Absorption of dark matter particles in atoms via Migdal-type effect

I.B. Samsonov

UNSW SYDNEY

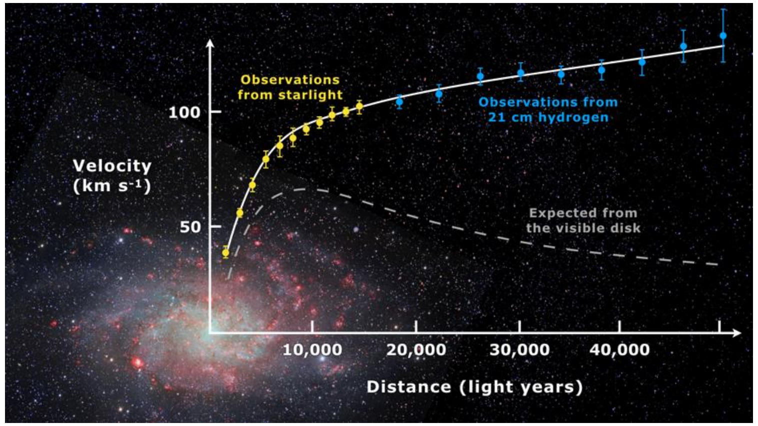
Based on

V.A. Dzuba, V.V. Flambaum, I.B.S.

Phys. Rev. D 109 (2024) 11

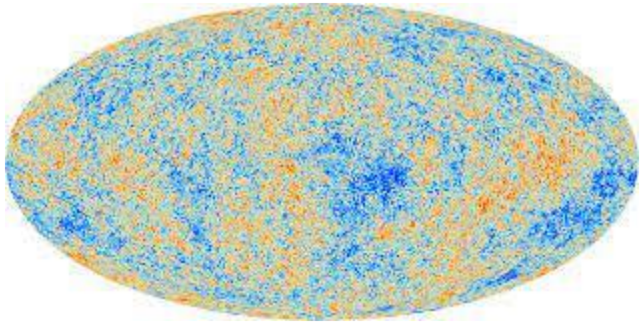
Cosmological evidence of cold dark matter model

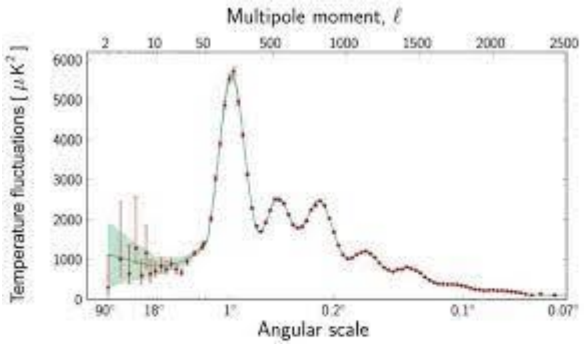
Flat rotation curves of galaxies



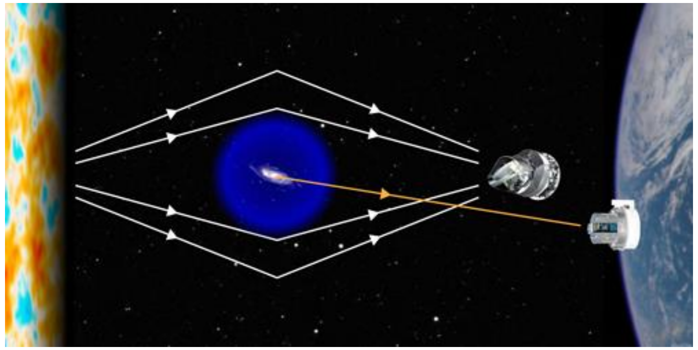
Gas distribution in Bullet cluster

Positions of peaks in power spectrum of CMB



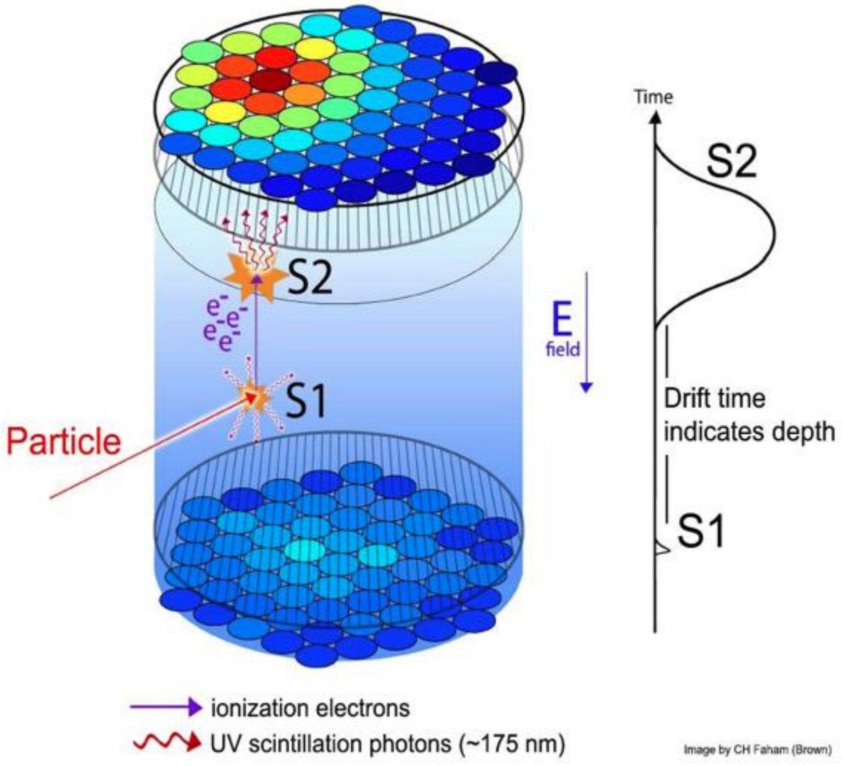


Gravitational lensing



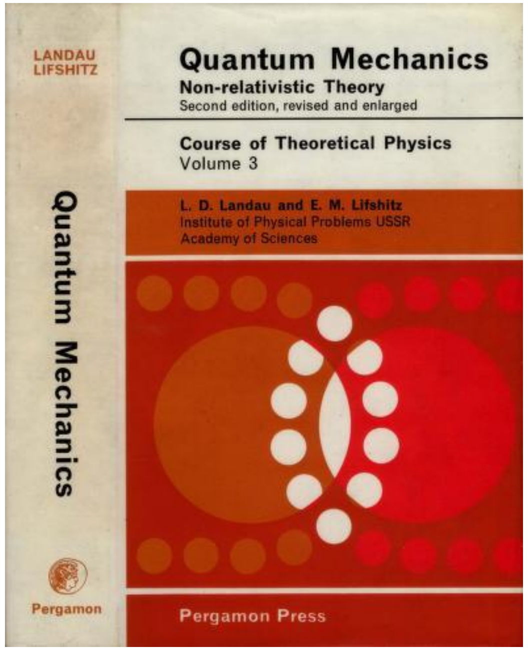
Direct DM detection with atomic recoil/ionization

- DM particle scatters elastically off atomic nucleus
- Atom is excited and/or ionized
- Electron and photon signals are detected with time projection chamber (TPC)
- Relevant experiments: XENONnT, LUX-ZEPLIN, PandaX,…



Credit: https://lux.physics.ucdavis.edu/

Atom ionization by jolt of nucleus



§41. Transitions under a perturbation acting for a finite time

PROBLEM 2. The nucleus of an atom in the normal state receives an impulse which gives it a velocity v; the duration τ of the impulse is assumed short in comparison both with the electron periods and with a/v, where a is the dimension of the atom. Determine the probability of excitation of the atom under the influence of such a "jolt" (A. B. Migdal 1939).

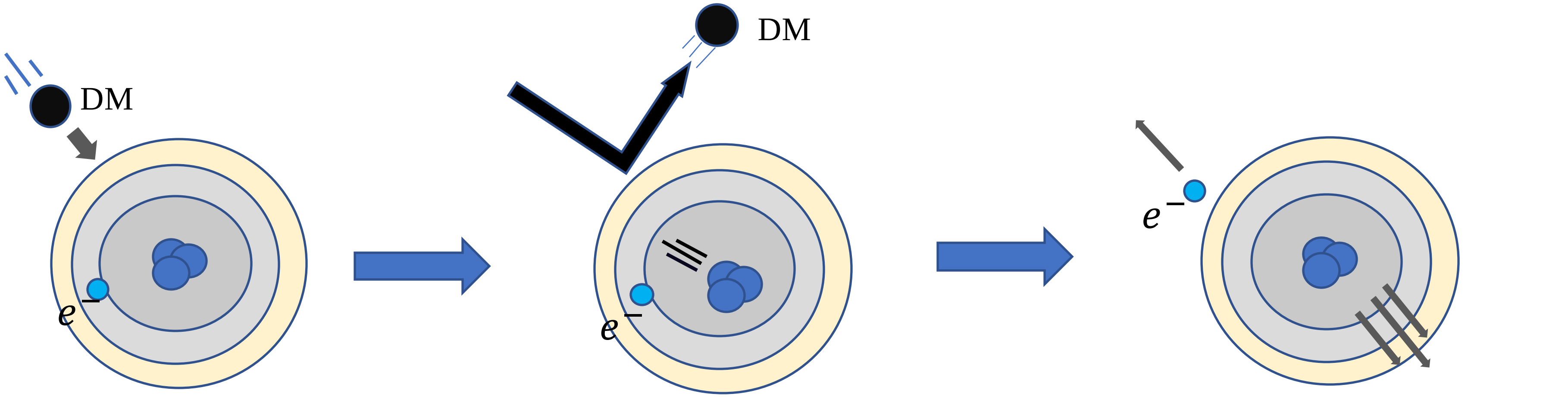
$$w_{k0} = |\langle k| \exp(-i\mathbf{q} \cdot \sum_a \mathbf{r}_a)|0\rangle|^2.$$

PROBLEM 3. Determine the total probability of excitation and ionization of an atom of hydrogen which receives a sudden "jolt" (see Problem 2).

PROBLEM 4. Determine the probability that an electron will leave the K-shell of an atom with large atomic number Z when the nucleus undergoes β-decay. The velocity of the β-particle is assumed large in comparison with that of the K-electron (A. B. Migdal and E. L. Feinberg 1941).

PROBLEM 5. Determine the probability of emergence of an electron from the K-shell of an atom with large Z in α-decay of the nucleus. The velocity of the α-particle is small compared with that of the K-electron, but the time which it takes to leave the nucleus is small in comparison with the time of revolution of the electron (A. B. Migdal 1941, J. S. Levinger 1953).

Atom ionization by a DM particle scattering off nucleus: Migdal scattering



1. DM scatters with atoms

2. Atomic electrons can't immediately follow the recoil nucleus. There is relative motion between them.

3. Before the electrons to catch up nucleus, some electrons are excited or ionized.

J.D. Vergados, H. Ejiri, Phys.Lett.B 606 (2005) 313, hep-ph/0401151
Ch.C. Moustakidis, J.D. Vergados, H. Ejiri, Nucl.Phys.B 727 (2005) 406, hep-ph/0507123
H. Ejiri, Ch.C. Moustakidis, J.D. Vergados, Phys.Lett.B 639 (2006) 218, hep-ph/0510042
J.D. Vergados, F.T. Avignone, P. Pirinen, P.C. Srivastava, M. Kortelainen, Phys.Rev.D 92 (2015) 1, 015015, 1504.02803
R. Bernabei, P. Belli, F. Montecchia, F. Nozzoli, F. Cappella, Int.J.Mod.Phys.A 22 (2007) 3155, 0706.1421

The Migdal Effect for DM detection

Fully fledged theoretical treatment of the Migdal effect for detection of DM particles was given in:

JHEP

Published for SISSA by Springer

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Published: *March 30, 2018*

Migdal effect in dark matter direct detection experiments

Masahiro Ibe,[a,b] Wakutaka Nakano,[a] Yutaro Shoji[a] and Kazumine Suzuki[a]

Subsequent works:

N. Bell, J. Dent, B. Dutta, S. Ghosh, J. Kumar, J. Newstead, Phys. Rev. D 104, 076013, 2021

N. Bell, J. Dent, R. Lang, J. Newstead, A. Ritter, Phys. Rev. D 105, 096015, 2022

J. Aalbers et al 2023 J. Phys. G: Nucl. Part. Phys. 50 013001

N. Bell, P. Cox, M. Dolan, J. Newstead, A. Ritter, Phys. Rev. D 109, L091902, 2024

The Migdal Effect for DM detection

M. Ibe, W. Nakano, Y. Shoji, K. Suzuki, JHEP 03 (2018) 194, [1707.07258]

the dark matter event rate for unit detector mass is given by

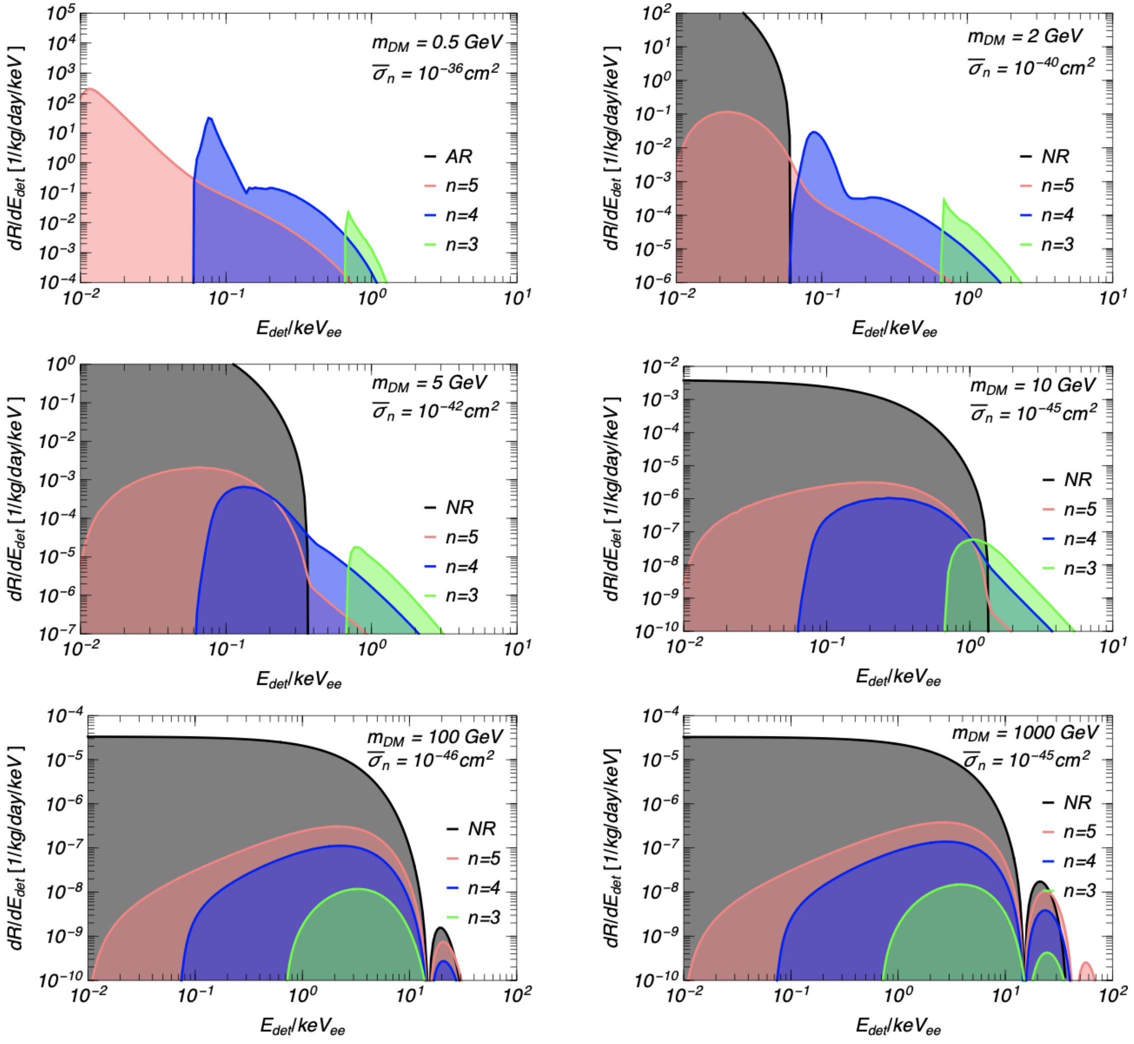
$$\frac{dR}{dE_R dv_{DM}} \simeq \frac{1}{m_A}\frac{\rho_{DM}}{m_{DM}}\frac{d\sigma}{dE_R} v_{DM} \tilde{f}_{DM}(v_{DM}),$$

$$\simeq \sum_{E^F_{ec}} \frac{1}{2}\frac{\rho_{DM}}{m_{DM}}\frac{1}{\mu_N^2} \tilde{\sigma}_N(q_A) \times |Z_{FI}(q_e)|^2 \times \frac{\tilde{f}(v_{DM})}{v_{DM}}$$

DM-nucleus scattering cross section (to be measured) → $\tilde{\sigma}_N(q_A)$

Electronic (atomic) matrix element (calculated) → $|Z_{FI}(q_e)|^2$

Dark matter distribution (modelled) → $\tilde{f}(v_{DM})$



Atomic ionization by scalar dark matter and solar scalars

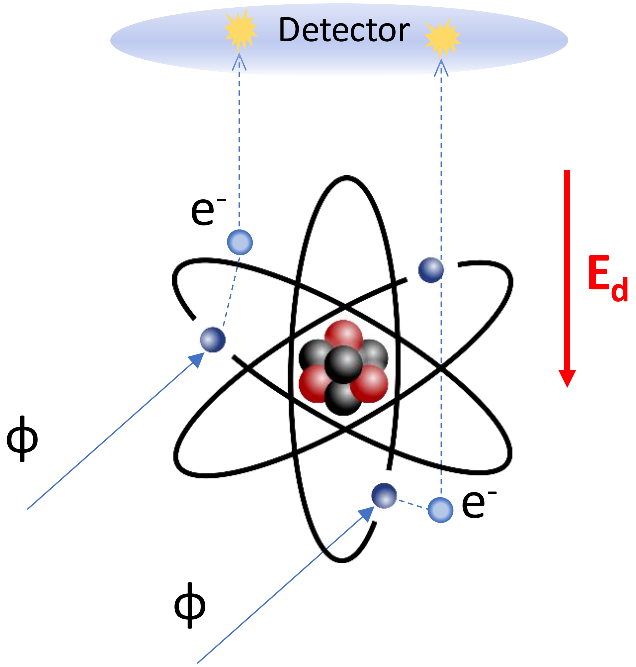
H. B. Tran Tan, A. Derevianko, V. Dzuba, V.V. Flambaum, PRL 127, 081301 (2021)

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

← Dirac electron

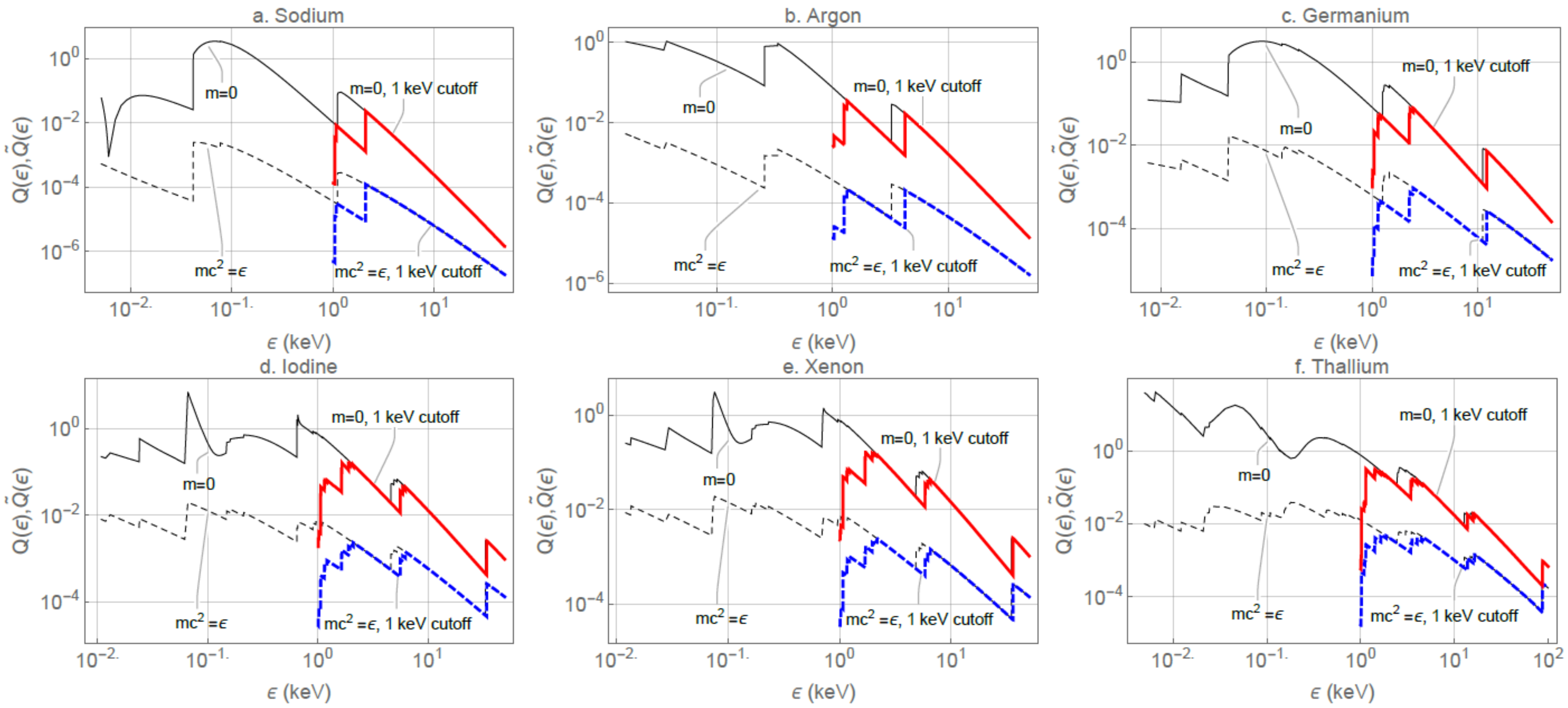
↑ scalar DM

- φ is scalar field DM (sgoldstino, dilaton, relaxon, moduli, Higgs-portal DM, etc.)
- φ is massless relativistic field with energy ε ~ 1-100 keV. It may be thermally produced in the Sun or in cosmic rays.
- Absorption of scalar causes atomic ionization (similar to photoelectric effect)→ detectable by current DM and solar axion searches.
- Relevant experiments: XENONnT, PandaX-II, EDELWEISS-III, DAMA/LIBRA, SABRE, SuperCDMS, ArDM, DarkSide-20k, DEAP-3600.



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: PRL 127, 081301 (2021) arXiv:2105.08296.



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

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

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:

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

- New limits from Xenon1T data:

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

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

Atom ionization by absorption of a scalar particle

PHYSICAL REVIEW D **109**, 115032 (2024)

Migdal-type effect in the dark matter absorption process

V. A. Dzuba,[*] V. V. Flambaum,[†] and I. B. Samsonov[‡]
School of Physics, University of New South Wales, Sydney 2052, Australia

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We propose a new mechanism of absorption of dark matter particles in atoms which resembles the Migdal effect of inelastic dark matter scattering. In this process, atoms may be ionized upon absorption of a scalar particle through the scalar-nucleon Yukawa-type interaction. The crucial difference from the inelastic dark matter scattering on atoms is that the total energy of the particle, including its rest mass mc^2 term, is transferred to the electron. As a result, the emitted electron kinetic energy is about 6 orders in magnitude bigger than that in the dark matter scattering process. This absorption process allows one to probe dark matter particles with a relatively small mass, in the range from 1 to 100 keV, that cannot be detected in the scattering process. It is also possible to detect hypothetical scalar particles emitted from the Sun. We calculate absorption cross sections of this process in Na, Si, Ar, Ge, I, Xe, and Tl target atoms and extract limits on the scalar-nucleon interaction constant from null results of the XENONnT experiment.

DOI: 10.1103/PhysRevD.109.115032

Atom ionization by absorption of a scalar particle

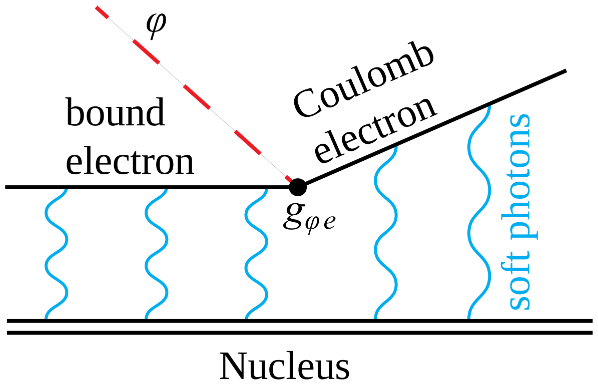
- More generally, scalar field can interact both with electron and nucleon:

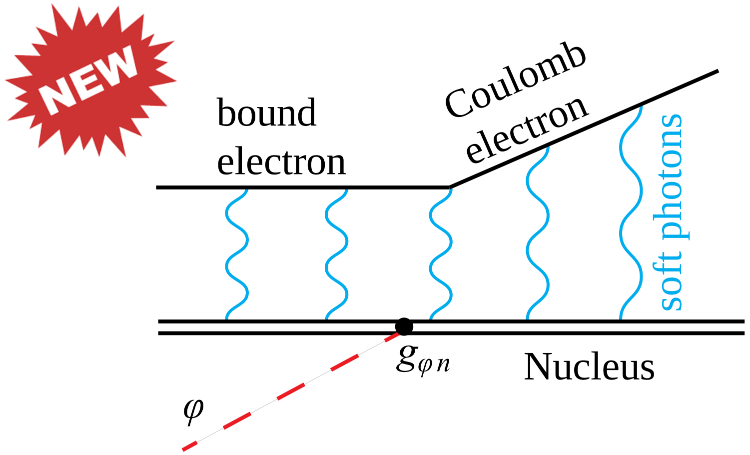
$$\mathcal{L}_{\text{int}} = g_{\phi n}\phi\bar{\psi}_n\psi_n + g_{\phi e}\phi\bar{\psi}_e\psi_e$$

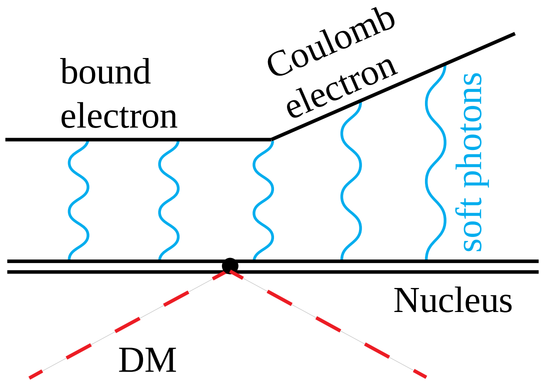
nucleon electron

- Two independent channels of atomic excitation or ionization:

C.f. Migdal scattering:







- Scalar particle is fully absorbed. Its rest mass is transferred into energy of ionized electrons!

- Consider plane wave scalar field with energy ω and momentum k:

$$\phi = \frac{1}{\sqrt{2\omega}}[e^{i(\vec{k}\vec{r}-\omega t)} + e^{-i(\vec{k}\vec{r}-\omega t)}]$$

- Absorption cross section of a scalar DM by an atom:

$$\sigma_\phi = 2\pi\frac{\omega}{k}\sum_{\mathrm{I,F}}|\langle \mathrm{F}|\bar{Q}|\mathrm{I}\rangle|^2$$

$$\langle \vec{r}_{e\,i}, \vec{r}_N|\mathrm{I}\rangle = e^{-i\vec{p}_\mathrm{i}\vec{r}_\mathrm{at}}\psi_\mathrm{i}(\vec{r}_{e\,i} - \vec{r}_N)$$ Initial state of the atom

$$\langle \vec{r}_{e\,i}, \vec{r}_N|\mathrm{F}\rangle = e^{-i\vec{p}_\mathrm{f}\vec{r}_\mathrm{at}}\psi_\mathrm{f}(\vec{r}_{e\,i} - \vec{r}_N)$$ Final state of the atom

- Operator for atomic transitions in the case when all A nucleons interact coherently:

$$\bar{Q} = Q_N + Q_e\,,$$

$$Q_N = \frac{g_{\phi n}A}{\sqrt{2\omega}}e^{i\vec{k}\vec{r}_N}\,,$$ Scalar-nucleus interaction operator

$$Q_e = \frac{g_{\phi e}}{\sqrt{2\omega}}\sum_{i=1}^{Z}\gamma^0_{(i)}e^{i\vec{k}\vec{r}_i}$$ Scalar-electron interaction operator

- Matrix element of the atomic transition due to scalar DM absorption:

$$M_{\rm fi}^{(N)} \equiv \langle {\rm F}|Q_N|{\rm I}\rangle = \frac{g_{\phi n}A}{\sqrt{2\omega}}\langle {\rm f}|\exp\left(-i\frac{m_e}{m_{\rm at}}\vec{k}\vec{R}\right)|{\rm i}\rangle$$

Suppression factor: $\frac{m_e}{m_{\rm at}} \ll 1$

$$M_{\rm fi}^{(e)} \equiv \langle {\rm F}|Q_e|{\rm I}\rangle \approx \frac{g_{\phi e}}{\sqrt{2\omega}}\langle {\rm f}|\sum_{l=1}^{Z} e^{i\vec{k}\vec{r}_{e\,l}}\gamma^0_{(l)}|{\rm i}\rangle$$

Ignore further as was calculated before

- Nuclear absorption matrix element is dominated by dipole term for $\langle\vec{k}\vec{R}\rangle m_e/m_{\rm at} \ll 1$
- This condition is satisfied for DM particles with momenta

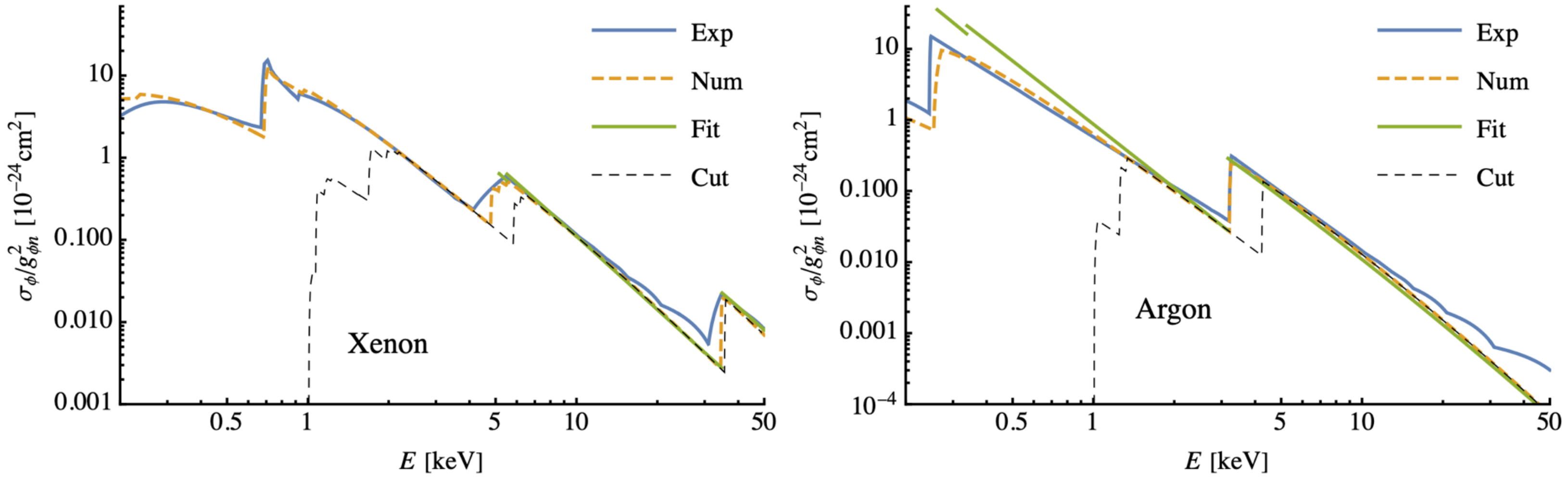
$$k \ll a_B^{-1} Z m_{\rm at}/m_e \approx AZ \times 6.8\,{\rm MeV}$$

- The corresponding absorption cross section is

$$\sigma_\phi = \pi g_{\phi n}^2 \frac{m_e^2}{m_p^2}\frac{k}{3}\sum_{\rm i,f}|\langle {\rm f}|\vec{R}|{\rm i}\rangle|^2$$

Our results [Phys. Rev. D 109 (2024) 11]

- Ionization cross sections by a massless scalar field through scalar-nucleon interaction in Xe and Ar atomic targets



- Comparison with photoionization cross section in the dipole approximation:

$$\sigma_\gamma = \frac{4\pi^2\alpha}{3}\omega \sum_{\rm i,f} |\langle {\rm f}|\vec{R}|{\rm i}\rangle|^2 \qquad \sigma_\phi = \pi g_{\phi n}^2 \frac{m_e^2}{m_p^2}\frac{k}{3}\sum_{\rm i,f} |\langle {\rm f}|\vec{R}|{\rm i}\rangle|^2$$

- Thus, scalar field ionization is related with the photoionization as

$$\boxed{\sigma_\phi = g_{\phi n}^2 \frac{m_e^2}{m_p^2}\frac{k}{\omega}\frac{\sigma_\gamma}{4\pi\alpha}}$$

- the photoionization cross section in the dipole approximation is applicable for photon wavelength greater than the typical size of the 1s atomic orbital,

$$k \ll Z/a_B \approx Z \times 3.7\,\mathrm{keV}$$

- for Xe atom, Z = 54, this holds for scalar particle momenta k≪200 keV
- The photoionization cross section may be measured experimentally for the detector medium. This allows one to effectively take into account interatomic and molecular interactions in the detector medium.

Our results [Phys. Rev. D 109 (2024) 11]

- The rate of absorption of scalar DM particles with emission of electrons:

$$R = \frac{1}{m_{\rm at}} \frac{\rho_{\rm DM}}{m_\phi} \int \sigma_\phi(v) f(v) v dv = \frac{g_{\phi n}^2}{4\pi\alpha} \frac{1}{m_{\rm at}} \frac{\rho_{\rm DM}}{m_\phi} \frac{m_e^2}{m_p^2} \langle v^2 \rangle \sigma_\gamma(m_\phi)$$

- Average DM velocity squared: $\langle v^2 \rangle = \int v^2 f(v) dv \approx 1.4 \times 10^{-6} c^2$

- Reported background in the XENONnT experiment is $R_{\rm error}$=1.3 events/(ton x year x keV)

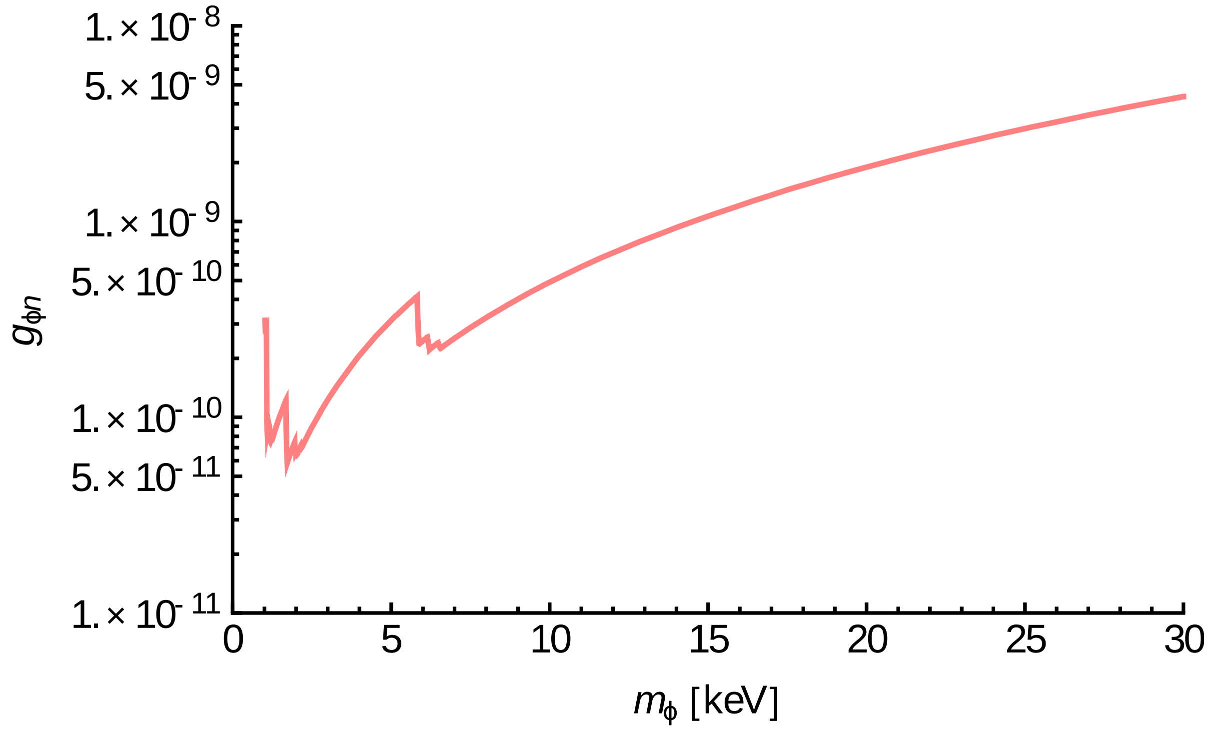
- Assuming that $R<R_{\rm error}$ (non-observation of dark matter) we find the limit

$$|g_{\phi n}| < \left(\frac{4\pi\alpha R_{\rm error} m_{\rm at} m_\phi m_p^2}{\sigma_\gamma \langle v^2 \rangle \rho_{\rm DM} m_e^2} \right)^{1/2}$$

- Taking ρ_{DM}=0.3 GeV/cm^3, m_ϕ=3 keV, we have: $|g_{\phi n}| < 1.2 \times 10^{-10}$

Our results:

- Exclusion plot for scalar-nucleon interaction constant:



Our results: relation with axion-ionization cross section

- Axio-ionization effect [A. Derevianko, V. A. Dzuba, V. V. Flambaum, M. Pospelov, Phys. Rev. D 82, 065006 (2010)]

$$\frac{\sigma_\phi}{\sigma_a} = \frac{4}{3}\frac{g_{\phi n}^2}{g_{ae}^2}\frac{v^2}{c^2}\frac{m_e^4}{m_p^2 m_\phi^2}$$

Our results: numerical calculations

- Dipole matrix elements are calculated numerically using relativistic Hartree-Fock method for a variety of atoms of interest: Na,Si, Ar, Ge, I, Xe, and Tl for DM particle energy from 0.2 to 50 keV.

	$\sigma_\phi/g^2_{\phi n}$, barn						
ω, keV	Na	Si	Ar	Ge	I	Xe	Tl
0.2000	2.591	10.44	1.068	15.82	5.101	5.166	7.292
0.2636	1.427	5.898	5.367	10.84	5.522	5.710	15.71
0.3474	0.7691	3.129	7.520	6.623	4.435	4.723	18.29
0.4578	0.4077	1.604	4.261	3.830	3.137	3.395	16.56
0.6034	0.2121	0.7988	2.245	2.128	2.033	2.216	11.56
0.7953	0.1083	0.3921	1.135	1.142	8.183	8.594	8.039
1.048	0.05418	0.1902	0.5585	0.5992	5.653	6.002	4.980
1.381	0.4707	0.09108	0.2682	2.188	3.225	3.465	2.881
1.821	0.2388	0.04299	0.1276	1.353	1.690	1.823	1.592
2.399	0.1151	0.2707	0.06016	0.6741	0.8535	0.9254	0.8533
3.162	0.05345	0.1330	0.02805	0.3245	0.4219	0.4590	2.039
4.168	0.02415	0.06242	0.1463	0.1531	0.2021	0.2201	1.168
5.493	0.01065	0.02838	0.07067	0.07004	0.5014	0.4754	0.5902
7.239	0.004620	0.01257	0.03279	0.03172	0.2472	0.2644	0.2897
9.541	0.001968	0.005450	0.01474	0.01419	0.1166	0.1254	0.1388
12.57	0.0008244	0.002317	0.006445	0.05453	0.05387	0.05805	0.06373
16.57	0.0003385	0.0009681	0.002752	0.02568	0.02388	0.02595	0.1317
21.84	0.0001352	0.0003966	0.001148	0.01151	0.01038	0.01125	0.06175
28.79	0.00005172	0.0001581	0.0004694	0.004952	0.004408	0.004782	0.02787
37.94	0.00001841	0.00006067	0.0001866	0.002051	0.01508	0.01616	0.01214
50.00	5.808×10^{-6}	0.00002172	0.00007158	0.0008176	0.006448	0.006957	0.004975

Our results: analytic fitting formula

- The ionization cross section is dominated by the contributions from 1s, 2s and 2p shells for DM particle energy above 1 keV. In this case, the cross section is well described by the following analytic function:

$$\sigma_\phi(\mathcal{E}) = \frac{g_{\phi n}^2}{3}\frac{m_e^2}{m_p^2}\frac{k}{\mathcal{E}}\left(\frac{\mathcal{E}_0}{\mathcal{E}}\right)^2 K(\mathcal{E}) a_B^2$$

where

$$K = K_{1s} + K_{2s} + K_{2p}\,,$$

$$K_{1s} = f_1(Z, \mathcal{E}+\mathcal{E}_{1s})\frac{384\pi\mathcal{E}_{1s}^4}{(\mathcal{E}_0 Z\mathcal{E})^2}\frac{e^{-4\nu_1 \mathrm{arccot}\nu_1}}{1-e^{-2\pi\nu_1}}$$

$$K_{2s} = f_2(Z, \mathcal{E}+\mathcal{E}_{2s})\frac{6144\pi e_2^3}{\mathcal{E}_0\mathcal{E}^2}\left(1+3\frac{e_2}{\mathcal{E}}\right) \times \frac{e^{-4\nu_2 \mathrm{arccot}(\nu_2/2)}}{1-e^{-2\pi\nu_2}}\,,$$

$$K_{2p} = f_2(Z, \mathcal{E}+\mathcal{E}_{2p})\frac{12288\pi e_3^4}{\mathcal{E}_0\mathcal{E}^3}\left(3+8\frac{e_3}{\mathcal{E}}\right) \times \frac{e^{-4\nu_3 \mathrm{arccot}(\nu_3/2)}}{1-e^{-2\pi\nu_3}}\,,$$

$$\frac{\mathcal{E}_{1s}}{\mathcal{E}_0} = -\frac{Z^2 - 7.49Z + 43.39}{2}\,,$$

$$\frac{\mathcal{E}_{2s}}{\mathcal{E}_0} = -0.000753Z^3 - 0.028306Z^2 - 0.066954Z + 2.359052\,,$$

$$\frac{\mathcal{E}_{2p}}{\mathcal{E}_0} = -0.000739Z^3 - 0.027996Z^2 + 0.128526Z + 1.435129\,.$$

$$f_1(Z,\mathcal{E}) = (5.368\times 10^{-7}Z - 1.17\times 10^{-4})\mathcal{E}/\mathcal{E}_0 - 0.012Z + 1.598\,,$$

$$f_2(Z,\mathcal{E}) = (-1.33\times 10^{-6}Z + 1.17\times 10^{-4})\mathcal{E}/\mathcal{E}_0 - 0.0156Z + 1.15\,.$$

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Summary

- Scalar DM particle with Yukawa interaction to nucleons is considered
- Atom can fully absorb this DM particle through DM-nucleus interaction => XENON-like experiments are sensitive to O(keV) scalar DM particles.
- Atomic electrons may be ionized with the kinematics similar to the Migdal effect
- Absorption cross section is dominated by the dipole term for DM particle mass $m<200$ keV.
- This absorption cross section is calculated numerically for atomic targets Na, Si, Ar, Ge, I, Xe, and Tl
- The absorption cross section is expressed via photoionization cross section. This allows one to effectively take into account interatomic interactions in the detector's medium if the the photoionization cross section is measured numerically.
- Limits on the scalar-nucleon interaction are obtained from non-observation of DM in the XENONnT experiment.