Atomic phenomena to search for GeV scale WIMPs:

enlightening the search for dark matter

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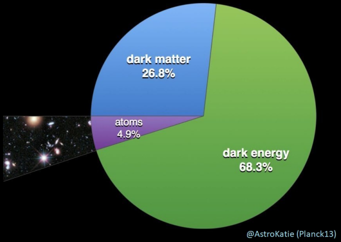
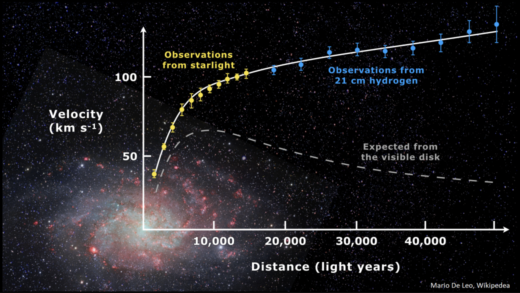
A. R. Caddell, V. V. Flambaum, B. M. Roberts, Phys. Rev. D **108**, 083030 (2023)
B. M. Roberts, V. Flambaum, Phys. Rev. D **100**, 063017 (2019).
B. M. Roberts, V. V. Dzuba, V. V. Flambaum, M. Pospelov, Y. V. Stadnik, Phys. Rev. D **93**, 115037 (2016).
B. M. Roberts, V. Flambaum, G. Gribakin, Phys. Rev. Lett. **116**, 023201 (2016).

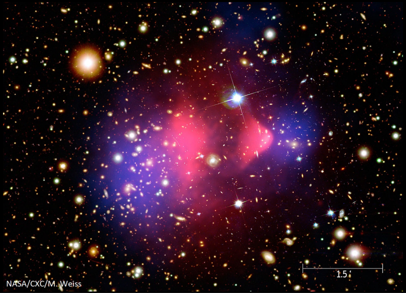
AIP Summer Meeting
4 December 2023

Dark Matter: what we know

- $\sim$ 80% of matter in the universe
- Rotation curves + velocity dispersion
- Gravitational lensing
- CMB spectrum
- Structure formation



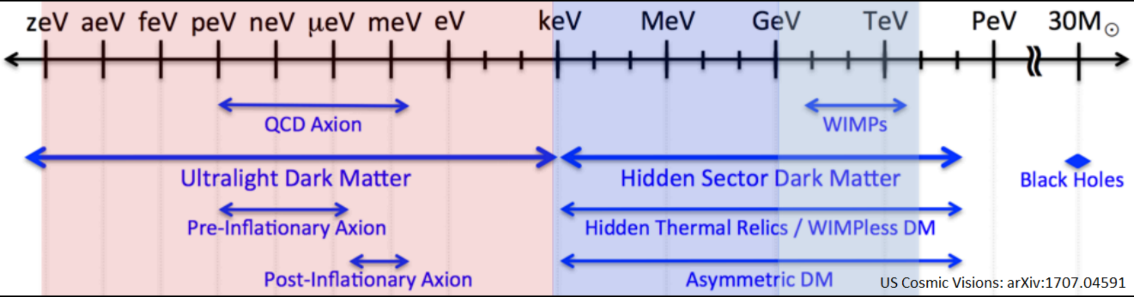




Dark matter: what we *don't* know

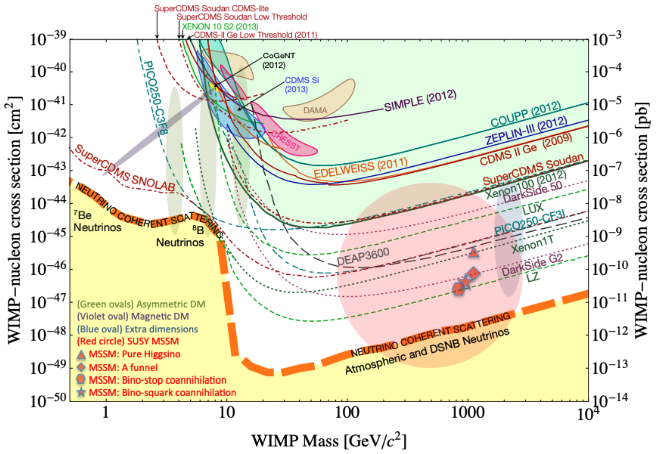
...everything else

- Possible mass range: spans 90(!!) orders-of-magnitude



- Very strong evidence for some kind of new particles/fields – but we have no idea where to look

Low-mass frontier



[arXiv:1310.8327]

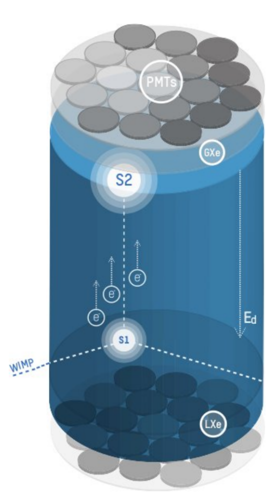
Lighter "WIMPs": less constrained

- $M_\chi > m_{\mathrm{Nuc.}}$: nuclear recoil

Atomic effects:

- $m_e < M_\chi < m_{\mathrm{Nuc.}}$: electron recoil
- $\mathrm{eV} < M_\chi < m_e$: absorption
- $M_\chi < \mathrm{eV}$: classical field

Lighter WIMPs: S1 vs. S2



[http://www.xenon1t.org/]

[img: XENON Collab.]

- $M_\chi \ll M_{\mathrm{Nuc.}}$: cannot cause appreciable nuclear recoil
- But can cause ionisations: assumed that S2≫S1
- High background noise in these regime though
- Usually S2-only signal is excluded due to background

Other proposals (+constraints) to search using S2-only:

PHYSICAL REVIEW D **96,** 043017 (2017)

New constraints and prospects for sub-GeV dark matter scattering off electrons in xenon

Rouven Essig,[1,*] Tomer Volansky,[2,†] and Tien-Tien Yu[1,3,‡]

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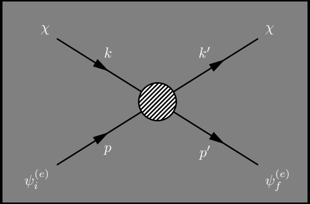
- $S1$ signal thought to be negligible
- In fact, it might be much larger than thought

WIMP-Electron ionisation



- Cause excitations, and **ionisations**
- q/E: momentum/energy transfer

$$dR = \frac{n_T \rho_{\rm DM}}{m_\chi c^2} \frac{{\rm d}\langle \sigma_{njl} v_\chi \rangle}{{\rm d}E} \, {\rm d}E$$

$$\frac{\langle {\rm d}\sigma v \rangle}{{\rm d}E} = \frac{\bar\sigma_e c \alpha^2}{2E_H} \int {\rm d}v \frac{f_\chi(v)}{v/c} \int_{q_-}^{q_+} a_0^2 q {\rm d}q \, |F_\chi^\mu(q)|^2 \, K(E,q)$$

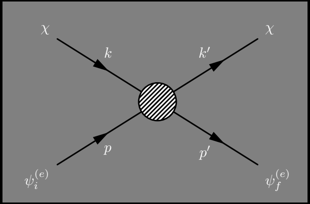
- Free-electron cross-section, $\bar\sigma_e$, and DM form-factor:

$$\hbar q_\pm = m_\chi v \pm \sqrt{m_\chi^2 v^2 - 2 m_\chi E}$$

$$K_{njl} \equiv E_H \sum_m \sum_f \left| \langle f | e^{i\boldsymbol{q}\cdot\boldsymbol{r}} | njlm \rangle \right|^2 \varrho_f(E)$$

- Following: Essig, Manalaysay, Mardon, Sorensen, Volansky, Phys.Rev.Lett.**109**,021301('12).

WIMP-Electron ionisation



- Cause excitations, and **ionisations**
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Particle Phys — Astrophys. — Atomic

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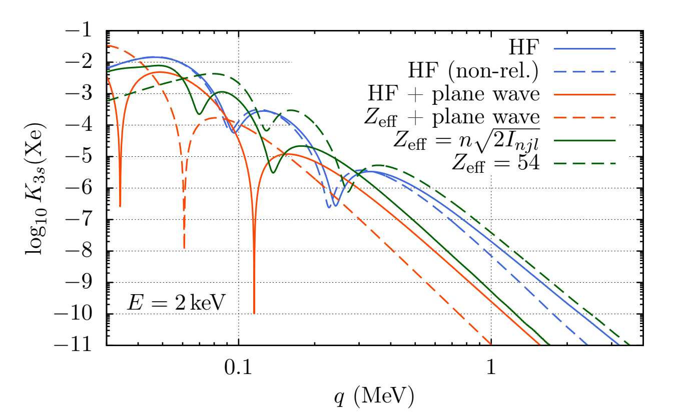
Different approximations: Atomic effects crucial

$$K = |\langle \mathrm{Xe}| e^{-i\boldsymbol{q}\cdot\boldsymbol{r}} |\mathrm{Xe}^+ + e^-\rangle|^2$$

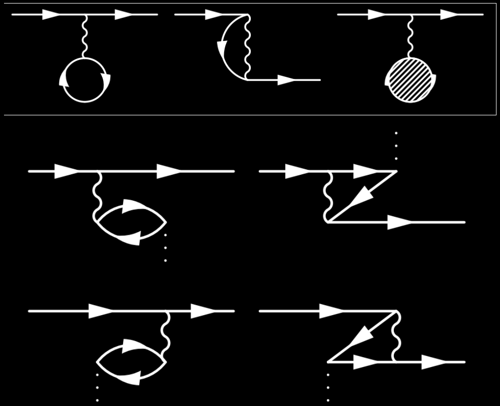
- Relativistic effects
- Plane waves vs. energy eigenstates
- Low-r scaling: $Z_{\rm eff}$
- details of atomic potential
- Orthogonality
- Many-body effects



Very common to use: plane wave + $Z_{\rm eff}$ + non-relativistic functions

- $\sim$ 4 orders of magnitude too small at $\sim$1 MeV!

ampsci: relativistic Hartree-Fock with RPA

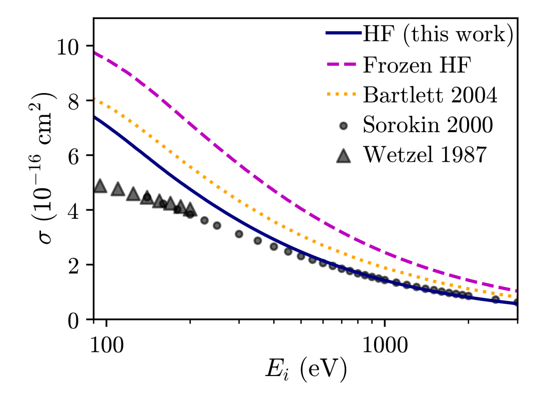


A. R. Caddell, V. Flambaum, BMR, arXiv:2305.05125

- github.com/benroberts999/ampsci
  - Atomic structure code: calculates $K(E,q)$
- github.com/benroberts999/AtomicIonisation
  - Tables of pre-calculated factors $K(E,q)$
  - Example rate/cross-section calculations

Test: electron-impact ionisation

- Experimental verification? Yes!
- Consider $M_\chi = m_e$, $\alpha_\chi = \alpha$
- For GeV WIMP, $E_{\rm impact} \sim$ keV
- Excellent agreement: better than dedicated



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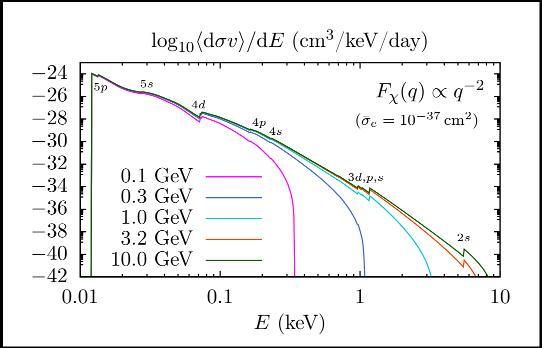
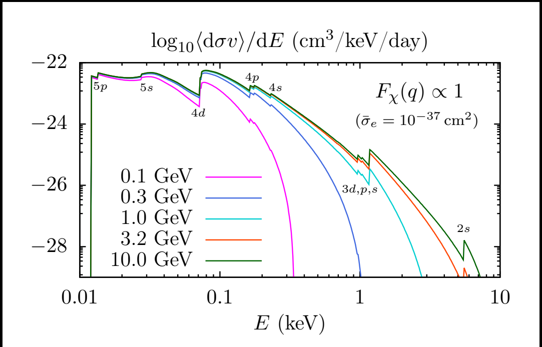
Calculated cross-sections





- Velocity-averaged σ: assume standard-halo model
- For contact interaction (right): no suppression!
- However, must account for detector response

Detector response + resolution

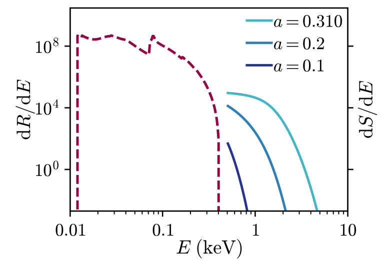
- Detector does not have perfect resolution: R (raw rate) vs S (observable rate)

$$\frac{dS}{dE} \approx \int \epsilon(E')\rho(E'-E)\frac{dR}{dE'}dE'$$

  - Probability events below threshold are detected above
  - Since "raw" event rate is exponentially enhanced at low E, can be large effect

Low-E detector resolution:

- Near-universally modelled as Gaussian
  - Totally fine for high energy
  - Clearly not OK for low energy!



Conclusion

- S1 (prompt scintillation signal) not very suppressed
- For heavy mediator, $m_\chi \gtrsim 0.1\,\text{GeV}$, $E_\text{thresh} \sim 0.5\,\text{keV}$ – no suppression
- Combined S1 and S2 possible for low-mass WIMPs – new discovery potential
- Tables of (mostly) model-independent ionisation factors made available
- Apply to your favourite DM model

Warnings

- Must use accurate atomic model for wavefunctions
- Highly dependent on modelling of low-energy detector response/resolution
- Highly velocity dependent: halo considerations more important than nuclear case

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Extra: atomic details

S1 and S2

S1 (scintillation)

$$R \propto \int_{E_{\mathrm{thresh.}}} \frac{\mathrm{d}\langle \sigma v \rangle}{\mathrm{d}E} \, \mathrm{d}E$$

- Low-energy threshold
- (hardware + software)
- Suppressed for electron recoils*
- Detector resolution very important

S2 (count electrons)

$$R \propto \int_0 \frac{\mathrm{d}\langle \sigma v \rangle}{\mathrm{d}E} \, \mathrm{d}E$$

- Electrons drifted upwards
- Scintillate in gaseous phase
- Energy agnostic: count electrons
- Secondary electrons

Why S1 thought to be small?

$$q_{\min} = m_\chi v - \sqrt{m_\chi^2 v^2 - 2 m_\chi E}$$

WIMP-induce ionisation:

- WIMP: $m_\chi \sim 10\,\text{GeV}$, $v_\chi \sim 10^{-3} c$
- Energy deposition: $\Delta E \sim \text{keV}$
- $\Rightarrow q \sim 1000\,\mathrm{a.u.} = 4\,\mathrm{MeV}$ momentum transfer
- $\therefore$ very suppressed

Simple Approach:

- Very large q: high-p tail of electron wavefunction: $r \sim q^{-1} \sim 10^{-3} a_B$
- Close to nucleus: s-states ($l = 0$) non-zero $\psi(0)$
- Close to nucleus: Oscillator-like wavefunctions: $\psi \sim A e^{-\beta r^2}$

$$\langle f | e^{-i\boldsymbol{q}\cdot\boldsymbol{r}} | i \rangle \propto e^{-q^2/8\beta}$$

Coulomb wave-functions:

Smooth function: $\langle f | e^{-i\mathbf{q}\cdot\mathbf{r}} | i \rangle \propto e^{-q^2/8\beta}$

Non-relativistic Coulomb Case:

$$\psi \sim A r^l \left[1 - \frac{Z}{l+1} r + \ldots \right]$$

- Coulomb wavefunctions contain a cusp, strongest $l = 0$:
- Lowest-order term: $\sim \int r^{l+l'+2} j_L(qr)\, dr$: Identically Zero
- Next term: $\sim \int r^{l+l'+3} j_L(qr)\, dr \propto Z\, q^{-(l+l'+4)}$
- $d\sigma \sim q^{-8}$ — s-waves dominate

Eighth power is still eighth power ..... but better than exponential

• BMR, V. Flambaum, and G. Gribakin, Phys. Rev. Lett. 116, 023201 (2016).

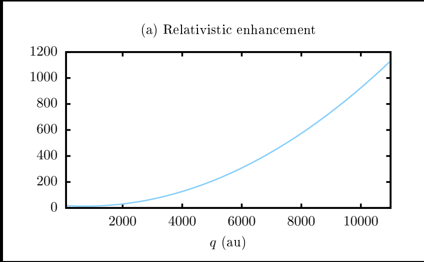
Dirac wave-functions

Relativistic Case is different:

$$\psi \sim Ar^{\gamma-1}\left[\gamma - \kappa + Br + \ldots\right] \qquad : \qquad \gamma = \sqrt{\kappa^2 - (Z\alpha)^2} \approx 1 - (Z\alpha)^2$$

$\kappa = -1$ for s-states, 1 for $p_{1/2}$

- Lowest-order term: $\sim \int r^{\gamma+\gamma'} j_L(qr)\, dr$: Non-Zero!
- $s, p_{1/2}$-waves: $d\sigma \sim q^{-6+2(Z\alpha)^2} \simeq q^{-5.7\ldots}$ for Xe, I.



$$e^{-q^2} \to q^{-8} \to q^{-6} \to q^{-6+2(Z\alpha^2)} \approx q^{-5.7..}$$

- Orders of magnitude enhancement

- BMR, V. Flambaum, and G. Gribakin, Phys. Rev. Lett. 116, 023201 (2016).

Outgoing electron wavefunction: Sommerfeld enhancement

For large p ($|p| = \sqrt{2m_e\varepsilon}$), plane waves should be OK?

$$\langle \boldsymbol{r}|\boldsymbol{p}\rangle = e^{i\boldsymbol{p}\cdot\boldsymbol{r}/\hbar}, \qquad \int \frac{d^3\boldsymbol{p}}{(2\pi\hbar)^3}\langle \boldsymbol{p}|\boldsymbol{p}\rangle = 1.$$

But high q means low-r – close to nucleus.
Continuum *energy* eigenstates:

$$\boxed{\int_{\varepsilon-\delta\varepsilon}^{\varepsilon+\delta\varepsilon} \langle \varepsilon' jlm|\varepsilon jlm\rangle \, d\varepsilon' = 1.}$$

enhanced near origin for Coulomb potentials.
Approximate sommerfeld enhancement:

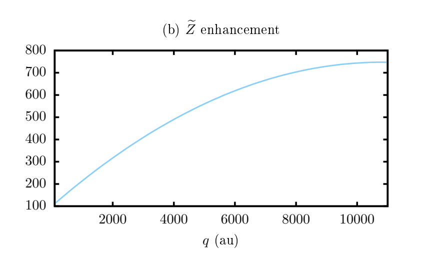
$$\left.\frac{K_{ns_{1/2}}}{K^{\rm pw}_{ns_{1/2}}}\right|_{r\to 0} \approx \frac{8\pi Z}{\left[1-\exp(-\frac{2\pi Z}{|p'|})\right] n^3|p'|},$$

- Orders of magnitude enhancement

Low-r scaling

As well as Sommerfeld enhancement (enhance continuum wavefunction as low-r), same for bound states

- Common approach: Use H-like wavefunctions with $Z_{\rm eff} = n\sqrt{|E|/R_y}$
- Works very well for many applications: fine at intermediate to large r
- Fails at low-r
- H-like functions: $\psi(0)^2 \sim Z_{\rm eff}^3$
- True wavefunctions: $\psi_{\rm inner}(0)^2 \sim Z^3$, $\psi_{\rm outer}(0)^2 \sim Z^1$



- Orders of magnitude "enhancement"