

Test of Beyond-Standard-Model Scenarios with sub-keV Germanium Detectors

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Neutrino and Dark matter are two portal for new physics beyond-Standard Model

TEXONO → Neutrino Physics at **Kuo-Sheng Reactor Neutrino Laboratory (KSNL)**

- Phys. Rev. D 93, 093012 (2016)
- Phys. Rev. D 91, 013005 (2015)

CDEX → Dark Matter Searches at **China Jin-Ping Underground Laboratory (CJPL)**

- Phys. Rev. Lett. , 120, 241301 (2018)
- Phys. Rev. D 95, 052006 (2017)
- Phys. Rev. D 95, 052006 (2017)

Outline

- **sub-keV Germanium detectors**
 - **Merits, Uniqueness, Competitive Edges**
- **Neutrino programs**
 - **Electromagnetic Properties**
 - **Atomic effect (MCRRPA Theory)**
- **Dark Matter searches at CJPL**
 - **WIMP**
 - **Sun Axion**
 - **Pseudoscalar and Vector super-WIMPs**
- **Summary**

Ge-Detector Merits, Uniqueness, Competitive Edges ...]

→ Excellent Resolution

- resolve structures (peaks, end points) , smoking-gun, signatures for certain BSM scenarios

→ Fast (enough) timing –

- slow detector response time [thermalization (bolometers) /drift (TPCs)] problematic in vetoing anti-coincidences at surface (reactor,accelerator) locations.

→ Matured Technology; Industry support

- Less (entry level) investment

• Constraints/Limitations:

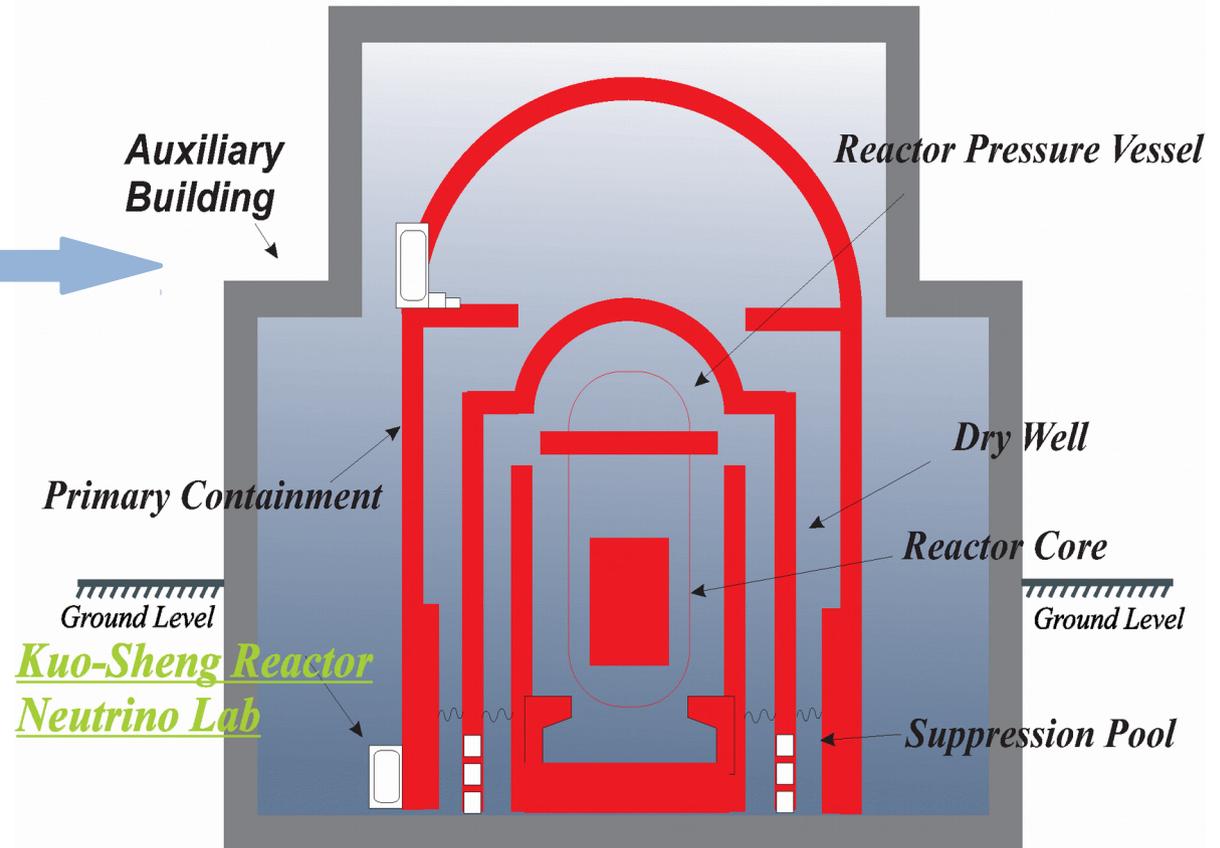
- It is not possible to differentiate between nuclear and electron recoil events via pulse shape analysis.
- Target Mass [or High Cost-per-unit-Mass]
(i.e. suited for physics requiring “good detectors” rather “big detectors”)

Kuo-Sheng Nuclear Power Plant

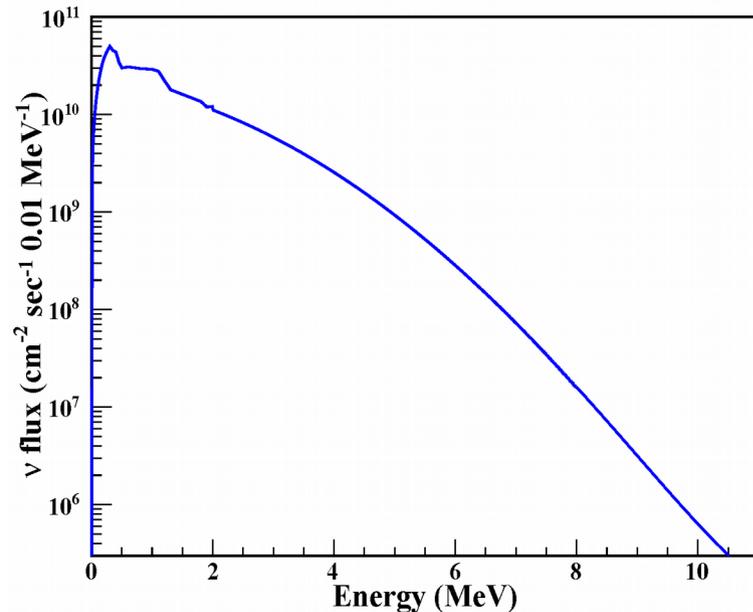
Total Capacity 2.9 GW each



Kuo-Sheng Nuclear Power Station : Reactor Building



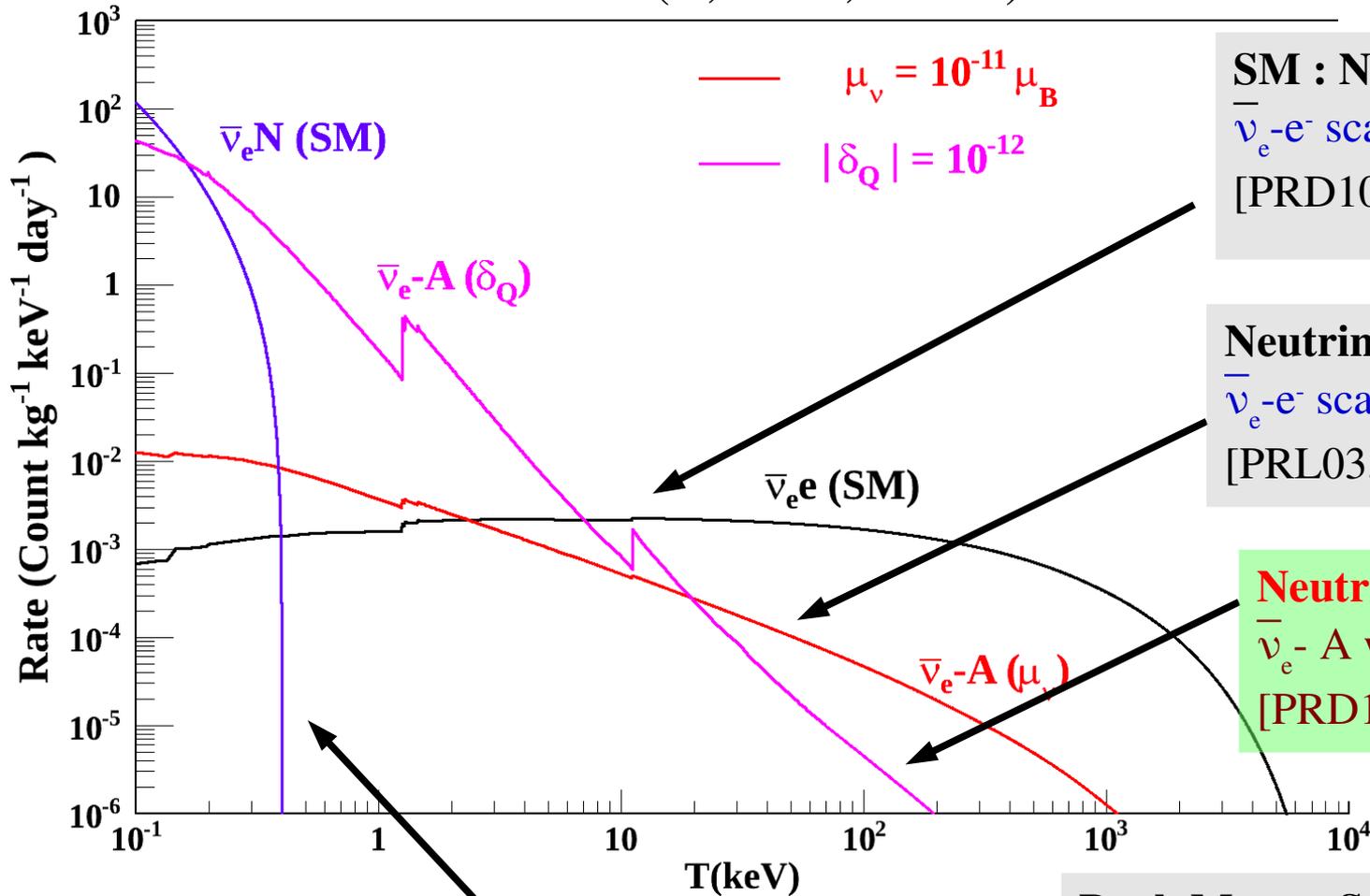
Reactor neutrino flux spectrum



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

TEXONO Physics Program : interactions by neutrino at reactor

recoil-(e⁻, atom, nuclei)



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]

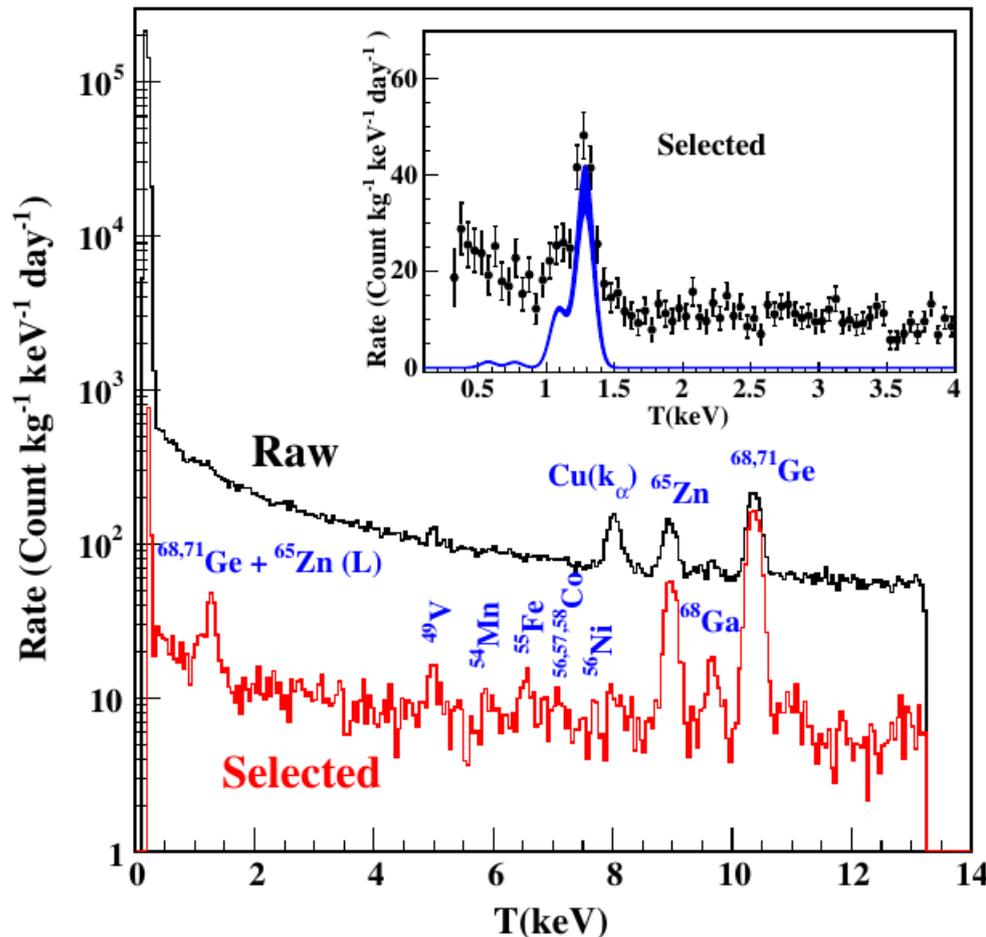
Axion at CJPL [PRD17]

Current threshold and background

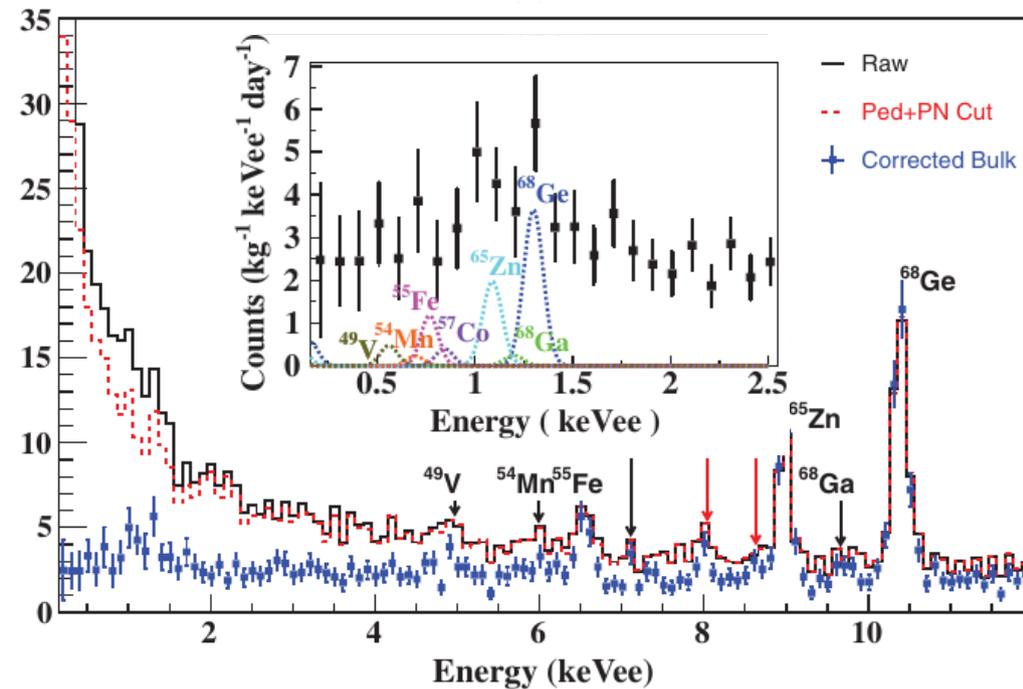
Lower electronic threshold with Point- Contact HPGe detectors

- Data available down to sub-keV measure-able energy
- Opportunity: Applying atomic physics at sub-keV

At KSNL Threshold of 300 eV_{ee}



At CJPL Threshold of 160 eV_{ee}



Phys. Rev. Lett., 120, 241301 (2018).

Neutrino interaction with atoms

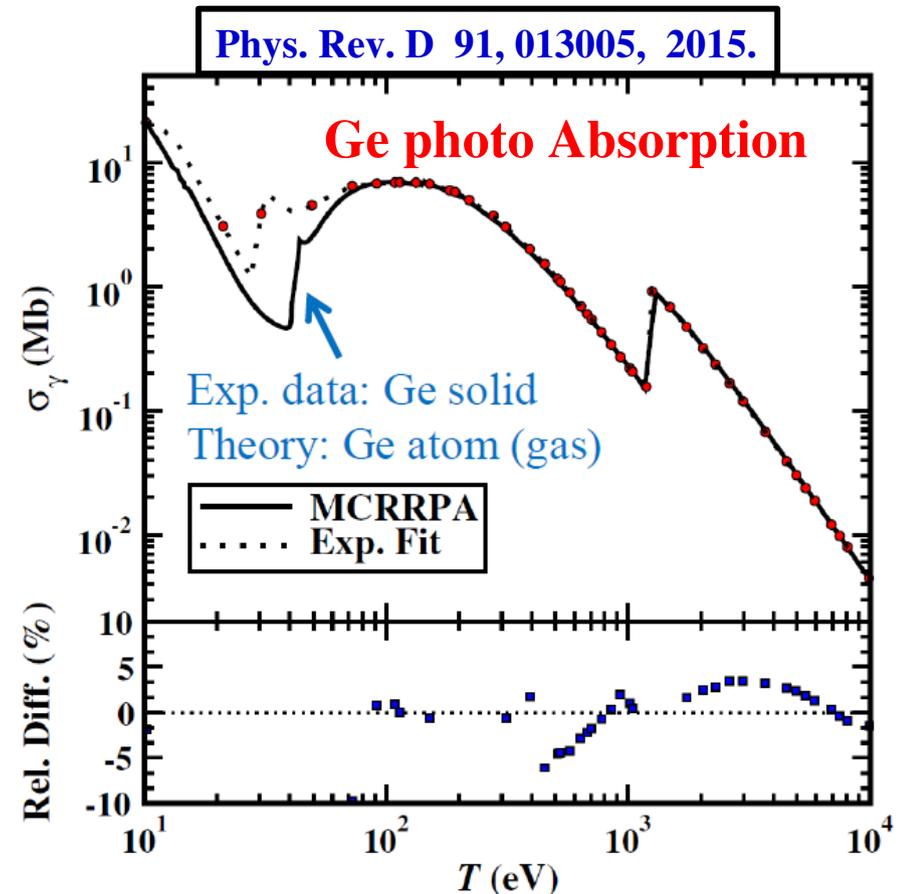
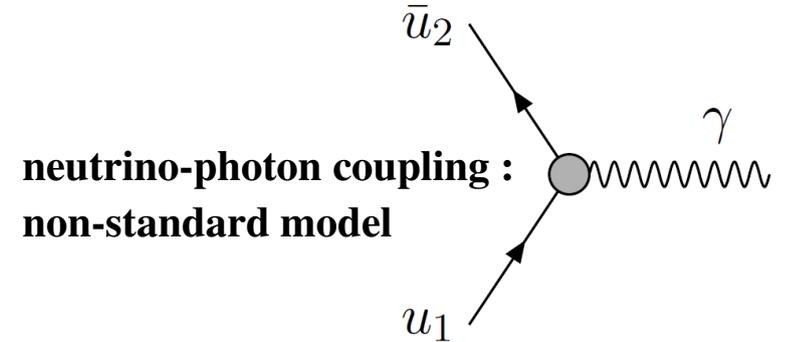
High energy : $\nu_e + e^- \rightarrow \nu_e + e^-$

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

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

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

- MRRPA 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 %



Neutrino Electromagnetic Form Factor

The complete set of neutrino electromagnetic form factors is:

1. Electric charge

2. Magnetic dipole moment

$$j_{\mu}^{\gamma} = \bar{\nu}(k_2, s_2) [F_1(q^2)\gamma_{\mu} - iF_2(q^2)i\sigma_{\mu\nu}q^{\nu} + F_3(q^2)\sigma_{\mu\nu}q^{\nu}\gamma_5 + F_4(q^2)(q^2\gamma_{\mu} - q_{\mu}\not{q})\gamma_5] \nu(k_1, s_1),$$

3. Electric dipole moment

4. Anapole moment

At $q^2 = 0$

$$F_1(0) = q, \quad F_2(0) = \mu, \quad F_3(0) = \epsilon, \quad F_4(0) = a,$$

The current best direct limits on

(q) neutrino millicharge,

(μ_{ν}) magnetic moments

→ **Ge-detectors with low thresholds at keV levels.**

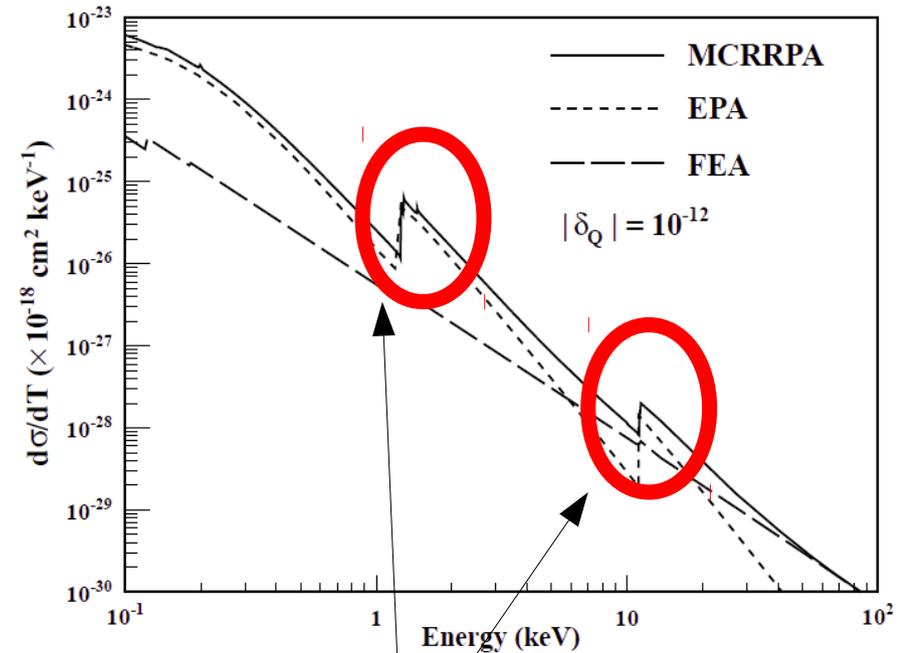
Neutrino milli-charge

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

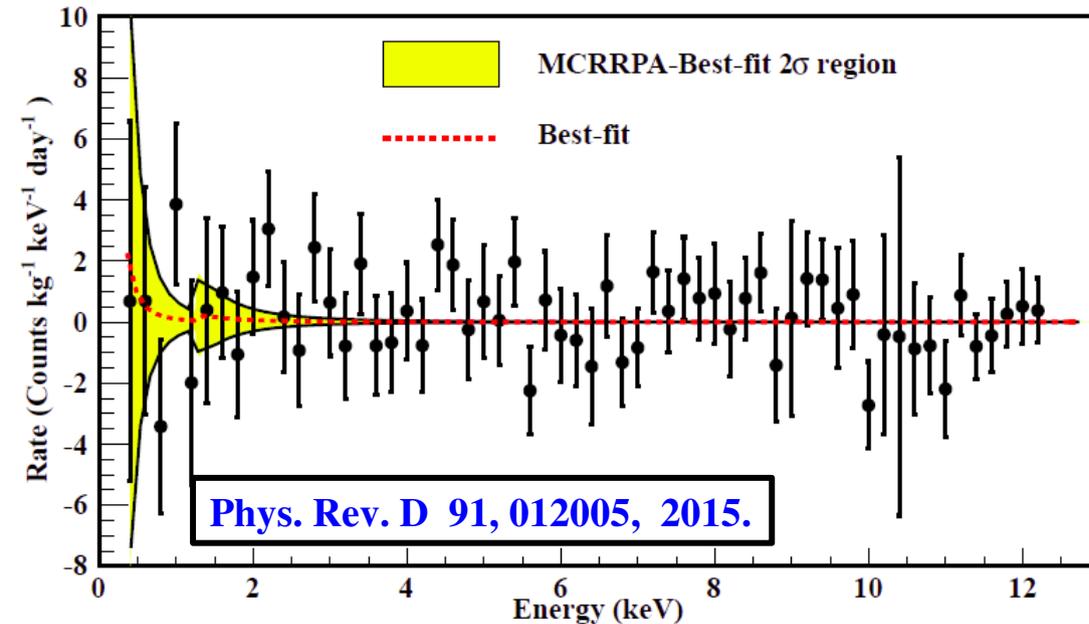
MCRRPA : Differential Cross-Section has enhancement at sub-keV.

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**



Neutrino Magnetic Moments

Search of μ_ν at low energy with Reactor $\bar{\nu}$ -e scattering

→ high signal rate & robustness:

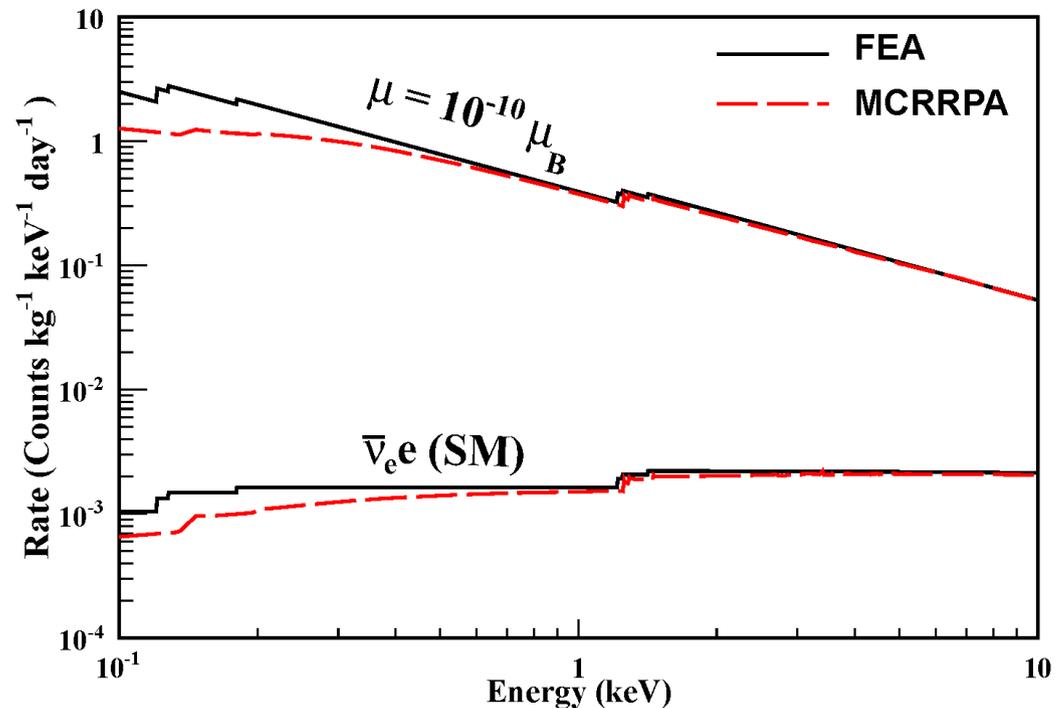
→ $\mu_\nu \gg \text{SM}$ [decouple irreducible bkg + unknown sources]

→ $T \ll E_\nu \rightarrow d\sigma/dT$ depends on total Φ_ν flux but NOT spectral shape

At $T \gg$ binding energy ,
MCRRPA agreed with FEA.

MCRRPA is $\sim 50\%$ smaller than
FEA at sub-keV

A slightly weaker limit on
 μ_ν (but more reliable)



TEXONO ($E_{\text{th}} = 12 \text{ keV}$)

$\mu_\nu < 7.4 \times 10^{-11} \mu_B$ at 90 % C. L.

GEMMA ($E_{\text{threshold}} = 2.8 \text{ keV}$)

$\mu_\nu < 2.9 \times 10^{-11} \mu_B$ at 90 % C. L.

Sterile Neutrino Magnetic Moment

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

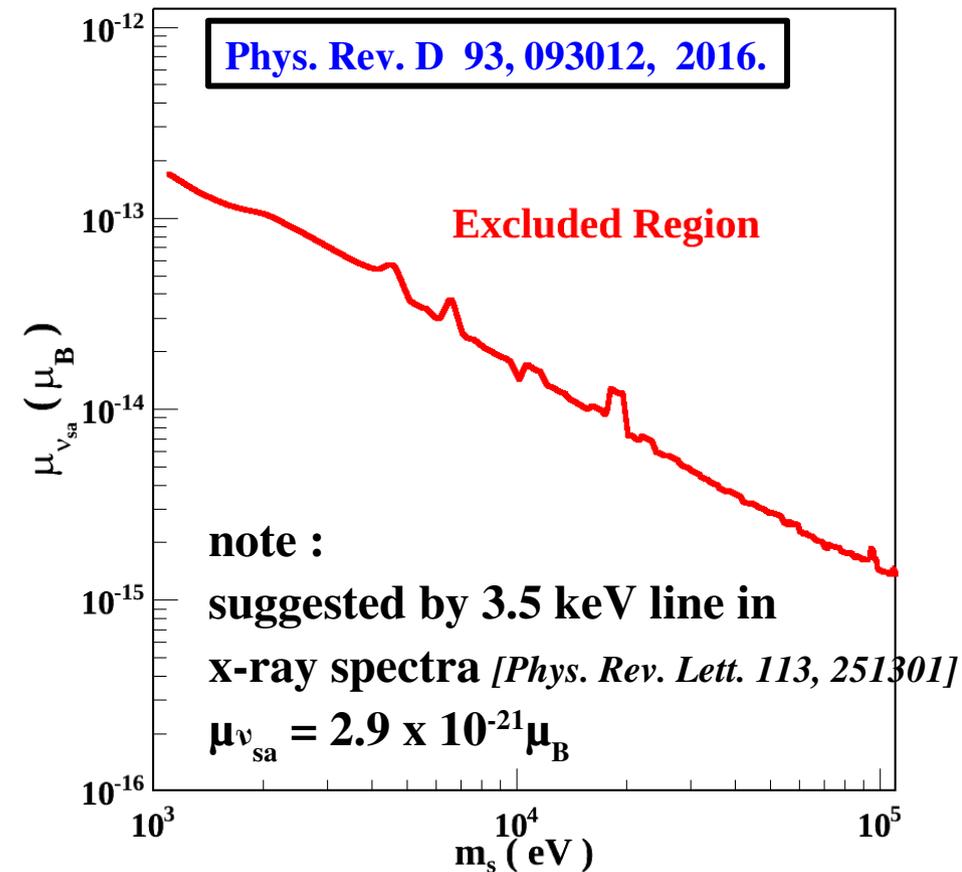
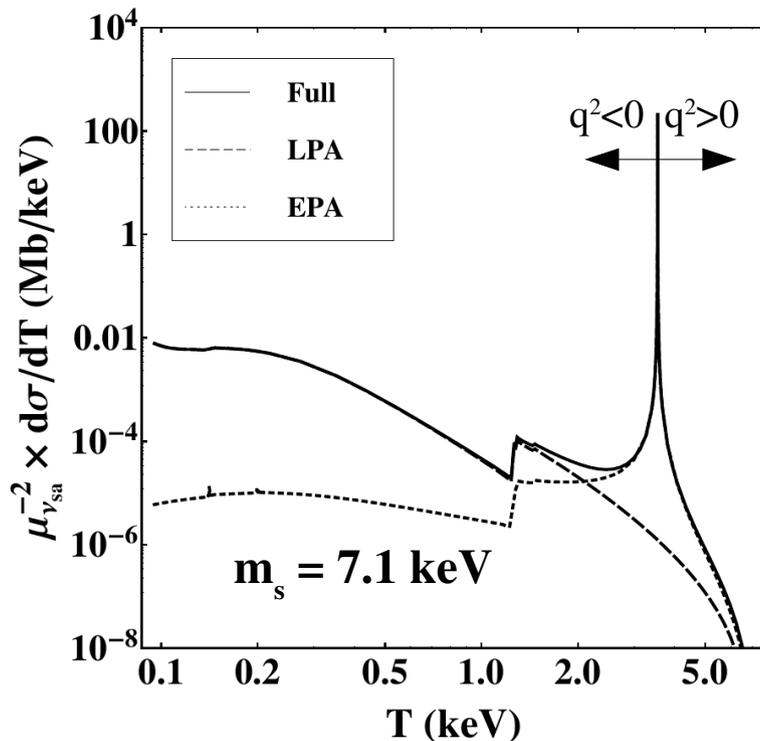
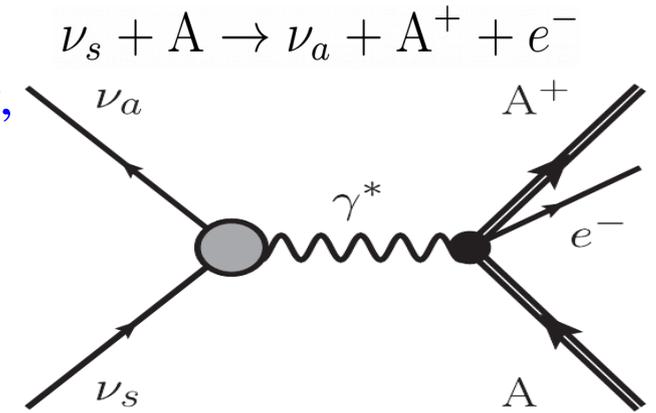
Under the assumption of sterile neutrino as cold dark matter,

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

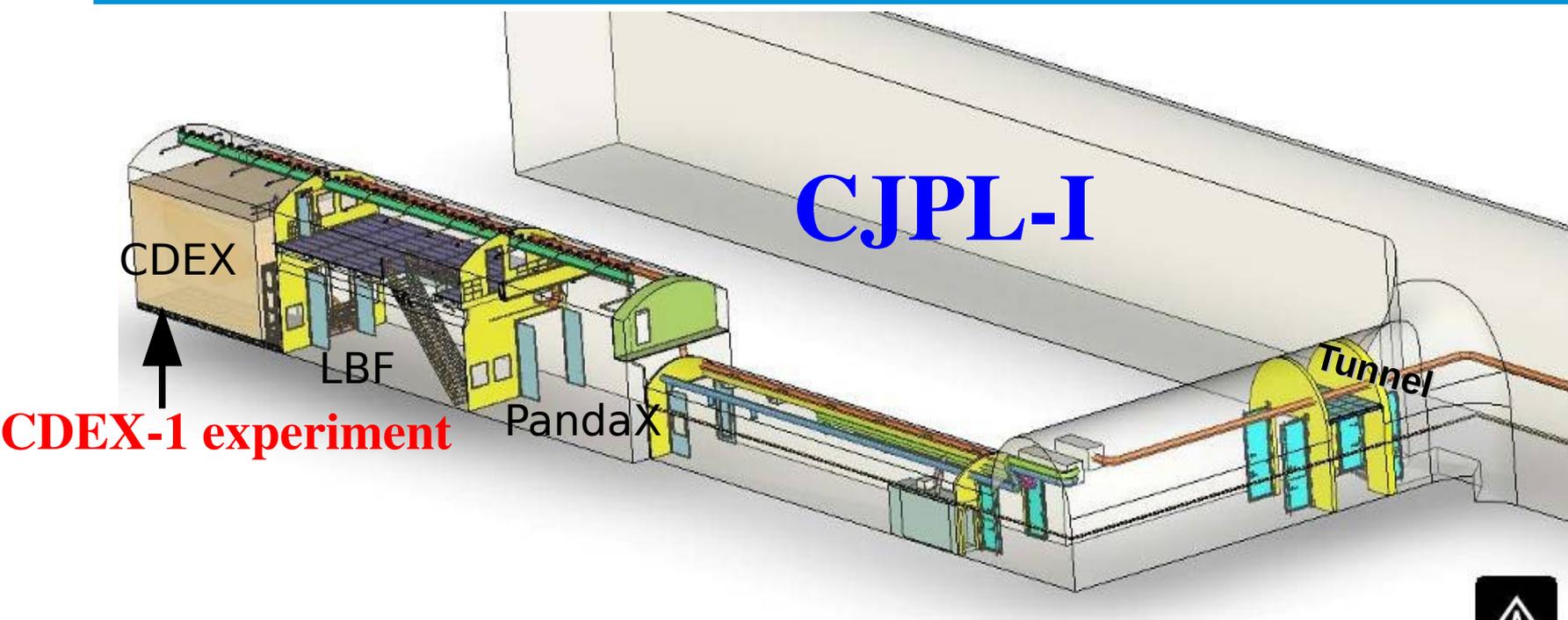
Non-Relativistic case

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

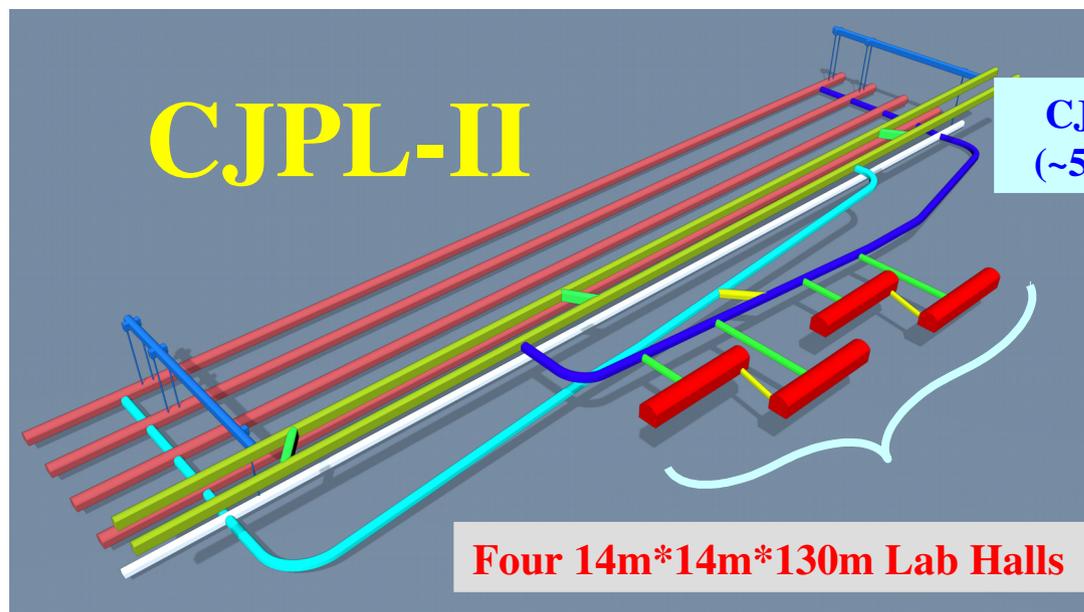
$q^2 < 0$: $\nu_a + A \rightarrow \nu_a + A^+ + e^-$, for all T



CDEX (CJPL-I and NEW Lab : CJPL-II)



CDEX-1 experiment



CJPL-I
(~500 m)

- plan :
 - ^{76}Ge double beta decay research
 - DM search : Sensitive in the range of 10GeV, $\sim 10^{-44} \text{ cm}^2$

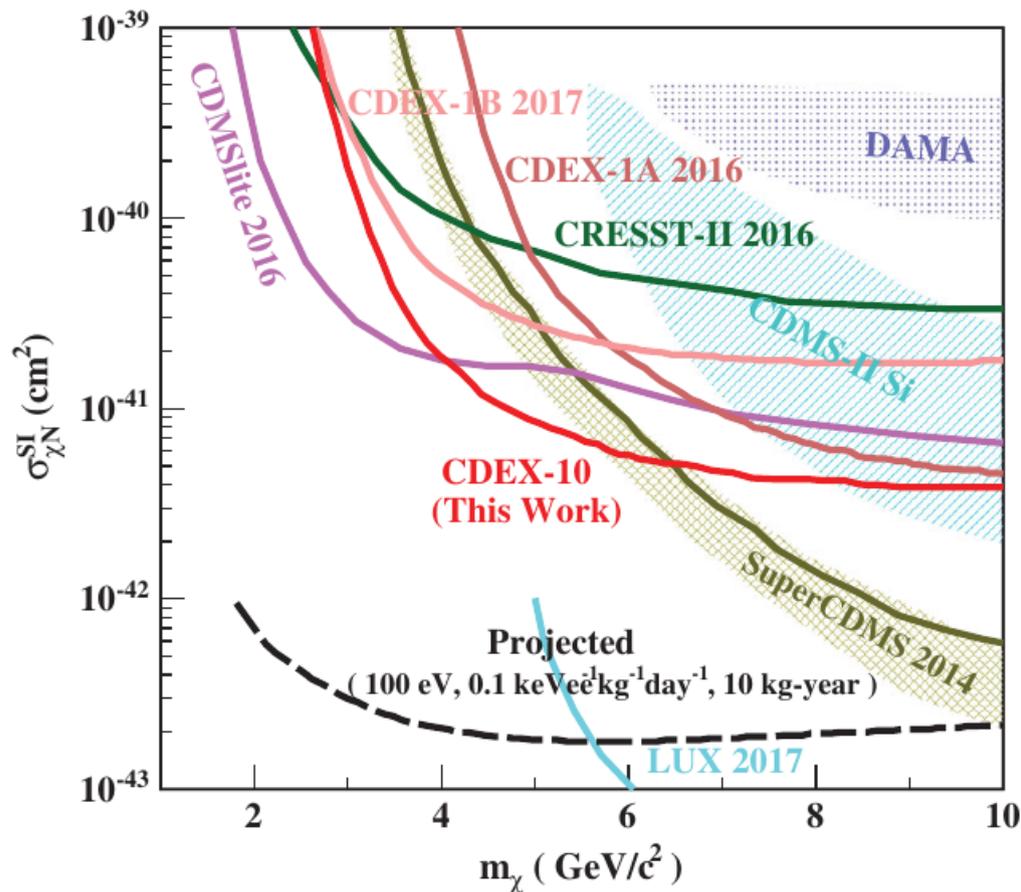
CDEX-1 Dark Matter Search

→ (Li Hau-Bin → 07/07 DM session at 16:30)

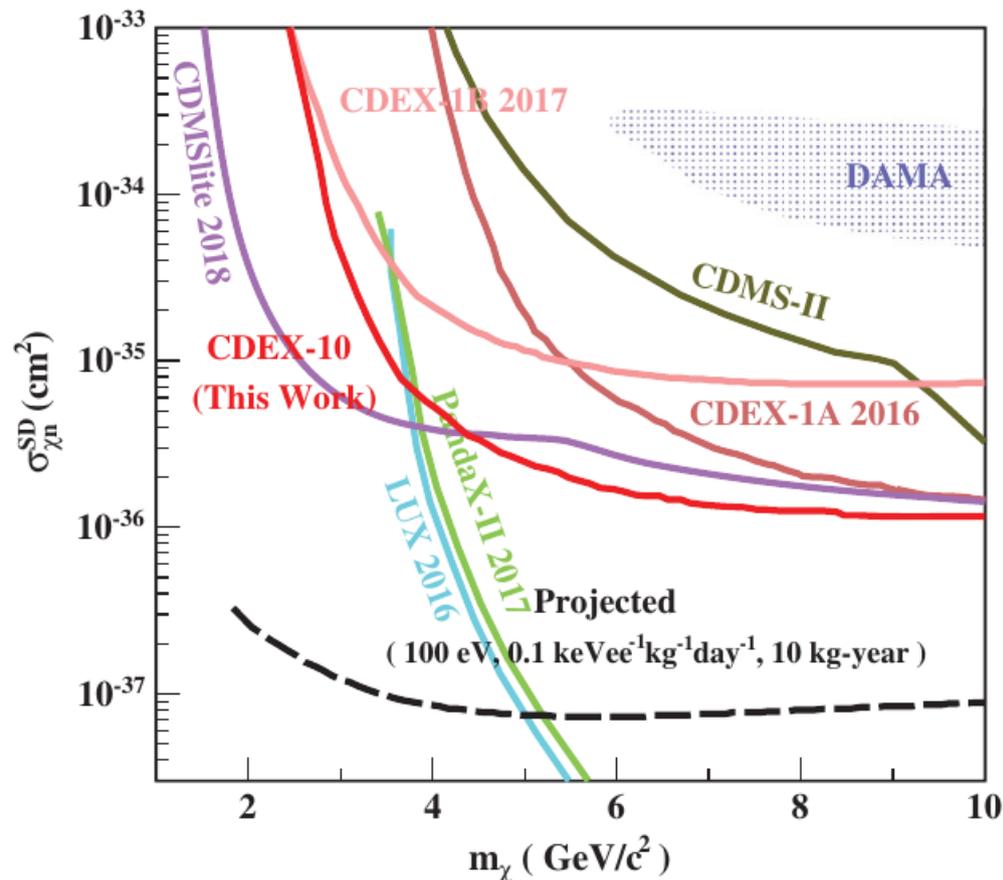
- 102.8 kg-days of data → CDEX-10 experiment with a 10 kg germanium detector
- Analysis threshold ~ 160 eV
- Q.F. adopted by TRIM software with 10% systematic uncertainty

Phys. Rev. Lett., 120, 241301 (2018).

Spin-independent



Spin-dependent



CDEX-1 Dark Matter Search

Solar axion :

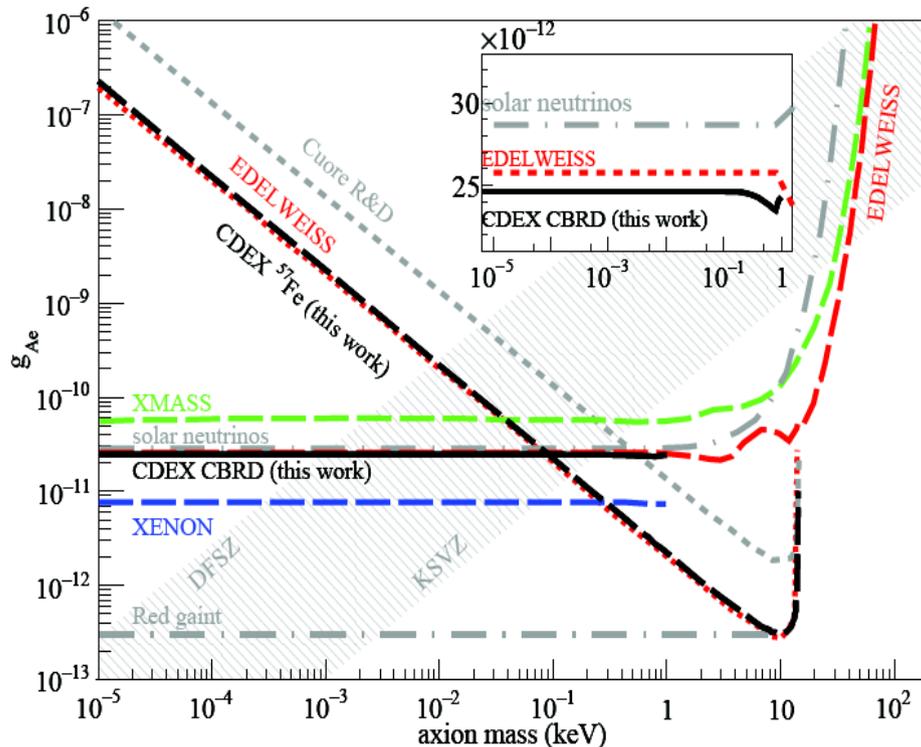
axion(a) from sun [g_{Ae}]

Compton(C): $\gamma+e \rightarrow e+a$

Bremsstrahlung(B): $e+Q \rightarrow e+Q+a$

Recombination(R): $e+I \rightarrow I+a$

De-excitation(D): $I^* \rightarrow I+a$

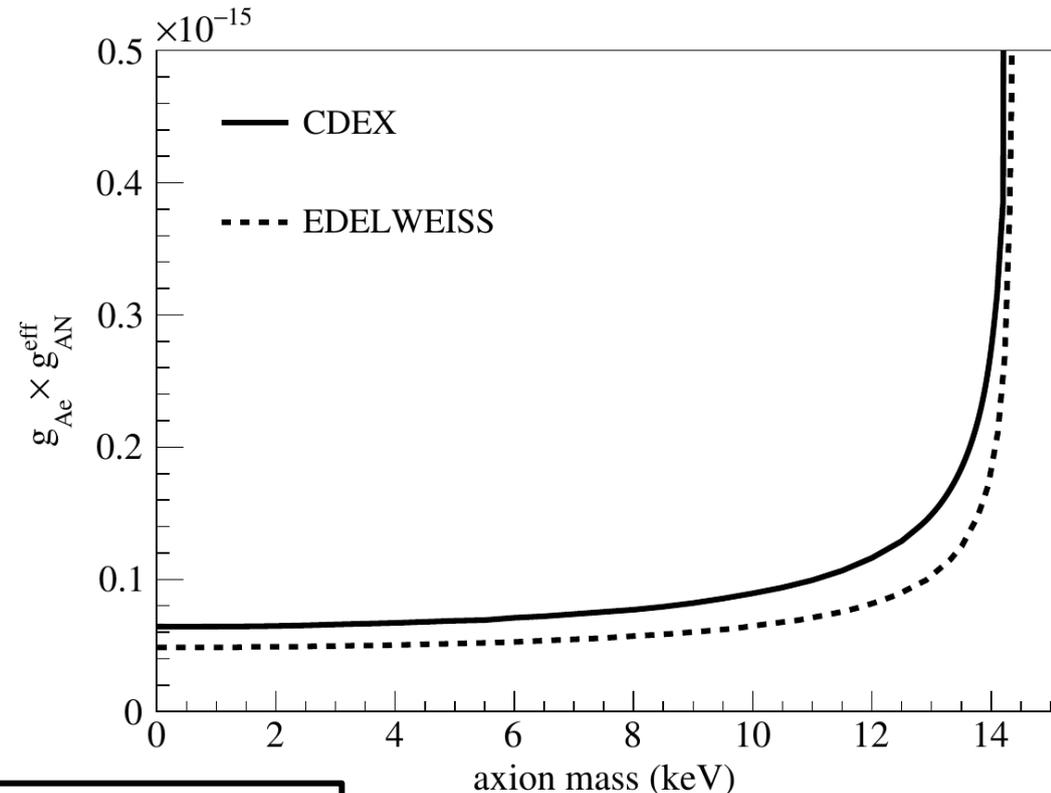


M1 transition from ^{57}Fe from Sun:

$$^{57}\text{Fe}^* \rightarrow ^{57}\text{Fe} + a \quad [g_{AN}^{\text{eff}}]$$

$$\Phi_{14.4} = \left(\frac{k_A}{k_\gamma}\right)^3 \times 4.56 \times 10^{23} (g_{AN}^{\text{eff}})^2$$

The model independent limit on $g_{AN}^{\text{eff}} \times g_{Ae}$



Search for bosonic super-WIMPs

Bosonic super-WIMPs is a lukewarm dark matter candidate
 : Motivated by Sterile neutrino, gravitino ...

Bosonic nature \longrightarrow they would deposit all energy essentially including their rest mass.

• Pseudoscalar case :

$$\frac{\sigma_{abs} v}{\sigma_{photo}(\omega = m_a) c} \simeq \frac{3m_a^2}{4\pi\alpha f_a^2}$$

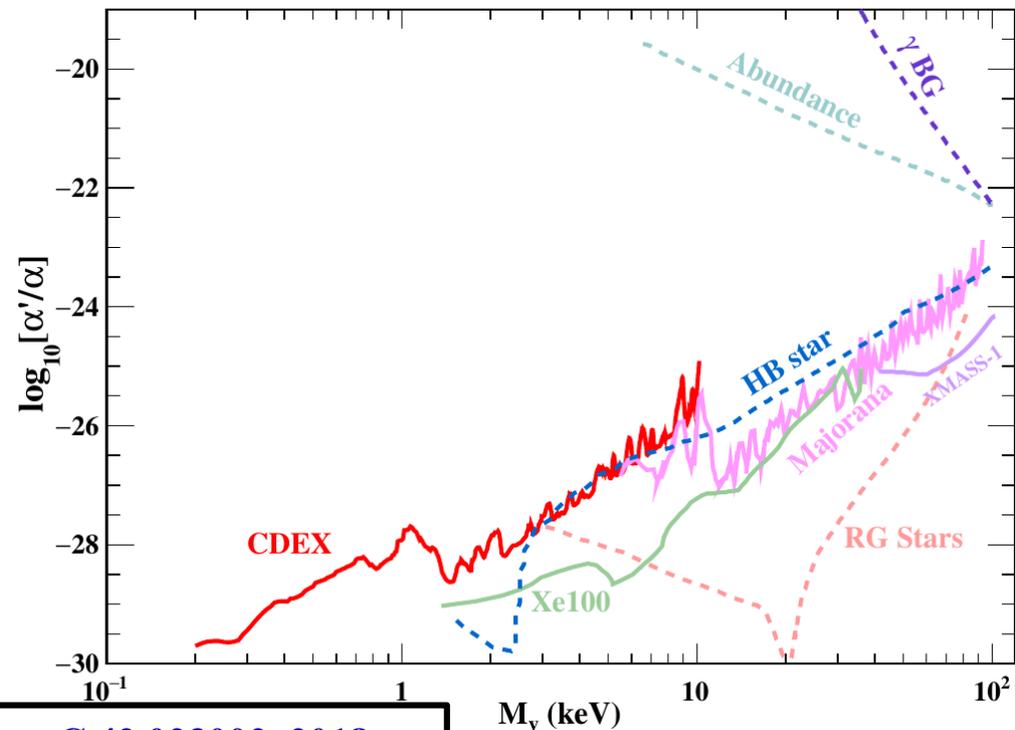
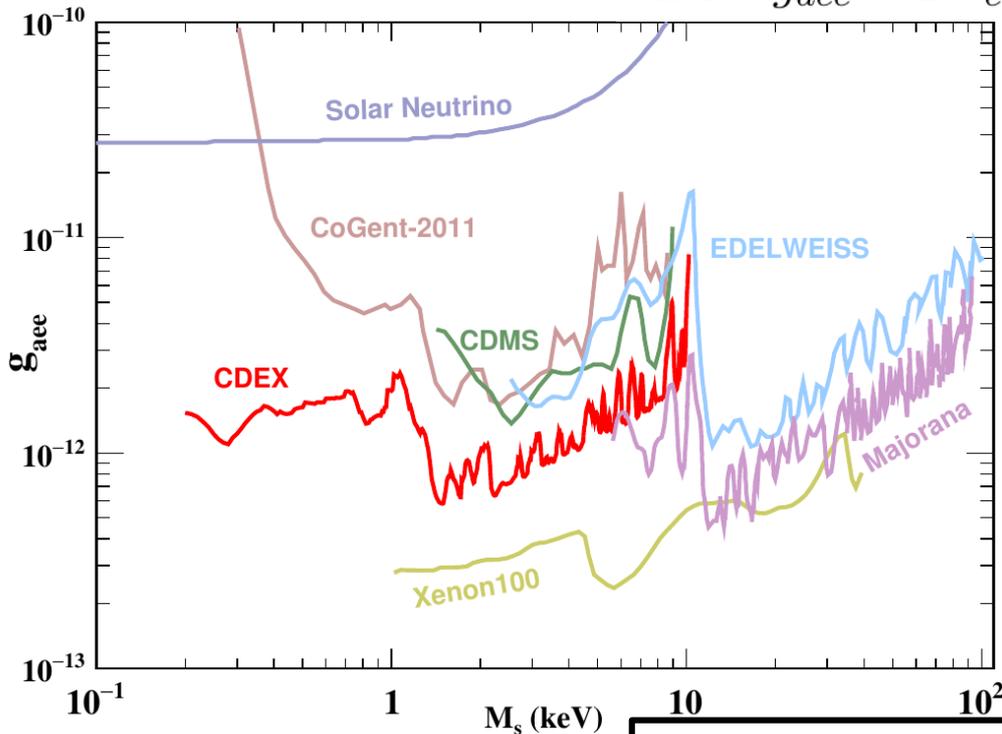
$$S_a = \frac{1.2 \times 10^{19}}{A} g_{aee}^2 \left(\frac{m_a}{\text{keV}} \right) \left(\frac{\sigma_{photo}}{\text{barn}} \right) \text{kg}^{-1} \text{day}^{-1}$$

where $g_{aee} = 2m_e/f_a$

• Vector boson case :

$$\frac{\sigma_{abs} v}{\sigma_{photo}(\omega = m_V) c} \simeq \frac{\alpha'}{\alpha}$$

$$S_V = \frac{4 \times 10^{23}}{A} \frac{\alpha'}{\alpha} \left(\frac{\text{keV}}{m_V} \right) \left(\frac{\sigma_{photo}}{\text{barn}} \right) \text{kg}^{-1} \text{day}^{-1}$$



Data from Chinese Phys. C 42 023002, 2018

Future Prospects

- ***Ab initio* many-body (MCRRPA) calculations for Ge & Xe atomic ionization performed with ~5% estimated error.**
 - **This atomic tool indispensable to study DM detector response to light DM signal and neutrino background.**
 - **Study on solar neutrino backgrounds in DM detection,**
- **Dark Cosmic Ray.....**
 - **Dark fermions couple to both dark photon and photon fields
→ carry a millicharge**
 - **charged DM accelerated by supernovae remnants**
 - **[JCAP 0907:014,2009]**
→ Dark Cosmic Rays

Summary

- **sub-keV Ge :**
 - New electro-cooled detector,
~ 200 eV threshold (KSNL) and 160 eV at CJPL
- **Neutrino:**
 - **Electromagnetic properties**
 - 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
 $\nu_s + A$ scattering , relevant for DM
- **Underground Lab:**
 - Ge-Techniques at CJPL
 - New axion results from CDEX@CJPL-I
 - CJPL-II commissioned soon

Pauli Exclusion Violating Decay

The Pauli exclusion principle (PEP) is a fundamental law of physics, but its physical origin is not well understood.

PEP violating transition from L-shell electron to fully occupied K-shell would manifest as x-ray line at 10.6 keV

Upper limit at 90% C L

$$< 0.025 \text{ counts kg}^{-1} \text{ day}^{-1}$$

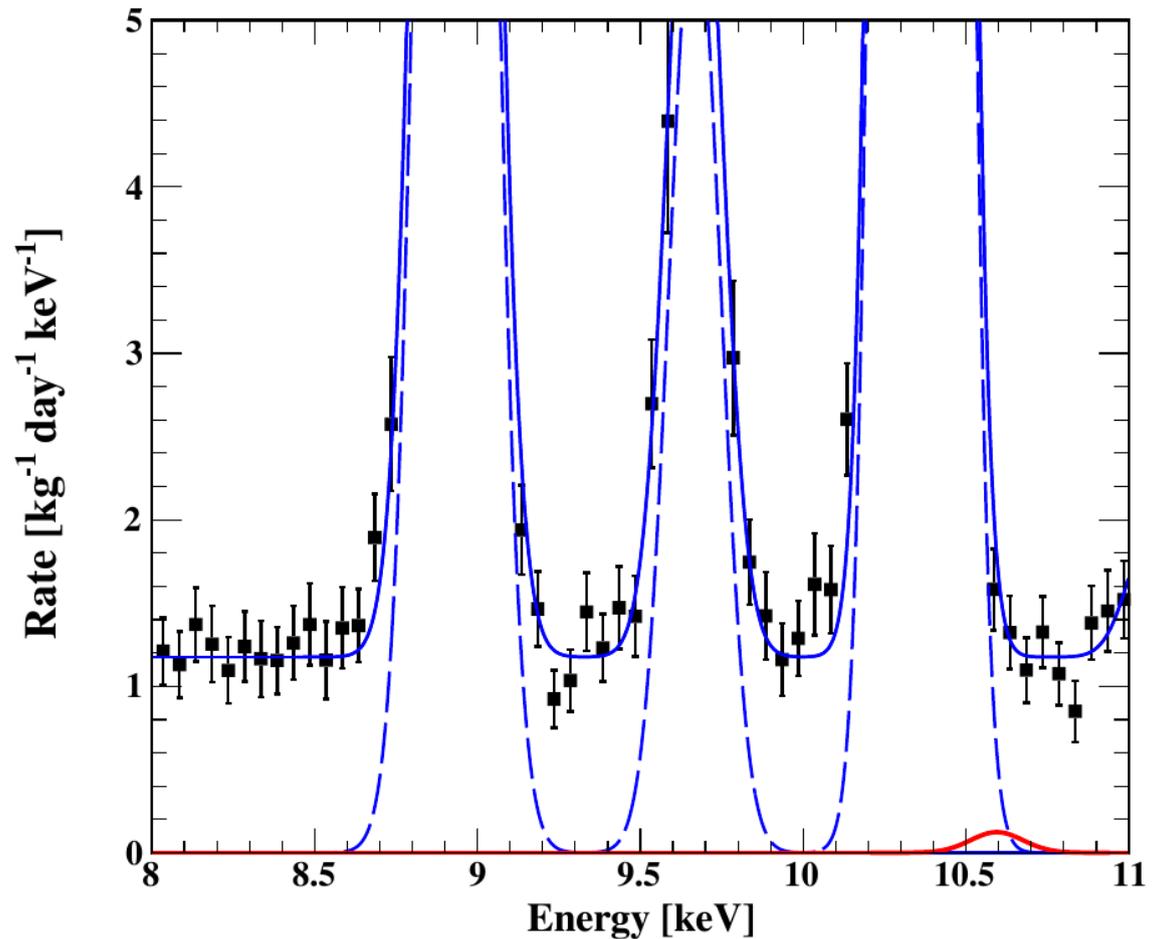
$$\tau > 2.8 \times 10^{30} \text{ sec}$$

Ge (k_{α}) Standard transition lifetime is

$$\tau = 1.7 \times 10^{-16} \text{ sec}$$

PEPV parameter

$$\beta^2/2 < 6.5 \times 10^{-48}$$



Data from Chinese Phys. C 42 023002, 2018

$$\text{DAMA/LIBRA } \beta^2/2 < 1.28 \times 10^{-47}$$

$$\text{MAJORANA } \beta^2/2 < 8.5 \times 10^{-48}$$