Studies of Neutrino Properties and Dark Matter Search with sub-keV Germanium Detectors

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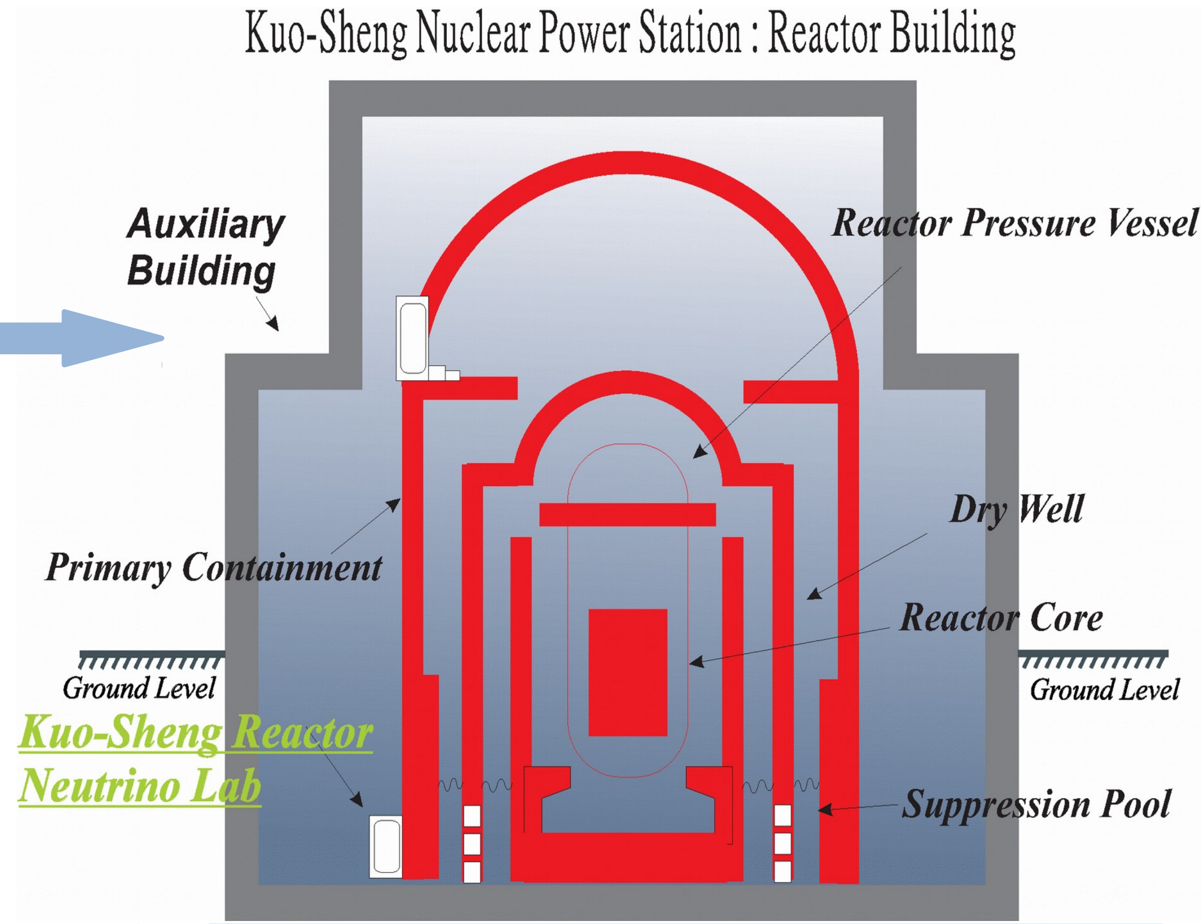
TEXONO **T**aiwan **EX**periment **O**n **N**eutrin**O** (since 1997)
Neutrino Physics at Kuo-Sheng Reactor Neutrino Laboratory **(KSNL)**

CDEX **C**hina **D**ark Matter **Ex**periment (birth 2009)
Dark Matter Searches at China Jin-Ping Underground Laboratory **(CJPL)**

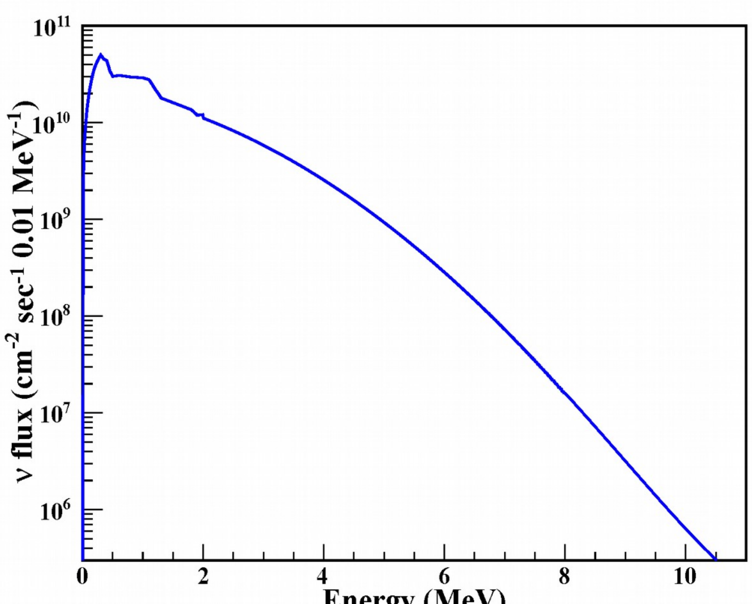
- **Overview :KSNL**
- **sub-keV Germanium detectors**
- **Neutrino programs**
  - **Electromagnetic Properties** (**Theory part by Wu Chih Pan → 24/07 Neutrino session at 13:30)**
  - **νN Coherent Scattering**
- **Dark Matter searches at CJPL** (**Prof Hao Ma→ 24/07 DM session at 17:00)**
- **Summary**

Kuo-Sheng Nuclear Power Plant

Total Capacity 2.9 GW each

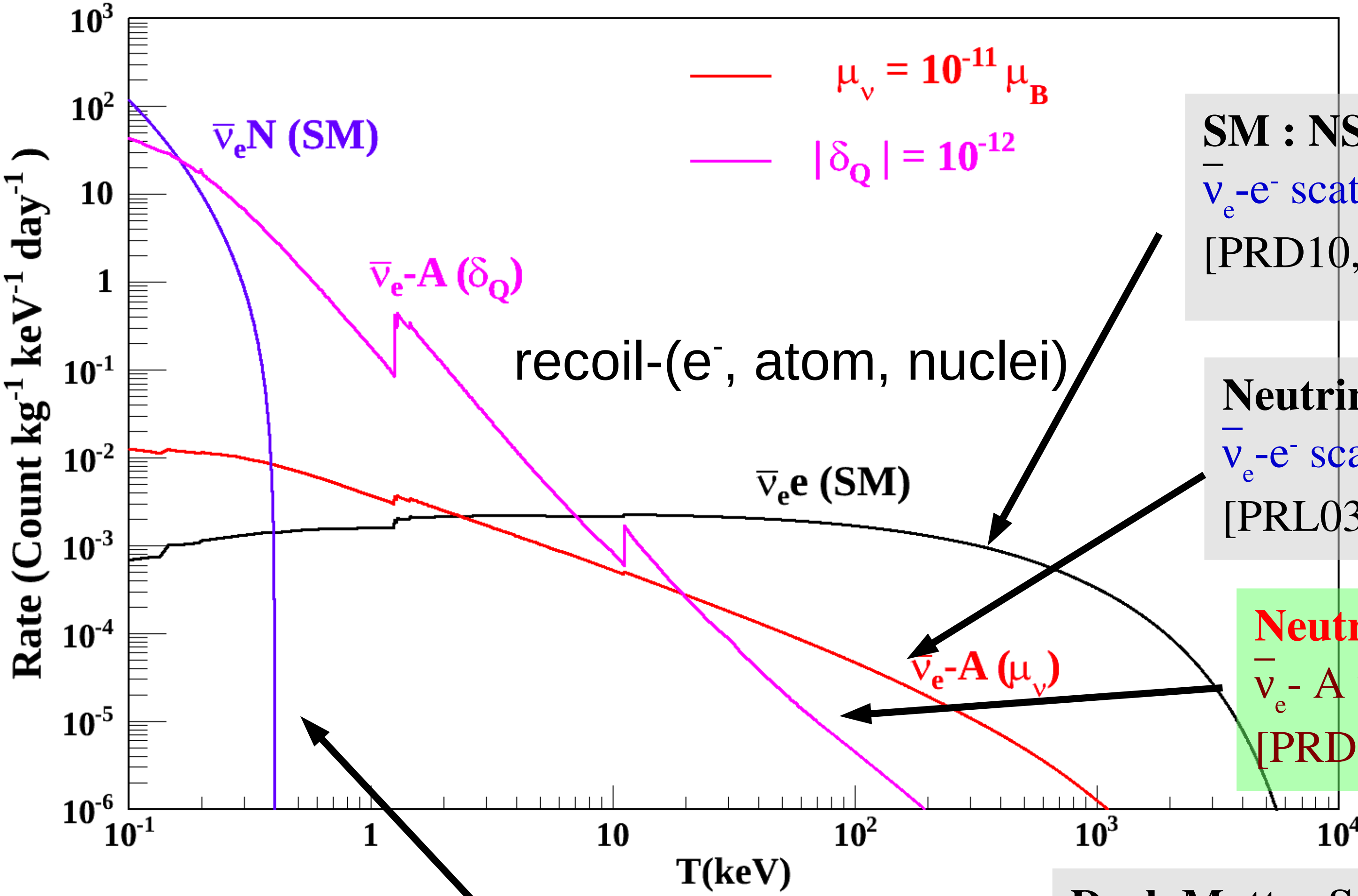


Reactor neutrino flux spectrum



- **Shallow site: ~10 m below ground level**
- ***Concrete overburden ~30 MWE***
- ***Lab: 28 m from core #1,***
- **$\Phi_{\nu} = 6.4\times10^{12}$ $cm^{-2}\,s^{-1}\,sr^{-1}$**

TEXONO Physics Program : interactions by neutrino at reactor



SM : NSI/BSM
$\bar{\nu}_e$-e^- scattering with 200 kg CsI
[PRD10,PRD10,PRD12,PRD15]

Neutrino Magnetic Moment
$\bar{\nu}_e$-e^- scattering with 1 kg HPGe
[PRL03,PRD05,PRD07,PRD15]

Neutrino milli-charge
$\bar{\nu}_e$- A with sub-keV ULEGe, PCGe
[PRD14,PRD15]

ν-Nuclei Coherent Scattering [goal]
sub-keV ULGe, PCGe [PRD2016]

Dark Matter Searches at
KSNL [PRD09,PRL13,AP14]
CDEX(CJPL) [PRD13,PRD14,PRD14,PRD16]
Axion at CJPL [PRD17]

Ge detector & sub-keV challenge

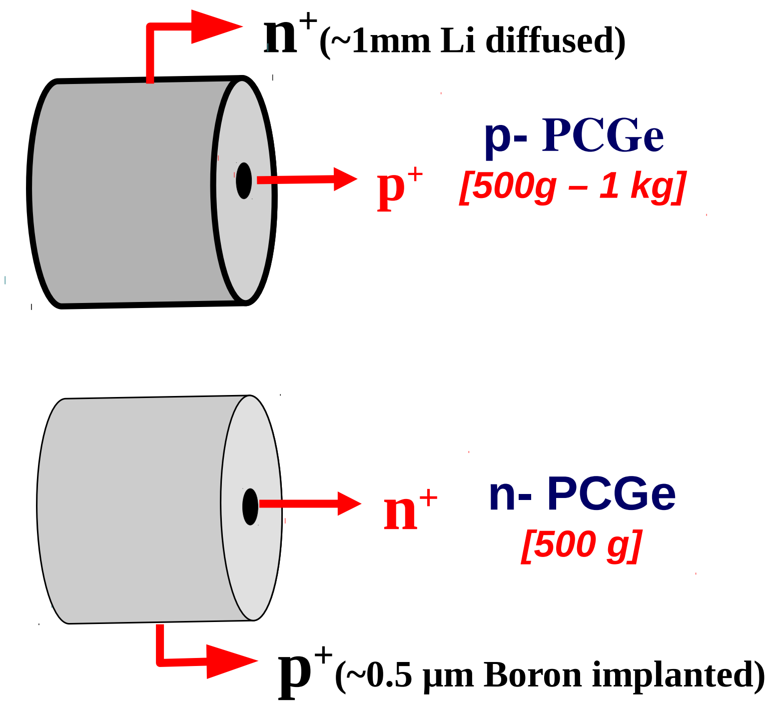
Motivation

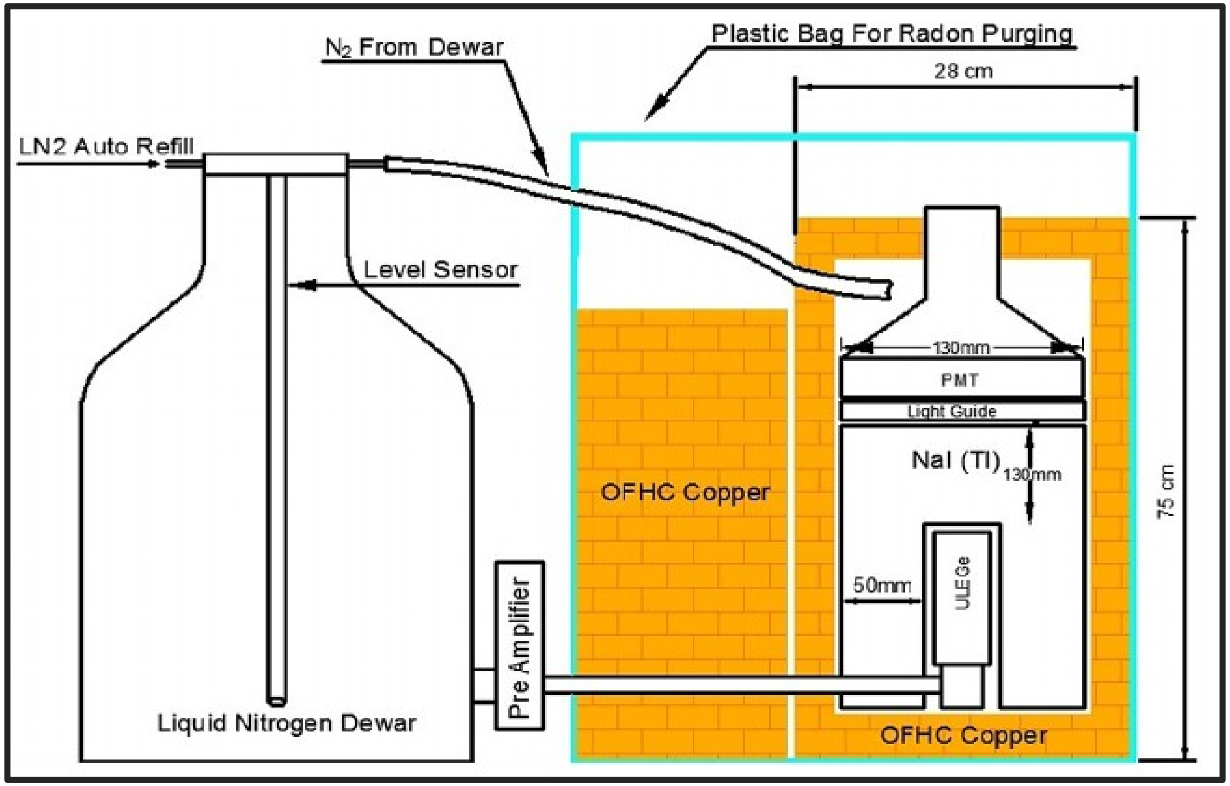
- **Allow Low Threshold Measurements(~100eV at kg mass scale)**
- **Neutrino physics at sub-keV :** neutrino electro-magnetic properties, νN-coherent scattering
- **Low-mass (~10 Gev)** WIMP Search.

Challenge

- **Near threshold : energy spectrum (noise leakage), pulse : (noise comparable to signal).**
- Bulk vs. Surface : algorithms, bulk-efficiency and surface-leakage at low energy.
- Quenching Factors : not well measured
- Energy Calibration : non-linearity of energy definition.
- Trigger Efficiencies near threshold : noise survive hardware threshold.
- Physics vs. Noise : PSD, eff.
- Background understanding : contributions from background and cosmic-induced isotopes at low energy.

sub-keV HPGe detector

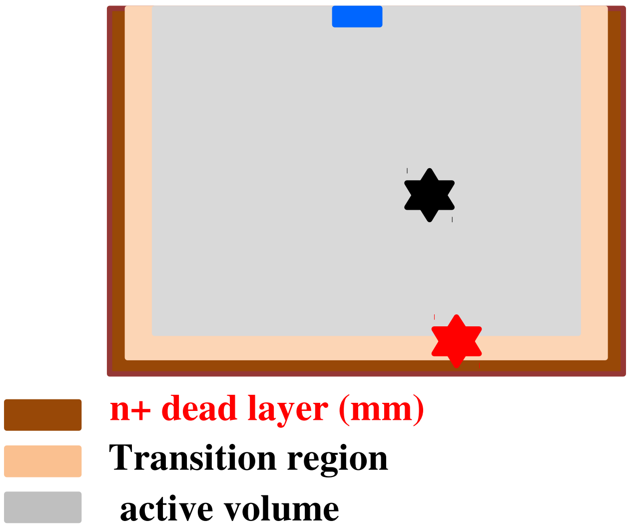


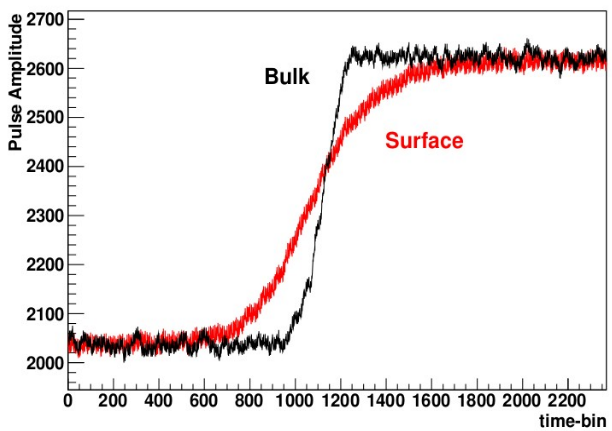


HPGe-Generation	Mass (g)	Pulsar FWHM (eV ee)	Threshold (eV ee)
G1	500	130	500
G2	900	100	300
G3	1430	soon	soon

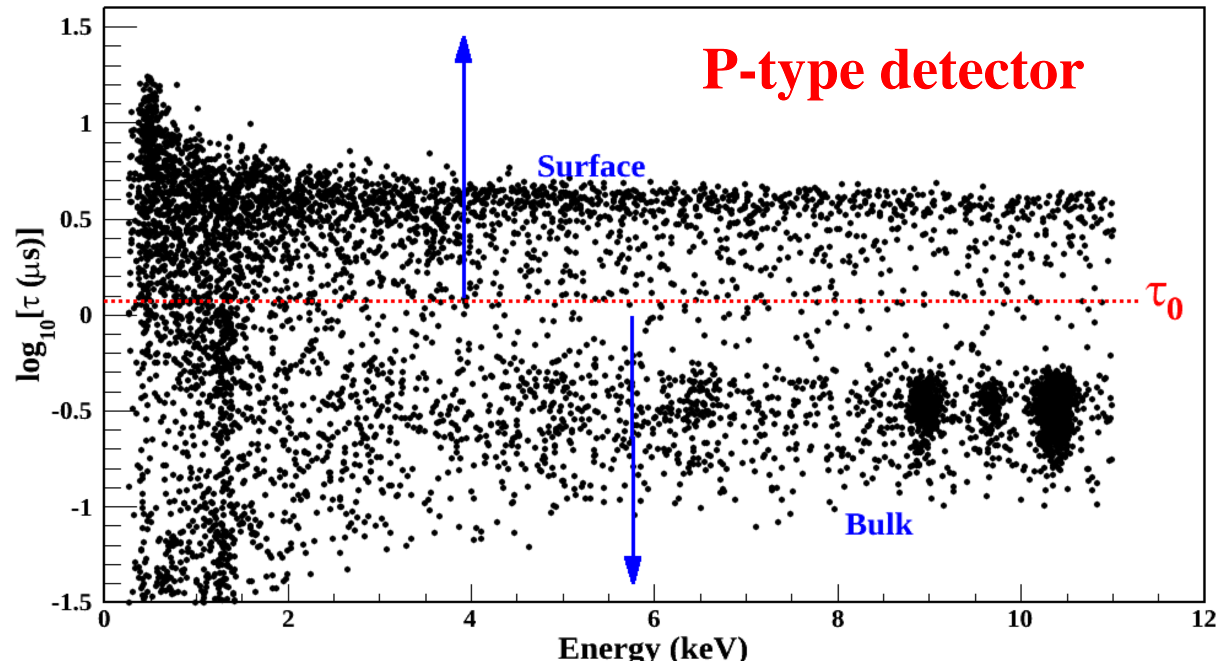
Special feature of PCGe : Bulk/Surface

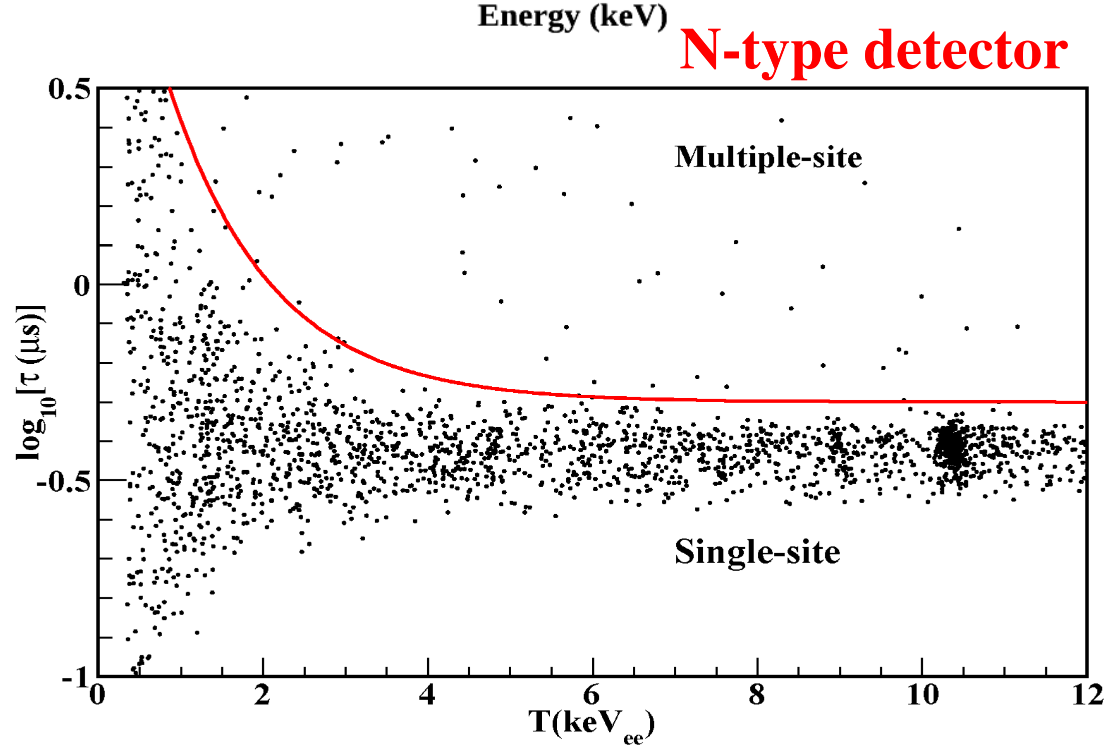
P-type PCGe-Detectors





- **A bless** (most background are surface)
- **A curse** (need to measure efficiency ε and leakage 1-λ at low E)

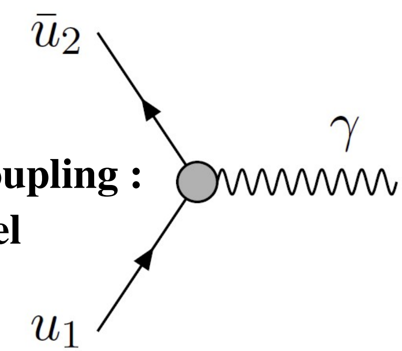




Neutrino interaction with atoms

(Wu chih Pan → 24/07 Neutrino session at13:30)

High energy : $\nu_e + e^- \rightarrow \nu_e + e^-$



neutrino-photon coupling :
non-standard model

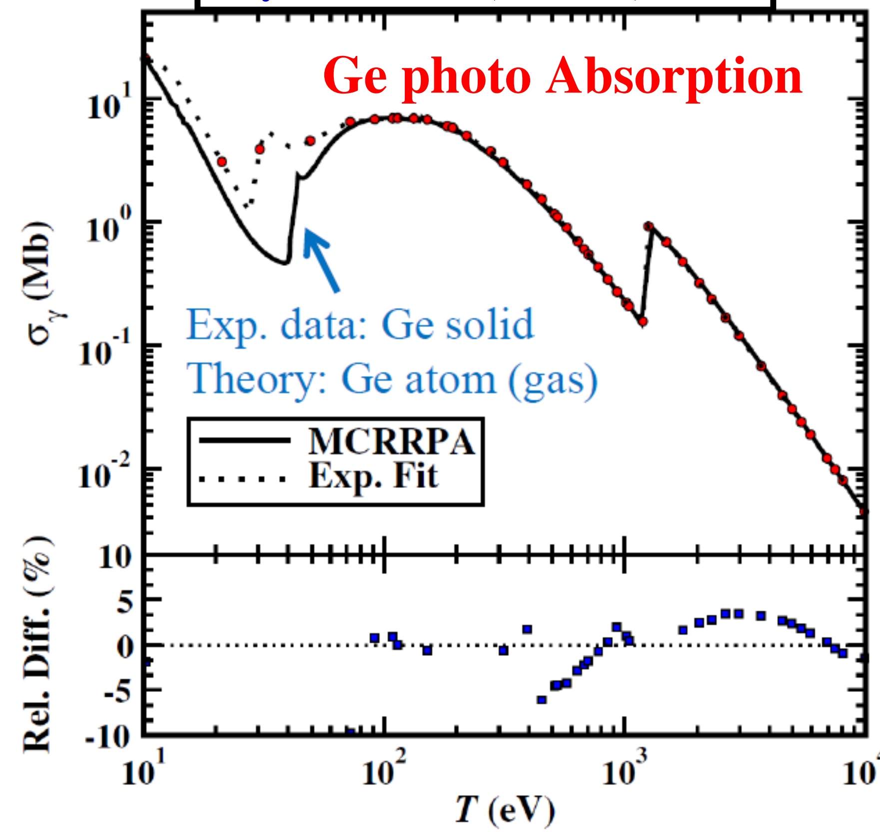
When transfer energy < binding energy of e$^-$,

$$\nu_e + A \rightarrow \nu_e + A^+ + e^-$$

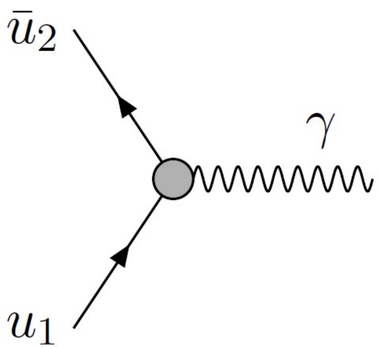
MCRRPA: **M**ulti **C**onfiguration **R**elativistic **R**andom **P**hase **A**pproximation

- MCRRPA describes well Ge response function up to 80 eV
- Above 80eV Ge-crystal can treated as atom-like
- Below 80eV condense state should considered.
- Above 80 eV, error < 5 %

Phys. Rev. D 91, 013005, 2015.



Neutrino milli-charge

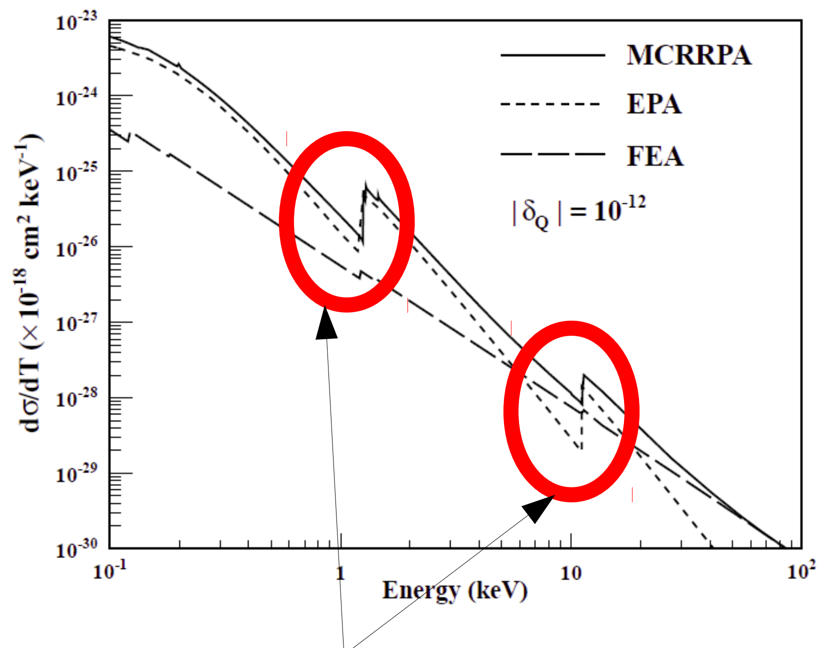


$\Gamma_{EM} = f_Q \gamma_\mu + \ldots$

f_Q : neutrino milli-charge

Free electron :

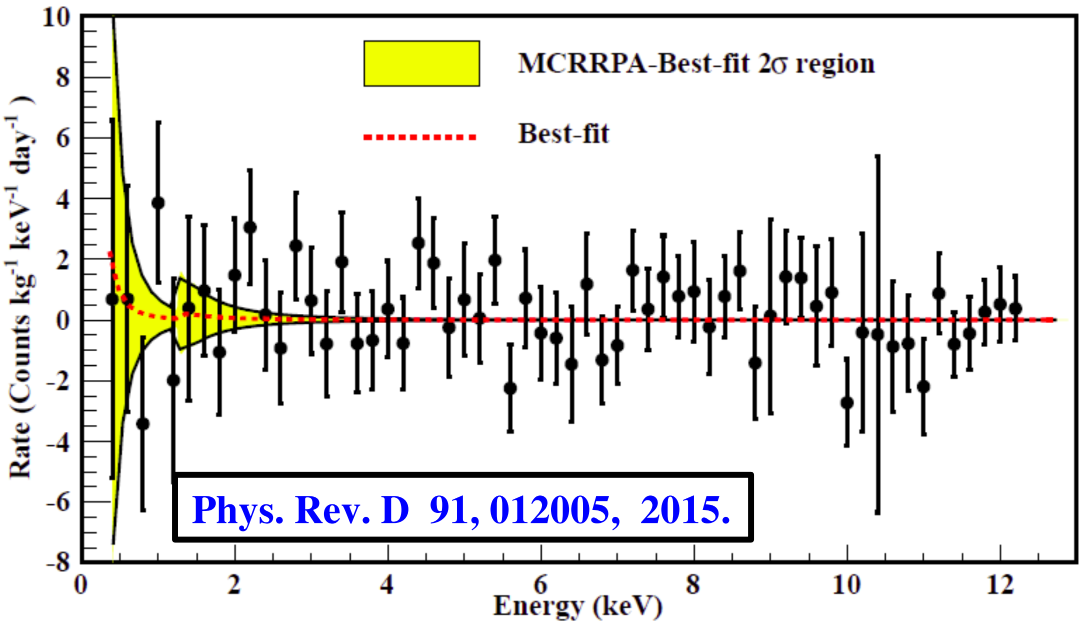
$$\left(\frac{d\sigma_{\delta_Q}}{dT}\right)_{FEA} = \delta_Q^2 \left[\frac{2\pi\alpha_{em}^2}{m_e}\right]\frac{1}{T^2},$$



Atomic Ionization Differential Cross-Section with full atomic physics many-body "MCRRPA" calculation enhancement at sub-keV.

Best-fit results on 0.5 kg PCGe threshold = 300 eV

→ $\delta_Q < 2.1 \times 10^{-12}$e at 90 % C. L.



- **K- and L-shell peaks at the specific binding energies with known intensity ratios → unique "smoking gun" signature**
  (different from cosmic-activation electron-capture background)
- **Goal $\delta_Q \sim 10^{-14}$e at 100 eV threshold**

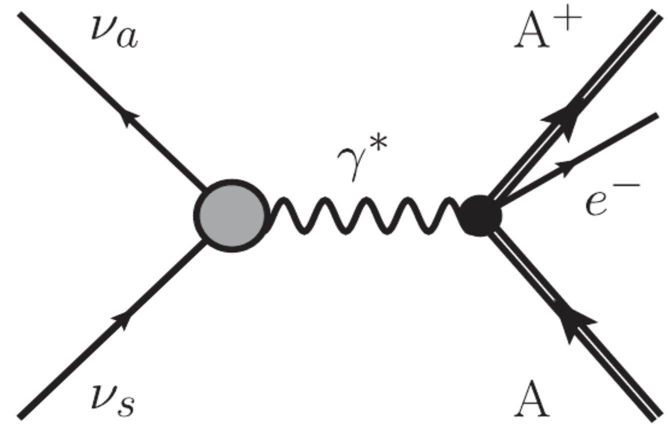
Sterile Neutrino Magnetic Moment

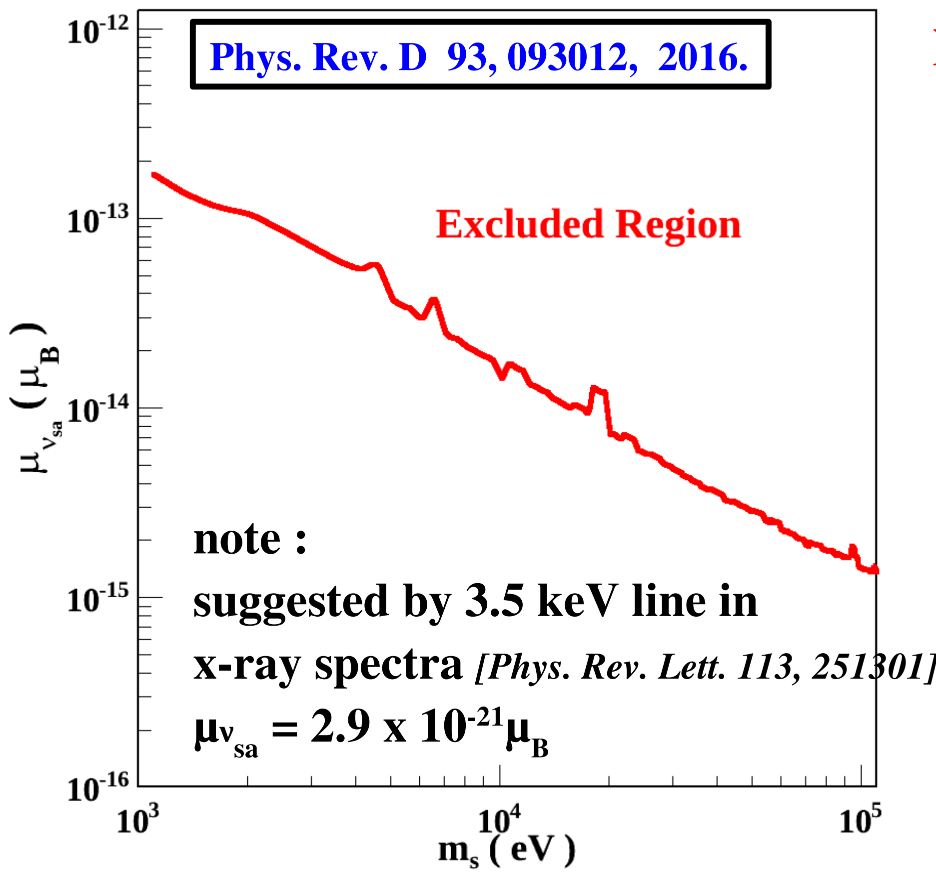
In Radiative Decay $\nu_a, \nu_s \rightarrow \nu_a + \gamma$

Under the assumption of sterile neutrino as cold dark matter, following parameters are adopted,

- Dark matter density = 0.4 GeVcm^{-3} ,
- Maxwellian velocity distribution with
- mean velocity = 220.0 km/s and V_{esc} = 533 km/s

$\nu_s + \mathrm{A} \rightarrow \nu_a + \mathrm{A}^+ + e^-$

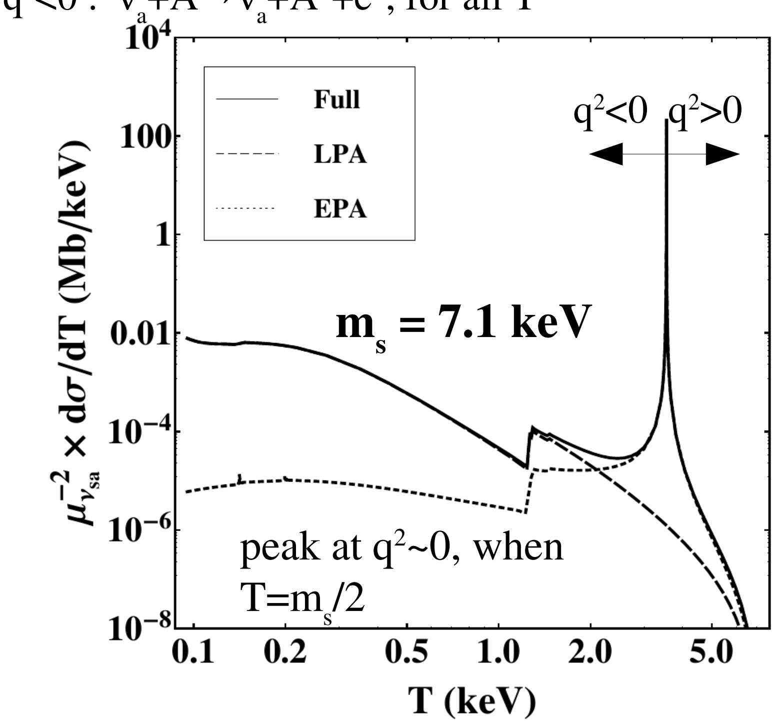




Non-Relativistic case

$q^2>0$: forward scattering $\nu_s + A \rightarrow \nu_a + A^+ + e^-$, $T>m_s/2$

$q^2<0$: $\nu_a + A \rightarrow \nu_a + A^+ + e^-$, for all T



νN Coherent Scattering

Current Focus !!

$$\nu_l + N \rightarrow \nu_l + N$$

A fundamental neutrino interaction never been observed experimentally

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

- Neutral current process.
- $\sigma \propto N^2$ for E_ν<50MeV (Coherent)

Reactor Neutrinos require following conditions to study the νN Coherent Scattering

➔ *Needs Background < 10 cpkkd, Target 1 cpkkd*

➔ *Needs Threshold < 200 eV_{ee}*

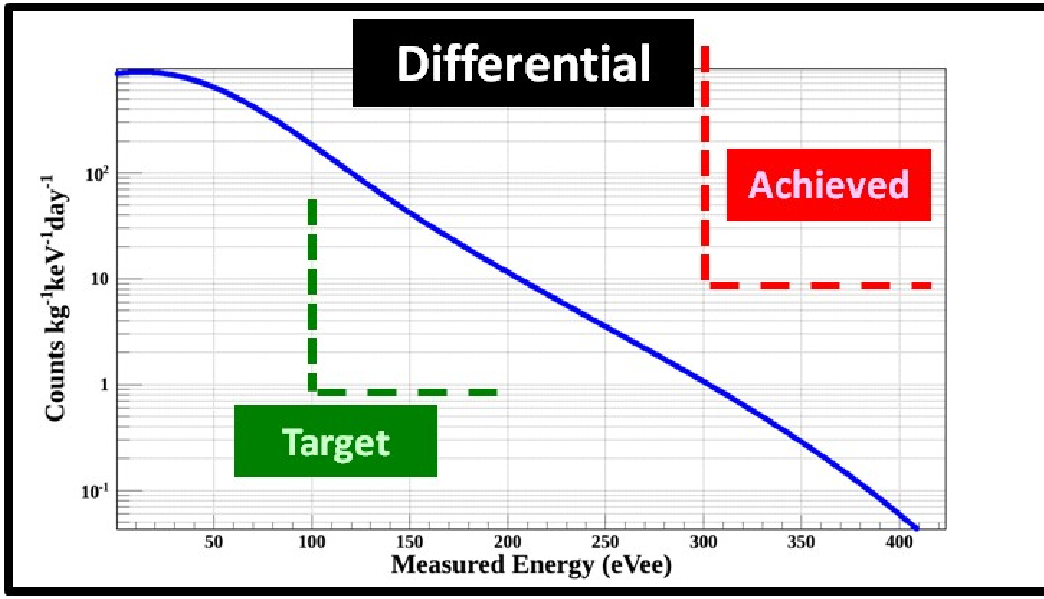
Important to study for ...

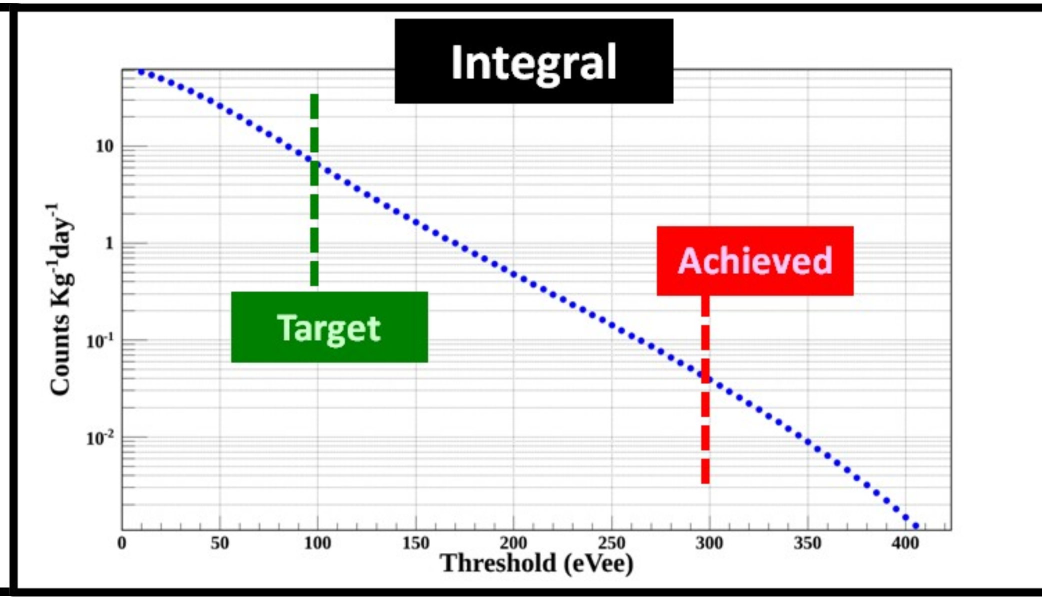
- νA_{el} Scattering is important to study the irreducible background for Dark matter search.
- Important role in Supernova Explosions.
- In study of Beyond Standard Model Physics.
- To study the Quantum Mechanical Coherency effects.
- Reactor monitoring.

vN Coherent Scattering

Improvements (plan) :

- **Background : cosmic correction, B/S correction, known sources, understanding (simulation).**
- **phys/noise : hardware improvement : cooling, electronic, PSD, noise-simulation.**





Decoherency

The scattering amplitude of individual nucleons adds with a finite relative phase angle to contribute to the cross section. The combined amplitude:

$$\mathcal{A} = \sum_{j=1}^{Z} e^{i\theta_j}\mathcal{X}_j + \sum_{k=1}^{N} e^{i\theta_k}\mathcal{Y}_k,$$

The Average phase mis-alignment angle follows:

$$e^{i(\theta_j-\theta_k)} - e^{-i(\theta_j-\theta_k)} = 2cos(\theta_j - \theta_k) = 2cos\langle\phi\rangle$$

Degree of coherency discribed as: $\alpha \equiv cos\langle\phi\rangle \in [0, 1]$

νN Coherent Scattering

The cross-section ratio between nucleus and neutron & partial-coherency and full-coherency :

$$\frac{\sigma_{\nu A_{el}}(Z,N)}{\sigma_{\nu A_{el}}(0,1)} = Z\epsilon^2[1+\alpha(Z-1)] + N[1+\alpha(N-1)] - 2\alpha\epsilon Z N$$

Phys. Rev. D 93, 113006, 2016.

The limiting conditions:-

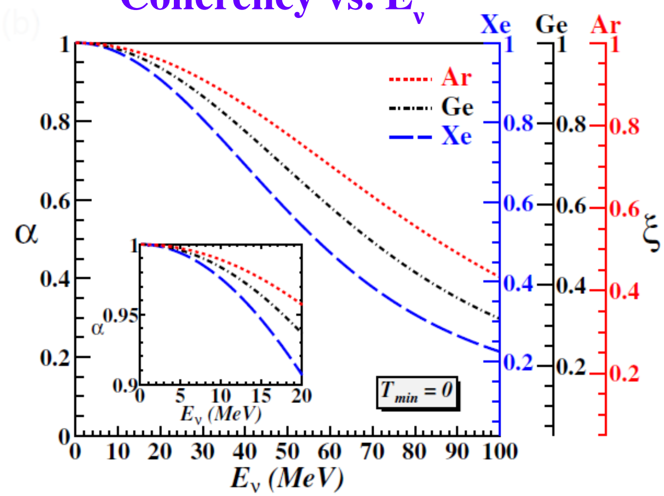
Full coherency: $\alpha = 1; \quad \sigma_{\nu A_{el}} \propto [\epsilon Z - N]^2$

Completely incoherent: $\alpha = 0; \quad \sigma_{\nu A_{el}} \propto [\epsilon^2 Z + N]$

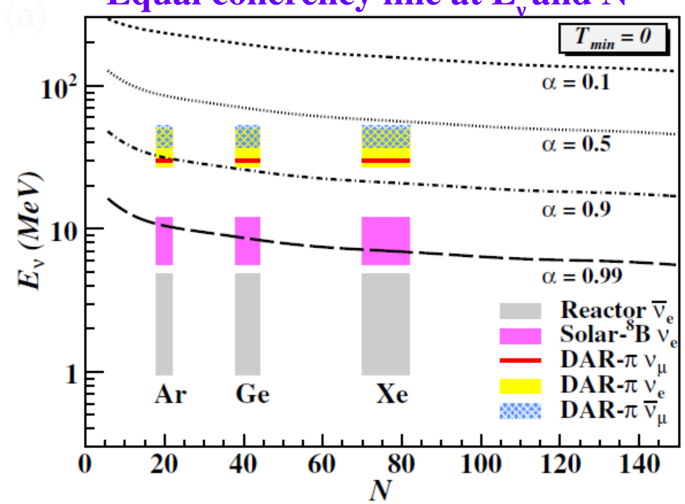
Partial coherency, the relative change in cross section, ξ:

$$\xi \equiv \frac{\sigma_{\nu A_{el}}(\alpha)}{\sigma_{\nu A_{el}}(\alpha=1)} = \alpha + (1-\alpha)\left[\frac{(\epsilon^2 Z + N)}{(\epsilon Z - N)^2}\right]$$

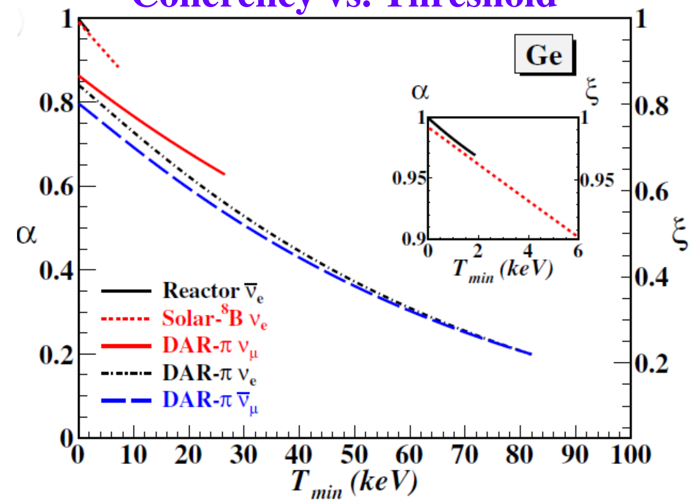
Coherency vs. E_ν



Equal coherency line at E_ν and N

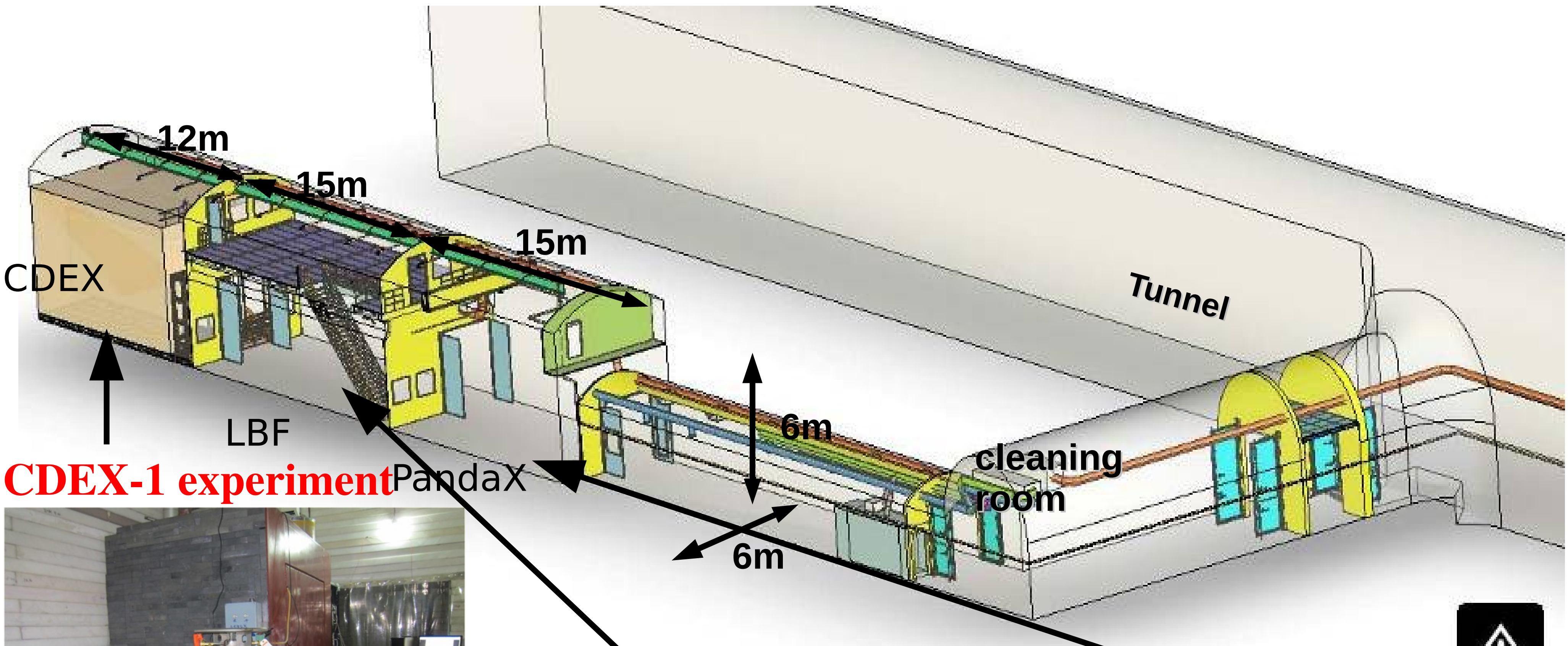


Coherency vs. Threshold



CDEX & CJPL-I

→ (Prof Hao Ma → 24/07 DM session at 17:00)



CDEX-1 experiment

Low background facility

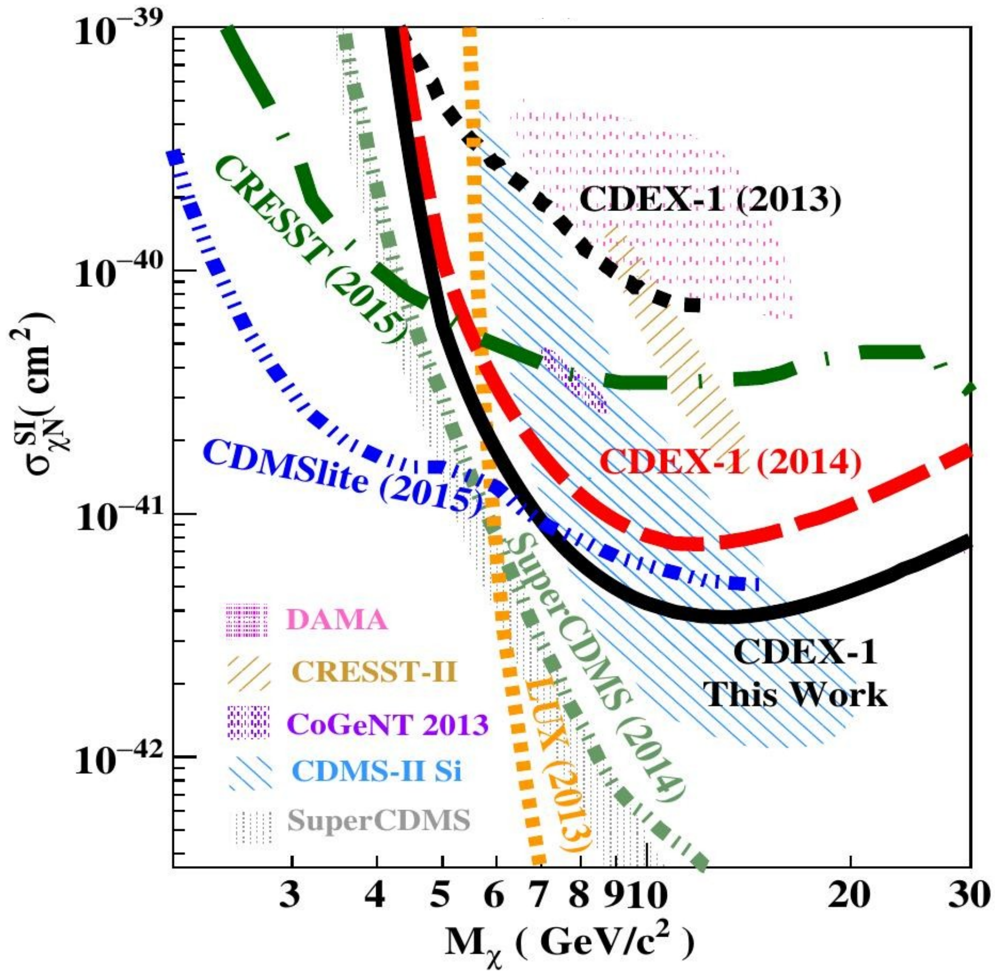
PandaX

CDEX-1 Dark Matter Search

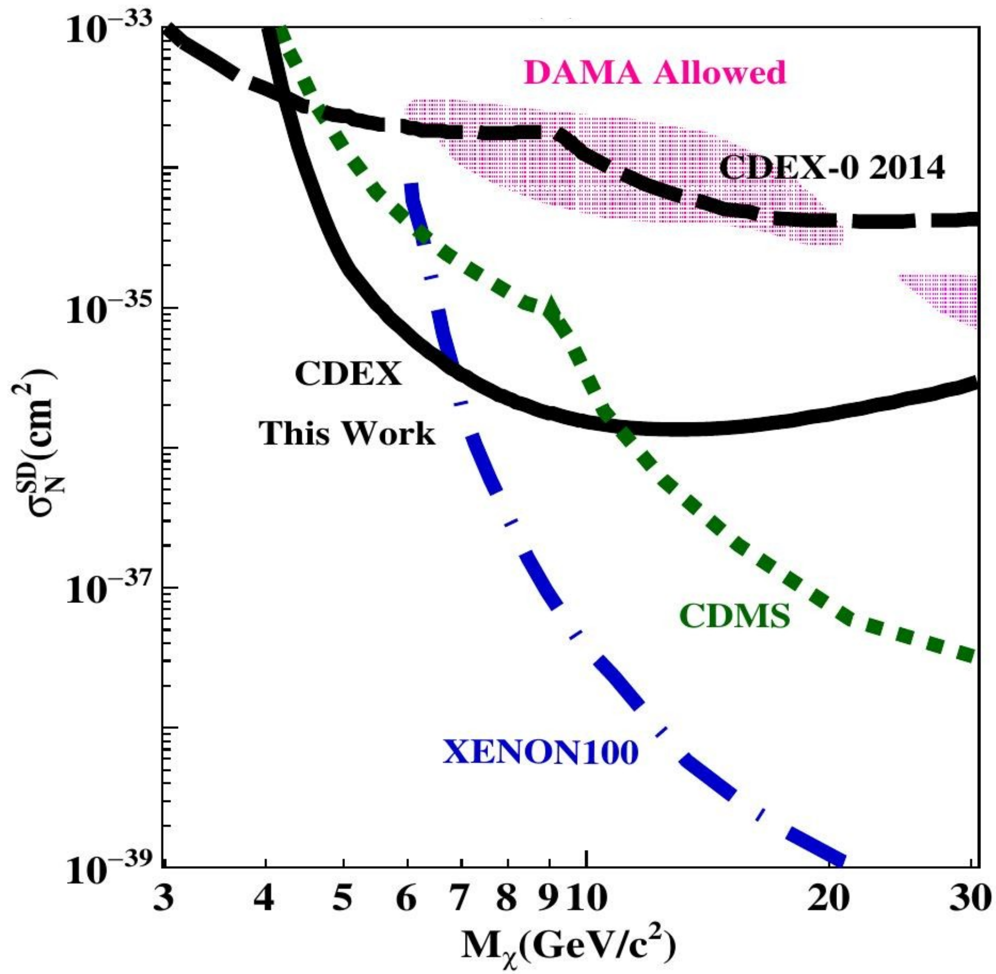
- 335 kg-days of data, Baseline design with NaI(Tl) Fiducial mass : 915 g
- Analysis threshold ~ 475 eV
- Q.F. adopted by TRIM software with 10% systematic uncertainty

[PRD 93 092003 (2016)]

Spin-independent



Spin-dependent



CDEX-1 Dark Matter Search

Solar axion :

M1 transition from ^{57}Fe from Sun:

$$^{57}\mathrm{Fe}^* \rightarrow {}^{57}\mathrm{Fe} + a\ [g_{AN}]$$

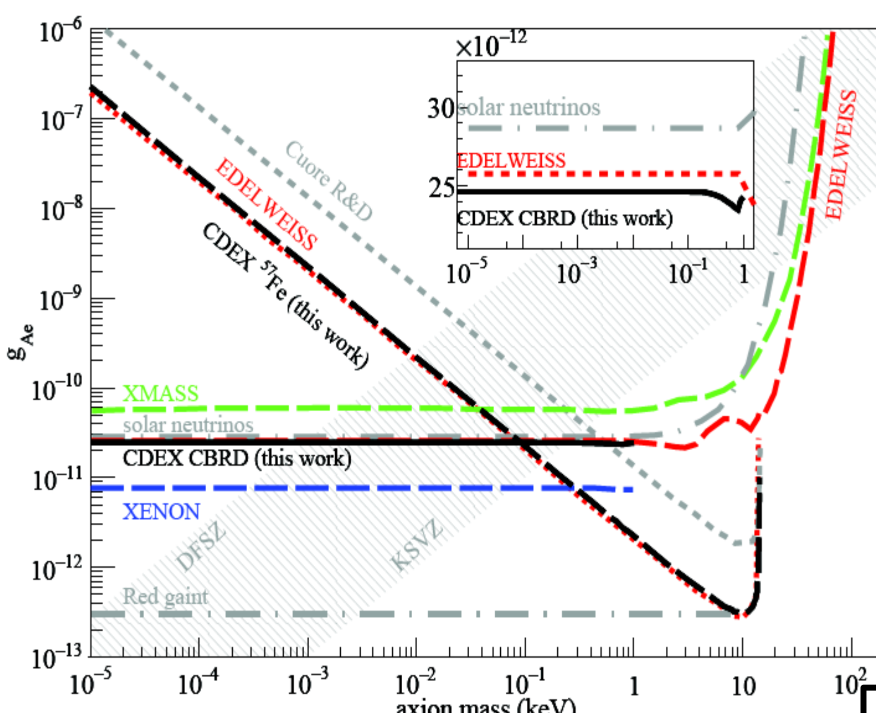
axion(a) from sun $[g_{Ae}]$

Compton(C): γ+e → e+a

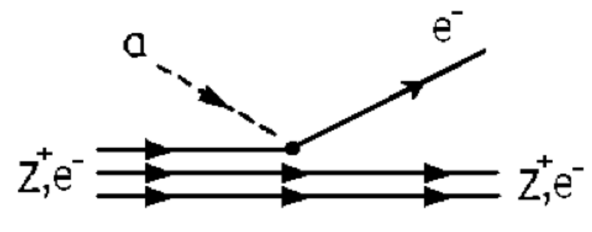
Bremsstrahlung(B): e+Q → e+Q+a

Recombination(R): e+I → I^-+a

De-excitaion(D): I* → I+a



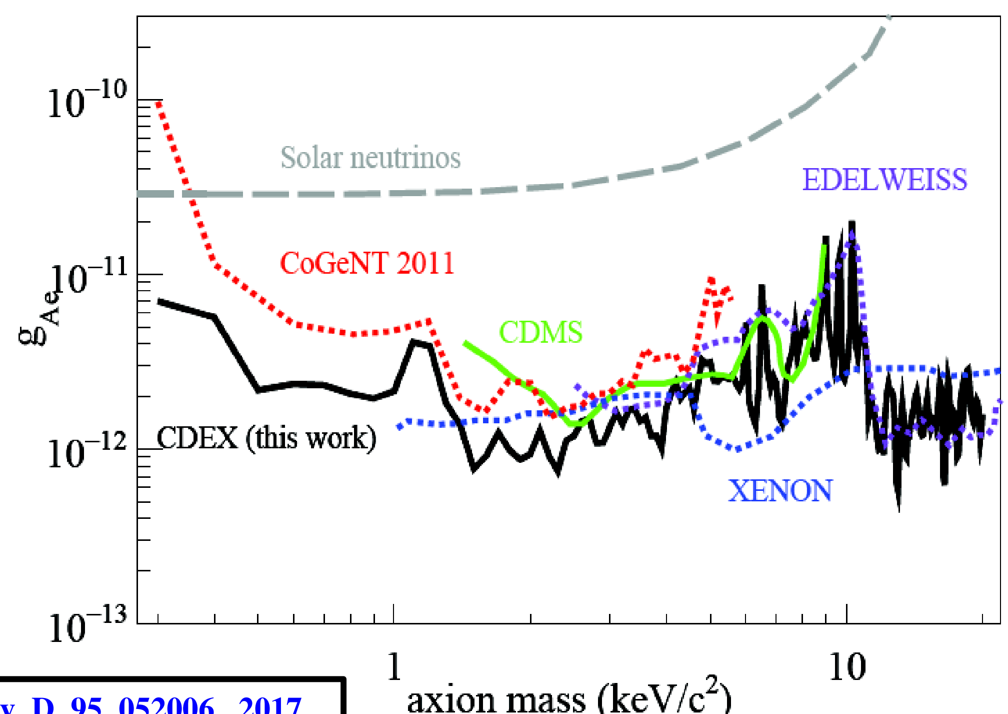
Galatical axion(DM) :



Axioelectric
or Photoelectric-like

Axioelectric detection :

a+e+Z → e+Z



Phys. Rev. D 95, 052006, 2017.

Summary & Prospects

- **sub-keV Ge plans :**
  - New electro-cooled detector, <200 eV threshold
  - Backgrond understanding.
  - Detector properties near noise edge, Noise simulation.
  - B/S calibration schemes.
- **Neutrino at KSNL:**
  - **Electromagnetic propteries**
    - Establish theoretical tools on Neutrino-Atoms interaction : MCRRPA.
    - Studies on neutrino electromagnetic properties
    - Enhancement and smoking-gun peak signatures for ν-milli-charge
    - Cross-section pole structures in non-relativistic ν_s+A scattering , relevant for DM
  - **νN coherent scattering.**
    - Goal ~100 eV threshold & background ~ cpkkd.
- **Dark Matter Searches at CJPL:**
  - Ge-Techniques at CJPL
  - New axion results from CDEX@CJPL-I
  - CJPL-II commissioned soon : a candidate site for future 1-ton Ge 0νββ