Dark Matter*

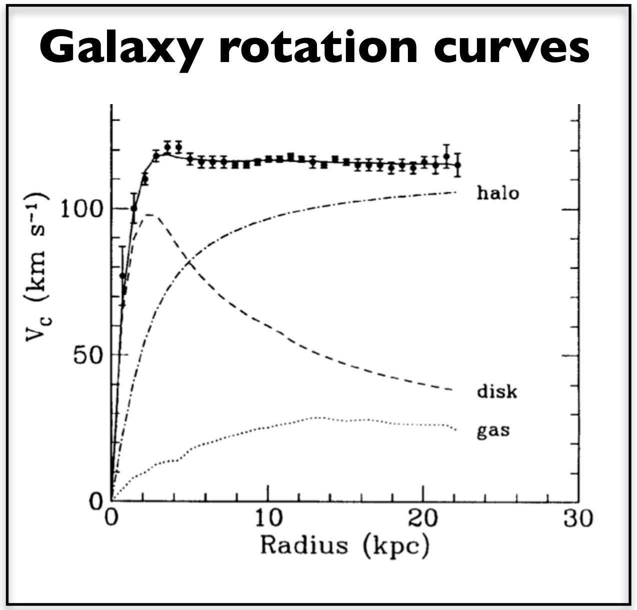
Christopher M^{c}Cabe

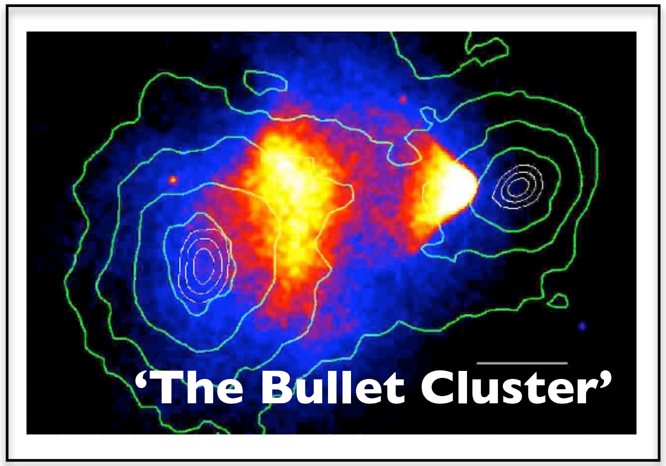
IOP HEPP & APP Annual Meeting
Imperial, 10th April 2019

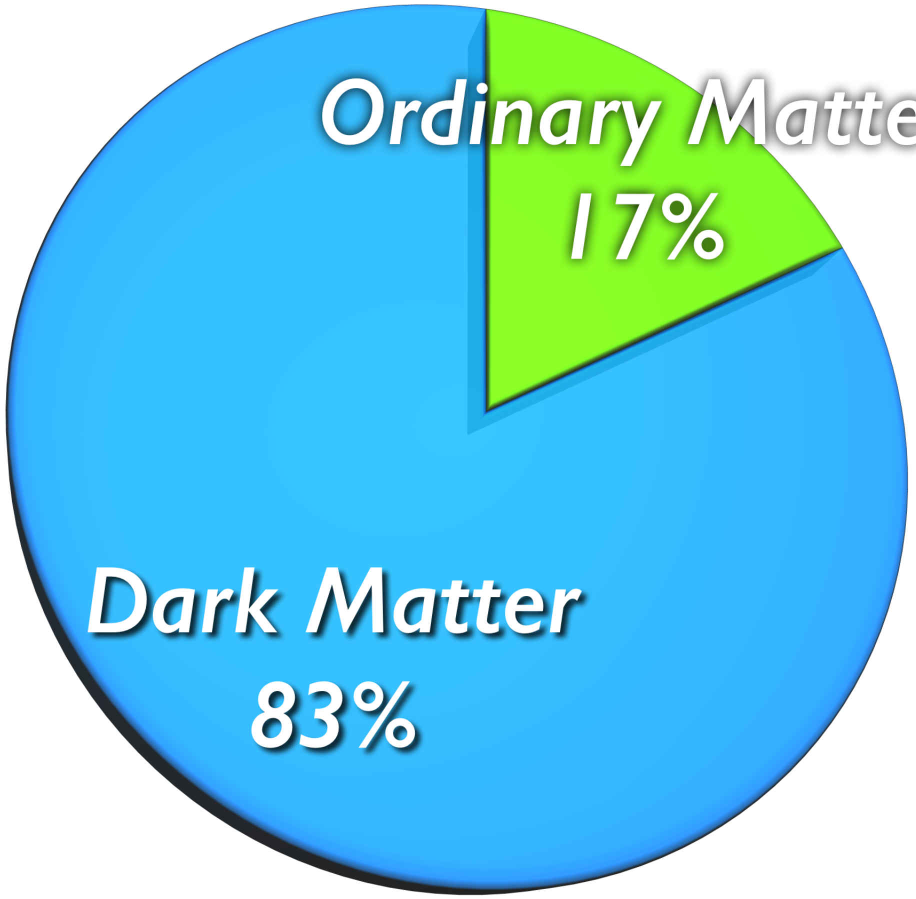
*my biased perspective

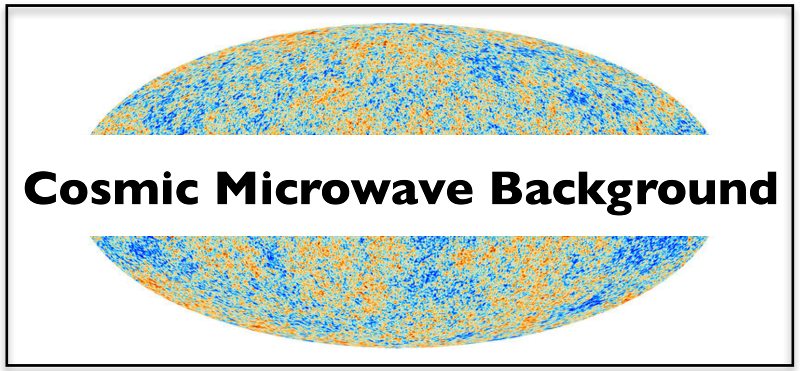
Evidence for dark matter

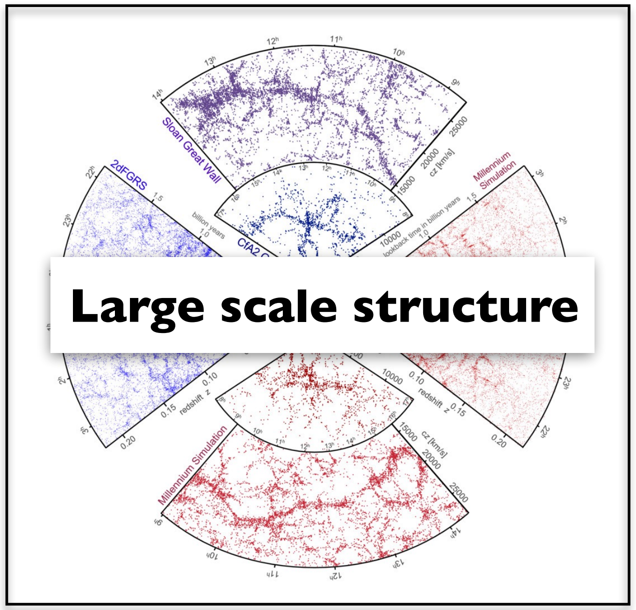
Matter in the Universe


Galaxy rotation curves


'The Bullet Cluster'

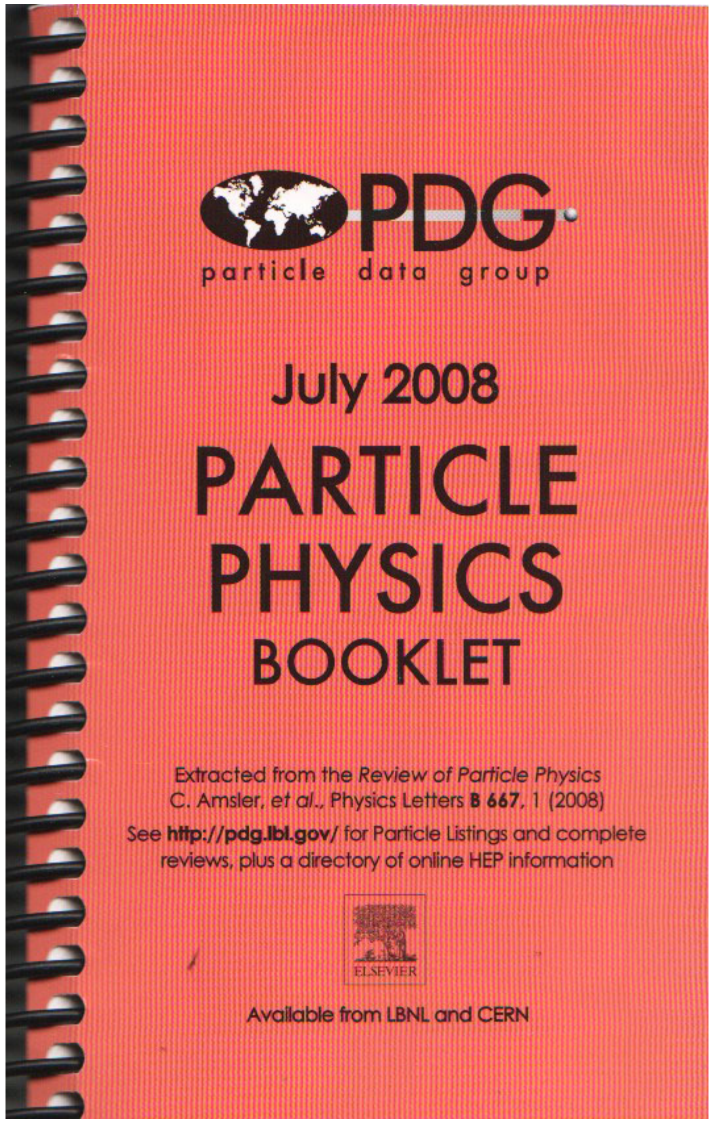



Cosmic Microwave Background


Large scale structure

Evidence from gravitational interactions over many distance scales

What would we like to know?



PDG
particle data group

July 2008

PARTICLE
PHYSICS
BOOKLET

Extracted from the *Review of Particle Physics*
C. Amsler, *et al.*, Physics Letters **B 667**, 1 (2008)
See **http://pdg.lbl.gov/** for Particle Listings and complete
reviews, plus a directory of online HEP information

ELSEVIER

Available from LBNL and CERN

Dark Matter Particle (X^0)

X^0 mass: $m = ?$

X^0 spin: $J = ?$

X^0 parity: $P = ?$

X^0 lifetime: $\tau = ?$

X^0 scattering cross-section on nucleons: $?$

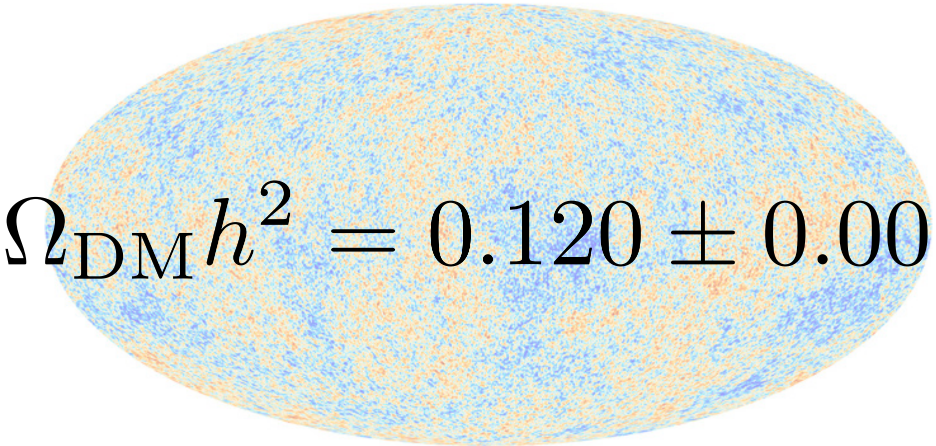
X^0 production cross-section in hadron colliders: $?$

X^0 self-annihilation cross-section: $?$

Why should DM interact with the SM?

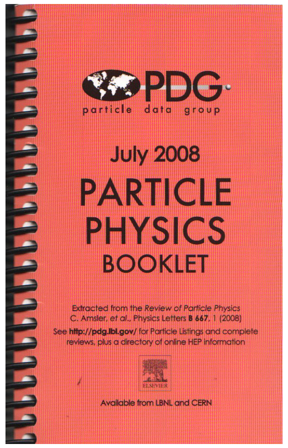
> *"Up to a point the stories of cosmology and particle physics can be told separately. In the end though, they will come together."*
>
> Steven Weinberg

Cosmology



$$\Omega_{\rm DM} h^2 = 0.120 \pm 0.001$$

Particle Physics



$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q + \cdots$$

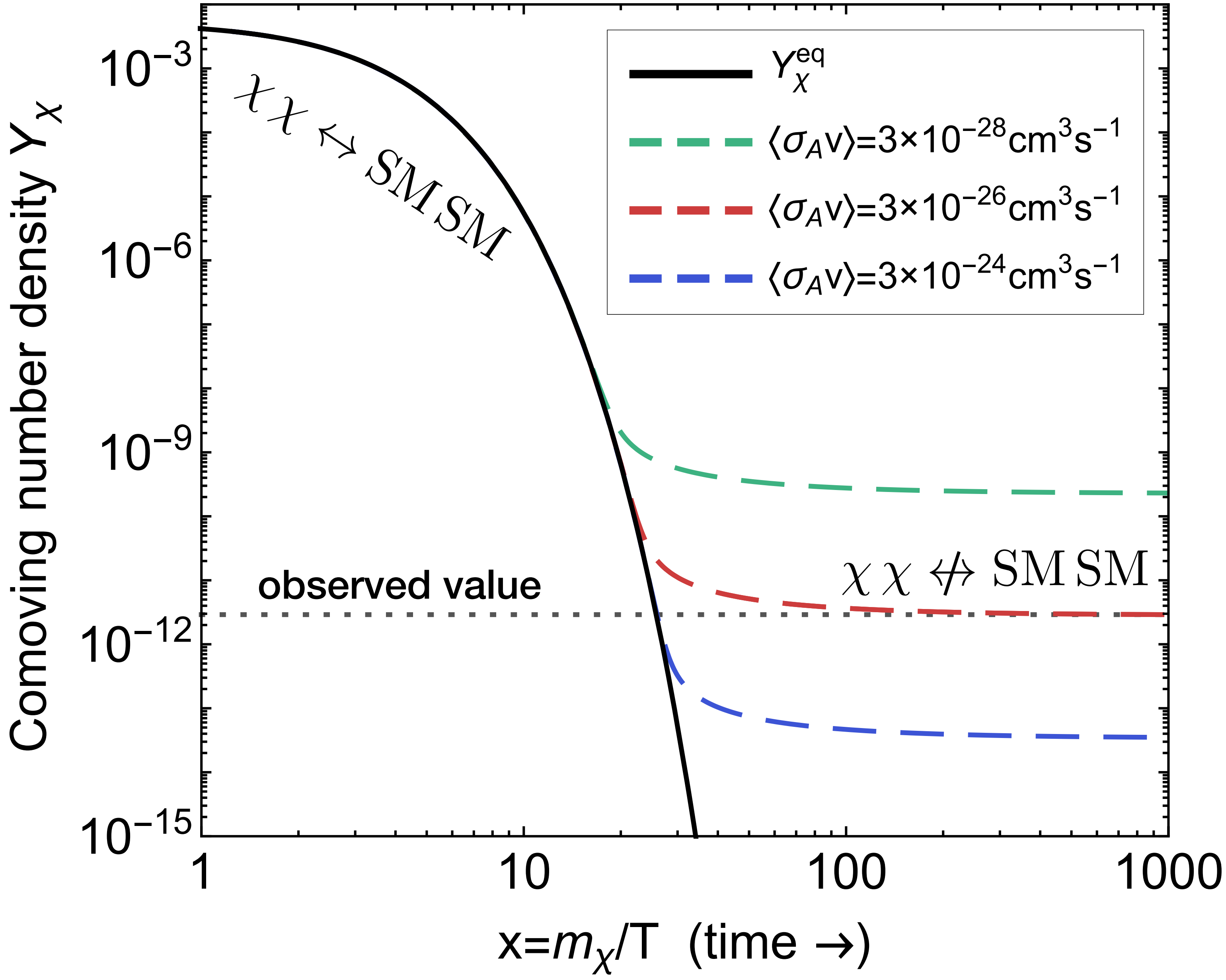
Suggests DM - Standard Model interactions are generic

&

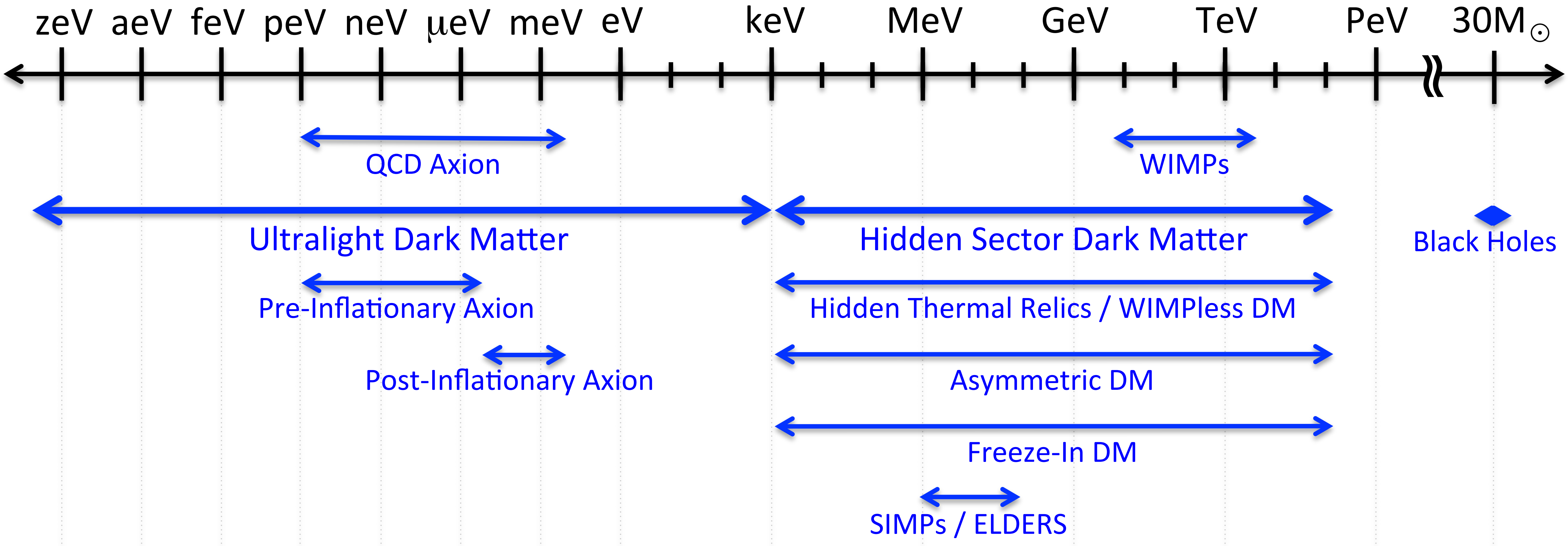
informs and limits the possible interactions

WIMPs: canonical example

Thermal freeze-out mechanism gives observed abundance



Theorists haven't stopped at WIMPs…

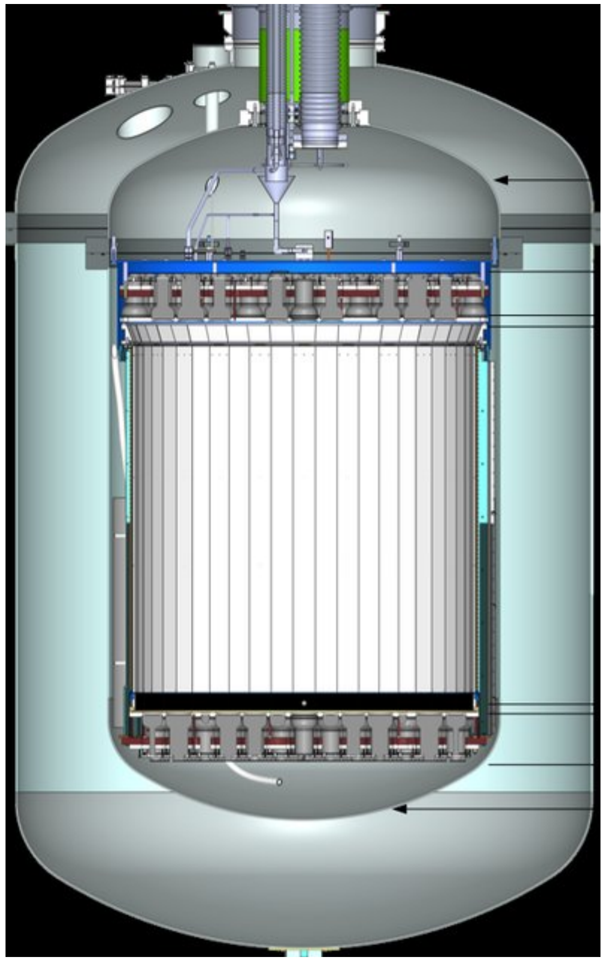


US Cosmic Visions

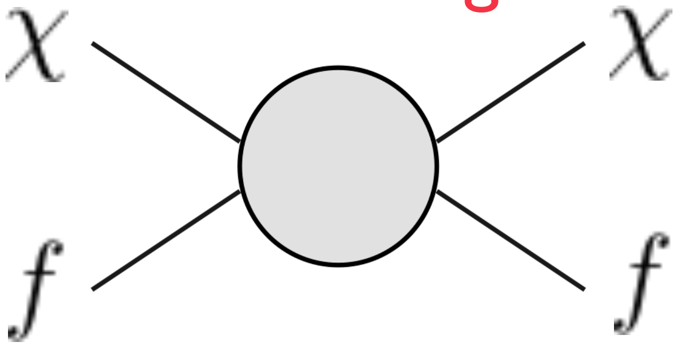
Many candidates outside the WIMP mass range all with SM interactions

Searching for DM - SM interactions

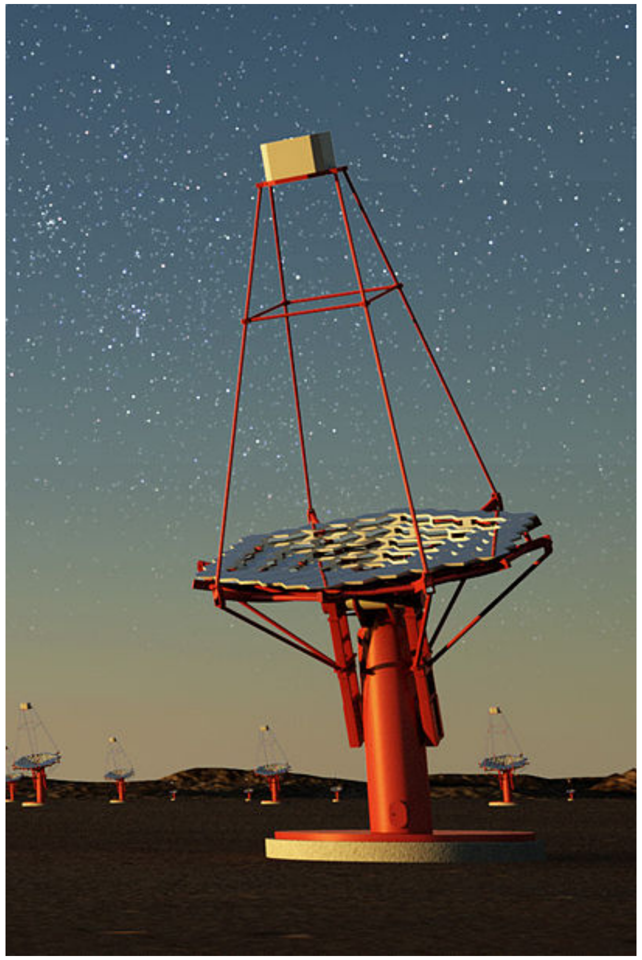
Direct detection



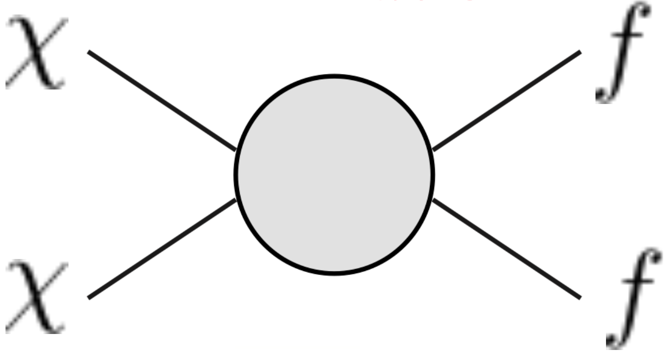
Scattering



Indirect detection

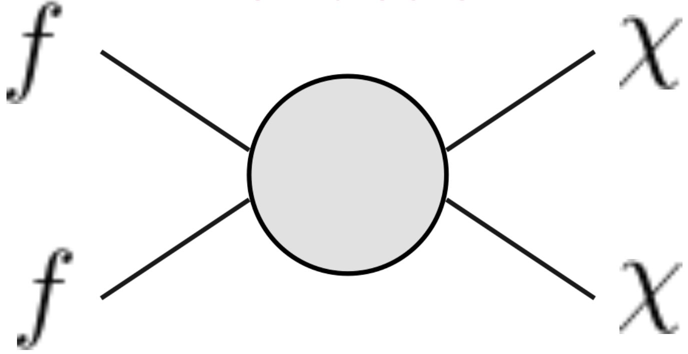


Annihilation



Collider

Production

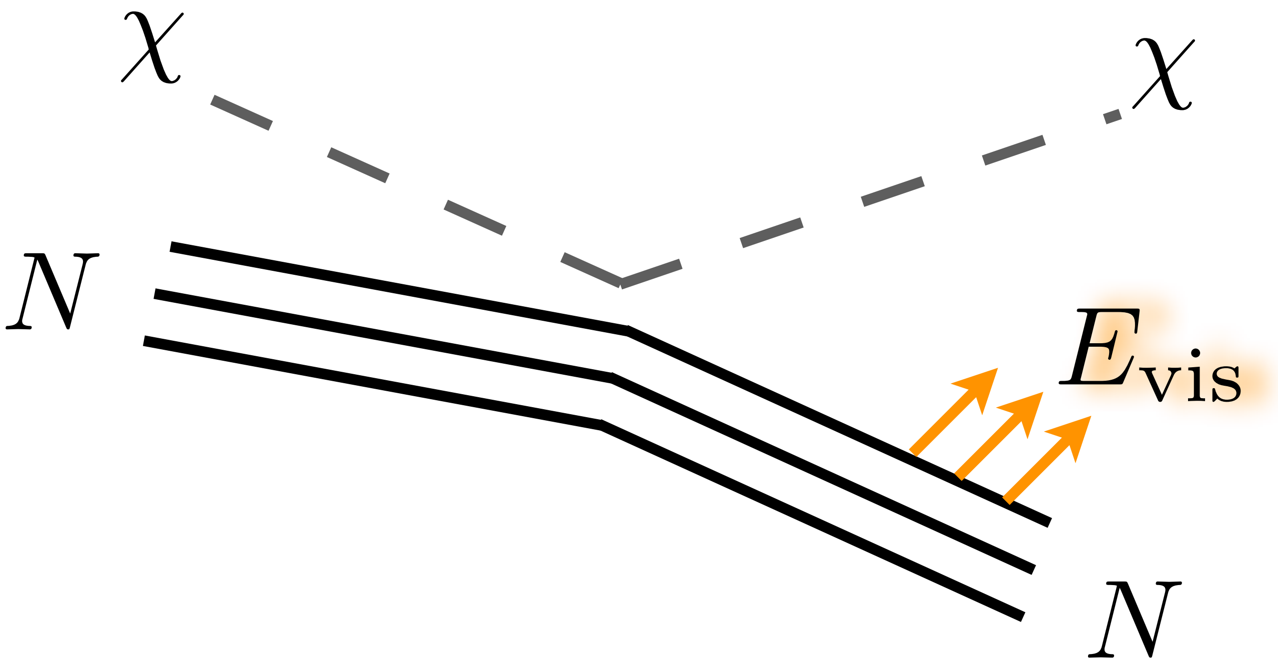


Direct detection

Basics of direct detection

Original aim: detect collisions of dark matter with a nucleus

Goodman & Witten (1985)

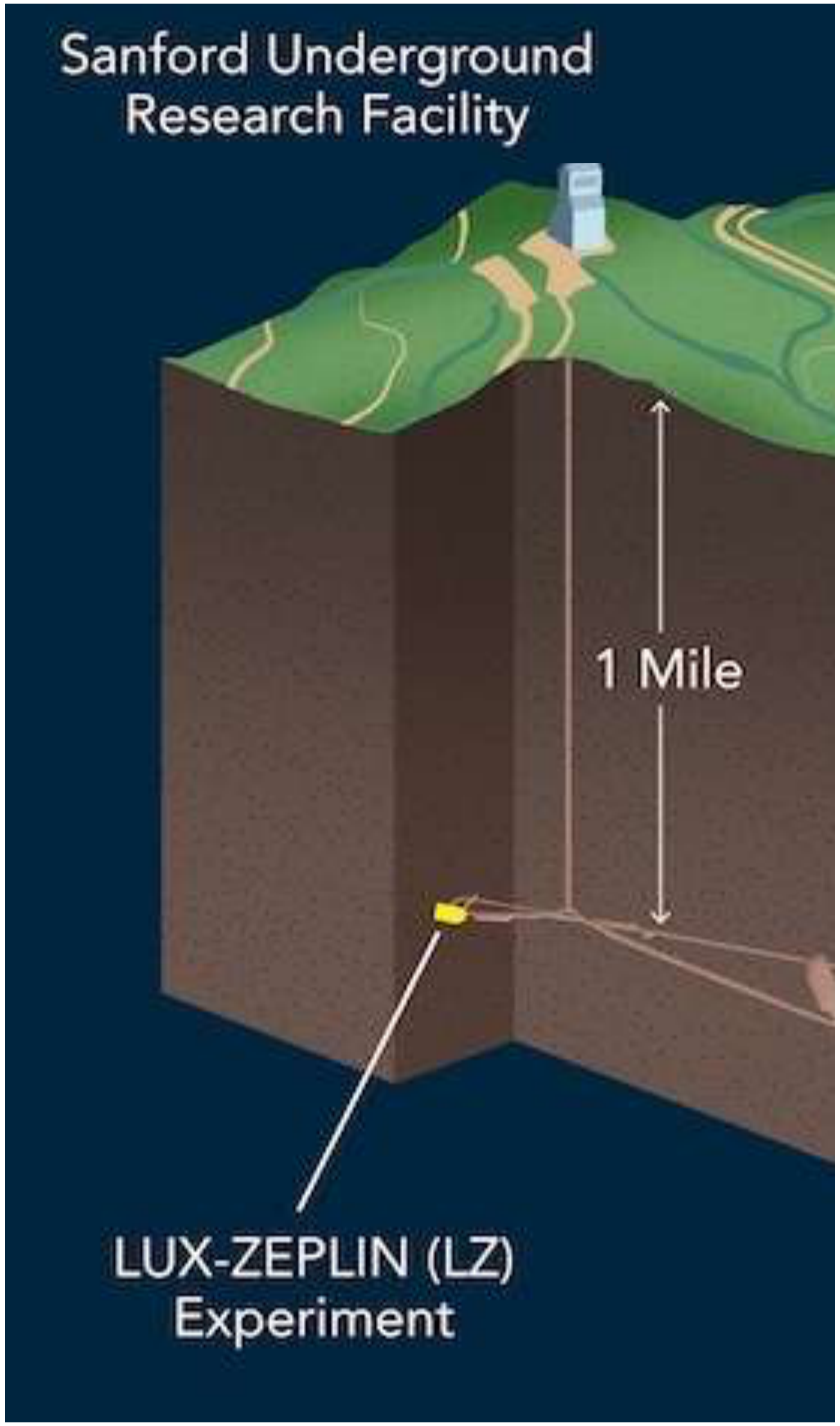


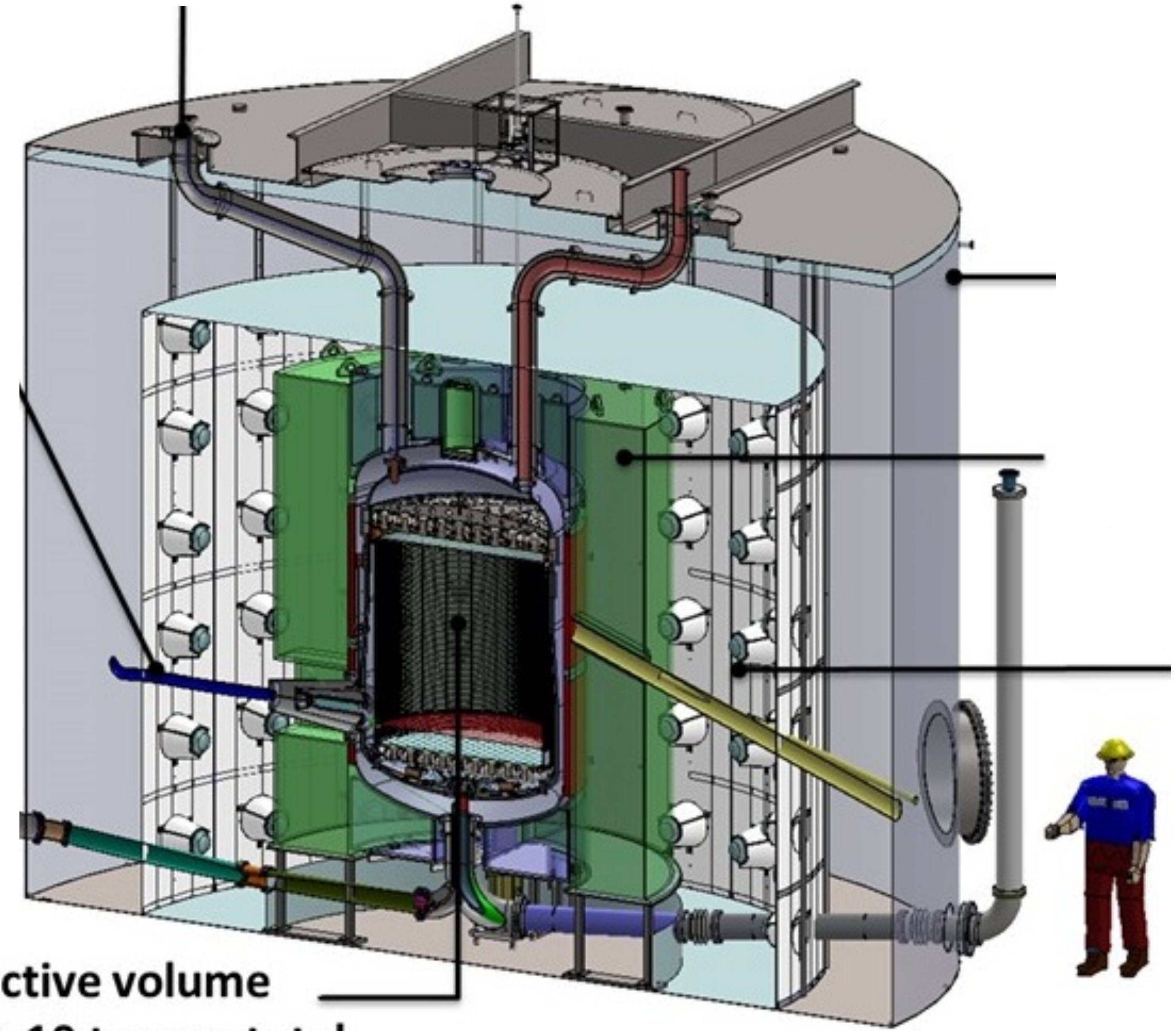
$$E_{\mathrm{vis}} \approx 1 - 100 \ \mathrm{keV}$$

Event rate: few events / year

Ultra-sensitive keV energy detectors

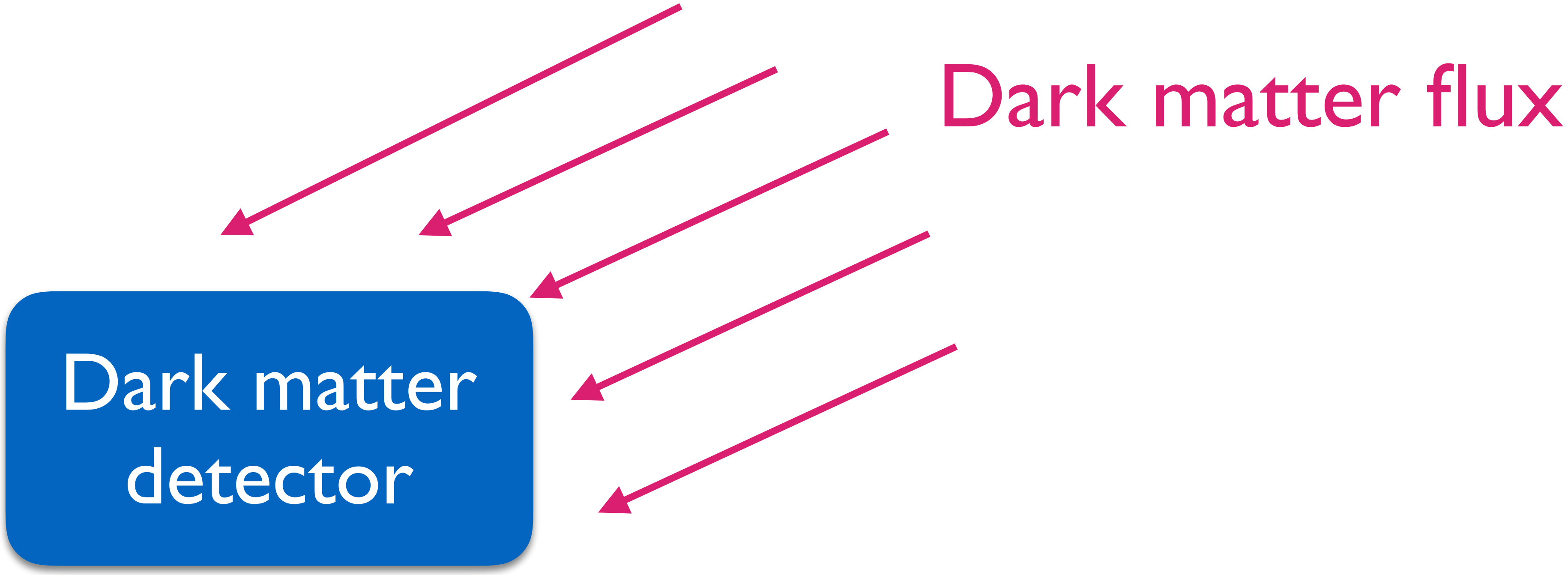
Example: the LZ detector





7 tonne active volume
liquid Xe TPC. 10 tonnes total

Basics of direct detection



Dark matter flux

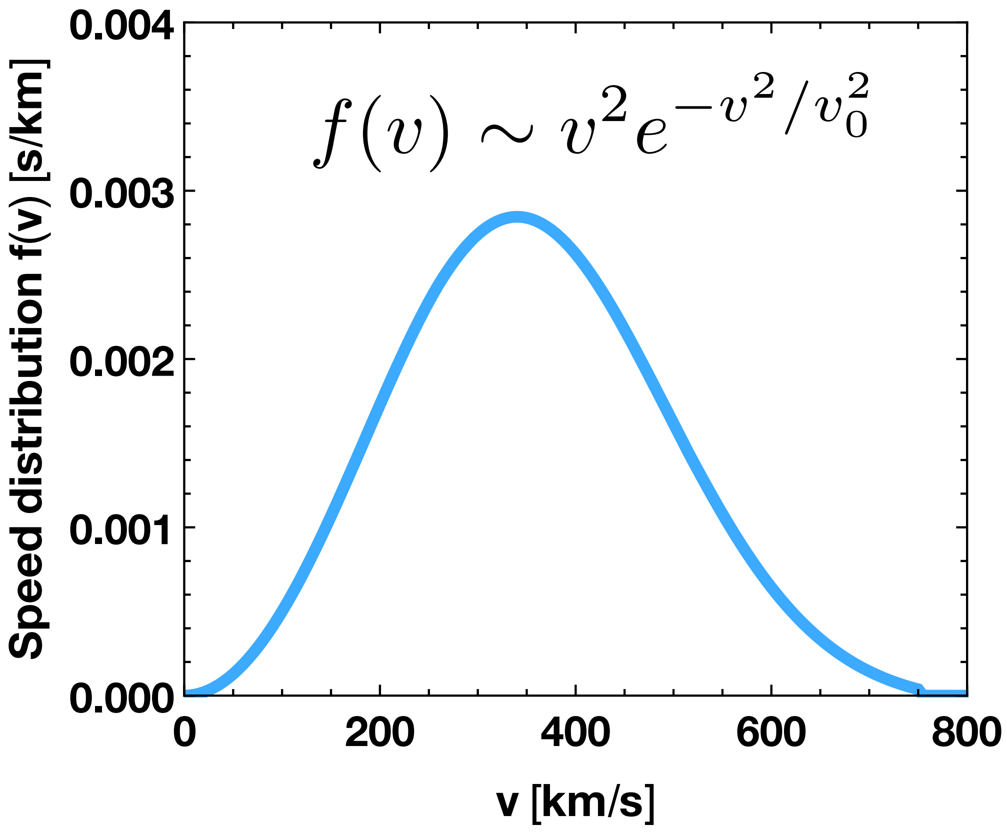
Dark matter detector

Event rate = *DM flux* × *particle physics*

Need to model the DM flux to extract the particle physics

SHM: simplest DM flux model

Need to specify velocity distribution and local density to get flux



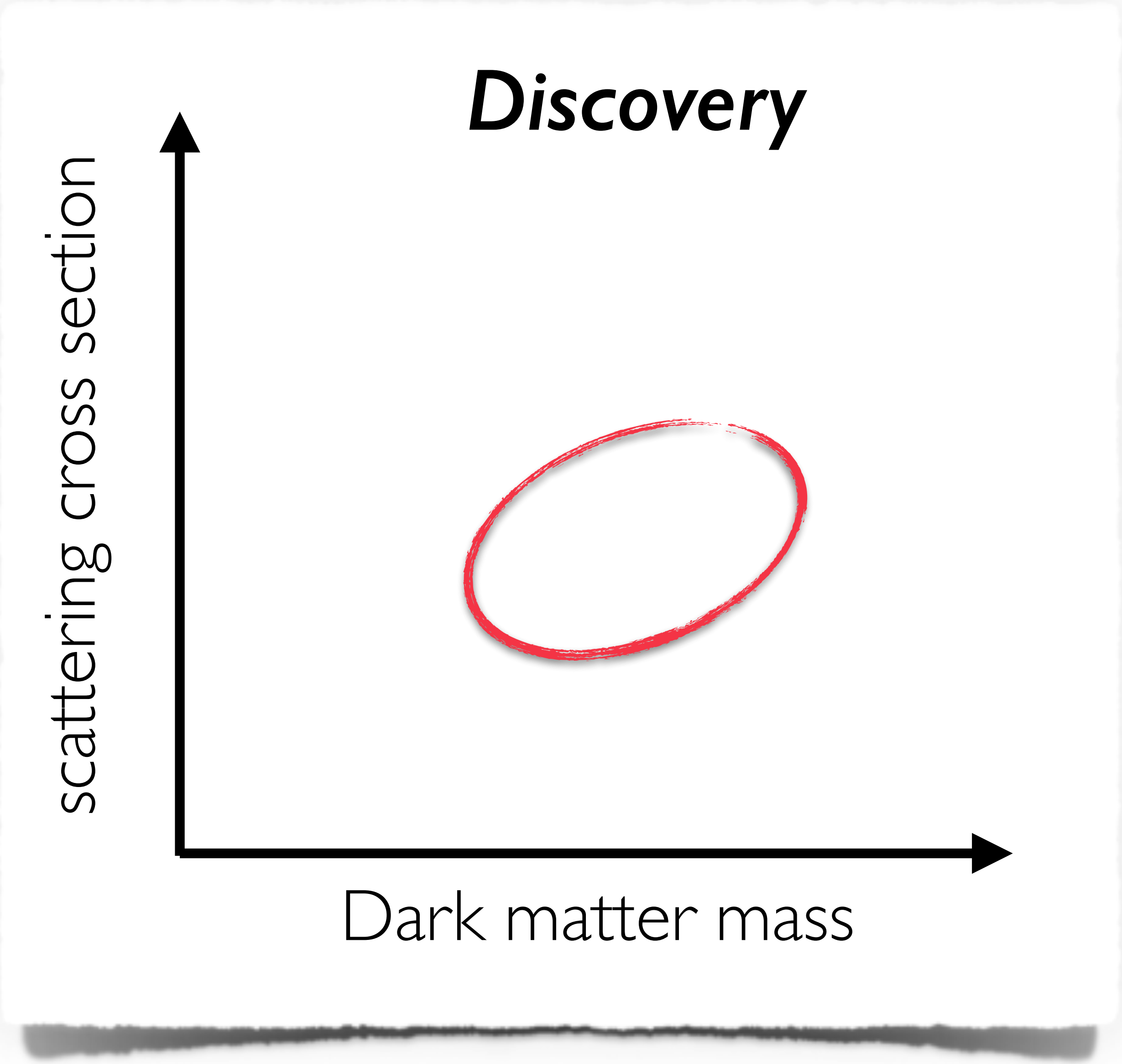
$$\rho_{\mathrm{DM}}(@\mathrm{Sun}) \sim 0.3\ \mathrm{GeV/cm^3}$$

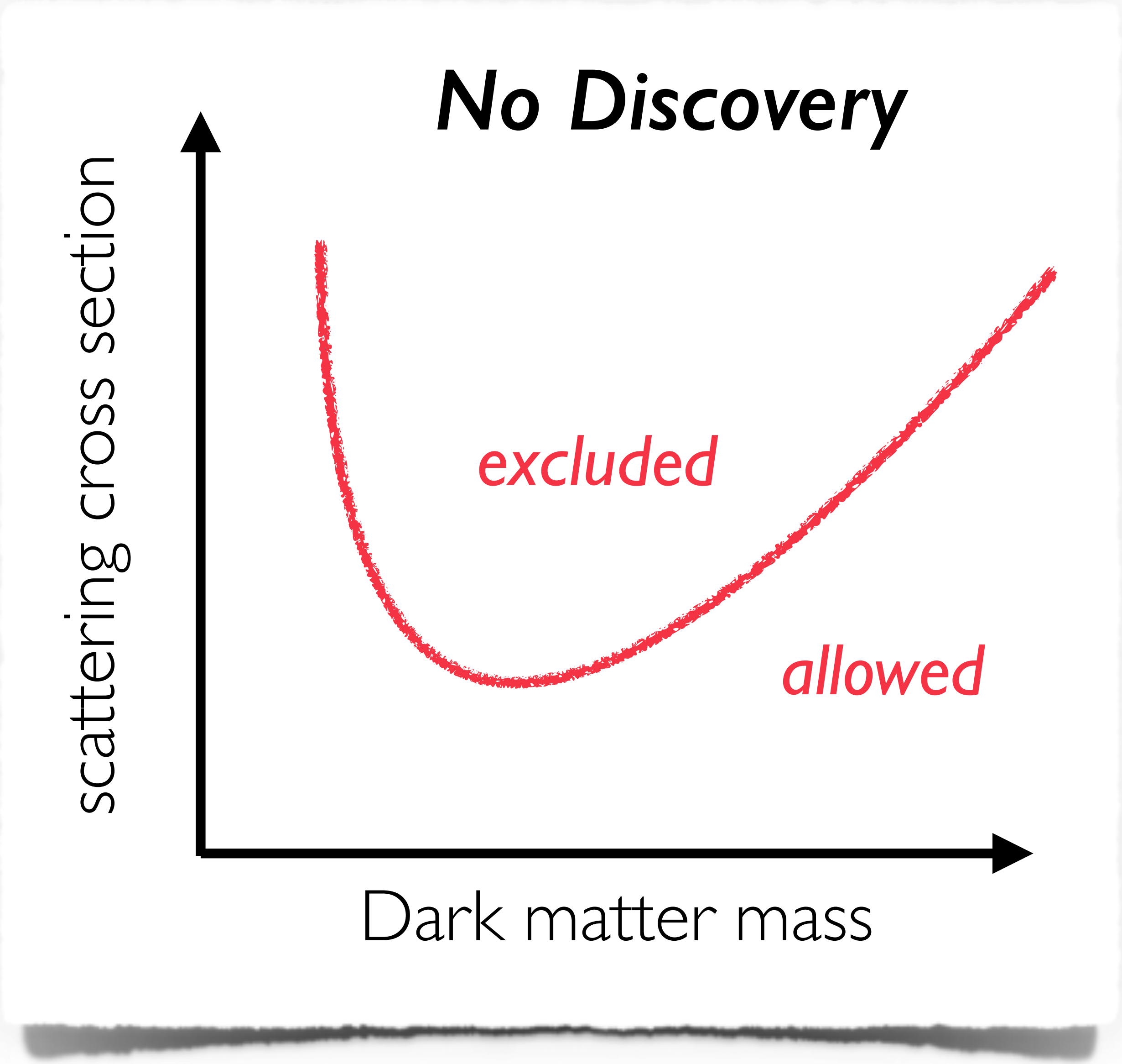
$$\phi_{\mathrm{thumb}} \sim 10^7 \left(\frac{m_{\mathrm{proton}}}{m_{\mathrm{DM}}}\right)\ \mathrm{particles/s}$$

Particle physics signals

Measurement/constraints on

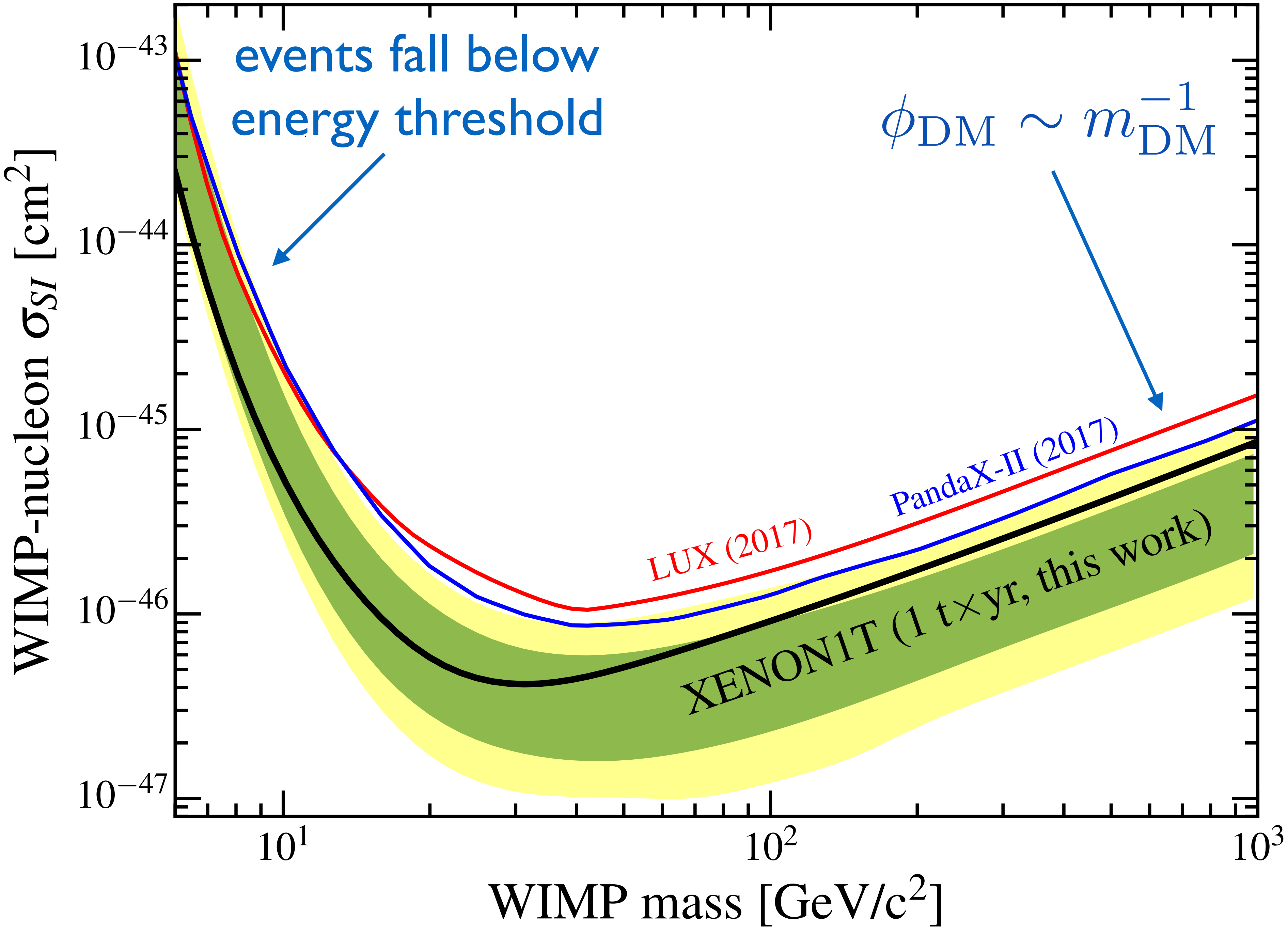
1. *Dark matter mass*
2. *Scattering cross section with nucleons*





Nuclear recoils: standard WIMP searches

XENON1T, PRL, arXiv:1805.12562



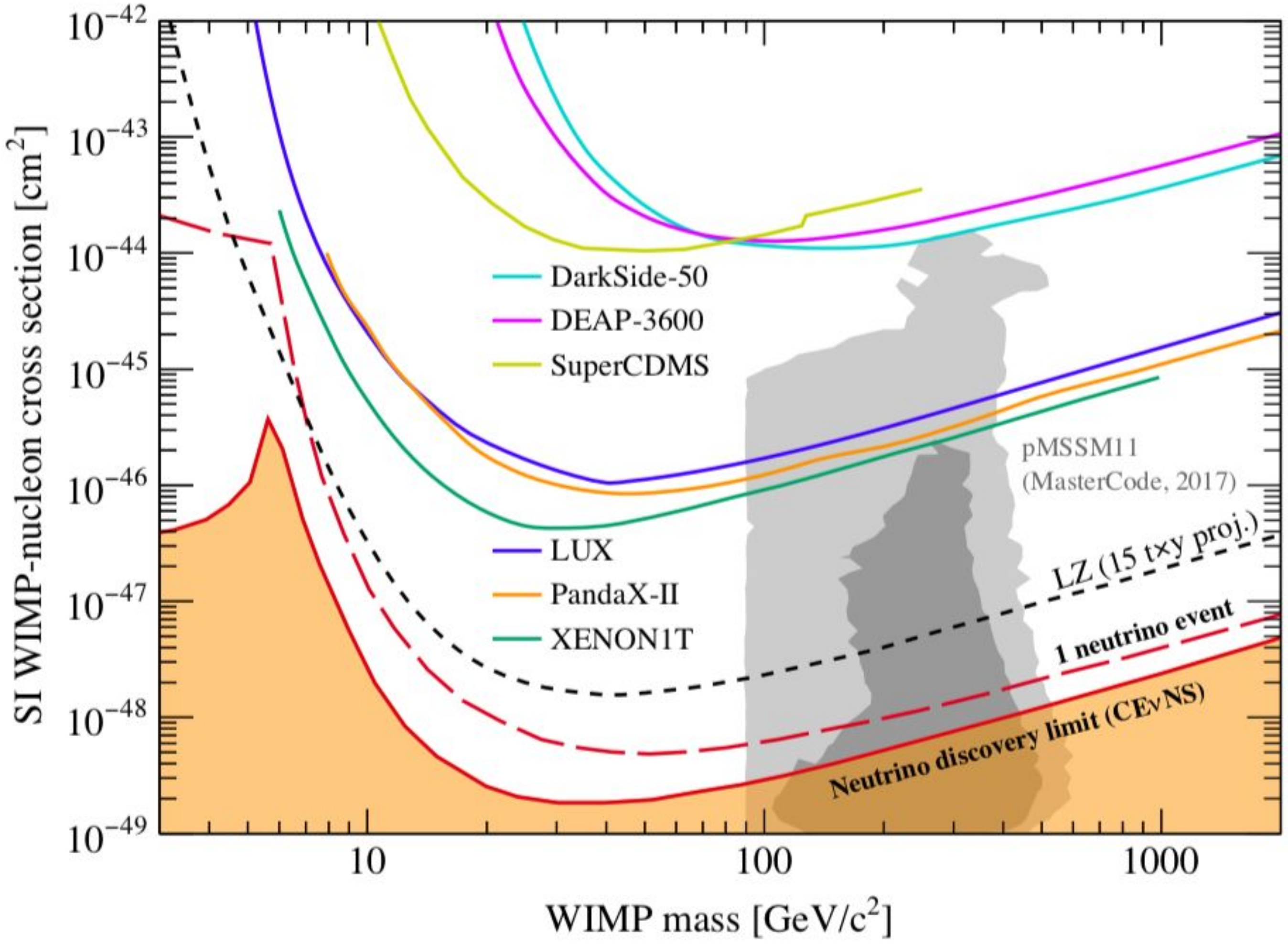
events fall below energy threshold

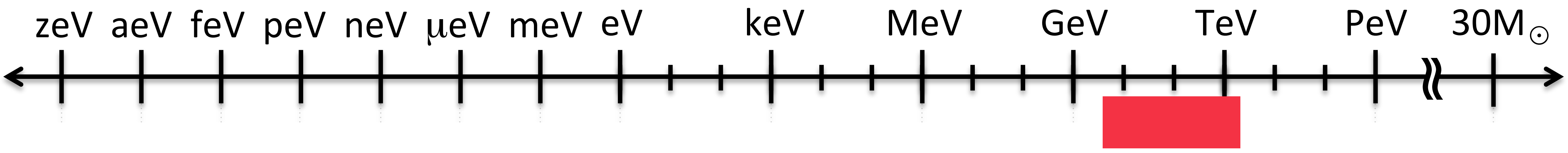
$$\phi_{\mathrm{DM}} \sim m_{\mathrm{DM}}^{-1}$$

xenon-based experiments

Nuclear recoils: standard WIMP searches

The search for WIMPs continues…



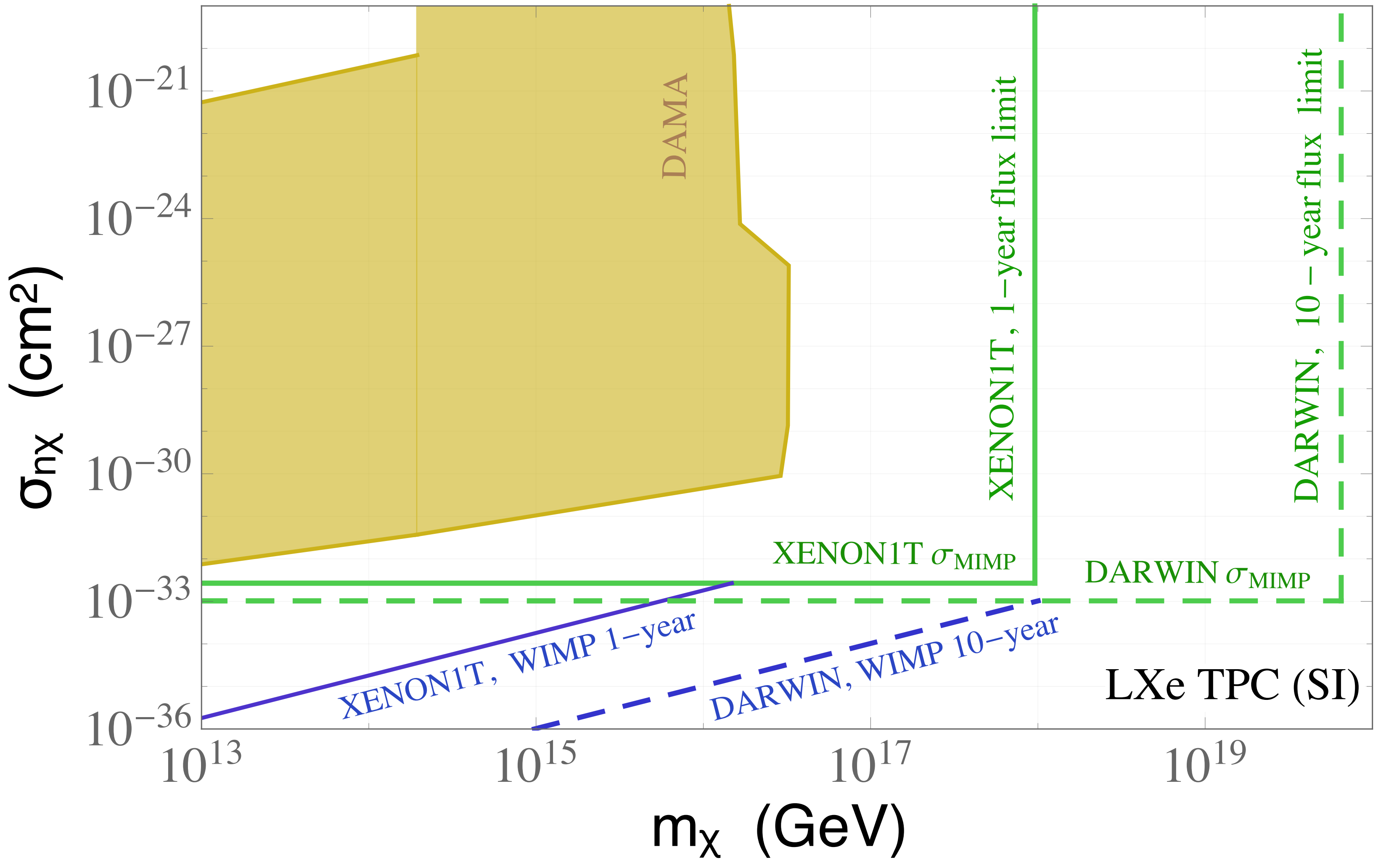


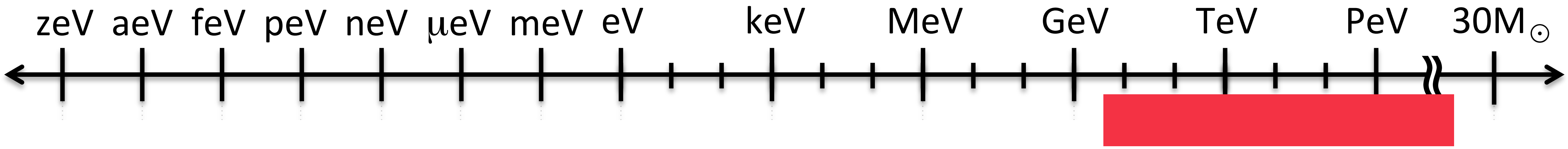
…what happens outside of this normal WIMP mass range?

Nuclear recoils: above the normal WIMP range

Xenon detectors can probe all the way to the Planck scale masses

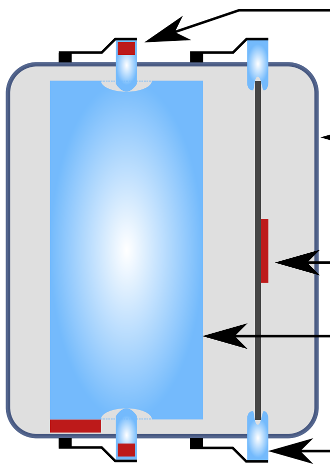
Bramante et al, PRD, arXiv:1803.08044





Nuclear recoils: below the normal WIMP range

CRESST-III



$CaWO_4$ iSticks
(with holding clamps & TES)

reflective and
scintillating housing

light detector (with TES)

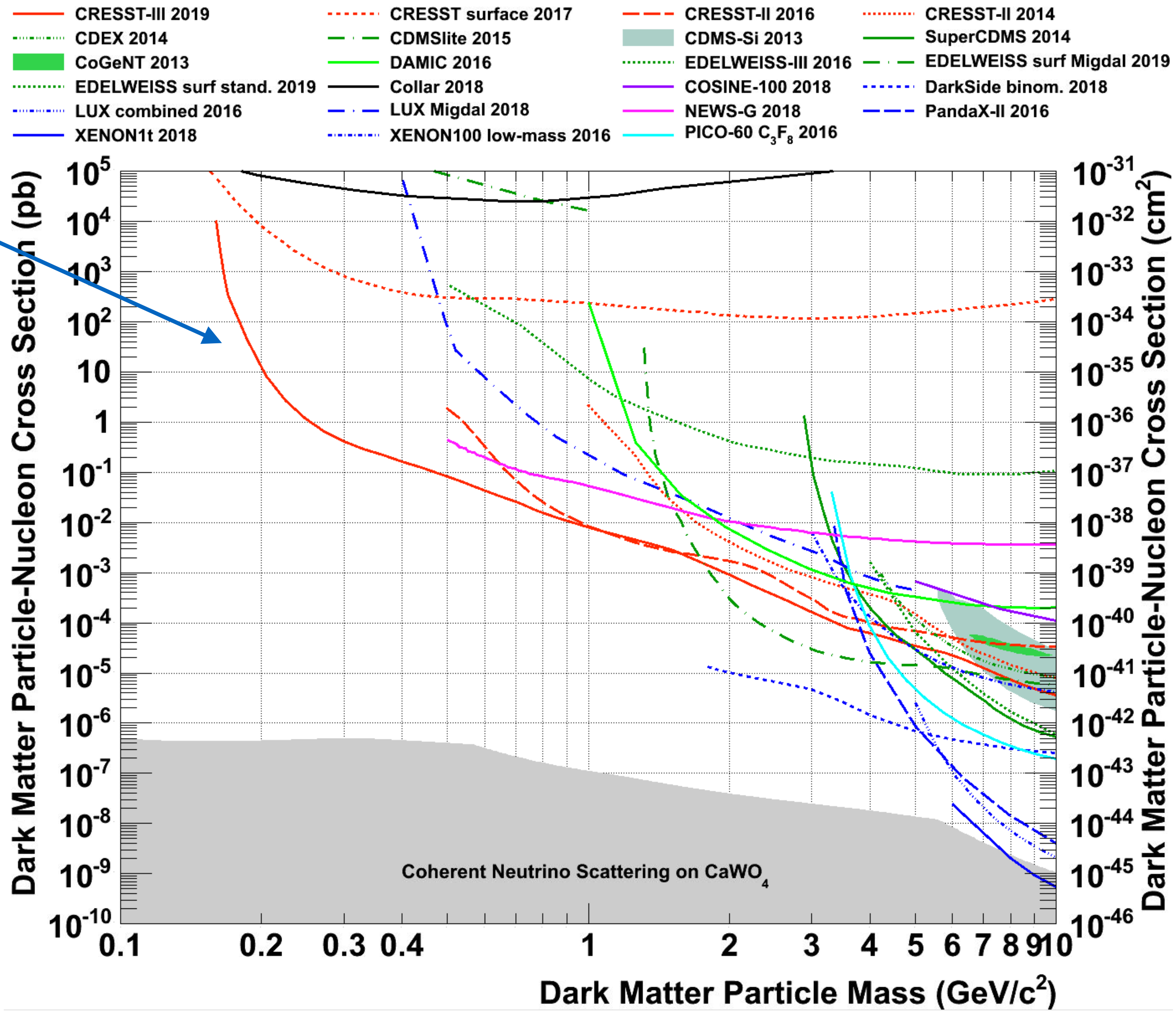
block-shaped target crystal
(with TES)

$CaWO_4$ light detector holding
sticks (with clamps)

Detector mass: 24 grams

Detector threshold: 30 eV

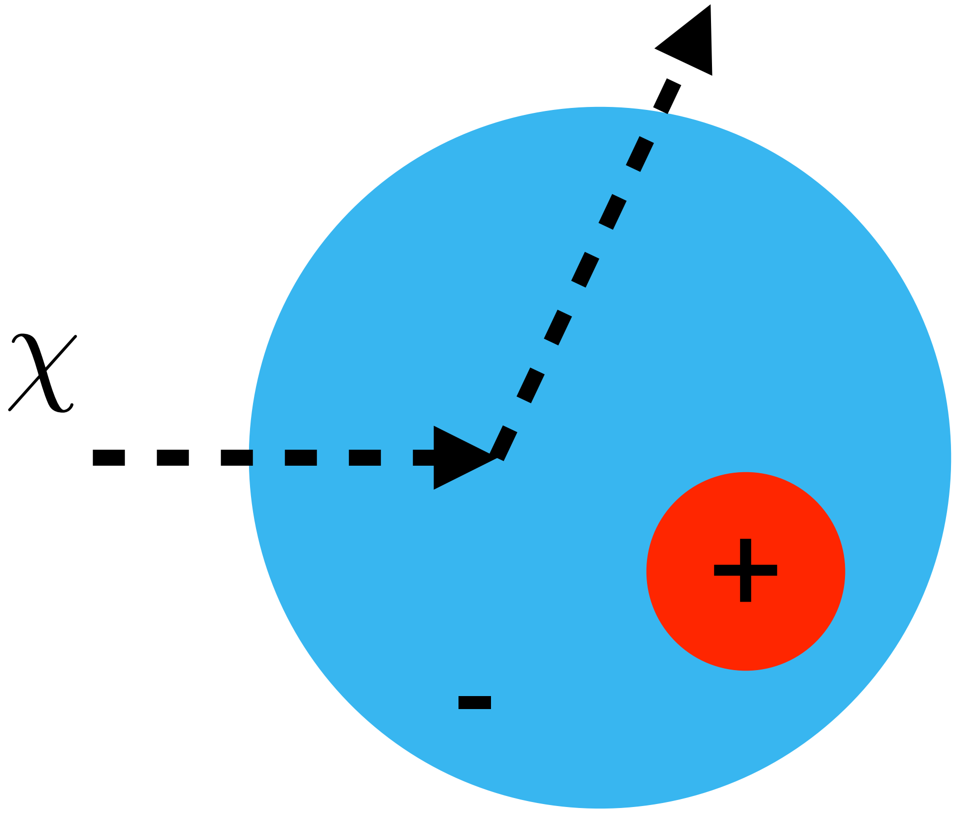
CRESST-III, arXiv:1904.00498



Beyond nuclear recoils: Migdal effect

Emission from the recoiling atom

sub-GeV dark matter in xenon:



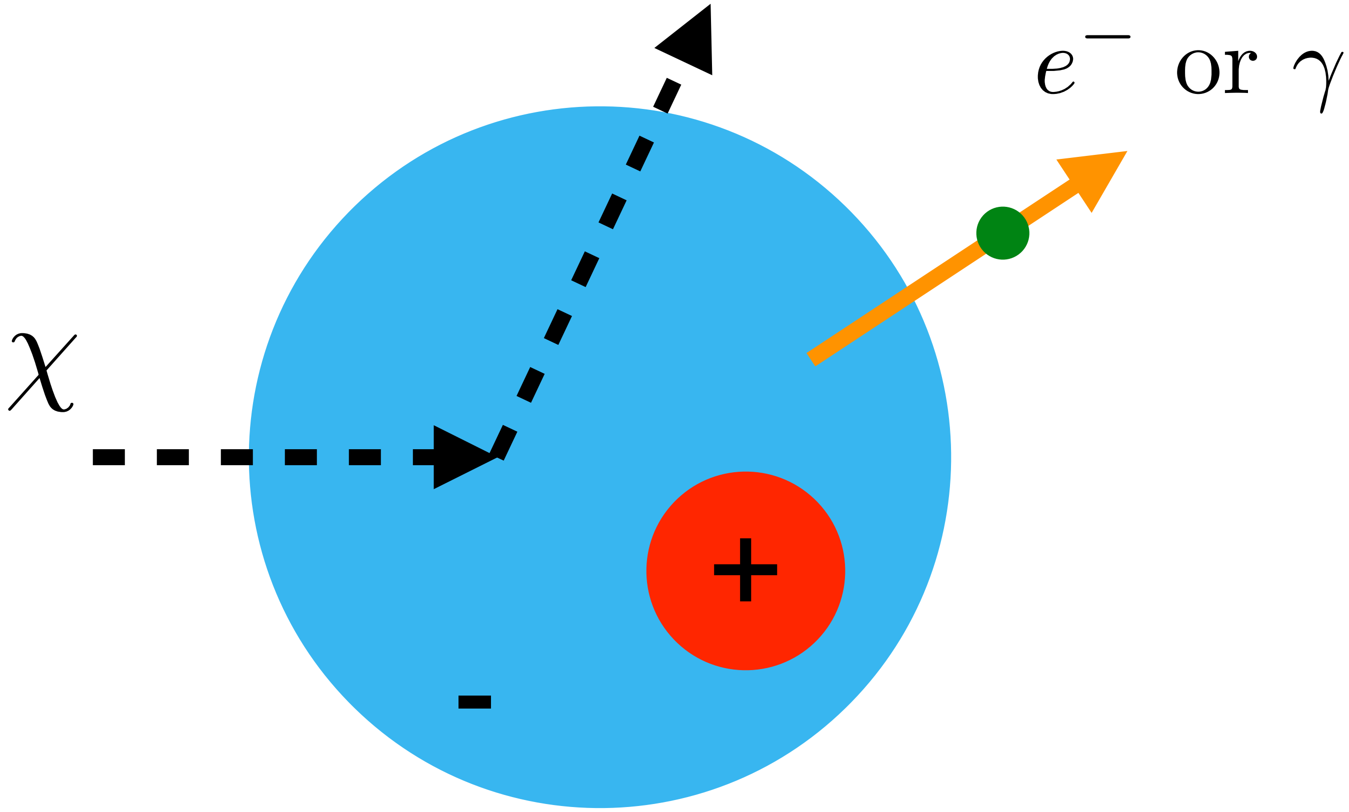
nucleus gets a nudge

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

nuclear recoil below energy threshold

Emission from the recoiling atom

sub-GeV dark matter in xenon:



nucleus gets a nudge

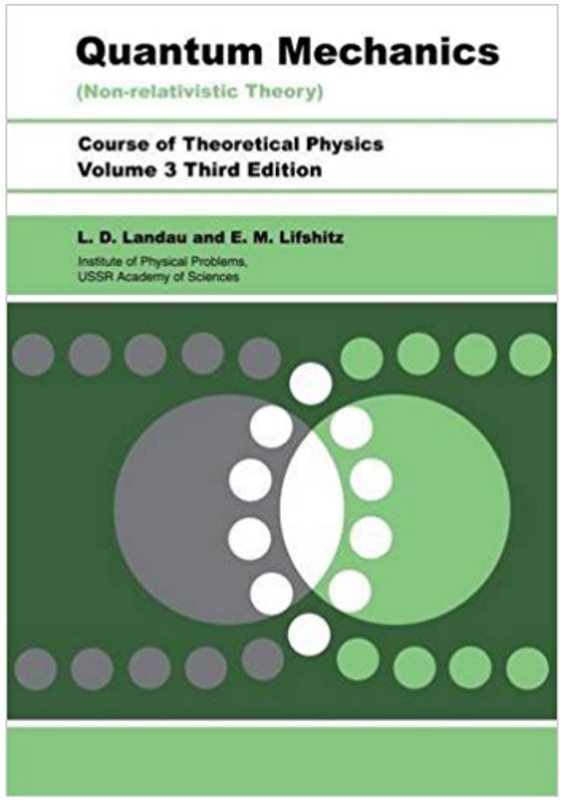
$$E_{\text{recoil}} \lesssim 0.1 \text{ keV}$$

nuclear recoil below energy threshold

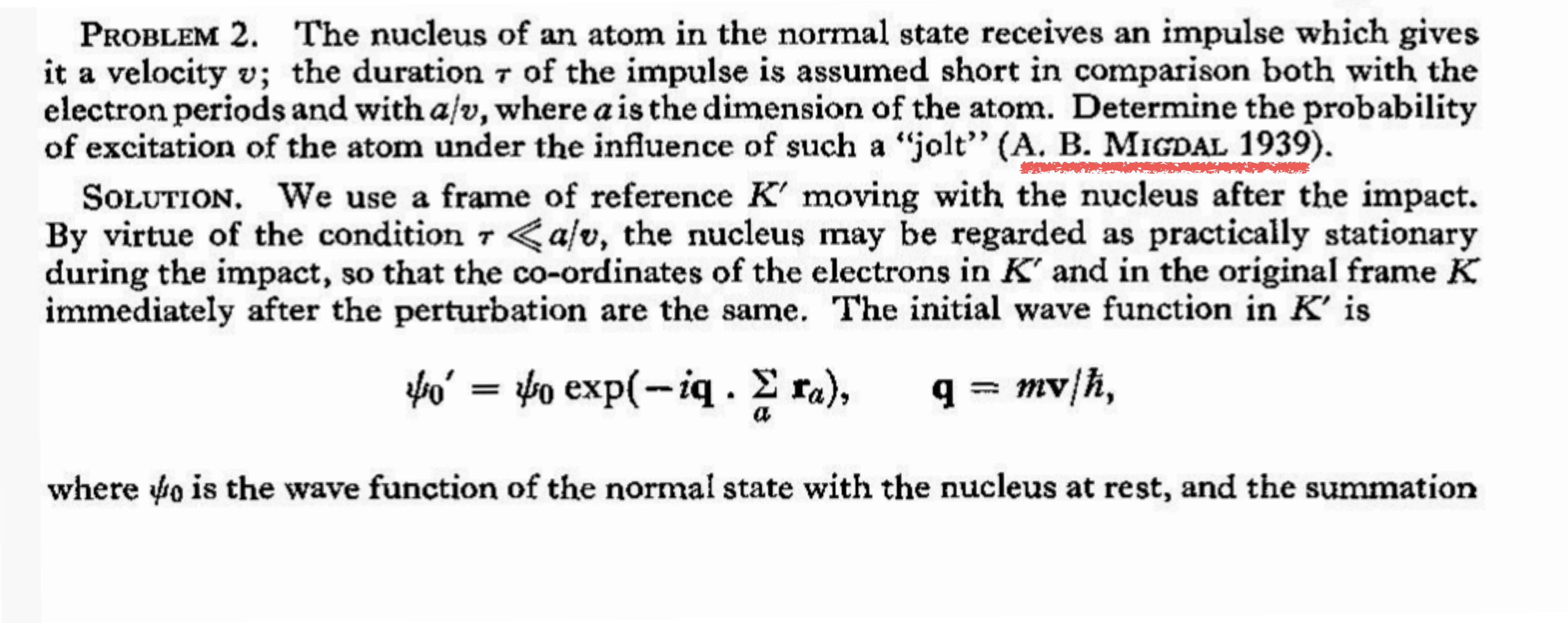
…but electrons and photons can be emitted from the atom

Migdal 1939
Kouvaris & Pradler PRL 1607.01789

Electron emission: Migdal effect



Quantum Mechanics
(Non-relativistic Theory)
Course of Theoretical Physics
Volume 3 Third Edition
L. D. Landau and E. M. Lifshitz
Institute of Physical Problems,
USSR Academy of Sciences

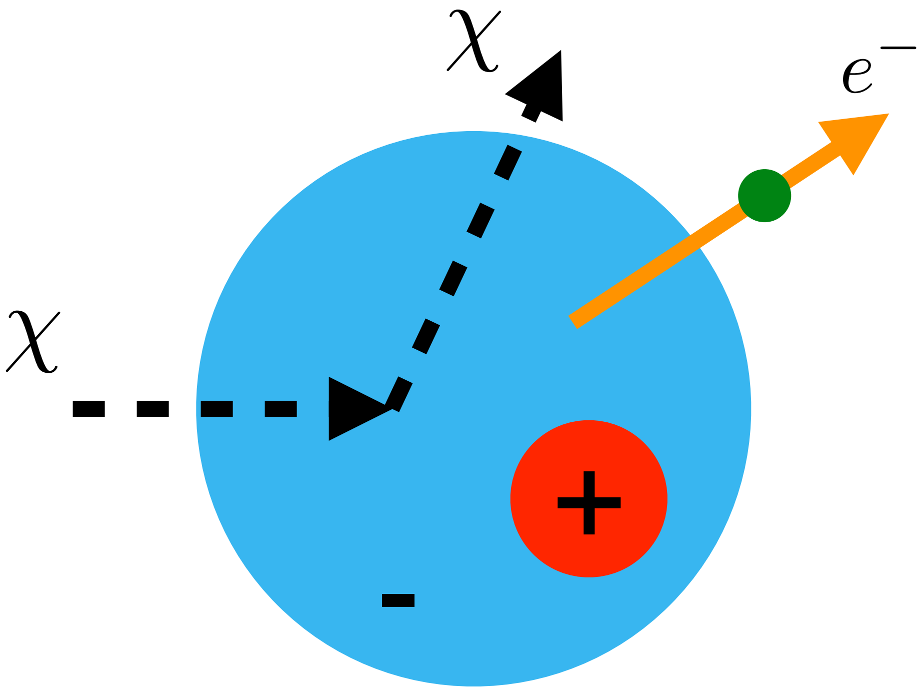


PROBLEM 2. The nucleus of an atom in the normal state receives an impulse which gives it a velocity v; the duration τ of the impulse is assumed short in comparison both with the electron periods and with a/v, where a is the dimension of the atom. Determine the probability of excitation of the atom under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

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

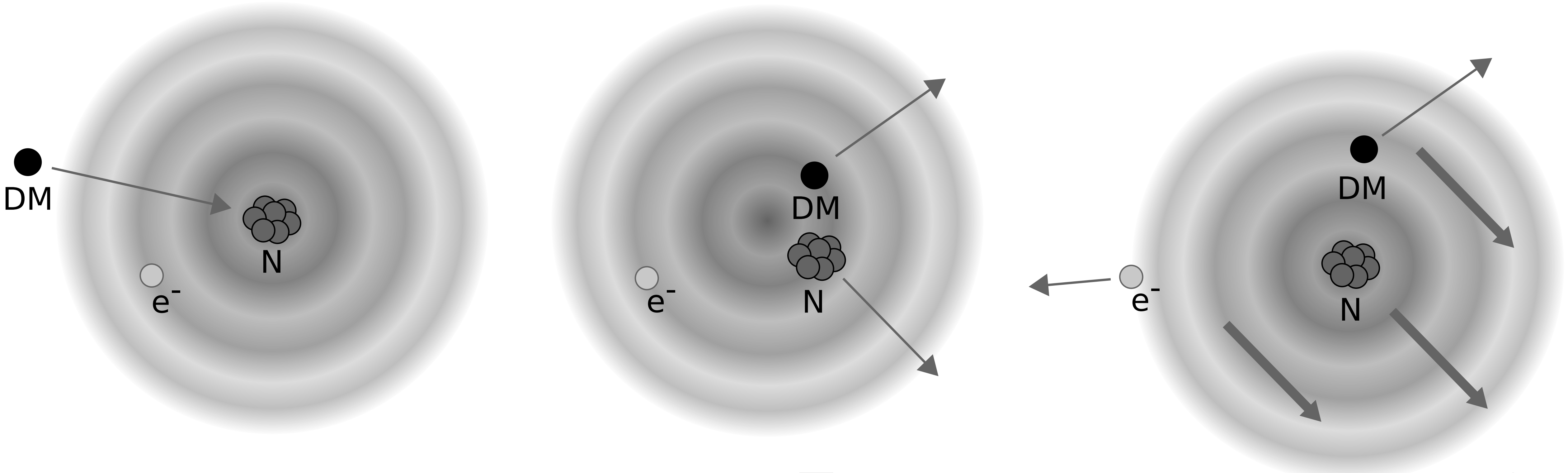
where ψ_0 is the wave function of the normal state with the nucleus at rest, and the summation



Atom emits an electron (Migdal effect)

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

Migdal effect: updated treatment

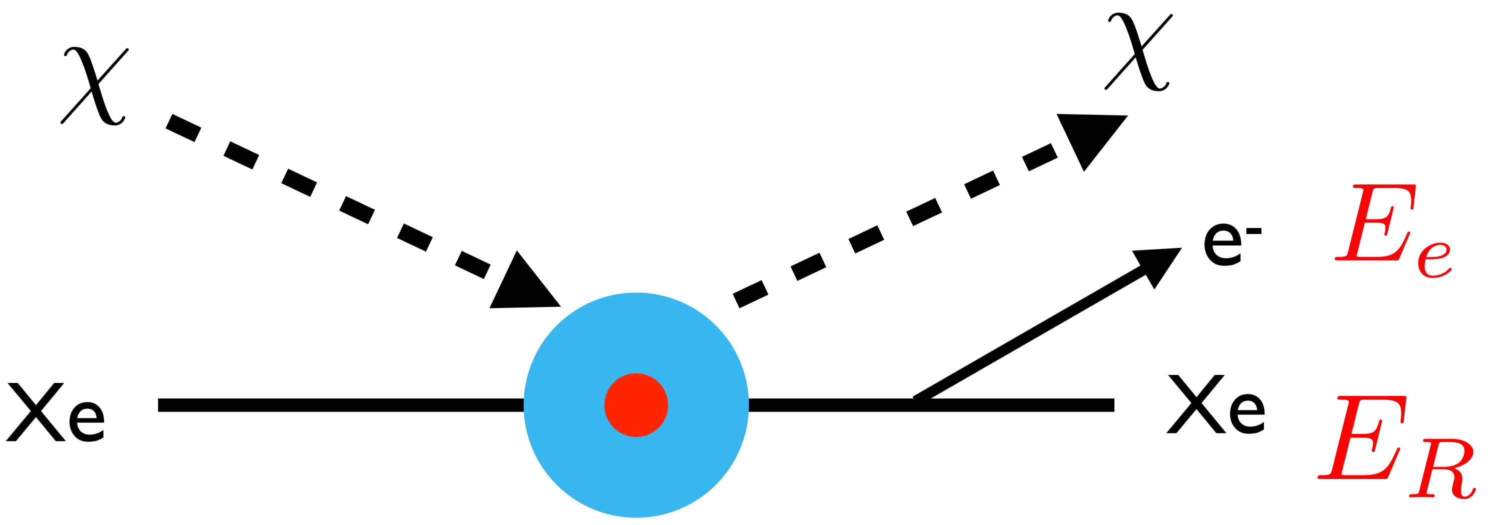


$$|\Phi_{ec}\rangle \qquad |\Phi'_{ec}\rangle = e^{-im_e \sum_i \mathbf{v}\cdot\hat{\mathbf{x}}_i}|\Phi_{ec}\rangle \qquad \mathcal{P} = \left|\langle\Phi^*_{ec}|\Phi'_{ec}\rangle\right|^2$$

"…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

Electron emission: Migdal effect



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

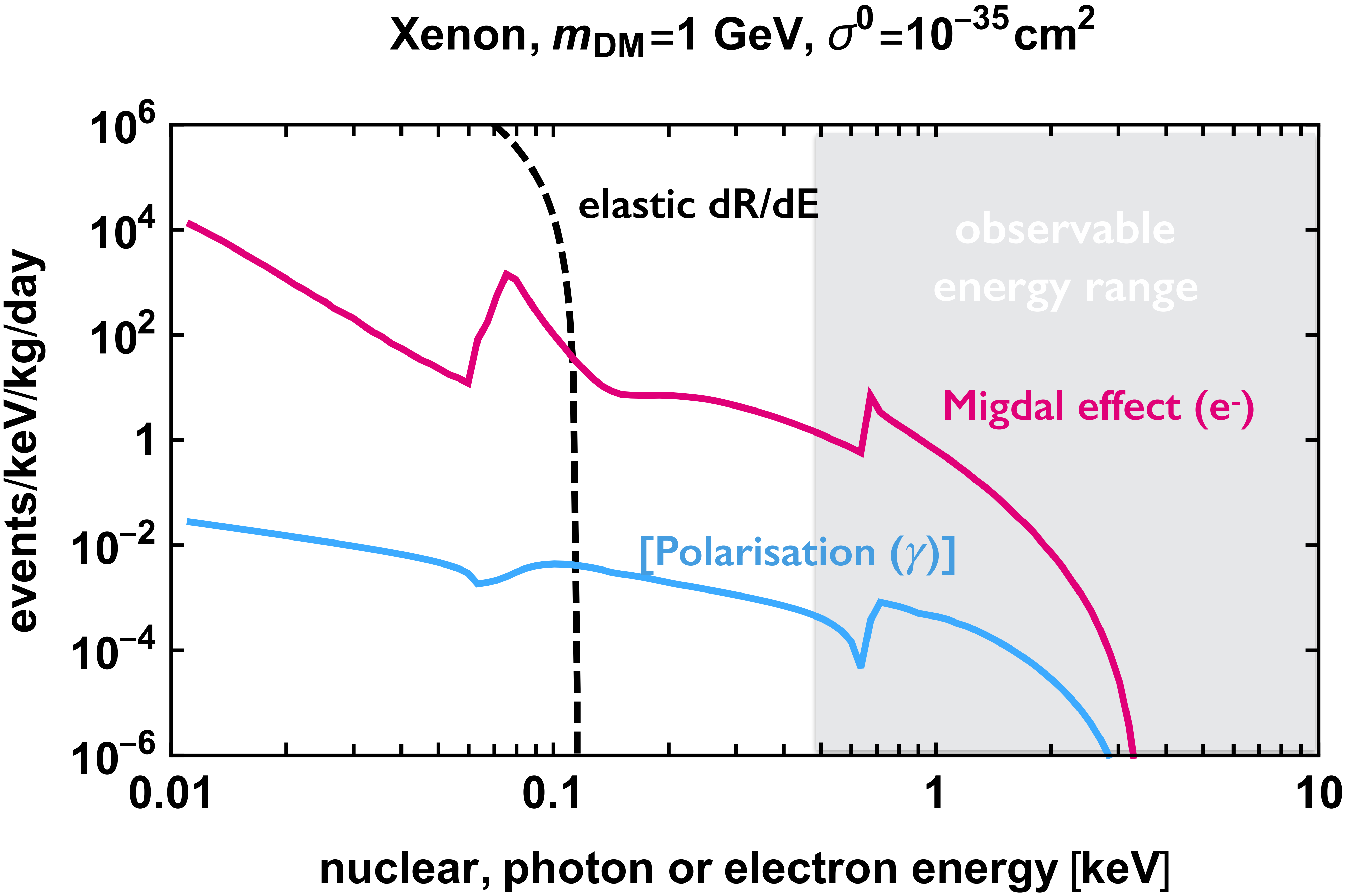
Usual 2->2 cross section

$\uparrow$

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

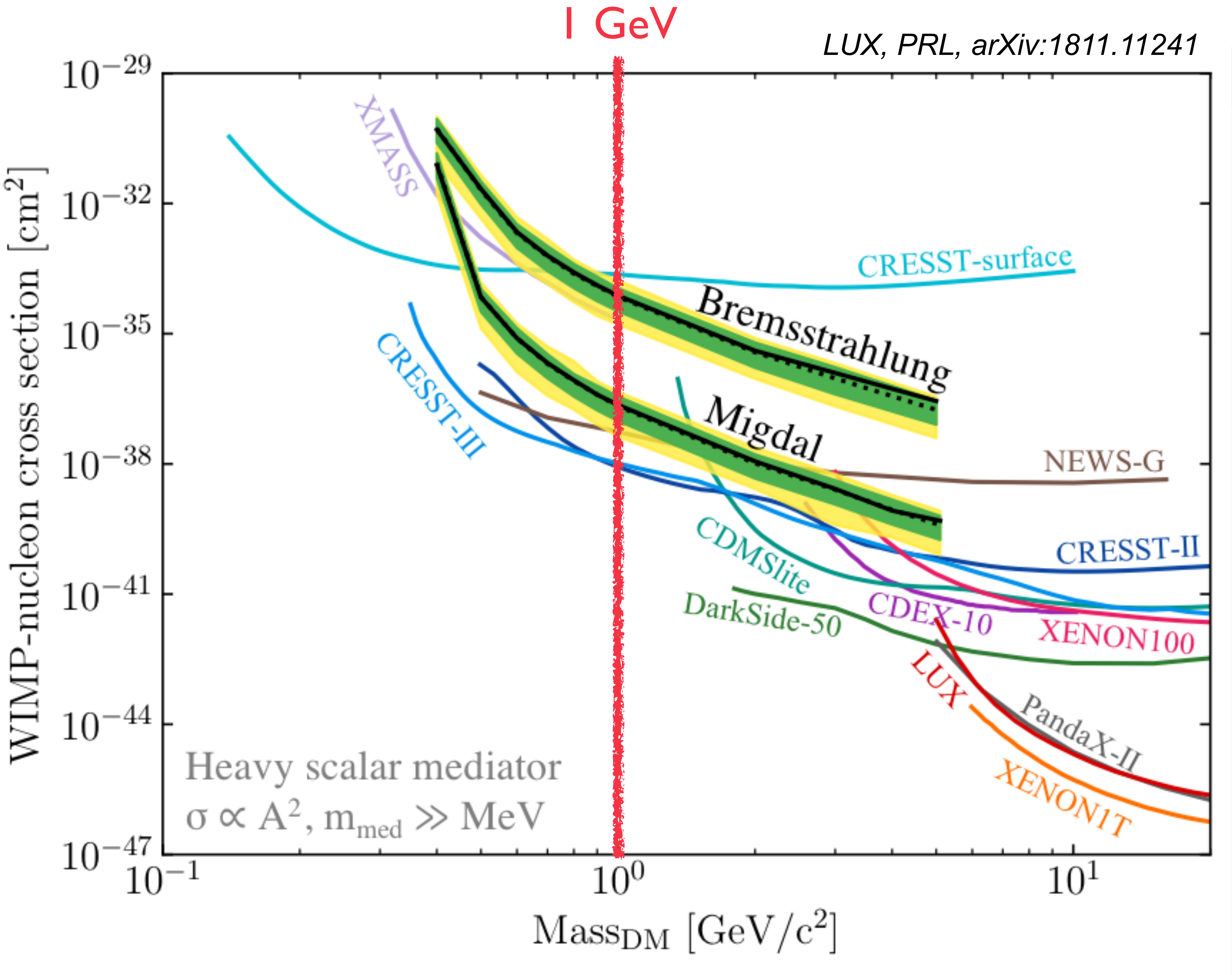
Calculated in Ibe, Nakano, Shoji, Suzuki, JHEP, arXiv:1707.07258 for different elements

sub-GeV DM signals in xenon



Migdal electrons observable even for $m_{\mathrm{DM}} \lesssim 1\ \mathrm{GeV}$

LUX (Xe) sensitive below 1 GeV

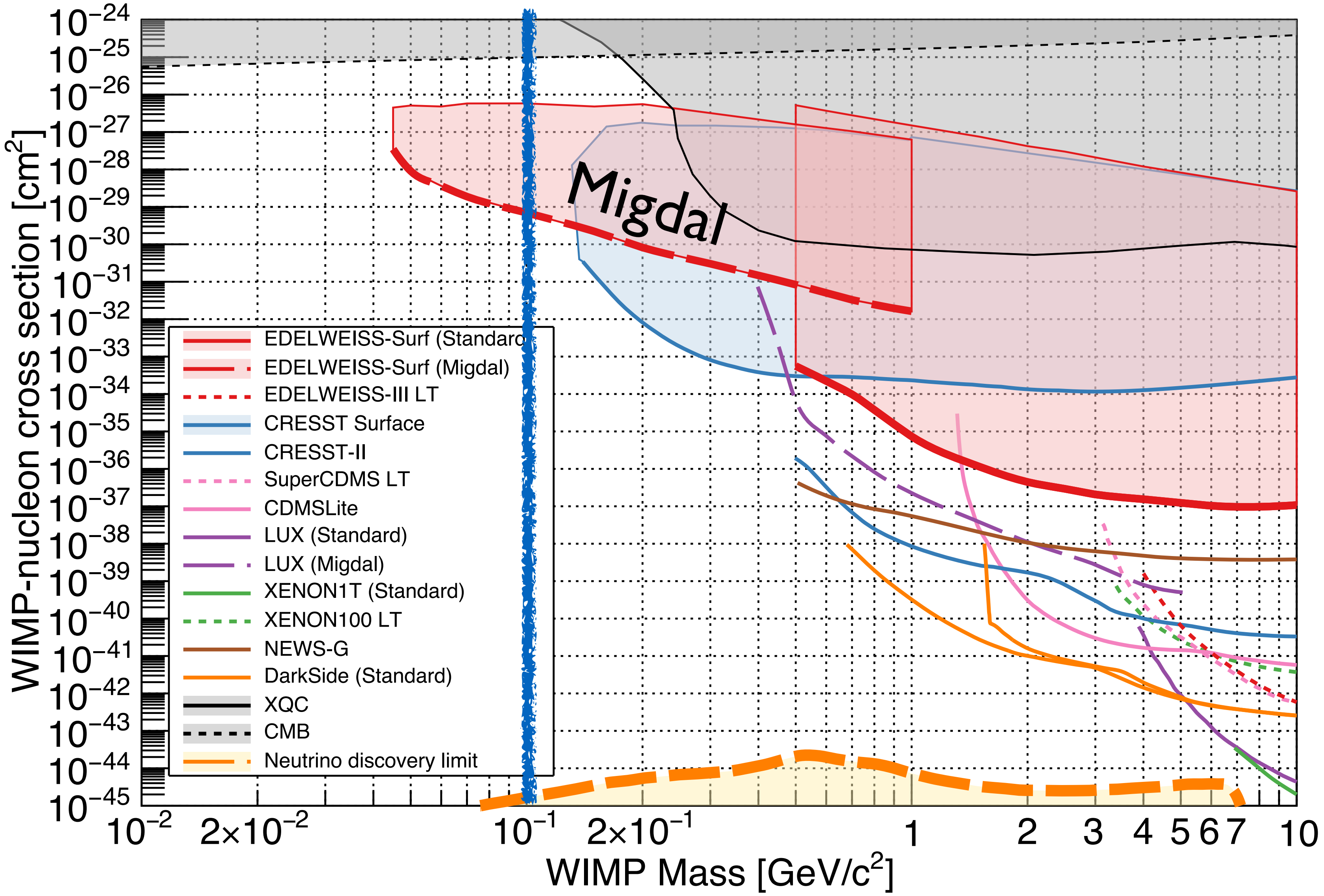


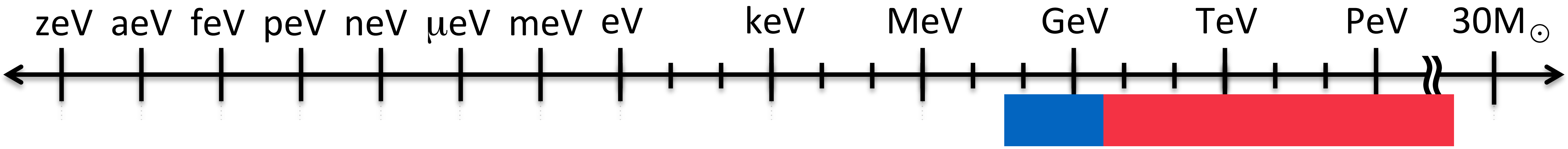
LUX, PRL, arXiv:1811.11241

Edelweiss (Ge) sensitive below 100 MeV

100 MeV

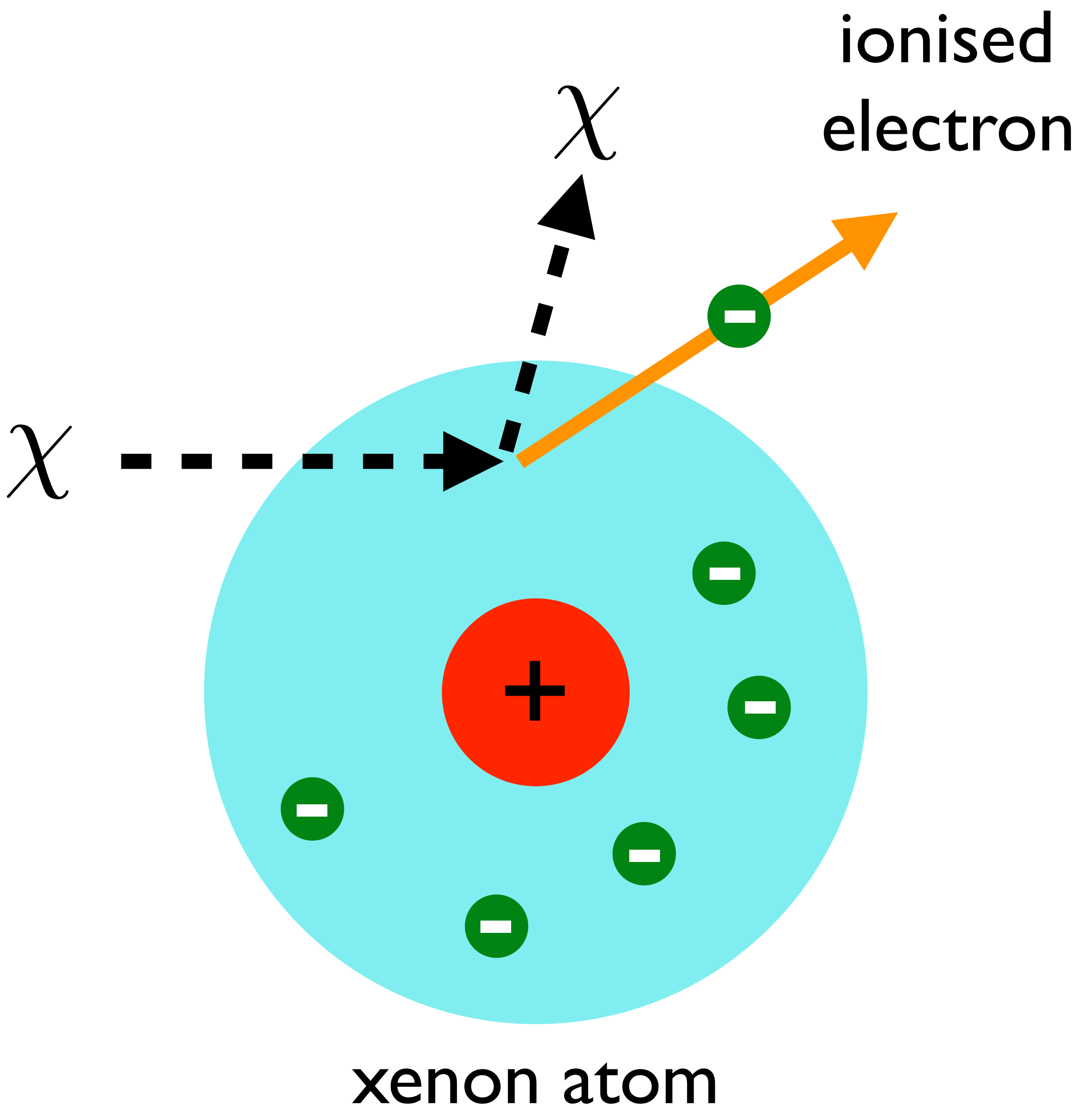
Edelweiss + Kavanagh
arXiv:1901.03588





Beyond nuclear recoils: electron scattering

Electron-ionisation in atoms



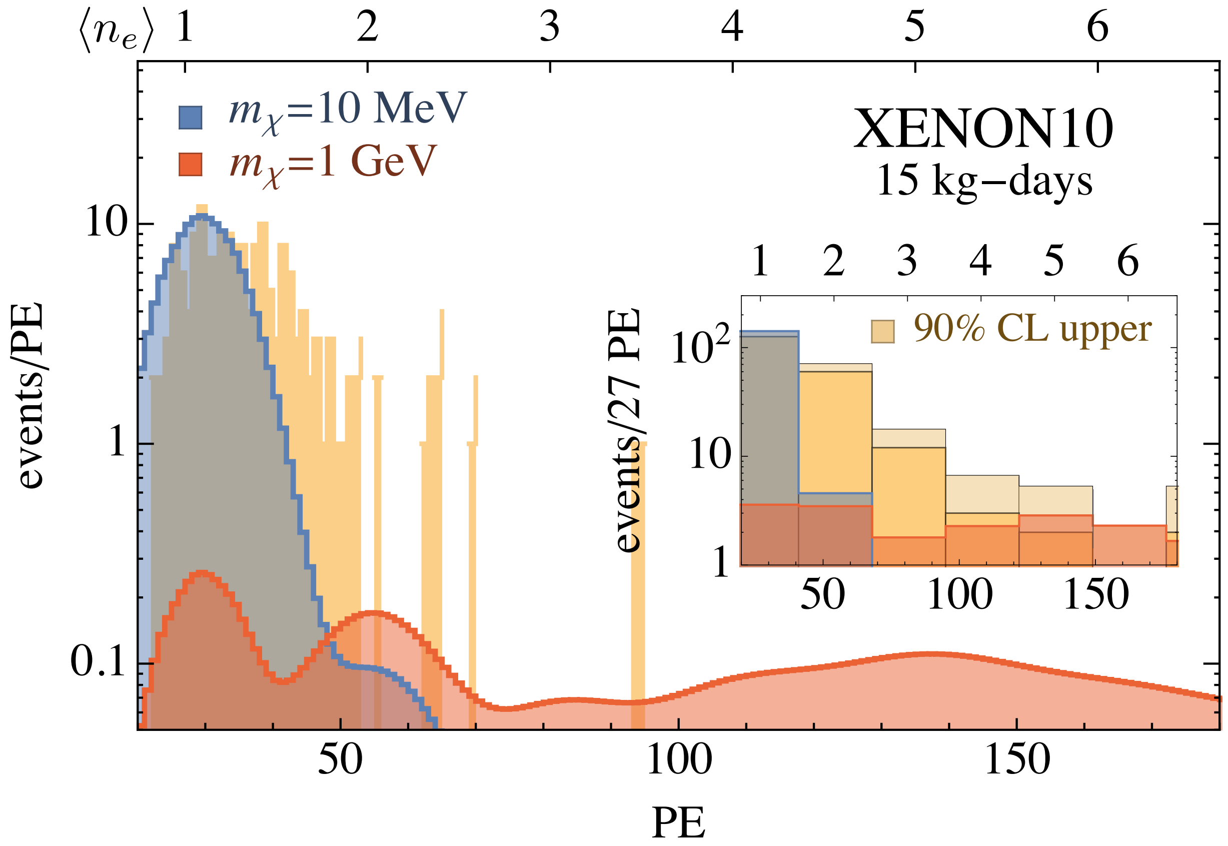
For ionisation, require:

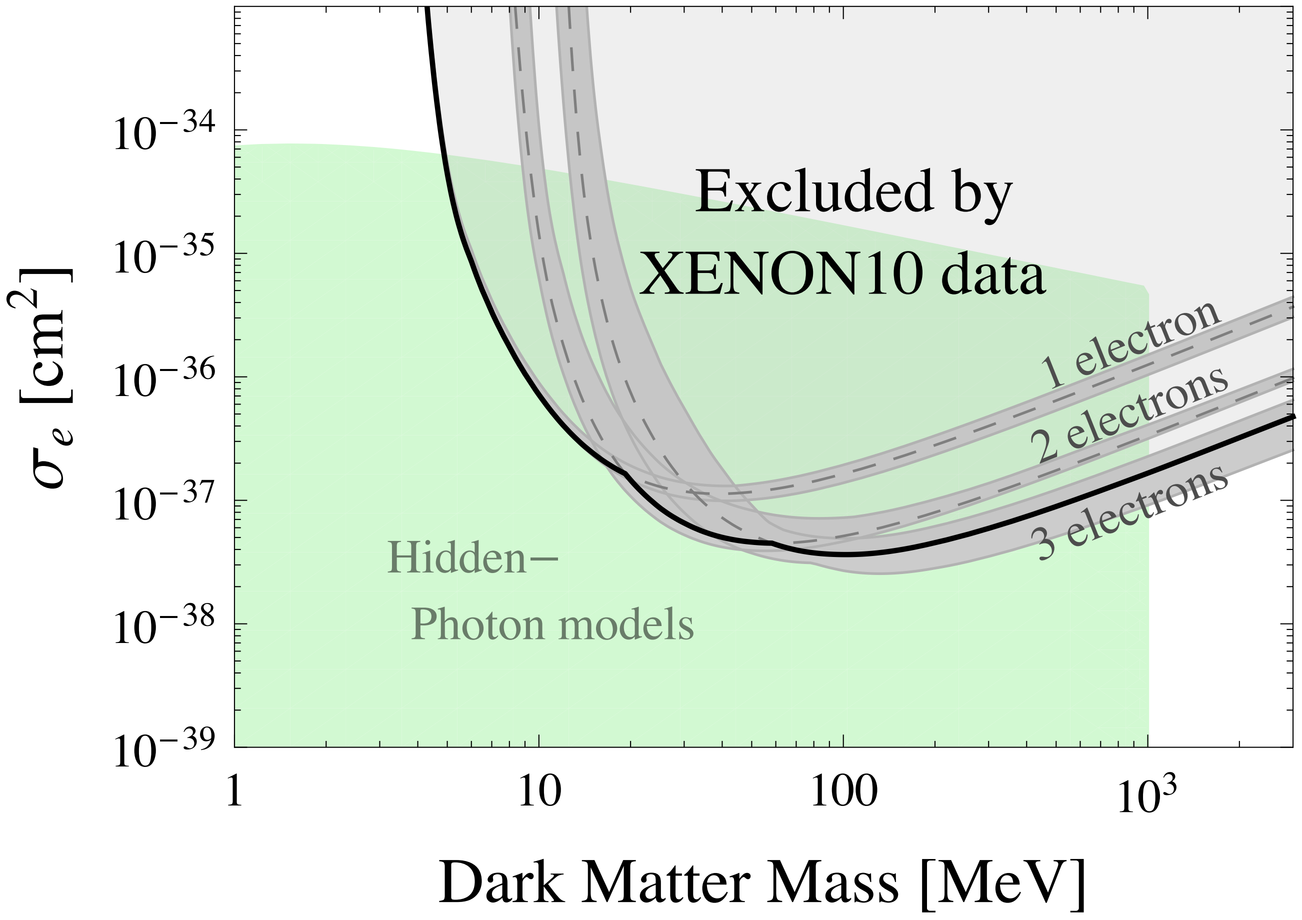
$$\frac{1}{2}m_{\rm DM}v_{\rm DM}^2 \gtrsim E_{\rm binding}(\sim 12\ {\rm eV})$$

$$\boxed{m_{\rm DM} \gtrsim 5\ {\rm MeV}}$$

Xenon electron-ionisation constraints

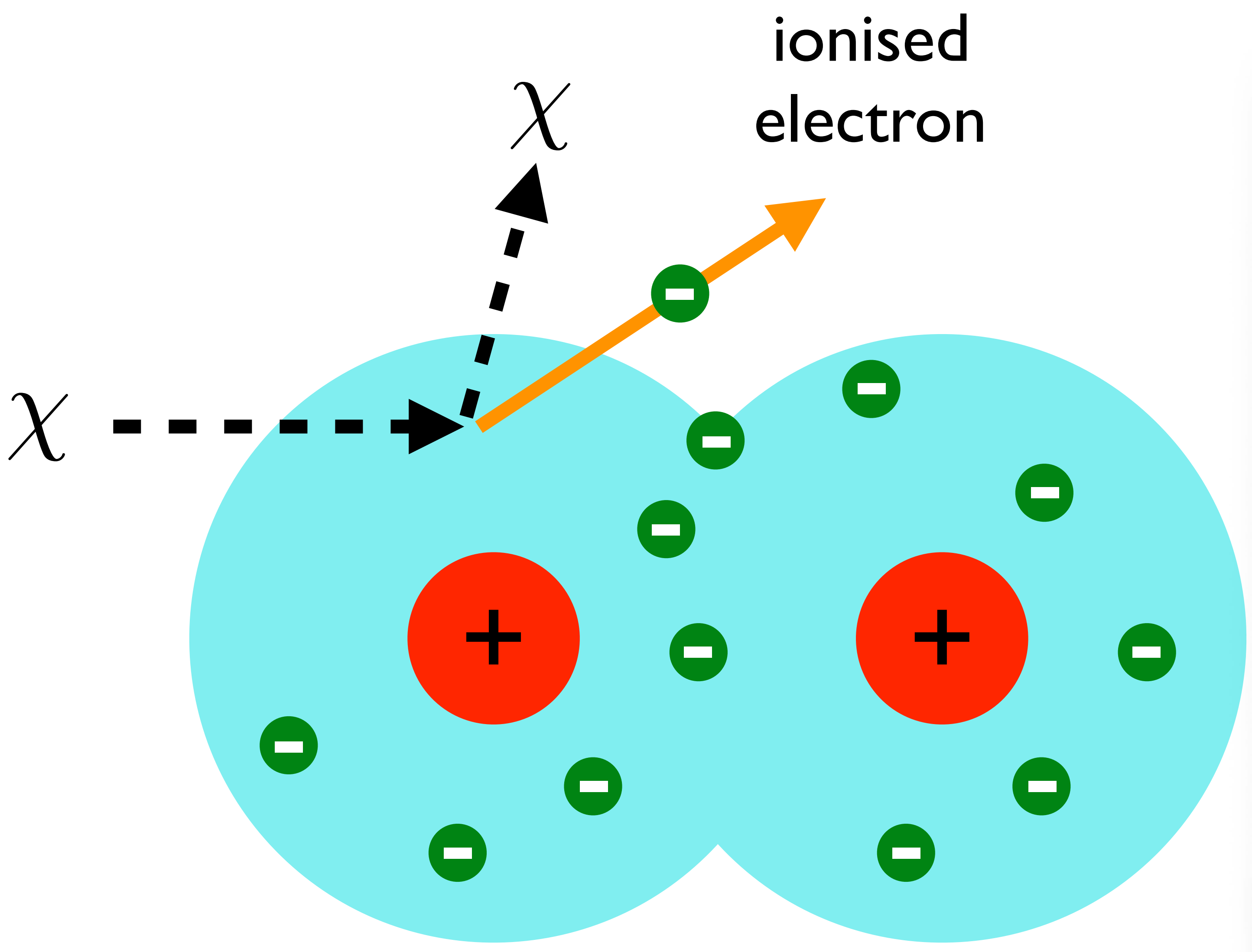
- ZEPLIN, XENON10 & XENON100 can measure single electrons (S2 only)
- *Also possible in argon (e.g. DarkSide-50)*





Essig et al, PRL, arXiv:1206.2644
Essig et al, PRD, arXiv:1703.00910

Electron ionisation in semi-conductors



ionised electron

semiconductor
(overlapping electrons)

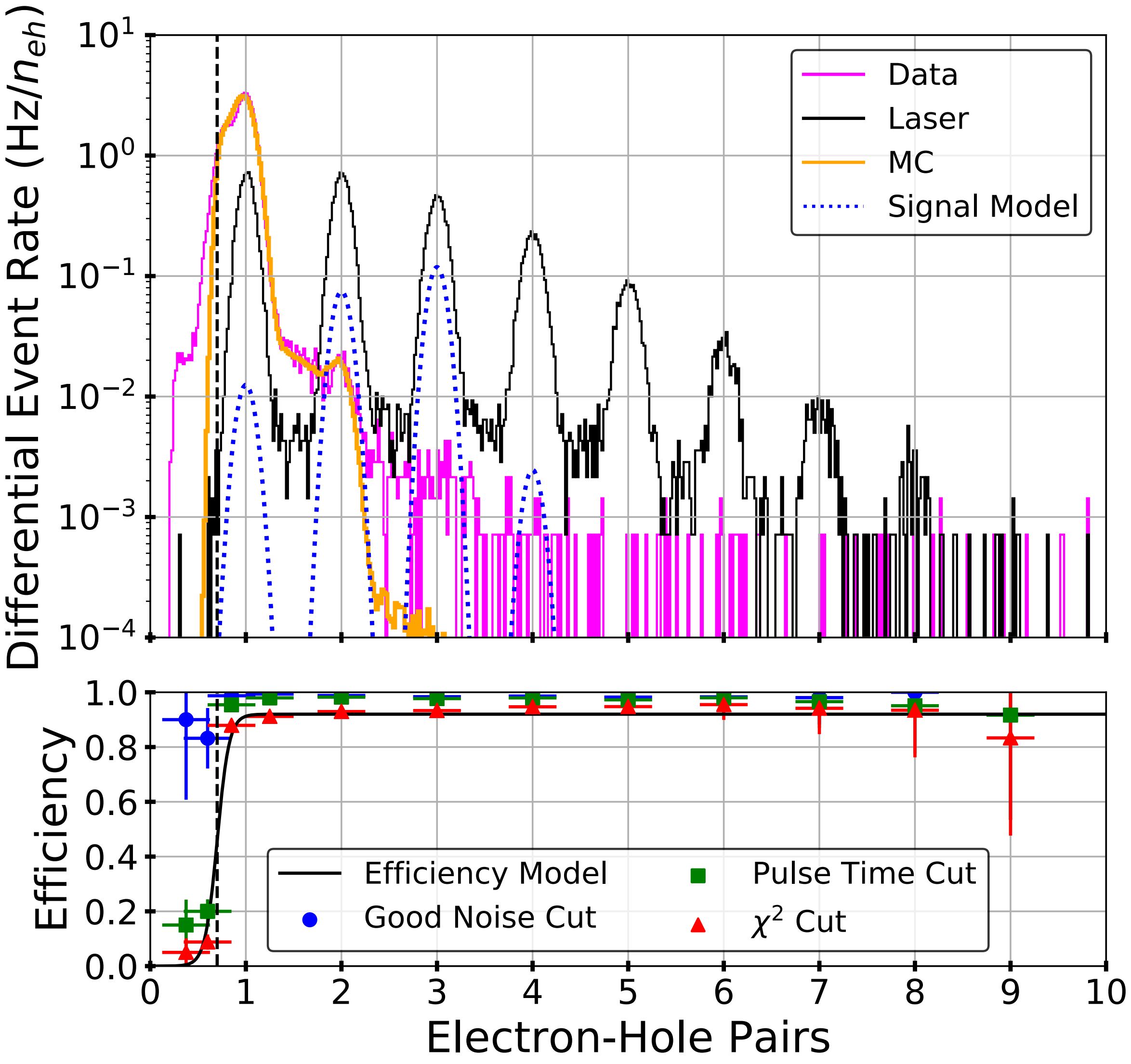
For ionisation, require:

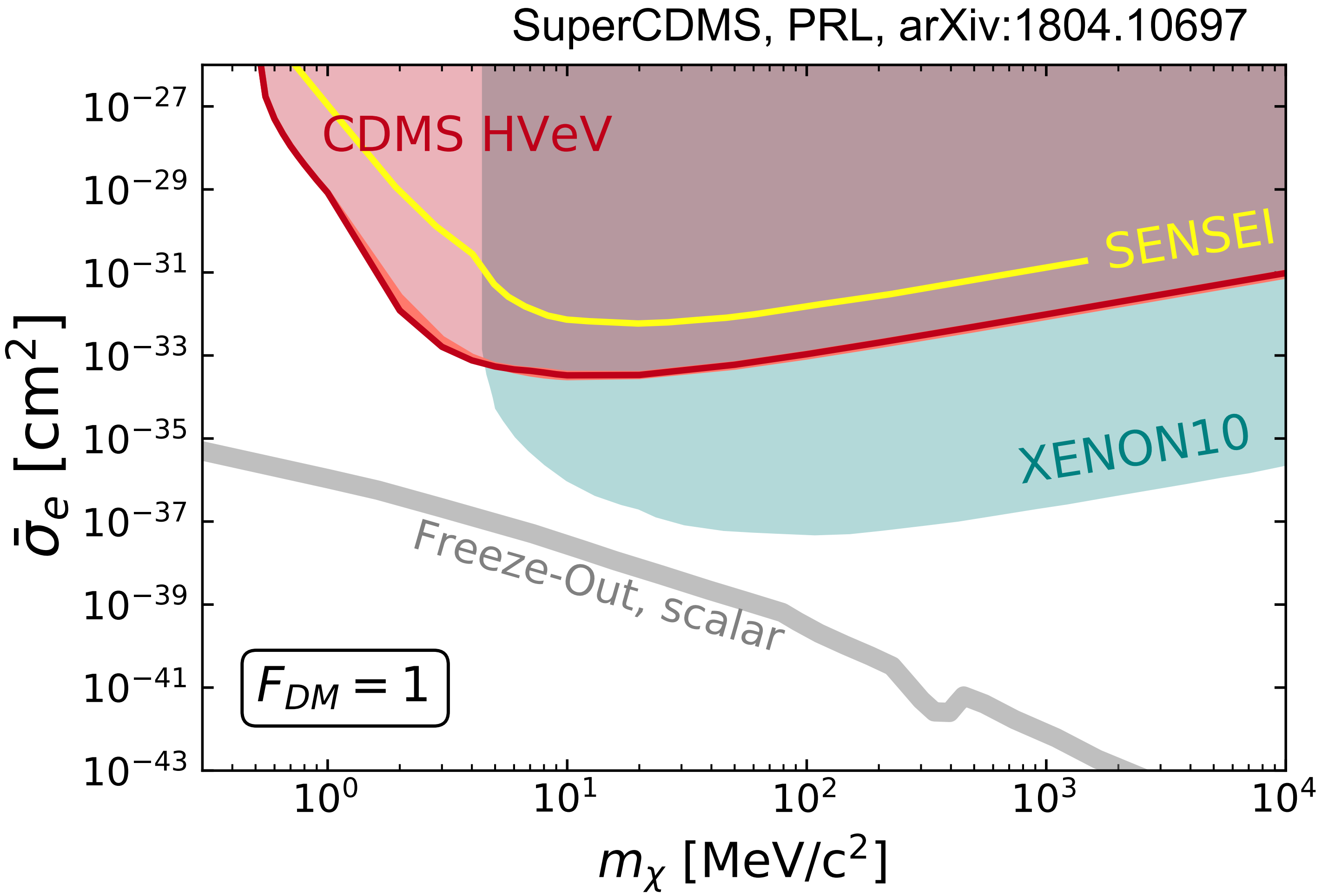
$$\frac{1}{2}m_{\mathrm{DM}}v_{\mathrm{DM}}^2 \gtrsim E_{\mathrm{binding}}$$

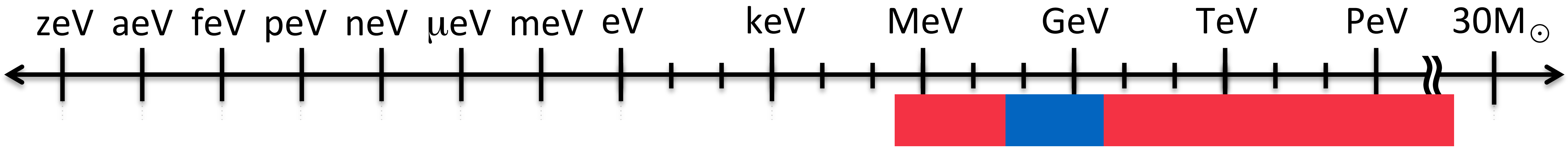
$$E_{\mathrm{binding}}^{\mathrm{semi\text{-}conduct}} \sim 1\ \mathrm{eV}$$

$$\boxed{m_{\mathrm{DM}} \gtrsim 0.5\ \mathrm{MeV}}$$

Electron ionisation in semi-conductors



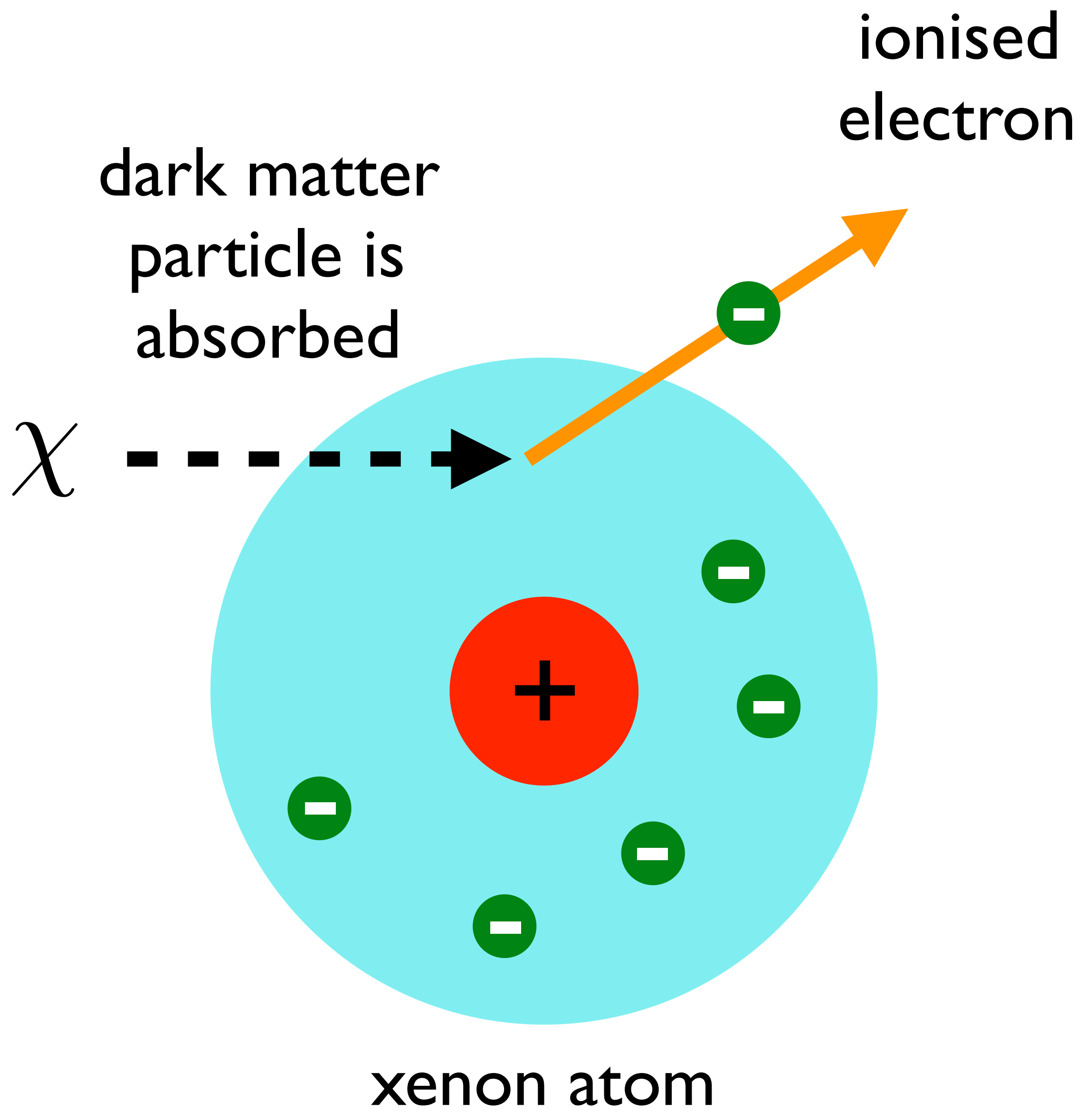

SuperCDMS, PRL, arXiv:1804.10697



Can we go to even lower masses?

Yes! Dark matter conversion

$$\mathcal{L} \supset V_\mu \bar{\psi}_e \gamma^\mu \psi_e \text{ or } A \bar{\psi}_e \gamma^5 \psi_e$$

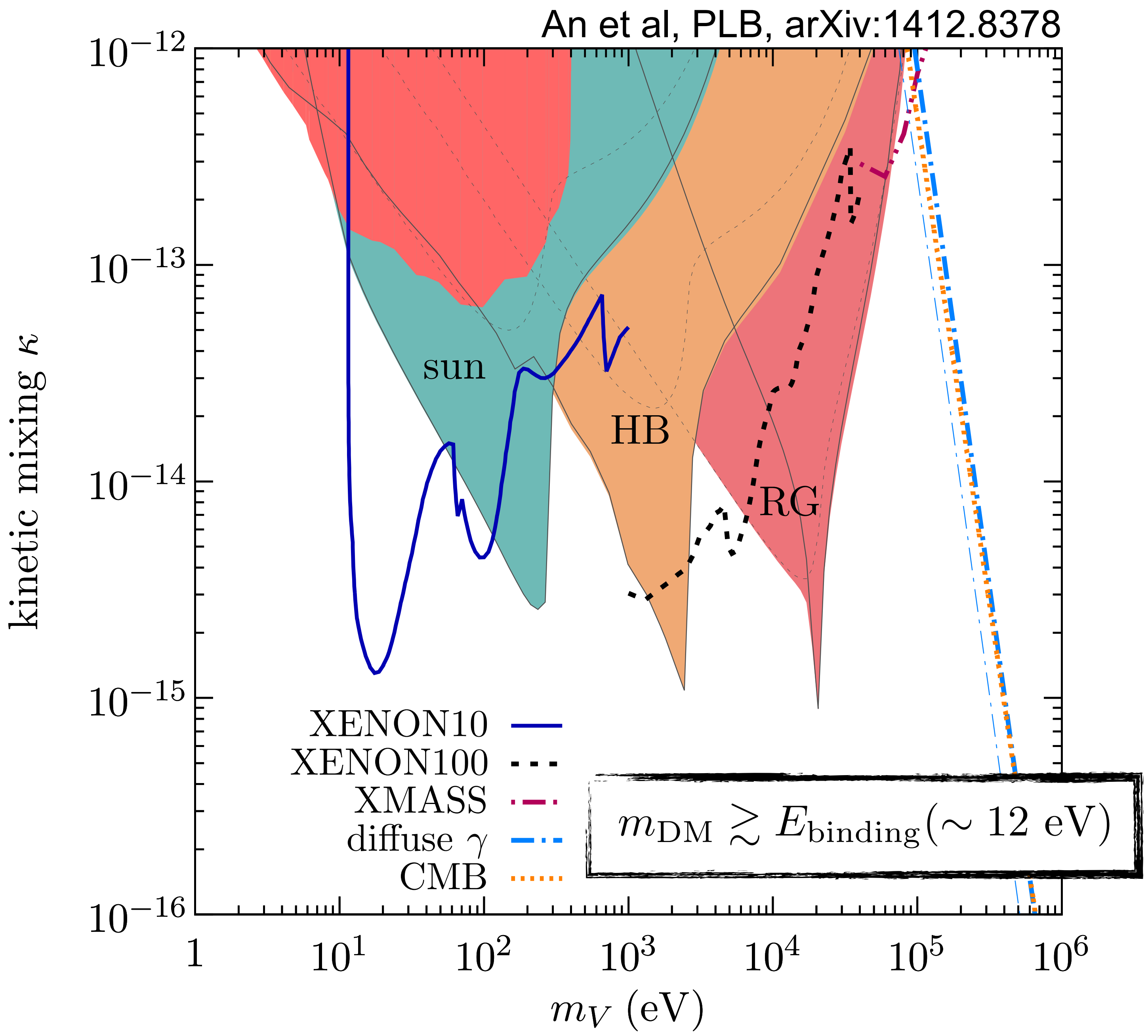


ionised electron

dark matter particle is absorbed

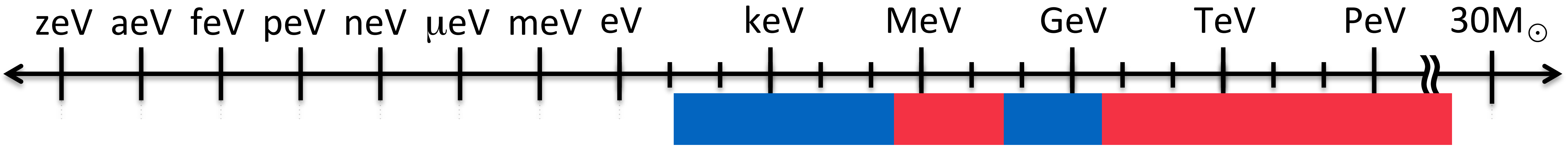
χ

xenon atom

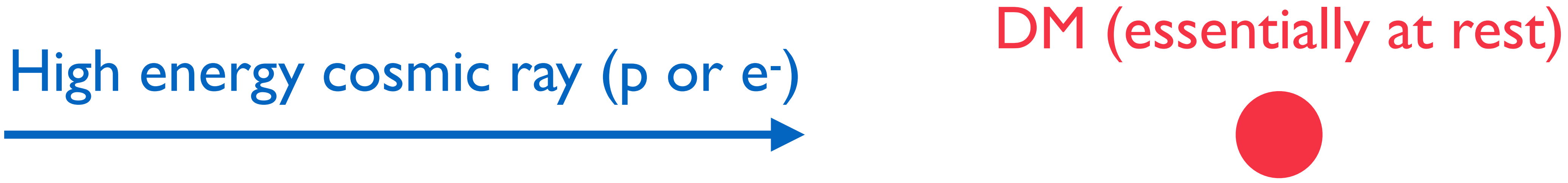


An et al, PLB, arXiv:1412.8378

$m_{\mathrm{DM}} \gtrsim E_{\mathrm{binding}} (\sim 12 \text{ eV})$



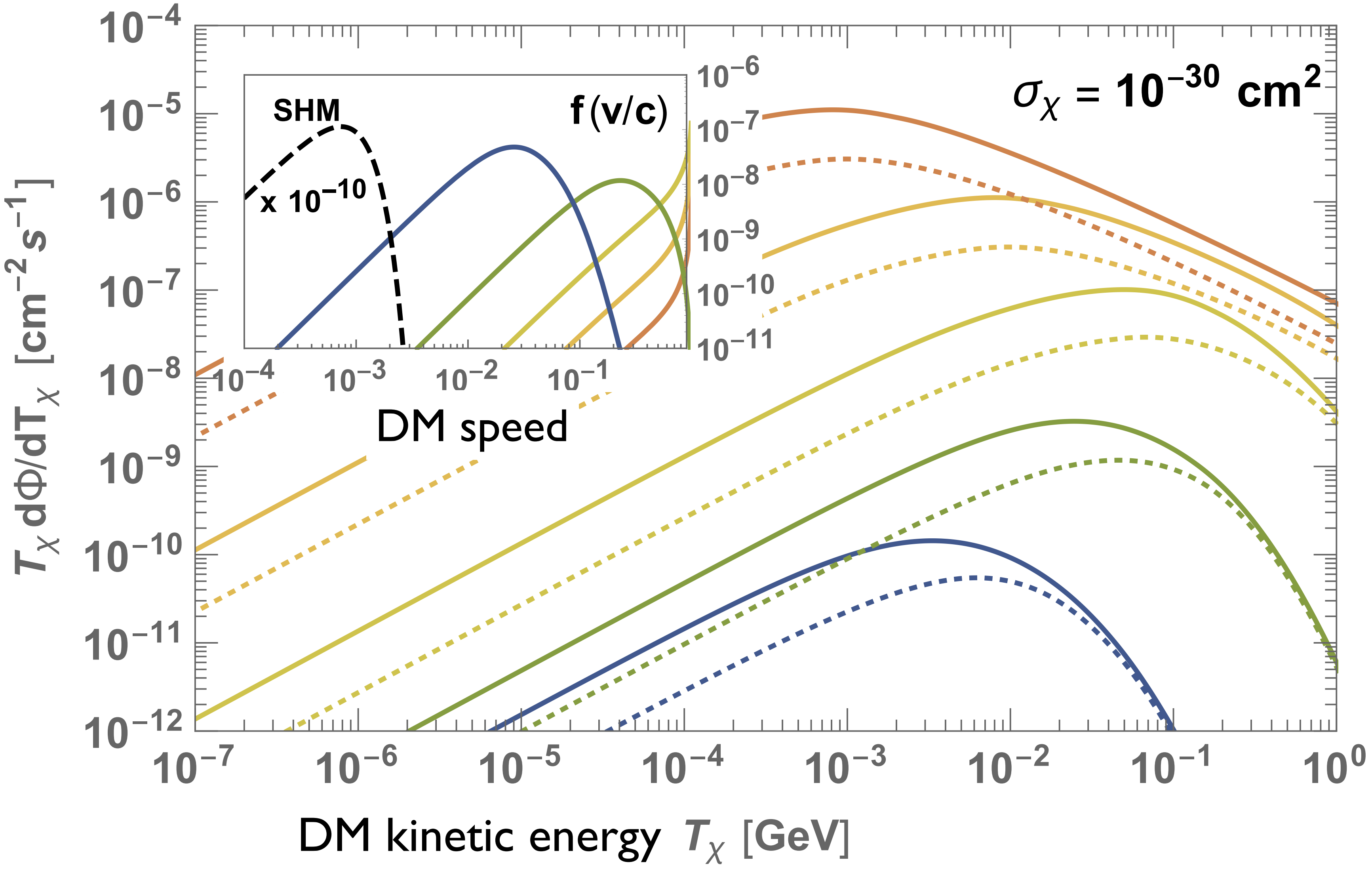
Yes! Semi-relativistic dark matter



High energy cosmic ray (p or e$^-$)

DM (essentially at rest)

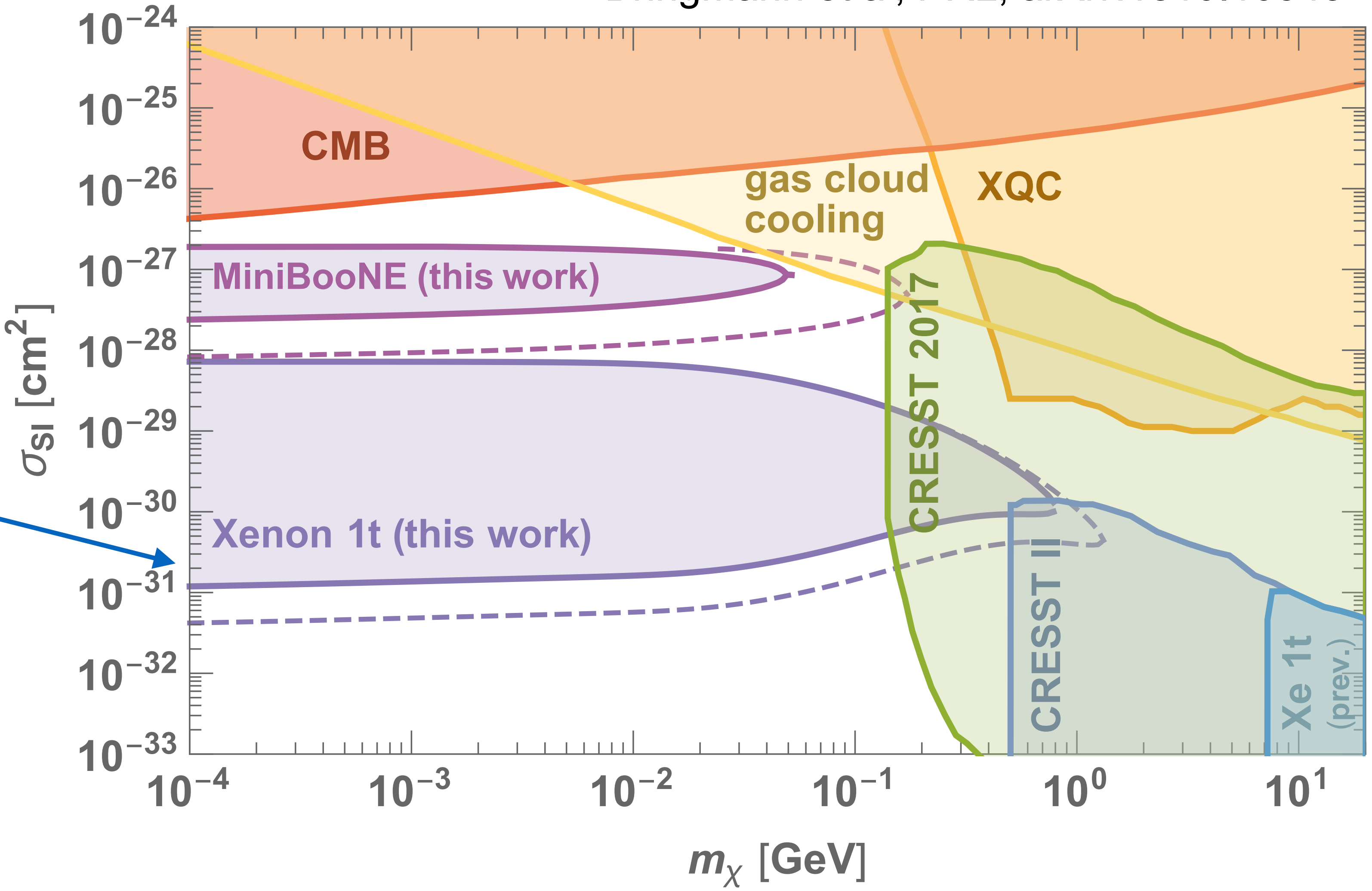
Small irreducible semi-relativistic DM component from cosmic rays scattering



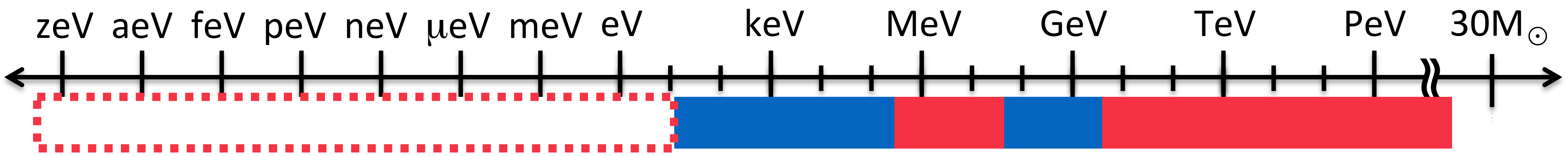
Bringmann et al,
PRL, arXiv:
1810.10543

Yes! Semi-relativistic dark matter

In principle, limits extend down to any mass



Bringmann et al, PRL, arXiv:1810.10543



Take home message

- ‘WIMP’ direct detection experiments are pretty versatile dark matter detectors

- They are sensitive to any DM that gives ~keV energies
  This does not only have to be a WIMP

- Nuclear scattering is important, but also interesting is
  - *electron scattering*
  - *mixed nuclear-electron signals*