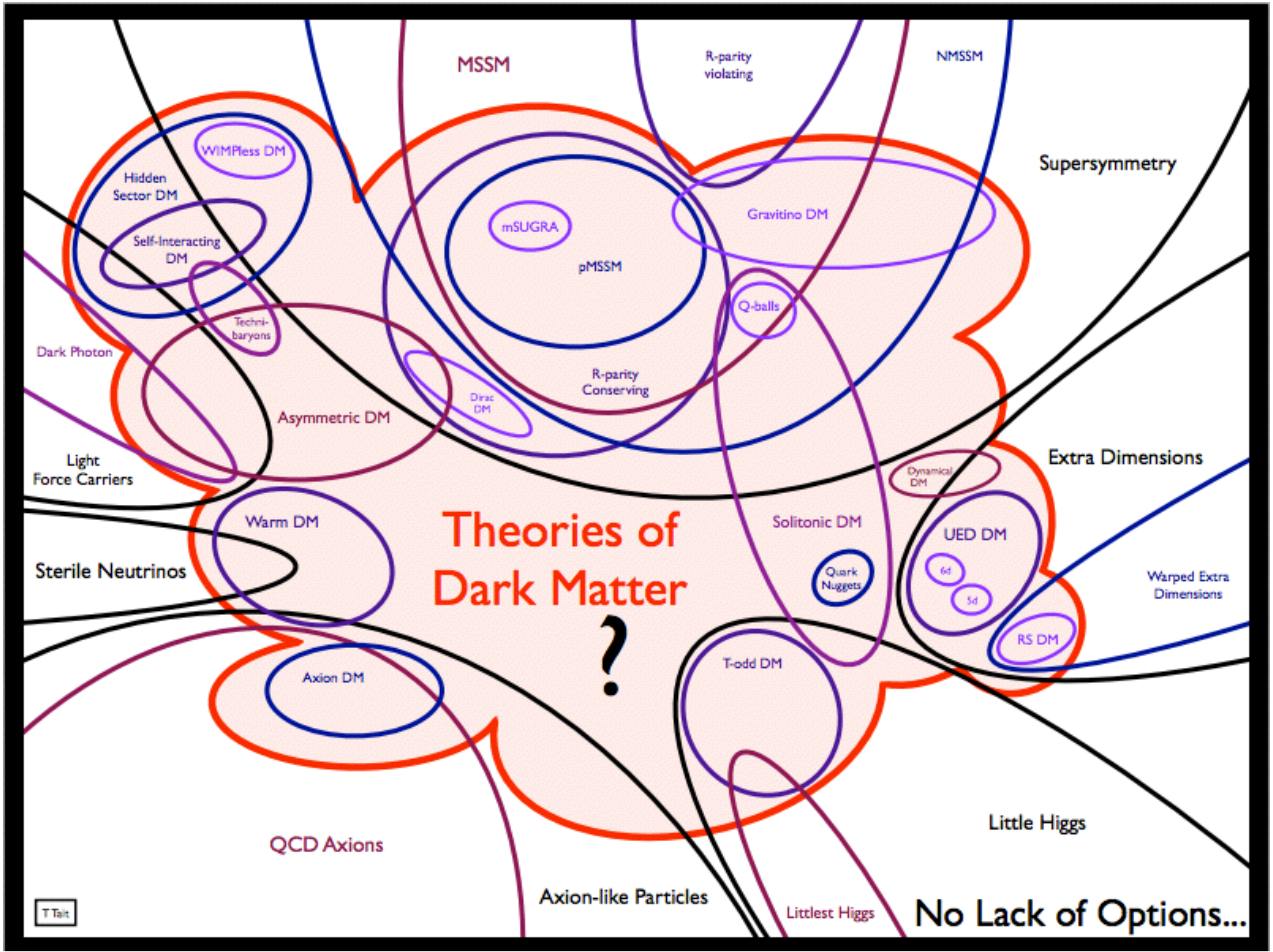
Novel Techniques for Detecting sub-GeV Dark Matter

Tien-Tien Yu
YITP - Stony Brook

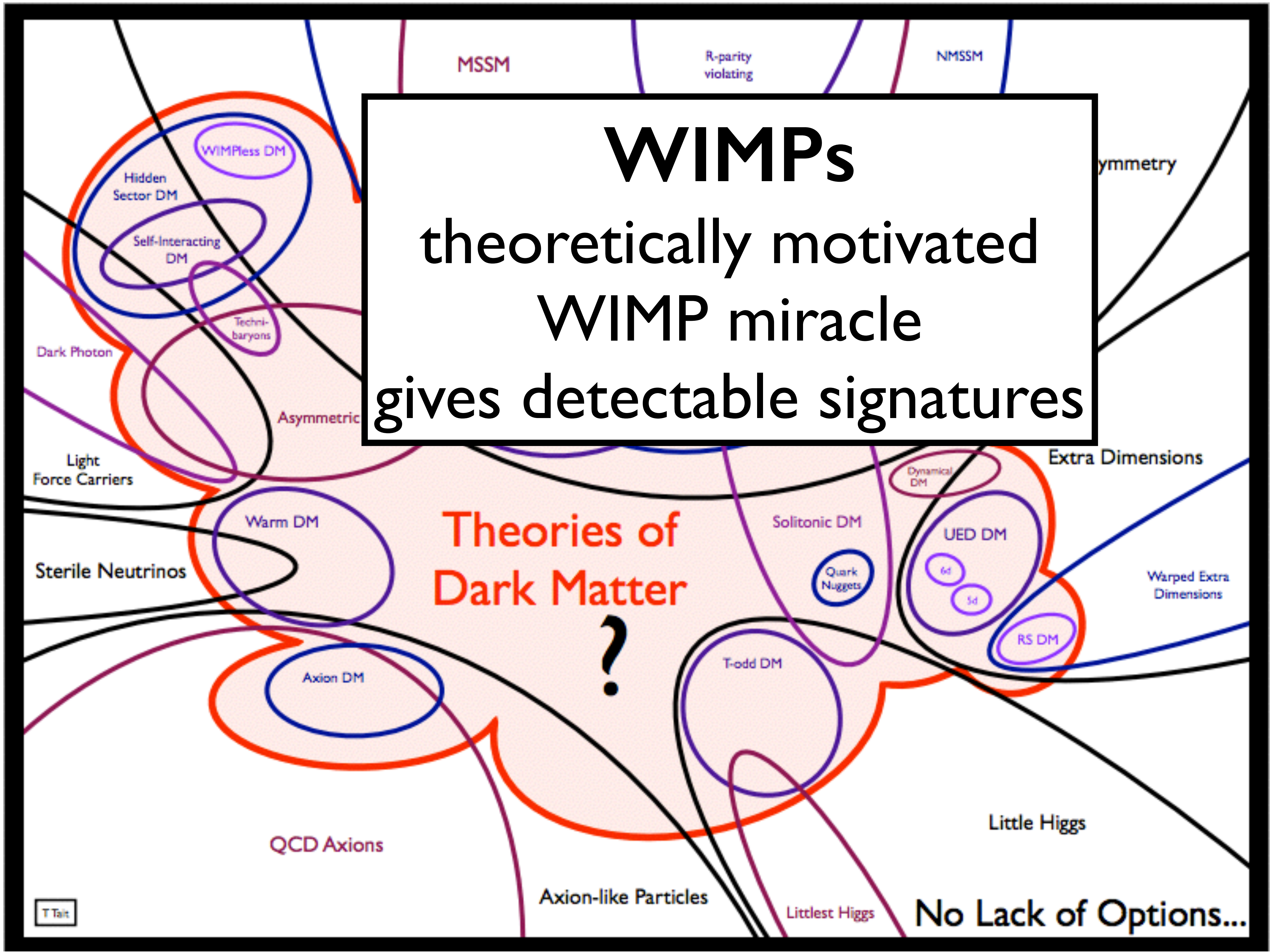
with Rouven Essig, Marivi Fernandez Serra, Jeremy Mardon,
Adrián Soto, Tomer Volansky
1504.XXXXX

April 29, 2015 UC Irvine Theory Seminar

candidates for DM



candidates for DM



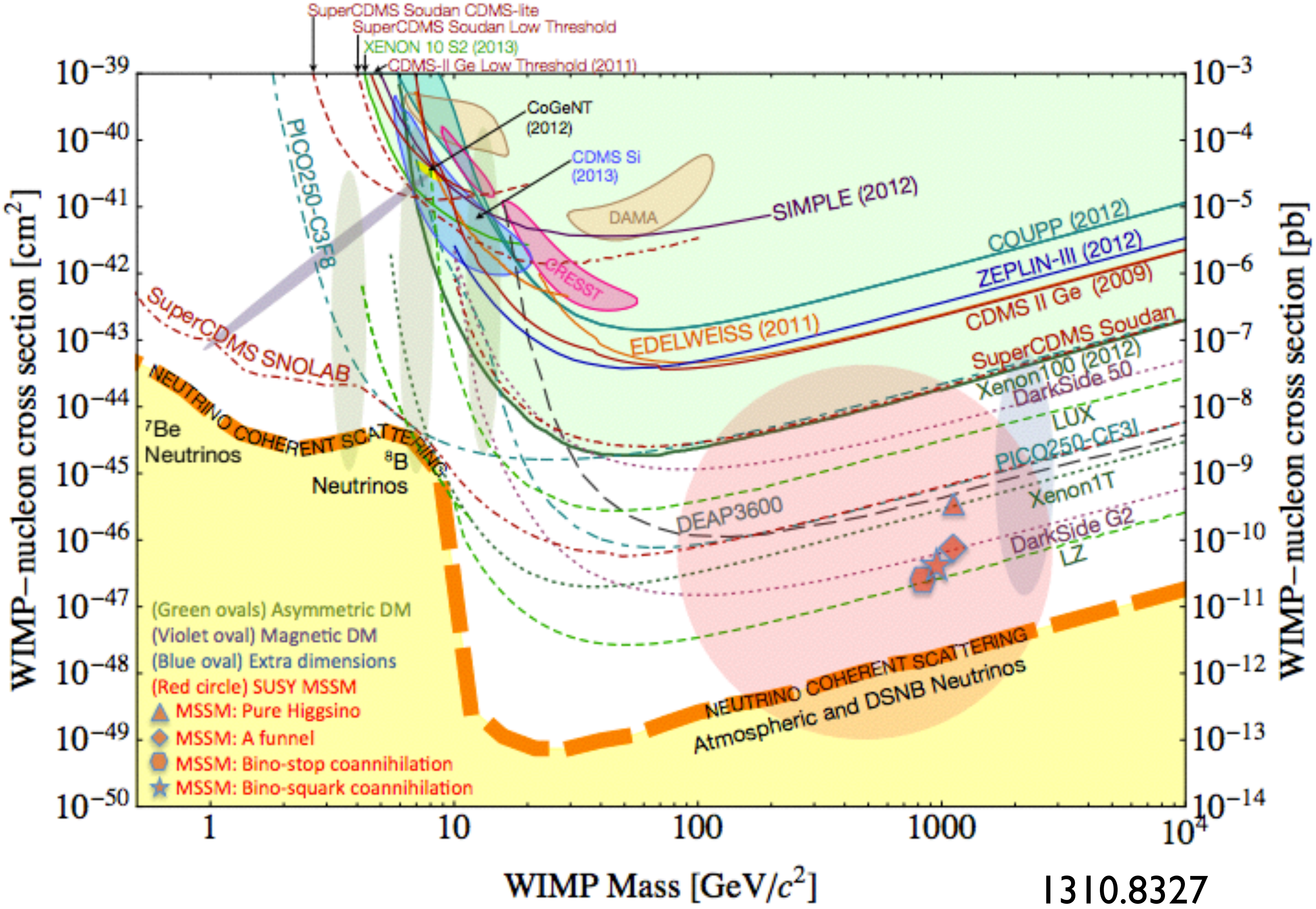
WIMPs

theoretically motivated

WIMP miracle

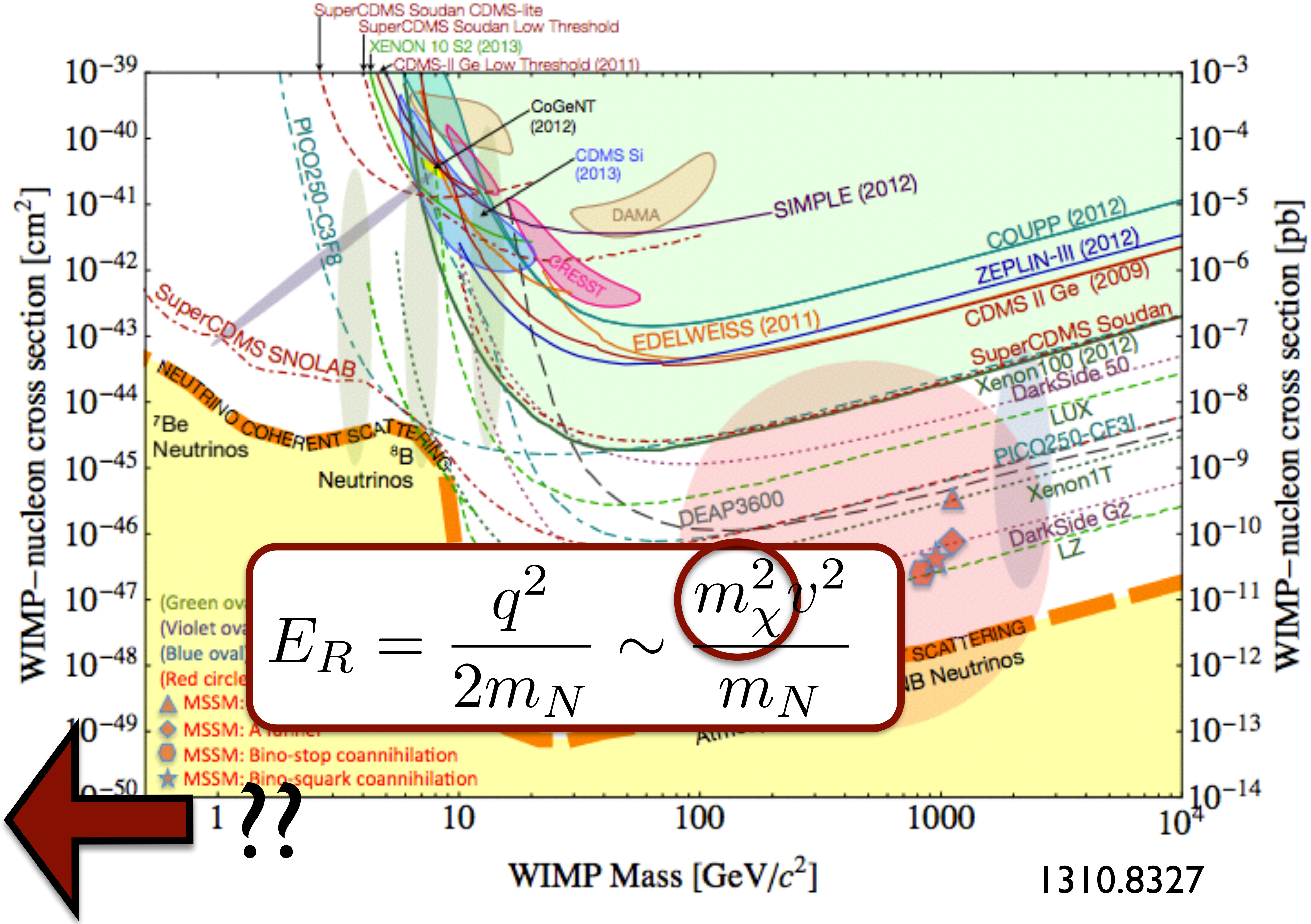
gives detectable signatures

current state of affairs



1310.8327

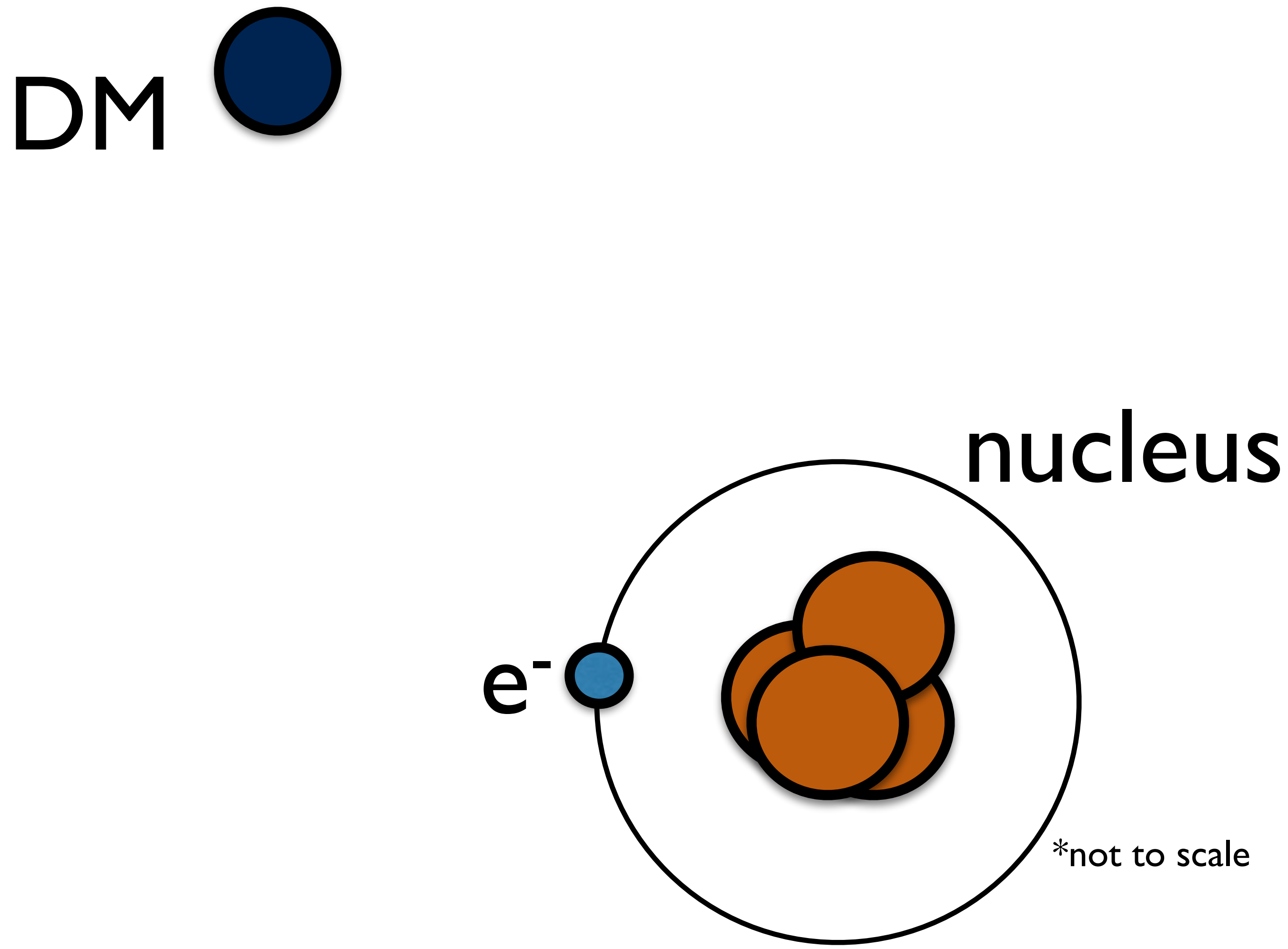
current state of affairs



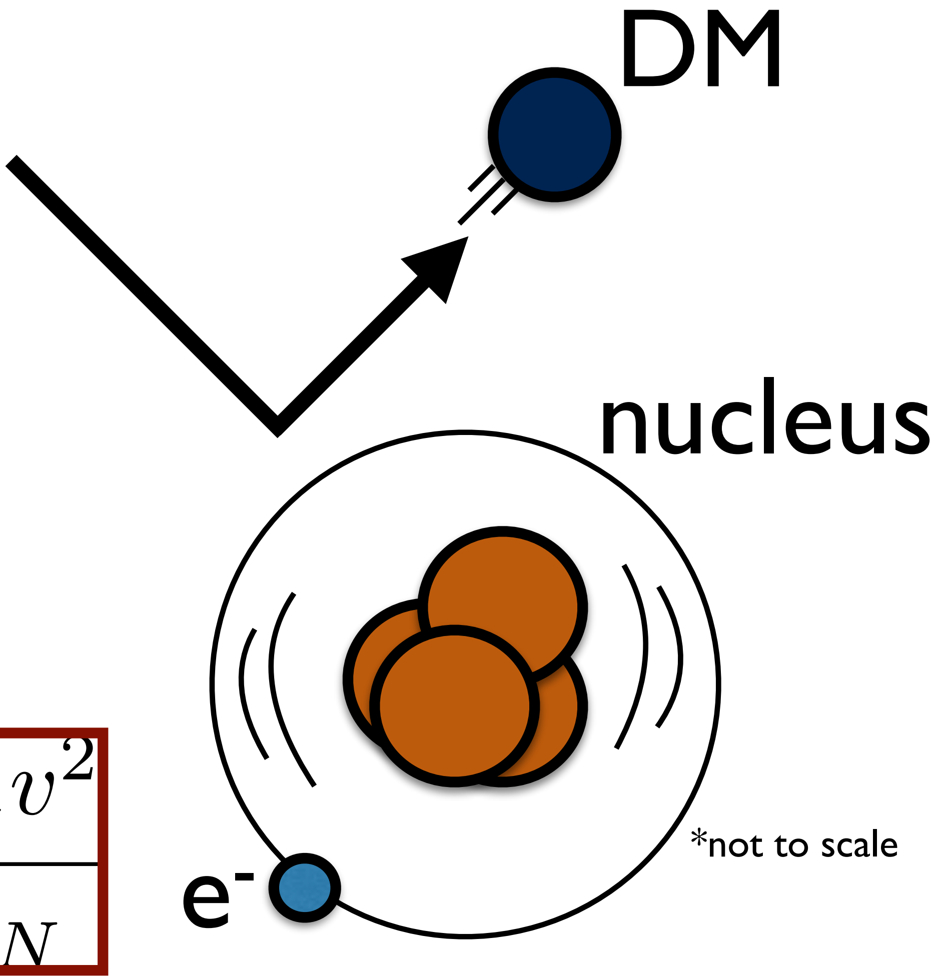
$$E_R = \frac{q^2}{2m_N} \sim \frac{\boxed{m_\chi^2} v^2}{m_N}$$

??

1310.8327



*not to scale



$$\boxed{E_R = \frac{q^2}{2m_N} \sim \frac{m_\chi^2 v^2}{m_N}}$$

signal:

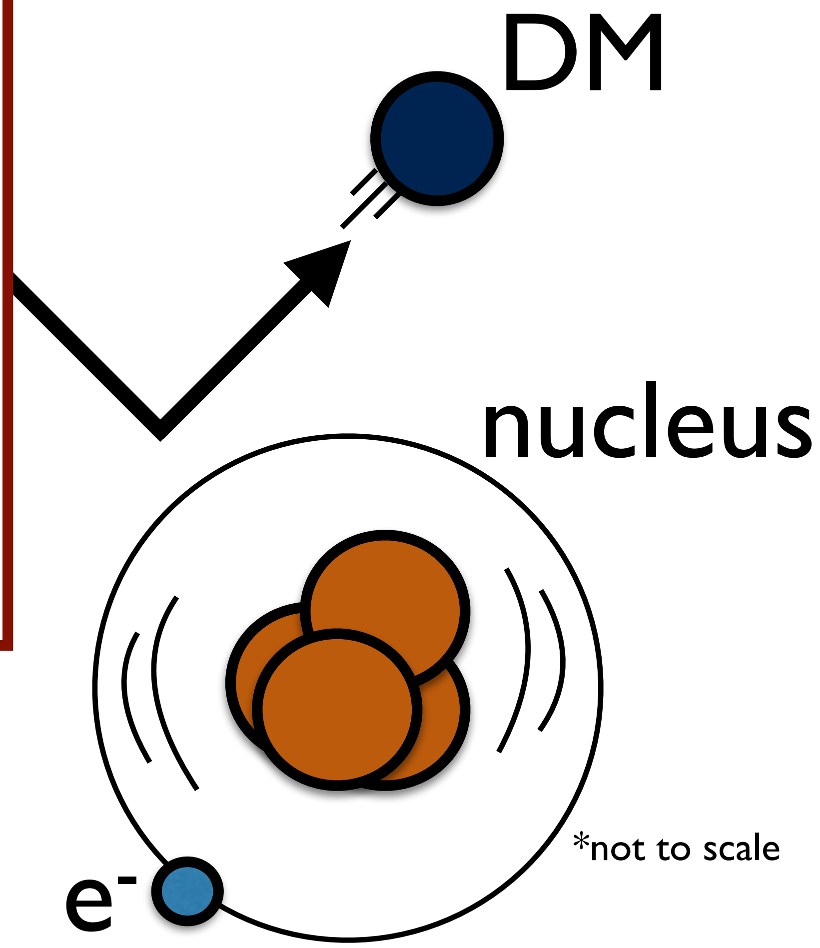
heat

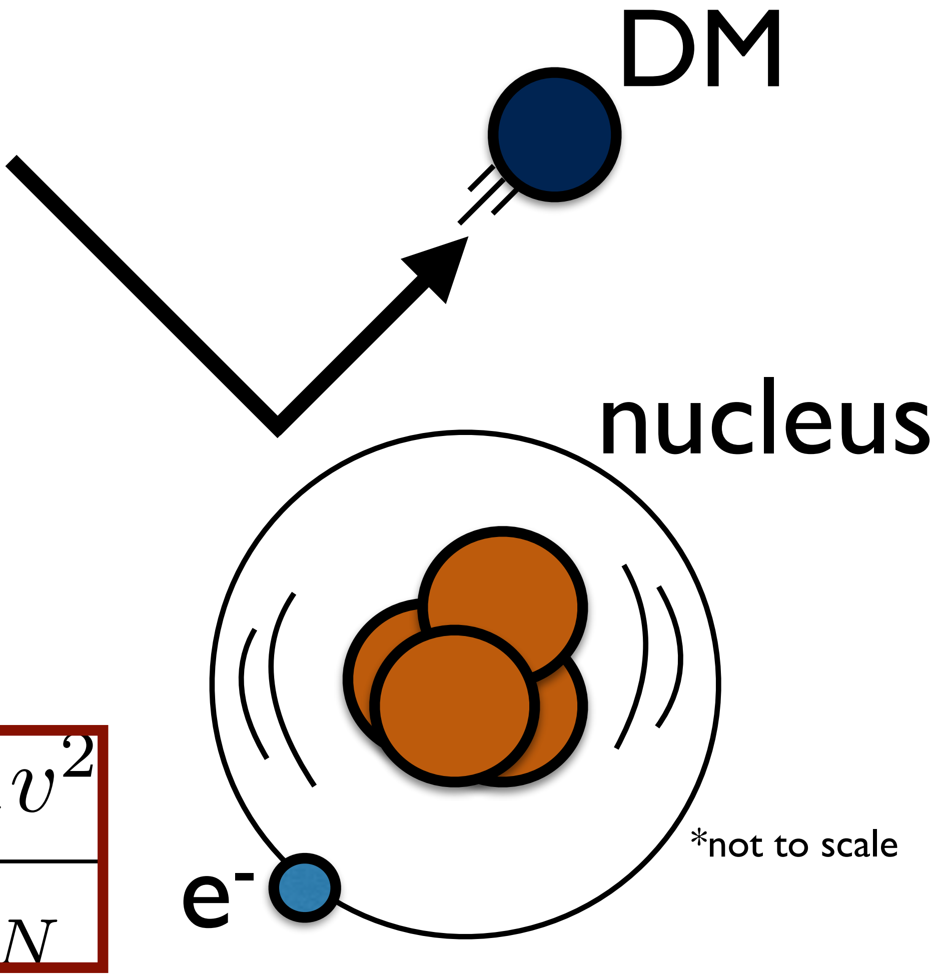
phonons

scintillation photons

ionization electrons

$$E_R = \frac{q^2}{2m_N} \sim \frac{m_\chi^2 v^2}{m_N}$$

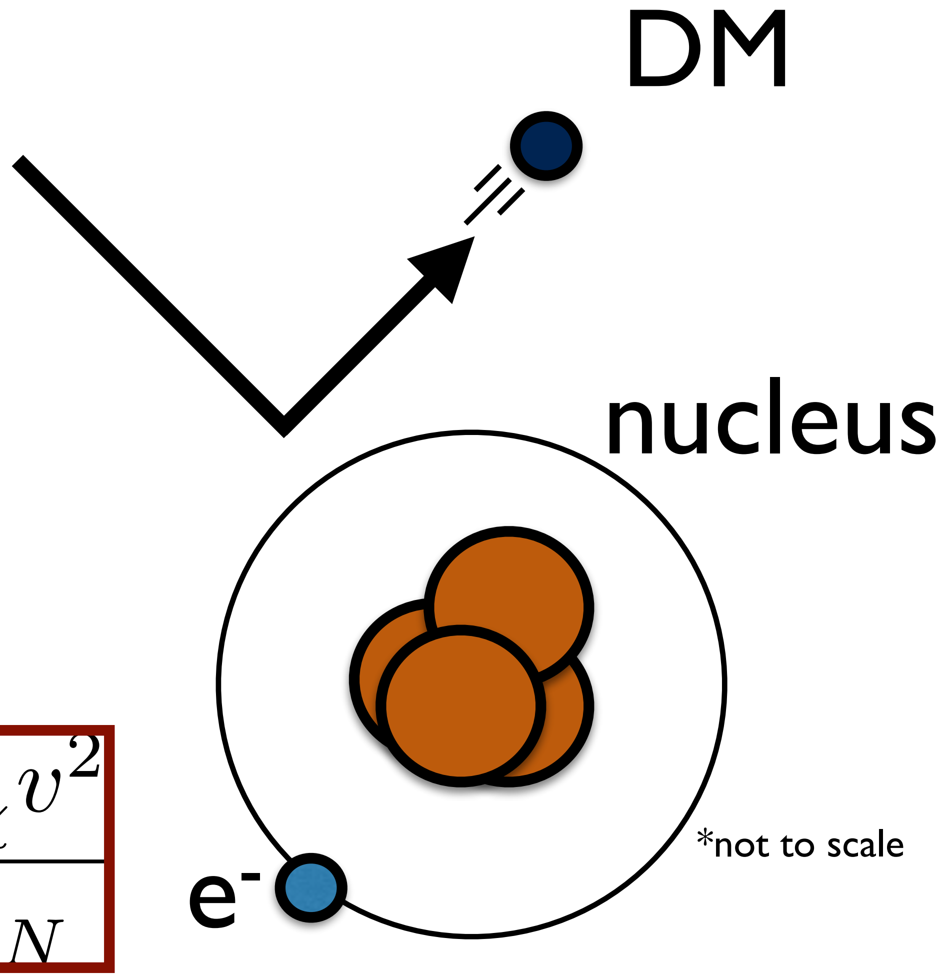




*not to scale

$$\boxed{E_R = \frac{q^2}{2m_N} \sim \frac{m_\chi^2 v^2}{m_N}}$$

$$m_\chi = 100 \text{ GeV}, E_R \sim 1 \text{ MeV}$$



$$\boxed{E_R = \frac{q^2}{2m_N} \sim \frac{m_\chi^2 v^2}{m_N}}$$

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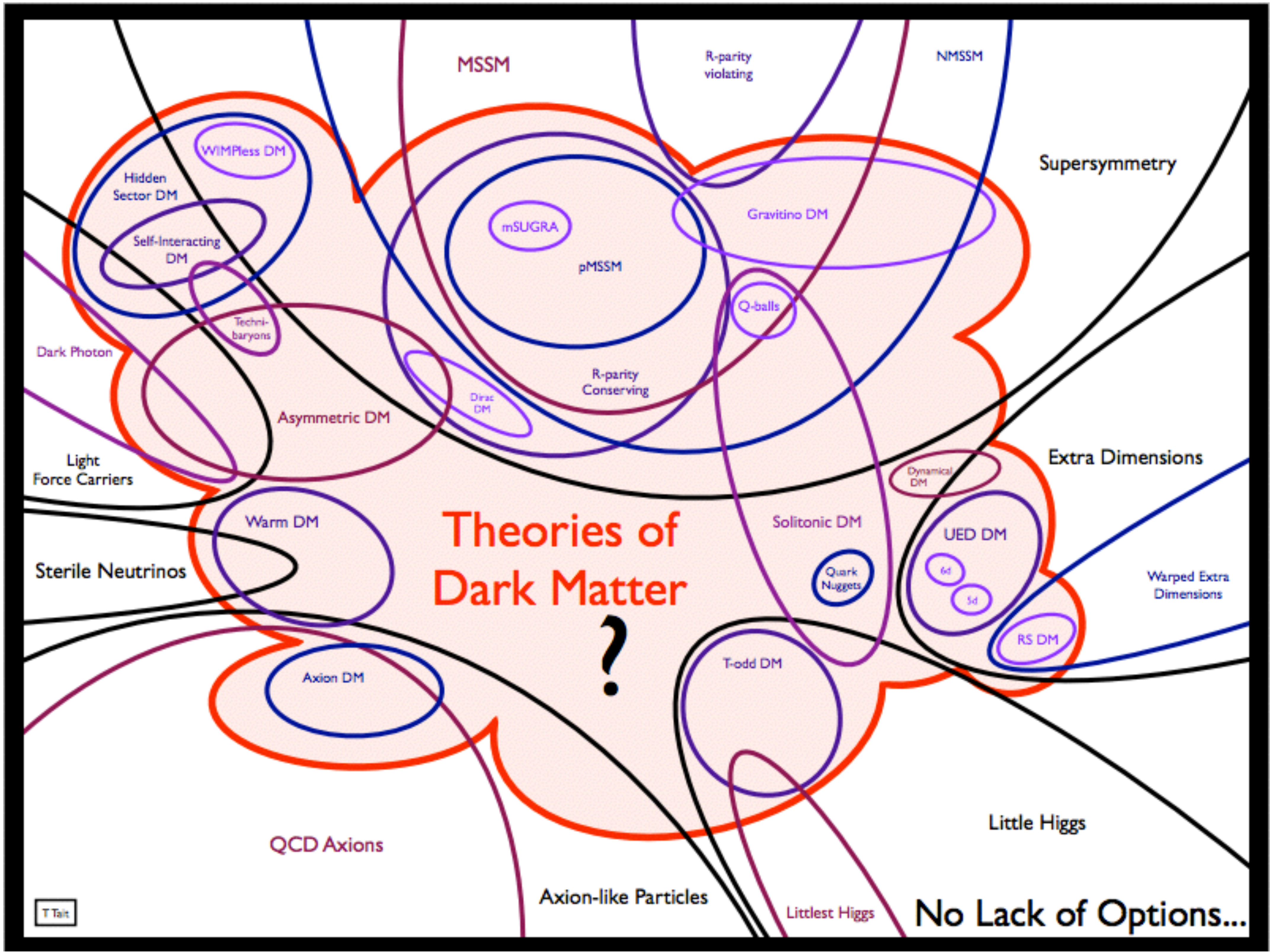
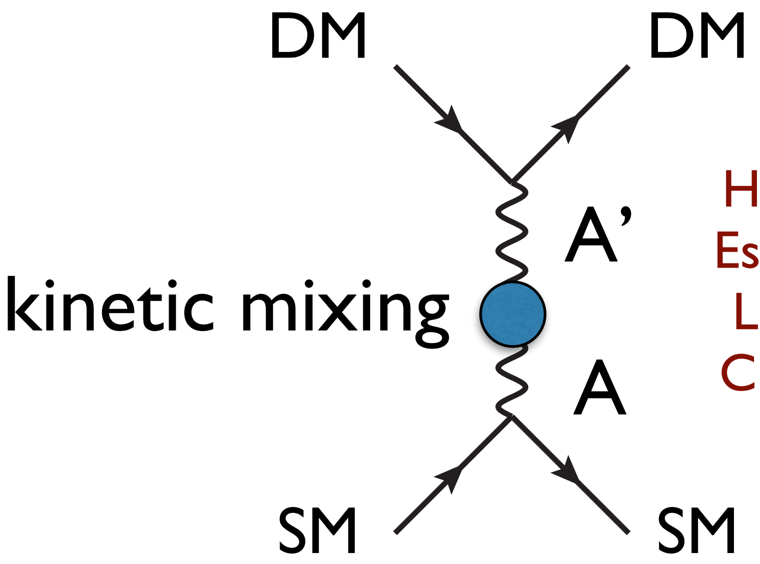
candidates for DM



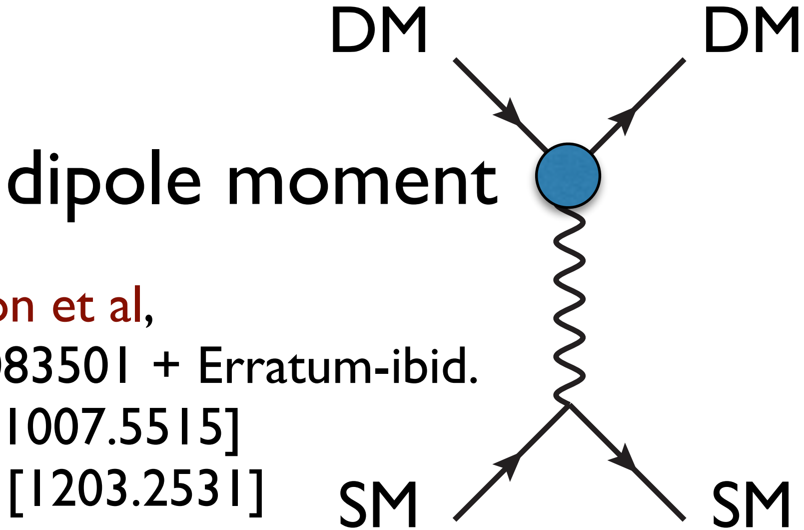
sub-GeV DM is theoretically motivated

Hidden Photon Mediator



Hall et al [0911.1120]
Essig et al [1108.5383]
Lin et al [1111.0293]
Chu et al [1112.0493]

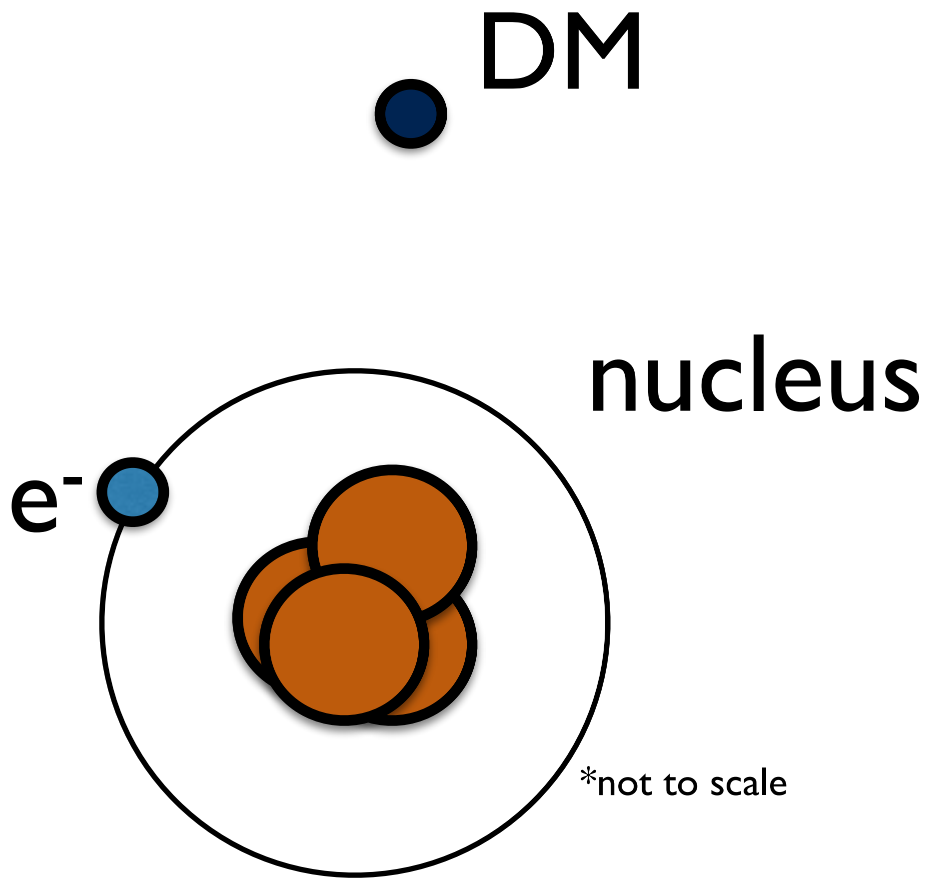
MDM/EDM



Sigurdson et al,
Phys. Rev. D70 (2004) 083501 + Erratum-ibid.
Banks et al [1007.5515]
Graham et al [1203.2531]
Kadota and Silk [1402.7295]

Strongly Interacting

Boddy et al [1408.6532]
Hochberg et al [1402.5143,1411.3727]



DM

nucleus

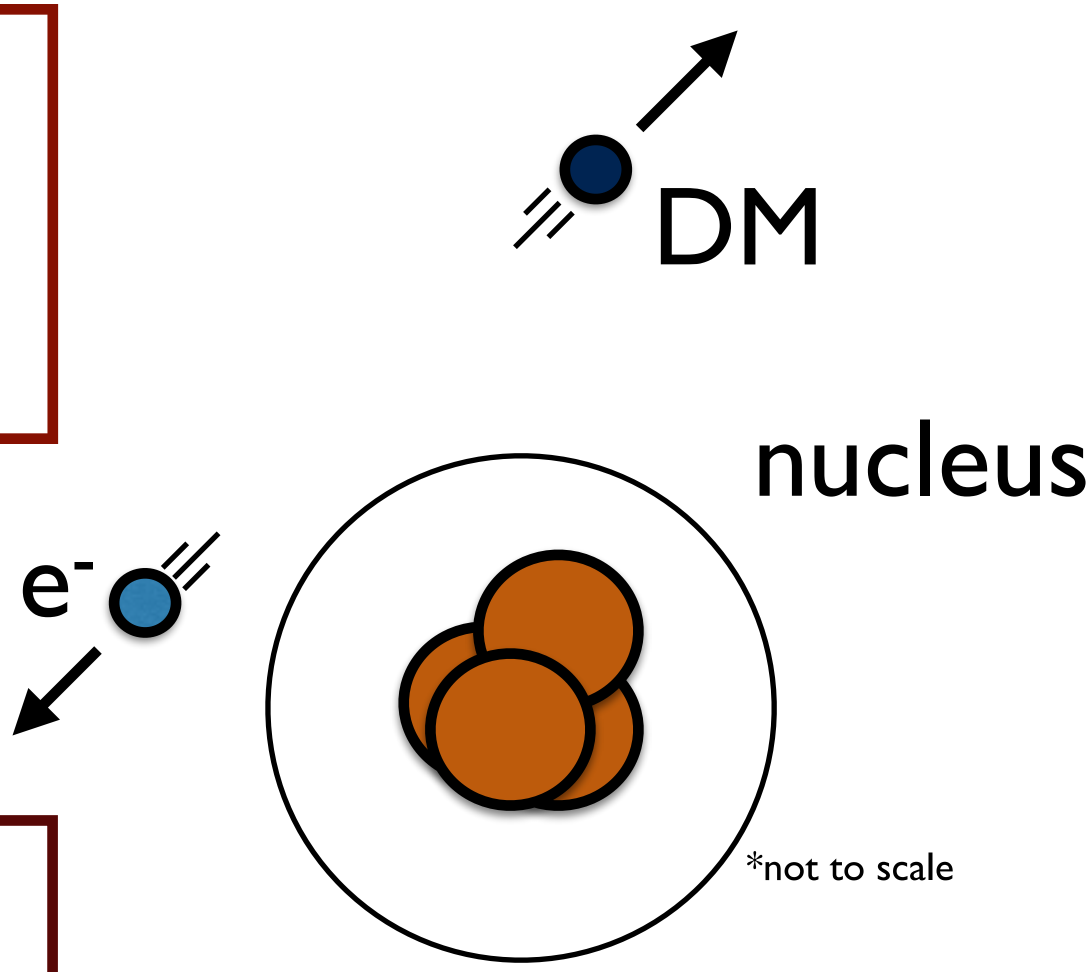
e$^-$

*not to scale

$$\Delta E_e = \vec{q}\cdot\vec{v} - \frac{q^2}{2\mu_{\chi N}}$$

$$\sim \frac{1}{2}\mathrm{eV} \times \left(\frac{\mathrm{m}_\chi}{\mathrm{MeV}}\right)$$

signal:
a few ionized
electrons



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$$m_\chi = 100\ \mathrm{MeV}, E_R \sim 50\ \mathrm{eV}$$

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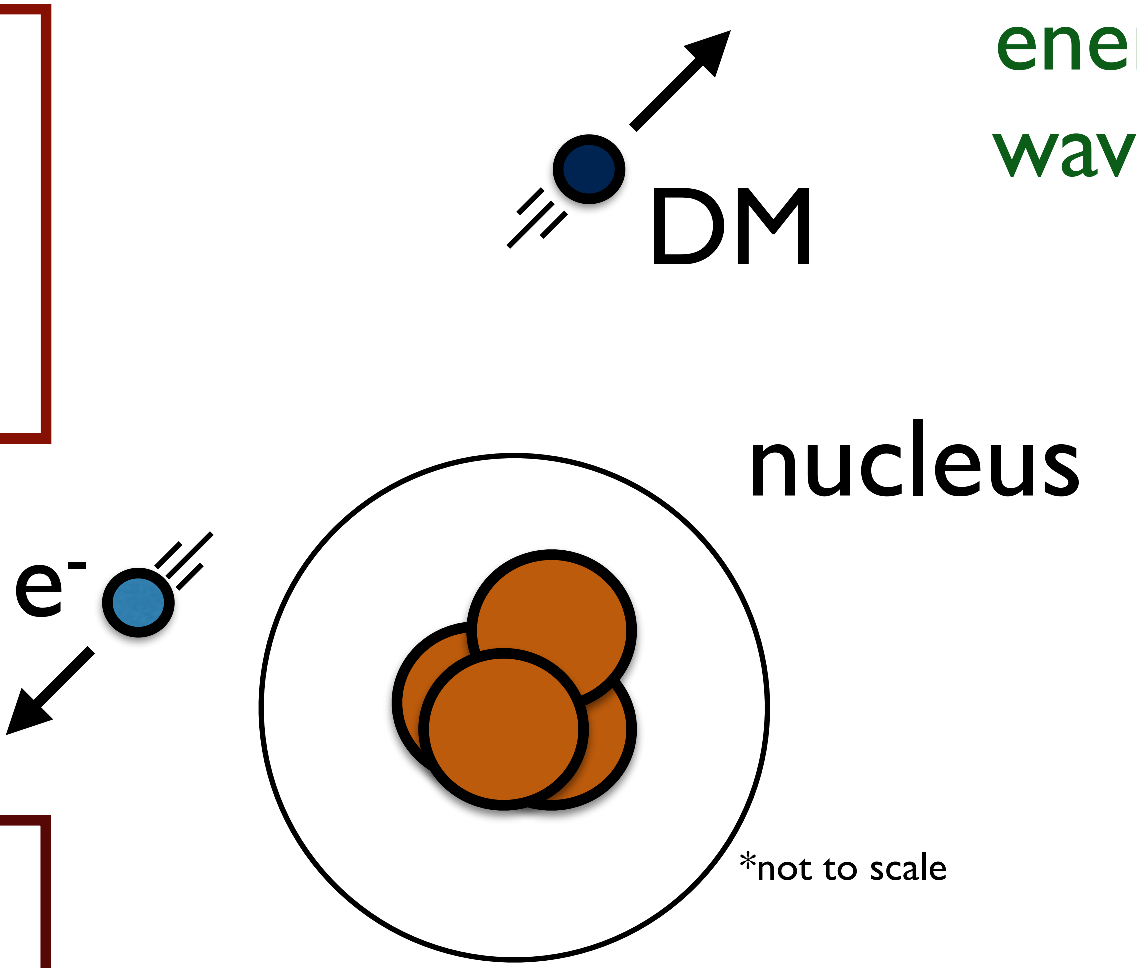


*sensitive to precise form of electron energy levels and wave functions in target

$$\begin{aligned}\Delta E_e &= \vec{q}\cdot\vec{v} - \frac{q^2}{2\mu_{\chi N}} \\ &\sim \frac{1}{2}\mathrm{eV} \times \left(\frac{\mathrm{m}_\chi}{\mathrm{MeV}}\right)\end{aligned}$$

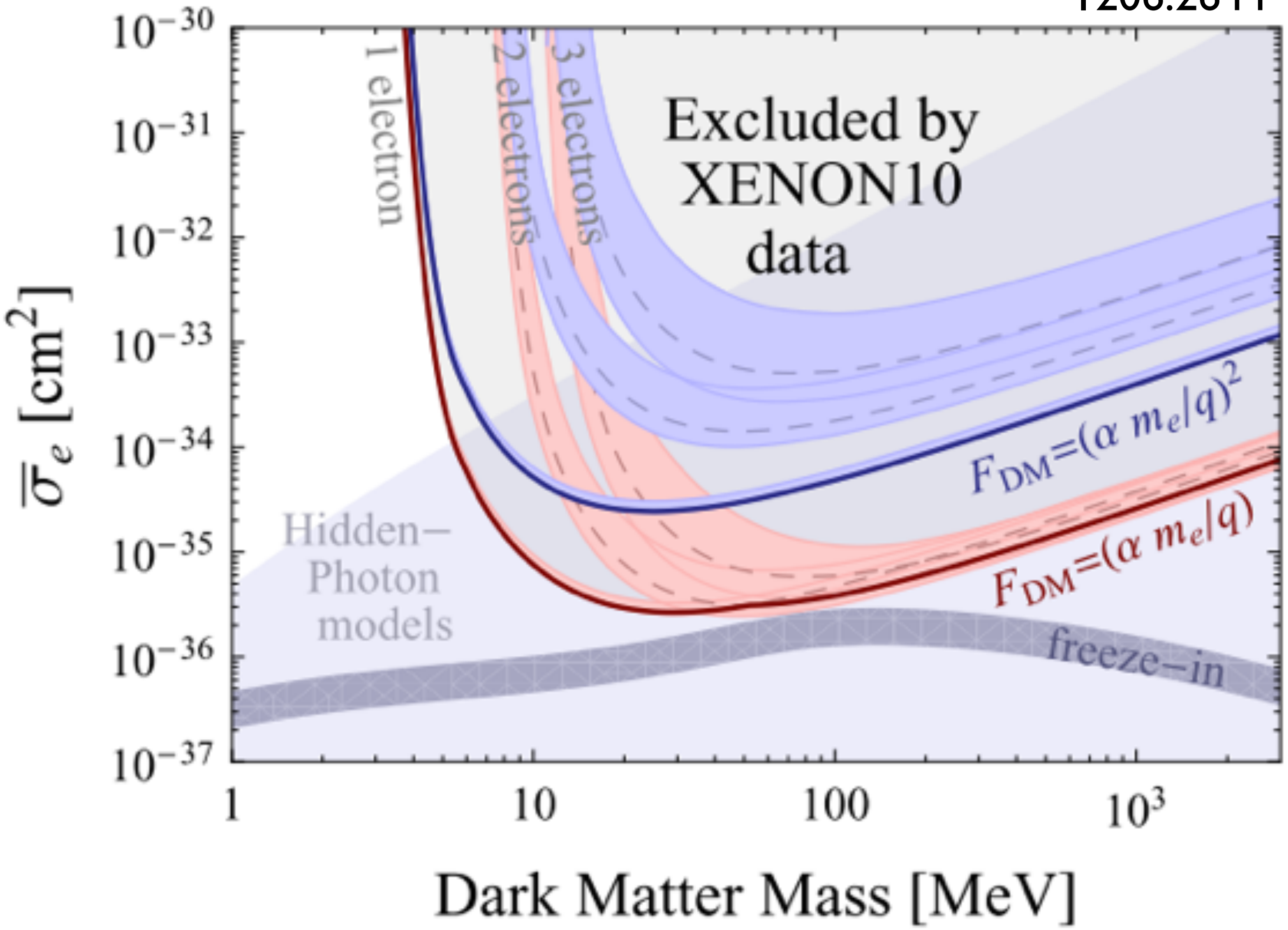
$$m_\chi = 100\ \mathrm{MeV}, E_R \sim 50\ \mathrm{eV}$$

electron scattering

XENON10 limits

R. Essig, A. Manalaysay, J. Mardon, P. Sorenson, T. Volansky

1206.2644



electron energy

- noble gases: ~10 eV
- semiconductors: ~1 eV

Calculation Ingredients

ingredients

particle physics

$$\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R} = \frac{\boxed{\overline{\sigma}_e}}{8\mu_{\chi e}^2}\int q\;\mathrm{d}q|f(k,q)|^2\boxed{|F_{DM}(q)|^2}\eta(v_{min})$$

$$\overline{\sigma}_e = \frac{\mu_{\chi e}^2}{16\pi m_\chi^2 m_e^2}\overline{|\mathcal{M}_{\chi e}(q)|^2}\Big|_{q^2=\alpha^2 m_e^2}$$

$$\sigma(q) = \overline{\sigma}_e \times |F_{DM}(q)|^2$$

ingredients

$$\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2}\int q\ \mathrm{d}q|f(k,q)|^2|F_{DM}(q)|^2\overset{\text{astrophysics}}{\boxed{\eta(v_{min})}}$$

$$\eta(v_{min}) = \int_{v_{min}} \frac{\mathrm{d}^3 v}{v} f_{MB}(\vec{v})$$

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

ingredients

solid state physics

$$\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2}\int q\;\mathrm{d}q\,\boxed{|f(k,q)|^2}|F_{DM}(q)|^2\eta(v_{min})$$

$$\left|f_{i\rightarrow i'}(\vec{q},\vec{k})\right|^2 = \frac{V}{(2\pi)^3}\int_{\mathrm{BZ}}\mathrm{d}^3k'\left|\int \mathrm{d}^3x\,\psi^*_{i',\vec{k}'}(\vec{x})\psi_{i,\vec{k}}(\vec{x})e^{i\vec{q}\cdot\vec{x}}\right|^2$$

probability of going from state i to i’

ingredients

$$\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2}\int q\ \mathrm{d}q|f(k,q)|^2|F_{DM}(q)|^2\eta(v_{min})$$

local DM density

$$R = N_T\frac{\rho_\chi}{m_\chi}\int_{E_{R,cut}}\mathrm{d}\ln E_R\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R}$$

number of target nuclei
per unit mass

energy threshold

ingredients

solid state physics

$$\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2}\int q\ \mathrm{d}q \boxed{|f(k,q)|^2} |F_{DM}(q)|^2\eta(v_{min})$$

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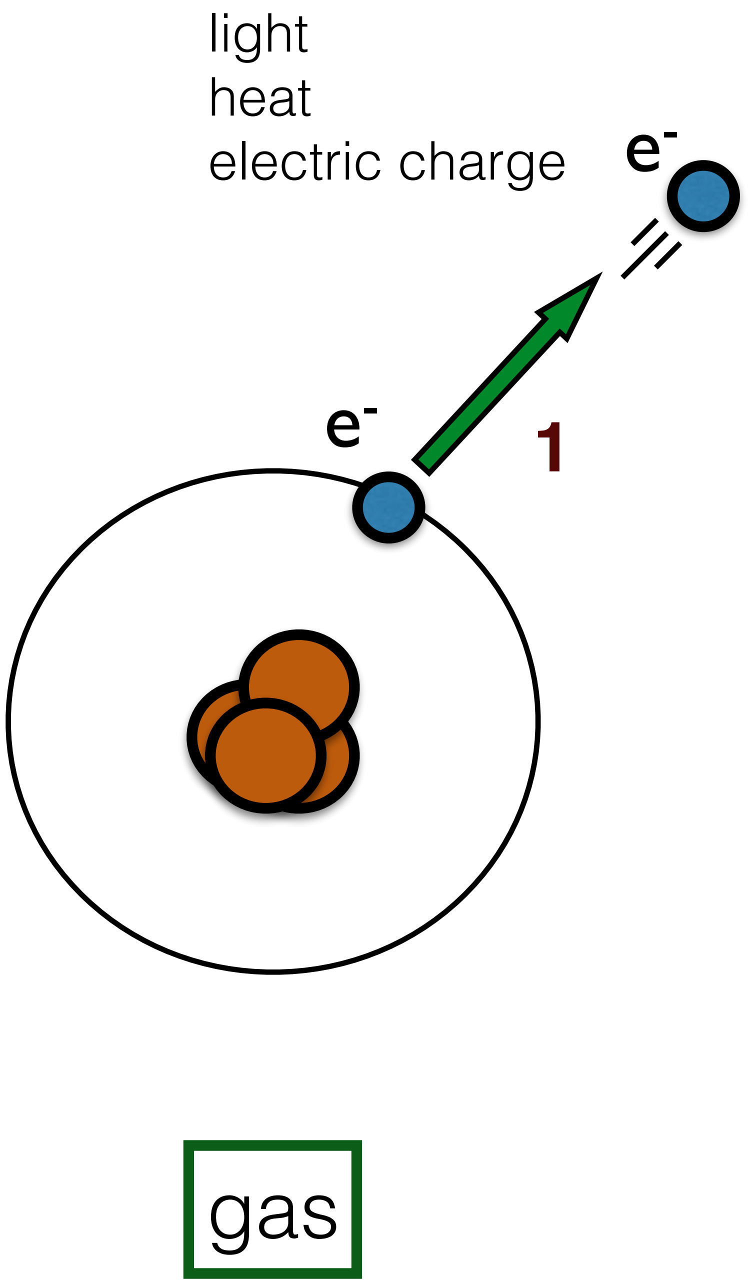
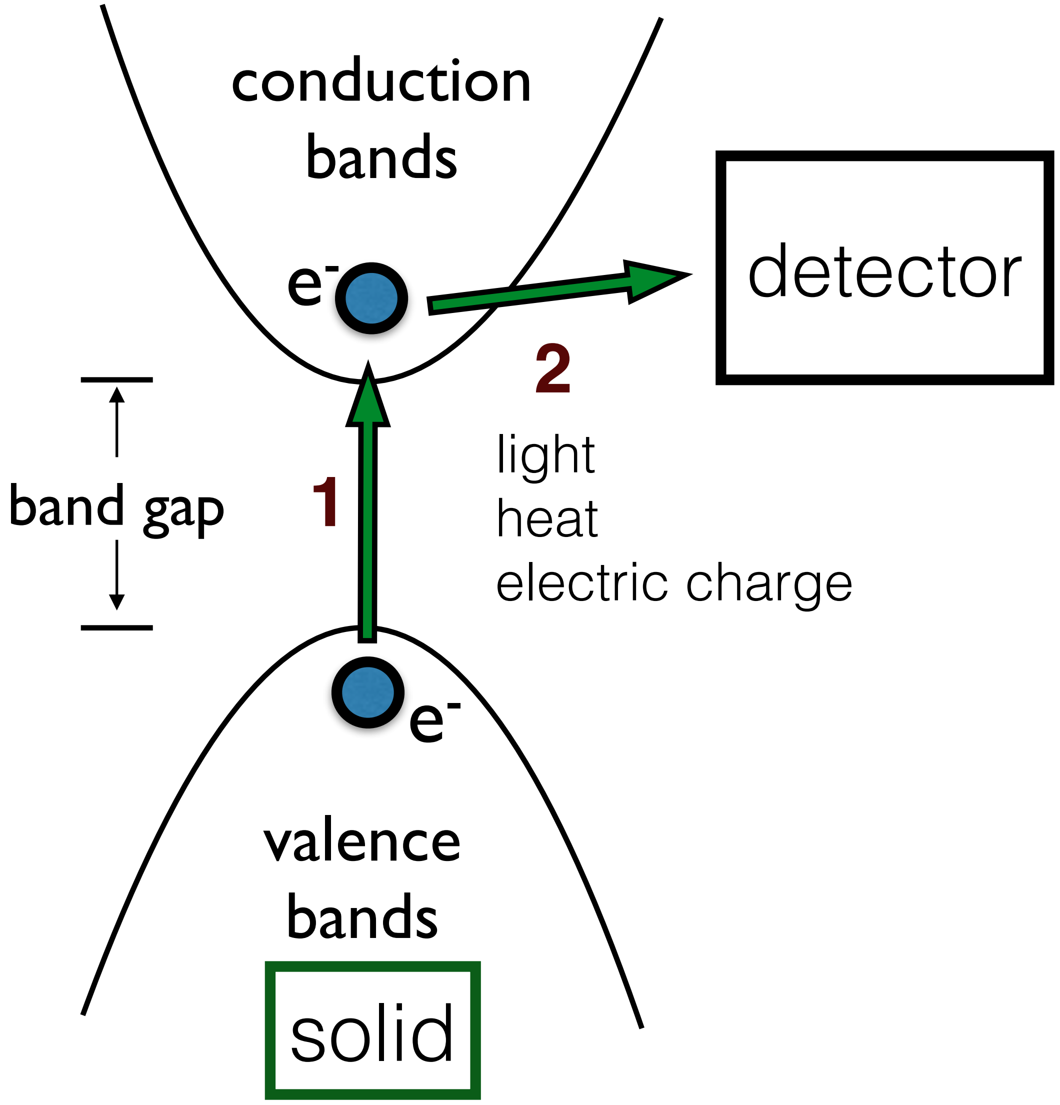
computationally difficult!

analytic

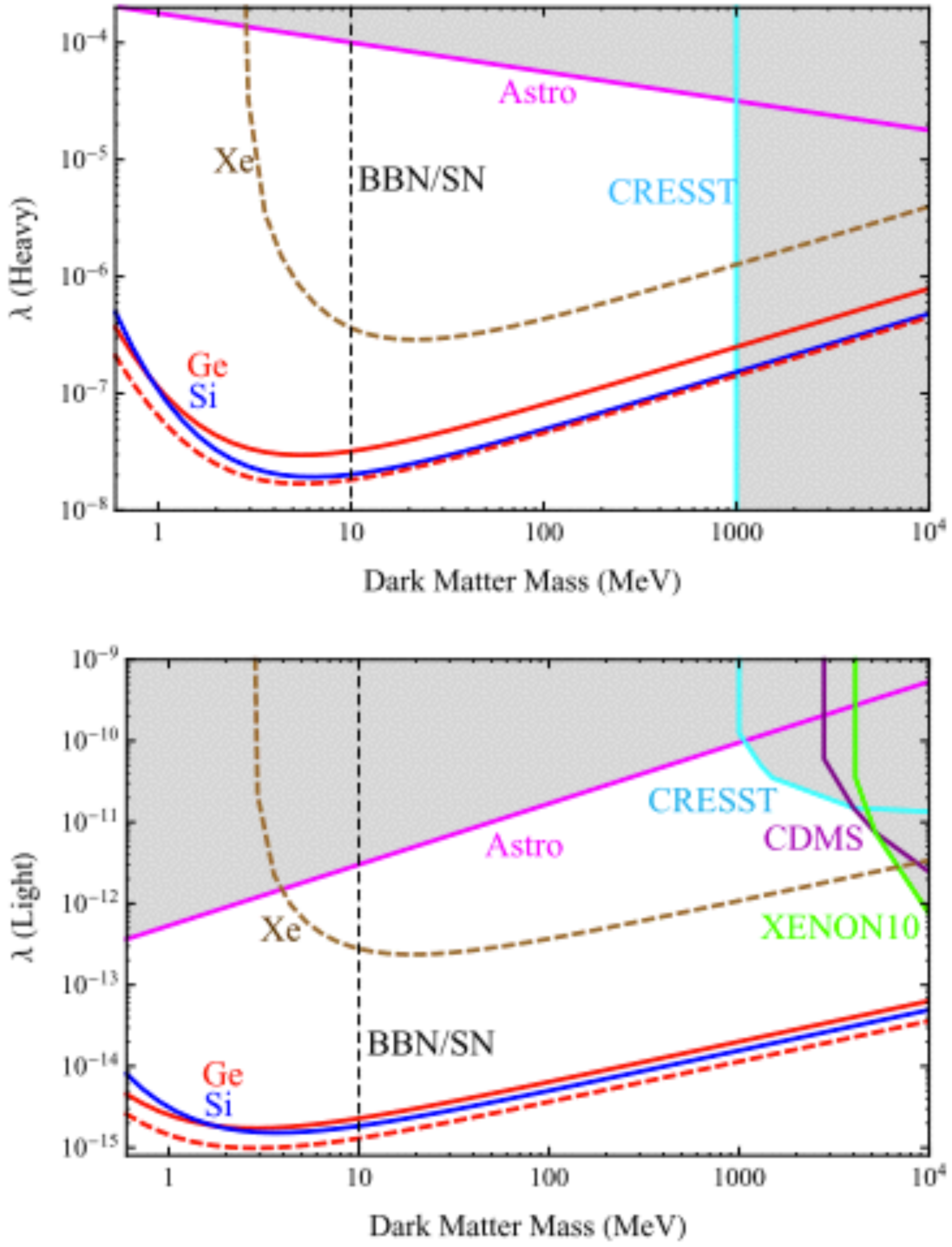
numerical





electrons in a solid are part
of a complicated, many-body system

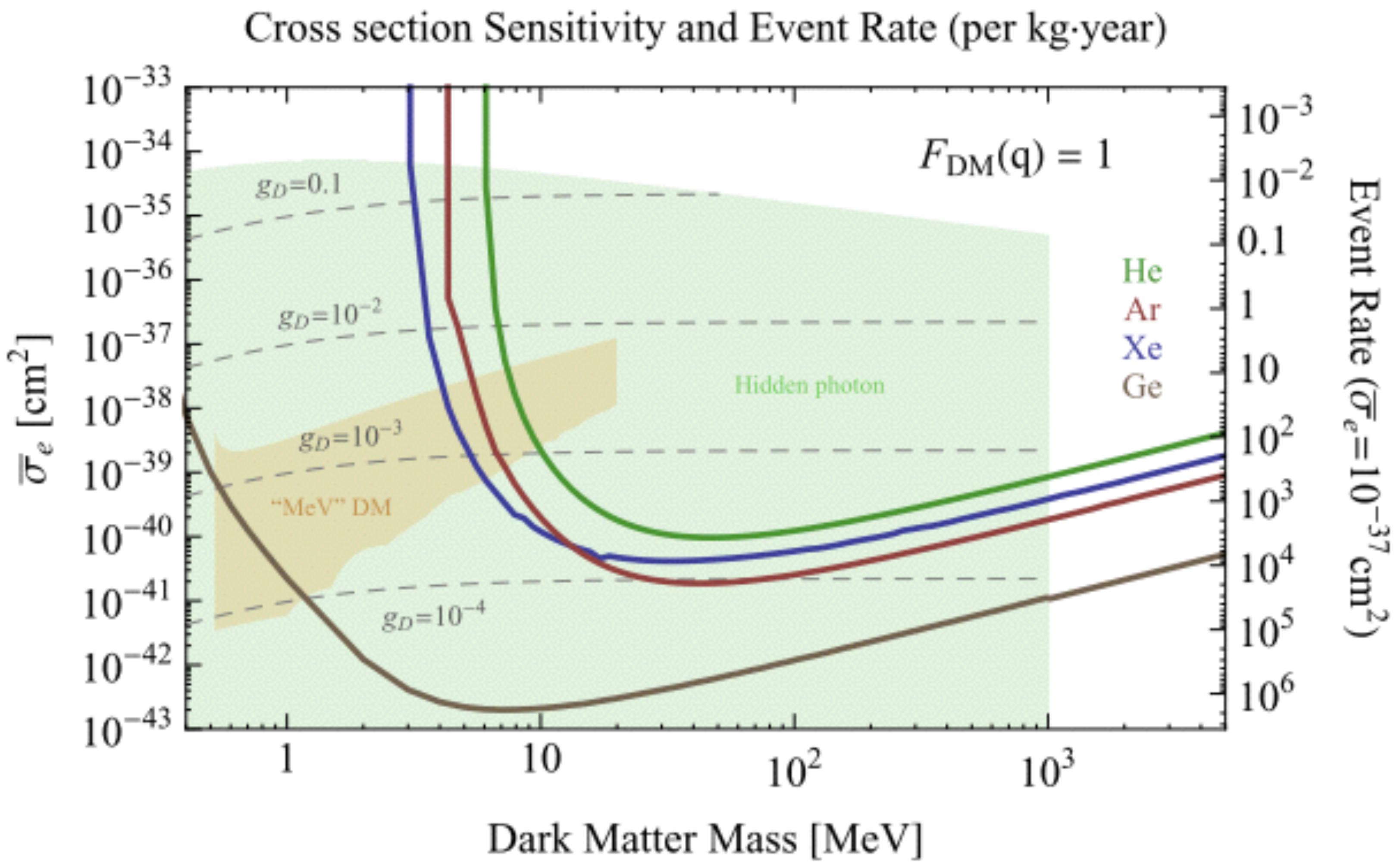
analytic approximations


1203.2531

- semi-classical approach
- initial wave functions are spherical
- plane wave final states with altered mass
- no interference
- good for high q

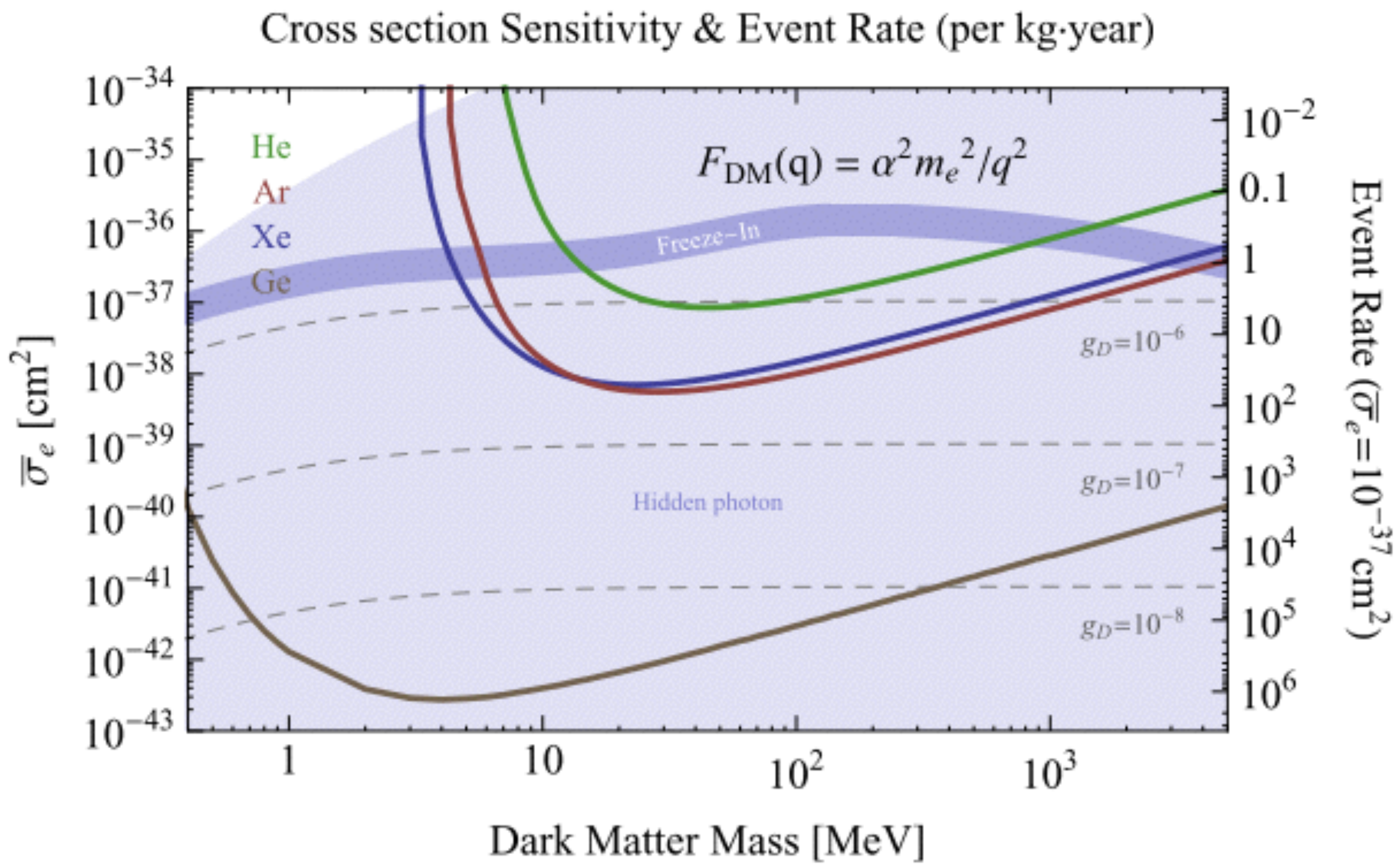
Single-electron detection

1108.5383



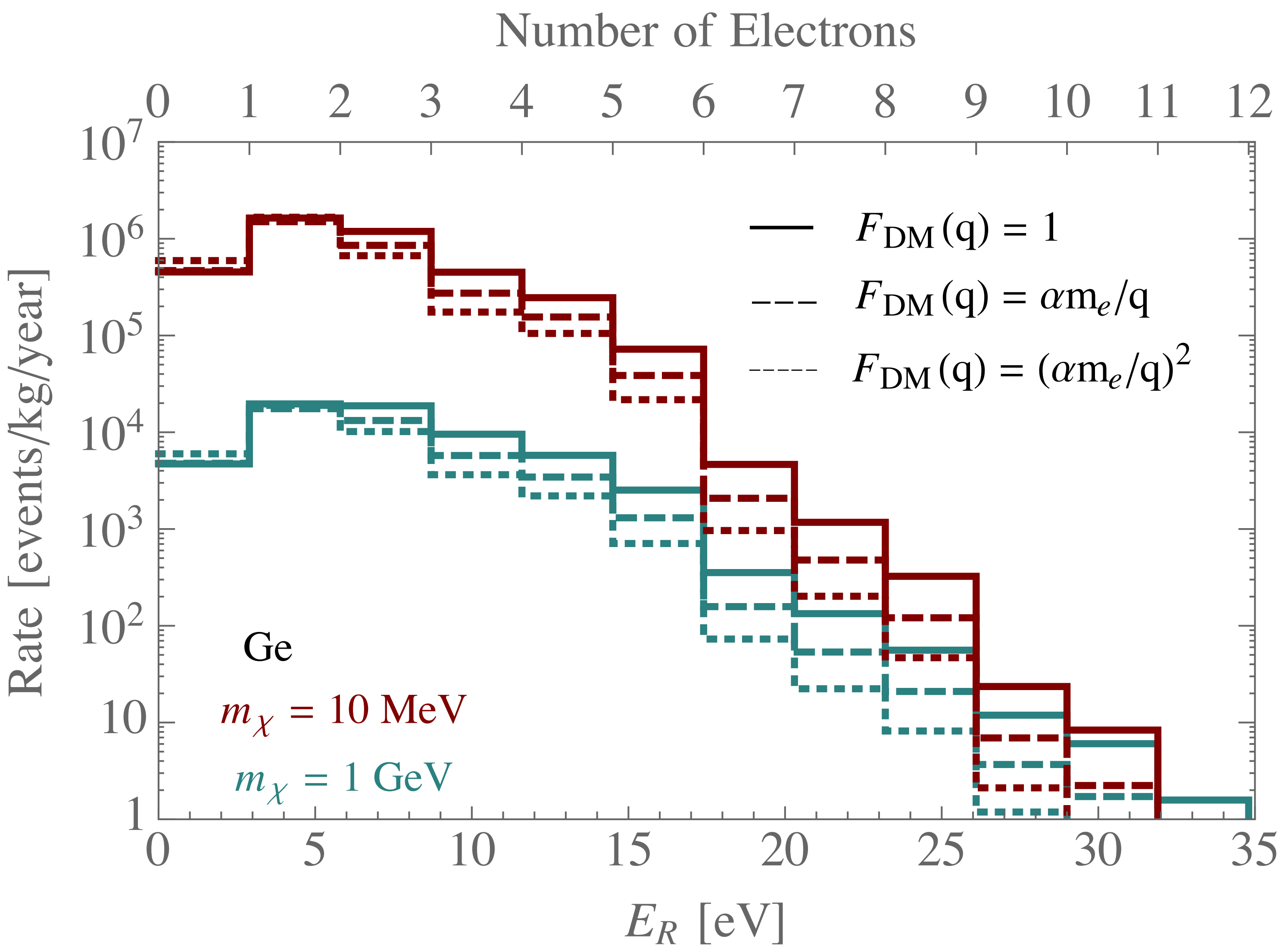
Single-electron detection

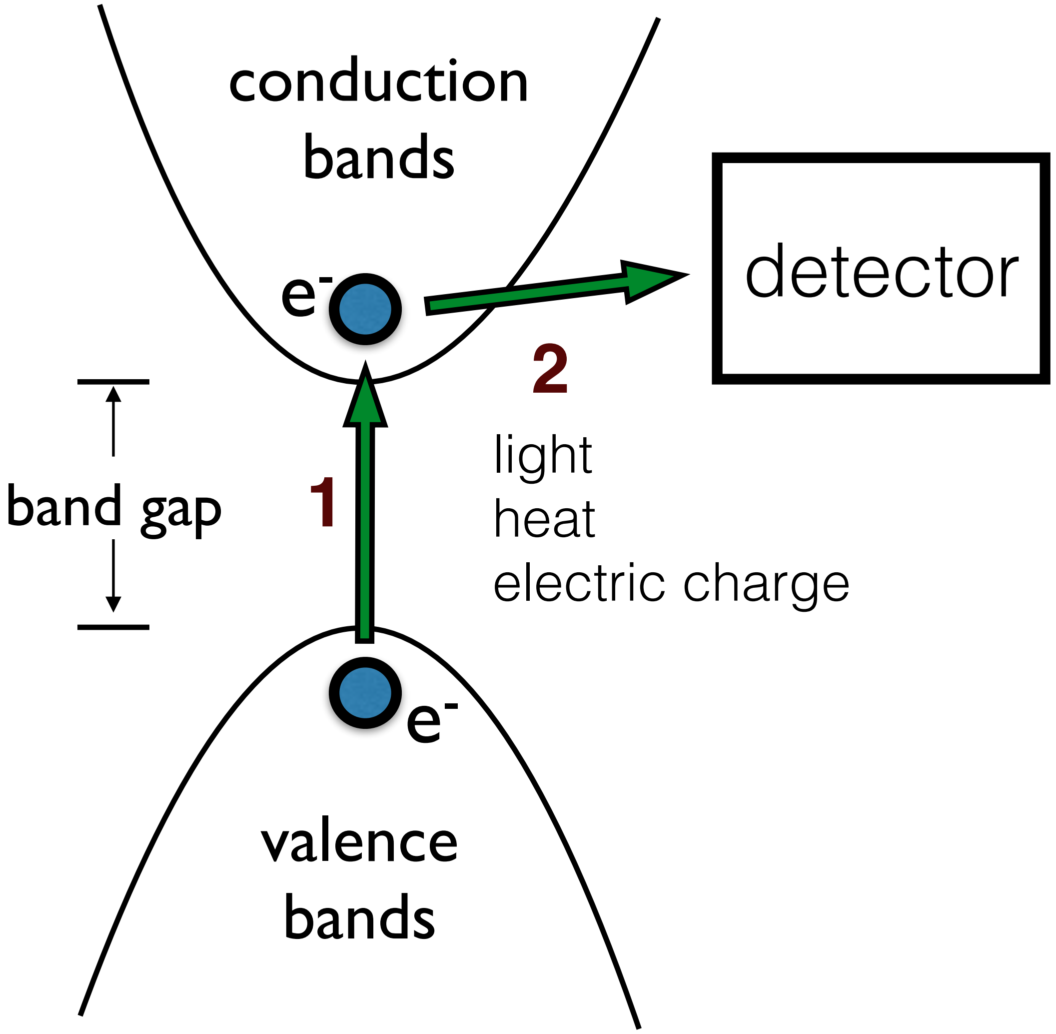
1108.5383



*assumed single-electron detection

Recoil energy spectrum





conduction bands

e^-

detector

2

light
heat
electric charge

band gap

1

e^-

valence bands

What happens in step 2?

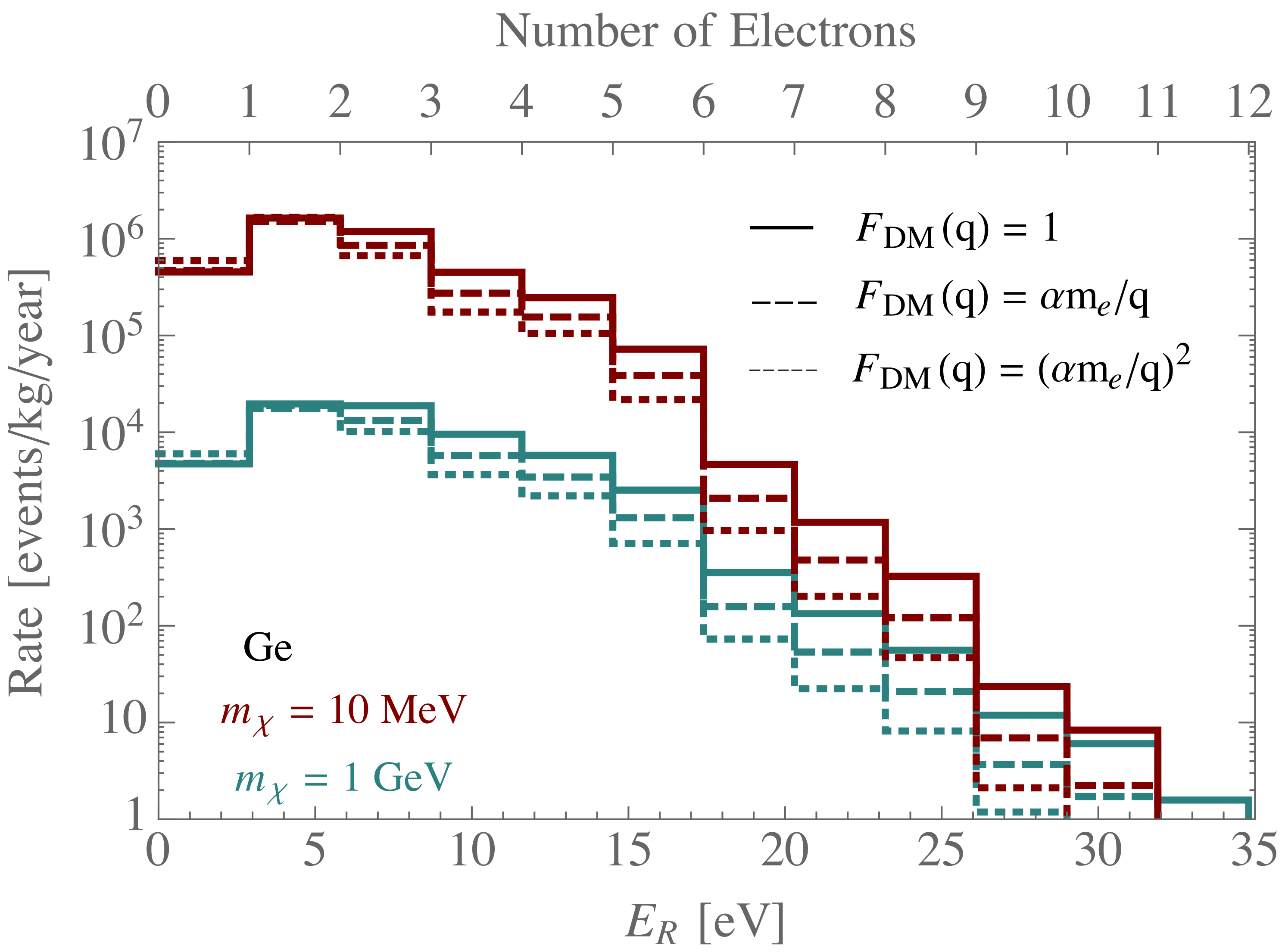
Energy to create an electron-hole pair

previously, we thought of the experimental parameter as recoil energy thresholds.

Instead, experimentalists measure actual number of electrons.

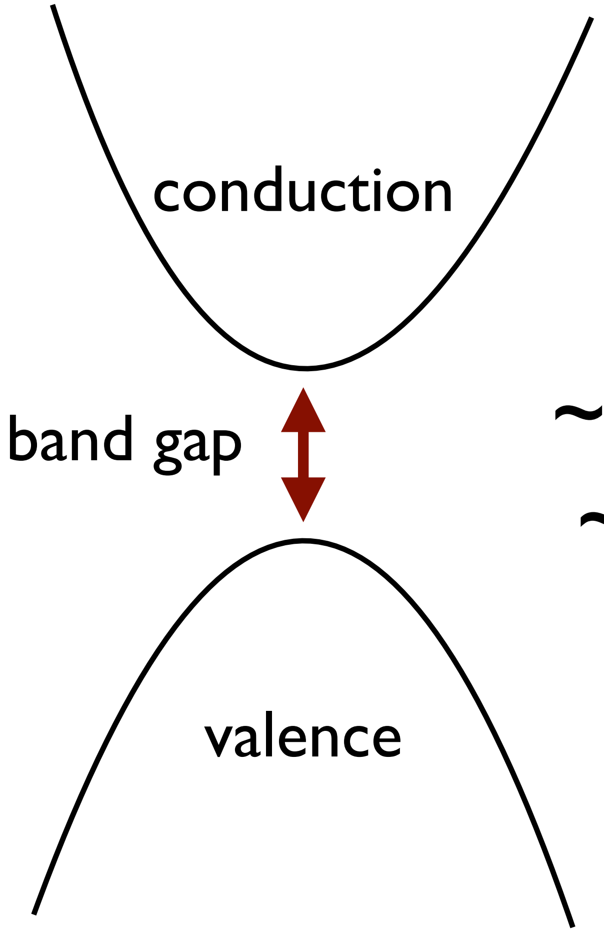
Can use the following conversion:
Ge: 2.9 eV/electron
Si: 3.6 eV/electron

Recoil energy spectrum



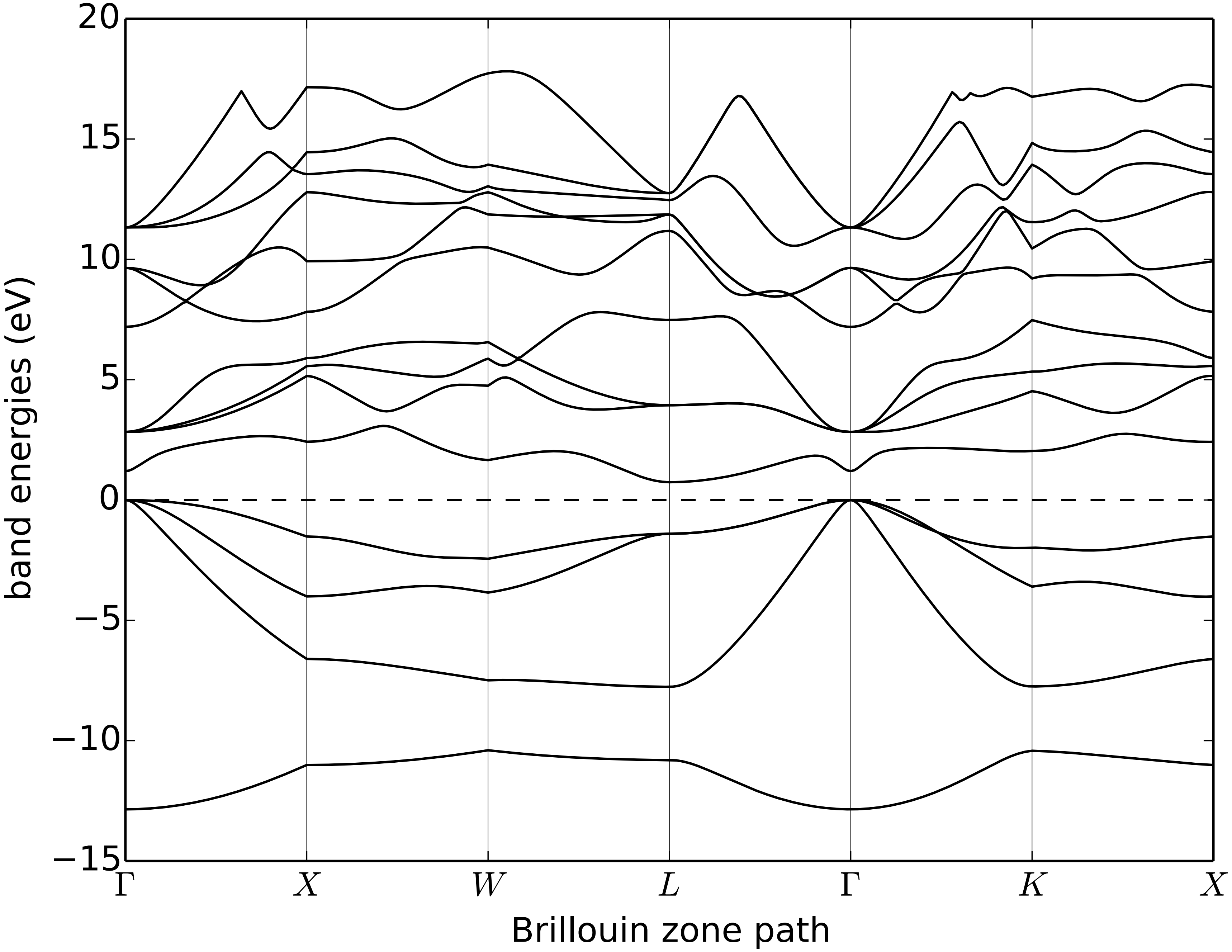
interlude

semiconductors



~0.67 eV for Ge
~1.11 eV for Si

Band structure



conduction bands

valence bands

k-points

semiconductors

- electron wave functions inside a crystal are complicated, but there are methods to approximate them
- we assume a wavefunction of the form:

$$\psi_{i,\vec{k}}(\vec{x}) = \frac{1}{\sqrt{V}} \sum_{G} \psi_i(\vec{k} + \vec{G}) e^{i(\vec{k}+\vec{G})\vec{x}}$$

lives in Brillouin Zone

reciprocal lattice vector

ingredients

solid state physics

$$\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2}\int q\ \mathrm{d}q \boxed{|f(k,q)|^2} |F_{DM}(q)|^2 \eta(v_{min})$$

$$\left|f_{i\rightarrow i'}(\vec{q},\vec{k})\right|^2 = \frac{V}{(2\pi)^3}\int_{\mathrm{BZ}} \mathrm{d}^3k' \left|\int \mathrm{d}^3x \psi^*_{i',\vec{k}'}(\vec{x})\psi_{i,\vec{k}}(\vec{x}) e^{i\vec{q}\cdot\vec{x}}\right|^2$$

probability of exciting an electron from valence band i to conduction band i’

ingredients

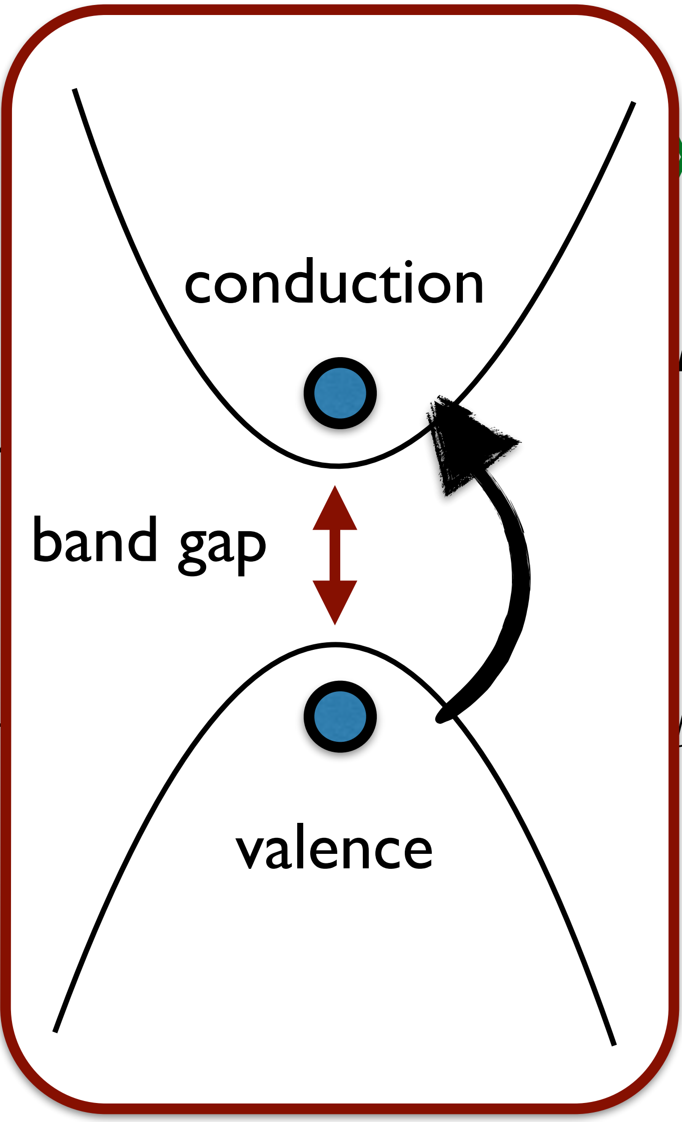
ysics

$$\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2}$$

$$F_{DM}(q)|^2\eta(v_{min})$$

$$\left|f_{i\to i'}(\vec{q},\vec{k})\right|^2 = \frac{V}{(2\pi)}$$

$$_{i',\vec{k}'}^{*}(\vec{x})\psi_{i,\vec{k}}(\vec{x})e^{i\vec{q}\cdot\vec{x}}\Big|^2$$



probability of exciting an electron from valence band i to conduction band i’

ingredients

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$$\frac{\mathrm{d}\langle \sigma v\rangle}{\mathrm{d}\ln E_R} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2}\int q\,\mathrm{d}q\,\boxed{|f(k,q)|^2}\,|F_{DM}(q)|^2\eta(v_{min})$$

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$$\Big\downarrow$$

$$\left|f_{i\to i'}(\vec{q},\vec{k})\right|^2 = \left|\sum_G \psi^*_{i'}(\vec{k}+\vec{G}+\vec{q})\psi_i(\vec{k}+\vec{G})\right|^2$$

mild directional dependence

we ignore for now

QUANTUM ESPRESSO

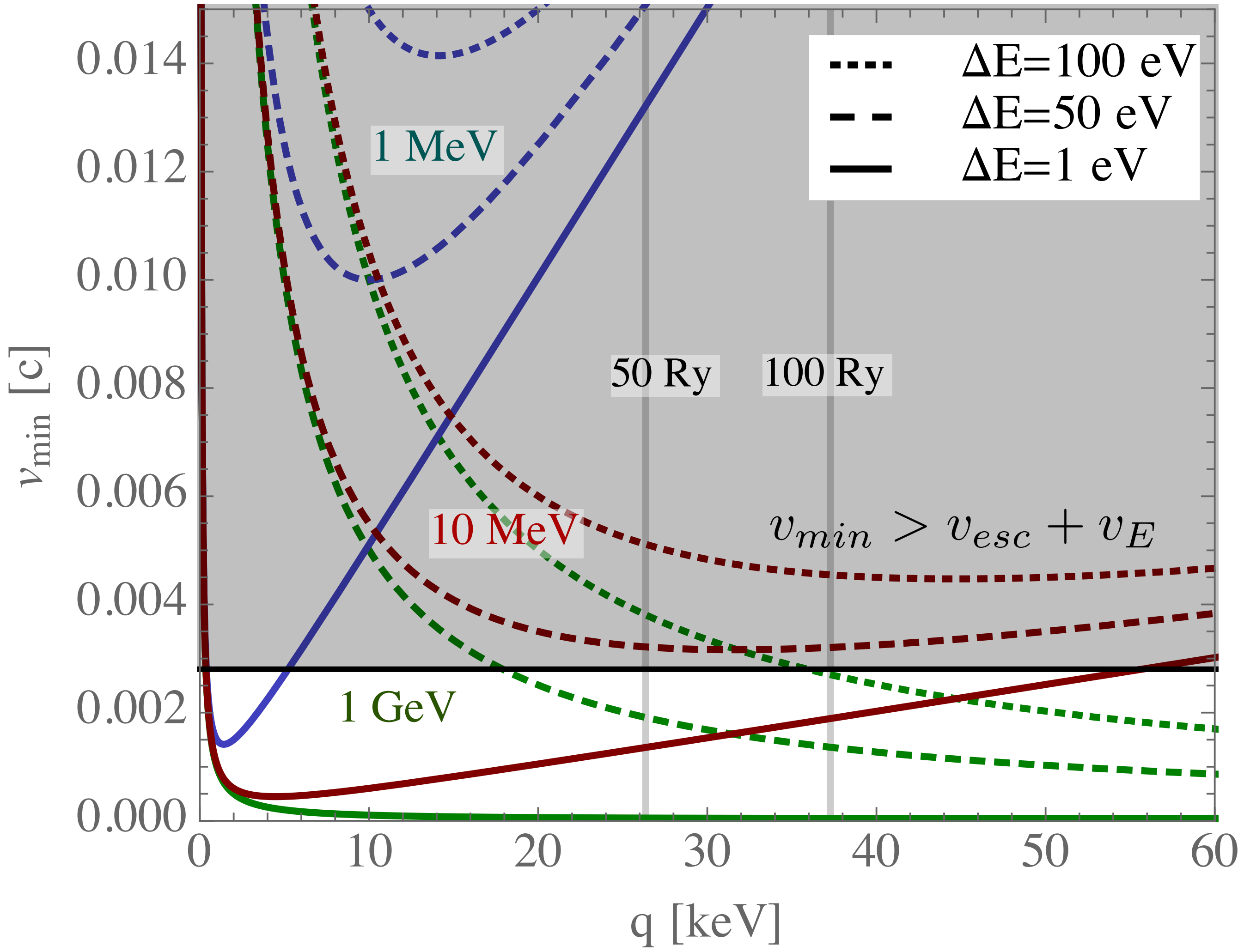
http://www.quantum-espresso.org/

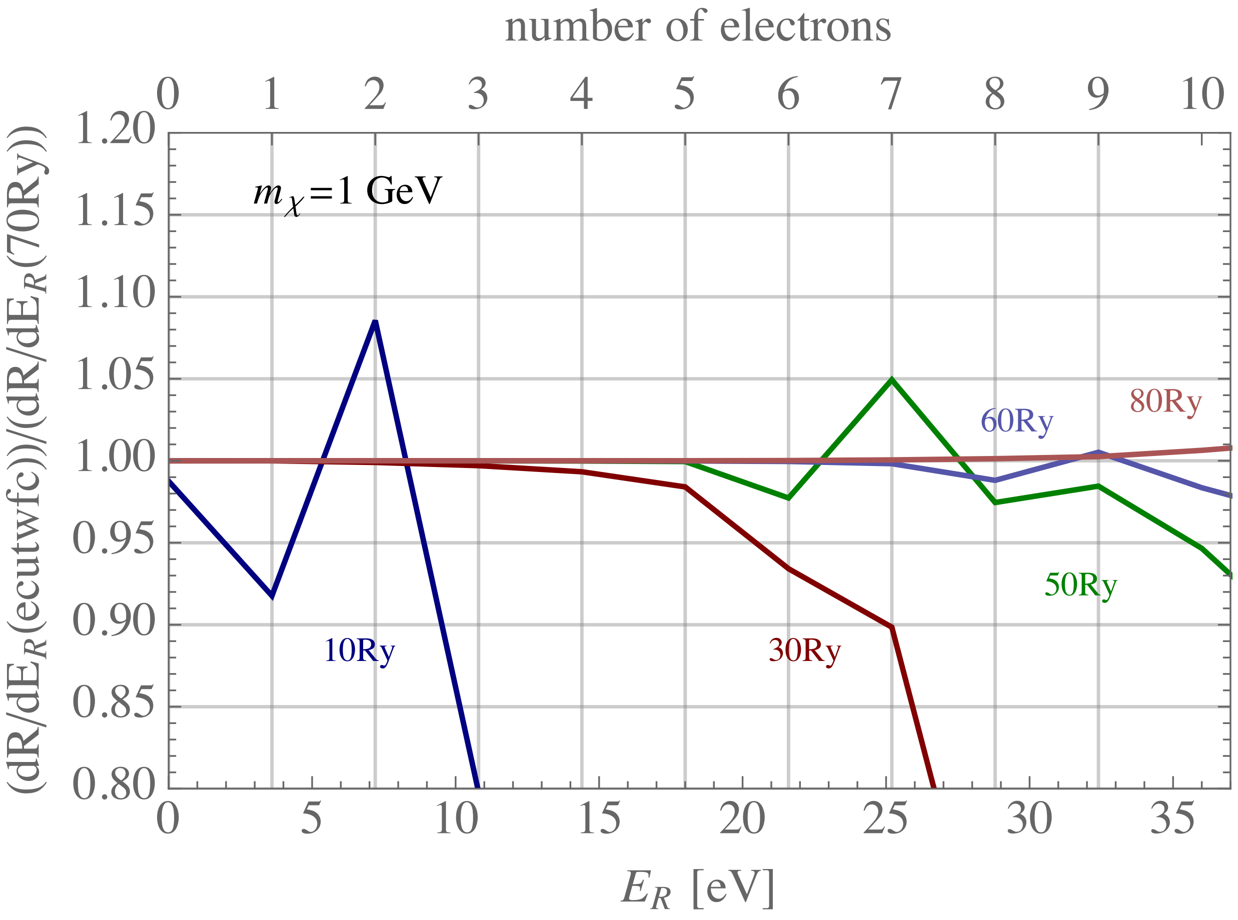
- open source code that calculates electronic structure within density functional theory (DFT) using plane waves and pseudopotentials

- use a mesh of 64 k-vectors, 100 bands, and a regular grid of G-vectors

$\frac{\left|\vec{k}+\vec{G}\right|^2}{2m_e} < E_c$ cut-off energy ~70 Ry

choosing parameters



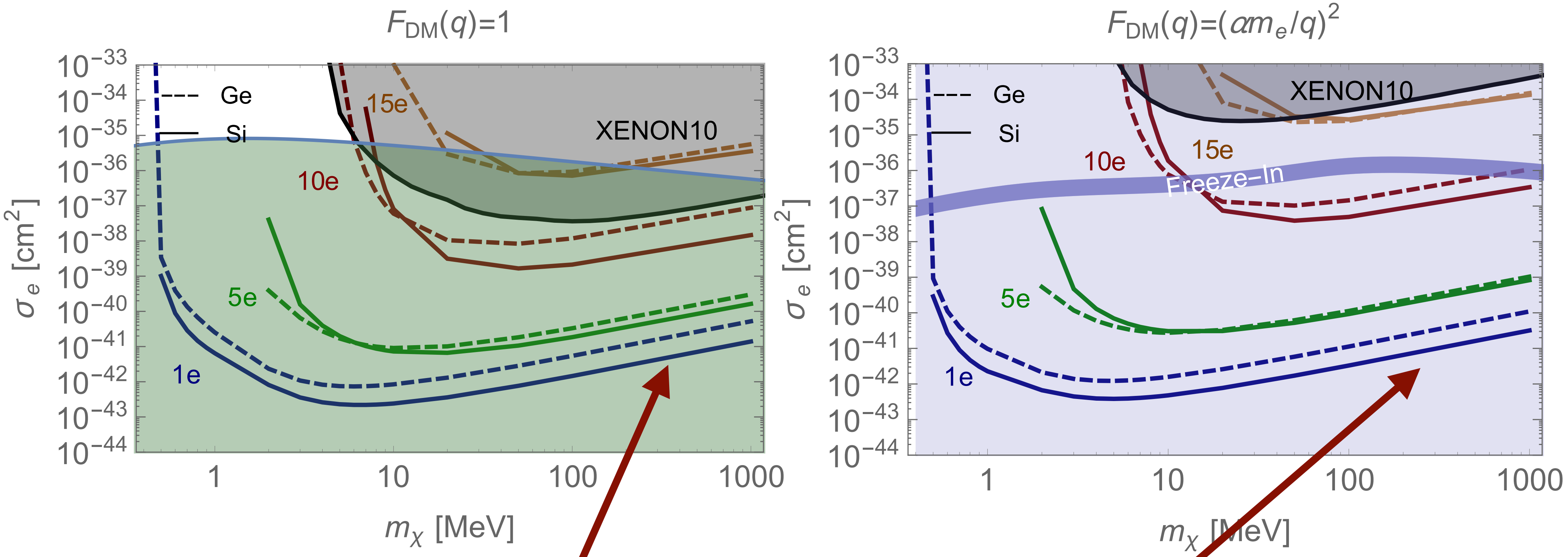


end of interlude

Cross-section reach vs. detector threshold

1 kg-year, zero background

***preliminary**



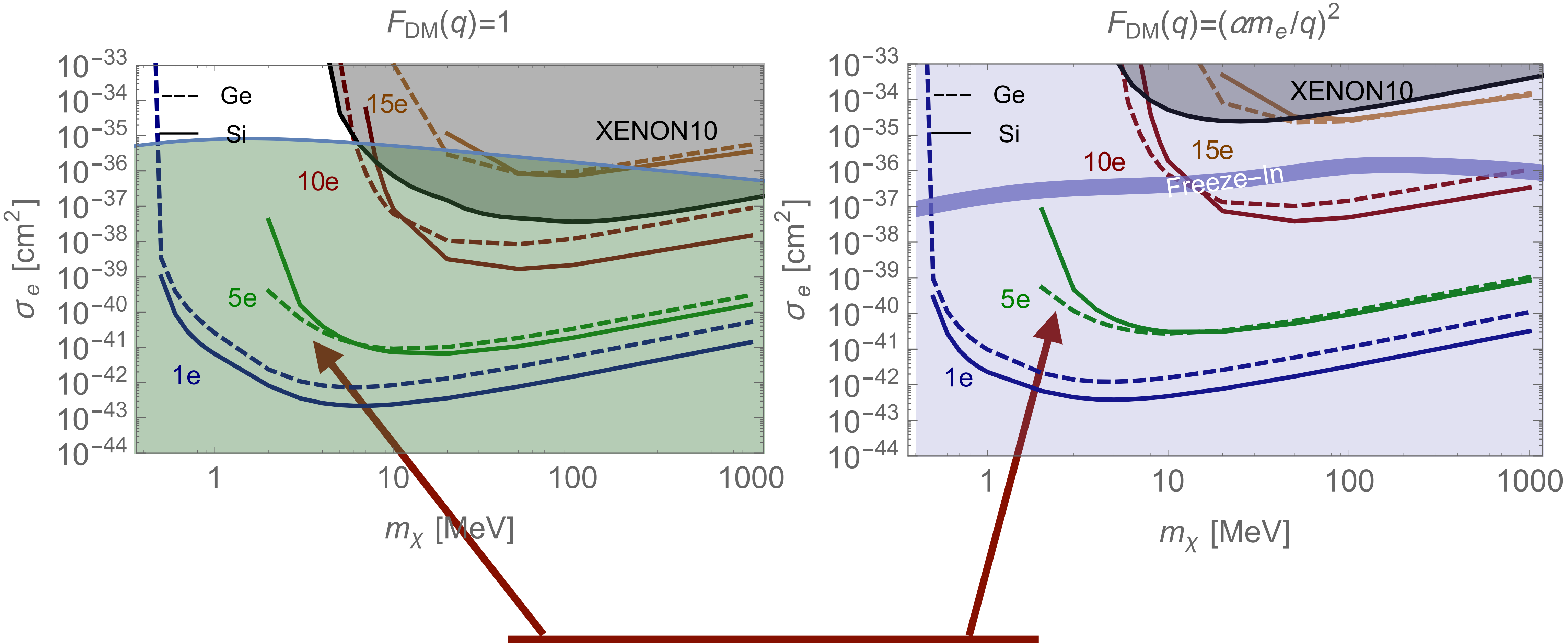
smaller atomic mass = more electrons per target mass

Si wins at high masses and low thresholds

Cross-section reach vs. detector threshold

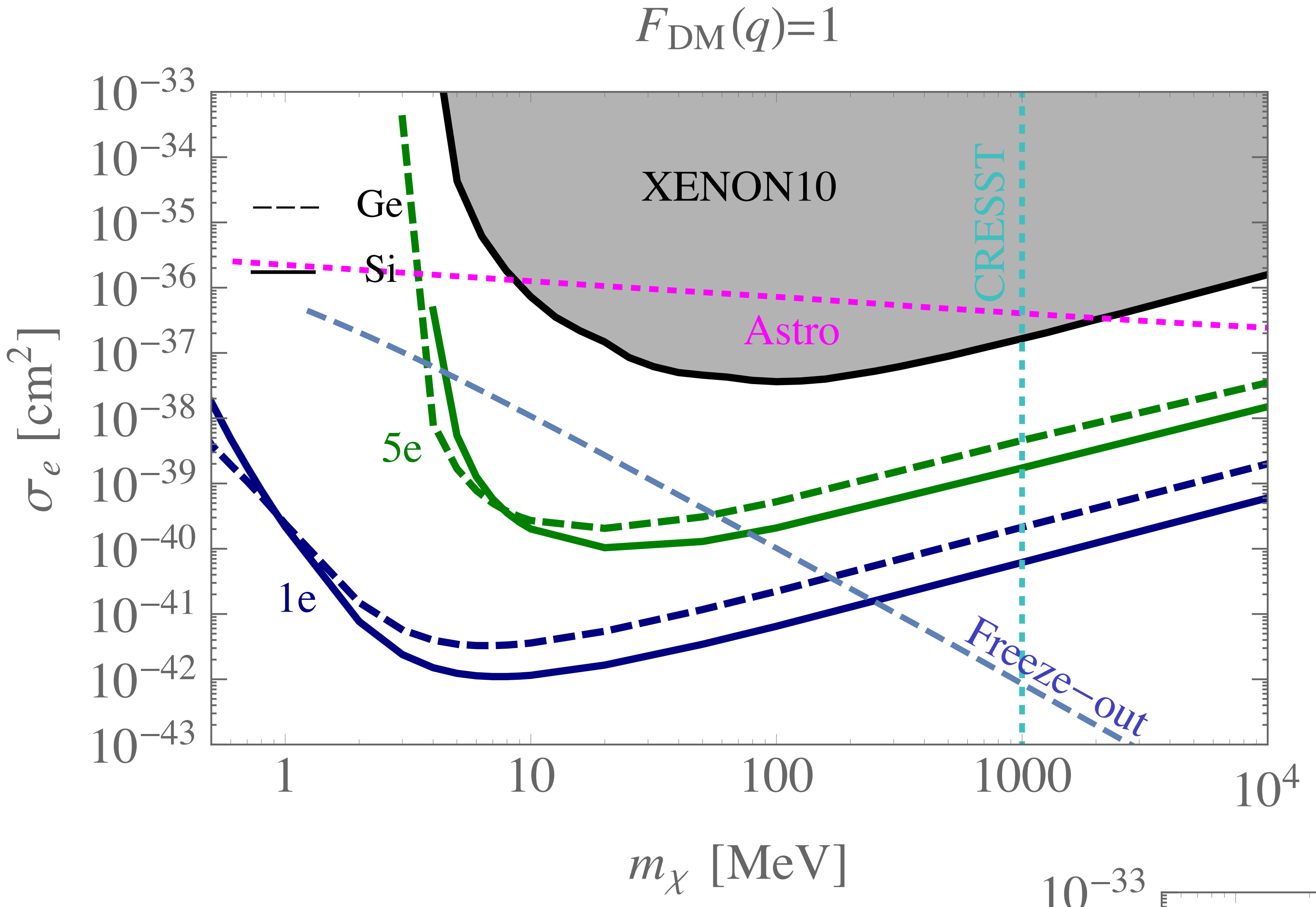
1 kg-year, zero background

***preliminary**



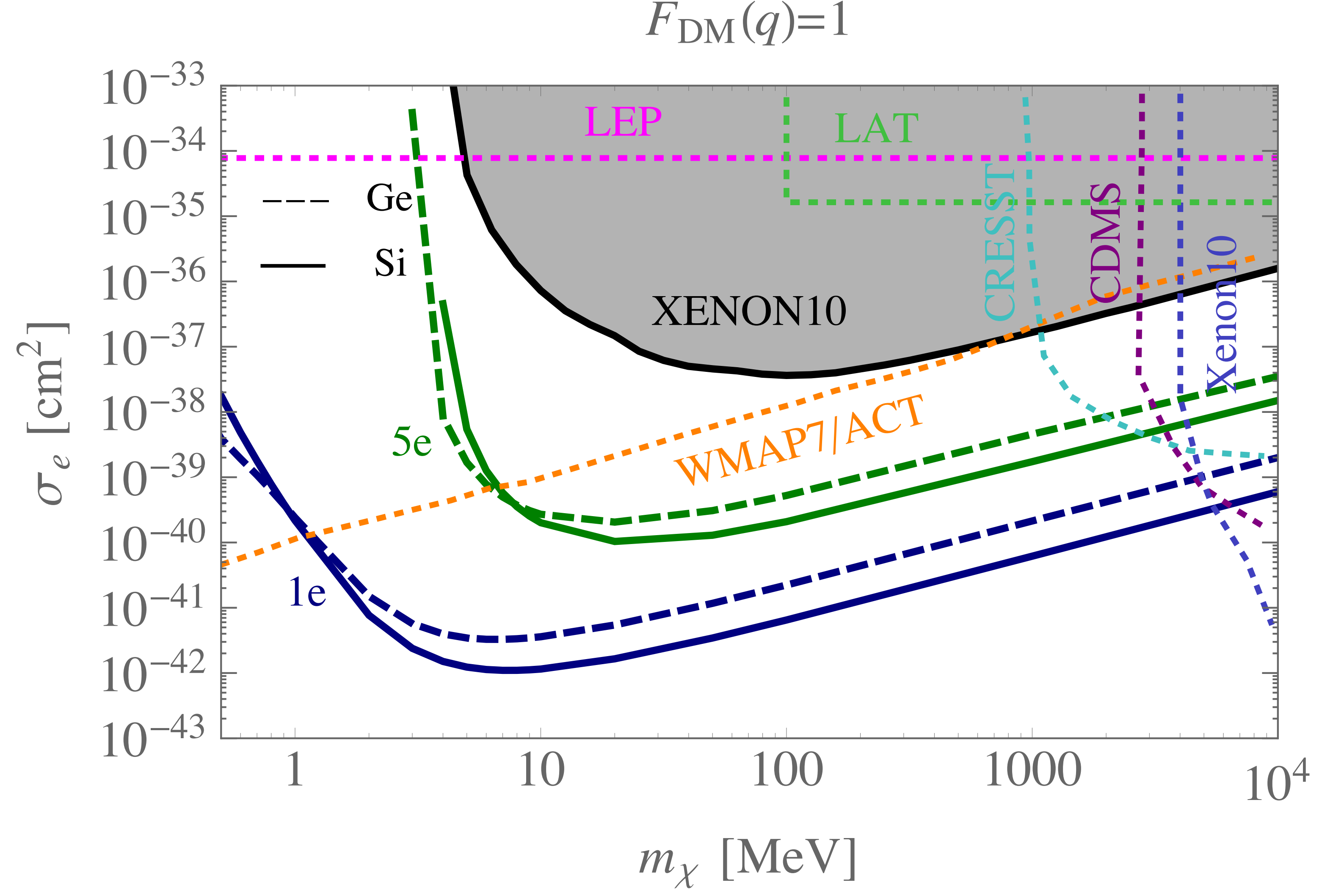
smaller bandgap = higher rate

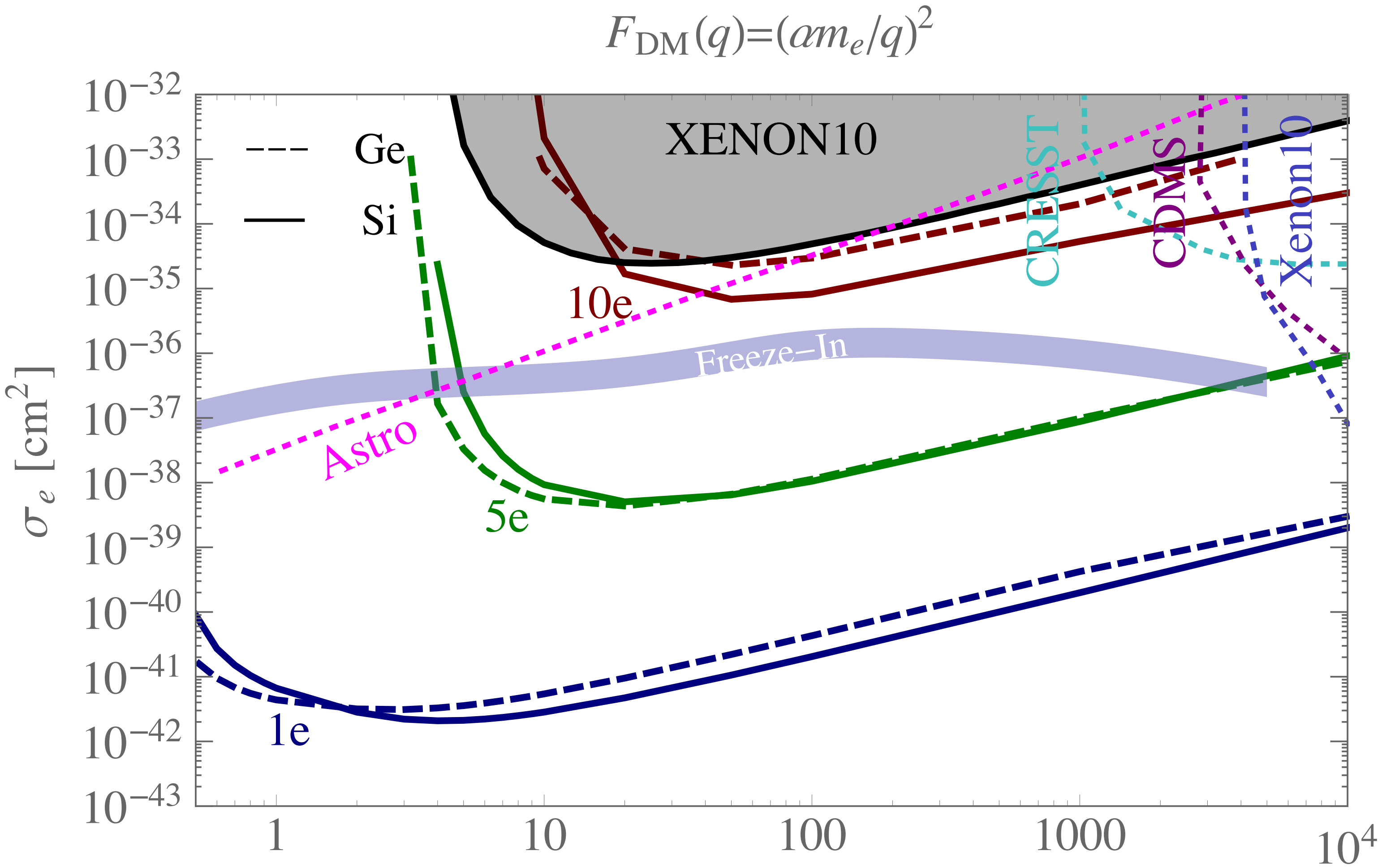
Ge wins at low masses and high thresholds


$F_{\rm DM}(q)$=1
XENON10
CREST
Ge
Si
Astro
5e
1e
Freeze–out
σ_e [cm^2]
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
1
10
100
1000
10^4
m_χ [MeV]

Heavy A'

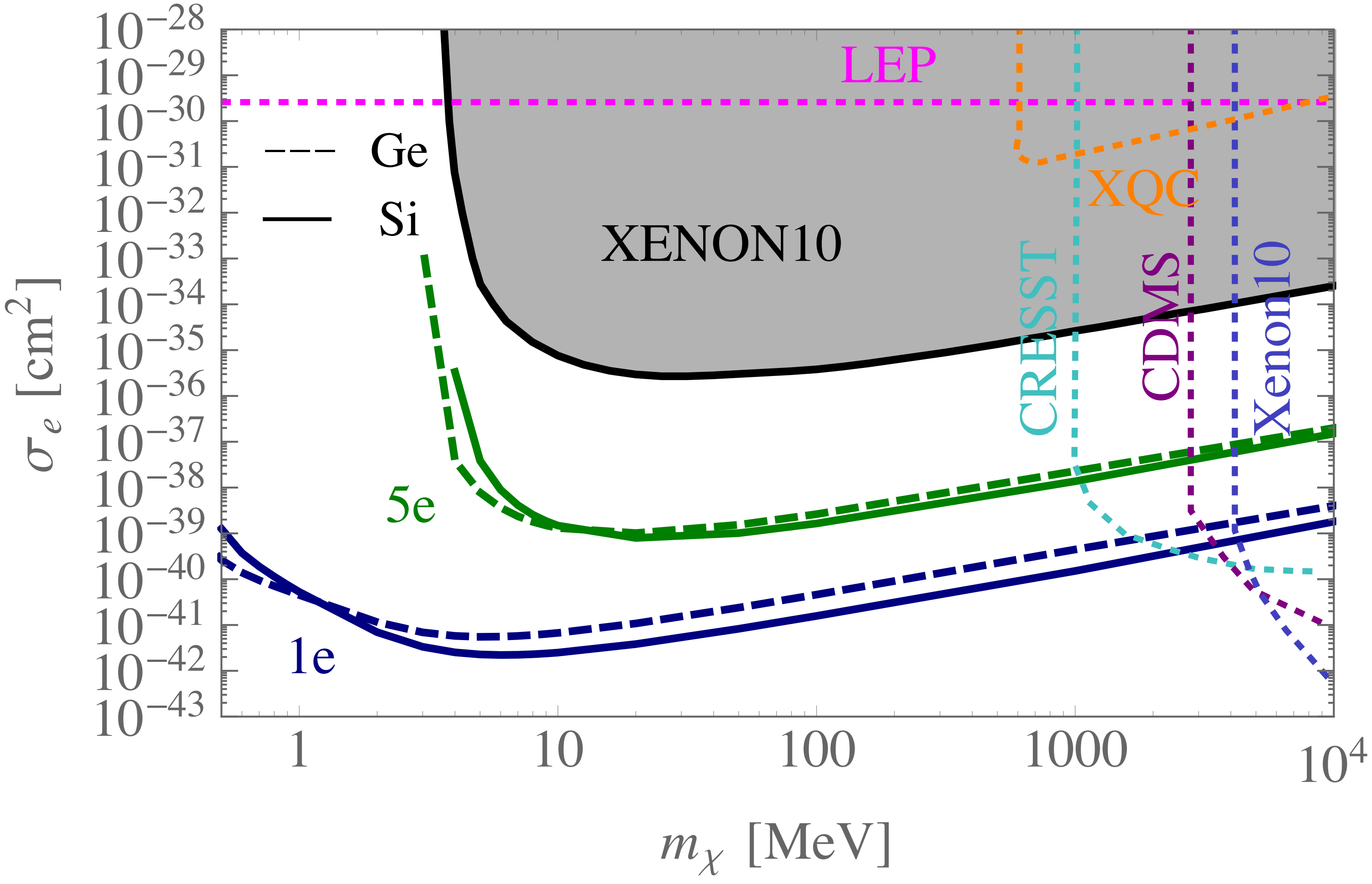
MDM


$F_{\rm DM}(q)$=1
LEP
LAT
Ge
Si
XENON10
CRESST
CDMS
Xenon10
WMAP7/ACT
5e
1e
σ_e [cm^2]
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
1
10
100
1000
10^4
m_χ [MeV]


$F_{\rm DM}(q)=(\alpha m_e/q)^2$
Ge
Si
XENON10
CRESST
CDMS
Xenon10
10e
Freeze−In
Astro
5e
1e
σ_e [cm^2]
m_χ [MeV]
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
1
10
100
1000
10^4

Light A'

EDM


$F_{\rm DM}(q)=\alpha m_e/q$
LEP
Ge
Si
XQC
XENON10
CRESST
CDMS
Xenon10
5e
1e
σ_e [cm^2]
m_χ [MeV]
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
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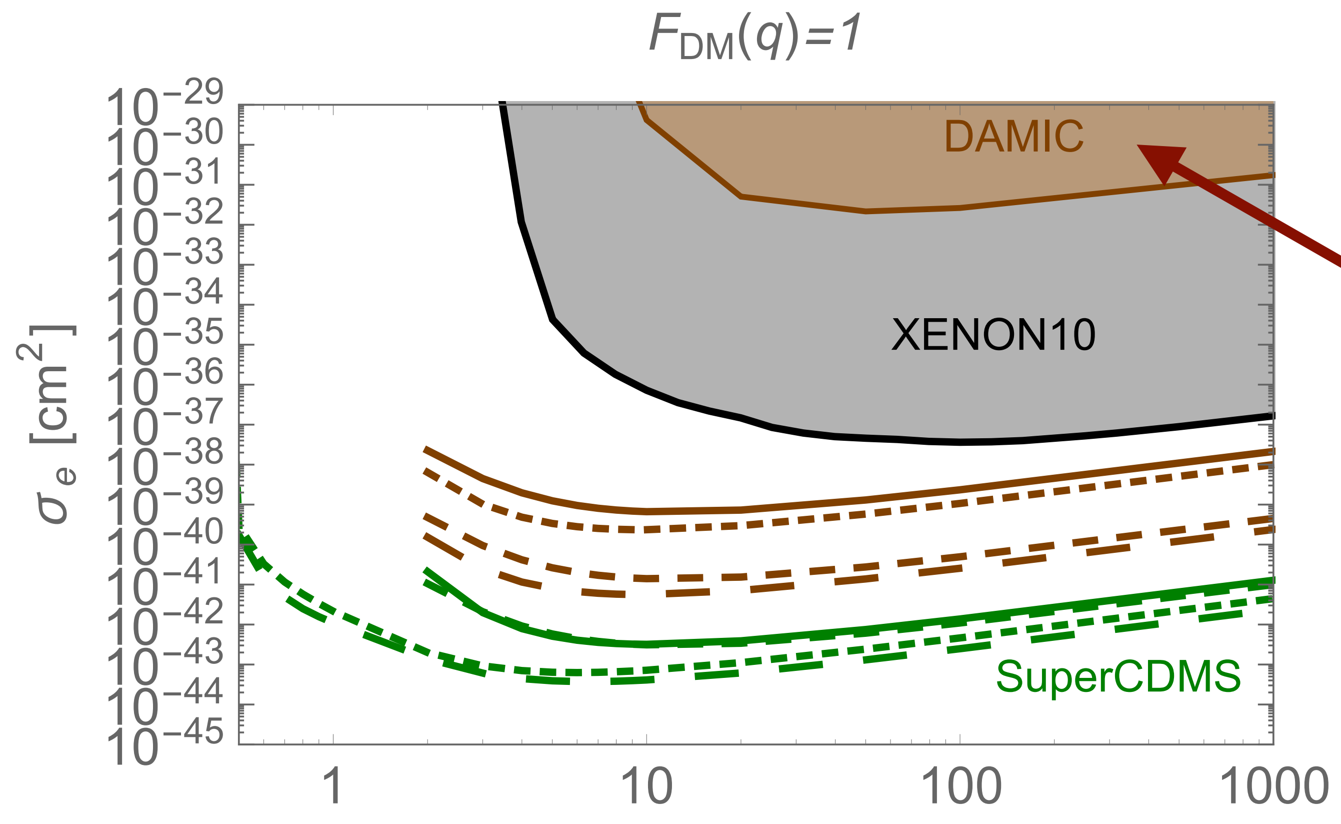
10^{-40}
10^{-41}
10^{-42}
10^{-43}
1
10
100
1000
10^4

Experimental projections



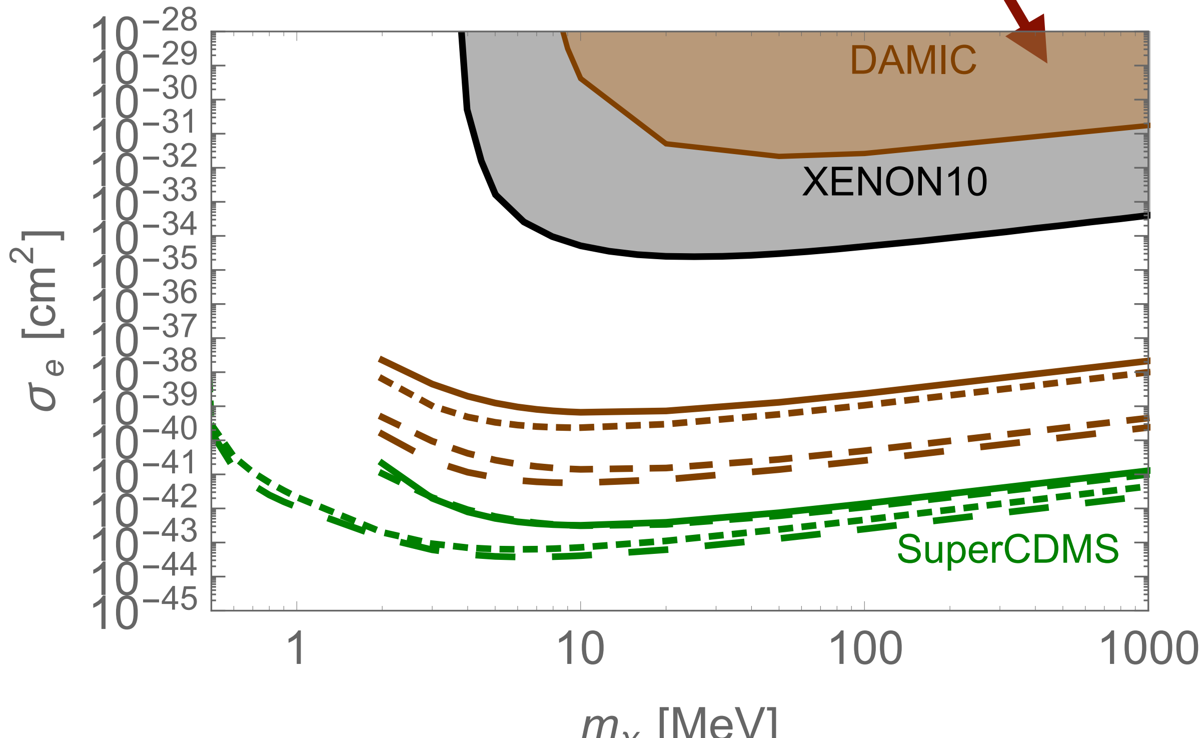
m_χ [MeV]

***preliminary**

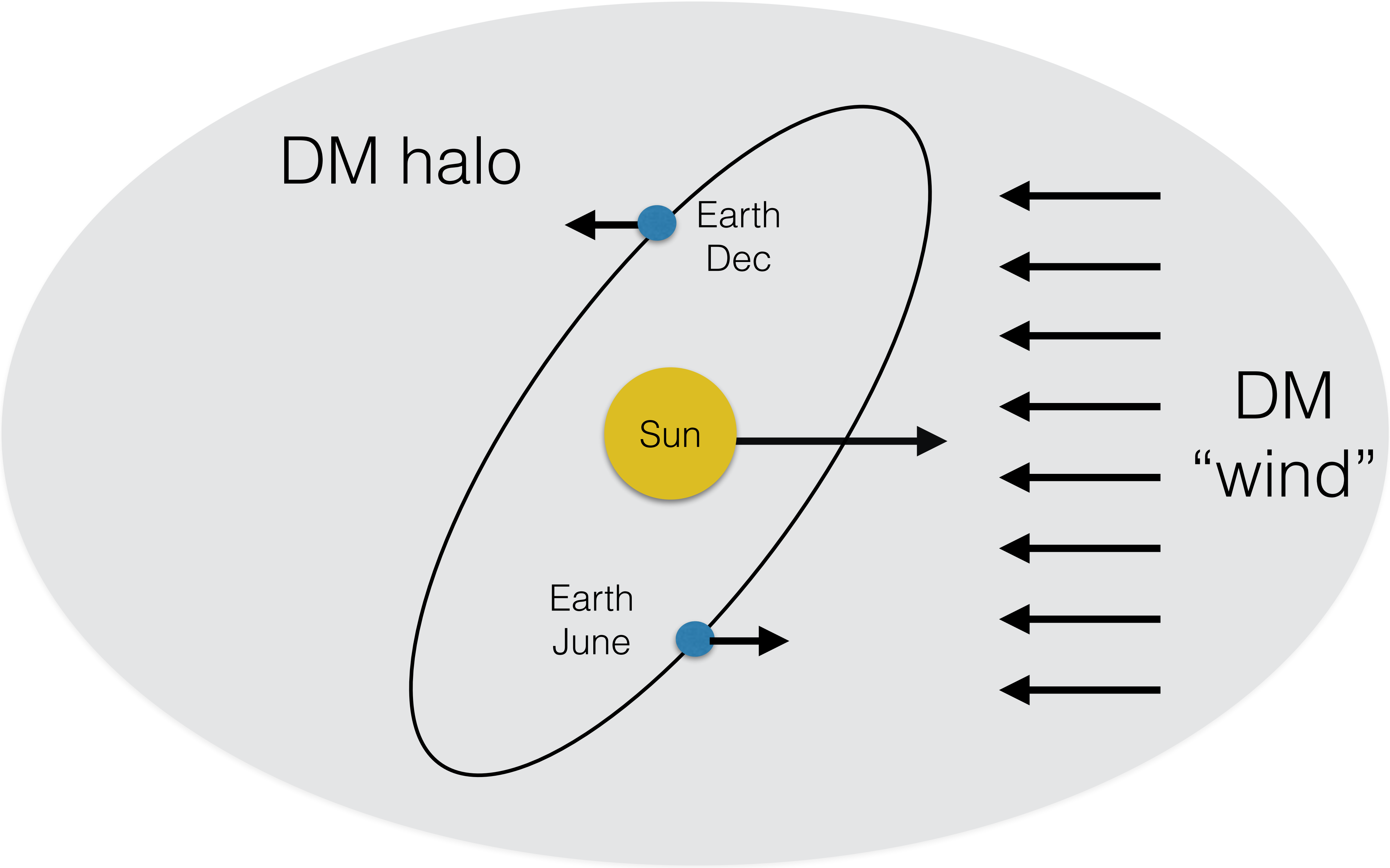
current DAMIC limit:
107 g-days, 11e

- **DAMIC**:
  1. 1 kg-day, 4e, 0.008=3.6 events
  2. 1 kg-day, 3e, 0.025=3.6 events
  3. 50 kg-days, 4e, 0.4=3.8 events
  4. 50 kg-days, 3e, 1.2=4.3 events
- **SuperCDMS**
  1. 20 kg-years, Ge, 4e, 3.6 events (eff=0.7)
  2. 20 kg-years, Ge, 1e, 3.6 events (eff=0.7)
  3. 10 kg-years, Si, 4e, 3.6 events (eff=0.7)
  4. 10 kg-years, Si, 1e, 3.6 events (eff=0.7)

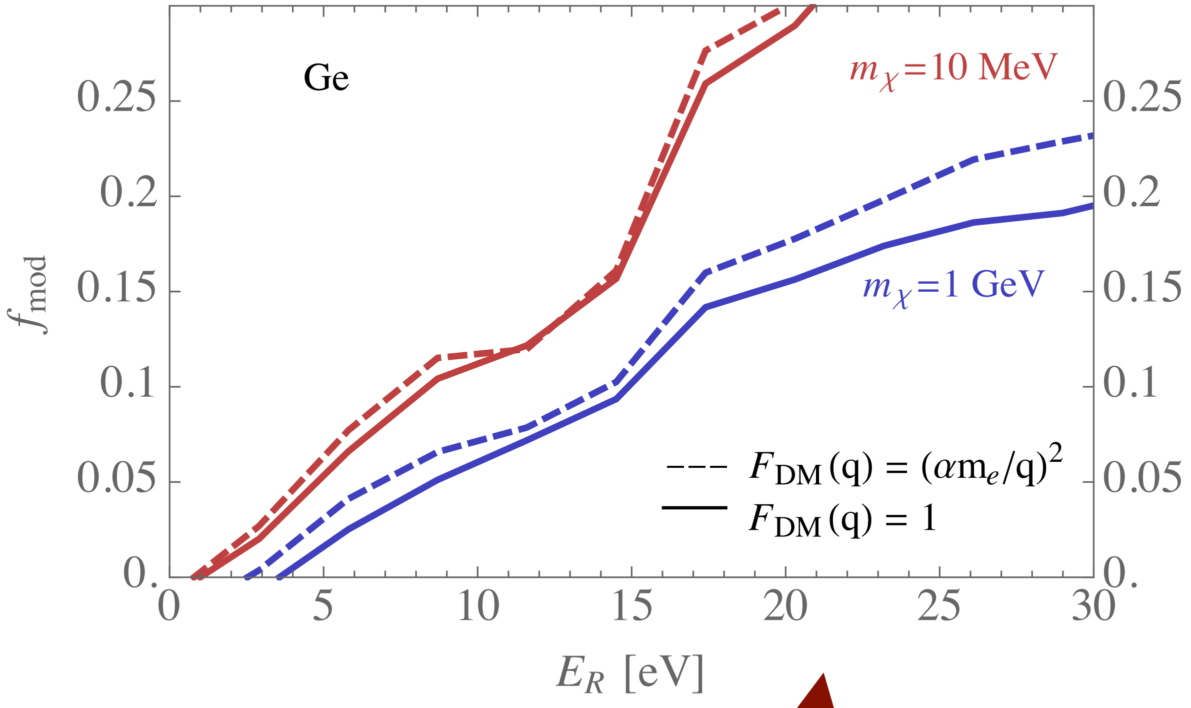
$F_{DM}(q)=(\alpha m_e/q)^2$



annual modulation

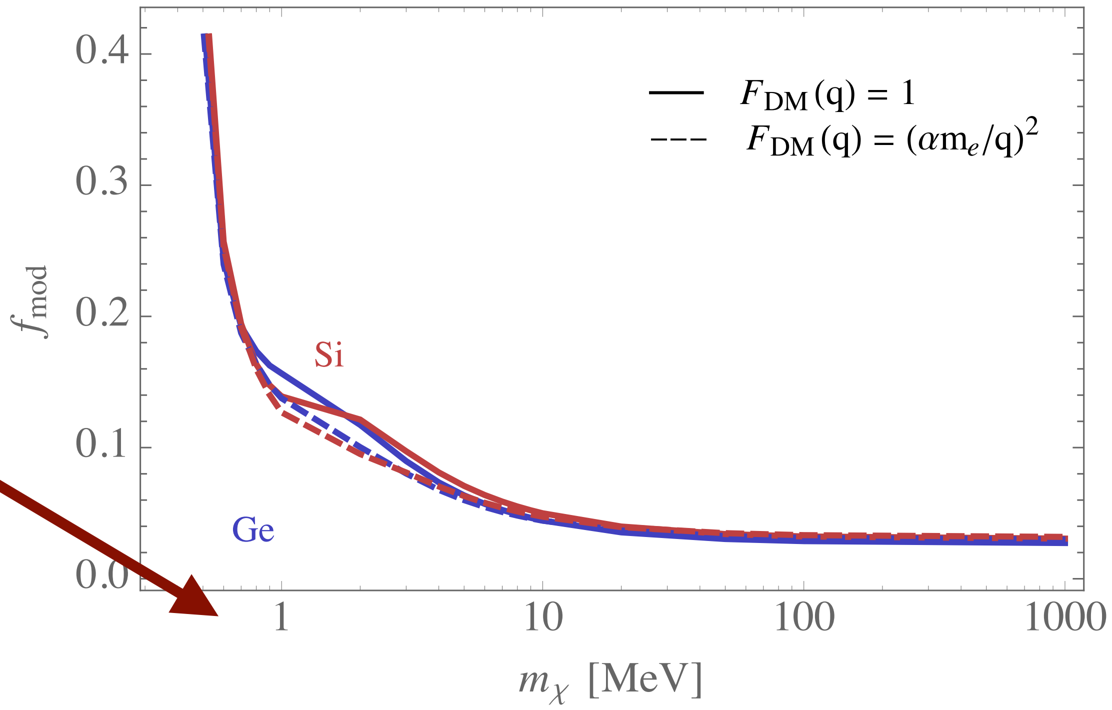


annual modulation



***preliminary**

$$f_{mod} = \frac{R_{max} - R_{min}}{2R_{mean}}$$



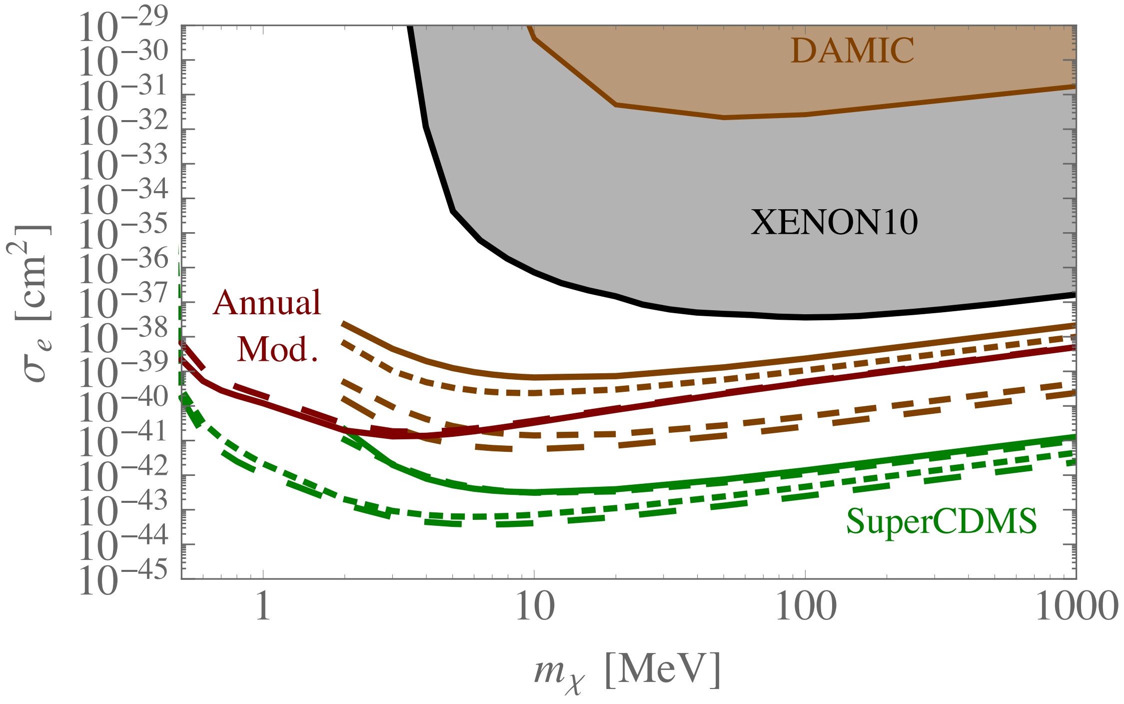
sits on tail of velocity distribution

could also consider gravitational focusing, c.f. 1308.1953

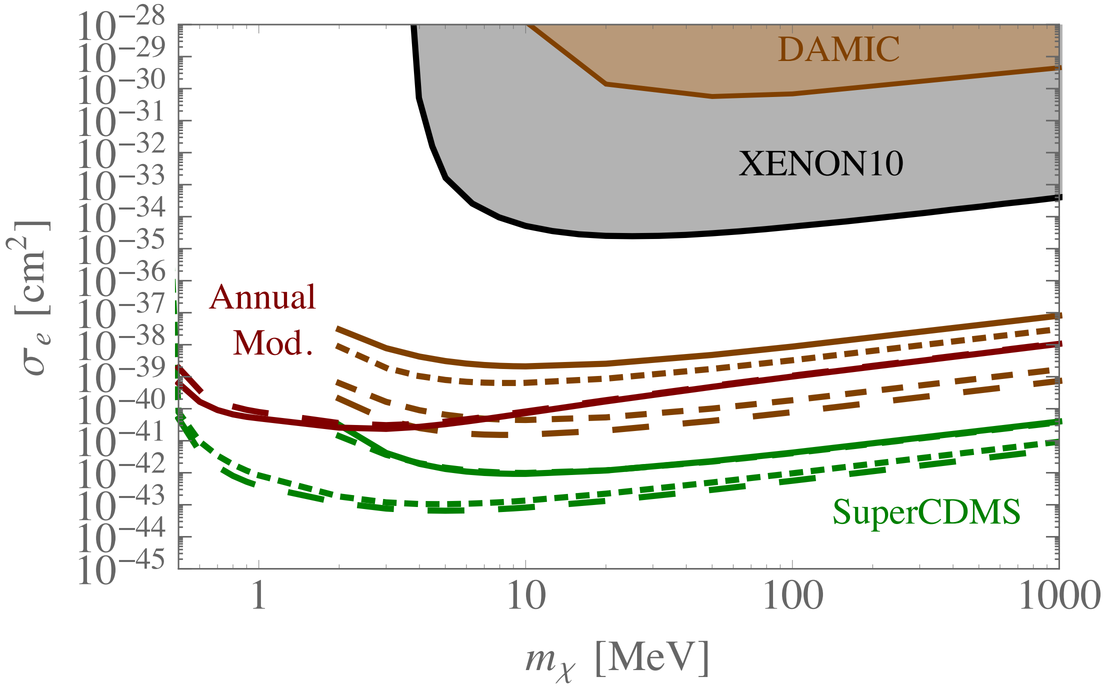
annual modulation

***preliminary**

$F_{\rm DM}(q)=1$



$F_{\rm DM}(q)=(\alpha m_e/q)^2$



conclusions

- sub-GeV dark matter is theoretically motivated
- but this mass range is currently unexplored by direct detection experiments, which rely on nuclear recoil.
- exchanging nuclear recoil for electron recoil is a possible resolution
- The best projections so far are theory predictions for noble gases
- semiconductor experiments have the potential to have a further reach due to the small band gap
- ongoing discussions with CDMS and DAMIC