Dark Matter: New Technologies

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LUX Co-Spokesperson
UC Berkeley and LBNL

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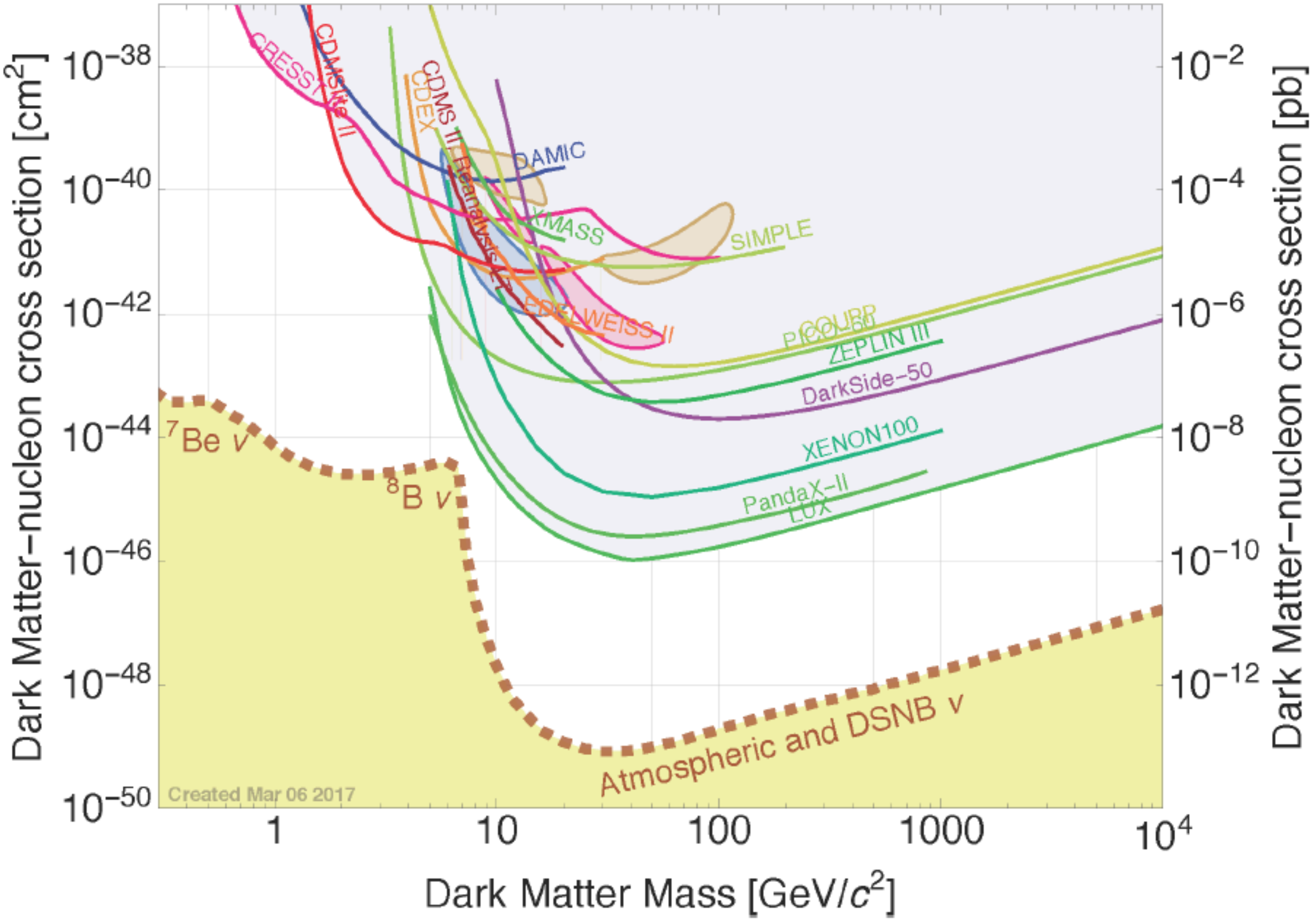
Current State of the Field



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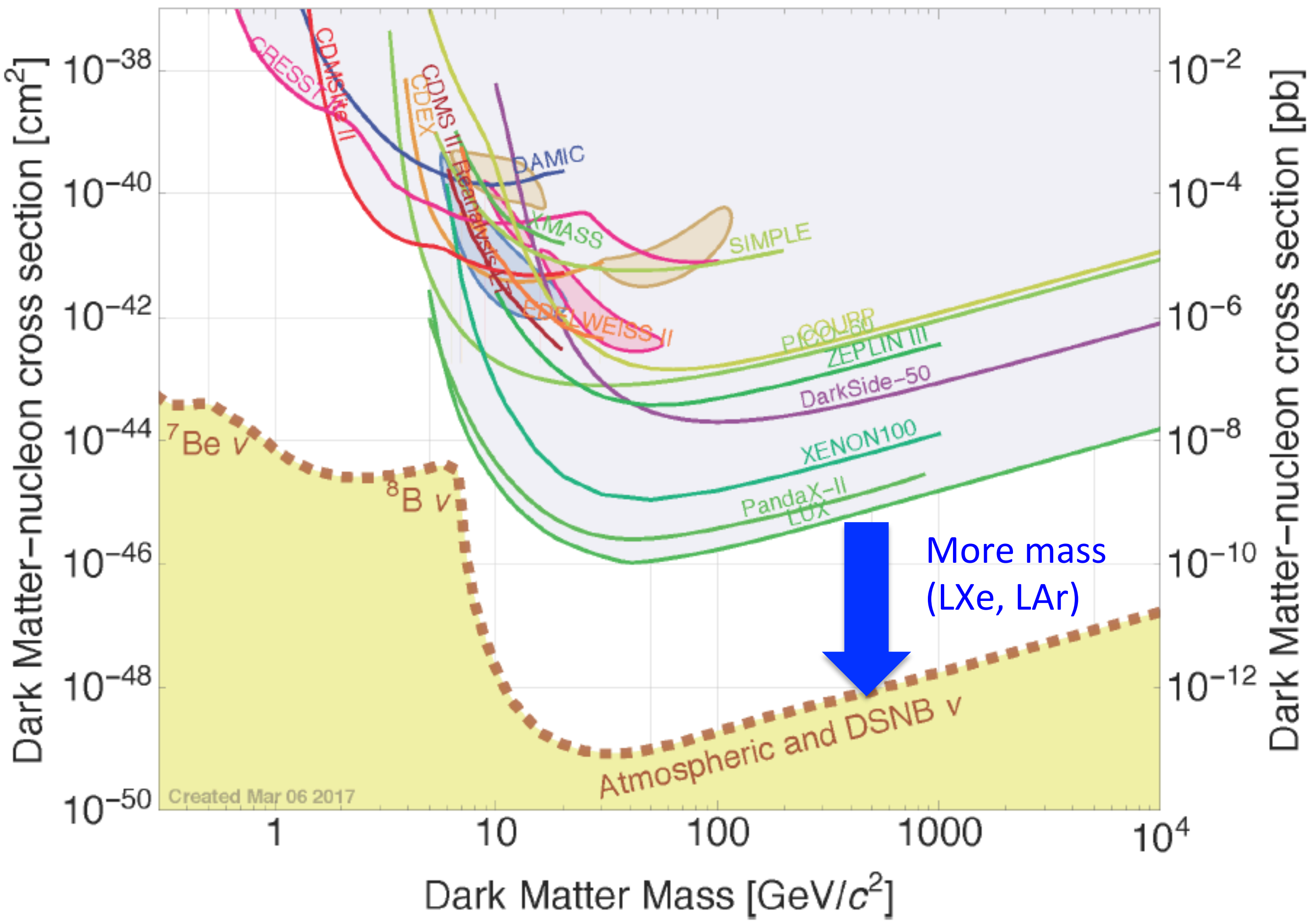
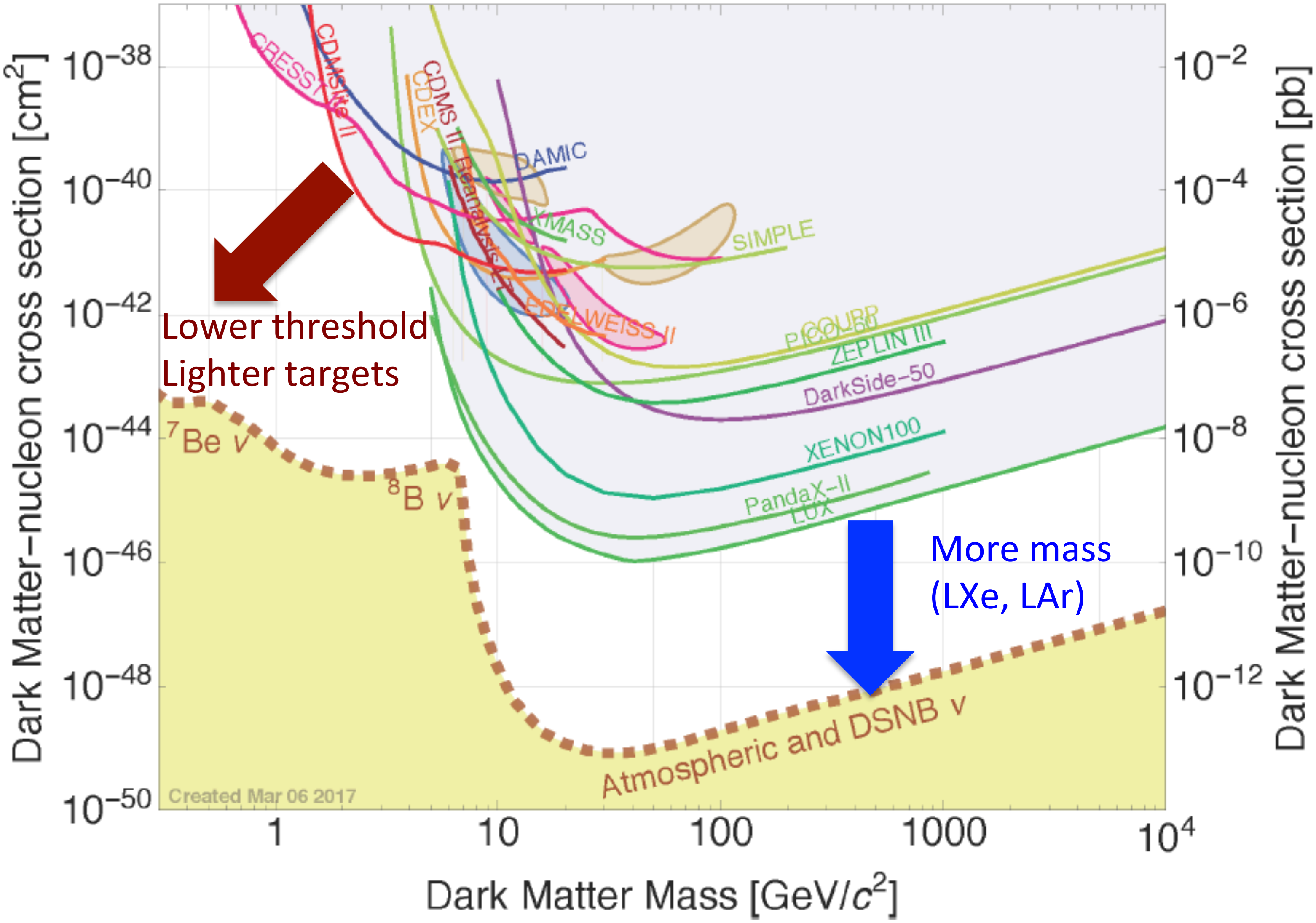


More mass
(LXe, LAr)

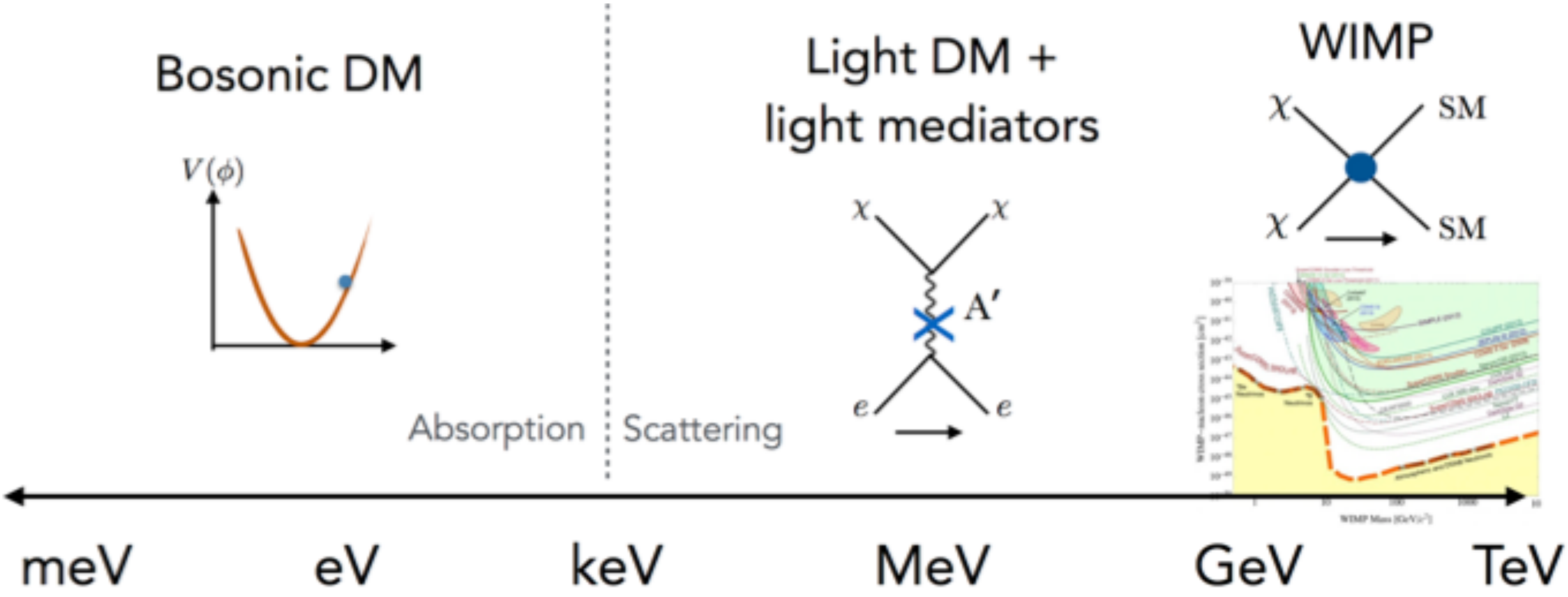
Current State of the Field



Lower threshold
Lighter targets

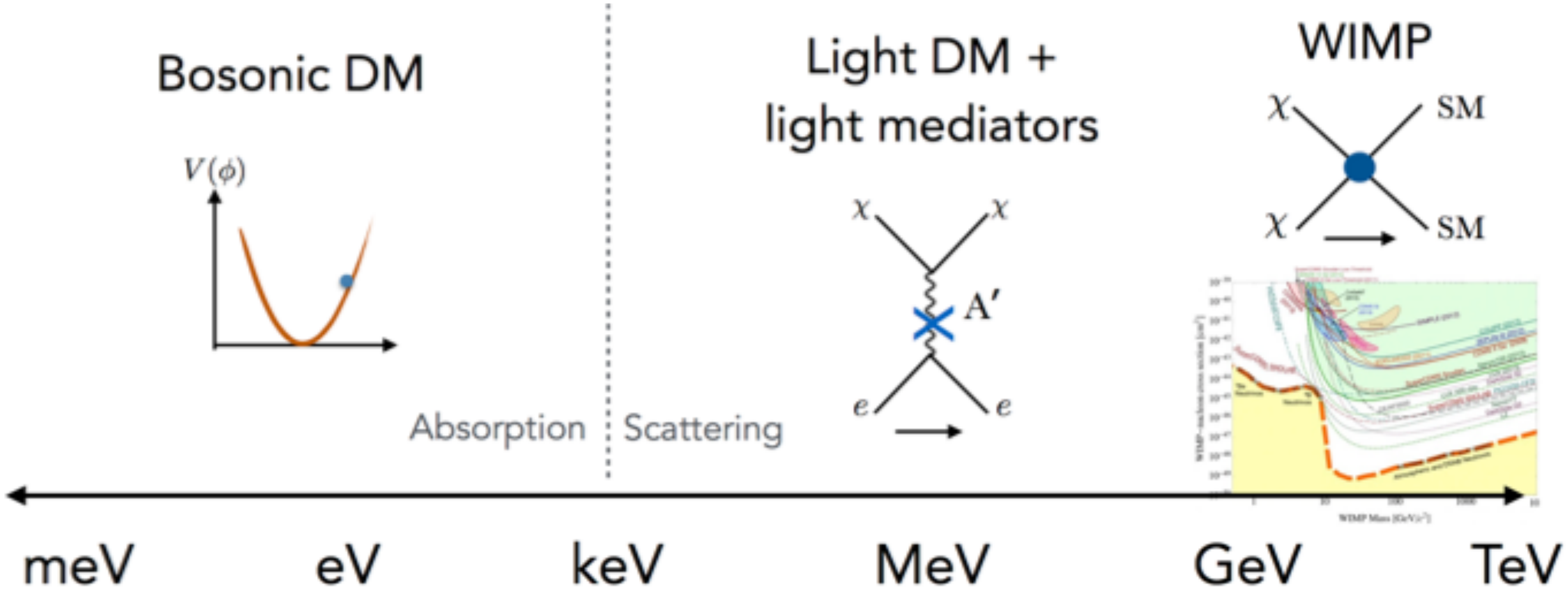
More mass
(LXe, LAr)

There’s plenty of room at the bottom



See Tracy Slatyer’s plenary talk for physics motivation for light dark matter (thermal, asymmetric, freeze-in, SIMP, ELDER…)

There’s plenty of room at the bottom



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.

sub-GeV DM

Distinguish two types of interactions, e.g.

σ_e vs m_{DM}

- dark photon mediator
- vector, coupling predominantly to leptons

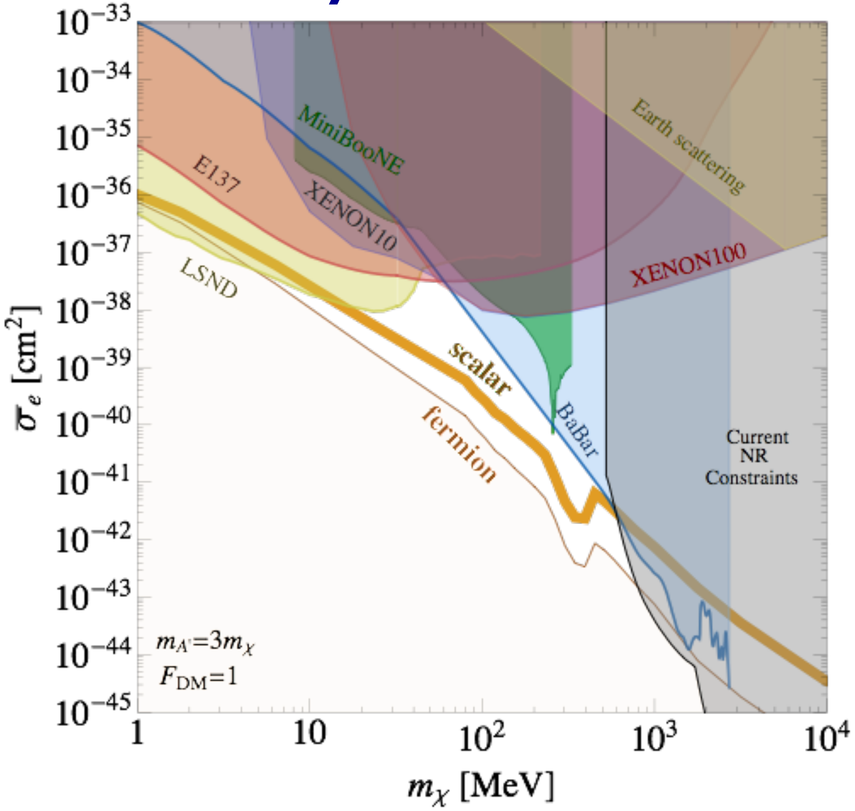
σ_N vs m_{DM}

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

Important to test interactions separately

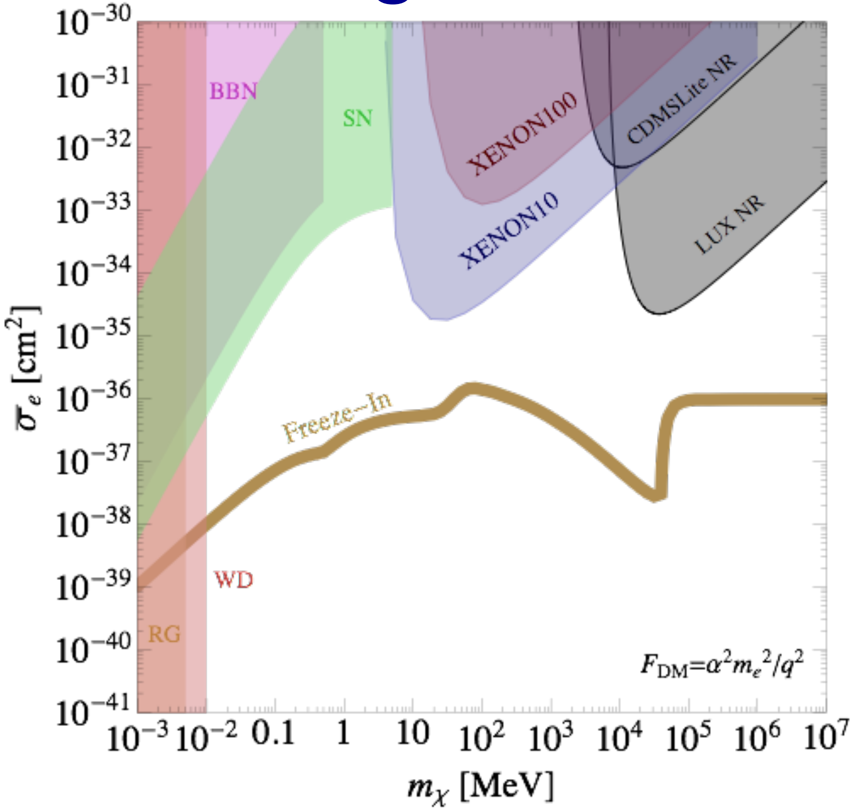
Benchmarks: dark-photon mediators

"Heavy"



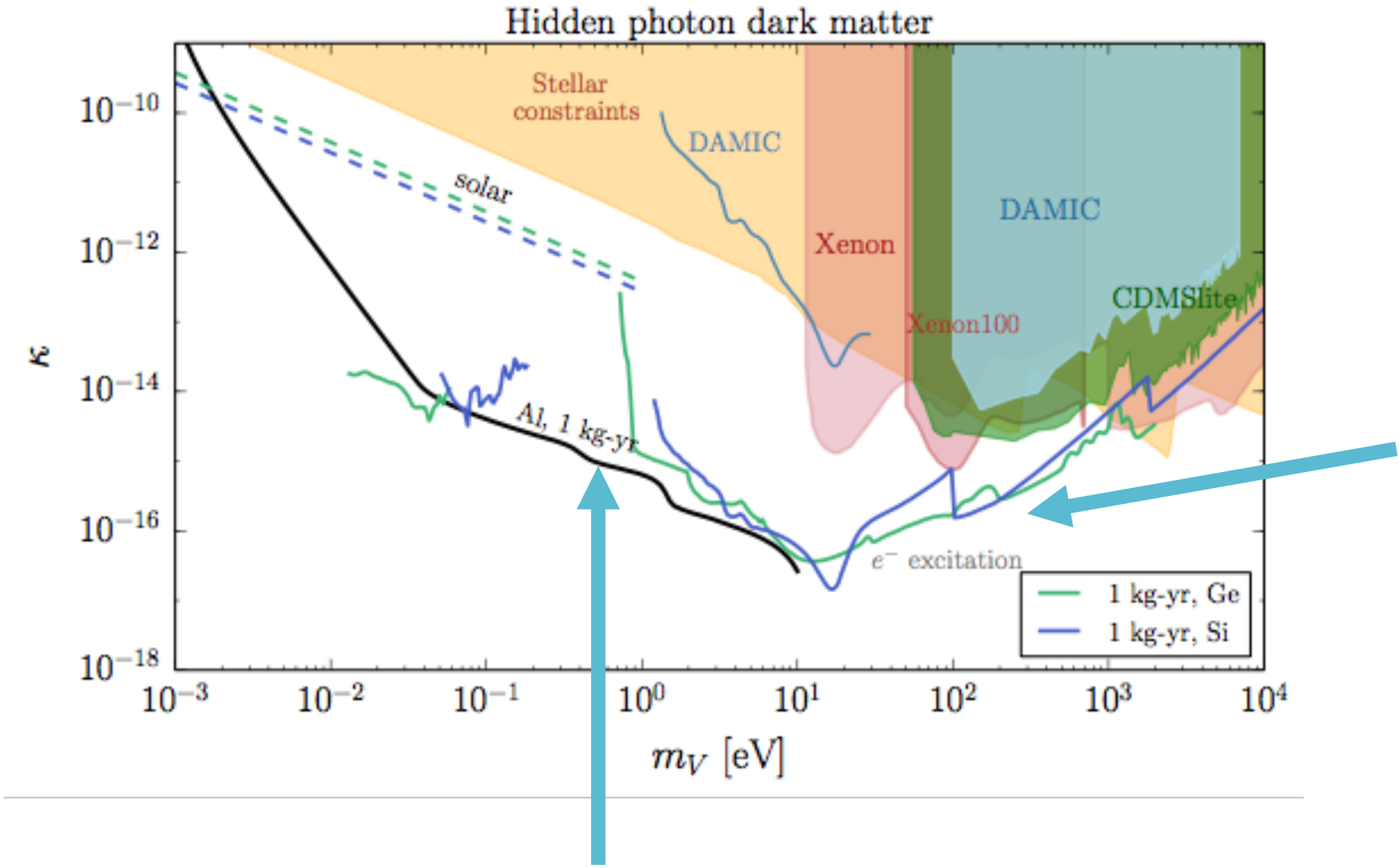
exciting complementarity with collider & beam-dump probes (for elastic scattering)

Ultralight



ultralight mediator scenario is uniquely probed by Direct Detection

Absorption

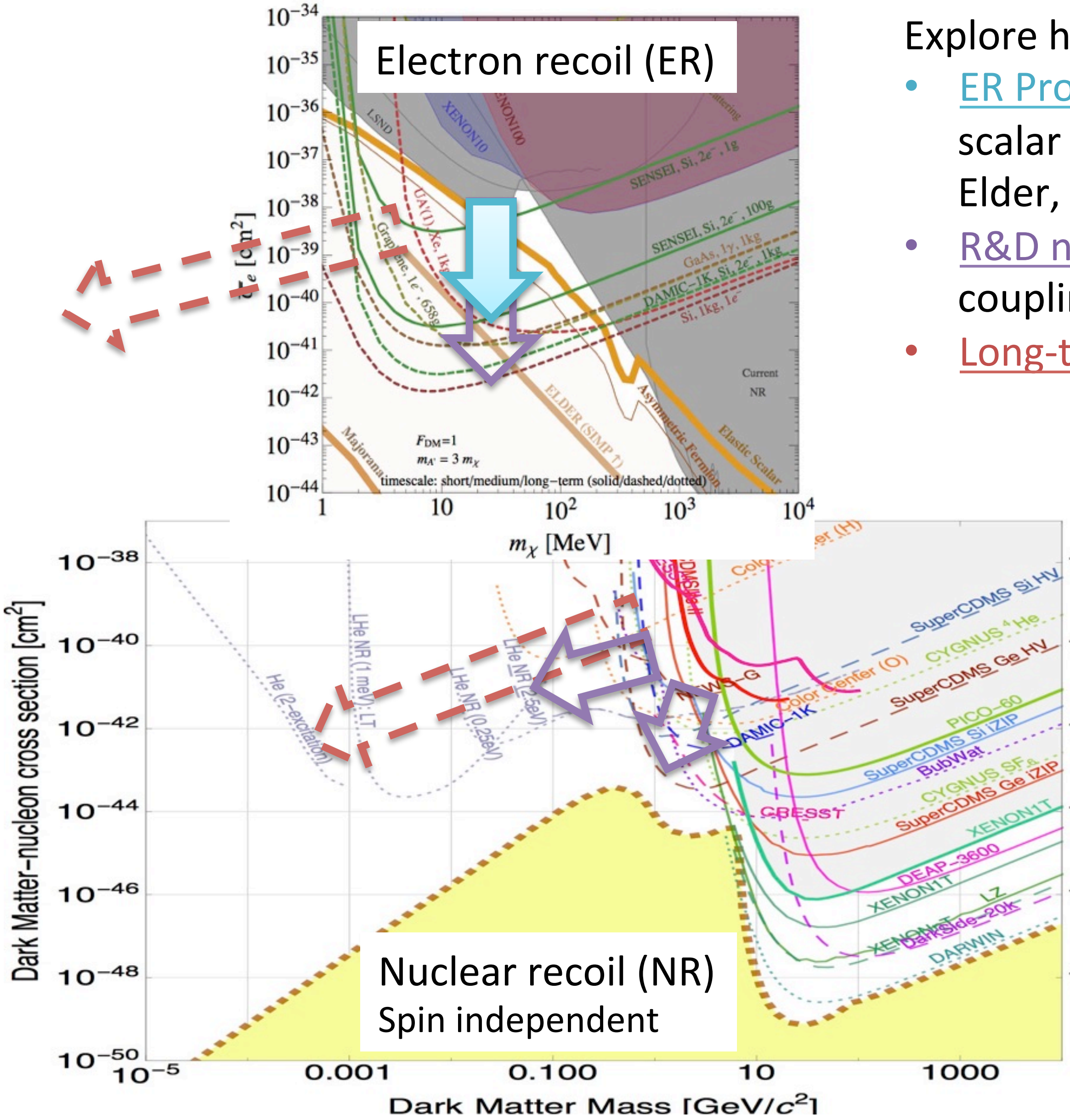


Si or Ge detector

superconductor

long-term R&D

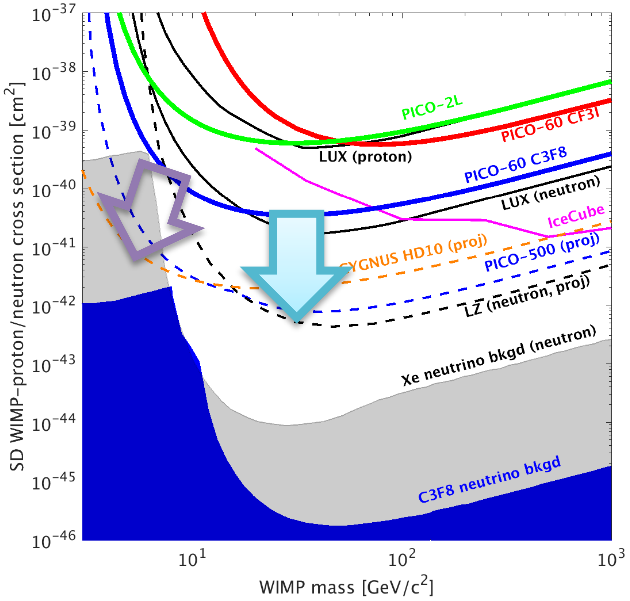
Direct Detection Summary Slide from Cosmic Visions



Explore hidden-sector targets:

- ER Projects ready now explore elastic scalar thermal relic, asymmetric, SIMP/ Elder, freeze-in
- R&D needed to push to weaker couplings & MeV-mass NR
- Long-term R&D to reach keV masses

Opportunities to explore WIMP-*p* SD scattering also ready now



Nigel Smith (WIMPs)	Gianpaolo Carosi (Axions)	This talk
XENON	ADMX	LXe bubble chamber
LUX/LZ	HAYSTAC	Water bubble chamber
DEAP	CAPP Haloscope (CULTASK?)	Directional gaseous TPC (CYGNUS)
DarkSide-50/-20k	ORGAN	Graphene (PTOLEMY G3)
CDEX	Orpheus	Internally amplified Ge
Edelweiss	MADMAX	Xenon charge-only
CRESST	QUAX	Scintillating crystals (GaAs, NaI)
SuperCDMS	LC-Circuit	Color centers
PICO	ABRACADABRA	Superfluid helium with TES readout
DAMIC/SENSEI	CASPEr	Superfluid helium with ionization
NEWS-G		
DRIFT		

This is not a fully exhaustive list; apologies if your favorite technology 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

Backgrounds for sub-GeV

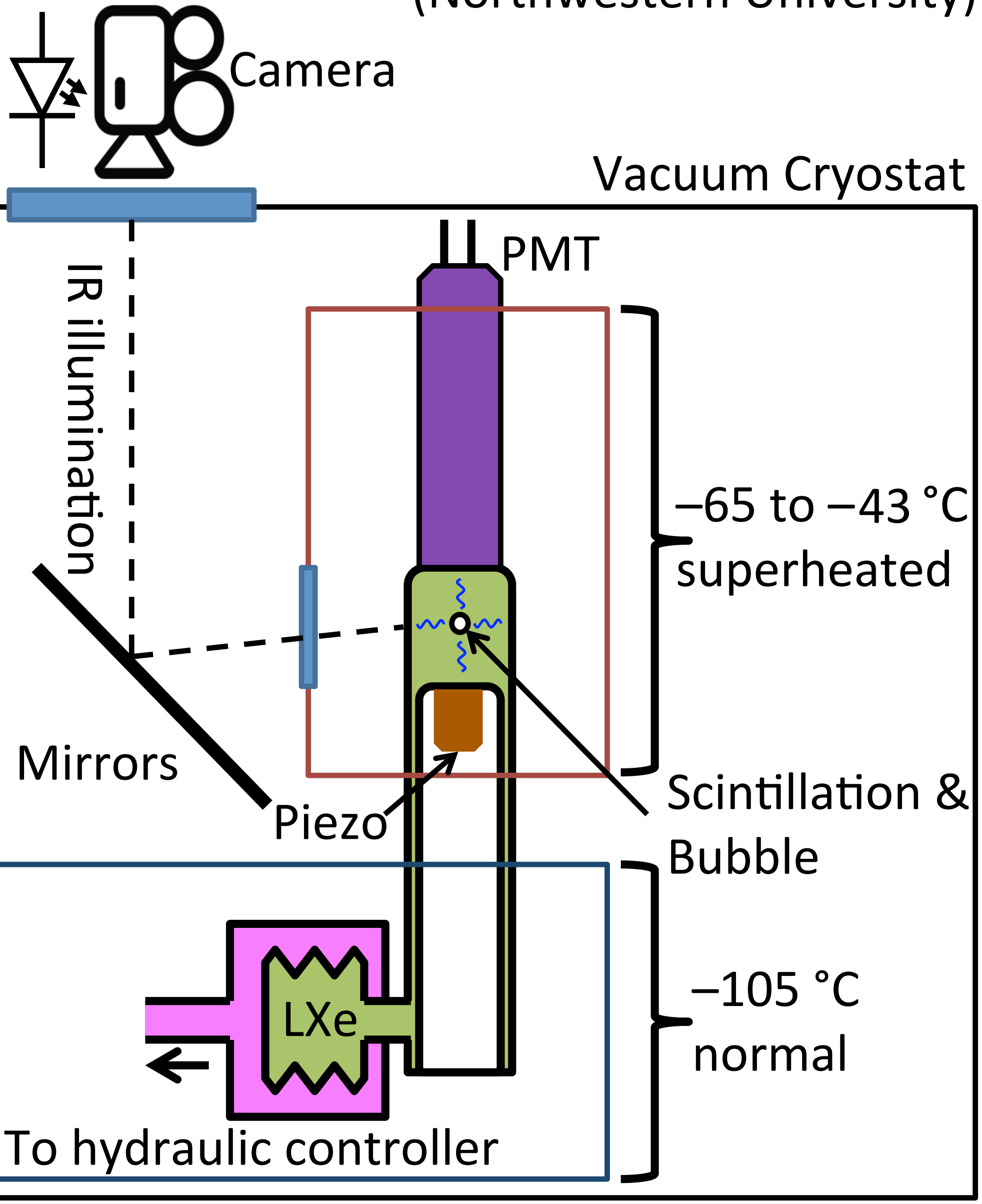
- Solar neutrino background is small
- Radiogenic backgrounds to few-eV electron recoil events likely <1 event/kg/year/eV (based on projections for measured values at O(50 eV))
- For sub-GeV searches, critical backgrounds are:
  - dark counts
  - EM interference
  - vibrations

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

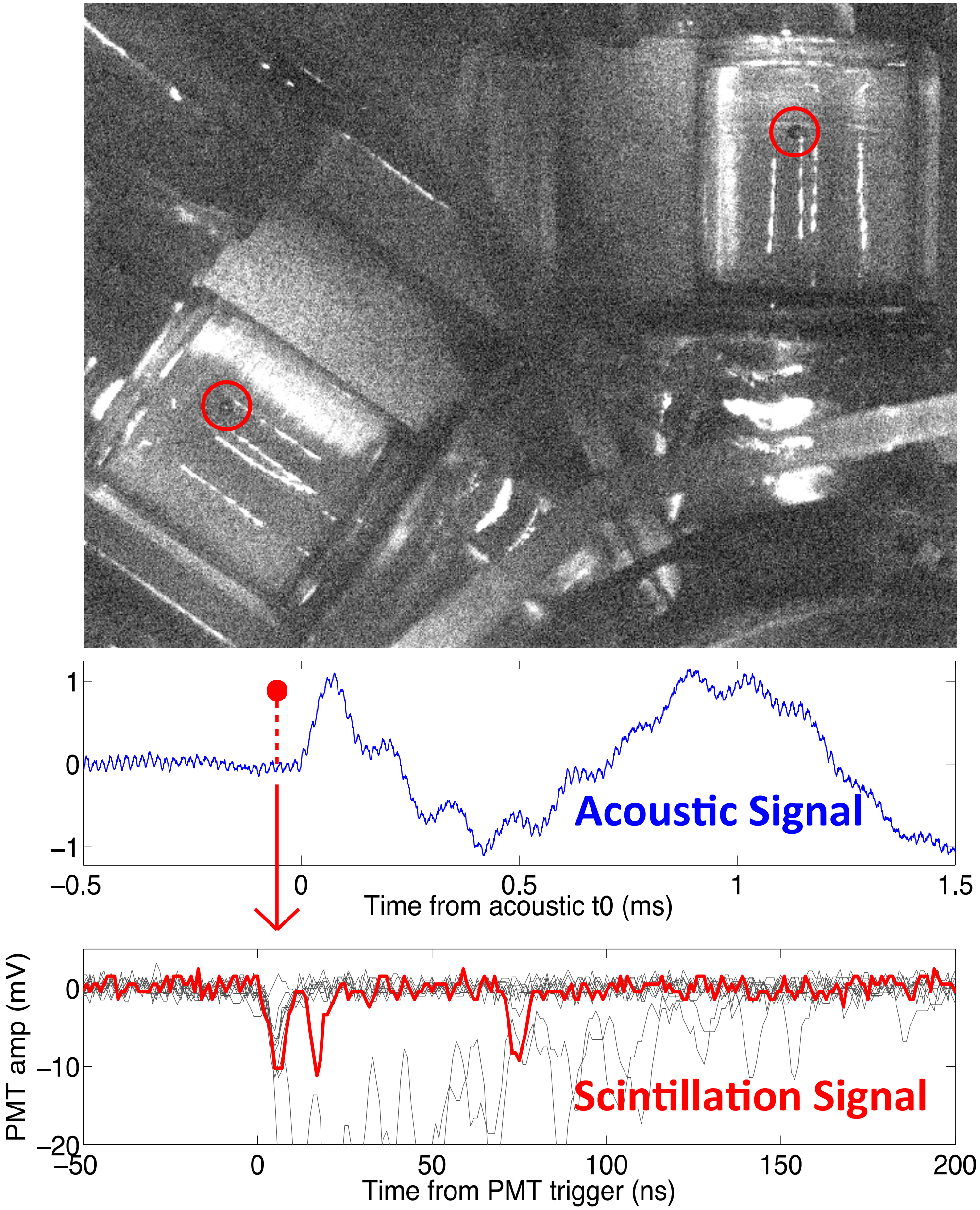
    arXiv:1702.08861
    [PRL **118**, 231301]

Xenon Bubble Chamber Prototype
(Northwestern University)



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



Water as a Bubble Chamber
(M. Szydagis, U Albany)

- Water does not naturally scintillate. BUT:
  - Can look at Cerenkov light from high energy interactions as ER veto
  - Better yet, can dope water with quantum dots, some of which can have triple the light yield of LXe
- Natural advantages of using H_2O
  - Cheap, non-cryogenic, and easy to purify; has lots of protons (sub-GeV DM target).
  - Can be passed through hydrophilic nano-pore membrane, new tech for any bubble chamber (or a TPC)!

CYGNUS HD10, a 10 m^3 gas time projection chamber

Gas mixture: SF6:4He, p ~ 1 atm.

- Possibility of switching from atmospheric pressure (search mode) operation to low pressure operation for (improved) directional confirmation of WIMP signal.
- Reduced diffusion via negative Ion drift (SF6)

Charge amplification via Micromegas

HD – high resolution charge readout via x/y strips (200 µm pitch) for improved

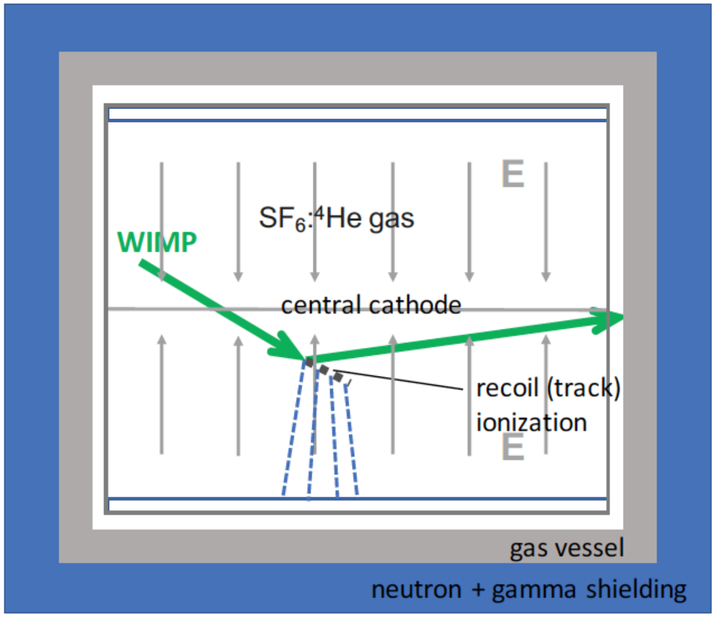
- 3D directionality with head-tail sensitivity
- Electron event rejection
- Fiducialization

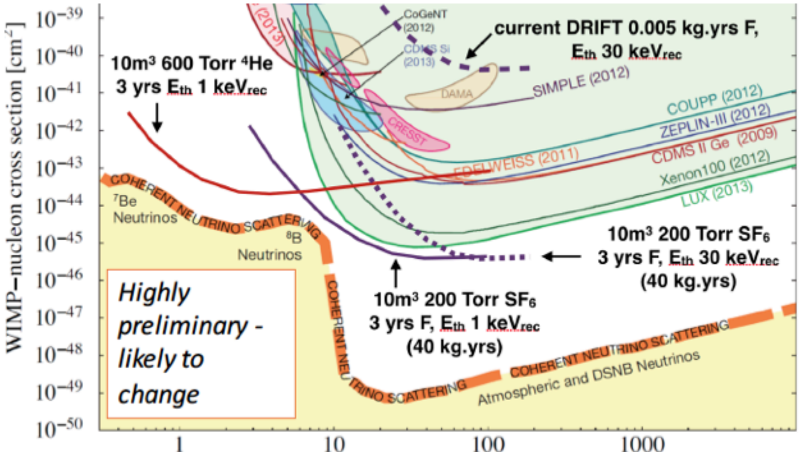
Redundant 3D fiducialization

- SF6 minority carriers
- Charge cloud profile

Helium target

- Improved sensitivity to low mass WIMP
- Longer recoil tracks, extending electron event discrimination to lower energies through Helium target





current DRIFT 0.005 kg.yrs F, E_{th} 30 keV$_{rec}$

10m^3 600 Torr ^{4}He 3 yrs E_{th} 1 keV$_{rec}$

10m^3 200 Torr SF$_6$ 3 yrs F, E_{th} 30 keV$_{rec}$ (40 kg.yrs)

10m^3 200 Torr SF$_6$ 3 yrs F, E_{th} 1 keV$_{rec}$ (40 kg.yrs)

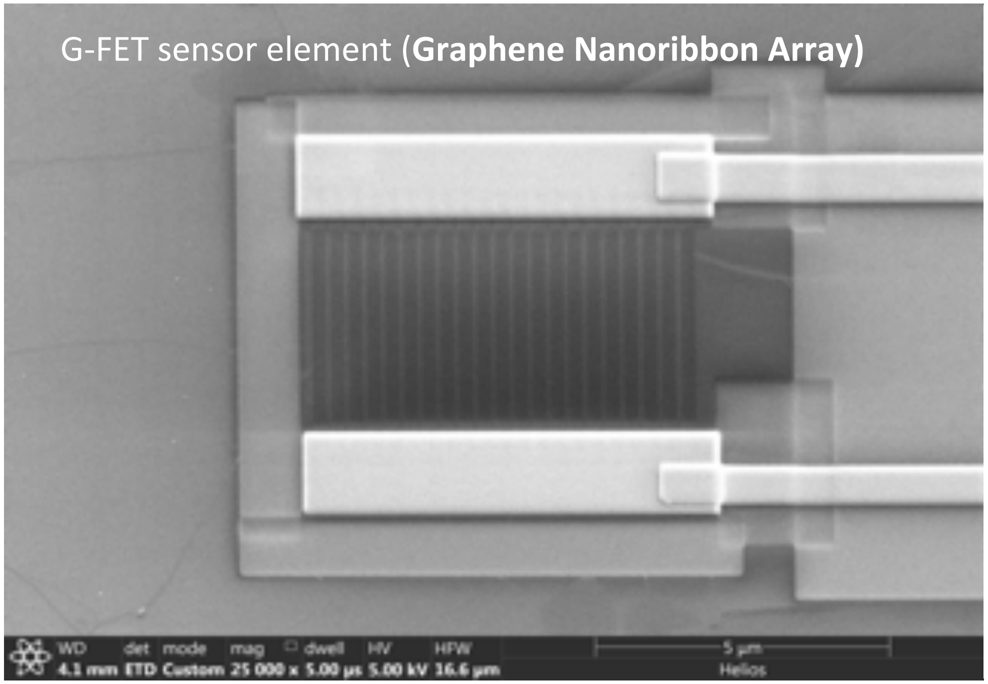
Highly preliminary - likely to change

PTOLEMY-G^3

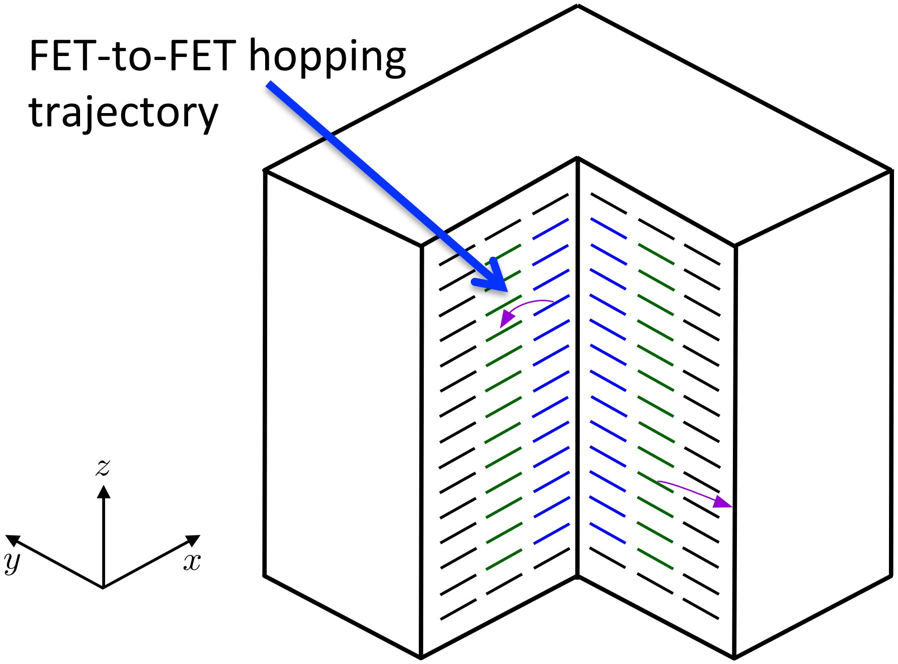
Detector: Graphene field-effect transistors (G-FETs) arranged into a fiducialized volume of stacked planar arrays – Graphene cube (G^3), with mass 1kg ~ 10^{10} cm^2 ~ 10^9 cm^3

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**

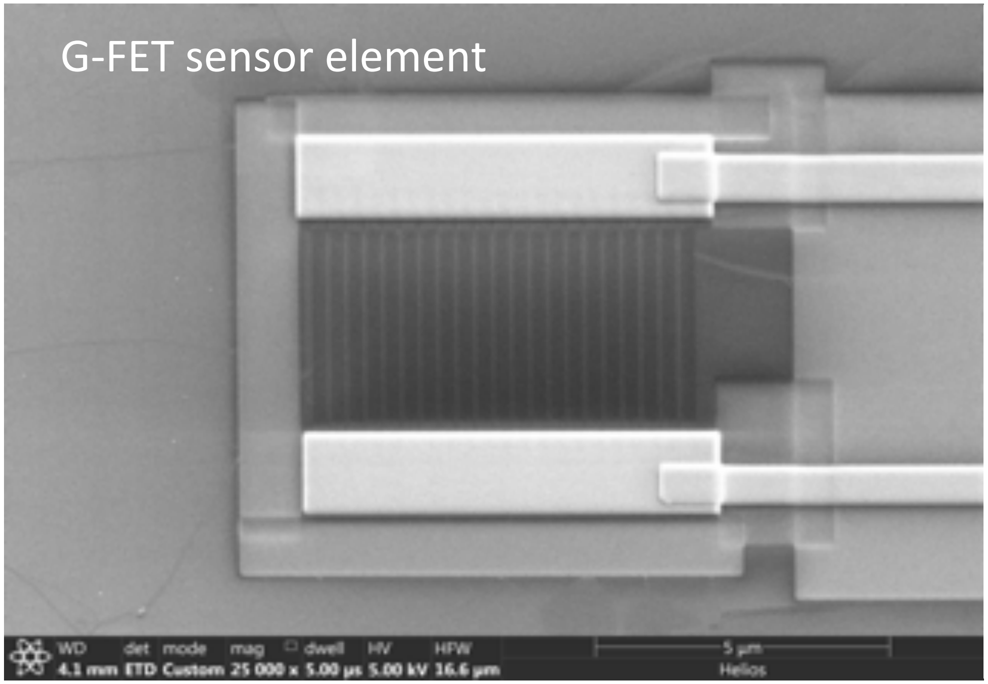


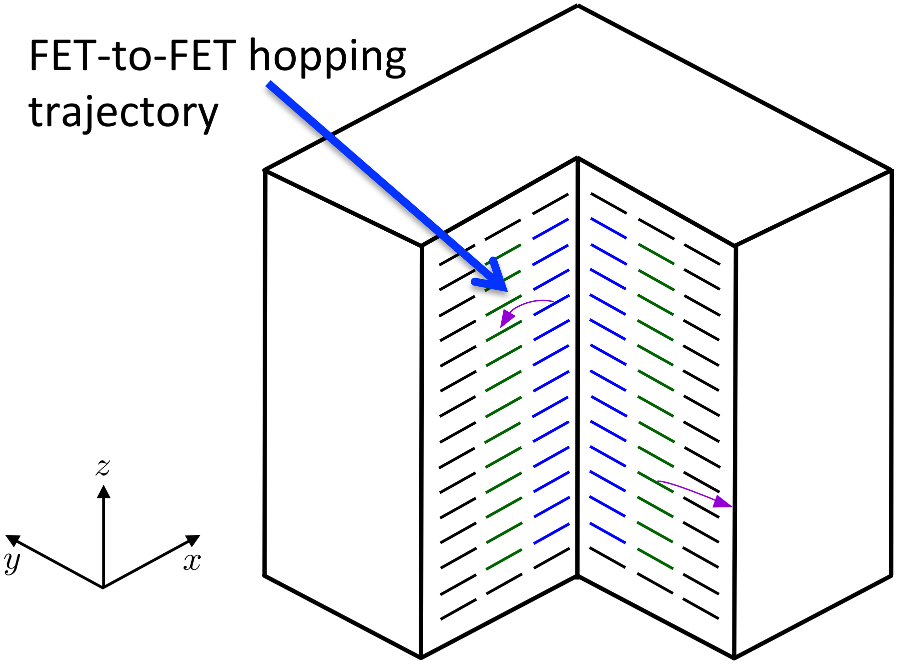
G-FET sensor element (**Graphene Nanoribbon Array)**



FET-to-FET hopping trajectory

Fiducialized Volume (G^3)





20 Graphene Nanoribbon Array (produced at Princeton University)

Resistance-Temperature (RT) and Current-Voltage (IV) curves in progress

Scalability to interdigitated capacitor with pixel areas of $1mm^2$ or larger

Stacked planar arrays of G-FETs

1kg ~ $10^{10}cm^2$ ~ 10^9cm^3

Cryogenically cooled (4.2K)

Cryopumping of gas contaminants on G^3 surface from line-of-sight trajectories

Low mass substrates with ALD dielectric produce a total cold mass lighter than one LHC magnet

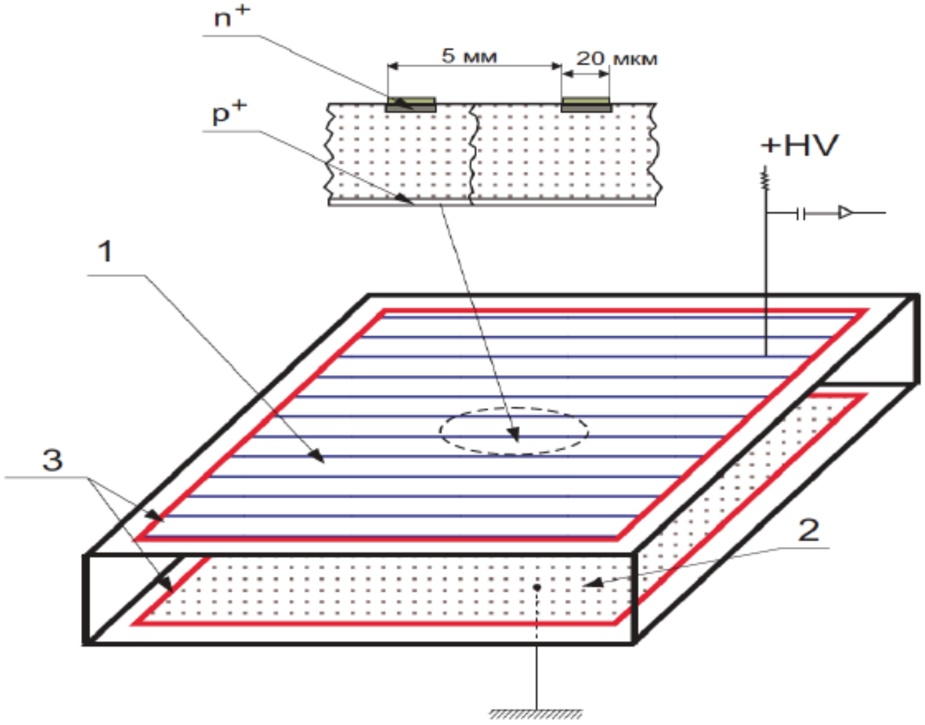
Germanium Detectors with Internal Amplification

(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.



Few-electron detection with two-phase Xe detectors
(P. Sorensen, A. Bernstein)

$U_{A'}(1)$

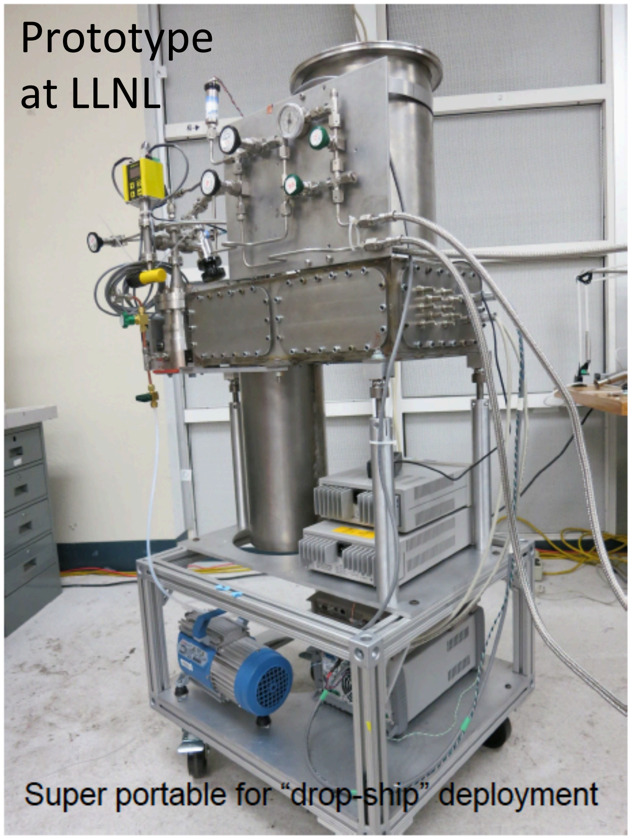
Idea: Deploy a small O(10) kg liquid xenon TPC with a focus on electron counting and mitigation of e- backgrounds.

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)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

3) 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

Scintillators with transition edge sensor readout

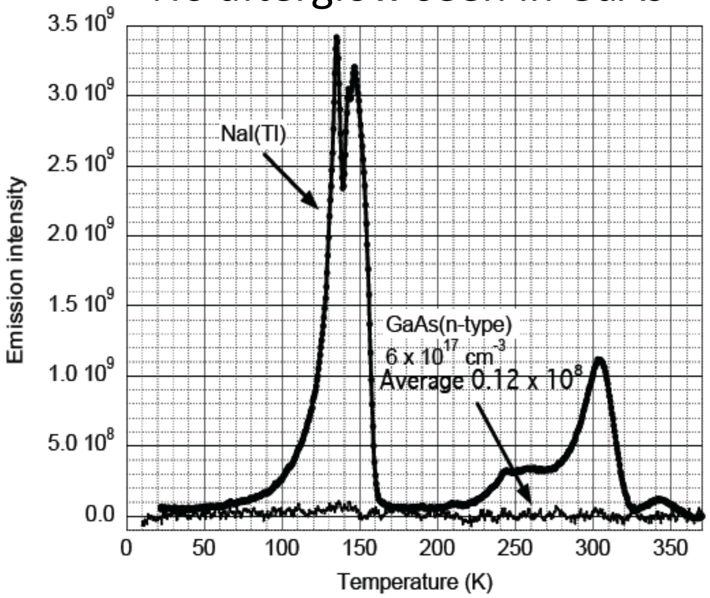
Sensitivity to dark matter – electron interactions.

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

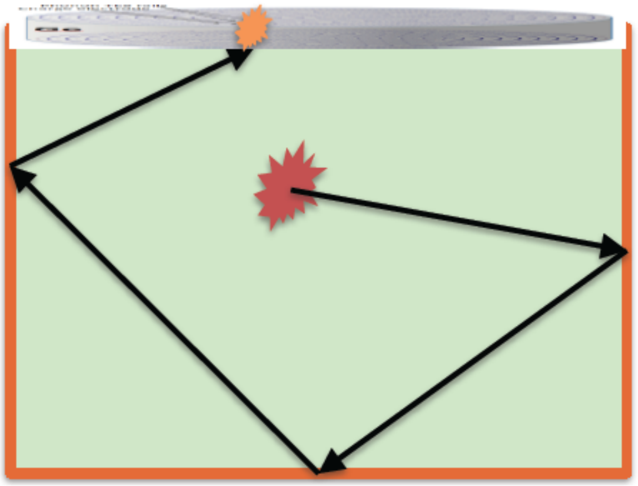
GaAs: Derenzo et al: 1607.01009

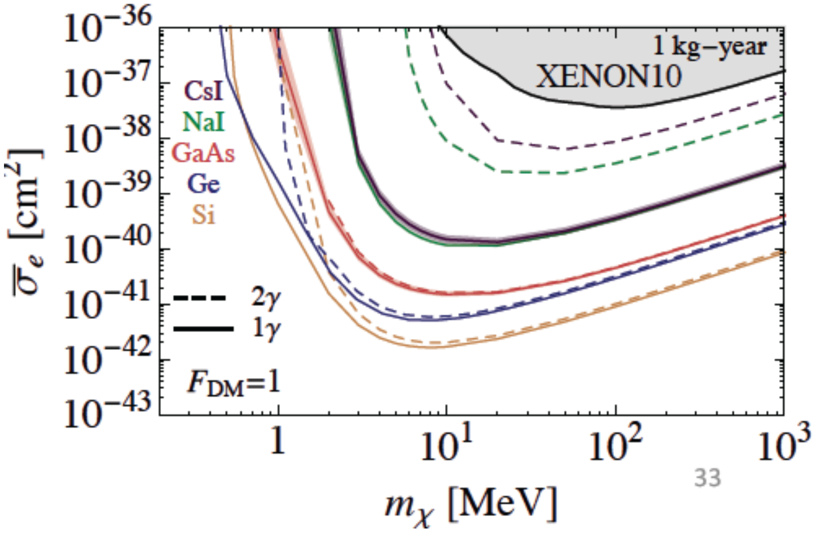
Pure NaI, CsI: J. Liu
83 photons/keV seen at 77K

No afterglow seen in GaAs



No E field = No dark current



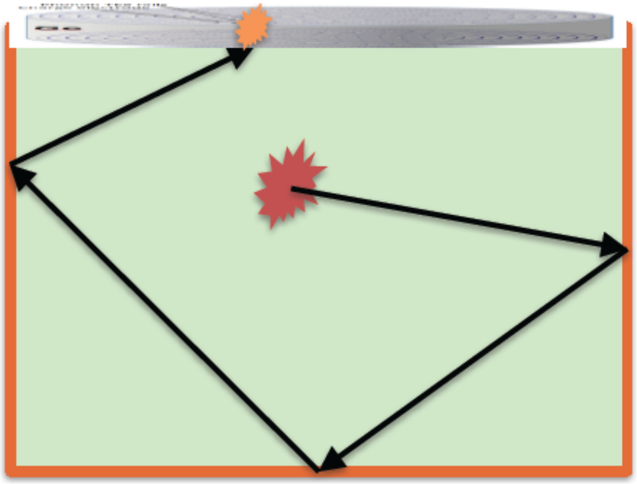


Scintillators with transition edge sensor readout

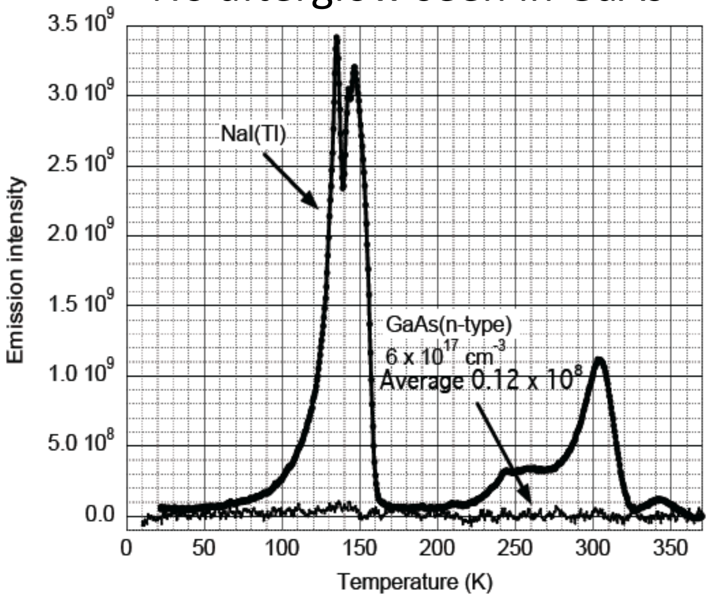
Or, choose your favorite scintillator (LXe, CaWO$_4$, …)

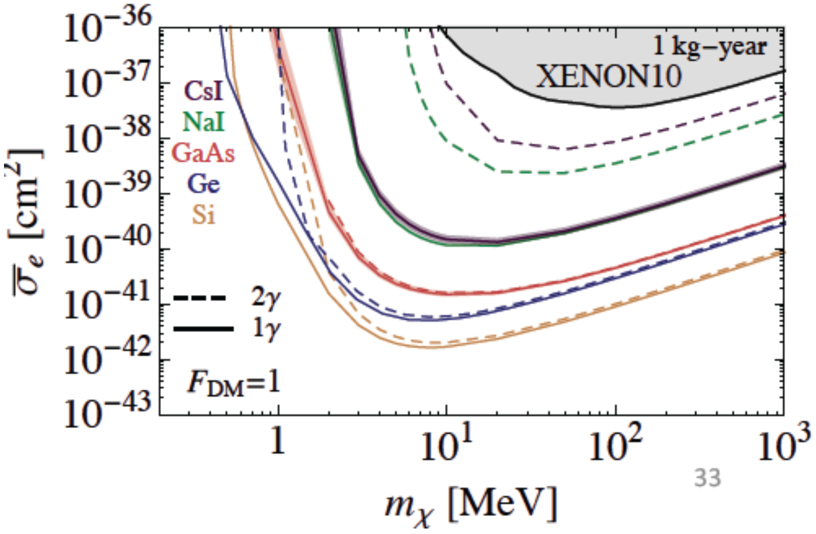
Maximize light yield and target mass, minimize band gap, afterglow, and background.

No E field = No dark current



No afterglow seen in GaAs





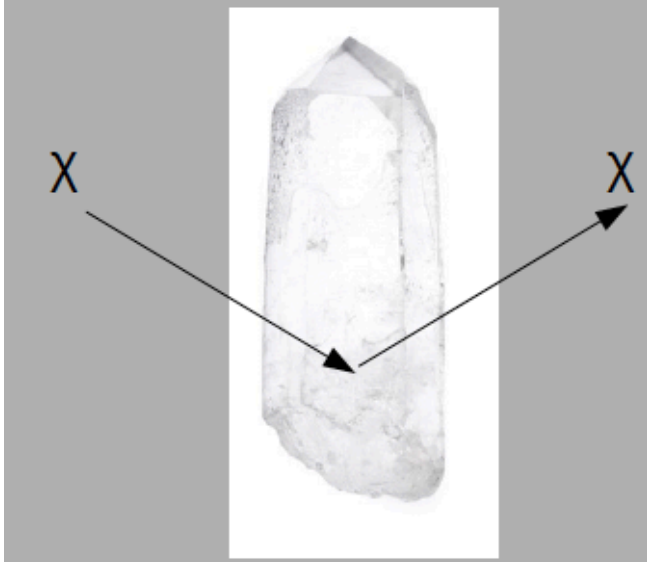
Color centers

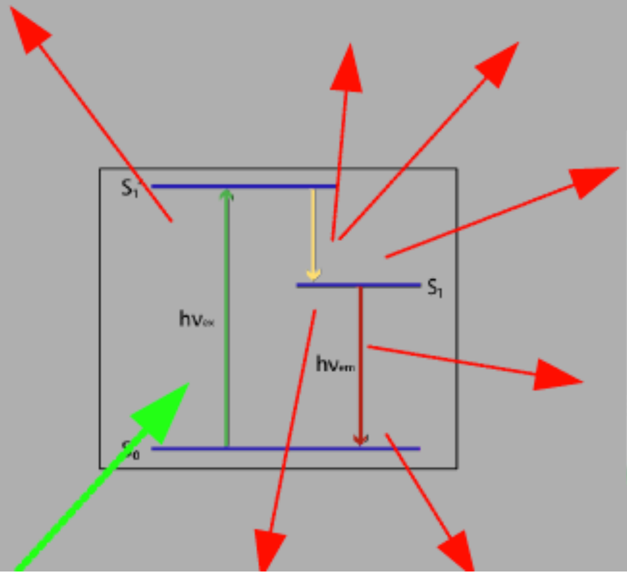
(R. Budnik and collaborators)

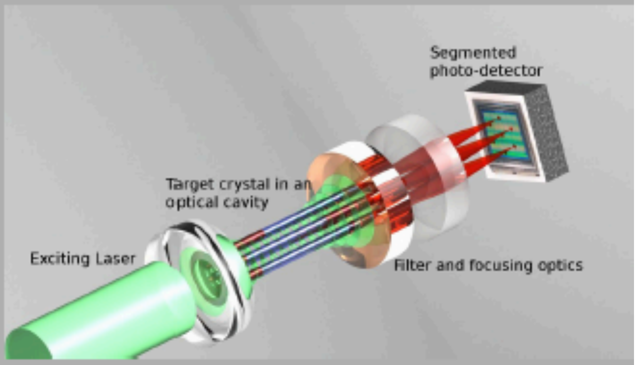
Transparent monocrystal hit by DM, dislocating an ion

The defect acquires an electron and probed by fluorescence repeatedly

DM mass sensitivity can go below 100 MeV

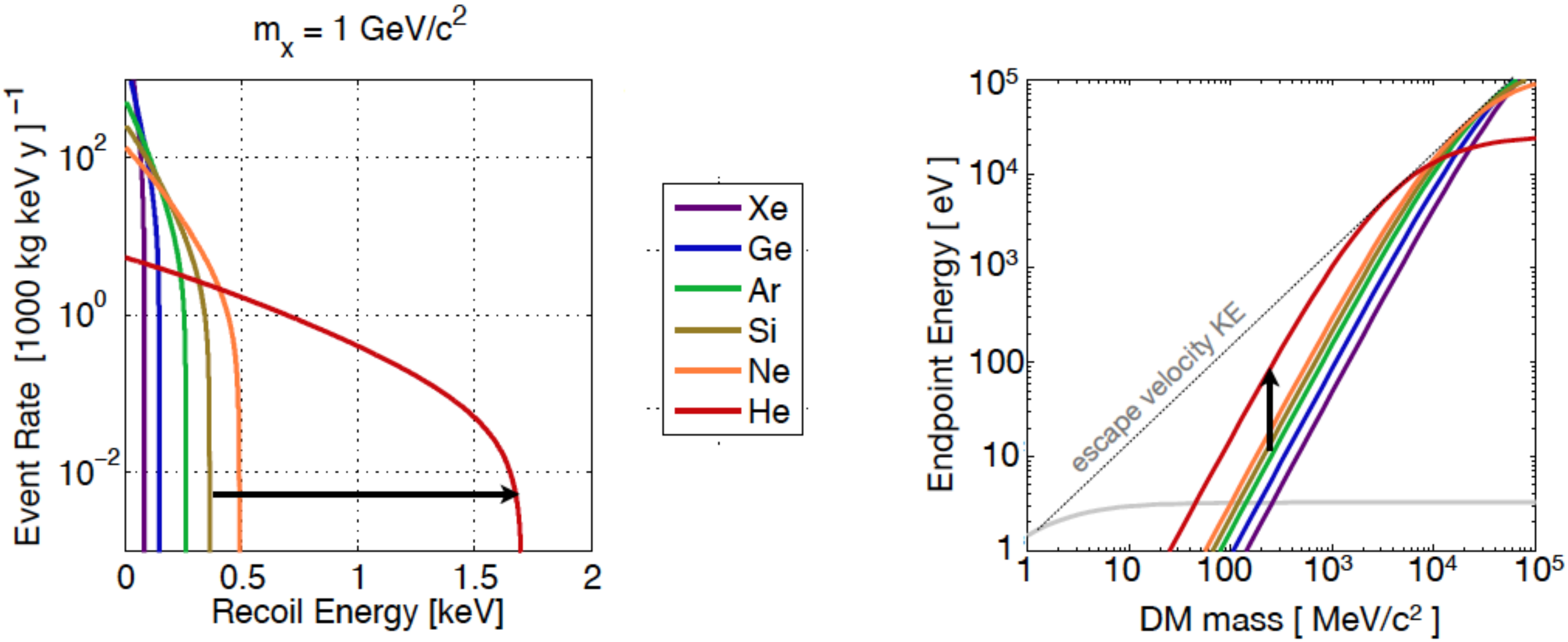






Why Superfluid Helium?

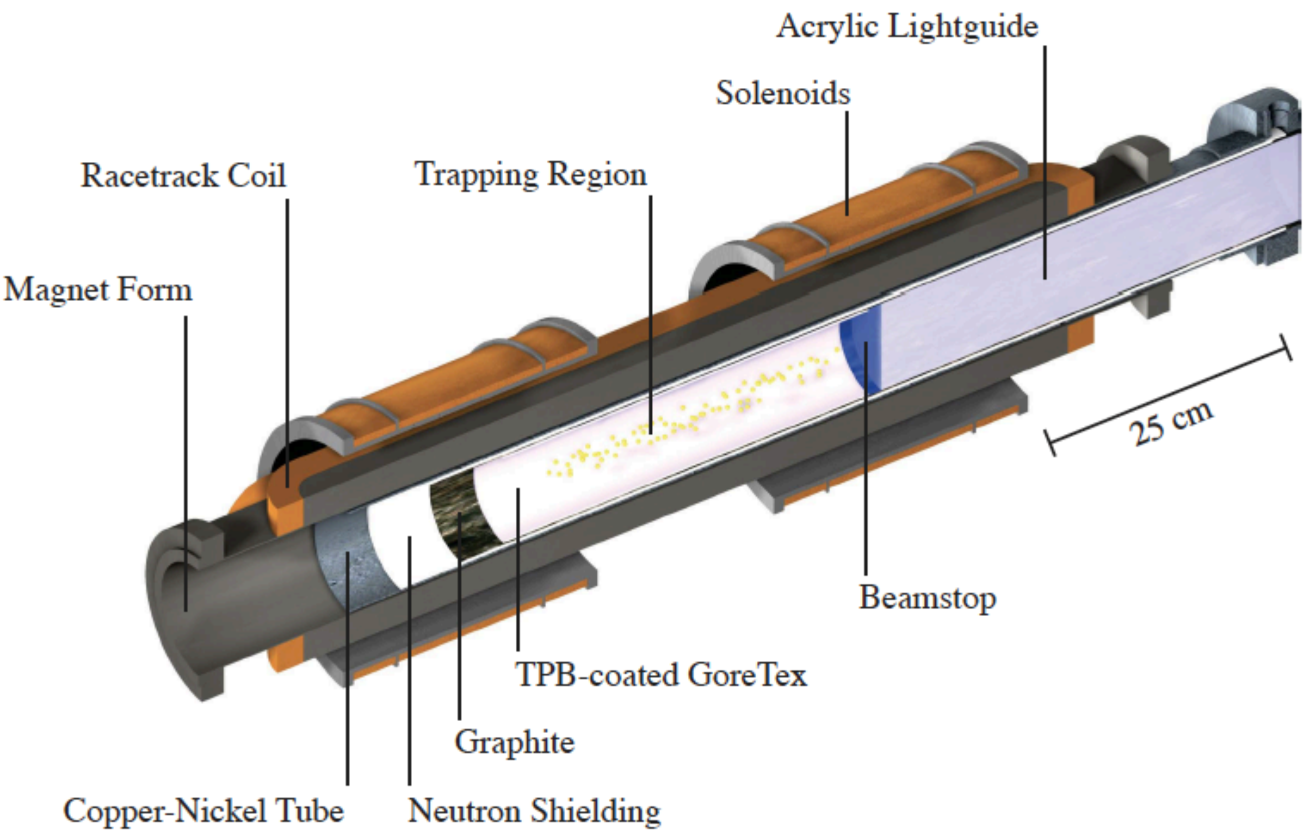
Light baryonic target with multiple signal channels, including light, charge, triplet excimers, phonons, and rotons.
(W. Guo and D. N. McKinsey, PRD 87, 115001 (2013).



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).

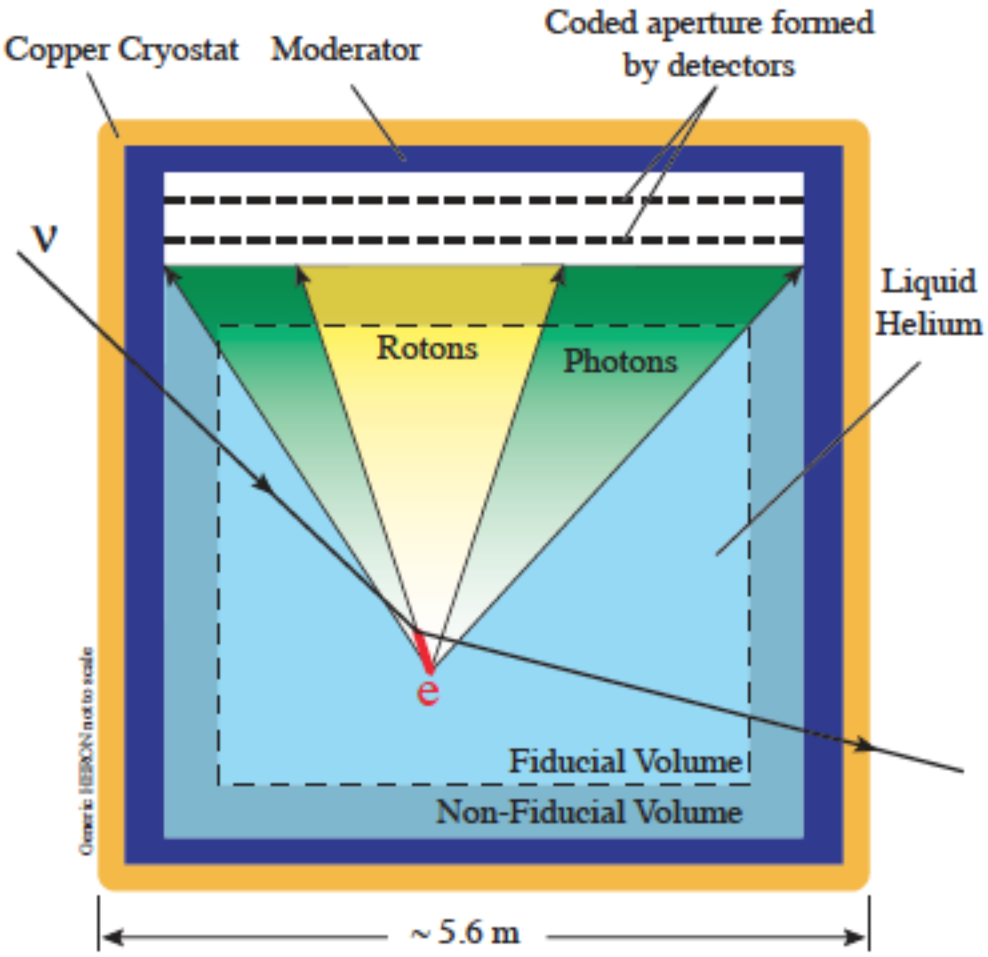


Superfluid helium-4 as a detector material

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)



Why Superfluid Helium-4?

- Liquid down to 0 K, allowing 10-100 mK-scale TES readout.
  - Take advantage of the great advances in TES technology
  - Take advantage of possible ~ 100% detection efficiency for photons, triplet excimers
  - Take advantage of the extremely low vapor pressure of superfluid helium at low temperatures, enabling quantum evaporation-based heat signal amplification.
- Helium is expected to have robust electronic excitation production efficiency, with a forgiving Lindhard factor, so nuclear recoil scintillation signals should be relatively large.
- Negligible target cost
- Low nuclear mass and charge -> low backgrounds from neutrino-nucleus scattering and gamma-nucleus scattering.
- Low vibration sensitivity: As a superfluid, small velocities don't generate excitations.
- Large ionization gap -> less signal quanta per keV than in super-, semiconductors. But no electron recoil background below 16 eV.
- Impurities easily removed from helium using cold traps and getters, and will literally fall out of the superfluid.

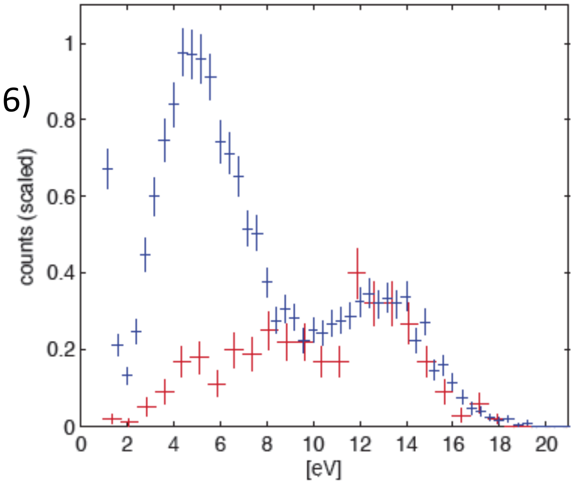
Reading Out Singlet Excitations (16 eV Photons)

Detecting photons is a simple calorimetry application. Operating calorimetry in LHe: less standard. Possible thanks to:

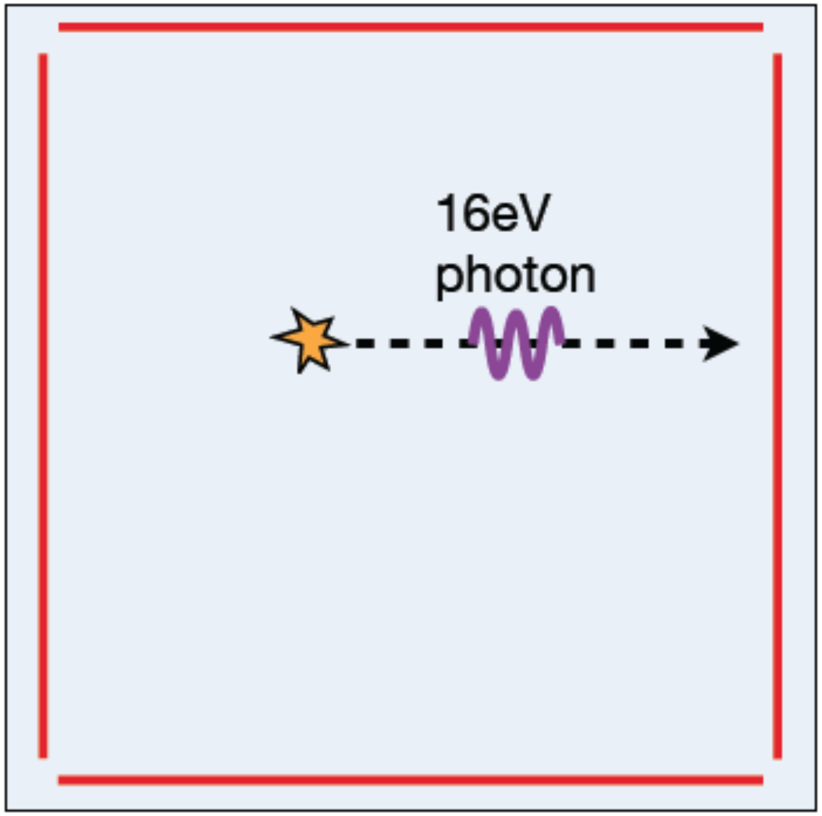
- Huge LHe-solid Kapitza resistance
- Fast conversion of photon energy to non-phonon excitations (e.g. Al quasiparticles)

Triplet excimers may also be read out using the same calorimetry!

F. Carter et al,
J Low Temp Phys (2016)
arXiv:1605.00694



Simple detector: box with calorimetry inside



Phonons and Rotons

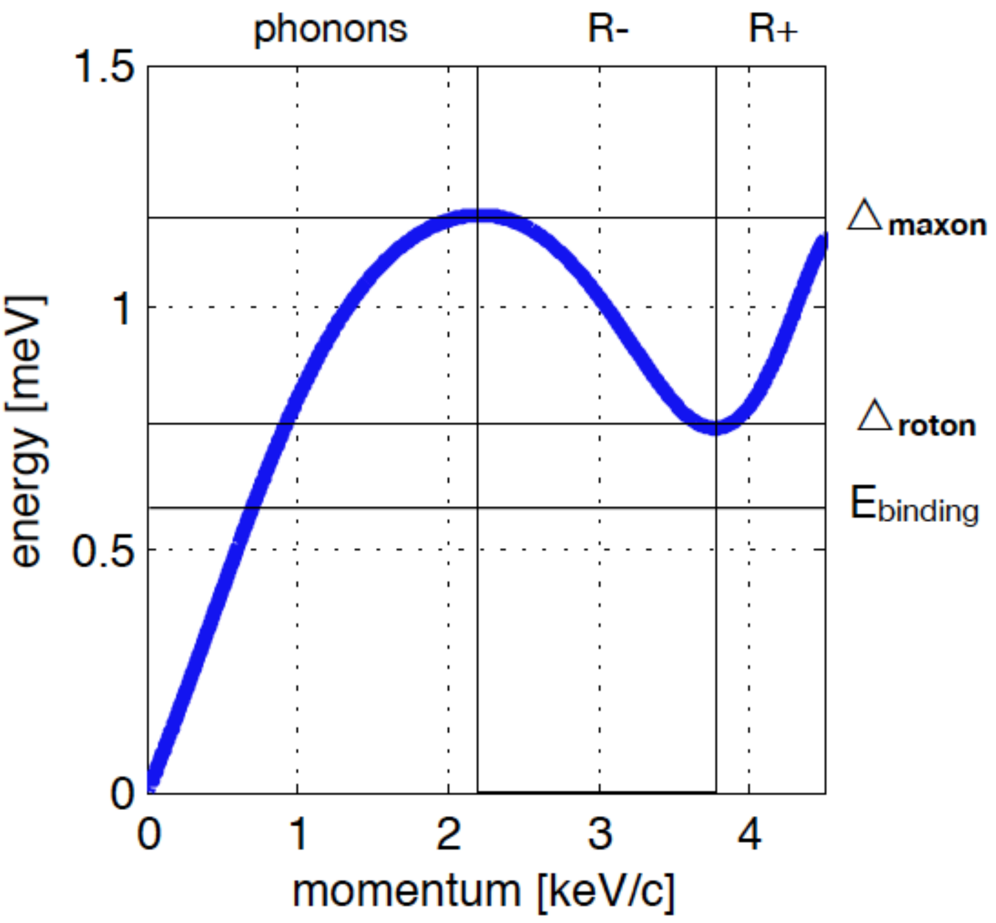
Superfluid supports vibrational modes (some non-intuitive).

Ballistic, ~150 m/s.

Enormous Kapitza resistance,
i.e. *tiny* probability of crossing into solid.

Few downconversion pathways.

Most signal expected in R- and R+ rotons, with absorption probability measured to be 2.8 x 10^{-3}.
See Brown and Wyatt, J. Phys.: Condens. Matter 15, 4717 (2003).

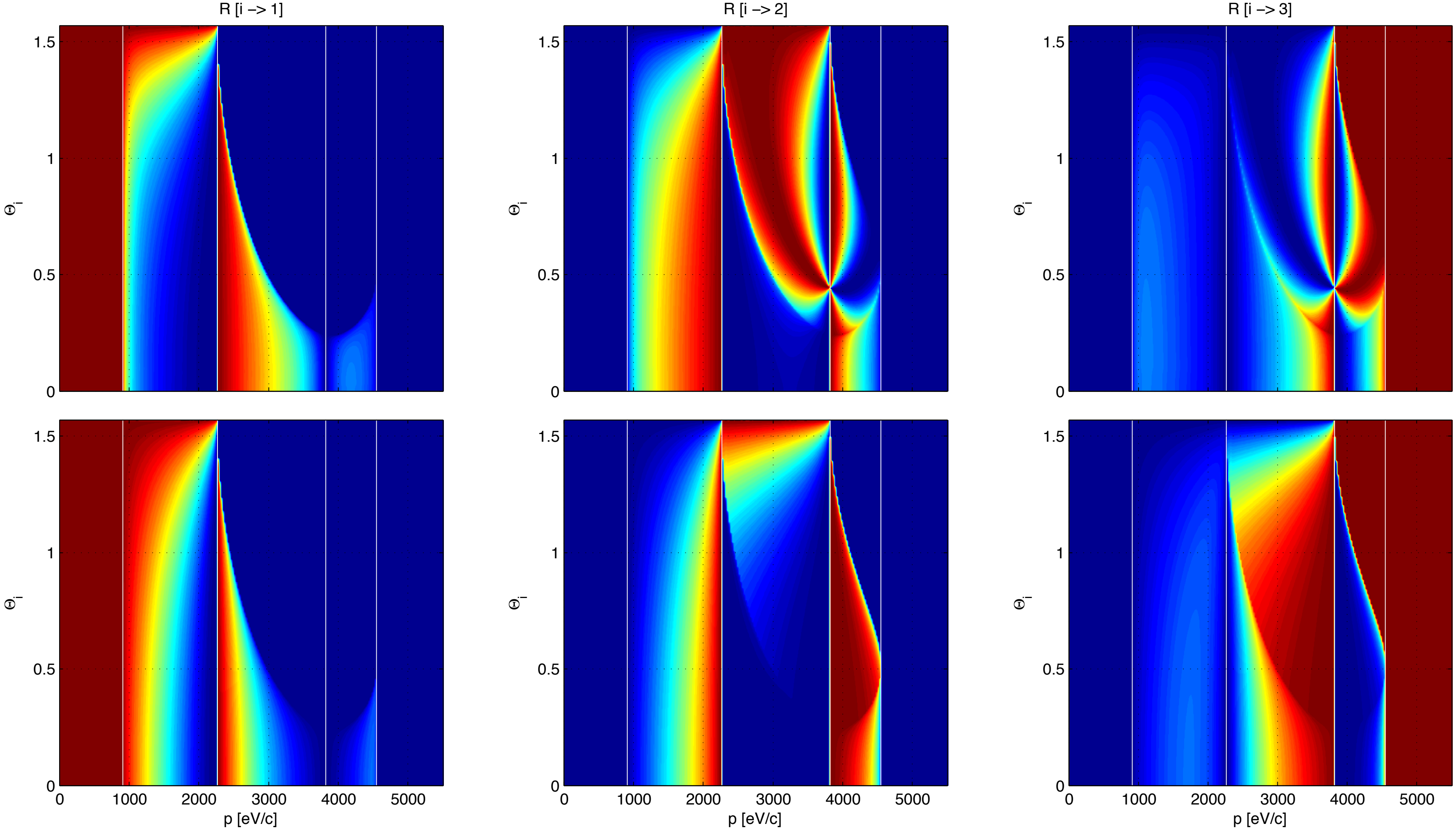


Phonons and rotons can change type when reflecting from surfaces

Calculations based on Tanatarov et al., arXiv:1004.3497

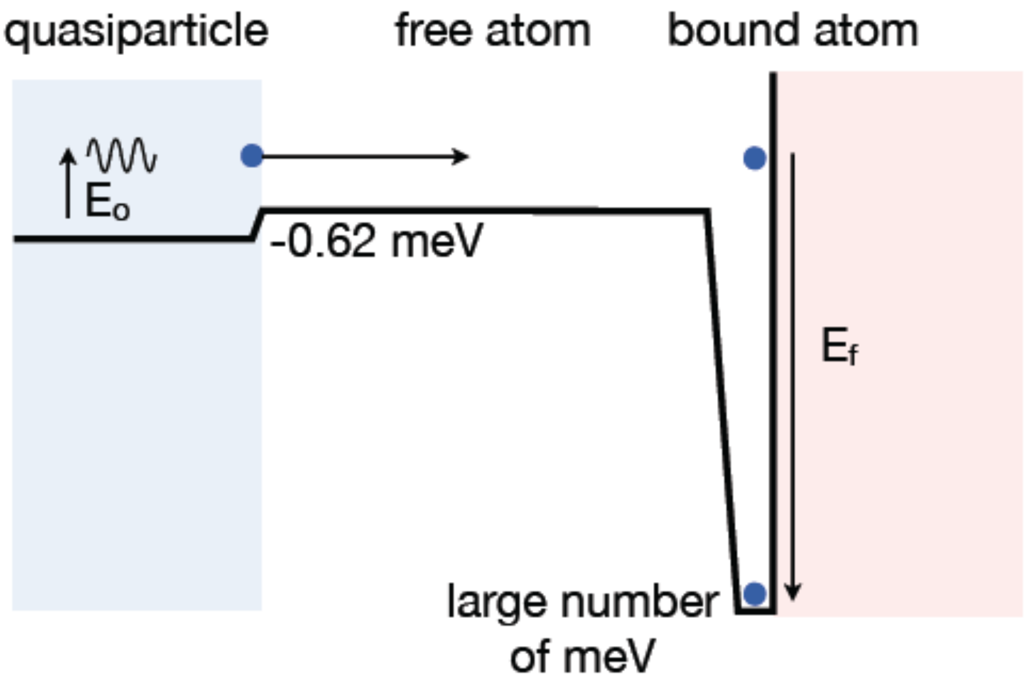
refection mode-change probabilities
(blue=0, red=1)

upper three: solid interface
lower three: vacuum interface



Quantum evaporation from superfluid helium – vacuum interface

Heat amplification from desorption – adsorption process
Adsorption gives 10-40 meV depending on surface

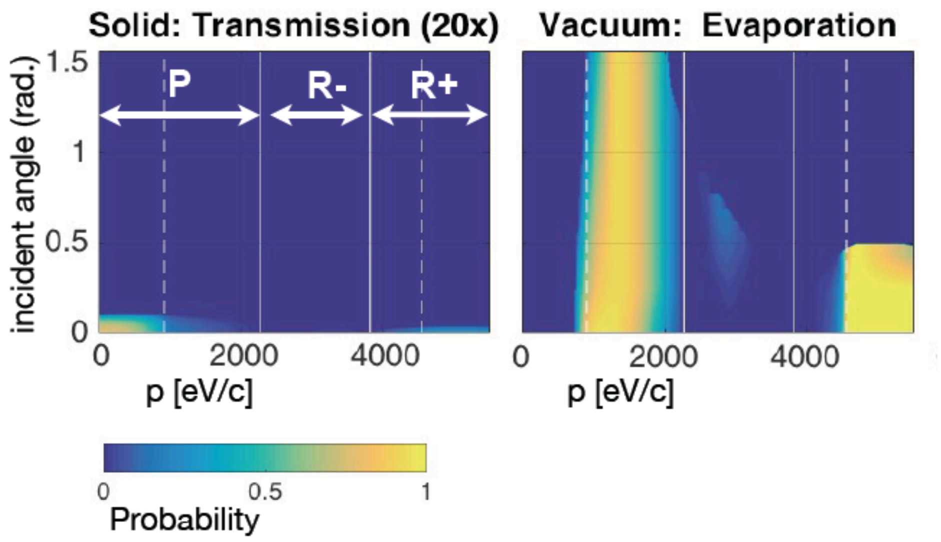


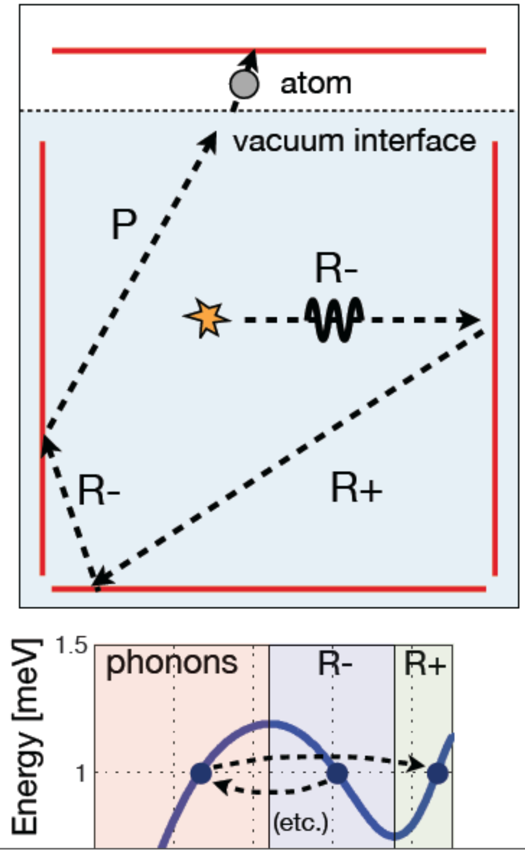
Reading out ^{4}He Quasiparticles (Quantum Evaporation)

Substantial amplification of heat signal through quantum evaporation, followed by helium atom adsorption

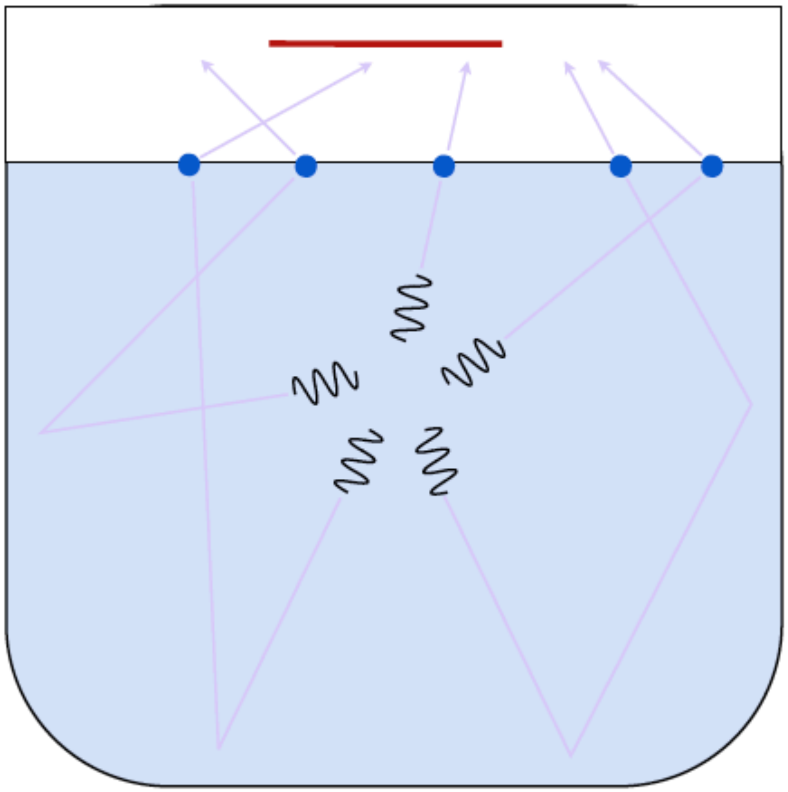
crossing into solid extremely suppressed
(Kapitza resistance)

...saved by significant probability
of single-atom evaporation at vacuum





Athermal Evaporation – Demonstrated by HERON R&D



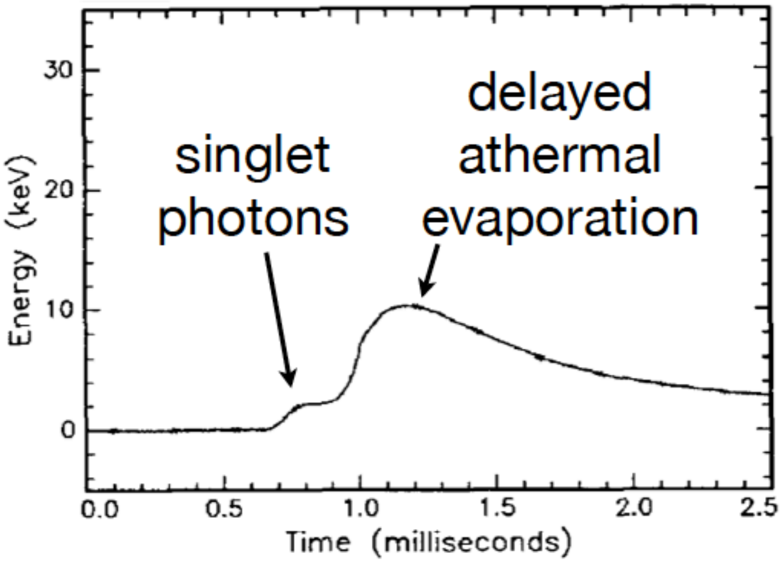


Fig. 2. (a) The calorimeter response (average of about 100 events) when an α particle is stopped in liquid helium. The collimated α tracks are (a) parallel and (b) perpendicular to the liquid surface.

Superfluid Helium Detector Concept

Signal channels:

1) Scintillation
2) Ballistic Triplet Excimers
3) Phonons/Rotons

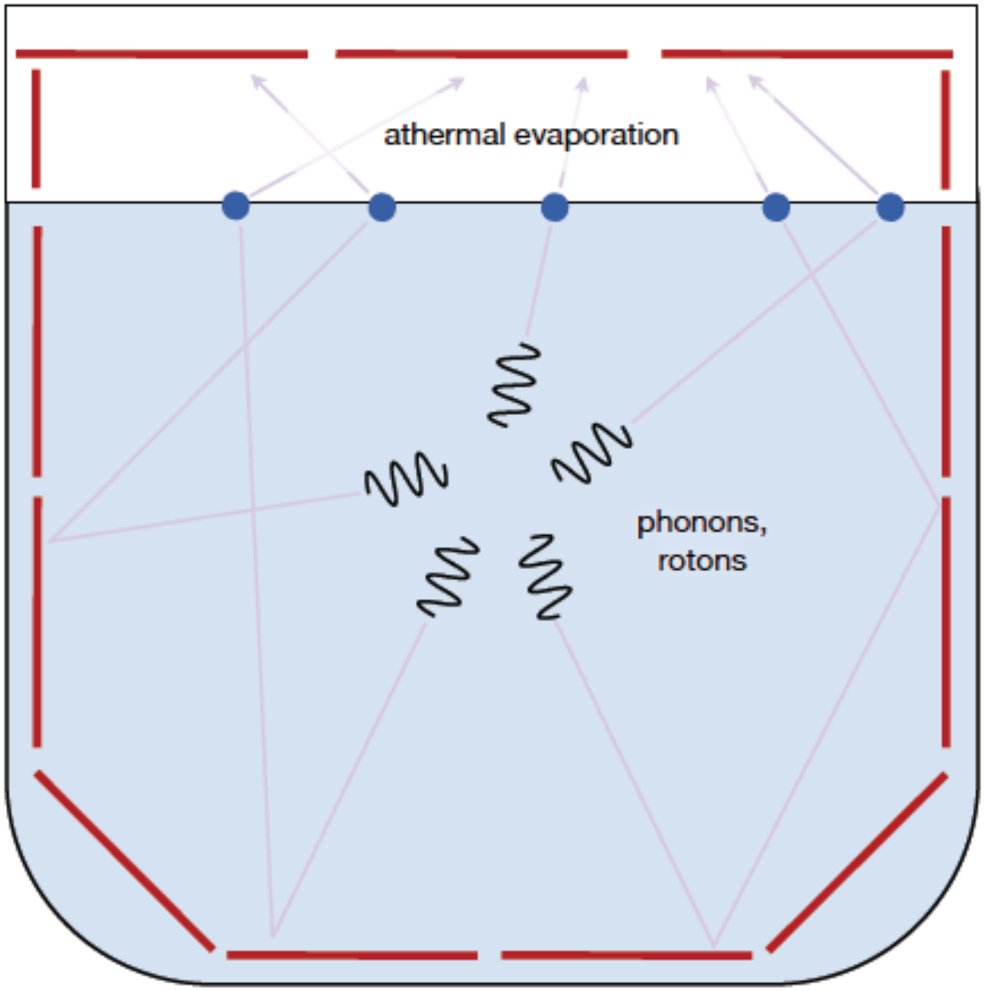
No drift field, and no S2 signal

- No worry of few-electron background
- Position reconstruction via signal hit patterns
- (Though could apply drift field to detect single electrons via roton/phonon production.)

Best for energies down to 300 eV.

Discrimination using signal ratios

Position reconstruction using signal hit patterns

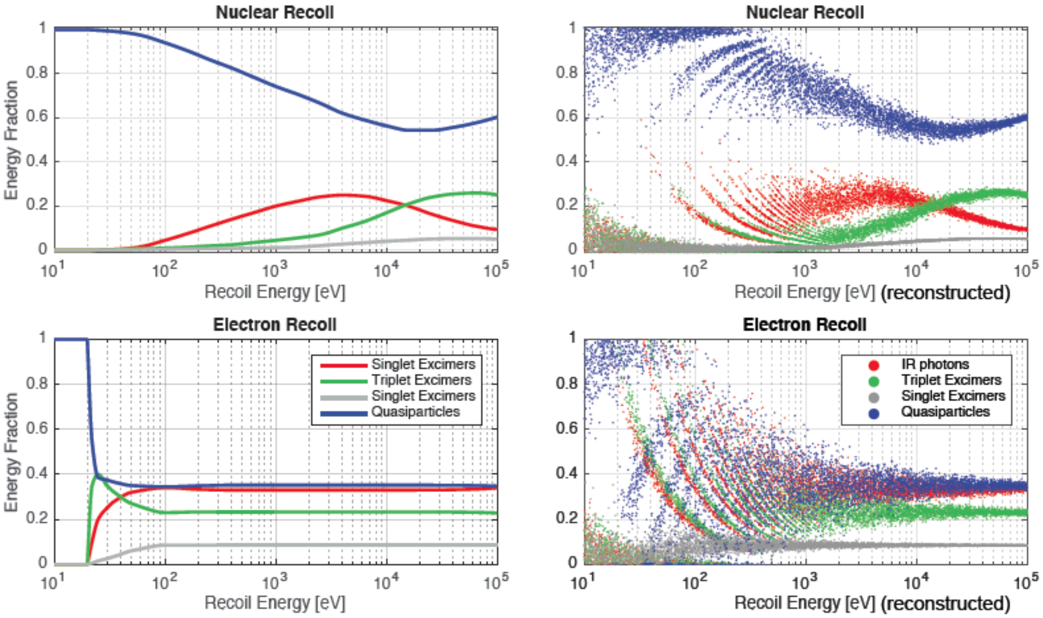


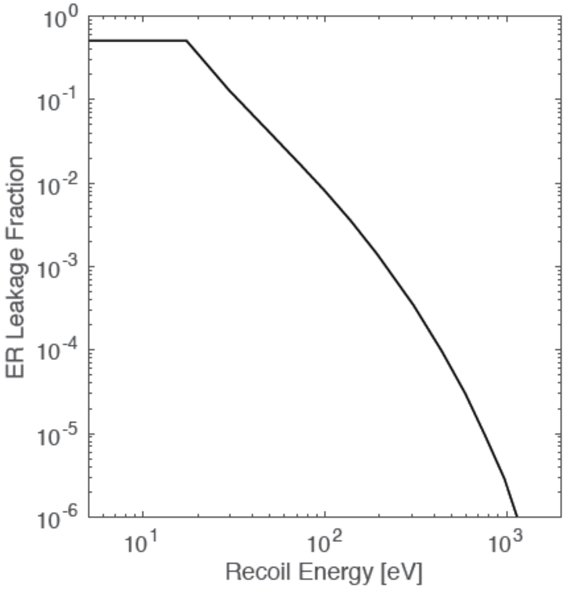
Electron recoil / nuclear recoil discrimination

Toy Monte Carlo detection efficiencies:

- singlet UV photons: 0.95 (4pi coverage by calorimetry)
- Triplet excimers: 5/6 (only solid surfaces)
- IR photons: 0.95 (similar to UV photons)

Excellent predicted discrimination at sub-keV energies





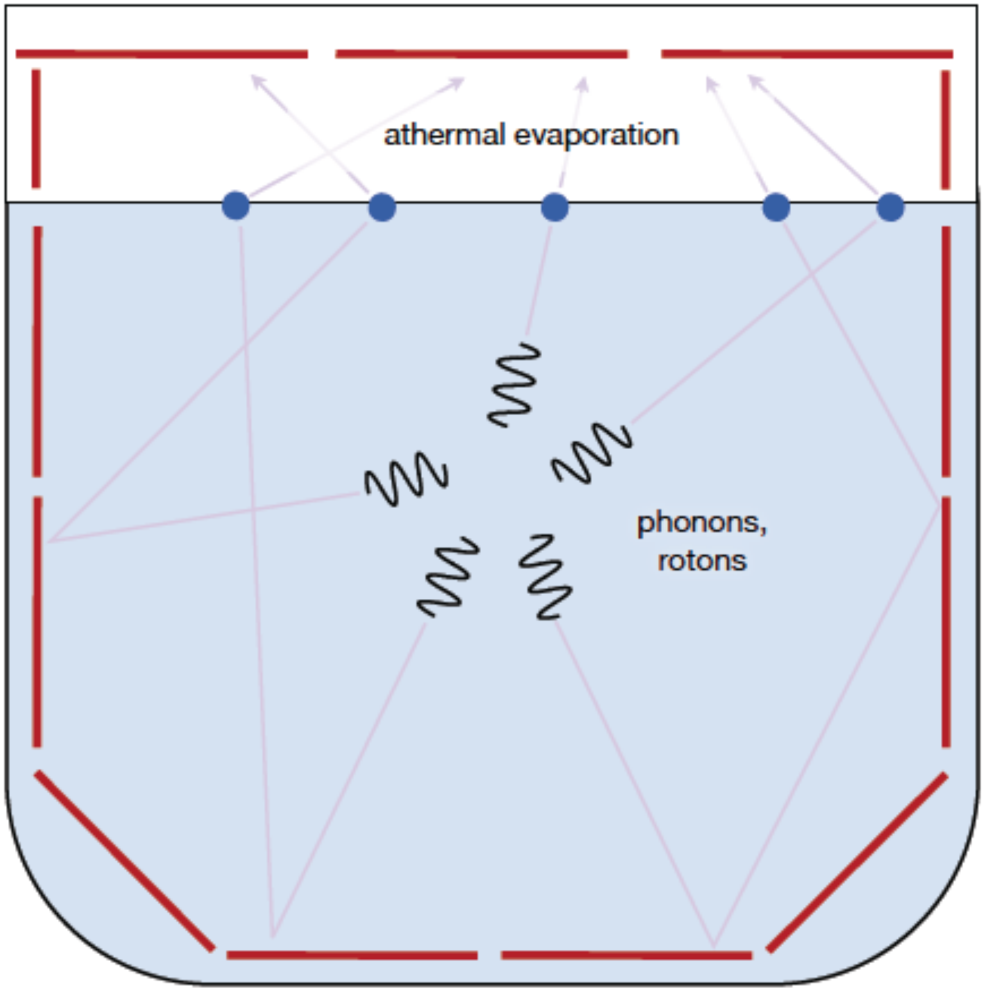
Heat-only Readout?

Signal channels:
Phonons
Rotons

Energies down to ~ few meV !!

Discrimination using roton/phonon signal ratios likely. Electron recoils, detector effects, nuclear recoils likely create different roton/phonon distributions.

Position reconstruction using signal hit patterns

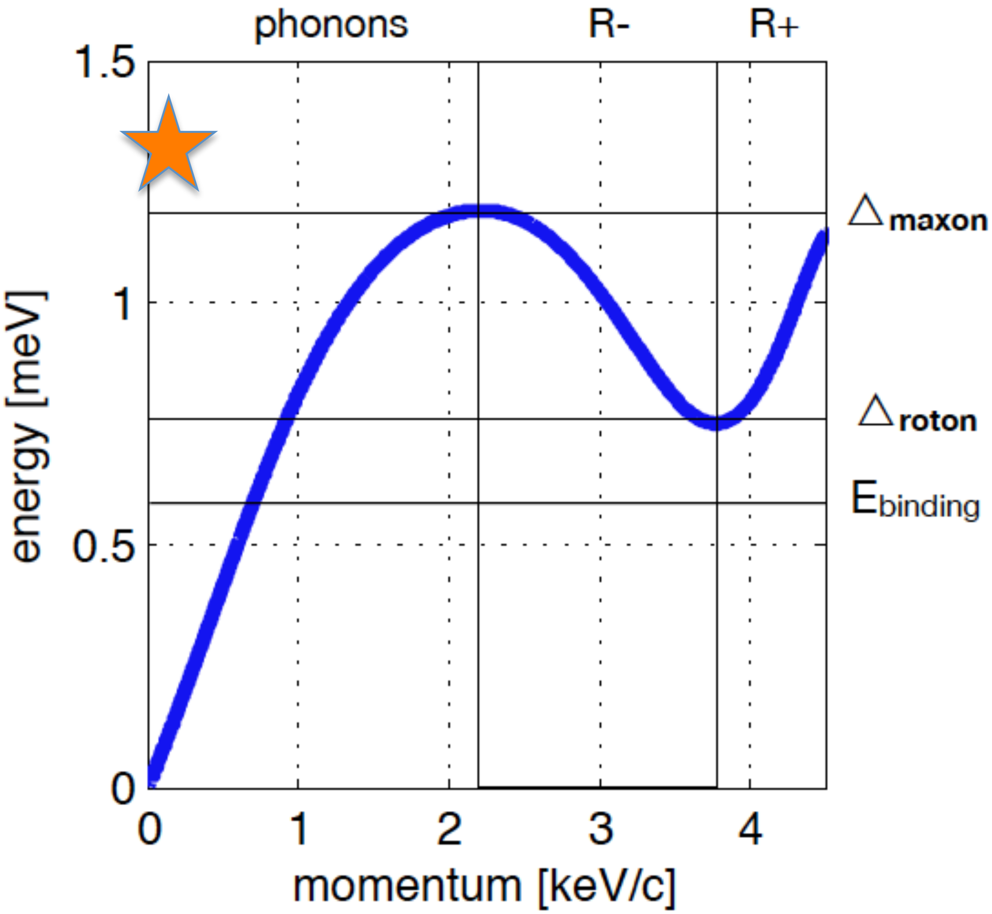


Projected sensitivity to keV-scale dark matter particles

K. Schutz and K. Zurek,
Phys. Rev. Lett. 117, 121302 (2016)
and S. Knapen, T. Lin, and K. Zurek,
arXiv:1611.06228.

Instead of coupling to a single nucleus, couple to virtual mode in the superfluid helium, which in turn decays to multi-excitations

Production of multi-excitations allows high energy transfer from the low-mass, low-momentum dark matter particle



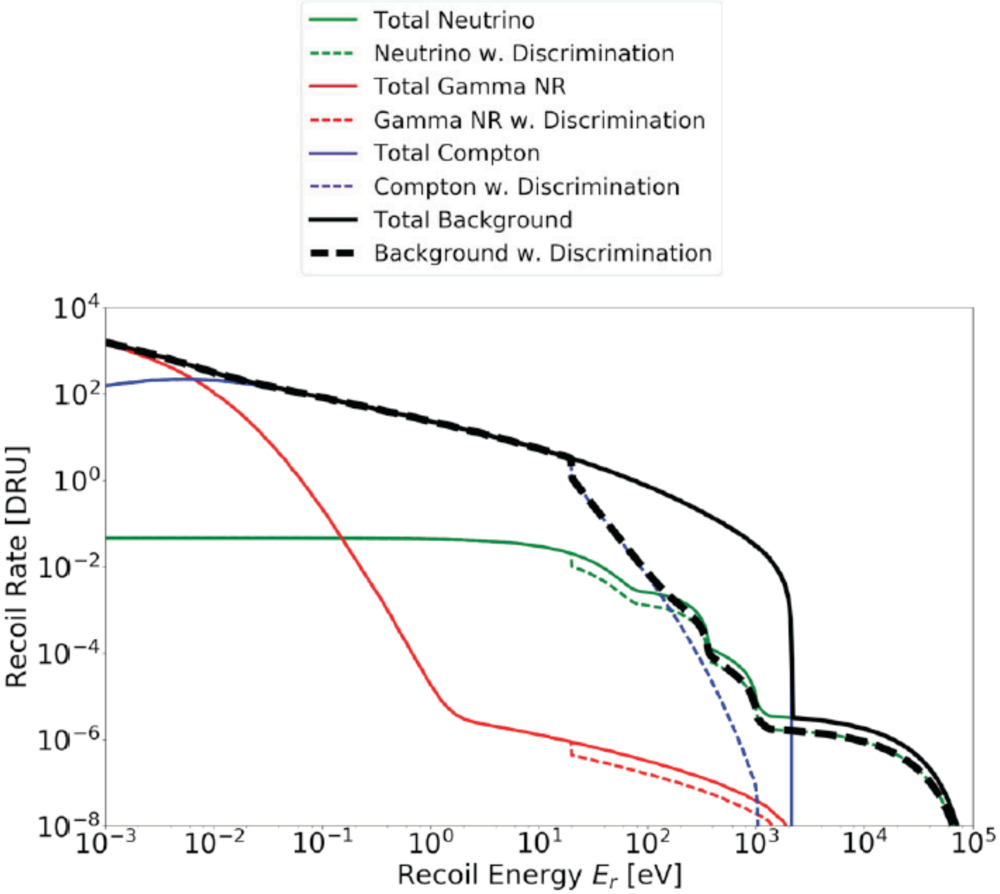
Expected Backgrounds

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)

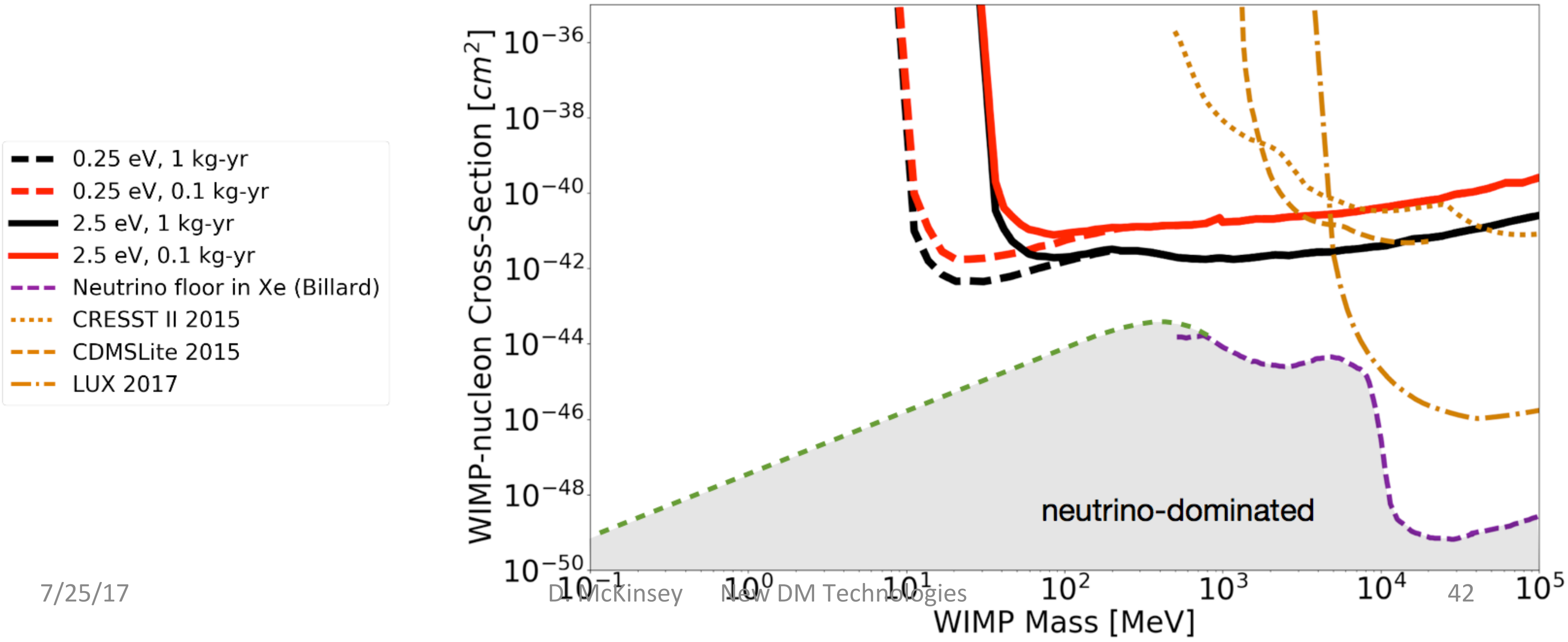
Arguments for low "detector" backgrounds:

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



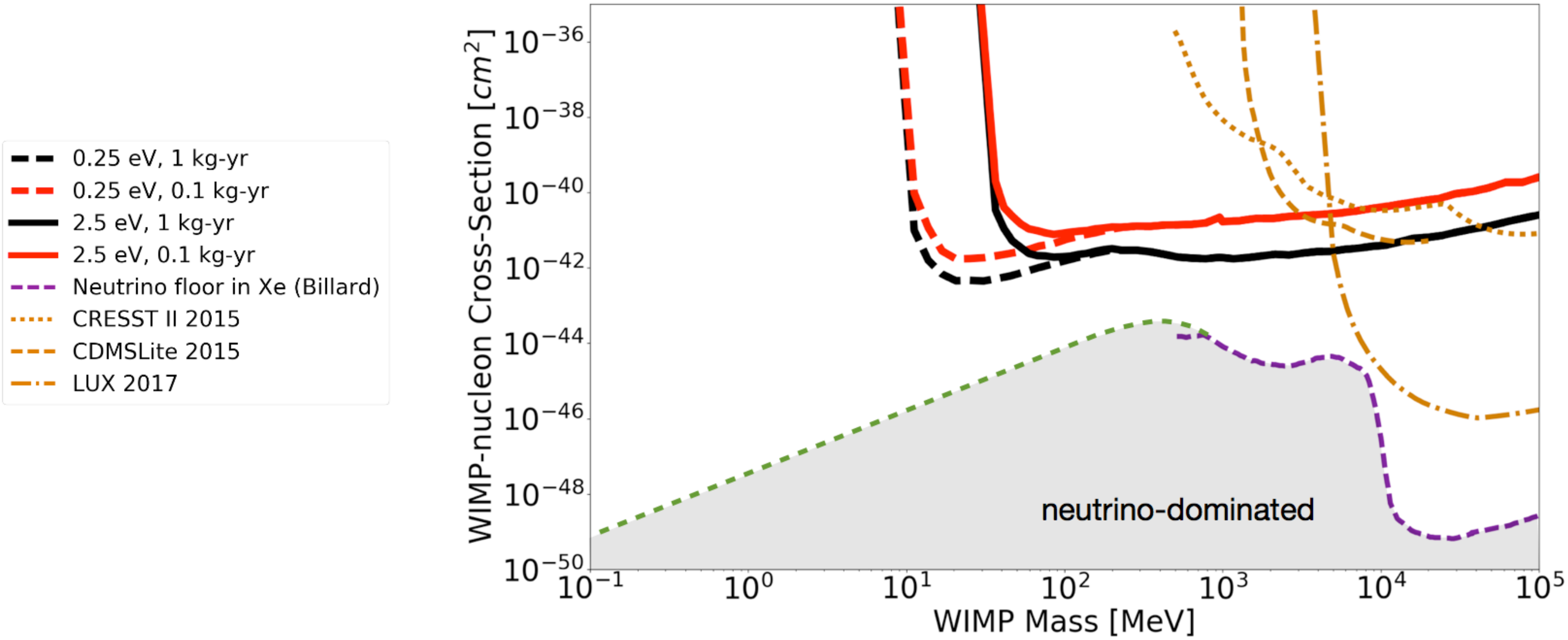
Projected Sensitivity

Initial sensitivity studies, taking neutrino and gamma ray backgrounds into account:
(with S. Hertel, UCB/LBL -> U. Massachusetts, Amherst
Junsong Lin, Andreas Biekert, Vetri Velan, UC Berkeley)



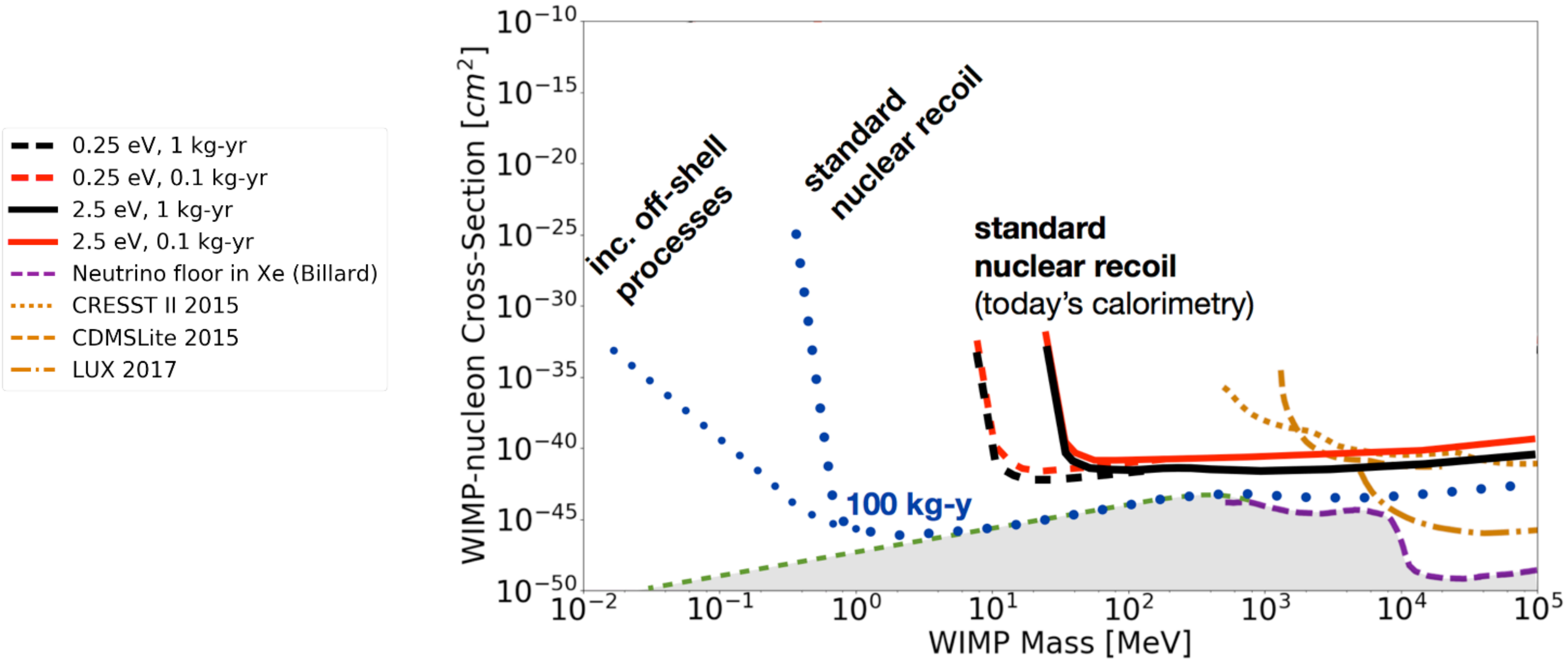
Projected Sensitivity

Even a small mass (~ kg) of superfluid helium can probe substantial dark matter parameter space



Projected Sensitivity

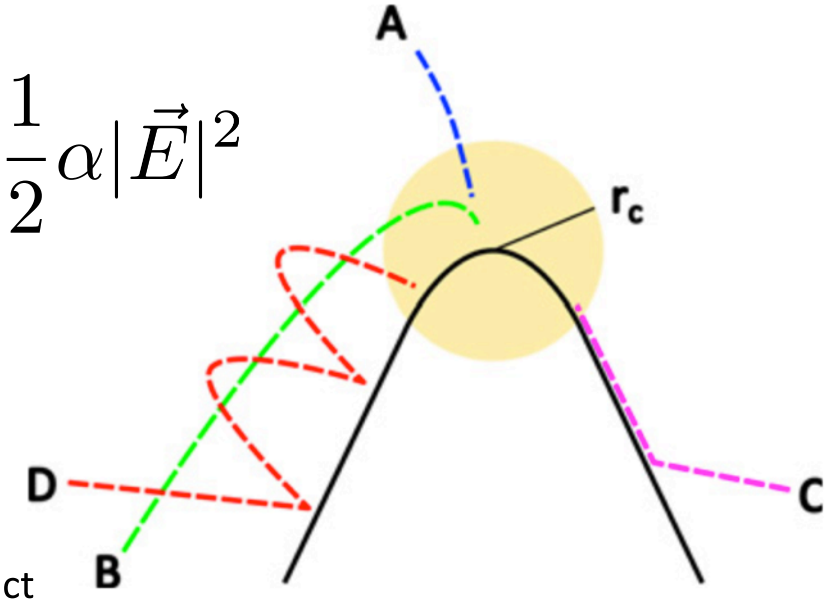
Larger target mass (~ 100 kg) of superfluid helium, with lower energy threshold (~ 10 meV) can push even lower in dark matter mass and cross-section



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

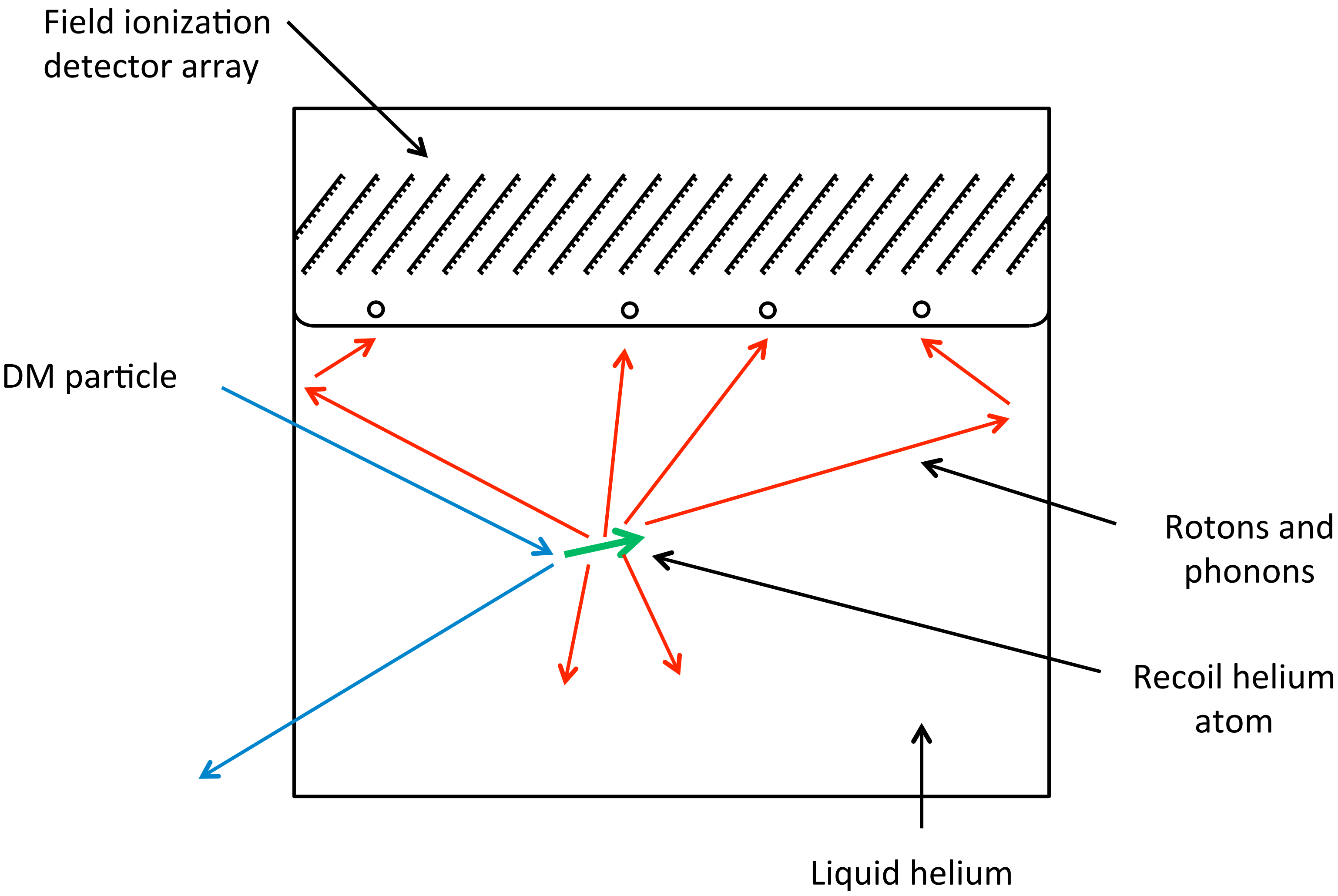
B) Orbital capture

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!

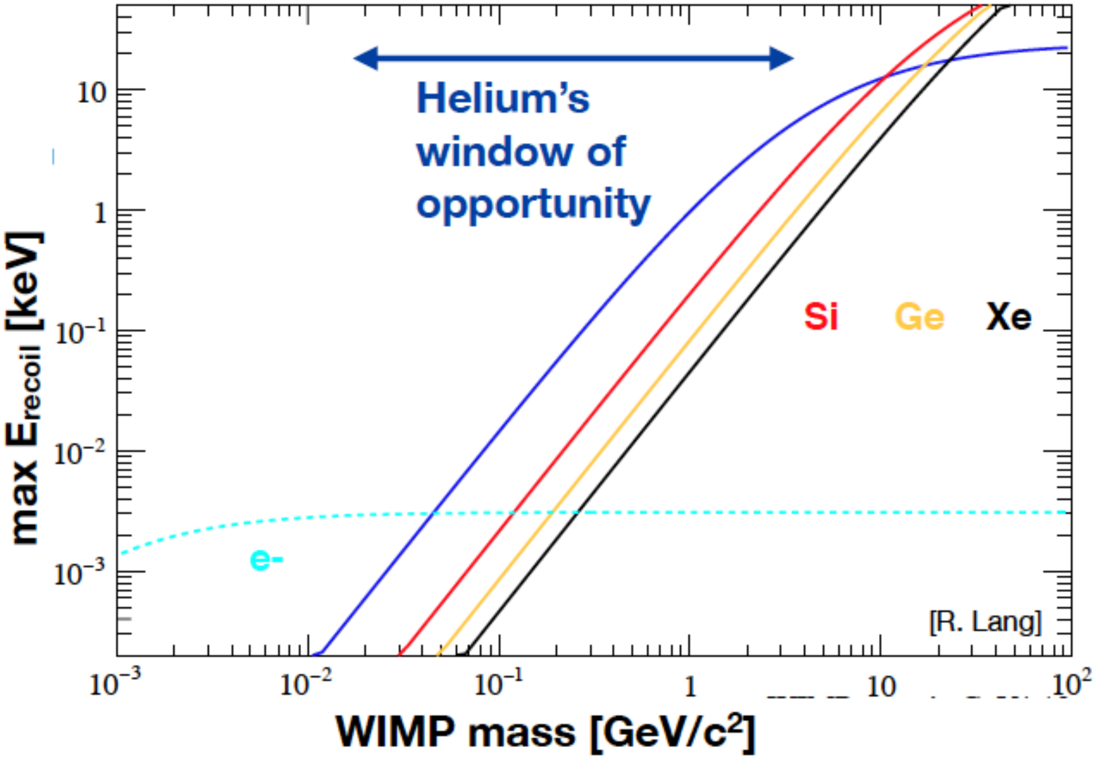
Backup

Helium-4 Nuclei: A Natural Match for Light Dark Matter Detection

Another view: maximum recoil energy for various targets, as a function of WIMP mass.

$$\max E_{recoil} = KE_x \left(\frac{4\, m_t\, m_x}{(m_t + m_x)^2} \right)$$

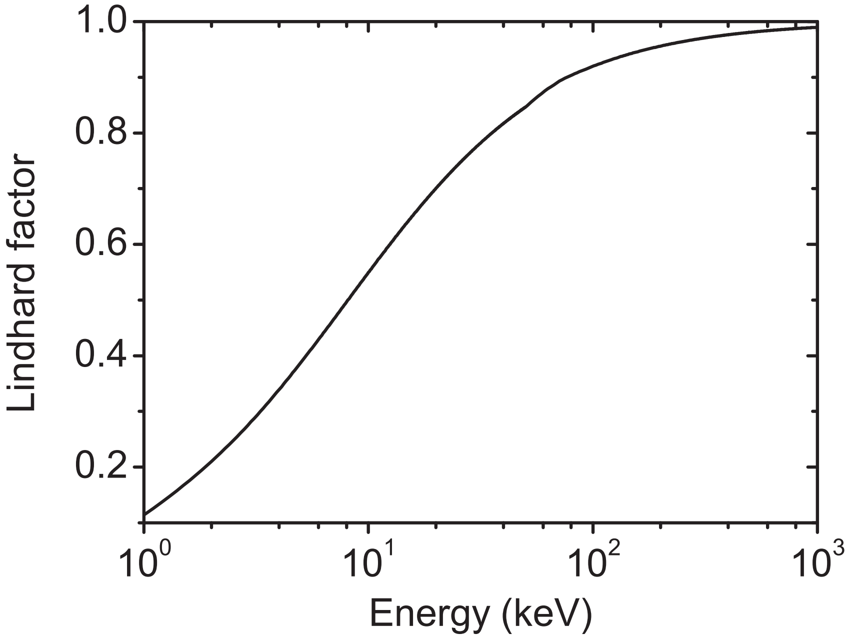
here,
v_x = galactic escape velocity, 540 km/s
nuclear form factors completely ignored
electron's atomic state similarly ignored



Why Superfluid Helium for Low-mass Dark Matter Detection?

(W. Guo and D. N. McKinsey, PRD 87, 115001 (2013).

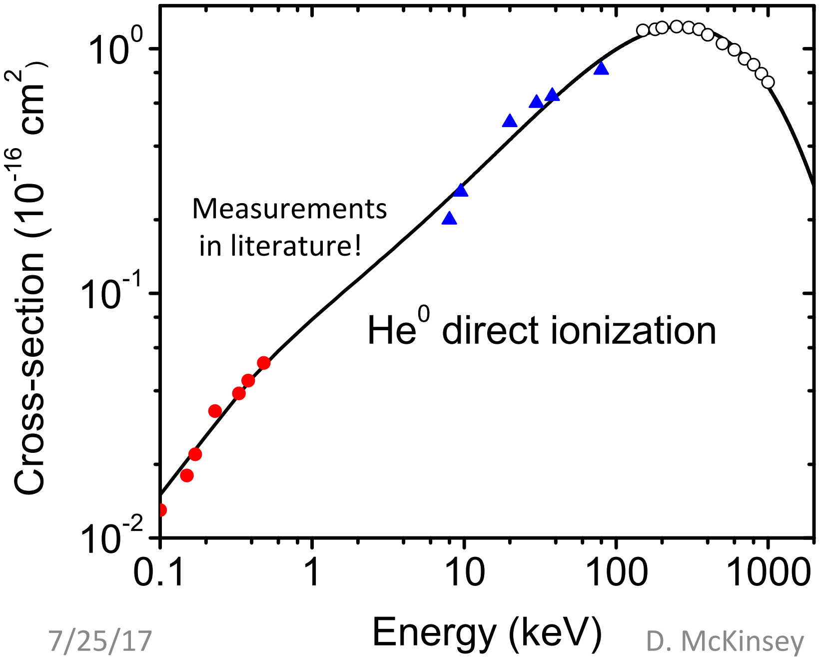
- Kinematic matching with light dark matter candidates.
  - Pull the energy depositions up in energy, to above threshold.
  - Gain access to more of the WIMP velocity distribution, for a given energy threshold.
- Superfluid helium offers multiple signals to choose from, and to separate dark matter signal from backgrounds (both electron recoils and detector backgrounds).
  - Prompt light
  - Delayed triplet excimers
  - Charge
  - Heat (roton and photon quasiparticles)

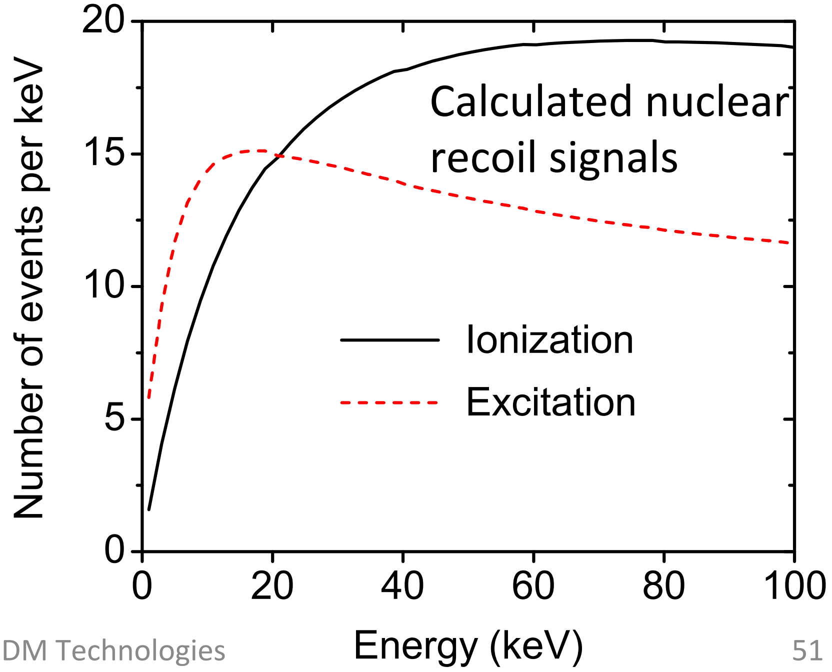


Liquid helium-4 predicted response (Guo and McKinsey, arXiv:1302.0534, Phys. Rev. D 87, 115001 (2013).)

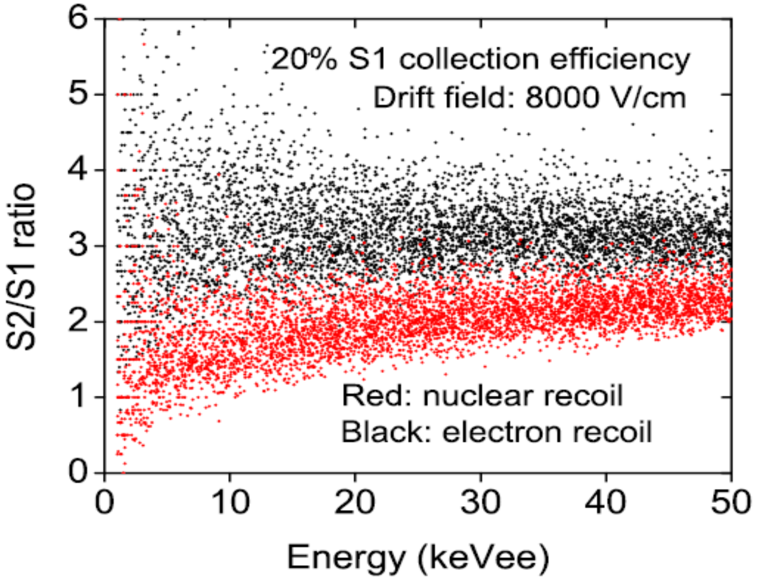
Liquid helium has lower electron scintillation yield for electron recoils (19 photons/keVee)

But, extremely high Leff, good charge/light discrimination and low nuclear mass for excellent predicted light WIMP sensitivity

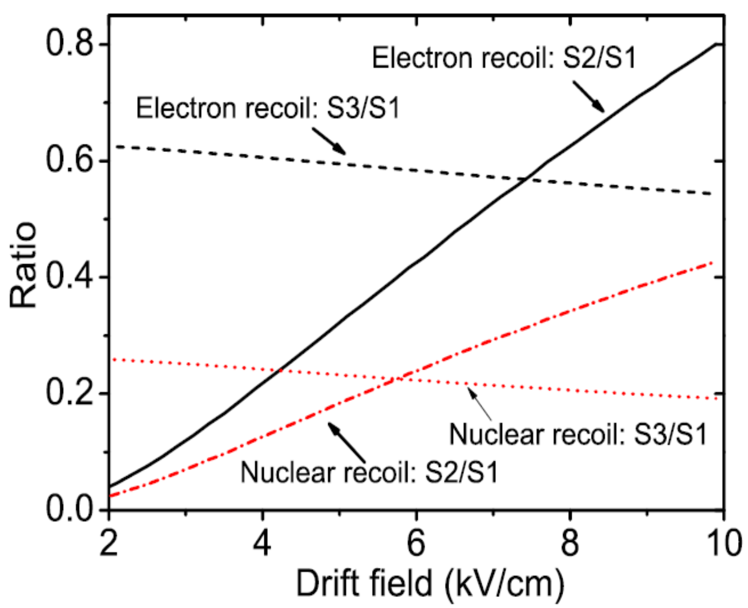


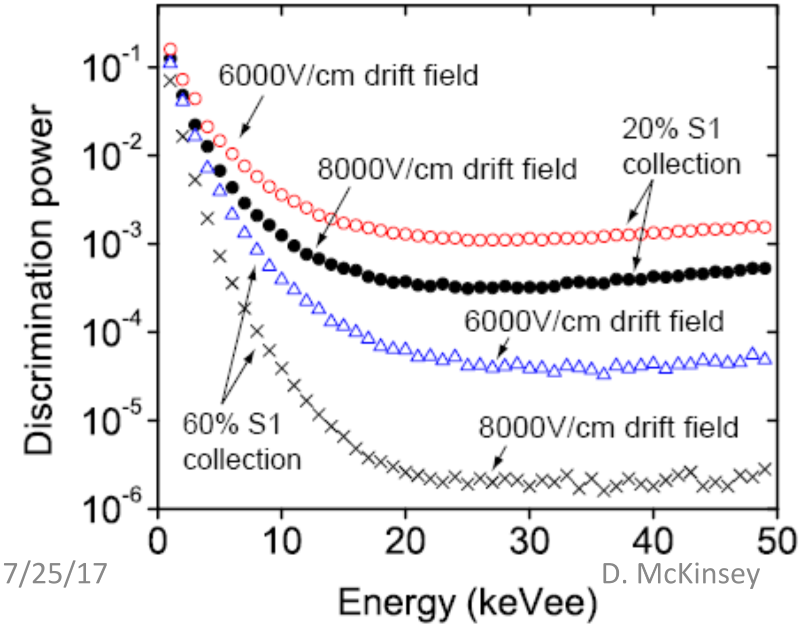


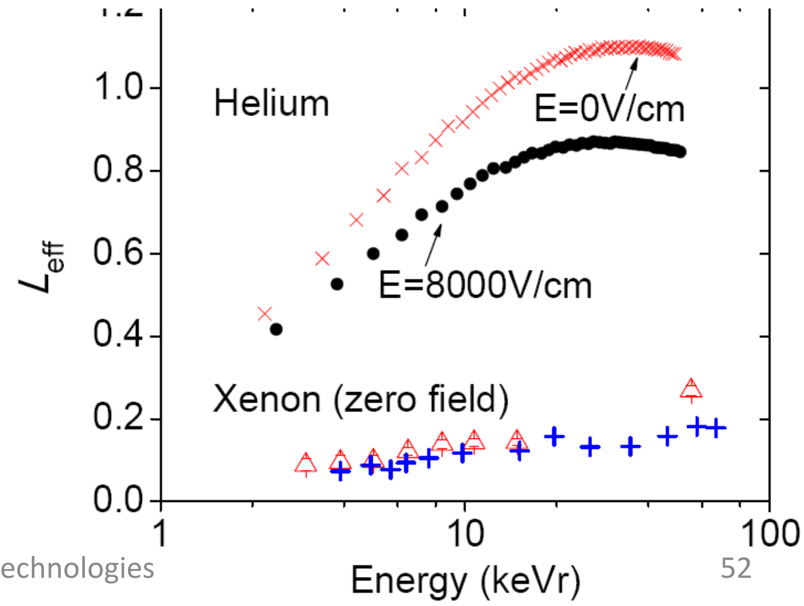
Predicted nuclear recoil discrimination and signal strengths in liquid helium



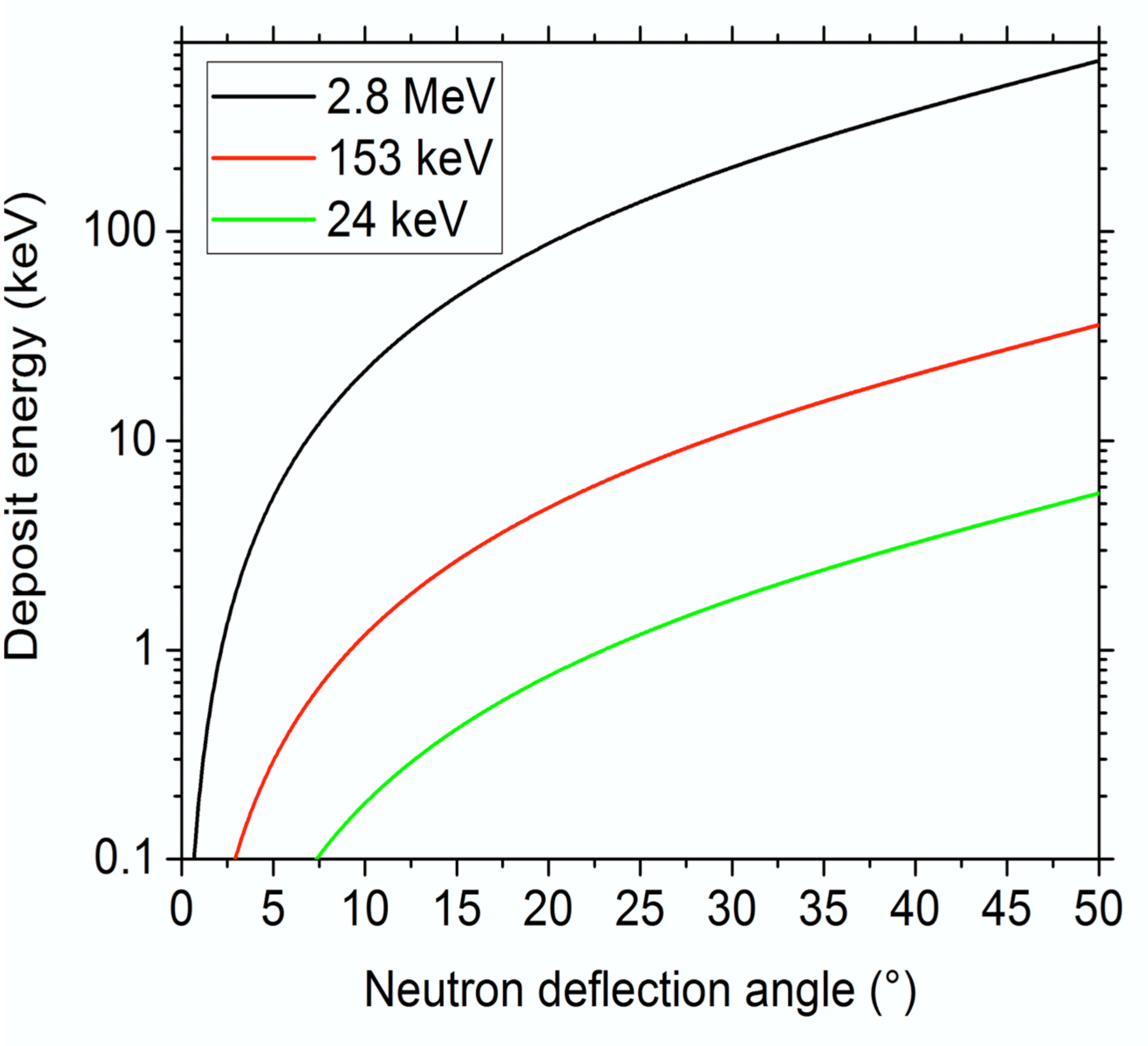
Event energy: 10 keV







Underway: Development of a NR light yield measurement



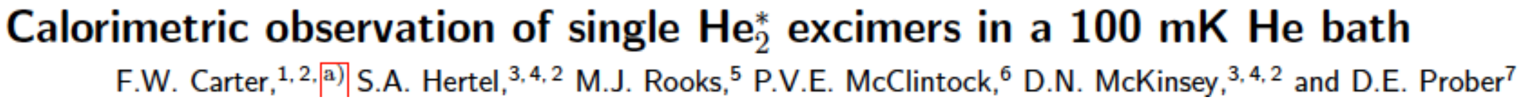
Scatter fast neutrons in LHe to measure light yield (as we have done previously in LXe, LAr, and LNe). This is yet to be measured in LHe!

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

How to detect triplet helium molecules?

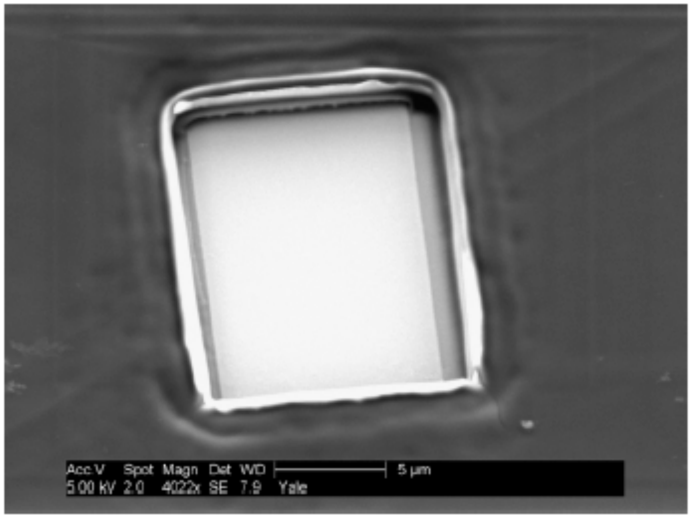
New demonstration: Transition Edge Sensor operated immersed in superfluid helium
See F. Carter et al, arXiv:1605.00694



Calorimetric observation of single He_2^* excimers in a 100 mK He bath

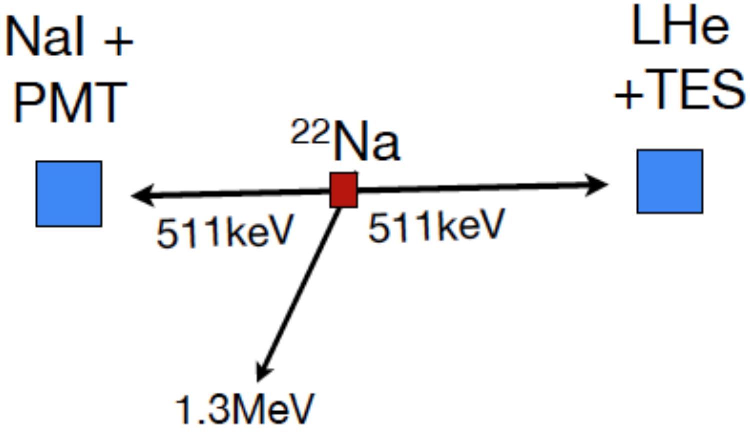
F.W. Carter,[1,2,a)] S.A. Hertel,[3,4,2] M.J. Rooks,[5] P.V.E. McClintock,[6] D.N. McKinsey,[3,4,2] and D.E. Prober[7]

The collection area here is just the transition edge sensor itself
Microscopic. One (max) excitation per recoil.



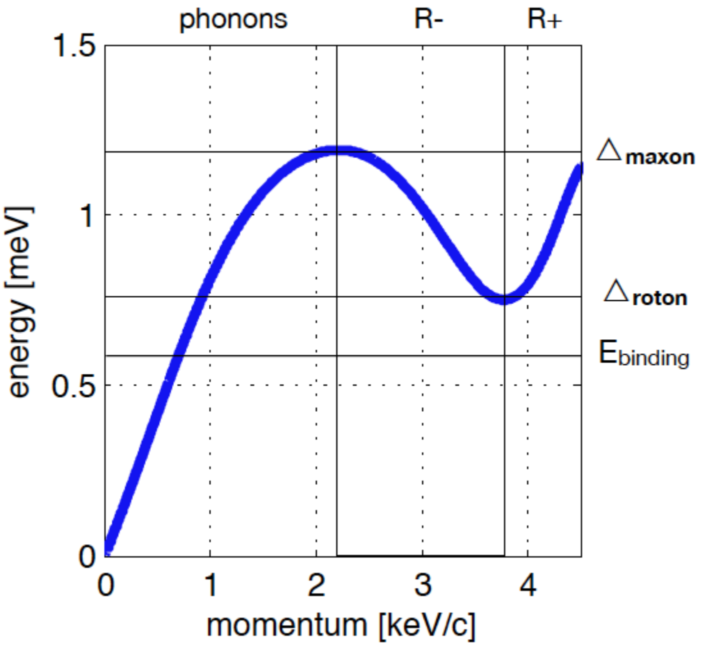
Coincidence: prompt singlet photon

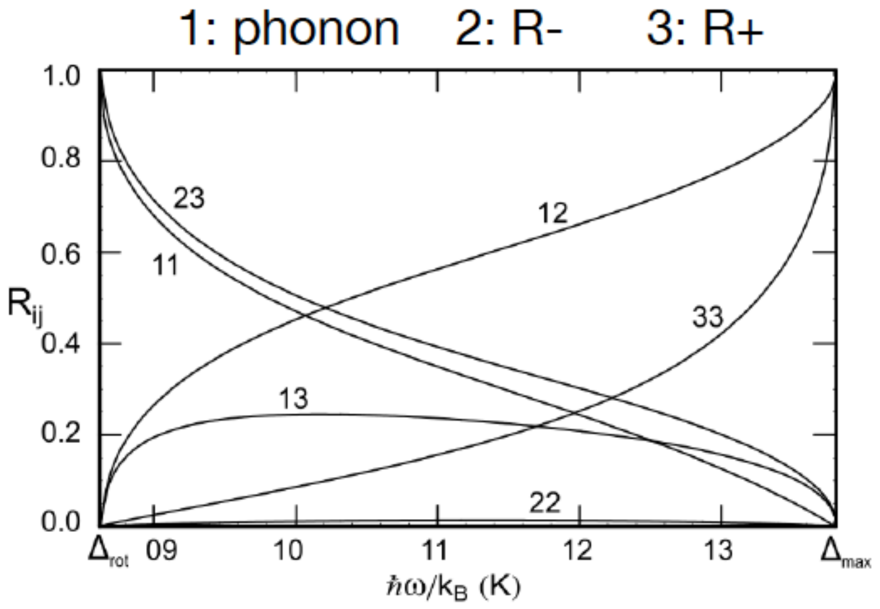
Non-coincidence: delayed triplet molecule (+untagged photons)

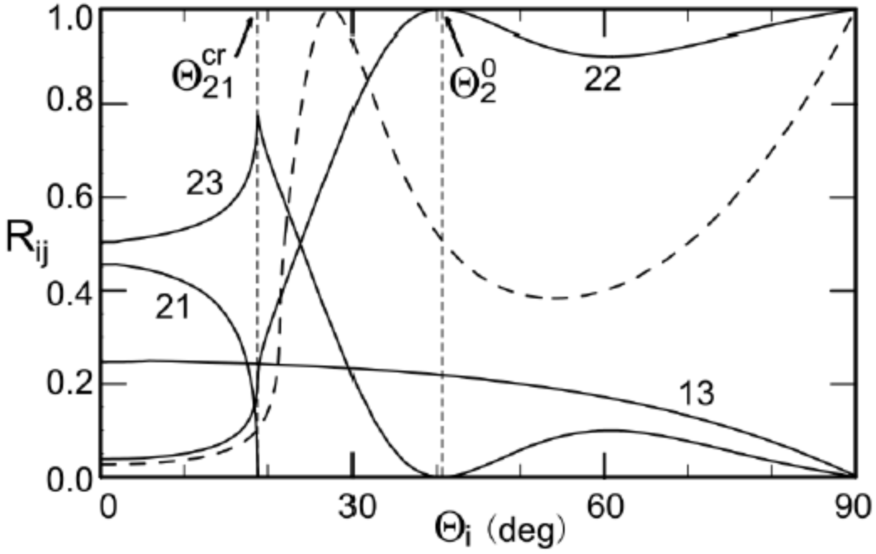


Phonon/roton reflectivities have complex energy and angular dependence

Tanatarov et al, arXiv:1004.3497v1





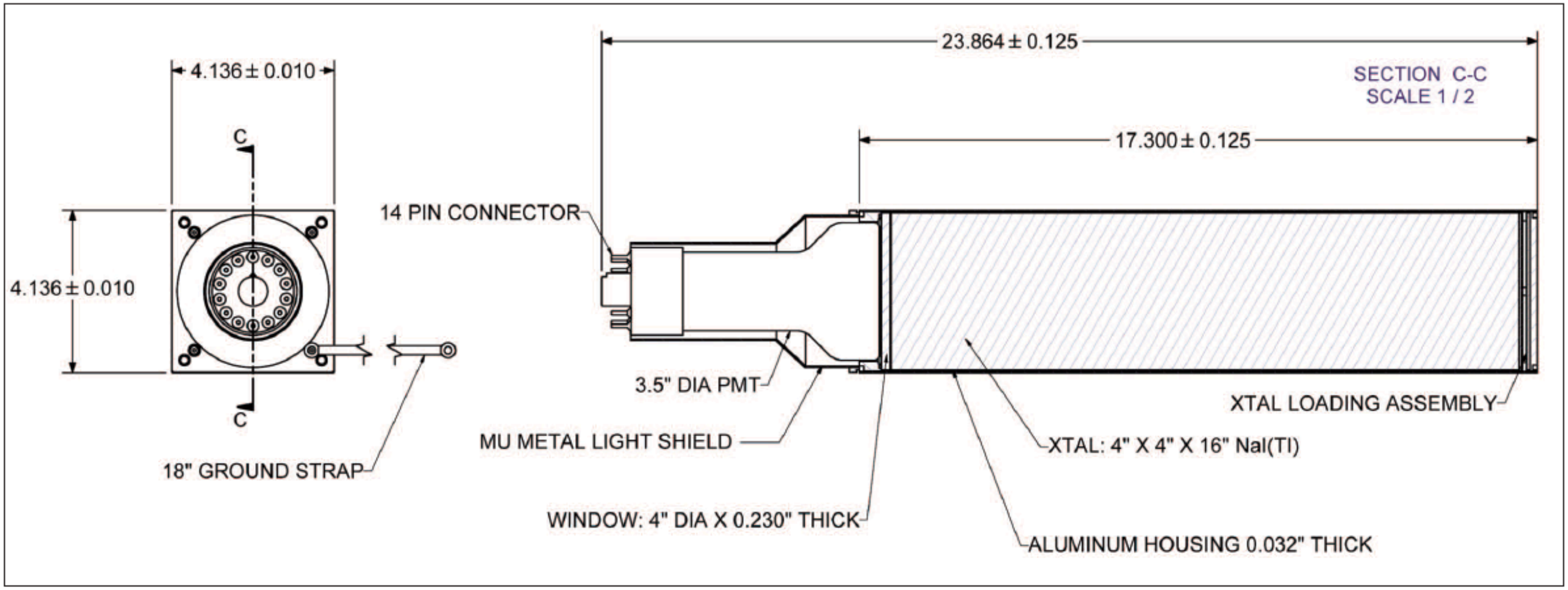


A mirrored box for heat collection

Analogy with light detectors, which collect scintillation light from a crystal or scintillating liquid, using a reflector around the scintillator to efficiently steer the light into a photomultiplier.

Here is a standard NaI detector, this one from Ortec:

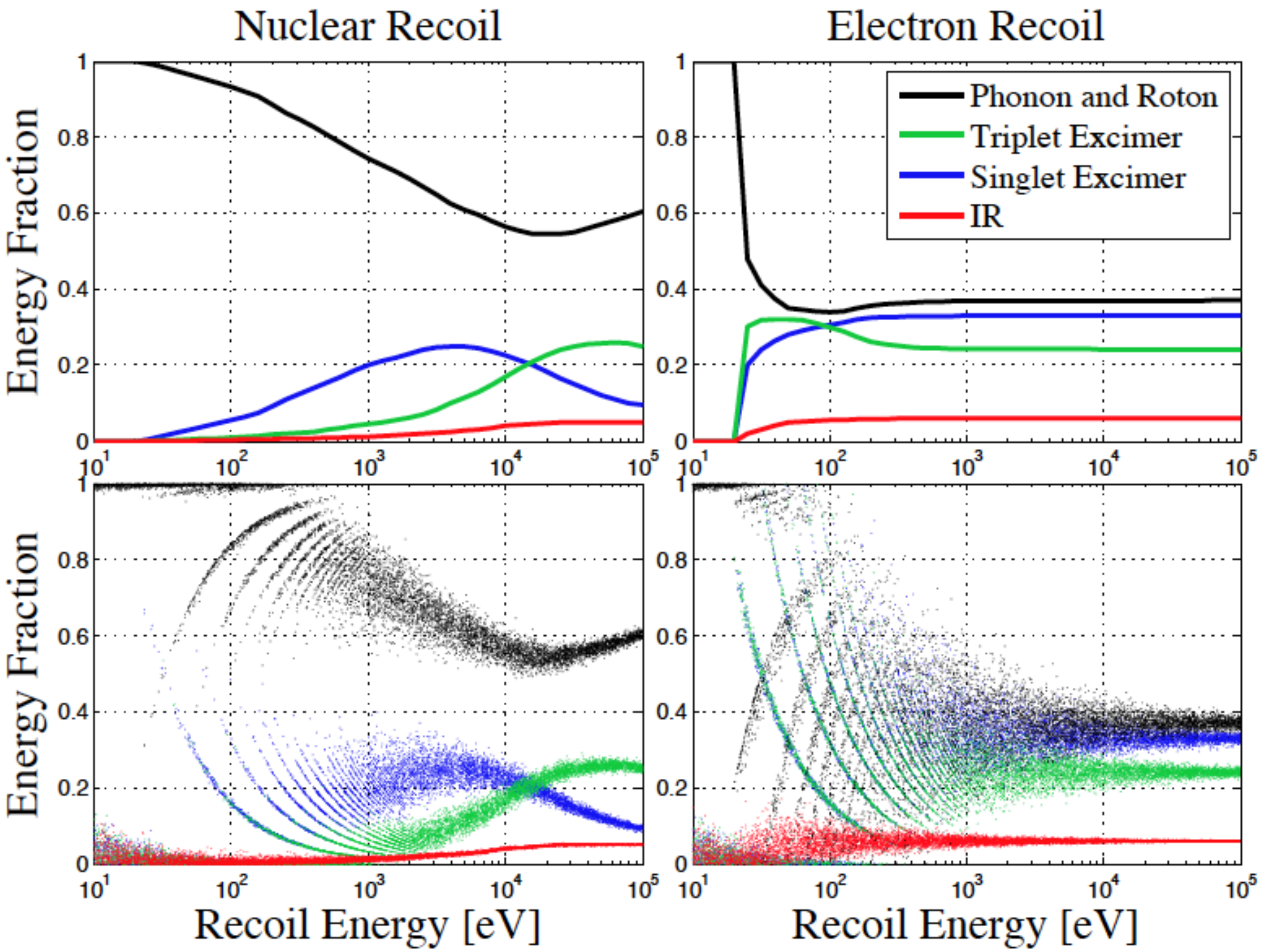
905-16 NaI Scintillation Detector, 4- x 4-in. crystal, 3-in. tube



Discrimination based on electronic excitation/heat ratio:

G. Seidel:

S. Hertel:



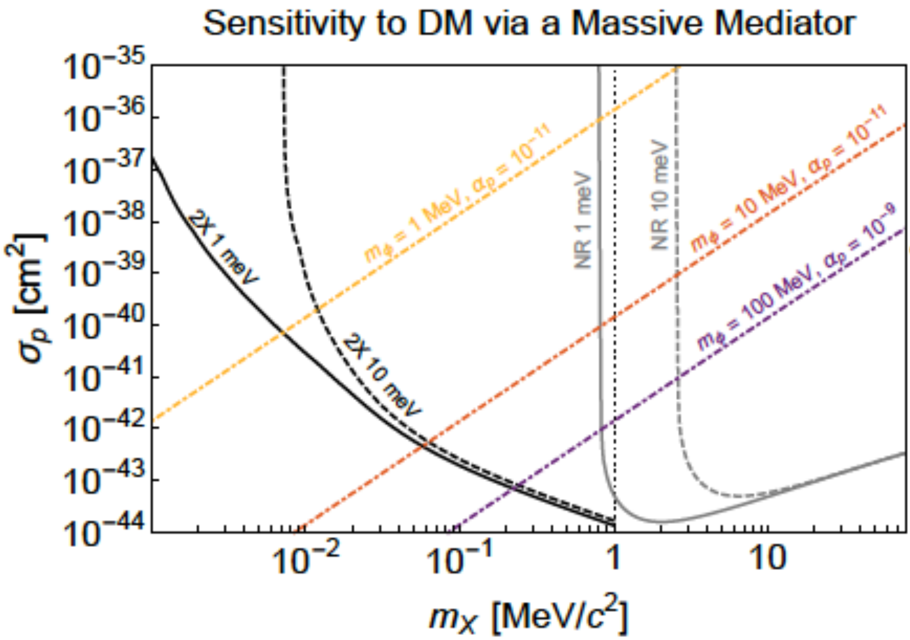
Discrimination without electronic excitations?

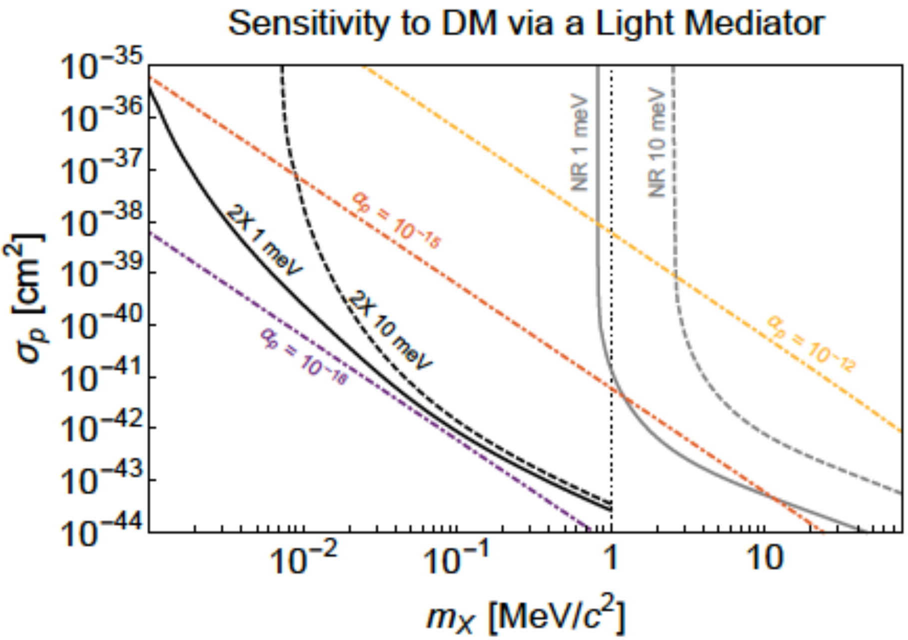
For very low energies, electronic excitations are heavily suppressed. Need to move to a scheme that doesn't rely on electronic excitations, only heat.

How to get particle identification without electronic excitations?

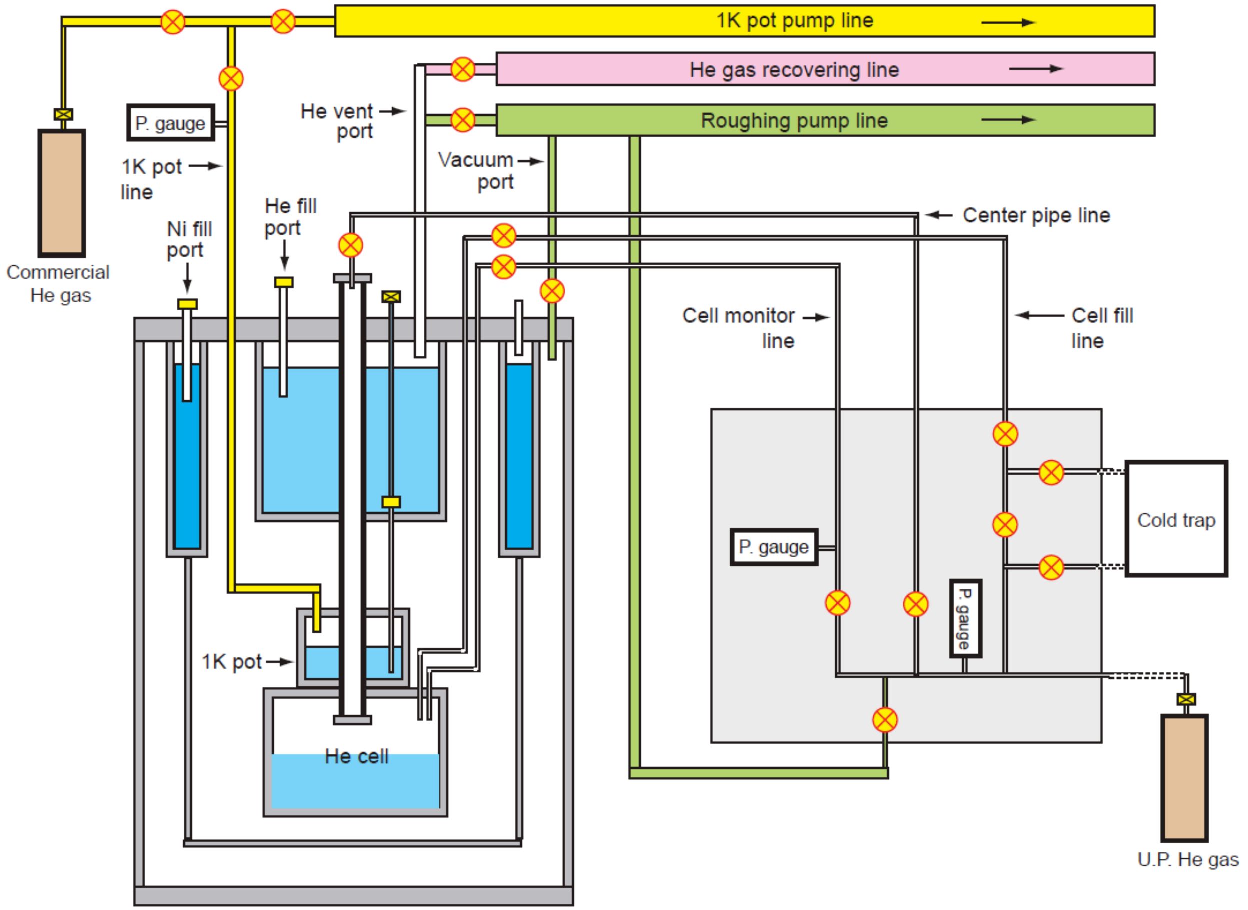
Possibly could look at roton/phonon ratio, or more generally the momentum distribution of the quasiparticles. Given that ER and NR have different dE/dx, it's quite plausible that they give different quasiparticle distributions. Higher dE/dx should result in a more thermalized (colder) quasiparticle distribution.

Projected sensitivity to keV-scale dark matter particles



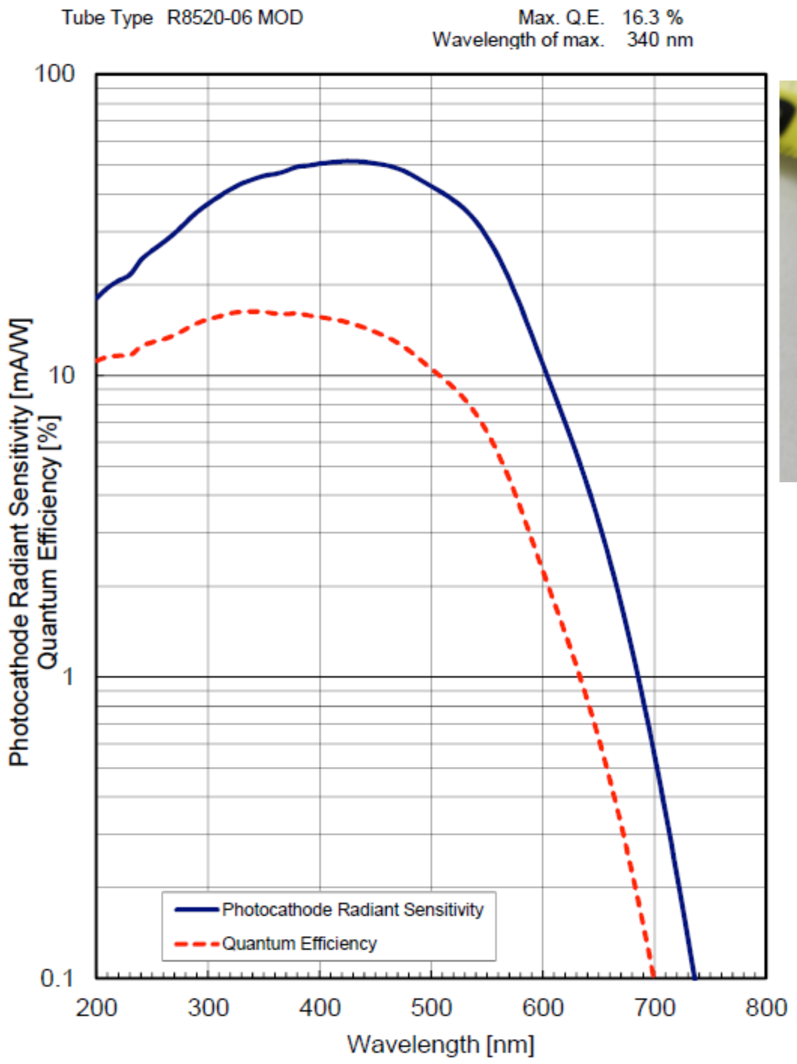


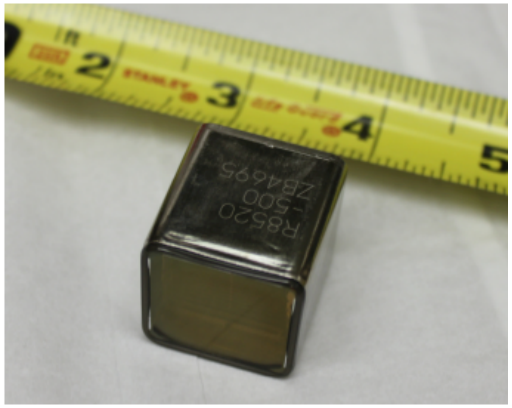
Liquid helium cryostat at UC Berkeley



- ➢ Cools down to ~1.5 K
  - o ^{4}He is superfluid below ~ 2.1 K
  - o ^{4}He scintillation normal versus superfluid

Light detection with PMTs, operating in superfluid helium





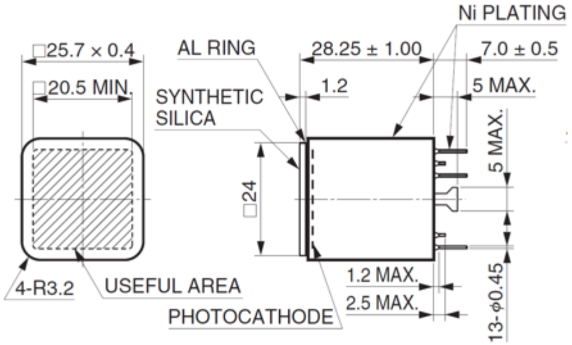
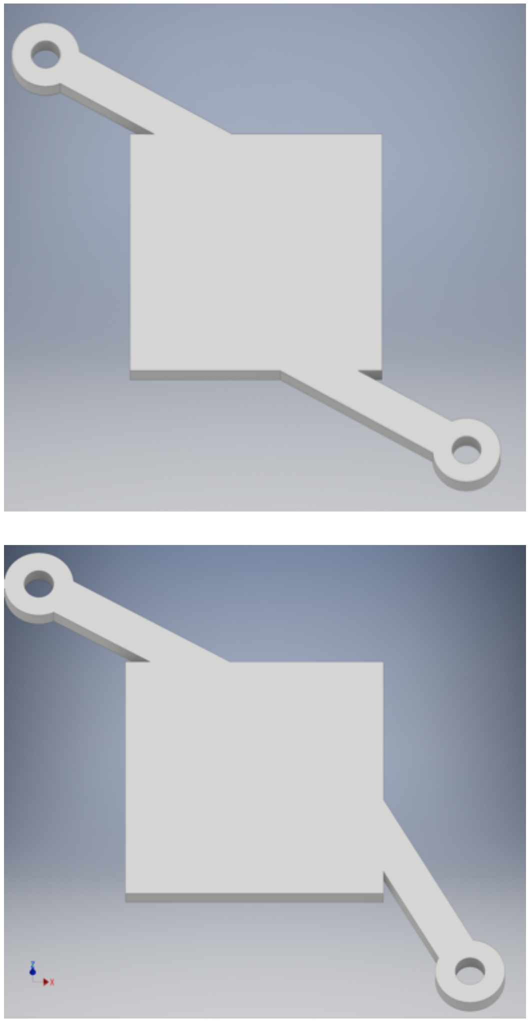
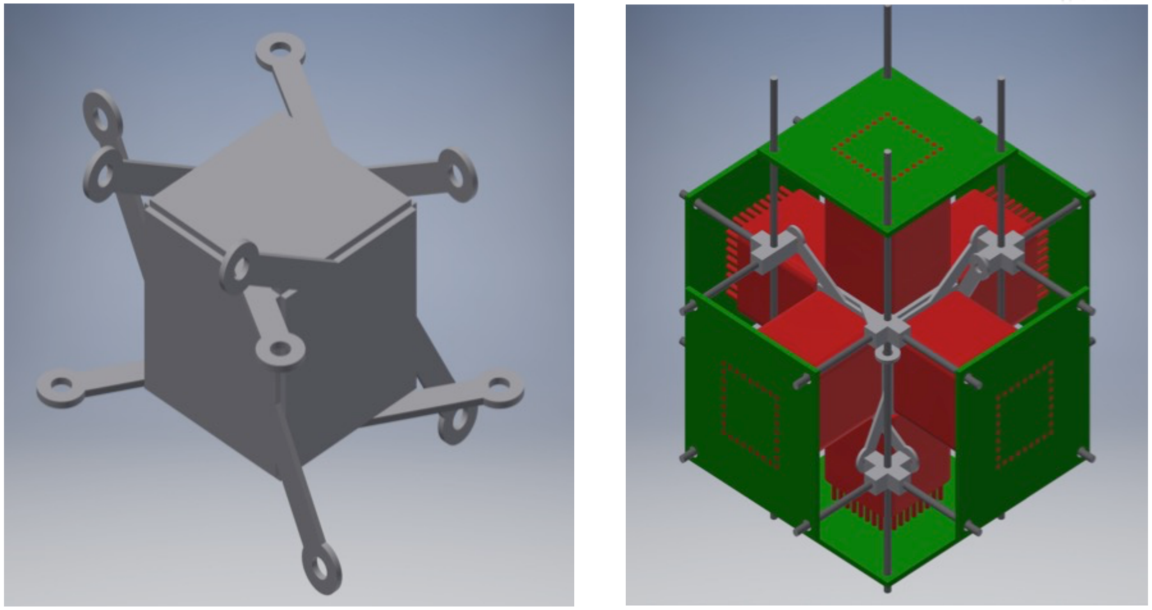


Figure 3: Dimensional outline (Unit: mm)

- ➢ 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

Helium cell design





- ➢ Mechanical mounting for the panel with TPB deposited
- ➢ A cube has 8 vertices, 6 panels × 2 = 12.
  - ○ 8 < 12. Cannot use diagonal. Off-diagonal design.
- ➢ Thickness of panels
  - ○ 0.5 mm in PMTs in helium scenario
  - ○ 2 mm in PMTs in vacuum scenarios

How low of an energy can be probed?

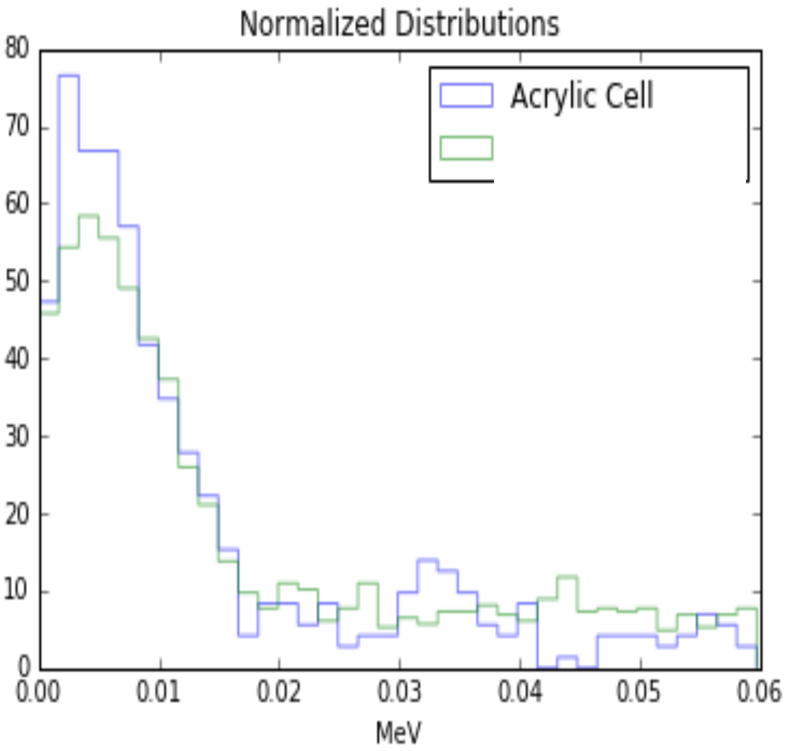
	Electron recoil (excited by electron)	Nuclear recoil (excited by neutron)
Light yield (photons/keV)	22	9 @ ~1 keV_{nr} (predicted prompt section, Ito 2013)
TPB conversion efficiency	1.35	
Light collection efficiency	0.5	
PMT quantum efficiency	0.14	
Photoelectrons/keV	2.1	0.85

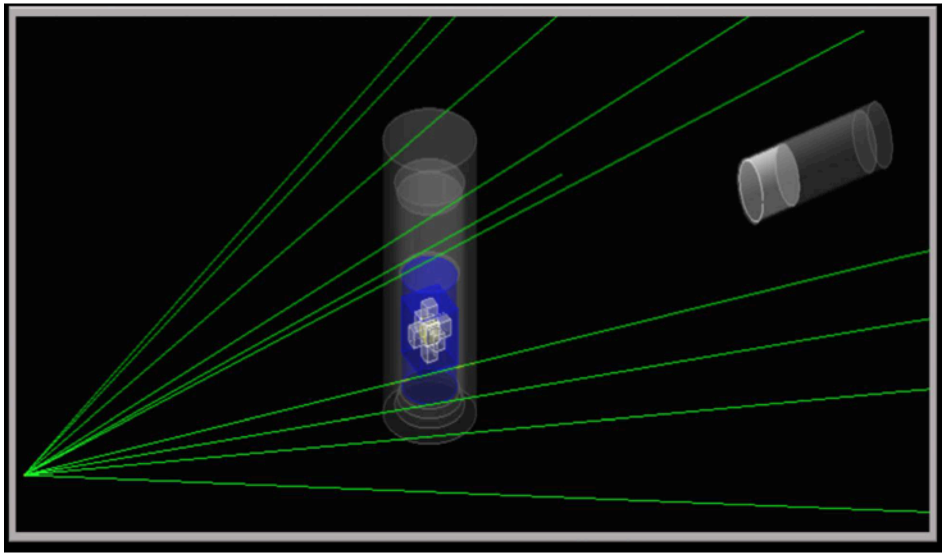
Aim for a few keVnr with this setup. The next experiment will use transition edge sensor readout at < 100 mK temperatures, with ~ 100% quantum efficiency.

Simulations

PMTs in liquid helium (submerged) or in vacuum

- Submerged scenario: More dead helium, thinner acrylic panel
- Vacuum scenario: Less dead helium, thicker acrylic panel





- No big difference in recoil spectrum
- Technically easier to implement design with PMTs submerged in liquid helium.