Dark Matter & Reactor Neutrino Physics with sub-keV Germanium Detectors

- Facilities: KSNL & CJPL
- Neutrinos: Physics with Ge at Reactor
- Dark Matter: Light WIMPs Searches

Henry T. Wong /王子敬

Academia Sinica, Taiwan /中央研究院 @

2nd International Workshop on

Particle Physics and Cosmology after Higgs and Planck

後希格斯與普朗克粒子物理與宇宙學國際研討會

October 8-9, 2014 - National Center for Theoretical Sciences, Hsinchu, Taiwan

October 10-11, 2014 - Fo-Guang-Shan, Kaohsiung, Taiwan

TEXONO-CDEX Collaboration

TEXONO

Taiwan EXperiment On NeutrinO *[since 1997]*:

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

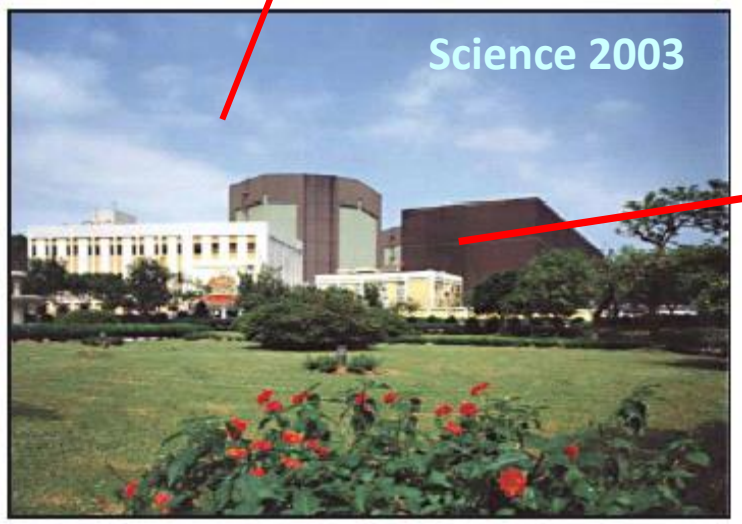
CDEX

China Dark Matter EXperiment *[birth 2009]*:

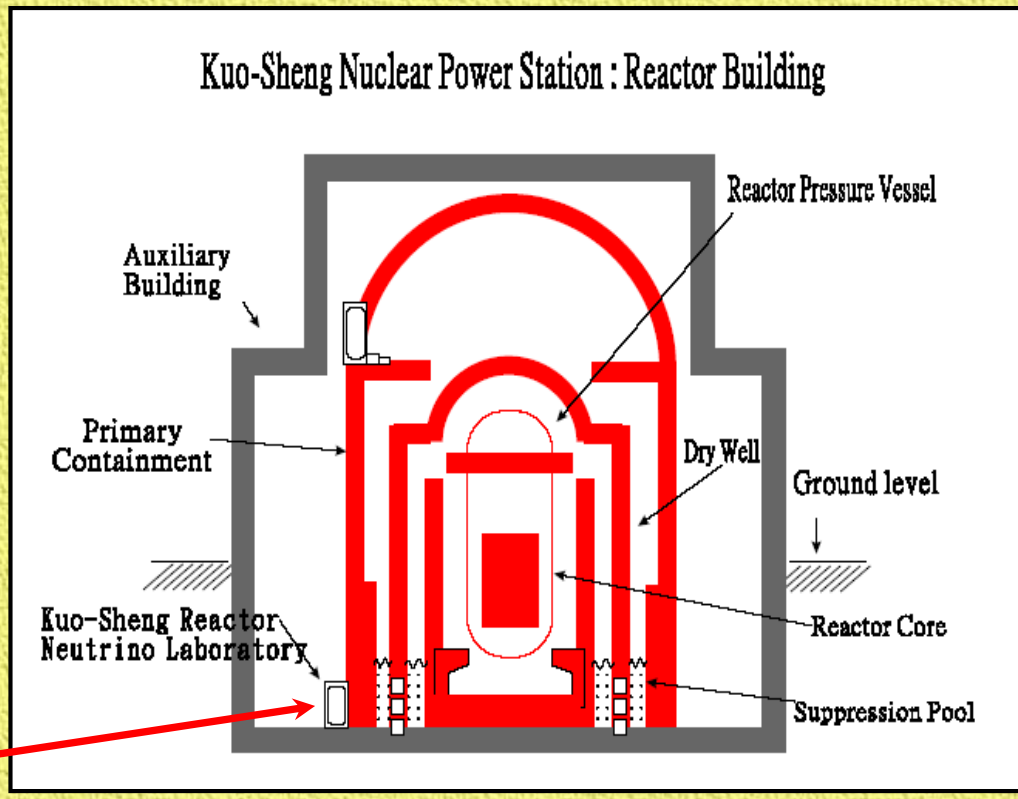
- Dark Matter Searches at China Jin-Ping Underground Laboratory (CJPL)
  - China (THU, CIAE, NKU, SCU,YLJHD)

Research Program: Low Energy Neutrino and Dark Matter Physics

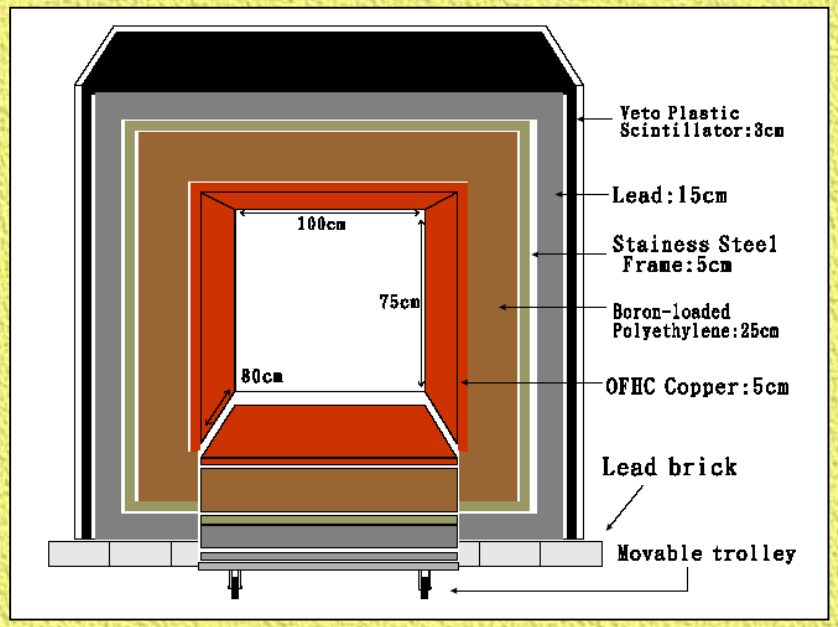
Kuo Sheng Reactor Neutrino Laboratory [KSNL]



Powerful collaboration. Scientists from Taiwan and mainland China are studying neutrino emissions from this nuclear power plant outside Taipei.



- **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

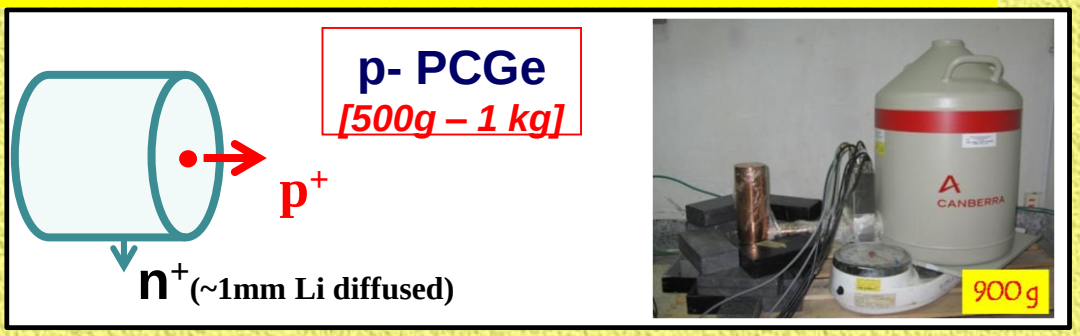
Configuration: **Modest yet Unique**

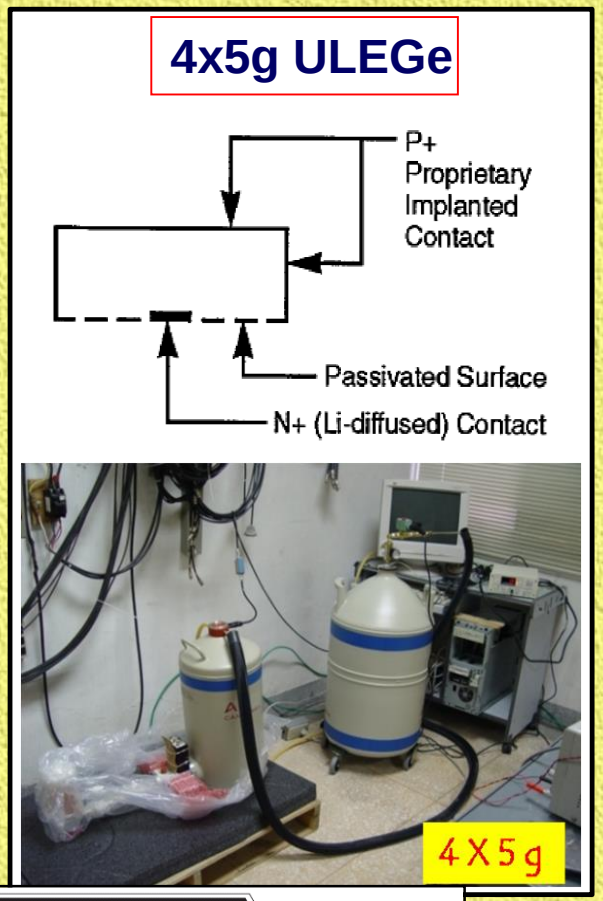
Flexible "Baseline" Design:

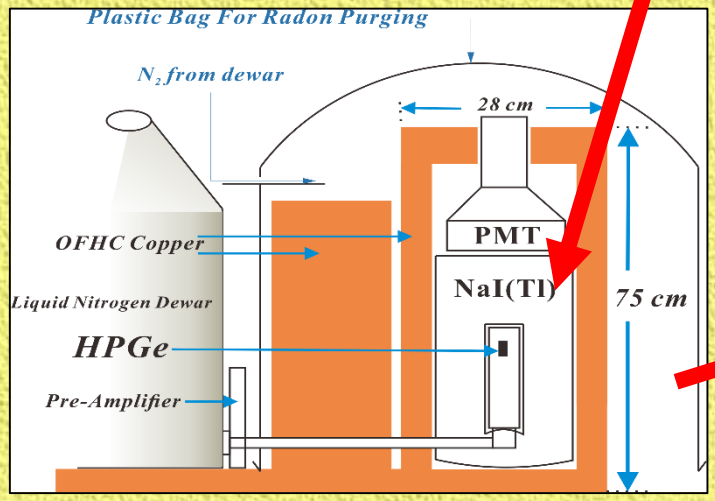
Allows different detectors conf. for different physics

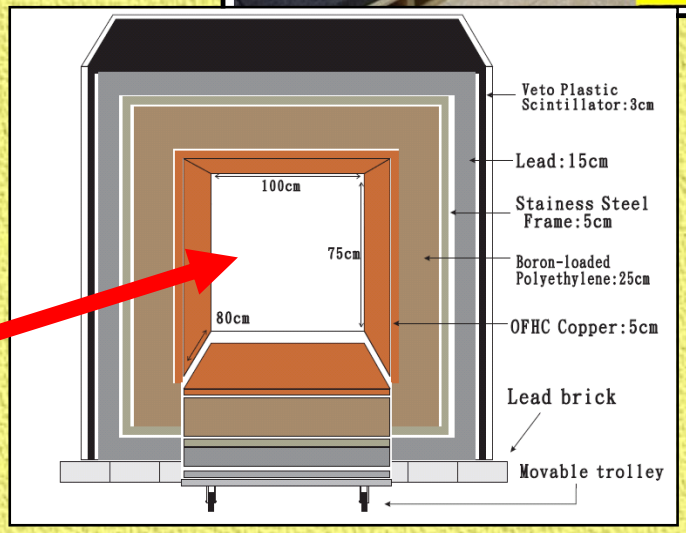
Baseline Hardware Design

[Both TEXONO@KSNL & CDEX-1@CJPL]









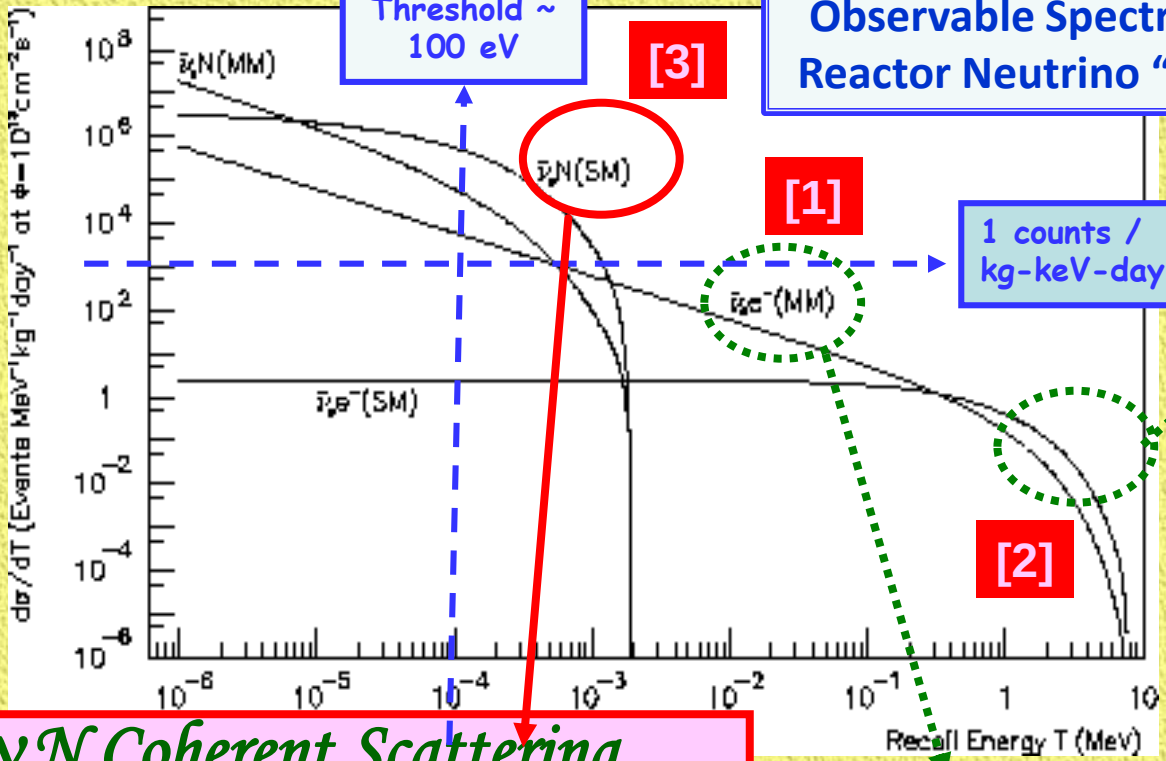
Neutrino Properties & Interactions at Reactor

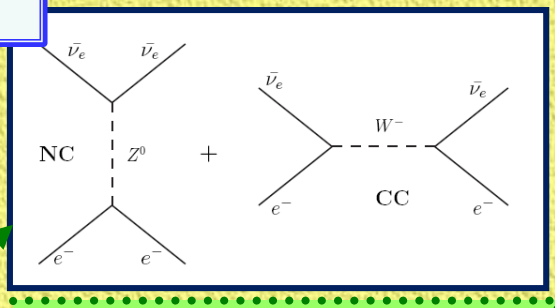
quality ← **Detector requirements** → **mass**

Threshold ~ 100 eV

[3]

Observable Spectra with Reactor Neutrino "Beam"





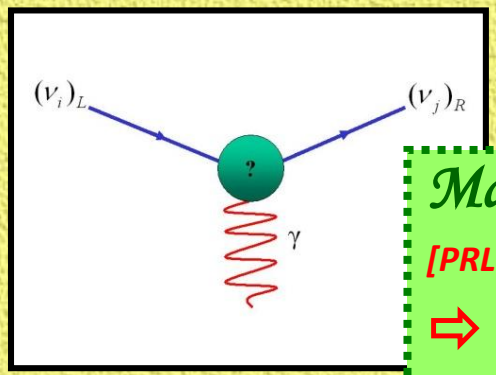
SM & NSI/BSM νe Scattering

[PRD10,PRD10,PRD12]

⇨ 200 kg CsI(Tl)

νN Coherent Scattering

- sub-keV O(kg) Ge
- Dark Matter Searches @ KSNL *[PRD09;PRL13,AP14]*
- DM@CDEX@CJPL *[PRD13,PRD14, arXiV: 1404.4946]*
- New Ideas .....

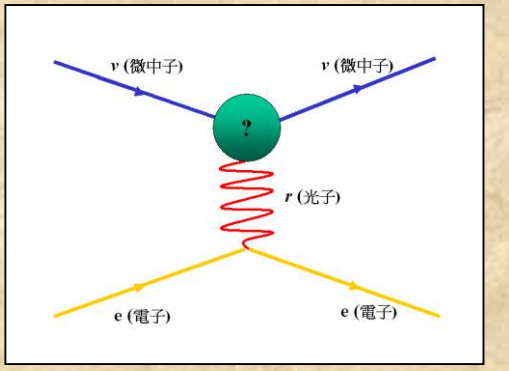


Magnetic Moments

[PRL03,PRD05,PRD07]

⇨ 1 kg HPGe

Reactor Neutrino @ KSNL : Summary



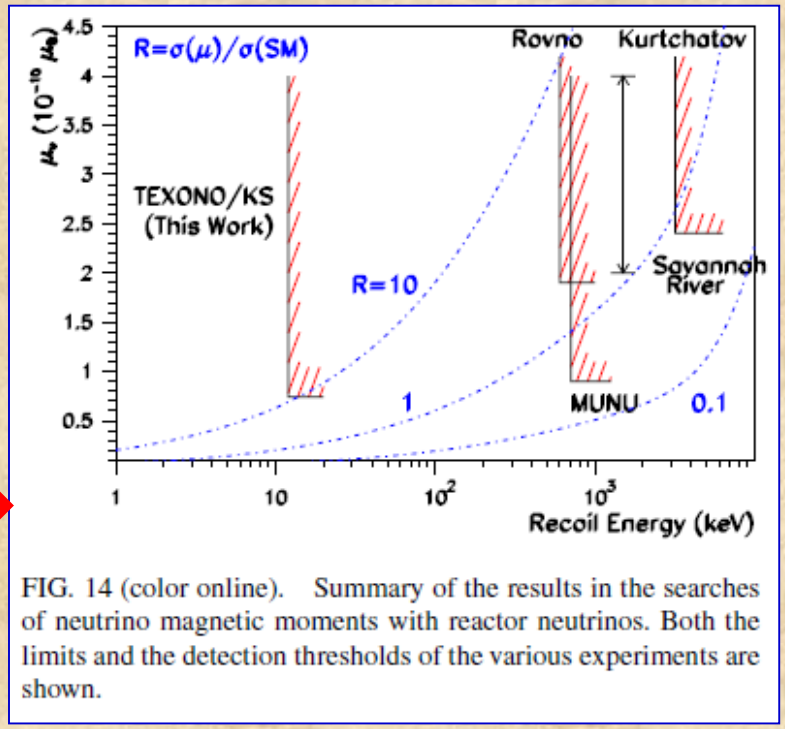
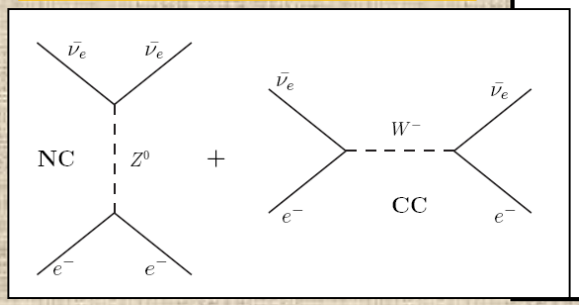
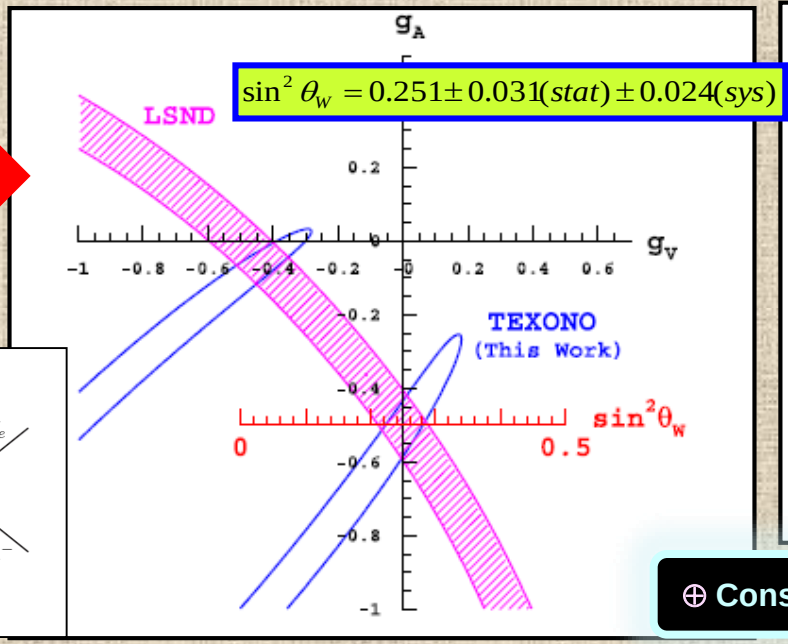
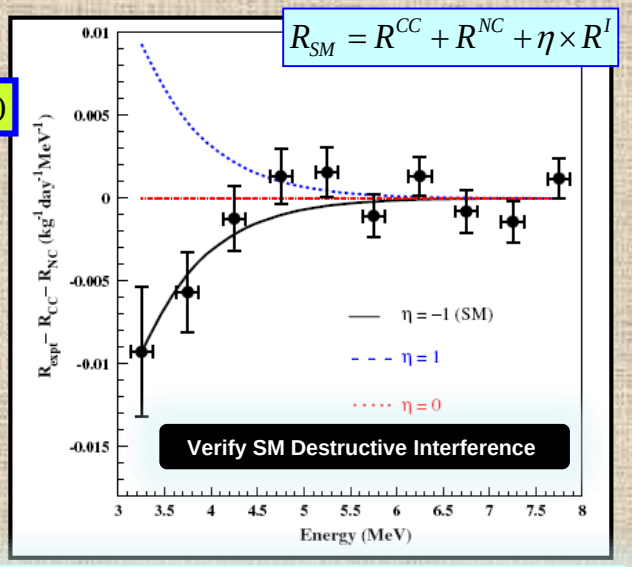


FIG. 14 (color online). Summary of the results in the searches of neutrino magnetic moments with reactor neutrinos. Both the limits and the detection thresholds of the various experiments are shown.







⊕ Constraints on Various Beyond SM Effects

NEW (!) : Neutrino "Milli-charge" *[+Chen, Liu, Chi; PRD14]*

Neutrino Electromagnetic Form Factors

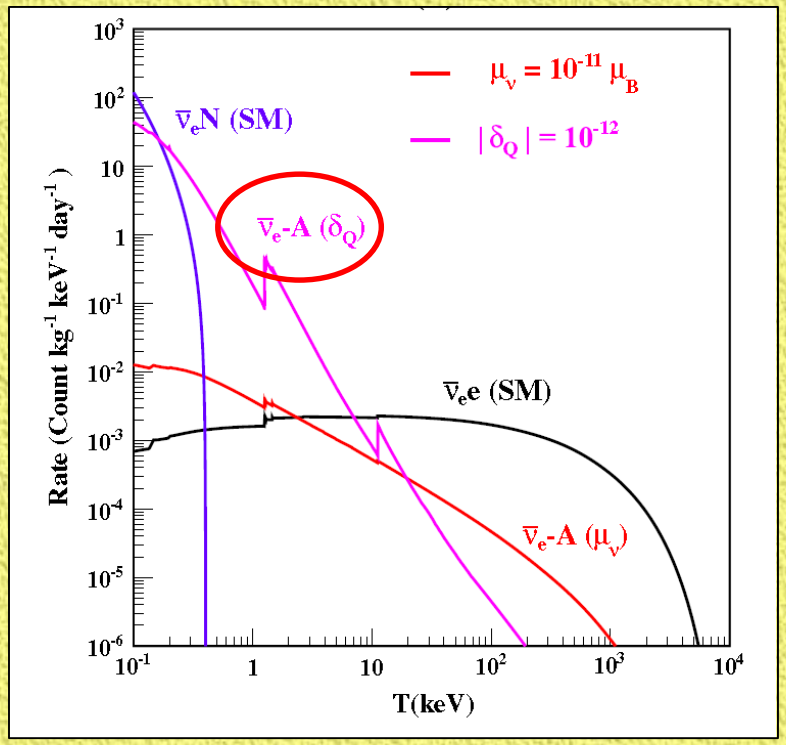
$$\Gamma^{\mu}_{\mathrm{em}} \equiv F_1 \cdot \gamma^{\mu} + F_2 \cdot \sigma^{\mu\nu} \cdot q_{\nu}$$

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

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

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

$$\overline{\nu_e} + \mathrm{A} \rightarrow \overline{\nu_e} + \mathrm{A}^+ + e^-,$$



- ☑ **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):** $\delta_Q \sim 10^{-14}$

Current Research Theme:

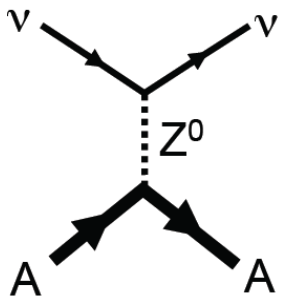
"sub-keV" Ge Detectors

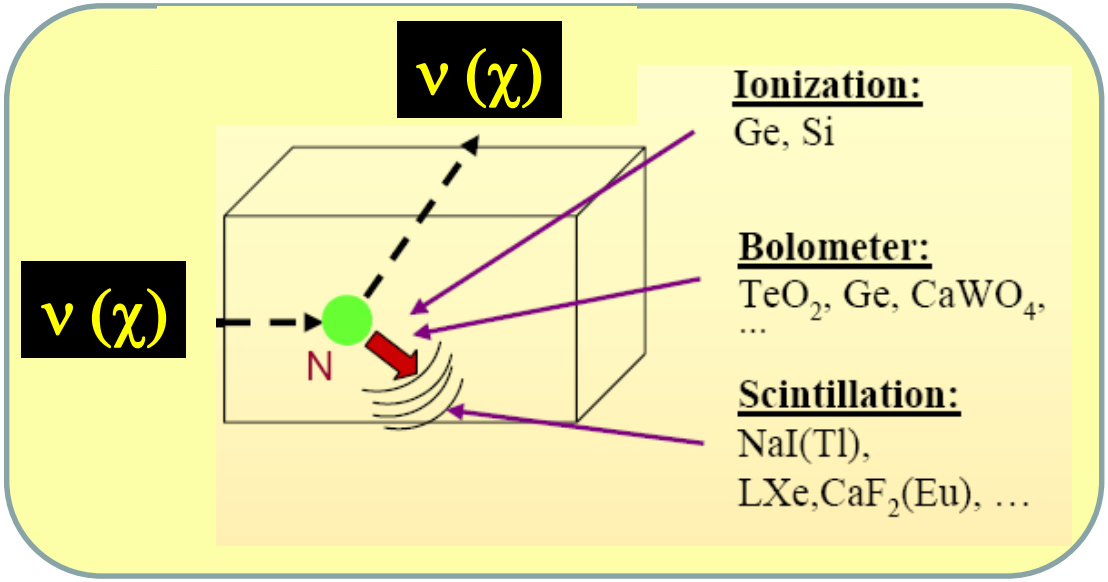
- **Physics Goals for *O[100 eV threhold⊕1 kg mass⊕1 cpkkd] detector* :**
  - **νN coherent scattering , potential applications to reactor monitoring**
  - **Low-mass WIMP searches ➡ *[CDEX Program @CJPL]***
  - **Explore ν/WIMP electromagnetic properties & interactions**
  - ***Open & Explore* new detector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

Neutrino-Nucleus Coherent Scattering :

Standard Model allowed and predicted processes :

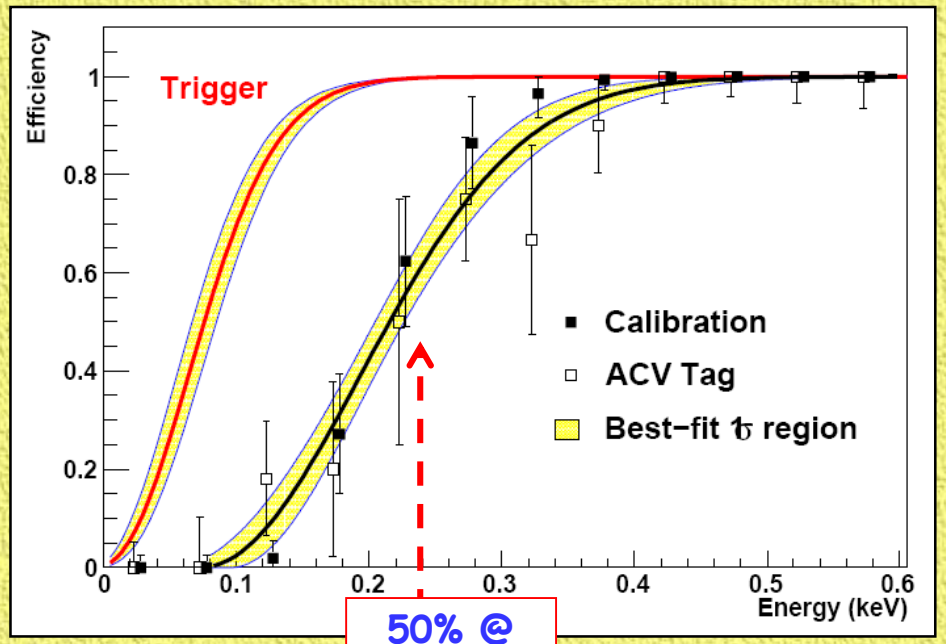
$$\nu + A \rightarrow \nu + A$$

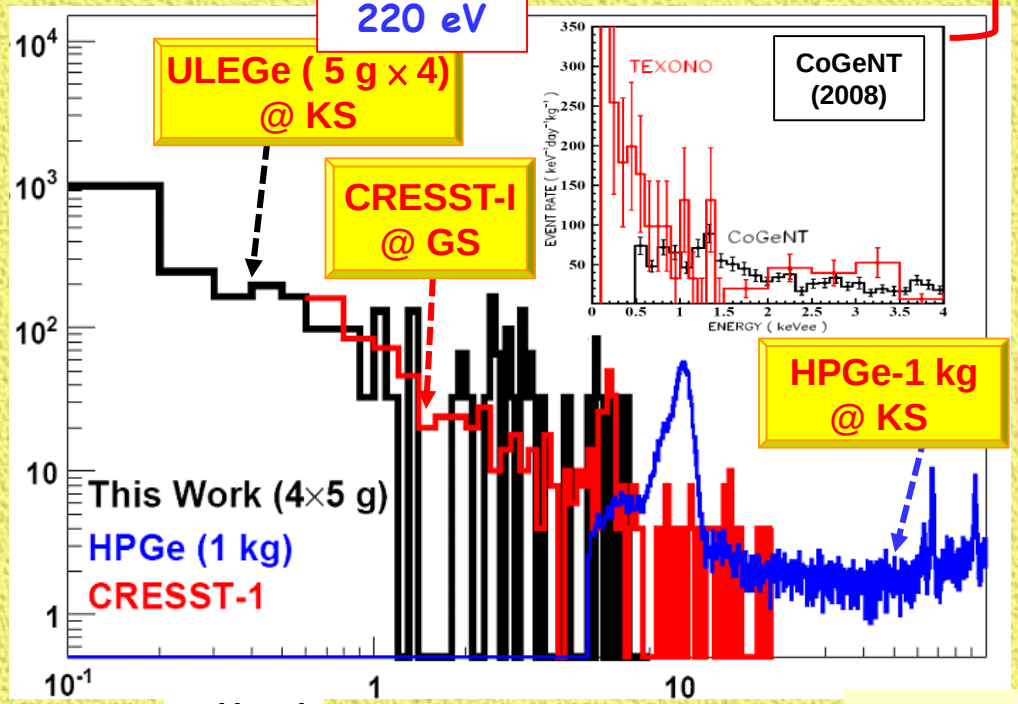


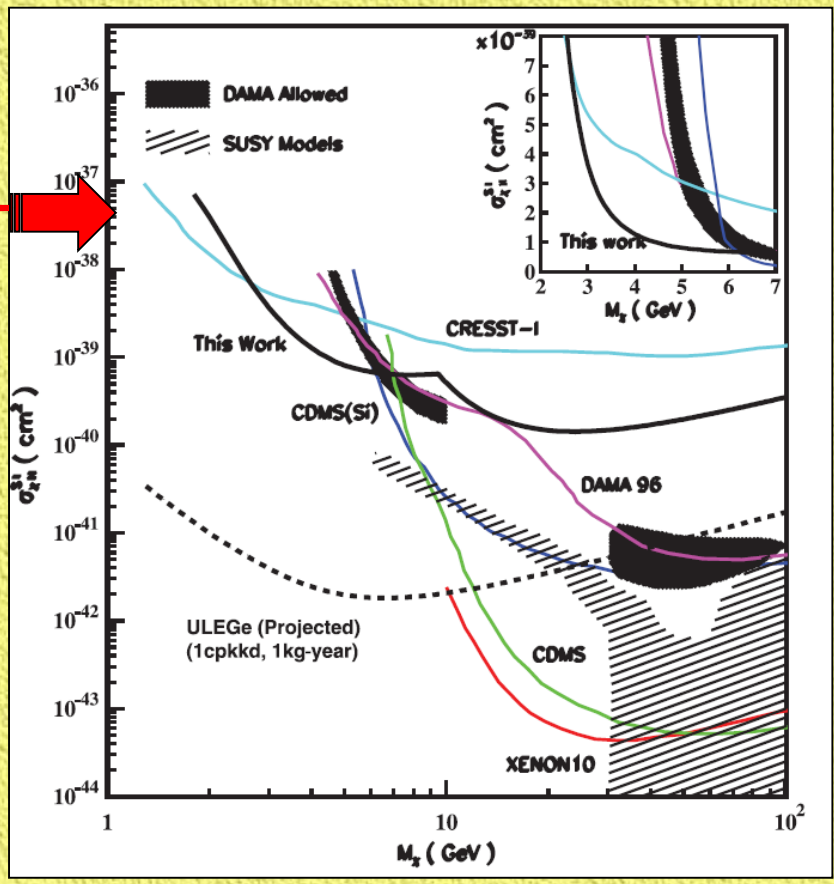


- Neutral current process (same for all ν-flavor)
- $\sigma \propto N^2$ @ $E_\nu < 50$ MeV
  - ⇒ *"Coherent" [probe "sees" the whole nucleus]*
- sensitive probe for BSM ; interest in reactor monitoring
- important process in stellar collapse & supernova explosion
- Irreducible background/analogous interaction in dark matter detection
- Ge at KSNL @ QF~0.2 : cut-off ~ 300 eV ;
  - Rate ~10 kg^{-1} day^{-1} @ threshold~100 eV

TEXONO @ KSNL :
Threshold & Efficiencies & Background for 20g ULEGe (2007)





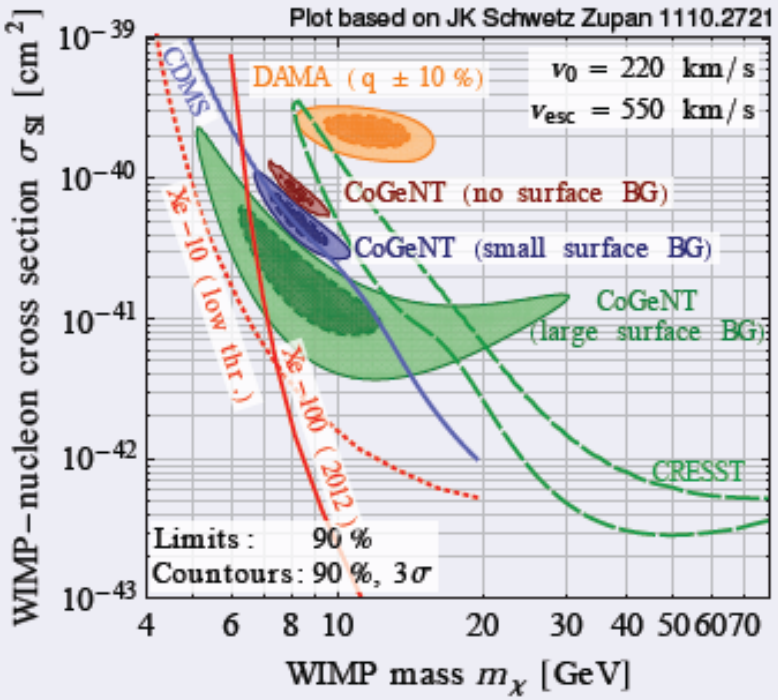


Much has happened world-wide since .....

Hints for light dark matter

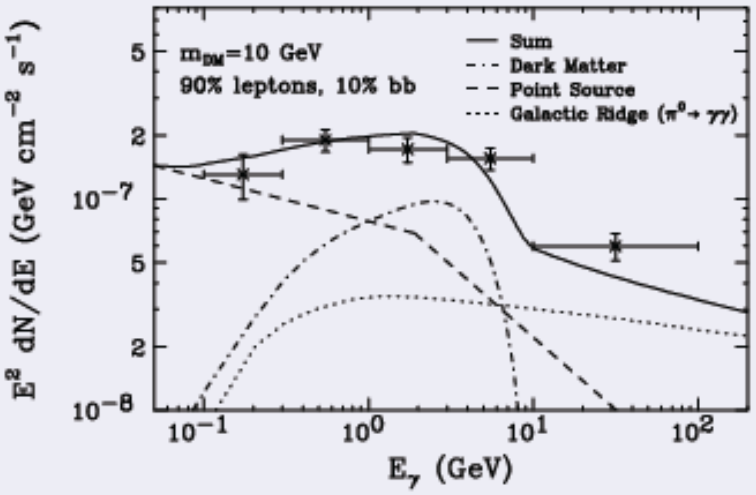
J. Kopp @ IDM12

On the Earth . . .



- Several intriguing direct detection signals
- But severe tension with null results

. . . and in the skies



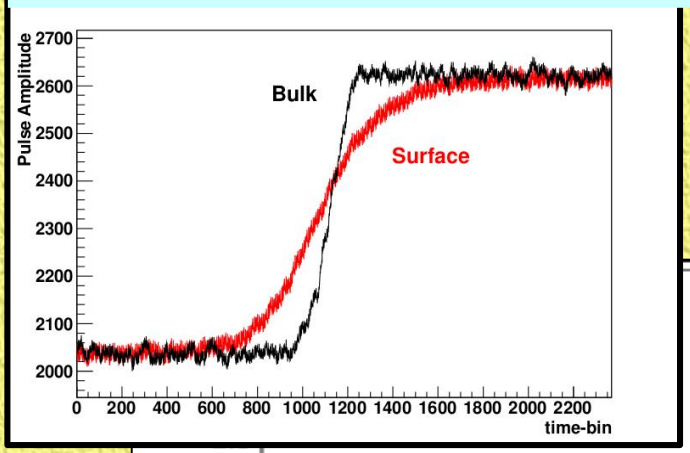
- An tentative γ ray excess from the Galactic Center
  Hooper Goodenough 0912.2998, 1010.2752, 1201.1303
  - Morphology $\neq$ point source
- Radio filaments
  Linden Hooper Yusef-Zadeh 1106.5493
- Isotropic radio background
  Hooper Belikov Jeltema Linden Profumo Slatyer 1203.3547

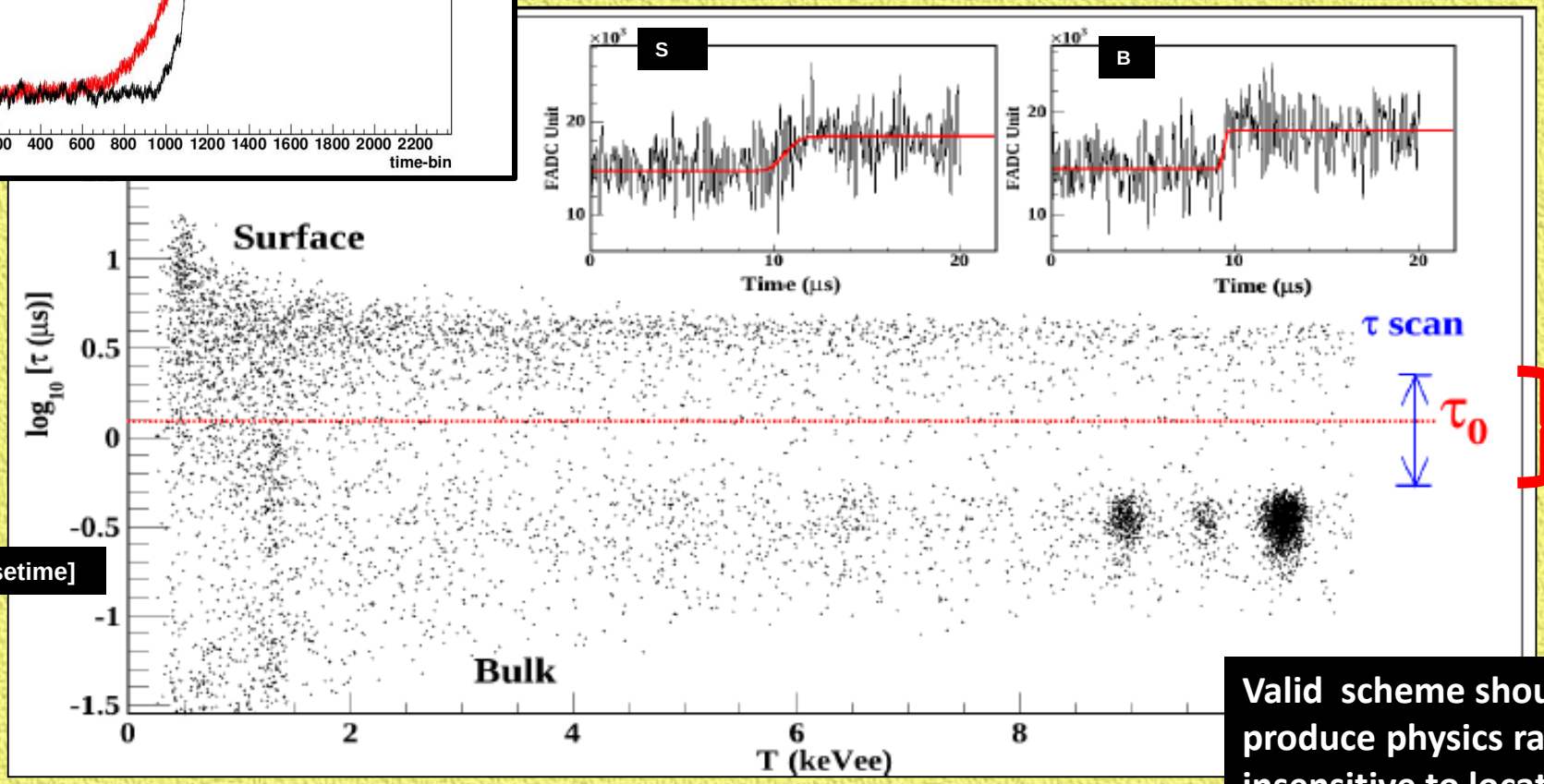
Sub-keV Ge Detector Techniques : Users' R&D Items

- 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 *[On-Going….]*

PSD for Surface Vs Bulk Events @ PCGe [AP14]

- n+ "inactive layer" is not totally dead; signals finite but slower rise time
- ACV+CRT tag (cosmic-induced high energy neutrons) ⇨ no surface band
- n-type PCGe ⇨ no surface band



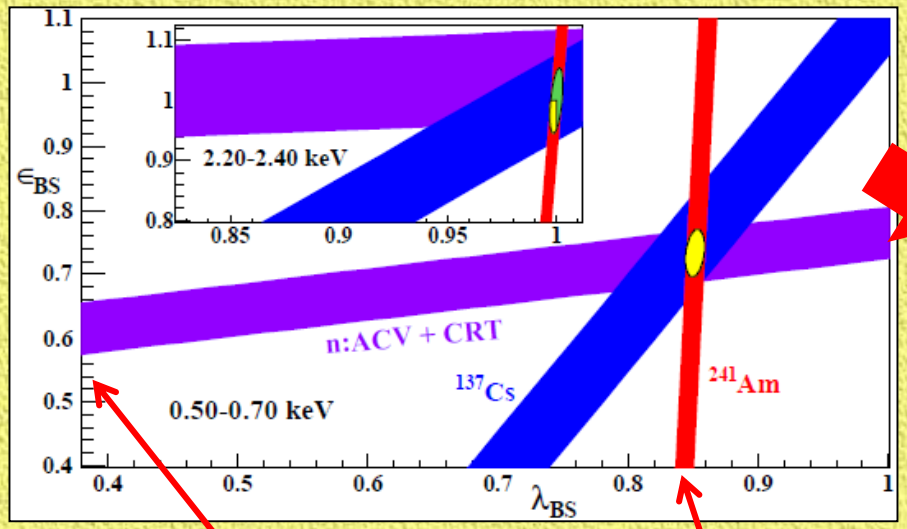


Valid scheme should produce physics rates insensitive to location

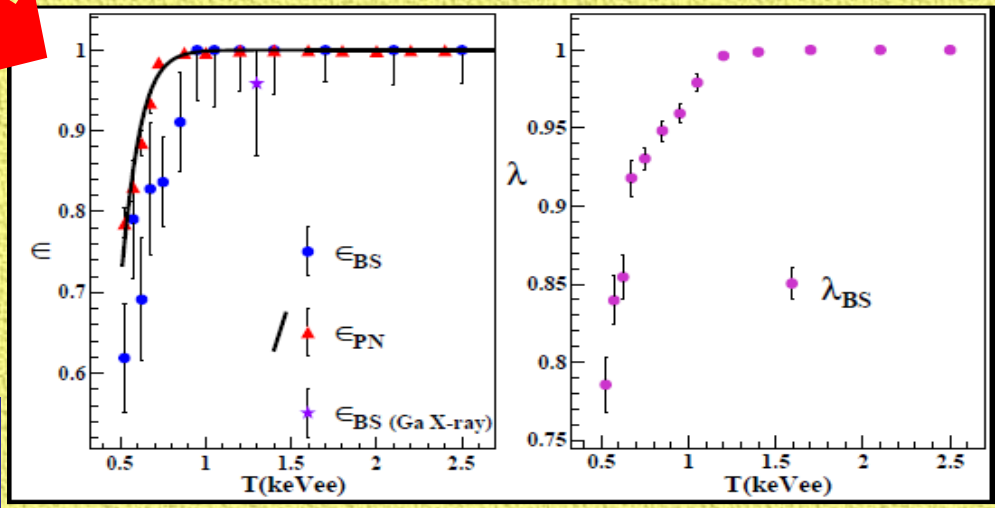
"Calibration" ≡ measure energy-dependent signal-retaining (ε_{BS}) & background-suppressing (λ_{BS}) efficiencies, related by the coupled equations [B,S=real ; B'S'=measured] :

$$B' = \epsilon_{BS} \cdot B + (1 - \lambda_{BS}) \cdot S$$
$$S' = (1 - \epsilon_{BS}) \cdot B + \lambda_{BS} \cdot S$$

Approach: Identify *THREE(+)* calibration data [low and high energy γ, cosmic-induced neutrons] where (B,S) are known & (B',S') measured ⊕ solve coupled equation for (ε_{BS}, λ_{BS})



KSNL: ^{241}Am, ^{137}Cs, cosmic-HE-n
CJPL: ^{241}Am, ^{57}Co, ^{137}Cs, ^{60}Co

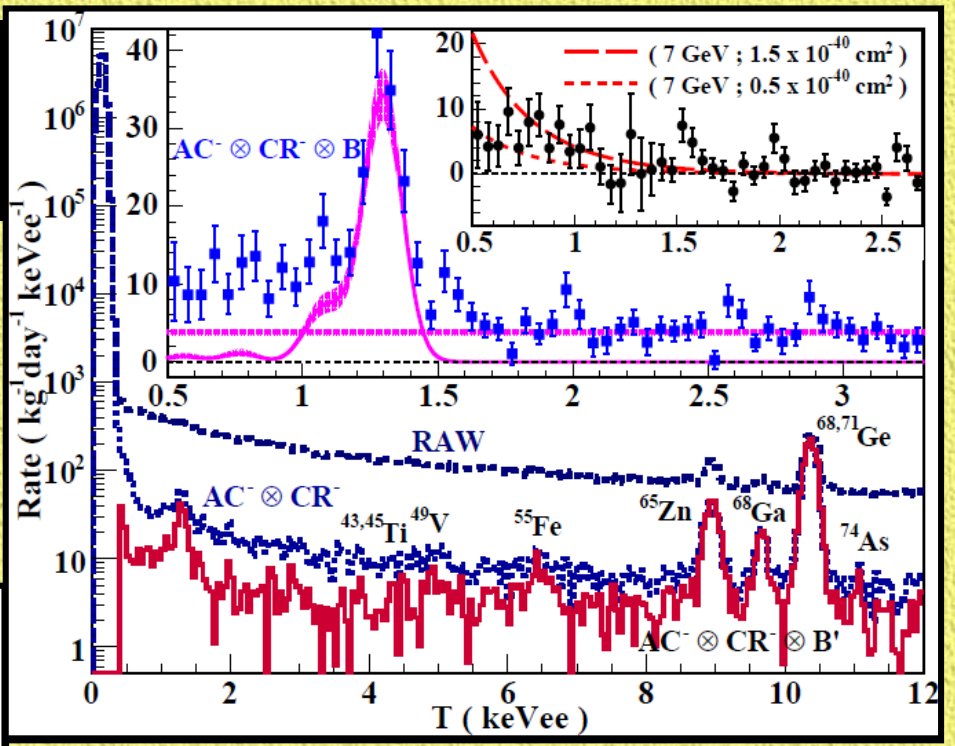


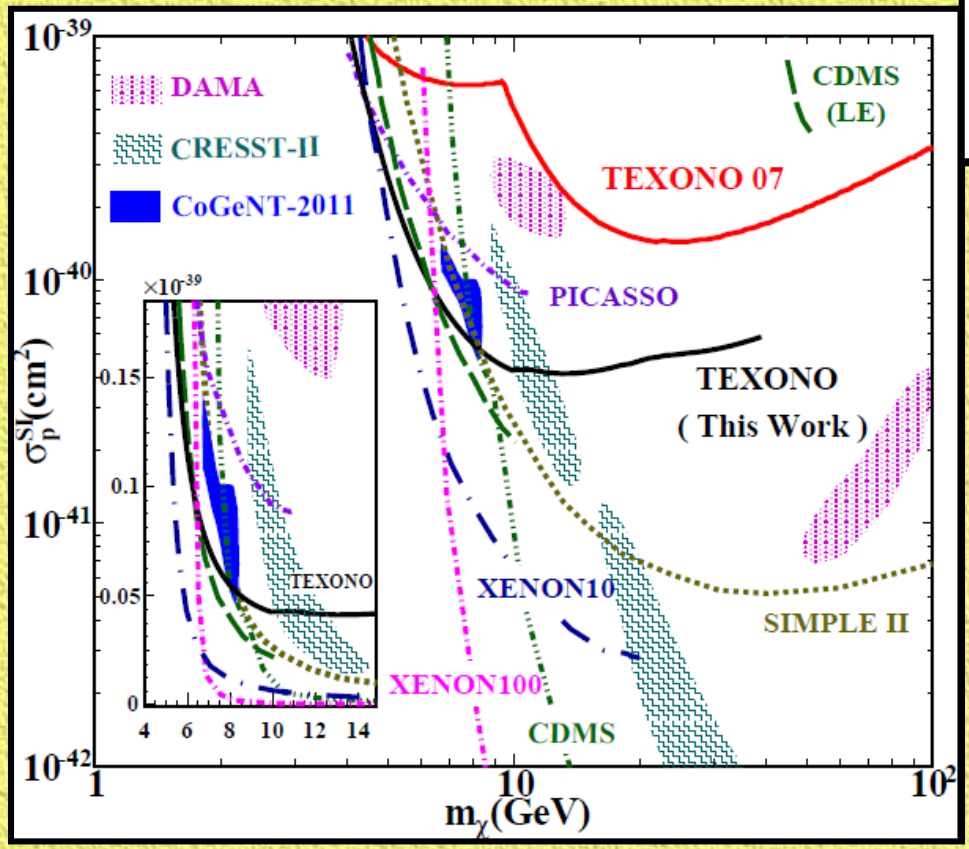
Bulk-Rich high-energy neutrons constrain ε_{BS}

Surface-Rich γ-rays constrain λ_{BS}

Light WIMP Searches @ KSNL with Ge

- *Learn & Establish Techniques*
- *Catalyze CDEX-1 @ CJPL*
- *Produce Physics Results !*



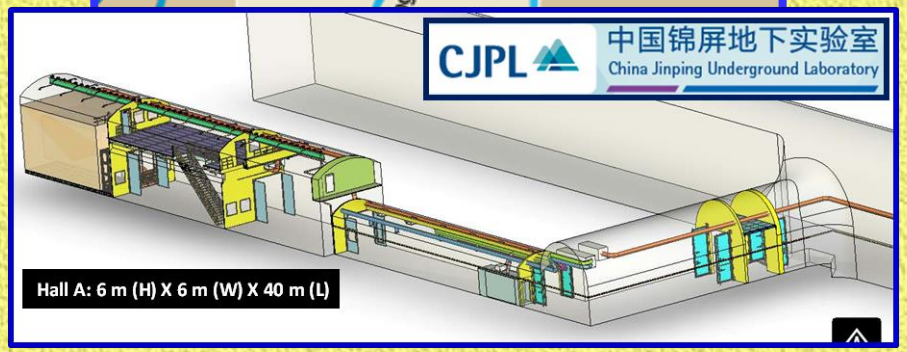


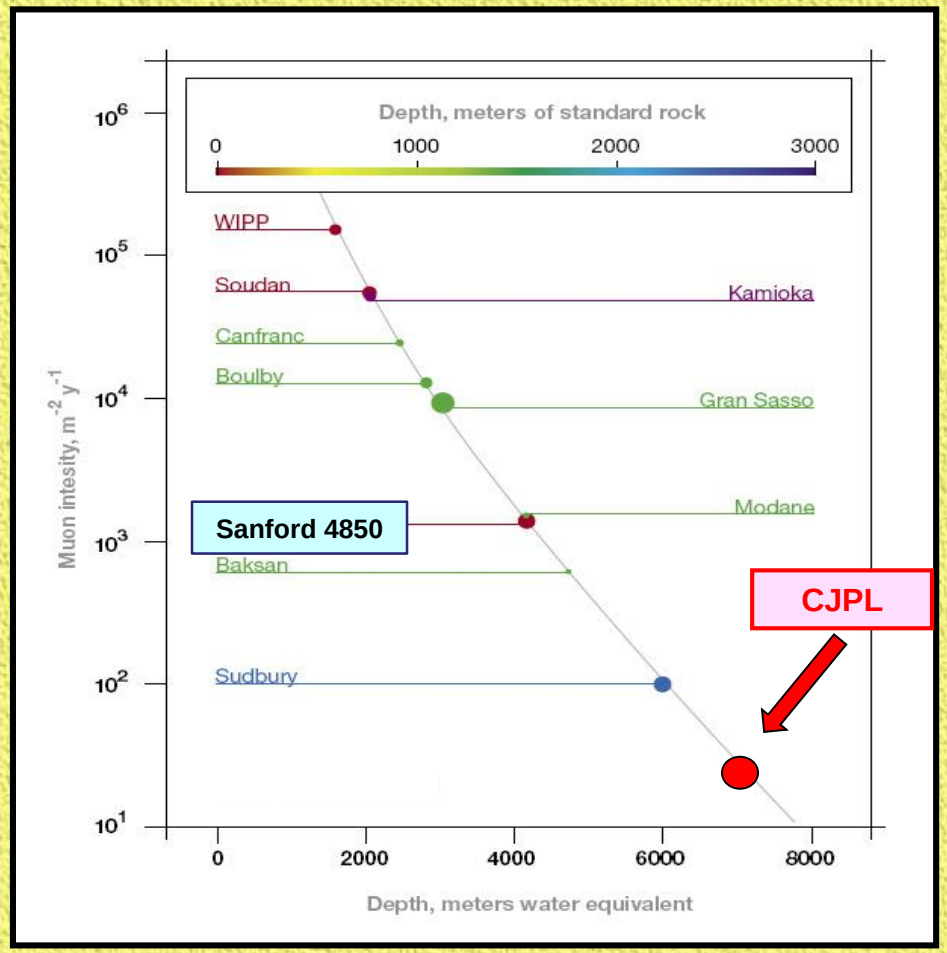
TEXONO@KSNL *[PRL13]* :

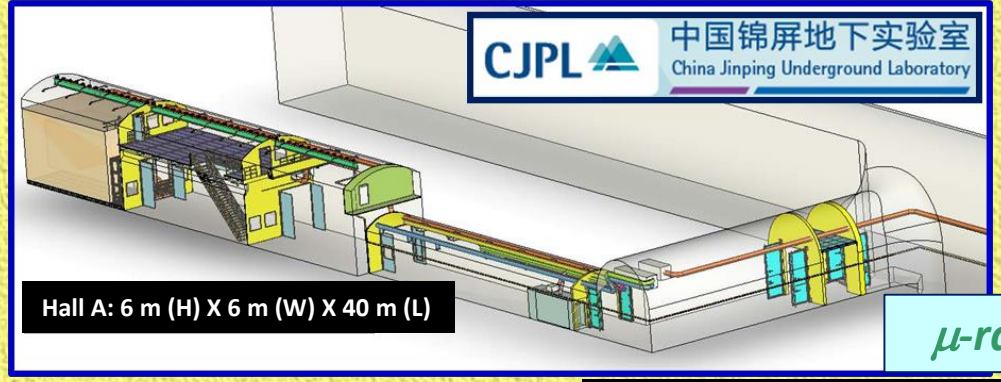
- 500 eV threshold
- probed and excluded some light WIMP allowed regions implied by other experiments.
- Provide probable explanations to CoGeNT-2011's excess

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

- 2400+ m rock overburden, drive-in road tunnel access
- 6X6X40 m cavern constructed *[managed by THU & EHDC]*
- CDEX-1 & Panda-X Dark Matter Program



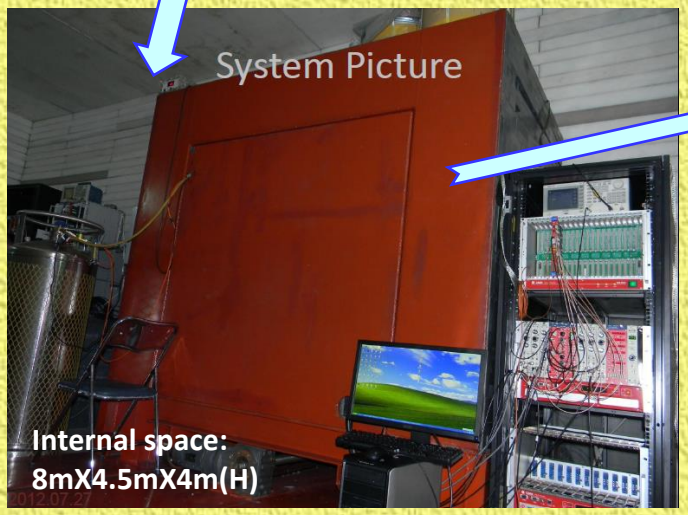


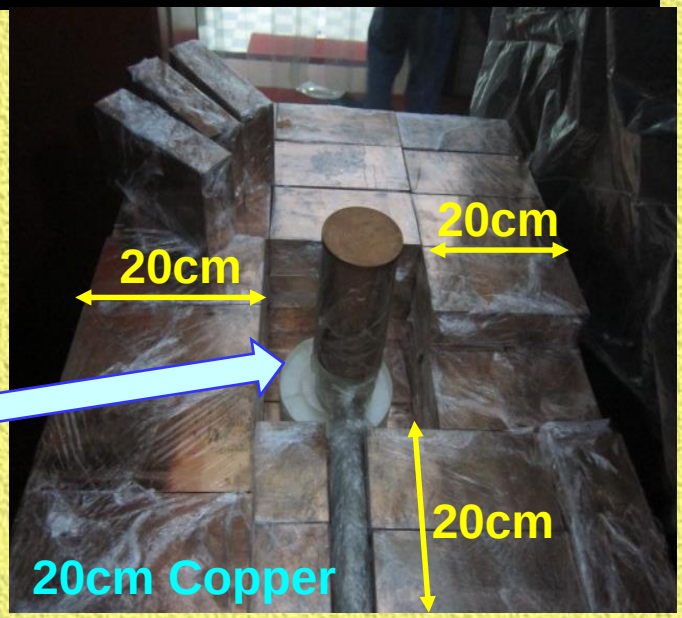


μ-rate ~ 6 per m² per month

CDEX-1 Data Taking @ CJPL :

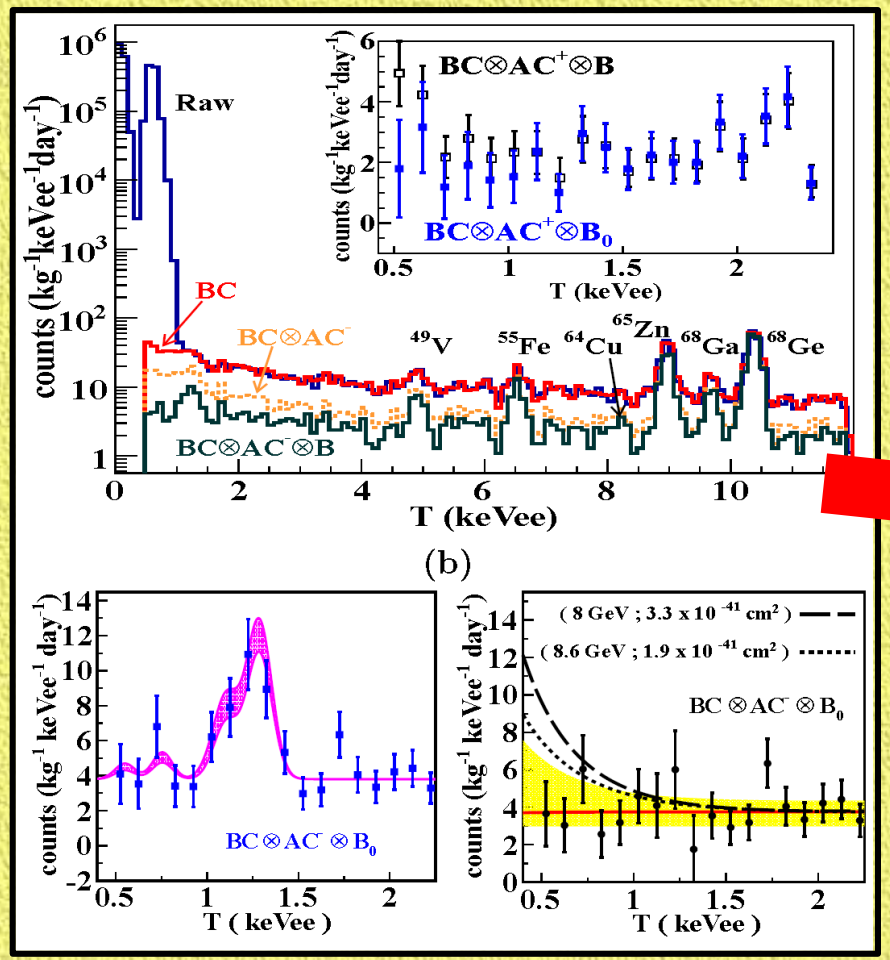
- Adopt KSNL Baseline Design
- Engineering Run 2011
- Physics Run June 2012

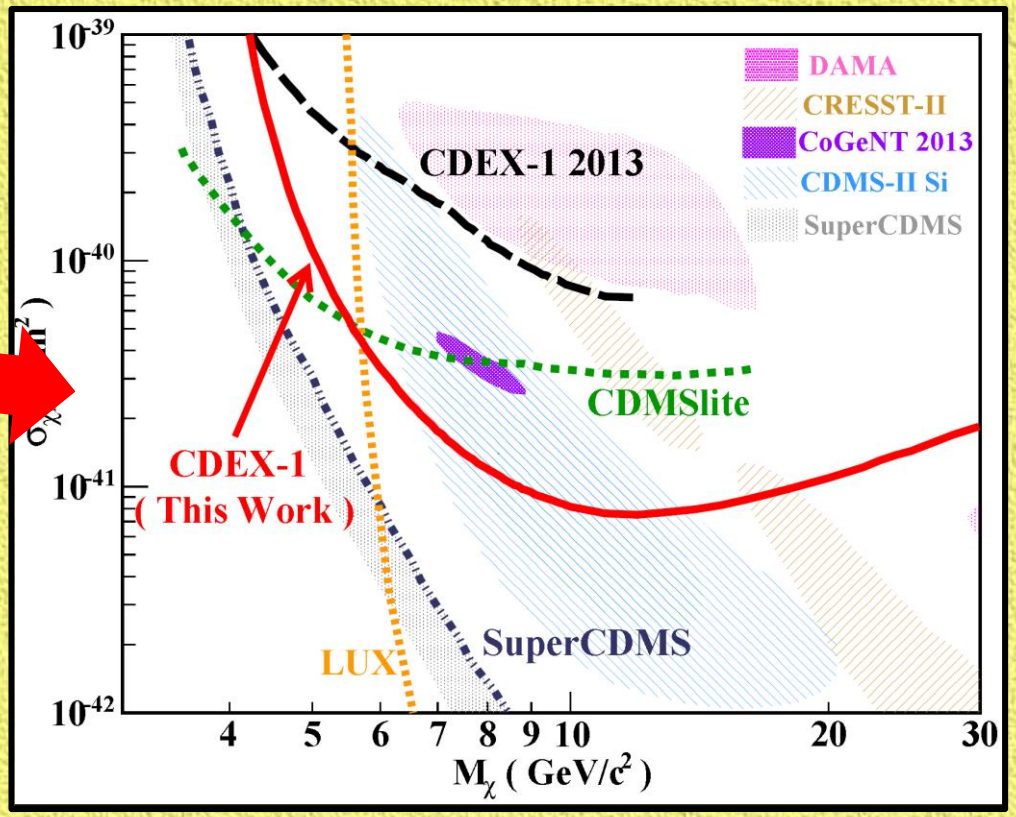




CDEX-1 @ CJPL 2014 *[PRD13, arXiv: 1404.4946]*

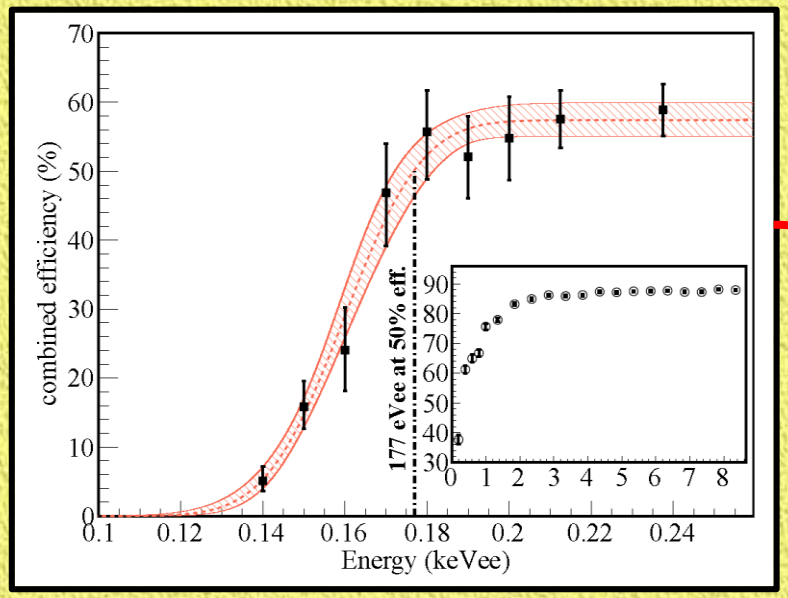
- *1 kg pPCGe @ 475 eVee threshold*
- *All events quantitatively accounted for ; No Residual Excesses at sub-keV*
- *Exclude CoGeNT-2013 excess as WIMP-induced, independent of interaction channels*

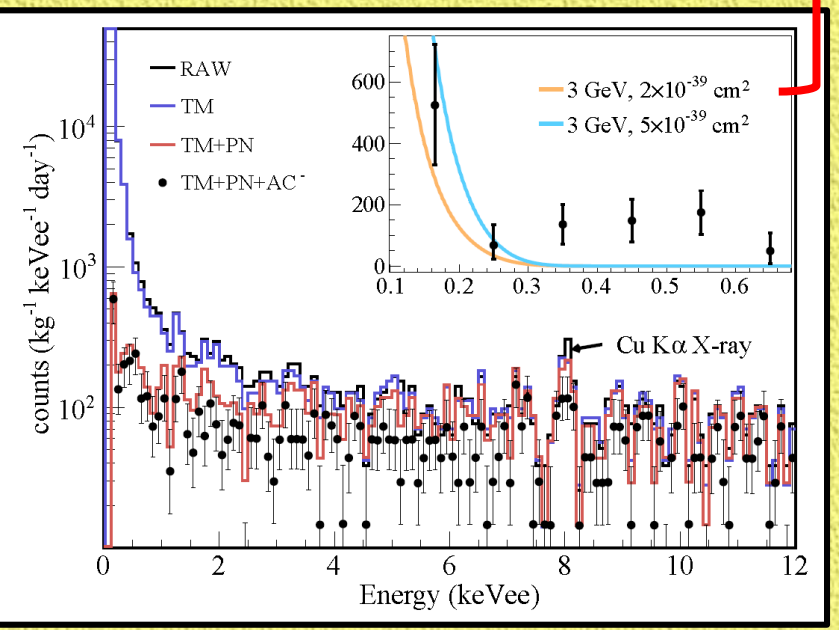


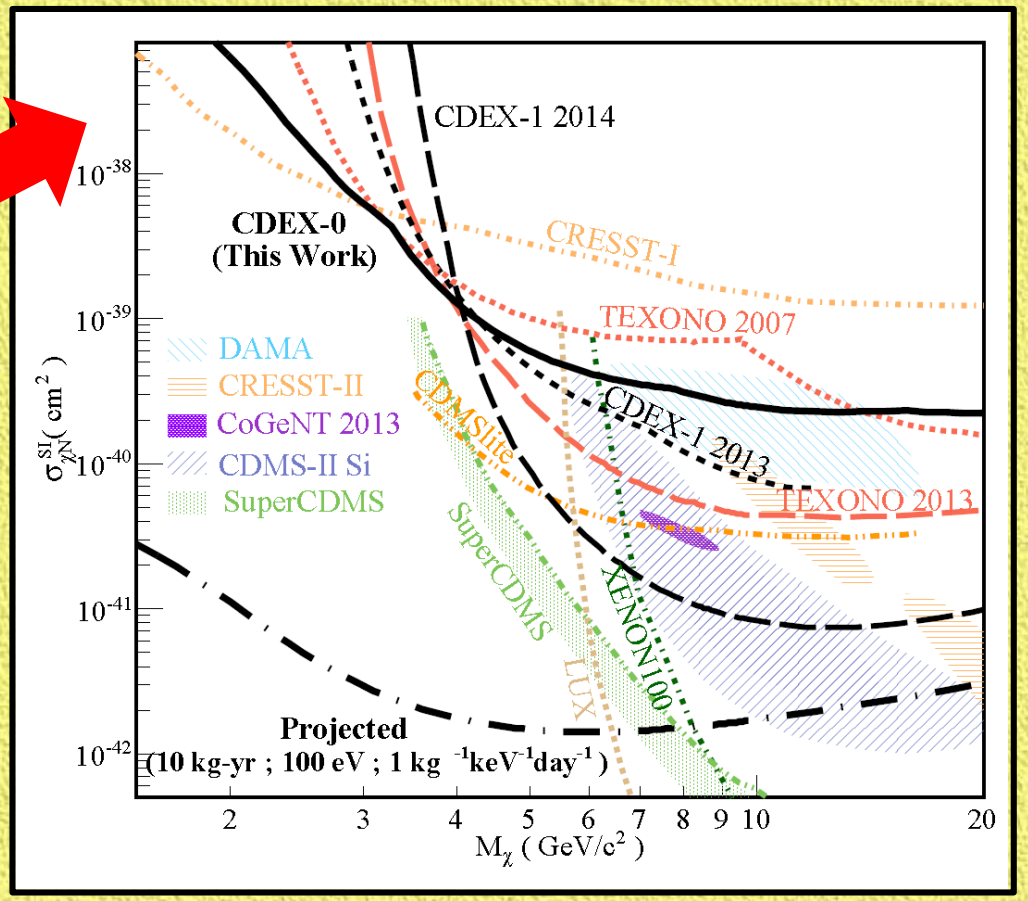


CDEX-0 *[20g prototype]* @CJPL 2014 *[PRD14]*

12g ULEGe e @ 177 eV$_{ee}$ Analysis Threshold

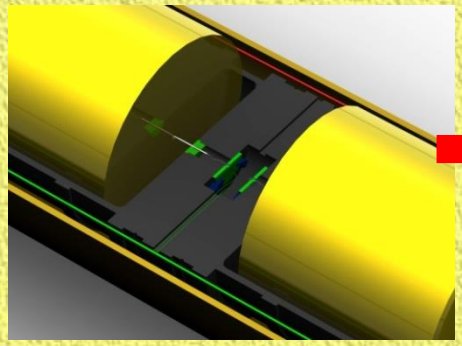




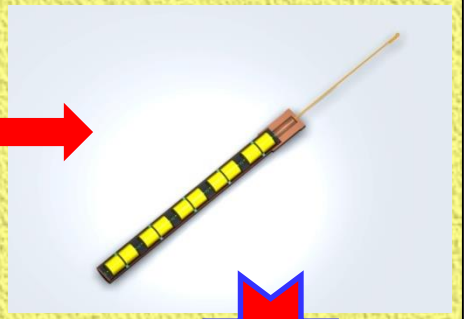


Design of CDEX-10 : with LAr Anti-Compton

Ge + JFET

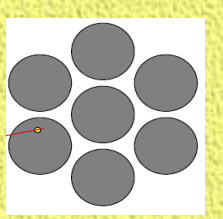


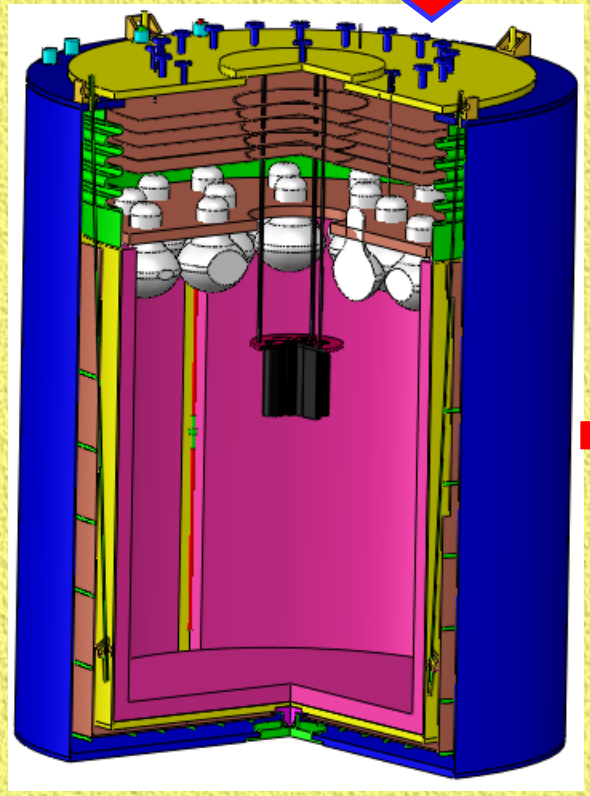
Ge Array in String

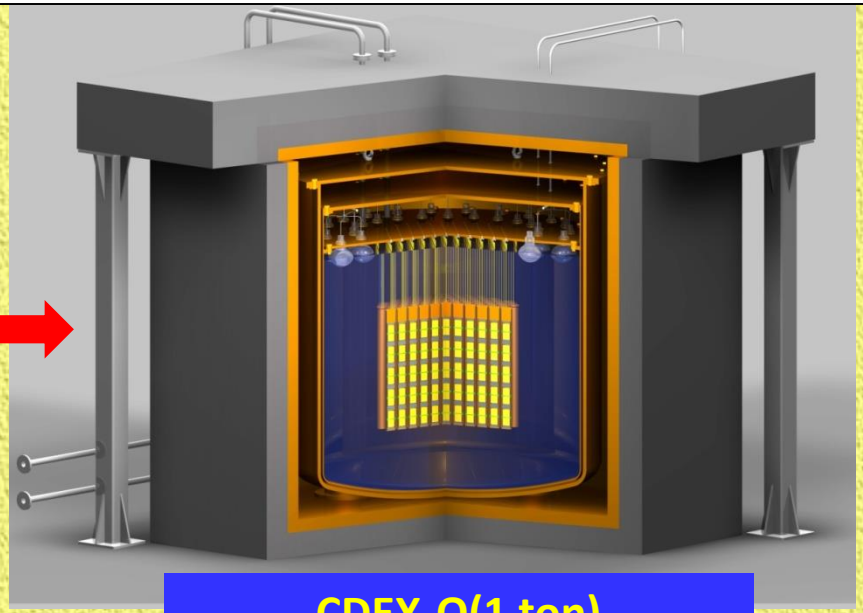


- PCGe in Arrays & Strings
- LiqAr (LiqN)as both cryogenics & active anti-Compton
- ~30-40 cm 4π shielding range
- Prototype 2014
- Baseline Design for Future O(1 ton) Expt for DM+0νββ

CDEX-10 (2014+)



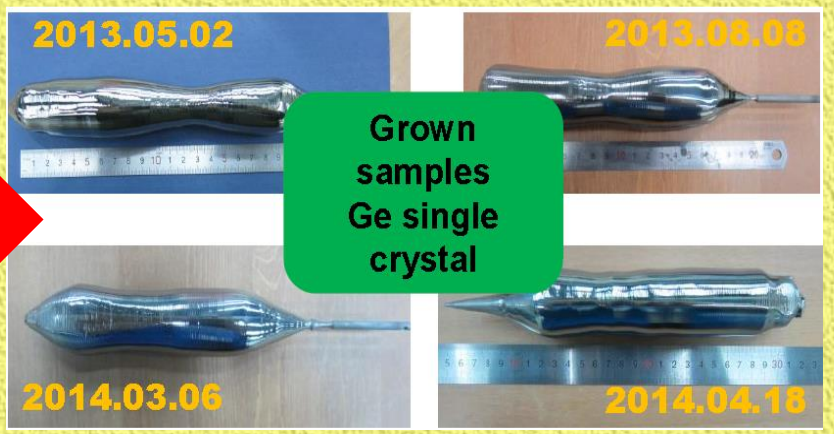




CDEX-O(1 ton)
Artist's Conception

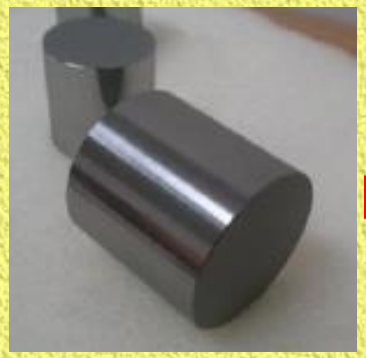
Ge Processing & Assembly Facility @ THU

Czochralski machine

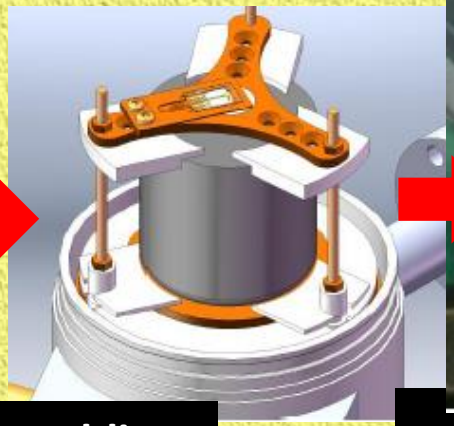


Grown samples Ge single crystal

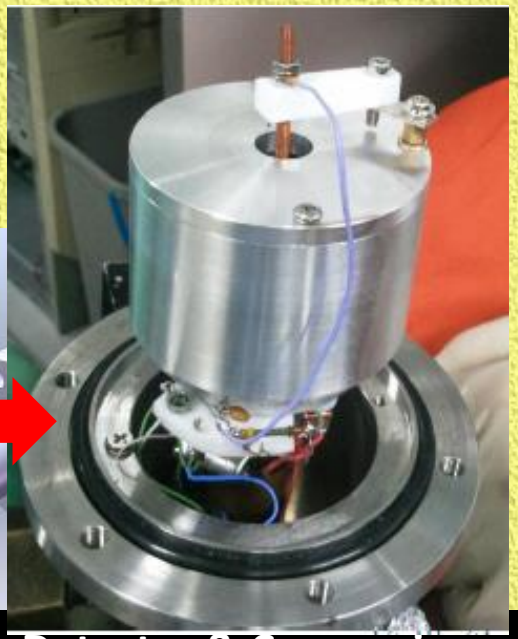
- Growth & Processing of raw Ge crystal
- Application-specific optimized assembly
- R&D on JFETs & Preamps
- Possible Future Commercial Marketing (THU)



Crystal

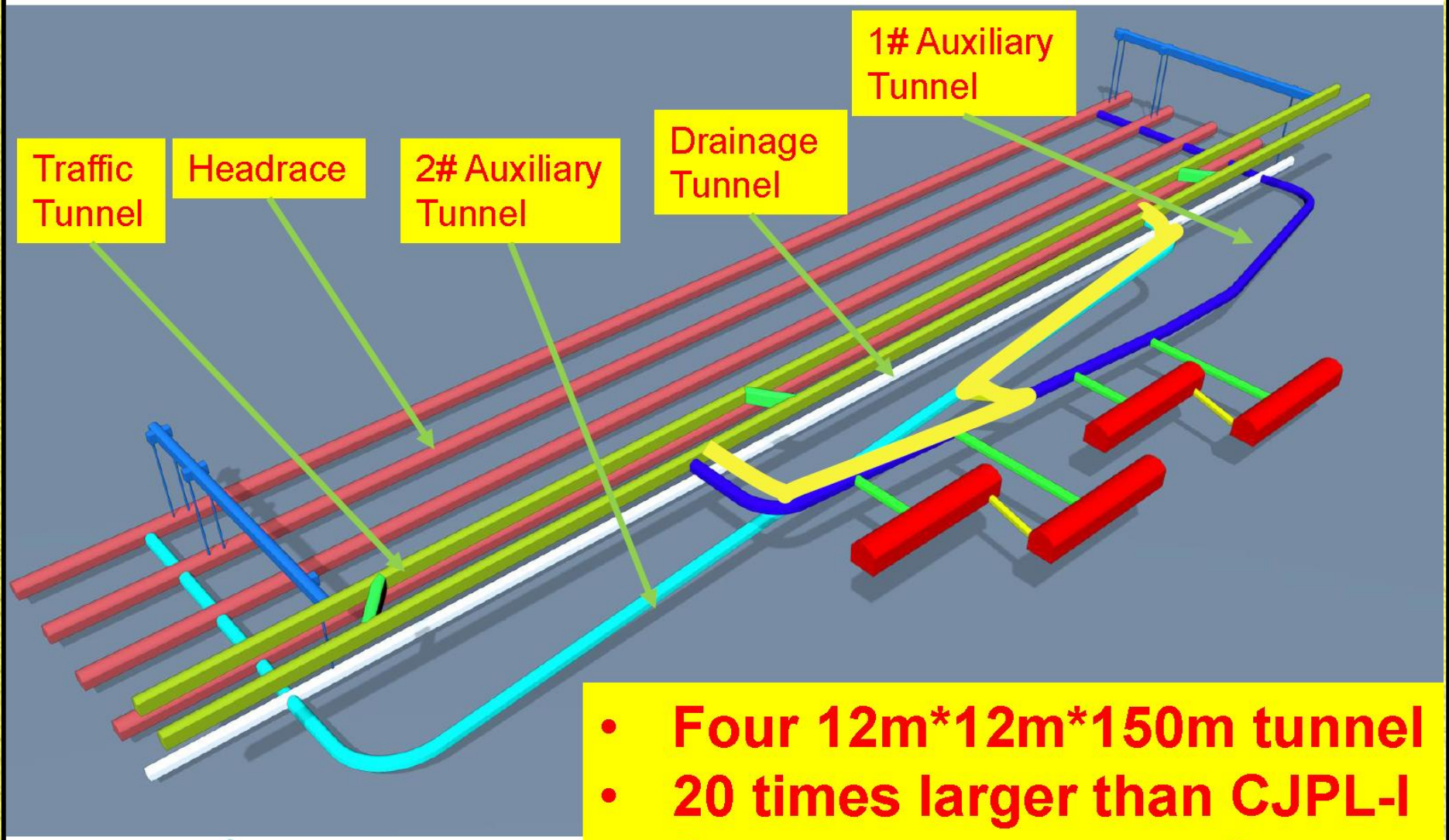


Processing & Assembling



Detector & Cryogenics

CJPL-II development



- Four 12m*12m*150m tunnel
- 20 times larger than CJPL-I
- Started by the end of 2014

CJPL

Summary & Prospects

- Competitive results on light WIMPs with sub-keV Ge with *TEXONO@KSNL* ; 10+ improvement at *CDEX-1@CJPL*
- Surface leakage to Bulk samples is important to PPCGe at low energy ; source of earlier positive signal claims
- Current Theme: lower threshold ; modulation studies ; background understanding
- CJPL: more space, CDEX: bigger target mass; acquire L-Ar & Ge-techniques
- KSNL: return to original goal νN coherent scattering $\oplus$ study exotic electromagnetic effects.