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

- Overview (Collaboration; Laboratory; Program)
- Neutrino Physics Program : Highlights
- R&D on sub-keV Ge Detectors
- Status & Plans

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March 2011 @

臺灣微中子實驗 TEXONO Taiwan EXperiment On NeutrinO 國聖

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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

Poineering Efforts : *"Zero-Background Experiment" !*

- **KS Expt: 1st large-scale particle physics experiment in Taiwan**
- **TEXONO Coll. : 1st big research Coll. % Taiwan & China**

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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

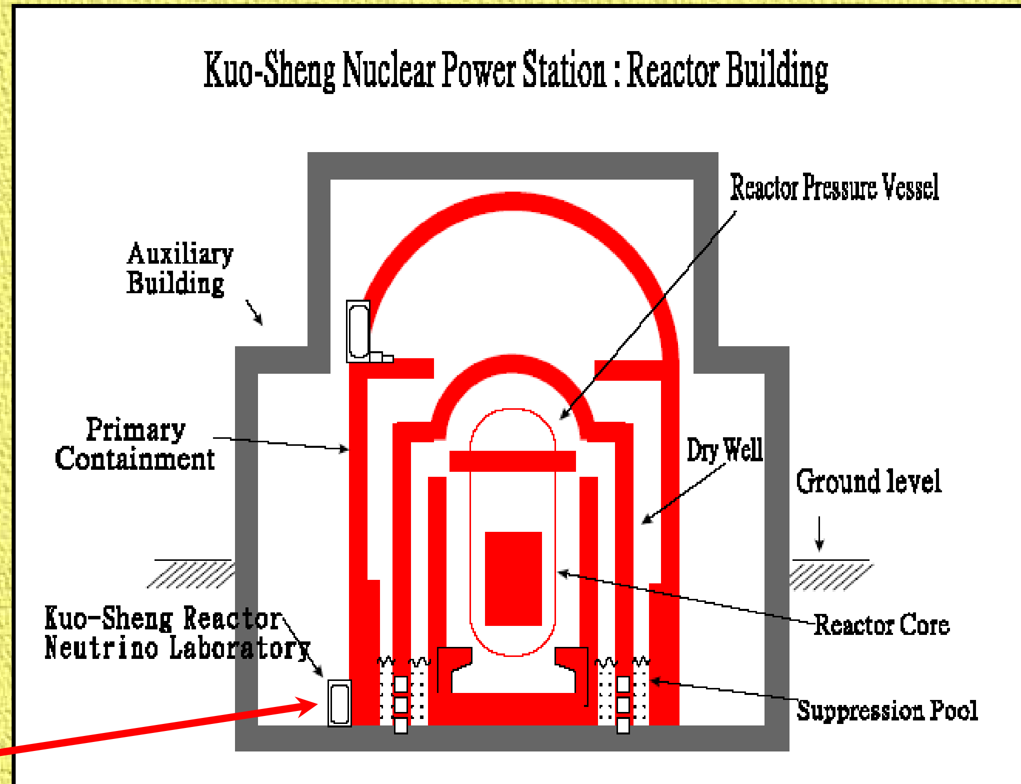
TOKYO—A hot campaign issue in Taiwan's presidential election in March 1996 was whether the island should drop its long-held objective of reuniting with the mainland and formally declare its independence. As a

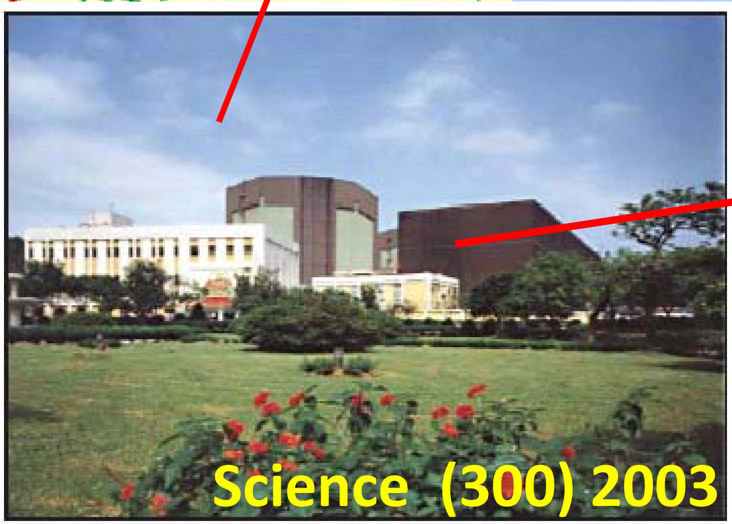
the mainland but is now a U.S. citizen. It was his idea to get Taiwanese scientists together with researchers at the Chinese Academy of Sciences' Institute of High Energy Physics (IHEP). That month, the two

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

- Need neutrino source to do neutrino physics : reactor is a high-flux, understood and controlled source $\Rightarrow$ *AND* free as well !!
- oscillation expts. $\Rightarrow$ $m_\nu \neq 0$ $\Rightarrow$ 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

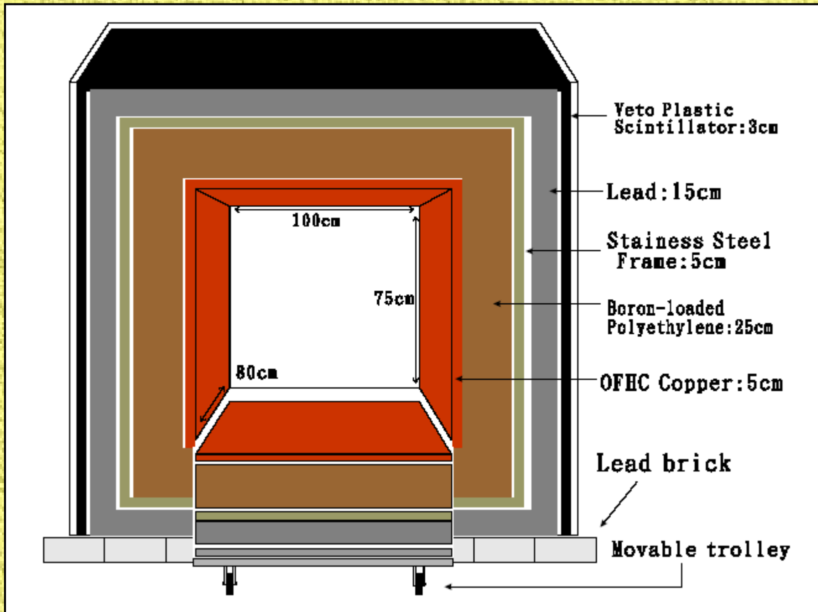
Kuo Sheng Reactor Neutrino Laboratory :





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**

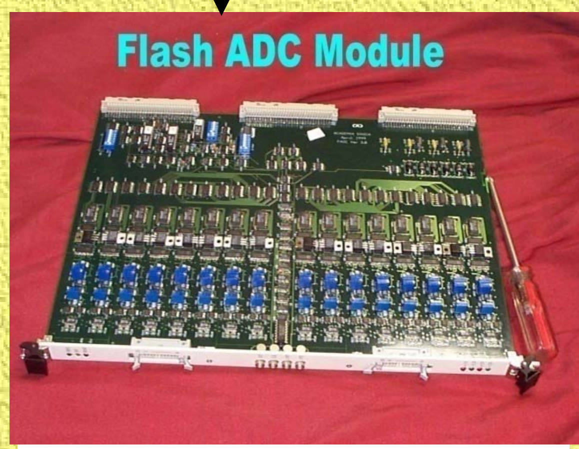
Flexible Design: **Allows different detectors conf. for different physics**

KS Laboratory : Detectors

ULB-HPGe [1 kg]

CsI(Tl) [200 kg]

ULE-ULB-HPGe
Prototype [20 g]



FADC Readout
[16 ch., 20 MHz, 8 bit]

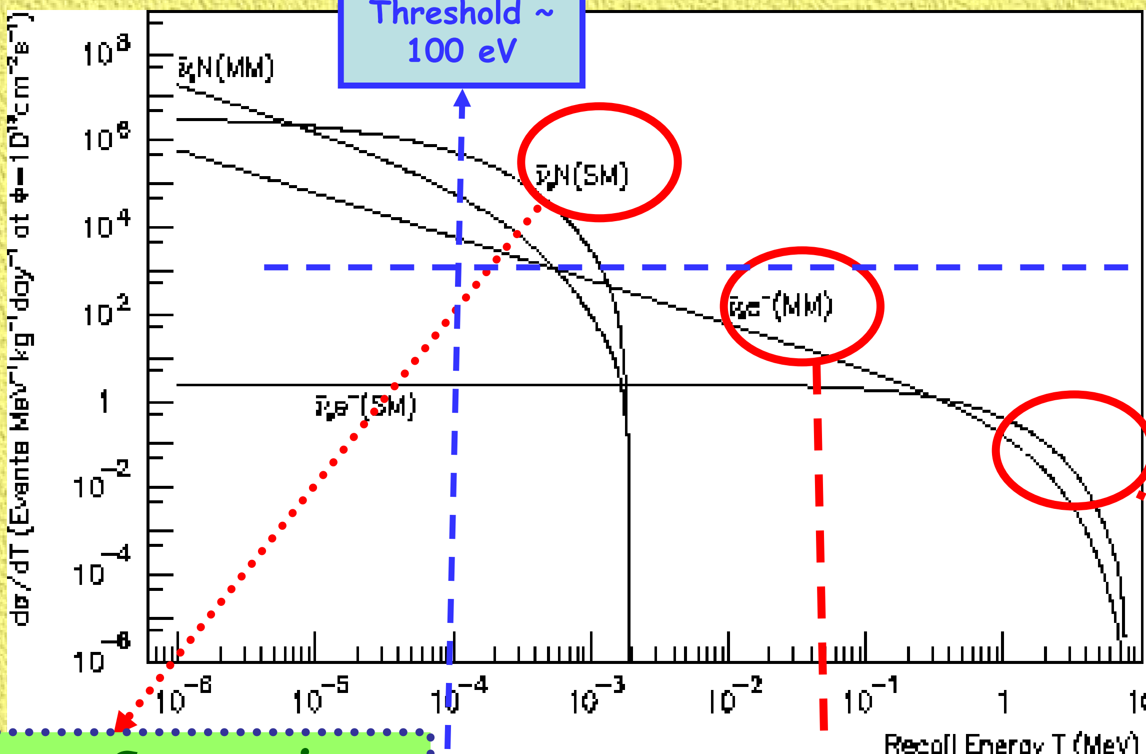
Multi-Disks Array [600 Gb]

Neutrino Properties & Interactions at Reactor

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

Threshold ~ 100 eV

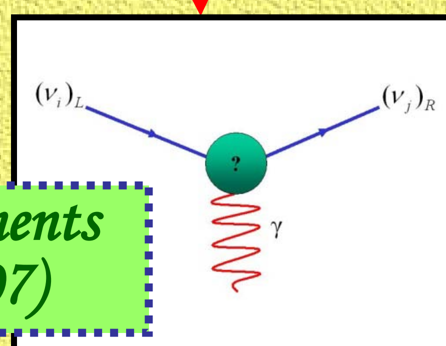
1 counts / kg-keV-day



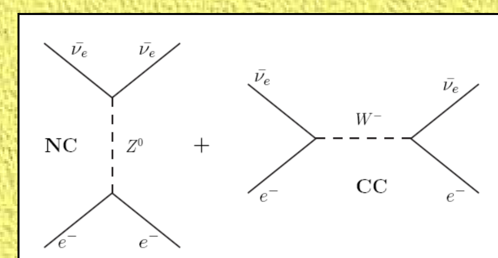
Standard Model
νe Scattering
(2⊗ PRD10)

νN Coherent Scattering

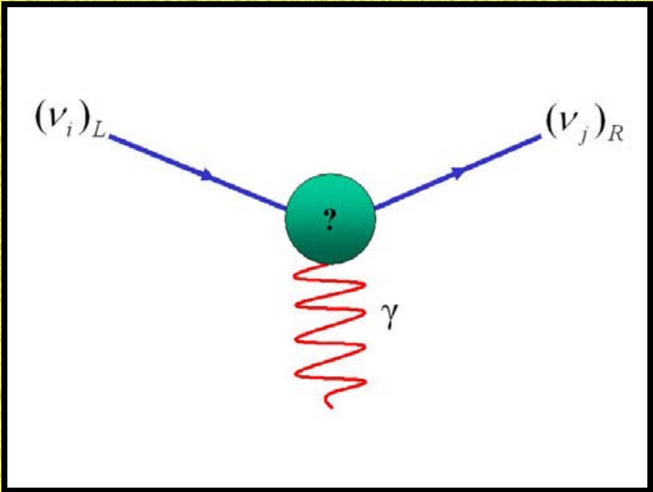
Dark Matter Searches (PRD-RC09)



Magnetic Moments (PRL03,PRD07)



Neutrino Electromagnetic Properties : Magnetic Moments



requires $m_\nu \neq 0$

e.g.

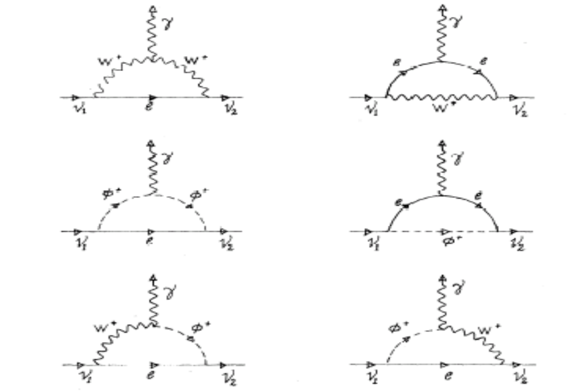


FIG. 1. Lowest-order diagrams for $\nu_1 \to \nu_2 + \gamma$ in the Dirac case, in the $SU(2) \times U(1)$ model with right-handed singlet neutrinos. ϕ is the standard Higgs doublet and e stands for a generic charged-lepton field.

- a ***conceptually*** **rich subject ; much neutrino physics & astrophysics can be explored**

ν-osc. : Δm_ν , U_{ij}

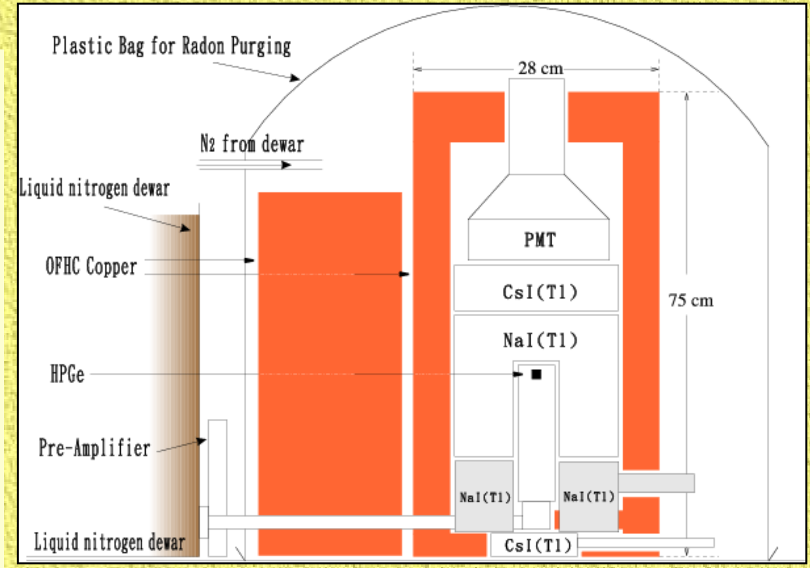
$0\nu\beta\beta$: m_ν , U_{ij} , ν_D/ν_M

μ_ν : m_ν , U_{ij} , ν_D/ν_M , $\nu \otimes \gamma$

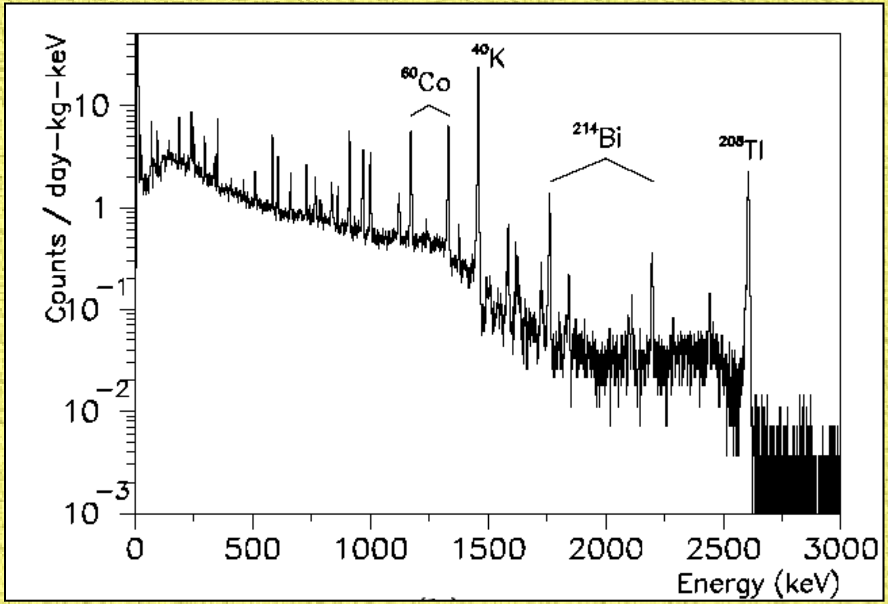
- **fundamental neutrino properties & interaction ; necessary consequences of neutrino masses/ mixings ; in principle can differentiate *Dirac/Majorana neutrinos***
- **explore roles of neutrinos in astrophysics**

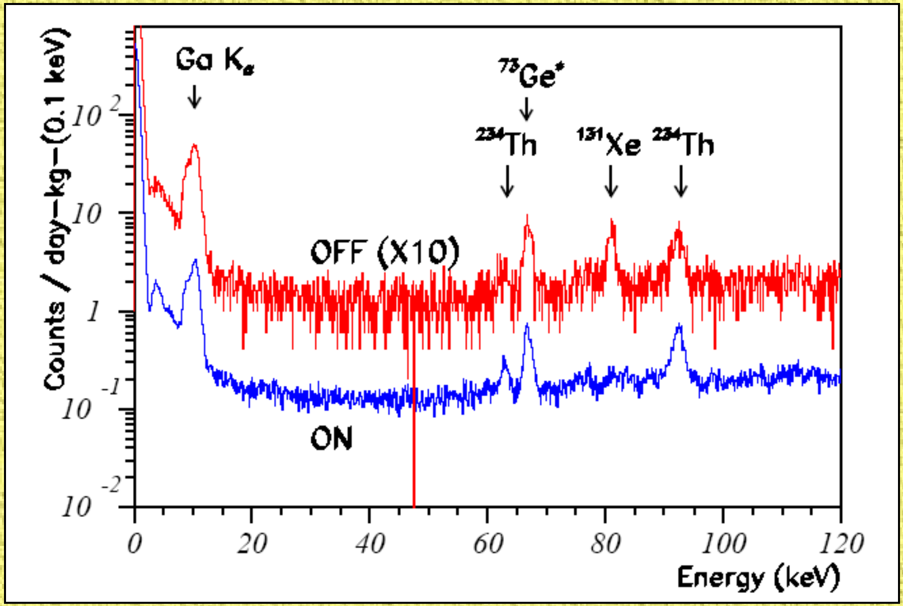
Magnetic Moment Searches @ KS

- 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 $\text{day}^{-1}\text{keV}^{-1}\text{kg}^{-1}$ (cpd)
  - DAQ threshold 5 keV analysis threshold 12 keV

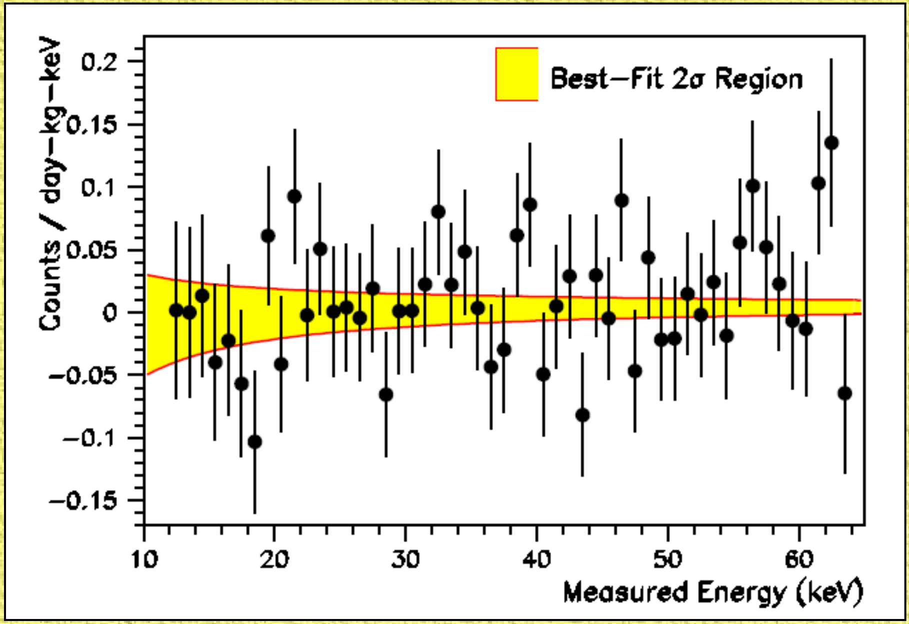


After-Cut Spectra ....





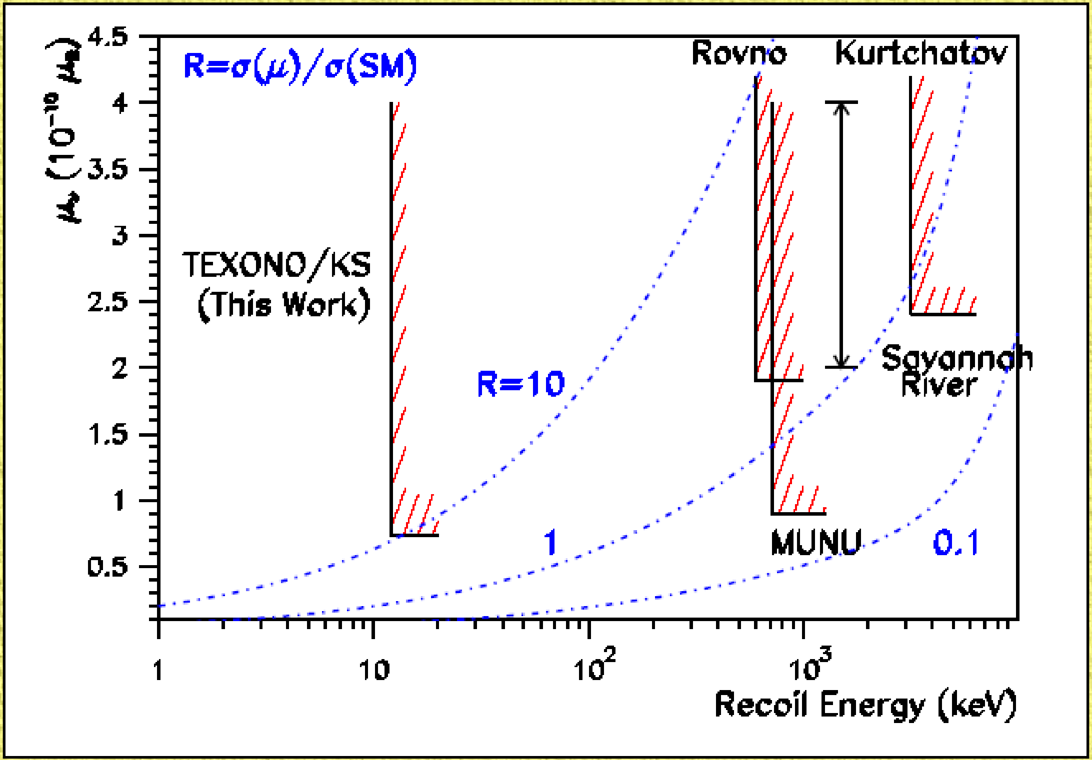
ON/OFF Residual Plot :



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

Direct Experiments at Reactors

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



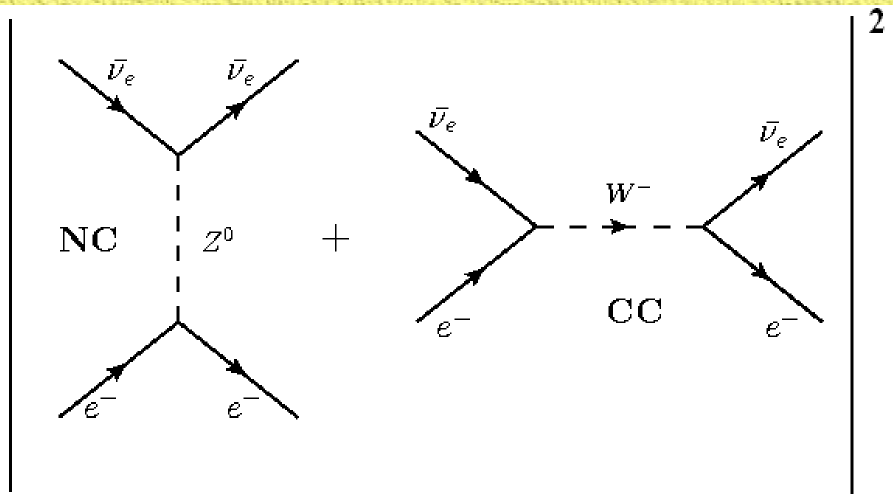
Search of μ_ν at low energy

⇒ **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]

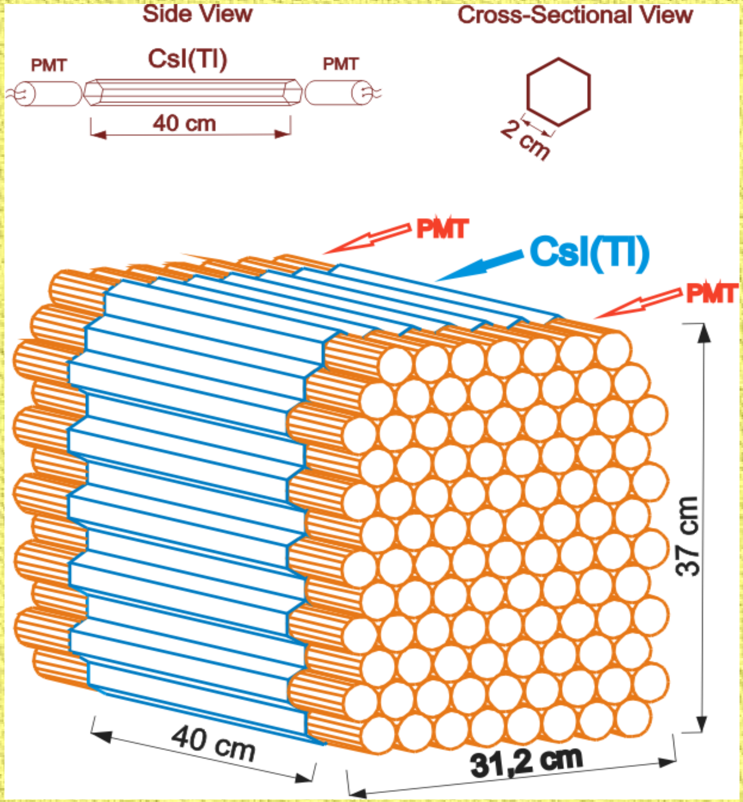
Neutrino-Electron Scattering Cross-Section

$\bar{\nu}_e + e^- \longrightarrow \bar{\nu}_e + e^-$

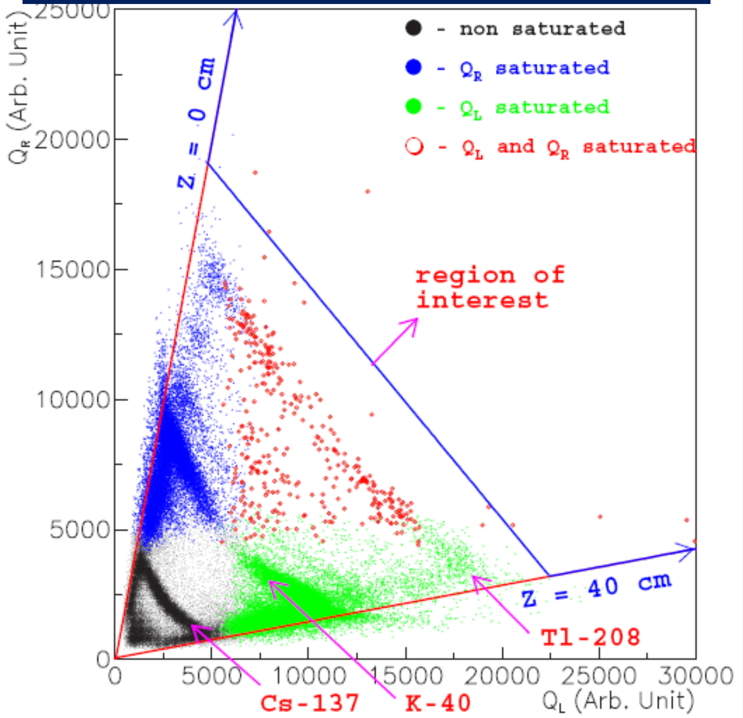


Uniqueness :

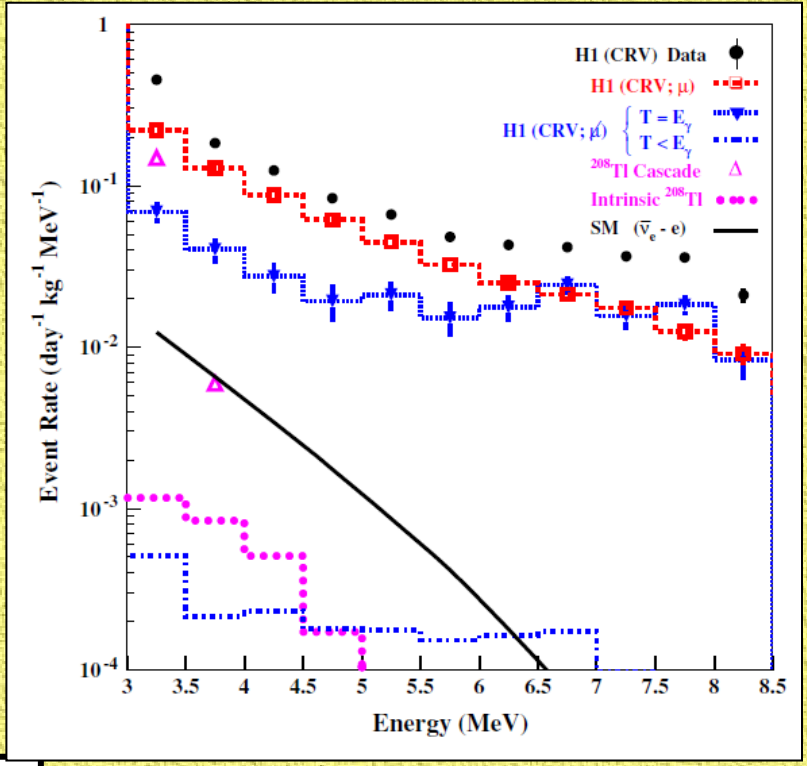
- **Electroweak physics at q~MeV**
- **ν_e-e system includes NC, CC & Interference term**



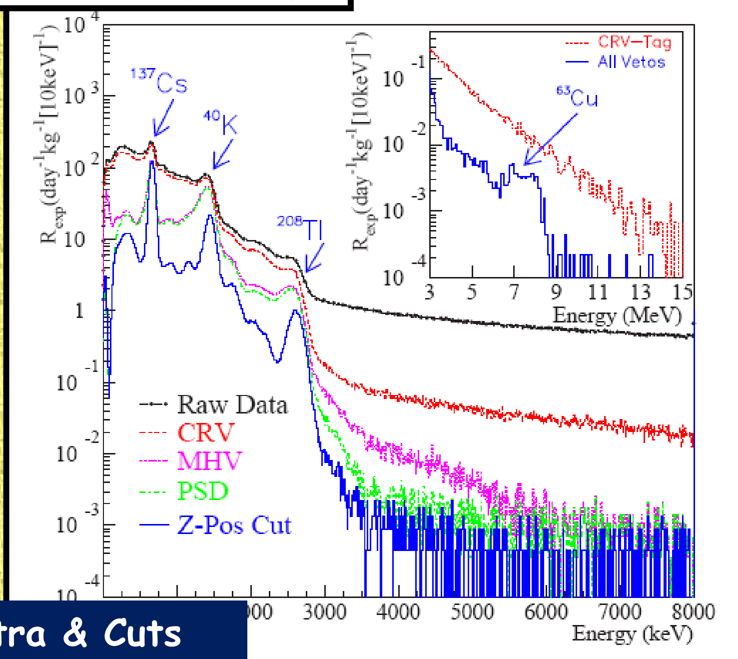
RAW DATA – PMT Left & Right



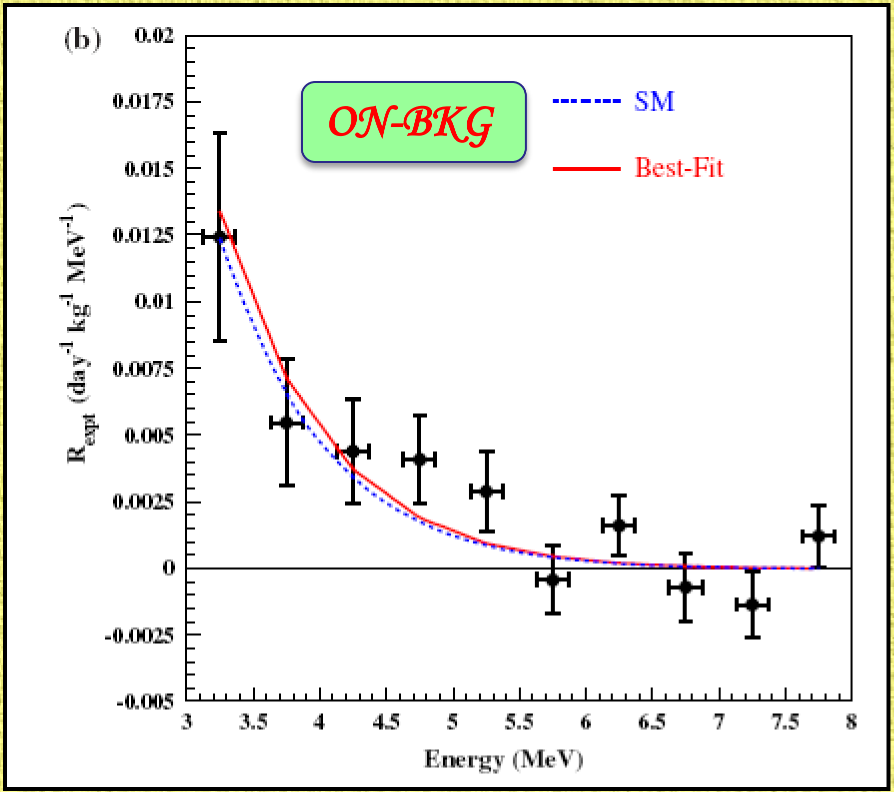
Final Spectra & Physics Channels

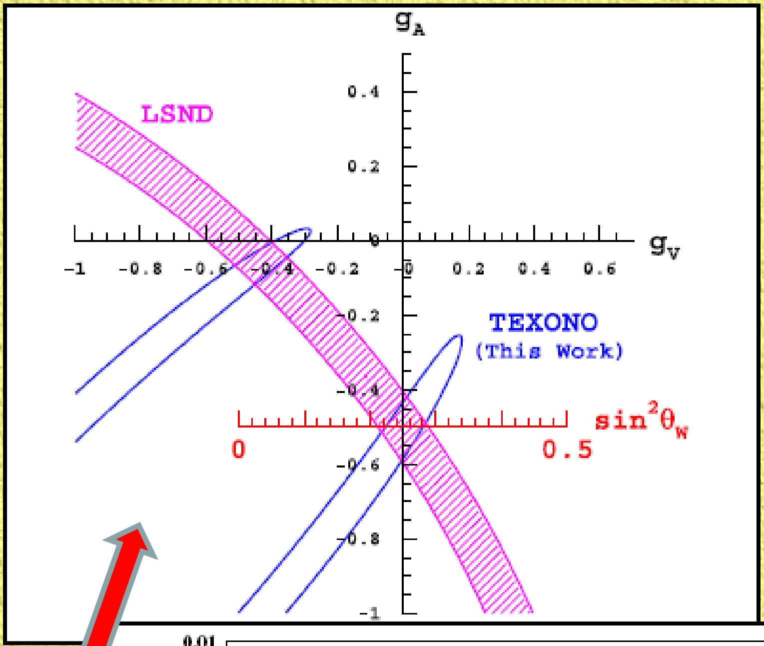


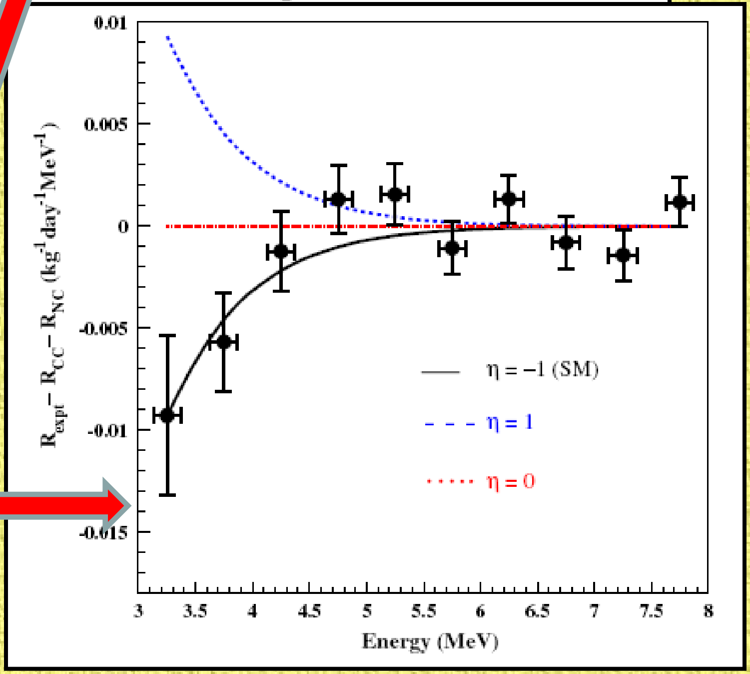
Energy Spectra & Cuts



CsI(Tl) 200 kg : Probe Electroweak Phys. [2 X PRD10]







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

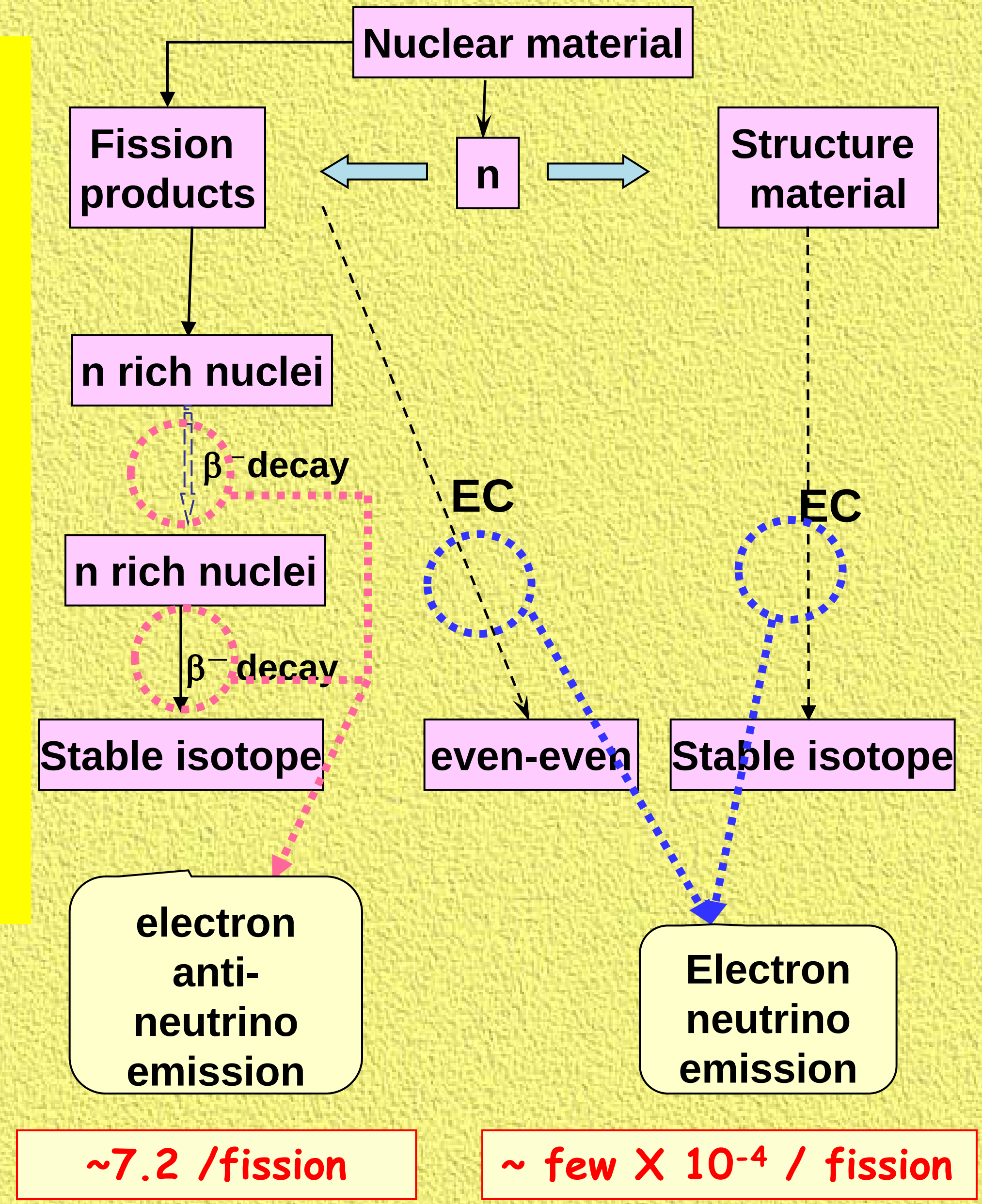
$$\sin^2 \theta_W = 0.251 \pm 0.031(stat) \pm 0.024(sys)$$

Verify SM Destructive Interference

⊕ Constraints on Various Beyond SM Effects

Electron Neutrinos @ Reactor (PRD 72, 2005)

- Evaluate ν_e flux at standard reactors
- Derive limits on μ_ν and Γ_ν for ν_e
- Explore ν_e flux enhancement in loaded reactor *(e.g. with Cr)*
- Study Potential applications :
  - ν_eNCC cross-section measurements,
  - θ_{13}
  - Pu-production monitoring



Exploration of possible Axion Emission at Reactor

Production:

Detection:

PRD 75 (2007)

TABLE I: A summary of magnetic transitions and their estimated fluxes at a typical 3 GW power reactor.

Channel	E_γ (keV)	Transitions	Φ_γ (fission^{-1})	Φ_γ (GCi)
^{10}B(n,α)^{7}Li*	478	M1 $(\frac{1}{2}^-) \to (\frac{3}{2}^-)$	0.28	0.68
p(n,γ)d	2230	Isovector M1	0.25	0.61
^{91}Y*	555	M4 $(\frac{9}{2}^+) \to (\frac{1}{2}^-)$	0.024	0.058
^{97}Nb*	743	M4 $(\frac{1}{2}^-) \to (\frac{9}{2}^+)$	0.055	0.13
^{135}Xe*	526	M4 $(\frac{11}{2}^-) \to (\frac{3}{2}^+)$	0.0097	0.023
^{137}Ba*	662	M4 $(\frac{11}{2}^-) \to (\frac{3}{2}^+)$	0.0042	0.010

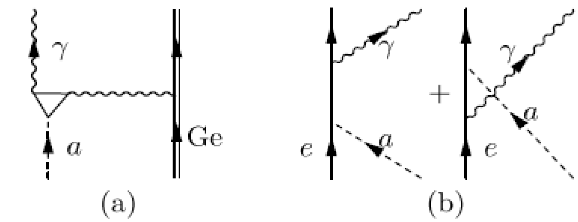
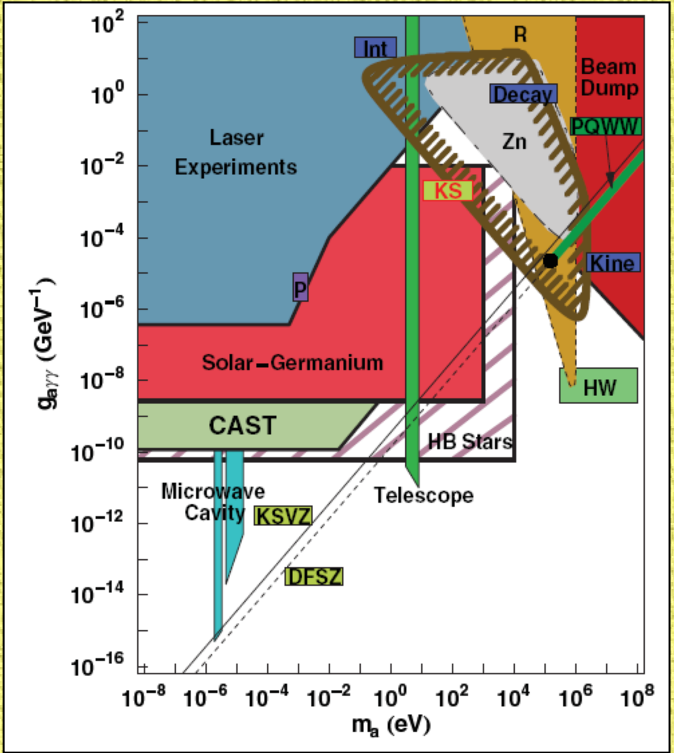
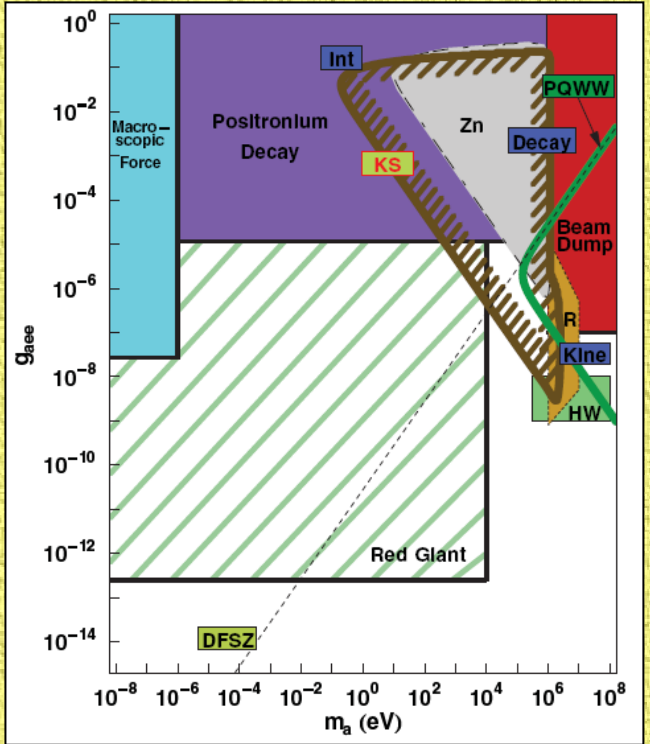


FIG. 1: Schematic diagrams of interactions of axions with matter, via (a) Primakoff and (b) Compton conversions.

- Improved laboratory limits on g_{aee} for $Br_a > 10^{-9}$
- Exclude DFSZ/KSVZ Models for axion mass 10^4-10^6 eV





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 :

$$\boxed{\nu + \mathrm{N} \rightarrow \nu + \mathrm{N}}$$

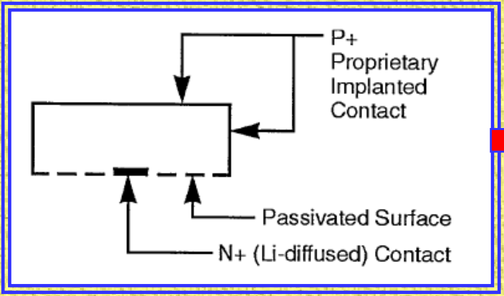
Standard Model Cross-Sections:

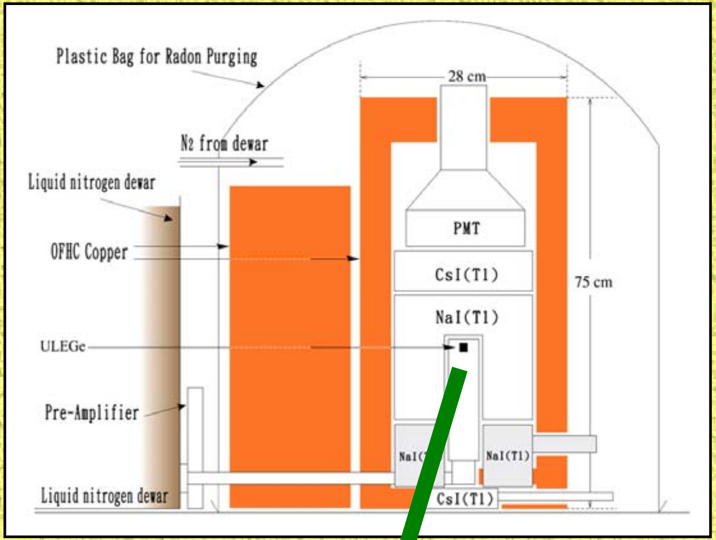
$$\left(\frac{d\sigma}{dT}\right)^{coh}_{SM} = \frac{G_F^2}{4\pi} m_N [Z(1-4\sin^2\theta_W) - N]^2 [1 - \frac{m_N T_N}{2E_\nu^2}]$$

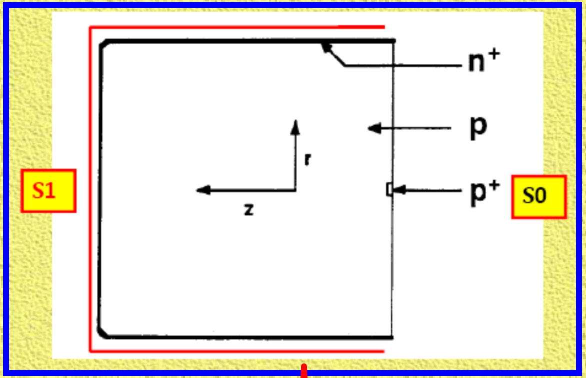
$$\sigma_{tot} = \frac{G_F^2 E_\nu^2}{4\pi} [Z(1-4\sin^2\theta_W) - N]^2$$

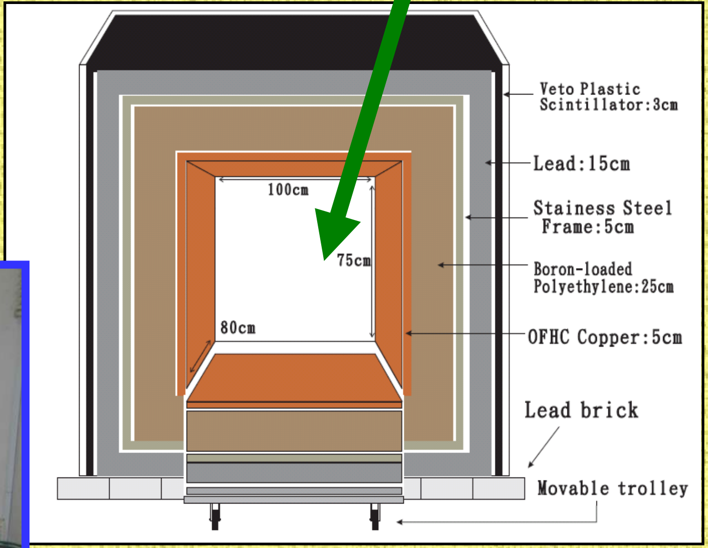
- a *fundamental neutrino interaction* never been experimentally-observed
- s∝~N^2 applicable at E_n<50 MeV where q^2r^2<1
- a sensitive *test to Stardard Model*
- important interaction/energy loss channel in *astrophysics* media
- a promising new detection channel for neutrinos; relative compact detectors possible (implications to *reactor monitoring*); *& the* channel for *WIMP direct detection* !
- Typical Rates for Ge at KSNL :

TEXONO-CDEX : ULEGe & PCGe @ KSNL & CJPL

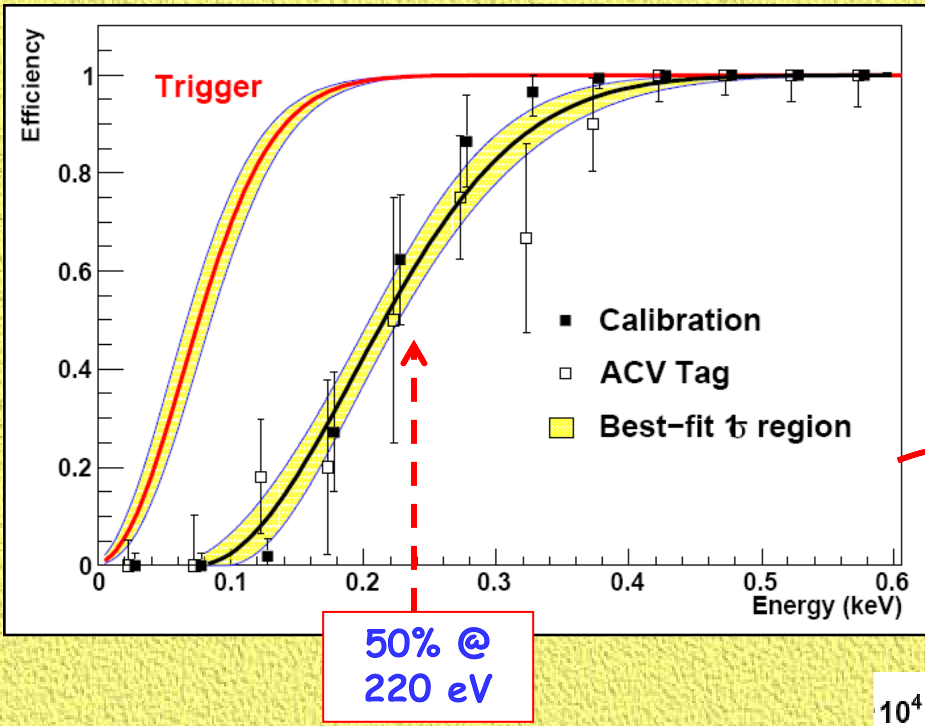




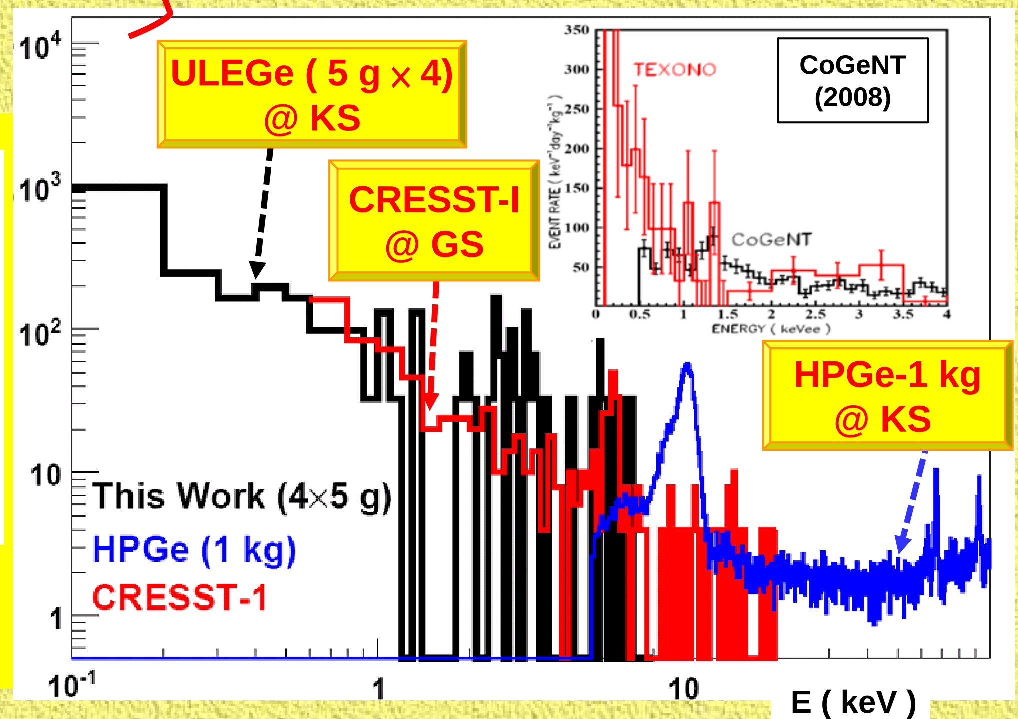




Threshold & Efficiencies & Background for 20g ULEGe (2007)



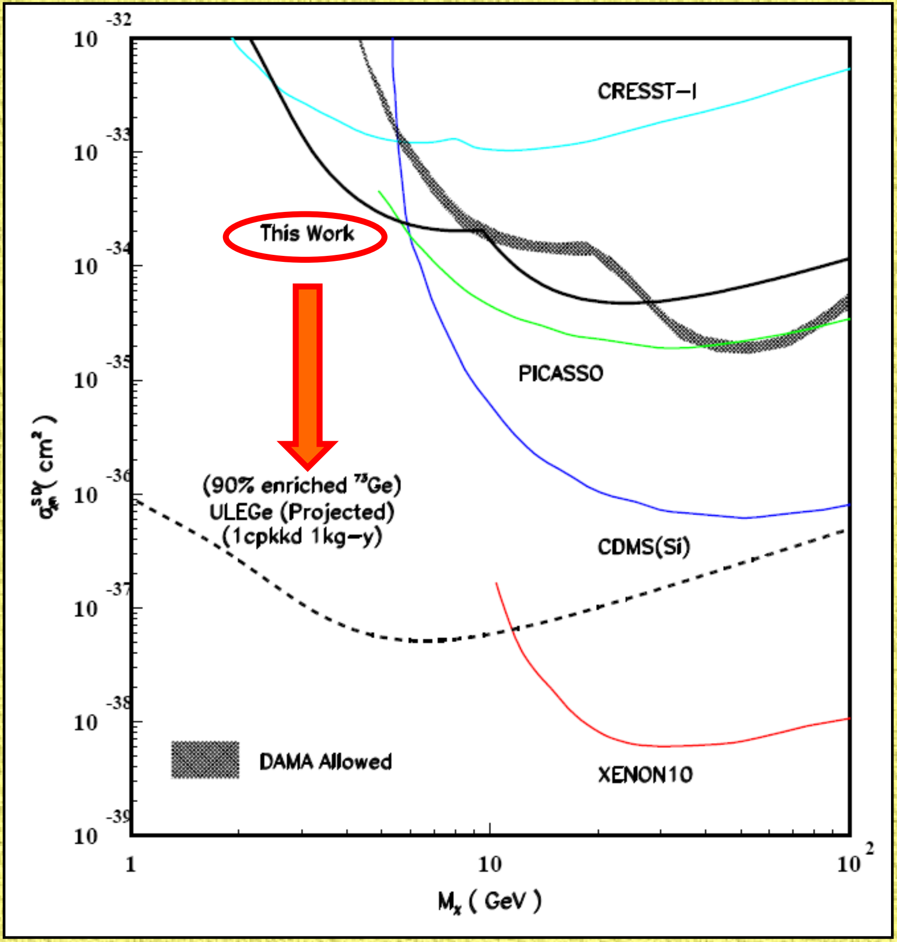
Dark Matter Searches Analysis

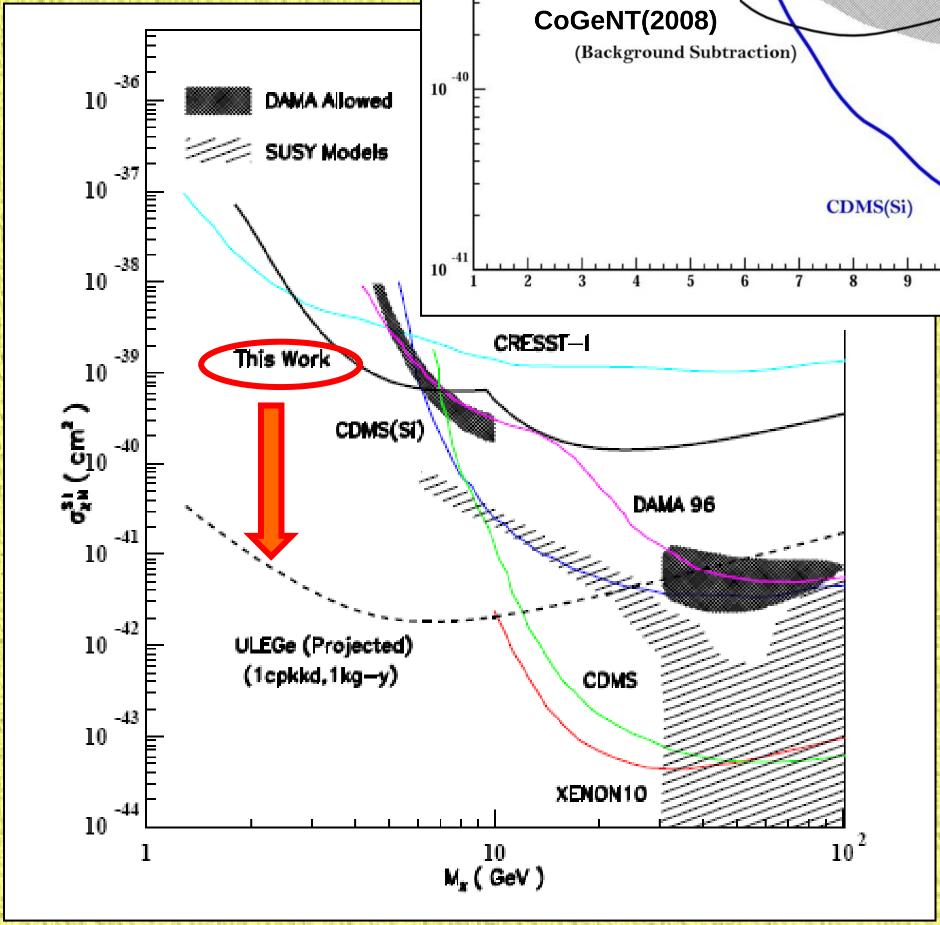


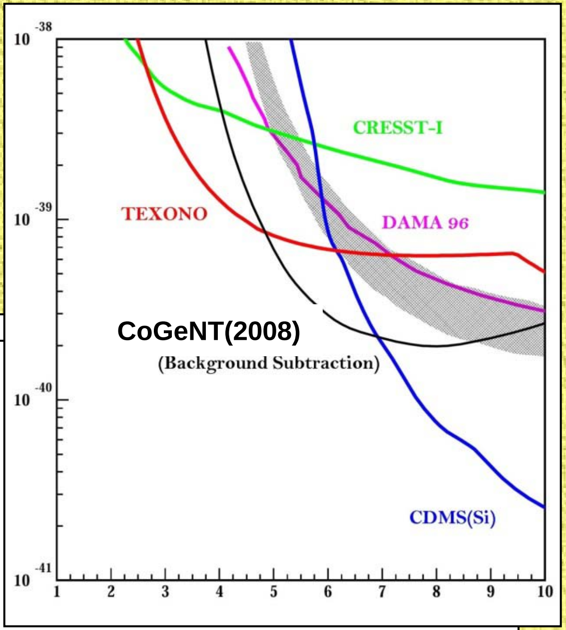
sub-keV Background :

* Not fully explained with conventional background modeling
* Intense work on hardware, software and data taking at new underground site

Limits on Low Mass WIMPs : Spin-Dependent & Independent Couplings (PRDRC09)

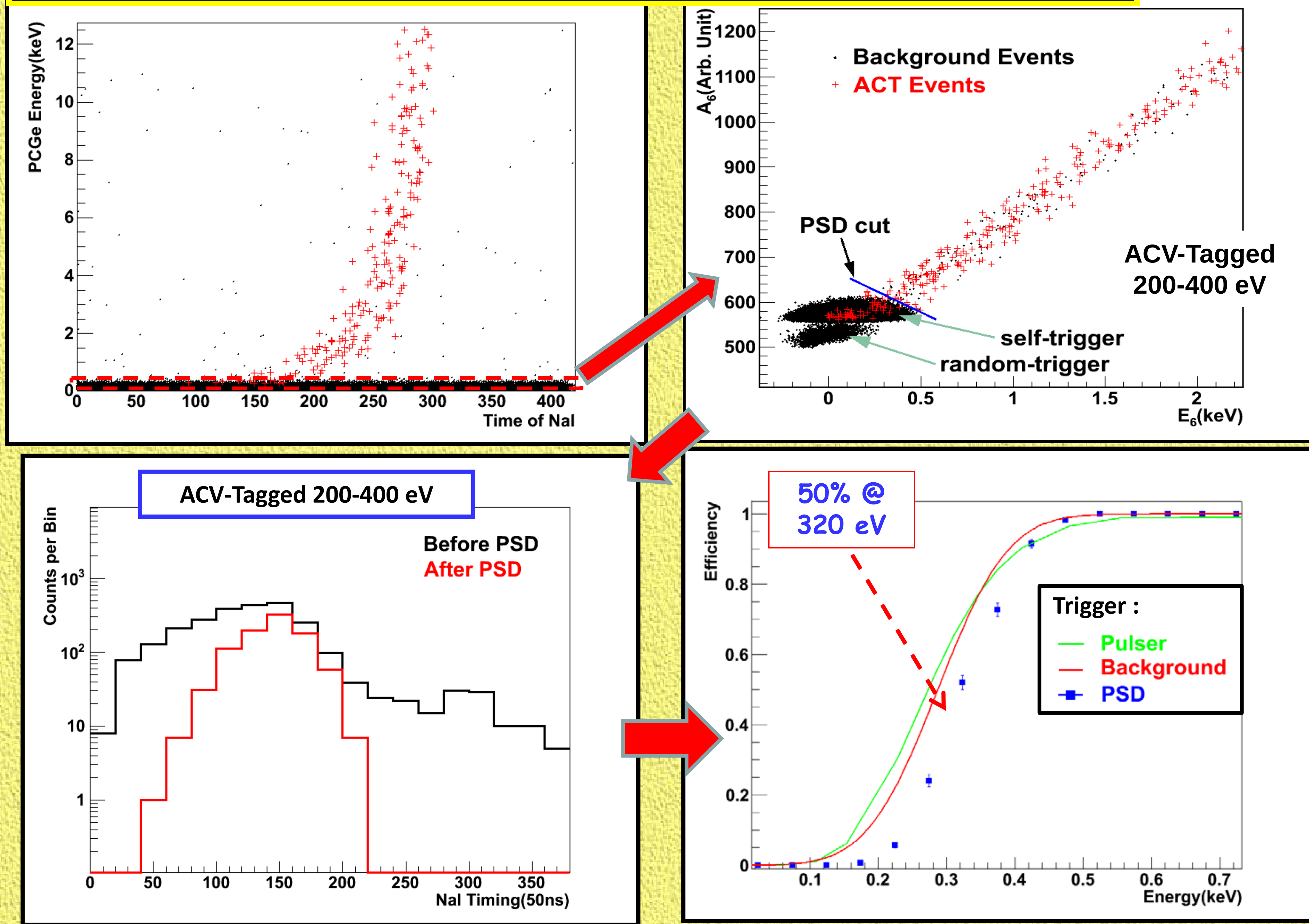






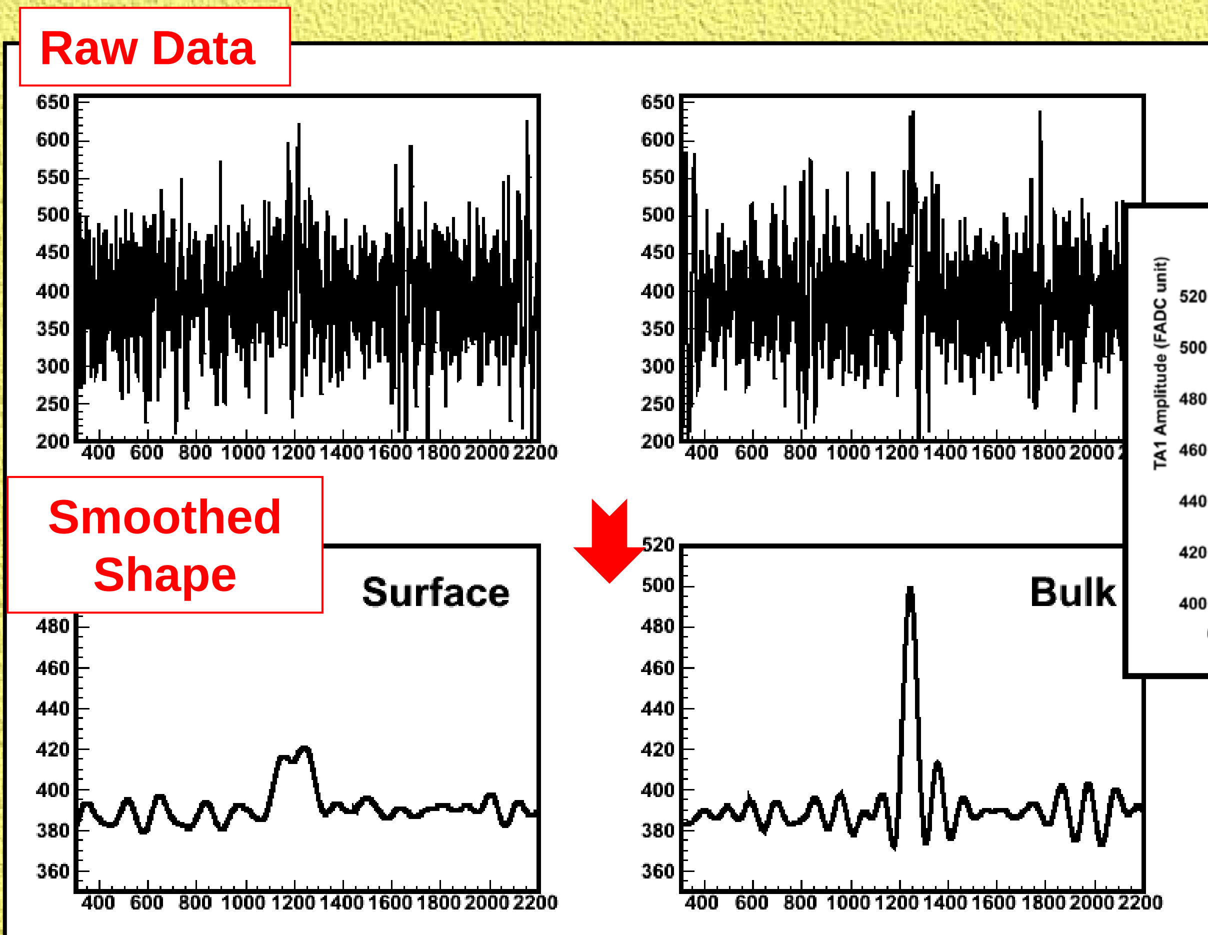
Latest : New CoGeNT 2010 Results (limits & allowed region) ;
intense theoretical interest and speculations on low-mass WIMPS

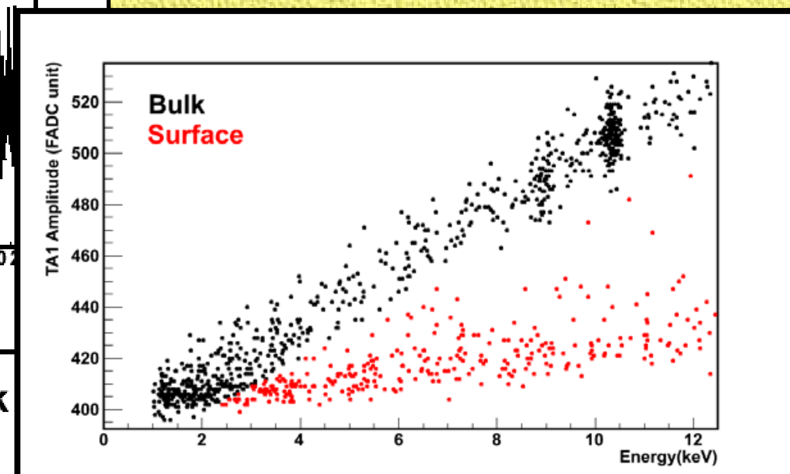
500g PCGe – Threshold & Selection Efficiency



PSD for Surface Vs Bulk Events @ PCGe

- 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





Typical Performance : Summary

Measurement	ULEGe	PCGe-1	PCGe-2
Detector Mass	4x5 gram	500 gram	900 gram
Pulser FWHM	~ 80 eV	~ 150 eV	~ 110 eV
Gamma Line Width (FWHM)	182.13 eV (^{55}Fe @ 6.49 keV)	266.56 eV (Ga @ 10.37 keV)	275.27 eV (Ga @ 10.37 keV)
RT Noise RMS	~ 17.44 eV	~ 91.925 eV	~ 84.26 eV
Trigger Discriminator level (in Noise-RMS)	4.3 σ	3.768 σ	3.719 σ
50% Trigger Efficiency	~ 80 eV	~ 180 eV	~ 143 eV
Trigger Rate	~ 5 Hz	~ 35 Hz	35-40 Hz
DAQ Dead Time	~ 10%	30-40%	14-20%
Noise Edge	~ 200 – 300 eV	~ 500 eV	~ 400 eV
50% Selection Efficiency	~ 200 eV	~ 300 eV	~ 300 eV

Status and Plans

- Competitive limits at *WIMP-mass < 10 GeV* obtained with sub-keV Ge prototype at a shallow depth reactor laboratory KSNL, for both spin-independent and spin-dependent couplings
- Studies on background understanding at *sub-keV* range
- Data taking as KSNL with 500g/900g Point-Contact Ge
- Evolving to dedicated dark matter searches at new deep underground laboratory at Sichuan CJPL 2010.
- Prepare towards detectors at 10-kg range
- *Goals :* open new *detection channel* and *detector window* for neutrino and dark matter physics ; available for *surprises*