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

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

Henry T. Wong /王子敬
Academia Sinica /中央研究院
June 2015 @

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

Nuclear Physics 2015 NDM '15 Neutrinos and Dark Matter in Nuclear Physics
Jyväskylä, Finland, June 1–5, 2015

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

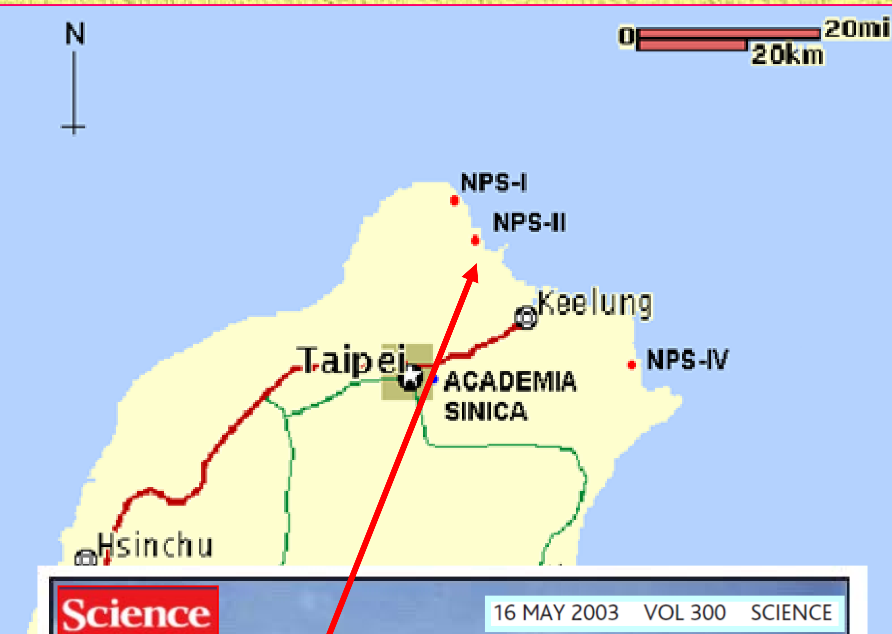
TEXONO Collaboration

[July 2013 @ Taipei]

CDEX Collaboration

[Dec 2012 @ Beijing]

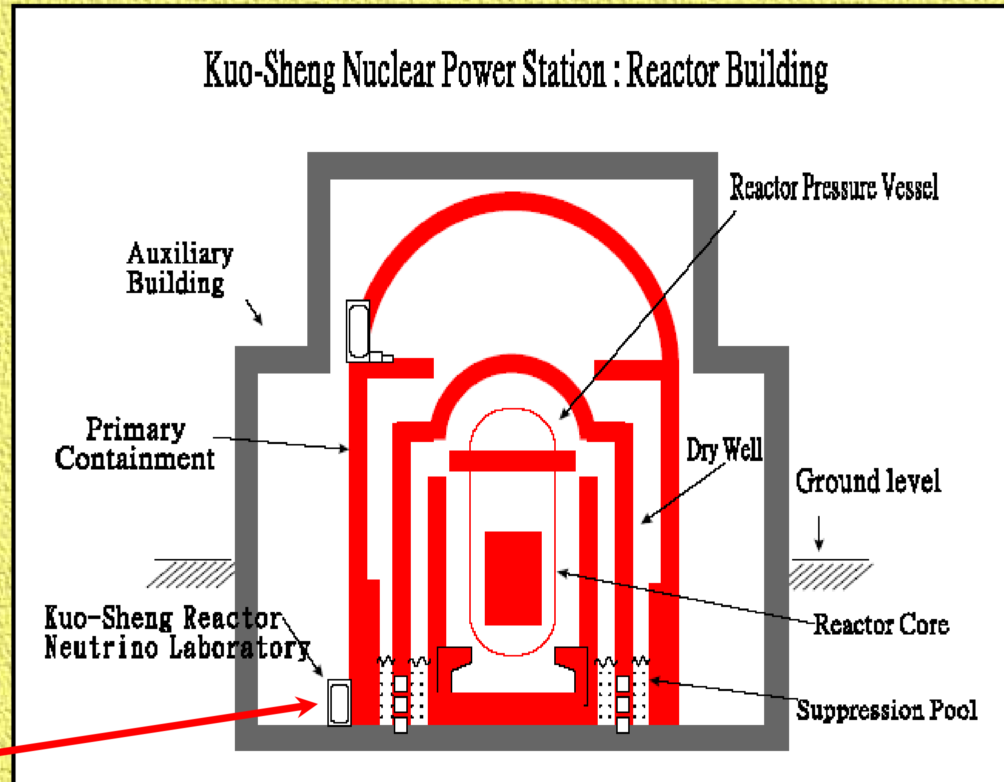
Kuo Sheng Reactor Neutrino Laboratory [KSNL]



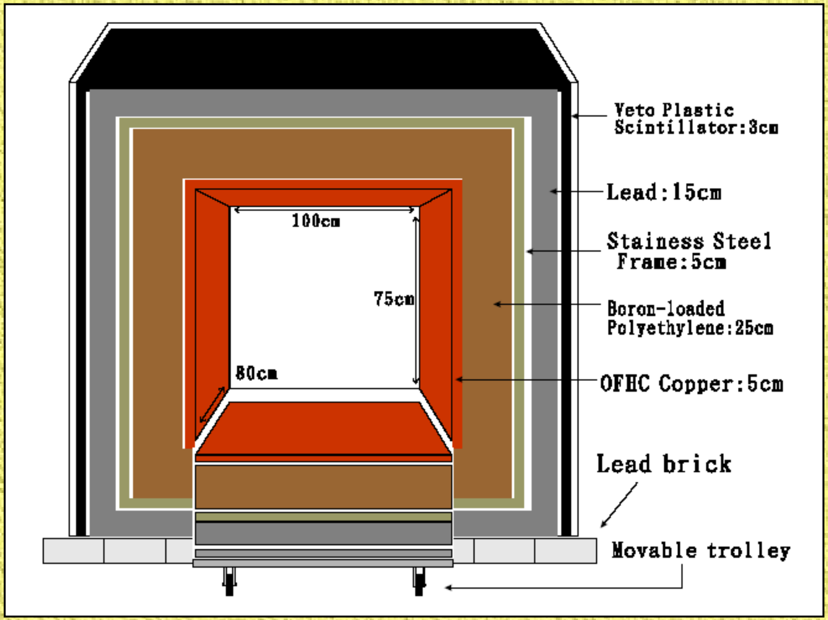

Science
AAAS
16 MAY 2003 VOL 300 SCIENCE
Taiwan-China Collaboration

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

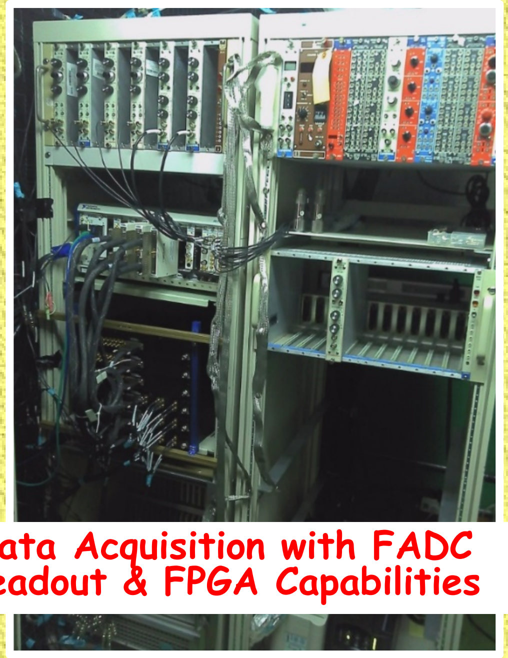
Flexible Design: Allows different detectors conf. for different physics

KSNL : Detectors Schematics

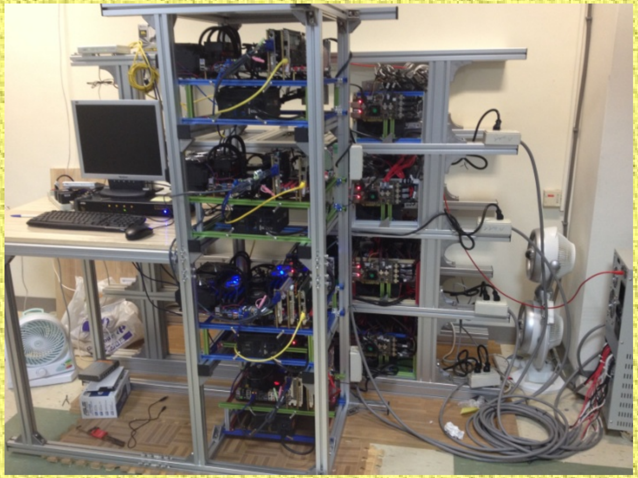
ULB-HPGe [1 kg]

CsI(Tl) [200 kg]

Sub-keV Ge
Detectors (20-900 g)



Data Acquisition with FADC
Readout & FPGA Capabilities

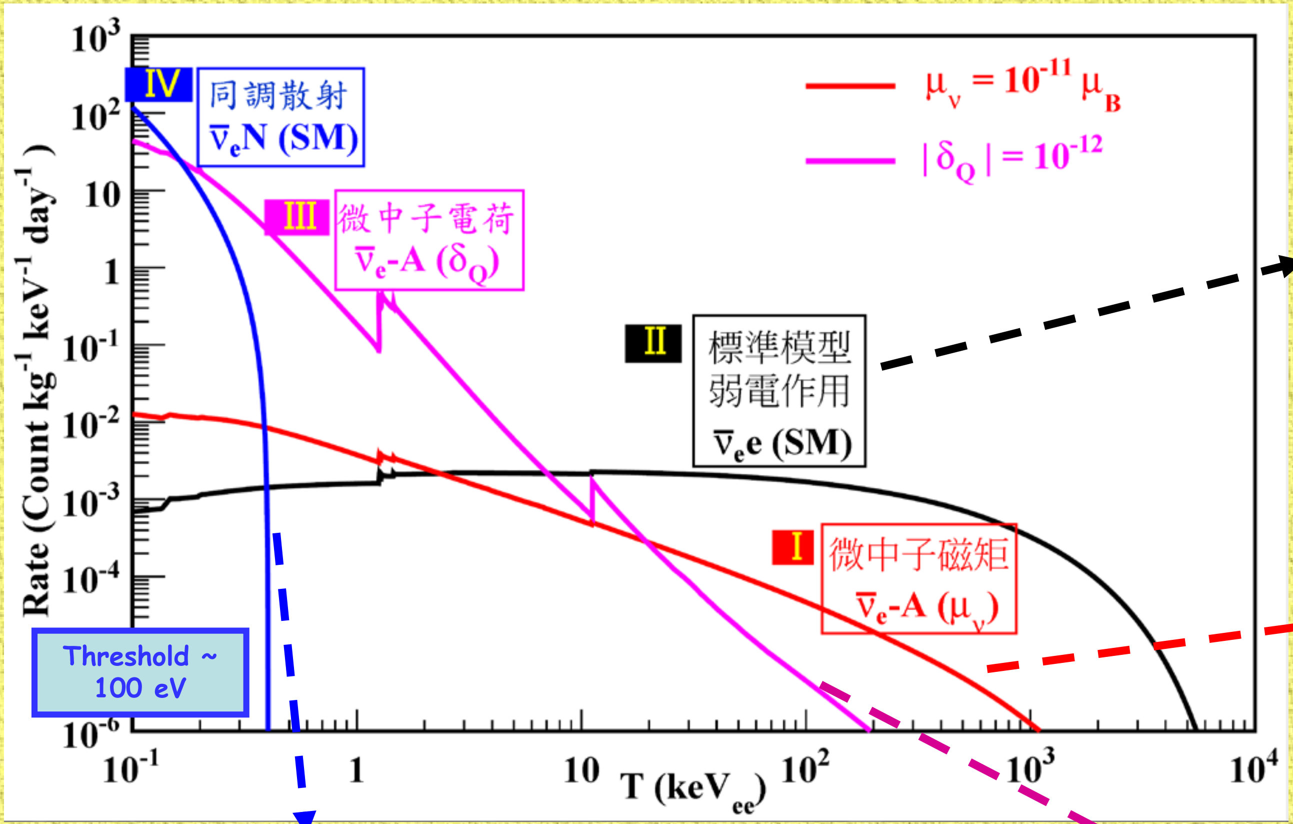


Multi-Disks Array [~300 Tb]

Neutrino Properties & Interactions at Reactor

Observable Spectra with Reactor Neutrino "Beam"

quality ⟵ **Detector requirements** ⟶ **mass**



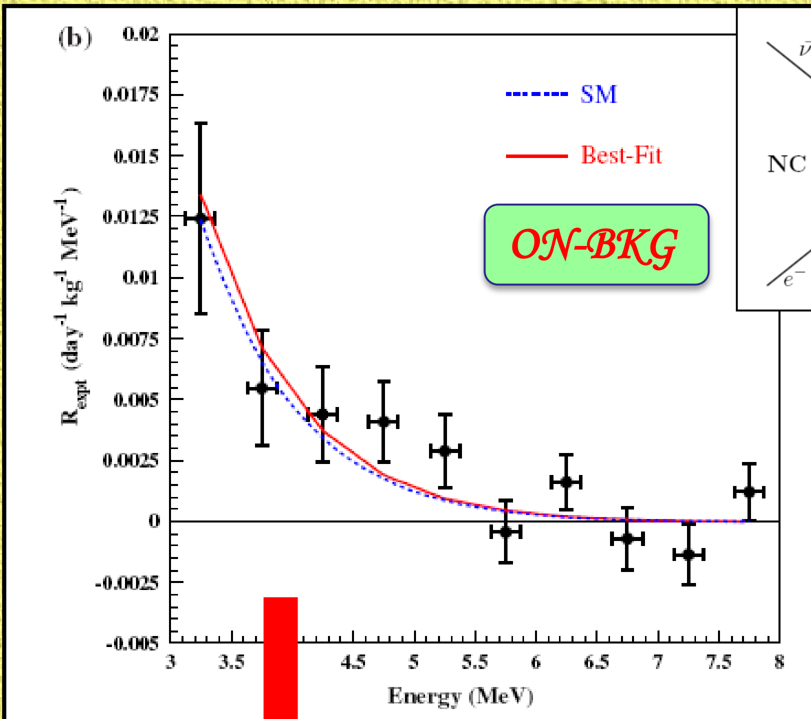
SM & NSI/BSM
ν-e Scattering
[PRD10,PRD10,PRD12]
⇨ 200 kg CsI(Tl)

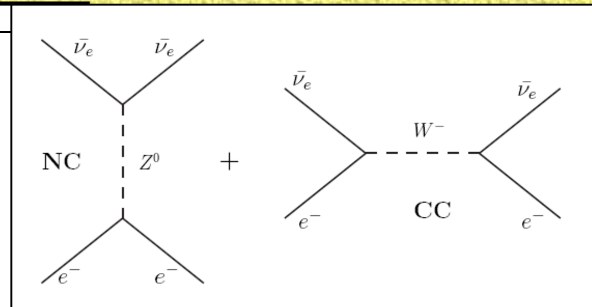
Magnetic Moments
[PRL03,PRD05,PRD07]
⇨ 1 kg HPGe

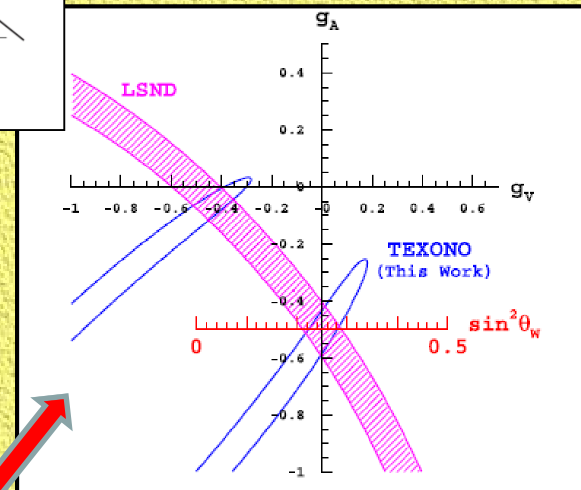
νN Coherent Scattering
⇨ sub-keV O(kg) ULEGe / PCGe
↳ Dark Matter Searches @ KSNL *[PRD09,PRL13,AP14]*
↳ CDEX Program@CJPL *[PRD13,PRD14,PRD14]*

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

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



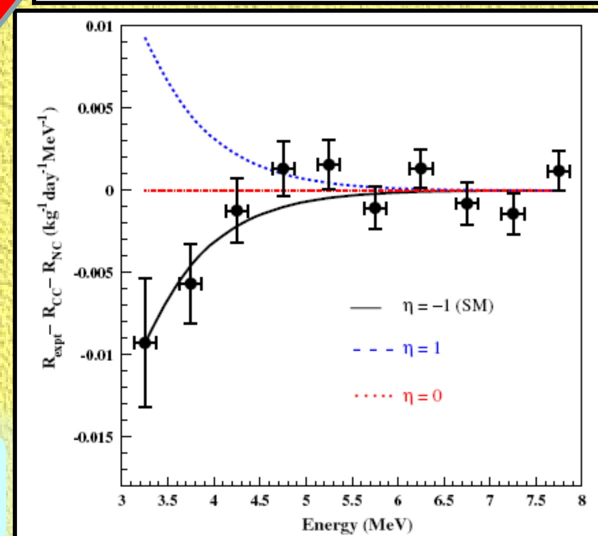




$$R = [1.08 \pm 0.21(stat) \pm 0.16(sys)] \times R_{SM}$$

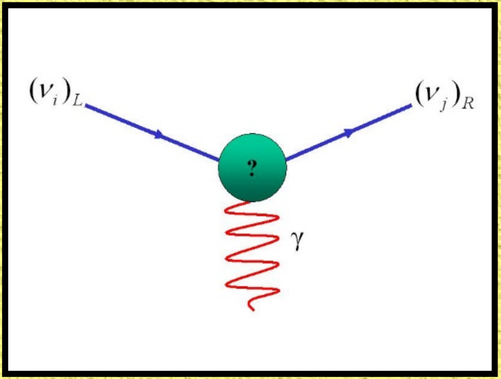
$$\sin^2\theta_W = 0.251 \pm 0.031(stat) \pm 0.024(sys)$$

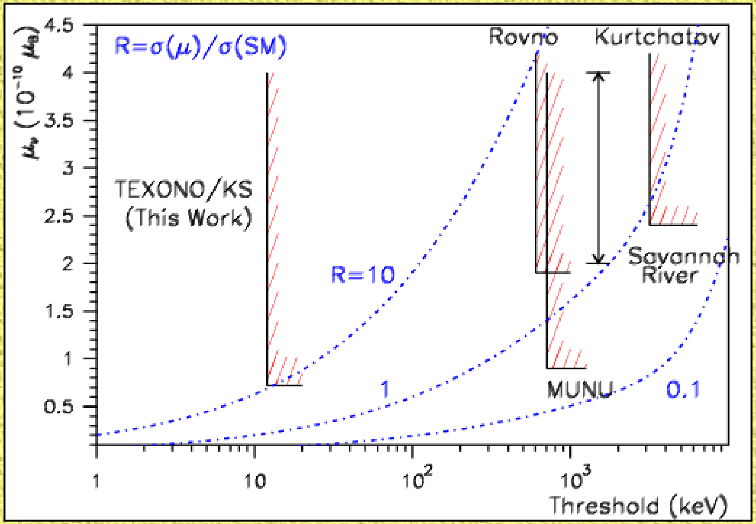
Verify SM Destructive Interference



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

Neutrino Electromagnetic Properties : Magnetic Moments





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

$\mu_\nu(\nu_e) < 7.2 \text{ X } 10^{-11}\ \mu_B$ [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)

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

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

Neutrino Electromagnetic Form Factors

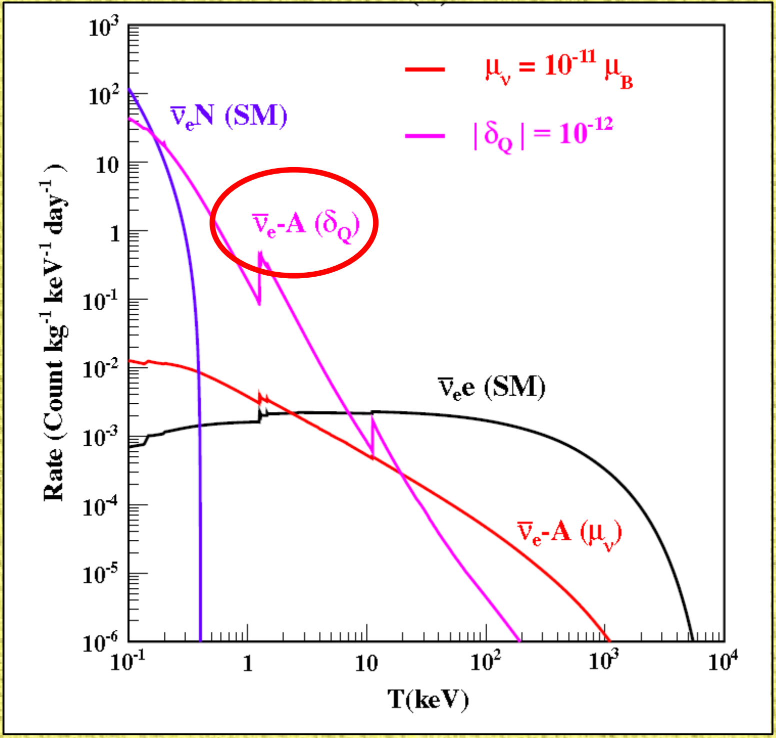
$$\Gamma^{\mu}_{em} \equiv F_1 \cdot \gamma^{\mu} + F_2 \cdot \sigma^{\mu\nu} \cdot q_{\nu}$$

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

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

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

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



- ☑ **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): $\delta_Q \sim 10^{-14}$**

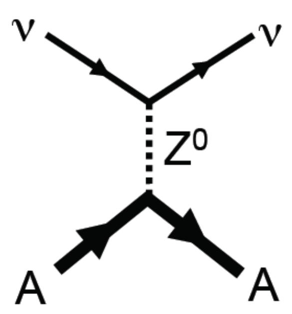
Current Research Theme:
"sub-keV" Ge Detectors

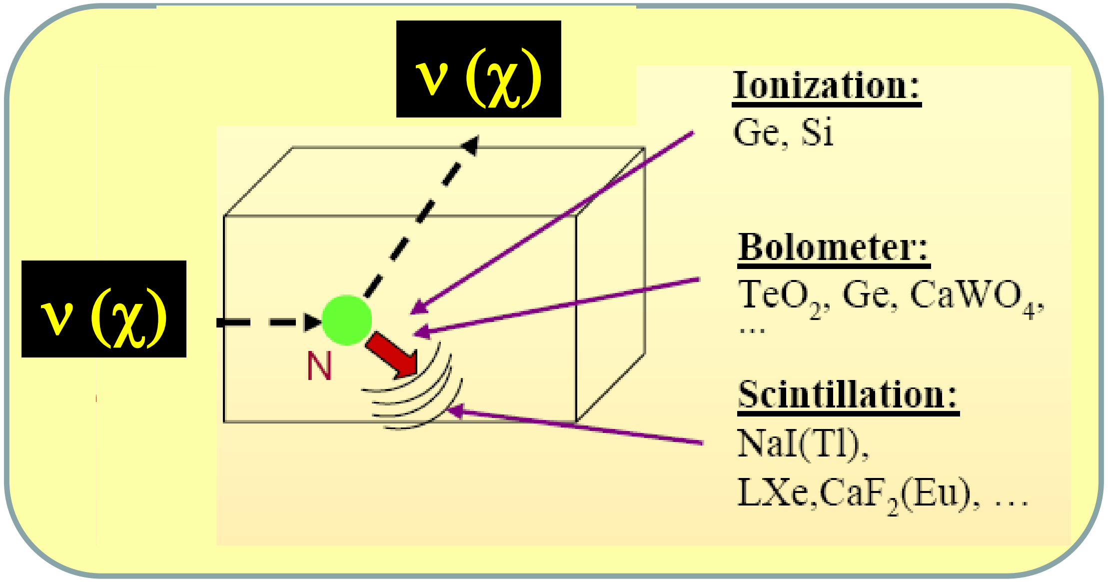
- **Physics Goals for *O[100 eV threhold⊕1 kg mass⊕1 cpkkd] detector* :**
  - **νN coherent scattering**
  - **Low-mass WIMP searches**
  - **Improve sensitivities on neutrino electromagnetic properties**
  - **Implications on reactor operation monitoring**
  - **Open new detector window & detection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

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

Standard Model Cross-Sections at KSNL

[with Quenching Function for Ge for nuclear recoils]

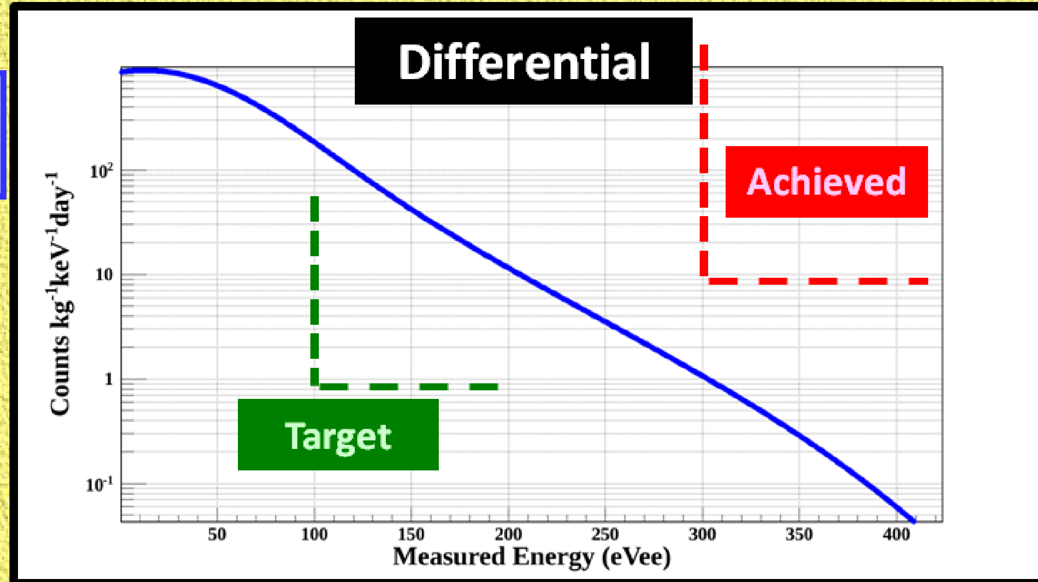
$$\left(\frac{d\sigma}{dT}\right)^{coh}_{SM} = \frac{G_F^2}{4\pi} m_N [Z(1 - 4\sin^2\theta_W) - N]^2 [1 - \frac{m_N T_N}{2E_\nu^2}]$$

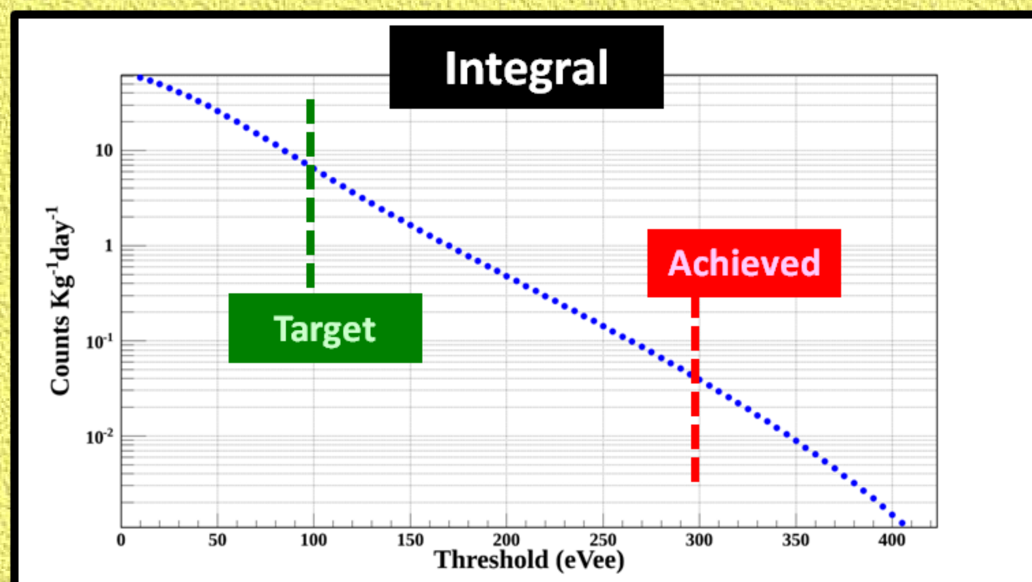
- **Needs Background < 10 cpkkd, Target → 1 cpkkd**

Current Focus !!

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

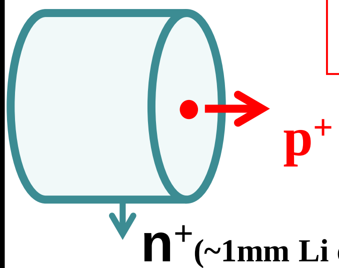
$$\sigma_{tot} = \frac{G_F^2 E_\nu^2}{4\pi} [Z(1 - 4\sin^2\theta_W) - N]^2$$



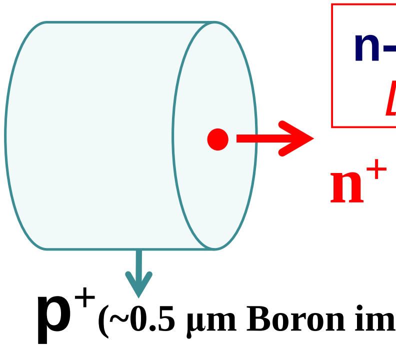


Baseline Hardware Design

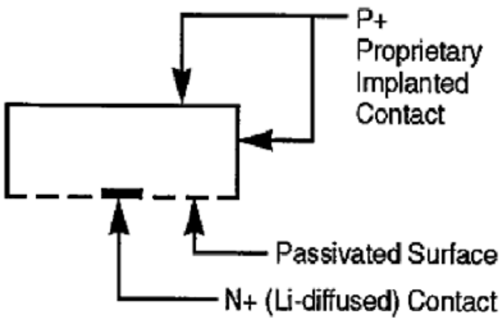
p- PCGe
[500g – 1 kg]

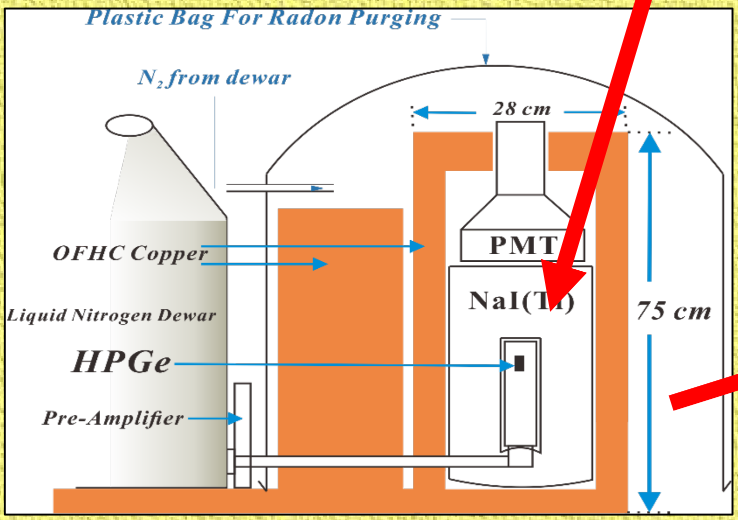


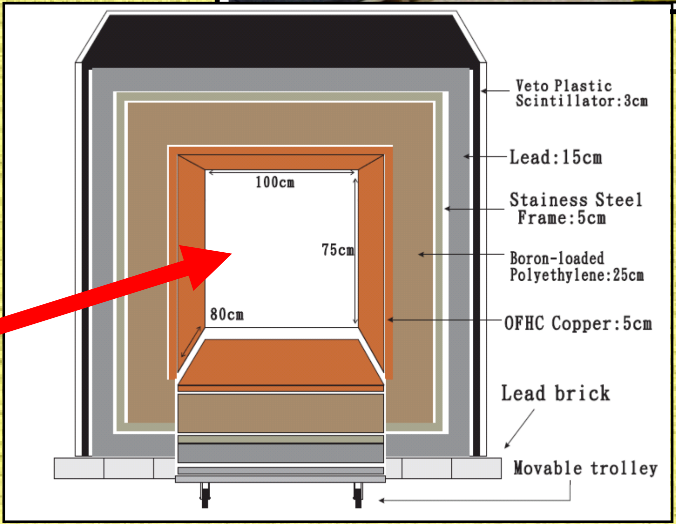
n- PCGe
[500 g]



4x5g ULEGe





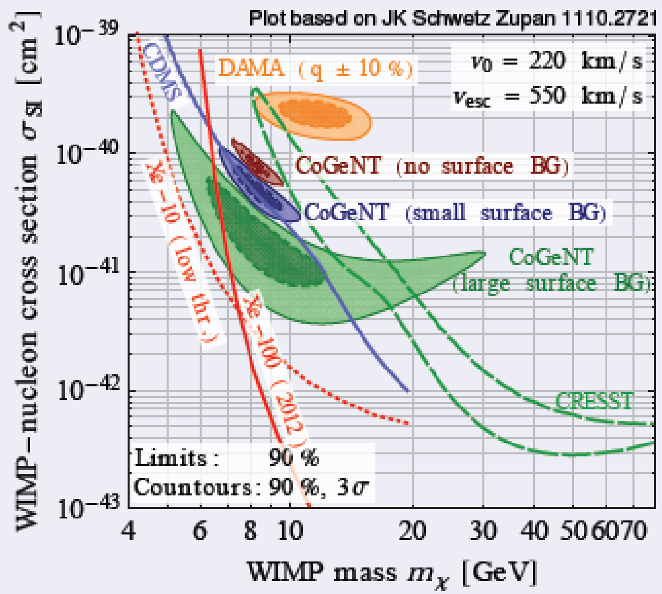


- **TEXONO @ KSNL (2007): 220 eV threshold with 20g ULEGe ; Opened window for "Light WIMPs" searches** *[PRD09]*
- **2010—2013: claimed evidence of GeV WIMPs from terrestrial experiments and astrophysics data** *[strength diminished by now]*

Hints for light dark matter

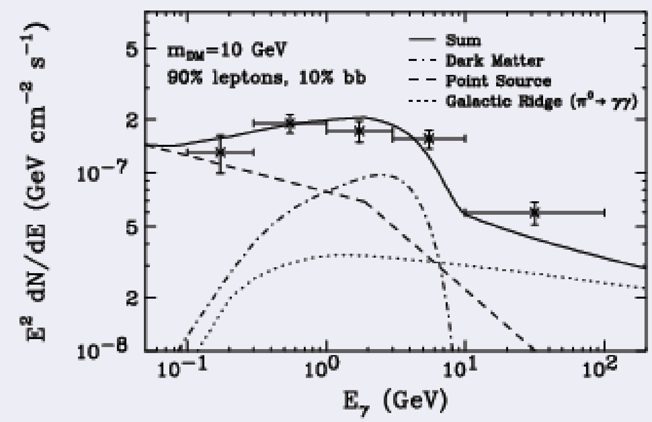
J. Kopp @ IDM12

On the Earth . . .



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

. . . and in the skies



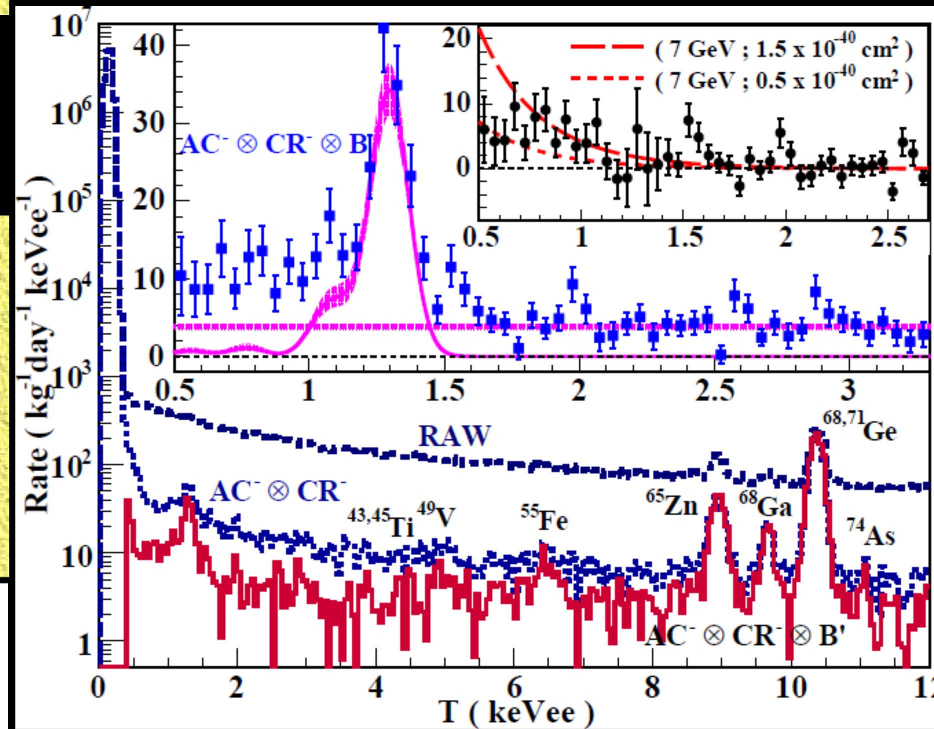
- An tentative γ ray excess from the Galactic Center
  Hooper Goodenough 0912.2998, 1010.2752, 1201.1303
  - Morphology $\neq$ point source
- Radio filaments
  Linden Hooper Yusef-Zadeh 1106.5493
- Isotropic radio background
  Hooper Belikov Jeltema Linden Profumo Slatyer 1203.3547

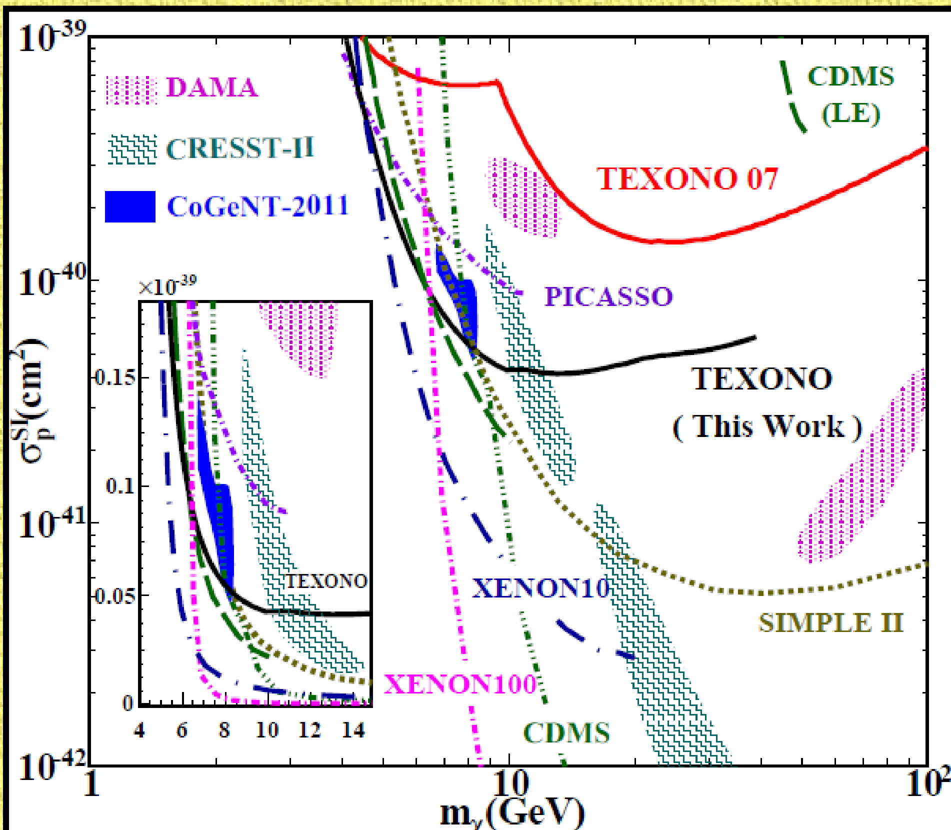
Sub-keV Ge Detector Techniques : Users' R&D Items

- 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

Light WIMP Searches @ KSNL with Ge

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



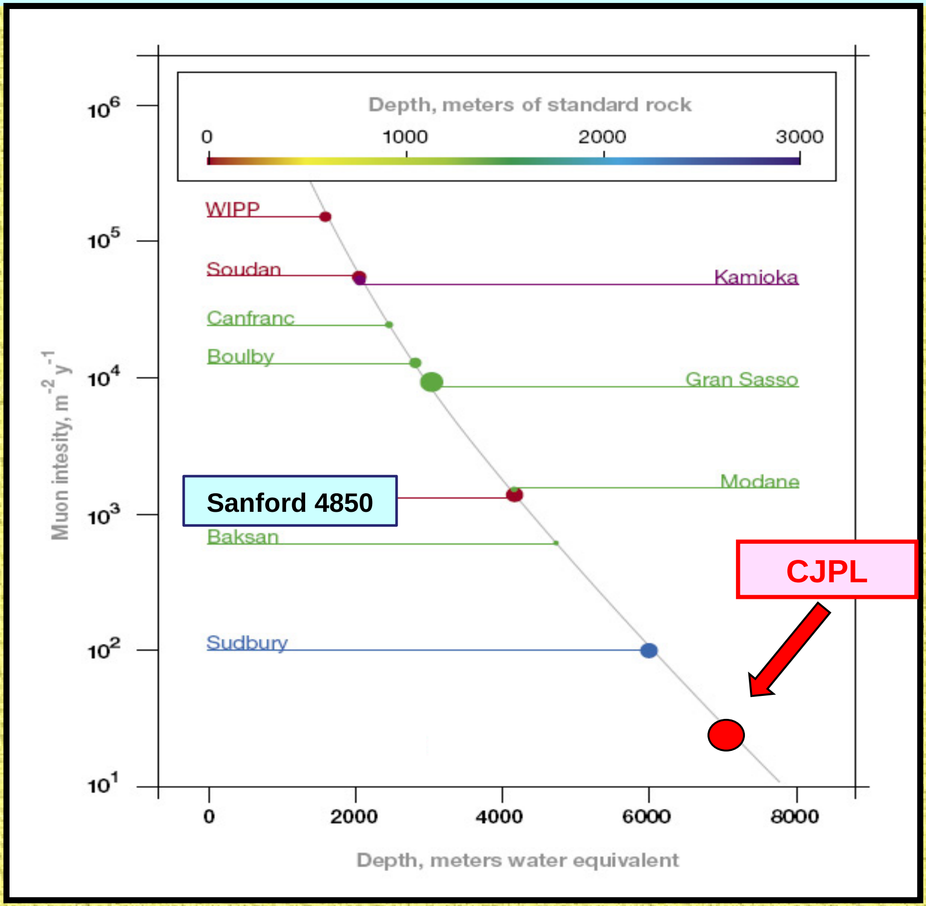


TEXONO@KSNL *[PRL13,AP14]* **:**

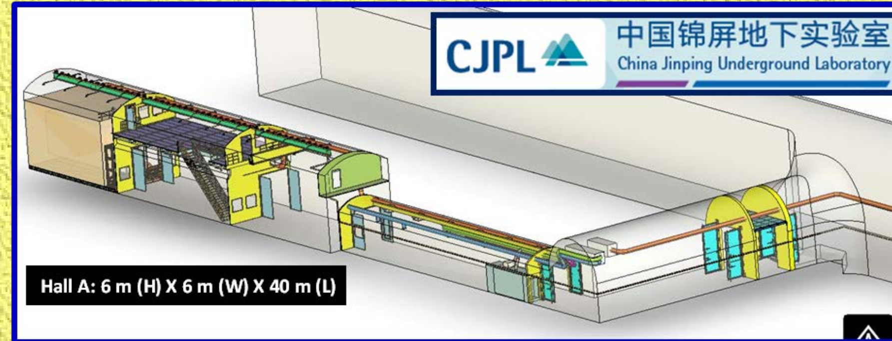
- 500 eV threshold
- devised schemes for B/S separation & efficiencies
- probed and excluded some light WIMP allowed regions
- Indicated: leakage of "Surface" background to "Bulk" samples can give false positive signals.

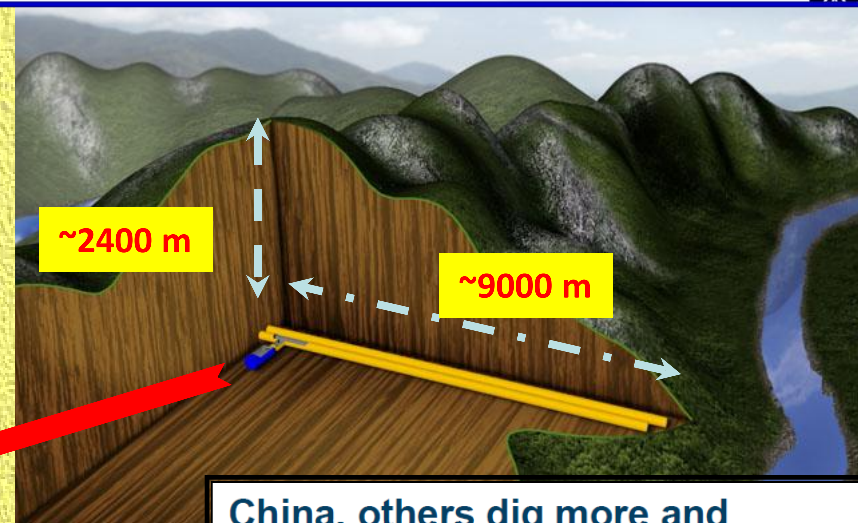
中国锦屏地下实验室
CJPL China Jinping Underground Laboratory

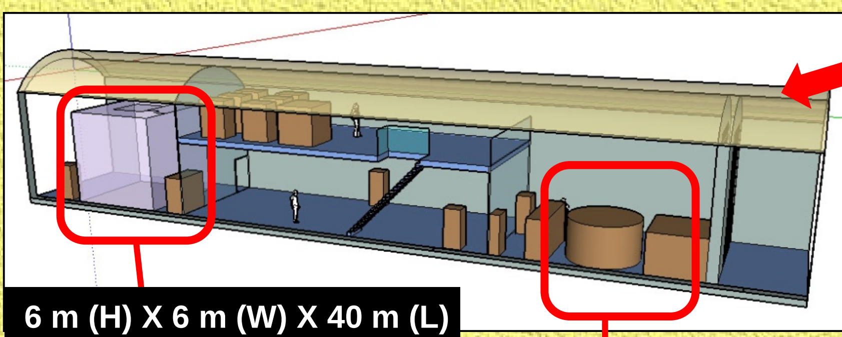
- **2400+ m rock overburden, drive-in road tunnel access**
- **~6 muons/m²-month** *(cf sea-level 100 Hz/m²)*
- **6X6X40 m cavern constructed** *[managed by THU & YLJHDC]*
- **CDEX-1 Dark Matter Program**



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

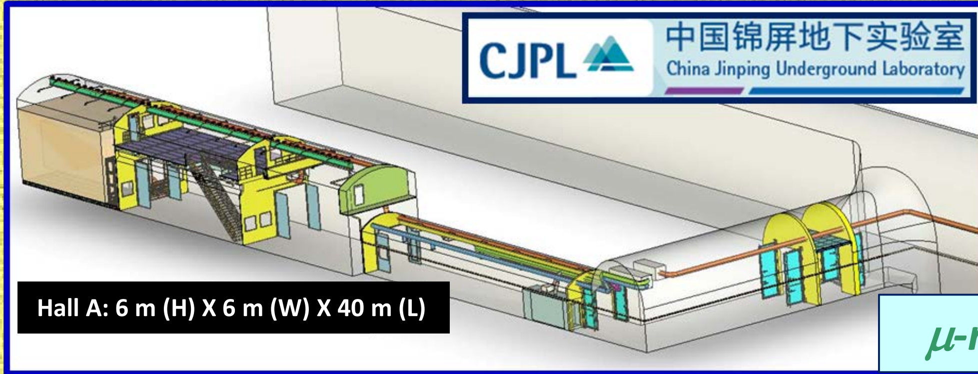
PARTICLE PHYSICS:

Chinese Scientists Hope to Make Deepest, Darkest Dreams Come True

Dennis Normile

Science AAAS

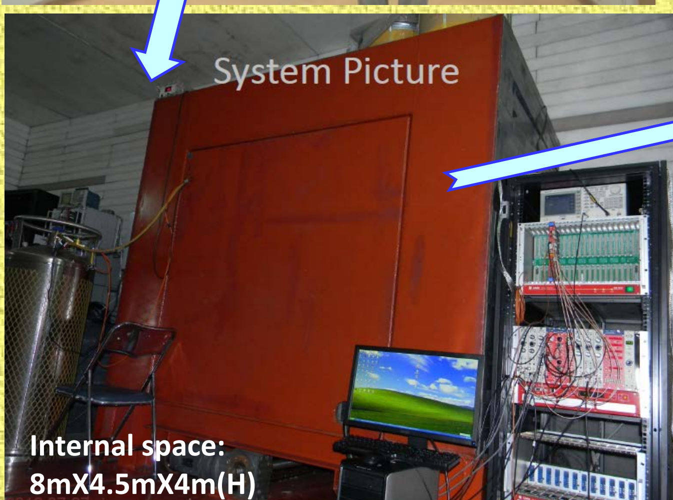
Science 5 June 2009:
Vol. 324. no. 5932, pp. 1246 - 1247
DOI: 10.1126/science.324_1246

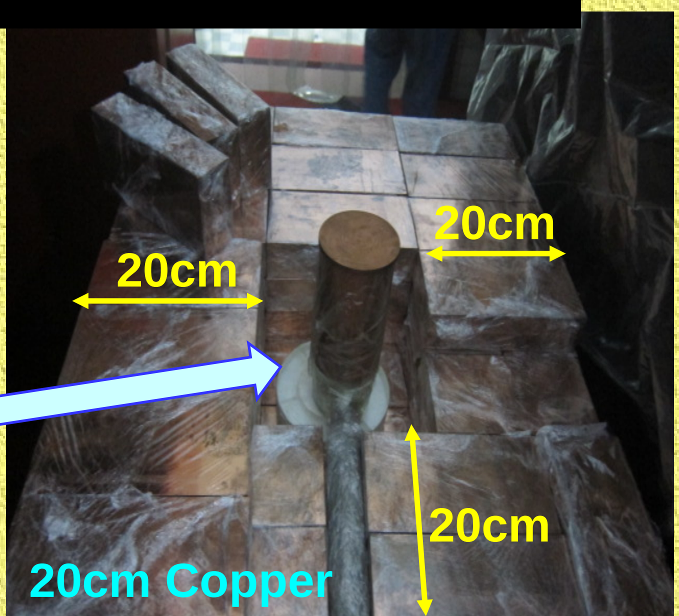


μ-rate ~ 6 per m^2 per month

CDEX-1 @ CJPL :

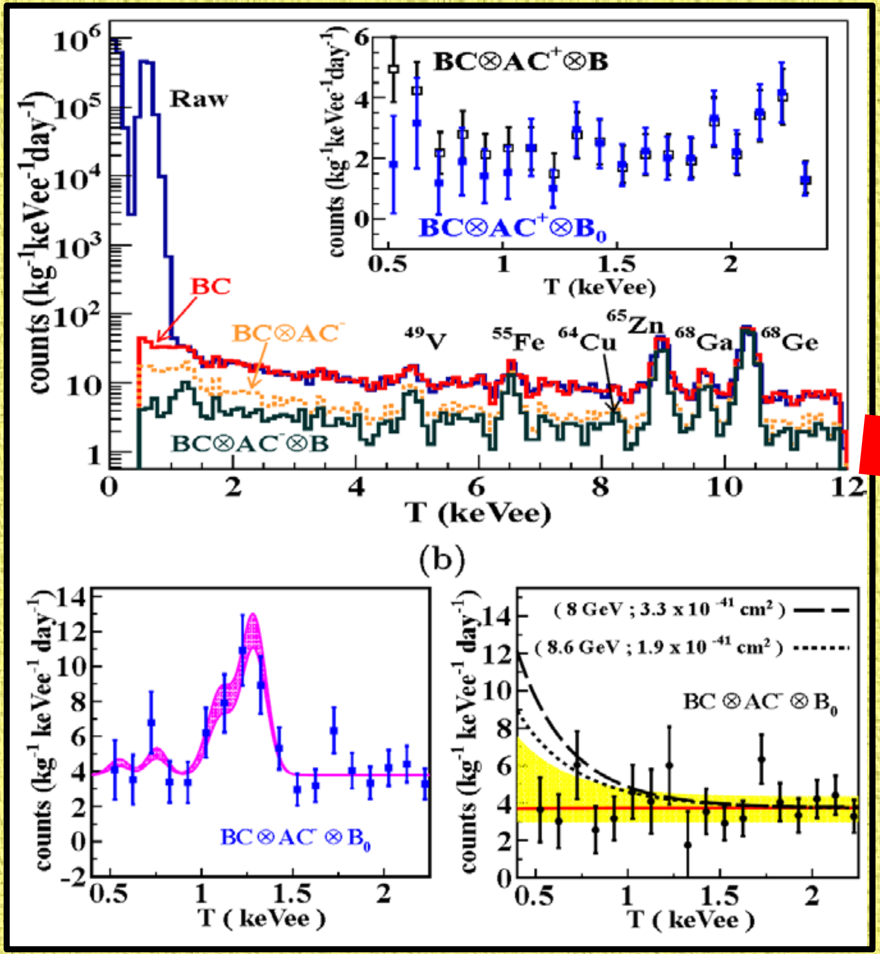
- Adopt KSNL Baseline Design
- Engineering Run 2011
- Physics Run June 2012
- First Results 2013

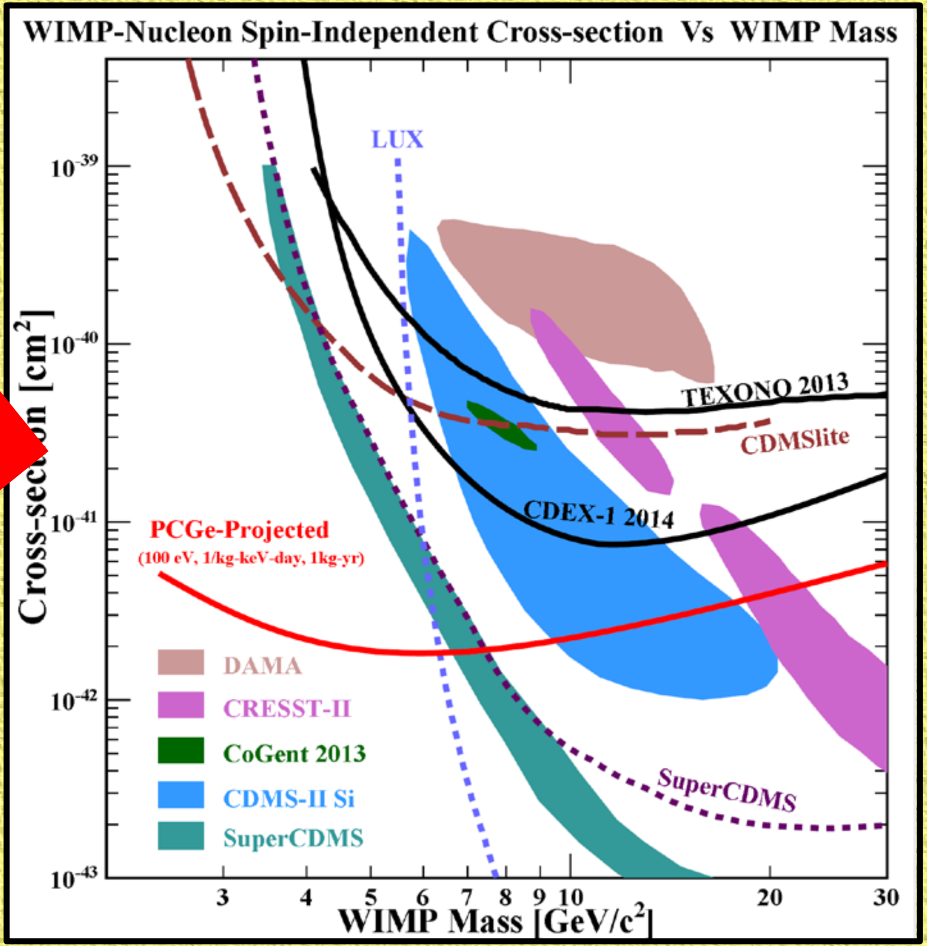




CDEX-1 @ CJPL 2014 *[PRD13, PRD14]*

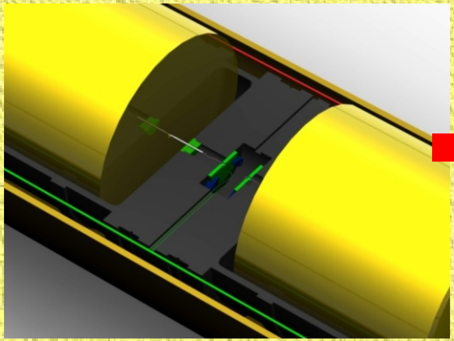
- ***1 kg pPCGe @ 475 eVee threshold***
- ***All events quantitatively accounted for ; No Residual Excesses at sub-keV***
- ***Exclude CoGeNT-2013 excess as WIMP-induced, independent of interaction channels***



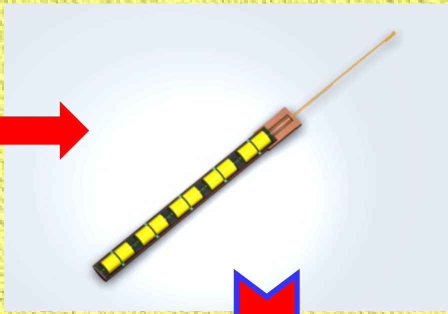


Design of CDEX-10 : with LAr Anti-Compton

Ge + JFET

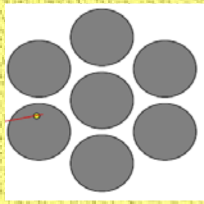


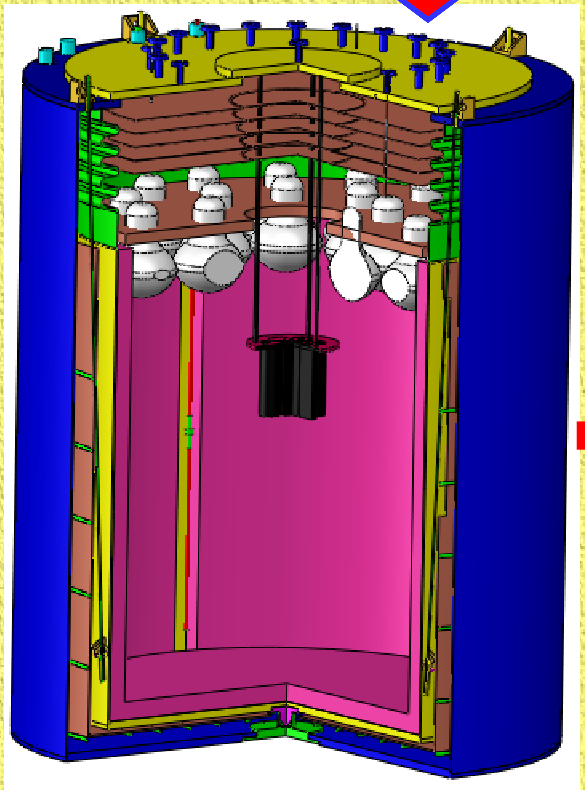
Ge Array in String

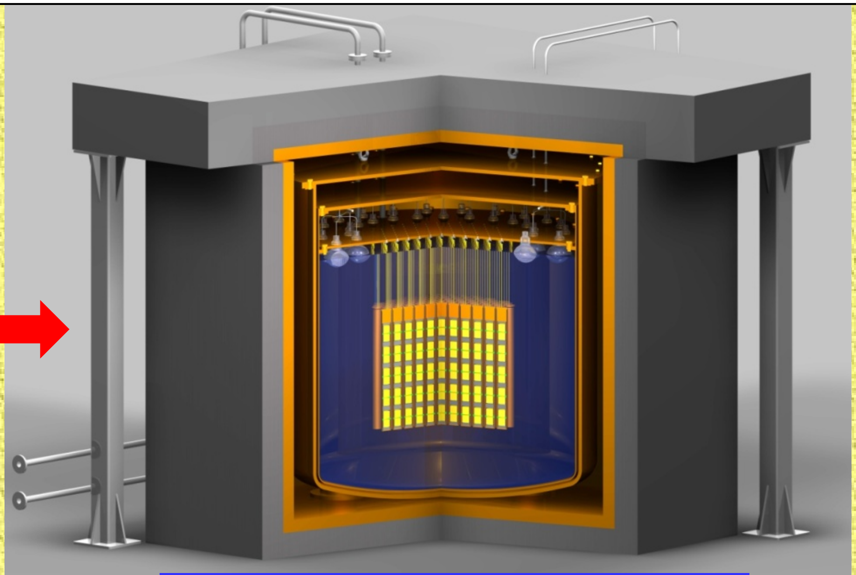


- PCGe in Arrays & Strings
- LiqN (LiqAr) as both cryogenics (& active anti-Compton)
- ~30-40 cm 4π shielding range
- Prototype 2014
- Baseline Design for Future O(1 ton) Expt for DM+0νββ

CDEX-10 (2015+)

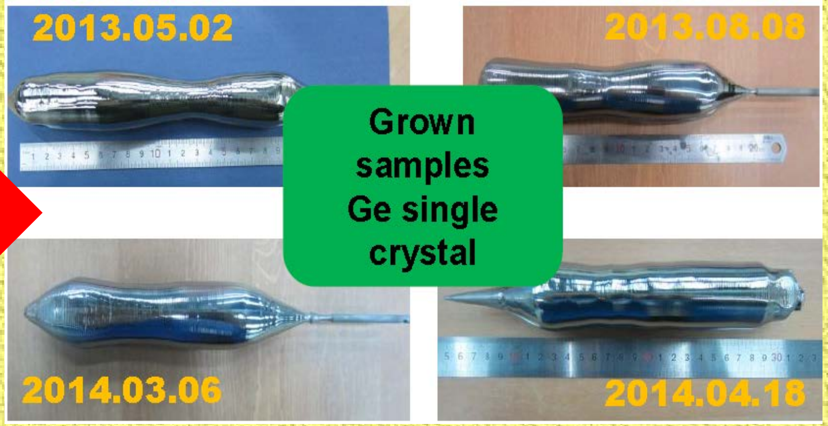






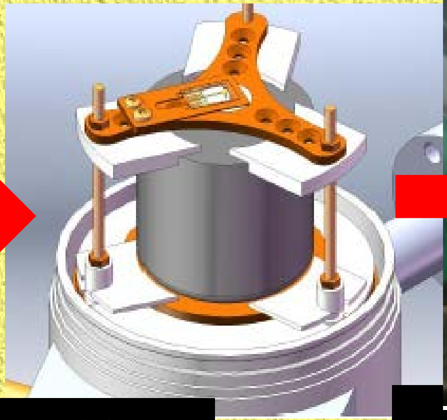
CDEX-(1 ton)
Artist's Conception

Ge Processing & Assembly Facility @ THU



- Growth & Processing of raw Ge crystal
- Application-specific optimized assembly
- R&D on JFETs & Preamps & ASICs

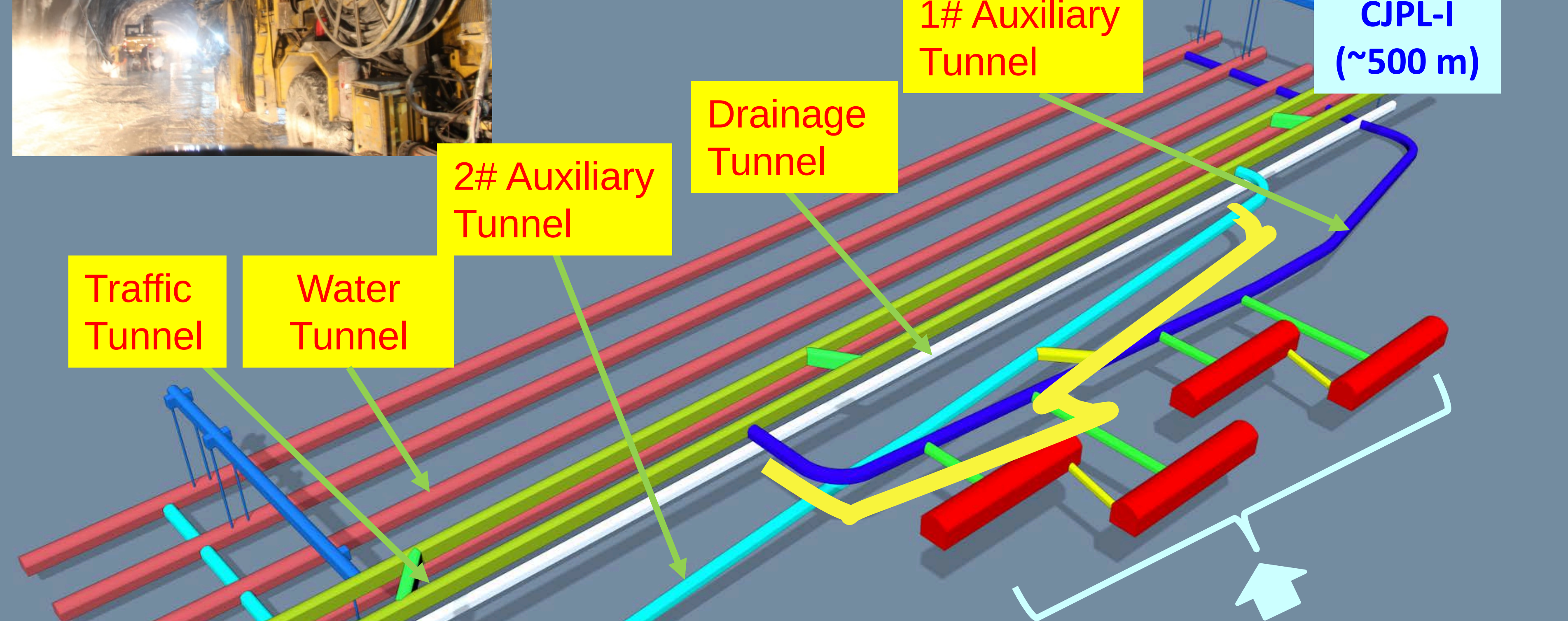
Crystal



Processing & Assembling

Detector & Cryogenics

NEW Lab : CJPL-II



- Four 14m*14m*130m Lab Halls [30+ > CJPL-I]
- Construction Started end 2014

Science V346, Nov 2014

PHYSICS

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)

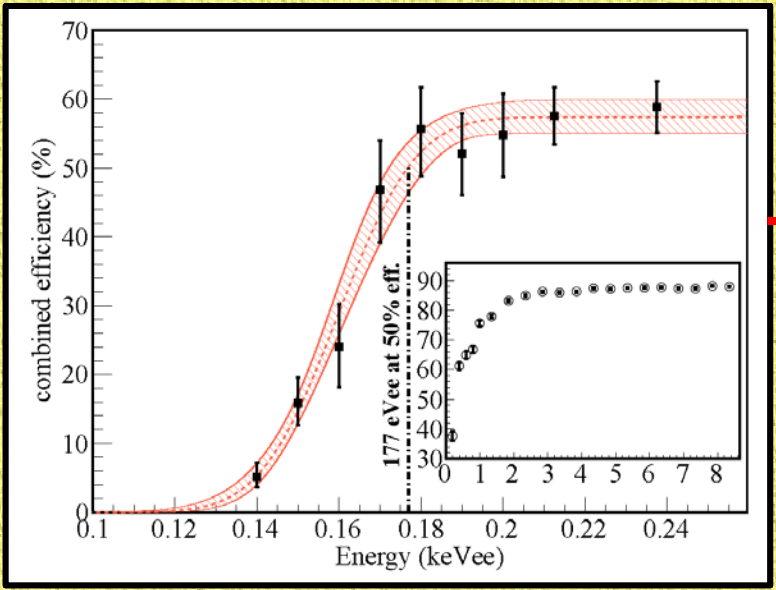
Summary & Prospects

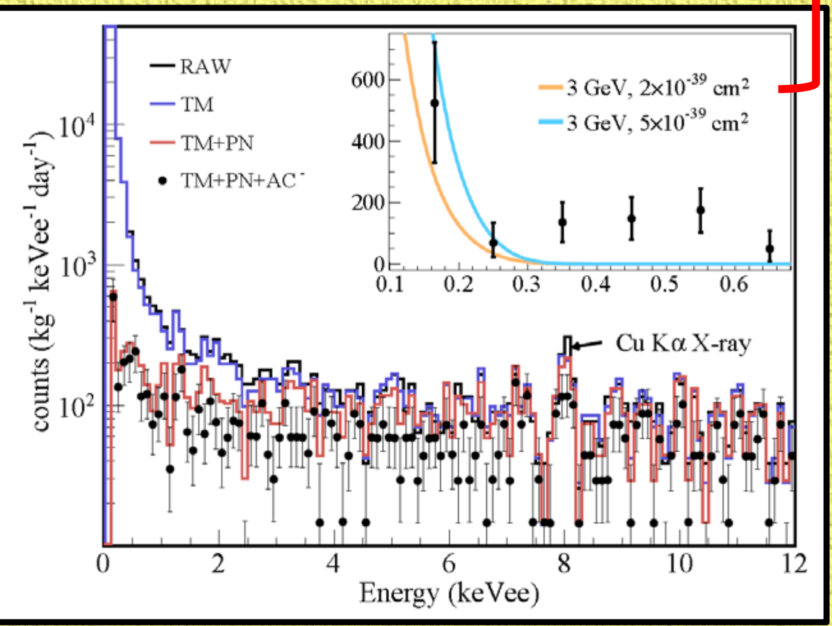
- Competitive results on light WIMPs with sub-keV Ge, *even at* a surface TEXONO@KSNL ; further improved with underground CDEX-1 @ CJPL
- Surface leakage to Bulk samples is important to PPCGe at low energy, origin of earlier "WIMP signal".
- CJPL-2: 30+ times more space, being built
- Ge-R&D + technology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

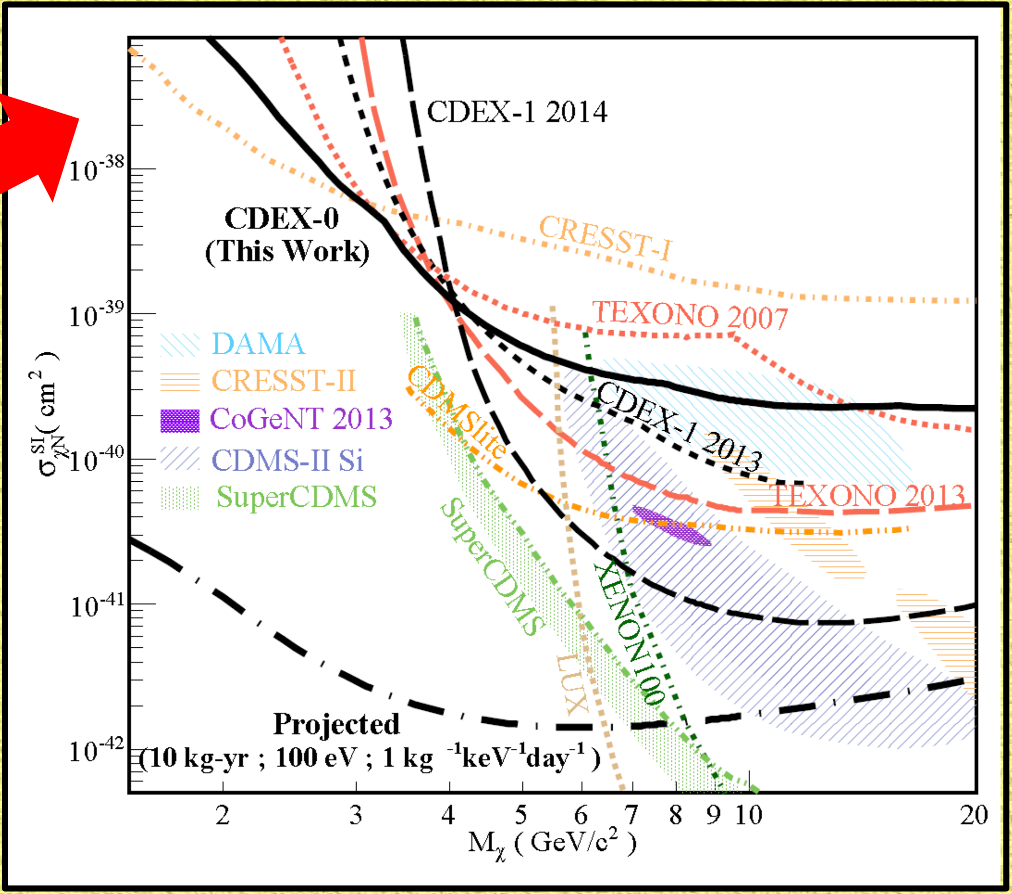
Back Up
Technical Materials

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

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

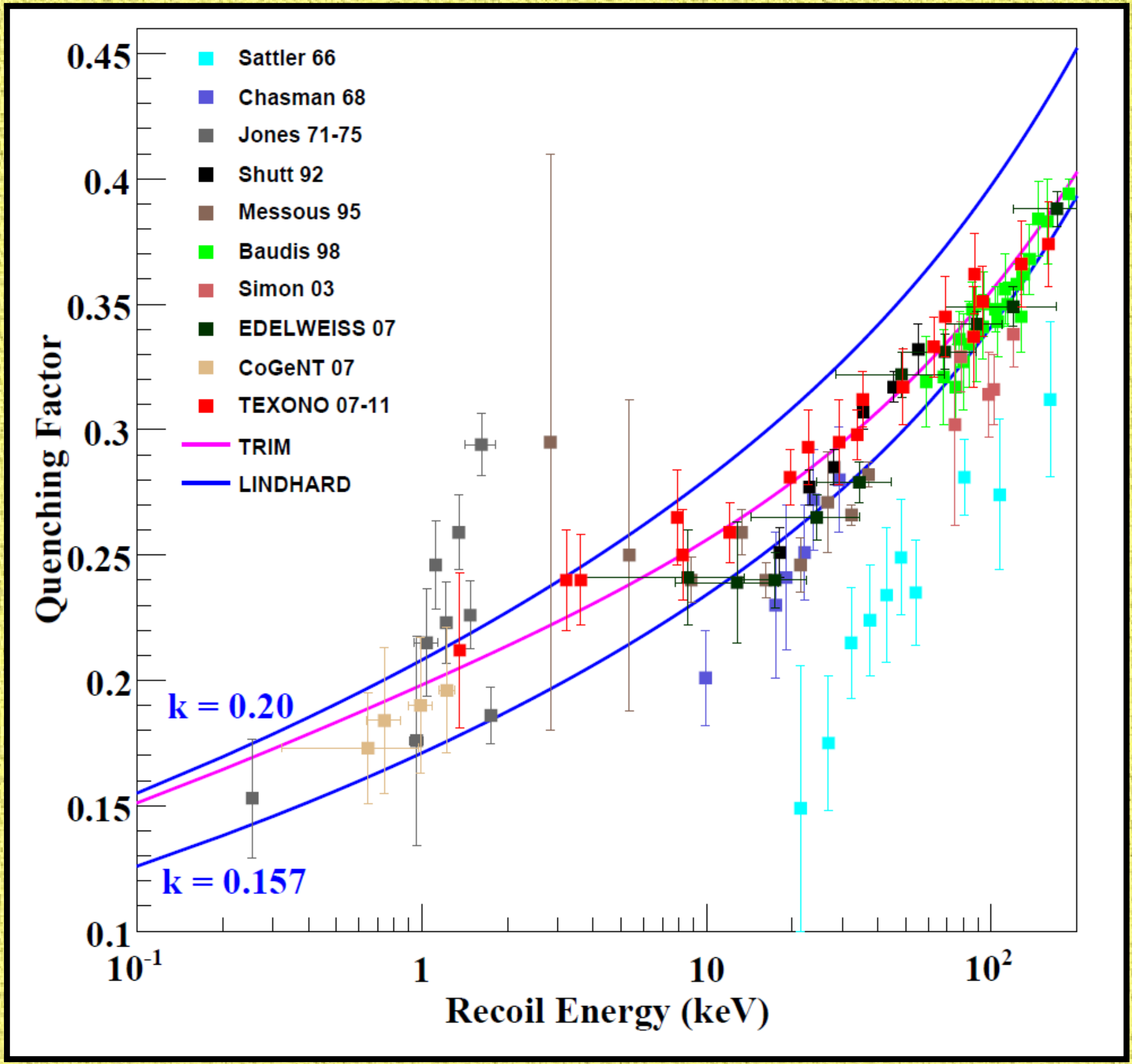


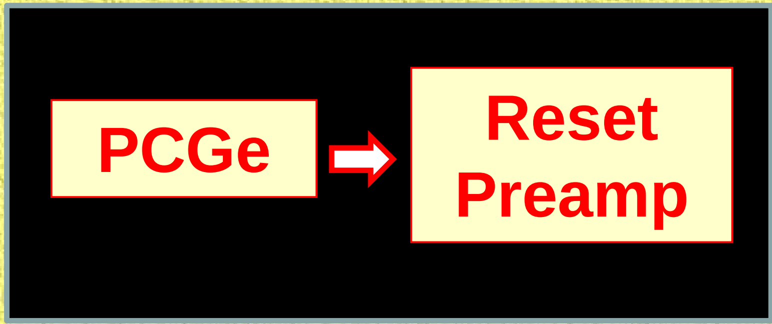


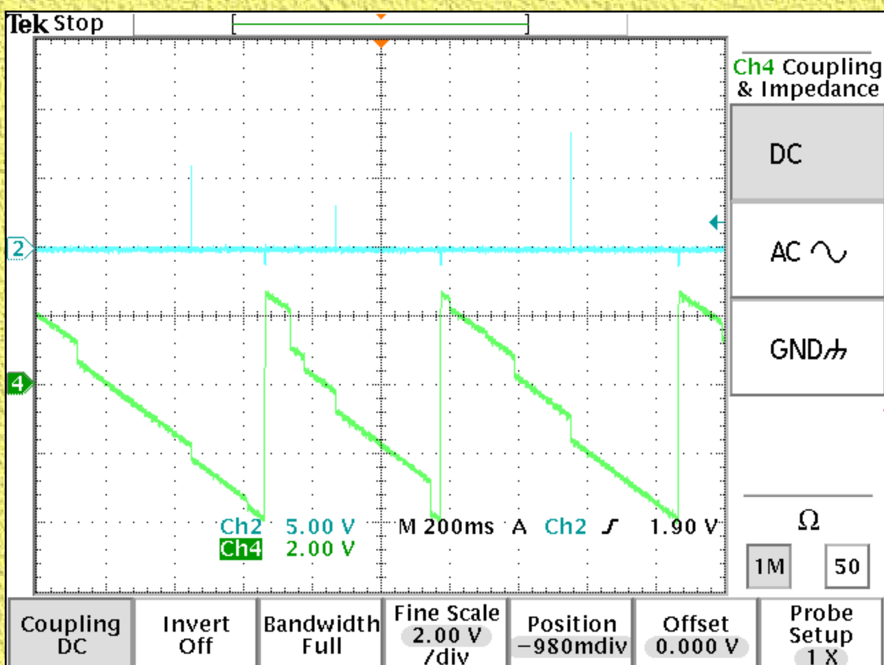


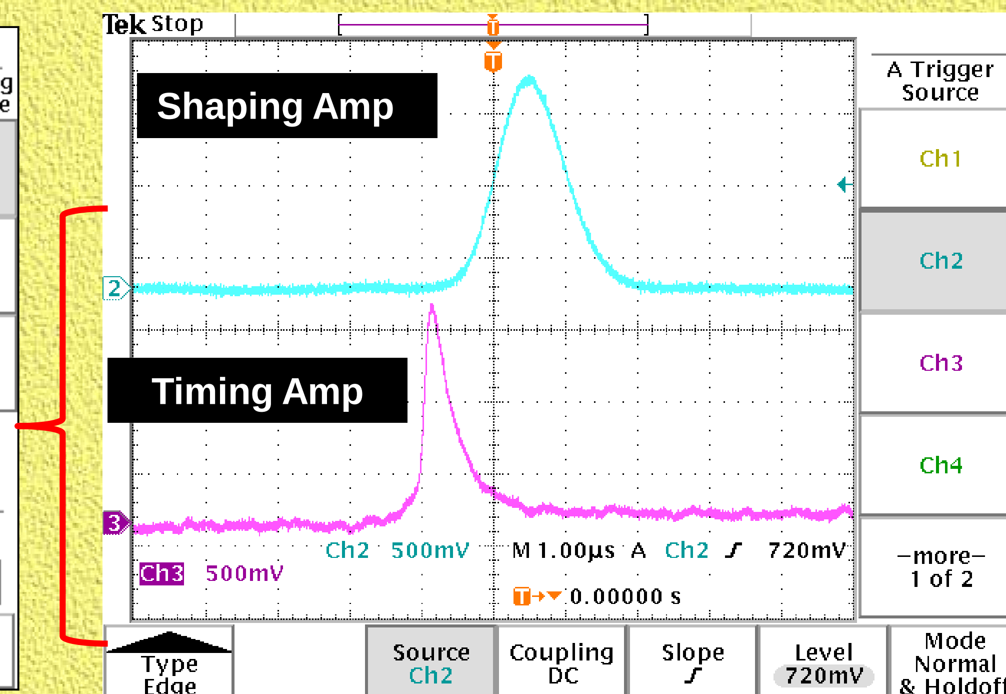
QF in Ge :

- ☑ Data available down to sub-keV measure-able energy
- ☑ TRIM Software : better match to data over extended energy









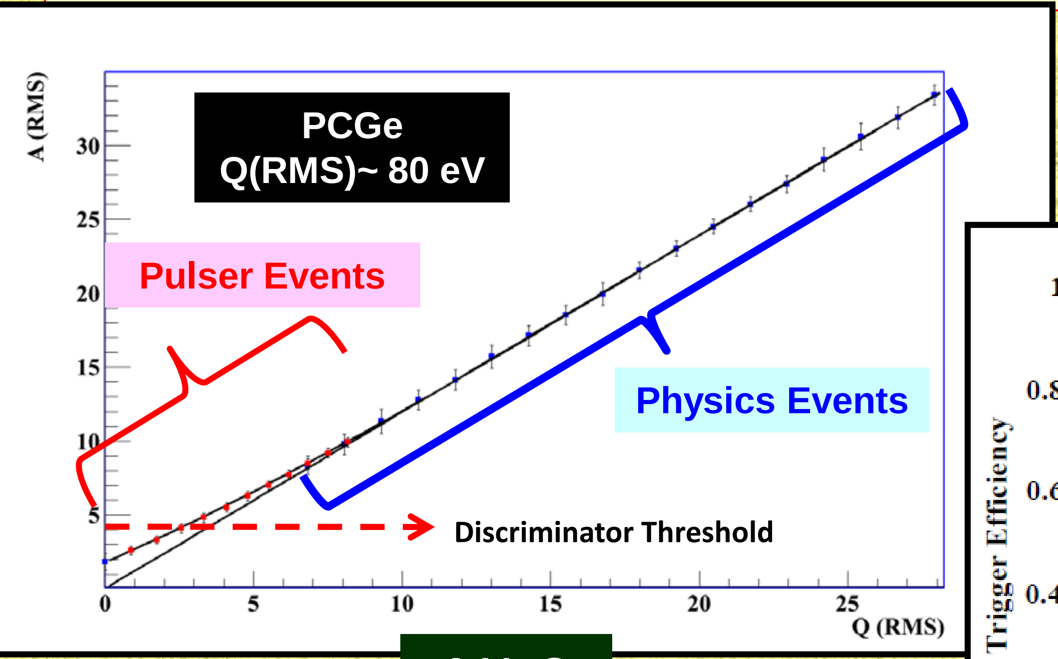
SA: Shaping time 0.5 μs to fit in one frame ; Typical operation in 6-12 μs

Energy Definition:

- Area of Shaping Amplifier Output with Optimized Integration Range
- Linear in Area (Q) , not in Amplitude (A) Near Noise-Edge

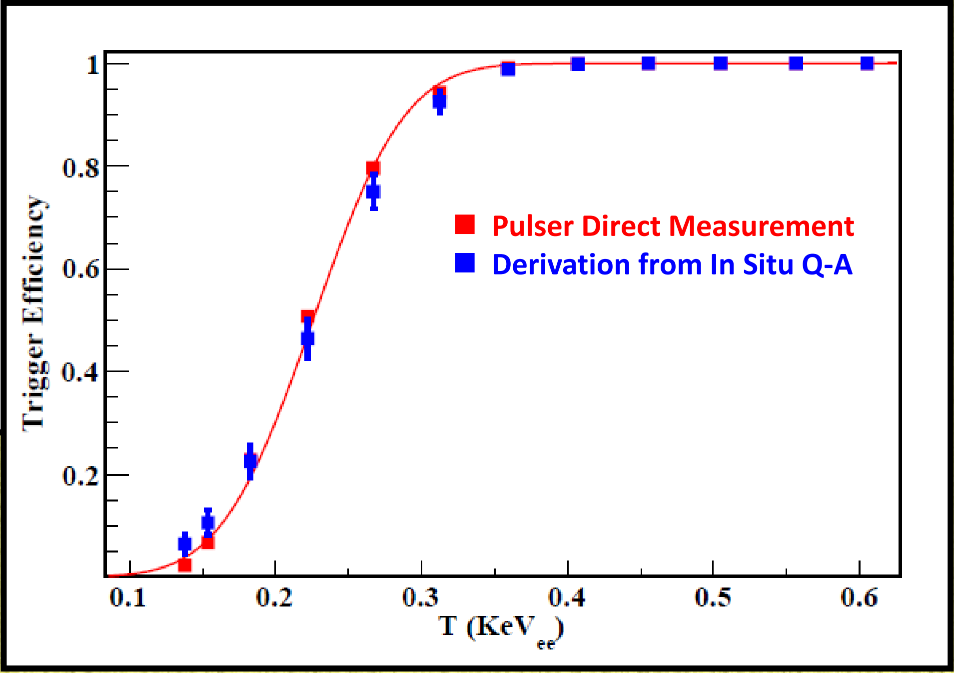
Energy Calibration:

- 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



A Vs Q

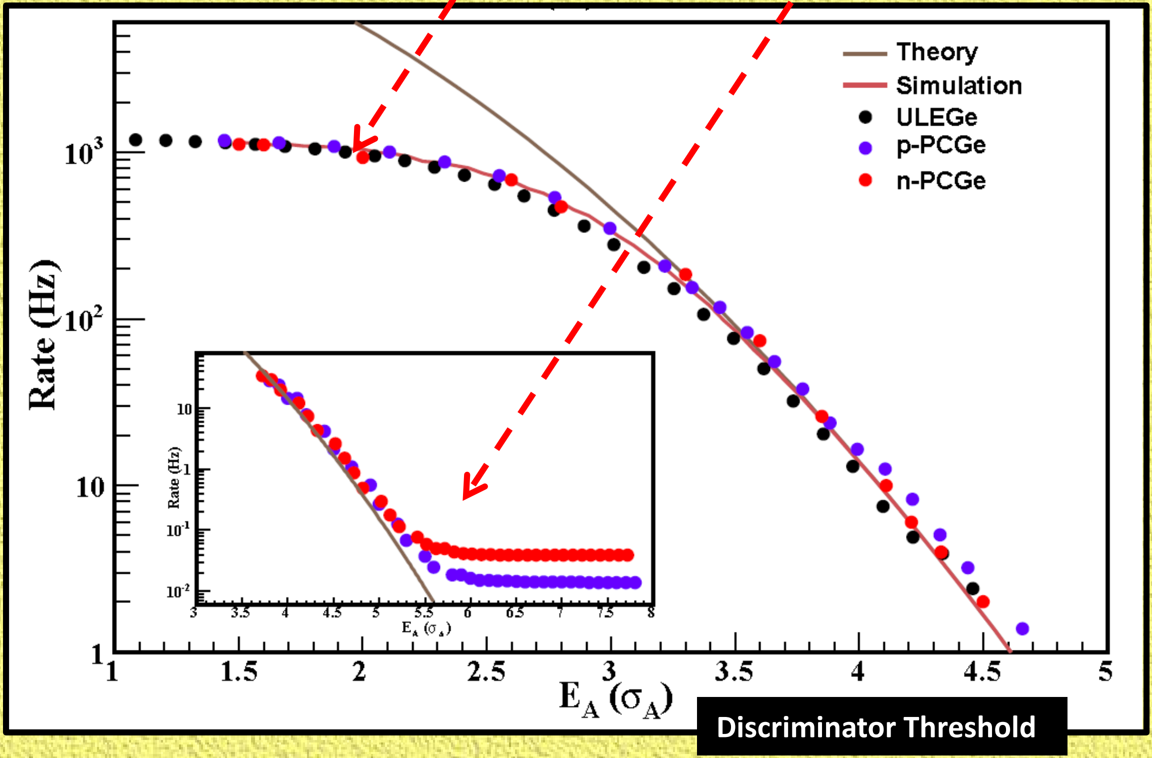
Trigger Efficiency



Trigger Rates :

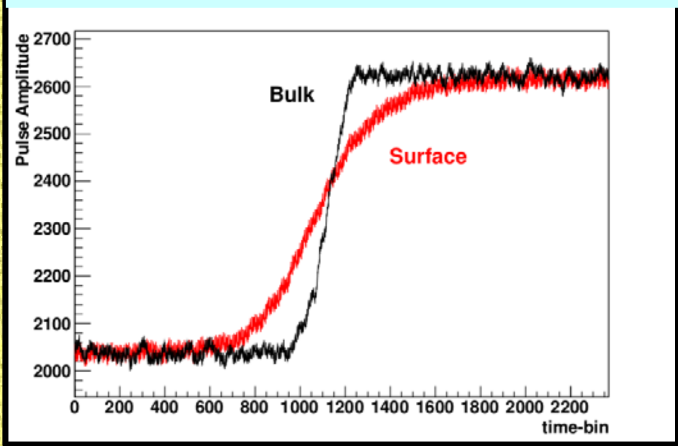
$$R \sim \frac{1}{4\tau}\, exp\left[-\frac{d^2}{2\,\sigma^2}\right]$$

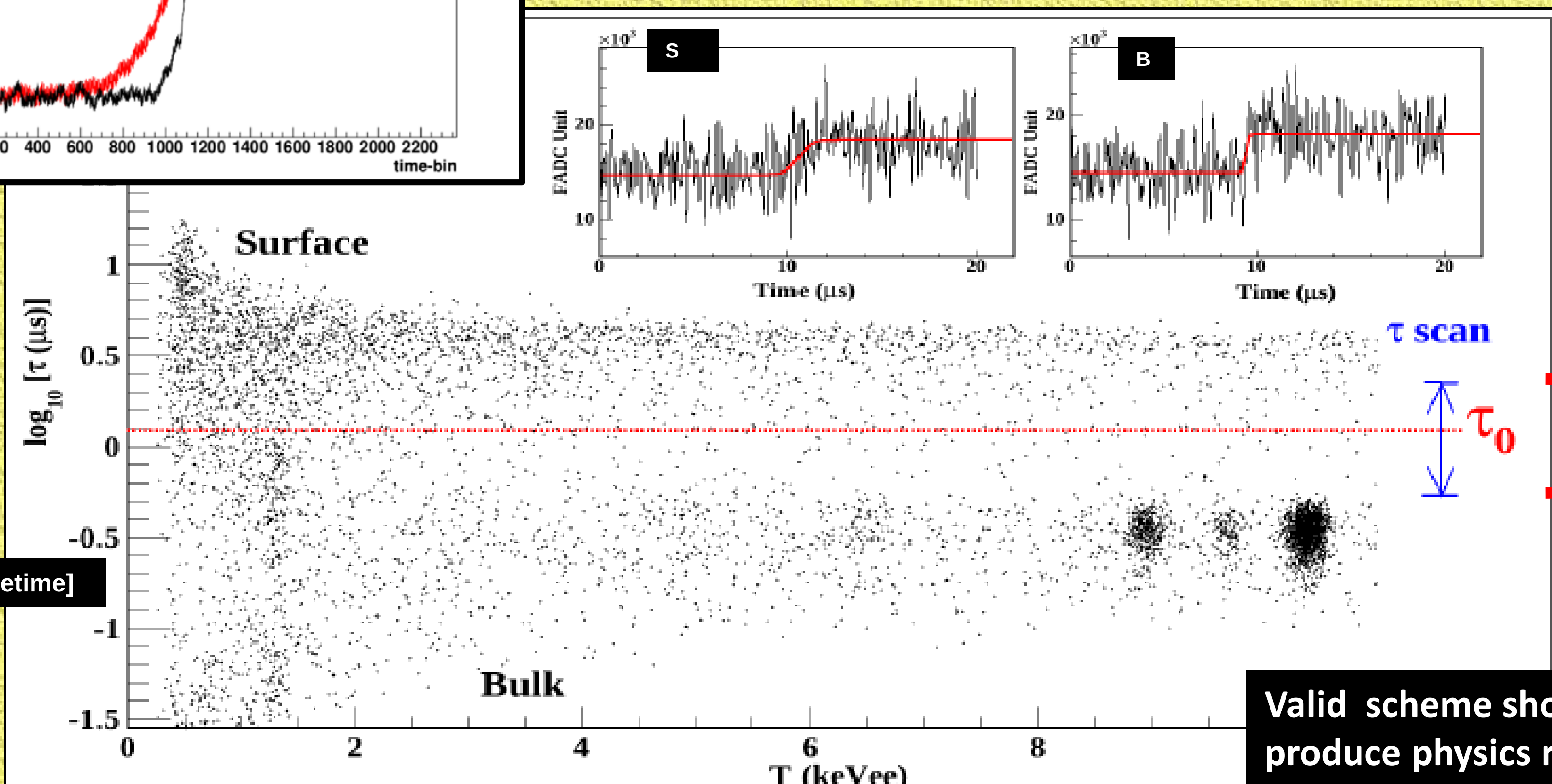
- Agreed with expectations
- A universal curve valid to all detectors with discriminator threshold in "Noise RMS" unit.
- Saturation at low threshold due to "Gate Width"
- Physics events start dominating at high threshold (background dependence)



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





log [Risetime]

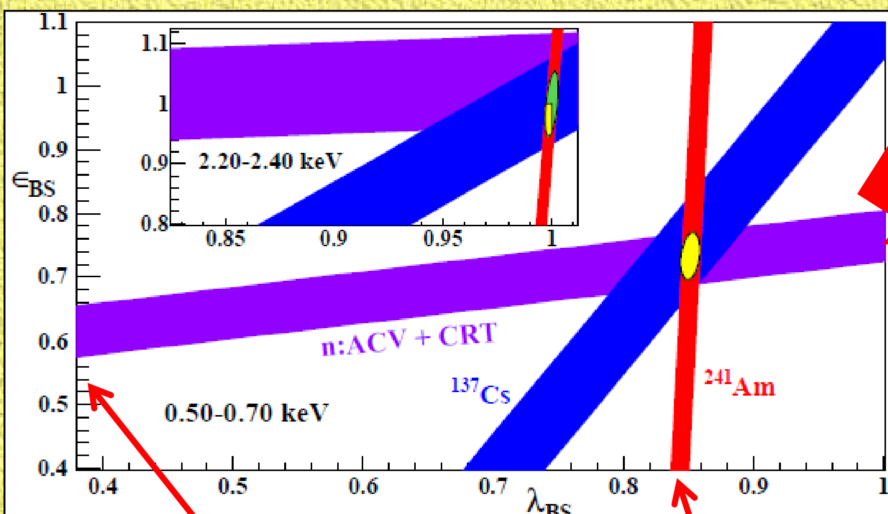
Valid scheme should produce physics rates insensitive to location

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

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

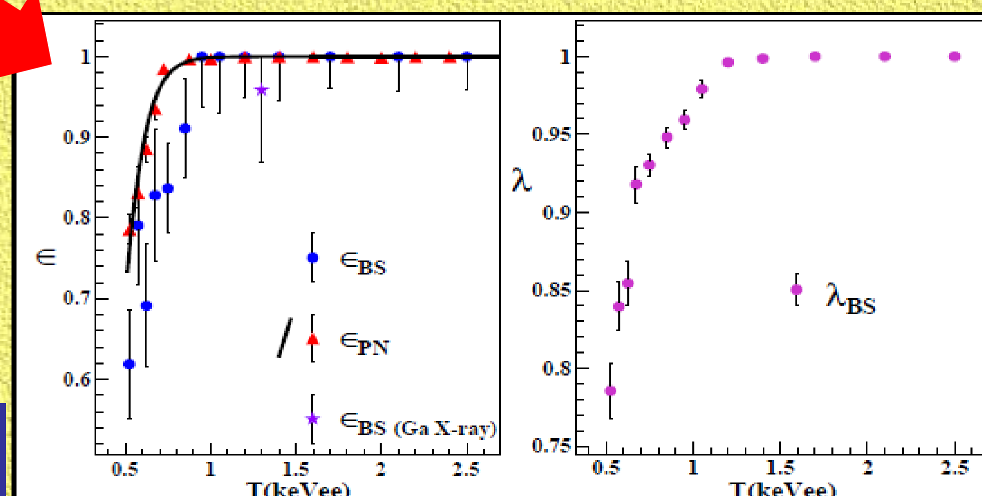
Approach: Identify *THREE(+)* calibration data [low and high energy γ, cosmic-induced neutrons] where (B,S) are known & (B',S') measured ⊕ solve coupled equation for (ε_{BS}, λ_{BS})

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}

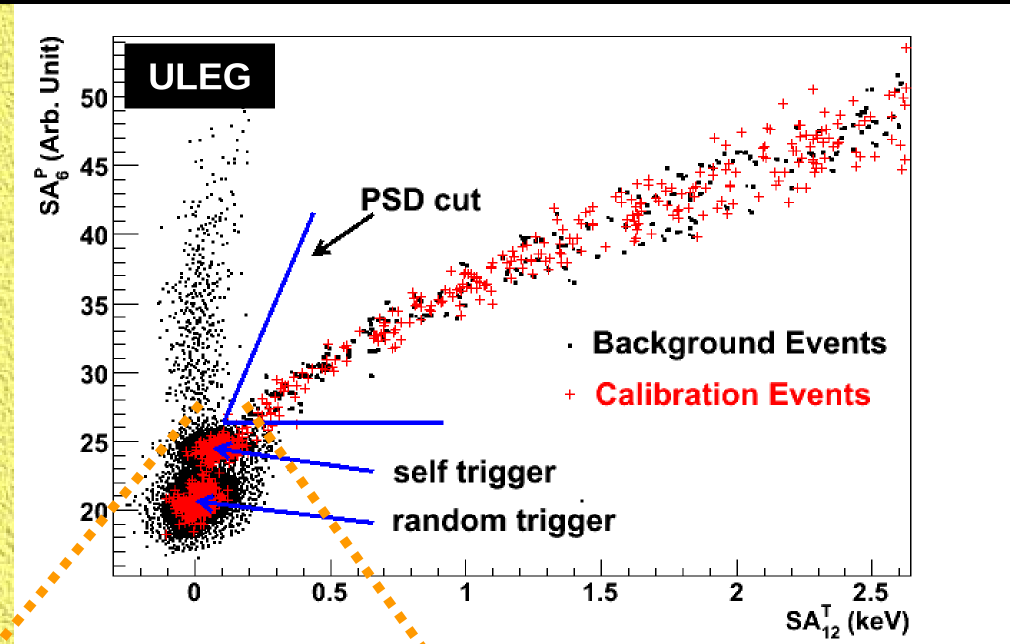
Surface-Rich γ-rays constrain λ_{BS}



PSD Selection to Suppress Electronic Noise

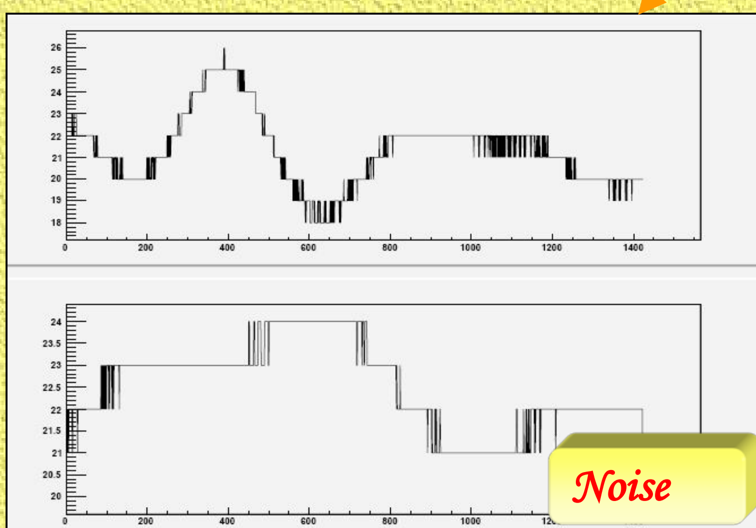
E.g. 1 ⇨ correlations in two readout of different gains & shaping times

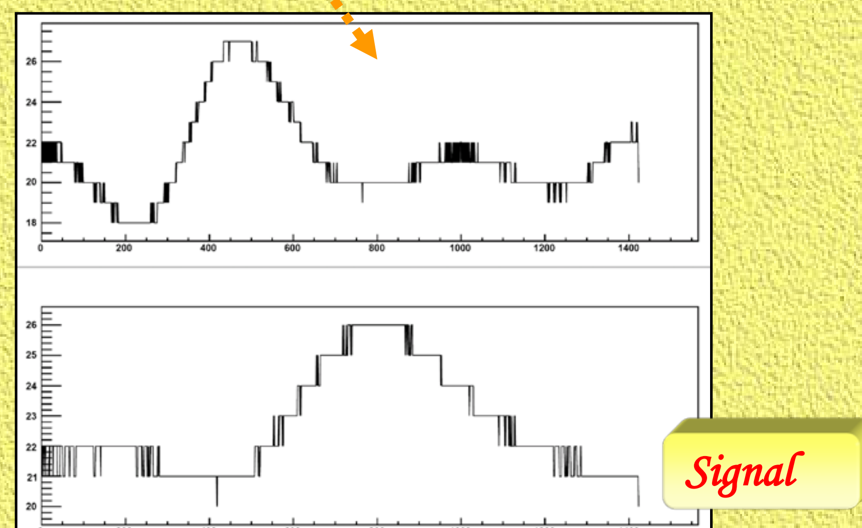
- look for specific +ve pulse fluctuations at specific & known timing



6μs

12μs





Phys-Vs-Noise Selection Efficiency