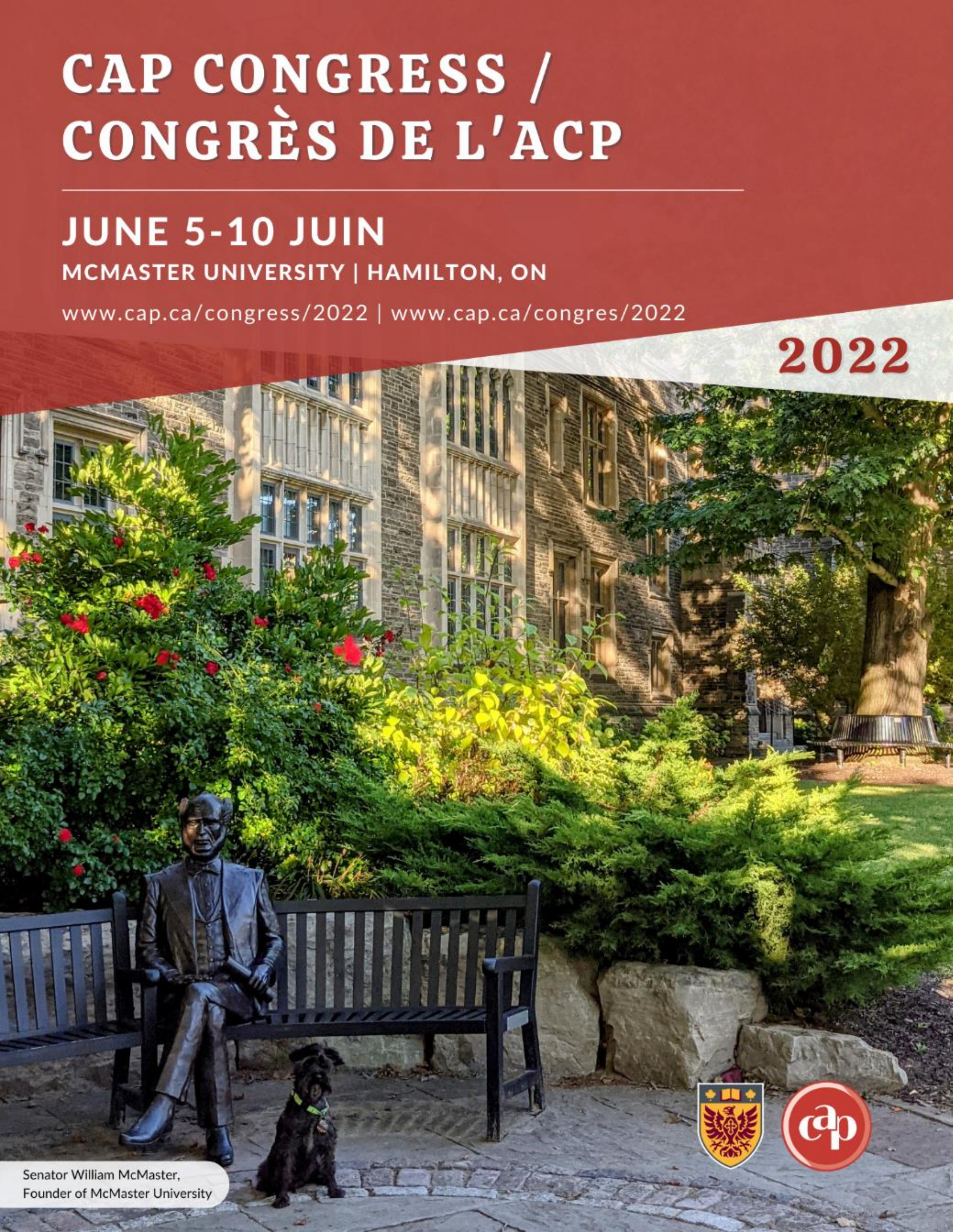


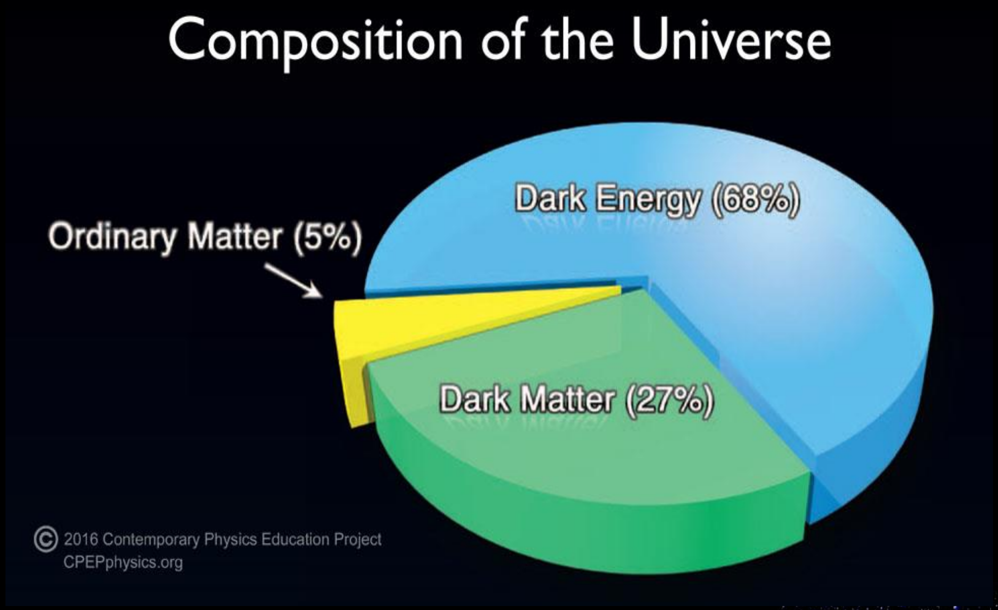
Spin-dependent dark matter-electron interactions

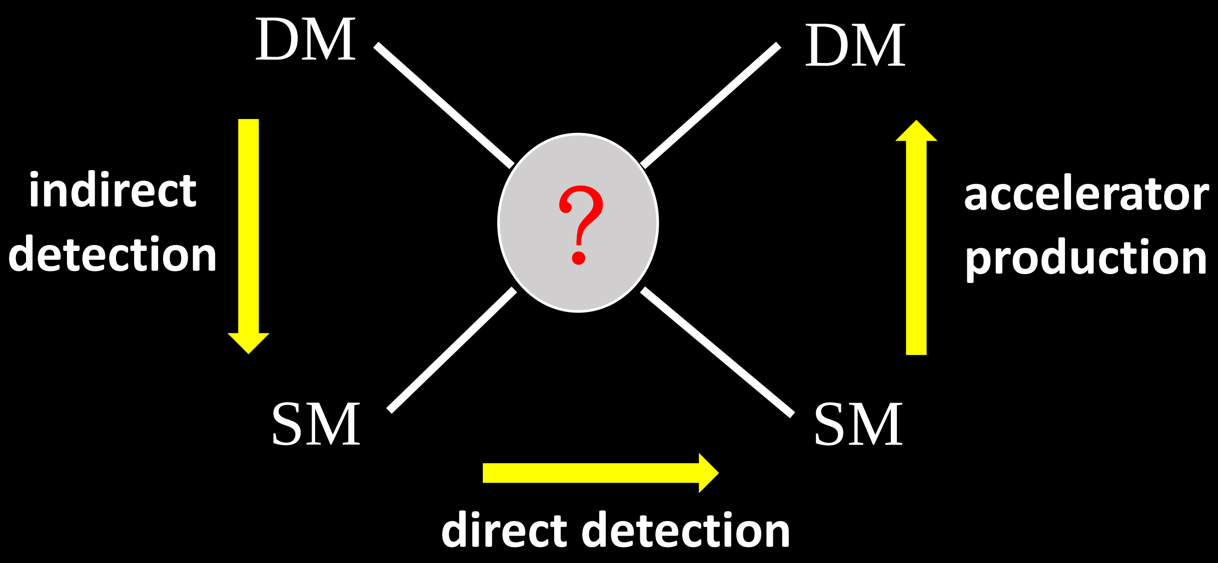
Chih-Pan Wu

Université de Montréal

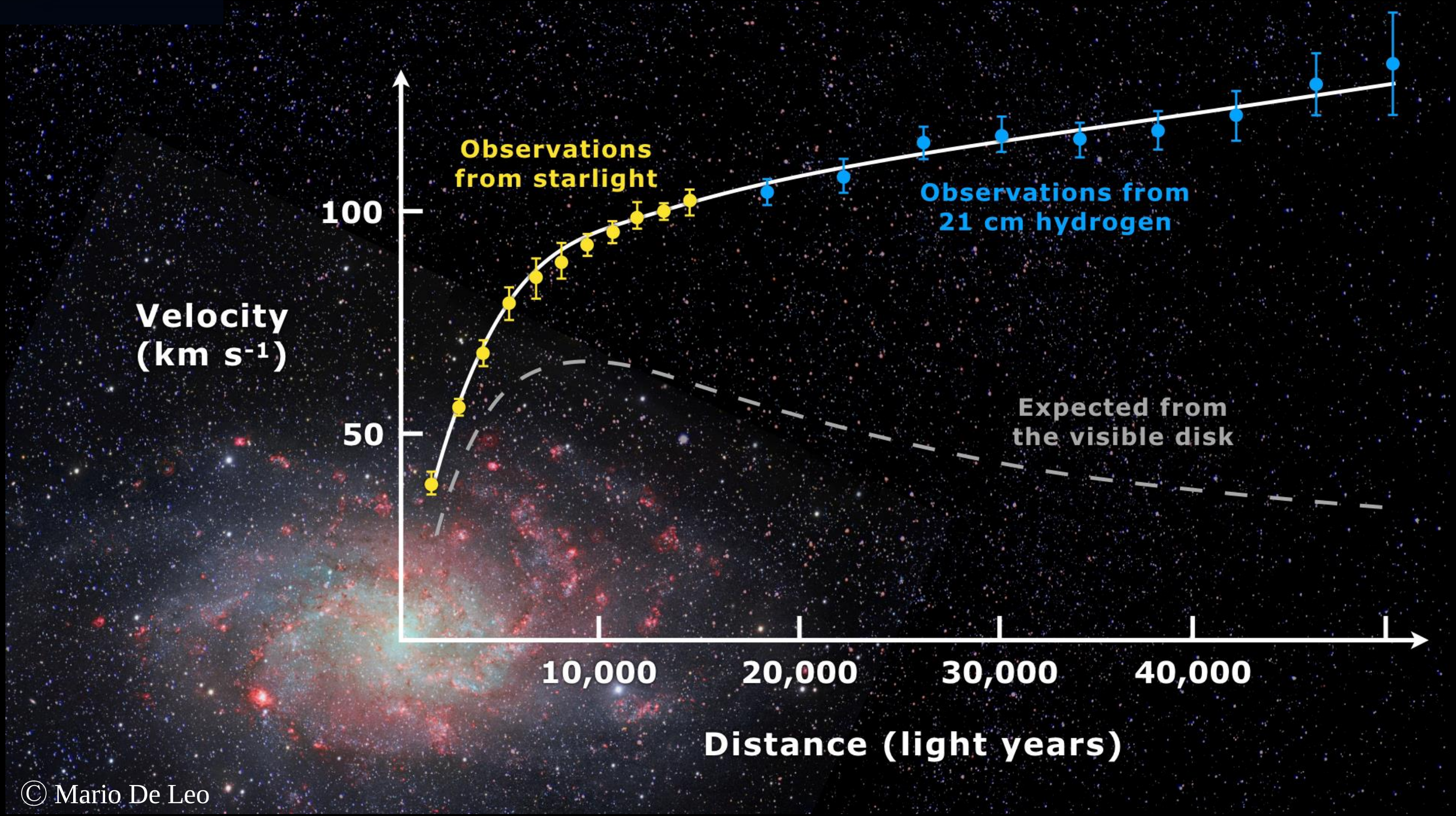
Co-author: C.-P. Liu, Jiunn-Wei Chen, Hsin-Chang Chi, Mukesh K. Pandey, Lakhwinder Singh, Henry T. Wong

Reference: arXiv: 2106.16214, will be published on PRD soon



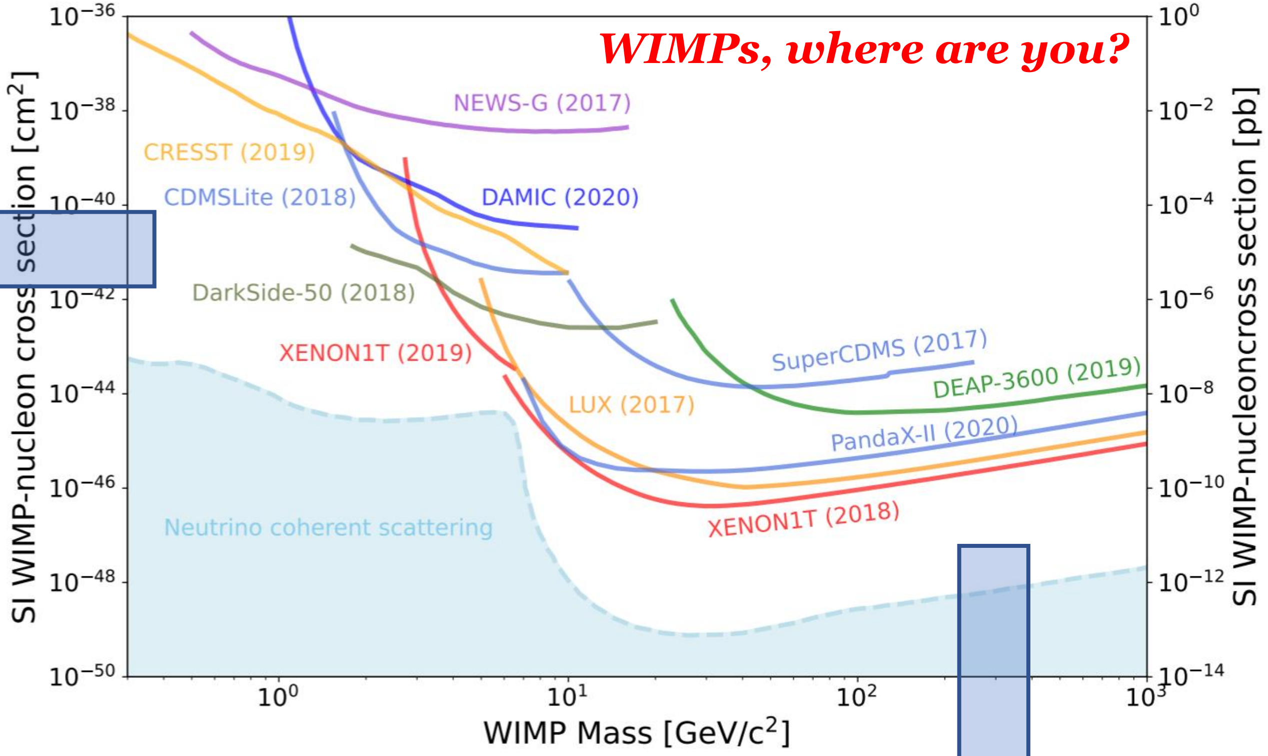



Dark Matter Ring in Galaxy Cluster Cl 0024+17 (ZwCl 0024+1652)
Hubble Space Telescope • ACS/WFC
NASA, ESA, and M.J. Jee (Johns Hopkins University) STScI-PRC07-17a



Next Steps for DM Direct Detection

Better resolution
Lower threshold



New ideas:

Toward Sub-GeV mass
DM-nucleon --> DM-electron
Spin-indep. --> Spin-dep.

Larger detector size
Clearer background

P.A. Zyla *et al*. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020).

Why Spin-Dependent DM-e Interaction?

$$\mathscr{L}^{(\mathrm{LO})} = c_1 \left(\chi^\dagger \mathbb{1}_\chi \chi\right) \cdot \left(e^\dagger \mathbb{1}_e\right) + c_4 \left(\chi^\dagger \vec{S}_\chi \chi\right) \cdot \left(e^\dagger \vec{S}_e e\right)$$

- SI term: a scalar DM with a scalar-scalar coupling, or a fermionic DM with a scalar-scalar or vector-vector coupling to electrons
- SD term: a fermionic DM with an pseudovector-pseudovector or tensor-tensor coupling.
- DM-e v.s. DM-n:
    - electron weakly bound in atoms; nucleon tightly bound in nuclei
    - electron recoils (ER) are easier to detect
    - coherent enhancement happens only for SI DM-n case

Atomic Response Functions

$$R_{\rm SI}^{\rm (ion)}(T,q) = \sum_{\mathscr{F}} \overline{\sum_{\mathscr{I}}} \, |\langle \mathscr{F} | \sum_{i=1}^{Z} e^{i\vec{q}.\vec{r}_i} | \mathscr{I} \rangle|^2 \, \delta(E \ldots)\,,$$

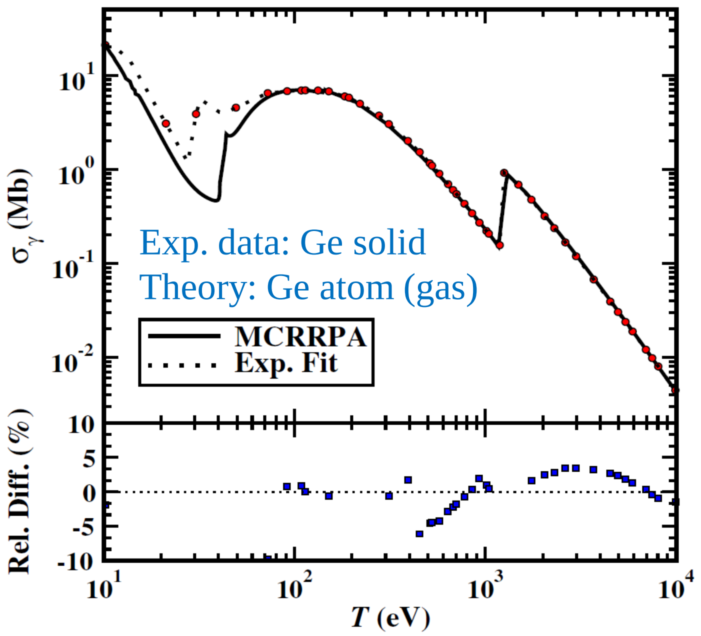
$$R_{\rm SD}^{\rm (ion)}(T,q) = \sum_{\mathscr{F}} \overline{\sum_{\mathscr{I}}} \sum_{k} \, |\langle \mathscr{F} | \sum_{i=1}^{Z} e^{i\vec{q}.\vec{r}} \sigma_{i,k}^{\rm D} | \mathscr{I} \rangle|^2 \, \delta(E \ldots)$$

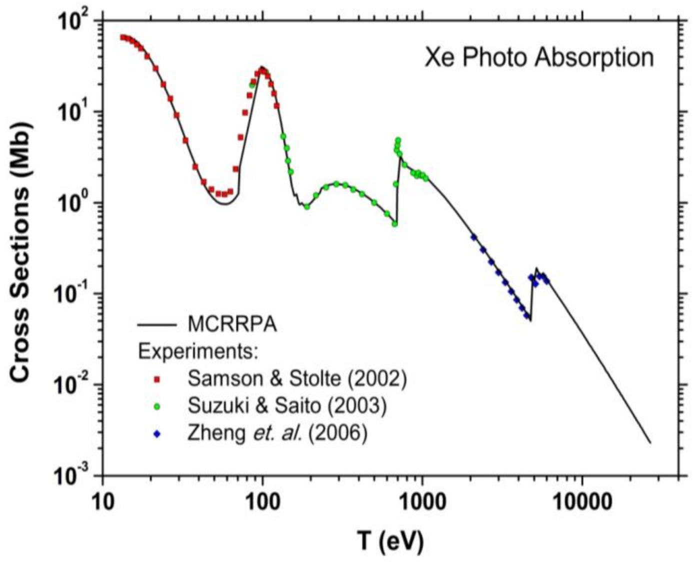
Ab initio many-body atomic methods:

- Multi-Configuration Dirac-Fock
- (MC) Relativistic Random-Phase Approx.
- Frozen Core Approx.

Benchmarked with photoabsorption data and some approximation schemes:

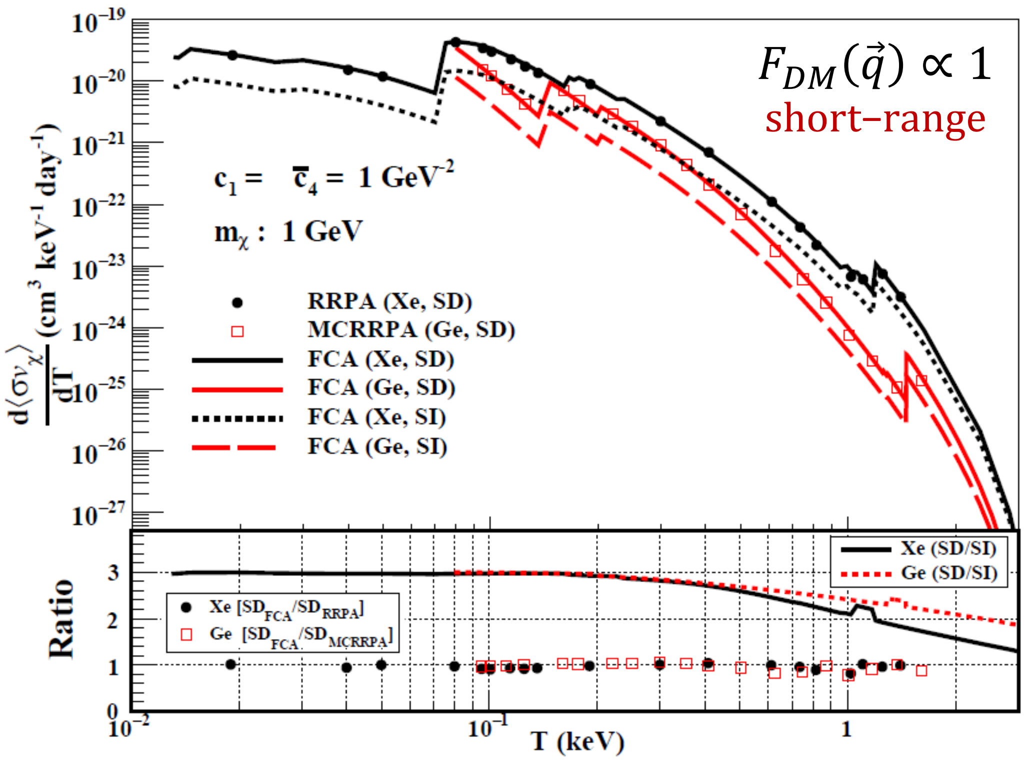
Equivalent Photon Approx., Free Electron Approx.

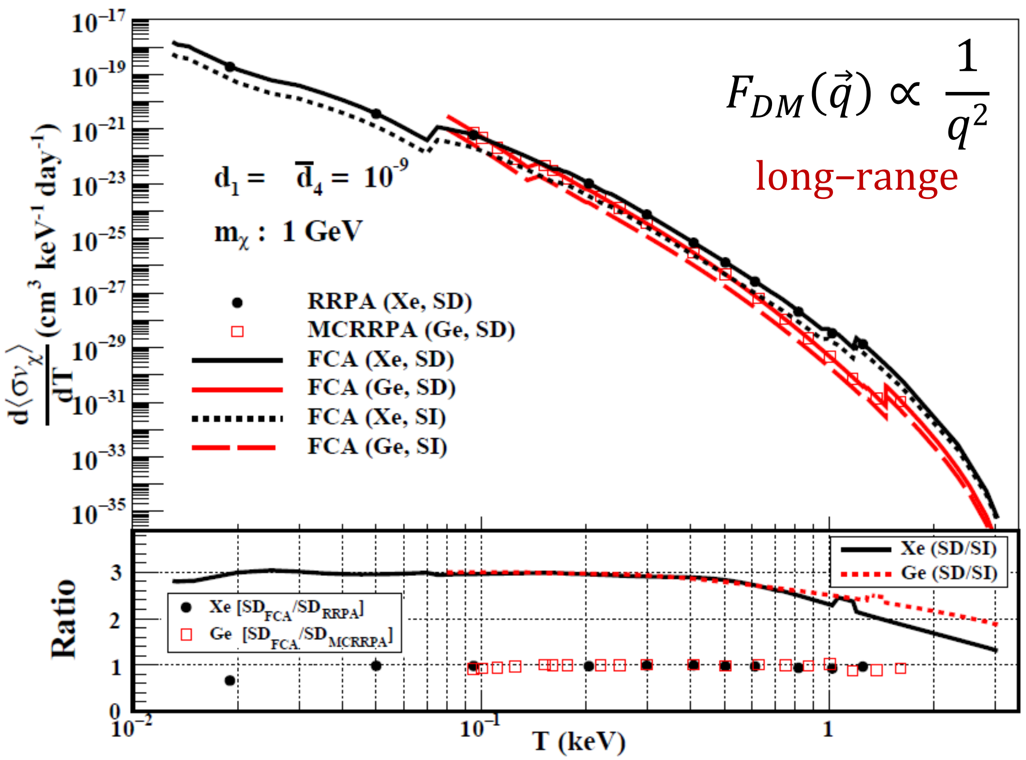




Relativistic Effects (Spin-Orbit Coupling)

Non-relativistic limit: $\mathcal{R}^{(\mathrm{ion})}_{\mathrm{SD}}(T,q) = 3\mathcal{R}^{(\mathrm{ion})}_{\mathrm{SI}}(T,q)$

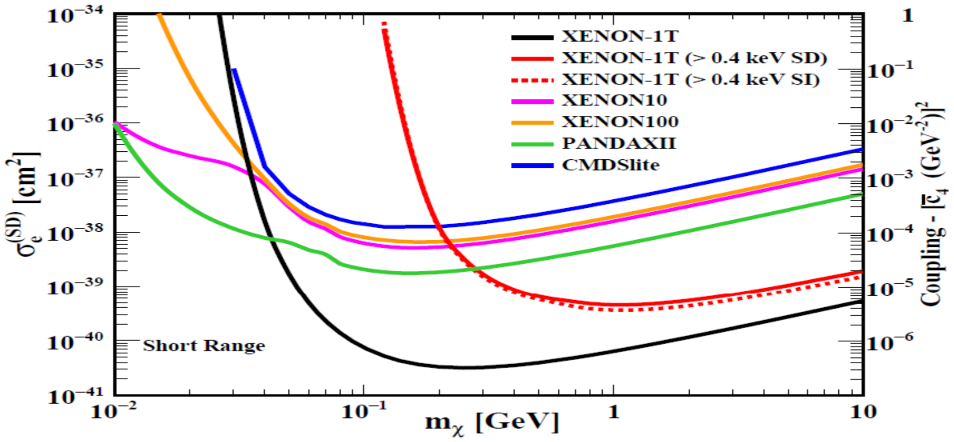


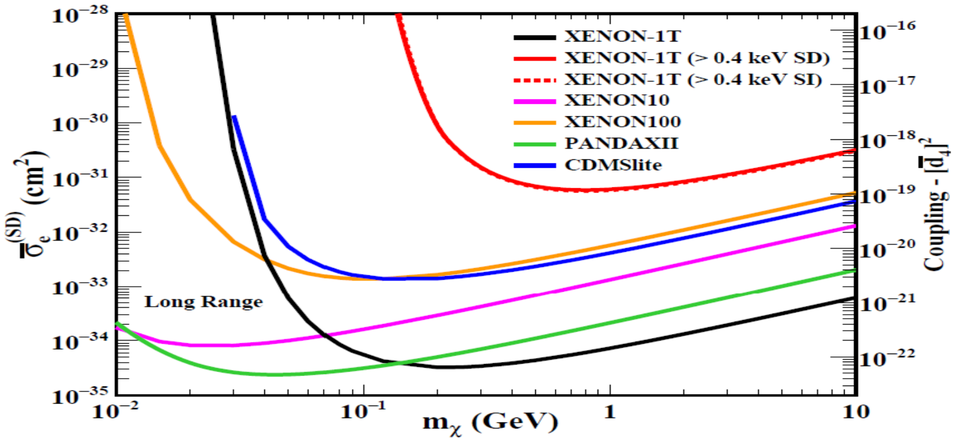


Exclusion Limits on DM-e Interactions

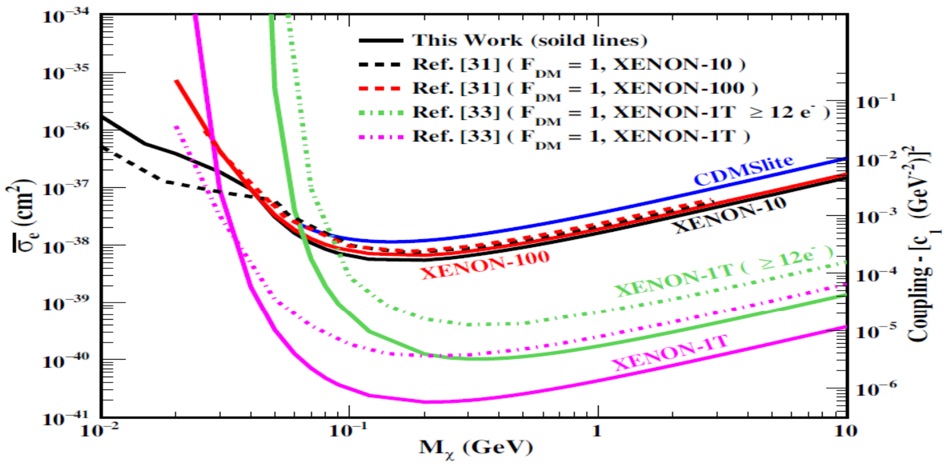
Short Range | **Long Range**

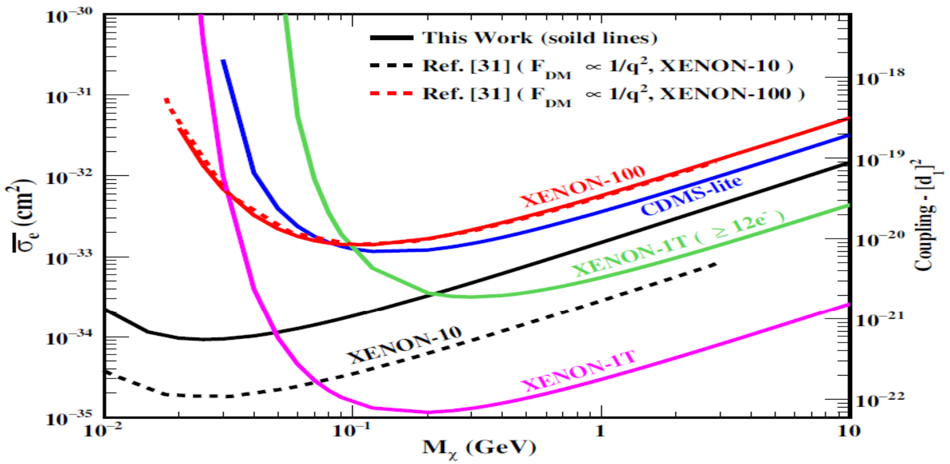
SD:





SI:





Take Home Message

- DM searches with lighter masses or new interactions become more important for the design of next generation detectors.
  (Direct Detection is valuable complement to collider bound!)

- For LDM-electron interactions, atomic transition plays an important role because ionization channel dominates the scattering process

- Atomic treatment with relativistic effect is required, although in some cases people still can reduce to NR limit and have simple relation between SI and SD interaction

Thanks for your attention!

Reference:

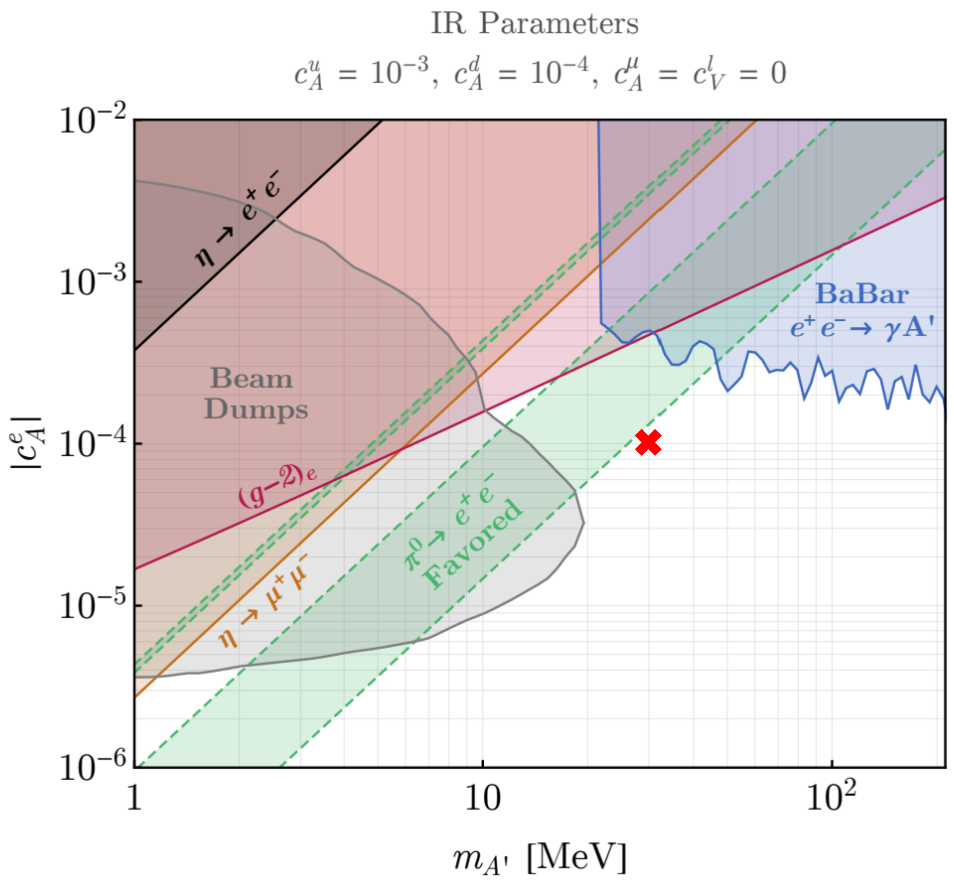
Mukesh K. Pandey *et al.*, Phys. Rev. D **102**, 123025 (2020); arXiv:1812.11759 [hep-ph].

C.-P. Liu *et al.*, arXiv:2106.16214 [hep-ph].

What We've Done in This Work

- SD DM-e interaction should be considered together with SI interaction, to provide a more comprehensive understanding about the nature of DM & its interaction.
- We set a limit on the SD & SI DM-e cross sections at leading order with state-of-the-arts atomic many-body calculations and current best experiment data.
- One can differentiate the shape of SD and SI recoil spectra at high energies when spin obit interaction becomes more relevant; or new detector design with spin polarizable target and known spin states of the ionized electrons.

SD Scenario I



- by the exchange of heavy axial-vector boson coupled to both electron and DM.

  $c_4 \sim c_{eA} c_{\chi A}/m_A^2$

- Our constraint: $|c_4| \lesssim (100\ \mathrm{GeV})^{-2}$

  can be realized with $|c_{\chi A}| \lesssim 10^{-3}$

  not strong comparing with the scenario of strongly coupled dark sectors

Y. Kahn, G. Krnjaic, S. Mishra-Sharma, and T. M. P. Tait, *J. High Energ. Phys.* **2017**, 2; arXiv:1609.09072 [hep-ph].

SD Scenario II

- an exchange of a pseudoscalar particle, a by the interaction Lagrangian

$$\mathcal{L}_I = c_{\chi a}/f_a \ \bar{\chi}\gamma_\mu\gamma_5\chi\partial^\mu a + c_{ea}/f_a \ \bar{e}\gamma_\mu\gamma_5 e\partial^\mu a$$

- If the m_a is much smaller than the momentum transfer, then low energy χ-e scattering can be described by a contact interaction $\sim c_4'\bar{\chi}\gamma_\mu\gamma_5\chi\bar{e}\gamma^\mu\gamma_5 e$ with $c_4' = c_{\chi a}c_{ea}/f_a^2$

- Our constraint $c_4 \sim (100 \text{ GeV})^{-2}$ and astrophysical bound $c_{ea}/f_a \sim 1/(10^9 \text{ GeV})$ imply $|c_{ea}/c_{\chi a}| \sim 10^{-14}$ and the χ-χ int. through exchanges of a is perturbative

Long-Range SD Scenario

- The requirement of perturbative unitary on the axial-vector coupling to DM gives a lower bound for the mediator mass $m_A > \sqrt{2/\pi}\, c_{\chi A} m_\chi$
- In our exclusion plot, the m_χ range is fully covered if $c_{\chi A} \sim 10^{-4}$
- If $c_{\chi A} > 10^{-4}$ such that unitarity is not satisfied perturbatively. However, it is expected that unitarity can still be recovered non-perturbatively in this case. For example, the large strong coupling constant at low energies does not break the unitarity of QCD, although perturbative unitarity might be broken.

Dark Matter Direct Detection

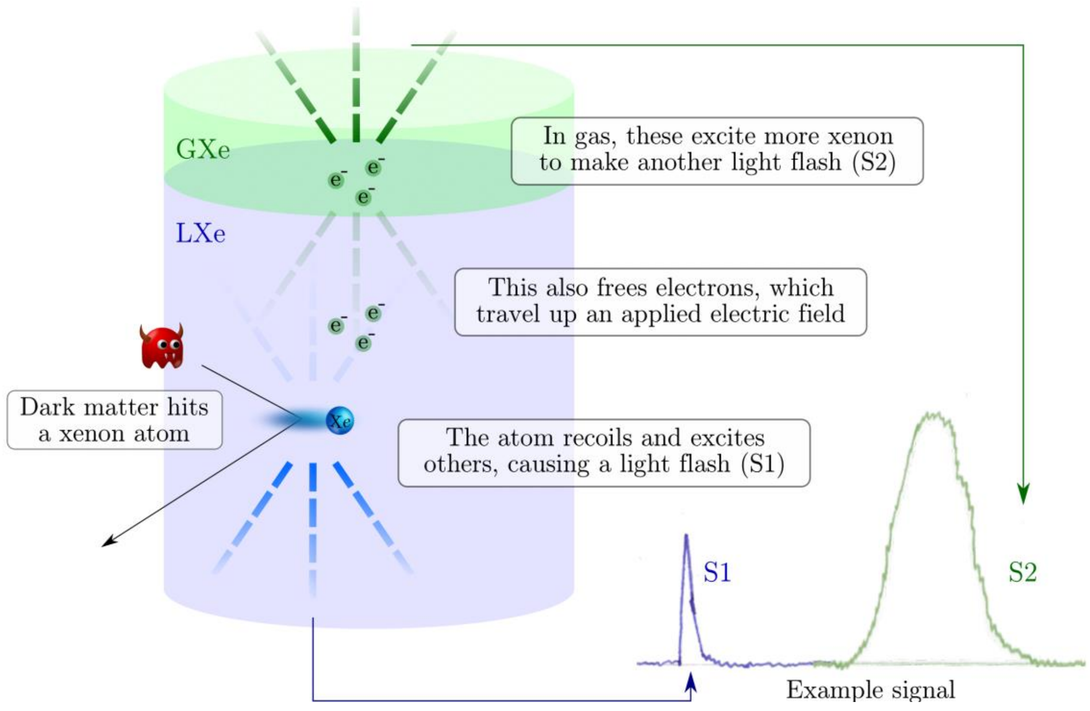
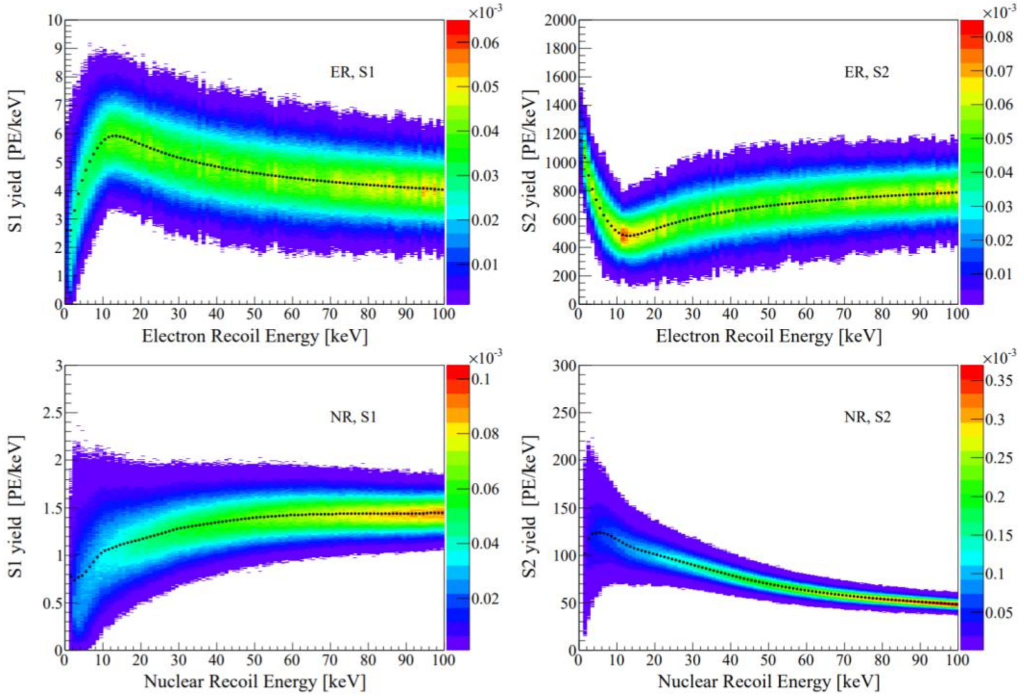


Photo from XENON Collaboration website.

Discrimination of
Nuclear Recoil (NR) & Electronic Recoil (ER)



E. Aprile *et al*., Journal of Cosmology and Astroparticle Physics 2016, 027 (2016).

Dark Matter Candidates

Portals to the Dark Sector:

Portal	Particles	Operator(s)
"Vector"	Dark photons	$-\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}$
"Axion"	Pseudoscalars	$\frac{a}{f_a} F_{\mu\nu}\widetilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i\mu\nu}\widetilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
"Higgs"	Dark scalars	$(\mu S + \lambda S^2) H^\dagger H$
"Neutrino"	Sterile neutrinos	$y_N L H N$

Effective Field Theory:

$$\begin{aligned}\mathcal{L}_{\rm int} &= \chi^+ \mathcal{O}_\chi \chi^- N^+ \mathcal{O}_N N^- \equiv \mathcal{O}\, \chi^+\chi^- N^+ N^- \\ &= \sum_{N=n,p} \sum_i c_i^{(N)} \mathcal{O}_i \chi^+\chi^- N^+ N^-\end{aligned}$$

$$\begin{aligned}
&\mathcal{O}_1 = \mathbf{1}, \quad \mathcal{O}_2 = (v^\perp)^2, \quad \mathcal{O}_3 = i\vec{S}_N \cdot (\vec{q} \times \vec{v}^\perp), \\
&\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N, \quad \mathcal{O}_5 = i\vec{S}_\chi \cdot (\vec{q} \times \vec{v}^\perp), \quad \mathcal{O}_6 = (\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q}), \\
&\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp, \quad \mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp, \quad \mathcal{O}_9 = i\vec{S}_\chi \cdot (\vec{S}_N \times \vec{q}) \\
&\mathcal{O}_{10} = i\vec{S}_N \cdot \vec{q}, \quad \mathcal{O}_{11} = i\vec{S}_\chi \cdot \vec{q}. \quad \mathcal{O}_{12} = \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp).
\end{aligned}$$

For Example,
millicharged U(1) DM int. can be related to the-leading-order $\mathcal{O}_1$ term with non-relativistic reduction.

Ab initio Theory for Atomic Ionization

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

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

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

Random Phase Approx.: Expand

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

Linear coupled differential equations for one-electron orbital wave functions:

$$[h + V_{HF}]u_a(\vec{r}) = \varepsilon_a u_a(\vec{r}) - \textstyle\sum_b \lambda_{ab} u_b(\vec{r})$$

$$[h + V_{HF} - \varepsilon_a - \omega]\, w_{a+}(\vec{r}) = -[v(\vec{r}) + V_{HF}^{(+)}]\, u_a(\vec{r}) - \textstyle\sum_b \lambda_{ab}^{(+)} u_b(\vec{r})$$

$$[h + V_{HF} - \varepsilon_a + \omega]\, w_{a-}(\vec{r}) = -[v^{\dagger}(\vec{r}) + V_{HF}^{(-)}]\, u_a(\vec{r}) - \textstyle\sum_b \lambda_{ab}^{(-)} u_b(\vec{r})$$

Multipole Expansion for RRPA Matrix Elements

$$\langle \Psi_f^{(-)} | v_+ | \Psi_i \rangle = \sum_\alpha \Lambda_\alpha (\langle w_{\alpha+} | v_+ | u_\alpha \rangle + \langle u_\alpha | v_+ | w_{\alpha-} \rangle) + \sum_{a,b} ([C_a]_+^\star C_b + C_a^\star [C_b]_-) \langle \psi_a | v_+ | \psi_b \rangle$$

Transition matrix elements of atomic ionization by electroweak interactions:

$$\langle \Psi_f | v_+^{(\gamma)} | \Psi_i \rangle = \frac{4\pi\alpha}{q^2} \left\{ j_0^{(\gamma)} \left\langle \Psi_f \middle| \int d^3x e^{i\vec{q}\cdot\vec{x}} \hat{\mathcal{J}}^0(\vec{x}) \middle| \Psi_i \right\rangle + \sum_{\lambda=\pm1,0} (-1)^\lambda j_\lambda^{(\gamma)} \left\langle \Psi_f \middle| \int d^3x e^{i\vec{q}\cdot\vec{x}} \hat{\epsilon}^{-\lambda} \cdot \hat{\vec{\mathcal{J}}}(\vec{x}) \middle| \Psi_i \right\rangle \right\}$$

$$e^{i\vec{q}\cdot\vec{x}} = \sum_{J=0}^{\infty} \sqrt{4\pi(2J+1)}\, i^J j_J(\kappa r) Y_J^0(\Omega_x)$$

$$\hat{e}_{(\lambda=\pm1)}\, e^{i\vec{q}\cdot\vec{x}} = \sum_{J\geq1} i^J \sqrt{2\pi(2J+1)} \left\{ \mp j_J(kr) \mathcal{Y}_{JJ1}^{\lambda} - \frac{1}{k} \nabla \times [j_J(kr) \mathcal{Y}_{JJ1}^{\lambda}] \right\}$$

$$\hat{e}_{(\lambda=0)}\, e^{i\vec{q}\cdot\vec{x}} = \frac{-i}{k} \sum_{J\geq0} i^J \sqrt{4\pi(2J+1)}\, \nabla\, [j_J(kr)\, Y_{J0}]$$

$$v_+^{(\gamma)} = \frac{4\pi\alpha}{q^2} \left\{ \sum_{J=0}^{\infty} \sqrt{4\pi(2J+1)}\, i^J [j_0^{(\gamma)} \hat{C}_{J0}(k) - j_3^{(\gamma)} \hat{L}_{J0}(k)] + \sum_{J\geq1}^{\infty} \sqrt{2\pi(2J+1)}\, i^J \sum_{\lambda=\pm1} j_\lambda^{(\gamma)} [\hat{E}_{J-\lambda}(k) - \lambda \hat{M}_{J-\lambda}(k)] \right\}$$

Central-Field Hartree-Fock Potential

The Hartree-Fock potential is given by the sum of the local “direct” and non-local “exchange” parts of the interaction, $V_{\mathrm{HF}} = U^{\mathrm{dir}} + U^{\mathrm{exch}}$

$$U^{\mathrm{dir}}\psi_a(\boldsymbol{r}) = e^2 \sum_{n\neq a}^{N} \int \frac{\psi_n^\dagger(\boldsymbol{r}')\psi_n(\boldsymbol{r}')}{|\boldsymbol{r}-\boldsymbol{r}'|} \mathrm{d}^3 r' \psi_a(\boldsymbol{r})$$

$$U^{\mathrm{exch}}\psi_a(\boldsymbol{r}) = -e^2 \sum_{n\neq a}^{N} \int \frac{\psi_n^\dagger(\boldsymbol{r}')\psi_a(\boldsymbol{r}')}{|\boldsymbol{r}-\boldsymbol{r}'|} \mathrm{d}^3 r' \psi_n(\boldsymbol{r})$$

The first-order corrections to the HF potential $V_{\mathrm{HF}}^{(\pm)}$ in RRPA equations by replacing

$$\text{direct:}\quad \psi_n^\dagger(\boldsymbol{r}')\psi_n(\boldsymbol{r}') \to \psi_n^\dagger(\boldsymbol{r}')w_{b\pm}(\boldsymbol{r}') + w_{b\mp}^\dagger(\boldsymbol{r}')\psi_n(\boldsymbol{r}')$$

$$\text{exchange:}\quad \psi_n^\dagger(\boldsymbol{r}')\psi_n(\boldsymbol{r}) \to \psi_n^\dagger(\boldsymbol{r}')w_{b\pm}(\boldsymbol{r}) + w_{b\mp}^\dagger(\boldsymbol{r}')\psi_n(\boldsymbol{r})$$

Other Approximations for the Potential

$$V^{(a)}(r) = \frac{Z^{(a)}(r)}{r}$$

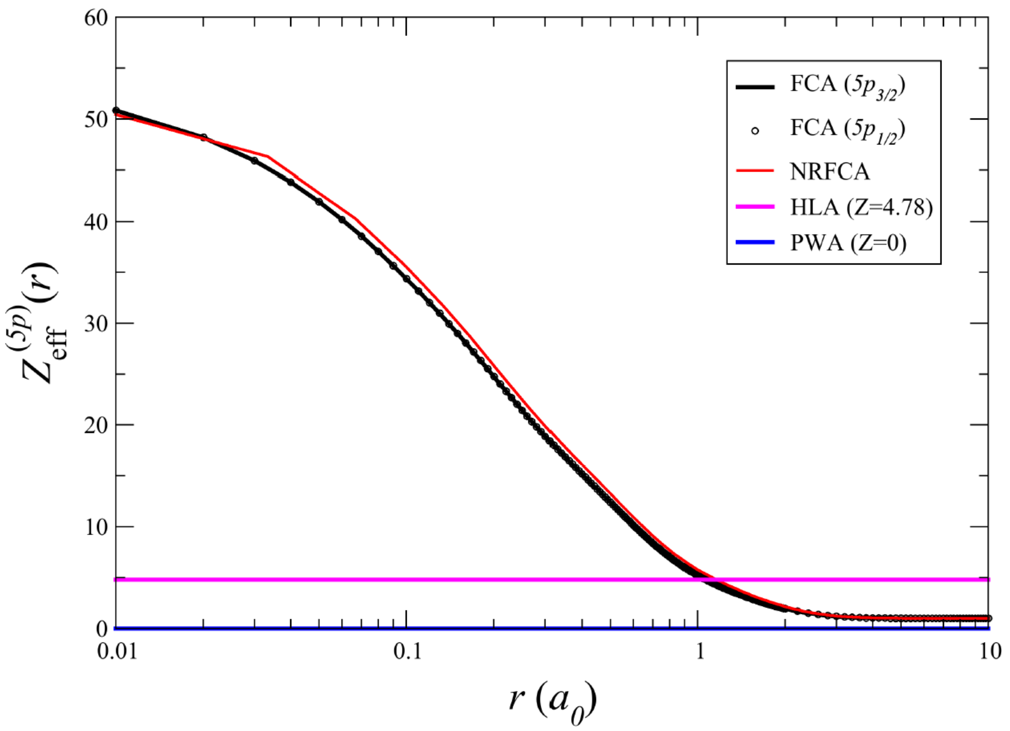
Plane Wave Approx. (PWA): $Z^{(\mathrm{a})}(r) = 0$, treat ionized electron as a free particle

Hydrogen-Like Approx. (HLA): $Z^{(a)}_{\mathrm{HLA}}(r) = n_a \sqrt{\frac{-E_B^{(a)}}{\mathrm{Ry}}}\,,$

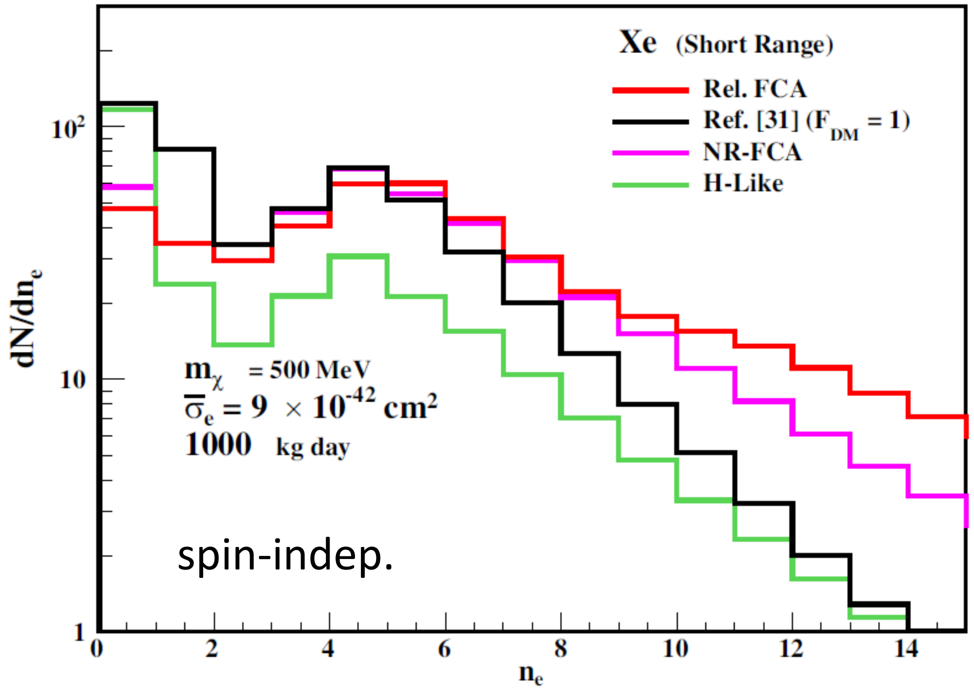
assumes the ionized electron behaves like a hydrogen-like electron. The effective charge is simply from a unscreened point source at the atomic center with its magnitude fixed by the orbital binding energy E_B

Frozen Core Approx. (FCA):
$V_{\mathrm{HF}}^{(\pm)} = 0$, no perturbation to HF potential for solving continuum states WF

Effective charge for Xe 5p orbital



Asymptotic → 1



Mukesh K. Pandey *et al*., Phys. Rev. D **102**, 123025 (2020); arXiv:1812.11759 [hep-ph].

Folding with DM Velocity Spectrum

$$\frac{d\mathcal{R}}{dT} = \frac{\rho_\chi N_T}{m_\chi} \frac{d\langle\sigma v_\chi\rangle}{dT}$$

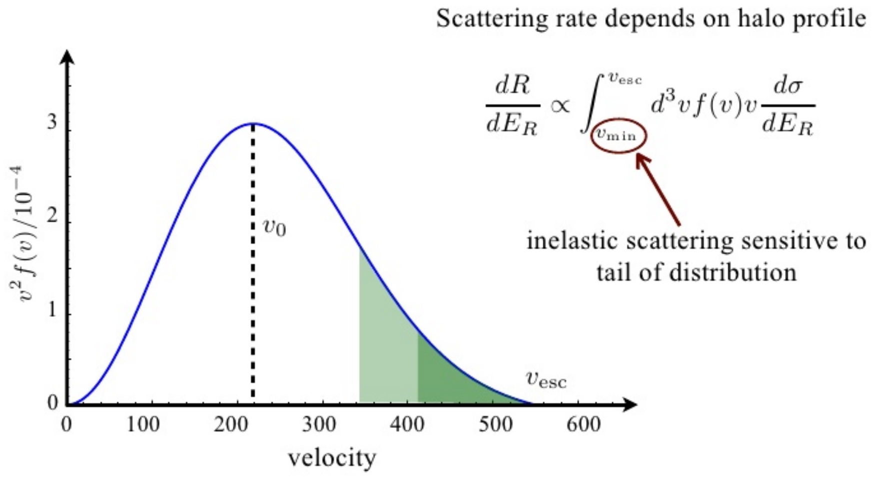
$$\frac{d\langle\sigma v_\chi\rangle}{dT} = \int_{v_{\min}}^{v_{\max}} d^3 v_\chi f(\vec{v}_\chi) v_\chi$$

$$\times \frac{1}{2\pi v_\chi^2} \int_{q_-}^{q_+} dq q \left[\left| c_1 + \frac{d_1}{q^2} \right|^2 \right] R(T,q)$$

$$\eta(\tilde{v}_{\min}) = \int_{v_{\min}}^{v_{\max}} d^3 v_\chi f(\vec{v}_\chi) \frac{1}{v_\chi} \Theta(v_\chi - \tilde{v}_{\min})$$

has analytic form with Standard Halo Model velocity spectrum

Standard Halo Model



$$\frac{1}{K} e^{-\frac{|\vec{v}_\chi + \vec{v}_E|^2}{v_0^2}} \Theta(v_{esc} - |\vec{v}_\chi + \vec{v}_E|)$$

v_0 = 220 km/s ~ 10^{-3} c
v_E = 232 km/s
v_{esc} = 544 km/s