Low Energy [Neutrino &] Dark Matter Physics with sub-keV Germanium Detectors

- Overview (Collaboration; Program; History)
- Facilities : KSNL & CJPL
- Detector & Physics Highlights
- Dark Matter Results & Plans

Henry T. Wong /王子敬

Academia Sinica /中央研究院

Nov/Dec 2015 @

PROSPECTS IN LOW MASS DARK MATTER 2015

微中子 臺灣實驗 TEXONO Taiwan EXperiment On NeutrinO 國聖

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

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)**

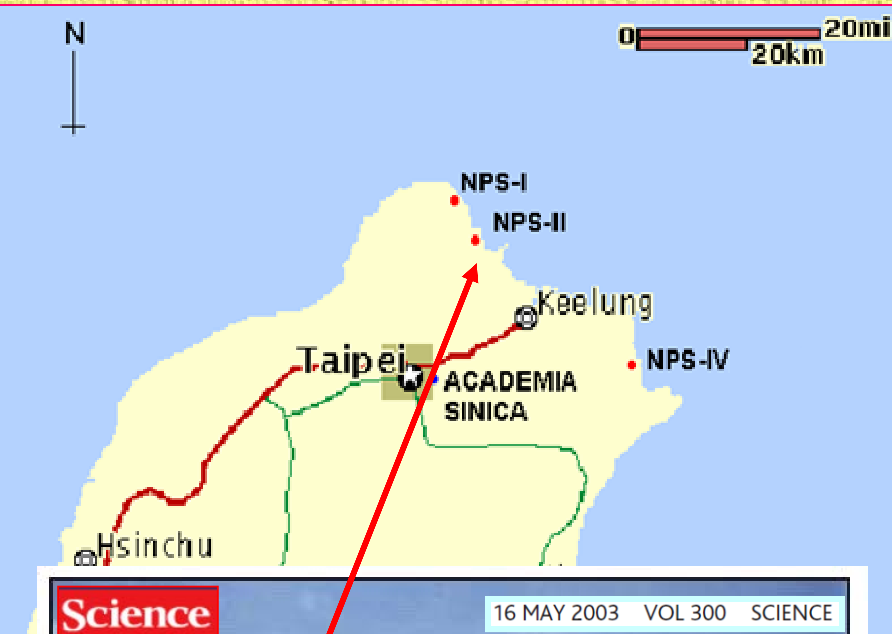
CDEX *China Dark Matter EXperiment* *[birth 2009]*:

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

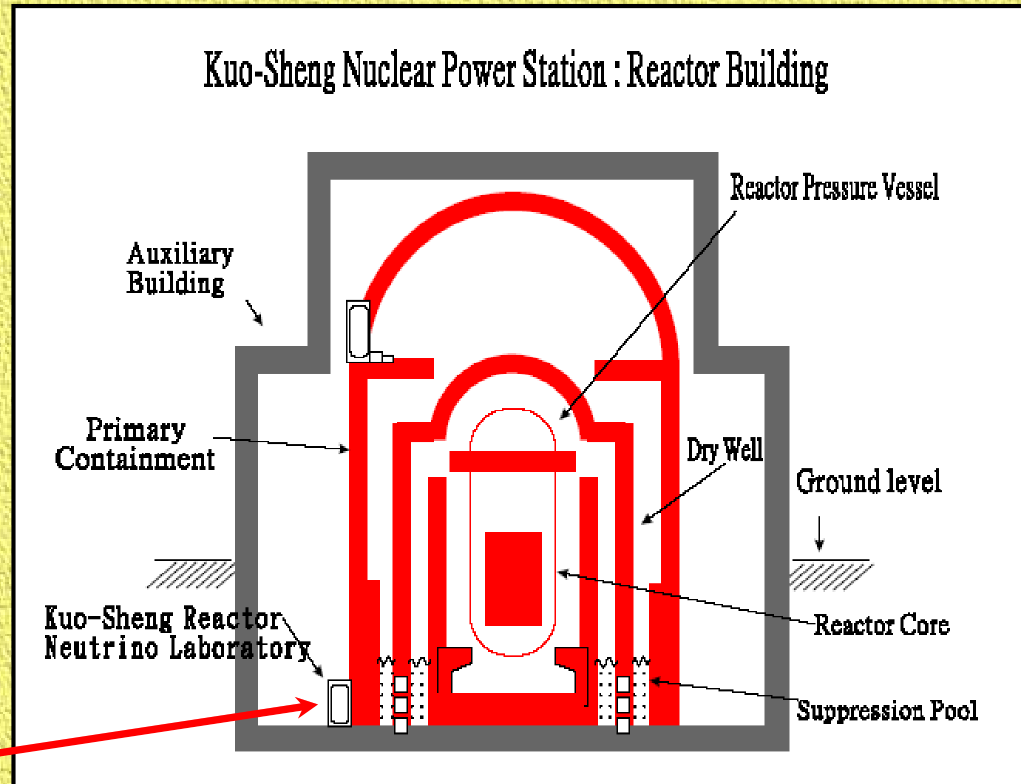
Kuo Sheng Reactor Neutrino Laboratory [KSNL]




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

A Bridge Over Troubled Waters

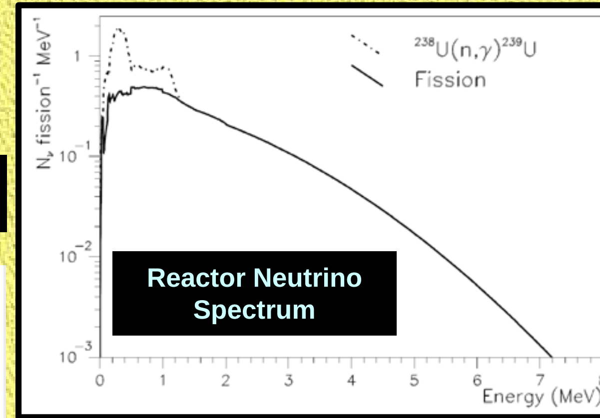
Researchers from Taiwan and the mainland have hit scientific pay dirt with the first—and so far the only—collaboration between two institutions across the Taiwan Strait

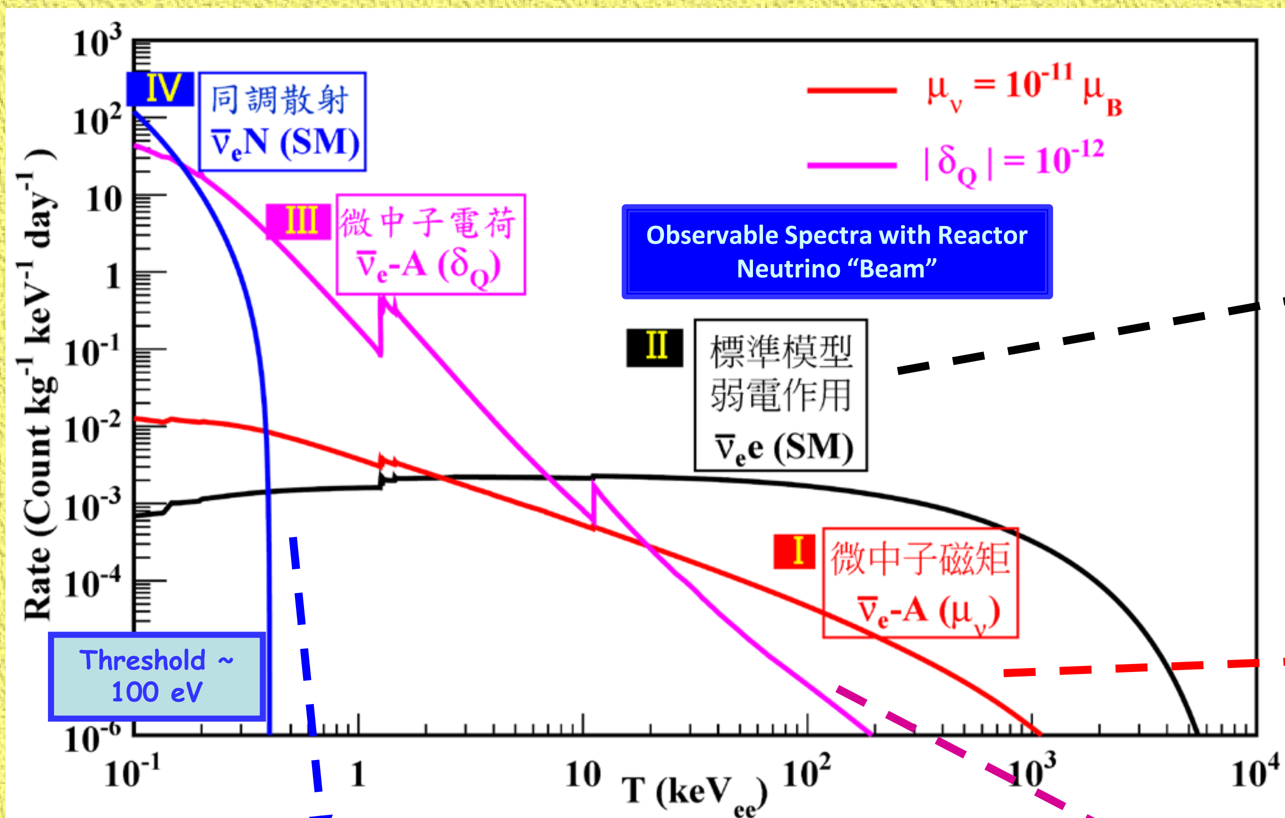


- **28 m from core#1 @ 2.9 GW**
- **Shallow site : ~30 *mwe* overburden**
- **~10 m below ground level**

Neutrino Properties & Interactions at Reactor

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





SM & NSI/BSM
ν-e Scattering
[PRD10,PRD10,PRD12,PRD15]
⇨ 200 kg CsI(Tl)

Magnetic Moments
[PRL03,PRD05,PRD07]
⇨ 1 kg HPGe

νN Coherent Scattering *[Current Theme]*
⇨ sub-keV O(kg) ULEGe / PCGe
- Dark Matter Searches @ KSNL *[PRD09,PRL13,AP14]*
- CDEX Program@CJPL *[PRD13,PRD14,PRD14]*

Neutrino Milli-charge *[PRD14]*
⇨ sub-keV O(kg) ULEGe / PCGe

Details with "Backup Slides" ..

Current Research Theme:

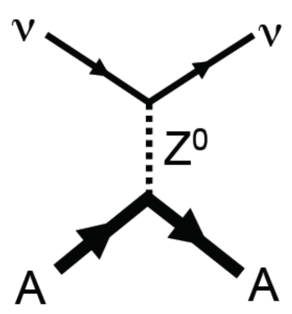
"sub-keV" Ge Detectors

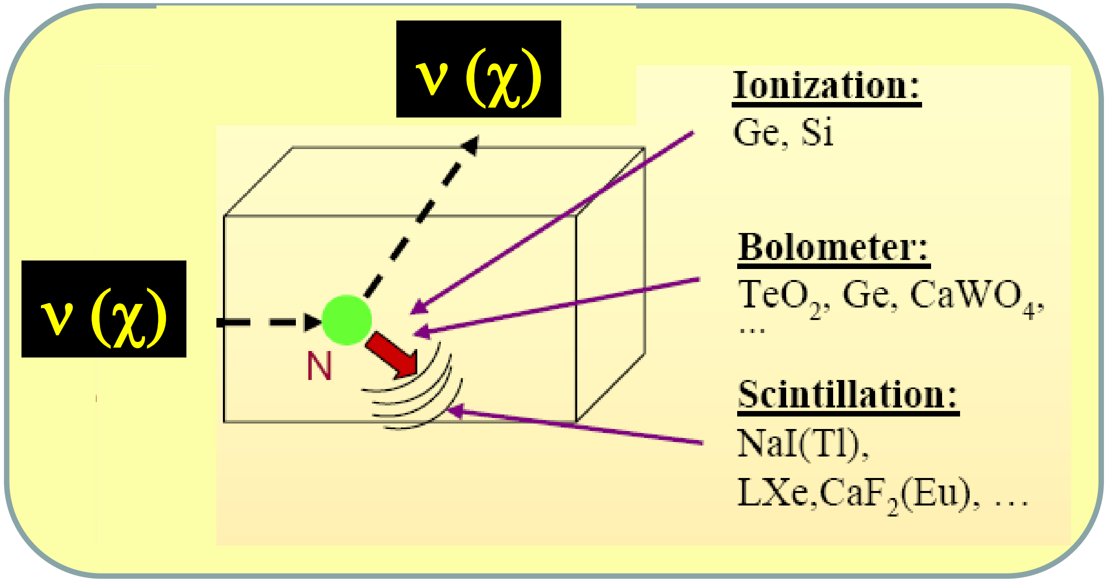
- **Physics Goals for *O[100 eV threhold⊕1 kg mass⊕1 cpkkd] detector* :**
  - **νN coherent scattering**
  - **Low-mass WIMP searches**
  - **Improve sensitivities on neutrino electromagnetic properties**
  - **Implications on reactor operation monitoring**
  - **Open new detector window & detection channel available for surprises**

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
- 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 eV

Standard Model Cross-Sections at KSNL

[with Quenching Function for Ge for nuclear recoils]

$\nu + N \rightarrow \nu + N$

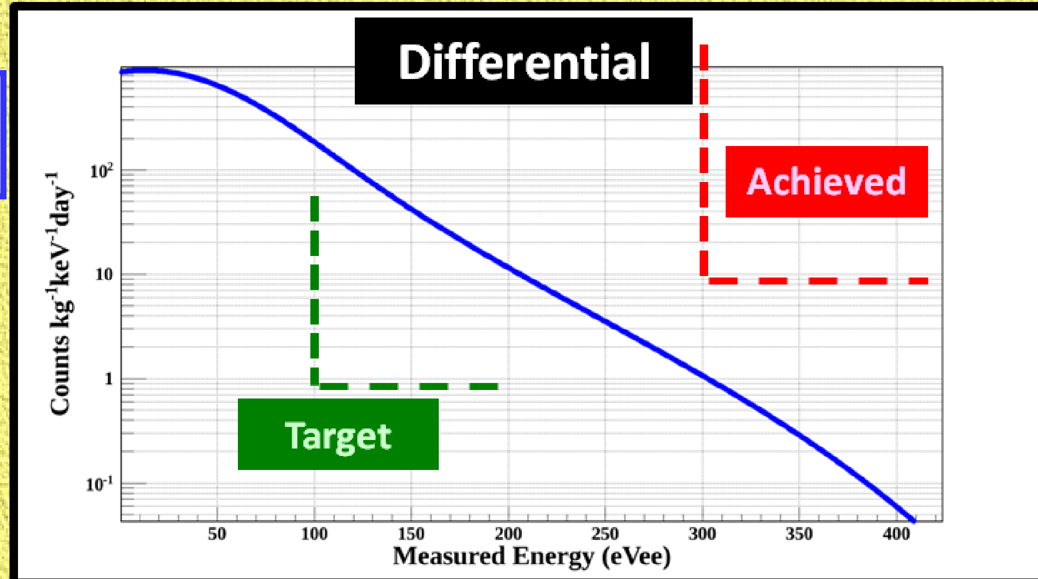
$$\left(\frac{d\sigma}{dT}\right)^{coh}_{SM} = \frac{G_F^2}{4\pi} m_N [Z(1 - 4\sin^2\theta_W) - N]^2 [1 - \frac{m_N T_N}{2E_\nu^2}]$$

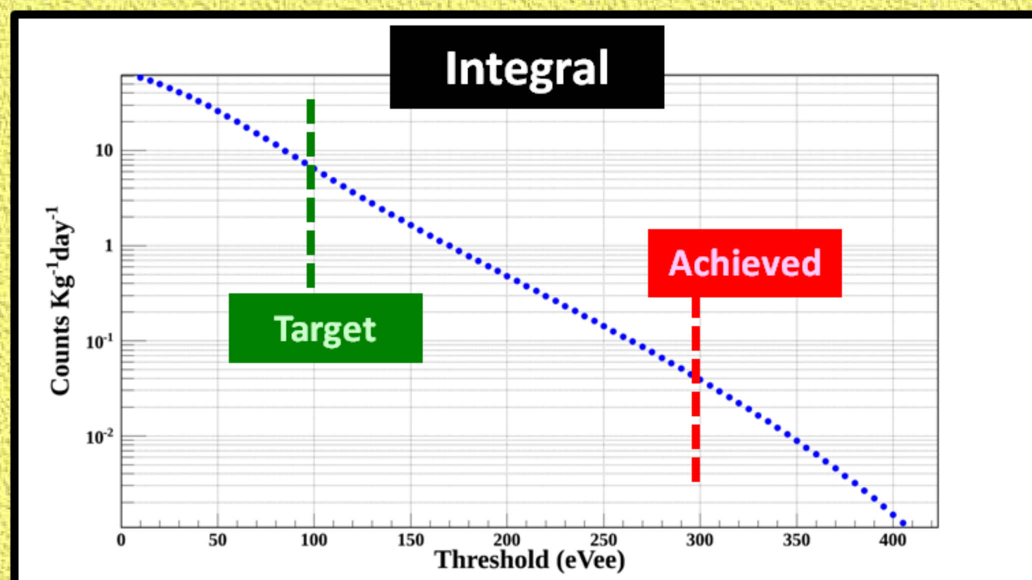
- **Needs Background < 10 cpkkd, Target →1 cpkkd**

Current Focus !!

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

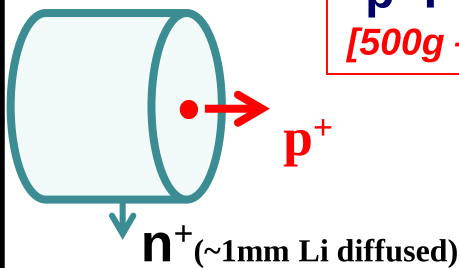
$$\sigma_{tot} = \frac{G_F^2 E_\nu^2}{4\pi} [Z(1 - 4\sin^2\theta_W) - N]^2$$

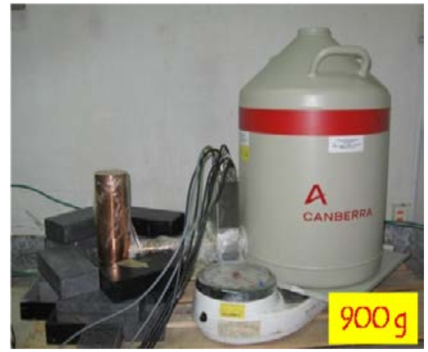




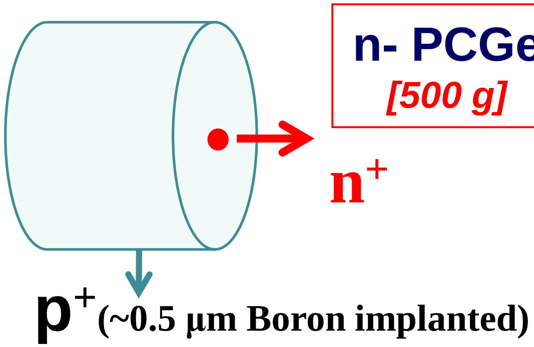
Baseline Hardware Design

p- PCGe
[500g – 1 kg]

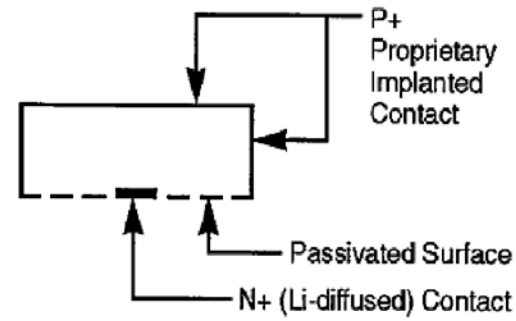


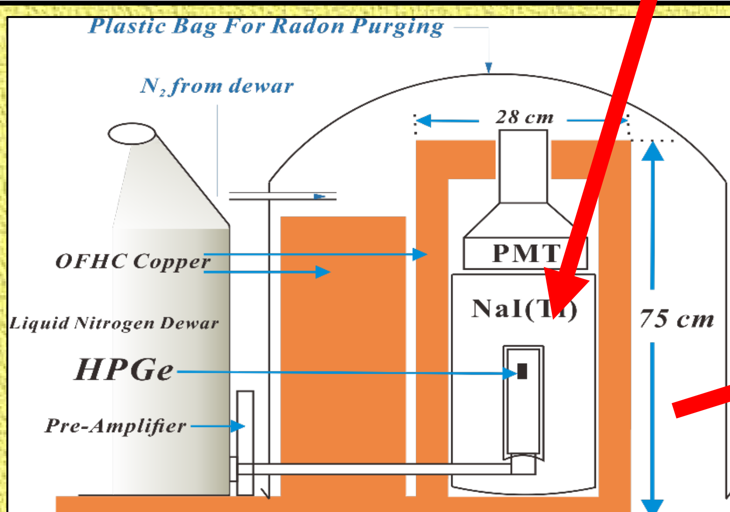


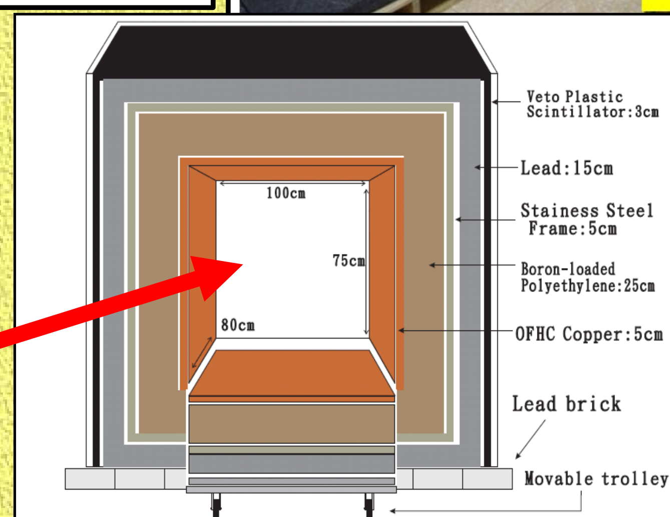
n- PCGe
[500 g]



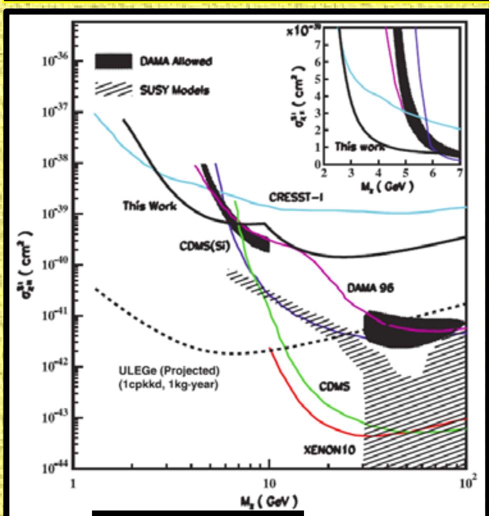
4x5g ULEGe



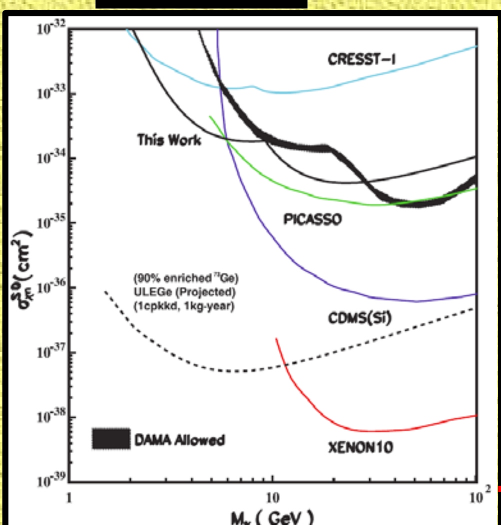




- **TEXONO @ KSNL (2007): 220 eV threshold with 20g ULEGe ; Opened window for "Light WIMPs" searches** *[PRD09]*
- **2010—2013: claimed evidence of GeV WIMPs from terrestrial experiments and astrophysics data** *[strength diminished by now]*



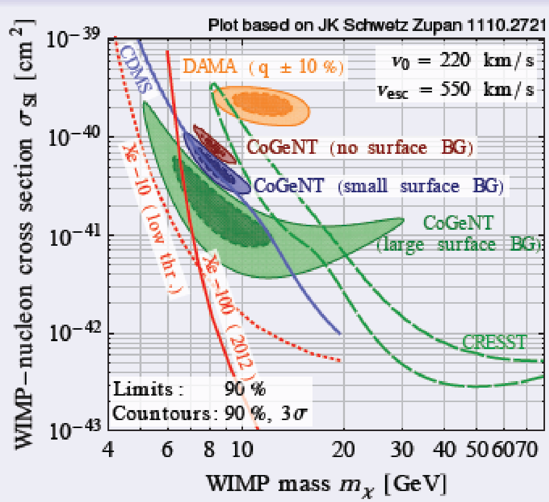
PRD 2009



J. Kopp @ IDM12

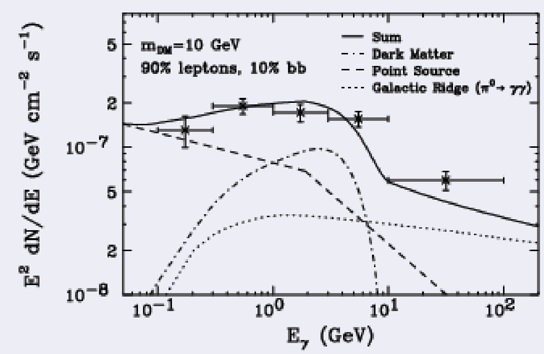
Hints for light dark matter

On the Earth . . .



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

. . . and in the skies



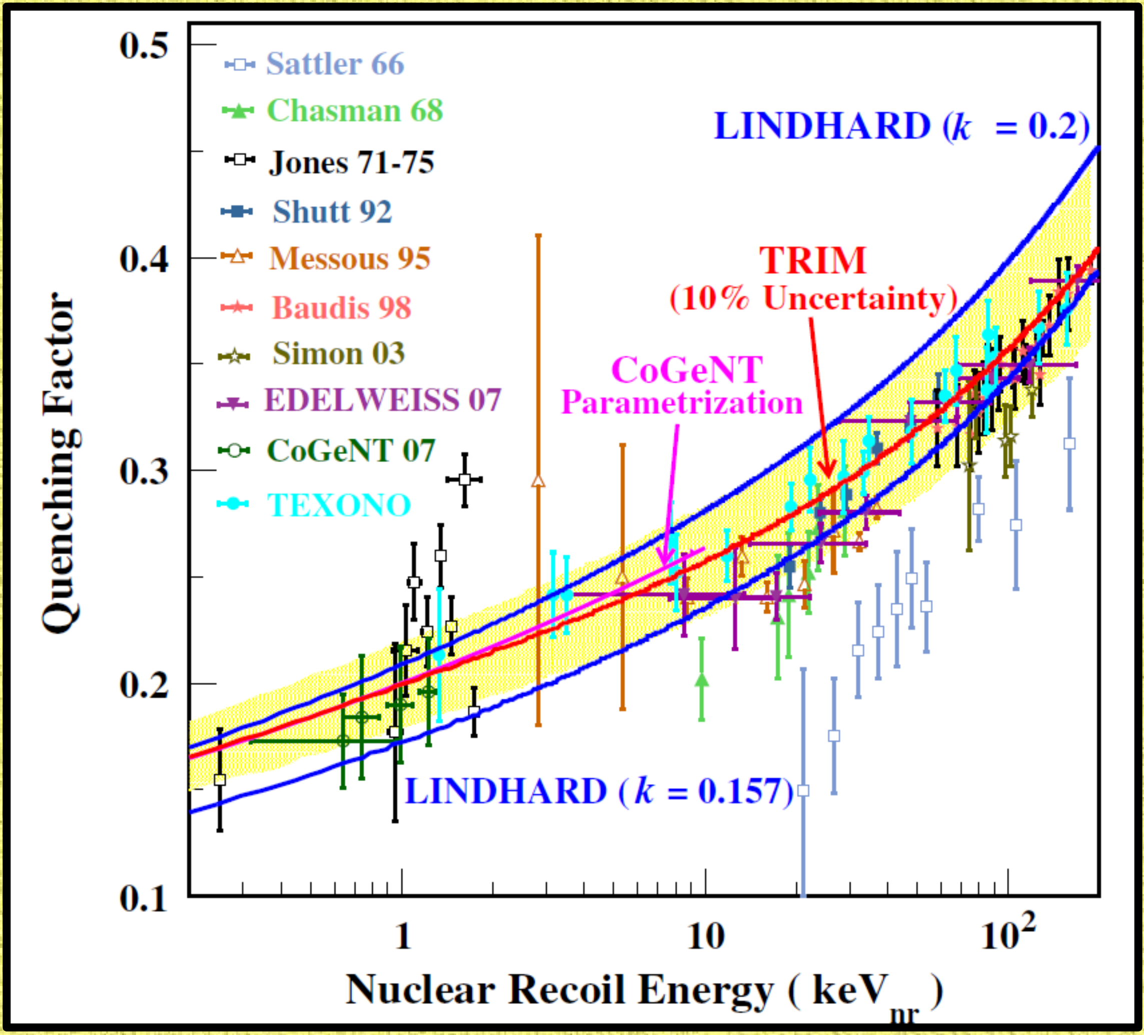
- An tentative γ ray excess from the Galactic Center
  Hooper Goodenough 0912.2998, 1010.2752, 1201.1303
  - Morphology $\neq$ point source
- Radio filaments
  Linden Hooper Yusef-Zadeh 1106.5493
- Isotropic radio background
  Hooper Belikov Jeltema Linden Profumo Slatyer 1203.3547

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

Technical Details with "Backup Slides" ……..

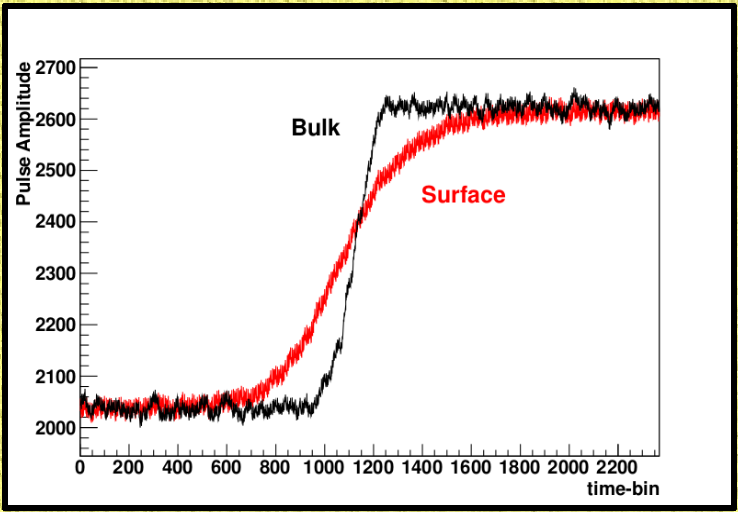
“Quenching Factor” in Ge :

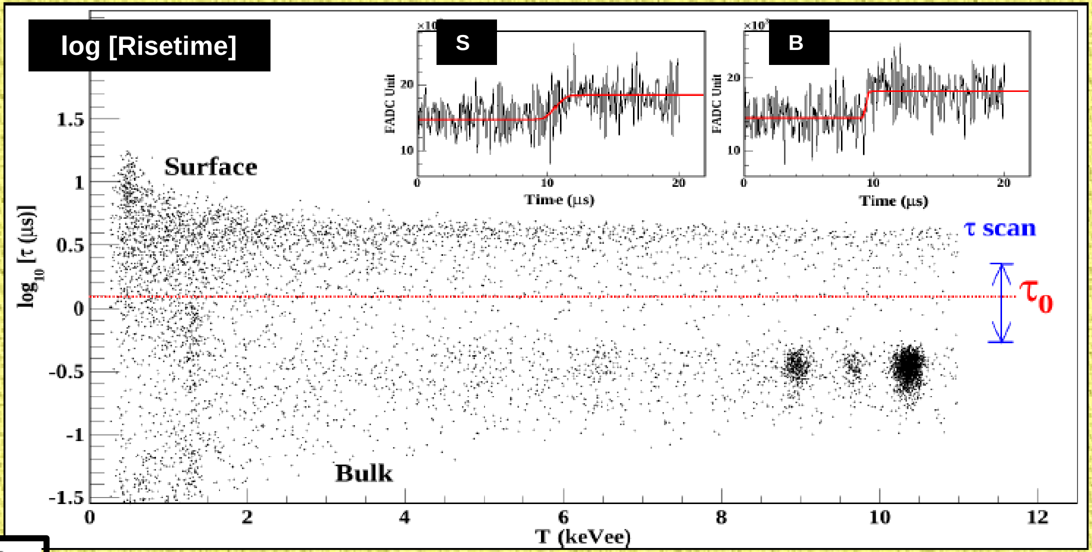


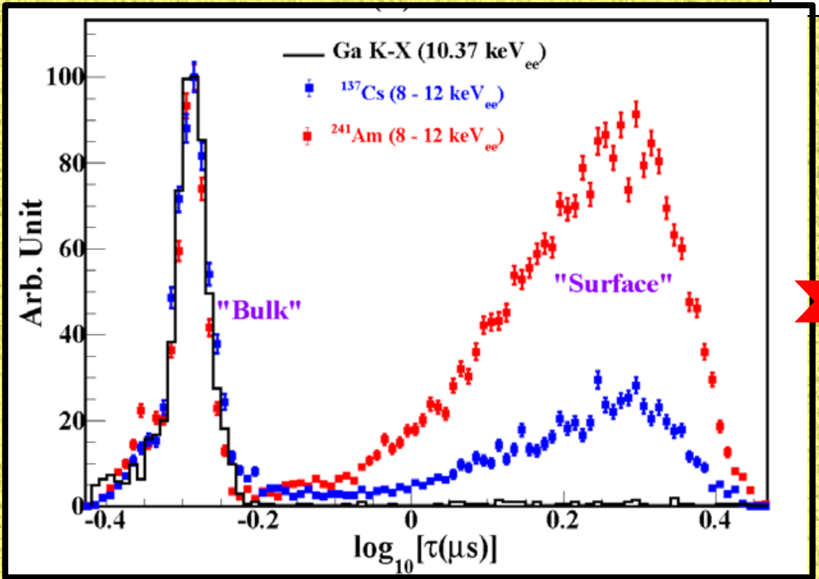
- ☑ Data available down to sub-keV measure-able energy
- ☑ TRIM Software : better match to data over extended energy
- ☑ Systematic Assignment : use different schemes , & TRIM+-10% ; adopt the most conservation constraints.

PSD for Surface Vs Bulk Events @ PCGe[AstroPart.Phys. 2014]

- n+ "inactive layer" is not totally dead; signals finite but slower rise time
- AC-XCR+ events (neutron rich) samples do not show strong surface band
- Understand/Measure Efficiencies and Suppression Factors





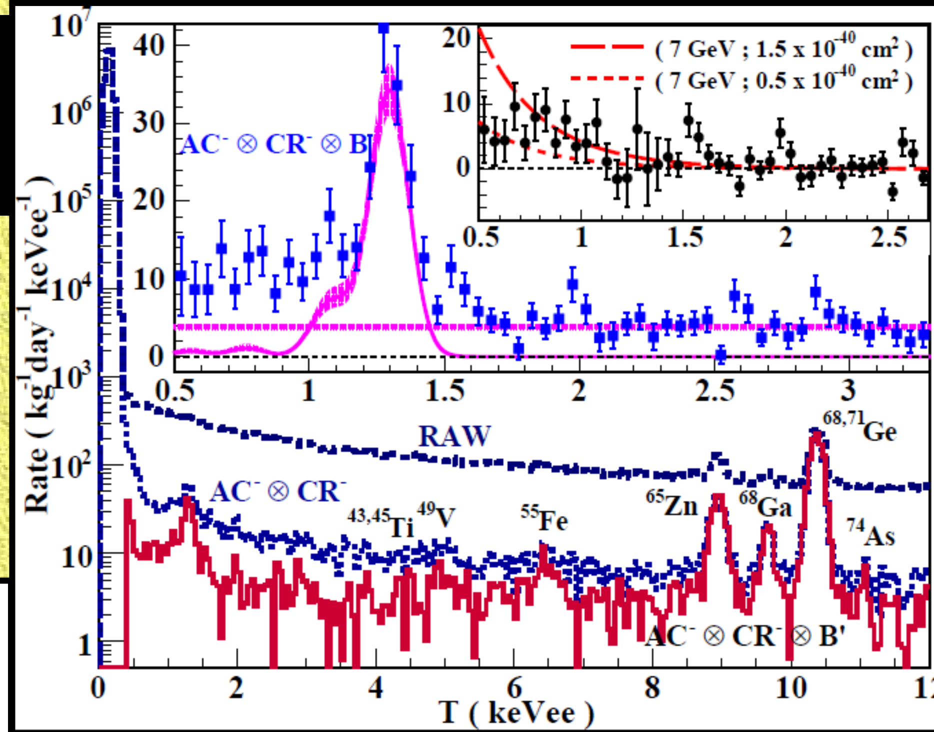


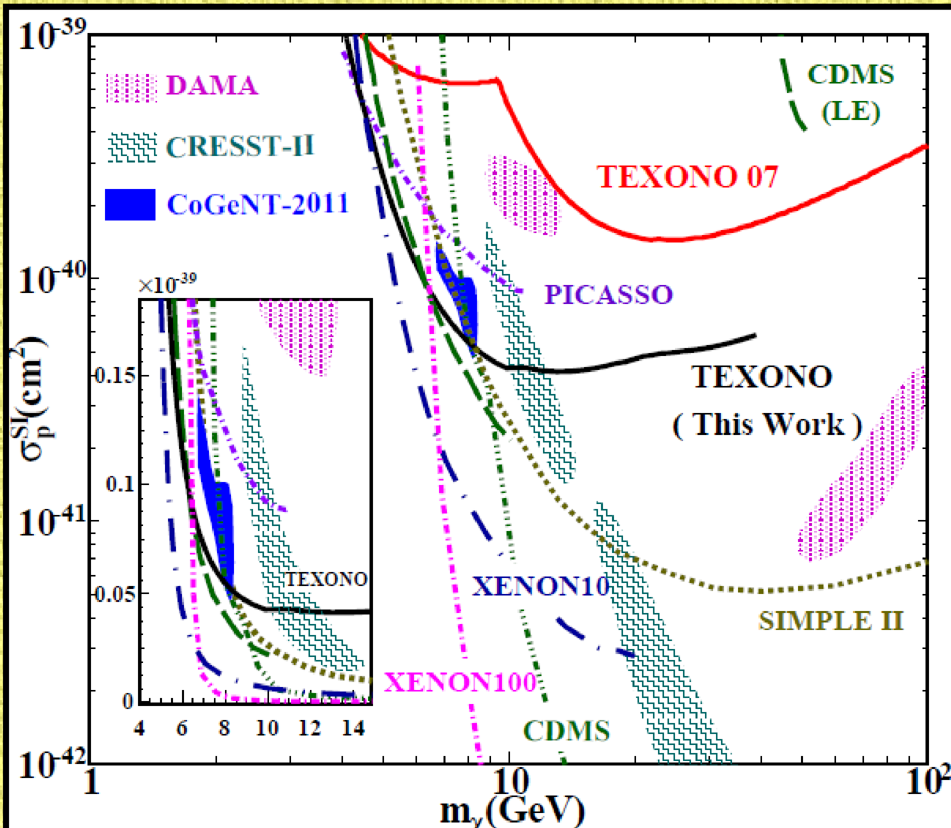
Different Background Sources give Identical TA-risetime in Bulk but Varying in Surface

- *[AC+XCR+XBulk]* background events valid for efficiency studies for ν/χ signals
- Surface TA-risetime distributions provide understanding of background

Light WIMP Searches @ KSNL with Ge

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



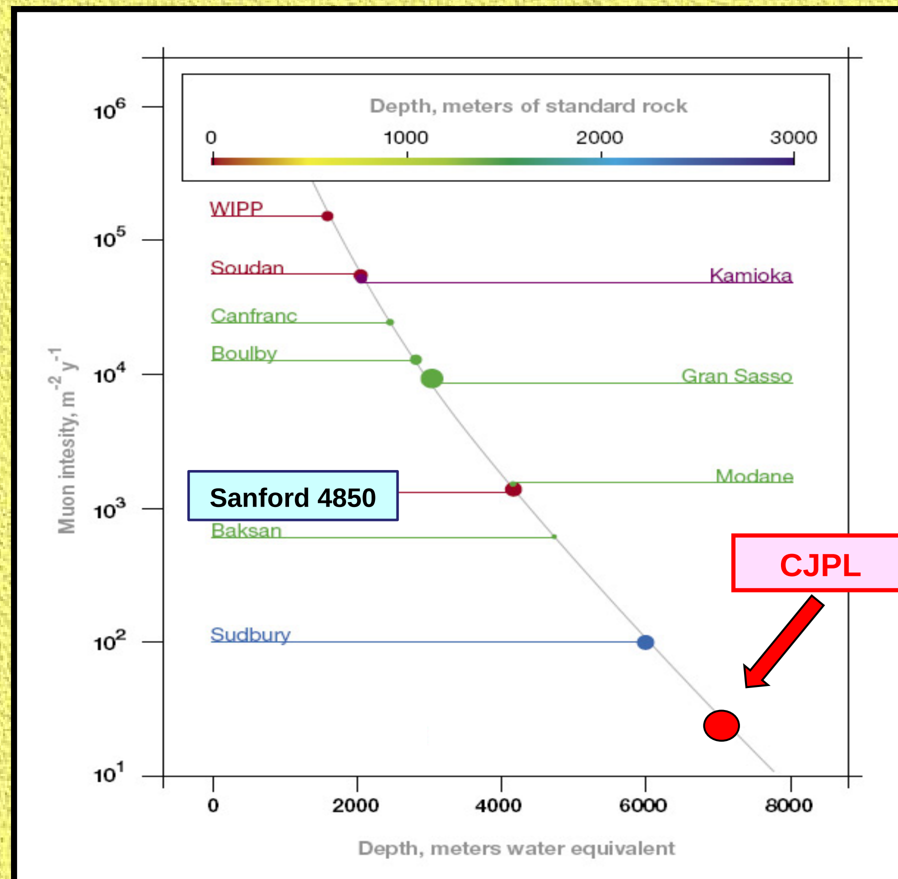


TEXONO@KSNL *[PRL13,AP14]* :

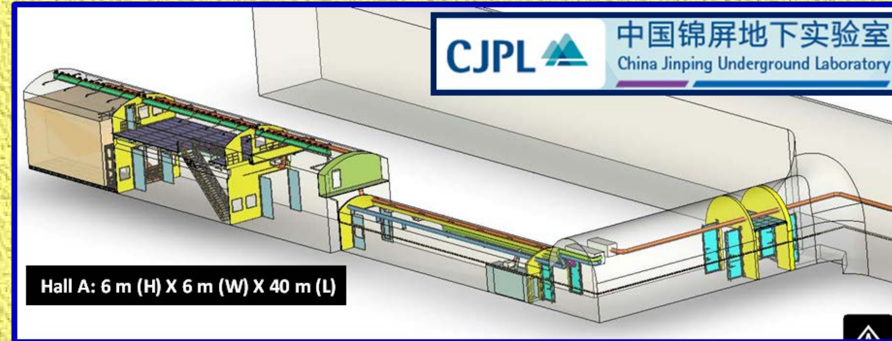
- 500 eV threshold
- devised schemes for B/S separation & efficiencies
- probed and excluded some light WIMP allowed regions
- Indicated: leakage of “Surface” background to “Bulk” samples can give false positive signals.

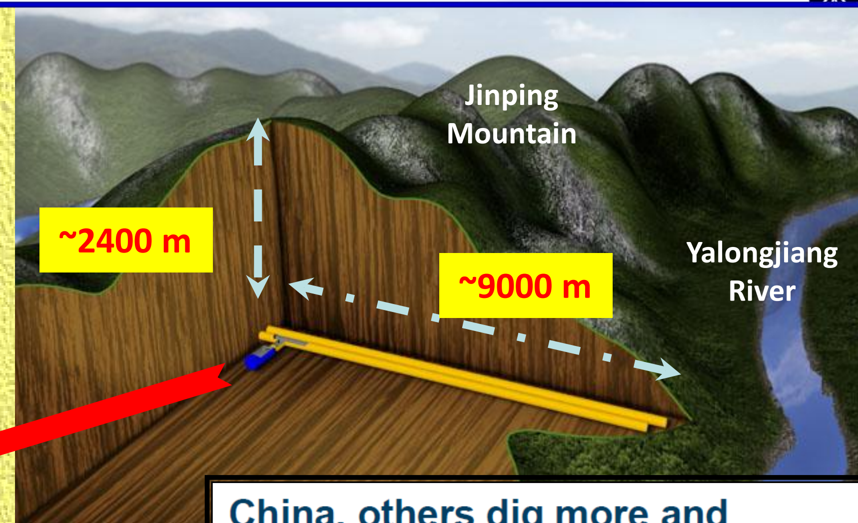
CJPL 中国锦屏地下实验室 China Jinping Underground Laboratory

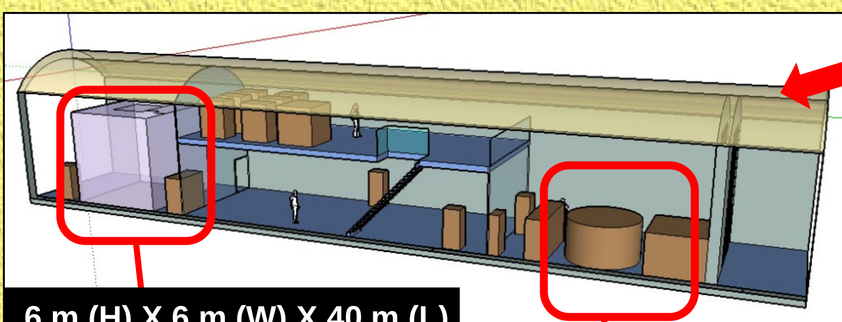
- ☑ 2400+ m rock overburden, drive-in road tunnel access
- ☑ ~6 muons/m^2-month (*cf sea-level 100 Hz/m^2*)
- ☑ Identified 2008 ; CJPL-I Inaugurated Dec 2010
- ☑ 6X6X40 m cavern constructed *[managed byTHU & YLJHDC]*
- ☑ 1st Generation CDEX-1 & PandaX Dark Matter Program



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







CDEX-1

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

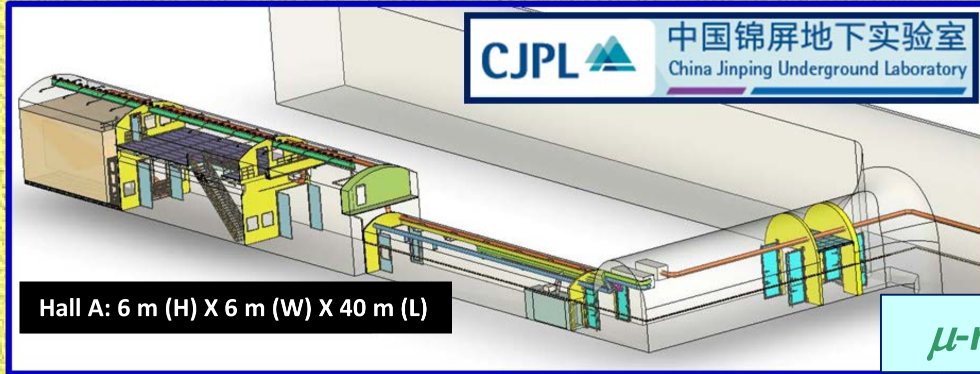
PARTICLE PHYSICS:

Chinese Scientists Hope to Make Deepest, Darkest Dreams Come True

Dennis Normile

Science AAAS

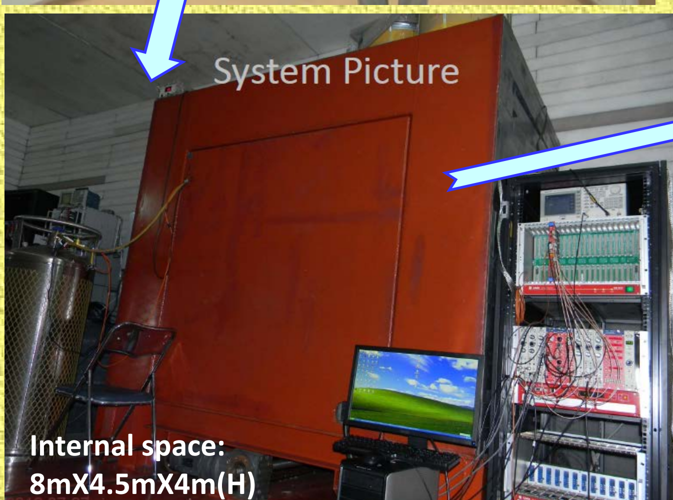
Science 5 June 2009:
Vol. 324. no. 5932, pp. 1246 - 1247
DOI: 10.1126/science.324_1246

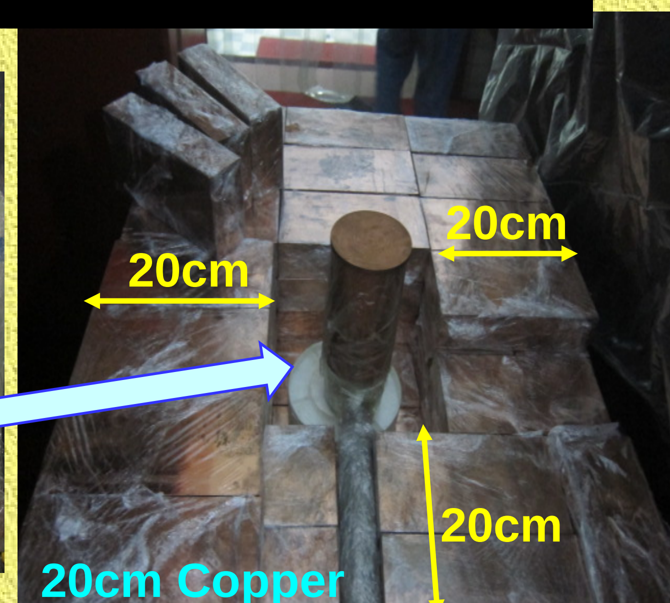


μ-rate ~ 6 per m^2 per month

CDEX-1 @ CJPL :

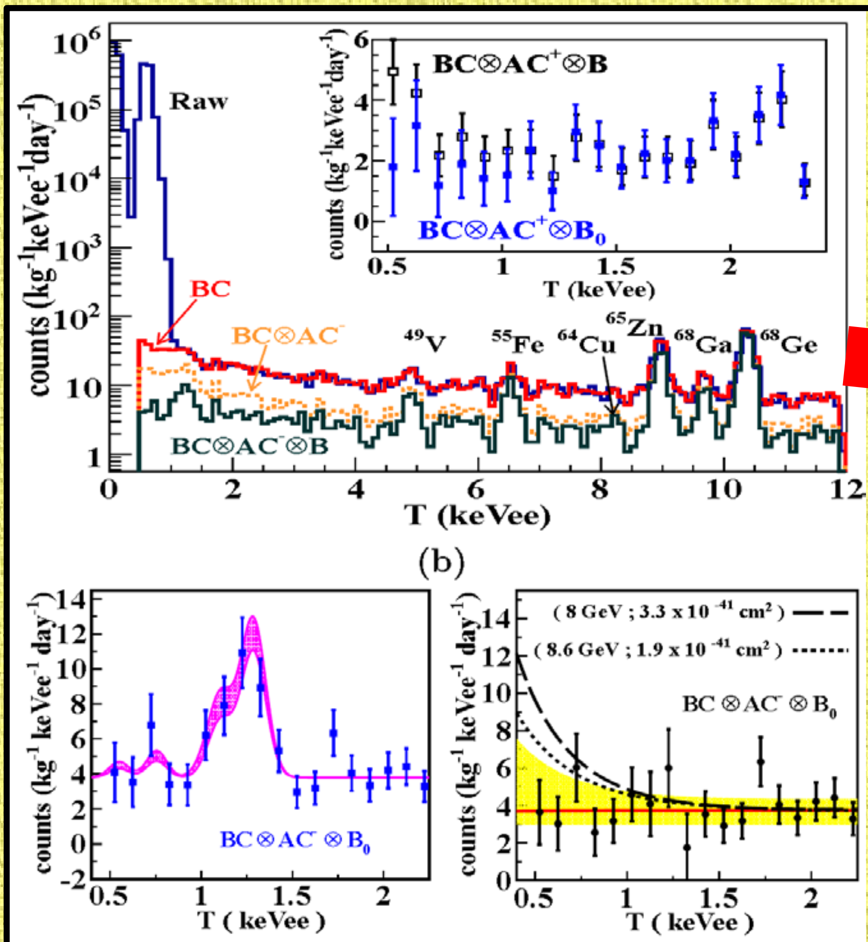
- Adopt KSNL Baseline Design
- Engineering Run 2011
- Physics Run June 2012
- First Results 2013

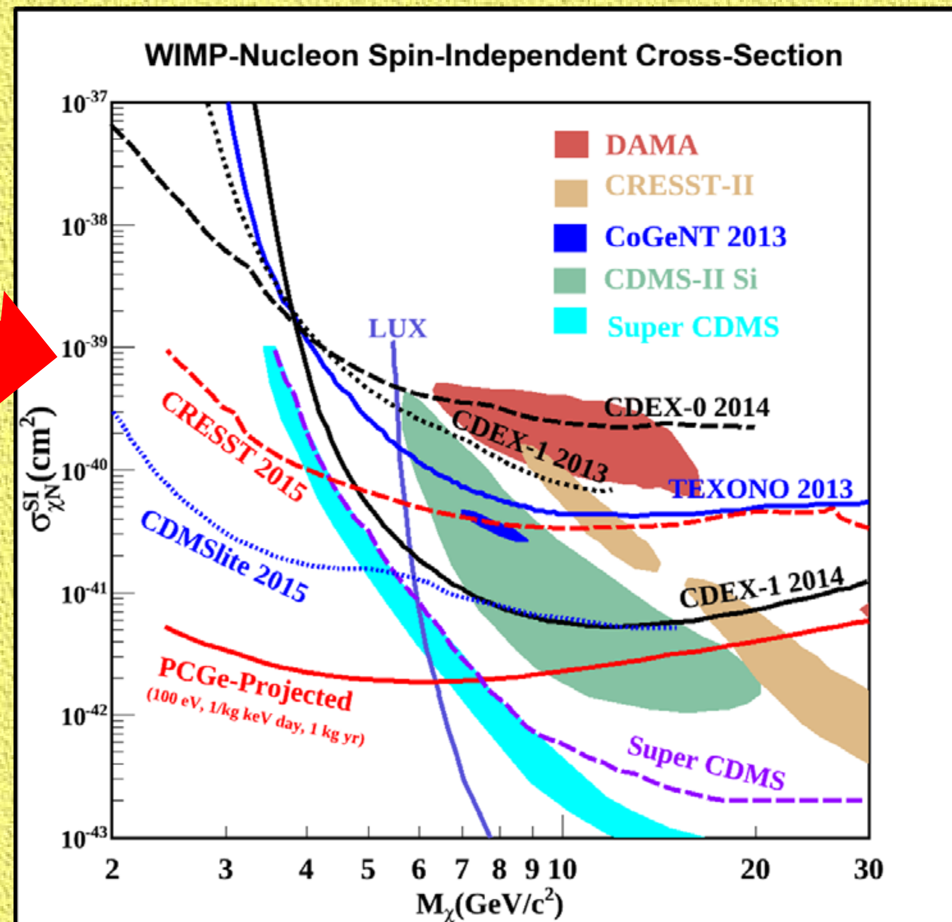




CDEX-1 @ CJPL 2014 *[PRD13, PRD14]*

- *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*



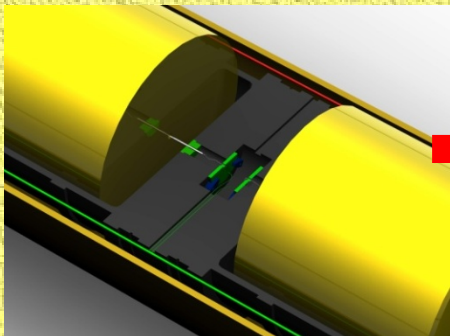


CDEX-1 Current Efforts:

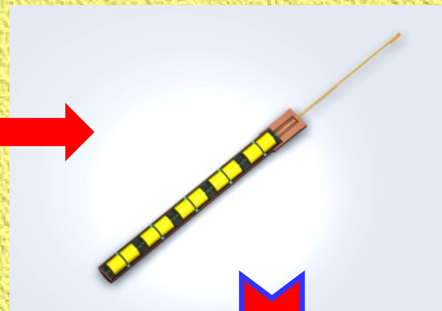
- More Data
- 2nd pPCGe at 200 eVee threshold
- Modulation Studies
- Other Physics Channels

Design of CDEX-10 : with LAr Anti-Compton

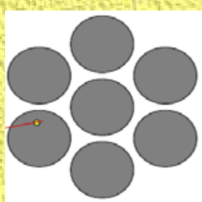
Ge + JFET

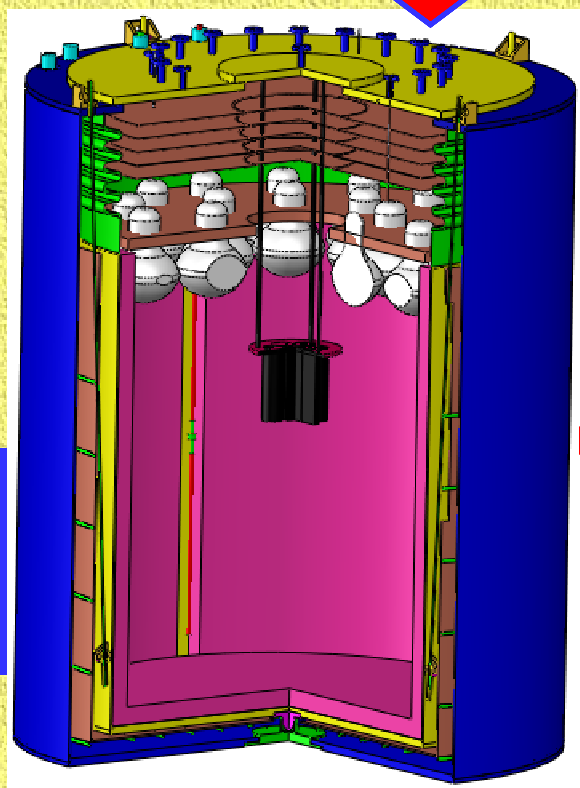


Ge Array in String

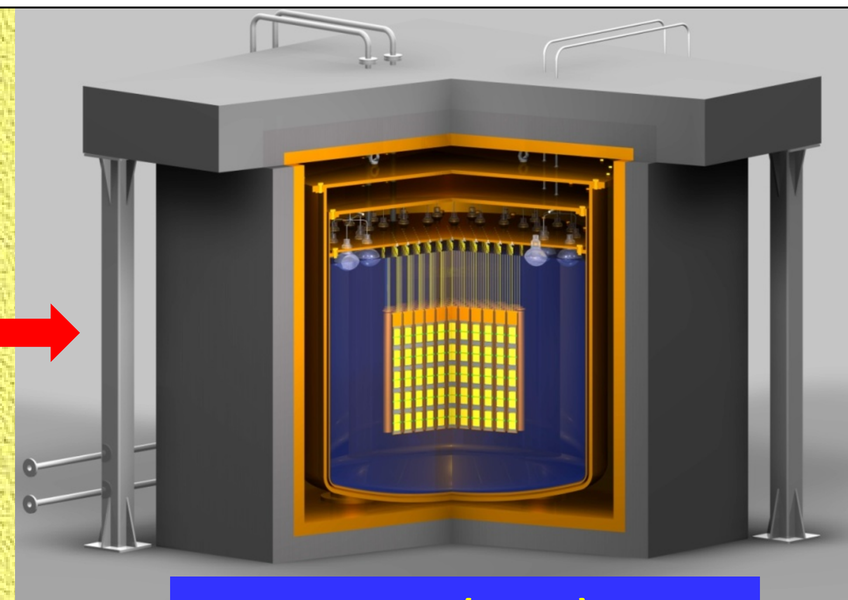


- **PCGe in Arrays & Strings**
- **LiqN (LiqAr) as both cryogenics (& active anti-Compton)**
- **Goal: a "0νββ Bkg-Grade" Expt. for DM Searches**
- **Baseline Design for Future O(1 ton) Expt. for 0νββ (+DM)**





CDEX-10
(Prototype : 2015+)



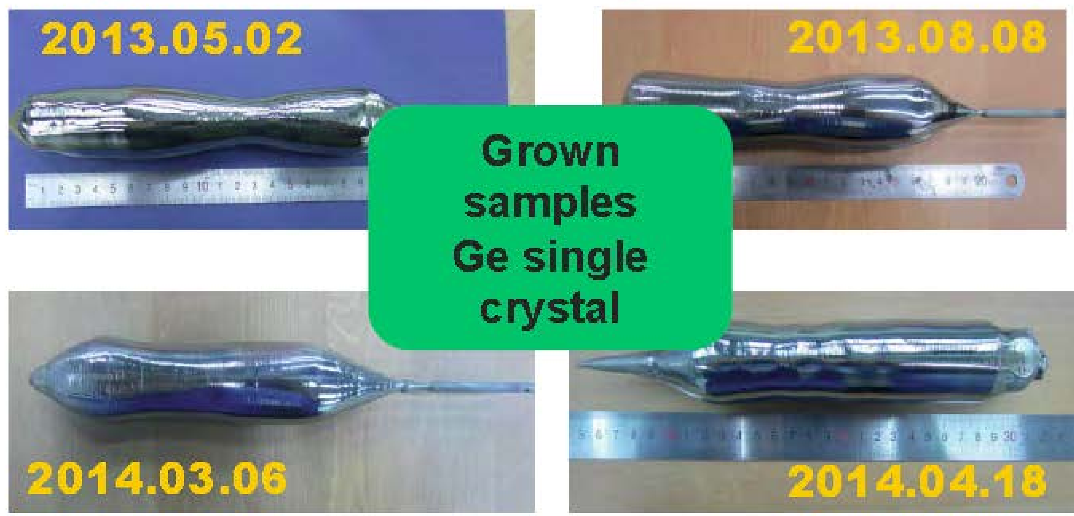
CDEX-(1 ton)
Artist's Conception

Ge Crystal Growth Facilities @ THU

Zone refining machine

Czochralski machine

Cutting & Polishing



Grown samples Ge single crystal

Ge Detector Fabrication @ THU

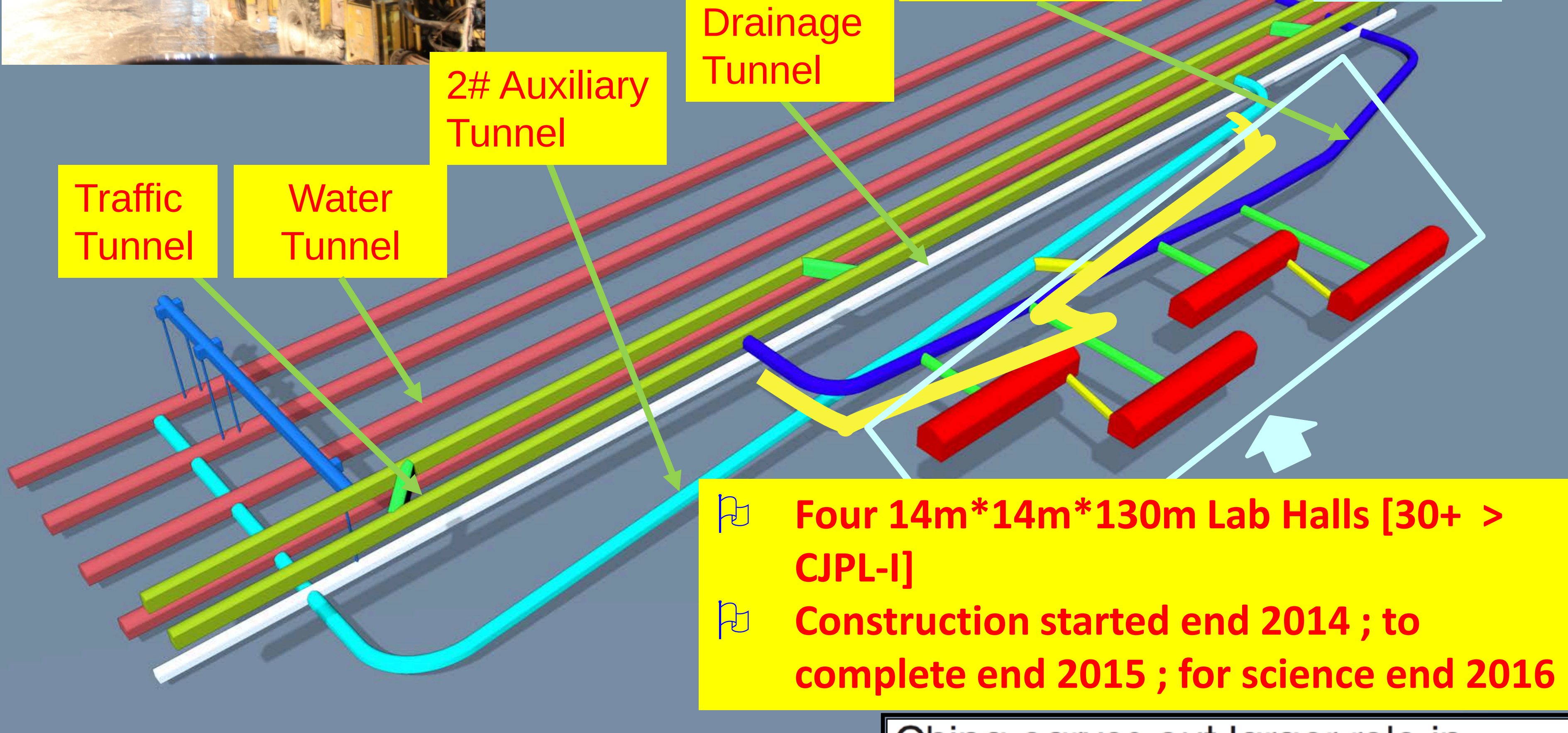
- Application-specific optimized assembly
- Coupled with -- R&D on JFETs & Preamps & ASICs

PLUS

Major R&D Program @ THU

- Electroformed (Ultra-Clean) Copper Production Line
- Enrichment of Ge76 for Double Beta Decay

NEW Lab : CJPL-II



- Four 14m*14m*130m Lab Halls [30+ > CJPL-I]
- Construction started end 2014 ; to complete end 2015 ; for science end 2016

PHYSICS

Science V346, Nov 2014

China supersizes its underground physics lab

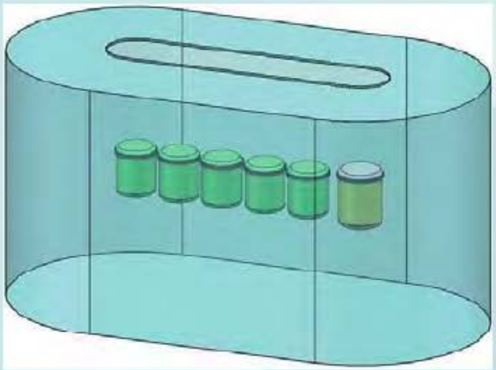
Planned expansion could pave way for "ultimate dark matter experiment"

China carves out larger role in underground science

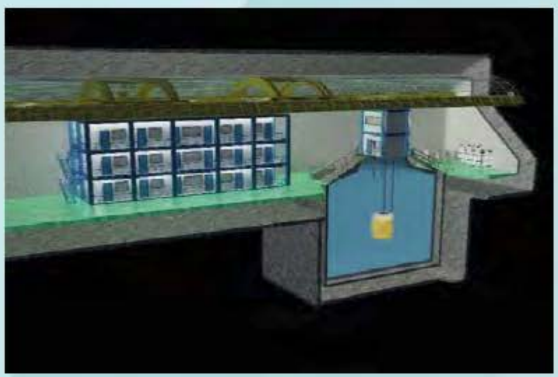
As it is doing in so many areas of science, China is racing onto the world stage of underground astroparticle physics.

Physics Today **68**(1), 23 (2015)

CDEX&PANDAX enlarge excavation projects



PANDAX

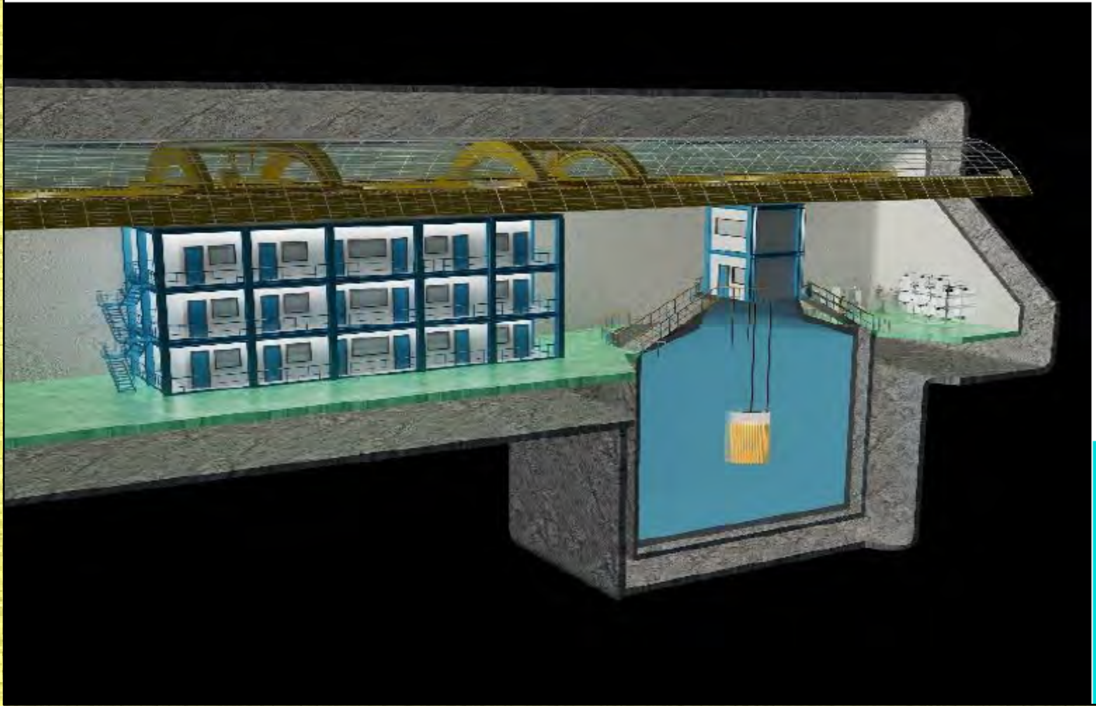


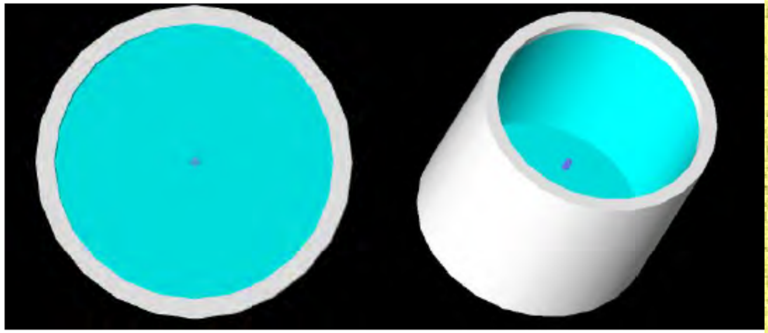
CDEX

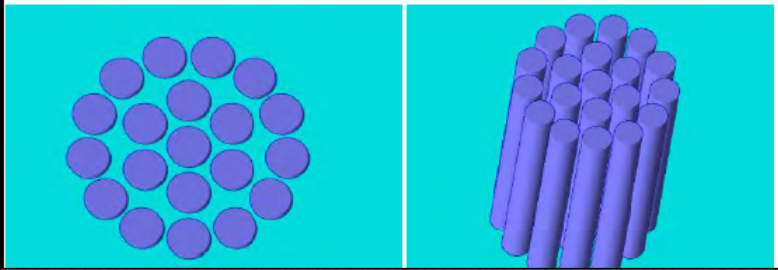
NO	Project	Begin Date	Finnish Plan date
1	Enlarge excavation for PANDAX upper layer	2015/10/01	2015/11/25
2	Enlarge excavation for PANDAX lower layer	2015/11/26	2015/12/25
3	PANDAX Foundation excavation	2015/12/26	2016/03/25
4	PANDAX Foundation lining	2016/03/26	2016/05/15
5	PANDAX Corbels lining	2016/05/16	2016/06/15
6	Steady CDEX Hall	2015/10/01	2015/11/15
7	Enlarge excavation for CDEX	2015/11/16	2015/12/15
8	CDEX Foundation excavation	2015/12/16	2016/02/15
9	CDEX Foundation lining	2016/02/16	2016/03/31

CDEX-200 : Space available in CJPL-II

- LN_2 as a cooling and passive shielding system
  : Goal: Background from outside of Ge < 10^{-3}cpkkd
- New space for CDEX: ϕ18m * 30m;
- CDEX-200 space ready in 2016.

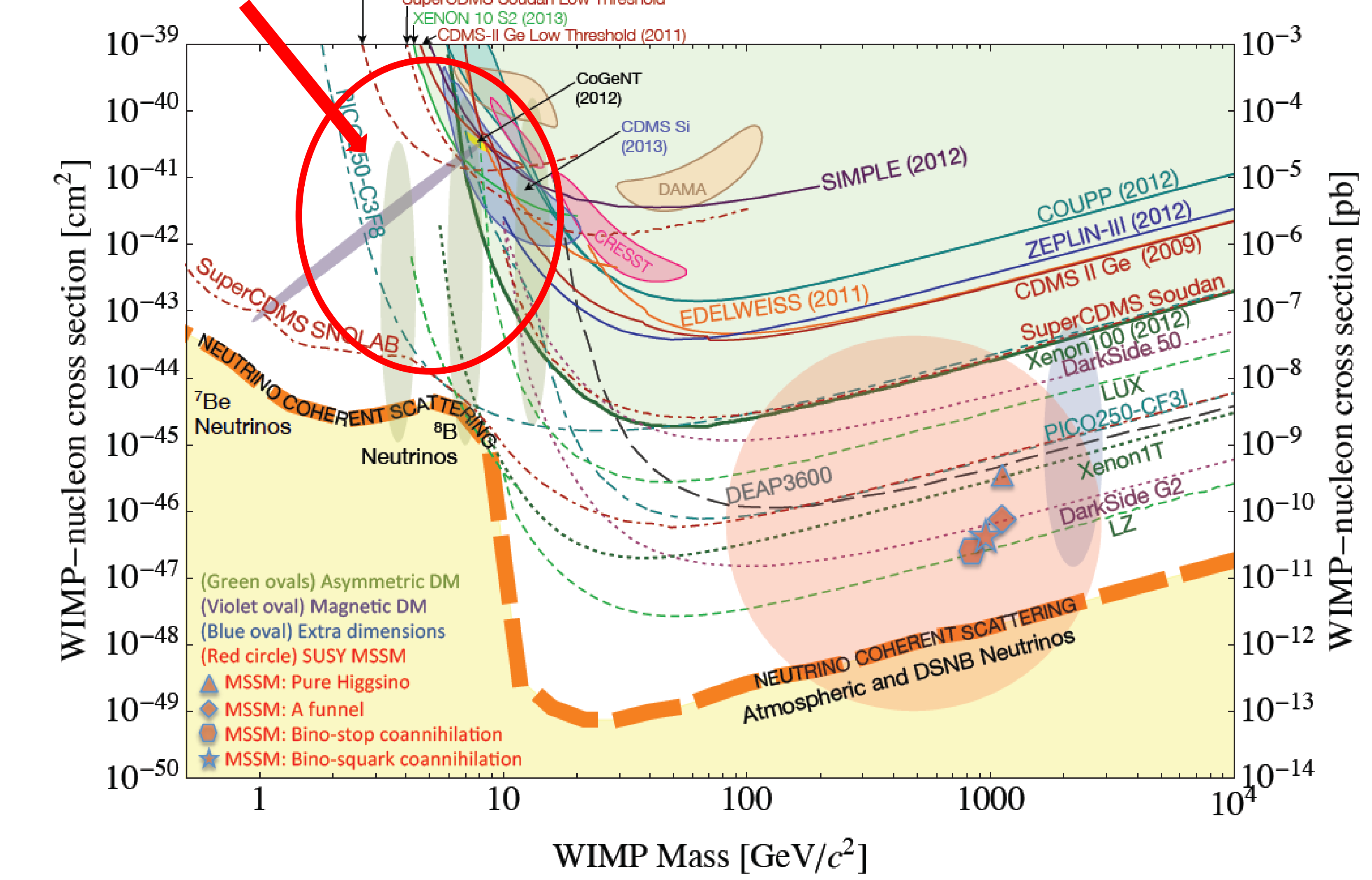


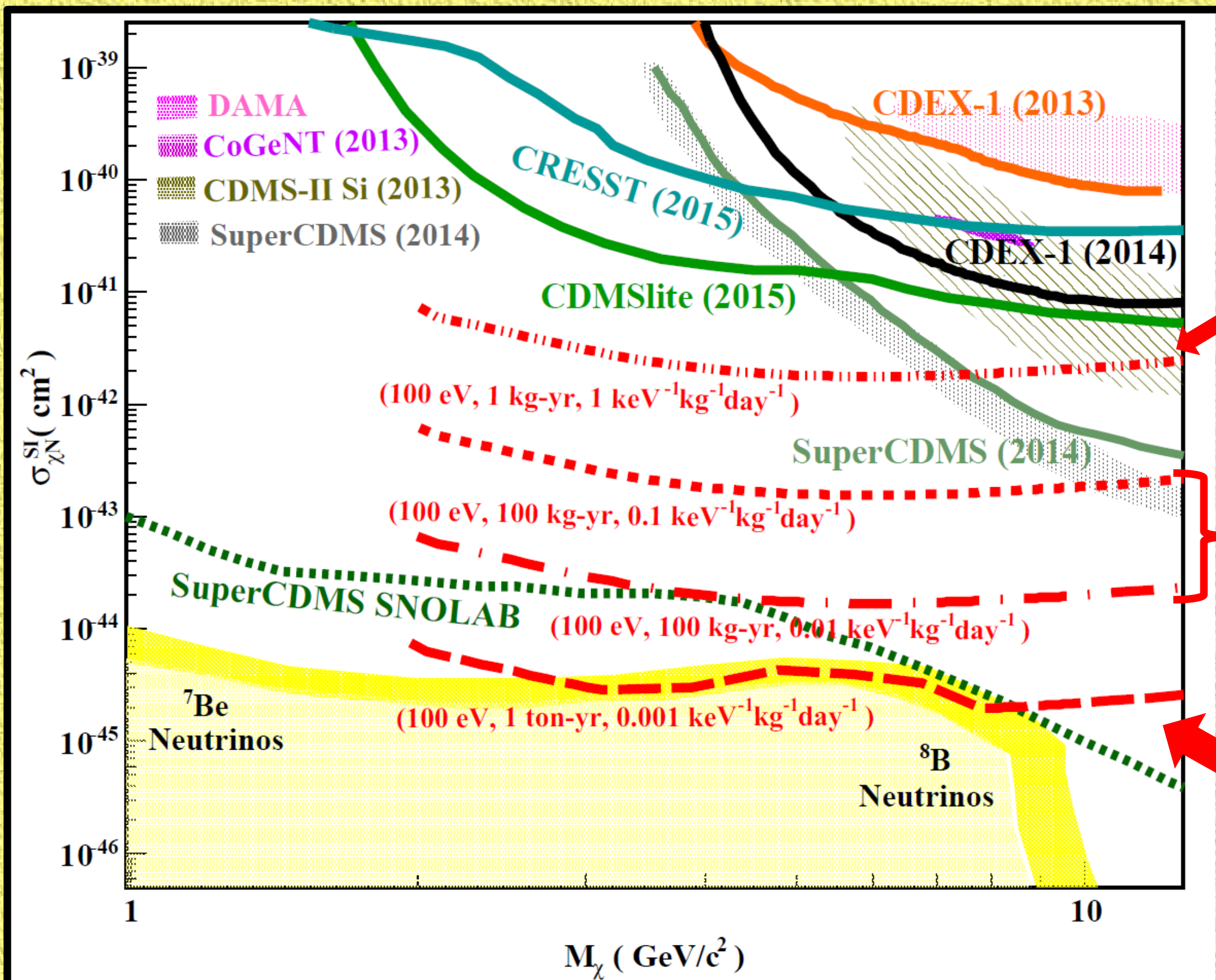




Spin-Independent σ(χN) Exclusion Plot

CDEX-DM Progam:
Explore Light-WIMP Region





CDEX-1 : Realistic Reach

CDEX-10/100 :

- **Reach @ $0\nu\beta\beta$ Grade Bkg Control**
- **Spread -- H3 Bkg & Subtraction**

CDEX-1ton :

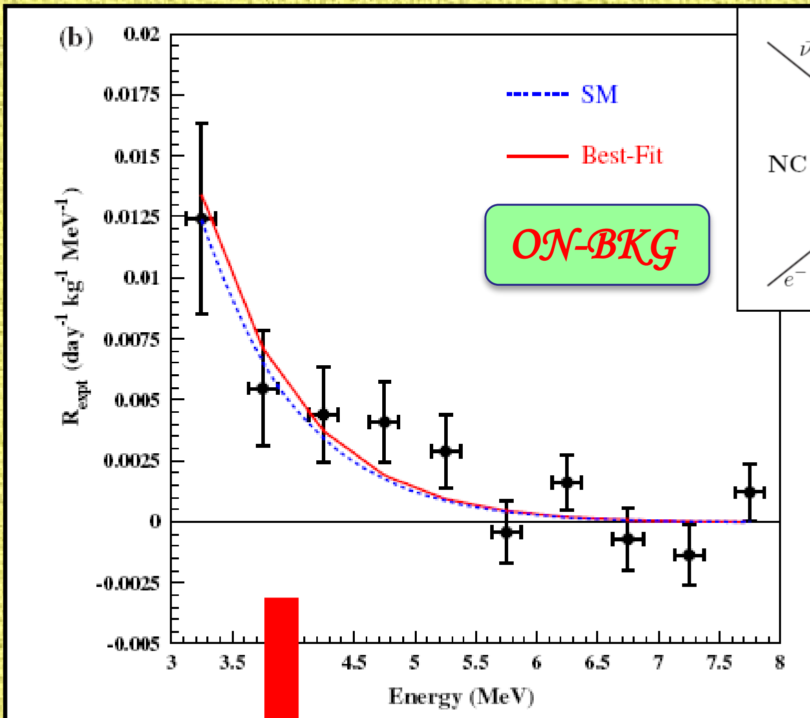
- **Reach @ $0\nu\beta\beta$ Grade Bkg & Underground Ge-Growth**

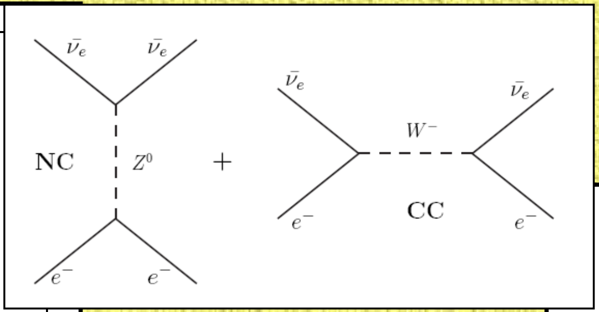
Summary & Prospects

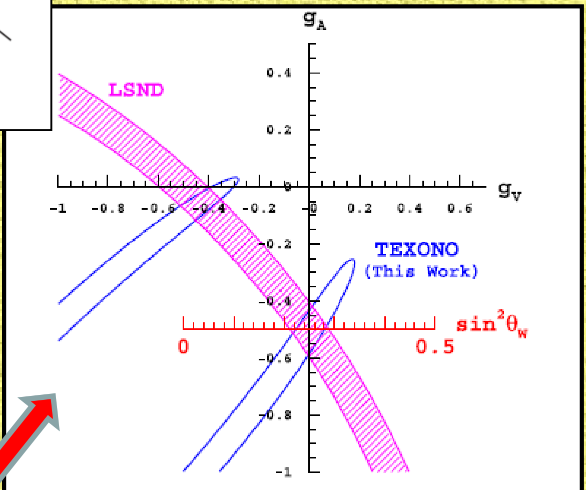
- Competitive results on light WIMPs with sub-keV Ge, *even at* a surface TEXONO@KSNL ; further improved with underground CDEX-1 @ CJPL
- Surface leakage to Bulk samples is important to PPCGe at low energy, origin of earlier "WIMP signal".
- CJPL-2: 30+ times more space, being built
- Ge-R&D + technology acquisition ⇨ next generation DM (+DBD) experiment @ CJPL
- KSNL: more matured to return to original goal
  - ⚐ νN coherent scattering

Back Up
Technical Materials

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



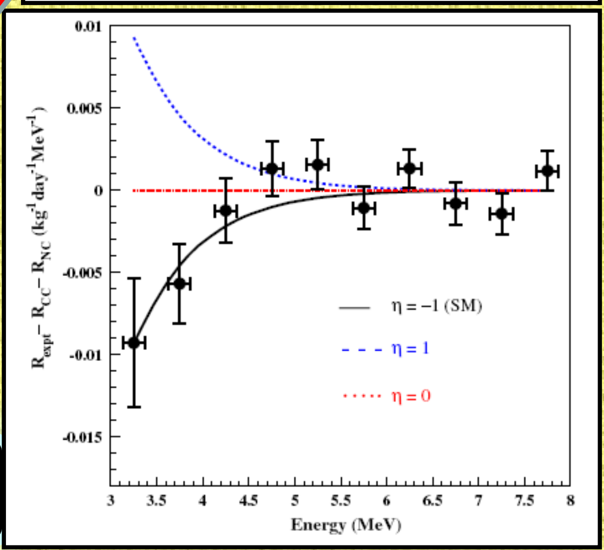




$$R = [1.08 \pm 0.21(stat) \pm 0.16(sys)] \times R_{SM}$$

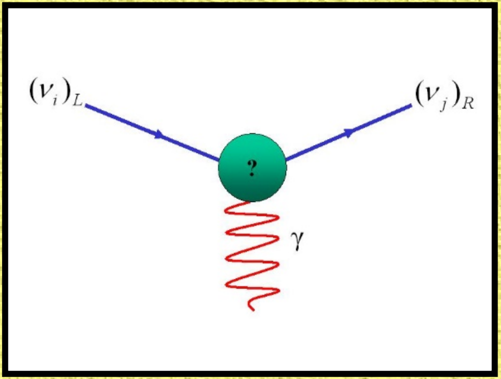
$$\sin^2\theta_W = 0.251 \pm 0.031(stat) \pm 0.024(sys)$$

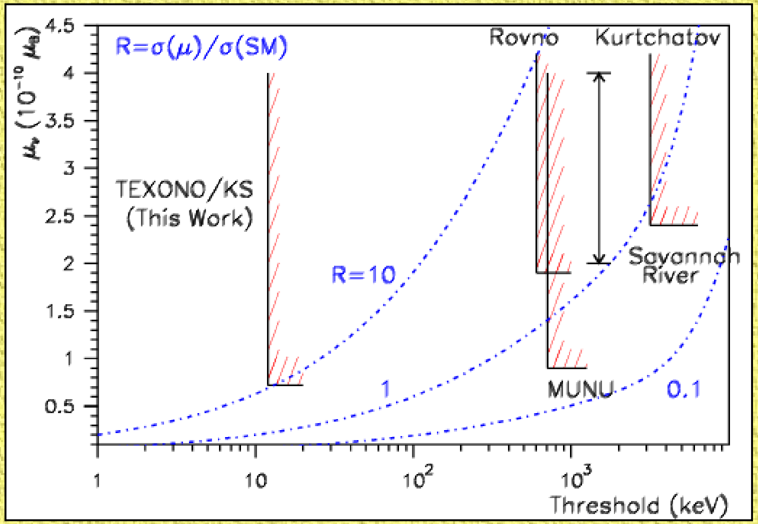
Verify SM Destructive Interference



⊕ 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 ⇒ dσ/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

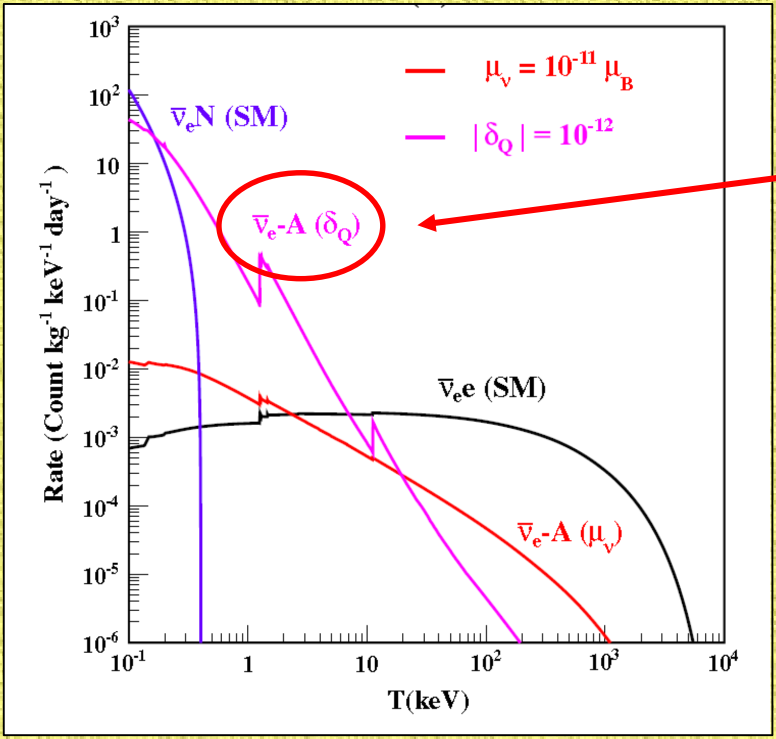
$$\Gamma^{\mu}_{em} \equiv F_1 \cdot \gamma^{\mu} + F_2 \cdot \sigma^{\mu\nu} \cdot q_{\nu}$$

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

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

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

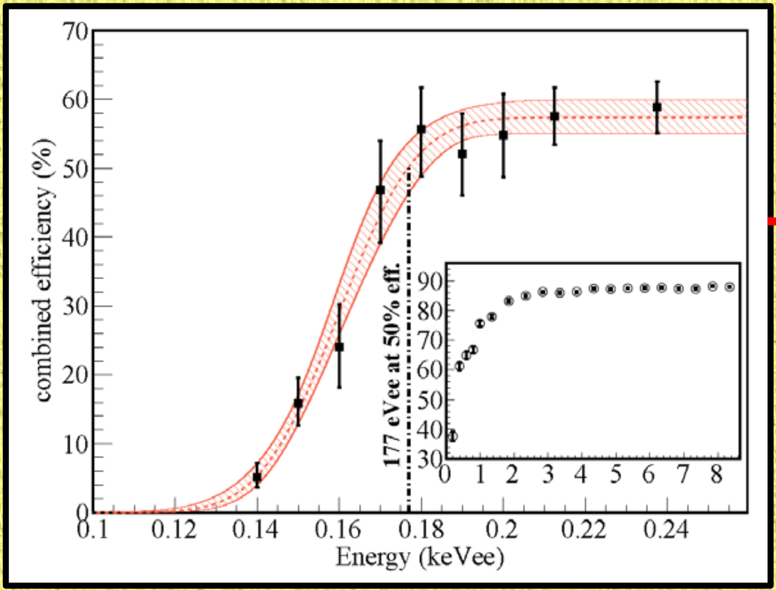
$$\overline{\nu_e} + A \rightarrow \overline{\nu_e} + A^+ + e^-,$$

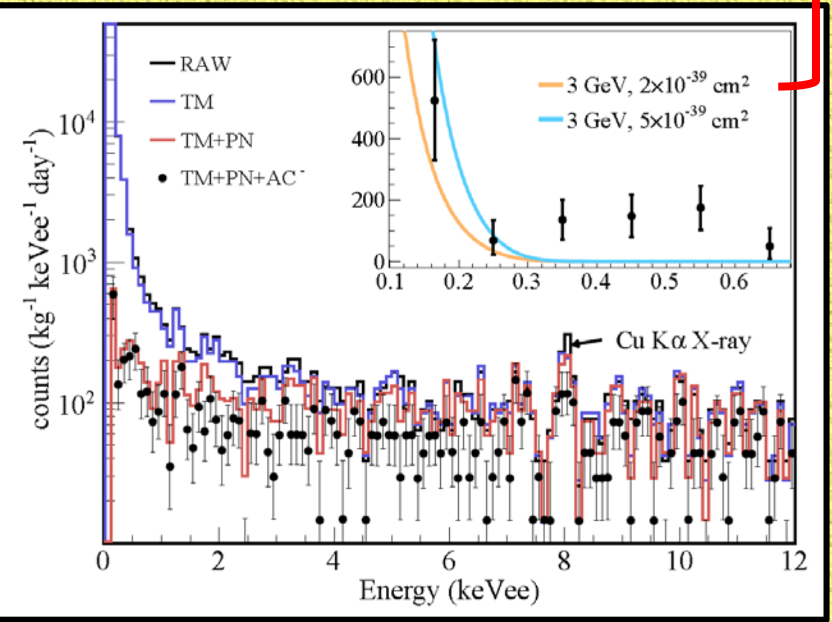


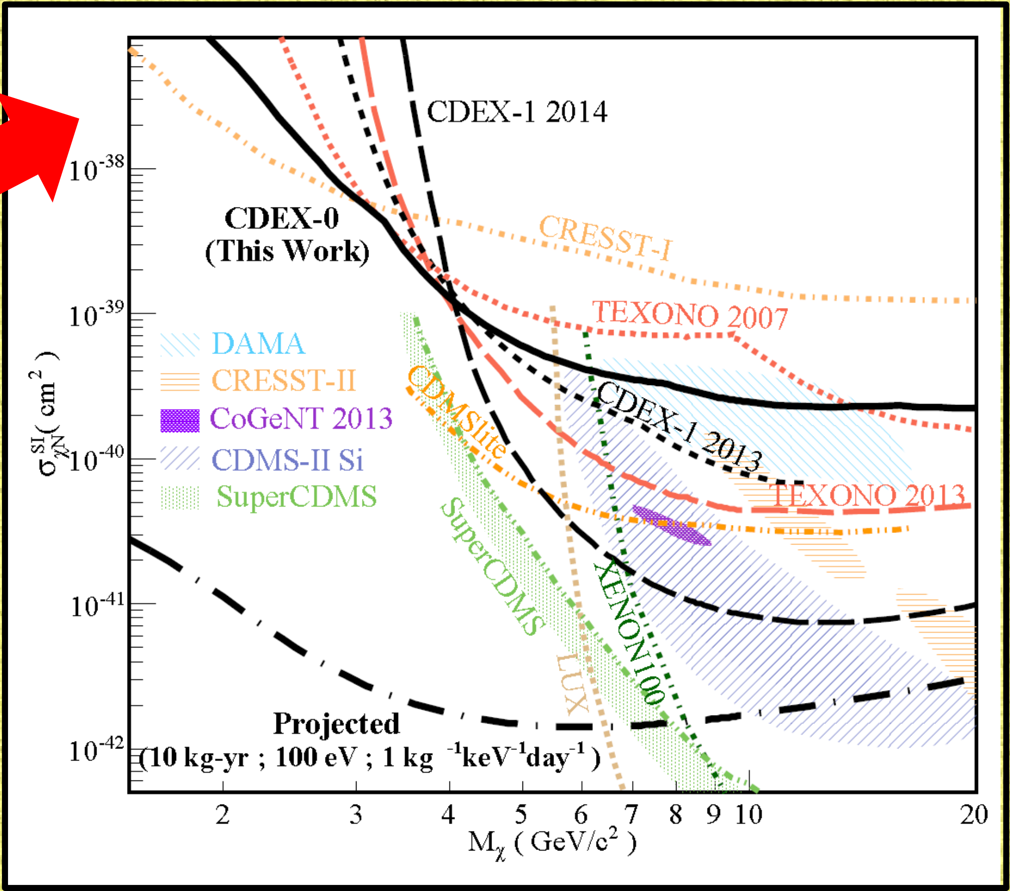
- ☑ **Identify New Twist - Cross-section enhanced at low energy transfer ("minimum ionizing")**
- ☑ **Smoking-gun signatures for positive signals: peaks at known K/L binding energy at known ratios *[different from cosmic-activation electron-capture background]***
- ☑ **Present Bound : $\delta_Q < 10^{-12}$**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

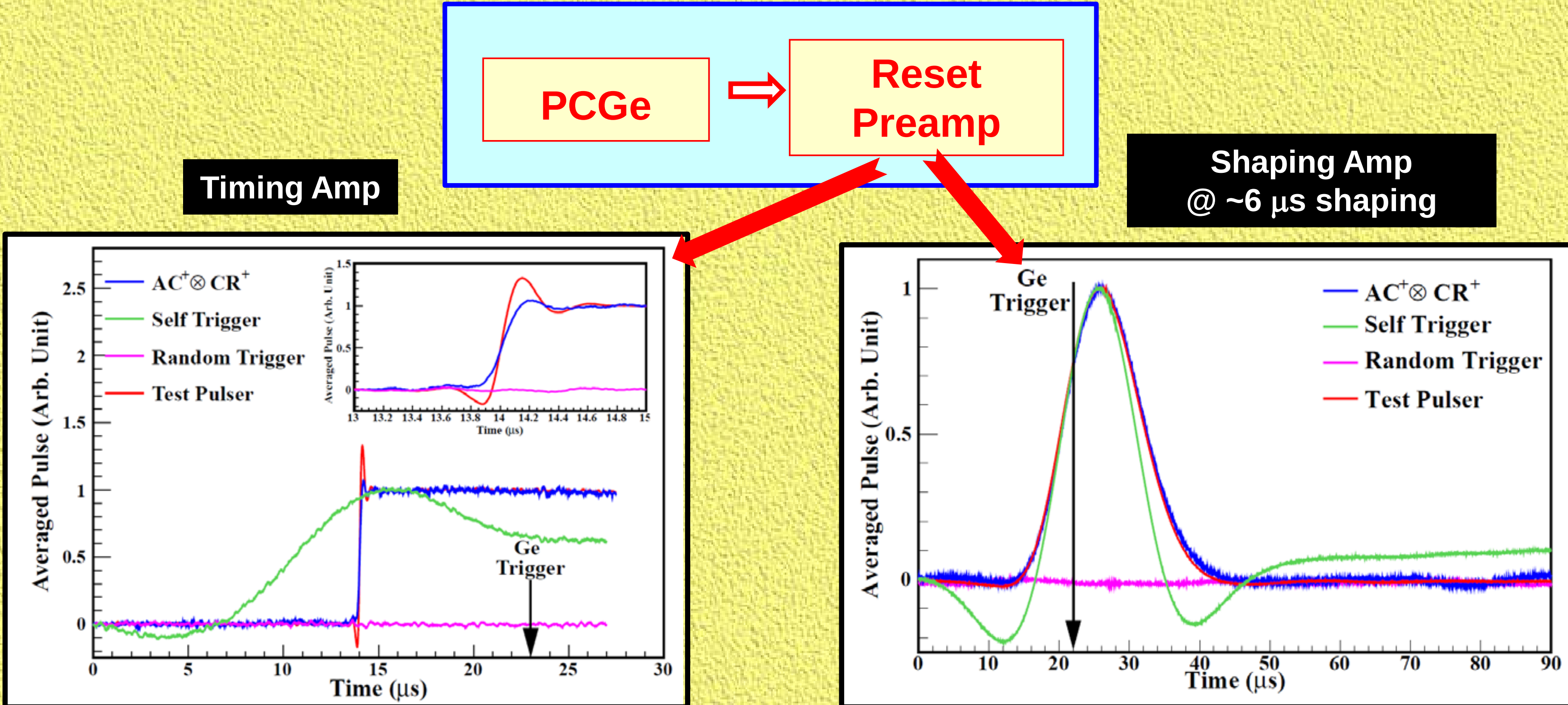
CDEX-0 *[20g prototype]* @CJPL 2014 *[PRD14]*

12g ULEGe e @ 177 eV_{ee} Analysis Threshold









☑ **Test Pulser :** faster than TA , identical output to SA

↳ valid for studying trigger, energy calibration ; not Bulk/Surface effects

☑ **Self-trigger electronic noise** events different from **Physics** events ***[AC+XCR+]*** in both TA & SA *[AC==NaI Anti-Compton ; CR==Cosmic-Ray Panel]*

↳ use pulse shape analysis to select physics events near/below threshold

☑ TA & SA pulse identical all over “Bulk” fiducial volume

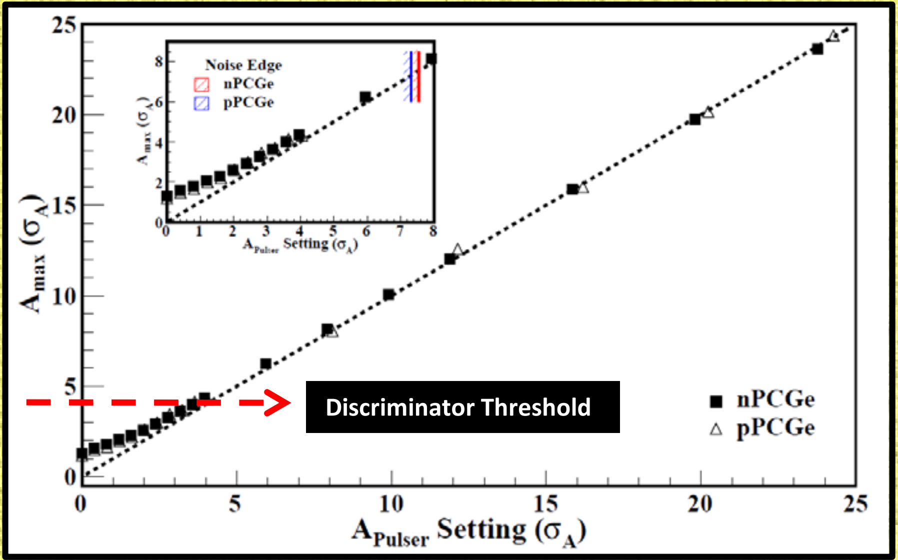
↳ ***[AC+XCR+XBulk]*** background events used for efficiency studies for ν/χ signals

Energy Definition:

- Both Amplitude or Area of Shaping Amplifier Output
- Linear & Well-Behaved above Electronics Threshold.

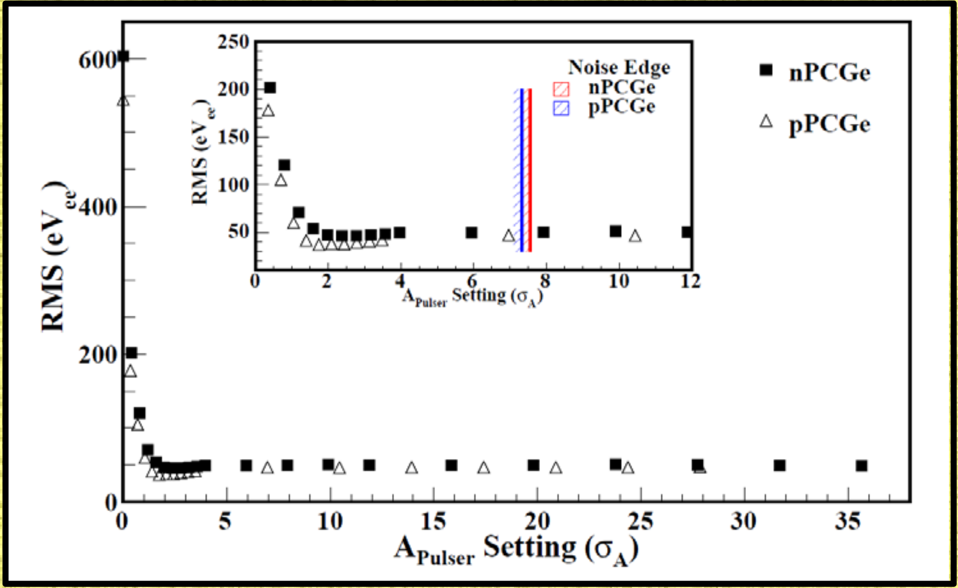
Energy Calibration:

- Random Trigger to define Pedestals
- X-ray Sources up to 60 keV
- Internal Lines (1-12 keV) from in situ data
- Precision Pulser for low energy interpolation



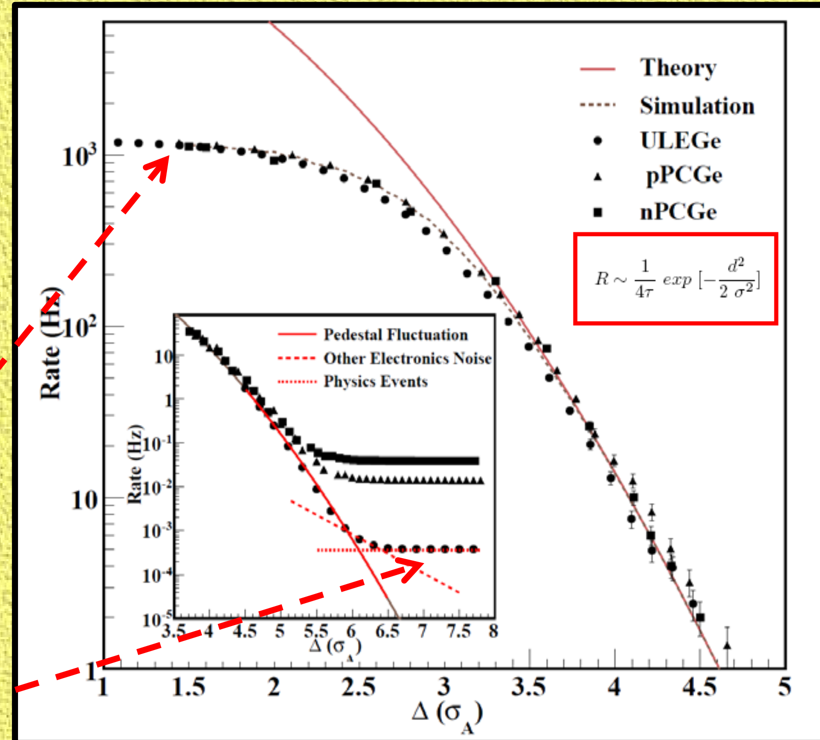
Pulser SA Amplitude Vs Input

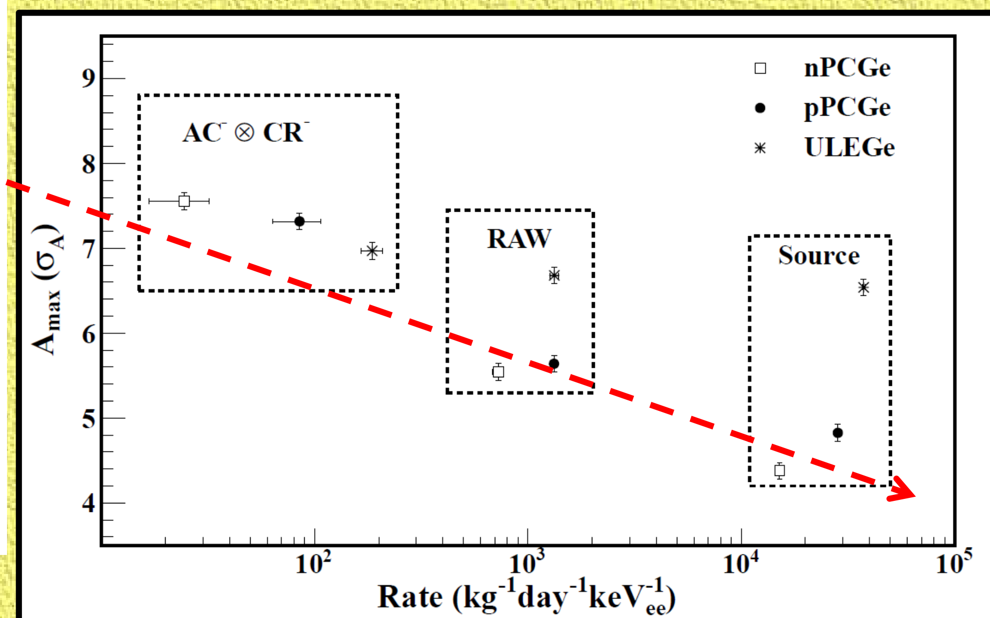
Pulser SA FWMH Vs Input



Trigger Rates :

- ☑ Agreed with expectations
- ☑ A universal curve valid to all detectors with discriminator threshold in "Pedestal RMS" unit.
- ☑ Saturation at low threshold due to "Gate Width"
- ☑ Excess in high threshold due to dominating physics events
- ☑ Electronics "threshold" depends on physics background level for the same detector (lower background implies higher threshold)





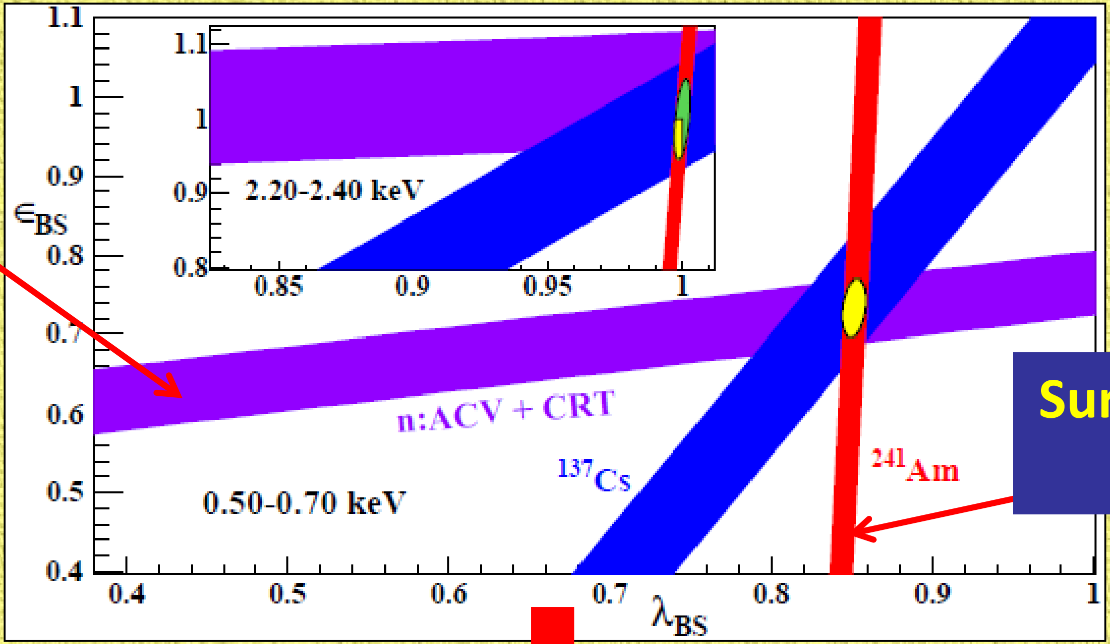
"Calibration" ≡ measure energy-dependent signal-retaining (ε_{BS}) & background-suppressing (λ_{BS}) efficiencies, related by the coupled equations [B,S=real ; B'S'=measured] :

$$\begin{aligned} B' &= \epsilon_{\mathrm{BS}} \cdot B + (1-\lambda_{\mathrm{BS}}) \cdot S \\ S' &= (1-\epsilon_{\mathrm{BS}}) \cdot B + \lambda_{\mathrm{BS}} \cdot S \end{aligned}$$

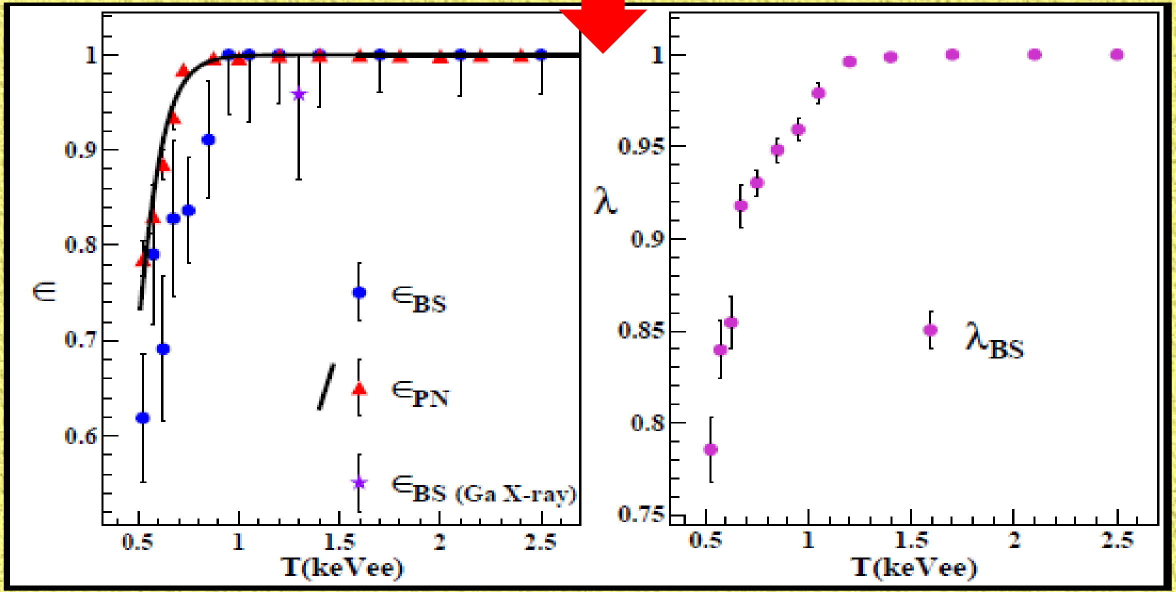
Approach: Identify *THREE* calibration data [low and high energy γ, cosmic-induced neutrons] where (B,S) are known & (B',S') measured ⊕ solve coupled equation for (ε_{BS}, λ_{BS})

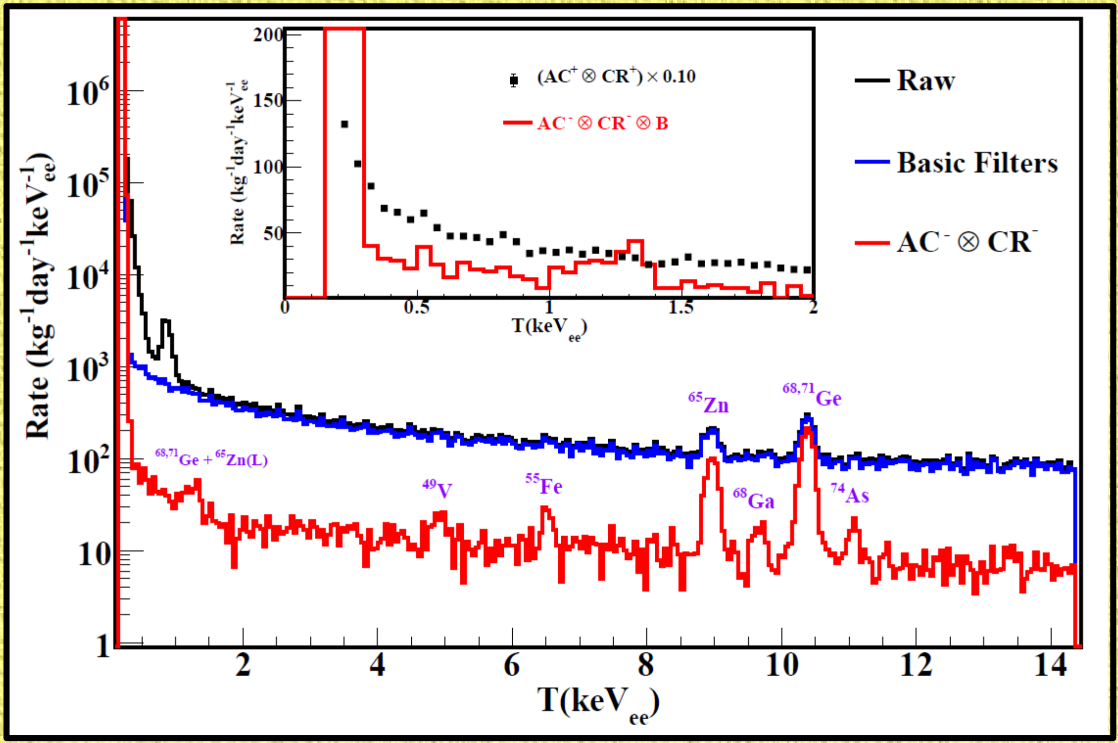
Solving Coupled Equations in (ε_{BS} , λ_{BS})

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



Surface-Rich γ-rays constrain λ_{BS}





Typical Analysis Sequence:

RAW → Basic → ACXCR → B/S …..

… [→ sub-noise-edge PSD]

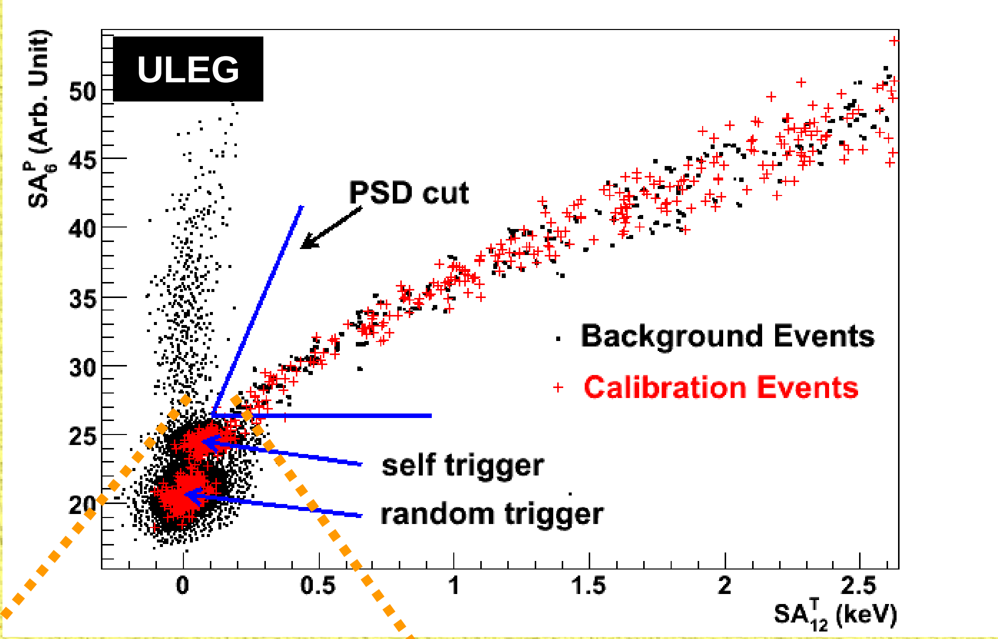
e.g. 500g pPCGe

- ☑ **RMS-pedestal ~41 eV ; Pulser FWHM ~110 eV**
- ☑ **AC- X CR- X B threshold at ~311 eV** ***[no external tags]***
- ☑ **AC+ X CR+ X B threshold at ~197 eV** ***[doubly external tags]***

PSD Selection to Suppress Electronic Noise

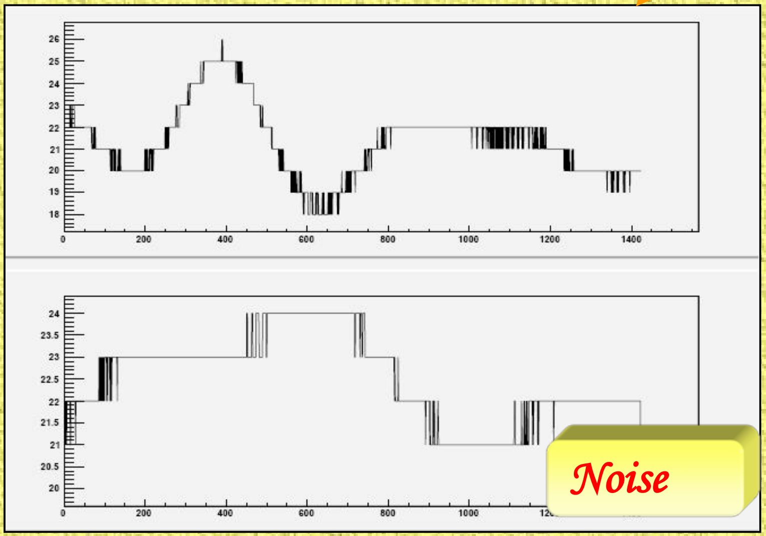
E.g. ⇨ correlations in two readout of different gains & shaping times

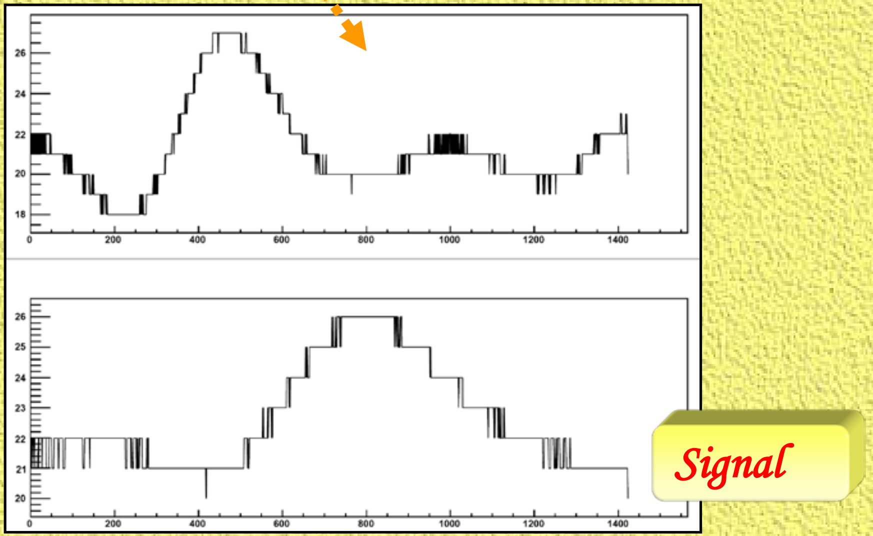
◎ **look for specific +ve pulse fluctuations at specific & known timing**



6μs

12μs





Phys-Vs-Noise Selection Efficiency