Stockholm University

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Developments in sub-GeV dark matter direct detection

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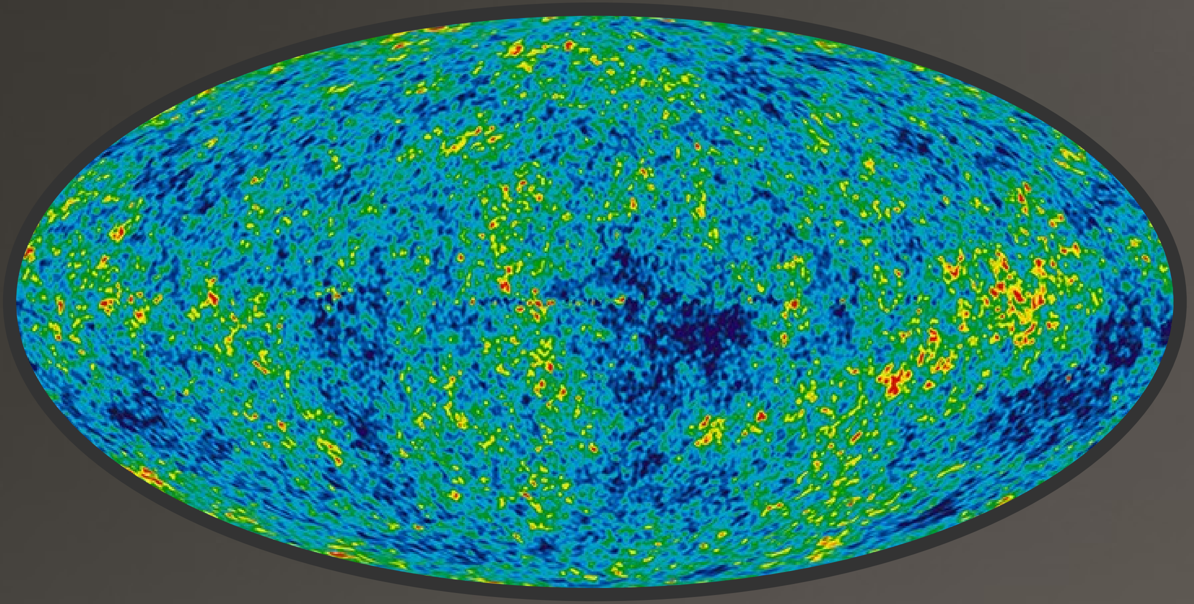
Outline

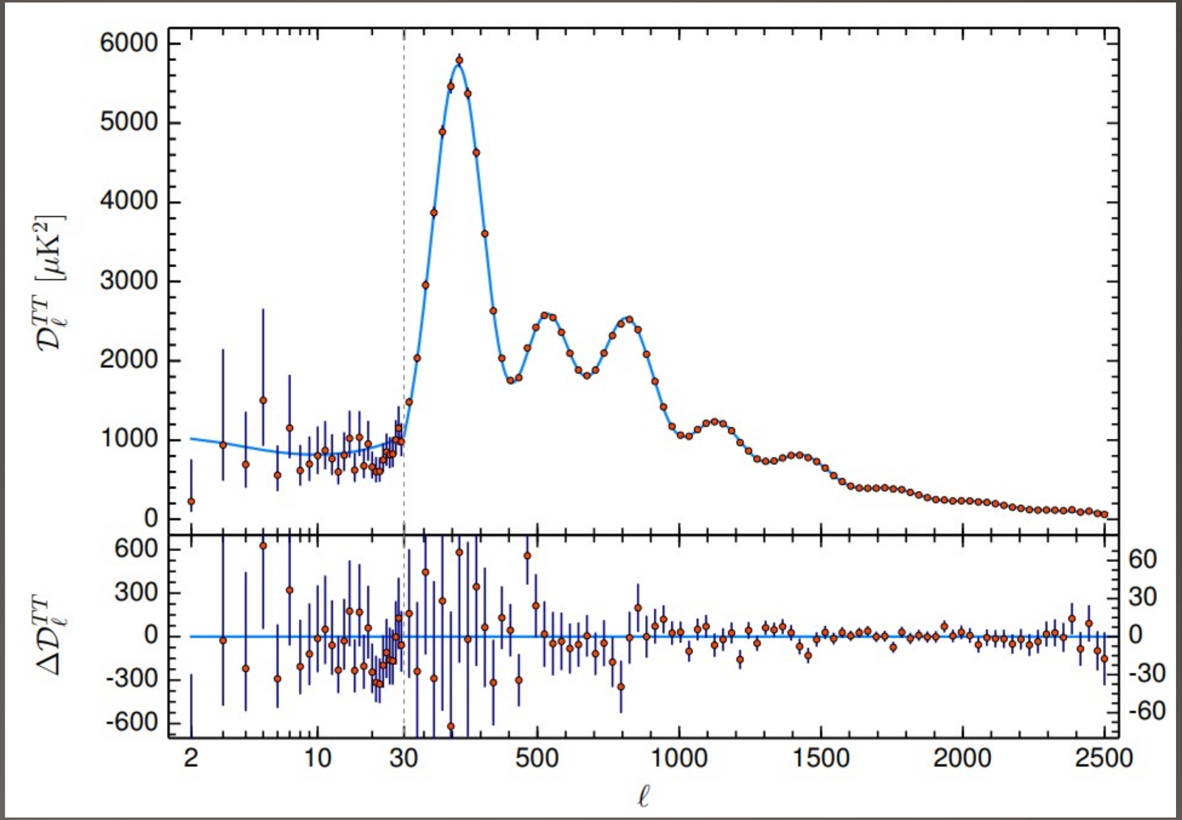
- Brief motivation for particle dark matter (DM)
- DM parameter space
- WIMPs – The miracle and tragedy
- Sub-GeV DM direct detection
    - Electron Recoil
    - Nuclear Recoil
- Directionality and modulating signals

Cosmological Evidence



ESA and the Planck Collaboration
CMB Anisotropies

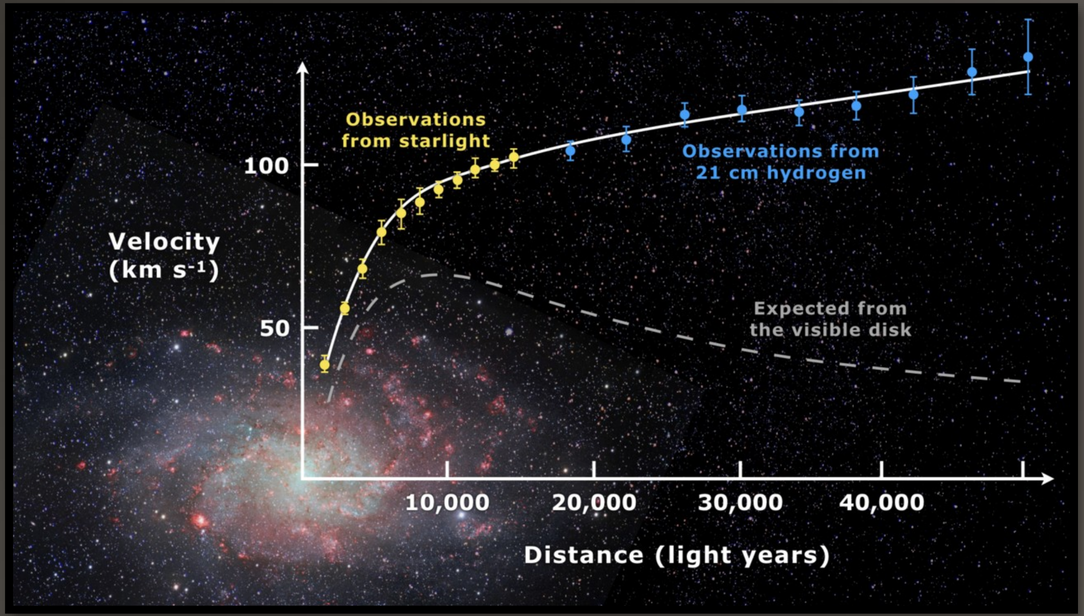
$$\Omega_c h^2 = 0.1198 \pm 0.0012$$



Planck results: 2020, A&A, 641, A6
2020, A&A, 641, A5

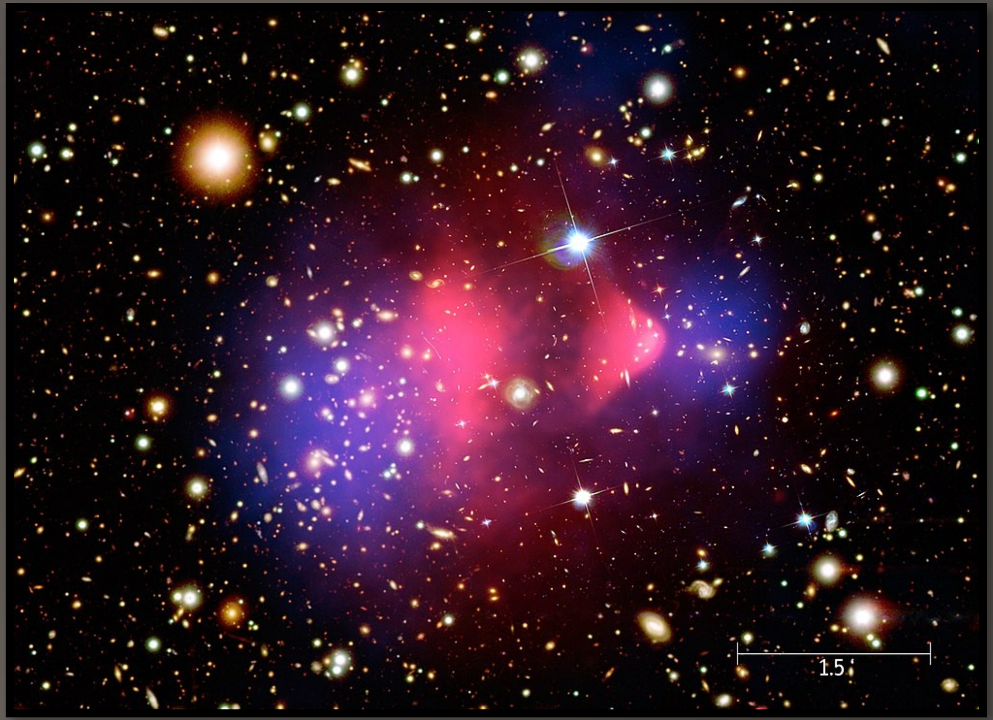
Astrophysical Evidence

Galactic rotation curves



Solid: Observed
Dashed: Expected from visible disk

Bullet cluster

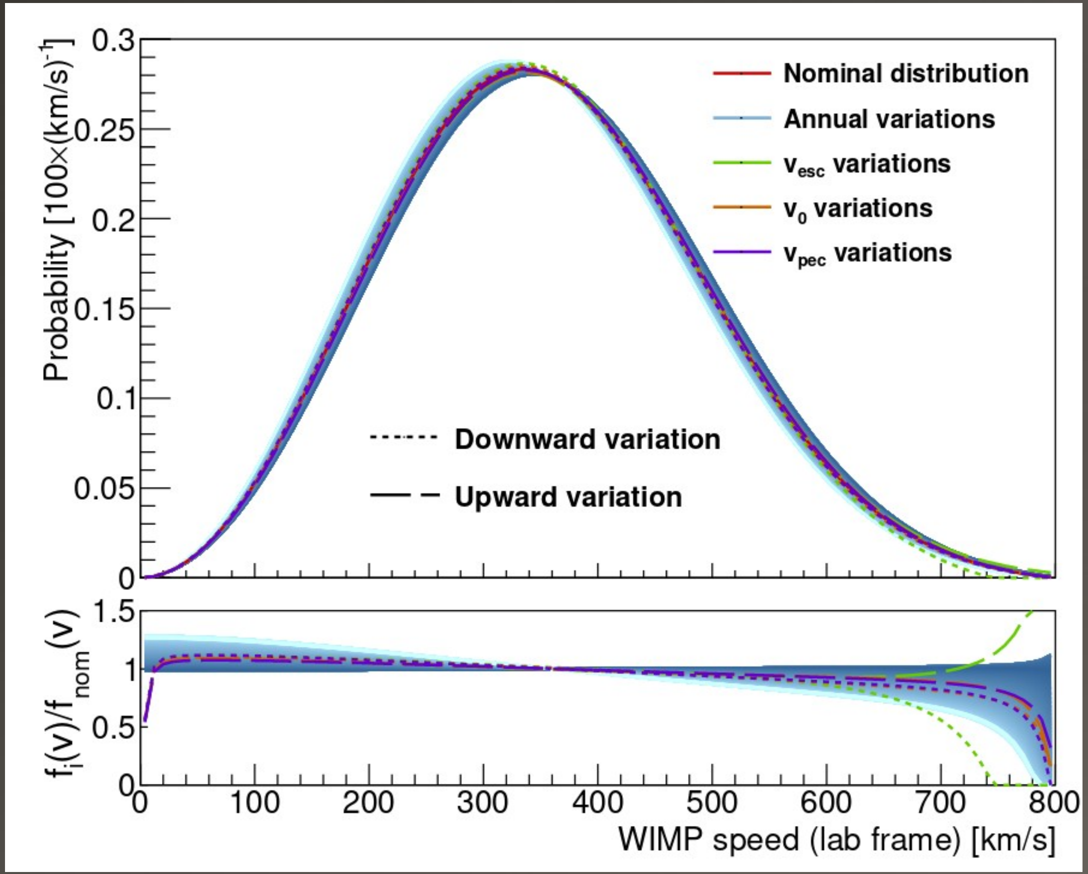


Blue: Mass from grav lensing
Pink: Baryonic mass from x-rays

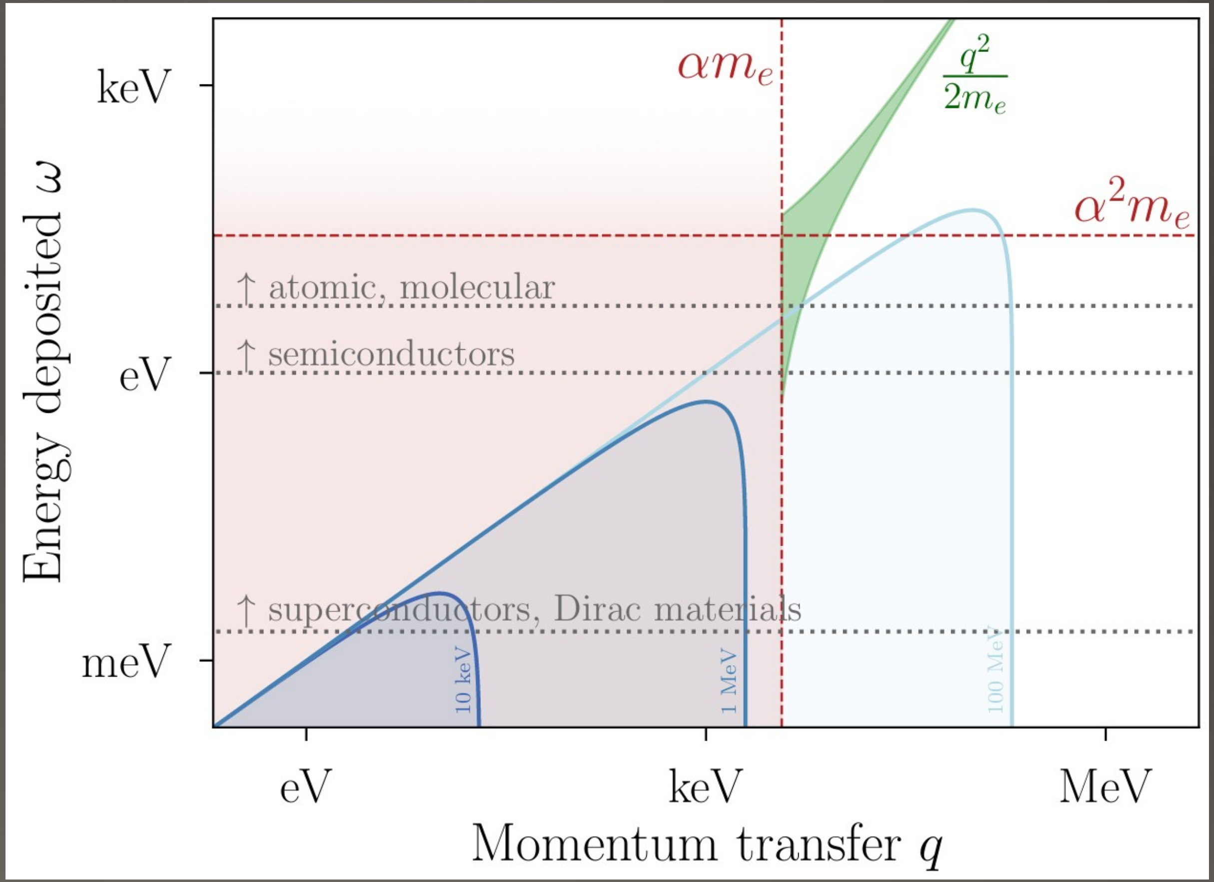
Corbelli & Salucci, MNRAS 1999
Bosma, Astronomical Journal, 1989

X-ray: NASA/CXC/CfA/M.Markevitch et al.;
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

Local DM Phase Space

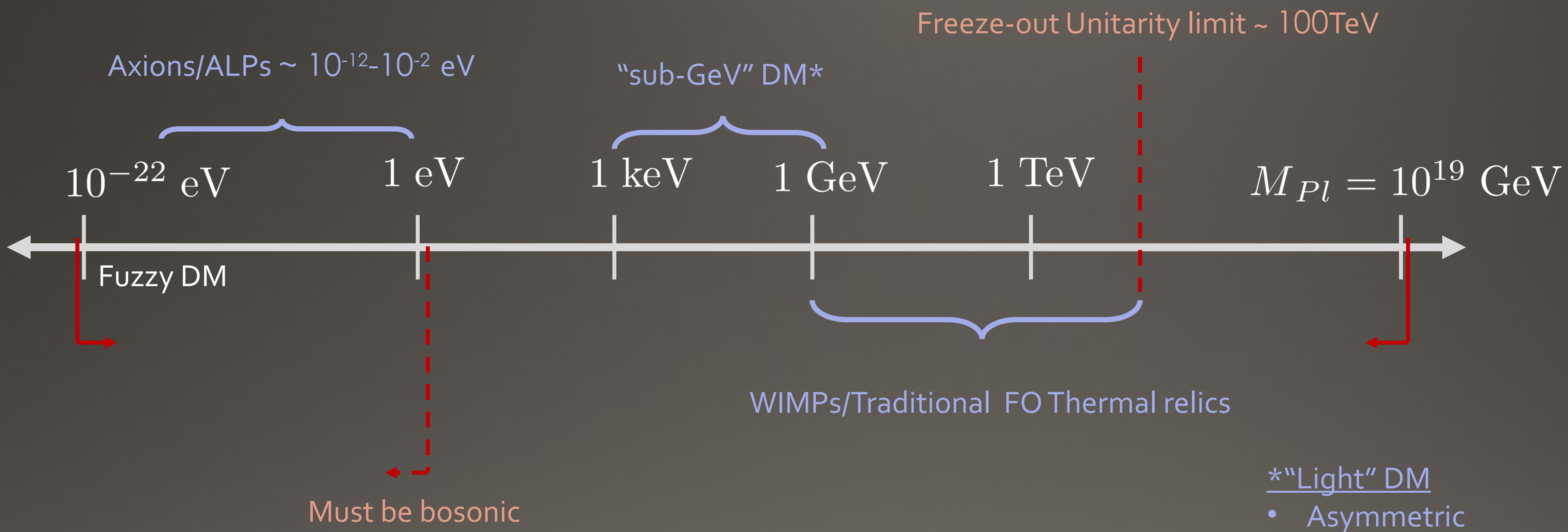


Baxter, D., et al. "*Recommended conventions for reporting results from direct dark matter searches*." The European Physical Journal C 81.10 (2021): 1-19.



Lin, Tongyan. "*Sub-GeV dark matter models and direct detection*." SciPost Physics Lecture Notes (2022): 043.

DM Mass Range



Freeze-out Unitarity limit ~ 100TeV

Axions/ALPs ~ 10^{-12}-10^{-2} eV

“sub-GeV” DM*

10^{-22} eV

1 eV

1 keV

1 GeV

1 TeV

$M_{Pl} = 10^{19}$ GeV

Fuzzy DM

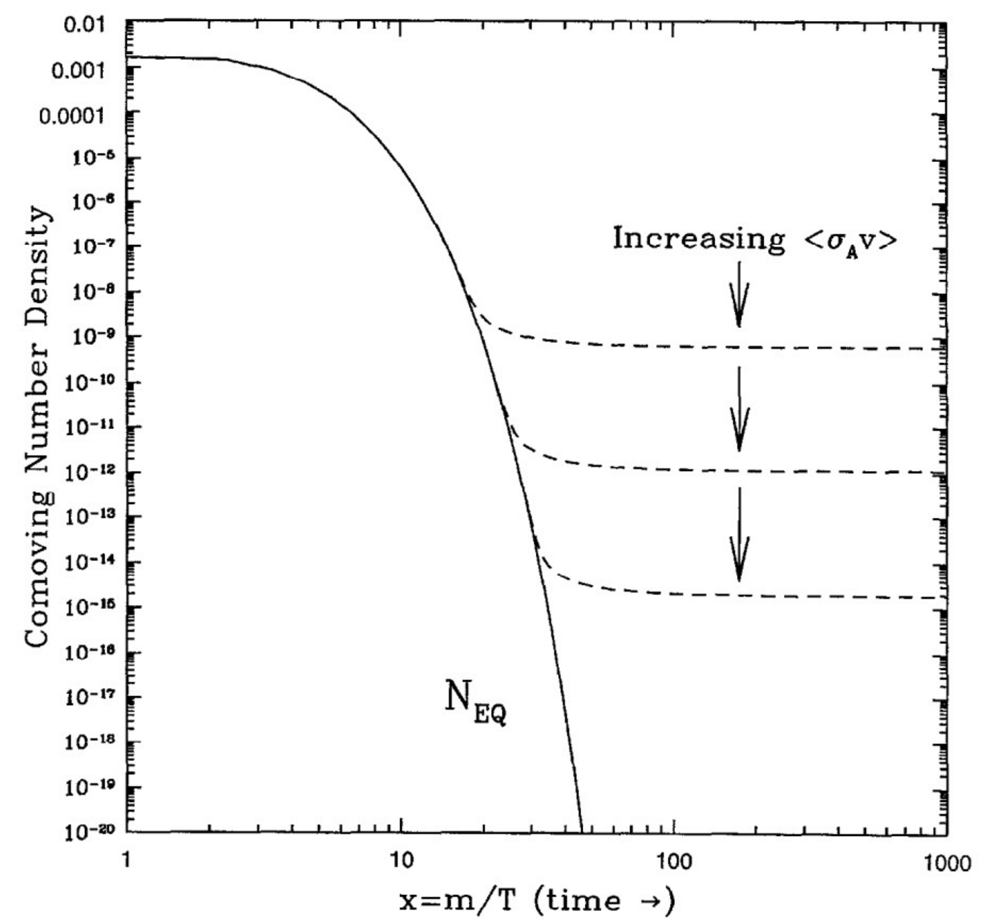
WIMPs/Traditional FO Thermal relics

Must be bosonic

(NOT TO SCALE)

*“Light” DM
- Asymmetric DM
- Hidden sector
- ELDER/SIMPs
- Freeze-In
- ...etc

WIMPs: The Miracle and Tragedy



Griest et. al: Phys Rep. 1996

$$\Omega_c h^2 \sim \frac{1}{\langle \sigma v \rangle}$$

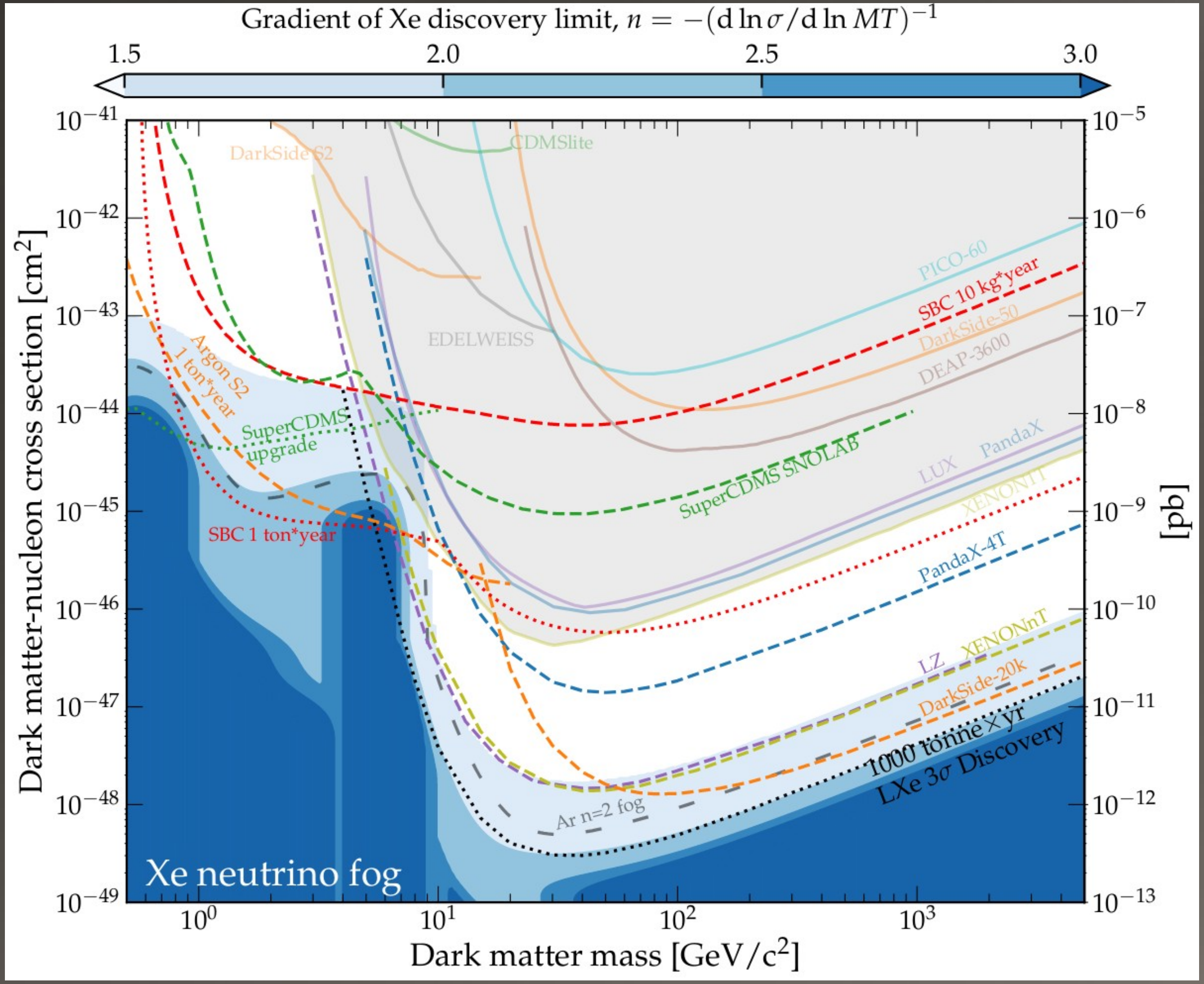
Predicts:

$$\langle \sigma v \rangle_{FO} \approx 3 \times 10^{-26}\ \mathrm{cm}^3 \mathrm{s}^{-1}$$

Subject to constraints from :

- CMB (recombination)
- Fermi-LAT (Dwarf spheroidal galaxy observations)
- BBN
- LEP, LHC, AMS,…etc

WIMPs: The Miracle and Tragedy

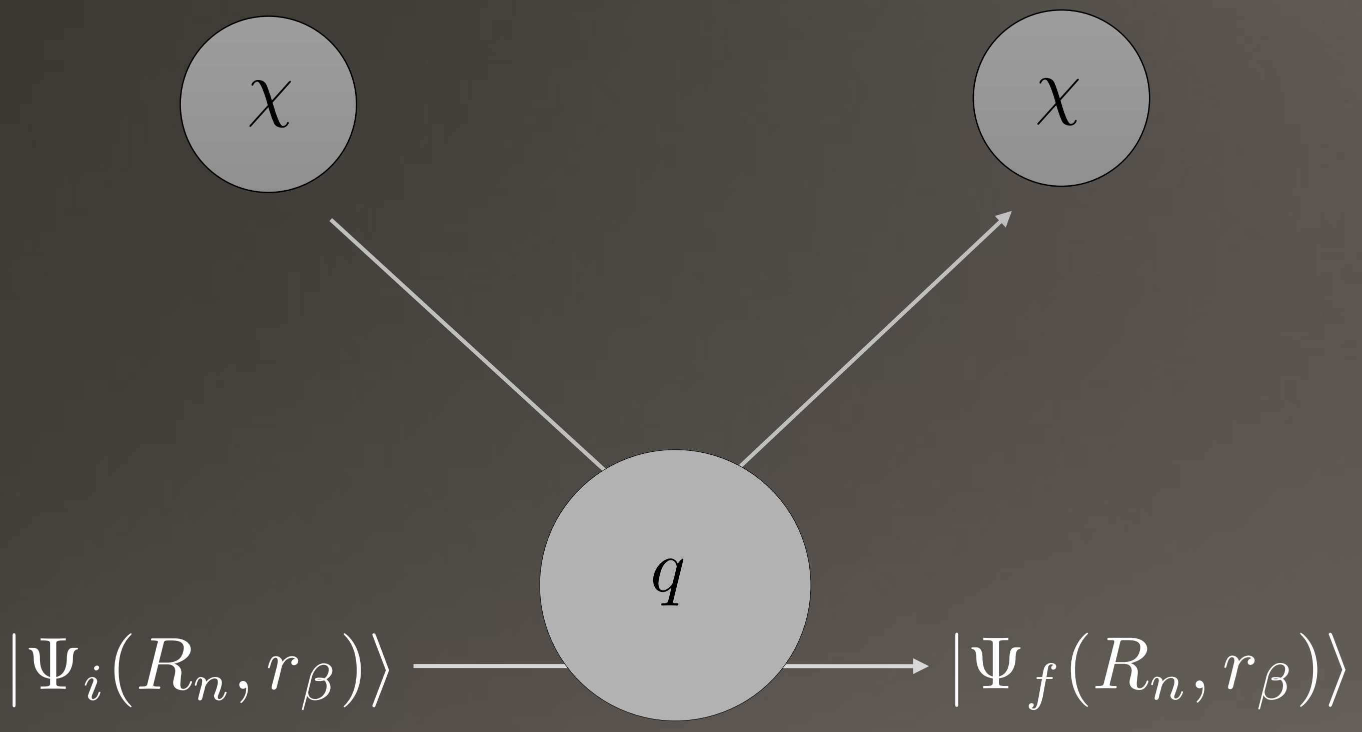


- Noble gasses: Very effective at probing masses above 1 GeV
- Will encounter irreducible neutrino fog in next generation
- Linear at high masses due to number density
- Loss of sensitivity due to threshold at low masses

Akerib, D. S., et al. "*Snowmass2021 Cosmic Frontier Dark Matter Direct Detection to the Neutrino Fog*." arXiv:2203.08084 (2022).

Sub-GeV Direct Detection

$$\langle v_\chi \rangle \approx 300\mathrm{km/s}$$



$$|\Psi_i(R_n, r_\beta)\rangle \longrightarrow |\Psi_f(R_n, r_\beta)\rangle$$

Kinematics

$$\Delta E = \vec{q} \cdot \vec{v}_\chi - \frac{q^2}{2\mu_{\chi,m}}$$

$$|q| \sim m_\chi v_\chi \approx \mathcal{O}(\mathrm{KeV}) \left(\frac{m_\chi}{1\,\mathrm{MeV}} \right)$$

R_i : Nuclear coordinates

r_β : Electron coordinates

Interaction Rate

$$\frac{d\mathrm{R}}{d\ln E_r} = \frac{N_T\rho_\chi\bar{\sigma}_e}{8\pi_\chi\mu^2_{\chi,m_T}}\int\frac{d^3\vec{q}}{q}\eta(v_{\min})|F_{\mathrm{DM}}(q)|^2|f_{i\to f}(q)|^2$$

Photon Rate

Mean inverse velocity

$$\eta(v_{\min}) = \int\frac{d^3\vec{v}}{v}g(v)\Theta(v-v_{\min})$$

Dark matter form factor

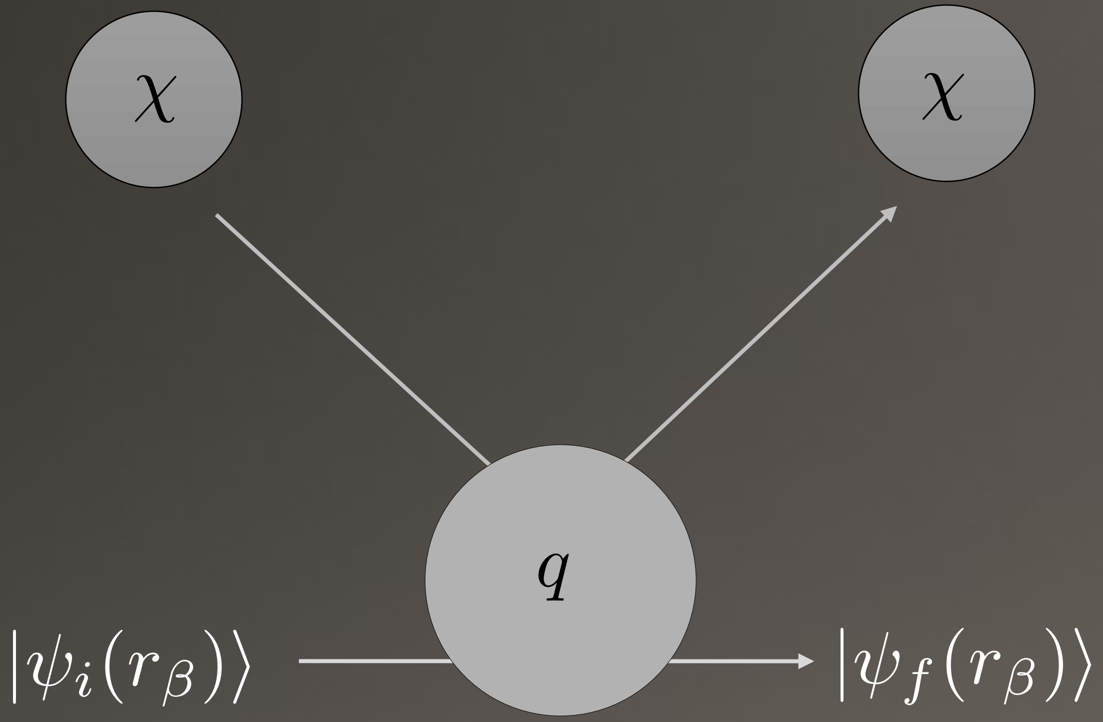
$$F_{\mathrm{DM}}(q) = \begin{cases} 1 & ,\ \text{Heavy mediator} \\ \left(\dfrac{\alpha m_e}{q}\right)^2 & ,\ \text{Light mediator}\end{cases}$$

Transition form factor

$$f_{i\to f}(q) = \int d^3\vec{R}\,d^3\vec{r}\,\Psi^*_f(R_i,r_\beta)e^{i\vec{q}\cdot(\vec{r}_\beta,\vec{R}_i)}\Psi_i(R_i,r_\beta)$$

$$\boxed{f_{i\to f}(q) = \int d^3\vec{k}\,\tilde{\Psi}^*_f(k+q)\tilde{\Psi}_i(k)}$$

Electron Recoil: Charge Signal



Electron scattering

$$\Delta E_r = (m_\chi^2/m_{\mathrm{T}}) \times 10^{-6}$$

$$\Delta E \sim \mathcal{O}(\text{few eV}) \left(\frac{m_\chi}{1\,\mathrm{MeV}}\right)^2$$

What has such transition energies?

- Semiconductor band gaps
- Maybe atomic ionization

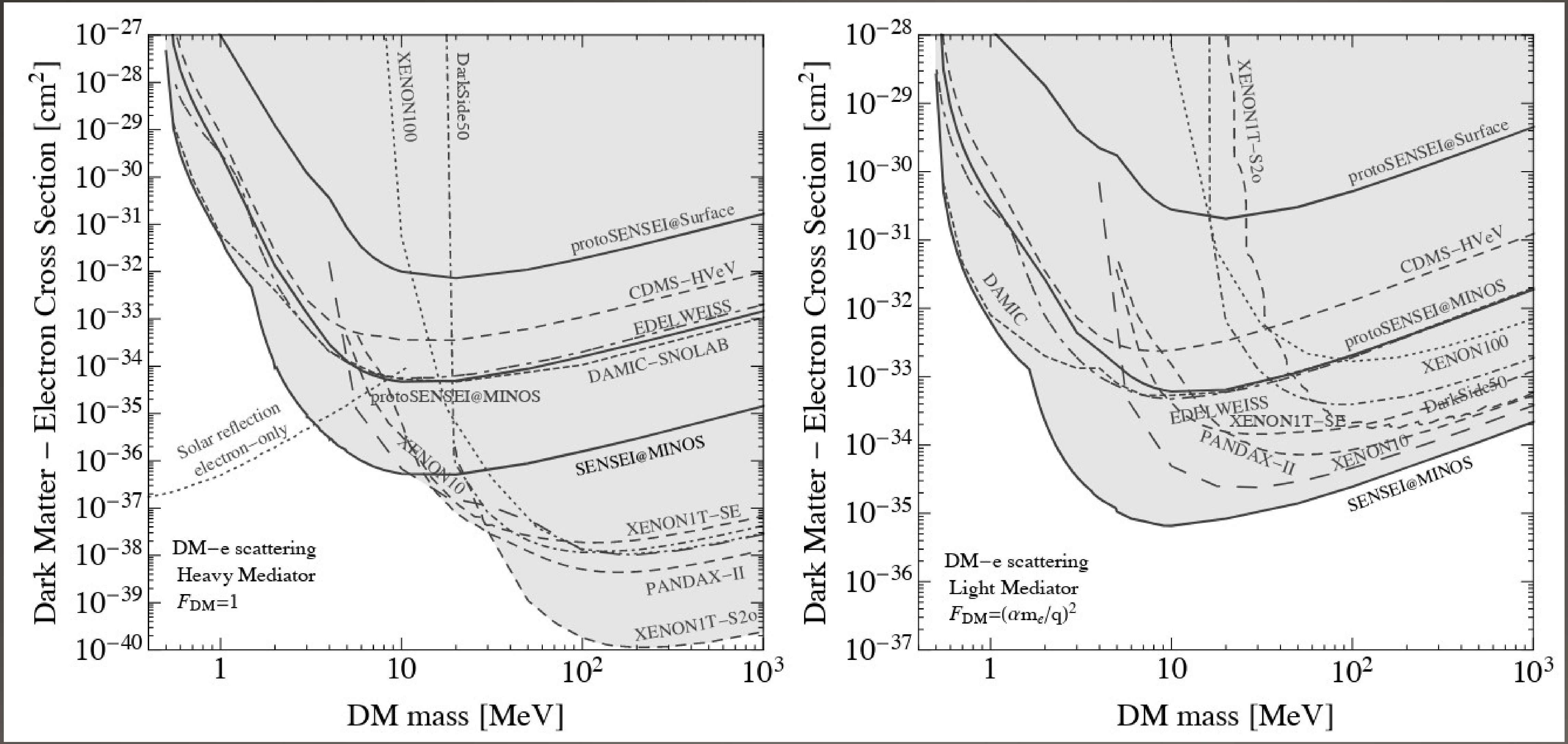
Electrons in crystals (exciton generation)

$$|\psi_i\rangle \sim u_v(r)e^{ik'\cdot r} \qquad |\psi_f\rangle \sim u_c(r)e^{ik\cdot r}$$

Electrons in atoms (ionization)

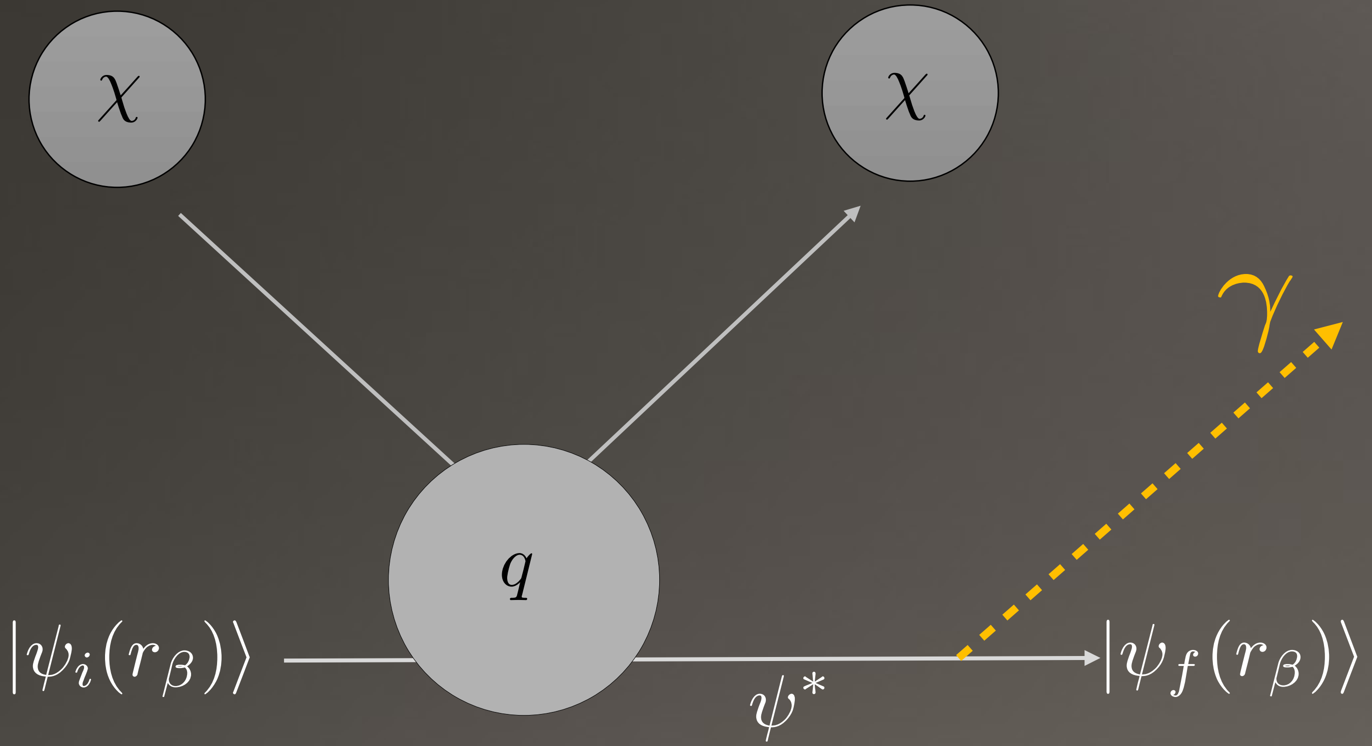
$$|\psi_i\rangle \sim \psi_{\mathrm{STO}}(r_\beta) \qquad |\psi_f\rangle \sim e^{ik\cdot r},\ r \gg a_0$$

Semiconductor CCDs



Essig R., et al. "*Snowmass2021 Cosmic Frontier The landscape of low-threshold dark matter direct detection in the next decade*" arXiv:2203.08297 (2022).

Electron Recoil: Photon Signal



Electron scattering

$$\Delta E_r = (m_\chi^2/m_\mathrm{T}) \times 10^{-6}$$

$$\Delta E \sim \mathcal{O}(\text{few eV}) \left(\frac{m_\chi}{1\,\mathrm{MeV}}\right)^2$$

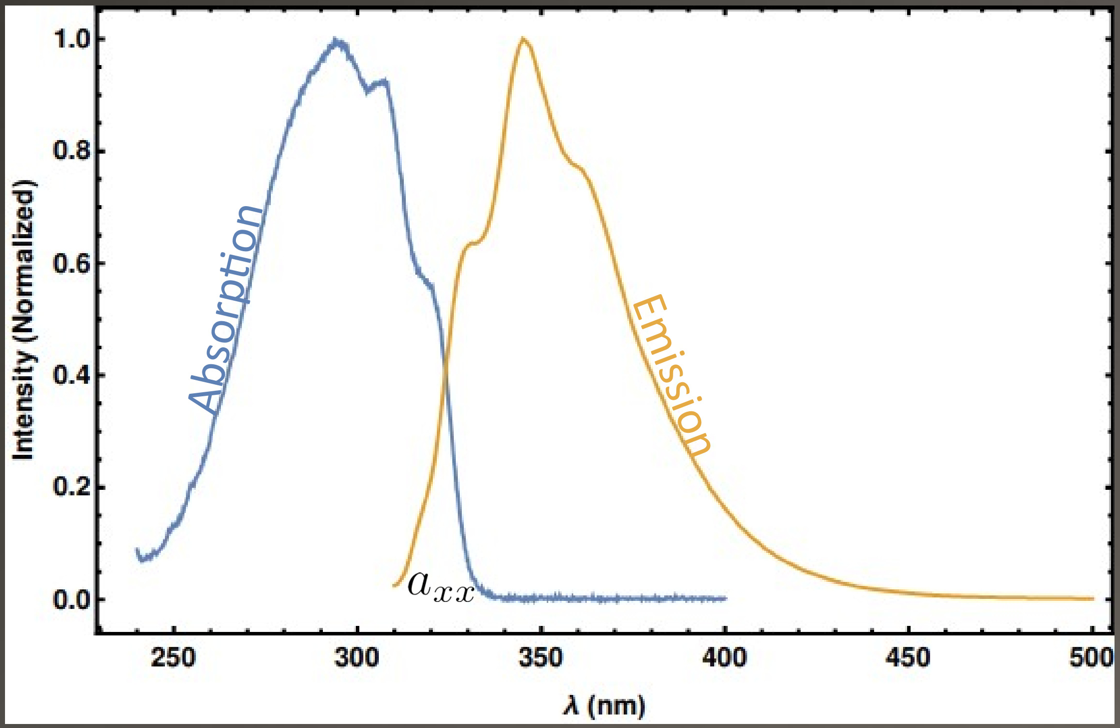
Electrons in crystals (exciton generation)

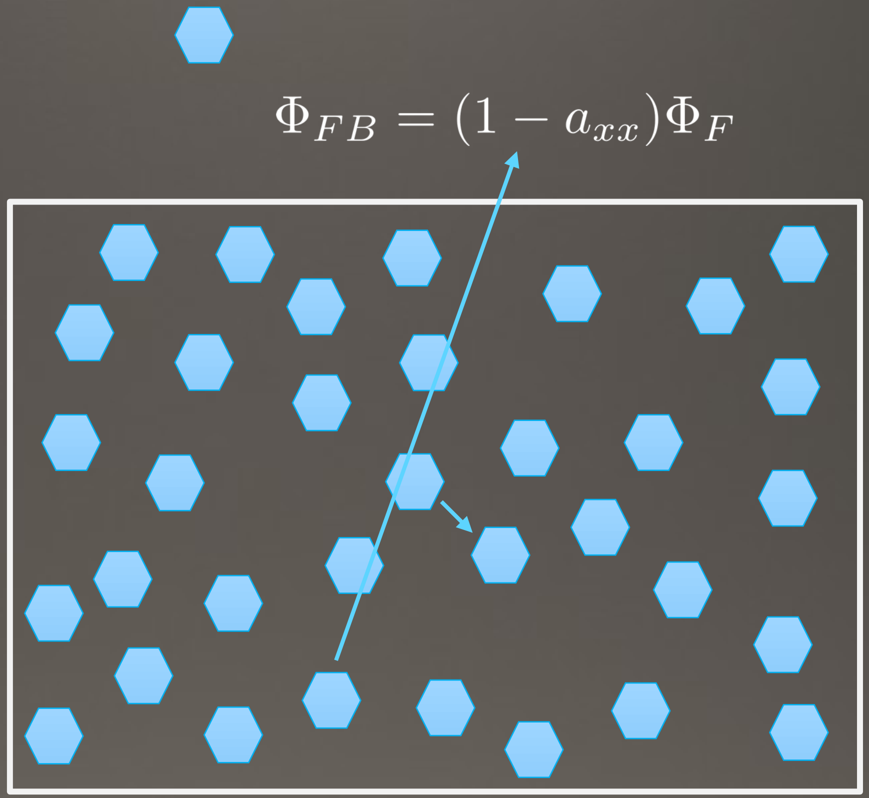
$$|\psi_i\rangle \sim u_v(r)e^{ik'\cdot r} \quad |\psi\rangle^* \sim u_c(r)e^{ik\cdot r}$$

Electrons in molecules and atoms

$$|\psi_i\rangle \sim \psi_{\mathrm{lcao}}(r_\beta) \quad |\psi\rangle^* \sim \psi^*_{lcao}(r_\beta)$$

Fluorescence with DM

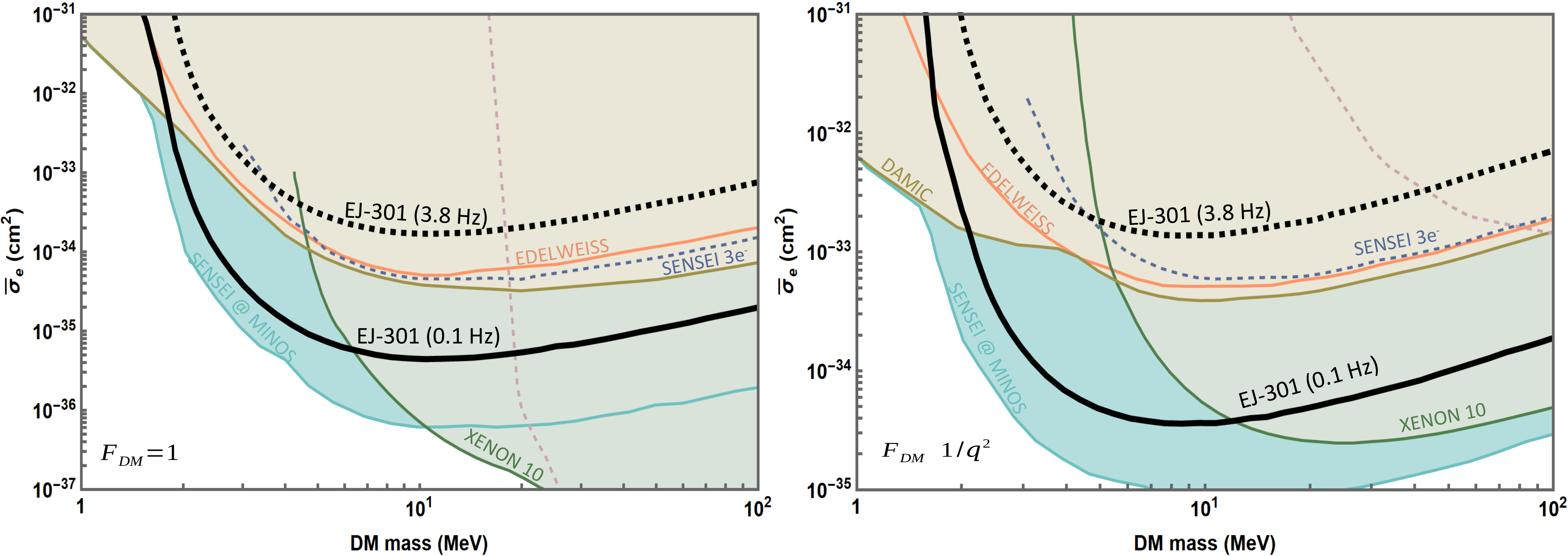




$$\Phi_{FB} = (1 - a_{xx})\Phi_F$$

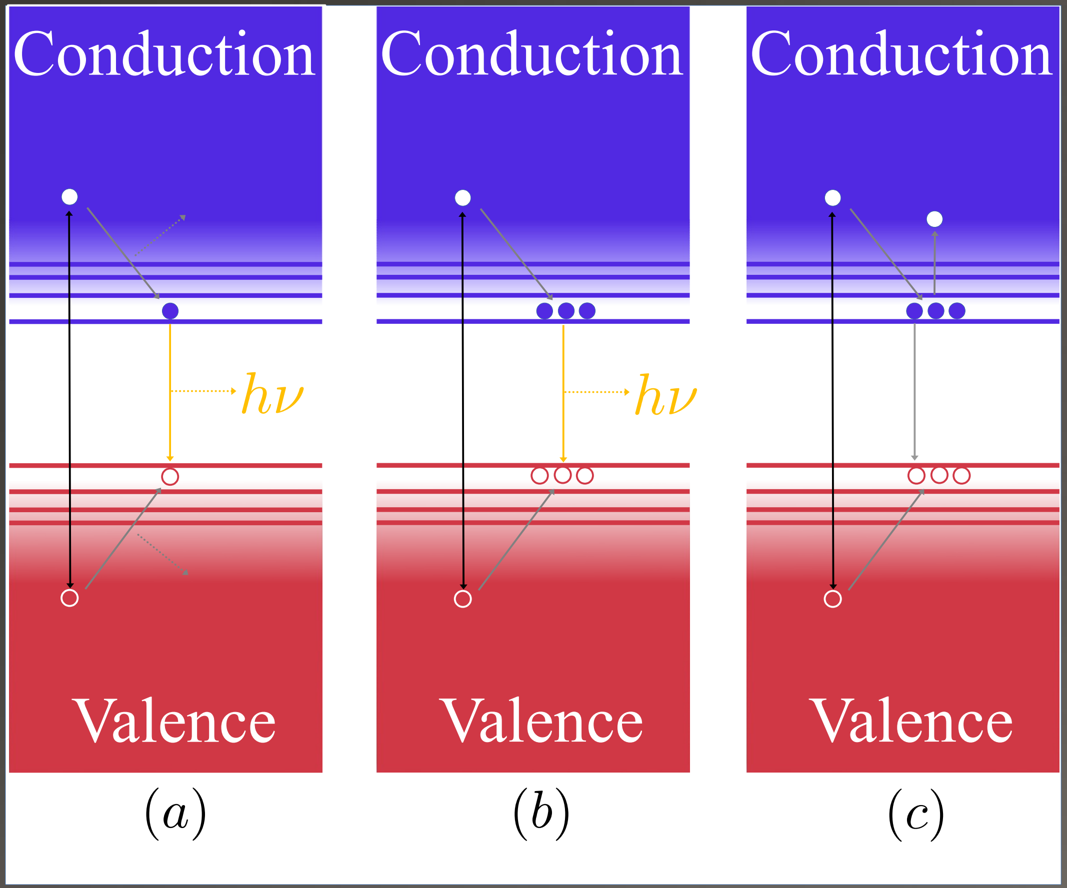
Solid Trans-Stibene:
$\Phi_{FB} = 0.65$

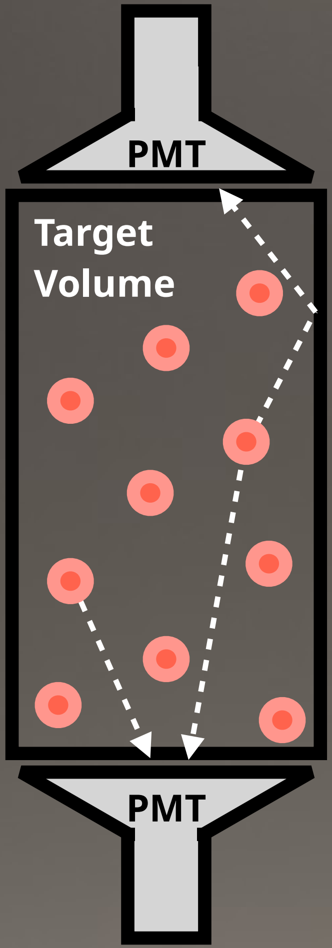
Results: EJ-301



Blanco ‘19: 1912.02822

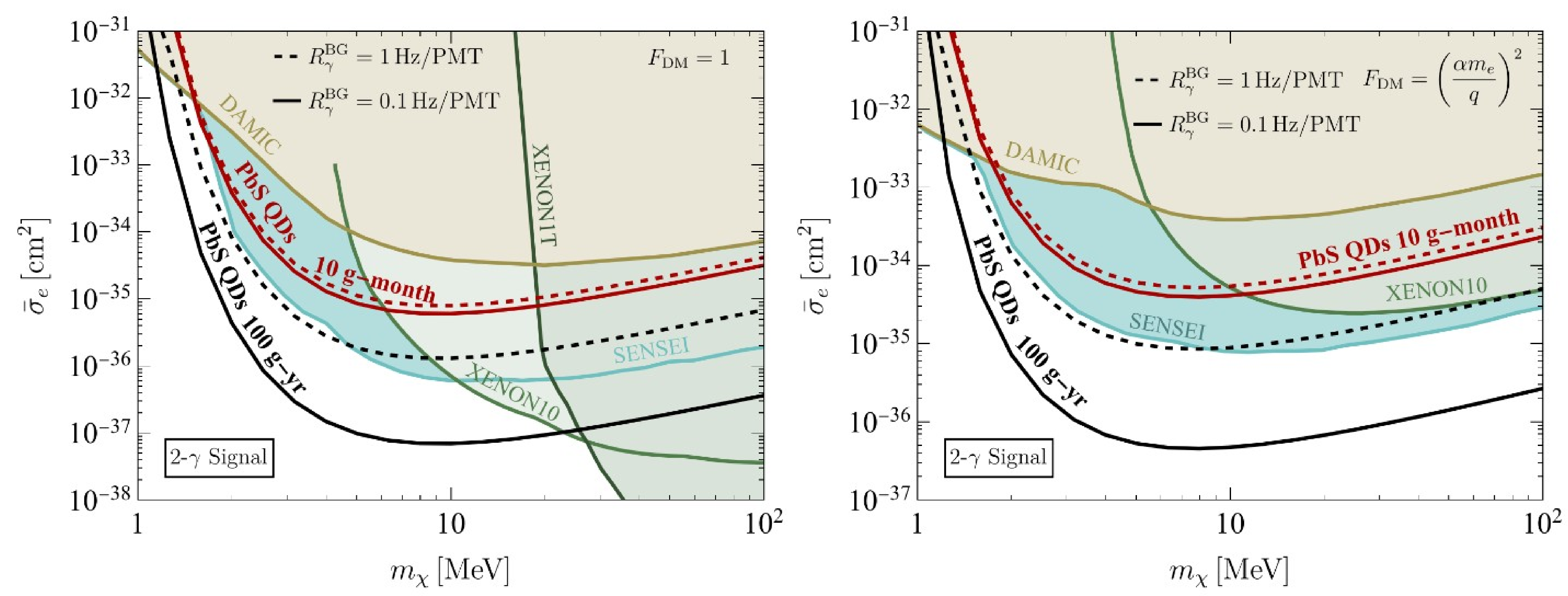
Quantum Dots





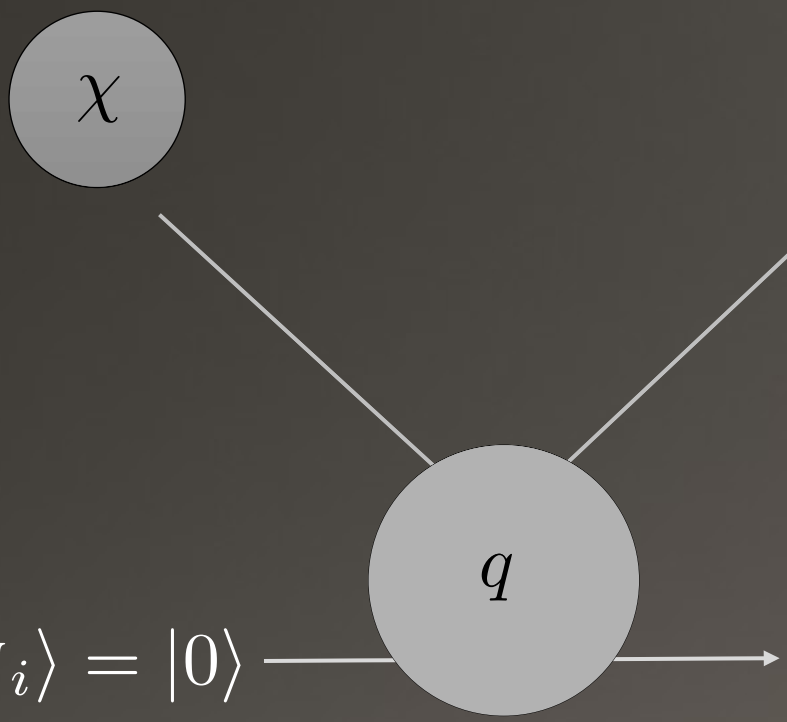
- Absorption: (b) Creation of a "hot" exciton – an electron/hole pair with energy significantly larger than the bandgap
- Non-Radiative Transition: (b) MEG – multi-exciton generation when energy is greater than twice the bandgap. Creates several band-edge excitons.
- Emission: (b) Radiative recombination of several band-edge excitons producing several coincident photons

PbS Quantum Dots



Blanco ‘22: 2208.05967

Nuclear Recoil: Phonon Signal



$$|\Psi_i\rangle = |0\rangle$$

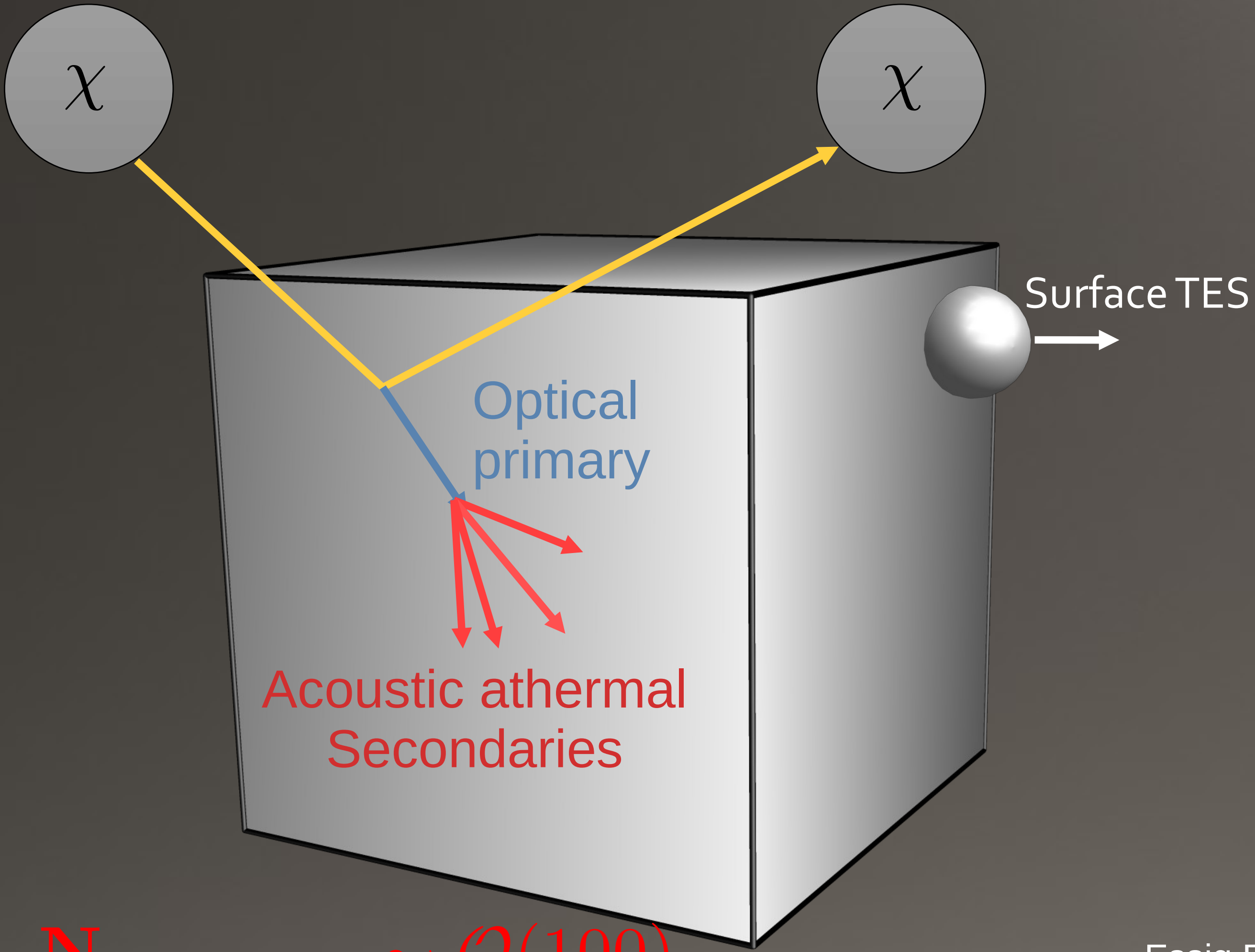
$$|\Psi_f\rangle = a^\dagger(k)\,|0\rangle$$

Nuclear scattering

$$\Delta E \sim \mathcal{O}(\text{few eV})\left(\frac{m_\chi}{100\,\text{MeV}}\right)^2\left(\frac{m_N}{130\,\text{GeV}}\right)^{-1}$$

$$\omega \sim \mathcal{O}(10\text{-}100\ \text{meV})$$

Calorimeters



χ

χ

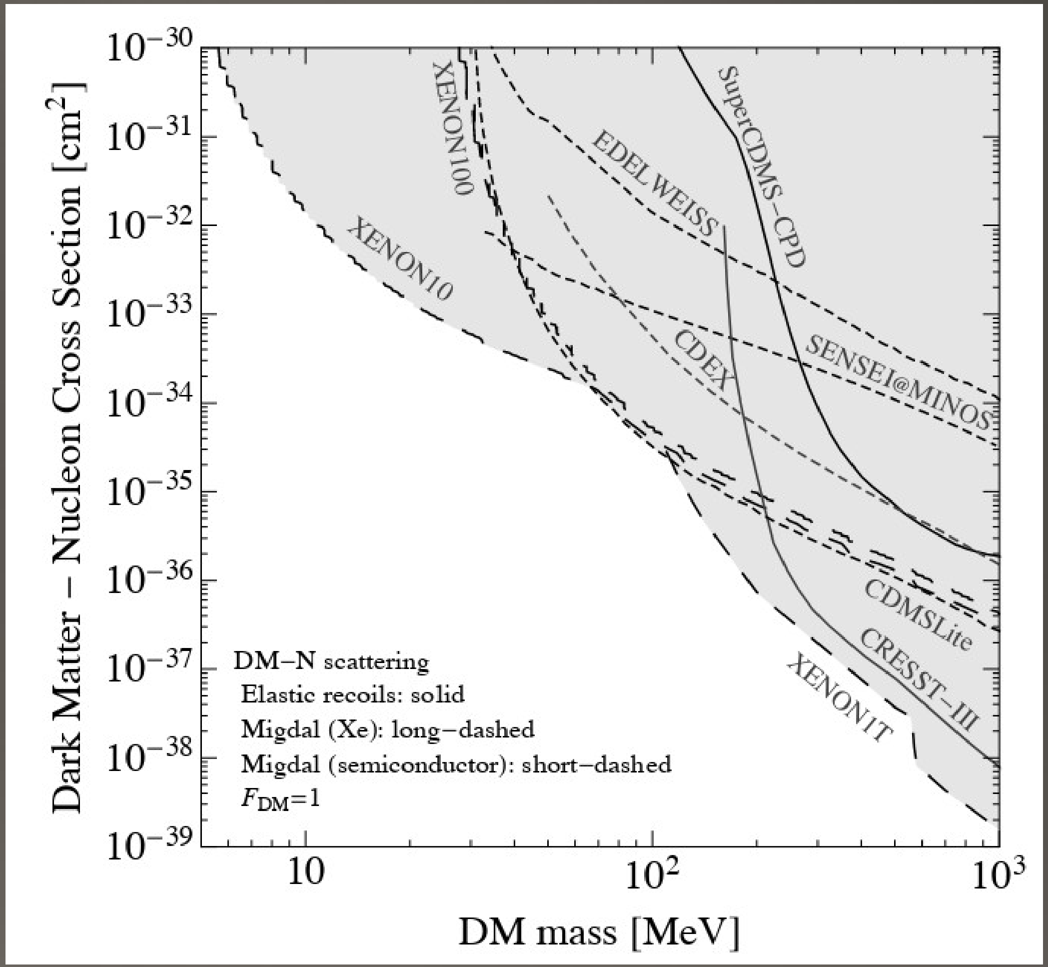
Surface TES

Optical primary

Acoustic athermal Secondaries

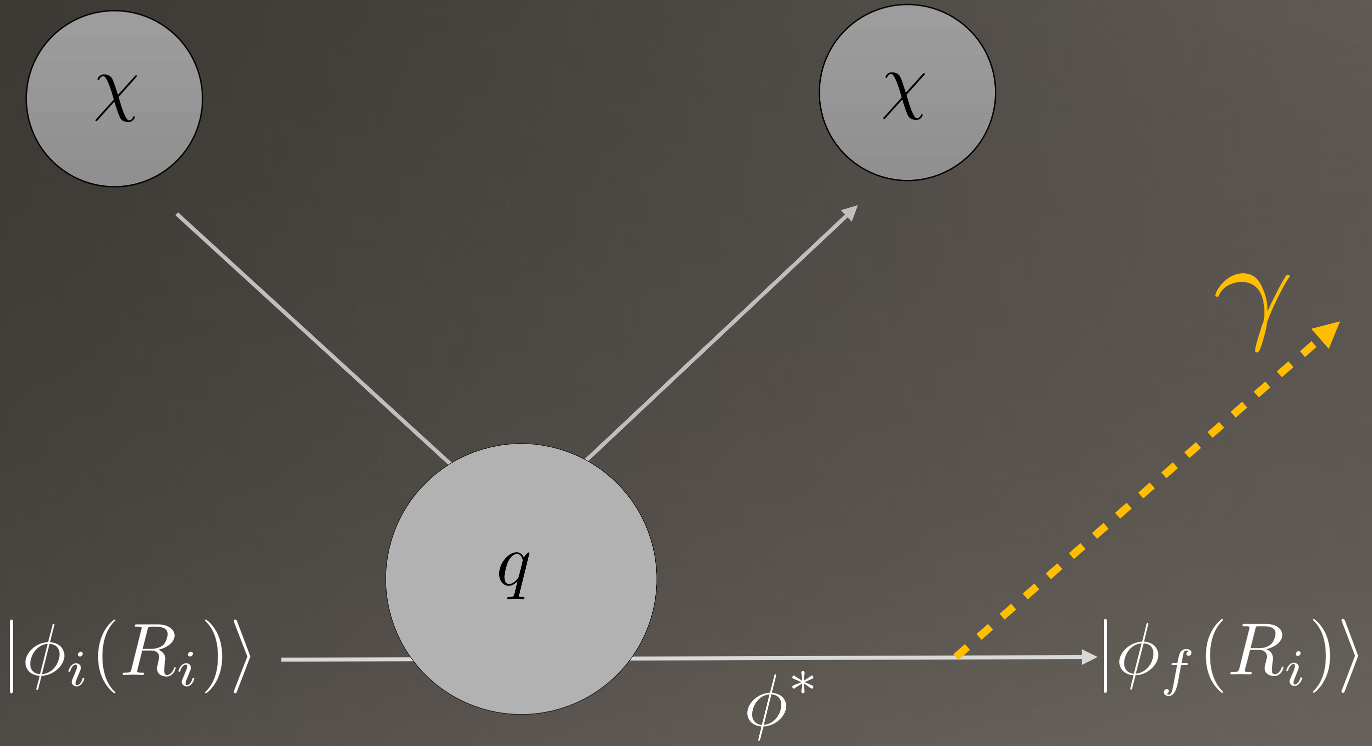
$\mathbf{N}_{\mathbf{accoustic}} \sim \mathcal{O}(100)$

$E_0 \sim 10 - 100\ \mathrm{meV}$



Essig R., et al. "*Snowmass2021 Cosmic Frontier The landscape of low-threshold dark matter direct detection in the next decade*" arXiv:2203.08297 (2022).

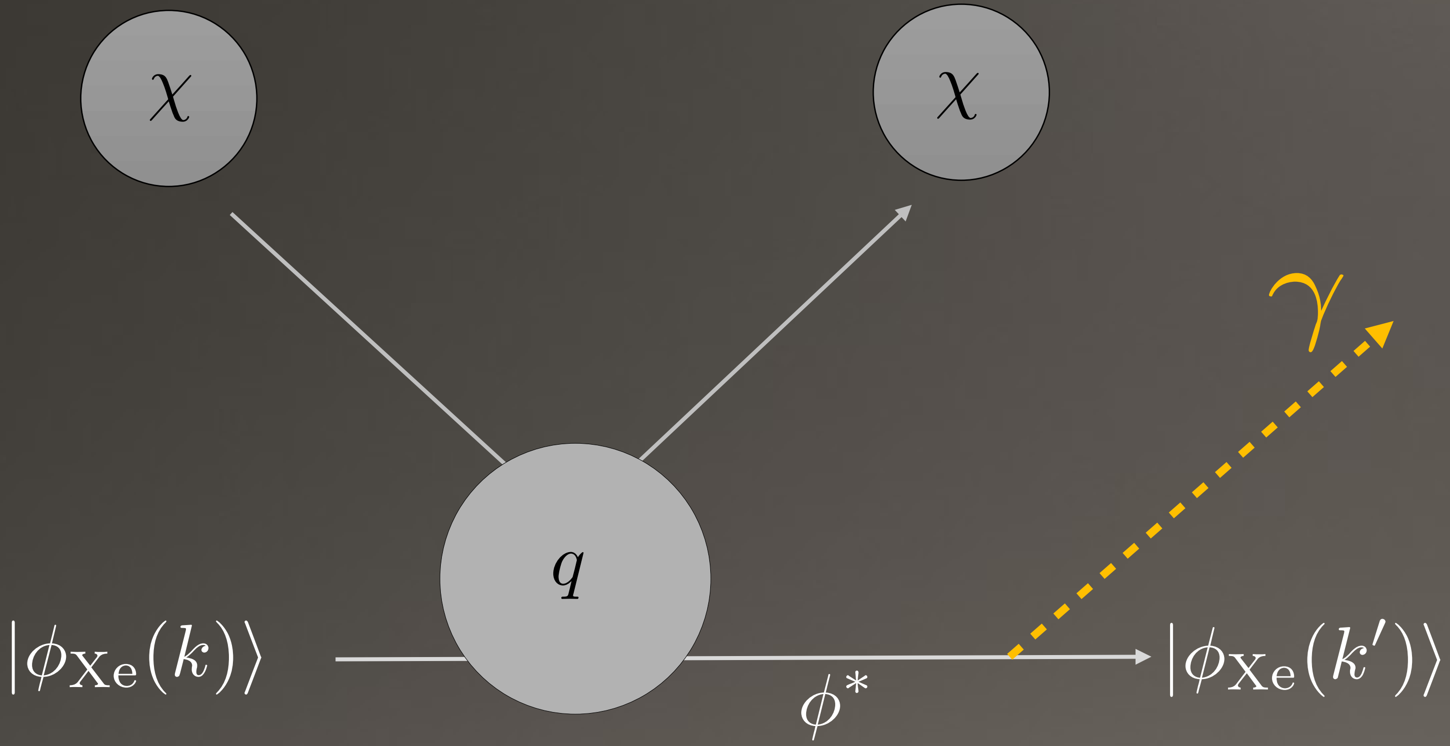
Nuclear Recoil: Photon Signal



Nuclear scattering

$$\Delta E \sim \mathcal{O}(\text{few eV}) \left(\frac{m_\chi}{100\,\text{MeV}}\right)^2 \left(\frac{m_N}{130\,\text{GeV}}\right)^{-1}$$

Direct Atomic Photoemission

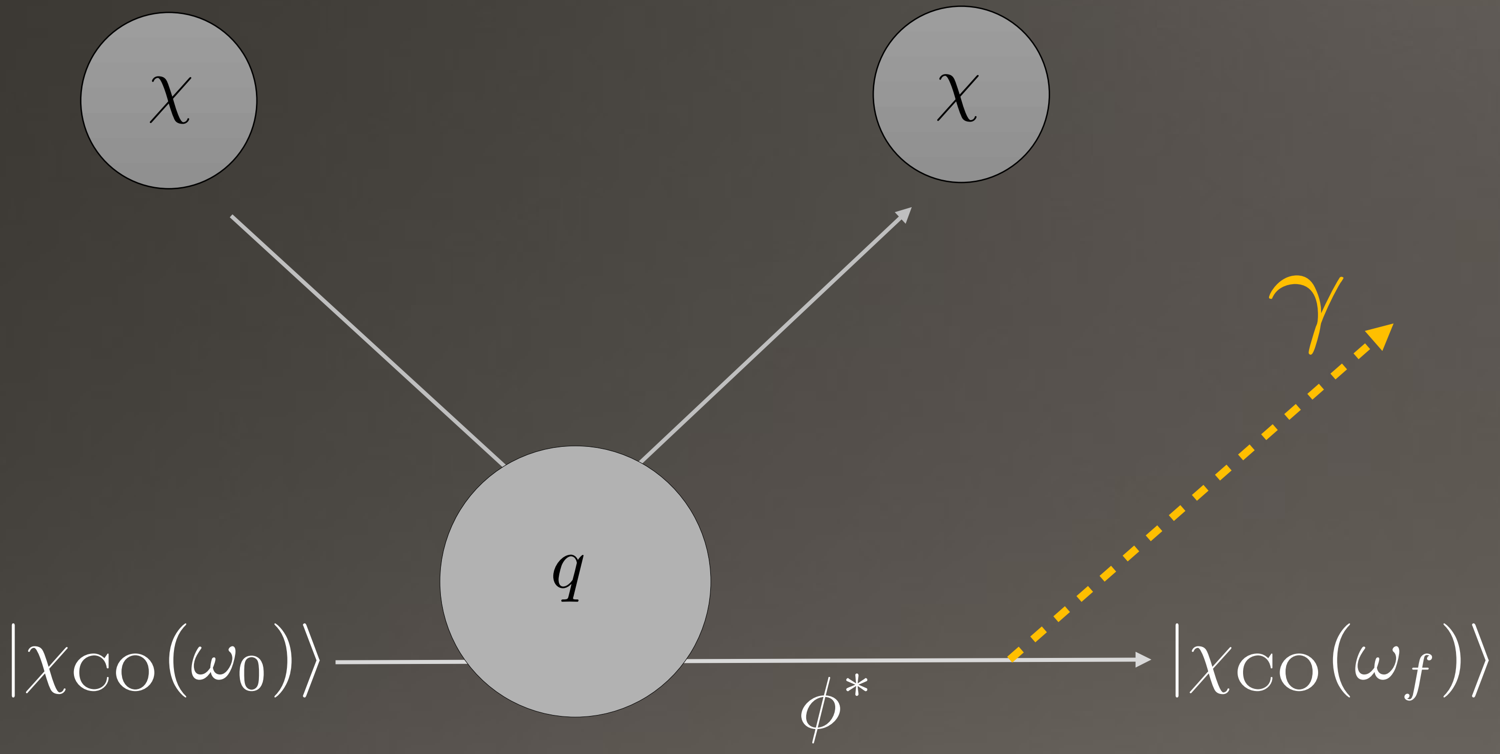


$\Delta E \sim \mathcal{O}(\text{few keV})$

Scintillation signal in TPCs

ϕ^* : Virtual state

Molecular excitations



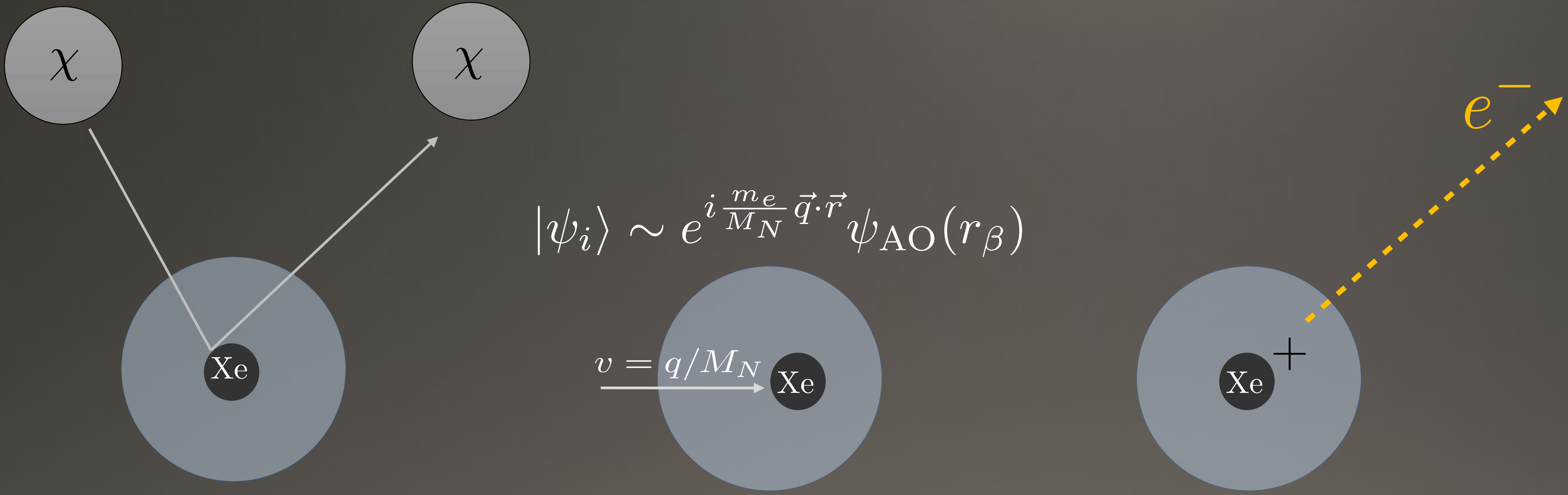
$$\Delta E \sim \mathcal{O}(10\text{-}100\ \mathrm{meV})$$

Like fluorescence but with excited roto-vibrational states

See e.g. Essig '19 1907.07682

$$\phi^* : |\chi_{\rm CO}(\omega')\rangle$$

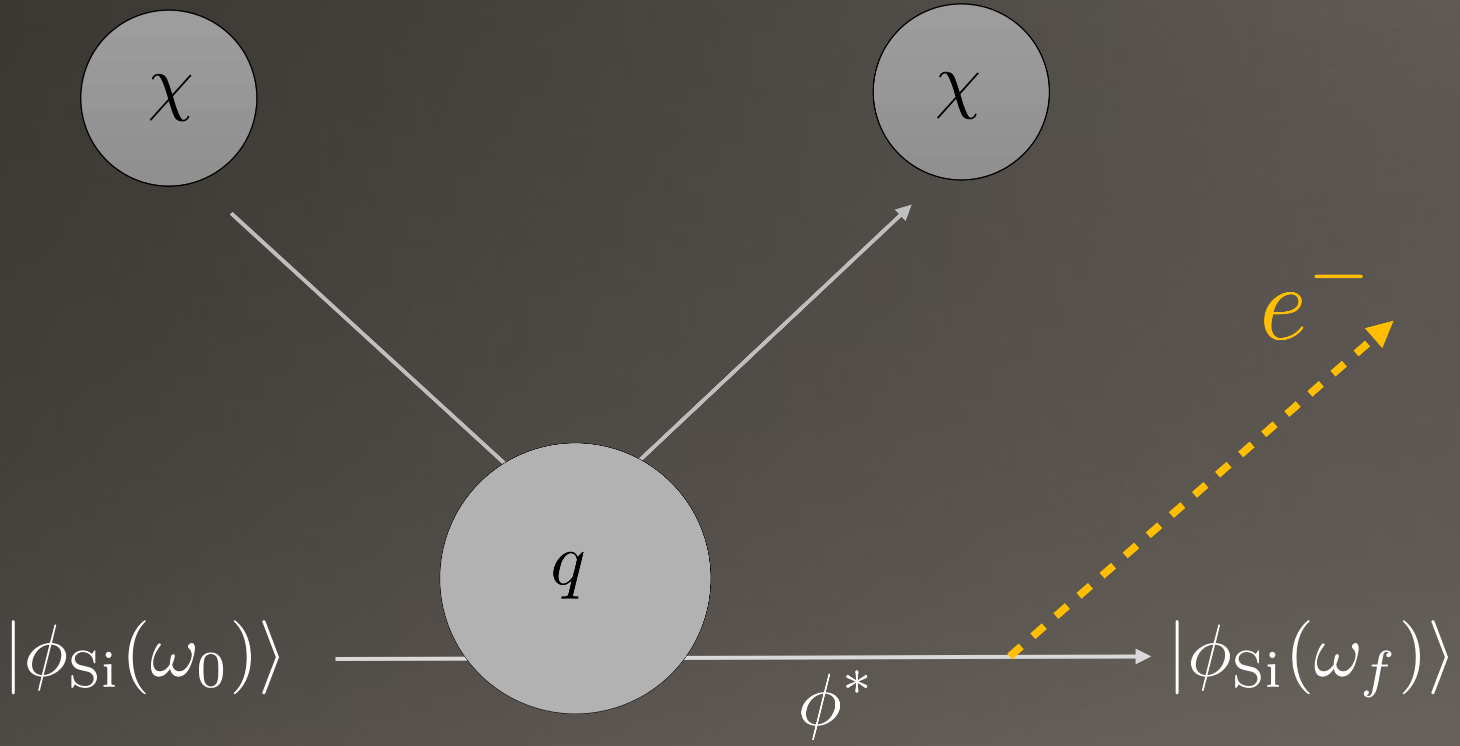
The Migdal Effect: Atoms



$$|\psi_i\rangle \sim e^{i\frac{m_e}{M_N}\vec{q}\cdot\vec{r}}\psi_{\mathrm{AO}}(r_\beta)$$

$$f_{i\to f} = \langle\psi_{AO}|\, e^{i\frac{m_e}{M_N}\vec{q}\cdot\vec{r}}\, |\psi_k(r)\rangle_{ion}$$
$$\approx \frac{i m_e \vec{q}}{M_N}\cdot\langle\psi_{AO}|\, \vec{r_i}\, |\psi_k(r)\rangle_{ion}$$

The Migdal Effect: Semiconductors



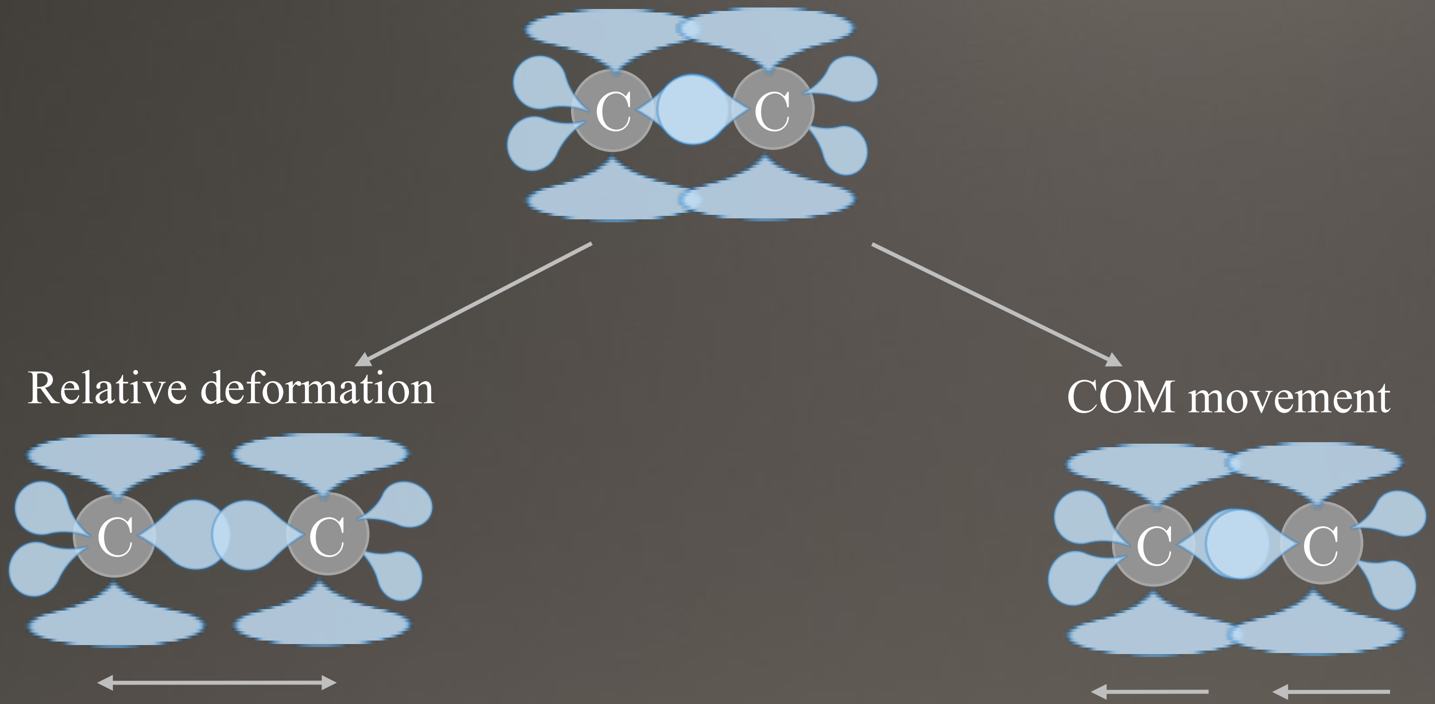
A Bremm-like amplitude

$$f_{i\to f} \sim \frac{m_e}{M_N}$$

See e.g. Knapen ‘21 2011.09496

ϕ^* : virtual vibrational states

The Molecular Migdal Effect(s)



Relative deformation

COM movement

Non-adiabatic coupling caused by effects beyond Born-Oppenheimer

COM recoil effect is the molecular analog of the semiclassical Migdal effect

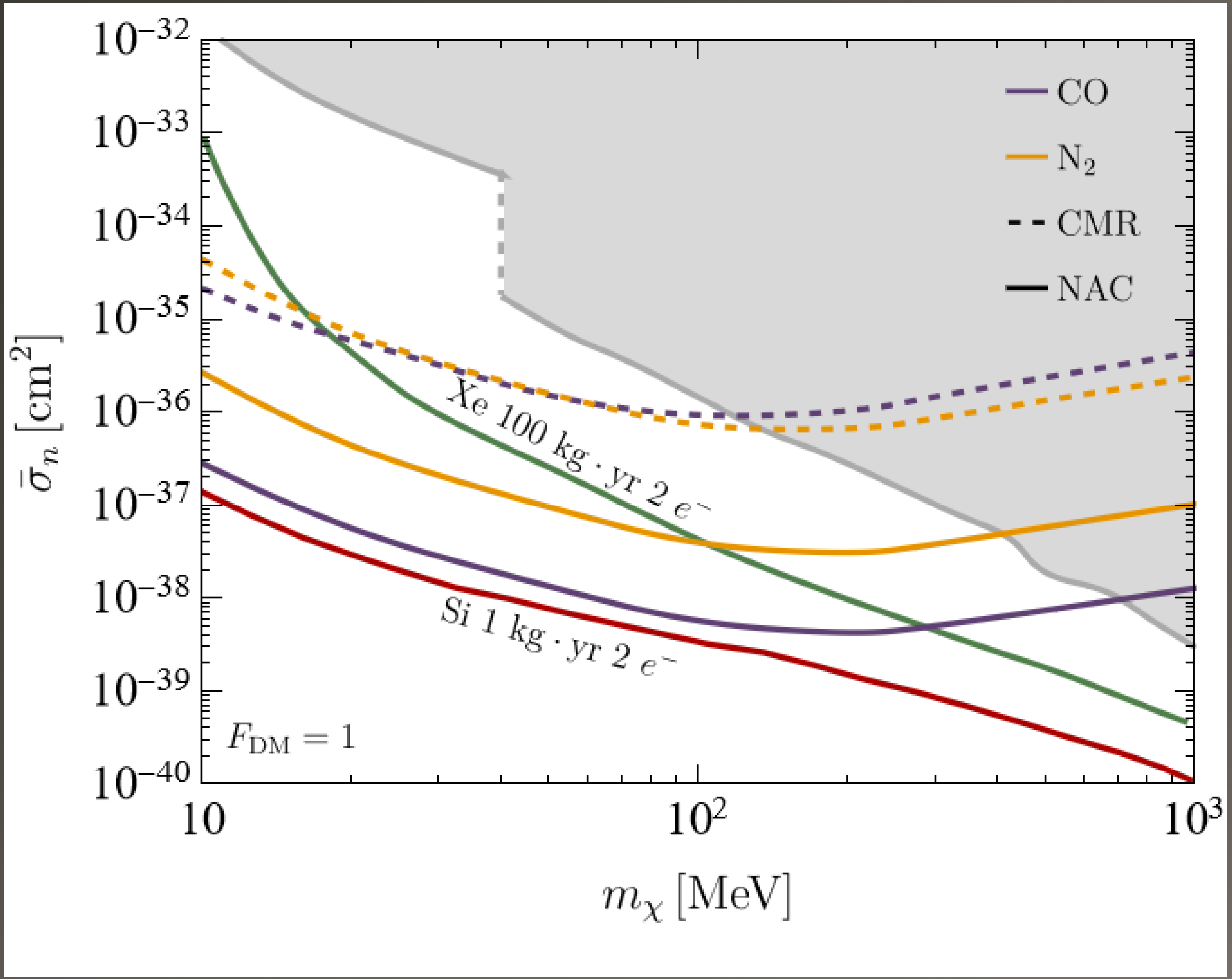
$$f_{e,NAC} \sim \sum_{\beta} \langle \psi^*_{MO} | \frac{\partial}{\partial R_i} | \psi_{MO}(r) \rangle$$

$$f_{e,CMR} = \sum_{\beta} \langle \psi^*_{MO} | e^{i \frac{m_e}{M_N} \vec{q} \cdot \vec{r}_\beta} | \psi_{MO}(r) \rangle$$

$$P_{NAC} \sim \frac{m_e}{M_N}$$

$$P_{CMR} \sim \frac{m_e}{M_{mol}}$$

Migdal Effect(s)



- NAC will dominate over CMR for molecules
- Is there NAC in silicon?
- Optimal molecular targets?

Blanco ‘22: 2208.09002

Directional Detection

$$\eta\left(v_{\min}\right) = \int \frac{4\pi v^2 dv}{v} g_\chi(v)\Theta\left(v - v_{\min}\right)$$

$$g_\chi(\vec{q}) \equiv \int d^3u\, f(\vec{u} + \vec{v}_\oplus)\,\delta\left(\Delta E - \vec{q}\cdot\vec{u} - \frac{q^2}{2m_\chi}\right)$$

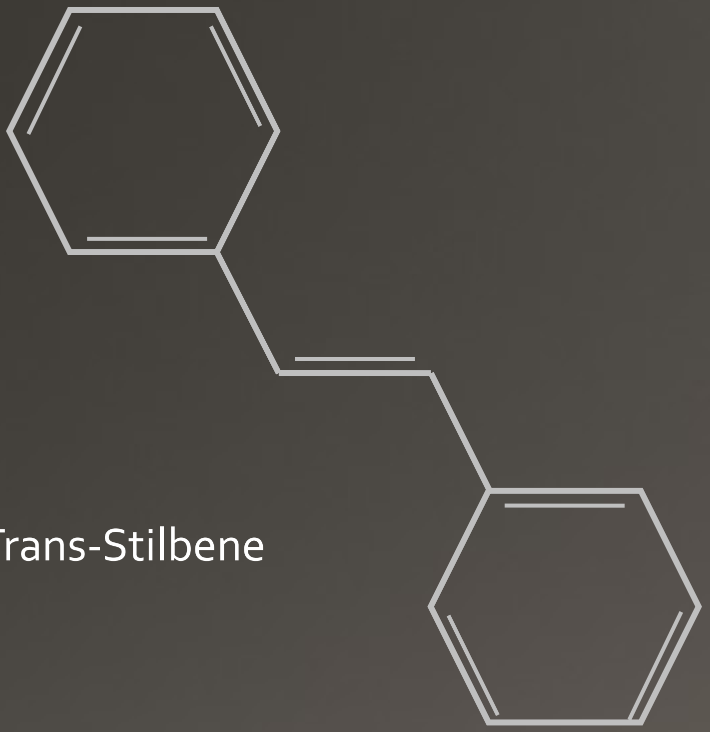
$$= \frac{\pi v_0^2}{q N_0}\left(e^{-v_-^2/v_0^2} - e^{-v_{\mathrm{esc}}^2/v_0^2}\right)$$

$$f_0(\vec{v}) = \exp(-|\vec{v}|^2/2\sigma_0^2)\Theta(|\vec{v}|^2 - v_{\mathrm{esc}}^2)/N_0$$

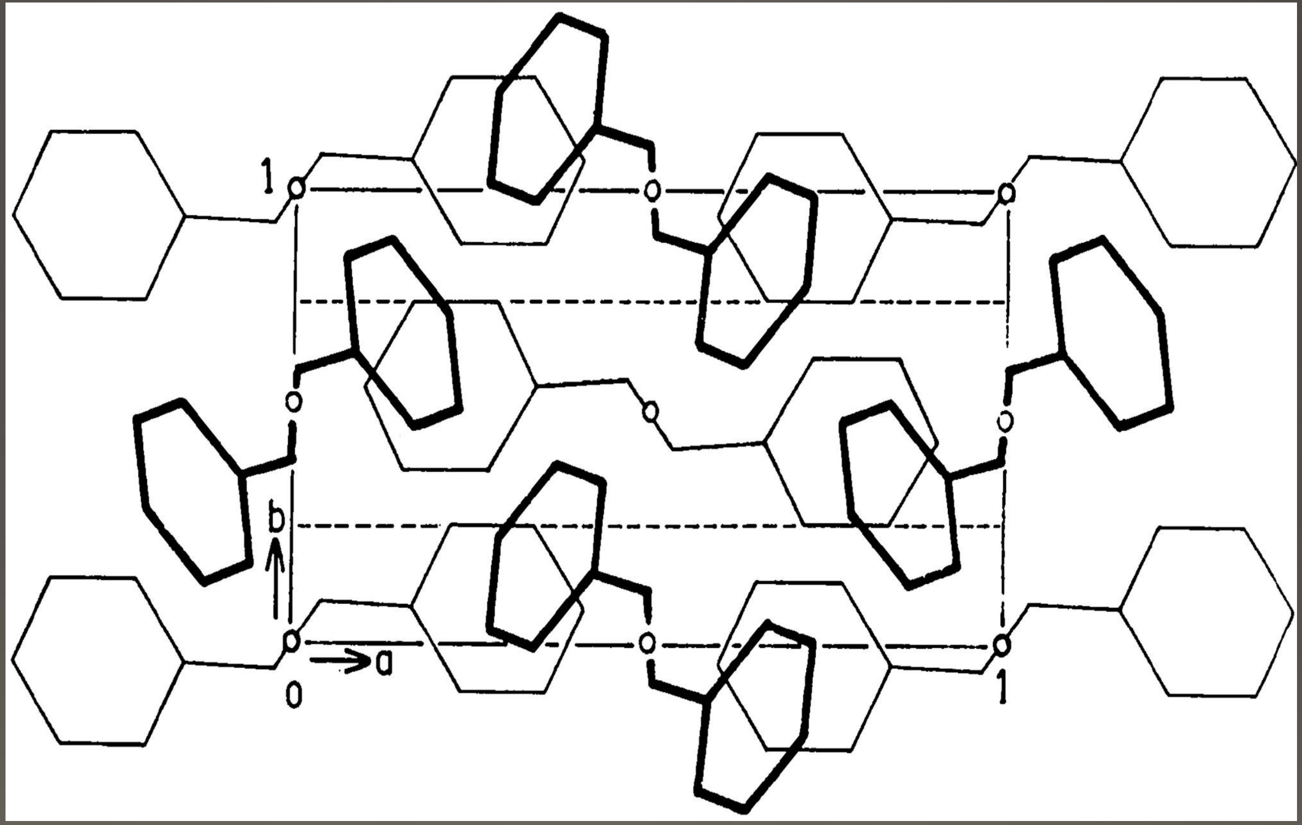
$$\vartheta = 2\pi \times \left(\tfrac{t}{24\,\mathrm{h}}\right),\ \theta_e \approx\ 42^\circ$$

$$\vec{\hat{v}}_\oplus(t) = \begin{pmatrix} \cos\beta & -\sin\beta & 0 \\ \sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \sin\theta_e \sin\vartheta \\ \sin\theta_e \cos\theta_e(\cos\vartheta - 1) \\ \cos^2\theta_e + \sin^2\theta_e \cos\vartheta \end{pmatrix},$$

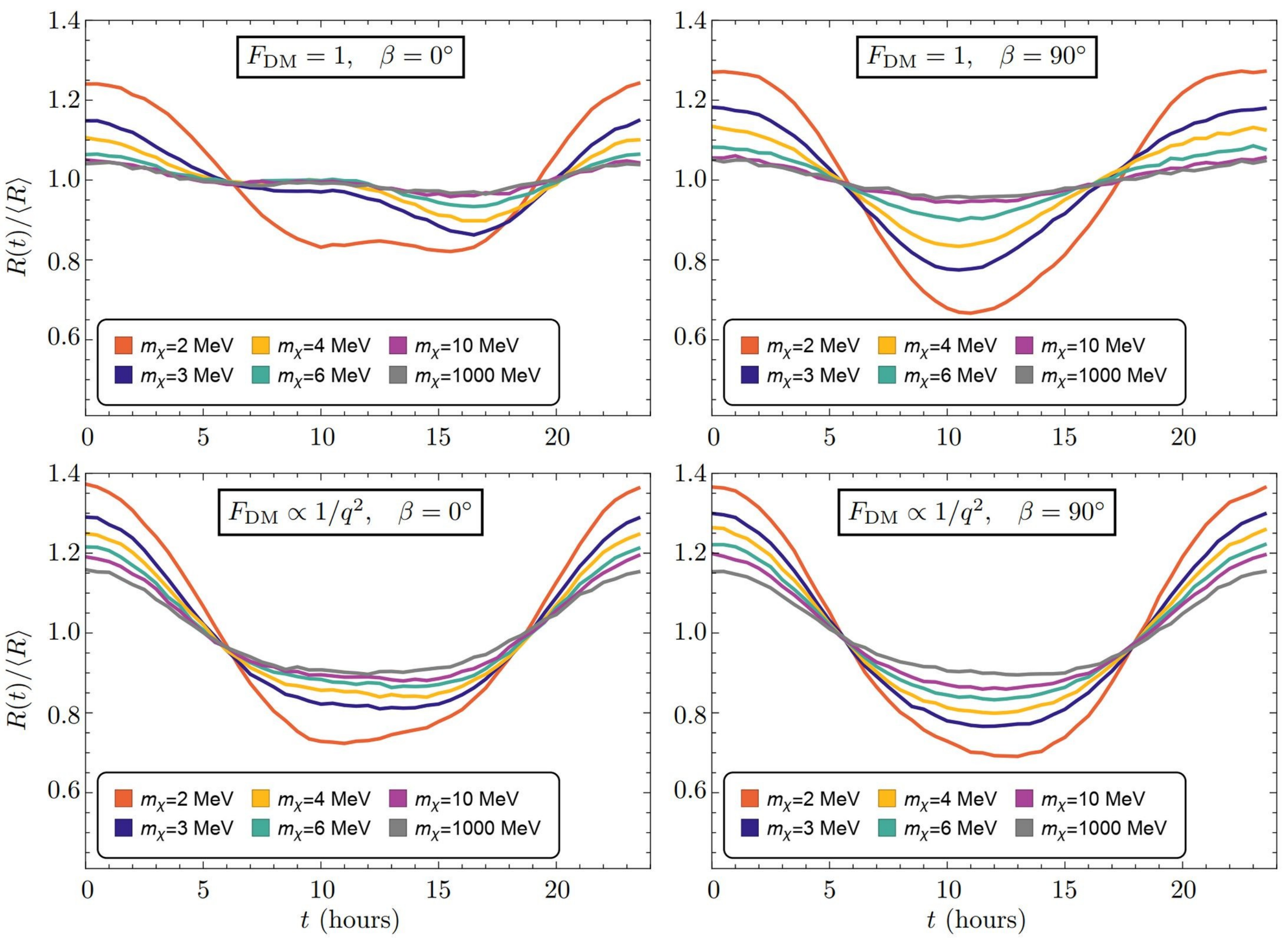
Trans-Stilbene



Trans-Stilbene



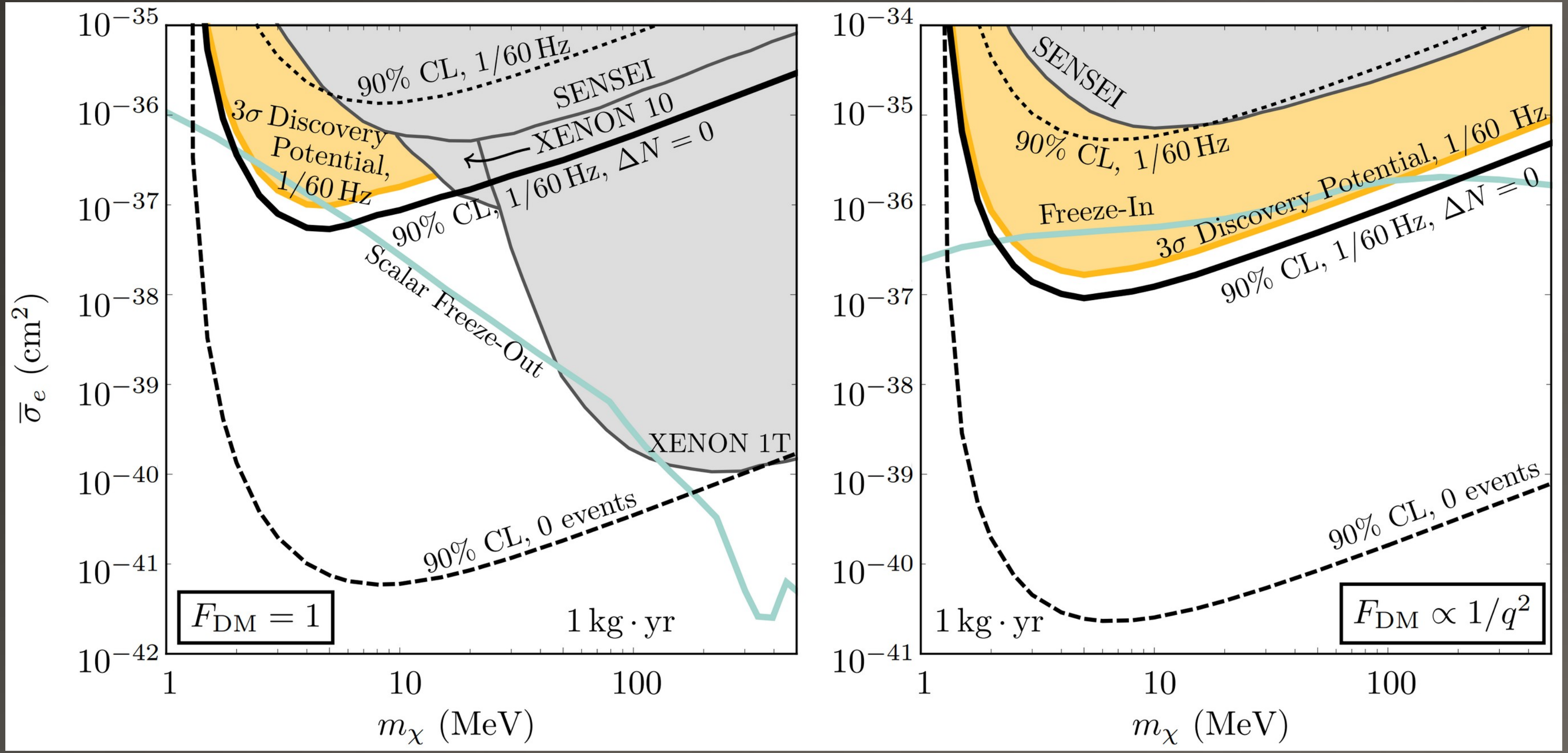
Daily Modulation



Normalized modulation signals for a variety of DM masses, m_χ = 2–1000 MeV, for a crystal in $\beta = 0°$ and $\beta = 90°$ orientations. Above 10 MeV, the rate relaxes into a function of time that is nearly independent of the DM mass and with modulation amplitude only mildly dependent on the crystal orientation. The peak-to-trough modulation amplitudes are as large as 60% at low masses and 10% at high masses for $F_{\rm DM} = 1$, increasing to 70% at low masses and 25% at high masses for $F_{\rm DM} = (\alpha m_e/q)^2$.

Blanco ‘21: 2103.08601

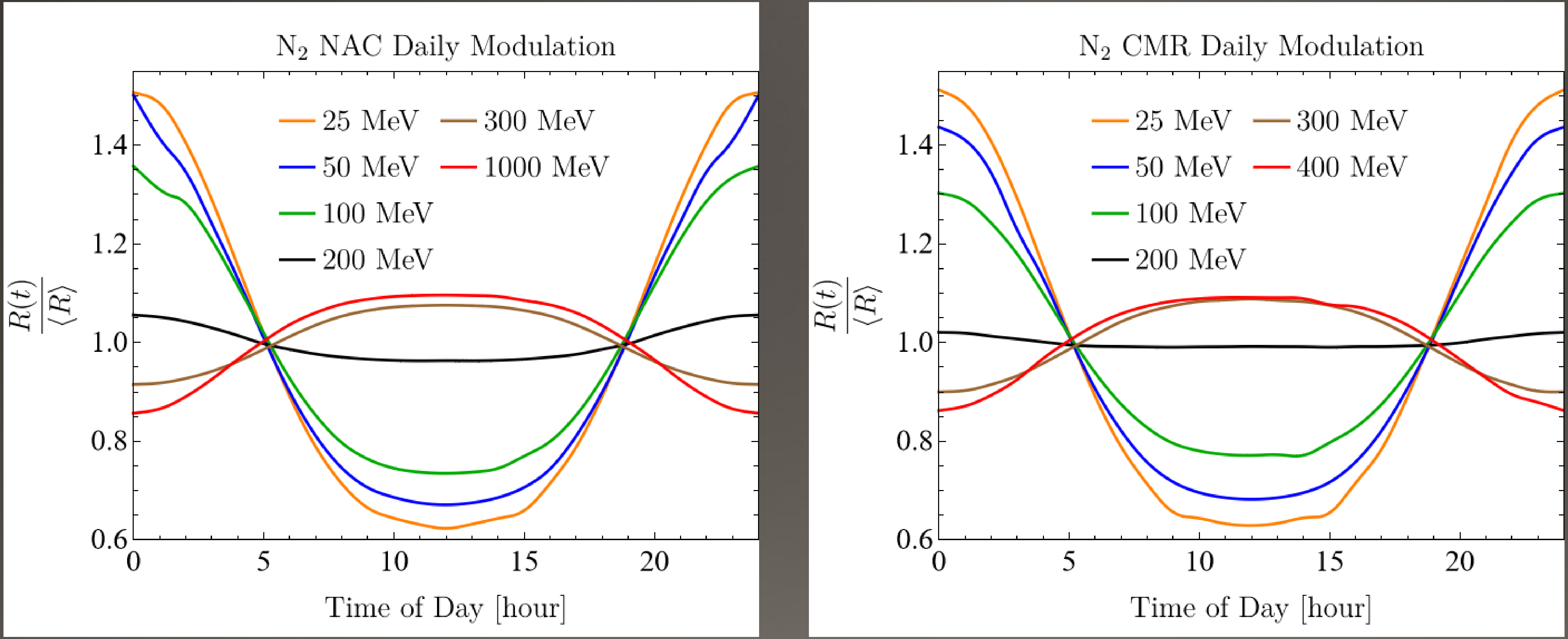
Sensitivity & Reach: Solid



Blanco ‘21: 2103.08601

The capability of a 1 kg · year t-stilbene experiment to detect or exclude DM models with $F_{\rm DM} = 1$ or $F_{\rm DM} = (\alpha m_e/q)^2$ couplings to electrons, shown with existing limits from SENSEI, XENON 10, and XENON 1T. The dotted and dashed lines show the 90% CL exclusions that can be set from the total number of events, without considering modulation effects, for $R = 1/60\,\mathrm{Hz\,kg}^{-1}$ ($N_{\rm events} \approx 5.26\times10^5$) and for $N_{\rm events} = 0$, respectively. The orange shaded regions indicate parameter space that leads to a sufficiently large modulation signal that a 1 kg · year experiment could observe a 3σ detection, given a total observed rate of $R = 1/60\,\mathrm{Hz\,kg}^{-1}$. The solid black “$\Delta N = 0$” lines show the improved limit that can be set from a null result exhibiting no daily modulation but the same total observed rate.

Directional Molecular Migdal Effect



Blanco '22: 2208.09002

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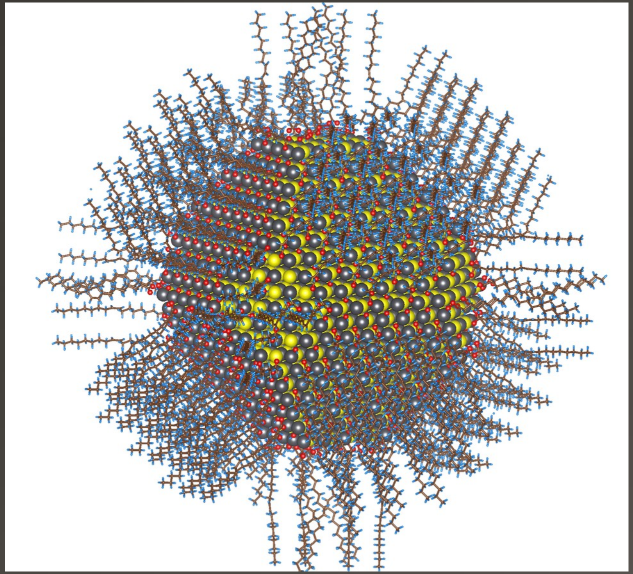
QDs vs Bulk Semiconductors

$$f_i(\mathbf{q}) = \int d^3\mathbf{r}\,\Psi_n(\mathbf{r})e^{i\mathbf{q}\cdot\mathbf{r}}\Psi^\star_{n'}(\mathbf{r})$$

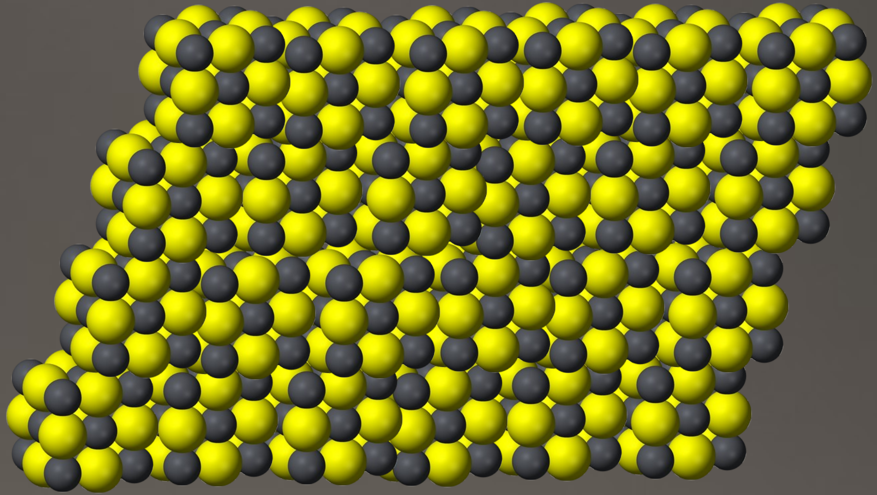
Zherebetskyy et al., Science 344, 1380 (2014)



$\xrightarrow{\hspace{2cm}}$

$R \sim 10$ nm

$$\Psi(\mathbf{r}) = u_k(\mathbf{r})\psi_{n_i}(\mathbf{r})$$



$\xrightarrow{\hspace{3cm}}$

$R \to \infty$ nm

$$\Psi(\mathbf{r}) = u_k(\mathbf{r})e^{i\mathbf{k}\cdot\mathbf{r}}$$