Novel Small-Gap Materials as Charge Detectors

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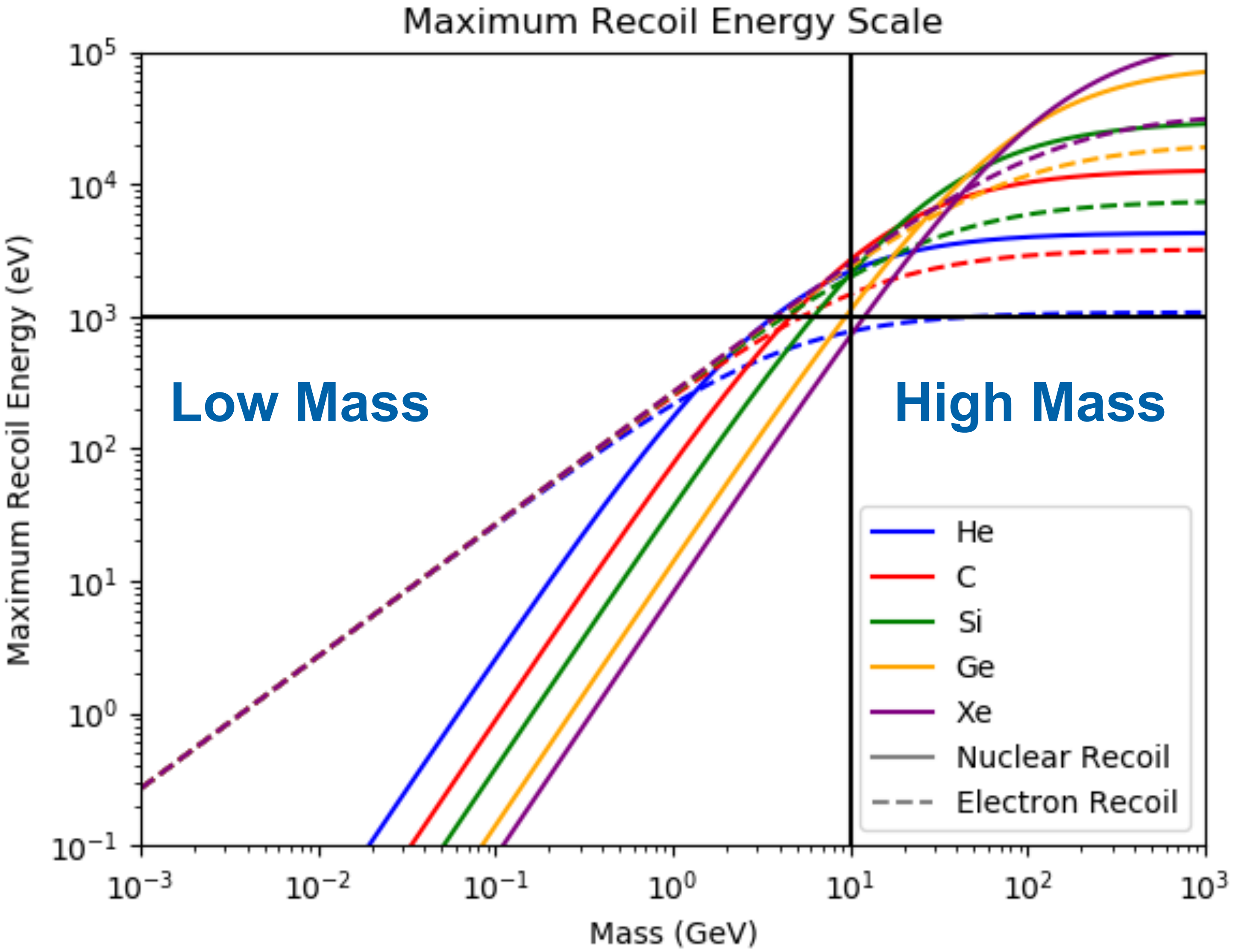
May 8, 2020

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



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

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

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

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

General Idea

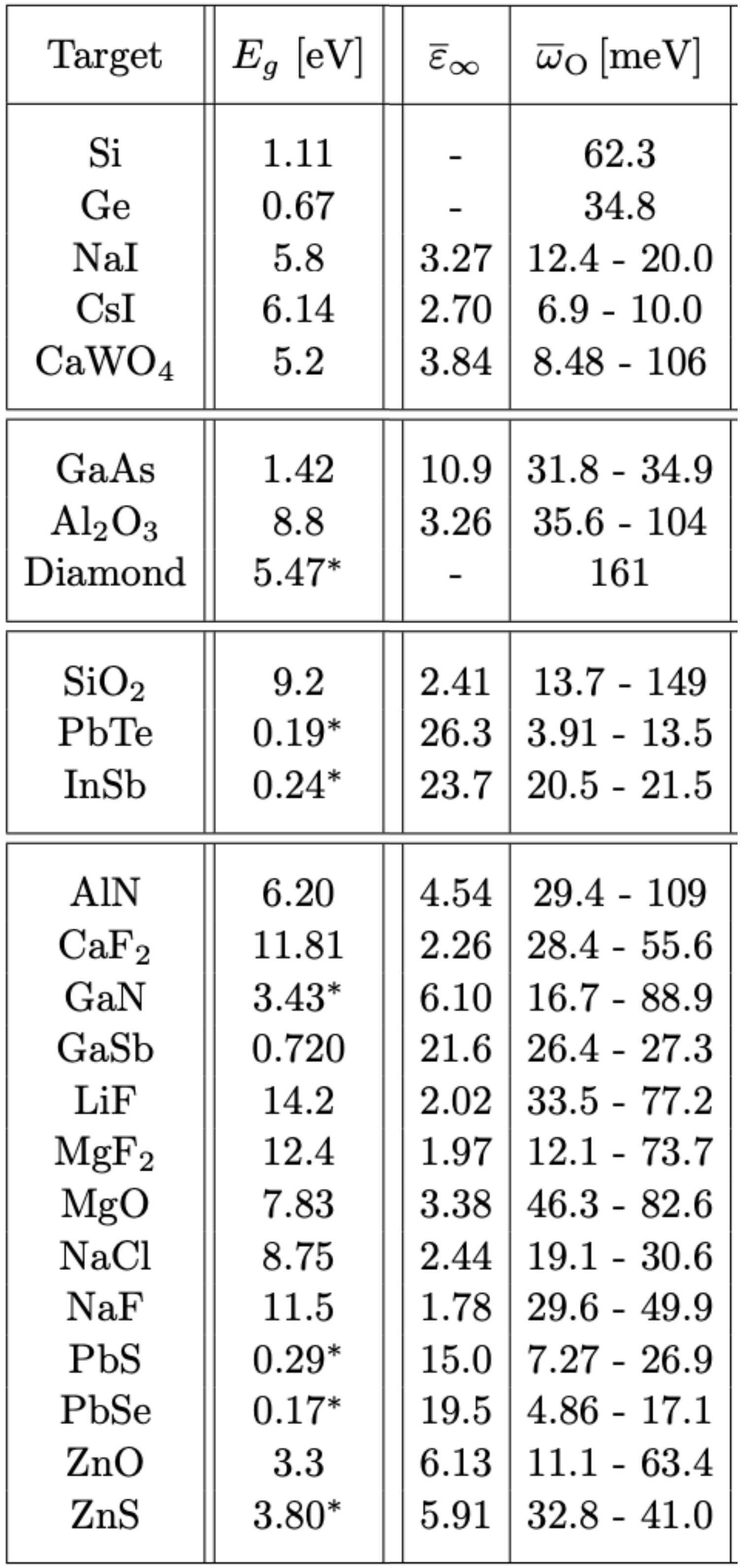
- Low-threshold rare-event searches would greatly benefit from new detector materials with small gaps or long-lived phonon modes

- 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, neutrino science
  - Inherently useful for other sub-eV processes

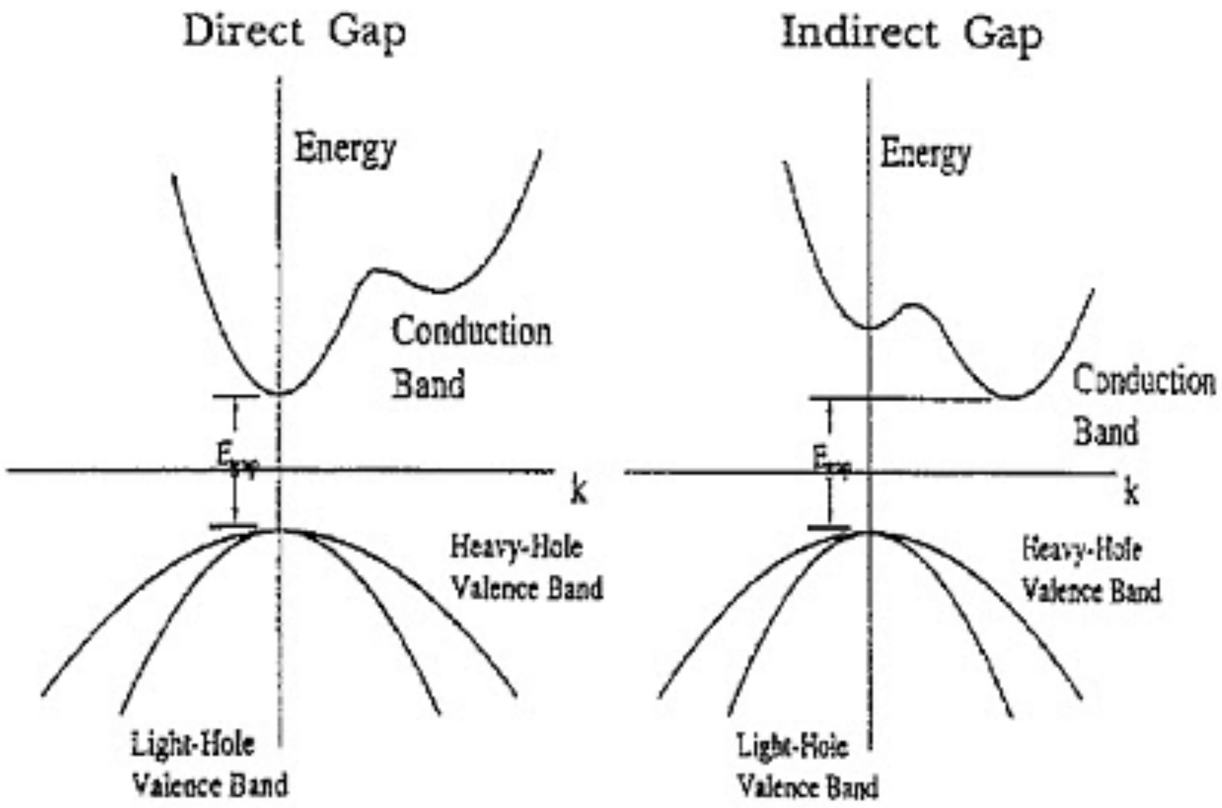
- Motivates developing technology driven by *intrinsic* microphysics rather than heterostructures

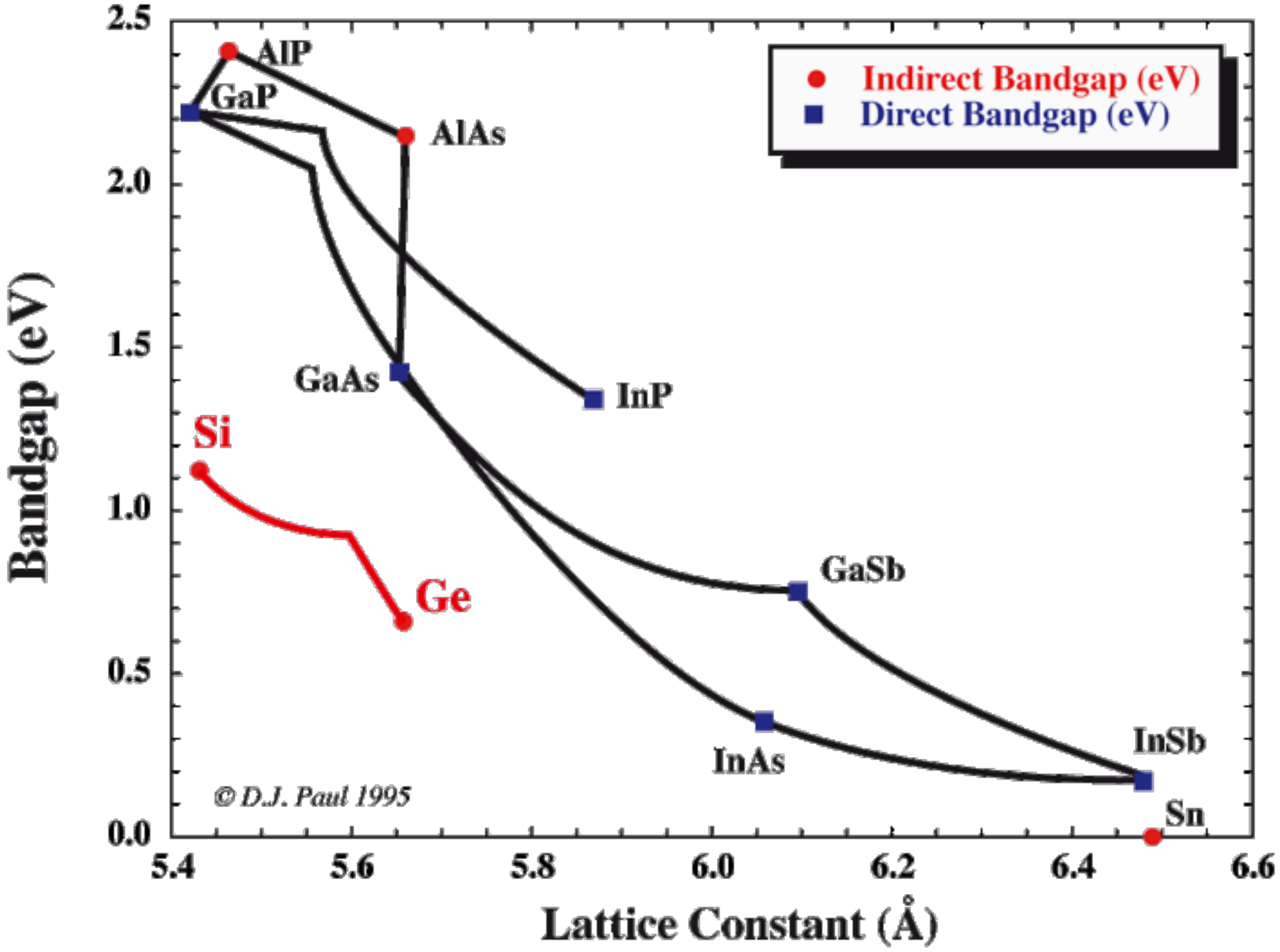
https://arxiv.org/pdf/1910.10716.pdf



Target	E_g [eV]	$\bar{\varepsilon}_\infty$	$\overline{\omega}_O$ [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
$CaWO_4$	5.2	3.84	8.48 - 106
GaAs	1.42	10.9	31.8 - 34.9
Al_2O_3	8.8	3.26	35.6 - 104
Diamond	5.47*	-	161
SiO_2	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_2	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_2	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*

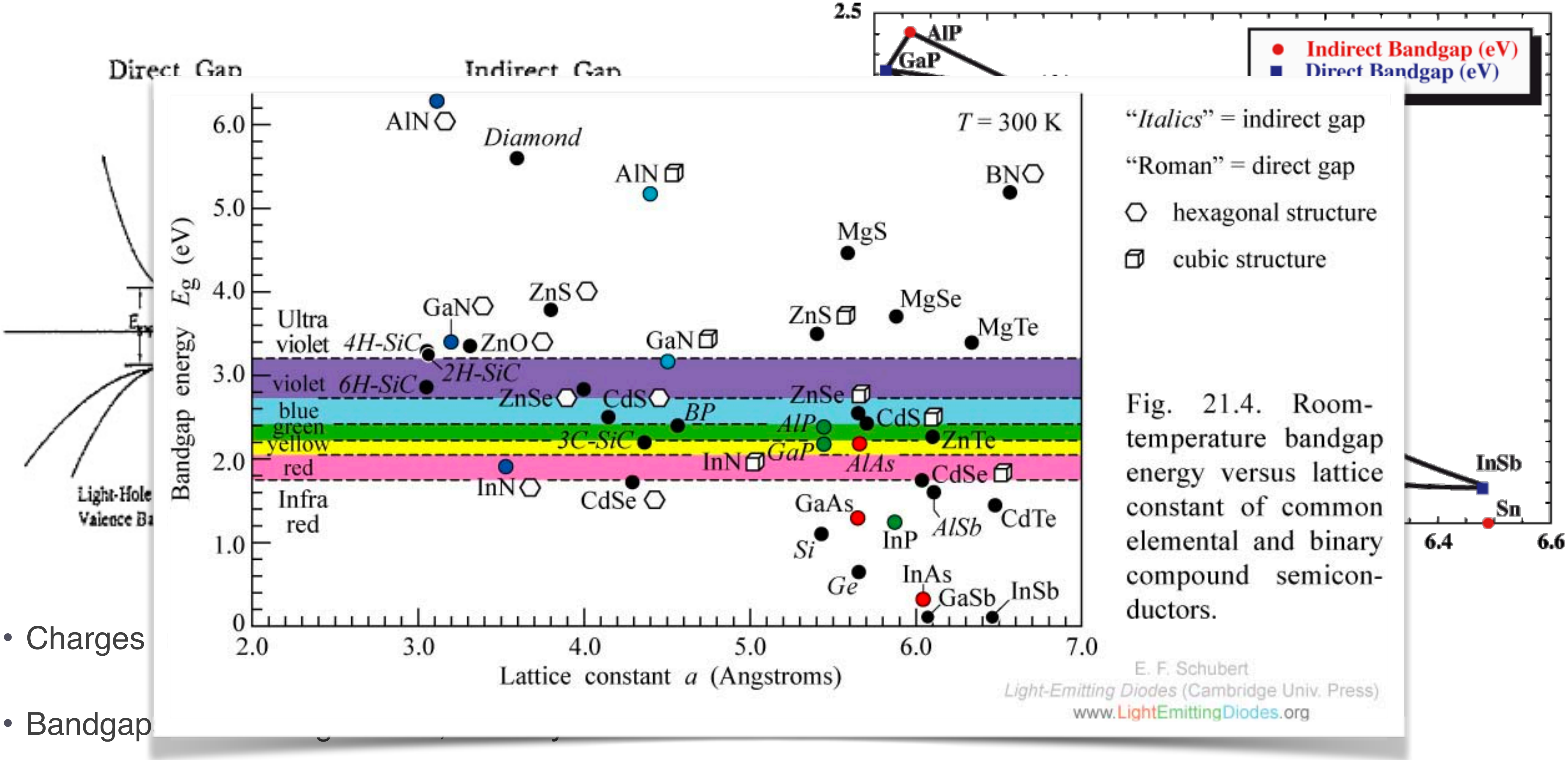


Fig. 21.4. Room-temperature bandgap energy versus lattice constant of common elemental and binary compound semiconductors.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

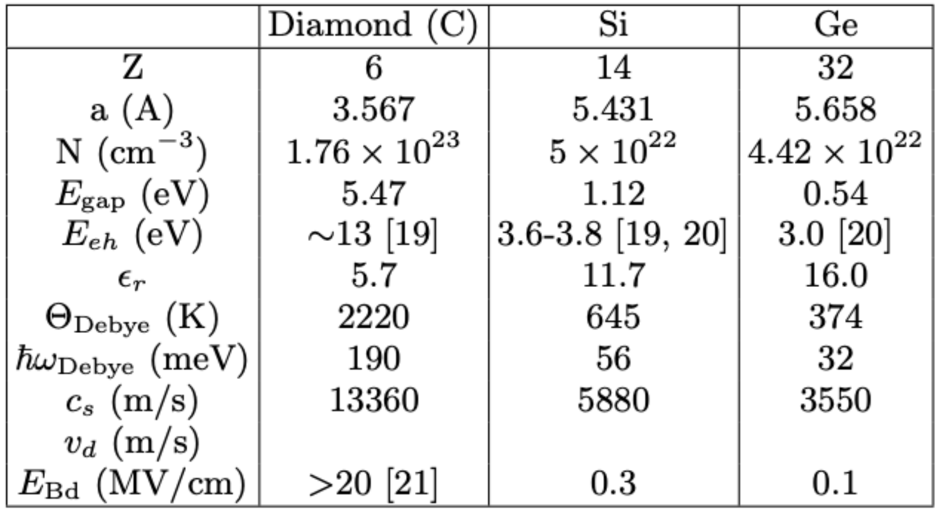
- Charges
- Bandgap
- Indirect bandgaps require more energy to liberate electrons thermally, but are still sensitive radiation down to bandgap energies (though the efficiency is reduced)

See Kurinsky, Yu, Hochberg, Cabrera (1901.07569) for diamond study

SiC Study in Prep w/ Hochberg, Lin, Griffin, Inzani, and Yu

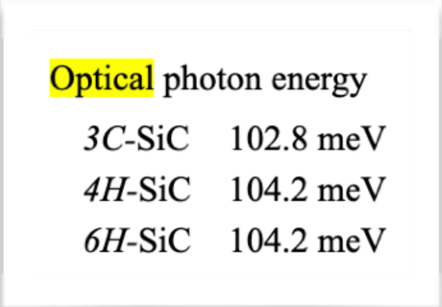
Carbon Detectors

- Carbon has a lighter nucleus than either Si or Ge, giving it a kinematic advantage for low-mass Nuclear recoils
- Diamond and SiC are semiconductors with long-lived charge and phonon excitations
- Both crystals Can withstand >10x larger electric fields than Si or Ge, and has many orders of magnitude lower leakage current even at room temperature
- Radiation hard; ~10x larger displacement energies (studied by RD42)
- SiC is also strongly polar, allowing for direct photon absorption even in the sub-gap region by creation of optical phonons
  - In many ways intermediate between Si and diamond
- Promising for low-mass NR and absorption of Bosonic DM down to meV masses

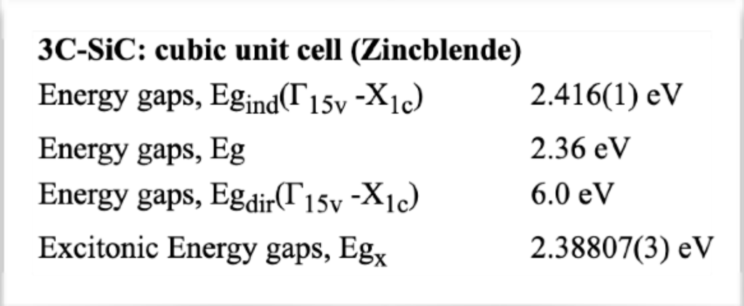


	Diamond (C)	Si	Ge
Z	6	14	32
a (A)	3.567	5.431	5.658
N (cm^{-3})	1.76×10^{23}	5×10^{22}	4.42×10^{22}
E_{gap} (eV)	5.47	1.12	0.54
E_{eh} (eV)	~13 [19]	3.6-3.8 [19, 20]	3.0 [20]
ϵ_r	5.7	11.7	16.0
Θ_{Debye} (K)	2220	645	374
$\hbar\omega_{\mathrm{Debye}}$ (meV)	190	56	32
c_s (m/s)	13360	5880	3550
v_d (m/s)			
E_{Bd} (MV/cm)	>20 [21]	0.3	0.1

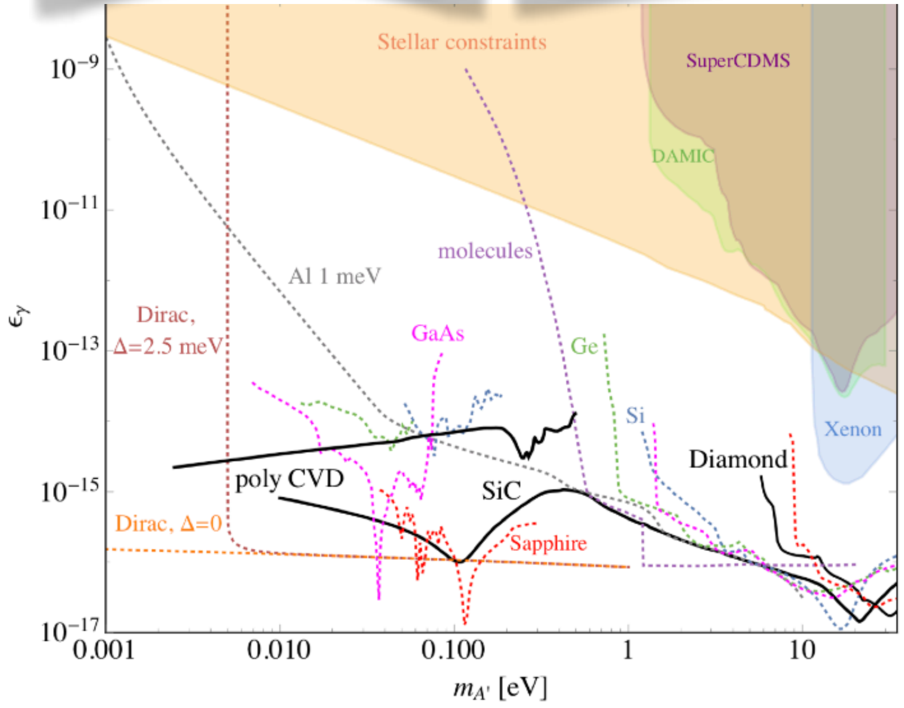
TABLE I. Material properties of diamond, Si, and Ge (from Refs. [22–24] unless otherwise stated).



Optical photon energy	
3C-SiC	102.8 meV
4H-SiC	104.2 meV
6H-SiC	104.2 meV

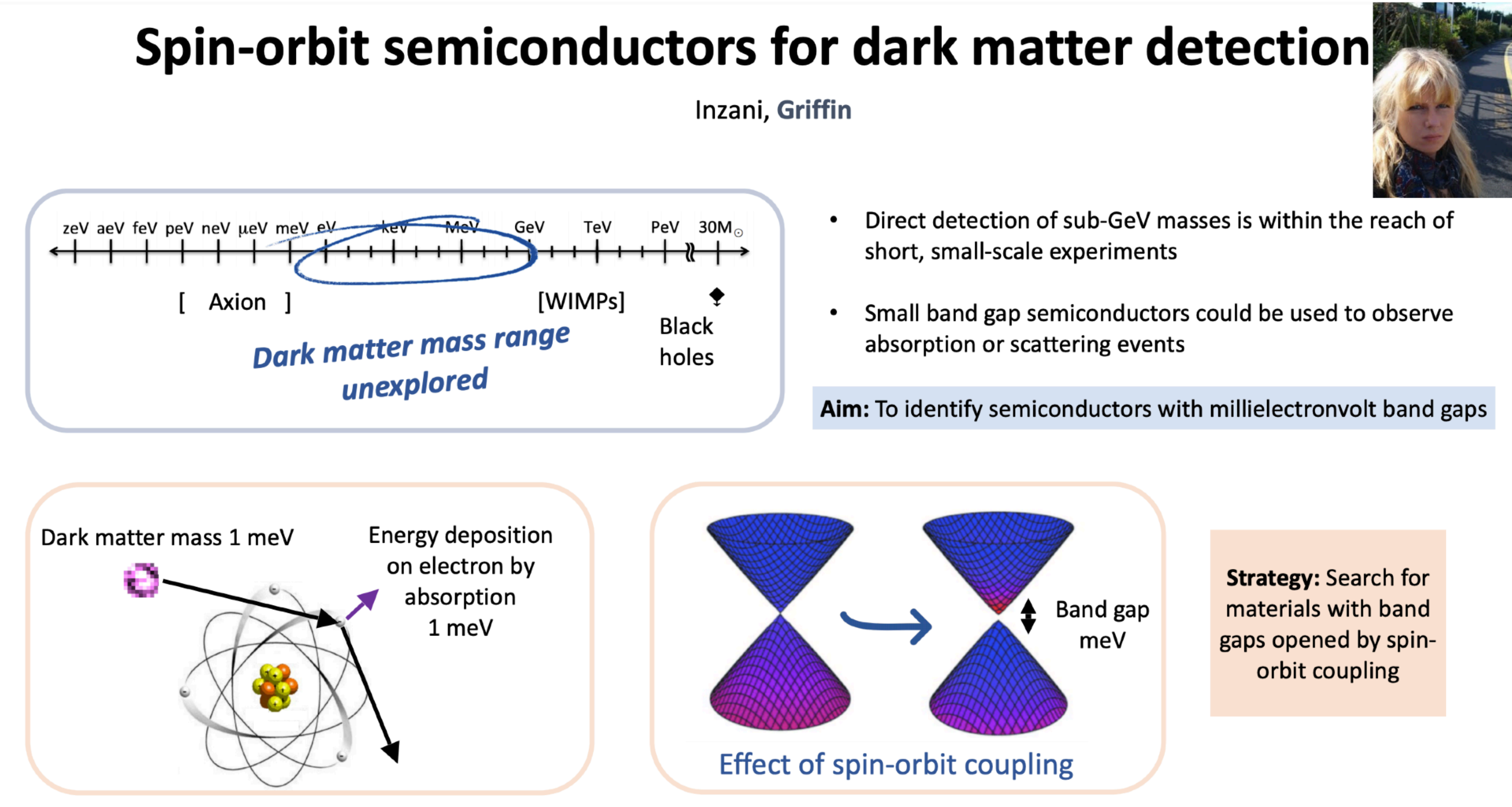


3C-SiC: cubic unit cell (Zincblende)	
Energy gaps, $Eg_{\mathrm{ind}}(\Gamma_{15v}\text{-}X_{1c})$	2.416(1) eV
Energy gaps, Eg	2.36 eV
Energy gaps, $Eg_{\mathrm{dir}}(\Gamma_{15v}\text{-}X_{1c})$	6.0 eV
Excitonic Energy gaps, Eg_x	2.38807(3) eV



From Sub-GeV DM Workshop (L. Wagner)

https://astro.fnal.gov/ldm/



Spin-orbit semiconductors for dark matter detection

Inzani, **Griffin**

Dark matter mass range unexplored

- 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

Dark matter mass 1 meV

Energy deposition on electron by absorption 1 meV

Effect of spin-orbit coupling

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

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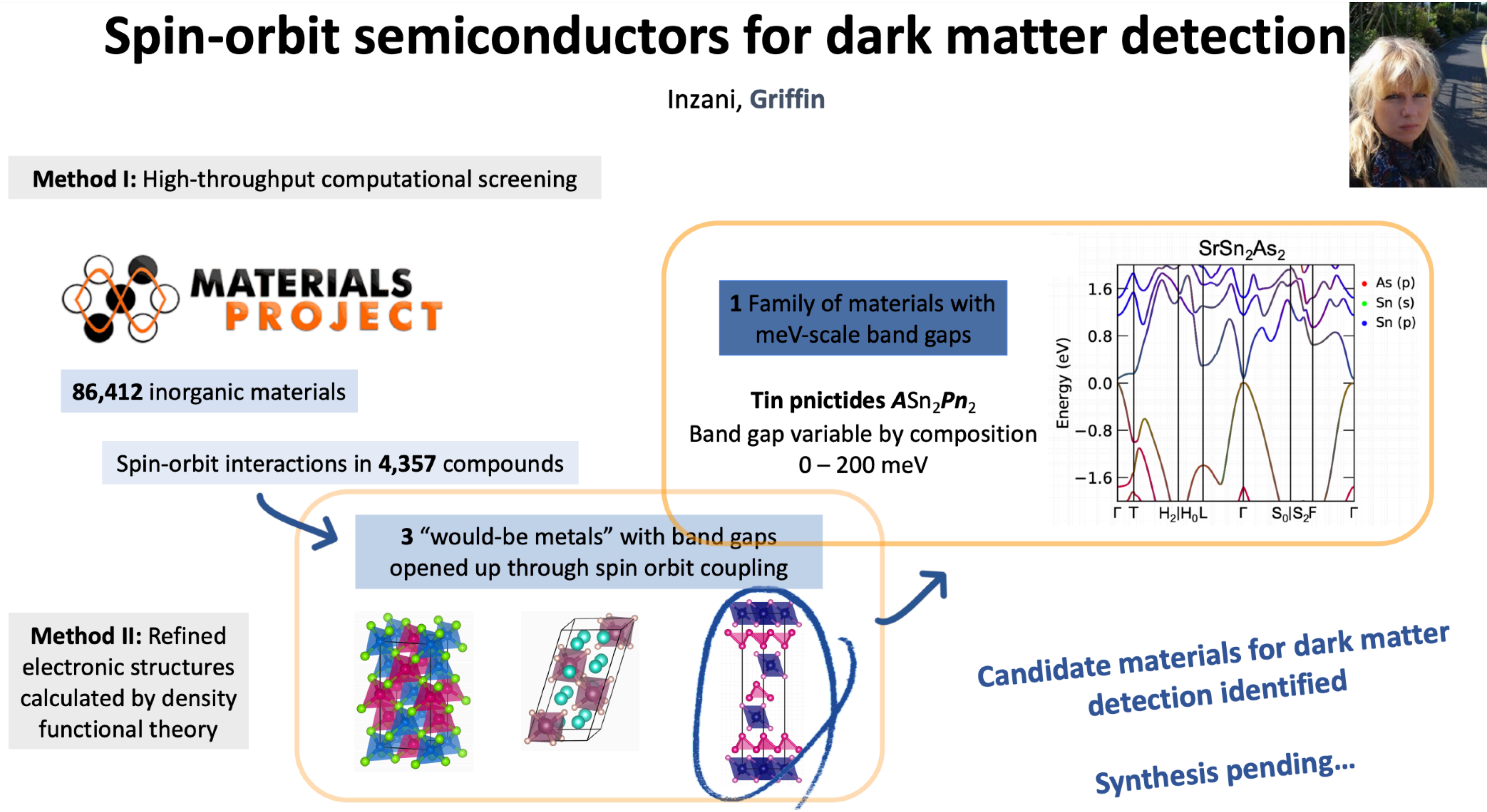


Spin-orbit semiconductors for dark matter detection

Inzani, **Griffin**

Method I: High-throughput computational screening

MATERIALS PROJECT

86,412 inorganic materials

Spin-orbit interactions in **4,357** compounds

Method II: Refined electronic structures calculated by density functional theory

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

1 Family of materials with meV-scale band gaps

Tin pnictides $A\mathrm{Sn}_2Pn_2$
Band gap variable by composition
0 – 200 meV

Candidate materials for dark matter detection identified

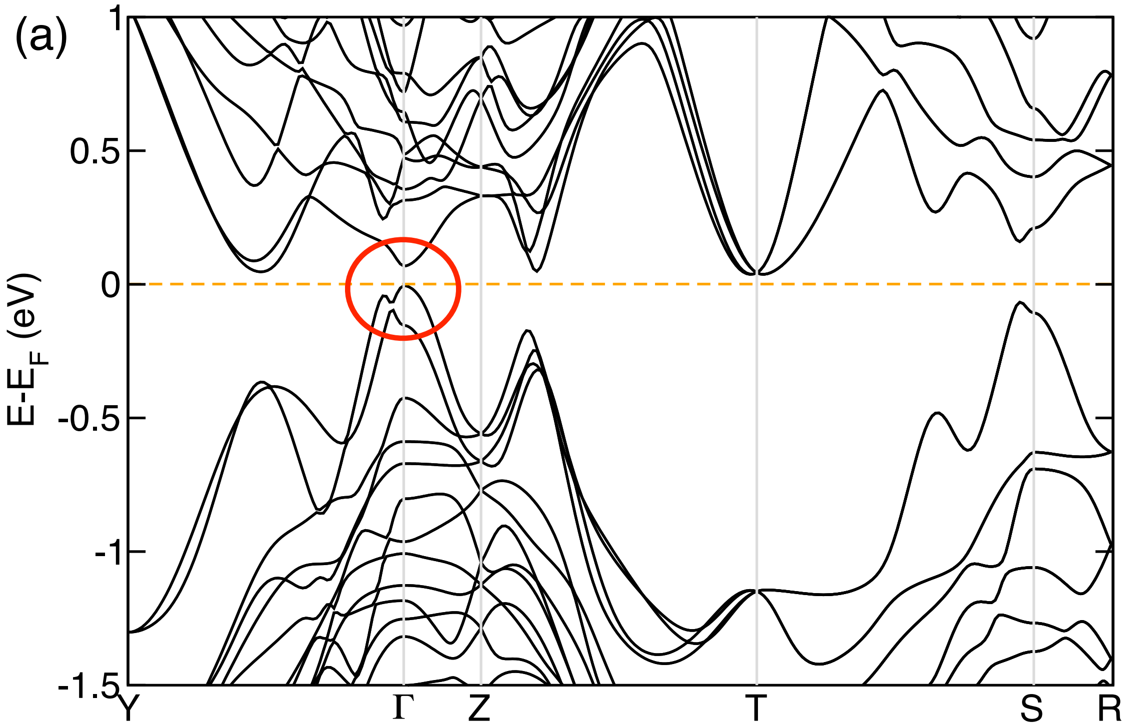
Synthesis pending…

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 ($ZrTe_5$)

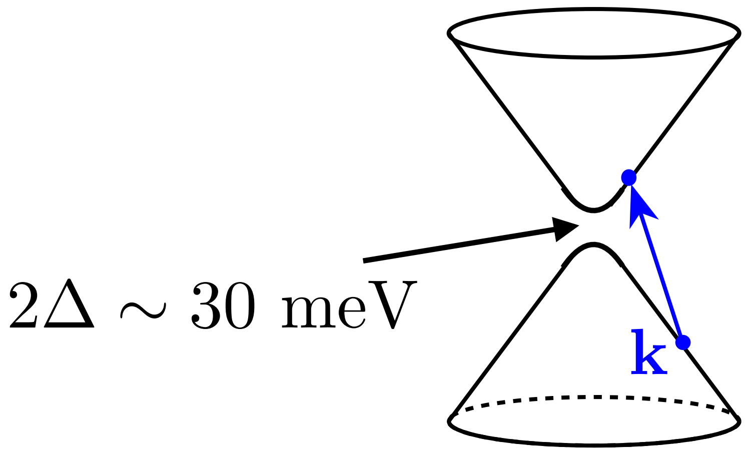


- meV excitation energies
- Anisotropic (bands and crystal)
- (Theoretically) insulating at zero temperature

Potential new class of materials for DM detection!

What is a Dirac material?

$ZrTe_5$ 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:

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

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

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

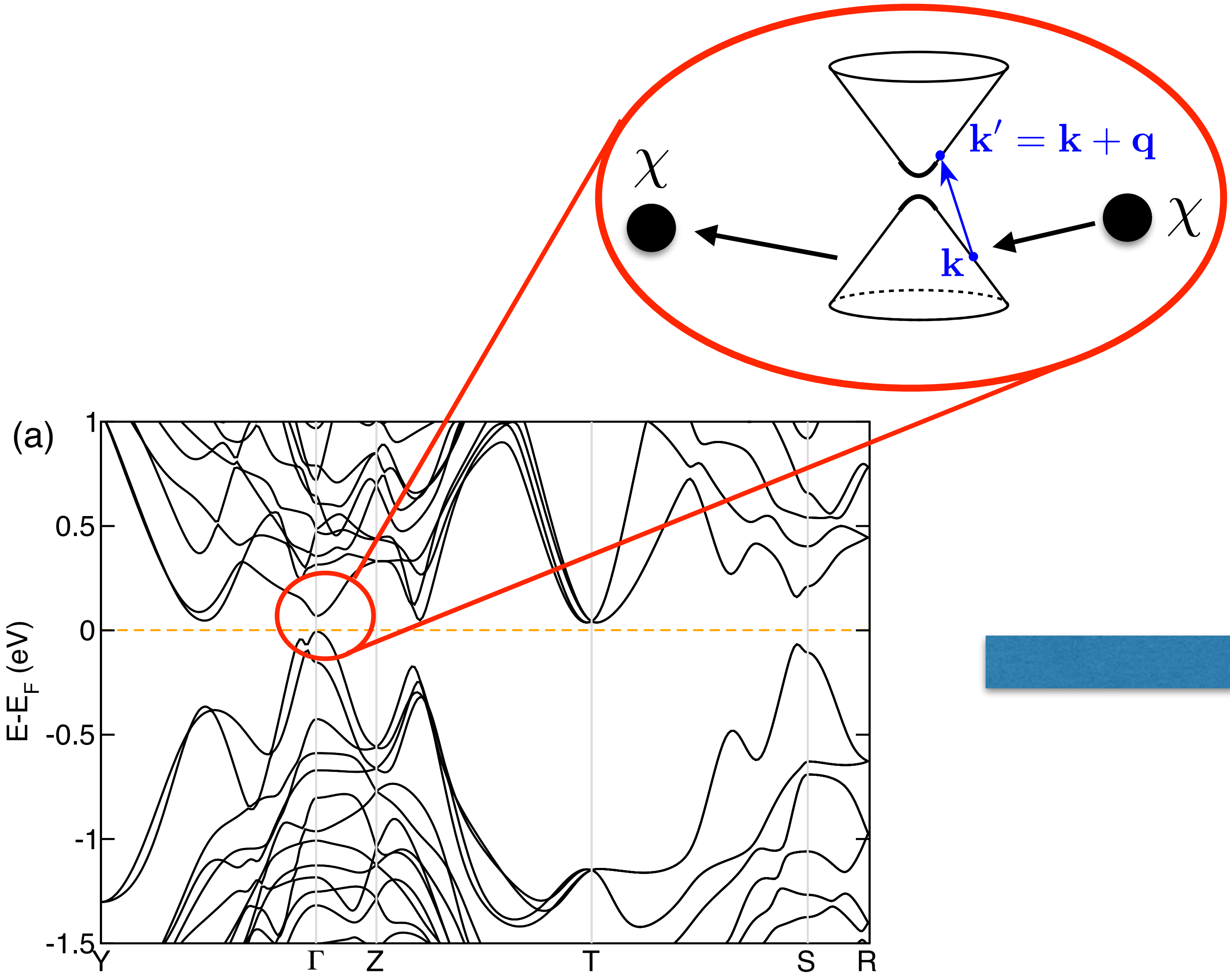
$$v_{F,z} \sim 6.5 \times 10^{-4}\, c \ll v_{F,x},\, v_{F,y}$$

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

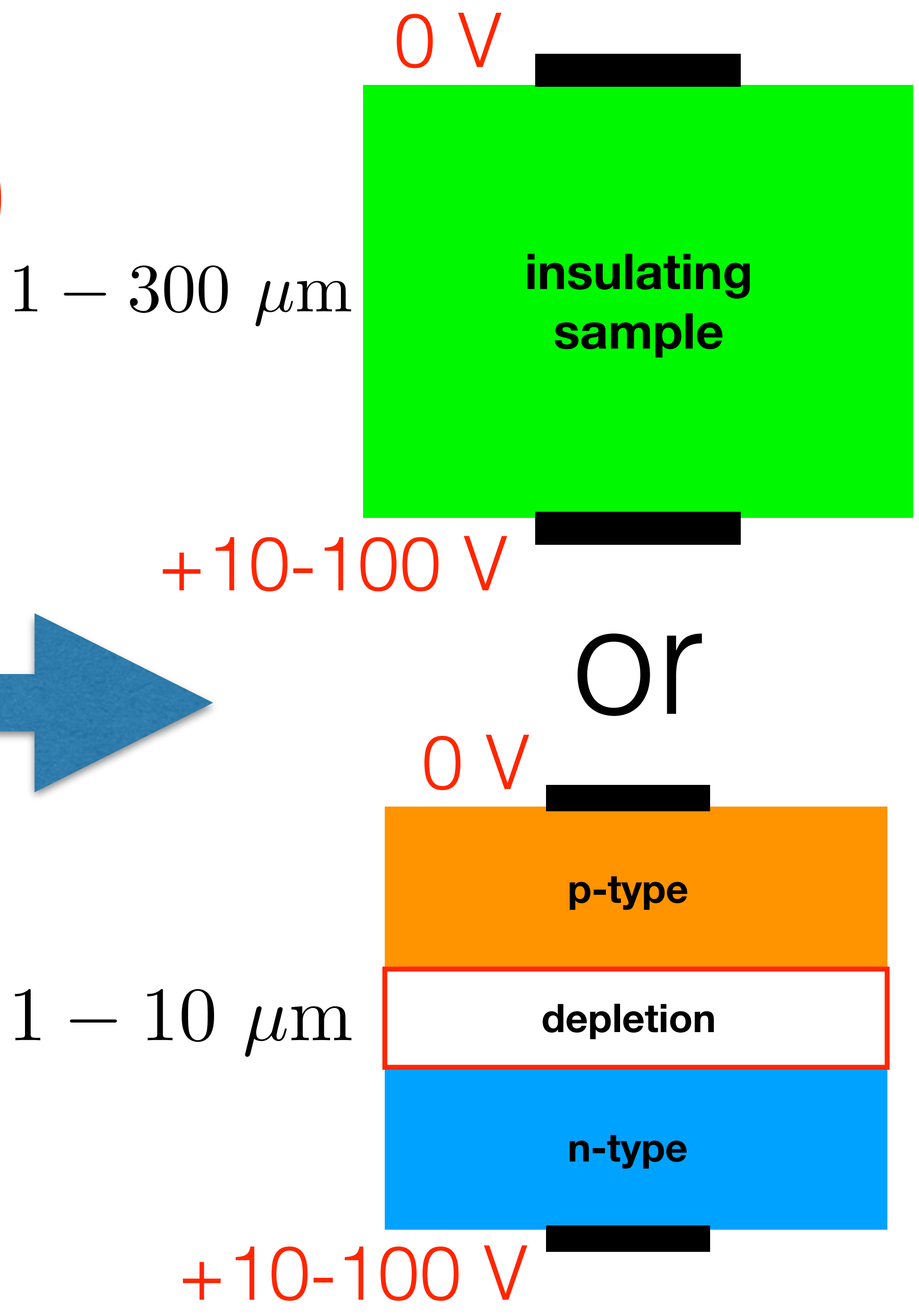
No scattering if DM is
slower than v_F, but this depends
on direction of q!

Strong directional dependence

Detection by charge avalanche



ZrTe$_5$ band diagram



0 V

$1 - 300\ \mu\mathrm{m}$

insulating sample

+10-100 V

or

0 V

p-type

$1 - 10\ \mu\mathrm{m}$

depletion

n-type

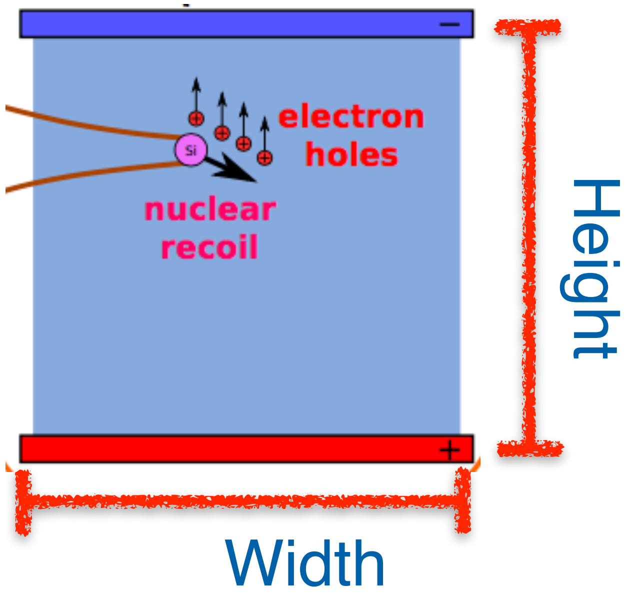
+10-100 V

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

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

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

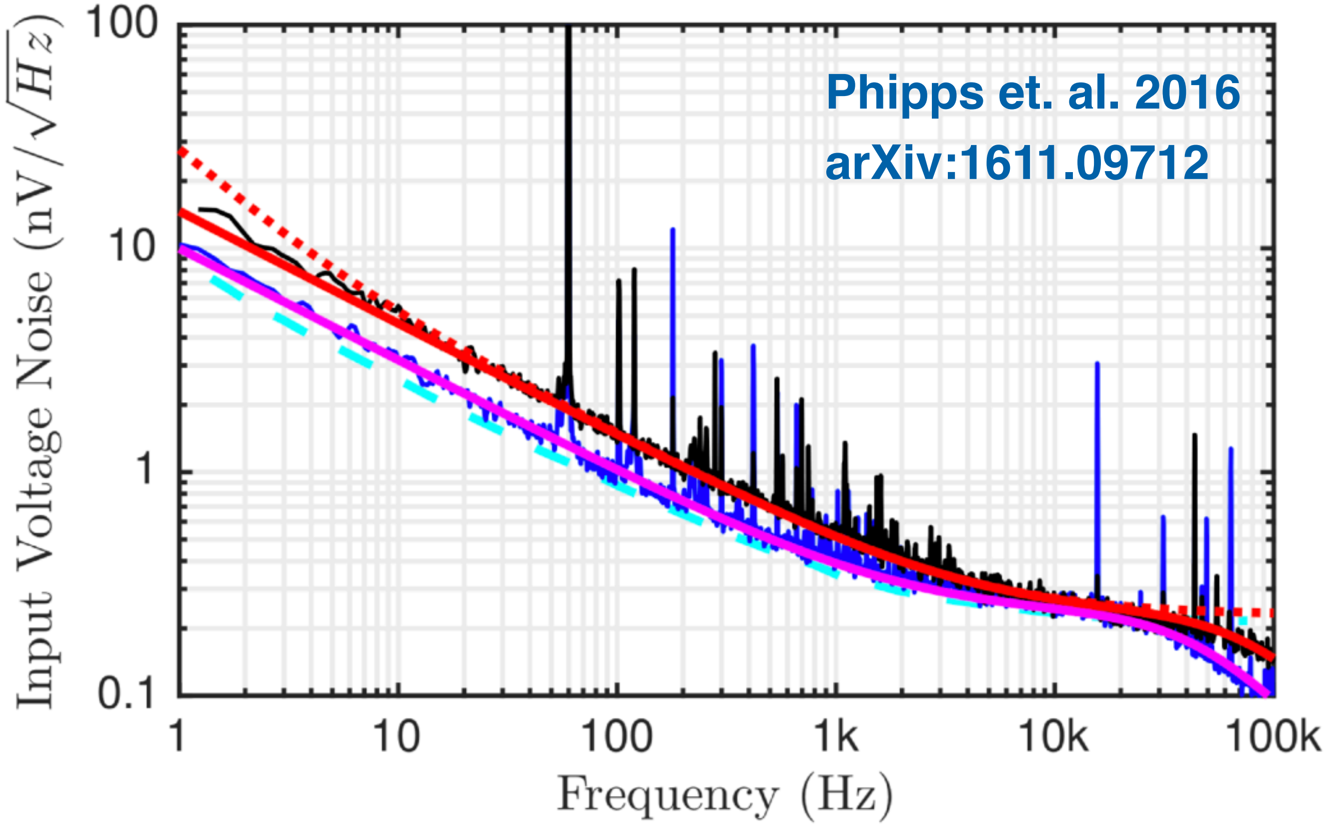


- Charge resolution is determined by detector+readout capacitance, voltage noise, and 1/f cutoff

- 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



Phipps et. al. 2016
arXiv:1611.09712

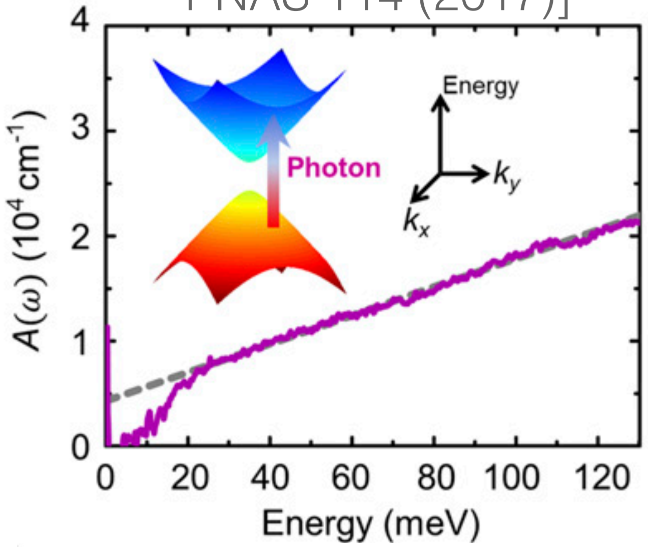
Design	Dimensions	Mass (mg)	Temp. (K)	V_{Bias}	σ_E	σ_q
Single Cell	16 mm^2 × 0.5 mm	28	4.2 K	10 V	13–39 eVee	1–3e^-
Segmented	1 mm^2 × 0.5 mm	1.8			1.3–3.9 eVee	0.1–0.3e^-/segment

Kurinsky, Yu, Hochberg, Cabrera (1901.07569)

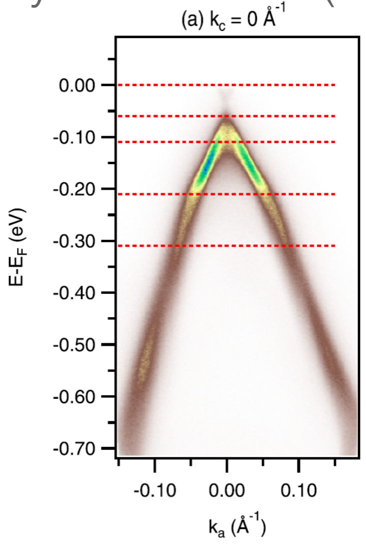
ZrTe5 state of the art

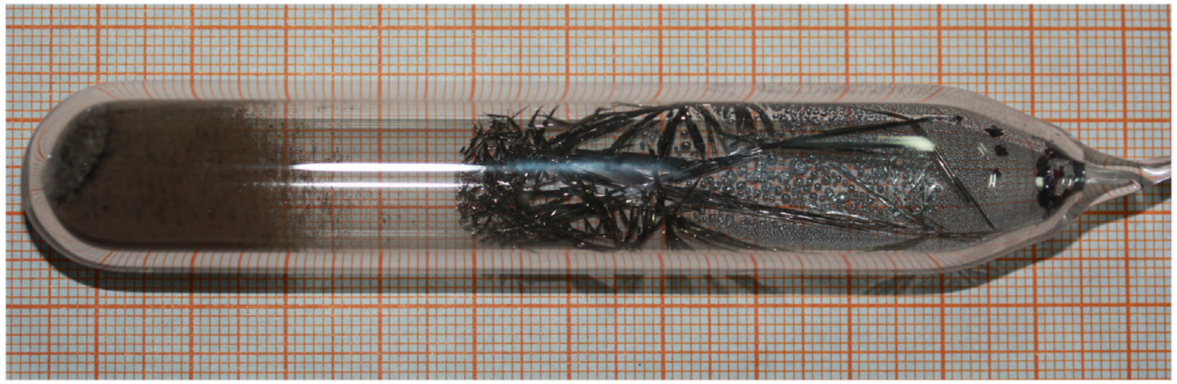
- Gap is ~20 meV at 4.5 K, band structure is very close to linear near BZ center
- ~50 mg single crystals have been grown at Brookhaven and in China
- Fermi level can be manipulated with epitaxial strain and/or Te concentration
- **Need to measure dielectric function and Fermi velocities in an insulating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

[Z.-G. Chen et al., PNAS 114 (2017)]

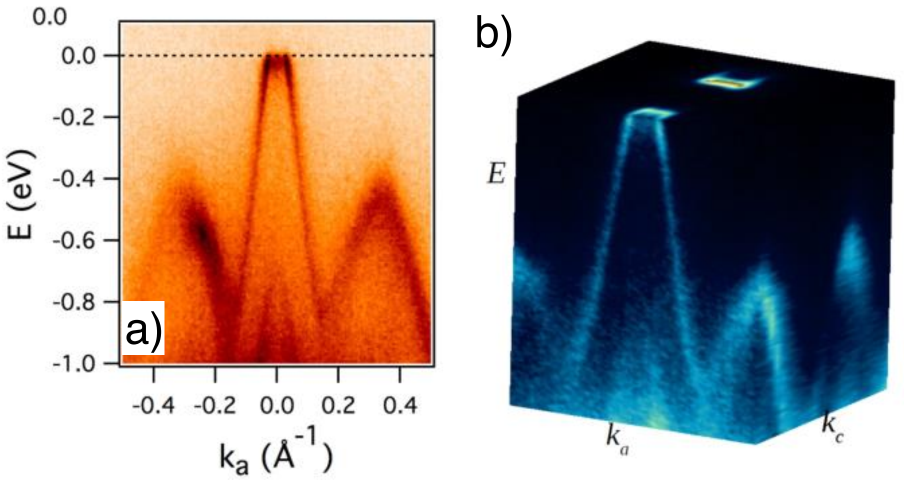


[H. Xiong et al., Phys. Rev. B 95 (2017)]

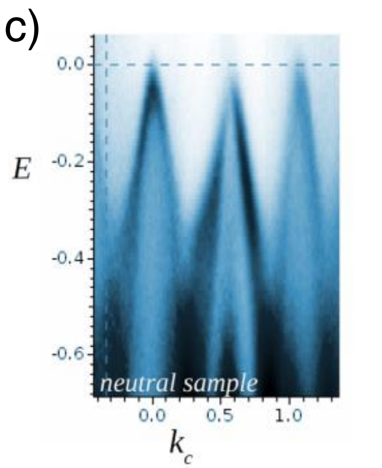




[Y.-Y. Lv et al, J. Cryst. Growth 457 (2017)]



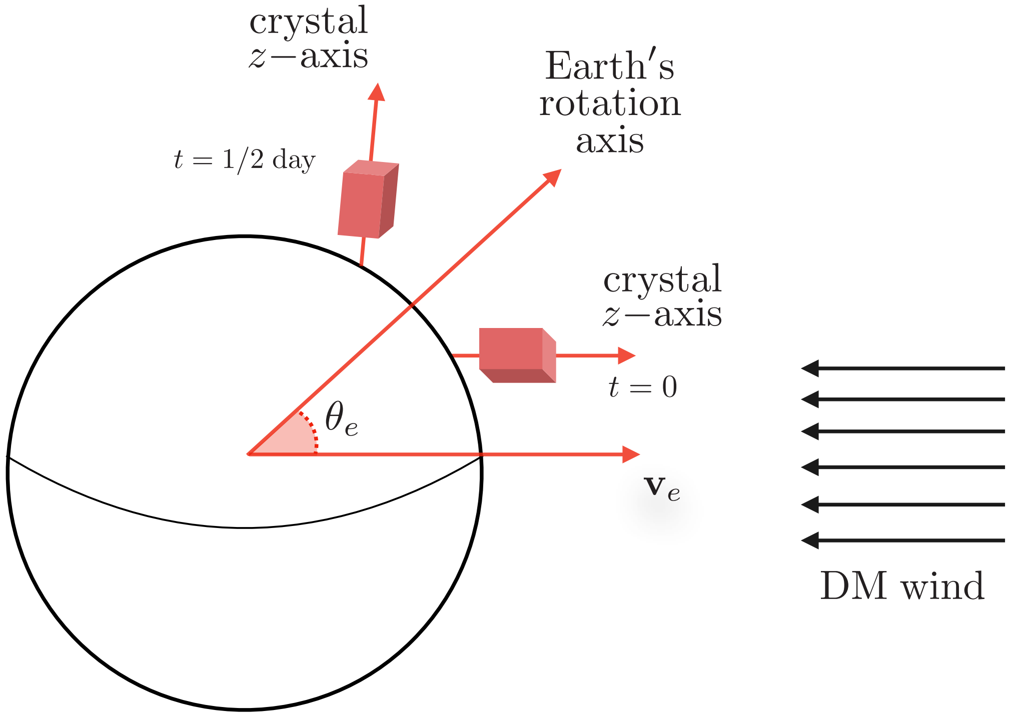
[Q. Li et al., Nature Phys. 2016]

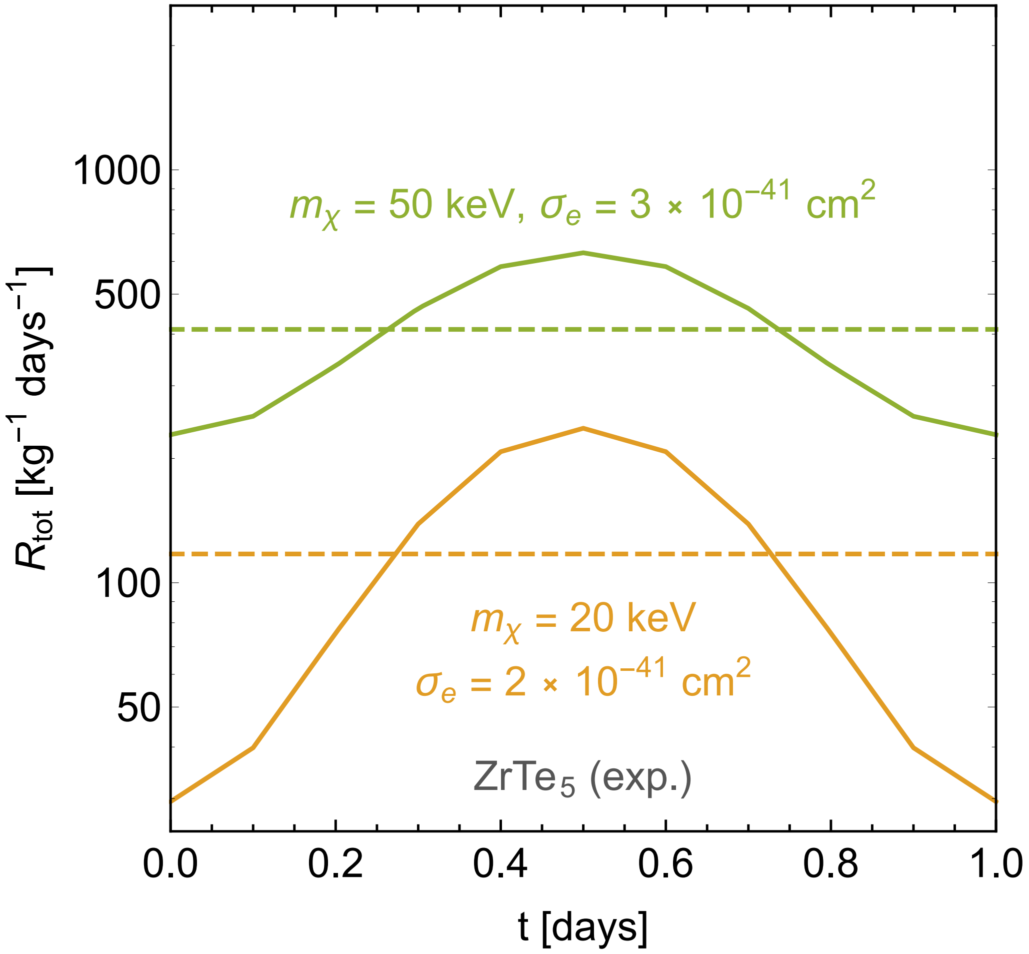


[Q. Li, preliminary]

Directional detection

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



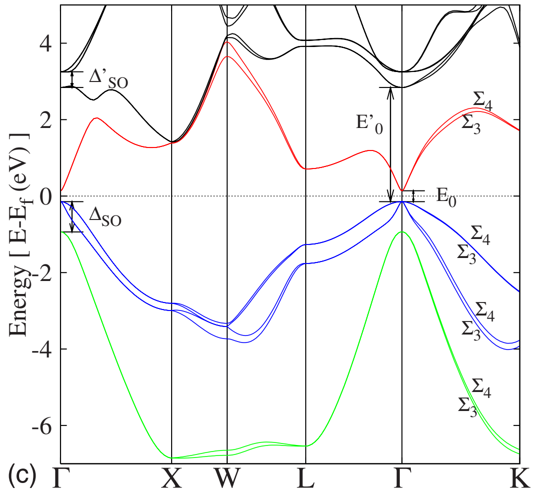


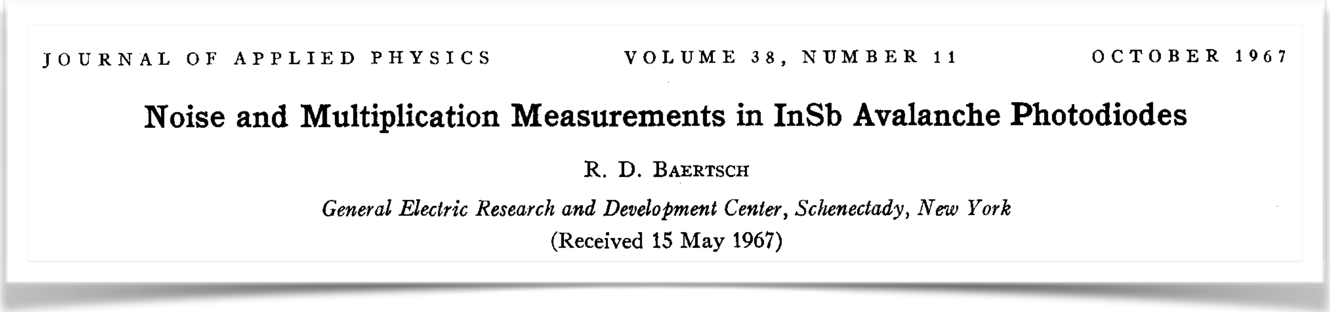
[Coskuner, Mitridate, Olivares, Zurek, arXiv:1909.09170; Geilhufe, Kahlhoefer, Winkler, arXiv:1910.02091]

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 ~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



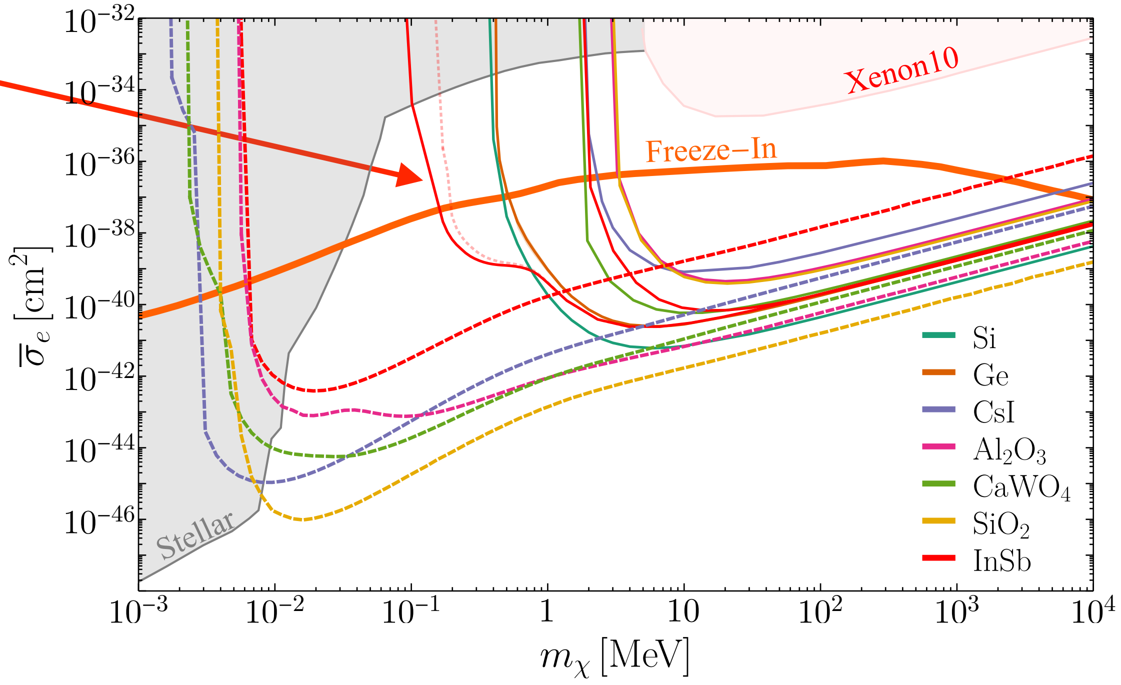

JOURNAL OF APPLIED PHYSICS VOLUME 38, NUMBER 11 OCTOBER 1967

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