Atomic Physics Technique in Light Dark Matter Direct Search

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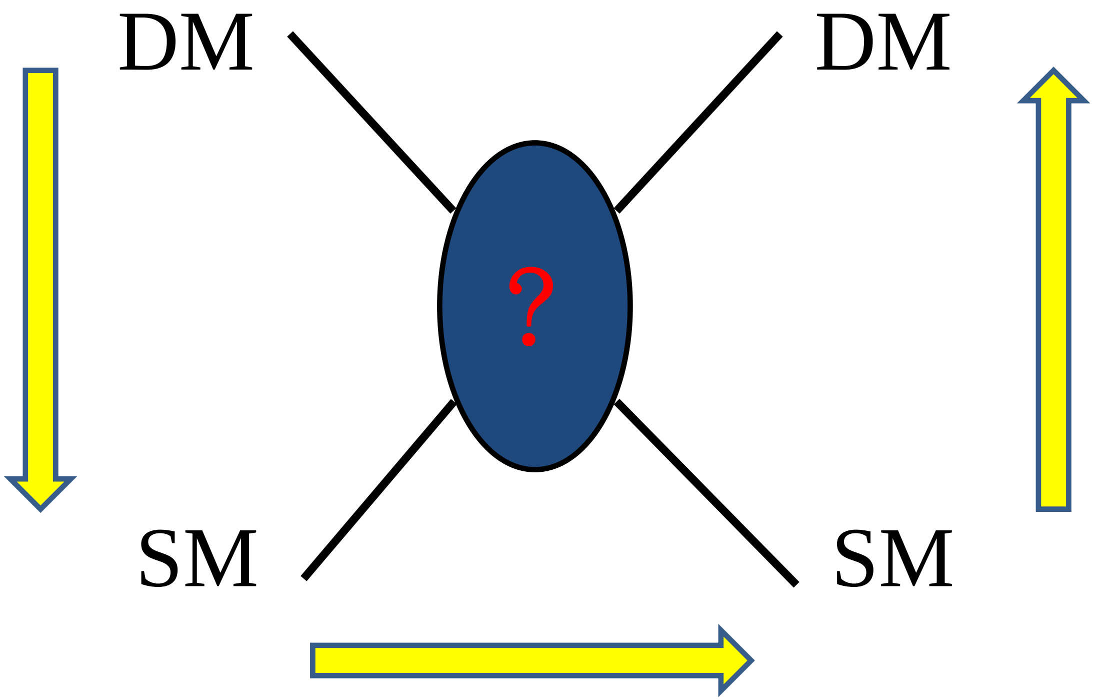
Strategies: Search for Dark Matters

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.

DM Effective Interaction with Electron or Nucleons

Leading order (LO):

short range

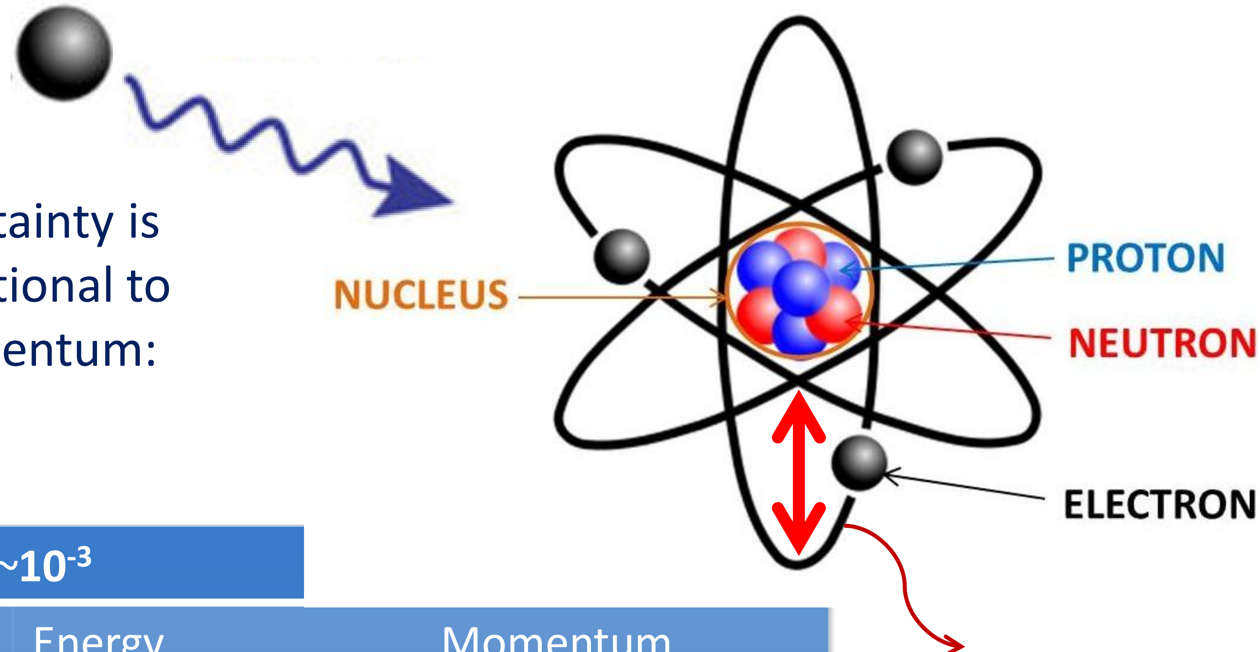
$$L_{\text{int}}^{(\text{LO})} = \sum_{f=e,p,n} \Big\{ c_1^{(f)} (\chi^\dagger \chi)(f^\dagger f) + c_4^{(f)} (\chi^\dagger \vec{S}_\chi \chi) \cdot (f^\dagger \vec{S}_f f) + d_1^{(f)} \frac{1}{q^2} (\chi^\dagger \chi)(f^\dagger f) + d_4^{(f)} \frac{1}{q^2} (\chi^\dagger \vec{S}_\chi \chi) \cdot (f^\dagger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

spin-indep. long range spin-dep.

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

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

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

Response Function for Atomic Ionization

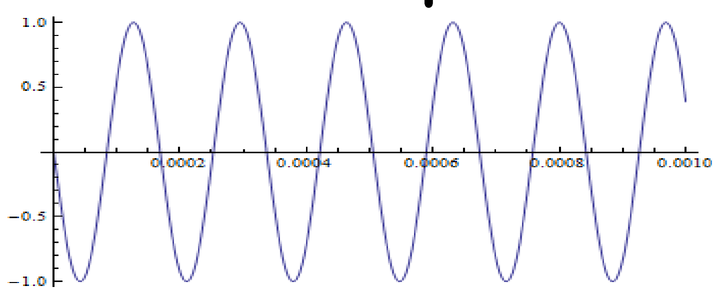
$$R_L \equiv \sum_{m_{j_f}} \sum_{m_{j_i}} \int \frac{d^3 \vec{p}_r}{(2\pi)^3} |\langle f | \rho^{(A)}(\vec{q}) | i \rangle|^2 \delta\left(T - B - \frac{q^2}{2M} - \frac{p_r^2}{2\mu_{\rm red}}\right)$$

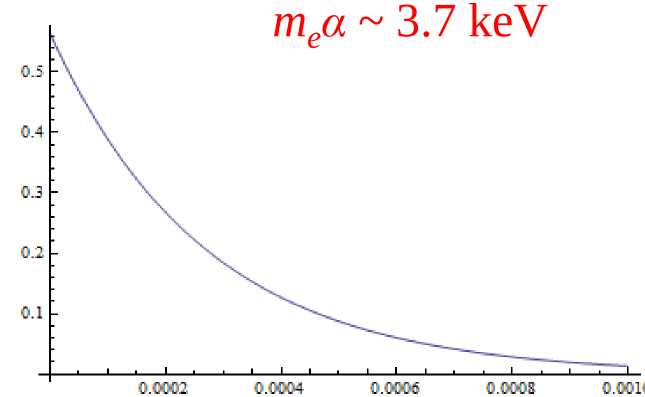
Continuous WF:
$\propto \mathrm{Exp}[i\, p_r\, r]$
$p_r = (2 m_e T)^{1/2}$

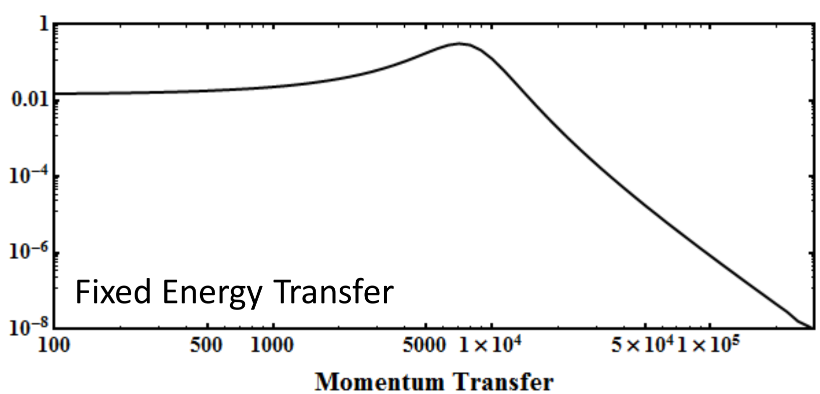
$\rho^{(e)}(\vec{q}) = e^{i \frac{\mu}{m_e} \vec{q} \cdot \vec{r}}$ Highly oscillated

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

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







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

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)
- Suppression of WF overlap when large $q >> (2 m_e T)^{1/2}$

Ab initio Theory for Atomic Ionization

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 $\psi_\alpha(t)$

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

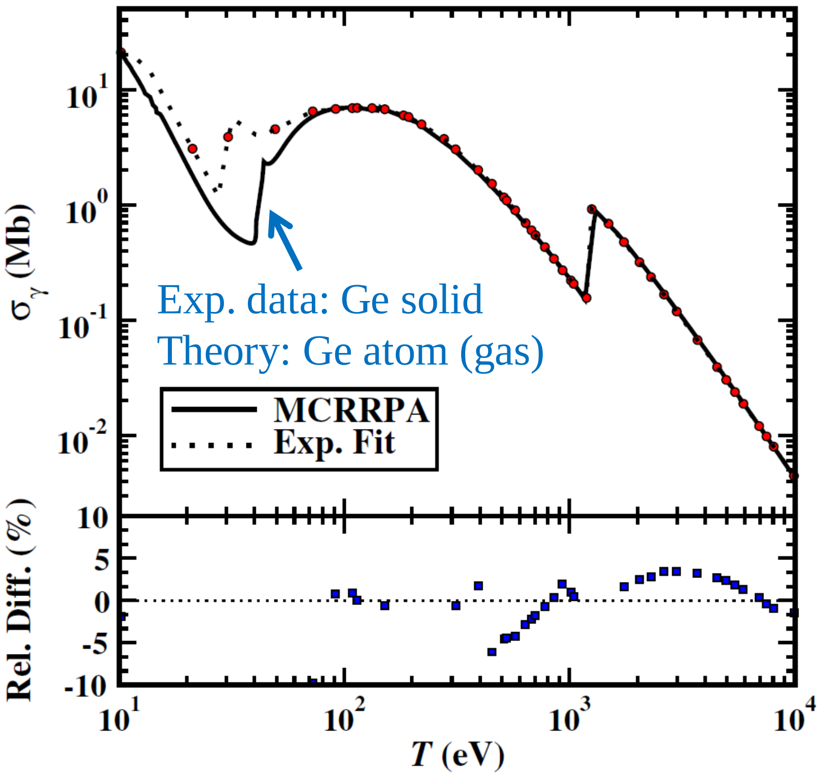
MCRRPA: multiconfiguration relativistic random phase approximation

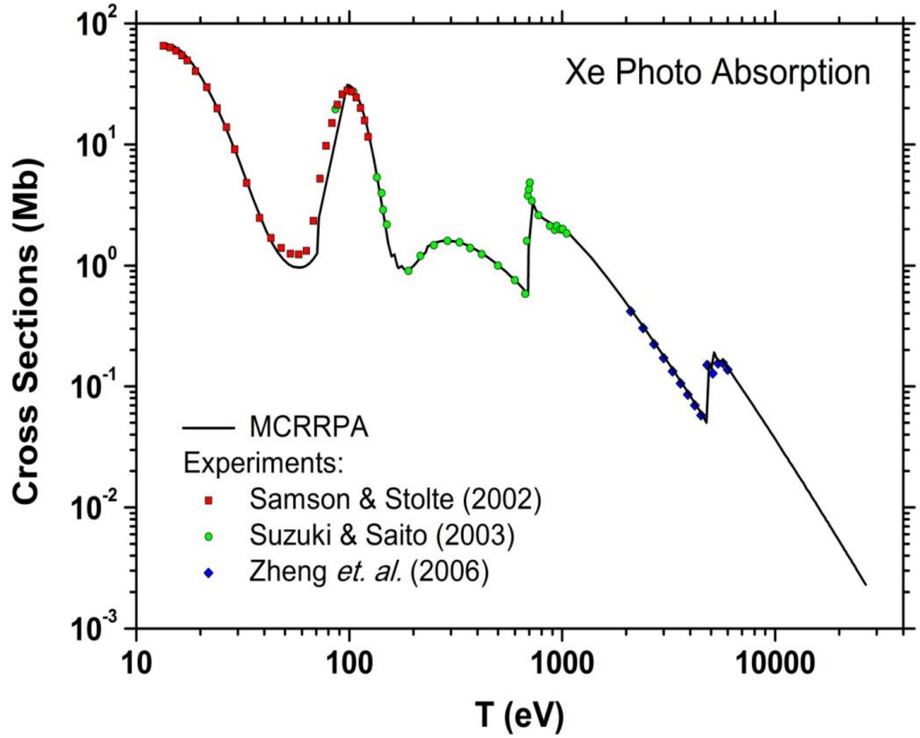
RPA: Expand $u_a(\vec{r},t)$ into time-indep. orbitals in power of external potential

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

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

Benchmark: Ge & Xe Photoionization





Above 100 eV error under 5%.

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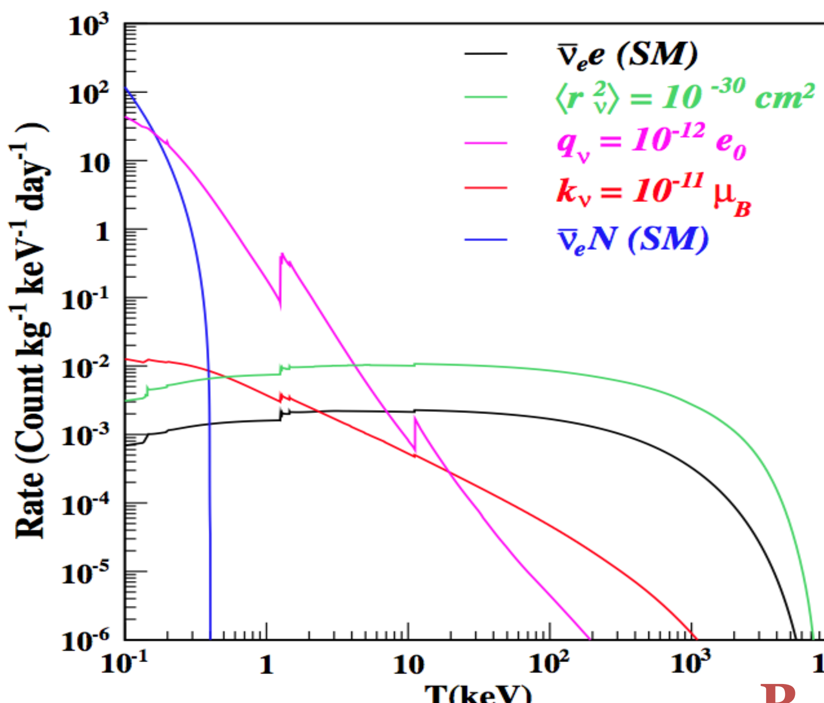
Applications I: Neutrino EM Properties

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



Reference:
Phys. Lett. B **731**, 159, arXiv:1311.5294 (2014).
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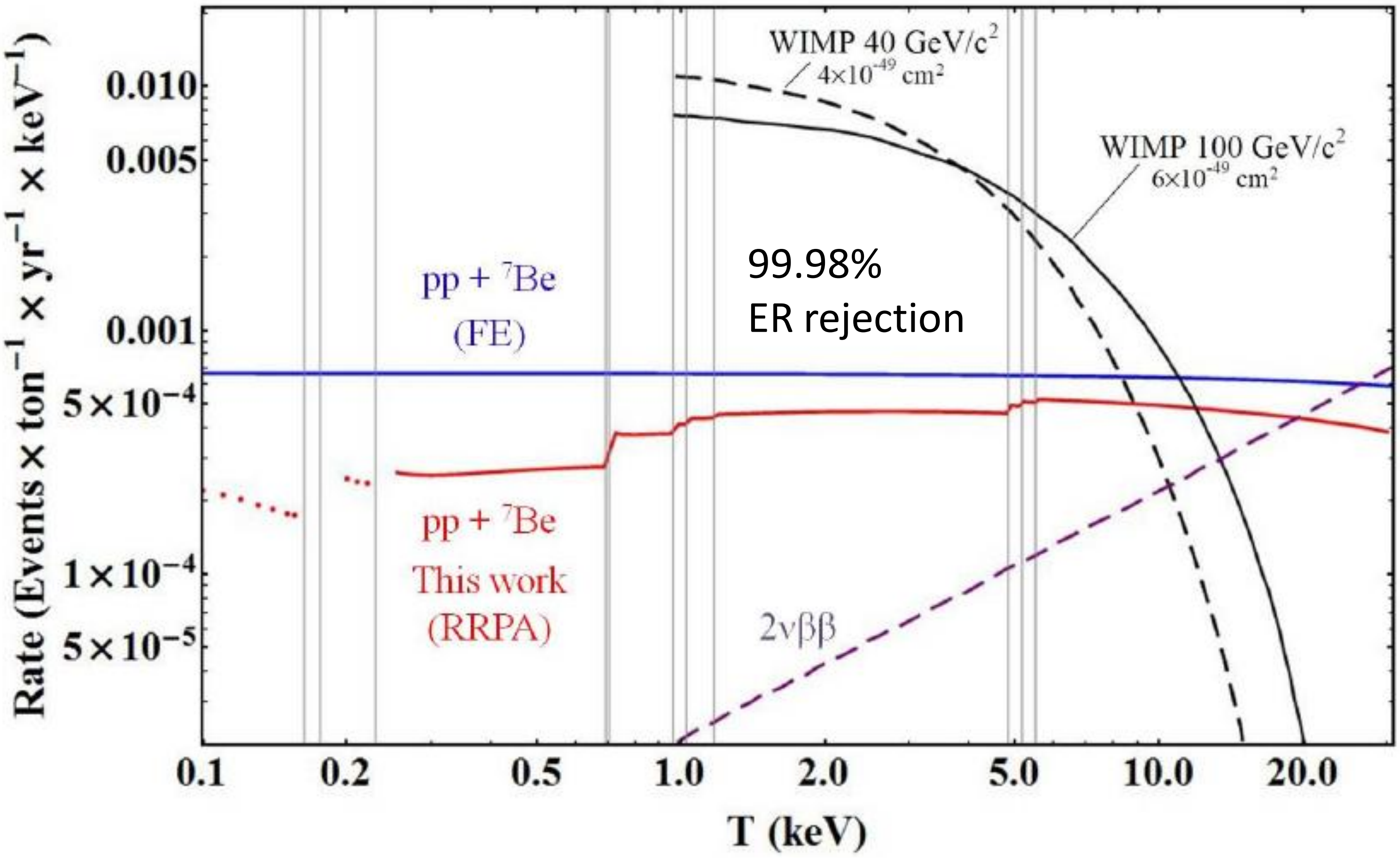
Applications II: Solar ν Background in LXe Detectors



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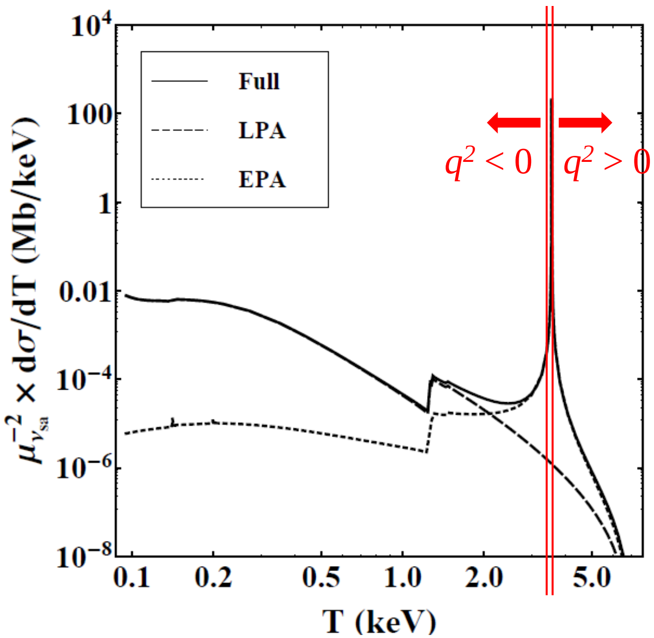
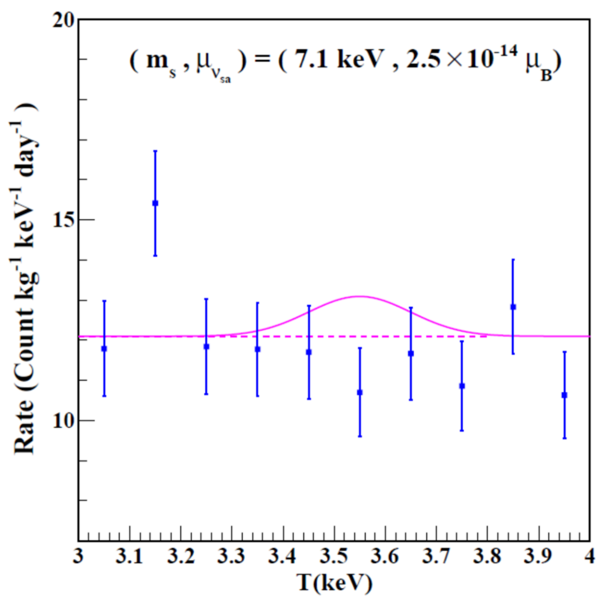
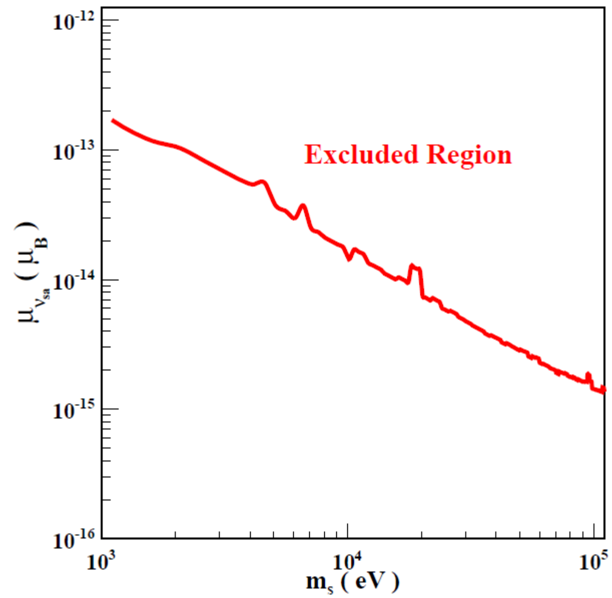
J.-W. Chen *et. al.*, arXiv:1610.04177 (2016).

Applications III:
Sterile Neutrino Direct Constraint



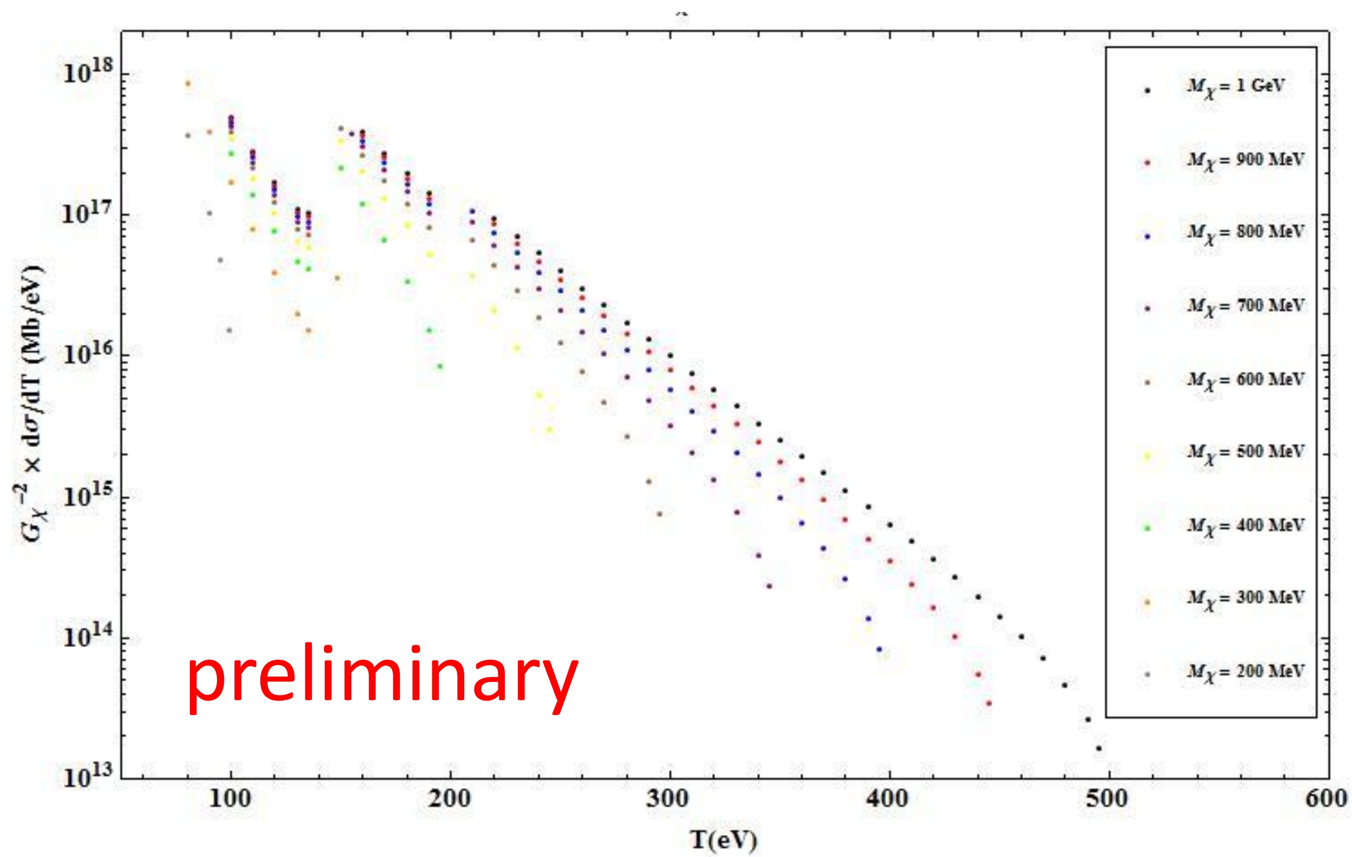




- Non-relativistic massive sterile neutrinos decay into SM neutrino.
- At m_s = 7.1 keV, the upper limit of $\mu_{\nu sa} < 2.5*10^{-14}\ \mu_B$ at 90% C.L.
- The recent X-ray observations of a 7.1 keV sterile neutrino with decay lifetime $1.74*10^{-28}\ s^{-1}$ can be converted to $\mu_{\nu sa} = 2.9*10^{-21}\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

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

DM Scatter off Ge (interact with e^-)



As T increased, the minimal momentum transfer (at forward angle) increased, which leads to stronger form factor suppression (caused by wave function overlaps).

Summary

- Atomic correction is very important for LDM search, because
  1. Kinematic energies of LDMs are below the atomic scale,
  2. Interactions with nucleon will face a energy transfer cutoff when the LDM mass becomes much lower than GeV,
  3. Free electron assumption fails to describe the interactions with electron.
- *Ab initio* many-body calculations of Ge & Xe atomic ionization performed with ~5% estimated error. That can be applied for
  1. Constraining neutrino EM properties,
  2. Study on solar neutrino backgrounds in DM detection,
  3. Calculating DM atomic ionization cross sections.

Reference:

1. J.-W. Chen, H.-C. Chi, C.-P. Liu, C.-L. Wu, and C.-P. Wu, Phys. Rev. D **92**, 096013 (2015).
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Thanks for your attention!

Source: DM v.s. Neutrino

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

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

- 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:

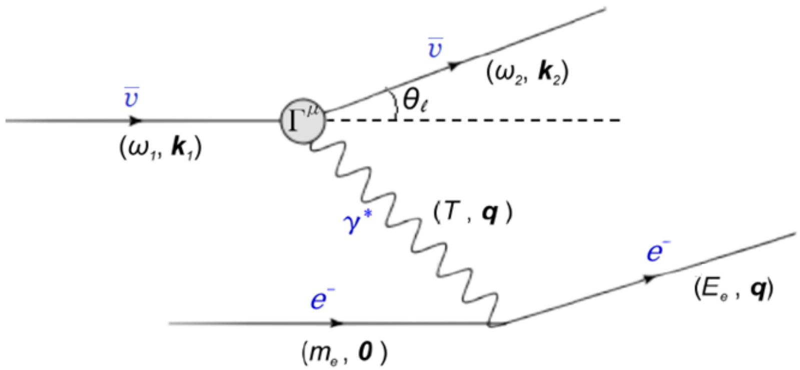
    $m_\chi v_\chi - (m_\chi^2 v_\chi^2 - 2m_\chi T)^{1/2} \sim m_\chi v_\chi + (m_\chi^2 v_\chi^2 - 2m_\chi T)^{1/2}$

    >> outgoing electron momentum

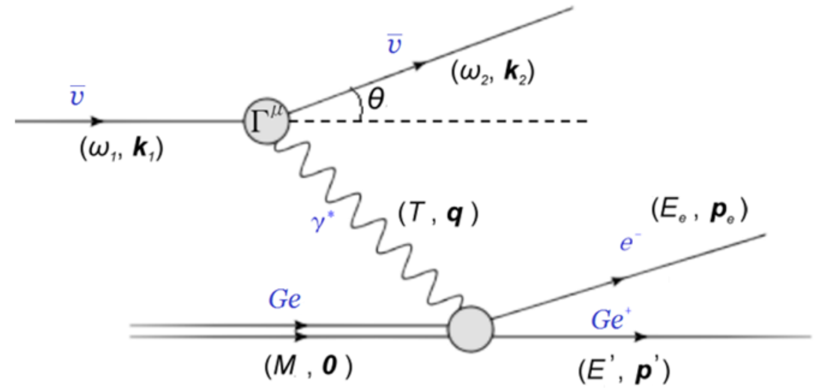
    because $2m_e T << 2m_\chi T < m_\chi^2 v_\chi^2$ $\qquad q^2 << 0$

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

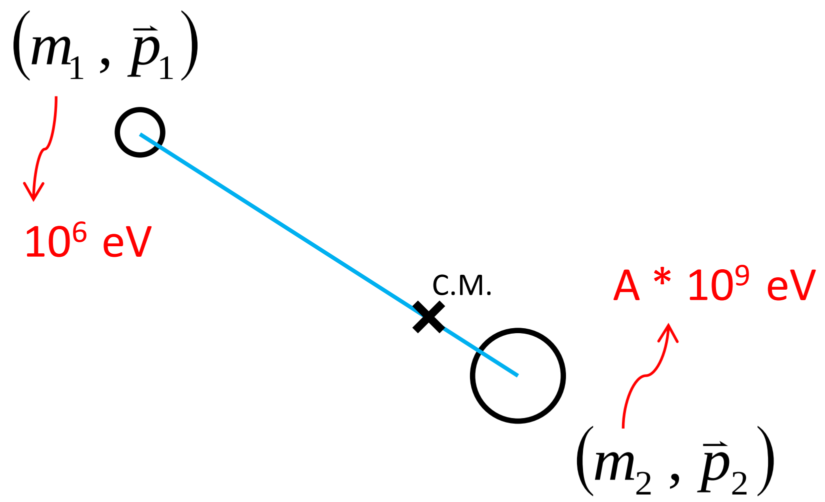
Energy and momentum transfer can be shared by nucleus and electrons
→ Inelastic scattering
(energy loss in atomic energy level)
→ Phase space suppression

Reduce Mass System for Atom

Two particles can reduce to one system at their center of mass, with internal motion:

$$\frac{\vec{p}_1^{\,2}}{2m_1} + \frac{\vec{p}_2^{\,2}}{2m_2} = \frac{\vec{p}_{tot}^{\,2}}{2M} + \frac{\vec{p}_{rel}^{\,2}}{2\mu} = T - B$$

$$\begin{cases} M = m_1 + m_2 \\ \mu = \dfrac{m_1 m_2}{m_1 + m_2} \end{cases}, \quad \begin{cases} \vec{p}_{tot} = \vec{p}_1 + \vec{p}_2 \\ \vec{p}_{rel} = \mu\left(\vec{v}_1 - \vec{v}_2\right) \end{cases}$$



If the system received a 4-momentum transfer $(T, \vec{q})$, then the relative momentum would be:

$$\vec{p}_{rel} = \begin{cases} \dfrac{\mu}{m_1}\vec{q} \ \ (\text{hit } m_1) \\ \dfrac{\mu}{m_2}\vec{q} \ \ (\text{hit } m_2) \end{cases} \approx \sqrt{2\mu(T-B)} \ \ (\text{for } \mu << M)$$

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

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

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

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

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

- The initial state of the hydrogen atom at the ground state, the spatial part $|I\rangle_{\text{spat}} = |1s\rangle$

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

DM-Hydrogen Differential Cross Sections

- **For elastic scattering & excitation to the final discrete level (*nl*):**

target mass

$$\left.\frac{d\sigma^{(nl)}}{dT}\right|_{c_1^{(e)}} = \frac{1}{2\pi}\frac{m_{\rm H}}{v_\chi^2}|c_1^{(e)}|^2 R^{(nl)}\left(\kappa = \frac{\mu}{m_e}q\right)$$

$$\text{with} \quad q^2 = 2M_{\rm H}(T - (E_{nl} - E_{1s}))$$

$$R^{(nl)}(\kappa) = \sum_{m_l} |\langle n l m_l | e^{i\vec{\kappa}\cdot\vec{r}} | 1s\rangle|^2$$

=> 1

In free electron elastic scattering

- **For ionization processes:**

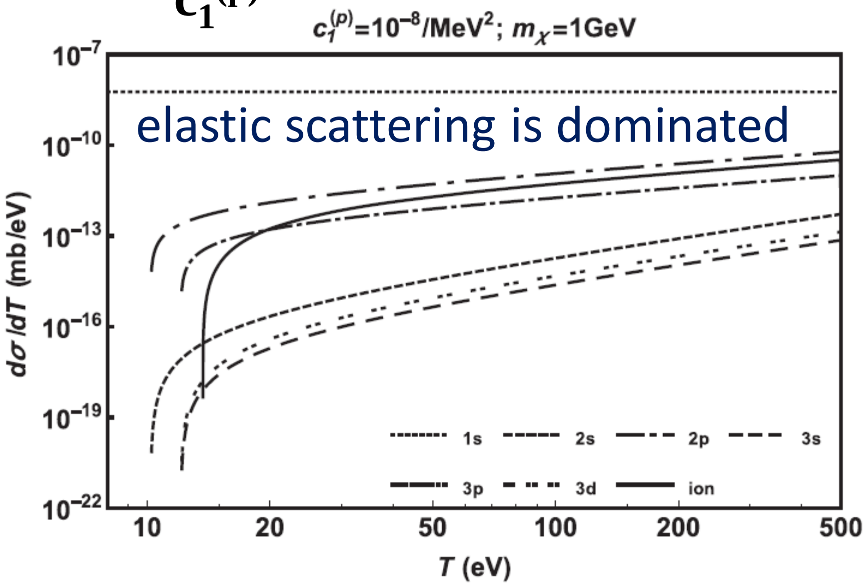
$$\left.\frac{d\sigma^{(\rm ion)}}{dT}\right|_{c_1^{(e)}} = \frac{1}{2\pi}\frac{m_\chi}{v_\chi}k_2 \int d\cos\theta |c_1^{(e)}|^2 R^{(\rm ion)}\left(\kappa = \frac{\mu}{m_e}q\right)$$

$$R^{(\rm ion)}(\kappa) = \int d^3 p_r |\langle \vec{p}_r | e^{i\vec{\kappa}\cdot\vec{r}} | 1s\rangle|^2 \delta\left(T - B - \frac{\vec{q}^2}{2M} - \frac{\vec{p}_r^2}{2\mu}\right)$$

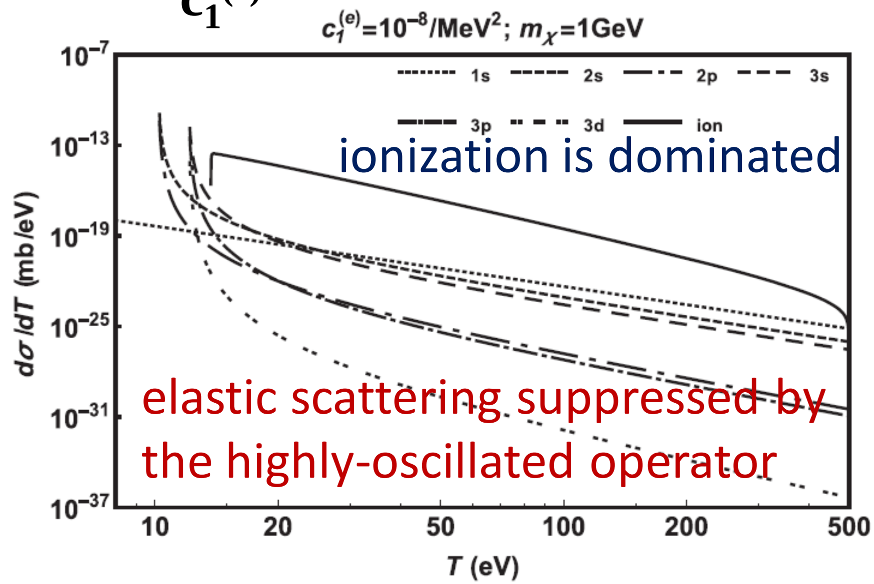
Proton v.s. Electron Recoil

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

Sterile Neutrino Direct Detection

ν_s : **massive, non-relativistic**

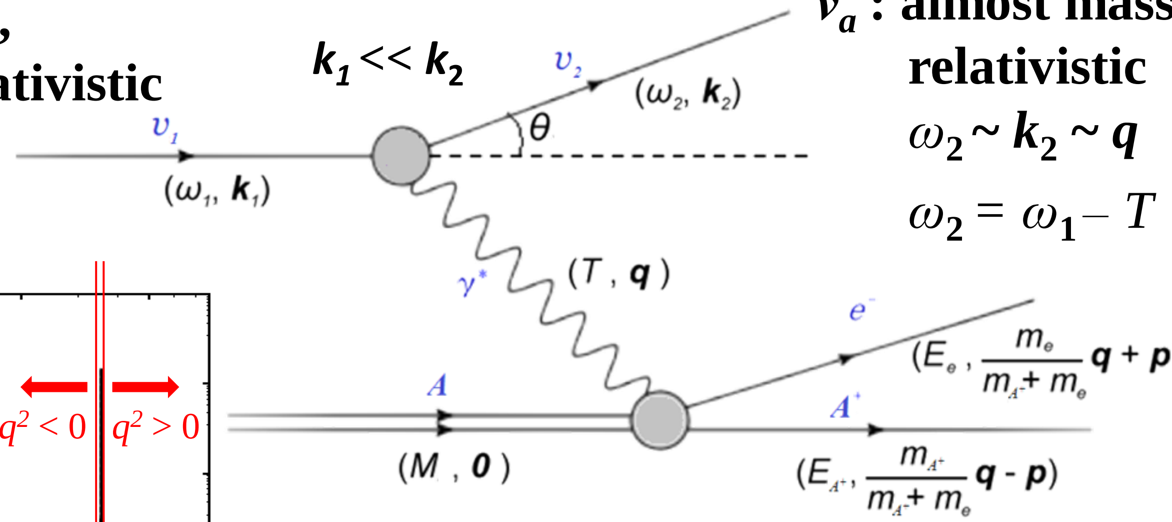
$\omega_1 \sim m_s$

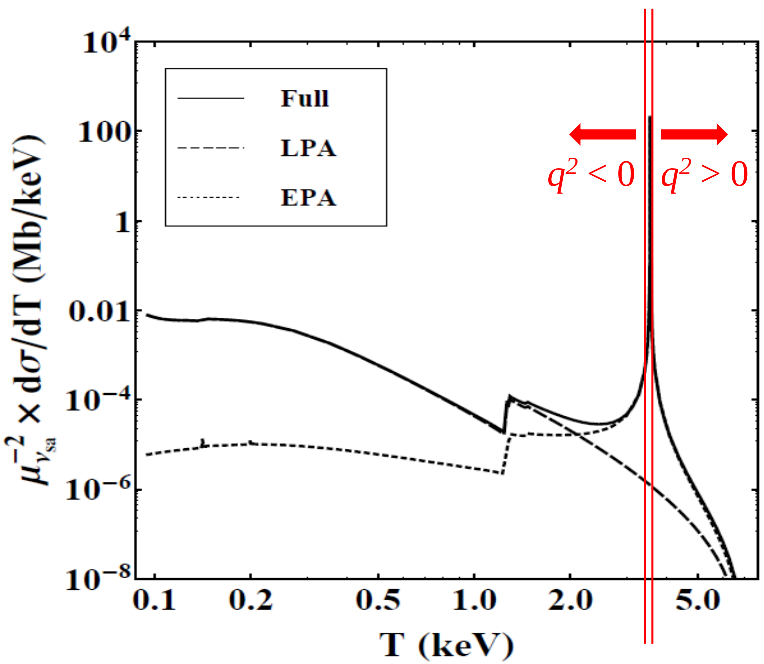
$\boldsymbol{k_1 << k_2}$

ν_a : **almost massless, relativistic**

$\omega_2 \sim \boldsymbol{k}_2 \sim \boldsymbol{q}$

$\omega_2 = \omega_1 - T$





(a) $m_s = 7.1\,\mathrm{keV}$

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

$q^2 > 0$ at forward scattering when $T > \omega_1/2$

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

$q^2 < 0$ for all possible scattering angle & T

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