A brief introduction to the

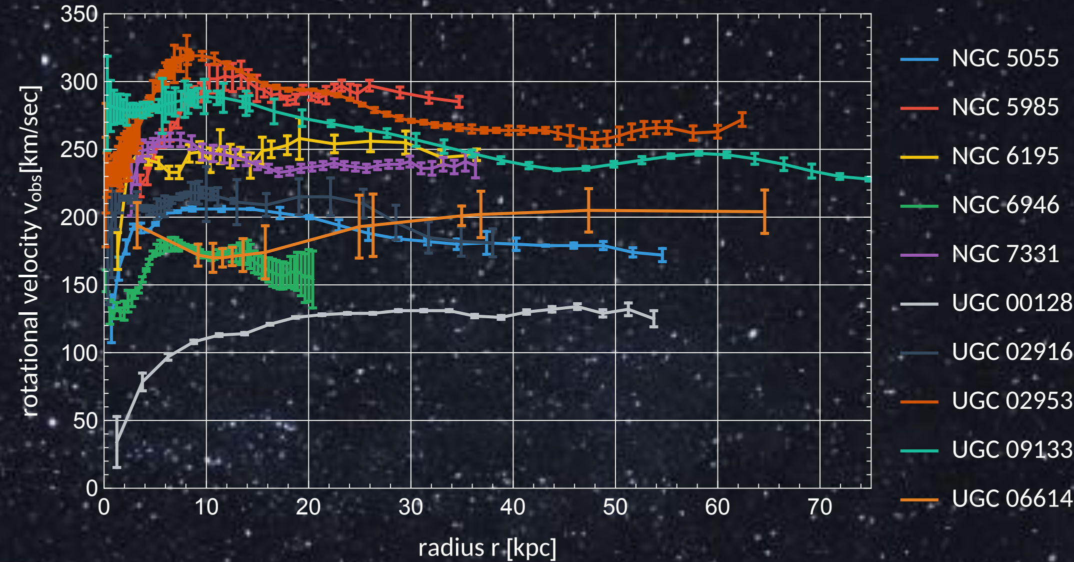
Direct Detection of Dark Matter

How do we know about dark matter?

(a) Fritz Zwicky and the Coma cluster

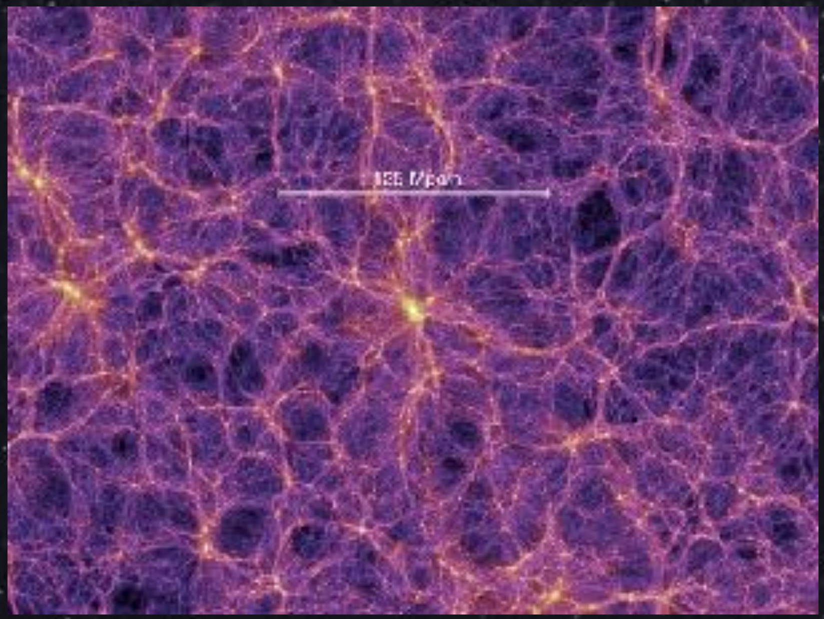
Photo: F. Clark (1971)
F. Zwicky, Helv. Phys. Acta 6 (1933), 249

(b) Galactic rotation curves



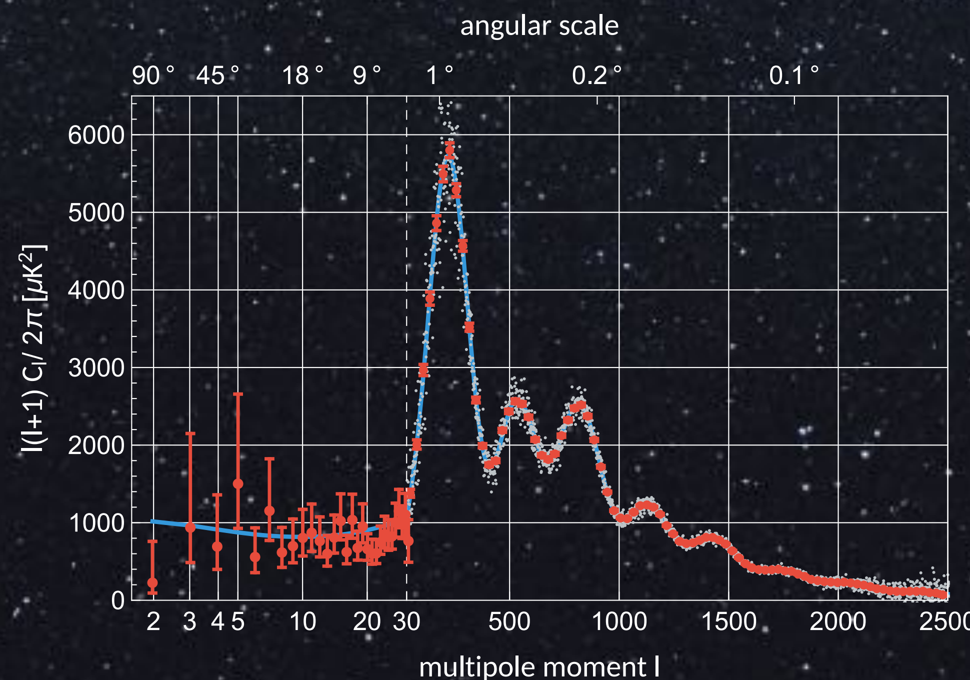
F. Lelli et al., Astron. J. 152 (2016), 157

(c) Cosmological structure formation



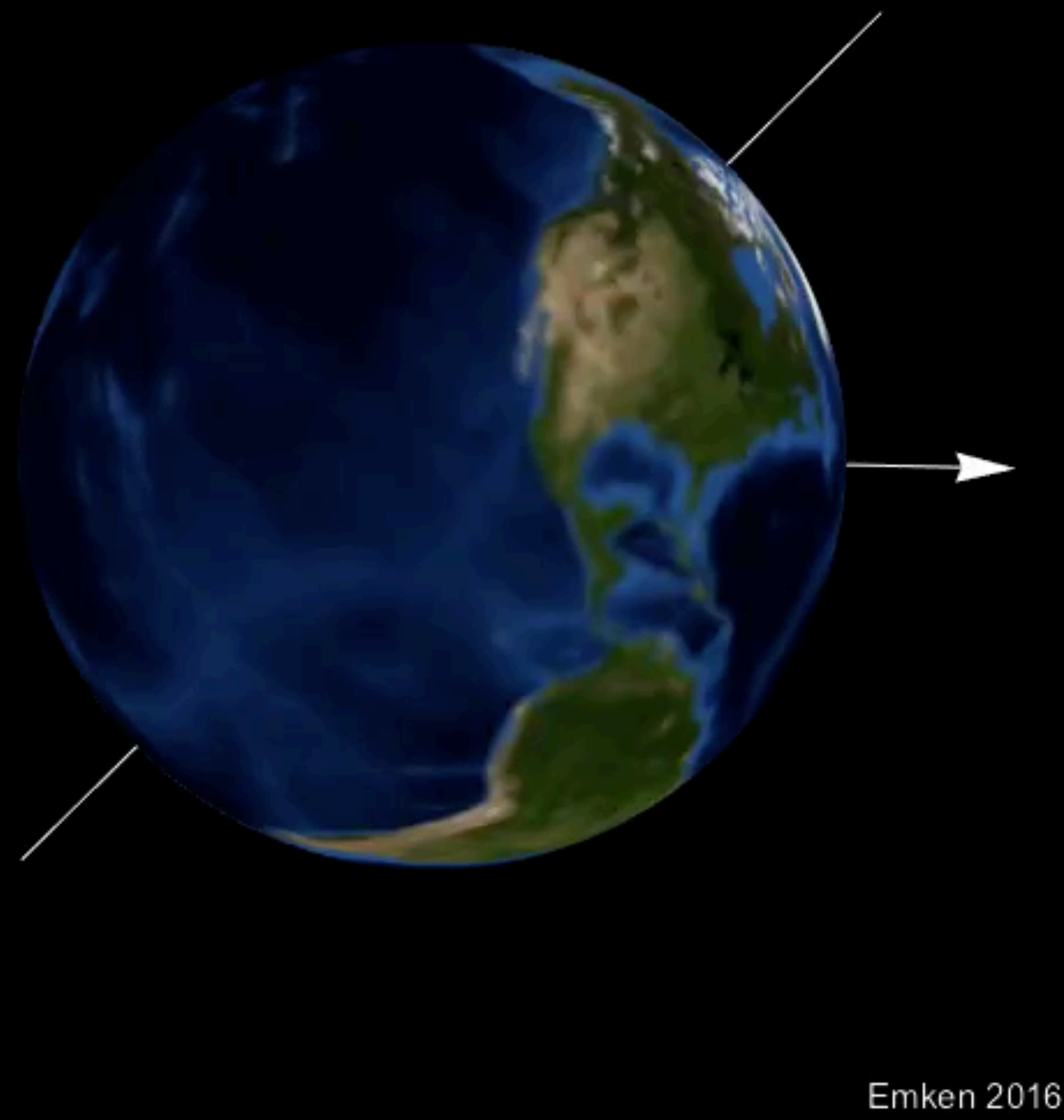
Springel et al., Nature 435 (2005), 629-636

(d) Cosmic microwave background

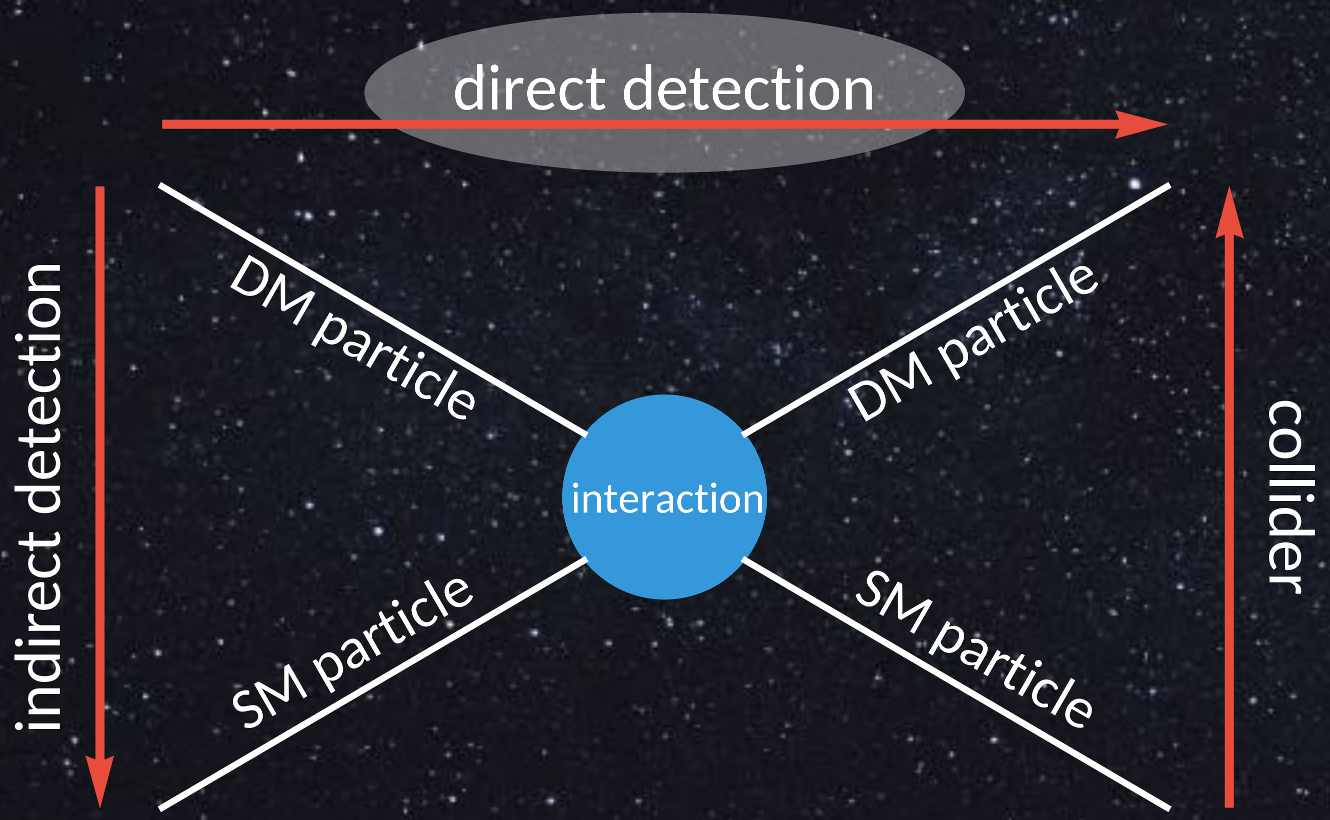


Planck Collaboration, Planck Legacy Archive, (2018)

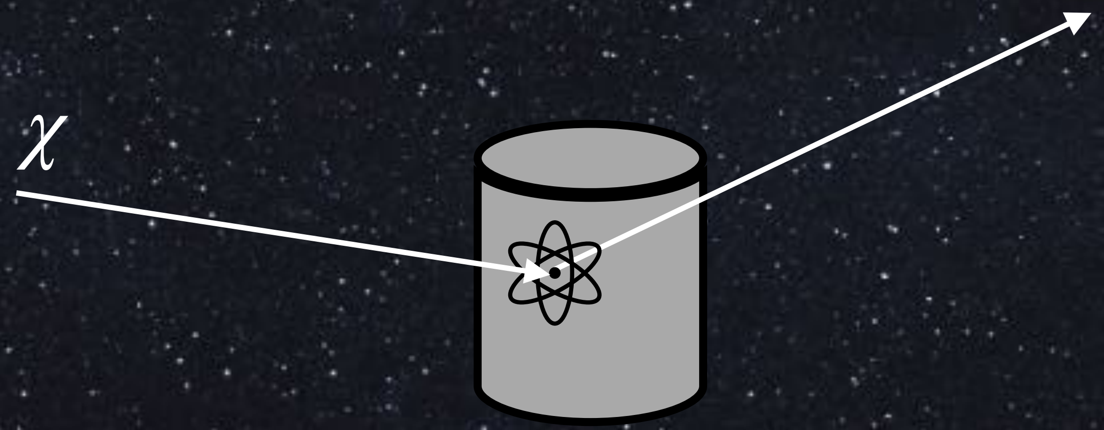
The dark matter “wind”



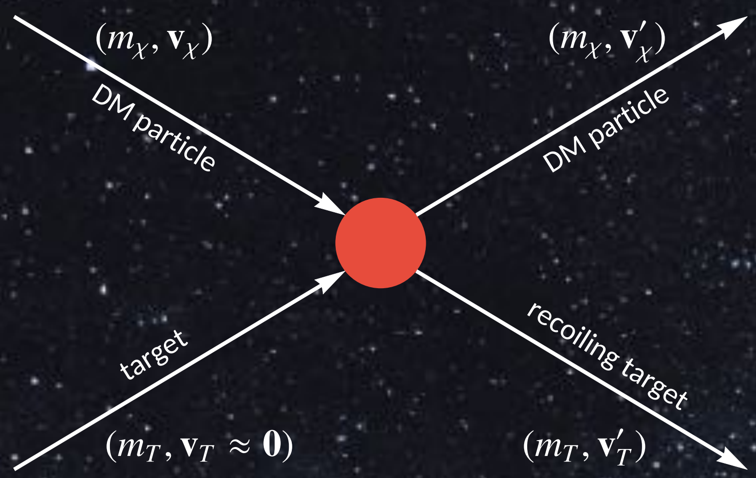
Direct detection of dark matter



Basic idea: Measure the energy deposit of a DM-matter collision inside a detector.



Detecting DM via nuclear recoils



Nuclear recoils as observable for GeV-scale DM searches.

M.W. Goodman and E. Witten, Phys.Rev. D31 (1985) 3059
I. Wasserman, Phys. Rev. D33 (1986) 2071
A.K. Drukier et al., Phys. Rev. D33 (1986) 3495

Event spectrum:

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = N_T \frac{\rho_\chi}{m_\chi} \iiint \mathrm{d}^3\mathbf{v}\, v f_\chi(\mathbf{v}) \frac{\mathrm{d}\sigma_N}{\mathrm{d}E_R} \Theta(v - v_{\min}(E_R)) \,.$$

Detector size

Particle physics

Astrophysics

Kinematics

DM velocity distribution:

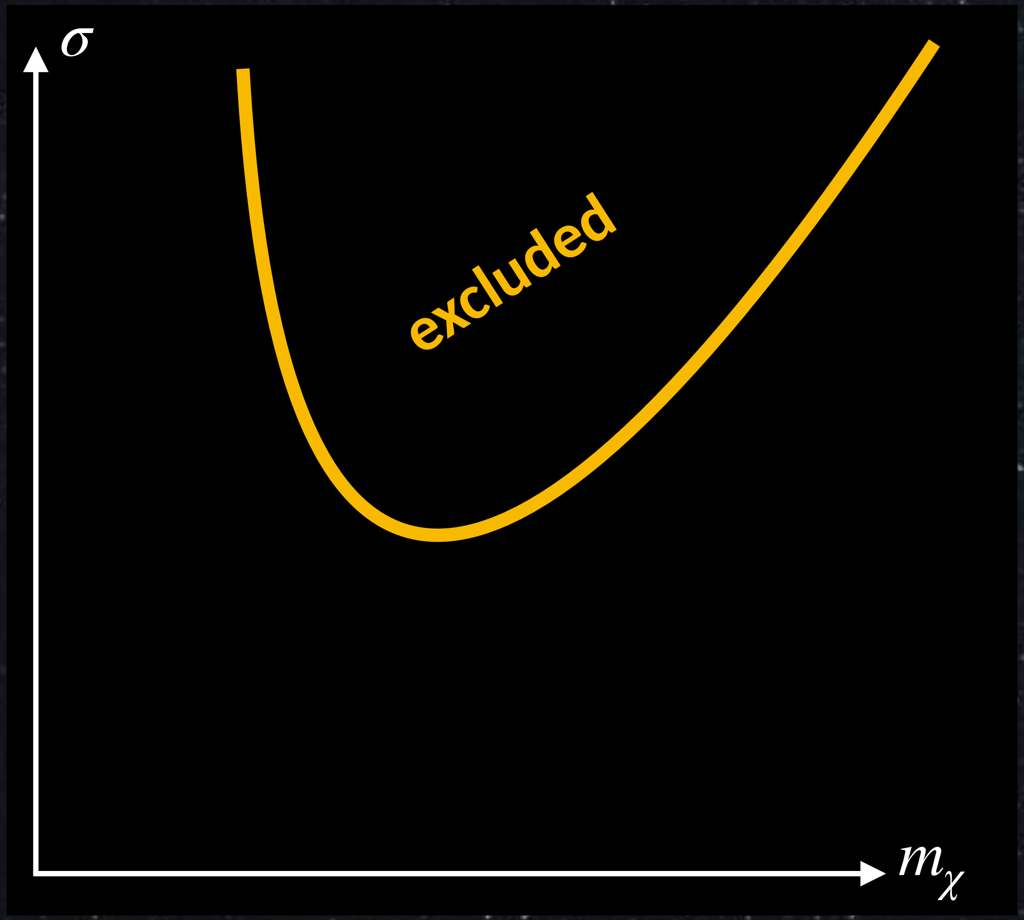
$$f_{\mathrm{halo}}(\mathbf{v}) = \frac{1}{N_{\mathrm{esc}} \pi^{3/2} v_0^3} \exp\left(-\frac{\mathbf{v}^2}{v_0^2}\right) \Theta(v_{\mathrm{gal}} - |\mathbf{v}|)$$

sharp speed cutoff

What a direct detection experiment can find

No signal, only background (null result). **OR** **A signal!**

- Understanding exclusion limits from direct detection



- What does it take to *discover* dark matter?
  - A signal excess?
  - Detection of an annual modulation?
  - Directional detection?
  - Confirmation by a second experiment, or another type of experiments, e.g. colliders?

Direct Detection of Dark Matter via electron recoils

J. Kopp et al., Phys. Rev. D80 (2009) 083502
R. Essig et al., Phys. Rev. D85 (2012) 076007

Instead of nuclear recoils, search for DM-electron interactions.

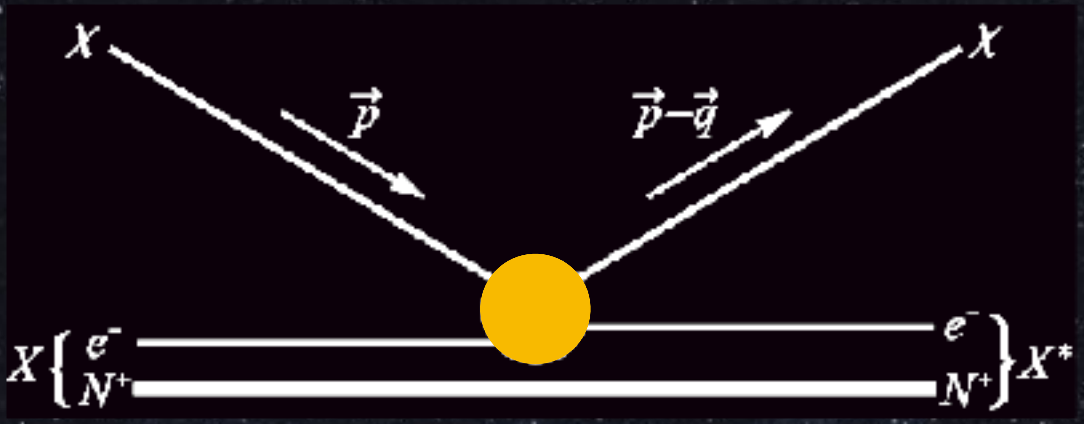


Figure from Essig et al., [arXiv:1509.01598]

- Different kinematics:

$$E_e^{\max} = \frac{1}{2}\mu_{\chi N} v^2 \lesssim E_\chi \sim 0.5\,\text{eV}\left(\frac{m_\chi}{\text{MeV}}\right)$$

Compare to

$$E_{\text{NR}}^{\max} = \gamma E_\chi$$

$$\gamma \approx 4\frac{m_\chi}{m_N} \ll 1 \quad \text{for } m_\chi \ll m_N$$

- No kinematic penalty: $E_e \leq E_\chi$.
- Lowest DM mass to excite/ionize an electron in...
  - ...an isolated atom:

$$E_B \approx 10\,\text{eV}$$

$$\Rightarrow \quad m_\chi^{\min} \approx 5\,\text{MeV}$$

  - ...a semiconductor:

$$E_{\text{gap}} \approx 1\,\text{eV}$$

$$\Rightarrow \quad m_\chi^{\min} \approx 500\,\text{keV}$$

Lee et al., PRD 92 (2015) 083517
Essig et al., JHEP 1605 (2016) 046

DM induced electron transitions & ionizations

- Complication: Target electrons are bound states, energy eigenstates, but not momentum eigenstates.

$$\frac{\mathrm{d}R_{\mathrm{ion}}}{\mathrm{d}E_e} = \frac{1}{m_N}\frac{\rho_\chi}{m_\chi}\sum_{nl}\frac{\langle \mathrm{d}\sigma_{\mathrm{ion}}^{nl} v\rangle}{\mathrm{d}E_e}$$

Ionization form factor

$$\frac{\mathrm{d}\langle \sigma_{\mathrm{ion}}^{nl} v\rangle}{\mathrm{d}E_e} = \frac{\sigma_e}{8\mu_{\chi e}^2 E_e}\int \mathrm{d}q\, q \left|F_{\mathrm{DM}}(q)\right|^2 \left|f_{\mathrm{ion}}^{nl}(k',q)\right|^2 \eta\left(v_{\mathrm{min}}(\Delta E_e, q)\right)$$

- Depending on the target, this requires condensed matter theory.
- The ionization form factor only applies to a certain class of DM models.

Catena, R., TE, Spaldin N., Tarantino, W., PRR 2 (2020) 033195

Recent results on DM electron scattering experiments

- Semiconductor target experiments

1. SENSEI
   Barak et al, PRL 125 (2020) 17, 171802
   Abramoff et al., PRL 122 (2019) 161801
   Crisler et al., PRL 121 (2018) 061803
2. SuperCDMS
   Agnese et al., PRL 121 (2018) 051301
3. DAMIC at SNOLAB
   Aguilar-Arevalo et al., [arXiv:1907.12628]

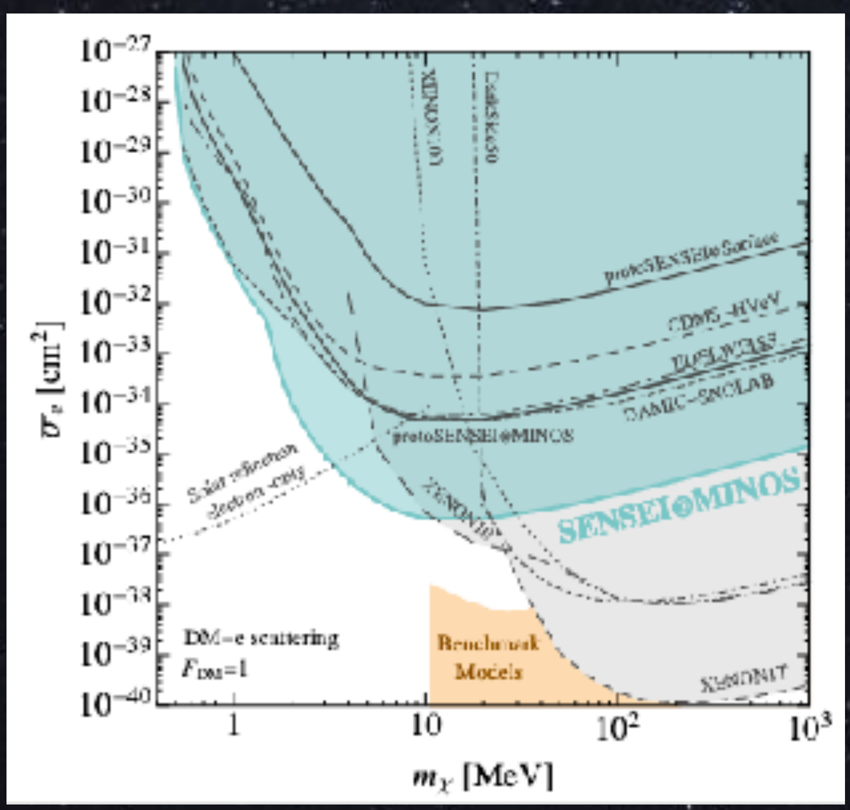


Figure from [2004.11378].

- Liquid noble gas targets

1. XENON10, XENON100, XENON1T
   Essig et al., PRL 109 (2012), 021301
   Essig et al., PRD 96 (2017), 043017
   Aprile et al.,PRL 123 (2019), 251801
2. DarkSide-50 (liquid argon)
   Agnes et al., PRL 121 (2018) 111303

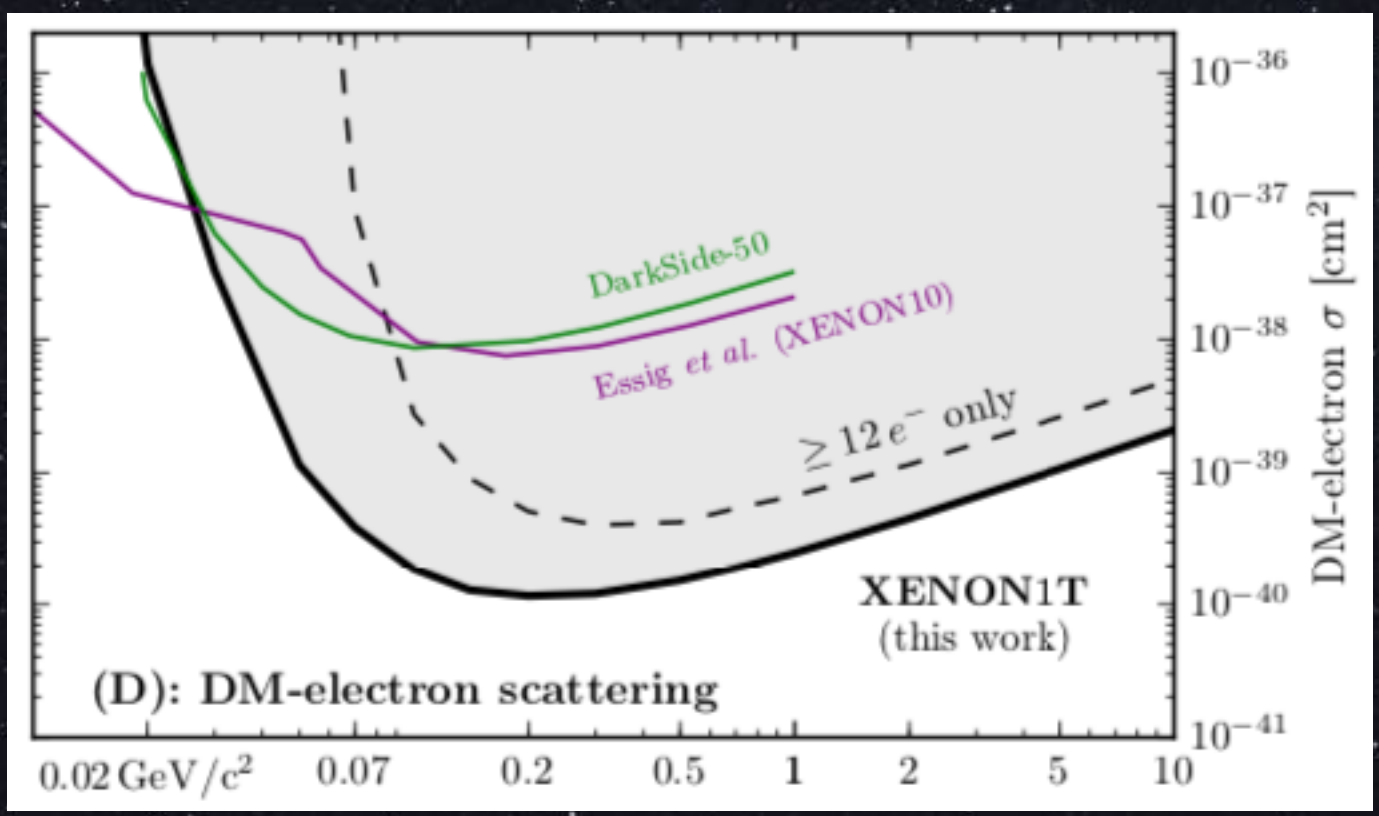


Figure from [1907.11485].