Dark Matter Substructure under the Electron Scattering Lamppost

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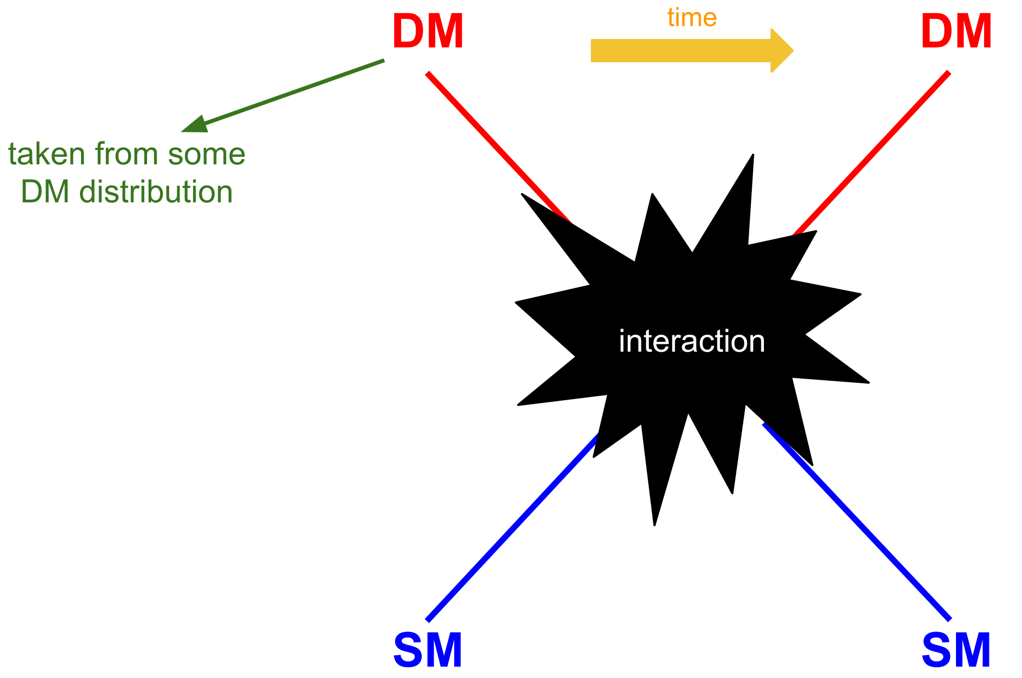
Cosmology from Home

Outline

1. Introduction
2. Substructure in the *Gaia* era
3. DM detection with electron recoil (ER) experiments
4. Forecasts for next-generation ER experiments
5. Prospects for Astroparticle physics

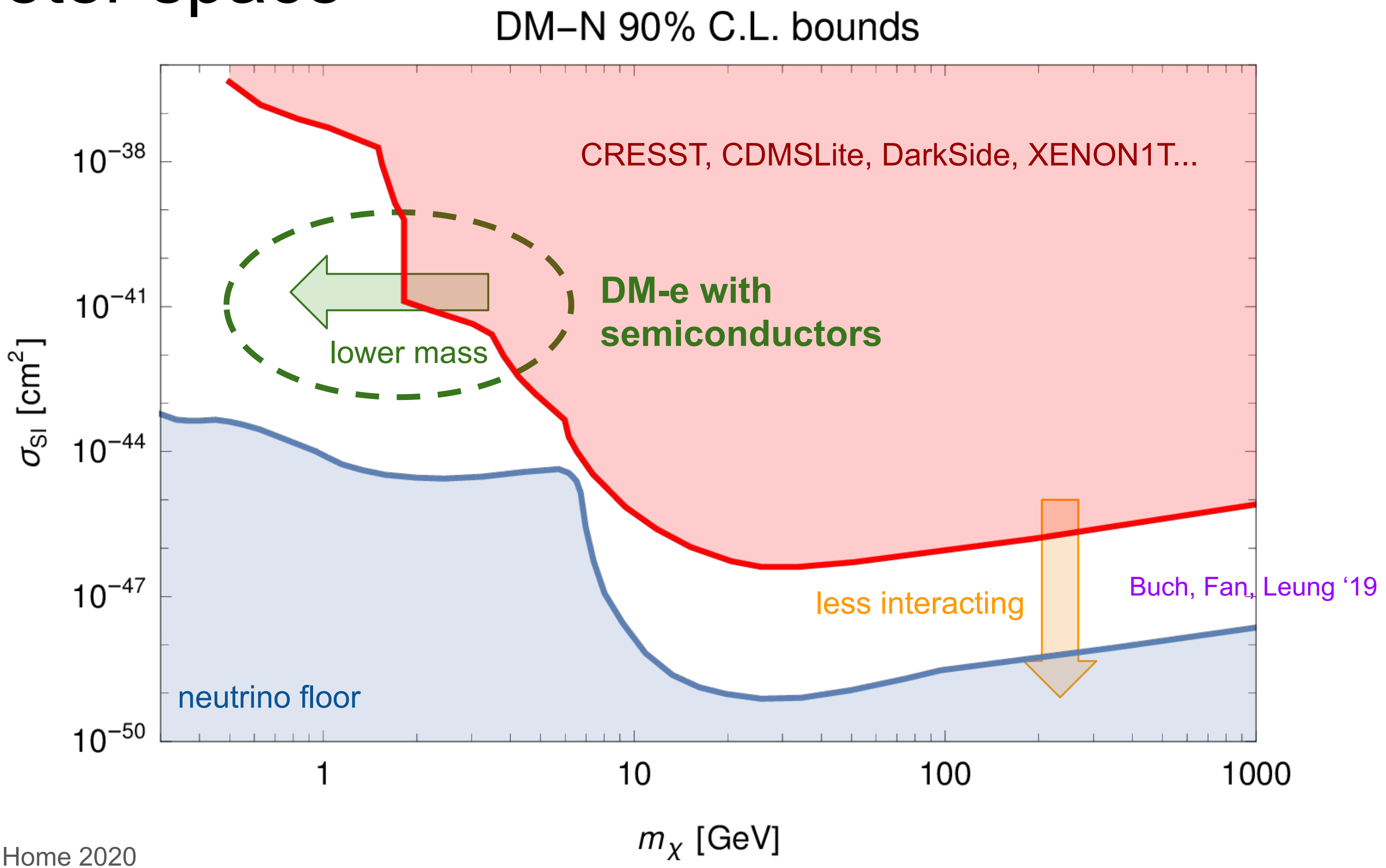
1. Introduction

Direct Detection (DD): *wait and see*



Goodman, Witten, ‘84

Parameter space



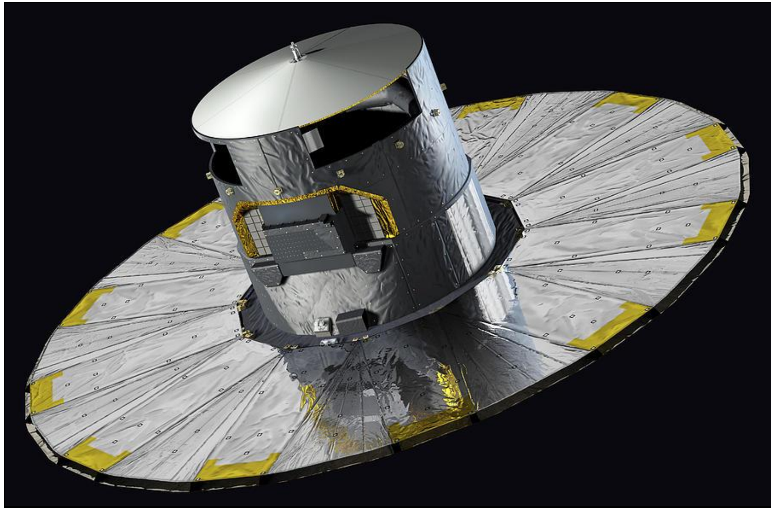
Motivation

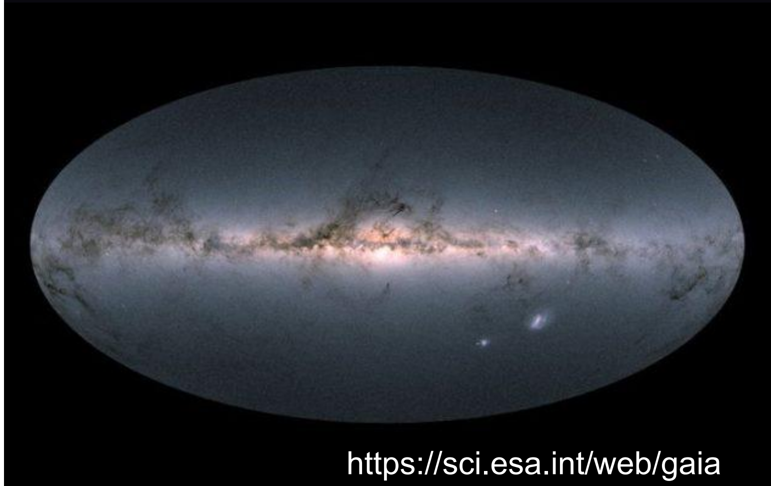
- What are the prospects of detecting a DM signal with next-generation electron recoil experiments for a given DM velocity distribution?
- Assuming discovery, can we distinguish the effects of DM substructure such as streams in a statistically significant way?
- Warning: Unrelated to the recent Xenon1T ER excess! The recoil energies are ~O(keV) in their case, while we focus on ~O(10 eV).

2. Substructure in the *Gaia* era

Gaia in numbers

- ESA satellite launched 2013
  - @ L2: 1.5 million km from Earth; anti-Sun
  - Successor to *Hipparcos* (1989-1993)
  - End: 12/31/2022
- Astrometry + photometry + spectrometry
- **DR2:** positions, parallaxes (24 μas), and proper motions of **1.3 billion** stars: **1% of Milky Way stars**
- 1 PB completed dataset



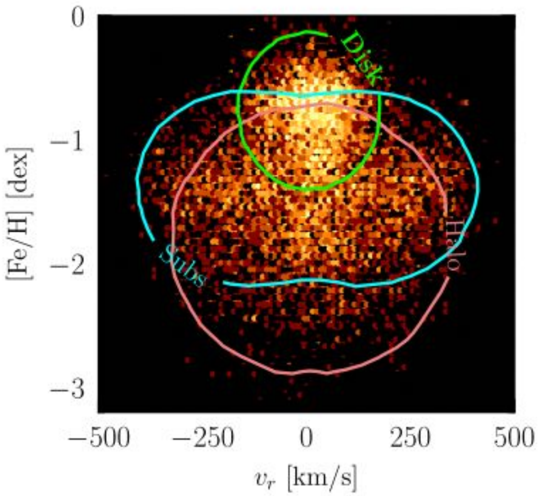


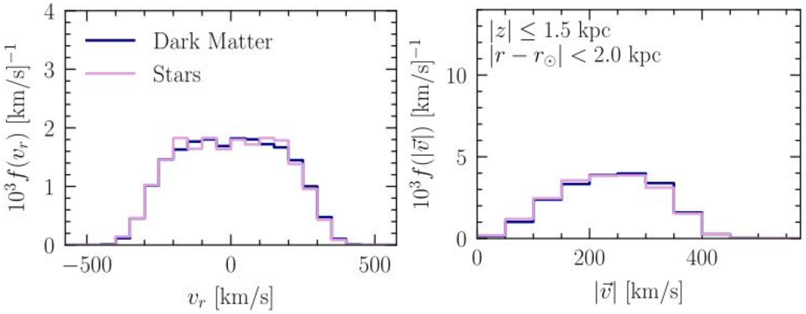
Discoveries with *Gaia*

- *Gaia*: Milky Way (MW) stellar substructure from history of mergers:
  - Debris flow:
    - *Gaia* Enceladus/Sausage
  - Streams
    - Nyx
    - S1, S2a, S2b
- Expected: stars ***and*** DM are tidally stripped in subhalo merger events
- *Old*: stellar rotation curves ⇒ Dark Matter (DM) in a Halo
  - Standard Halo Model (SHM): ***v*=220 km/s**
- *New*: need to move Beyond SHM (BSHM)

BSHM: *Gaia* Enceladus/Sausage

- Debris flow: spatially mixed, warm kinematic stellar substructure
- Formed from merger of dwarf galaxy, with mass $M \sim 10^{7\text{-}8}\ M_{Sun}$
- DM distribution from stars?
  - *FIRE-2* simulations: accreted low metallicity (read: older) stars **correlate** with DM

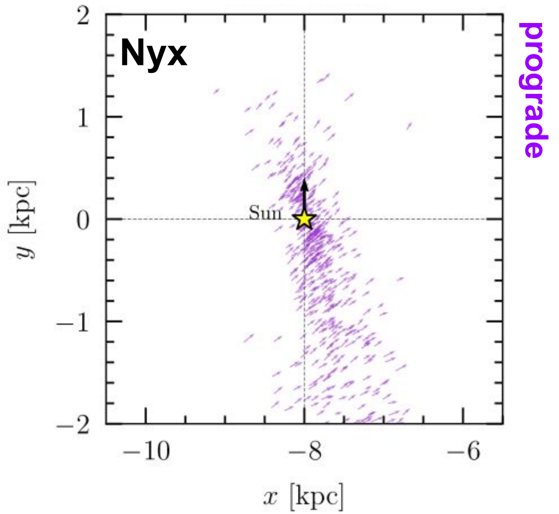


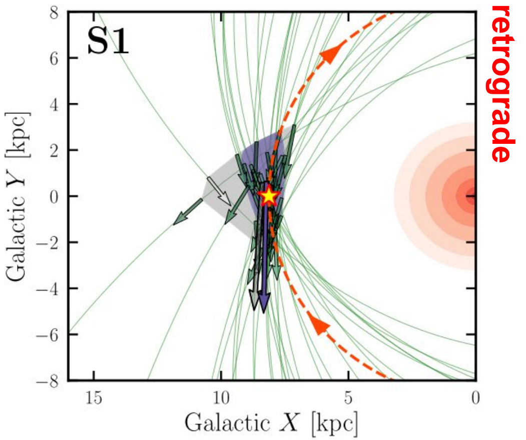


[Belokurov, et al. 1802.03414; Necib, et al. arXiv:1807.02519; Necib, et al. arXiv:1810.12301]

BSHM: Streams

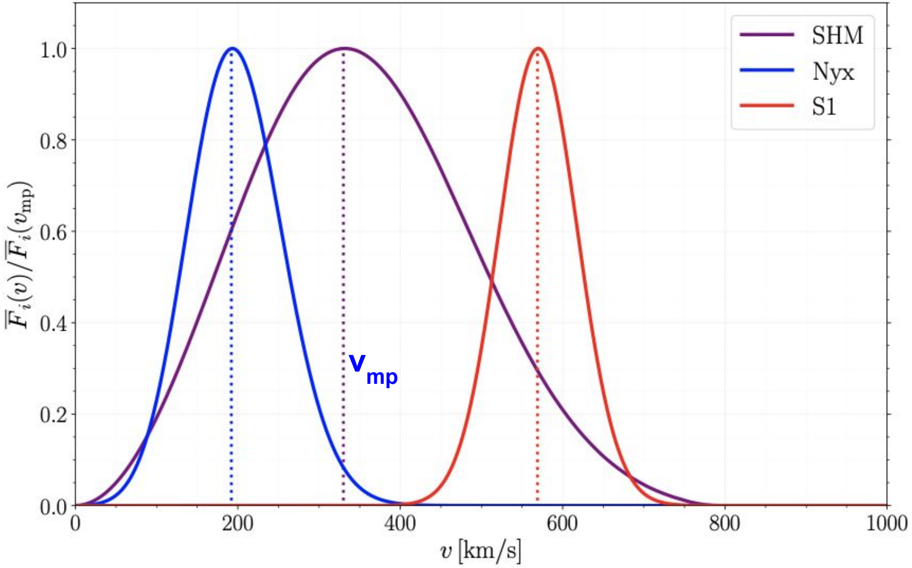
- Spatially localized, cold kinematic stellar substructures
- Formed by recent mergers (dwarf spheroidals)
- A few:
    - **Nyx** [Necib, et al. arXiv:1907.07190]
    - **S1, S2a, S2b** [Myeong, et al. 1804.07050; O'Hare, et al. arXiv:1909.04684]
- DM distribution from stars?
    - *FIRE-2* simulations: no perfect stars-DM correlation; *but* mergers of dwarf spheroidals are better [Necib, et al. arXiv:1810.12301; O'Hare, et al. arXiv:1909.04684]



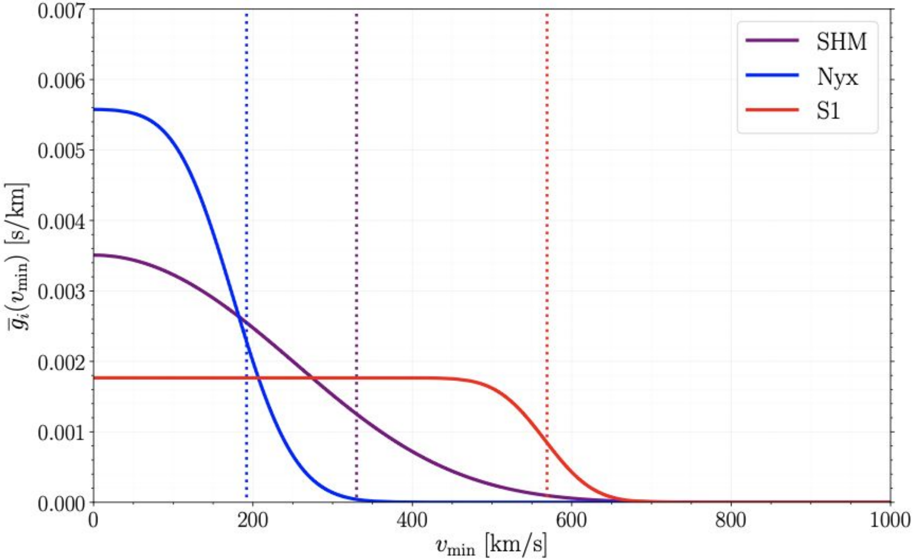


Substructure Properties

$$g(0) = \left\langle \frac{1}{v} \right\rangle \sim \frac{1}{\langle v \rangle} \sim \frac{1}{v_{\rm mp}}$$

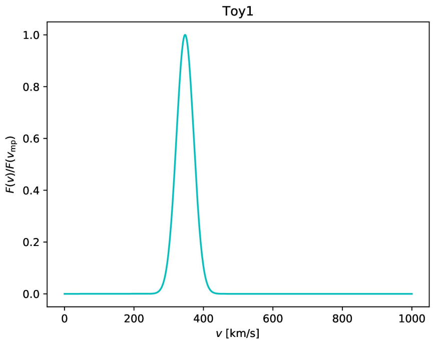


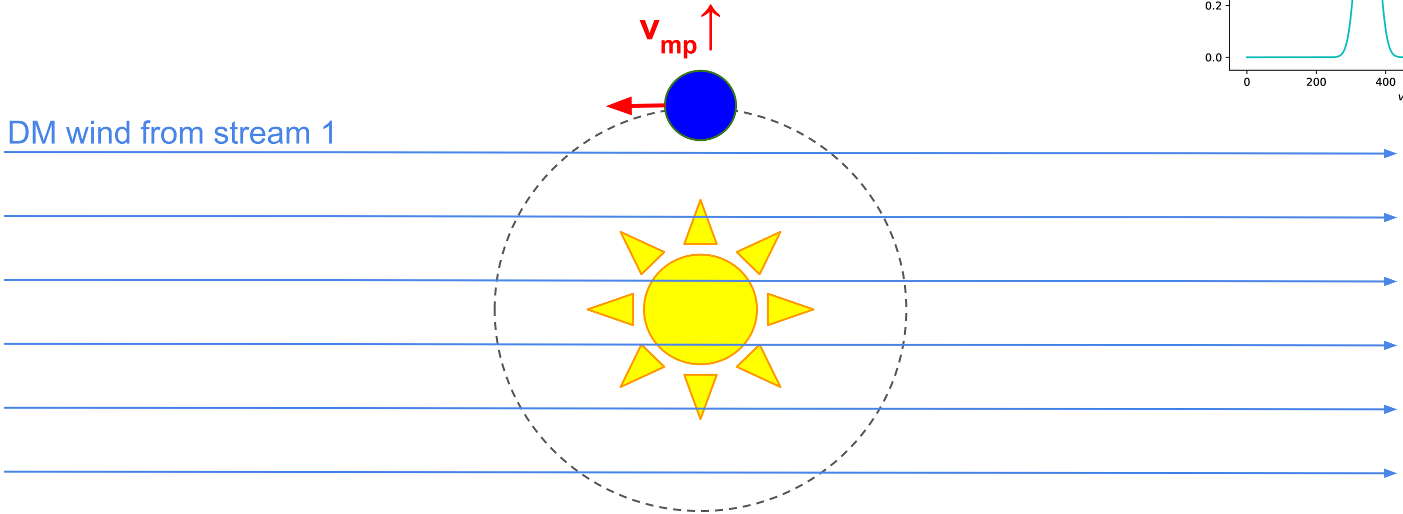
$$F(v) = v^2 \int \mathrm{d}\Omega \; f(\mathbf{v})$$



$$g(v_{\rm min}) = \int_{v_{\rm min}}^{v_{\rm esc}} \mathrm{d}v \; \frac{F(v)}{v}$$

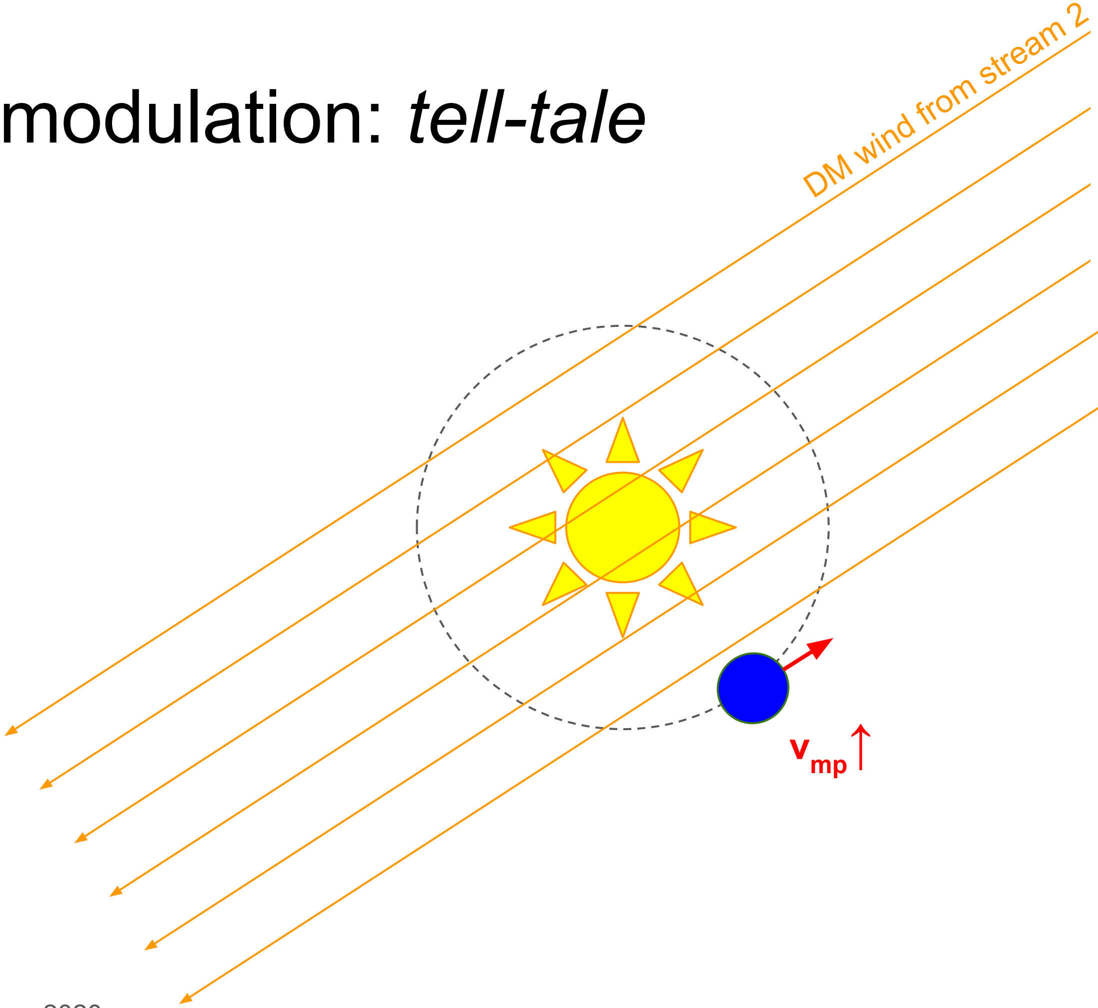
Annual modulation: *tell-tale*

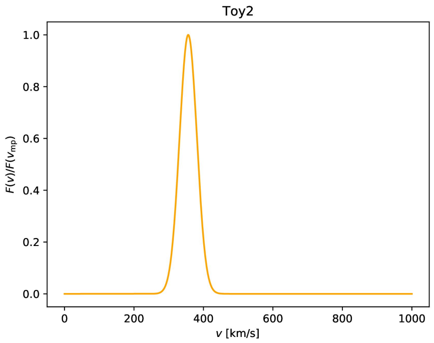




Drukier, Freese, Spergel '86
Freese, Lisanti, Savage '12

Annual modulation: *tell-tale*



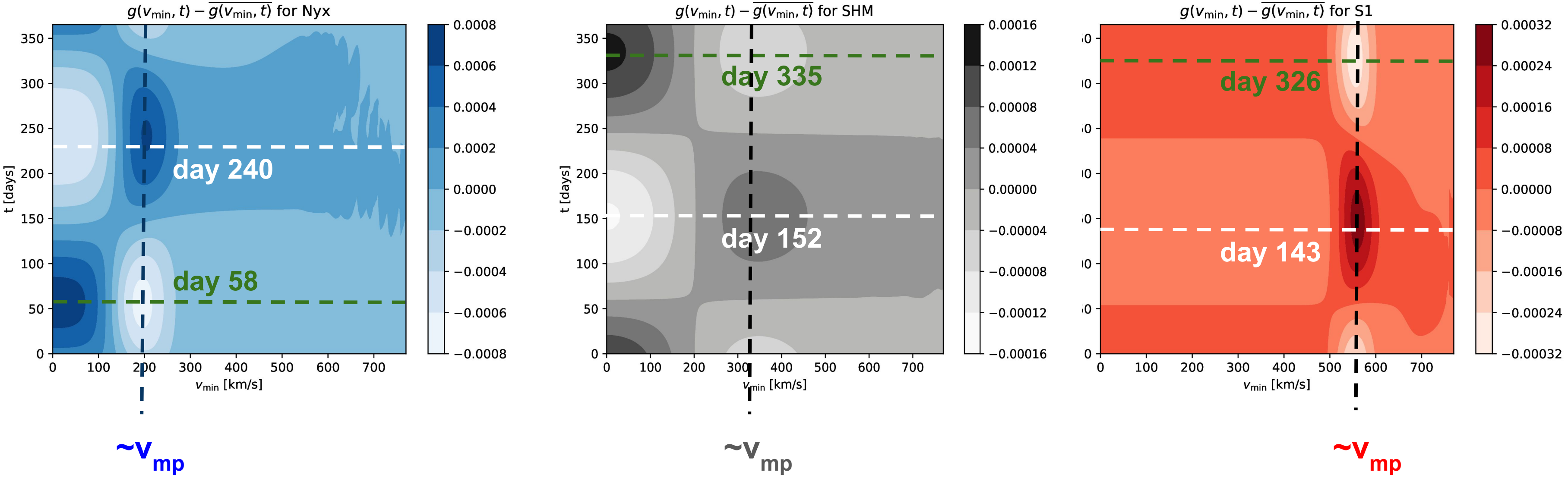


Drukier, Freese, Spergel '86
Freese, Lisanti, Savage '12

Annual modulation

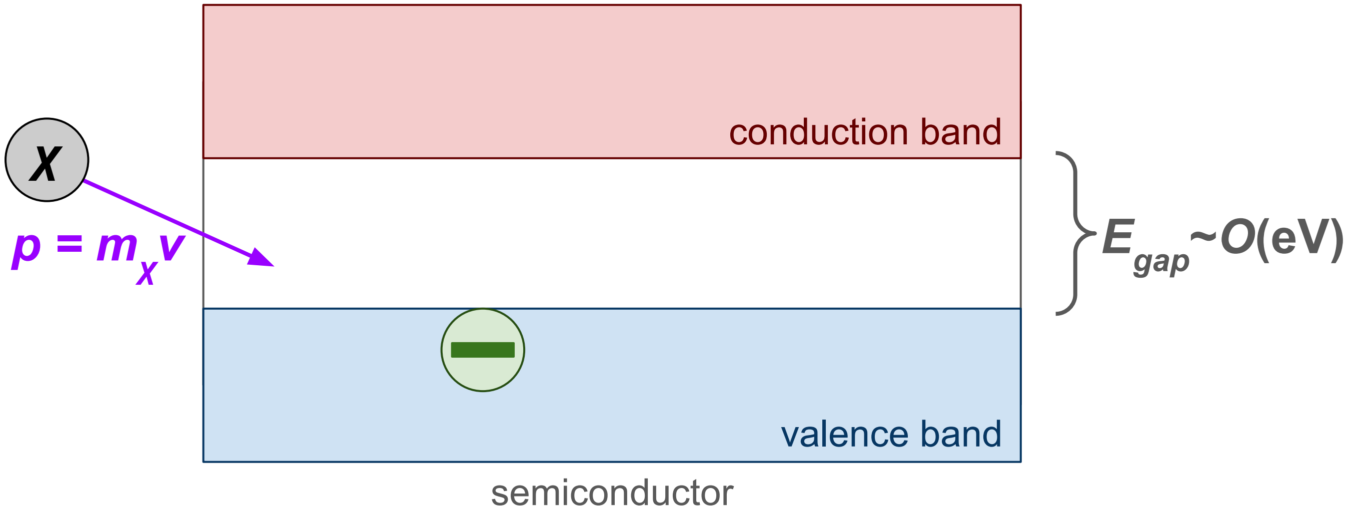
Component	$v_{\rm mp}$ [km/s]	t_c [days]	b
SHM	330	152	0.491
Gaia halo	304	152	0.491
Gaia Sausage	259	151	0.477
Nyx stream	192	218	0.860
S1 stream	569	144	0.419
S2a stream	275	358	0.676
S2b stream	227	151	1.00

different phases for different distributions



3. DM detection with ER experiments

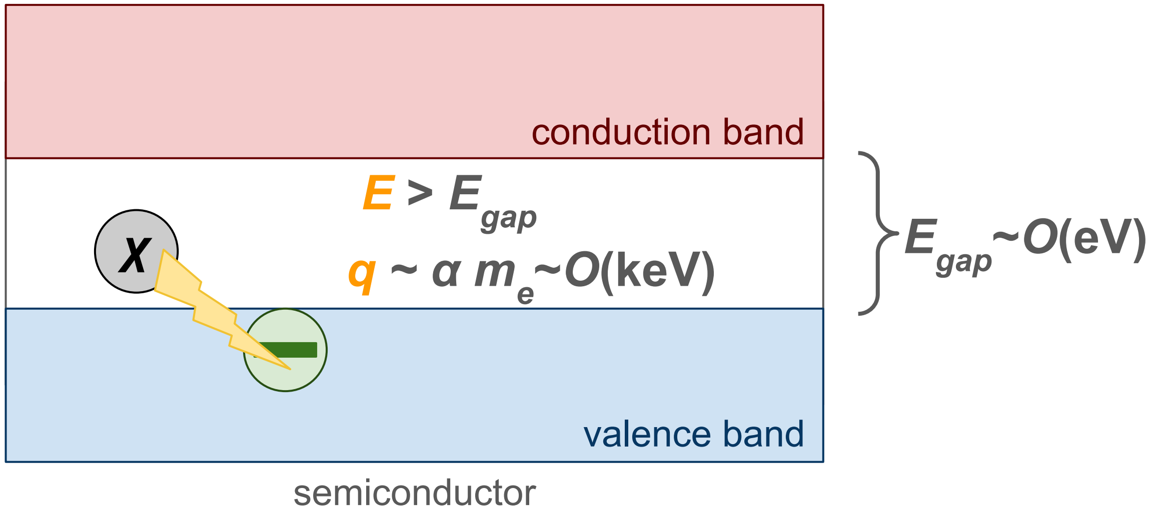
DM-e DD with semiconductors: *cartoon*



DM velocity ***v*** taken from velocity distribution

Graham, Kaplan, Rajendran, Walters '12

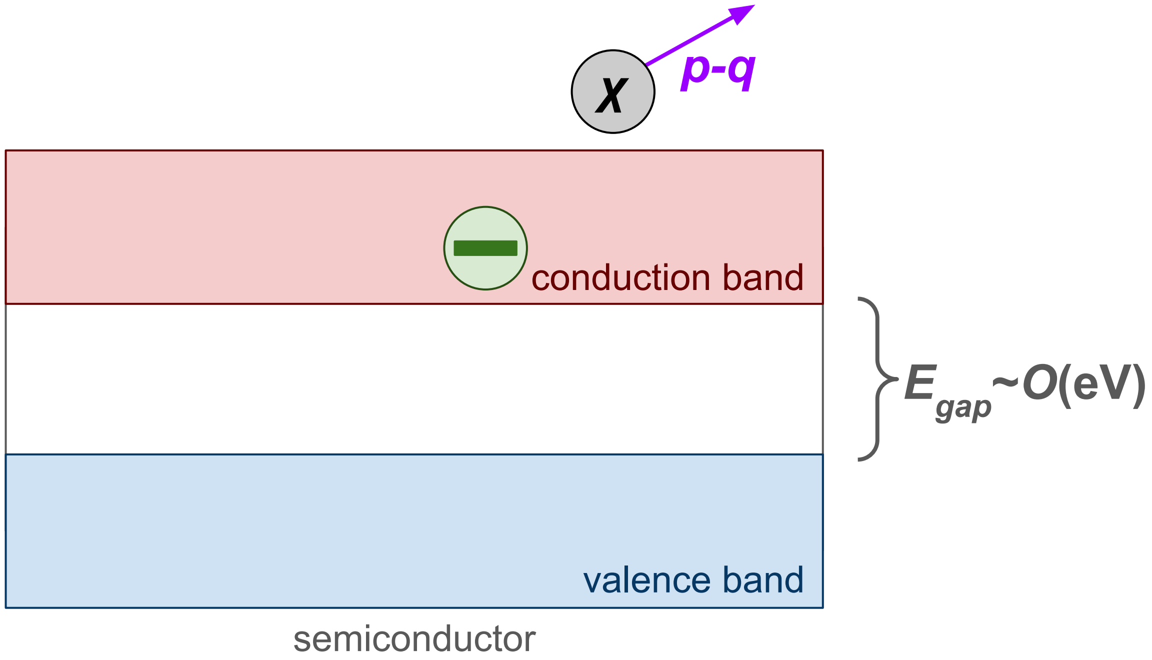
DM-e DD with semiconductors: *cartoon*



DM probes semiconductor by depositing energy ***E*** and transferring momentum ***q***

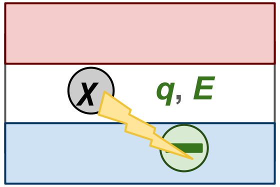
Graham, Kaplan, Rajendran, Walters ‘12

DM-e DD with semiconductors: *cartoon*



Graham, Kaplan, Rajendran, Walters '12

Differential rate: *spectrum*



local number density

response function

$$\frac{dR}{dE} \propto \frac{\rho_\chi}{m_\chi} \int dq\, \sigma_e(q) \left| f_{sc}(q, E) \right|^2 g(v_{min}(q, E))$$

particle physics

astrophysics

$$v_{min} = \frac{q}{2m_\chi} + \frac{E}{q}$$

Essig, Fernández-Serra, Mardon, Soto, Volansky, Yu, ‘15

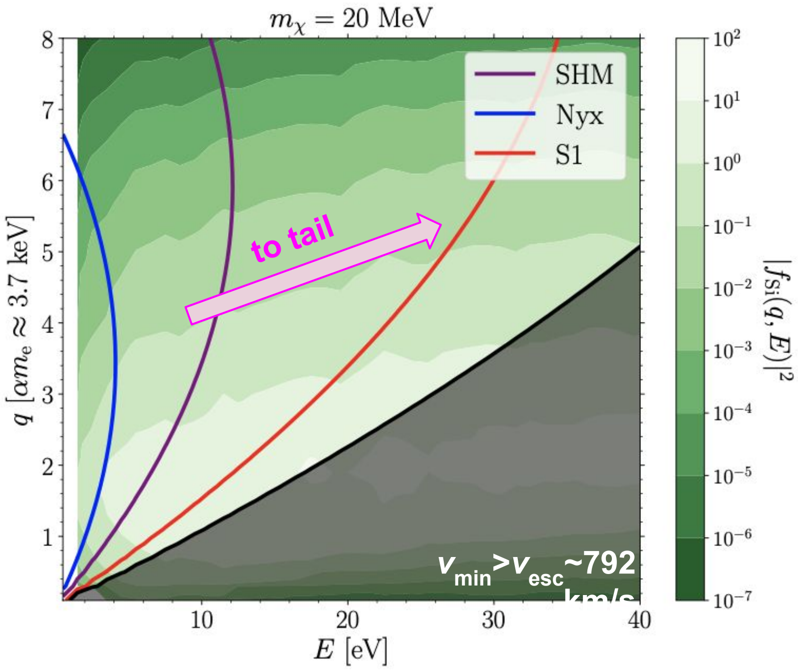
$$g(v_{min}) = \int_{v_{min}}^{v_{esc}} dv\, \frac{F(v)}{v}$$

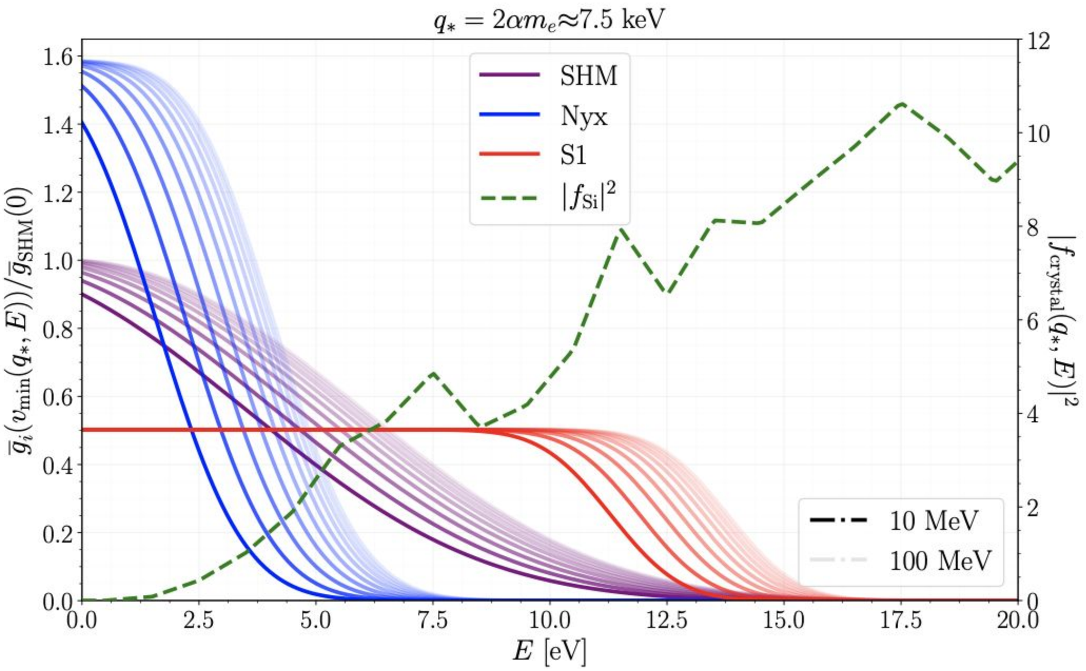
$$F(v) = v^2 \int d\Omega\, f(\mathbf{v})$$

DM *speed* distribution

Kinematics

$$v_{\min} = \frac{q}{2m_\chi} + \frac{E}{q} = v_{\mathrm{mp}}$$

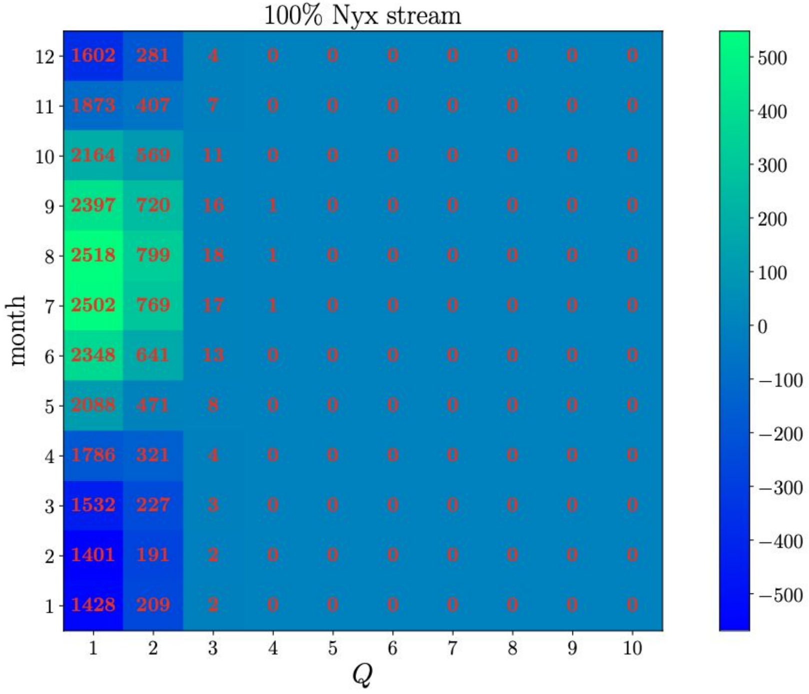


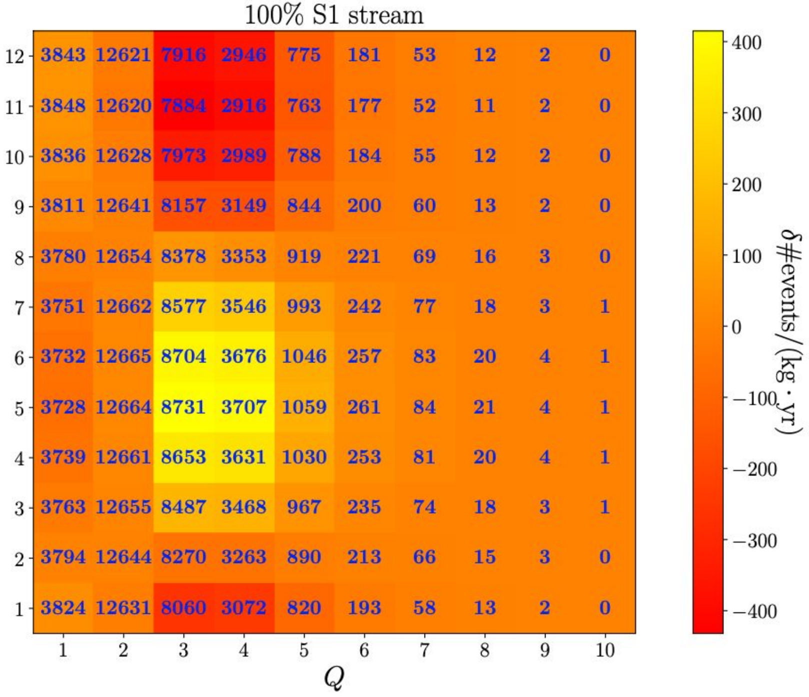


$$\frac{dR}{dE} \propto \int \mathrm{d}q \ldots |f_{\mathrm{sc}}(q, E)|^2 g(v_{\min}(q, E))$$

Experimental Spectra

$$Q = \left(1 + \left\lfloor \frac{E - E_{\rm gap}}{\varepsilon} \right\rfloor\right) \Theta(E - E_{\rm gap}) \ ,$$





4. Forecasts for next-generation ER experiments

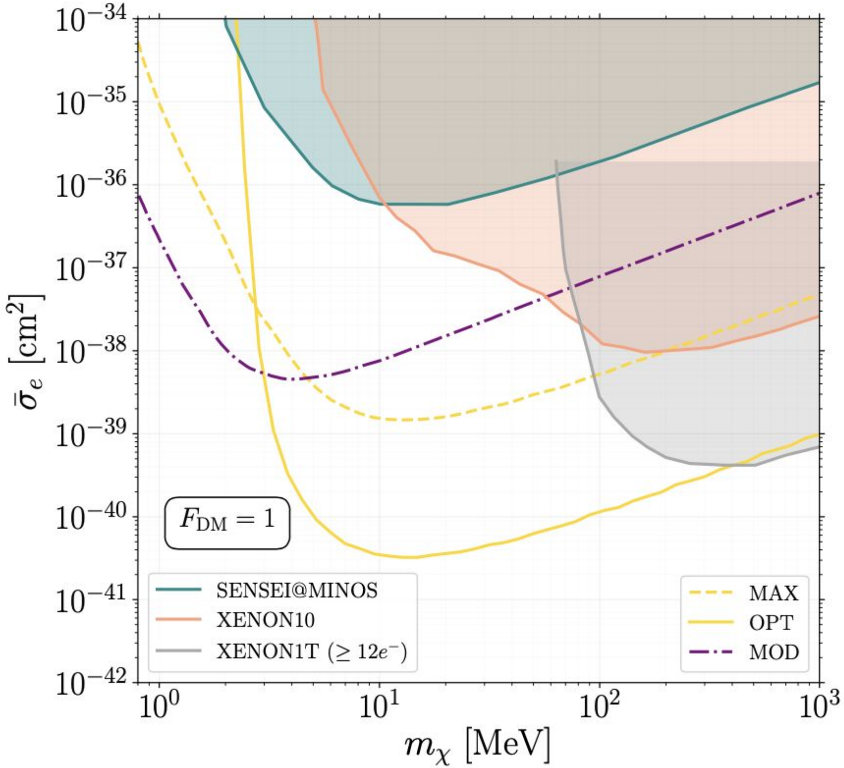
Challenges

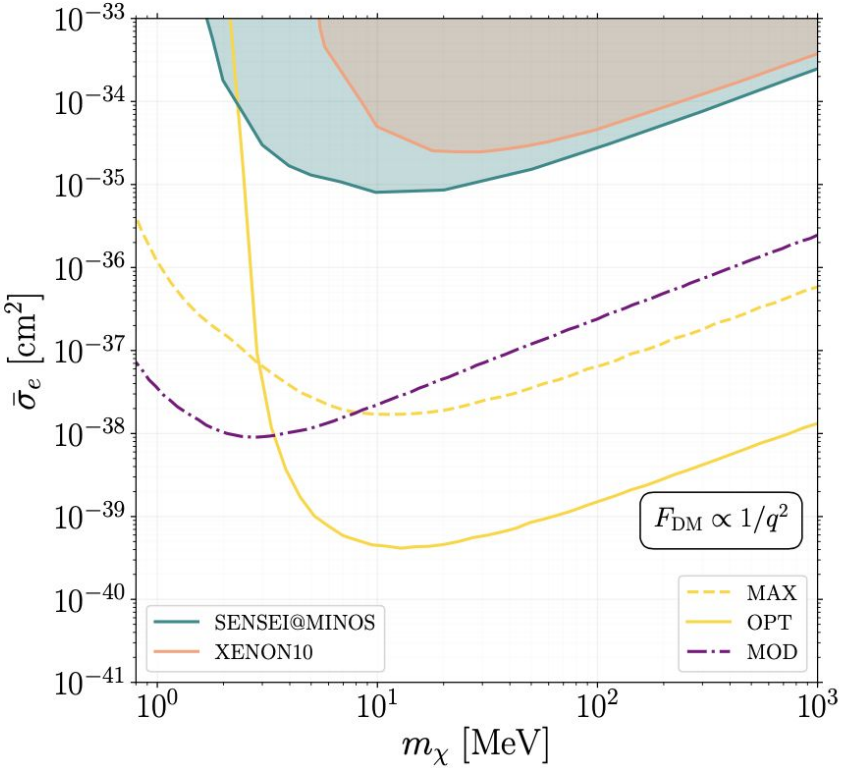
- DM substructures are very different from SHM and among themselves:
  - Variety in $\boldsymbol{v_{mp}}$ and ***phases***
  - ⇒ **cannot** use the same analysis method as for pure SHM: one size does not fit all!

~~Challenges~~ Opportunities!

- DM substructures are very different from SHM and among themselves:
  - Variety in $\boldsymbol{v_{mp}}$ and ***phases*** (exploit this!)
  - ⇒ **cannot** use the same analysis method as for pure SHM: one size does not fit all!
- Key: distribution $\boldsymbol{v_{mp}}$ & ***phase*** features ⇒ ***spectra E*** & ***t*** features
- Do **not** "collapse" time-dependent spectra (2D) into time-summed spectra (1D), or single number (total # events):
  - $\frac{dR}{dE}(E,t) \longrightarrow \frac{dR}{dE}(E) \longrightarrow R$: less and less information
  - ⇒ counts on ***E-t*** bins instead

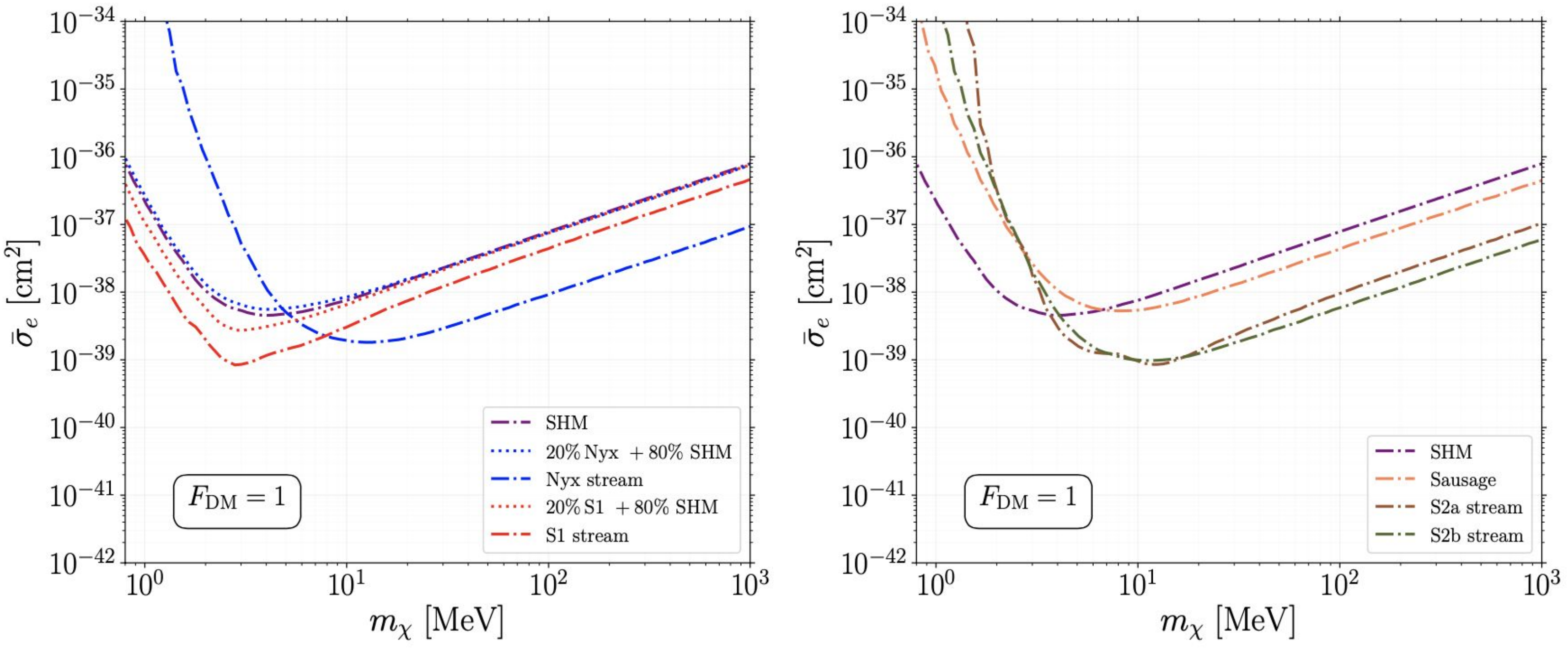
Exposure = 1 kg-year





Astro⟶DD: 5σ *Discovery Reach*

Exposure = 1 kg-year



Astro⟶DD: 5σ *Discovery Reach*

5. Prospects for Astroparticle physics

Two-way street

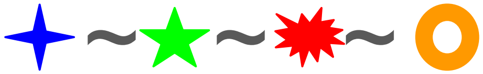
INPUT

- Astrophysics
- Direct Detection

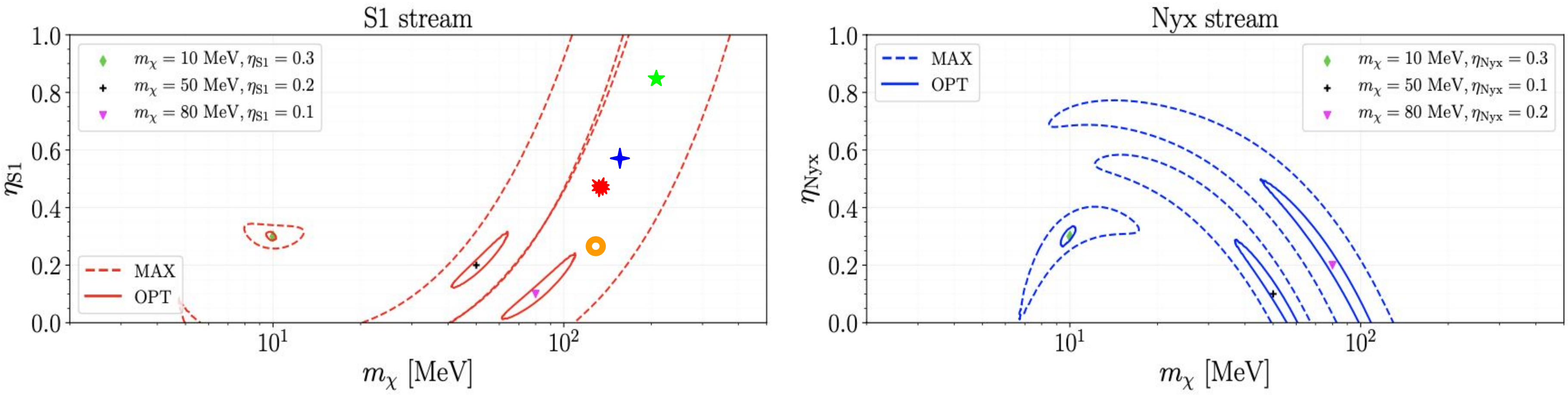
OUTPUT

- Direct Detection
- Astrophysics

Exposure = 1 kg-year



indistinguishable within 1σ

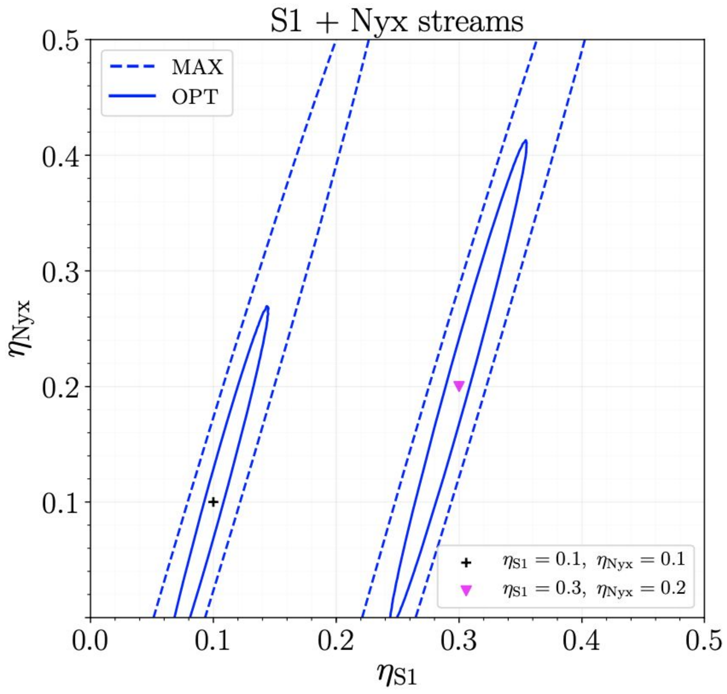


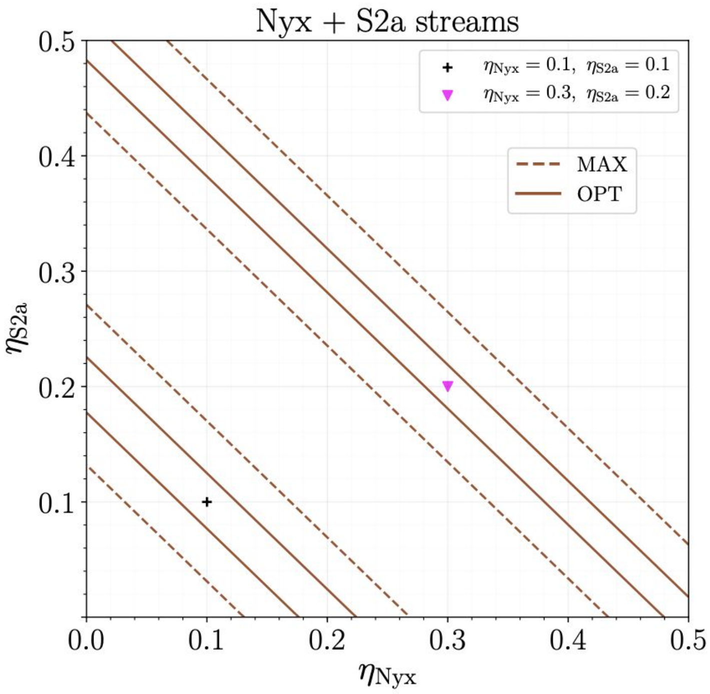
$\sigma_e = 10^{-38}$ cm^2

DD⟶Astro: *Degeneracy*

swordfish: Edwards, Weniger ‘17
Buch, Fan, Leung ‘19

Exposure = 1 kg-year





***m*= *20* MeV**
σ_e=10^{-38} cm^2

DD⟶Astro: *Degeneracy*

swordfish: Edwards, Weniger ‘17
Buch, Fan, Leung ‘19

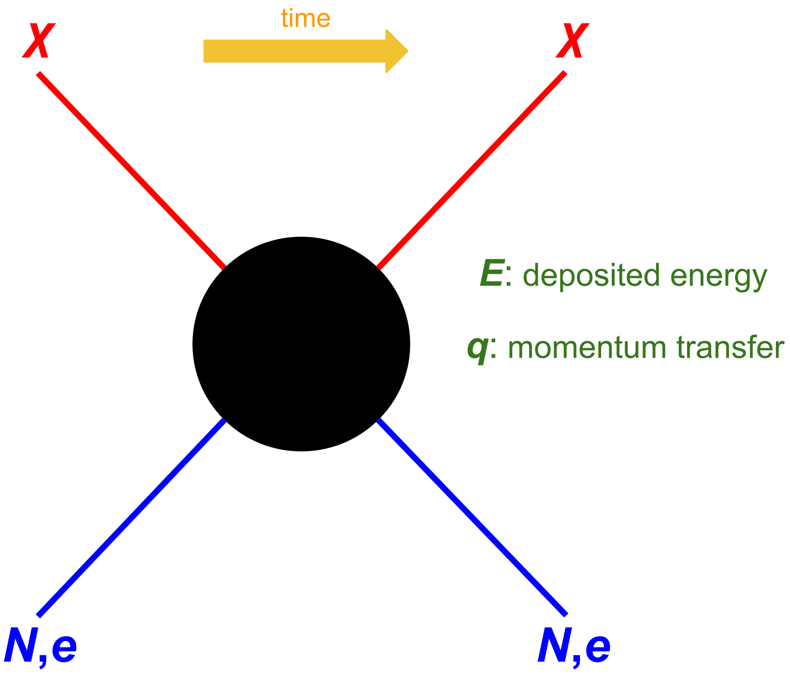
Conclusions

- Dawn of ***golden age*** of astrometry and Dark Matter Direct Detection
  - *Gaia* ⇒ Beyond Standard Halo Model (Sausage, streams…)
  - New technology ⇒ New Direct Detection experiments
- Astrophysics↔Direct Detection
- Double call for
  - Astrophysicists: better measure substructure properties; DM↔stars correlation
  - Particle Physicists: methods to better exploit features of differential rates in ***E-t***

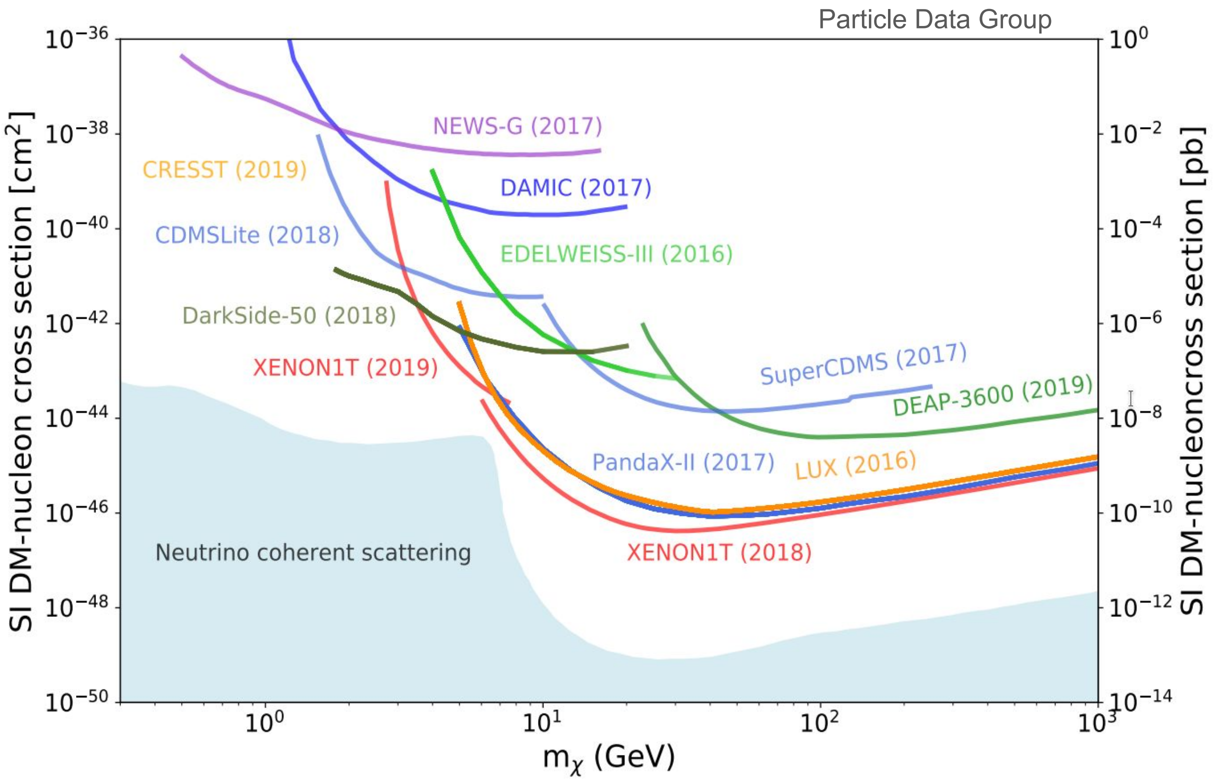
Backup slides

DD targets

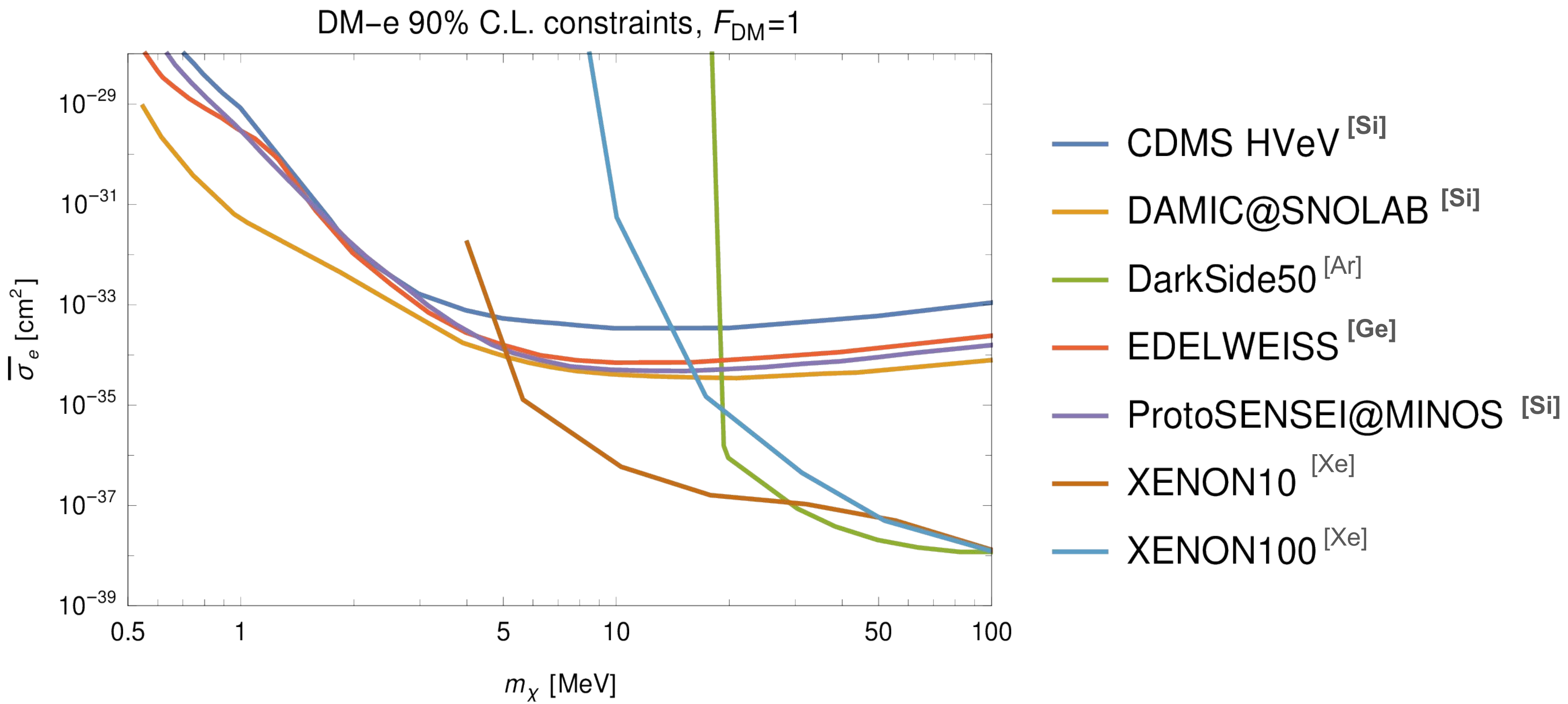
- Nuclei
  - m_χ~10 GeV, E~keV, q~10 MeV
    - XENON, LUX, PandaX, DarkSide…
- Electrons
  - *Atoms:* m_χ~100 MeV, E~10eV, q~1 keV
    - XENON, DarkSide
  - *Semiconductors:* m_χ~10 MeV, E~1eV, q~1 keV
    - SENSEI, CDMS, EDELWEISS...



Bounds: DM-N DD

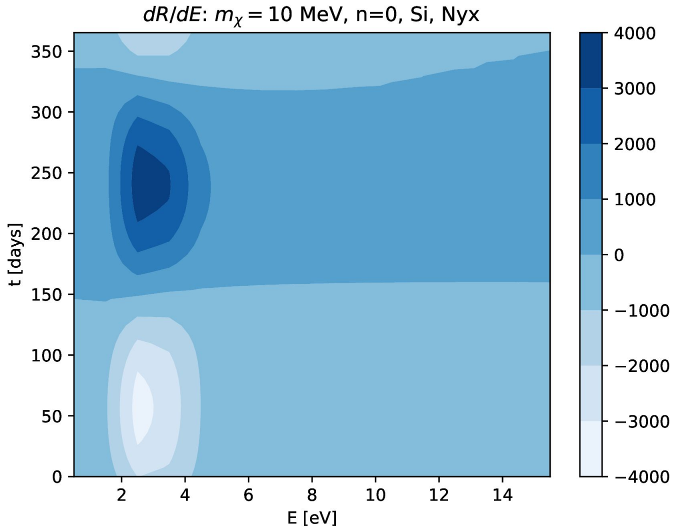


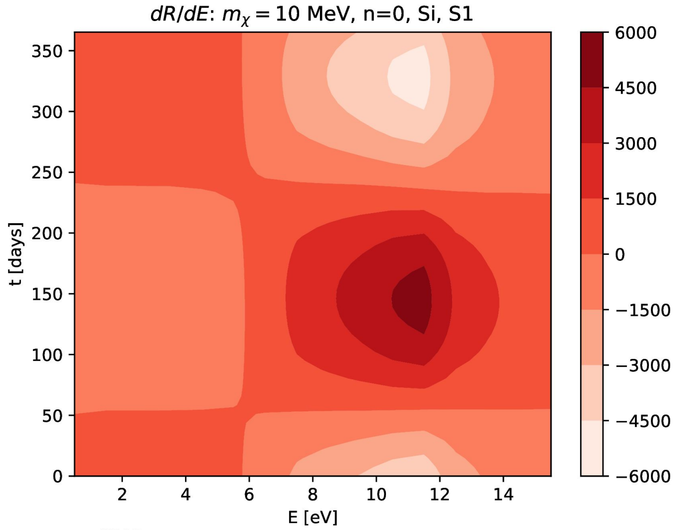
Bounds: DM-e DD

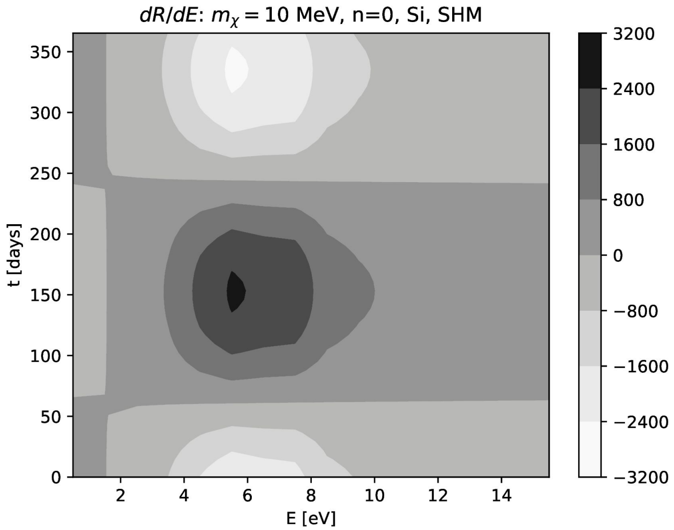


Spectrum

$$\frac{dR}{dE} = N_T \frac{\rho_\chi}{m_\chi} \overline{\sigma}_e \alpha \frac{m_e^2}{\mu_{\chi e}^2} \int \mathrm{d}q \;\; \frac{F_{DM}(q)^2}{q^2} |f_{\mathrm{sc}}(q, E)|^2 g(v_{\mathrm{min}}(q, E))$$


dR/dE: $m_\chi = 10$ MeV, n=0, Si, Nyx
t [days]
E [eV]
0
50
100
150
200
250
300
350
2
4
6
8
10
12
14
4000
3000
2000
1000
0
−1000
−2000
−3000
−4000


dR/dE: $m_\chi = 10$ MeV, n=0, Si, S1
t [days]
E [eV]
0
50
100
150
200
250
300
350
2
4
6
8
10
12
14
6000
4500
3000
1500
0
−1500
−3000
−4500
−6000


dR/dE: $m_\chi = 10$ MeV, n=0, Si, SHM
t [days]
E [eV]
0
50
100
150
200
250
300
350
2
4
6
8
10
12
14
3200
2400
1600
800
0
−800
−1600
−2400
−3200