Neutrino & Dark Matter Physics with sub-keV Germanium Detectors

- Overview (Collaboration; Program)
- Facilities : KSNL & CJPL
- Detector & Phyics: Highlights

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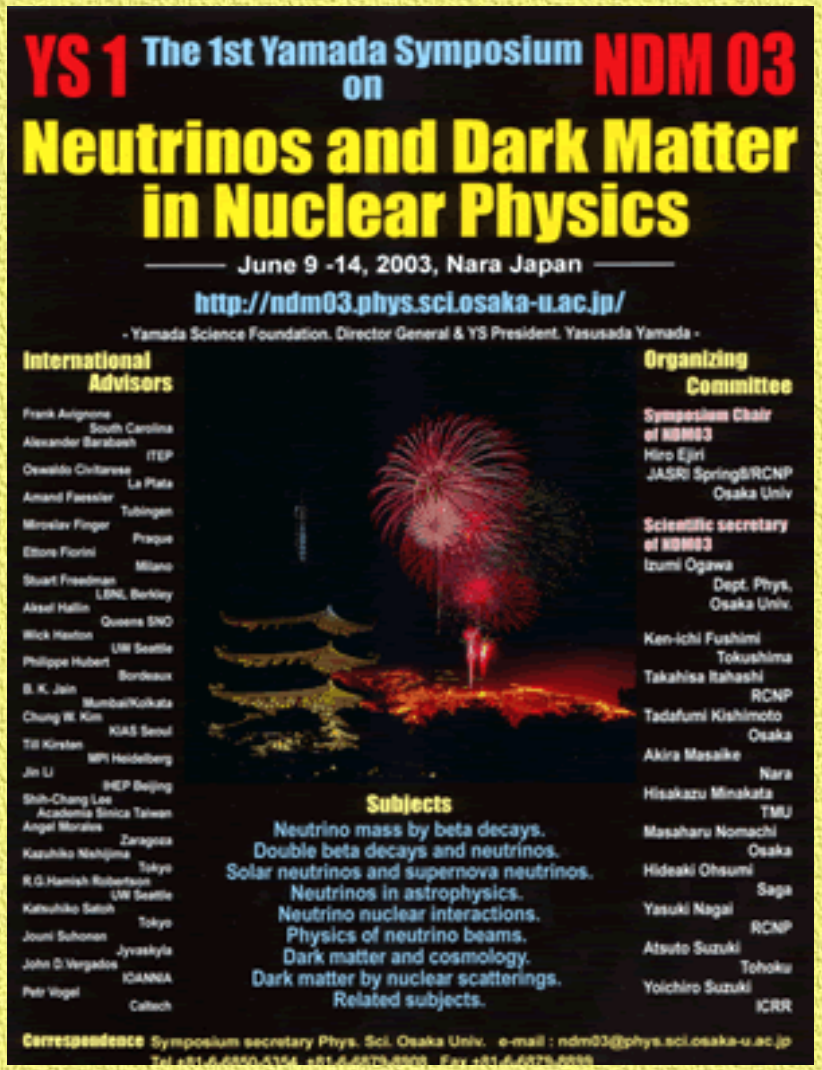
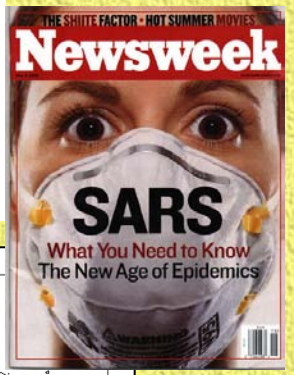
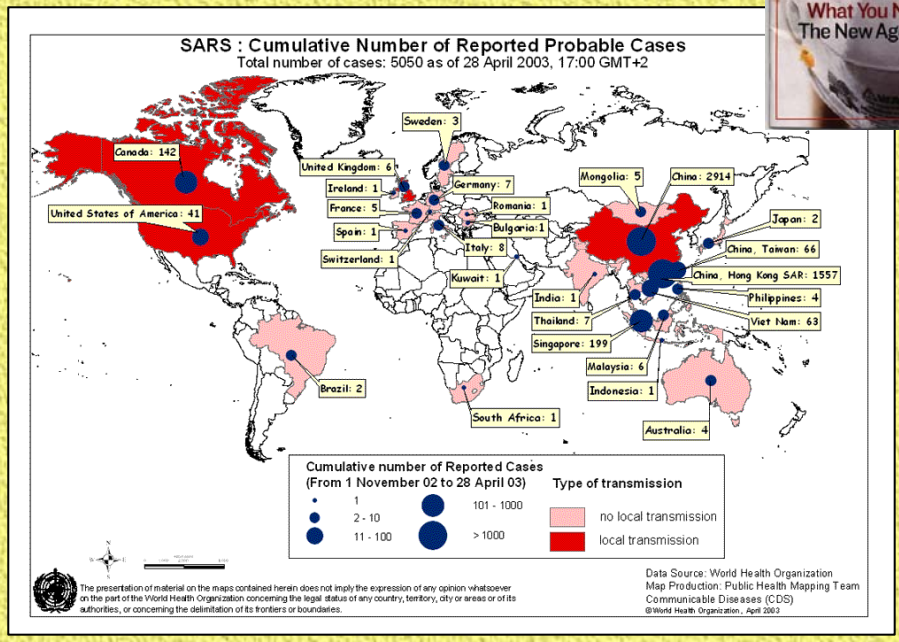
@ NDM @ Nara, June 2012



A Memorable Event in spite of – OR because of – our (from Taiwan & China) absence, since we were prevented from travels due to the SARS epidemic in 2003 in our regions.





Gratitude to Prof. Ejiri for understanding and support.

TEXONO-CDEX Collaboration

TEXONO

Taiwan EXperiment On NeutrinO *[since 1997]*:

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

CDEX

China Dark Matter EXperiment *[birth 2009]*:

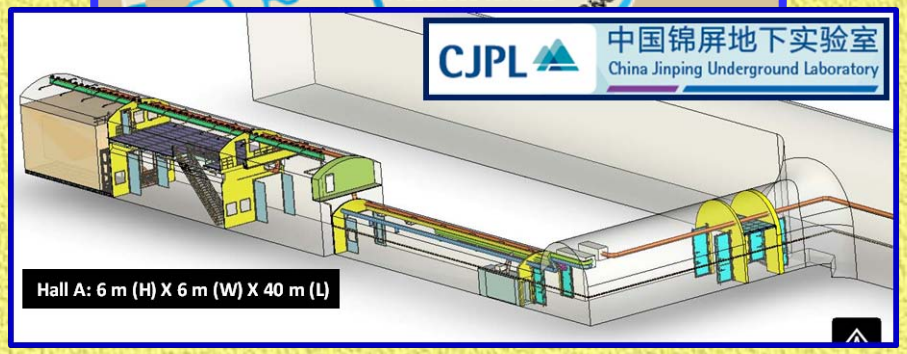
- Dark Matter Searches at China Jin-Ping Underground Laboratory (CJPL)
  - China (THU, CIAE, NKU, SCU,EHDC)

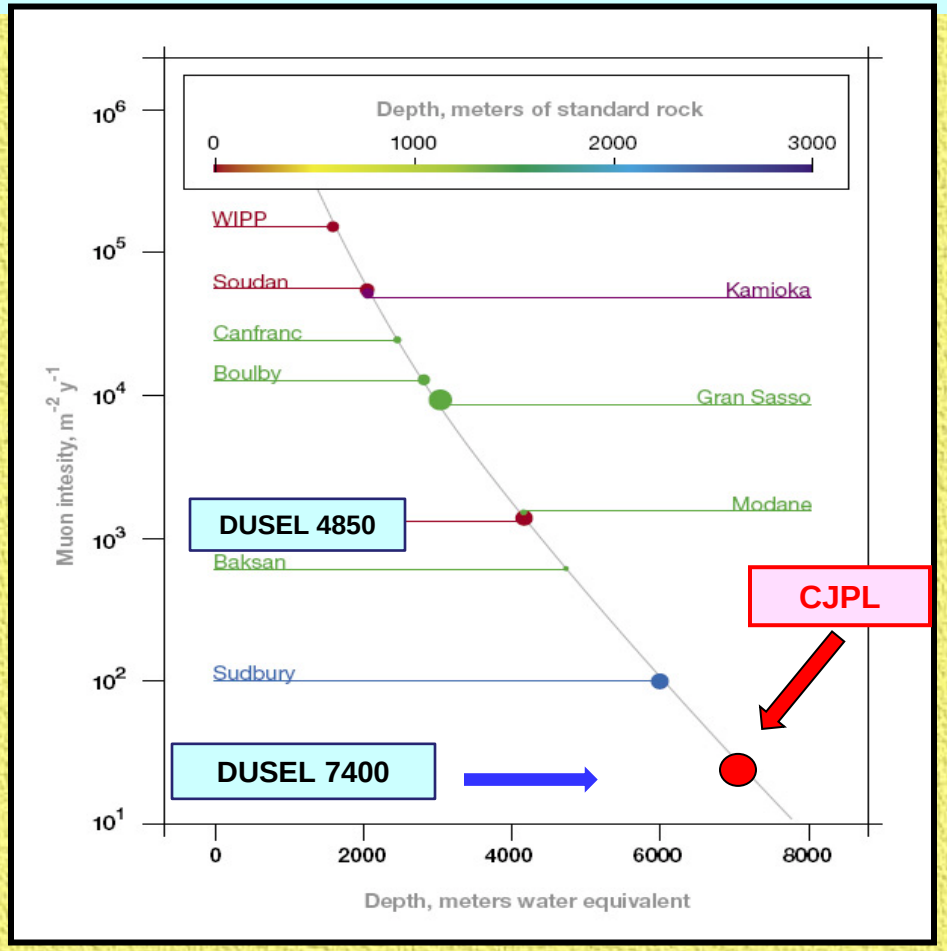
Research Program: Low Energy Neutrino and Dark Matter Physics

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

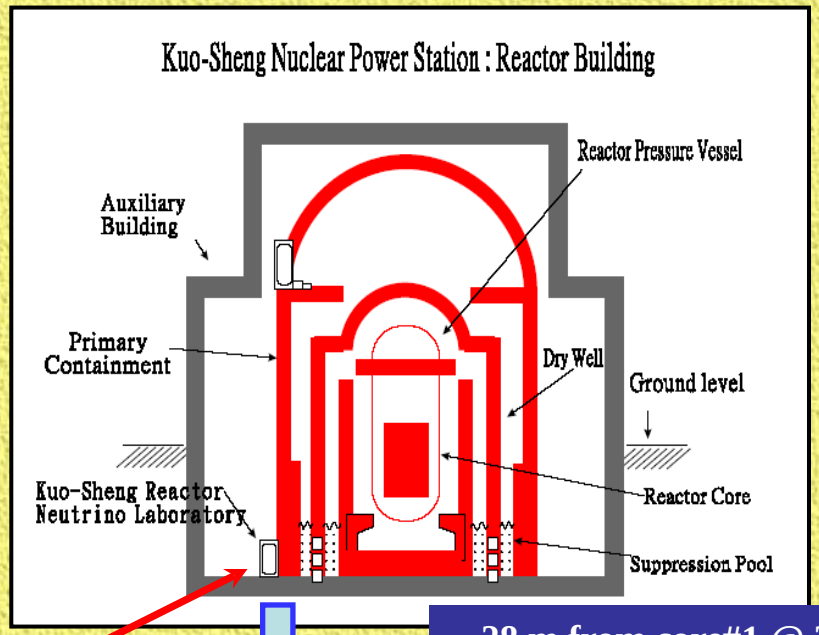
Details: WuYC's Report

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

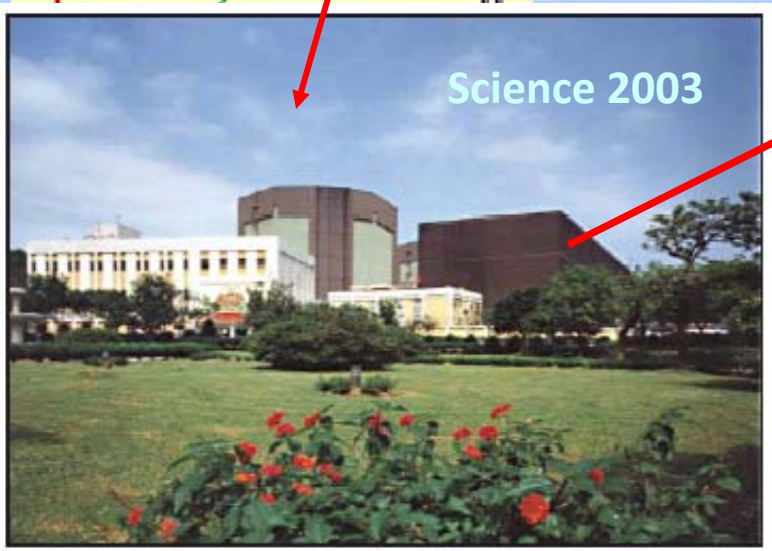




Kuo Sheng Reactor Neutrino Laboratory (KSNL)



28 m from core#1 @ 2.9 GW



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

Neutrino Physics *at (L~0)* Reactor ??
Rationale :

- Need neutrino source to do neutrino physics : reactor is a high-flux, understood and controlled source ⇒ *AND* free as well !!
- oscillation expts. ⇒ $m_\nu \neq 0$ ⇒ anomalous ν properties & interactions
- Experimental neutrino physics has been full of surprise
- Worth exploring any experimentally accessible parameter space
- May place constraints to interpretation of precision oscillation data
- Explore new detection channels for future studies
- NEW:: studies of sterile neutrinos

KSNL : Detectors Schematics

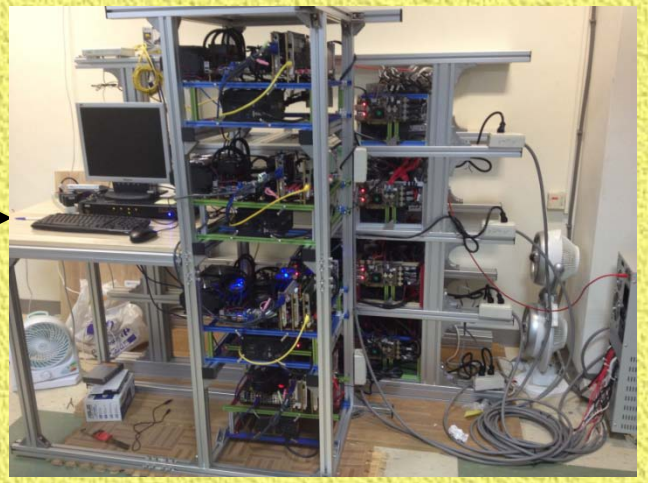
ULB-HPGe [1 kg]

CsI(Tl) [200 kg]

Sub-keV Ge Detectors (20-900 g)

FADC Readout

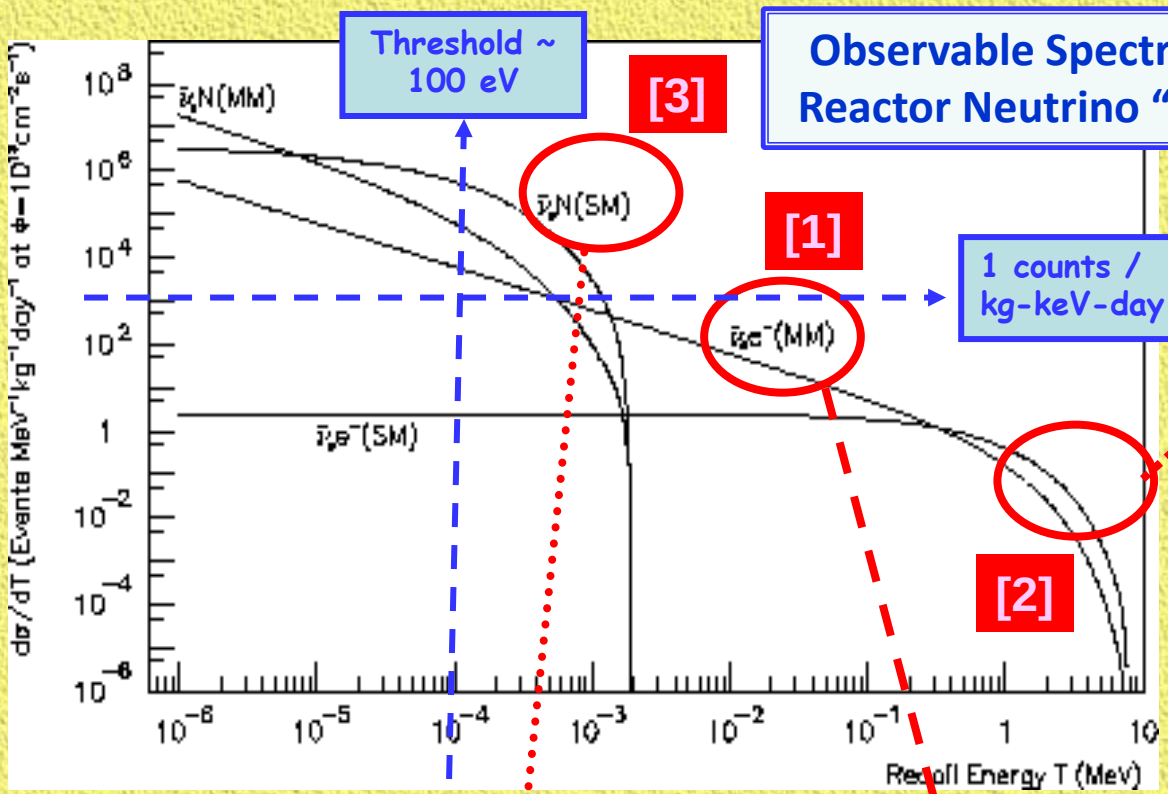
[16 ch., 20 MHz, 8 bit]

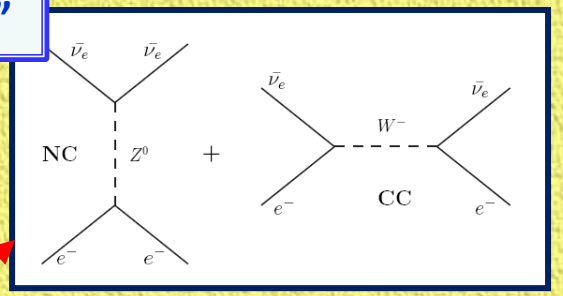


Multi-Disks Array [~300 Tb]

Neutrino Properties & Interactions at Reactor

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





SM & NSI/BSM νe Scattering (2⊗ PRD10,PRD12)

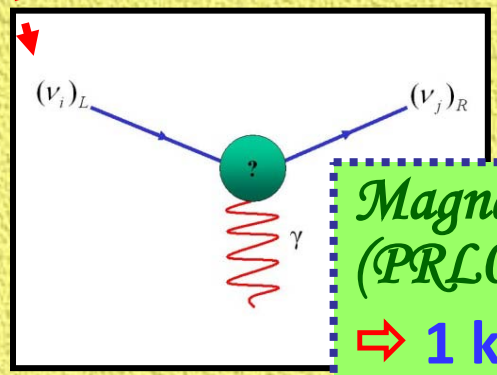
⇨ 200 kg CsI(Tl)

Details: M Deniz's Report

νN Coherent Scattering

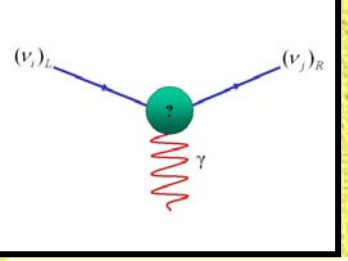
↳ Dark Matter Searches (PRD-RC09)

⇨ sub-keV O(kg) ULEGe / PCGe

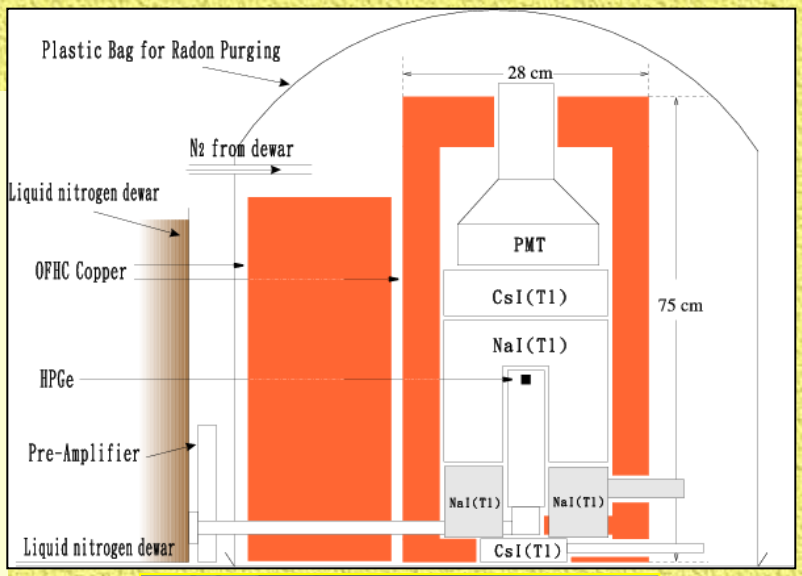


Magnetic Moments (PRL03,PRD05,PRD07)

⇨ 1 kg HPGe



Magnetic Moment Searches @ KSNL



- simple compact *all-solid* design : HPGe (mass 1 kg) enclosed by active NaI/CsI anti-Compton, further by passive shieldings & cosmic veto
- selection: single-event after cosmic-veto, anti-Comp., PSD
- TEXONO data (571/128 days) ON/OFF) [PRL2003; PRD 2007]
  - background comparable to underground CDM experiment : ~ 1 day^{-1}keV^{-1}kg^{-1} (cpd)
  - DAQ threshold 5 keV analysis threshold 12 keV

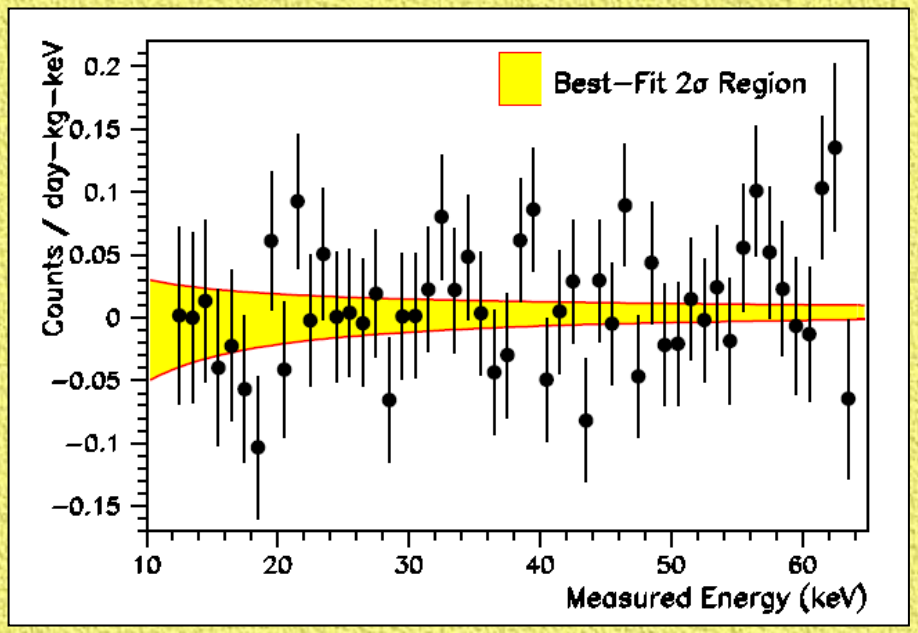
Search of μ_ν at low energy

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

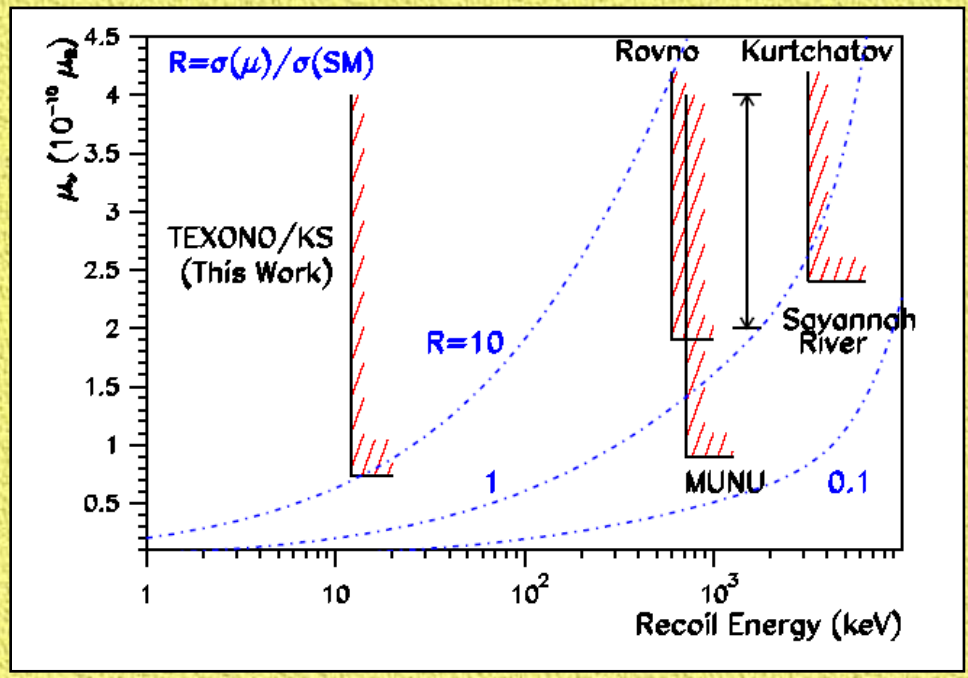
⇒ high signal rate & robustness:

- 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]

ON/OFF Residual Plot :



$\mu_\nu(\bar{\nu}_e) < 7.2 \times 10^{-11}\ \mu_B$ @ 90% CL



Current Research Theme:

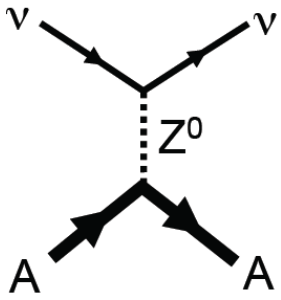
"sub-keV" Ge Detectors

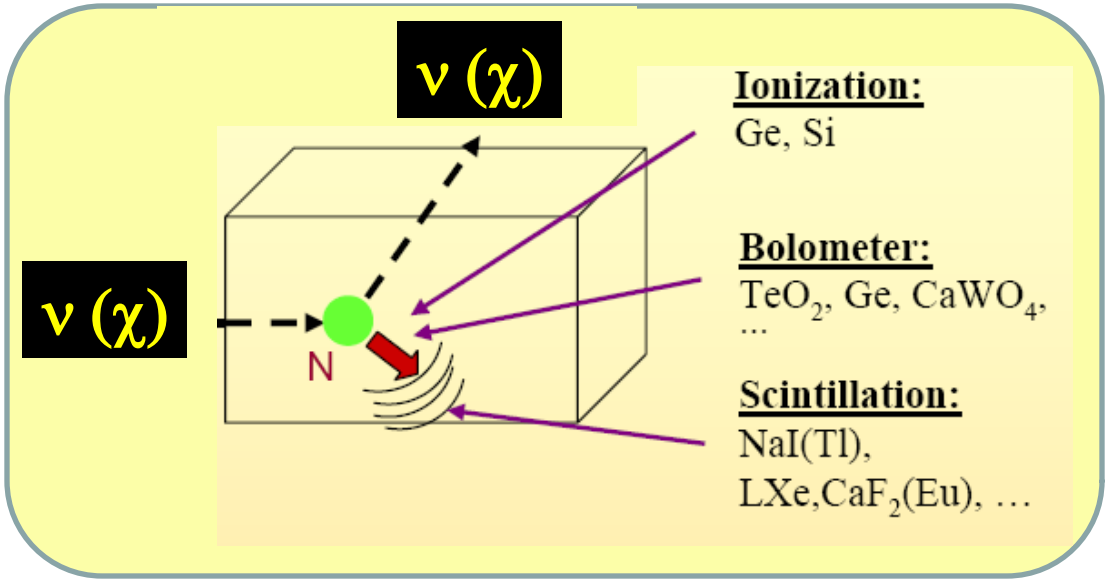
- **Physics Goals for *O[100 eV threhold⊕1 kg mass⊕1 cpkkd] detector* :**
  - **νN coherent scattering**
  - **Low-mass WIMP searches**
  - **Improve sensitivities on neutrino magnetic moments**
  - **Implications on reactor operation monitoring**
  - **Open new detector window & detection channel available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

Neutrino-Nucleus Coherent Scattering :

Standard Model allowed and predicted processes :

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





Condition: $q R << 1$

$$\frac{d\sigma}{d(\cos\theta)} = \frac{G_F^2}{8\pi} Q_W^2 E_\nu^2 (1+\cos\theta) F(Q^2)^2$$

F(Q²) : Nuclear Form Factor

Effective Weak Charge :

$$Q_W = N - (1 - 4\sin^2\theta_W)Z$$

$$\sigma \simeq 0.42 \times 10^{-44} N^2 (E/1\ \text{MeV})^2\ \text{cm}^2$$

per atom

$$\sigma \simeq 2.5 \times 10^{-18} \frac{N^2}{A} (E/1\ \text{MeV})^2\ \frac{\text{cm}^2}{\text{kg}}$$

per kg materials

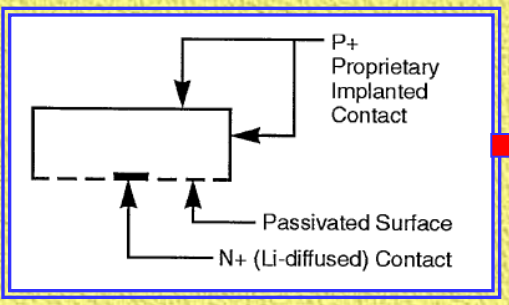
- **Neutral current process**
  - $\Rightarrow$ **same for all ν-flavor (leading order)**
- $\sigma \propto N^2 \Rightarrow$ ***"Coherent"*** *[probe "sees" the whole nucleus]*
  - **coherency** $E_\nu < 50$ MeV
  - **intermediate** $50 < E_\nu < 200$ MeV *[depends on q / θ]*
  - **incoherent** $E_\nu > 200$ MeV *[$\sigma \propto N$]*
- $\sigma \propto E_\nu^2 \Rightarrow$

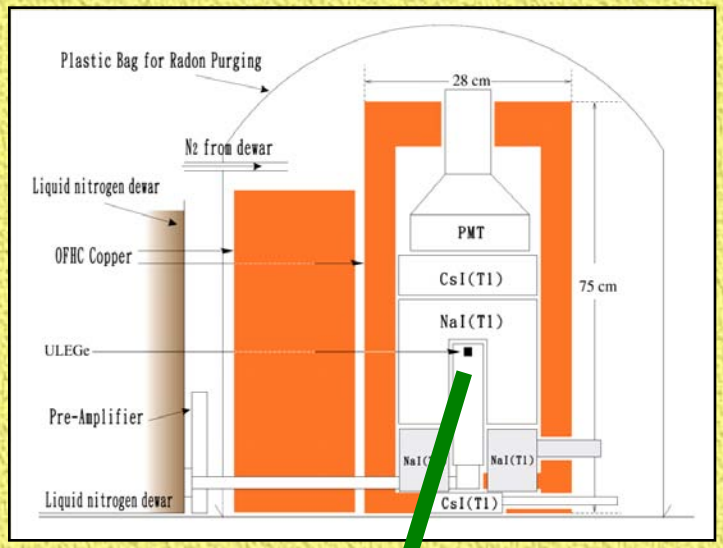
  e.g. **at O(10 MeV)**
  - ν**–A coherent** ~ 10^{-39} cm^{-2}
  - $\bar{\nu}_e$**–p CC** ~ 10^{-40} cm^{-2}
  - ν**–e elastic** ~ 10^{-43} cm^{-2}
- **important process in stellar collapse & supernova explosion**
- **analogous interaction used in dark matter detection**
- **Typical Rates for Ge at KSNL :**

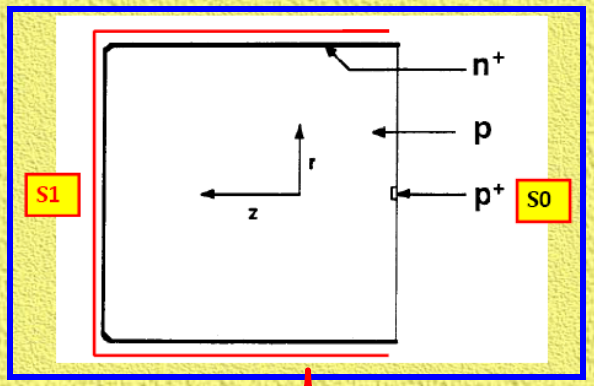
  ~10 kg^{-1} day^{-1} @ threshold~100 eV & QF~0.2

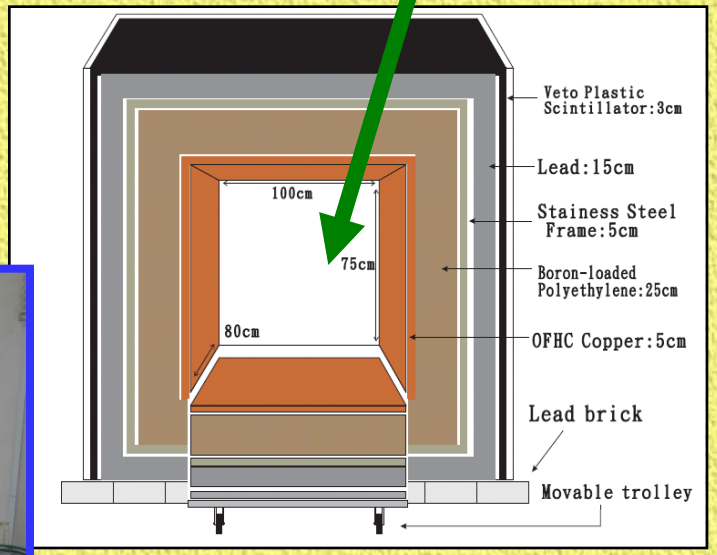
[Also : Ideas with stopped-pion neutrinos]

TEXONO-CDEX : ULEGe & PCGe @ KSNL & CJPL

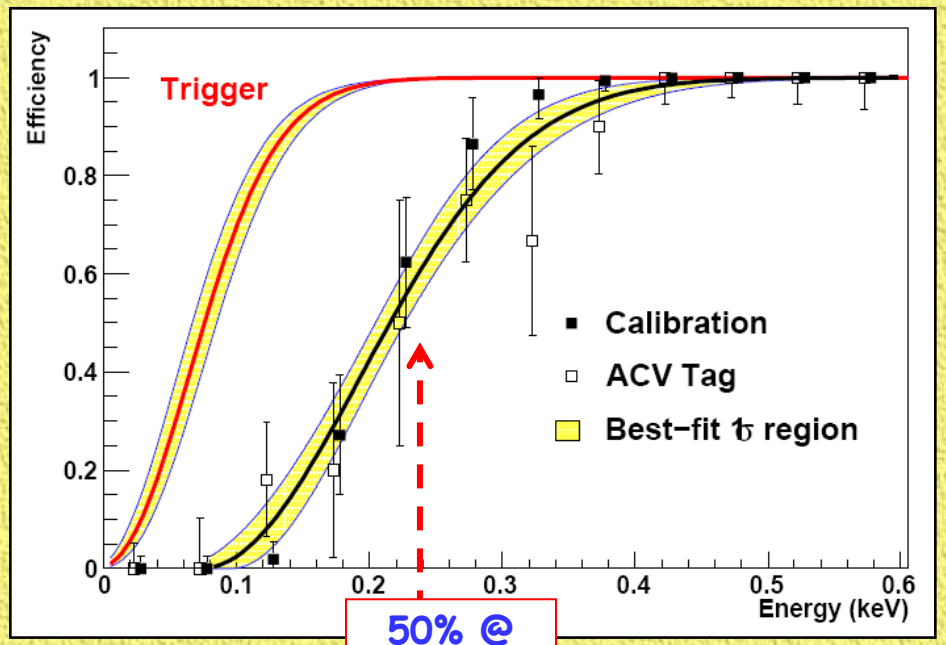


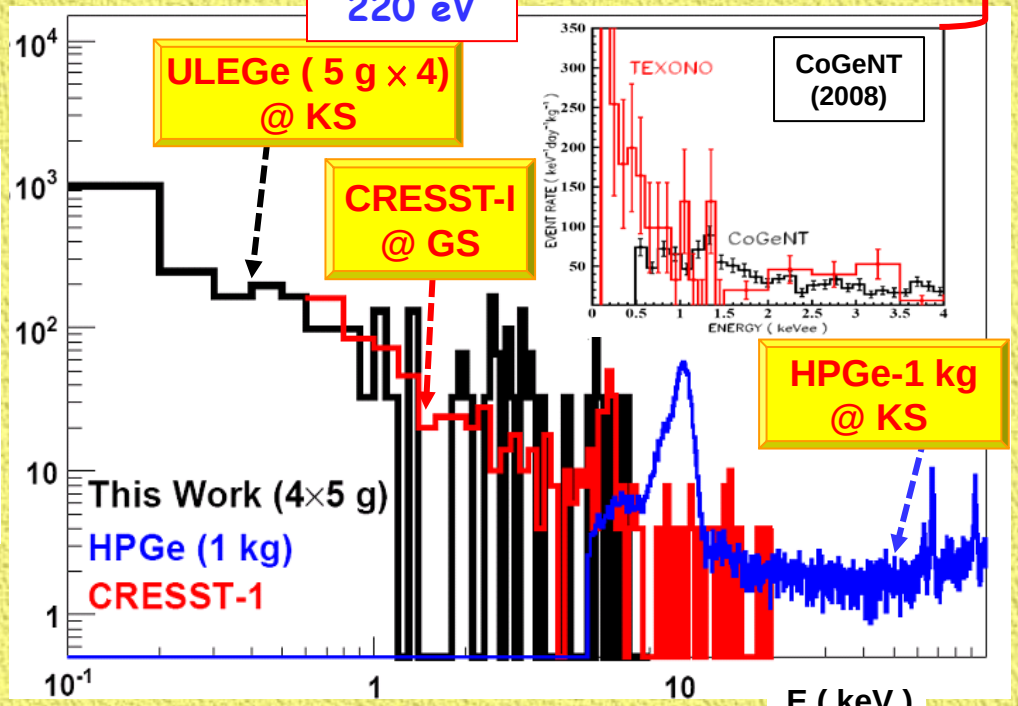


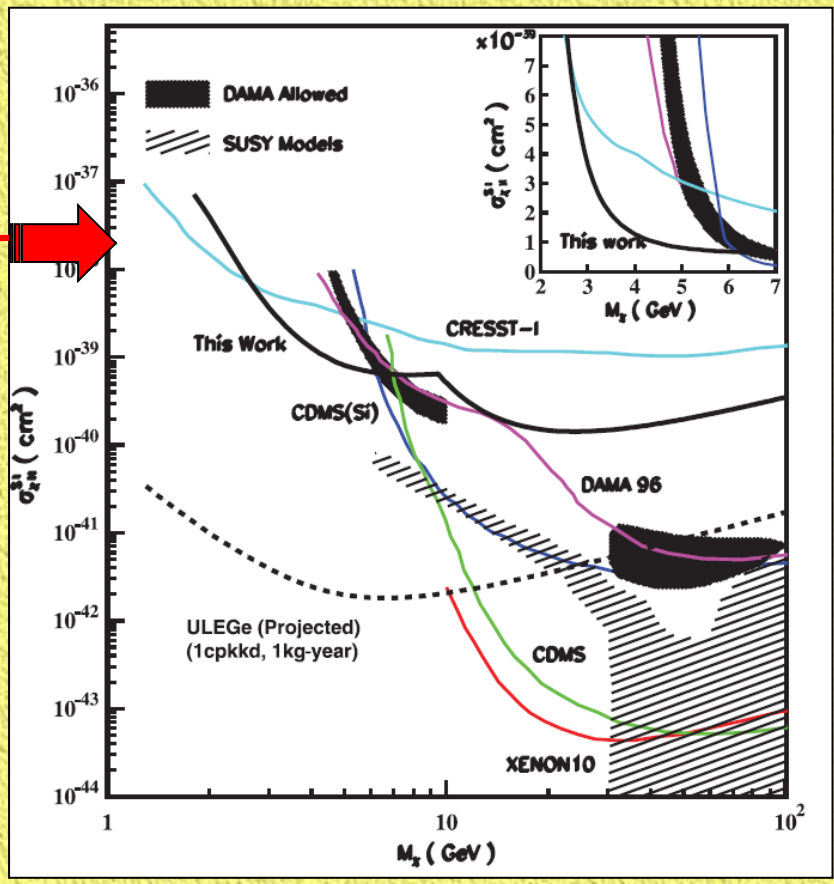




TEXONO-CDEX @ KSNL :
Threshold & Efficiencies & Background for 20g ULEGe (2007)







Hurdles / Challenges / Opportunities : Excess of sub-keV Events

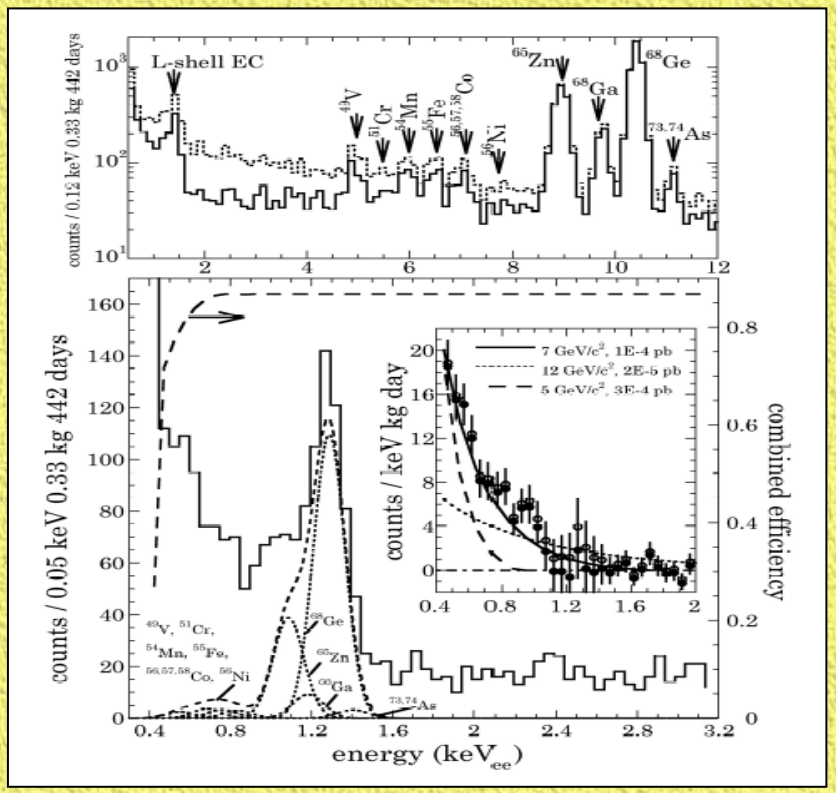
- *NOT* fully explained with conventional background modeling
- *INTENSE* efforts on background understanding with detector hardware, calibration measurements, analysis software and data taking at the new *China Jinping Underground Laboratory*
- *MUST* solve this problem before scaling the summit of νN coherent scattering with reactor neutrinos.

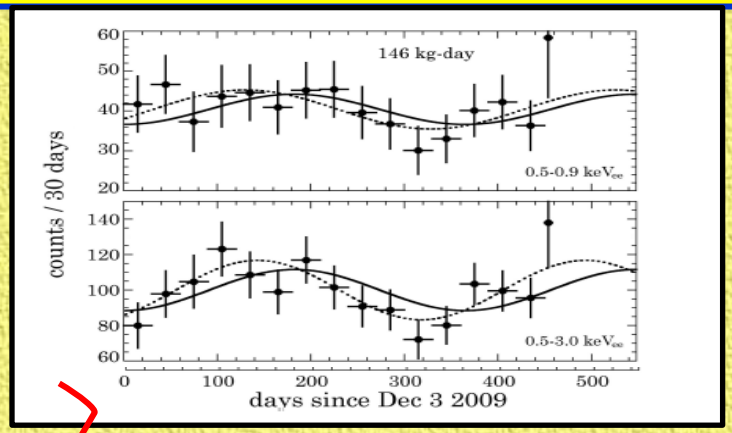
CoGeNT @ US 2007: Demonstrate use of "Point-Contact Ge Detector"

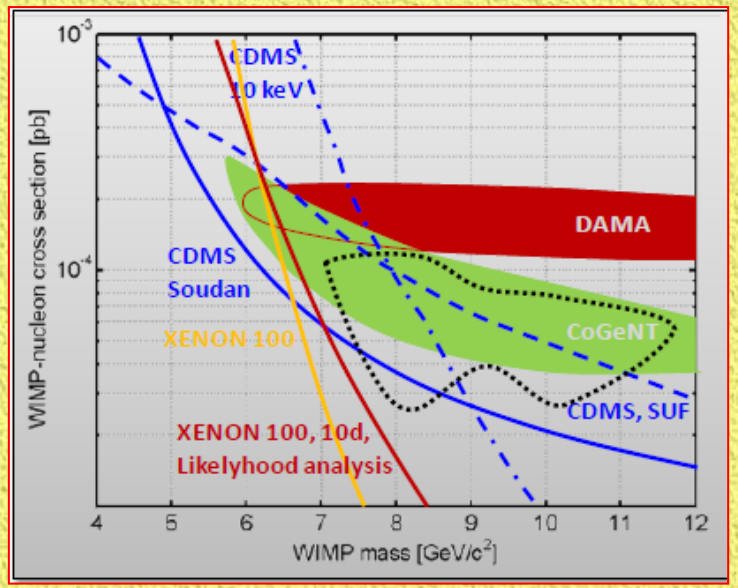
2010 *(PRL11: limits & allowed region)* / 2011 *(PRL11: 2.8σ annual modulation)*

⇨ **intense theoretical interest and speculations on low-mass WIMPS**

⇨ **Allowed region & AM *challenged* by others & *defended* by CoGeNT**







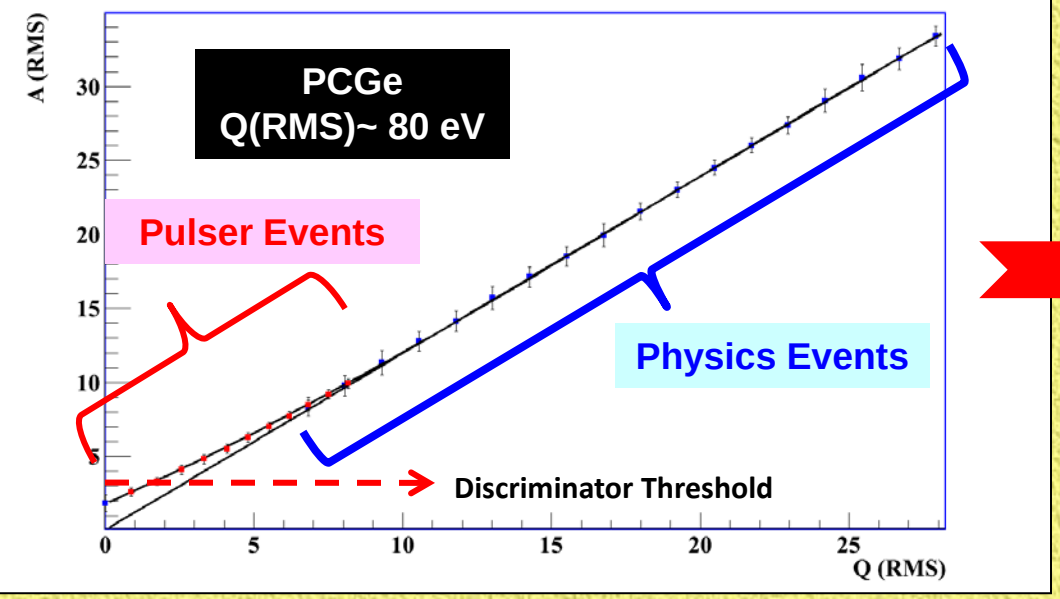
"Some" Low-Mass Dark Matter Models:

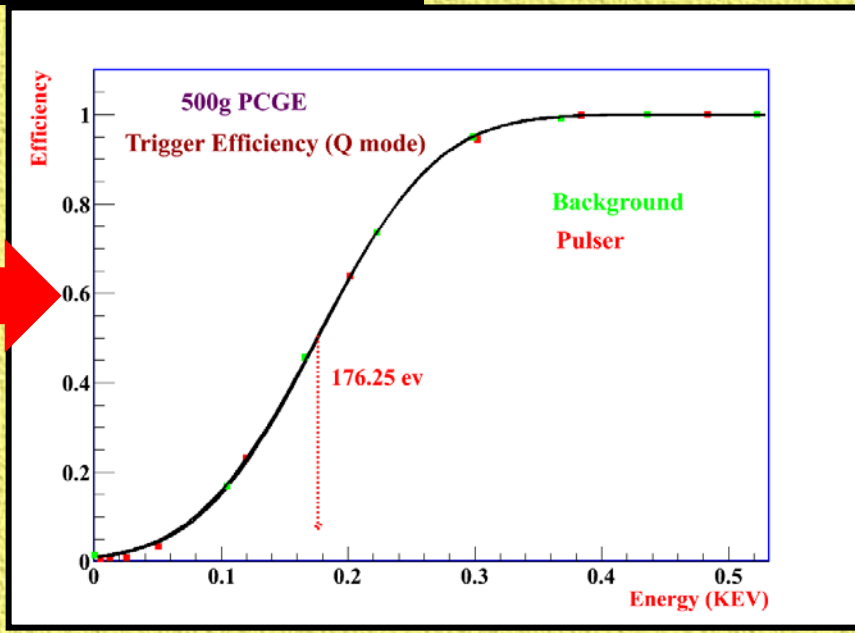
- Generic SUSY Framework ; Light SUSY *[PRD 72, 083521(2005)..]*
- Composite DM ; Q-Balls *[PRL 89, 101302(2002)..]*
- WIMPless DM *[PLB 670, 37 (2008)..]*
- Mirror DM *[PRD 80, 091701(2009)..]*
- Asymmetric DM *[PRD 79, 115016(2009)..]*
- Singlet Fermion DM *[JHEP 0905, 036(2009)..]*
- MeV DM *[PRD 77, 087302(2008)..]*
- Leptophilic DM *[PRD 80, 083502 (2009)..]*
- Axion-Like Particles
- ***OR …*** Alternative Astrophysics DM ρ-v modeling may favor lower recoil energy (e.g. solar system bound) *[PRL 81, 5726(1998)..]*
- Many other theory work ……..

Sub-keV Ge Detector Techniques : R&D Items

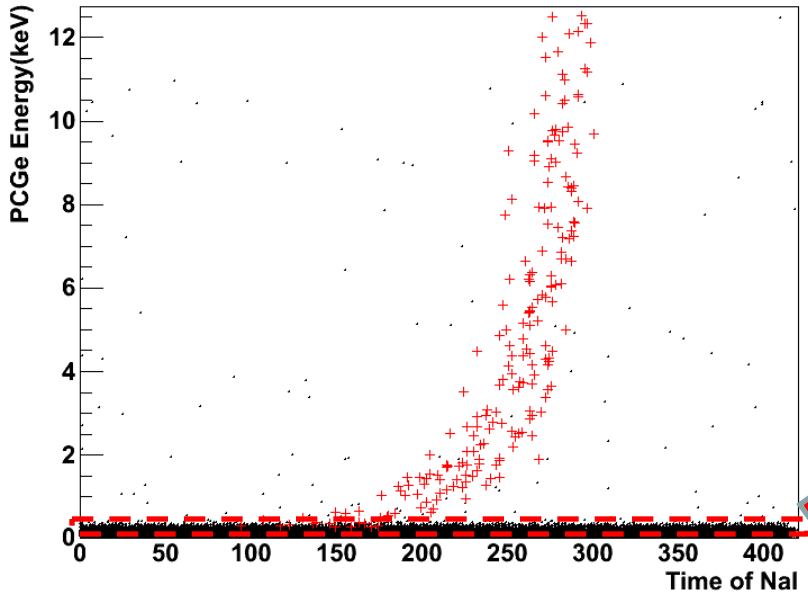
- Quenching Factors -- nuclear recoils' Ionization Yields
- Energy Definition & Calibration
- Trigger Efficiencies near threshold
- Physics Vs Noise Pulse-Shape Selection -- algorithms & efficiencies
- Bulk Vs Surface Events Selection – algorithms & efficiencies

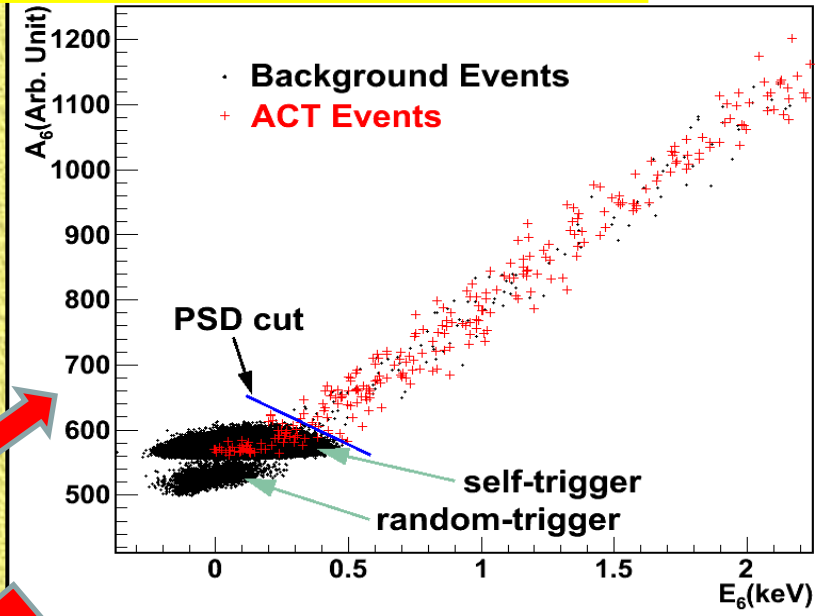
Trigger Efficiency via Pulser Calibration

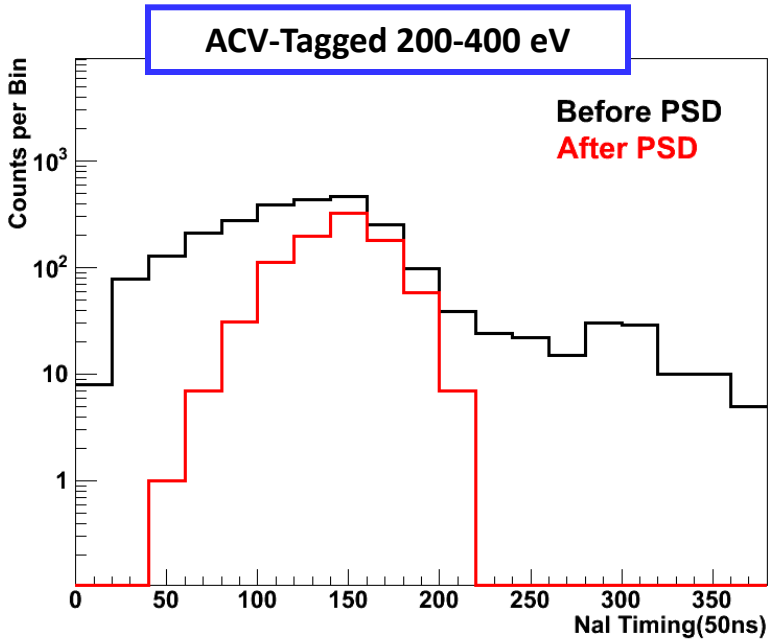


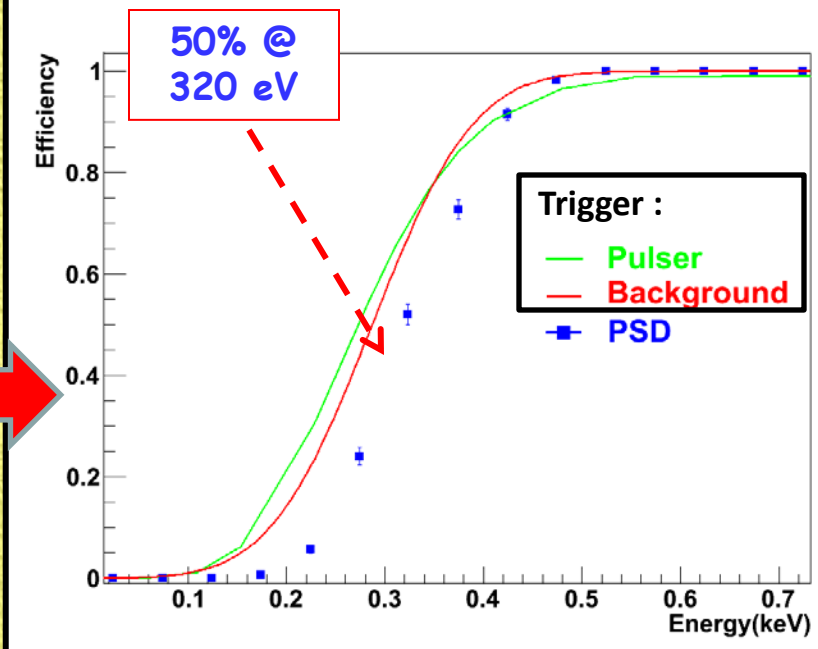


Threshold & Phys-Vs-Noise Selection Efficiency



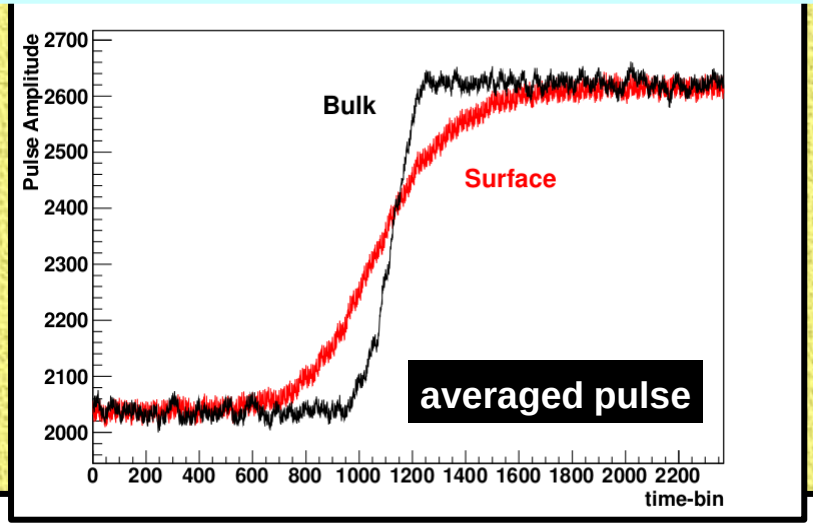


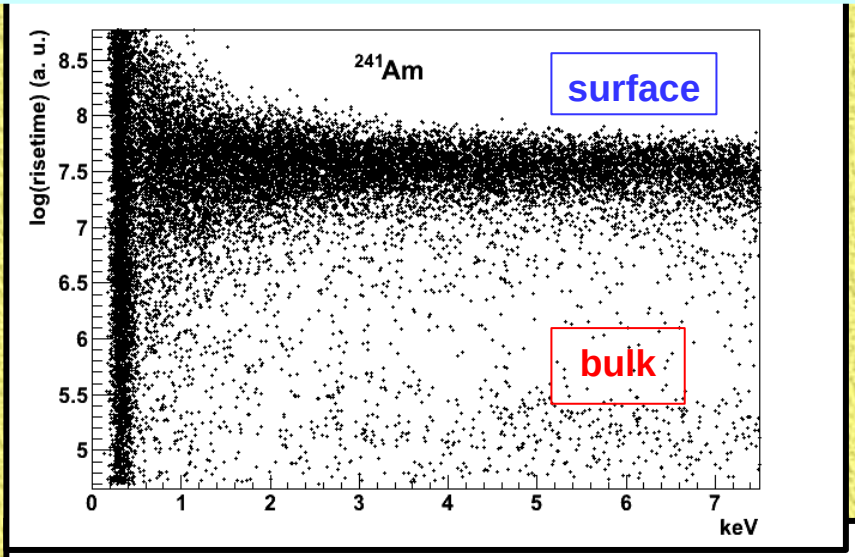


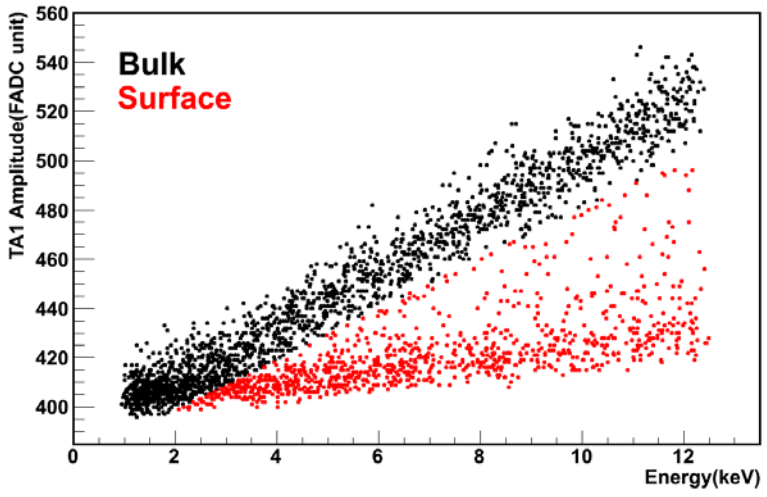


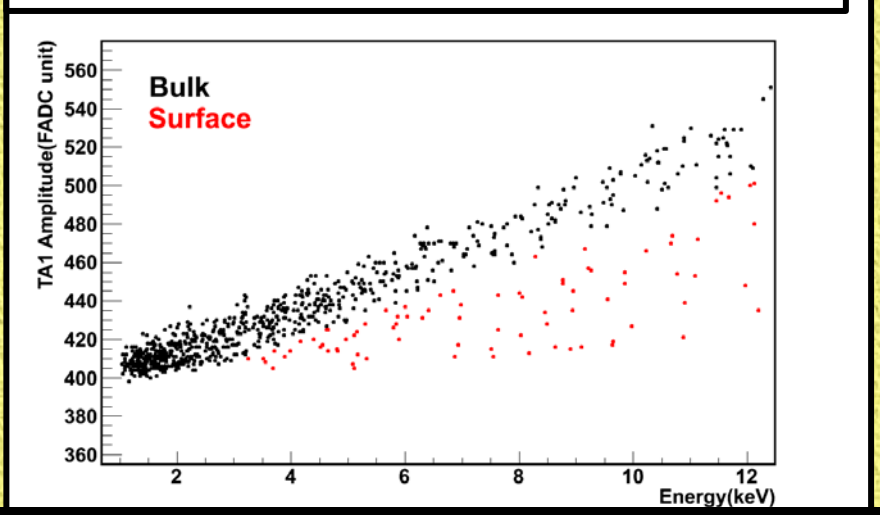
PSD for Surface Vs Bulk Events @ PCGe

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







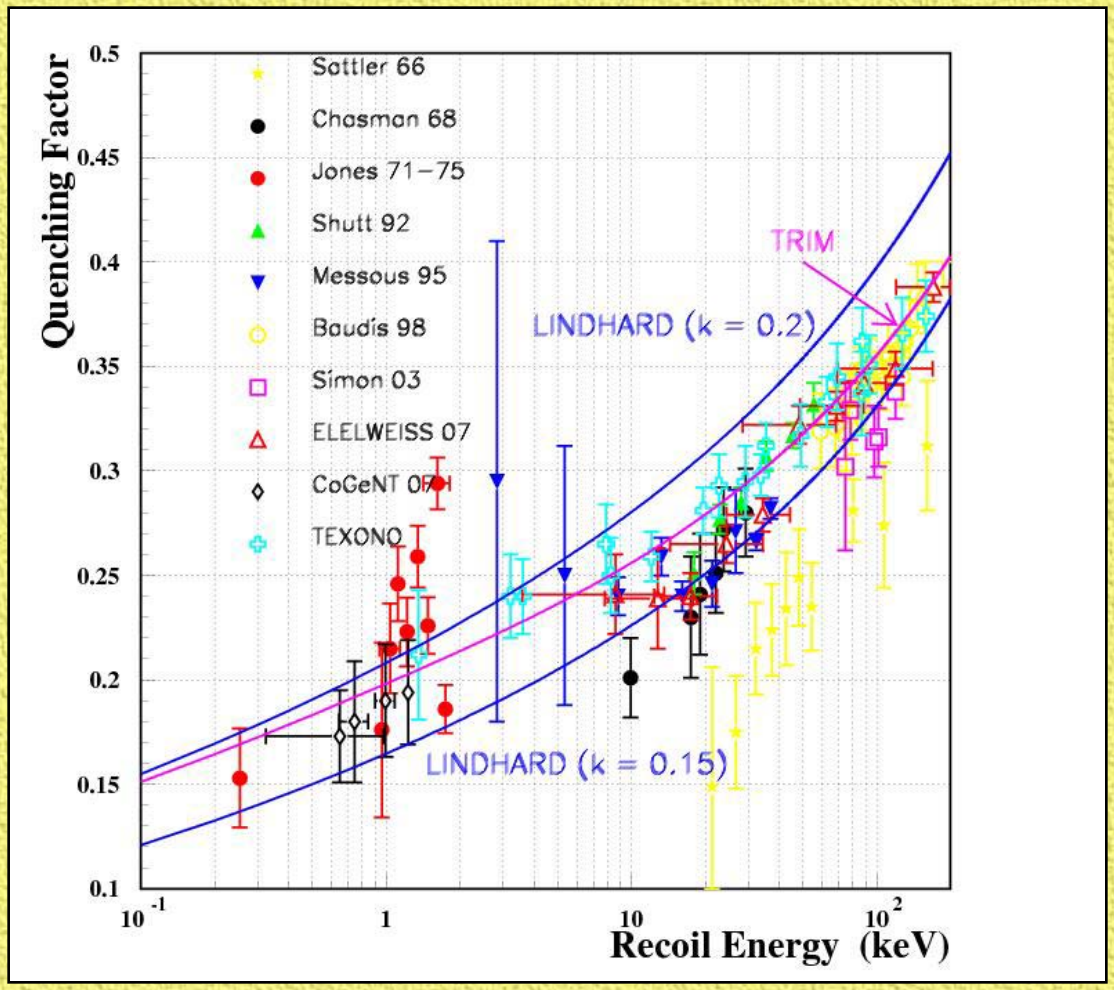


γ-rich background: cosmic veto & anti-Compton trigger

n-rich background: cosmic trigger & anti-Compton veto

Quenching Factor [Ionization Yield → Energy] :

- TRIM Simulation Software (better fits to available data over extended energy)



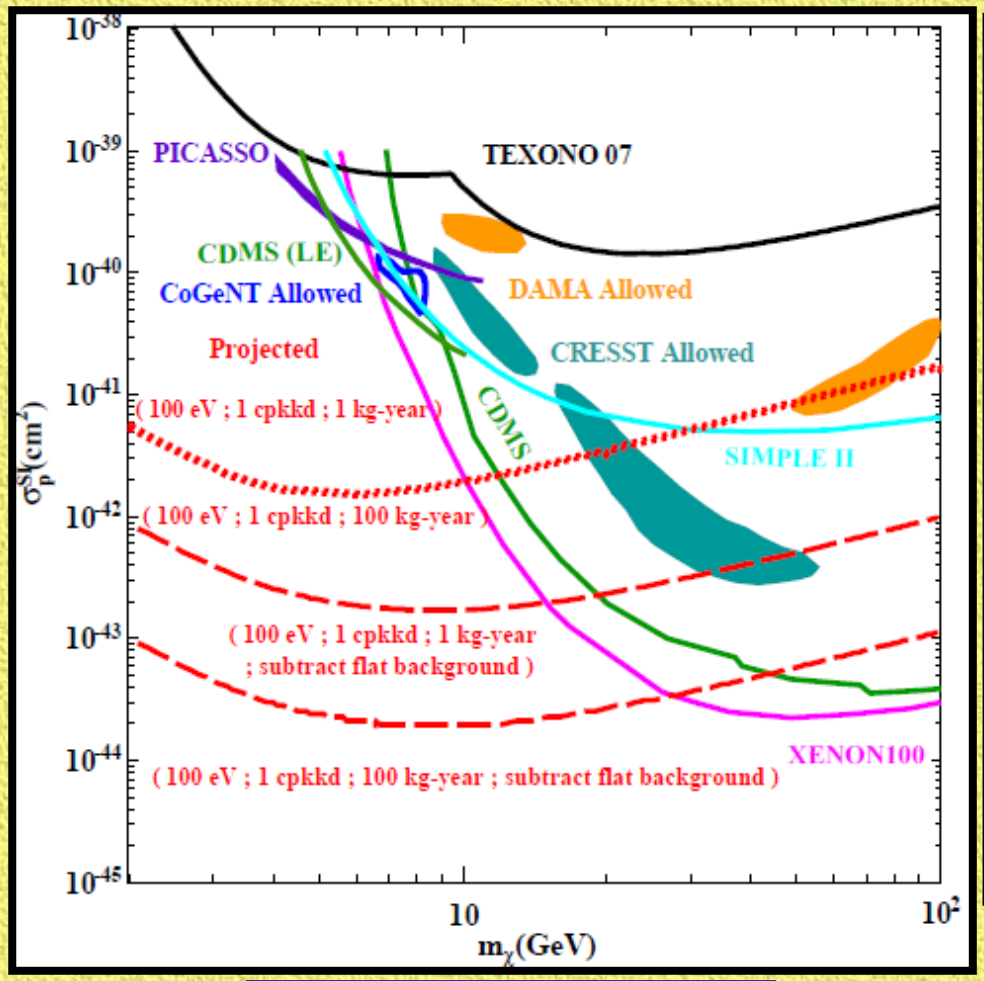
TEXONO-CDEX @ CJPL

- **2011-12:** Repeat PRD-09 measurement with 20-g ULEGe & 1-kg PCGe
- **2012-15:** 10-kg range PCGe array , with Liquid Argon Anti-Compton ; Acquisition of Ge and LAr detector technology ; Explore new possibilities …
- **2015 & Beyond:** Evaluate 1-ton scale experiment, Explore Double Beta Decay program
- **2010+:** characterize background at CJPL ; set up low background material screening facilities

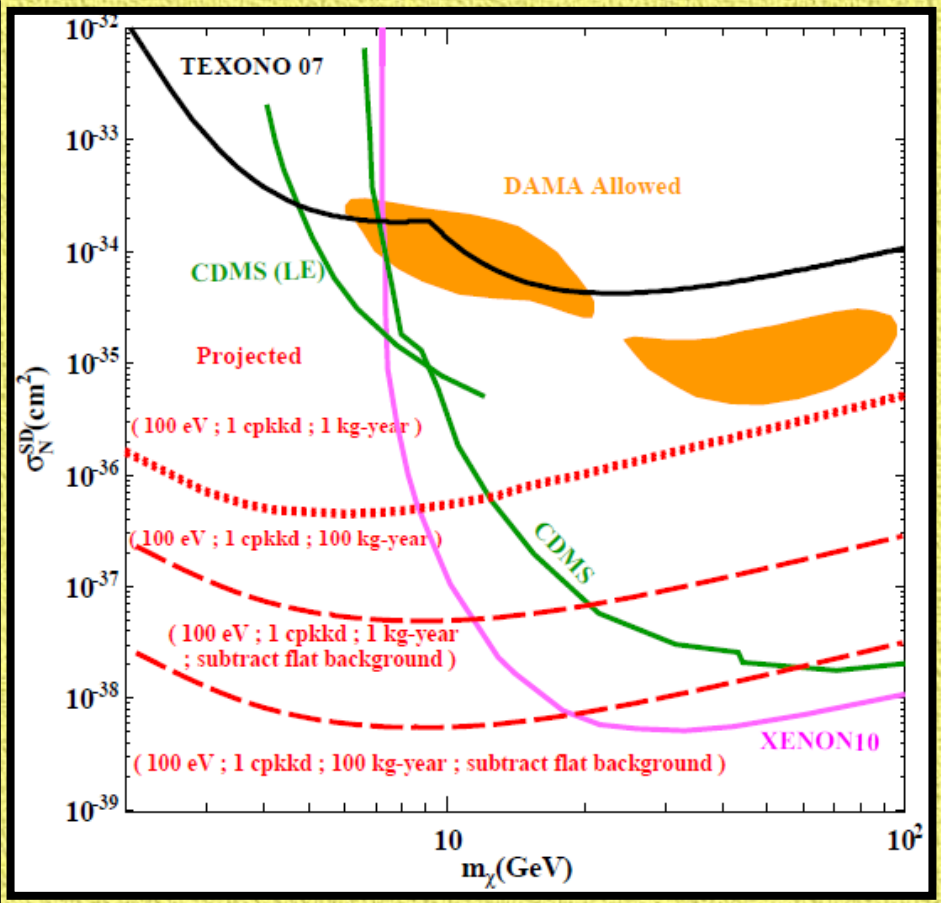
New Ideas Welcomed !!

Data Taking @ CJPL - Engineering Run Feb-Oct 2011

Projected Sensitivities on Low Mass WIMPs @ CJPL



Spin-Independent



Spin-dependent on neutron

Status and Plans and Prospects

- CJPL is the deepest operating underground laboratory in the world. Engineering Data 2011; Physics Data 2012.
- CDEX-TEXONO Dark Matter Program @ CJPL focuses on sub-keV Ge detectors and low-mass WIMP region.
- Focuses at KSNL: sub-keV Ge to support dark matter program *AND* towards ν-N coherent scattering
- Intense efforts on Ge & LAr Detector R&D + Background Understanding @ sub-keV.
- *Goals :* open new *detection channel* and *detector window* for neutrino and dark matter physics ; available platform for *innovations & surprises*