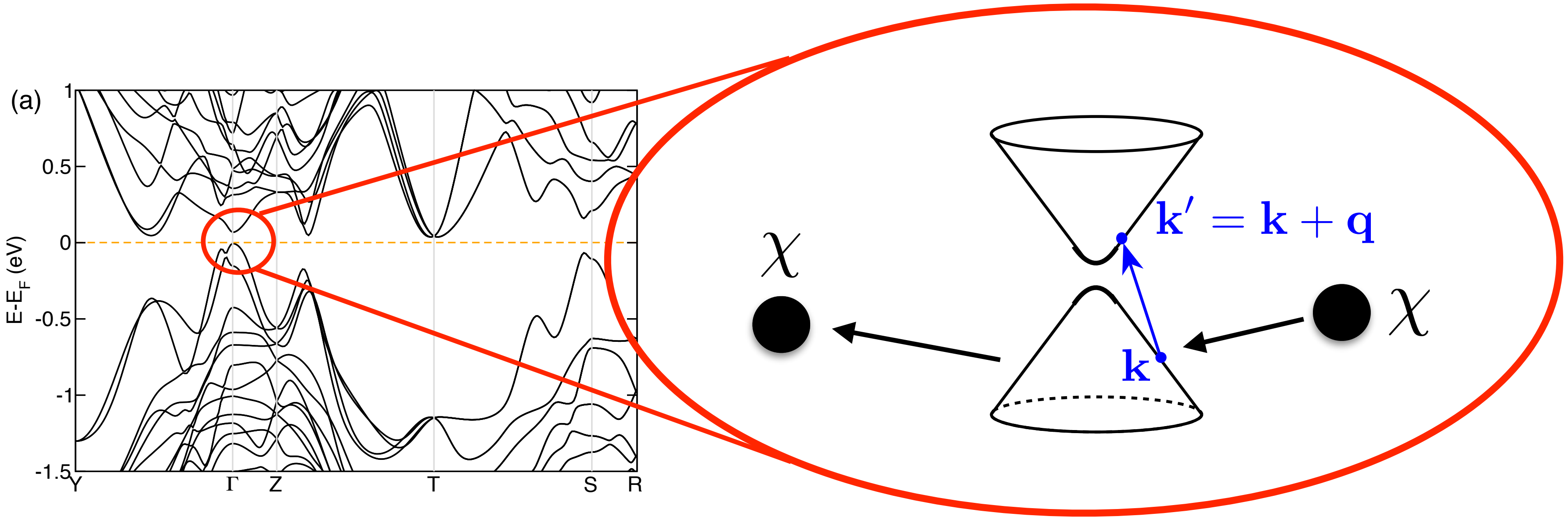
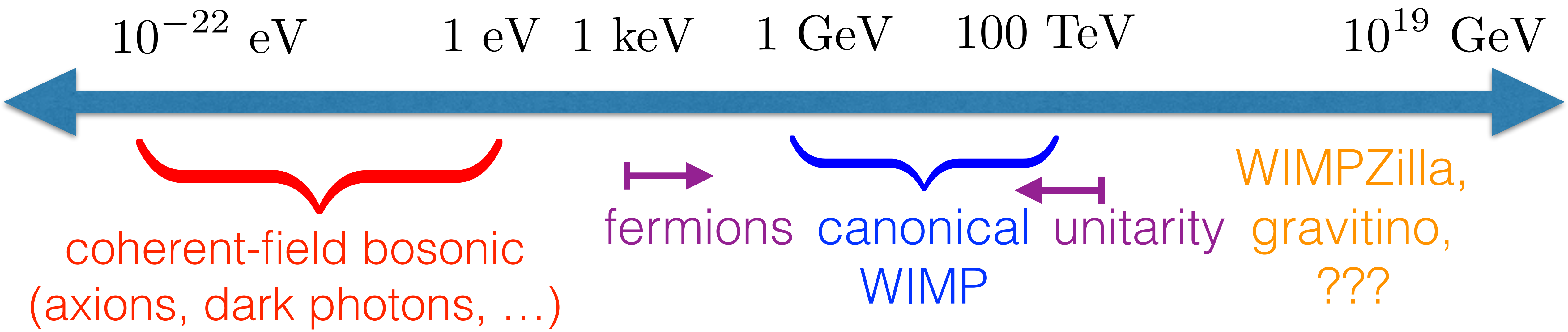


Searching for keV freeze-in dark matter with Dirac materials

Yoni Kahn, Princeton University

KITP workshop “HEP at the Sensitivity Frontier”
5/17/2018

Dark matter everywhere



10^{-22} eV $\quad$ 1 eV $\quad$ 1 keV $\quad$ 1 GeV $\quad$ 100 TeV $\quad$ 10^{19} GeV

coherent-field bosonic
(axions, dark photons, …)

fermions

canonical
WIMP

unitarity

WIMPZilla,
gravitino,
???

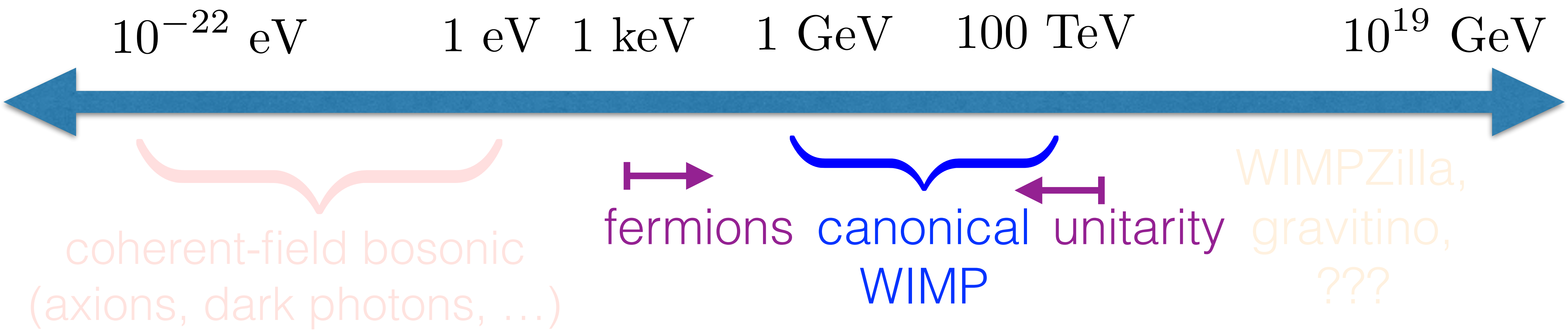
50 orders of magnitude in mass!

Non-gravitational interactions not guaranteed (e.g. gravitino)
but terrestrial detection strategies needed for all masses

Virialized DM has $v_{\mathrm{DM}} \sim 10^{-3} c$

$$\Longrightarrow \boxed{\mathrm{KE}_{\mathrm{DM}} \sim 10^{-6} m_{\mathrm{DM}}}$$

But what is it?



10^{-22} eV

1 eV

1 keV

1 GeV

100 TeV

10^{19} GeV

coherent-field bosonic
(axions, dark photons, …)

fermions

canonical
WIMP

unitarity

WIMPZilla,
gravitino,
???

keV-TeV: energy deposits from single-particle scattering

[Goodman, Witten PRD 1985; Drukier, Freese, Spergel PRD 1986]

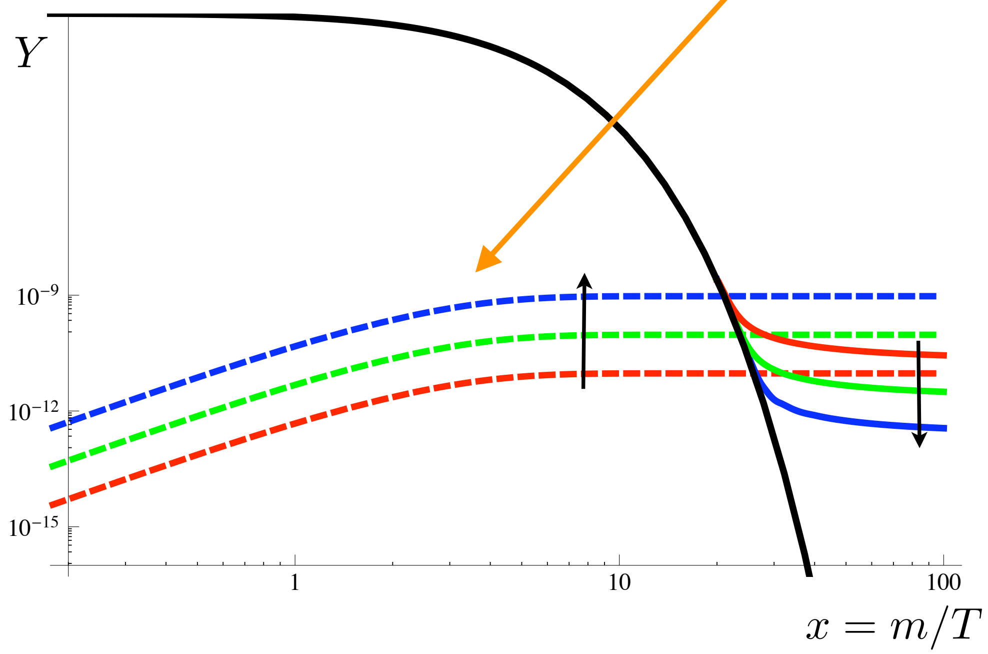
and many others:
DAMIC
SENSEI
CRESST
…

Freeze-in through dark photon

$$\mathcal{L} \supset \frac{\varepsilon}{2} F_{\mu\nu} F'^{\mu\nu} - i g_D \bar{\chi} \gamma^\mu \chi A'_\mu$$

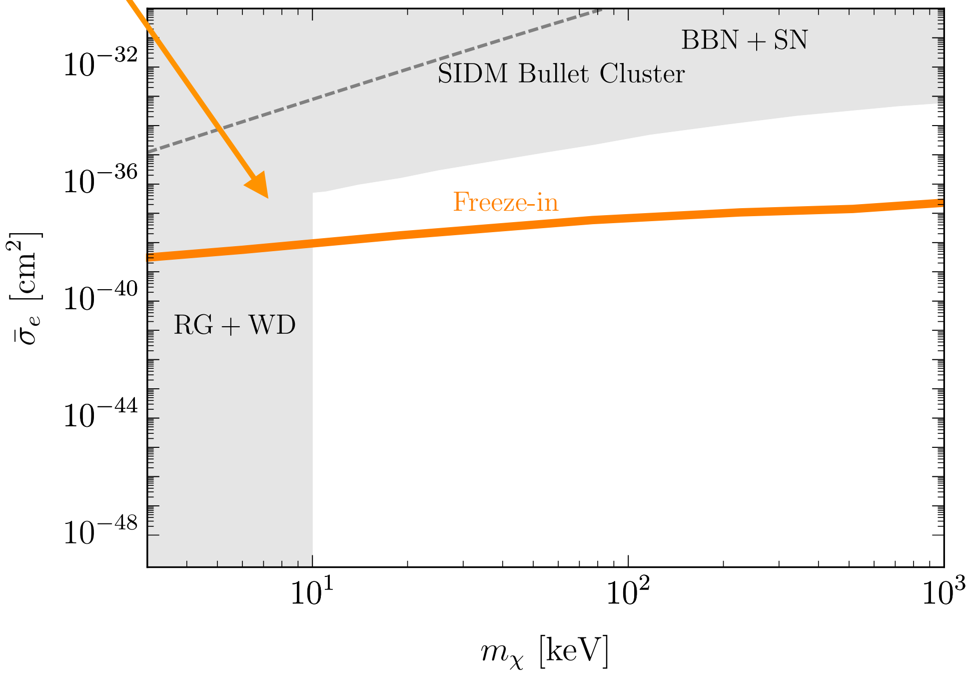
$m_{A'} \ll \mathrm{keV}$

$\alpha_D \varepsilon^2 \sim 10^{-28}$



[Hall et al., JHEP 2010]

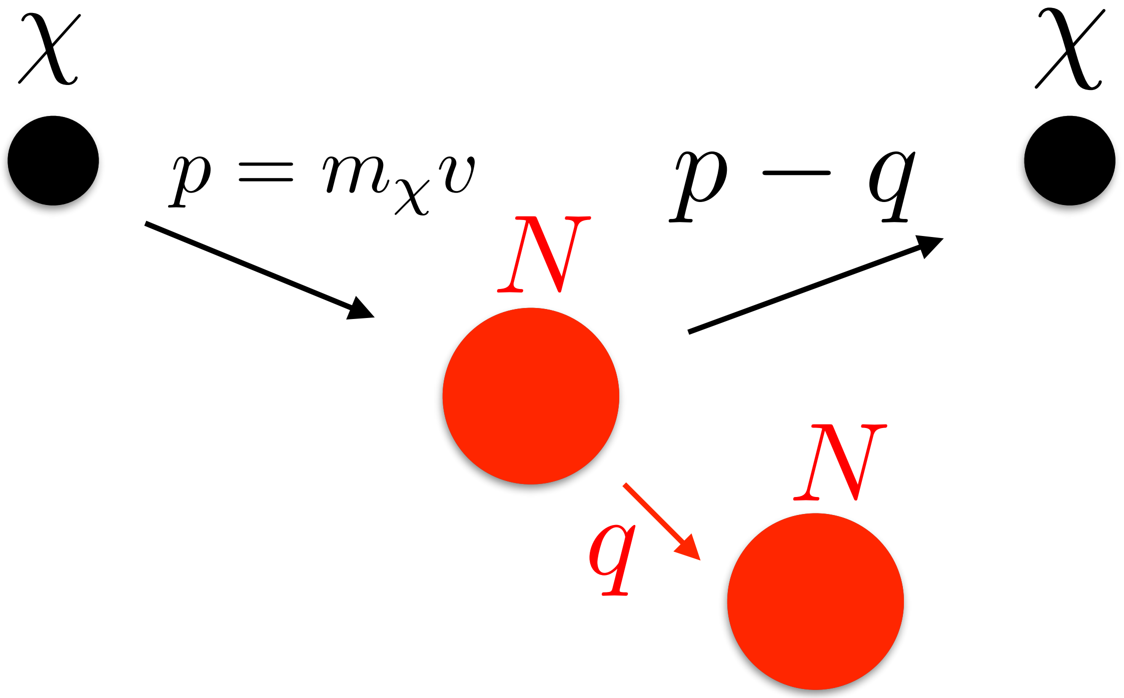
$m_\chi \in [10\ \mathrm{keV}, \mathcal{O}(\mathrm{MeV})]$



[U.S. Cosmic Visions Commun. Rept. 2017]

Parameter space for keV DM is wide open!
Including lower limit of particle DM

Nuclear recoil: tough for light DM!



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

Only available for $m_\chi \sim m_N$, still far below typical thresholds

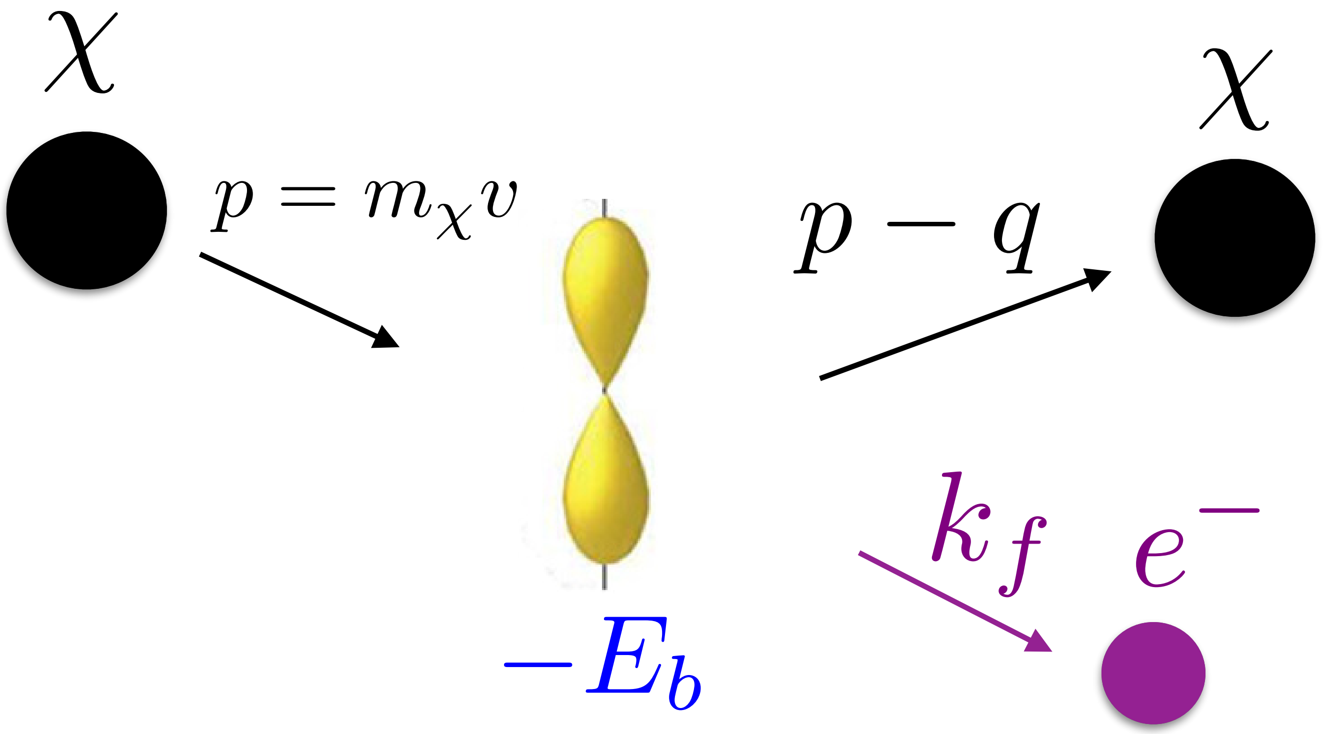
"Ping pong ball on bowling ball" kinematics:

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

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

Electron recoil: DM-induced ionization

[Essig, Mardon, Volansky PRD 2012]



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

Two key features:

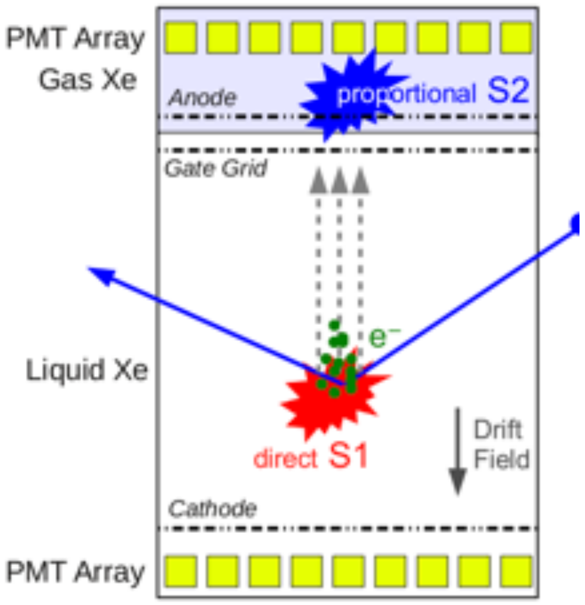
1. Initial state not a momentum eigenstate: k_f and q independent

2. Wavefunction suppression at large q:

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

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

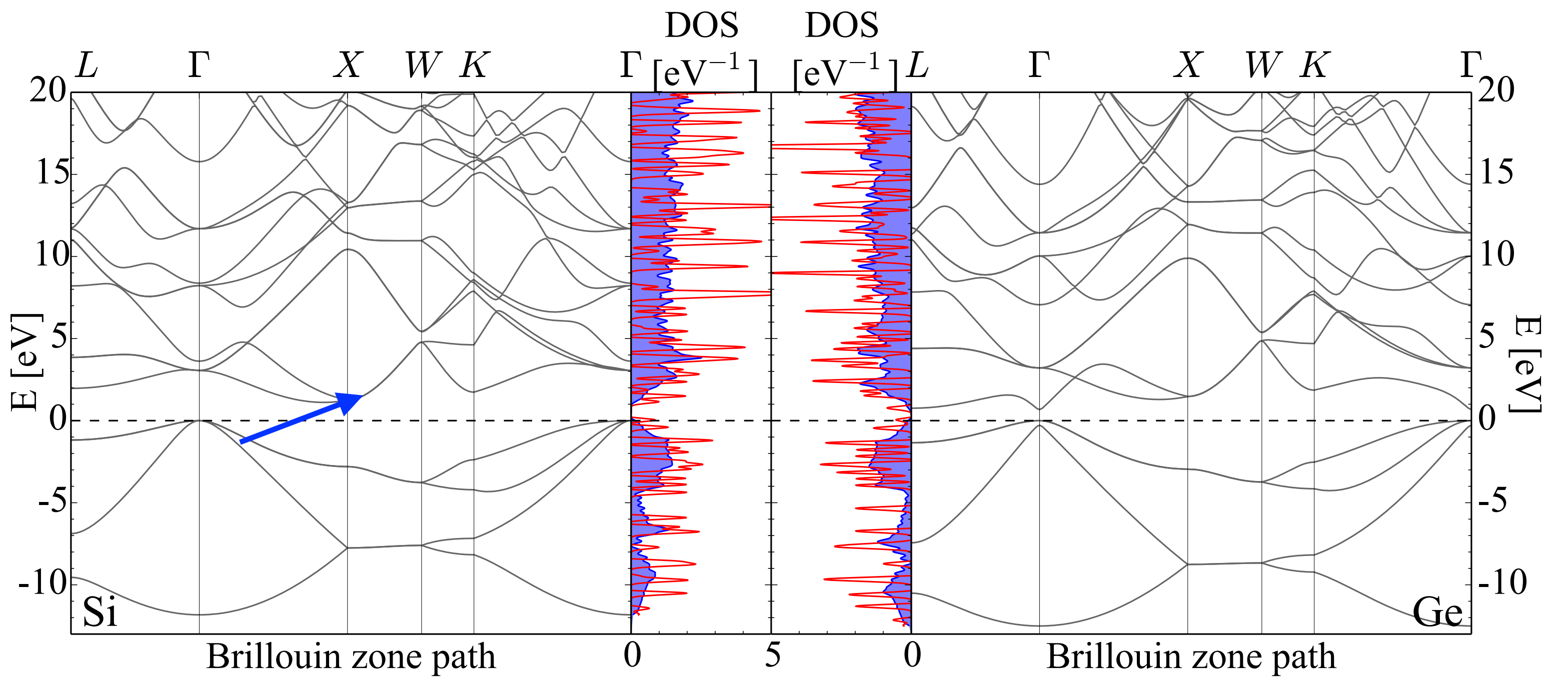
Atoms and semiconductors



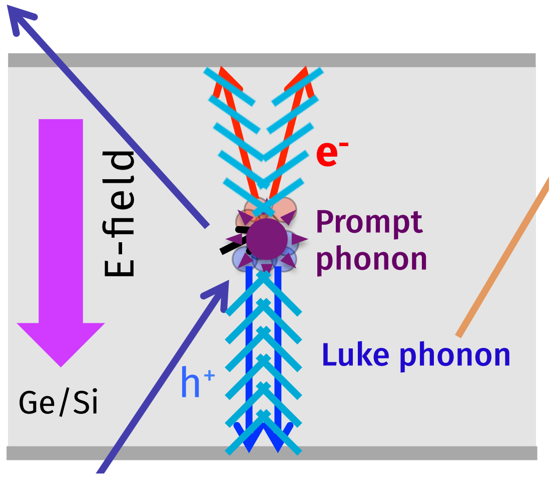
Noble liquids - Xe, Ar, …
Signal: S2 only
[Essig et al, PRD 2017;
DarkSide collab. 2018]

Atomic ionization energies
are ~10's of eV

$\Longrightarrow$ 10 MeV threshold



Semiconductors - Si, Ge, …
[Essig et al, JHEP 2016; Lee et al. PRD 2015]

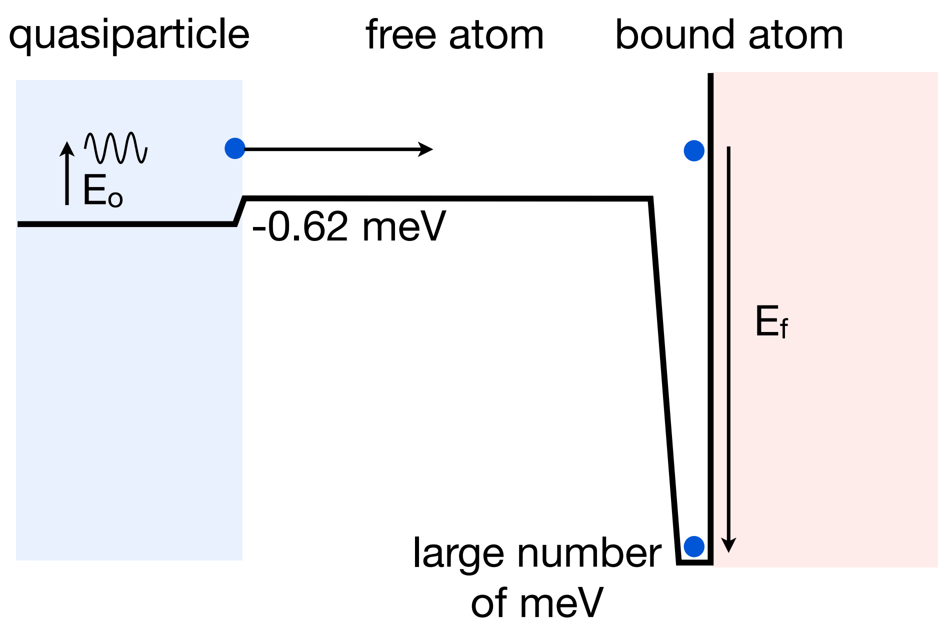


Band gap as small as 0.5 eV

$\Longrightarrow$ 0.5 MeV threshold

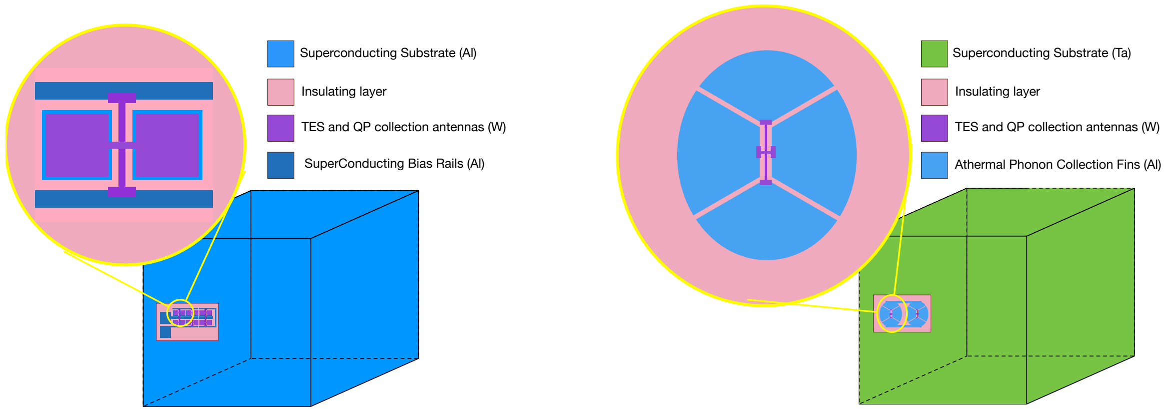
keV DM needs meV sensitivity

Superfluids
(long-lived quasiparticles,
surface amplification)



[Hertel, McKinsey, 2016]

Superconductors
(meV gap to break Cooper pair,
detect with TES)



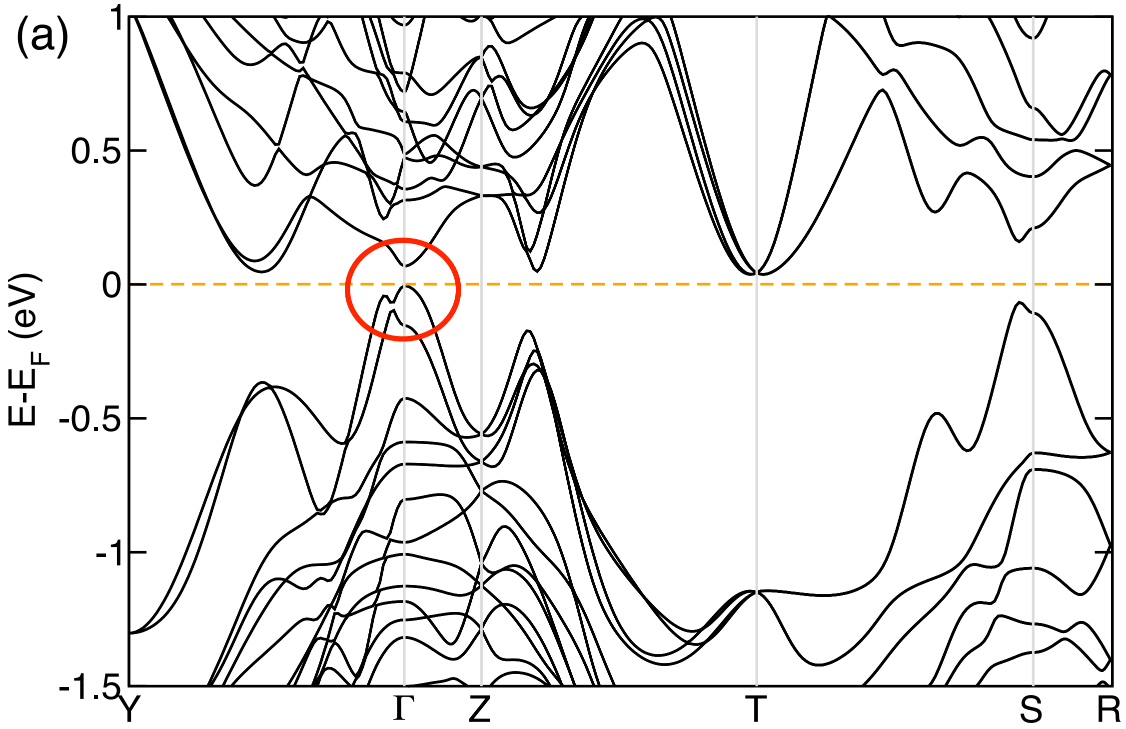
[Hochberg, Pyle, Zhao, Zurek JHEP 2016]

Common issue: poor response to dark photon mediator
freeze-in target not accessible

Dirac materials for DM

[Hochberg, **YK**, Lisanti, Zurek, Grushin, Ilan, Liu, Weber, Griffin, Neaton,
Phys. Rev. D 2018, 1708.08929]

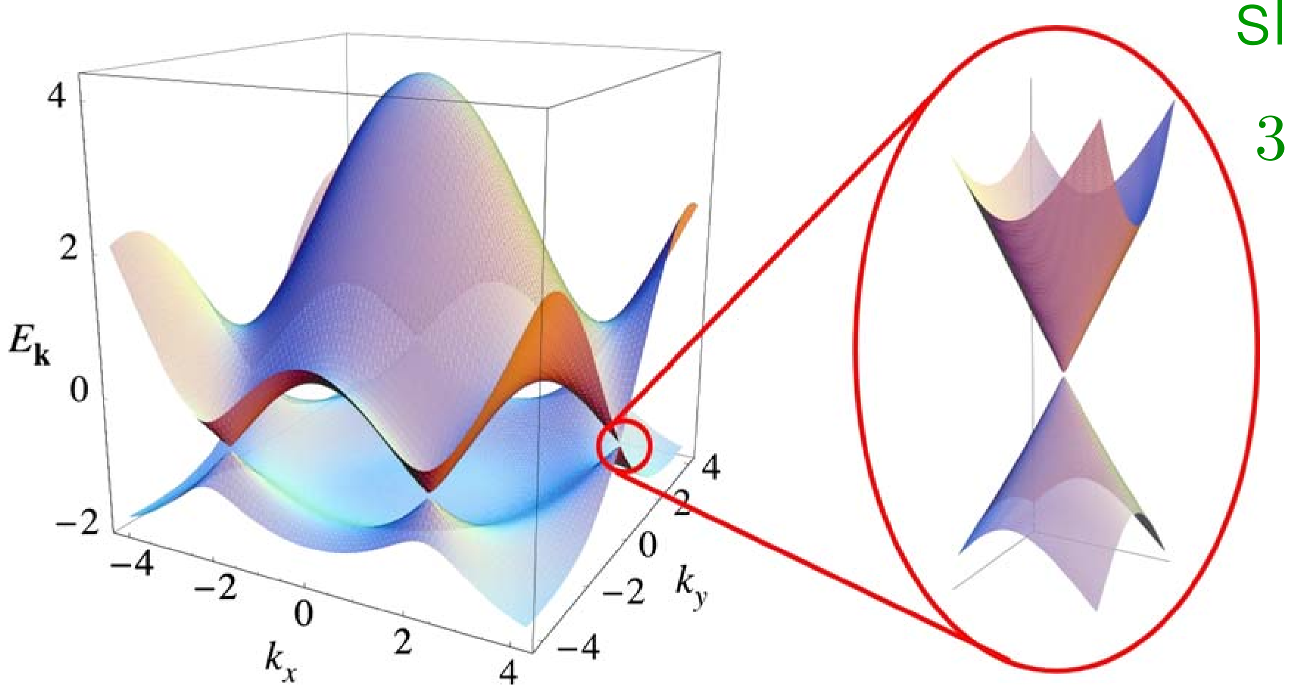
3D Dirac semimetal ($ZrTe_5$)



- meV excitation energies
- Anisotropic (bands and crystal)
- No in-medium screening

New class of materials for DM detection!
Capable of directional detection at meV-eV energies

Dirac semimetals ~ ultra-low-gap semiconductors



slope of cone = v_F

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

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

Dirac dispersion:

$\Delta \lesssim \mathcal{O}(\mathrm{meV})$

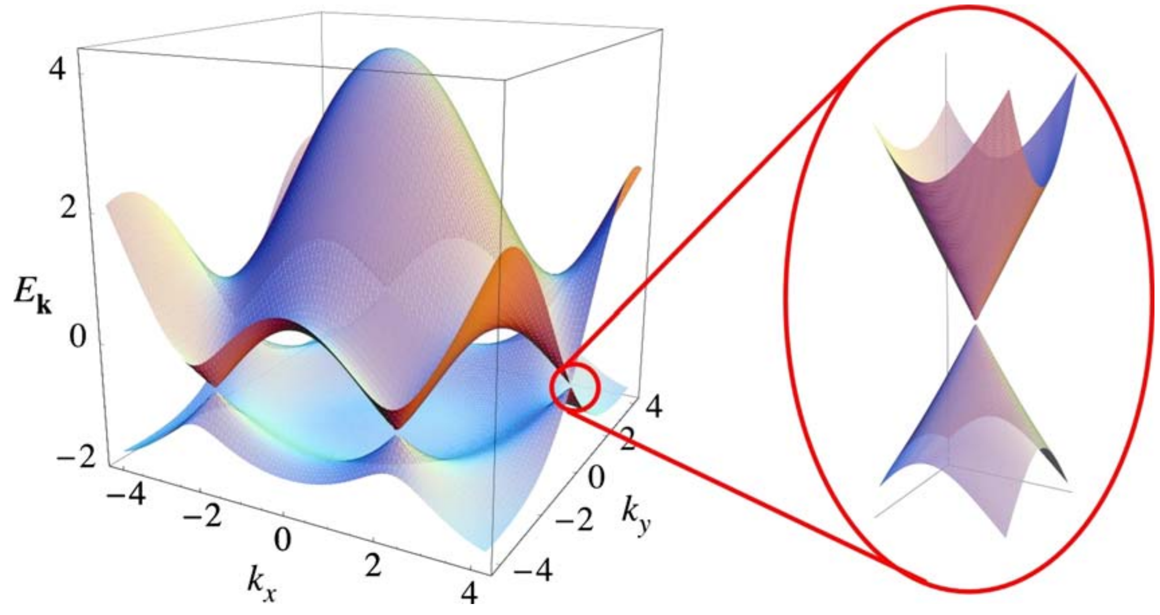
$$E_{\mathbf{k}}^{\pm} = \pm\sqrt{v_F^2 \mathbf{k}^2 + \Delta^2}$$

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

Pointlike Fermi surface but high conductivity

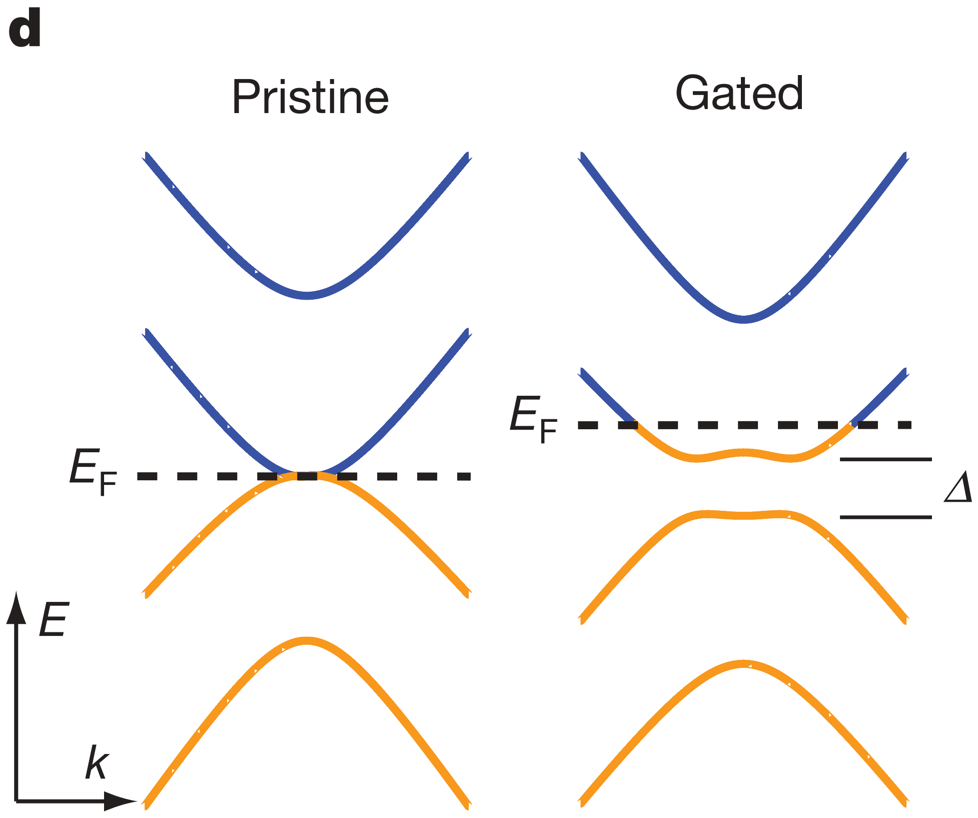
2D Graphene for keV DM?

Monolayer



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

Bilayer



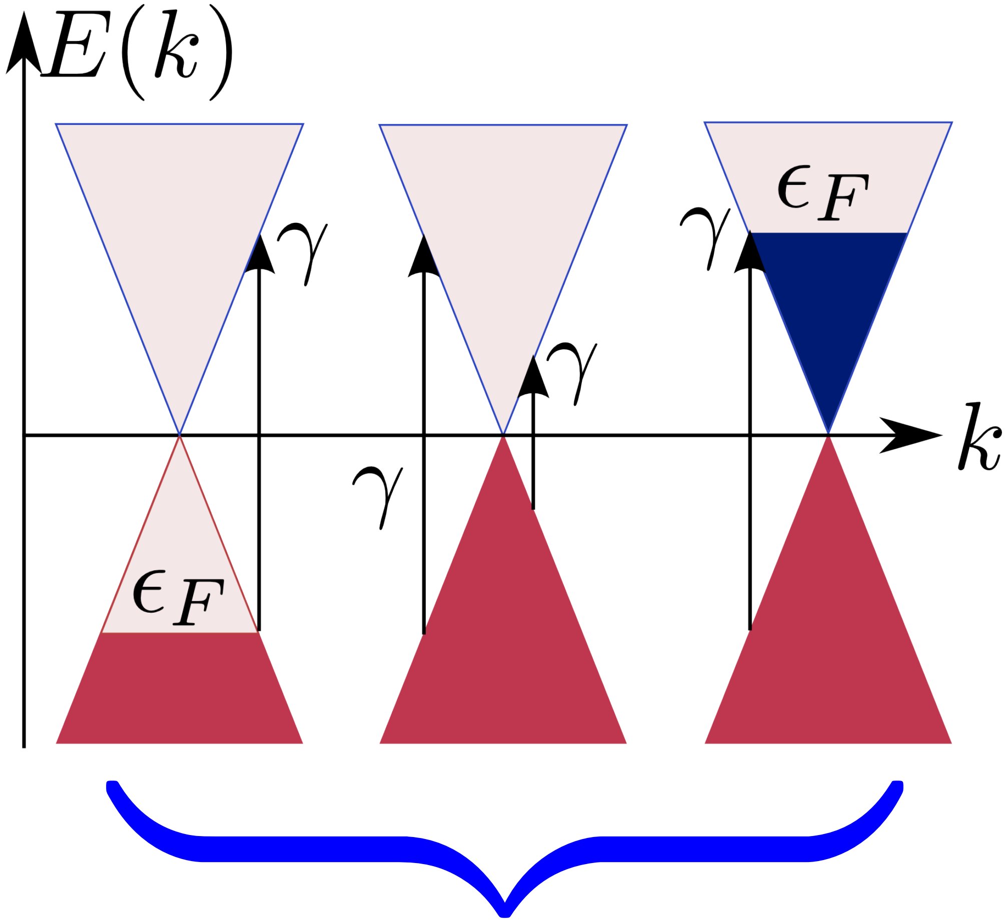
[Zhang et al, Nature Lett. 2009]

Gap Δ is continuously tunable 0-250 meV

Newton vs. Fermi

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

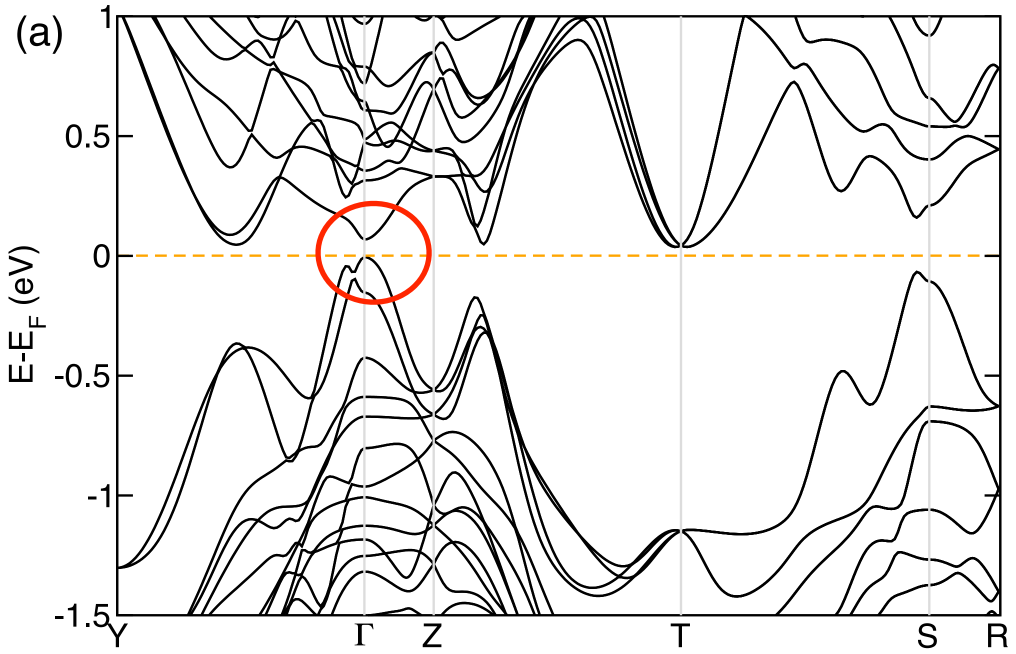
$v_F = 3 \times 10^{-3}c$

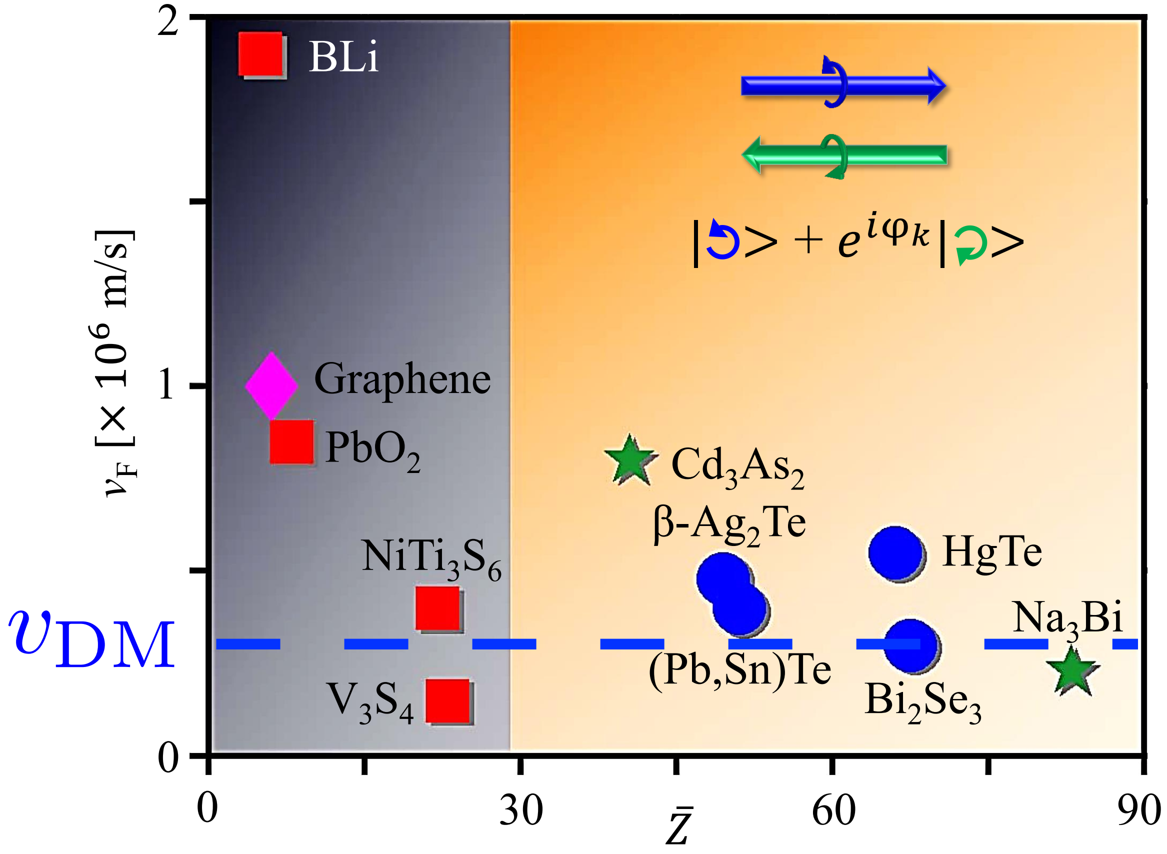


kinematically forbidden for $v_{\rm DM} < v_F$

Unfortunate coincidence for DM direct detection!
(Also 2D targets not ideal when electron is not ejected)

Dirac semimetals = “3D Graphene”



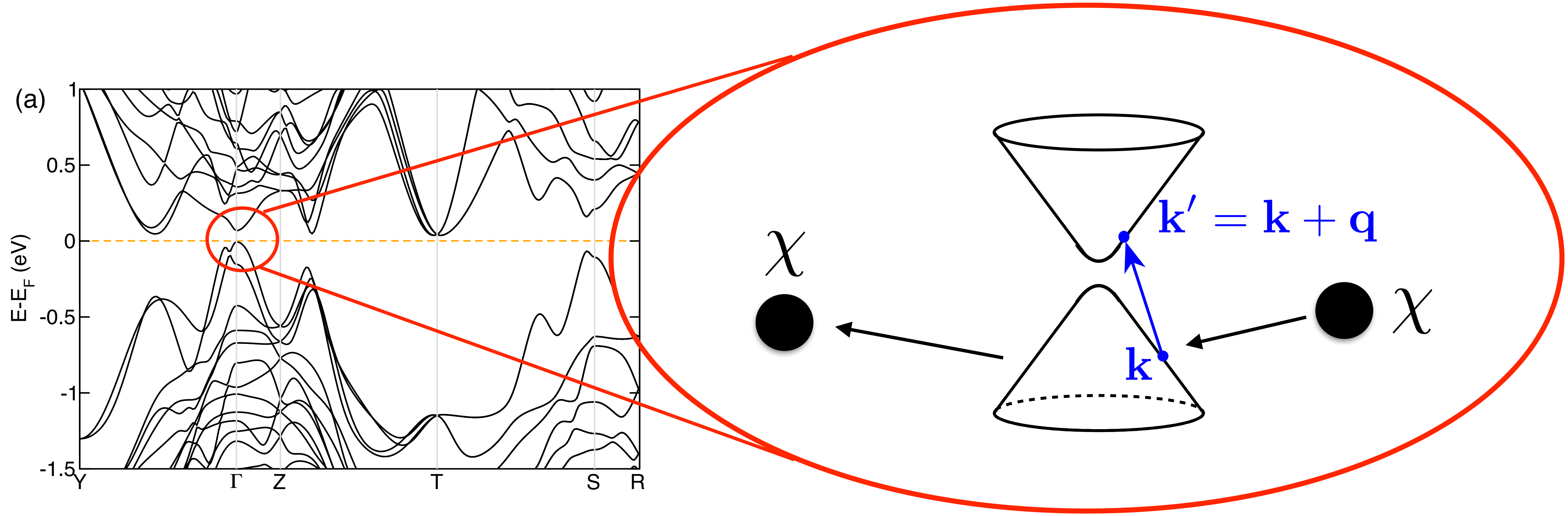


[Dolui & Das 1412.2607]

Advantages over graphene:

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

Scattering rate



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

$F_{\rm DM}(q)$: 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:

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

must be computed numerically

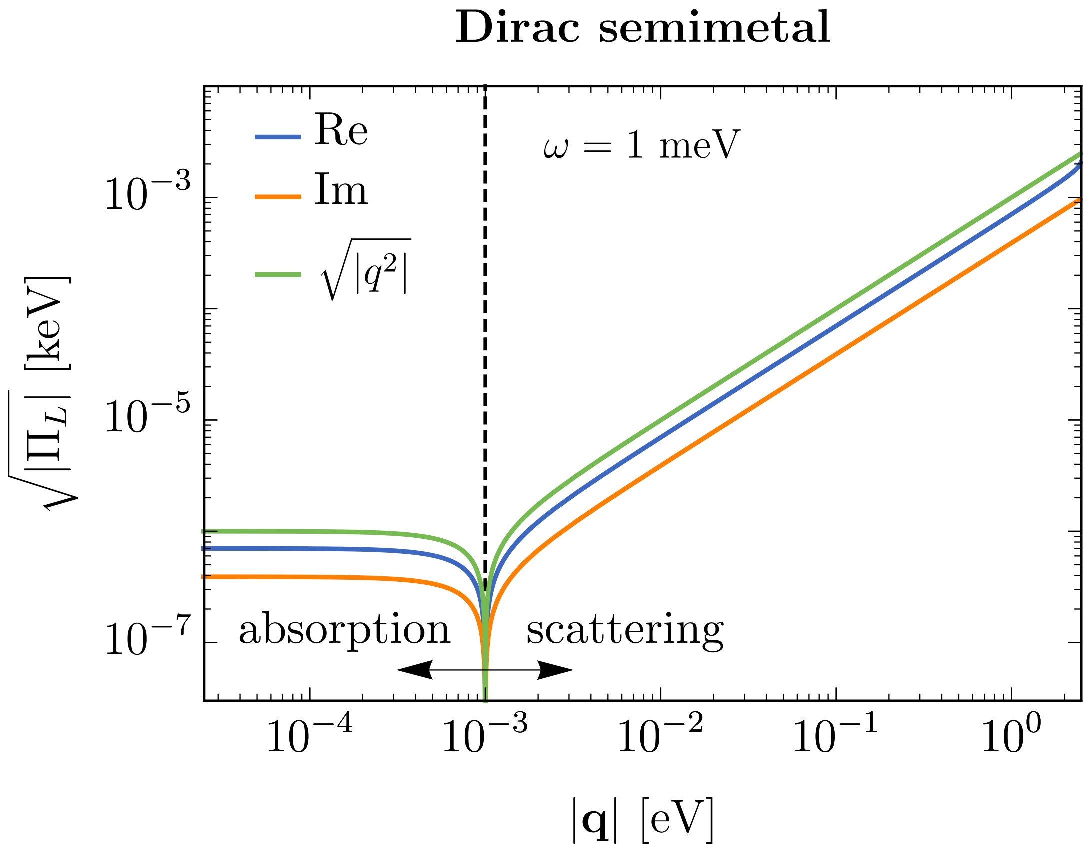
[Essig et al., JHEP 2016]

In-medium effects

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

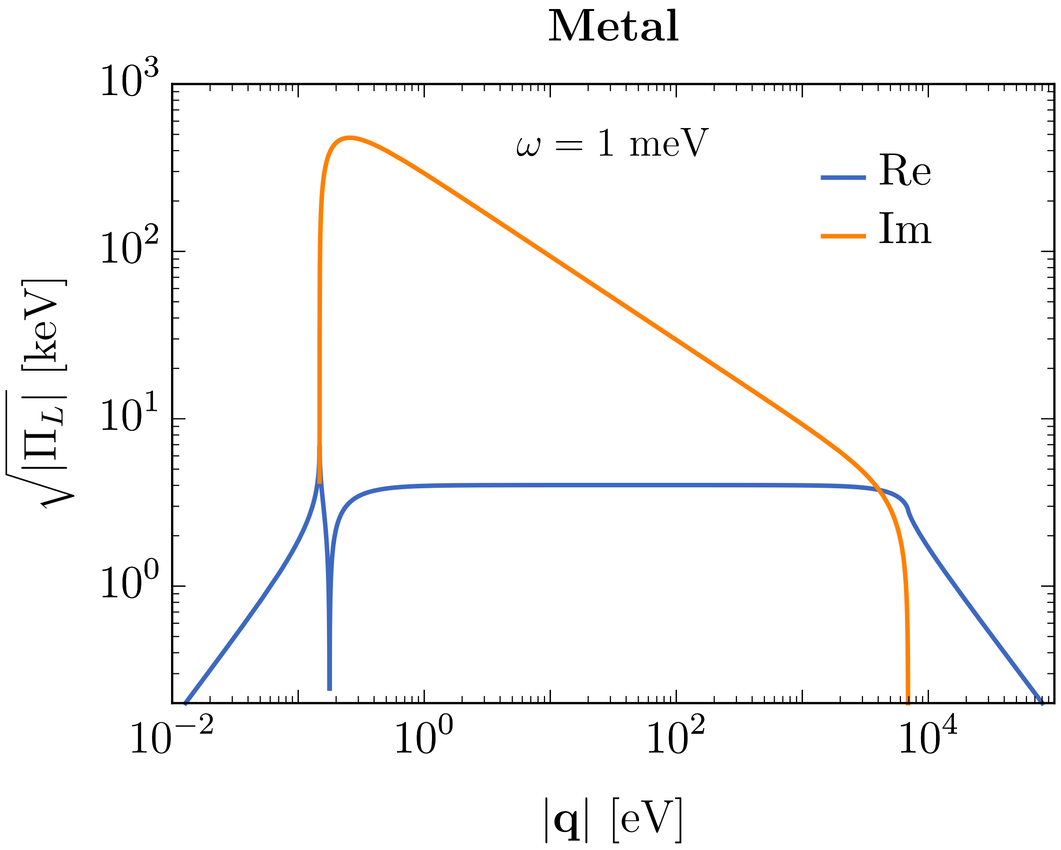
[An, Pospelov, Pradler, 1302.3884 and 1304.3461; Hochberg, Pyle, Zhao, Zurek, 1512.04533]

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

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

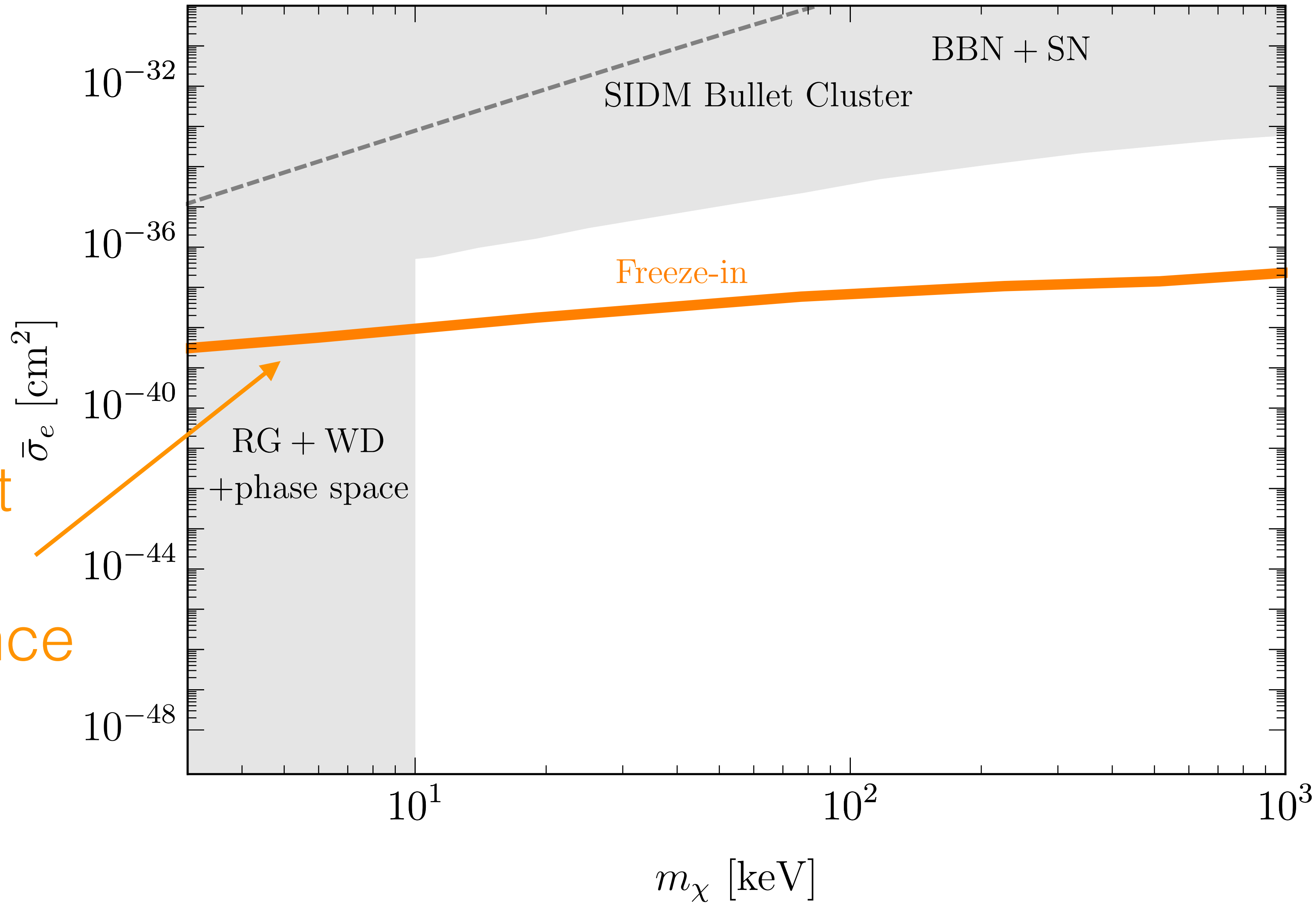
Dirac materials are carbon-copy of 3+1 QED!
Back to Peskin & Schroeder…

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

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

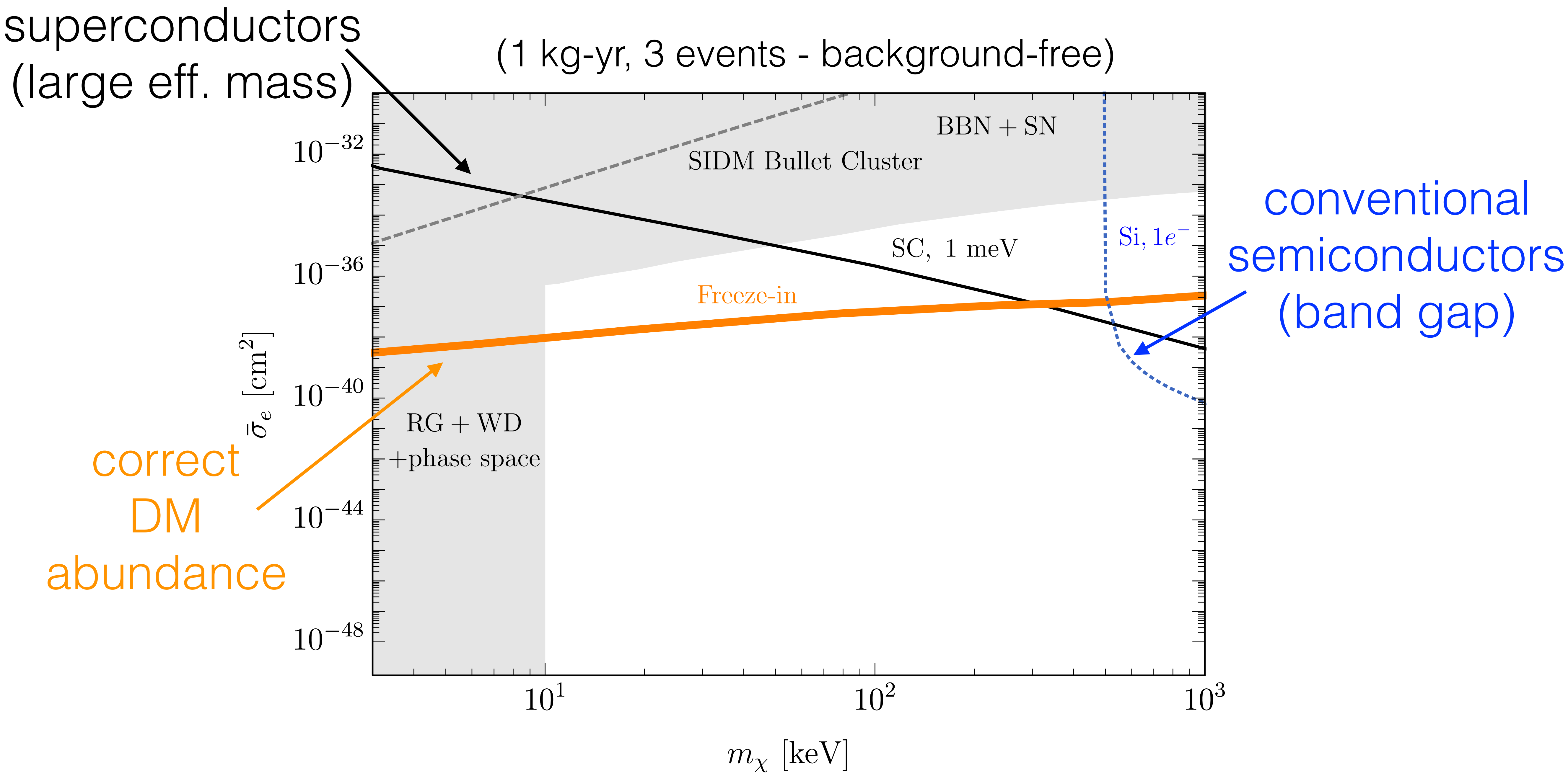
Ward identity to the rescue:
dark photon does not acquire
an in-medium mass in Dirac materials!

Freeze-in DM direct detection

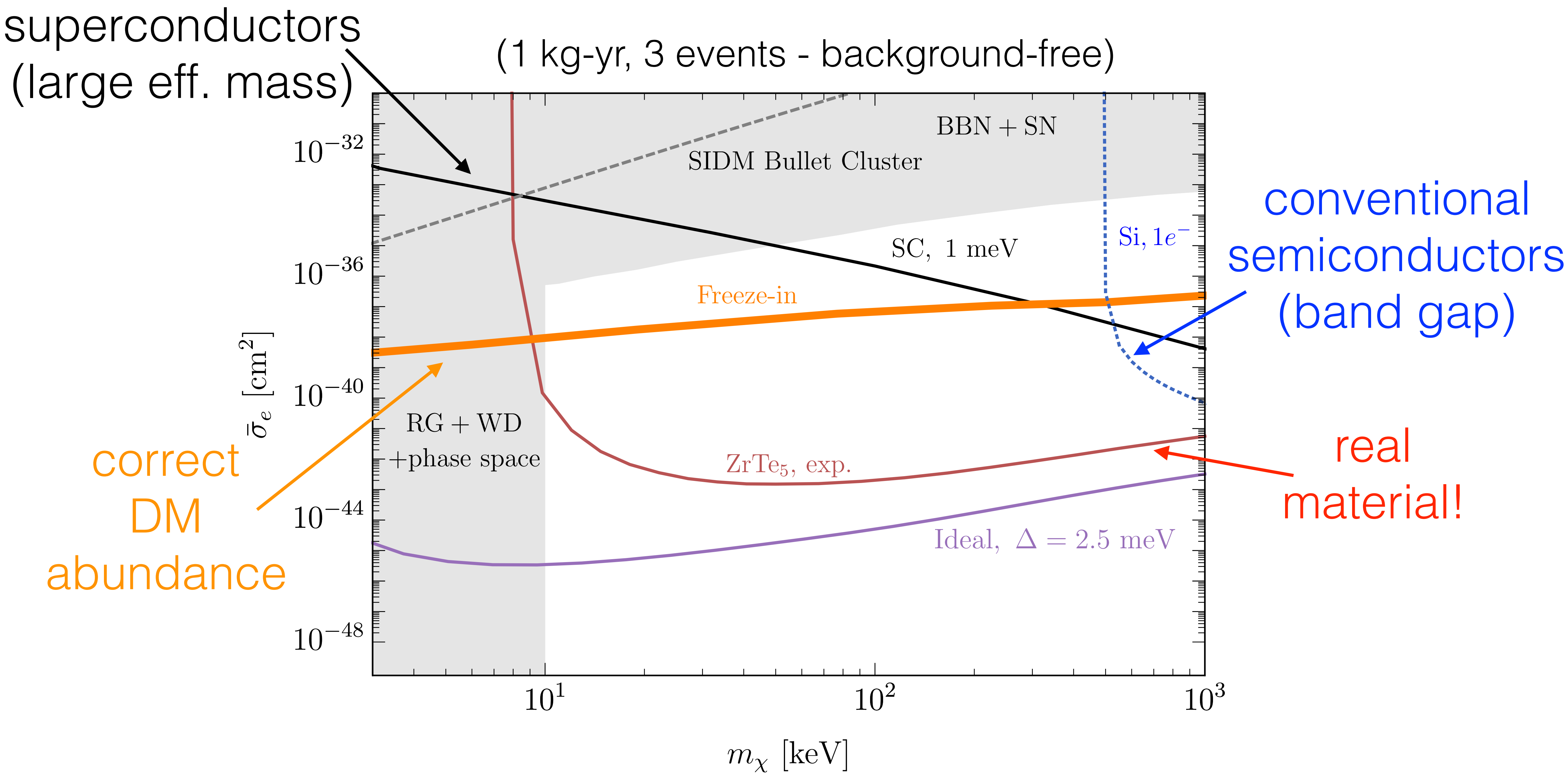


correct
DM
abundance

Freeze-in DM direct detection



Freeze-in DM direct detection


superconductors
(large eff. mass)

(1 kg-yr, 3 events - background-free)

conventional
semiconductors
(band gap)

correct
DM
abundance

real
material!

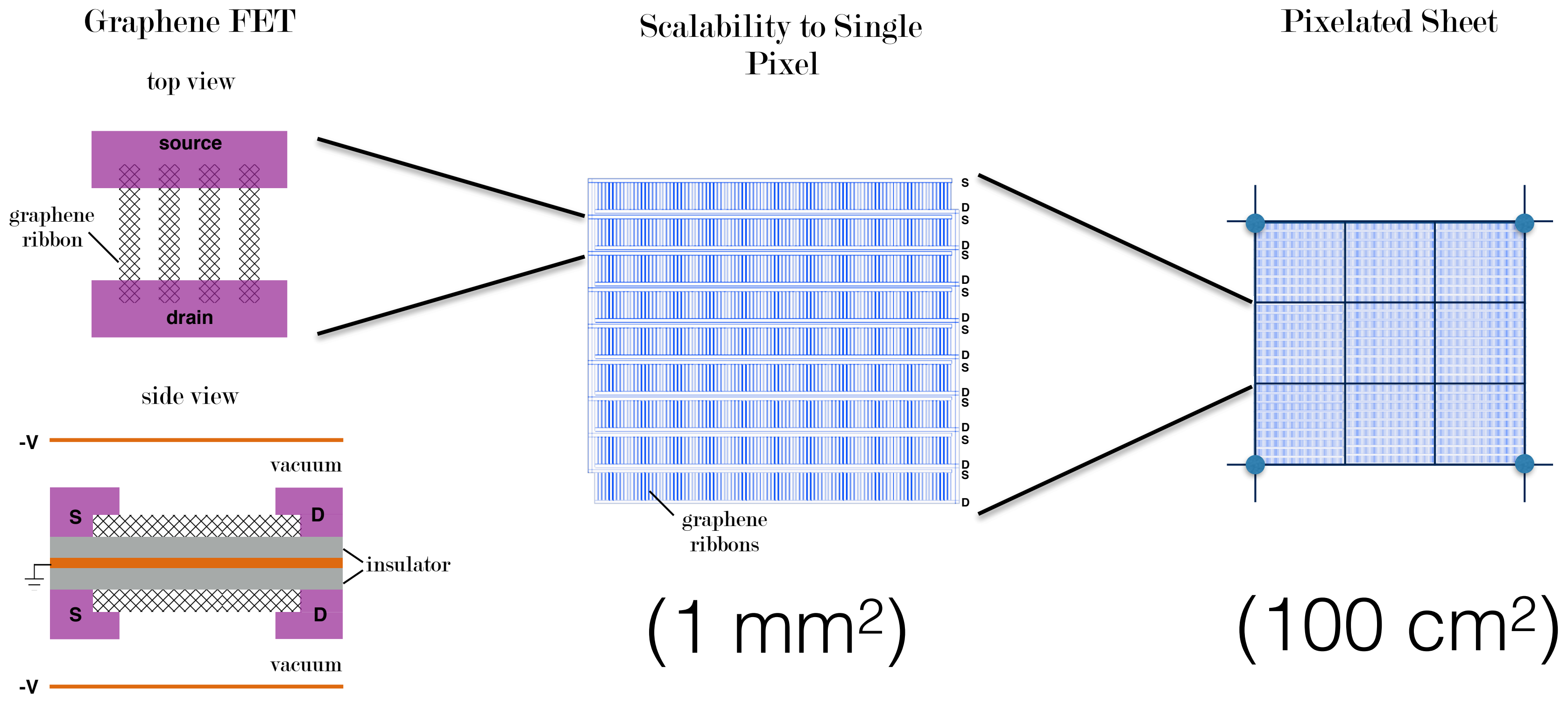
Dirac materials win because light mediator stays light

Readout??

- Charge (graphene FET?)
- Photons (single-IR photon detector?)
- Phonons (TES/MKID? Phonon production not well understood in Dirac materials)
- Something clever with semiclassical electron orbits (Fermi arcs in Weyl semimetals?)

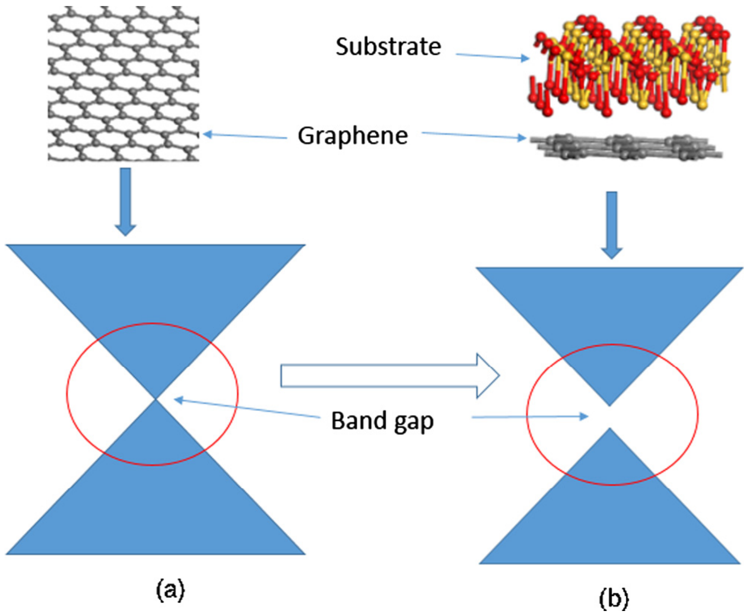
Graphene FET details

[Hochberg, YK, Lisanti, Tully, Zurek, PLB 2016]

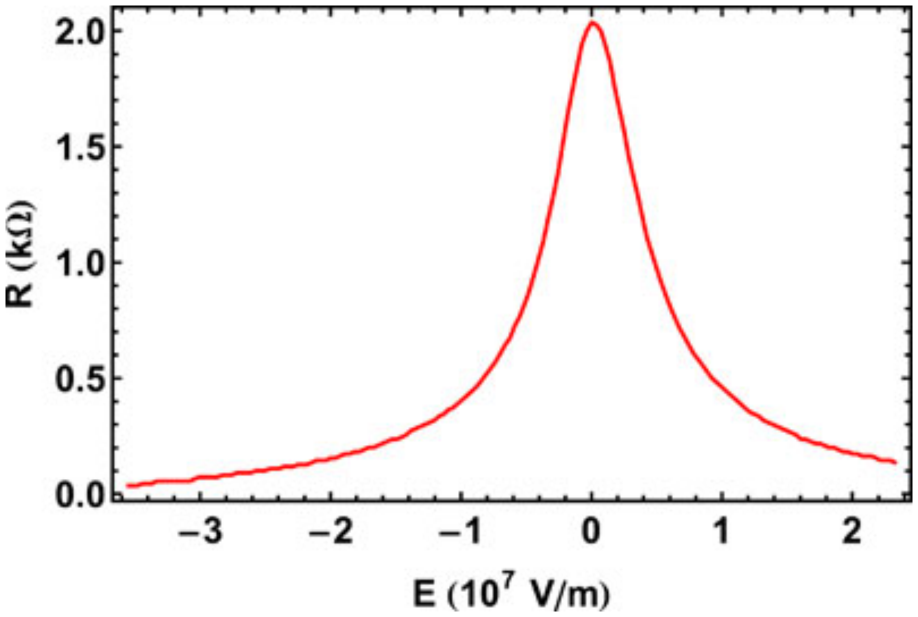


(1 mm^2)

(100 cm^2)



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

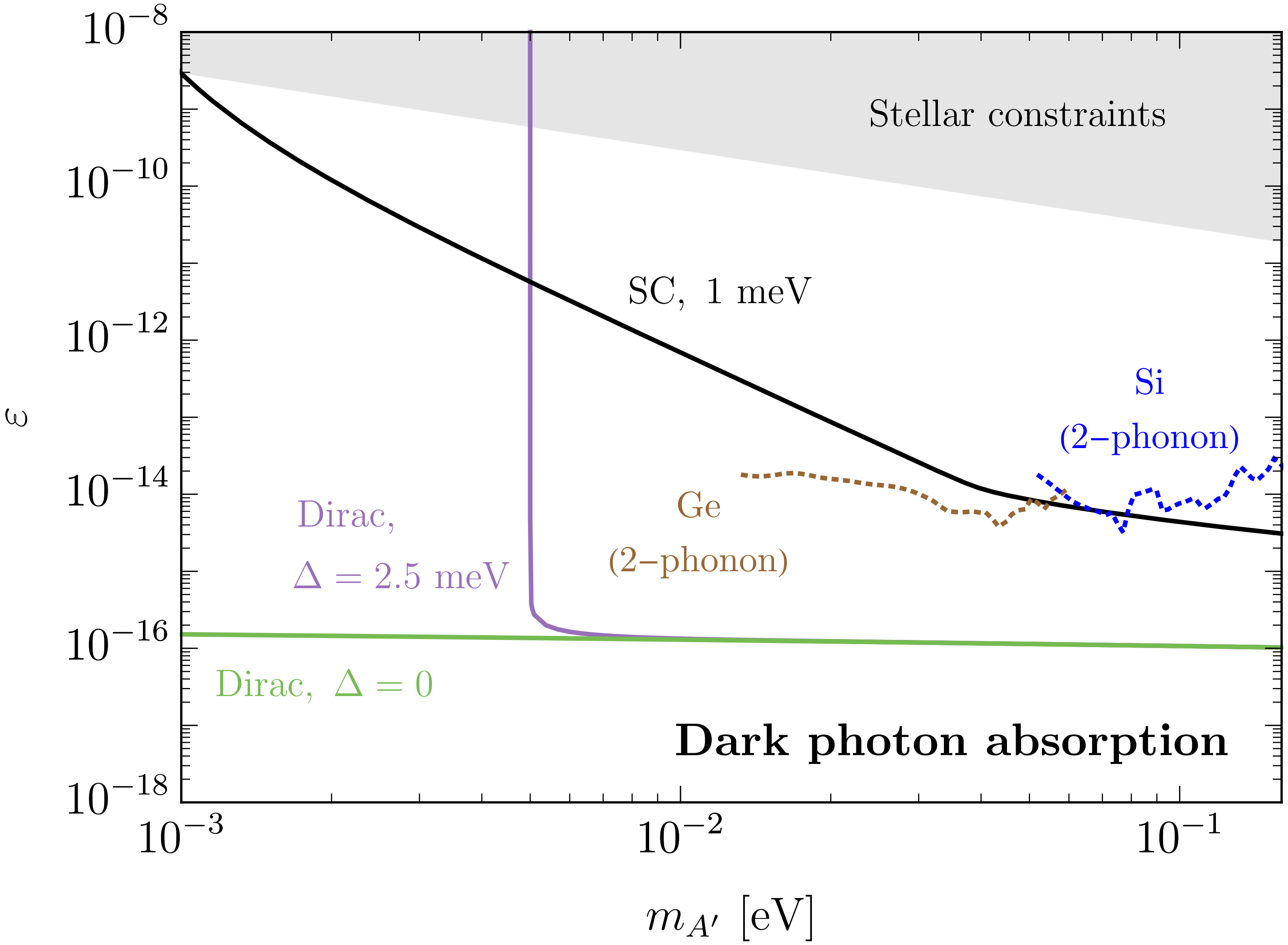


[Foxe et al., IEEE Nano 2012]

Large resistance drop with change in local electric field

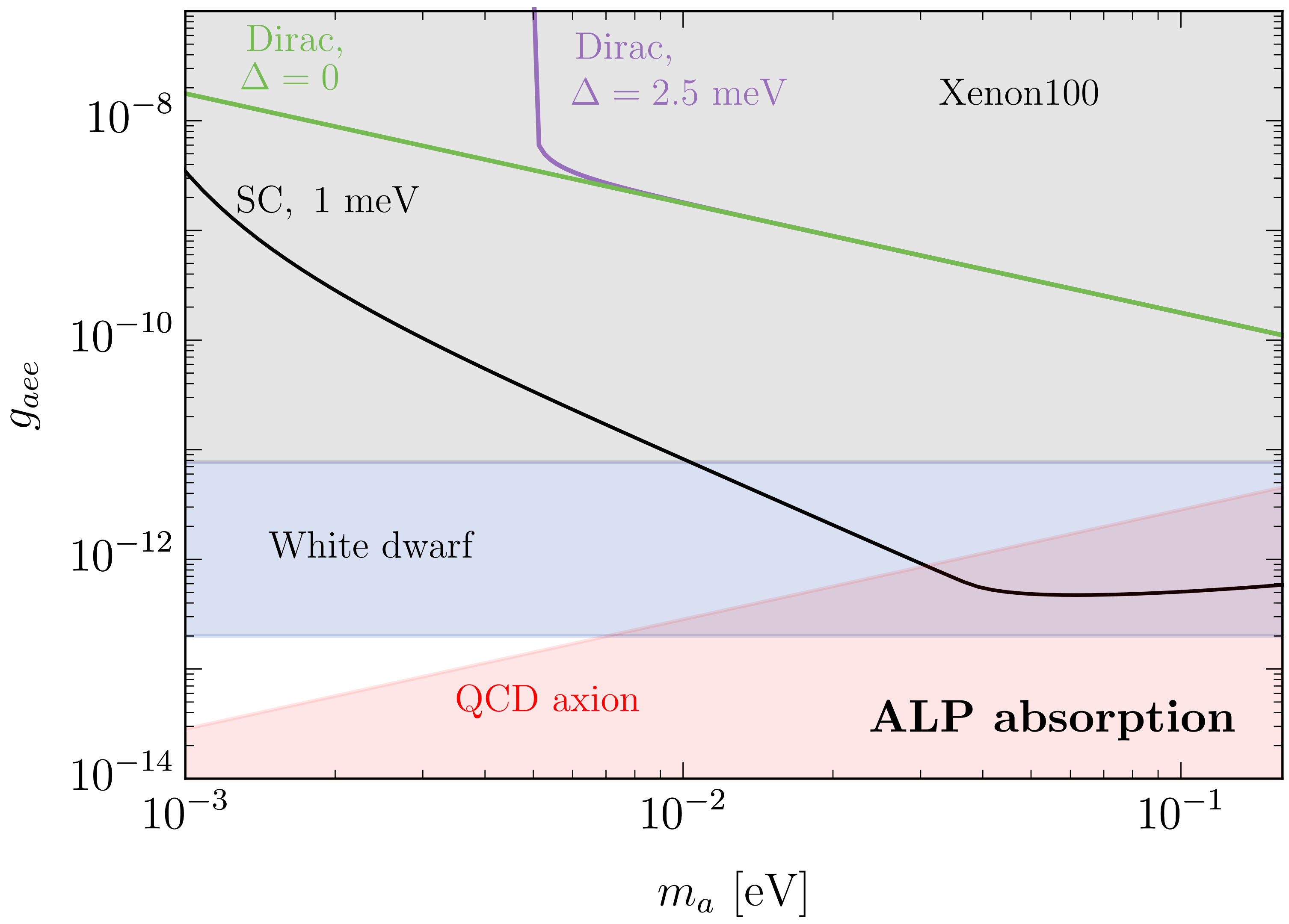
Bonus: absorption

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



Semimetals still beat superconductors!

Semimetal absorption reach: axion-like particles



Not really competitive…

Towards directional detection with semimetals

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

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

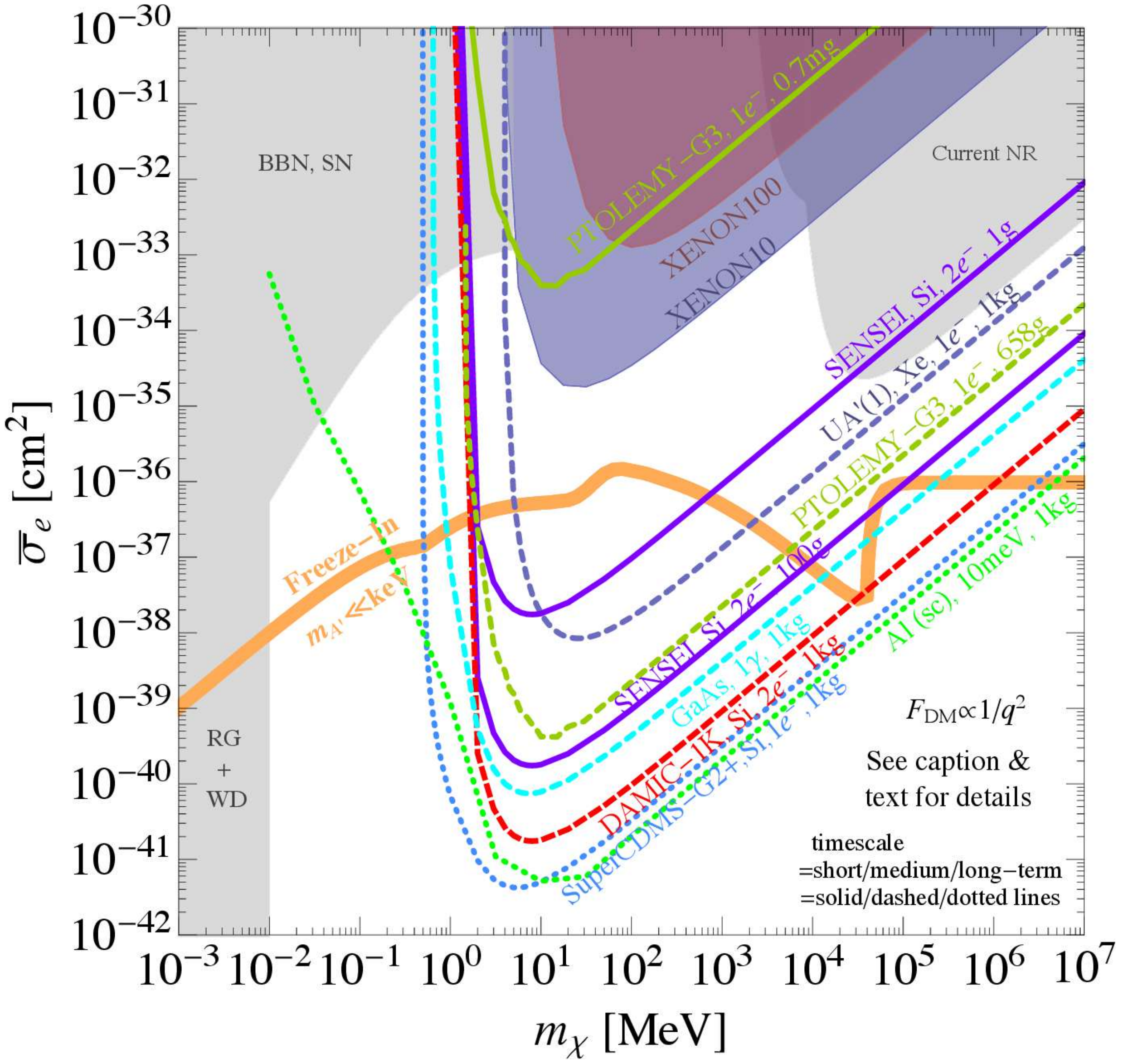
Realistic materials can be highly anisotropic in both background dielectric tensor and Fermi velocities

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

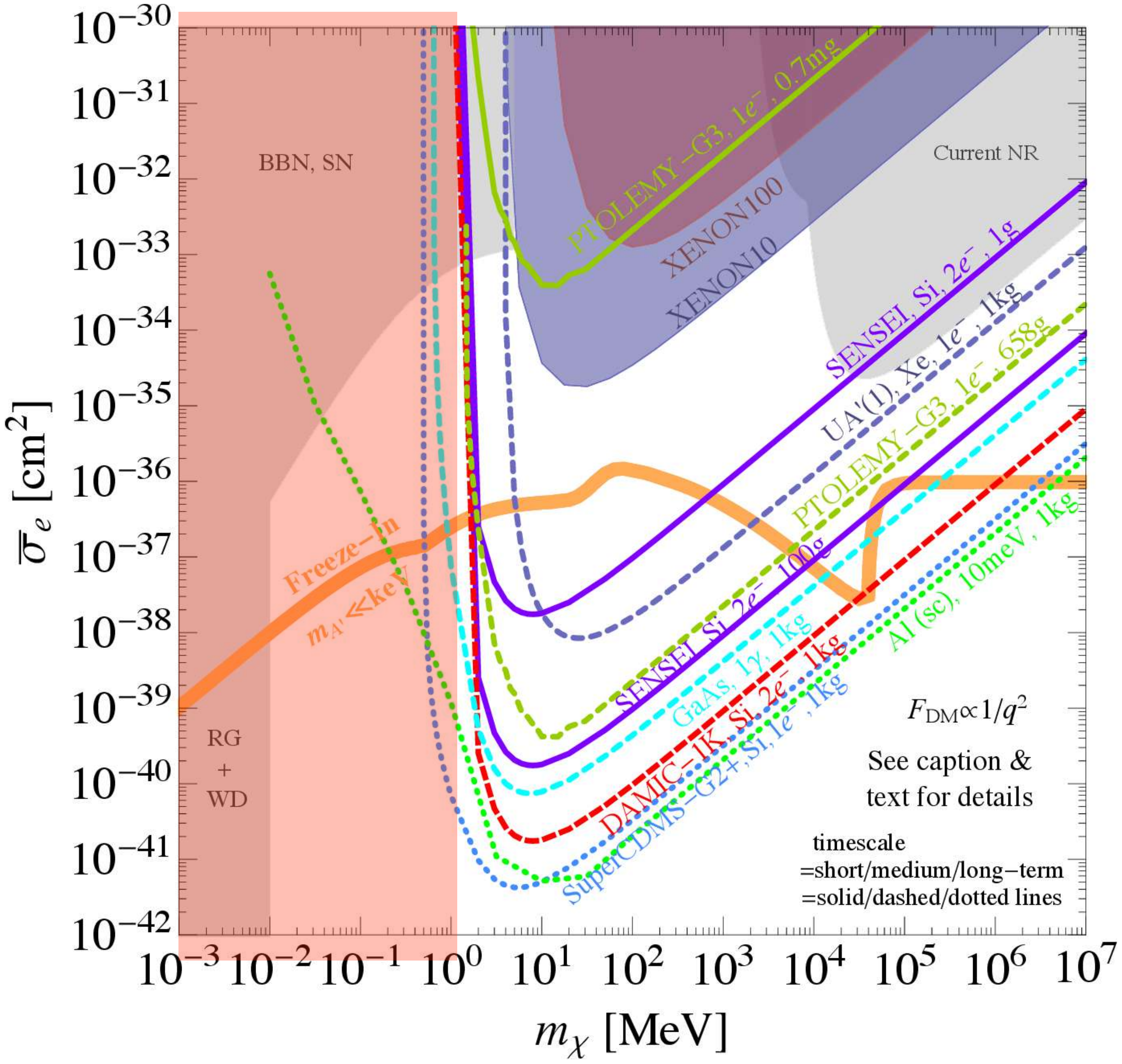
Outlook



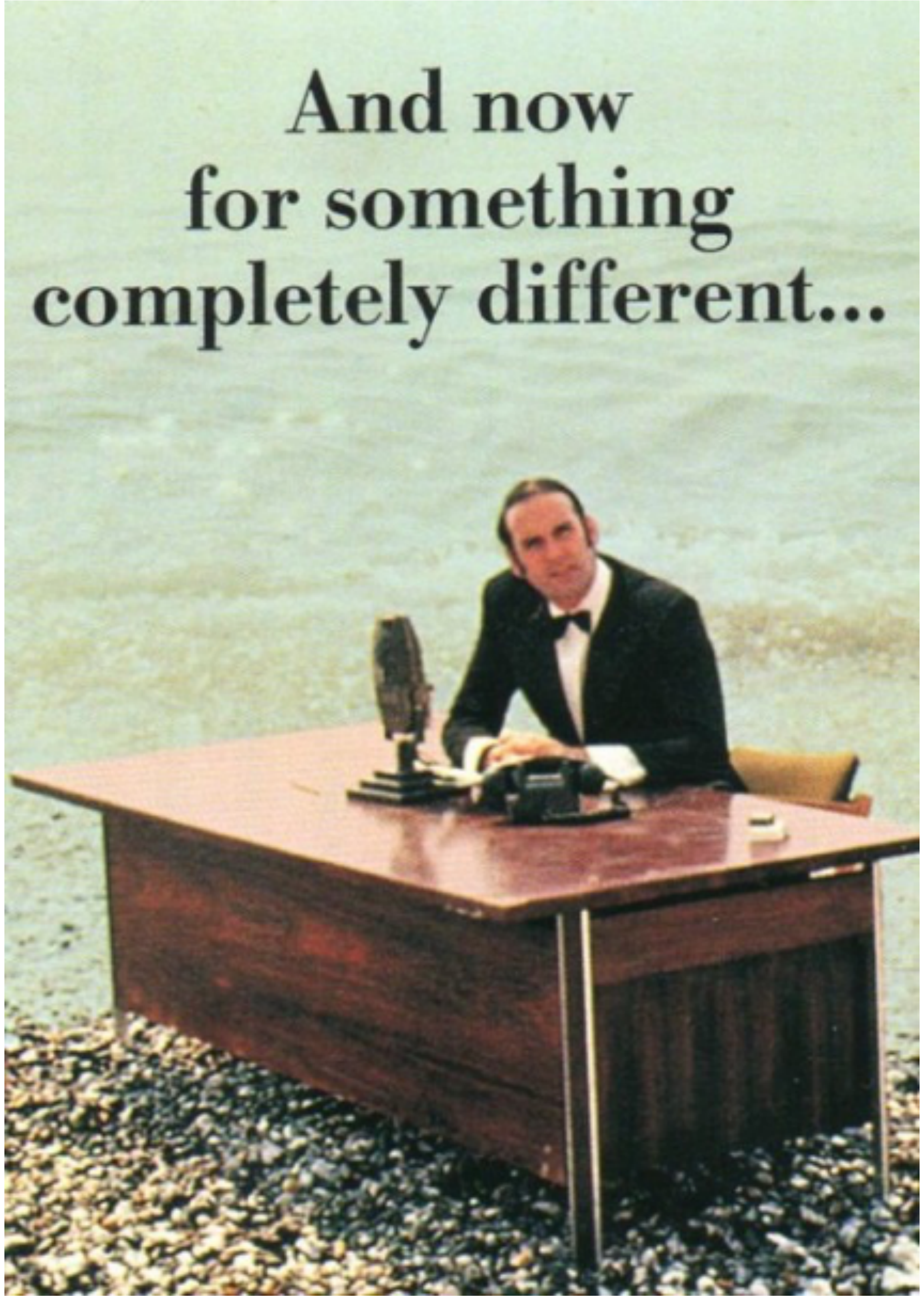
[…, **YK**, …, U.S. Cosmic Visions community report, 2017]

Outlook

semimetals!



[…, **YK**, …, U.S. Cosmic Visions community report, 2017]



ABRACADABRA:

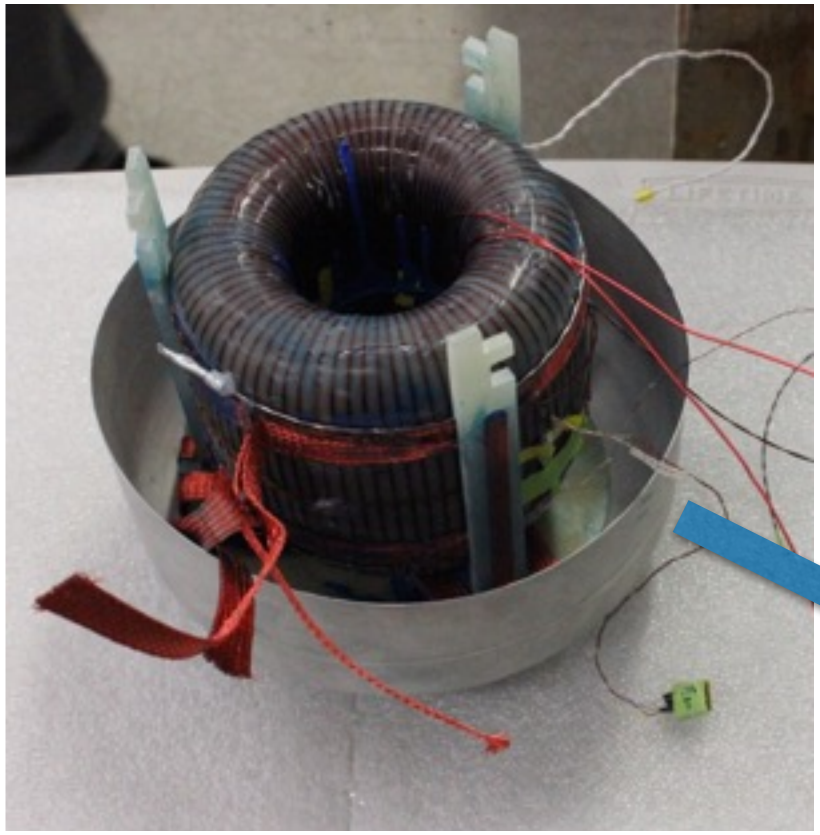
a sneak peak at the current prototype

ABRACADABRA

Janet Conrad, Joe Formaggio, Joshua Foster, Sarah Heine, Reyco Henning, **YK**, Joe Minervini, Jonathan Ouellet, Kerstin Perez, Alexey Radovinsky, Nick Rodd, Ben Safdi, Chiara Salemi, Jesse Thaler, Daniel Winklehner, Lindley Winslow

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL
UNIVERSITY OF MICHIGAN
PRINCETON UNIVERSITY

ABRA-10cm

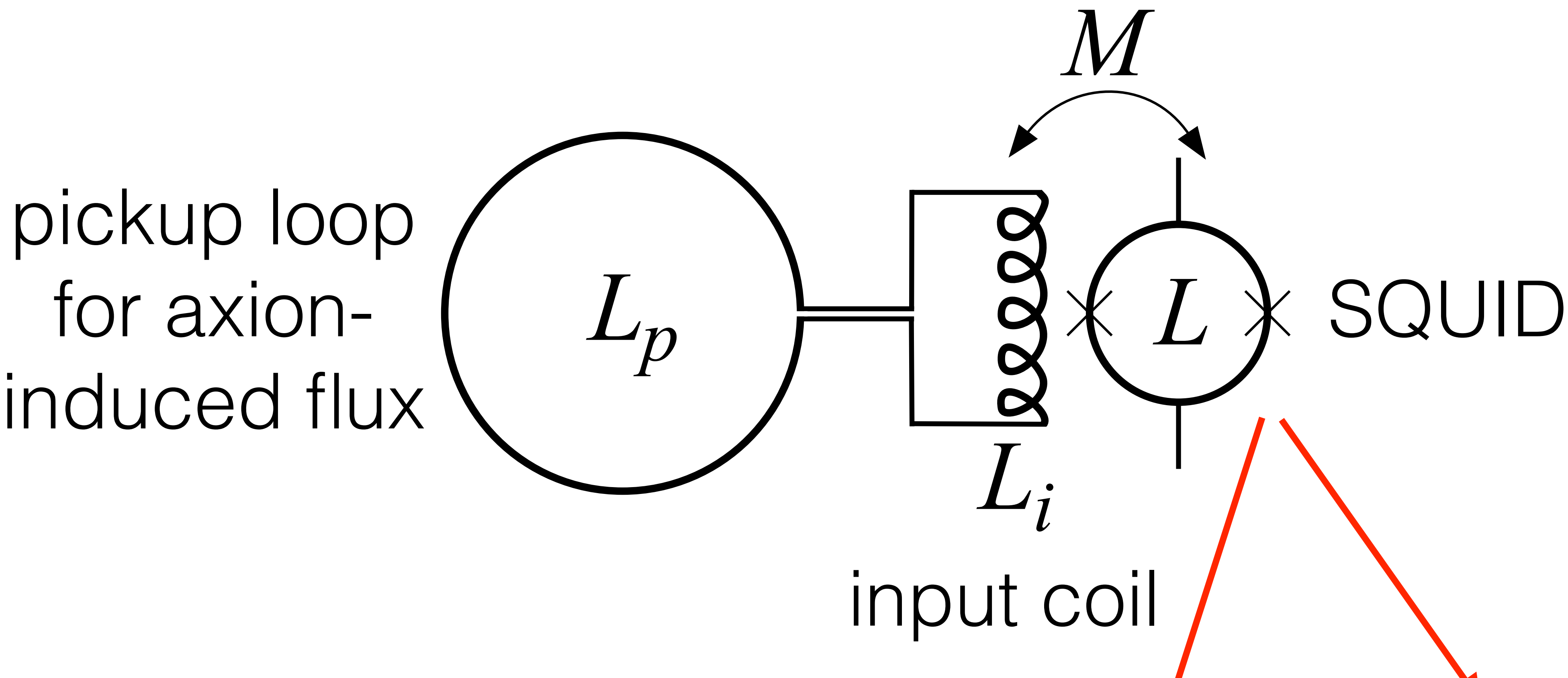


1 T superconducting toroid, diameter 12 cm

wrapped
in aluminum
shielding

inside
dilution fridge
(T = 0.1 K)

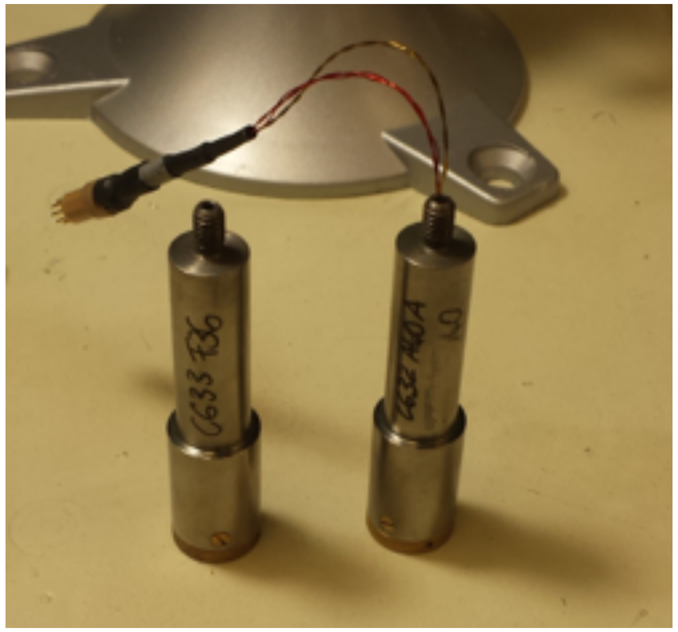
SQUID broadband readout



pickup loop for axion-induced flux

input coil

SQUID

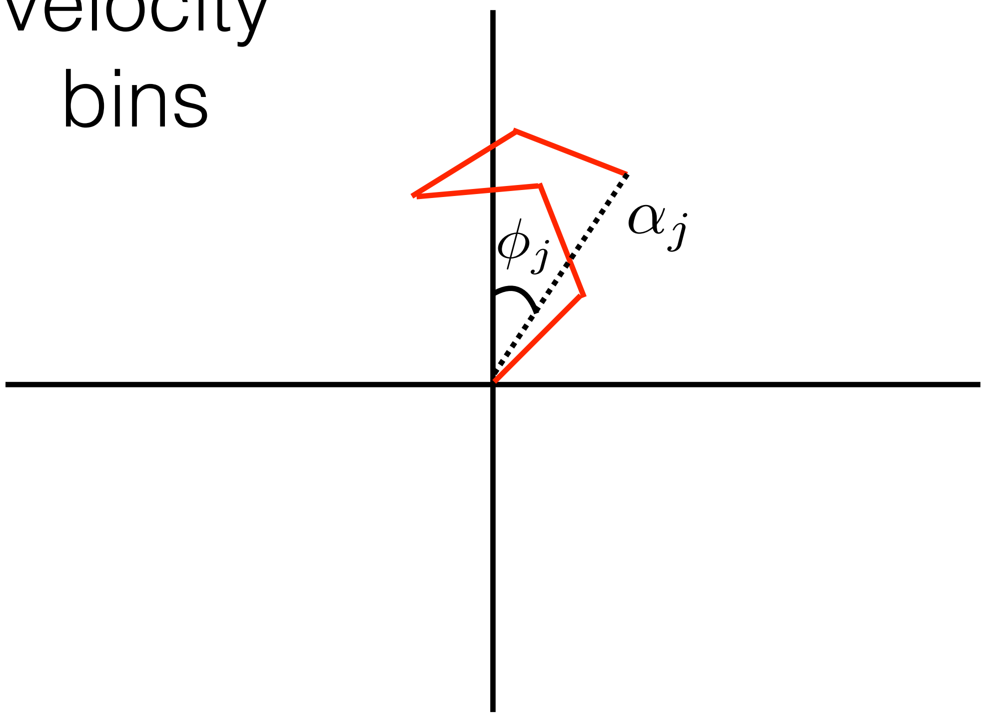


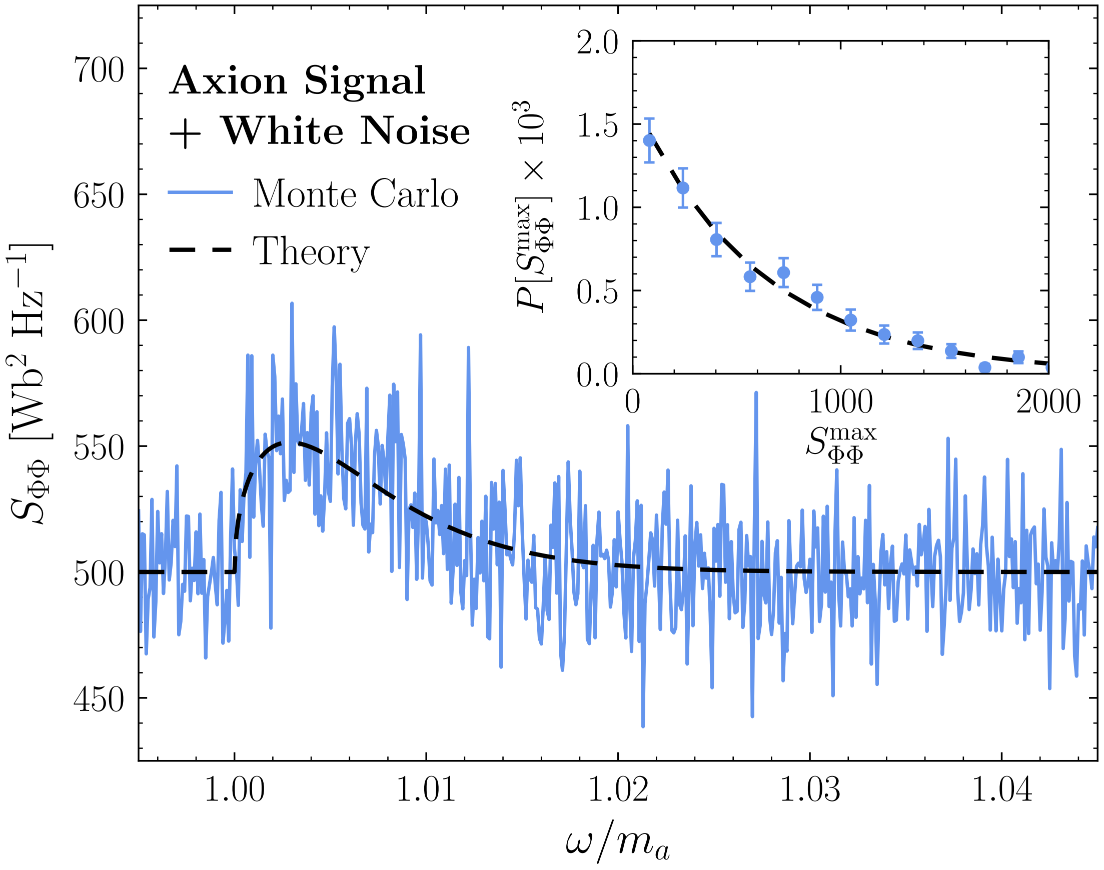
Data analysis

[Foster, Safdi, Rodd, arXiv:1711.10489]

$$a(t) = \frac{\sqrt{\rho_{\rm DM}}}{m_a}\sum_j \alpha_j \sqrt{f(v_j)\Delta v}\cos\left[m_a\left(1+\frac{v_j^2}{2}\right)t+\phi_j\right]$$

velocity bins





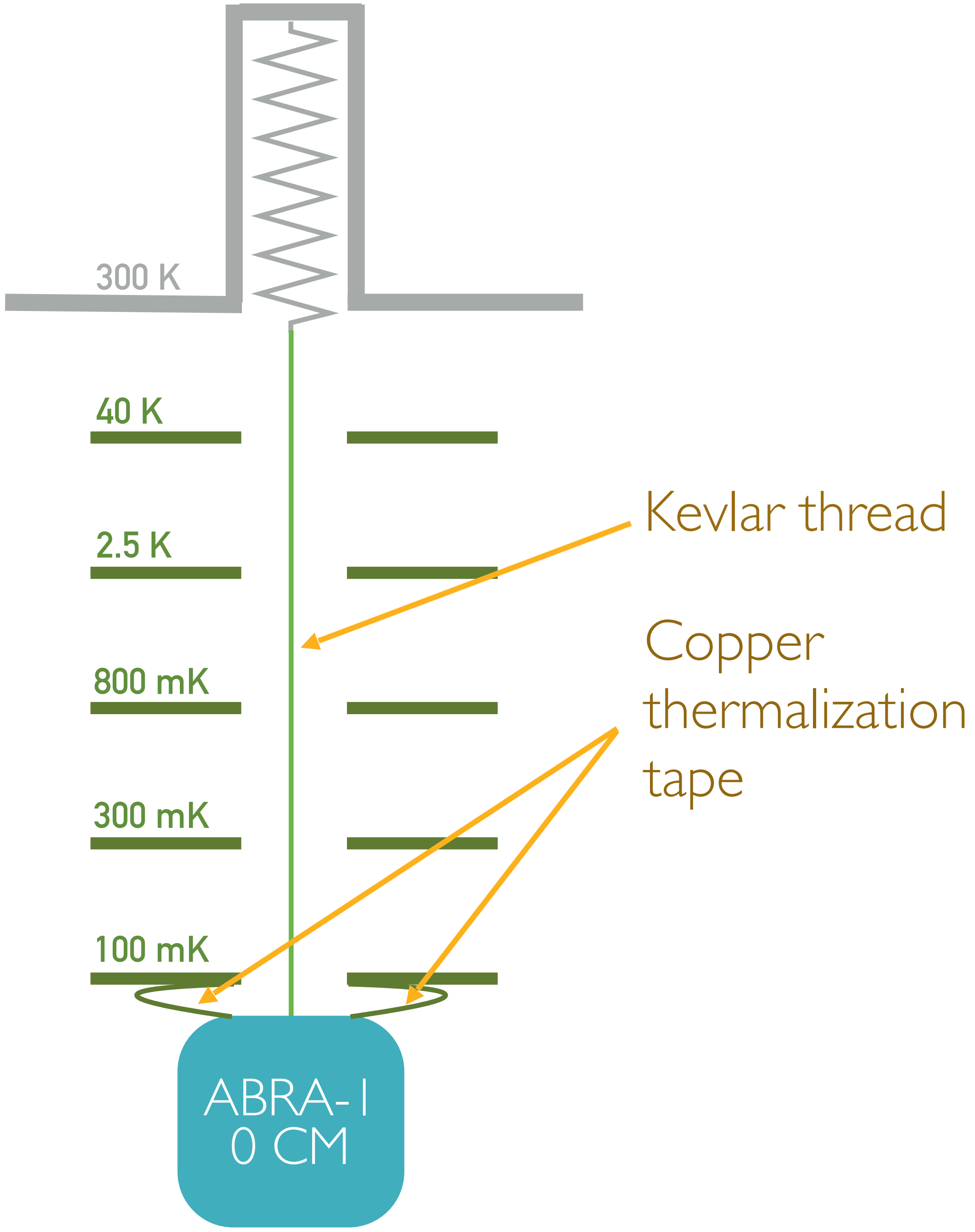
$$\Phi_n \propto \sqrt{g_{a\gamma\gamma}^2 B_{\rm max}^2 V_B^2 \rho_{\rm DM}}\sum_j \alpha_j\sqrt{f(v_j)\Delta v}$$

$$\times \cos\left[m_a\left(1+\frac{v_j^2}{2}\right)n\Delta t+\phi_j\right]$$

$$S_{\Phi\Phi}(\omega) = A\,\frac{\pi f(v)}{2m_a v}\alpha^2\Big|_{v=\sqrt{2\omega/m_a-2}}$$

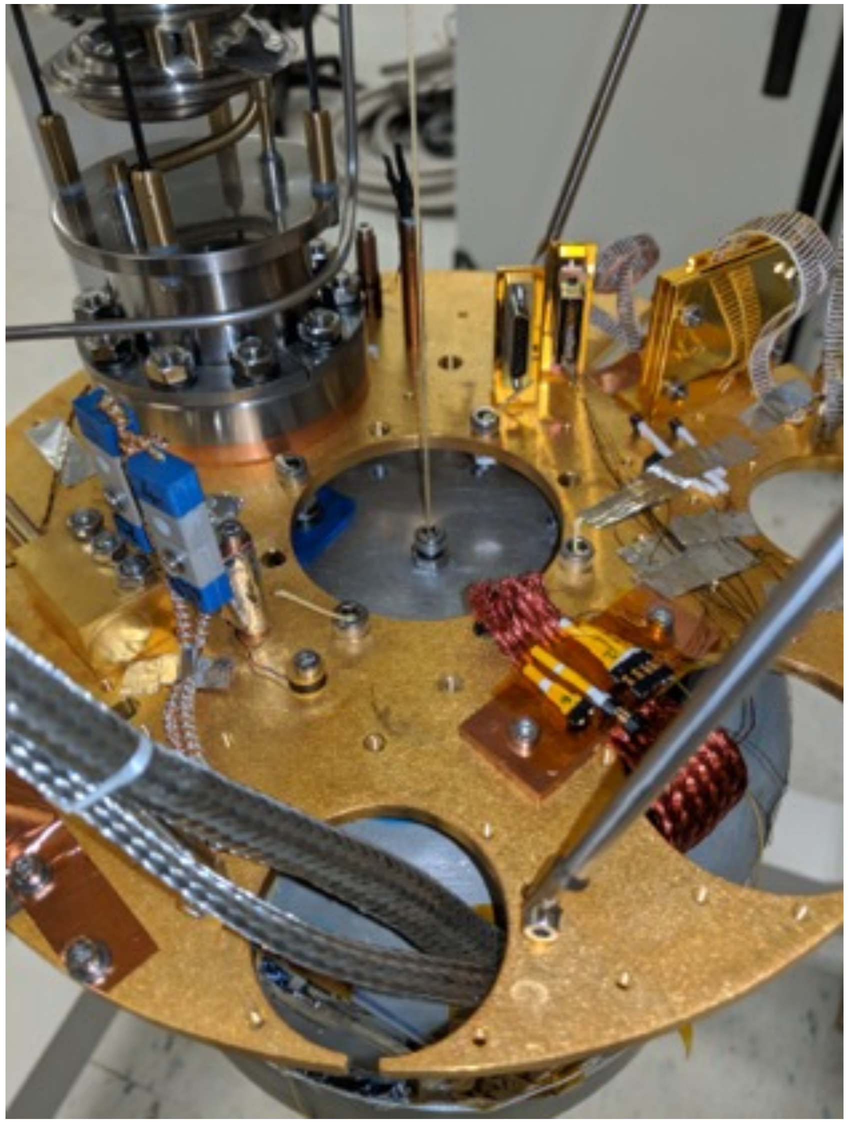
$$P\left[S_{\Phi\Phi}(\omega)\right] = \frac{1}{\lambda(\omega)}e^{-S_{\Phi\Phi}(\omega)/\lambda(\omega)}$$

Vibrational isolation

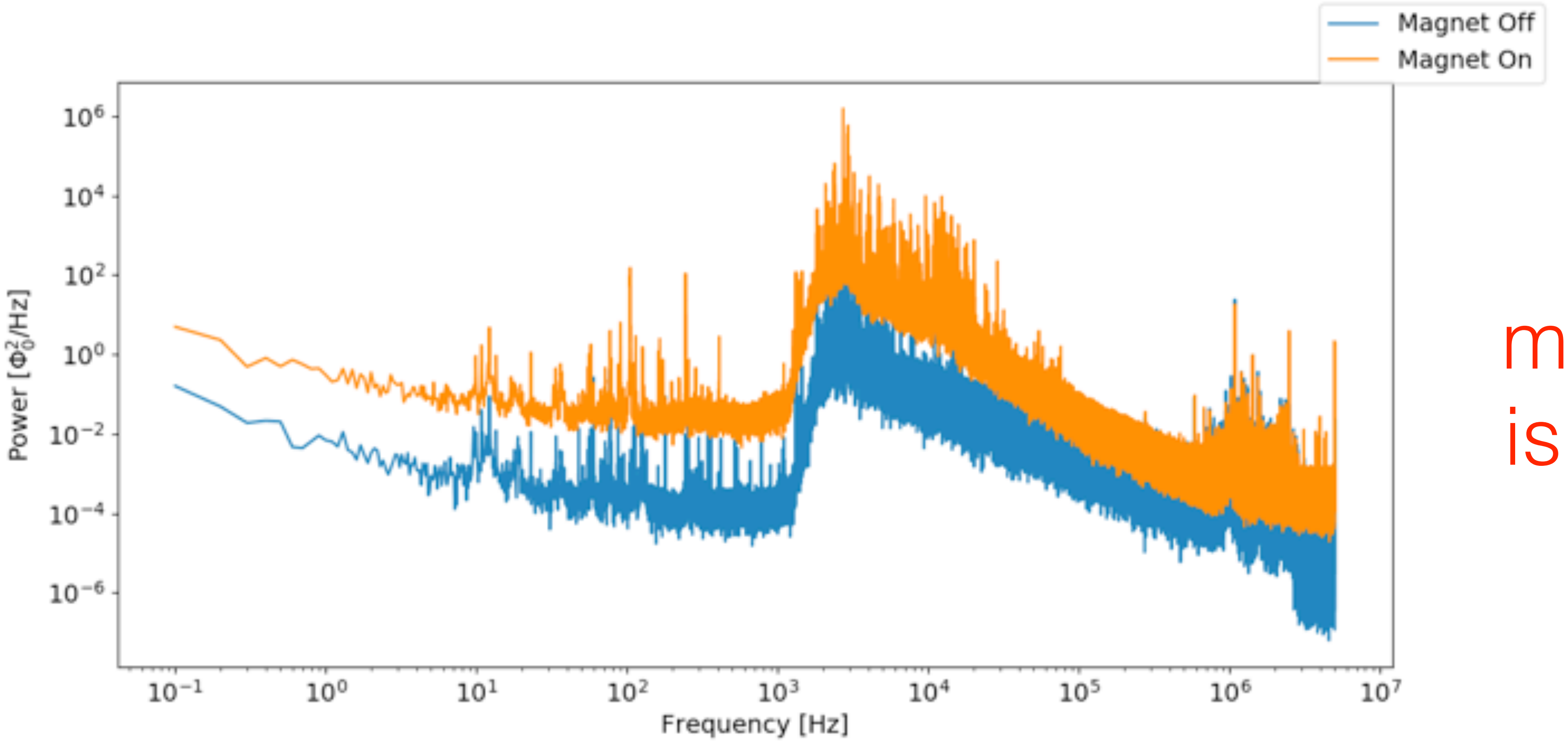


Kevlar thread

Copper thermalization tape

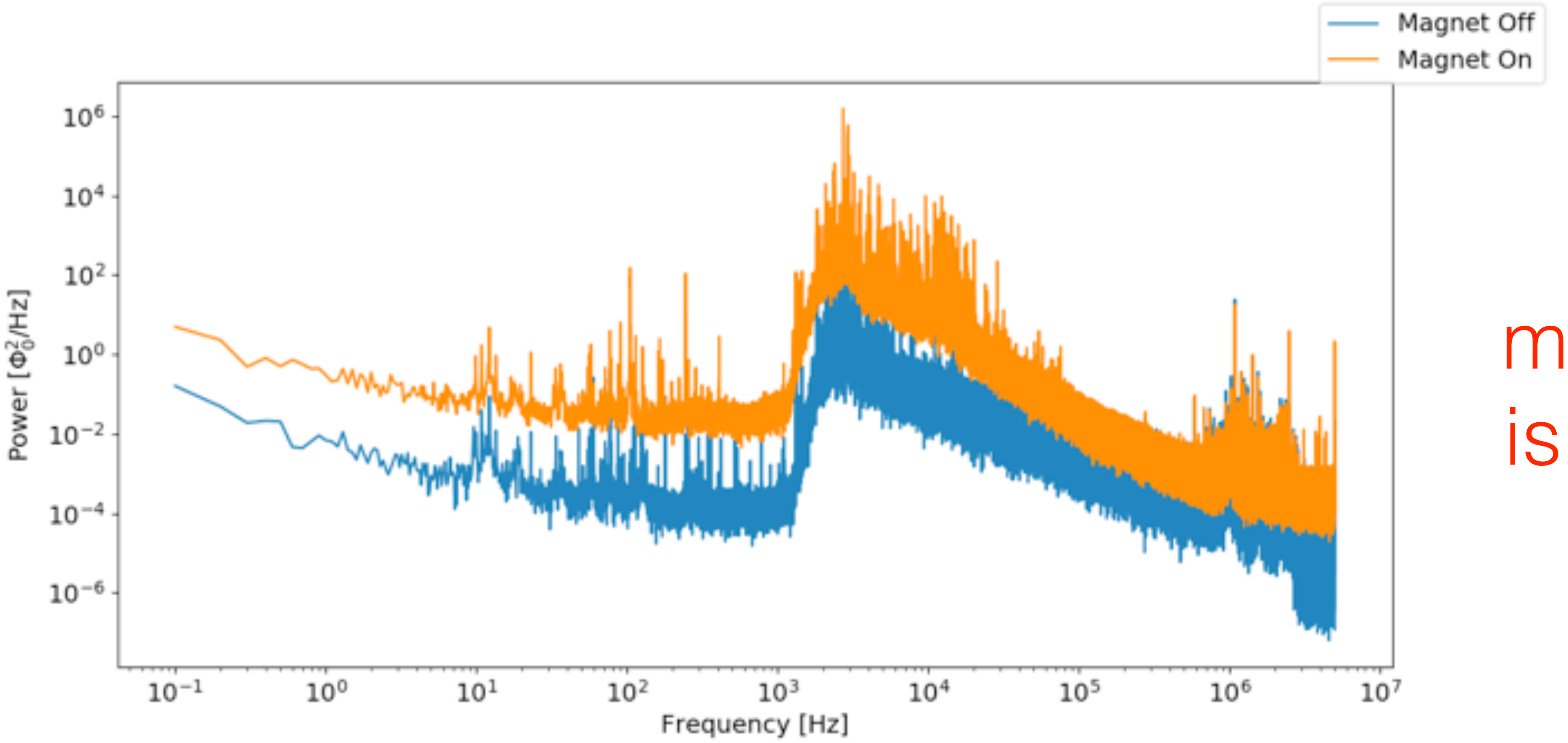


Proto-data

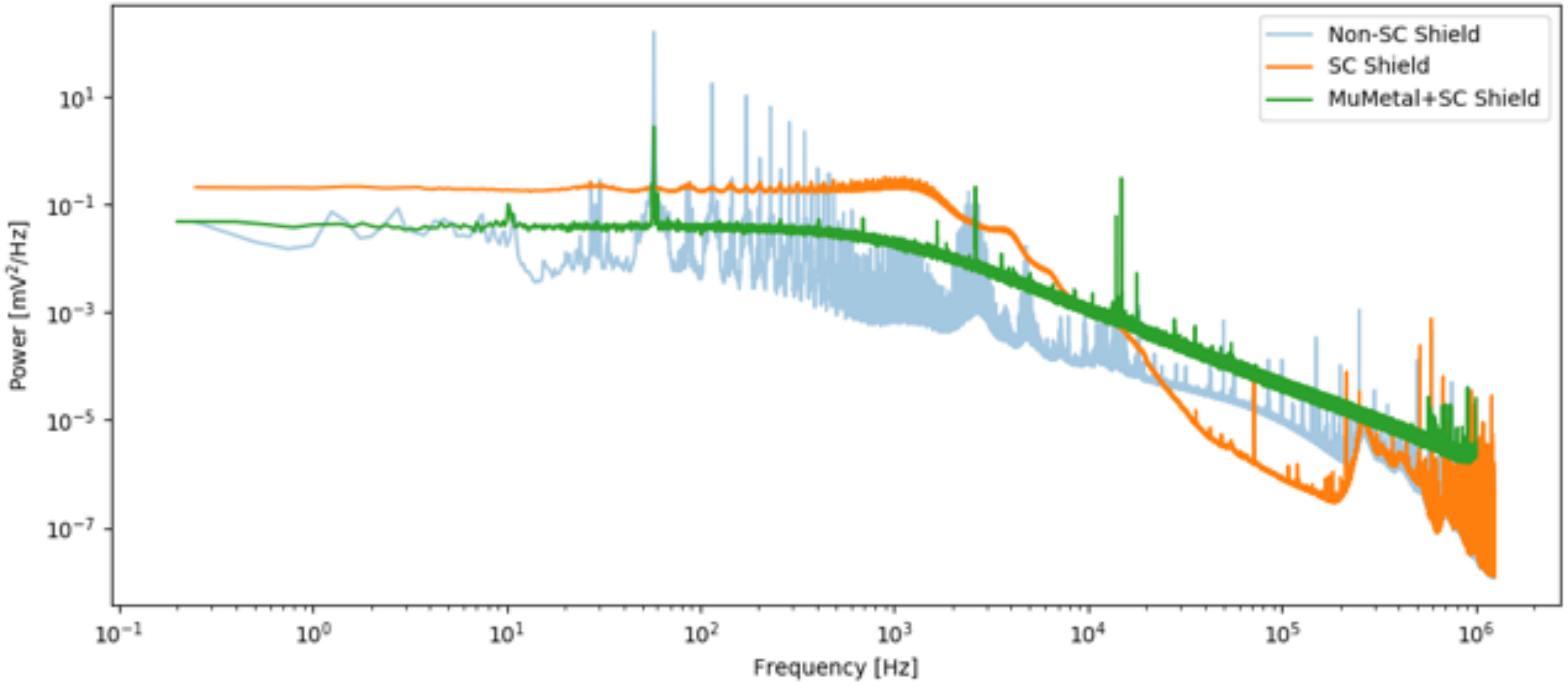


magnet is noisy

Proto-data

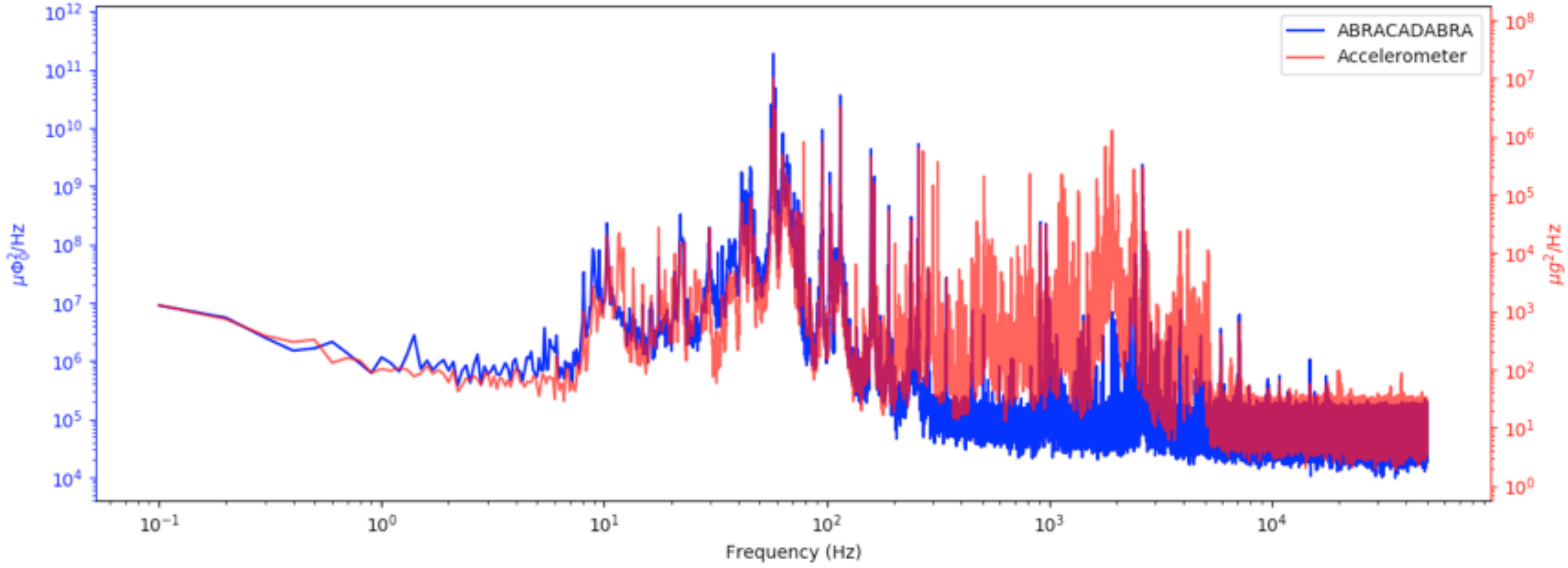


magnet is noisy



shielding works (at low freq.)

Vibrations dominate

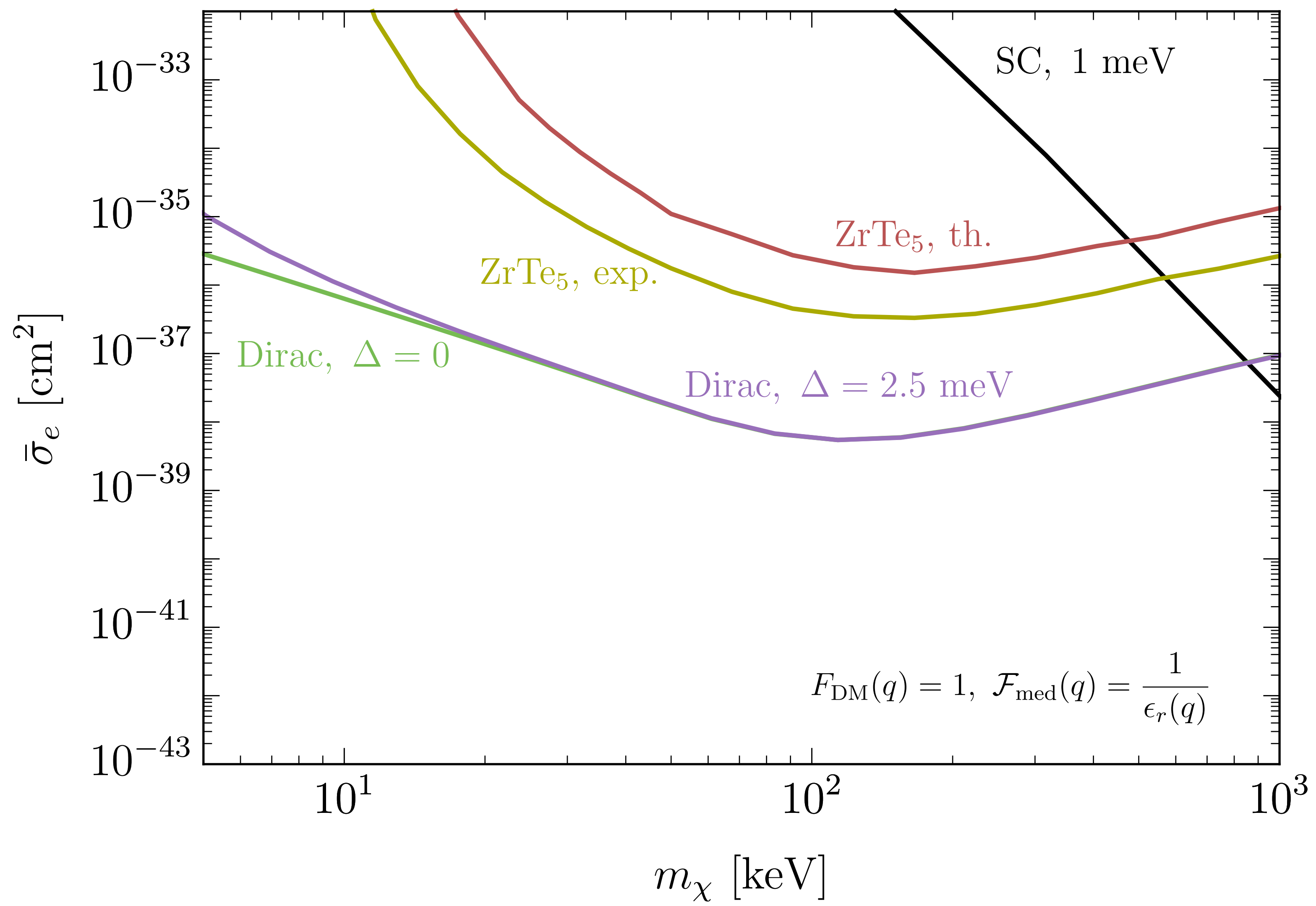


Goal of ABRA-10cm is to identify as many sources of noise as possible which will scale up in a larger-scale (~1m) experiment

First data-taking
starts next week -
stay tuned!

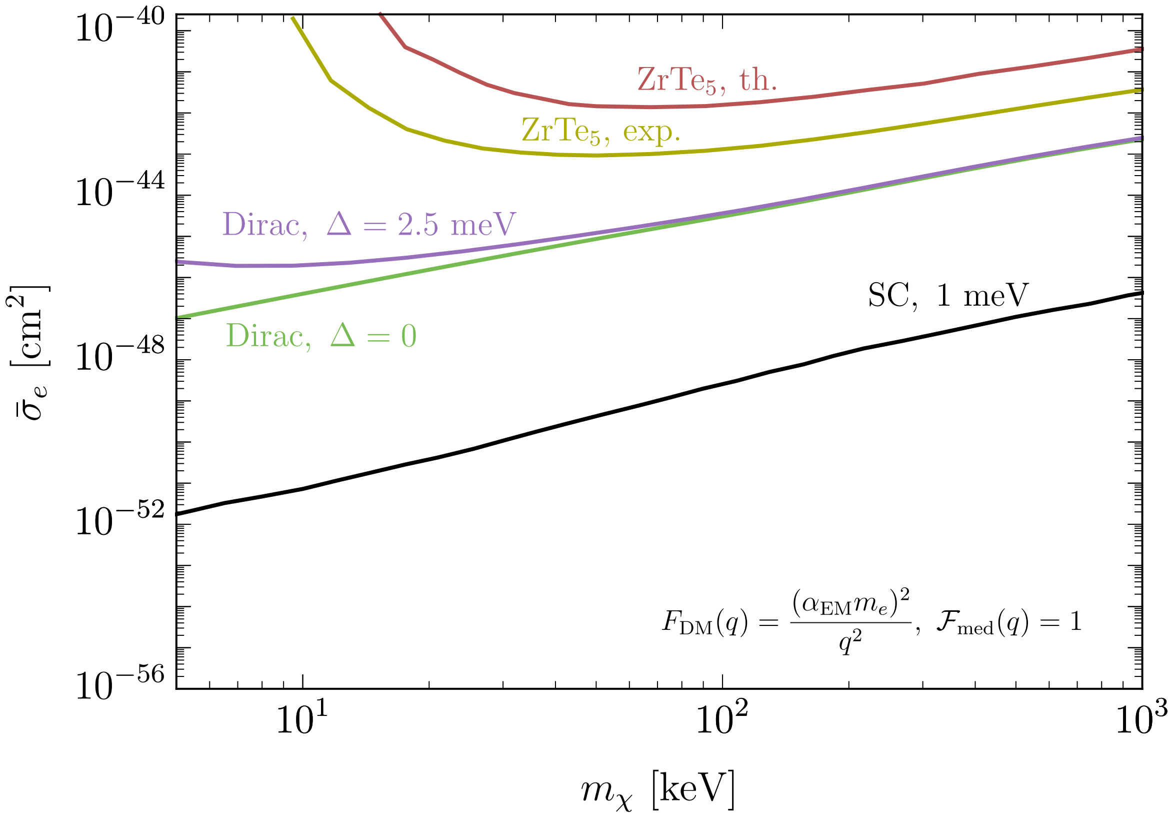
Backup slides

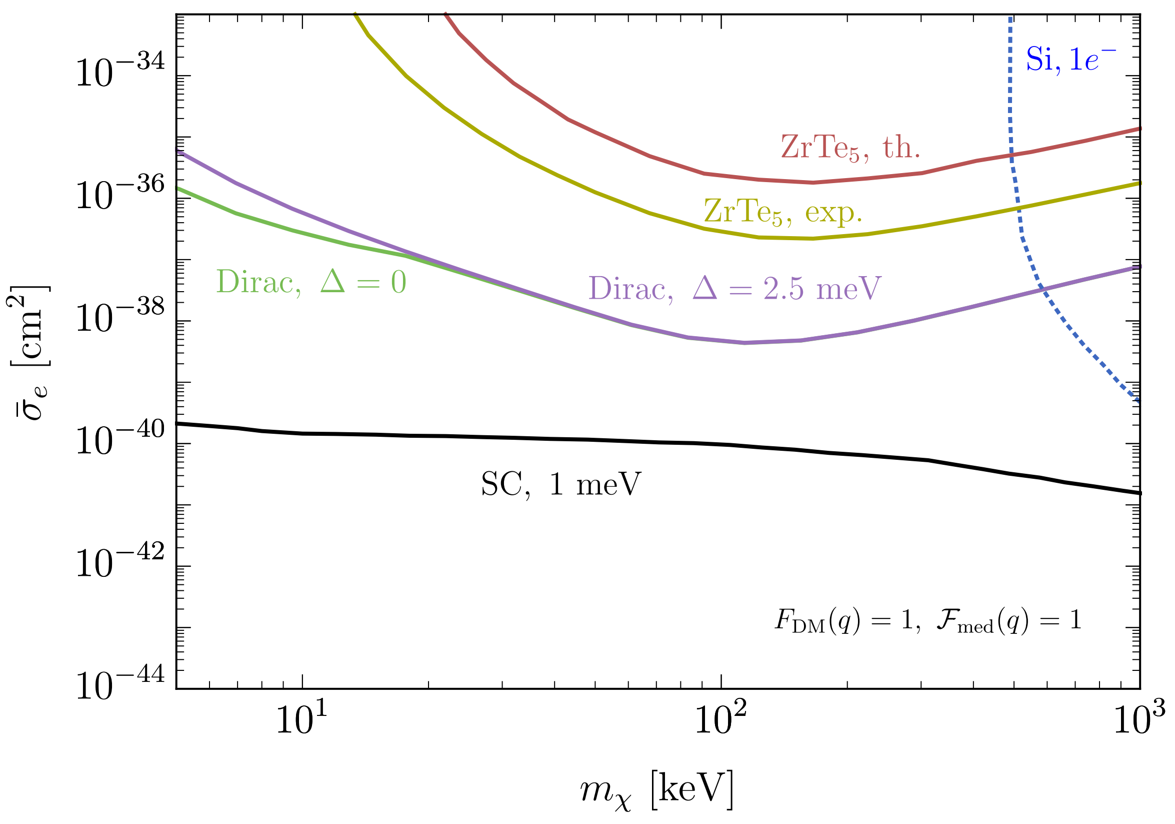
Semimetal scattering reach: heavy dark photon



(Severe constraints from BBN)

Semimetal scattering reach: light and heavy scalar med.





(Severe constraints from BBN, stellar emission)