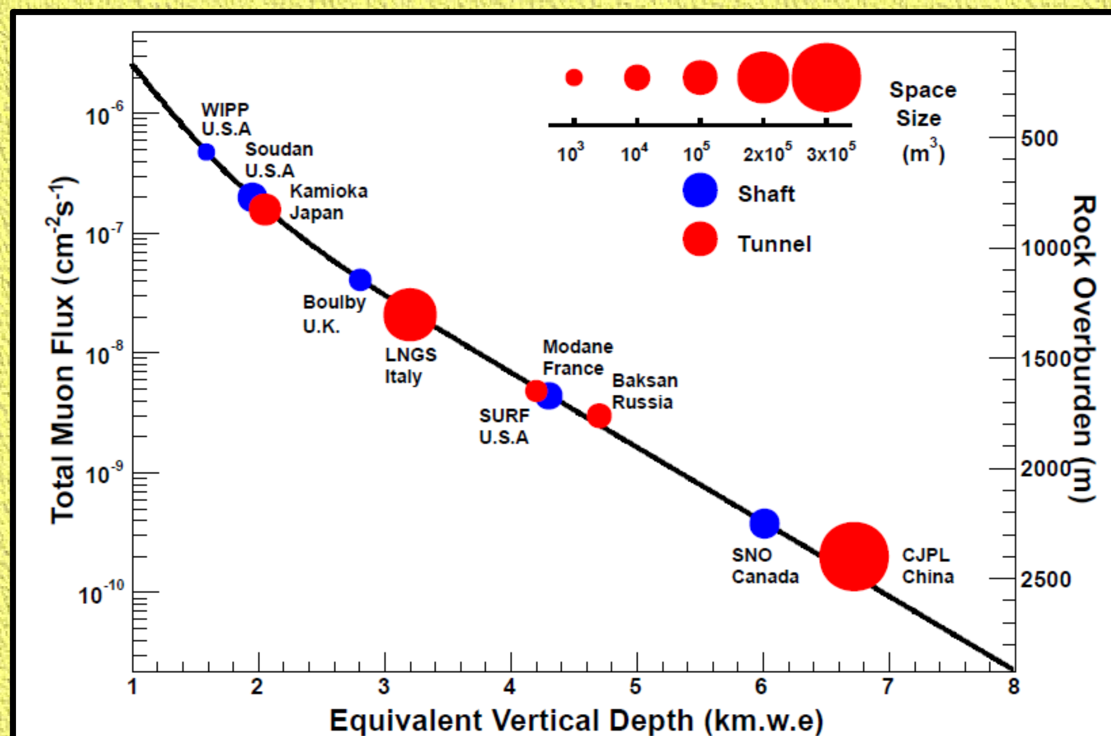


中国锦屏地下实验室

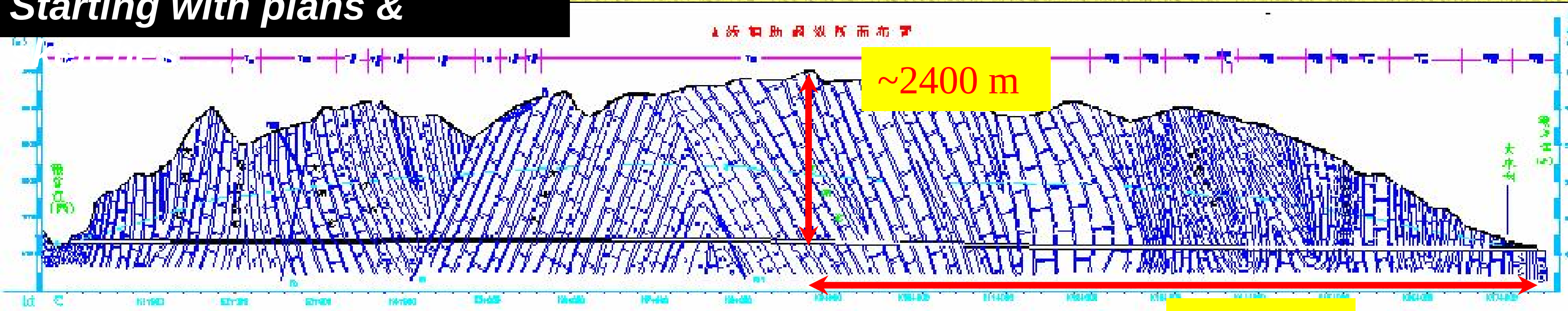
China Jinping Underground Laboratory

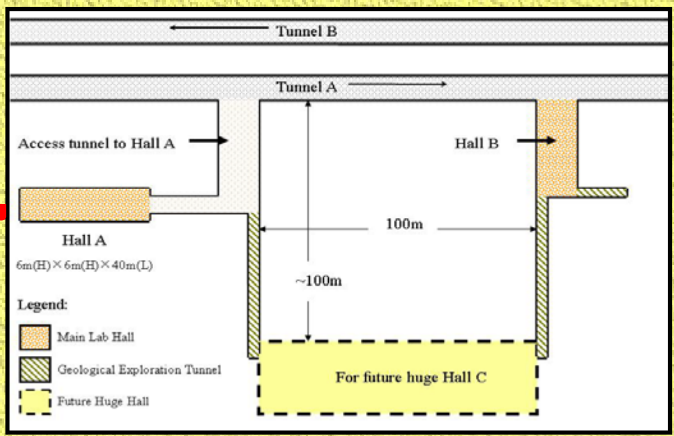
- **Merits:** 2400+ m rock overburden ; drive-in road tunnel access ; superb supporting infrastructures
- Operated & Managed by **THU & YLRHDC**
- **CJPL-I (2010):** 6X6X40 m cavern
- ***CJPL-II (2017-18)*** : *[4X(14X14X130 m) Halls] + Pits*

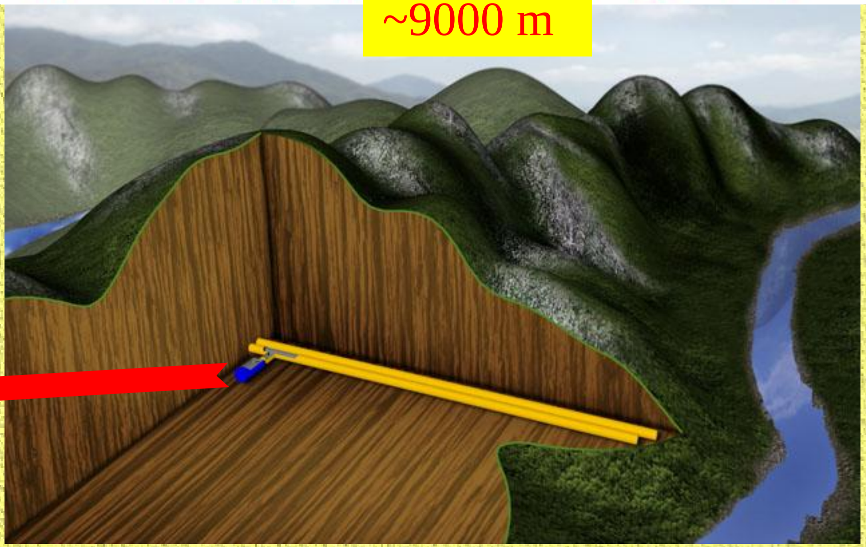


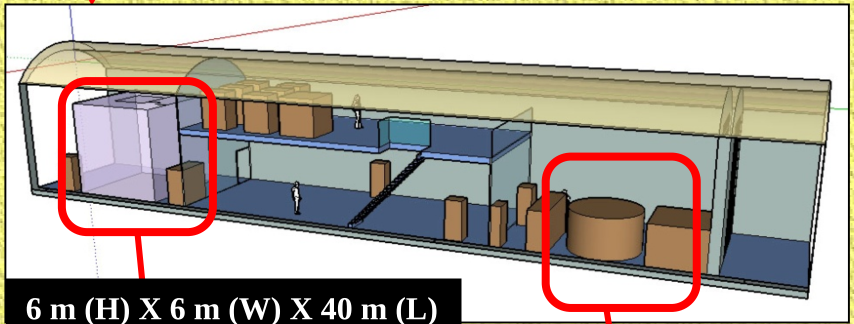


Starting with plans &









6 m (H) X 6 m (W) X 40 m (L)

CDEX-TEXONO

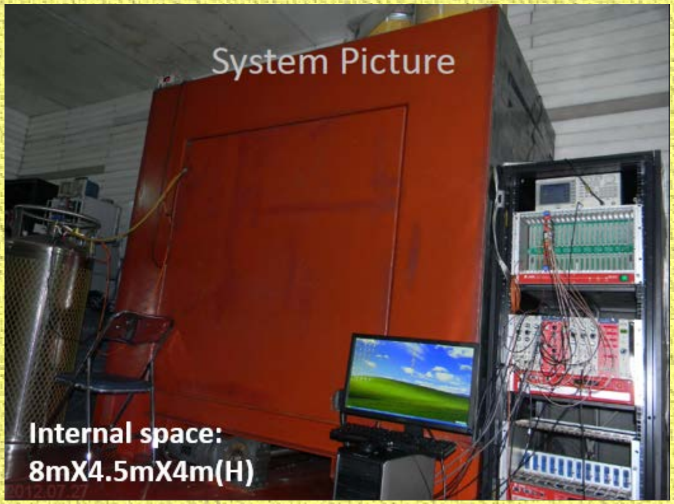
PandaX

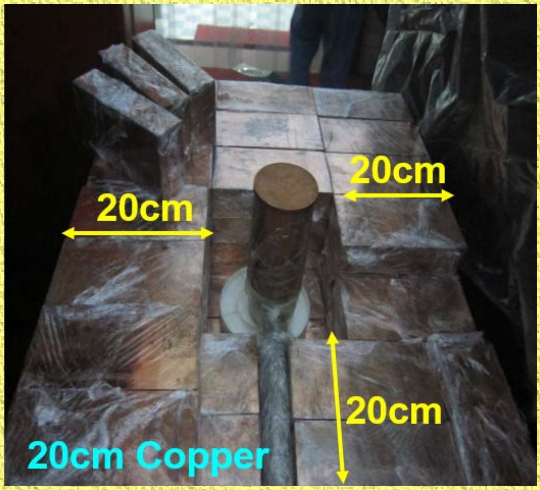
China, others dig more and deeper underground labs

From tiny to gargantuan, experiments are in the works to exploit the shielding from cosmic rays that being deep underground offers.

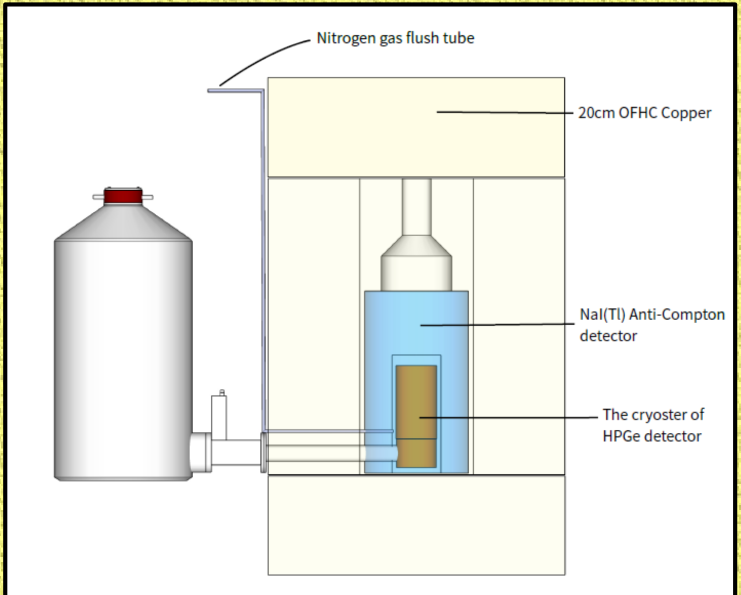
Physics Today September 2010

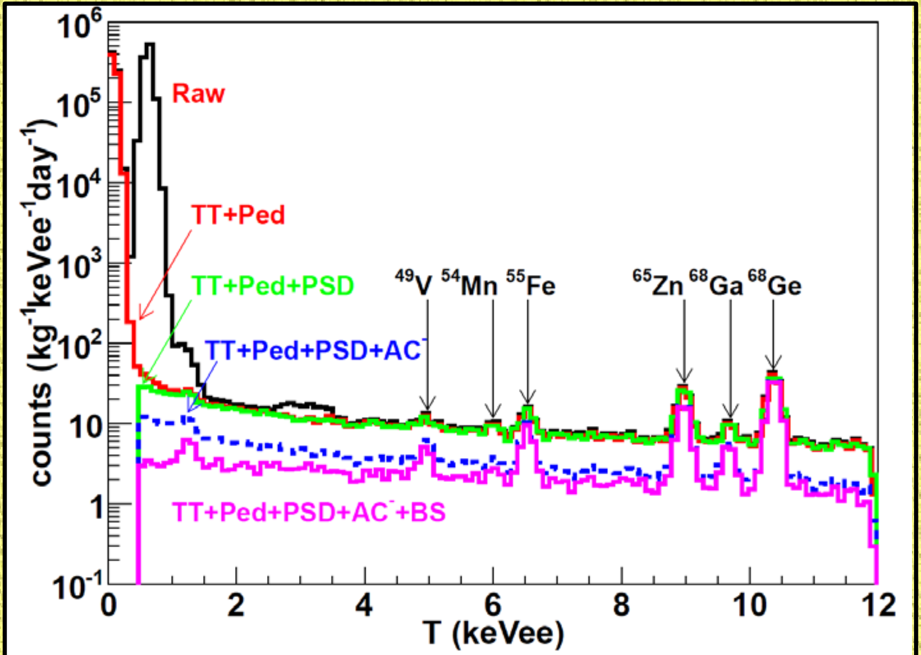
CDEX-1 @ CJPL-I



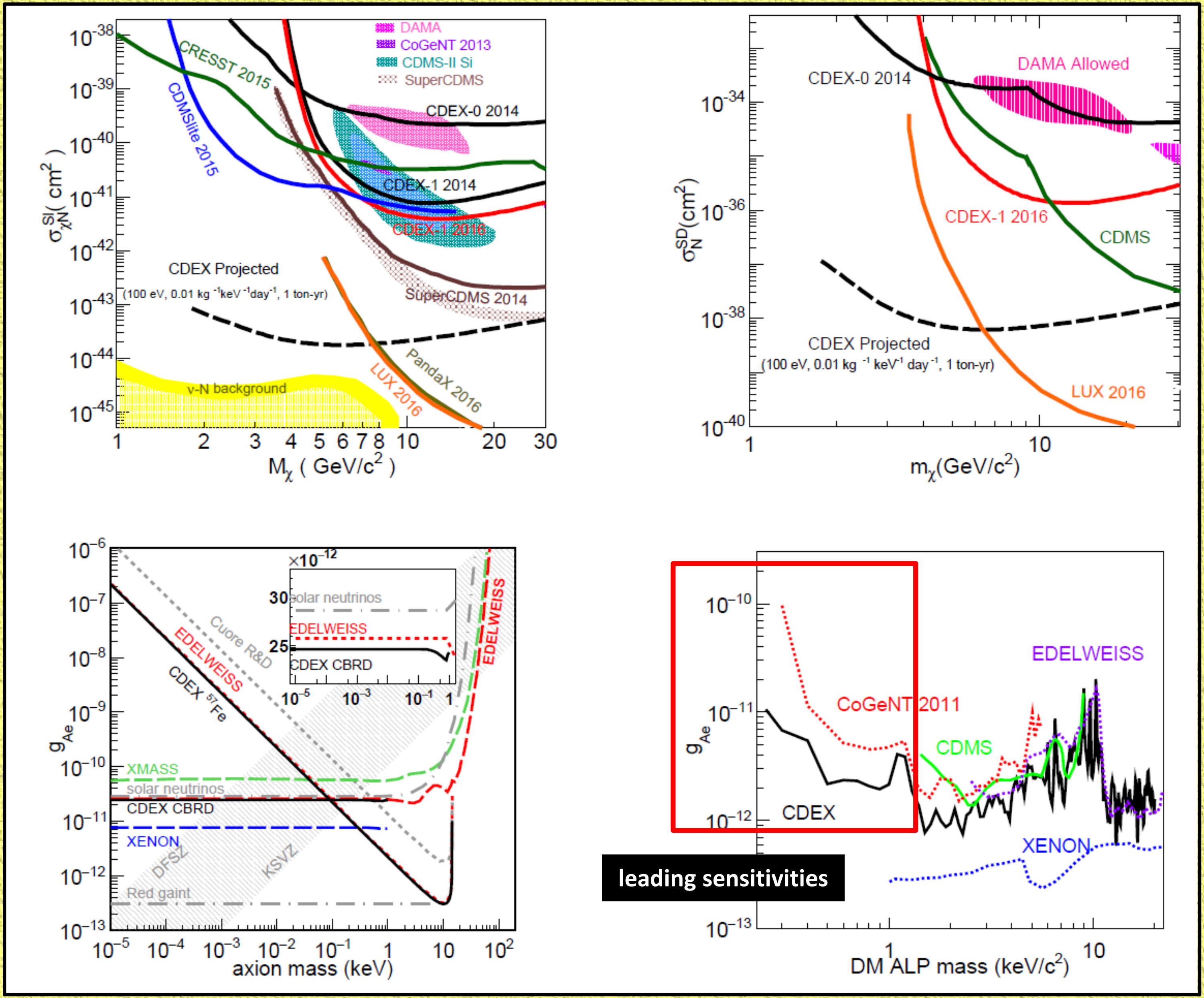


Threshold (published results): 450 eVee





CDEX-1 Results on χN SI/SD ; solar & DM Axions



leading sensitivities

CJPL-Phase II

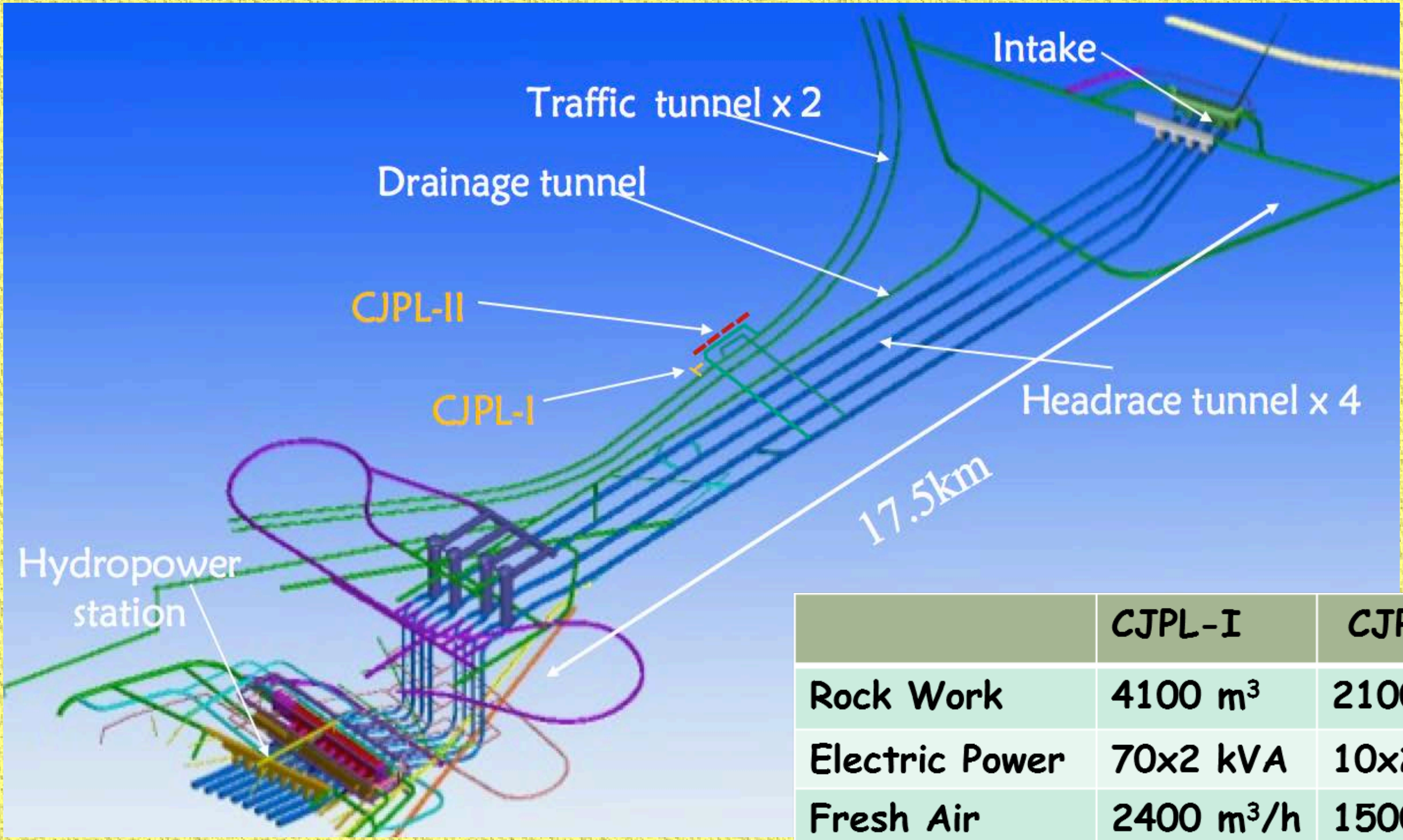
- ☑ ~500m west to CJPL-1
- ☑ Construction started 2014
- ☑ Rock Excavation completed May 2016
- ☑ To be Commissioned *So*

PHYSICS

Science V346, Nov 2014

China supersizes its underground physics lab

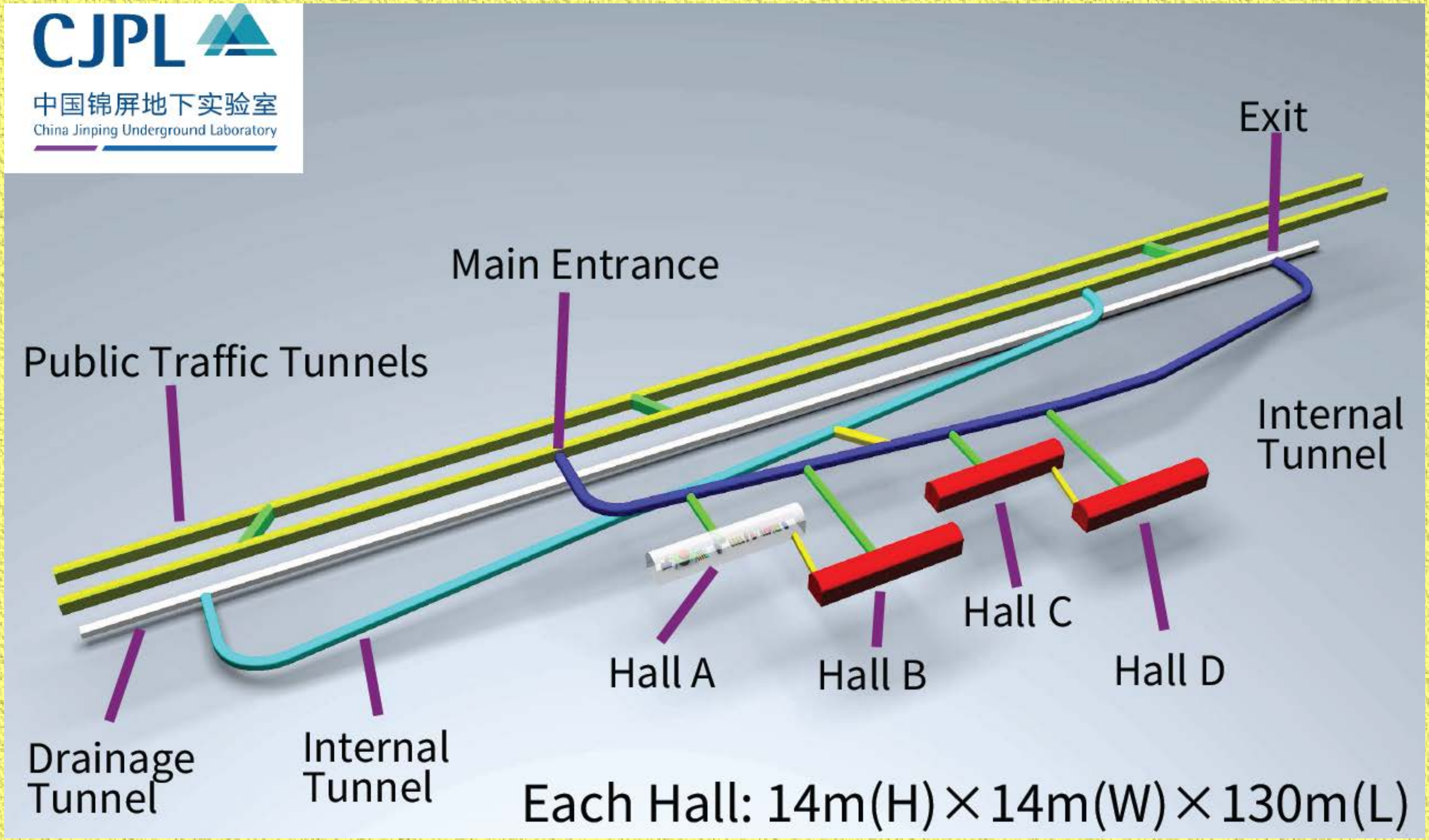
Planned expansion could pave way for “ultimate dark matter experiment”



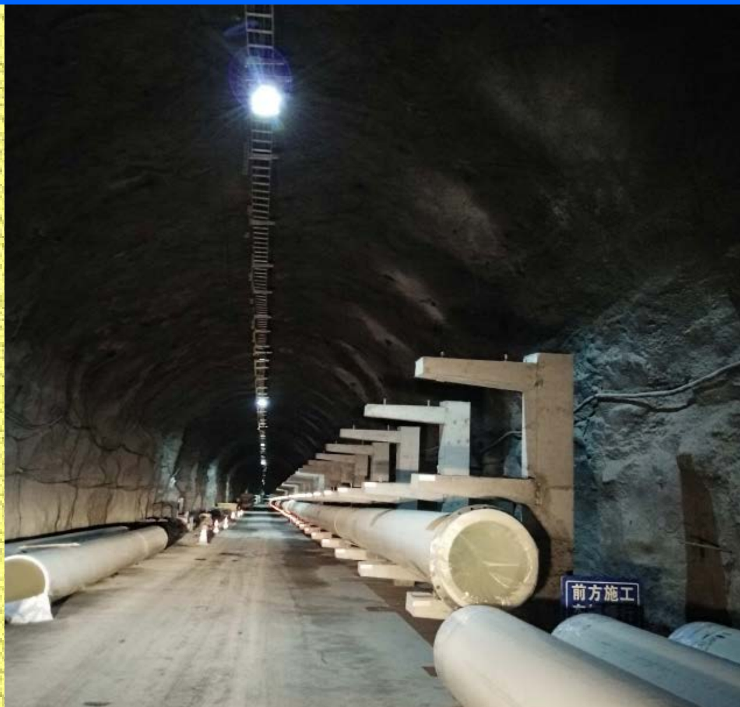
	CJPL-I	CJPL-II
Rock Work	4100 m^3	210000+151000m^3
Electric Power	70x2 kVA	10x2 MVA
Fresh Air	2400 m^3/h	15000x3 m^3/h

CJPL-II Layout

- ☑ 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

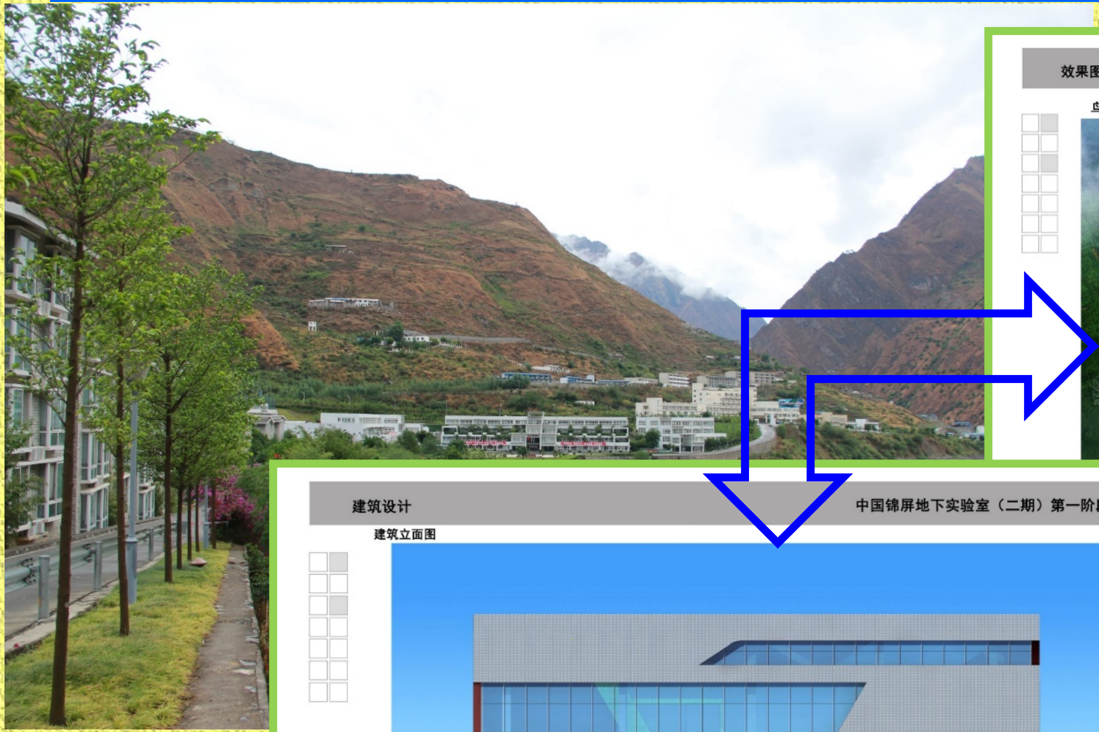


CJPL-II Civil Engineering

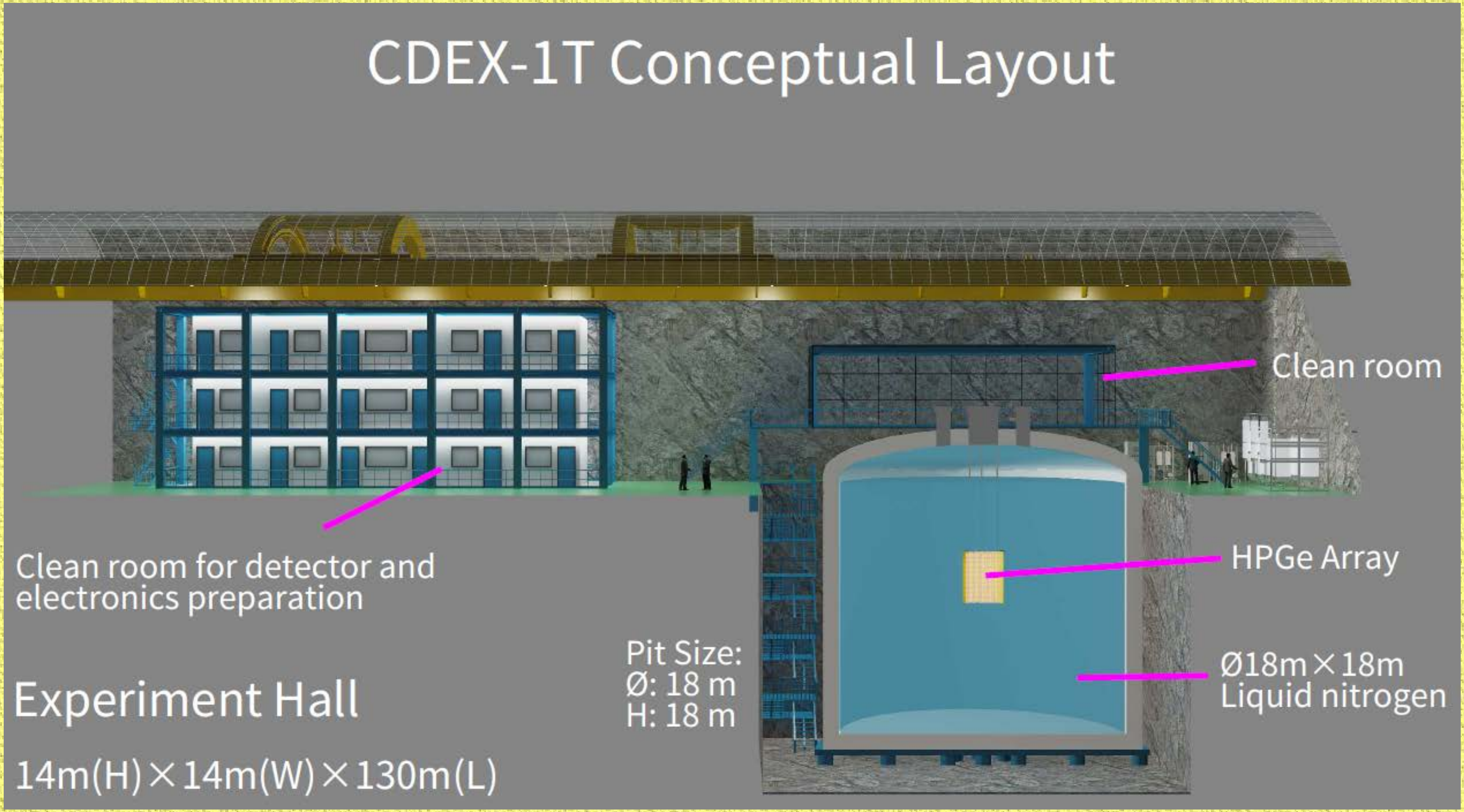


Plan of Ground Laboratory (~2020)

- offices, workshops, meeting venues, accommodation, logistics (~150 people)



CDEX-1T (HPGe DM & 0νββ) Projects



CJPL-II Hall-C Pit

LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

Mission: "The collaboration aims to develop a phased, Ge-76 based double-beta decay experimental program with discovery potential at a half-life significantly longer than 10^{27} years, using existing resources as appropriate to expedite physics results."

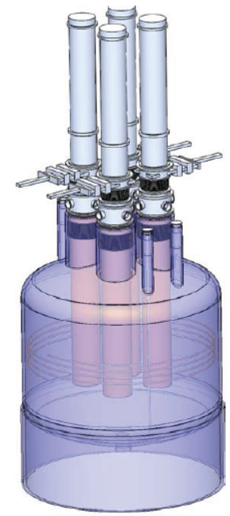
Select best technologies, based on what has been learned from GERDA and the MAJORANA DEMONSTRATOR, as well as contributions from other groups and experiments.

First phase:

- up to 200 kg
- modification of existing GERDA infrastructure at LNGS
- BG goal 0.6 c /(FWMH t y)
- start by 2021

Subsequent stages:

- staged 1000 kg
- timeline connected to U.S. DOE down select process
- BG: goal 0.1 c /(FWHM t y)
- Location: TBD
- Required depth (Ge-77m) under investigation



- ☑ **Towards Ton-scale enriched-Ge76 experiment for neutrinoless double beta decay experiment to cover the "Inverted Hierarchy"**
- ☑ **Cast : mainly GERDA, Majorana, CDEX groups**
- ☑ **CDEX group – build a case of hosting this experiment at CJPL-II**
- ☑ **Great Opportunities (Expensive Problems) in Nuclear Physics –** ***nuclear matrix elements, g_A in nuclear process……***

Summary & Outlook

- TEXONO@KSNL contributed to neutrino electro-magnetic and electro-weak physics, incl. best cross-section measurement among two of the fundamental leptons.
- CDEX@CJPL (+TEXONO) ➡ competitive results in low-mass WIMPs with sub-keV detectors
- Frontline for low threshold germanium detectors & physics applications like νN measurement
- CJPL @ China adds to the world's arsenal of low-background facility.
- Collaboration with Atomic/Nuclear/QCD communities has yielded fruits and expanded horizons to both.