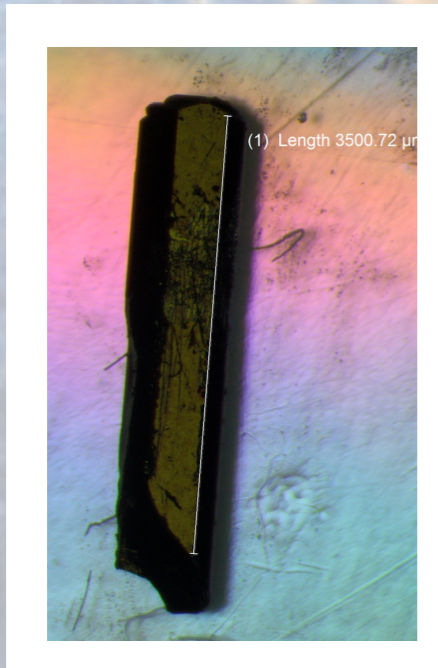
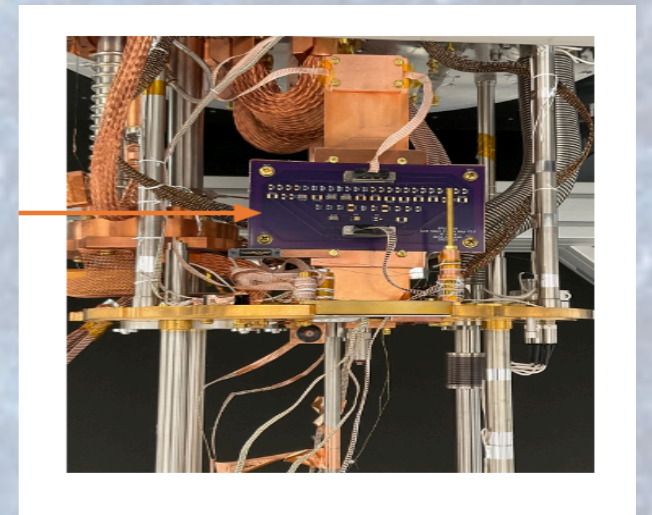


# SPLENDOR: Narrow-gap semiconductors for light DM



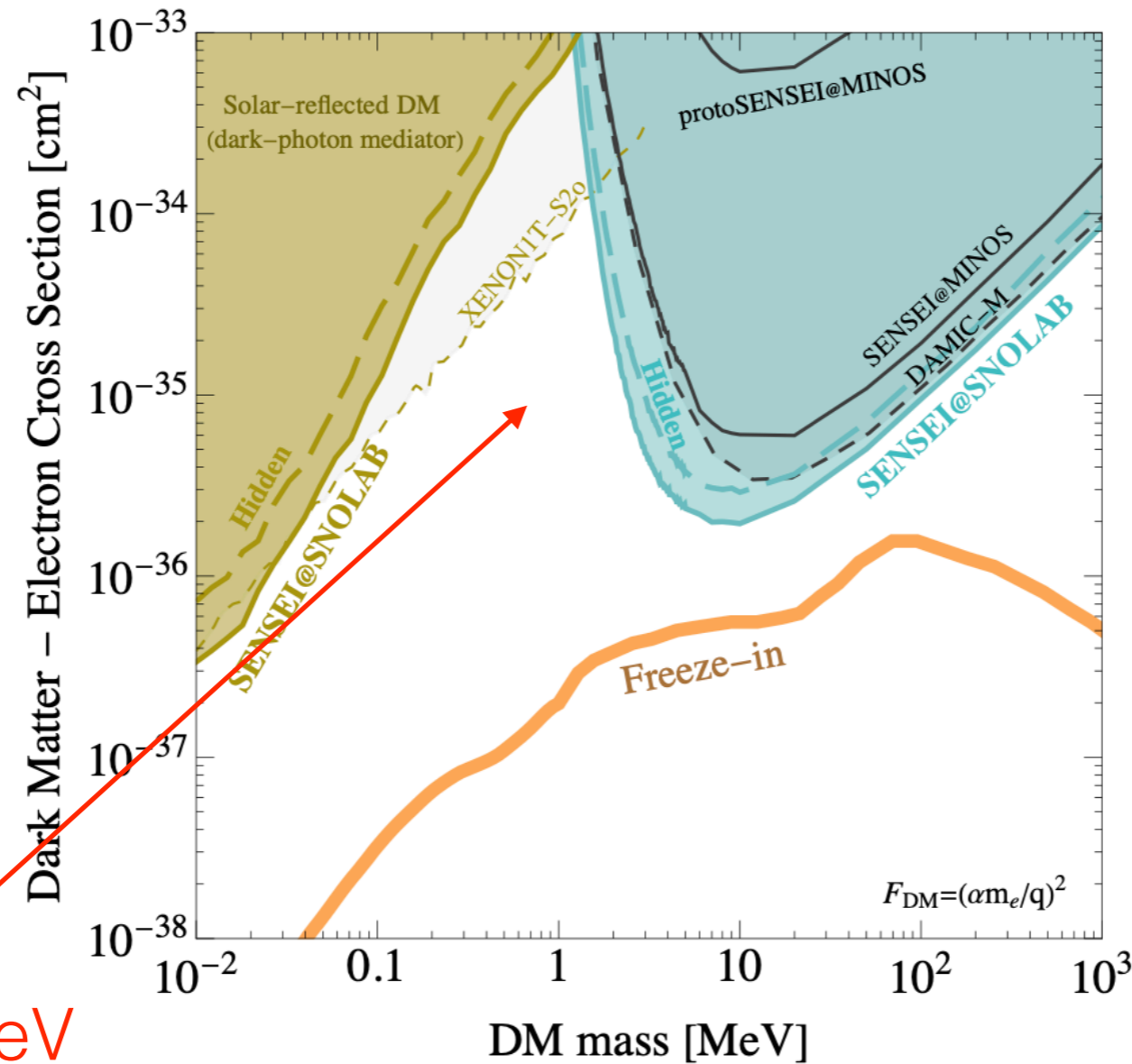
Yoni Kahn (UIUC)



CETUP\*, 6/24/24

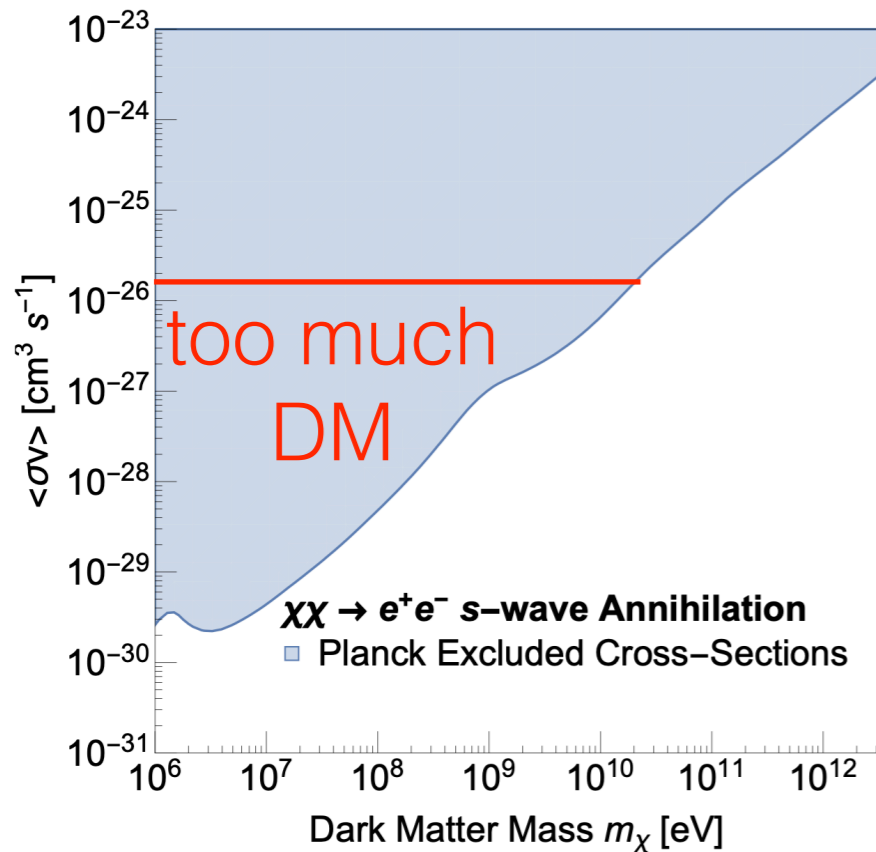


# Sub-GeV DM: we are approaching our targets!

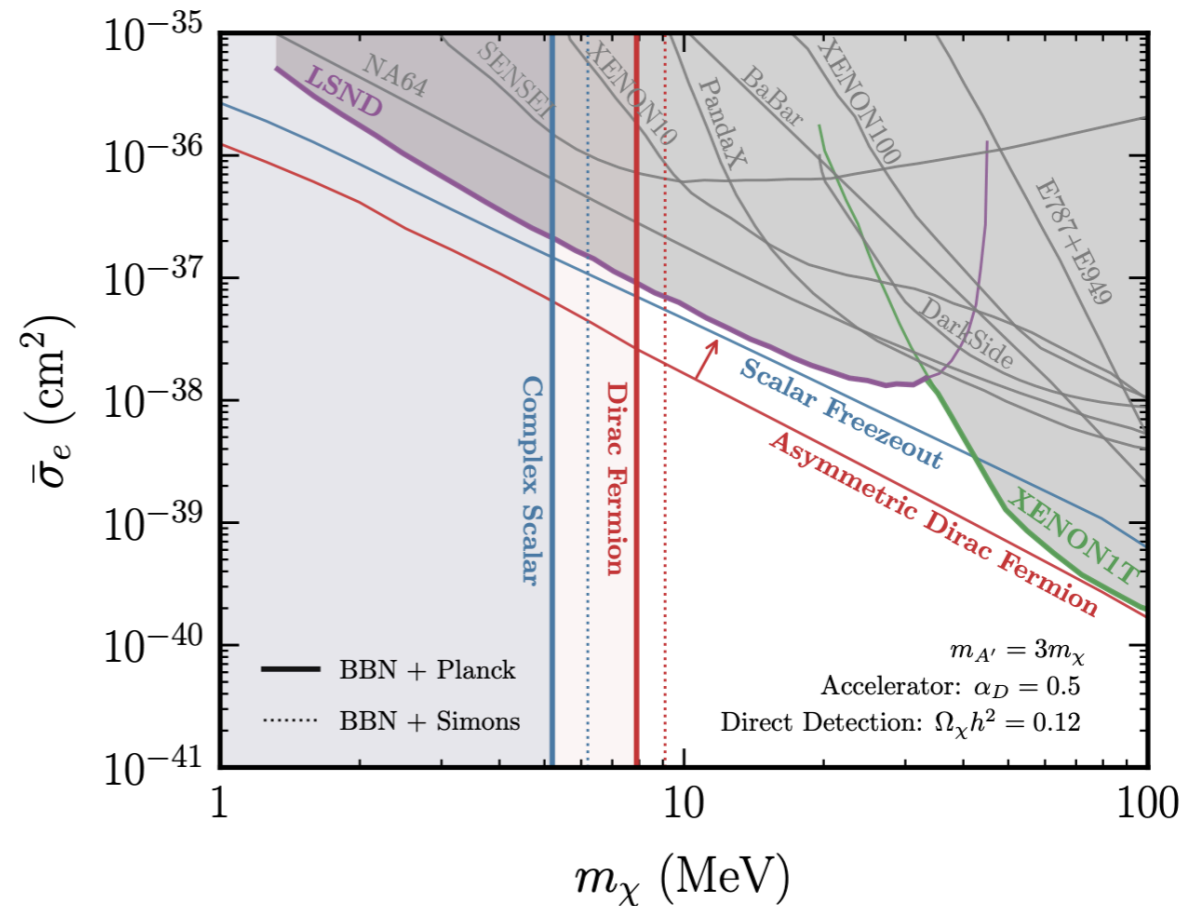


but so far  $< 1$  MeV  
is wide open

# Sub-GeV DM: a universe of constraints



One in a billion late-time DM annihilations would ionize half the universe!

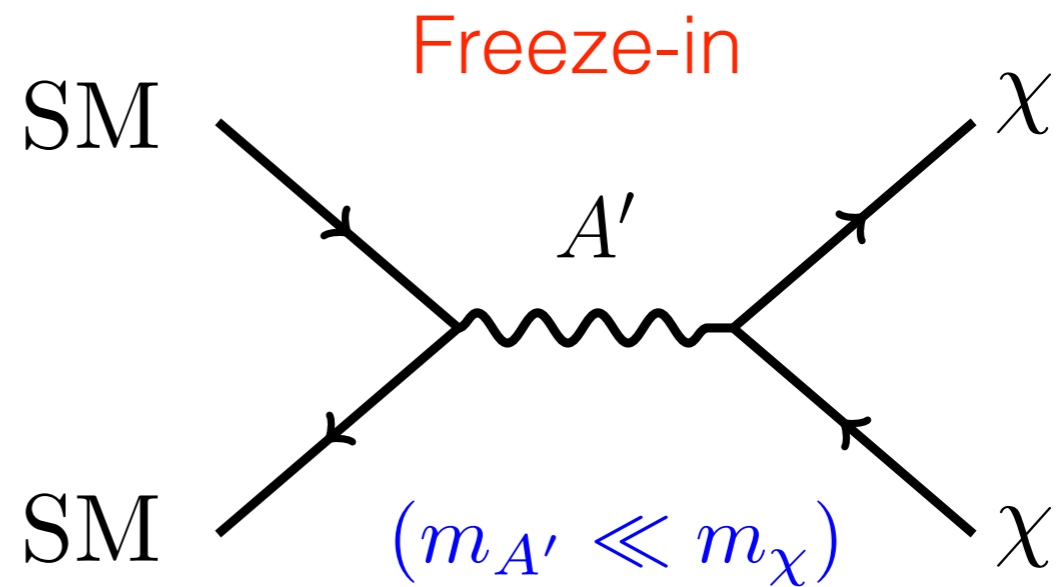
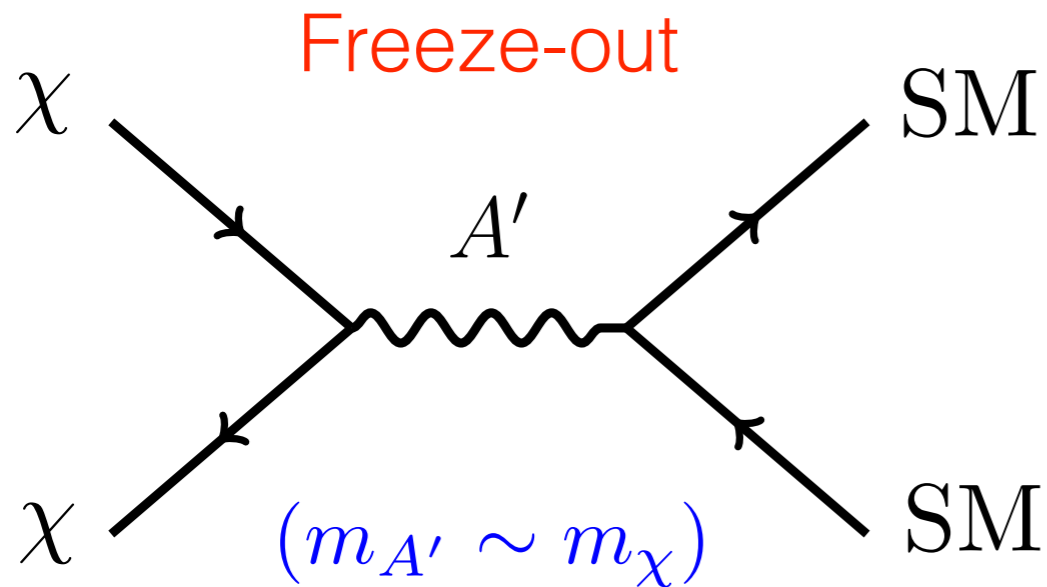


Extra stuff at  $T \sim \text{MeV}$  changes expansion rate of universe during BBN

Need a particle physics model with a consistent thermal history to make sense of experiments

# Dark photon benchmark

$$\mathcal{L} \supset -\frac{m_{A'}^2}{2} A'_\mu A'^\mu + A'_\mu (\kappa e J_{\text{EM}}^\mu + g_D J_D^\mu)$$



DM is a scalar or Majorana fermion,  $m_\chi \gtrsim 5 \text{ MeV}$

DM never in chemical equilibrium:  
no constraints on mass or spin

In both cases, non-relativistic limit is a coupling to charge density:

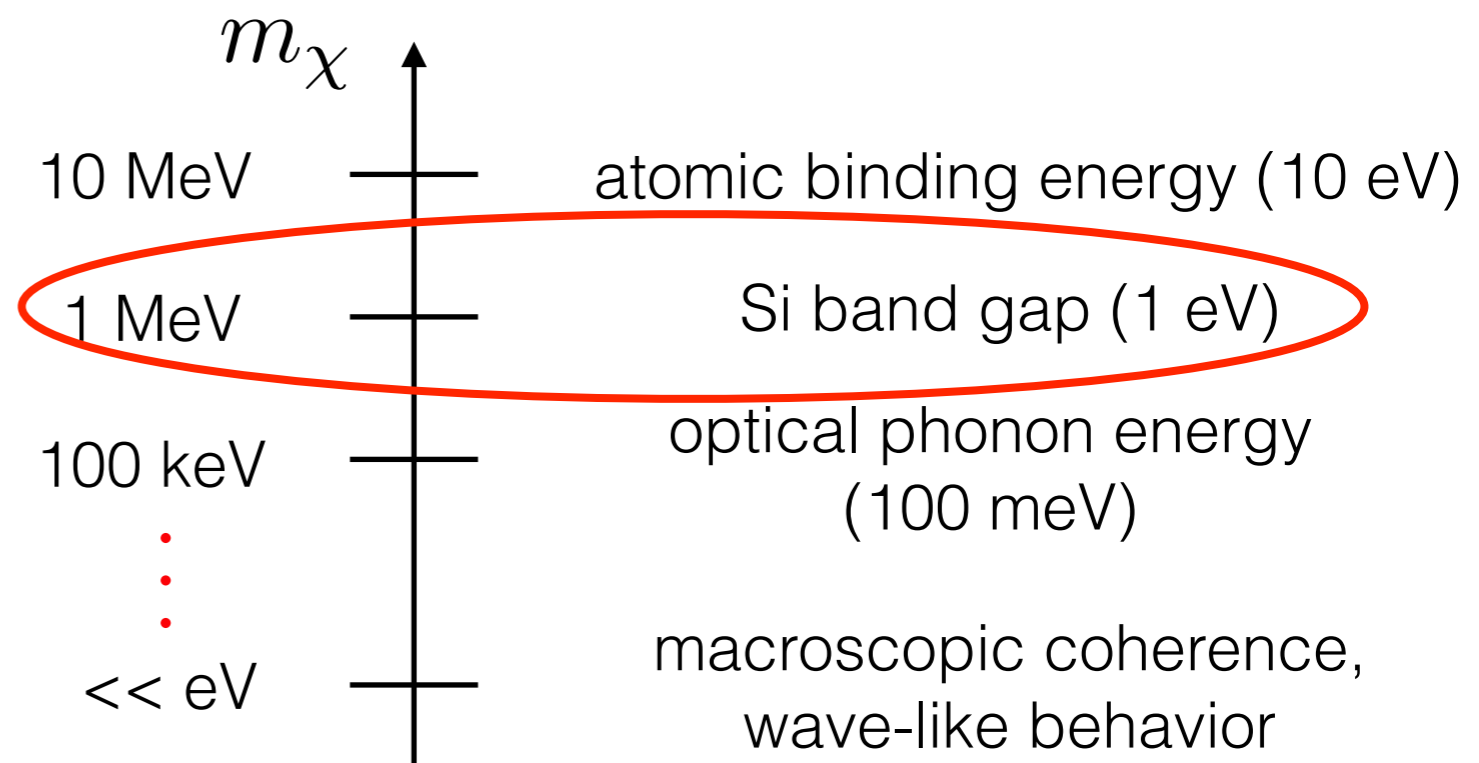
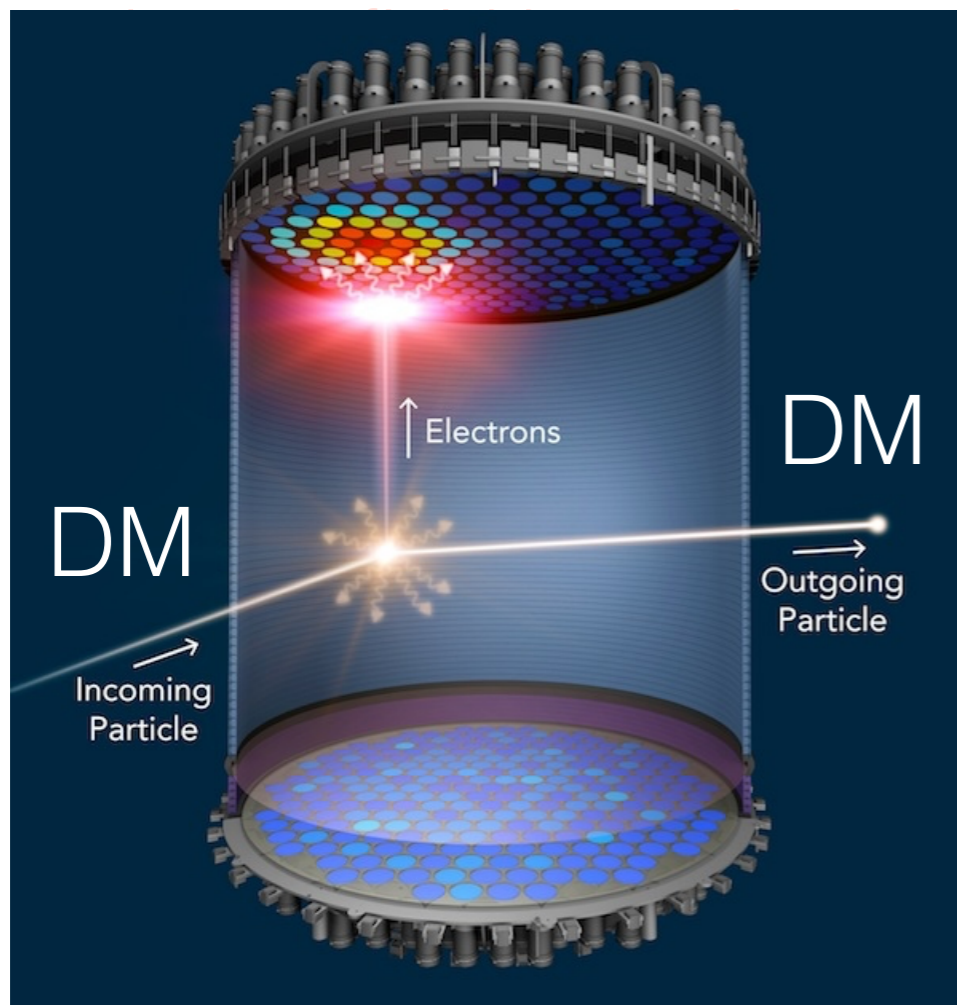
$$\hat{H}_{\text{int}} = \int \frac{d^3 \mathbf{q}}{(2\pi)^3} e^{i\mathbf{q} \cdot \hat{\mathbf{r}}_x} V(\mathbf{q}) \hat{\rho}(\mathbf{q})$$

← Yukawa potential  
← SM charge density

# Is your detector a bag of free particles?

$$v_{\text{DM}} \sim 10^{-3} \implies p_{\text{DM}} \simeq 10^{-3} m_{\text{DM}}, \quad E_{\text{DM}} \simeq 10^{-6} m_{\text{DM}}$$

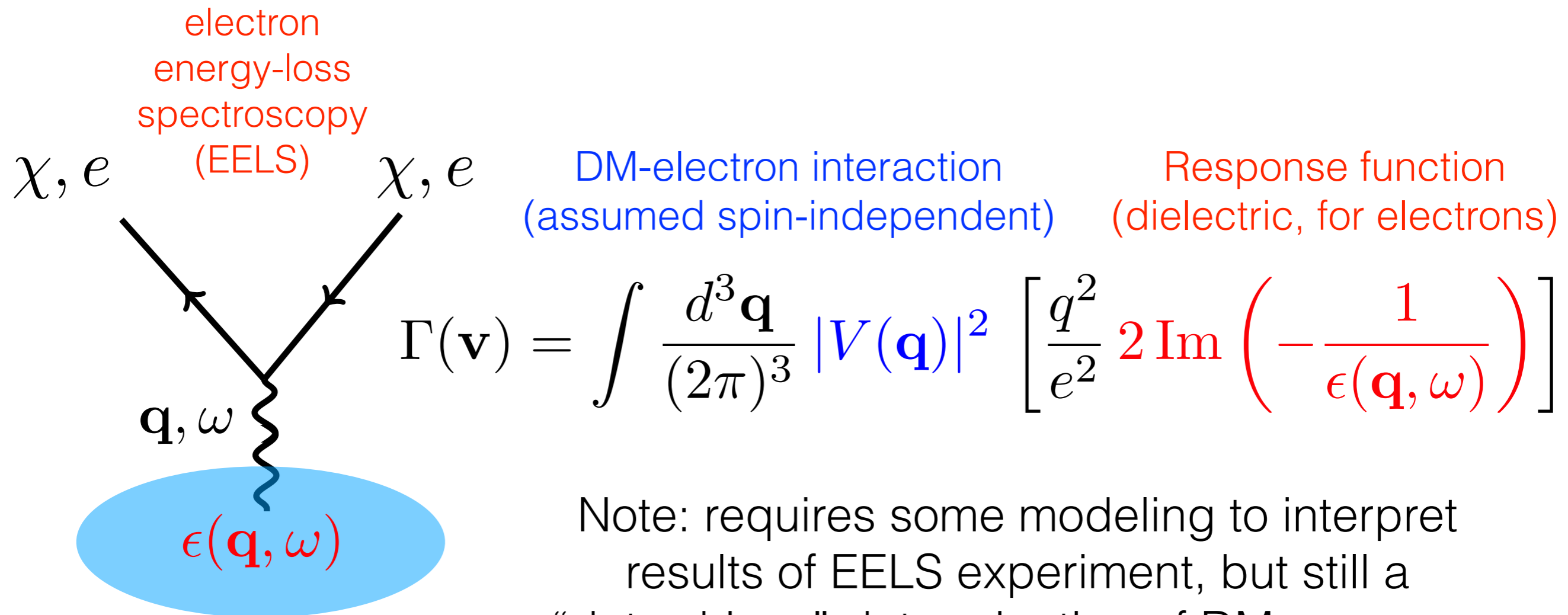
“Free” =  $E_{\text{DM}}, p_{\text{DM}}$  are the largest scales in the system.



Sub-MeV detection via electron scattering: novel materials!

# Measuring electron response

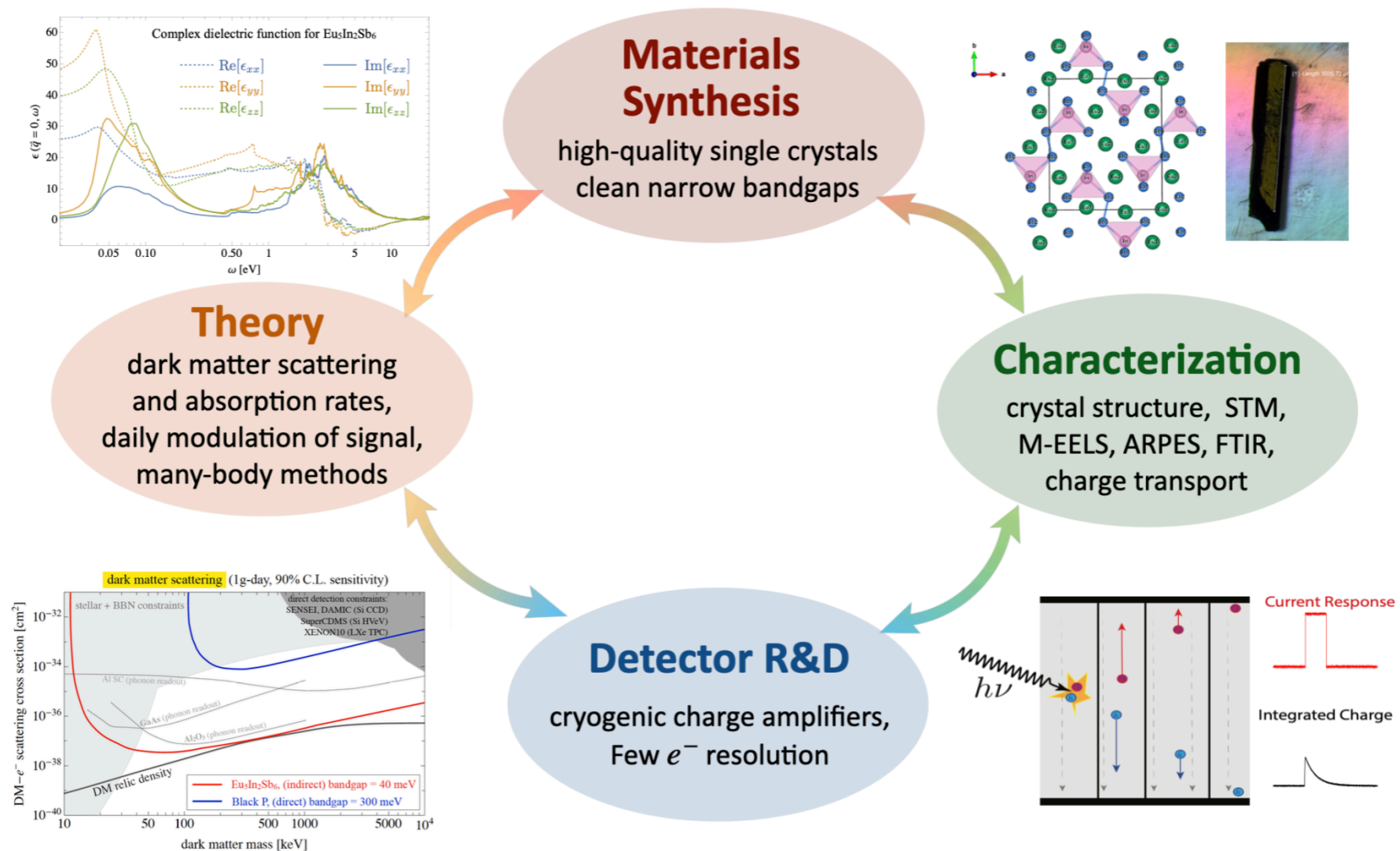
Just like deep inelastic scattering lets us measure strong QCD effects with QED probes, electrons can act as “proxy” for DM



Note: requires some modeling to interpret results of EELS experiment, but still a “data-driven” determination of DM response






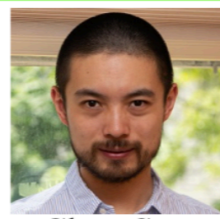







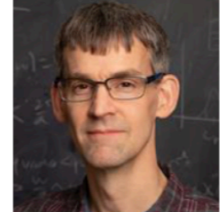
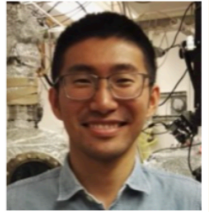














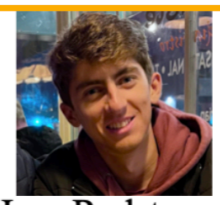
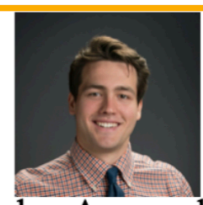
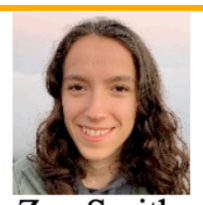
# The SPLENDOR program

Search for **P**articles of **L**ight dark matt**E**r with **N**arrow-gap semicon**D**uct**O**rs




Goal: sub-MeV DM-electron scattering at the freeze-in target via charge detection in sub-eV-gap materials

# The SPLENDOR team

<b>Theory</b>										
	Daniele Alves LANL, T-2	Michael Graesser LANL, T-2	Jianxin Zhu LANL, T-4	Chris Lane LANL, T-4	Liz Peterson LANL, T-4	Chen Sun LANL, T-2	Yoni Kahn UIUC	Christian Boyd UIUC		
	<b>Materials</b>									
		Priscila Rosa LANL, MPA-Q	Filip Ronning LANL, IMS	Nick Sirica LANL, CINT	Matthew Cook LANL, MST-16	Theresa Kucinski LANL, MST-16	Peter Abbamonte UIUC	Jin Chen UIUC	Cat Kengle UIUC	
		<b>Detector R&amp;D</b>								
			Sean Thomas LANL, MPA-Q	Pinghan Chu LANL, P-1	Ralph Massarczyk LANL, P-1	Andrea Albert LANL, P-1	Caleb Fink LANL, MPA-Q	Betty Young Santa Clara U	Arran Phipps CSUEB	Noah Kurinsky SLAC
										
			Wanyi Nie LANL, CINT	Sam Meijer LANL, NEN-2	Alex Leder LANL, P-1	Jita Mazumdar LANL, P-1	Sam Watkins LANL, P-1	Ivar Rydstrom Santa Clara U	Jadyn Anczarski SLAC	Zoe Smith SLAC

POSTDOC  
  STUDENT

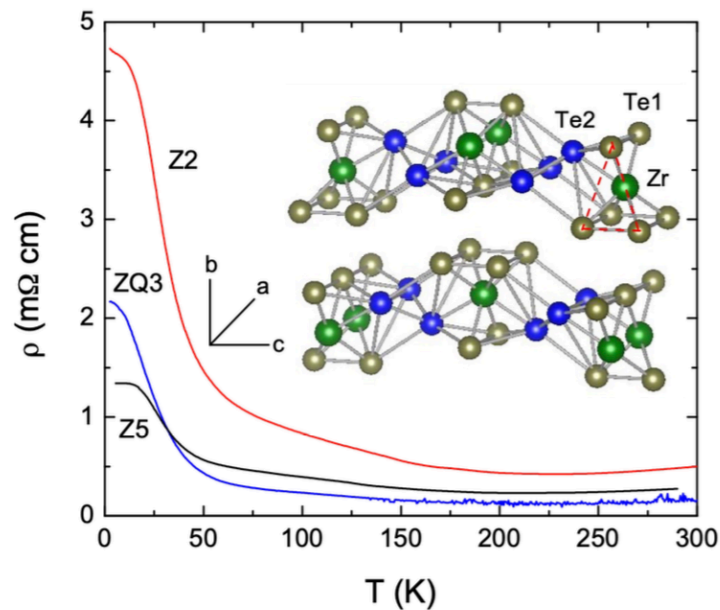


Amazing work by all of these people, won't cite everyone by name in this talk: **this is a true team effort!**



# Materials synthesis: candidates

linear scale

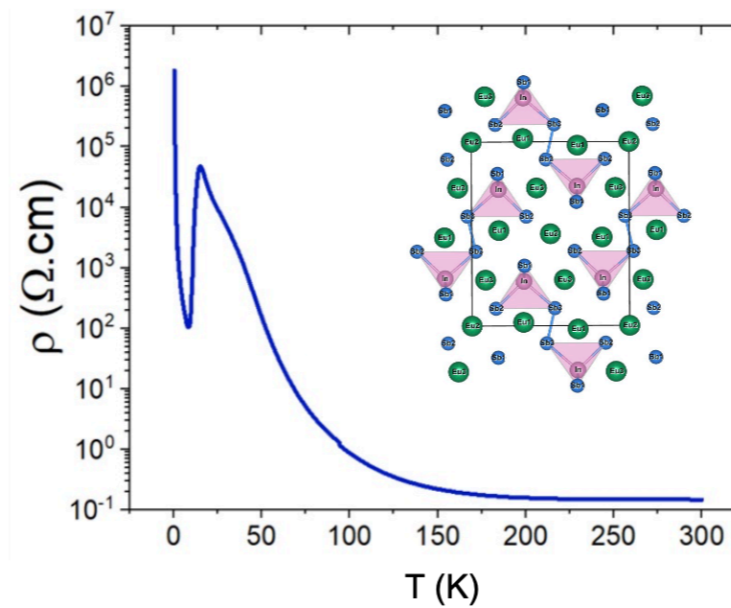


**ZrTe<sub>5</sub>**

factor of **10** increase in resistivity from 300 K → 10 K, indicating in-gap impurities and high dark currents

B. Xu *et al.*, *Phys. Rev. Lett.* **121**, 2018

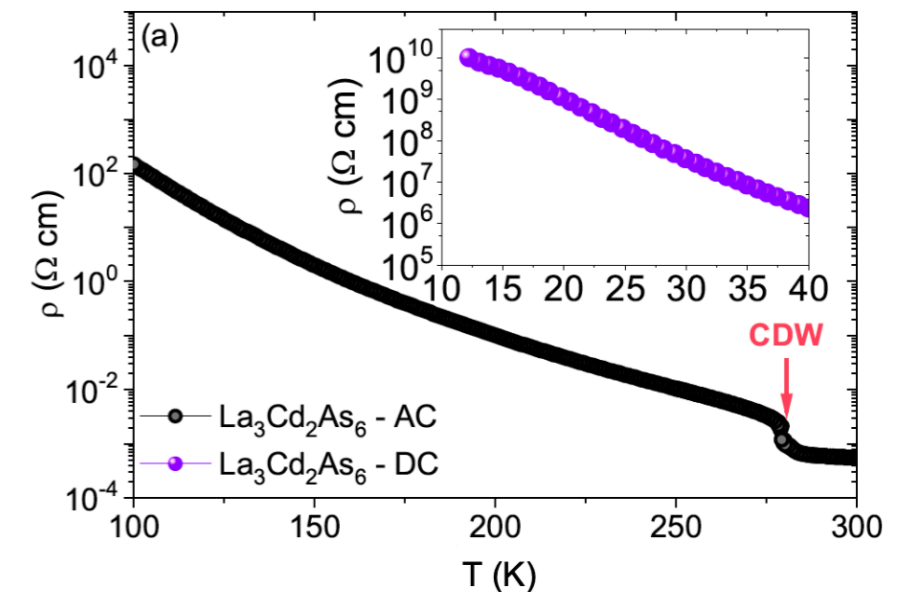
log scale!!



**Eu<sub>5</sub>In<sub>2</sub>Sb<sub>6</sub>**

factor of **10<sup>7</sup>** increase in resistivity from 300 K → 10 K, indicating clean gap and strongly suppressed dark currents

PFS Rosa, SM Thomas, ..., F Ronning, *npj Quantum Materials* **5**, 52 (2020).



**La<sub>3</sub>Cd<sub>2</sub>As<sub>6</sub>**

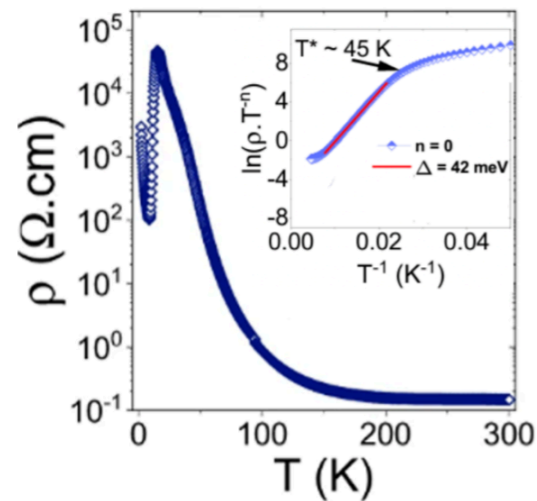
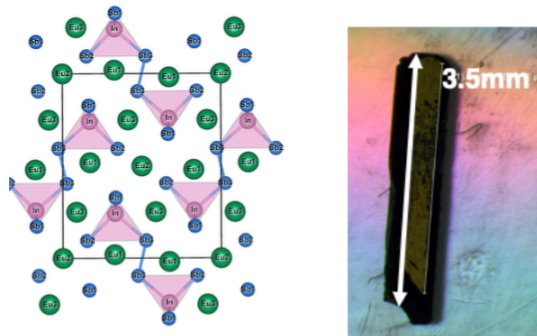
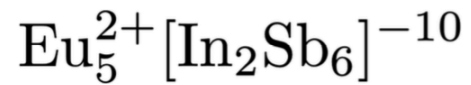
factor of **10<sup>14</sup>** increase in resistivity from 300 K → 10 K, indicating clean gap and strongly suppressed dark currents

MM Piva, SM Thomas, ..., F Ronning, PFS Rosa, *Chemistry of Materials* **33**, 4122 (2021).

When we first went looking for a narrow-gap material, ZrTe<sub>5</sub> seemed promising, but these lanthanides are **exponentially** better!

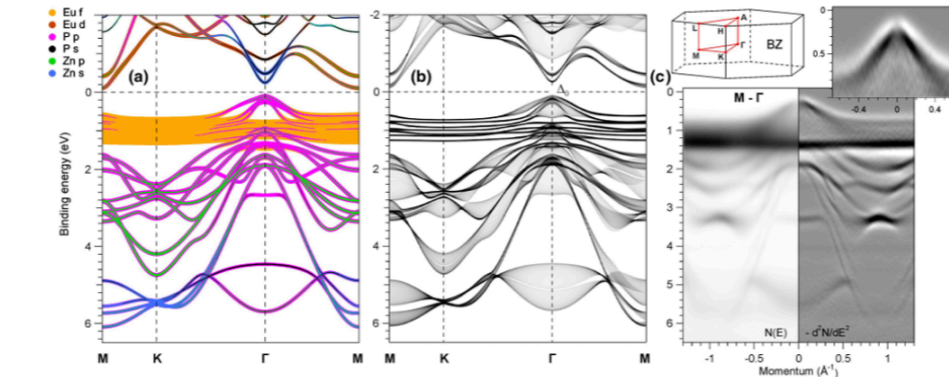
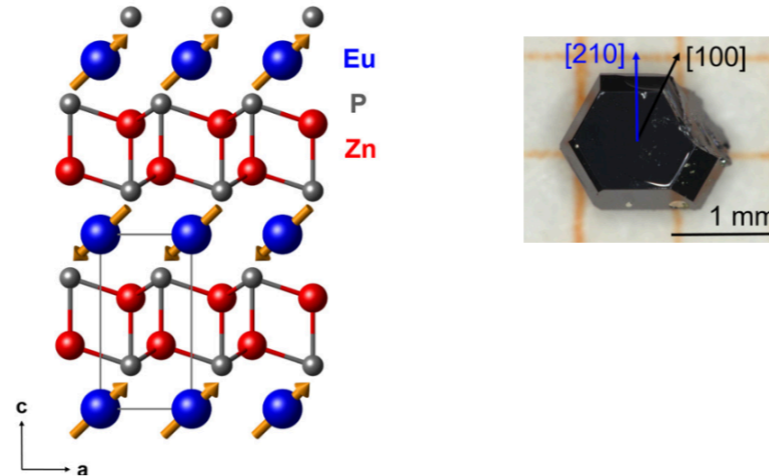
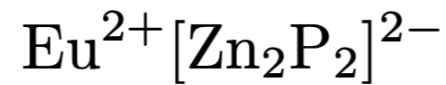
# Materials synthesis: in practice

## Zintl phase (Proposed)



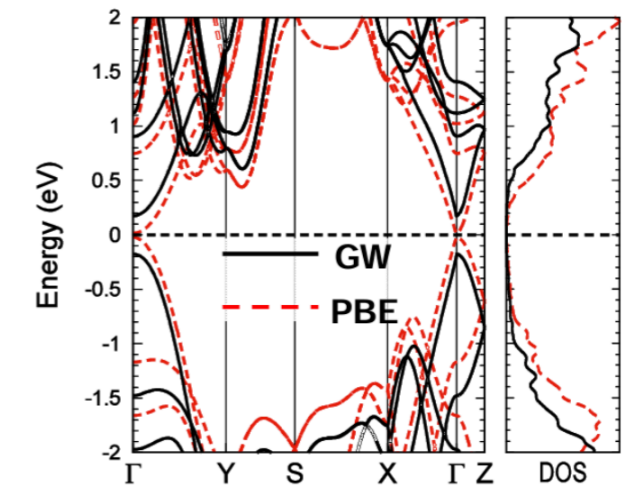
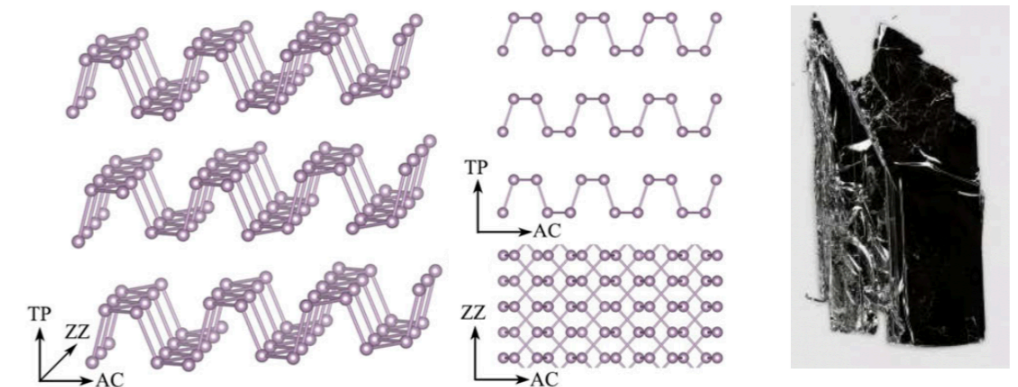
PFS Rosa *et al.*, *npj Quantum Materials* **5**, 52 (2020).

## Zintl phase (Cleavable)



Kreber *et al.* *Phys. Rev. B* **108**, 045116 (2023).

## Black Phosphorus (benchmark)



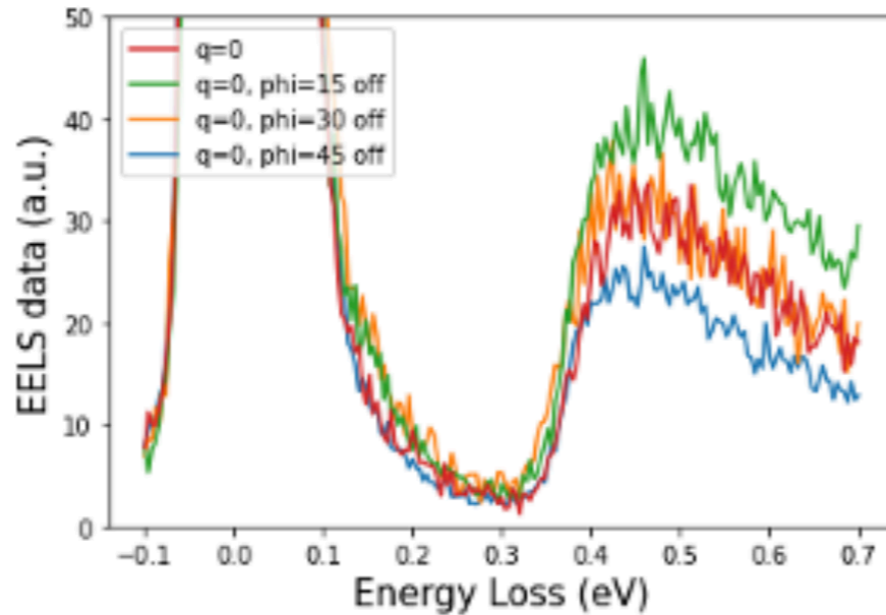
Guan *et al.* *Phys. Rev. B* **94**, 045414 (2016).

All viable for ~gram-scale crystals!

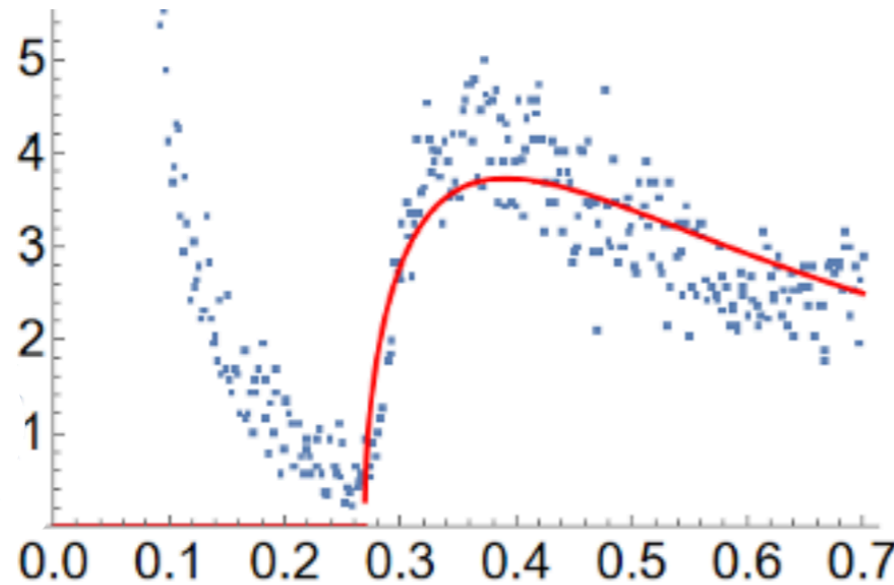
# Characterization: benchmarking

Validate pipeline on black phosphorus (0.3 eV gap):

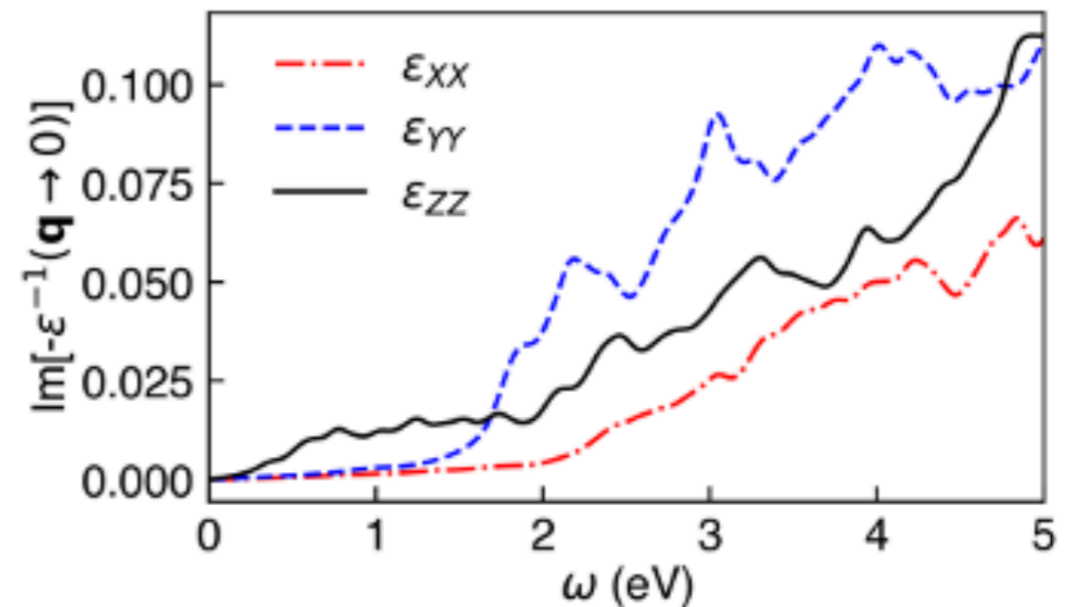
EELS  
( $q = 0$ )



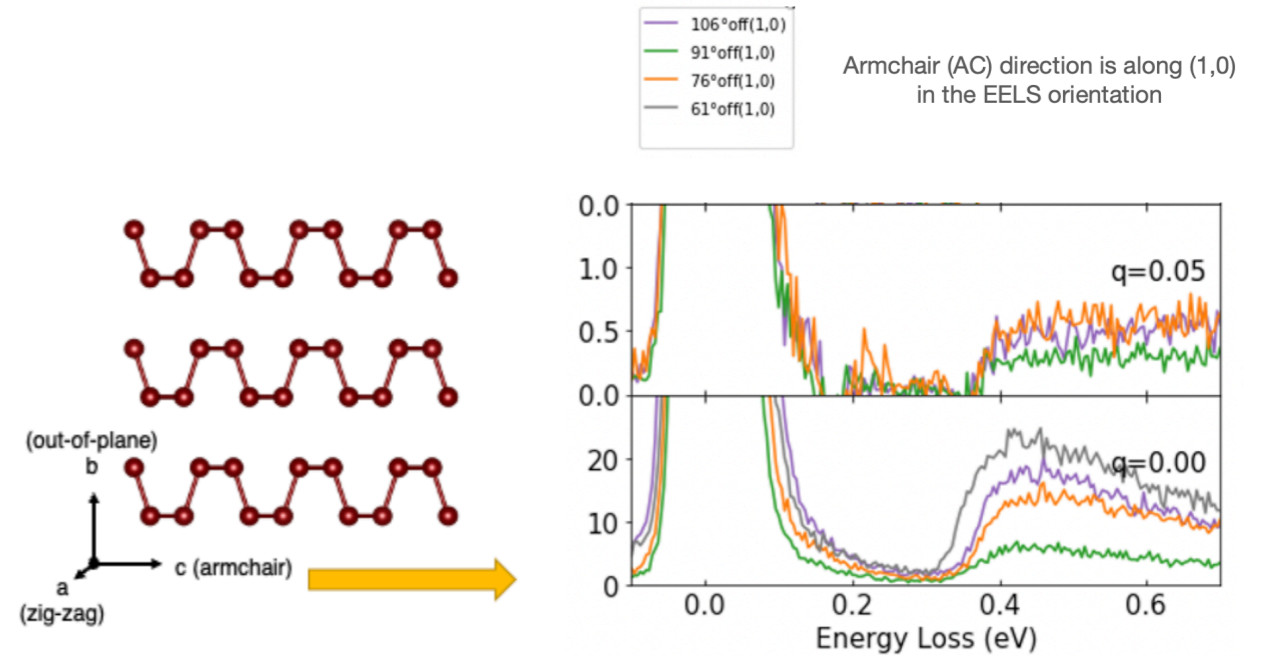
two-band  
model



DFT



EELS (finite  $q$ )



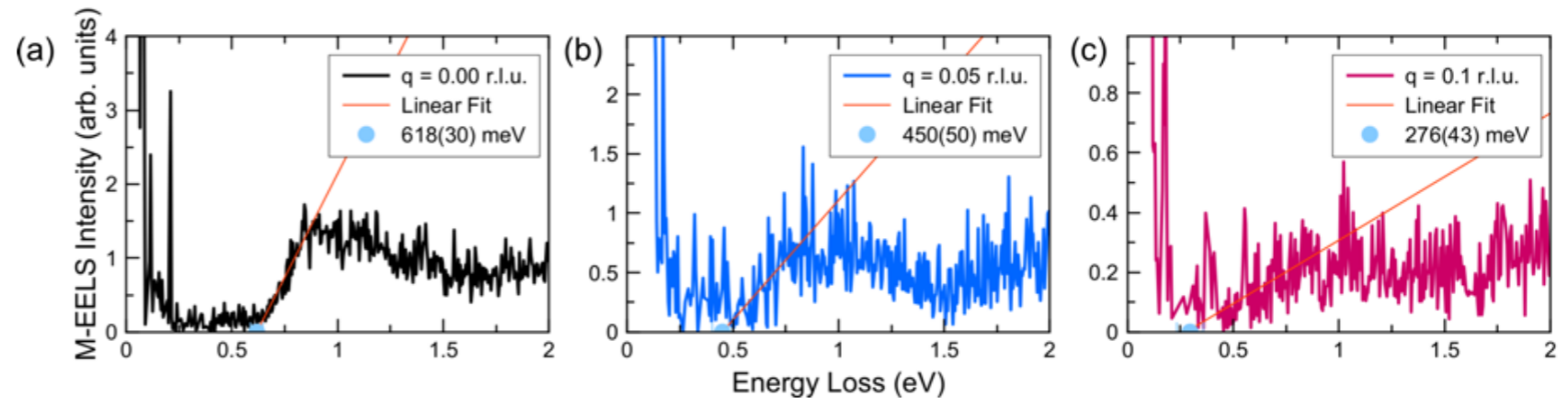
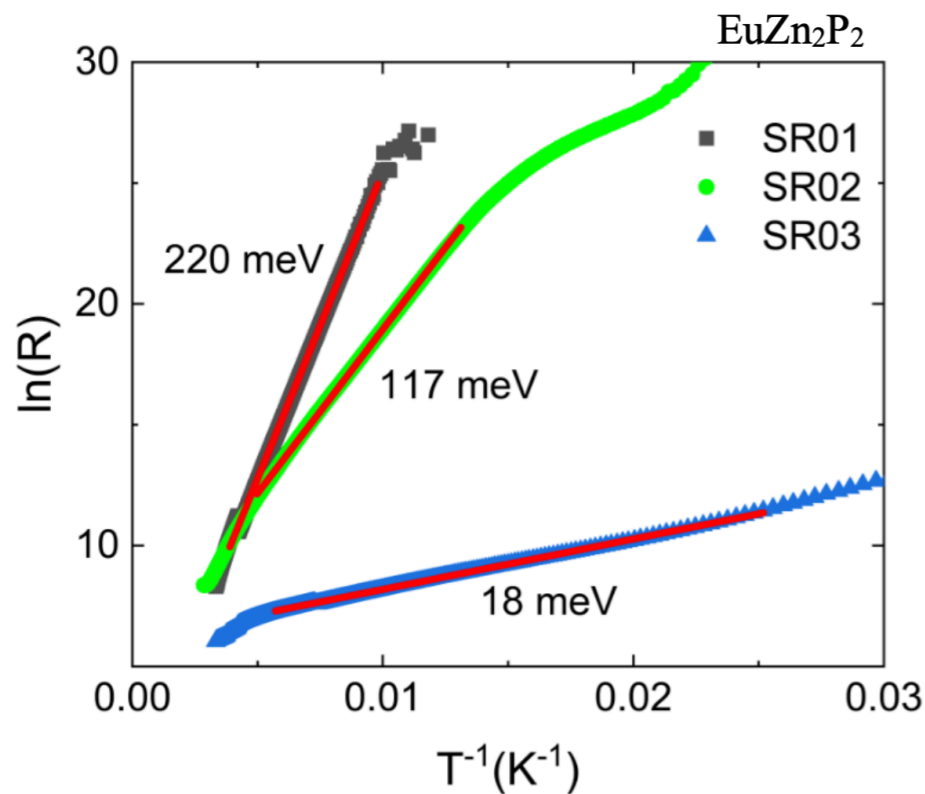
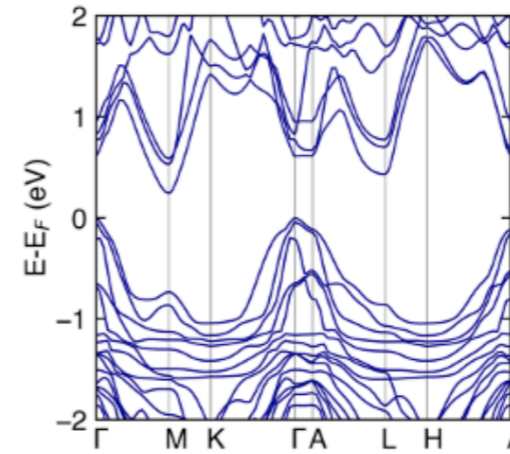
Excellent agreement for both direct gap and anisotropy

# Characterization of $\text{EuZn}_2\text{P}_2$

Pristine  $\text{EuZn}_2\text{P}_2$

$$E_g^{\text{direct}} = 610 \text{ meV}$$

$$E_g^{\text{indirect}} = 244 \text{ meV}$$



EELS nails the direct gap,  
but **indirect gap is tricky**:  
finite momentum probes surface  
rather than bulk

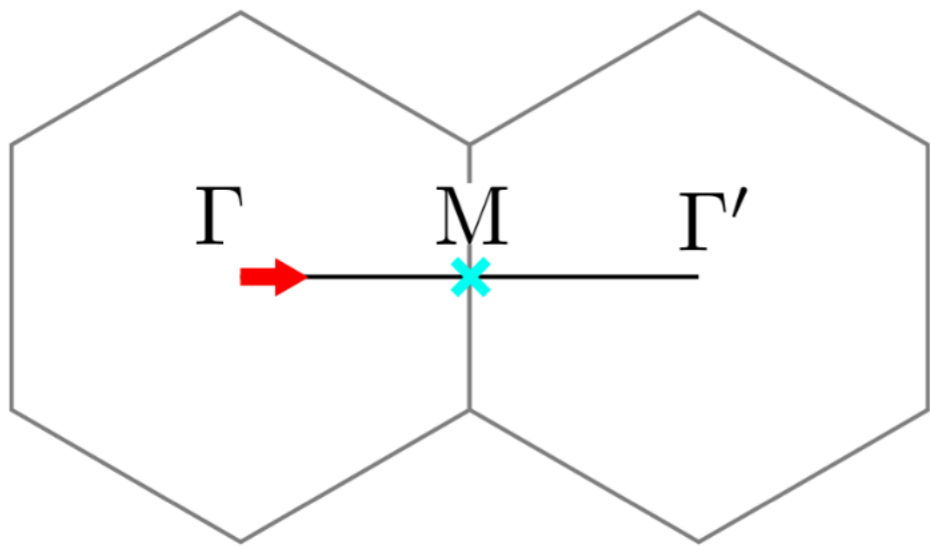
Activated behavior

$$\rho(T) = Ae^{\Delta/k_B T}$$

Lightly doped  
Semiconductors

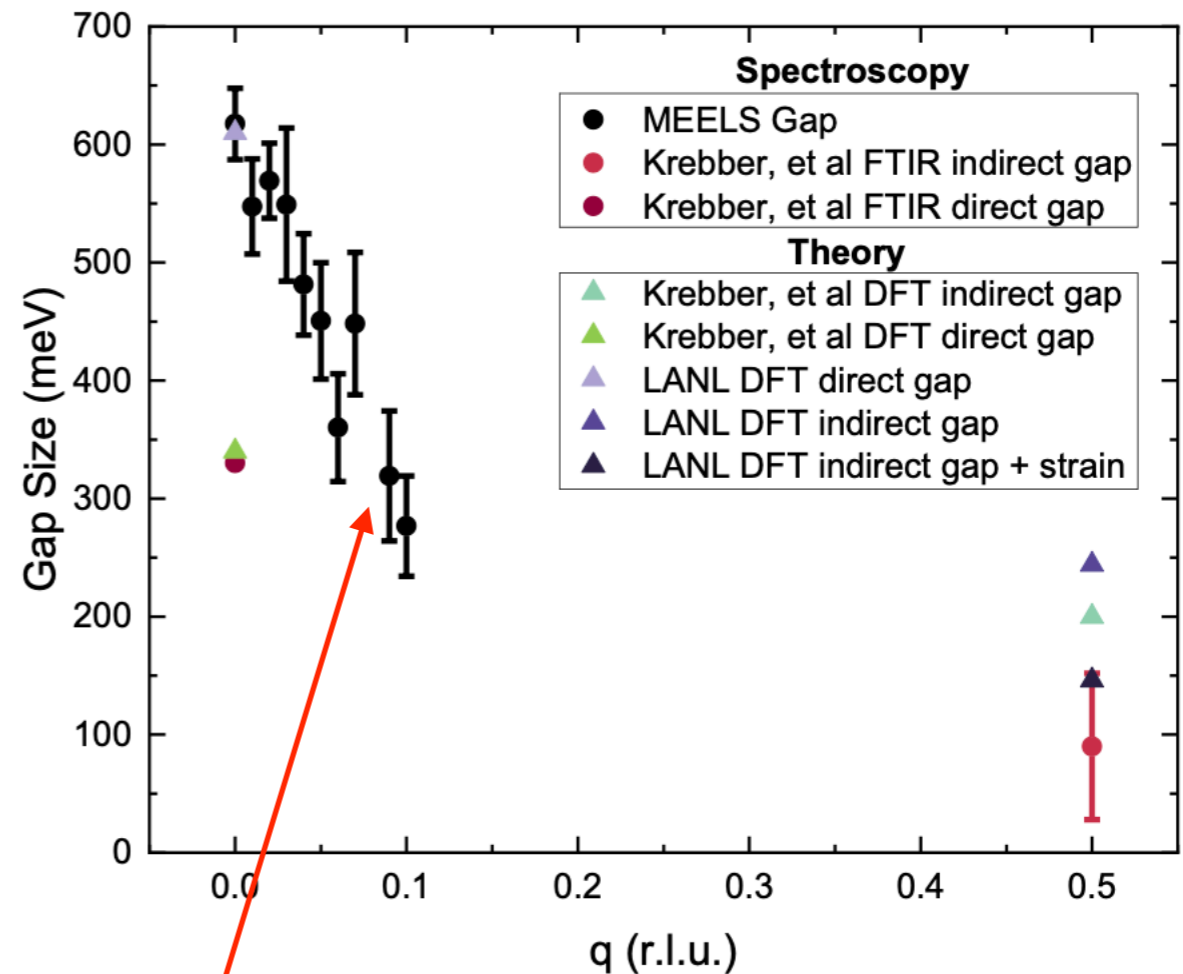
$$\rho(T) = A \exp[(T_0/T)^\beta]$$

# Characterization: band gap



M-EELS q range

DFT predicted indirect gap location



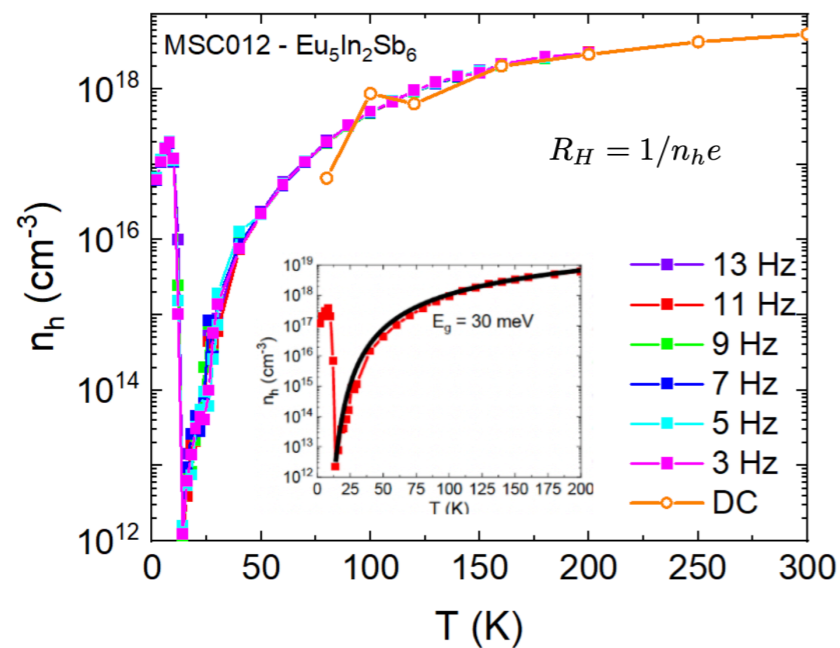
$$q_{\min} = \frac{\omega_{\min}}{v_{\max}} \simeq 36 \text{ eV} \left( \frac{\omega_{\text{gap}}}{100 \text{ meV}} \right)$$

Strategy: validate DFT by measuring direct gap and anisotropy, then use DFT to extract finite-q response relevant for DM scattering

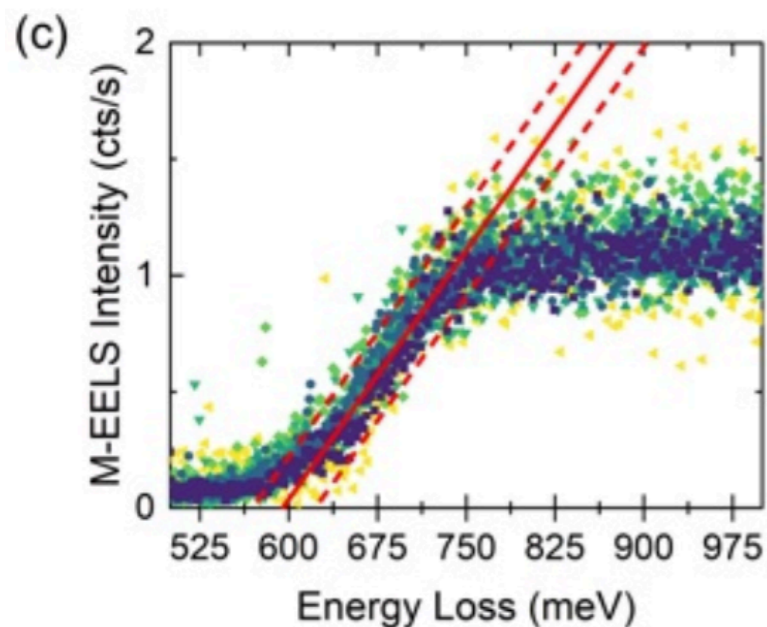
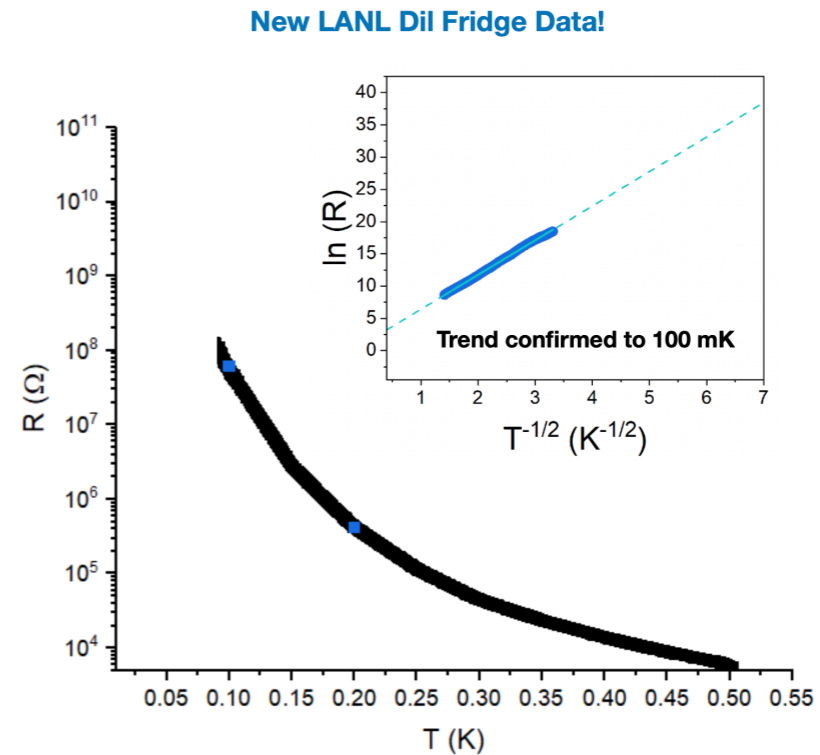
# Characterization of $\text{Eu}_5\text{In}_2\text{Sb}_6$

Hall effect: fit with 30 meV gap

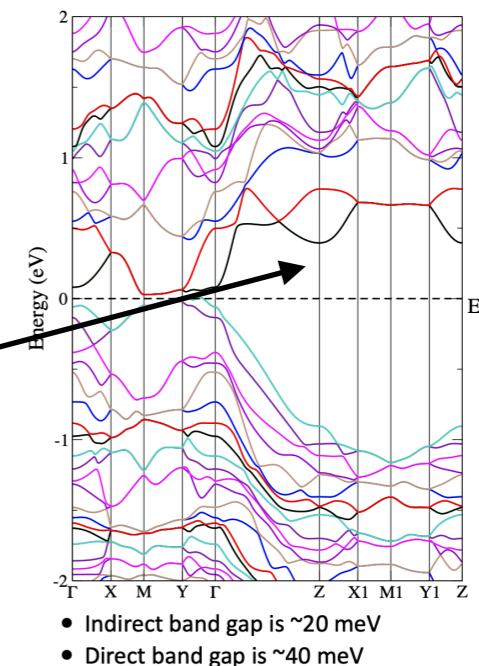
Resistivity is exponential



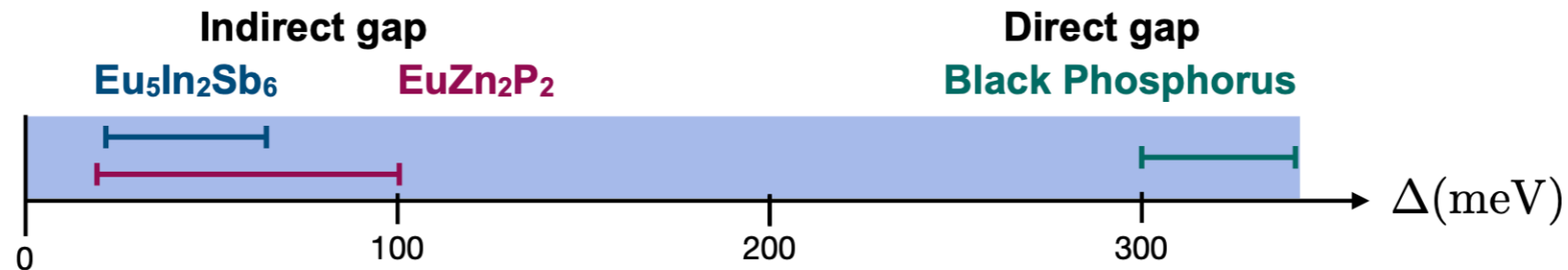
Mobility at 2 K  $\mu_h = \mathcal{O}(10) \text{ V.cm}^2/\text{s}$



Material doesn't cleave well, so EELS only measures a gap averaged over entire BZ



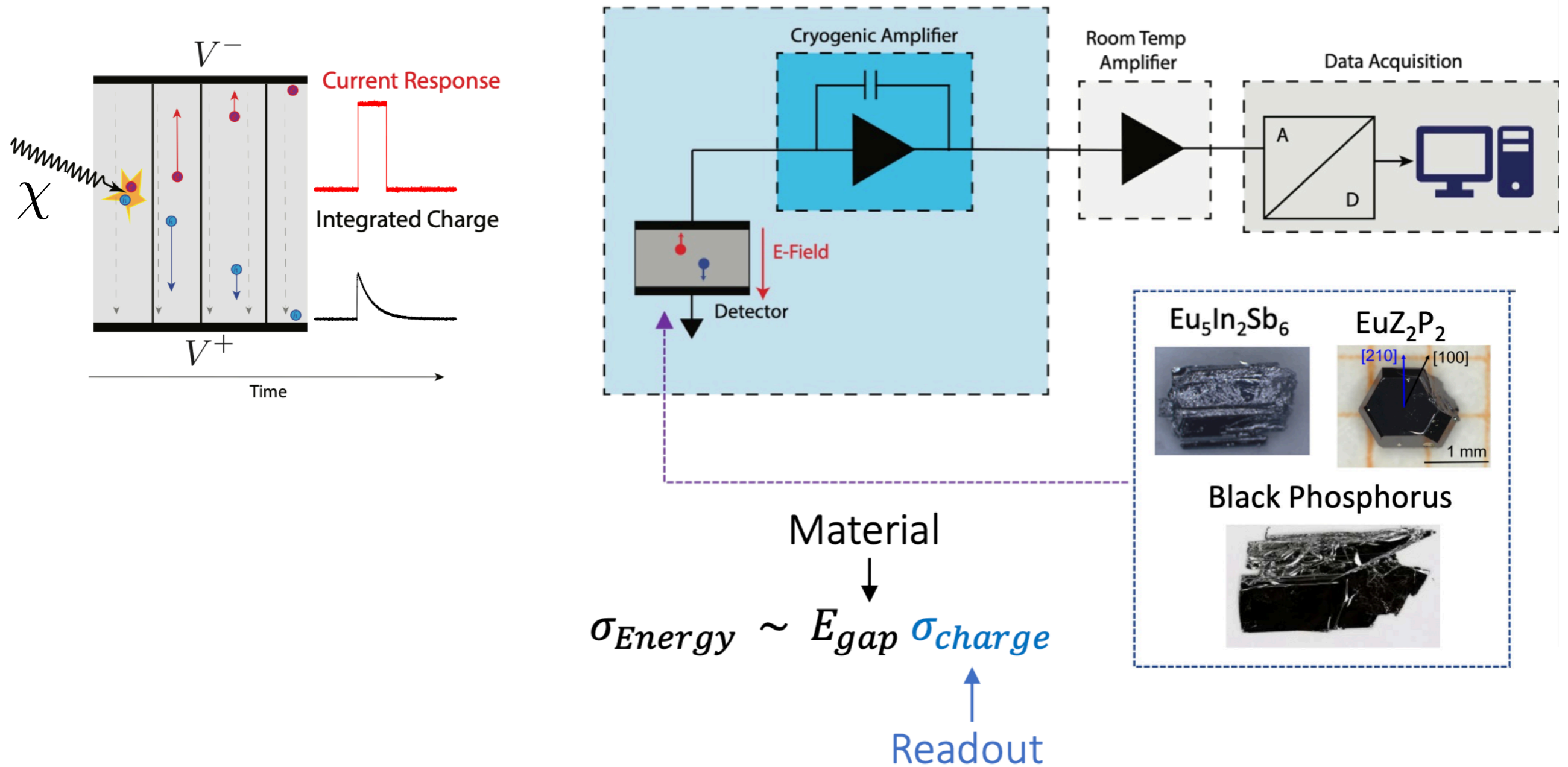
# Characterization: summary



	<b>Eu<sub>5</sub>In<sub>2</sub>Sb<sub>6</sub></b>	<b>EuZn<sub>2</sub>P<sub>2</sub></b>	<b>Black Phosphorus</b>
<b>Mobility</b>	$\mu_h = \mathcal{O}(10) \text{ V.cm}^2/\text{s}$	$\mu_h = \mathcal{O}(1) \text{ V.cm}^2/\text{s}$	$\mu_h = \mathcal{O}(0.1) \text{ V.cm}^2/\text{s}$
<b>Direct Gap (EELS)</b>	600-800meV	620 meV	<b>300 meV</b>
<b>Direct Gap (FTIR)</b>	500 meV	330 meV	<b>340 meV</b>
<b>Direct Gap (Theory)</b>	<b>40 meV</b>	610 meV	<b>300 meV</b>
<b>Indirect Gap (EELS)</b>	Upcoming sputtering/ annealing system for finite-q experiments	Upcoming higher-resolution higher-q experiments	N/A
<b>Indirect Gap (FTIR)</b>	<b>60 meV</b>	<b>90 meV</b>	N/A
<b>Indirect gap (Theory)</b>	<b>20 meV</b>	240 meV (smaller with strain)	N/A
<b>Charge gap (Transport)</b>	<b>42 meV</b>	<b>18 - 100 meV</b>	-

our desired detector material: indirect gap likely 20-60 meV

# Detector concept



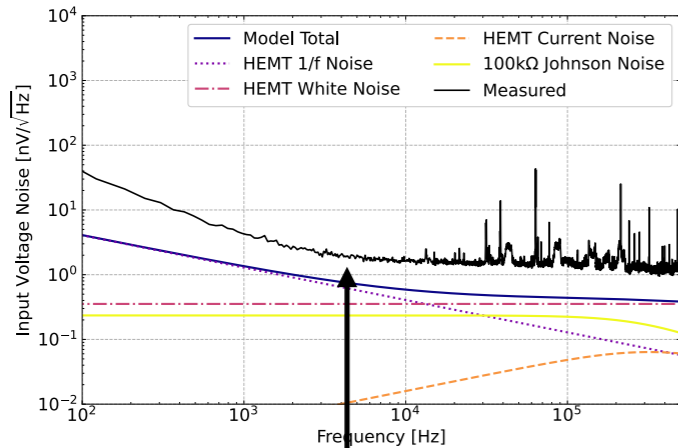
Goal: “universal” capacitive charge amplifier with few e- resolution



# Detector: current status

## Amplifier Prototype Testing

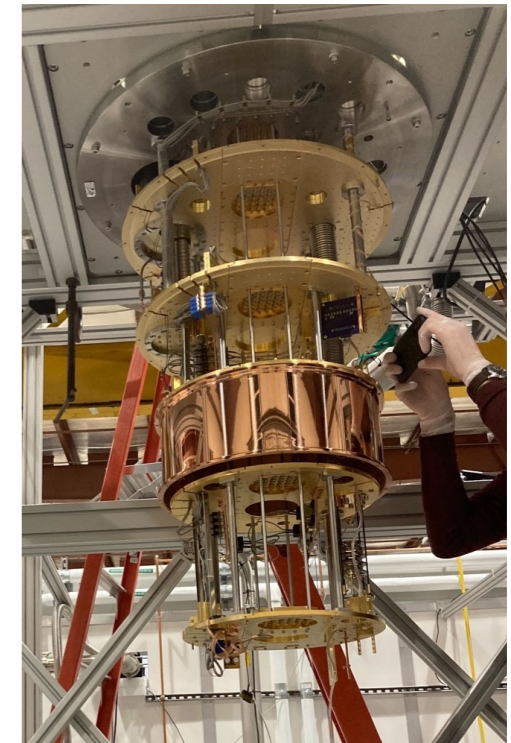
Testing of complete amplifier in dilution refrigerator – **DONE!**



Integrated measured voltage noise across expected capacitance results in charge resolution of 7 electrons

Reduction of EMI should give 2-3 electron resolution!

$$\sigma_{charge} \sim N_V \left( C_{parasitic} + C_{input} + C_{detector} \right) \sim 5-10 \text{ pF}$$



Just put out paper on progress of charge amp!



[arXiv:2311.02229](https://arxiv.org/abs/2311.02229) [physics.ins-det]

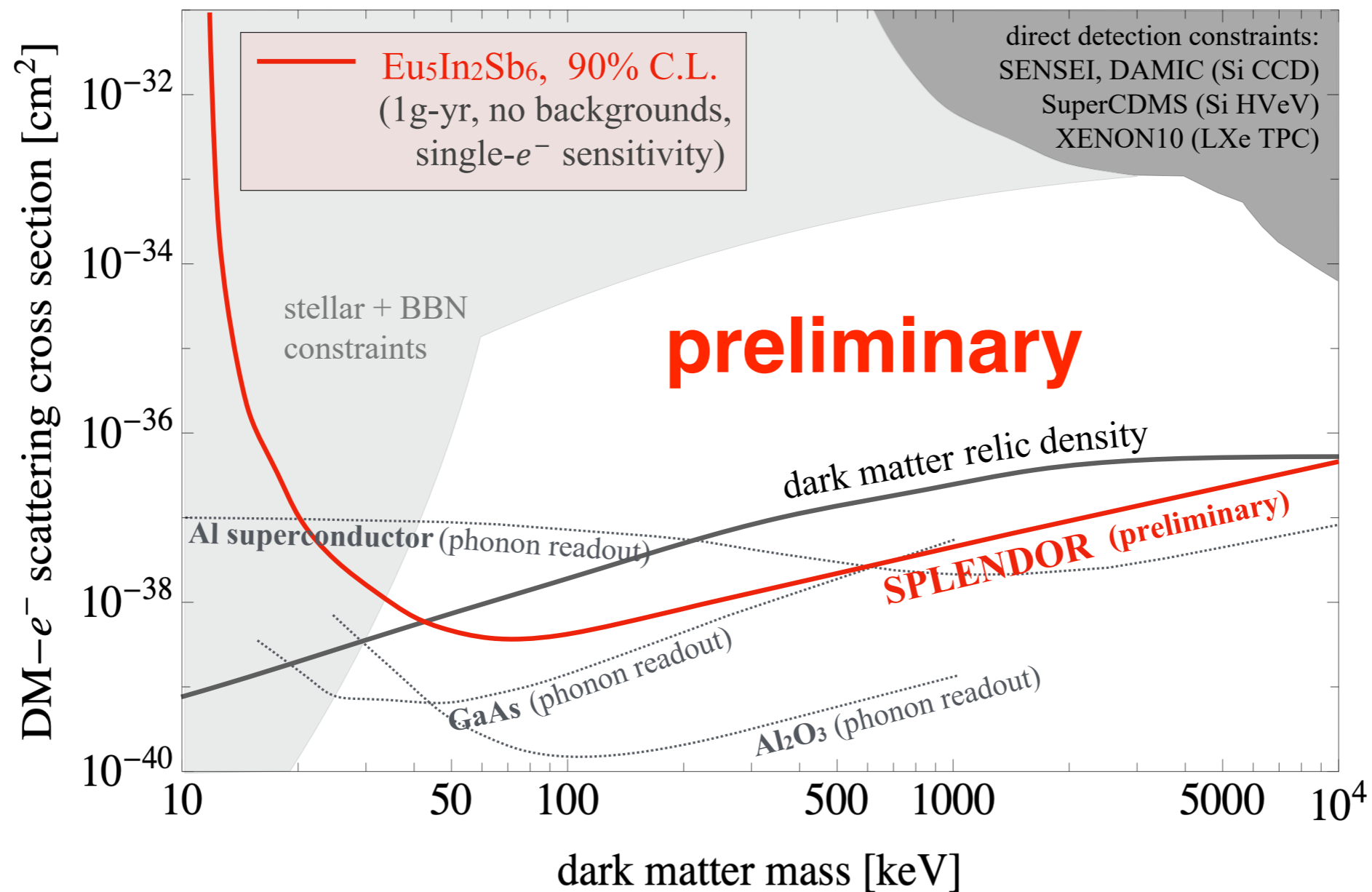
**Two-Stage Cryogenic HEMT Based Amplifier For Low Temperature Detectors**

J. Anczarski,<sup>1,2,3,\*</sup> M. Dubovskov,<sup>4</sup> C. W. Fink,<sup>5</sup> S. Kevane,<sup>1,2,3</sup> N. A. Kurinsky,<sup>2,3</sup> S. J. Meijer,<sup>5</sup> A. Phipps,<sup>6</sup> F. Ronning,<sup>5</sup> I. Rydstrom,<sup>4</sup> A. Simchony,<sup>1,2,3</sup> Z. Smith,<sup>1,2,3</sup> S. M. Thomas,<sup>5</sup> S. L. Watkins,<sup>5</sup> and B. A. Young<sup>4</sup>

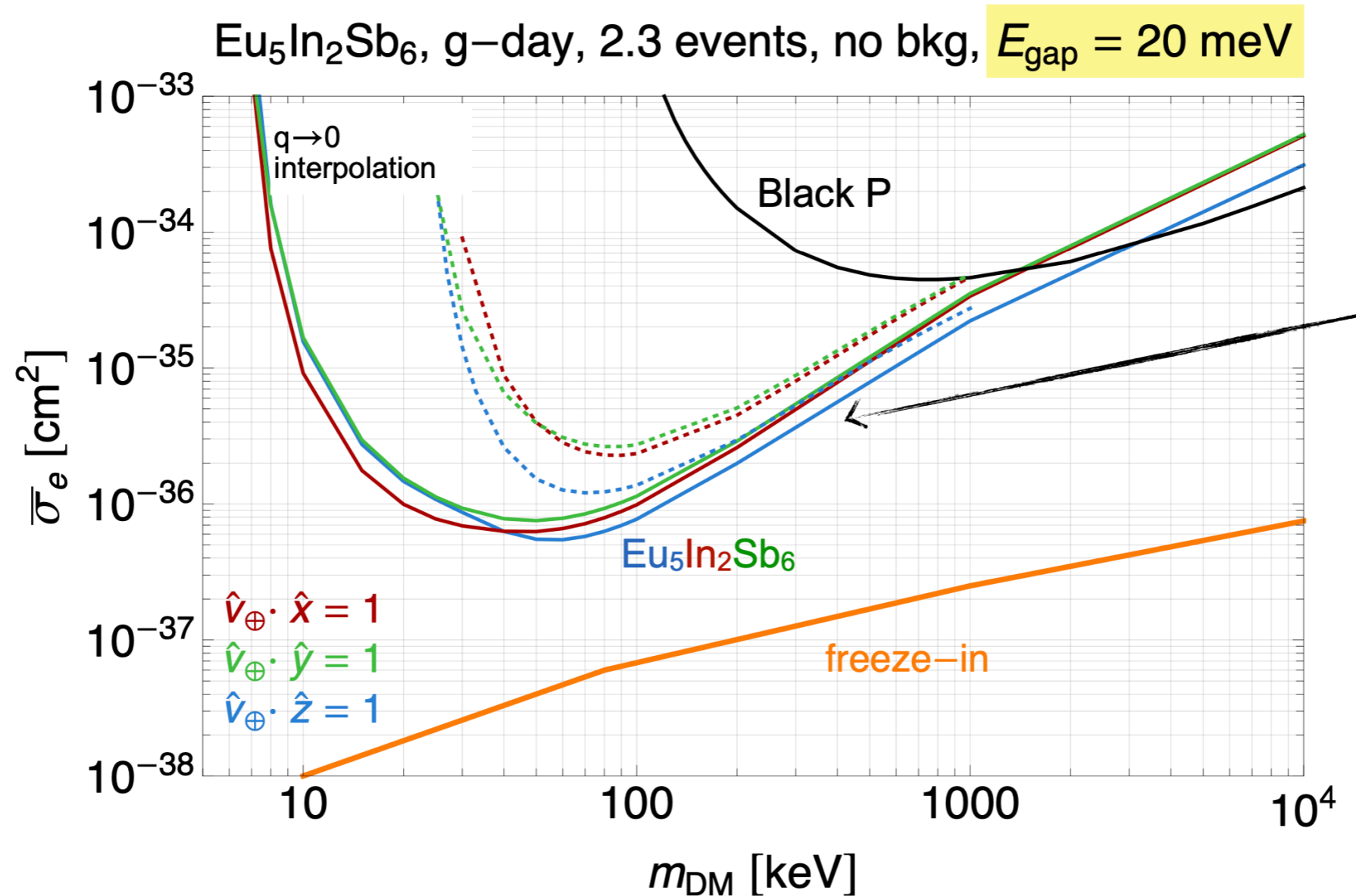
<sup>1</sup>Stanford University, Stanford, CA 94305, USA  
<sup>2</sup>SLAC National Accelerator Laboratory, Menlo Park, CA, 94025, USA  
<sup>3</sup>Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA, 94035, USA  
<sup>4</sup>Santa Clara University, Santa Clara, CA 95053, USA  
<sup>5</sup>Los Alamos National Laboratory, Los Alamos, NM 87545, USA  
<sup>6</sup>California State University, East Bay, Hayward CA 94542, USA

# Theory: reach projections

Assuming 20 meV gap:



# Theory: daily modulation

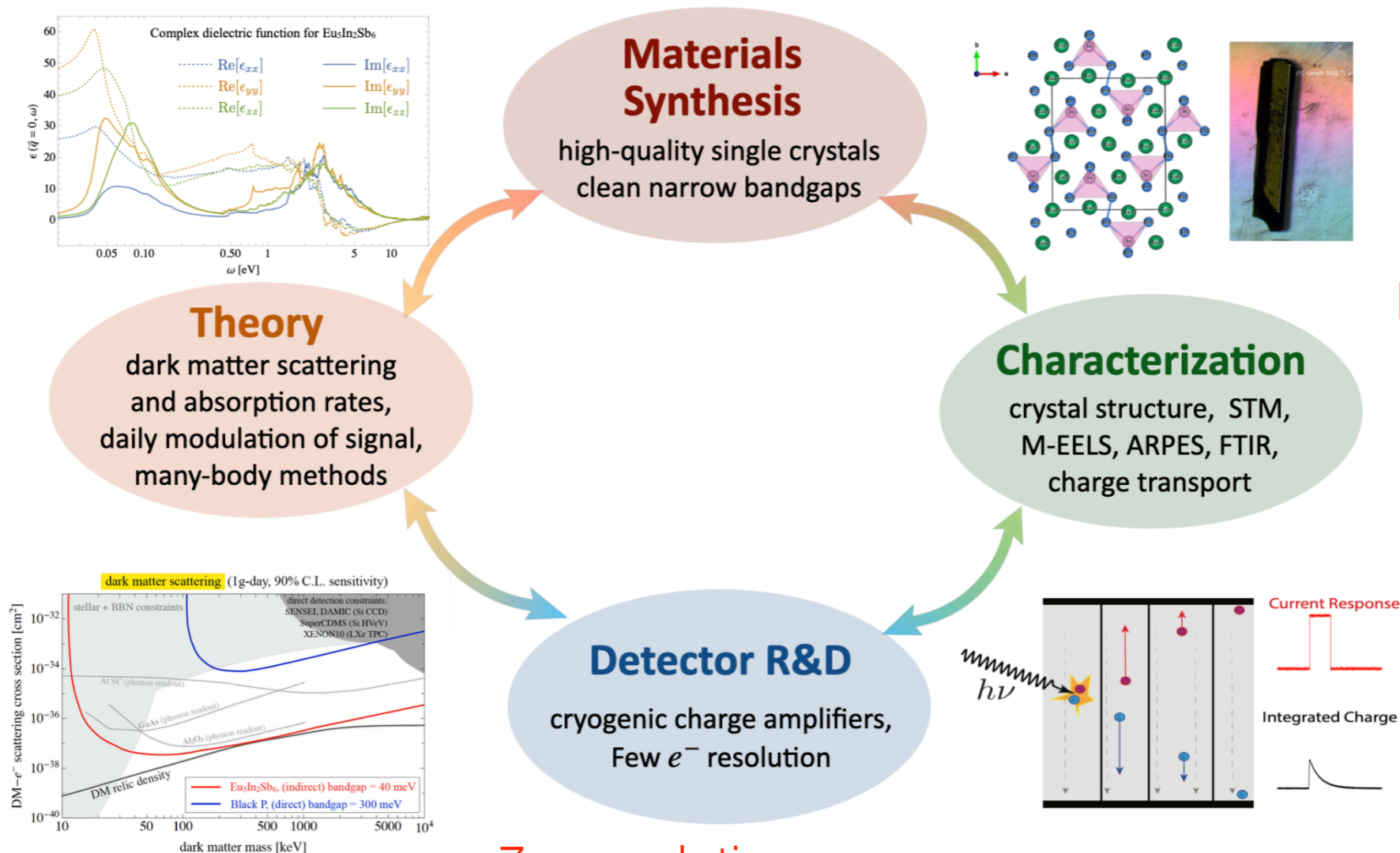


Expect ~20% daily modulation (full calculation forthcoming)

# Conclusion

two candidate materials  
plus commercially-purchased  
benchmark

Potential for  
first DM search  
below 500 keV



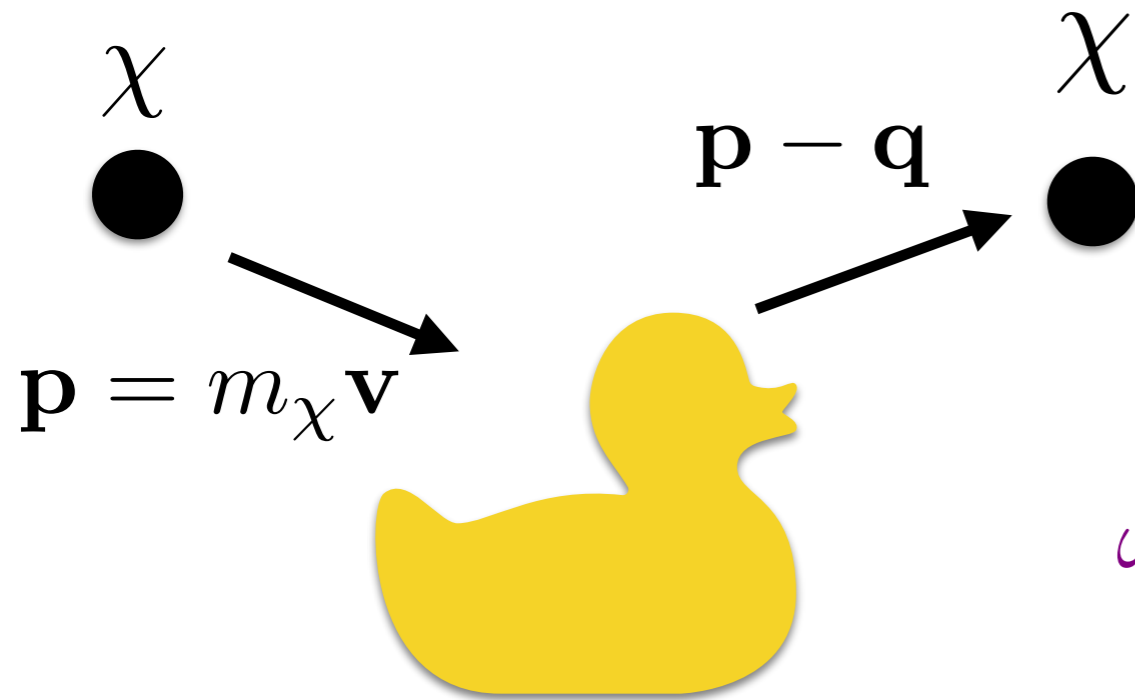
EELS works!  
But must be  
combined  
with theory  
modeling

7 $e^-$  resolution now,  
expect 2 or 3  $e^-$

Paper coming this fall, stay tuned!

Backup

# Response functions



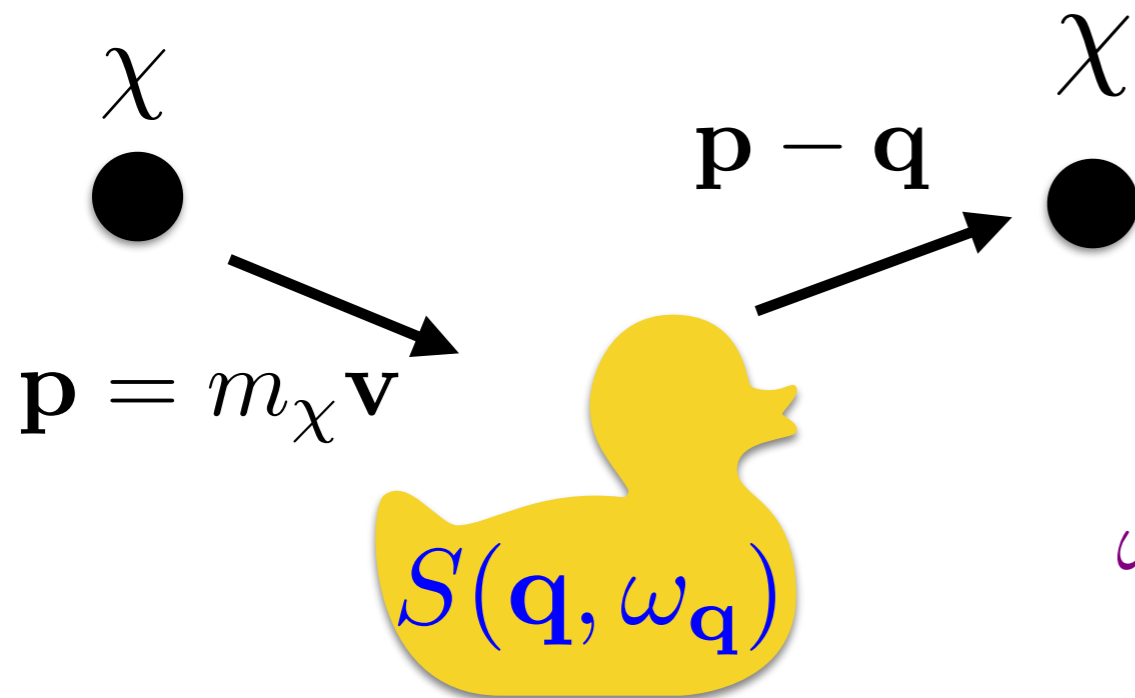
(insert your favorite  
detector here)

Energy deposited by DM:

$$\omega_{\mathbf{q}} = \frac{\mathbf{p}^2}{2m_\chi} - \frac{(\mathbf{p} - \mathbf{q})^2}{2m_\chi} = \mathbf{q} \cdot \mathbf{v} - \frac{q^2}{2m_\chi}$$

if your target is not a free particle, it is not a momentum eigenstate!

# Response functions



Energy deposited by DM:

$$\omega_{\mathbf{q}} = \frac{\mathbf{p}^2}{2m_\chi} - \frac{(\mathbf{p} - \mathbf{q})^2}{2m_\chi} = \mathbf{q} \cdot \mathbf{v} - \frac{q^2}{2m_\chi}$$

does the target have an energy eigenstate at  $\omega_{\mathbf{q}}$ ?

$$S(\mathbf{q}, \omega_{\mathbf{q}}) \propto \sum_f |\langle f | \sum_j e^{i\mathbf{q} \cdot \mathbf{r}_j} | i \rangle|^2 \delta(\omega_f - \omega_{\mathbf{q}})$$

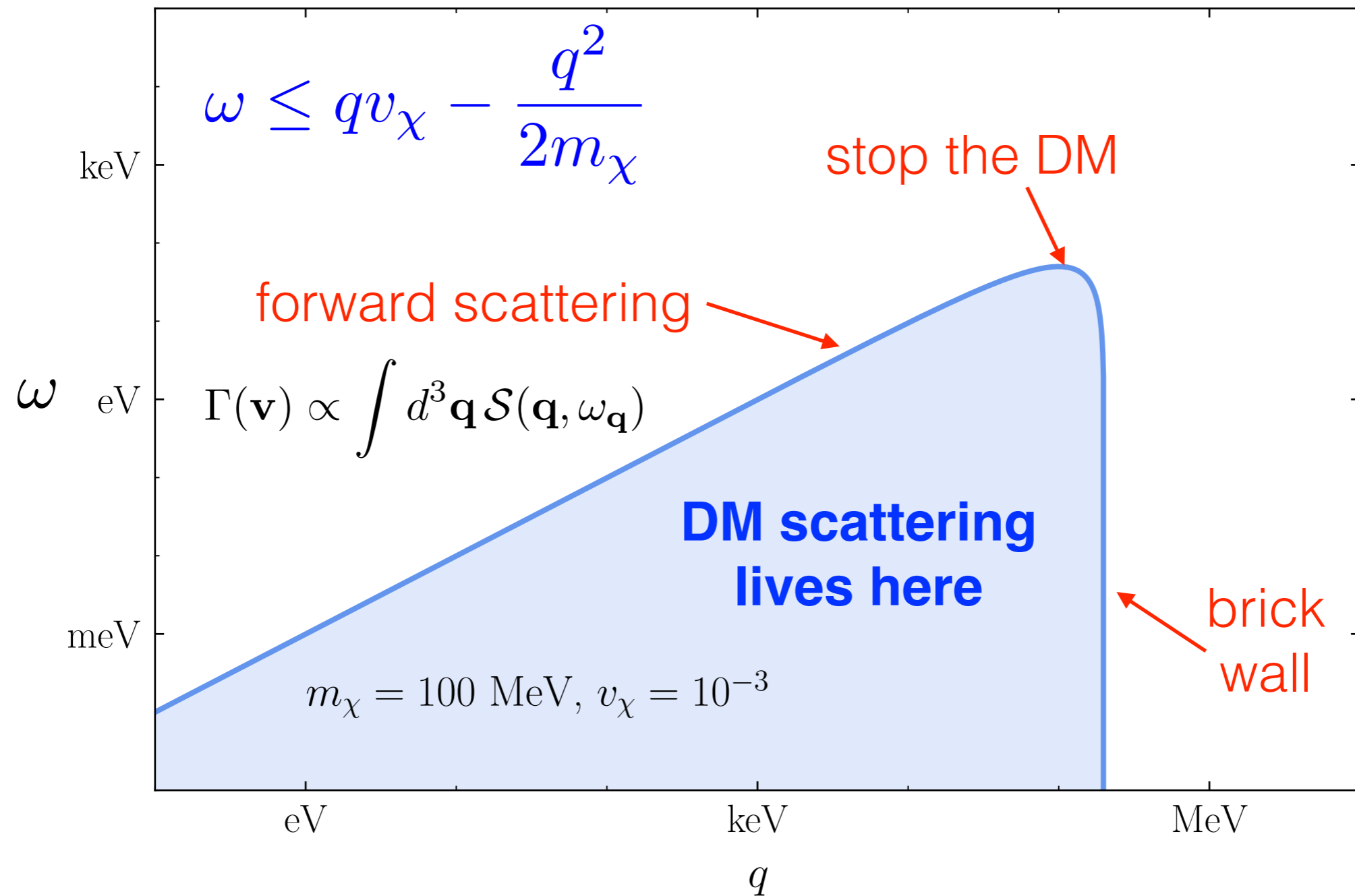
$$R \sim \int d^3 \mathbf{v} f(\mathbf{v}) \int d^3 \mathbf{q} F^2(\mathbf{q}) S(\mathbf{q}, \omega_{\mathbf{q}})$$

DM properties

Material properties

General framework that works for **any** many-body system

# Sub-GeV DM kinematics



Under-explored energy/momentum regime: too high for CM, too low for materials science