Title: New Directions in Dark Matter Direct Detection

Date: Apr 04, 2017 01:00 PM

URL: http://pirsa.org/17040029

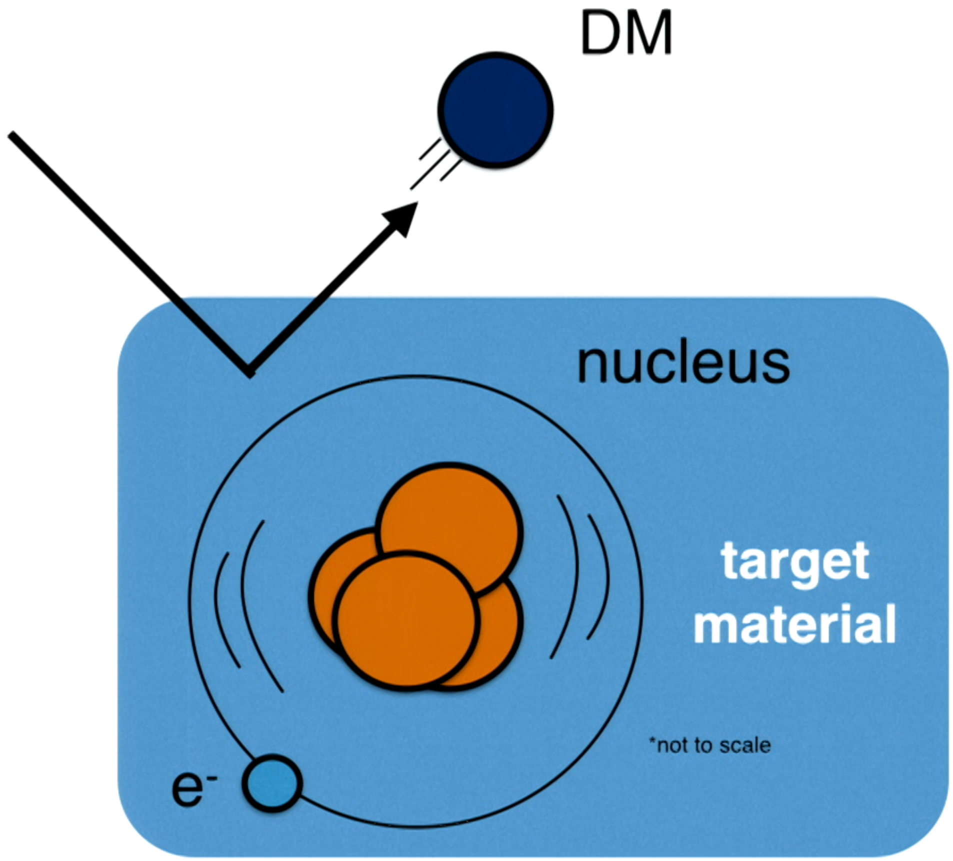
Abstract: <p>Sub-GeV dark matter is a theoretically motivated but largely unexplored paradigm of dark matter. In this talk, I will discuss recent work on the direct detection of sub-GeV dark matter through dark matter-electron scattering. I will present some motivated models that can be probed with these techniques as well as projections for current and near-term noble liquid, semiconductor, and scintillator experiments. Finally, I will discuss some new techniques that may allow us to more robustly discriminate between dark matter signatures and background.</p>

New Directions for DM Direct Detection

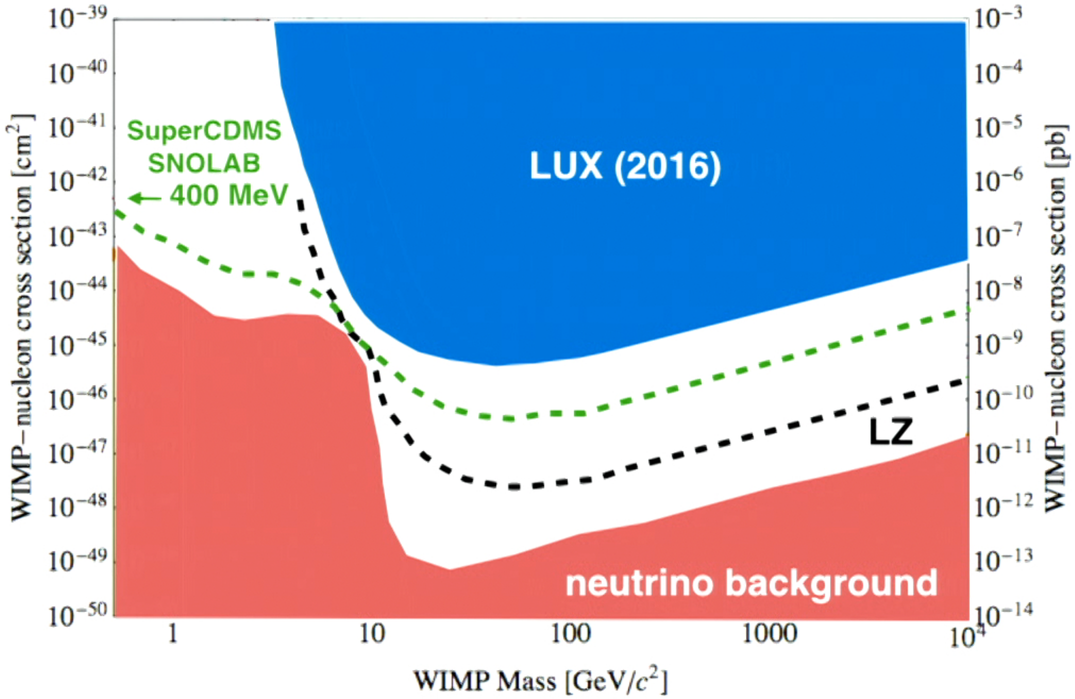
Tien-Tien Yu (CERN)

Perimeter Institute — April 4, 2017

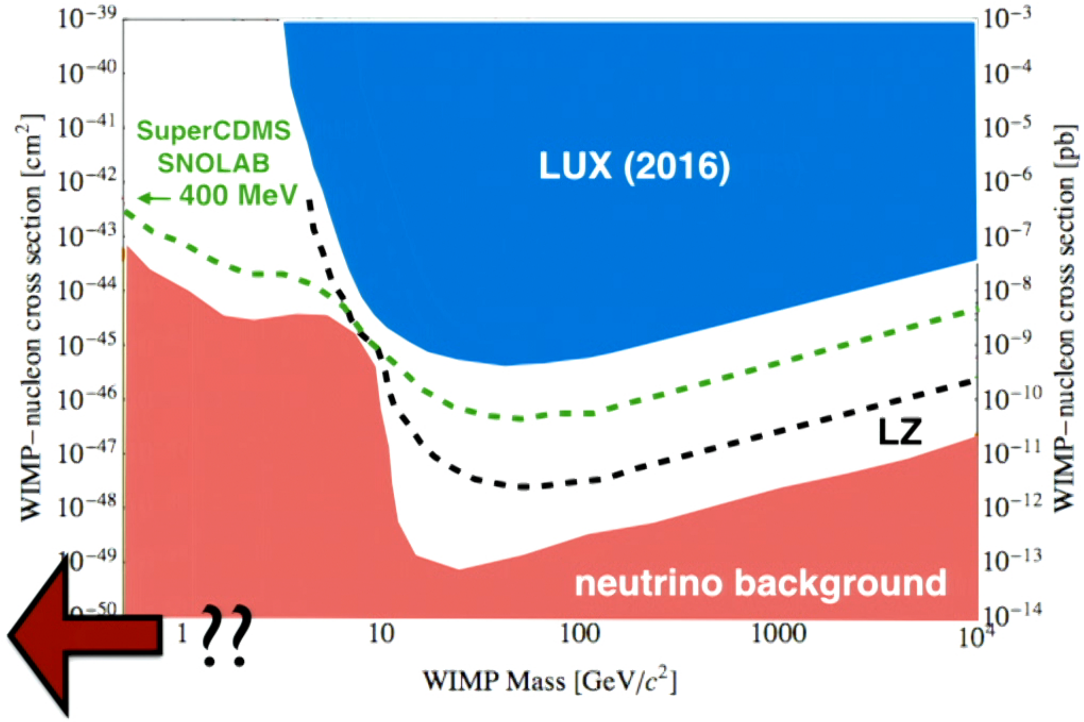
DM direct detection



DM direct detection

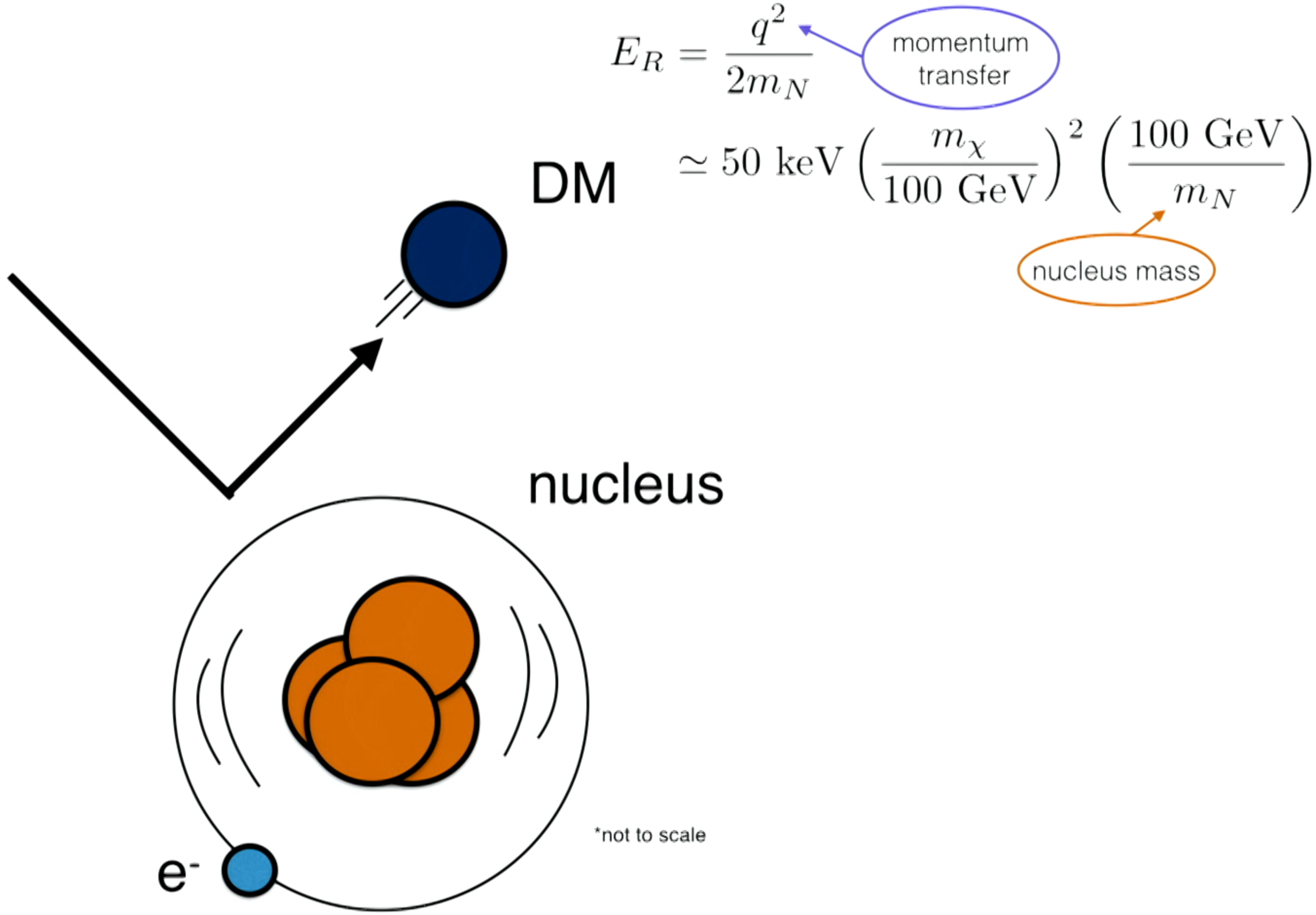


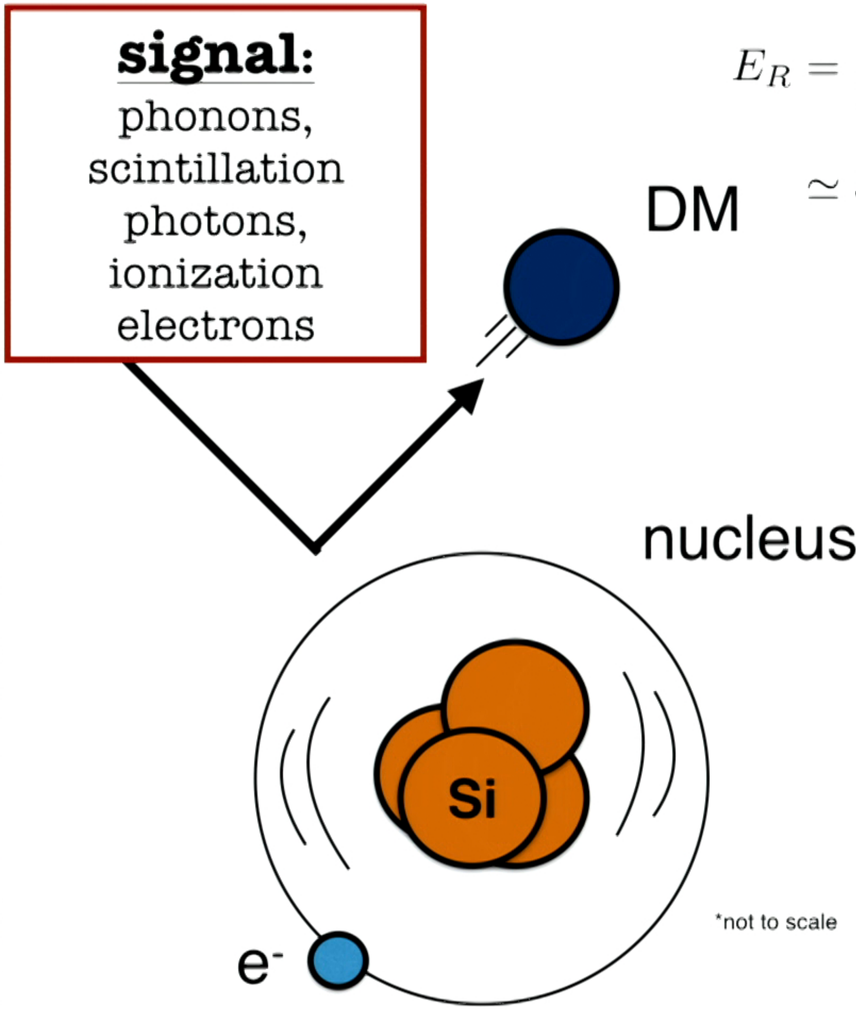
DM direct detection



$$E_R = \frac{q^2}{2m_N}$$

$$\simeq 50 \text{ keV} \left(\frac{m_\chi}{100 \text{ GeV}}\right)^2 \left(\frac{100 \text{ GeV}}{m_N}\right)$$





$$E_R = \frac{q^2}{2m_N}$$

momentum transfer

$$\simeq 50 \text{ keV} \left(\frac{m_\chi}{100 \text{ GeV}}\right)^2 \left(\frac{100 \text{ GeV}}{m_N}\right)$$

nucleus mass

$$m_N = 28 \text{ GeV}$$

$$m_\chi = 100 \text{ GeV}$$

$$E_R \sim 100 \text{ keV}$$

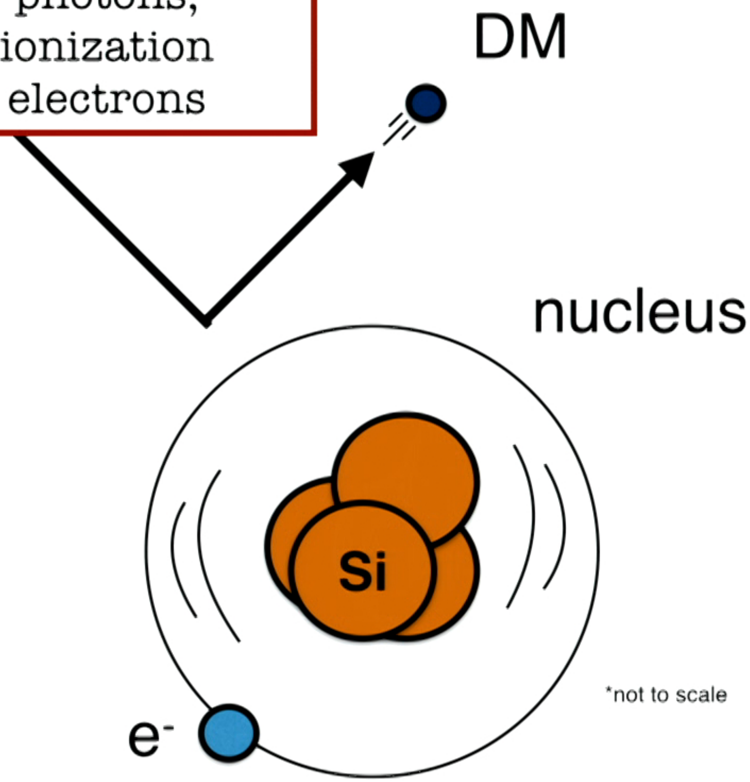
signal:
phonons,
scintillation
photons,
ionization
electrons

$$E_R = \frac{q^2}{2m_N}$$

momentum transfer

$$\simeq 50\ \text{keV} \left(\frac{m_\chi}{100\ \text{GeV}}\right)^2 \left(\frac{100\ \text{GeV}}{m_N}\right)$$

nucleus mass



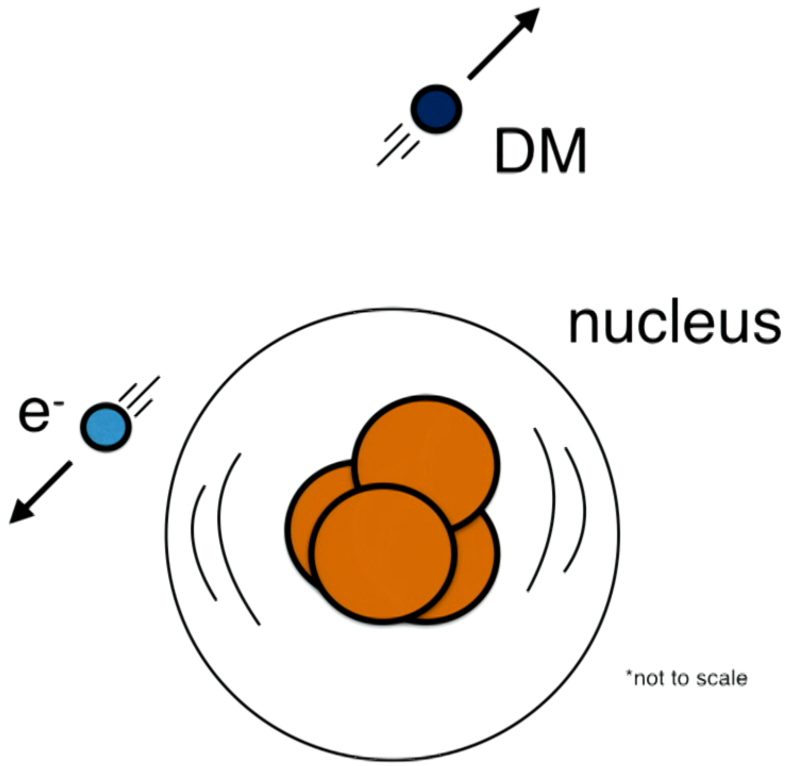
$$m_N = 28\ \text{GeV}$$

$$m_\chi = 100\ \text{MeV}$$

$$E_R \sim 0.1\ \text{eV}$$

signal:
a few ionized electrons

$$E_R = \vec{q} \cdot \vec{v} - \frac{q^2}{2\mu_{\chi N}}$$
$$\sim \frac{1}{2}\text{eV} \times \left(\frac{m_\chi}{\text{MeV}}\right)$$



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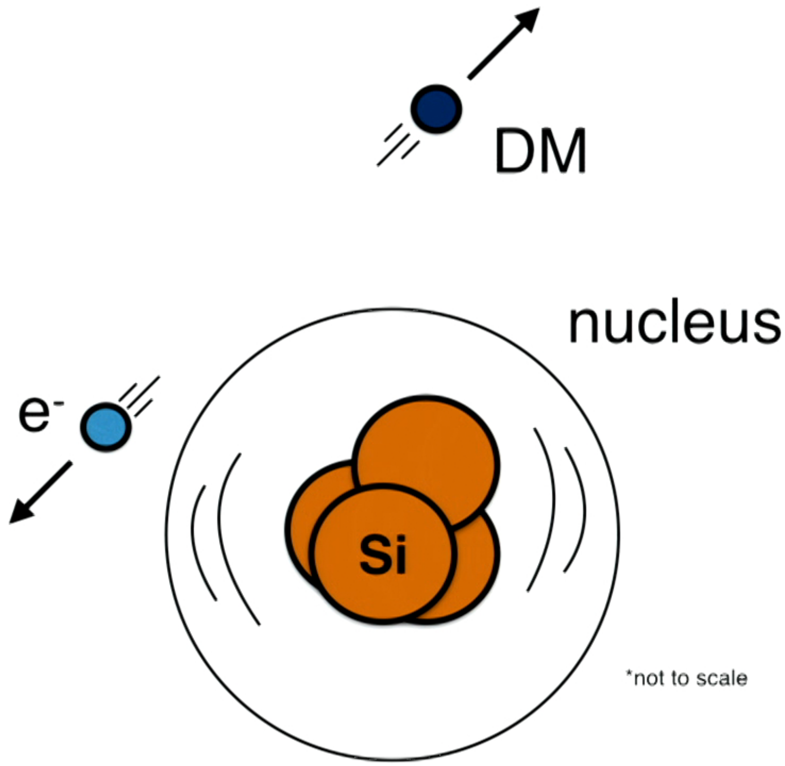


$$m_N = 28 \text{ GeV}$$

$$m_\chi = 100 \text{ MeV}$$

$$E_R \sim 50 \text{ eV}$$

Calculation

ingredients

astrophysics

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

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

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

ingredients

particle physics

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

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

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

ingredients

material dependent

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

$$|f(k,q)|^2 = \left|\int d^3x\psi_f^*(\vec{x})\psi_i(\vec{x})e^{i\vec{q}\cdot\vec{x}}\right|^2$$

wave-function overlap between initial and final electron states

probability of going from state i to i'

ingredients

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

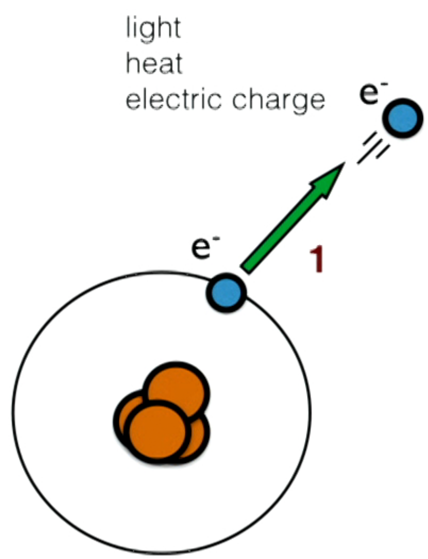
local DM density

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

number of target nuclei per unit mass

energy threshold

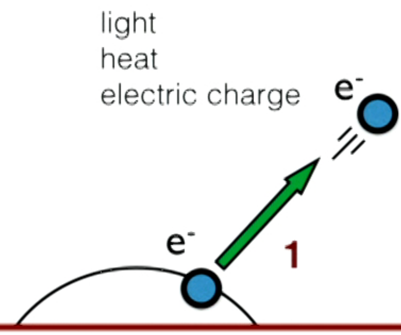
noble liquid



$$|f_{ion}^{nl}(k',q)|^2 = \frac{4k'^3}{(2\pi)^3}\sum_{l'L}(2l+1)(2l'+1)(2L+1)$$

$$\times \begin{bmatrix} l & l' & L \\ 0 & 0 & 0 \end{bmatrix}^2 \left| \int r^2 dr R_{k'l'}(r) R_{nl}(r) j_L(qr) \right|^2$$

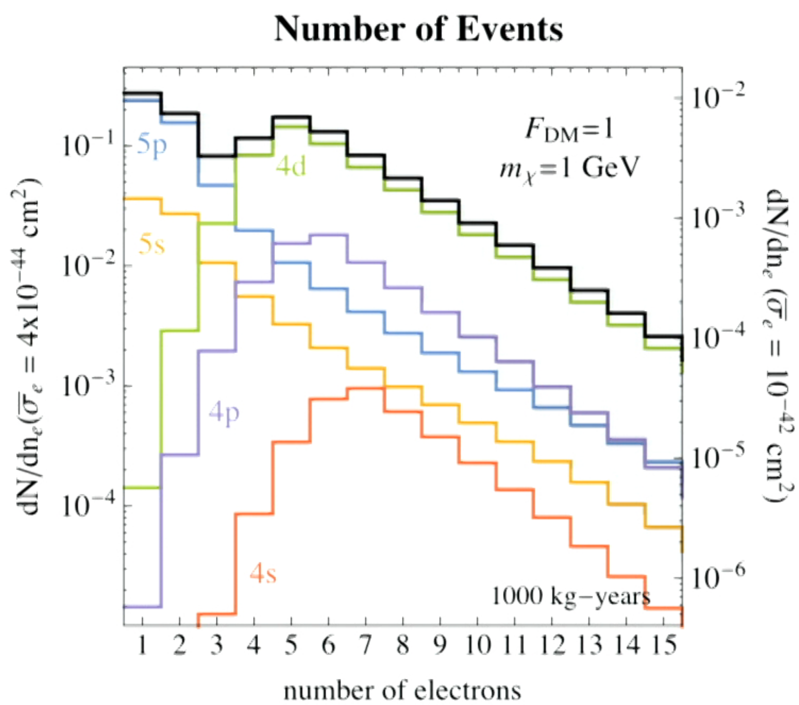
noble liquid



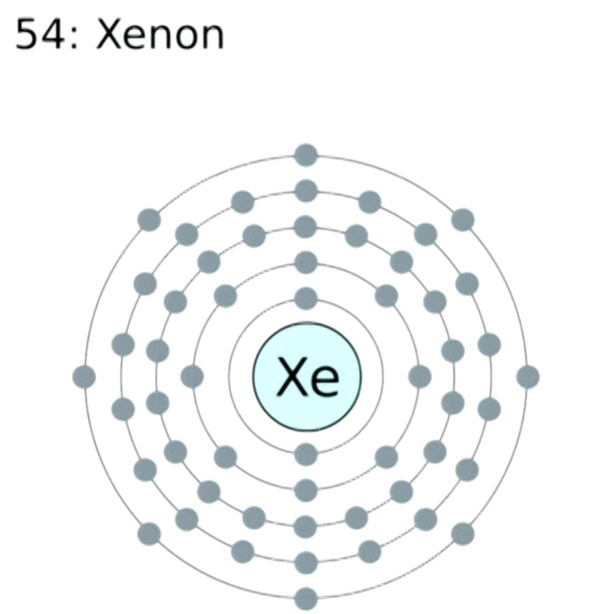
electron wave functions calculated
with Hartree-Fock method
for atoms

$$|f_{ion}^{nl}(k',q)|^2 = \frac{4k'^3}{(2\pi)^3}\sum_{l'L}(2l+1)(2l'+1)(2L+1)$$
$$\times \begin{bmatrix} l & l' & L \\ 0 & 0 & 0 \end{bmatrix}^2 \left| \int r^2 dr R_{k'l'}(r) R_{nl}(r) j_L(qr) \right|^2$$

XENON



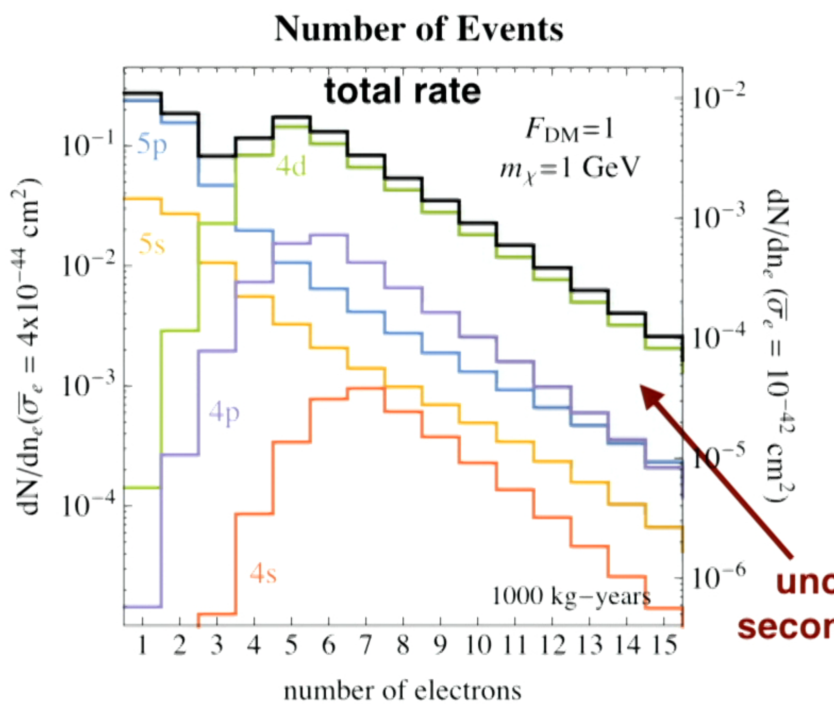
Essig, Volansky, TTY [1703.00910]

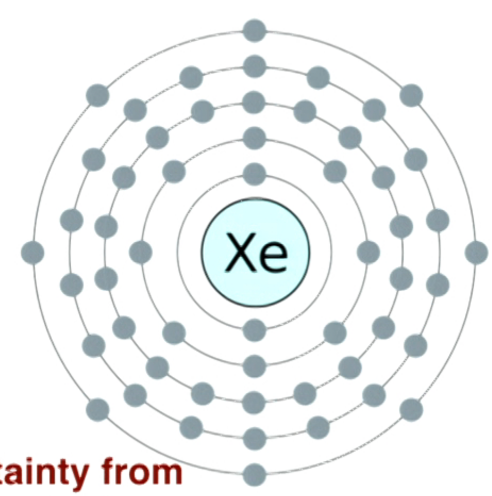


http://commons.wikimedia.org/wiki/Category:Electron_shell_diagrams

Electron configuration:
[Ar] 3d10 4s2 4p6 4d10 5s2 5p6

XENON

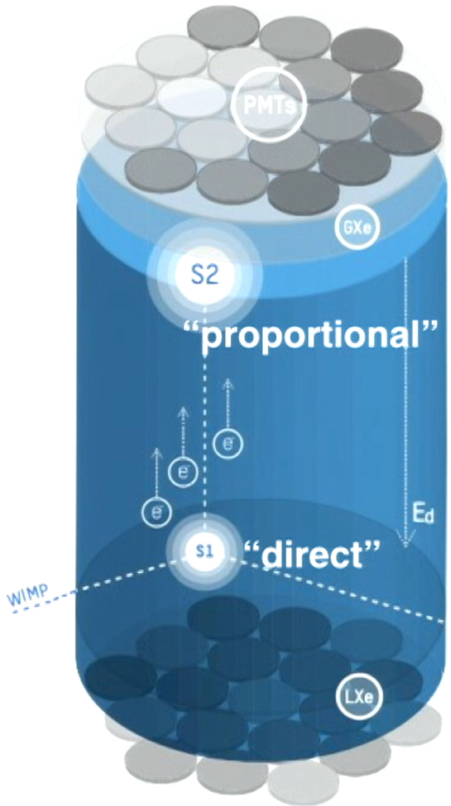




Essig, Volansky, TTY [1703.00910]

Electron configuration:
[Ar] 3d10 4s2 4p6 4d10 5s2 5p6

a XENON detector



https://commons.wikimedia.org/wiki/File:2phaseTPC_b.jpg

i.e. XENON10, XENON100, XENON1T, LUX

DM-electron scattering

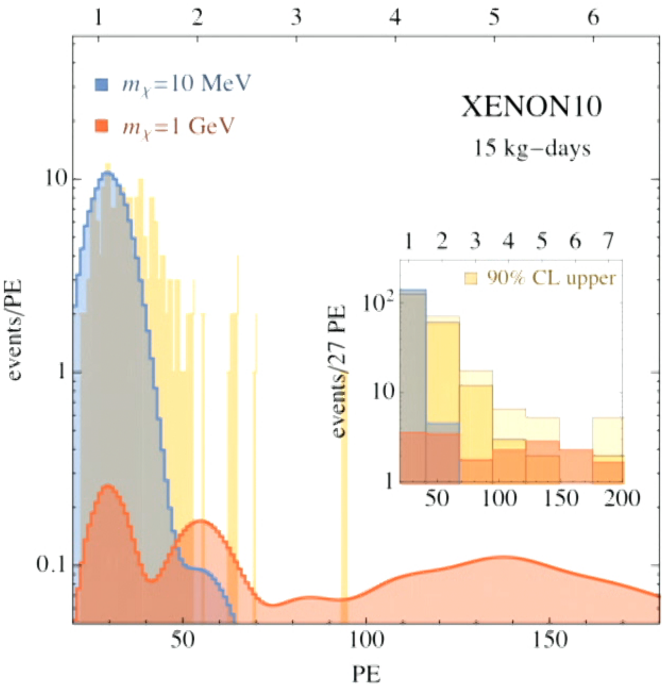
=

S2 only signal

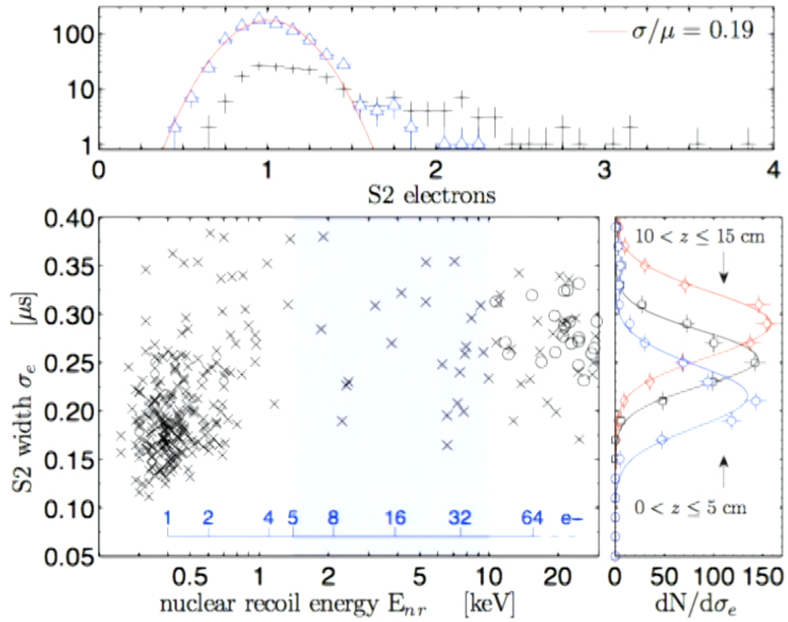
measures **P**hoto**E**lectrons

XENON10

ne~27 PE



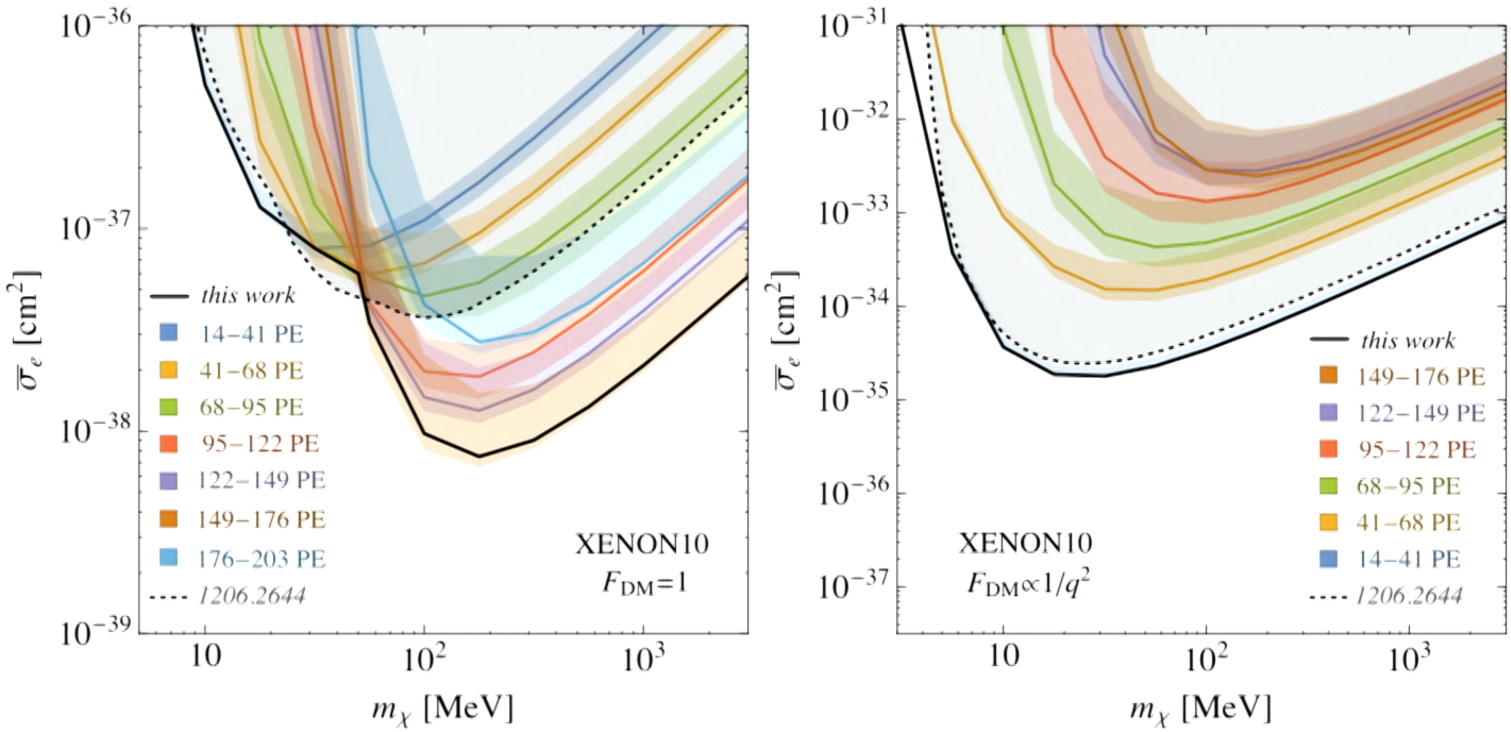
Essig, Volansky, TTY [1703.00910]



XENON10 Collaboration

Phys.Rev.Lett. **110** (2013) 249901

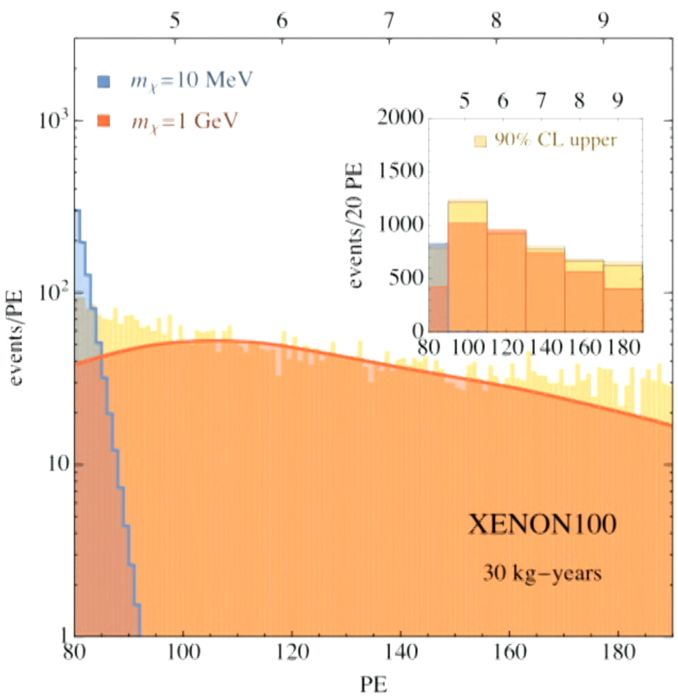
XENON10



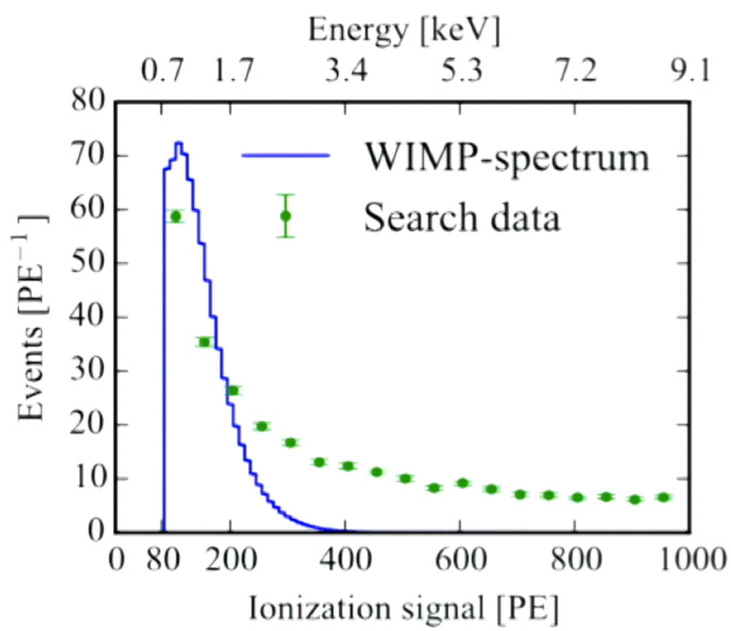
Essig, Volansky, TTY [1703.00910]

XENON100

ne~20 PE

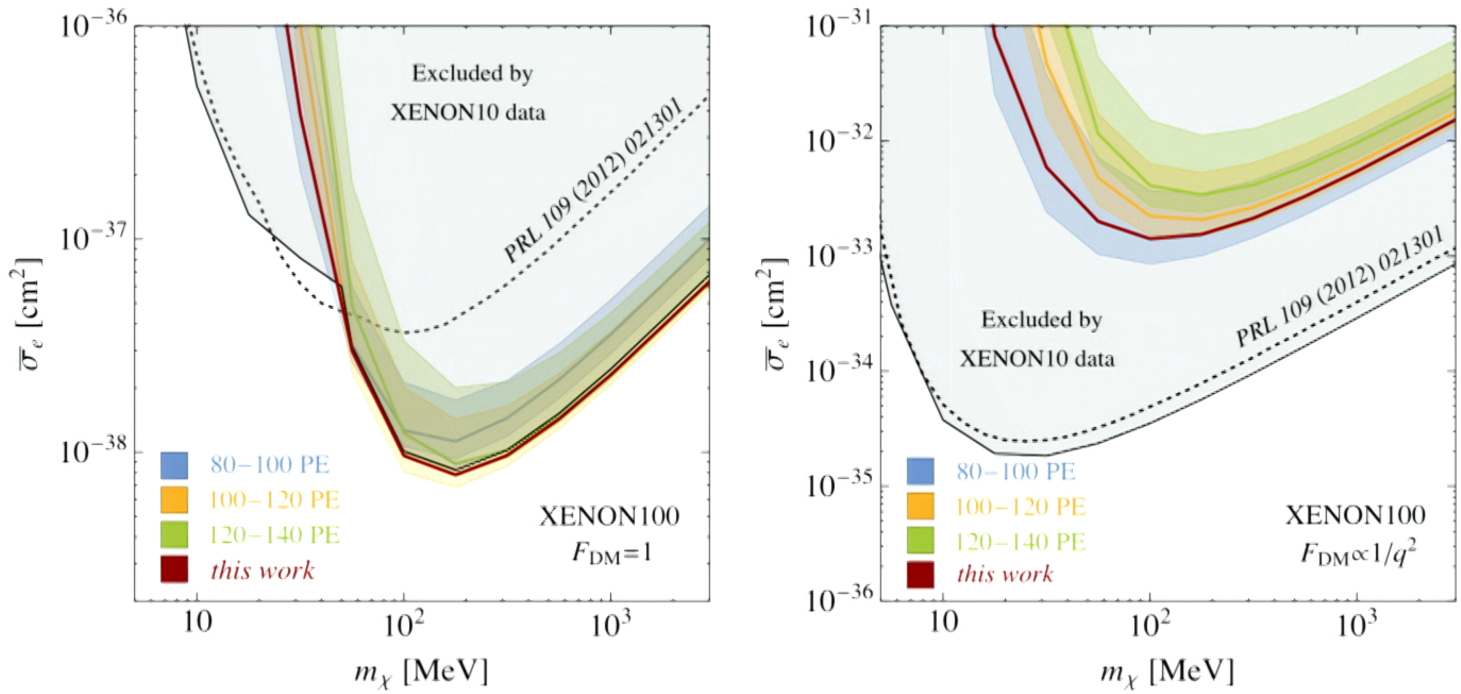


Essig, Volansky, TTY [1703.00910]



Phys.Rev. D94 (2016) no.9, 092001

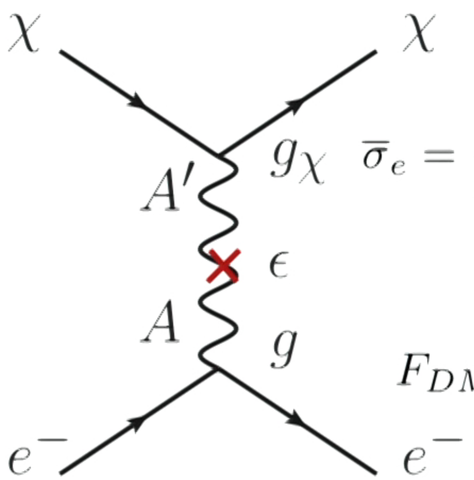
XENON100



Essig, Volansky, TTY [1703.00910]

A Model: Hidden Photon

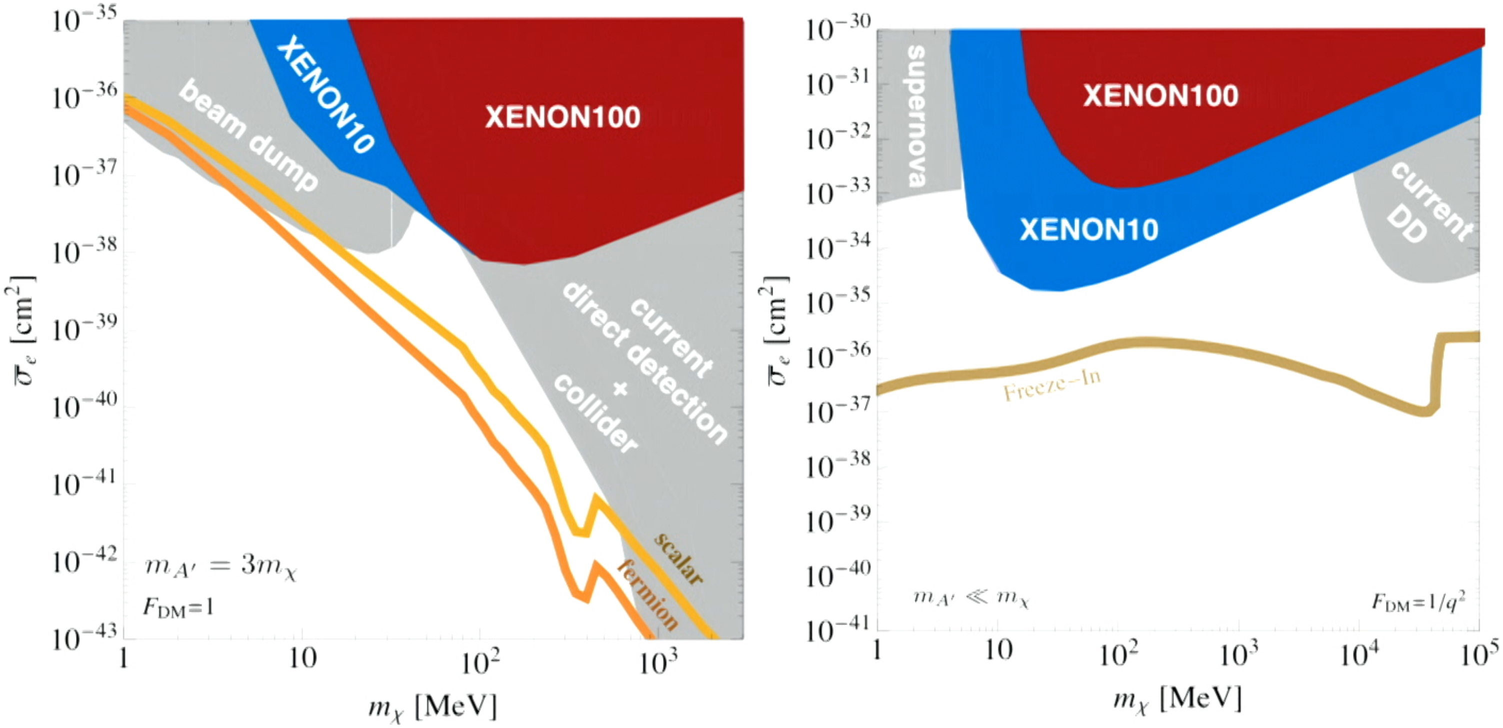
$$\mathcal{L} = F_{\mu\nu}^2 + {F'}_{\mu\nu}^2 + m_{A'}^2 A'^2_\mu + g_\chi J_\chi^\mu A'_\mu + g J_e^\mu (A_\mu + \epsilon A'_\mu)$$



$$\overline{\sigma}_e = \frac{16\pi\mu_{\chi e}^2 \alpha\epsilon^2\alpha_\chi}{(m_{A'}^2 + \alpha^2 m_e^2)^2} \simeq \begin{cases} \frac{16\pi\mu_{\chi e}^2\alpha\epsilon^2\alpha_D}{m_{A'}^4}, & m_{A'} \gg \alpha m_e \\ \frac{16\pi\mu_{\chi e}^2\alpha\epsilon^2\alpha_D}{(\alpha\, m_e)^4}, & m_{A'} \ll \alpha m_e \end{cases}$$

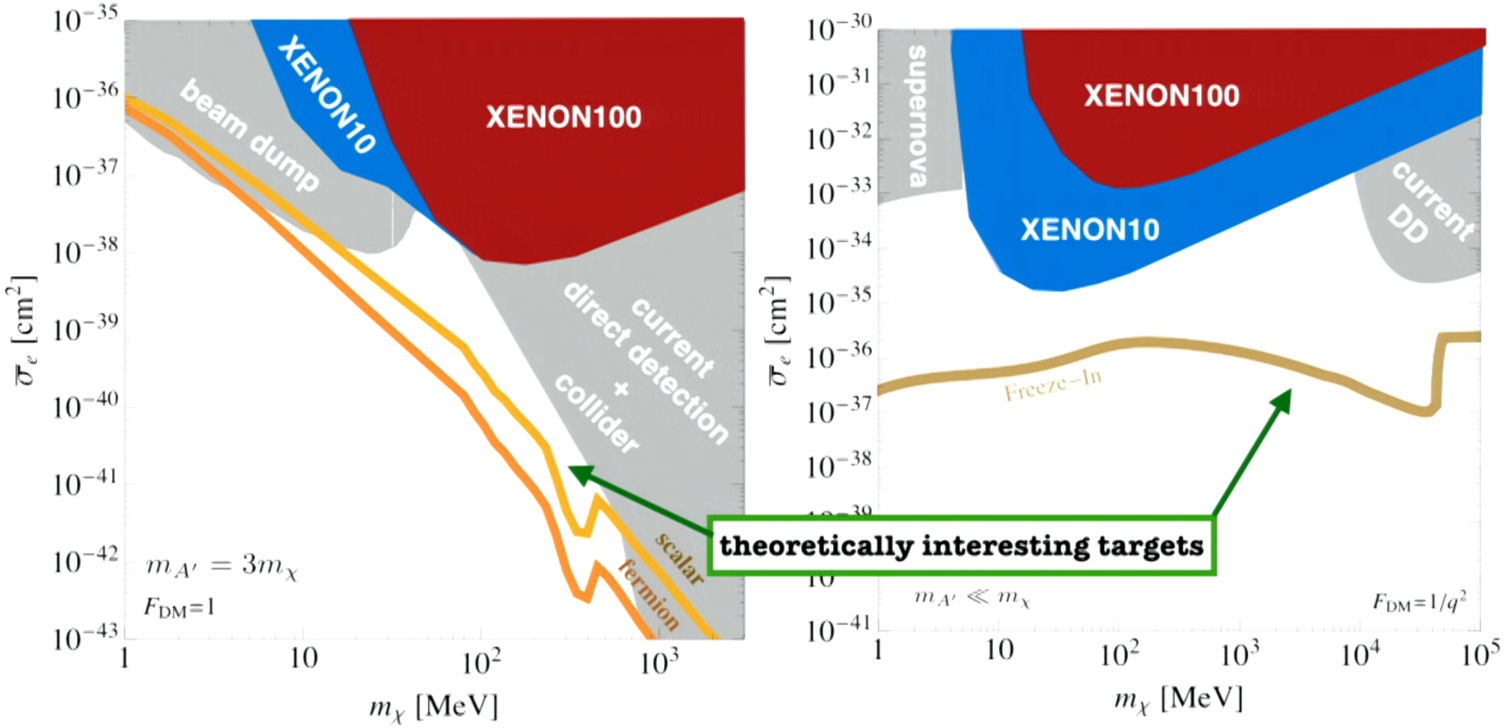
$$F_{DM}(q) = \frac{m_{A'}^2 + \alpha^2 m_e^2}{m_{A'}^2 + q^2} \simeq \begin{cases} 1\,, & m_{A'} \gg \alpha m_e \\ \frac{\alpha^2 m_e^2}{q^2}\,, & m_{A'} \ll \alpha m_e \end{cases}$$

dark photon



Essig, Volansky, TTY [1703.00910]

dark photon



Essig, Volansky, TTY [1703.00910]

electron energy

- noble gases: $\Delta E_e \sim 10 \text{ eV}$
- semiconductors: $\Delta E_e \sim 1 \text{ eV}$

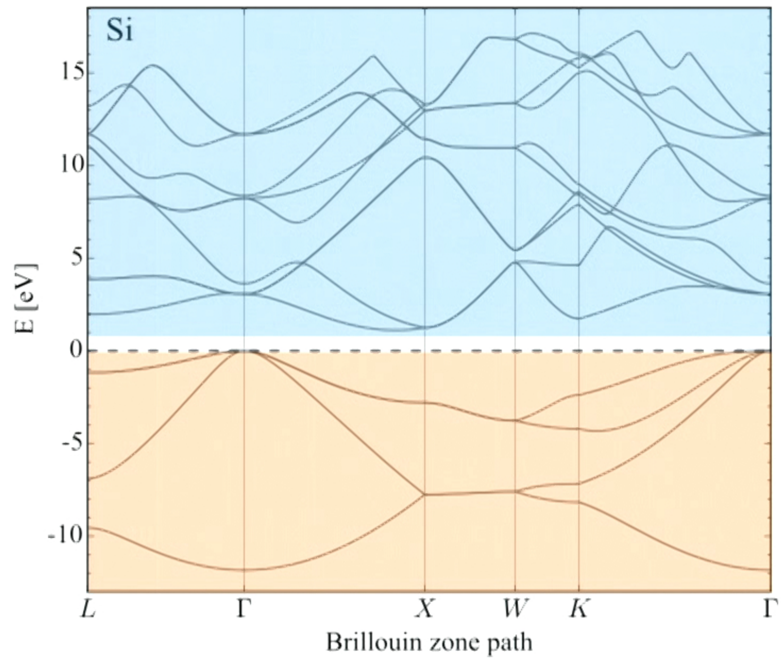
sets the limit in lower mass reach

number density

- xenon: 1.4 x 10^{22} atoms/cm^3
- silicon: 5.0 x 10^{22} atoms/cm^3

sets the limit in lower cross-section reach

Semiconductor targets



empty conduction band

band gap

filled valence band

Essig, Fernandez-Serra, Mardon, Soto, TTY [1509.01598] JHEP 1605 (2016) 046

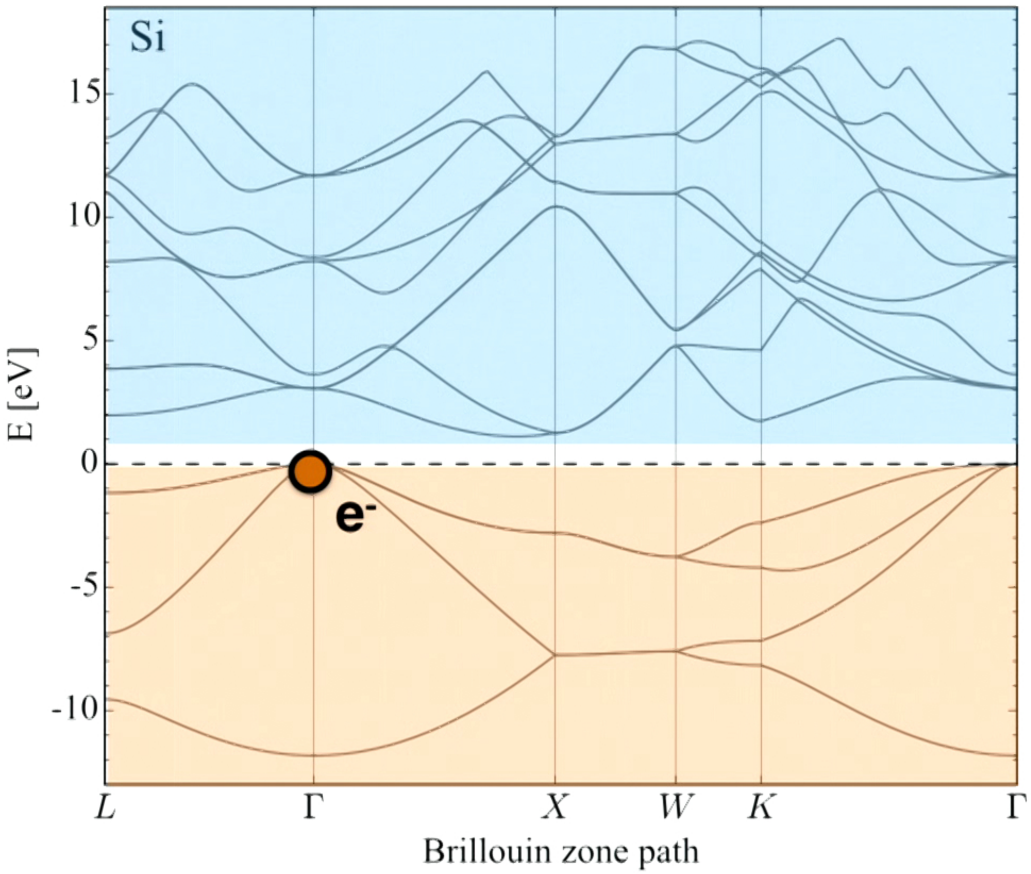
see also:

Essig, Mardon, Volansky [1108.5383] Phys.Rev. D85 (2012) 076007

Graham, Kaplan, Rajendran, Walters [1203.2531] Phys.Dark Univ. 1 (2012) 32-49

Lee, Lisanti, Mishra-Sharma, Safdi [1508.07361] Phys.Rev. D92 (2015) 083517

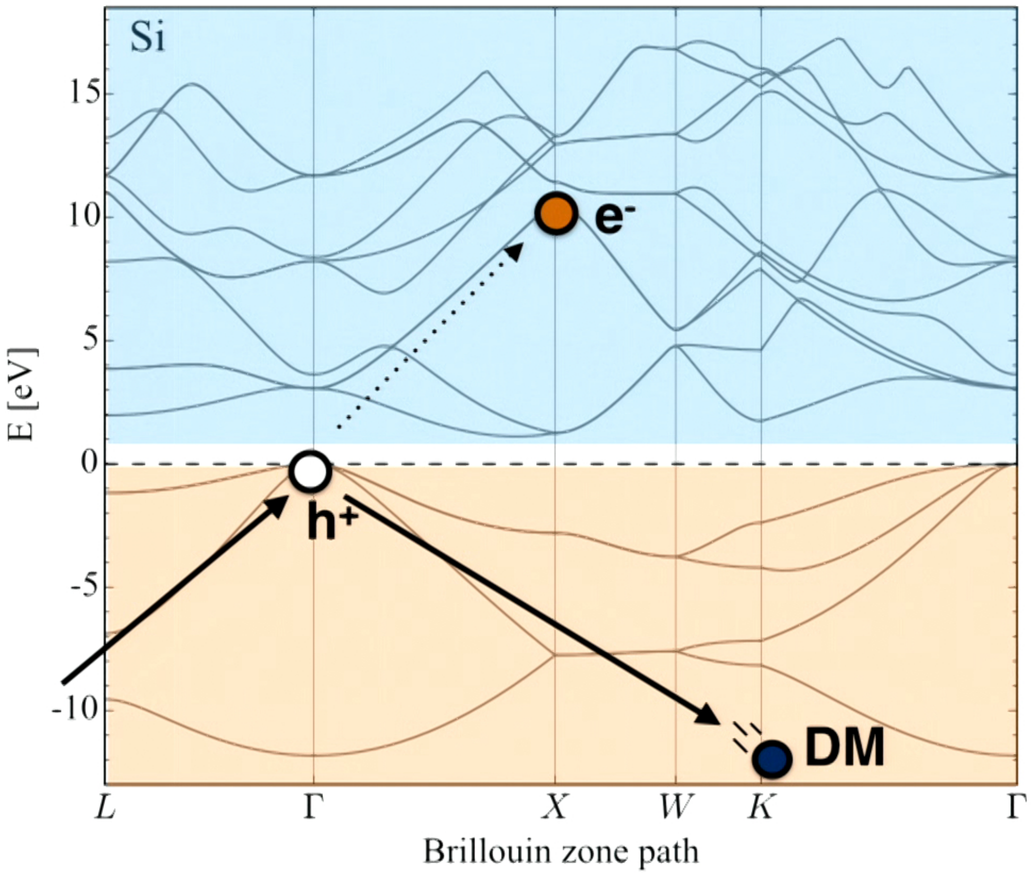
Semiconductor targets



band gap [eV]

Ge	0.67
Si	1.1
GaAs	1.5
NaI	5.9
CsI	6.4

Semiconductor targets



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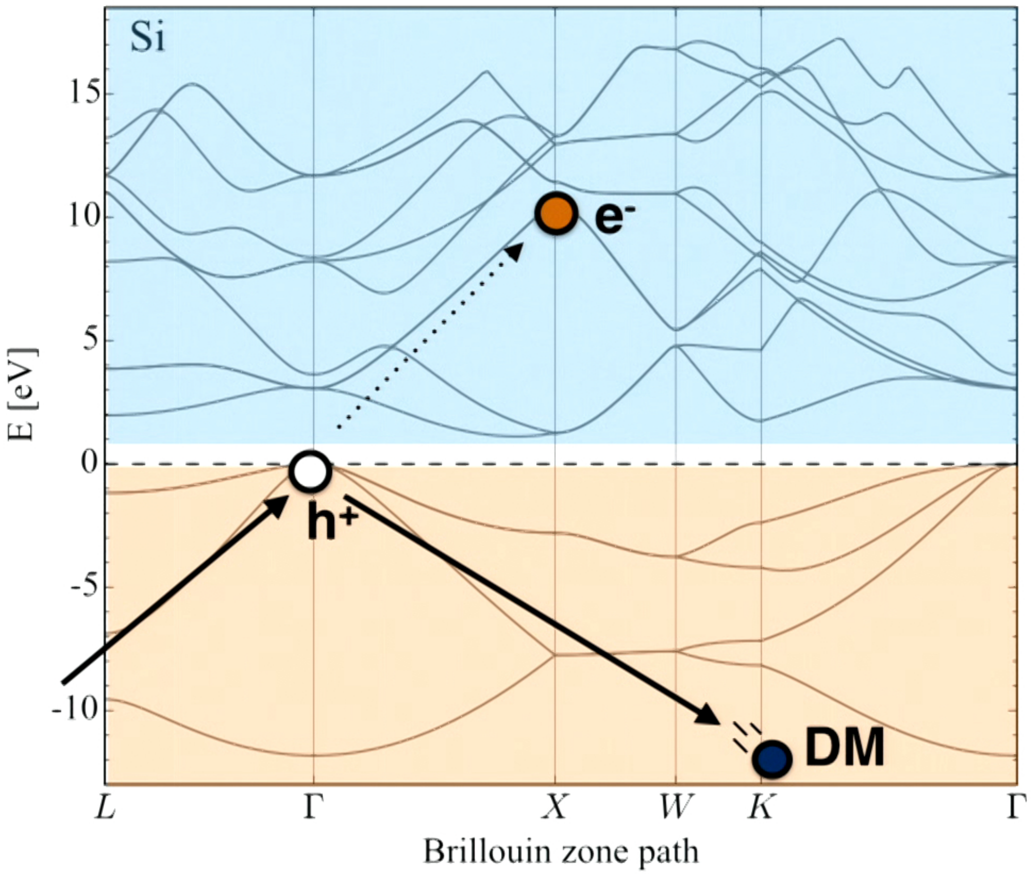
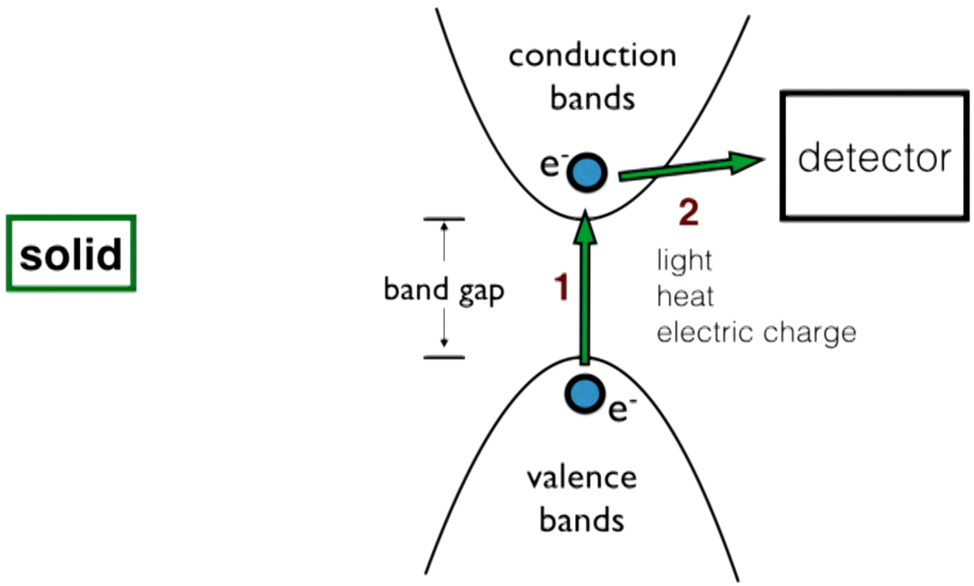
Semiconductor targets



apply an electric field and extract the electron(s) "ionization"

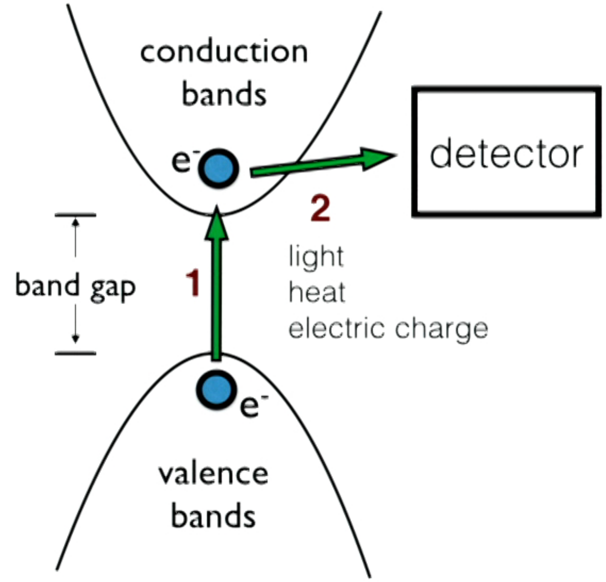
e^-/h^+ recombine to produce photon(s) "scintillation"



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

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

solid



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

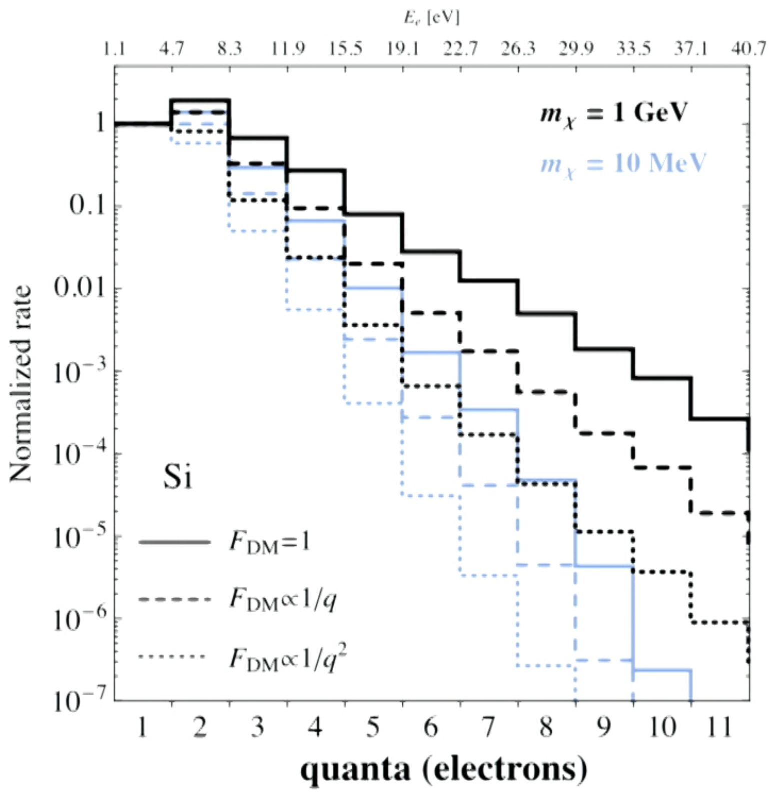
QUANTUM ESPRESSO

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

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

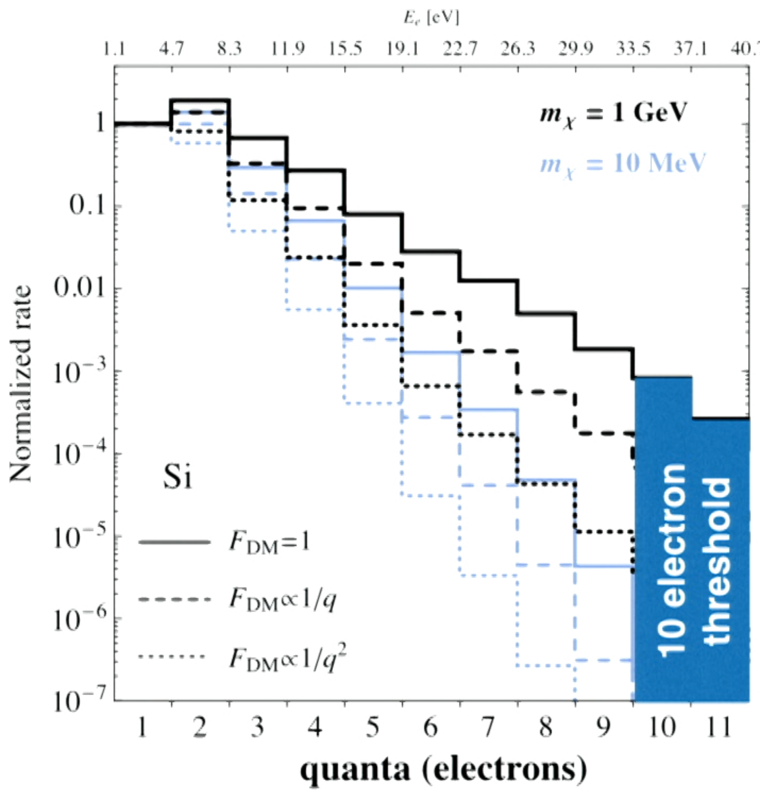
http://ddldm.physics.sunysb.edu/

silicon



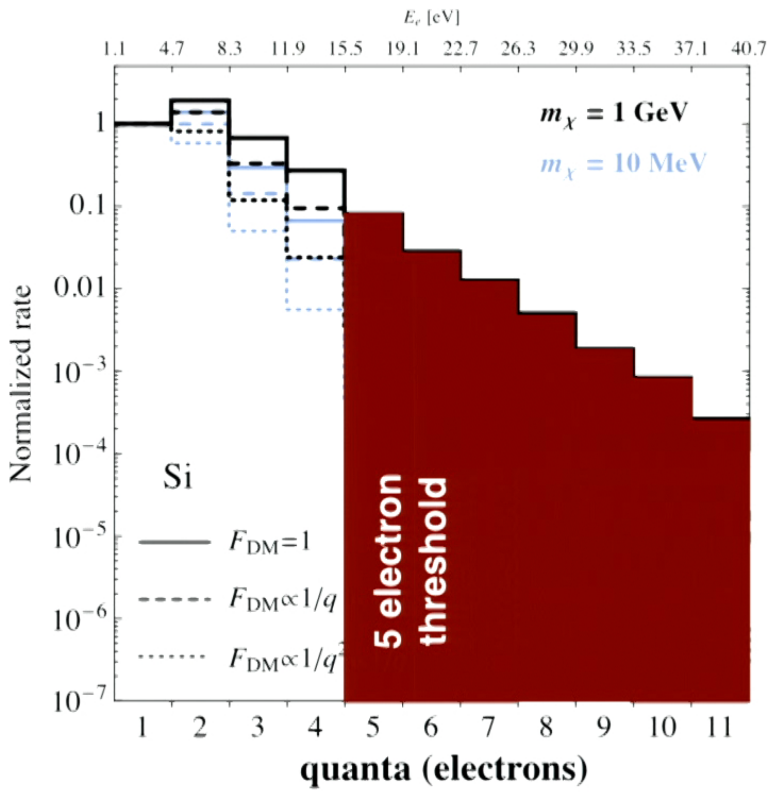
Essig, Fernandez-Serra, Mardon, Soto, TTY [1509.01598]

silicon



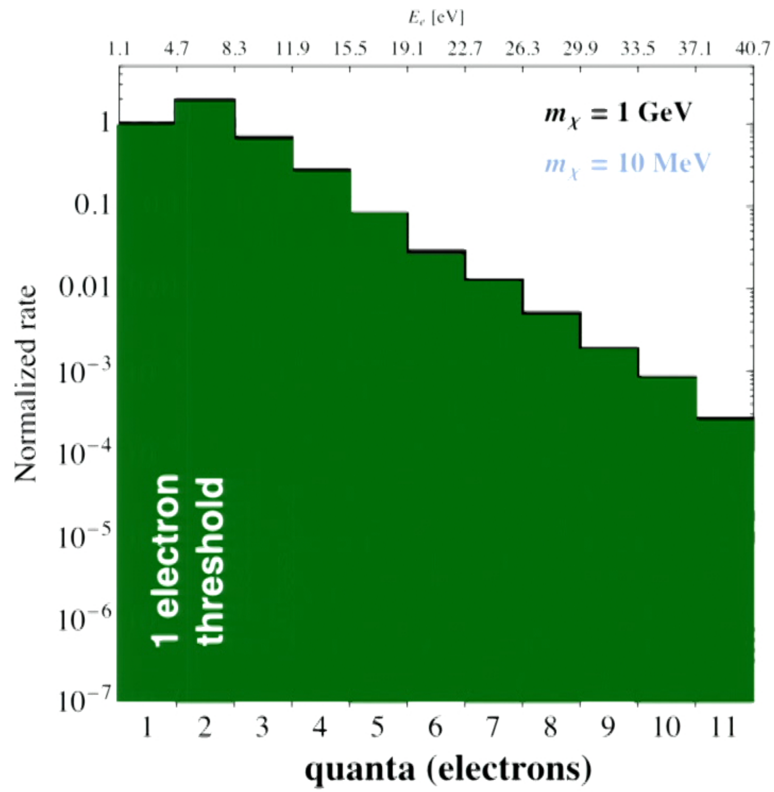
Essig, Fernandez-Serra, Mardon, Soto, TTY [1509.01598]

silicon



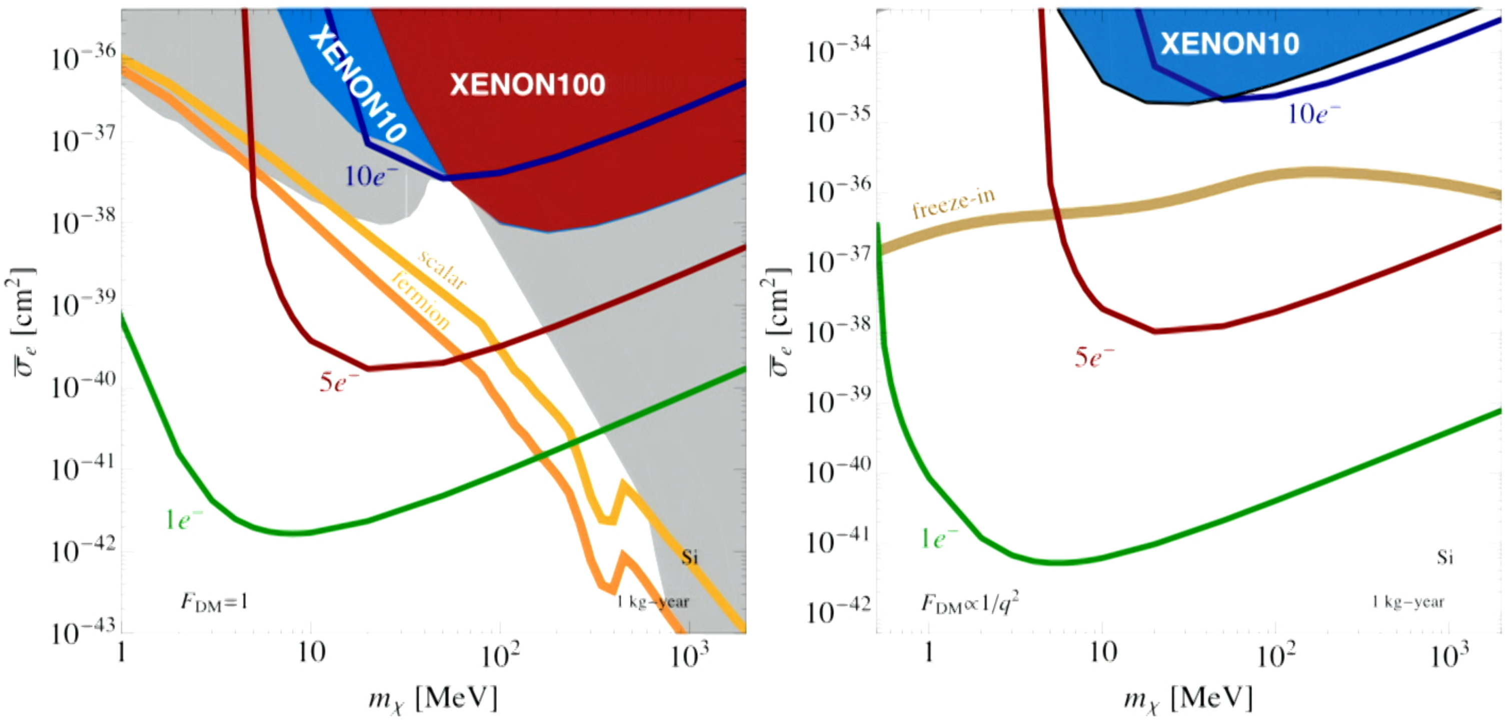
Essig, Fernandez-Serra, Mardon, Soto, TTY [1509.01598]

silicon



Essig, Fernandez-Serra, Mardon, Soto, TTY [1509.01598]

silicon



Essig, Fernandez-Serra, Mardon, Soto, TTY [1509.01598]

SENSEI

Sub-**E**lectron-**N**oise **S**kipper CCD **E**xperimental **I**nstrument

CERN: Tien-Tien Yu

Fermilab: Javier Tiffenberg, Yann Guardincerri, Miguel Sofo Haro

LBNL: Steve Holland, Christopher Bebek

Stanford University*: Jeremy Mardon

Stony Brook: Rouven Essig

Tel Aviv University: Tomer Volansky

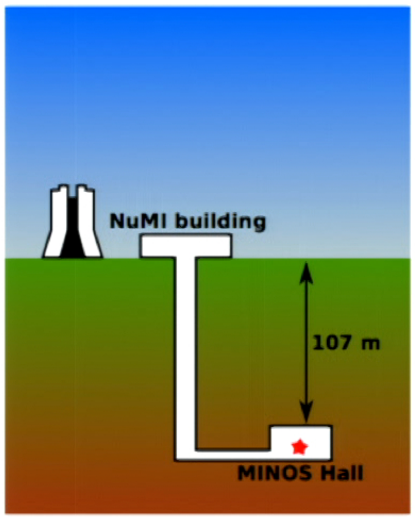
Experimentalists
Theorists

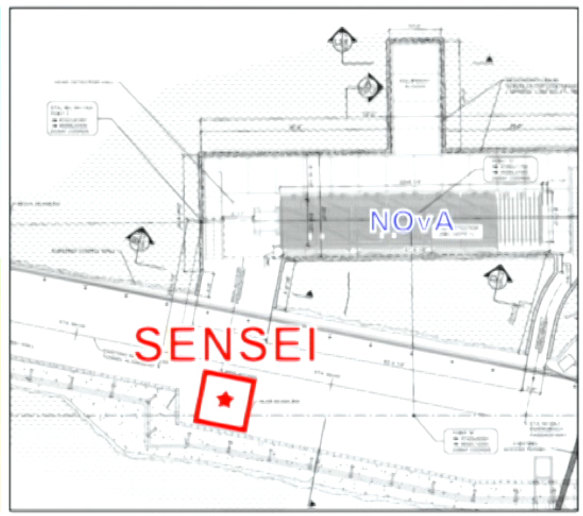
SENSEI

Sub-**E**lectron-**N**oise **S**kipper CCD **E**xperimental **I**nstrument

Whats next: Installation @MINOS & low radiation package

Technology demonstration: installation at shallow underground site





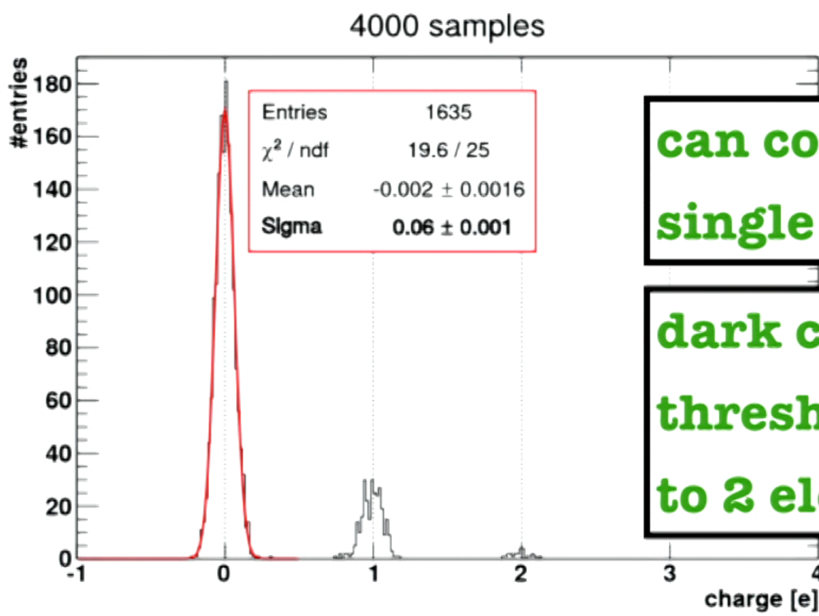
J. Tiffenberg

Fermilab

SENSEI

Sub-**E**lectron-**N**oise **S**kipper CCD **E**xperimental **I**nstrument

Charge in pixel distribution. Counting electrons: 0, 1, 2..



can count single electrons!

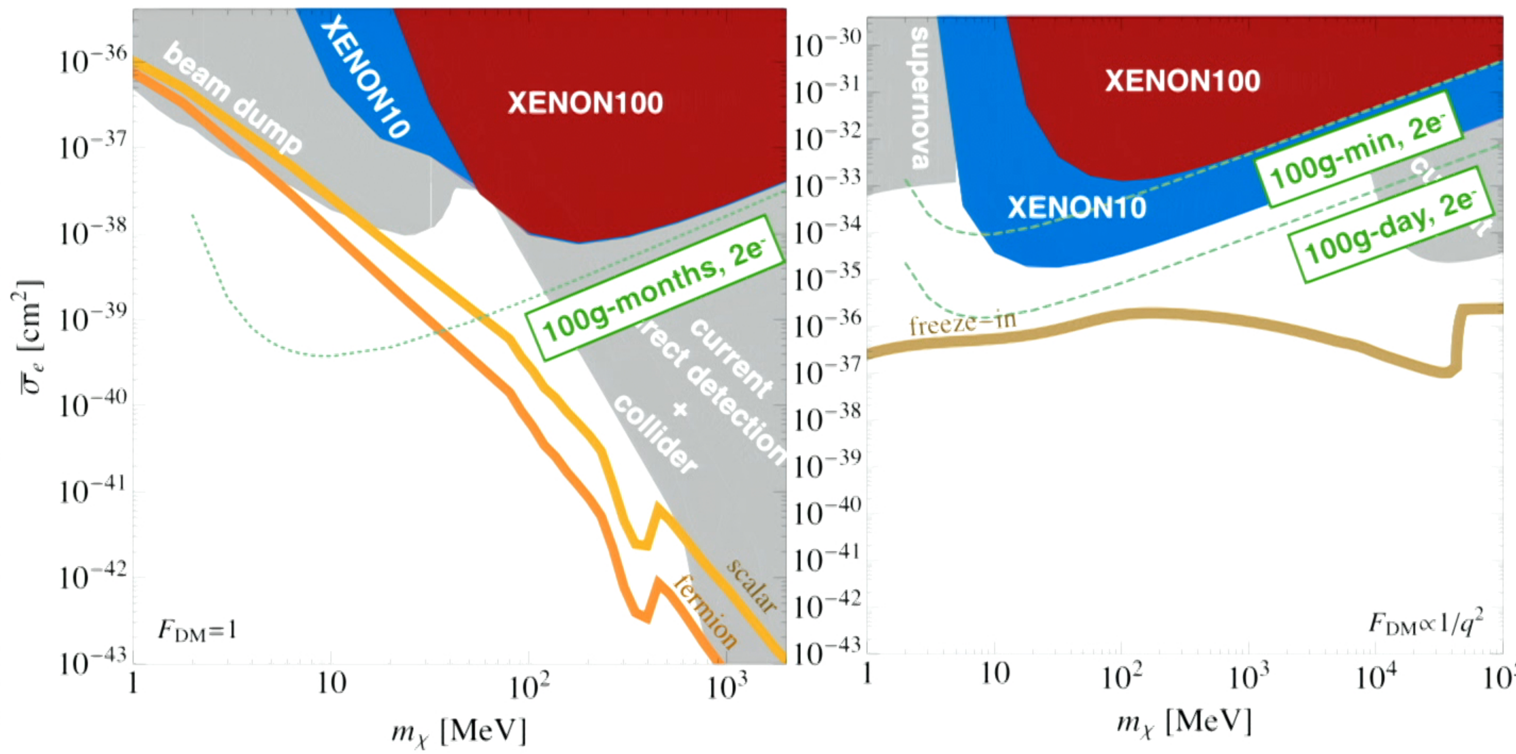
dark current limits threshold to 2 electrons

J. Tiffenberg

Fermilab

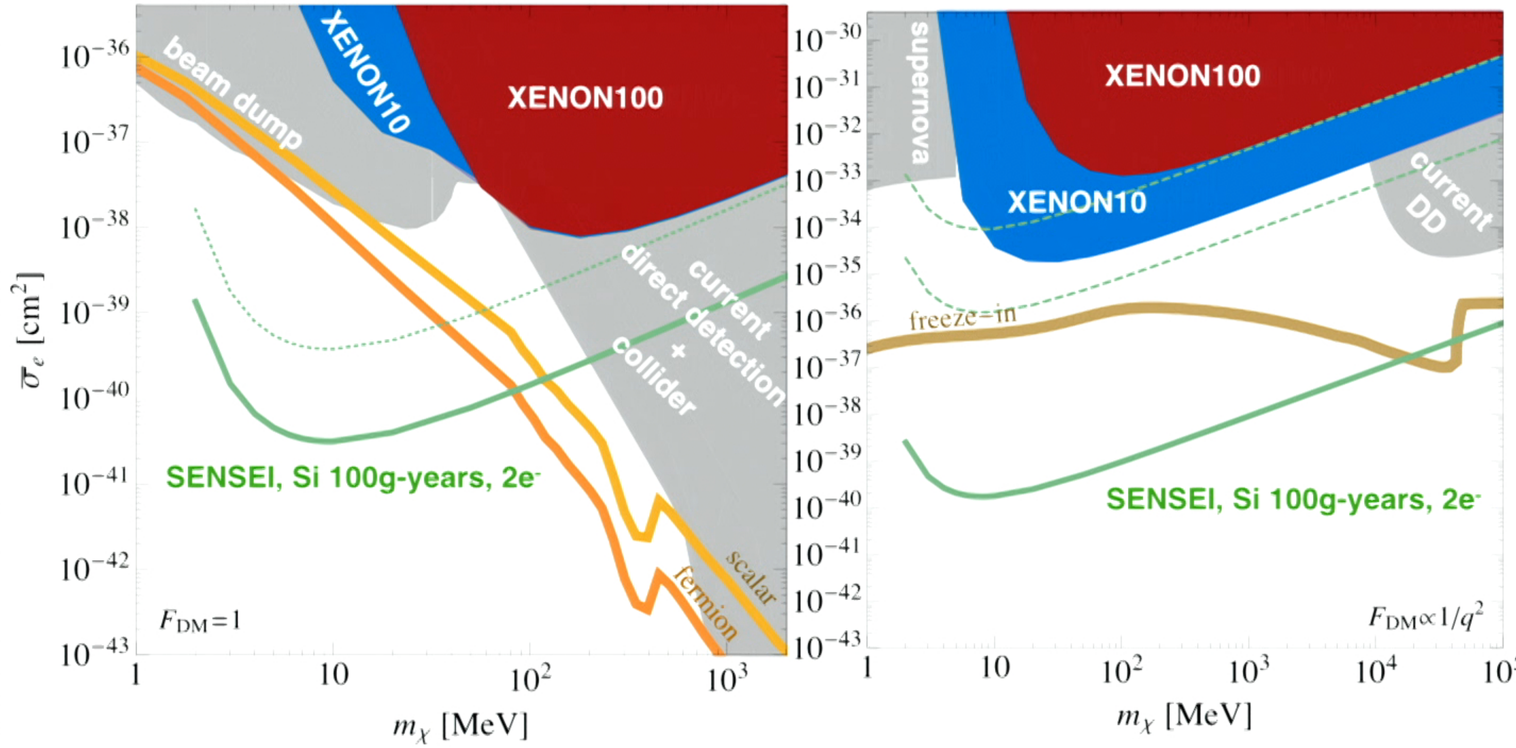
19 SENSEI collaboration meeting March 10, 2017

SENSEI



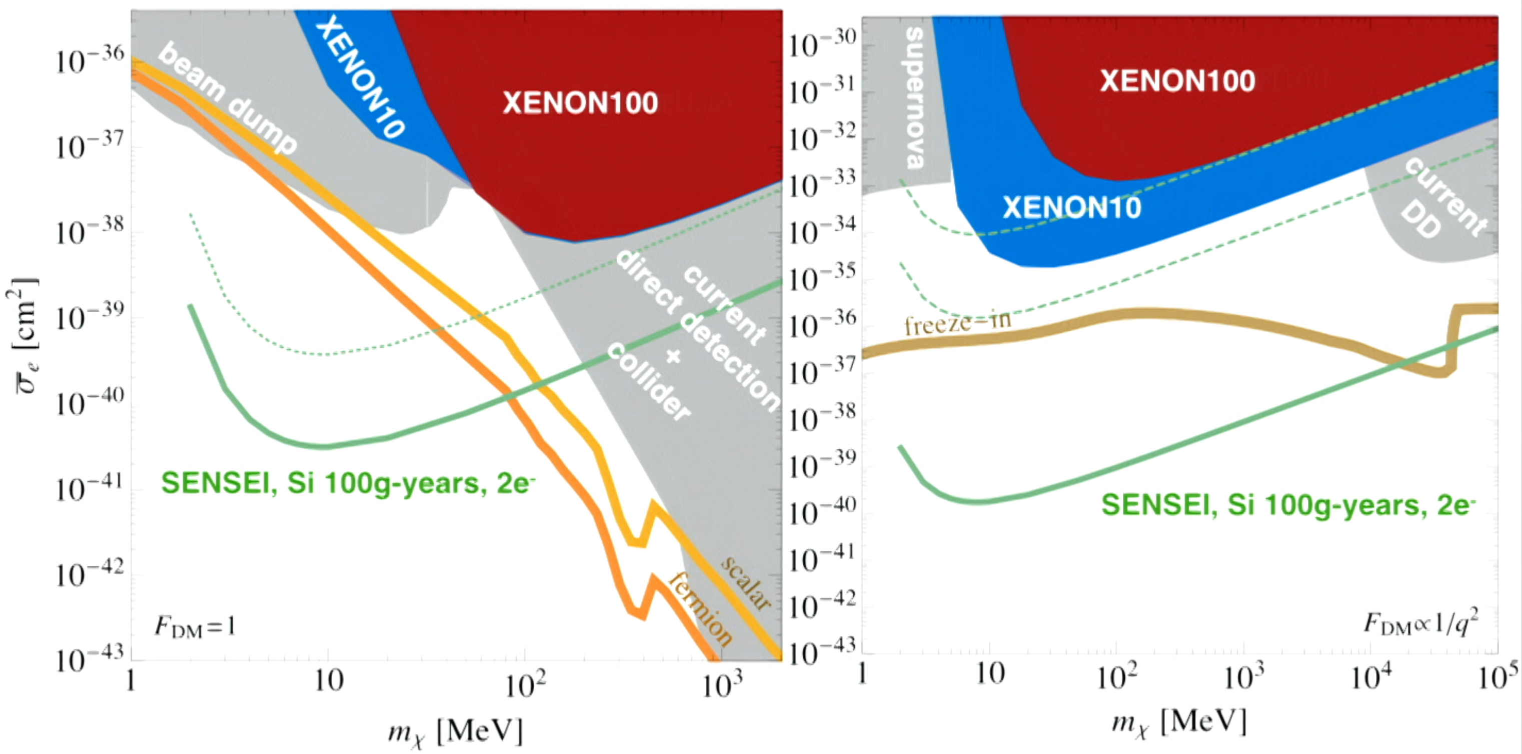
beam dump
XENON10
XENON100
100g-months, 2e-
current direct detection + collider
scalar
fermion
$F_{DM}=1$
$\overline{\sigma}_e$ [cm^2]
m_χ [MeV]
supernova
XENON100
XENON10
100g-min, 2e-
100g-day, 2e-
freeze-in
$F_{DM} \propto 1/q^2$
m_χ [MeV]

SENSEI



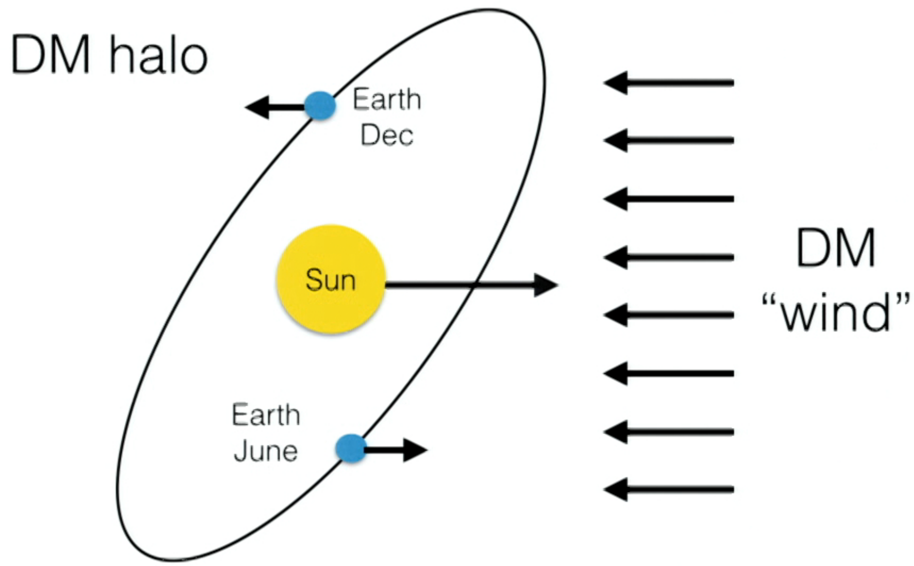
beam dump
XENON10
XENON100
current direct detection + collider
SENSEI, Si 100g-years, 2e-
scalar
fermion
$F_{DM}=1$
$\overline{\sigma}_e$ [cm^2]
m_χ [MeV]
supernova
XENON100
XENON10
current DD
freeze-in
SENSEI, Si 100g-years, 2e-
$F_{DM} \propto 1/q^2$
m_χ [MeV]

SENSEI

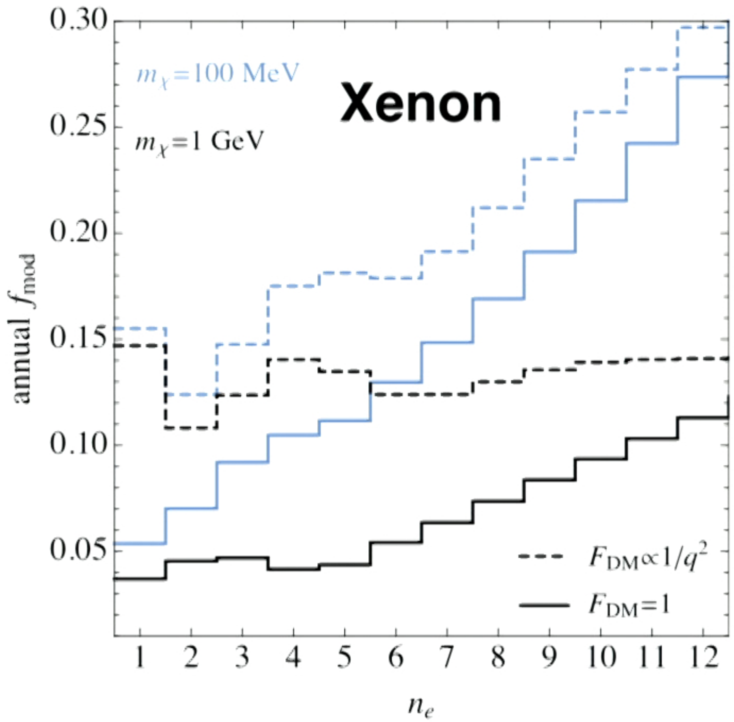


beam dump
XENON10
XENON100
current direct detection + collider
SENSEI, Si 100g-years, 2e-
scalar
fermion
$F_{DM}=1$
σ_e [cm^2]
m_χ [MeV]
supernova
XENON100
XENON10
current DD
freeze-in
SENSEI, Si 100g-years, 2e-
$F_{DM} \propto 1/q^2$
m_χ [MeV]

annual modulation



annual modulation



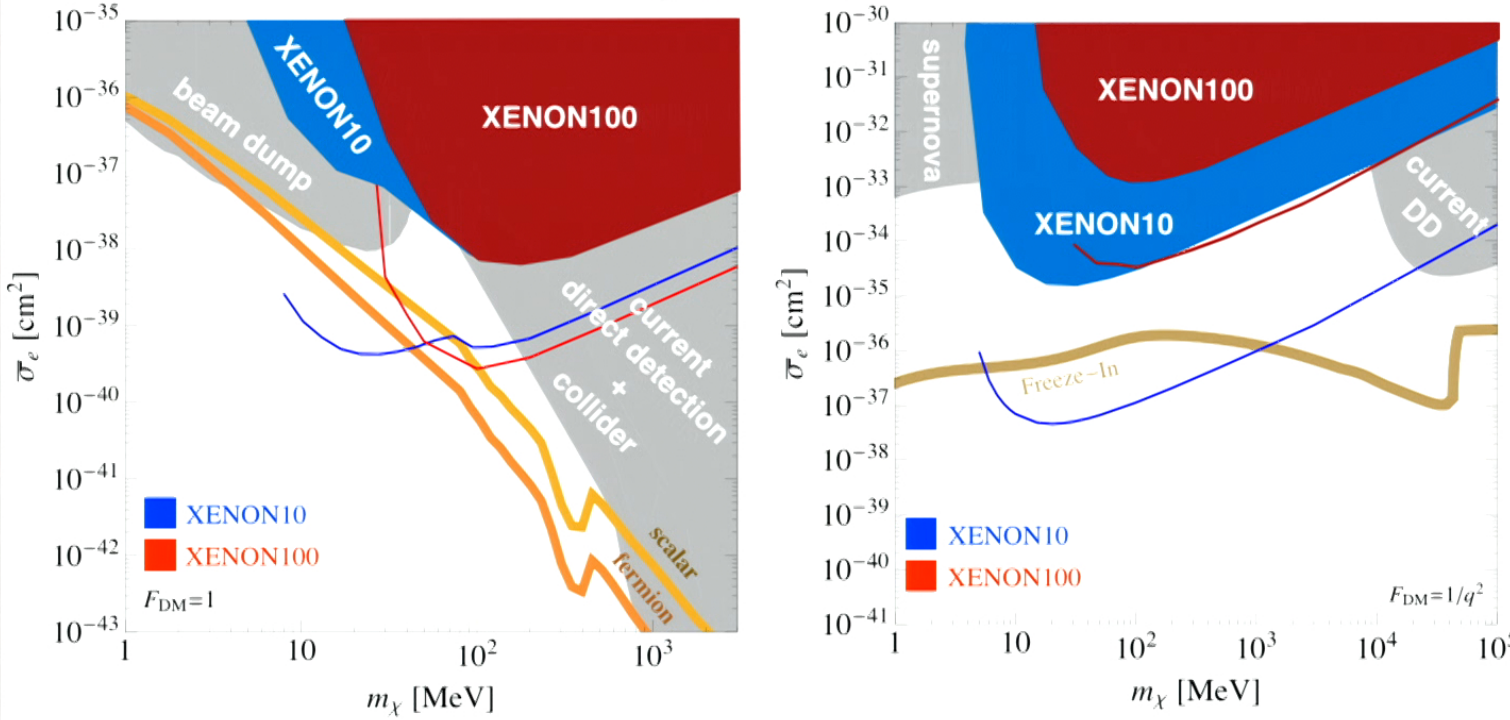
$$f_{mod} = \frac{R_{max} - R_{min}}{2R_{mean}}$$

$$sig = \frac{f_{mod} S}{\sqrt{S+B}}$$

***sig*=1.645=90%CL**

annual modulation

1000 kg-years, 90%CL



Essig, Volansky, TTY [1703.00910]

ingredients

solid state physics

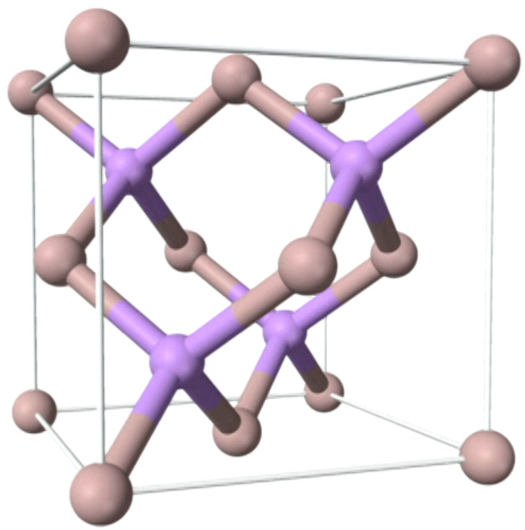
$$\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2}\int q\ \mathrm{d}q\,|f(k,q)|^2|F_{DM}(q)|^2\eta(v_{min})$$

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

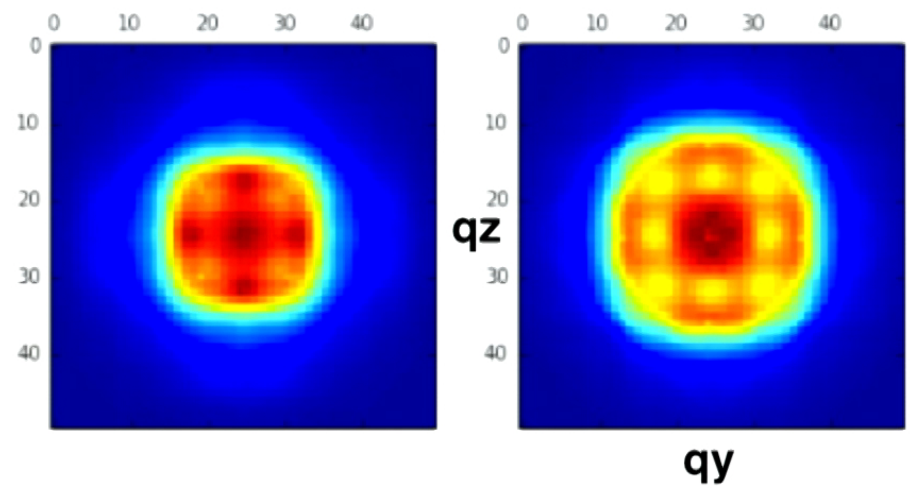
contains directional dependence
***potentially powerful signal discrimination!**

directionality

Gallium Arsenide (GaAs)



https://en.wikipedia.org/wiki/File:Gallium-arsenide-unit-cell-3D-balls.png

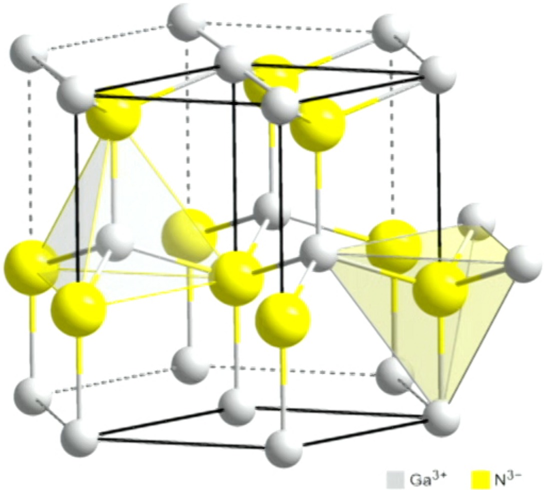


Essig, Mardon, Soto, Volansky, TTY (in preparation)

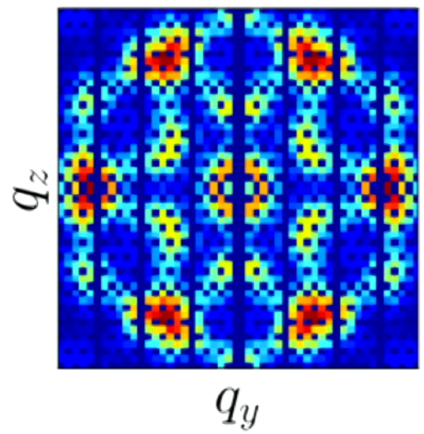
preliminary

directionality

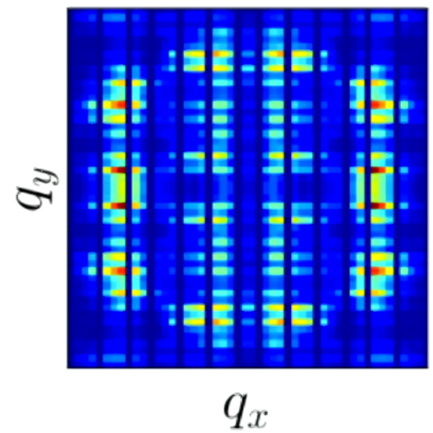
Gallium Nitride (GaN)



https://en.wikipedia.org/wiki/File:Wurtzite_polyhedra.png



y vs z

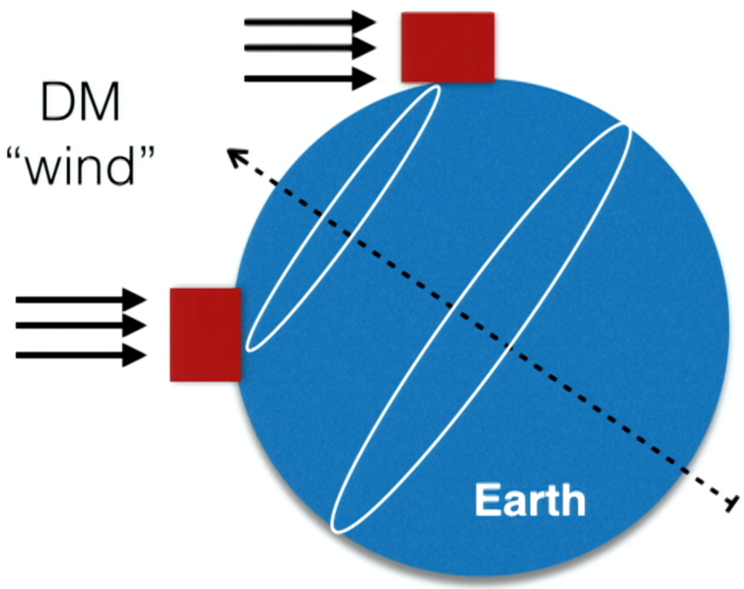


x vs y

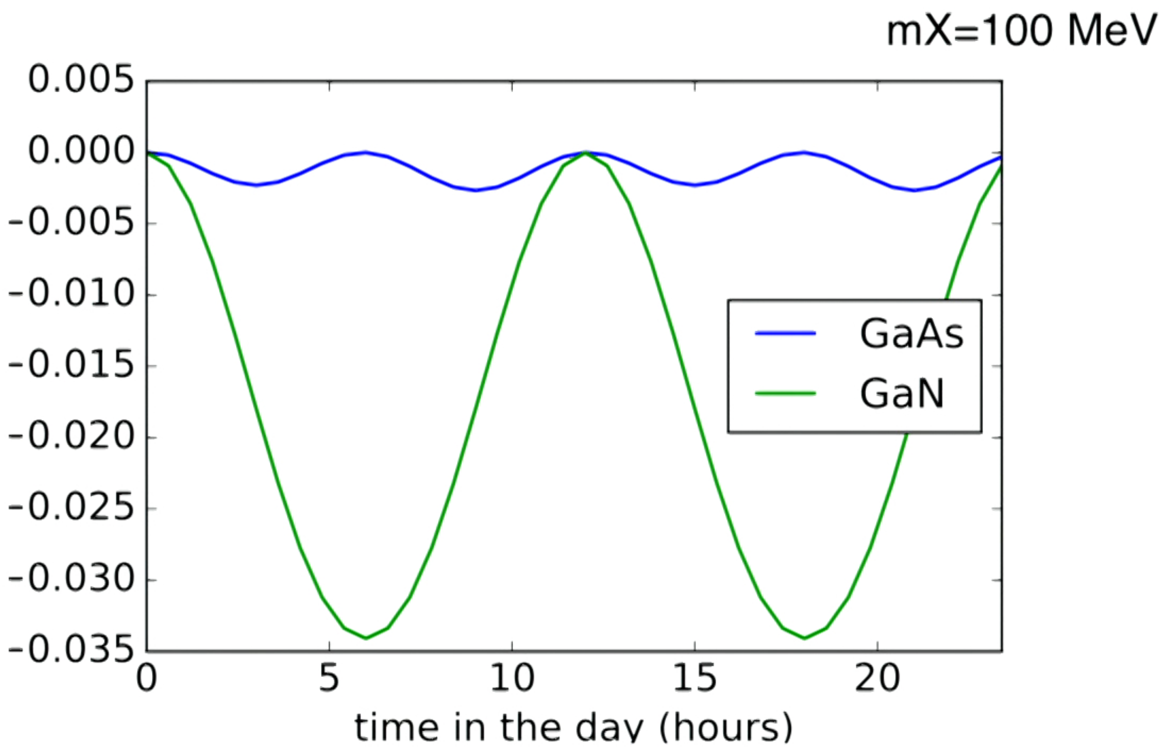
Essig, Mardon, Soto, Volansky, TTY (in preparation)

preliminary

directionality



directionality



Essig, Mardon, Soto, Volansky, TTY (in preparation)

preliminary

conclusions

- DM-electron scattering allows us to reach sub-GeV DM masses
- current constraints come from XENON10/XENON100 S2-only analyses
- near-future semiconductor targets like SENSEI will reach unprecedented sensitivity
- sensitivity to velocity tail means large modulation in rate
- rigid structure of crystal may allow for directional detection