Dirac materials and narrow-gap semiconductors for keV-MeV freeze-in DM

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In collaboration with:
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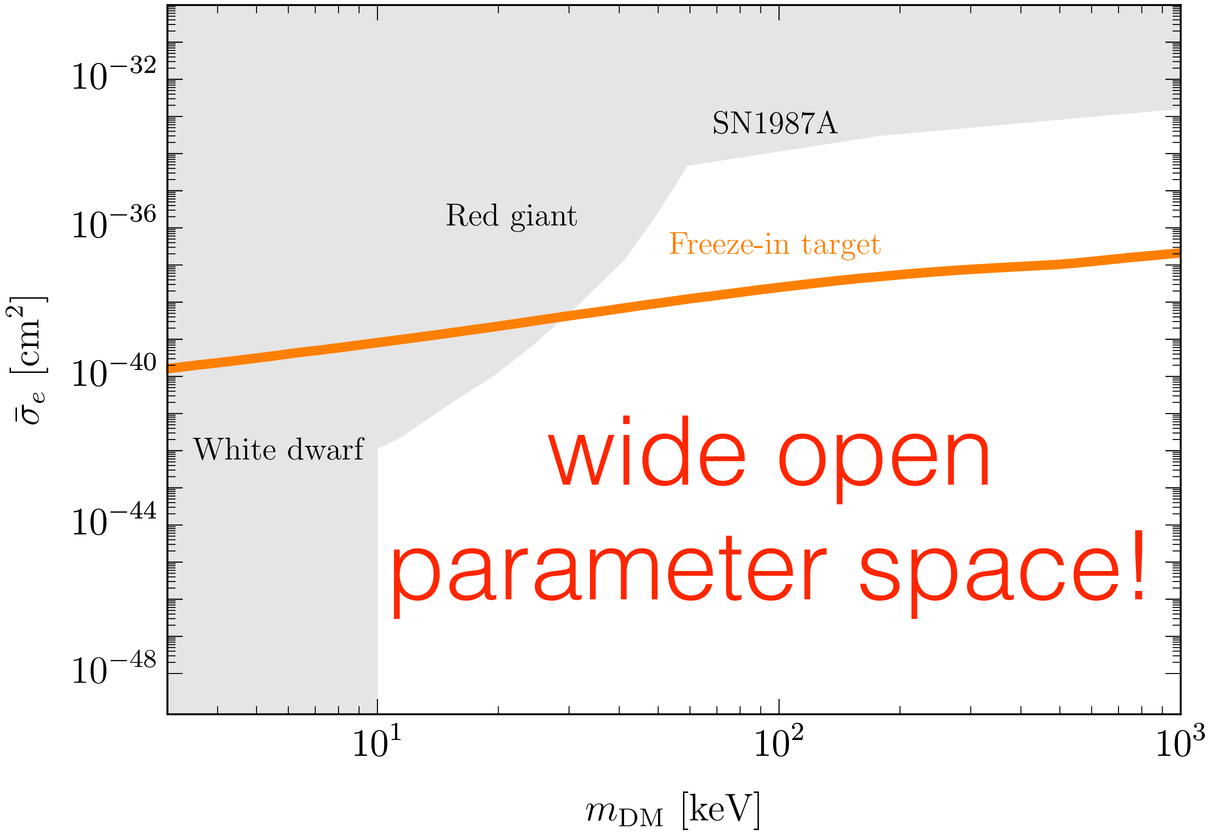
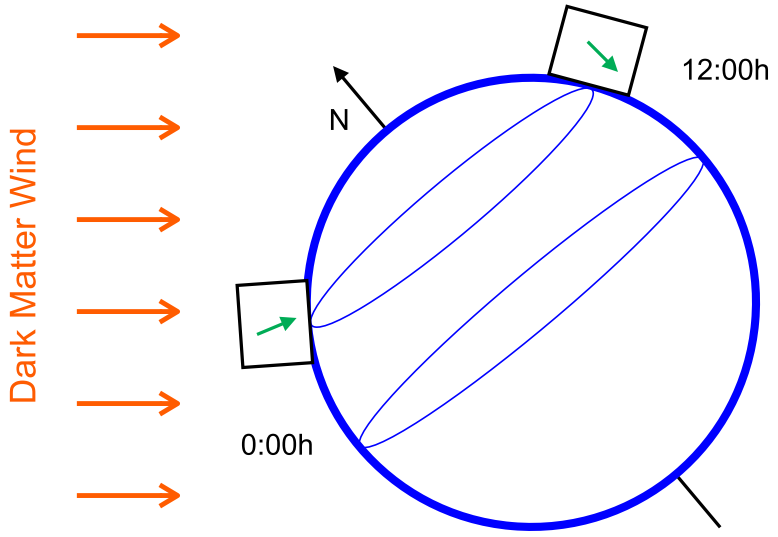
Fermilab: A. Para, P. Rubinov

Concept: DM-electron scattering at low gap energies

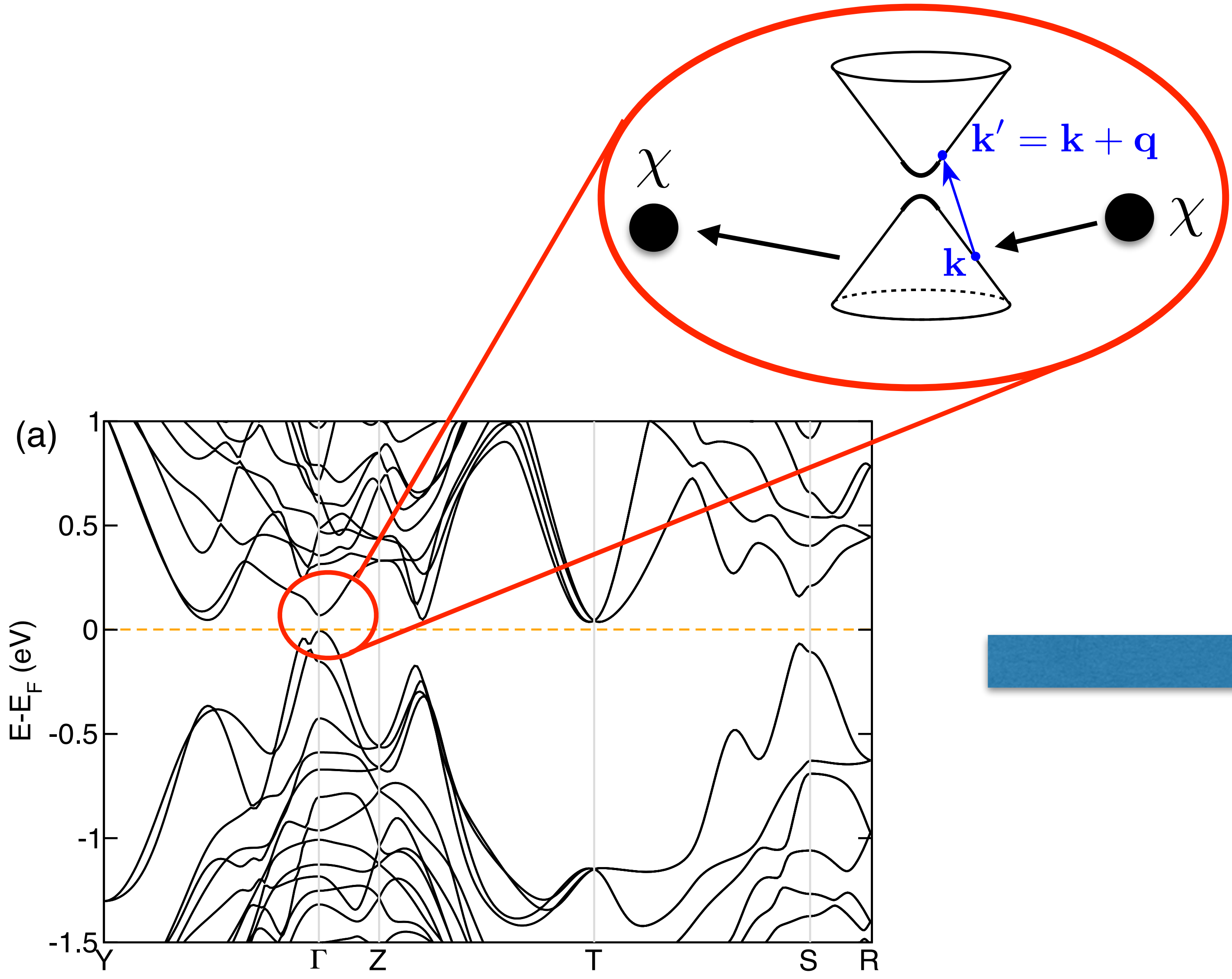
- We are going after **DM-electron scattering** (c.f. Tongyan's talk on Wed.) at the **freeze-in** target (c.f. all the Tues. afternoon theory talks) in the mass range 20 keV — 1 MeV
- Need materials with **~30 meV excitation energy** for the lowest-mass DM
- We will use **charge amplification** rather than phonon detection - energy threshold is set by **material** rather than detector
- One of our proposed materials ($ZrTe_5$) is **highly anisotropic**, leading to **strong daily and annual modulations** which can help mitigate isotropic backgrounds



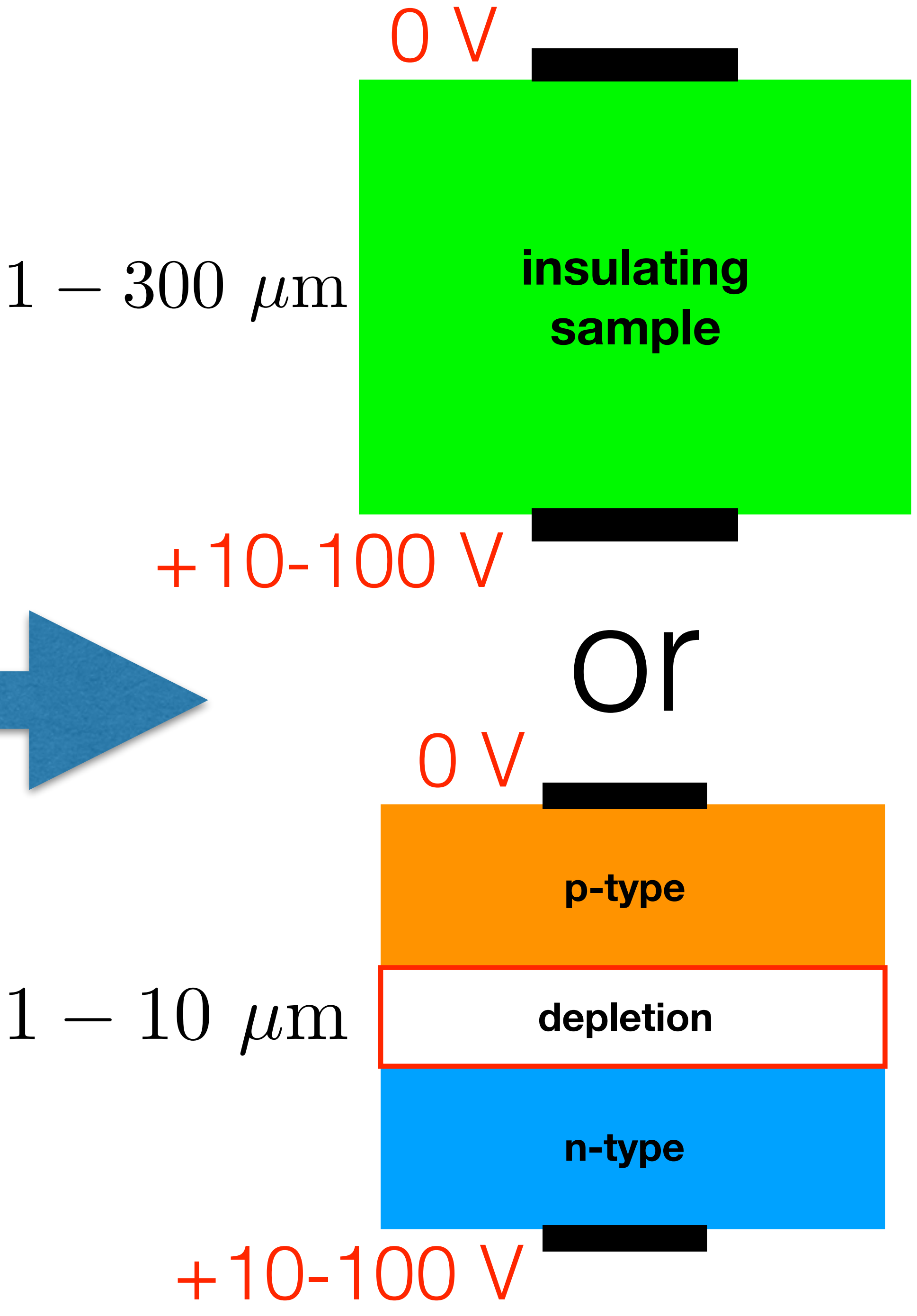
wide open parameter space!



Detection by charge avalanche



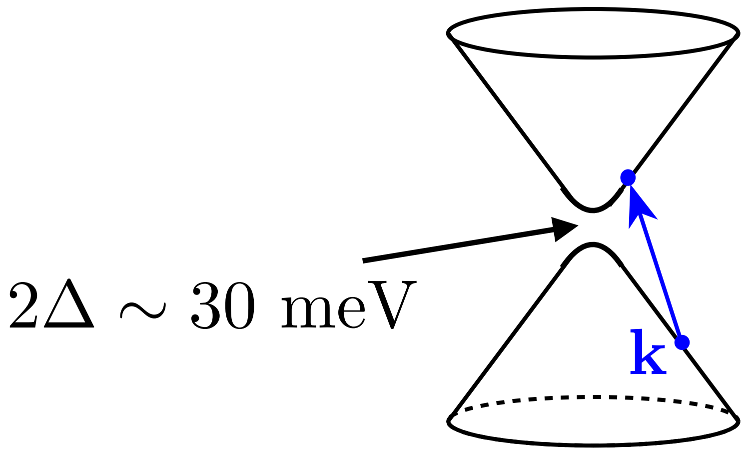
ZrTe$_5$ band diagram



Operates like an APD or a SiPM (c.f. Claudio's talk on Tues.): 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

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:

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

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

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

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

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

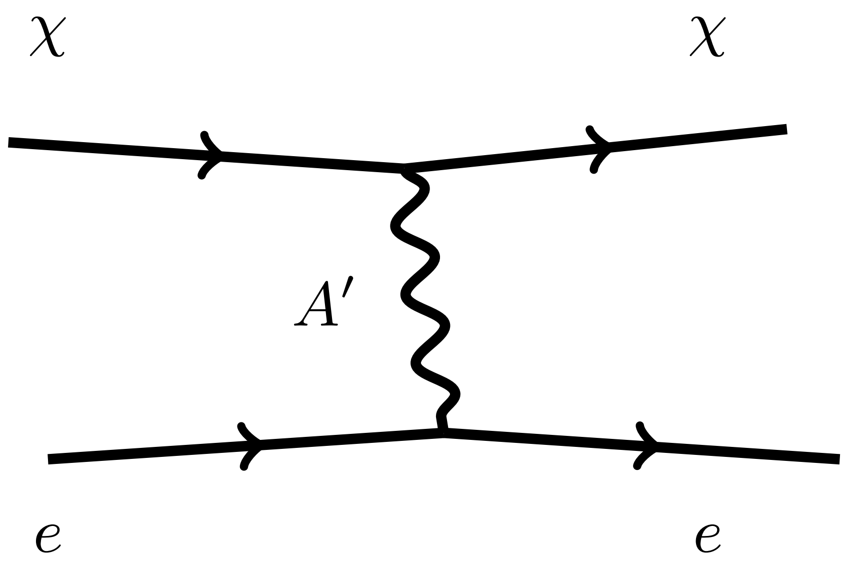
No scattering if DM is slower than v_F, but this depends on direction of q!

Strong directional dependence

Importance of the dielectric function

$$R \sim \int d^3q \, d\Phi |F_{\rm DM}(q)|^2 |\mathcal{F}_{\rm med}(q)|^2 |f_{\rm excit.}(q)|^2$$

Ultralight dark photon mediator:



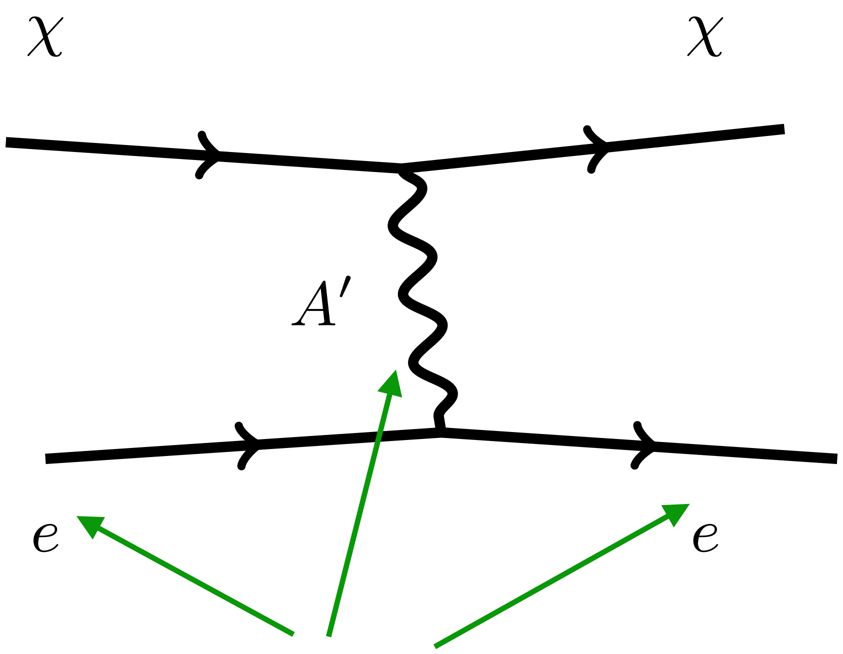
$$\frac{1}{q^2 - m_{A'}^2} \rightarrow \frac{1}{q^2} \quad \text{for} \quad m_{A'}^2 \ll q^2$$

$$\mathbf{q} \sim m_{\rm DM} v_{\rm DM} \sim \ \rm eV$$

Importance of the dielectric function

$$R \sim \int d^3q \, d\Phi \, |F_{\rm DM}(q)|^2 \, |\mathcal{F}_{\rm med}(q)|^2 \, |f_{\rm excit.}(q)|^2$$

Ultralight dark photon mediator:



not in vacuum!

$$\frac{1}{q^2 - m_{A'}^2} \to \cancel{\frac{1}{q^2}} \quad \text{for} \quad m_{A'}^2 \ll q^2$$

$$\mathbf{q} \sim m_{\rm DM} v_{\rm DM} \sim \text{eV}$$

$$\frac{1}{q^2} \to \frac{1}{q^2 - \Pi(q)}$$

If material has strong response to EM fields (e.g. metal), mediator picks up large effective mass, suppressing rate. In narrow-gap semiconductors, this **does not happen**

Importance of the dielectric function

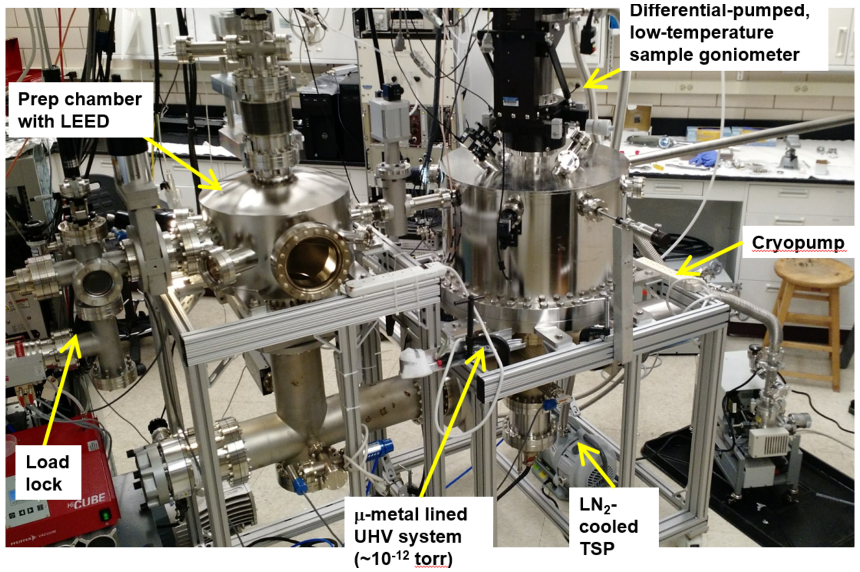
$$R \sim \int d^3q\, d\Phi |F_{\mathrm{DM}}(q)|^2 |\mathcal{F}_{\mathrm{med}}(q)|^2 |f_{\mathrm{excit.}}(q)|^2$$

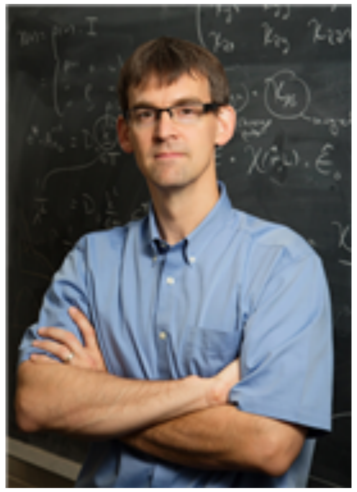
Ultralight dark photon mediator:

$$|F_{\mathrm{DM}}|^2 |\mathcal{F}_{\mathrm{med}}(q)|^2 |f_{\mathrm{excit.}}(q)|^2 = \frac{|\langle \psi_f | e^{i\mathbf{q}\cdot\mathbf{x}} | \psi_i \rangle|^2}{(q^2 - \Pi(q))^2} \equiv -\frac{1}{q^4} \mathrm{Im}\left(\frac{1}{\epsilon(\mathbf{q})}\right)$$

This is a key material property — and UIUC has the tools to measure it!

momentum-resolved electron energy-loss spectroscopy (M-EELS)

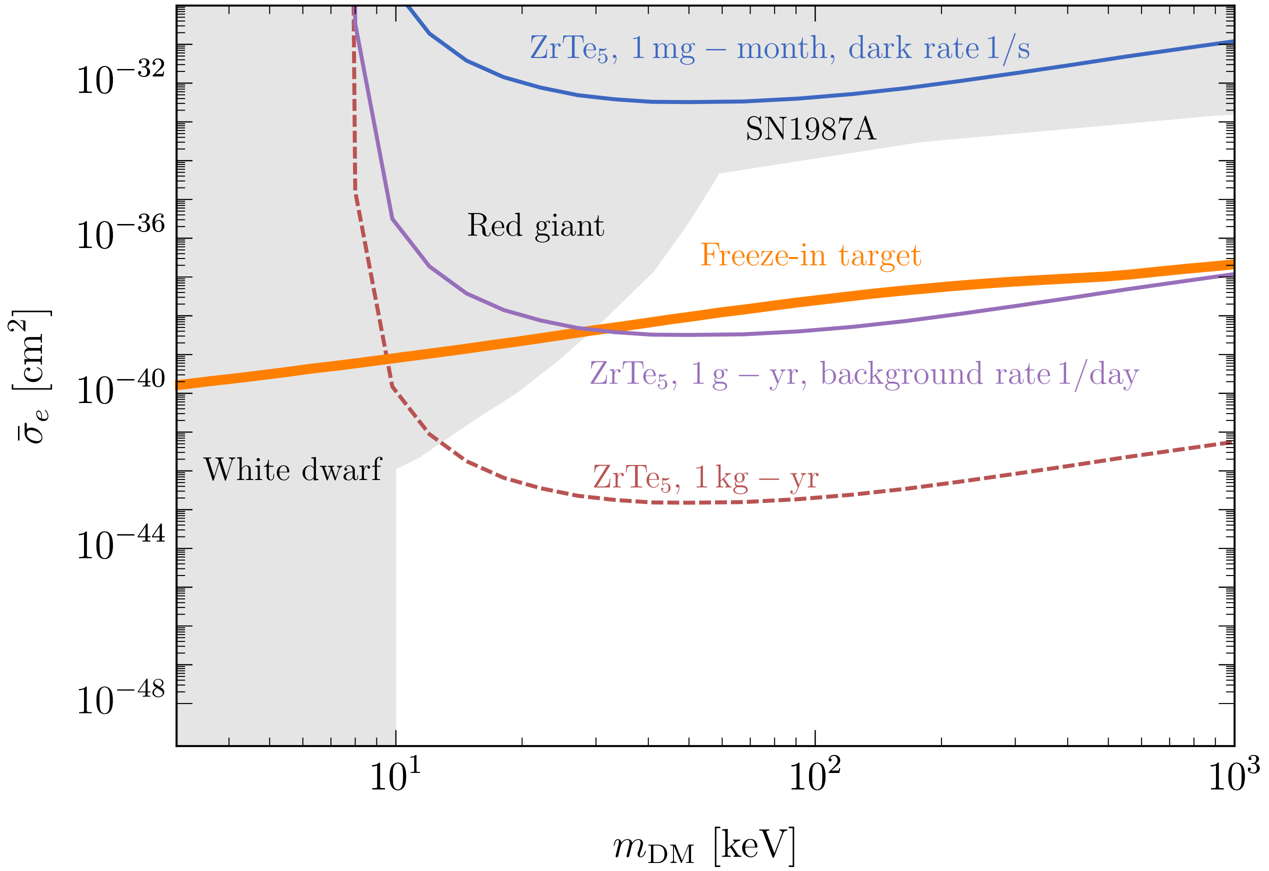


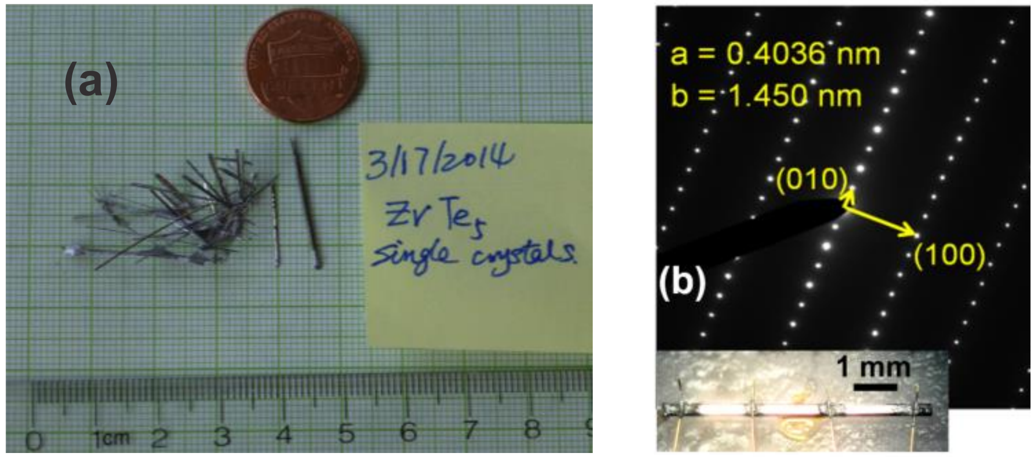


Projected sensitivity

(based on YK, Griffin, Hochberg, Lisanti, Zurek, et al., PRD 2018 [1708.08929])

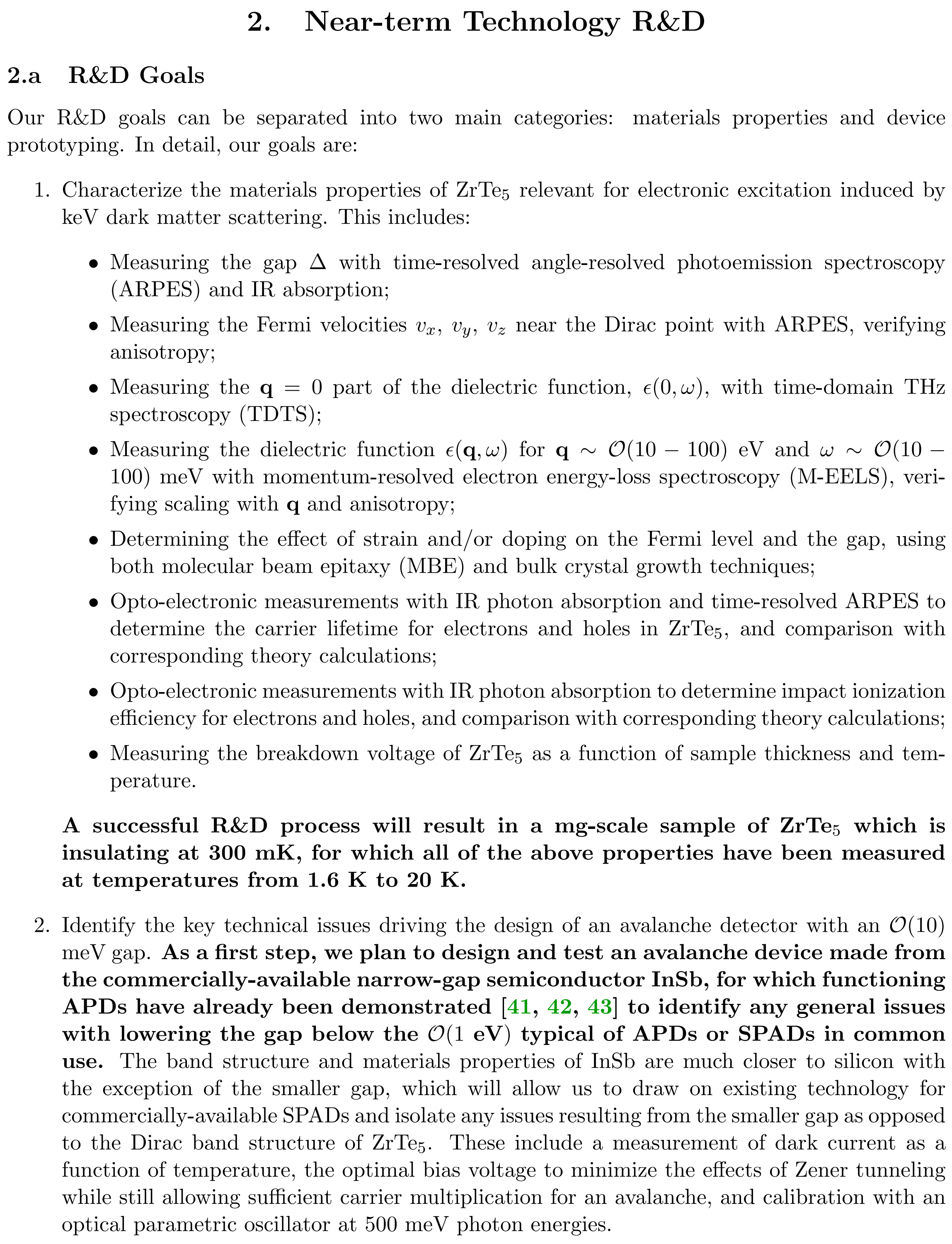
- Parameters for $ZrTe_5$ which determine DM rate are **band structure** (Fermi velocities and gap) and **dielectric function**: we use the measured value for the former and calculated value for the latter
- Obtaining a mg sample is easy, challenge will be **placing the Fermi level in the gap** and/or making a p-n junction
- **Dark rate is the largest expected background by far** for such a low-mass detector with no radioisotopes
- **Even with dark rates of Hz**, can achieve first ever limits on DM below 500 keV!





Status of R&D

We submitted a BRN proposal on the R&D track



2. Near-term Technology R&D

2.a R&D Goals

Our R&D goals can be separated into two main categories: materials properties and device prototyping. In detail, our goals are:

1. Characterize the materials properties of ZrTe$_5$ relevant for electronic excitation induced by keV dark matter scattering. This includes:
   - Measuring the gap Δ with time-resolved angle-resolved photoemission spectroscopy (ARPES) and IR absorption;
   - Measuring the Fermi velocities v_x, v_y, v_z near the Dirac point with ARPES, verifying anisotropy;
   - Measuring the $\mathbf{q} = 0$ part of the dielectric function, $\epsilon(0, \omega)$, with time-domain THz spectroscopy (TDTS);
   - Measuring the dielectric function $\epsilon(\mathbf{q}, \omega)$ for $\mathbf{q} \sim \mathcal{O}(10 - 100)$ eV and $\omega \sim \mathcal{O}(10 - 100)$ meV with momentum-resolved electron energy-loss spectroscopy (M-EELS), verifying scaling with $\mathbf{q}$ and anisotropy;
   - Determining the effect of strain and/or doping on the Fermi level and the gap, using both molecular beam epitaxy (MBE) and bulk crystal growth techniques;
   - Opto-electronic measurements with IR photon absorption and time-resolved ARPES to determine the carrier lifetime for electrons and holes in ZrTe$_5$, and comparison with corresponding theory calculations;
   - Opto-electronic measurements with IR photon absorption to determine impact ionization efficiency for electrons and holes, and comparison with corresponding theory calculations;
   - Measuring the breakdown voltage of ZrTe$_5$ as a function of sample thickness and temperature.

   A successful R&D process will result in a mg-scale sample of ZrTe$_5$ which is insulating at 300 mK, for which all of the above properties have been measured at temperatures from 1.6 K to 20 K.

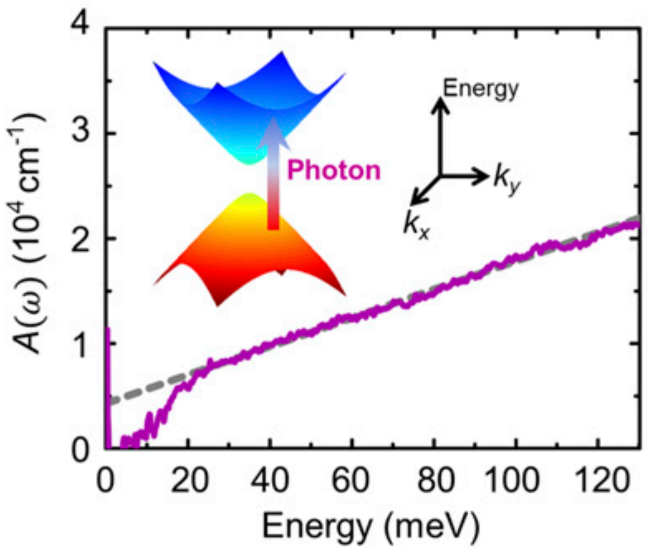
2. Identify the key technical issues driving the design of an avalanche detector with an $\mathcal{O}(10)$ meV gap. **As a first step, we plan to design and test an avalanche device made from the commercially-available narrow-gap semiconductor InSb, for which functioning APDs have already been demonstrated [41, 42, 43] to identify any general issues with lowering the gap below the $\mathcal{O}(1$ eV$)$ typical of APDs or SPADs in common use.** The band structure and materials properties of InSb are much closer to silicon with the exception of the smaller gap, which will allow us to draw on existing technology for commercially-available SPADs and isolate any issues resulting from the smaller gap as opposed to the Dirac band structure of ZrTe$_5$. These include a measurement of dark current as a function of temperature, the optimal bias voltage to minimize the effects of Zener tunneling while still allowing sufficient carrier multiplication for an avalanche, and calibration with an optical parametric oscillator at 500 meV photon energies.

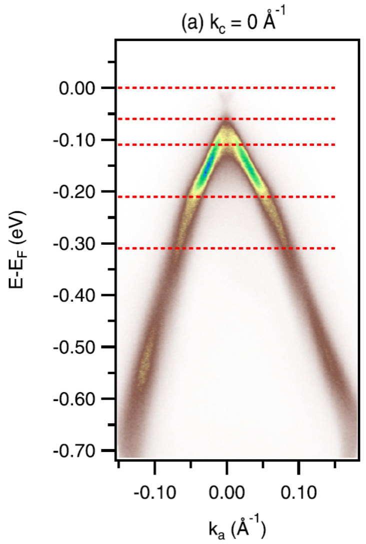
measure material properties (does ZrTe$_5$ behave in the wild like we calculate it to behave?)

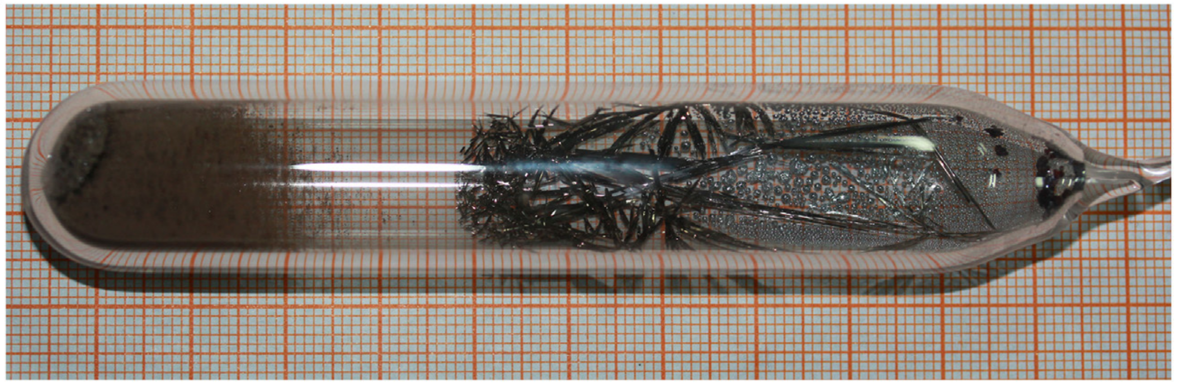
practice making an APD out of another, commercially-available narrow-gap semiconductor

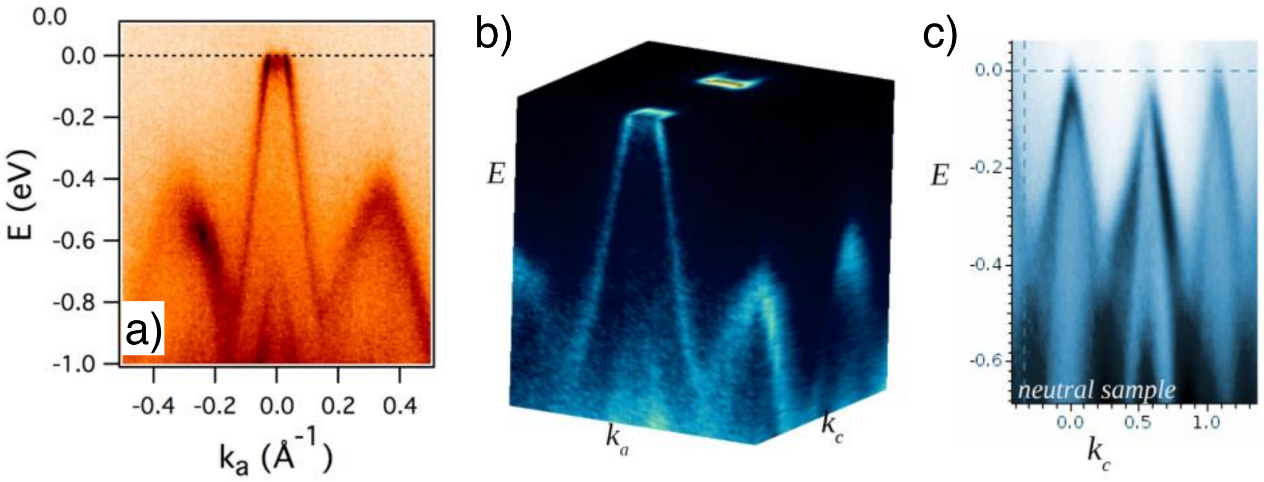
ZrTe5 state of the art

- Gap is ~20 meV at 4.5 K, band structure is very close to linear near BZ center
- ~50 mg single crystals can be grown at Brookhaven
- 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 expertise and machinery to do this



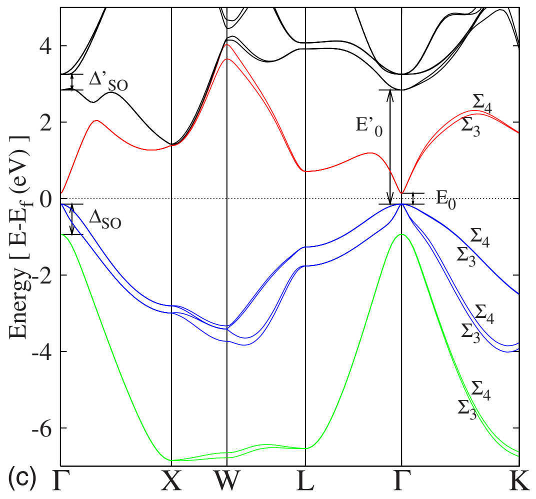


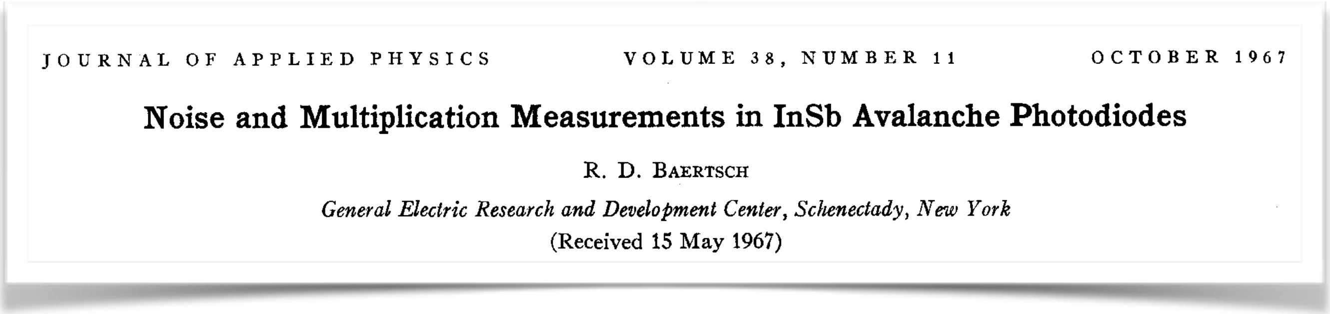




In the meantime: InSb APD

- 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 our own device at UIUC, test at Fermilab, calculate DM sensitivity
- Novel elements: **cryogenic temperatures, SQUID current sensor readout** in linear gain mode

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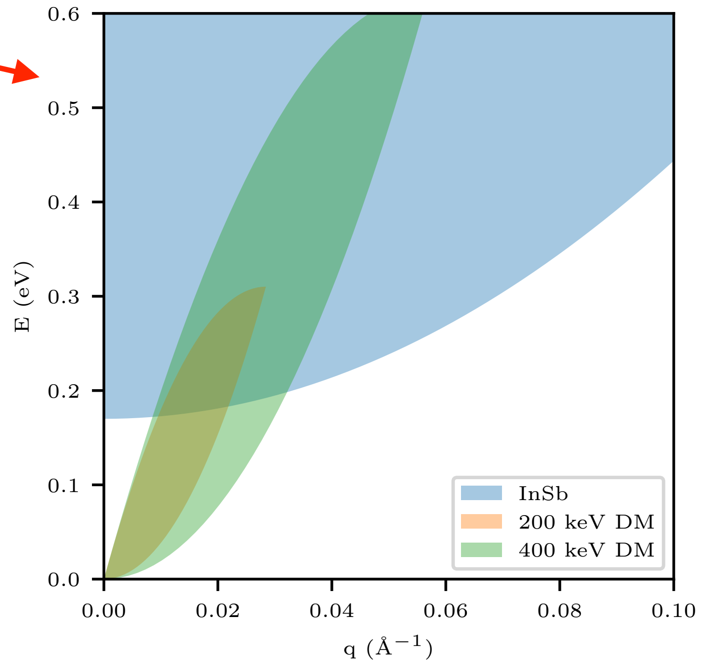
Noise and Multiplication Measurements in InSb Avalanche Photodiodes

R. D. Baertsch

General Electric Research and Development Center, Schenectady, New York

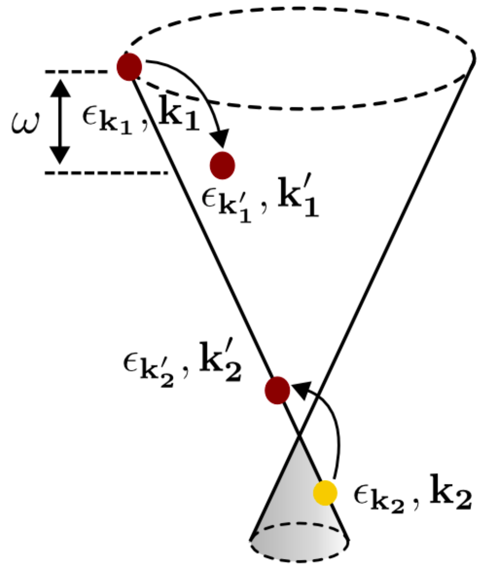
(Received 15 May 1967)



Future prospects (i.e. years 3-4 of our proposal)

- Optimize readout: exponential or linear gain? Impact ionization efficiency? Quenching circuit? Temperature dependence of afterpulsing?
- Prototype calibration with CO_2 laser (117 meV) at 300 mK
- Background mitigation strategy: exploit daily and annual modulations
- Dark rate measurements with **goal of 1/day at 10 mK for 1g target mass** after isotropic background subtraction

Carrier Multiplication (Inter-band)



Absorption

$|\mathbf{q}| \ll \omega$