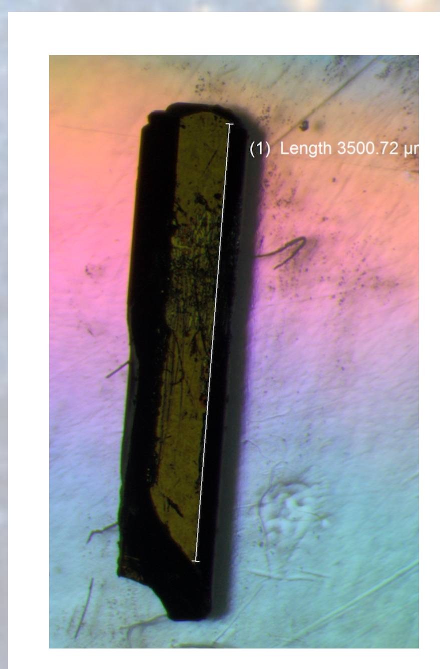
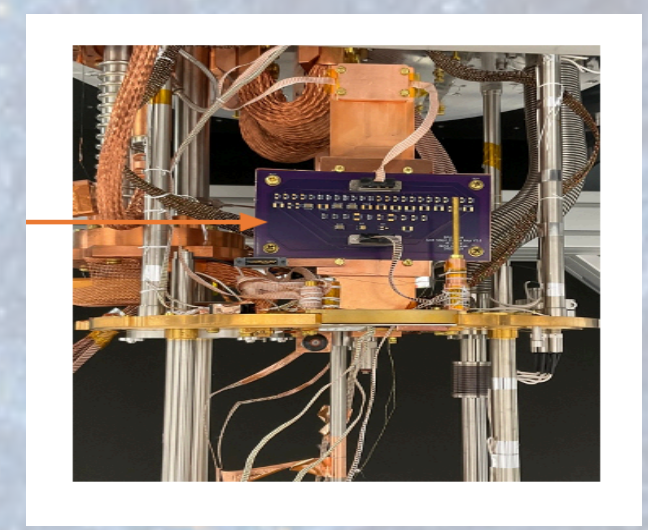
SPLENDOR: Narrow-gap semiconductors for light DM

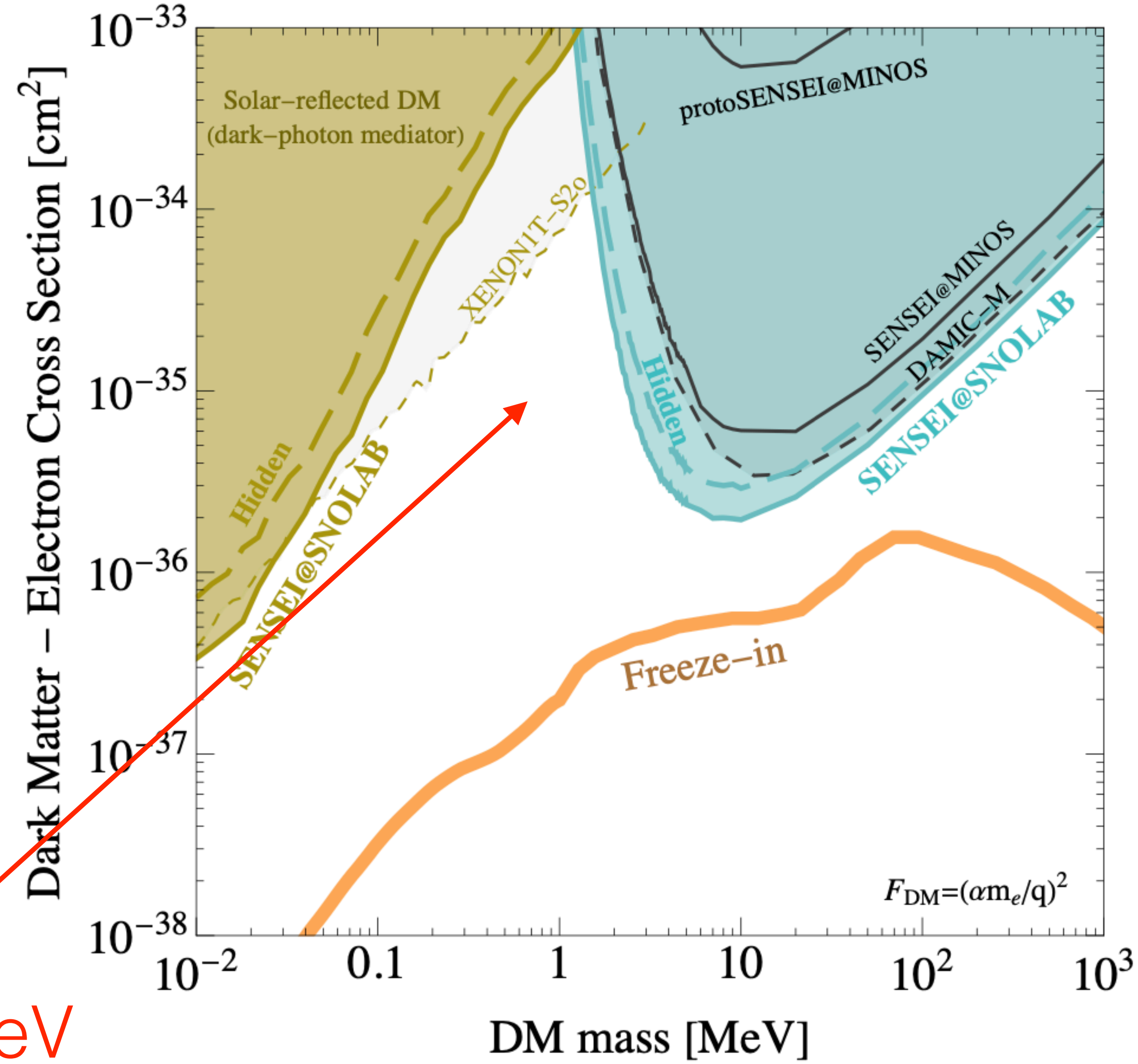


Yoni Kahn (UIUC)



ALPS2024, 4/4/24

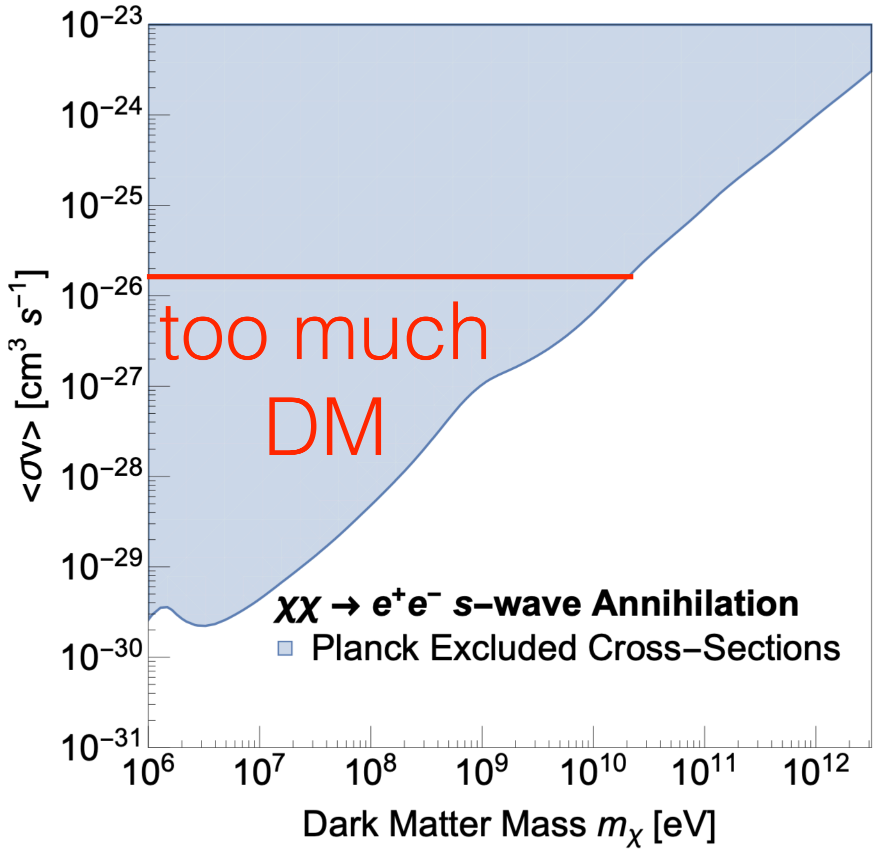
Sub-GeV DM:
we are approaching our targets!



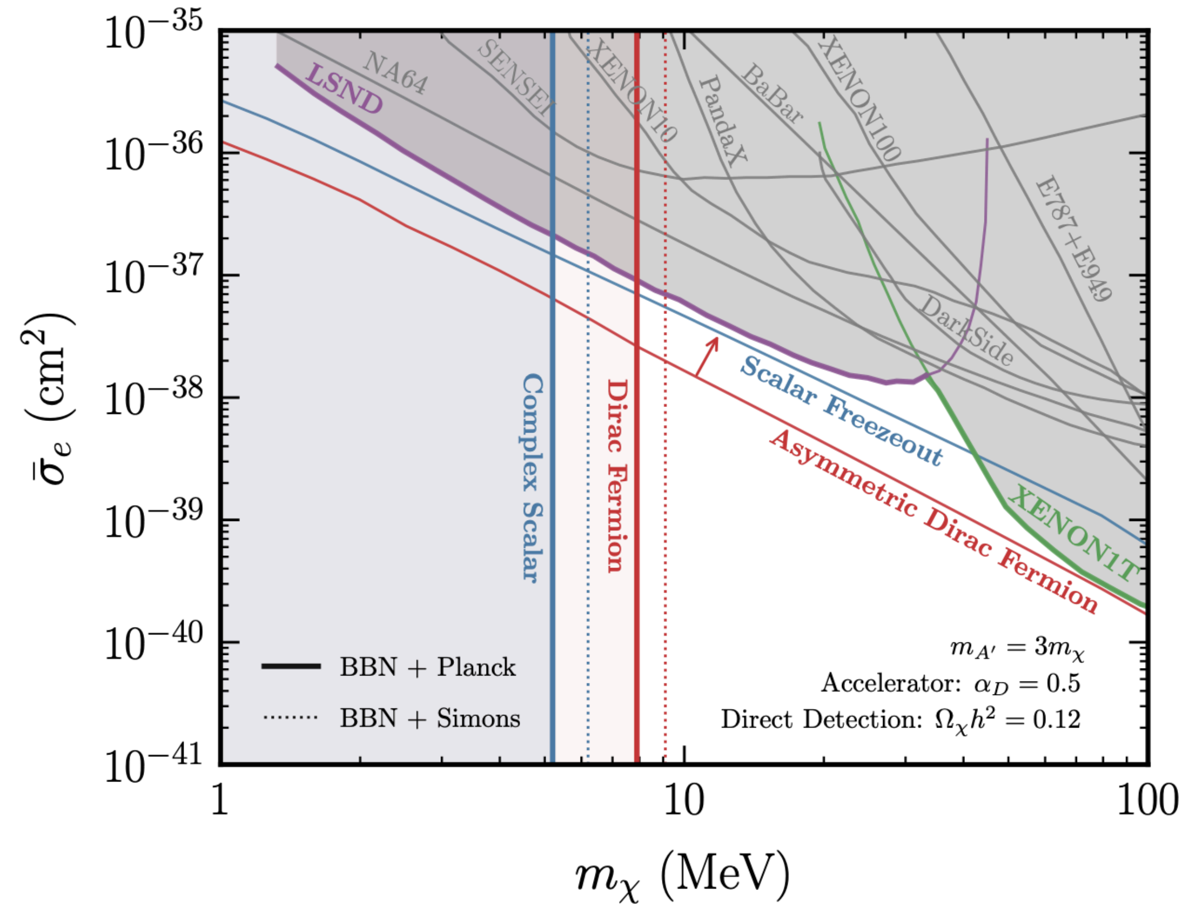
but so far < 1 MeV
is wide open

[SENSEI collab., arXiv:2312.13342]

Sub-GeV DM:
a universe of constraints



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



Extra stuff at T ~ MeV changes expansion rate of universe during BBN

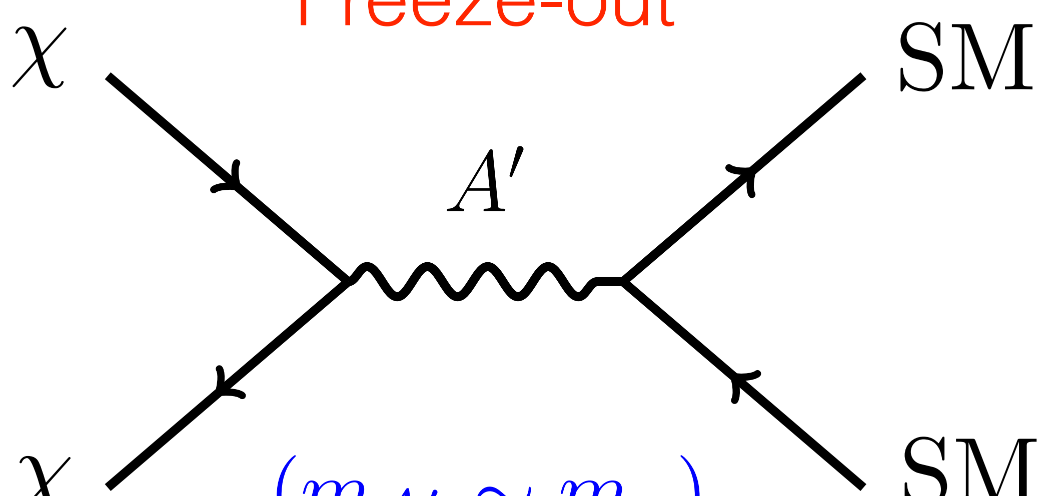
Need a particle physics model with a consistent thermal history to make sense of experiments

 [Liu, Slatyer, Zavala, PRD 2016; Giovanetti, Lisanti, Liu, Ruderman, PRL 2022]

Dark photon benchmark

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

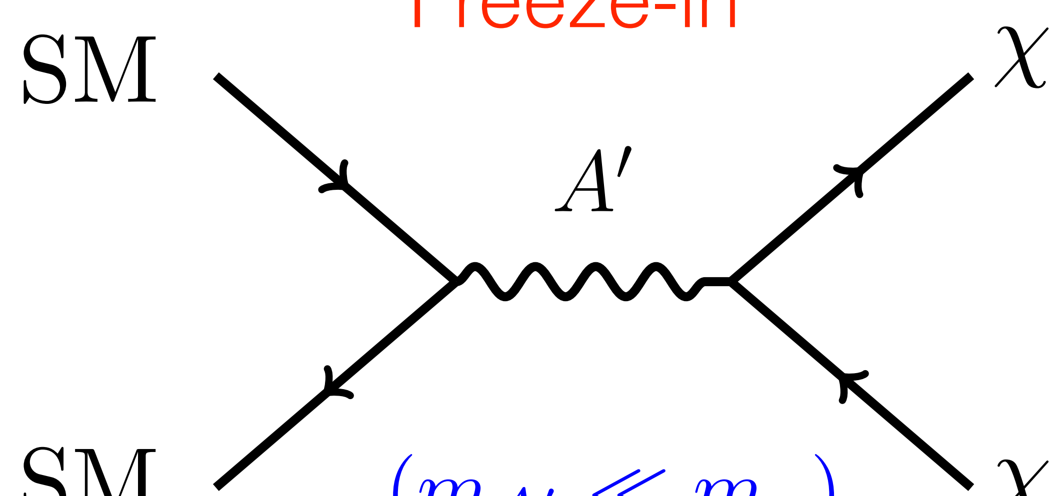
Freeze-out



$(m_{A'} \sim m_\chi)$

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

Freeze-in



$(m_{A'} \ll m_\chi)$

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

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

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

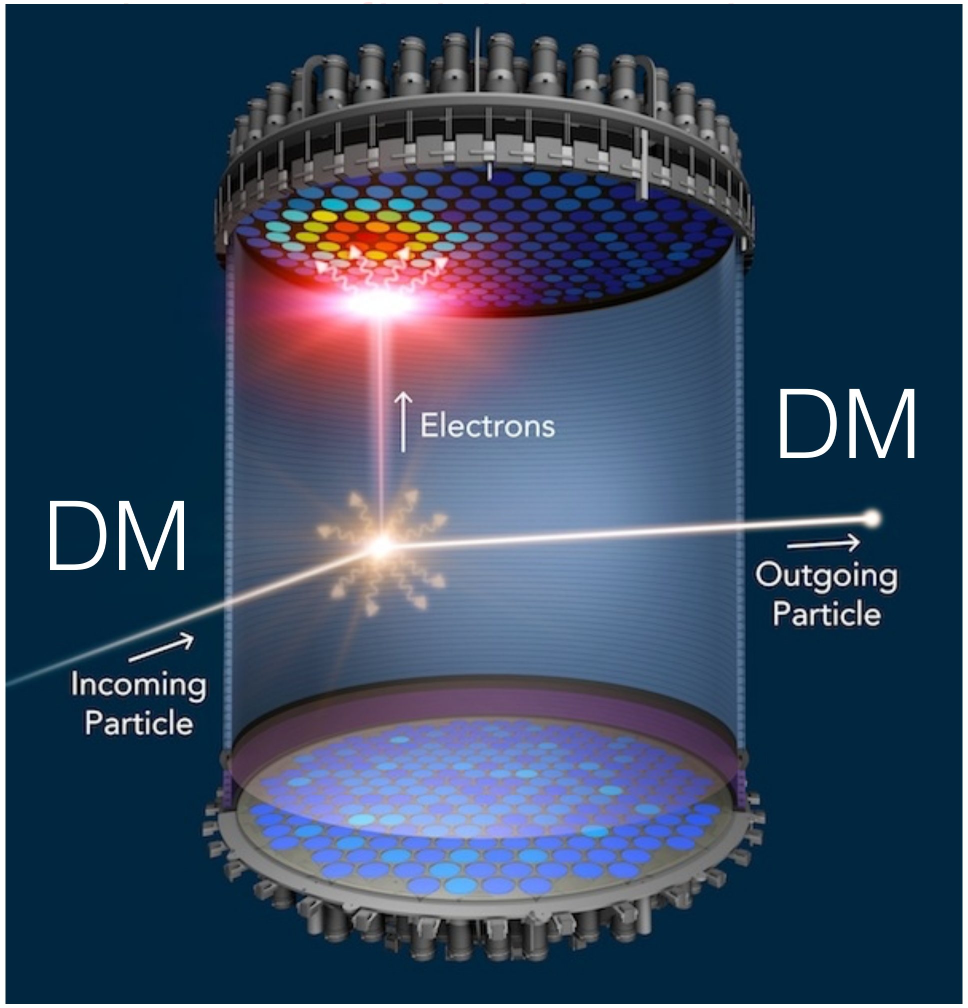
Yukawa potential

SM charge density

[Hochberg et al. (**YK**), PRL 2021; Knapen, Kozaczuk, Lin, PRD 2021]

Is your detector a bag of free particles?

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



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

m_χ

10 MeV — atomic binding energy (10 eV)

1 MeV — Si band gap (1 eV)

100 keV — optical phonon energy (100 meV)

⋮

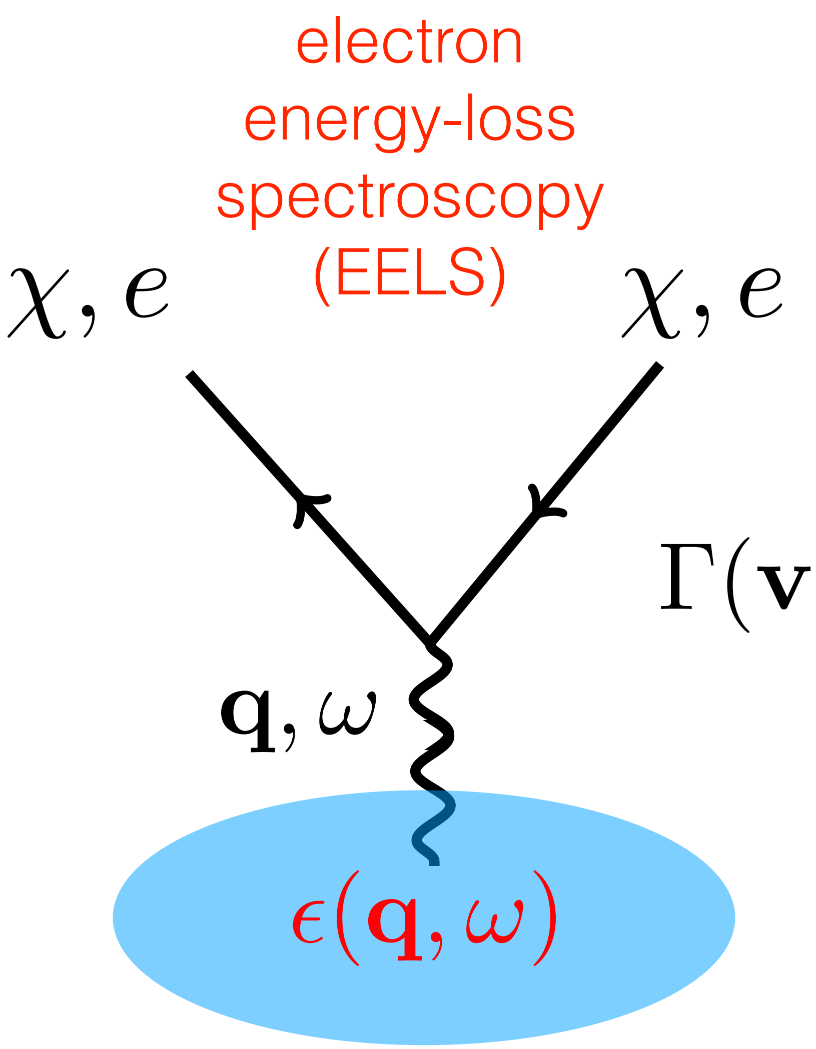
<< eV — macroscopic coherence, wave-like behavior

Sub-MeV detection via electron scattering: novel materials!

[**YK** and Lin, Rep. Prog. Phys. 2022; image credit LZ collab.]

Measuring electron response

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



DM-electron interaction (assumed spin-independent)

Response function (dielectric, for electrons)

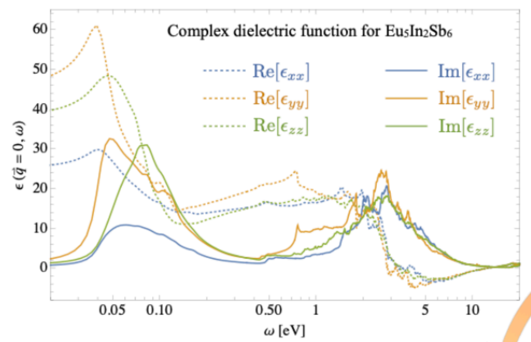
$$\Gamma(\mathbf{v}) = \int \frac{d^3\mathbf{q}}{(2\pi)^3} |V(\mathbf{q})|^2 \left[\frac{q^2}{e^2}\, 2\,\mathrm{Im}\left(-\frac{1}{\epsilon(\mathbf{q},\omega)}\right)\right]$$

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

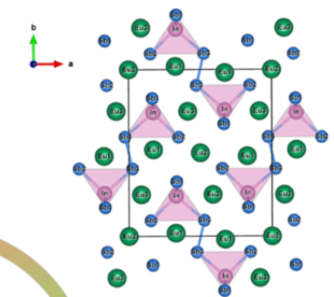
[Pines and Nozieres Phys. Rev. 1959;
Berggren, Hochberg, **YK**, Kurinsky, Lehmann, Yu, PRL 2021]

The SPLENDOR program

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

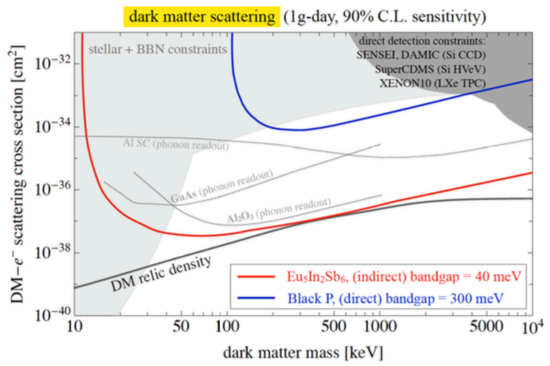


Materials Synthesis
high-quality single crystals
clean narrow bandgaps

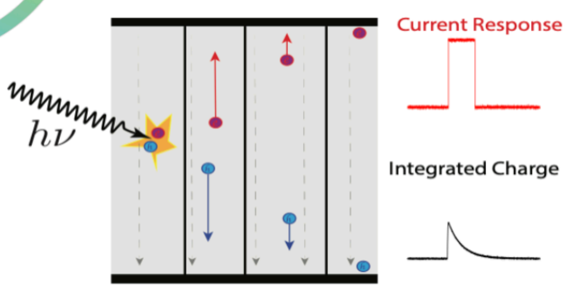


Theory
dark matter scattering
and absorption rates,
daily modulation of signal,
many-body methods

Characterization
crystal structure, STM,
M-EELS, ARPES, FTIR,
charge transport

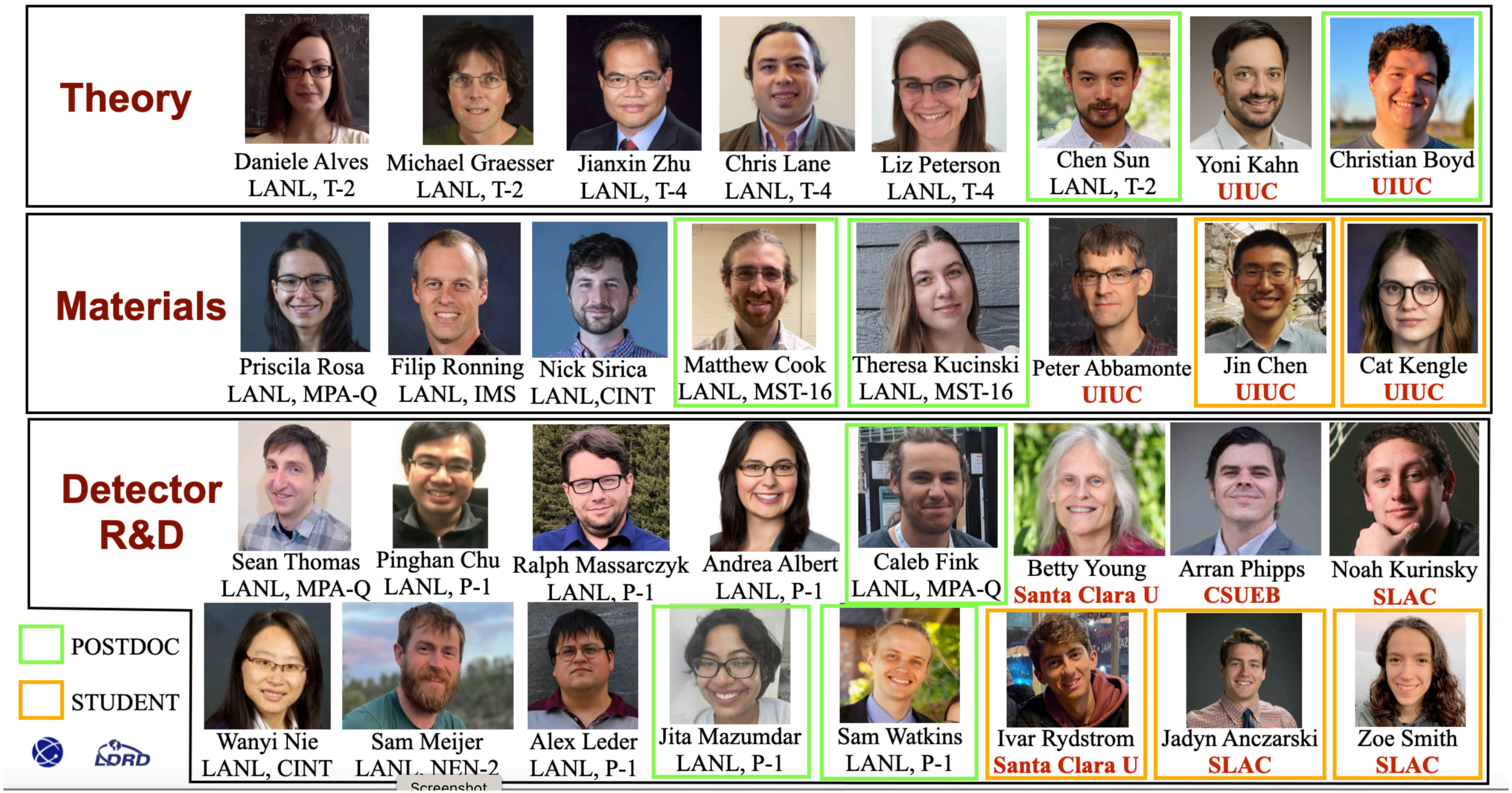


Detector R&D
cryogenic charge amplifiers,
Few e^- resolution



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

The SPLENDOR team

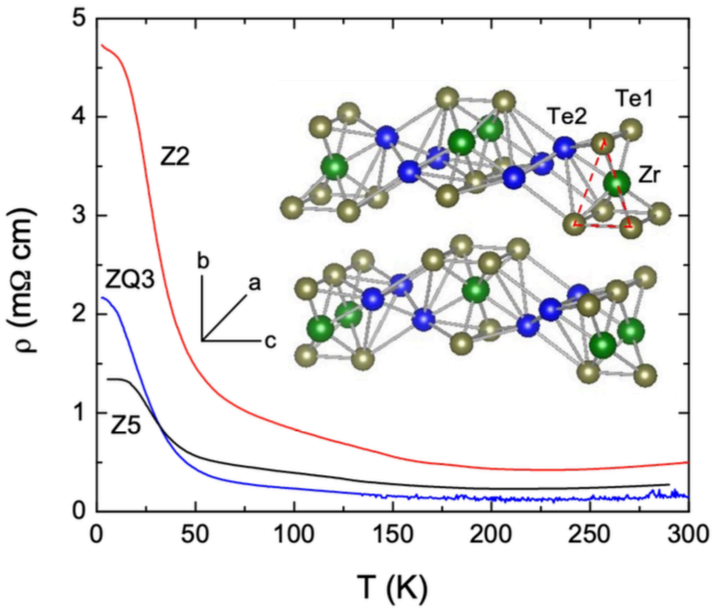


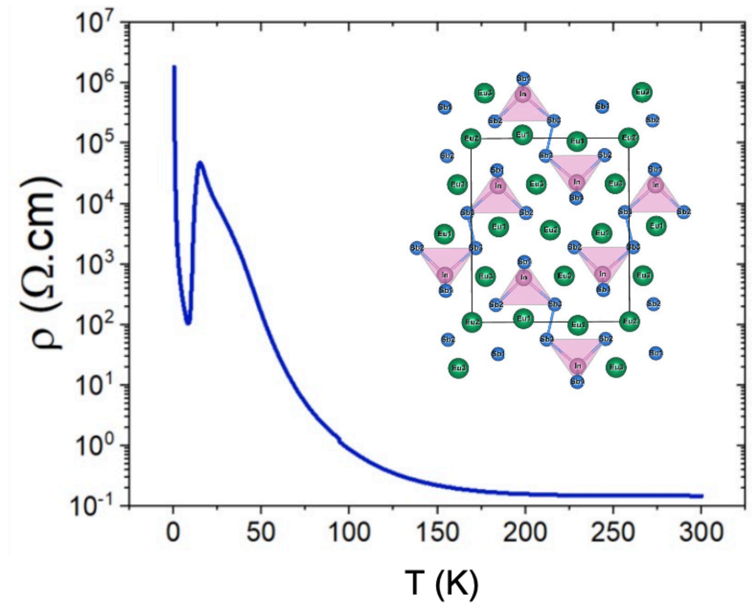
Amazing work by all of these people, won't cite everyone by name in this talk: **this is a true team effort!**

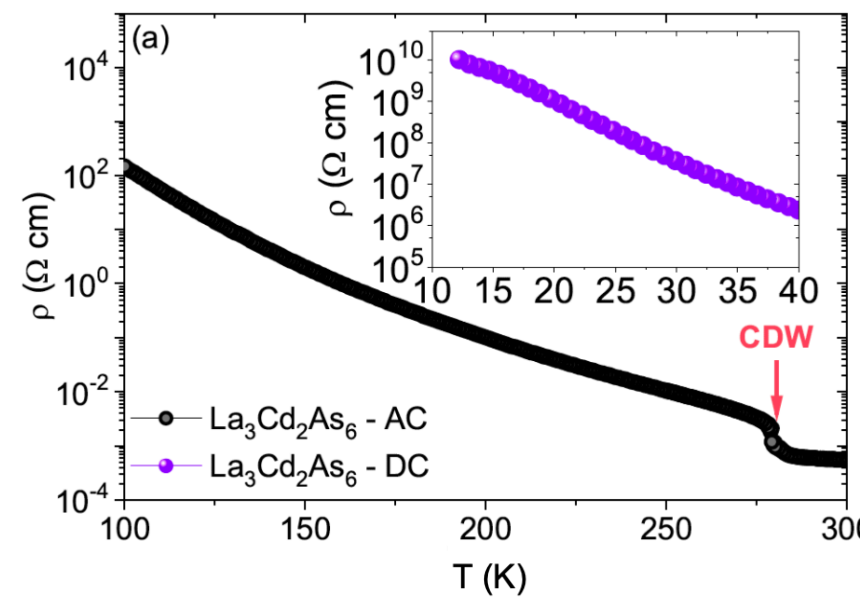
Materials synthesis: candidates

linear scale

log scale!!







$ZrTe_5$

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

$Eu_5In_2Sb_6$

factor of **10^7** 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).

$La_3Cd_2As_6$

factor of **10^{14}** increase in resistivity from 300 K→10 K, indicating clean gap and strongly suppressed dark currents

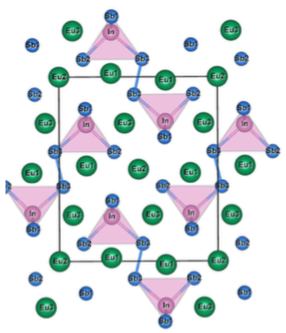
MM Piva, SM **Thomas**, …, F **Ronning**, PFS **Rosa**, *Chemistry of Materials* 33, 4122 (2021).

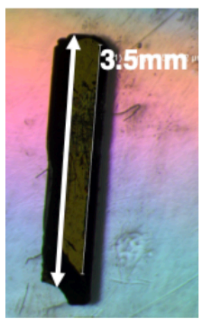
When we first went looking for a narrow-gap material, $ZrTe_5$ seemed promising, but these lanthanides are exponentially better!

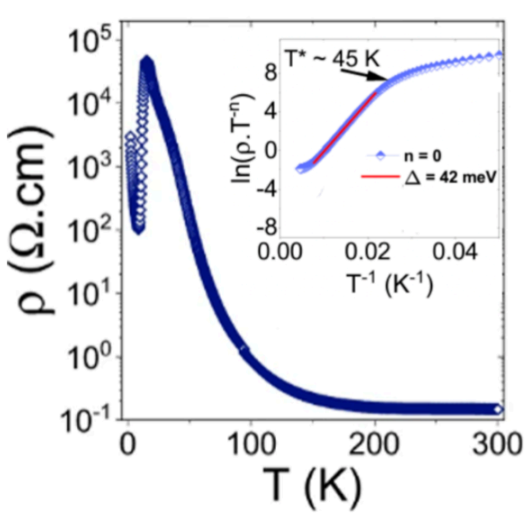
Materials synthesis: in practice

Zintl phase (Proposed)

$$Eu_5^{2+}[In_2Sb_6]^{-10}$$



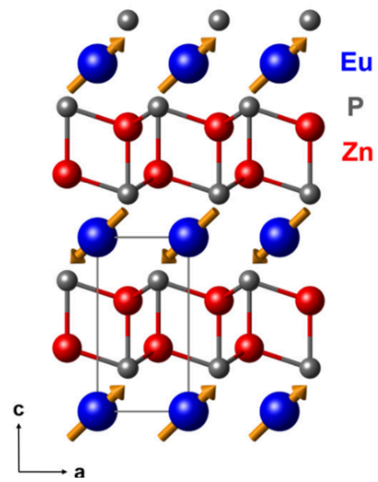


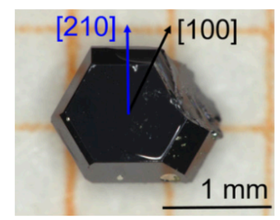


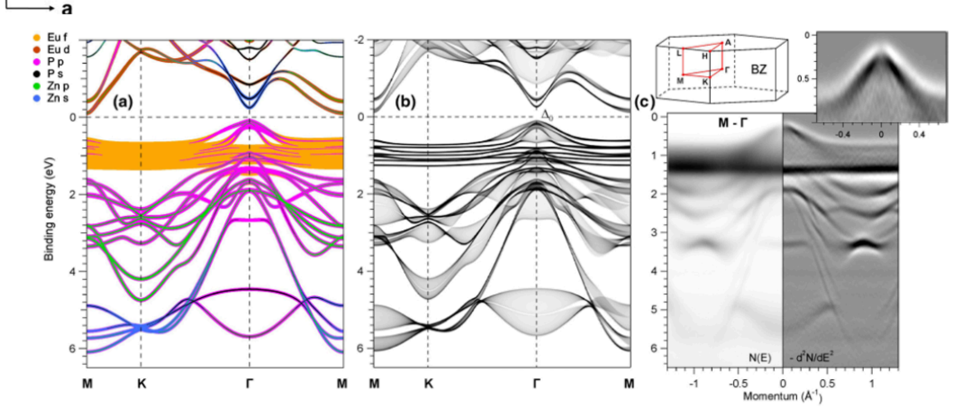
PFS Rosa *et al.*, *npj Quantum Materials* **5**, 52 (2020).

Zintl phase (Cleavable)

$$Eu^{2+}[Zn_2P_2]^{2-}$$

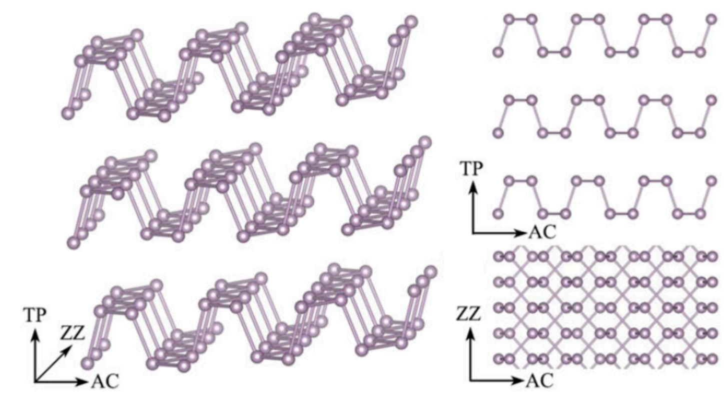


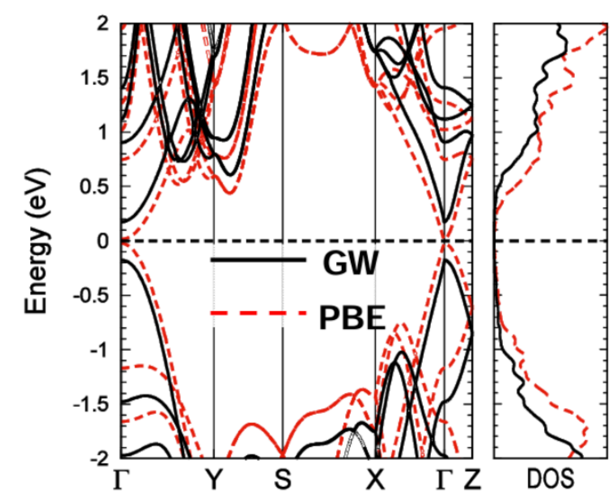




Krebber *et al.* Phys. Rev. B 108, 045116 (2023).

Black Phosphorus (benchmark)





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

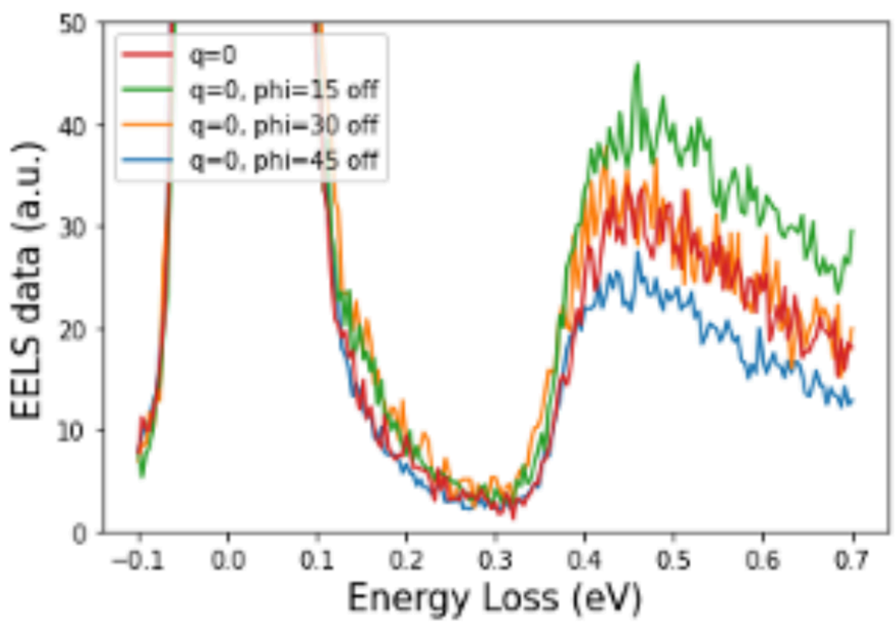
All viable for ~gram-scale crystals!

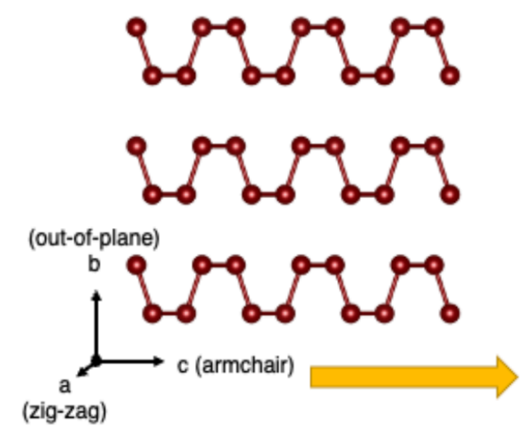
Characterization: benchmarking

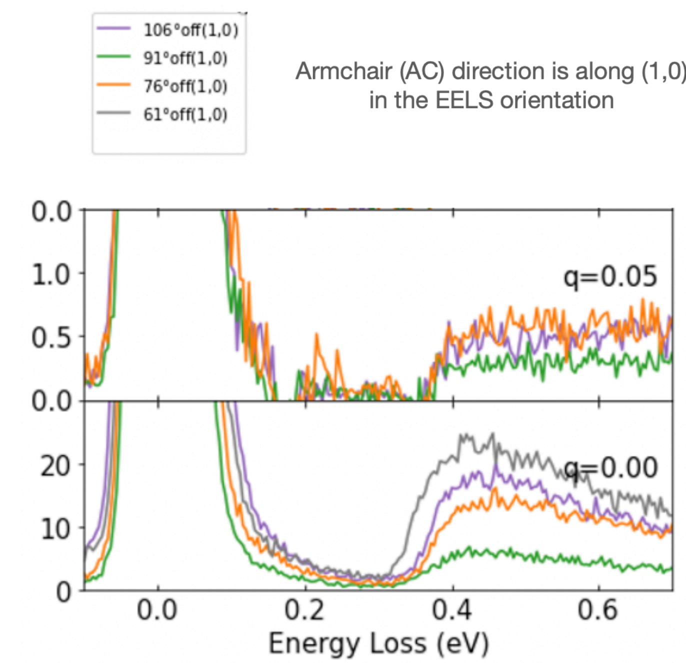
Validate pipeline on black phosphorus (0.3 eV gap):

EELS (finite q)

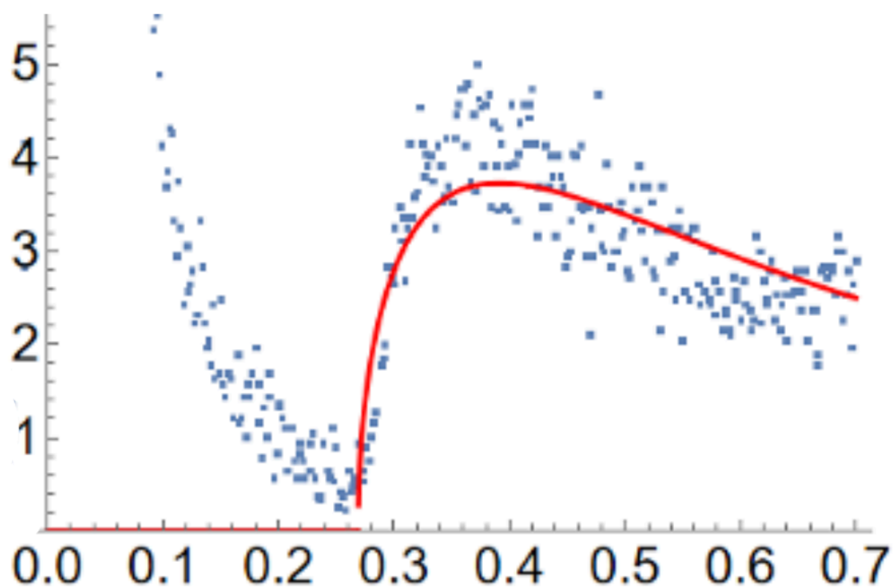
EELS
(q = 0)



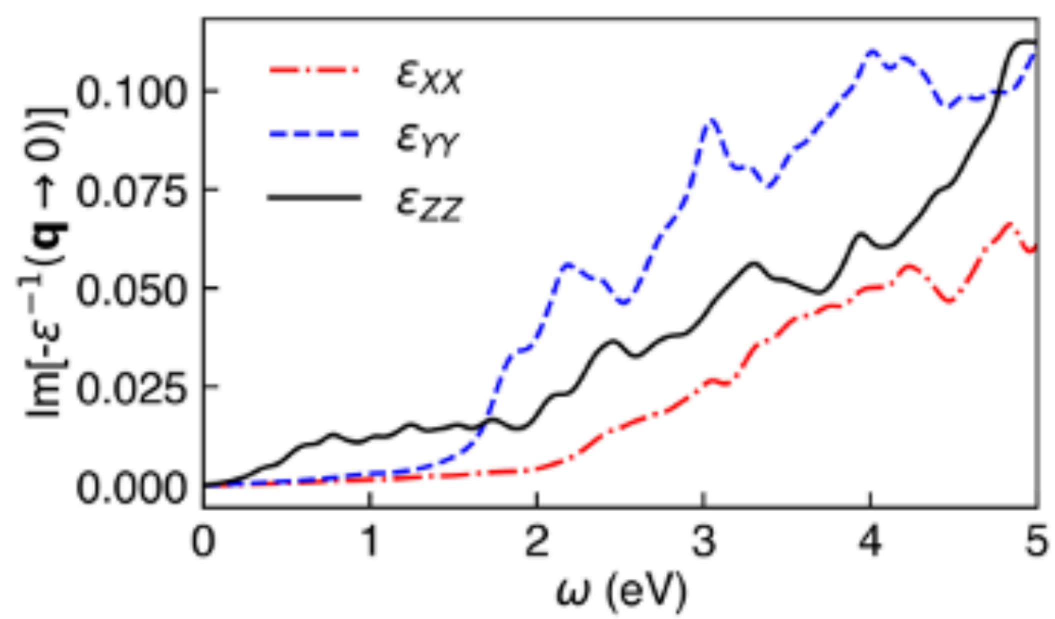




two-band
model

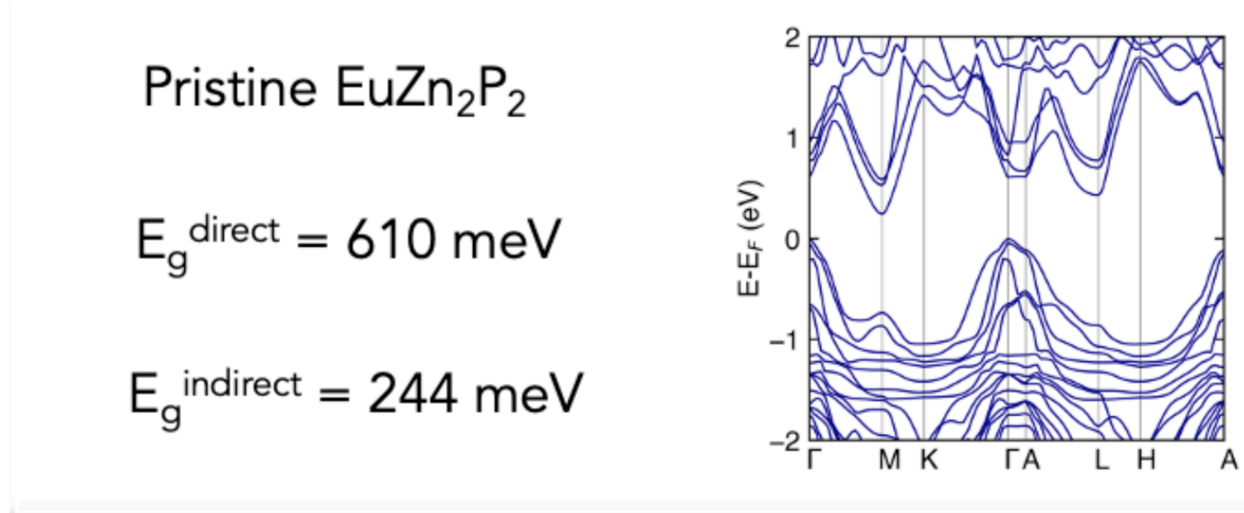


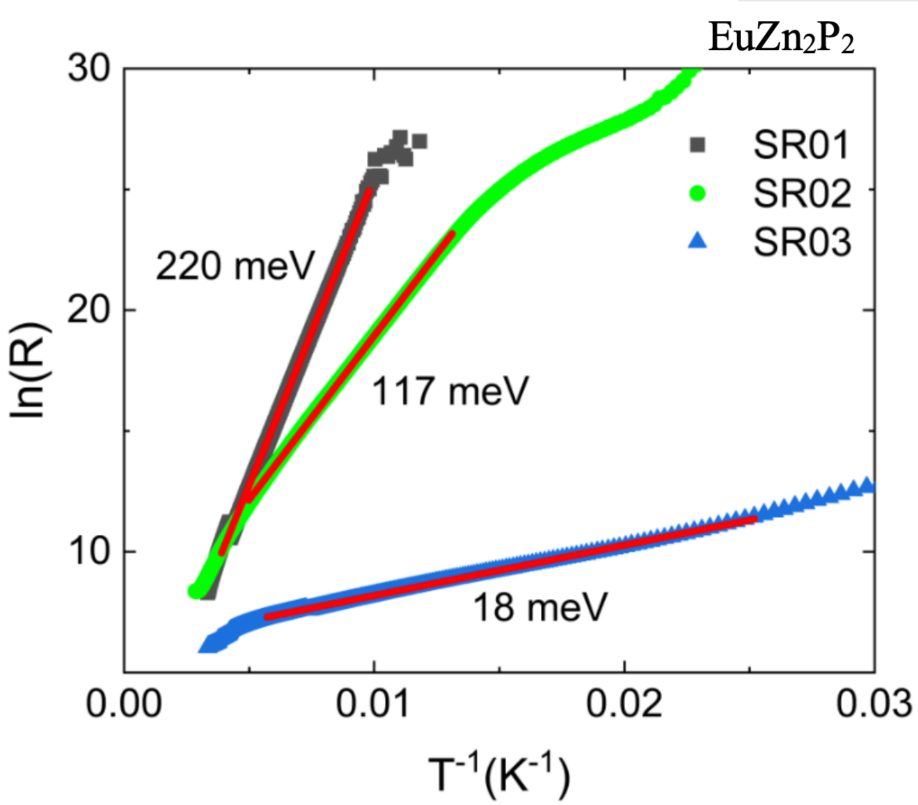
DFT

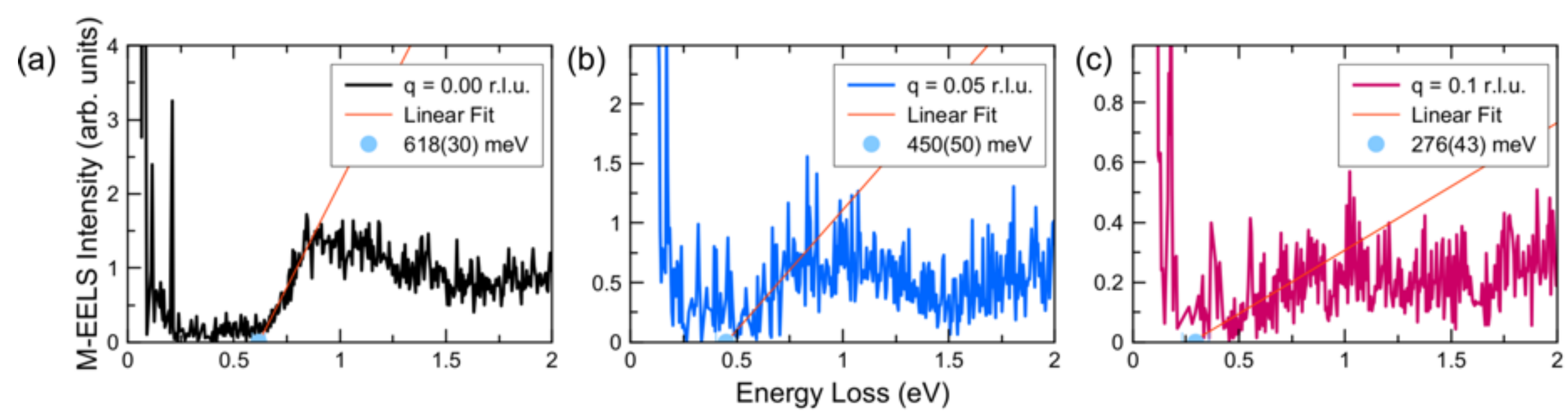


Excellent agreement for both direct gap and anisotropy

Characterization of $EuZn_2P_2$





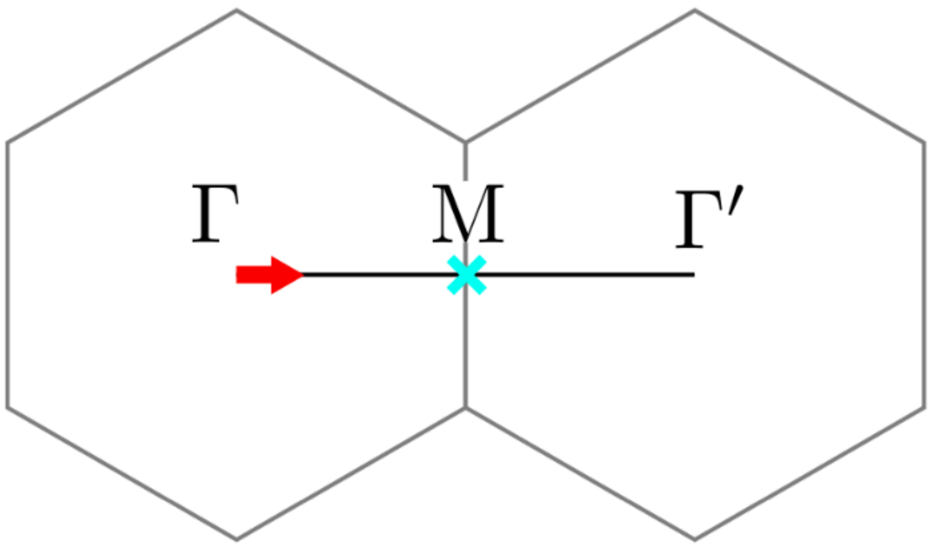


Activated behavior $\rho(T) = Ae^{\Delta/k_B T}$

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

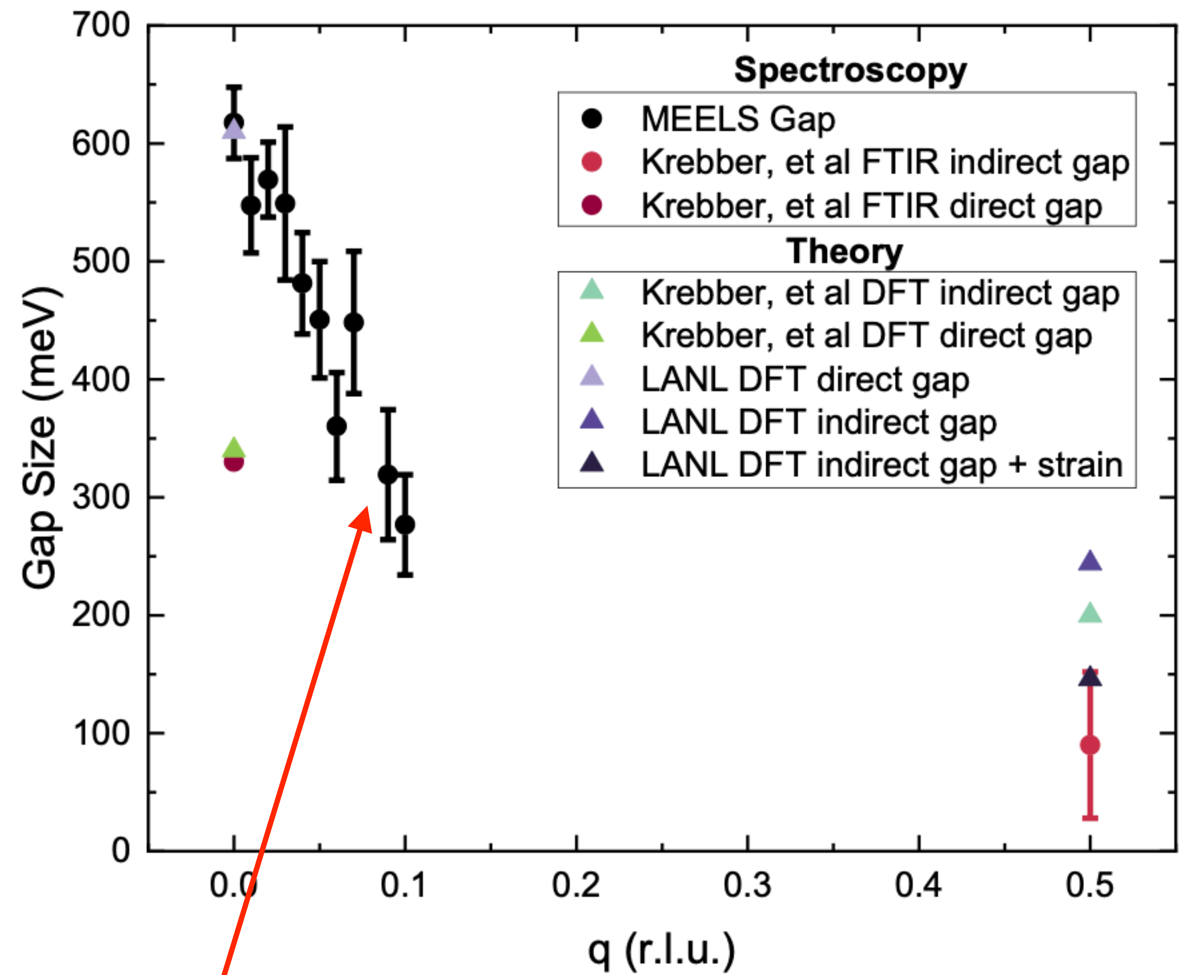
EELS nails the direct gap, but indirect gap is tricky: finite momentum probes surface rather than bulk

Characterization: band gap



M-EELS q range

DFT predicted indirect gap location

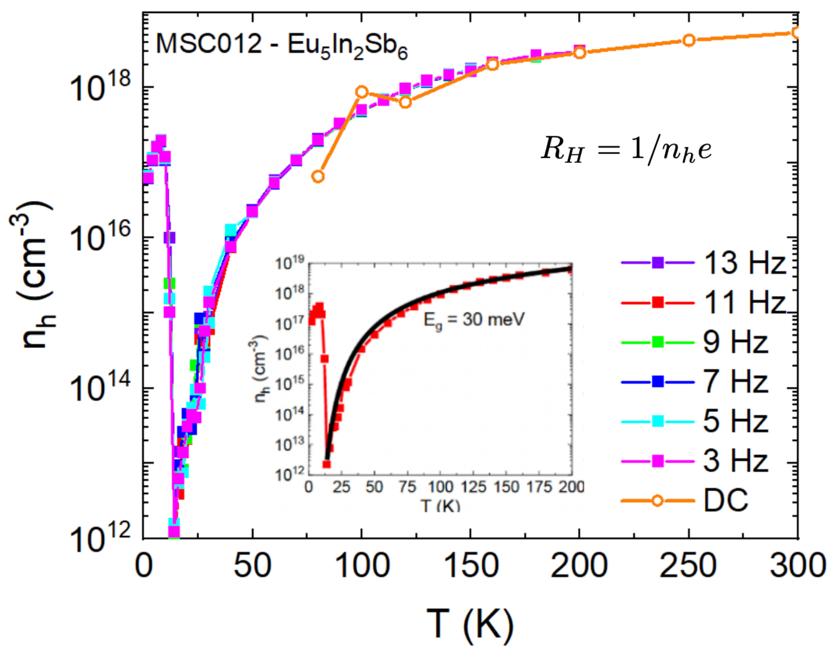


$$q_{\rm min} = \frac{\omega_{\rm min}}{v_{\rm max}} \simeq 36 \text{ eV} \left(\frac{\omega_{\rm gap}}{100 \text{ meV}} \right)$$

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

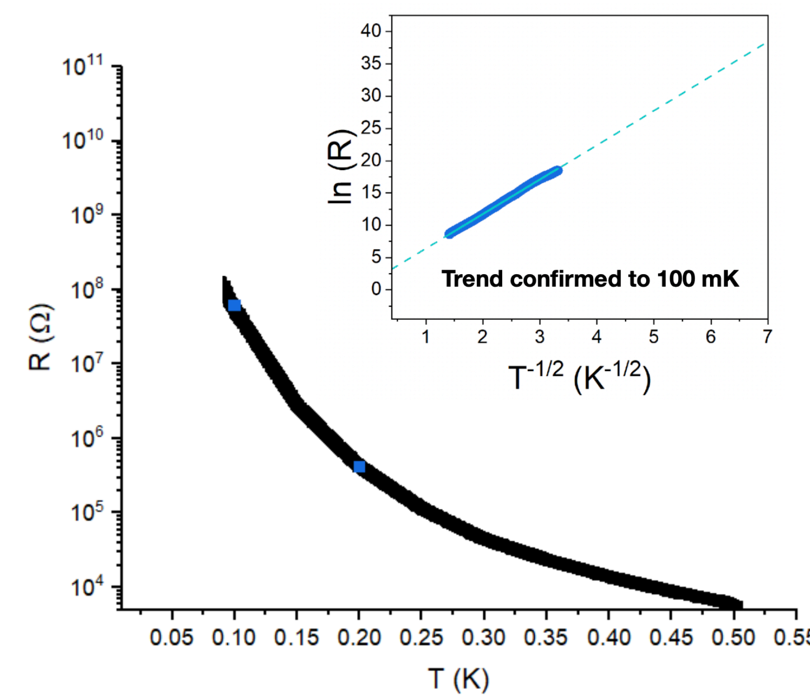
Characterization of $Eu_5In_2Sb_6$

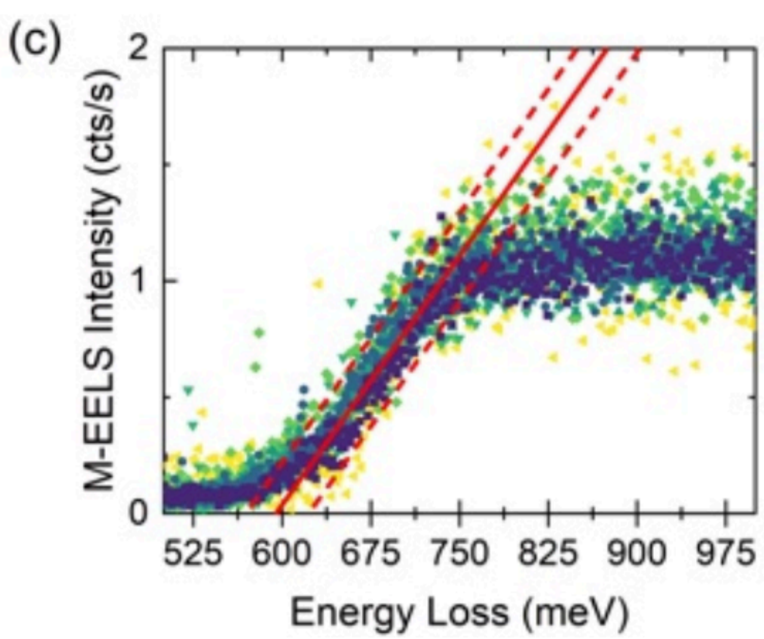
Hall effect: fit with 30 meV gap



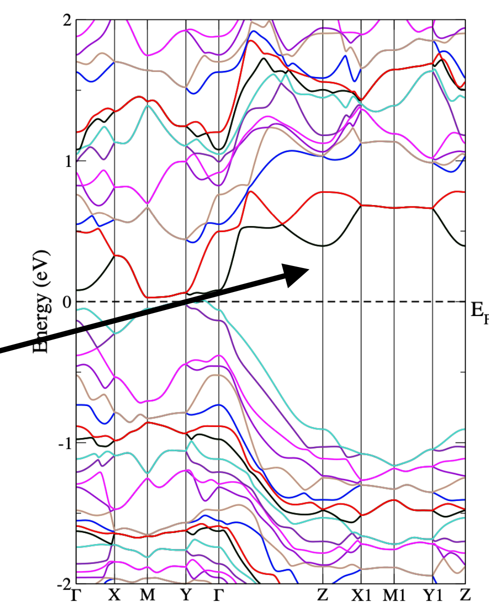
Mobility at 2 K $\mu_h = \mathcal{O}(10)\ \mathrm{V.cm^2}/s$

Resistivity is exponential



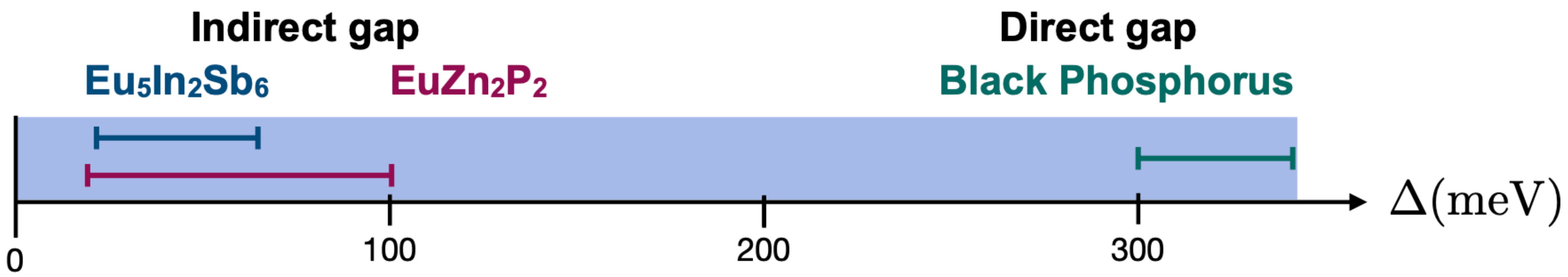


Material doesn't cleave well, so EELS only measures a gap averaged over entire BZ



- Indirect band gap is ~20 meV
- Direct band gap is ~40 meV

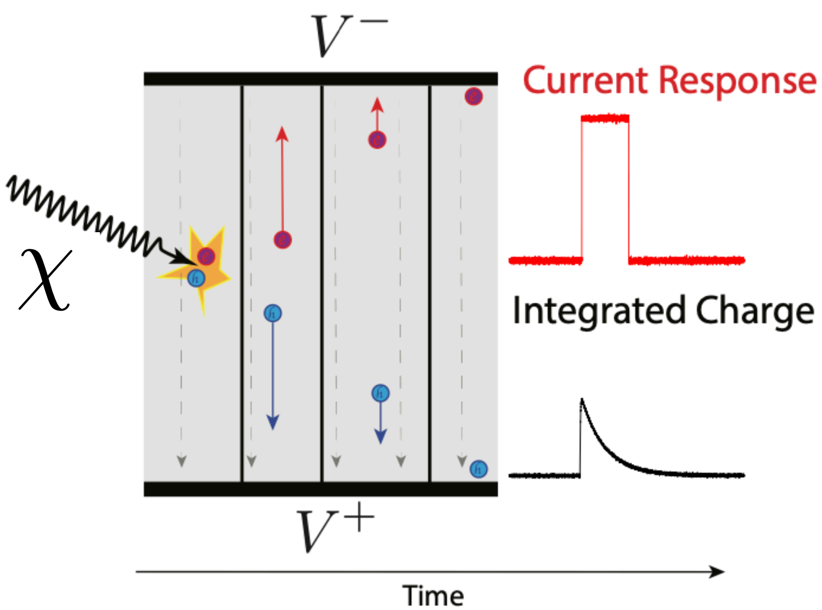
Characterization: summary

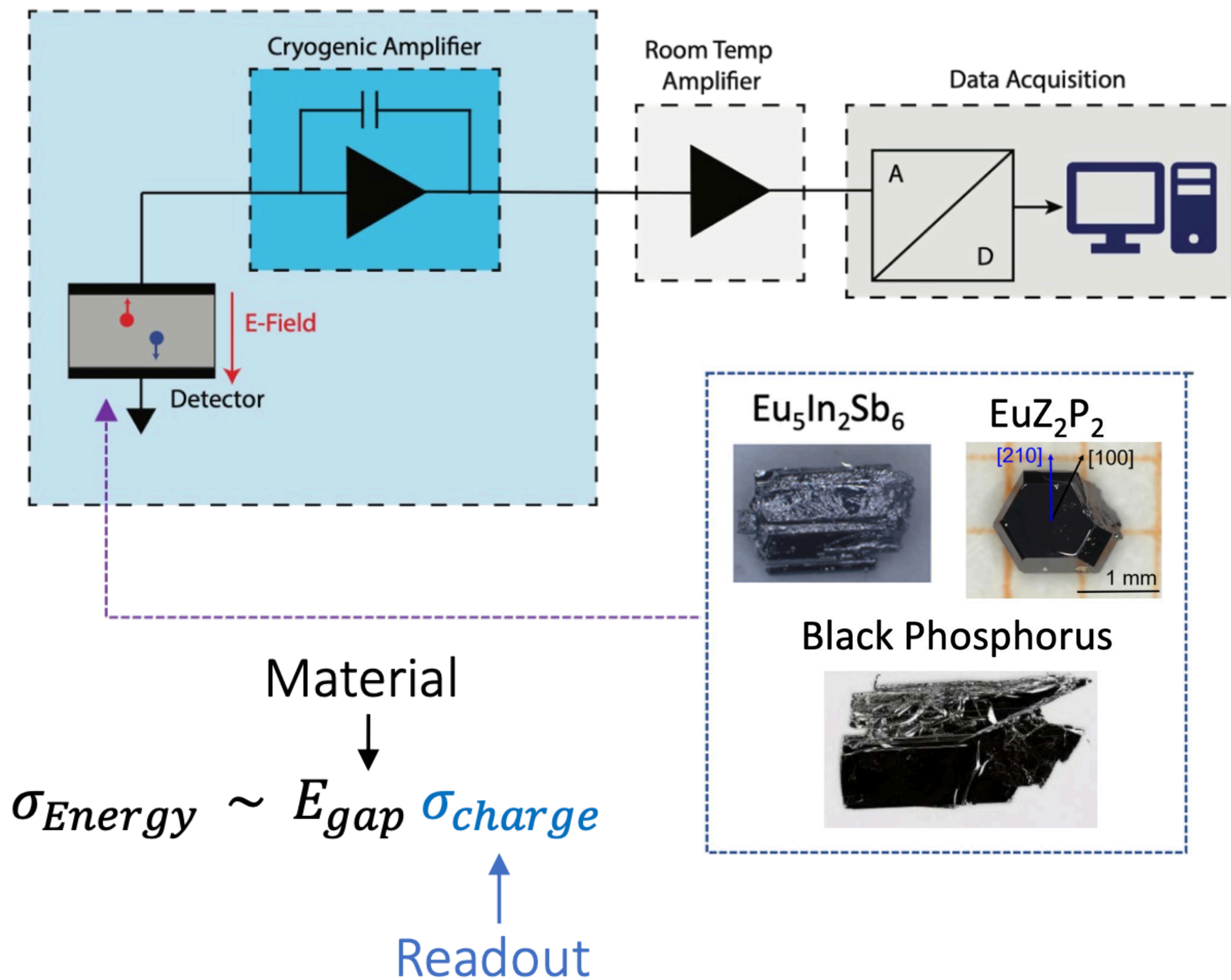


	$Eu_5In_2Sb_6$	$EuZn_2P_2$	Black Phosphorus
Mobility	$\mu_h = \mathcal{O}(10)\ \mathrm{V.cm^2}/s$	$\mu_h = \mathcal{O}(1)\mathrm{V.cm^2/s}$	$\mu_h = \mathcal{O}(0.1)\ \mathrm{V.cm^2}/s$
Direct Gap (EELS)	600-800meV	620 meV	**300 meV**
Direct Gap (FTIR)	500 meV	330 meV	**340 meV**
Direct Gap (Theory)	**40 meV**	610 meV	**300 meV**
Indirect Gap (EELS)	Upcoming sputtering/ annealing system for finite-q experiments	Upcoming higher-resolution higher-q experiments	N/A
Indirect Gap (FTIR)	**60 meV**	**90 meV**	N/A
Indirect gap (Theory)	**20 meV**	240 meV (smaller with strain)	N/A
Charge gap (Transport)	**42 meV**	**18 - 100 meV**	-

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

Detector concept



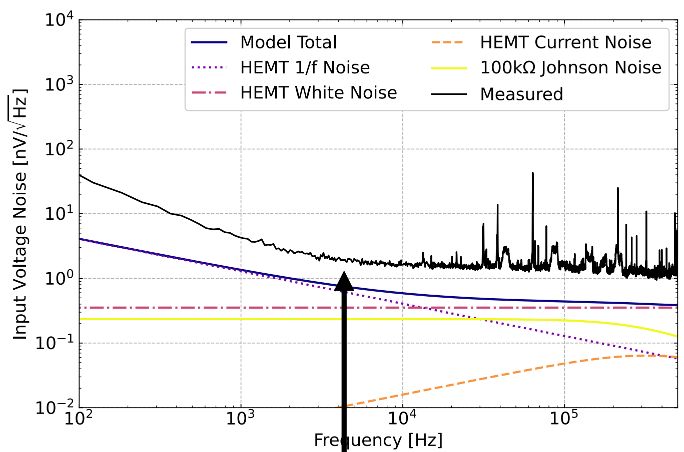


Goal: "universal" capacitive charge amplifier with few e- resolution

Detector: current status

Amplifier Prototype Testing

Testing of complete amplifier in dilution refrigerator – DONE!

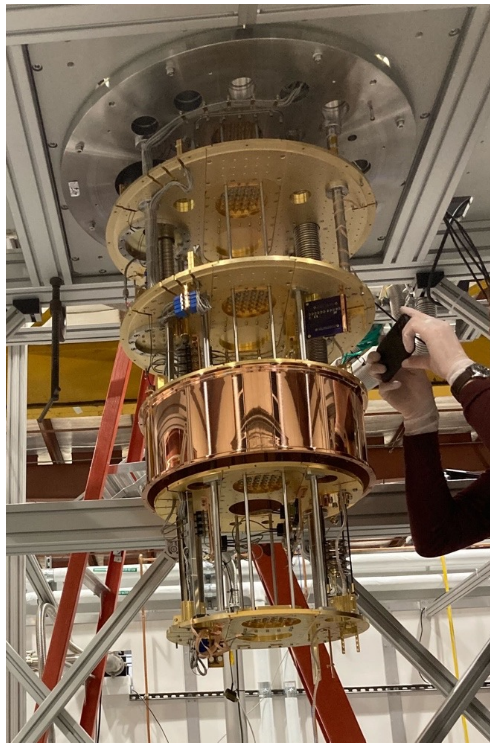


Integrated measured voltage noise across expected capacitance results in charge resolution of 7 electrons

Reduction of EMI should give 2-3 electron resolution!

~5-10 pF

$$\sigma_{charge} \sim N_V \left(C_{parasitic} + C_{input} + C_{detector}\right)$$



arXiv:2311.02229 [physics.ins-det]

Just put out paper on progress of charge amp! →

Two-Stage Cryogenic HEMT Based Amplifier For Low Temperature Detectors

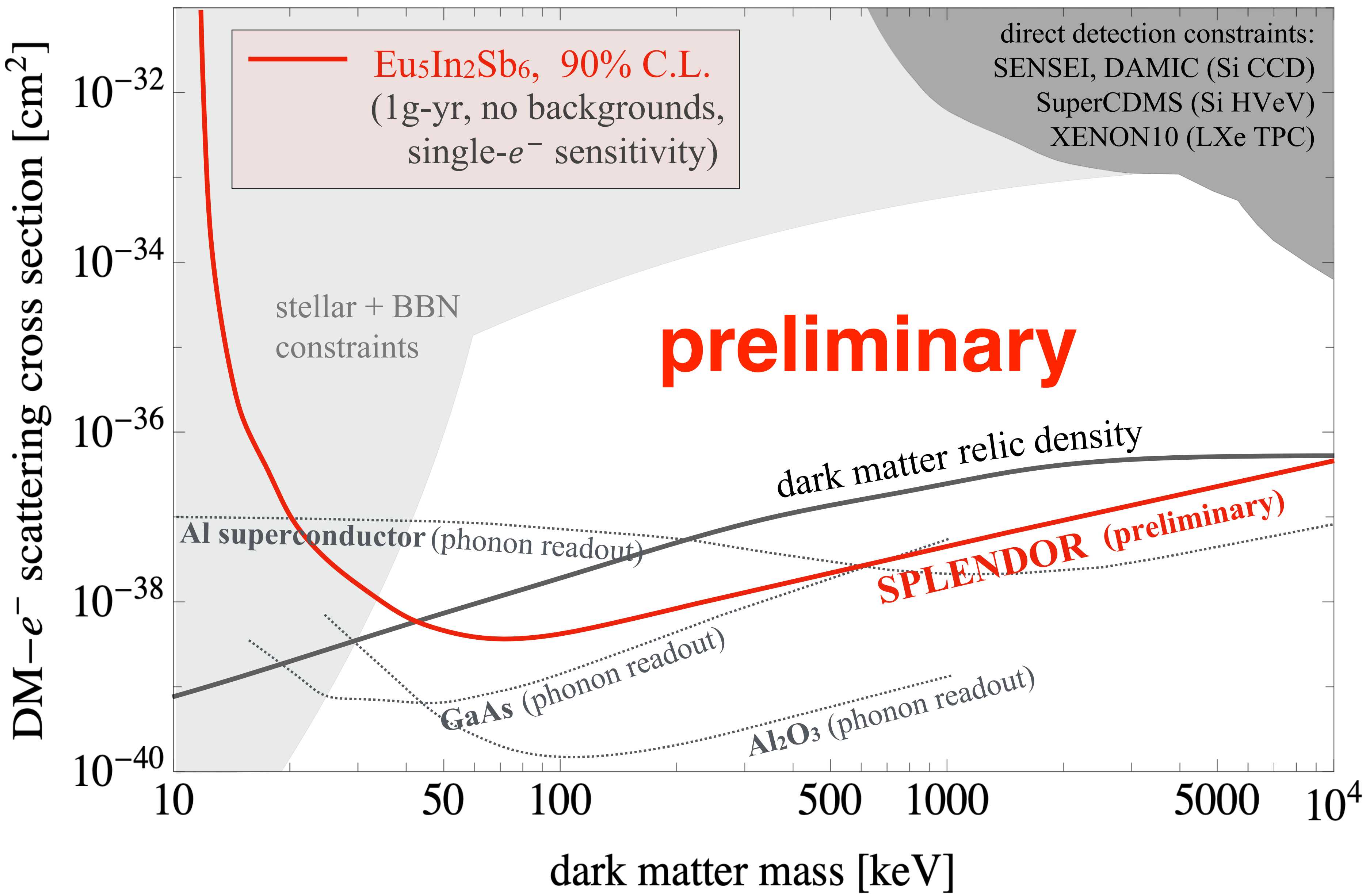
J. Anczarski,[1,2,3,*] M. Dubovskov,[4] C. W. Fink,[5] S. Kevane,[1,2,3] N. A. Kurinsky,[2,3] S. J. Meijer,[5] A. Phipps,[6] F. Ronning,[5] I. Rydstrom,[4] A. Simchony,[1,2,3] Z. Smith,[1,2,3] S. M. Thomas,[5] S. L. Watkins,[5] and B. A. Young[4]

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

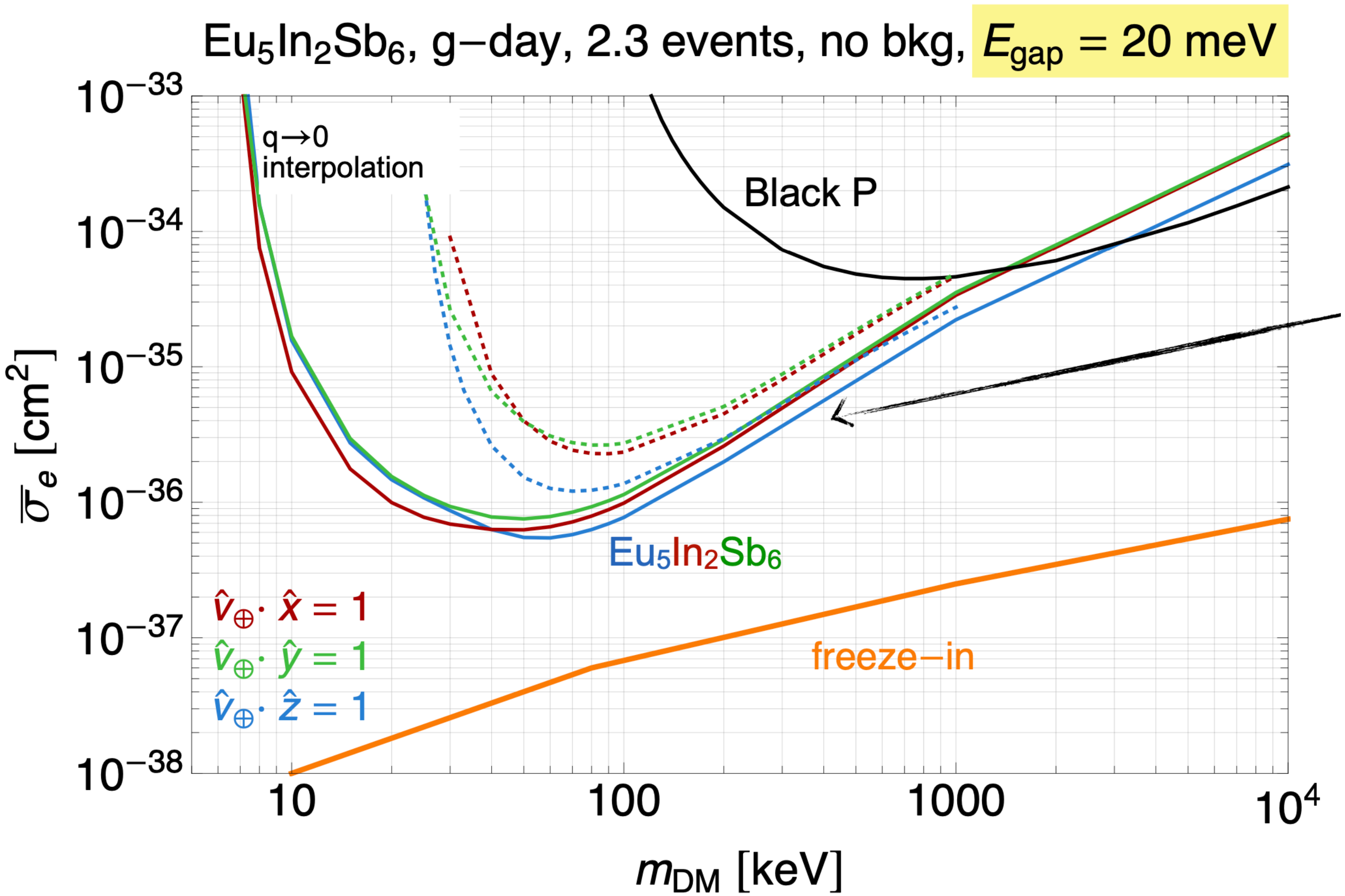
Los Alamos NATIONAL LABORATORY

Theory: reach projections

Assuming 20 meV gap:



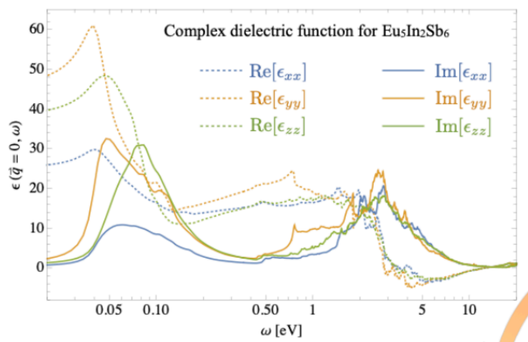
Theory: daily modulation



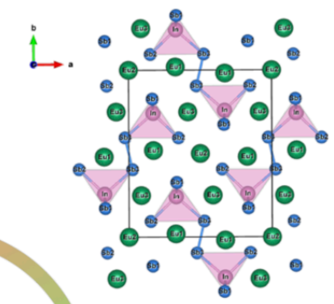
Expect ~20% daily modulation (full calculation forthcoming)

Conclusion

two candidate materials
plus commercially-purchased
benchmark



Materials Synthesis
high-quality single crystals
clean narrow bandgaps

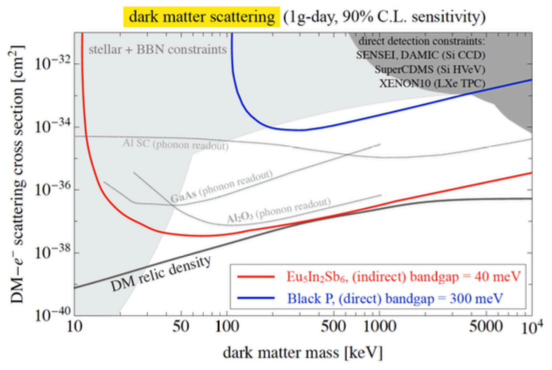


Potential for
first DM search
below 500 keV

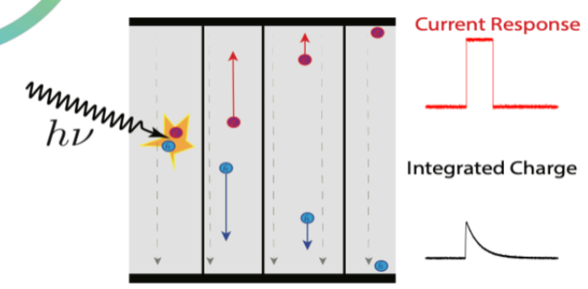
Theory
dark matter scattering
and absorption rates,
daily modulation of signal,
many-body methods

Characterization
crystal structure, STM,
M-EELS, ARPES, FTIR,
charge transport

EELS works!
But must be
combined
with theory
modeling



Detector R&D
cryogenic charge amplifiers,
Few e^- resolution

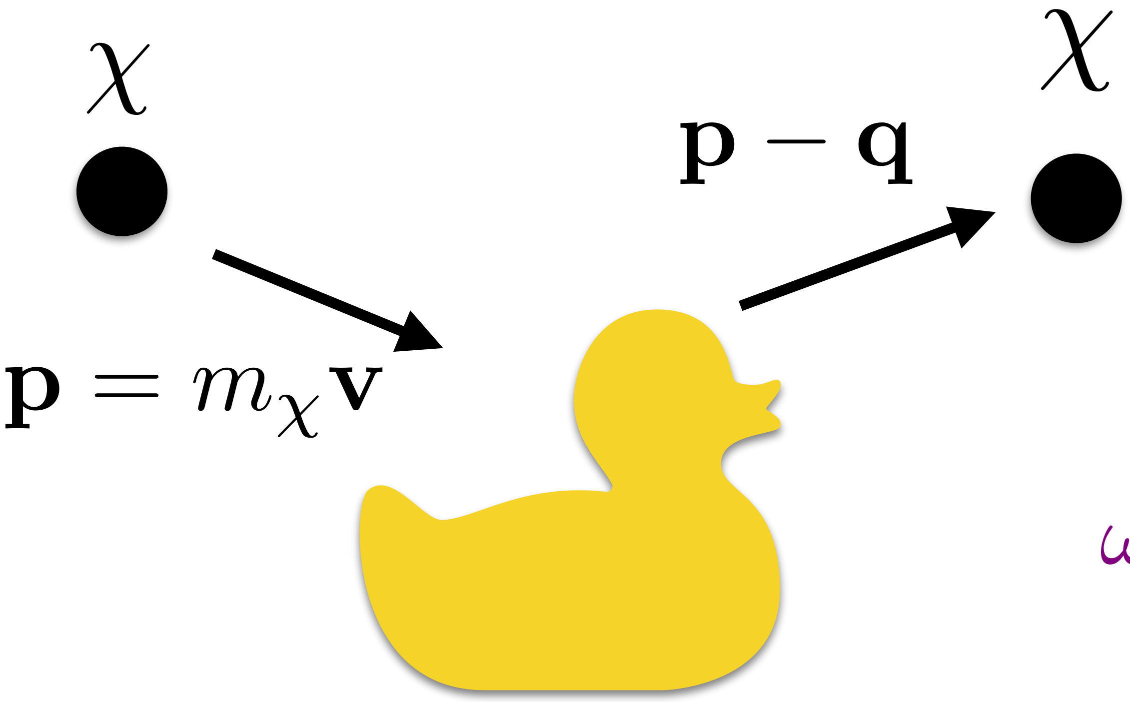


7e- resolution now,
expect 2 or 3 e-

Paper coming this summer, stay tuned!

Backup

Response functions



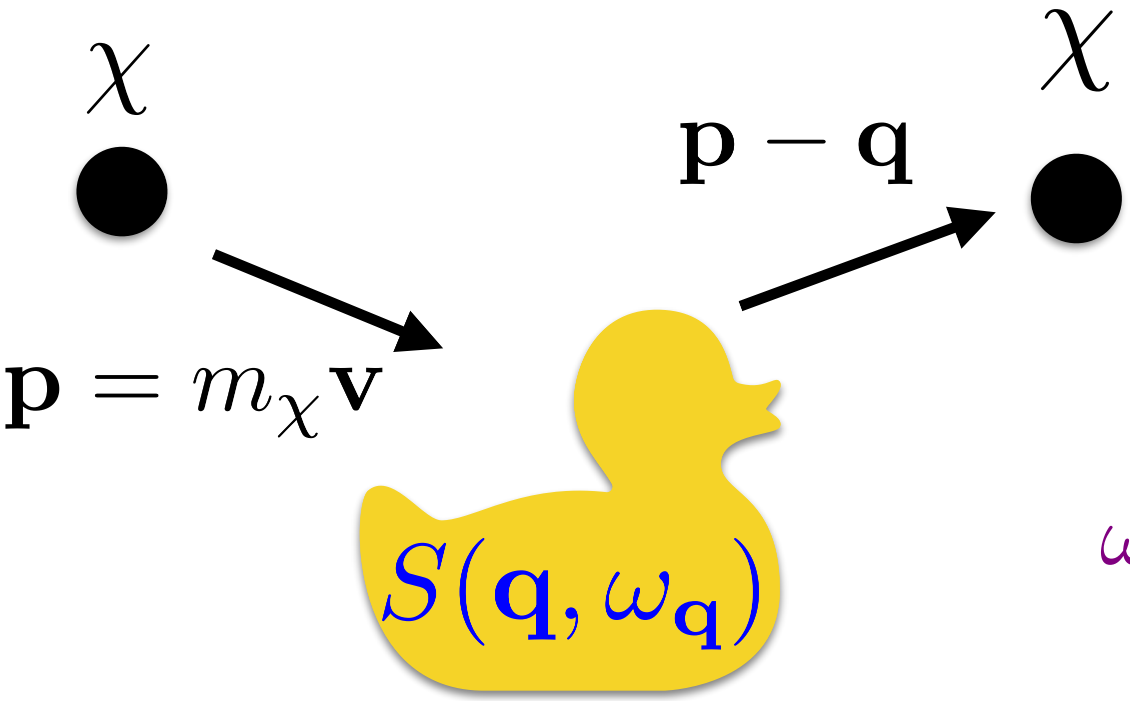
(insert your favorite detector here)

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



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

Energy deposited by DM:

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

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

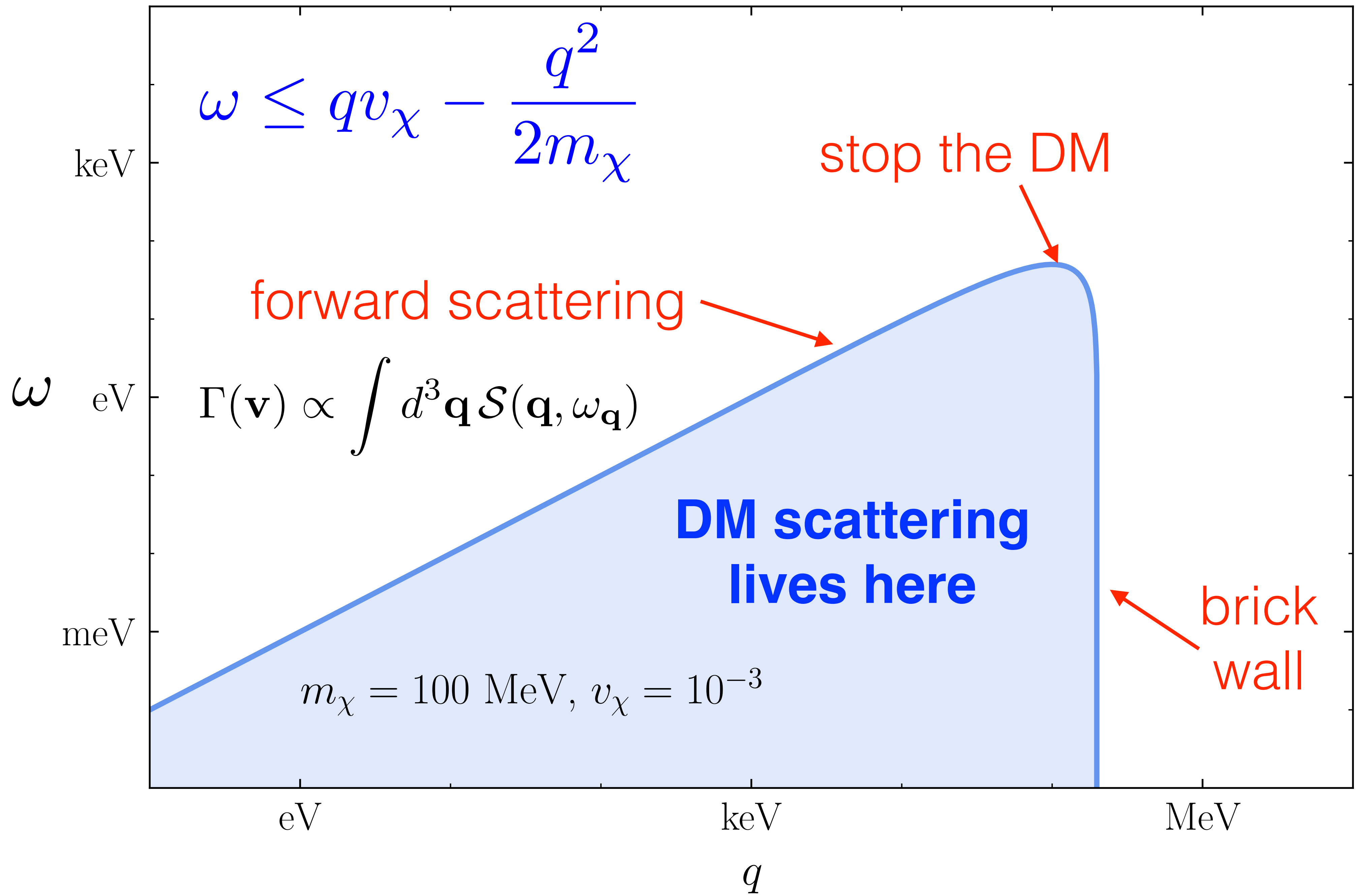
$$R \sim \int d^3\mathbf{v}\, f(\mathbf{v}) \int d^3\mathbf{q}\, F^2(\mathbf{q}) S(\mathbf{q}, \omega_\mathbf{q})$$

DM properties | Material properties

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

[Trickle, Zhang, Zurek, Inzani, Griffin, JHEP 2020; **YK** and Lin, Rep. Prog. Phys. 2022]

Sub-GeV DM kinematics



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