Atomic ionization by scalar dark matter and solar scalars

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Relativistic Hartree-Fock calculations corrected several orders of magnitude error. Born approximation does not work due to violation of orthogonality condition between bound and continuum electron wave functions.

New limits on electron-scalar coupling from Xenon1T data.

Data files for scalars and axions: arXiv:2105.08296.

Calculations for Na, I, Tl, Xe, Ar, Ge atoms

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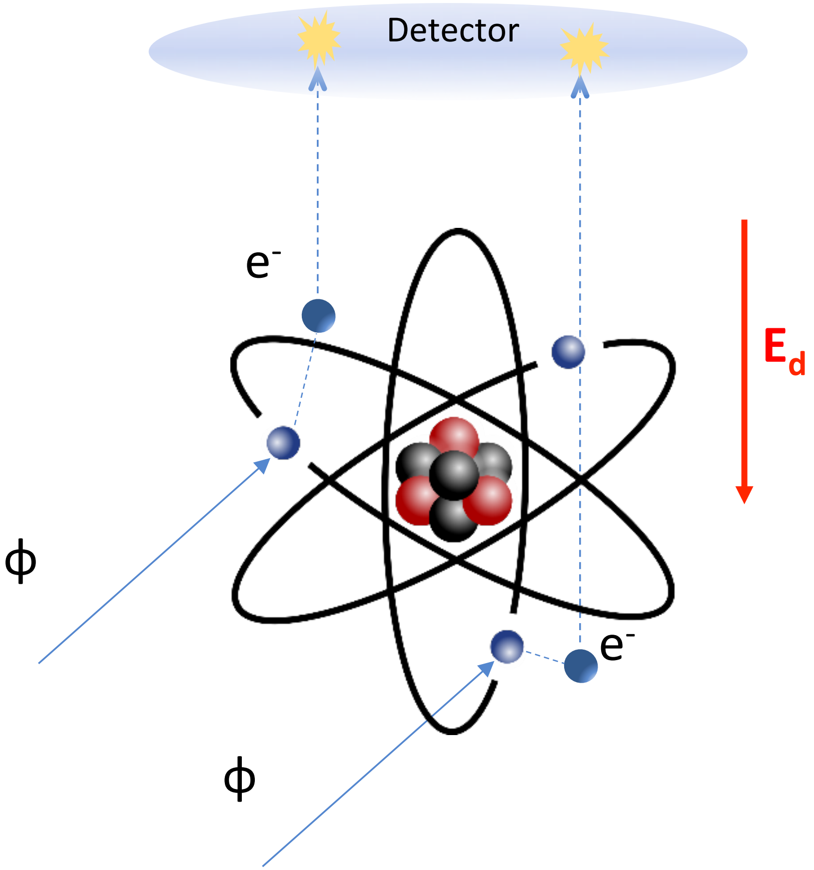
Atomic ionization by scalars

$$\mathcal{L}_{\phi\bar{e}e} = \sqrt{\hbar c}\, g_{\phi\bar{e}e}\,\phi\bar{\psi}\psi$$

- ϕ : scalar familon, sgoldstino, dilaton, relaxon, moduli, Higgs-portal DM, etc.
- Absorption of scalar causes atomic ionization (similar to photoelectric effect)→ detectable by current DM and solar axion searches.
- Xenon1T, PandaX-II, EDELWEISS-III, DAMA/LIBRA, SABRE, SuperCDMS, ArDM, DarkSide-20k, DEAP-3600.



Pitfall: wrong wave functions → wrong results

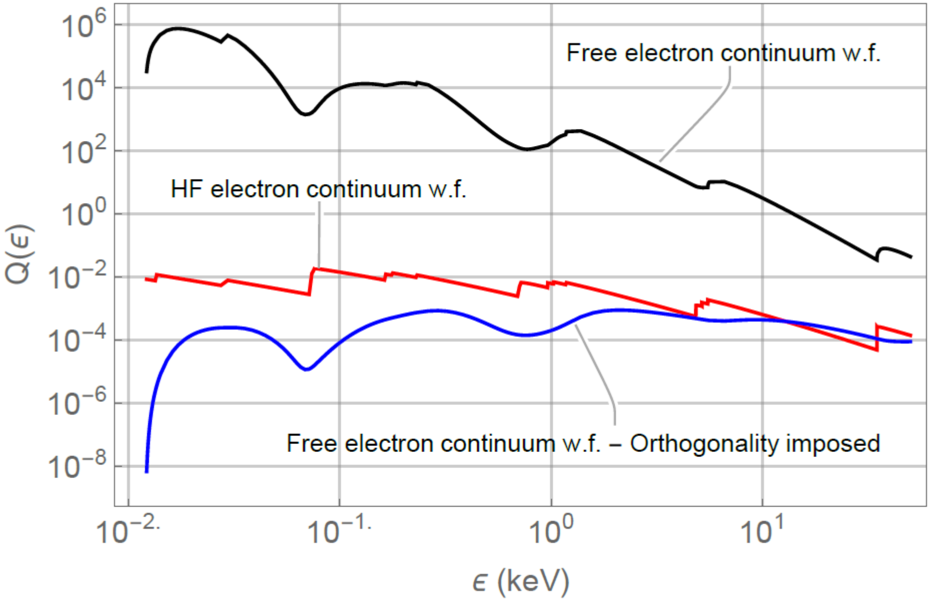
- <u>Orthogonality condition → Born approximation does not work!</u>
- Previous work Int. J. Mod. Phys. A 21:1445-1470, 2006: plane wave continuum function → errors by many orders of magnitude.
- Pitfall also exists for axioelectric effect → affects low-energy cross section only.
- Relativistic Hartree-Fock calculations for scalars and axions.

$$M_{b\to c} \sim \int \left(f_b f_c - \alpha^2 g_b g_c\right) j_0\left(k_\phi r\right) dr$$

$$= \int \left(f_b f_c - \alpha^2 g_b g_c\right) dr + \int \left(f_b f_c - \alpha^2 g_b g_c\right)\left(j_0\left(k_\phi r\right) - 1\right) dr$$

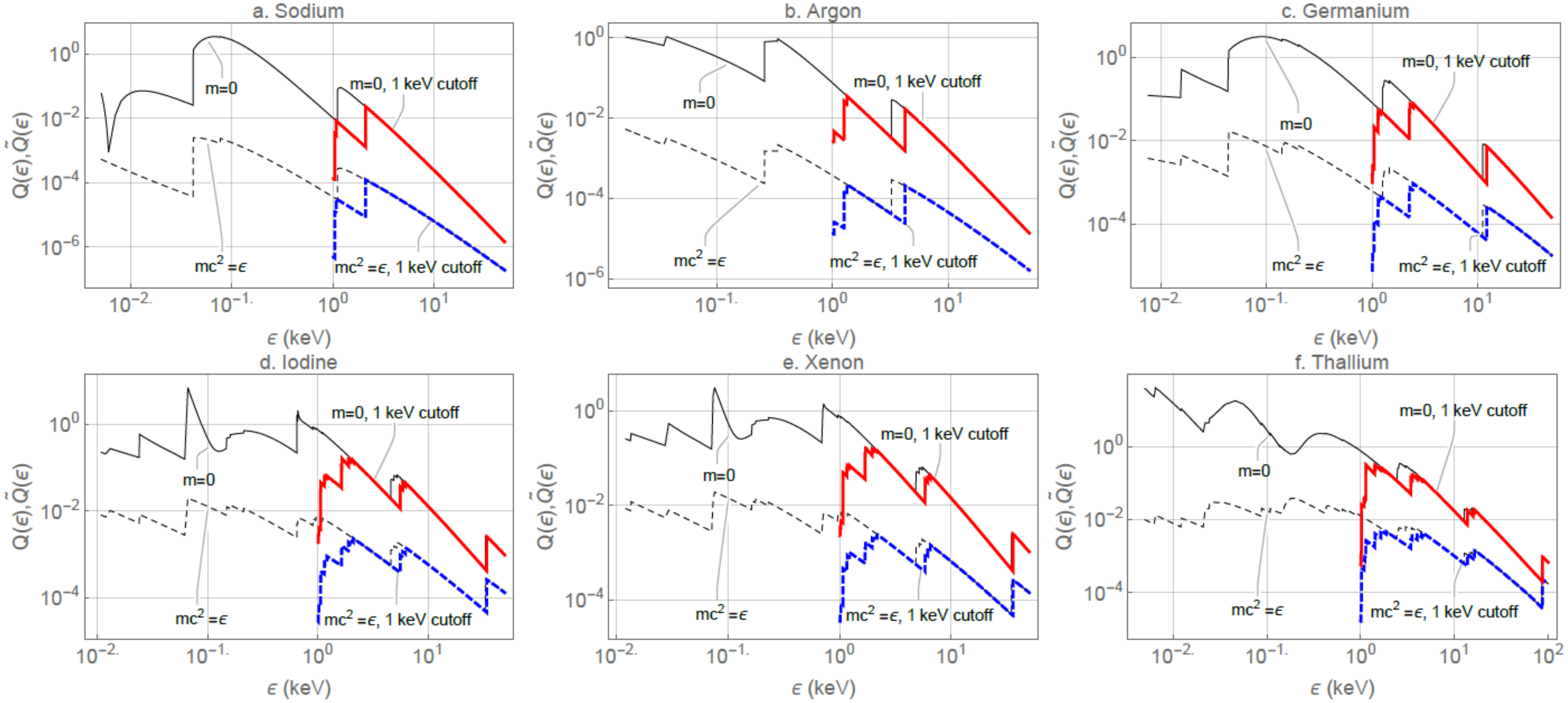
$$= \underbrace{\int \left(f_b f_c + \alpha^2 g_b g_c\right) dr}_{0} - \underbrace{2\alpha^2 \int g_b g_c \, dr}_{\text{relativistic}}$$

$$+ \int \left(f_b f_c - \alpha^2 g_b g_c\right) \underbrace{\left(j_0\left(k_\phi r\right) - 1\right)}_{\approx \frac{k_\phi^2 r^2}{6} \ll 1} dr$$



Results: cross sections for Na, Ar, Ge, I, Xe, Tl

- With and without 1 keV cutoff.
- Accuracy a few %, up to 10% near threshold.
- Accurate scalar and axion data, relativistic Hartree-Fock calculations: arXiv: 2105.08296.



$$\sigma_\phi = g^2_{\phi\bar{e}e}(c/v)Q(\epsilon)a_0^2$$

$$\frac{\sigma_\phi\left(m_\phi=0\right)}{\sigma_\gamma\left(\varepsilon_\gamma=\varepsilon_\phi\right)} \approx \frac{g^2_{\phi\bar{e}e}}{4\pi\alpha}$$

←

Check against photoelectric experimental data

Scalar DM and solar scalar limits from Xenon1T data

- Detection rate for scalar DM:

$$R \approx \frac{4.8}{A} \frac{\tilde{Q}(m = \frac{\epsilon}{c^2})}{\text{year}} \left(\frac{g_{\phi \bar{e} e}}{10^{-17}} \right)^2 \left(\frac{\text{keV}}{mc^2} \right) \left(\frac{M}{\text{ton}} \right)$$

- Detection rate for solar scalar:

$$R \approx \frac{8.3}{A} \frac{\tilde{Q}(m = 0)}{\text{year}} \left(\frac{g_{\phi \bar{e} e}}{10^{-15}} \right)^4 \left(\frac{\text{keV}}{\epsilon} \right)^2 \left(\frac{M}{\text{ton}} \right)$$

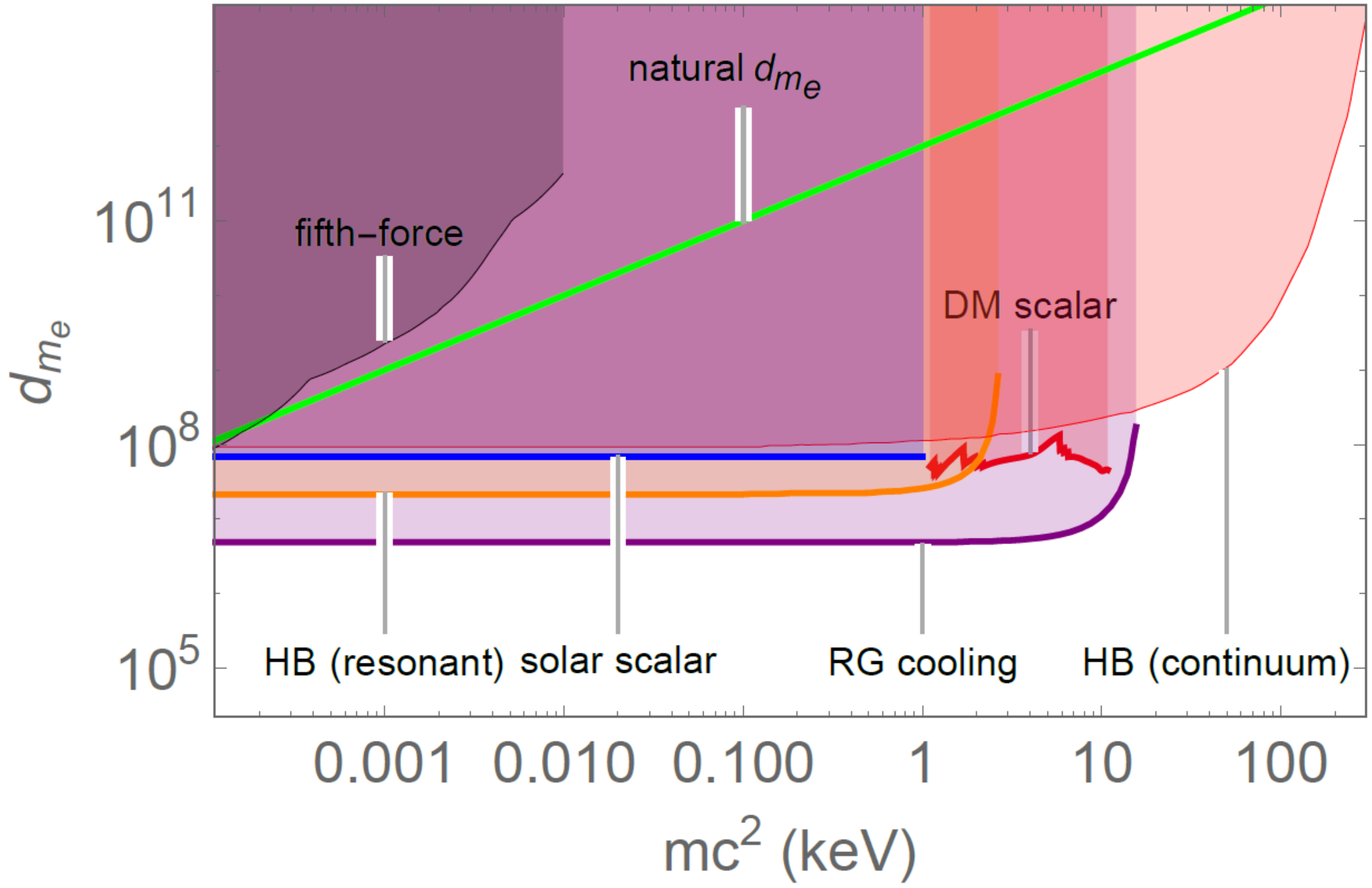
- <u>New limits from Xenon1T data:</u>

$$|g_{\phi \bar{e} e}|_{\text{DM}} \approx 8.2 \times 10^{-15} \qquad |g_{\phi \bar{e} e}|_{\text{solar}} \approx 1.0 \times 10^{-14}$$

$$g_{\phi \bar{e} e} = \sqrt{4\pi} d_{m_e} m_e / m_P \quad \longrightarrow \quad |d_{m_e}|_{\text{solar}} \leq 6.8 \times 10^7$$

Comparison with astrophysical bounds

- Direct limits well inside naturalness region.
- Always better than fifth-force & comparable to HB star cooling.
- An order of magnitude less stringent than RG star cooling → similar to Xenon1T axion limit.



Relativistic effects increase ionisation by WIMP scattering on electrons by up to 3 orders of magnitude!

Ionization of atoms by slow heavy particles, including dark matter
B.M. Roberts, V.V. Flambaum, G.F. Gribakin, Phys. Rev. Lett. 116, 023201 (2016)]

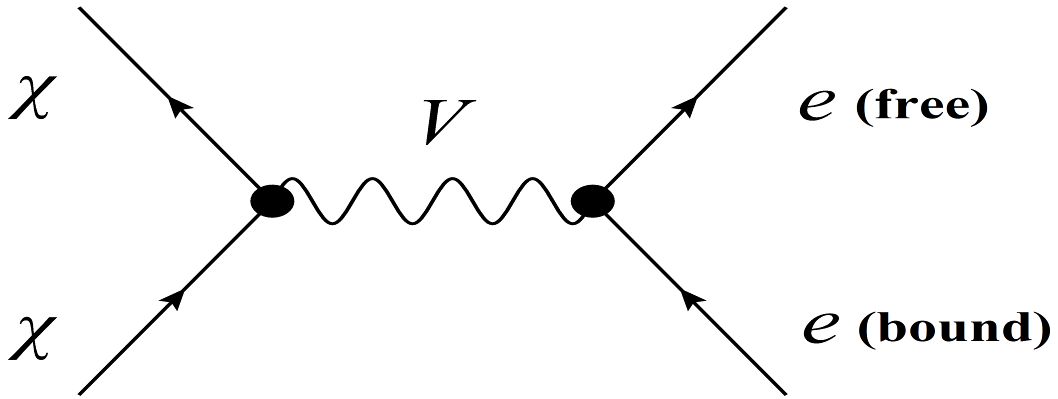
Dark matter scattering on electrons: Accurate calculations of atomic excitations and implications for the DAMA signal. B. M. Roberts, V. A. Dzuba, V. V. Flambaum, M. Pospelov, and Y. V. Stadnik, Phys. Rev. D 93, 115037 (2016)

Electron-interacting dark matter: implications from DAMA/LIBRA-phase2 and prospects for liquid xenon and NaI detectors, B. M. Roberts, V. V. Flambaum, Phys. Rev. D 100, 063017 (2019).

Relativistic Hartree-Fock calculations for Na, I, Xe, Tl, Ge atoms, scalar and vector portals. Annual modulation due to variation of velocity of WIMPs 20 - 50%

WIMP-Electron Ionising Scattering

- Search for annual modulation in $\sigma_{\chi e}$ (velocity dependent)



- Previous analyses treated atomic electrons *non-relativistically. Plane wave for outgoing electron,* $Z_{effective}$ *for bound electrons.*
- Non-relativistic treatment of atomic electrons inadequate for m_χ > 1 GeV. Coulomb interaction is important for outgoing electron.

Why are electron relativistic effects so important?

[Roberts, Flambaum, Gribakin, *PRL* **116**, 023201 (2016)],

- Slow heavy particle produces an adiabatic perturbation of atom. Usually transitions produced by an adiabatic perturbation are suppressed exponentially, as $\exp(-q^2 R^2)$, q is the momentum transfer. No ionization?
- However, the singular Coulomb potential produces a cusp of electron wave function near the nucleus or even infinity for the relativistic Dirac s-wave function at r=0 for a point-like nucleus. As a result, the exponential suppression is replaced by a power suppression q^{-n} . The effect comes from small distances where the electron is ultra-relativistic.

Why are electron relativistic effects so important?

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[Roberts, Dzuba, Flambaum, Pospelov, Stadnik, *PRD* 93, 115037 (2016)]

- Non-relativistic and relativistic contributions to $\sigma_{\chi e}$ are very different for large q

(for scalar, pseudoscalar, vector and pseudovector interaction portals):

Non-relativistic [s-wave, $\psi \propto r^{0}(1 - Zr/a_B)$ as $r \to 0$)], tends to constant as $r \to 0$:

$$d\sigma_{\chi e} \propto 1/q^{8}$$

Relativistic [$s_{1/2}$, $p_{1/2}$-wave, $\psi \propto r^{\gamma-1}$ as $r \to 0$, $\gamma^2 = 1 - (Z\alpha)^2$], increases as $r \to 0$:

$$d\sigma_{\chi e} \propto 1/q^{6-2(Z\alpha)^2} \qquad (d\sigma_{\chi e} \propto 1/q^{5.7} \text{ for Xe and I})$$

- Relativistic contribution to $\sigma_{\chi e}$ dominates by several orders of magnitude for large q!

Accurate relativistic atomic calculations

[Roberts, Flambaum, Gribakin, *PRL* **116**, 023201 (2016)],
[Roberts, Dzuba, Flambaum, Pospelov, Stadnik, *PRD* **93**, 115037 (2016)]

- Performed accurate (*ab initio* Hartree-Fock-Dirac) relativistic atomic calculations of $\sigma_{\chi e}$ for Na, Ge, I, Xe and Tl, and event rates of various experiments: DAMA, XENON10, XENON100
- Outgoing electron in the Hartree-Fock field (not plane wave, the problem is not reduced to momentum distribution of atomic electrons!)
- 3 parameter problem: m_χ, m_V, α_χ; *vector or scalar interaction vertex*

$$\langle \mathrm{d}\sigma v_\chi \rangle = \frac{4\alpha_\chi^2}{\pi} \int_0^\infty \mathrm{d}v \, \frac{f_\chi(v)}{v} \int_{q_-}^{q_+} \mathrm{d}q \, \frac{q}{(q^2 + m_v^2 c^2)^2}$$

$$\times \sum_{n,\kappa} m_e \sqrt{2 m_e (\Delta E - I_{n\kappa})} K_{n\kappa} \mathrm{d}(\Delta E)$$

$$K_{n\kappa}(\Delta E, q) = \sum_{\kappa'} \sum_{m,m'} |\langle \varepsilon \kappa' m' | e^{i\boldsymbol{q}\cdot\boldsymbol{r}} | n \kappa m \rangle|^2 \qquad q_\pm = k \pm \sqrt{k^2 - 2 m_\chi \Delta E}$$

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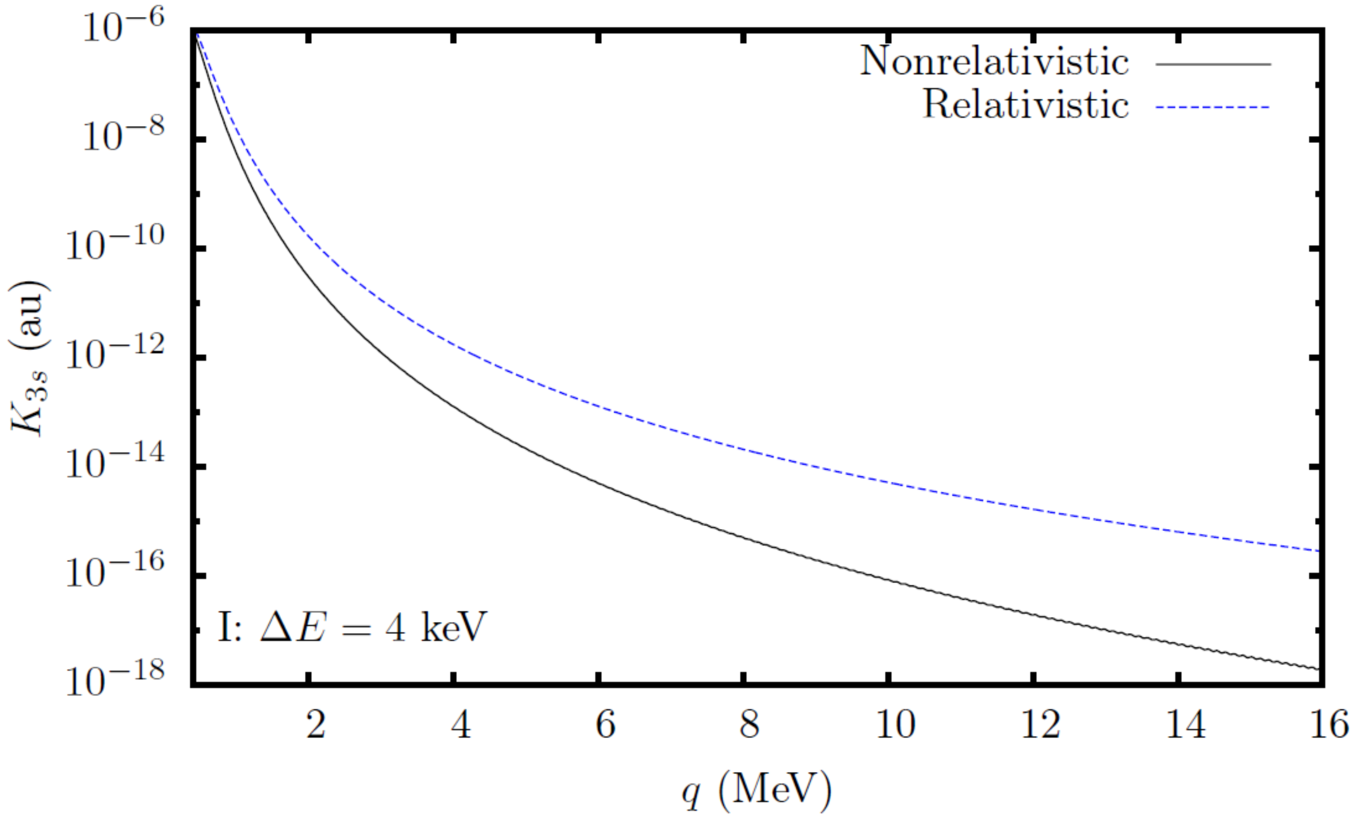

Calculated atomic-structure functions for ionisation of I from 3*s* atomic orbital as a function of *q*; Δ*E* = 4 keV, vector interaction portal

Accurate relativistic atomic calculations

[Roberts, Flambaum, Gribakin, *PRL* **116**, 023201 (2016)],
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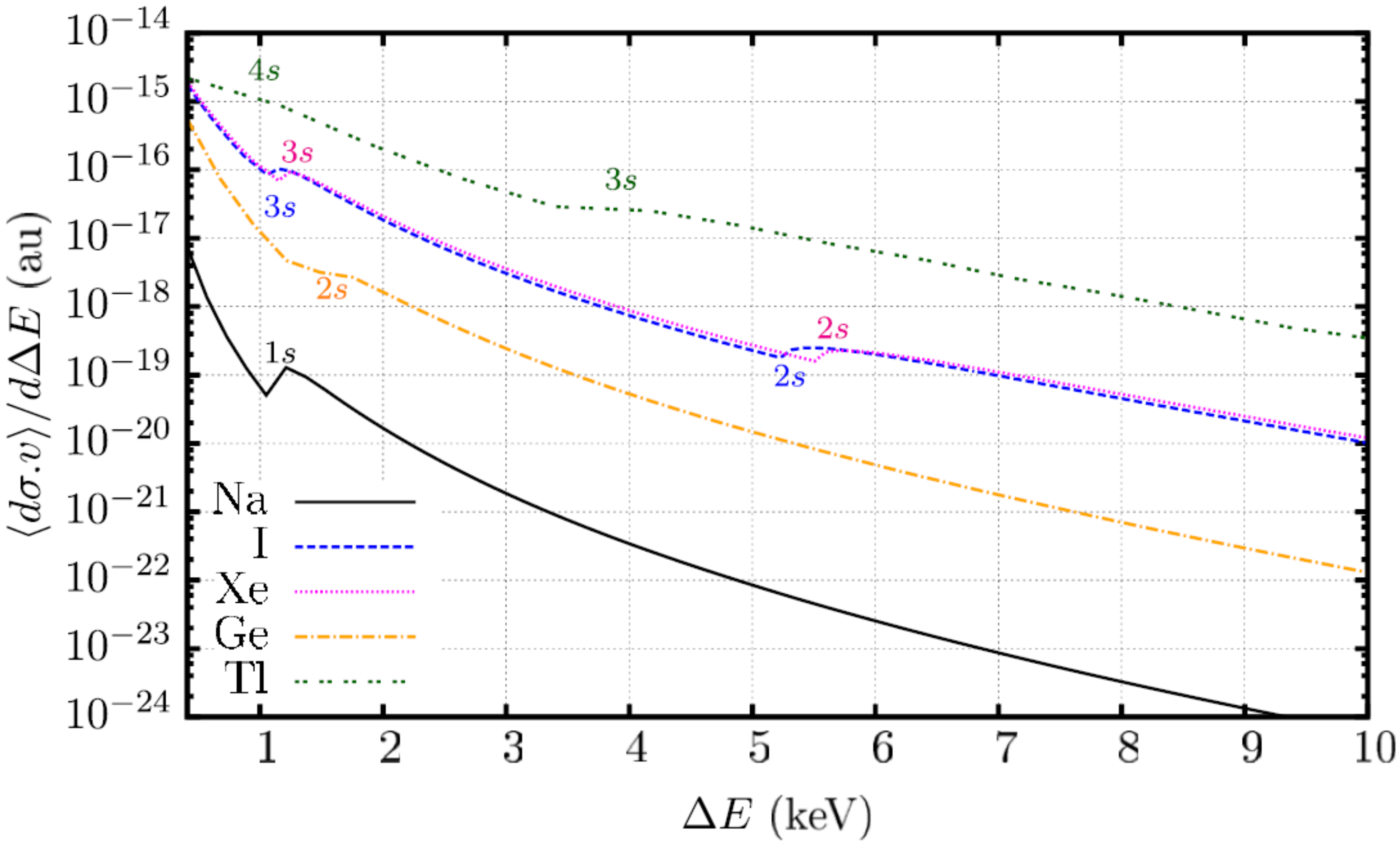
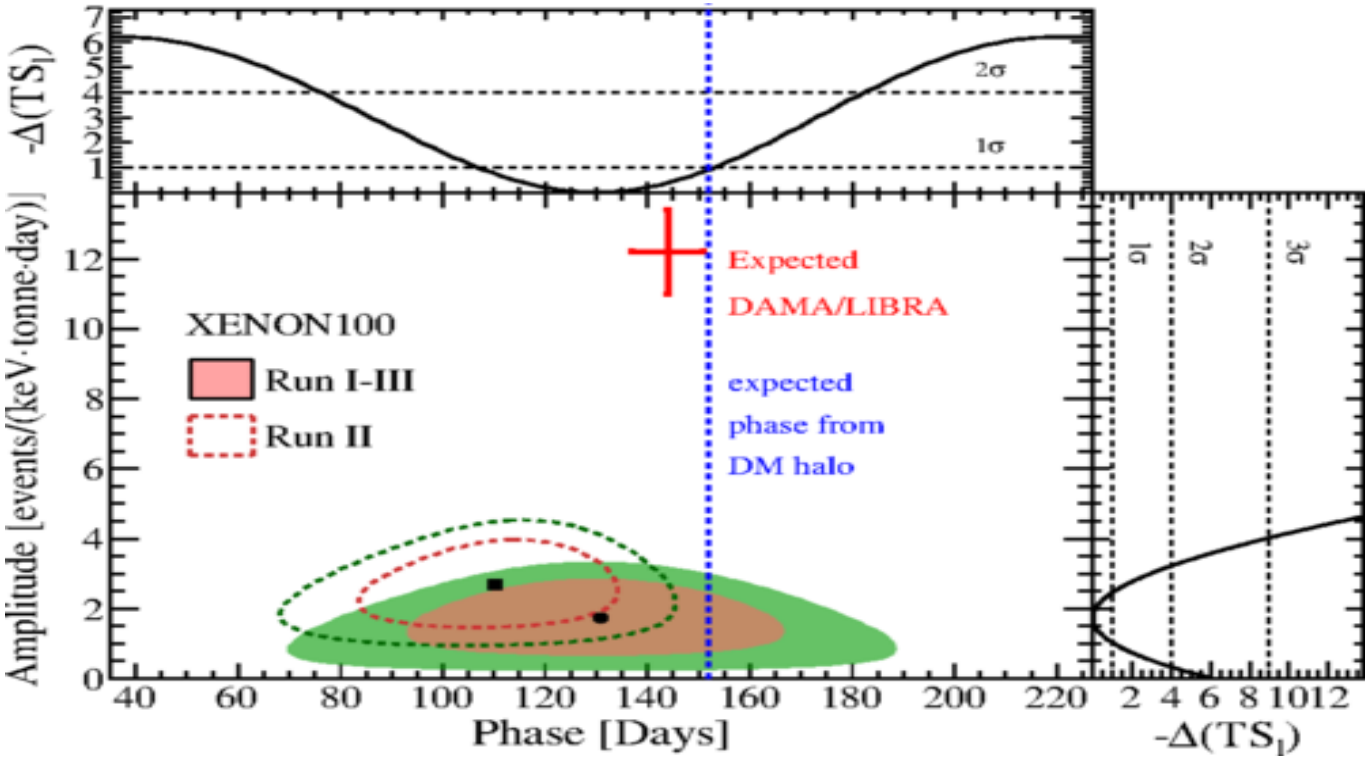


Calculated differential $\sigma_{\chi e}$ as a function of total energy deposition (ΔE); m_χ = 10 GeV, m_V = 10 MeV, α_χ = 1, vector interaction portal. Annual modulation due to variation of velocity of WIMPs 20 - 50%

Constraints from XENON Collaboration using our atomic calculations

[XENON Collaboration, *PRL* 118, 101101 (2017)]



Conclusion

- Relativistic Hartree-Fock calculations correct several orders of magnitude error for the dark matter scalars and solar scalars.
- Plane wave approximation does not work due to violation of orthogonality condition between bound and continuum electron wave functions → Error up to 8 orders of magnitude!
- Such effect also exists for axions but the error is significant for small axion energies only.
- New limits on electron-scalar coupling from Xenon1T data.
- Data files for scalars and axions: arXiv:2105.08296.
- Relativistic effects increase ionisation by WIMP scattering on electrons by up to 3 orders of magnitude. Plane wave approximation does not work. Annual modulation due to variation of velocity of WIMPs is 20 - 50%. Results for DAMA/LIBRA and XENON collaborations.

Why are electron relativistic effects so important?

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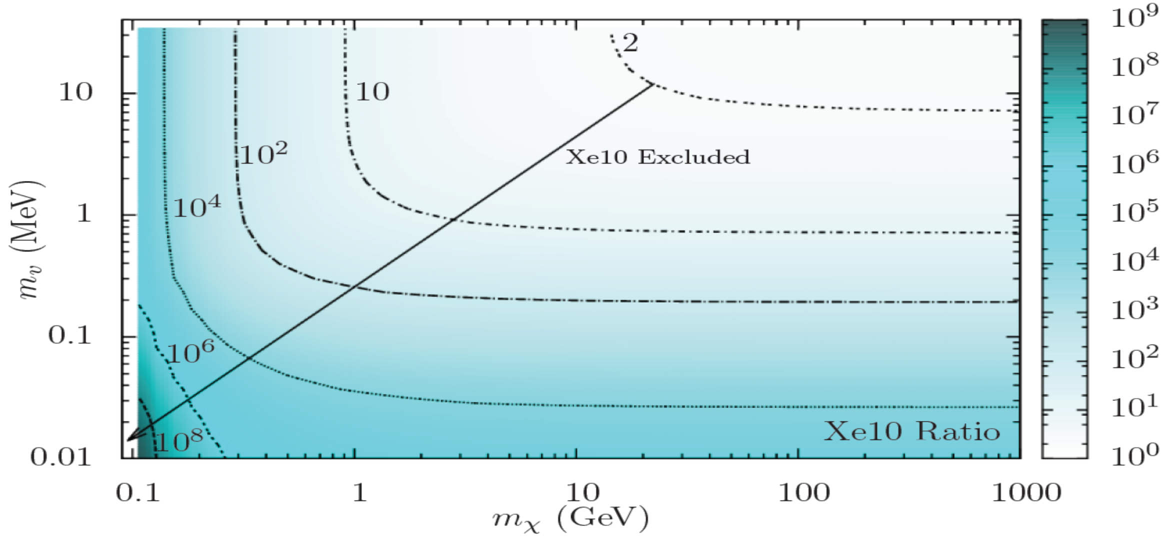
- Slow heavy particle produces an adiabatic perturbation of atom. Usually transitions produced by an adiabatic perturbation are suppressed exponentially, as $\exp(-q^2 R^2)$, q is the momentum transfer. No ionization?
- However, the singular Coulomb potential produces a cusp of electron wave function near the nucleus or even infinity for the relativistic Dirac s-wave function at r=0 for a point-like nucleus. As a result, the exponential suppression is replaced by a power suppression q^{-n} . The effect comes from small distances where the electron is ultra-relativistic.

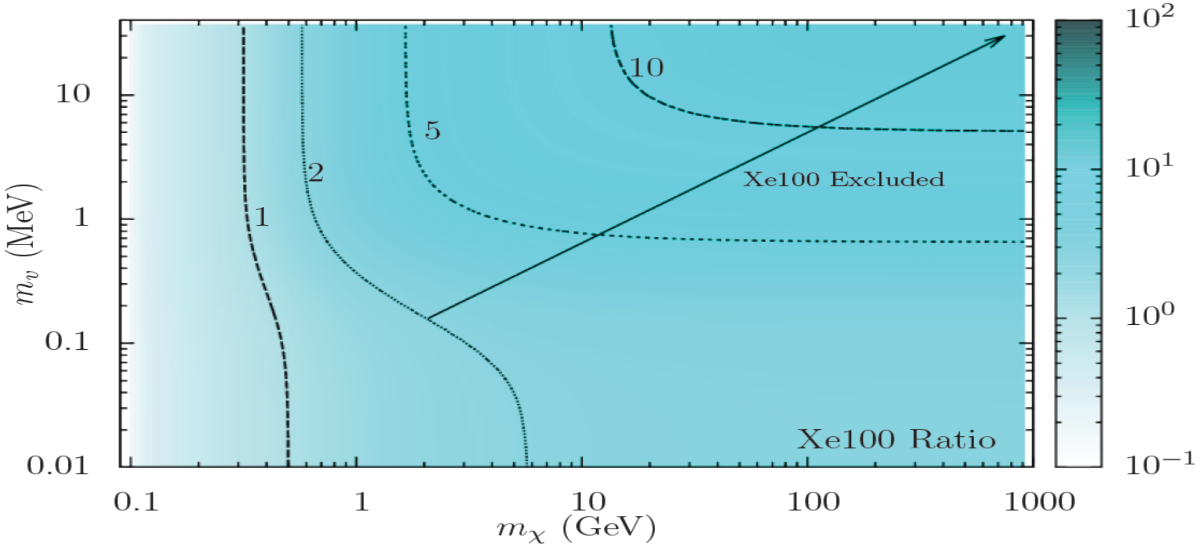
Can the DAMA result be explained by the ionising scattering of WIMPs on electrons?

[Roberts, Flambaum, Gribakin, *PRL* 116, 023201 (2016)],
[Roberts, Dzuba, Flambaum, Pospelov, Stadnik, *PRD* 93, 115037 (2016)]

XENON10 (expected/observed ratio)



XENON100 (expected/observed ratio)



- Using results of XENON10 and XENON100, we find no region of parameter space in m_χ and m_V that is consistent with interpretation of DAMA result in terms of “ionising scattering on electrons” scenario.

Why are electron relativistic effects so important?

[Roberts, Flambaum, Gribakin, *PRL* **116**, 023201 (2016)],
[Roberts, Dzuba, Flambaum, Pospelov, Stadnik, *PRD* **93**, 115037 (2016)]

- Consider $m_\chi \sim 10$ GeV, $\langle v_\chi \rangle \sim 10^{-3}c$
- $\langle q \rangle \sim \langle p_\chi \rangle \sim 10$ MeV >> $m_e = 0.5\ MeV$

  => Relativistic process on atomic scale!
- Large $q \sim 1000$ a.u. corresponds to small $r \sim 1/q \ll a_\mathrm{B}/Z$
- Largest contribution to $\sigma_{\chi e}$ comes from innermost atomic orbitals – for $\langle \Delta E \rangle \sim \langle T_\chi \rangle \sim 5$ keV:
  - Na (1*s*)
  - Ge (2*s*)
  - I (3*s*/2*s*)
  - Xe (3*s*/2*s*)
  - Tl (3*s*)

Relativistic effects increase ionisation by dark matter WIMP scattering on electrons by up to 3 orders of magnitude!

[Roberts, Flambaum, Gribakin, PRL 116, 023201 (2016)]

- Important for numerous existing and future dark matter detectors.
- Detailed relativistic many-body calculations in

[Roberts, Dzuba, Flambaum, Pospelov, Stadnik, Phys. Rev. D 93, 115037, 2016,
Roberts, Flambaum, Phys. Rev. D 2019,]

- DAMA collaboration claims detection of dark matter, others – no detection.

Possible explanation: scattering of dark matter on electrons (instead of scattering on nuclei).

- Our calculations show tension between DAMA and XENON results. XENON used our calculations in PRL 2017.