Reactor Neutrino Physics with sub-keV Germanium Detectors

- **Overview: TEXONO-CDEX Collaboration & Kuo-Sheng Reactor Neutrino Laboratory**
- **Highlights on New Development**
  - New Underground Laboratory in China
  - State Electroweak Results on ν-e Scattering
  - New Channels on Neutrino Magnetic Moments
    - μ_ν-induced atomic ionization
  - Neutrino-Nucleus Coherent Scattering R&D Status

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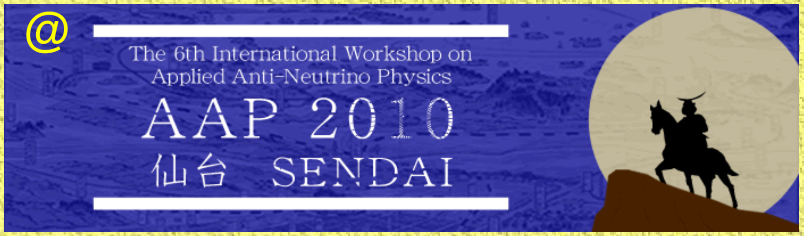


Neutrino Physics *at (L~0)* Reactor ?? Rationale :

- 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 neutrino sources & detection channels for future studies & *"applications".*

TEXONO-CDEX Collaboration

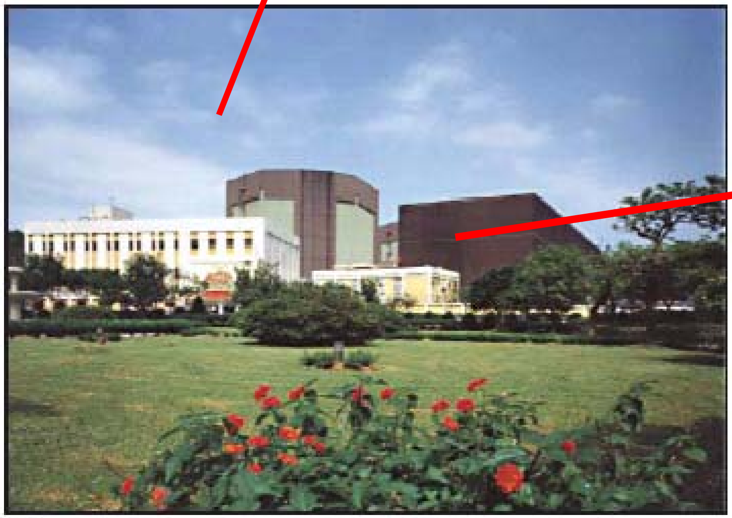
TEXONO *Taiwan EXperiment On NeutrinO* *[since 1997]* :

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

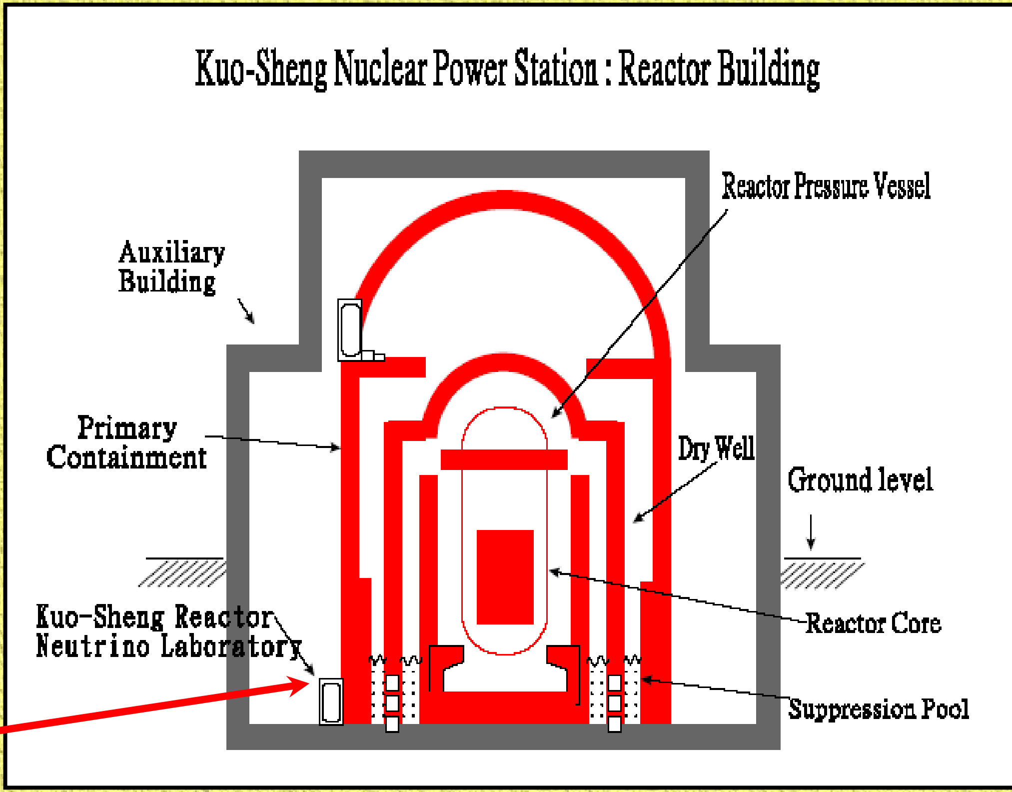
CDEX *China Dark Matter EXperiment* *[birth 2009]* :

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

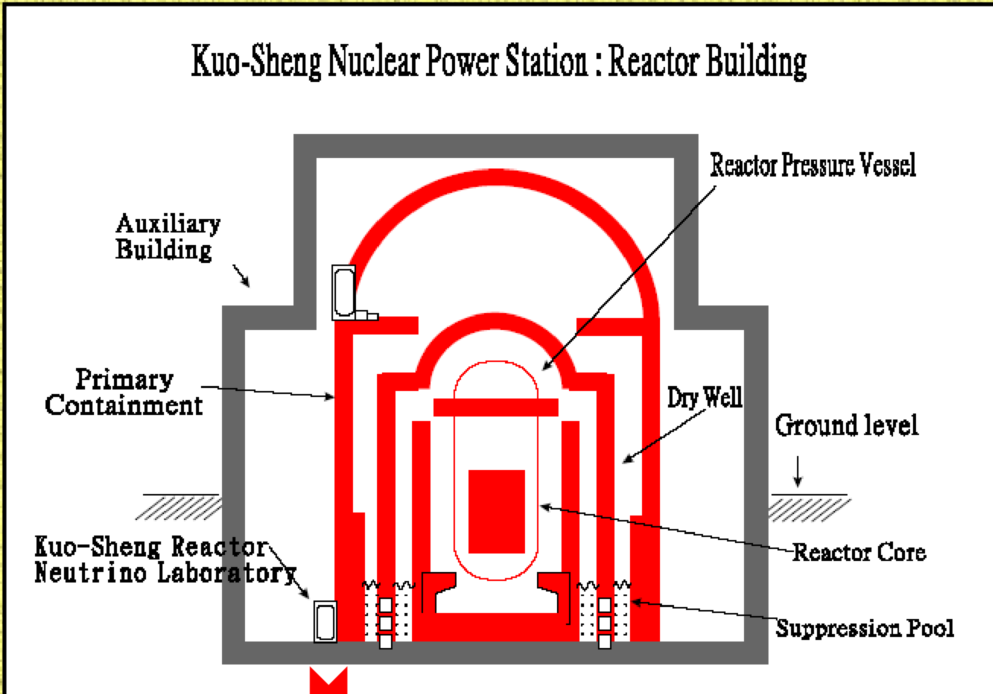
Kuo Sheng [國 聖] Reactor Neutrino Laboratory :



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 …..)*

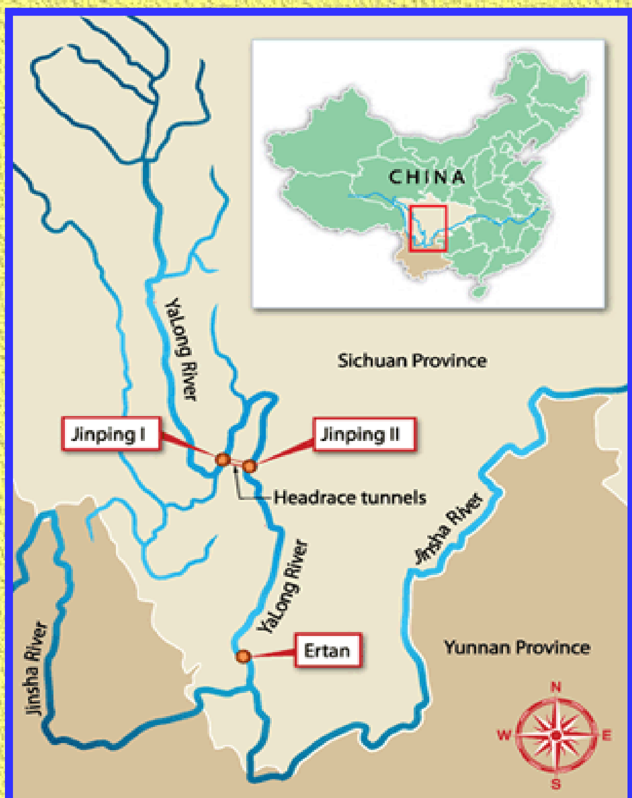
Inner Target Volume

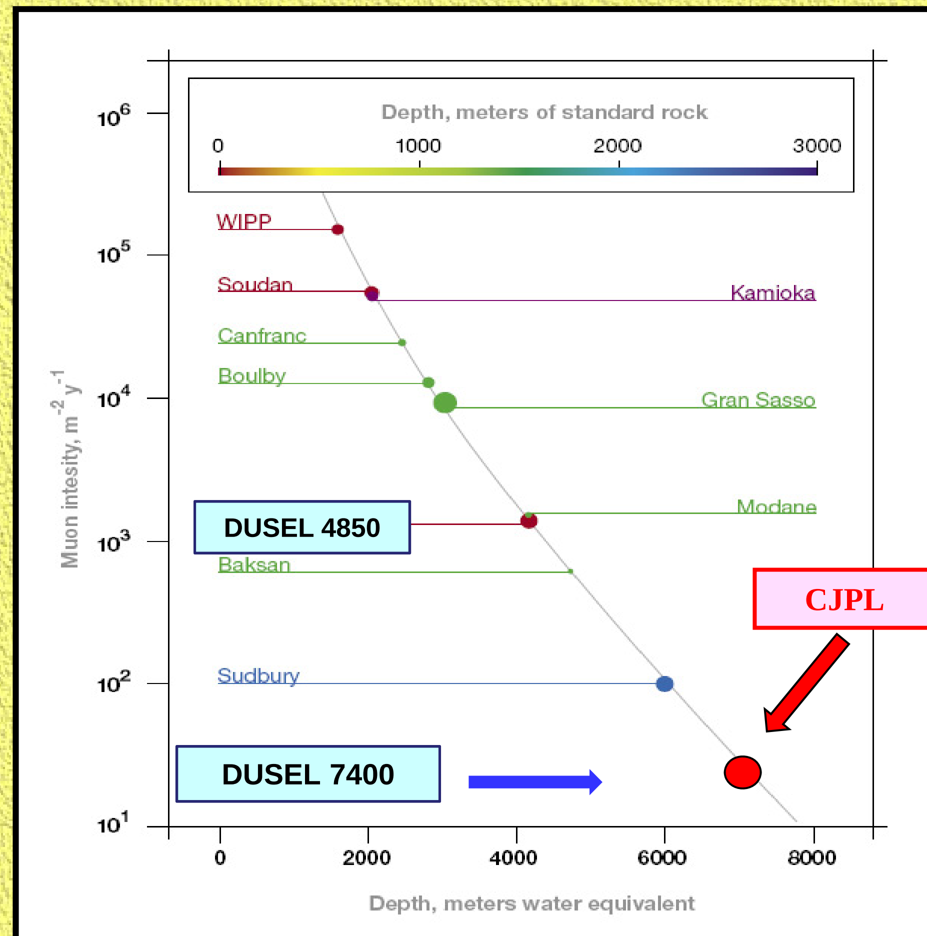
Configuration: Modest yet Unique

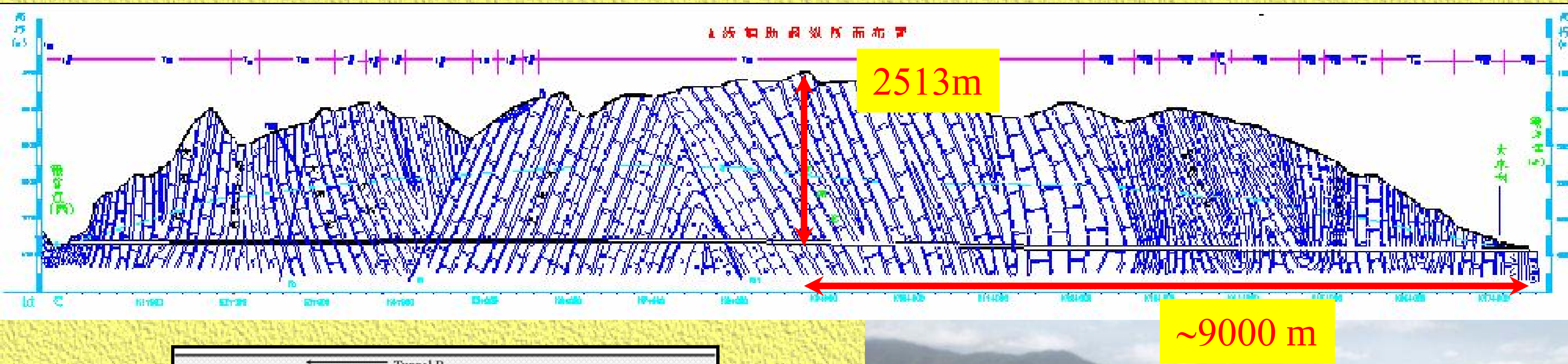
Flexible Design: Allows different detectors conf. for different physics

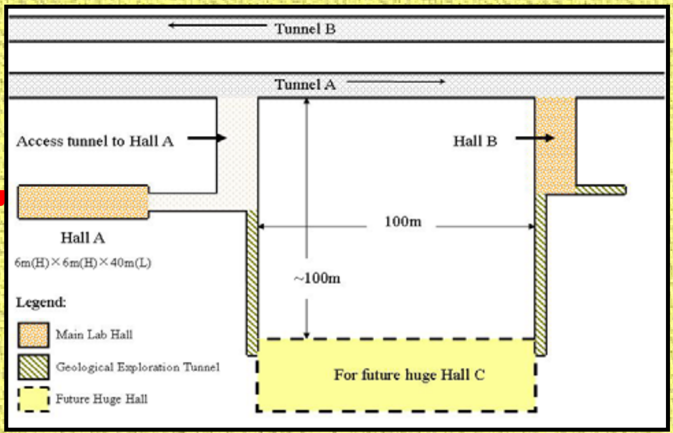
China Jin-Ping Underground Laboratory (CJPL) 中國四川錦屏

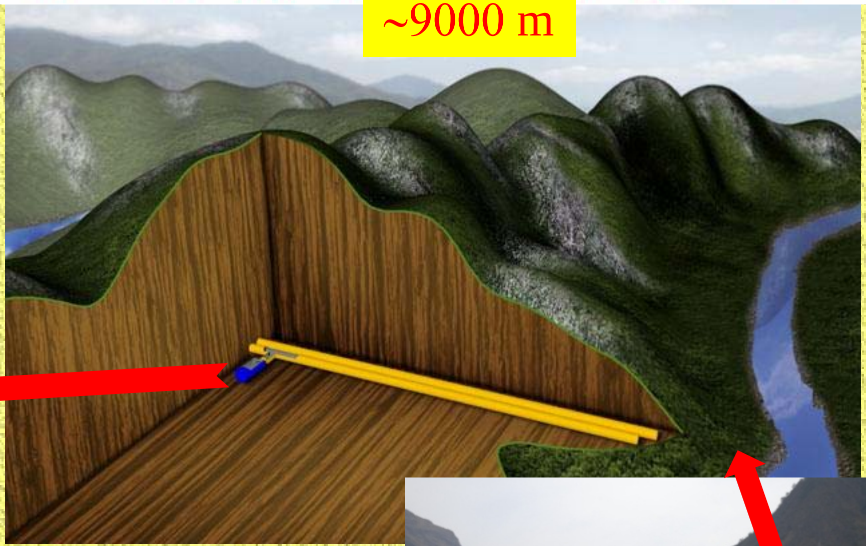
- ◎ 2500+ m rock overburden, drive-in road tunnel access
- ◎ 6X6X40 m cavern under construction [THU & EHDC]
- ◎ DM-Search: 20 g ULEGe 2010 ; 1000 g PCGe 2011

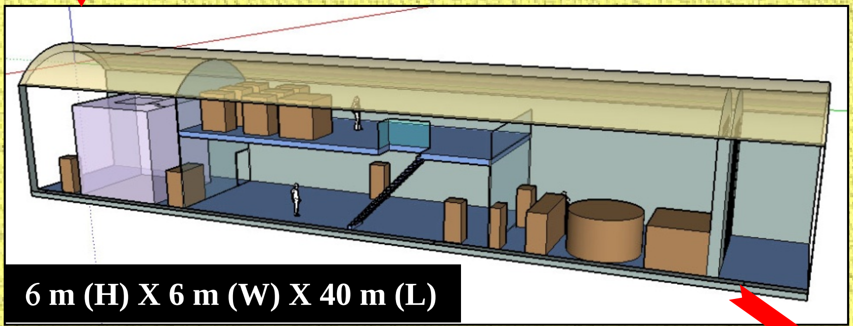





2513m
~9000 m


Tunnel B
Tunnel A
Access tunnel to Hall A
Hall B
100m
Hall A
6m(H)×6m(H)×40m(L)
~100m
Legend:
Main Lab Hall
Geological Exploration Tunnel
Future Huge Hall
For future huge Hall C

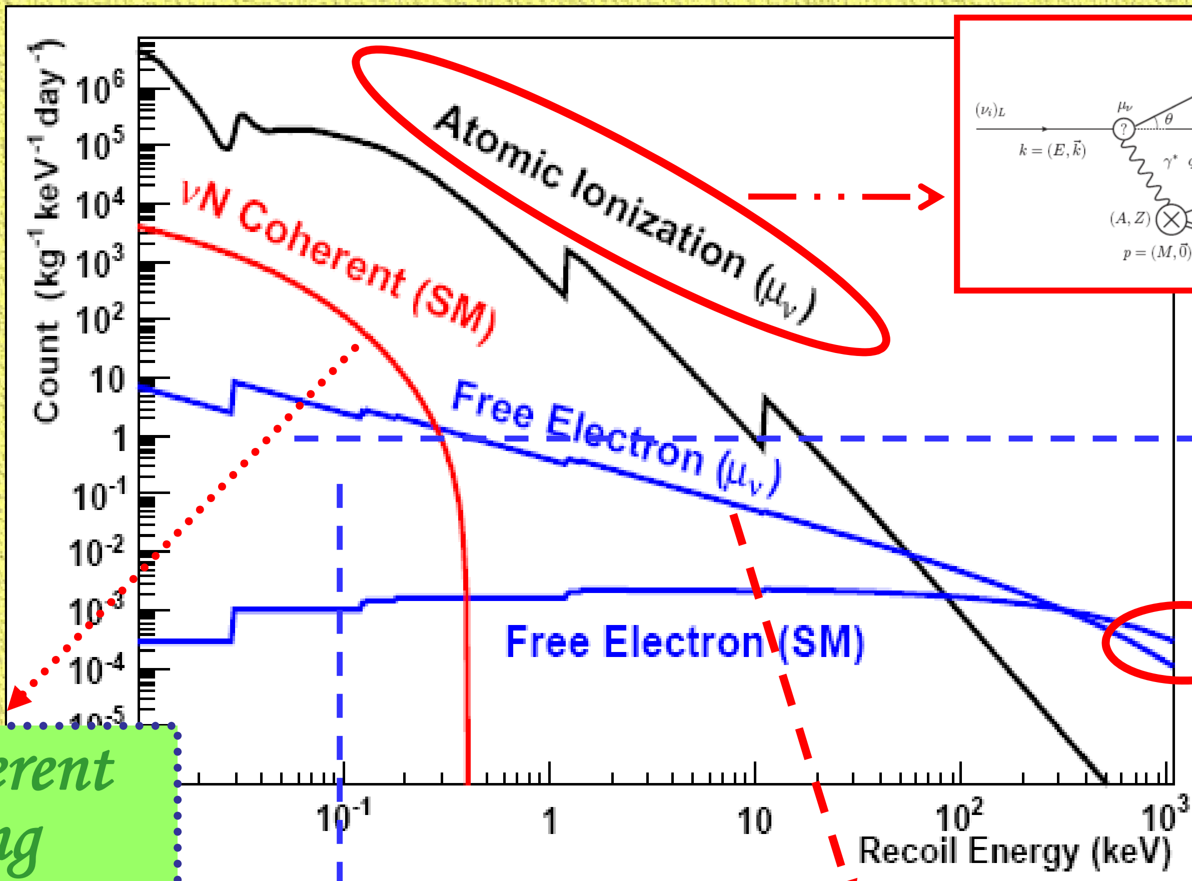


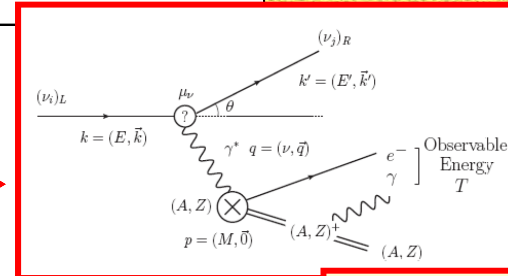

6 m (H) X 6 m (W) X 40 m (L)


6月20日土建工程建成并通过验收
Excavation Completed :
June 20, 2010

Neutrino Properties & Interactions at Reactor

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





New Channel Identified (PRL2010)

1 counts / kg-keV-day

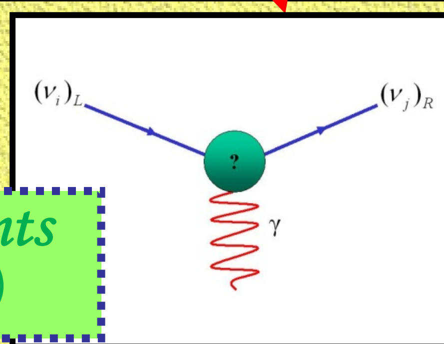
Threshold ~ 100 eV

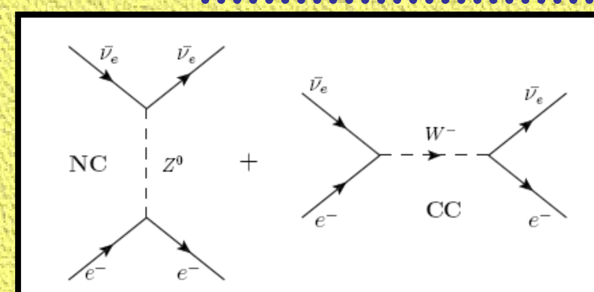
Standard Model νe Scattering (PRD10a,b)

νN Coherent Scattering

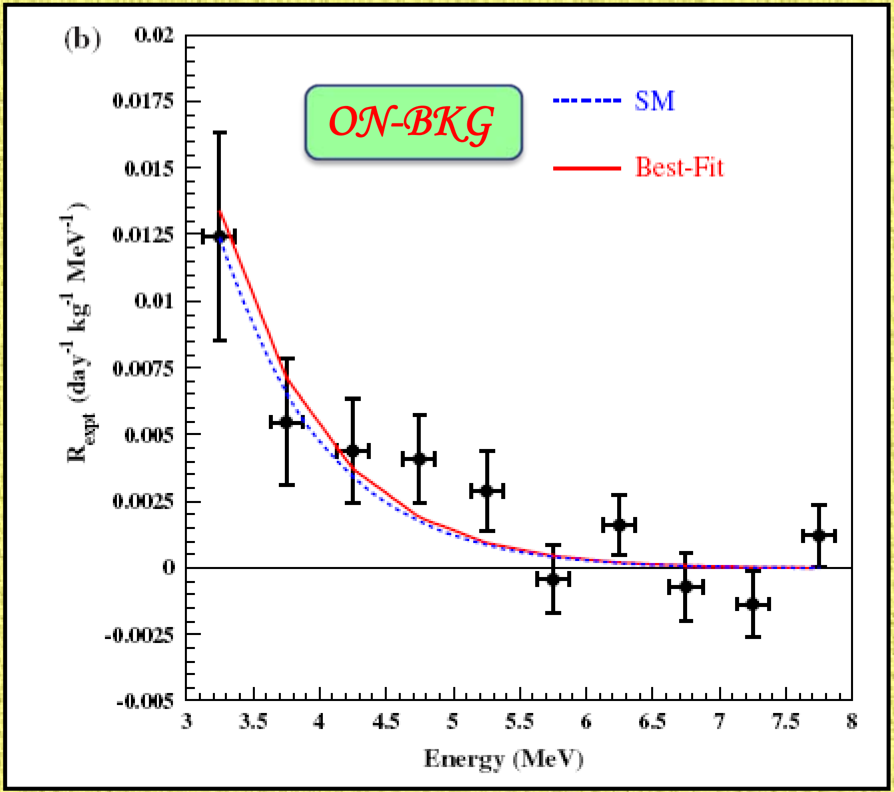
⇒ Dark Matter Searches (PRDRC09)

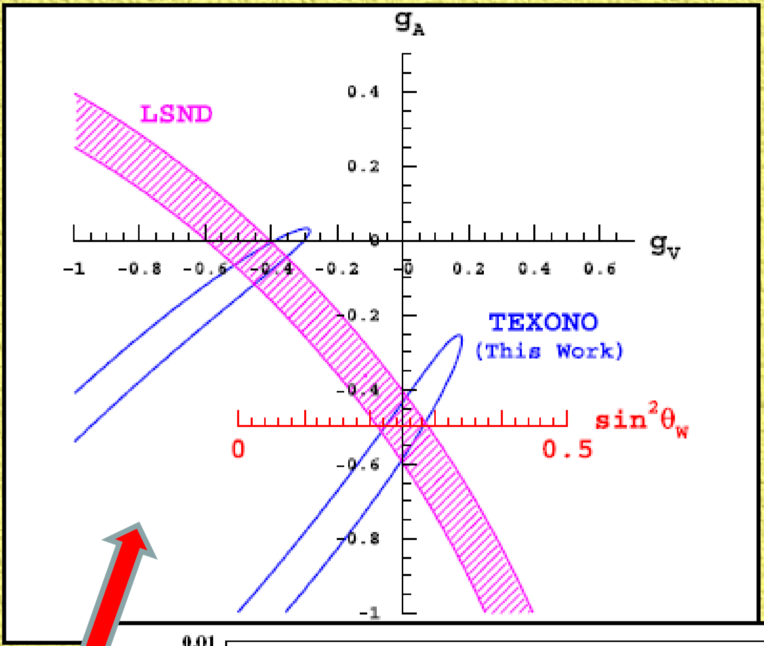
Magnetic Moments (PRL03,PRD07)

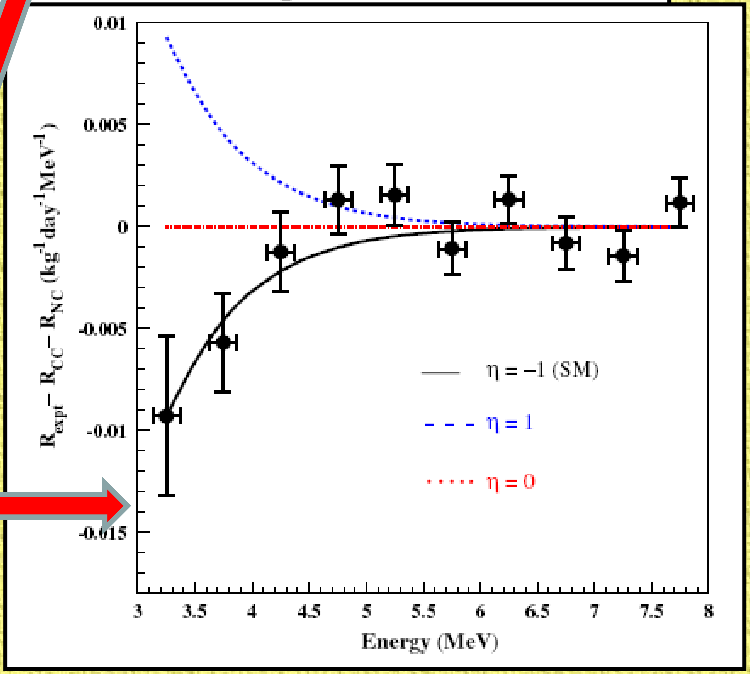




CsI(Tl) 200 kg : Probe Electroweak Phys. [PRD10]







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

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

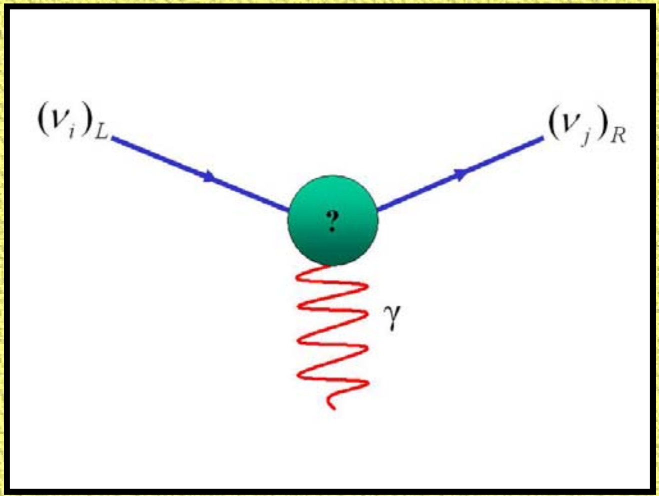
Verify SM Destructive Interference

⊕ **Constraints on Various Beyond SM Effects**

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 Electromagnetic Properties : Magnetic Moments



requires $\mathbf{m_\nu \neq 0}$

e.g.

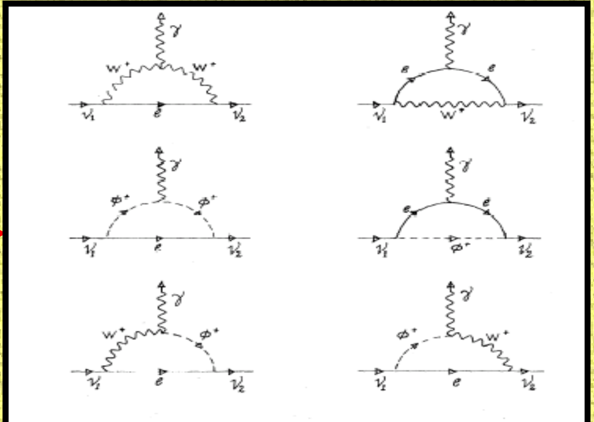


FIG. 1. Lowest-order diagrams for $\nu_1 \to \nu_2 + \gamma$ in the Dirac case, in the SU(2)×U(1) model with right-handed singlet neutrinos. ϕ is the standard Higgs doublet and e stands for a generic charged-lepton field.

- **fundamental neutrino properties & interaction ; necessary consequences of neutrino masses/ mixings**
- **in principle can differentiate *Dirac/Majorana neutrinos***
  - **If Signals observed > $10^{-14}\ \mu_B$**

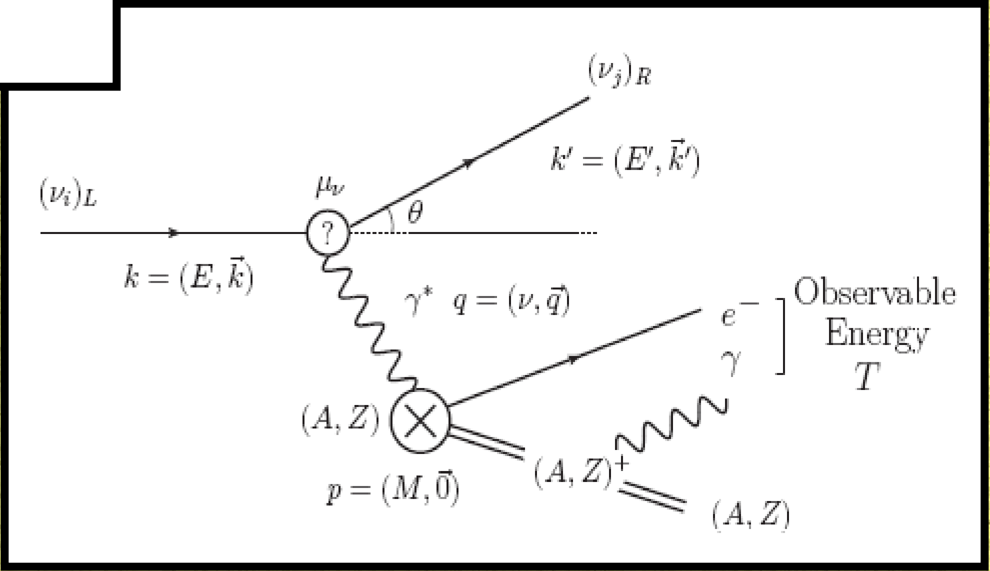
    ⇒ Majorana Neutrinos ***[Naturalness Argument]***
- **explore roles of neutrinos in astrophysics**
  - **Astro. & particle phys. model dependent bounds**

    $\mu_\nu < 10^{-10} - 10^{-12}\ \mu_B$

New Channel : μ_ν-induced Atomic Ionization [PRL10]

- Significant Enhancement of cross-section at $Q^2 \rightarrow 0$
- Neutrino energy loss (observable energy) ~ atomic binding energy
- resembles relativistic charged particles being "minimum ionizing" with matter.

$$\nu + (A,Z) \rightarrow \nu + (A,Z)^+ + e^-$$
$$(A,Z)^+ \rightarrow (A,Z) + \gamma\,'s \quad .$$



μ_ν-induced Atomic Ionization

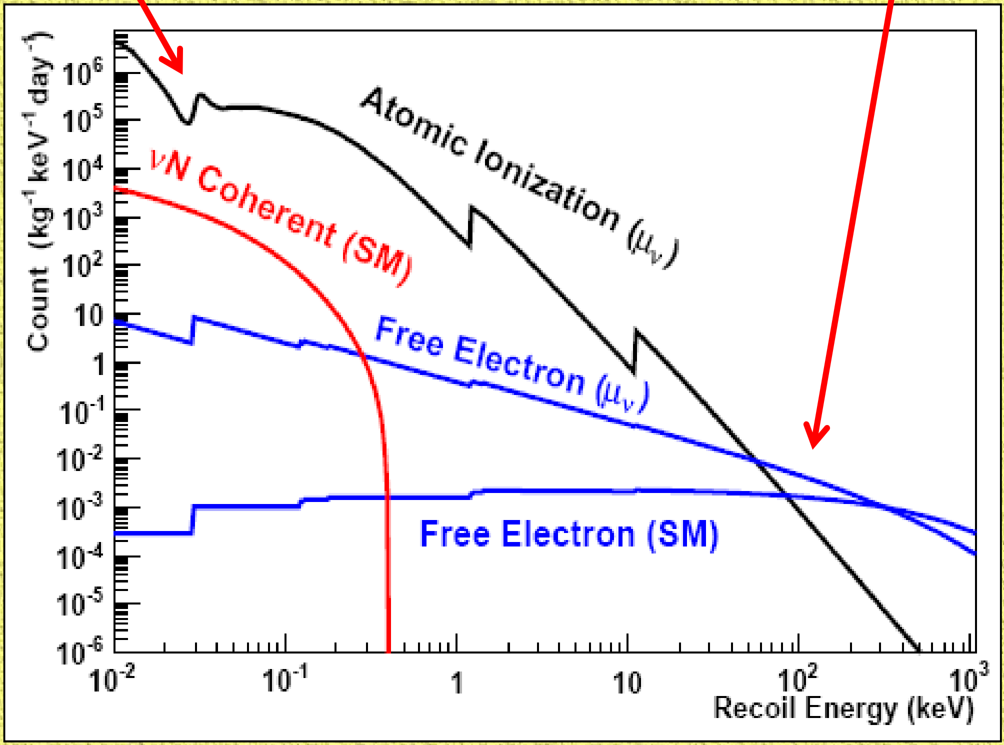
- Significant Enhancement at atomic energies when Neutrino Energy Loss < 10 keV
- Can have "applications" if Nature prefers μ_ν close to present limits

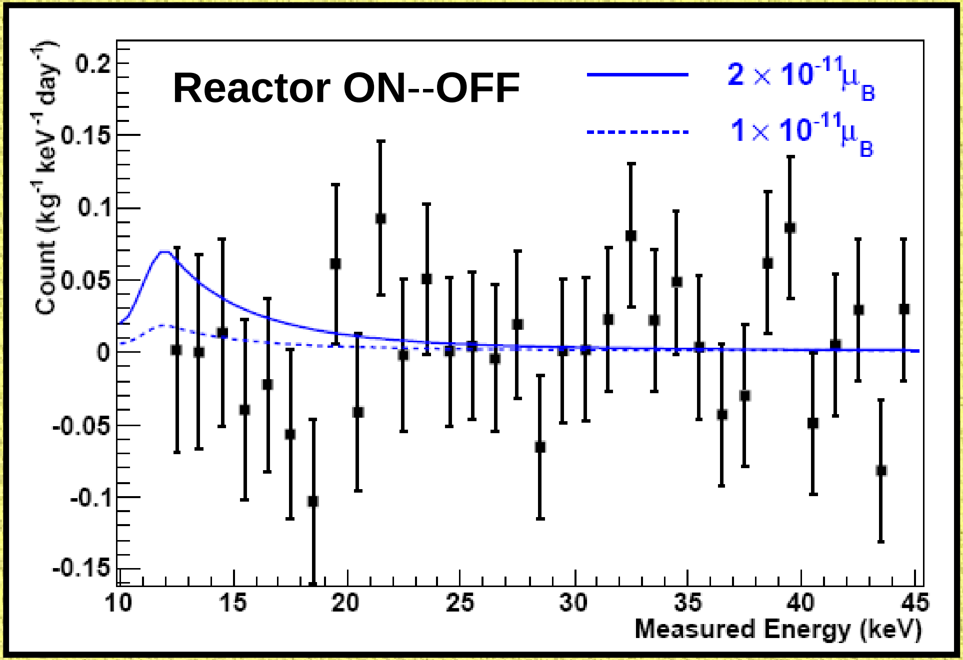
$$\left(\frac{d\sigma}{dT}\right)^{AI} \simeq \mu_\nu^2 \, \frac{\alpha_{em}}{\pi} \, \left(\frac{E_\nu}{m_e}\right)^2 \, \frac{1}{T} \, \underline{\sigma_{\gamma A}(E_\gamma = T)}$$

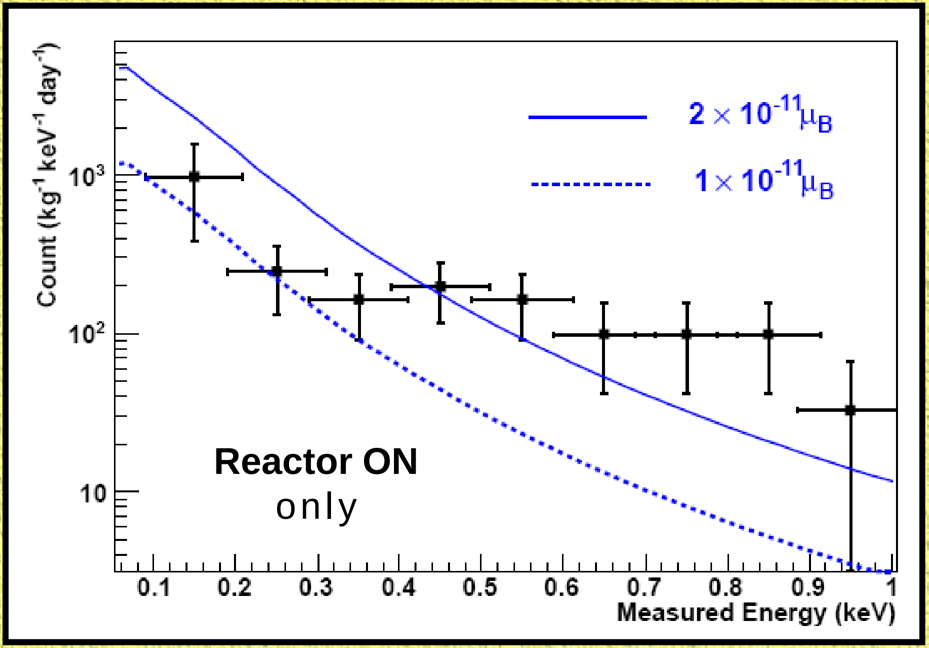
$$\left(\frac{d\sigma}{dT}\right)^{FE} = \frac{\pi \alpha_{em}^2 \mu_\nu{}^2}{m_e^2}\left[\frac{1 - T/E_\nu}{T}\right]$$

Equivalent Photon Approximations:

- Related Interactions of Virtual Photons at $q^2 \rightarrow 0$ to photo-electric cross section of real photons.







PRD07: 1-kg HPGe

$\mu_\nu < 1.9 \times 10^{-11}\ \mu_B$

PRDRC09: 20-g ULEGe

$\mu_\nu < 1.3 \times 10^{-11}\ \mu_B$

Projected Sensitivities : → $10^{-13}\ \mu_B$

@ Thr.~100 eV ; BKG~1 cpkkd ; ON-OFF 1%

Neutrino-Nucleus Coherent Scattering :

[basics covered in earlier talk (Reyna)]

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

Standard Model Cross-Sections:

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

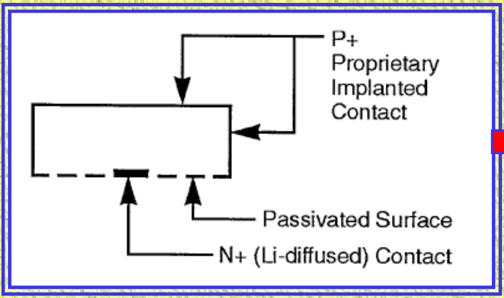
$$\sigma_{tot} = \frac{G_F^2 E_\nu^2}{4\pi} [Z(1 - 4\sin^2\theta_W) - N]^2$$

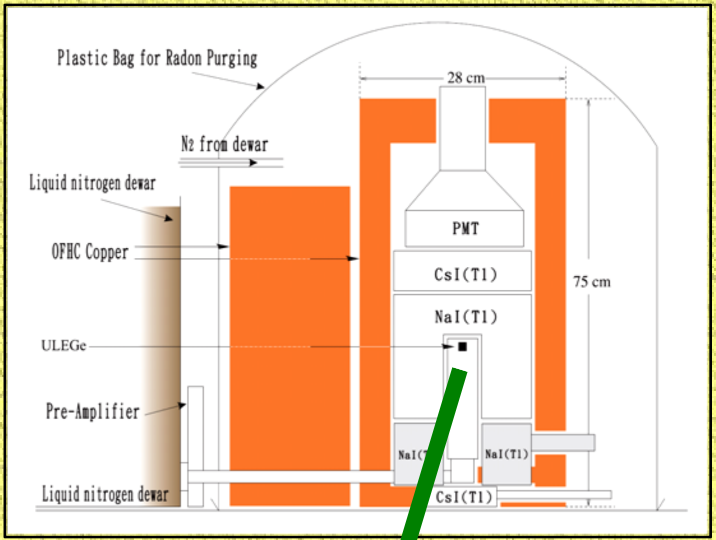
- **Typical Rates for Ge at KSNL :**

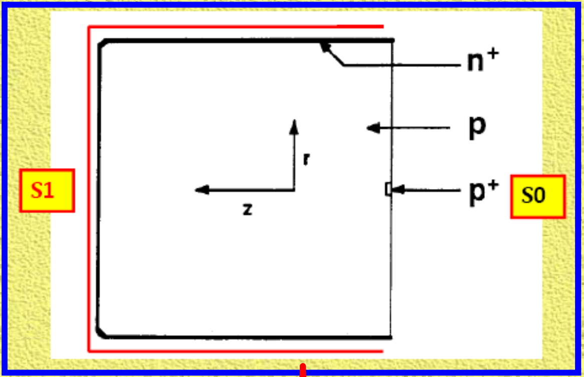
  ~10 kg^{-1} day^{-1} @ threshold~100 eV & QF~0.2

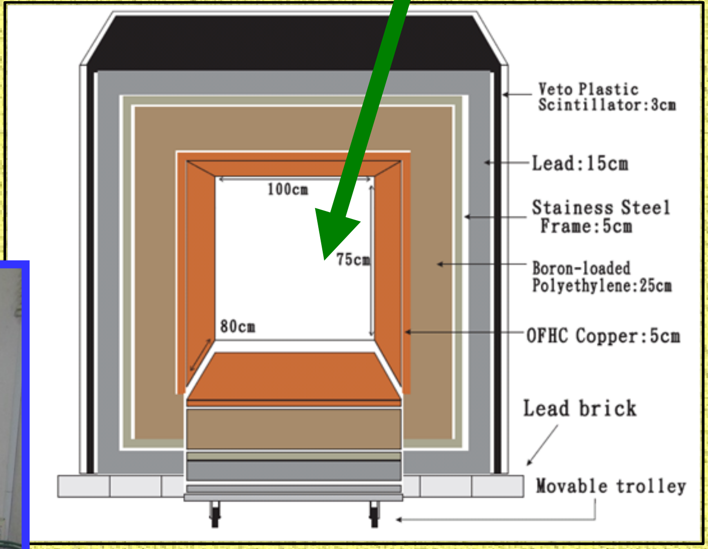
- **Bottom Line :**
  - O(1 kg) modular mass achieved with Point Contact Germanium Detector *[Luke 80's, CoGeNT-2007]*
  - few X 100 eV threshold, more hardware & software R&D to get to ~100 eV
  - Need understanding ⇒ suppression of sub-keV background *[some interest that those are WIMP-induced !!]*

TEXONO-CDEX : ULEGe & PCGe @ KSNL & CJPL

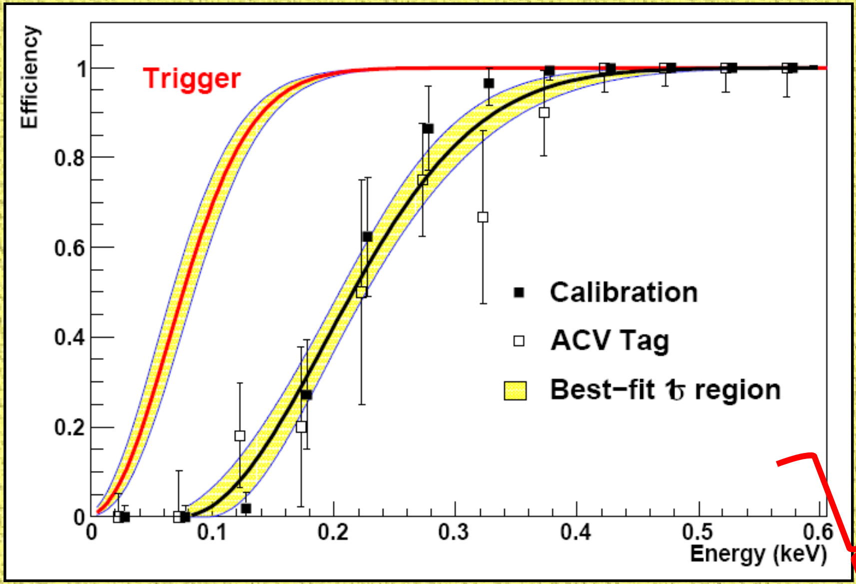


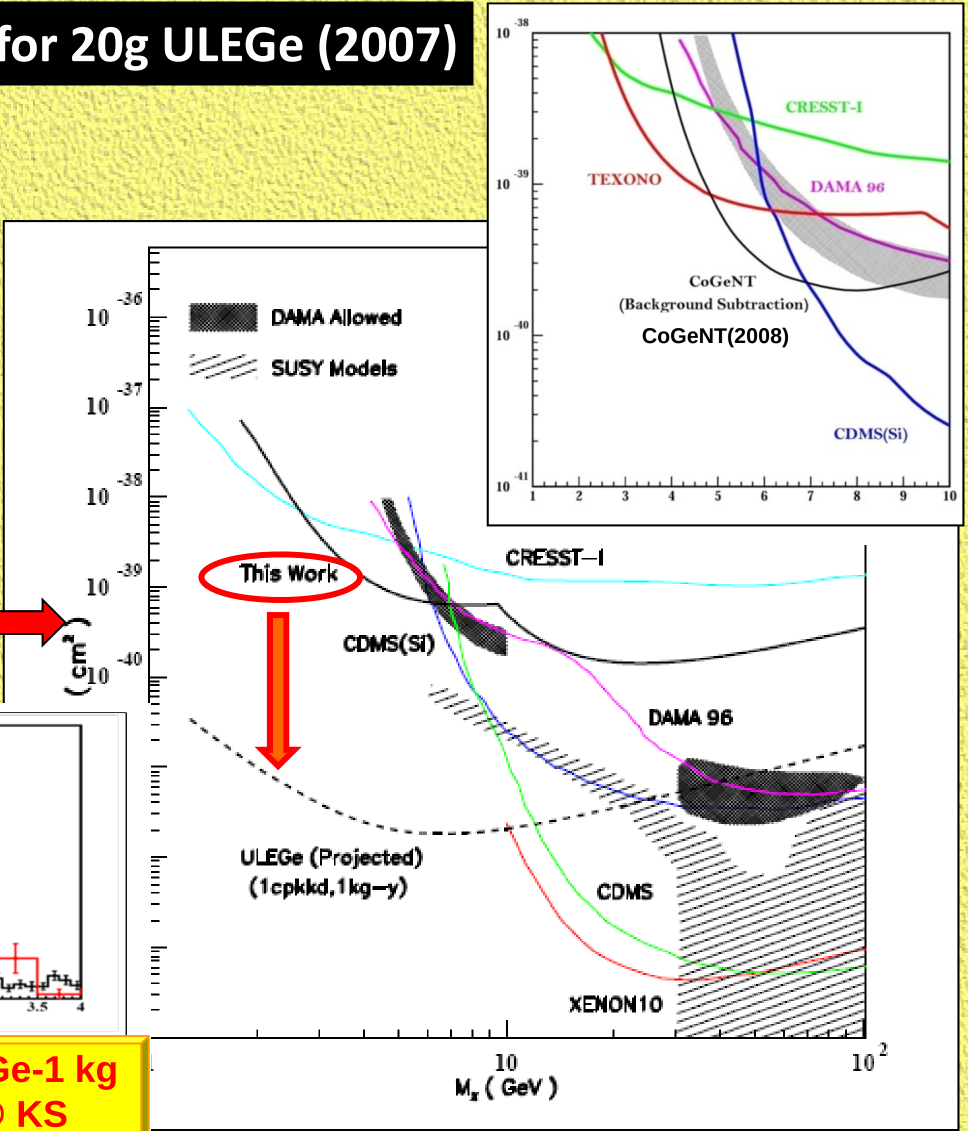


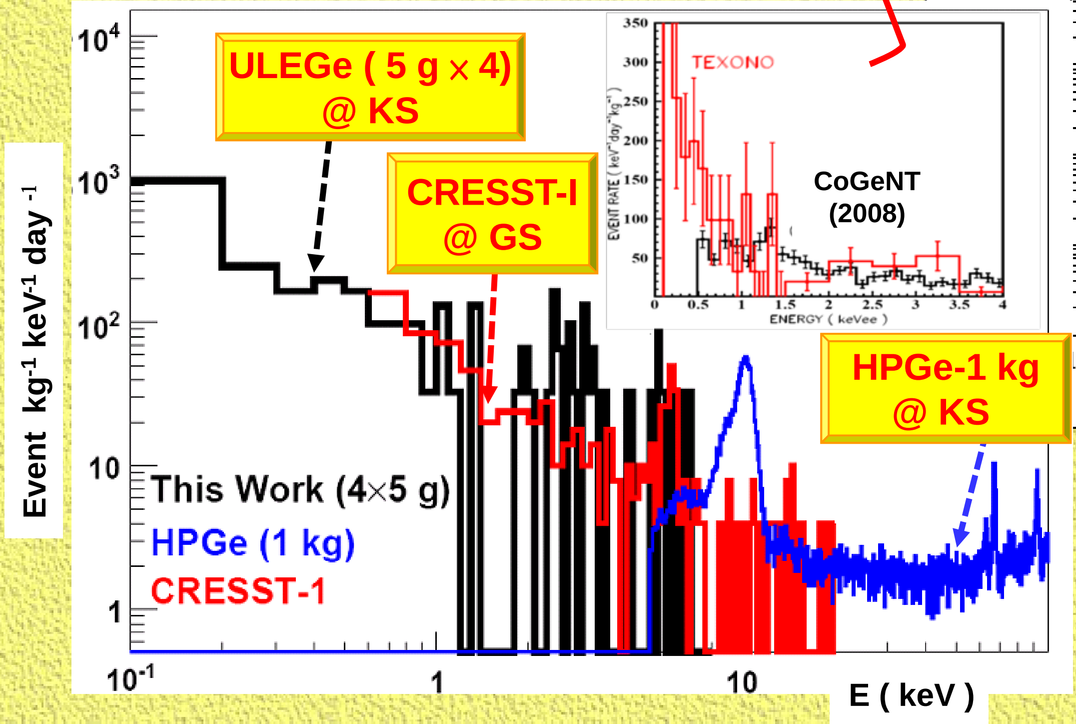




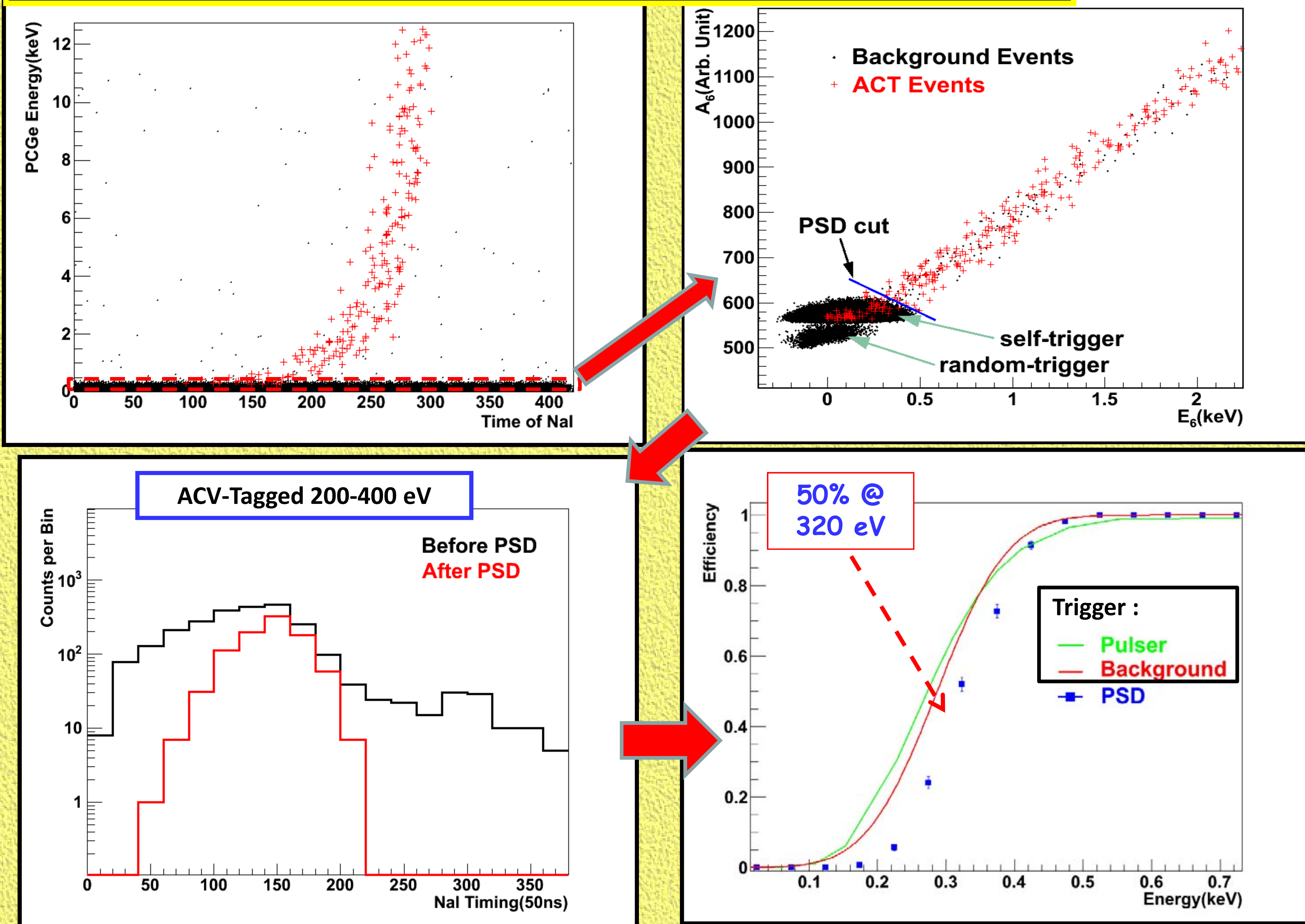
Threshold & Efficiencies & Background for 20g ULEGe (2007)







500g PCGe – Threshold & Selection Efficiency

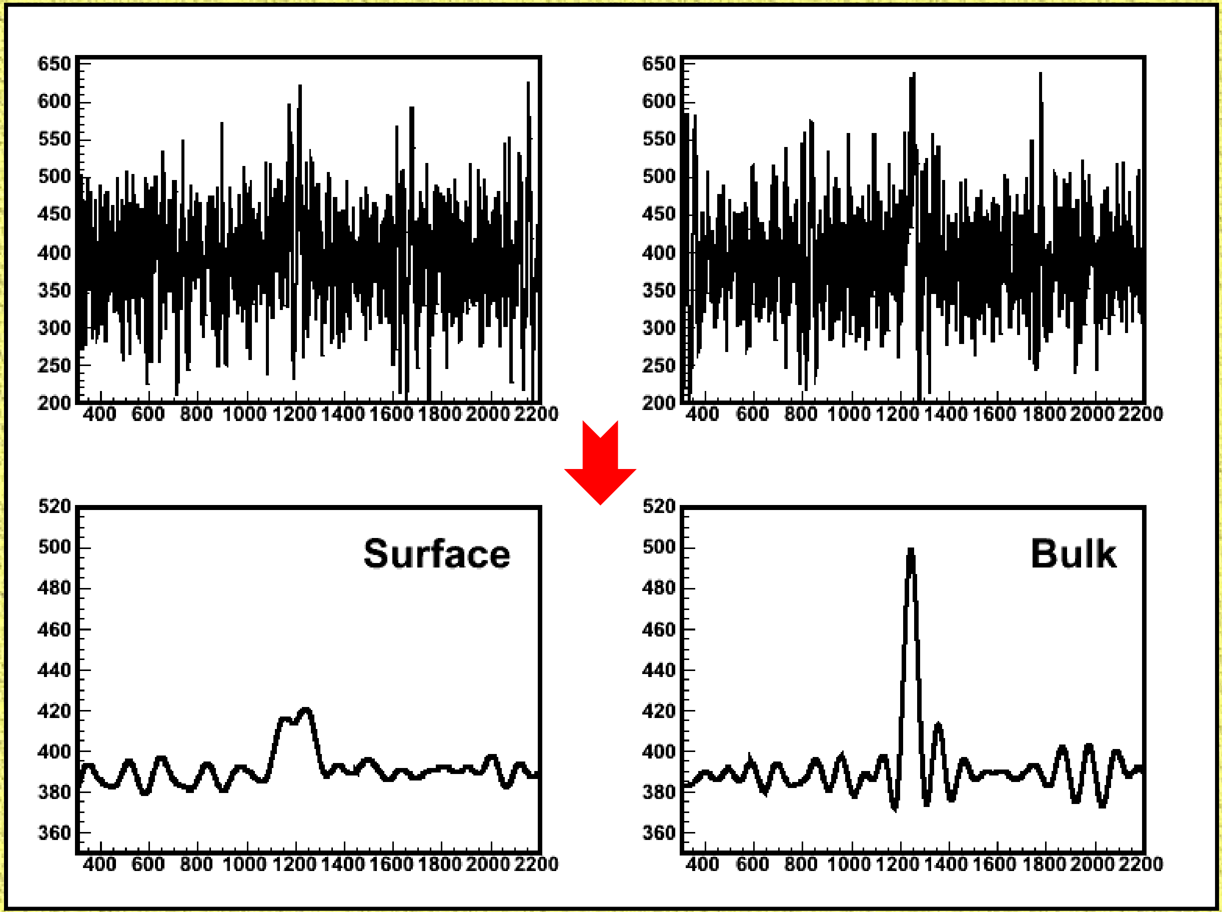


PSD for Surface Vs Bulk Events @ PCGe

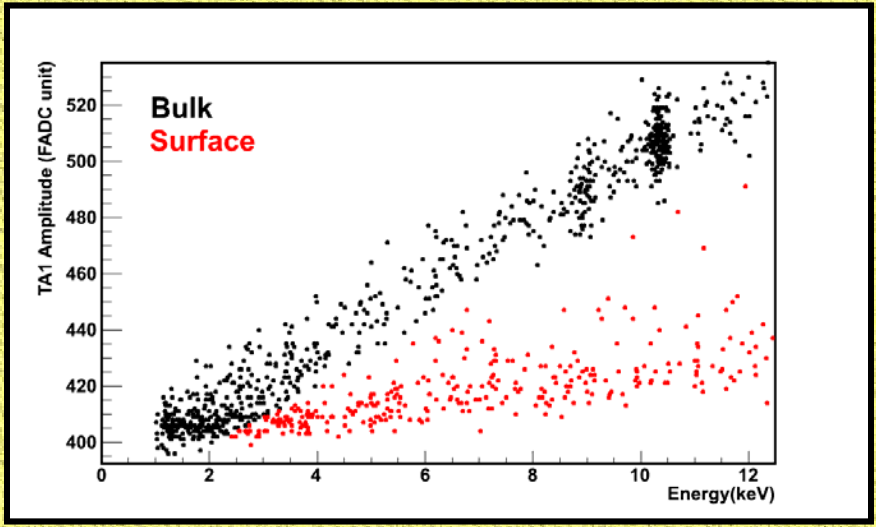
- Timing Amp (fast) pulse shapes at 200 MHz FADC
- Surface Vs Bulk events down to 2 keV
- n+ "inactive layer" is not totally dead; signals finite
- ACV+CRT events (neutron rich) samples do not show surface band

Raw Data

Smoothed Shape

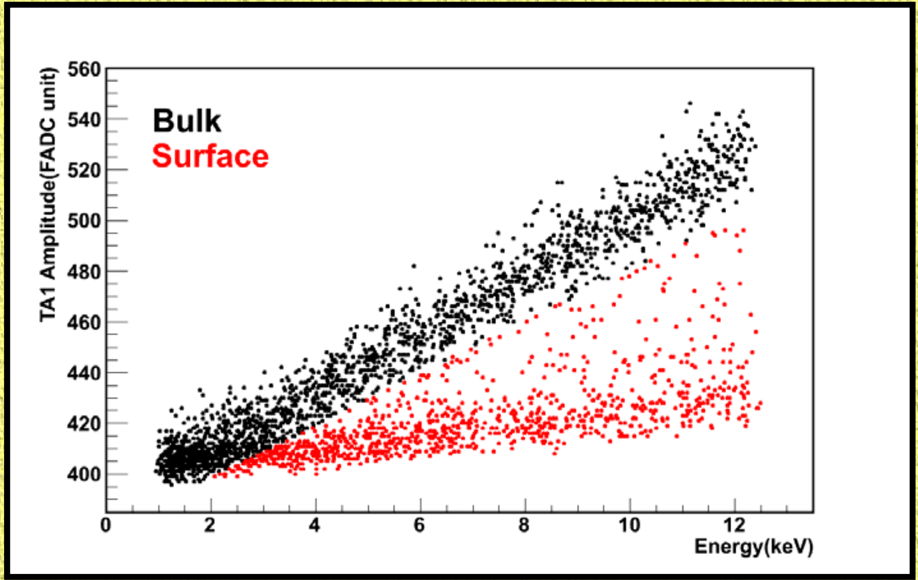


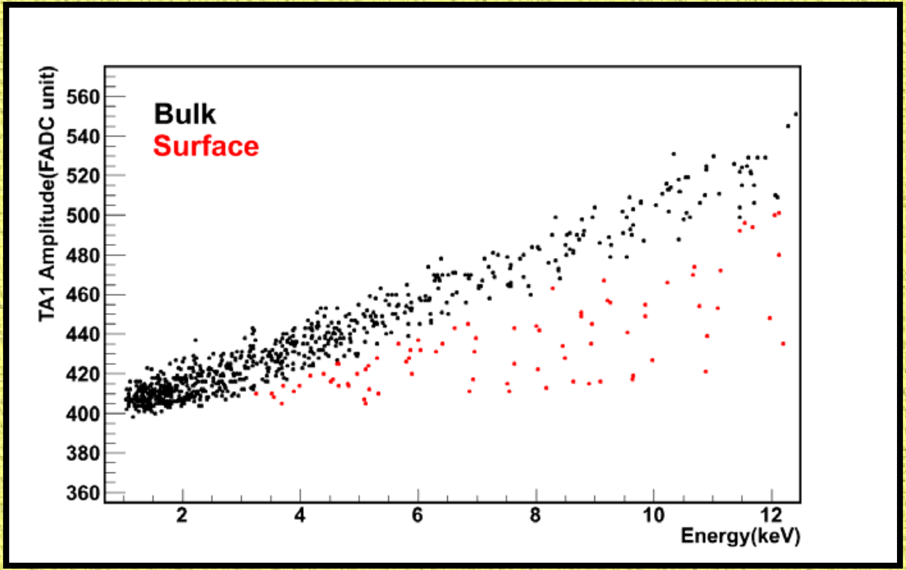
Signal Candidates:
[CRV+ACV] cosmic & anti-Compton veto



γ-rich background: [CRV+ACT] cosmic veto & anti-Compton trigger

n-rich background:
[CRT+ACV] cosmic trigger & anti-Compton veto





Summary & Outlook

- There exist Interesting Physics & Valid Applications *with* Reactor Neutrinos
- Involve exploring new DetectorTechniques & Detection Channels
- Sub-keV Ge detectors are Promising Avenue

New Windows Opened : "Available for Surprises ! "

Our Story ("Applications" of Reactor Neutrinos) : bring us to new detection windows, detector techniques, interaction mechanisms, subjects & laboratory !!