Dark Matter: New Techniques

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LUX Co-Spokesperson
UC Berkeley and LBNL

Berkeley
UNIVERSITY OF CALIFORNIA
BERKELEY LAB

ZPW 2019
Zurich, Switzerland
January 11, 2019

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^ for keV-GeV Direct Detection

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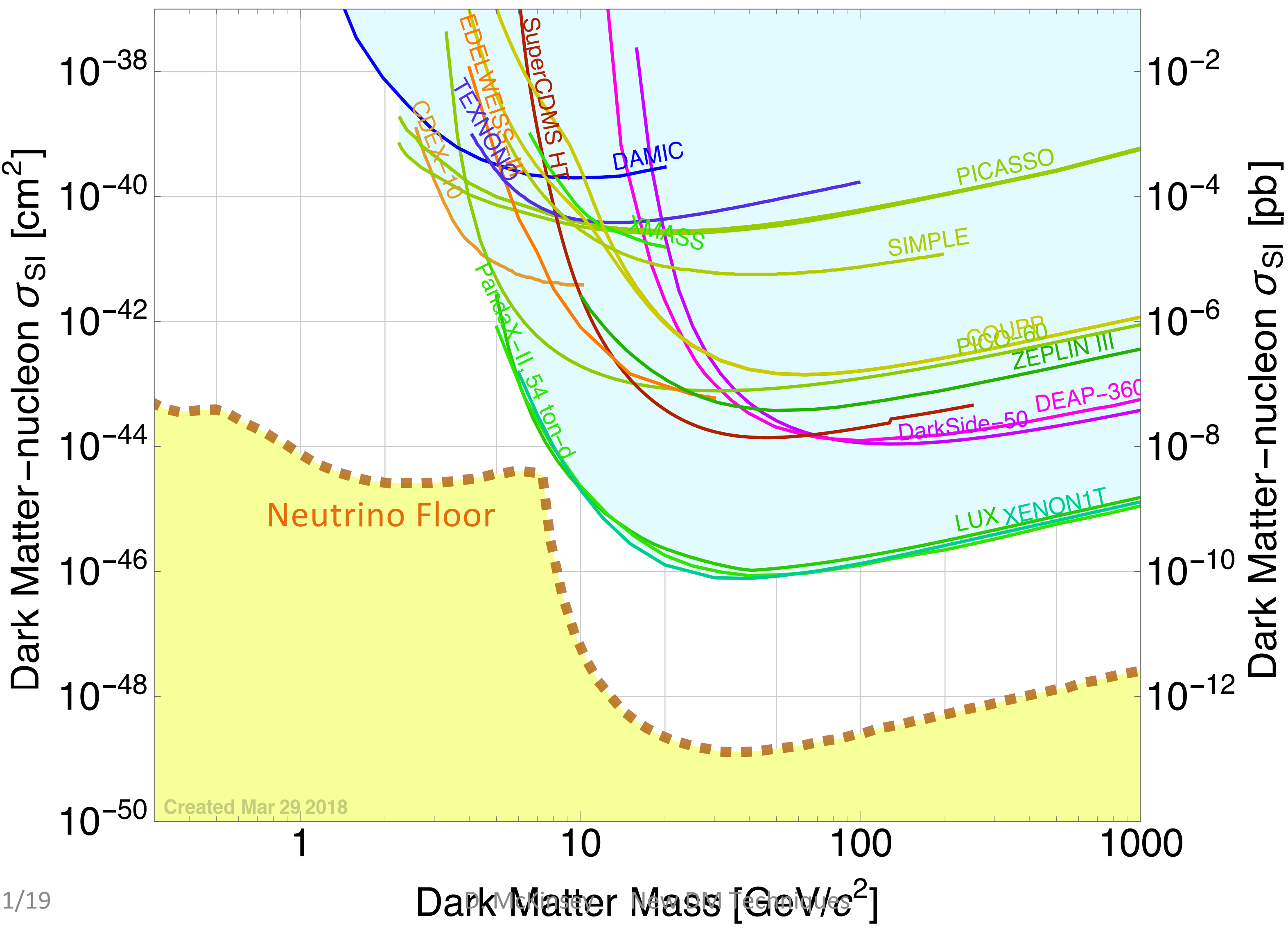
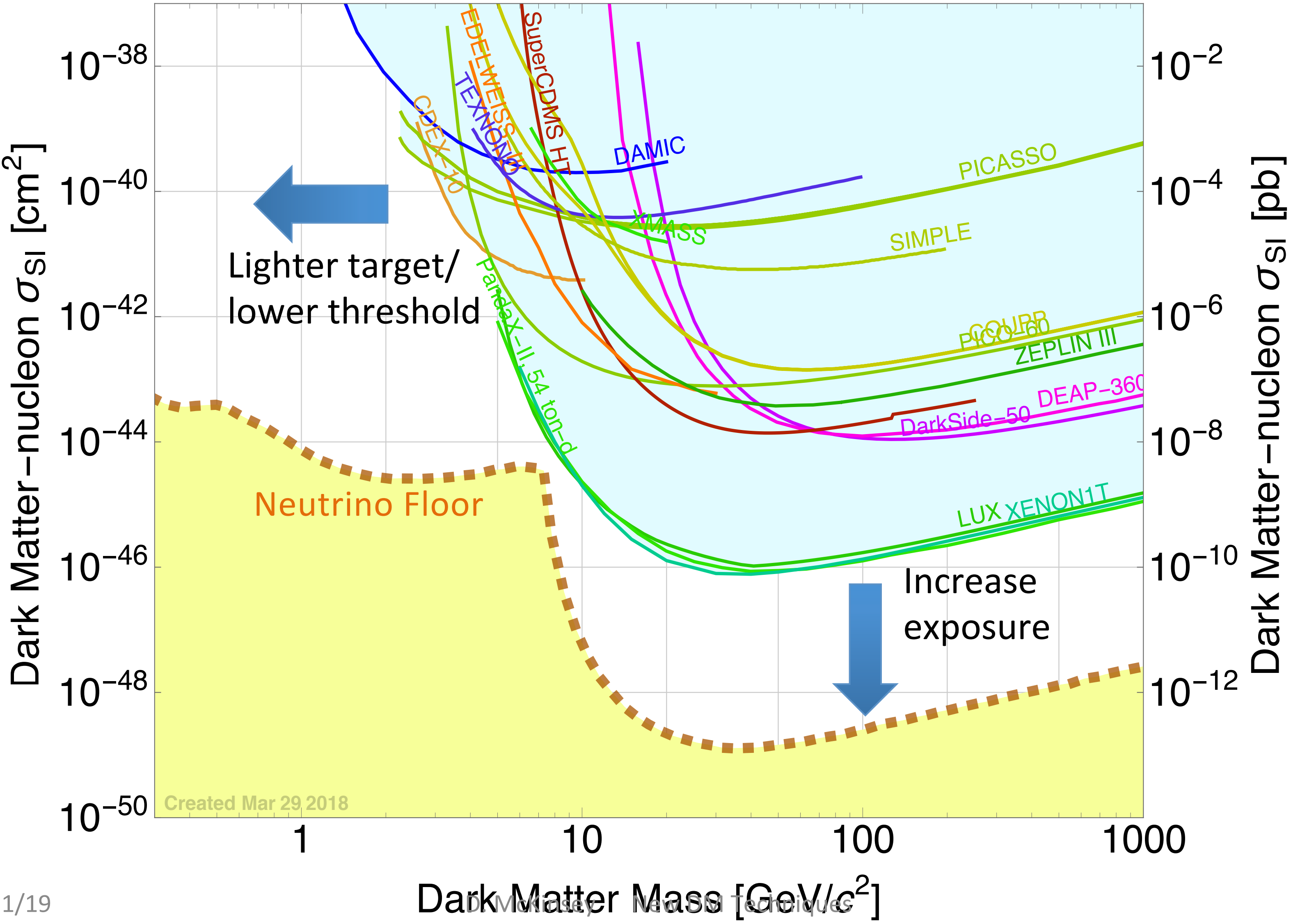
Dark Matter Nuclear Recoils: Current Landscape



Dark Matter Nuclear Recoils: Future Directions

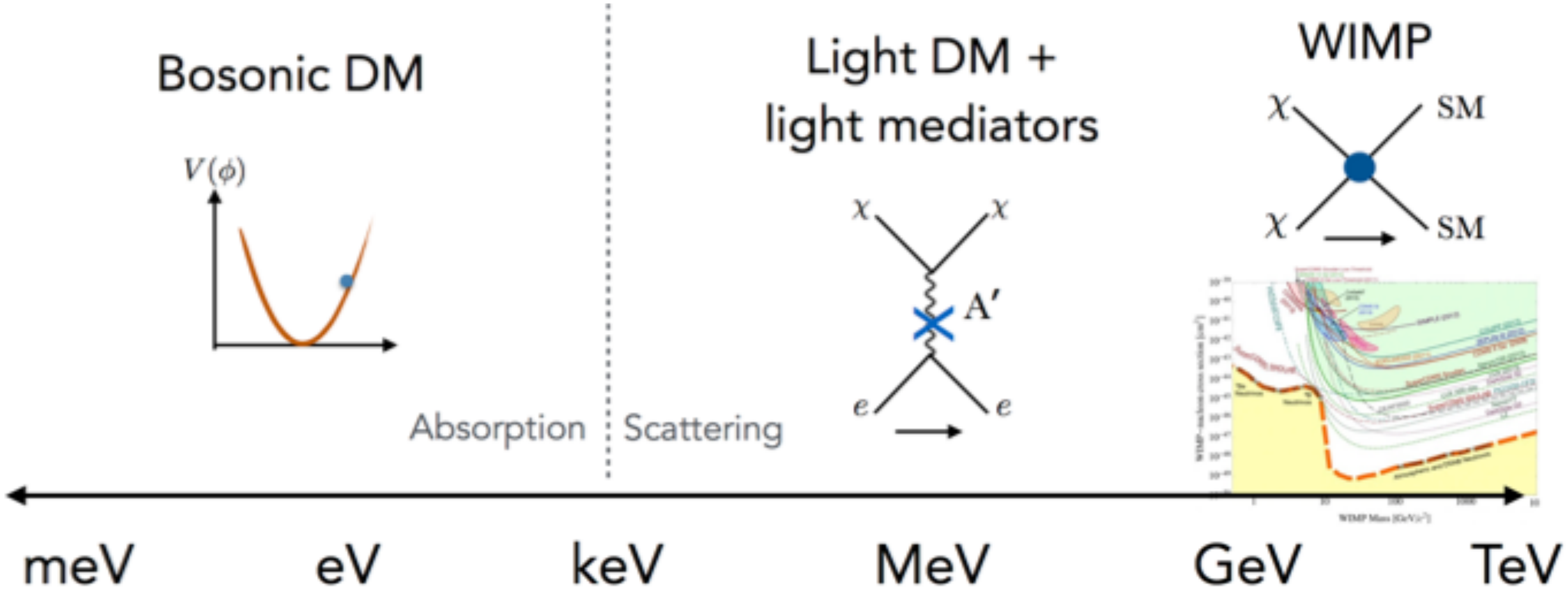


Lighter target/
lower threshold

Neutrino Floor

Increase
exposure

There's plenty of room at the bottom



Bosonic DM

Absorption

Scattering

Light DM +
light mediators

WIMP

meV eV keV MeV GeV TeV

Non-trivial requirements:

- low thresholds
- control of radioactive backgrounds
- control of dark counts & instrumental backgrounds

US Cosmic Visions: New Ideas in Dark Matter

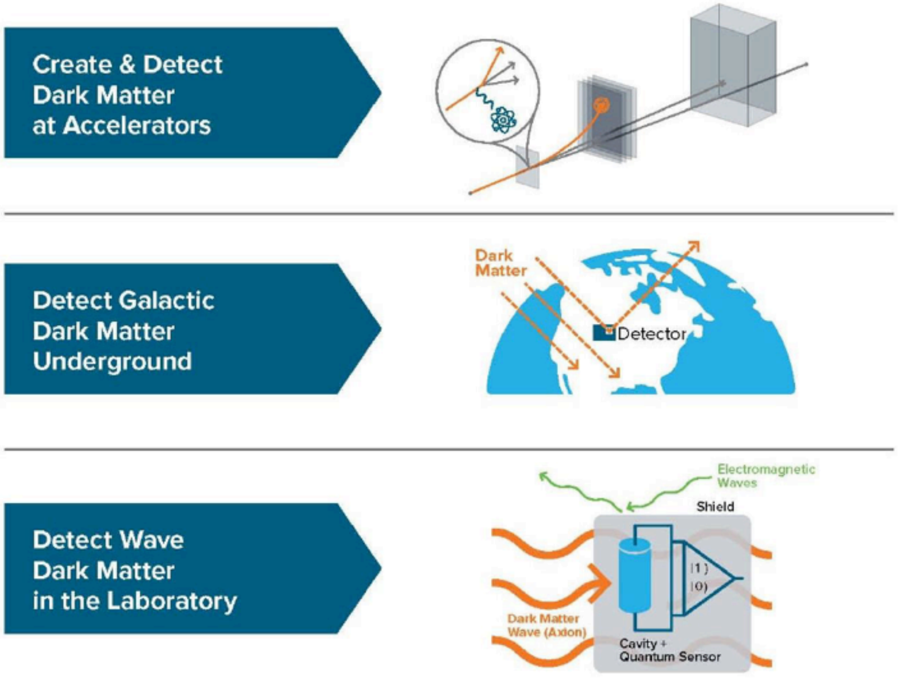
- Many of the technologies discussed here were compiled in the Cosmic Visions Dark Matter effort in the US, driven by the DOE Office of High Energy Physics.
- Investigating low-cost & high-impact opportunities in Dark Matter (DM) science
  - The G2 experiments (ADMX, LZ, and SuperCDMS) are flagships of the US Dark Matter program and obvious priority
  - “New Ideas in Dark Matter” workshop focused on *complementary* science that can be done by small projects <$10M (some much less)
  - 100+ talks in 4 working groups, presenting new ideas, proposals, and science and R&D results
- See https://indico.fnal.gov/conferenceDisplay.py?confId=13702
- See arXiv:1707.04591
- A few of the ideas for direct detection described in this talk.

US DOE High Energy Physics Basic Research Needs Study for Dark Matter Small Projects

- Workshop held in Washington DC, Oct 15-18.
- Will result in a report, public early this year.

Provenance:

- In 2014 the Particle Physics Project Prioritization Panel(P5) identified the search for dark matter as one of the five priority science drivers for the High-Energy Physics Program: "*There are many well-motivated ideas for what the dark matter should be. These include weakly interacting massive particles (WIMPs), gravitinos, axions, sterile neutrinos, asymmetric dark matter, and hidden sector dark matter. It is therefore imperative to search for dark matter along every feasible avenue.*"
- Some of these scenarios –including WIMP searches—are the purview of larger experiments. However, much of the well- motivated parameter space for dark matter can be explored by small experiments in the near future. This corresponds to another recommendation of P5, namely that *"The HEP program should contain a portfolio of small projects to enable an uninterrupted flow of high-priority science results."*



Create & Detect Dark Matter at Accelerators

Detect Galactic Dark Matter Underground

Detect Wave Dark Matter in the Laboratory

sub-GeV DM

Distinguish two types of interactions, e.g.

σ_e vs m_{DM}

- dark photon mediator
- vector, coupling predominantly to leptons

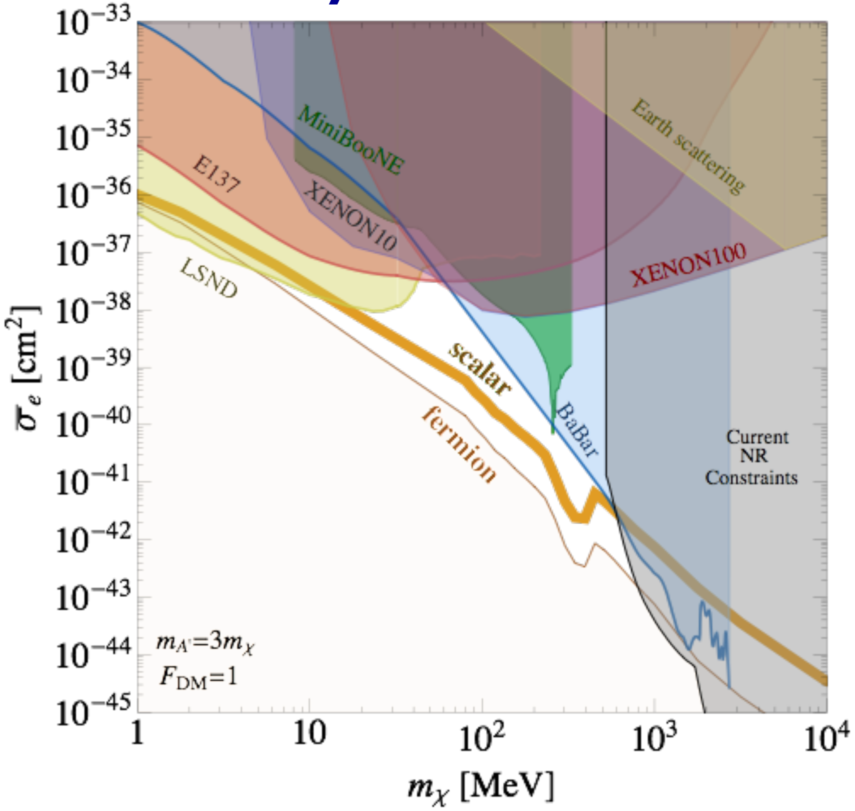
σ_N vs m_{DM}

- dark photon mediator
- vector, coupling predominantly to quarks
- scalar

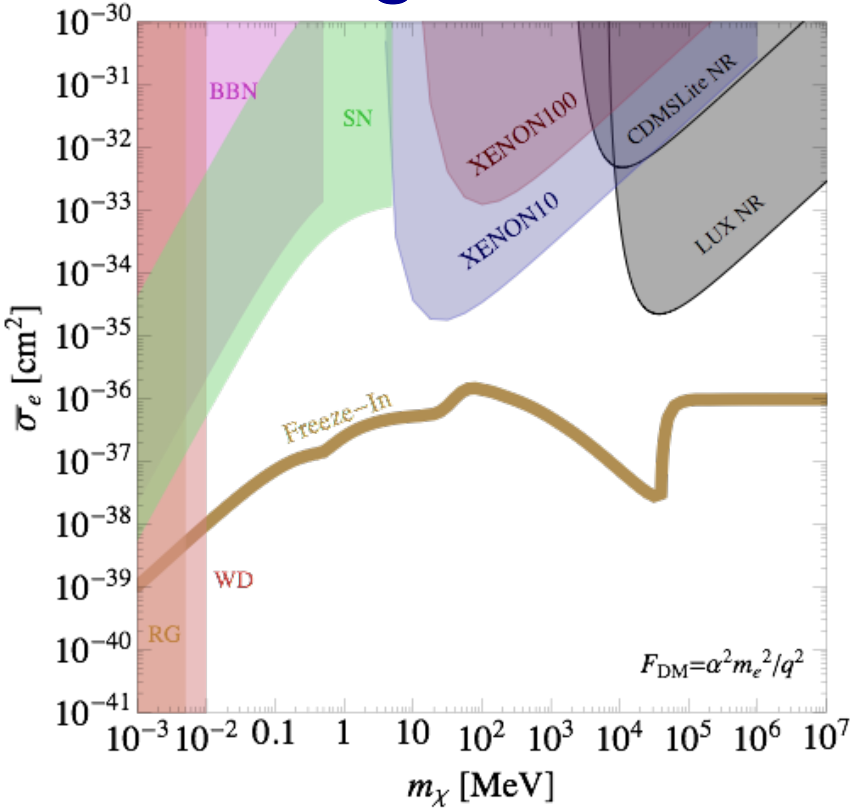
Important to test interactions separately

Benchmarks: dark-photon mediators

“Heavy”



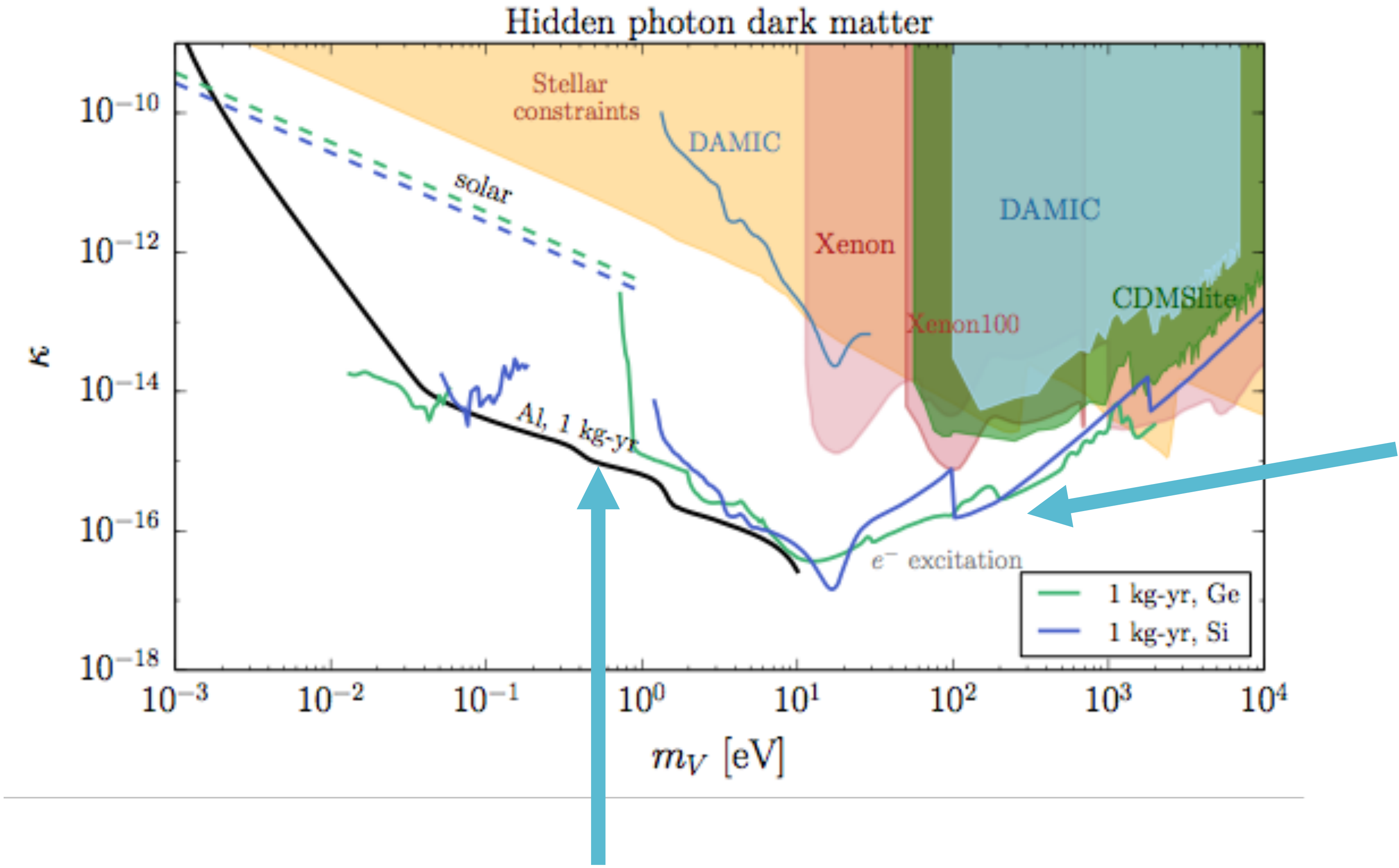
Ultralight



exciting complementarity with collider & beam-dump probes (for elastic scattering)

ultralight mediator scenario is uniquely probed by Direct Detection

Absorption



Si or Ge detector

superconductor

long-term R&D

Marc Schumann (WIMPs)	Federica Petricca (Light DM)	This talk (DM) (sub-GeV new techniques)
DAMA/LIBRA	Argon S2-only	LXe bubble chamber
COSINE	DarkSide-LowMass	Snowball chamber
DarkSide-50	LUX: Xe Migdal effect	Xenon S2-only
XENON1T	DAMIC	Graphene
PICO	NEWS-G	Internally amplified Ge
DarkSide-20k	SuperCDMS	Color centers
PandaX-4T	CRESST	Scintillating crystals (GaAs, CsI, NaI)
LUX/ZEPLIN		Polar crystals
XENONnT		Diamond
DARWIN		Superconductors
		Superfluid helium

This is not a fully exhaustive list; apologies if your favorite new technique is not covered!

Low Mass Dark Matter: The Wild West of Direct Detection

Low Mass Dark Matter:
The Wild West of Direct Detection

Small homesteads, wide open (parameter) spaces

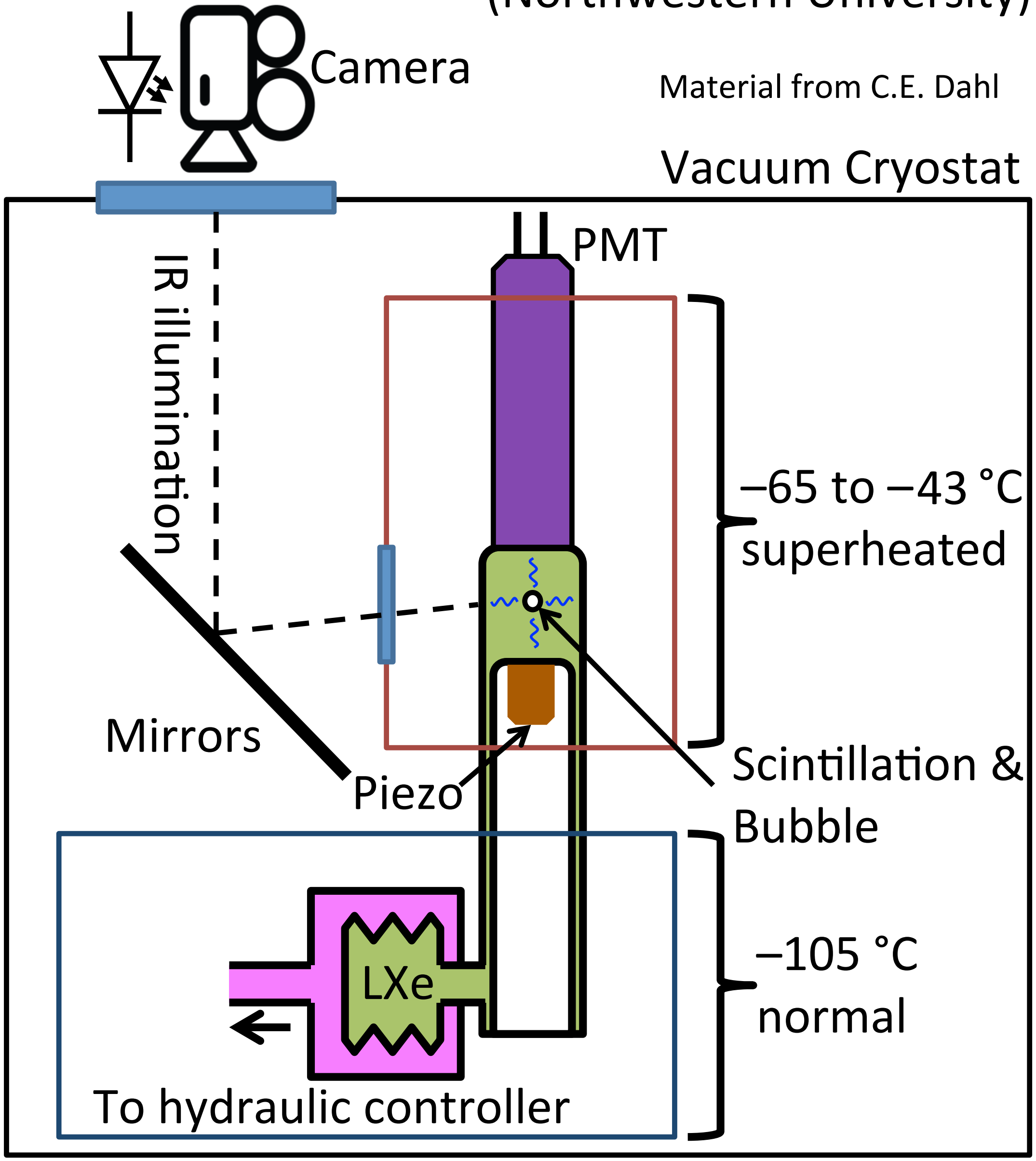
Scintillating Bubble Chamber

- **Concept:** Coincident scintillation and bubble nucleation by nuclear recoils
  - Extreme electron recoil discrimination as in freon bubble chambers
  - Event-by-event energy from scintillation signal
  - Now demonstrated in liquid xenon

  arXiv:1702.08861
  [PRL **118**, 231301]

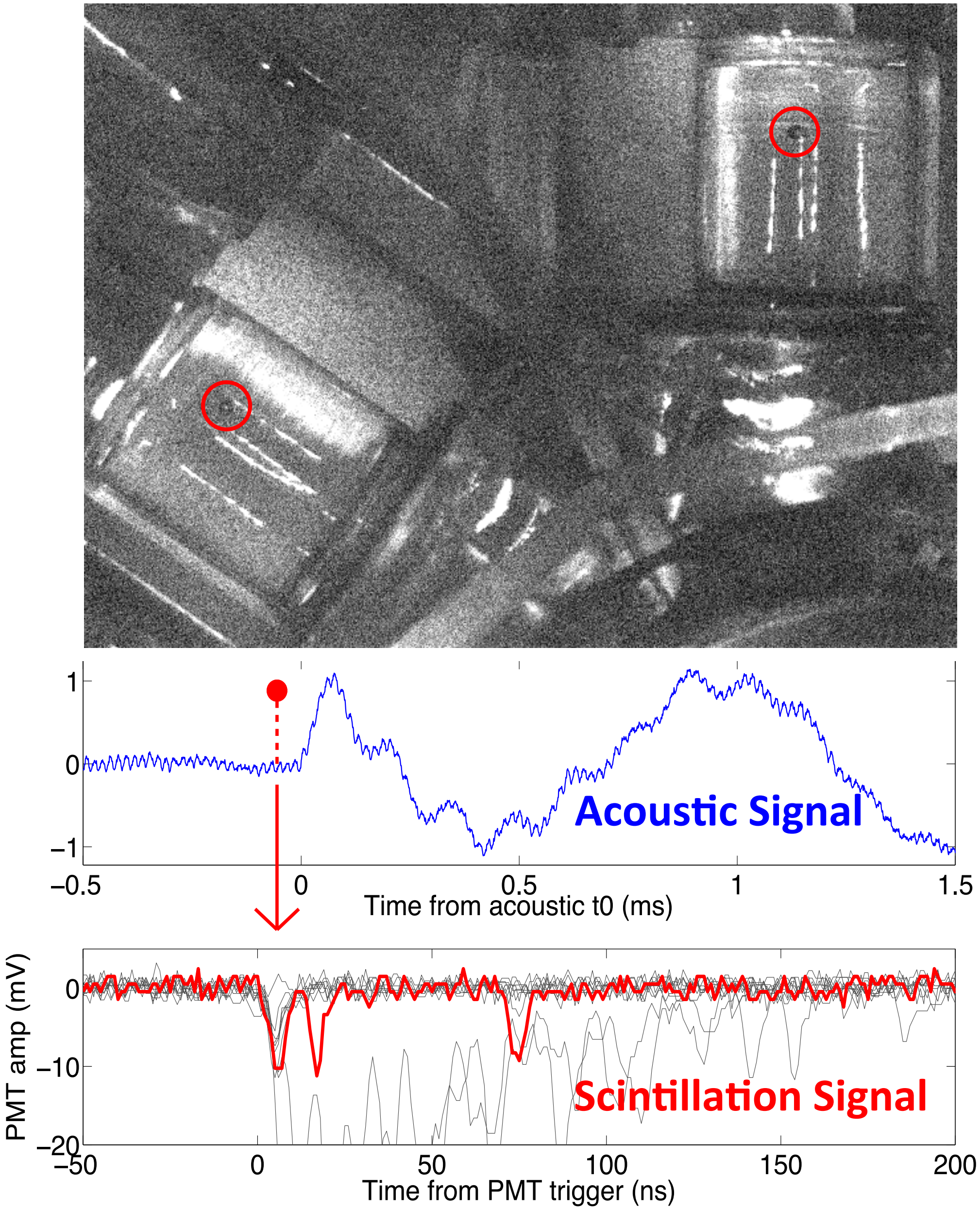
Xenon Bubble Chamber Prototype
(Northwestern University)

Material from C.E. Dahl



Scintillating Bubble Chamber

- Potential for sub-keV thresholds and light nuclei (Ar, Ne, …)
  - Better low-threshold electron discrimination than freon chambers
  - Low-energy NR calibrations underway
- CEnNS physics in reach at *O*(10) kg scale
- Unique 1−10 GeV/c^2 WIMP sensitivity at ton-scale



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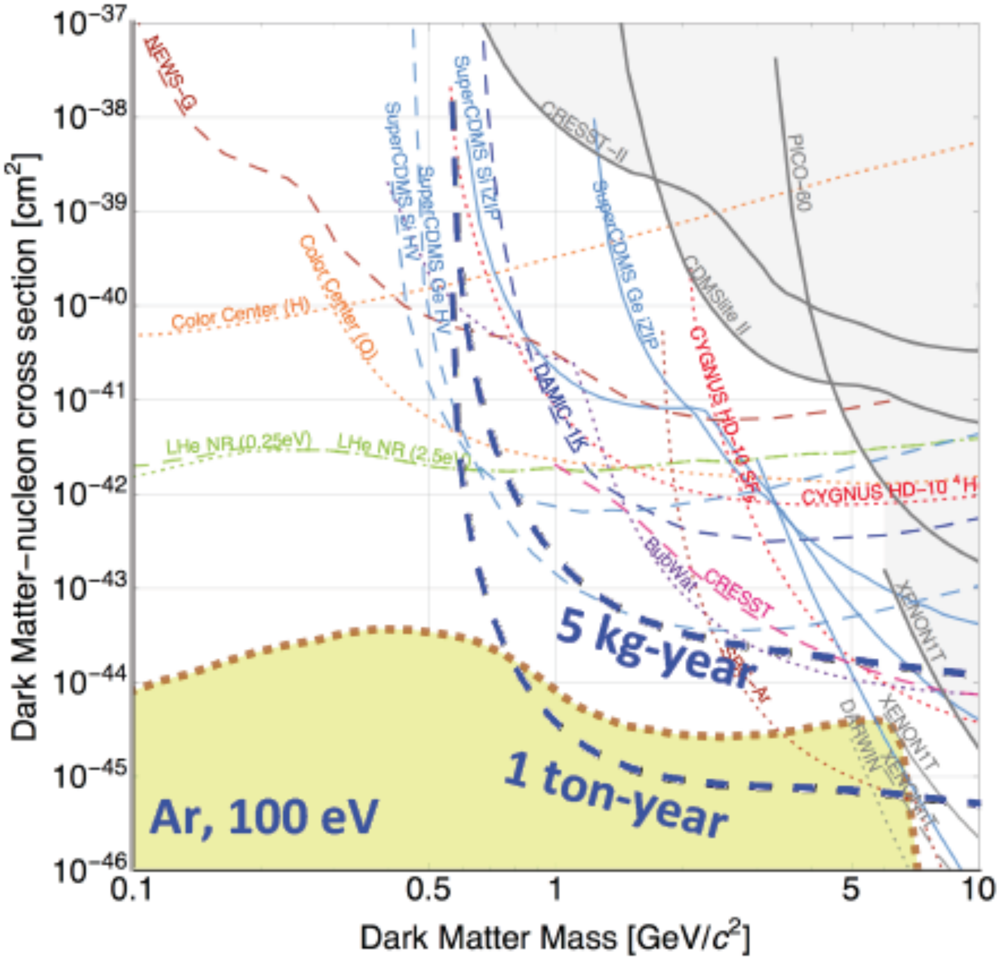
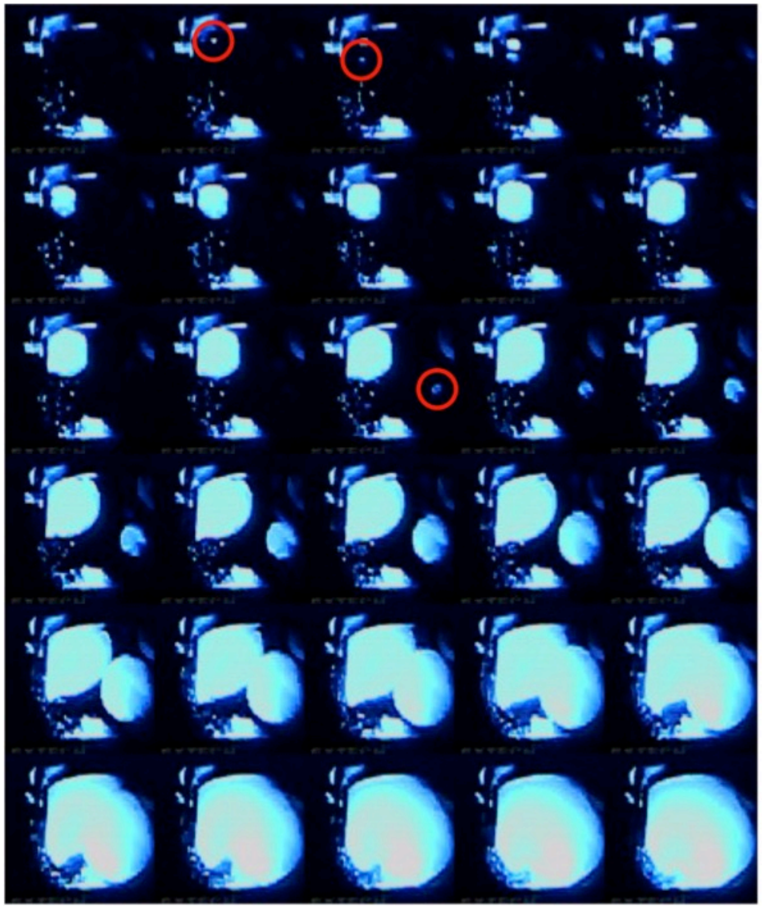


Snowball Chamber: Supercooled Water for Low-Mass Dark Matter

- Analogous to bubble chamber but opposite direction: liquid water is supercooled, and incoming particle can trigger nucleation (snowball)
- First observation in the world of neutron-induced nucleation in supercooled H_2O
  - arXiv:1807.09253
  - 20 mL in smooth, cleaned quartz vessel
  - No statistically significant effect so far from gammas (662 keV ^{137}Cs)
- Advantages:
  - Hydrogen target to use for searching for O(1) GeV DM
  - Water is relatively inexpensive and easy to purify, even on very large scales



Material from M. Szydagis, SUNY Albany

Few-electron detection with two-phase Xe detectors

Idea: Deploy a small O(10) kg liquid xenon TPC with a focus on electron counting and mitigation of e- backgrounds.

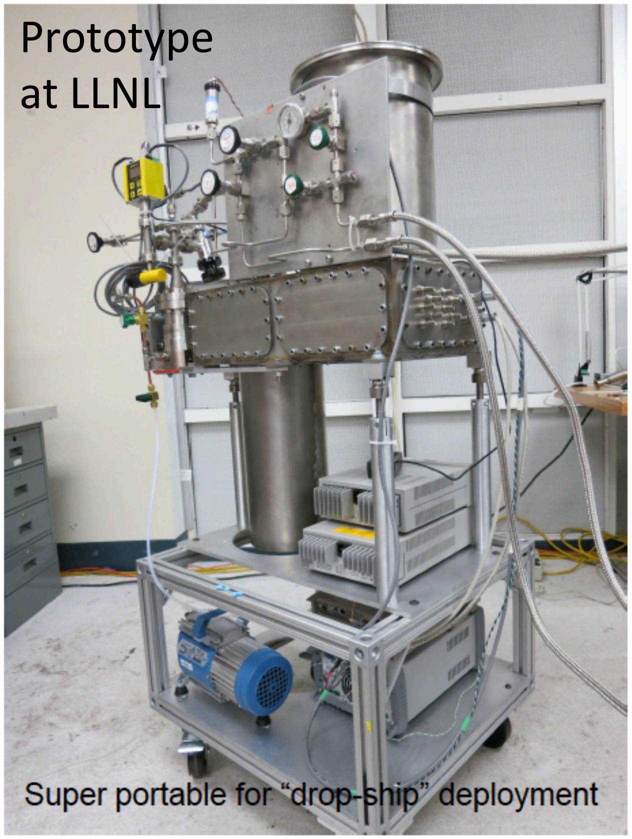
Ways to reduce electron backgrounds:

1) Larger electron emission field
    - XENON achieved ~5.5 kV/cm
    - Suspect >7 kV/cm needed for substantial reduction of e-train bkgd

2) Better purification
    - Trapping of electrons on impurities is a major source of e-train background.
    - Can move to a detector design with no plastics to reduce outgassing (a la ZEPLIN-III)

3) Infrared photons to liberate trapped e-
    - Liquid surface trapping potential is 0.34 eV
    - 940 nm LEDs readily available (1.3 eV photon), trigger on S2

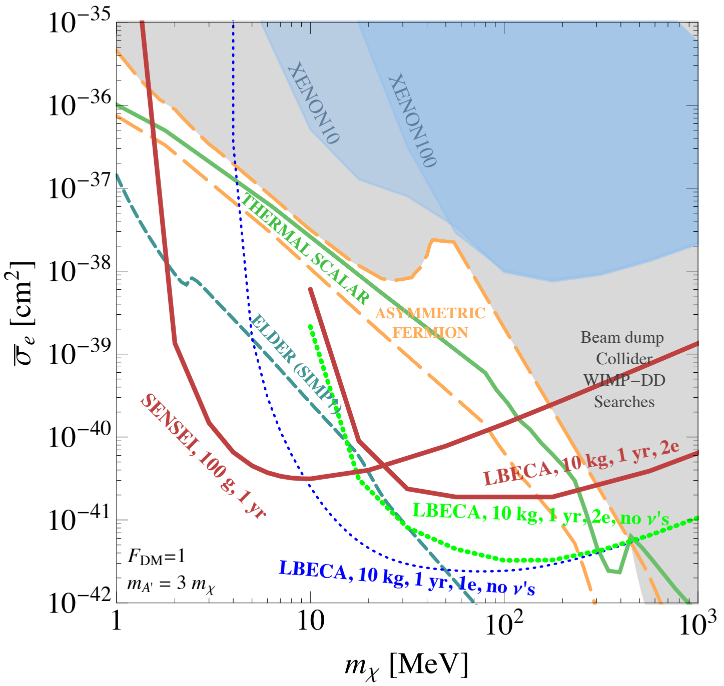
4) Last resort: HV switching
    - Divert trapped electrons back to gate electrode
    - Possible in principle, may actually work quite well

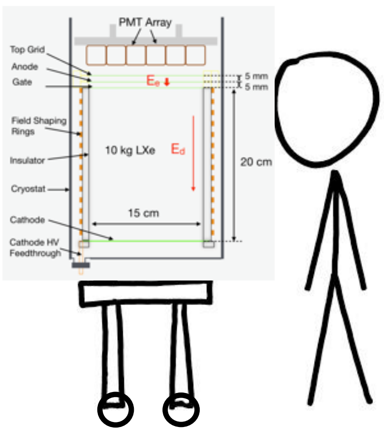


Prototype at LLNL

Super portable for “drop-ship” deployment

LBECA: a low background electron counting apparatus





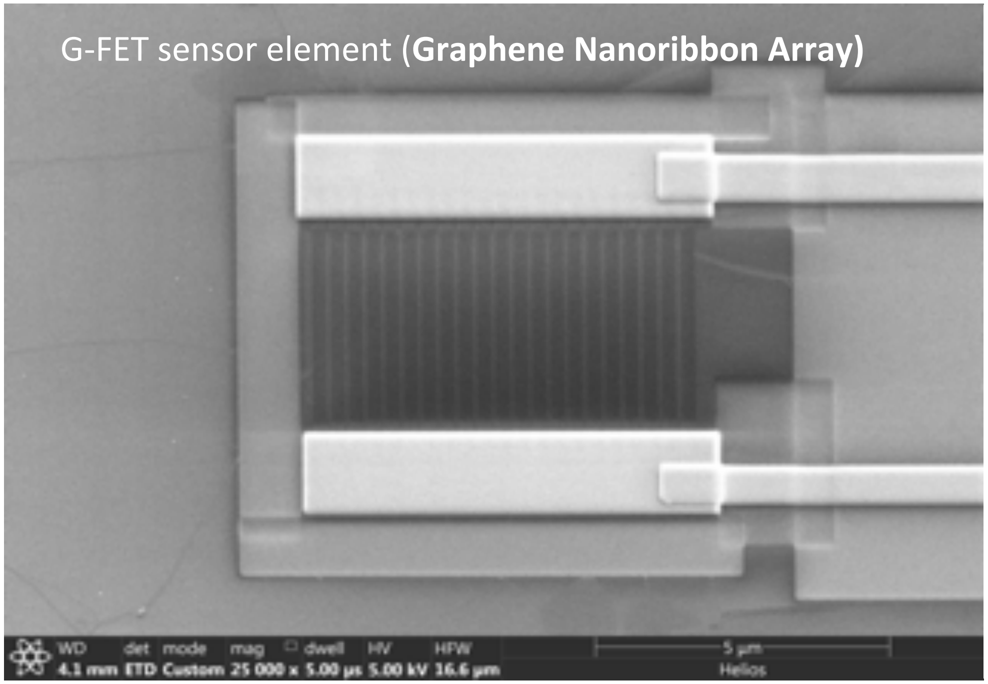
- **What:** ~10 kg of liquid xenon, high-efficiency, well-resolved single electron counting and (x,y) resolution, low electron backgrounds
- **Why:** probe MeV-to-GeV DM that scatters off electrons, and ~10 eV-to-keV DM that is absorbed by electrons
- **When:** we aspire to obtain a background-free 2-electron signal threshold in two years
- **Where:** deployment at SURF or Boulby
- **Who:** Thriving proto-collaboration of theorists, LZ and Xenon-nT collaborators - **LBL/LLNL/Purdue/ Stonybrook/UCSD**
- **How:** A movable, quasi-table-top experiment (no shovels required)
- **Why, more concretely:** Expected sensitivity (for heavy mediator)

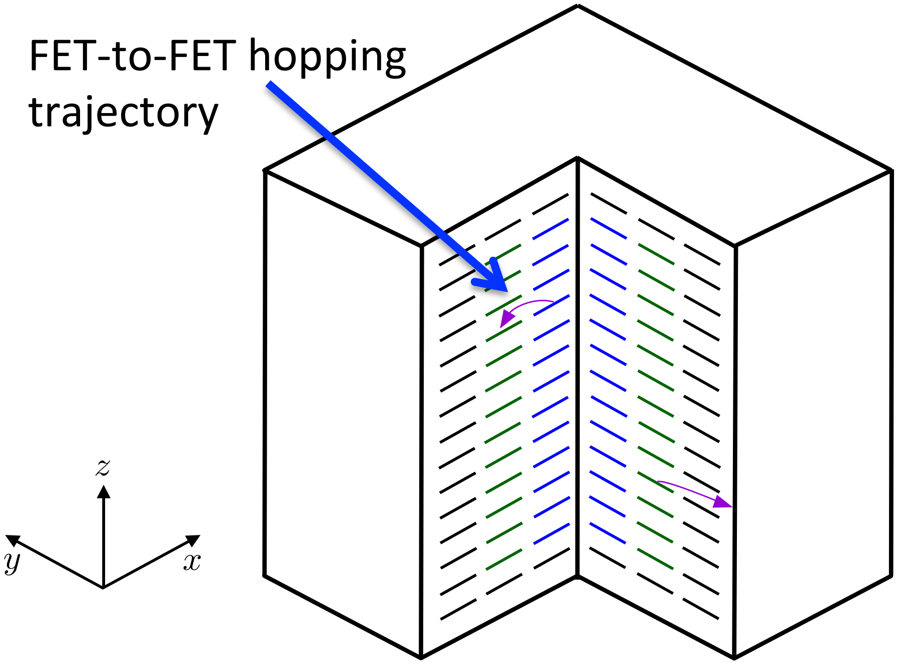
PTOLEMY-G^3

Detector: Graphene field-effect transistors (G-FETs) arranged into a fiducialized volume of stacked planar arrays – Graphene cube (G^3), with mass 1kg ~ 10^{10} cm^2 ~ 10^9 cm^3

Will look for MeV dark matter scattering events that liberate an electron from a graphene target, in the absence of any other activity in the G^3

See Y. Hochberg, Y. Kahn, M. Lisanti, C. Tully, K. Zurek, **arXiv:1606.08849**


G-FET sensor element (**Graphene Nanoribbon Array)**


FET-to-FET hopping trajectory

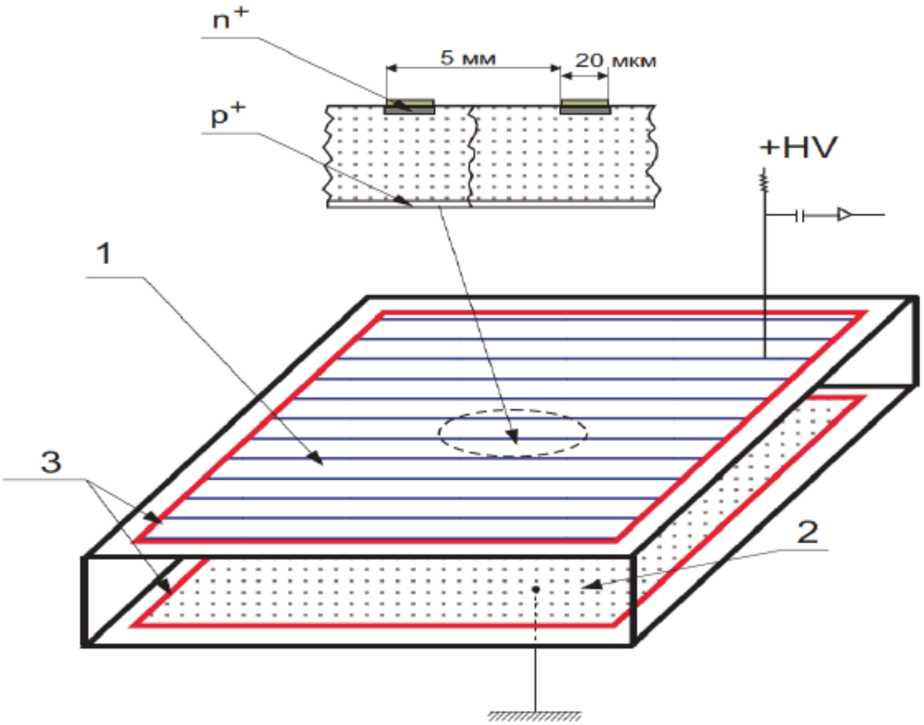
Germanium Detectors with Internal Amplification

(Dongming Mei, U South Dakota)

This experiment would use an ionization amplification technology for Ge in which very large localized E-fields are used to accelerate ionized excitations produced by particle interaction to kinetic energies larger than the Ge bandgap, at which point they can create additional electron-hole pairs, producing intrinsic amplification.

This amplified charge signal could then be read out with standard high-impedance JFET- or HEMT-based charge amplifiers.

Such a system would potentially be sensitive to single ionized excitations produced by DM interactions with both nuclei and electrons. In addition, purposeful doping of the Ge could lower the ionization threshold by a factor of 10, to ~ 100 meV, making the detector sensitive to 100 keV DM via electron recoils.



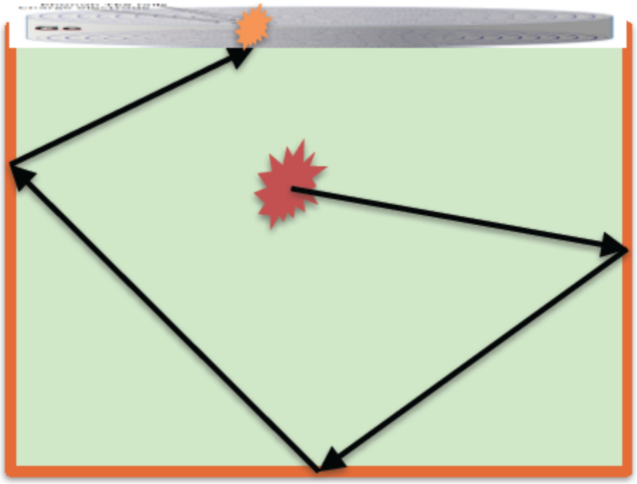
Scintillators with transition edge sensor readout

Sensitivity to dark matter – electron interactions.

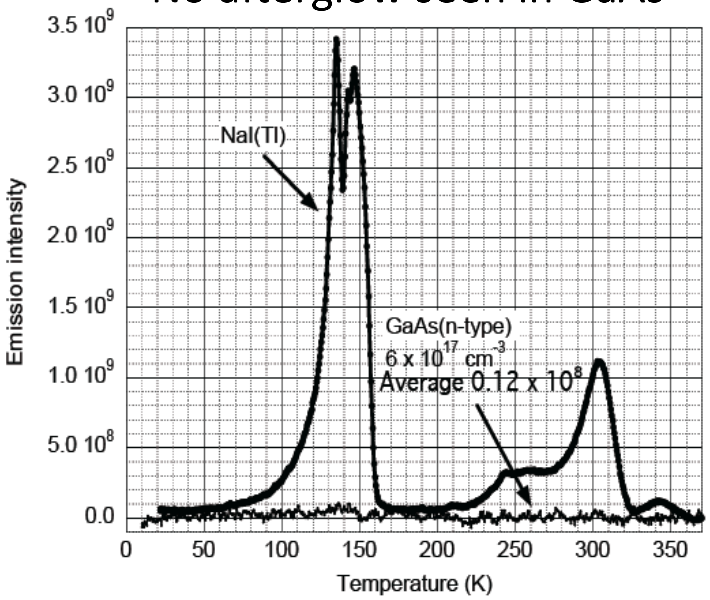
Philosophy: Running in equilibrium, use TES detection efficiency and photon energy resolution to minimize dark counts.

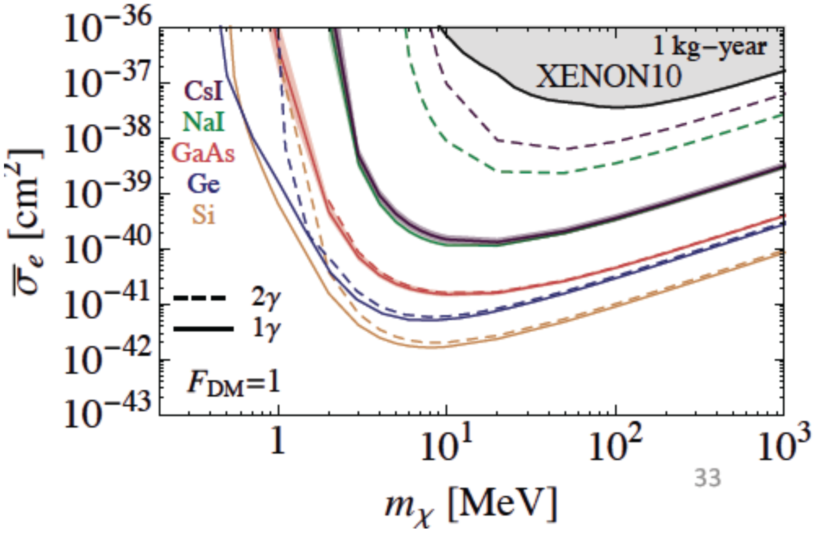
GaAs: Derenzo et al: 1607.01009, 1802.09171

No E field = No dark current



No afterglow seen in GaAs



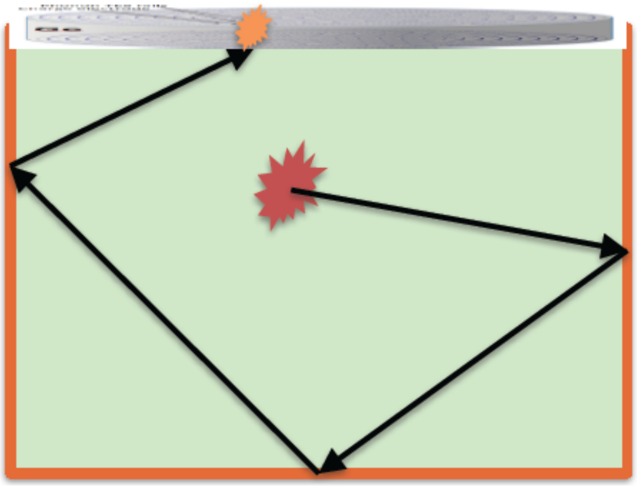


Scintillators with transition edge sensor readout

Or, choose your favorite scintillator (CsI, NaI, $CaWO_4$, …)

Maximize light yield and target mass, minimize band gap, afterglow, and background.

No E field = No dark current



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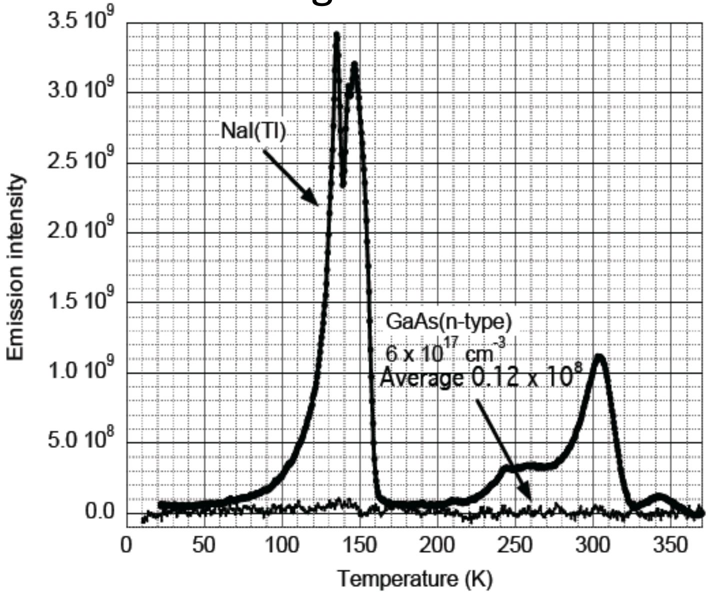
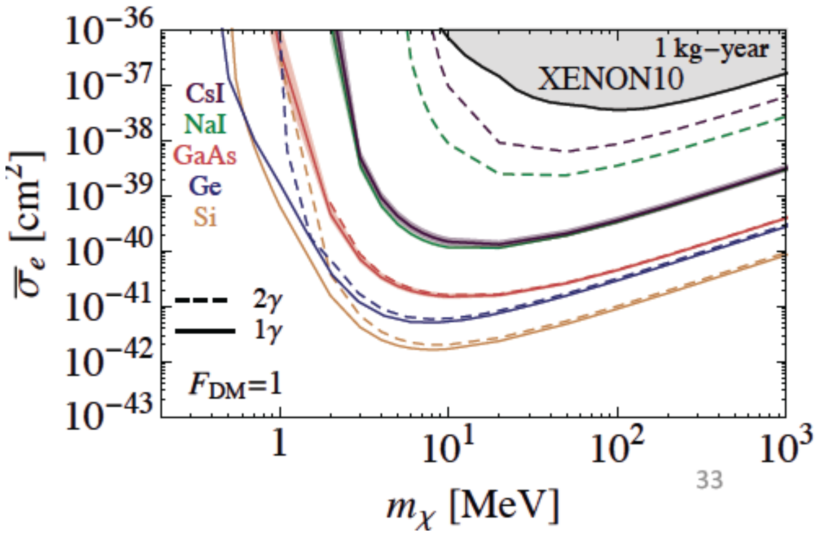
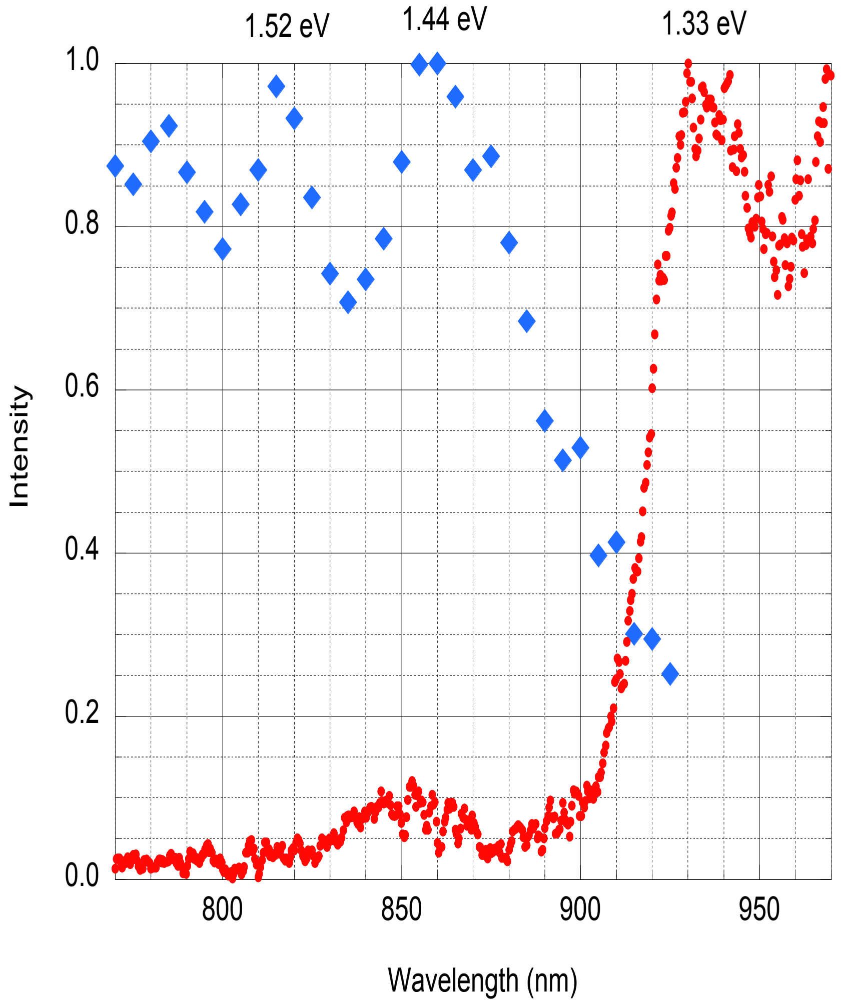
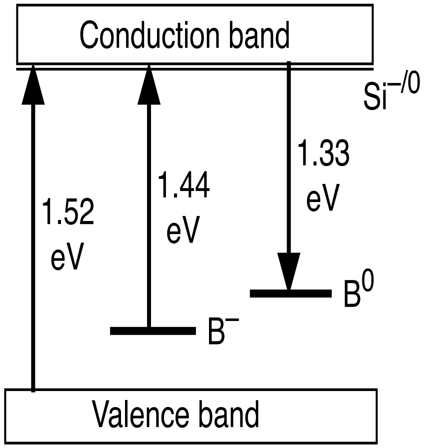




GaAs(Si,B) Optical Excitation/Emission Spectra at 10K

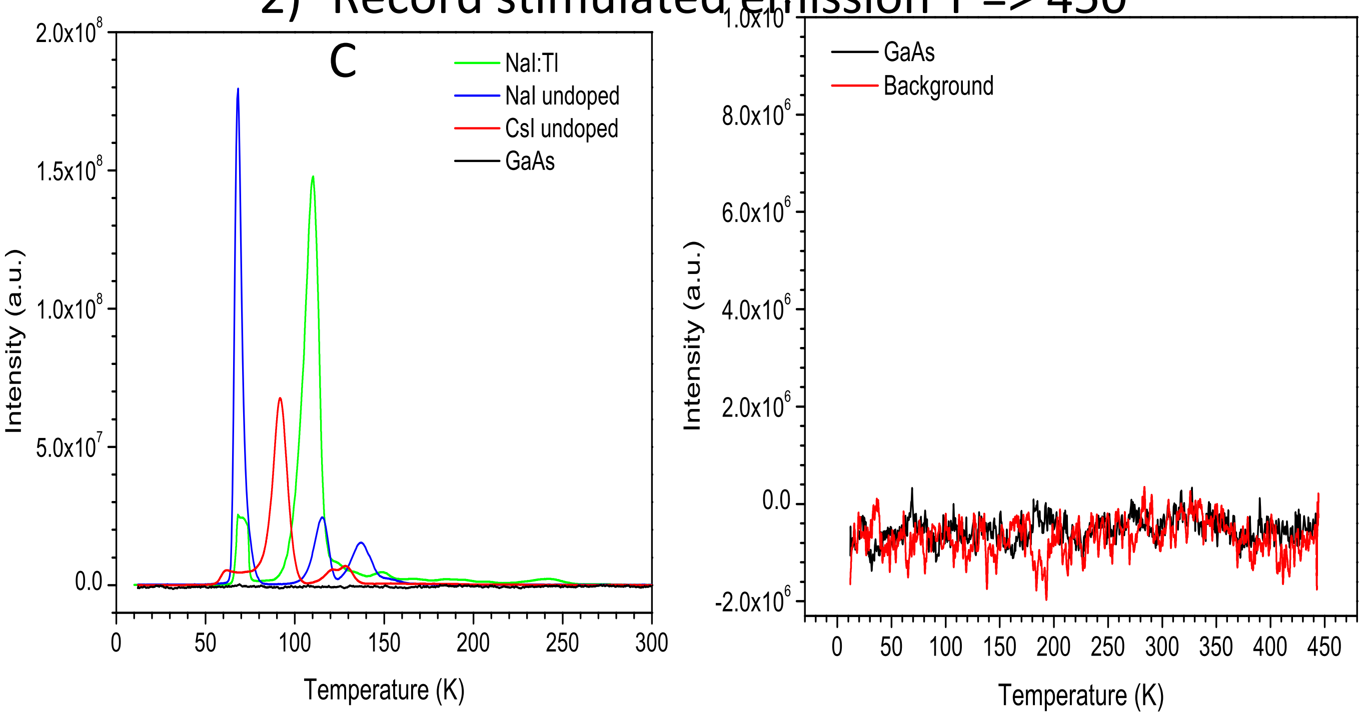




- Silicon and boron doping essential
- Stokes shift 0.11 eV
- Low self-absorption

Afterglow: Thermally Stimulated Luminescence

1) 50 keVp X-ray bombardment 10K for 30 minutes
2) Record stimulated emission T => 450 C

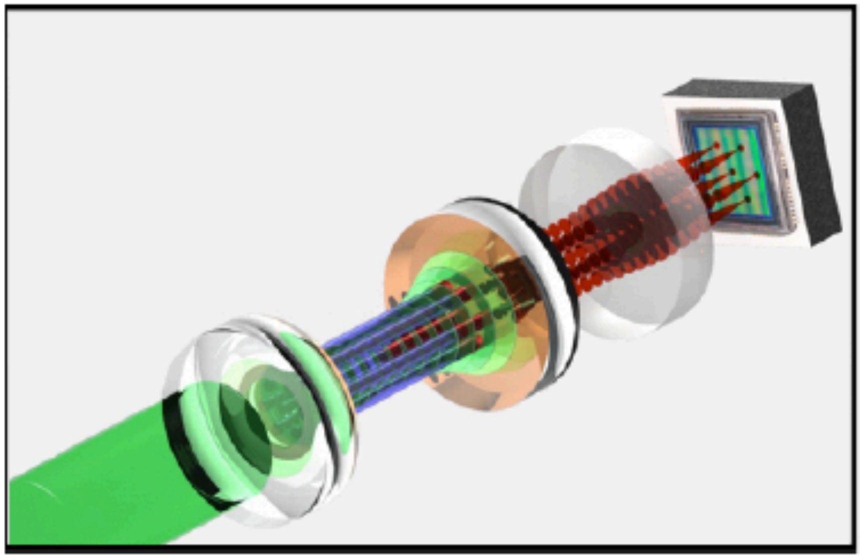


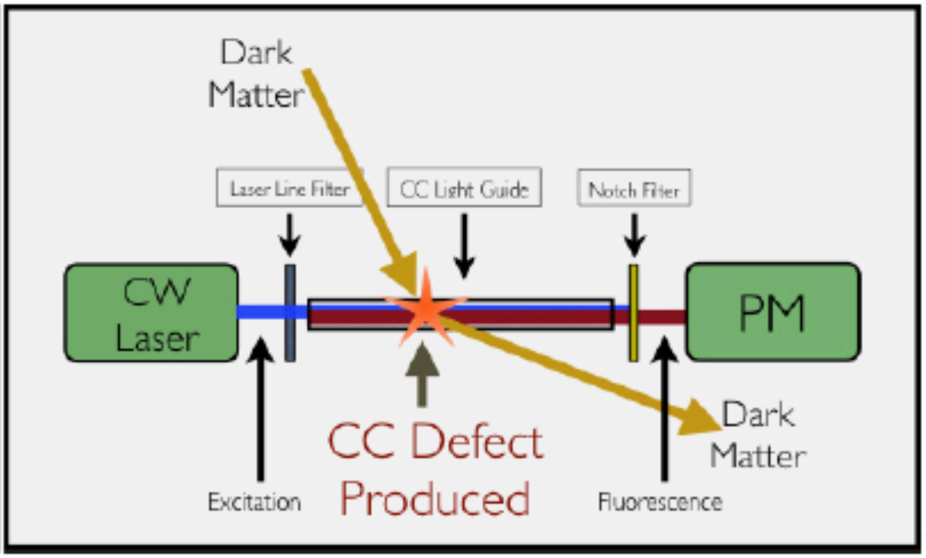
Any metastable radiative states in n-type GaAs annihilated by donor electrons => no afterglow

Color centers

(R. Budnik and collaborators, 1705.03016)

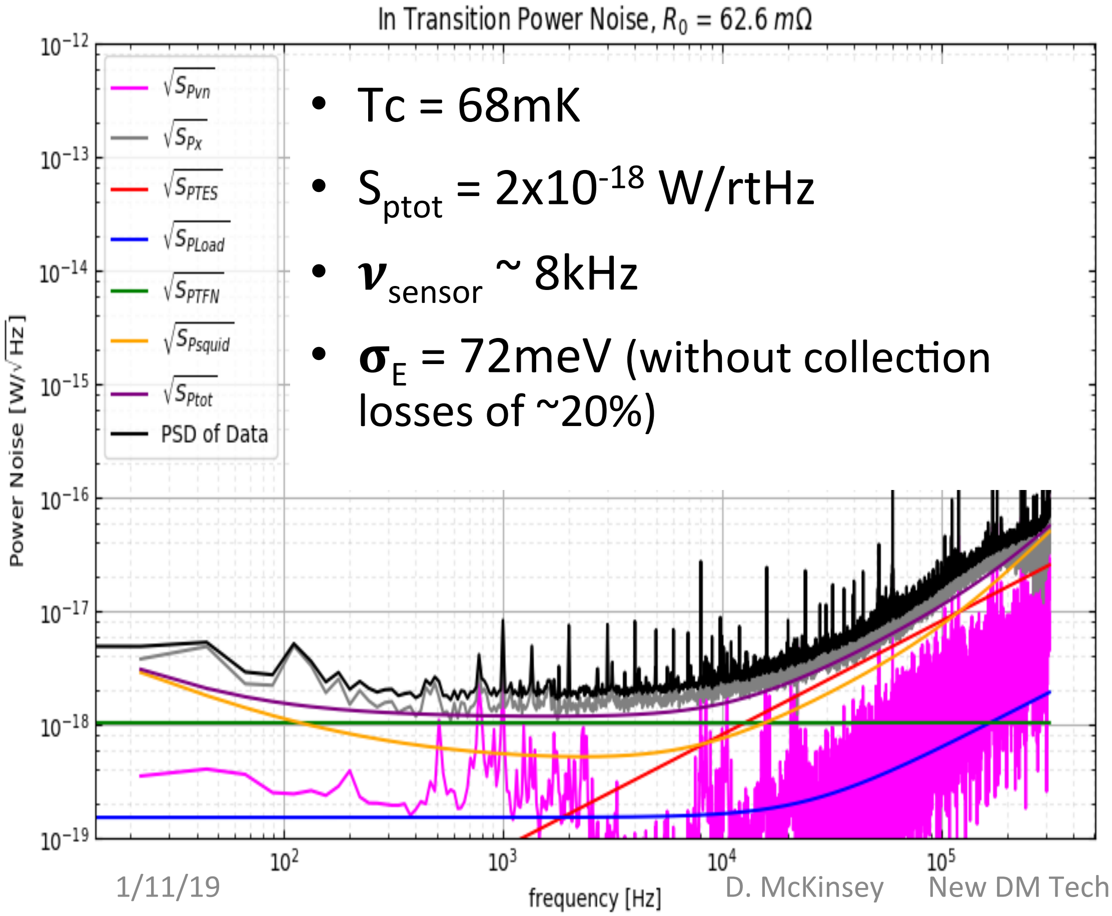
- Transparent crystal hit by DM, dislocating an ion
- The defect acquires an electron and is probed by fluorescence repeatedly
- DM mass sensitivity can go below 100 MeV



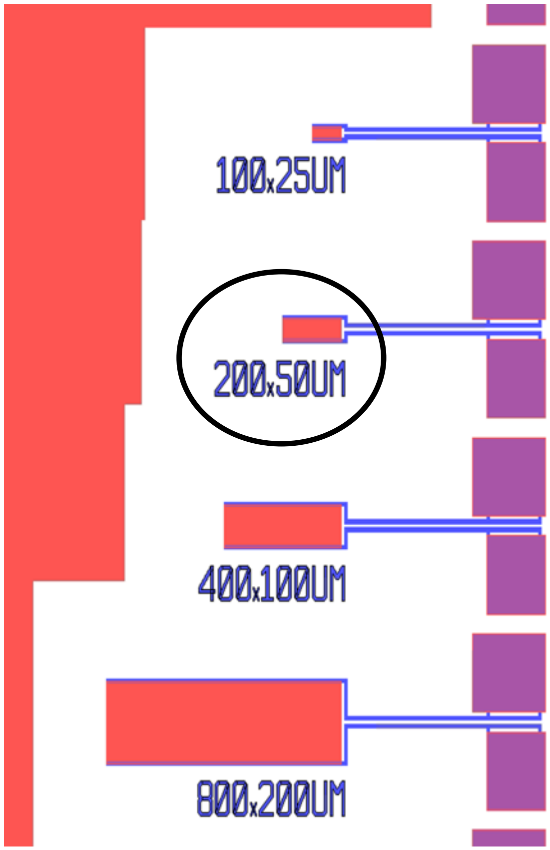


Recent Progress: TES R&D from M. Pyle et al.

Light Mass Dark Matter Experimental Driver: Energy Threshold

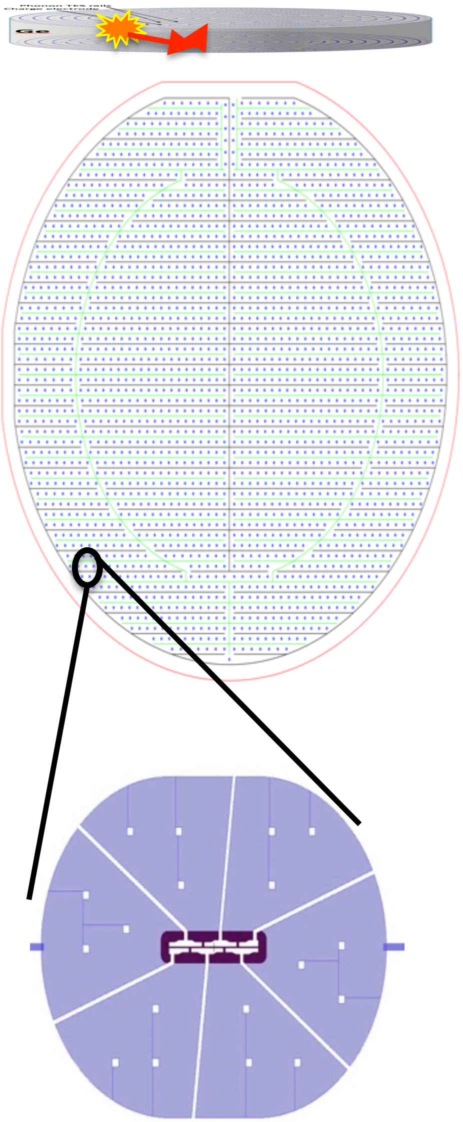


- Tc = 68mK
- S_{ptot} = 2x10^{-18} W/rtHz
- ν_{sensor} ~ 8kHz
- σ_E = 72meV (without collection losses of ~20%)

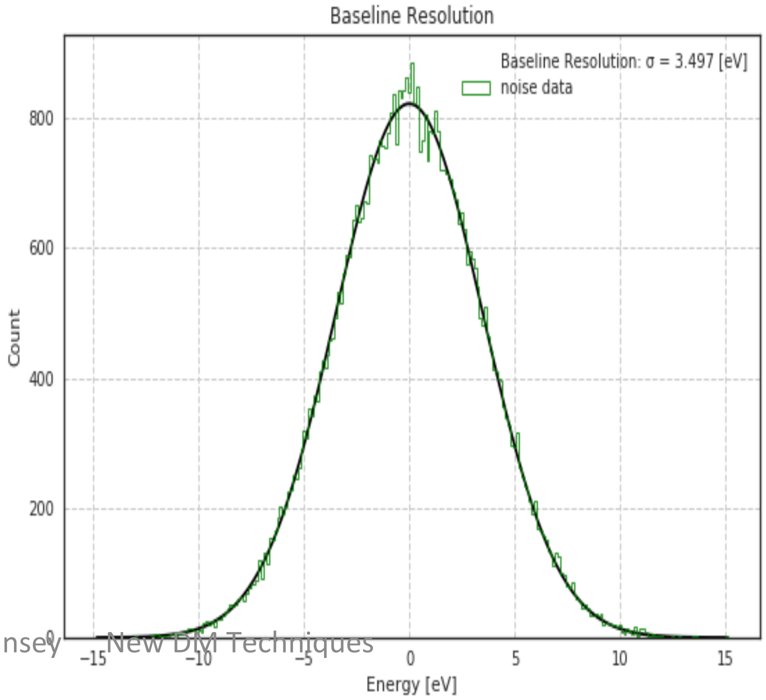


- Environmental noise pickup not problematic for > 100meV experimental applications
- Measured sensitivity with x1.4 of theoretical sensitivity

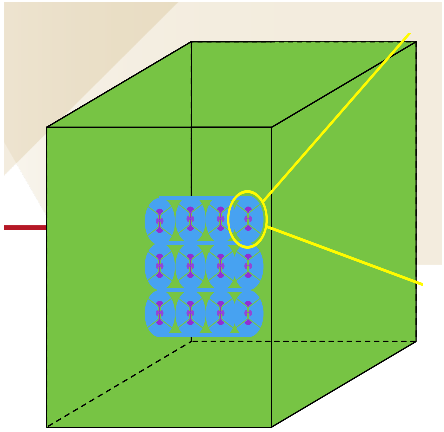
Recent Progress: Large Area Photon Calorimeters



- 3” diameter 1mm thick Si wafer (45.6 cm^2)
- Distributed athermal phonon sensors
  - Athermal Phonon collection time estimated to be ~20us
  - 2.5% sensor coverage
- Tc= 41.5mK
- **17% Athermal Phonon Collection Efficiency**
- **Measured Baseline σ_E =3.5 ± 0.25 eV**



Shovel ready now: 1cm^2 and 1cm^3 Calorimeters with 200 meV resolution

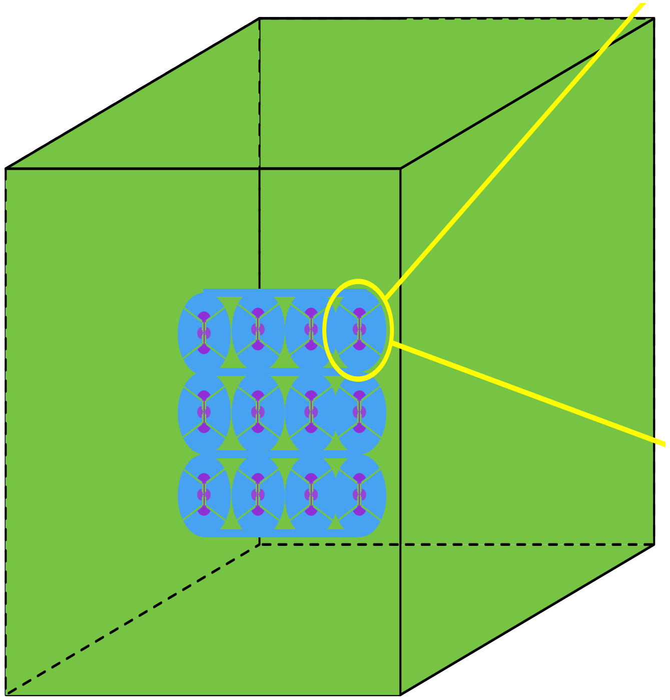


New 1cm^3 Prototype Test Des

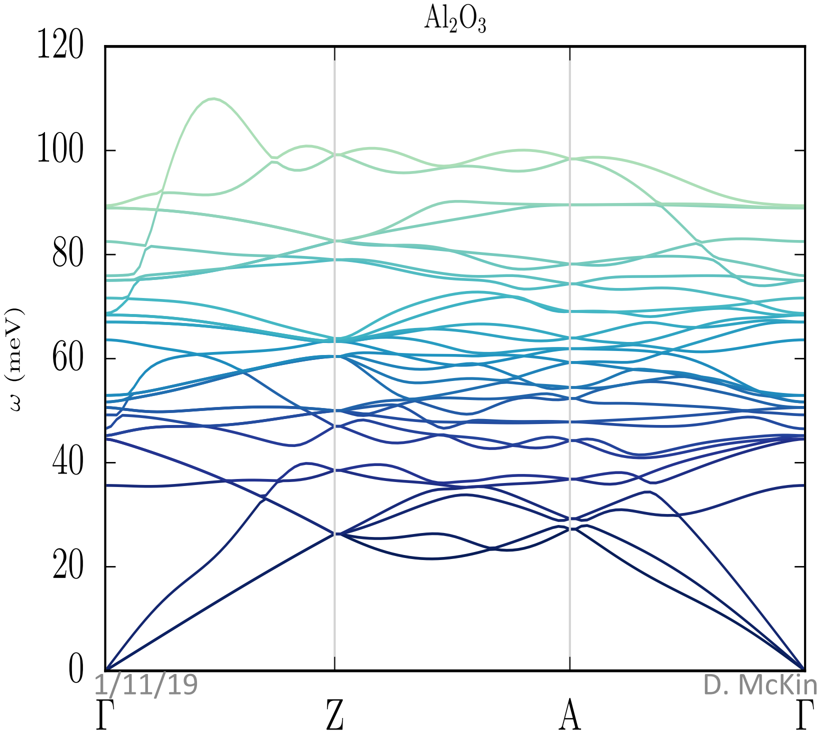
Photon Detector + W TES test structures bound the technically possible parameter space

- 1cm^2 Si: 1MeV-100 MeV ERDM with GaAs
- 1cm^2 Si: NRDM from Superfluid He
- 1cm^3 Al2O3/GaAs: 1keV-100MeV ERDM (new R&D)

# TES	**100**
TES Dimensions	50um x 2um x40 nm
TES Rn	320mOhm
Fin Length	125um
W/Al Overlap	15um
Fractional Al Coverage	1%
Tc	40mK
Bias Power	48fW
Power Noise	5.1e-19 W/rtHz
Phonon absorption time	106us
Sensor fall time	97us
Collection efficiency	19%
σ_E	**220 meV**



Polar Crystal Calorimeter Dark Matter Searches

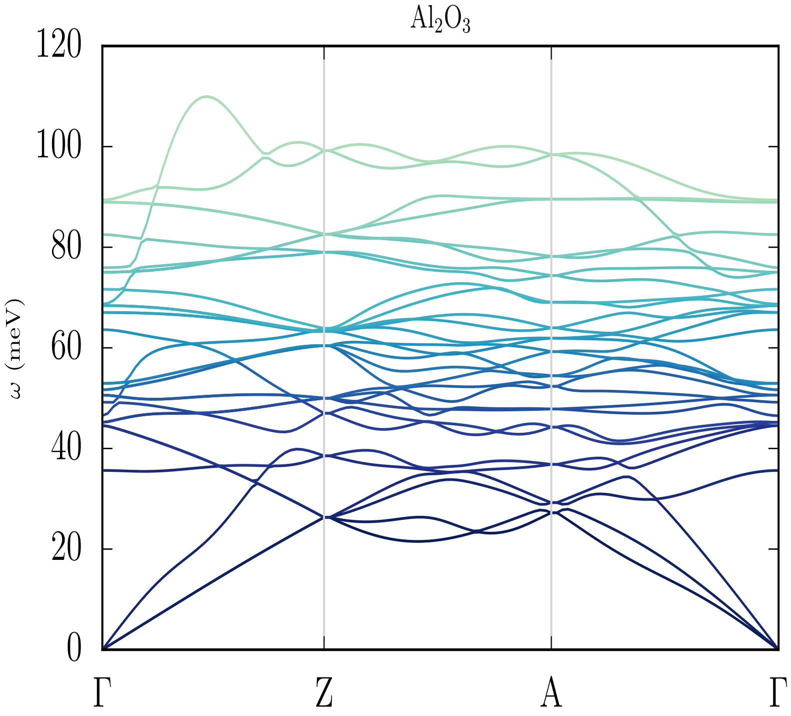


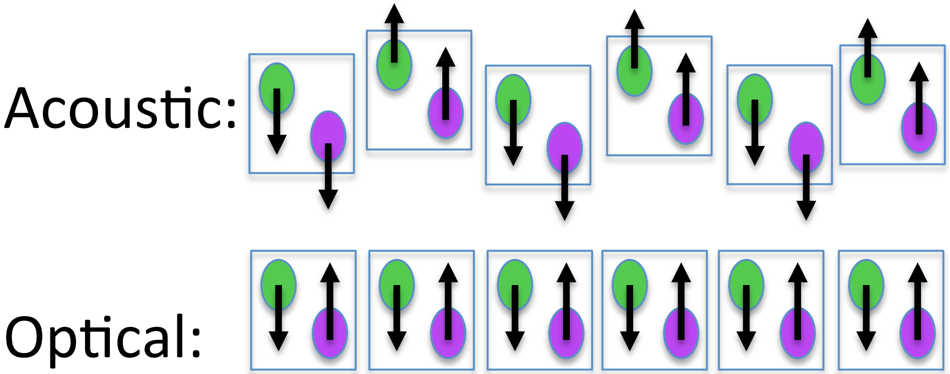
S. Griffin, S. Knapen, T. Lin, M. Pyle, K. Zurek

1712.06598
1807.10291

Optical Phonons: Ideal for <1MeV Dark Matter Searches

Optical Phonons have an energy from 30-100meV at p=0, therefore they are perfectly kinematically matched to 1 MeV dark matter

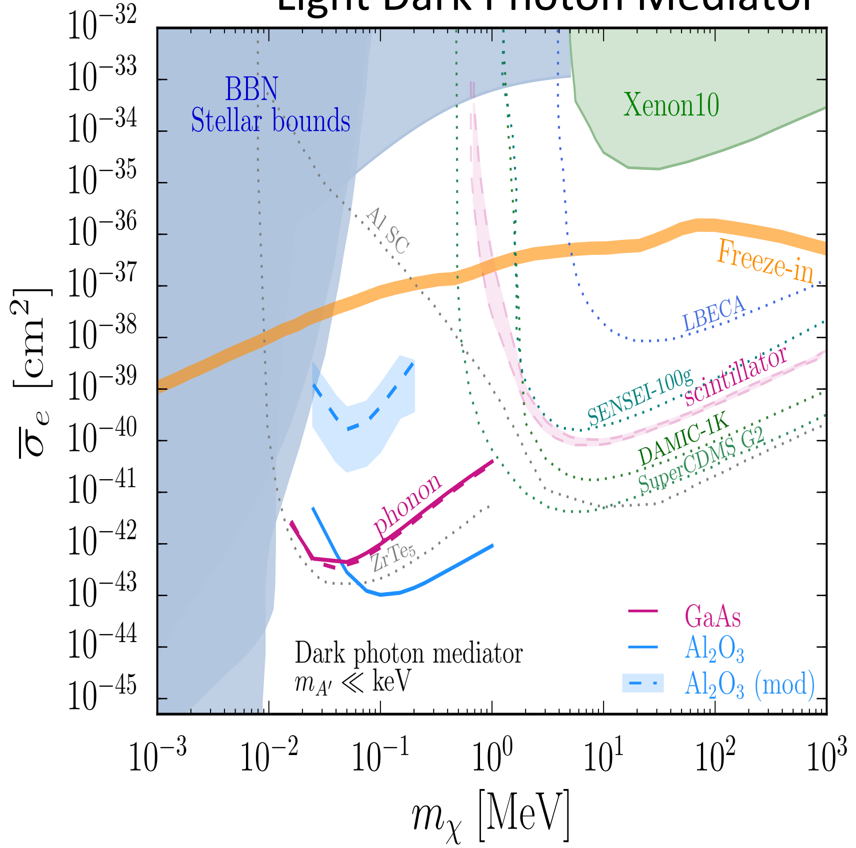




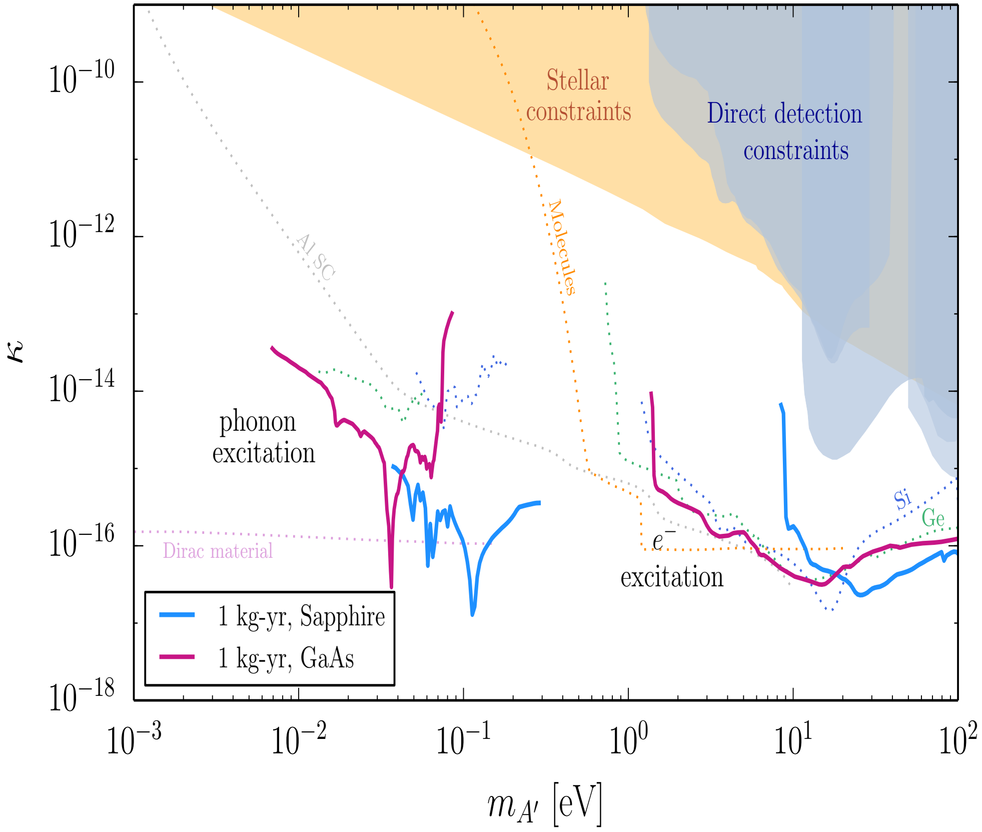
Polar crystal optical phonons have very strong E&M couplings … ideal for dark photon couplings

Single Optical Phonon DM Sensitivity Reach

Light Dark Photon Mediator



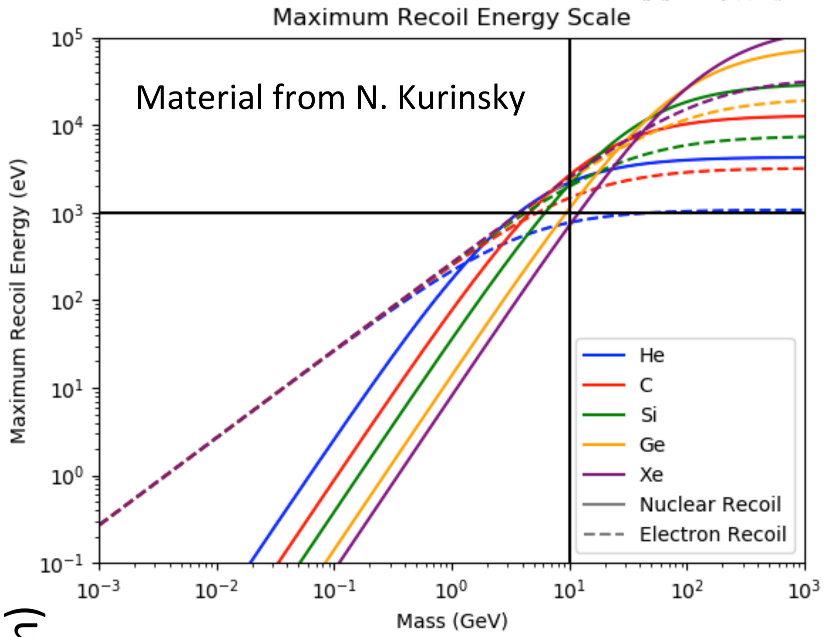
Dark Photon Absorption

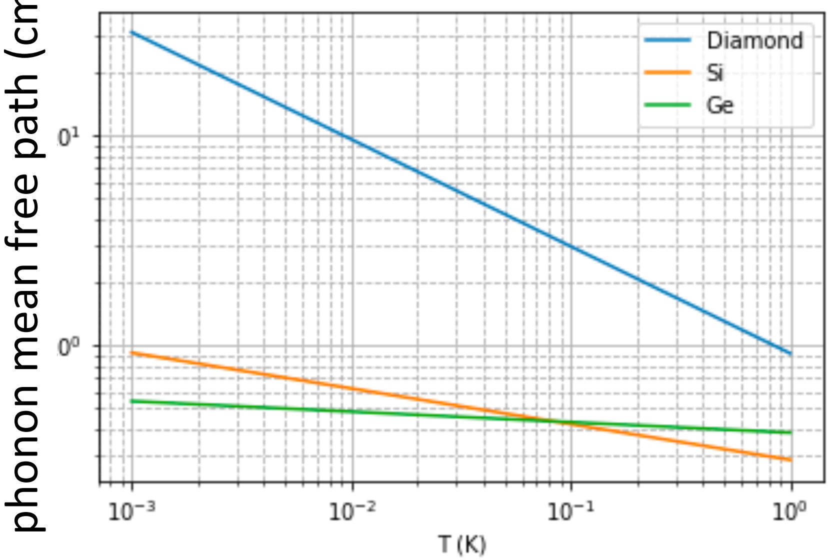


- Exposure: 1kgyr
- Backgrounds: None
    - x100 4π Active Photon Veto (NaI or CsI scintillating slabs at 10mK)
    - Excellent Environmental Noise Suppression
- Baseline Resolution σ_E : 5 meV (GaAs) – 15 meV (Al$_2$O$_3$)

Diamond Detectors (“Semiconductor”)

- Lighter targets better kinematic match to light DM
- Crystalline carbon (diamond) has many potential advantages over other semiconductors
  - Excellent isotopic purity (less signal loss)
  - More energetic and long-lived phonon modes; velocity 3x higher than Si (higher bandwidth)
  - Phonon mean free path 10x higher at sub-K temperatures (allows larger crystals)
- Larger bandgap (~5.4 eV) than Si (~1.2 eV) and Ge (0.5 eV), so harder to generate an electron-hole pair; benefit to NR rather than ER
- Much better at holding large electric field!
  - A 1 eV resolution diamond detector could achieve 0.001 e-h pair resolution at 2.5 kV/cm
  - Significant potential for ER/NR discrimination
  - High-purity diamond is essentially an insulator at room temperature: resistivity of ~TΩ-cm
- No impurity states < 0.5 eV: low susceptibility to IR, and lower chance of sustaining dark rates

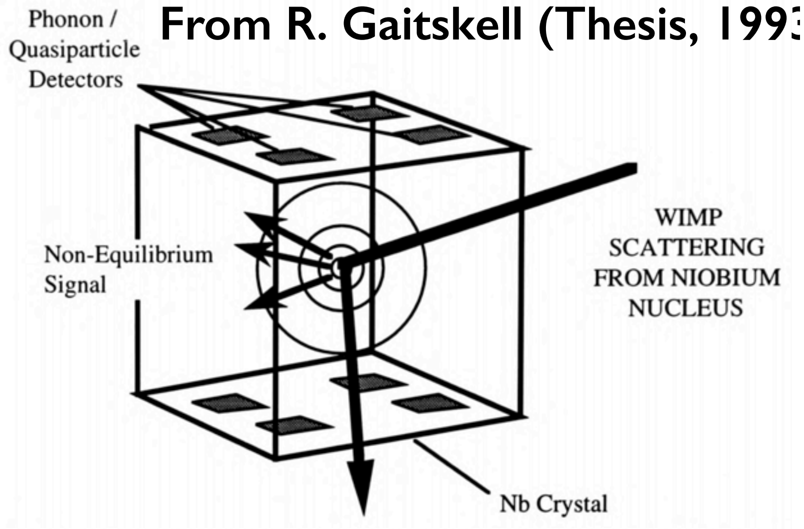


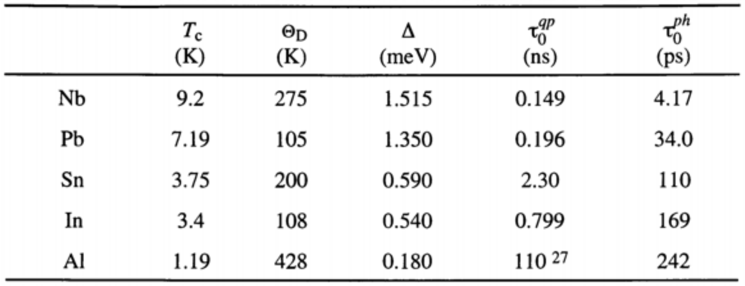


Superconducting Targets

- In the long-term, weakly bound quantum systems will allow us to reach the keV fermionic lower bound for ERDM and the meV scale for bosonic dark matter
- The design drivers for superconducting (SC) detectors are less obvious (ArXiv:1512.04533)
  - Collect quasiparticles (Al, Zn) or phonons (Ta, Nb)?
    - Favored method depends on Tc (known) and quasiparticle lifetime (largely unknown for pure, large crystals)
  - How well do film and bulk properties of SCs correlate?
  - No gain mechanism as in He or semiconductors.
  - Need to electrically isolate sensor from substrate while still collecting excitation.
    - Can use higher T_c trapping regions
    - Need to try different combinations of sensor materials and geometries to optimize energy collection.
- Backgrounds largely untested
- Blackbody radiation req'ts very stringent
- Designs must be ~mm-scale, so scaling up will be hard.

From R. Gaitskell (Thesis, 199





	T_c (K)	Θ_D (K)	Δ (meV)	τ_0^{qp} (ns)	τ_0^{ph} (ps)
Nb	9.2	275	1.515	0.149	4.17
Pb	7.19	105	1.350	0.196	34.0
Sn	3.75	200	0.590	2.30	110
In	3.4	108	0.540	0.799	169
Al	1.19	428	0.180	110[27]	242

Table 3.3.1. Parameters for a number superconductors. Taken from Ref. **[36]** unless otherwise indicated.

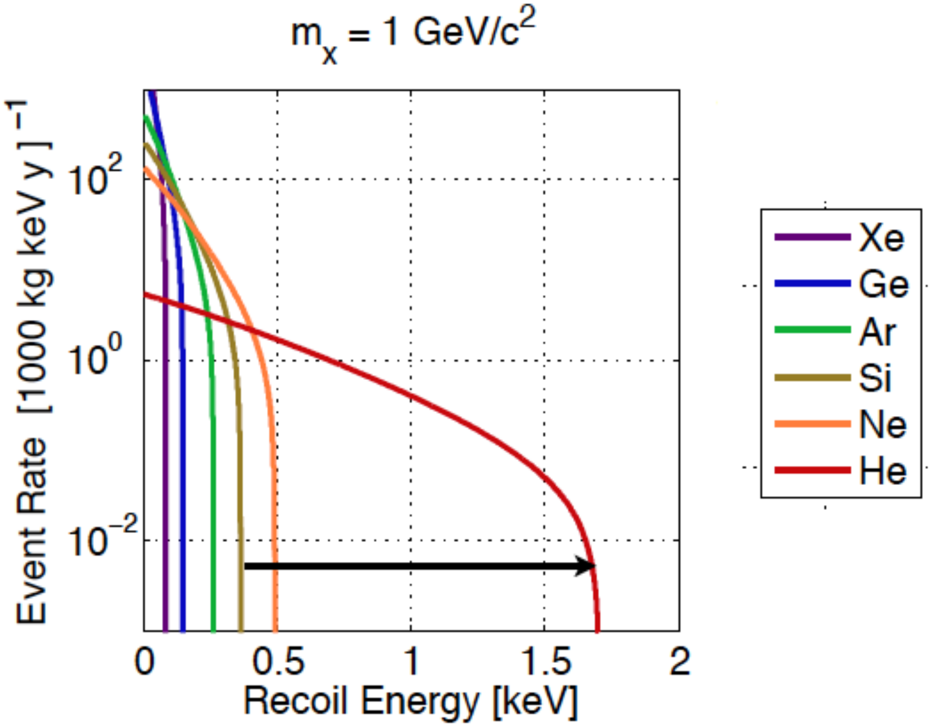
Effective quasiparticle and phonon lifetimes are a rate balance:

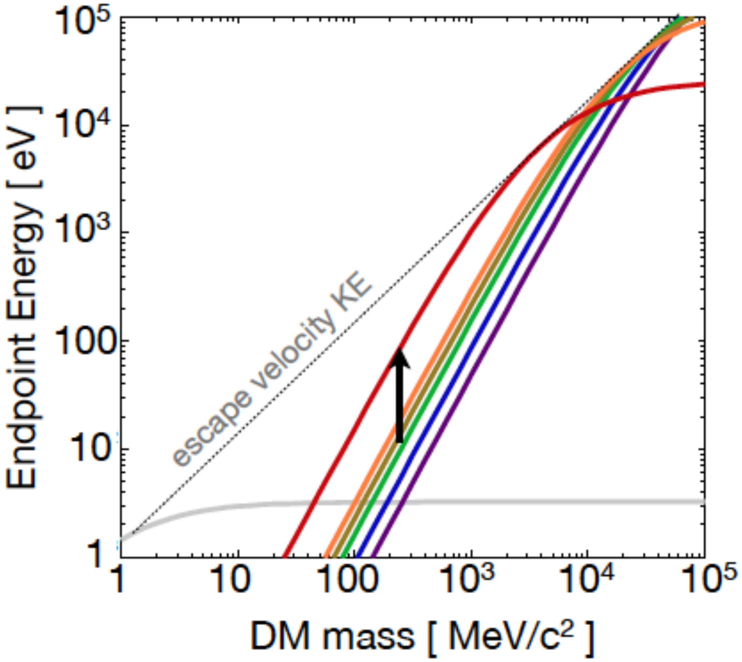
$$\tau_{eff} = \frac{\tau_r}{2}\left(1+\frac{\tau_{\phi\phi}}{\tau_{pb}}\right)$$

Material from N. Kurinsky

Helium for light dark matter detection

Light baryonic target with multiple signal channels, including light, charge, triplet excimers, phonons, and rotons.
(W. Guo and D. N. McKinsey, PRD 87, 115001 (2013).
Also see new paper on arXiv:1810.06283

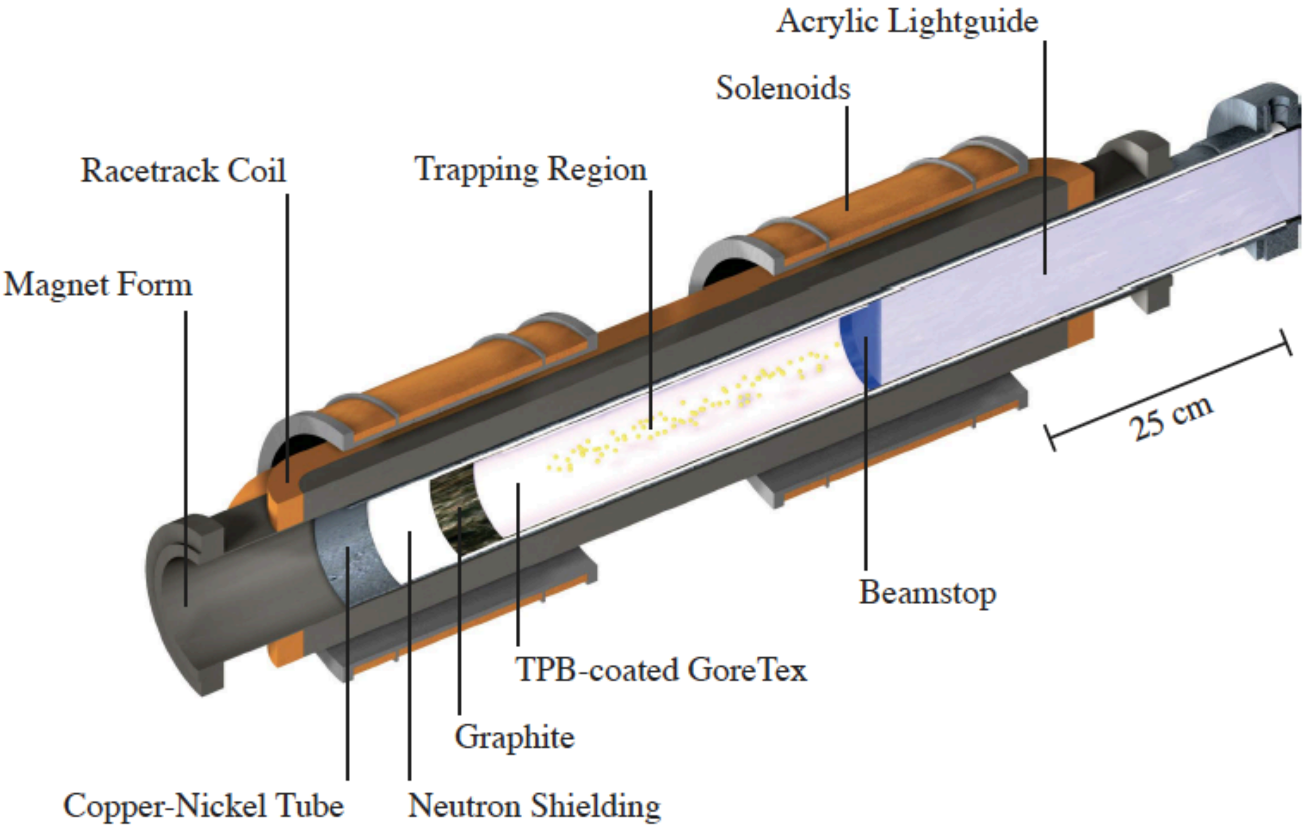




Superfluid helium-4 as a detector material

- Search for the neutron electric dipole moment: R. Golub and S.K. Lamoreaux, Phys. Rep. **237**, 1-62 (1994).

Measurement of neutron lifetime: P.R. Huffman et al, Nature **403**, 62-64 (2000).

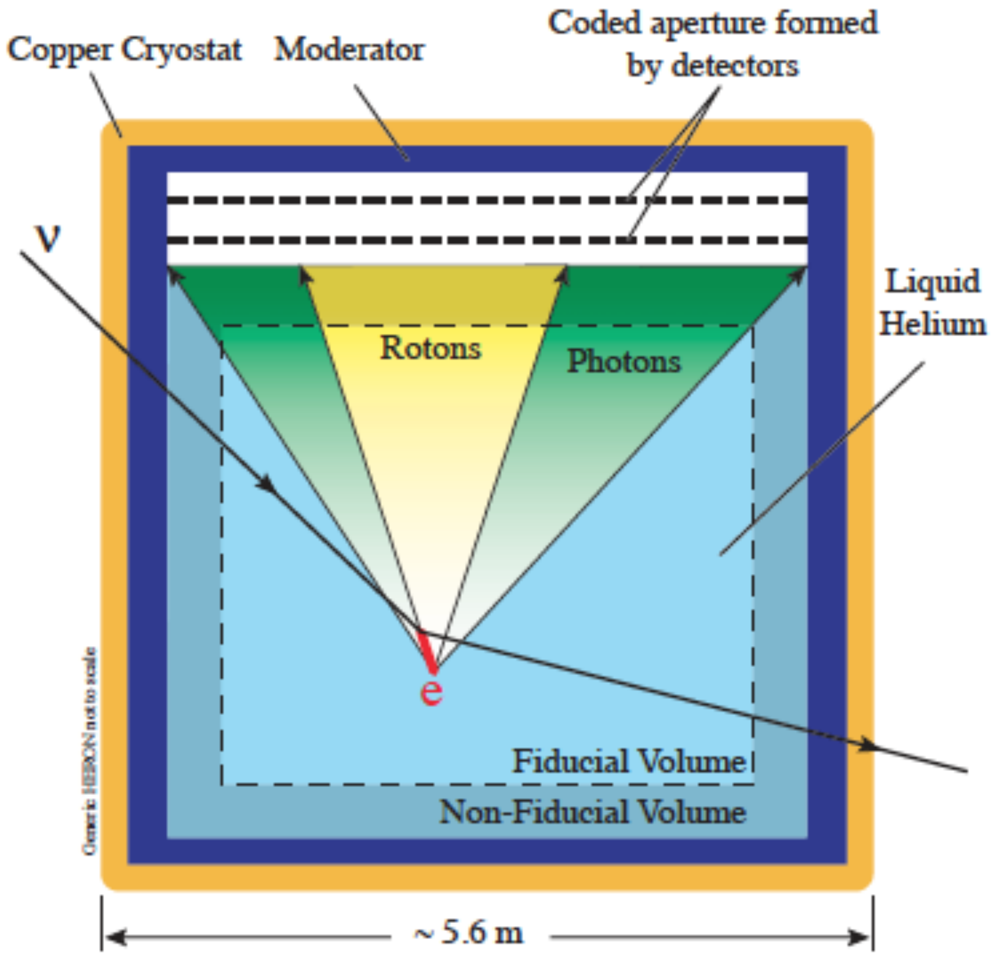


Superfluid helium-4 as a detector material

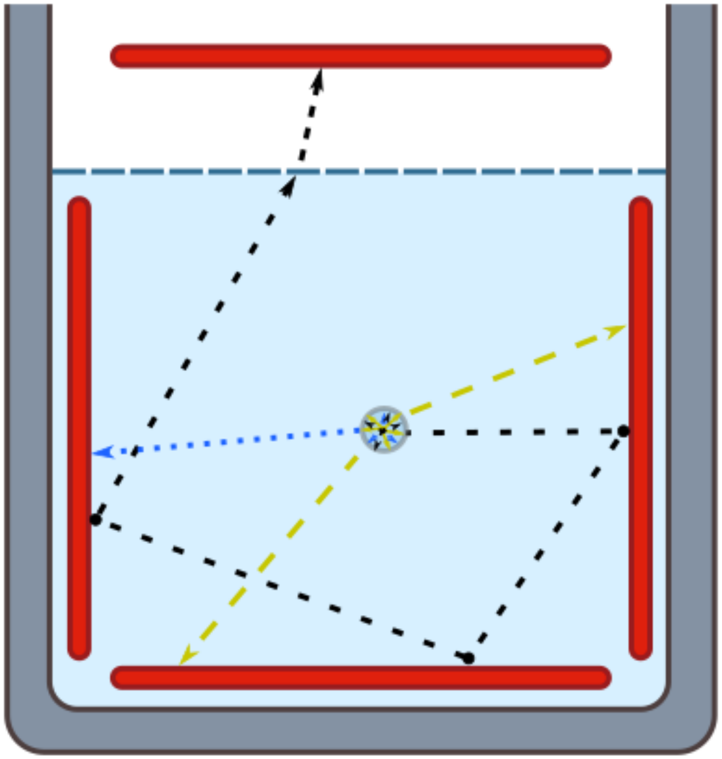
Proposed for measurement of pp solar neutrino flux using roton detection (HERON): R.E. Lanou, H.J. Maris, and G.M. Seidel, Phys. Rev. Lett. **58**, 2498 (1987).

Two signal channels, heat and light. Both measured with a bolometer array.

Also, “HERON as a dark matter detector?” in “Dark Matter, Quantum Measurement” ed Tran Thanh Van, Editions Frontieres, Gif-sur-Yvette (1996)



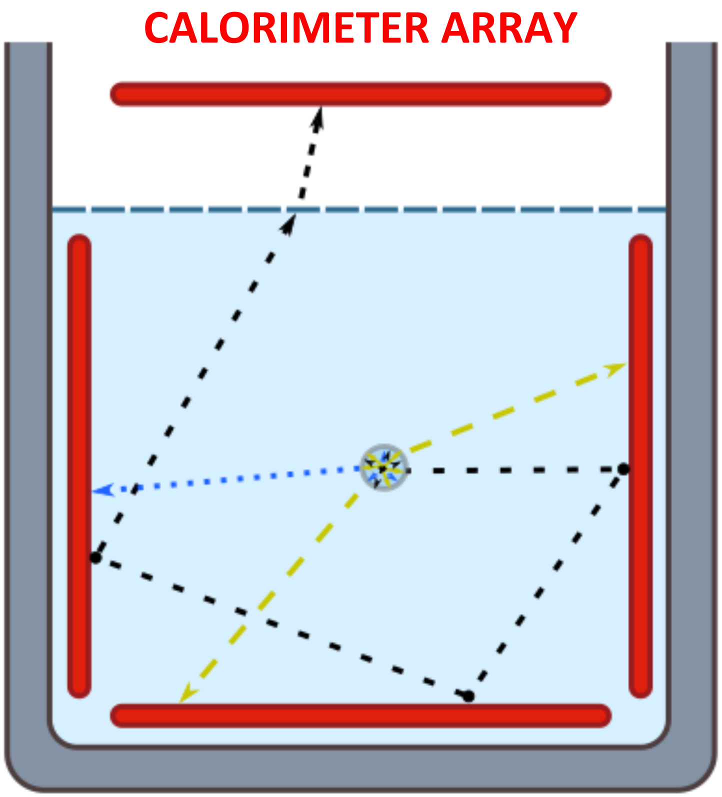
Superfluid Helium as a Dark Matter Target



Advantages of He-4

- Kinetic energy transfer from sub-GeV dark matter more efficient than on other nuclei
- Cheap
- Easy to purify; intrinsically radiopure
- Remains liquid/superfluid down to absolute zero
- Monolithic, scalable
- Calorimetry for signal readout

Proposed Detector: HeRALD



Helium **R**oton **A**pparatus for **L**ight **D**ark Matter

O(1 kg) cubic mass of helium, operated at ~50 mK in dilution refrigerator

5 calorimeter arrays immersed in helium, instrumented with transition-edge sensors (TES's)

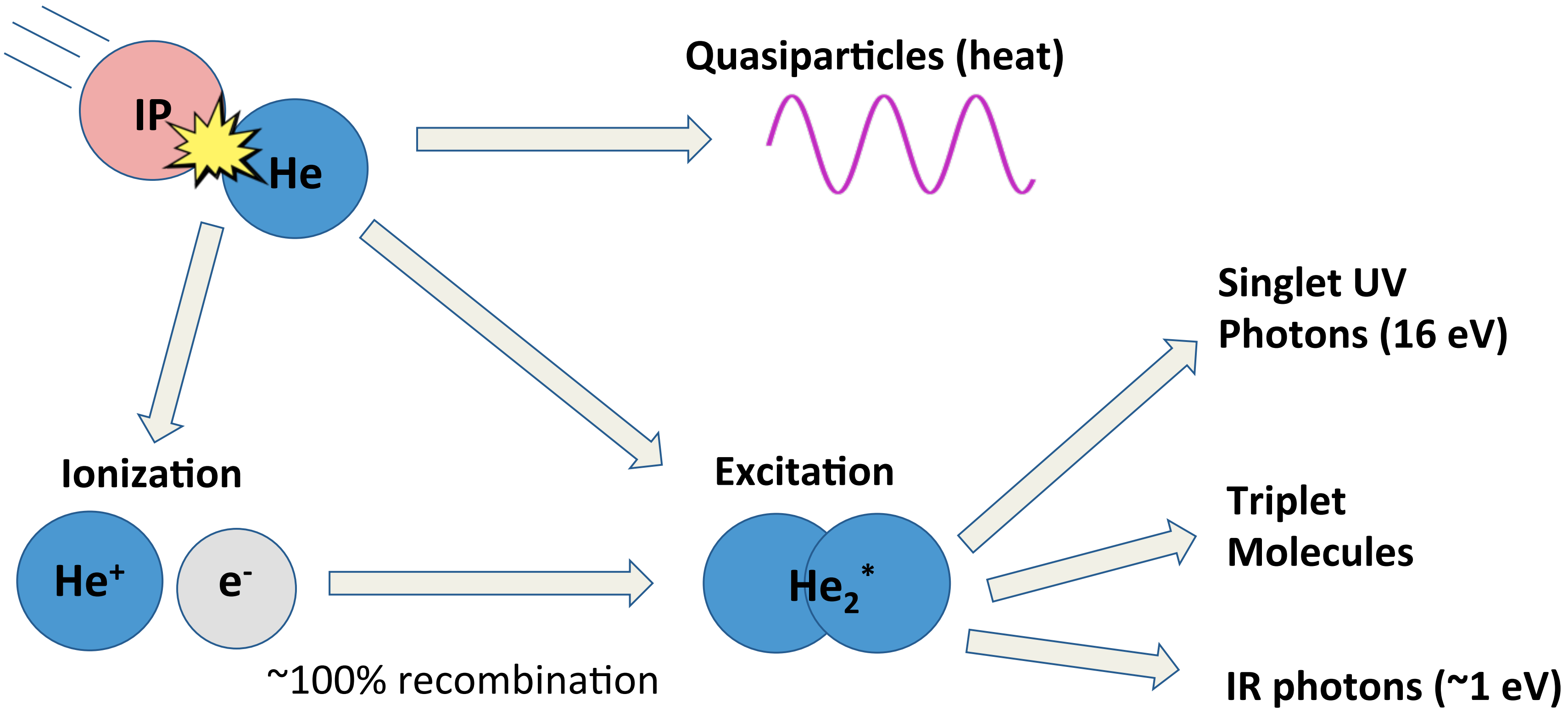
- Detect UV photons, triplet excimers, IR photons

Vacuum layer between helium and 6th TES array

- Detect quasiparticles via quantum evaporation

arXiv:1810.06283

Recoils in Helium (generic incident particle IP)



IP

He

Quasiparticles (heat)

Ionization

He^+

e^-

~100% recombination

Excitation

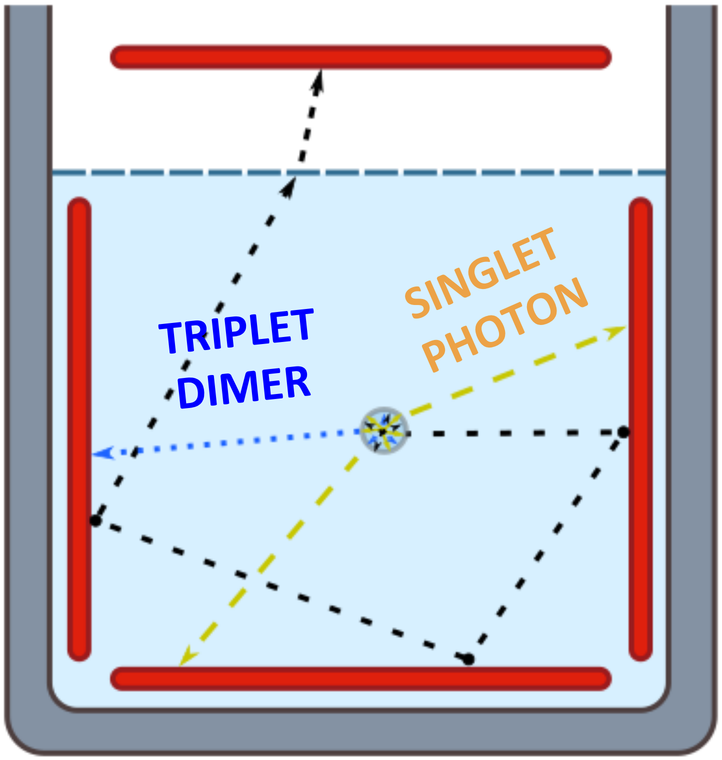
He_2^*

Singlet UV Photons (16 eV)

Triplet Molecules

IR photons (~1 eV)

Detecting Excimer Signal



Singlet decay (16 eV) ∿

- Lifetime of few ns
- Photons hit detector walls after **~ns**, detected directly by TES
- Weak thermal coupling between helium and calorimeter (*Kapitza resistance)*

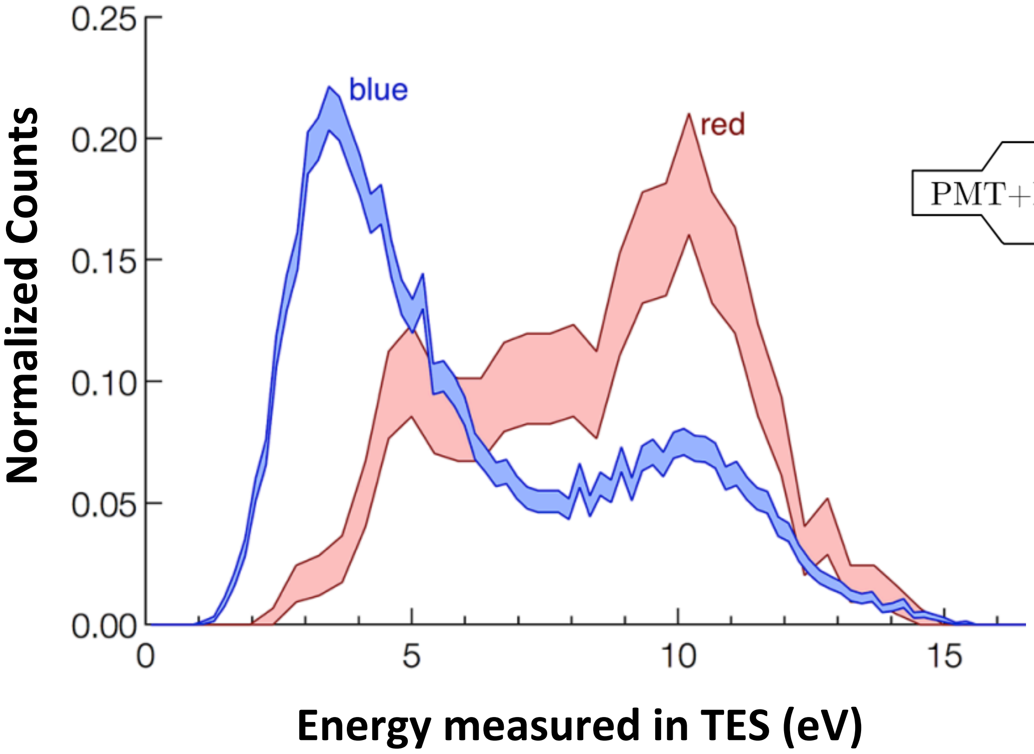
Triplet decay (16 eV)

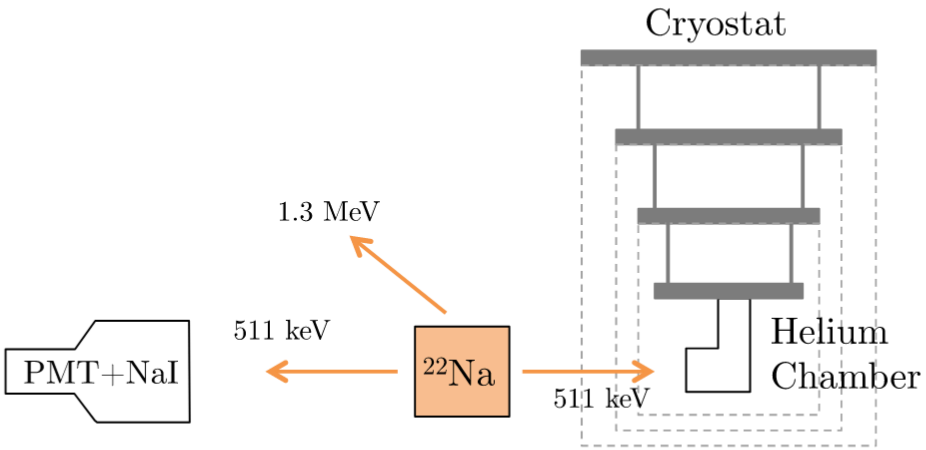
- Lifetime of 13 seconds (McKinsey et al, Phys Rev A **59**, 200 (1999).
- Helium dimer molecule travels ballistically at speed ~1-10 m/s, measured by calorimeter after **few ms**

IR (~1 eV)

Detecting Excimer Signal

Carter et al., J Low Temp Phys 186, 183 (2017)





Observation of singlet/triplet excimers by *Carter et al.*

- Titanium TES in 100 mK ^{4}He bath

Singlets from TES coincident with PMT; triplets from only TES

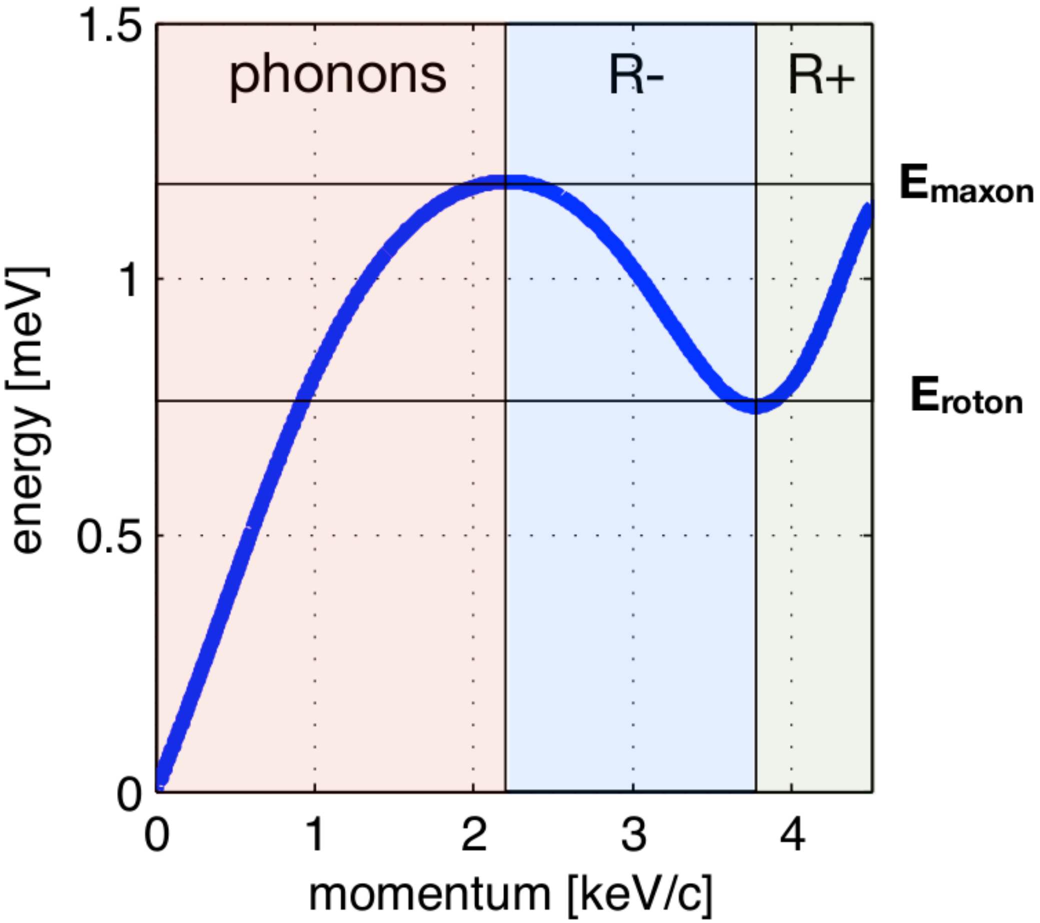
Quasiparticles in ^{4}He

Quasiparticles: collective excitations in superfluid helium

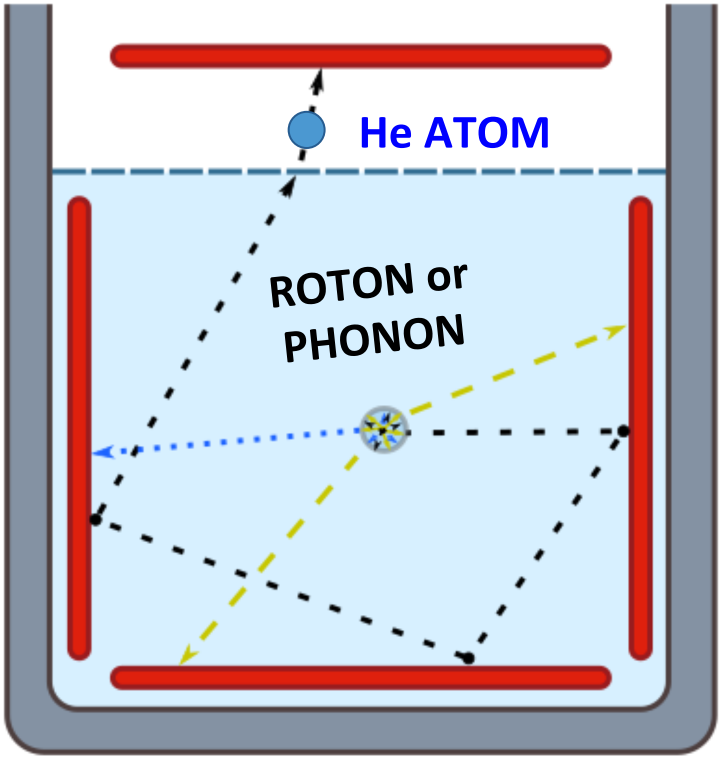
Long-lived, speeds of ~100 m/s

Classified based on momentum: **Phonons**, **R-** rotons, **R+** rotons (roton ≈ high-momentum phonon)

At interface, can transform from one type to another if energy conserved



Detecting Quasiparticle Signal



Recoils produce ~0.8 meV phonons and rotons

Propagate ballistically, bounce around the detector **(few ms)**

Transmission of quasiparticles into the wall suppressed by Kapitza resistance

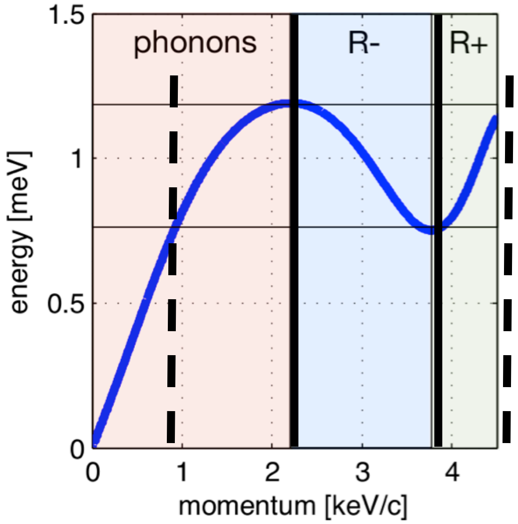
Quantum evaporation of a helium atom into vacuum, followed by energy deposit on top TES

Quasiparticle Propagation

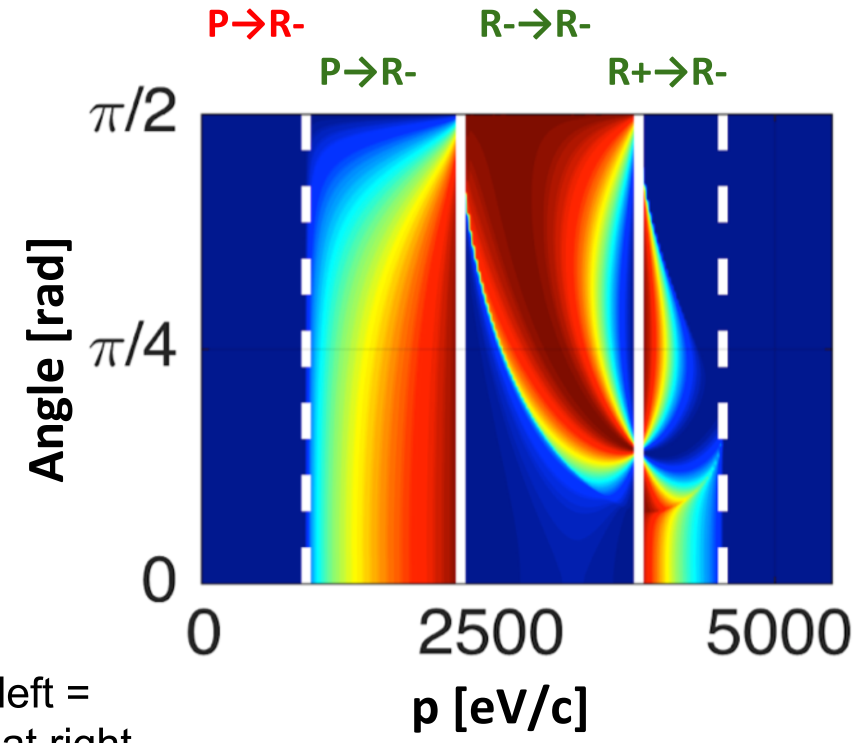
In ^{4}He bulk, quasiparticles move freely

At interface, can be transmitted, reflected, or transformed (if E conserved)

We simulate probabilities for q.p. interactions (e.g. at right: reflection at helium-solid interface)



Reflection as R-
(allowed; forbidden)



Note:
Black lines at left =
White lines at right

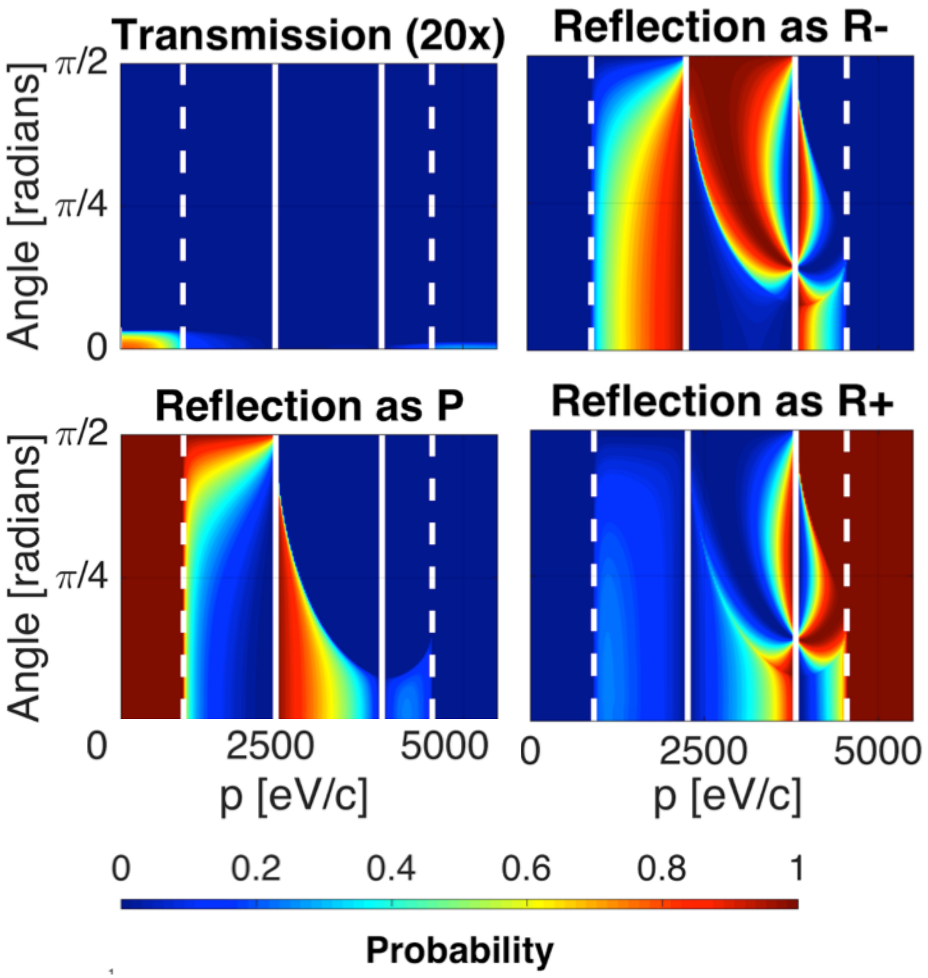
Quasiparticle Propagation

Simulated all reflection/transmission probabilities †

Transmission highly suppressed, as expected; allows ballistic movement without decay

Reflection as same flavor most likely, but significant chance of changing flavor

Helium-Solid Interface



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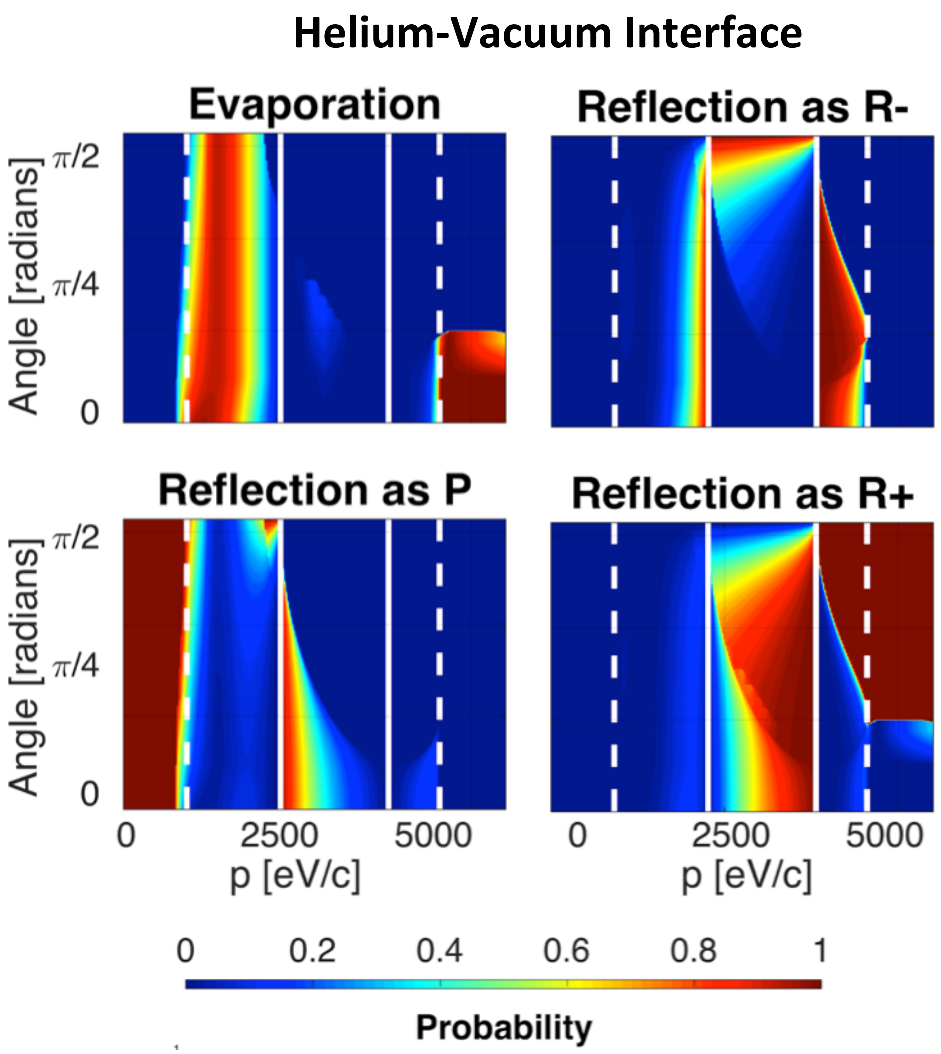
† Probabilities based on calculations in *Phys. Rev. B* ***77****, 174510 (2008)*.

Quasiparticle Propagation

At helium-vacuum interface, transmission (quantum evaporation) is most likely for phonons



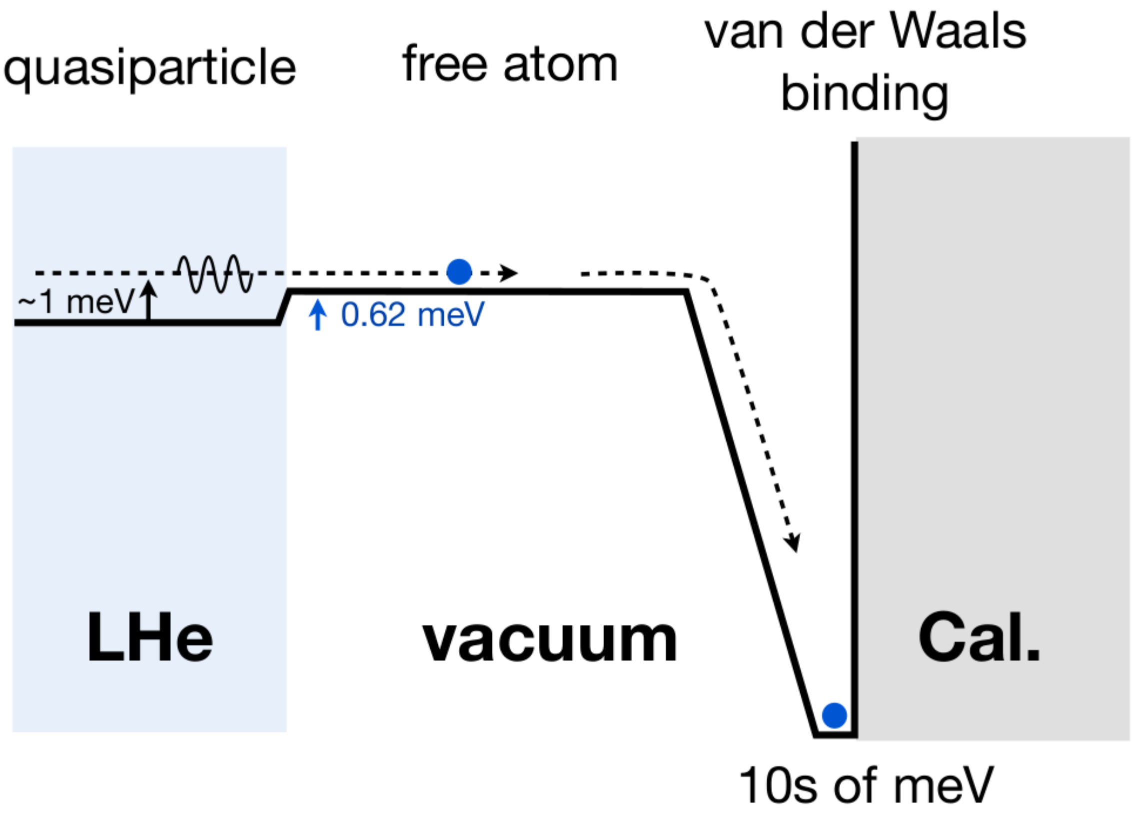
Detecting Quasiparticle Signal

Binding energy between helium and solid amplifies signal

1 meV recoil energy → up to 40 meV detectable energy

Thermal energy negligible (μeV)

Film burner to remove helium from calorimeter

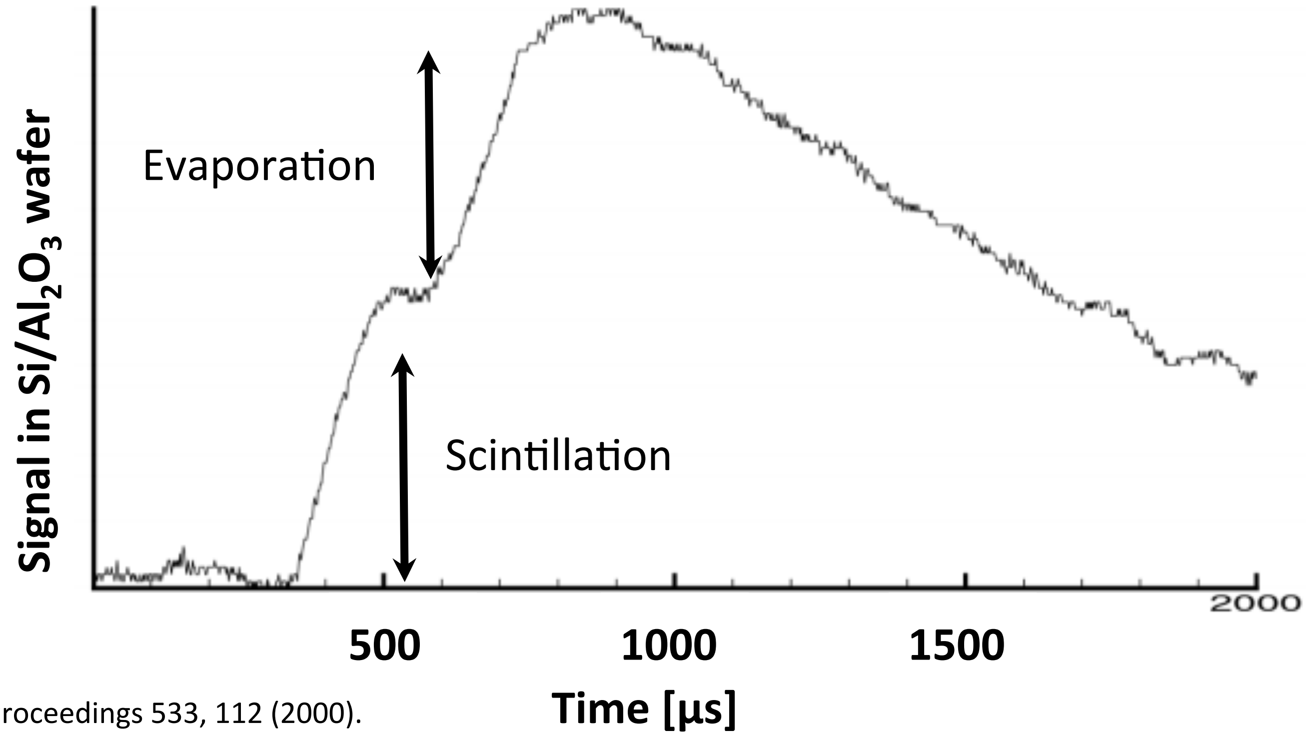


Previous work by HERON

HERON: proposed *pp* neutrino observatory

R&D at right shows simultaneous detection of photons and rotons

Achieved 300 eV threshold at 30 mK

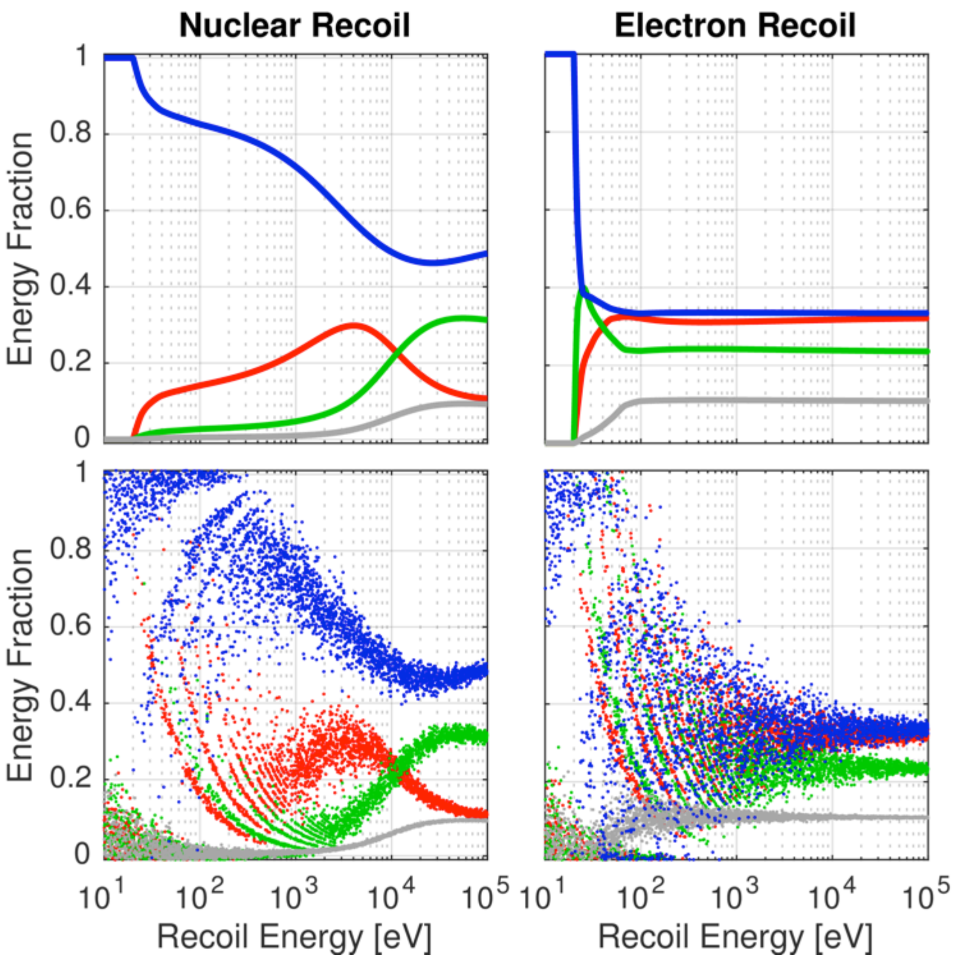


Source: J. S. Adams et al. AIP Conference Proceedings 533, 112 (2000).
Also see: J. S. Adams et al. Physics Letters B 341 (1995) 431-434.

Energy Partitioning

Means

Simulated Poisson Statistics



🟩 Singlet
🟥 Triplet
▬ IR
🟦 Phonons/Rotons

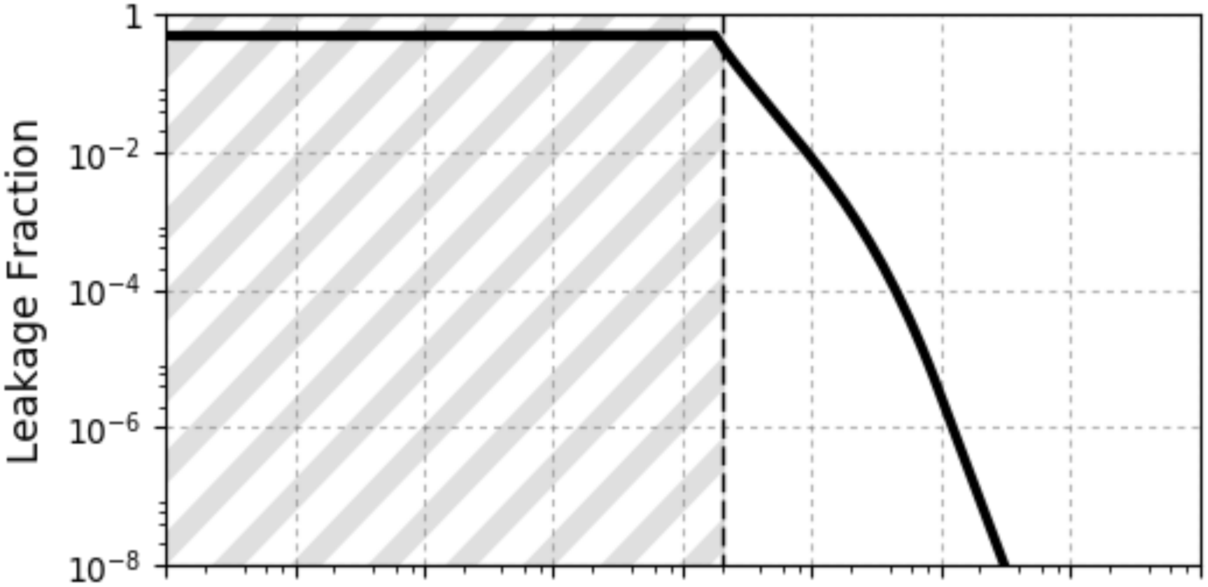
Discrimination

Discriminate by ratio of quasiparticles to other energy

Compton scattering background dominant above 20 eV

Suppress:
~300 events/kg/day →
~0.05 events/kg/day

ER acceptance at 50% NR acceptance



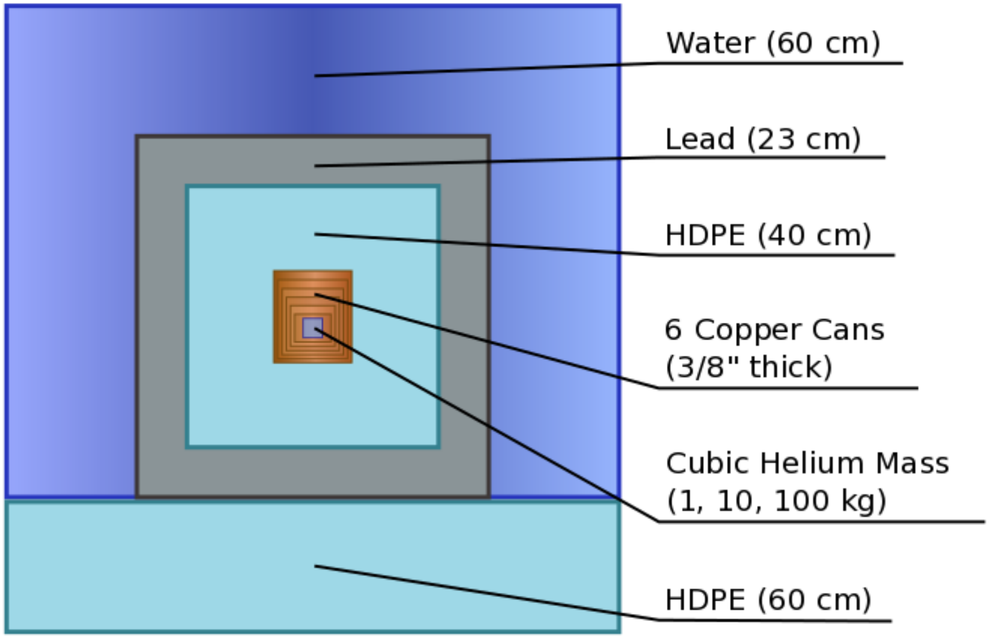
Expected Backgrounds

Backgrounds included:

- Neutrino nuclear coherent scattering
- Gamma-ray electron recoil backgrounds (similar to SuperCDMS)
- Note: Helium itself is naturally radiopure, and easily purified of contaminants
- Gamma-ray nuclear recoil backgrounds (see Robinson, PRD 95, 021301 (2017)

Arguments for low "detector" backgrounds:

- Low-mass calorimeter, easy to hold
- Target mass highly isolated from environment (superfluid: friction-free interfaces)



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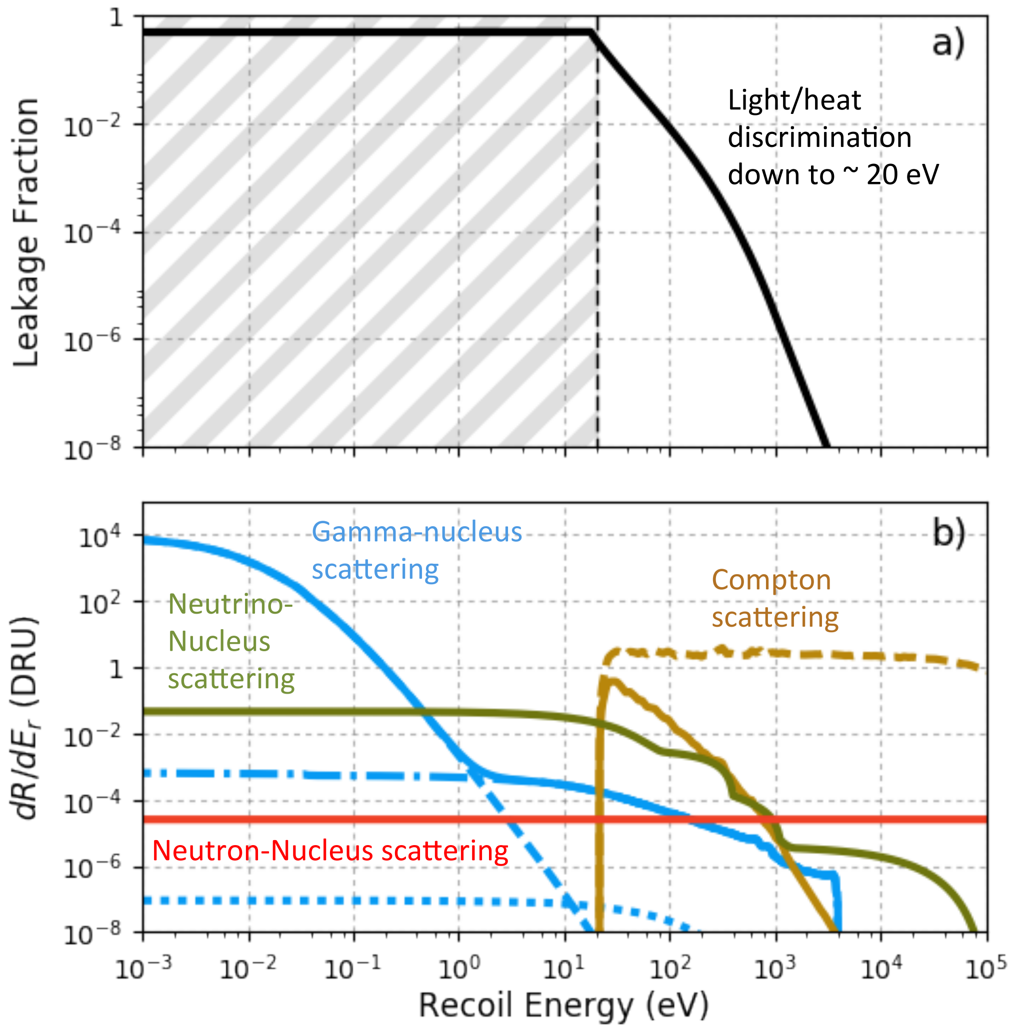
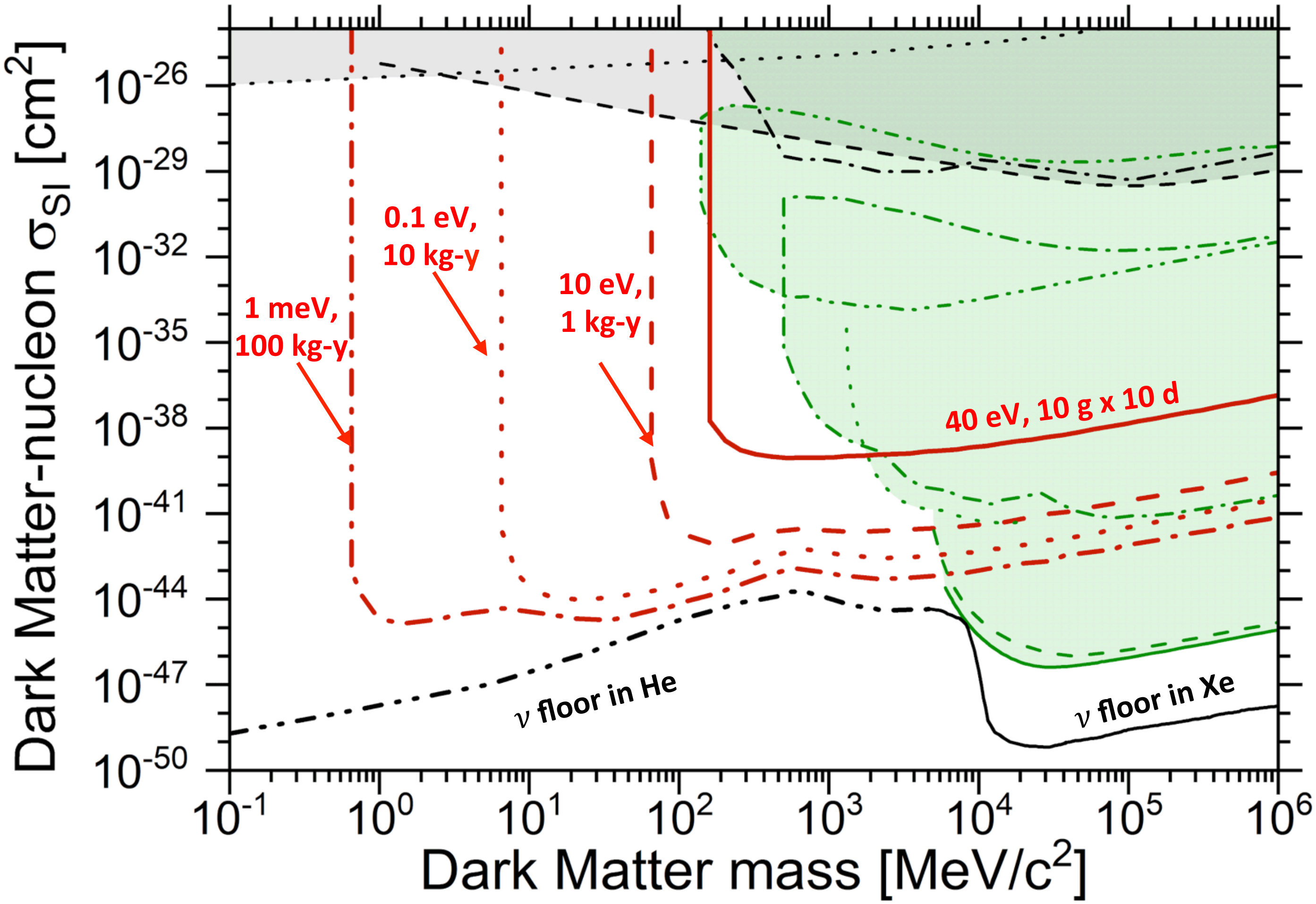
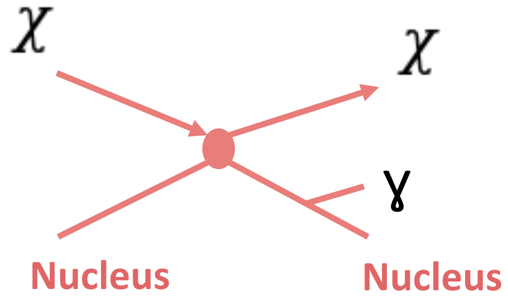


Projected Sensitivity

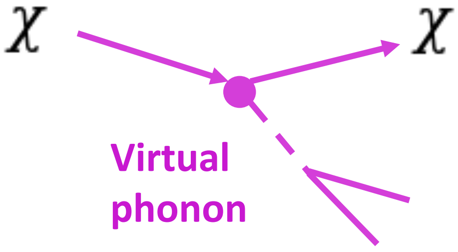


Extending Sensitivity

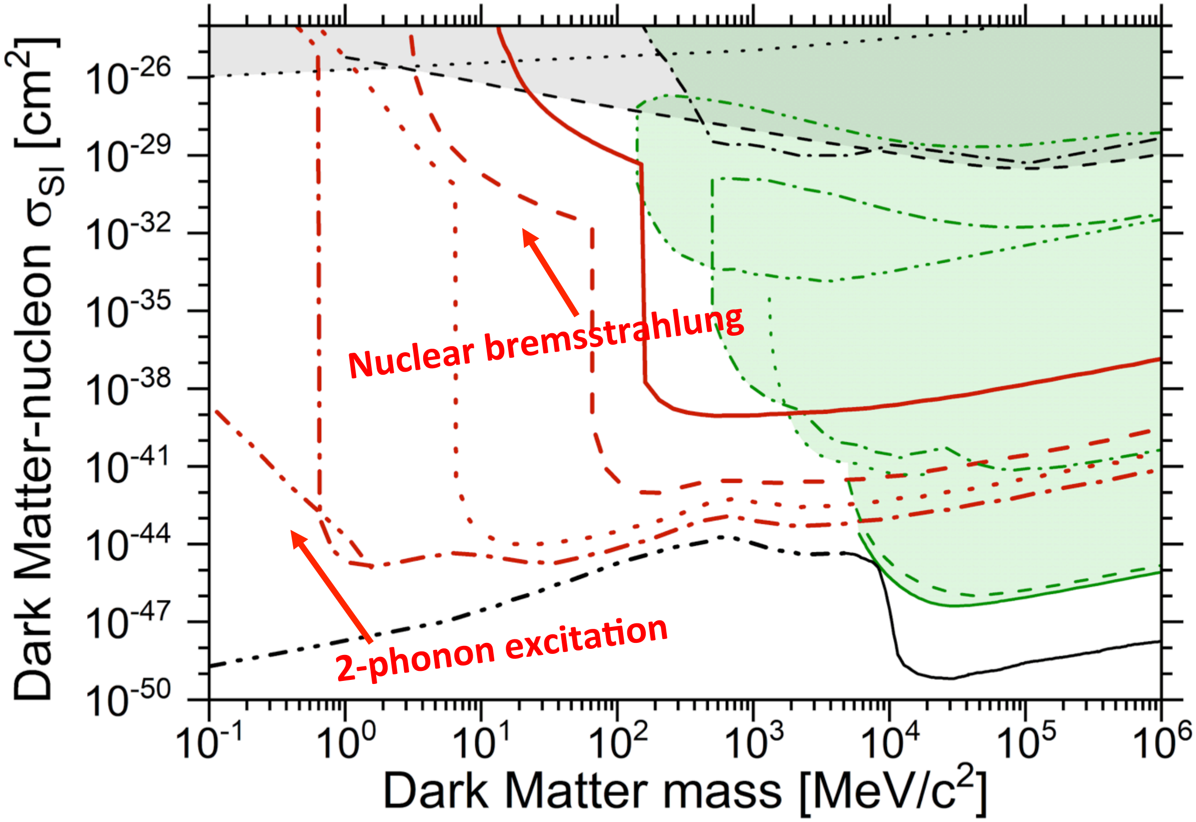
Nuclear bremsstrahlung



2-phonon excitation

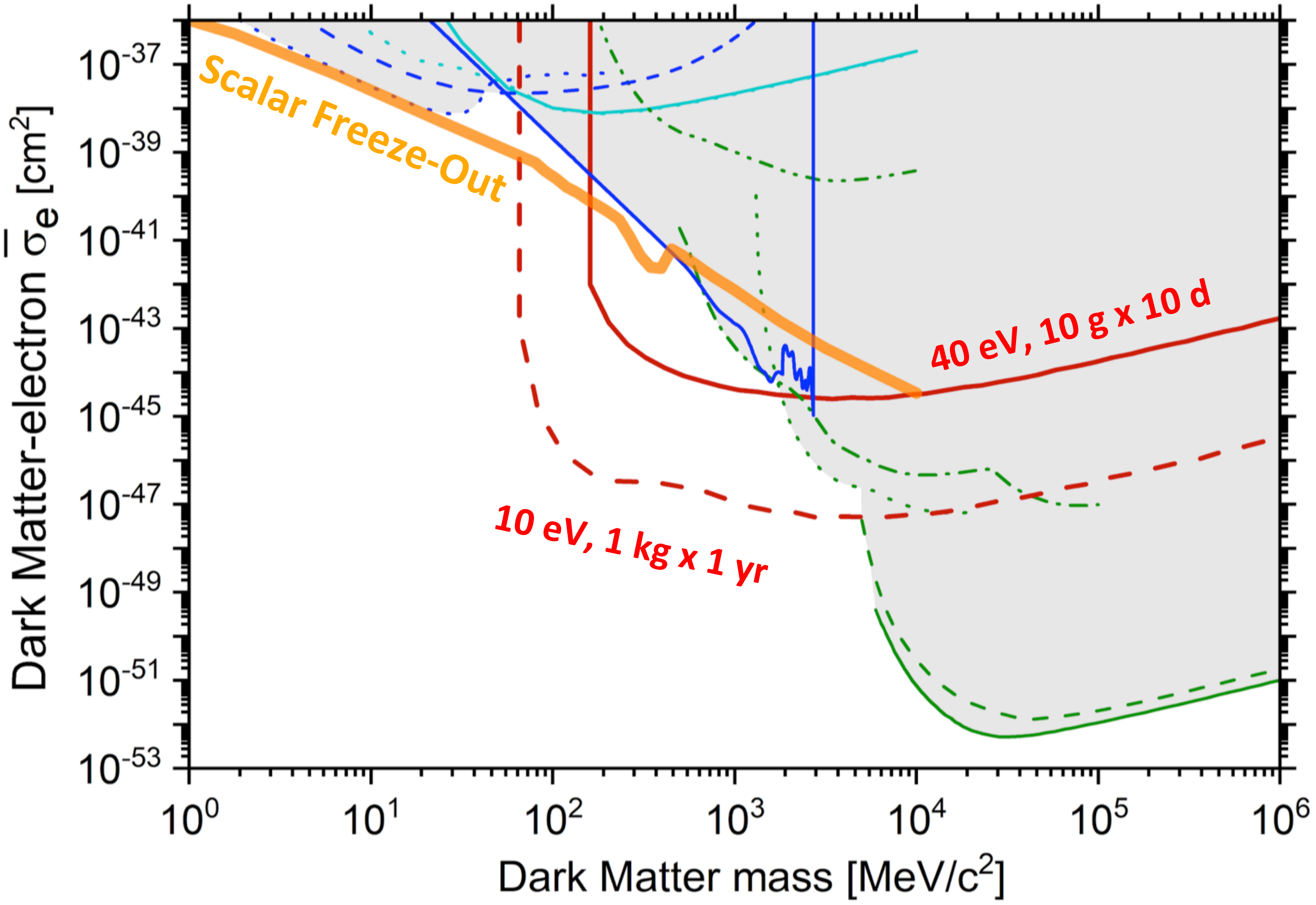


See: *C. McCabe. Phys. Rev. D 96, 043010 (2017).*
C. Kouvaris and J. Pradler. Phys. Rev. Lett. 118, 031803 (2017)
K. Schutz and K. M. Zurek. Phys. Rev. Lett. 117, 121302 (2016)



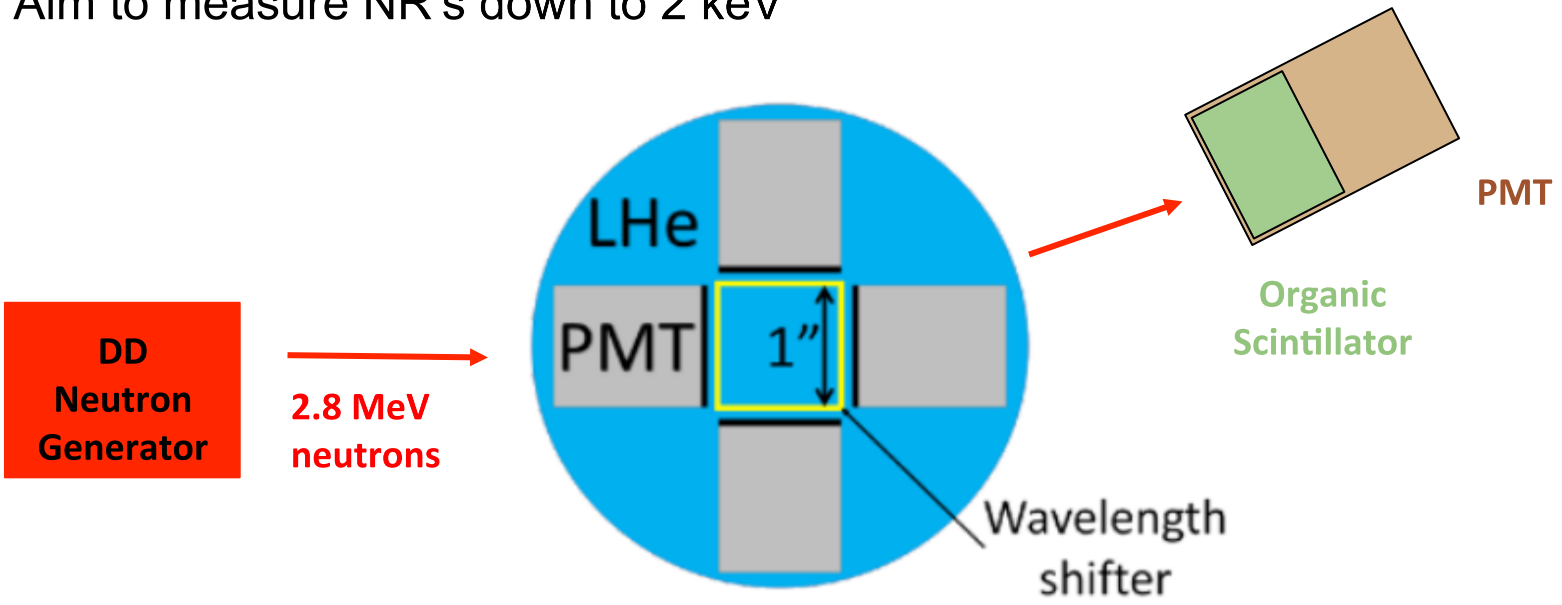
Dark Photon Sensitivity

Use DM-nucleon limits to constrain DM-e scattering, if mediated by a heavy dark photon (F_{DM}= 1)



Measurement of Nuclear Recoil Light Yield in Superfluid ^{4}He

- Will be first measurement of the ^{4}He nuclear recoil light yield!
- Aim to measure NR's down to 2 keV



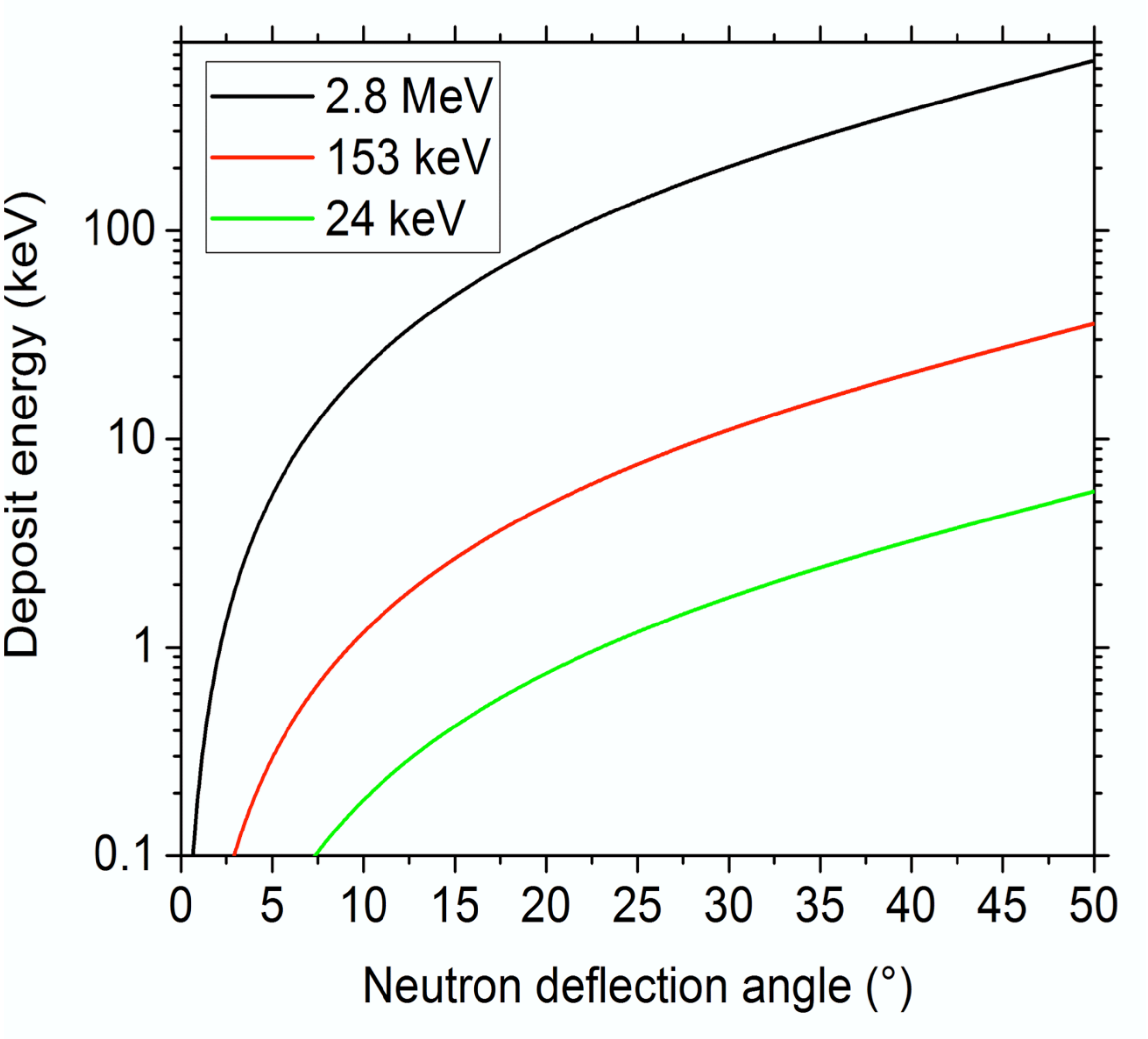
DD Neutron Generator

2.8 MeV neutrons

PMT

Organic Scintillator

Underway: Development of a NR light yield measurement

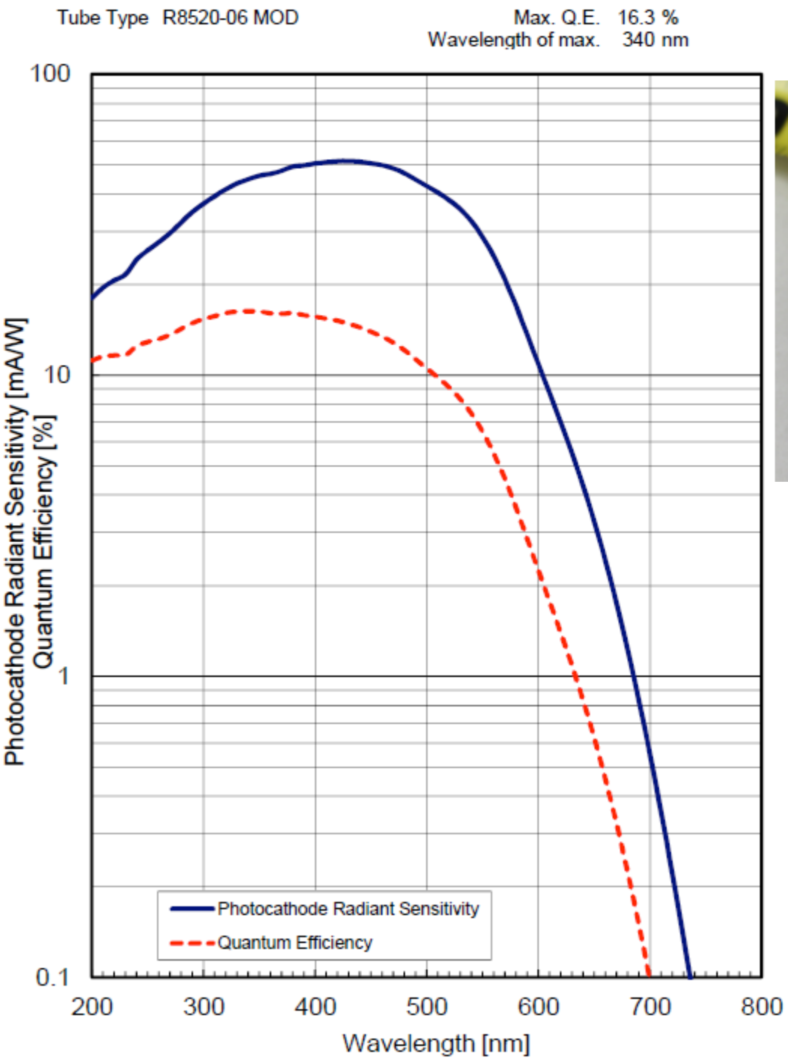


Scatter fast neutrons in LHe to measure light yield (as we have done previously in LXe, LAr, and LNe). This is yet to be measured in LHe!

Neutron sources available:

- DD neutron generator
  - 2.8 MeV and 10^6 n/s
- ^{88}Y-Be photoneutron
  - 153 keV and ~10^3 n/s
- ^{124}Sb-Be photoneutron
  - 24 keV and ~10^3 n/s

Light detection with PMTs, operating in superfluid helium



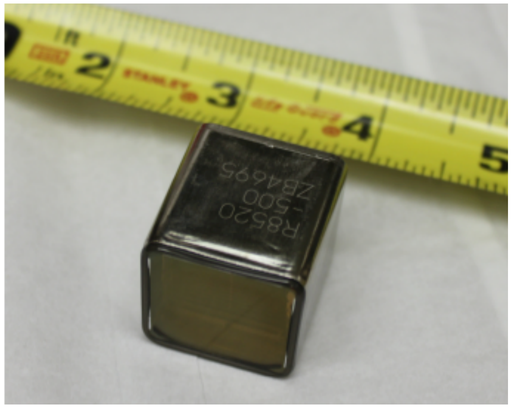
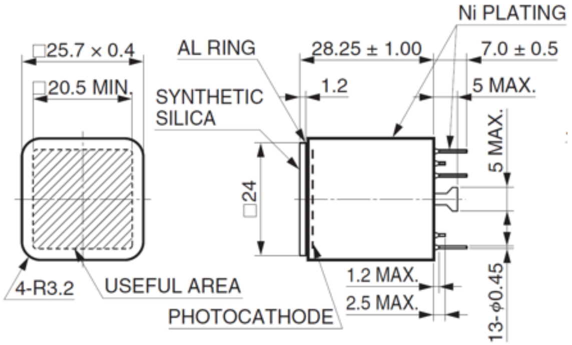


Figure 3: Dimensional outline (Unit: mm)



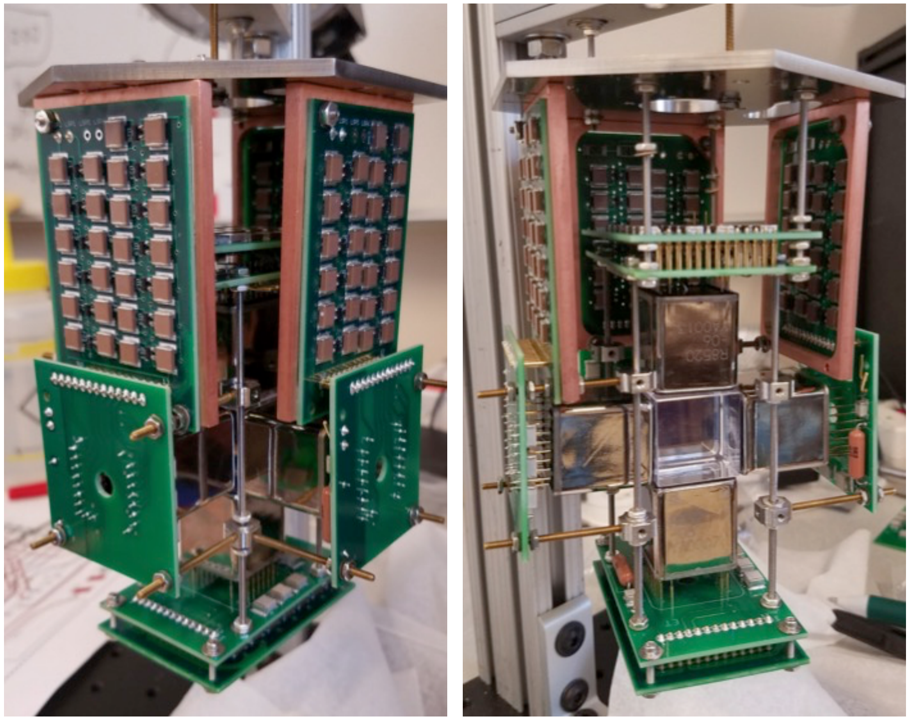
- ➢ Pt underlay to avoid positive charge accumulated in cathode
- ➢ Demonstrated to work at milli-Kelvin temperature
- ➢ Pt underlay decreases QE
  - ○ 16% with Pt versus 30% in XENON100

Measurement of Nuclear Recoil Light Yield in Superfluid ^{4}He

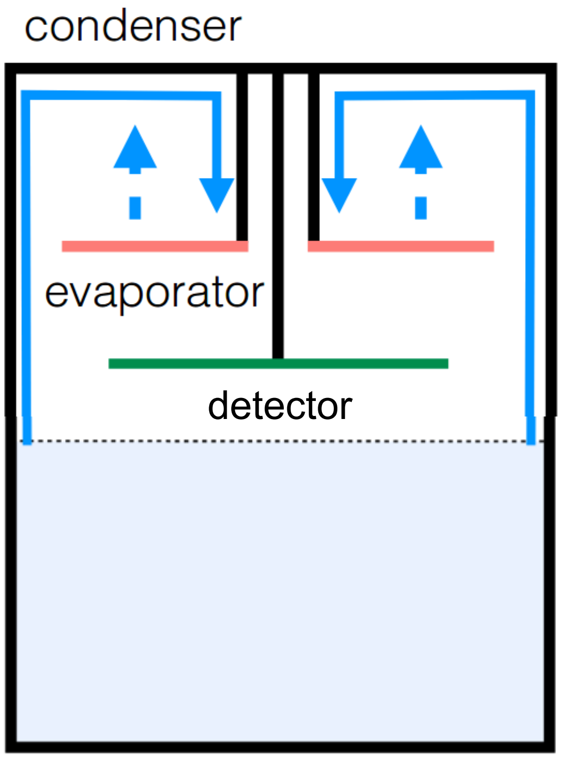
Detector assembly finished!
Cooled down to 1.4 K.

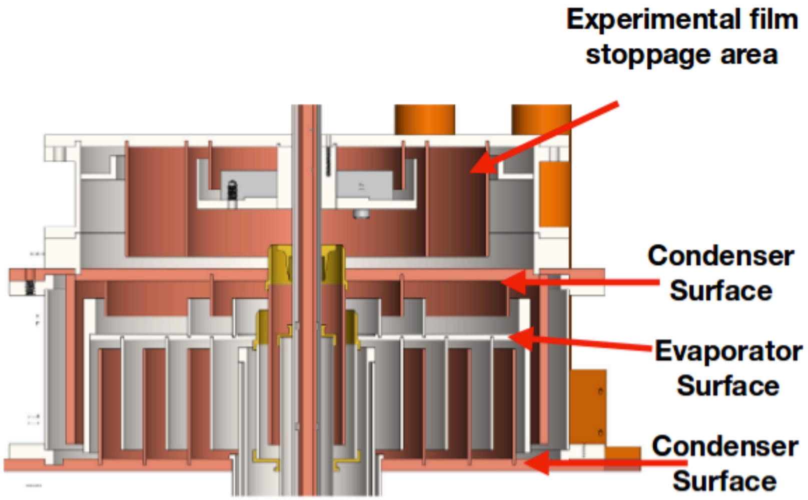
PMT's biased with Cockroft-Walton generator

First (room-temperature) signal recorded in the PMTs



Film Burner





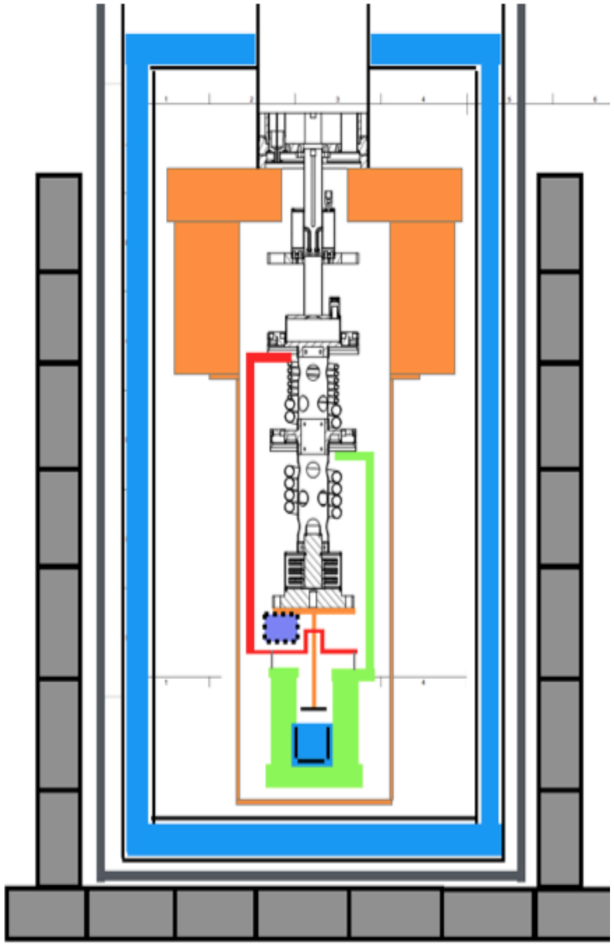
UMASS
AMHERST

- Remove superfluid helium that is stuck to the detector surfaces
- Group is designing film burner based on HERON design
- Studying knife edge device to thin the film

Superfluid Helium Detector

Leiden (wet, low-vibration) dilution refrigerator being set up in McKinsey lab at UCB. Dry fridge being set up at UMass

First tests being designed, with TES, SQUIDs, helium film burner, shielding



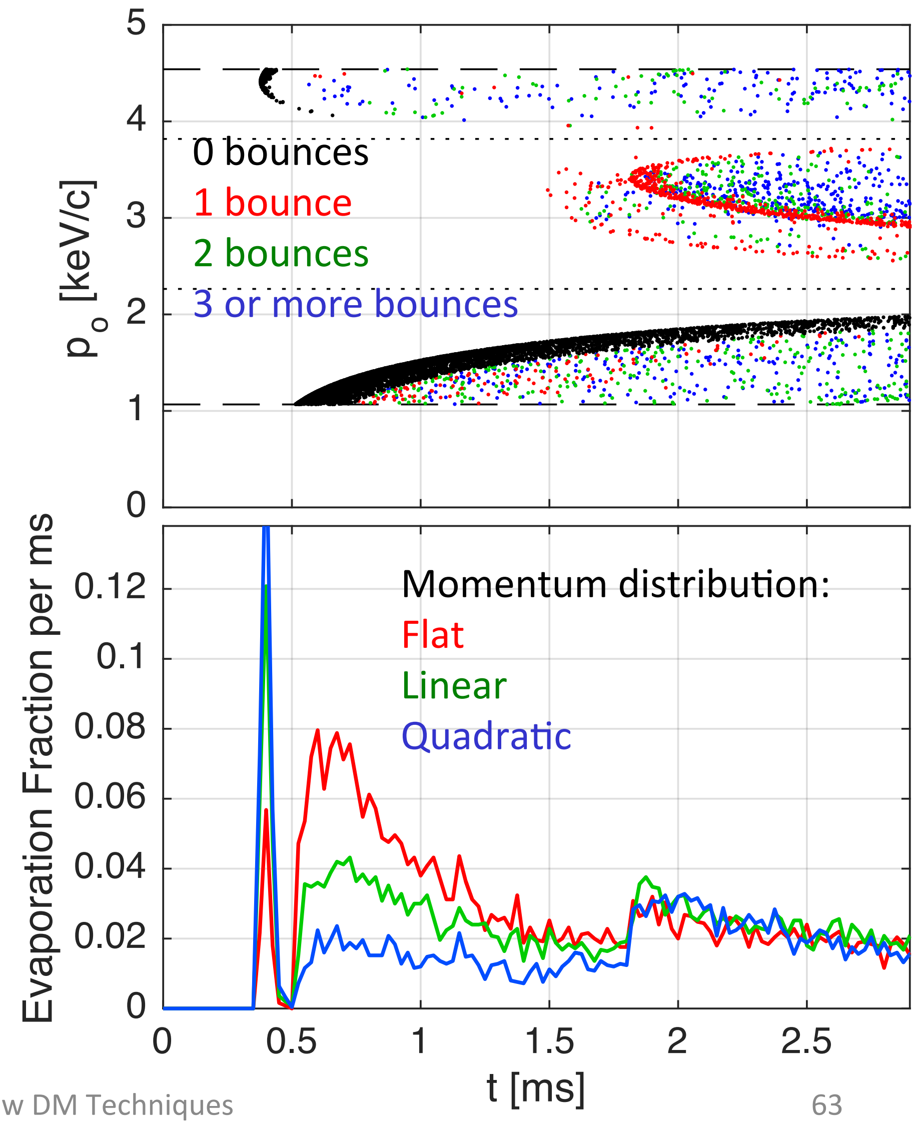
Discrimination without electronic excitations?

For very low energies, electronic excitations are heavily suppressed. Need to move to a scheme that doesn't rely on electronic excitations, only heat.

How to get particle identification without electronic excitations?

Possibly could look at roton/phonon ratio, or more generally the momentum distribution of the quasiparticles. Given that ER and NR have different dE/dx, it's quite plausible that they give different quasiparticle distributions. Higher dE/dx should result in a more thermalized (colder) quasiparticle distribution.

Pulse-shape discrimination looks plausible!

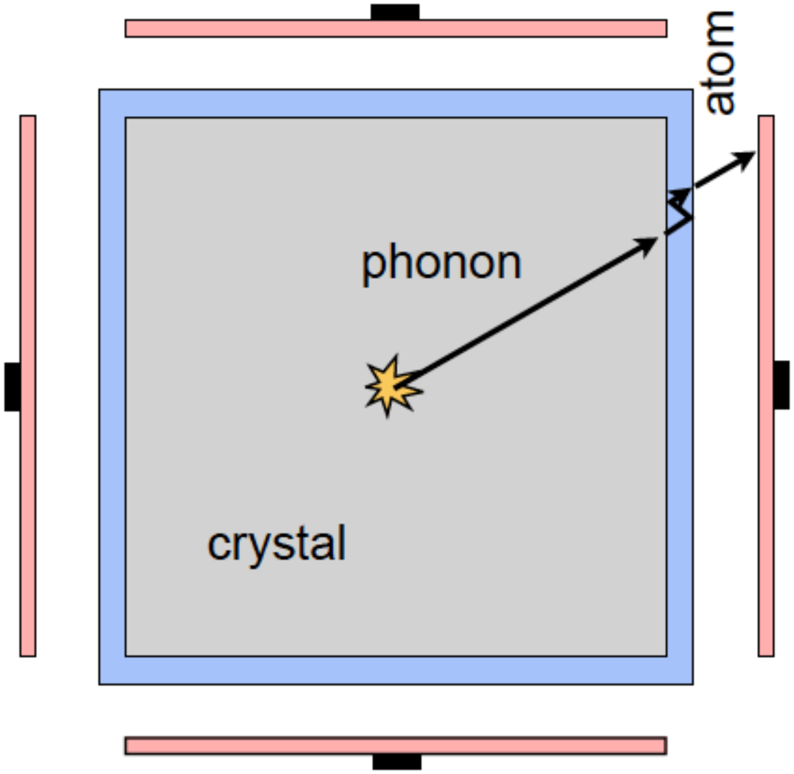


Readout of Solids Via Helium Evaporation

Generalized evaporation-based detector

Similar philosophy:

- Separate the target and the calorimetry
- Smaller absorber seen by TES array
- Use helium atoms to jump the gap



Crystals with long phonon mean free path
(pick your favorite crystal, sensitive to your favorite dark matter model)

Swappable targets, natural 4pi coverage.

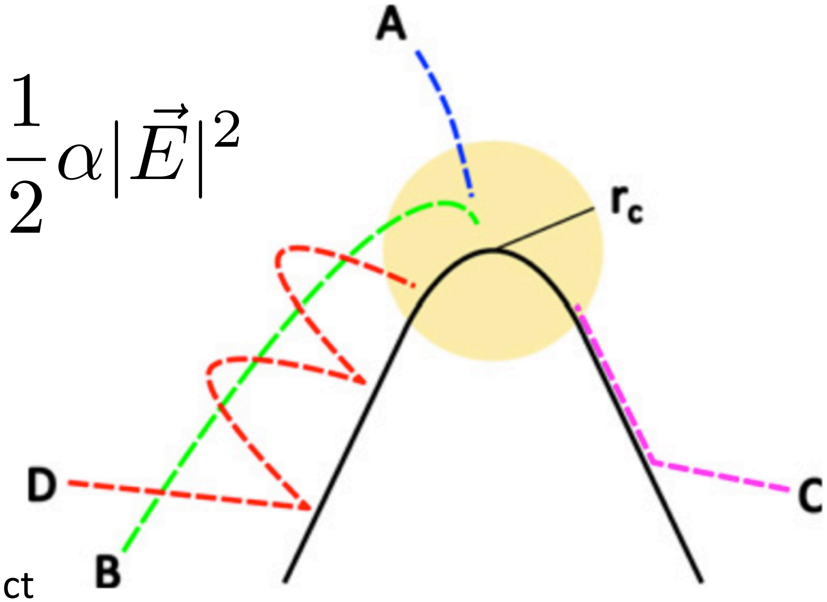
Coat surface with several layers of helium (unsaturated film) at third layer binding energy is within few percent of bulk value

<u>Or</u> material having low binding energy for helium,
helium on cesium: ^{4}He – 3.8 K; ^{3}He – 1.9 K

Superfluid helium readout via field ionization
(See arXiv:1706.00117)

Goal: an even more sensitive way to detect He atoms produced through quantum evaporation, reaching energy sensitivity of 1 meV

$$U_{\text{int}} = \frac{1}{2}\alpha|\vec{E}|^2$$



A) Direct impact

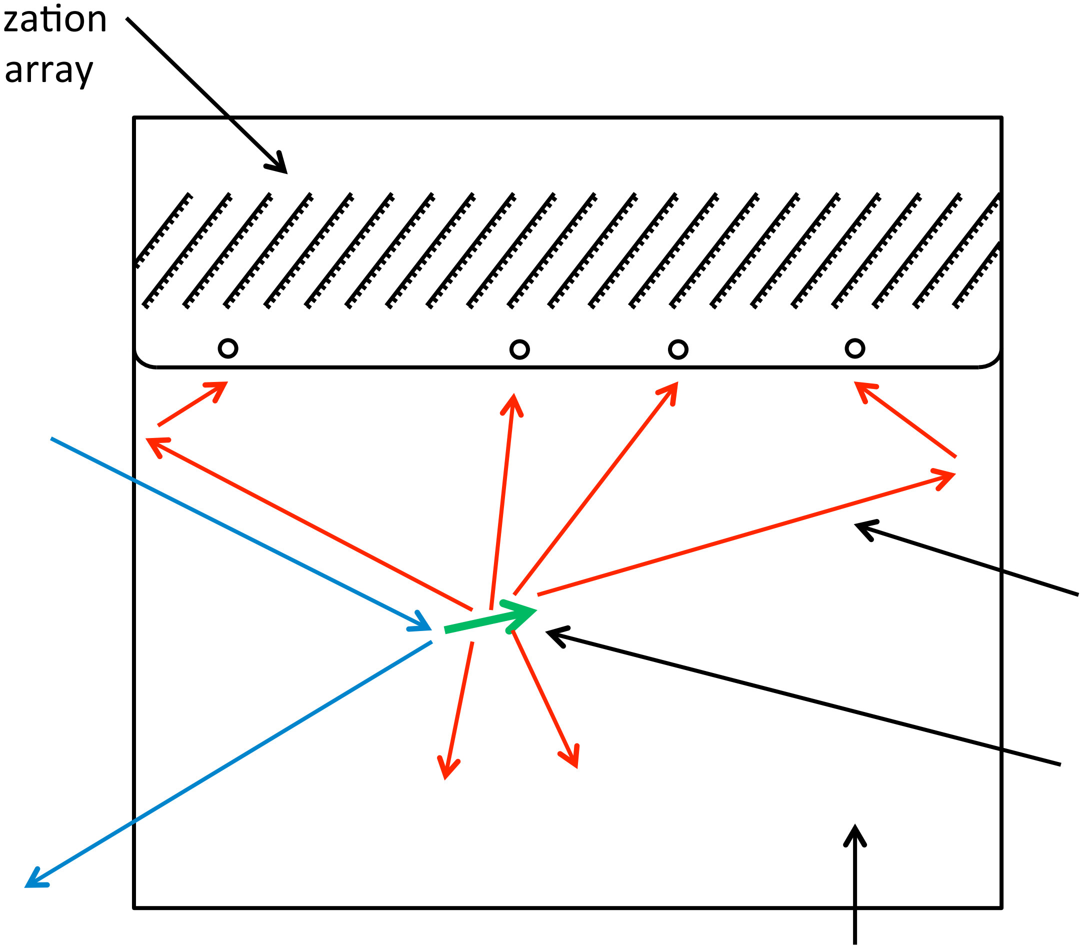
B) Orbital capture

C) Surface diffusion

D) Bouncing

The polarization force draws helium to the tip, where the field gradient is highest.

Superfluid helium readout via field ionization (See arXiv:1706.00117)



Field ionization detector array

DM particle

Rotons and phonons

Recoil helium atom

Liquid helium

Summary and Outlook

Rising theoretical interest in low-mass dark matter

Lots of open parameter space, can be probed by small (inexpensive) experiments

Many proposed approaches, which is appropriate as the field discovers which approaches work and which do not.

Much lower energy thresholds will bring new technical challenges, primarily instrumental backgrounds.

Expect rapid development in this area!