Dark Matter-electron scattering in the *Gaia* era

Manuel A. Buen-Abad

with Jatan Buch, JiJi Fan, & Shing Chau Leung

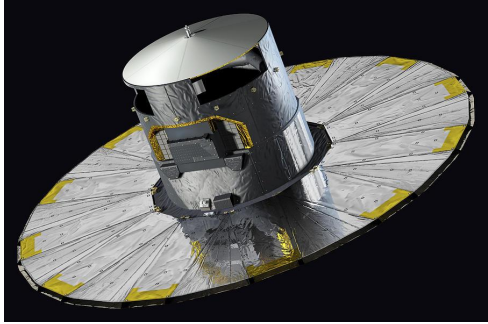
2007.13750, github.com/ManuelBuenAbad/dame_dd

03/24/2021

BROWN

ASPEN CENTER FOR PHYSICS

Gaia and substructure

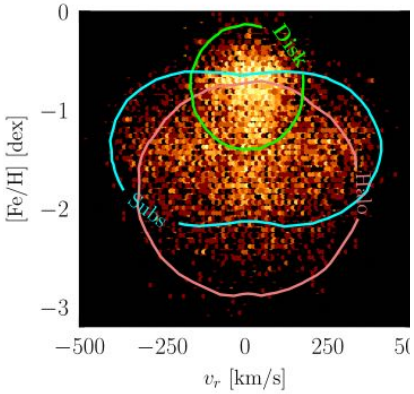


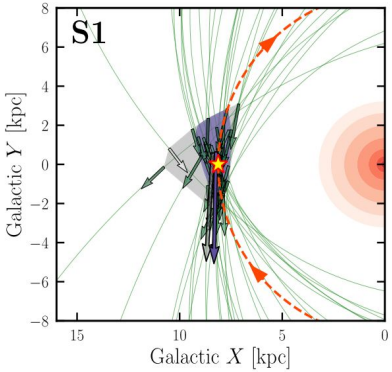
- Discoveries of stellar substructures (from mergers)
  - Debris flow (Gaia/Enceladus Sausage)
  - Streams (S1, S2a, S2b, Nyx)
- Since both stars & DM merge:

  stellar substructure ⇒ **DM substructure**
  - *Some* local DM could be in substructures

    Need to move Beyond Standard Halo Model (BSHM)

Necib, *et al.* 1807.02519;
O'Hare *et al.* 1909.04684.





retrograde

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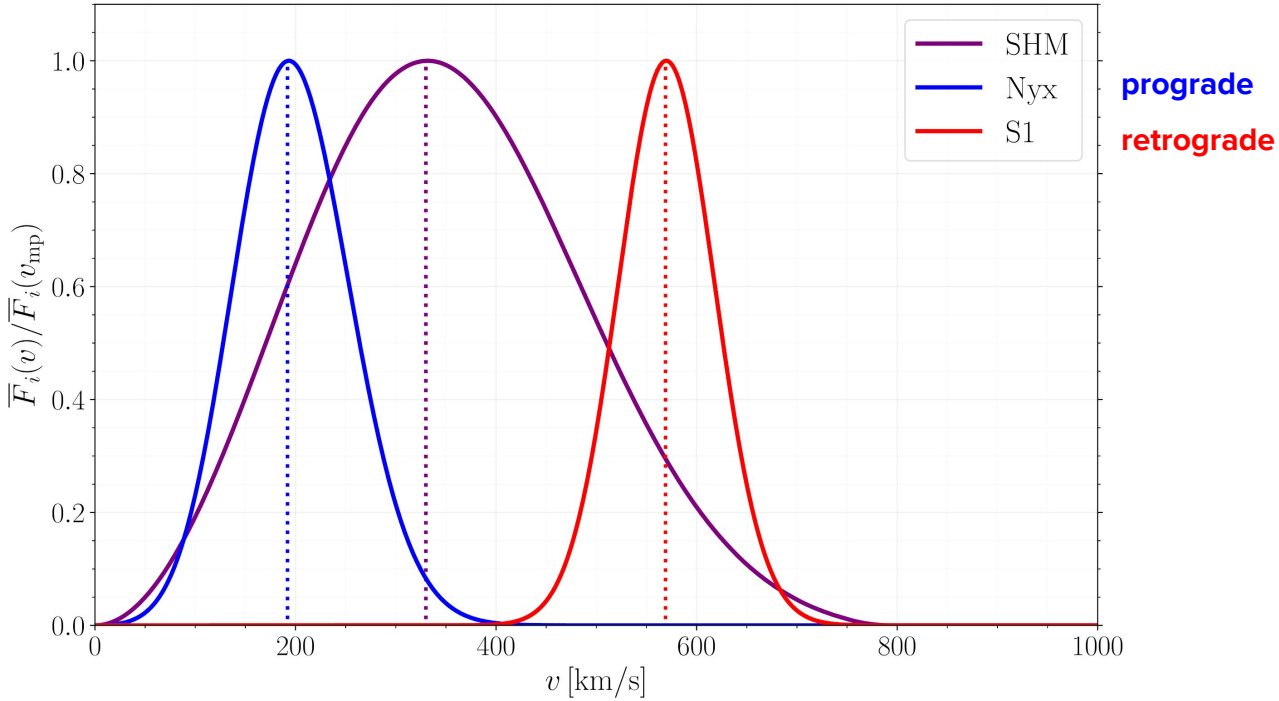
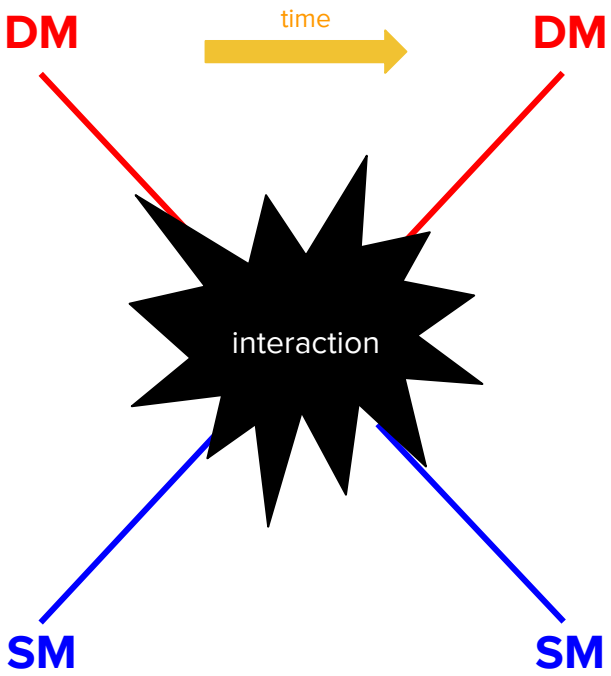
DM distribution: BSHM



Why is it important? Direct Detection!



Goodman, Witten, '84

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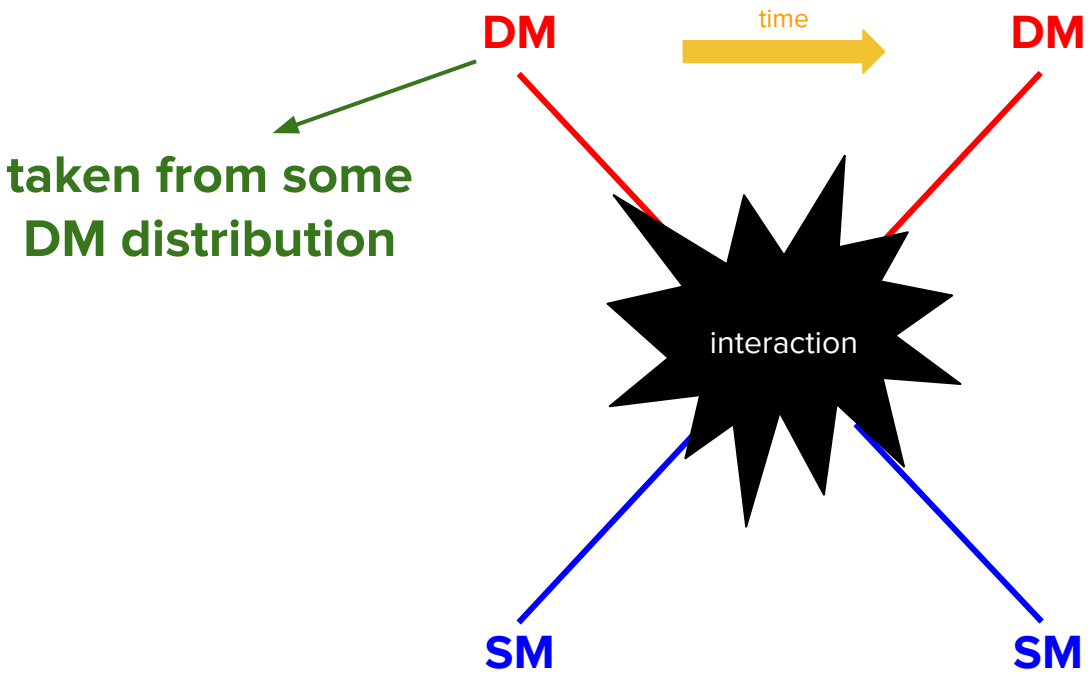


Watch **Anna-Maria**'s talk!
Th Apr 1st, 10:20 am

Goodman, Witten, '84

This talk: DM-e DD with semiconductors

DM-e scattering in semiconductors

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

DM-e scattering in semiconductors

local number density

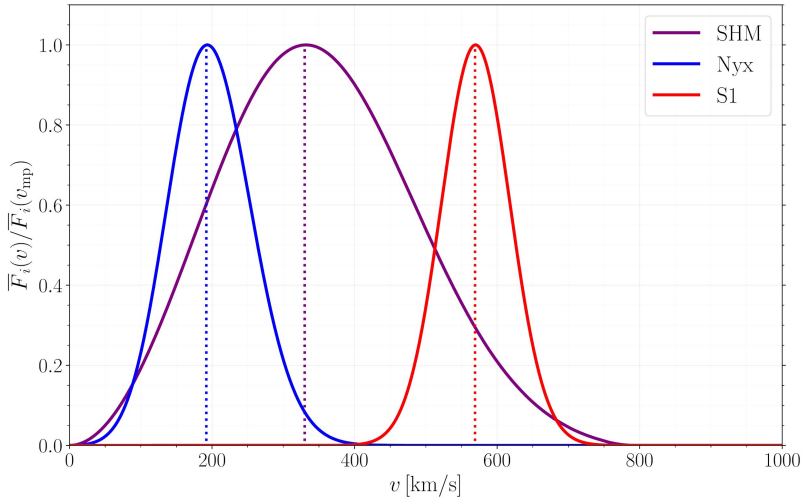
response function

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

particle physics

astrophysics

DM-e scattering in semiconductors



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

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

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

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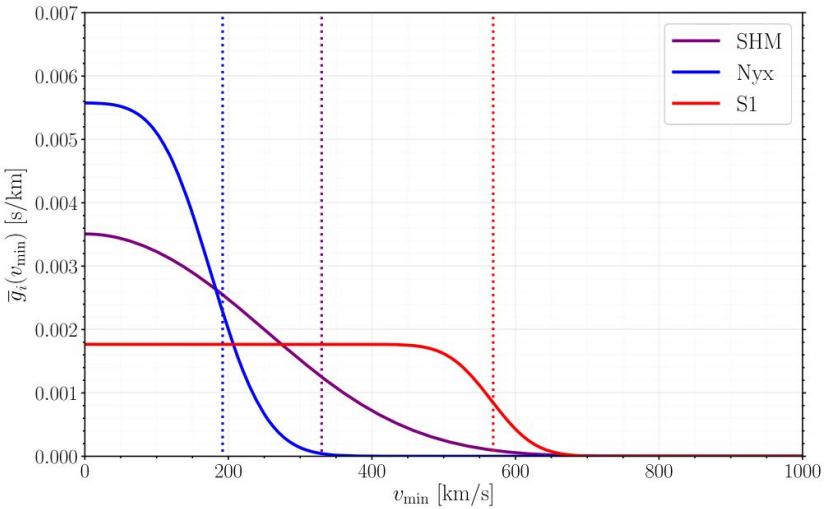
DM-e scattering in semiconductors



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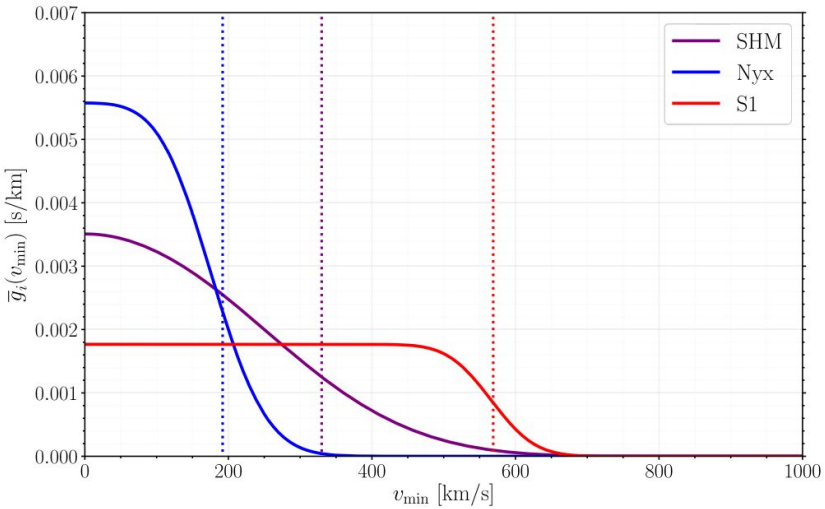
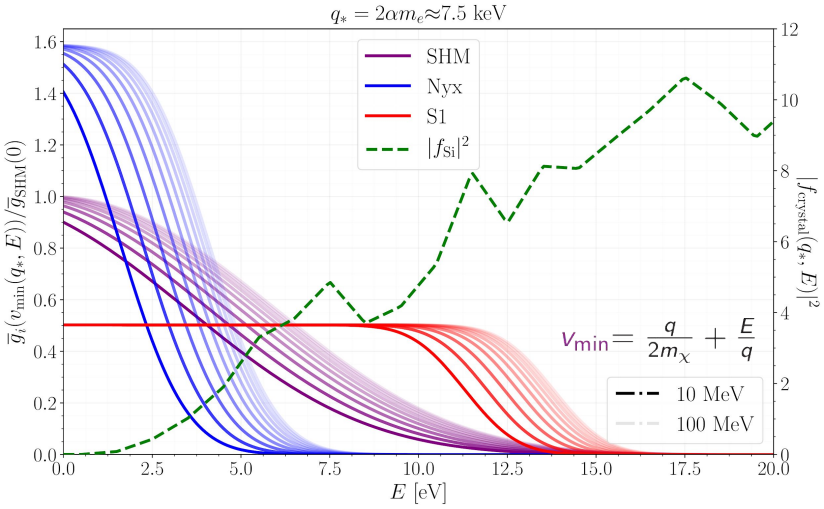
DM-e scattering in semiconductors





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

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Challenges

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

~~Challenges~~ Opportunities!

- DM substructures are very different from SHM and among themselves:
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- Key: distribution $\boldsymbol{v_{mp}}$ & ***phase*** features ⇒ ***spectra E*** & ***t*** features

~~Challenges~~ Opportunities!

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- Key: distribution v_{mp} & ***phase*** features ⇒ ***spectra E*** & ***t*** features
- Our paper: ***E-t*** binning, simple likelihood ratio analysis
  - *Phys. Rev. D* 102 (2020) 8, 083010; arXiv:2007.13750
  - For code visit github.com/ManuelBuenAbad/dame_dd
  - Semiconductor form factors from QEdark

Two-way street

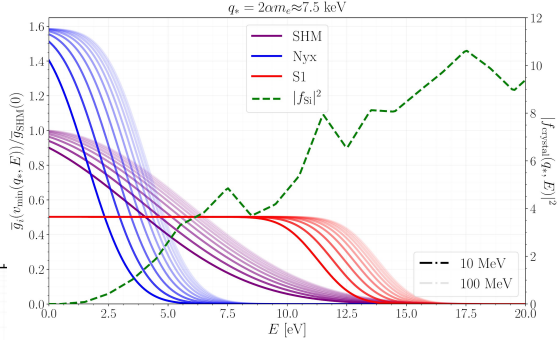
INPUT

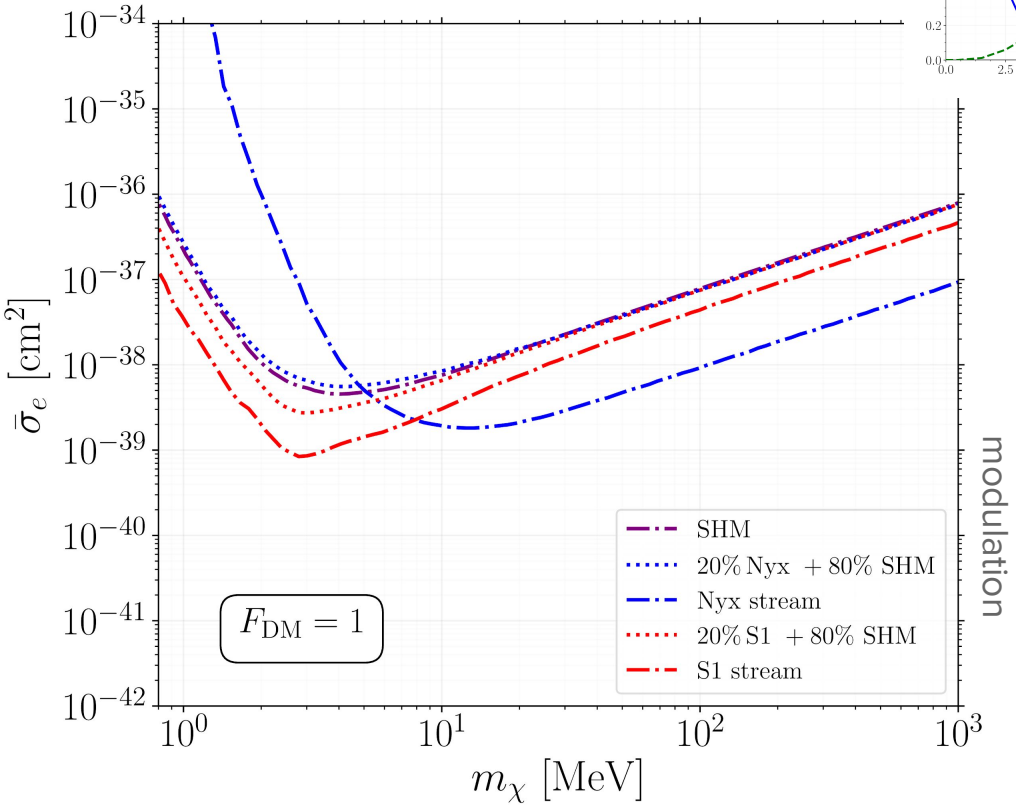
- Astrophysics
- Direct Detection

OUTPUT

- Direct Detection
- Astrophysics

Astro⟶DD: *5σ Discovery Reach*





modulation

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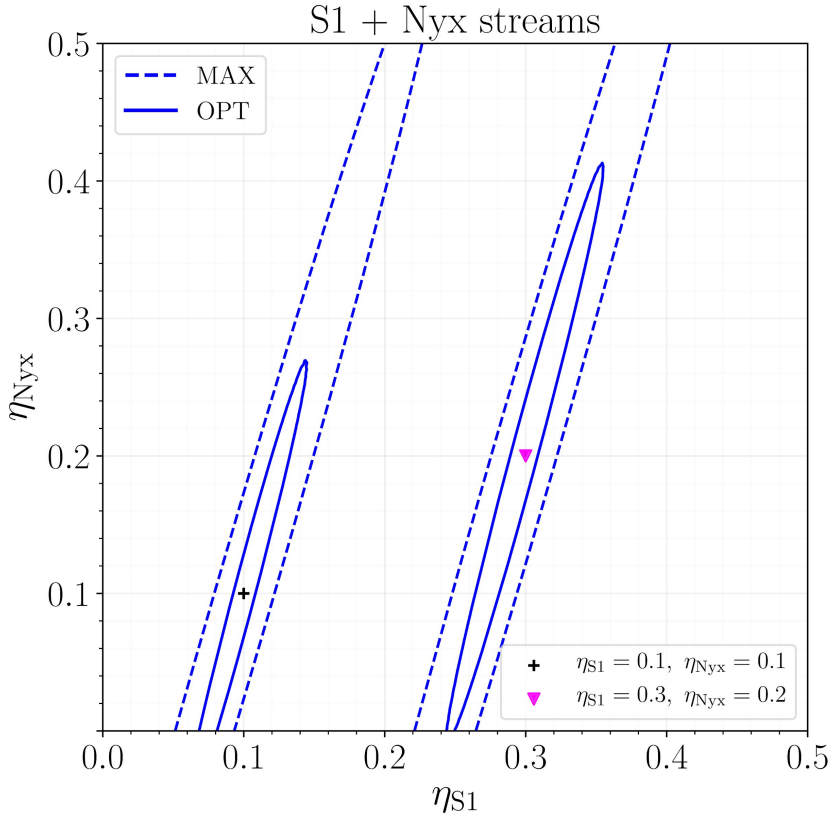
DD⟶Astro: *Disentangling Substructure*



m_χ = 20 MeV
$\sigma_e = 10^{-38}$ cm^2

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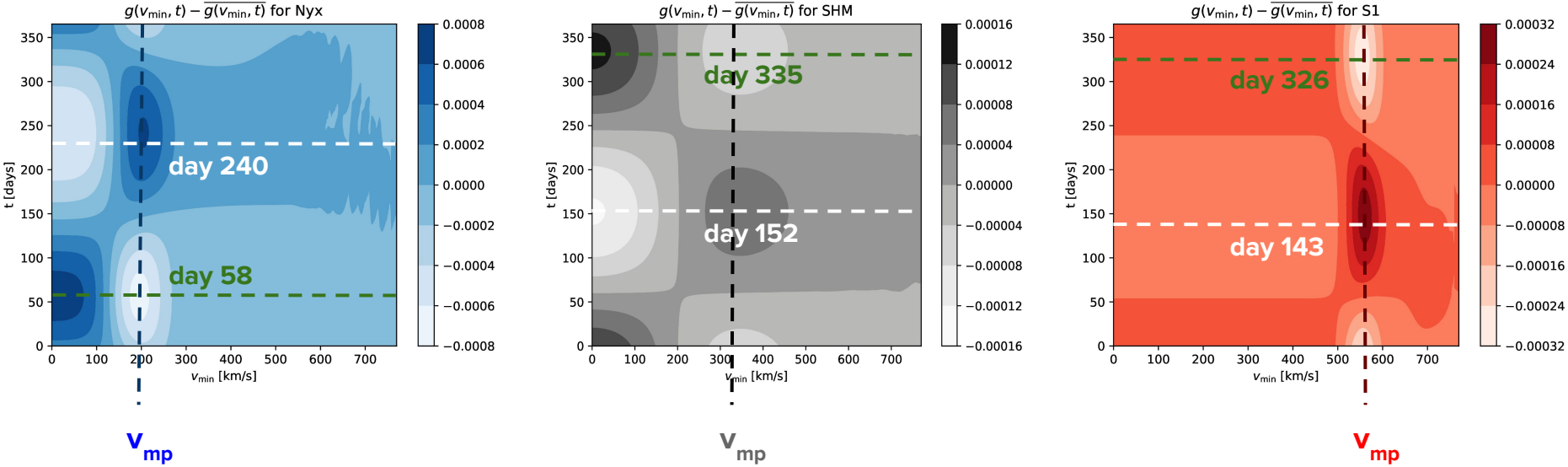
Conclusions

- 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: **new methods** to better exploit features of differential rates in ***E-t***
- **¡Gracias!**

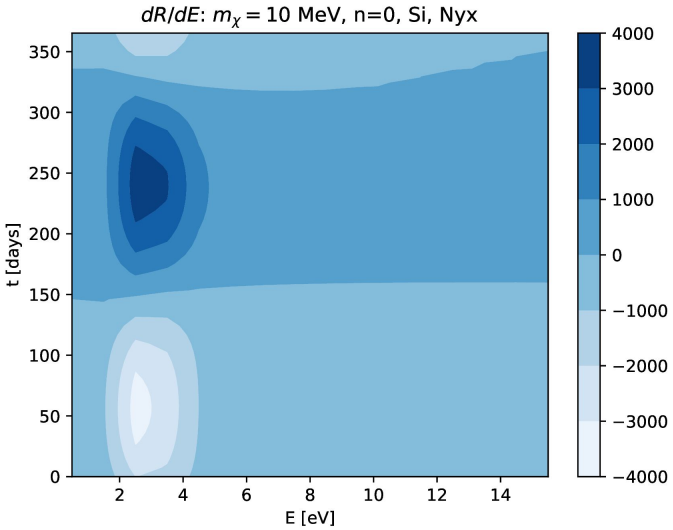
Backup slides

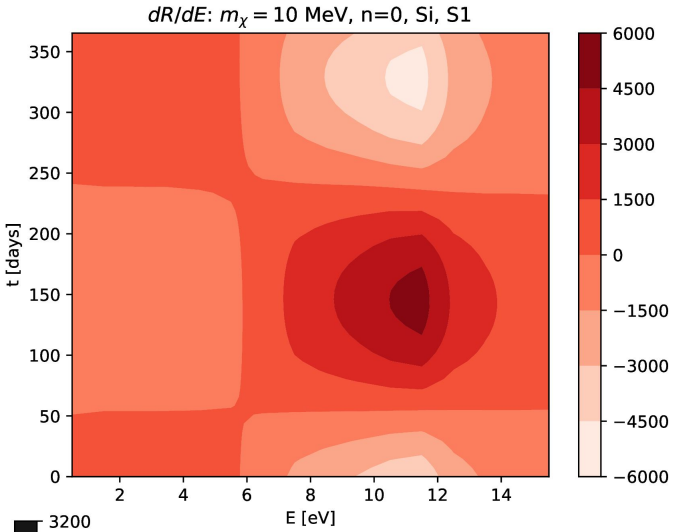
Annual modulation

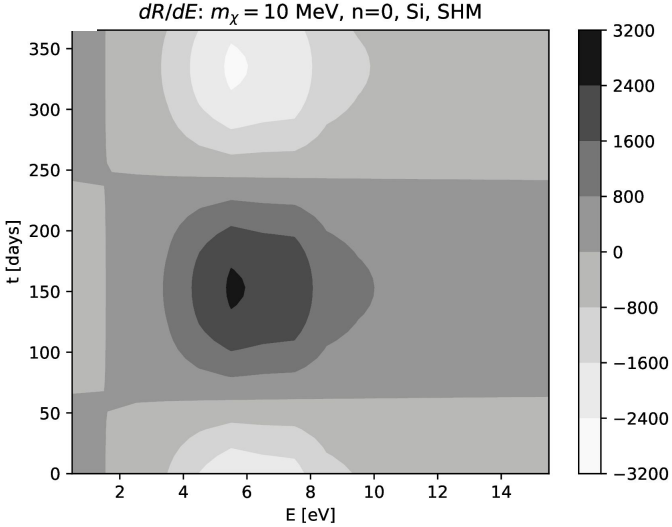
different phases for different distributions



v_{mp} v_{mp} v_{mp}


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

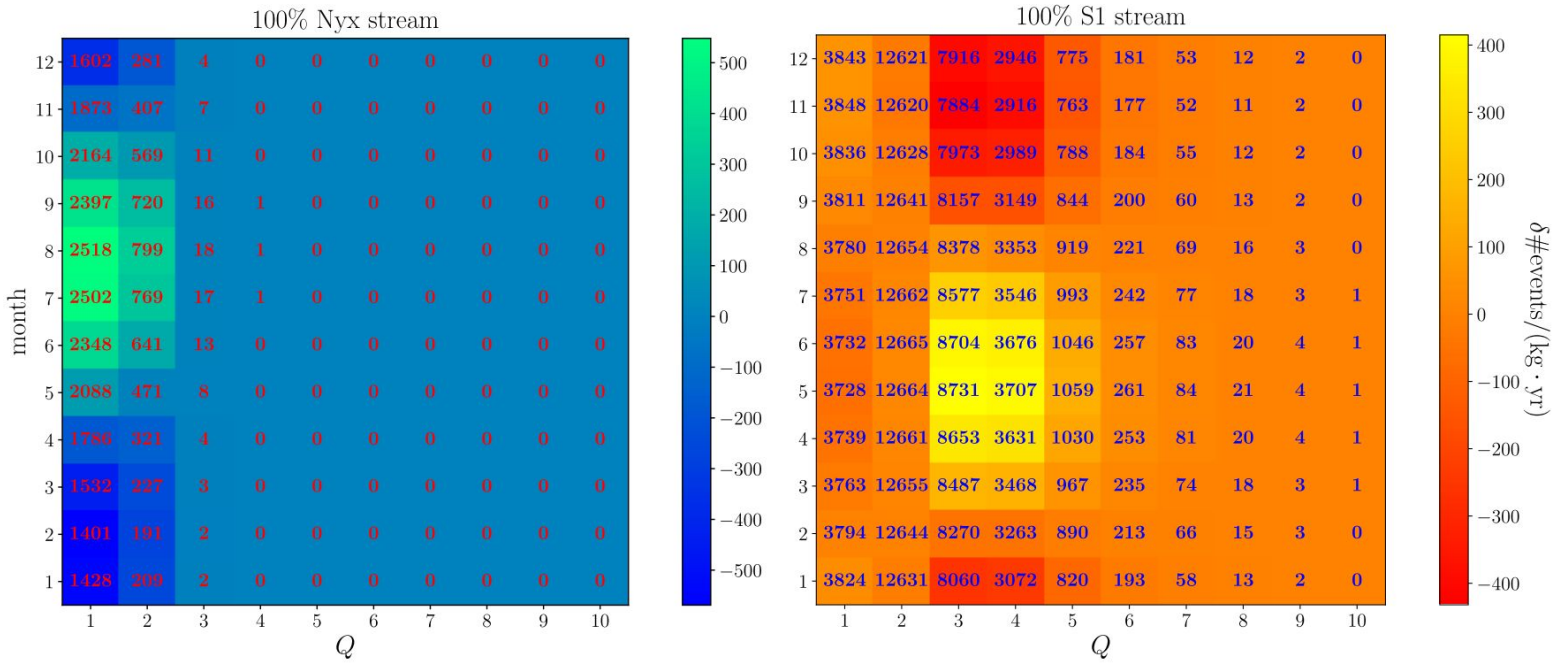

dR/dE: $m_\chi = 10$ MeV, n=0, Si, S1
t [days]
E [eV]
0
50
100
150
200
250
300
350
2
4
6
8
10
12
14
6000
4500
3000
1500
0
−1500
−3000
−4500
−6000


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

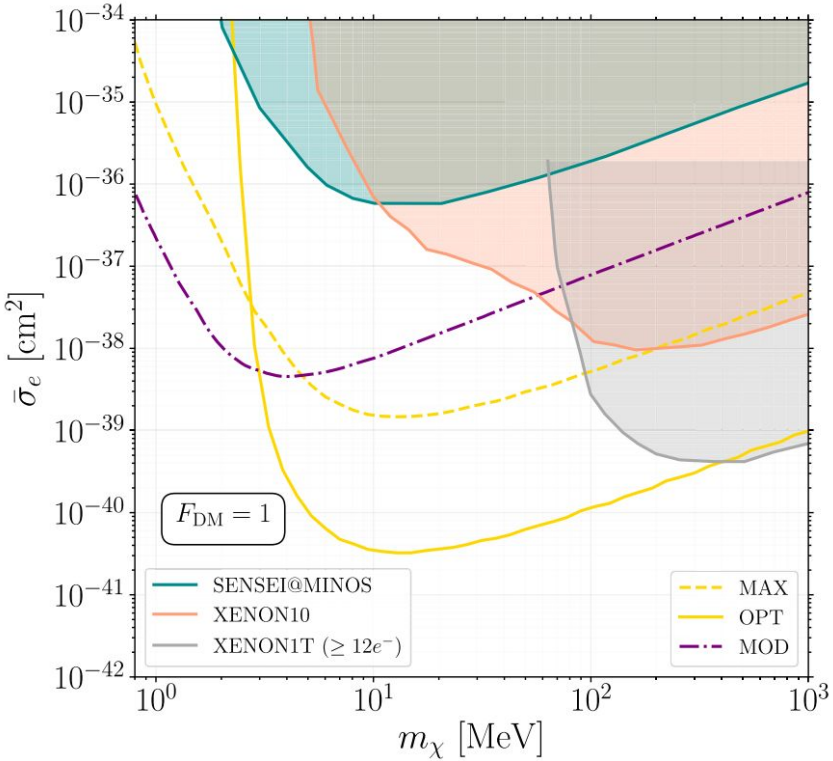
E-t binning

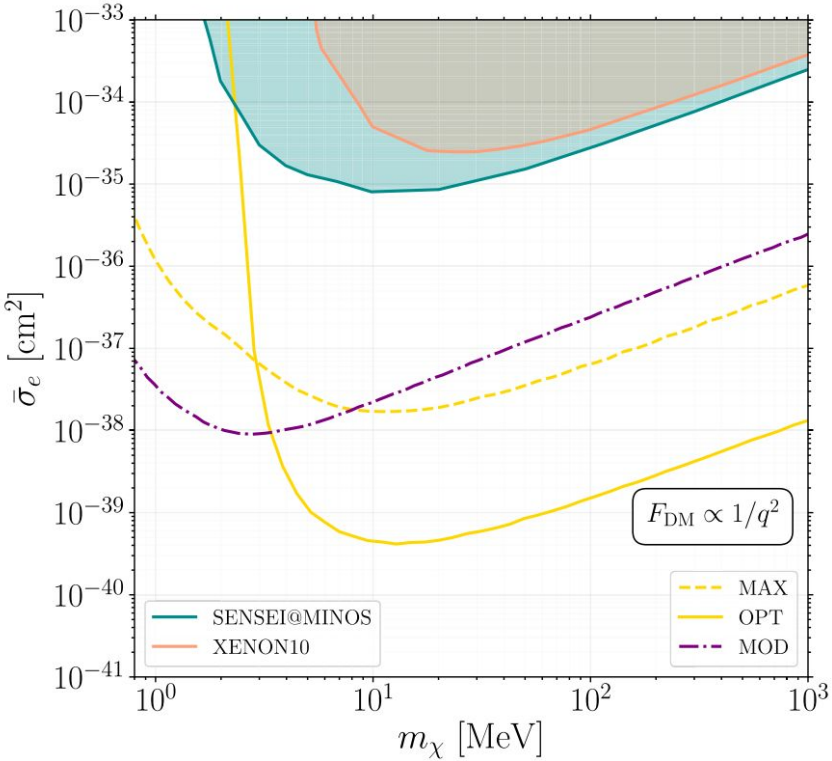
$$Q = \left(1 + \left\lfloor \frac{E - E_{\text{gap}}}{\varepsilon} \right\rfloor\right)\Theta(E - E_{\text{gap}}), \qquad (8)$$

where E_{gap} is the band-gap energy of the semiconductor and ε the mean energy per electron-hole pair. $E_{\text{gap}} = 1.2$ eV and $\varepsilon = 3.8$ eV for silicon, while $E_{\text{gap}} = 0.67$ eV and $\varepsilon = 2.9$ eV for germanium.



More Results: *5σ Discovery Reach (SHM)*





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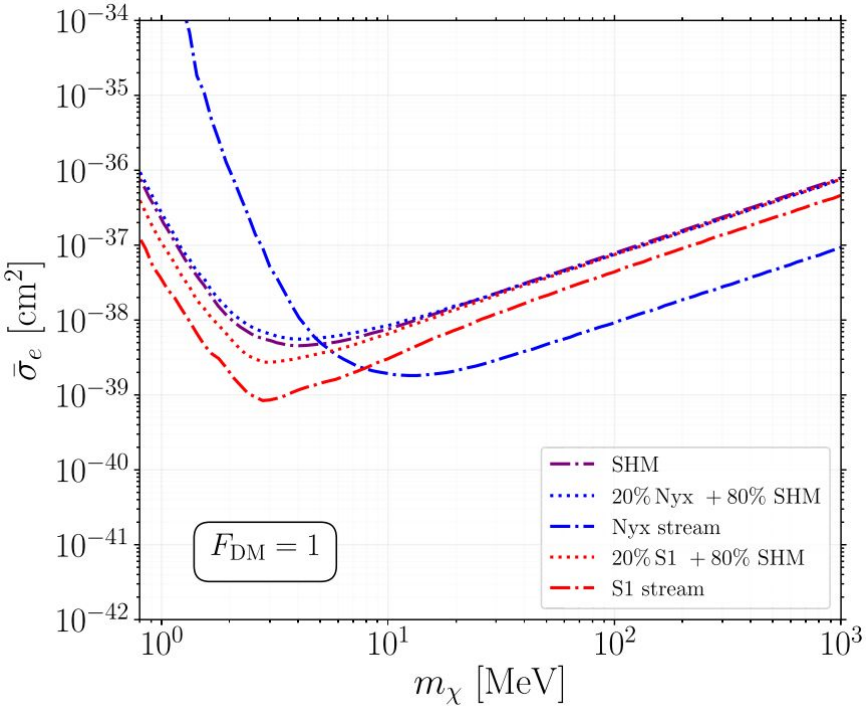
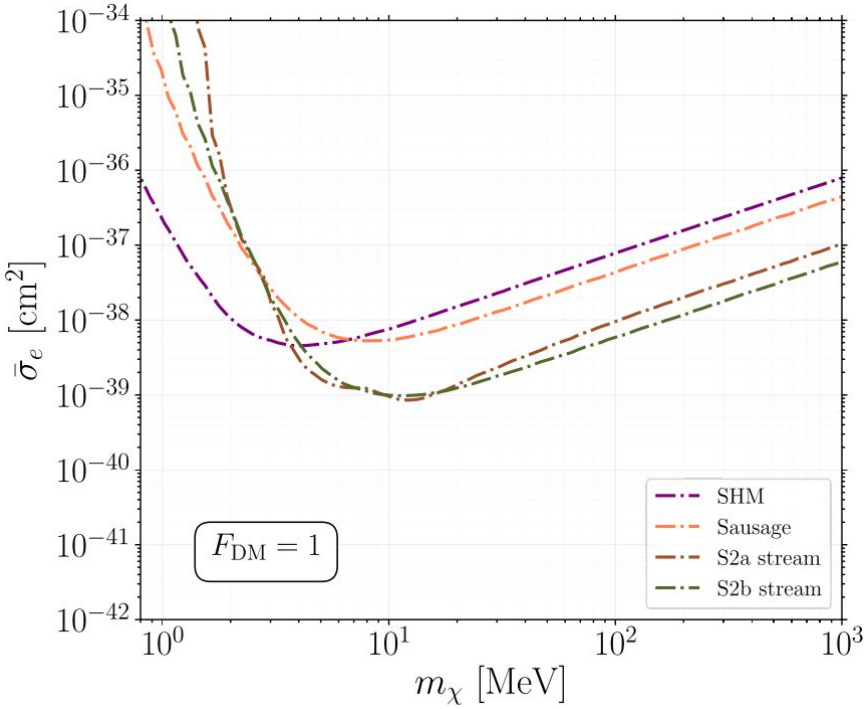
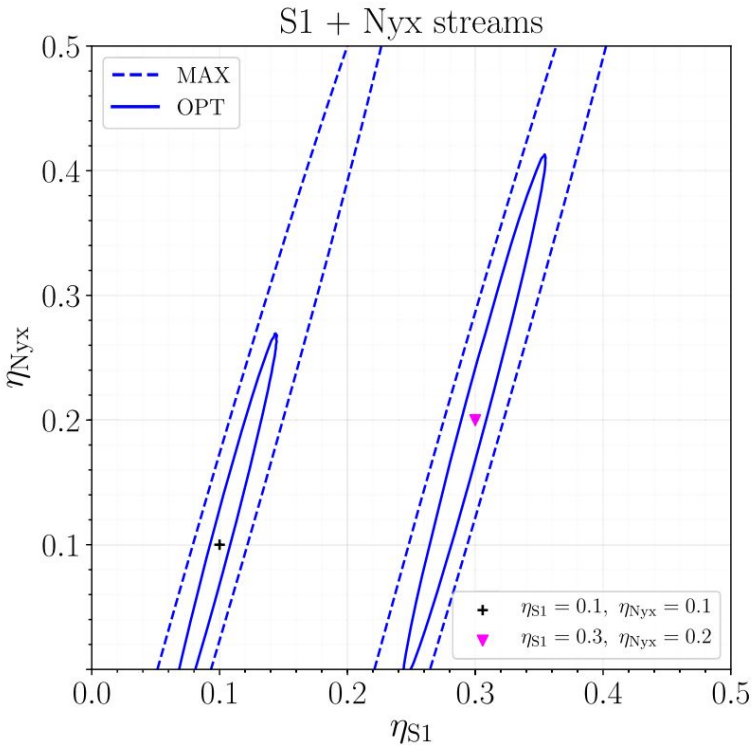
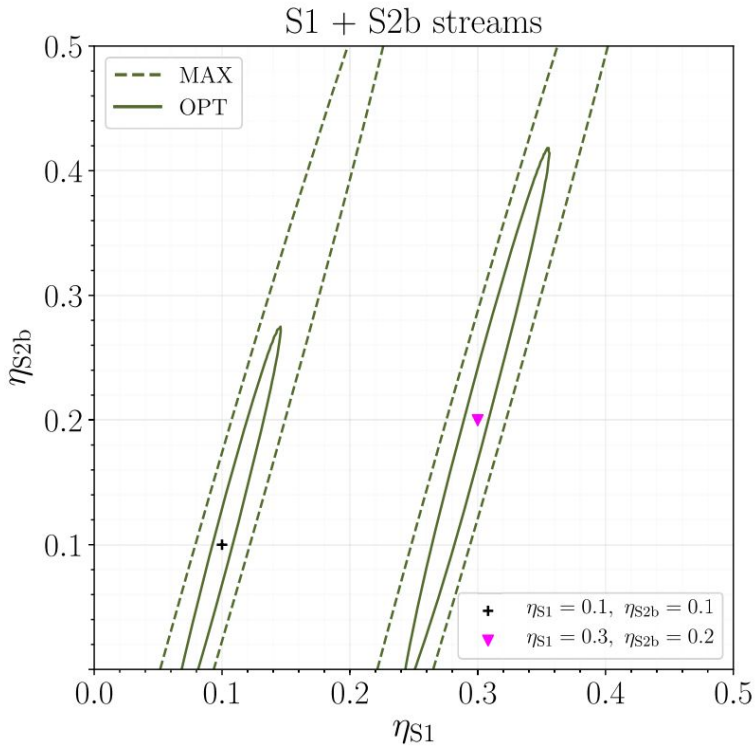
More Results: *5σ Modulation Discovery Reach*





More Results: *Substructure Degeneracy*





m_χ = 20 MeV & $\sigma_e = 10^{-38}$ cm^2

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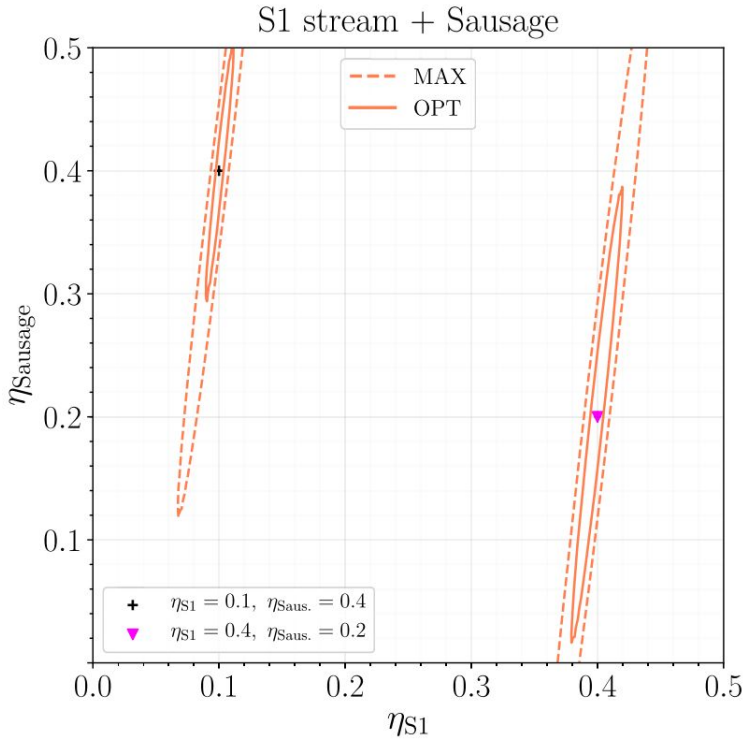
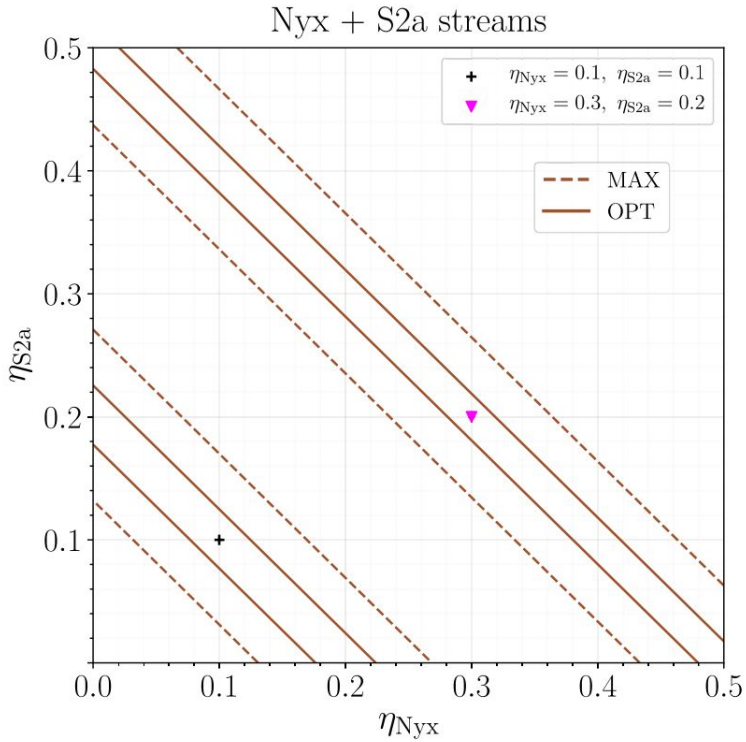
More Results: *Substructure Degeneracy*





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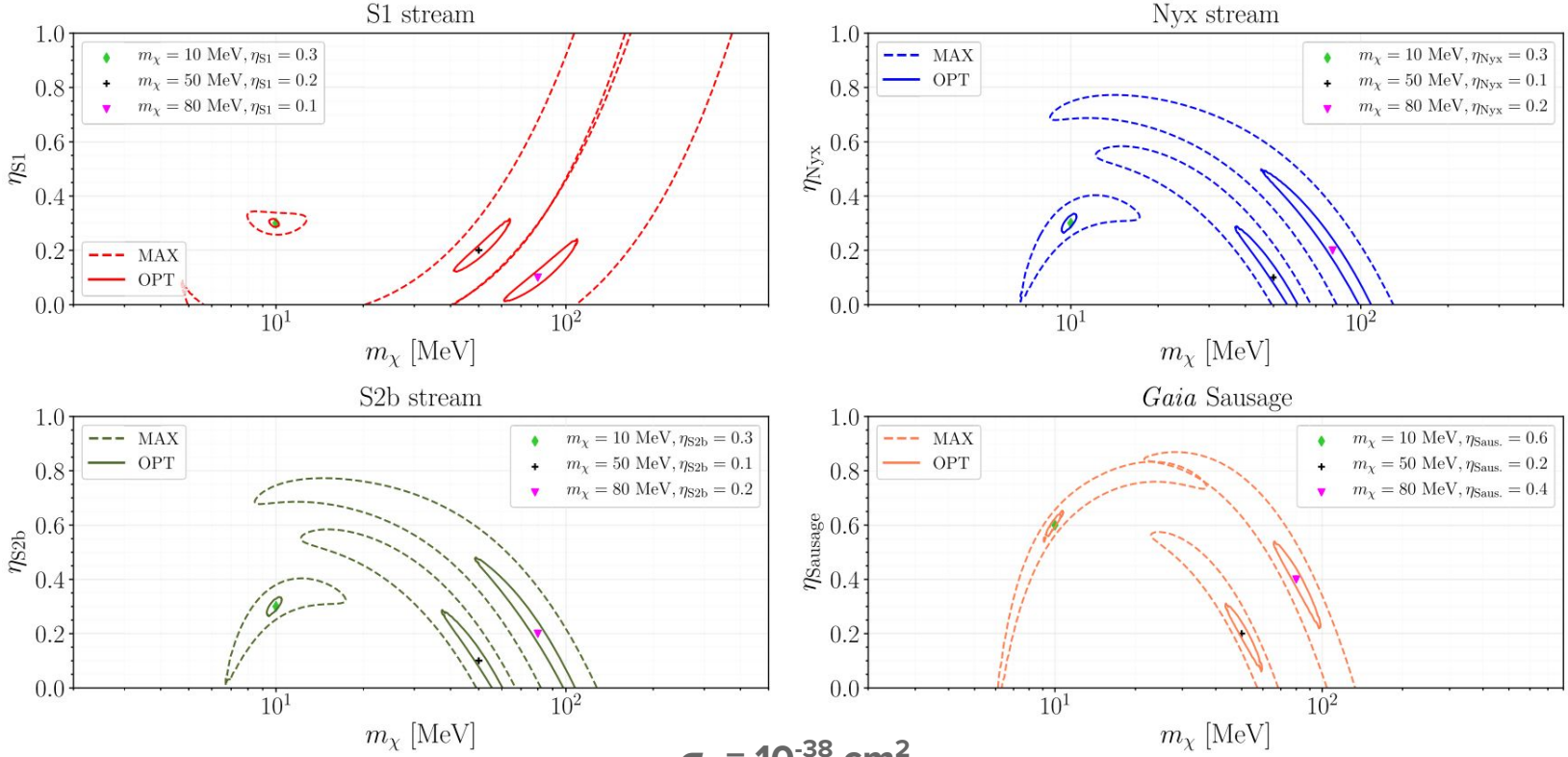
More Results: *Mass vs. Substructure Fraction*



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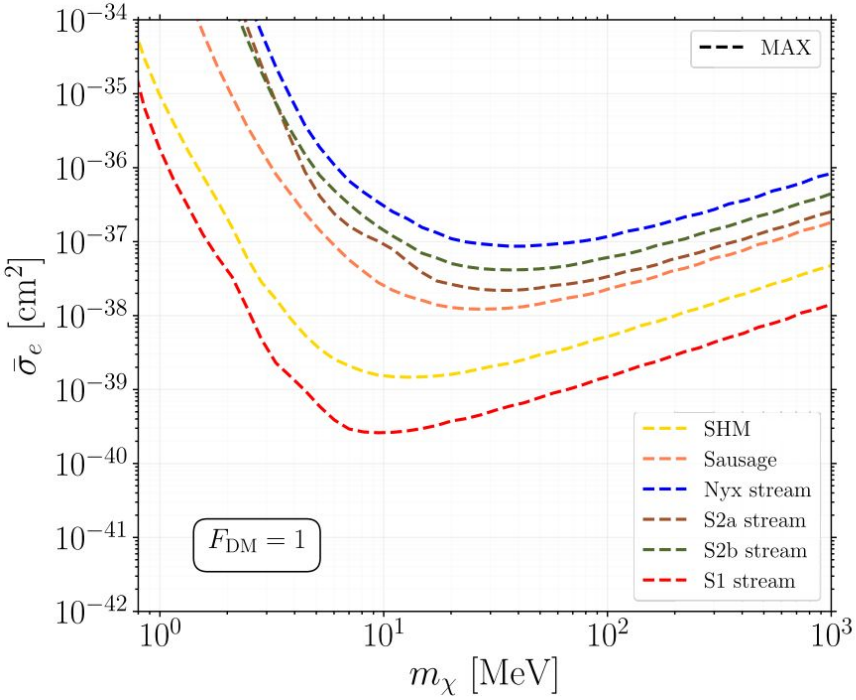
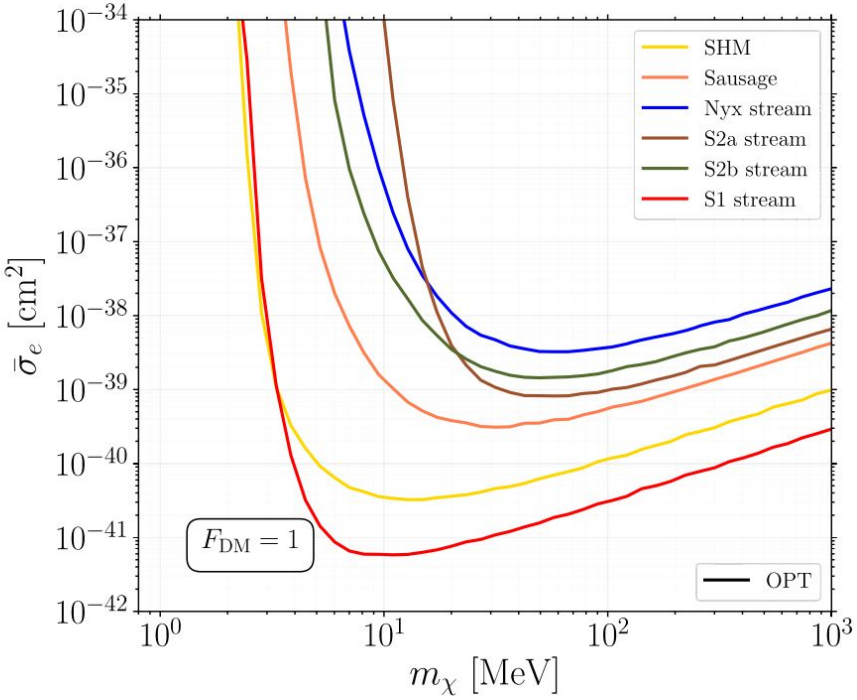
More Results: *5σ Discovery Reach*

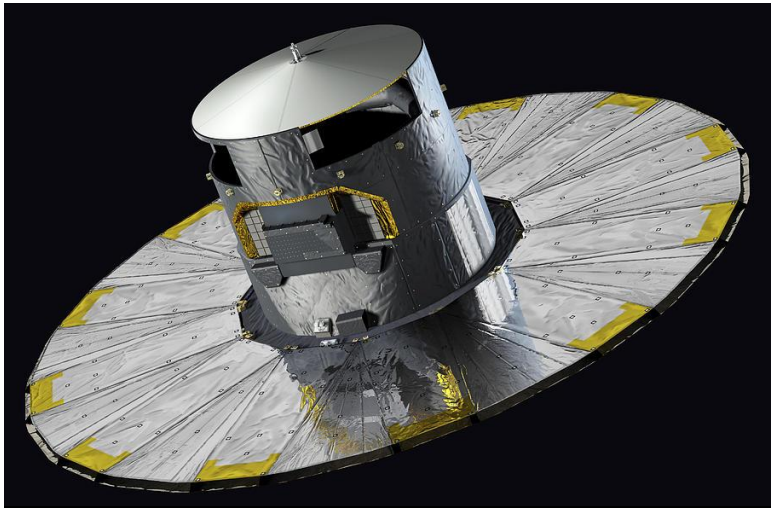


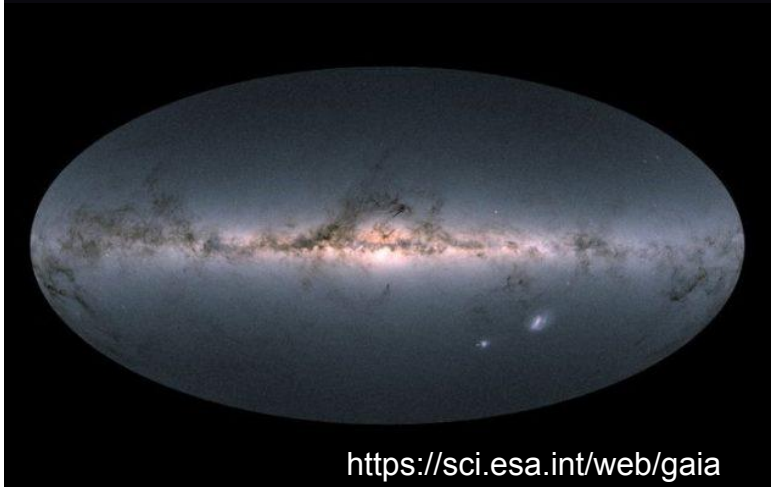


1. *Gaia* and substructures

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





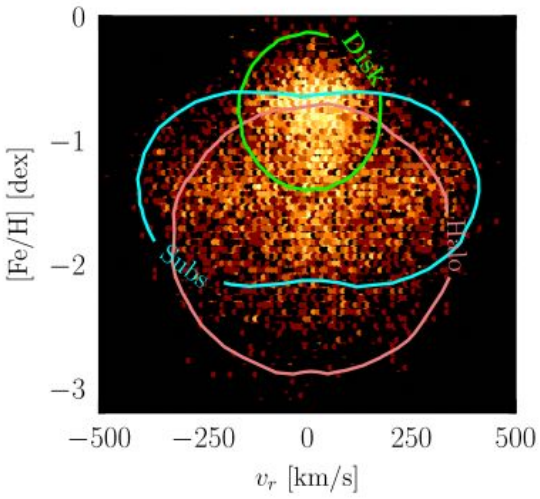
https://sci.esa.int/web/gaia

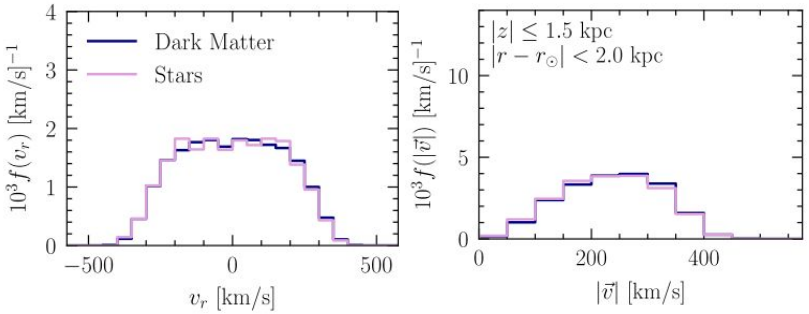
Discoveries with *Gaia*

- *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 swallowed in mergers
- *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

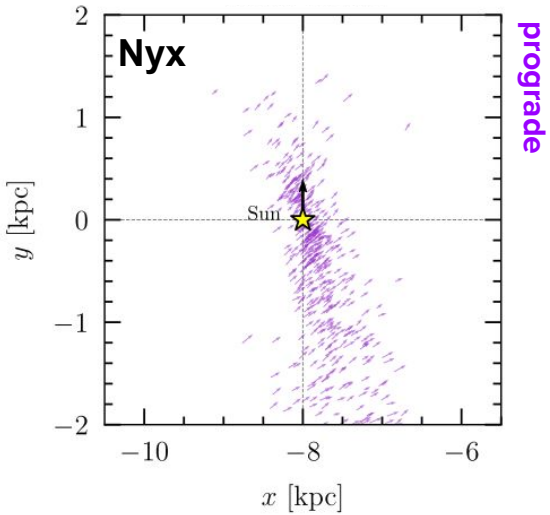


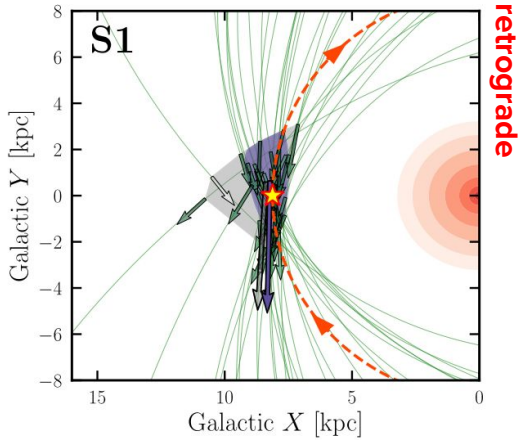


[Belokurov, et al. 1802.03414; Necib, et al. arXiv:1807.02519; Necib, et al. arXiv:1810.12301]

BSHM: Streams

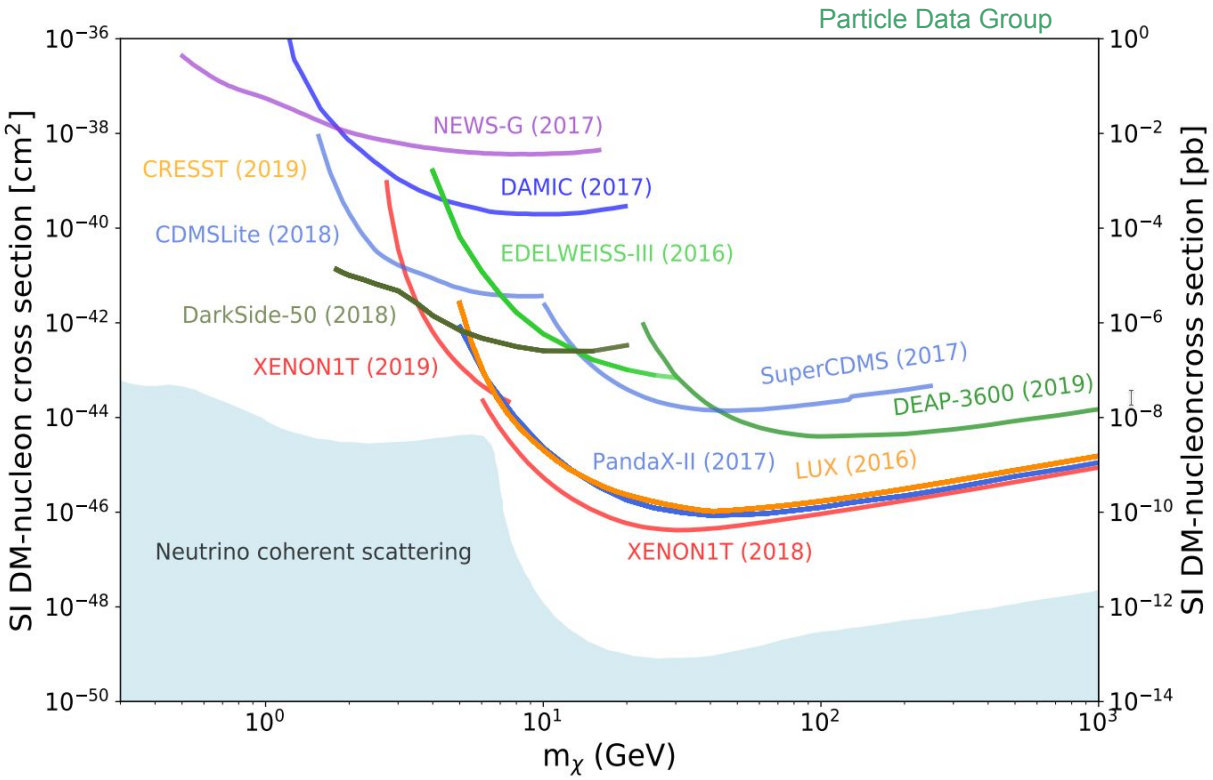
- Spatially localized, cold kinematic stellar substructures
- Formed by recent mergers (dwarf spheroidals)
- A few:
  - **Nyx** [Necib, et al. arXiv:1907.07190]
  - **S1, S2a, S2b** [Myeong, et al. 1804.07050; O'Hare, et al. arXiv:1909.04684]
- DM distribution from stars?
  - *FIRE-2* simulations: no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



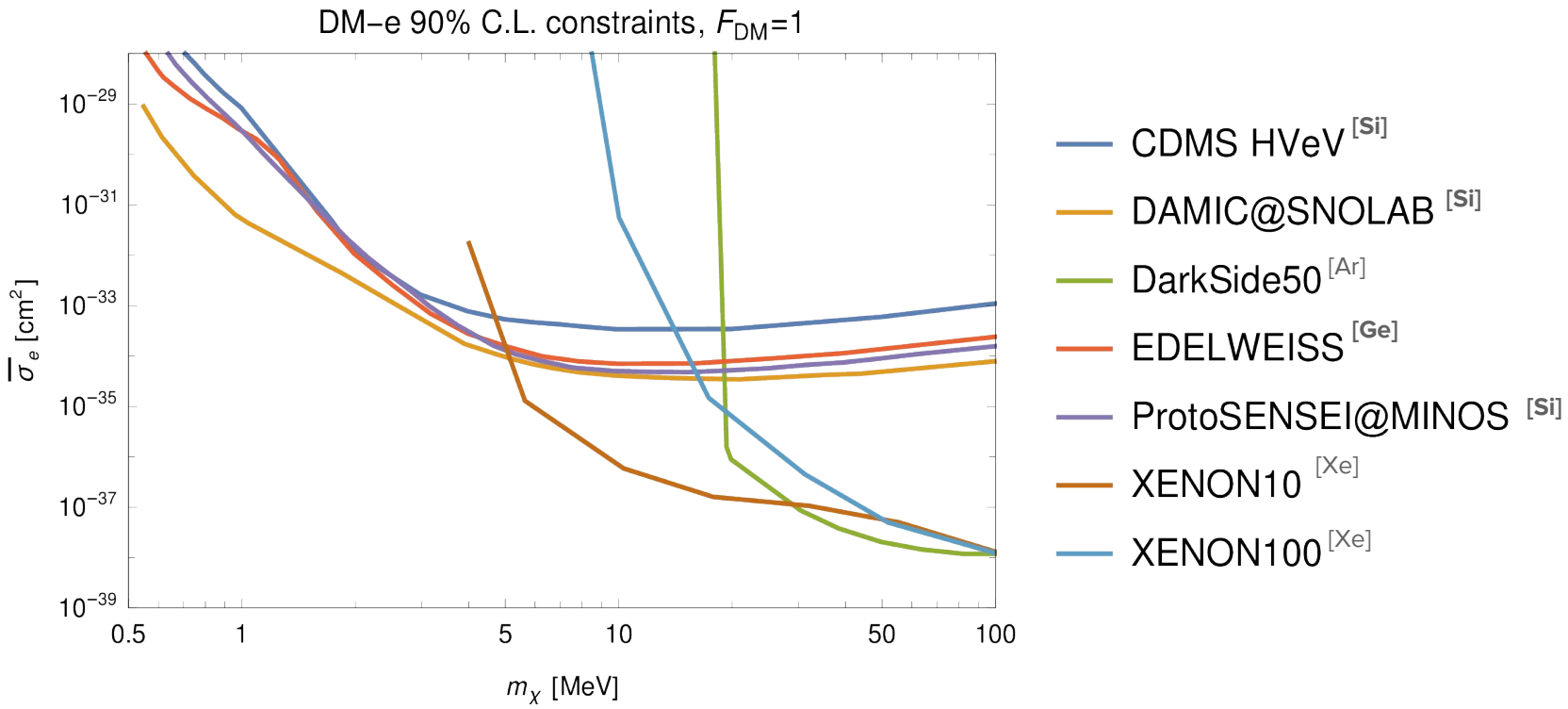


2. Dark Matter Direct Detection

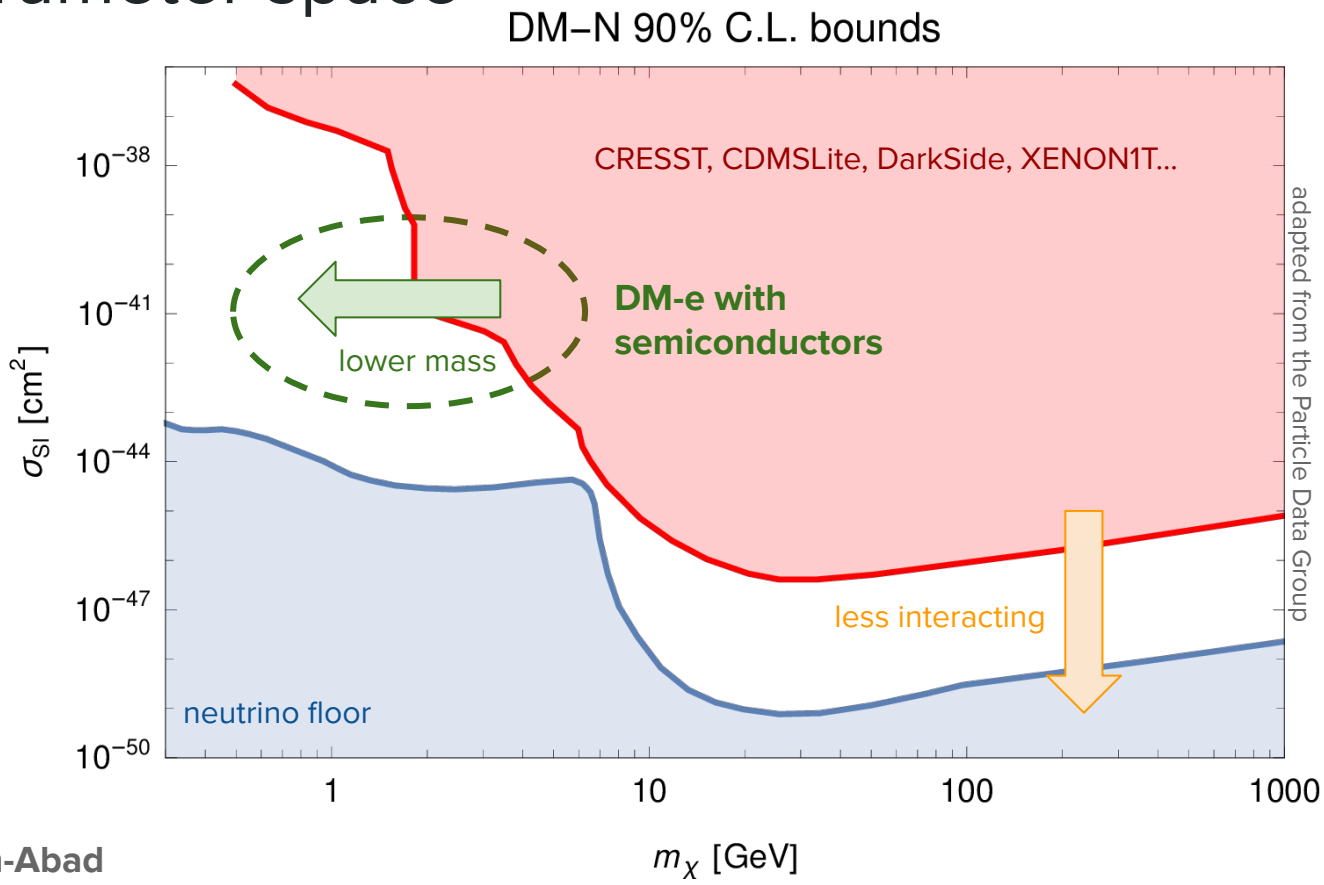
Bounds: DM-N DD



Bounds: DM-e DD



DD Parameter space



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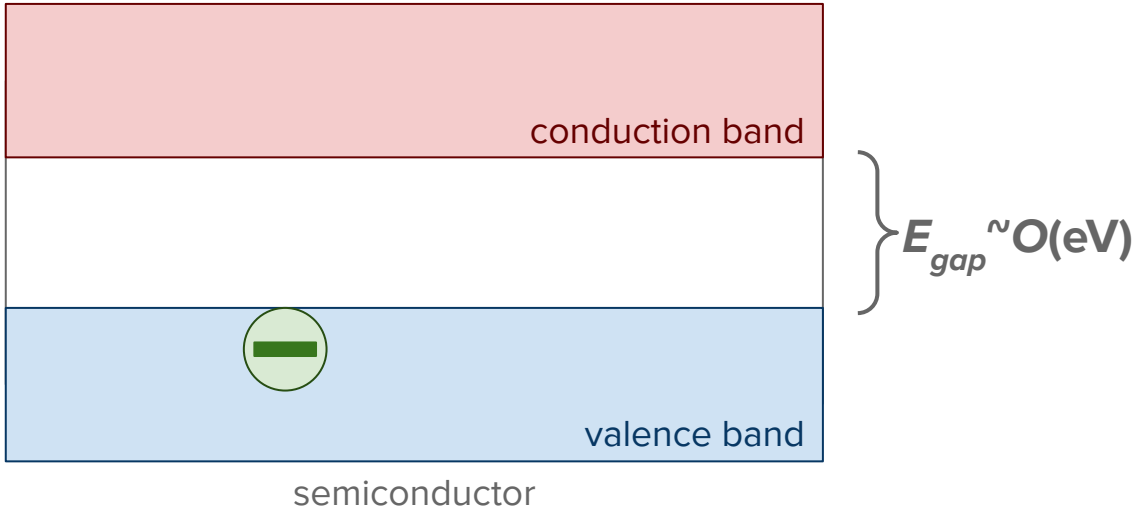
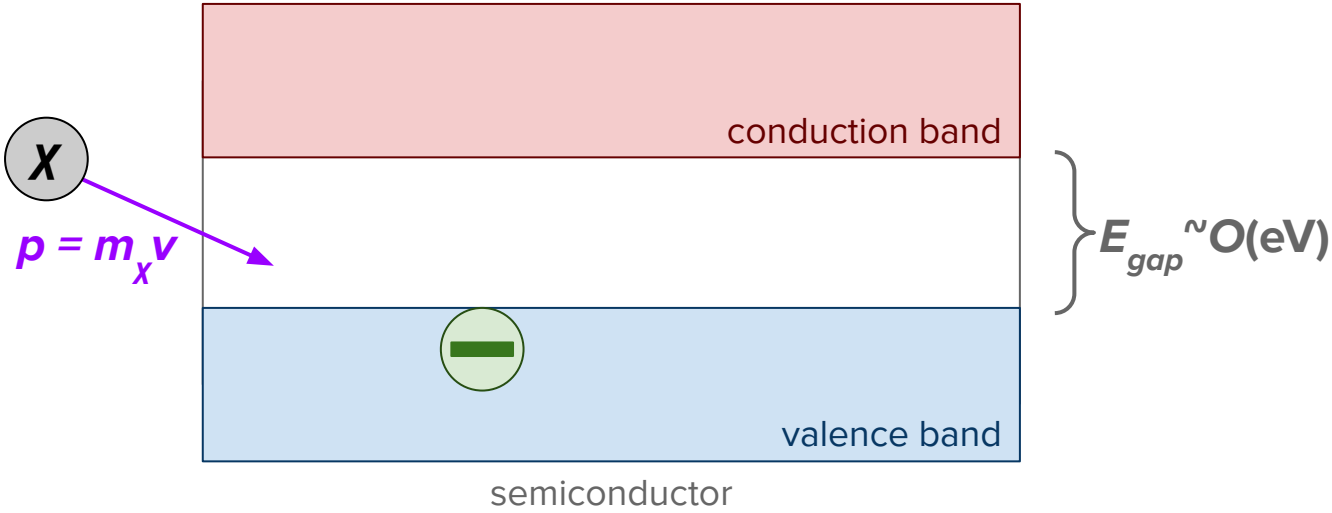
DM-e DD with semiconductors: *cartoon*



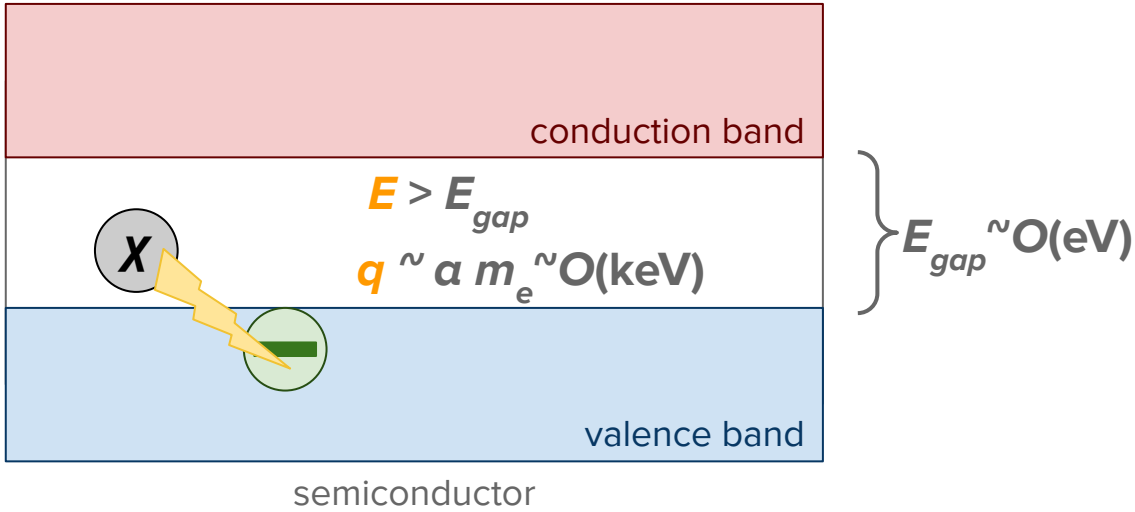
Graham, Kaplan, Rajendran, Walters '12

DM-e DD with semiconductors: *cartoon*



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

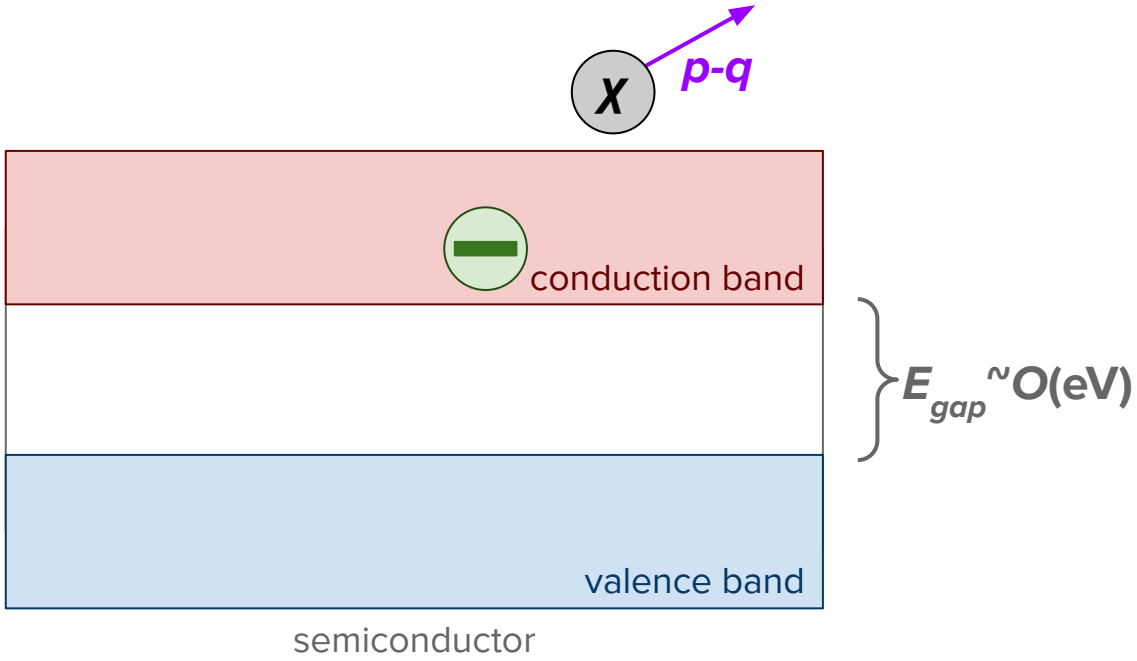
DM-e DD with semiconductors: *cartoon*



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

Spectrum

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

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

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

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

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

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

DM *speed* distribution

Gaia recap

Gaia: astrophysics input is *complicated*.

BSHM: *some* of local DM density could come from:

- Enceladus/Sausage
- Streams
  - Nyx
  - S1
  - ...

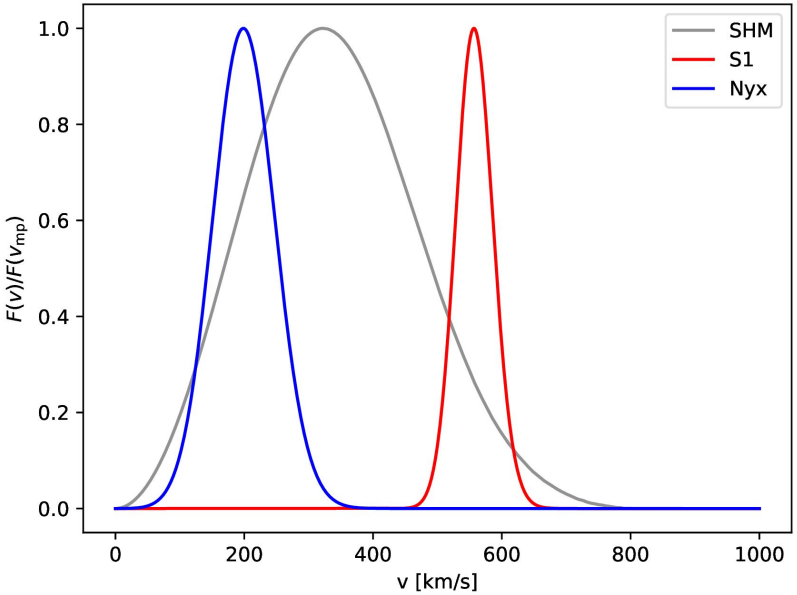
$$g(v_{\min}) = \int_{v_{\min}}^{v_{\rm esc}} \mathrm{d}v \, \frac{F(v)}{v}$$

3. DM-e DD after *Gaia*

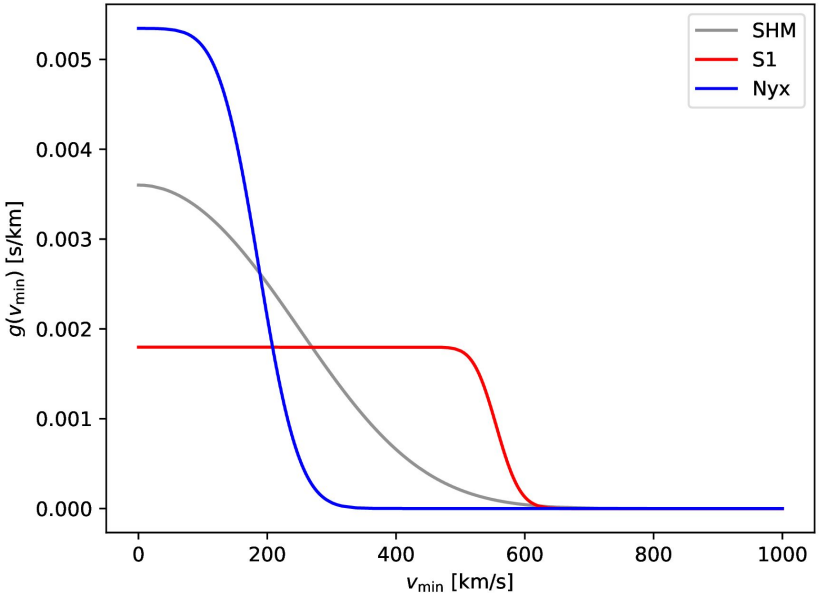
Assumption:

DM distr. = stellar distr.

Substructure Properties



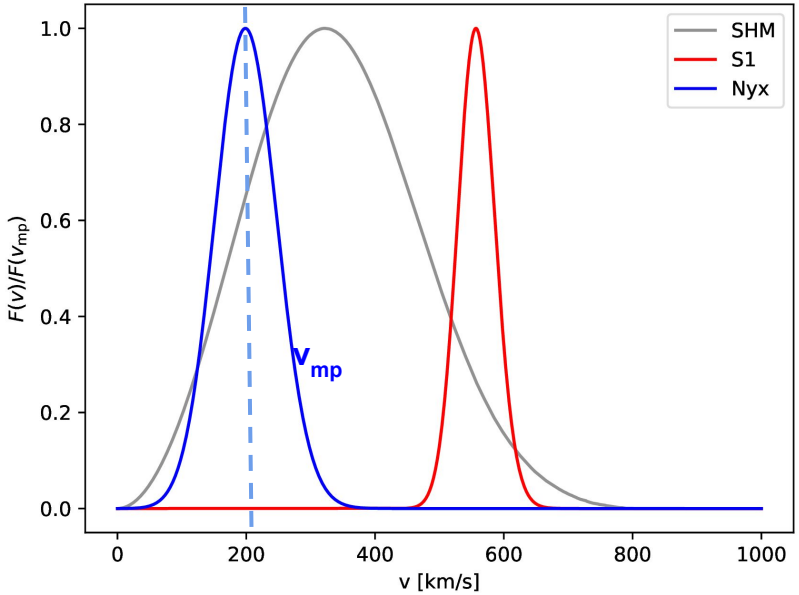
$$F(v) = v^2 \int d\Omega \; f(\mathbf{v})$$



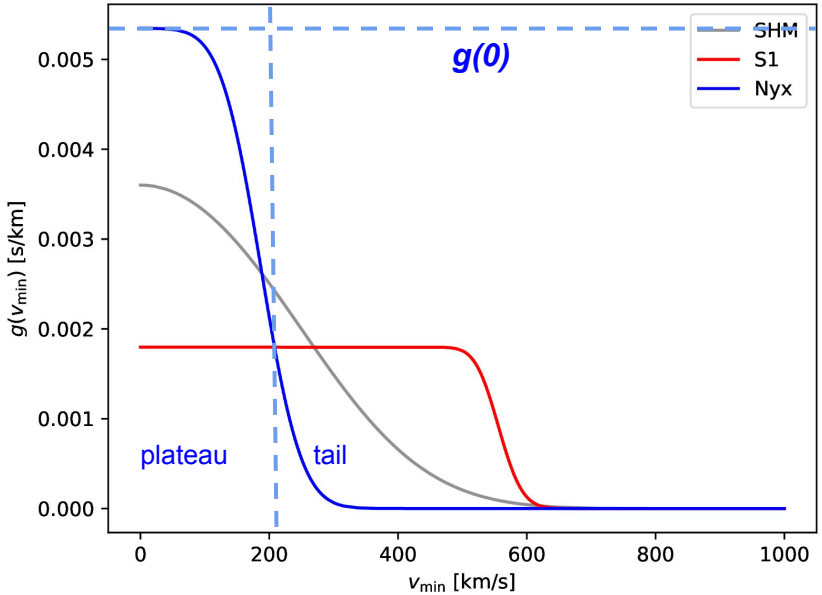
$$g(v_{\rm min}) = \int_{v_{\rm min}}^{v_{\rm esc}} dv \; \frac{F(v)}{v}$$

Substructure Properties

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



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



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

Substructure Properties

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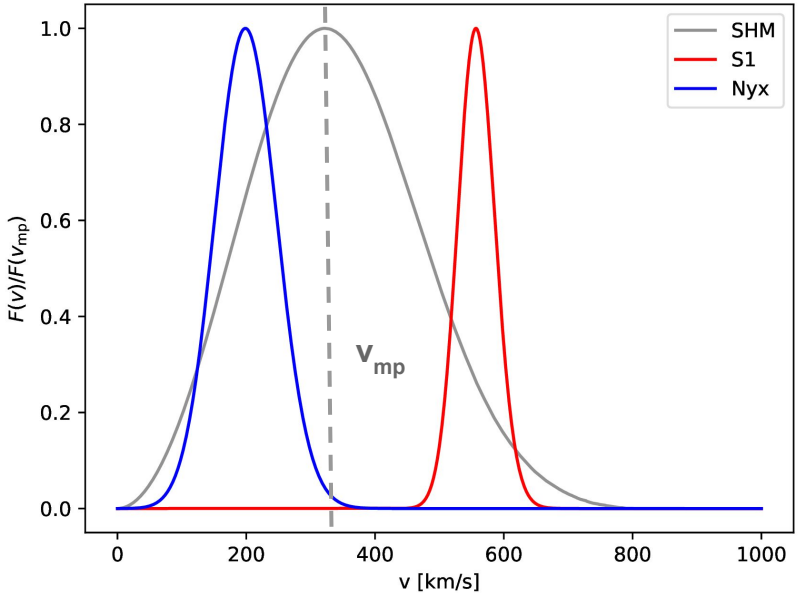

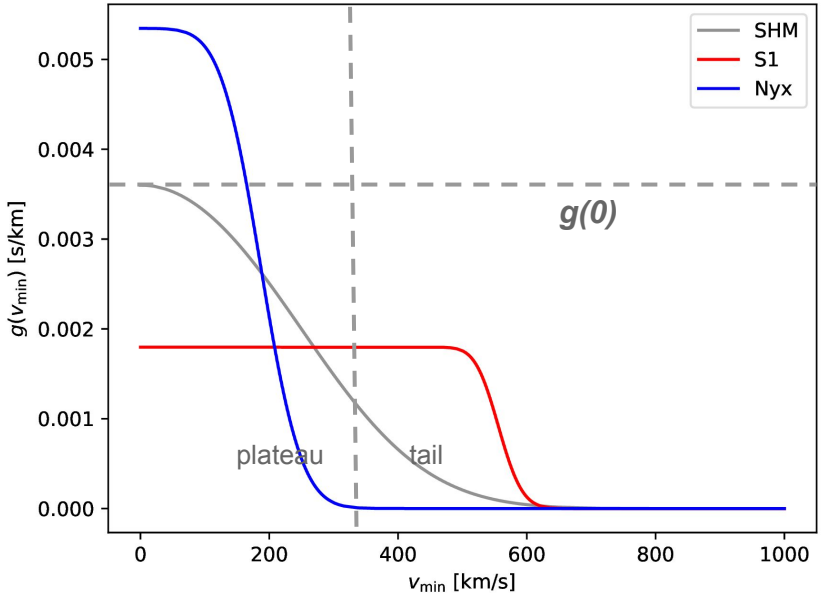

$$F(v) = v^2 \int d\Omega \; f(\mathbf{v})$$

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

Substructure Properties

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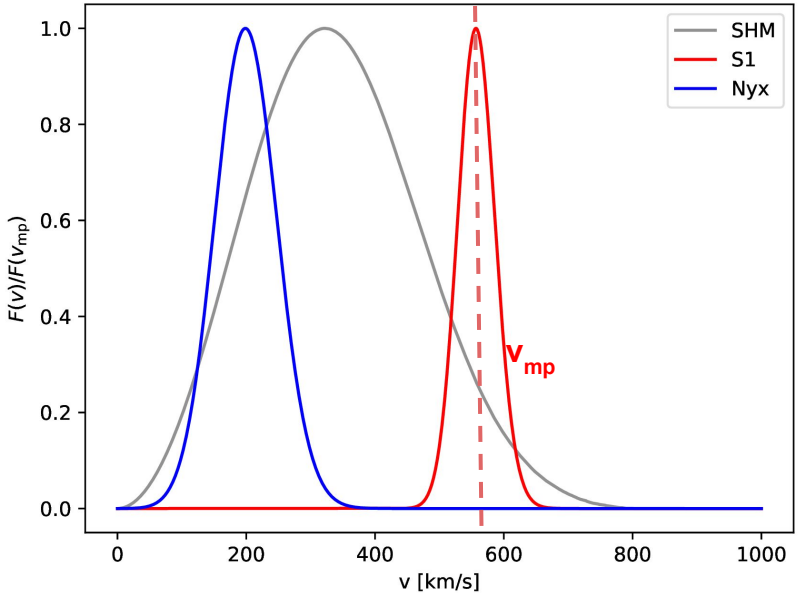
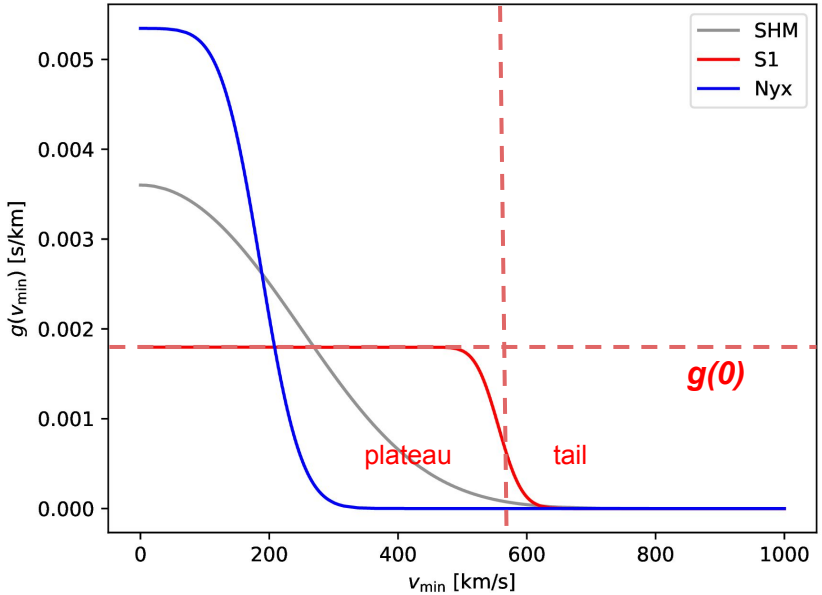
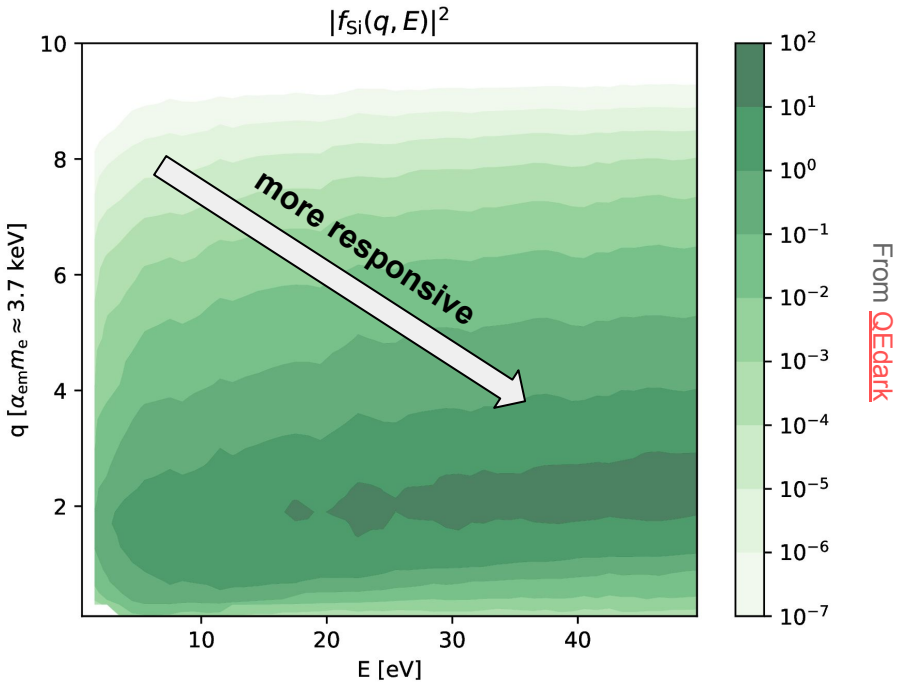




$$F(v) = v^2 \int \mathrm{d}\Omega \; f(\mathbf{v})$$

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

Kinematics

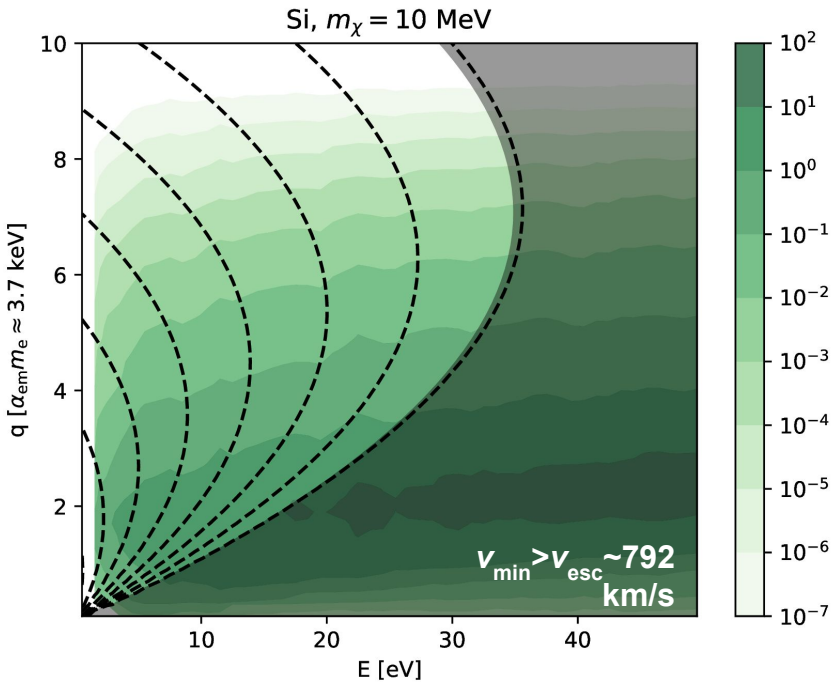


From QEdark

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

Kinematics

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

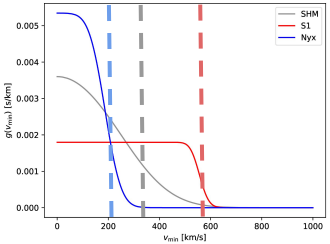


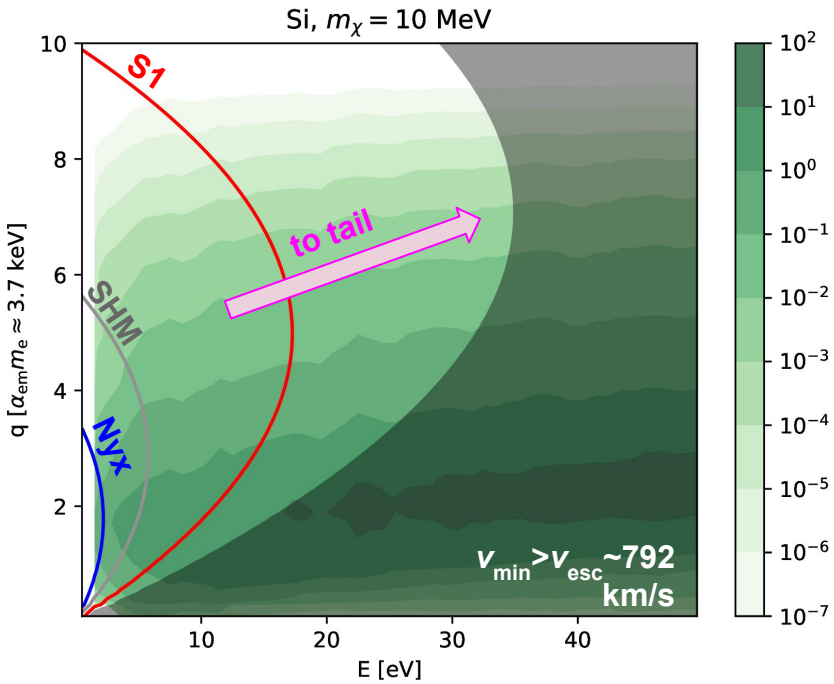
$$\frac{dR}{dE} \propto \int dq \; \ldots |f_{sc}(q, E)|^2 g(v_{\min}(q, E))$$

Kinematics

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

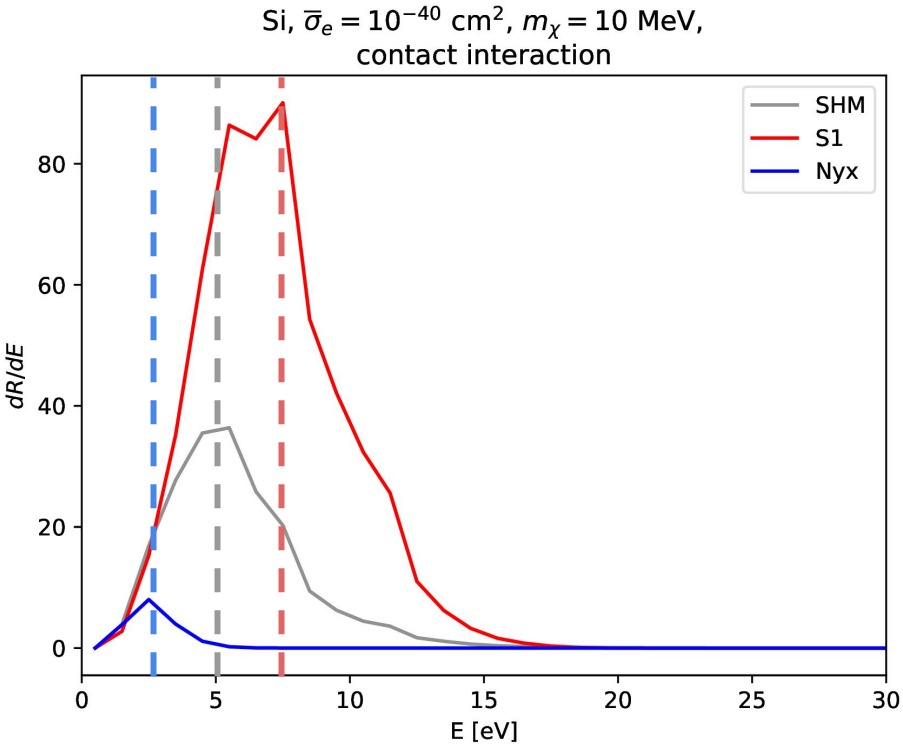
199 km/s
322 km/s
557 km/s

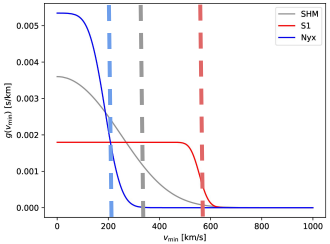


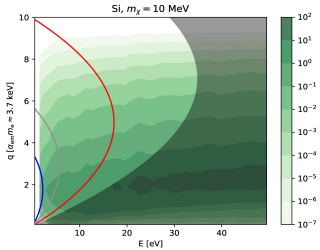


$$\frac{dR}{dE} \propto \int dq \; \ldots |f_{\mathrm{sc}}(q, E)|^2 g(v_{\min}(q, E))$$

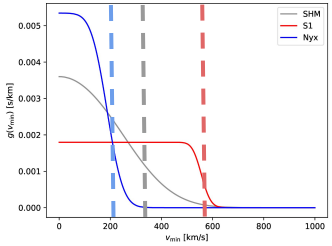
Spectra

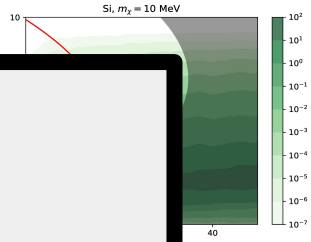

Si, $\overline{\sigma}_e = 10^{-40}$ cm^2, $m_\chi = 10$ MeV,
contact interaction
SHM
S1
Nyx
dR/dE
E [eV]
0
20
40
60
80
0
5
10
15
20
25
30


SHM
S1
Nyx
v_{min} [km/s]


Si, $m_\chi = 10$ MeV
E [eV]

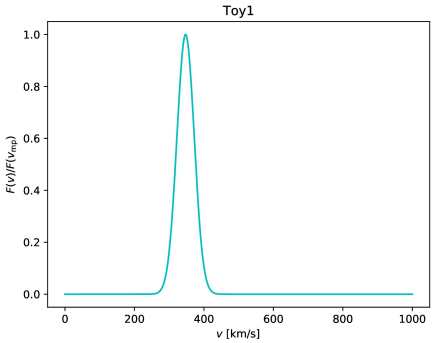
Spectra

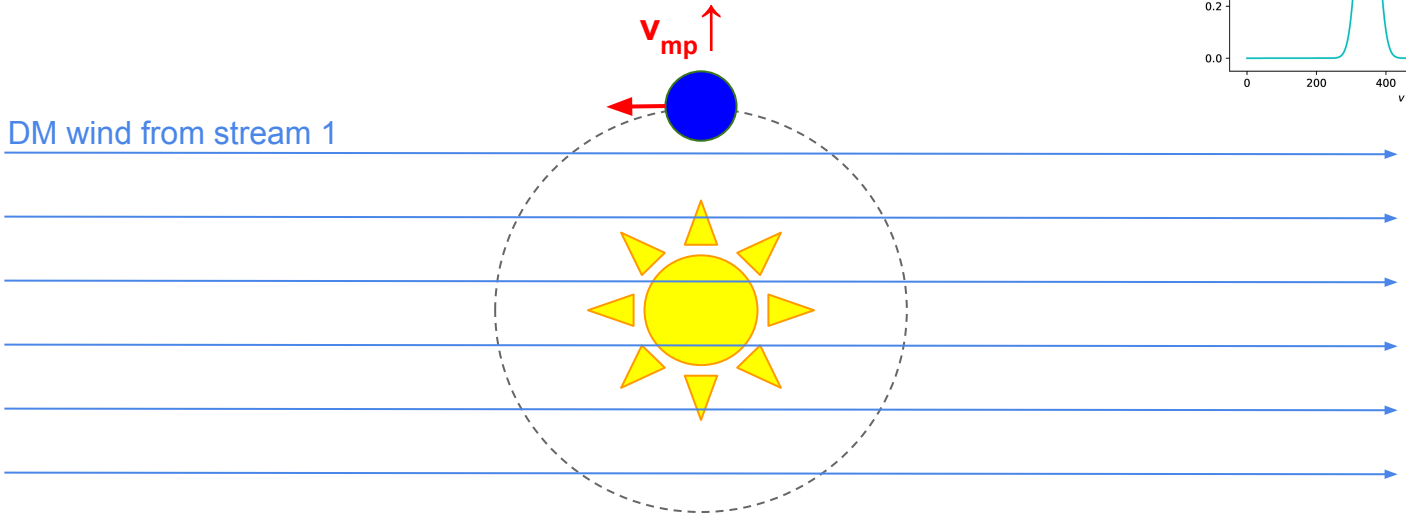




ONE SIZE DOES
***NOT* FIT ALL**

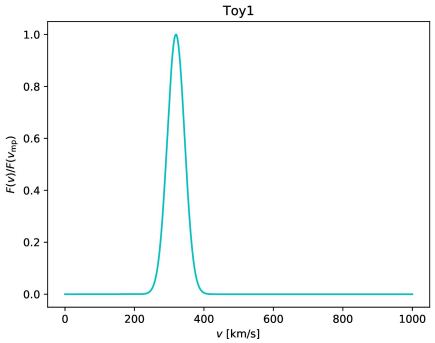
Annual modulation: *tell-tale*

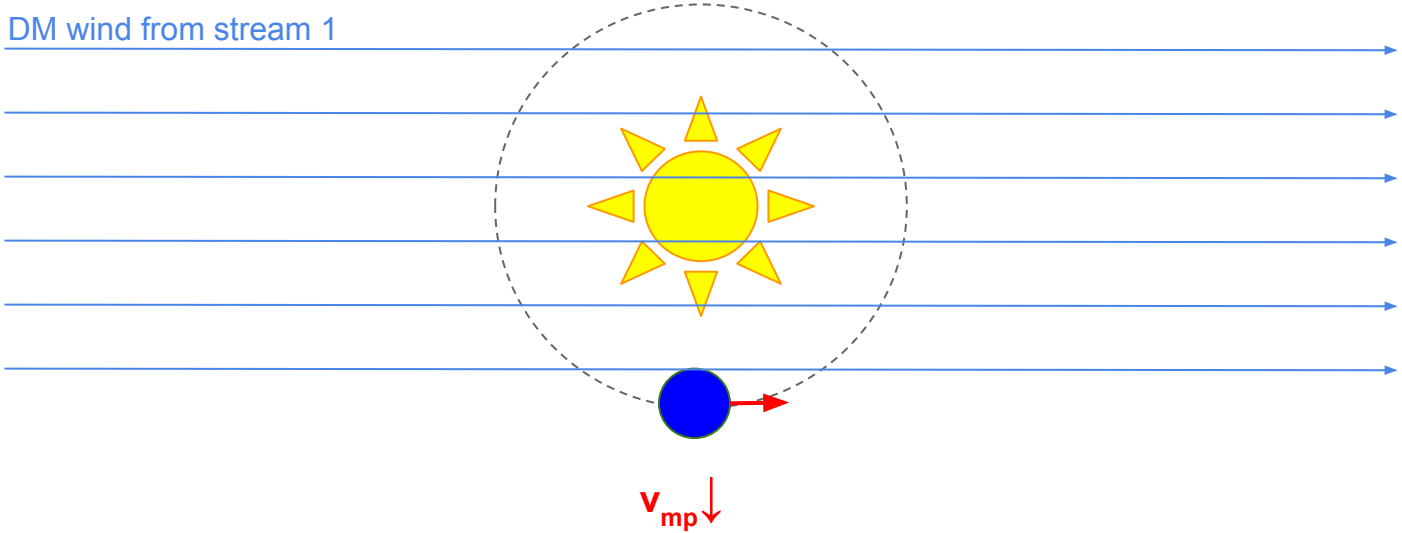




Drukier, Freese, Spergel ‘86
Freese, Lisanti, Savage ‘12

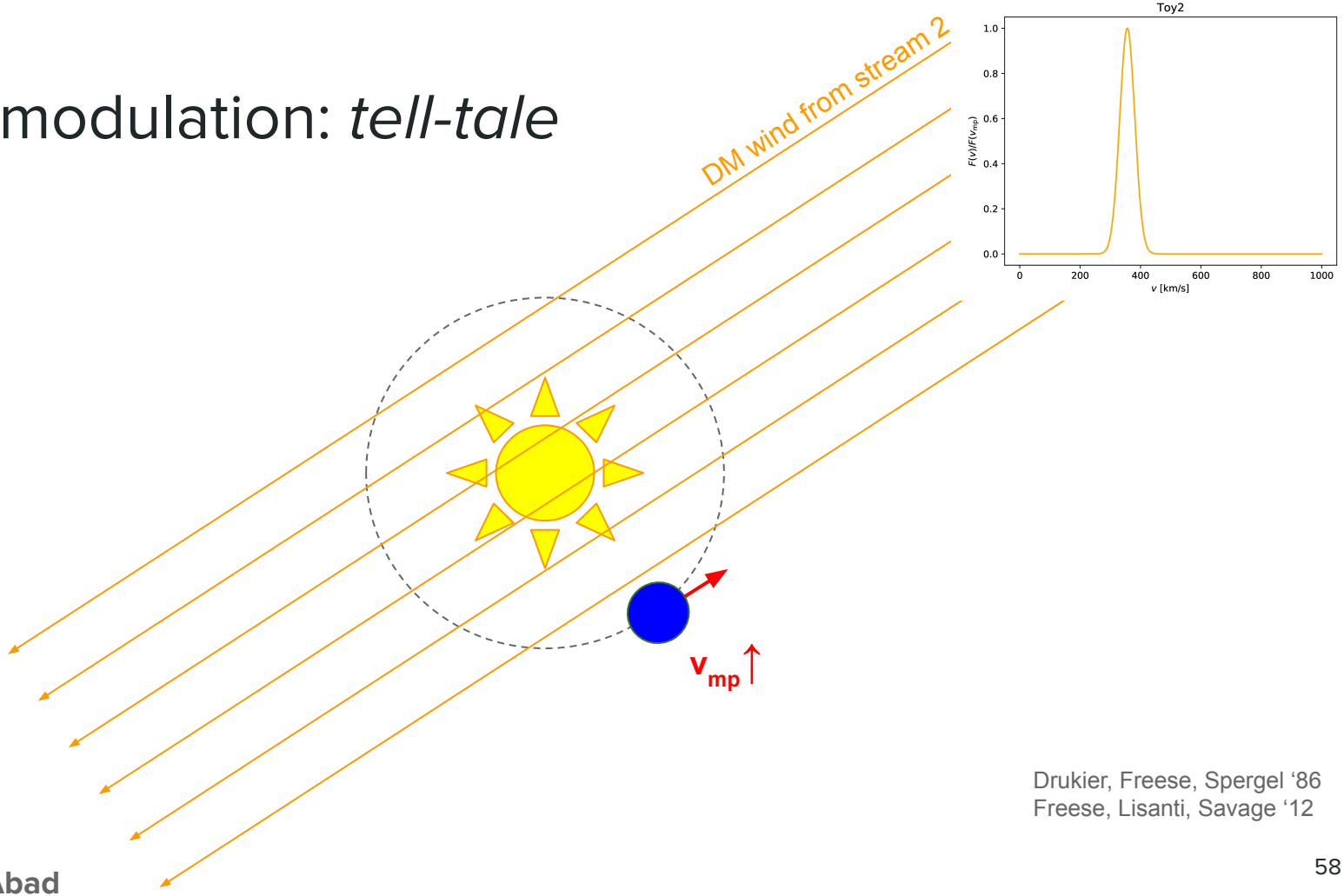
Annual modulation: *tell-tale*





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

Annual modulation: *tell-tale*



Drukier, Freese, Spergel ‘86
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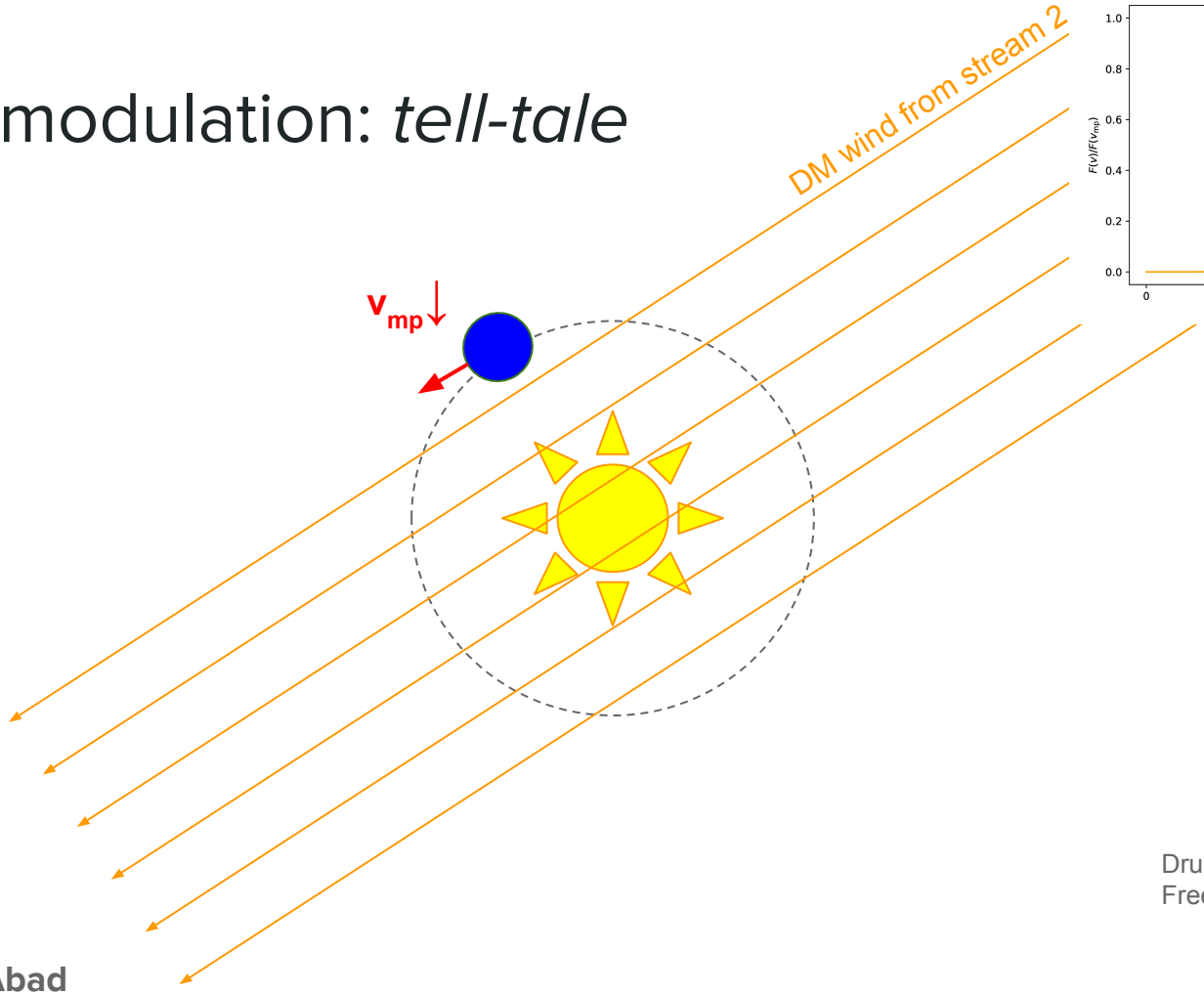
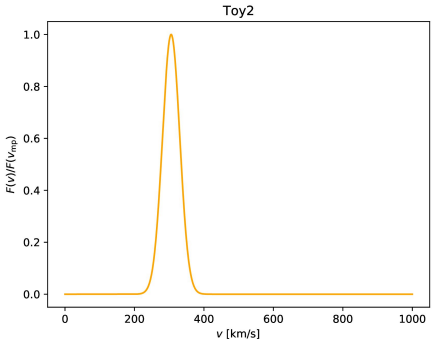
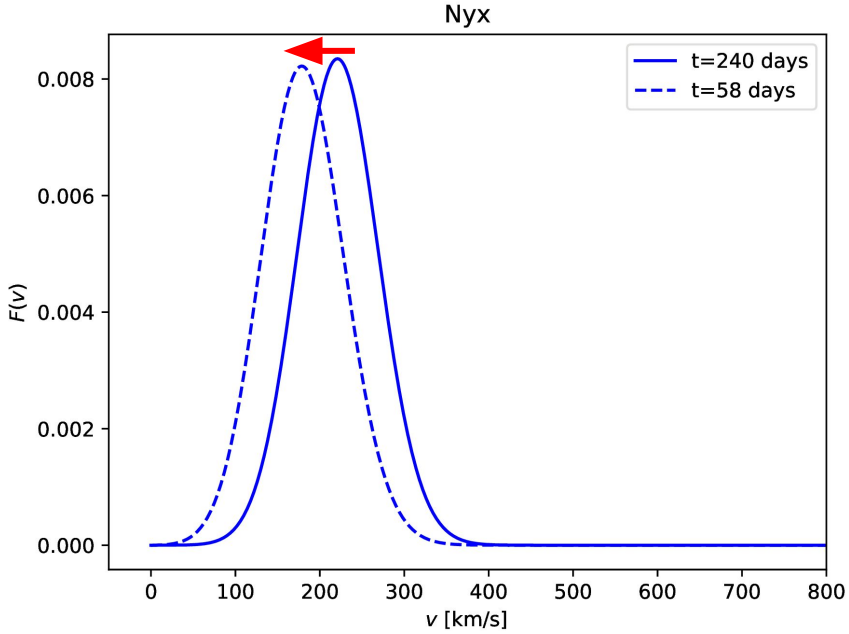
Annual modulation: *tell-tale*

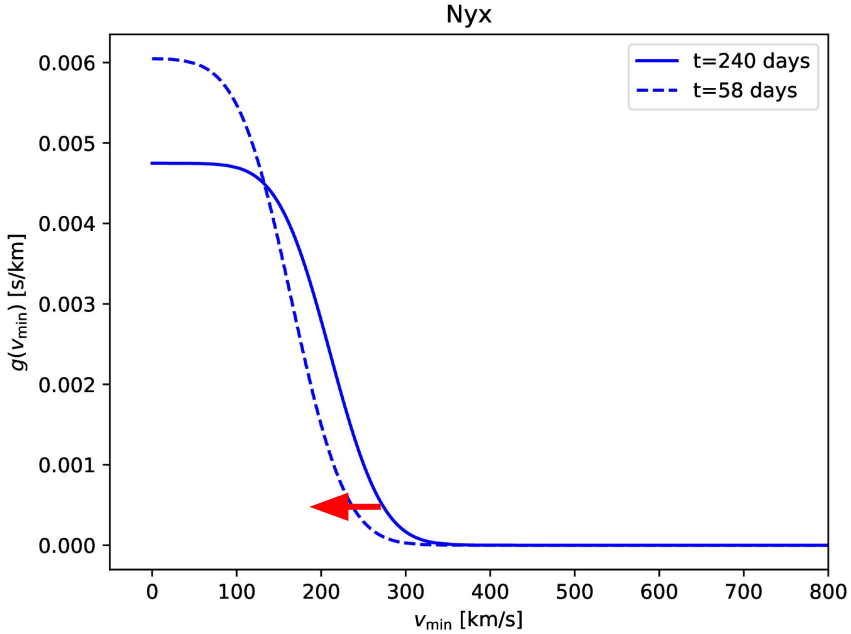




Drukier, Freese, Spergel ‘86
Freese, Lisanti, Savage ‘12

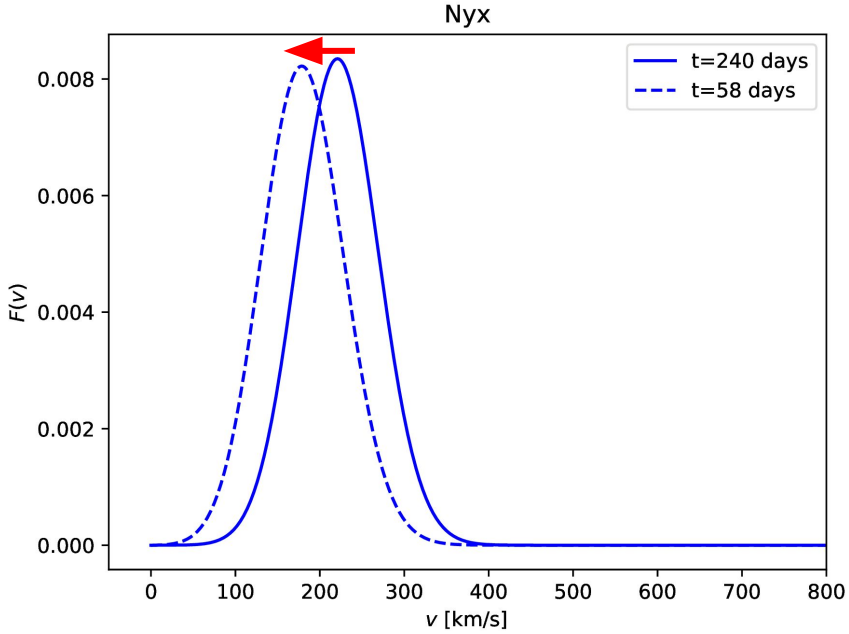
Annual modulation: distributions

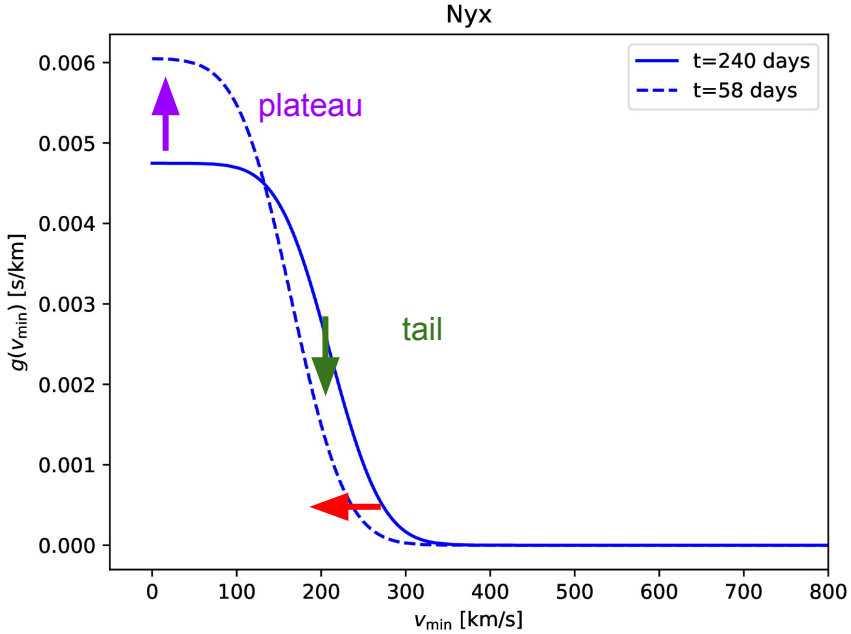




Annual modulation: distributions

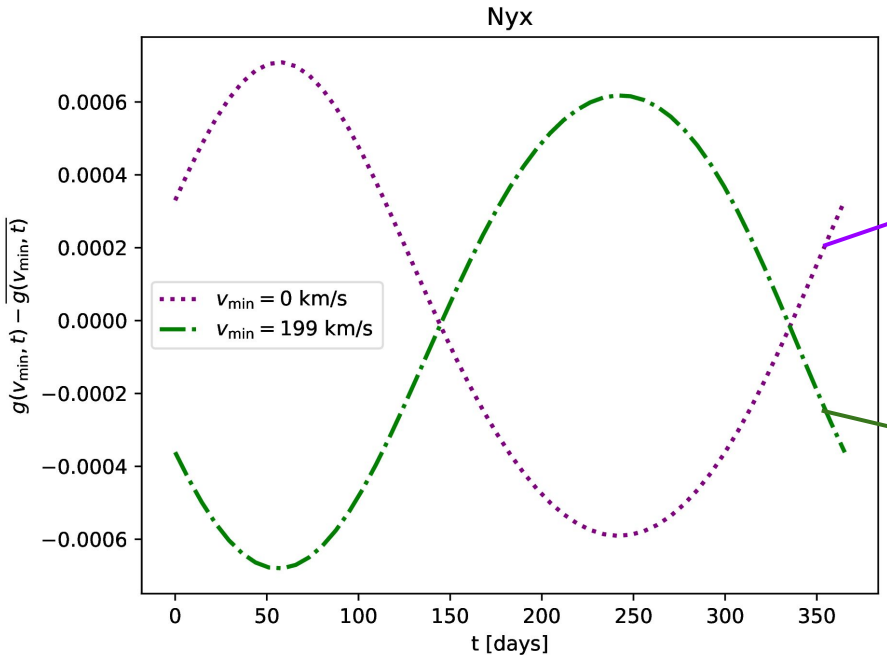
$$g(0) = \left\langle \frac{1}{v} \right\rangle \sim \frac{1}{\langle v \rangle} \sim \frac{1}{v_{\rm mp}}$$

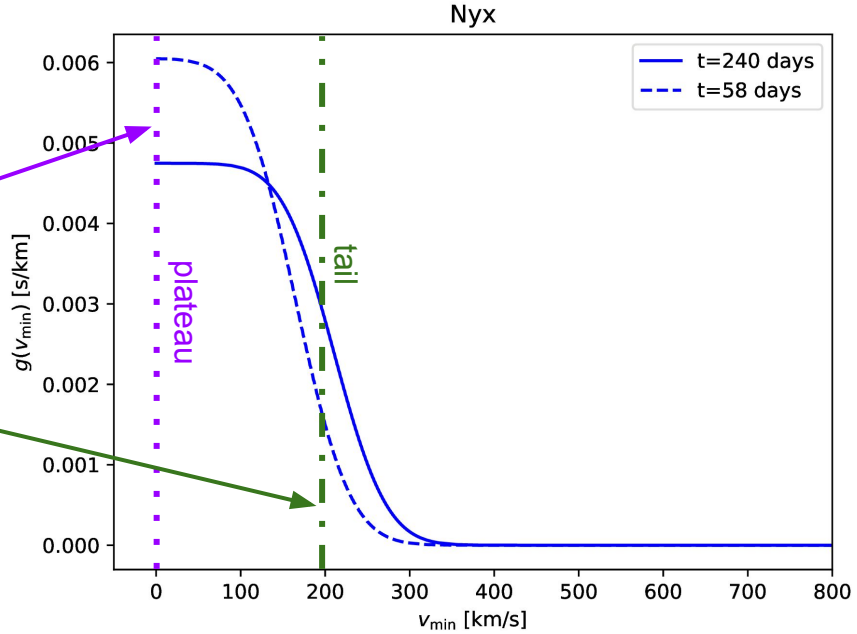




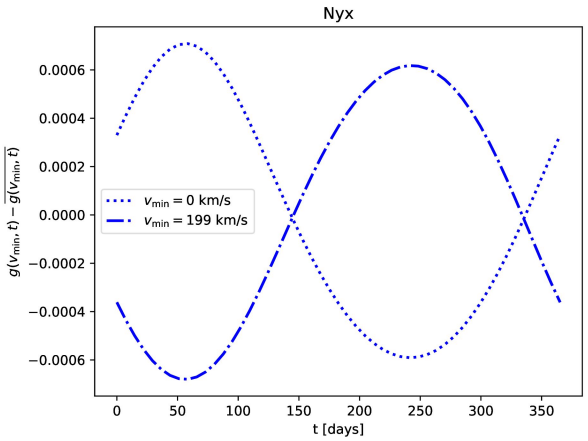
Annual modulation: distributions

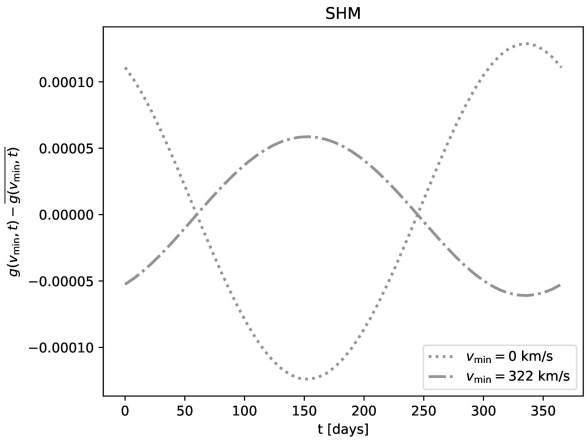
$$g(0) = \left\langle \frac{1}{v} \right\rangle \sim \frac{1}{\langle v \rangle} \sim \frac{1}{v_{\rm mp}}$$

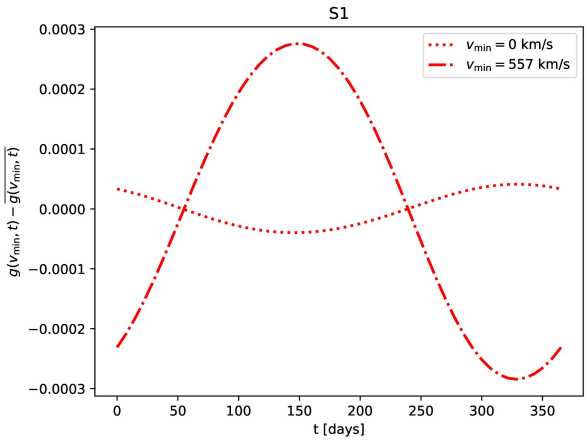




Annual modulation: distributions

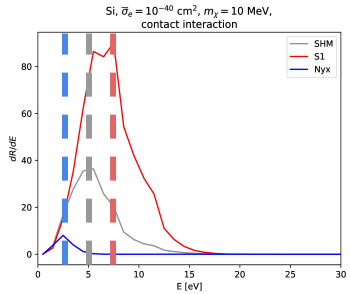


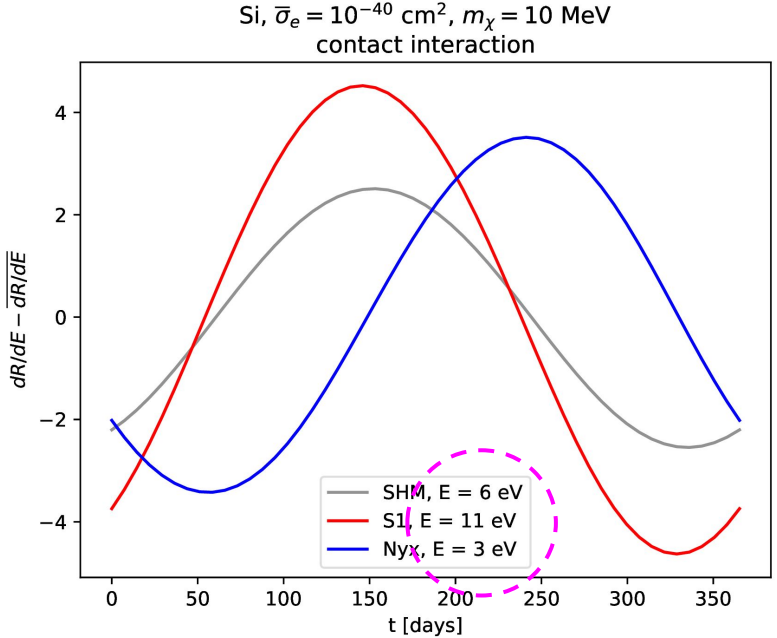




different **phases** at different **velocities** for different **distributions**

Annual modulation: spectra





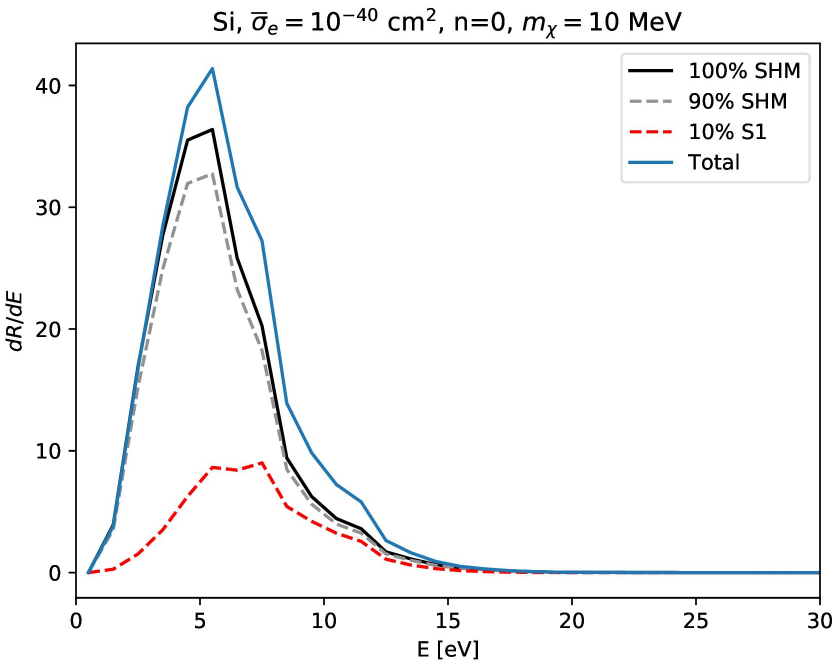
different **phases** at different **energies** for different **distributions**

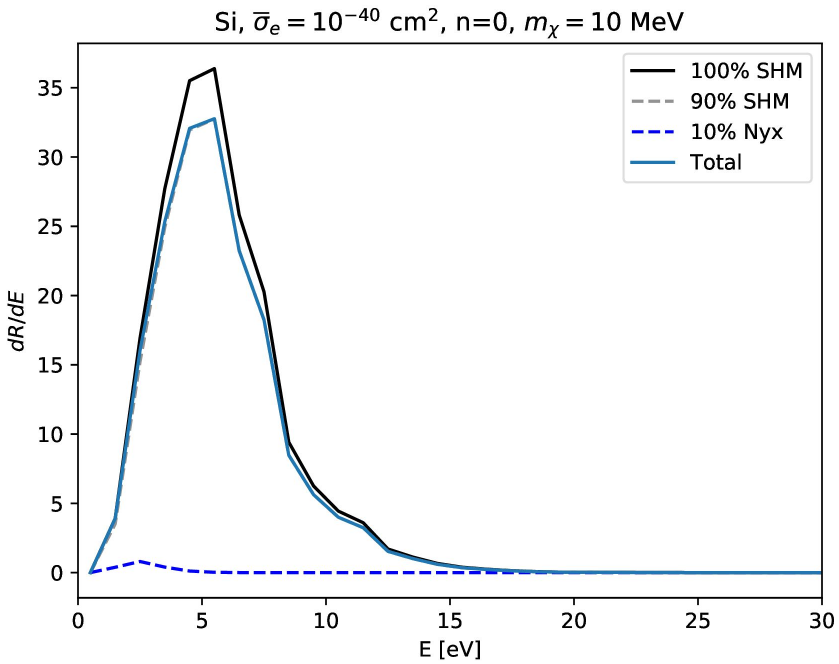
Annual modulation: spectra

Si, $\overline{\sigma}_e = 10^{-40}$ cm^2, $m_\chi = 10$ MeV
contact interaction

ONE SIZE DOES
***NOT* FIT ALL**

different **phases** at different **energies** for different **distributions**


Si, $\overline{\sigma}_e = 10^{-40}$ cm^2, n=0, $m_\chi = 10$ MeV
100% SHM
90% SHM
10% S1
Total
dR/dE
E [eV]
0
10
20
30
40
0
5
10
15
20
25
30


Si, $\overline{\sigma}_e = 10^{-40}$ cm^2, n=0, $m_\chi = 10$ MeV
100% SHM
90% SHM
10% Nyx
Total
dR/dE
E [eV]
0
5
10
15
20
25
30
35
0
5
10
15
20
25
30