DISCRETE 2022

7-11 November 2022

Kongresshaus Baden-Baden

Atomic responses for Dark matter scattering off electrons with Ge & Xe Detectors

Mukesh Kumar Pandey
Department of Physics,
National Dong Hwa University
Taiwan

Co-author:

Jiunn-Wei Chen(NTU), Chih-Pang Wu (University of Montreal, Canada), Chen-Pang Liu, Hsin-Chang Chi(NDHU), Henry T. Wong(IOP, Academia Sinica, TEXONO Collaboration) , Lakhwinder Singh(CUSB, India)

References:

1. Mukesh K. Pandey et al ., Phys. Rev. D 102, 123025 (2020); arXiv:1812.11759.
2. C.-P. Liu et al., PHYS. REV. D 106, 063003 (2022); arXiv:2106.16214

Outline of the talk

1. What is the need of this study(Motivation)
2. About Dark matter
3. Why Atomic Physics ?
3. Brief outline about Theoretical approach
4. Result and discussions
5. Conclusion

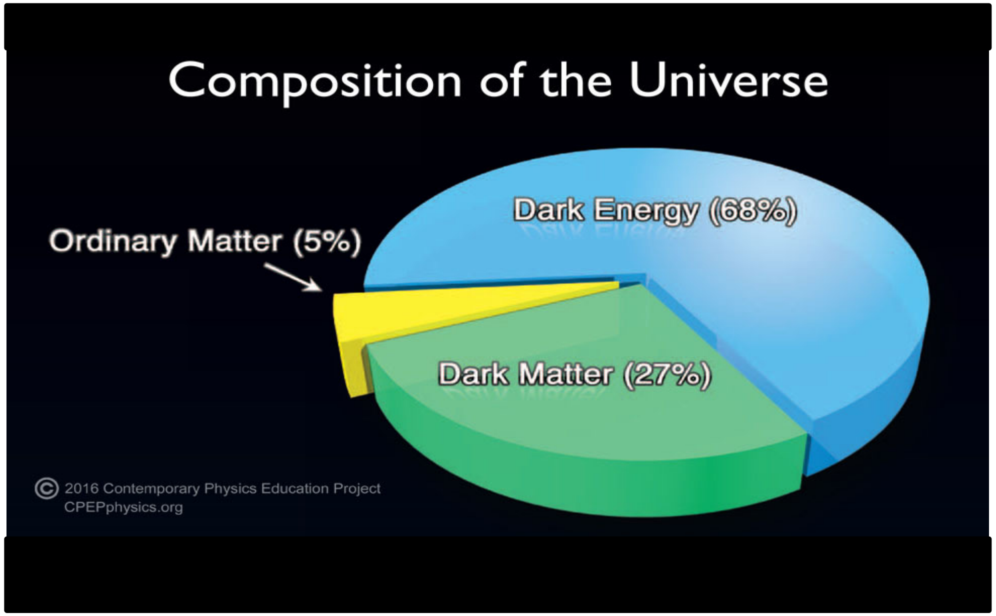
A smaller question

What's the minimum set of particles and interactions that builds the material world?

This is a problem particle physicists worry about. They are driven to look for "New Physics".

Hint of New Physics

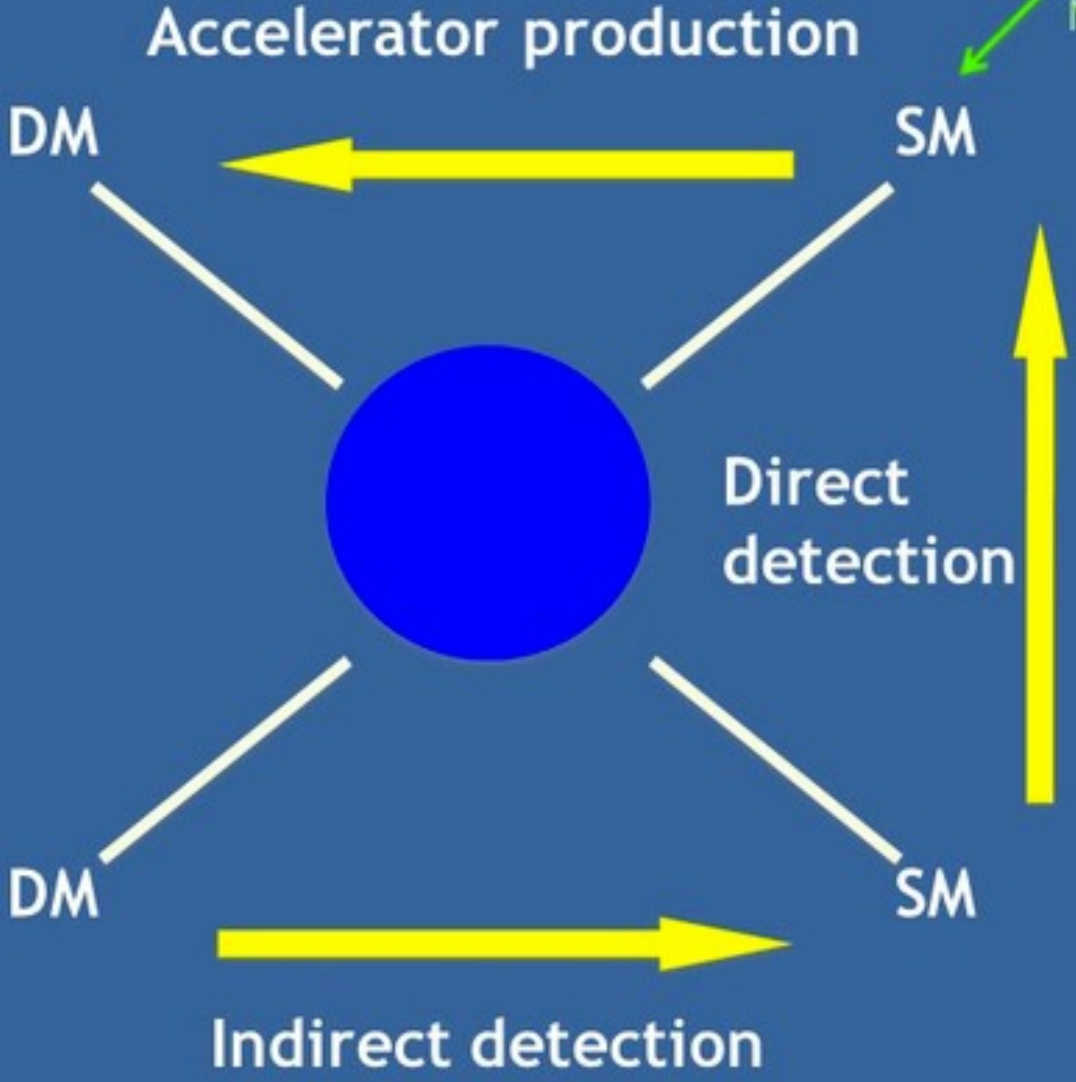
- Neutrino
- Dark matter
- Dark energy



© 2016 Contemporary Physics Education Project
CPEPphysics.org

They are "Portals" to New Physics!

Strategies: search for Dark Matter



SM: Standard Model particle

Accelerator production

DM

SM

Direct detection

DM

SM

Indirect detection

- » Production in accelarators (LHC)
- » Indirect detection:
  - search for annihilation/decay products of χ's (self-antiparticle)
- » Direct detection:
  - χ-nucleus elastic scattering

Why Atomic Physics?

Why Atomic Physics?

- Energy scales: Atomic (~ eV) Reactor neutrino (~ MeV) WIMP (~ GeV)
- Neutrino: NNM atomic ionization signal larger at lower energy scattering (current Ge detector threshold 0.1 keV)
- DM: direct detection, velocity slow (~ 1/1000), max energy 1 keV for mass 1 GeV DM.

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

- Incident momentum $\sim$ 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 $\sim$ 10 keV and below
  - barely overcome the atomic thresholds
  - For Innermost orbital, binding energy $\sim$ 11 keV (Ge) and 34 keV (Xe)
- Phase-space suppression (Ex: WIMP-e scattering)

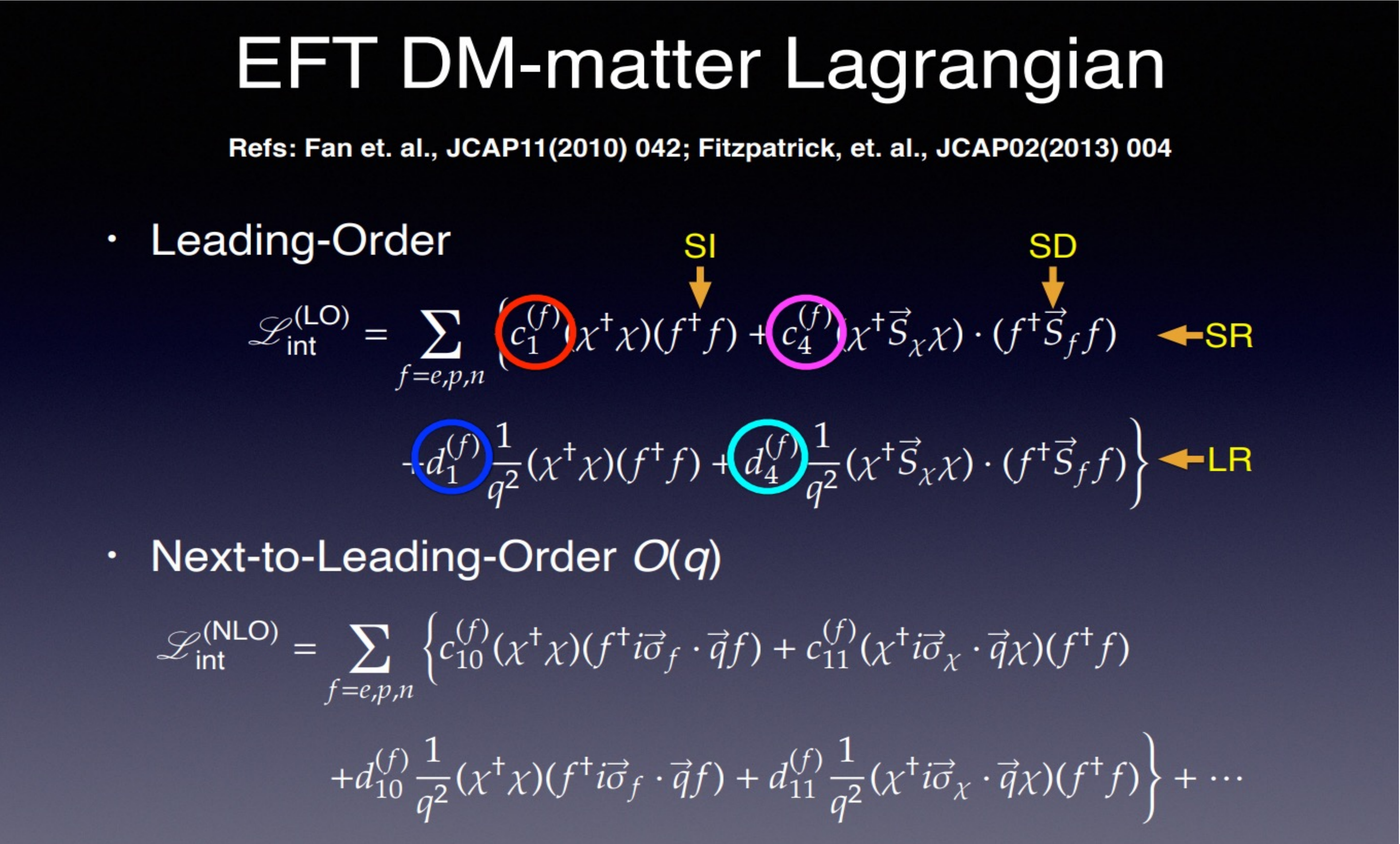
Opportunity: Applying atomic physics at keV (low for nuclear physics but high for atomic physics)

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.



EFT DM-matter Lagrangian

Refs: Fan et. al., JCAP11(2010) 042; Fitzpatrick, et. al., JCAP02(2013) 004

- Leading-Order

$$\mathscr{L}_{\text{int}}^{(\text{LO})} = \sum_{f=e,p,n} \Big\{ \boxed{c_1^{(f)}} \overset{\text{SI}}{\downarrow} (\chi^\dagger \chi)(f^\dagger f) + \boxed{c_4^{(f)}} (\chi^\dagger \vec{S}_\chi \chi) \cdot \overset{\text{SD}}{\downarrow} (f^\dagger \vec{S}_f f) \quad \leftarrow \text{SR}$$

$$+ \boxed{d_1^{(f)}} \frac{1}{q^2} (\chi^\dagger \chi)(f^\dagger f) + \boxed{d_4^{(f)}} \frac{1}{q^2} (\chi^\dagger \vec{S}_\chi \chi) \cdot (f^\dagger \vec{S}_f f) \Big\} \leftarrow \text{LR}$$

- Next-to-Leading-Order $O(q)$

$$\mathscr{L}_{\text{int}}^{(\text{NLO})} = \sum_{f=e,p,n} \Big\{ c_{10}^{(f)} (\chi^\dagger \chi)(f^\dagger i\vec{\sigma}_f \cdot \vec{q} f) + c_{11}^{(f)} (\chi^\dagger i\vec{\sigma}_\chi \cdot \vec{q} \chi)(f^\dagger f)$$

$$+ d_{10}^{(f)} \frac{1}{q^2} (\chi^\dagger \chi)(f^\dagger i\vec{\sigma}_f \cdot \vec{q} f) + d_{11}^{(f)} \frac{1}{q^2} (\chi^\dagger i\vec{\sigma}_\chi \cdot \vec{q} \chi)(f^\dagger f) \Big\} + \cdots$$

where χ and f denote the DM and fermion fields, respectively, S_χ, S_f are their spin operators (scalar DM particles have null S_χ), the DM 3-momentum transfer |q| depends on the DM energy transfer T and its scattering angle θ

Differential Cross Section

Example: a $c_1^{(e)}$ type interaction with NR DM

$$d\sigma|_{c_1^{(e)}} = \frac{2\pi}{v_\chi} \boxed{\sum_F \overline{\sum_I} |\langle F|c_1^{(e)}\rho(\vec{q})|I\rangle|^2 \delta(T - E_{\mathrm{CM}} - (E_F - E_I))} \frac{d^3k_2}{(2\pi)^3}$$

- All dynamical information in response functions
- E_{CM} for CM recoil, E_F-E_I for internal state change
- Biggest challenge: many-body wave functions for the initial and final states

Folding with DM Velocity Spectrum

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

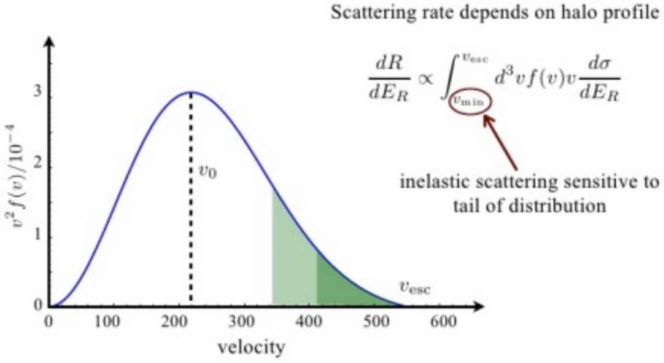
$$\frac{d\left\langle \sigma v_\chi \right\rangle}{dT} = \int_{v_{\min}}^{v_{\max}} d^3 v_\chi f(\vec{v}_\chi) v_\chi$$

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

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

has analytic form with Standard Halo Model velocity spectrum

Standard Halo Model



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

v_0 = 220 km/s ~ 10^{-3} c

v_E = 232 km/s

v_{esc} = 544 km/s

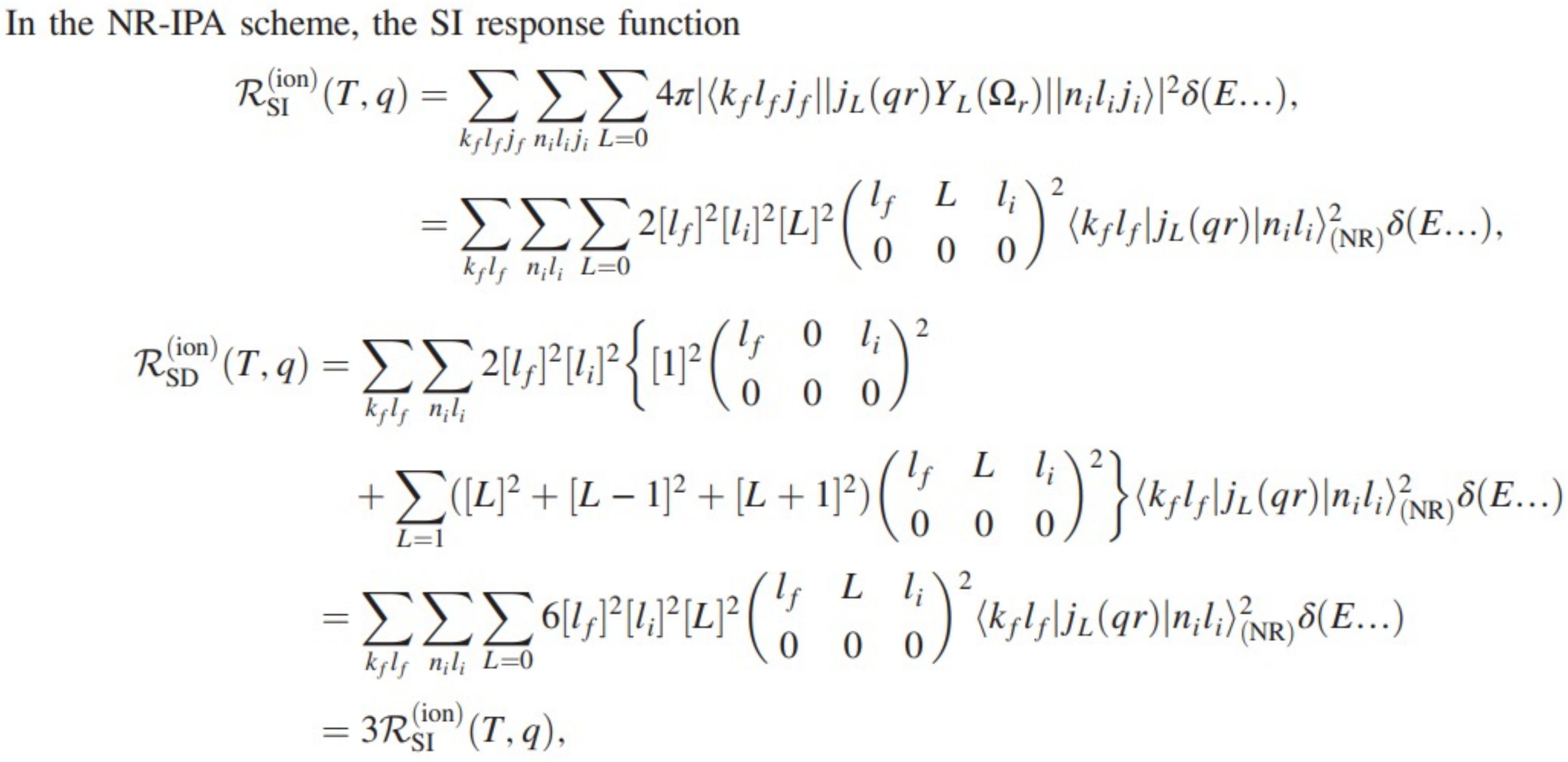
To explore the impact of uncertainties in the DM velocity spectrum, we follow Ref.

G. Belanger, A. Mjallal, and A. Pukhov, Recasting direct detection limits within micrOMEGAs and implication for non-standard dark matter scenarios, Eur. Phys. J. C 81, 239 (2021).

vary $(v_0, v_{\rm esc}, v_E)$ in the range of (220 ±18, 232±10, 544±63)km/s.

Response Function

The full information of how the detector atom responds to the incident DM particle is encoded



In the NR-IPA scheme, the SI response function

$$\mathcal{R}_{\mathrm{SI}}^{(\mathrm{ion})}(T,q)=\sum_{k_f l_f j_f}\sum_{n_i l_i j_i}\sum_{L=0}4\pi|\langle k_f l_f j_f||j_L(qr)Y_L(\Omega_r)||n_i l_i j_i\rangle|^2\delta(E\ldots),$$

$$=\sum_{k_f l_f}\sum_{n_i l_i}\sum_{L=0}2[l_f]^2[l_i]^2[L]^2\begin{pmatrix} l_f & L & l_i \\ 0 & 0 & 0\end{pmatrix}^2\langle k_f l_f|j_L(qr)|n_i l_i\rangle^2_{(\mathrm{NR})}\delta(E\ldots),$$

$$\mathcal{R}_{\mathrm{SD}}^{(\mathrm{ion})}(T,q)=\sum_{k_f l_f}\sum_{n_i l_i}2[l_f]^2[l_i]^2\left\{[1]^2\begin{pmatrix} l_f & 0 & l_i \\ 0 & 0 & 0\end{pmatrix}^2\right.$$

$$\left.+\sum_{L=1}([L]^2+[L-1]^2+[L+1]^2)\begin{pmatrix} l_f & L & l_i \\ 0 & 0 & 0\end{pmatrix}^2\right\}\langle k_f l_f|j_L(qr)|n_i l_i\rangle^2_{(\mathrm{NR})}\delta(E\ldots)$$

$$=\sum_{k_f l_f}\sum_{n_i l_i}\sum_{L=0}6[l_f]^2[l_i]^2[L]^2\begin{pmatrix} l_f & L & l_i \\ 0 & 0 & 0\end{pmatrix}^2\langle k_f l_f|j_L(qr)|n_i l_i\rangle^2_{(\mathrm{NR})}\delta(E\ldots)$$

$$=3\mathcal{R}_{\mathrm{SI}}^{(\mathrm{ion})}(T,q),$$

R(T, q) is evaluated by well-benchmarked procedure based on an *ab-inito* method, the (multi-configuration) relativistic random phase approximation, (MC)RRPA.

To expedite the computation, we performed (MC)RRPA calculations only for selected data points, and the full computation is done with an additional approximation: the frozen-core approximation (FCA).

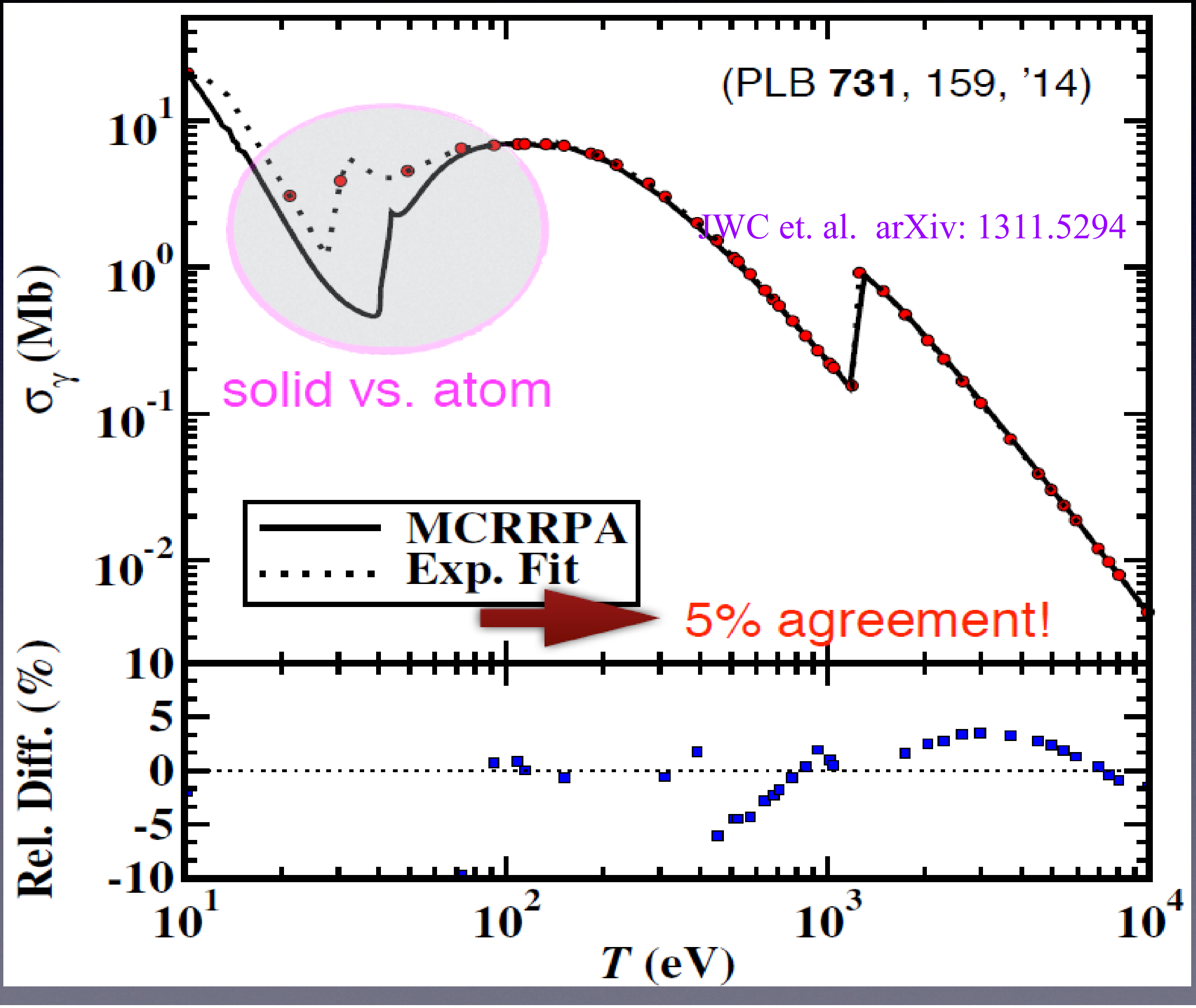
The FCA has a discrepancy less than 20% for all our calculations.

Results we’ve got:

Important Lessons

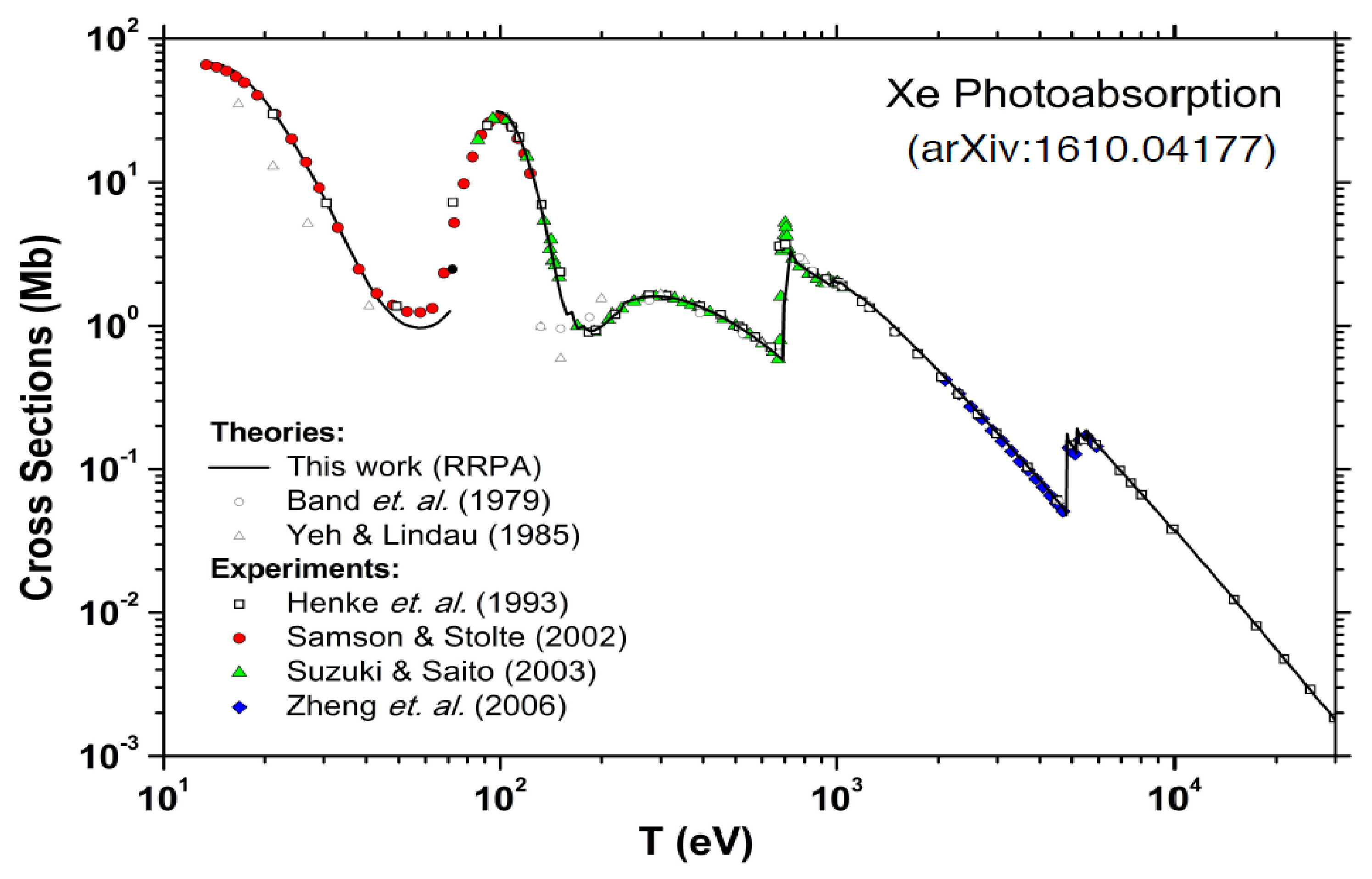
- Benchmark, benchmark, benchmark.
- Relativistic and MB effects are important.
- Spin-orbit interaction is critical in SD responses.

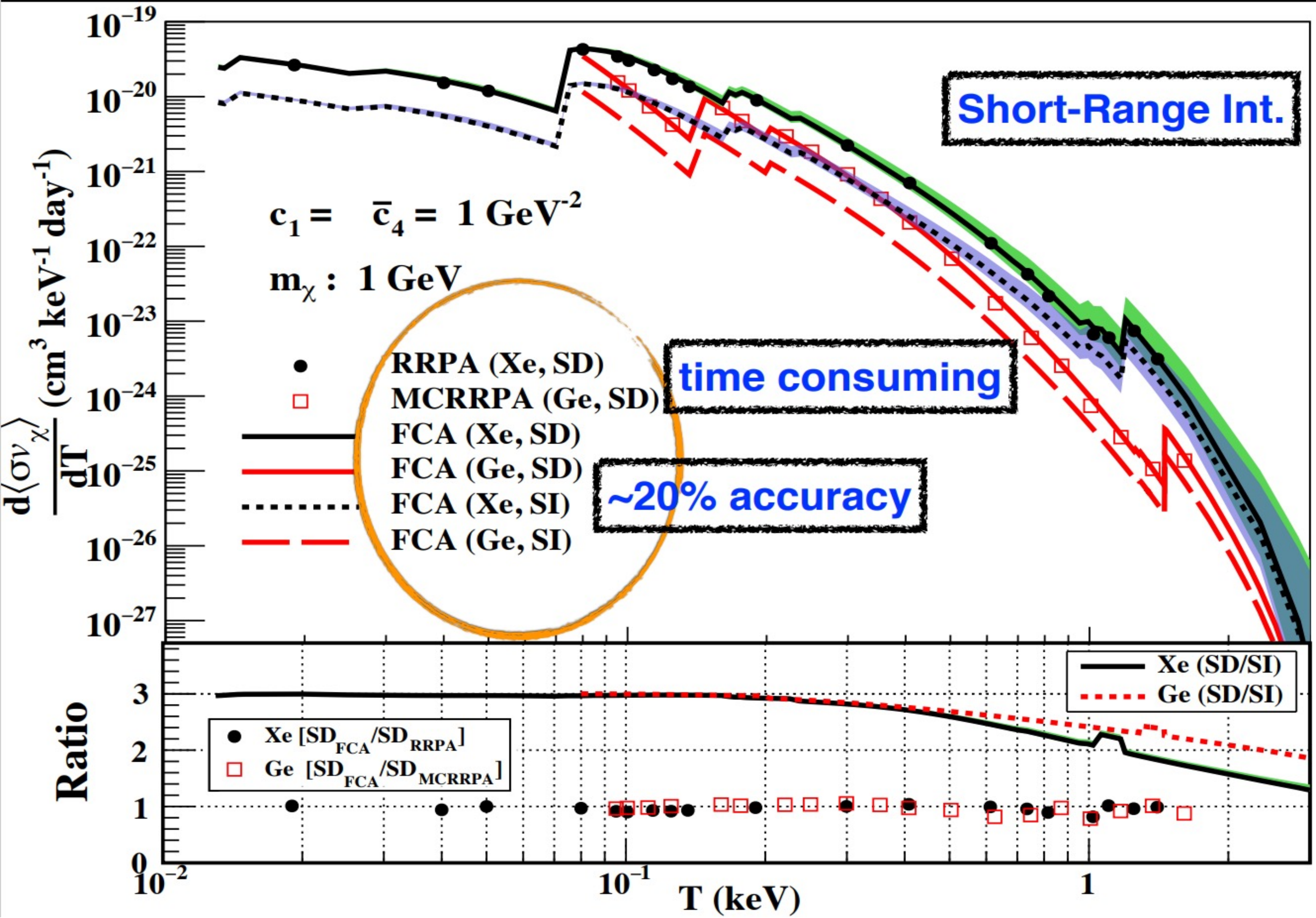
Benchmark: Ge Photoionization



The main error are located at 10 to 100 eV for Ge case. It may come from the solid effects but in our calculations where we only consider one Ge atom.

Benchmark: Xe Photoionization

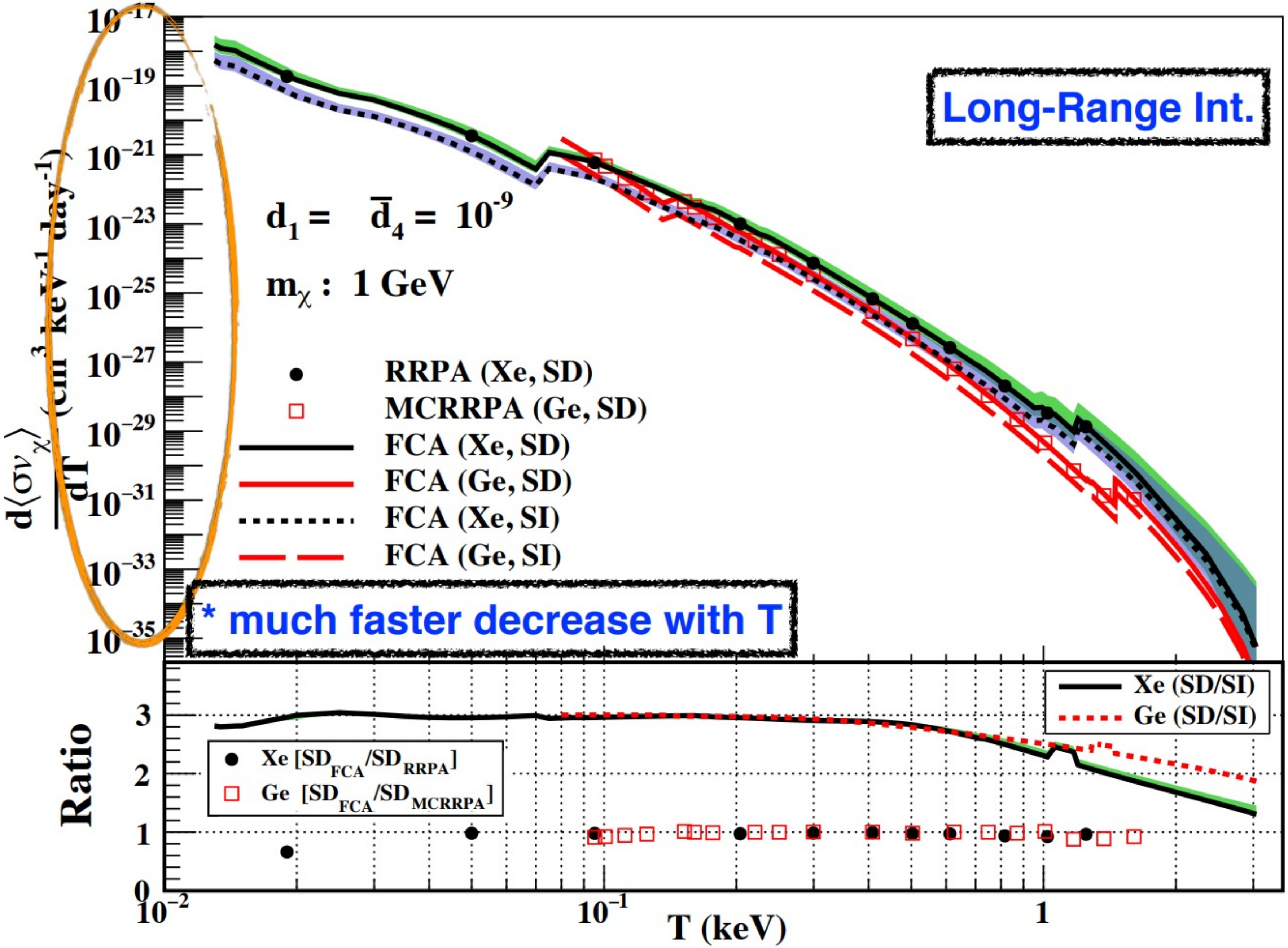




Short-Range Int.

time consuming

~20% accuracy



Long-Range Int.

*** much faster decrease with T**

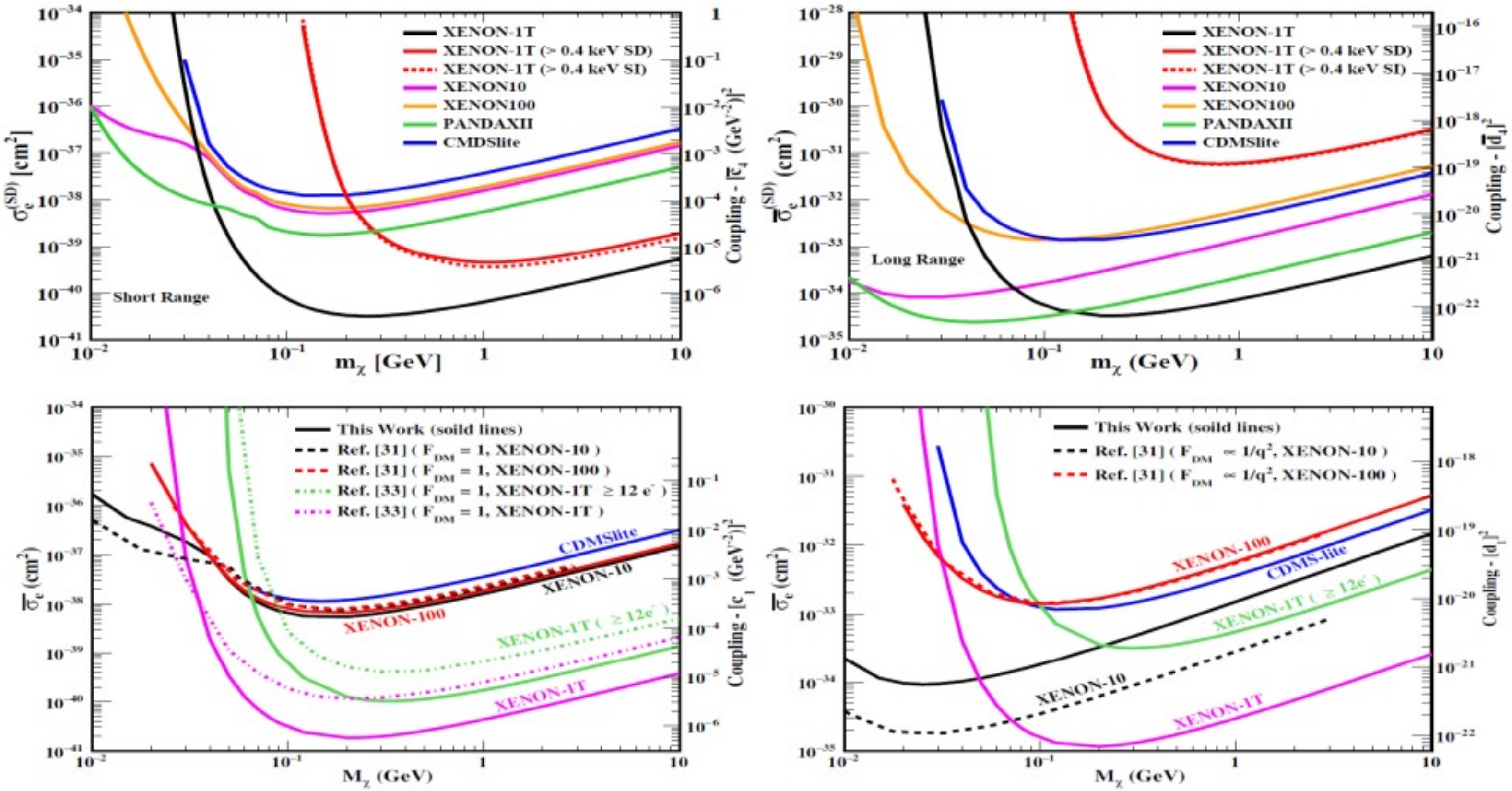
Exclusion Limits on DM-e Interactions

Short Range

Long Range

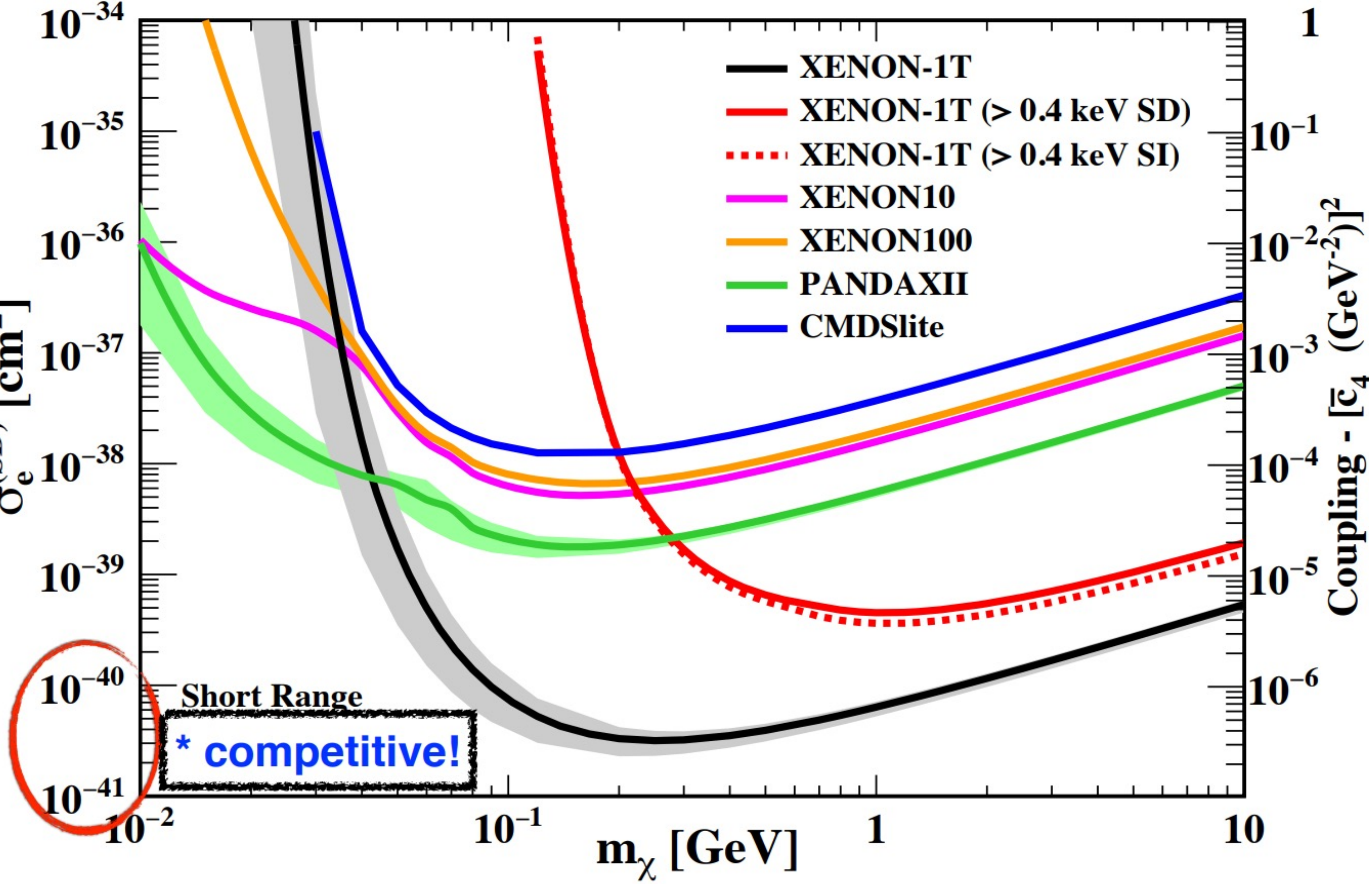
SD:

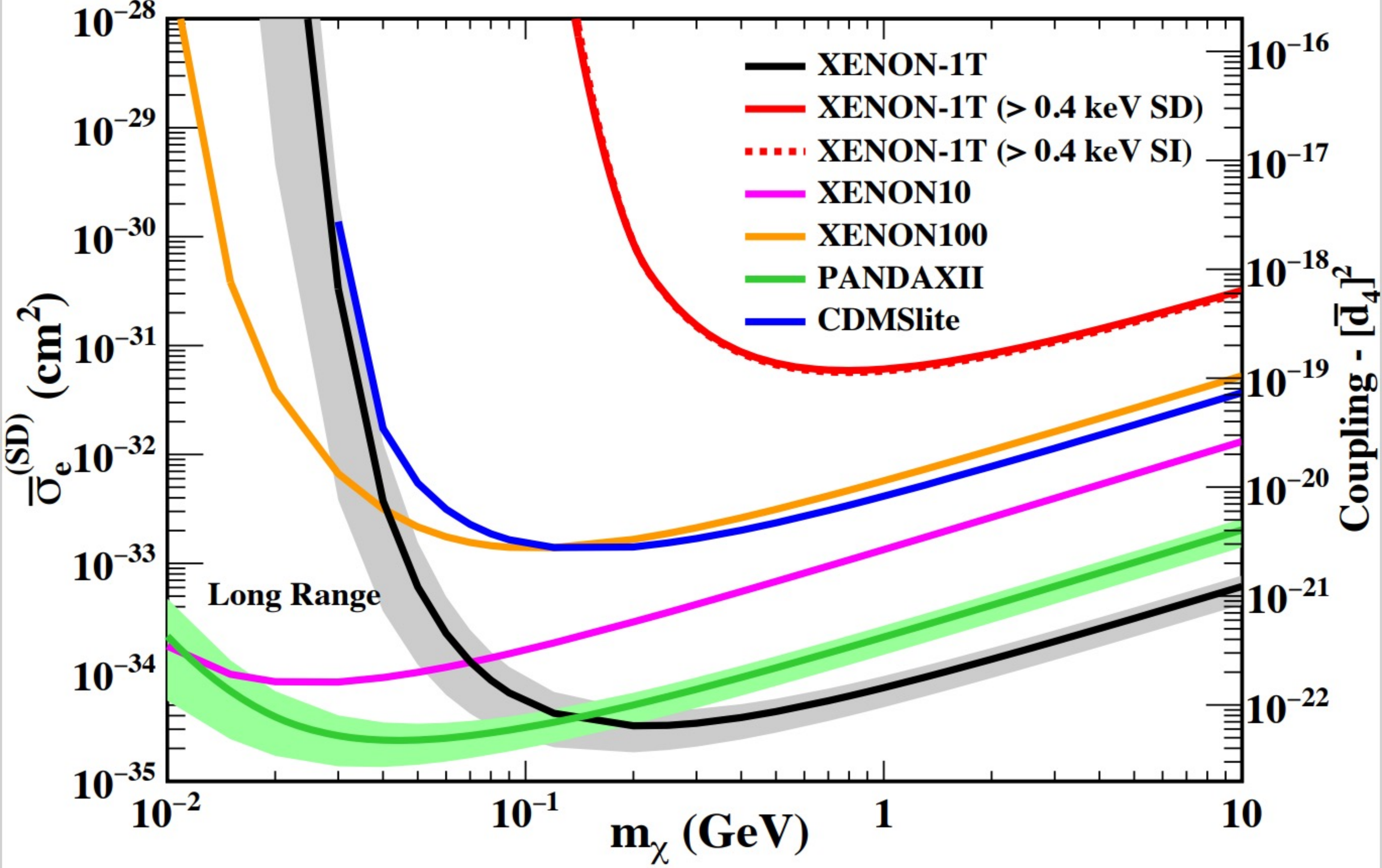
SI:



[31] R. Essig, T. Volansky, and T.-T. Yu, Phys. Rev. D 96, 043017 (2017).

[33]E. Aprile et al. (XENON Collaboration), Phys. Rev. Lett. 123, 251801 (2019)

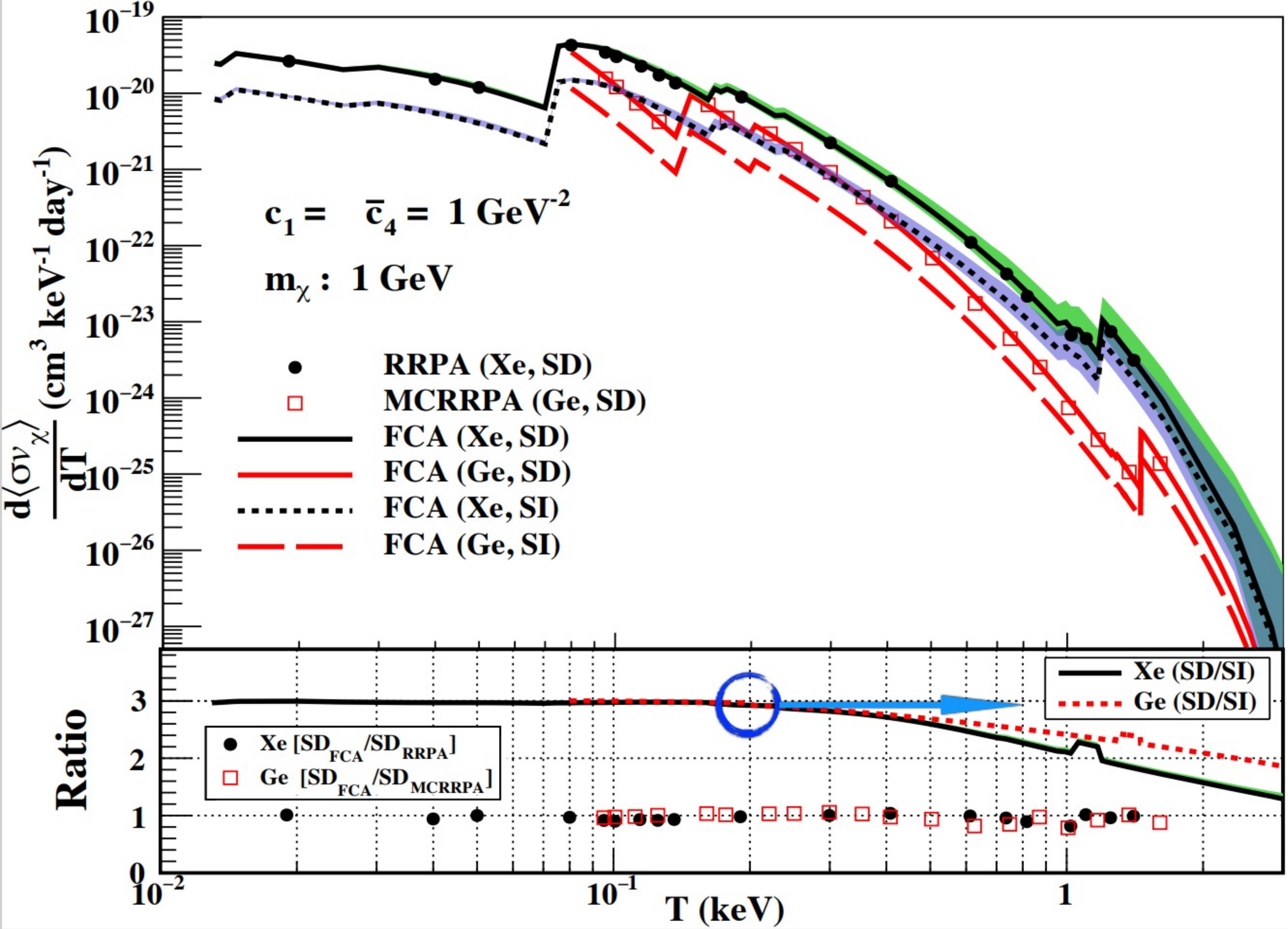

XENON-1T
XENON-1T (> 0.4 keV SD)
XENON-1T (> 0.4 keV SI)
XENON10
XENON100
PANDAXII
CMDSlite
$\sigma_e^{(SD)}$ [cm^2]
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-2}
10^{-1}
1
10
m_χ [GeV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Coupling - $[\bar{c}_4\ (\text{GeV}^{-2})]^2$
Short Range
* competitive!

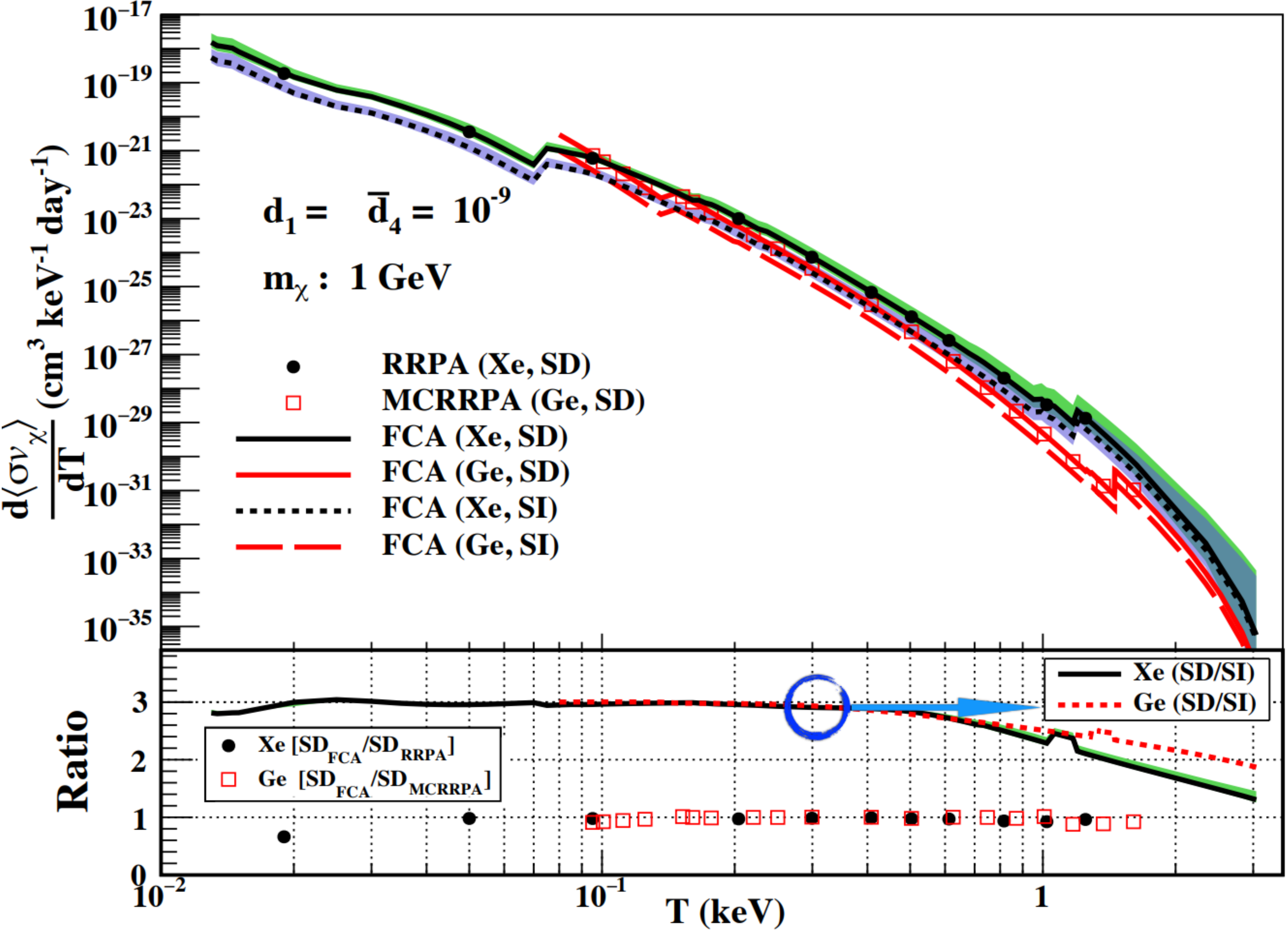

XENON-1T
XENON-1T (> 0.4 keV SD)
XENON-1T (> 0.4 keV SI)
XENON10
XENON100
PANDAXII
CDMSlite
Long Range
$\overline{\sigma}_e^{(SD)}$ (cm^2)
Coupling - $[\overline{d}_4]^2$
m_χ (GeV)
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-2}
10^{-1}
1
10

How to distinguish the SD/SI signals?

Opt. 1: Spectral Shape

- Because of SOI, SI and SD signals start to have different spectral shape as *T* increases.


$c_1 = \bar{c}_4 = 1\ \mathrm{GeV}^{-2}$
m_χ : 1 GeV
RRPA (Xe, SD)
MCRRPA (Ge, SD)
FCA (Xe, SD)
FCA (Ge, SD)
FCA (Xe, SI)
FCA (Ge, SI)
$\frac{d\langle\sigma v_\chi\rangle}{dT}$ (cm^3 keV^{-1} day^{-1})
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
Ratio
3
2
1
0
Xe (SD/SI)
Ge (SD/SI)
Xe [SD_{FCA}/SD_{RRPA}]
Ge [SD_{FCA}/SD_{MCRRPA}]
10^{-2}
10^{-1}
1
T (keV)



10^{-17}
10^{-19}
10^{-21}
10^{-23}
10^{-25}
10^{-27}
10^{-29}
10^{-31}
10^{-33}
10^{-35}
$\frac{d\langle\sigma v_\chi\rangle}{dT}$ (cm^3 keV^{-1} day^{-1})
$d_1 = \bar{d}_4 = 10^{-9}$
m_χ : 1 GeV
● RRPA (Xe, SD)
□ MCRRPA (Ge, SD)
FCA (Xe, SD)
FCA (Ge, SD)
FCA (Xe, SI)
FCA (Ge, SI)
Ratio
0
1
2
3
Xe (SD/SI)
Ge (SD/SI)
● Xe [SD$_{FCA}$/SD$_{RRPA}$]
□ Ge [SD$_{FCA}$/SD$_{MCRRPA}$]
10^{-2}
10^{-1}
1
T (keV)

Summary

- 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
- SD DM-electron interactions are important to unravel the nature of DM and its interactions with matter.
- Precision spectral shape measurements of DM scattering can distinguish SD from SI interactions.

Soon, we are going to provide Data of Atomic Response function for DM and Atomic interaction on our group web site.

https://web.phys.ntu.edu.tw/~jwc/DarkMatterandNeutrinoGroup/

Thanks

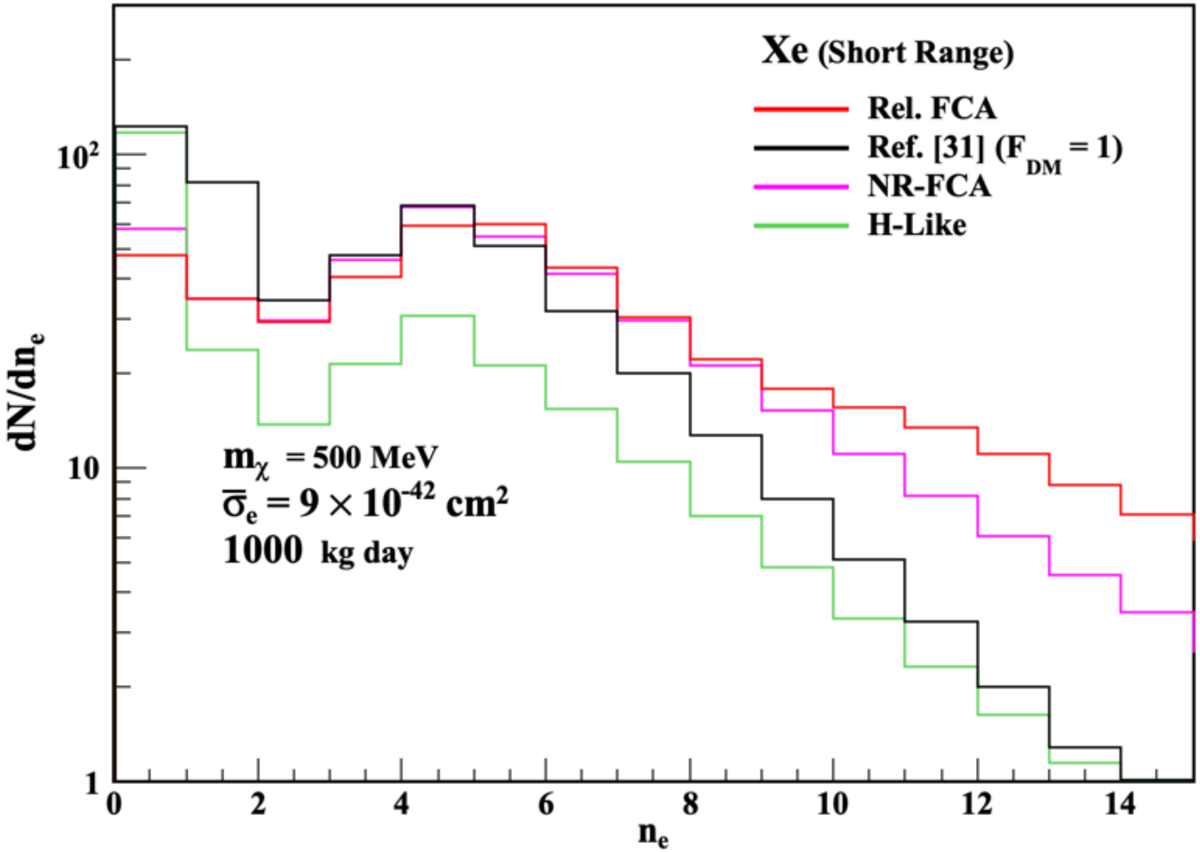
- The works are supported by the NSTC, NCTS, TEXONO, of Taiwan(R.O.C).

- Thank you all for your attention.

Backup slides

Comparisons of expected event numbers as a function of ionized electron number

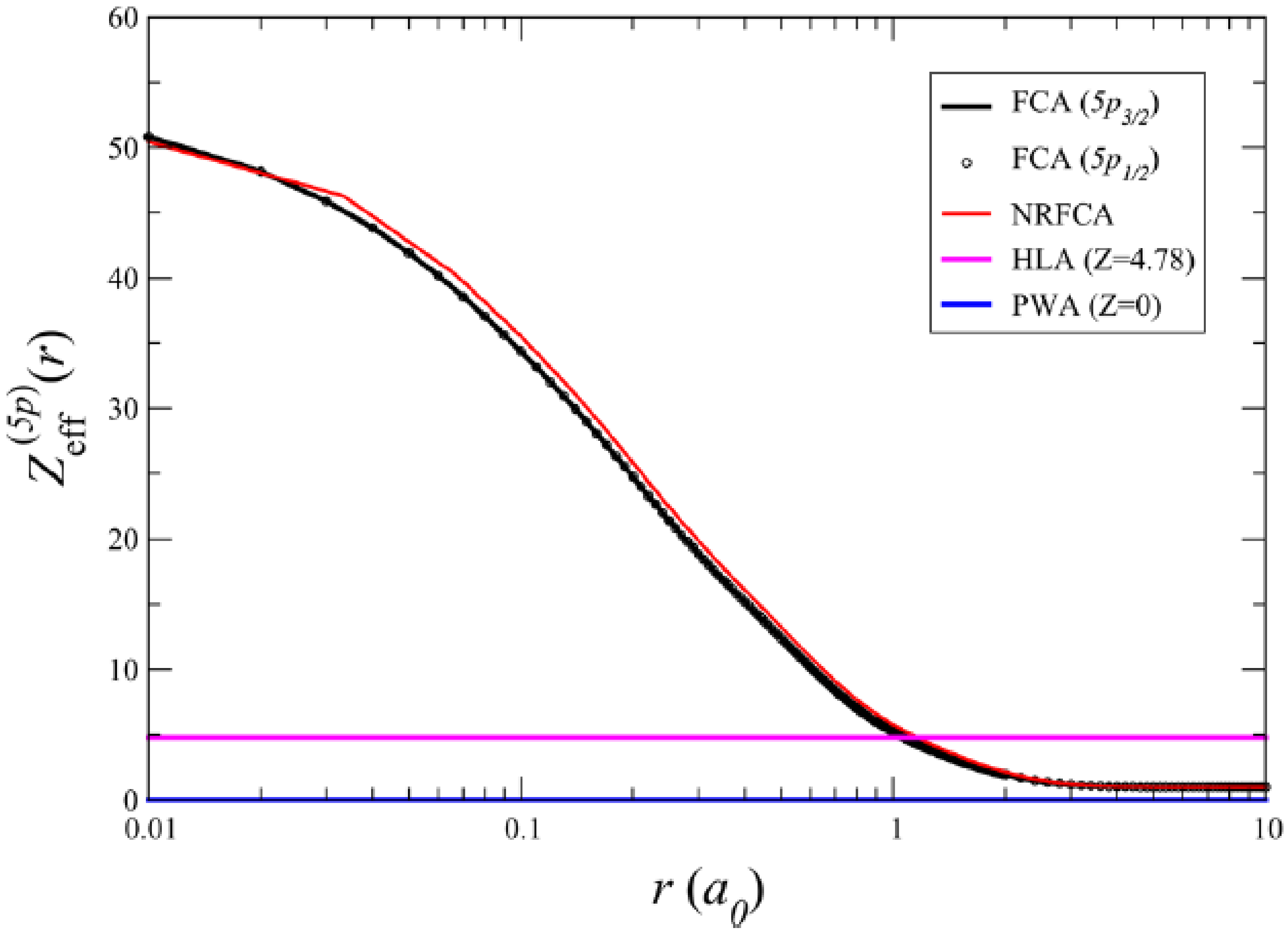
To further trace the main origin of this discrepancy, we performed two additional sets of calculations:



Comparisons of expected event numbers as a function of ionized electron number derived in this work (relativistic FCA, red), nonrelativistic FCA (magenta), hydrogenlike approximation (green), and from Ref. [31] (black) for Xe detectors with 1000 kg-year exposure, assuming DM mass m_χ = 500 MeV, and DM-electron interaction strengths (left) c1 = 5.28 × 10

The difference between the NR-FCA and Ref. [31] is most likely due to different formulations of the effective Coulomb potential felt by an ionized electron. However, no further comment can be made as the detail is not explicitly given in Refs. [30,31]. On the other hand, we did find the results of Ref. [31] fall in between NRFCA and HLA, so perhaps is the reconstructed Coulomb potentials

COMPARISON OF ATOMIC APPROACHES TO CONTINUUM STATES.



The effective charge $Z_{\mathrm{eff}}^{\ (5P)}$ felt by the electron ionized from a 5p orbital derived from the approaches of FCA, NRFCA, HLA, and PWA. Note that the difference between relativistic $5p_{3/2}$ and $5p_{1/2}$ is barely visible..