



# Novel Small-Gap Materials as Photodetectors

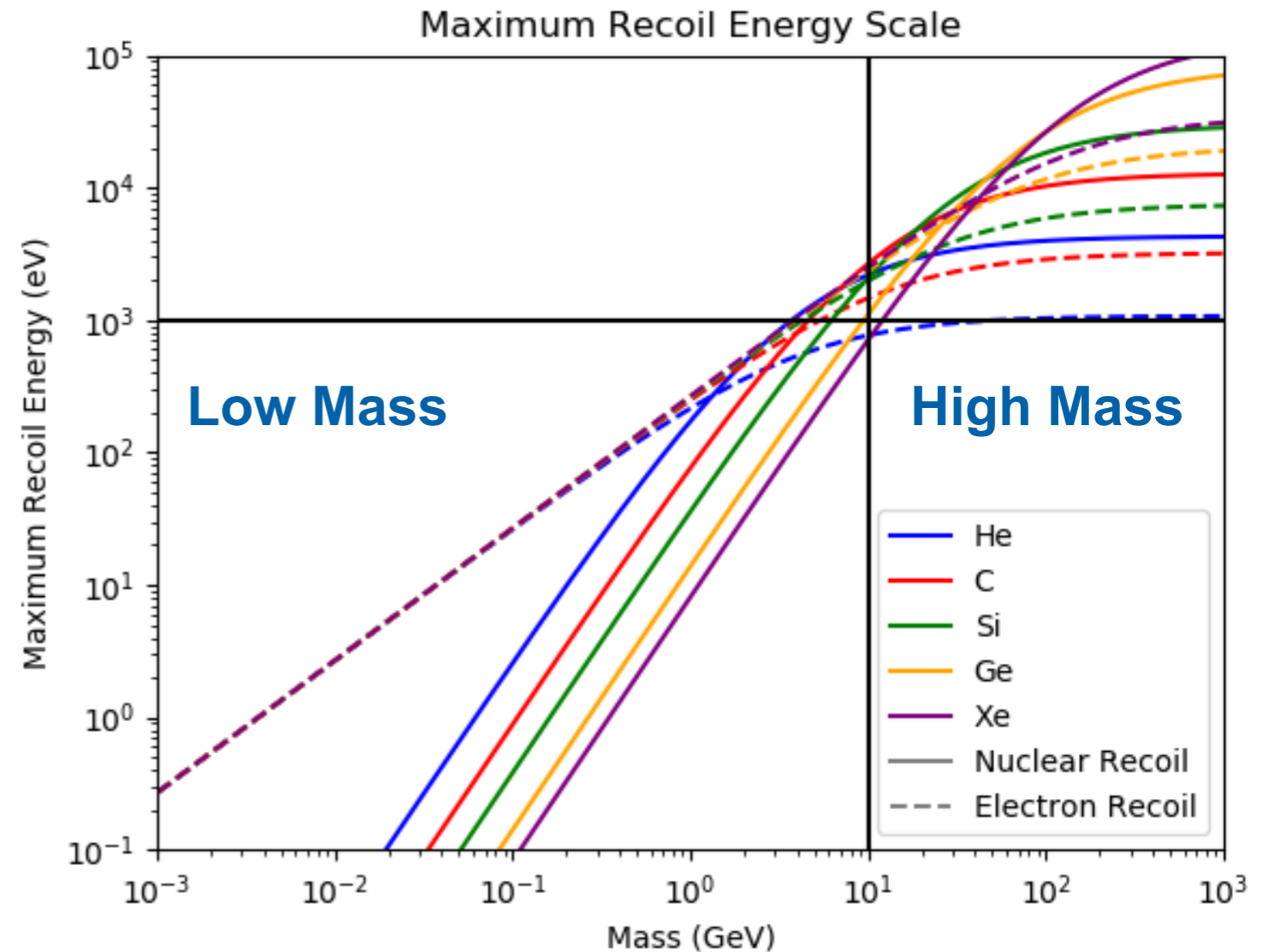
Noah Kurinsky, Yoni Kahn (UIUC)

CPAD 2019

December 10, 2019

# DM Collision Kinematics

- Recoil energy for a typical WIMP velocity depends on target mass and recoil type
- Electron and nuclear recoils have different kinematics; nuclear recoils are simple elastic collisions, electron recoils are largely inelastic and depend on electron orbital and kinematics within the bound electron-atom system
- In addition to momentum transfer for a fixed velocity, using a velocity and angular distribution yields an expected energy spectrum



$$\Delta E_{NR} \leq \frac{1}{2m_N} q_{max}^2 = \frac{m_N v^2}{2} \left( \frac{2m_\chi}{m_\chi + m_N} \right)^2$$

$$\Delta E_{ER} \leq \frac{1}{2} \mu_{N\chi} v^2 = \frac{m_N v^2}{2} \left( \frac{m_\chi}{m_\chi + m_N} \right)$$

$$m_{\chi, NR} \geq \frac{\sqrt{2m_T \sigma_E}}{v}$$

$$m_{\chi, ER} \geq \frac{2\sigma_E}{v^2}$$

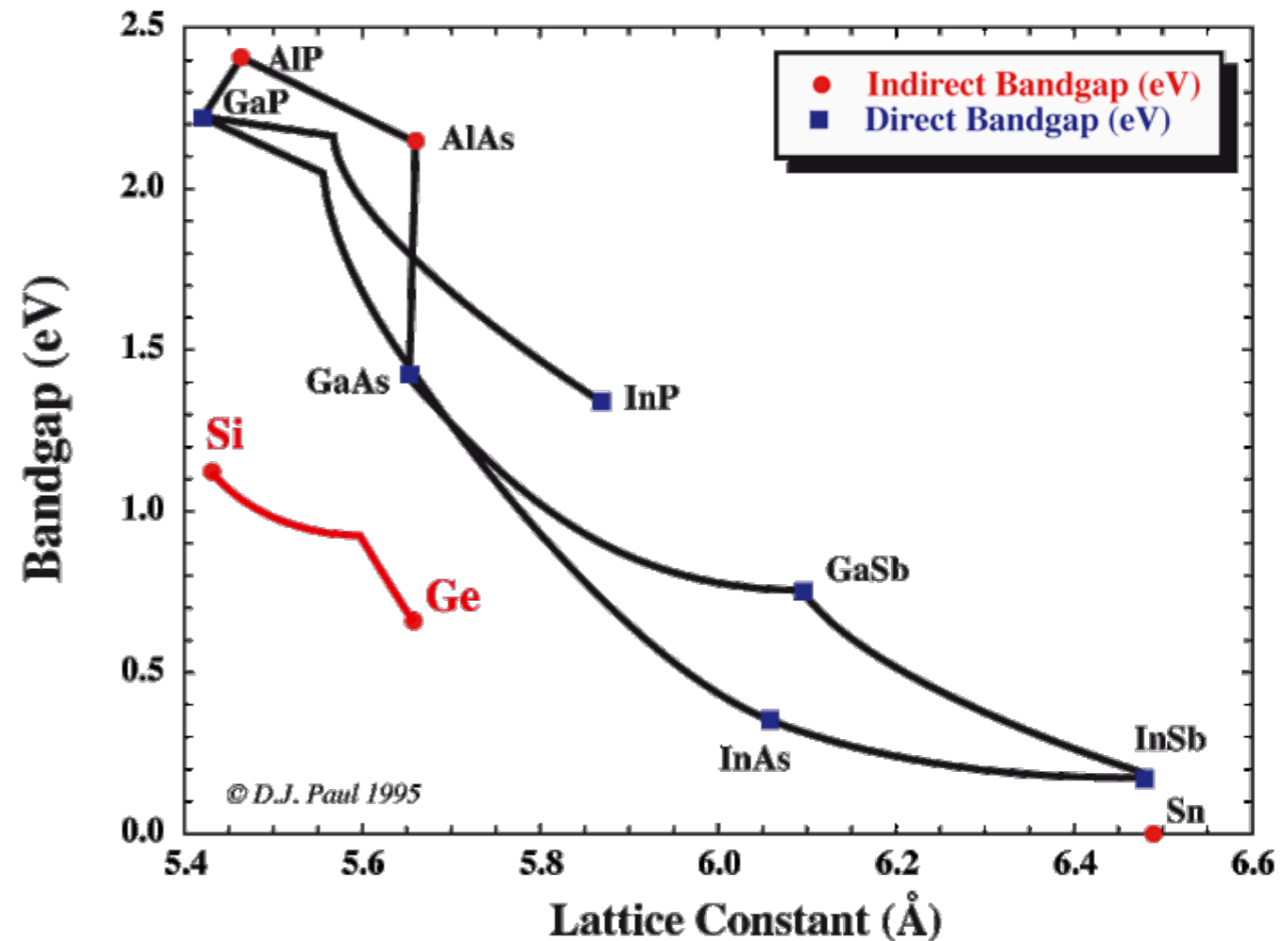
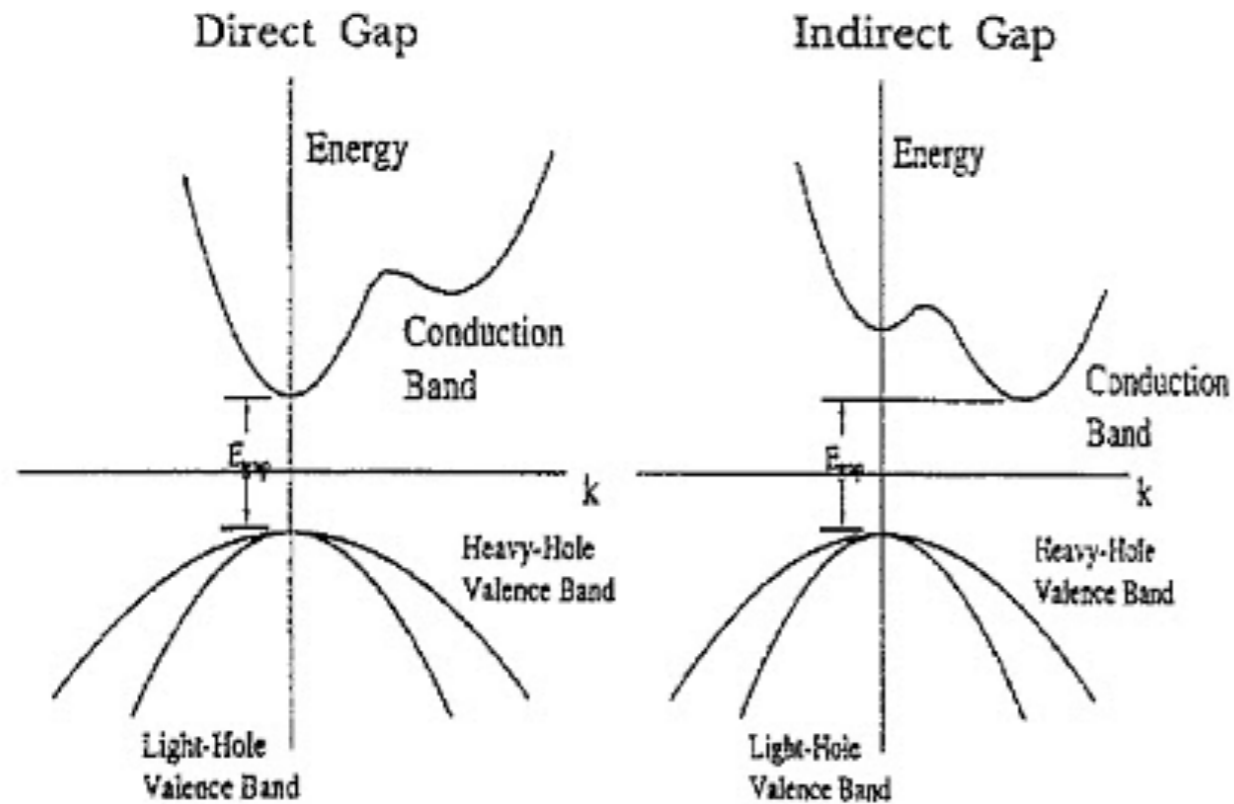
# General Idea

- Low-mass dark matter searches would greatly benefit from new detector materials with small gaps or long-lived phonon modes
- In the case of materials with small energy gaps, the technology challenges are identical to the early days of Si, Ge, etc photodiodes, with some exceptions
  - We have the advantage of years of R&D into single-charge resolving Si detectors
  - We can reliably make APDs from many materials down to the single electron level, and SiPMs are a mature technology
- Technology challenge: develop single charge resolved materials with small gaps at temperatures compatible with low dark rates
  - Driven by DM science
  - Inherently useful for other sub-eV processes
- Motivates developing technology driven by *intrinsic* microphysics rather than heterostructures

<https://arxiv.org/pdf/1910.10716.pdf>

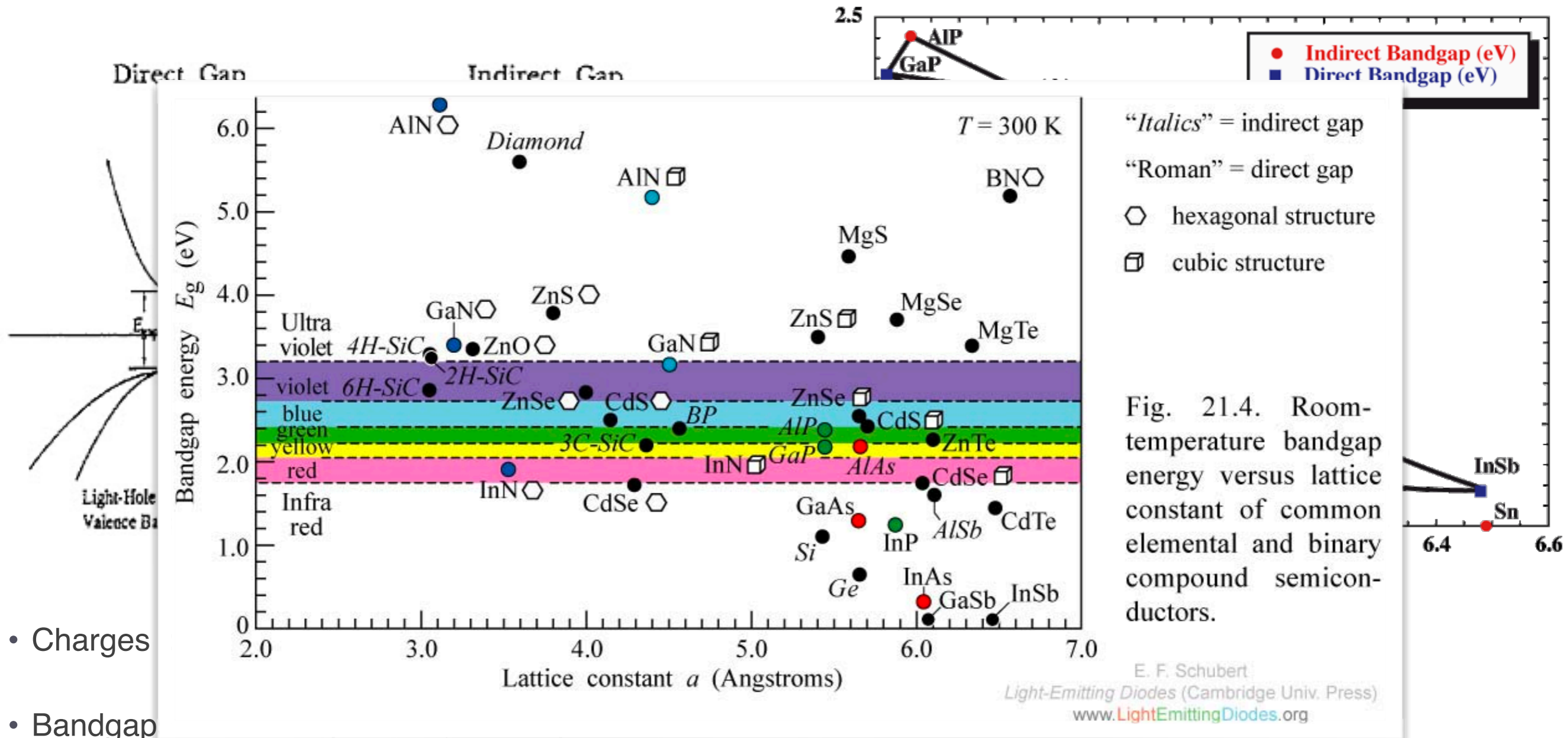
Target	$E_g$ [eV]	$\bar{\epsilon}_\infty$	$\bar{\omega}_O$ [meV]
Si	1.11	-	62.3
Ge	0.67	-	34.8
NaI	5.8	3.27	12.4 - 20.0
CsI	6.14	2.70	6.9 - 10.0
CaWO <sub>4</sub>	5.2	3.84	8.48 - 106
GaAs	1.42	10.9	31.8 - 34.9
Al <sub>2</sub> O <sub>3</sub>	8.8	3.26	35.6 - 104
Diamond	5.47*	-	161
SiO <sub>2</sub>	9.2	2.41	13.7 - 149
PbTe	0.19*	26.3	3.91 - 13.5
InSb	0.24*	23.7	20.5 - 21.5
AlN	6.20	4.54	29.4 - 109
CaF <sub>2</sub>	11.81	2.26	28.4 - 55.6
GaN	3.43*	6.10	16.7 - 88.9
GaSb	0.720	21.6	26.4 - 27.3
LiF	14.2	2.02	33.5 - 77.2
MgF <sub>2</sub>	12.4	1.97	12.1 - 73.7
MgO	7.83	3.38	46.3 - 82.6
NaCl	8.75	2.44	19.1 - 30.6
NaF	11.5	1.78	29.6 - 49.9
PbS	0.29*	15.0	7.27 - 26.9
PbSe	0.17*	19.5	4.86 - 17.1
ZnO	3.3	6.13	11.1 - 63.4
ZnS	3.80*	5.91	32.8 - 41.0

# Classical Picture of Semiconductors



- Charges produced, and minimum photon energy, determined by material bandgap
- Bandgaps can be engineered, but only to some extent
- Indirect bandgaps require more energy to liberate electrons thermally, but are still sensitive radiation down to bandgap energies (though the efficiency is reduced)

# Classical Picture of Semiconductors *Updated*

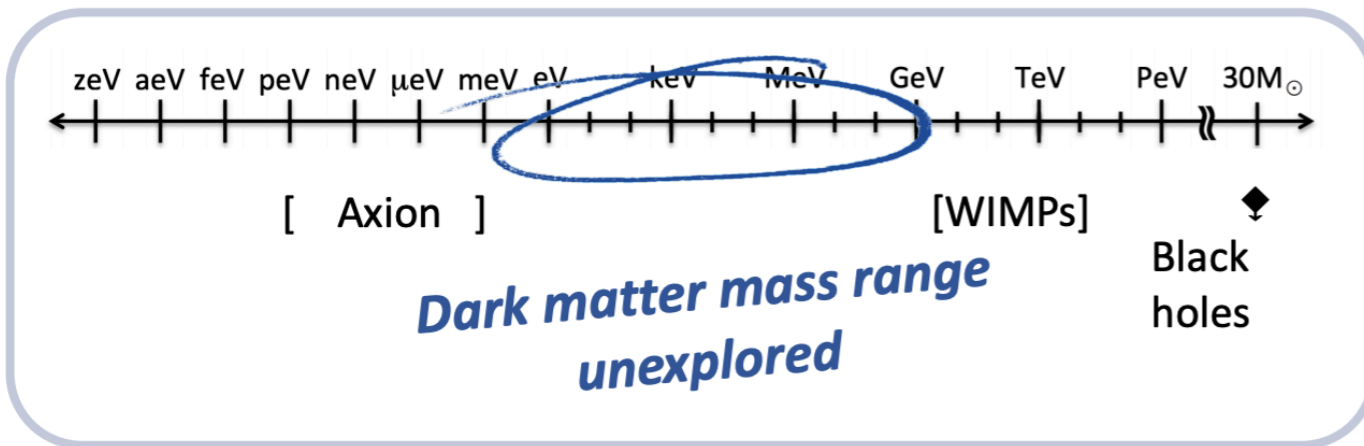


- Charges
- Bandgap

- Indirect bandgaps require more energy to liberate electrons thermally, but are still sensitive radiation down to bandgap energies (though the efficiency is reduced)

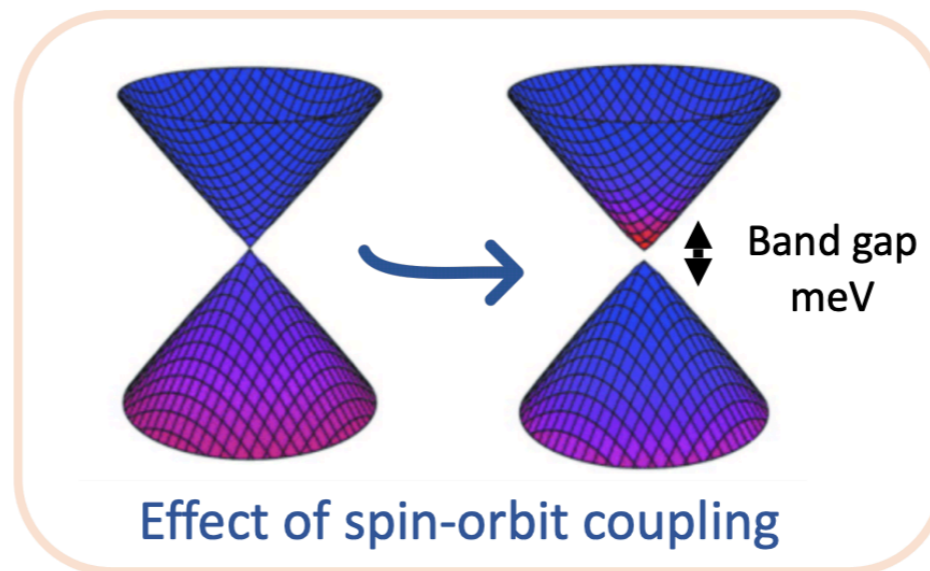
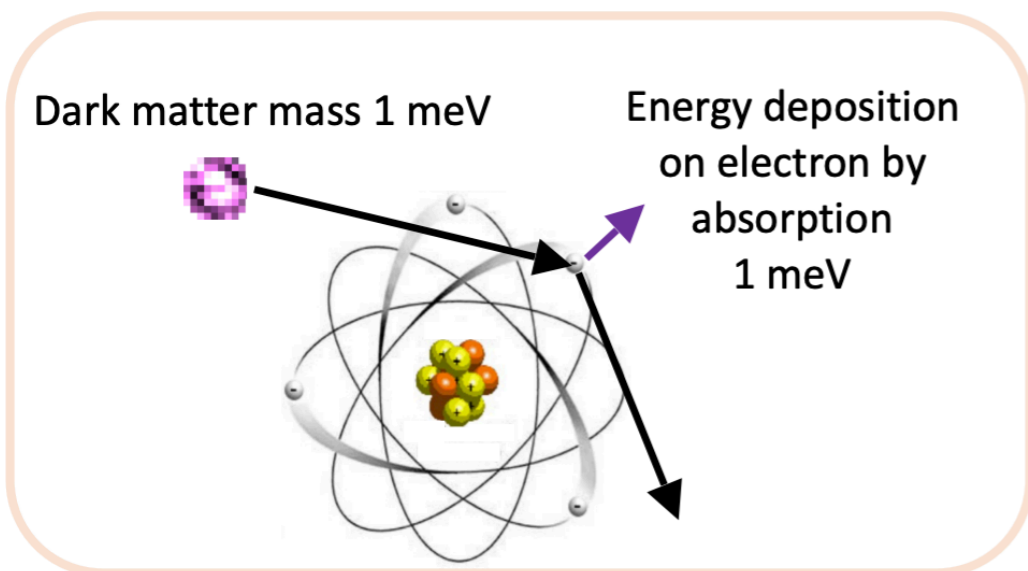
# Spin-orbit semiconductors for dark matter detection

Inzani, Griffin



- Direct detection of sub-GeV masses is within the reach of short, small-scale experiments
- Small band gap semiconductors could be used to observe absorption or scattering events

**Aim:** To identify semiconductors with millielectronvolt band gaps



**Strategy:** Search for materials with band gaps opened by spin-orbit coupling

<https://indico.fnal.gov/event/20385/session/55/contribution/39/material/slides/0.pdf>

## Spin-orbit semiconductors for dark matter detection

Inzani, Griffin



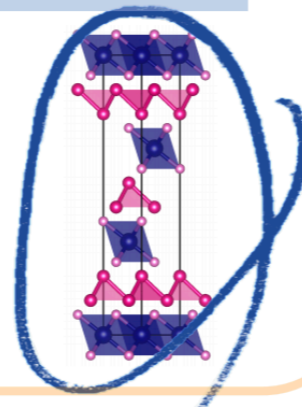
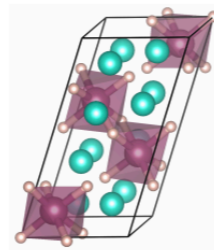
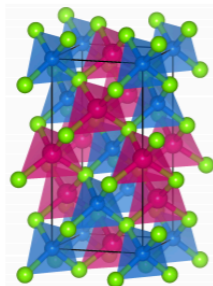
Method I: High-throughput computational screening



86,412 inorganic materials

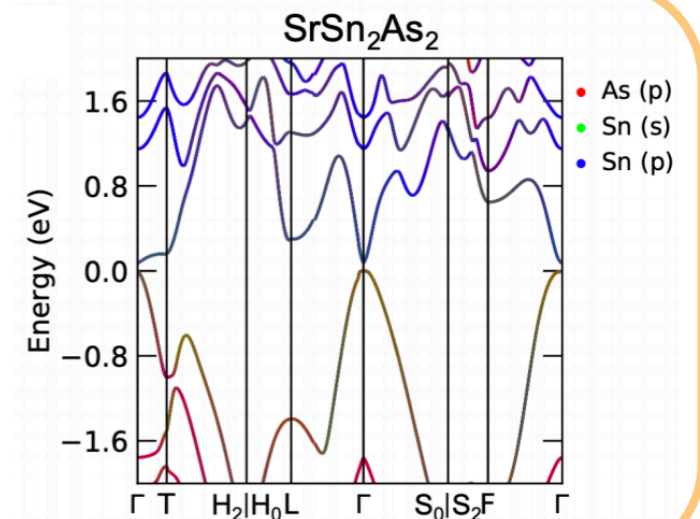
Spin-orbit interactions in 4,357 compounds

3 "would-be metals" with band gaps opened up through spin orbit coupling



1 Family of materials with meV-scale band gaps

Tin pnictides  $ASn_2Pn_2$   
Band gap variable by composition  
0 – 200 meV



Method II: Refined electronic structures calculated by density functional theory

Candidate materials for dark matter detection identified

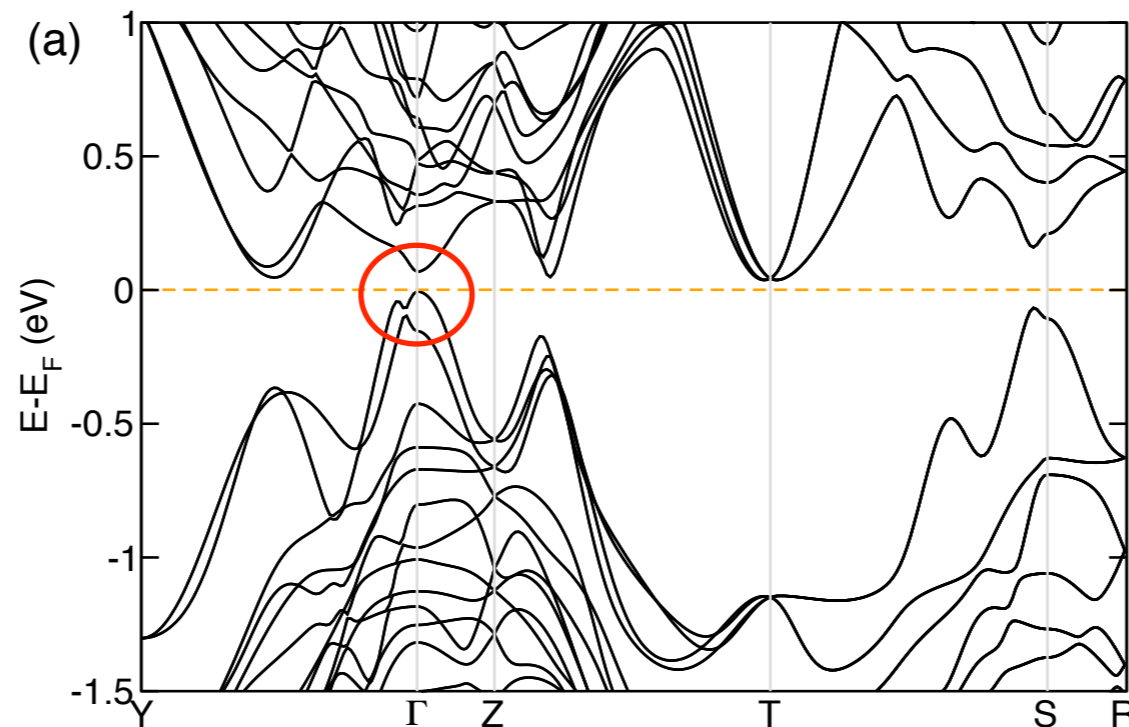
Synthesis pending...

<https://indico.fnal.gov/event/20385/session/55/contribution/39/material/slides/0.pdf>

# Dirac materials for DM

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

## 3D Dirac semimetal ( $\text{ZrTe}_5$ )



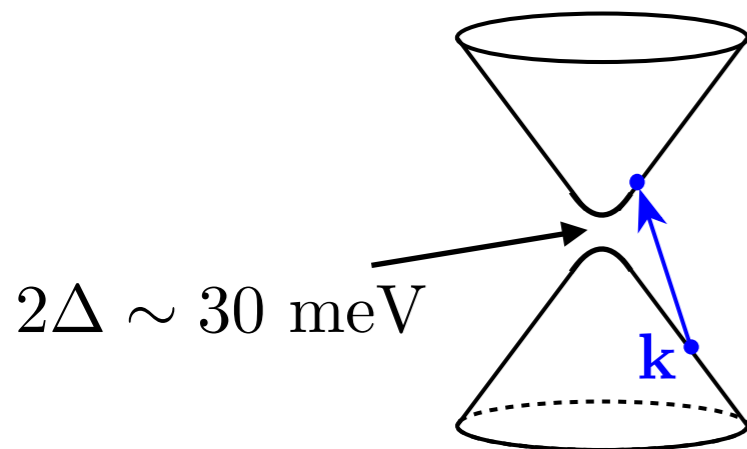
- meV excitation energies
- Anisotropic (bands and crystal)
- (Theoretically) insulating at zero temperature

Potential new class of materials for DM detection!



# What is a Dirac material?

ZrTe<sub>5</sub> is a “Dirac material” with highly anisotropic band structure



DM has a quadratic dispersion, so solving energy-momentum conservation with a linear dispersion leads to curious effects:

$$v_{\min}(|\mathbf{q}|, \omega_{\ell, \ell+\mathbf{q}}) = \frac{\sqrt{v_{F,\perp}^2 (\ell + \mathbf{q})_{\perp}^2 + v_{F,z}^2 (\ell_z + q_z)^2} + \sqrt{v_{F,\perp}^2 \ell_{\perp}^2 + v_{F,z}^2 \ell_z^2}}{|\mathbf{q}|} + \frac{|\mathbf{q}|}{2m_{\chi}}$$

$$E(\mathbf{k}) = \pm \sqrt{v_{F,x}^2 k_x^2 + v_{F,y}^2 k_y^2 + v_{F,z}^2 k_z^2 + \Delta^2}$$

$$v_{F,x} \sim v_{F,y} \sim 1.6 \times 10^{-3} c$$

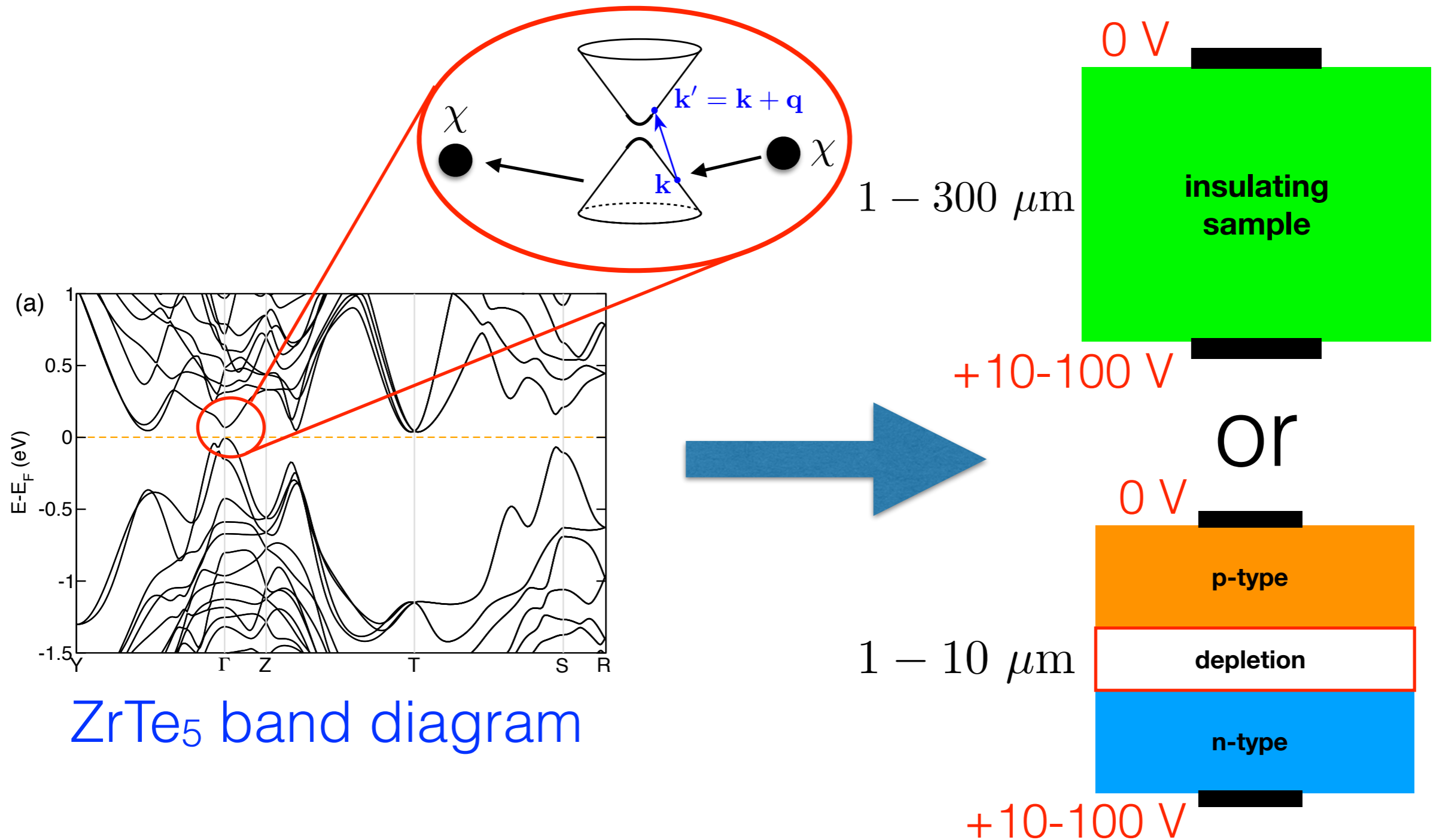
$$v_{F,z} \sim 6.5 \times 10^{-4} c \ll v_{F,x}, v_{F,y}$$

Like a rescaled relativistic (“Dirac”) electron if space were anisotropic

No scattering if DM is slower than  $v_F$ , but this depends on direction of  $\mathbf{q}$ !

**Strong directional dependence**

# Detection by charge avalanche



Would operate like an APD or a SiPM:

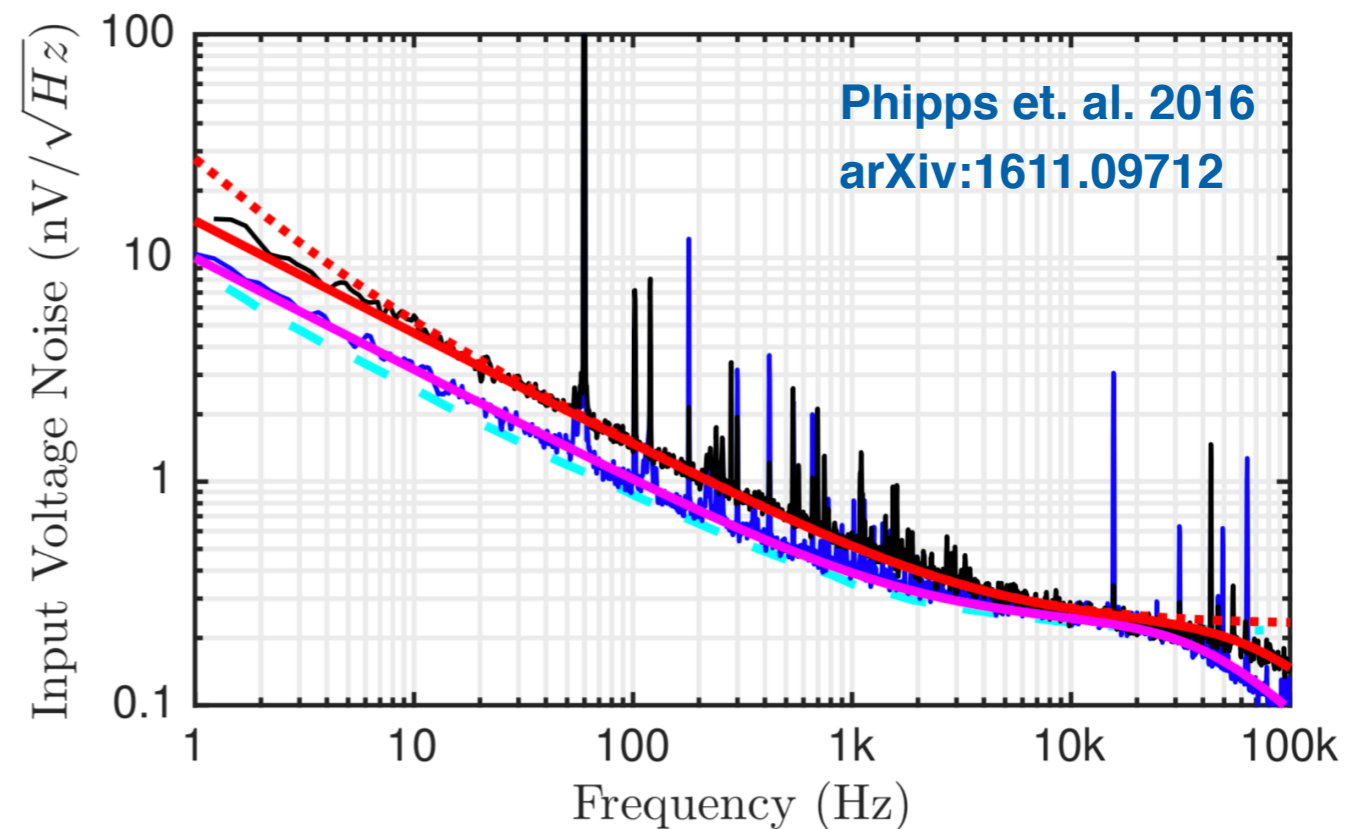
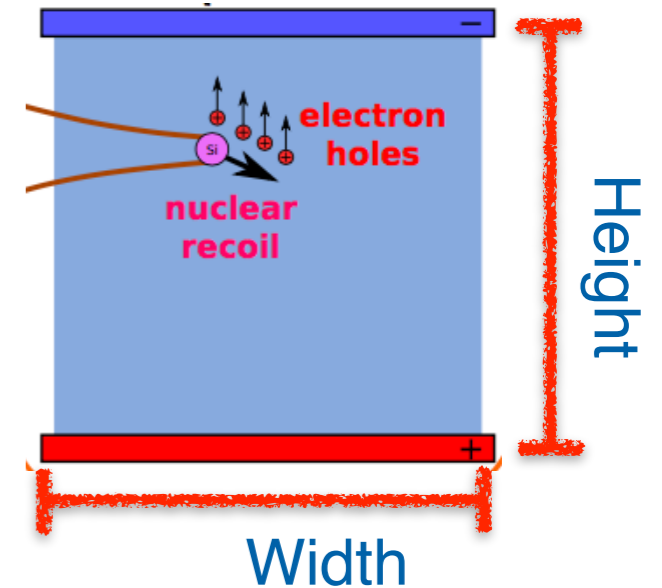
e-h pair created in insulating layer is accelerated, **impact ionization leads to charge cascade**: mA for exponential gain, 10-100 e for linear gain

# Cryogenic Single Charge Detector

- Charge resolution is determined by detector+readout capacitance, voltage noise, and 1/f cutoff
- Capacitance and volume directly trade off, allowing for larger pixels to have the same charge resolution in a material with lower permittivity, or lower resolution in pixels of the same size
- Recent HEMT amplifiers have achieved performance at 4.2K sufficient for single-charge ionization-chamber style detectors for low-rate signals at ~mg masses
- For diamond (epsilon~4) examples explored in table below

$$\sigma_q \geq \frac{N_v(C_{\text{det}} + C_{\text{in}})}{\epsilon_q \sqrt{\tau}}$$

$$\sigma_q \approx 35 \frac{(C_{\text{det}} + C_{\text{in}})/(250 \text{ pF})}{(C_{\text{in}}/100 \text{ pF})^{1/4}}$$

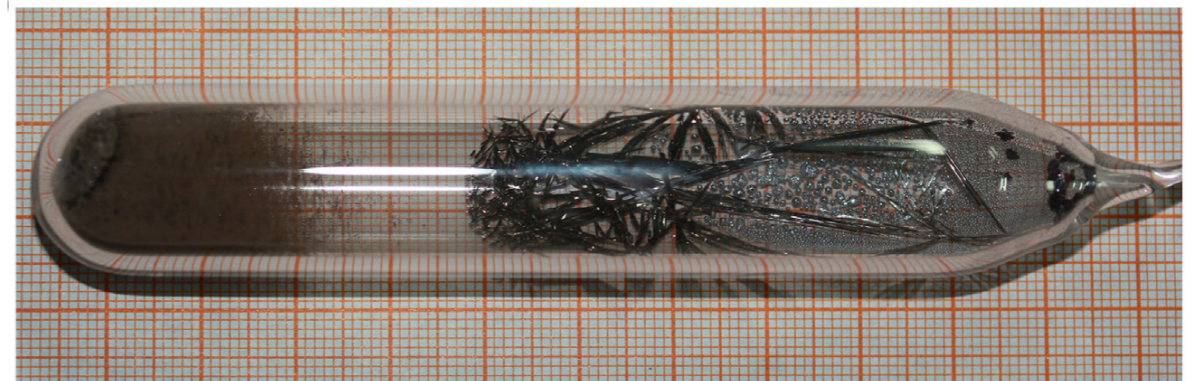
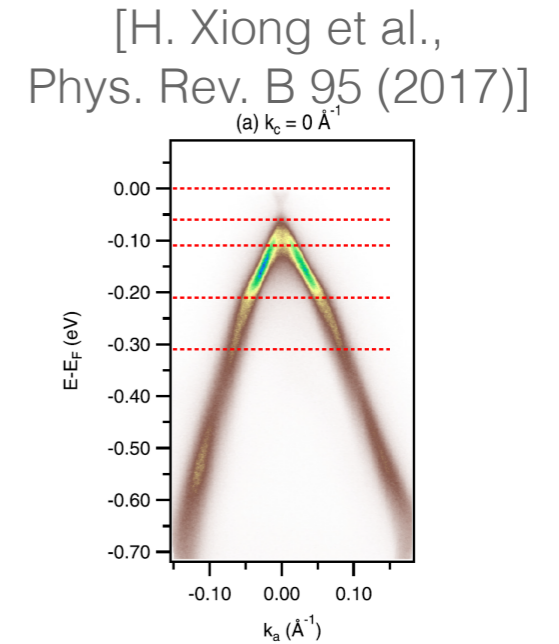
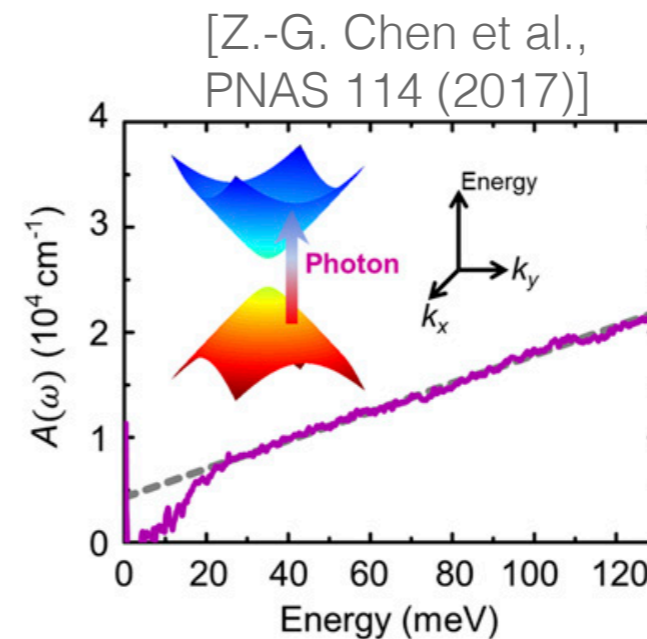


Design	Dimensions	Mass (mg)	Temp. (K)	$V_{\text{Bias}}$	$\sigma_E$	$\sigma_q$
Single Cell	16 mm <sup>2</sup> × 0.5 mm	28	4.2 K	10 V	13–39 eVee	1–3e <sup>-</sup>
Segmented	1 mm <sup>2</sup> × 0.5 mm	1.8			1.3–3.9 eVee	0.1–0.3e <sup>-</sup> /segment

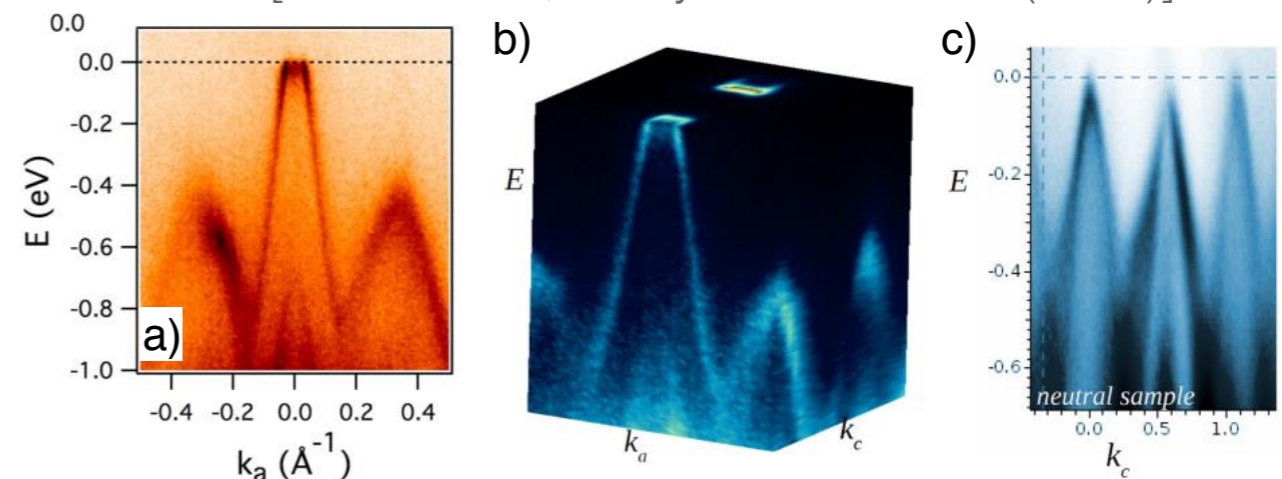
Kurinsky, Yu, Hochberg, Cabrera (1901.07569)

# ZrTe5 state of the art

- Gap is  $\sim 20$  meV at 4.5 K, band structure is very close to linear near BZ center
- $\sim 50$  mg single crystals have been grown at Brookhaven and in China
- Fermi level can be manipulated with epitaxial strain and/or Te concentration
- **Need to measure dielectric function and Fermi velocities in an insulating sample:** UIUC has unique expertise and equipment to do this



[Y.-Y. Lv et al, J. Cryst. Growth 457 (2017)]

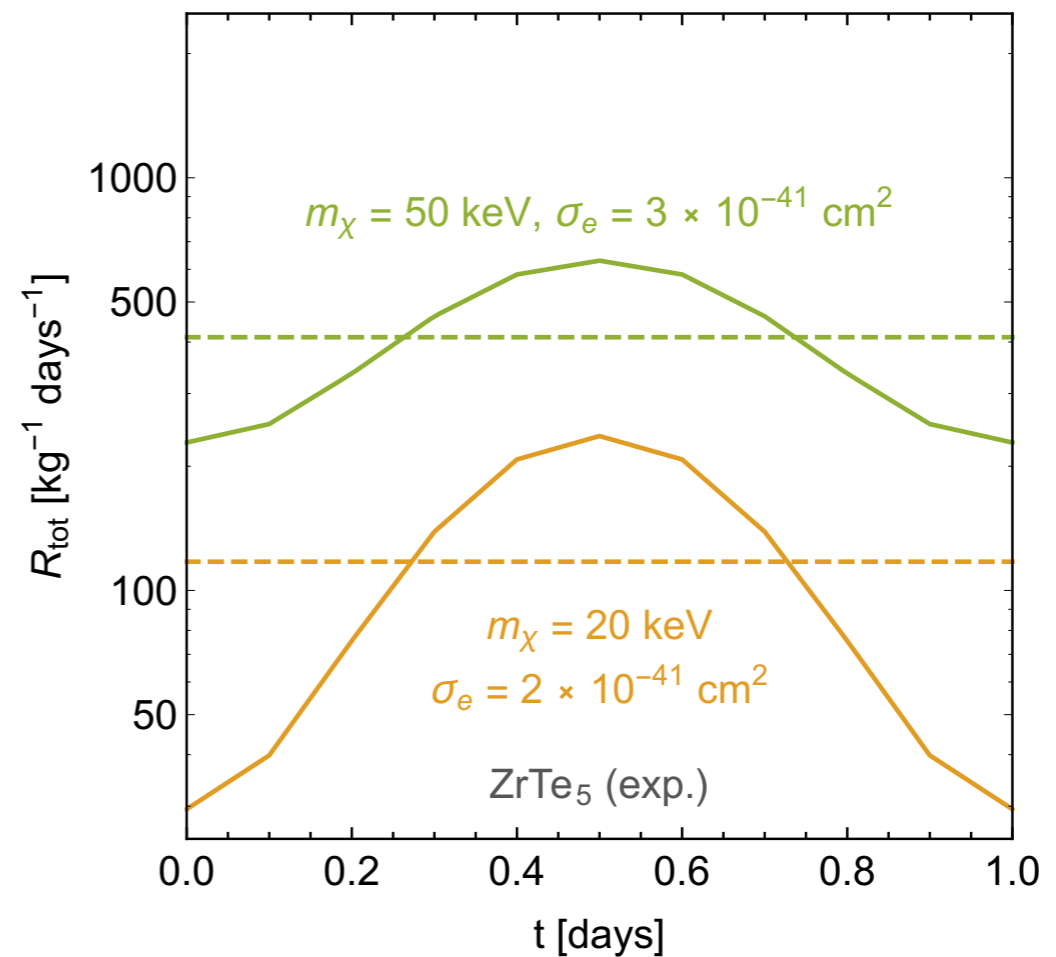
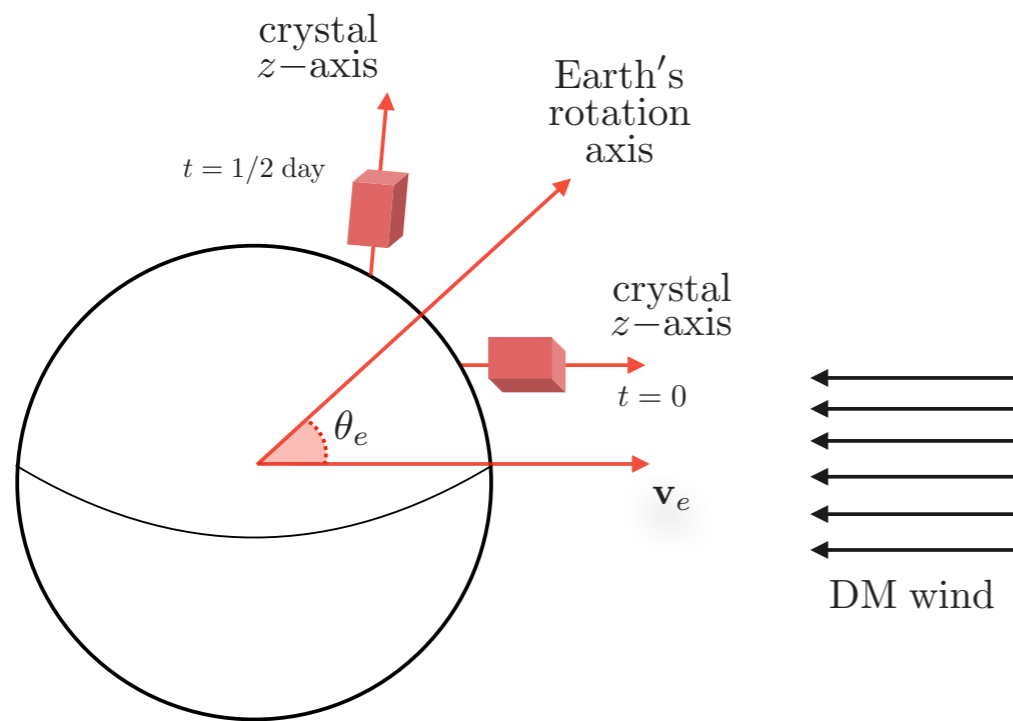


[Q. Li et al., Nature Phys. 2016]

[Q. Li, preliminary]

# Directional detection

With a charge detector, there is always a “dark rate” (impurities, thermal, stray light, etc), but this is isotropic

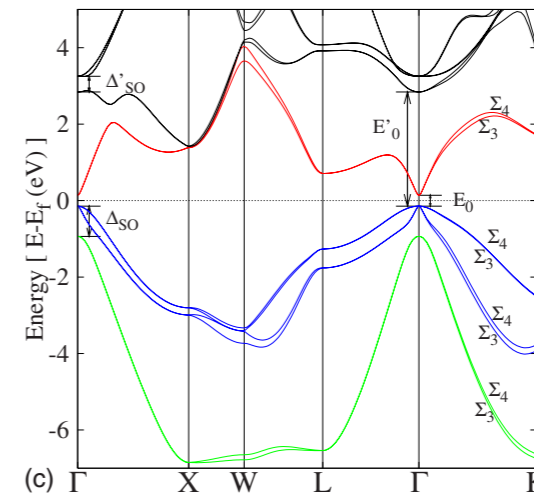


[Coskuner, Mitridate, Olivares, Zurek, arXiv:1909.09170; Geilhufe, Kahlhoefer, Winkler, arXiv:1910.02091]

Daily modulation of event rate is a smoking gun for DM

# Alternative: InSb APD

- Making an avalanche device out of a new material is hard. **Practice on an easier material**
- InSb has a gap of  $\sim 235$  meV and was first made into an APD in 1967 (!!)
- Large gap isn't great for lightest DM, but **still sensitive to DM down to 200 keV**
- To do: make a device, test at mK temperatures, calculate DM sensitivity
- Novel elements: **cryogenic temperatures, SQUID current sensor readout** in linear gain mode



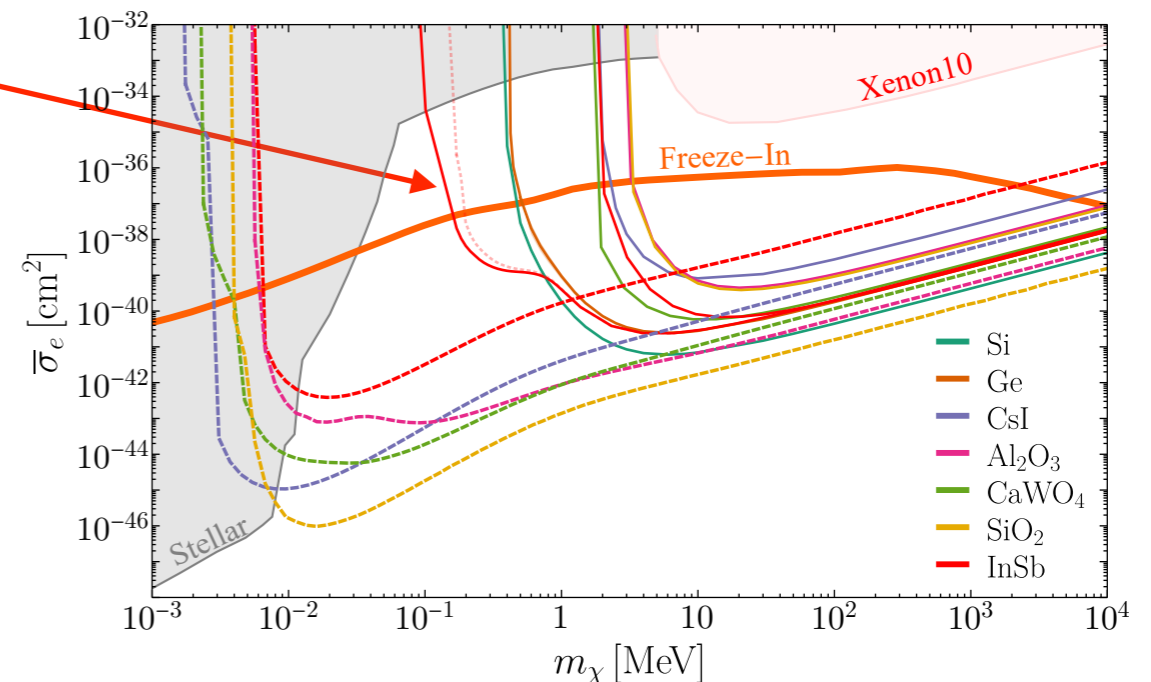
JOURNAL OF APPLIED PHYSICS VOLUME 38, NUMBER 11 OCTOBER 1967

**Noise and Multiplication Measurements in InSb Avalanche Photodiodes**

R. D. BAERTSCH

*General Electric Research and Development Center, Schenectady, New York*

(Received 15 May 1967)

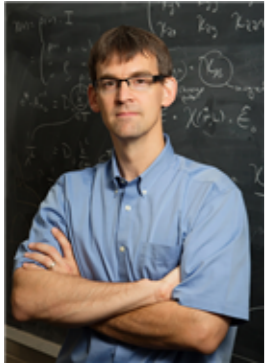


[Griffin et al., arXiv:1910.10716]

# Summary of Work Needed

- Identify candidate materials
  - So far InSb, ZrTe5, *new materials identified by materials project*
- Establish testing program to validate theoretical properties
  - Resistance vs. temperature (RRR) and current-mode dark count measurements
  - Room temperature/cryogenic permittivity
  - Charge lifetimes and diffusion lengths
  - Characterize impact ionization in pure samples; determines monolithic or avalanche readout mode
- Establish cryogenic readout
  - ASICs being developed by CNRS for use with low capacitance HEMT amplifiers
  - Work starting at FNAL to develop integrated charge amplifiers at 4K
- Dark matter search is the ‘black box’ test that established technological viability; dark rates approaching single events/day are the long-term goal, but even Hz/mm is an excellent start
  - High dark rates in low-gap materials still translate to low dark rates at higher energies with adequate timing resolution

# Current state of the collaboration



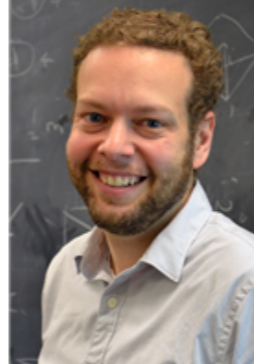
P. Abbamonte  
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F. Mahmood  
(UIUC)



Y. Kahn  
(UIUC)



L. Wagner  
(UIUC)



J. Eckstein  
(UIUC)

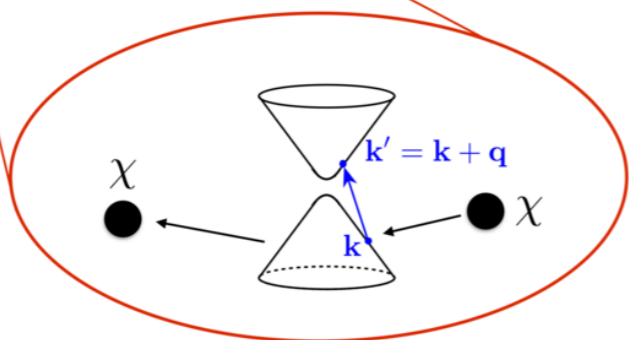
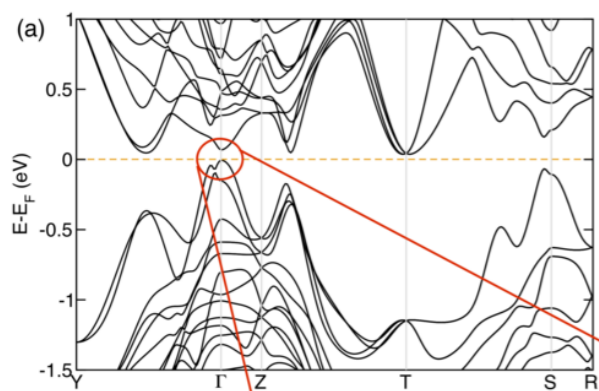


D. Van Harlingen  
(UIUC)

measurement of  $S(\mathbf{q}, \omega)$  with  
THz/IR spectroscopy  
and M-EELS

calculation of  
event rate,  
materials search

detector prototype  
fabrication (MBE,  
SQUID current sensor)



J. Filippini  
(UIUC)



N. Kurinsky  
(FNAL)

prototype testing at  
low-background  
cryogenic facility