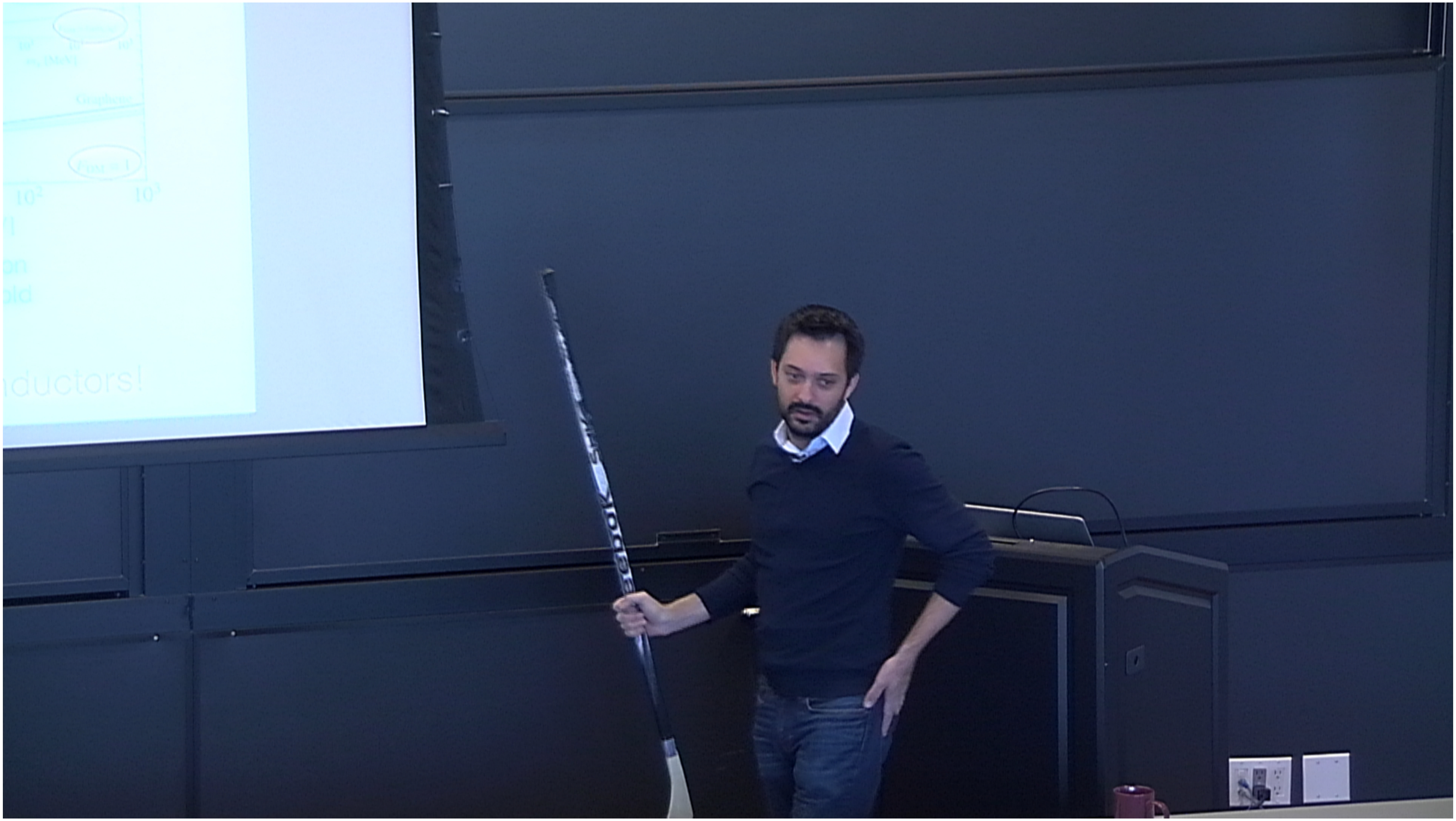
Title: (Directional) Detection of Dark Matter with Graphene

Date: Nov 22, 2016 01:00 PM

URL: http://pirsa.org/16110085

Abstract: <p>Two-dimensional materials such as graphene sheets can serve as excellent detectors for dark matter (DM) with couplings to electrons. The ionization energy of graphene is O(eV), making it sensitive to DM as light as an MeV, and the ejected electron may be detected without rescattering in the target, preserving directional information. I will describe the first experimental proposal for directional detection of MeV-GeV scale DM, which can be implemented in the PTOLEMY relic neutrino experiment and has comparable sensitivity to proposals using semiconductor targets. I will also describe some potential avenues for using gapless systems like Weyl semimetals to detect DM down to the keV limit for warm DM.</p>


Graphene
10^2
10^3
ductors!

(Directional) Detection of Dark Matter with Graphene

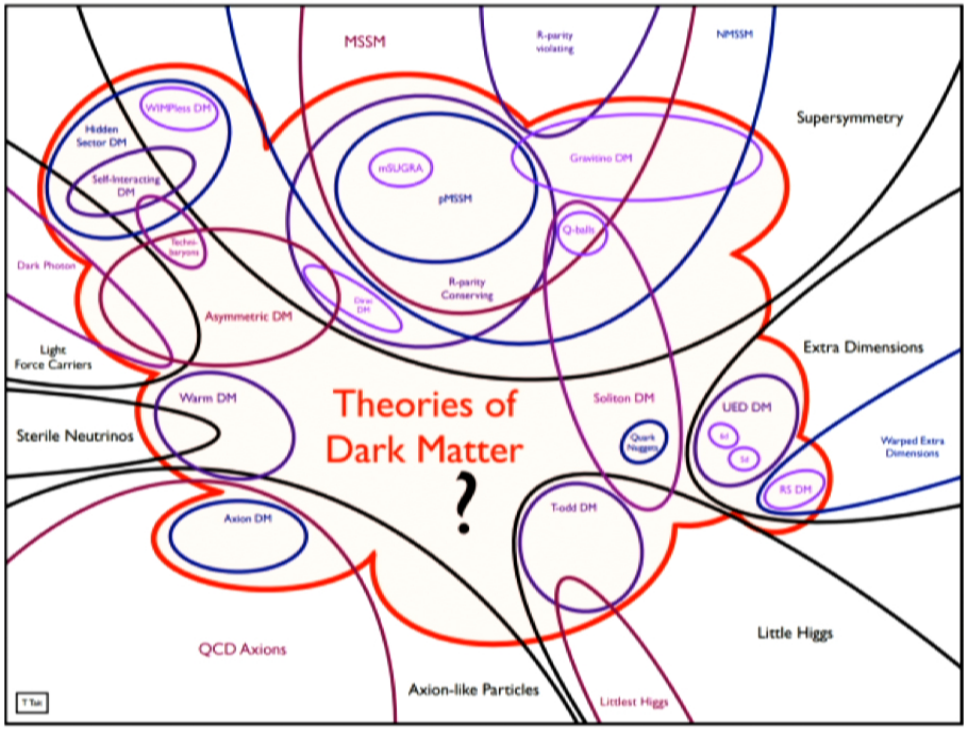
Yoni Kahn, Princeton University

w/Mariangela Lisanti, Yonit Hochberg, Christopher Tully, Kathryn Zurek

arXiv:1606.08849

PI seminar 11/22/16

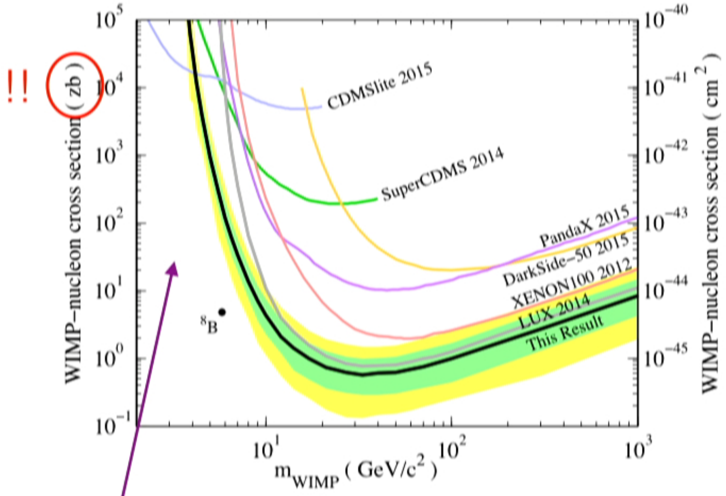
DM exists - what is it?



[T. Tait]

WIMPS - and beyond

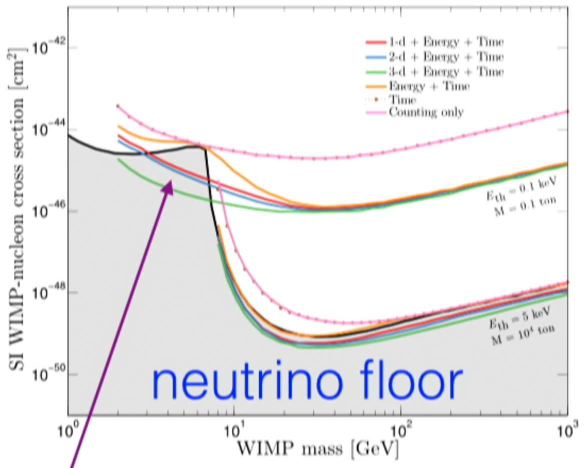
Today:



[LUX collab., 2016]

what's over here?

Idealized future:



[O'Hare et al., 1508.08061]

directional detection helps

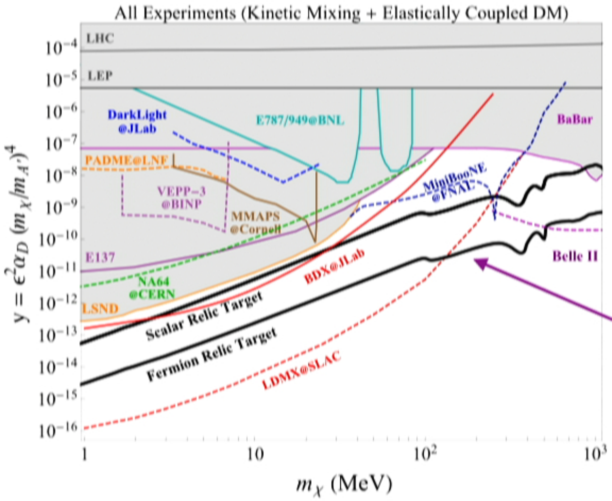
Sub-GeV DM?

Theory motivation:

$$\frac{\Omega_\chi}{\Omega_{DM}} \sim 10^{-3}\left(\frac{\alpha}{\alpha_D}\right)^2\left(\frac{m_\chi}{100\ \mathrm{MeV}}\right)^2$$

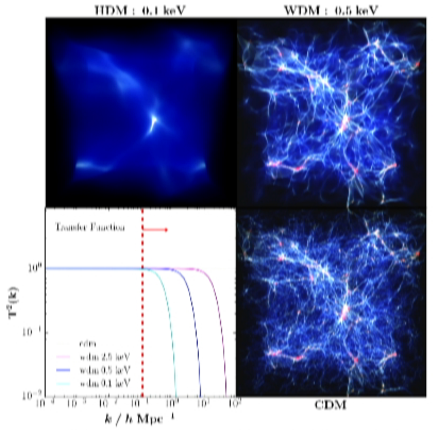
$$(m_\chi > M_{med})$$

WIMP “miracle” **also** applies
to light mediators, MeV DM



[SLAC Dark Sectors Workshop 2016 report]

Astrophysical constraints:



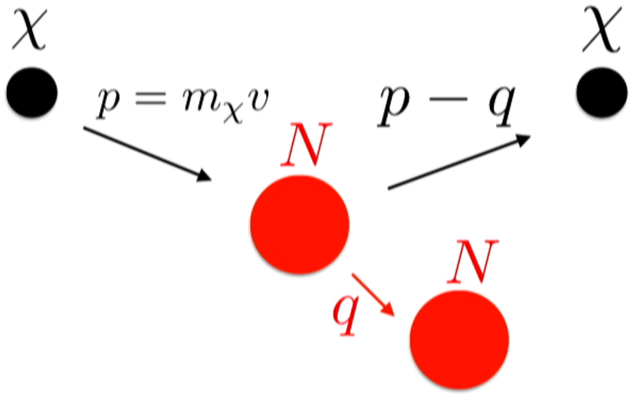
[Baur et al., 1512.01981]

Lyman α forest:

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

need to look here!

“Standard” direct detection: nuclear recoil



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

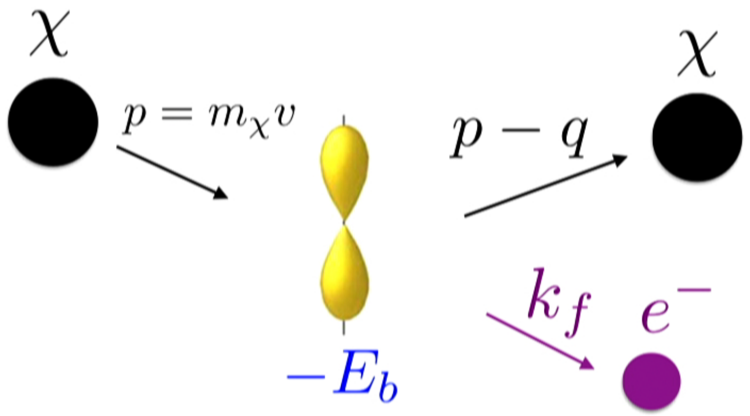
Only available for $m_\chi \sim m_N$, way below keV thresholds

“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

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:

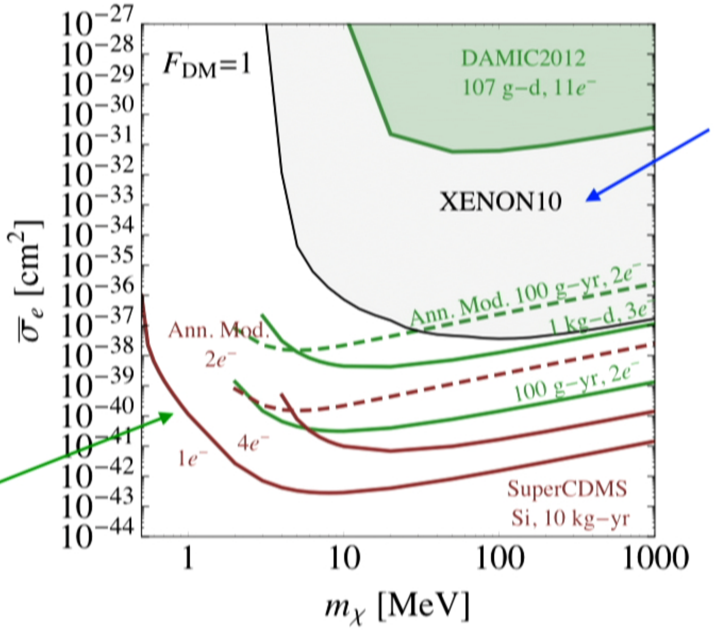
1. Initial state not a momentum eigenstate: k_f and q independent

2. Wavefunction suppression at large q:

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

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

Sub-GeV detection strategies



[Essig et al., 1509.01598]

Atomic ionization:
initial e$^-$ induces
secondary
ionization e$^-$s

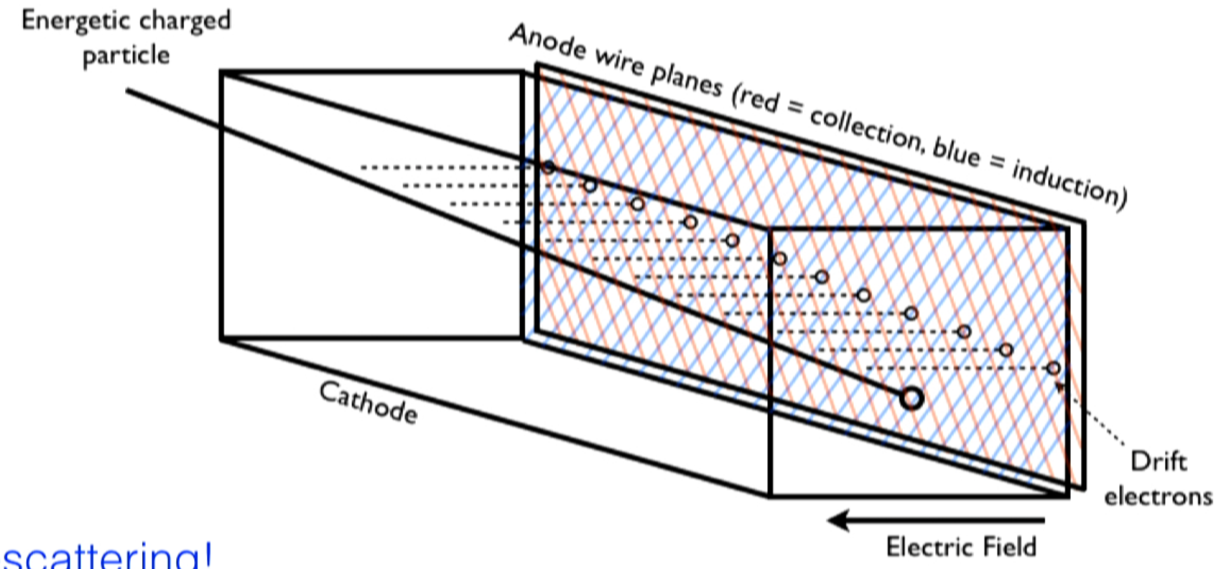
semiconductor
excitation:
excited conduction
band e$^-$ produces
secondary e/h pairs

Secondaries produce signal:

lose kinematic info, backgrounds difficult

Directional detection strategies

All currently use gas time-projection chambers (TPCs)



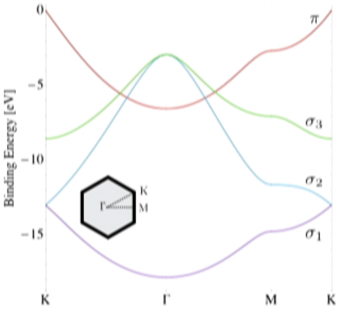
rescattering!

Gas (CF_4, CS_2, Xe) is also target:

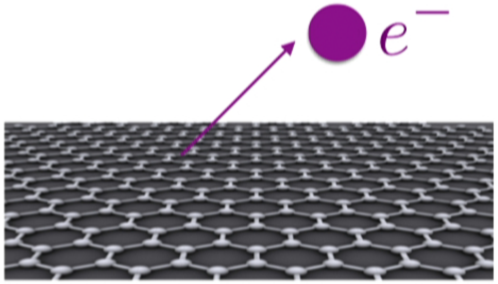
2-20 keV thresholds, no sensitivity to MeV DM

Graphene for MeV DM

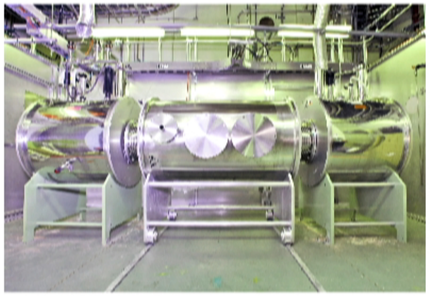
Advantages:



eV binding energies



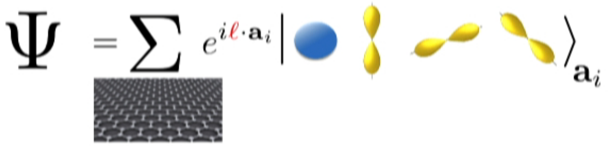
observe primary,
no rescattering



borrow an experiment!

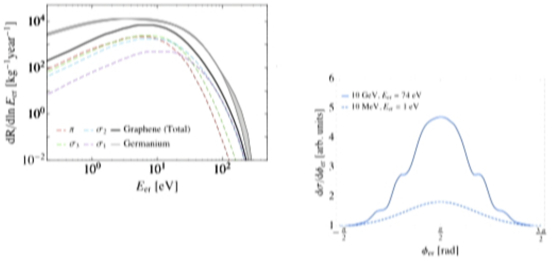
Outline

1. Electrons in graphene

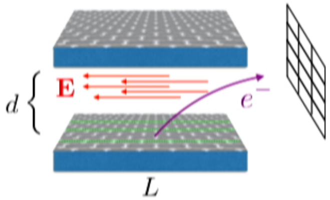


$$\Psi = \sum e^{i\ell\cdot\mathbf{a}_i} | \quad \rangle_{\mathbf{a}_i}$$

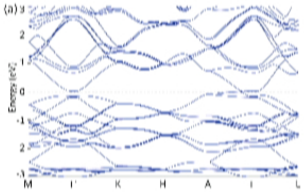
2. Rates and directional detection



3. Implementation in PTOLEMY



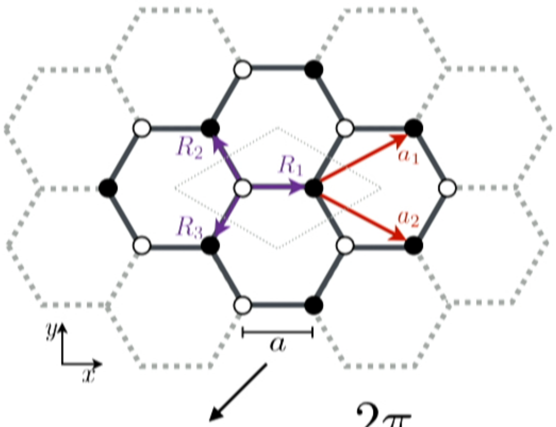
(4. Towards keV DM?)



Electrons in graphene

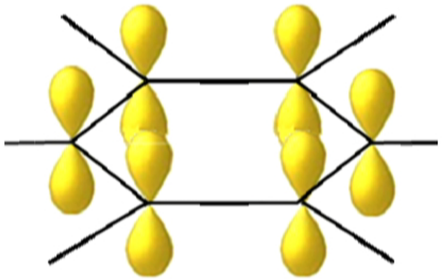
Graphene 101

1-atom thick lattice of carbon

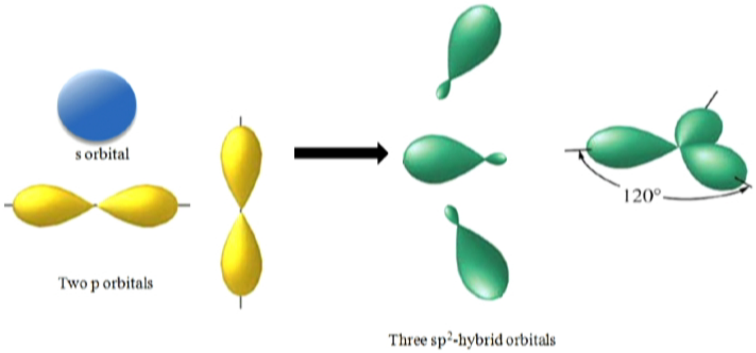


$$0.142 \text{ nm} \simeq \frac{2\pi}{8.7 \text{ keV}}$$

4 valence electrons per atom:



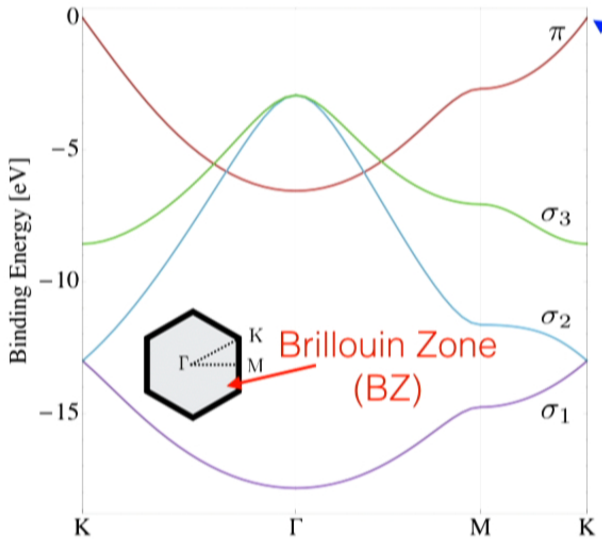
π electrons



σ electrons

Electron energies

Binding energy depends on lattice momentum ℓ :



Dirac point: massless charge carriers, FQHE, all "interesting" properties

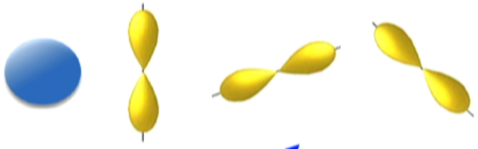
can dominate DM scattering cross section, need to treat these too!

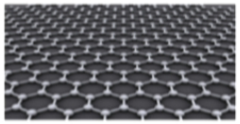
To eject electron to vacuum, need to overcome work function

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

(tunable)

Electron wavefunctions

Tight-binding model: $\Psi = \sum e^{i\ell\cdot\mathbf{a}_i} \Big|$  $\Big\rangle_{\mathbf{a}_i}$



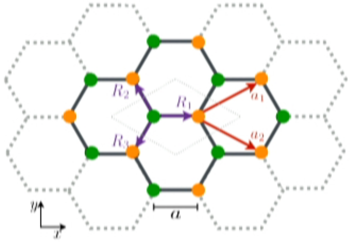
solve eigenvalue problem

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

$\ell \in \mathrm{BZ}$

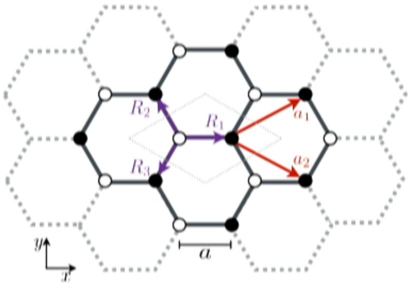


phase difference between A and B sublattices

Quasi-localized electrons

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

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



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

Scattering localized to a few unit cells:

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

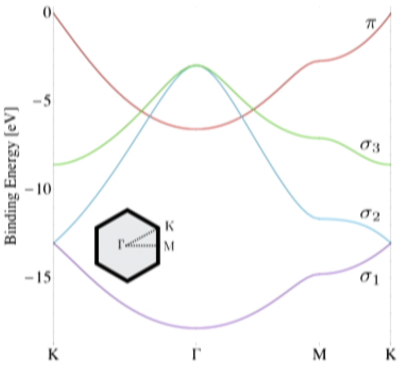
Rates and distributions

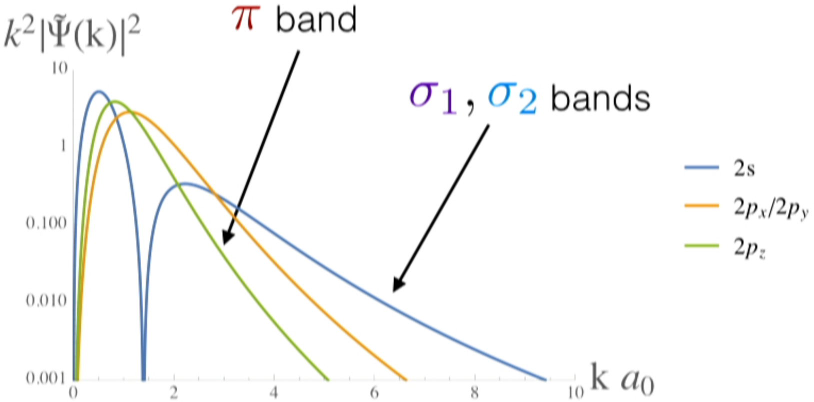
Cross sections and rates

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





π band

σ_1, σ_2 bands

Sum over bands, integrate over BZ and DM velocity:

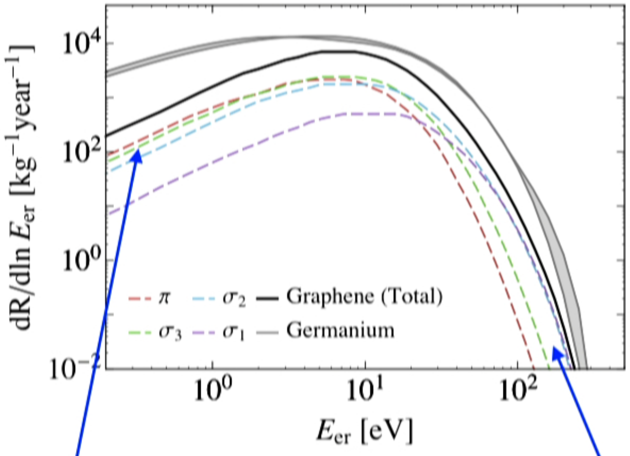
$$R = 2\sum_{i=\pi,\sigma_{1,2,3}}\frac{\rho_\chi}{m_\chi}\,N_{\rm C}\,A_{\rm uc}\int_{\rm BZ}\frac{d^2\ell}{(2\pi)^2}\,d^3v\,g(\mathbf{v})\;v\,\sigma_i(\ell)$$

Directionally-averaged rate

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

Energy spectrum

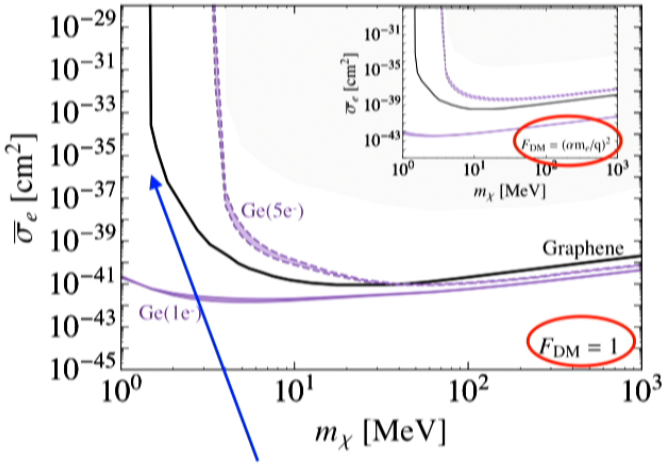
(F$_{DM}$ = 1, 100 MeV DM)



Binding energy dominates

Momentum tail dominates

Reach



work function sets threshold

Comparable reach to conventional semiconductors!

Directional detection

Key observation: ionized e$^-$ kinematics
highly correlated with initial DM direction

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

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

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

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

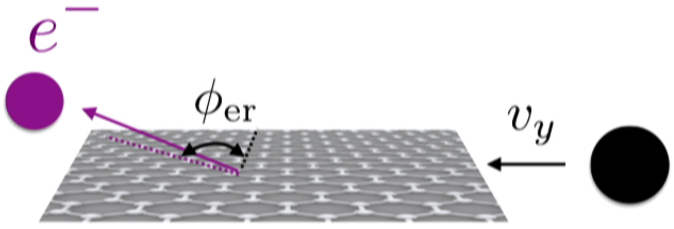
Diffraction effects when $k_f \sim 2\pi/a$

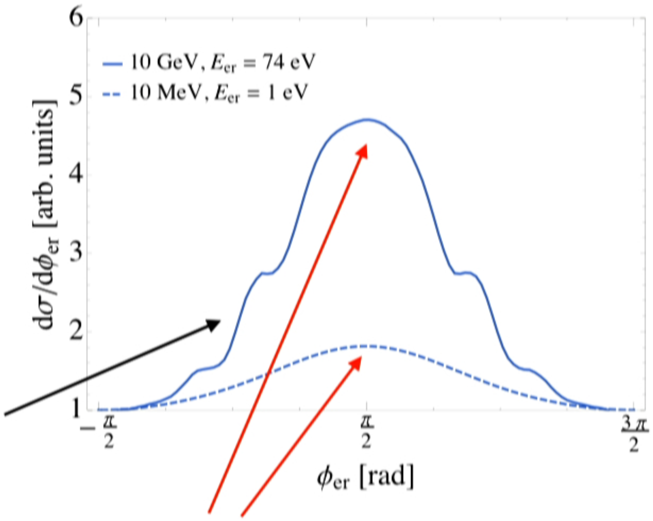
Two-dimensional target: directional information preserved!

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

Parallel DM stream

$$g(\mathbf{v}) = \delta(\mathbf{v} - v_{\text{esc}}\mathbf{y})$$





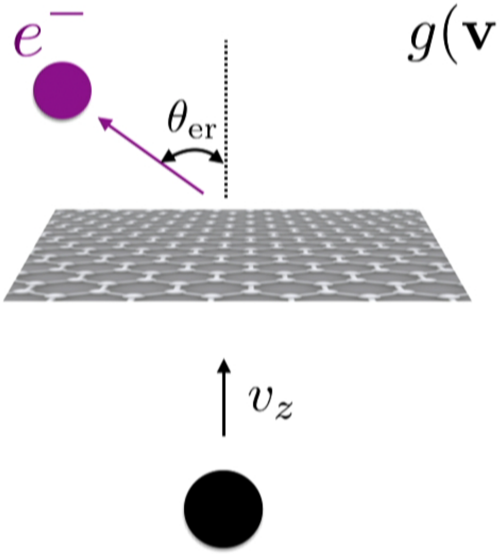
Diffraction for special $k_f = 2\pi/a$

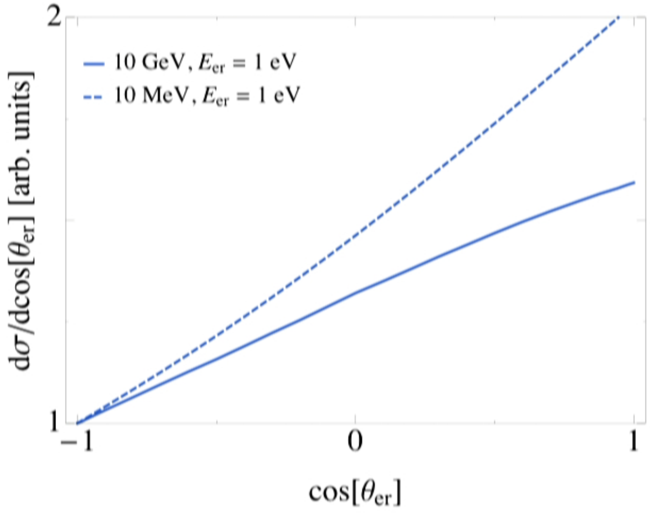
Forward scattering peak

Large angular correlations,
regardless of DM mass or recoil energy

Perpendicular DM stream

$$g(\mathbf{v}) = \delta(\mathbf{v} - v_{\rm esc}\mathbf{z})$$

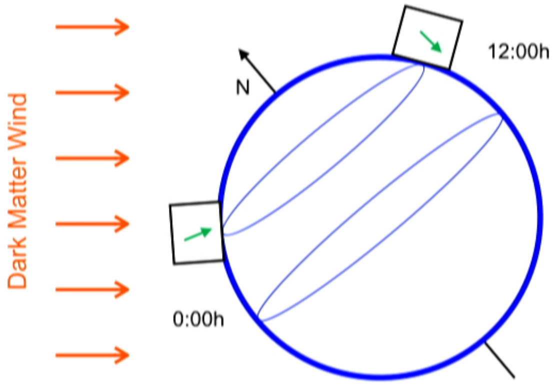




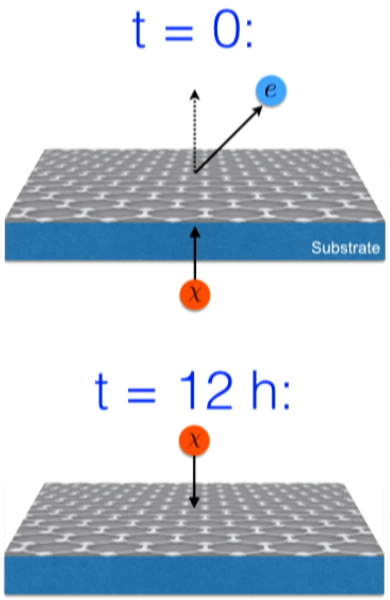
$$\widetilde{\phi}_{2\mathrm{p}_z}(\mathbf{q}-\mathbf{k}) \approx \widetilde{\mathcal{N}}\, a_0^{3/2} \frac{a_0\,(q_z - k_z)}{\left(a_0^2\,|\mathbf{q}-\mathbf{k}|^2 + (Z_{\rm eff}/2)^2\right)^3}$$

Numerator suppresses forward scattering for heavy DM

Daily head-tail modulation



[D. Spergel, PRD 1988]



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

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

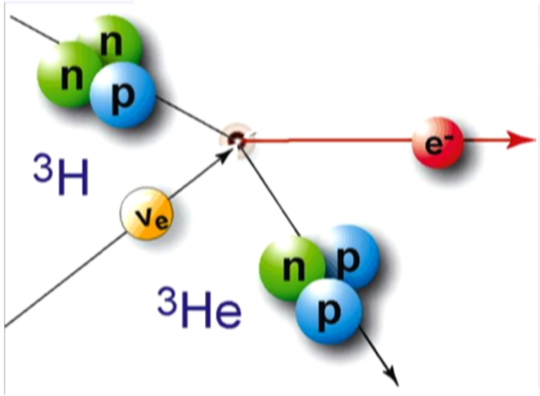
Implementation with PTOLEMY

[S. Betts et al., 1307.4738]

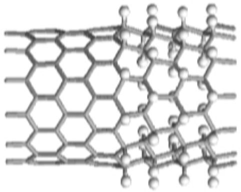
PTOLEMY for CvB

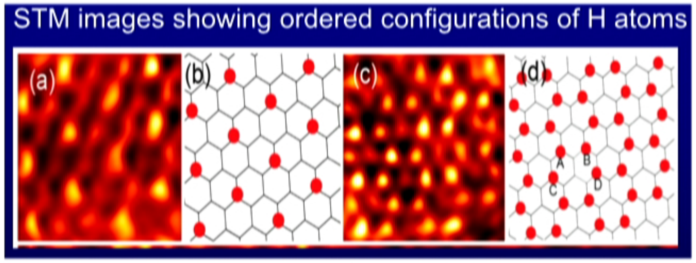
[C. Tully]

Look for cosmic neutrinos through capture on tritium



Molecular excitations too large, use tritiated graphene instead





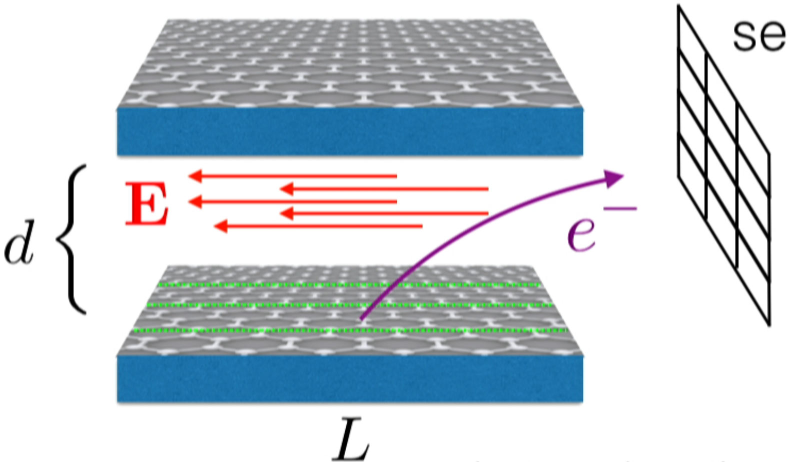
Borrow pure (un-tritiated) graphene for a DM experiment?

Same target, same signal, very similar readout!

Goal: 100 g tritium = 0.4 kg graphene

PTOLEMY for MeV DM

(preliminary)



$$z_{\rm cal} = v_\perp \Delta t$$

$$y_{\rm cal} - y_{\rm sheet} = v_y \Delta t$$

$$E_{\rm tot} \implies v_x$$

$$\mathbf{E} > 40{\rm kV/cm} \left(\frac{E_e}{1\ {\rm eV}}\right)\left(\frac{L}{1\ {\rm cm}}\right)\left(\frac{0.1\ {\rm mm}}{d}\right)^2$$

Low energies allow compact geometry, modest E-fields

Timing from conductivity measurements (?)

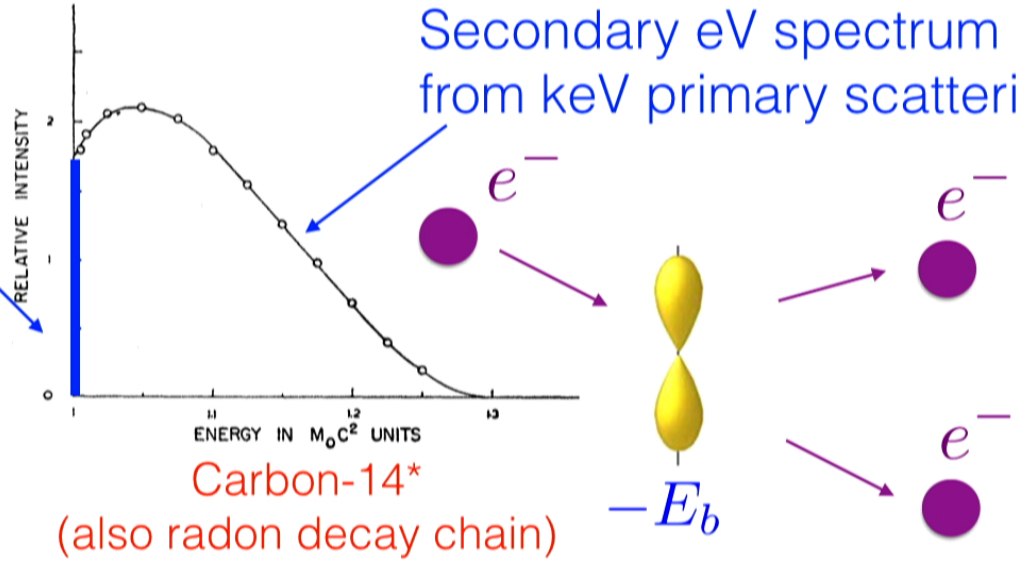
Need large active volume: ~10 m x 10 m x 10 m

Backgrounds

Two categories:

Primary eV spectrum

Secondary eV spectrum from keV primary scattering



Carbon-14*
(also radon decay chain)

Full simulation of secondary eV spectrum ongoing

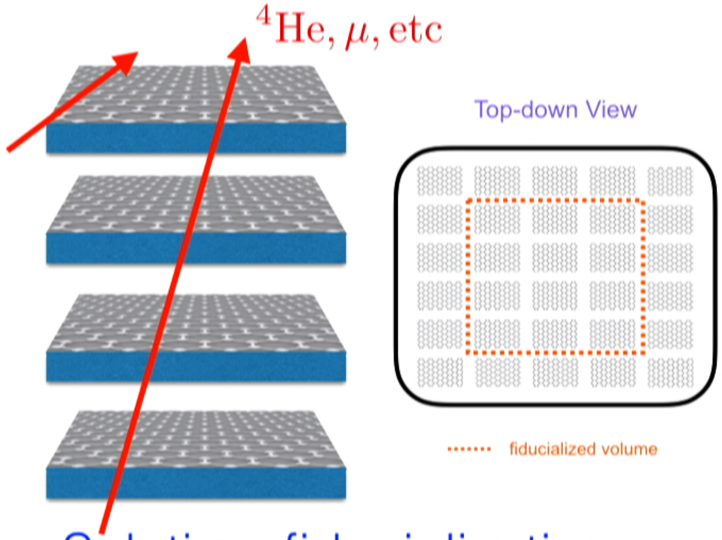
*Borexino: ^{14}C fraction of 10^{-18}

Surface vs. volume

“Surface events”: significant background for CDMS, Xenon, etc.

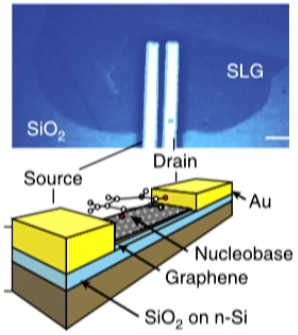
Surfaces are:

Detector boundaries



Solution: fiducialization
(large active volume)

Where contaminants stick



[Dontschuk et al., Nature Comm. 2015]

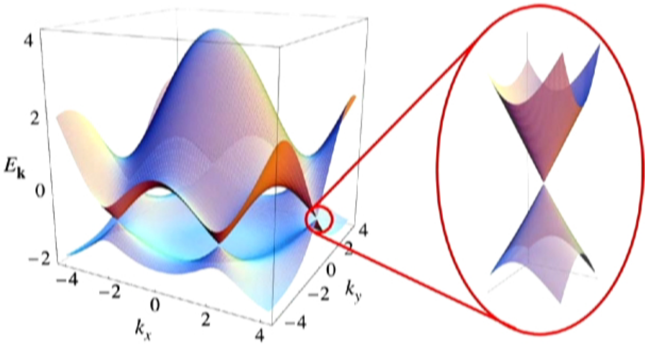
Graphene can detect single molecules!

Towards keV DM
(very preliminary!)

Graphene for keV DM?

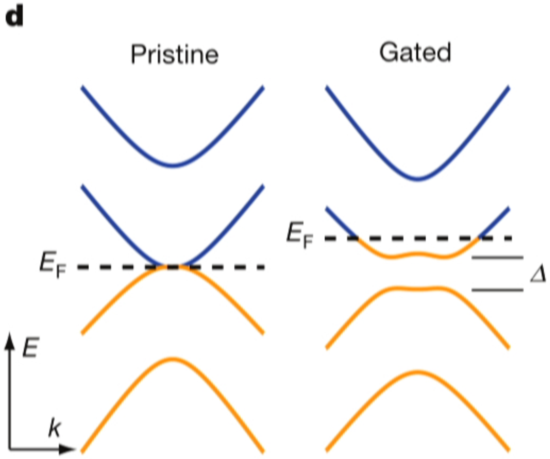
Warm DM limit of ~keV has ~meV kinetic energy

Monolayer



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

Bilayer



[Zhang et al, Nature Lett. 2009]

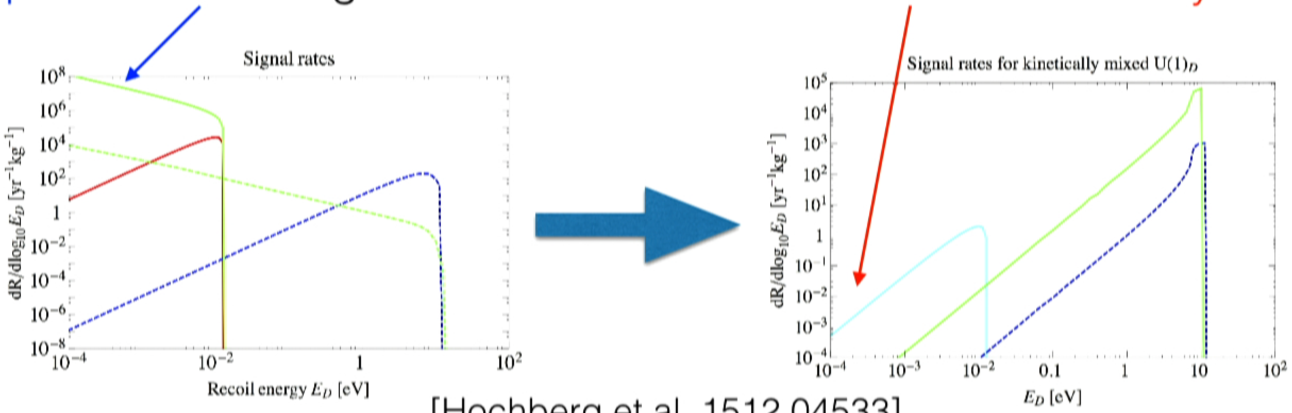
Gap Δ is continuously tunable 0-250 meV!

Optical response

Superconductors also have a ~meV gap…

expected for ultralight mediator

mediator is effectively ~keV



[Hochberg et al. 1512.04533]

…but kinetically-mixed dark photon gets a large effective mass

Graphene:

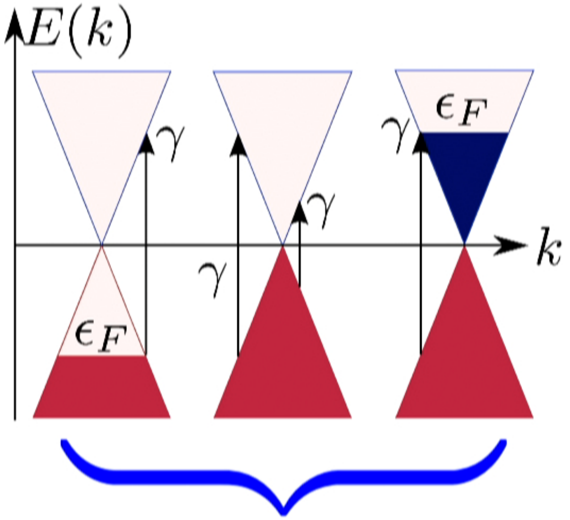
pointlike Fermi surface = suppressed optical response

(Also true for superfluid helium, see
[Guo & McKinsey 1302.0534],[Schutz & Zurek 1604.08206])

Newton vs. Fermi

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

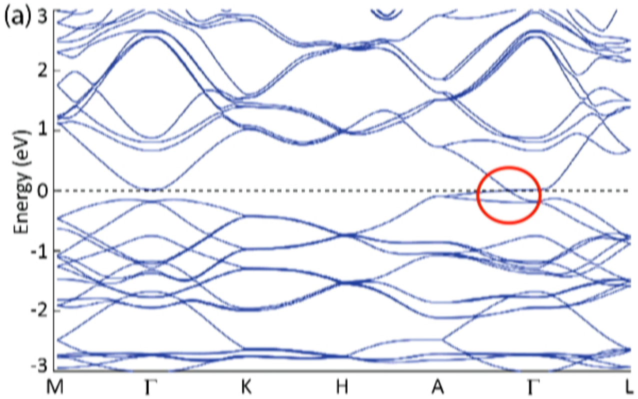
$v_F = 3 \times 10^{-3} c$



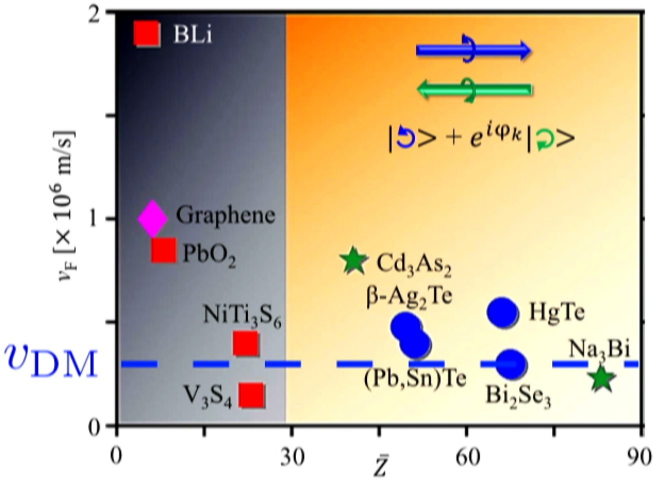
kinematically suppressed for $v_{\rm DM} < v_F$

Unfortunate coincidence for DM direct detection!

Weyl semimetals = “3D Graphene”



[Jenkins et al. 1605.02145]



[Dolui & Das 1412.2607]

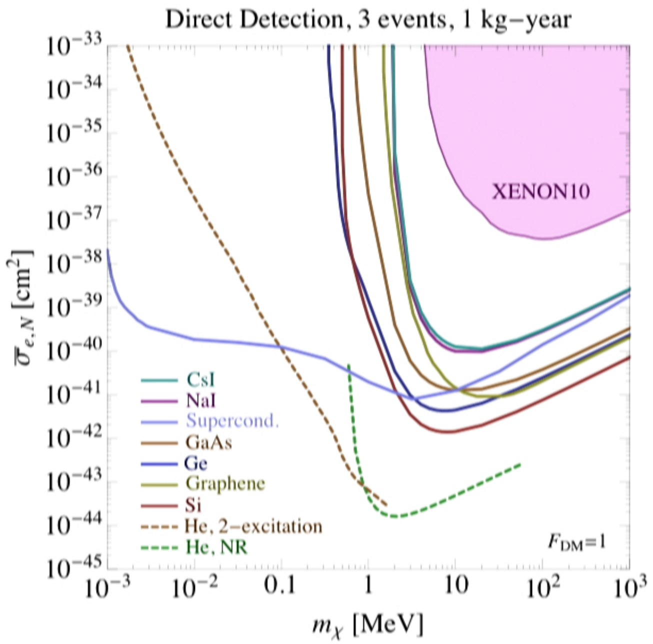
Advantages over graphene:

- Smaller Fermi velocity = more phase space
- Bulk material = more exposure
- Topological response
  (negative magnetoresistance, chiral current)

Conclusions

- Graphene has competitive reach to semiconductors with additional advantage of directional detection
- Expect similar results for any 2D material with ~eV ionization energies (e.g. monolayer gold)
- PTOLEMY engineering run could be an MeV DM search!
- Intriguing possibilities with Weyl semimetals for keV-MeV DM

Outlook



Material	$m_{\rm DM,th}$ (theoretical)	Technology	Challenges	(Optimistic) Timescale
Noble liquids (Xe, Ar)	few MeV	two-phase TPC	dark counts	existing
Semiconductors (Si, Ge)	$\sim 0.1 - 1$ MeV	CCDs & Calorimeter	dark counts (?)	$\sim 1 - 2$ years
Scintillators (GaAs, NaI, CsI)	$\sim 0.5 - 1$ MeV	Calorimeter: $\sigma_E \sim 0.2$ eV	sensitivity & afterglow (?)	$\lesssim 5$ years
Superconductors (Al)	~ 1 keV	Calorimeter: $\sigma_E \sim 1$ meV	sensitivity & unknown backgrounds	$\sim 10 - 15$ years
Superfluid He (NR)	~ 1 MeV	Calorimeter: $\sigma_E \sim 1$ eV	sensitivity & unknown backgrounds	$\lesssim 5$ years
Bond Breaking	$\sim$ few MeV	color centers	sensitivity & unknown backgrounds	$\lesssim 5$ years
Superfluid He (2-excitation)	~ 1 keV	Calorimeter $\sigma_E \sim 10$ meV	sensitivity & unknown backgrounds	$\sim 5 - 10$ years
2D-targets (graphene)	few MeV	based on PTOLEMY	low exposure, unknown backgrounds	$\sim 5 - 10$ years

[SLAC Dark Sectors Workshop 2016 report]

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