Atomic corrections for direct detection of neutrinos and dark matters

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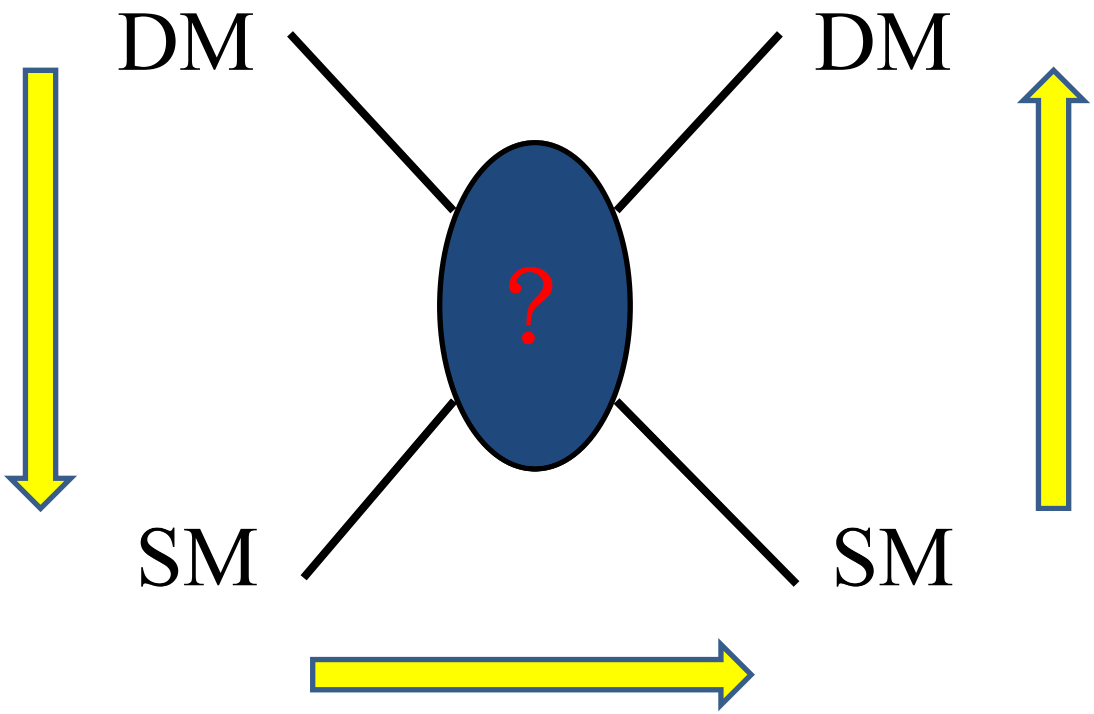
(NCTS Experimental Collaboration Program 2)

Strategies: Search for Dark Matters

indirect detection

search for annihilation or decay products of DMs



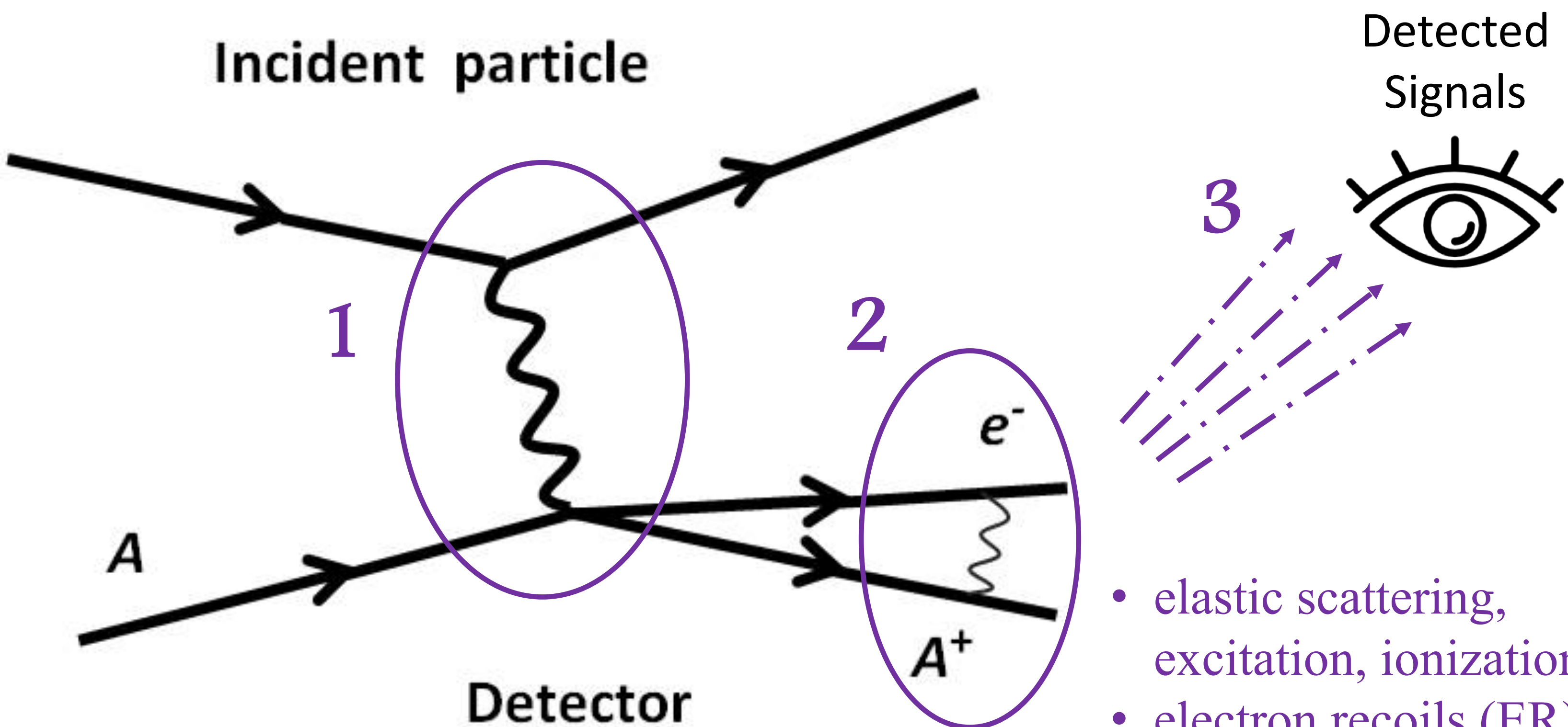
accelerator production

Ex: LHC

direct detection

Using Semiconductor (Ex: high-purity Ge) or scintillator (Ex: liquid-Xe or crystal) to detect the existence of DM.

Scattering Diagrams and Detector Response



- elastic scattering, excitation, ionization
- electron recoils (ER) or nucleus recoils (NR)

1. **The particle-detector interaction**
2. ***dσ/dT*** **for the primary scattering process**
3. **The following energy loss mechanism**

DM Effective Interaction with Electron or Nucleons

Leading order (LO):

short range

$$\mathcal{L}_{\rm int}^{(\rm LO)} = \sum_{f=e,p,n} \Big\{ c_1^{(f)} (\chi^\dagger \chi)(f^\dagger f) + c_4^{(f)} (\chi^\dagger \vec{S}_\chi \chi) \cdot (f^\dagger \vec{S}_f f) + d_1^{(f)} \frac{1}{q^2} (\chi^\dagger \chi)(f^\dagger f) + d_4^{(f)} \frac{1}{q^2} (\chi^\dagger \vec{S}_\chi \chi) \cdot (f^\dagger \vec{S}_f f) \Big\}$$

spin-indep. long range spin-dep.

Differential cross section for spin-independent contact interaction with electron ($c_1^{(e)}$) :

$$d\sigma\big|_{c_1^{(e)}} = \frac{2\pi}{v_\chi} \sum_F \overline{\sum_I} \left| \langle F | c_1^{(e)} e^{i \frac{\mu}{m_e} \vec{q} \cdot \vec{r}} | I \rangle \right|^2 \times \delta(T - E_{\rm c.m.} - (E_F - E_I)) \frac{d^3 k_2}{(2\pi)^3}$$

Initial & final states of detector material

Source : DM v.s. Neutrino

- Neutrino
  - $m_\nu \to 0,\ E_\nu \sim k_\nu$ (few keV ~ MeV)
  - For given energy transfer T, 3-momentum transfer region:

    $T < Q < 2E_\nu - T$ $\quad q^2 < 0$

- Cold Dark Matter
  - $m_\chi >> m_e,\ E_\chi \sim 1/2\, m_\chi v_\chi^2,\ k_\chi \sim m_\chi v_\chi$
  - For given energy transfer T, 3-momentum transfer region:

    $m_\chi v_\chi - (m_\chi^2 v_\chi^2 - 2m_\chi T)^{1/2} \sim m_\chi v_\chi + (m_\chi^2 v_\chi^2 - 2m_\chi T)^{1/2}$

    >> outgoing electron momentum

    because $2m_e T << 2m_\chi T < m_\chi^2 v_\chi^2$ $\quad q^2 << 0$

Atomic Response Function

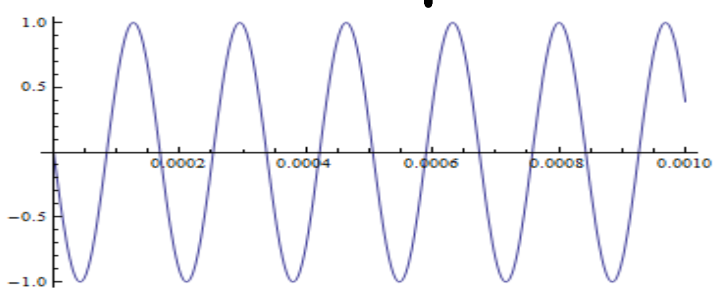
$$R_L \equiv \sum_{m_{j_f}} \overline{\sum_{m_{j_i}}} \int \frac{d^3\vec{p}_r}{(2\pi)^3} |\langle f|\rho^{(A)}(\vec{q})|i\rangle|^2 \delta\left(T - B - \frac{q^2}{2M} - \frac{p_r^2}{2\mu_{\mathrm{red}}}\right)$$

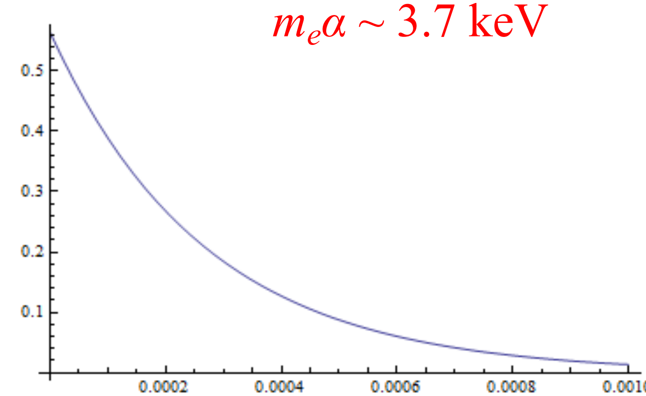
Continuous WF:
$\propto \mathrm{Exp}[i\, p_r\, r]$
$p_r = (2m_e T)^{1/2}$

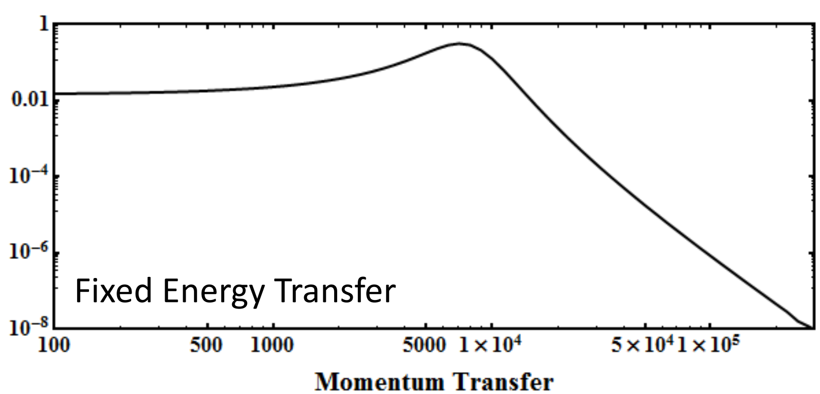
$$\rho^{(e)}(\vec{q}) = e^{i\frac{\mu}{m_e}\vec{q}\cdot\vec{r}}$$ Highly oscillated

$$\rho^{(p)}(\vec{q}) = e^{-i\frac{\mu}{m_p}\vec{q}\cdot\vec{r}}$$ 1/2000 smaller

bound WF:
$\propto \mathrm{Exp}[-Z\, m_e \alpha\, r]$
$m_e \alpha \sim 3.7\ \mathrm{keV}$





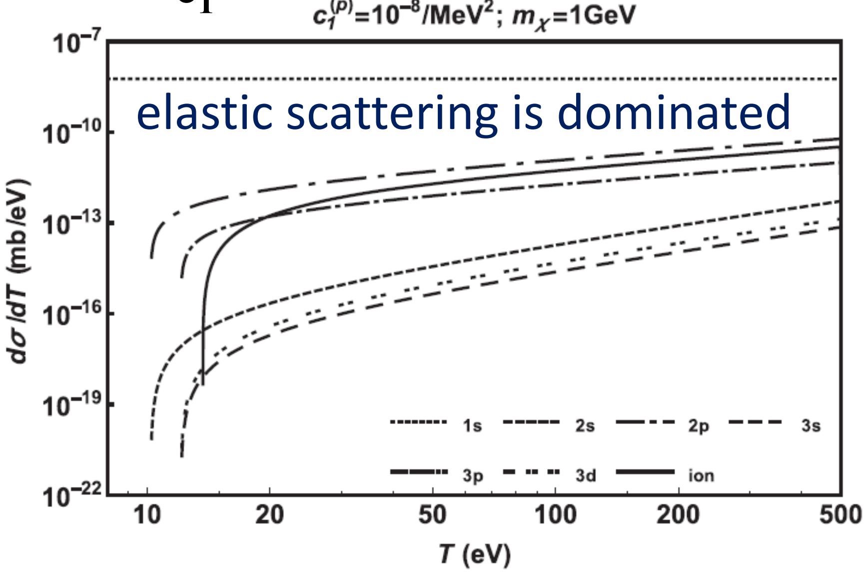


Maximum contribution when $p_r \sim \mu/m\; q >> Z\, m_e \alpha$

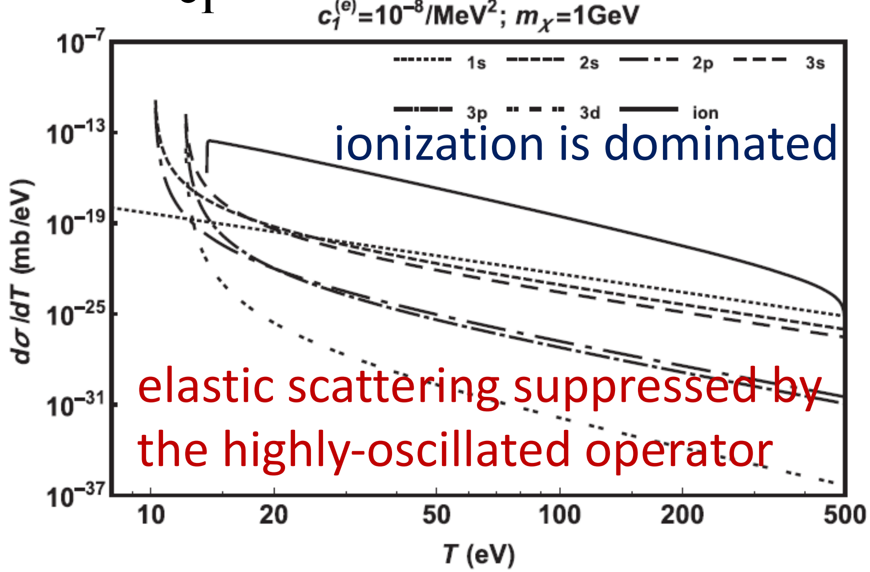
NR v.s. ER : Hydrogen Toy Model

Spin-independent contact interaction with proton and electron

$c_1^{(p)}$



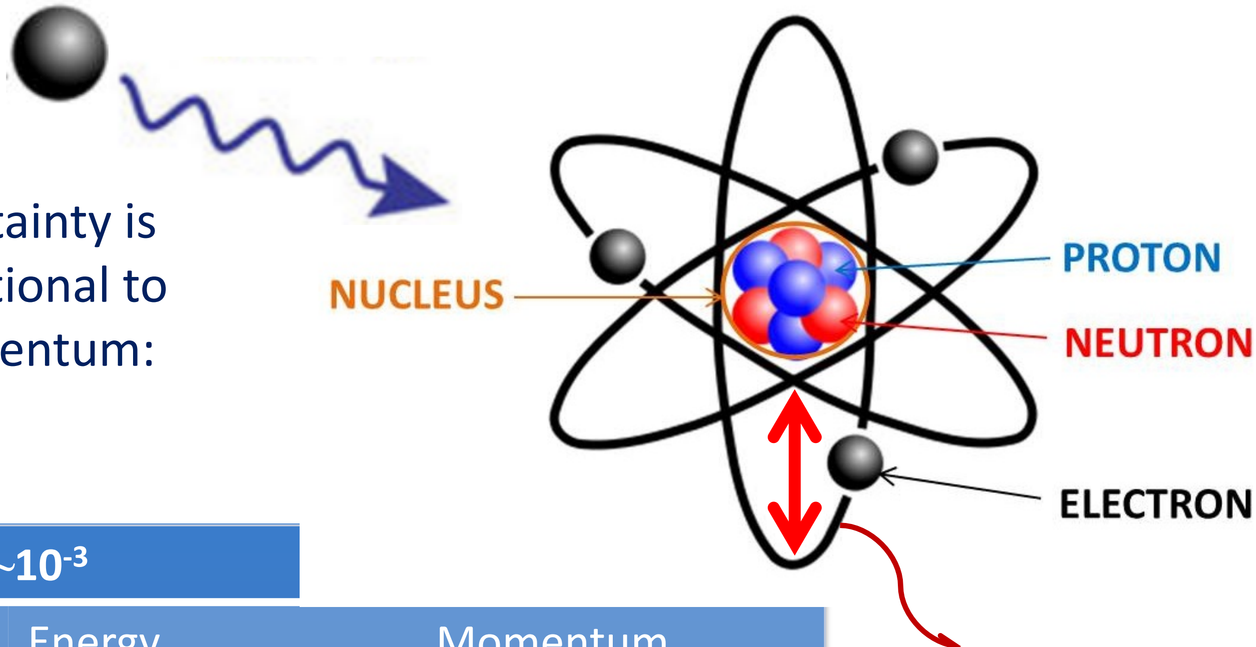
$c_1^{(e)}$



But in free electron case, this suppression doesn't exist, will be wrong for interactions with electron.

➡ Free electron assumption will be several orders of magnitude over estimation for ER

Why we study Atomic Response ?



The space uncertainty is inversely proportional to its incident momentum:

$\lambda \sim 1/p$

LDM with velocity ~10^{-3}		
Mass	Energy	Momentum
1 GeV	m_χ + 500 eV	1 MeV
100 MeV	m_χ + 50 eV	100 keV
Neutrino Sources		
Reactor ν	~ few MeV	Same as energy
Solar ν (pp)	~ few hundred keV	Same as energy

Atomic size is related to its orbital momentum:

$Z m_e \alpha \sim Z$*3.7 keV

Z: effective charge

When atomic structures should be considered (free target approx. fail)?

- Incident momentum ~ 100 keV and below
  - The wavelengths of incident particles are about the same order with the size of the atom.
  - For Innermost orbital, the related momentum $\sim Z m_e \alpha \sim Z * 3$ keV (Z = effective nuclear charge)
- Energy transfer ~ 10 keV and below
  - barely overcome the atomic thresholds
  - For Innermost orbital, binding energy ~ 11 keV (Ge) and 34 keV (Xe)
- Strong phase-space suppression for DM-e scattering

Ab initio Theory for Atomic States

MCDF: multiconfiguration Dirac-Fock method

Dirac-Fock method: $\psi(t)$ is a Slater determinant of one-electron orbitals $u_a(\vec{r},t)$

and invoke variational principle $\delta\langle\overline{\psi}(t)|\, i\frac{\partial}{\partial t} - H - V_I(t)\,|\psi(t)\rangle = 0$

to obtain eigenequations for $u_a(\vec{r},t)$.

multiconfiguration: Approximate the many-body wave function $\Psi(t)$

by a superposition of configuration functions $\psi_\alpha(t)$

$$\Psi(t) = \sum_\alpha C_\alpha(t)\,\psi_\alpha(t)$$

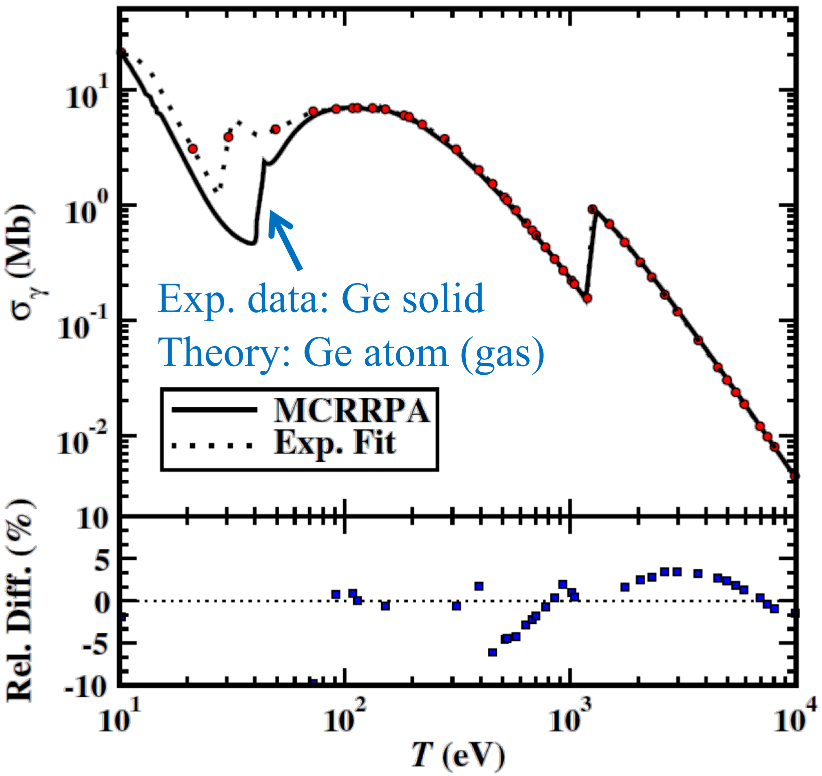
MCRRPA: multiconfiguration relativistic random phase approximation

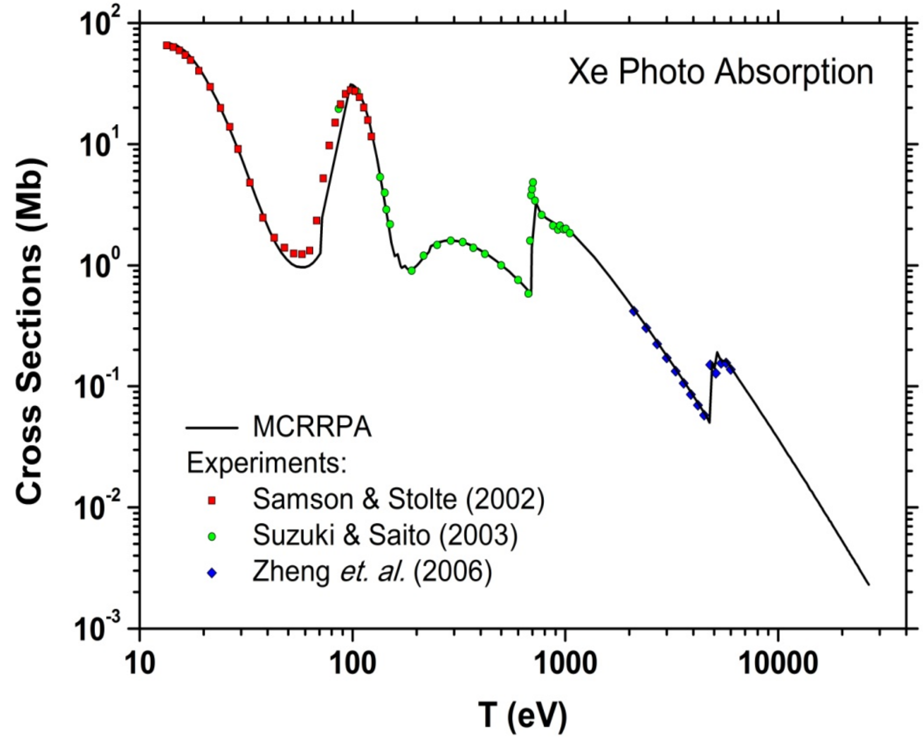
RPA: Expand $u_a(\vec{r},t)$ into time-indep. orbitals in power of external potential

$$u_a(\vec{r},t) = e^{i\varepsilon_a t}\left[u_a(\vec{r}) + w_{a+}(\vec{r})e^{-i\omega t} + w_{a-}(\vec{r})e^{i\omega t} + \ldots\right]$$

$$C_a(t) = C_a + [C_a]_+ e^{-i\omega t} + [C_a]_- e^{i\omega t} + \ldots$$

Benchmark : Ge & Xe Photoionization





Above 100 eV error under 5%.

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I. H. Suzuki and N. Saito, J. Electron Spectrosc. Relat. Phenom. **129**, 71 (2003).

L. Zheng *et al*., J. Electron Spectrosc. Relat. Phenom. **152**, 143 (2006).

Recent Outputs

- Constraints on millicharged particles with low threshold germanium detectors at Kuo-Sheng Reactor Neutrino Laboratory
  @Lakhwinder Singh, 11:05 Dec. 29
- Constraints on spin-independent dark matter scattering off electrons with germanium and xenon detectors @Mukesh Kumar Pandey, 12:05 Dec. 30
- Discovery Power of Multi-ton Xenon Detectors in Light Dark Matter Searches and Exotic Neutrino Properties @Chung-Chun Hsieh, 14:45 Dec. 31

Thanks for your attention !!

Related Talks:

Lakhwinder Singh, 11:05 Dec. 29

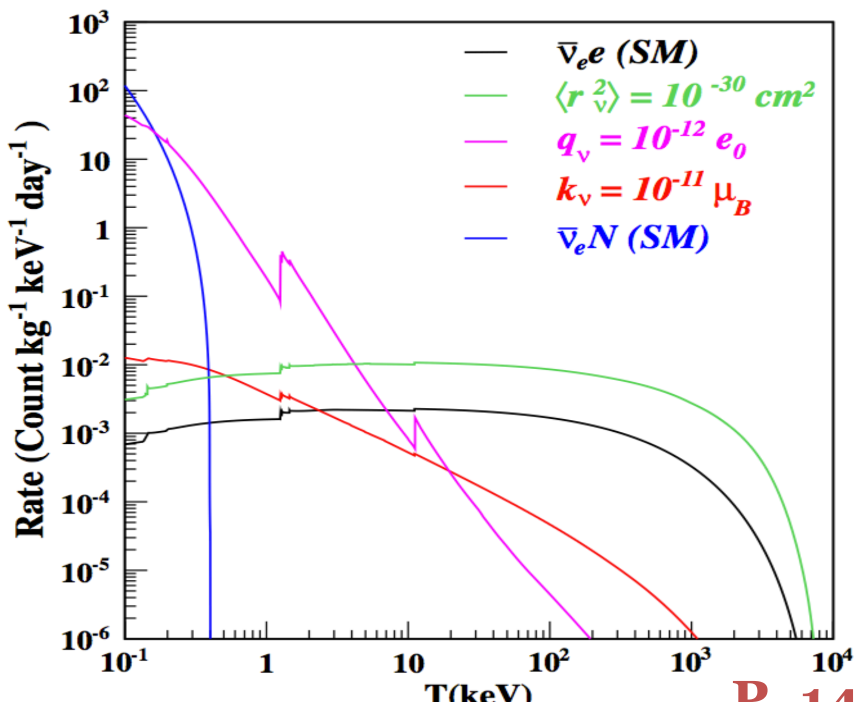
Mukesh K. Pandey, 12:05 Dec. 30

Chung-Chun Hsieh, 14:45 Dec. 31

Applications I: Neutrino EM Properties

Data set	Reactor-$\bar{\nu}_e$ Flux ($\times 10^{13}$ cm^{-2} s^{-1})	Data strength Reactor on/off (kg-days)	Analysis Threshold (keV)	Bounds at 90% C.L. $\kappa_{\bar{\nu}_e}^{(\mathrm{eff})}$ ($\times 10^{-11} \mu_B$)	$q_{\bar{\nu}_e}$ ($\times 10^{-12}$)	$\langle r_{\bar{\nu}_e}^2 \rangle^{(\mathrm{eff})}$ ($\times 10^{-30}$ cm^2)
TEXONO 187 kg CsI [9]	0.64	29882.0/7369.0	3000	< 22.0	< 170	< 0.033
TEXONO 1 kg Ge [5,6]	0.64	570.7/127.8	12	< 7.4	< 8.8	< 1.40
GEMMA 1.5 kg Ge [7,8]	2.7	1133.4/280.4	2.8	< 2.9	< 1.1	< 0.80
TEXONO point-contact Ge [4,17]	0.64	124.2/70.3	0.3	< 26.0	< 2.1	< 3.20
Projected point-contact Ge	2.7	800/200	0.1	< 1.7	< 0.06	< 0.74
Sensitivity at 1% of SM	...	...	...	~ 0.023	~ 0.0004	~ 0.0014

微中子 臺灣實驗 TEXONO Taiwan EXperiment On NeutrinO



Reference:
Phys. Lett. B **731**, 159, arXiv:1311.5294 (2014).
Phys. Rev. D **90**, 011301(R), arXiv:1405.7168 (2014).
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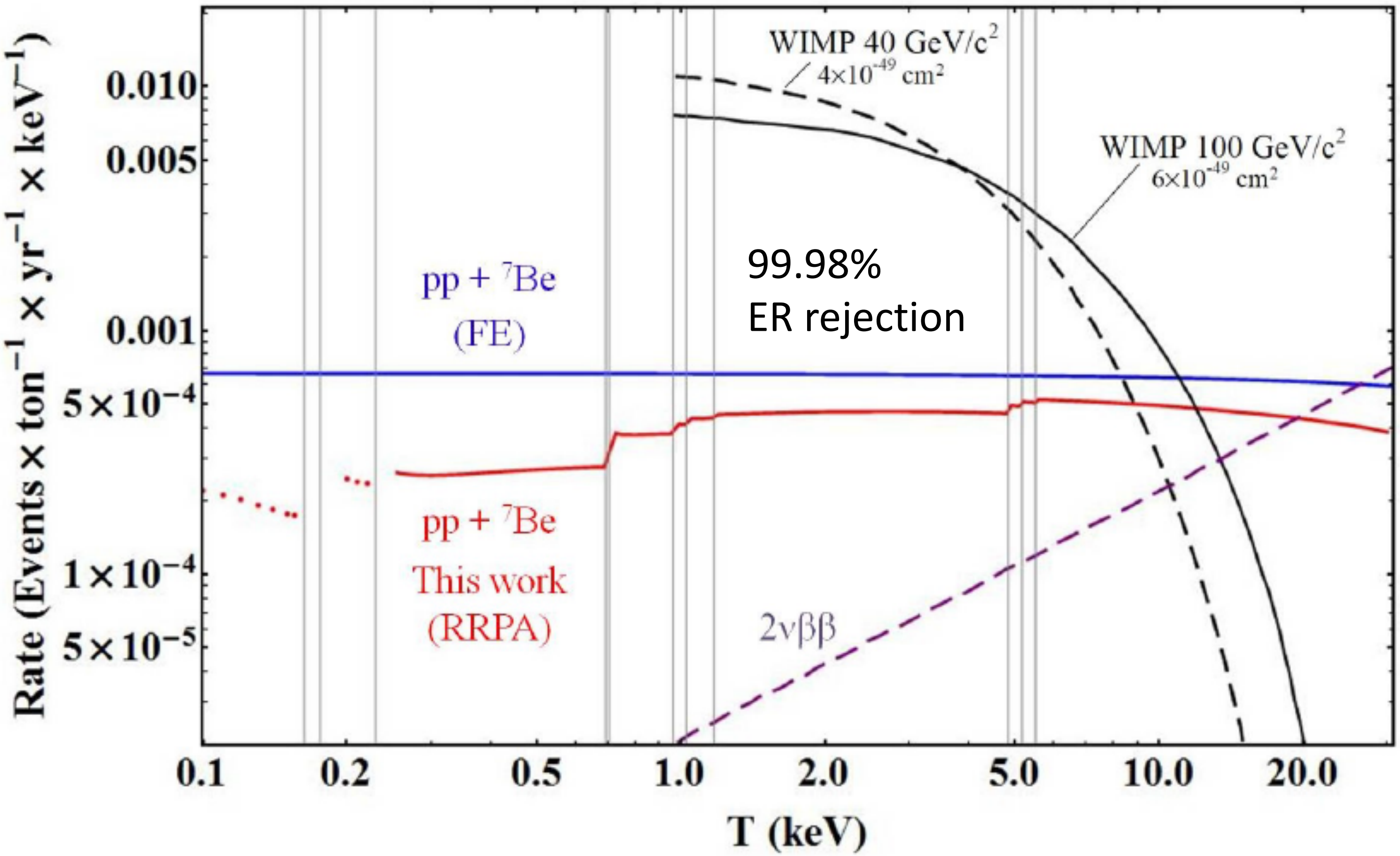
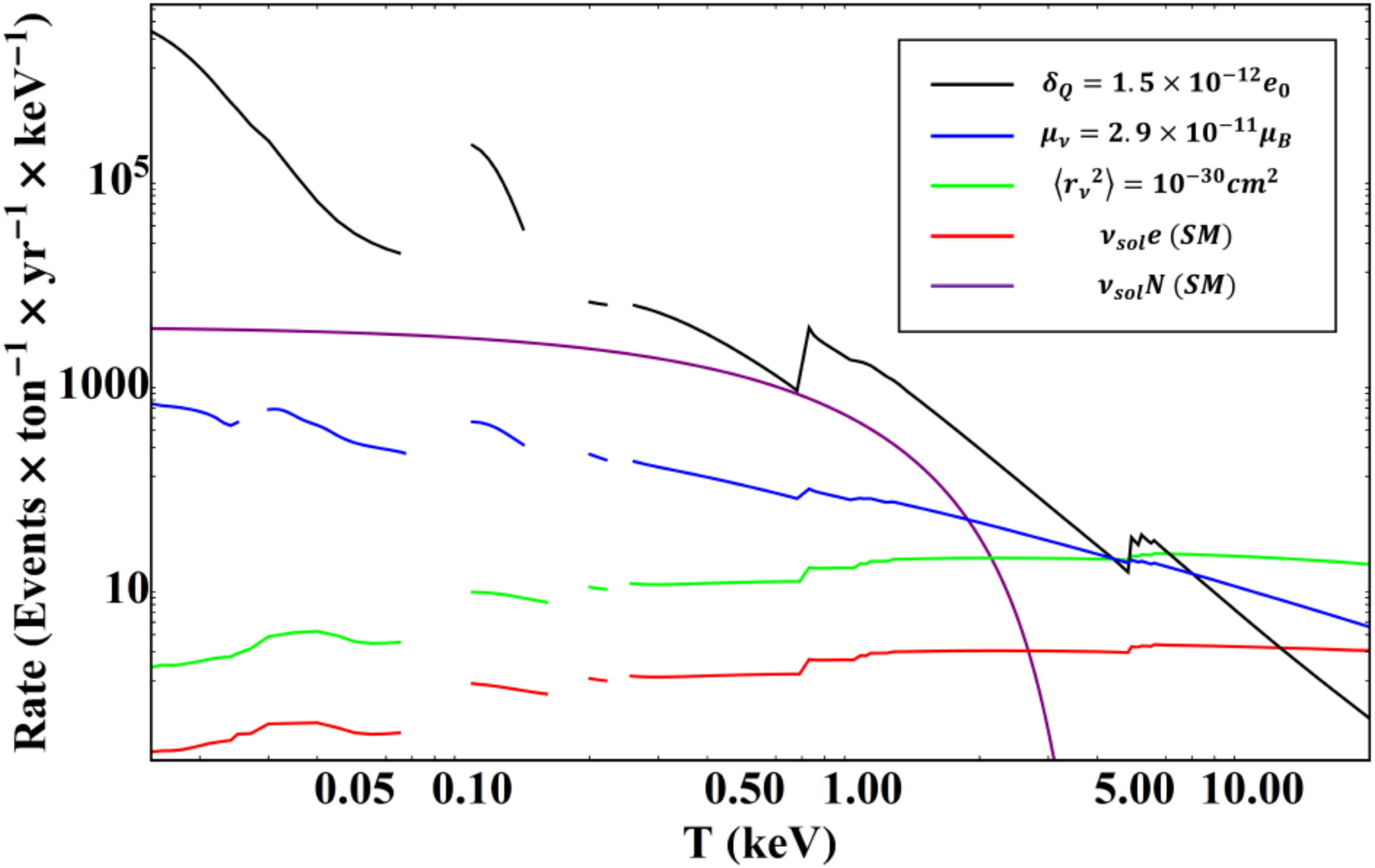
Applications II:
Solar ν Background in LXe Detectors



J. Aalbers *et. al.* (DARWIN collaboration), arXiv:1606.07001 (2016).

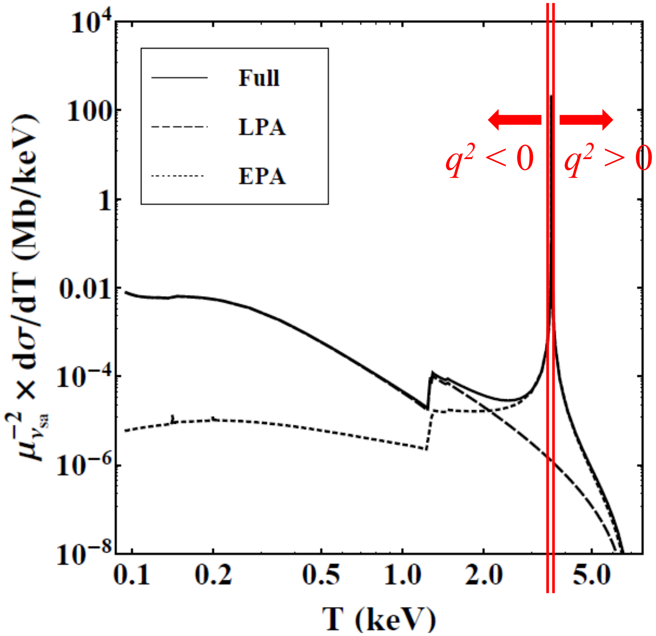
J.-W. Chen *et. al.*, arXiv:1610.04177 (2016).

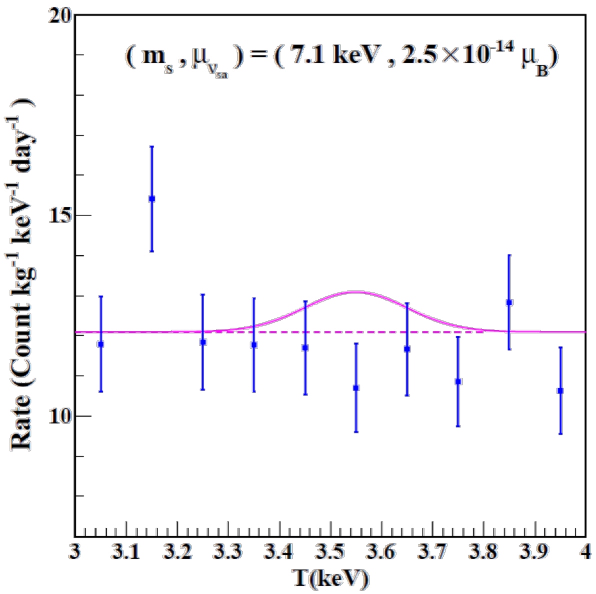
Applications II-2: Solar ν As Signals in LXe Detectors

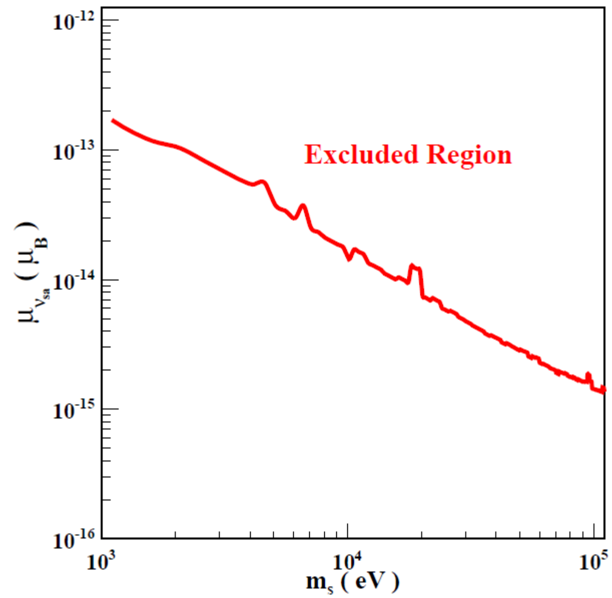


J.-W. Chen *et. al*., will be published soon.

Applications III: Sterile Neutrino Direct Constraint



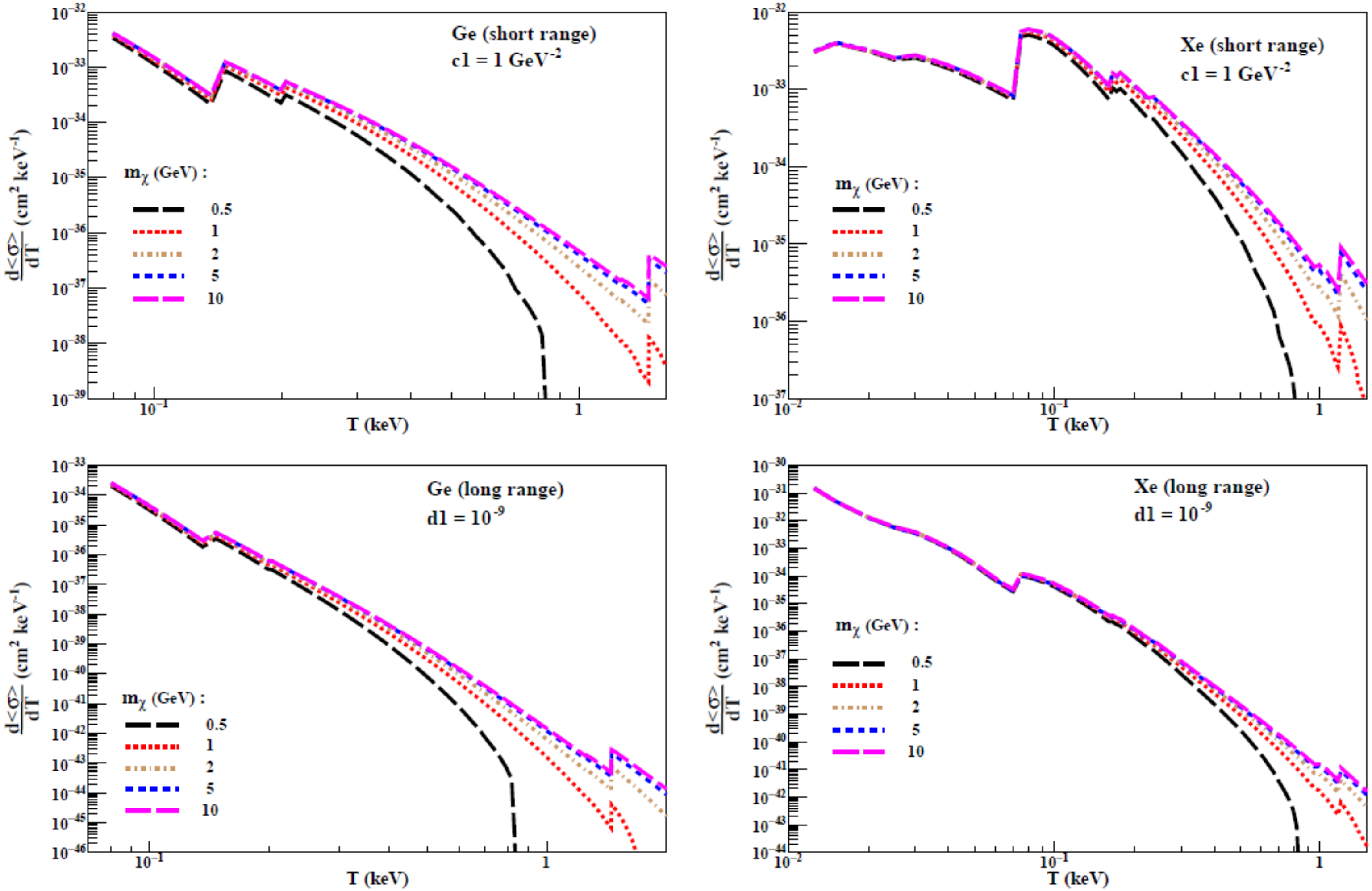




- Non-relativistic massive sterile neutrinos decay into SM neutrino.
- At m_s = 7.1 keV, the upper limit of $\mu_{\nu sa} < 2.5*10^{-14}\ \mu_B$ at 90% C.L.
- The recent X-ray observations of a 7.1 keV sterile neutrino with decay lifetime $1.74*10^{-28}\ s^{-1}$ can be converted to $\mu_{\nu sa} = 2.9*10^{-21}\ \mu_B$, much tighter because its much larger collecting volume.

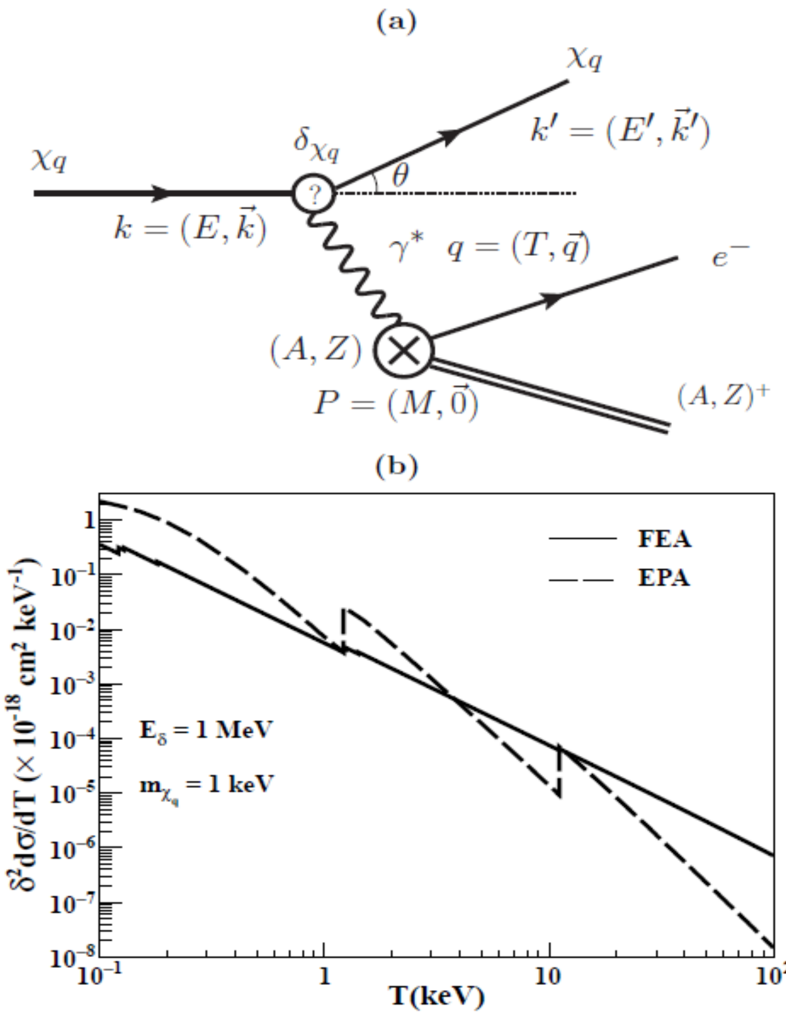
J.-W. Chen *et al.*, Phys. Rev. D **93**, 093012, arXiv:1601.07257 (2016).

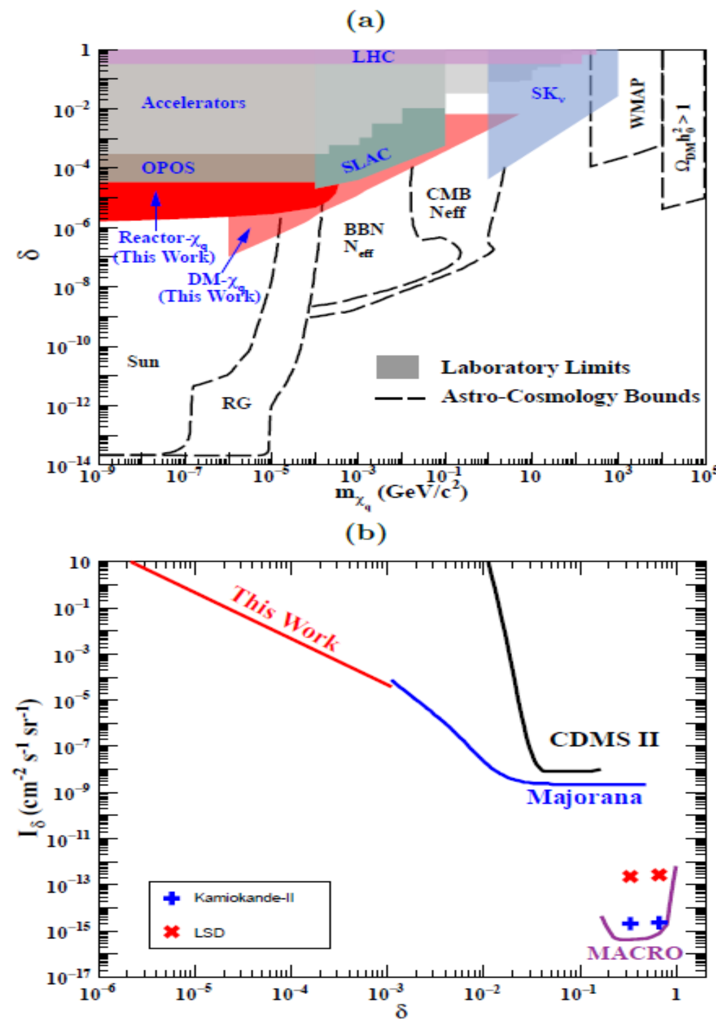
Applications IV:
Spin-Indep. DM-e Scattering in Ge & Xe



J.-W. Chen *et. al.*, will be published soon.

Applications V: Constraints on millicharged DM particles

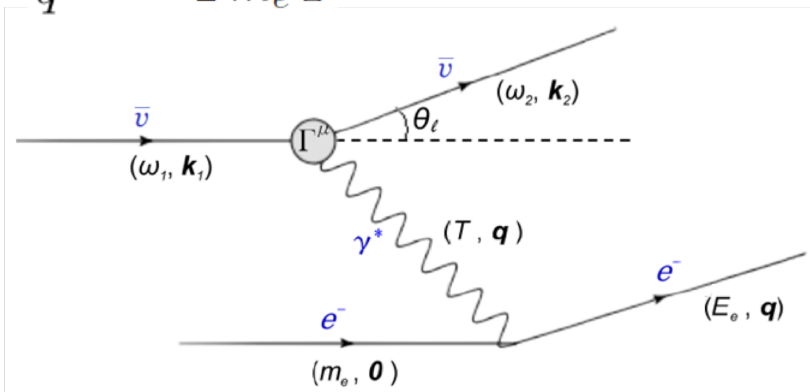




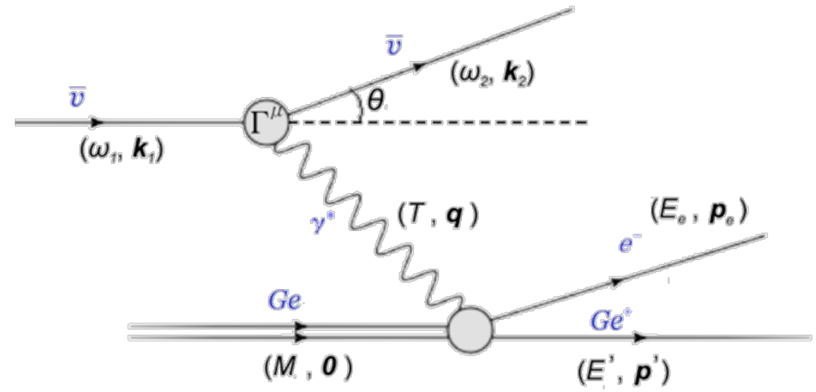
L. Singh *et. al*. (TEXONO Collaboration), arXiv:1808.02719 (2018).

Target: Free e/n v.s. Atom

$$q^2 = -2\, m_e\, T$$



$$\nu + A \rightarrow \nu' + A^{+} + e^{-}$$



Phase space is fixed in 2-body scattering

→ 4-momentum transfer is fixed

→ scattering angle is fixed

→ Maximum energy transfer is limited

by a factor $r = \dfrac{4\, m_{inc}\, m_{tar}}{(m_{inc} + m_{tar})^2}$

Energy and momentum transfer can be shared by nucleus and electrons

→ Inelastic scattering
(energy loss in atomic energy level)

→ Phase space suppression

Toy Model : Analytic Hydrogen WFs

$$\langle 100|\vec{r}\rangle = \frac{1}{\sqrt{\pi}} Z^{\frac{3}{2}} e^{-Z\bar{r}},$$

exp.-decay with the rate ∝ orbital momentum ~ 3.7 keV

$$\langle nlm_l|\vec{r}\rangle = \frac{1}{(2l+1)!}\sqrt{\frac{(n+l)!}{2n(n-l-1)!}}\left(\frac{2Z}{n}\right)^{\frac{3}{2}} e^{-\frac{Z\bar{r}}{n}}\left(\frac{2Z\bar{r}}{n}\right)^{l}$$

$$ {}_1F_1\left(-(n-l-1), 2l+2, \frac{2Z\bar{r}}{n}\right) Y_l^{m_l *}(\theta,\phi),$$

$$\langle \vec{\bar{p}}_r|\vec{\bar{r}}\rangle = e^{\frac{\pi Z}{2\bar{p}_r}}\Gamma\left(1-\frac{iZ}{\bar{p}_r}\right) e^{-i\vec{\bar{p}}_r\cdot\vec{\bar{r}}}\, {}_1F_1\left(\frac{iZ}{\bar{p}_r}, 1, i(p_r r + \vec{\bar{p}}_r\cdot\vec{\bar{r}})\right)$$

Oscillated like sin/cos function with frequency ∝ electron momentum ~ $(2m_eT)^{1/2}$

- The initial state of the hydrogen atom at the ground state, the spatial part $|I>_{spat} = |1s>$

1. **elastic scattering**: $<F|_{spat} = <1s|$
2. **discrete excitation** (ex): $<F|_{spat} = <nlm_l|$
3. **ionization** (ion): $<F|_{spat} = <\vec{p}_r|$

Reference:

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Thanks for your attention!