Dirac Attack!*

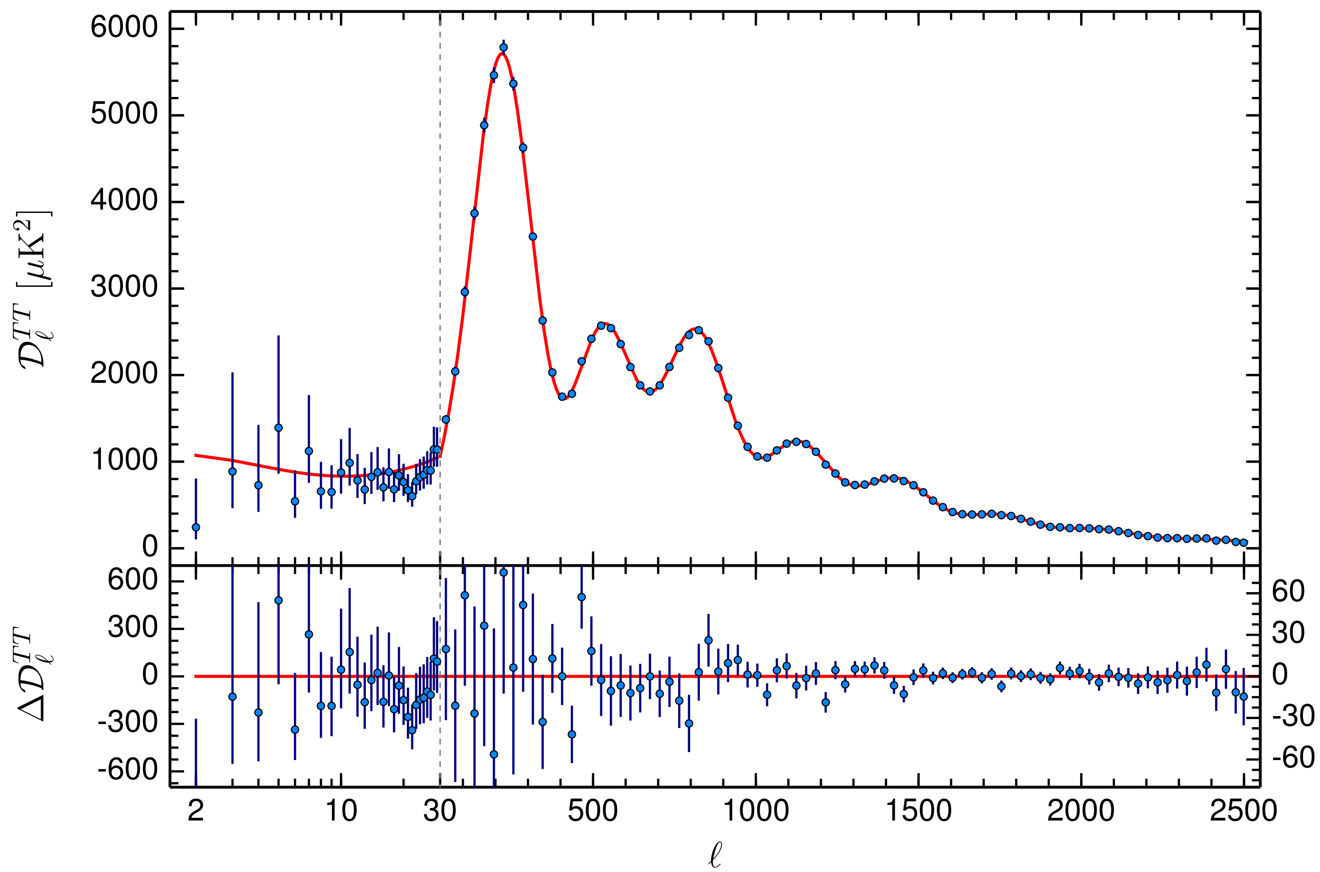
Searching for Light Dark Matter with Dirac Materials

Yoni Kahn, Princeton University

10/31/2017

*With apologies to the MIT physics department intramural hockey team…

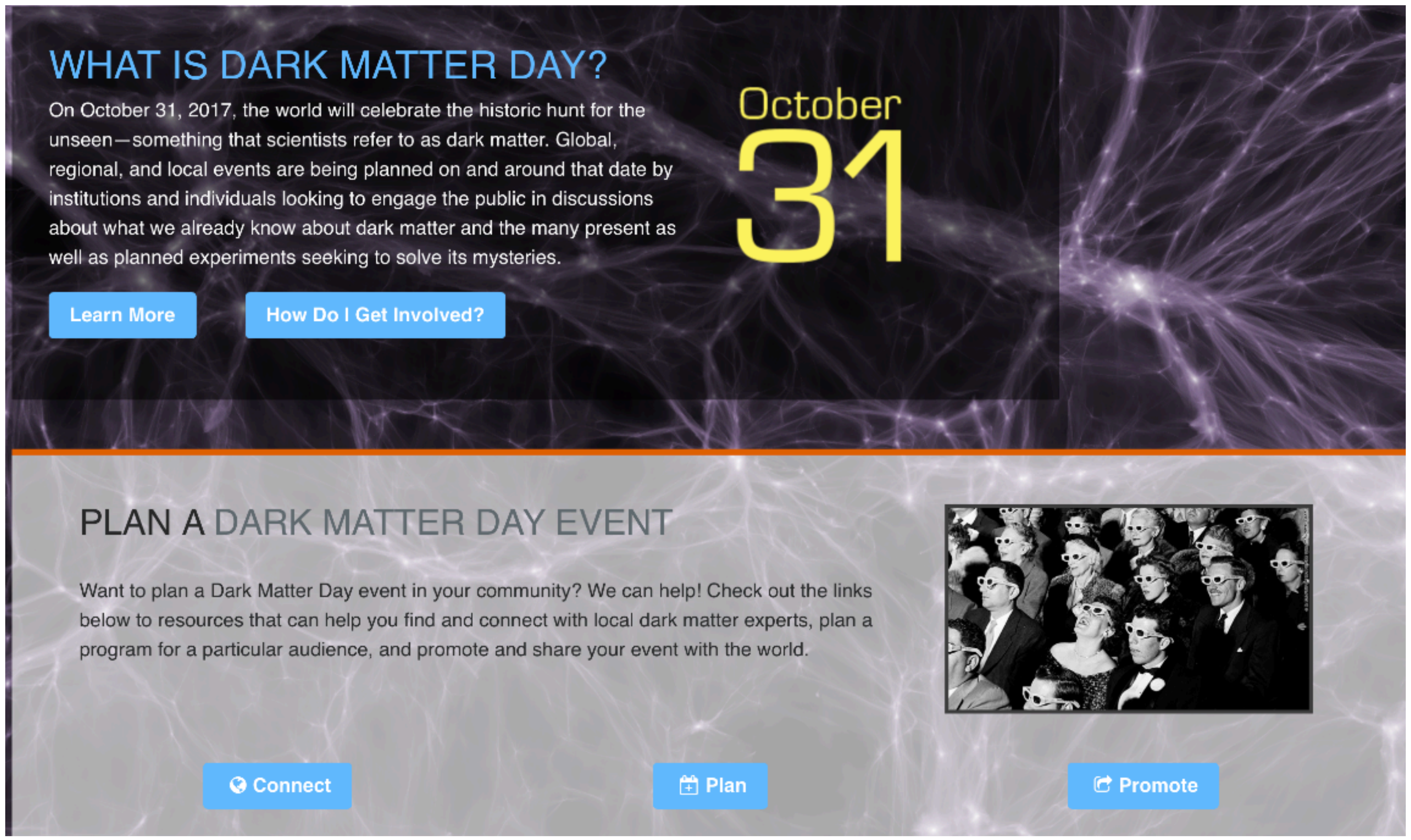
Dark matter exists!



Parameter	[1] *Planck* TT+lowP
$\Omega_b h^2$	0.02222 ± 0.00023
$\Omega_c h^2$	0.1197 ± 0.0022
$100\theta_{MC}$	1.04085 ± 0.00047
τ	0.078 ± 0.019
$\ln(10^{10} A_s)$	3.089 ± 0.036
n_s	0.9655 ± 0.0062
H_0	67.31 ± 0.96
Ω_m	0.315 ± 0.013
σ_8	0.829 ± 0.014
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014

[Planck collab., 2015]

Aside: Dark Matter Day?



Newsweek

What Is Dark Matter Day? Scientists Launch First-Ever Event Celebrating Universe's Biggest Mystery

Dark matter makes up most of the universe, but scientists have no idea what it is.

By Hannah Osborne

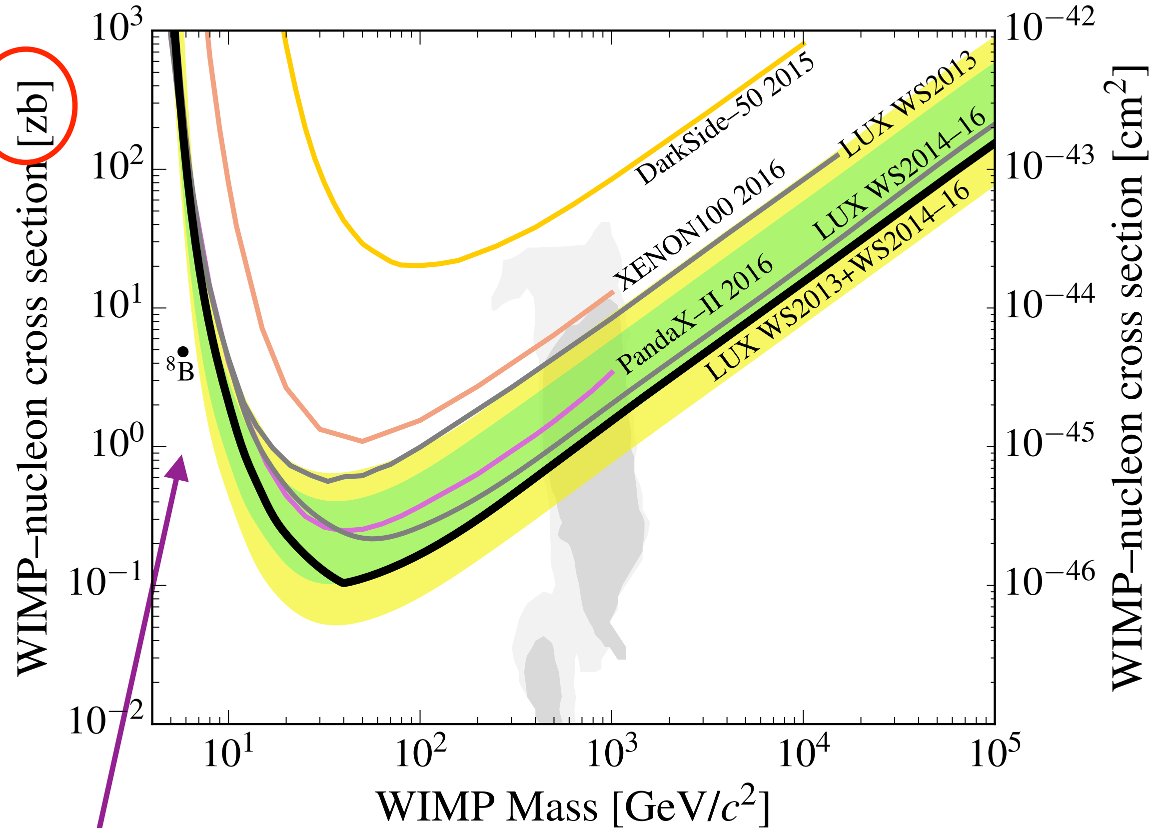
October 30, 2017

The Milky Way galaxy.

ESA/Hubble & NASA

But is it a WIMP?

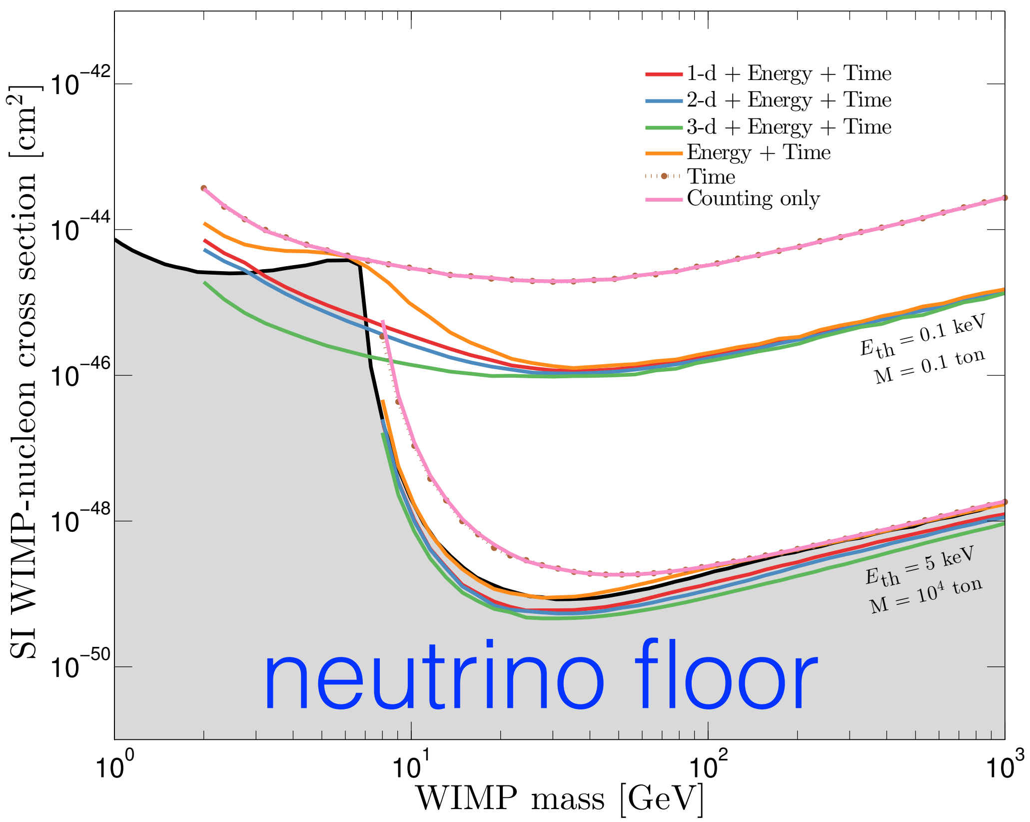
Today:



[LUX collab., 2016]

what's over here?

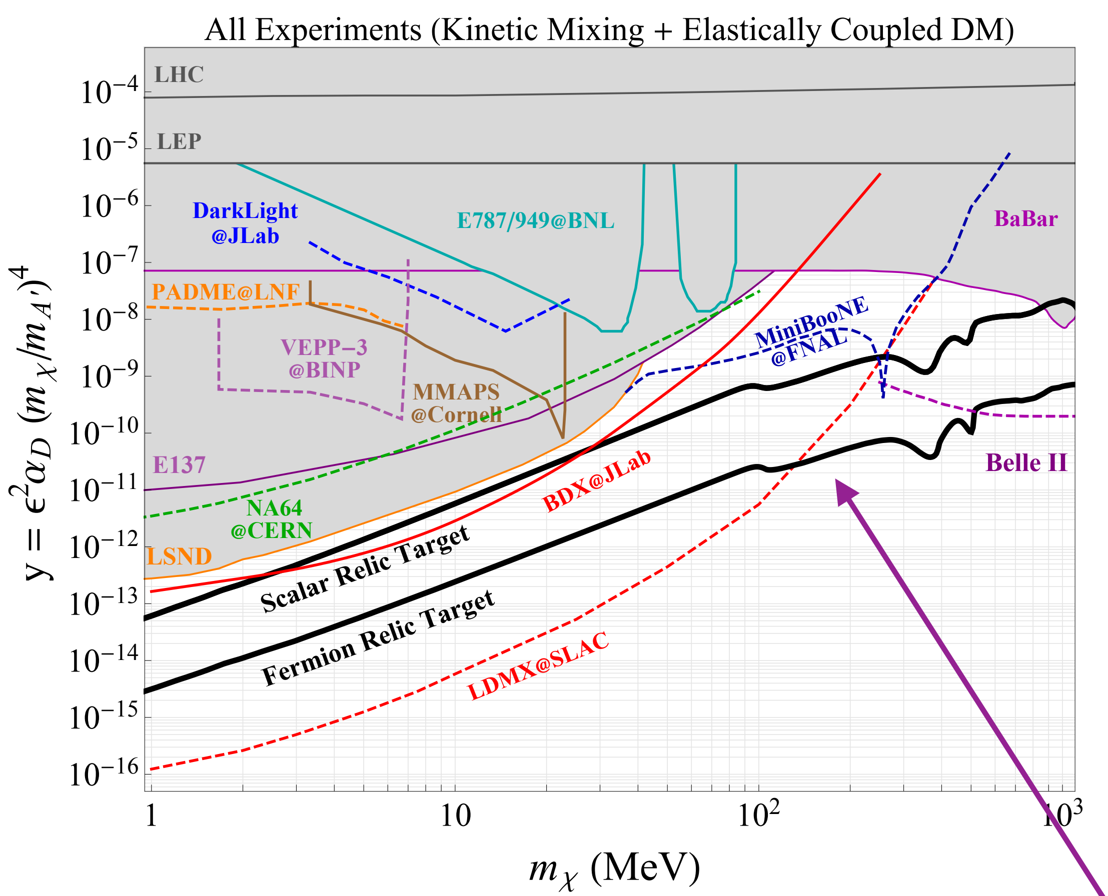
Idealized future:



[O'Hare et al., 1508.08061]

Sub-GeV DM

Theory motivation:

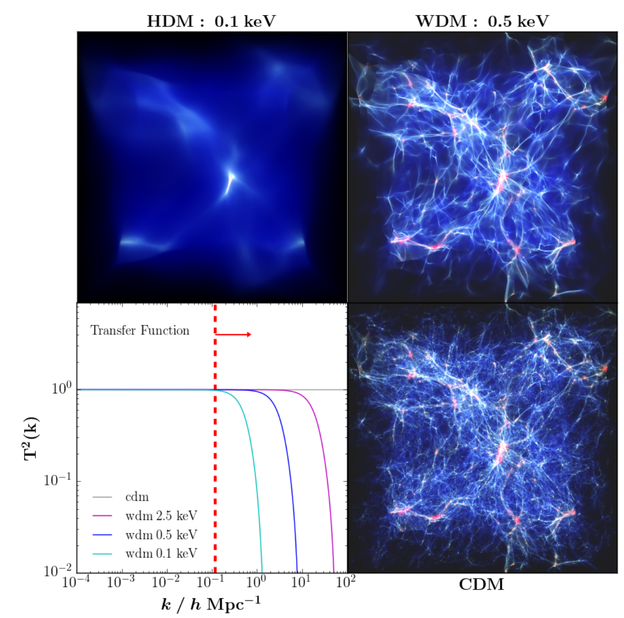


[SLAC Dark Sectors Workshop 2016 report]

MeV DM + MeV mediator + smallish couplings gives right relic abundance too!
Not just WIMPs

need to look here!

Astrophysical constraints:

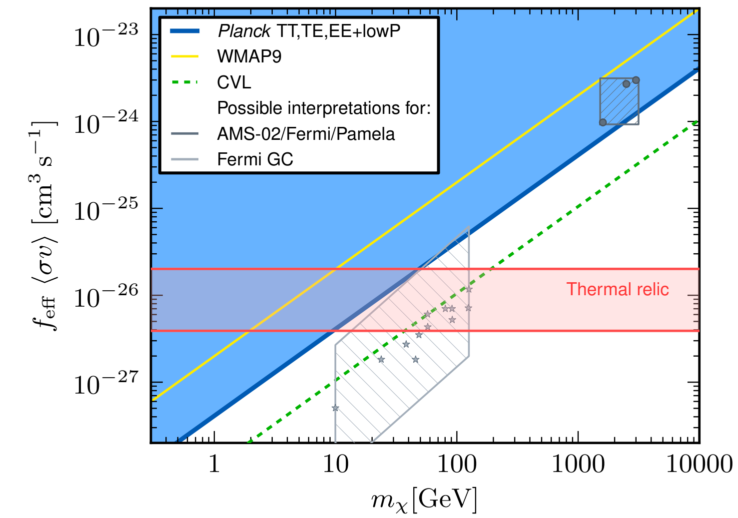


[Baur et al., 1512.01981]

Lyman α forest:

$m_{\mathrm{DM}} \gtrsim 3\ \mathrm{keV}$

(if thermally produced)



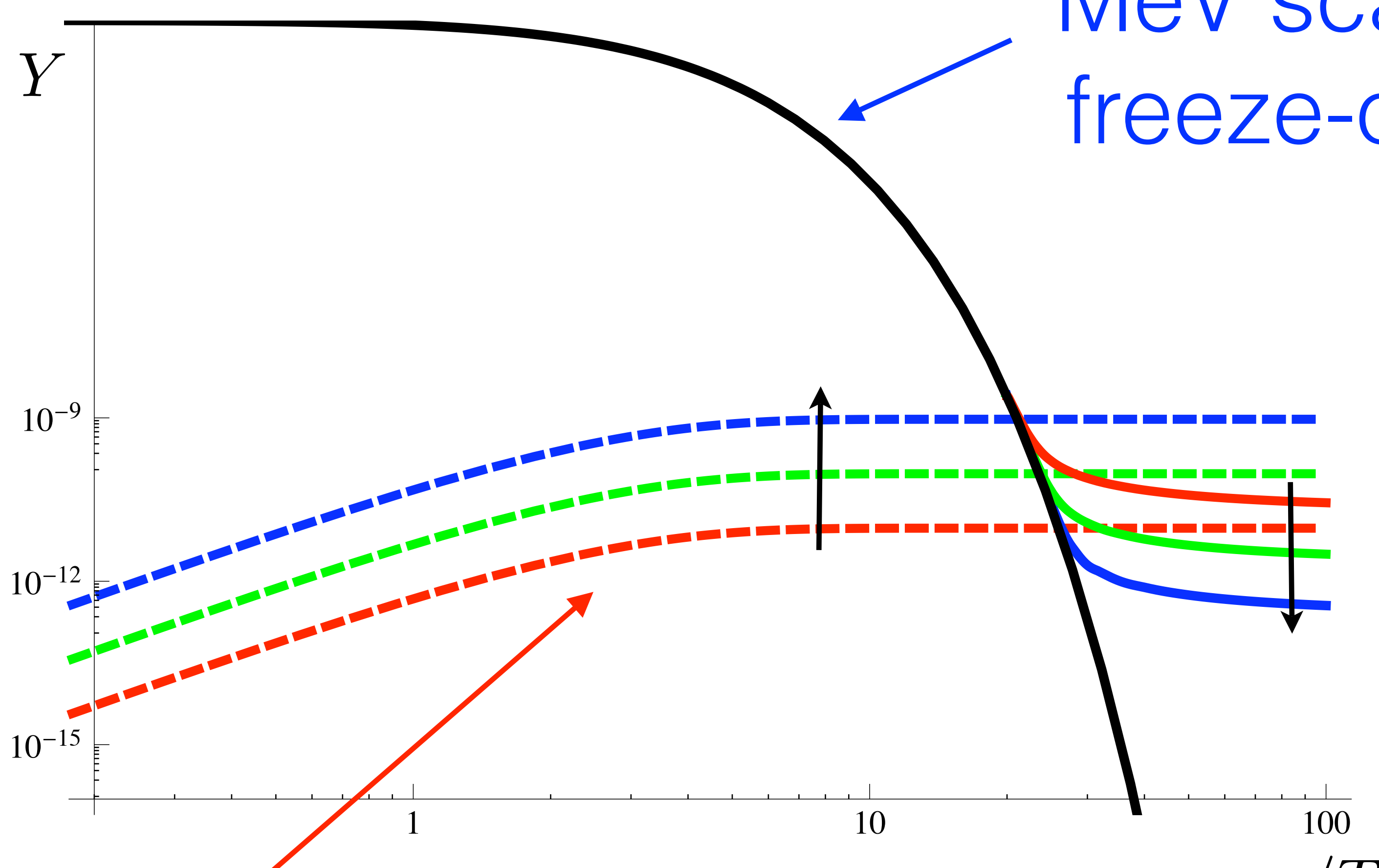
[Planck collab., 1502.01589]

CMB power injection: thermal relic can't annihilate through s-wave

Dark photon models

$$\mathcal{L} \supset \frac{\varepsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$

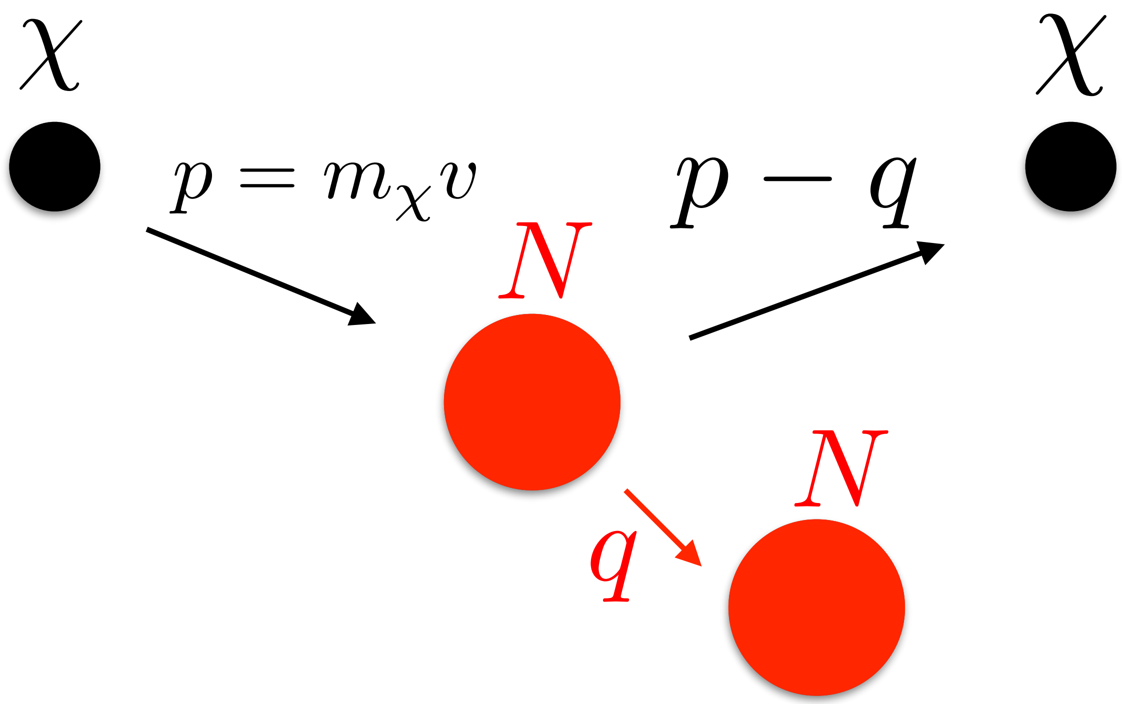
MeV scalar freeze-out: $m_{A'} \gtrsim \mathrm{MeV}$, $\alpha_D \varepsilon^2 \sim 10^{-9}$



[Hall et al., JHEP 2010]

keV fermion freeze-in: $m_{A'} \ll \mathrm{keV}$, $\alpha_D \varepsilon^2 \sim 10^{-28}$

“Standard” direct detection: nuclear recoil



$$\frac{1}{2} m_\chi v^2 \sim 1 \text{ eV} \left(\frac{m_\chi}{\text{MeV}} \right)$$

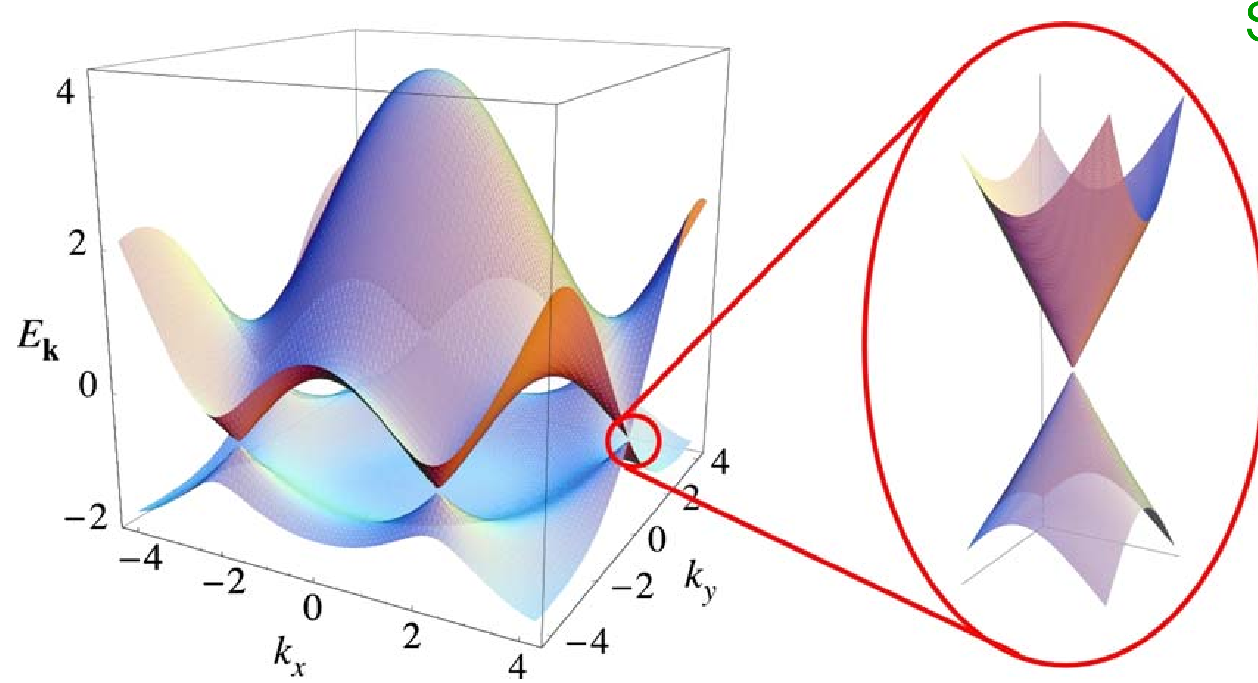
Only available for $m_\chi \sim m_N$,
way below keV thresholds

“Ping pong ball on bowling ball” kinematics:

$$q \sim 2 m_\chi v, \;\; E_{\text{NR}} = \frac{q^2}{2 m_N} \sim 10^{-4} \text{ eV} \left(\frac{m_\chi}{\text{MeV}} \right)^2 \left(\frac{10 \text{ GeV}}{m_N} \right)$$

Need MeV targets (electron) and eV thresholds for MeV DM;
even smaller (meV) thresholds for keV DM

Dirac materials: intro



slope of cone = v_F

$3 \times 10^{-3} c$ for graphene

[Castro Neto et al., Rev. Mod. Phys. 2009]

Dirac dispersion:

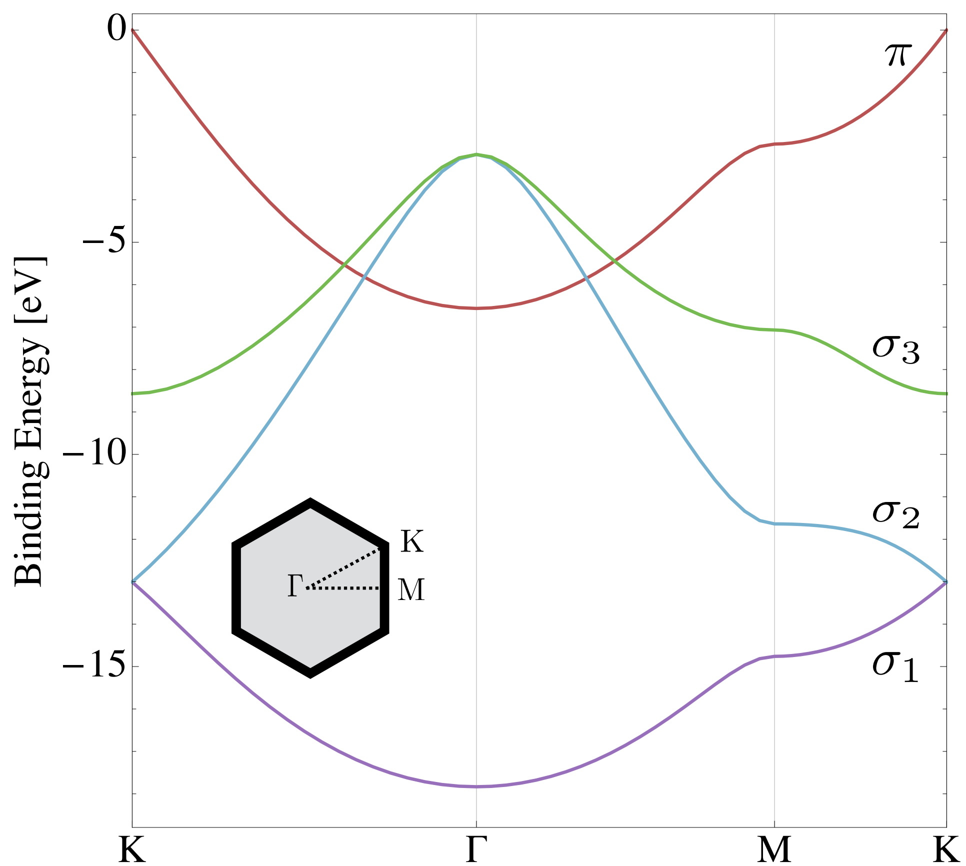
$$E^{\pm}_{\mathbf{k}} = \pm\sqrt{v_F^2 \mathbf{k}^2 + \Delta^2}$$

Electrons behave “relativistically” with $c \to v_F, \alpha \to \dfrac{\alpha}{\kappa v_F}$

Pointlike Fermi surface but high conductivity $(\Delta \lesssim \mathcal{O}(\mathrm{meV}))$

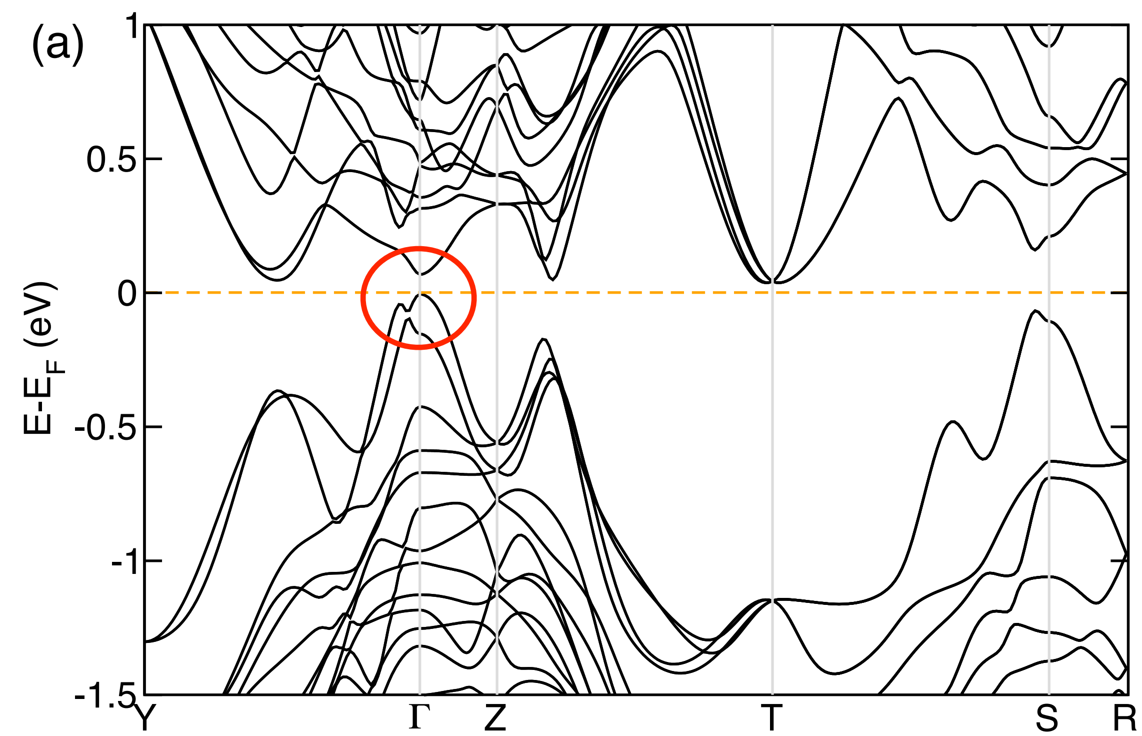
Dirac materials for DM

2D Graphene



- eV ionization energies
- Large conductivity change when one electron removed

3D Dirac semimetal ($ZrTe_5$)



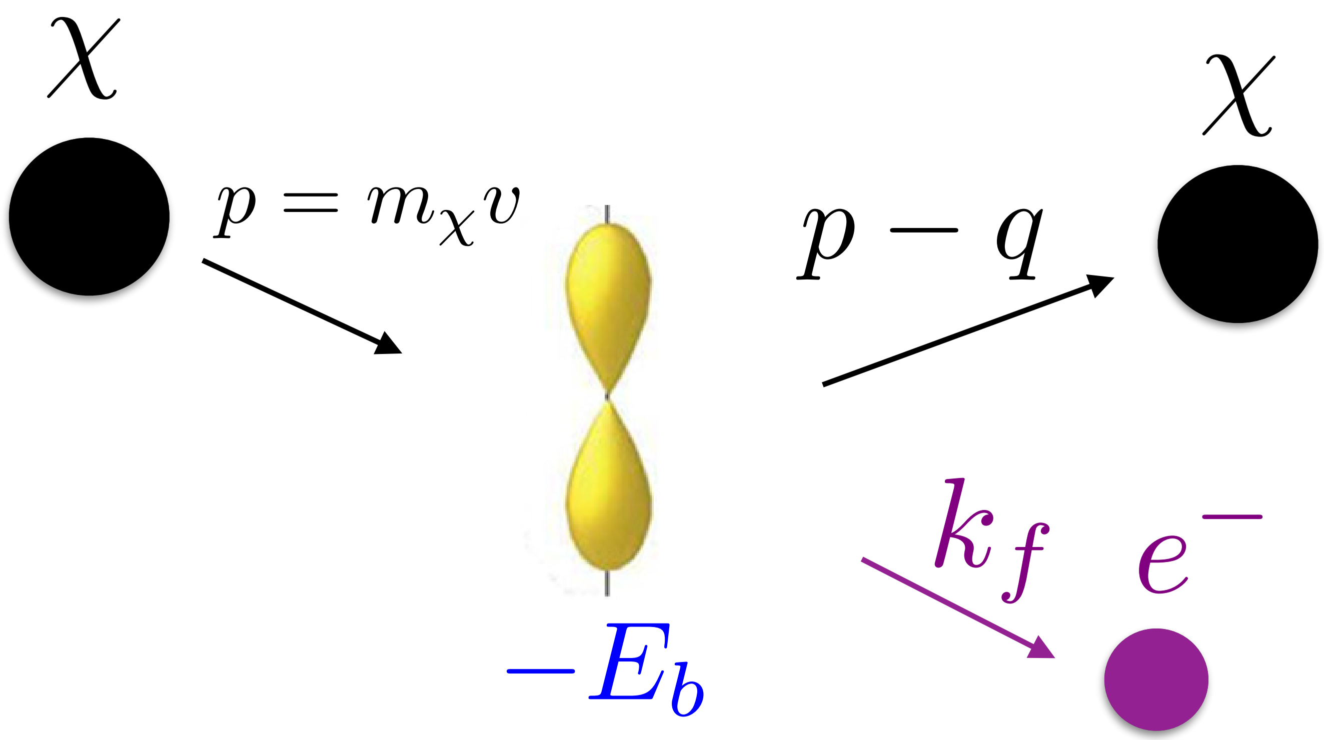
- meV-scale excitation energies
- No in-medium screening

New class of materials for DM detection!

MeV-GeV DM w/graphene

[Hochberg, YK, Lisanti, Tully, Zurek, Phys. Lett. B 2017, 1606.08849]

DM-induced ionization



$$\Delta E_e \equiv E_b + \frac{k_f^2}{2m_e} = \vec{q} \cdot \vec{v} - \frac{q^2}{2m_\chi}$$

Two key features:

1. Initial state not a momentum eigenstate: k_f and q independent

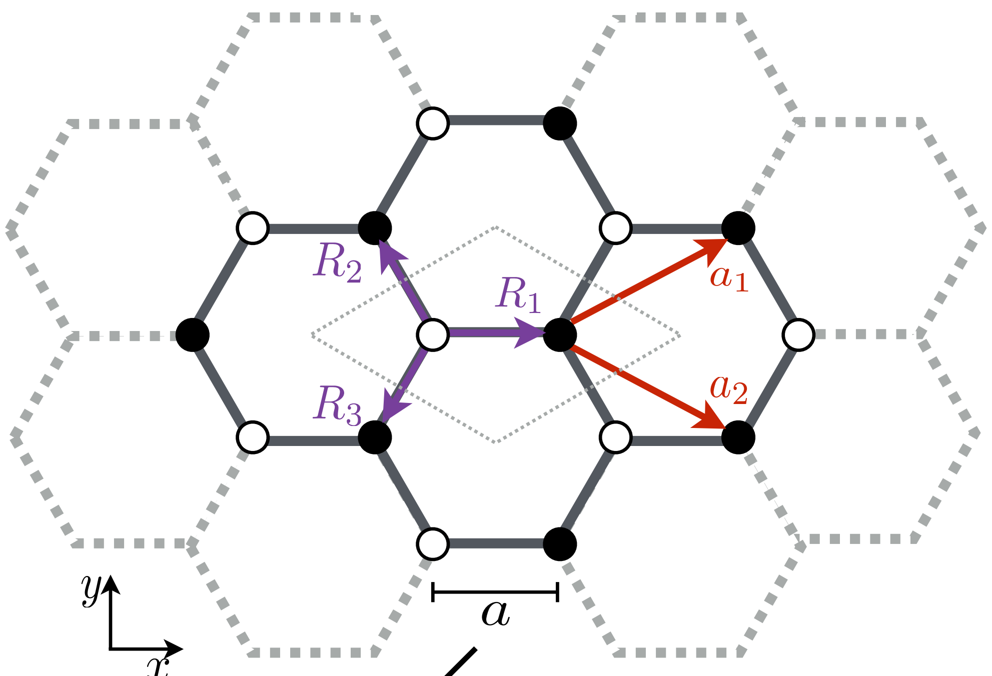
2. Wavefunction suppression at large q:

$$q_{\text{typ}} \sim \frac{1}{a_0} \sim 4 \text{ keV}$$

$v \sim 10^{-3} \implies$ rate maximized for $\Delta E_e \lesssim 4 \text{ eV}$

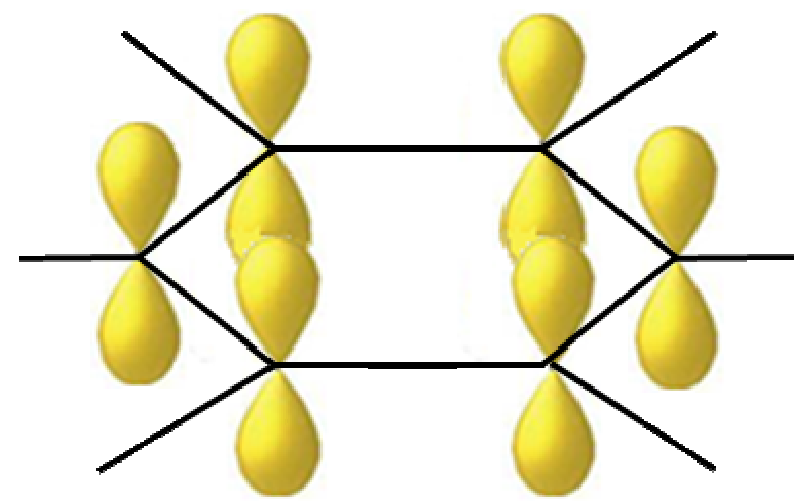
Graphene 101

1-atom thick lattice of carbon

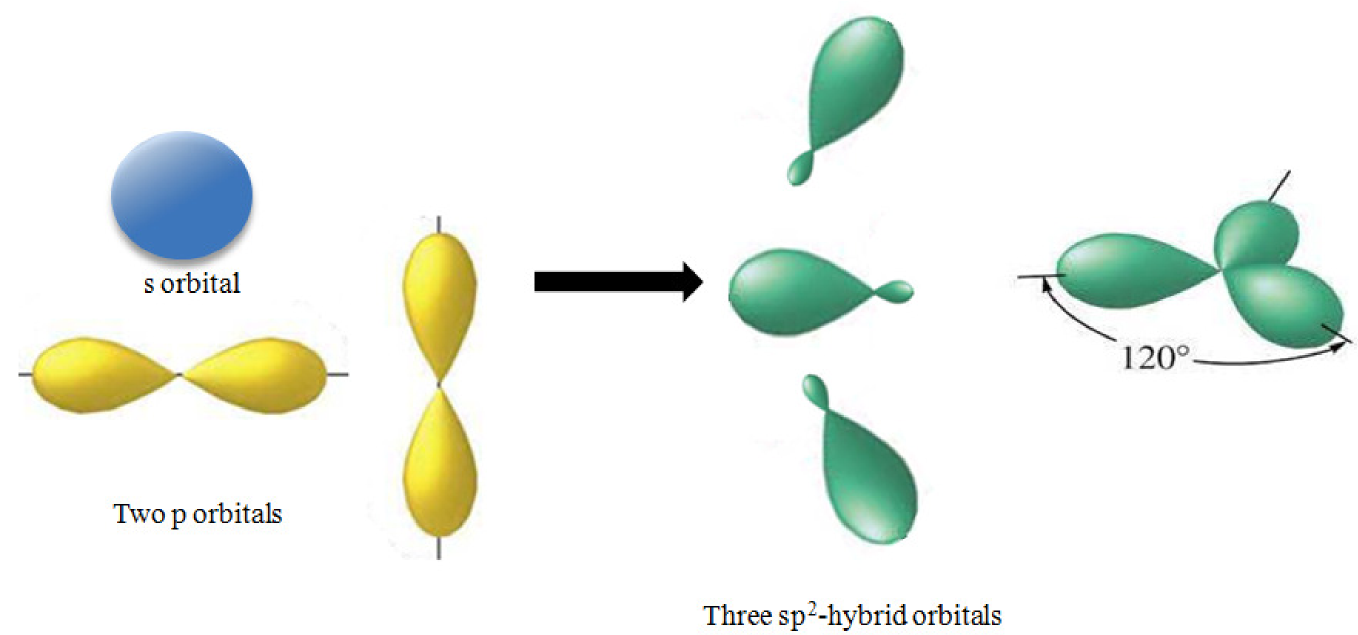


$$0.142 \text{ nm} \simeq \frac{2\pi}{8.7 \text{ keV}}$$

4 valence electrons per atom:



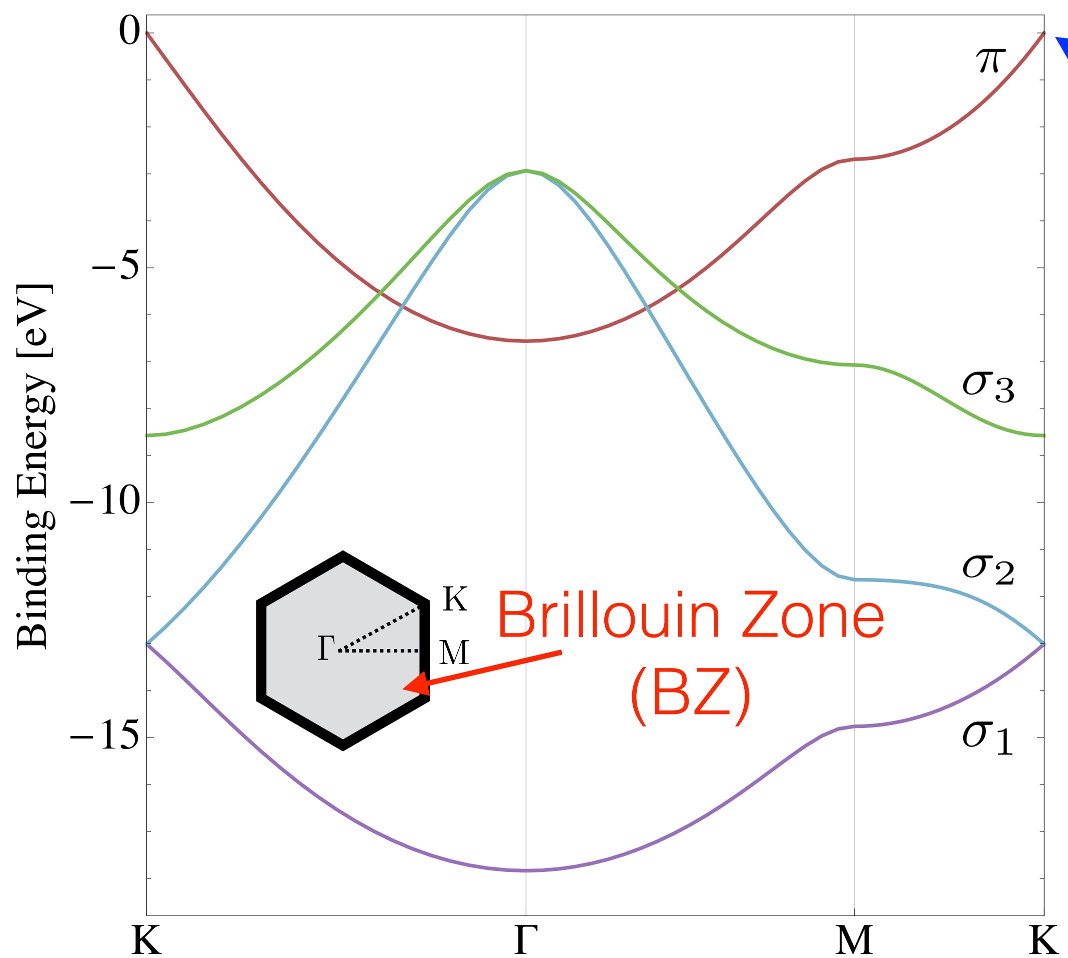
π electrons



σ electrons

Electron energies

Binding energy depends on lattice momentum ℓ :



Dirac point: massless charge carriers, large electron mobility

can dominate DM scattering cross section, need to treat these too!

To eject electron to vacuum, need to overcome work function

$$E_{\text{ion}} = E_b + \Phi \qquad \sim 4 \text{ eV}$$

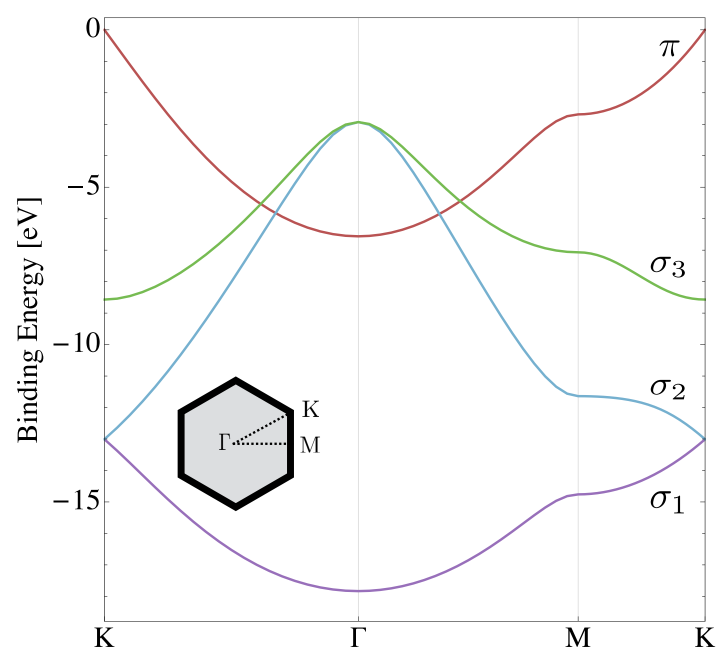
(tunable)

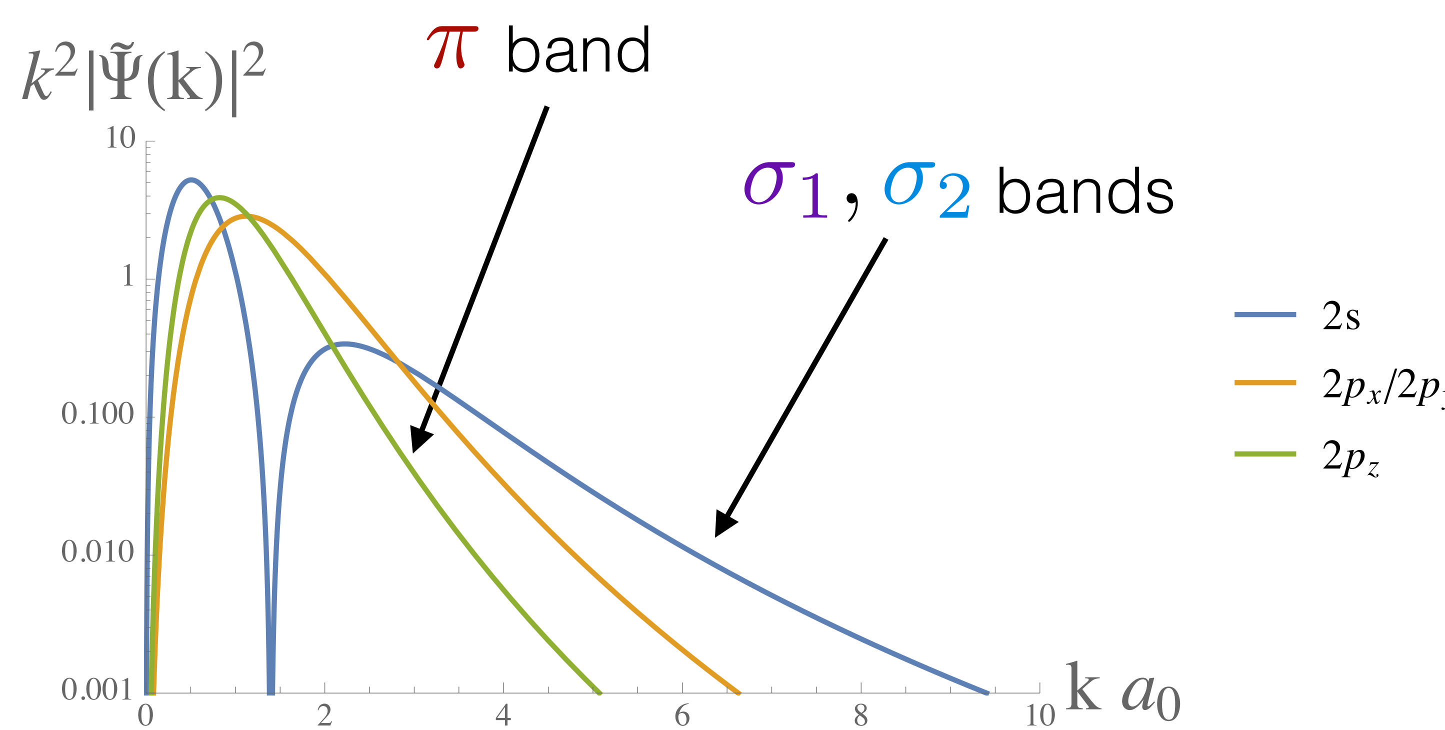
Cross sections and rates

Single point in BZ:

$$v\,\sigma_i(\ell) = \frac{\bar{\sigma}_e}{\mu_{e\chi}^2}\int \frac{d^3k_f}{(2\pi)^3}\,\frac{d^3q}{4\pi}\,|F_{\rm DM}(q)|^2\,\left|\widetilde{\Psi}_i(\ell,\mathbf{q}-\mathbf{k}_f)\right|^2\delta\left(\frac{k_f^2}{2m_e}+E_i(\ell)+\Phi+\frac{q^2}{2m_\chi}-\mathbf{q}\cdot\mathbf{v}\right)$$

Note: no Fermi factor





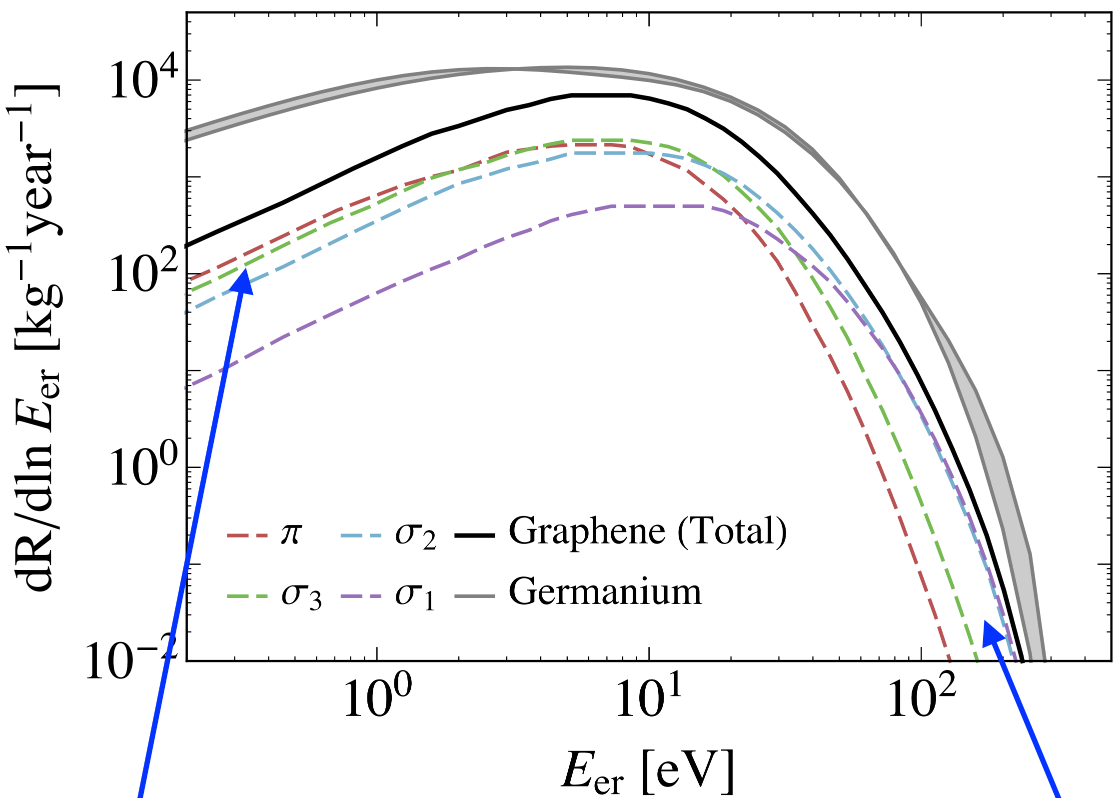
Sum over bands, integrate over BZ and DM velocity:

$$R = 2\sum_{i=\pi,\sigma_{1,2,3}}\frac{\rho_\chi}{m_\chi}\,N_{\rm C}\,A_{\rm uc}\int_{\rm BZ}\frac{d^2\ell}{(2\pi)^2}\,d^3v\,g(\mathbf{v})\;v\,\sigma_i(\ell)$$

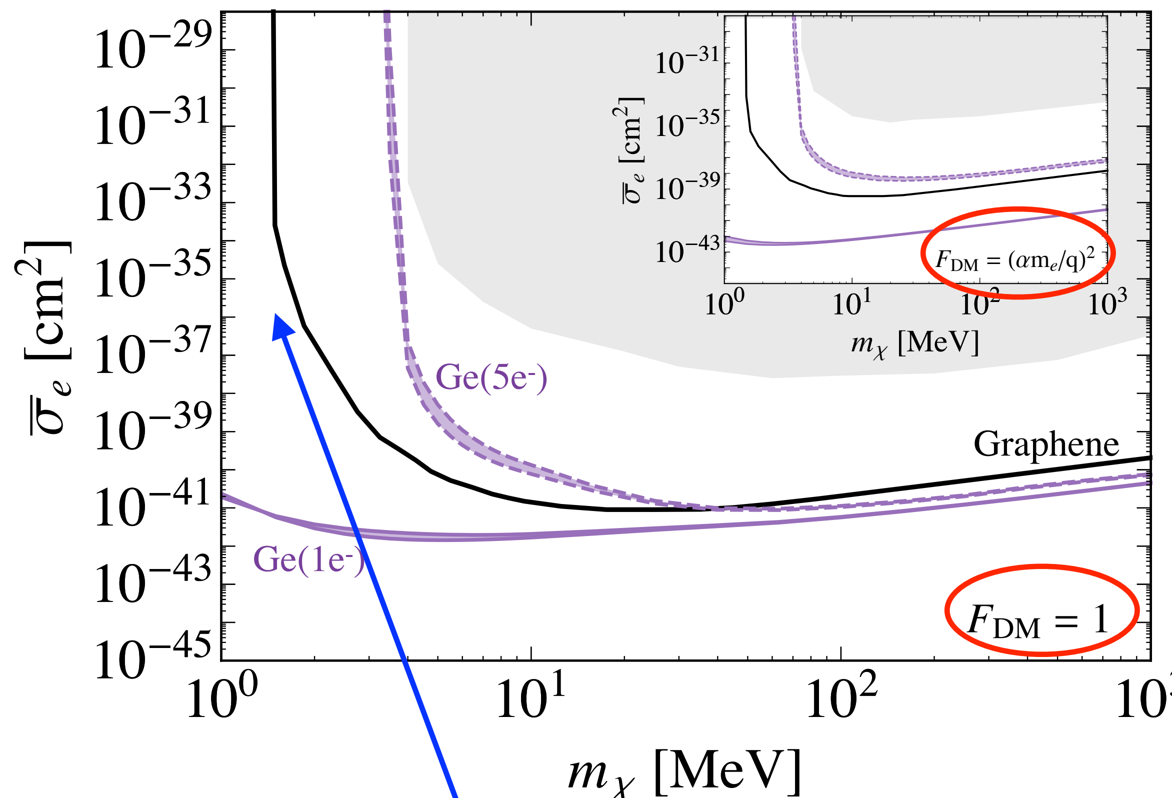
Directionally-averaged rate

$g(\mathbf{v}) \equiv g(v)$, Standard Halo Model

Energy spectrum
(F_{DM} = 1, 100 MeV DM)



Reach



Binding energy dominates

Momentum tail dominates

work function sets threshold

Comparable reach to conventional semiconductors!

Directional detection

Key observation: ionized e[-] kinematics
highly correlated with initial DM direction

$$\widetilde{\phi}(\mathbf{q}-\mathbf{k}_f) \sim \frac{1}{\left(a_0^2\,|\mathbf{q}-\mathbf{k}_f|^2 + (Z_{\text{eff}}/2)^2\right)^{l+1}}$$

Dominated by min. allowed q,
kinematics forces $\mathbf{q} \parallel \mathbf{v}$

Minimized when $\mathbf{k}_f \parallel \mathbf{q} \parallel \mathbf{v}$

$$\widetilde{\Psi}_\pi(\ell,\mathbf{k}) \propto \widetilde{\phi}_{2p_z}(\mathbf{k})\left\{1 + e^{i\varphi_\ell}\left(e^{i(\ell+\mathbf{k})\cdot\mathbf{R}_1} + e^{i(\ell+\mathbf{k})\cdot\mathbf{R}_2} + e^{i(\ell+\mathbf{k})\cdot\mathbf{R}_3}\right)\right\}$$

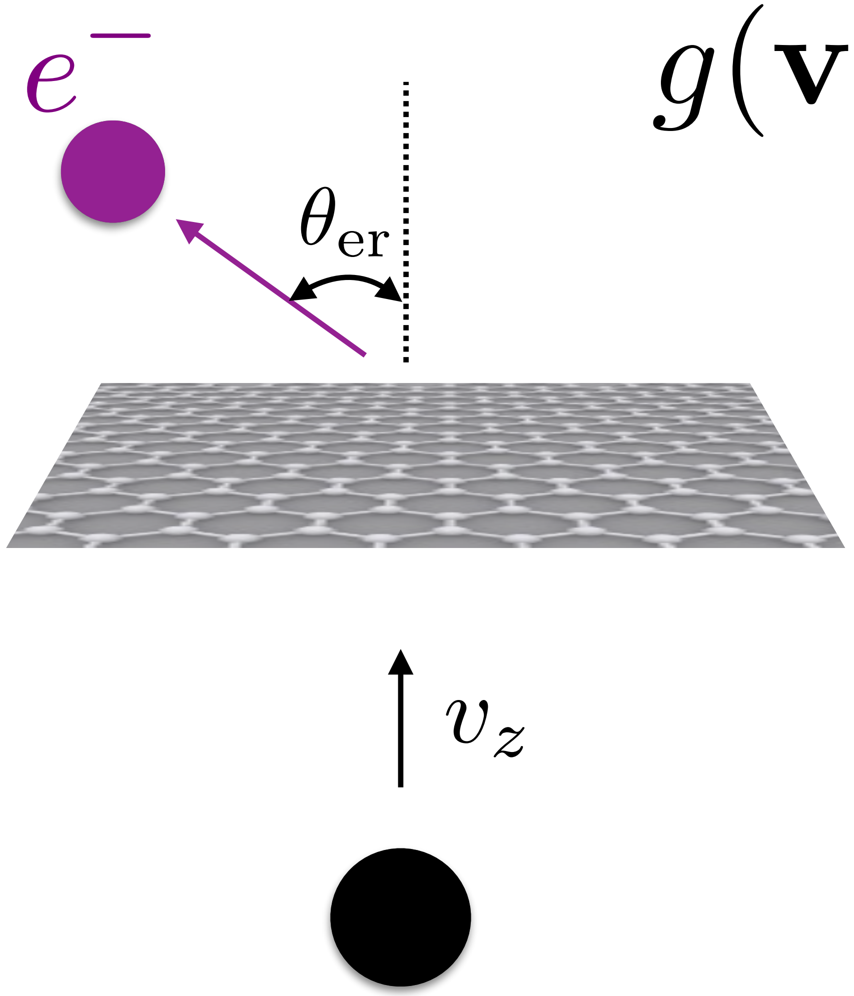
Diffraction effects when $k_f \sim 2\pi/a$

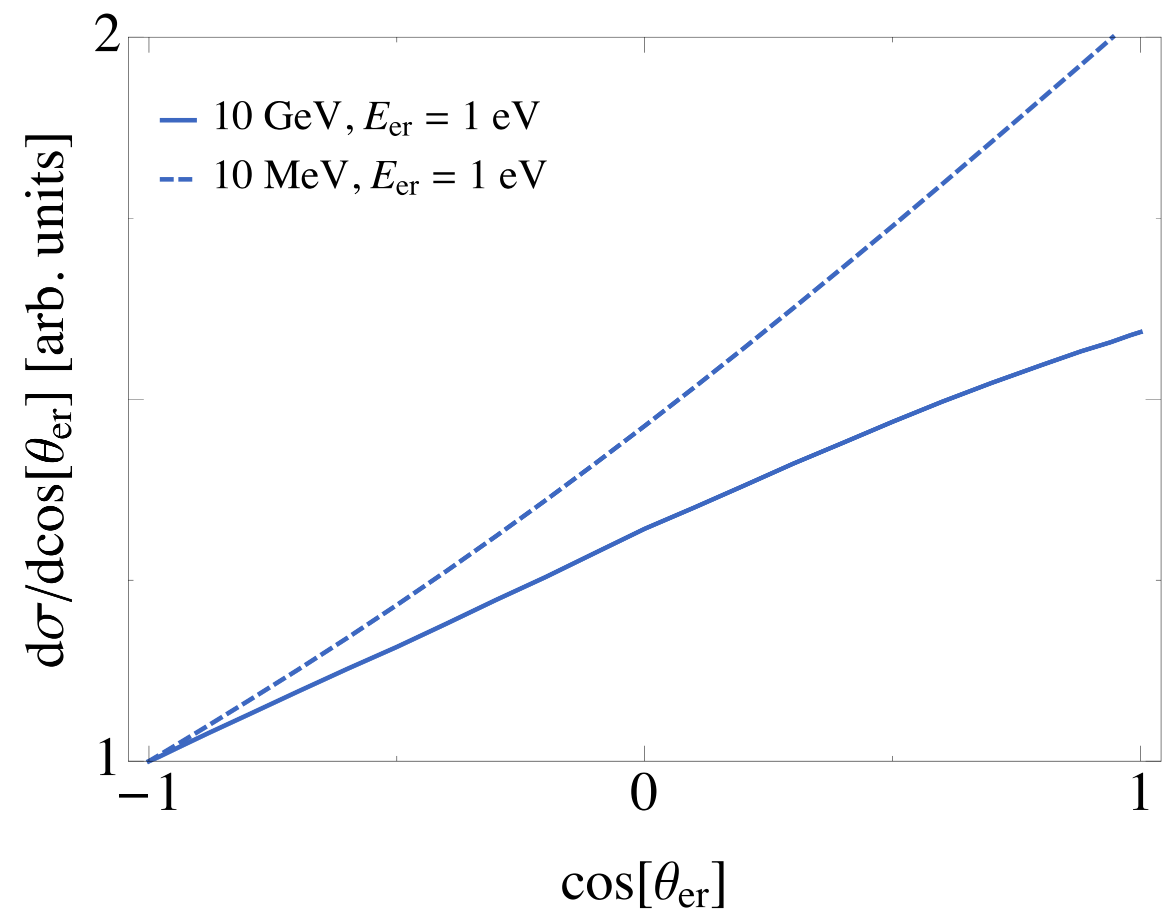
Two-dimensional target: directional information preserved!

(not just graphene: e.g. monolayer gold [Drukier et al., 1206.6809])

Perpendicular DM stream

$$g(\mathbf{v}) = \delta(\mathbf{v} - v_z \mathbf{z})$$





$$\widetilde{\phi}_{2\mathrm{p}_z}(\mathbf{q}-\mathbf{k}) \approx \widetilde{\mathcal{N}}\, a_0^{3/2} \frac{a_0\,(q_z - k_z)}{\left(a_0^2\,|\mathbf{q}-\mathbf{k}|^2 + (Z_{\rm eff}/2)^2\right)^3}$$

Numerator suppresses forward scattering for heavy DM

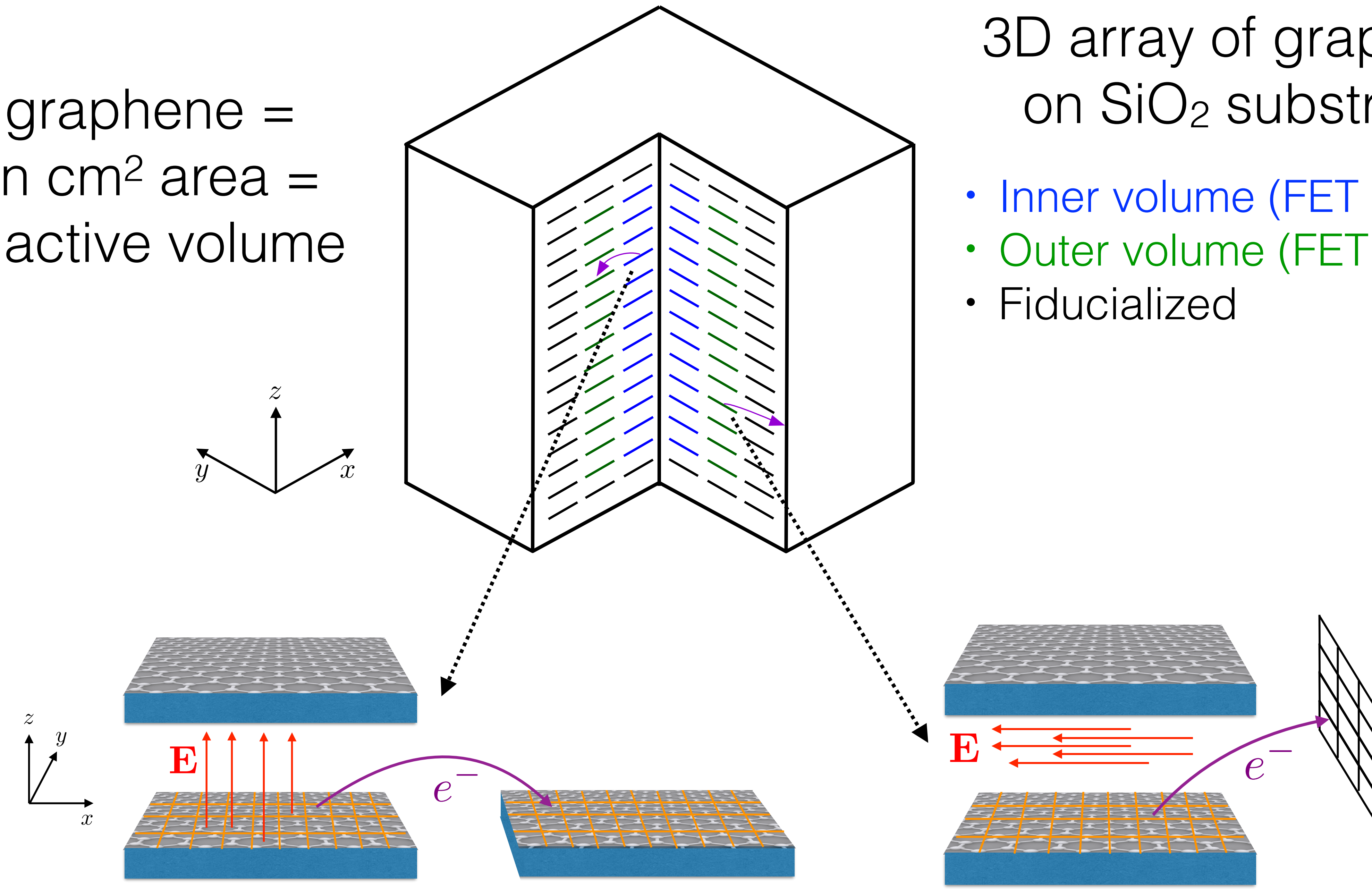
PTOLEMY-G^3

(under development at LNGS)

0.4 kg graphene =
10 billion cm^2 area =
1000 m^3 active volume

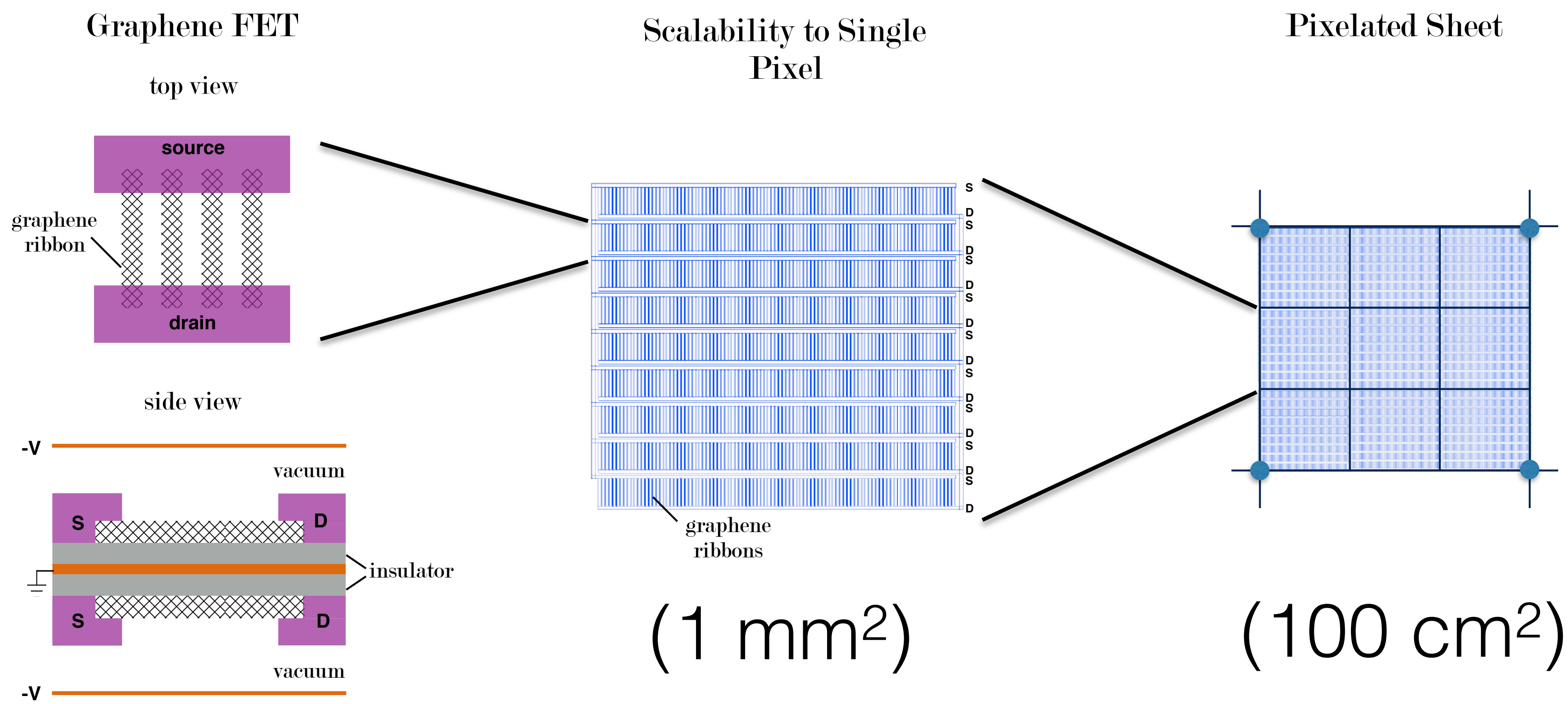
3D array of graphene on SiO_2 substrate:

- Inner volume (FET to FET)
- Outer volume (FET to cal.)
- Fiducialized



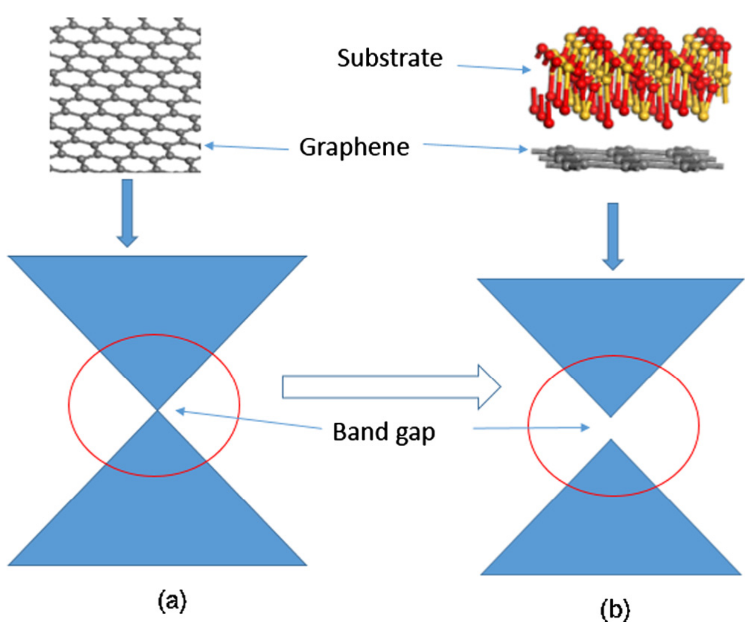
Graphene FET can act as target and detector!

Graphene FET details

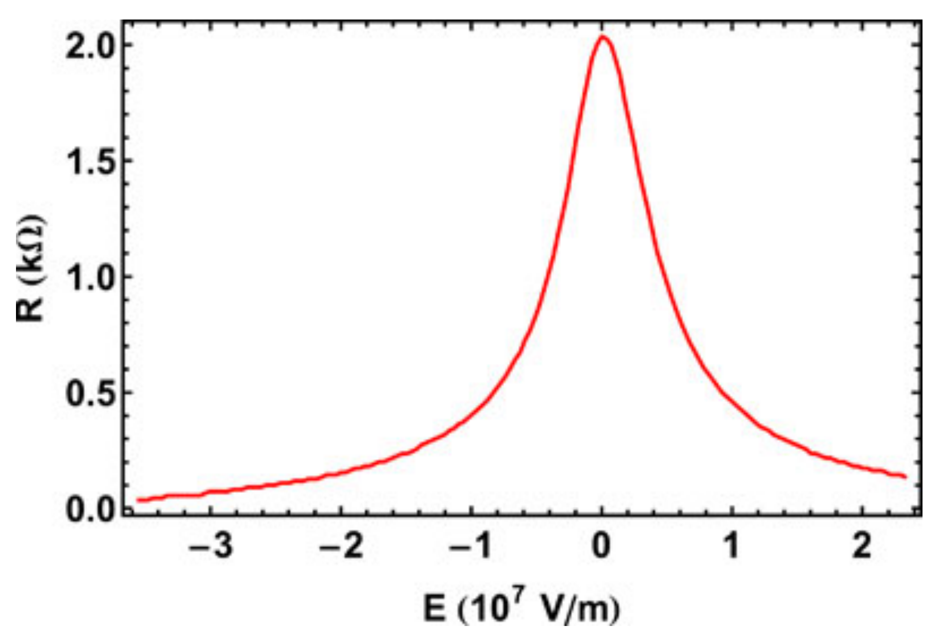


(1 mm^2)

(100 cm^2)



[Kiarii et al., Chem Phys. Lett 2017]

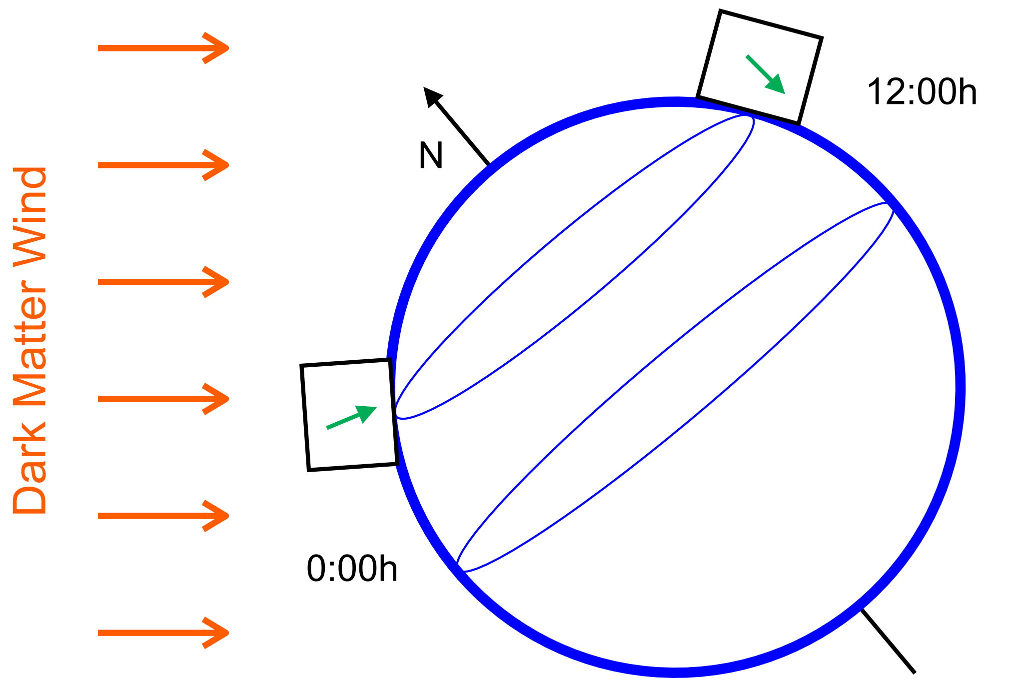


[Foxe et al., IEEE Nano 2012]

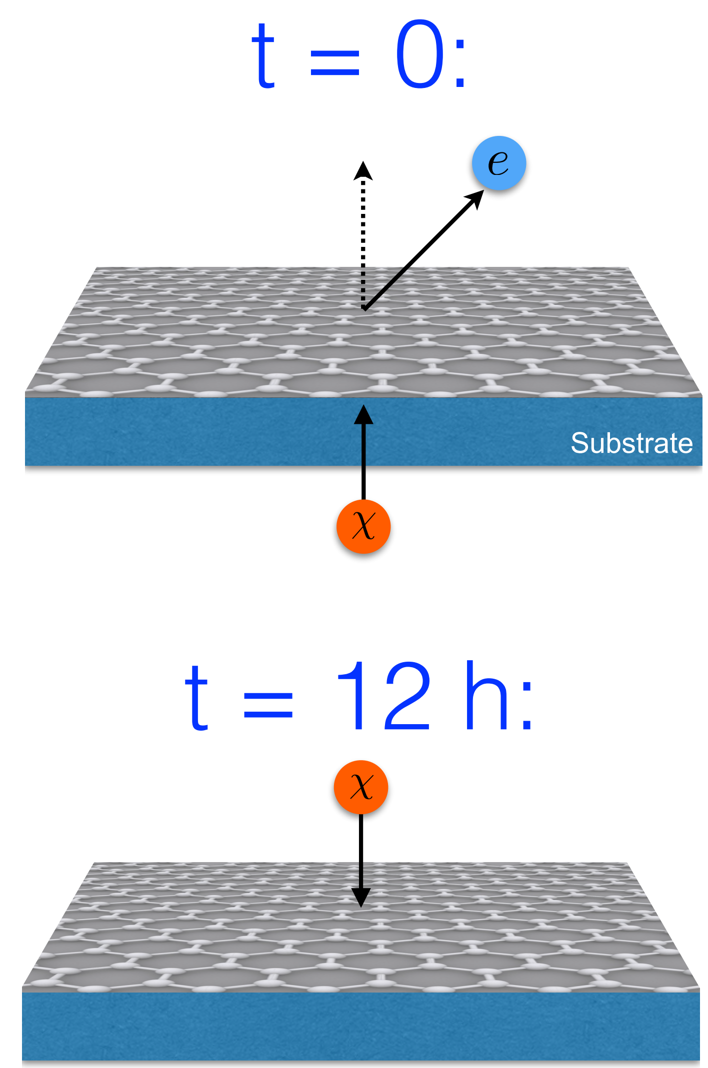
Large resistance drop with change in local electric field

Directional detection w/PTOLEMY-G^3

Zeroth-order: head-tail discrimination



[D. Spergel, PRD 1988]



$$R(t=0) \simeq 2R(t=12\text{ h})$$

$\Longrightarrow$ 70 events to exclude unmodulated rate at 95% c.l.

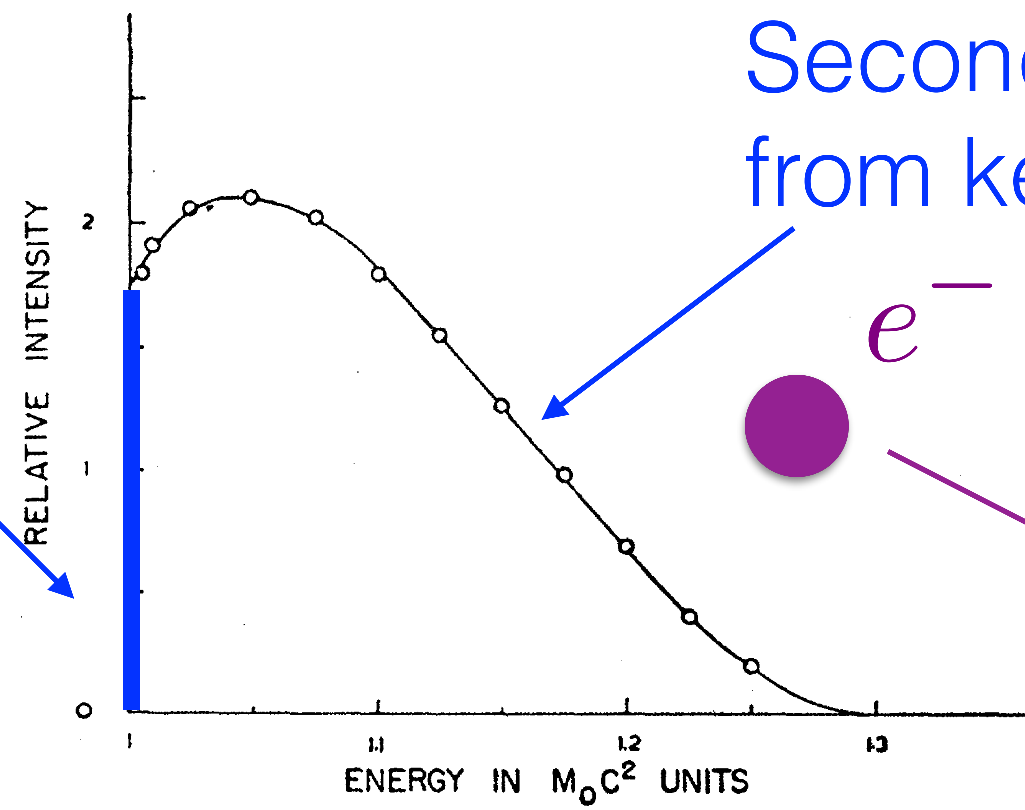
Use FET time-of-flight and pixellation for full 3D directionality

Backgrounds

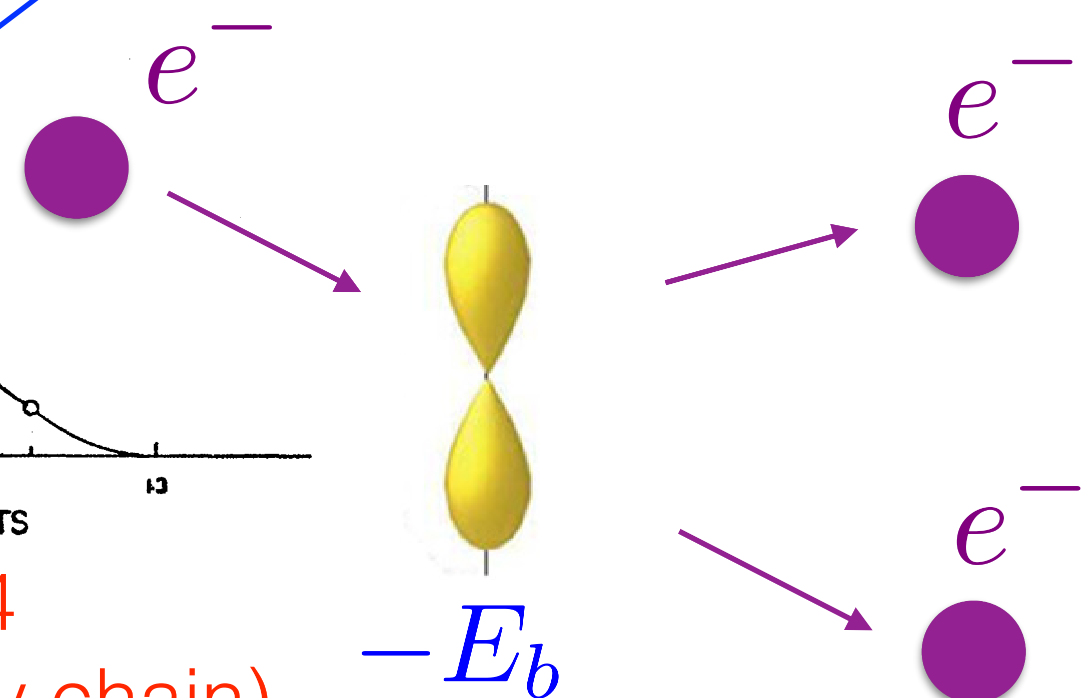
Two categories:

Primary eV spectrum

Secondary eV spectrum from keV primary scattering



Carbon-14
(also radon decay chain)



Borexino: ^{14}C fraction of 10^{-18}, can get 10^{-23} w/mass spectroscopy

Would reduce background to 1-2 events/yr

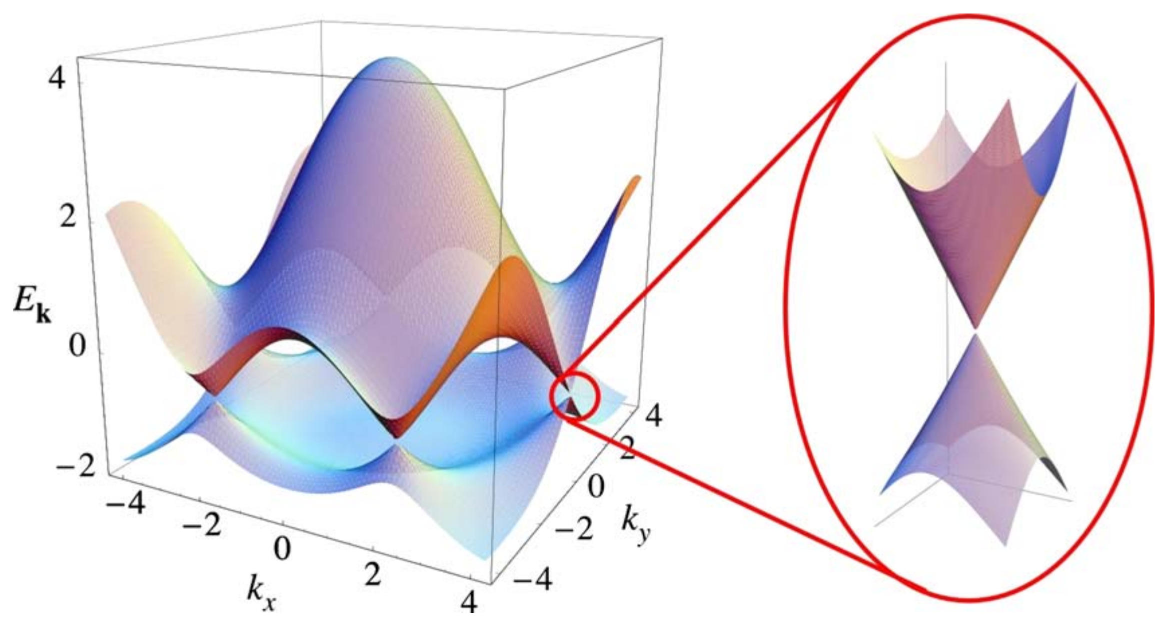
keV-MeV DM w/semimetals

[Hochberg, YK, Lisanti, Zurek, Grushin, Ilan, Liu, Weber, Griffin, Neaton, 1708.08929]

Graphene for keV DM?

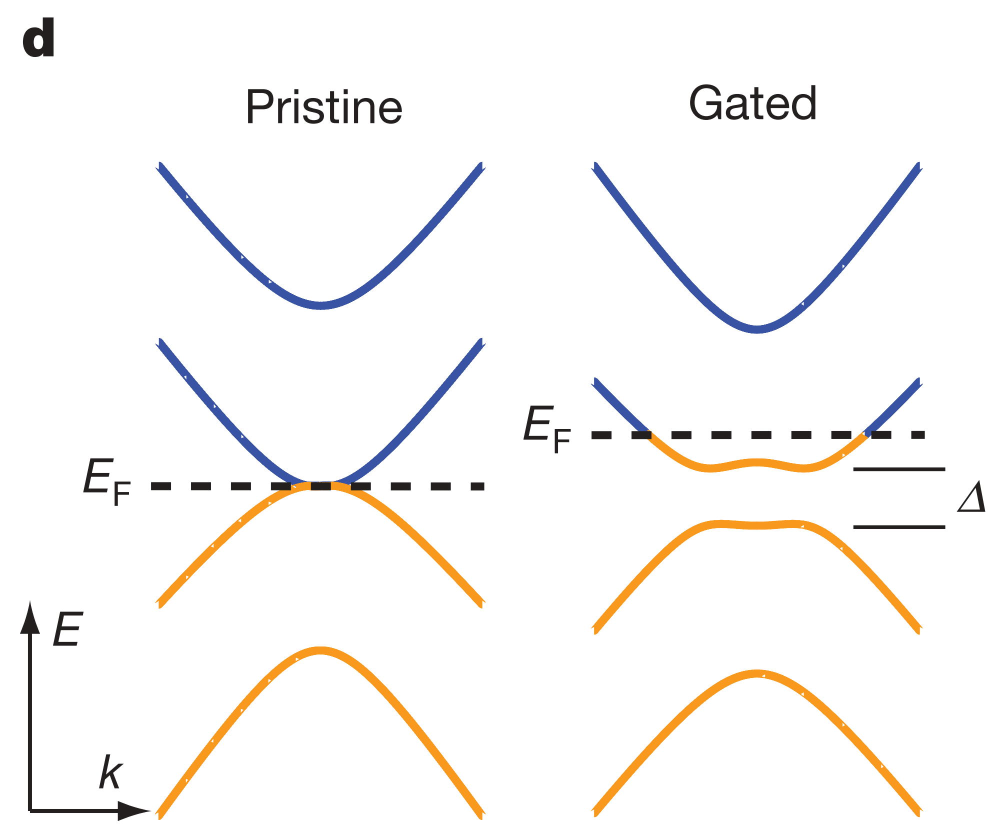
Recall: keV DM has ~meV kinetic energy

Monolayer



[Castro Neto et al., Rev. Mod. Phys. 2009]

Bilayer



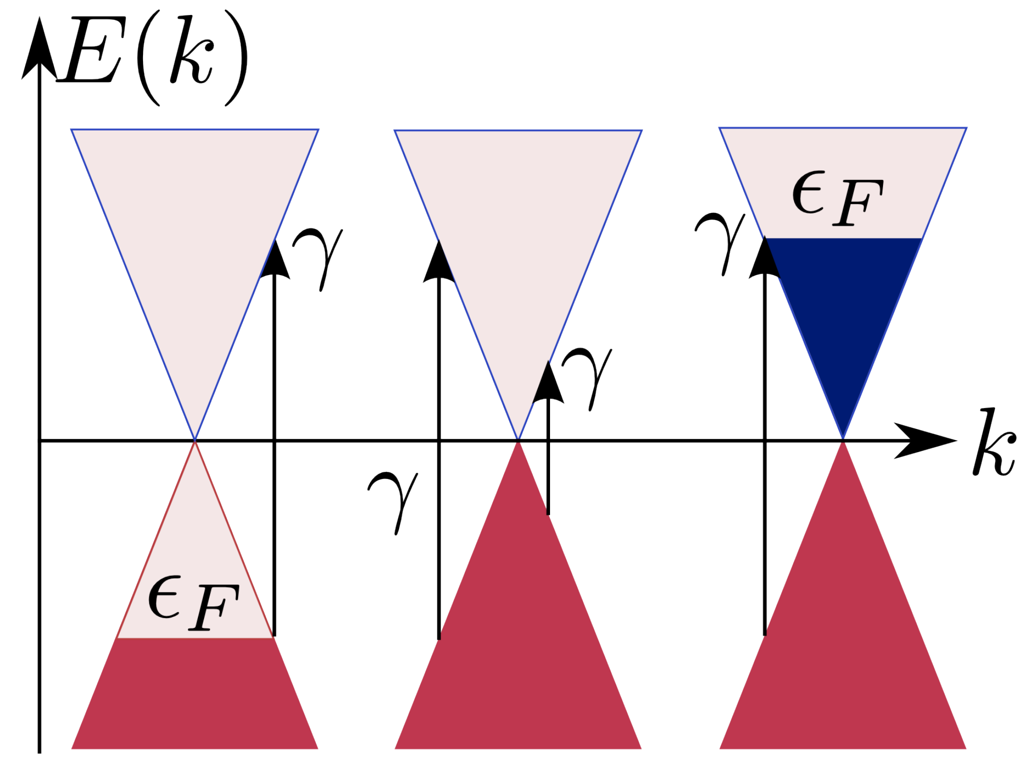
[Zhang et al, Nature Lett. 2009]

Gap Δ is continuously tunable 0-250 meV

Newton vs. Fermi

$v_{\rm DM} \sim 10^{-3} c$

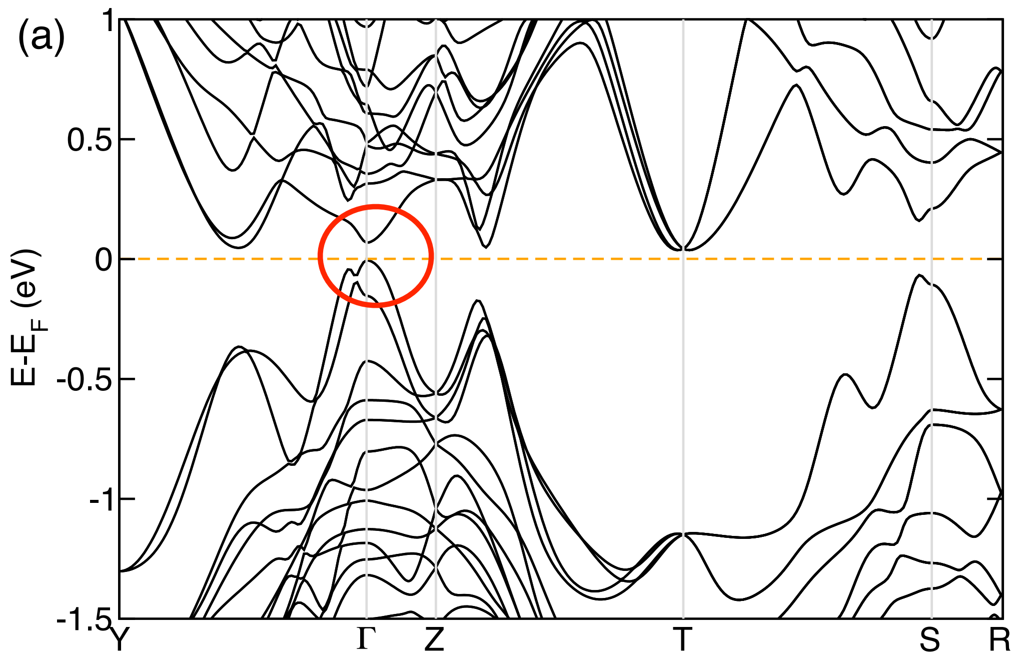
$v_F = 3 \times 10^{-3} c$

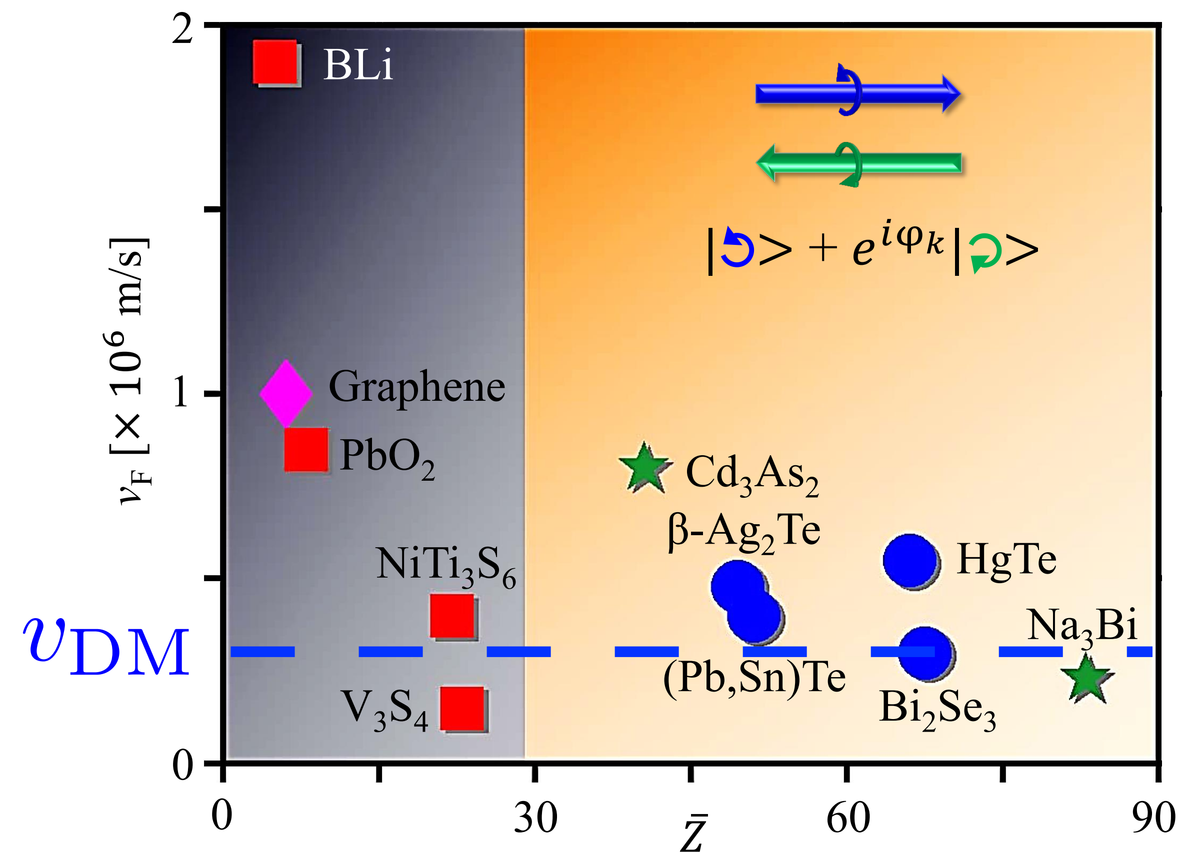


kinematically forbidden for $v_{\rm DM} < v_F$

Unfortunate coincidence for DM direct detection!

Dirac semimetals = "3D Graphene"



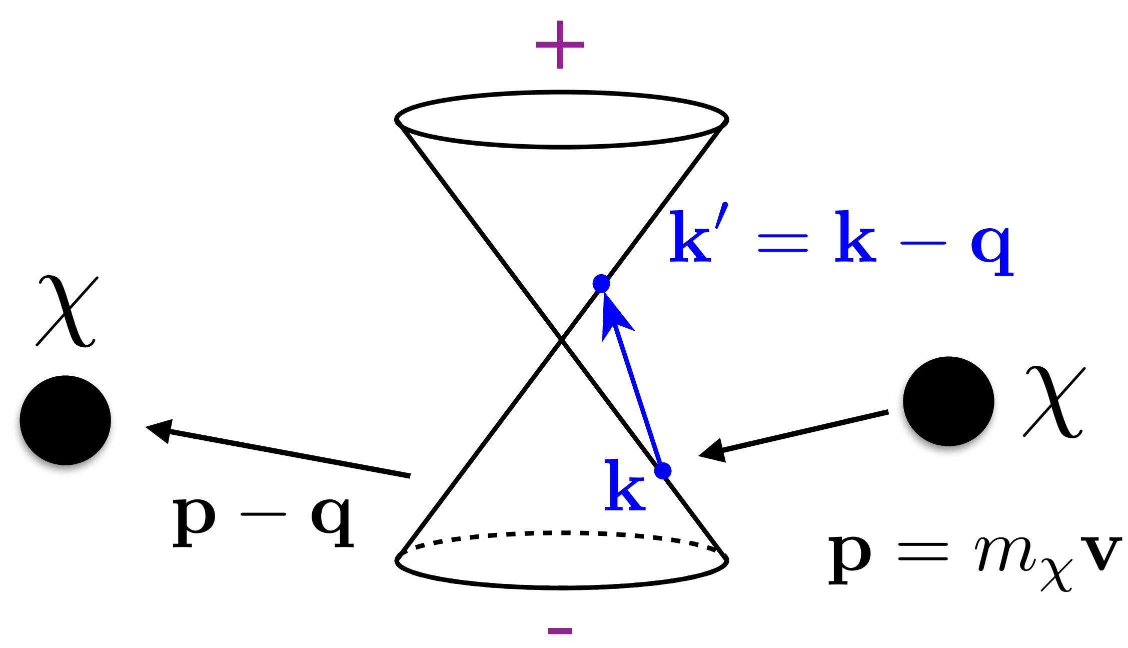


[Dolui & Das 1412.2607]

Advantages over graphene:

- Many candidate materials, range of Fermi velocities
- Bulk material: more exposure
- Anisotropic crystal: directionality for excitations

Scattering rate



$$R_{-,\mathbf{k}\to+,\mathbf{k}'} = \frac{\rho_\chi}{m_\chi}\frac{\overline{\sigma}_e}{8\pi\mu_{\chi e}^2}\int d^3\mathbf{q}\,\frac{1}{|\mathbf{q}|}\eta\left(v_{\min}(|\mathbf{q}|,\omega_{\mathbf{k}\mathbf{k}'})\right)|F_{\rm DM}(q)|^2|\mathcal{F}_{\rm med}(q)|^2|f_{-,\mathbf{k}\to+,\mathbf{k}'}(\mathbf{q})|^2$$

Lots of form factors:

$F_{\rm DM}(q)$: DM model. Const. for heavy mediator, ~$1/q^2$ for light med.

$\mathcal{F}_{\rm med}(q)$: Effects of target medium. Can have strong q^2 dependence!

$f_{-,\mathbf{k}\to+,\mathbf{k}'}(\mathbf{q})$: Wavefunction overlap btw. initial and final electron states

Transition form factor

Wavefunctions near Dirac point are simple!
Just borrow results from Peskin & Schroeder…

$$H_{\boldsymbol{\ell}} = \begin{pmatrix} 0 & v_F \boldsymbol{\ell}\cdot\boldsymbol{\sigma} - i\Delta \\ v_F \boldsymbol{\ell}\cdot\boldsymbol{\sigma} + i\Delta & 0 \end{pmatrix}, \qquad E^{\pm}_{\boldsymbol{\ell}} = \pm\sqrt{v_F^2 \boldsymbol{\ell}^2 + \Delta^2}.$$

$$f_{-,\mathbf{k}\to+,\mathbf{k}'}(\mathbf{q}) \equiv \int d^3\mathbf{x}\, \Psi^*_{+,\mathbf{k}'}(\mathbf{x})\Psi_{-,\mathbf{k}}(\mathbf{x})\, e^{i\mathbf{q}\cdot\mathbf{x}}$$

Wavefunctions are just plane-wave eigenspinors:

$$|f_{-,\mathbf{k}\to+,\mathbf{k}'}(\mathbf{q})|^2 = \frac{1}{2}\frac{(2\pi)^3}{V}\left(1 - \frac{\boldsymbol{\ell}\cdot\boldsymbol{\ell}'}{|\boldsymbol{\ell}||\boldsymbol{\ell}'|}\right)\delta(\mathbf{q} - (\boldsymbol{\ell}' - \boldsymbol{\ell}))$$

Compare to semiconductors:

$$\left|f_{i\vec{k}\to i'\vec{k}'}(\vec{q})\right|^2 = \left|\sum_{\vec{G}\vec{G}'} \frac{(2\pi)^3\delta^3(\vec{k}+\vec{q}-\vec{k}'-\vec{G}')}{V} u^*_{i'}(\vec{k}'+\vec{G}+\vec{G}')u_i(\vec{k}+\vec{G})\right|^2$$

must be computed numerically

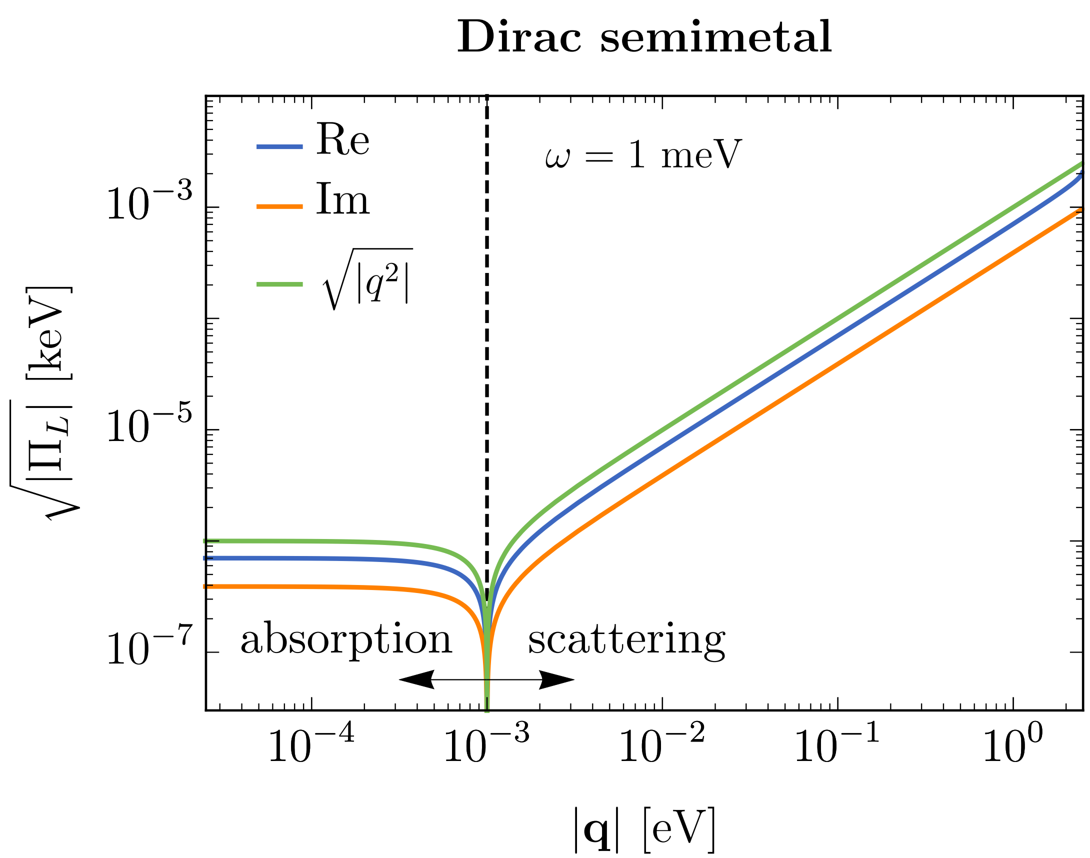
[Essig et al., JHEP 2016]

In-medium effects

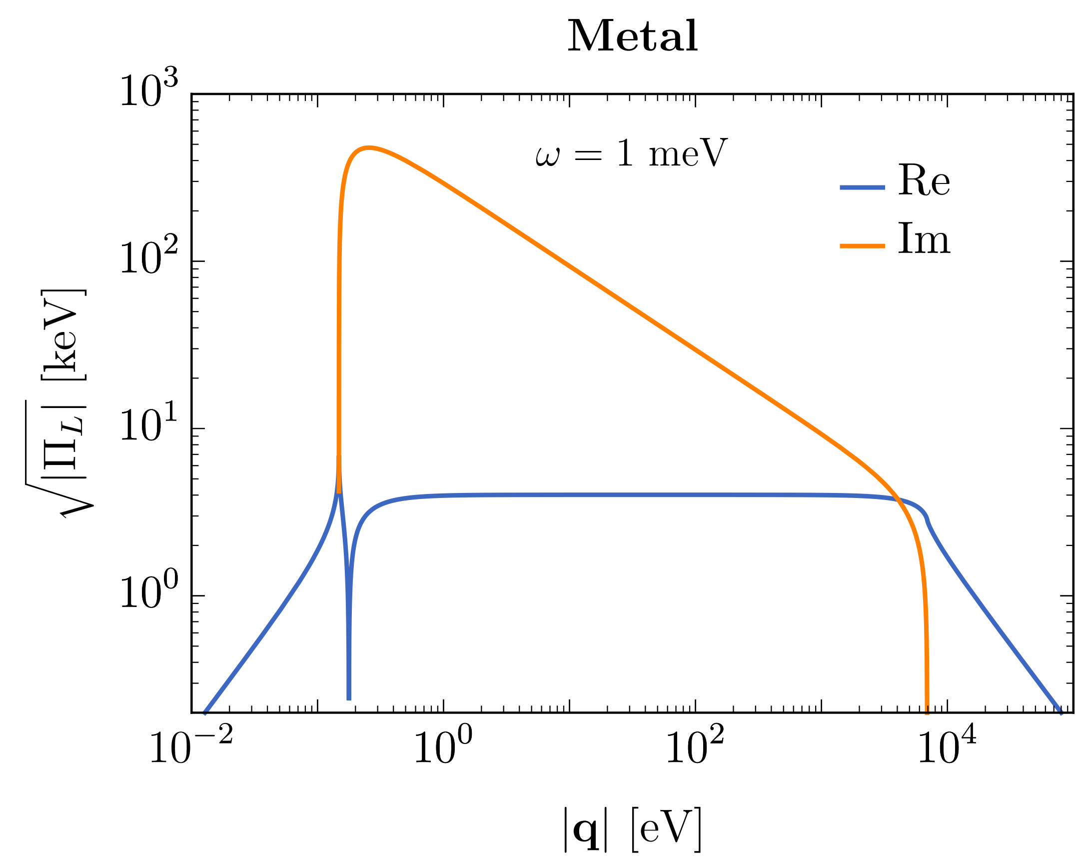
$$\mathcal{L} \supset -\frac{\varepsilon}{2} F_{\mu\nu} F'^{\mu\nu} \implies \mathcal{L} \supset \varepsilon e \frac{q^2}{q^2 - \Pi_{T,L}} \tilde{A}'^{T,L}_{\mu} J^{\mu}_{\mathrm{EM}}$$

[An, Pospelov, Pradler, 1302.3884 and 1304.3461; Hochberg, Pyle, Zhao, Zurek, 1512.04533]

Dark photon coupling to charged matter depends on dielectric properties of medium



scales as q^2 : charge renormalization



complicated behavior: keV-scale effective mass

In-medium form factor

$$\Pi(\mathbf{q},\omega) = q^2(1-\epsilon_r(\mathbf{q},\omega))$$

Dirac materials are carbon-copy of 3+1 QED!
Back to Peskin & Schroeder…

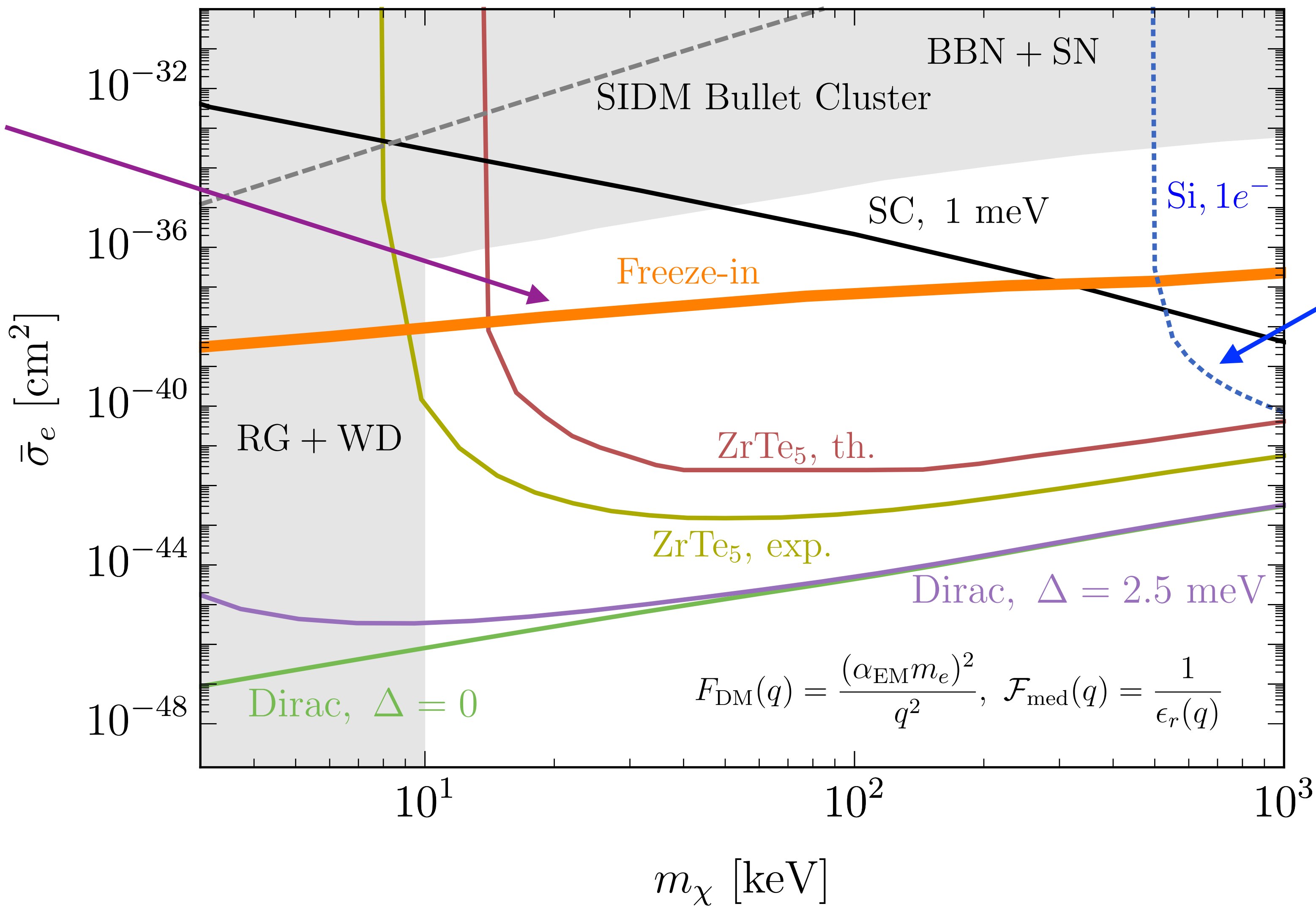
$$(\epsilon_r)_{\text{semimetal}} = 1 + \frac{e^2 g}{24\pi^2 \kappa v_F} \ln\left(\frac{4\Lambda^2}{\omega^2/v_F^2 - \mathbf{q}^2}\right)$$

$$\mathcal{F}_{\text{med}}(q) = \frac{1}{\epsilon_r(q)} \text{“}=\text{”}\ \frac{e(q)}{e_0}$$

Ward identity to the rescue:
dark photon does not acquire
an in-medium mass in Dirac materials!

Scattering reach (dark photon mediator)

covers all of freeze-in target below a keV!



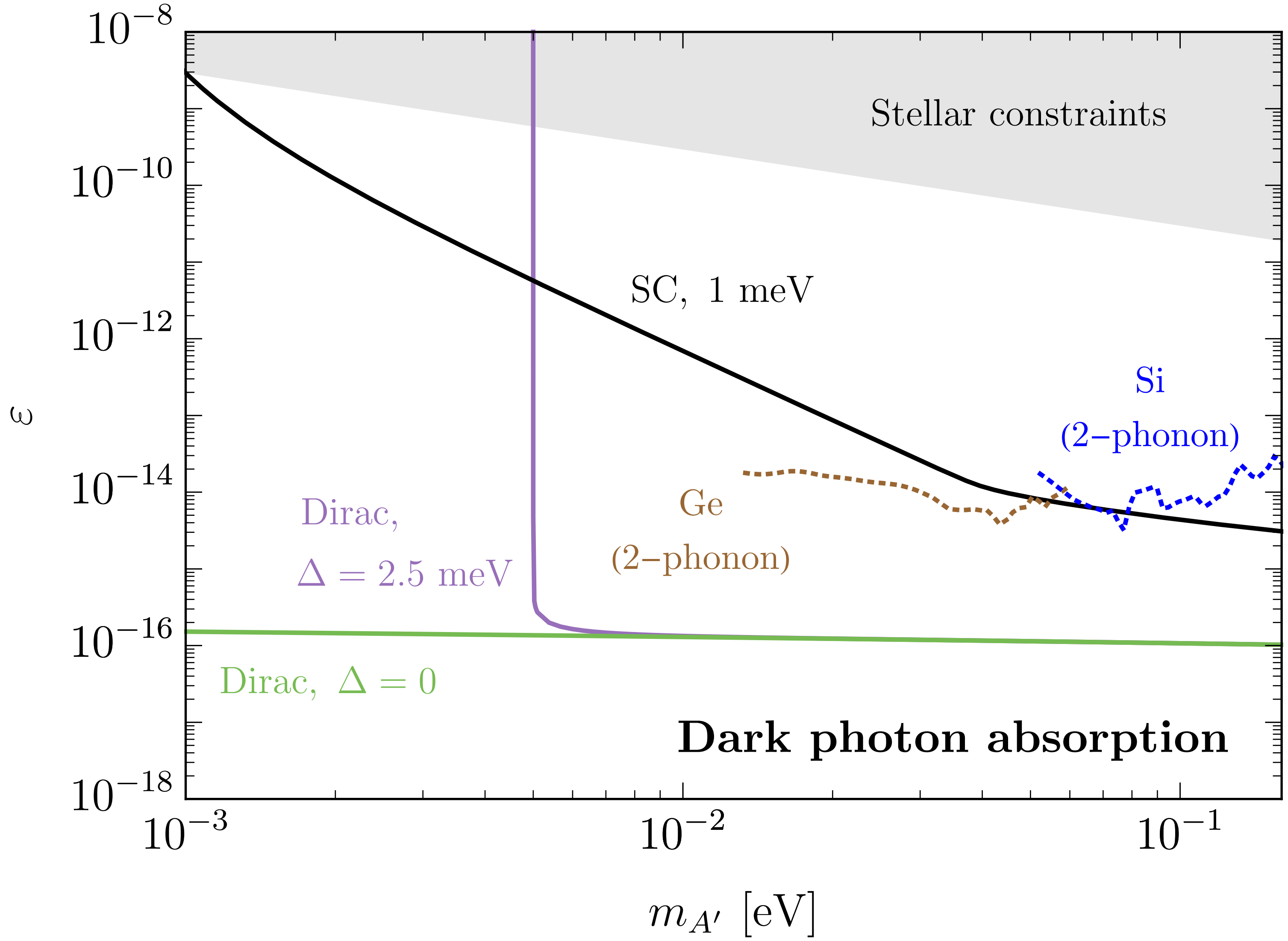
conventional semiconductors

Semimetals beat superconductors:

in-medium form factor is ~1, light dark photon stays light

Bonus: absorption!

$$R_{\mathrm{abs}} = \frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi}\langle n_T \sigma_{\mathrm{abs}} v_{\mathrm{rel}}\rangle_{\mathrm{DM}} \xrightarrow{\text{optical theorem}} \frac{1}{\rho_T}\rho_\chi \varepsilon_{\mathrm{eff}}^2 \,\mathrm{Im}\,\epsilon_r$$



Semimetals still beat superconductors!

Towards directional detection with semimetals

$$(\epsilon_r)_{ii} = 1 - \frac{1}{\mathbf{q}^2}\frac{e^2 g}{24\pi^2 \kappa_{ii}\, v_{F,x}v_{F,y}v_{F,z}}\left\{-\widetilde{\mathbf{q}}^2 \ln\left|\frac{4\widetilde{\Lambda}^2}{\omega^2-\widetilde{\mathbf{q}}^2}\right| - i\pi\widetilde{\mathbf{q}}^2\Theta(\omega-|\widetilde{\mathbf{q}}|)\right\}$$

$$\widetilde{\mathbf{q}} = (v_{F,x}q_x, v_{F,y}q_y, v_{F,z}q_z)$$

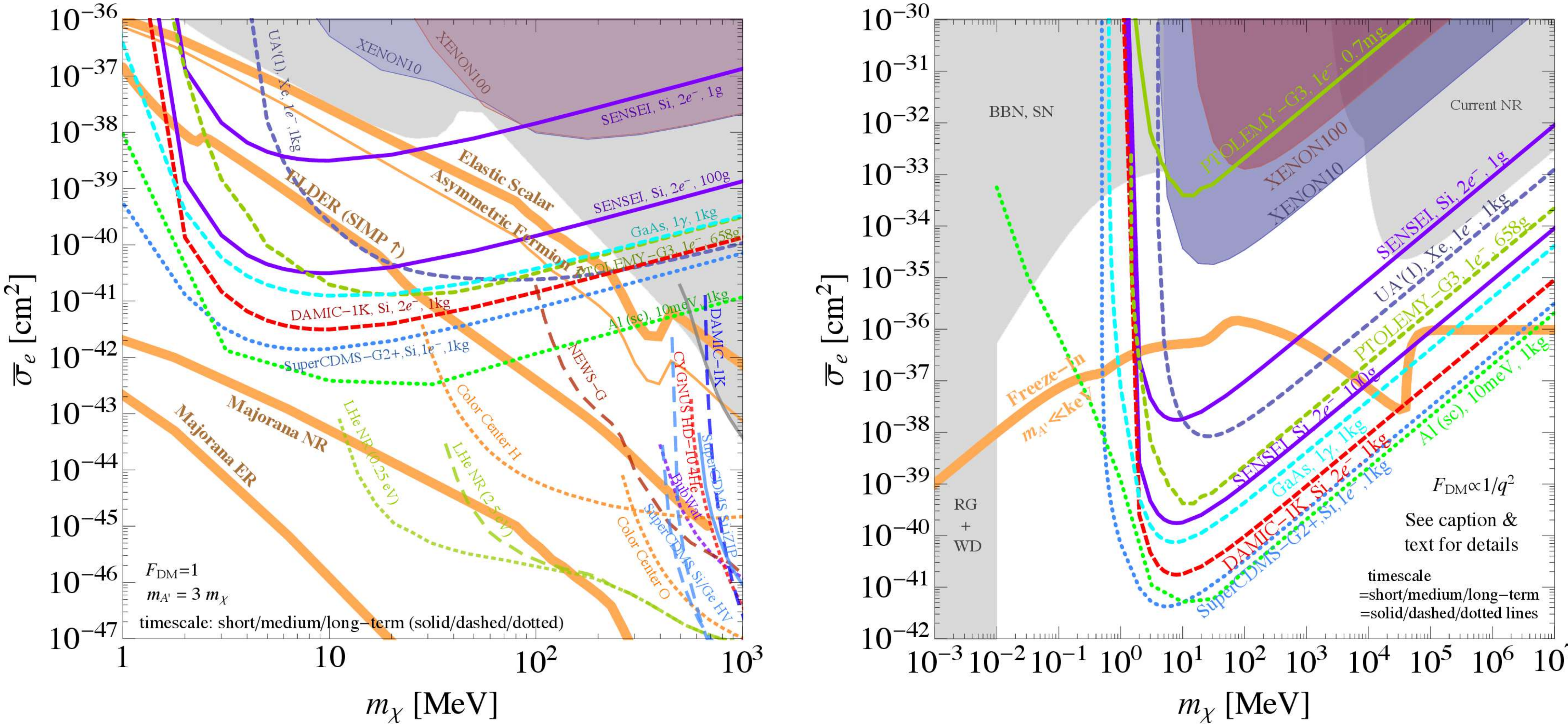
Realistic materials can be highly anisotropic in both background dielectric tensor and Fermi velocities

E.g. $ZrTe_5$:

Parameter	value (th.)
$v_{F,1}$	$2.9 \times 10^{-3}c$ ($v_{F,x}$)
$v_{F,2}$	$5.0 \times 10^{-4}c$ ($v_{F,y}$)
$v_{F,3}$	$2.1 \times 10^{-3}c$ ($v_{F,z}$)

Parameter	value (th.)
κ_{xx}	187.5
κ_{yy}	9.8
κ_{zz}	90.9

Outlook: keV-MeV DM

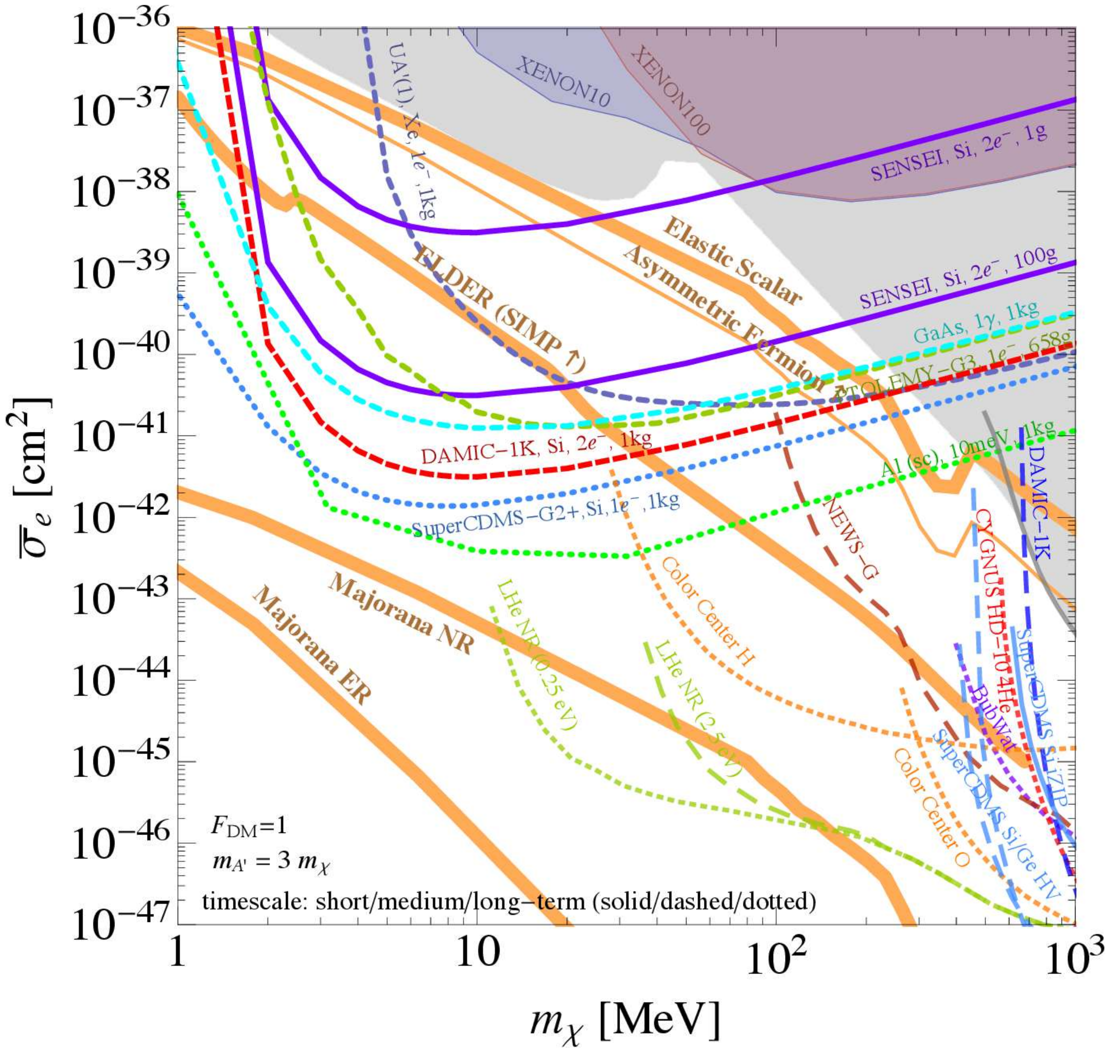


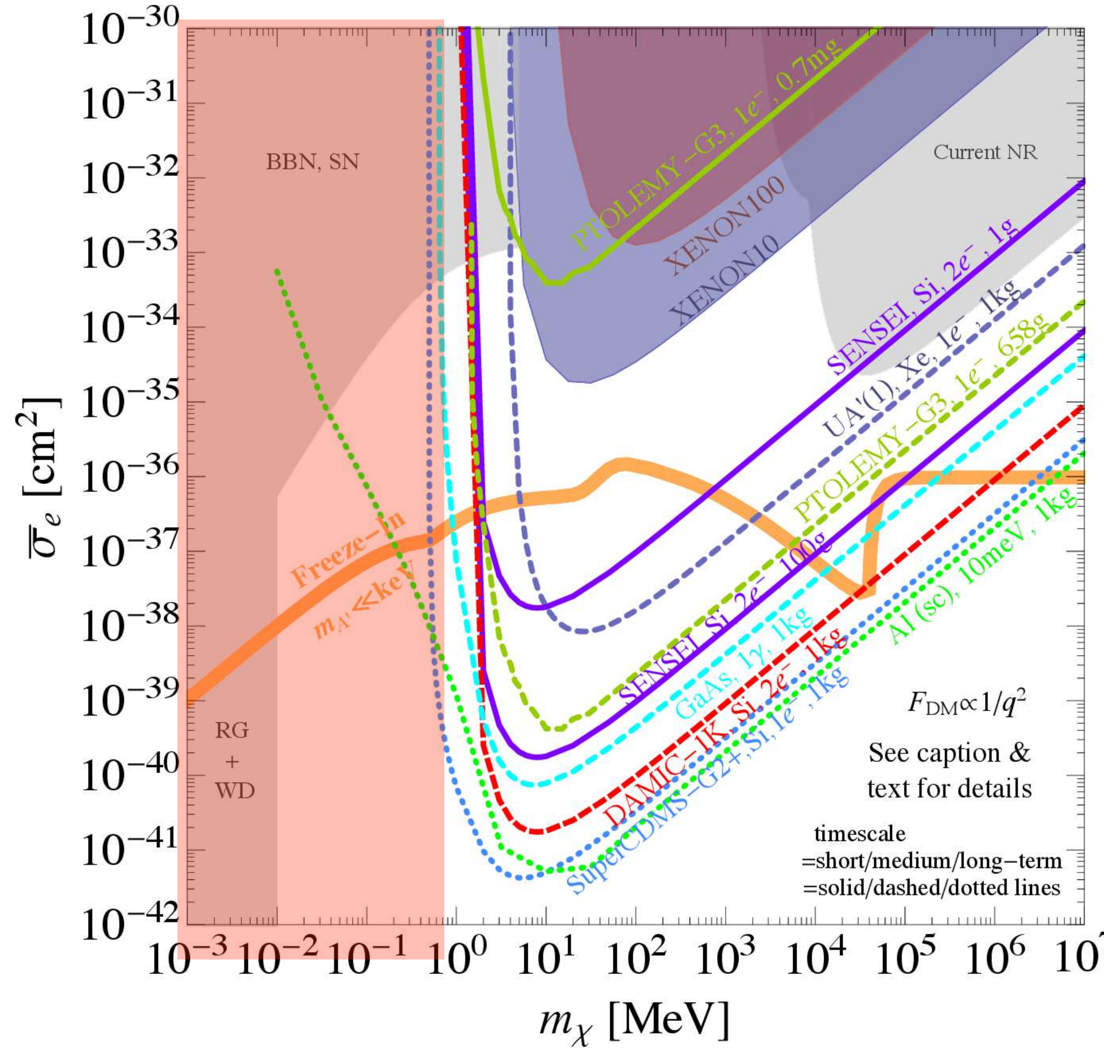
[U.S. Cosmic Visions community report, 2017]

Many experiments, lots of open parameter space:
exciting times!

Outlook: keV-MeV DM

semimetals!





[U.S. Cosmic Visions community report, 2017]

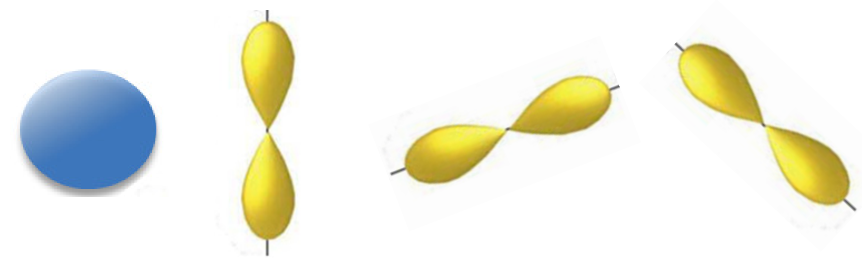
Many experiments, lots of open parameter space:
exciting times!

Backup slides

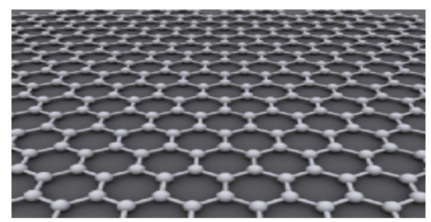
Electron wavefunctions

Tight-binding model:

$$\Psi = \sum e^{i\ell\cdot\mathbf{a}_i} \Big|$$



$$\Big\rangle_{\mathbf{a}_i}$$



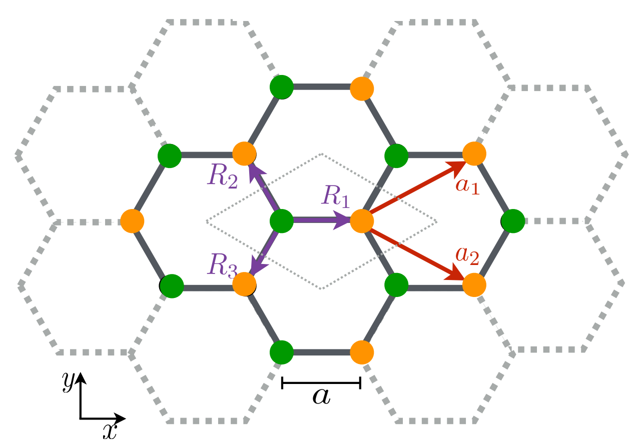
solve eigenvalue problem

E.g. π band:

$$\Psi_\pi(\ell,\mathbf{r}) = \sum_{\mathbf{K}=m\mathbf{a}_1+n\mathbf{a}_2} e^{i\ell\cdot\mathbf{K}}\left(\phi^A_{2\mathrm{p_z}}(\mathbf{r}-\mathbf{K}) + e^{i(\ell\cdot\mathbf{R}_1+\varphi_\ell)}\phi^B_{2\mathrm{p_z}}(\mathbf{r}-\mathbf{R}_1-\mathbf{K})\right)$$

lattice momentum

$\ell \in \mathrm{BZ}$

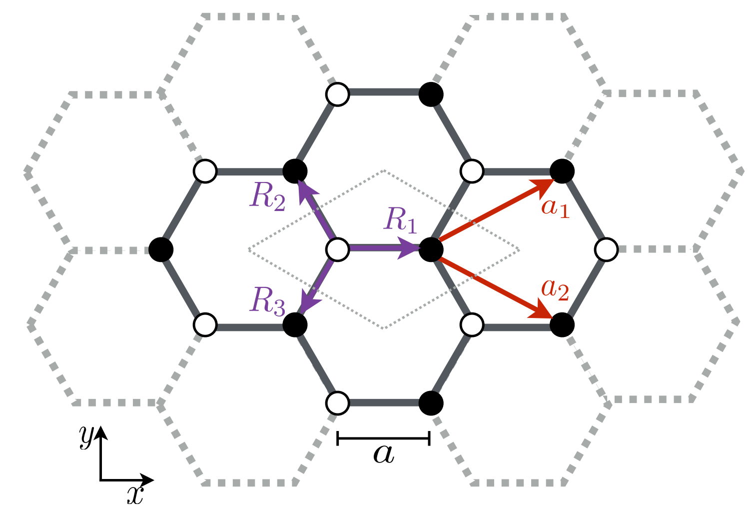


phase difference between
A and B sublattices

Quasi-localized electrons

$$v_{\min}(\ell, E_{\rm er}, q) = \frac{E_{\rm er} + E(\ell) + \Phi}{q} + \frac{q}{2m_\chi}$$

Take v = $v_{\rm esc}$: $q_{min} = 2\ \text{keV}$



$$0.142\ \text{nm} \simeq \frac{2\pi}{8.7\ \text{keV}}$$

Scattering localized to a few unit cells:

$$\Psi_\pi(\ell, \mathbf{r}) \approx \mathcal{N}_\ell \left(\phi_{2\rm p_z}(\mathbf{r}) + e^{i\varphi_\ell} \sum_{j=1}^{3} e^{i\ell\cdot\mathbf{R}_j}\, \phi_{2\rm p_z}(\mathbf{r} - \mathbf{R}_j) \right)$$

Tight-binding diagonalization

$$\mathcal{H}\Psi_\pi = E_\pi(\ell)\Psi_\pi$$

$$\Psi_\pi(\ell, \mathbf{r}) = C_A(\ell)\,\Phi_A(\ell, \mathbf{r}) + C_B(\ell)\,\Phi_B(\ell, \mathbf{r})$$

on-site energy (0 by convention)

$$\begin{pmatrix} \epsilon_{2\mathrm{p}} & t\,f(\ell) \\ t\,f(\ell)^* & \epsilon_{2\mathrm{p}} \end{pmatrix} \begin{pmatrix} C_A \\ C_B \end{pmatrix} = E_\pi(\ell) \begin{pmatrix} 1 & s\,f(\ell) \\ s\,f(\ell)^* & 1 \end{pmatrix} \begin{pmatrix} C_A \\ C_B \end{pmatrix}$$

transfer integral:

$$\int d^3r\, \phi^*_{2\mathrm{p}_z}(\mathbf{r})\, H\, \phi_{2\mathrm{p}_z}(\mathbf{r} - \mathbf{R}_j) = -3.03 \text{ eV}$$

overlap integral:

$$\int d^3r\, \phi^*_{2\mathrm{p}_z}(\mathbf{r})\, \phi_{2\mathrm{p}_z}(\mathbf{r} - \mathbf{R}_j) = 0.129$$

$$\implies E_\pi(\ell) = \frac{\epsilon_{2\mathrm{p}} \pm t|f(\ell)|}{1 \pm s|f(\ell)|}$$

$$C_B/C_A = \pm e^{i\varphi_\ell},\ \ \varphi_\ell = -\arctan\left(\frac{\mathrm{Im} f(\ell)}{\mathrm{Re} f(\ell)}\right)$$

Explicit wavefunctions

For self-consistent calculation, assume hydrogenic orbitals, tune Z_{eff} to match overlap integrals:

$$\phi_{2\mathrm{p}_z}(\mathbf{r}) = \mathcal{N}\, a_0^{-3/2}\, \frac{r}{a_0}\, e^{-Z_{\mathrm{eff}}\, r/2a_0}\, \cos\theta \qquad Z_{\mathrm{eff}} = 4.03$$

$$\left.\begin{aligned}\phi_{2\mathrm{p}_x}(\mathbf{r}) &= \mathcal{N}\, a_0^{-3/2}\, \frac{r}{a_0}\, e^{-Z_{\mathrm{eff}}\, r/2a_0}\, \sin\theta\cos\phi \\ \phi_{2\mathrm{p}_y}(\mathbf{r}) &= \mathcal{N}\, a_0^{-3/2}\, \frac{r}{a_0}\, e^{-Z_{\mathrm{eff}}\, r/2a_0}\, \sin\theta\sin\phi\end{aligned}\right\} \; Z_{\mathrm{eff}} = 5.49$$

$$\phi_{2\mathrm{s}}(\mathbf{r}) = \mathcal{N}\, a_0^{-3/2} \left(1 - \frac{Z_{\mathrm{eff}} r}{2a_0}\right) e^{-Z_{\mathrm{eff}}\, r/2a_0} \qquad Z_{\mathrm{eff}} = 4.84$$

Physically motivated: 2D sheet breaks rotational symmetry

Forward scattering dominates

Take DM stream in z direction:

Energy conservation: $\delta(k_f^2/2m_e + E_b + \Phi + q^2/2m_\chi - qv\cos\theta_q)$

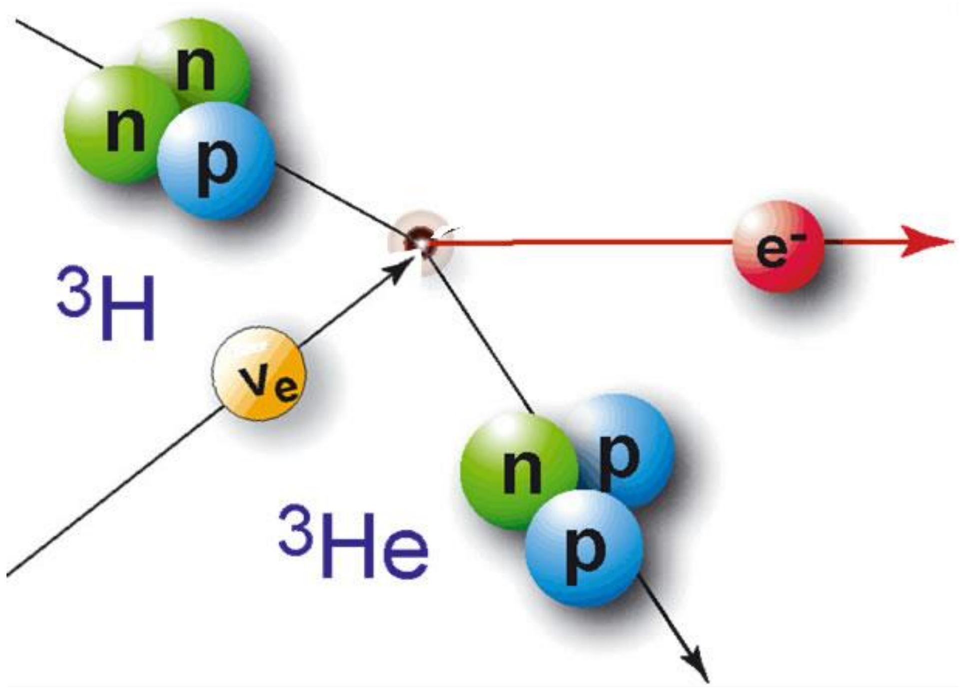
Delta function fixes θ_q :

$$\left.\begin{array}{l} \cos\theta_q = \dfrac{E_e + E_b + \Phi}{qv} + \dfrac{q}{2m_\chi v} \\ q_\pm = m_\chi v \pm \sqrt{m_\chi^2 v^2 - 2m_\chi(E_e + E_b + \Phi)} \end{array}\right\} \quad \theta_q(q_-) = 0$$

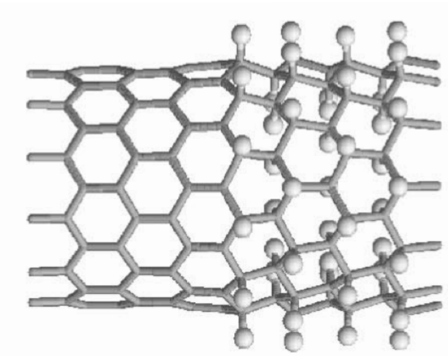
PTOLEMY for CvB

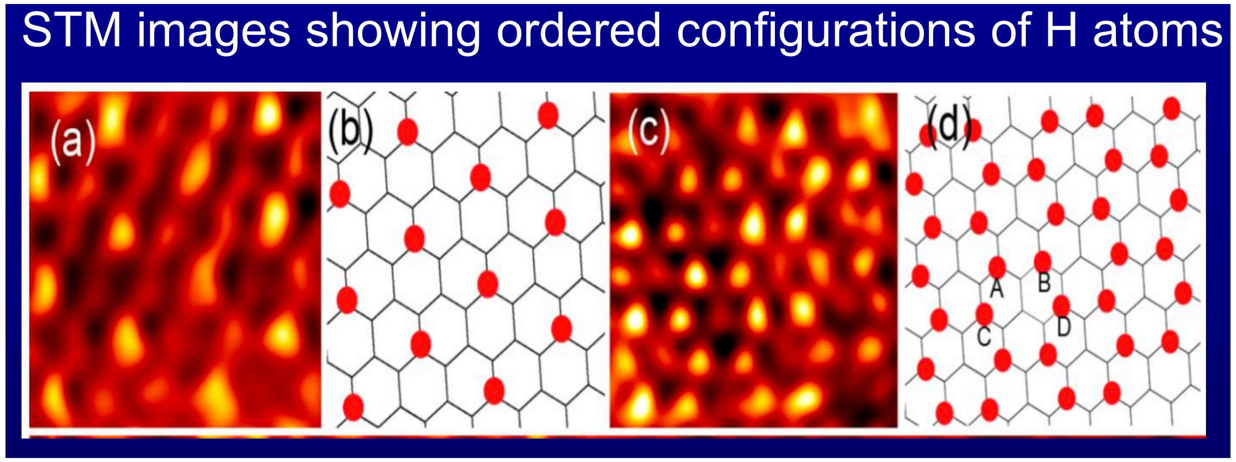
[C. Tully]

Look for cosmic neutrinos through capture on tritium



Molecular excitations too large, use tritiated graphene instead





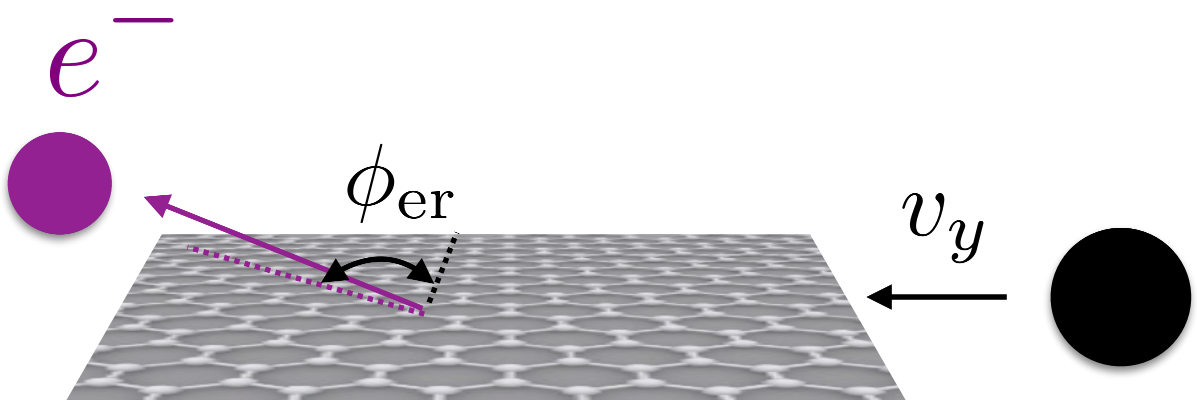
Borrow pure (un-tritiated) graphene for a DM experiment?

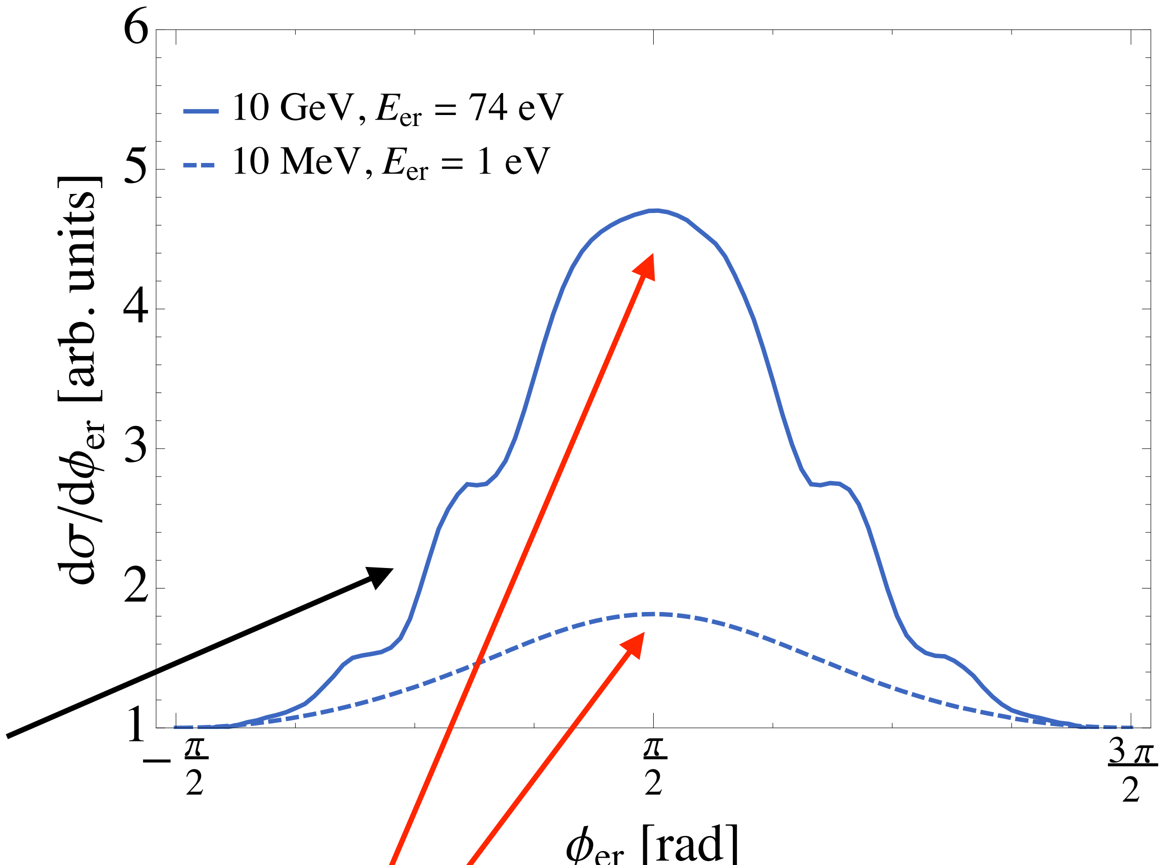
Same target, same signal, very similar readout!

Goal: 100 g tritium = 0.4 kg graphene

Graphene: parallel DM stream

$$g(\mathbf{v}) = \delta(\mathbf{v} - v_y \mathbf{y})$$



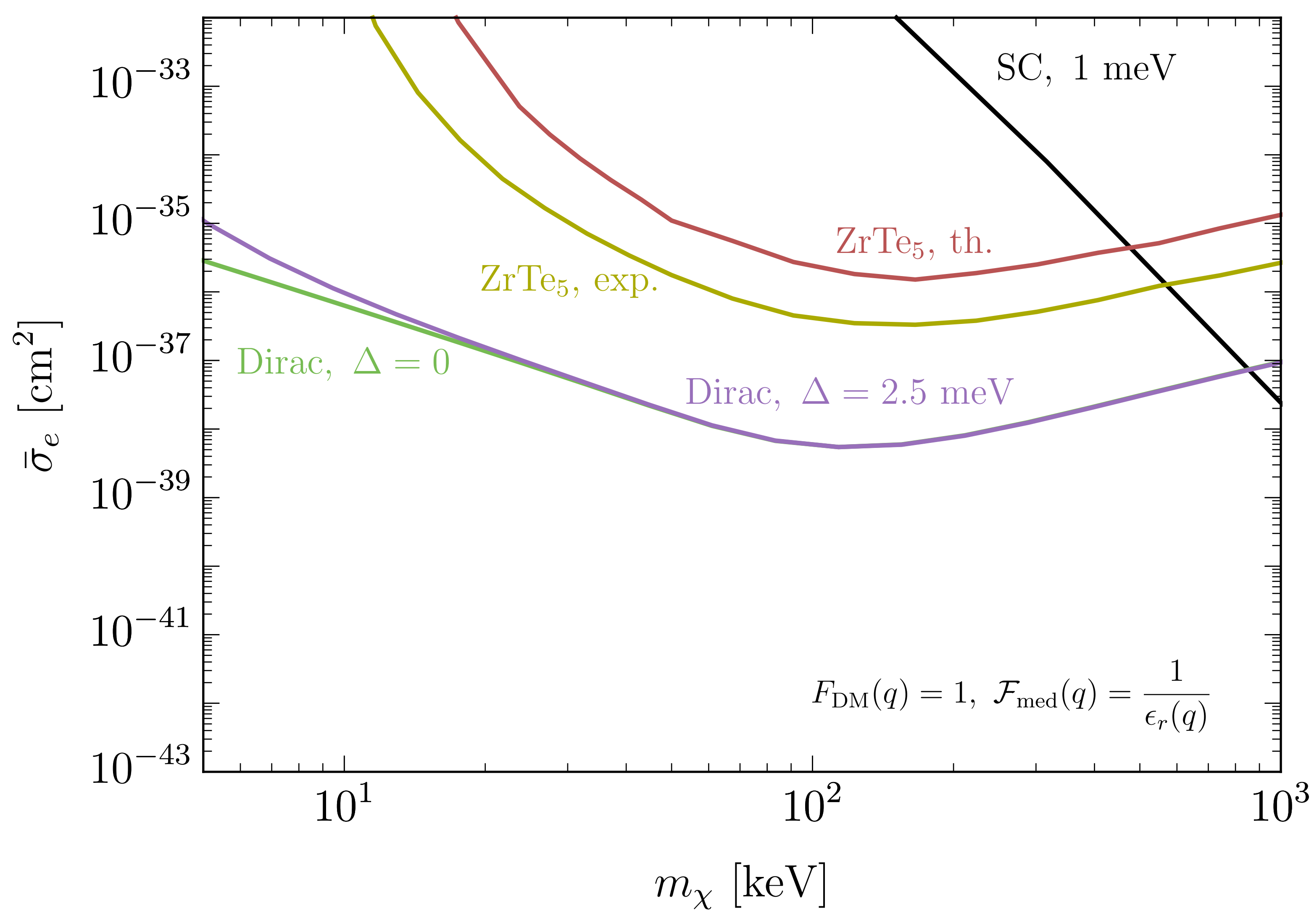


Diffraction for special $k_f = 2\pi/a$

Forward scattering peak

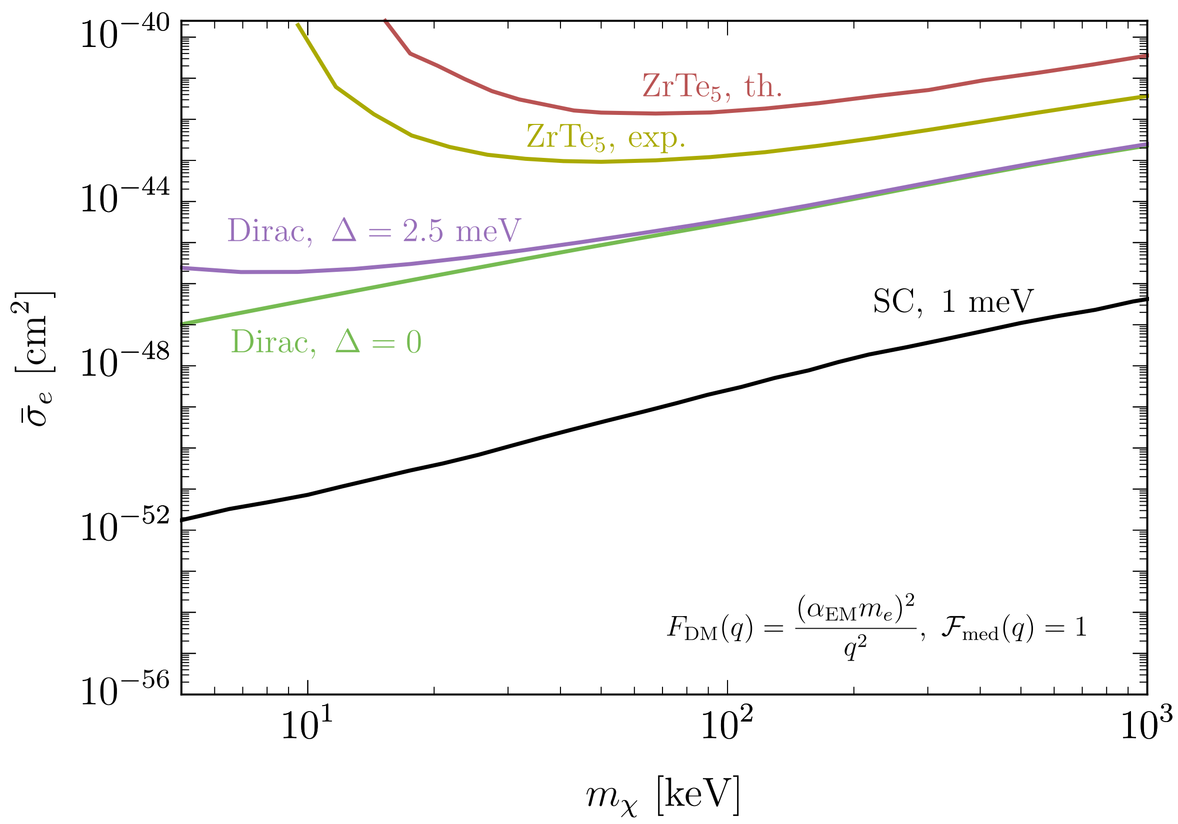
Large angular correlations,
regardless of DM mass or recoil energy

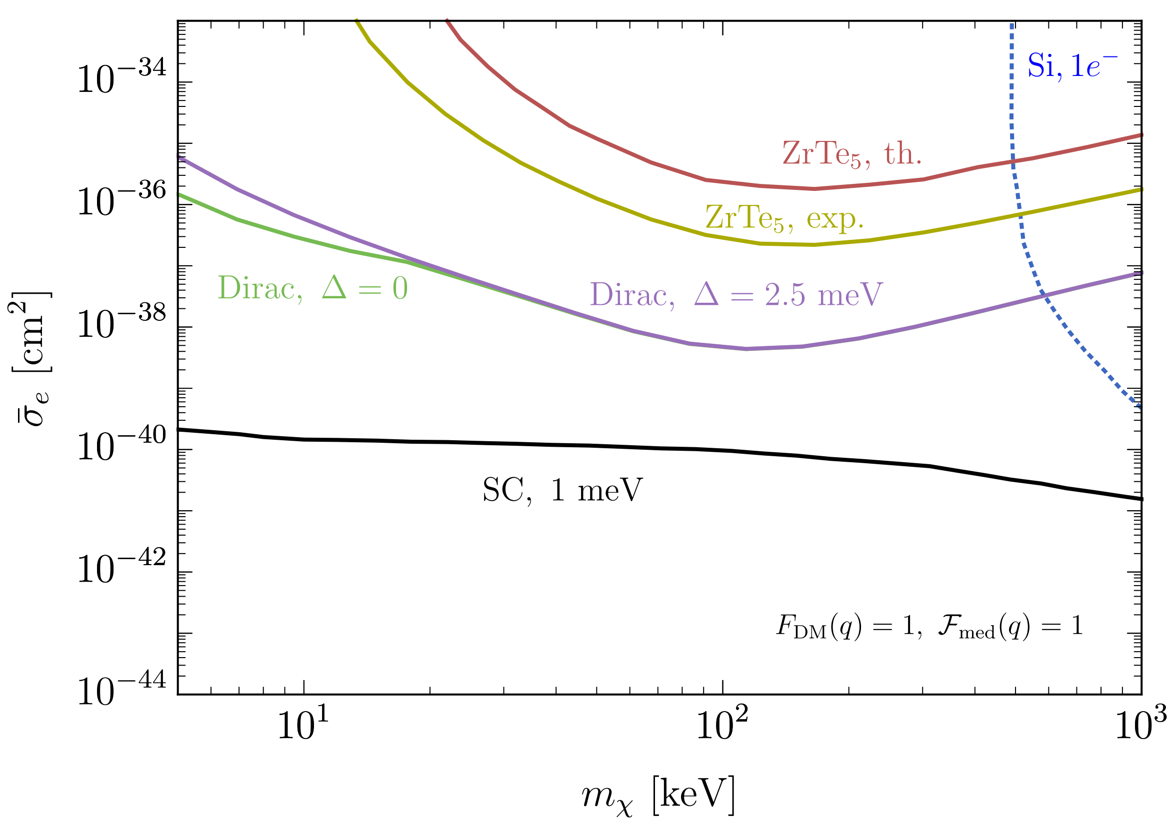
Semimetal scattering reach: heavy dark photon



(Severe constraints from BBN)

Semimetal scattering reach: light and heavy scalar med.





(Severe constraints from BBN, stellar emission)

Semimetal absorption reach: axion-like particles