THE HEBREW UNIVERSITY OF JERUSALEM

EXCESS2022, Feb 15-17 2022

The Migdal Effect

JHEP 1803(2018) 194, M. Ibe, W. Nakano, YS, K. Suzuki

Yutaro Shoji (Hebrew University of Jerusalem)

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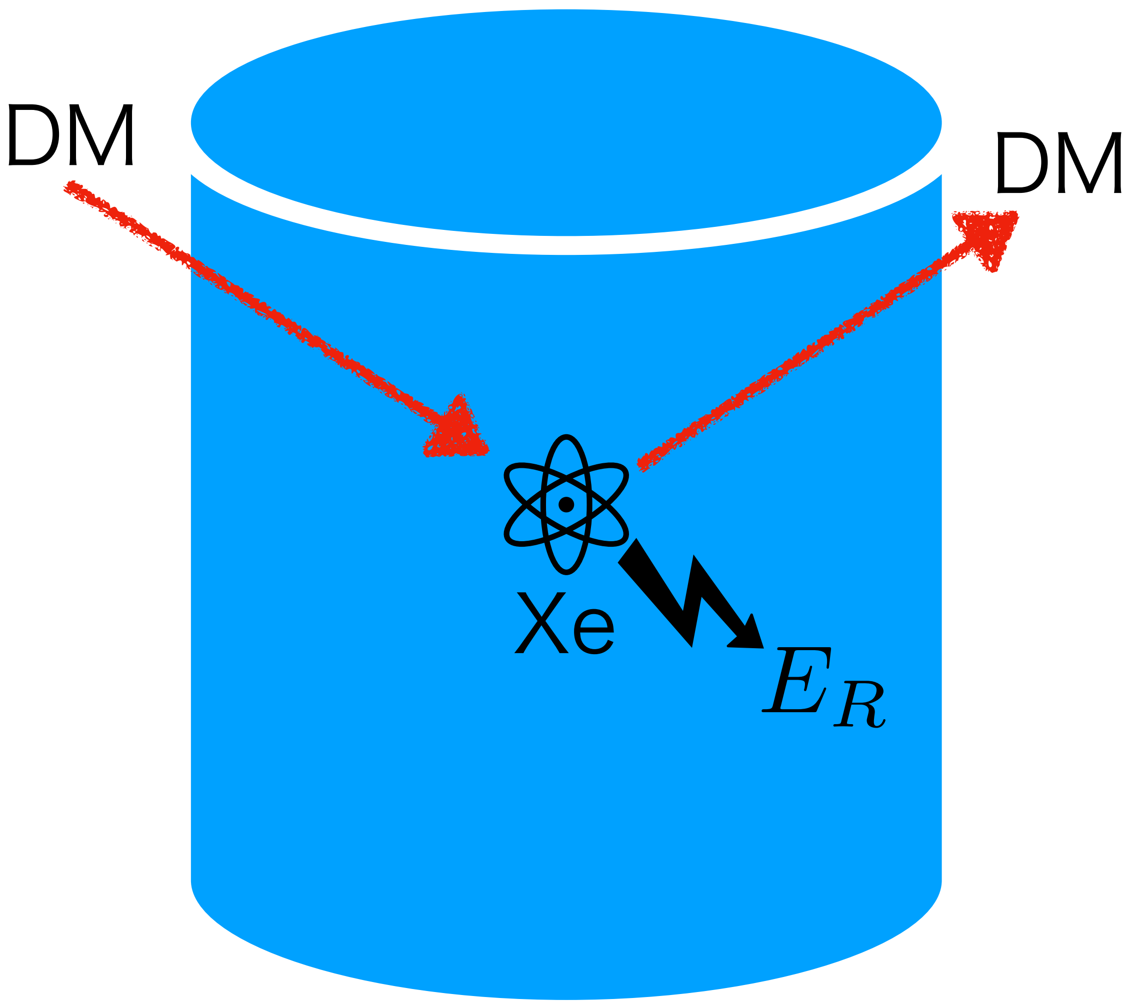
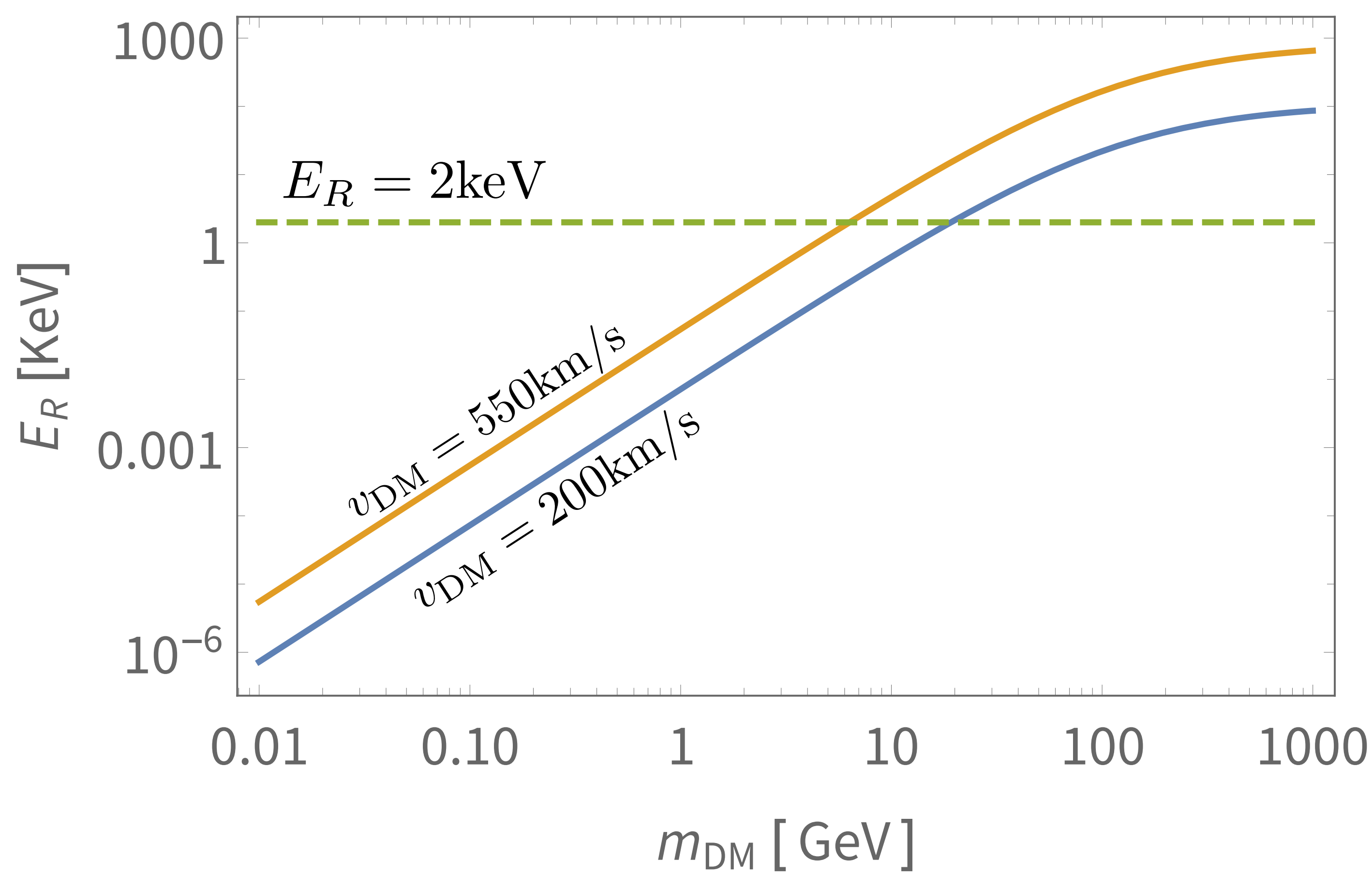


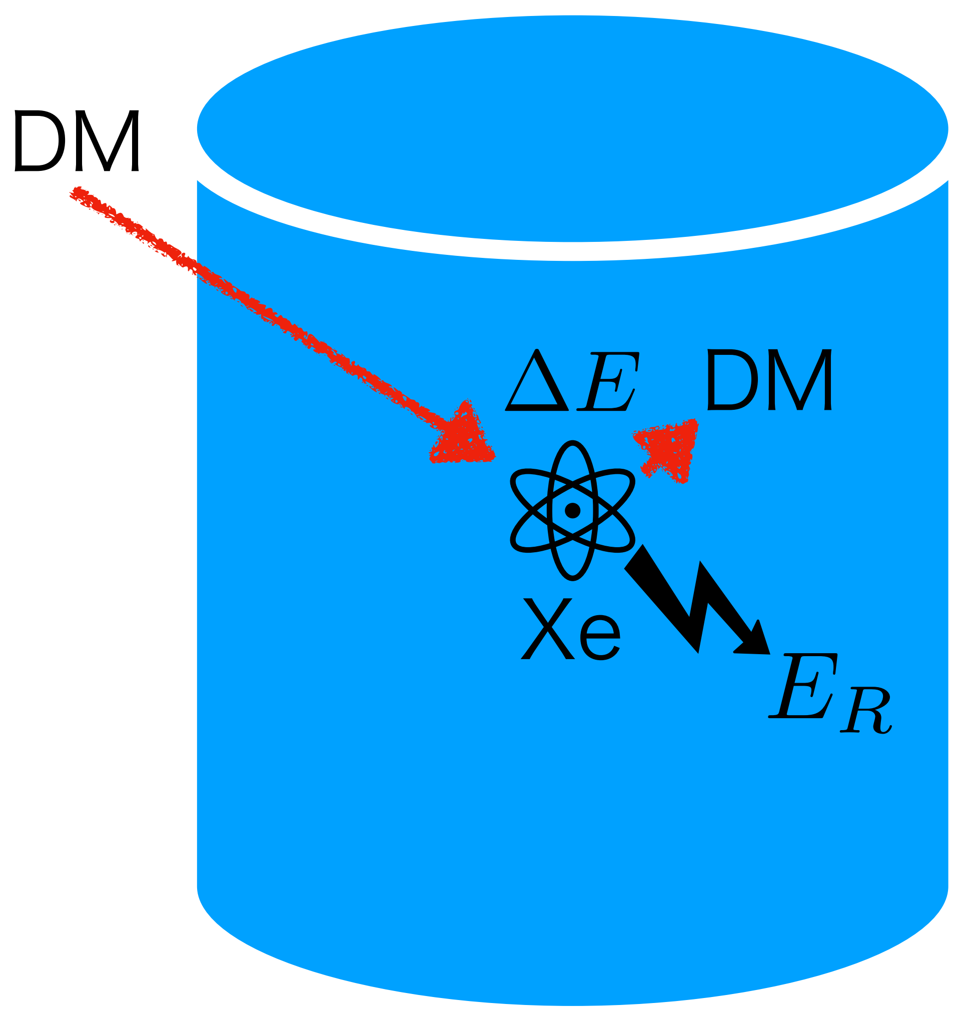
Energy Deposit (Elastic)

$$E_R^{\max} = 2\frac{\mu^2}{m_{\rm Xe}} v_{\rm DM}^2 \qquad \mu = \frac{m_{\rm Xe} m_{\rm DM}}{m_{\rm Xe} + m_{\rm DM}}$$



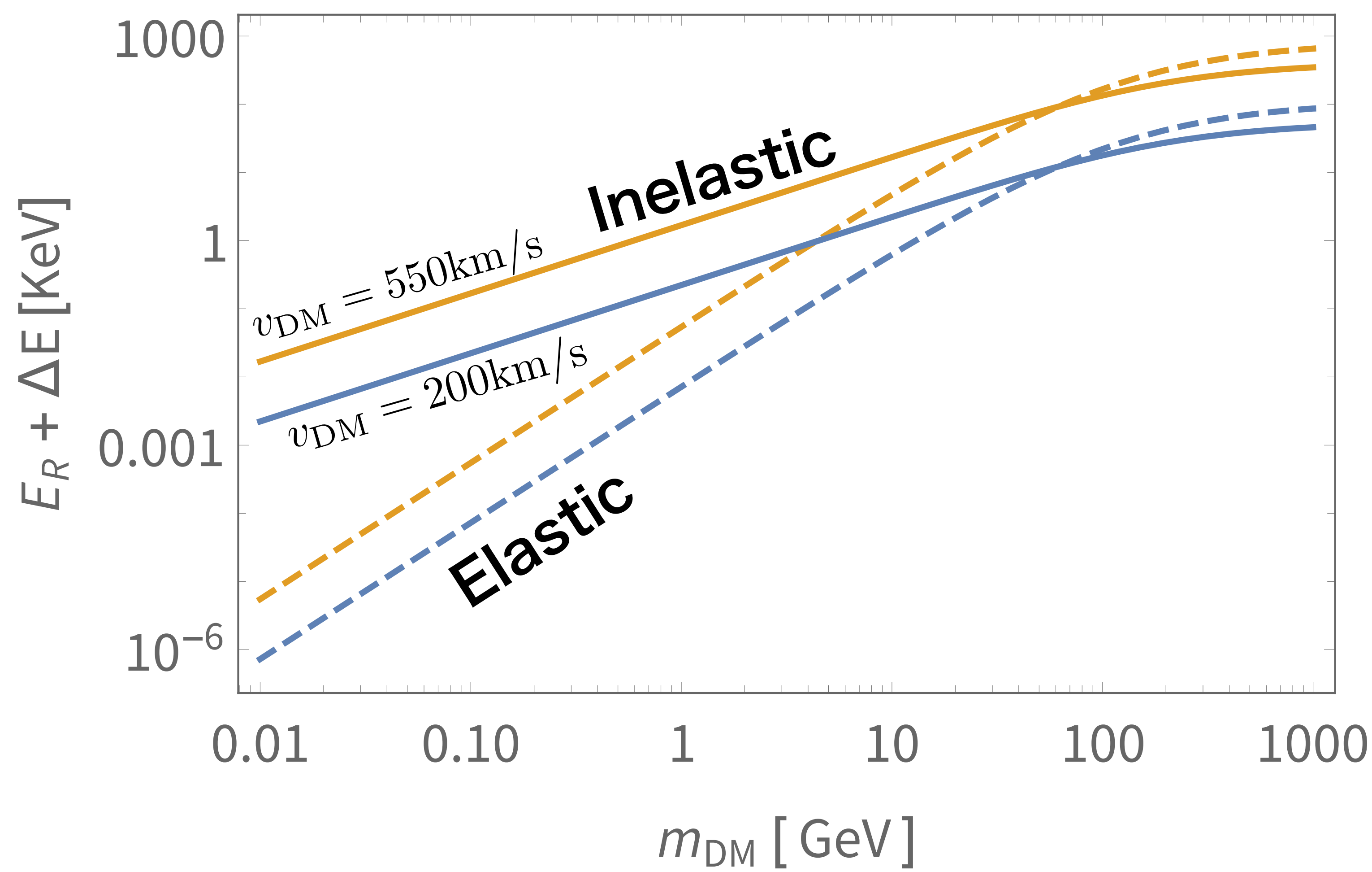
Dark Matter Direct Detection

Inelastic Scattering



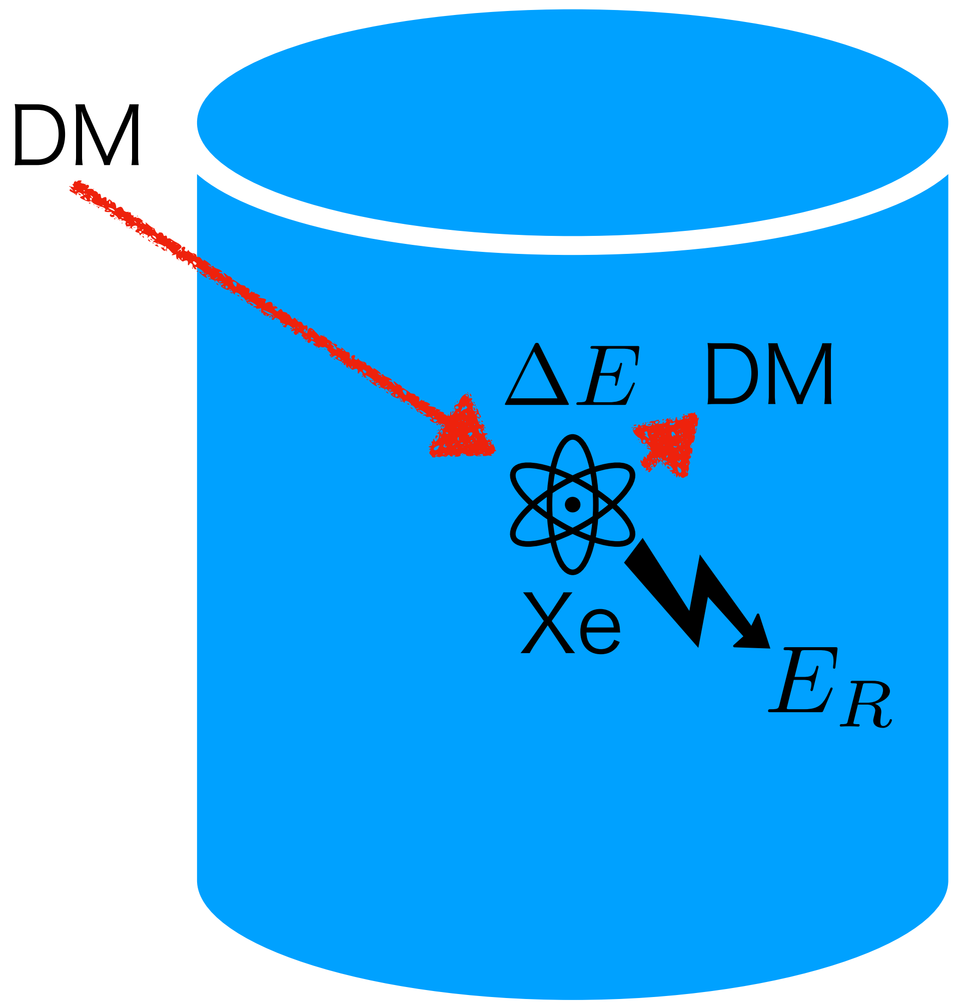
Energy Deposit (Inelastic)

$$E_R^{\max} = \frac{1}{2}\frac{\mu^2}{m_{\mathrm{Xe}}} v_{\mathrm{DM}}^2 \qquad \Delta E^{\max} = \frac{1}{2}\mu v_{\mathrm{DM}}^2$$

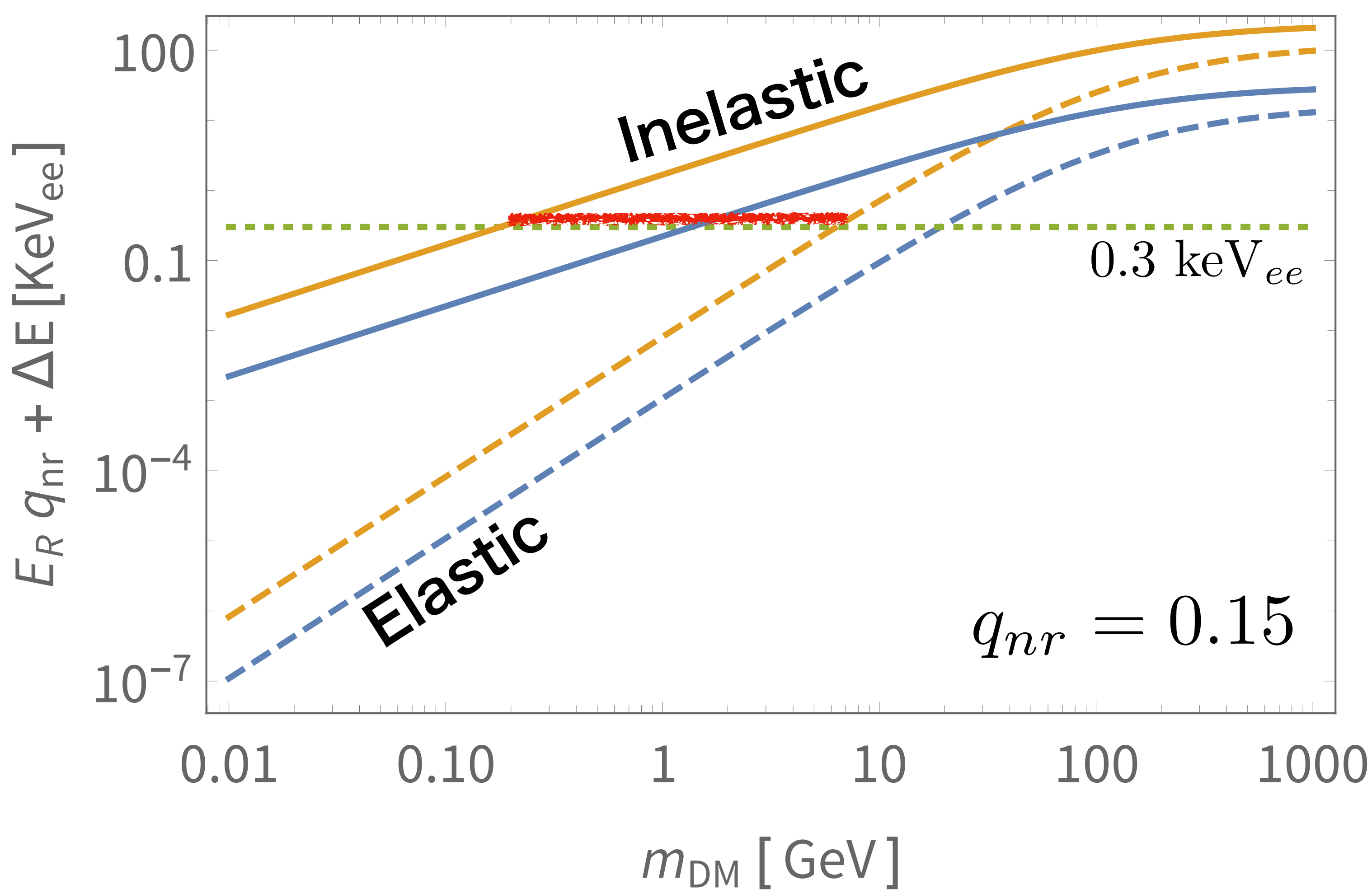


Dark Matter Direct Detection

Scintillation Efficiency

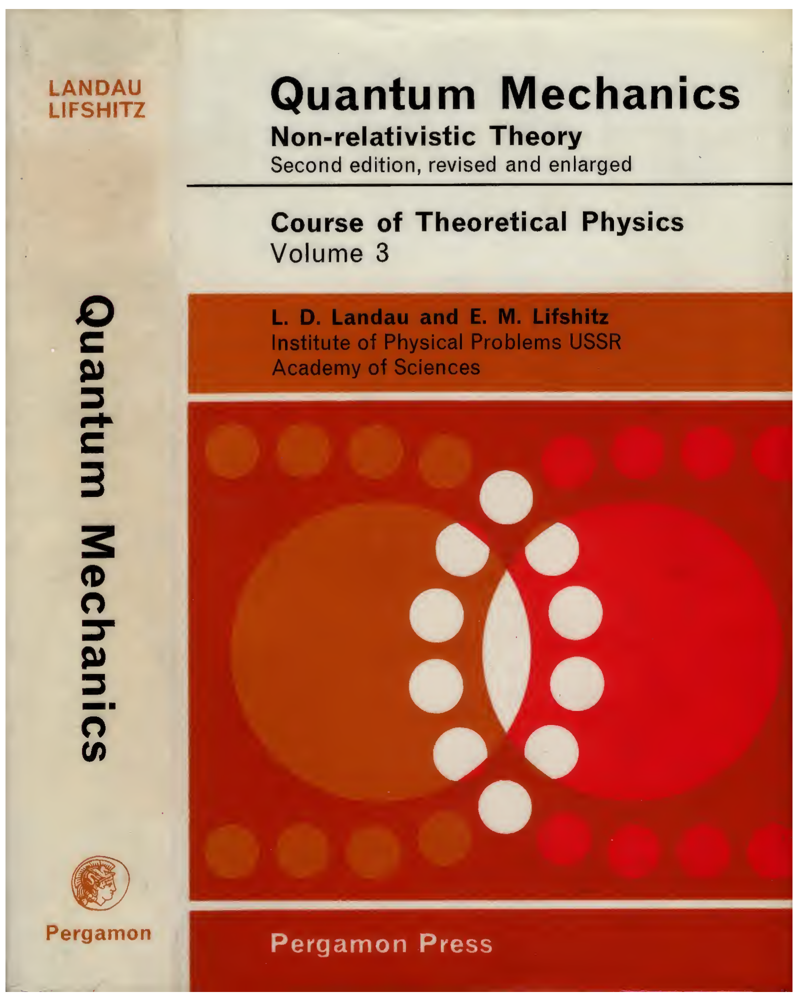


Detectable Energy



Migdal Problem

Migdal Problem
Original Problem



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).

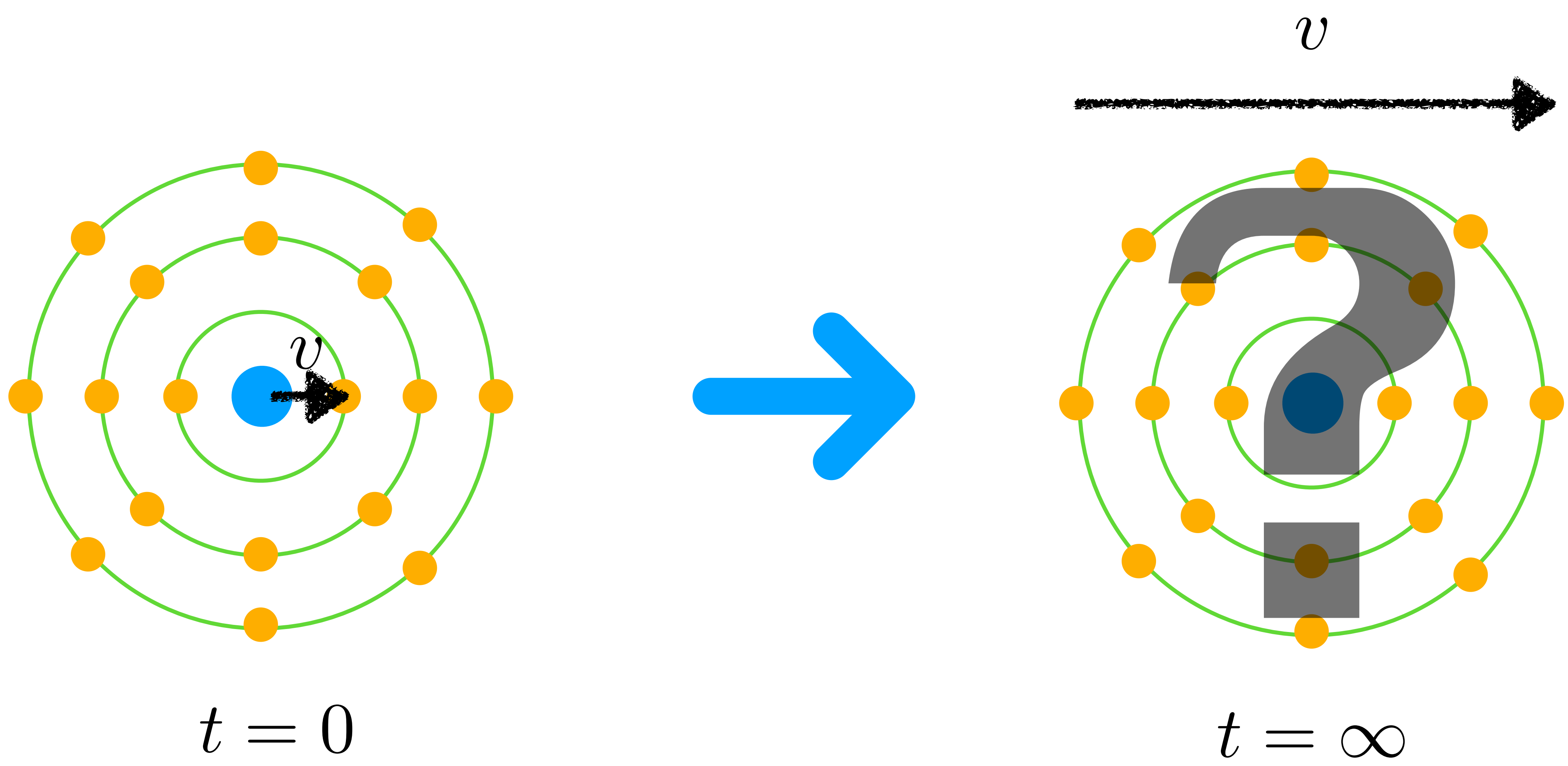
SOLUTION. We use a frame of reference K' moving with the nucleus after the impact. By virtue of the condition $\tau \ll a/v$, the nucleus may be regarded as practically stationary during the impact, so that the co-ordinates of the electrons in K' and in the original frame K immediately after the perturbation are the same. The initial wave function in K' is

$$\psi_0' = \psi_0 \exp(-i\mathbf{q} \cdot \sum_a \mathbf{r}_a), \qquad \mathbf{q} = m\mathbf{v}/\hbar,$$

where ψ_0 is the wave function of the normal state with the nucleus at rest, and the summation

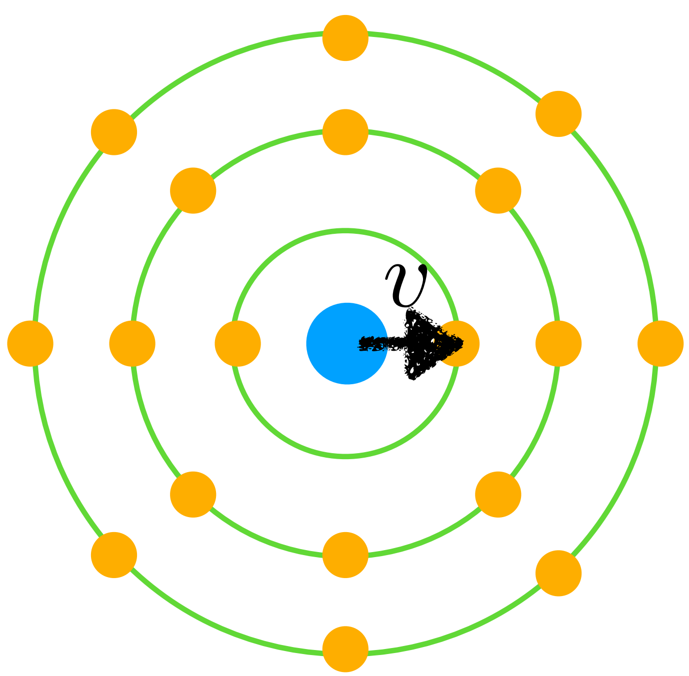
Migdal Problem

Original Problem



Migdal Problem
Original Problem

Lab frame

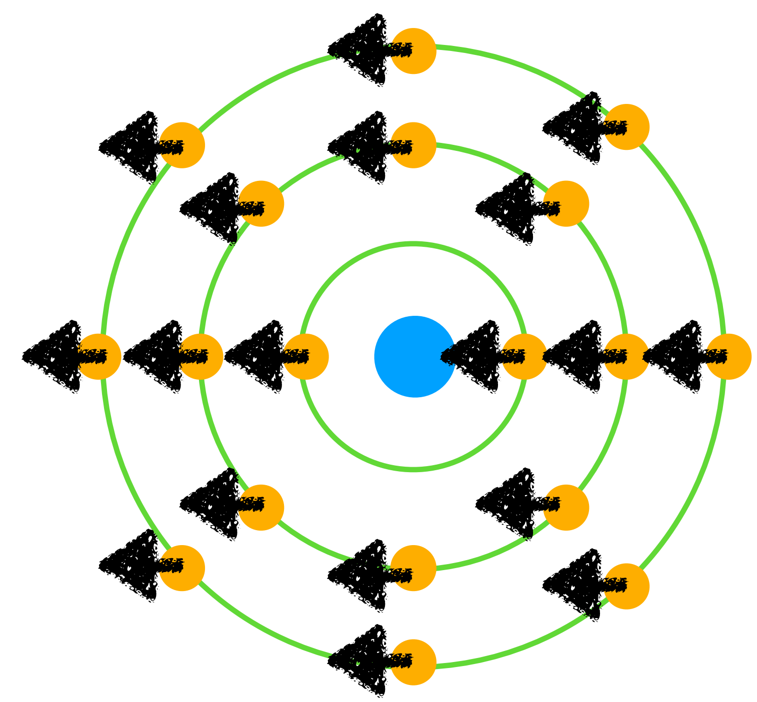


$t = 0$

$|\Psi_{\rm in}\rangle$

Electron WF

Rest frame of Nucleus



$t = 0$

$e^{-im_e v \sum_i \hat{x}_i}|\Psi_{\rm in}\rangle$

Migdal Problem

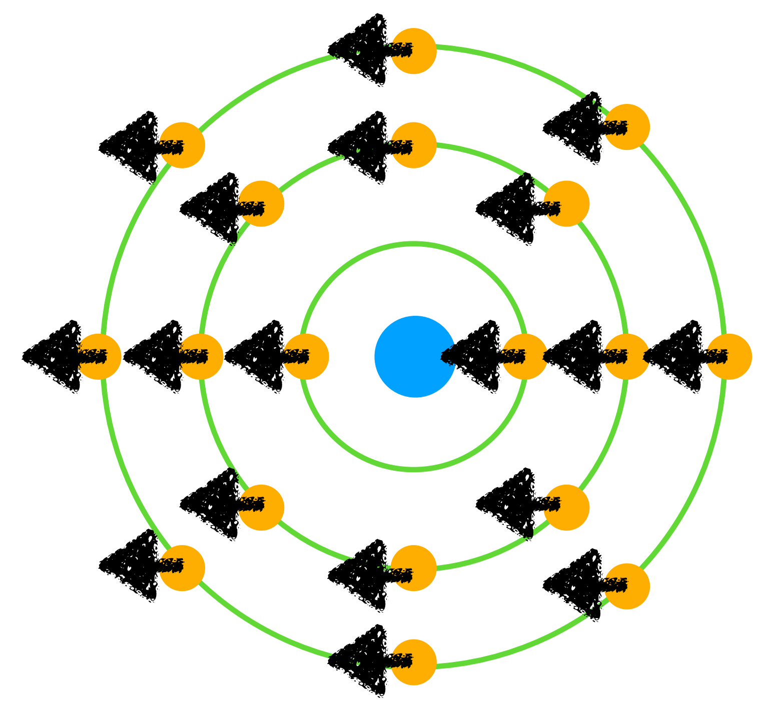
Original Problem

Electron energy eigenstates
in the rest frame of the nucleus

$$e^{-im_e v \sum_i \hat{x}_i}|\Psi_{\text{in}}\rangle = \sum_j c_j |\Psi_j\rangle$$

$$c_j = \langle \Psi_j | e^{-im_e v \sum_i \hat{x}_i} | \Psi_{\text{in}} \rangle$$

$|c_j|^2$: probability to observe $|\Psi_j\rangle$



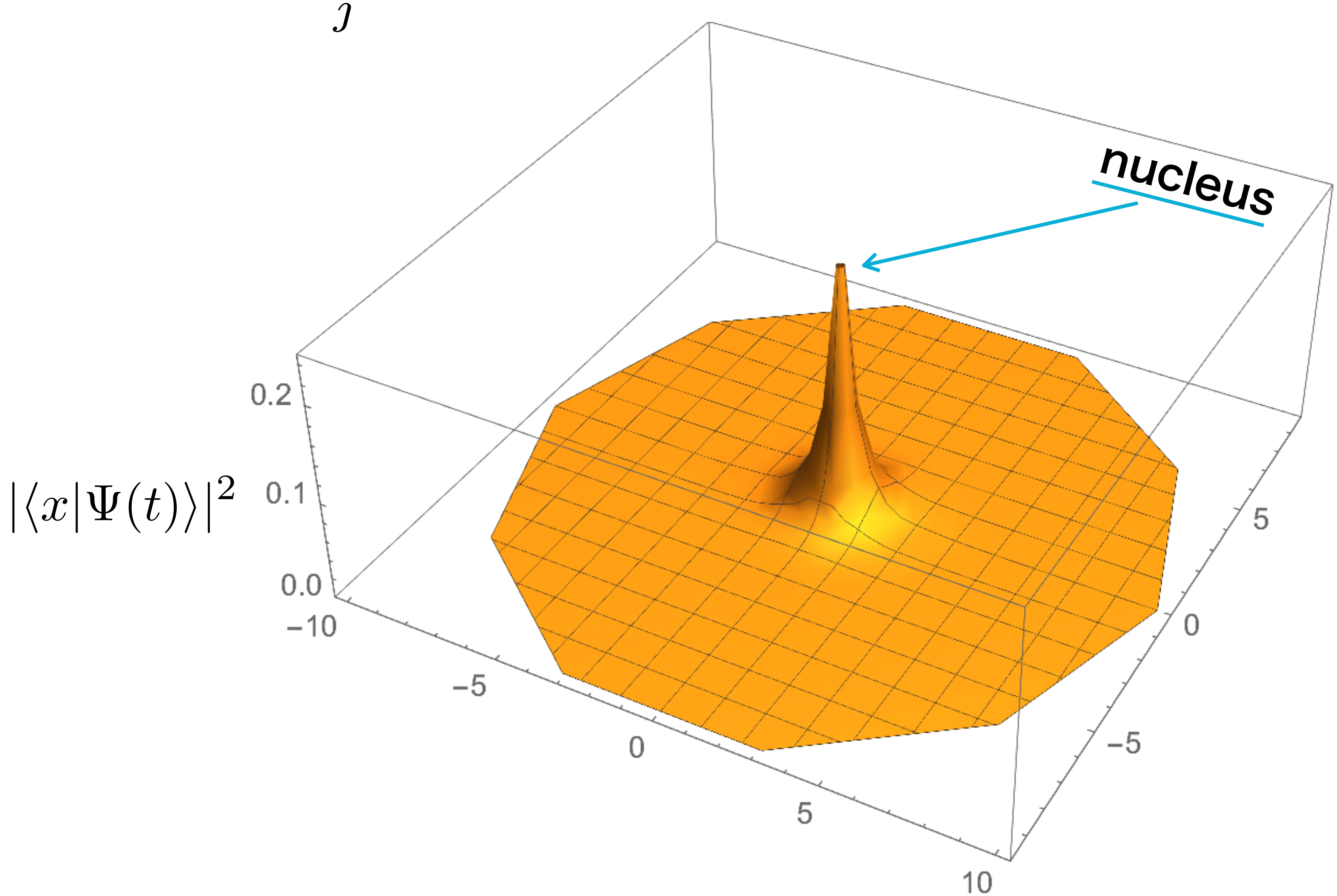
$t = 0$

$e^{-im_e v \sum_i \hat{x}_i}|\Psi_{\text{in}}\rangle$

Migdal Problem

Hydrogen atom example

$$|\Psi(t)\rangle = \sum_j e^{-iE_j t} c_j |\Psi_j\rangle$$: the time-dependent solution



$q_e a_B = 1.5$

Migdal Problem

Application to DM Direct Detection

ov 2004

THE ROLE OF IONIZATION ELECTRONS IN DIRECT NEUTRALINO DETECTION

J.D. Vergados[1*] and H. Ejiri[2]

1 Physics Department, University of Cyprus, 1678 Nicosia, Cyprus

ar 2006

Dark matter search by exclusive studies of X-rays following WIMPs nuclear interactions

H. Ejiri[1*], Ch. C. Moustakidis[2†], and J. D. Vergados[3‡]

1 INT, University of Washington, Seattle, WA 98195, USA;

Oct 2005

Direct dark matter search by observing electrons produced in neutralino-nucleus collisions

Ch. C. Moustakidis[1*], J. D. Vergados[2†], and H. Ejiri[3‡]

Theoretical direct WIMP detection rates for transitions to excited states.

J.D. Vergados[1], H. Ejiri[2] and K. G. Savvidy[3]

[1] *Theoretical Physics, University of Ioannina, Ioannina, Gr 451 10, Greece*

[2] *RCNP, Osaka University, Osaka, 567-0047, Japan and Nuclear Science, Czech Technical University, Brehova, Prague, Czech Republic. and*

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(Dated: March 6, 2018)

stro-ph] 11 Jun 2007

ROM2F/2007/05

to appear in Int. J. Mod. Phys. A

On electromagnetic contributions in WIMP quests

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Formulation

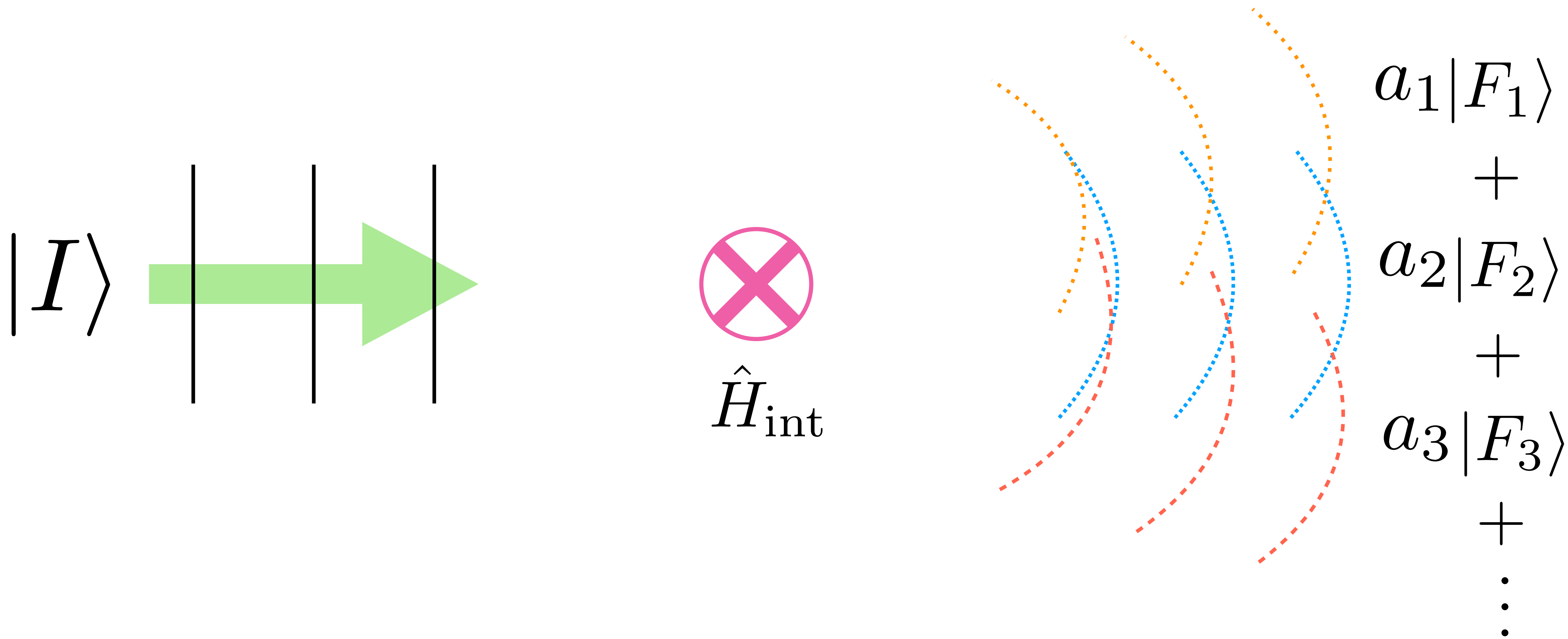
Formulation

Transition Amplitude

DM-nucleon interaction

$$T_{FI} \simeq \langle F|\hat{H}_{\rm int}|I\rangle$$

$$|F \text{ or } I\rangle = |\text{DM}\rangle \otimes |\text{atom}\rangle$$: Energy eigenstates



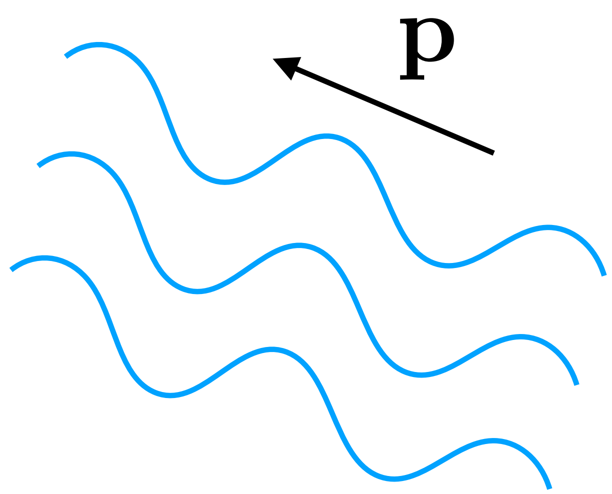
Formulation

Atomic States

$$|F \text{ or } I\rangle = |\text{DM}\rangle \otimes |\text{atom}\rangle$$

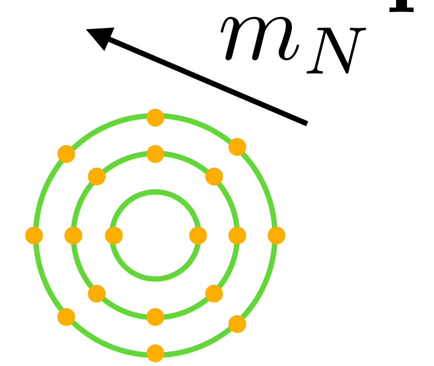
Ordinary plane wave

$$e^{-i\hat{\mathbf{x}}_N \cdot \hat{\mathbf{p}}_e} \times \left(\quad |\mathbf{p}\rangle_N \quad \otimes \quad e^{i\frac{m_e}{m_N}\mathbf{p}\cdot\hat{\mathbf{x}}_e}|\Psi\rangle \quad \right)$$



$|\mathbf{p}\rangle_N$

Nucleus plane wave



$e^{i\frac{m_e}{m_N}\mathbf{p}\cdot\hat{\mathbf{x}}_e}|\Psi\rangle$

Electron wave function

Formulation

Scattering cross-section

$$P_{I\to F} = |T_{FI}|^2 2\pi\delta(E_F - E_I)$$

Assuming contact interaction

$$\frac{d\sigma}{dE_R} \simeq \sum_{E_{\rm ec}^F} \frac{1}{2}\frac{m_A}{\mu^2 v_{\rm DM}^2}|F_N(q_A^2)|^2 \bar{\sigma}_N |Z_{FI}(\mathbf{q}_e)|^2$$

Nucleus form factor

Migdal factor

$$Z_{FI}(\mathbf{q}_e) = \langle \Psi_F | e^{-i\mathbf{q}_e\cdot\hat{x}} | \Psi_I \rangle$$

$$\mathbf{q}_e = \frac{m_e}{m_A}\mathbf{q}_A$$

$$\bar{\sigma}_N \simeq \frac{1}{16\pi}\frac{|\mathcal{M}_{\rm nuc}(q\to 0)|^2}{(m_N + m_{\rm DM})^2}$$

Electron Wave Functions

Migdal Factor

$$|Z_{FI}(q_e)|^2 = |\langle \Psi_F | e^{-i\mathbf{q}_e \cdot \hat{\mathbf{x}}} | \Psi_I \rangle|^2 \simeq |\langle \Psi_F | \mathbf{q}_e \cdot \hat{\mathbf{x}} | \Psi_I \rangle|^2$$

Xe ($q_e = m_e \times 10^{-3}$)

Excitations | Ionization | Initial states

(n, ℓ)	$\mathcal{P}_{\to 4f}$	$\mathcal{P}_{\to 5d}$	$\mathcal{P}_{\to 6s}$	$\mathcal{P}_{\to 6p}$	$E_{n\ell}$ [eV]	$\frac{1}{2\pi}\int dE_e \frac{dp^c}{dE_e}$
1s	–	–	–	7.3×10^{-10}	3.5×10^4	4.9×10^{-6}
2s	–	–	–	1.8×10^{-8}	5.4×10^3	3.0×10^{-5}
2p	–	3.0×10^{-8}	6.5×10^{-9}	–	4.9×10^3	1.3×10^{-4}
3s	–	–	–	2.7×10^{-7}	1.1×10^3	1.1×10^{-4}
3p	–	3.4×10^{-7}	4.0×10^{-7}	–	9.3×10^2	6.0×10^{-4}
3d	2.3×10^{-9}	–	–	4.3×10^{-7}	6.6×10^2	3.6×10^{-3}
4s	–	–	–	3.1×10^{-6}	2.0×10^2	3.6×10^{-4}
4p	–	4.1×10^{-8}	3.0×10^{-5}	–	1.4×10^2	1.5×10^{-3}
4d	7.0×10^{-7}	–	–	1.5×10^{-4}	6.1×10	3.6×10^{-2}
5s	–	–	–	1.2×10^{-4}	2.1×10	4.7×10^{-4}
5p	–	3.6×10^{-2}	2.1×10^{-2}	–	9.8	7.8×10^{-2}

(n, ℓ)	$4f$	$5d$	$6s$	$6p$
$E_{n\ell}$[eV]	0.85	1.6	3.3	2.2

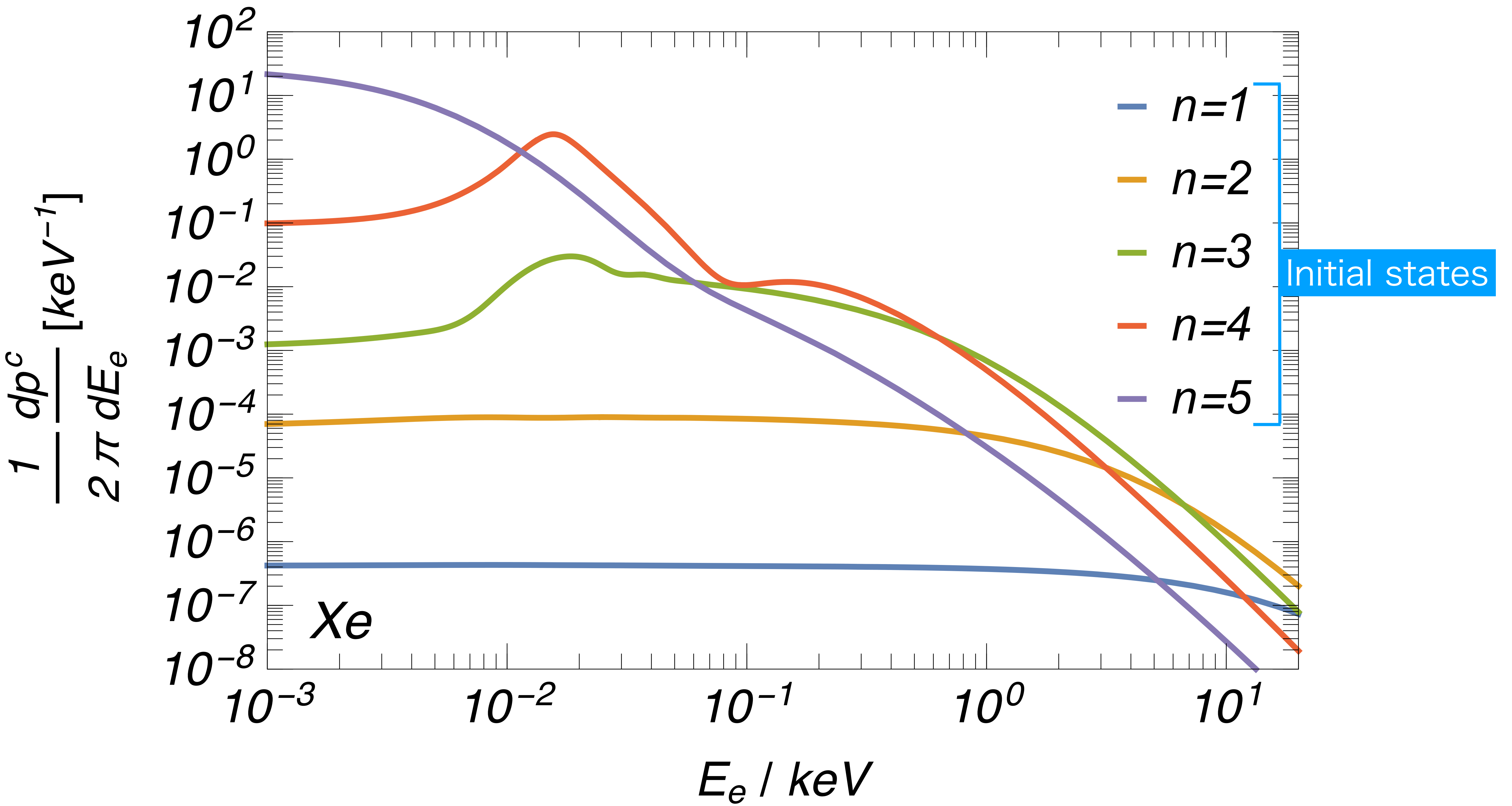
The probability scales as q_e^2

Energy Uncertainty ~20%

Electron Wave Functions

Migdal Electron Spectrum

$$|Z_{FI}(q_e)|^2 = |\langle\Psi_F|e^{-i\mathbf{q}_e\cdot\hat{\mathbf{x}}}|\Psi_I\rangle|^2 \simeq |\langle\Psi_F|\mathbf{q}_e\cdot\hat{\mathbf{x}}|\Psi_I\rangle|^2$$



Electron Wave Functions

Ionization Data

You can download the data for Ar, C, F, Ge, I, Na, Ne, Si, Xe

Cornell University

We gratefully acknowledge support from the Simons Foundation and member institutions.

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High Energy Physics – Phenomenology

Migdal Effect in Dark Matter Direct Detection Experiments

Masahiro Ibe, Wakutaka Nakano, Yutaro Shoji, Kazumine Suzuki

(Submitted on 23 Jul 2017 (v1), last revised 30 Mar 2020 (this version, v4))

The elastic scattering of an atomic nucleus plays a central role in dark matter direct detection experiments. In those experiments, it is usually assumed that the atomic electrons around the nucleus of the target material immediately follow the motion of the recoil nucleus. In reality, however, it takes some time for the electrons to catch up, which results in ionization and excitation of the atoms. In previous studies, those effects are taken into account by using the so-called Migdal's approach, in which the final state ionization/excitation are treated separately from the nuclear recoil. In this paper, we reformulate the Migdal's approach so that the "atomic recoil" cross section is obtained coherently, where we make transparent the energy-momentum conservation and the probability conservation. We show that the final state ionization/excitation can enhance the detectability of rather light dark matter in the GeV mass range via the {\it nuclear} scattering. We also discuss the coherent neutrino-nucleus scattering, where the same effects are expected.

Comments: Integrated probability data fixed and Si.dat added

Subjects: **High Energy Physics – Phenomenology (hep-ph)**; High Energy Physics – Experiment (hep-ex)

Cite as: arXiv:1707.07258 [hep-ph]
(or arXiv:1707.07258v4 [hep-ph] for this version)

Bibliographic data

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References (72)

Citations (15)

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Ancillary files (details):

- AtomData/Ar.dat
- AtomData/C.dat
- AtomData/F.dat
- AtomData/Ge.dat
- AtomData/I.dat

(4 additional files not shown)

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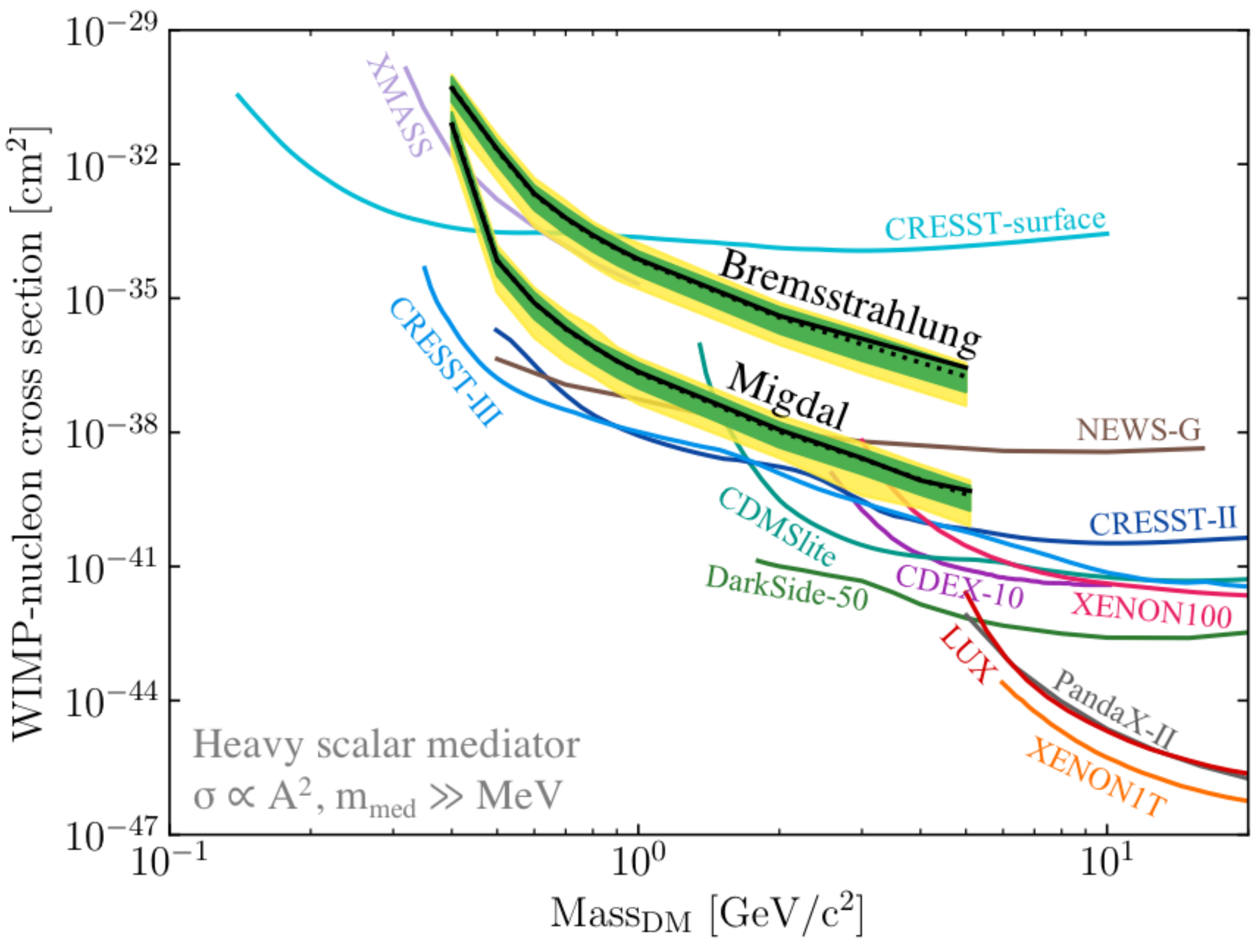
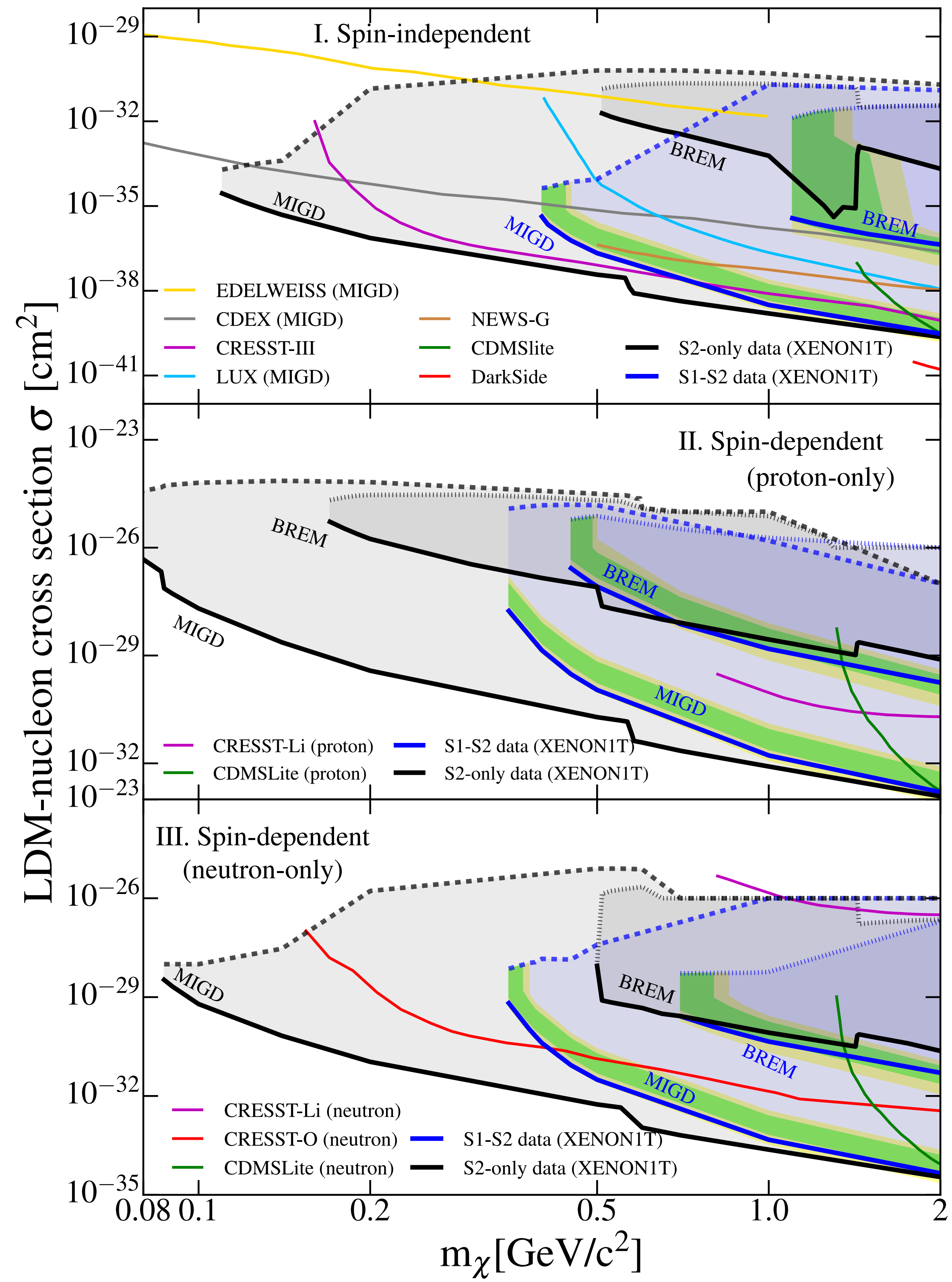
Experiments

Limit

Xenon detectors



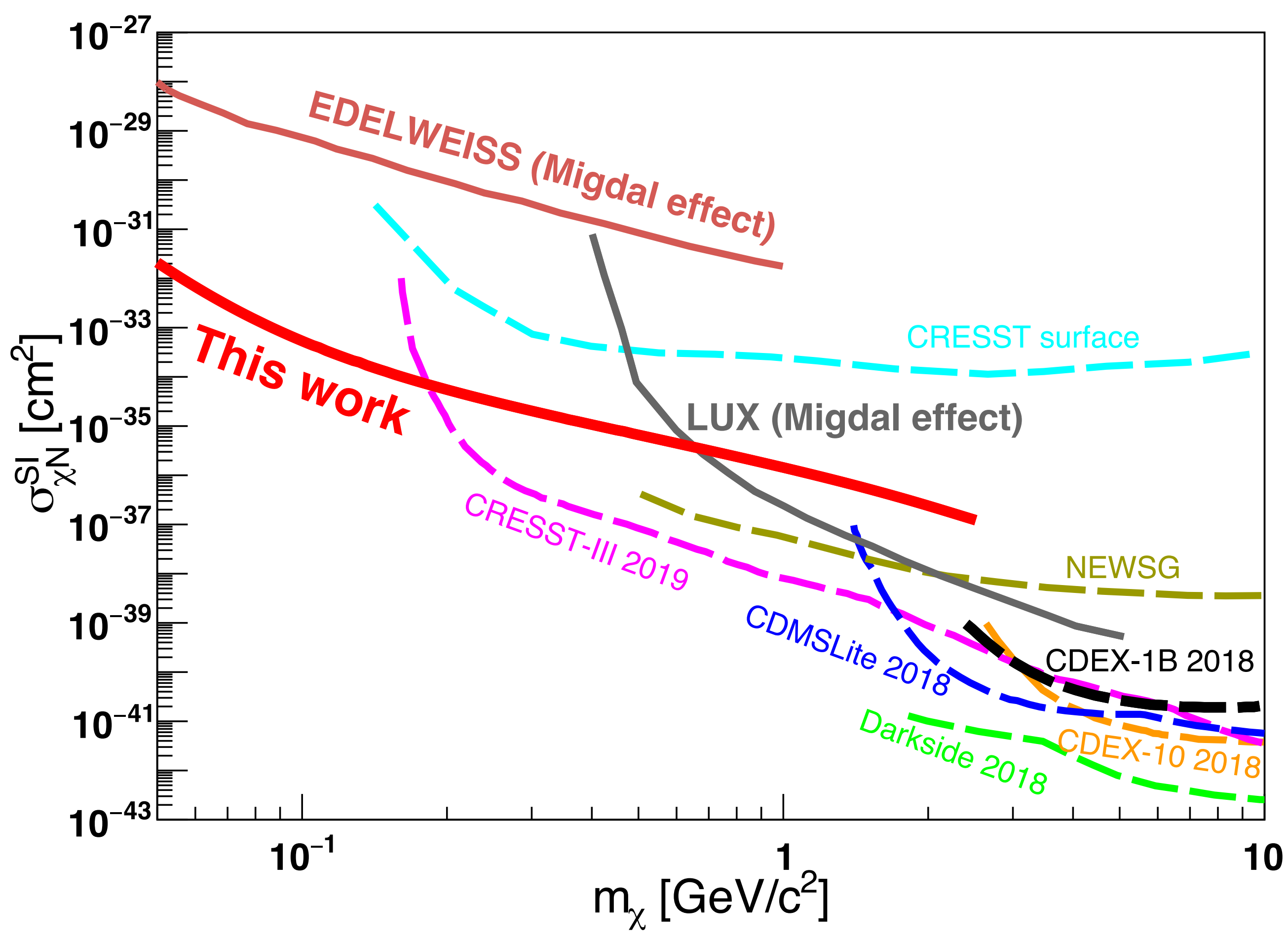
[LUX Collaboration, ’19]

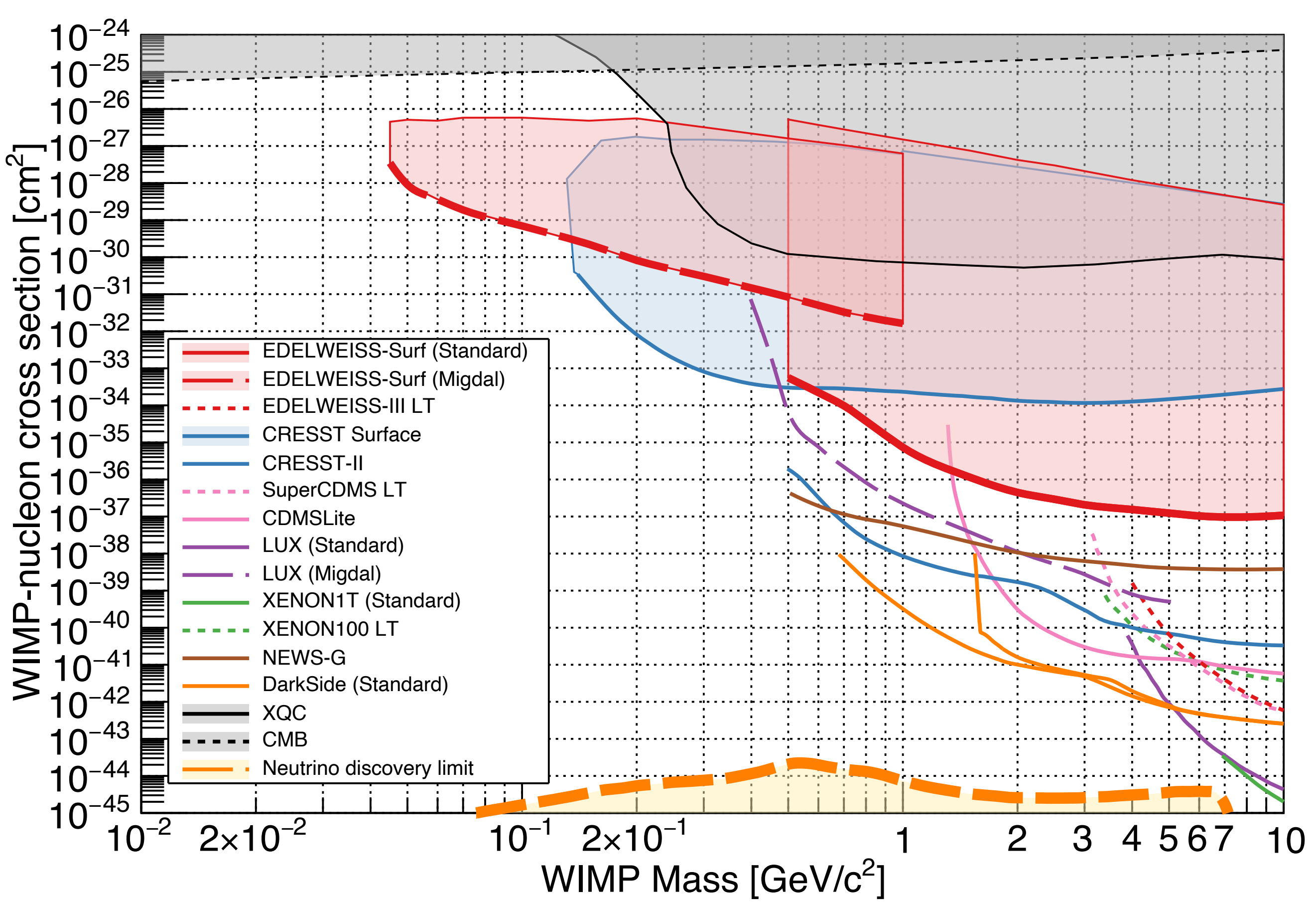


[XENON Collaboration, ’19]

Limit

Germanium detectors





[CDEX Collaboration, '19]

[EDELWEISS Collaboration, '19]

For theory, see also

[R. Essig, J. Pradler, M. Sholapurkar, T. T. Yu, '20; ZL Liang, L. Zhang, F. Zheng, P. Zhang, '20; S. Knapen, J. Kozaczuk, T. Lin, '21]

Measurement of Migdal effect

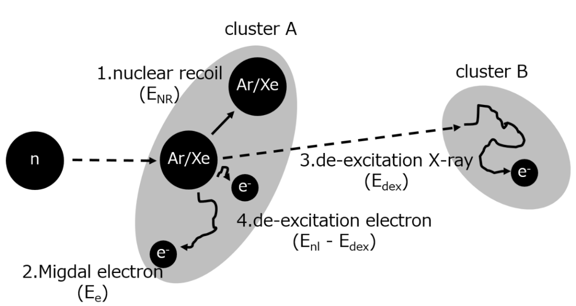
Proof of principle

MIRACLUE experiment

(Xe,Ar/characteristic X-ray)

Event topology of Migdal

- Situation
  - Migdal ionization (K-shell) --> Migdal electron and hole
  - X-ray by de-excitation
- Feature
  - two cluster (in the gaseous medium)
  - cluster-B is fixed energy
  - --> position sensitive gaseous detector



target	Ar 1atm	Xe 8atm
energy	4keV	30keV
X-ray absorption length	2.95cm	2.19cm
fluorescence yield	0.13	0.9

5

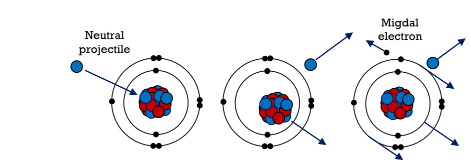
From K. Nakamura's slide

[K. D. Nakamura, K. Miuchi, S. Kazama, YS, M. Ibe, W. Nakano, '21]

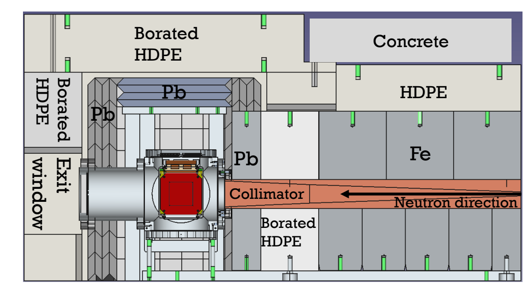
MIGDAL experiment

(CF_4/Migdal e^-)

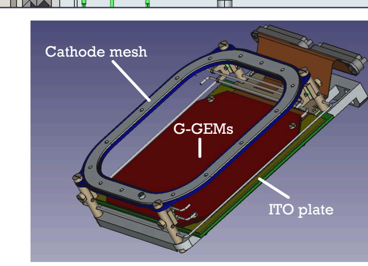
Overview of the MIGDAL experiment



Migdal event topology involves a nuclear recoil and electron recoil originating from the same vertex.



- The Migdal effect is currently being exploited to increase sensitivity to light WIMPs, but it has not been experimentally confirmed.
- We will utilise the increased Migdal probability of high energy neutron scattering to directly observe the Migdal Effect with a GEM-based OTPC in low pressure CF_4.
- We will use a low-pressure chamber where recoil tracks are long enough to be resolved by our camera.



TIMOTHY.MARLEY15@IMPERIAL.AC.UK 16/06/2021 3

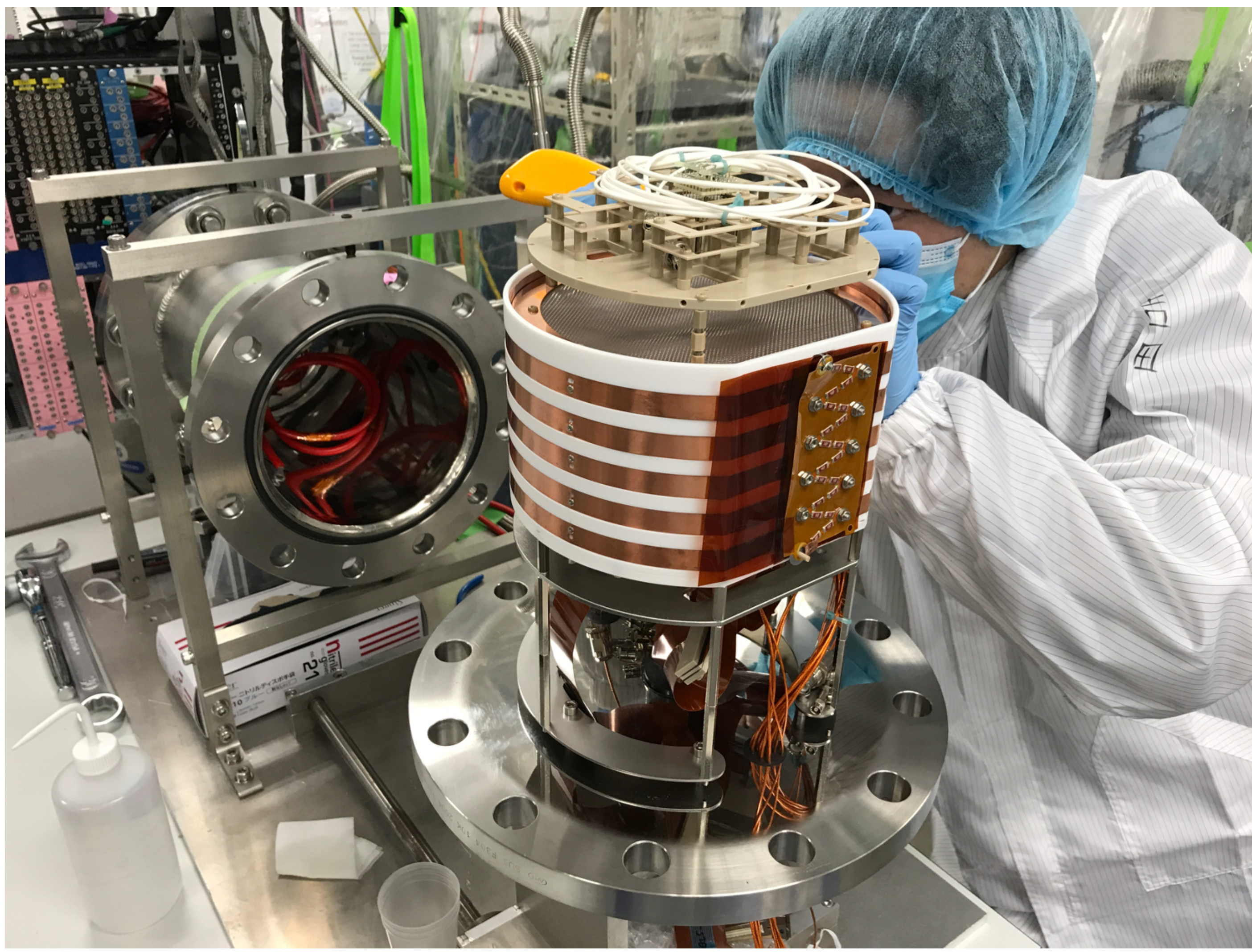
From T. Marley's slide

Measurement of Migdal effect

Proof of principle

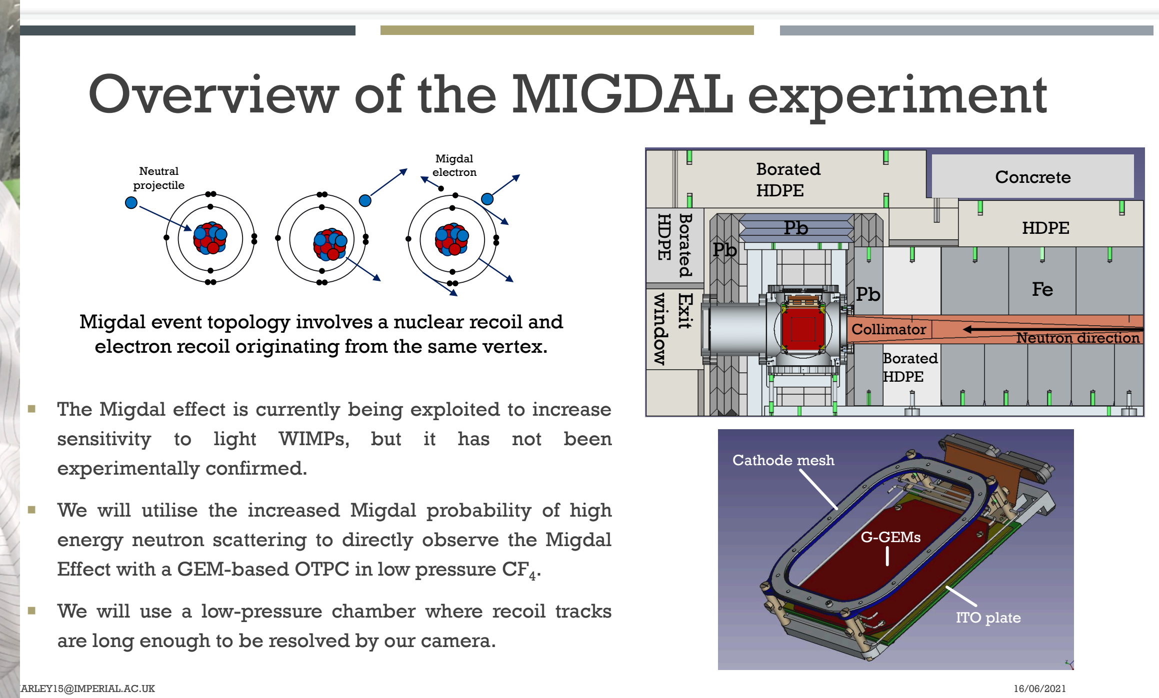
<u>MIRACLUE experiment</u>

(Xe,Ar/characteristic X-ray)



<u>MIGDAL experiment</u>

(CF4/Migdal e^-)



From T. Marley's slide

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Summary
The Migdal Effect

- Inelastic scattering effectively absorbs the kinetic energy of DM and can extend the sensitivity of detectors down to the sub-GeV DM-mass regime.

- We re-formulated the Migdal effect carefully and published the Migdal data.

- The Migdal effect is now used in various existing/proposed DM experiments and the proof-of-principle experiments are going on.

- If you have requests or questions, feel free to contact us.