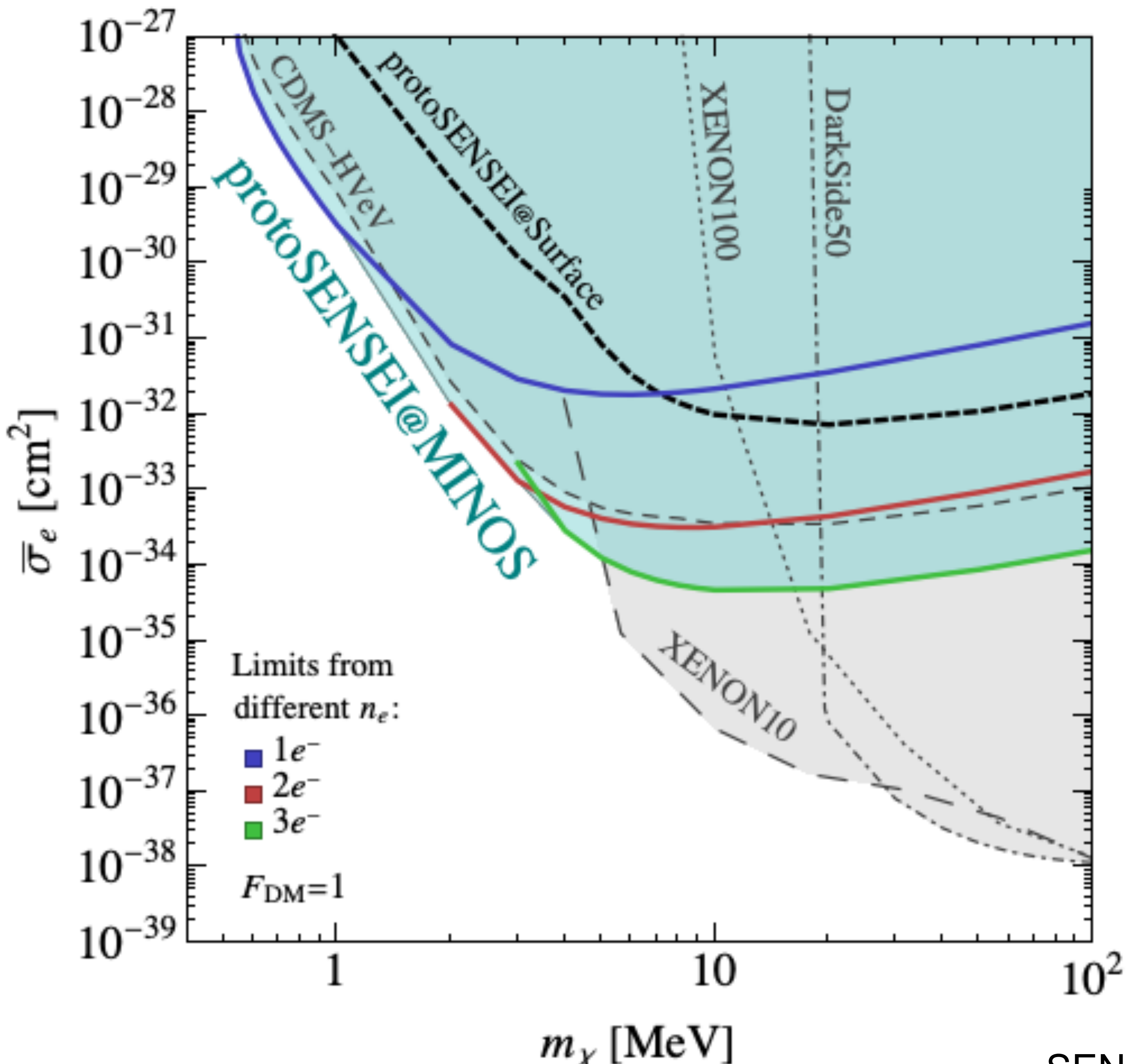
Dark matter — electron scattering

Christopher M^{c}Cabe

INFN-LNF, 17 September 2019

Semi-conductors (Si or Ge)

Lower mass sensitivity from kinematics



SENSEI, arXiv:1901.10478

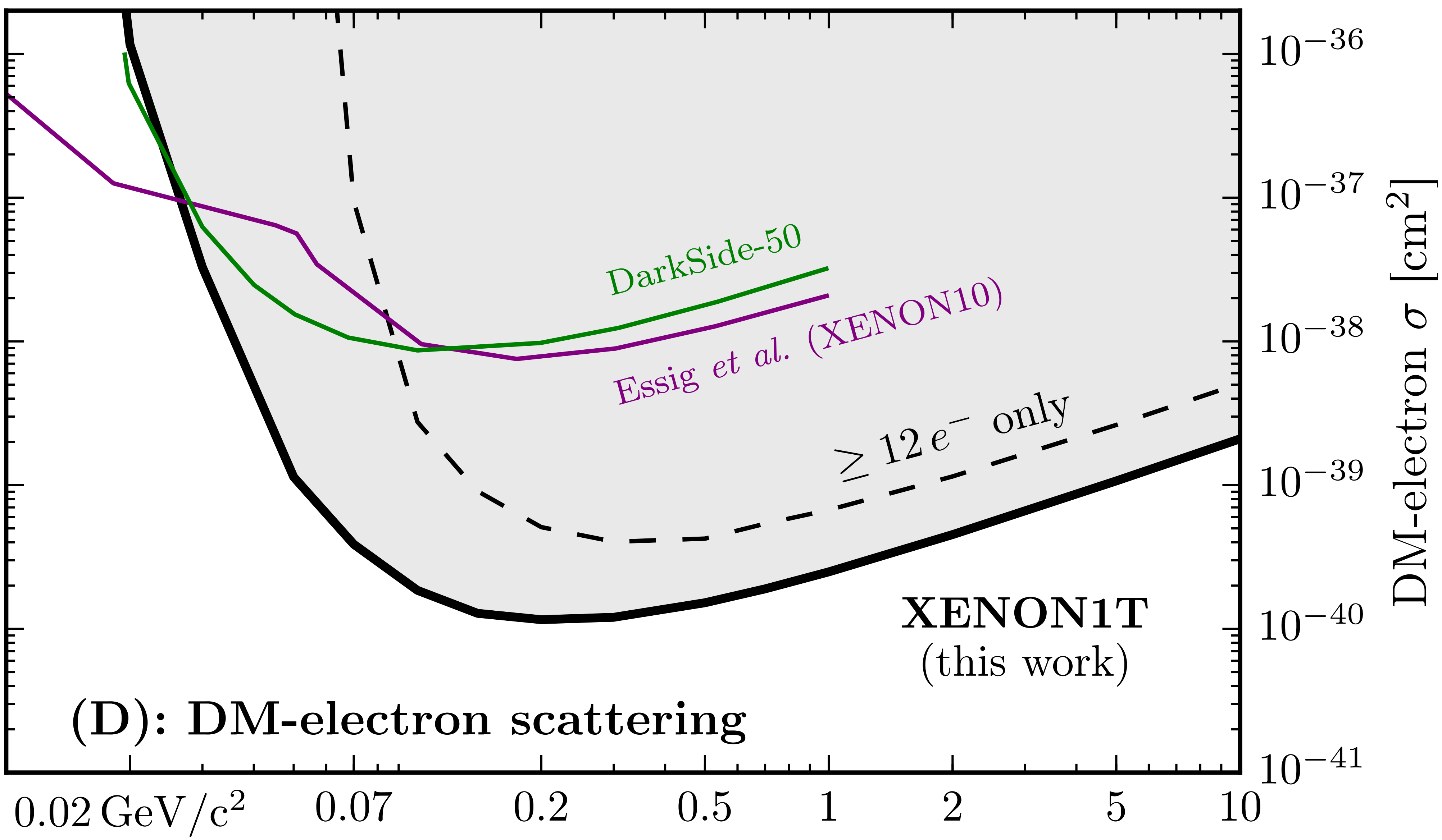
Atoms (Xe)

Lower mass sensitivity from kinematics

Essig et al, arXiv:1206.2644

Atoms (Xe)

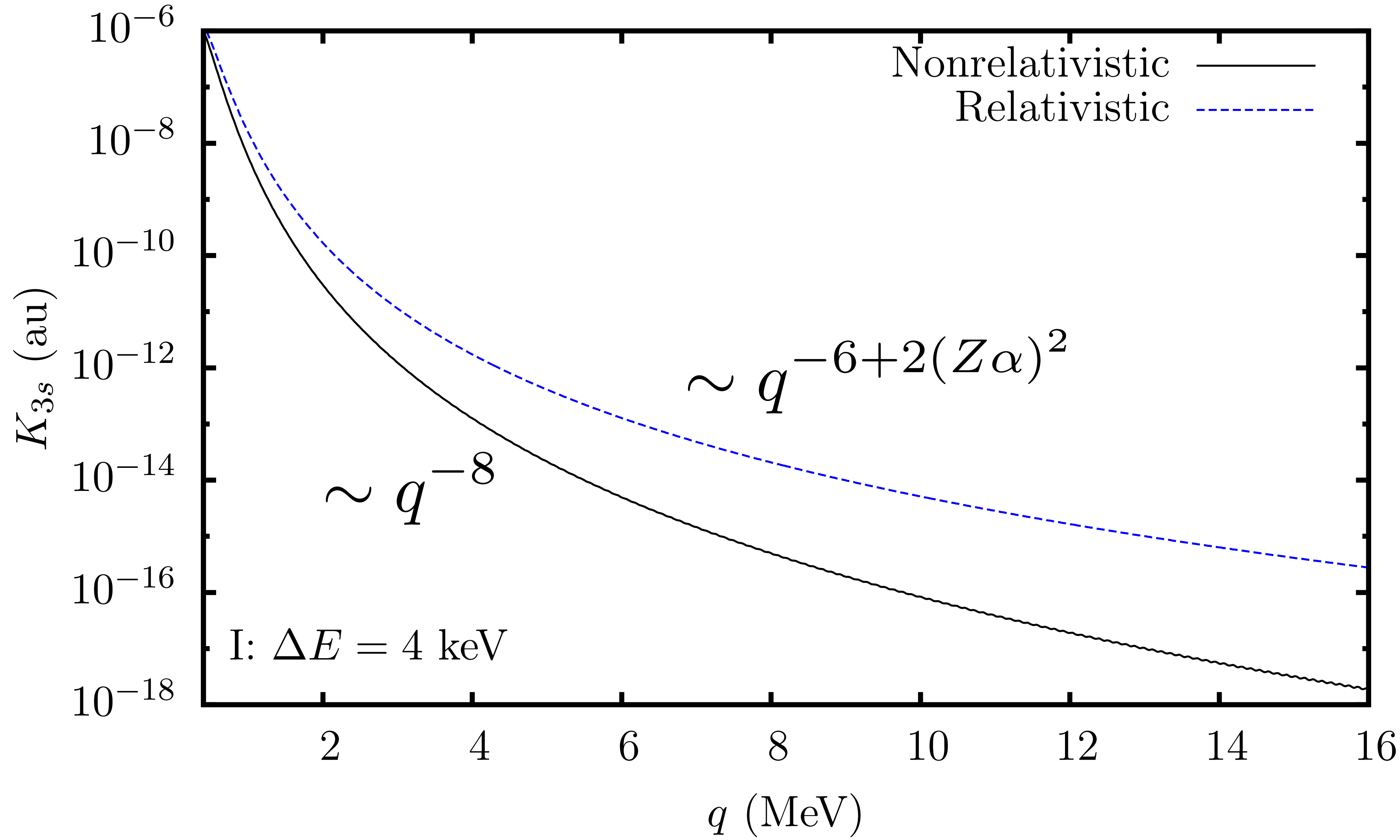
Lower mass sensitivity from kinematics



XENON1T, arXiv:1907.11485

Relativistic treatment

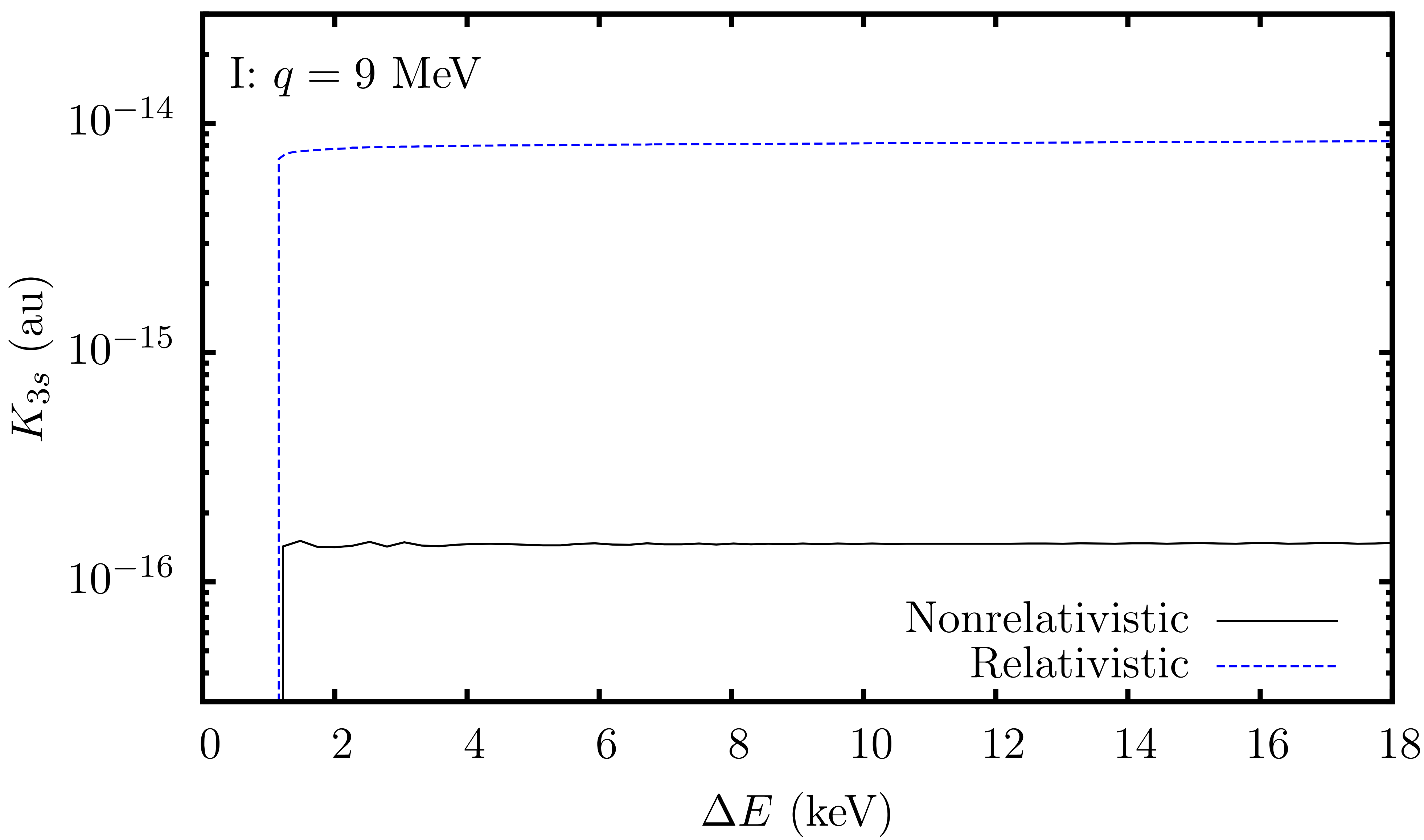
Form factor suppression less severe with relativistic calculation



Roberts et al,
arXiv:1509.09044 & arXiv:1604.04559

Relativistic treatment

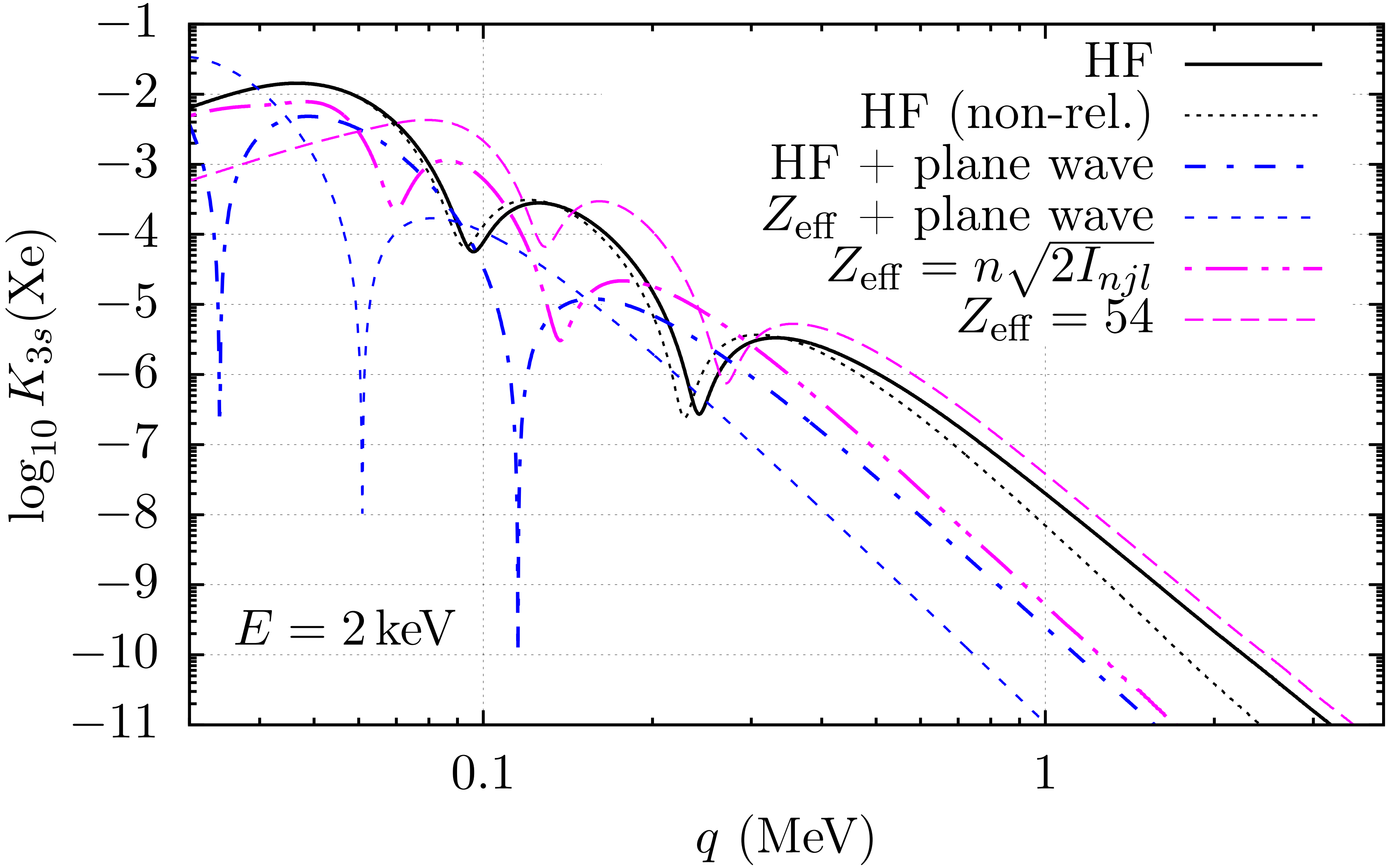
Form factor suppression less severe with relativistic calculation



Roberts et al,
arXiv:1509.09044 & arXiv:1604.04559

Relativistic treatment

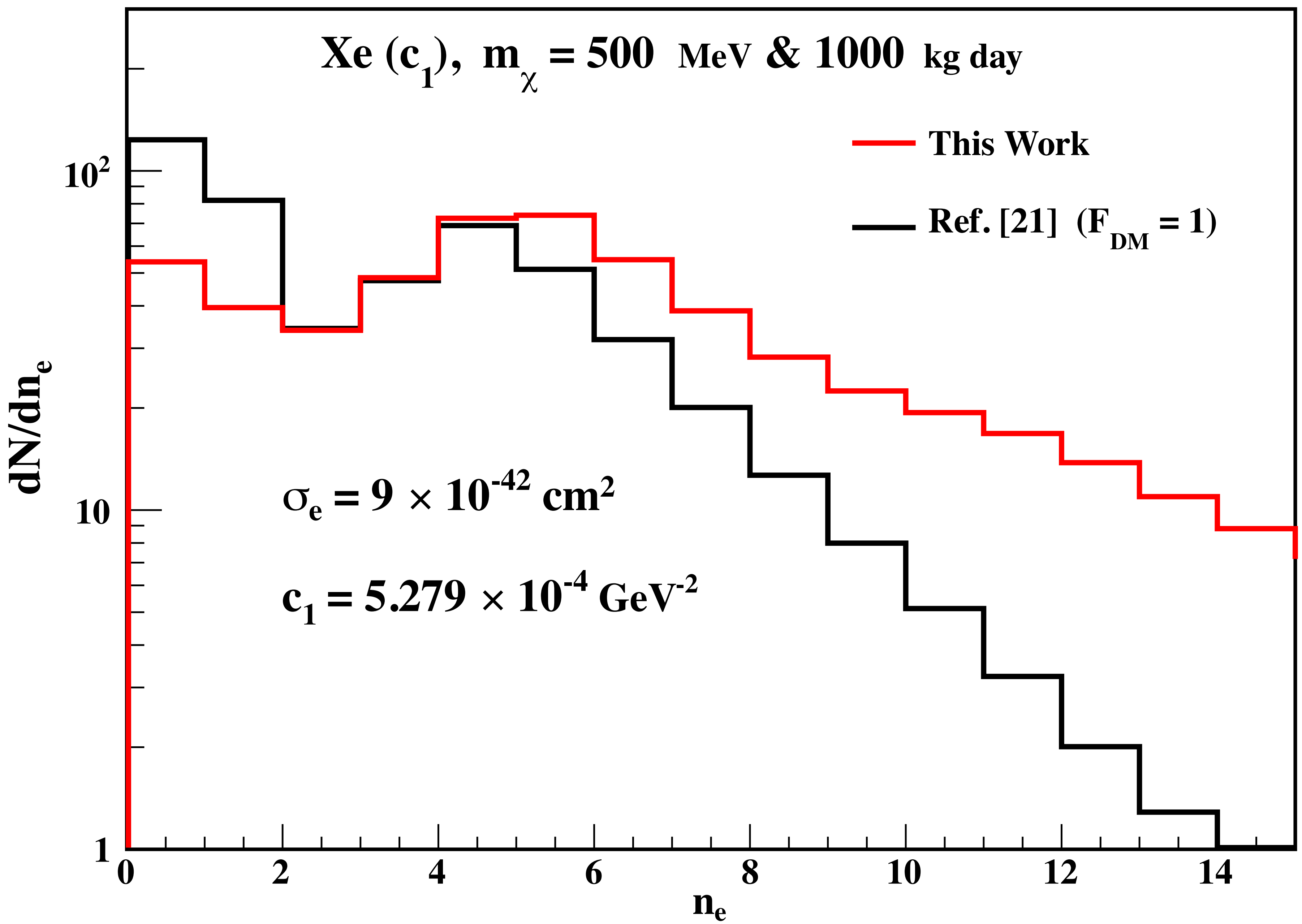
Different calculation techniques can lead to large variations



Roberts et al,
arXiv:1509.09044 & arXiv:1604.04559

Some inconsistency with Xe?

Pandey et al compares with Essig et al (Ref.[21])



Pandey et al arXiv:1812.11759

Including directionality: subtleties?

In general, both the electron wavefunctions and the DM velocity distribution will not be spherically symmetric. As noted in [9], the rate will then depend on the orientation of the target with respect to the galaxy. Here we ignore this interesting complication, and approximate the velocity distribution as being spherically symmetric. We can then use the d^3v integral to eliminate the δ-function in Eq. (A.12), giving

Essig et al arXiv:1509.01598

… but no directional electron scattering calculations in the literature (to my knowledge)

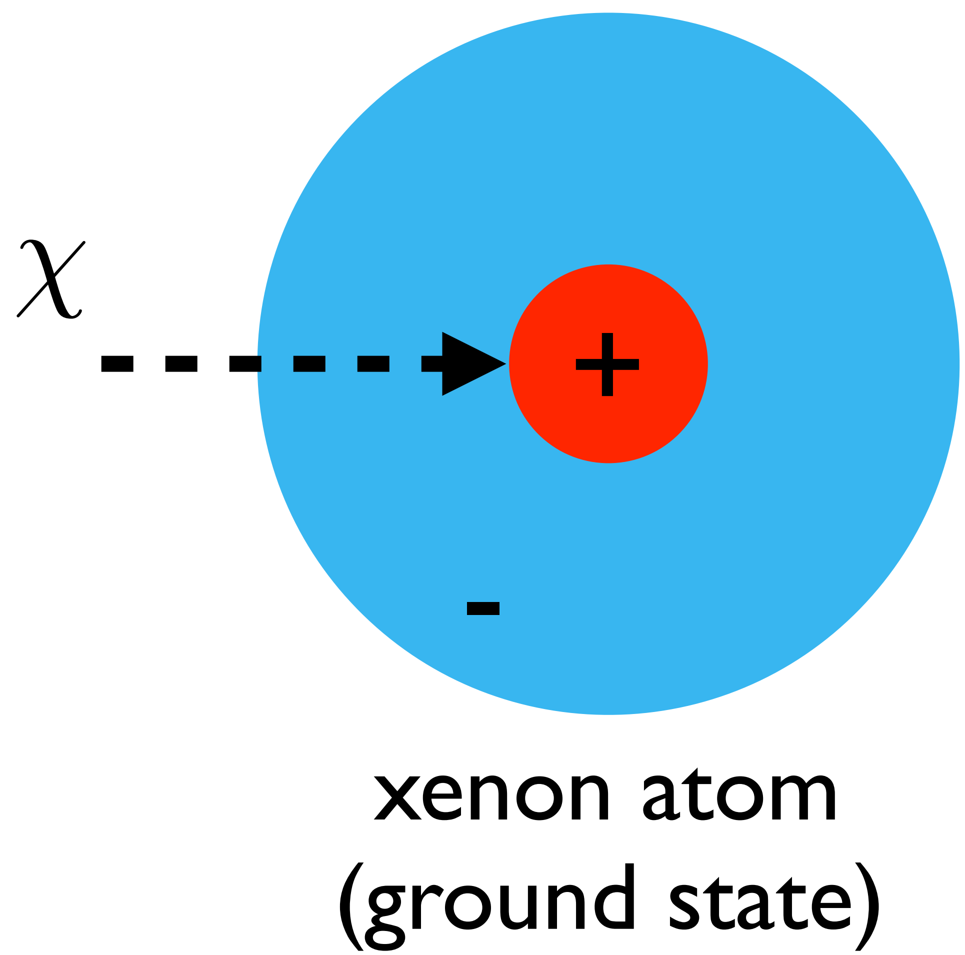
Migdal effect

Christopher McCabe

INFN-LNF, 17 September 2019

A more careful treatment of scattering

For sub-GeV dark matter:



A more careful treatment of scattering

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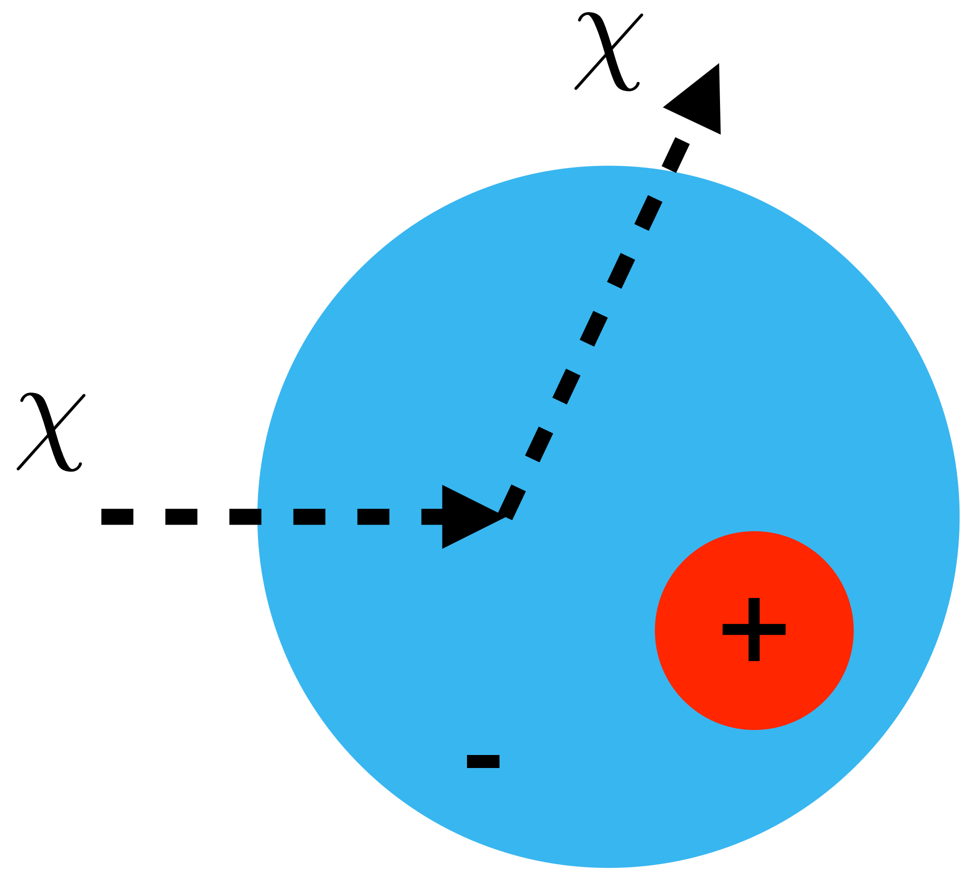


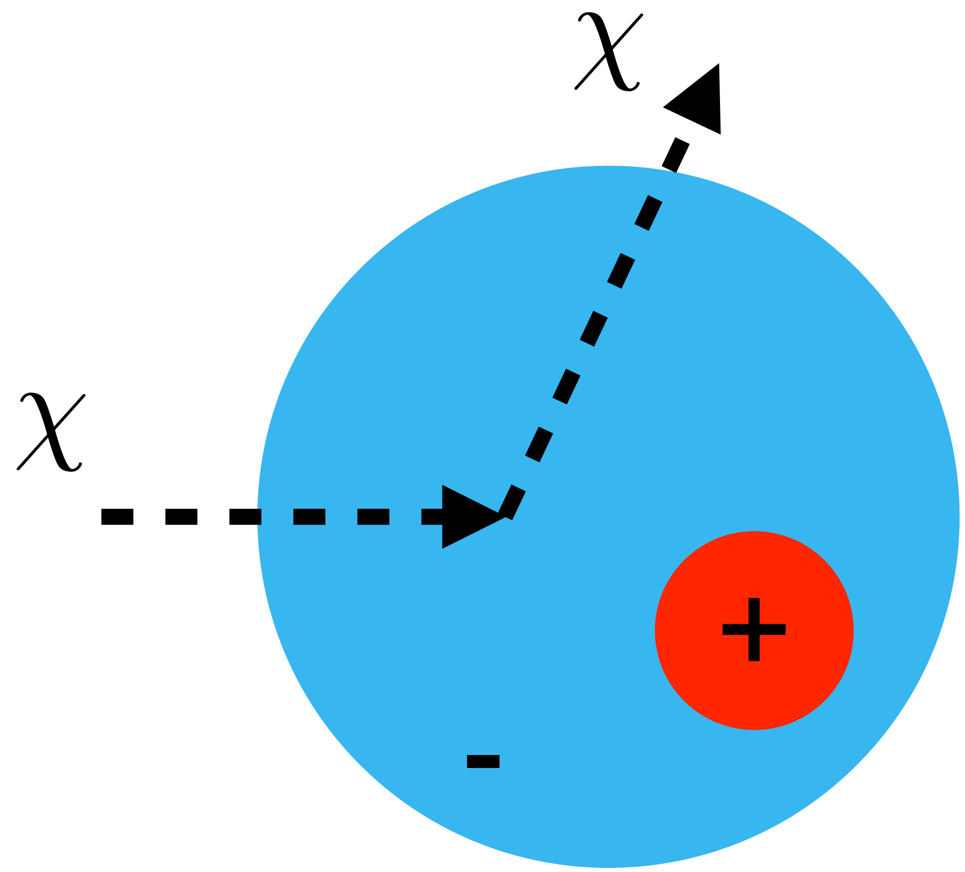
nucleus gets a nudge

$$E_{\mathrm{recoil}} \lesssim 0.1\ \mathrm{keV}$$

Below nuclear recoil detection threshold energy

A more careful treatment of scattering

For sub-GeV dark matter:



nucleus gets a nudge

$$E_{\rm recoil} \lesssim 0.1~{\rm keV}$$

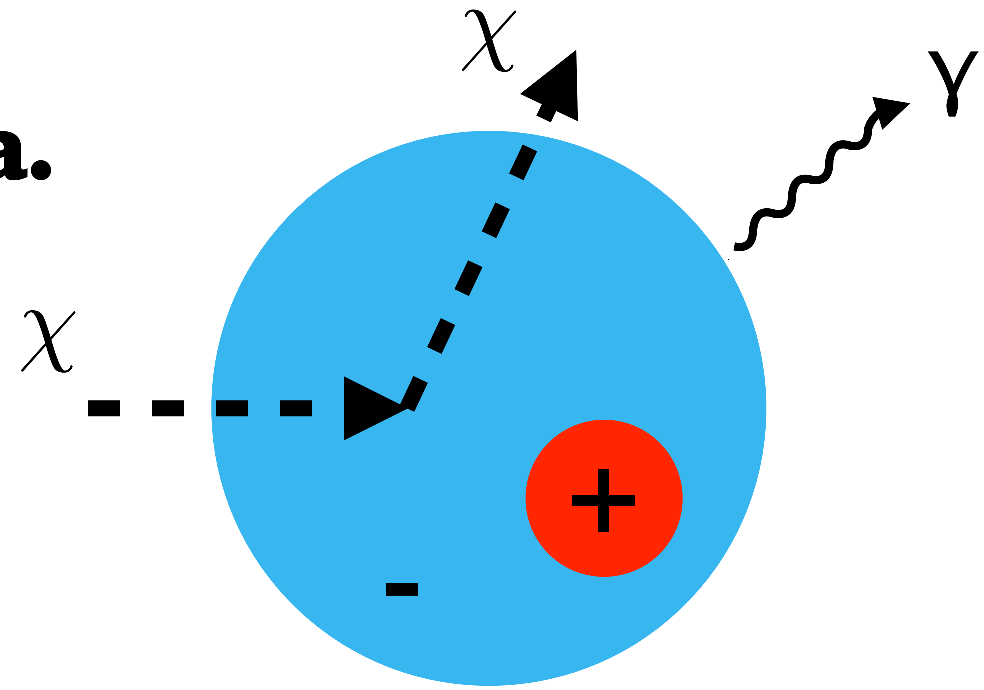
Below nuclear recoil detection threshold energy

...but photons and electrons can be emitted from the atom

Migdal 1939
Kouvaris & Pradler PRL 1607.01789

New (old) idea: emission from the atom

a.

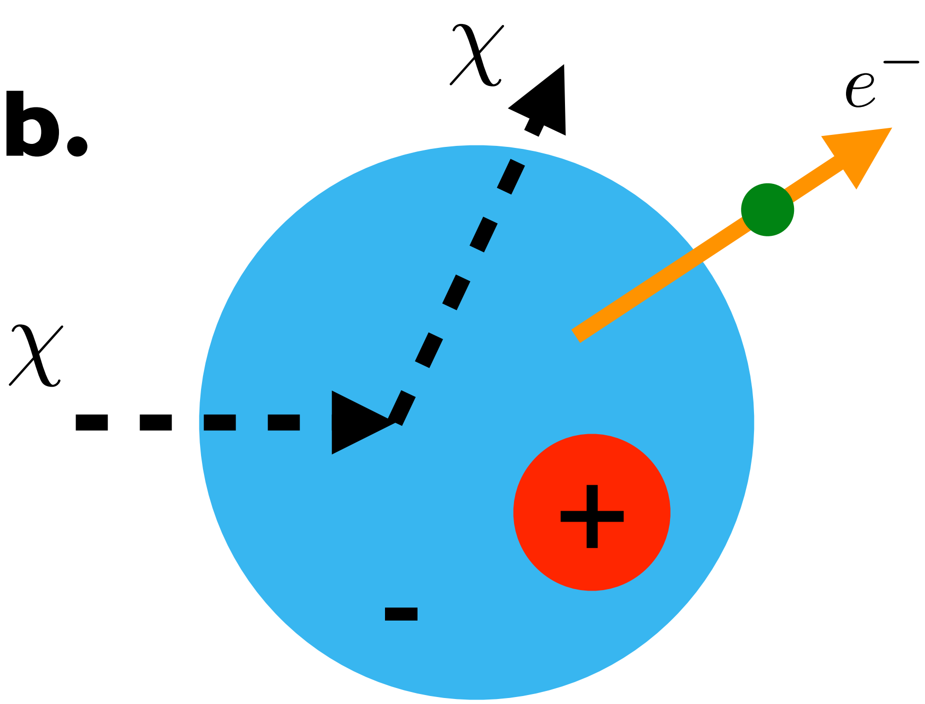


Polarised atom emits a photon

Scattering rate suppression factor ~10^{-8}

Kouvaris & Pradler PRL, arXiv:1607.01789
CM PRD, arXiv:1702.04730
Bell et al, arXiv:1905.00046

b.



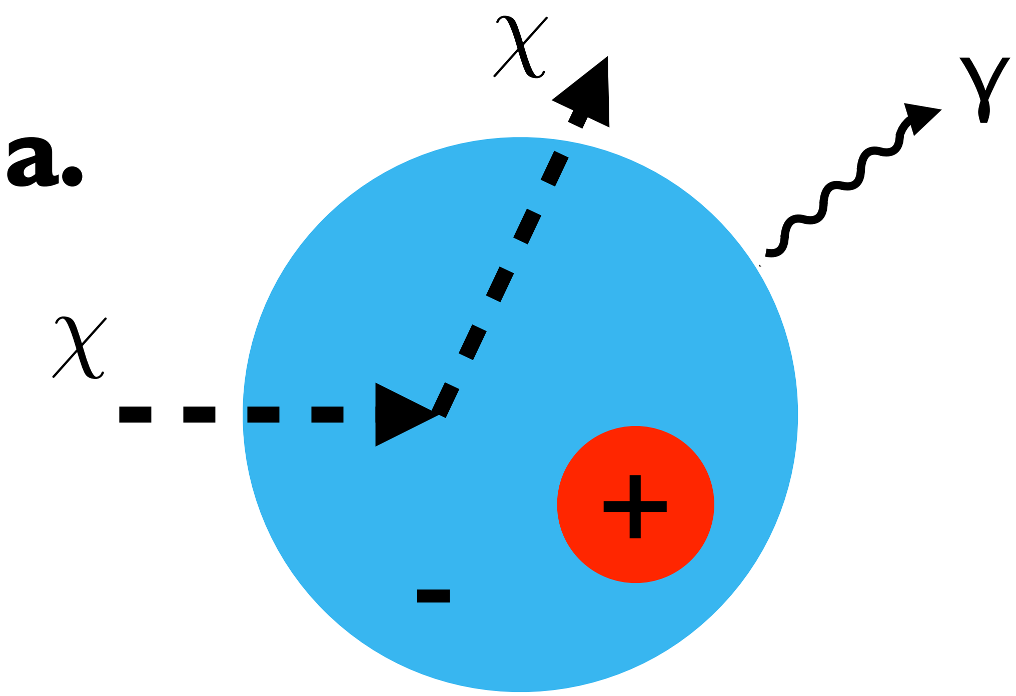
Atom emits an electron (Migdal effect)

Scattering rate suppression factor ~10^{-5}

Ibe, Nakano, Shoji, Suzuki, JHEP, arXiv:1707.07258
Dolan, Kahlhoefer, CM, PRL, arXiv:1711.09906
Baxter et al, arXiv:1908.00012
Essig et al, arXiv:1908.10881

a. Polarised atom emits a photon

Kouvaris & Pradler: 1607.01789, PRL



Positive charge displaced:
a dipole is formed

From the kinematics, easy to work out energies:

Maximum photon energy:

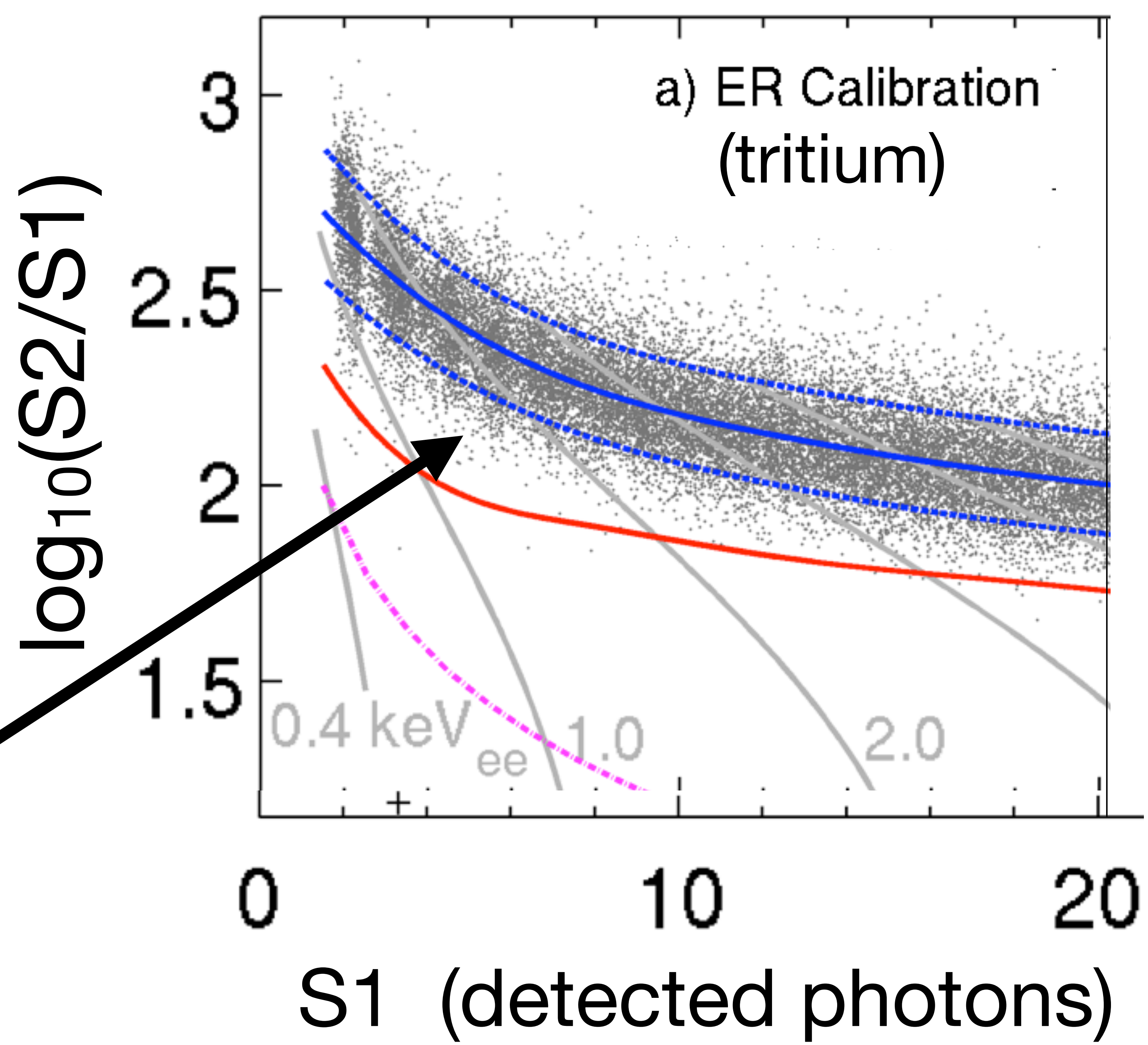
$$\omega^{\max} \approx 3\ \mathrm{keV} \cdot (m_{\mathrm{DM}}/1\ \mathrm{GeV})$$

Maximum nuclear recoil energy: $E_{\mathrm{R}}^{\max} \approx 0.1\ \mathrm{keV}$

$$\times\,(131/A)\,(m_{\mathrm{DM}}/1\ \mathrm{GeV})^2$$

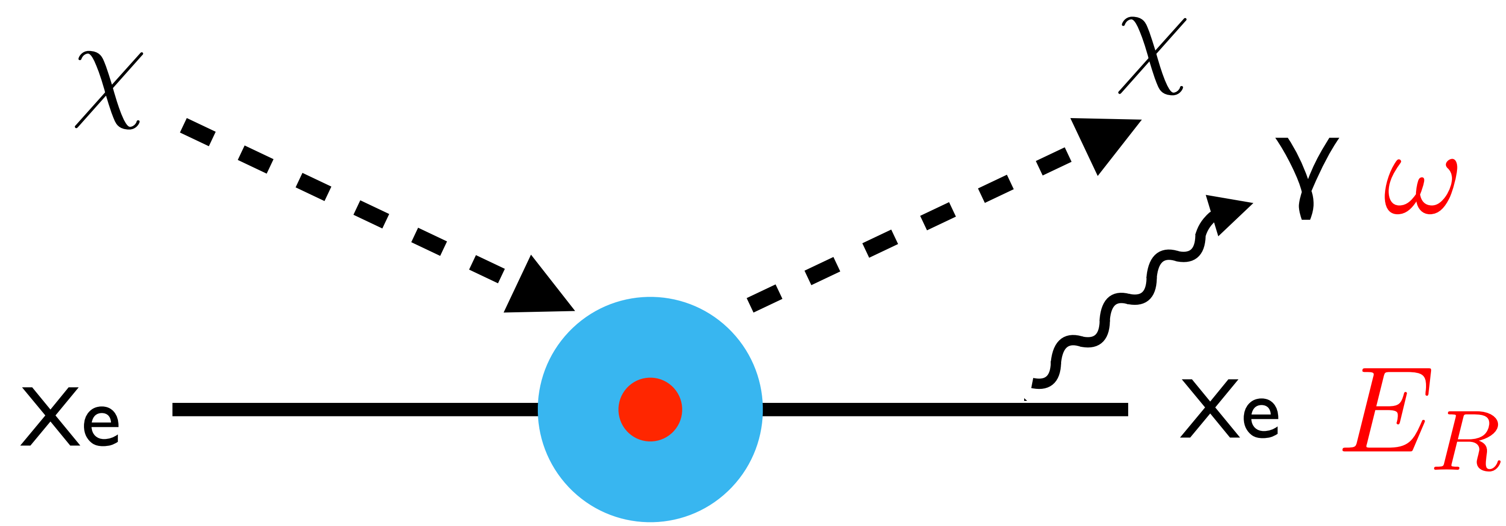
keV photons in LUX

$$\omega^{\max} \approx 3\,\mathrm{keV}\cdot(m_{\mathrm{DM}}/1\,\mathrm{GeV})$$



~keV photons are easily detected

What's the catch?



$$\frac{d\sigma}{dE_R d\omega} = \frac{4Z^2\alpha}{3\pi}\frac{1}{\omega}\frac{E_R}{m_N} \times \boxed{\frac{d\sigma}{dE_R}\Theta(\omega - \omega_{\rm max})}$$

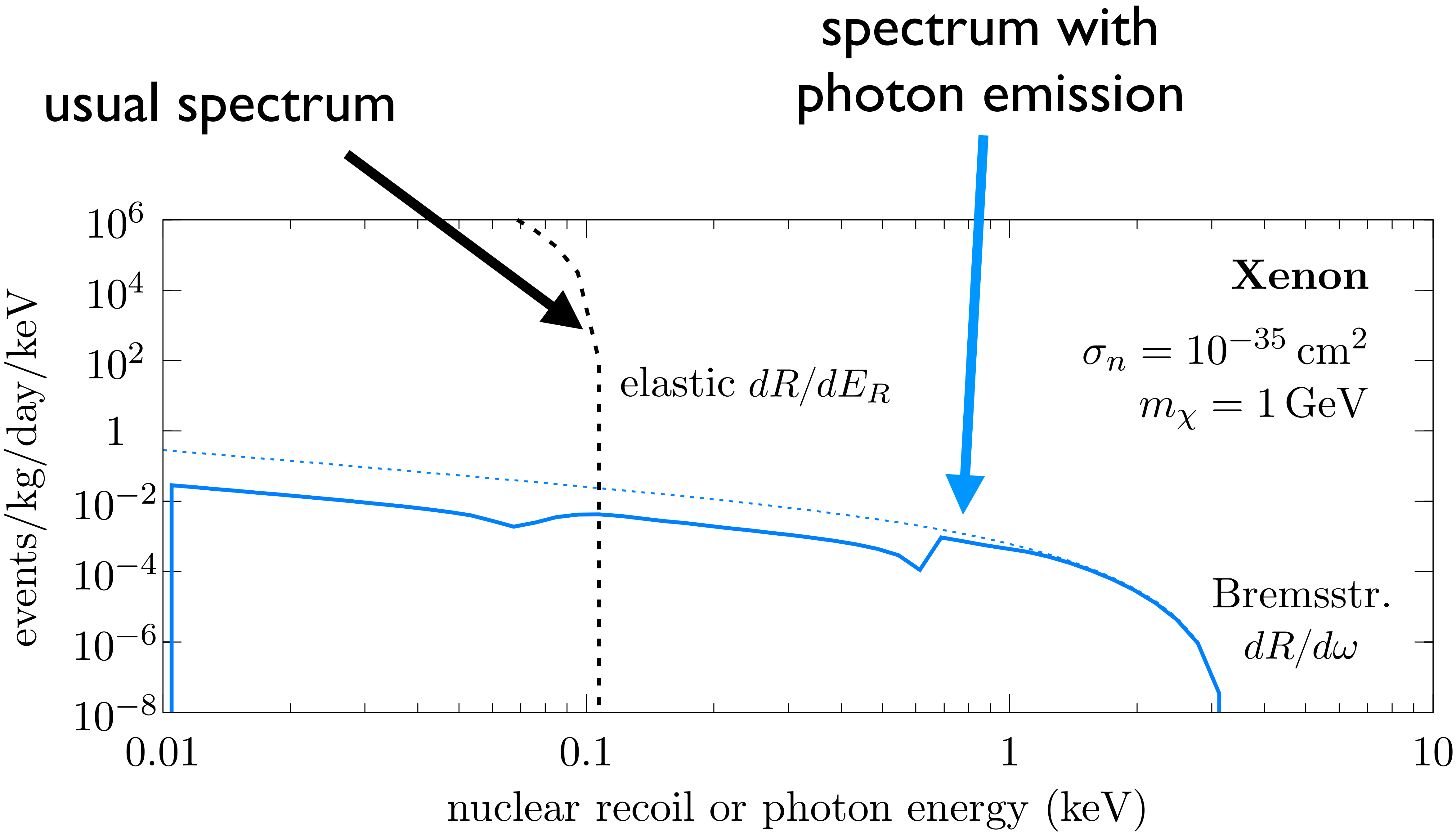
Usual 2->2 cross section

Price to pay

$$\simeq \frac{7\times 10^{-8}}{\omega}\left(\frac{E_R}{1\,\mathrm{keV}}\right)\times\frac{d\sigma}{dE_R} \quad (\mathrm{Xenon})$$

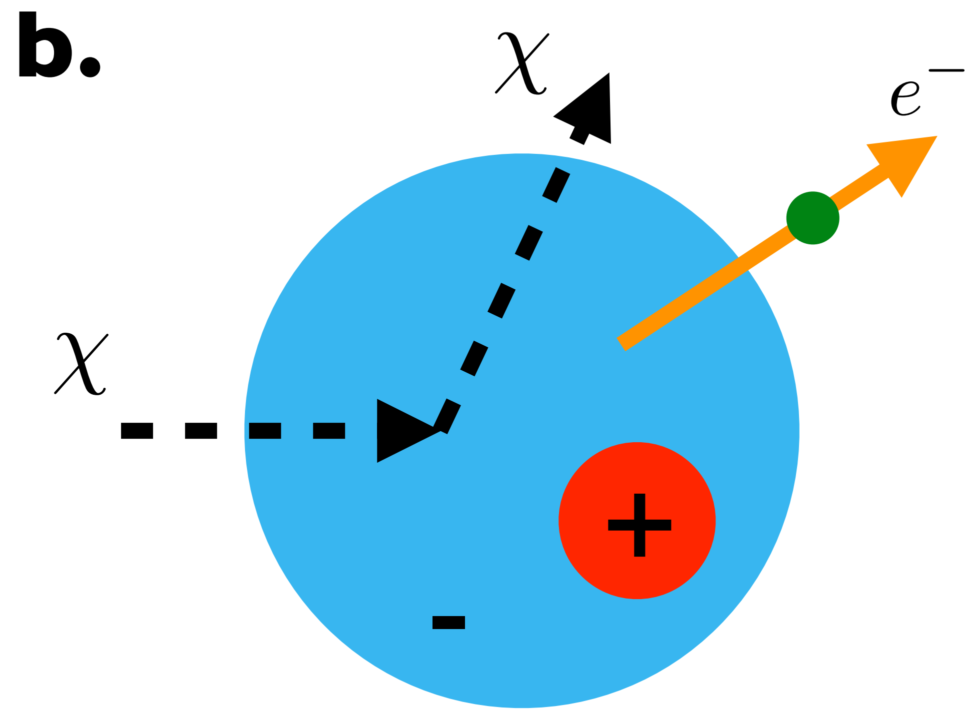
Approximate result:
full calculation involves
atomic scattering factors

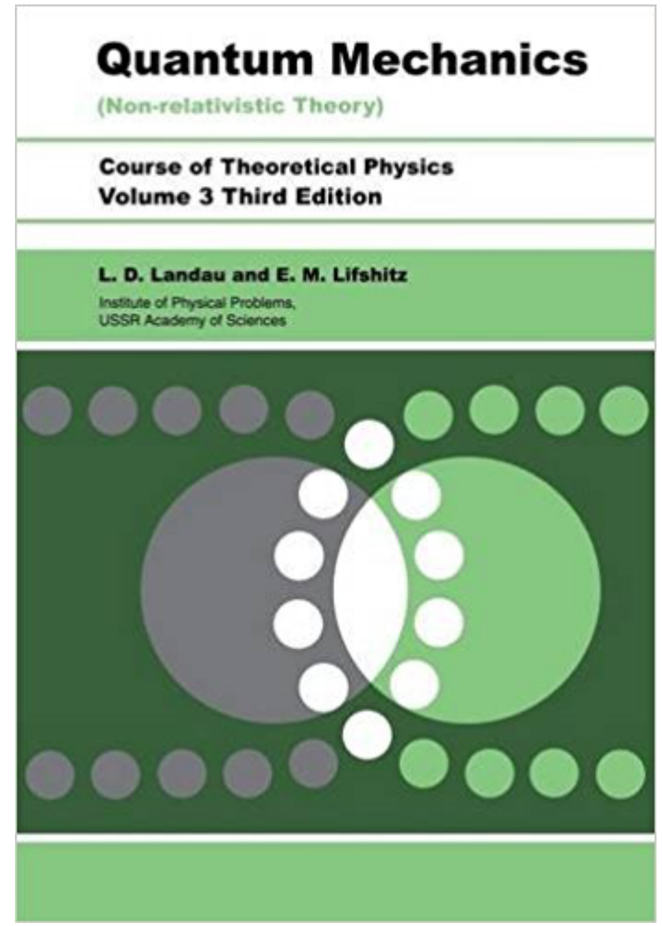
Energy spectrum



Photon spectrum extends to higher energy
but *is suppressed compared to the usual spectrum*

b. Atom emits an electron (Migdal effect)





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 effect: an old idea

With neutrons:

Ionisation induced by neutrons

G Baur†, F Rösel‡ and D Trautmann
Institut für Physik der Universität Basel, CH-4056 Basel, Switzerland

Received 17 January 1983, in final form 18 May 1983

Abstract. The ionisation of an atom by neutron bombardment is studied in a quantum-mechanical formulation. The total K-shell ionisation probability is calculated for hydrogen-like electronic wavefunctions. The semiclassical results of Migdal can be derived under certain assumptions; time delay effects are clearly exhibited and the experimental possibilities are briefly discussed.

Multiple ionisation effects due to recoil in atomic collisions

L Végh
Institute of Nuclear Research of the Hungarian Academy of Science, H-4001 Debrecen, PO Box 51, Hungary

Received 16 May 1983

Abstract. A description of atomic recoil excitation caused by the projectile nucleus is given using the two-potential formula. The relation of the direct and recoil ionisation amplitudes are discussed demonstrating that their interference in the dipole approximation may only be approximately destructive. The recoil mechanism can produce strong multiple ionisation and the strength of the satellite lines follow the binomial distribution strictly. The recoil ionisation in neutron-induced reactions, the lifetime of the inner-shell vacancy in recoiled ions and the recoil effects in the electron conversion coefficients are discussed.

With dark matter:

On electromagnetic contributions in WIMP quests

R. Bernabei, P. Belli, F. Montecchia, F. Nozzoli
Dip. di Fisica, Università di Roma "Tor Vergata" and INFN, sez. Roma "Tor Vergata", I-00133 Rome, Italy

F. Cappella, A. Incicchitti, D. Prosperi
Dip. di Fisica, Università di Roma "La Sapienza" and INFN, sez. Roma, I-00185 Rome, Italy

R. Cerulli
Laboratori Nazionali del Gran Sasso, INFN, Assergi, Italy

C.J. Dai, H.L. He, H.H. Kuang, J.M. Ma, X.D. Sheng, Z.P. Ye[1]
IHEP, Chinese Academy, P.O. Box 918/3, Beijing 100039, China

Abstract

The effect pointed out by A. B. Migdal in the 40's (hereafter named Migdal effect) has so far been usually neglected in the direct searches for WIMP Dark Matter candidates. This effect consists in the ionization and the excitation of bound atomic electrons induced by the recoiling atomic nucleus. In the present paper the related theoretical arguments are developed and some consequences of the proper accounting for this effect are discussed by some examples of practical interest.

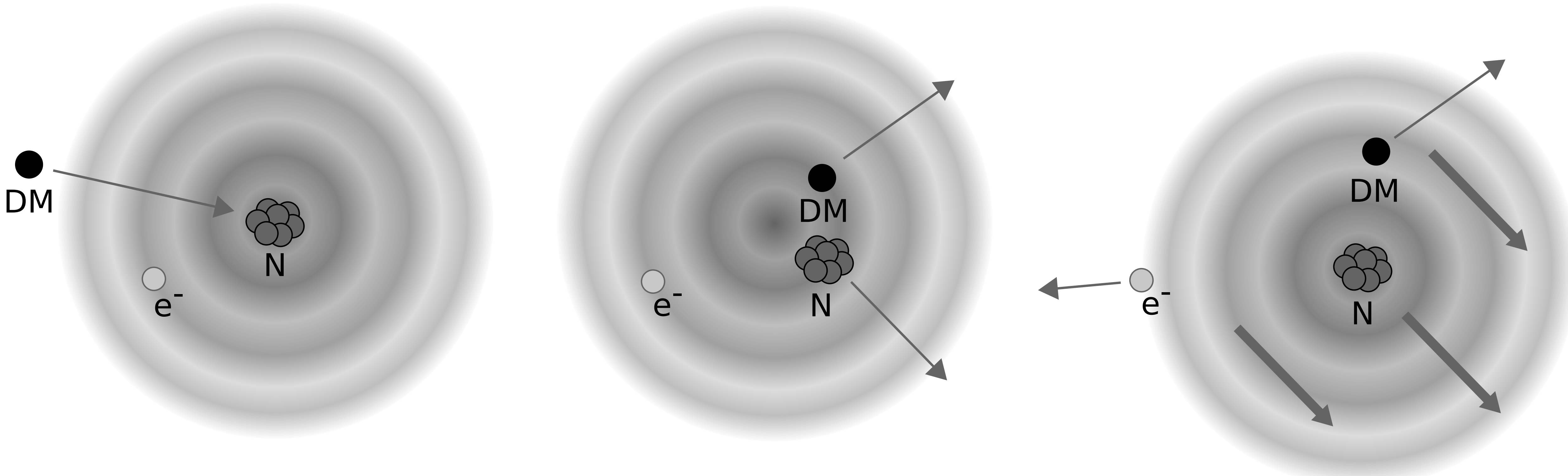
Role of nuclear charge change and nuclear recoil on shaking processes and their possible implication on physical processes

Prashant Sharma

Inter-University Accelerator Centre, Aruna Asaf Ali Marg, New Delhi 110067, India

Received 21 June 2017; received in revised form 23 August 2017; accepted 24 August 2017
Available online 1 September 2017

Migdal effect: updated treatment

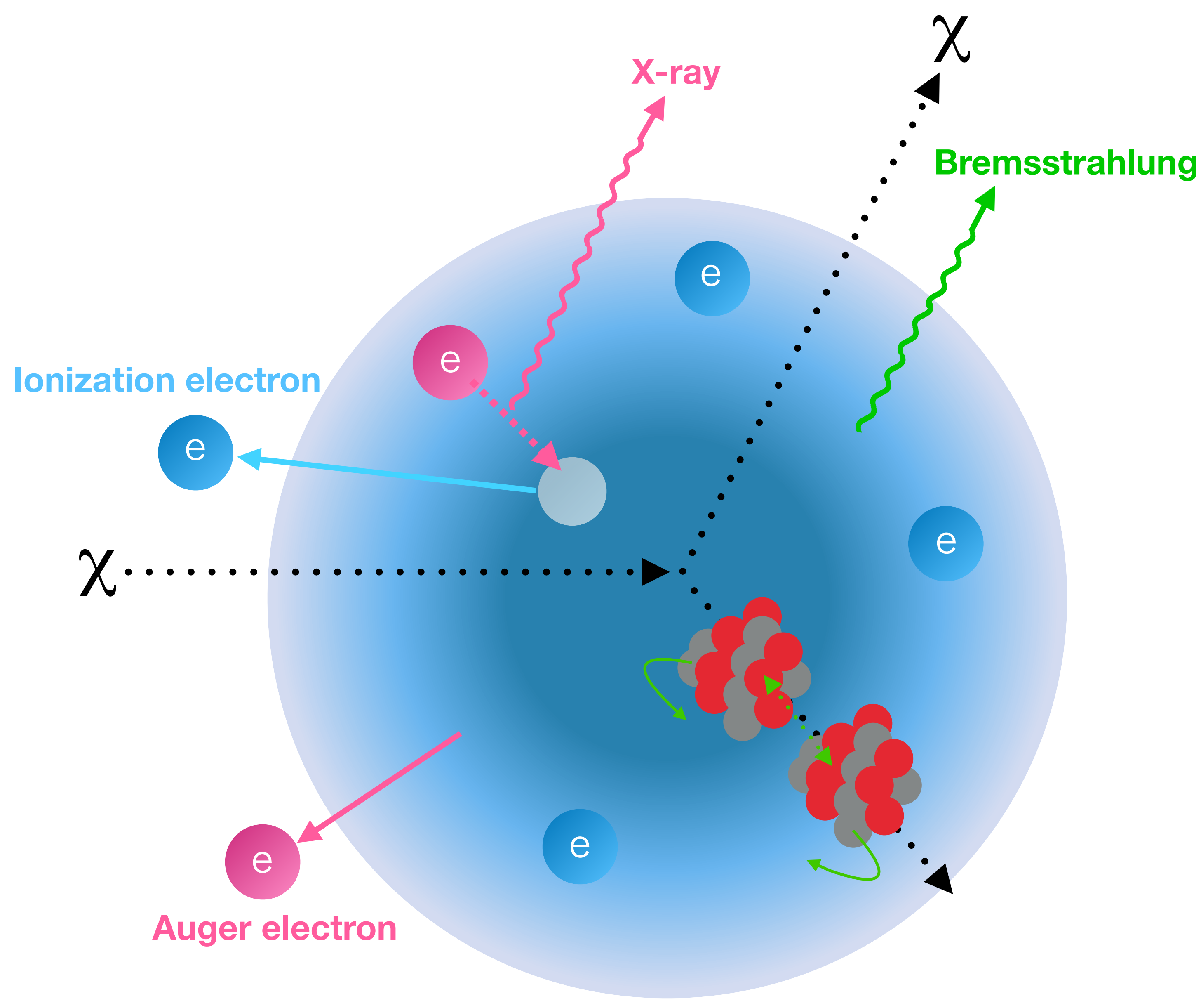


$$|\Phi_{ec}\rangle \qquad |\Phi'_{ec}\rangle = e^{-im_e \sum_i \mathbf{v}\cdot\hat{\mathbf{x}}_i}|\Phi_{ec}\rangle \qquad \mathcal{P} = |\langle\Phi^*_{ec}|\Phi'_{ec}\rangle|^2$$

"…it takes some time for the electrons to catch up, which causes ionisation of the atom."

Ibe, Nakano, Shoji, Suzuki, JHEP, arXiv:1707.07258
Dolan, Kahlhoefer, CM, PRL, arXiv:1711.09906
Baxter et al, arXiv:1908.00012
Essig et al, arXiv:1908.10881

Migdal effect: updated treatment



Ibe, Nakano, Shoji, Suzuki, JHEP, arXiv:1707.07258
Dolan, Kahlhoefer, CM, PRL, arXiv:1711.09906
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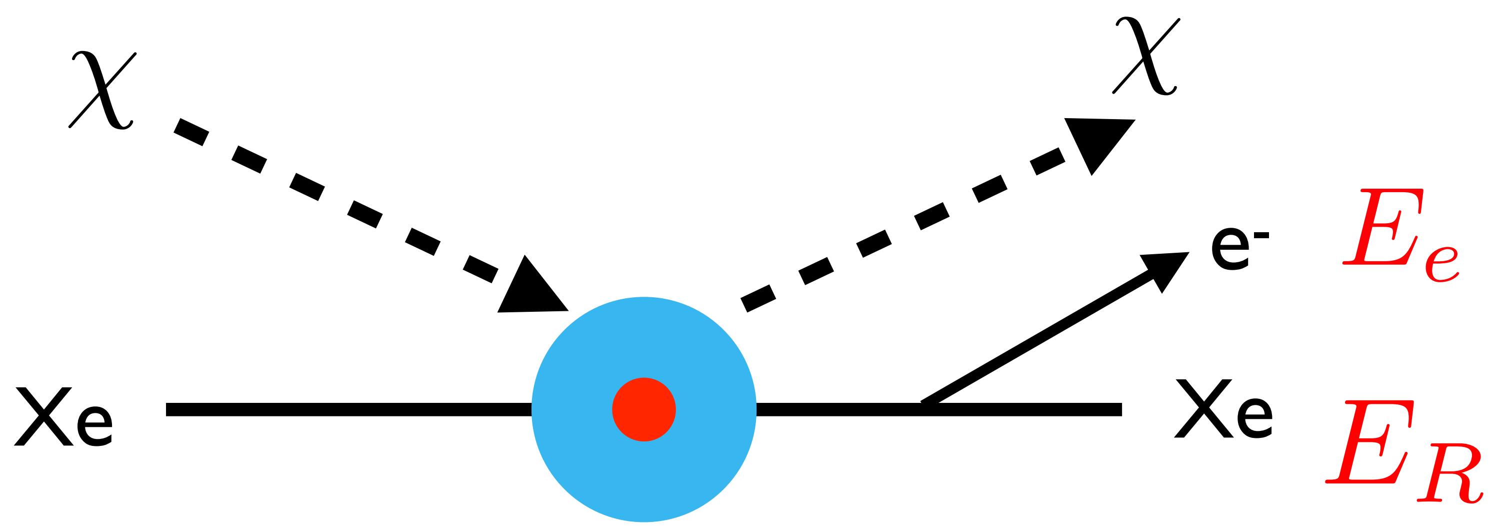
Migdal: cross section



$$\frac{d^2\sigma}{dE_R\, dE_e} = |Z_{\rm ion}(E_e, E_R)|^2 \boxed{\times \frac{d\sigma}{dE_R}}$$

Usual 2->2 cross section

'atomic form factor' ~ $\mathcal{P} = |\langle \Phi^*_{ec} | \Phi'_{ec} \rangle|^2 \sim 10^{-3}$

Calculated in Ibe, Nakano, Shoji, Suzuki, JHEP, 1707.07258

Form factor

Ionisation form factor for Migdal similar form to ionisation case:

$$Z_{FI}(\mathbf{q}_e) = \int \prod_i d^3\mathbf{x}_i \, \Phi^*_{E^F_{ec}}(\{\mathbf{x}\}) e^{-i\sum_i \mathbf{q}_e \cdot \mathbf{x}_i} \Phi_{E^I_{ec}}(\{\mathbf{x}\})$$

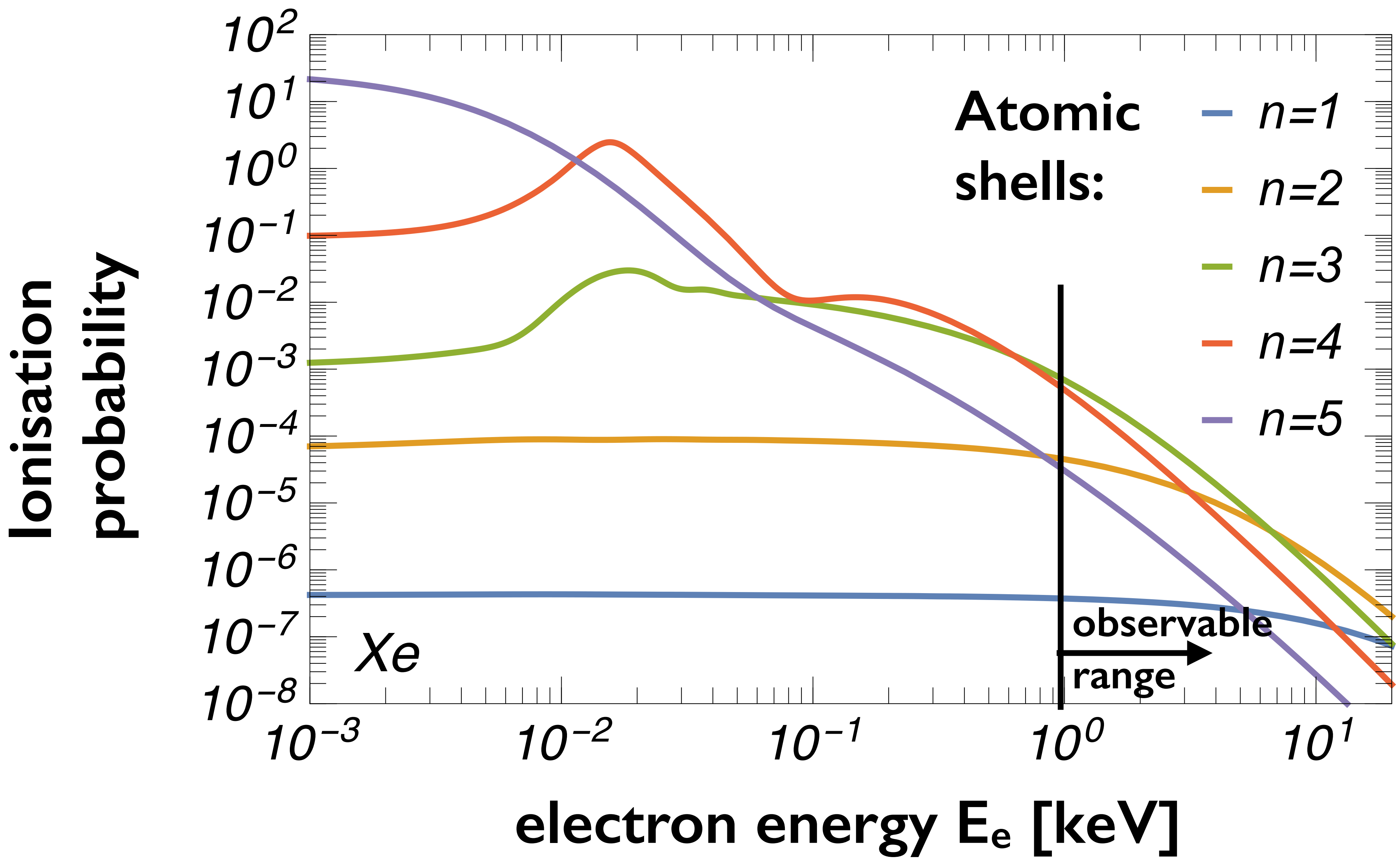
$$\mathbf{q}_e = m_e \mathbf{v}_F \ ,$$

Treatment for directional signals for ionisation and Migdal will be similar?

Ibe, Nakano, Shoji, Suzuki, JHEP, 1707.07258

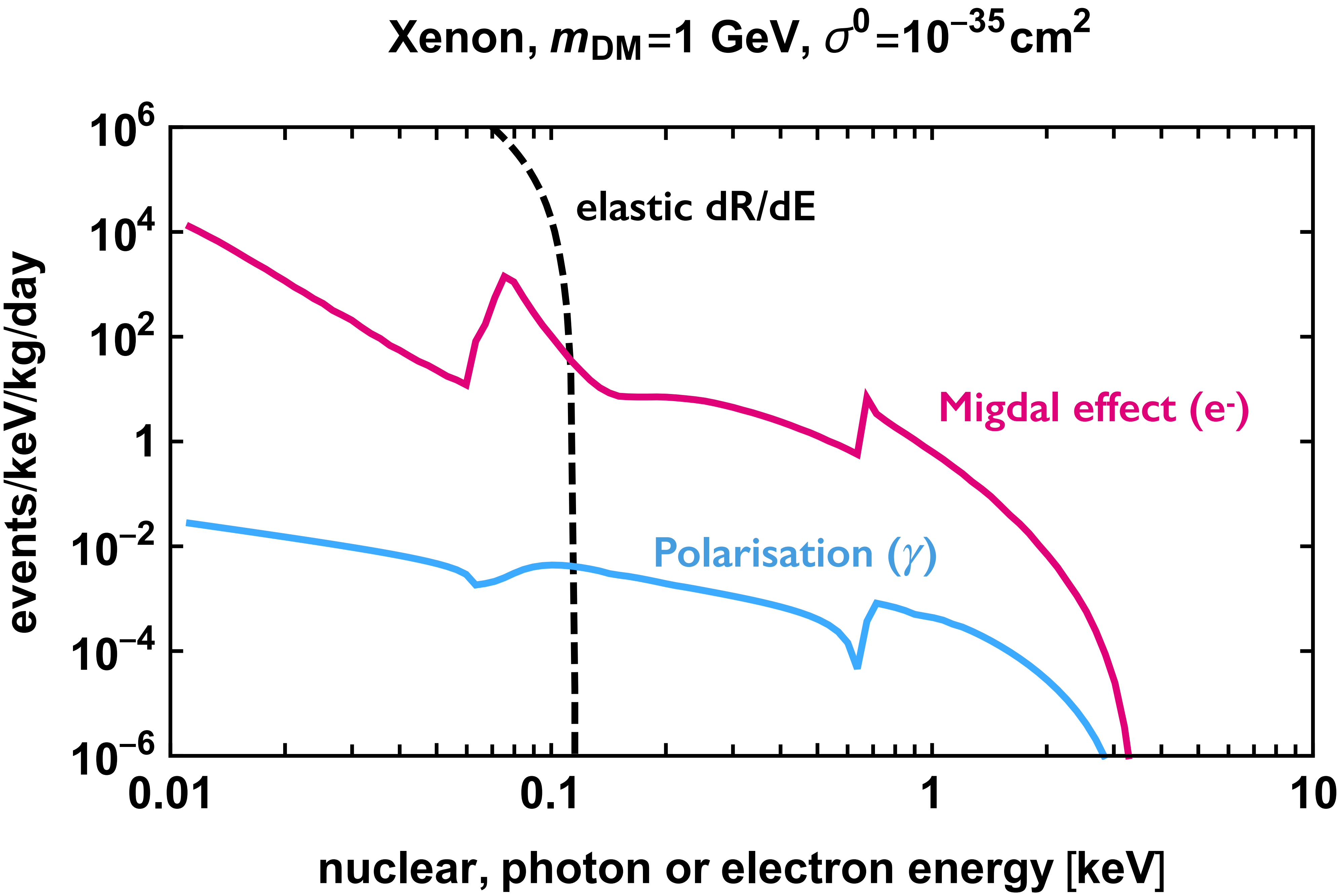
‘Atomic form factor’

Ibe, Nakano, Shoji, Suzuki, JHEP, arXiv:1707.07258



Ionisation probability E_e>0.5 keV: $\mathcal{P} = |\langle \Phi^*_{ec} | \Phi'_{ec} \rangle|^2 \sim 10^{-3}$

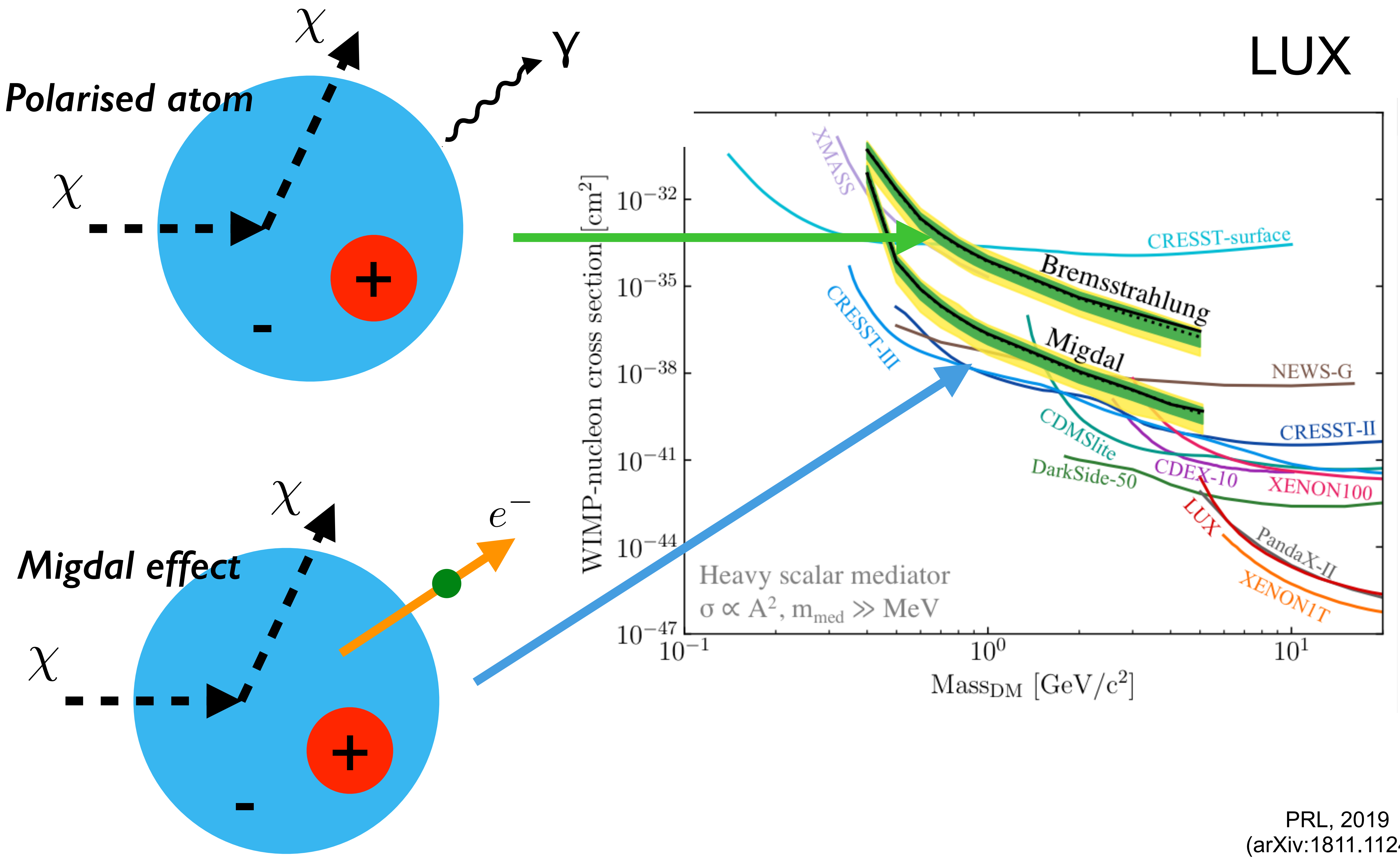
Scattering rates



Migdal (e-) spectrum still extends to higher energy
***but less suppressed** compared to polarisation (γ)*

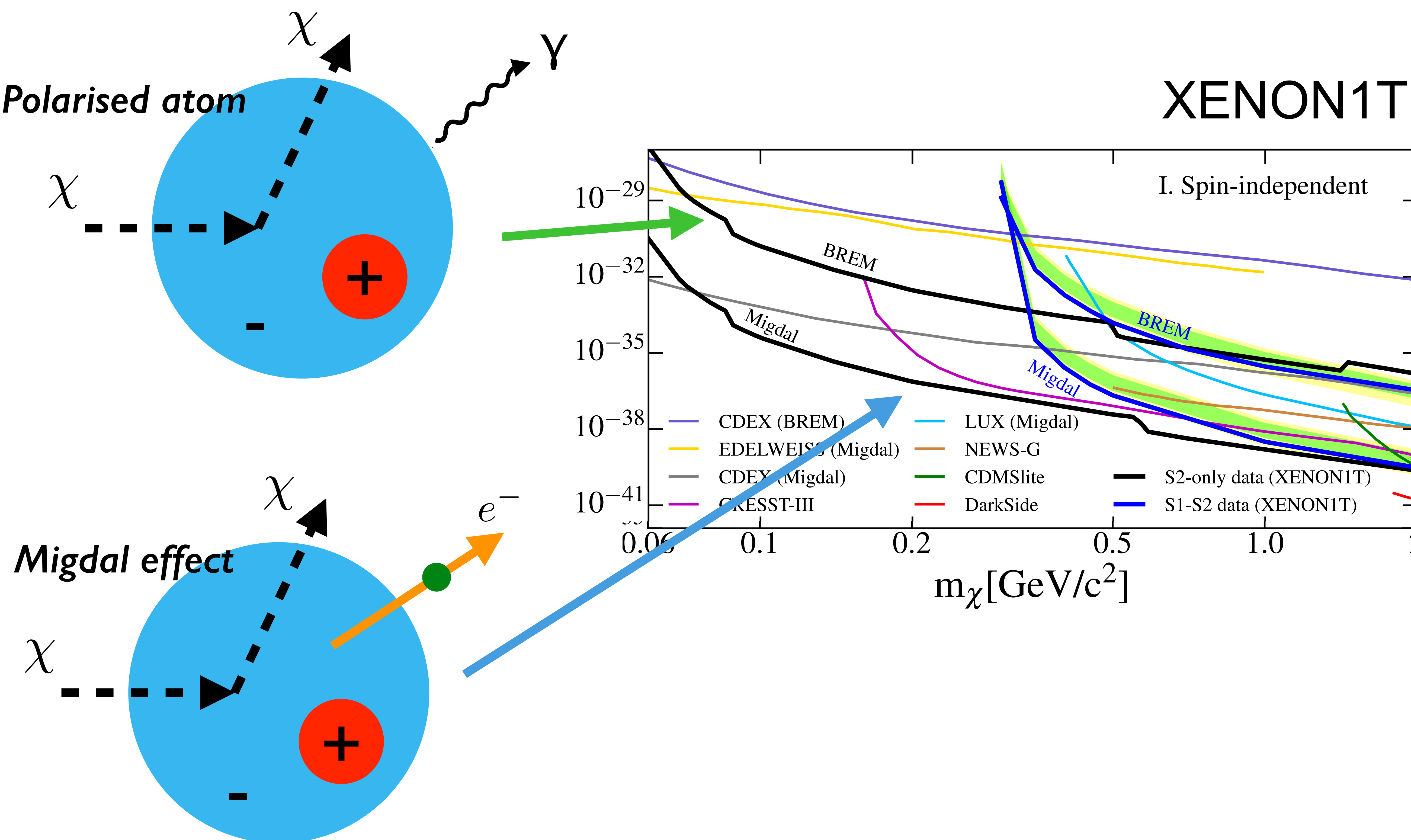
Bell et al, arXiv:1905.00046

Migdal effect: updated treatment



PRL, 2019
(arXiv:1811.11241)

Migdal effect: updated treatment



arXiv:1907.12771

Open question

Signal looks promising from a theory point of view

Challenges for experimental colleagues:

1. Can the Migdal effect be observed with neutron calibration data?