Prospects for Direct Detection of Sub-GeV Dark Matter

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ARC CoE for Dark Matter Particle Physics Annual Workshop
November 30, 2021

BOLD PEOPLE. VISIONARY SCIENCE. REAL IMPACT.

Outline

Particle Dark Matter

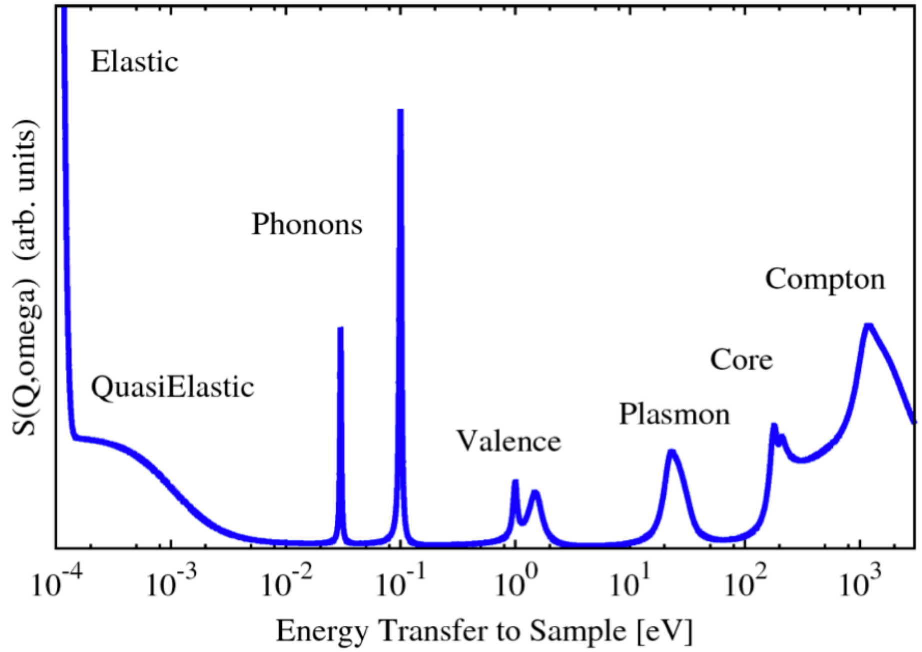
- Detection Challenges
- Direct Detection Landscape

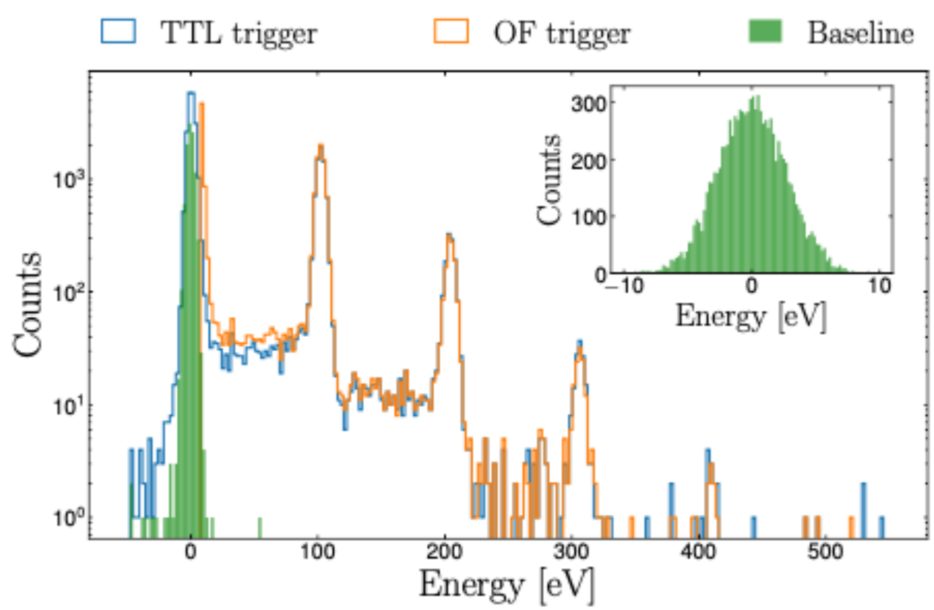
eV-Scale Detectors: HVeV

- Efficient Collection of Phonons
- Lowering Detection Threshold
- Understanding Backgrounds

Future Prospects

- Collective Excitations
- Single Phonon Detection
- Quantum Sensing for DM





Low Mass (< GeV) Dark Matter

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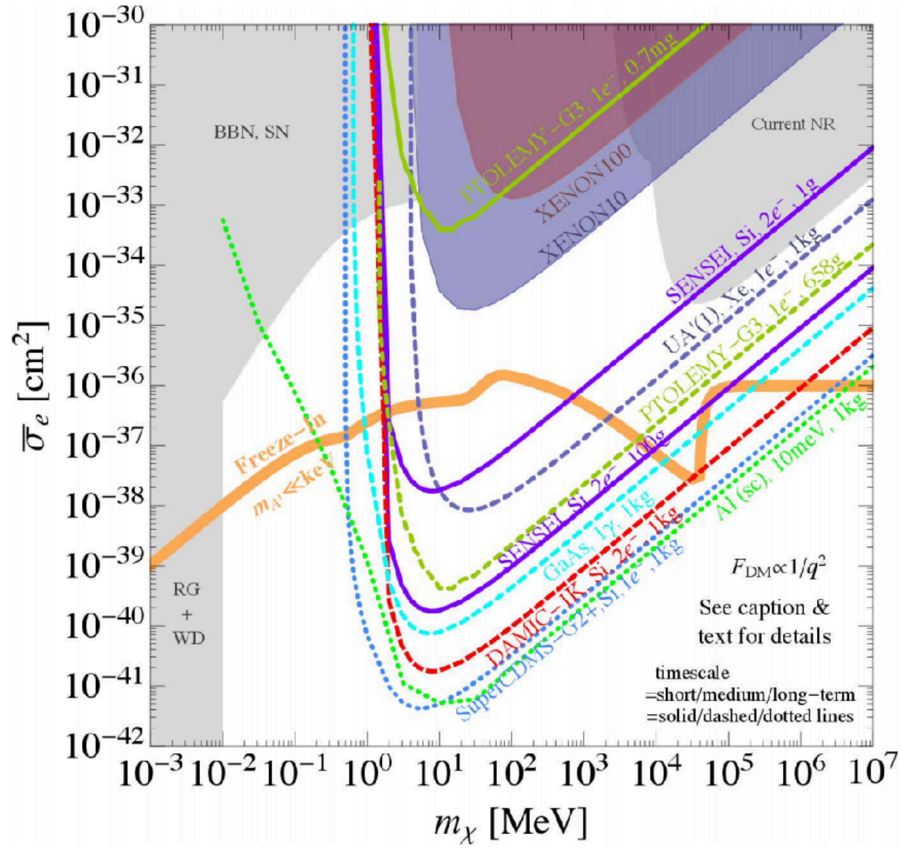
Dark matter in the keV-GeV mass range can produce the correct DM relic density if we introduce a new mediator between the DM and SM

Consider a massive ‘dark photon’ mediator coupled to a heavy particle which does not interact with SM as the only particles in a new ‘dark sector’

- If the mediator is heavier, dark matter can freeze out for the right coupling strengths in the same way as WIMP DM
- If the dark photon is the lighter particle, it can ‘freeze in’ as the ‘heavy’ DM decays into dark photons and SM particles

Much of the simplest parameter space completely unconstrained in the freeze-in scenario due to the momentum suppression

Lots of theory work done on these models in the last few years and multiple workshop reports



$$\langle \sigma_A v \rangle \propto \frac{g_D^4}{m_\chi^2}$$

Secluded

$$\langle \sigma_A v \rangle \propto \frac{g_D^2 g_{SM}^2 m_\chi^2}{m_{med}^4}$$

Direct

Low Mass (< GeV) Dark Matter

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$$R \sim \frac{1\text{Hz}}{\text{kg}} \left(\frac{\sigma_{e,p}}{10^{-36} cm^2}\right) \left(\frac{30\text{MeV}}{m_\chi}\right)$$

Relic density cross-sections for MeV DM correspond to Hz/kg event rates!

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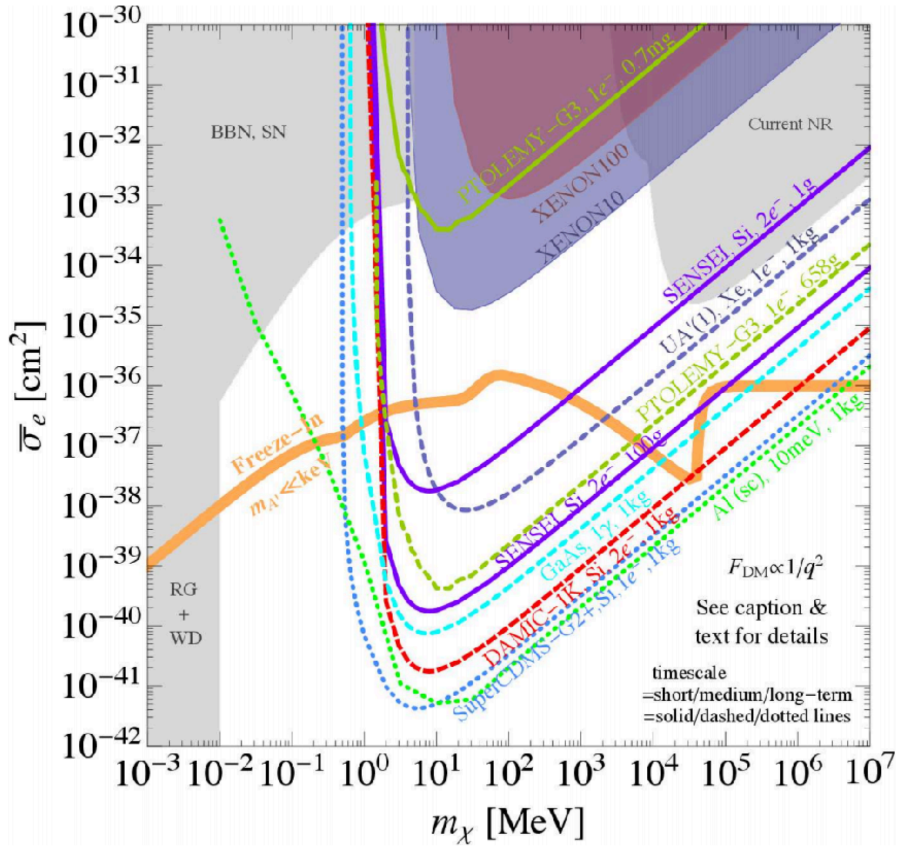

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Direct

Collision Kinematics

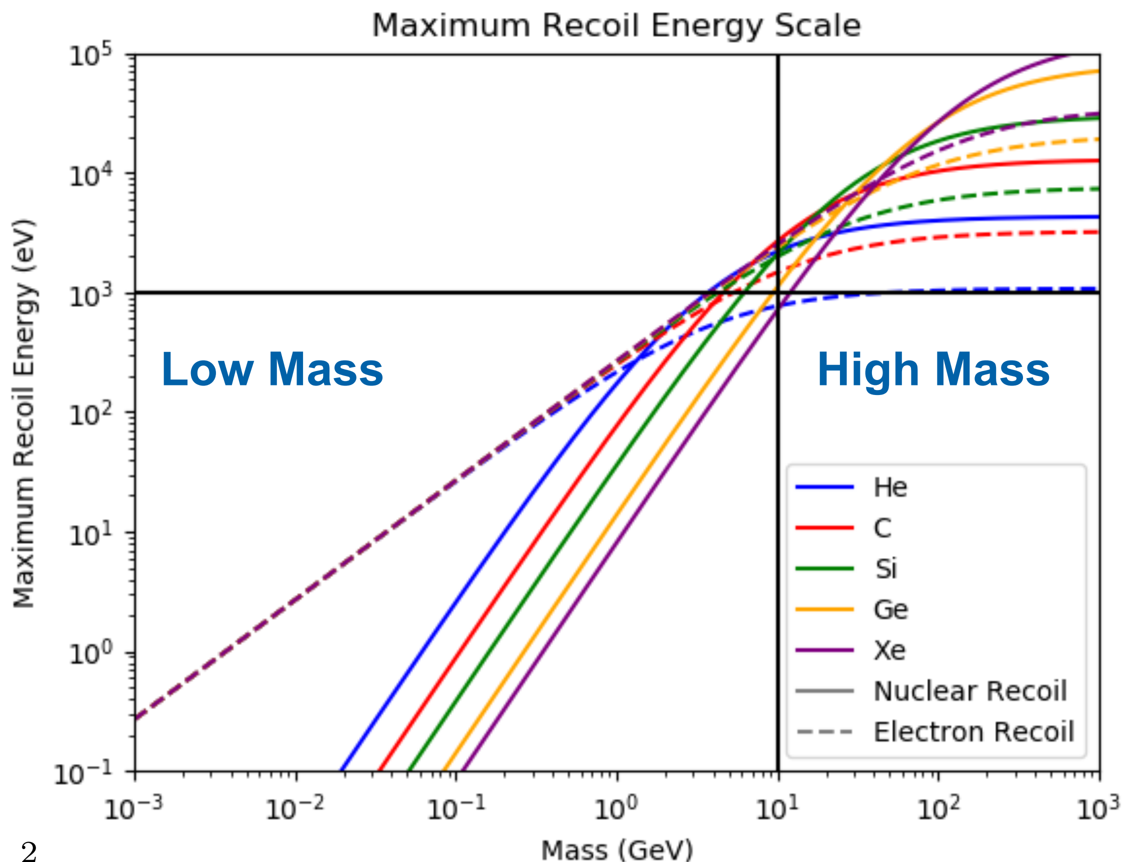
Recoil energy for typical DM velocity depends on target mass and recoil type

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

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

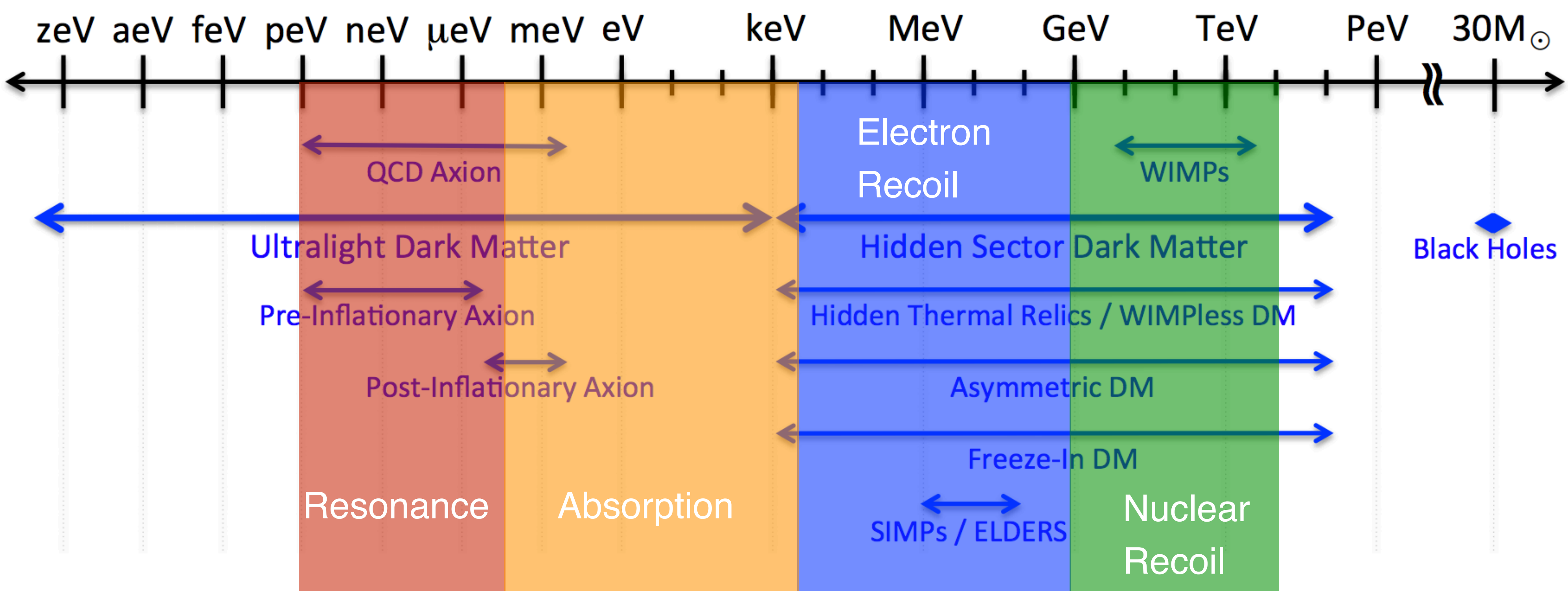
$$\Delta E_{ER} \leq \frac{1}{2} \mu_{N\chi} v^2 = \frac{m_N v^2}{2} \left(\frac{m_\chi}{m_\chi + m_N} \right)$$



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

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

(Some) Direct Searches for Dark Matter



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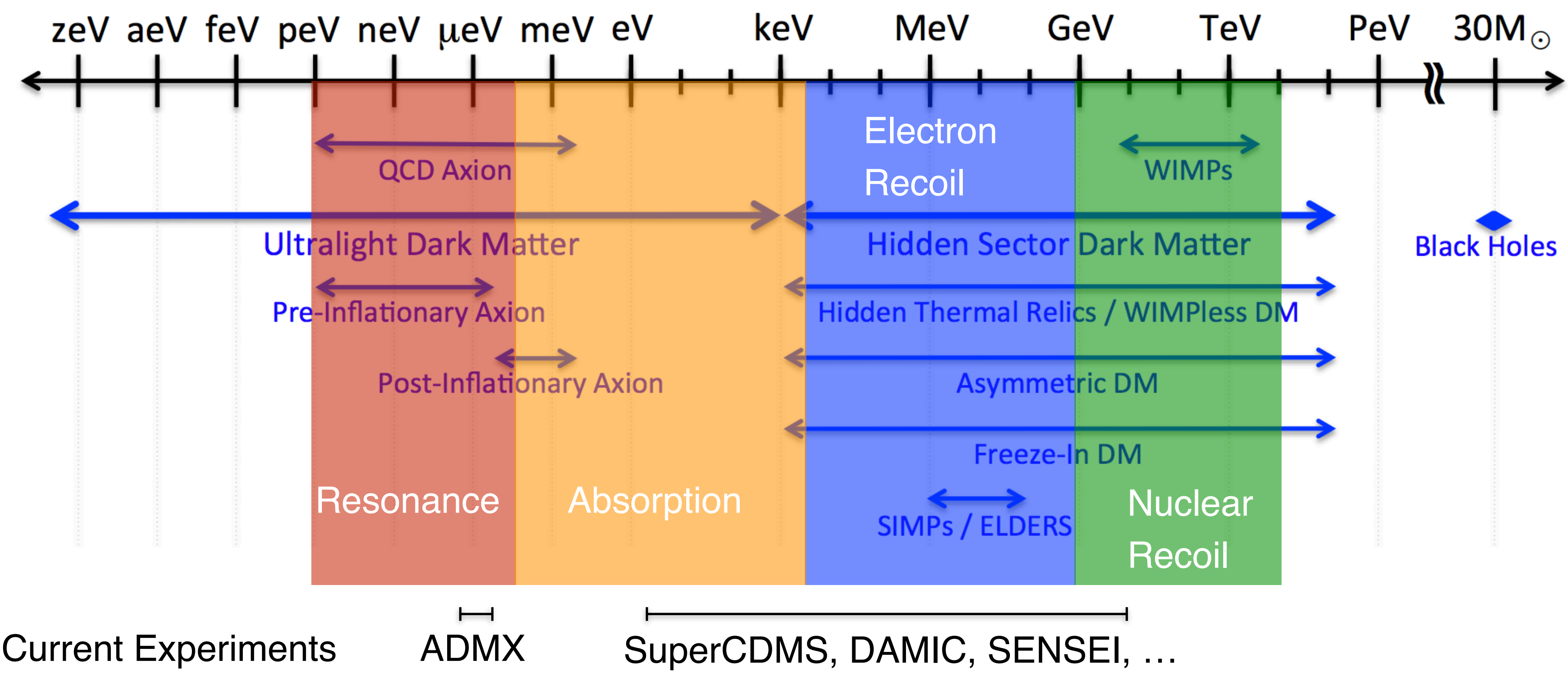

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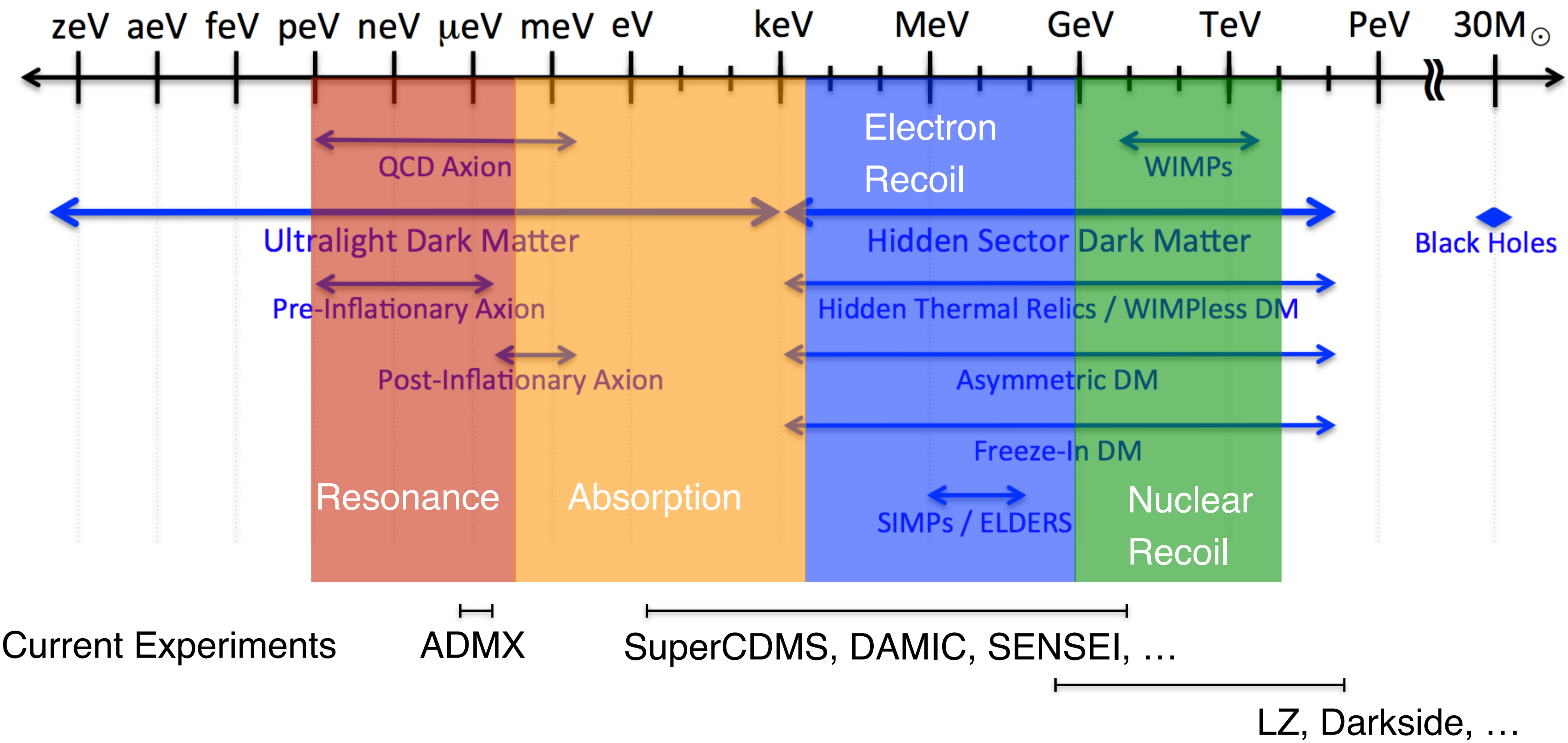

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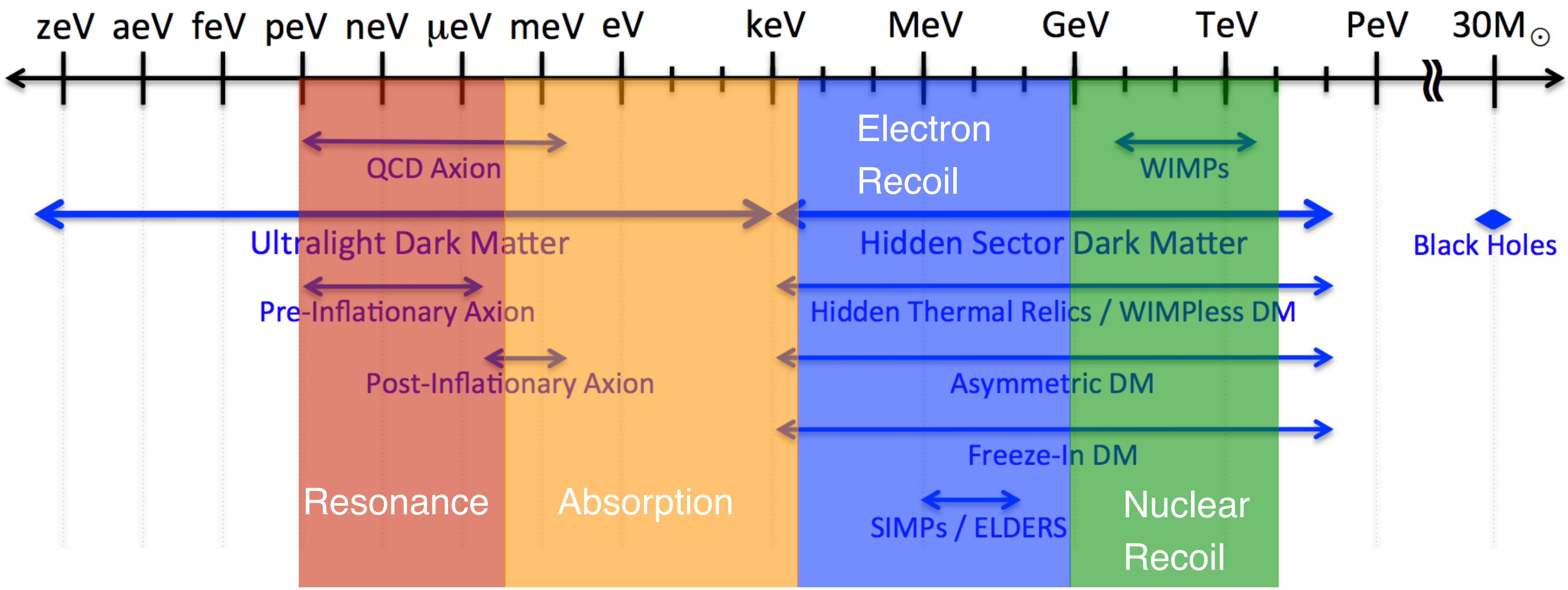
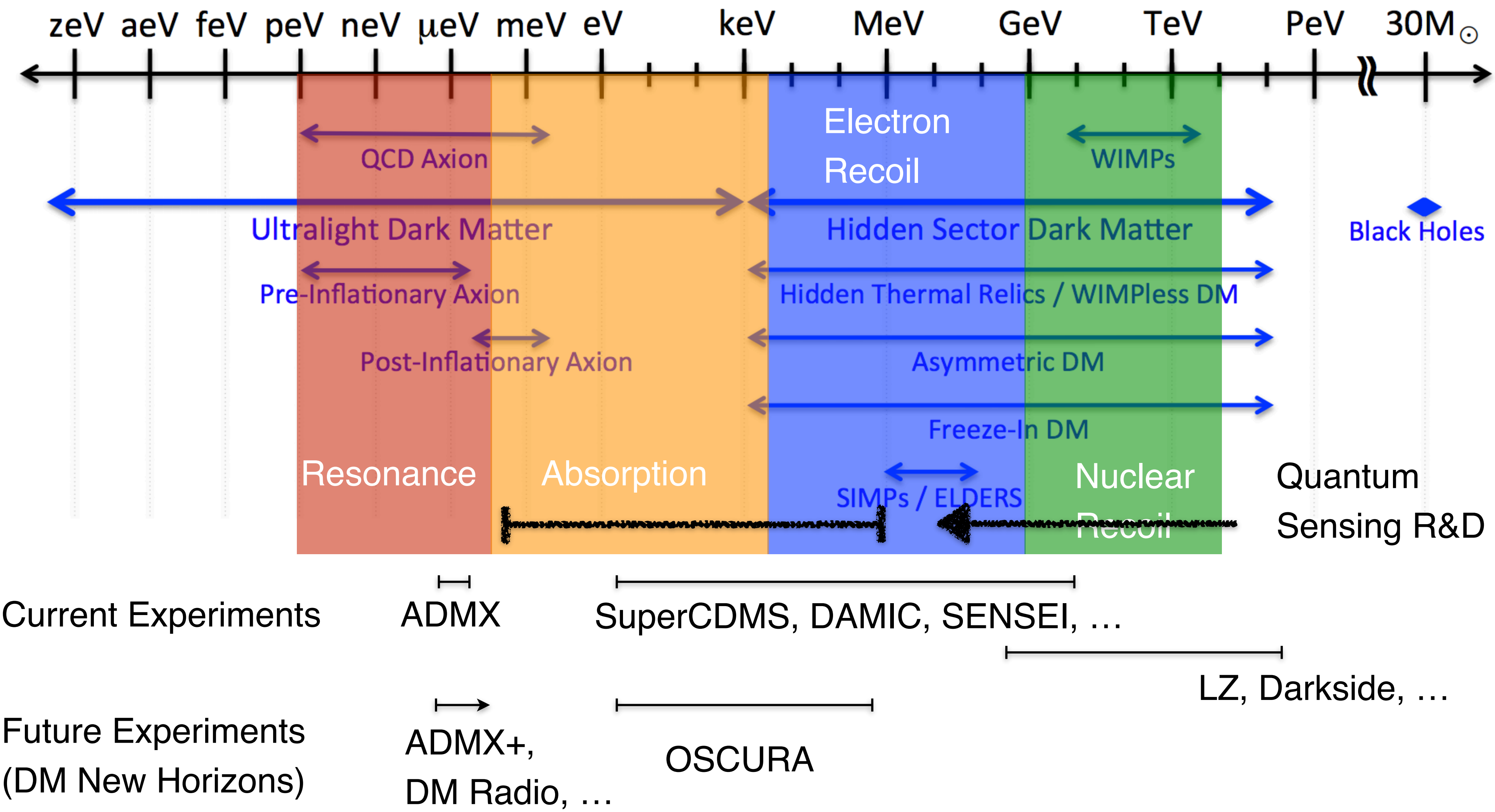


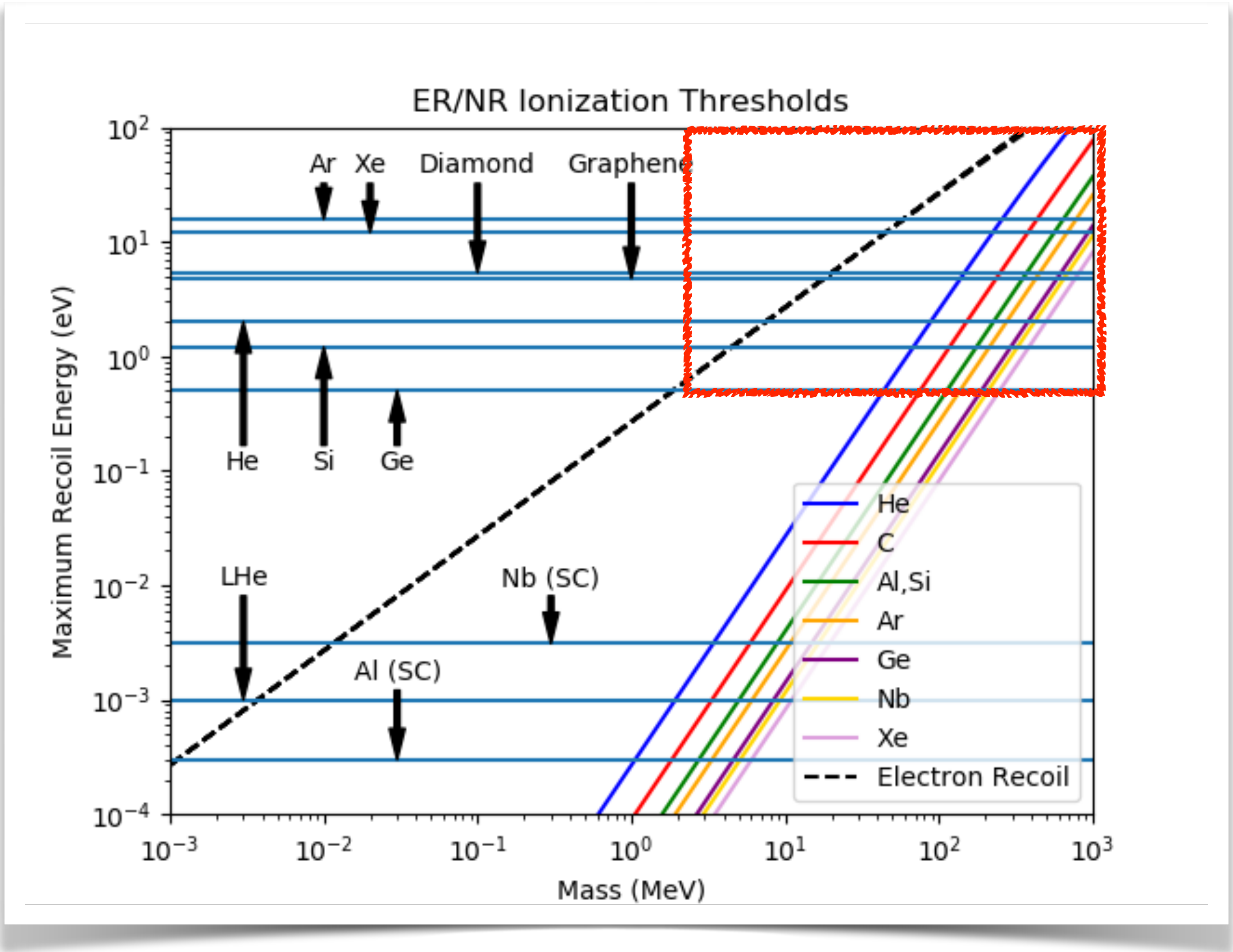
Current Experiments — ADMX — SuperCDMS, DAMIC, SENSEI, … — LZ, Darkside, …

Future Experiments (DM New Horizons) — ADMX+, DM Radio, … — OSCURA

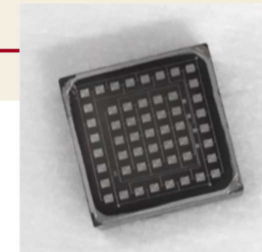
(Some) Direct Searches for Dark Matter



Searching for MeV-Scale DM: eV-Scale Thresholds

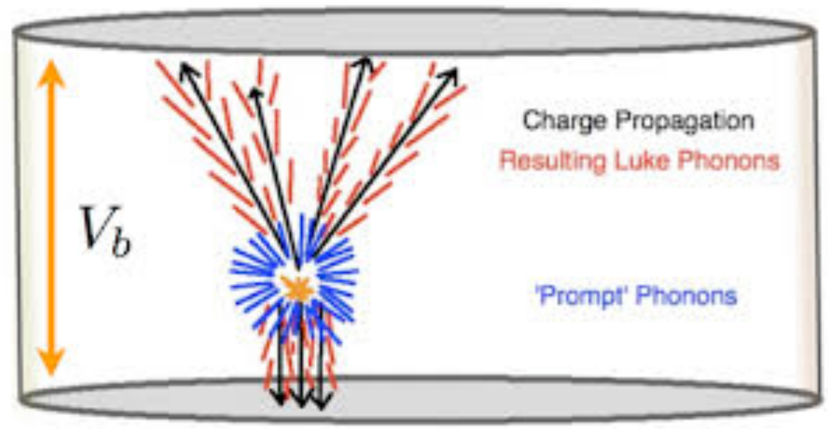


Athermal Phonon Sensors (SuperCDMS HVeV)



In any recoil event, all energy eventually returns to the phonon system

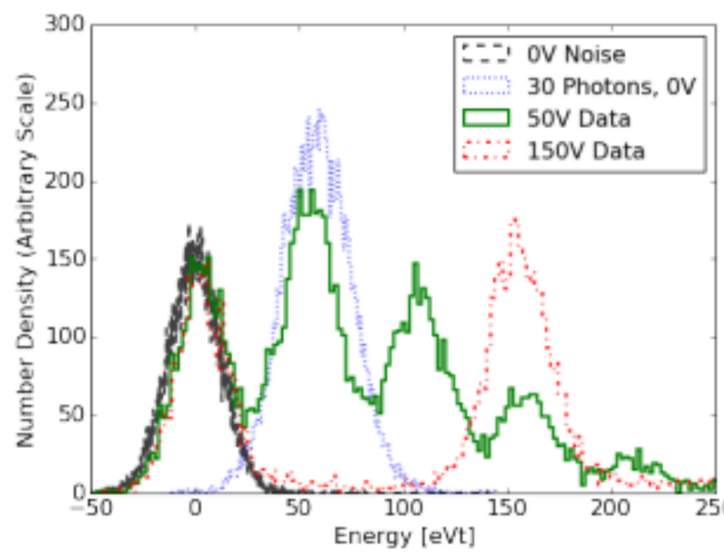
- Prompt phonons produced by interaction with nuclei
- Indirect-gap phonons produced by charge carriers reaching band minima
- Recombination phonons produced when charge carriers drop back below the band-gap



Phonons are also produced when charges are drifted in an electric field; makes sense by energy conservation alone

Total phonon energy is initial recoil energy plus Luke phonon energy, as shown at right

$$
\begin{aligned}
E_{phonon} &= E_{recoil} + V * n_{eh} \\
&= E_{recoil}\left[1 + V * \left(\frac{y(E_{recoil})}{\varepsilon_{eh}}\right)\right]
\end{aligned}
$$



Athermal phonons collected in superconducting aluminum fins and channeled into Tungsten TES, effectively decoupling crystal heat capacity from calorimeter (TES) heat capacity

Romani et. al. 2017 (https://arxiv.org/abs/1710.09335)

Optimal Readout and Triggering

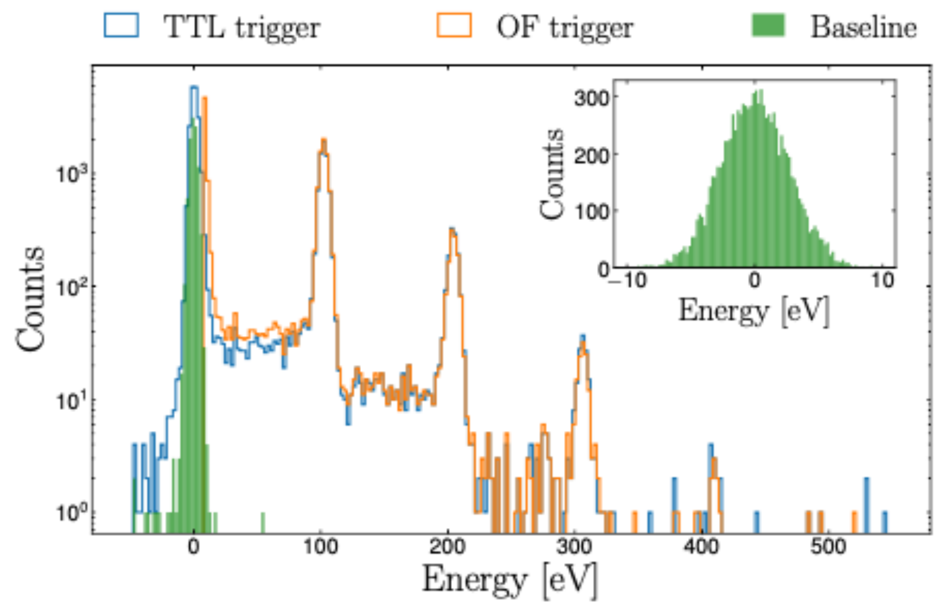
Best performance is by HVeV (gram-scale Si) detector; has repeatedly achieved 2.5 eV resolution, and <10 eV threshold, with the TES-based SuperCDMS sensors.

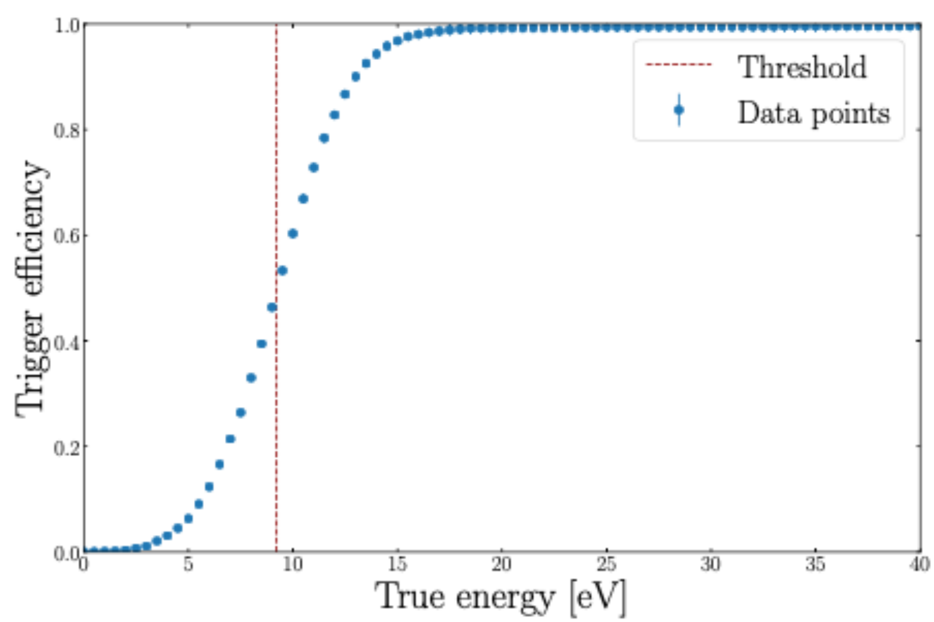
- This detector was run as a DM detector at Northwestern and NEXUS, and in the TUNL neutron beam

Run in continuous readout mode for trigger-free operation, triggering done offline

- Optimal filter trigger and processing with time-shifting and pileup rejection

Achieves >30% energy efficiency, implying that the intrinsic resolution of the TES arrays are less than 1eV

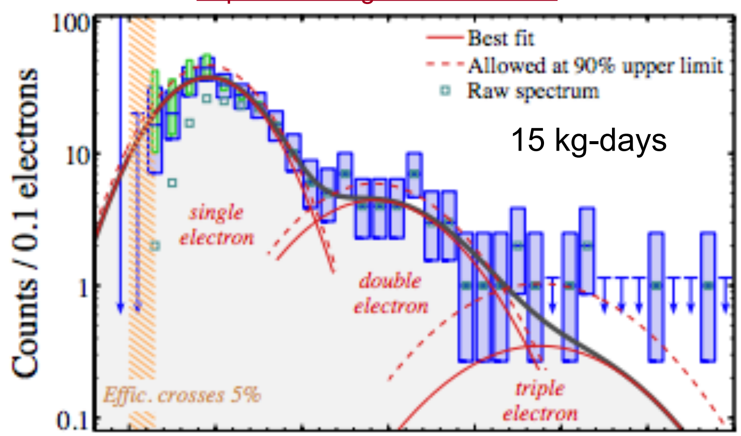


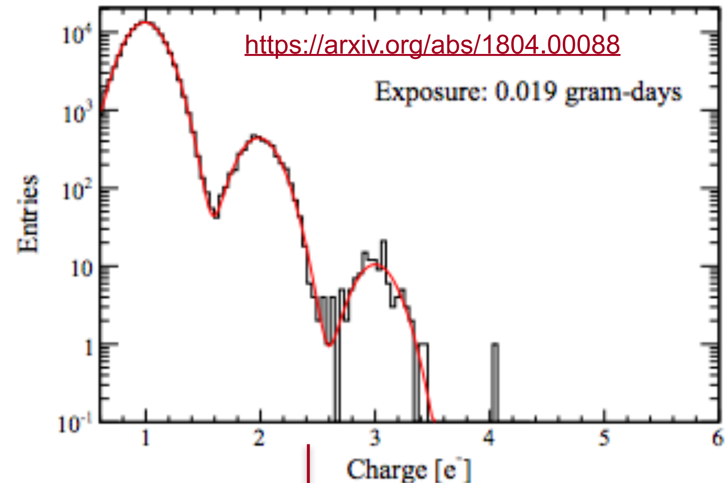


Ren et al (ArXiv:2012.12430)

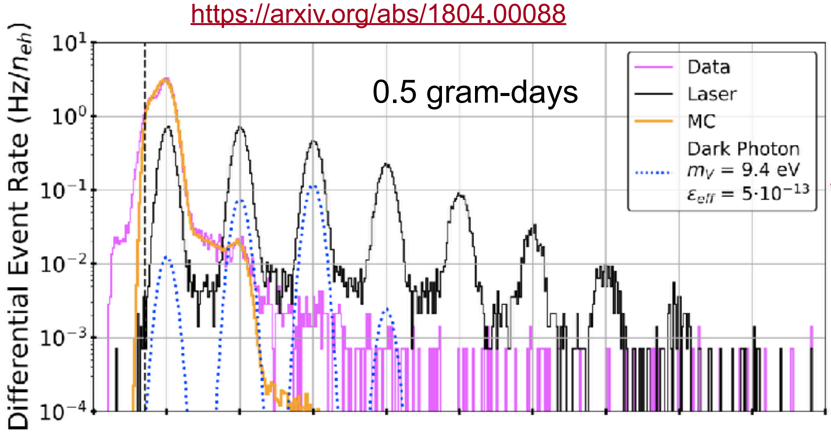
Comparison of ER Experiments (2018)

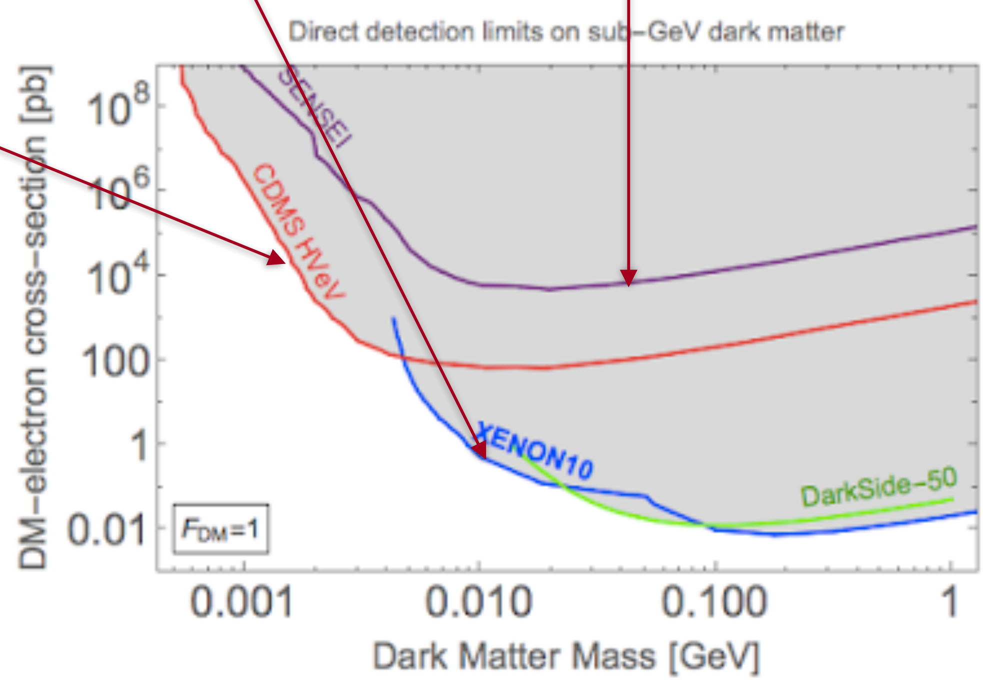
https://arxiv.org/abs/1206.2644





https://arxiv.org/abs/1804.00088



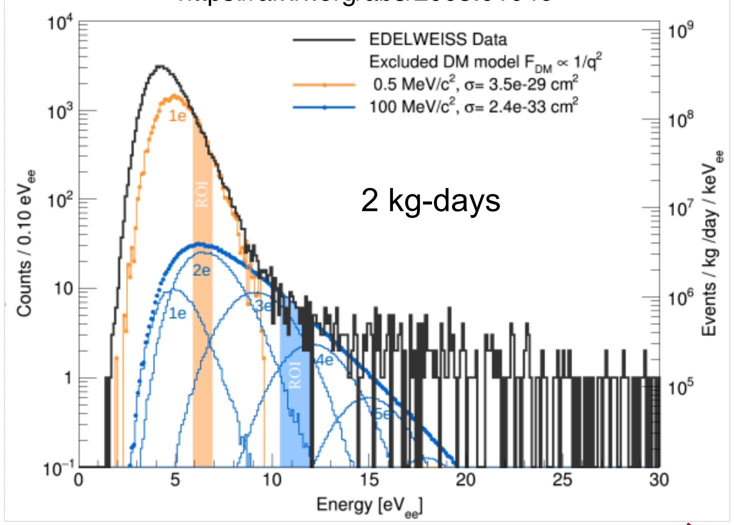


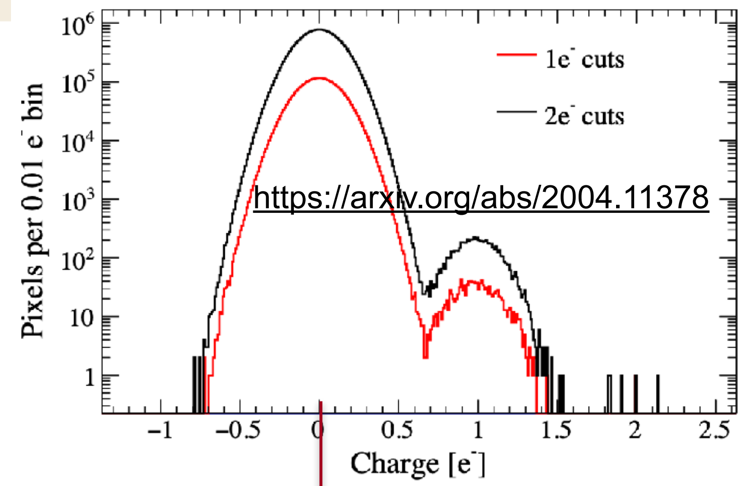
http://resonaances.blogspot.com/2018/05/dark-matter-goes-sub-gev.html

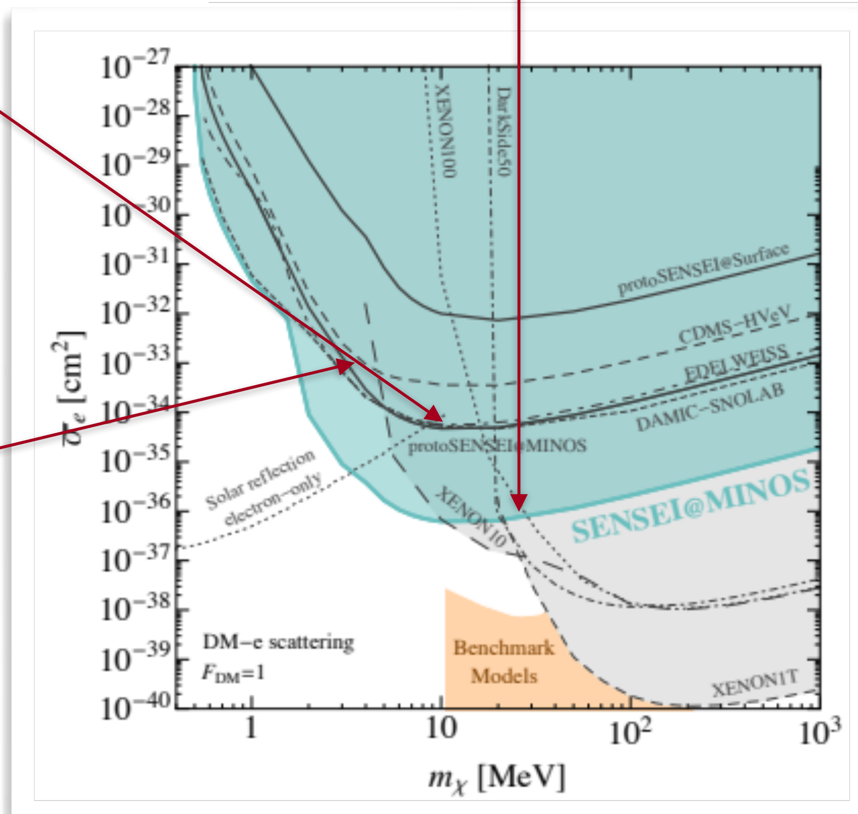
Comparison of ER Experiments (2020)

SLAC

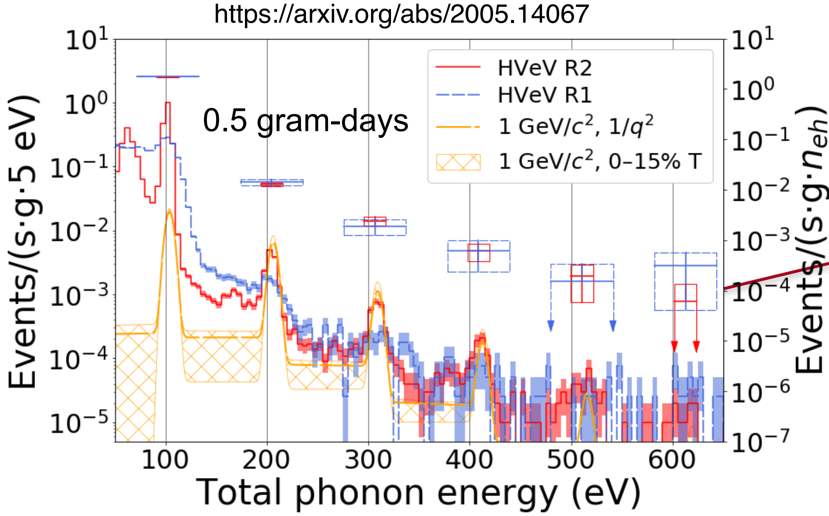
https://arxiv.org/abs/2003.01046



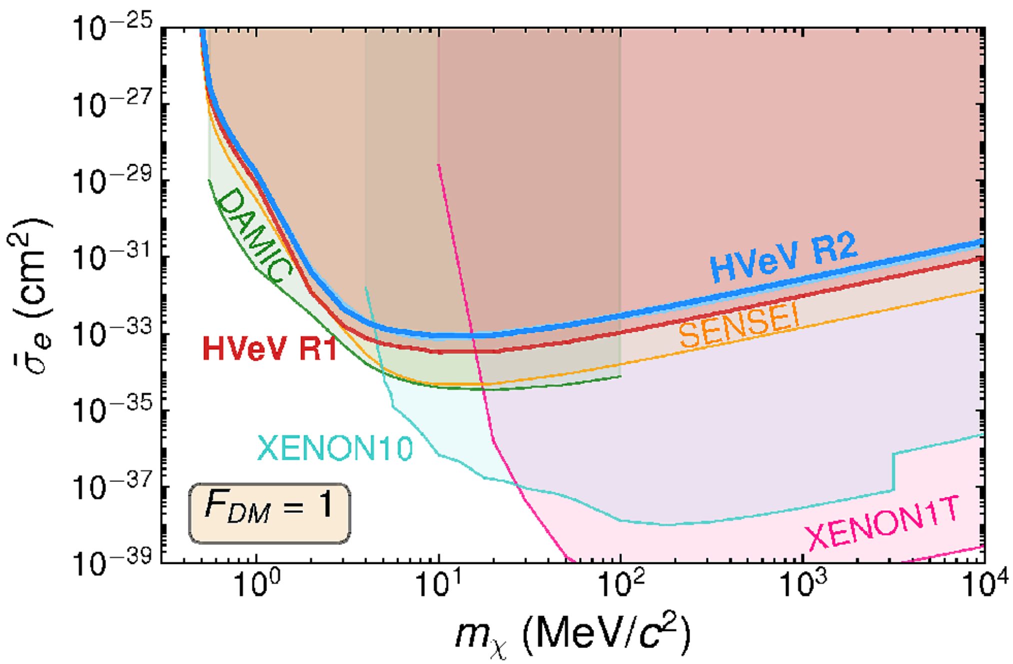


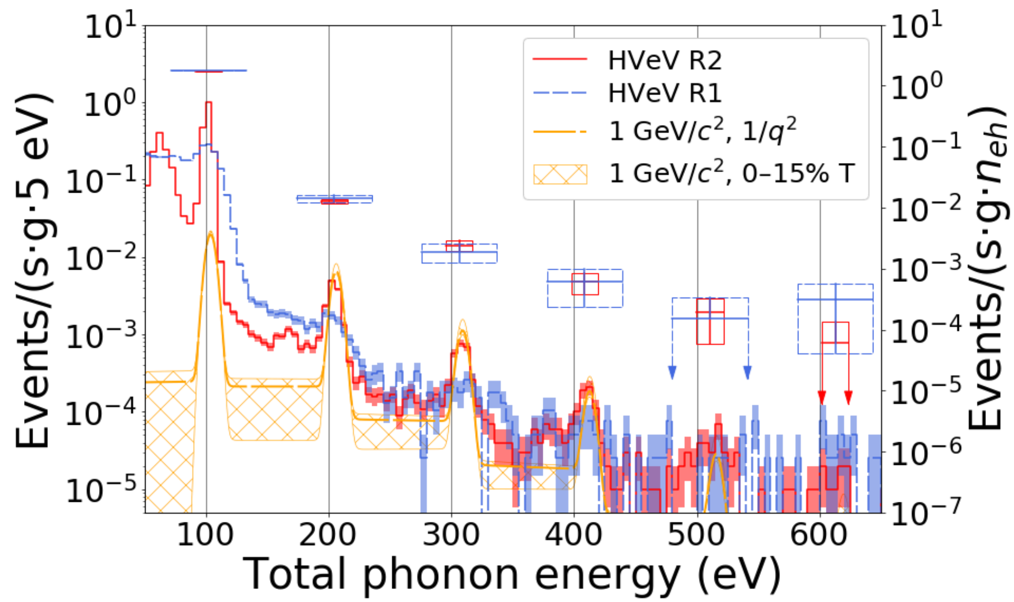


https://arxiv.org/abs/2005.14067



HVeV Run 2

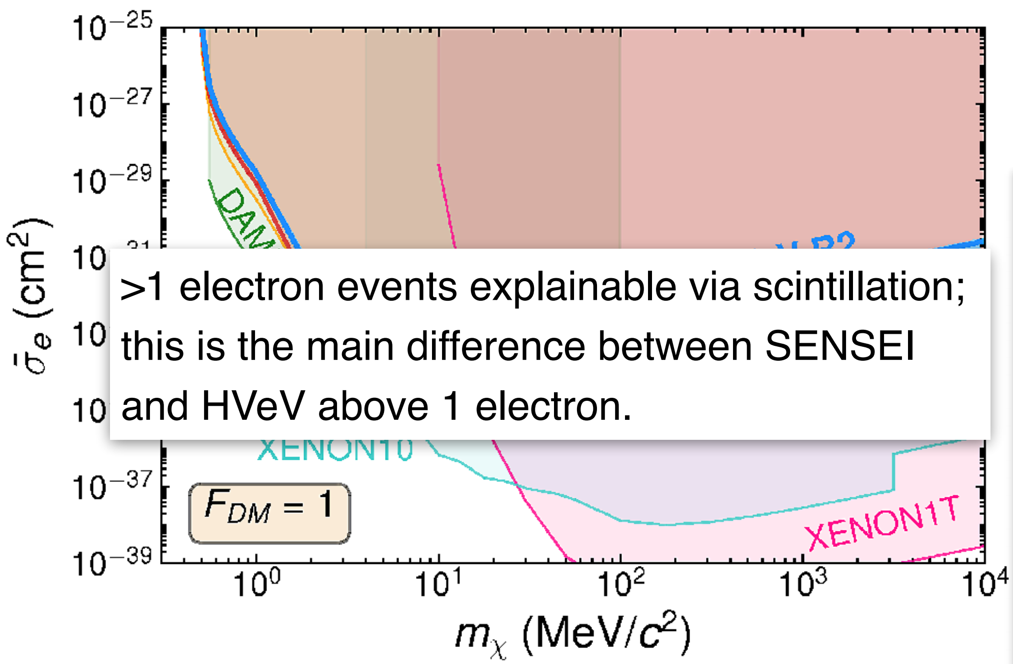




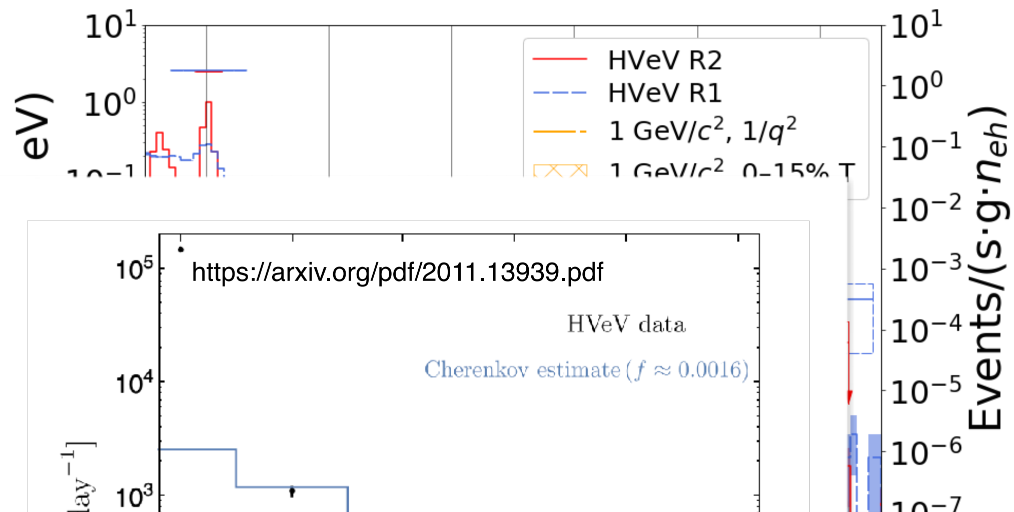
HVeV second run taken with 3 eV resolution detector over the course of 3 weeks:

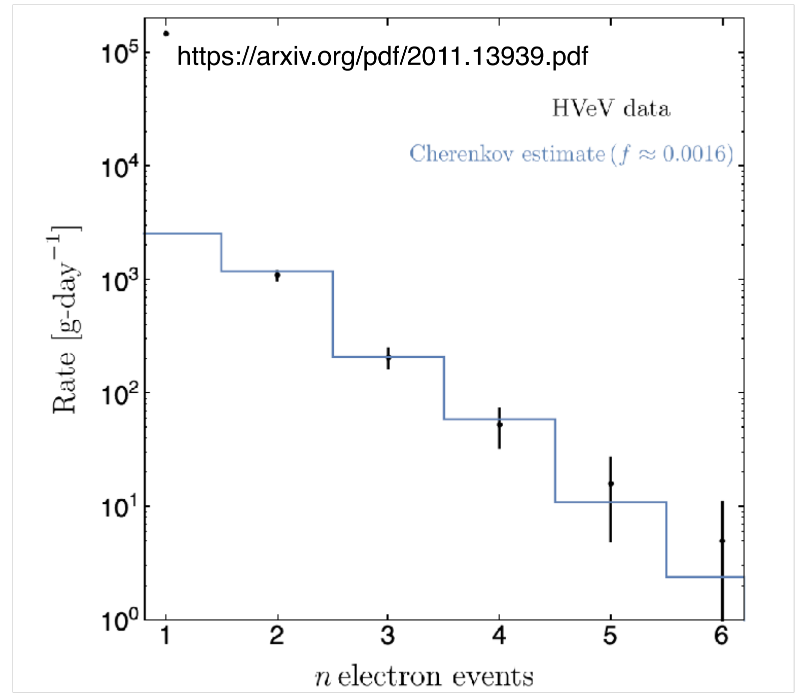
- 60V and 100V spectra show identical backgrounds; signal seen not voltage dependent
- Different prototype, run in a different lab, in a different state
- 0V data acquired with ~10 eV threshold, results still being analyzed
- Rates in *every charge bin* consistent with Run 1…that was completely unexpected

HVeV Run 2



>1 electron events explainable via scintillation; this is the main difference between SENSEI and HVeV above 1 electron.





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HVeV Run 3 Status

Science run finished earlier this year with 3 detectors (including detectors used for Runs 1-2, and a third new design)

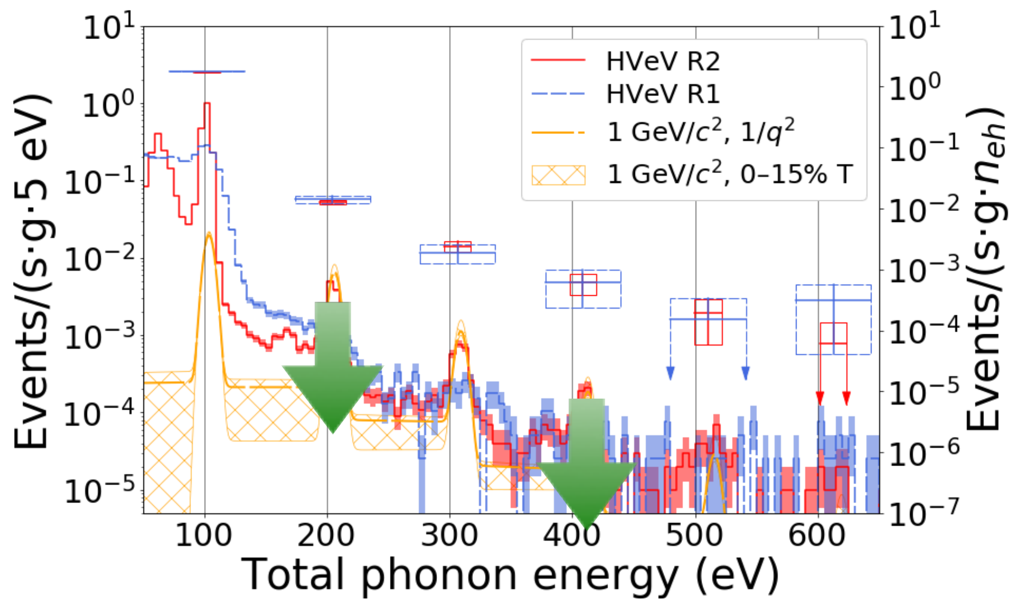
- Using coincidence in time to reject bursts of Cherenkov photons
- Building model of leakage pileup to project component of single charge leakage in second electron-hole pair bin
- Still expect single-electron bin is instrumental

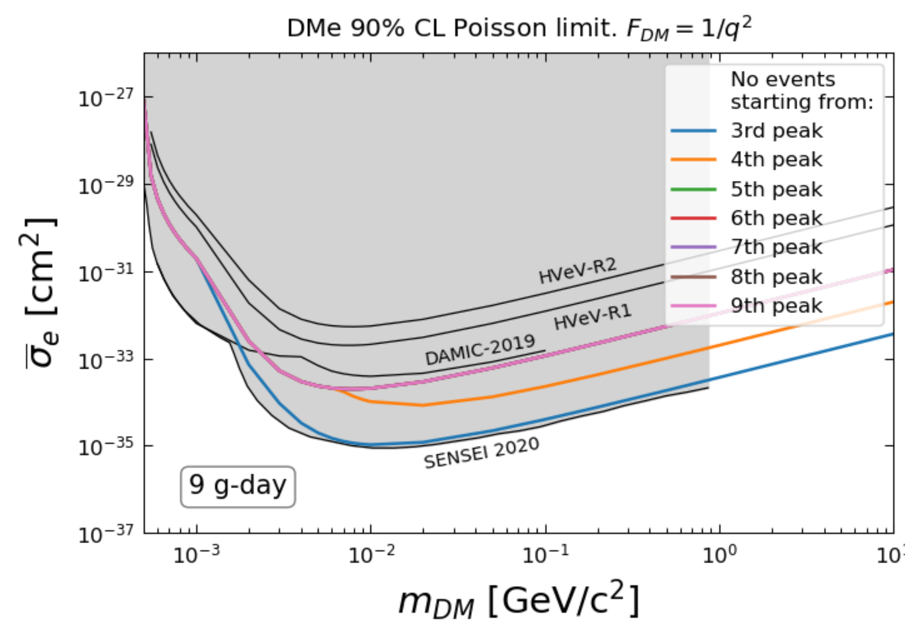
Run started 12/23, officially ended 2/9

- Accumulated ~1 g-days per calendar day
- ~40 g-days of exposure total

Quick turn around expected on analysis, new results by Early 2022

- *Many* auxiliary science results to follow on 0V-HV correlations





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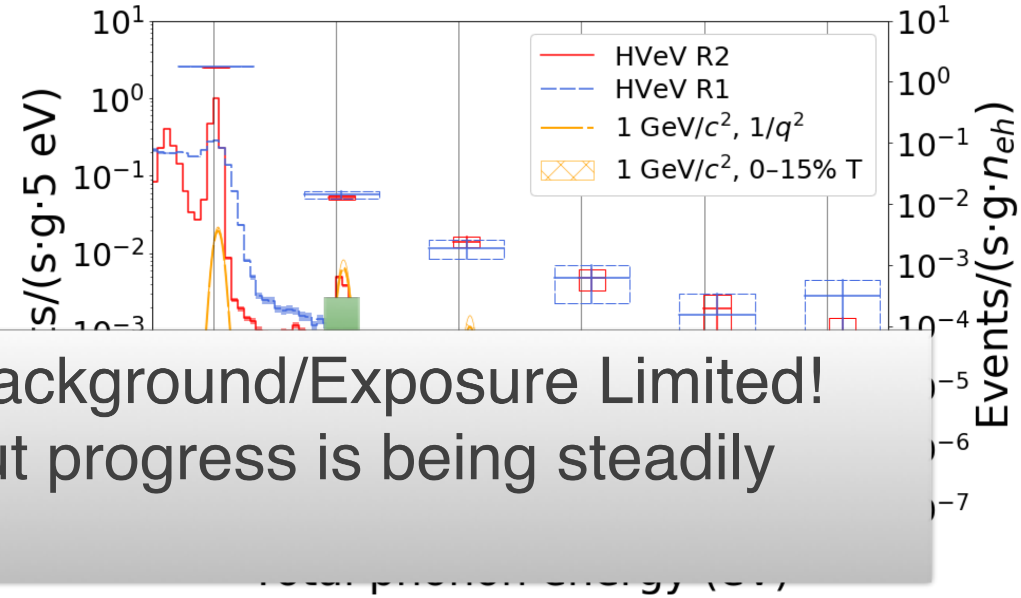

ERDM Above ~2 MeV Now Background/Exposure Limited!
Leakage R&D is important, but progress is being steadily made

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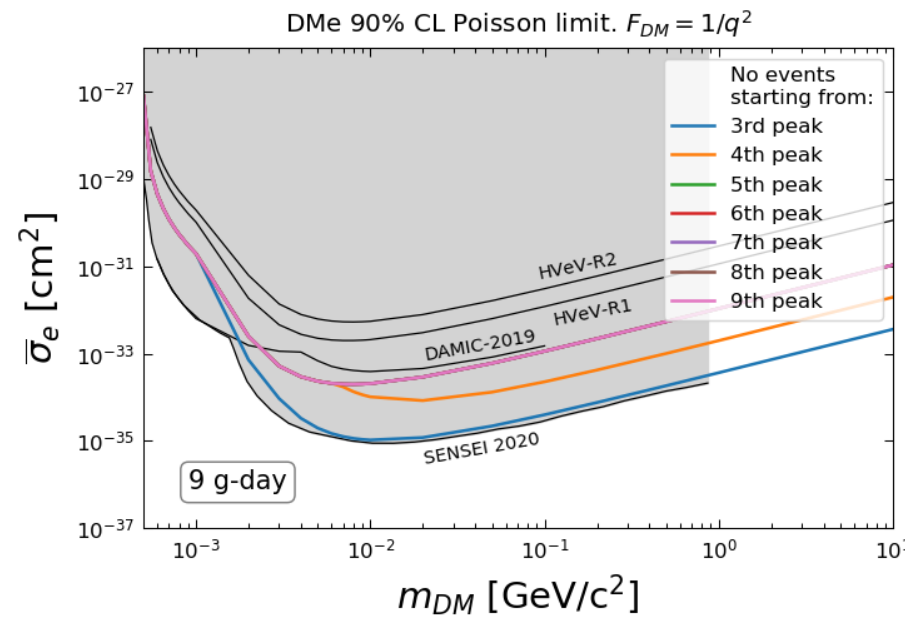
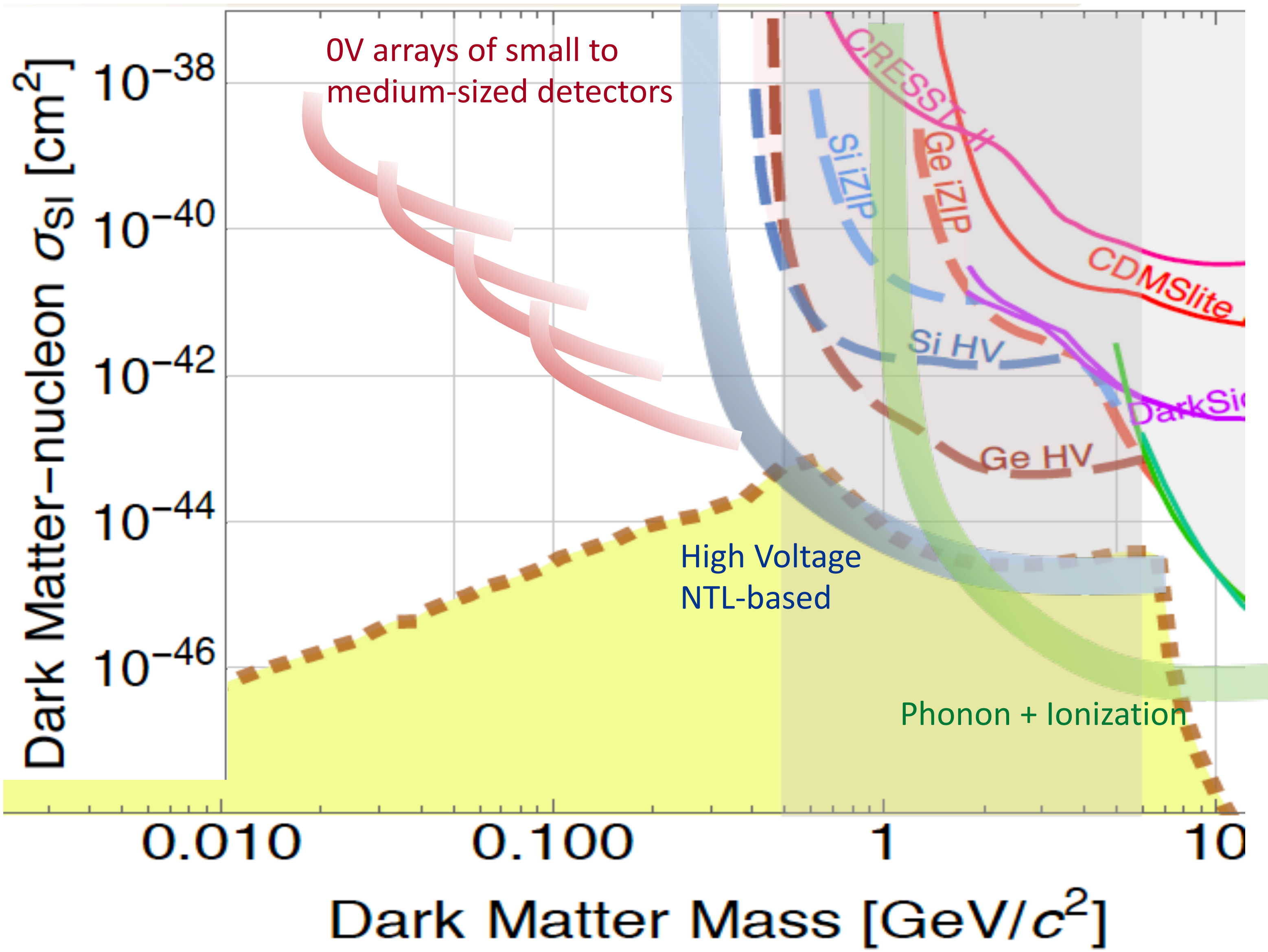


This is an Upgrade Path for SuperCDMS SNOLAB!



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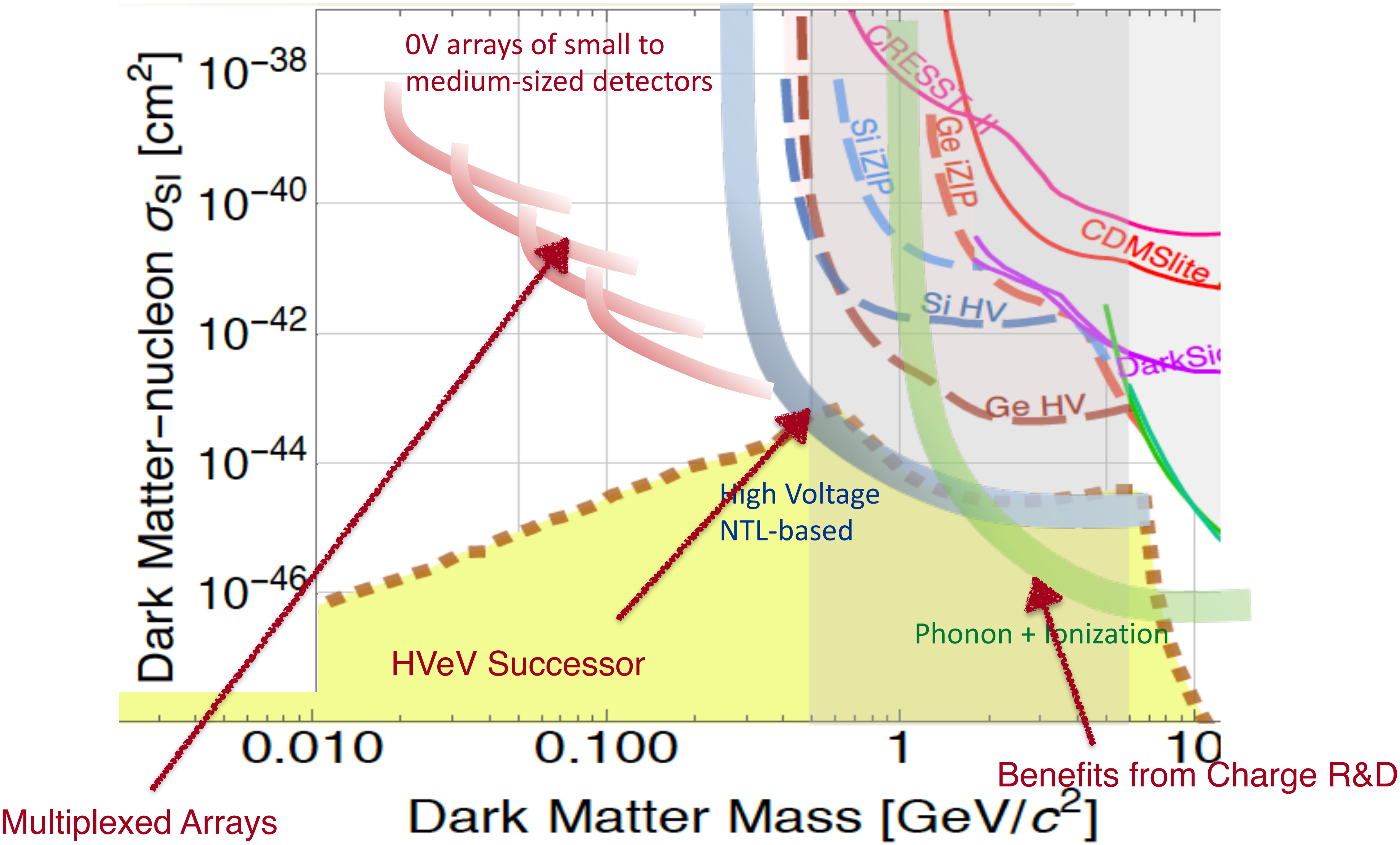
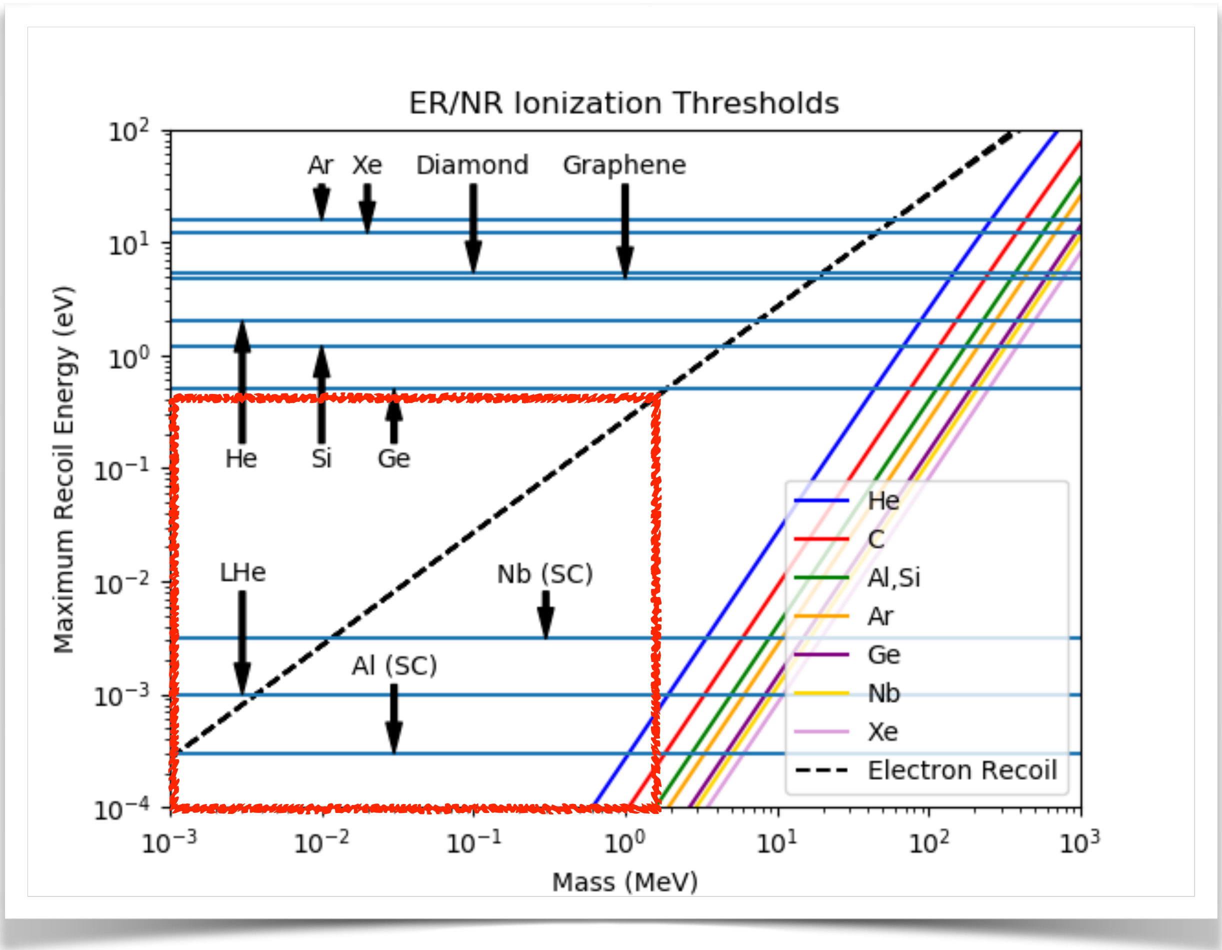
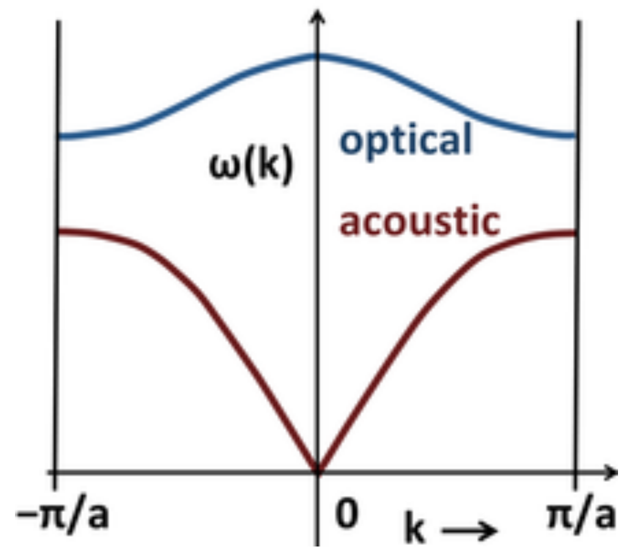


Quantum Sensing R&D For Dark Matter: meV Thresholds

SLAC





+ Phonons

Energy Scales in Ordered Systems

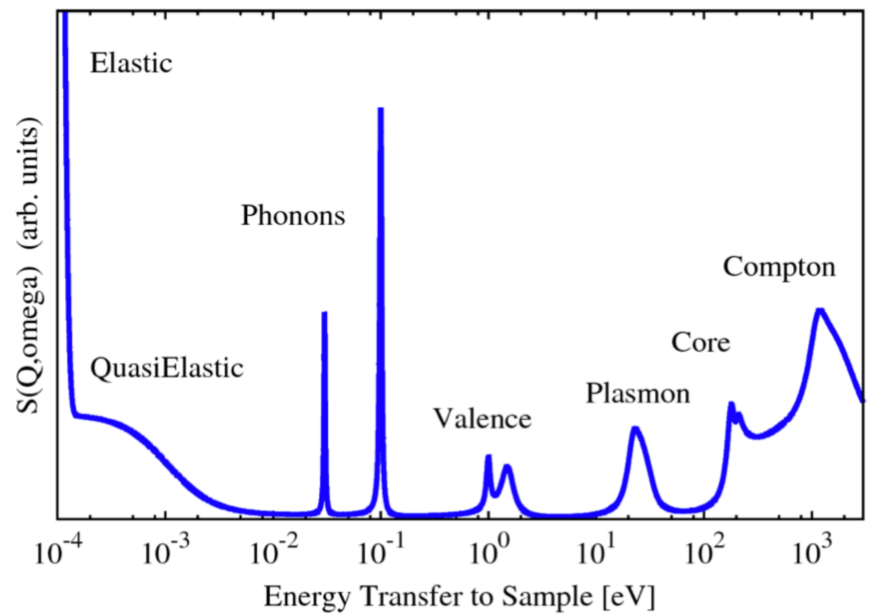
Both the eV energy scale, we can no longer treat heat as a continuous fluid; quantization becomes important

Even at the eV-scale, we begin to see materials respond differently due to collective effects

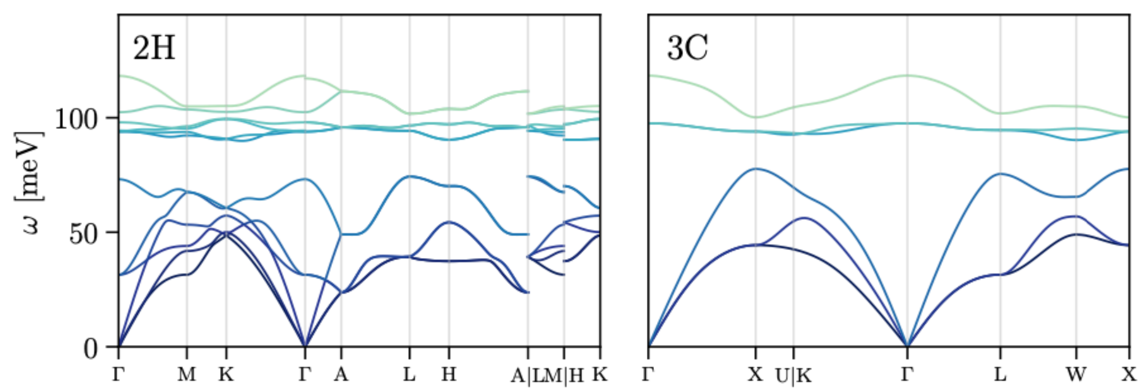
Near the meV scale, the free particle scattering picture has completely broken down; we're now talking about phonon production and Cooper pair breaking, or interactions on the same energy scale as the spin-orbit coupling

- Optical phonons have energies of around 100 meV
- Acoustic phonons have non-trivial dispersion relations
- Phonon signal becomes quantized and dependent on interaction coupling!

Material structure determines interaction picture as much as chemical makeup

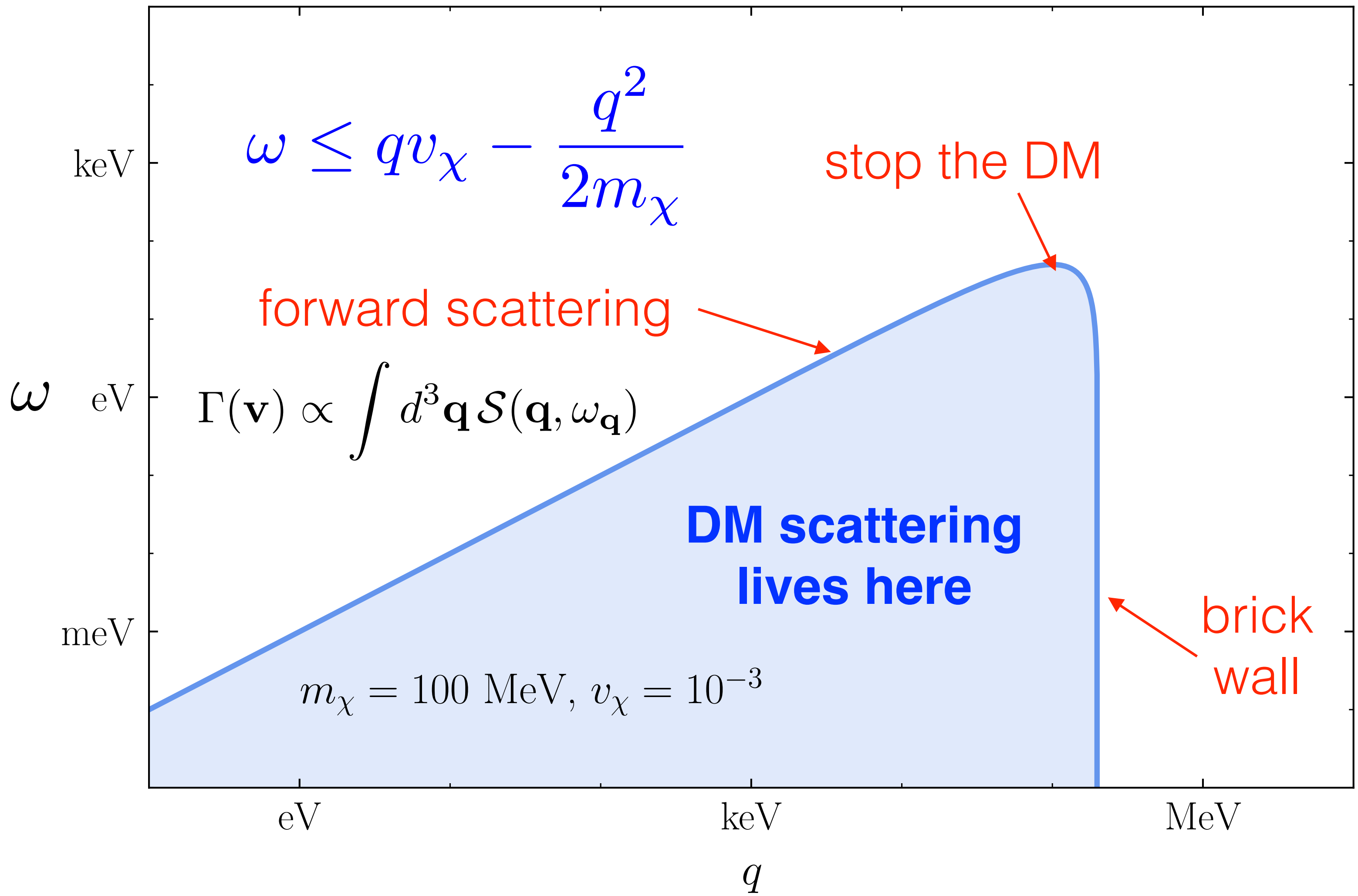


Phonon band structure in SiC



Griffin et. al. (2008.08560)

DM kinematics and the Response Function



Berggren, Hochberg, Kahn, **NK**, Lehman, Yu, ArXiv:2101.08263

Slides Courtesy Y. Kahn

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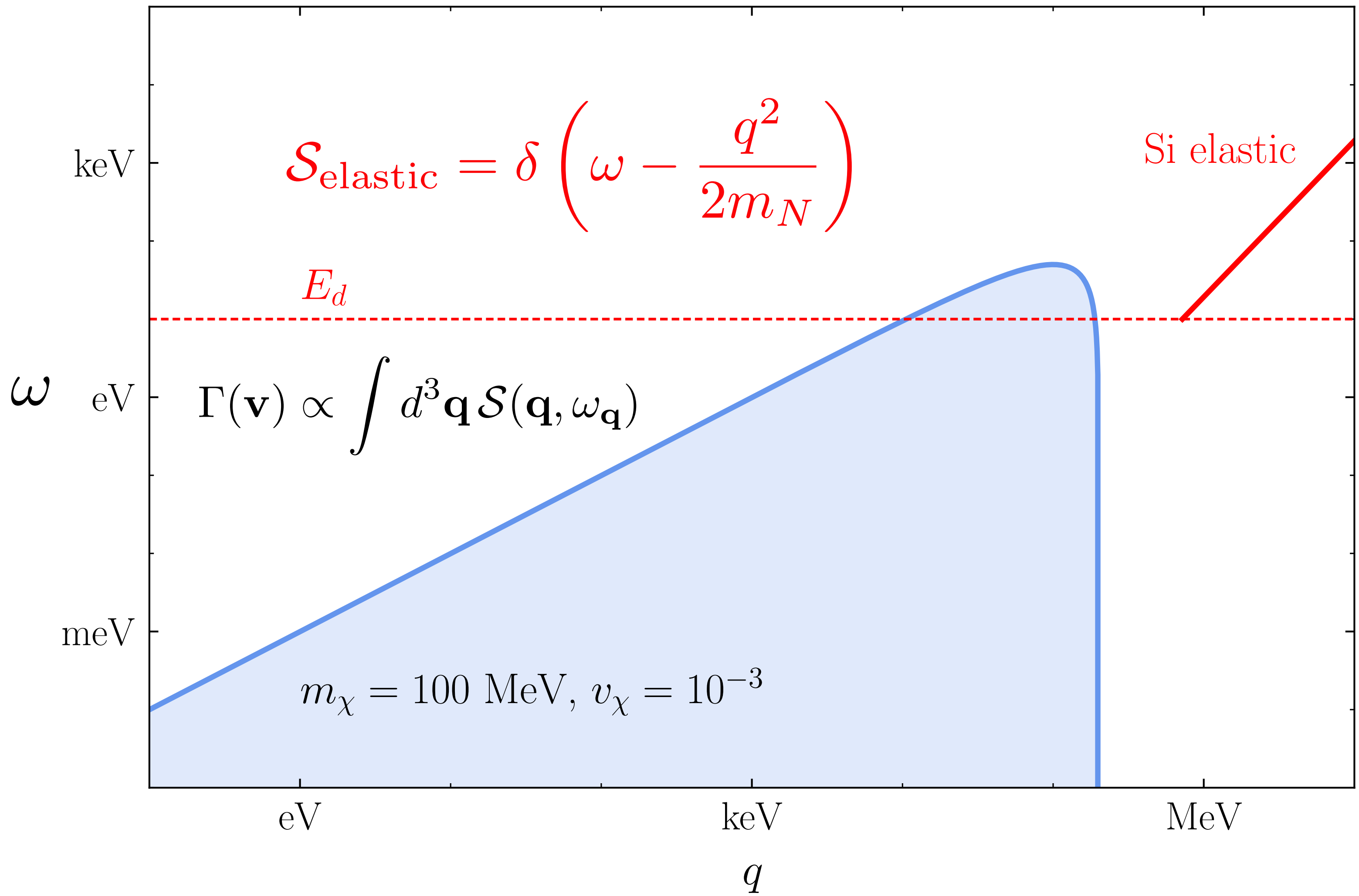

Delta function response = free particle

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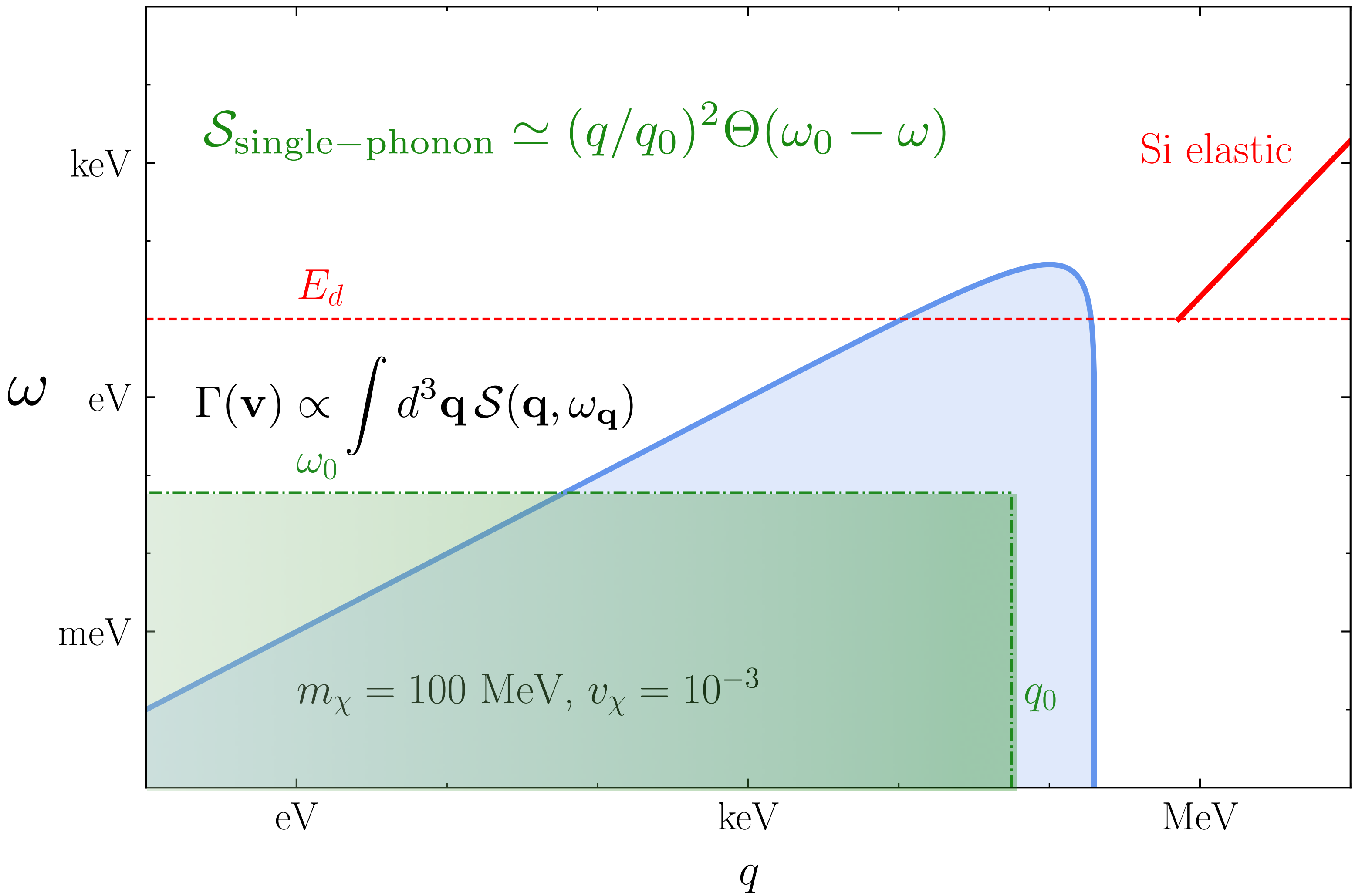

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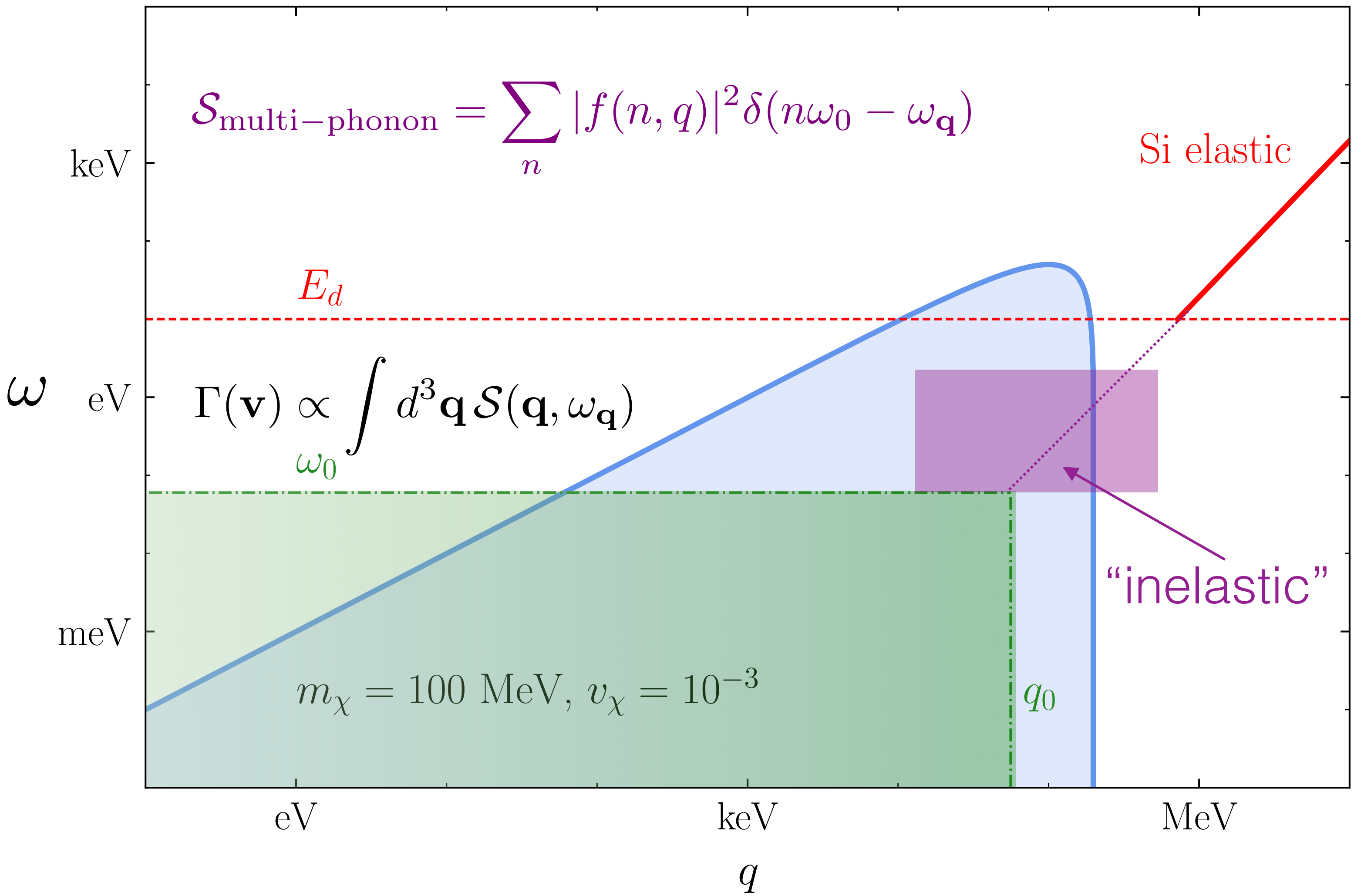

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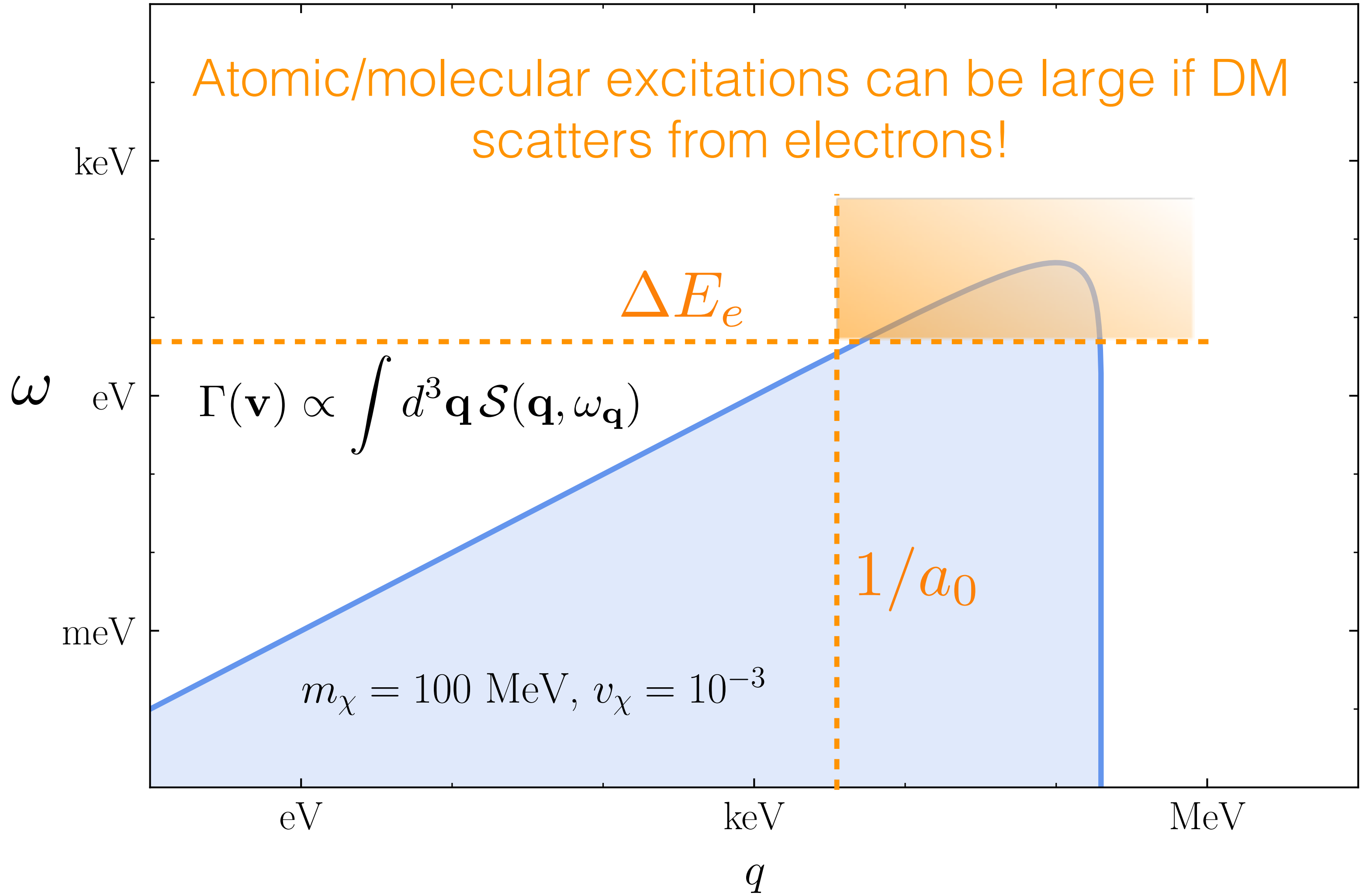

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Dielectric Function Formalism

In the low-energy regime, we can express electromagnetic interactions in terms of the loss function:

$$\frac{d^2\sigma}{d\Omega_2 d\hbar\omega_2} = r_0^2(\mathbf{e}_1 \cdot \mathbf{e}_2)^2 \left(\frac{\omega_2}{\omega_1}\right) S(\mathbf{q},\omega), \quad r_0 = \frac{e^2}{mc^2}$$

This same language can be used to describe DM interactions, because the structure factor is only determined by interactions within the target material:

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

The loss function is well-characterized in the literature, and toy models exist for different types of materials - doesn't require detailed DFT calculations

Recent paper explores a handful of new materials with data and toy models, reducing turnaround on material exploration from years to months

- Also allows us to determine generic features of a material useful for DM detection in different models

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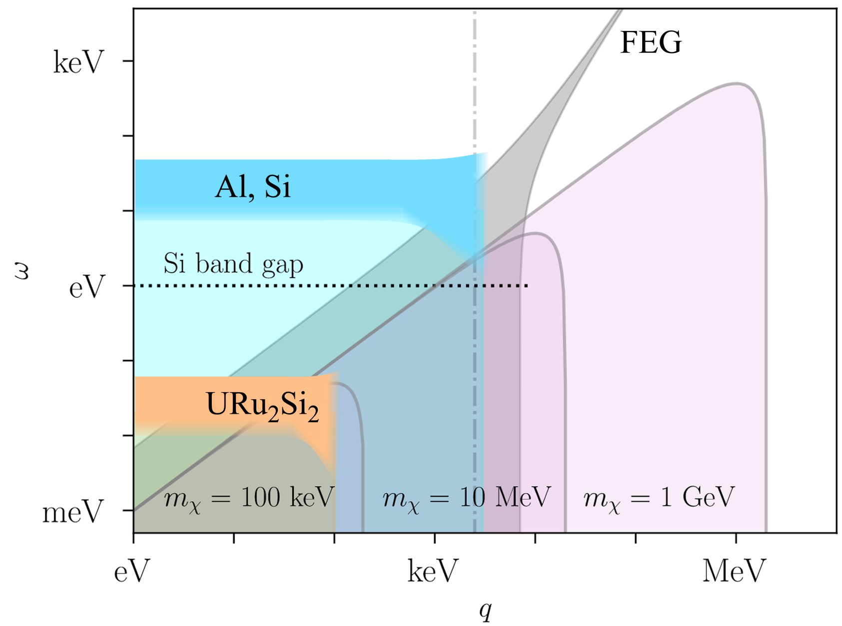

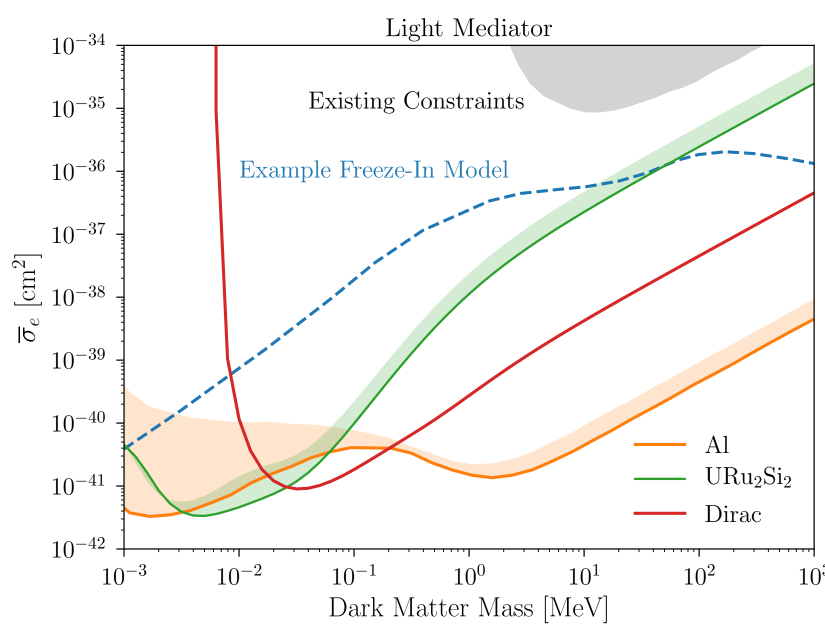

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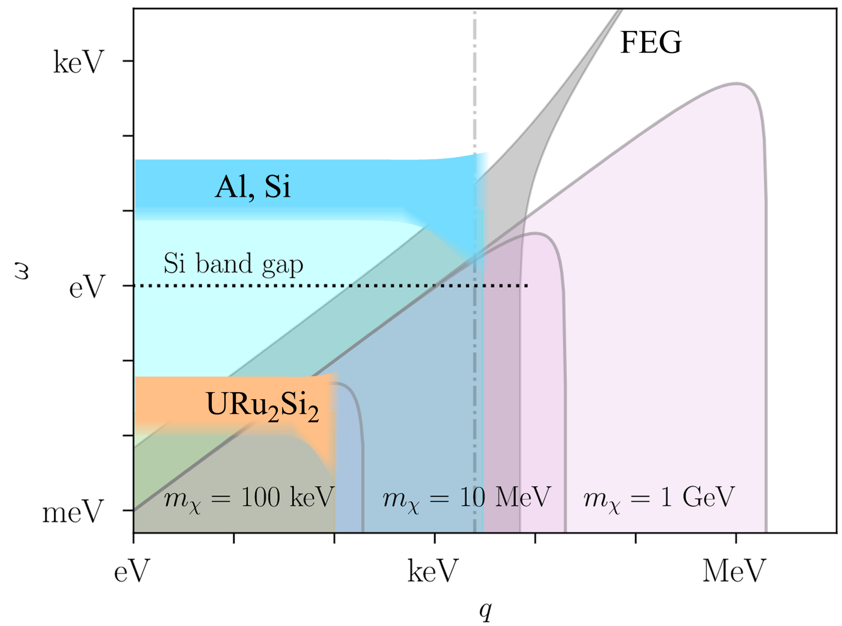
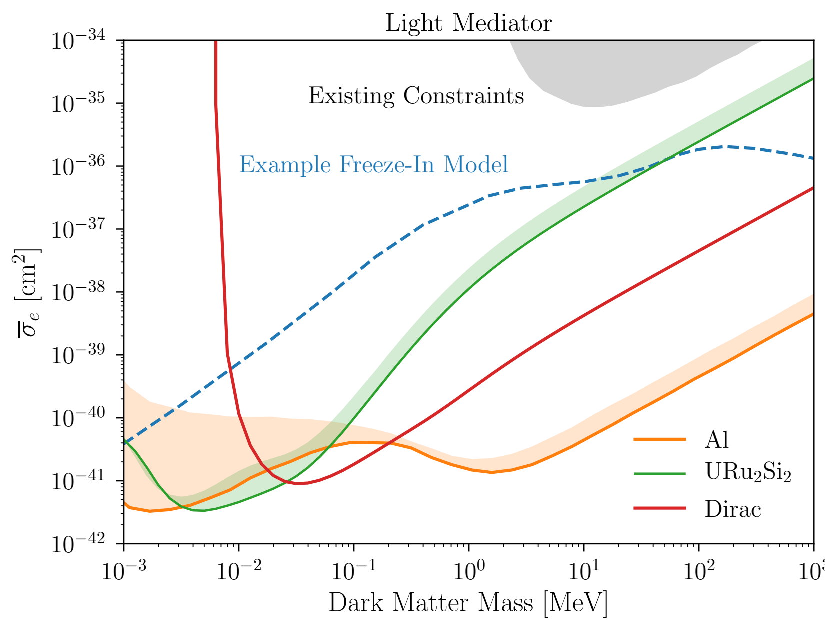




Dielectric Function Formalism

In the low-energy regime, we can express electromagnetic interactions in terms of the loss function:

$$\frac{d^2\sigma}{d\Omega_2 d\hbar\omega_2} = \boxed{r_0^2(\mathbf{e}_1 \cdot \mathbf{e}_2)^2 \left(\frac{\omega_2}{\omega_1}\right)} S(\mathbf{q}, \omega), \quad r_0 = \frac{e^2}{mc^2}$$

This same language can be used to describe DM interactions, because the structure factor is only determined by interactions within the target material:

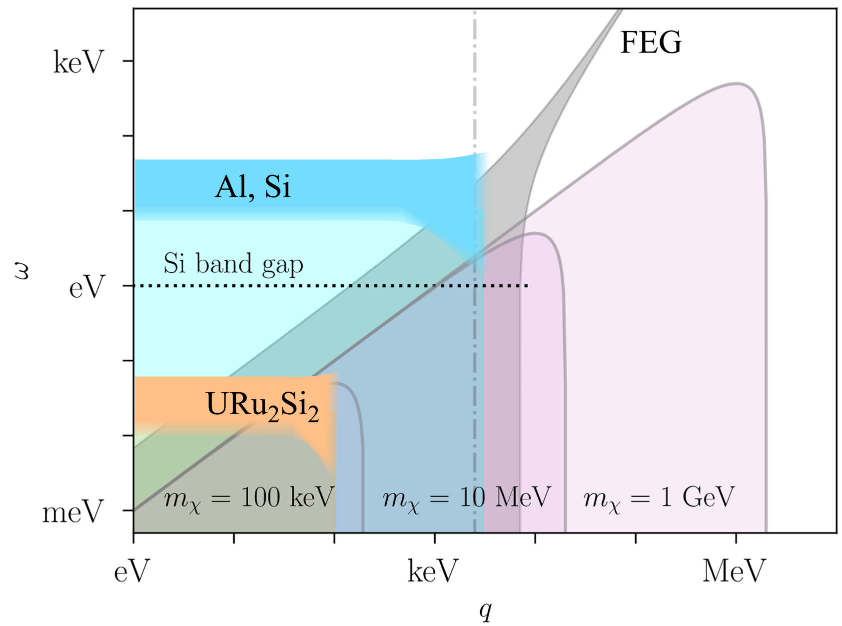
$$\Gamma(\mathbf{v}_\chi) = \int \frac{d^3\mathbf{q}}{(2\pi)^3} \boxed{|V(\mathbf{q})|^2} \left[2\frac{q^2}{e^2}\, \mathrm{Im}\left(-\frac{1}{\epsilon(\mathbf{q}, \omega_\mathbf{q})}\right)\right]$$

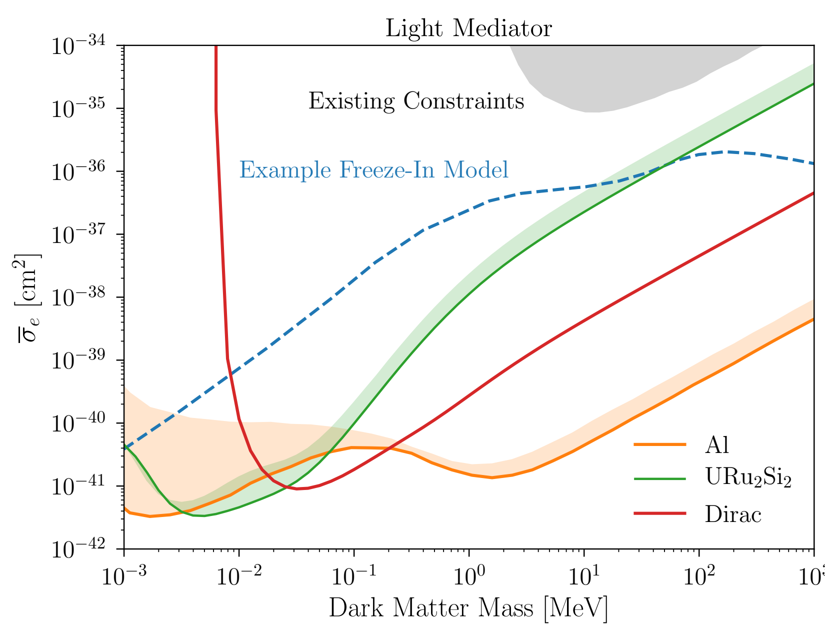
The loss function is well-characterized in the literature, and toy models exist for different types of materials - doesn't require detailed DFT calculations

Recent paper explores a handful of new materials with data and toy models, reducing turnaround on material exploration from years to months

- Also allows us to determine generic features of a material useful for DM detection in different models

Berggren, Hochberg, Kahn, **NK**, Lehman, Yu, ArXiv:2101.08263





Best Materials for keV-MeV DM (of Crystals)

Light dark photon mediator (Sec. III, Fig. 1)			
Detection channel	Quantity to maximize to reach ...		Best materials
	... lower m_χ	... lower $\overline{\sigma}_e$	
(Optical) phonons	ω_O^{-1} (Eq. (24))	quality factor Q defined in Eq. (27)	SiO_2, Al_2O_3, $CaWO_4$
Electron transitions	E_g^{-1} (Eq. (28))	depends on details of electron wavefunctions	InSb, Si
Nuclear recoils	$(A\omega_{\rm min})^{-1}$ (Eq. (29))	$(Z/A)^2\,\omega_{\rm min}^{-1}$ (Eq. (31))	diamond, LiF

SiC

Hadrophilic scalar mediator (Sec. IV, Figs. 2, 3)			
Detection channel	Quantity to maximize to reach ...		Best materials
	... lower m_χ	... lower $\overline{\sigma}_n$	
(Acoustic) phonons	$c_s/\omega_{\rm min}$ (Eq. (36))	Light mediator: $\omega_{\rm min}^{-1}$ (Eq. (35))	diamond, Al_2O_3
		Heavy mediator: c_s^{-1} or $\omega_{\rm ph}^{-1}$ or $A\omega_{\rm ph}$ depending on m_χ (Eqs. (37), (38), (39))	all complementary
Nuclear recoils	$(A\omega_{\rm min})^{-1}$ (Eq. (29))	Light mediator: $\omega_{\rm min}^{-1}$ (Eq. (40))	diamond, LiF
		Heavy mediator: A (Eq. (43))	CsI, Pb compounds

Easy to make a case for Diamond/SiC + Sapphire + low gap (InSb, etc) to carve out next round of low-mass (keV - GeV) dark matter parameter space
(from https://arxiv.org/pdf/1910.10716.pdf, Griffin et. al. 2019)

meV-Scale Resolution Development Paths

Multiple ways to achieve eV-scale or single quantum resolution with carbon-based crystals (large optical phonon energies); these are already substrates used in QIS

Charge readout

- Contact-free cryogenic charge readout (SLAC, CNRS)
- Charge-sensitive qubits (SLAC, JPL)

Athermal Phonon Readout

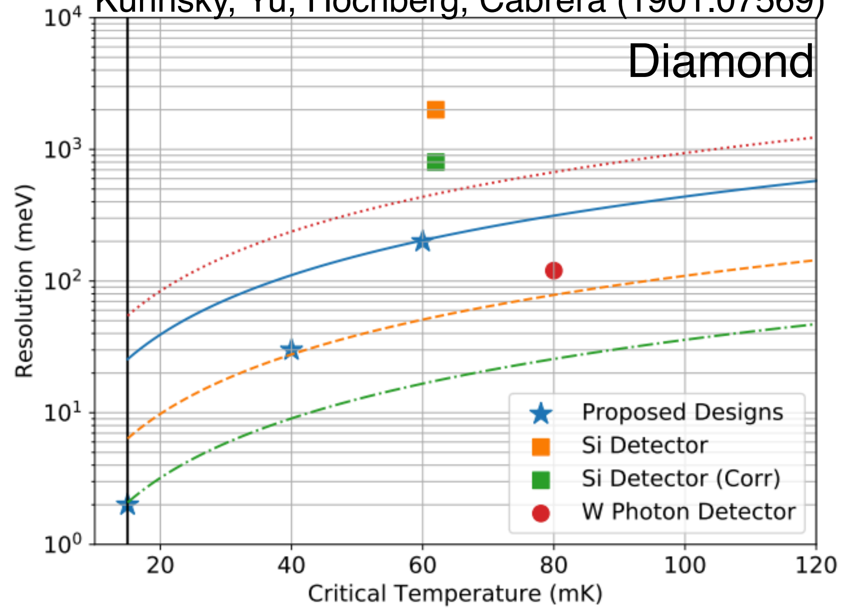
- TES (SuperCDMS + others)
- MKIDs (Caltech/FNAL/SLAC/LBL)
- Nanowires/QCDs

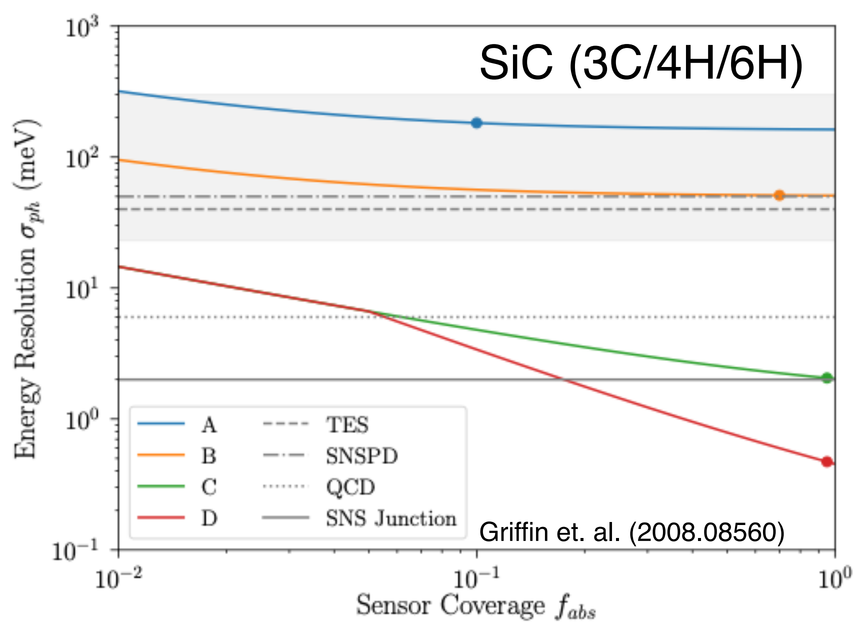
Thermal Phonon Readout

- TES thermometry— CRESST/MPI
- Ricochet-style readout - MIT/NW/others

Qubits as drop-in replacements for existing sensors are way ahead!

Kurinsky, Yu, Hochberg, Cabrera (1901.07569)



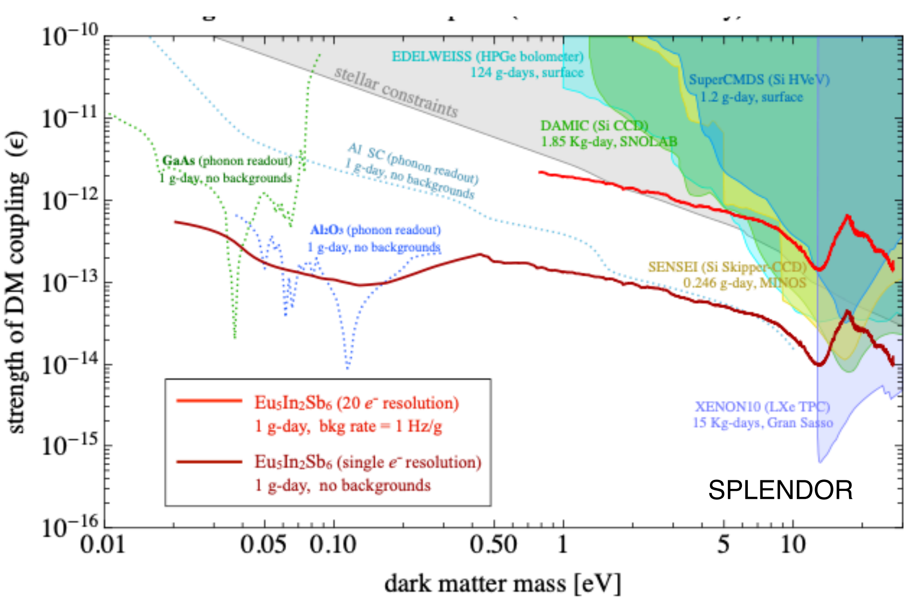


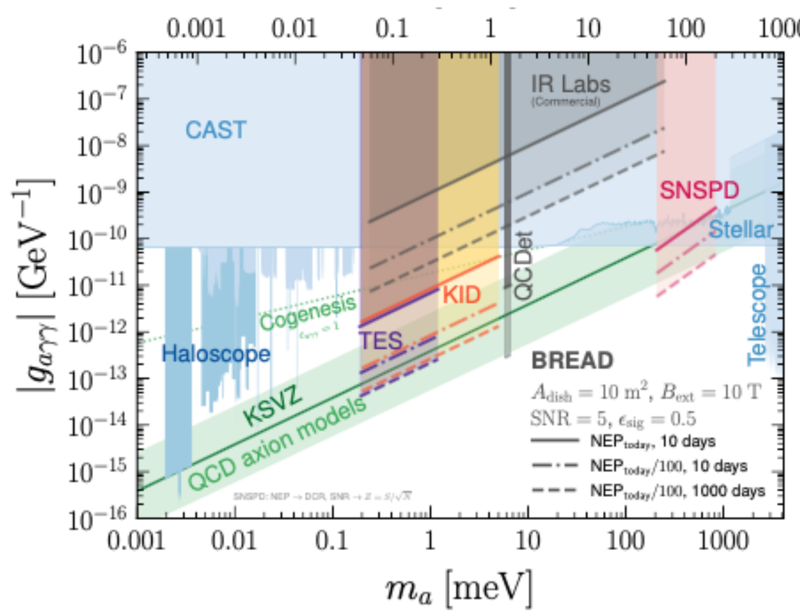
Griffin et. al. (2008.08560)

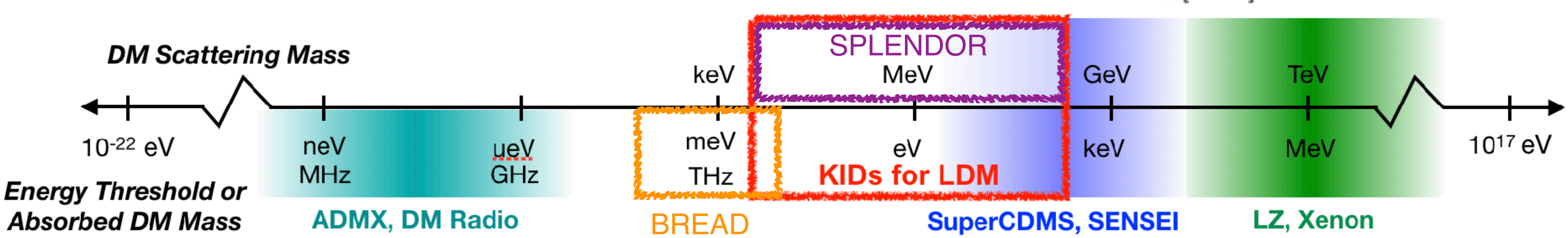
Quantum Sensing for Dark Matter Searches

Utilize superconducting sensors to search for dark matter in the meV-MeV regime, currently not probed by existing experiments

- Sensors derived from qubit co-design work; heavy overlap with QIS
- KIDs for phonon sensing (SuperCDMS)
- meV-gap materials with single charge readout (SPLENDOR)
- Single THz and IR photon sensors for wide-band axion searches (BREAD)







Qubits as Sensors

Article | Published: 16 June 2021

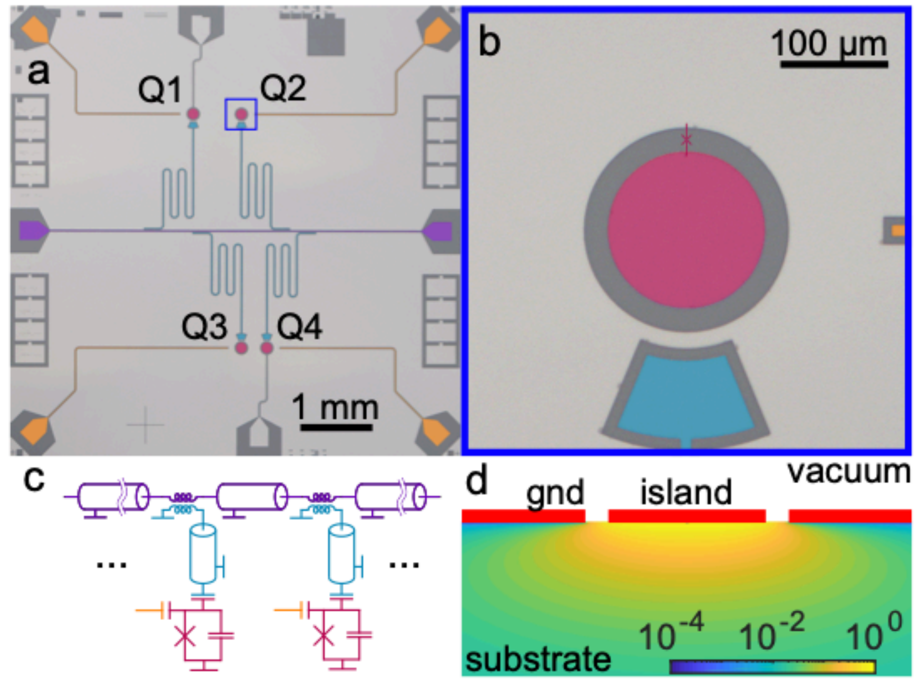
Correlated charge noise and relaxation errors in superconducting qubits

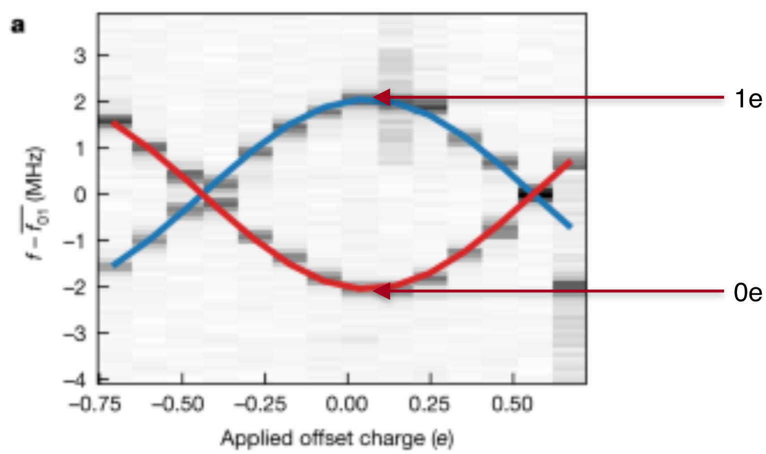
C. D. Wilen, S. Abdullah, N. A. Kurinsky, C. Stanford, L. Cardani, G. D'Imperio, C. Tomei, L. Faoro, L. B. Ioffe, C. H. Liu, A. Opremcak, B. G. Christensen, J. L. DuBois & R. McDermott

Nature **594**, 369–373 (2021) | Cite this article

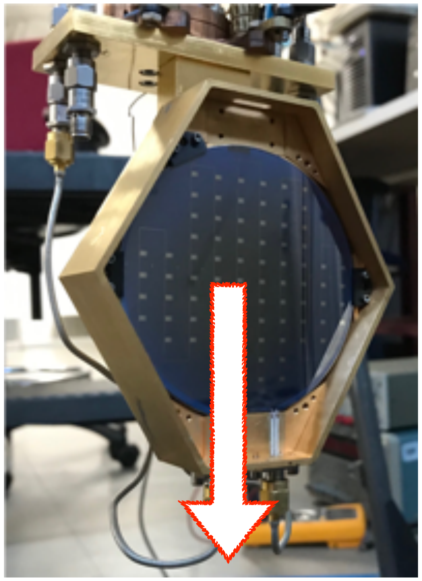
SLAC

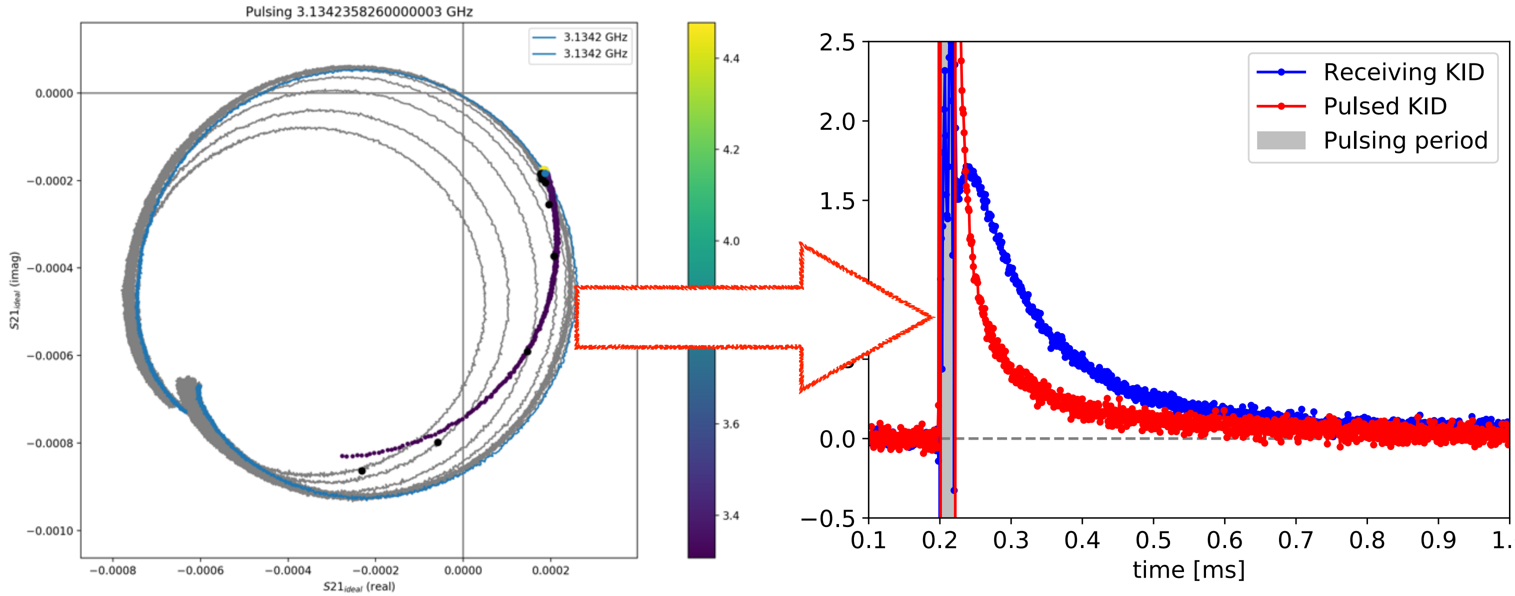
- Qubits, built on the 'cooper pair box' paradigm, are already intrinsically sensitive to energy differences of Delta (half the cooper pair binding energy)
- Studies of qubit chips have shown sensitivity to single charges in the substrate and to pair breaking from phonons (see Nature paper)
- The 'readout' part of the qubit is a solved problem; the remaining challenges are efficient collection of energy quanta and reduction of environmental noise
  - Both problems are important for achieving a scalable quantum computer!

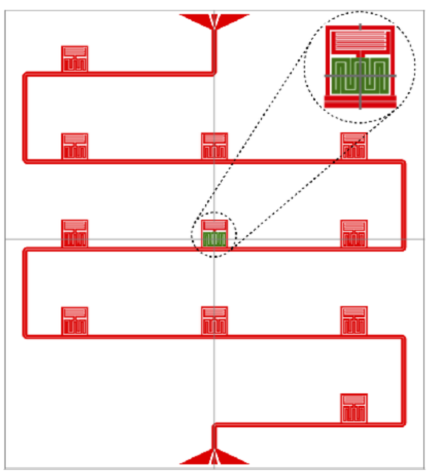




KIDs for DM







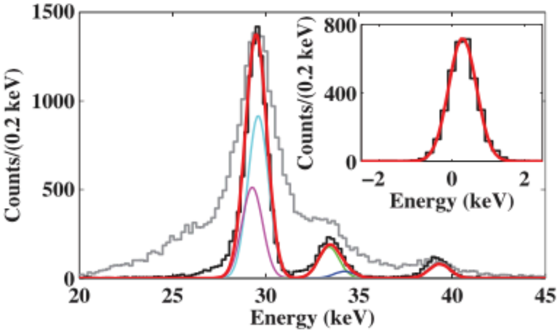
KIDs are superconducting structures with a resonance frequency that's exquisitely sensitive to energy deposition by the kinetic inductance effect

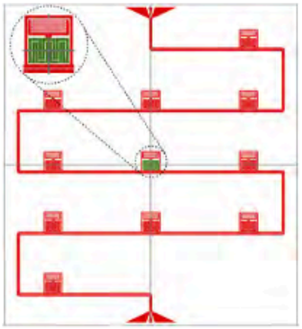
Operate in a narrow band; noise is simply limited by the amplifier thermal noise (low-frequency, EMI, etc much less problematic than TESs)

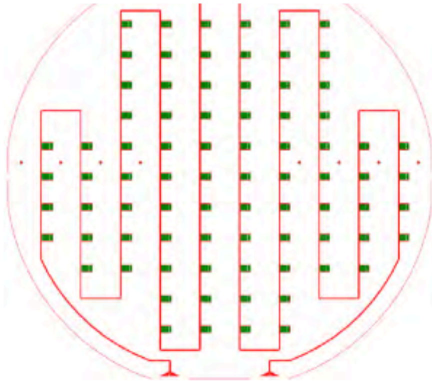
Devices made by Sunil Golwala's group at Caltech/JPL currently achieving eV-scale resolutions in a fairly high-background environment. Need to develop robust readout system, and move to underground cryostat with lower base temperature, to achieve sub-eV resolution.

- Targeting 1 eV resolution in 2021, 0.1 eV in 2022-23
- Lower resolution (O(10 meV) possible through parallel advances in amplifier technology

KID Performance To Date (S. Golwala)







Proof of principle: Moore+ APL 2012,

σ_E = 380 eV baseline w/20 KIDs

on 22 mm (small architecture) substrate

Small architecture, Al + Nb cap

σ_E^{KID} = 6 eV (Nb TLS-limited) on energy received in KID,

$\sigma_E^{sub} = (6 \text{ eV})/\eta_{ph} \approx 20$ eV on energy deposited in substrate for $\eta_{ph} \approx 0.3$

High-Δ, low TLS cap layer ($NbTiN_x$) → σ_E^{KID} = 1.5 eV, σ_E^{sub} = 5 eV

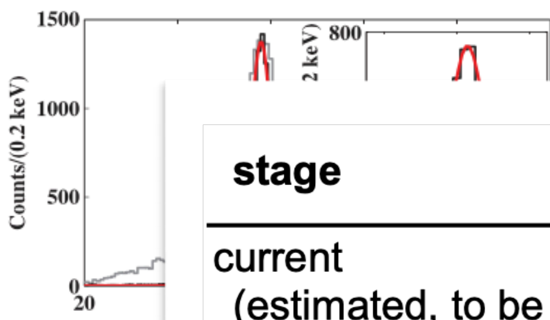
Large architecture, Al only

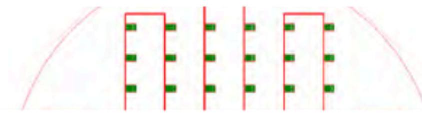
σ_E^{KID} = 5.3 eV for KID w/optimal Q_c and w/fixable EMI (60 Hz),

$\sigma_E^{sub} = (5.3 \text{ eV})\sqrt{320}/\eta_{ph} \approx 300$ eV for 320 KIDs (4% surface coverage)

EMI removed, Q_c solved $\longrightarrow \sigma_E^{sub} \approx (1.3 \text{ eV})\sqrt{320}/\eta_{ph} \approx 80$ eV

KID Performance To Date (S. Golwala)





stage	phonon energy rms small	phonon energy rms large
current (estimated, to be checked with fiber optic data)	20 eV	300 eV
immediate fixes (Q_c, TLS, EMI)	1-7 eV	80 eV
increase τ_{qp} to 1 ms via better BB shielding (free-space and in coaxes)	0.3-2 eV	25 eV
quantum-limited amplifier	50-350 meV	4 eV
T_c = 0.1 K	5-35 meV	400 meV
QIS-based amplifier (guess) (squeezing or qubit QND)	0.5-7 meV	80 meV

NR/ER discr. down to ~0.5 GeV!

NR/ER discr. down to 1 eh pair (E_R ~ 10 eV)

0.1 GeV reach for NRs w/o discr.

0.03 GeV reach for NRs w/o discr.

EMI removed, Q_c solved $\longrightarrow \sigma_E^{sub} \approx (1.3\text{ eV})\sqrt{320/\eta_{ph}} \approx 80$ eV

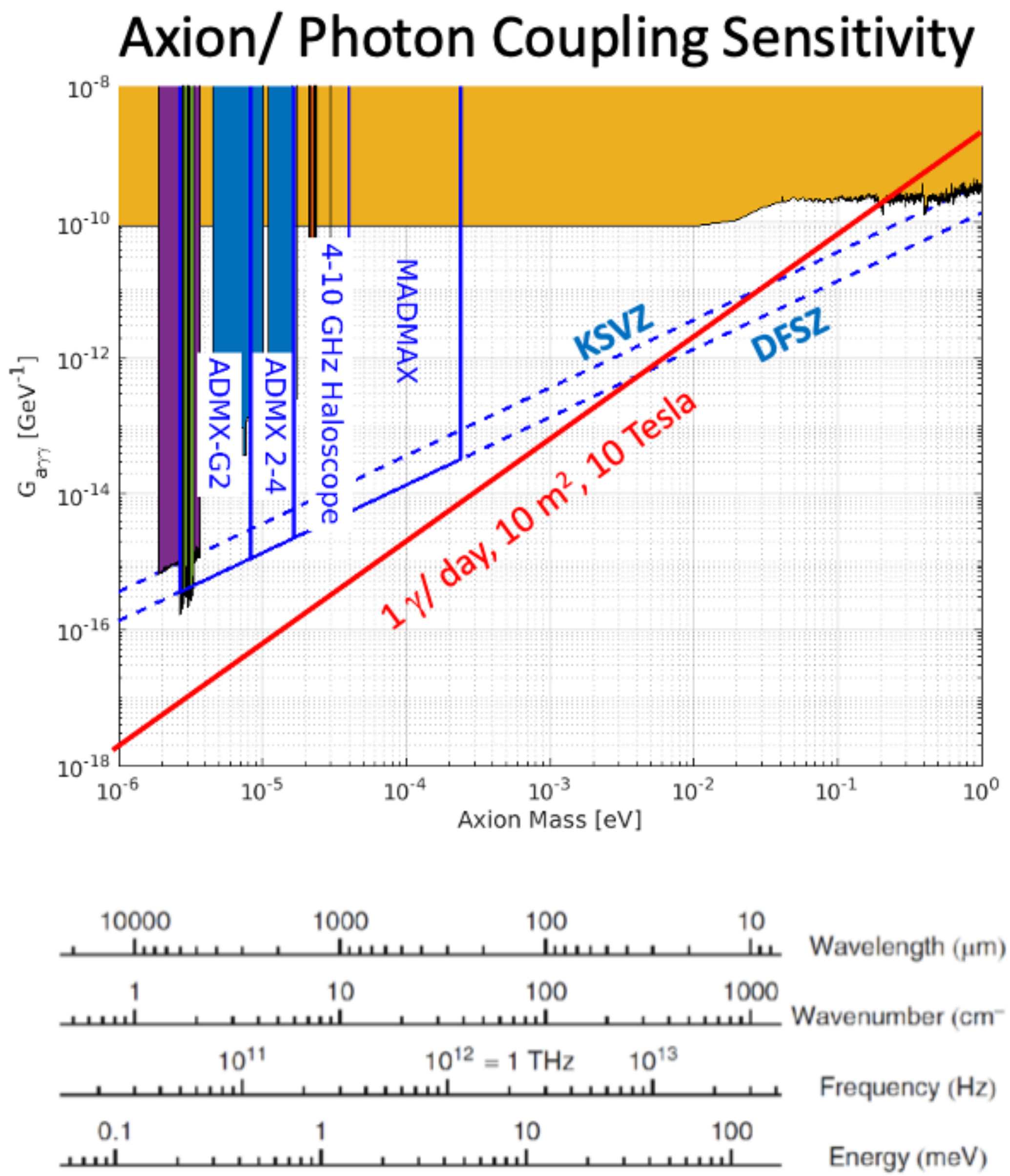
Wide-Band Axion Searches

Current gap in the ~meV-eV absorption regime limited by transition from resonant technologies

We can do wide-band axion searches with meV-threshold sensors! They need to couple to photons rather than phonons, which is accomplished via a waveguide

All technologies useful for phonon sensing are also useful for dark photon and axion searches in this mass range

- These are THz photons, which are technologically hard to probe and are in themselves an interesting field



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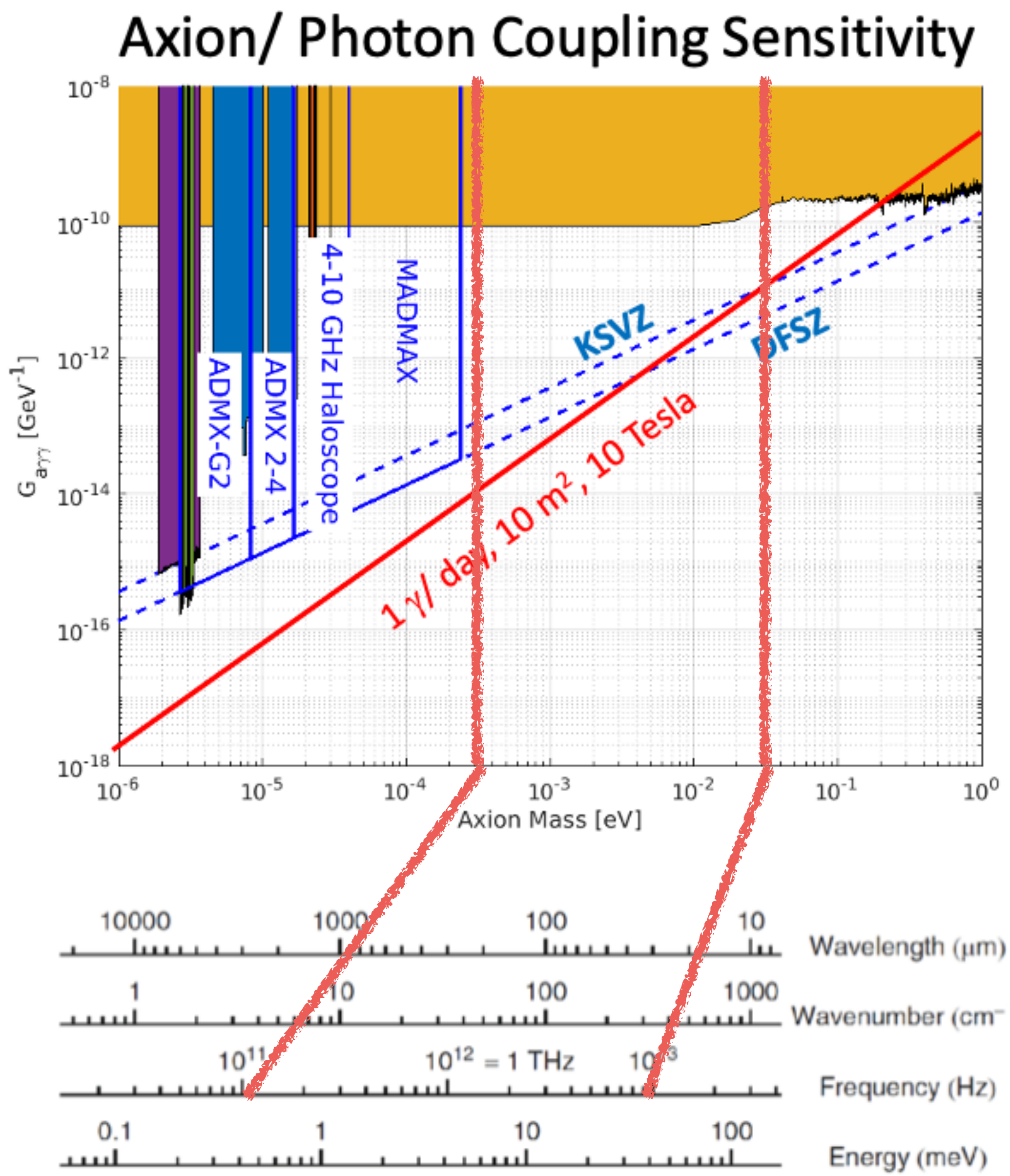


Wide-Band Axion Searches (BREAD)

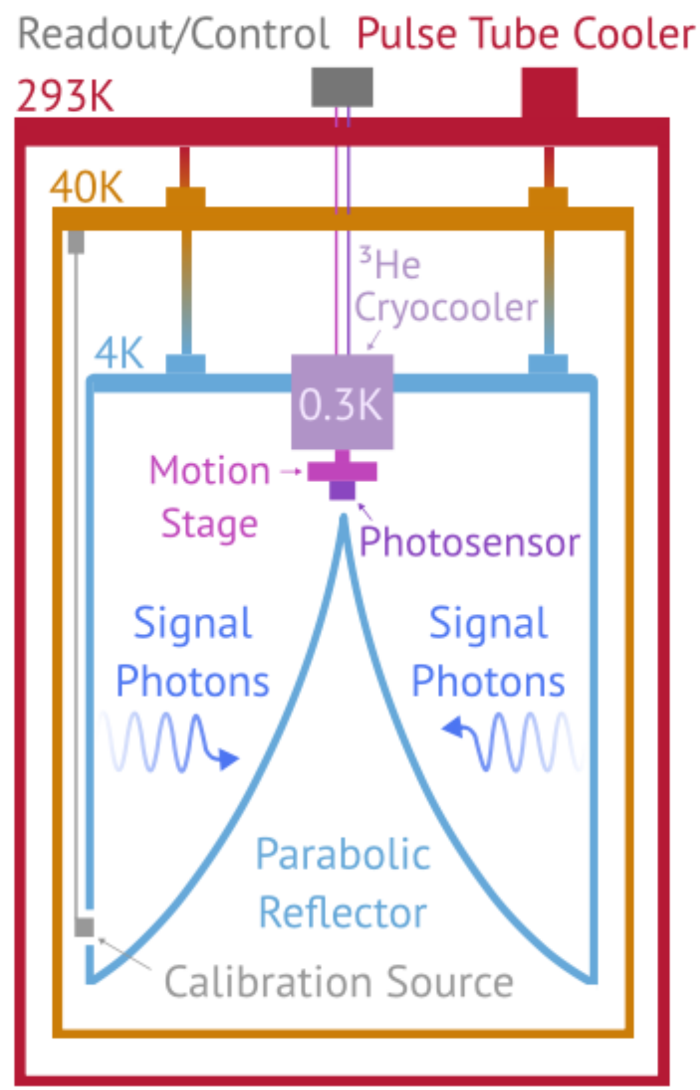
SLAC

Initial experiment will couple a 350 mK dish antenna to an existing quantum sensor (either SNSPD or MKID) to do a dark photon search

Many interesting technical challenges

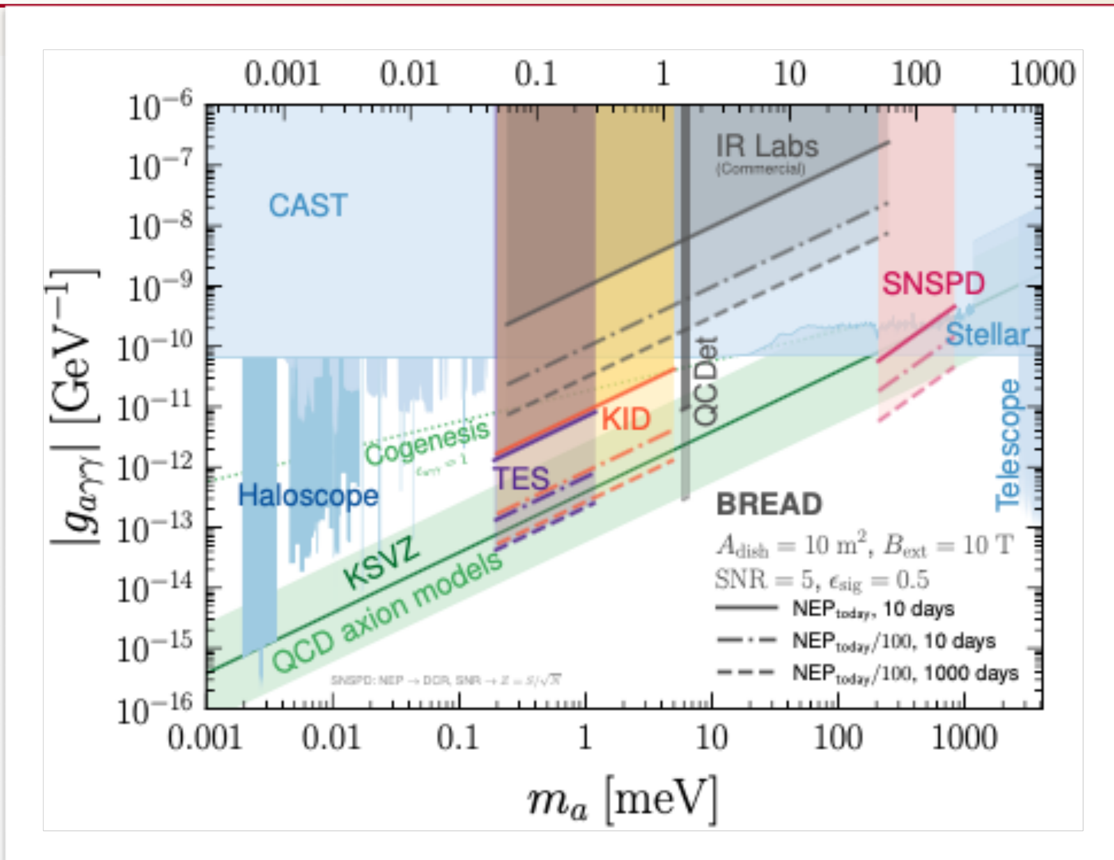
- Sub-Kelvin feedhorn design and characterization
- Development of THz optical paths
- Ability to calibrate wide-band sensors in the meV-eV regime
- Measurement of quantum efficiency in-situ

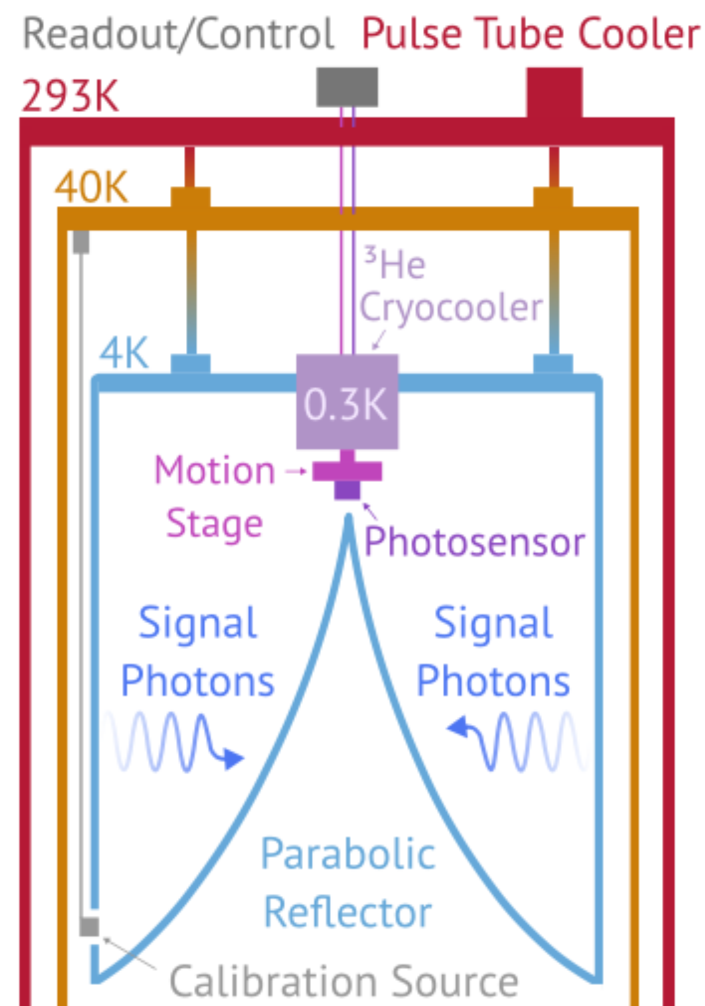
Initial prototype will run at FNAL in the next 1-2 years, ultimate experiment realized in 5-10 years alongside developments in quantum sensing



Liu et. al. (BREAD Collaboration), ArXiv.:2111.12103

Wide-Band Axion Searches (BREAD cont'd)





Change mass sensitivity by swapping photosensor; variety of stages planned with different detector technologies.

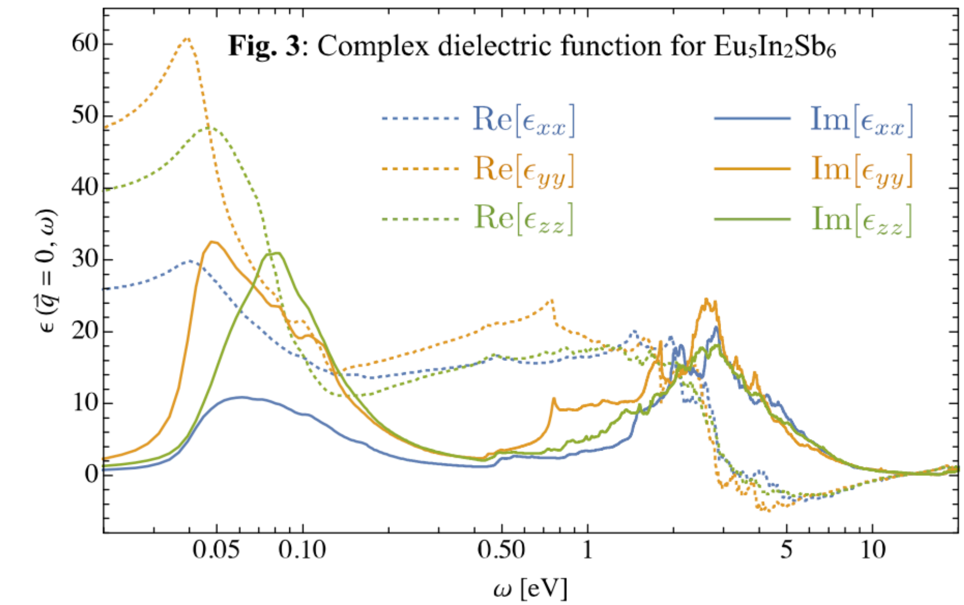
True THz sensitivity requires power noise only achieved in qubit-derived structures (e.g. quantum capacitance detector)

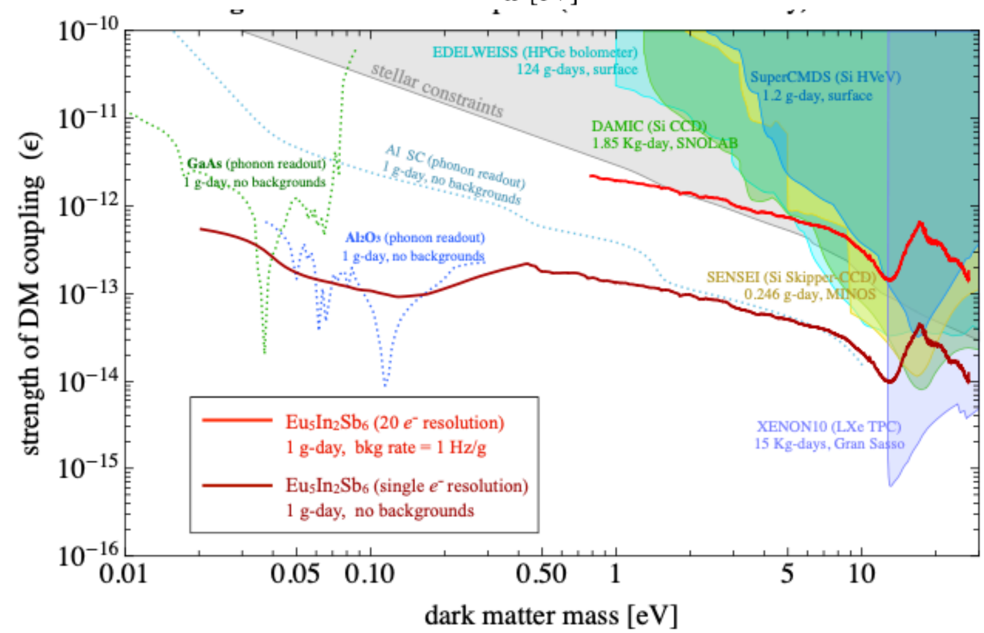
Liu et. al. (BREAD Collaboration), ArXiv.:2111.12103

Designer Materials for Light DM (SPLENDOR)

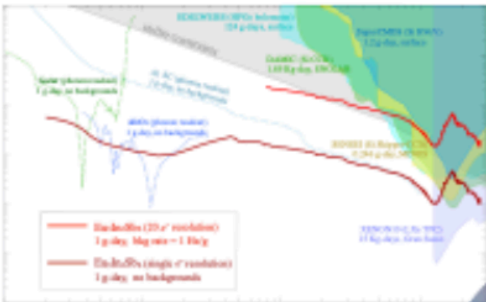
SLAC

- As discussed earlier, materials with high loss in the sub-eV regime (which are well matched to DM) are needed to efficiently probe low-mass DM
- Designer materials with magnetic ordering have tunable bandgaps and high density of states in the sub-eV regime
- g-day exposures can yield impressive science reach
- Single electron sensitivity is needed for greatest sensitivity



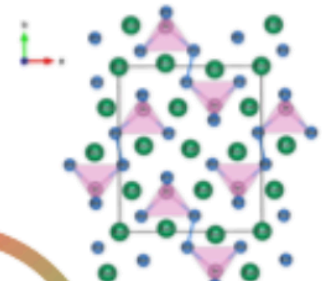


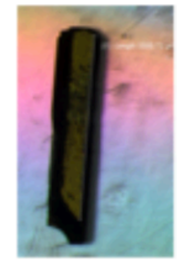
SPLENDOR: DM Detection w/ Quantum Materials



Materials Synthesis

High-quality single crystals with low noise response





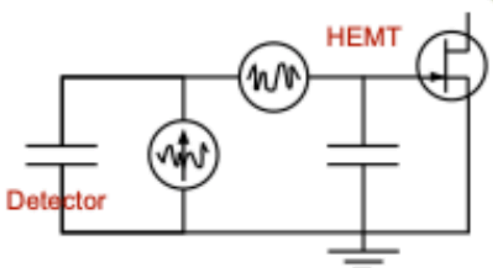
Theory

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

Dark Matter Detection With Quantum Materials

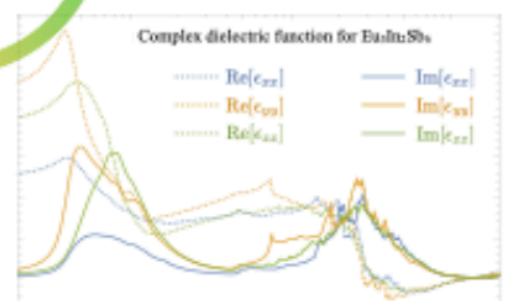
Characterization

M-EELS (dielectric loss function) ARPES (band structure), charge transport



Detection

cryogenic charge amplifiers, single e^- resolution



Conclusions

- Low mass DM searches (meV - MeV) require new detector technologies which are necessarily cryogenic due to the low photon backgrounds required
- Qubits and related devices already show promise for low occupancy in these energy ranges
- Combining the cryogenic expertise from low-background DM experiments with the hardware expertise of QIS is already bearing fruit
- Many different channels and experiments springing up; it is likely to be an interesting few years as new experiments come online.
- eV-scale searches are maturing and showing us new backgrounds as we try to realize meV-scale searches