Low Mass Dark Matter Searches

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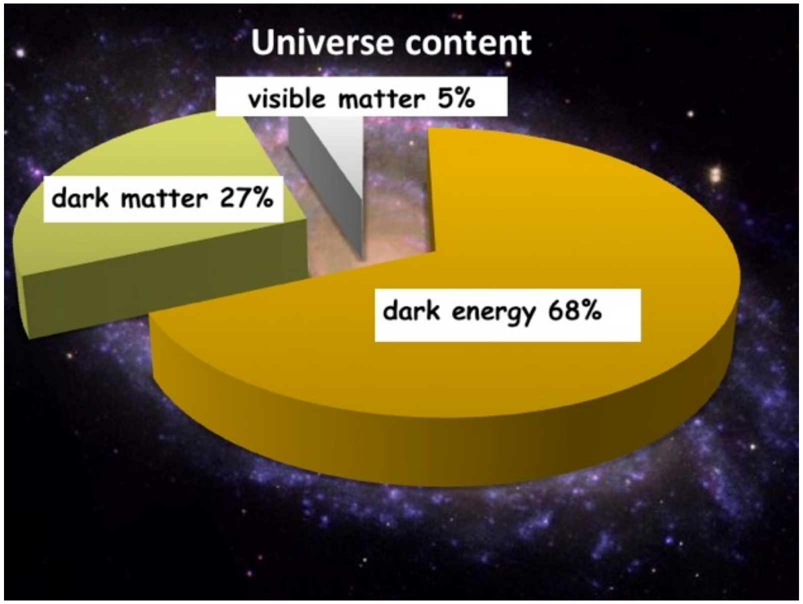
Composition of the Universe

The Higgs particle has been discovered, the last piece of the Standard Model.

But as successful as it has been, the Standard Model describes only 5% of the universe. The remaining 95% is in the form of dark energy and dark matter, whose fundamental nature is almost completely unknown.

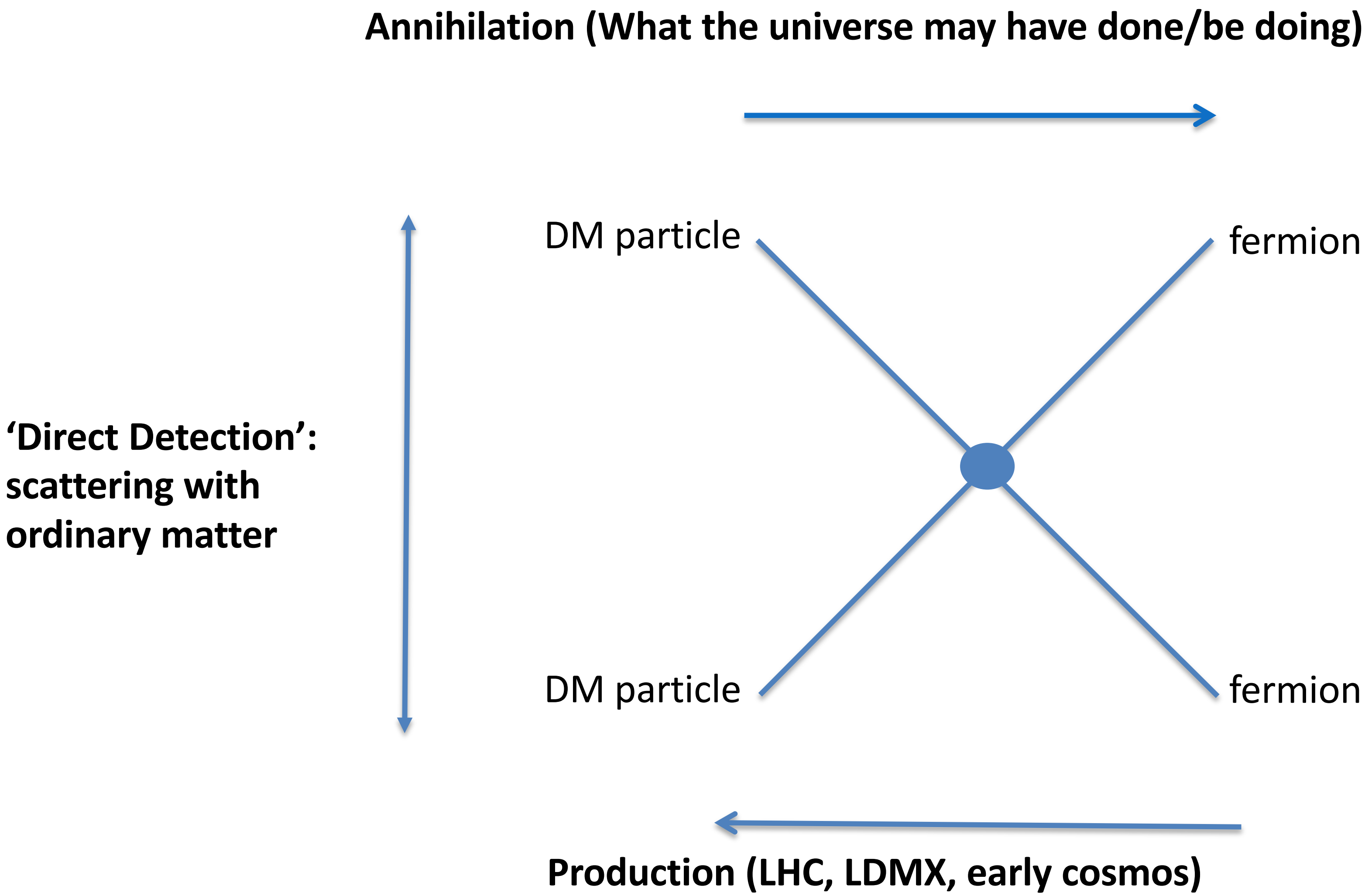
Discovery of the fundamental interactions and mass of the dark matter would likely provide important clues about the physics beyond the Standard Model. This may in turn lead us to learn new principles by which the Universe operates.

Image: X-ray: NASA/CXC/CfA/M.Markevitch et al.;
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.



www.quantumdiaries.org

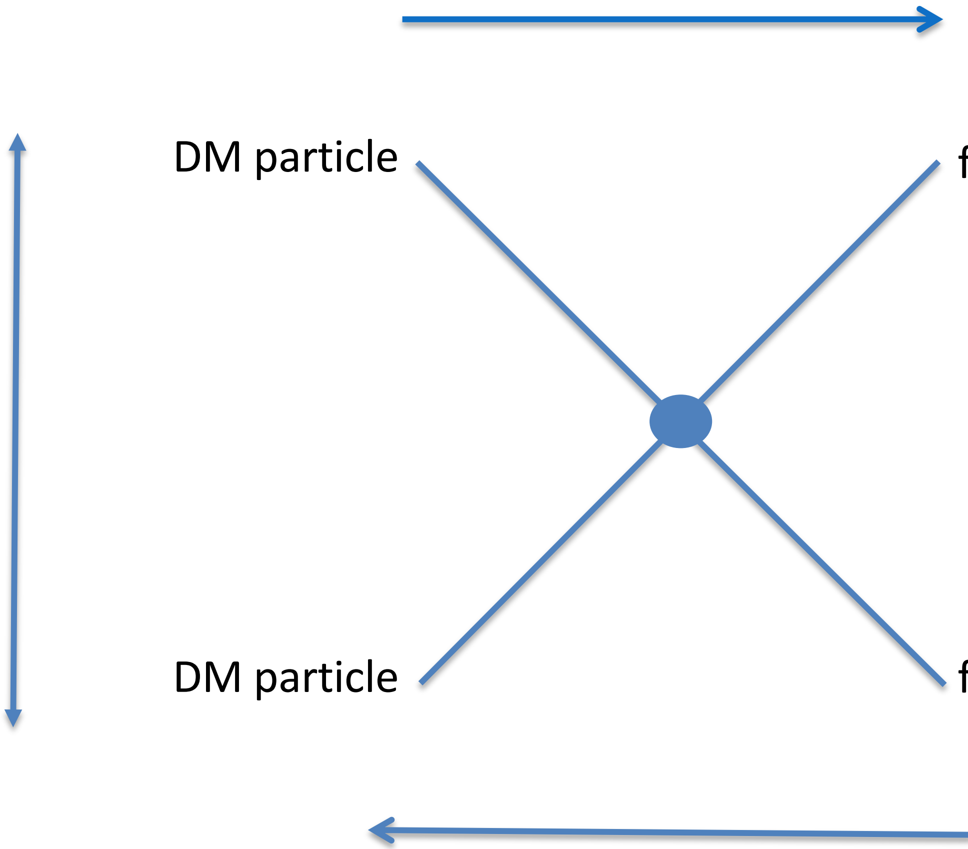
Dark matter interactions with ordinary matter



Dark matter interactions with ordinary matter

Annihilation (What the universe may have done/be doing)
(see next plenary talk by M. Cirelli)

'Direct Detection': scattering with ordinary matter
(this talk, upcoming plenary talk by B. von Krosigk)



Production (LHC, LDMX, early cosmos)
(See plenary talks by S. Passaggio, F. Kling, Y. Abulaiti

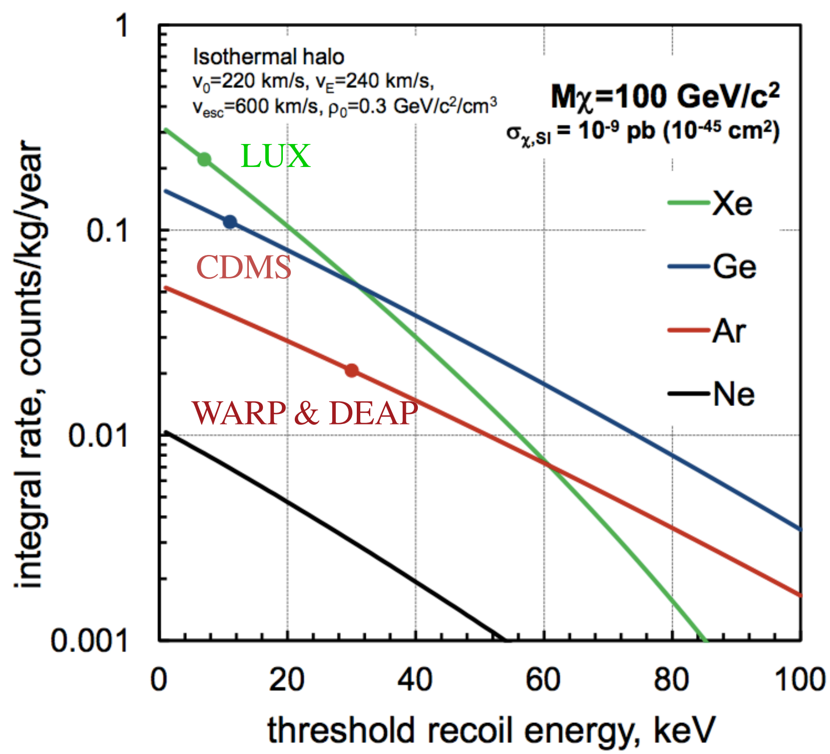
Weakly Interacting Massive Particle (WIMP) Direct Detection

Look for anomalous nuclear recoils in a low-background detector.

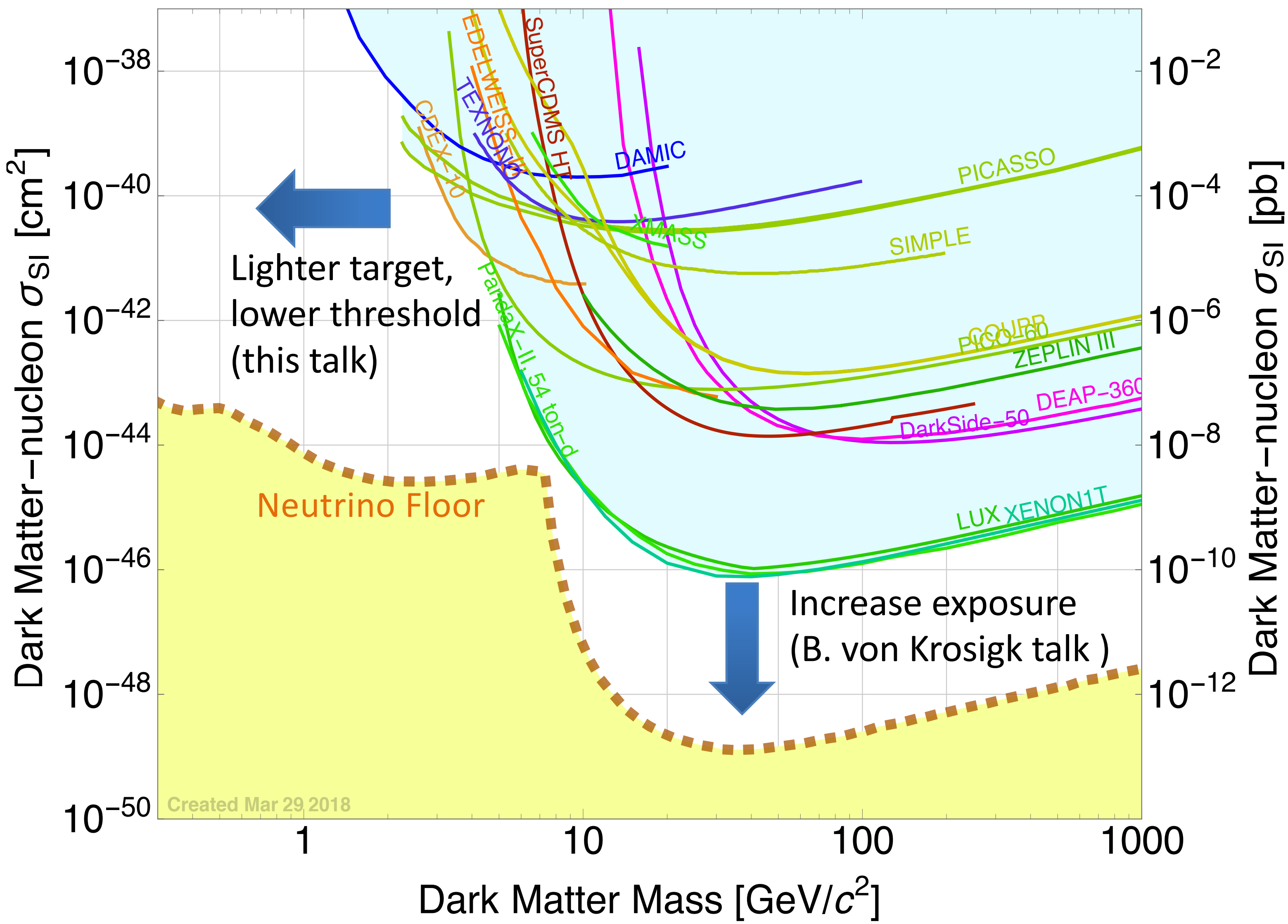
$R = N \rho <\sigma v>$. From <v> = 220 km/s, get order of 10 keV deposited.

Requirements:

- Low radioactivity
- Deep underground laboratory
- Low energy threshold
- Gamma ray rejection
- Scalability



Dark Matter Nuclear Recoils: Future Directions

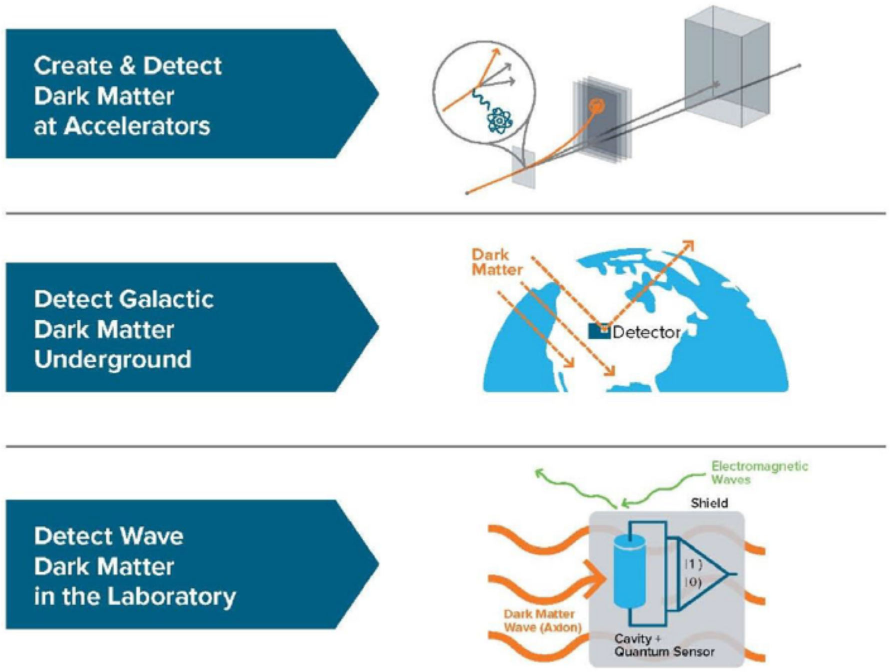


US DOE High Energy Physics Basic Research Needs Study for Dark Matter Small Projects

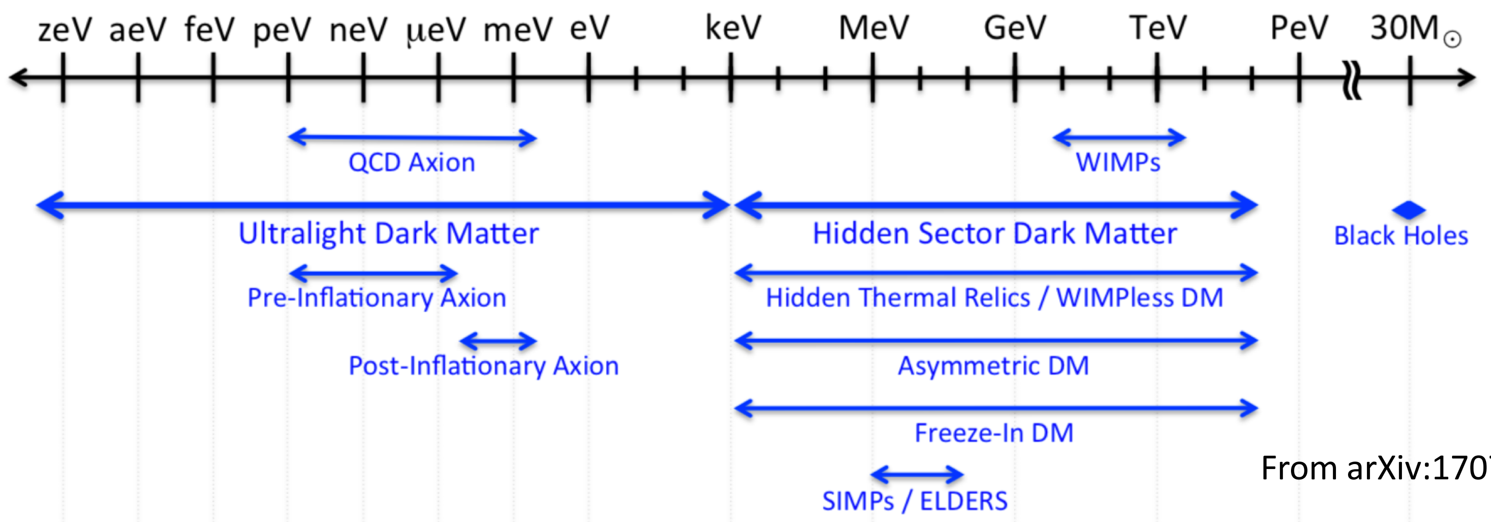
- Workshop held in Washington DC, Oct 15-18, 2018
- Resulted in a report to the Dept of Energy, "Basic Research Needs for Dark Matter Small Projects New Initiatives".

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."*

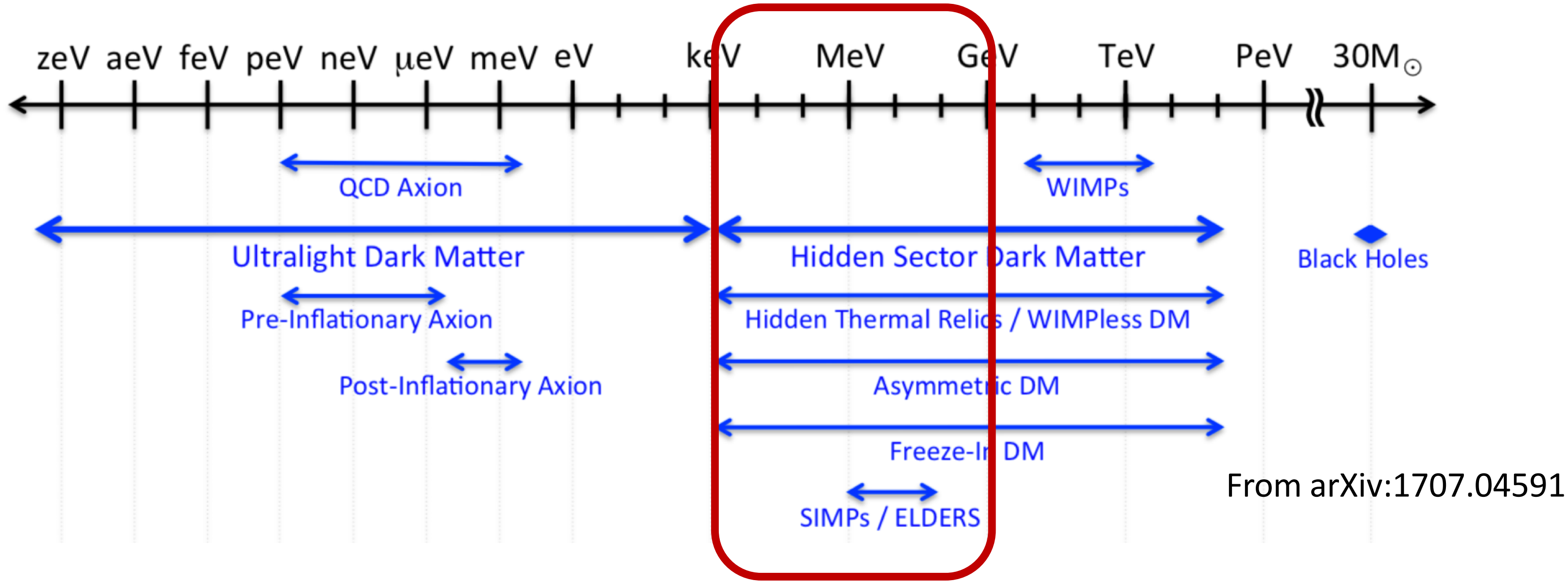


Dark Matter allowable mass range



From arXiv:1707.04591

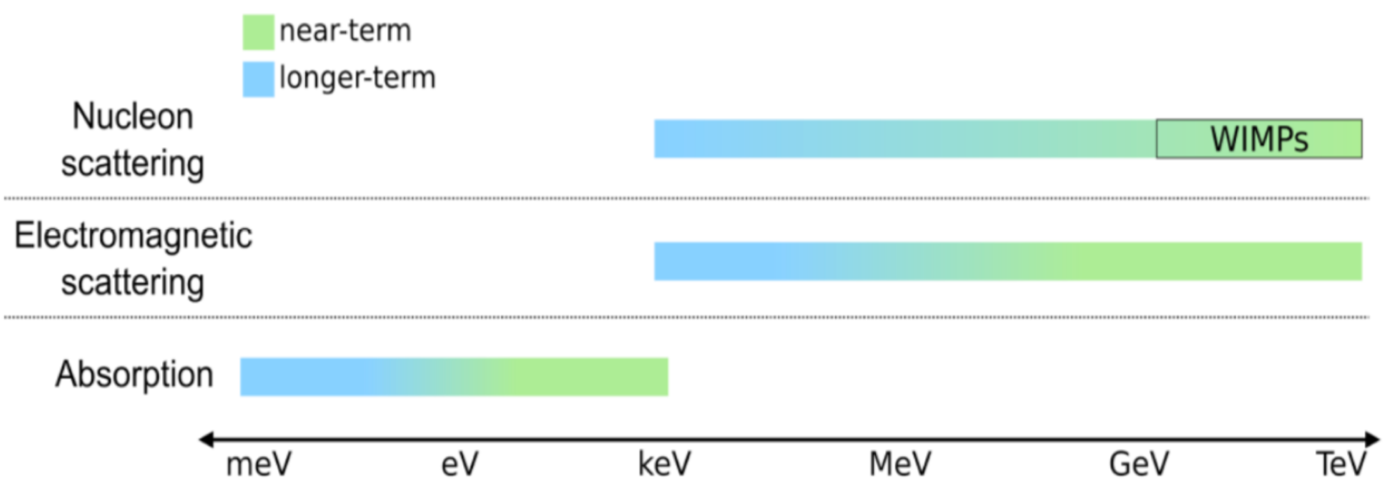
Dark Matter allowable mass range



- Unlike WIMPs, composed of particles that interact through the SM weak interactions, the dark matter sector may be instead disconnected from the visible one.
- See summary and references in M. Battaglierei et al., arXiv:1707.04591 .
- General symmetry arguments allow several types of "portal" interaction between generic hidden sectors and the Standard Model, which can be generated by radiative corrections.
- These modest couplings can play a key role in realizing the dark matter abundance, through several possible mechanisms. These include:
  - Determining the DM abundance via **thermal freeze-out** (like in the standard WIMP paradigm)
  - Depleting a thermal component in **Asymmetric DM**
  - Mediating the production of DM from a bath of SM particles in **freeze-in** scenarios
  - Maintaining kinetic equilibrium while hidden-sector dynamics depletes the DM number density **(SIMP/ELDER**)

Dark Matter interaction types

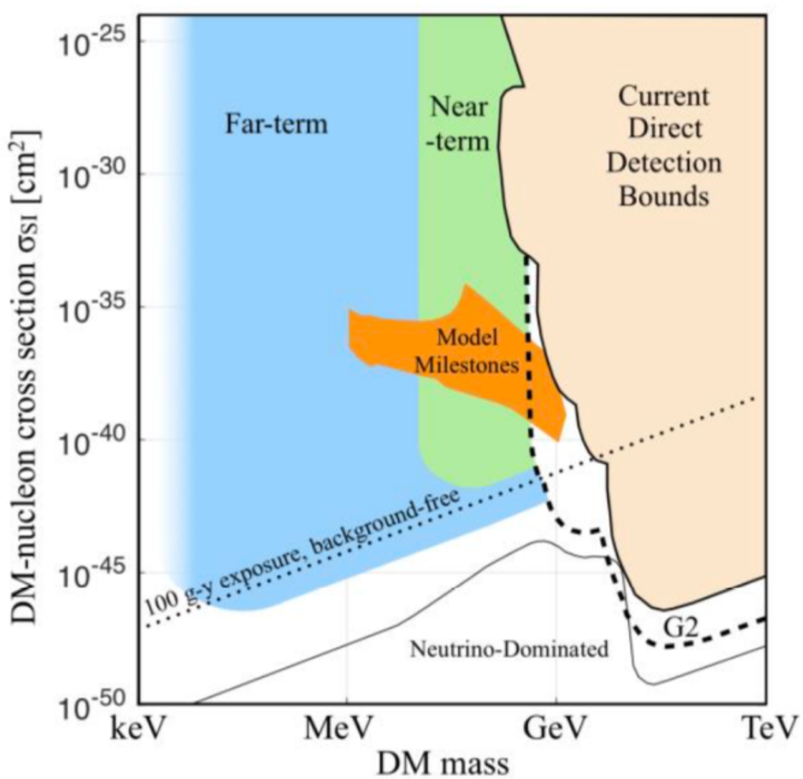
- The dark matter theory landscape has evolved in new directions in the last decade, emphasizing the need to probe non-WIMP dark matter candidates with a mass below about 1 GeV.
- Sharp theory targets exist in which dark matter interacts only with baryons or only with leptons, emphasizing the need for experiments that probe dark matter couplings to electrons *and* experiments that probe dark matter couplings to nuclei.
- ER: dark photon mediator or vector coupling predominantly to leptons
- NR: dark photon mediator, vector coupling predominantly to quarks, or scalar coupling



From BRN report

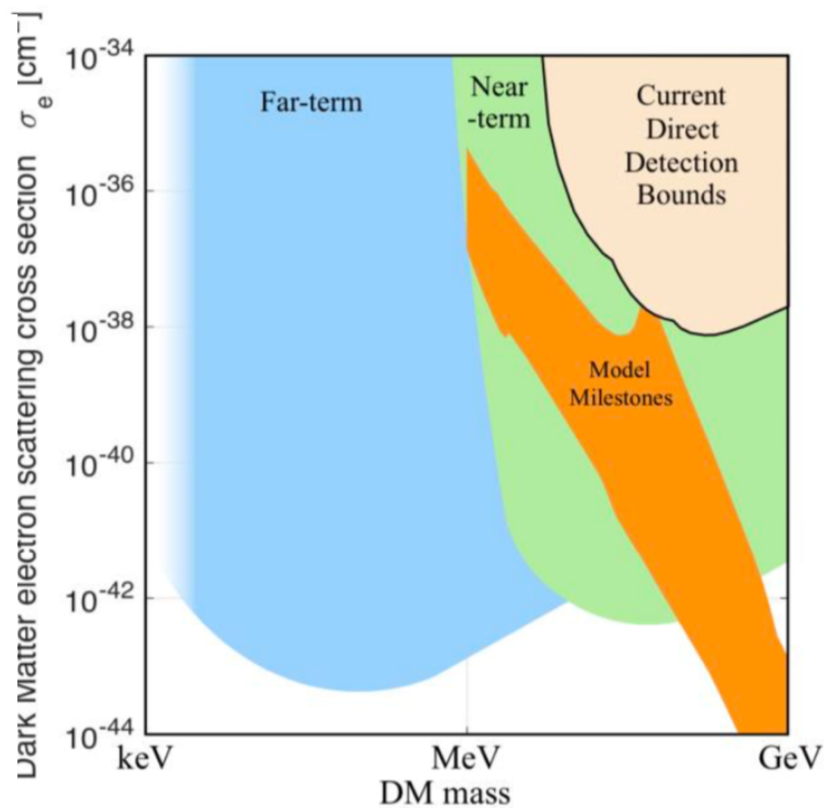
Dark Matter interaction types

DM - nuclear recoil (NR) interactions



DM - electron recoil (ER) interactions

HEAVY MEDIATOR



From BRN report

Outline

- Introduction
- Direct Detection of sub-GeV dark matter
- Experimental survey

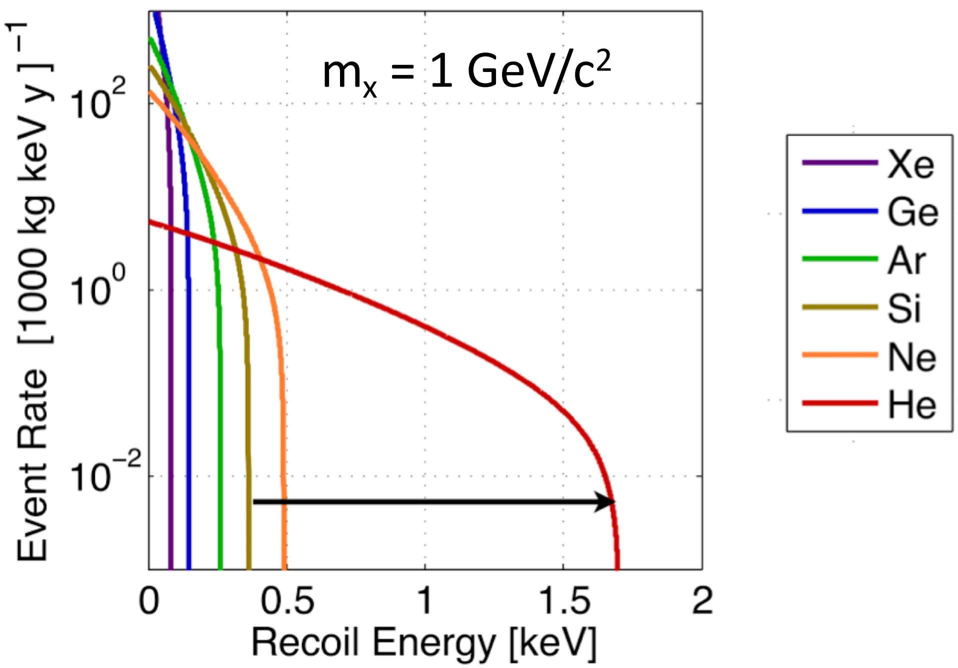
Light target nuclei and low energy thresholds for NRDM

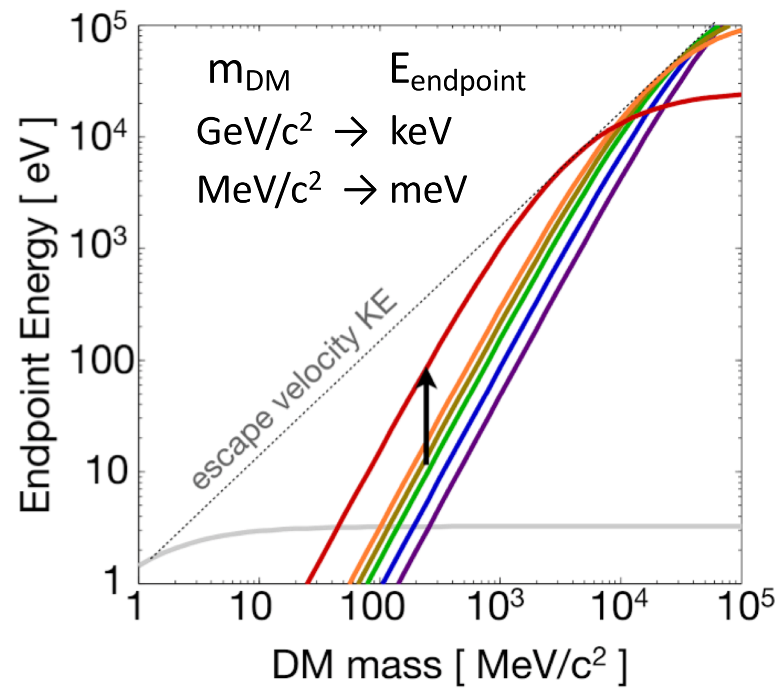
With sufficiently low threshold and/or a light target, lower dark matter masses may be probed.

Current thresholds are on the 10 eV scale**. Not the keV scale of tonne-scale direct detection experiments!**
Heading toward meV energy thresholds -> the topic of ongoing and future R&D.

This low threshold is challenging! But as in WIMP searches, searching for nuclear recoils continues to benefit from significant advantages including

a) Coherent enhancement of dark matter – nucleus scattering cross-sections
b) Gamma-ray and beta-decay background rejection through signal ratios
c) Relatively low nuclear recoil background (neutrons)

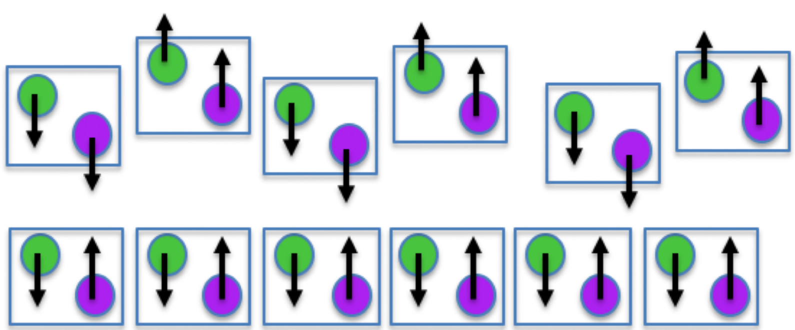


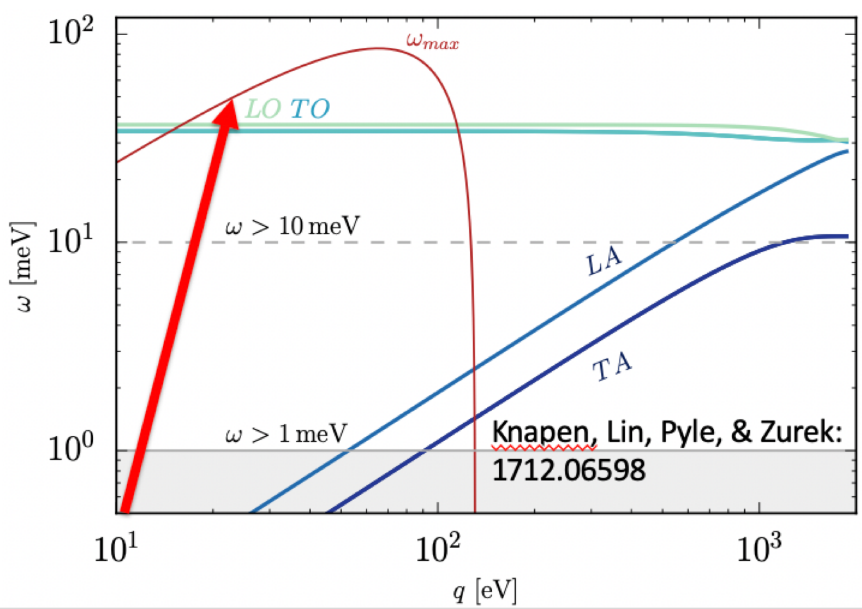


Coherent Excitations for ERDM

Coherent excitations:

- Vibrational energy scale in crystals is O(100 meV)
- For dark matter masses < 100 MeV, we can't use the simplifying approximation that the nucleus is free.
- DM scatters coherently with the entire crystal, producing a single phonon.
- The kinematics of optical phonon production are favorable; due to their gapped nature, all of the kinetic energy of the DM can potentially be used for phonon creation.
- Optical phonons modulate the electric dipole in polar crystals, so they have strong couplings to IR photons, and thus by extension, all DM models that interact through a kinematically mixed dark photon.





Low Bandgaps for ERDM

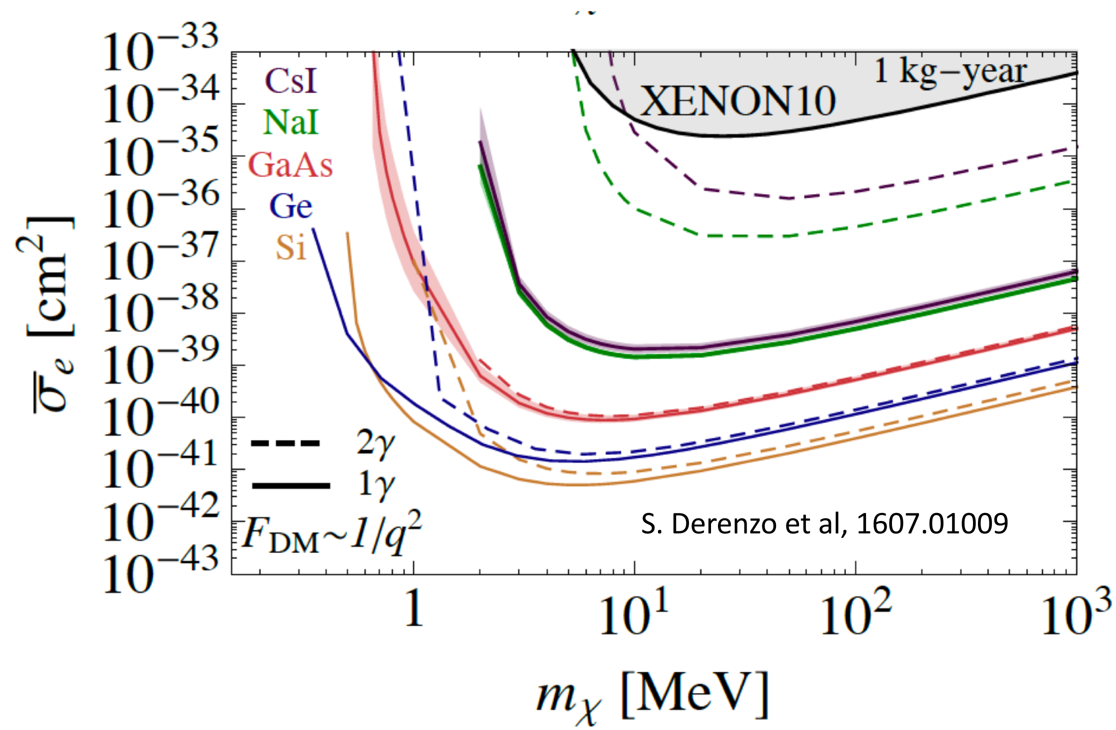
Low bandgaps:

- Just as with optical phonons, the gapped nature of an electronic excitations in semiconductors allows them to maximally extract kinetic energy when scattering with or absorbing DM.
- Due to a strong rate dependence upon energy, low bandgap semiconductors like Ge, Si (SENSEI and SuperCDMS HV), and GaAs (SPICE) are the preferred target candidates.

With GaAs one can collect both photons and phonons!

Can allow background rejection through phonon/photon ratio

Also, photon-photon and phonon-phonon coincidence should reduce instrumental backgrounds isolated to a single sensor.



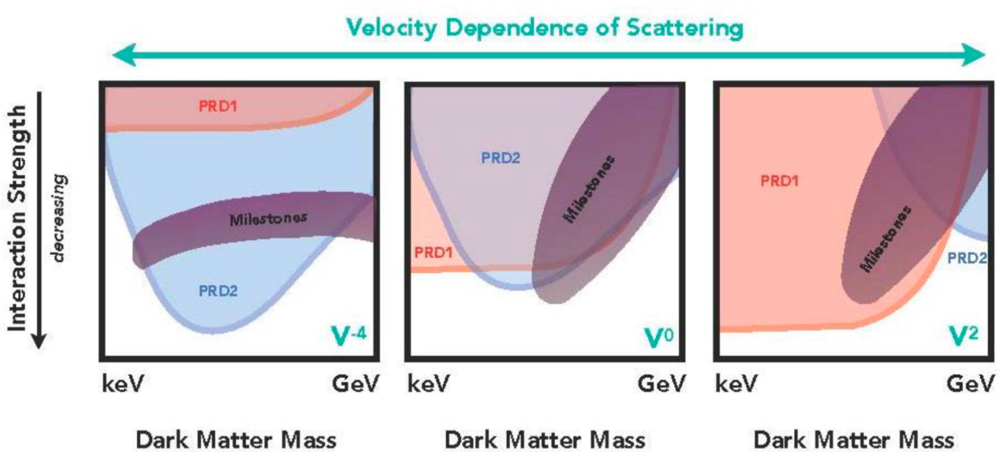
Complementarity with accelerator-based experiments

Direct detection and accelerator-based approaches are complementary (See the BRN and the Cosmic Visions white paper,

- Accelerator approaches are potentially able to produce and study dark sector particles that aren't DM. Thus, even if dark sector candidates were discovered using an accelerator approach, the scientific community would want to confirm that the particle was DM.
- Direct detection and accelerator approaches also have complementary model sensitivities. Since direct detection involves small momentum transfer *q* in the interaction, while accelerator based approaches naturally have larger *q*, dependence of the overall DM interaction rate on *q* will preferentially benefit one technique. For example, dark sectors that couple through a light mediator will yield interaction cross-sections that scale as q^{-4}, enabling high rates in direct detection experiments.

Ex: dark matter scattering with free electrons:

$$\sigma_{\rm scatter} = \frac{16\pi\alpha_e\alpha_X}{(m_\phi^2+\mathbf{q}^2)^2}\mu_{eX}^2$$

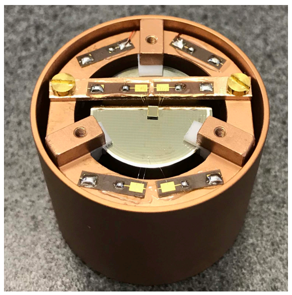


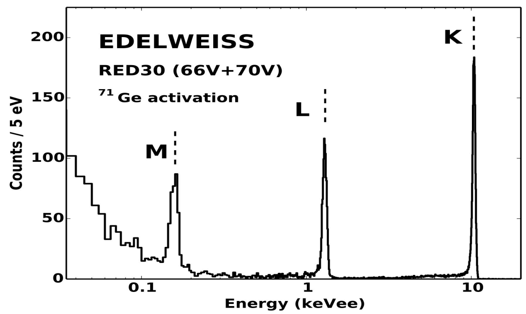
Direct detection: DM flux enhanced for low mass DM

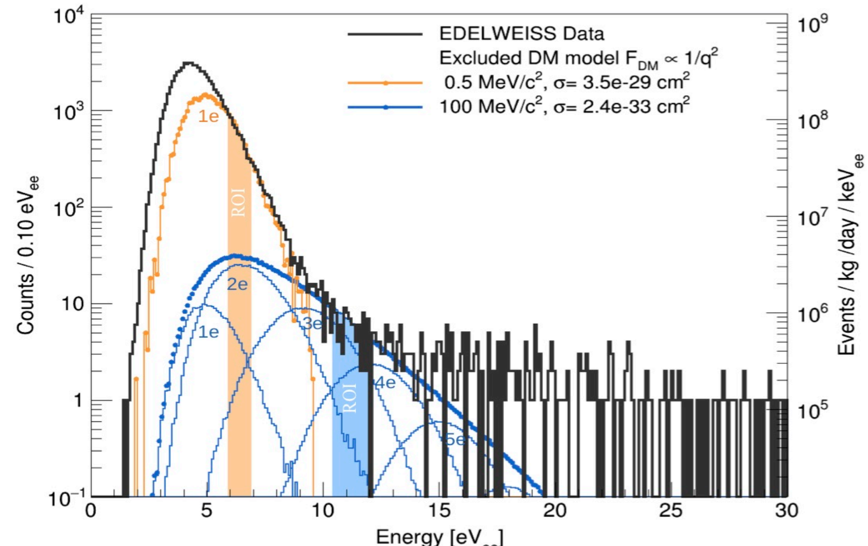
$$R = \sigma n_{DM} N_{exp}$$
$$= \sigma\frac{\rho_{DM}}{M_{DM}}N_{exp}$$

EDELWEISS Sub-GeV Dark Matter Searches

- Heat-and-Ionization Ge for direct searches of Dark Matter in the eV-GeV mass range, with particle ID
- 2019-2020: **33 g Ge detector at LSM** biased at 78V, **with single-electron sensitivity**

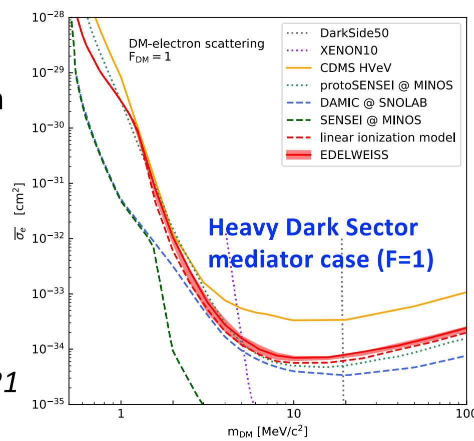


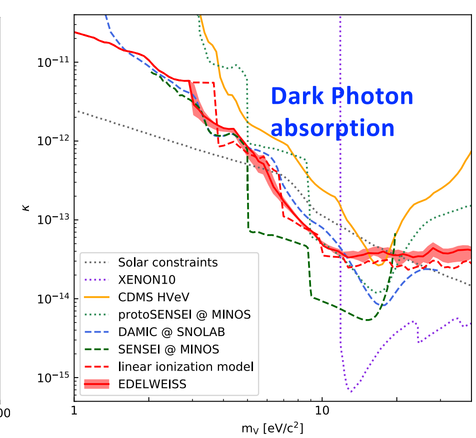




[PRL 125, 141401 (2020)]

- First Ge cryo detector with **sub-electron resolution (s = 0.53 electron-hole pair)**
- First Ge detector sensitive to **sub-MeV DM interaction with e$^-$** + 1-eV Dark Photons
- ***Synergy with RICOCHET: kg-scale array with evt-by-evt nuclear recoil ID down to 50 eV***
- ***New CRYOSEL R&D: electron tag using TES*** *(cf LTD19 conference)* ***to tag Heat-Only background*** *(cf EXCESS2021 workshop)*





Coming physics paper: Migdal searches

NEWS-G: Sub-keV dark matter search using Spherical Proportional Counter

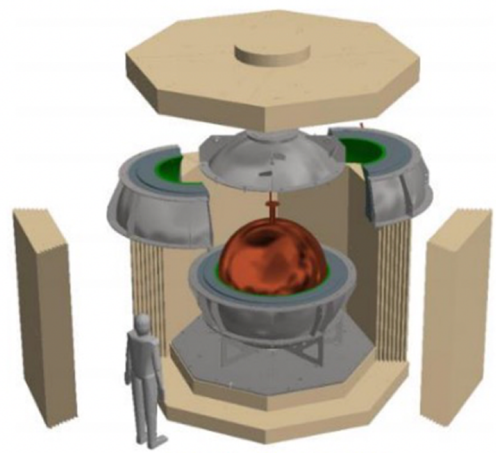
2019: Commissioning run with pure CH_4 of the experiment at the Laboratoire Souterrain de Modane.

First WIMP-proton cross-section limits SI and SD under preparation.

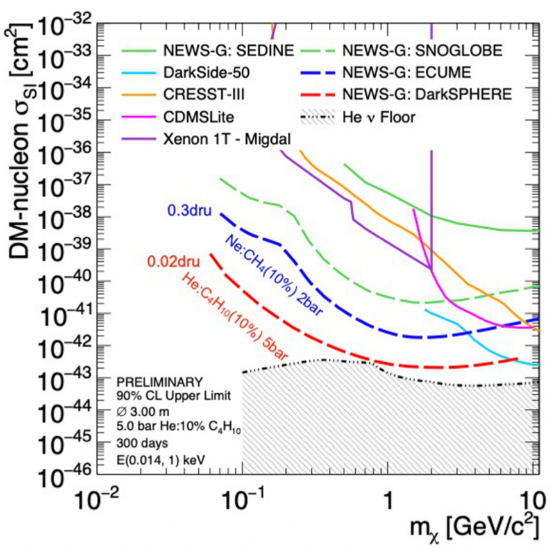
2021: Commissioning of the experiment at SNOLAB.

2022: ECUME 140 cm ⌀ sphere electroformed underground at SNOLAB

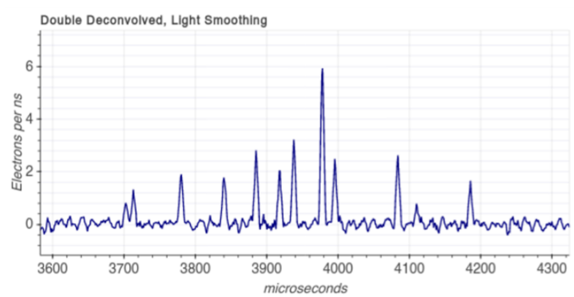
2025: DarkSPHERE 300 cm ⌀ sphere electroformed underground and water shielding at Boulby. Currently on conceptual design phase.



NEWS-G at Snolab : Compact Shielding (35 t)
40 cm of polyethylene
22 cm of low activity Pb
3 cm of Roman Pb
Stainless steal envelope flushed with N



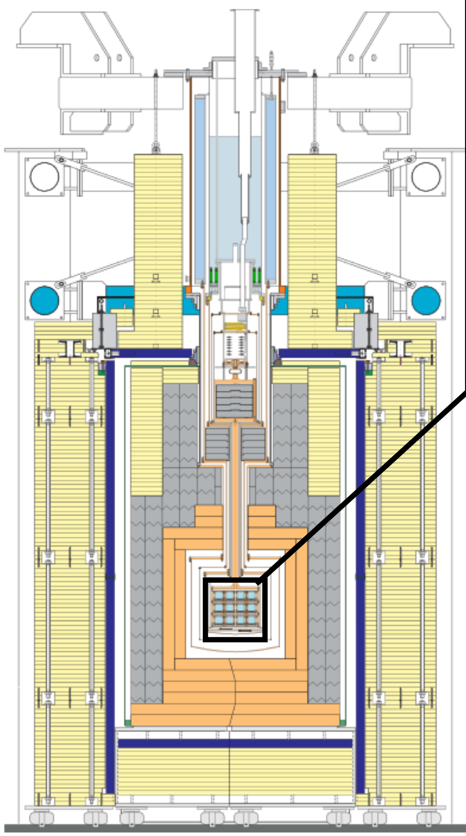
Multi-ball Achinos sensor for large detector operation



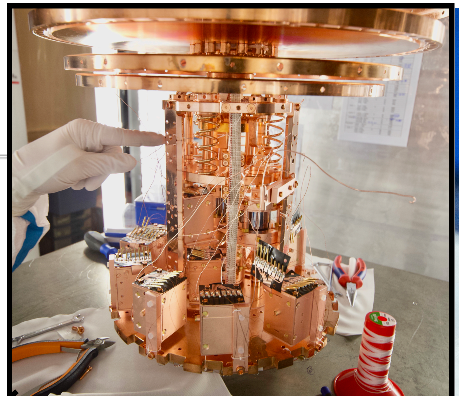
Individual primary electron detection
Laser induced events
135 mbar CH_4

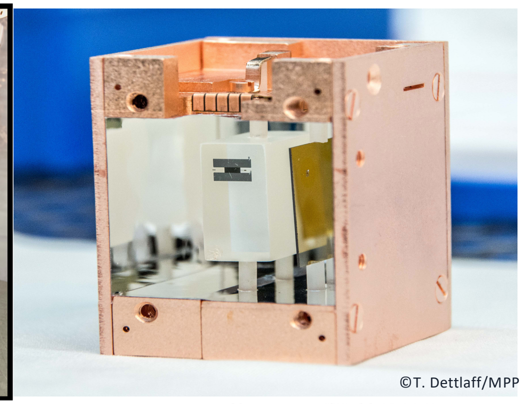
The CRESST Experiment (see parallel talk by T. Ortmann)

Cryogenic Rare Event Search with Superconducting Thermometers



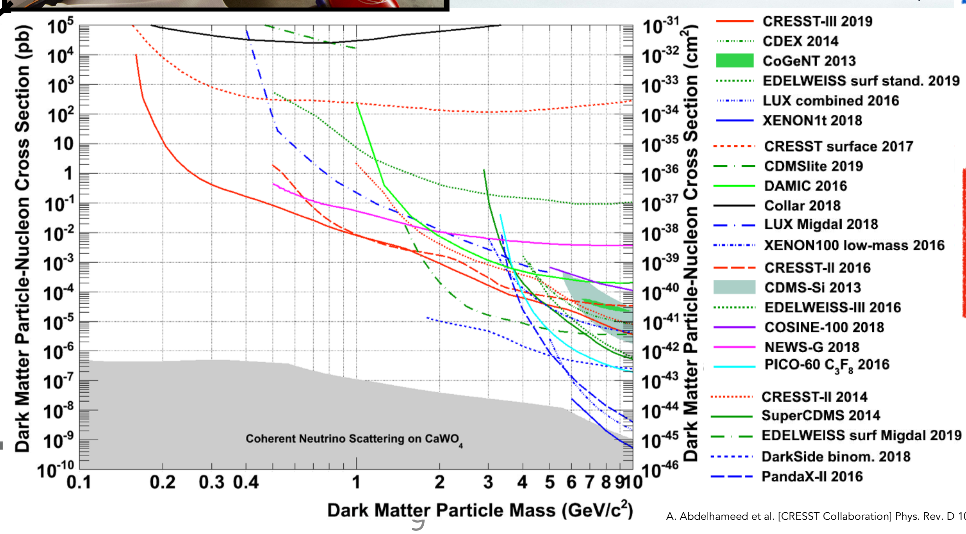
Dilution Refrigerator





Scintillating $CaWO_4$ cryogenic detector
+ cryogenic light detector
operated at ~15 mK

Readout: Transition Edge Sensor
Mass $CaWO_4$ = 24 g
E_{th} = 31 eV



Unprecedented sensitivity
DM masses < 1.7 GeV/c^2

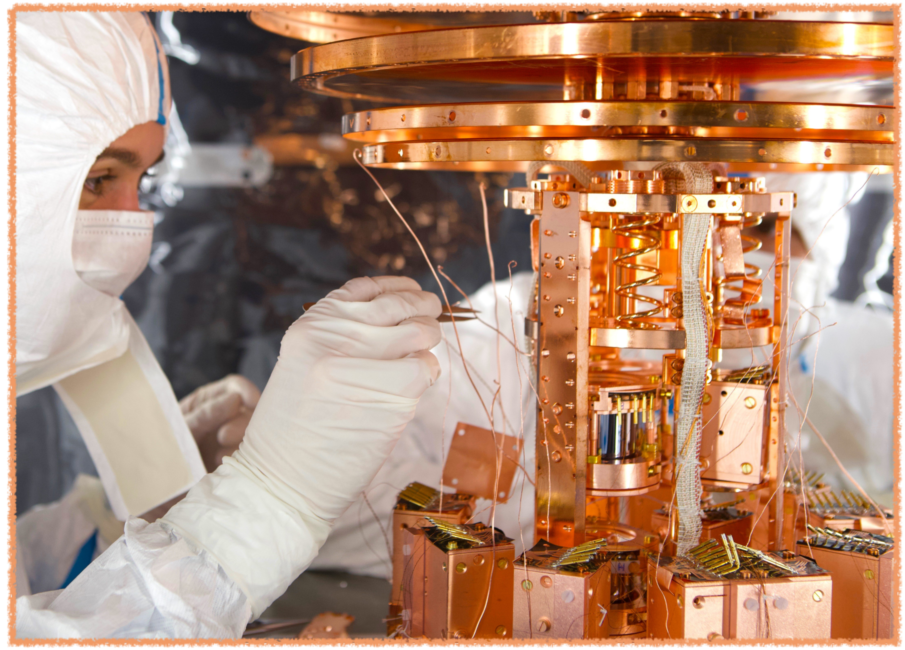
A. Abdelhameed et al. [CRESST Collaboration] Phys. Rev. D 100, DOI: 10.1103/PhysRevD.100.102002,

CRESST-III: status and plans

Upgrade of CRESST-III to read-out 48 -> 288 channels (96 CRESST-III modules 3.5kg)

Background:

- Current sensitivity limited by near-threshold rise of background
  - 2021-2022 experimental campaign to pinpoint the origin of background.



Readout:

- 2021 finalize procurement of:
  - SQUID read-out electronics
  - low T wiring
- 2022 finalize installation:
  - inside CRESST facility at LNGS

Detector R&D:

- 2021:
  - lower threshold
  - complementary materials
  - high production rate
- 2022:
  - Production and testing of detectors

2023: Restart data taking

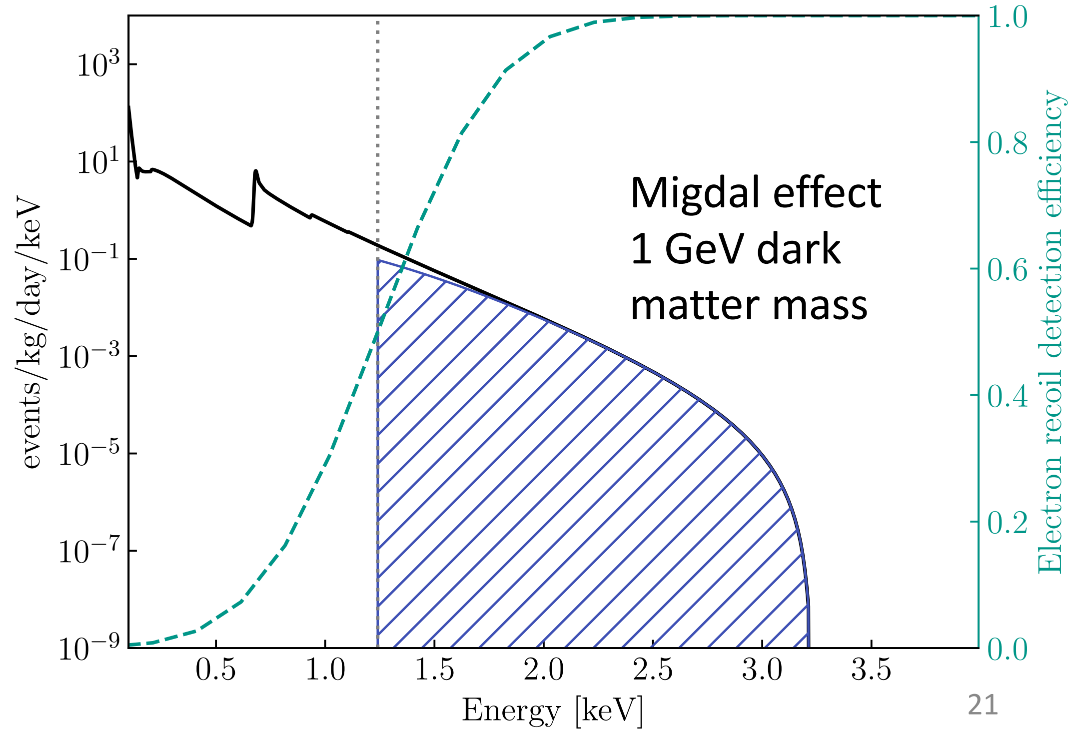
Sub-GeV DM with Two-Phase Xe

(following M. Dolan et al, Phys. Rev. Lett. 121, 101801 (2018) and M. Ibe et al, , JHEP 03, 194 (2018))

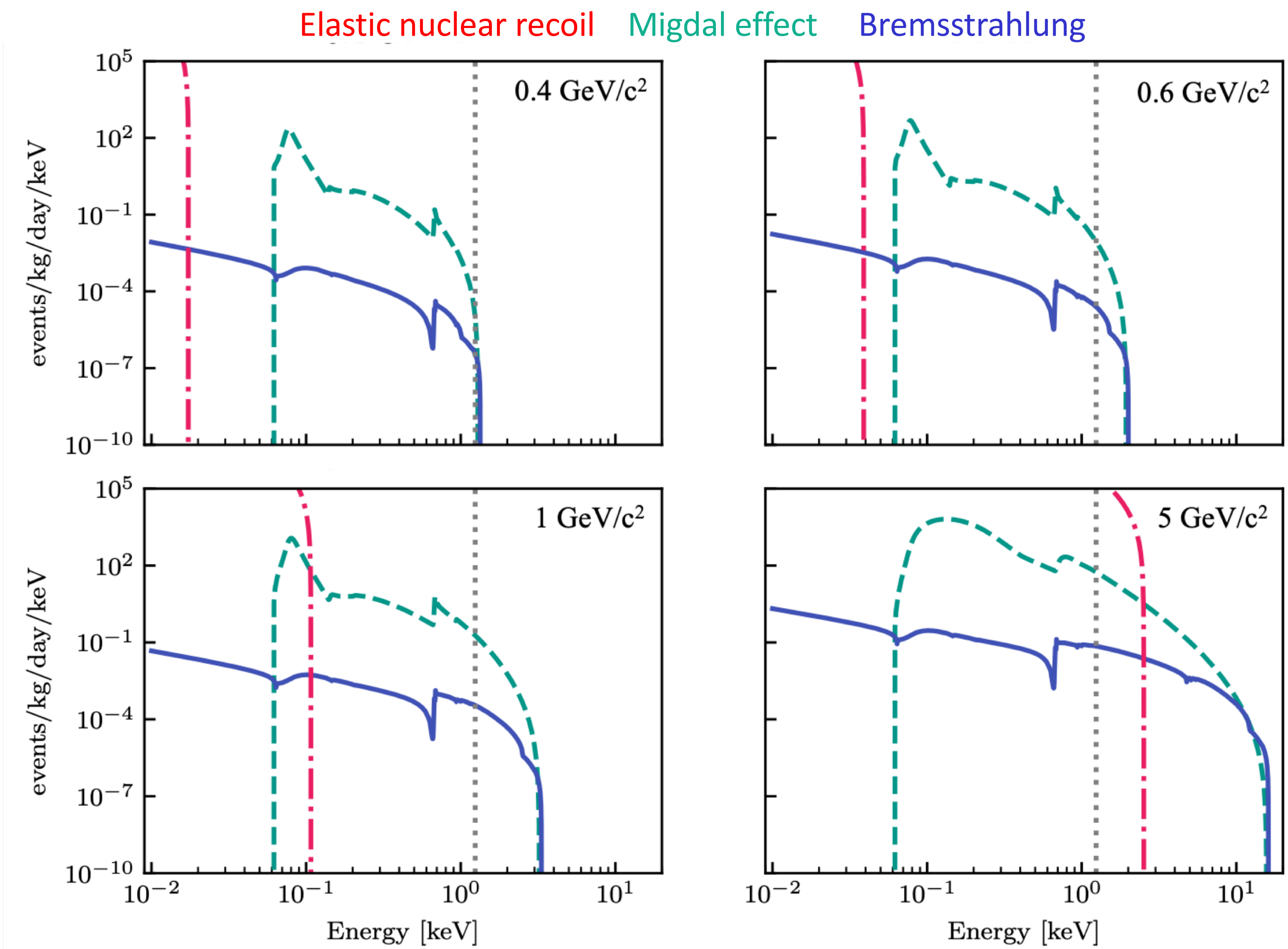
"Migdal effect": A. Migdal, "Ionization of atoms accompanying α- and β-decay", J. Phys. USSR 4 (1941) 449.

- The light yield for a nuclear recoil in LXe is practically 0 below 1.1 keV — can only look for $m_{DM} \gtrsim 5$ GeV.
- These detectors are more sensitive to lower energies of electron recoils (50% energy threshold):
  - Nuclear recoils = 3.3 keV in LUX
  - Electron recoils = 1.2 keV in LUX
- One can also look for charge-only signals, so-called "S2-only".

- Can detect sub-GeV DM via Bremsstrahlung and Migdal Effect
  - Emission of a photon from a xenon atom — nuclear interaction, but electron recoil signal



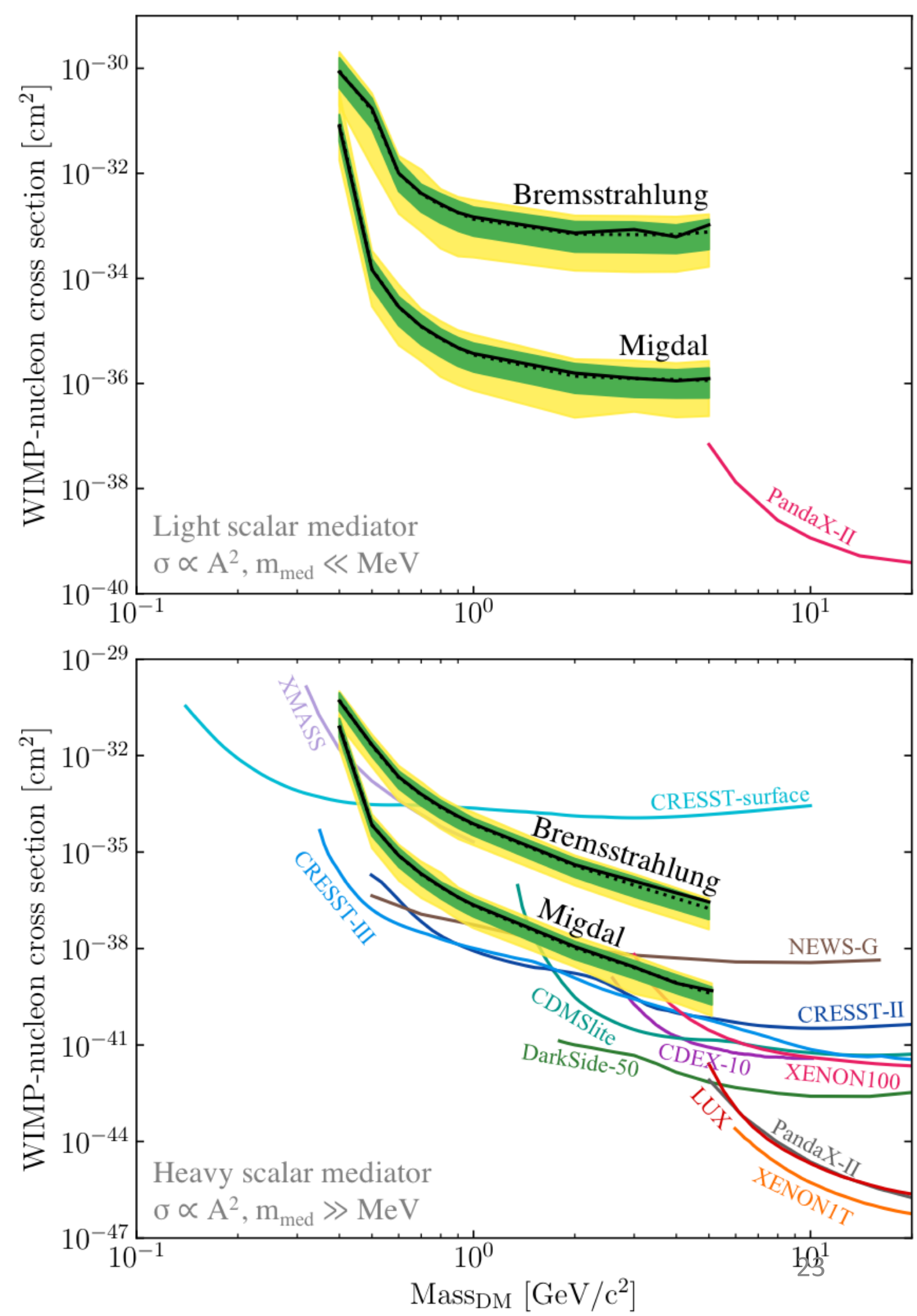
Sub-GeV DM with LXe



Sub-GeV DM with LUX

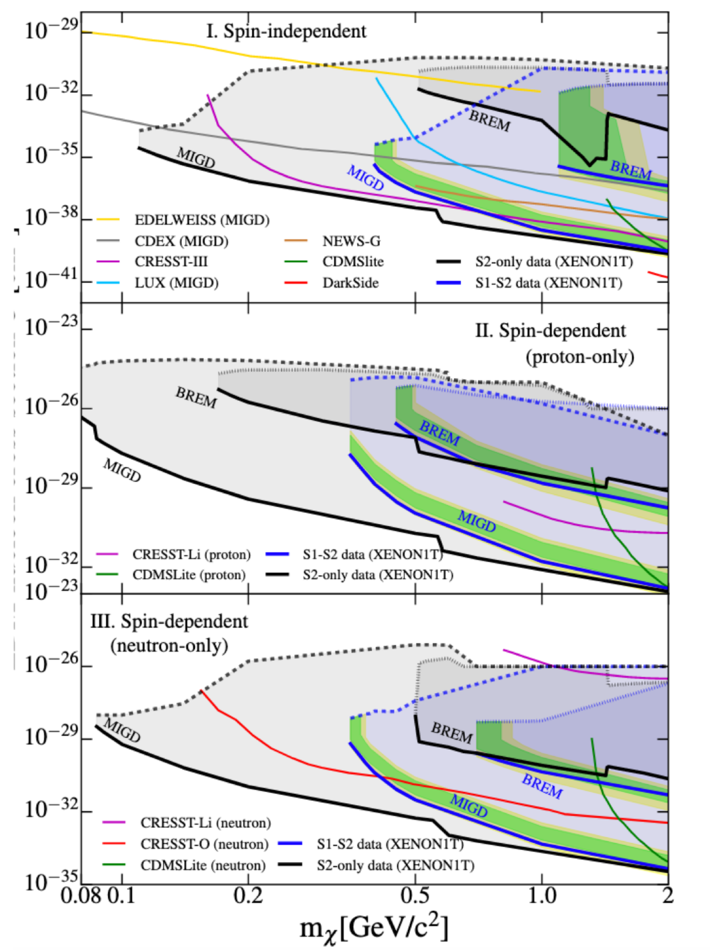
Limit for 95 live-days of data (WS2013, 13.8 tonne·day exposure).

LUX Collaboration,
Phys. Rev. Lett. **122**, 131301 (2019).

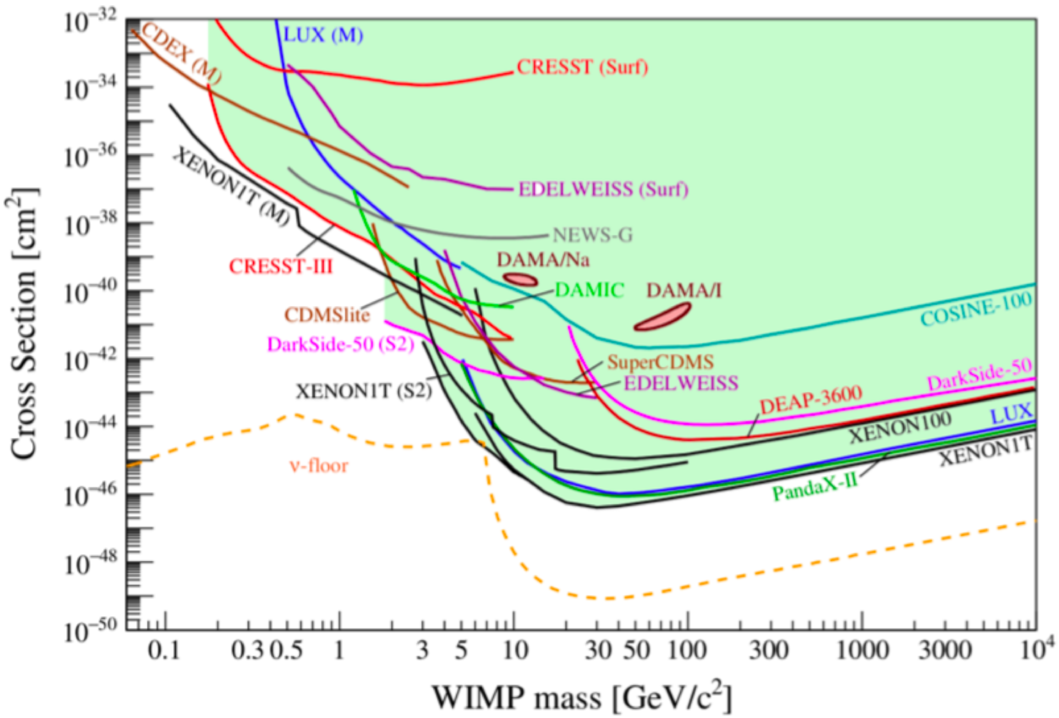


Sub-GeV DM with LXe

XENON collaboration,
Phys. Rev. Lett. 123, 241803 (2019) →

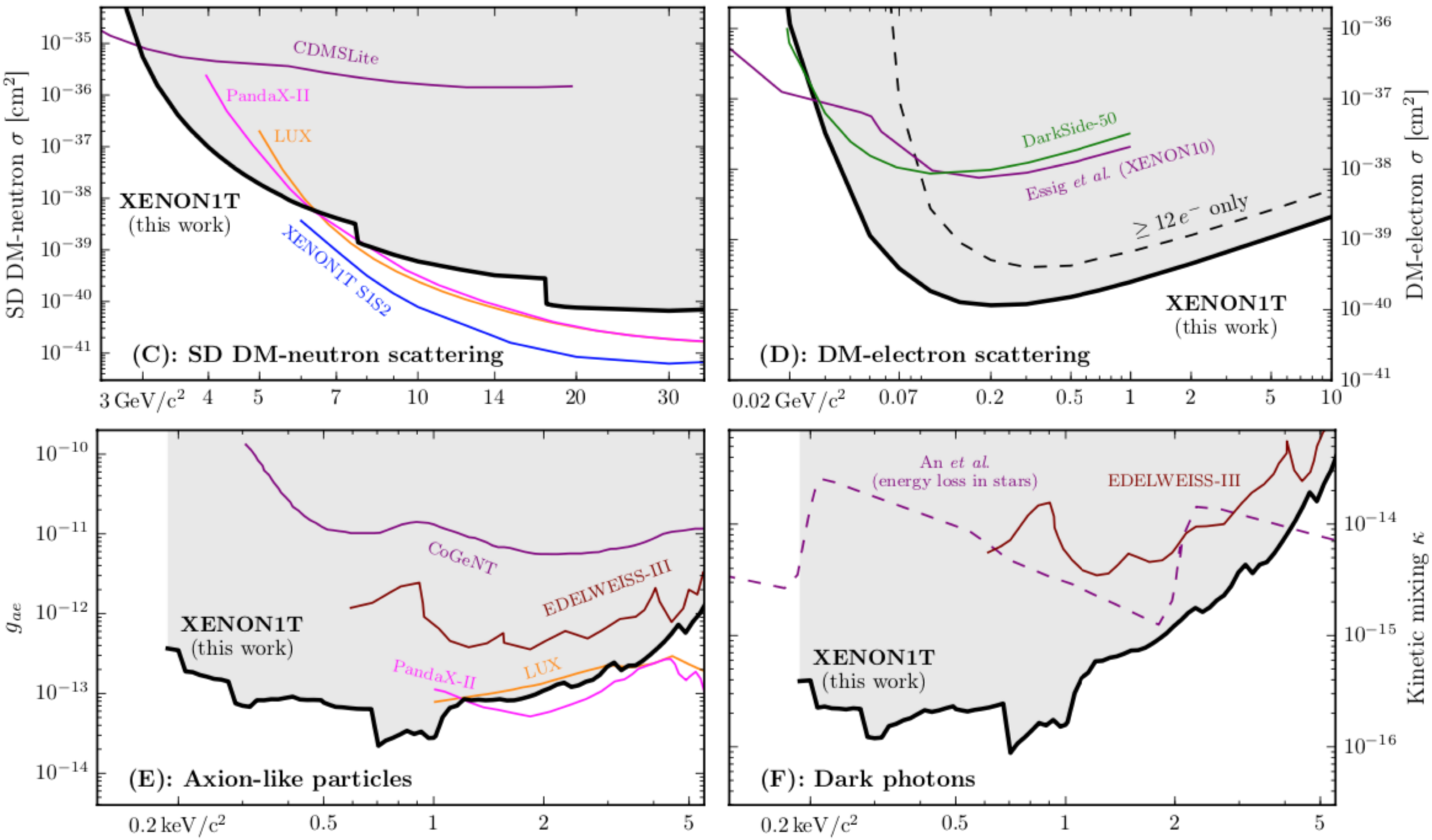


APPEC Committee Report, arXiv:2104.07634



Sub-GeV DM with LXe

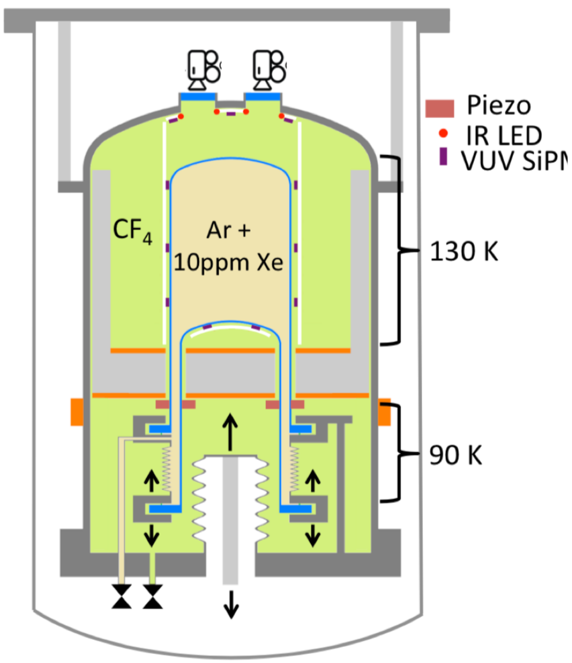
XENON collaboration, Phys. Rev. Lett. 123, 251801 (2019)

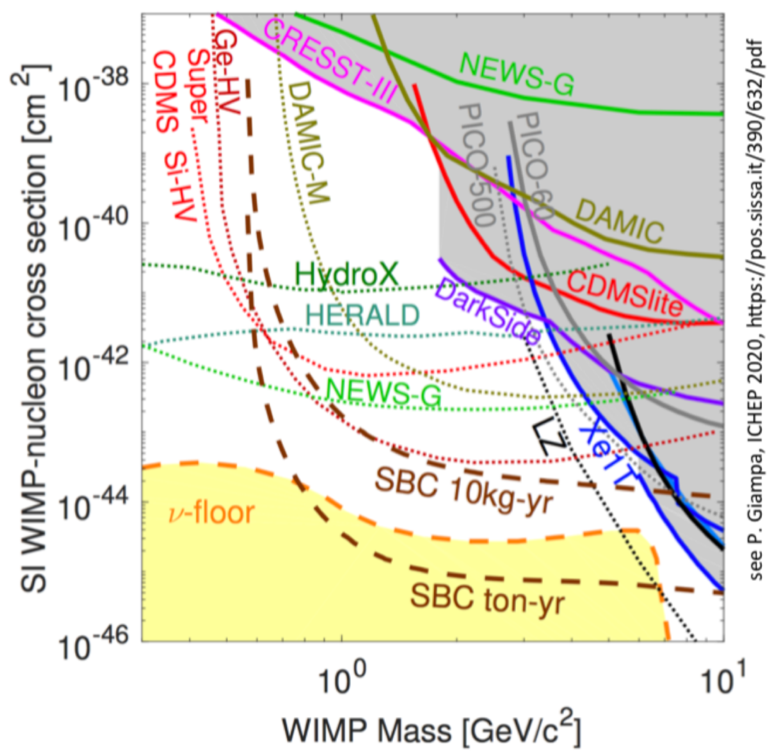


Scintillating Bubble Chamber (SBC)

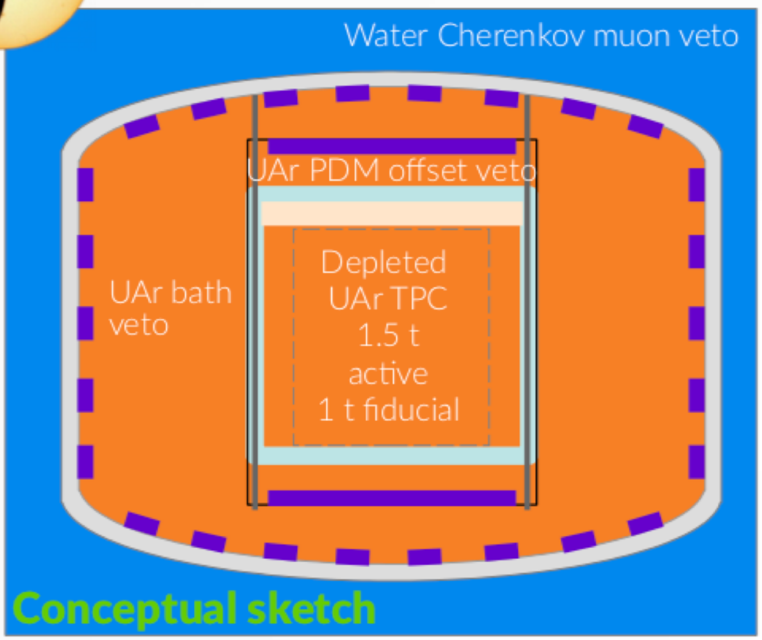
Idea: Combine scintillation signal of noble liquids (giving spectral information) with the gamma/beta rejection of bubble chambers:
See D. Baxter et al., Phys. Rev. Lett. 118, 231301 (2017)

Electronic recoil leakage < 10^{-7}, with high NR acceptance down to 1 keVnr

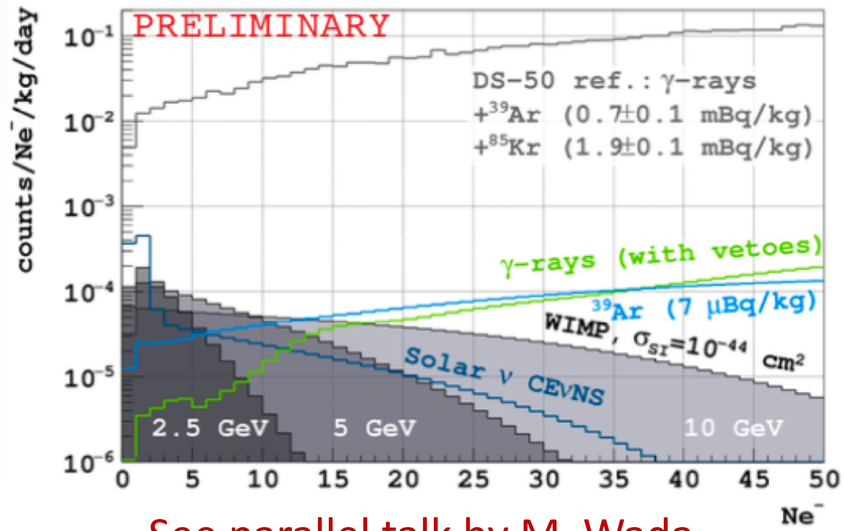




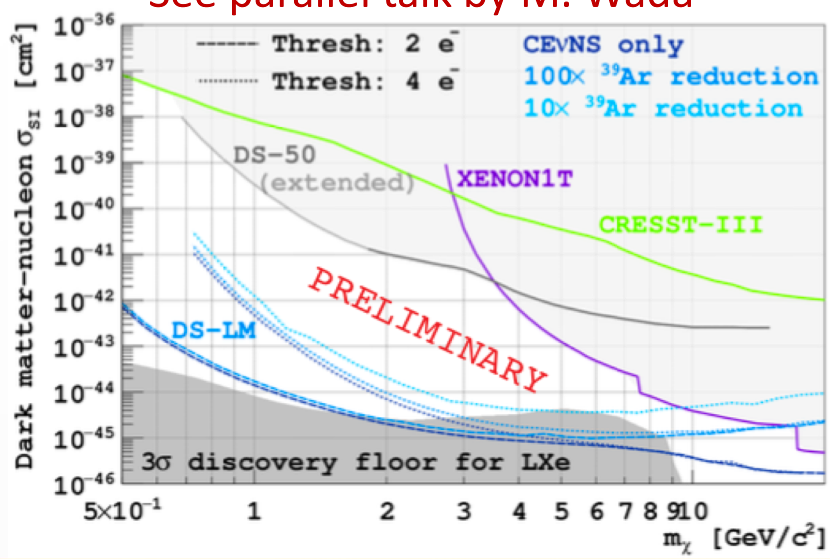
DarkSide-LowMass



- Dual-phase LAr TPC based on DarkSide-50
- Aiming for solar ν-floor with 1 t·yr exposure
- Lower backgrounds thanks to low-γ materials, γ-vetoes, and ^{39}Ar reduction with Urania and Aria
- Ongoing R&D to lower threshold, understand and decrease spurious electron backgrounds, and measure low-energy ionization response of LAr



See parallel talk by M. Wada

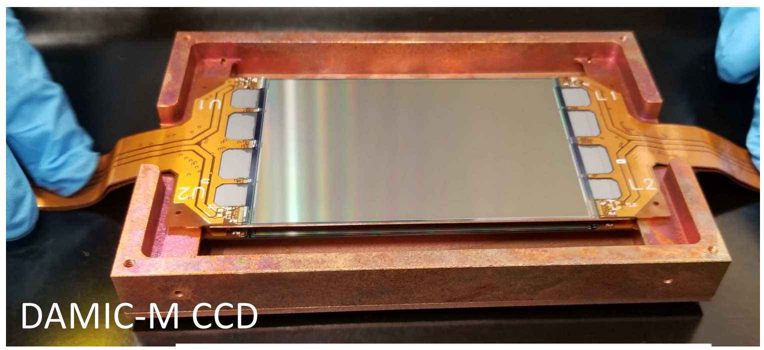


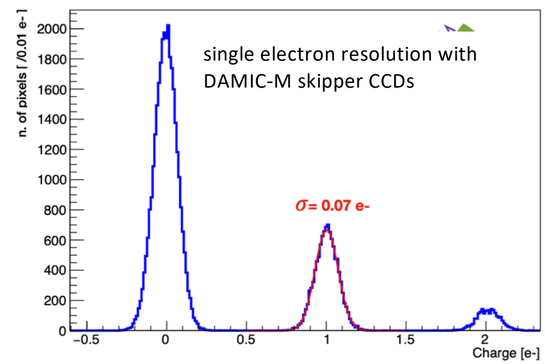
DAMIC at SNOLAB

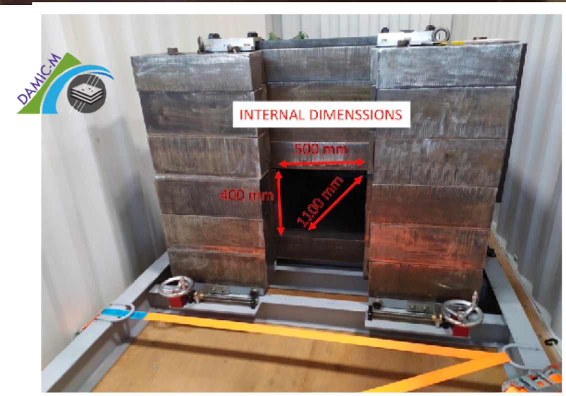
- Completed its science program with standard CCDs, now hosting a collaborative effort with DAMIC-M and SENSEI to operate skipper CCDs in a well characterized background environment
- Two 24 Mpix (DAMIC-M) and two 6 Mpix (SENSEI) skipper CCDs were installed on October 6th 2021
- **Goal:** Spectral measurement with improved energy threshold and spatial resolution to clarify excess reported in PRL 125, 241803 (2020)

DAMIC-M

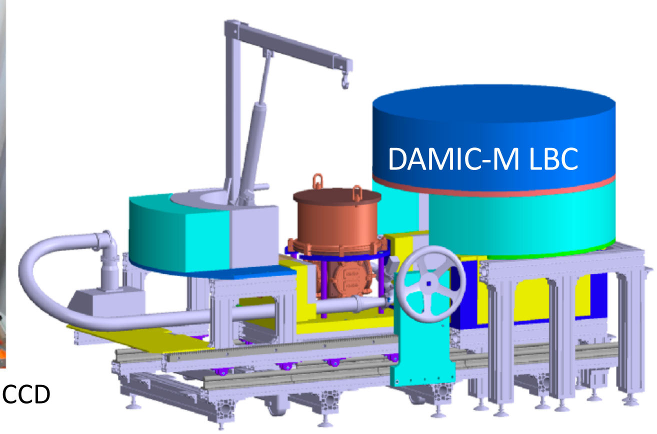
- kg-y exposure skipper CCDs detector at the LSM, France.
- Currently installing a Low Background Chamber at the LSM, with commissioning by end of 2021. Background characterization and a first search for light DM among the LBC goals
- Pre-production CCDs delivered and full production to start beginning of 2022
- Installation of full DAMIC-M detector scheduled for 2023-2024



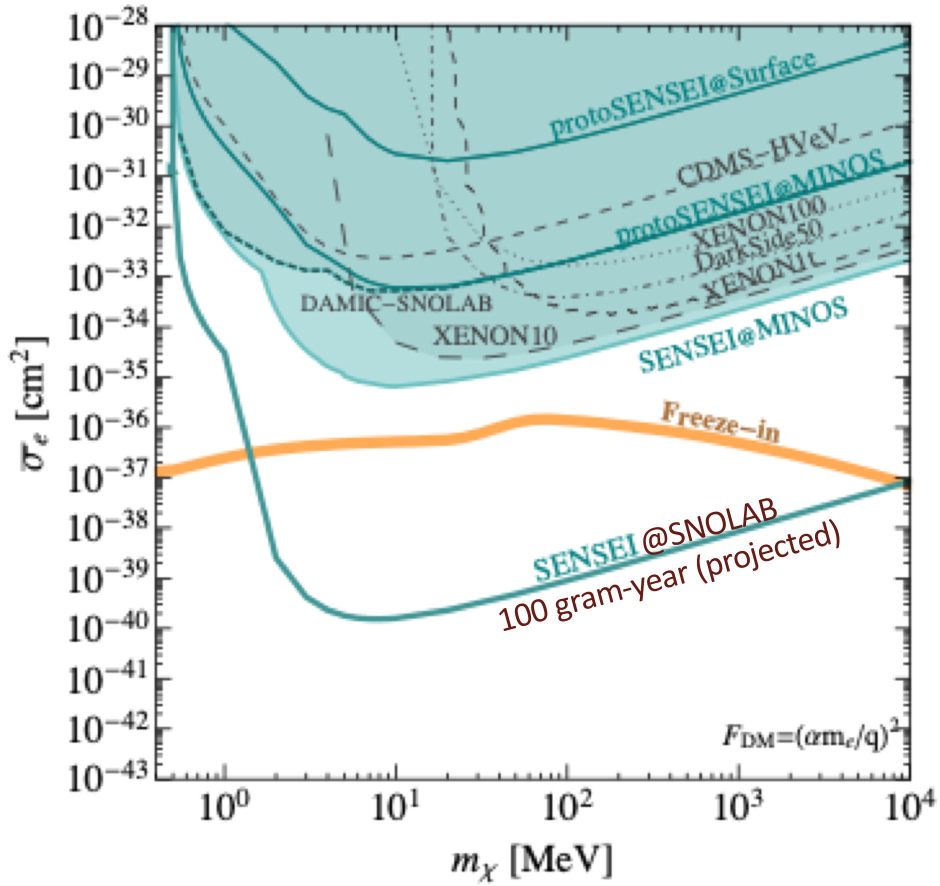




18-ton shielding in shipping container used for CCD transport



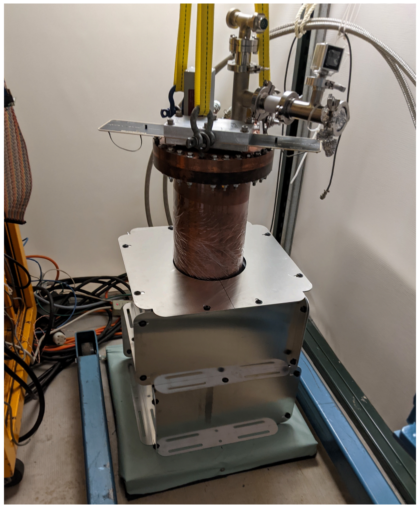
SENSEI Status and Plans



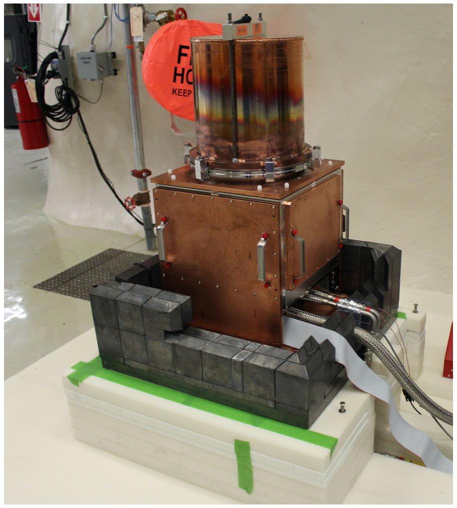
- 3 DM results w/ a Skipper-CCD at MINOS underground facility

1804.00088, PRL 1901.10478, PRL 2004.11378, PRL

- World-leading constraint on DM scattering via a light mediator



SENSEI@MINOS



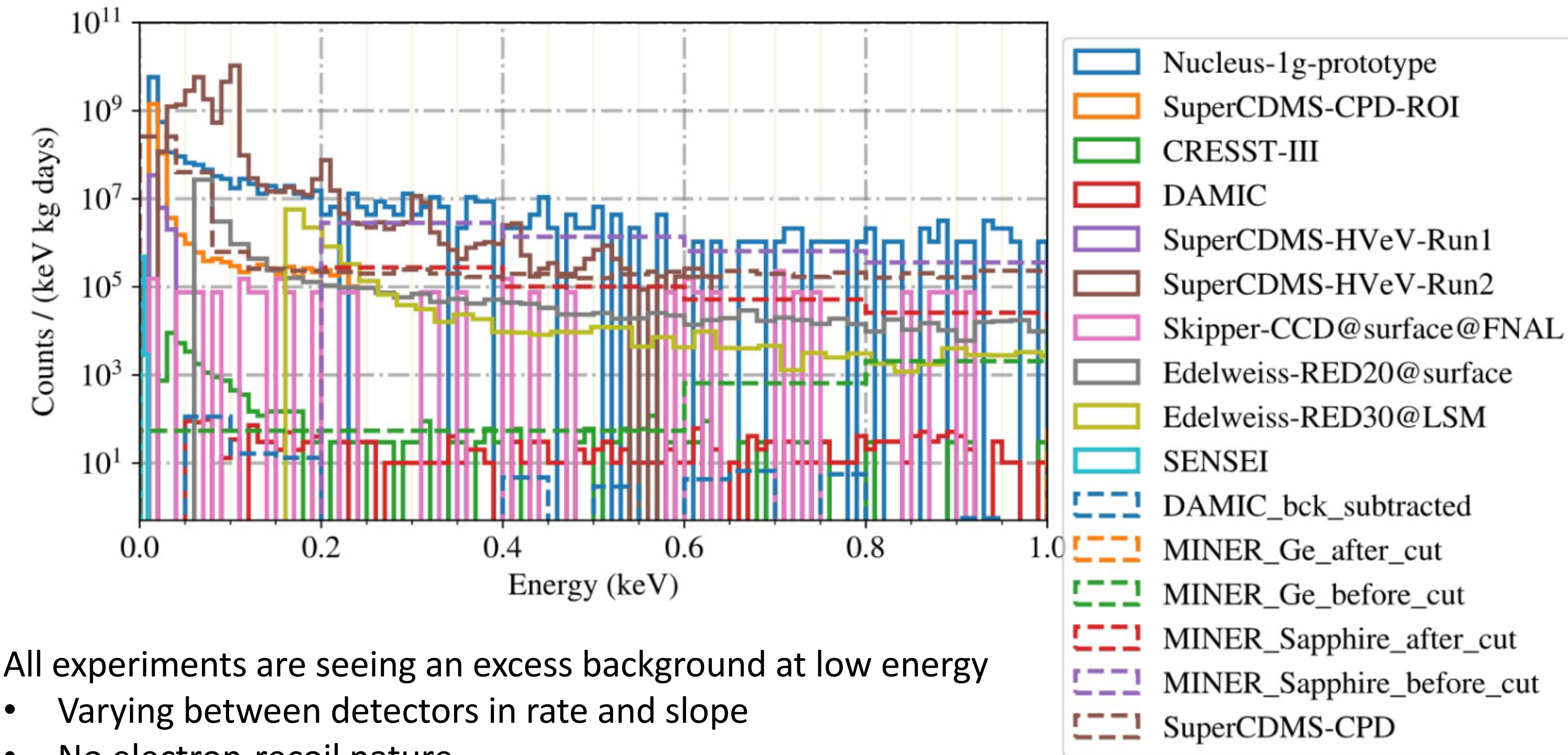
SENSEI@SNOLAB

- Significant progress in understanding origin of single-electron events 2011.13939, 2106.08347
- Installation of a O(10-gram) well-shielded detector at SNOLAB ongoing; will build up to O(100-gram) target mass in 2022

Substantial backgrounds seen at low energies

EXCESS workshop, see: https://indico.cern.ch/event/1013203/

See summary by J. Billard and R. Strauss



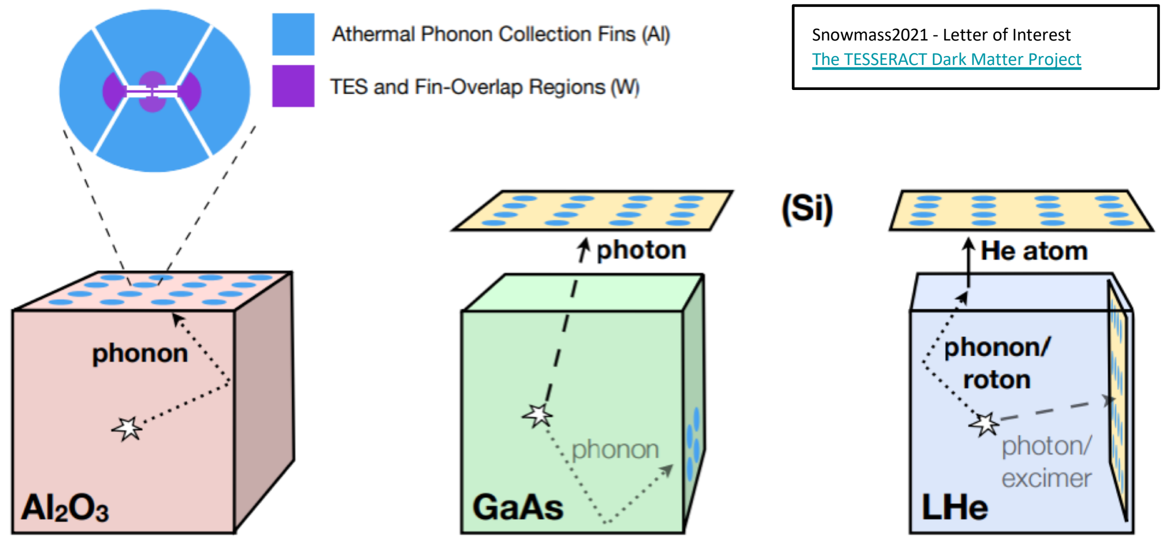
All experiments are seeing an excess background at low energy

- Varying between detectors in rate and slope
- No electron-recoil nature
- Multicomponent
- Some components get reduced with time

TESSERACT project (part of the DMNI suite of DOE-supported efforts)

- Managed by LBNL
- Funding for R&D and project development began in June 2020.
- One experimental design, and different target materials with complementary DM sensitivity. Zero E-field.
- All using TES readout
- ~40 people from 8 institutes
- Includes SPICE (polar crystals) and HeRALD (superfluid helium). These are historical names, now shorthand for the targets.

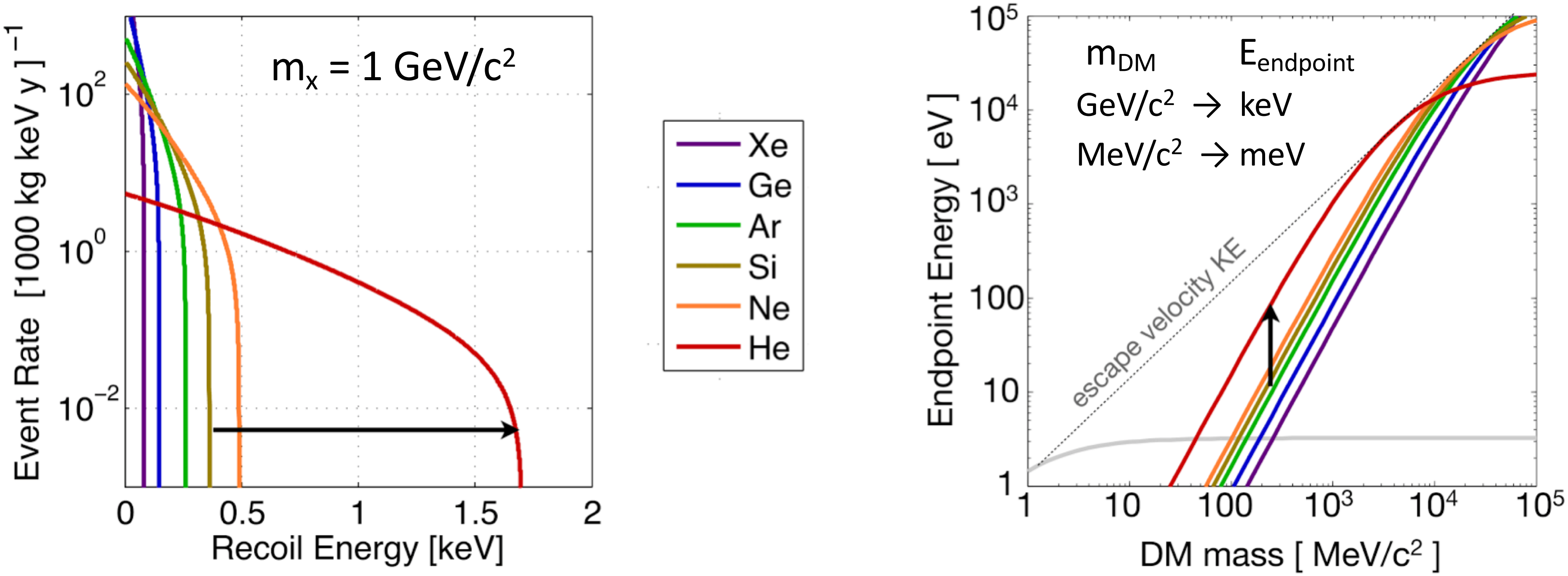
Snowmass2021 - Letter of Interest
The TESSERACT Dark Matter Project



Light baryonic target nuclei for NRDM

With sufficiently low threshold and/or a light target, lower dark matter masses may be probed.

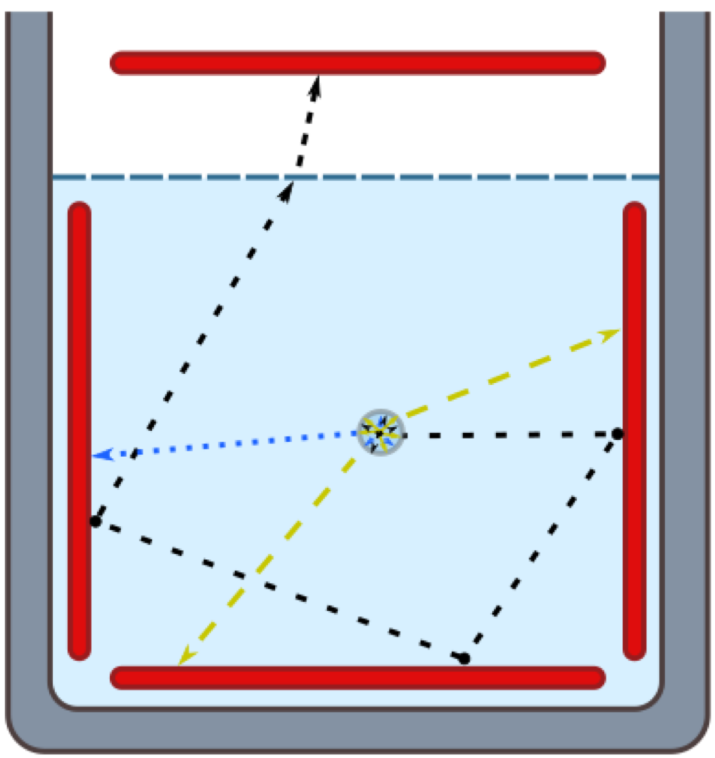
In TESSERACT, low thresholds will be achieved using TES readout, enabling reach to DM masses that cannot be reached by detectors that have only ionization or scintillation signals



Superfluid helium has significant additional advantages

- Quantum evaporation signal gain
- Multipixel background rejection through requiring coincidence
- Multiple signal channels (rotons, phonons, scintillation, triplet excimers)

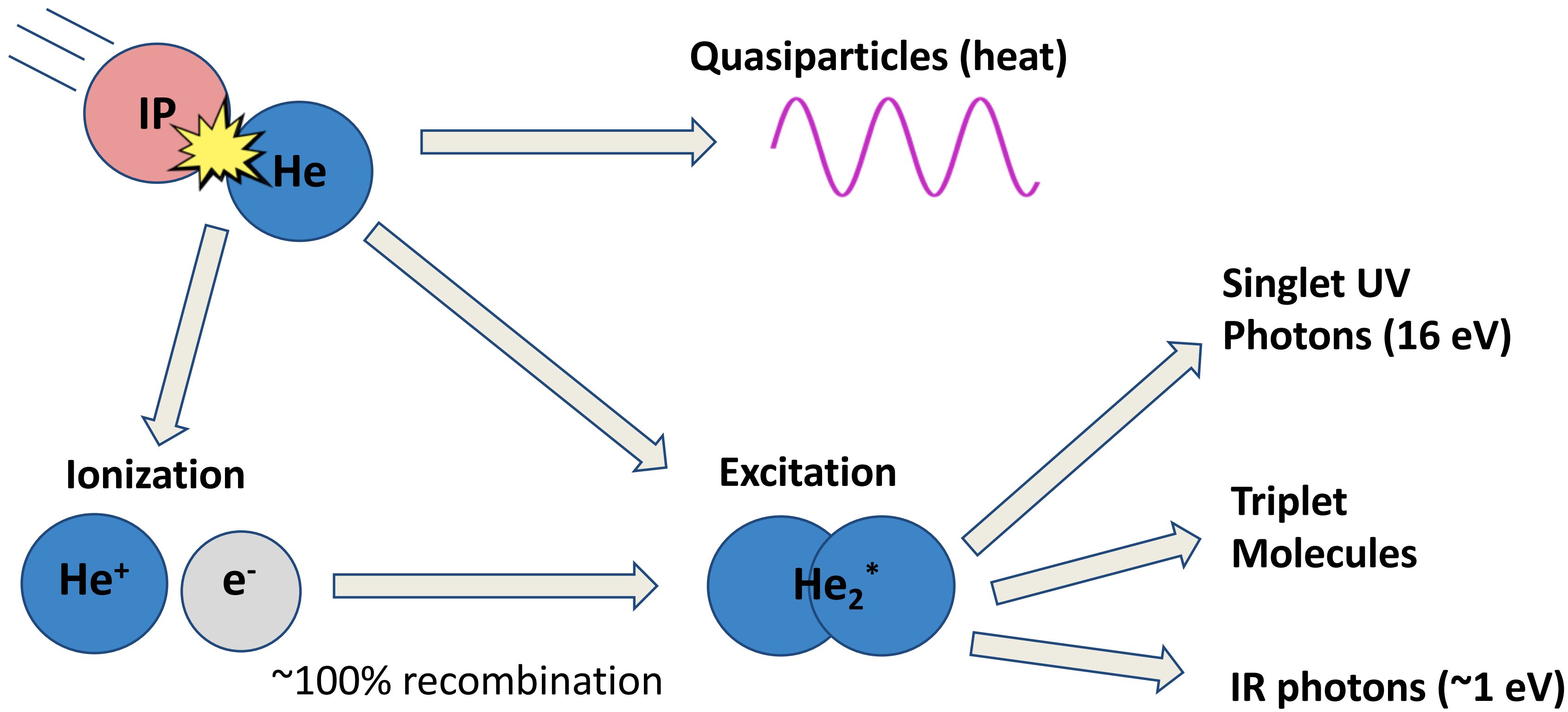
Superfluid Helium as a Dark Matter Target



Advantages of He-4

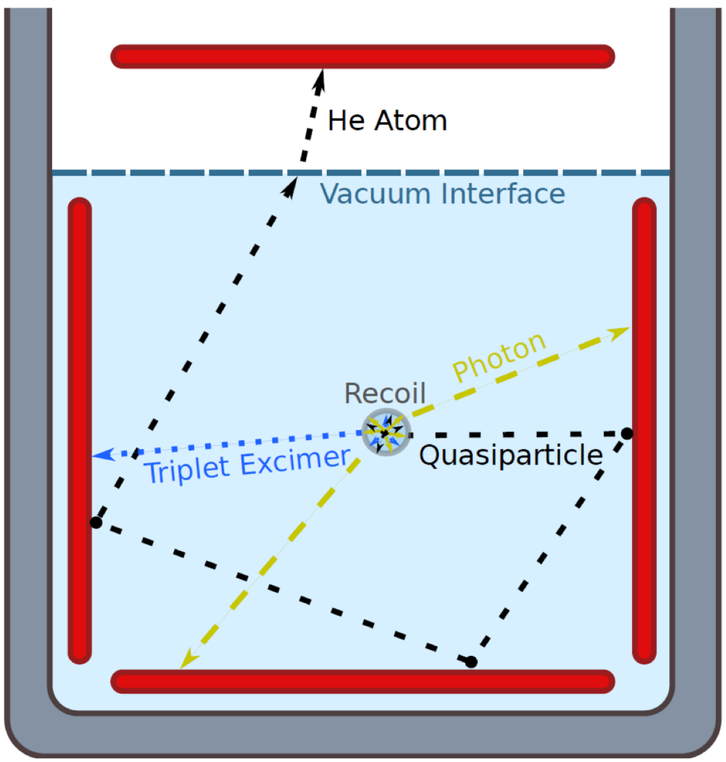
- Kinetic energy transfer from sub-GeV dark matter more efficient than on other nuclei
- Cheap
- Easy to purify; intrinsically radiopure
- Remains liquid/superfluid down to absolute zero
- Monolithic, scalable
- Calorimetry for signal readout

Recoils in Helium (generic incident particle IP)



Helium **R**oton **A**pparatus for **L**ight **D**ark matter (HeRALD)

HeRALD concept and sensitivity paper
PhysRevD.100.092007



- Operated at ~30-50 mK
- Calorimeters with TES readout
  - submerged in liquid
    - Detect **UV photons**, **triplet molecules** and **IR photons**
  - suspended in vacuum
    - Detect UV photons, IR photons and **He atoms** (evaporated by quasiparticles)

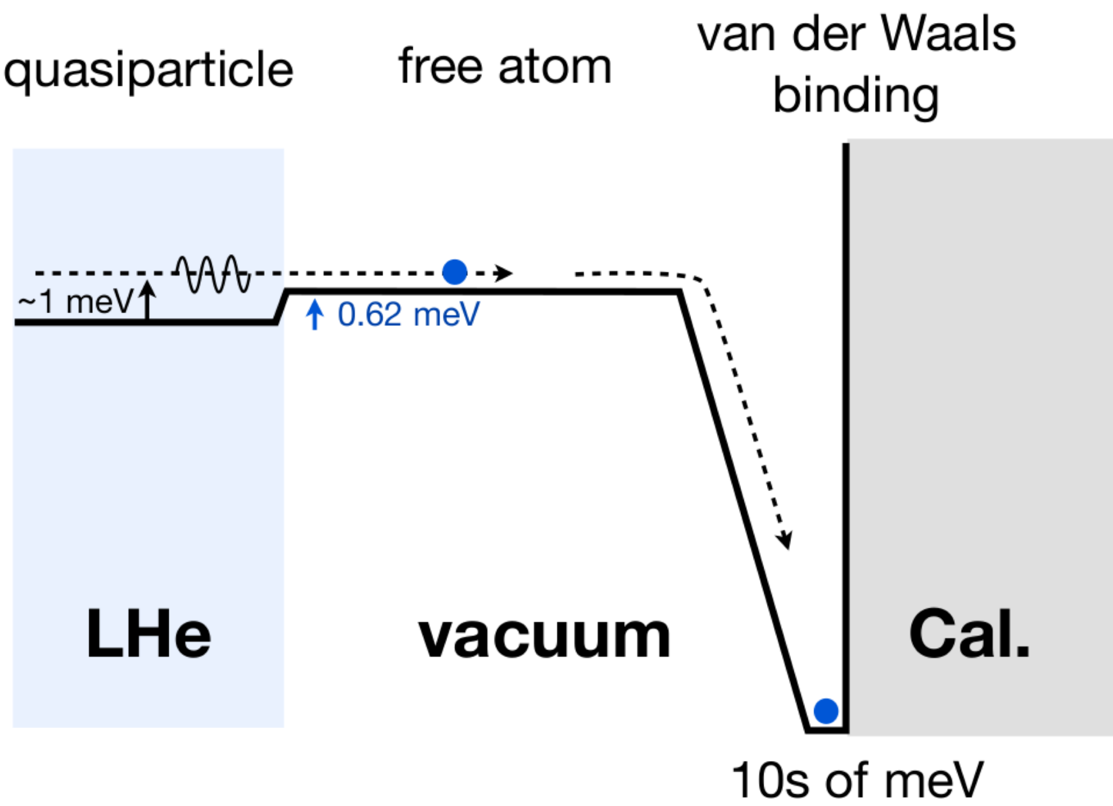
Detecting Quasiparticle Signal

Binding energy between helium and solid amplifies signal

1 meV recoil energy → up to 40 meV detectable energy

Thermal energy negligible (μeV)

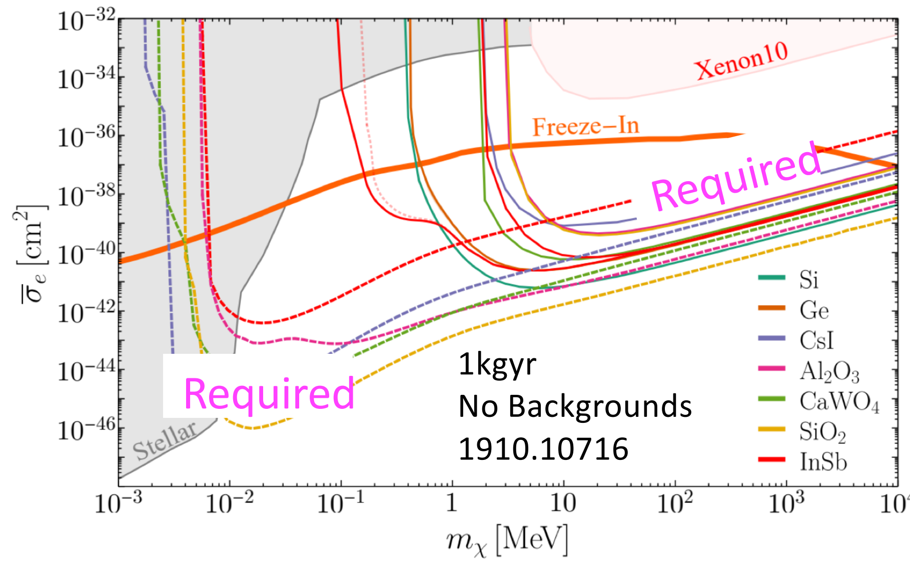
Film burner to remove helium from calorimeter

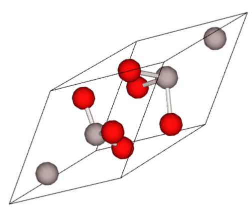


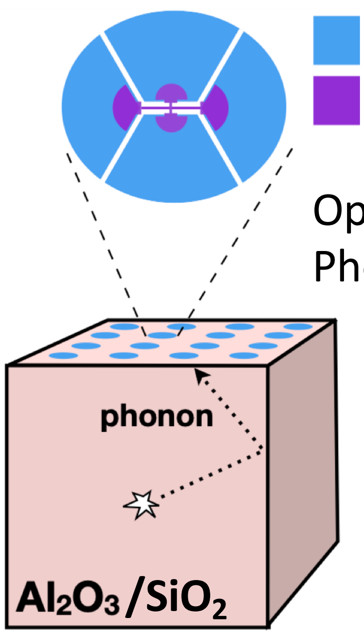
SPICE: **S**ub-ev **P**olar **I**nteractions **C**ryogenic **E**xperiment

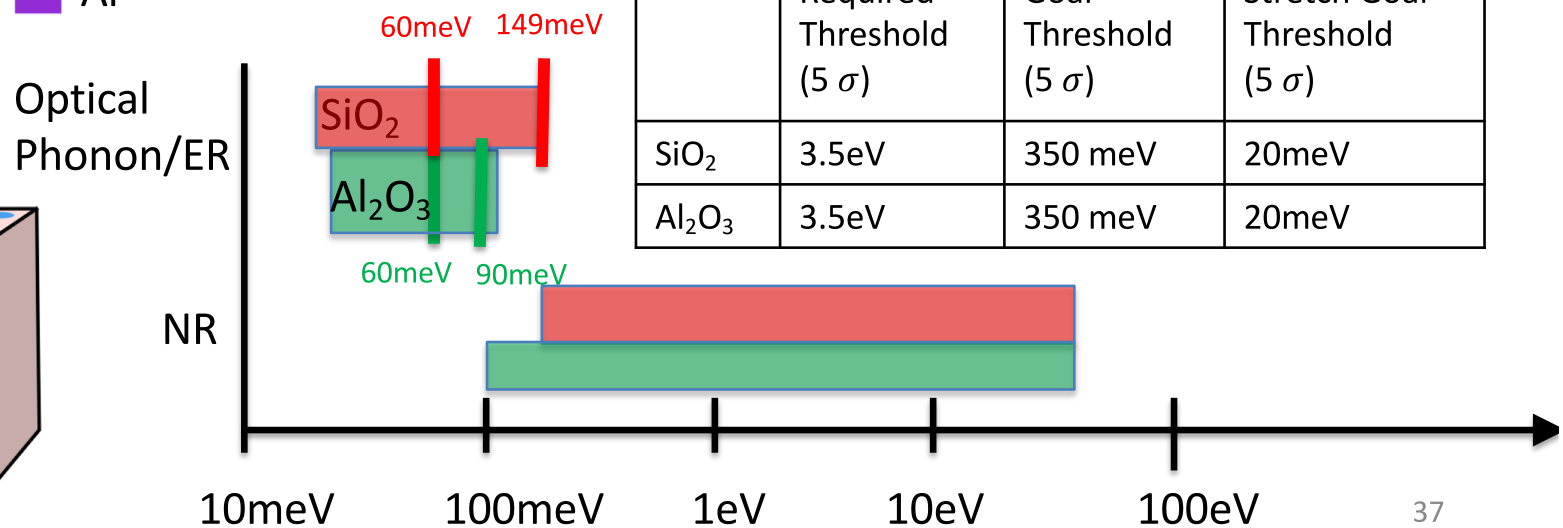
- In ionic crystals, optical phonons are oscillating electric dipoles!
- Very large coupling to photons (black in the IR)… Very large coupling to the dark photons
- 1712.06598
- 10-1000gyr exposure

Scattering via Light Dark Photon





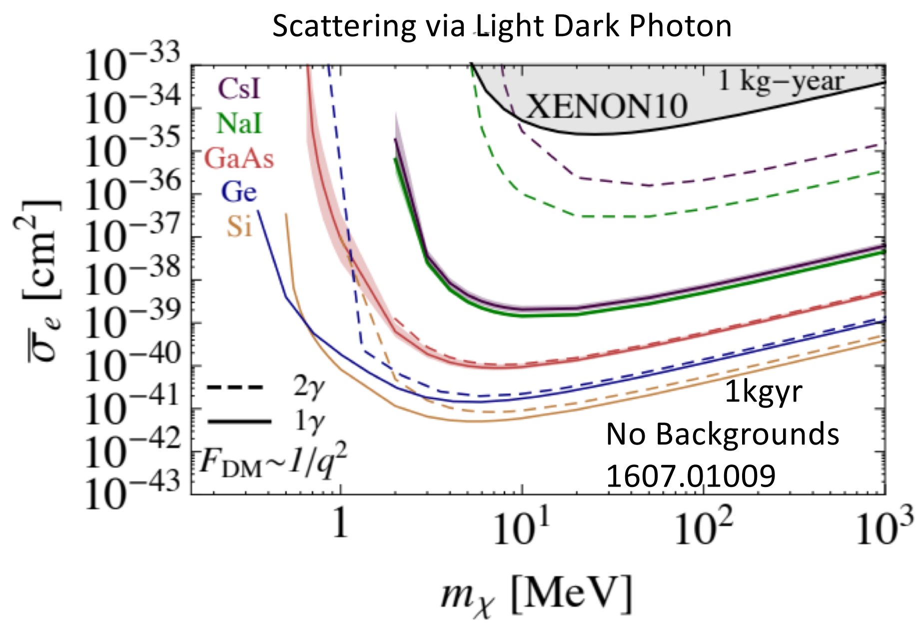




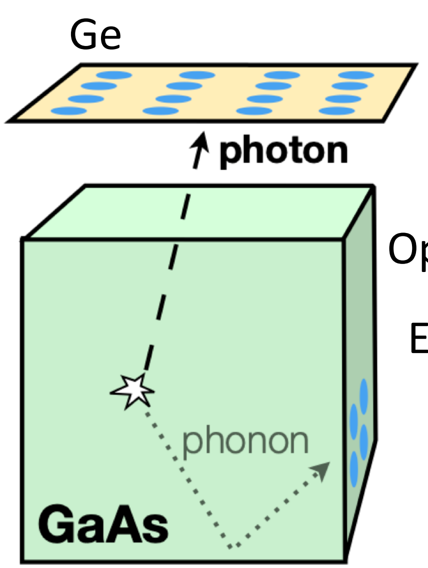
	Required Threshold (5 σ)	Goal Threshold (5 σ)	Stretch Goal Threshold (5 σ)
SiO_2	3.5eV	350 meV	20meV
Al_2O_3	3.5eV	350 meV	20meV

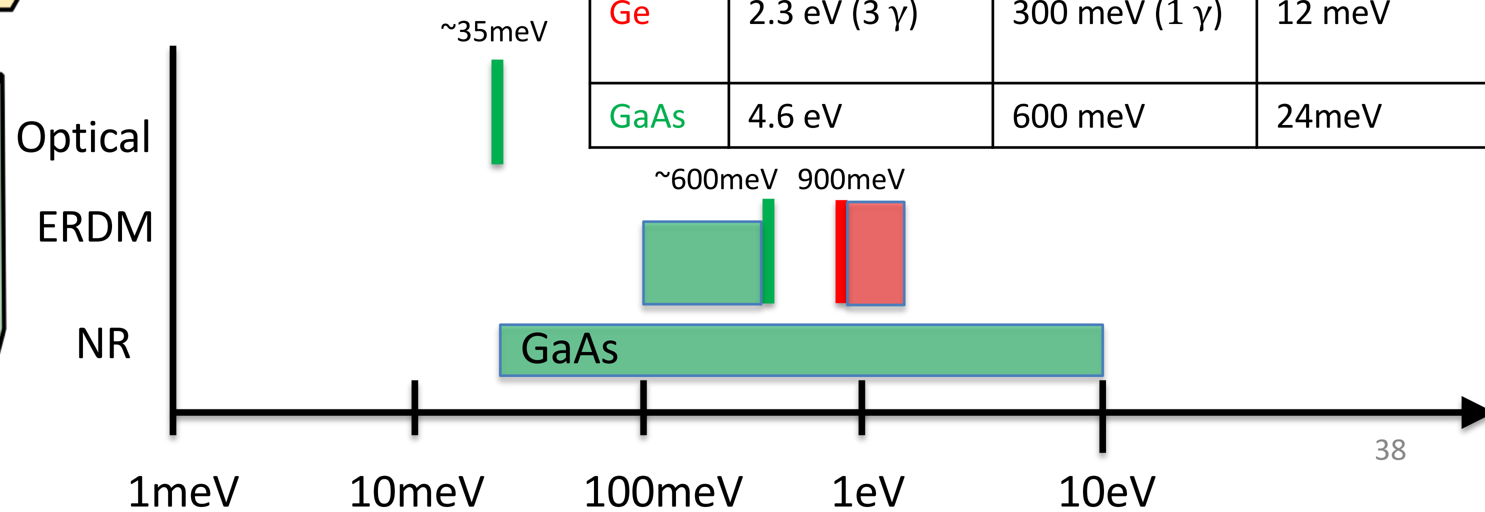
SPICE: GaAs ERDM

- "CRESST for ERDM"
- GaAs has very high scintillation yield (1802.09171)
- 10-1000gyr exposure
- Notice GaAs has worse background free reach than both Si and Ge! It's actually even worse than this because this doesn't include quantum efficiency suppression
- However, GaAs has background control:
  - 2 photon coincidence in 2 separate detectors
  - No charge leakage



	Required (5 σ)	Goal (5 σ)	Stretch Goal (5 σ)
Ge	2.3 eV (3 γ)	300 meV (1 γ)	12 meV
GaAs	4.6 eV	600 meV	24meV





Detector Performance Specifications

$$\sigma_E \sim \frac{\sqrt{4k_b T_c^2 G(\tau_{collect} + \tau_{sensor})}}{\epsilon_{collect}\epsilon_{sensor}}$$

Too close to bath temperature

Sensor Characteristics	Required	Goal	Stretch Goal
TES T_c	40 mK	20 mK	15 mK ~~10 mK~~
Total TES Volume	$[100\times400]\mu m\times40nm$	$[33\times133]\mu m\times40nm$	$[33\times133]\mu m\times40nm$
Bare TES noise σ_{TES}	40 meV	4 meV	2 meV
W/Al interface transmission probability $\epsilon_{W/Al}$	10^{-4}	10^{-4}	10^{-3}

Target Excitation Efficiencies	Required	Goal	Stretch Goal
Phonon collection efficiency $\epsilon_{collect}$	Si/Ge >99% Polar	>99.9%	>99.9%
GaAs scintillation efficiency ϵ_γ	25%	60%	60%
LHe quantum evaporation: efficiency $\epsilon_{collectHe}$	4%	10%	10%
LHe quantum evaporation: adsorption gain g_{He}	8×	16×	16×

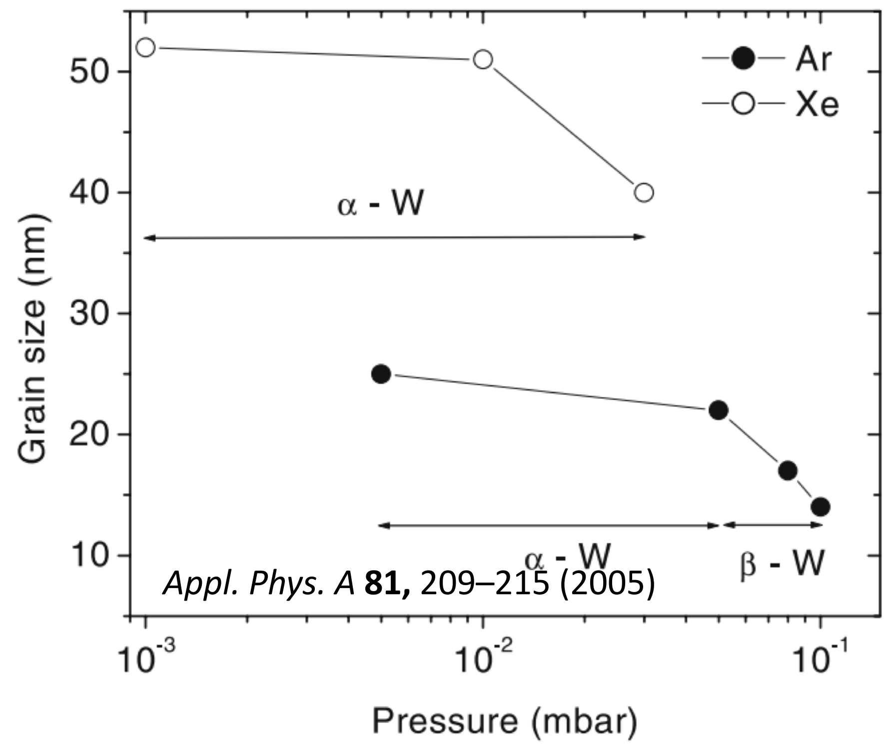
Resulting 5σ Recoil Energy Thresholds

Scaled from Si demonstrator (3.9 eV σ_{phonon}) by phonon velocity, mean free path, and sensor area.

	Required	Goal	Stretch Goal
1 cm^3 Al_2O_3/SiO_2 (phonon only)	**3.5 eV**	**350 meV**	**20 meV**
1 cm^3 GaAs (phonons GaAs + photons on Ge)	**2.8 eV** ($\sim 2-\gamma$)	**900 meV** ($1-\gamma$)	**35 meV** (optical phonon)
0.1×1× 1 cm^2 Ge-based photon sensor	2.3 eV	300 meV	12 meV
0.1×1× 1 cm^3 GaAs phonon sensor	4.6 eV	600 meV	24 meV
64 cm^3 LHe (evaporation via Si-based sensor)	**21 eV**	**570 meV**	**24 meV**
includes scaling by $\epsilon_{collectHe}\times g_{He}$			
0.1×4× 4 cm Si-based He evaporation sensor	6.7 eV	900 meV	38 meV

Low Tc W TES Fabrication (TAMU)

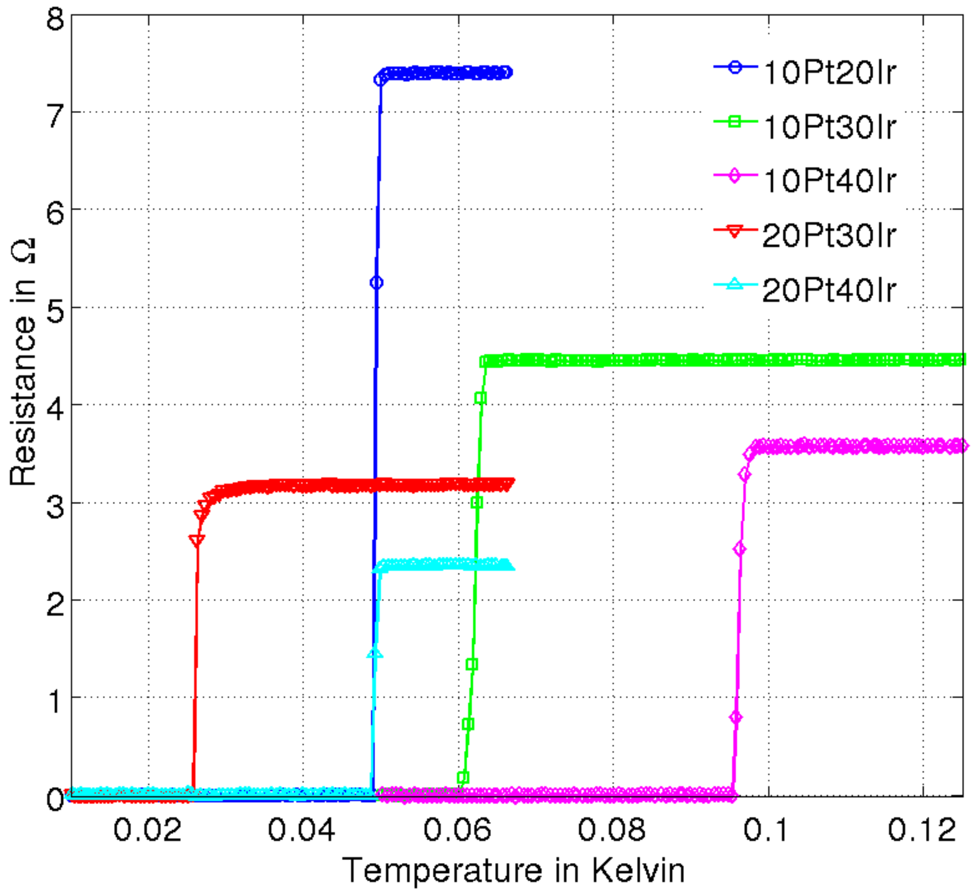
- What sets W T_c? 2 crystal configurations
  - Alpha: T_c=15mK
  - Beta: T_c~ 3K
- Goal: produce a stress free, alpha phase W film
- Bouziane et al: Xe plasma produces better alpha films



- Year 1 TESSERACT Progress: Produced W film with T_c= 19 mK
  New, have reached below 20 mK goal Tc

Low Tc IrPt Films (Argonne)

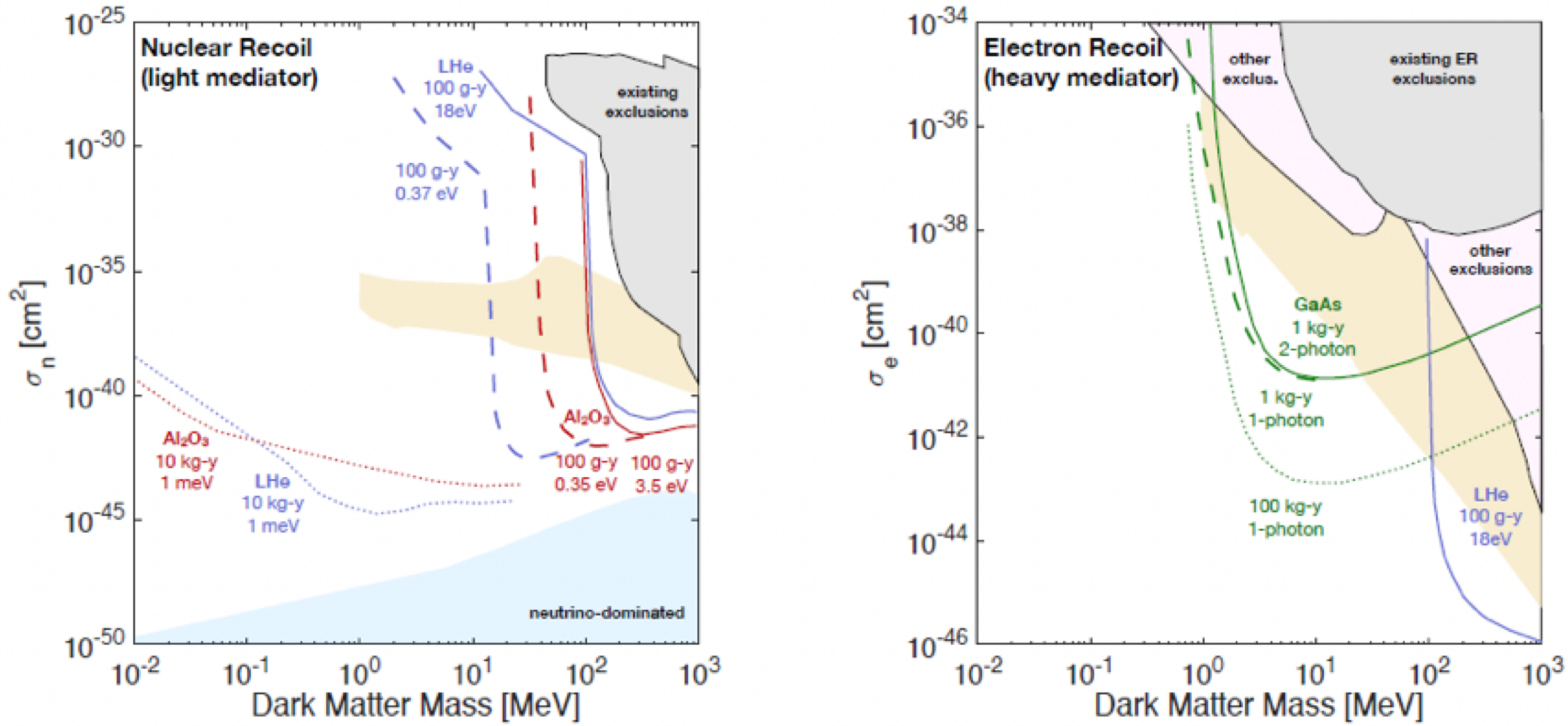
IrPt film Tc measurements



- Argonne has produced 25mK IrPt films **... nearing goal**
- Next steps:
  - map out space between 15-25mK
  - Test reproducibility
  - Measure TES characteristics

SPICE and HeRALD - projected sensitivity

Snowmass2021 - Letter of Interest
The TESSERACT Dark Matter Project



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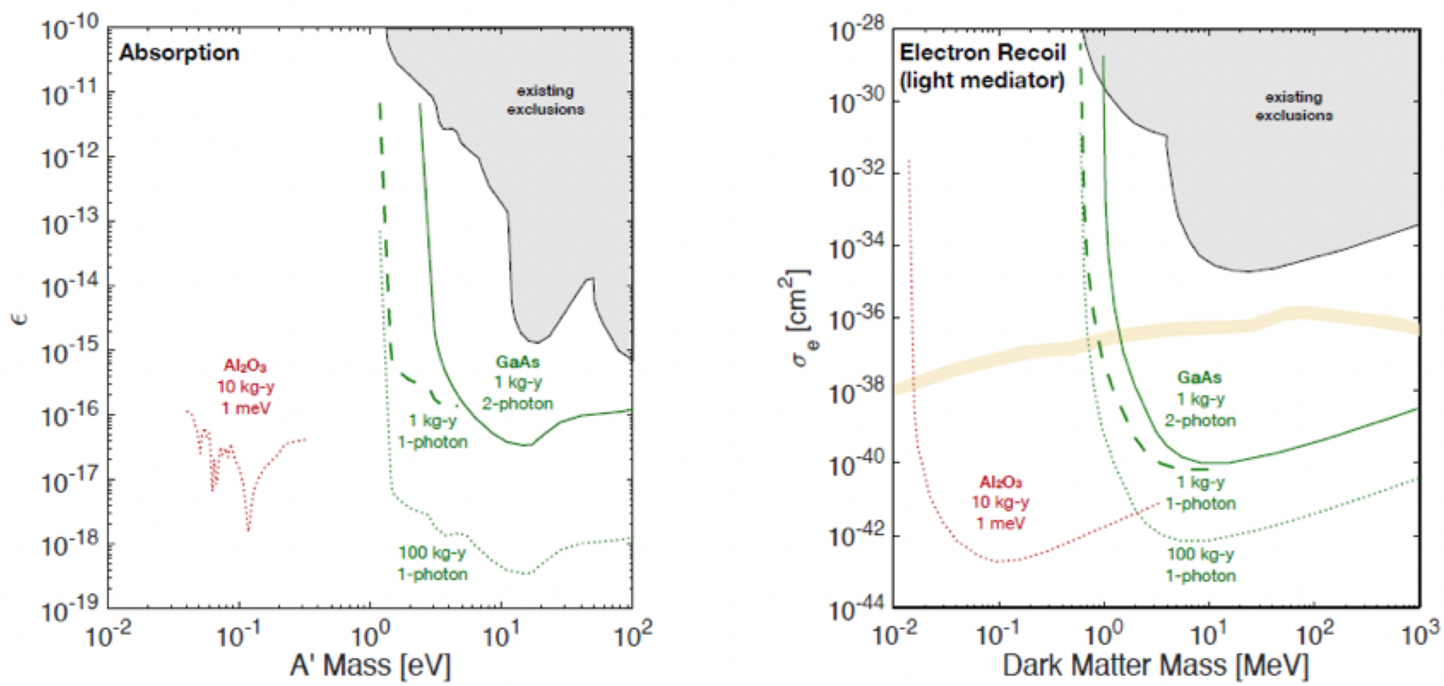


Readout of Solids Via Helium Evaporation

Generalized evaporation-based detector

Similar philosophy:

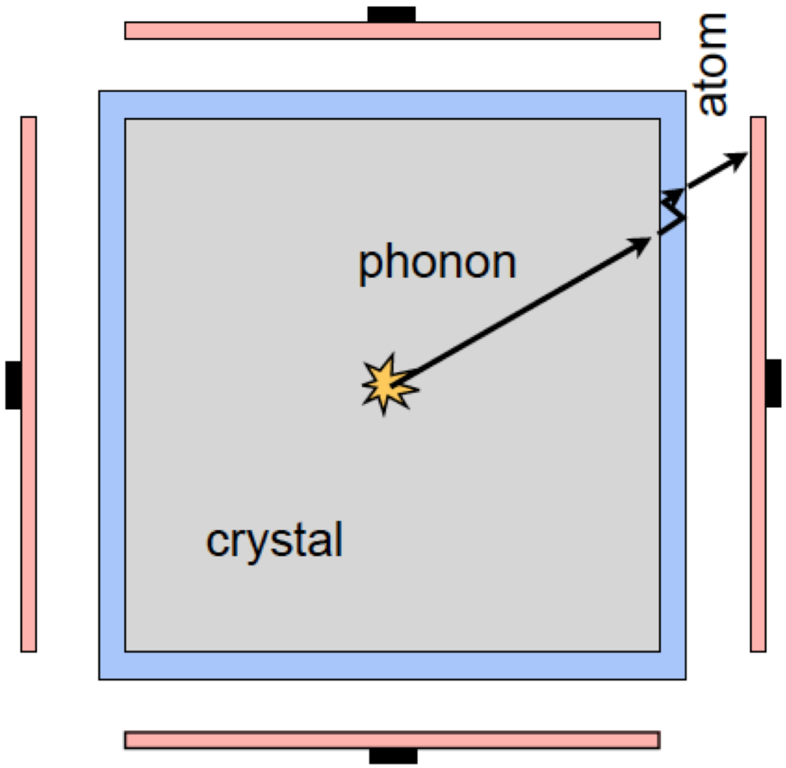
- Separate the target and the calorimetry
- Smaller absorber seen by TES array
- Use helium atoms to jump the gap

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



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 Slides

1)SPICE: Sub-ev Polar Interactions Cryogenic Experiment

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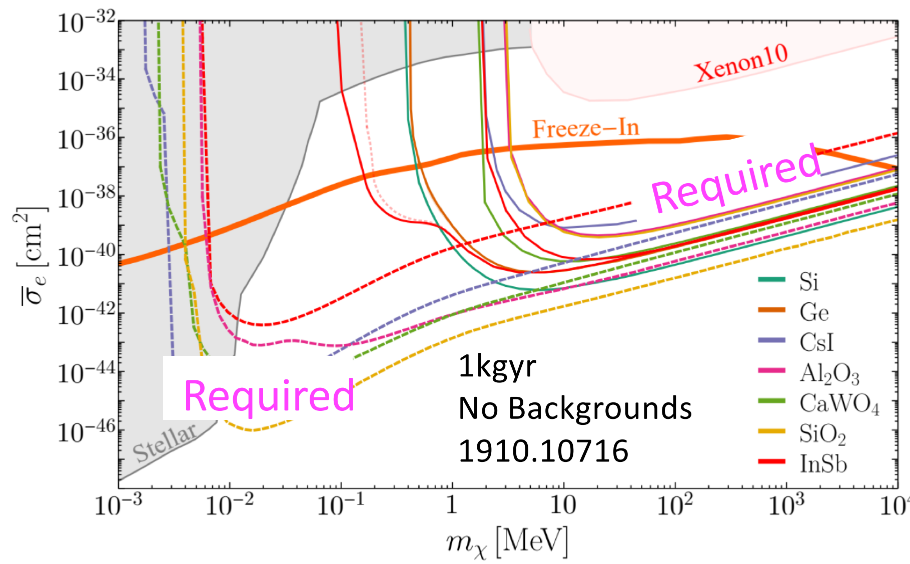

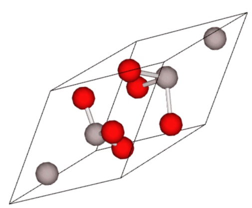

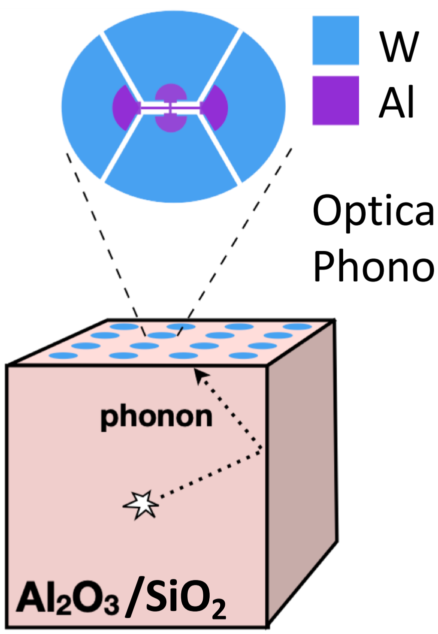

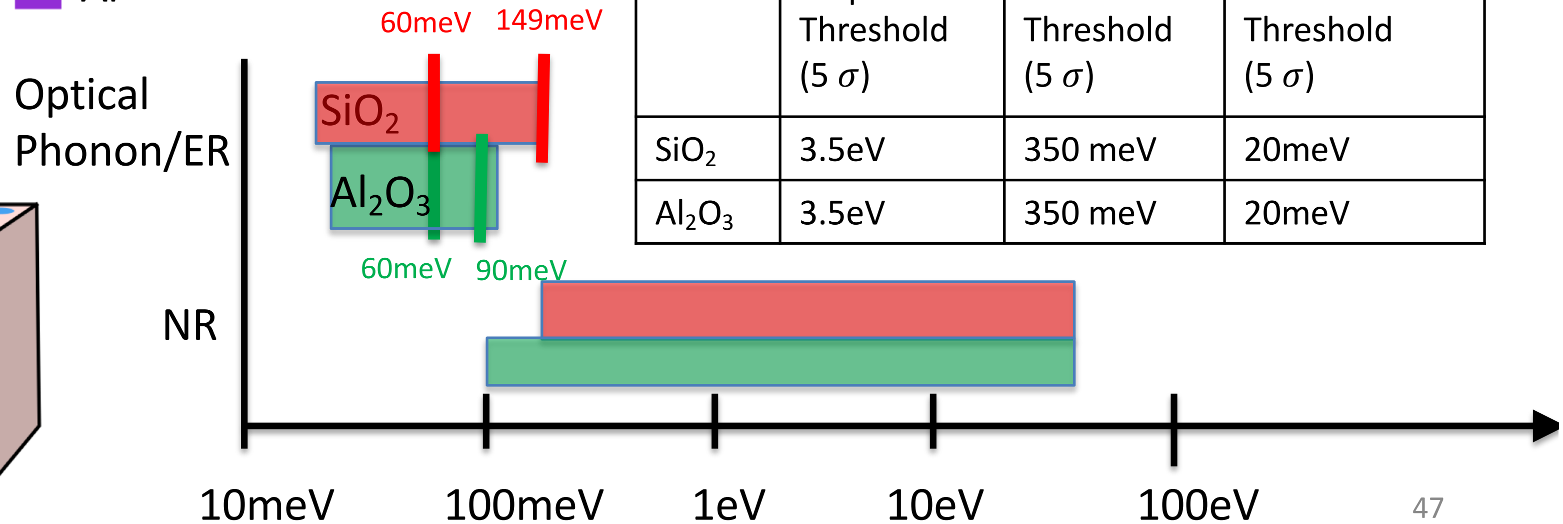

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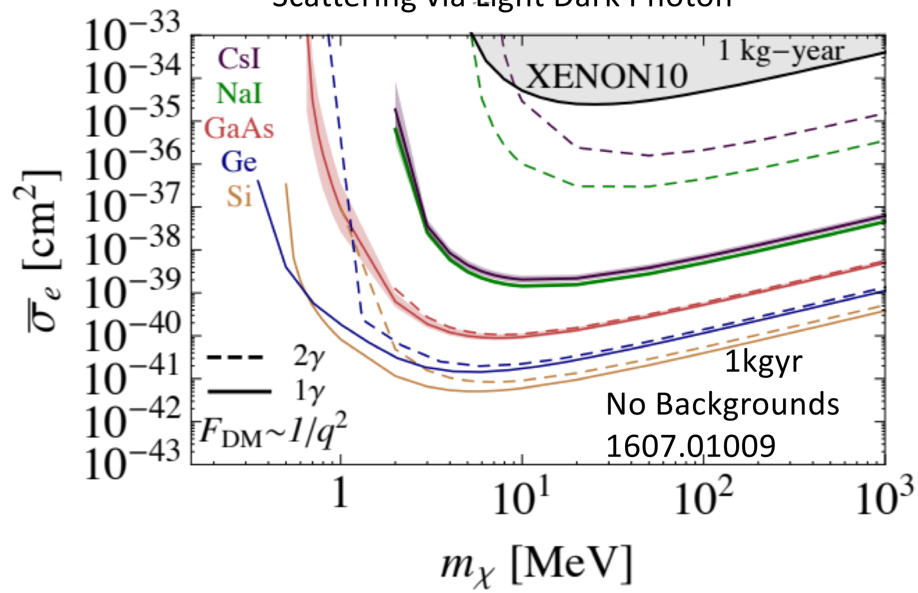

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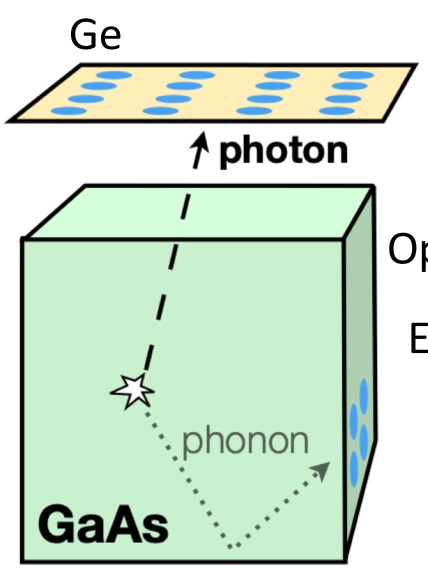
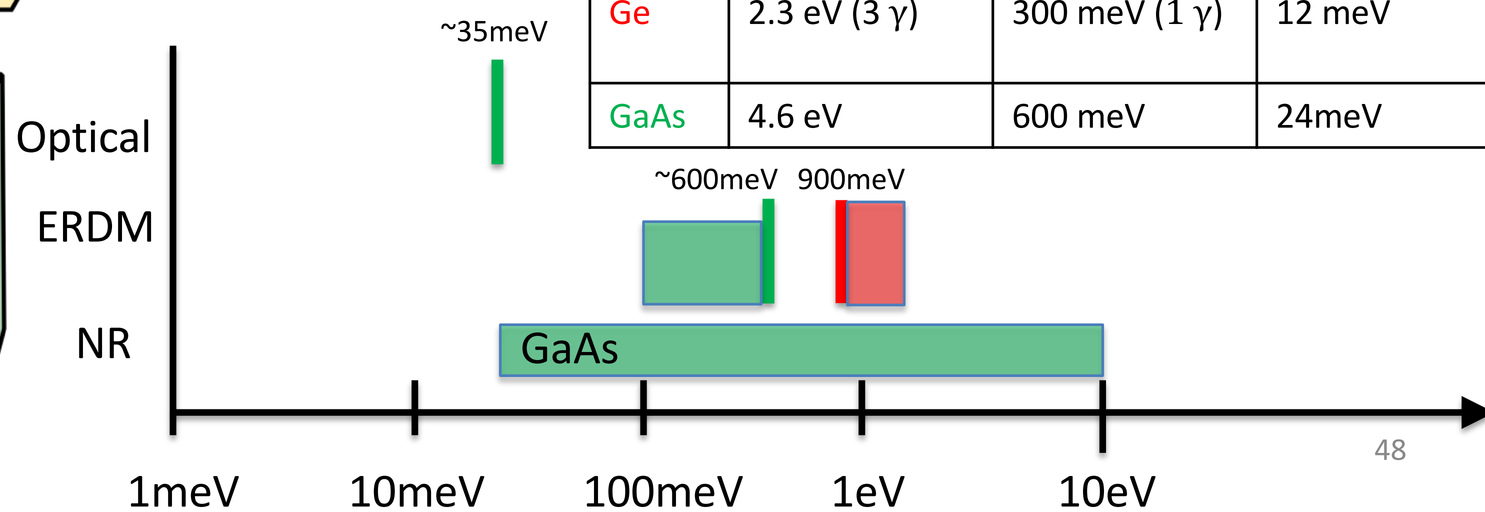
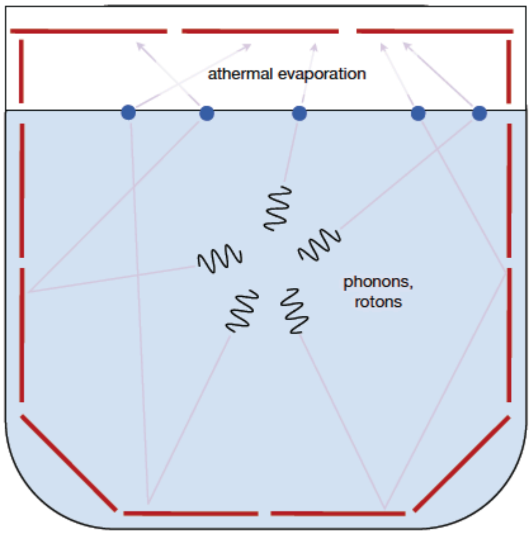
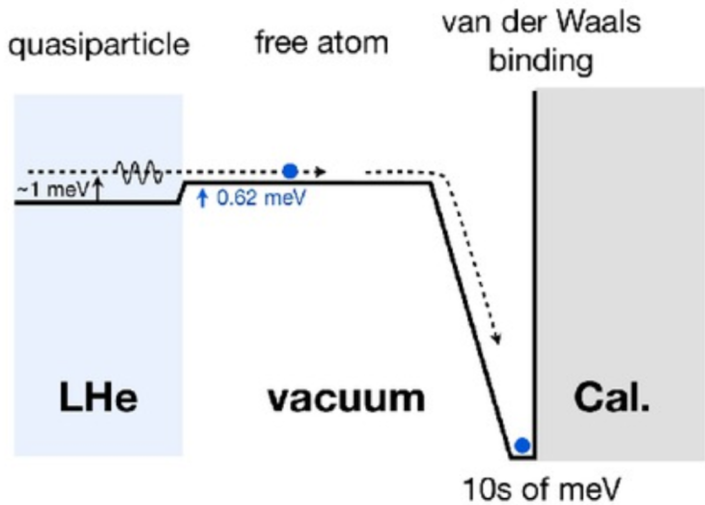


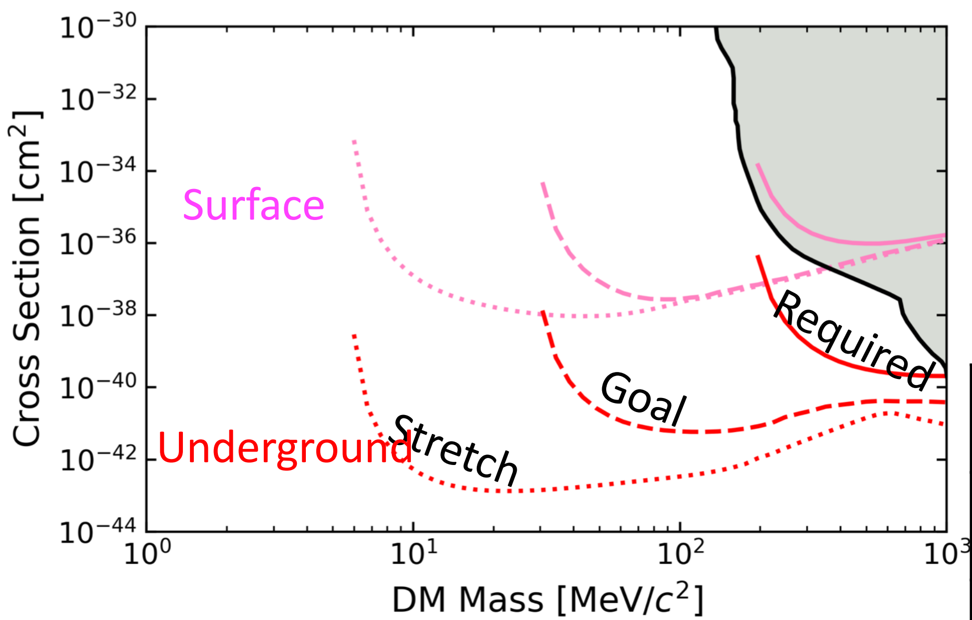


3) HeRALD: Helium Roton Apparatus for Light Dark matter



- 1810.06283
- Intrinsic Gain of ~x10 when He atom is adsorbed onto bare Si surface





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Si 4cmx4cm	6.7eV	900 meV	12 meV
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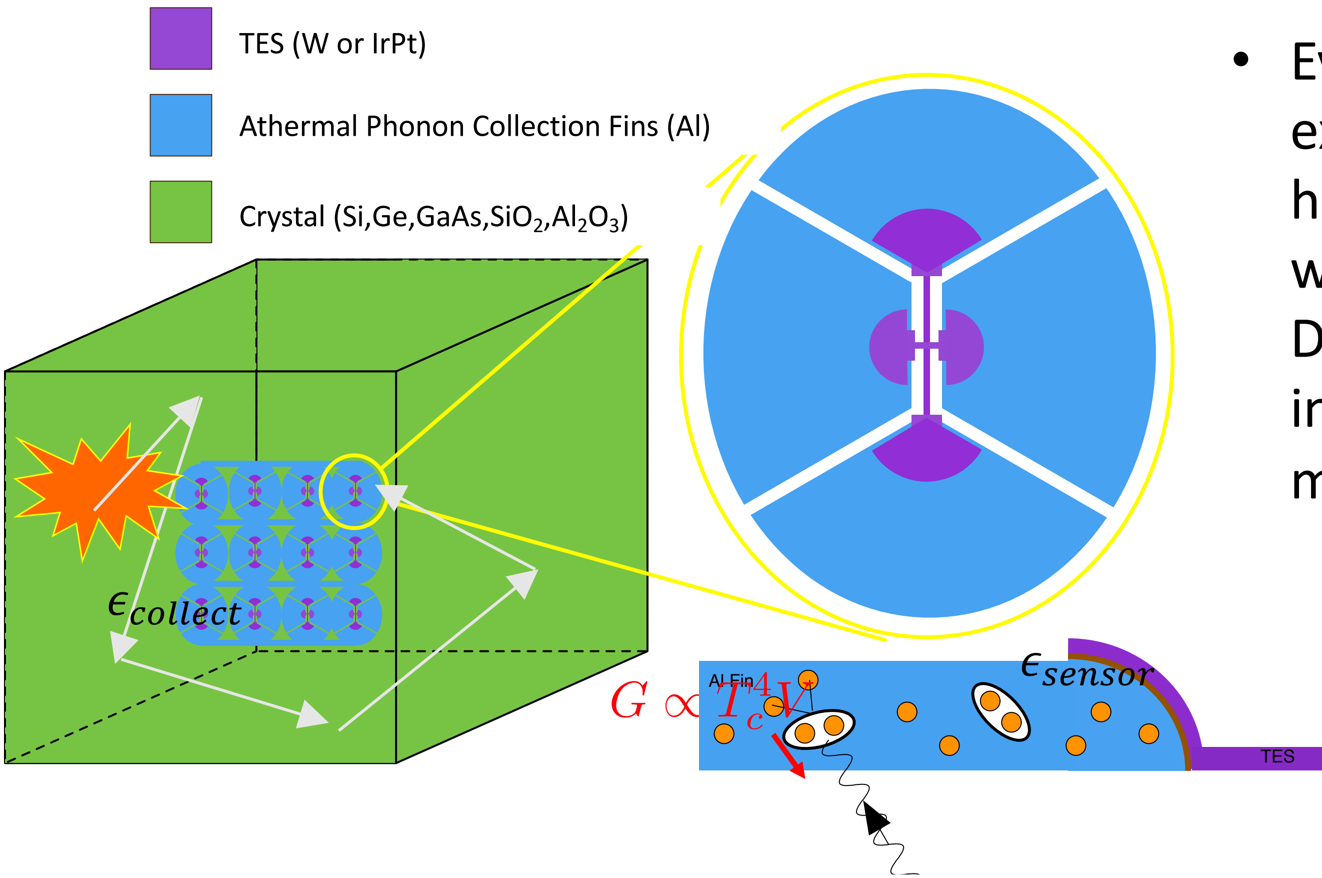
Athermal Phonon Detectors



- Everything identical except the substrate … having multiple targets with complementary DM science doesn't increase cost (time & money) significantly!

$$\sigma_E \sim \frac{\sqrt{4k_b T_c^2 G(\tau_{collect} + \tau_{sensor})}}{\epsilon_{collect}\epsilon_{sensor}}$$

Detector Performance Specifications

$$\sigma_E \sim \frac{\sqrt{4k_bT_c^2G(\tau_{collect}+\tau_{sensor})}}{\epsilon_{collect}\epsilon_{sensor}}$$

Too close to bath temperature

Sensor Characteristics	**Required**	**Goal**	Stretch Goal
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W/Al interface transmission probability $\epsilon_{W/Al}$	10^{-4}	10^{-4}	10^{-3}

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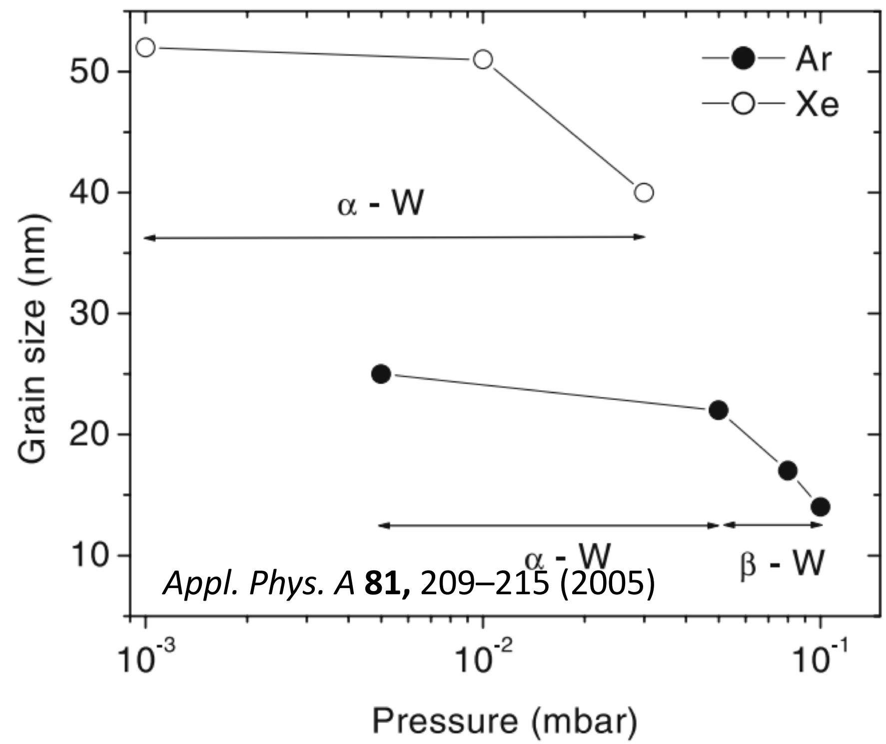
1.2.2.1: Low Tc W TES Fabrication (TAMU)

- What sets W T_c? 2 crystal configurations
  - Alpha: T_c=15mK
  - Beta: T_c~ 3K
- Goal: produce a stress free, alpha phase W film
- Bouziane et al: Xe plasma produces better alpha films

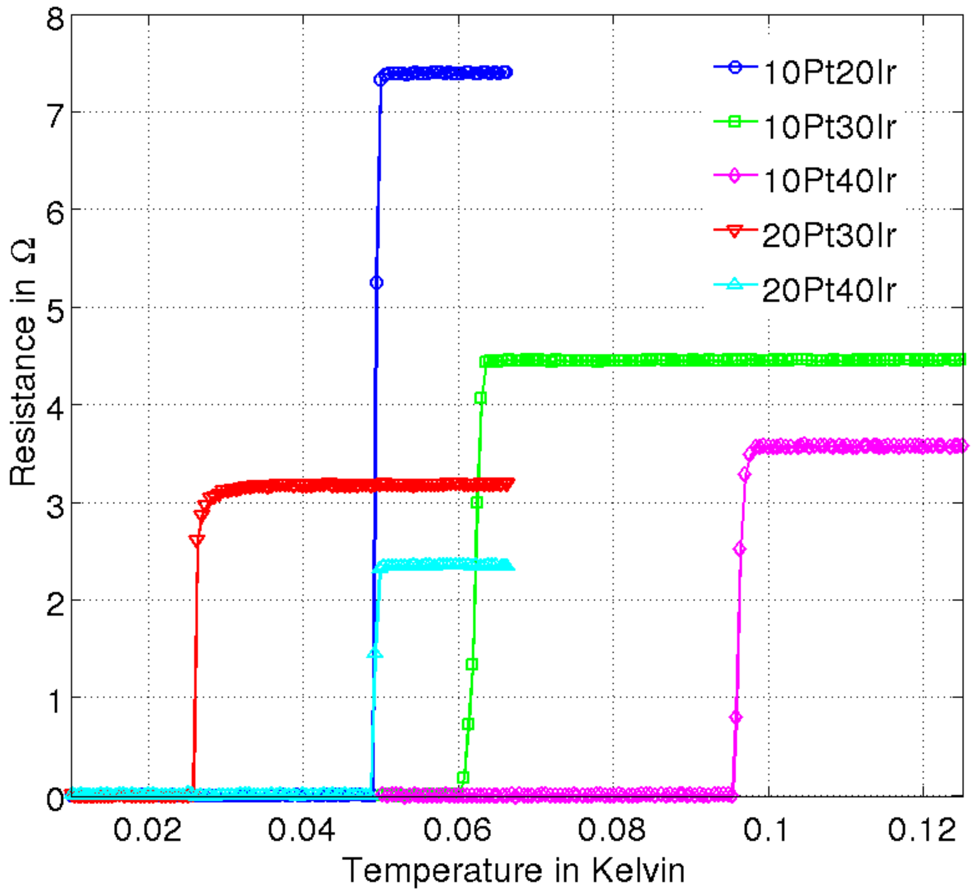


Appl. Phys. A **81,** 209–215 (2005)

- Year 1 TESSERACT Progress: Produced W film with T_c= 19mK
  New, have hit goal Tc
- Future Work Program:
  - Optimize low Tc film recipe for reproducibility and for maximum transition sharpness.

1.2.2.2: Low Tc IrPt Films (Argonne)

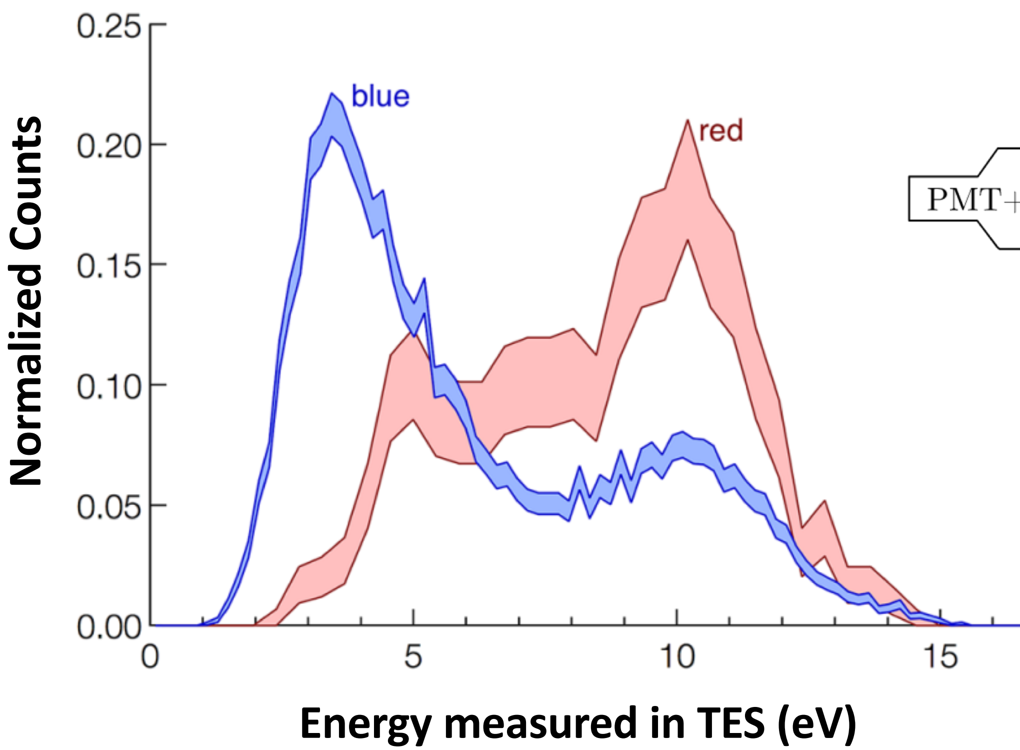
IrPt film Tc measurements

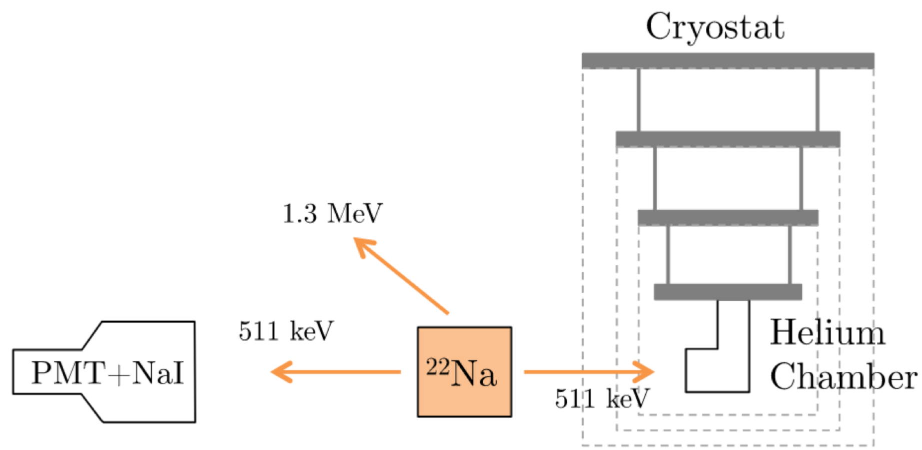


- Argonne has produced 25mK IrPt films … **nearing goal**
- Next steps:
  - map out space between 15-25mK
  - Test reproducibility
  - Measure TES characteristics

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

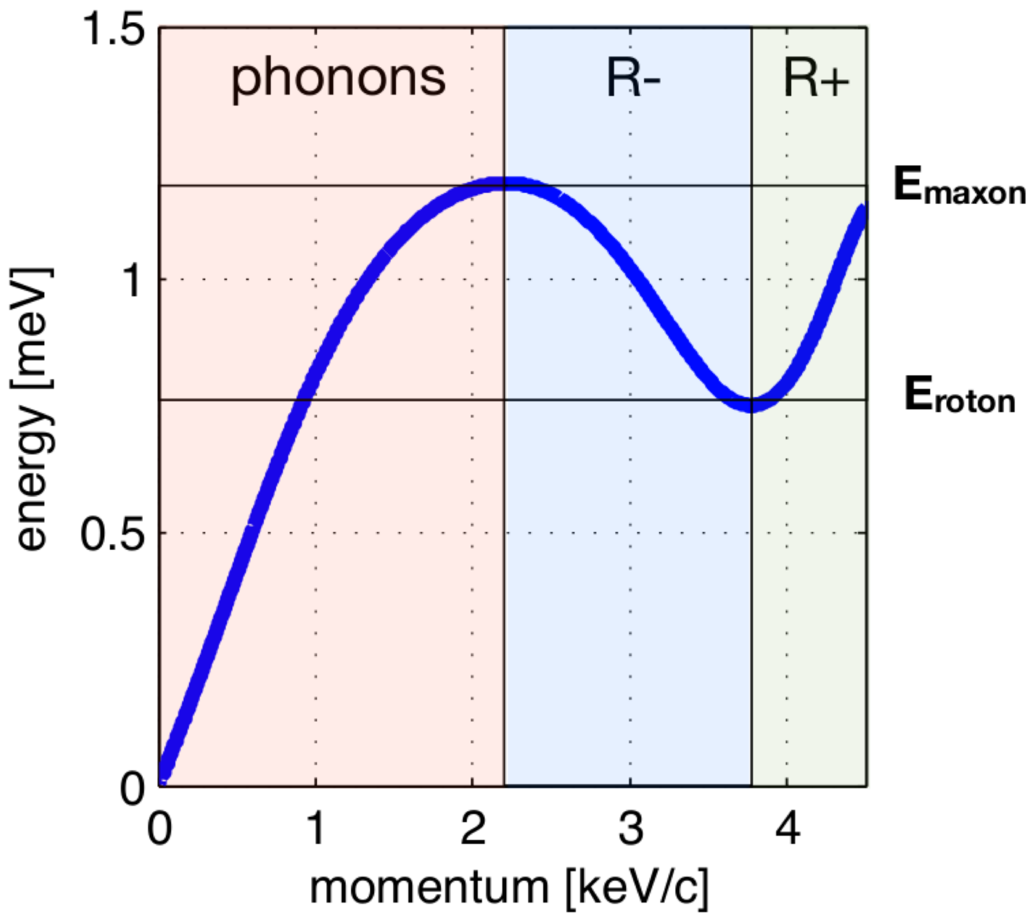
Quasiparticles in ^{4}He

Quasiparticles: collective excitations in superfluid helium

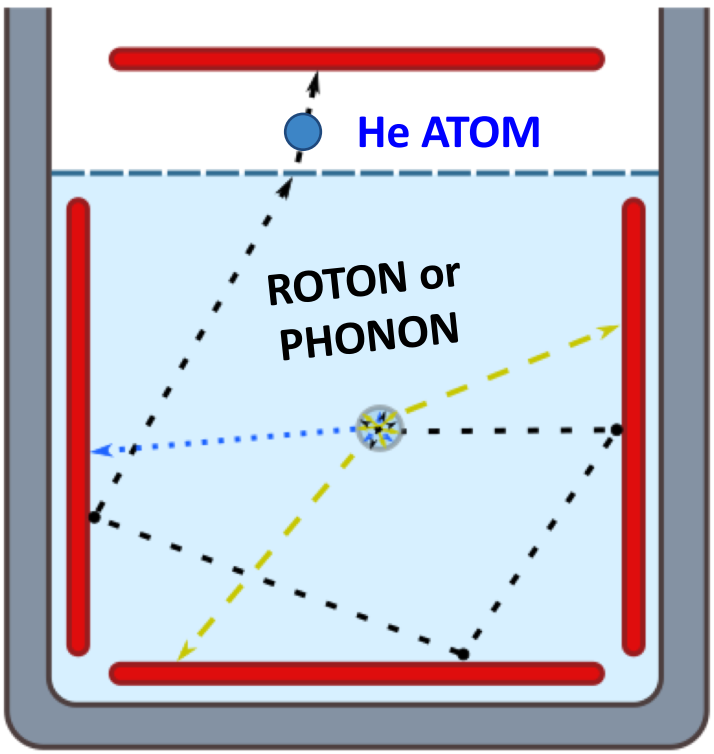
Long-lived, speeds of ~100 m/s

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



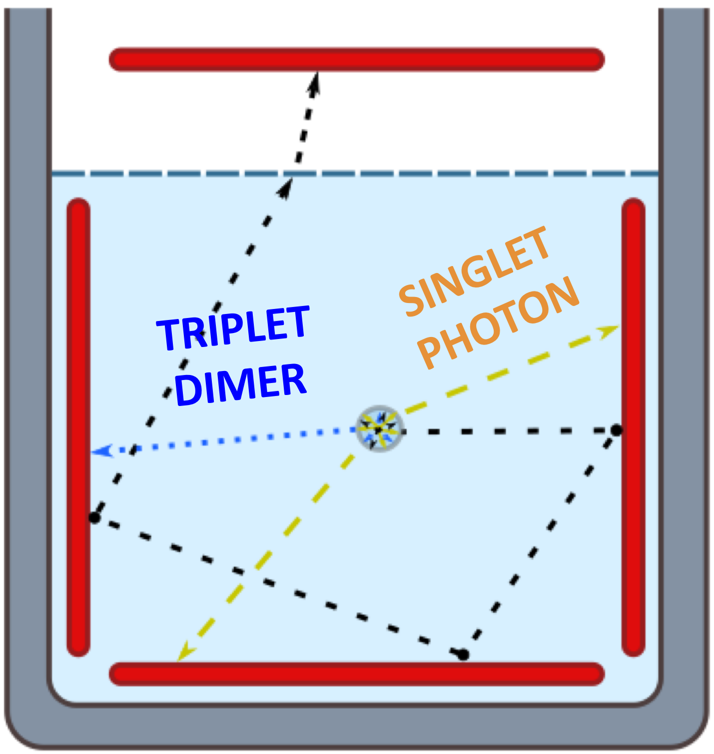
Recoils produce ~0.8 meV phonons and rotons

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

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**

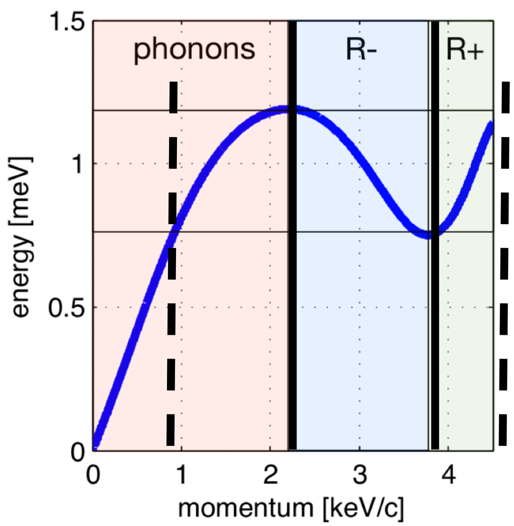
IR (~1 eV)

Quasiparticle Propagation

In ^{4}He bulk, quasiparticles move freely

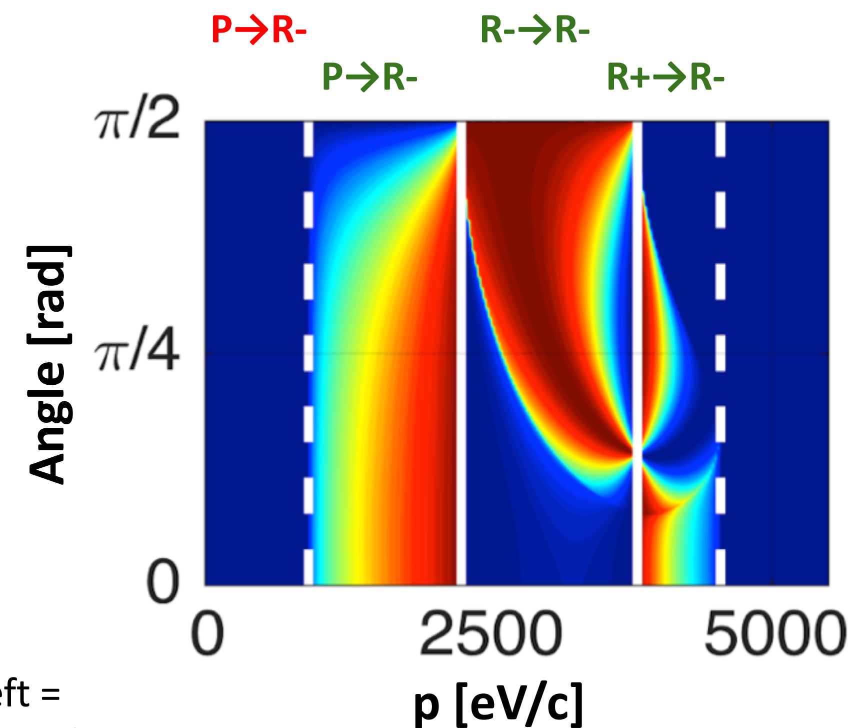
At interface, can be transmitted, reflected, or transformed (if E conserved)

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



Note:
Black lines at left =
White lines at right

Reflection as R-
(allowed; forbidden)



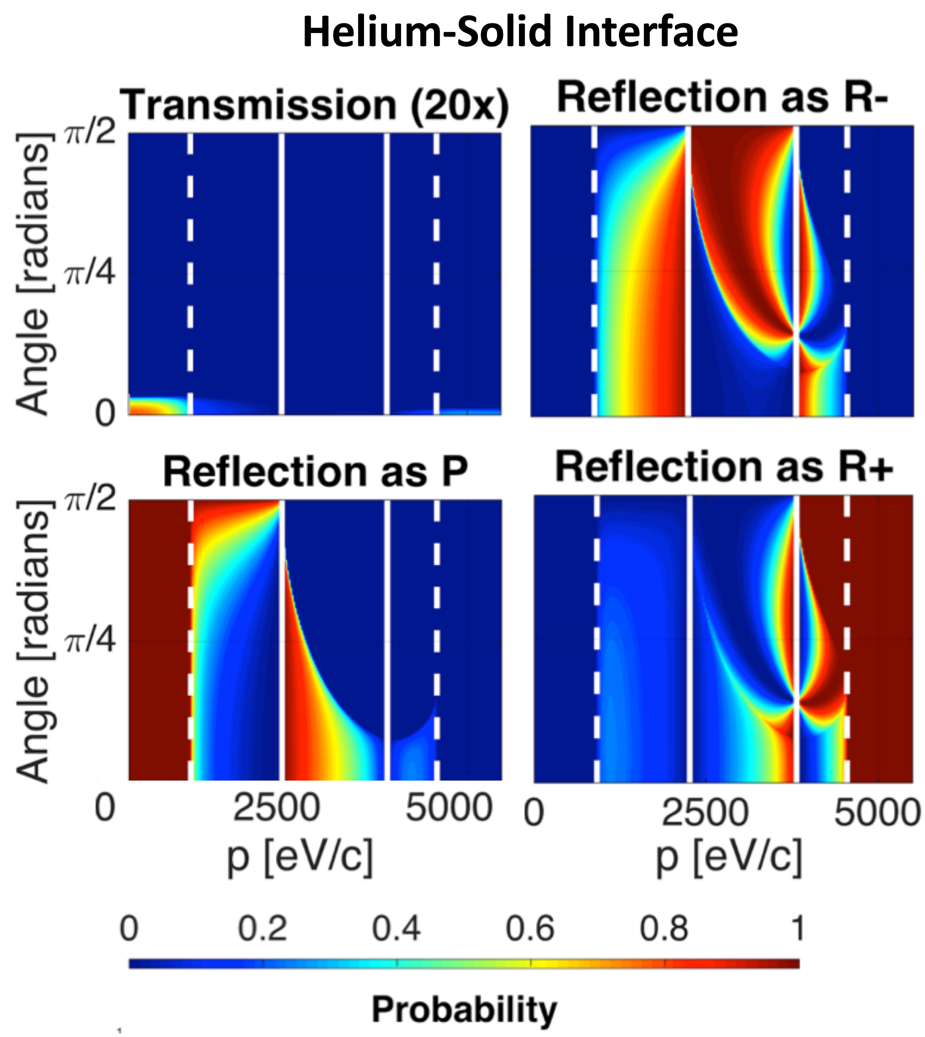
Quasiparticle Propagation

Simulated all reflection/transmission probabilities [†]

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

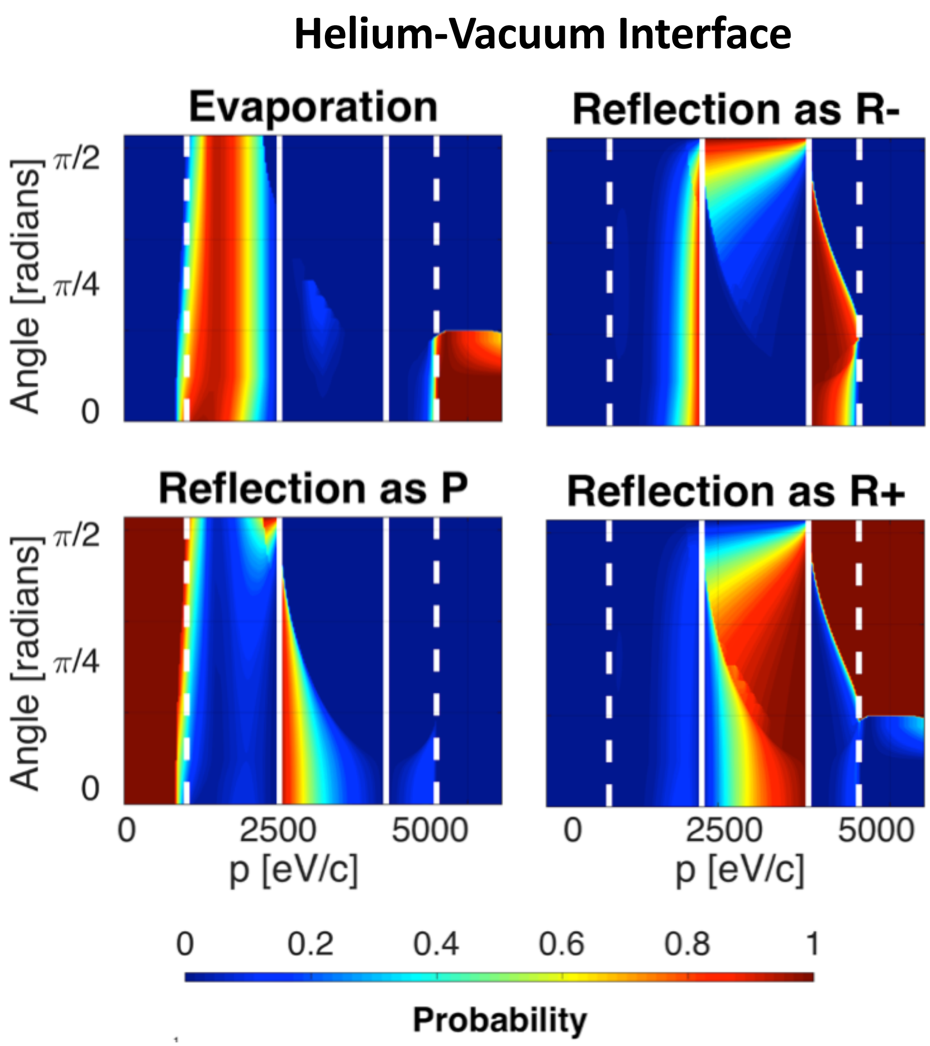
Reflection as same flavor most likely, but significant chance of changing flavor

[†] 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

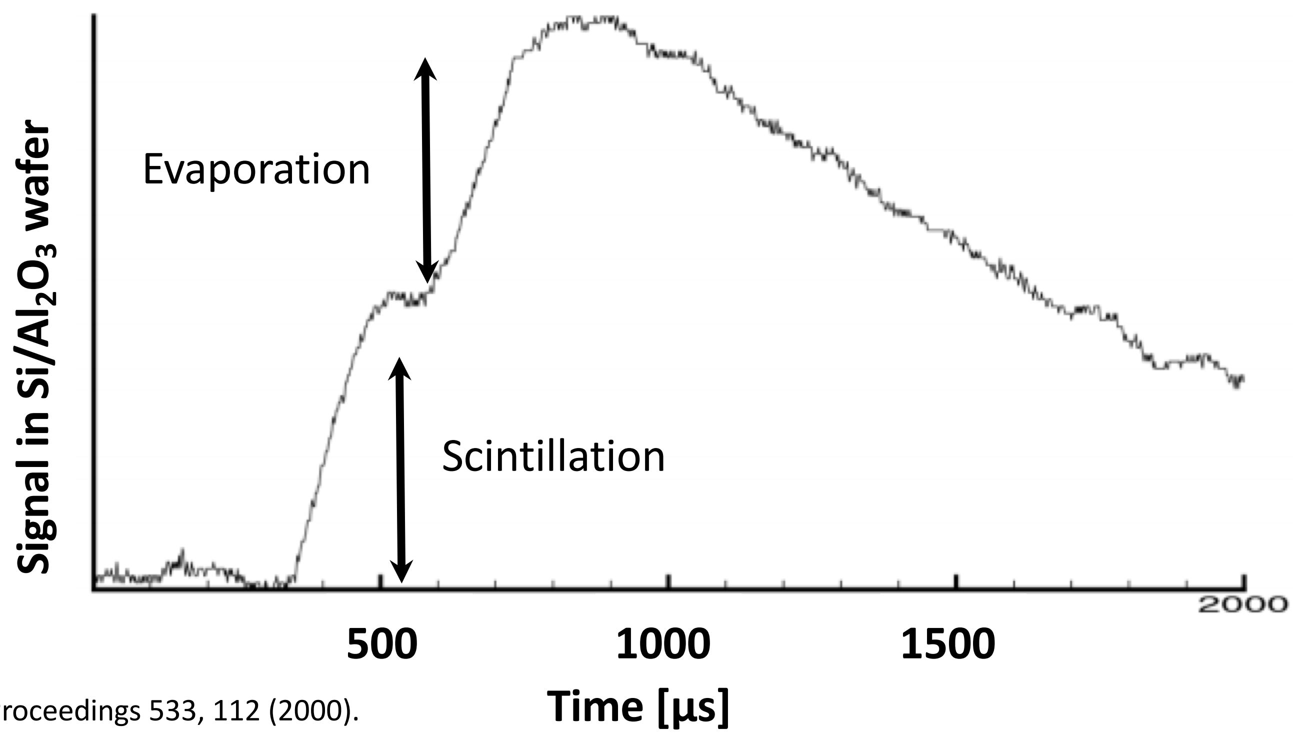


Previous work by HERON

HERON: proposed *pp* neutrino observatory

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

Achieved 300 eV threshold at 30 mK



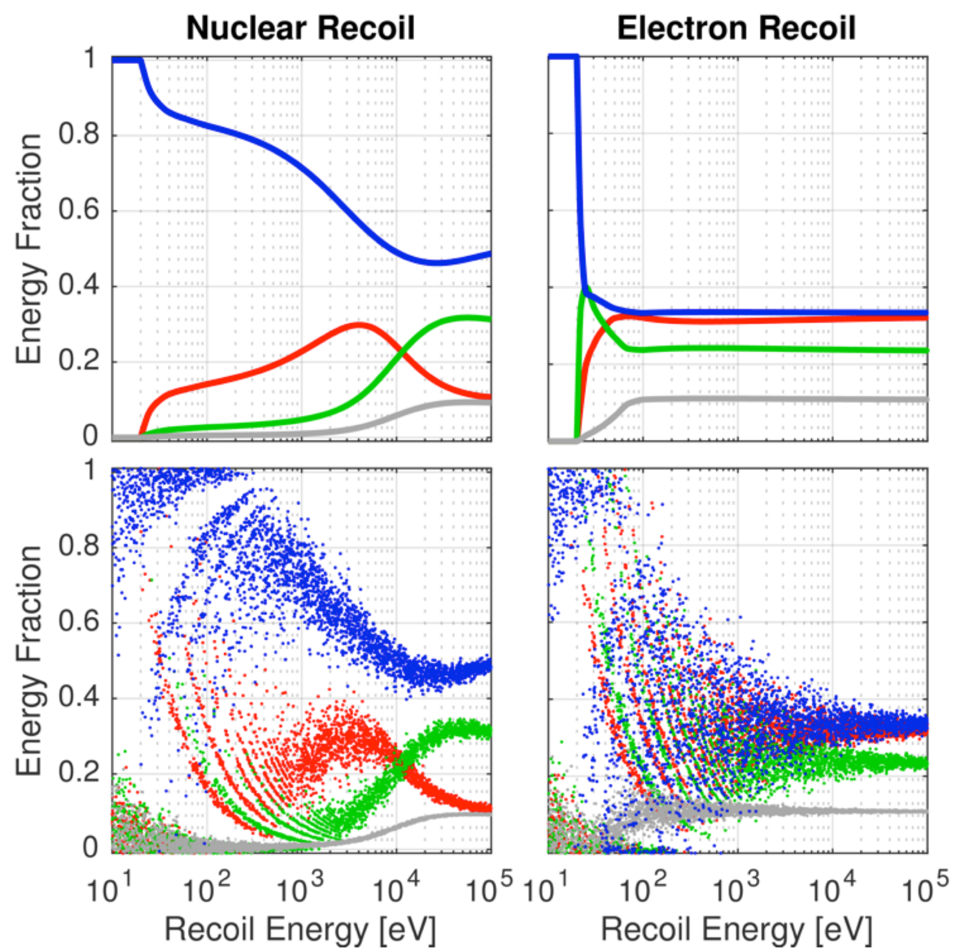
Source: J. S. Adams et al. AIP Conference Proceedings 533, 112 (2000).
Also see: J. S. Adams et al. Physics Letters B 341 (1995) 431-434.

Energy Partitioning

Means

Singlet
Triplet
IR
Phonons/Rotons

Simulated Poisson Statistics



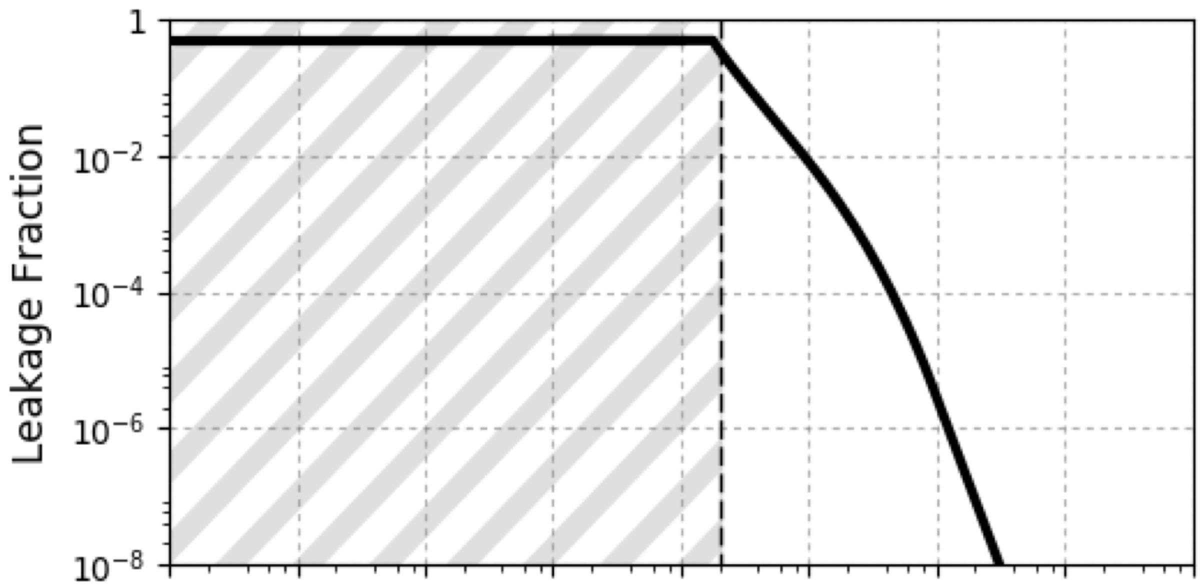
Discrimination

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

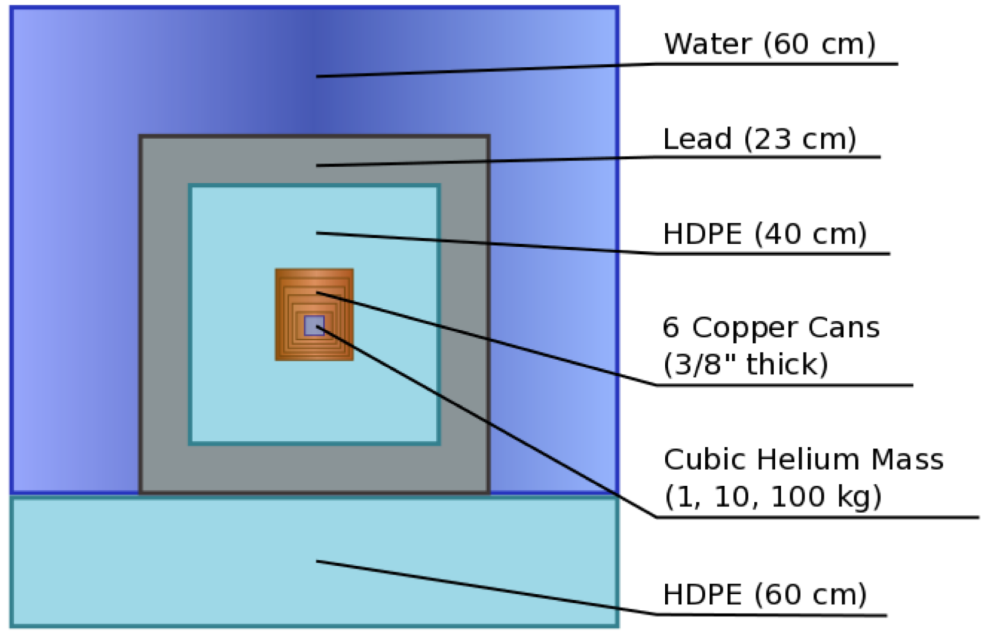
ER acceptance at 50% NR acceptance



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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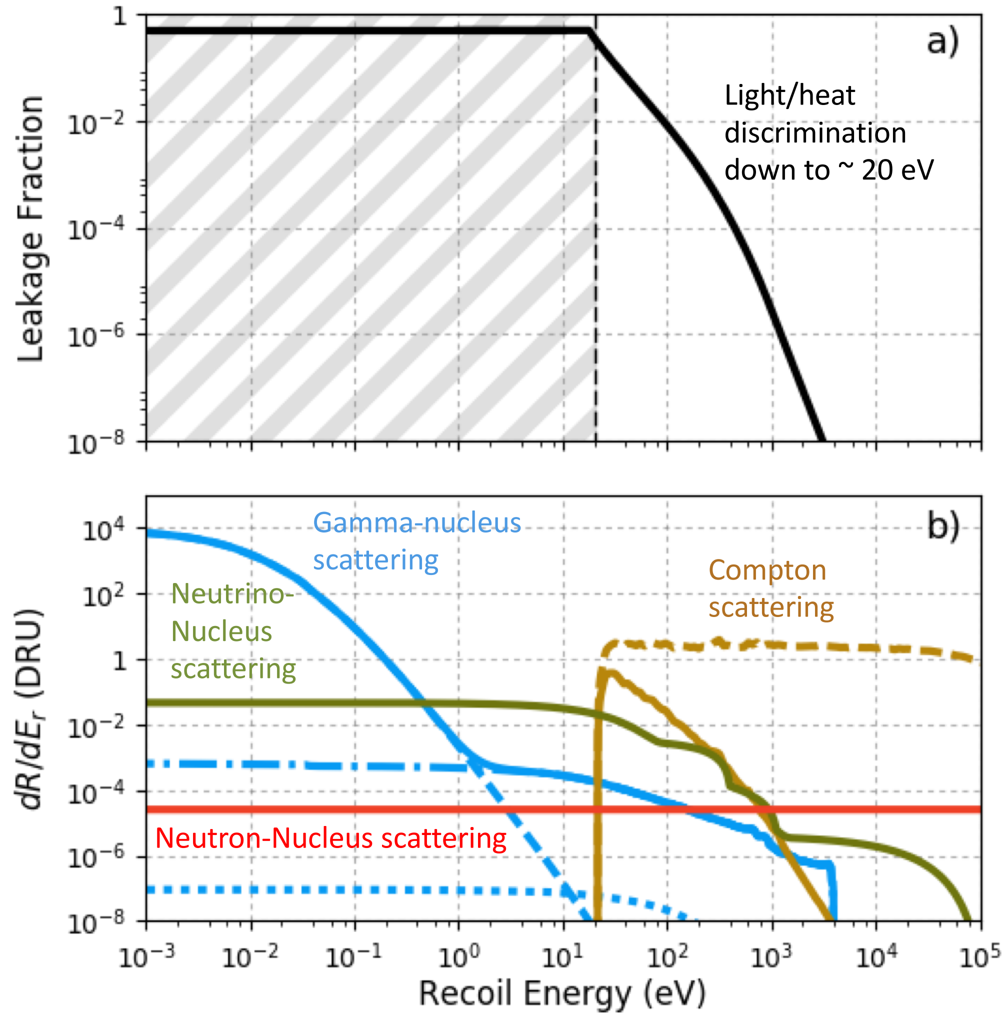
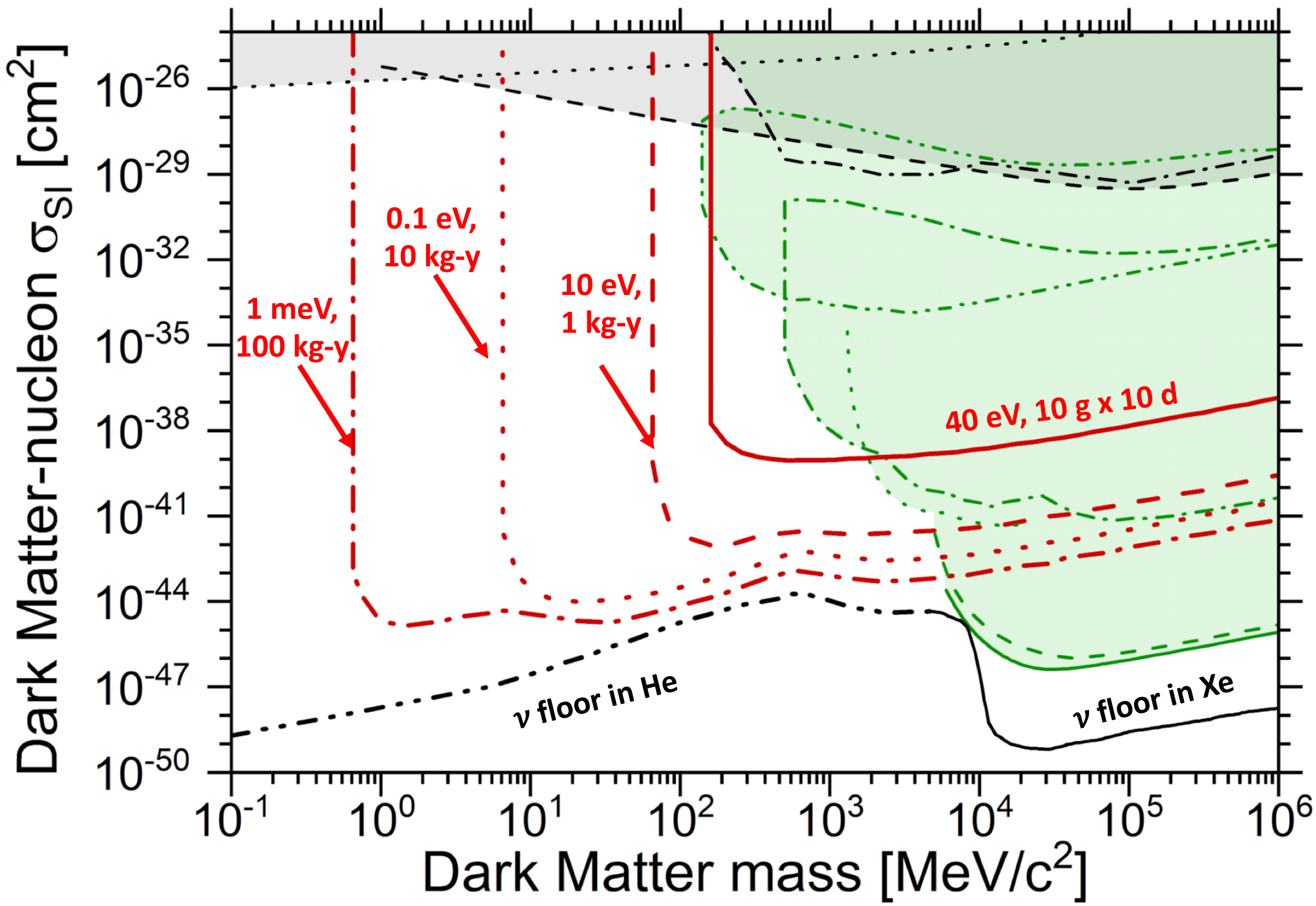
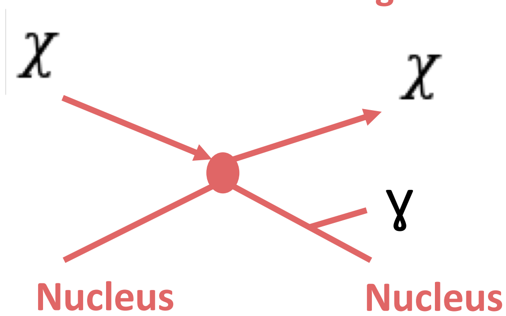
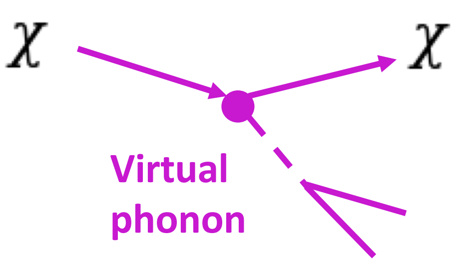


Projected Sensitivity

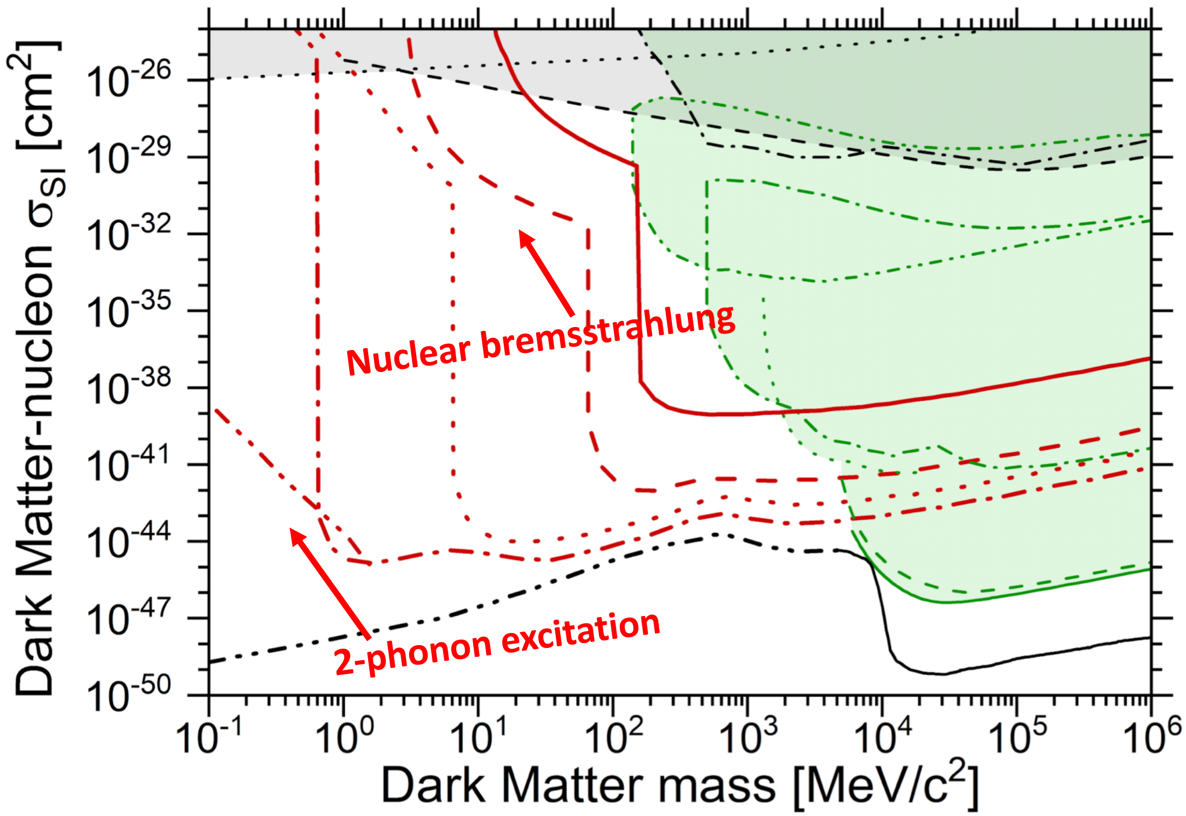


Extending Sensitivity





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)

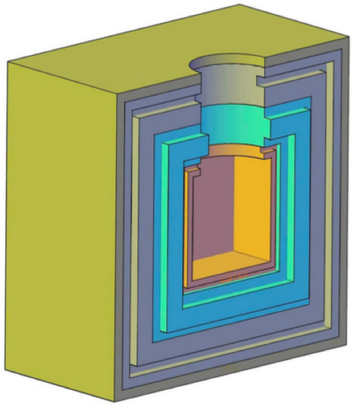


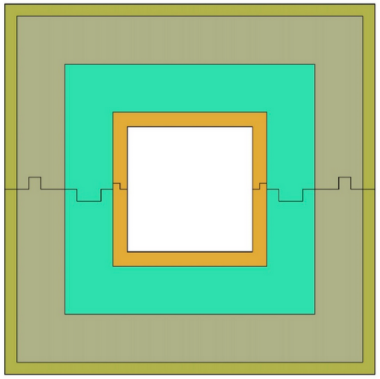
Progress on Shielding Design

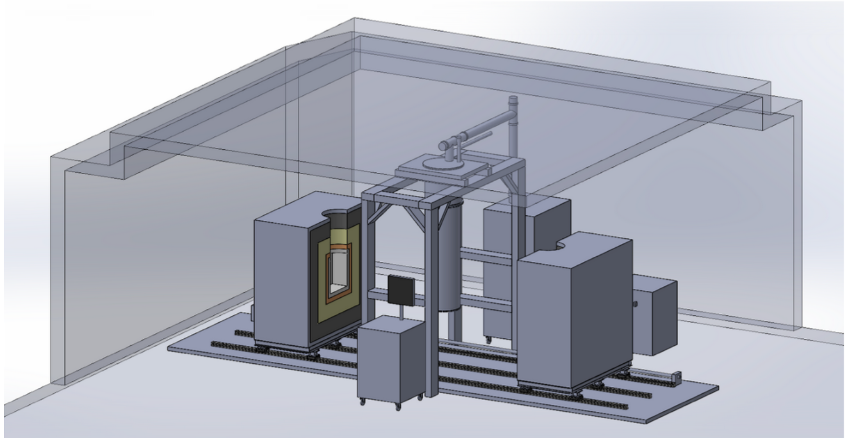
The experiments will be operated in an underground laboratory. Discussions are just beginning with underground labs.

The shielding design has converged on a compact lead/polyethylene approach. Shielding will come off on rails so as to enable quick and straightforward access to the cryostat. There will be two copies of the setup, for enabling both SPICE and HeRALD.

Significant emphasis on vibrational and EM noise suppression. Substantial R&D effort is being devoted to reducing these instrumental backgrounds, and this R&D will feed into the engineering design.

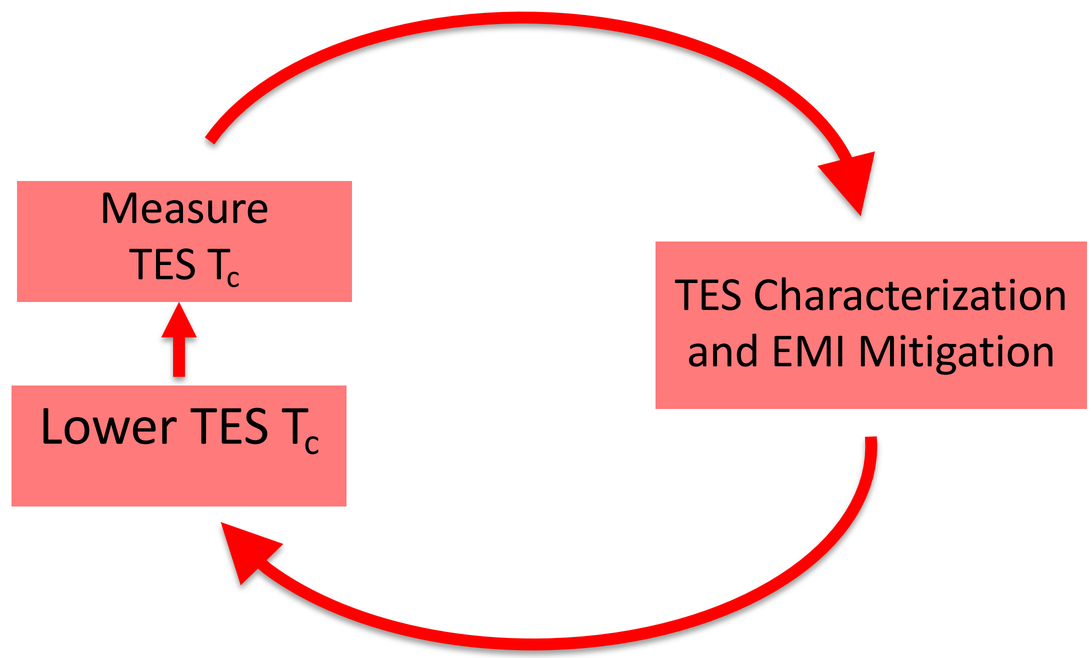






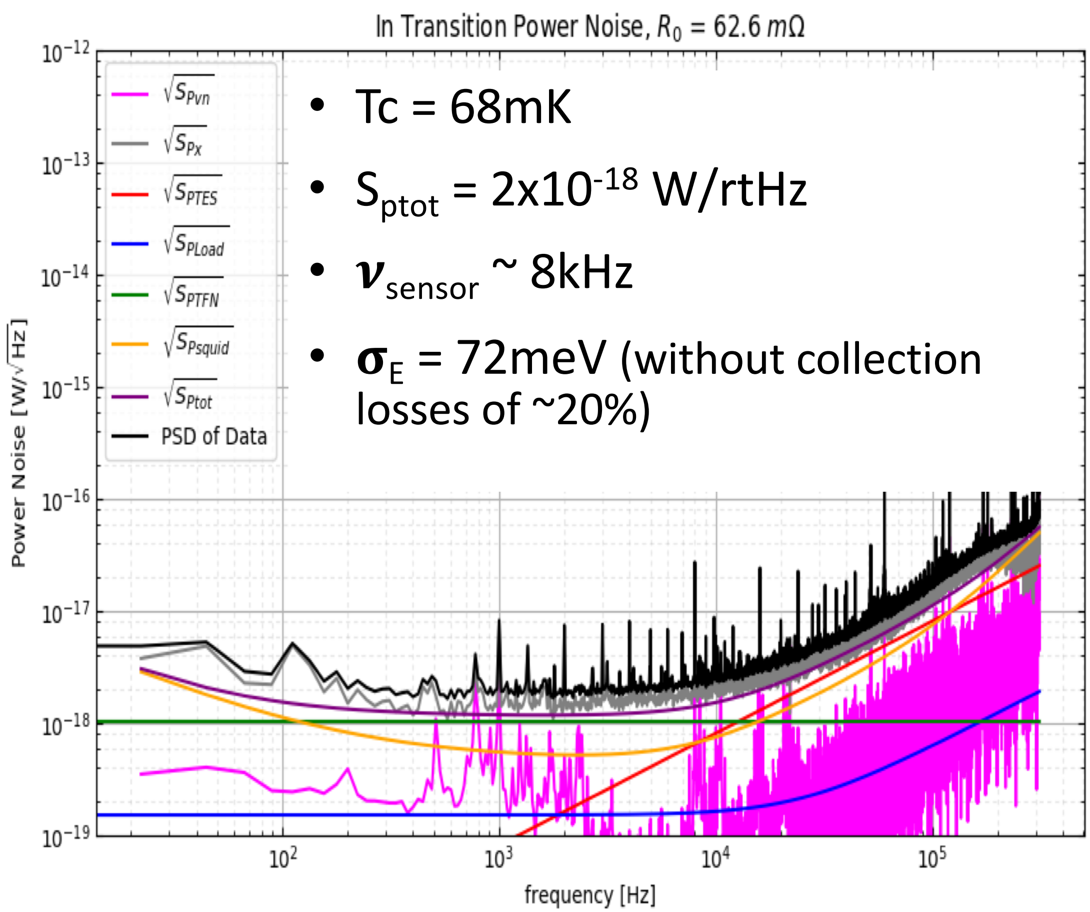
Major R&D goal: Develop ultra sensitive TES

Work ongoing on fabrication (TAMU and ANL) and testing (UC Berkeley, LBNL, UMass)

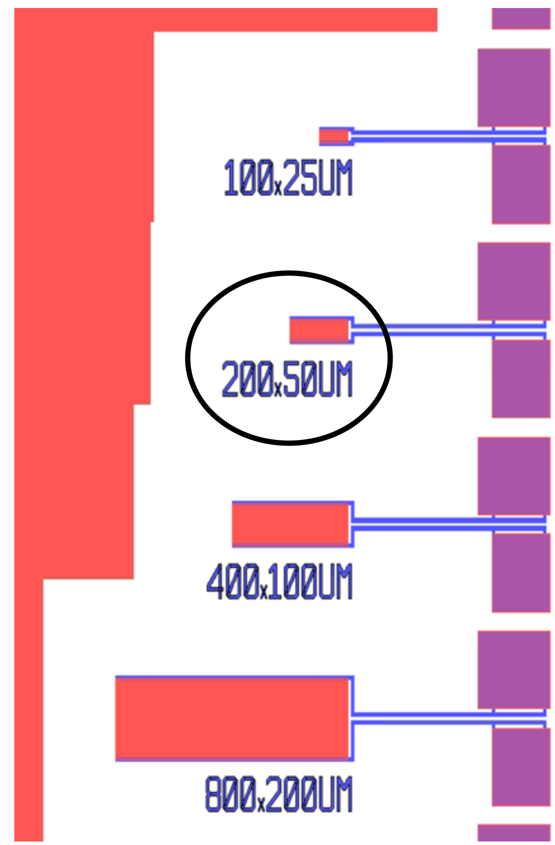


Recent Progress:
TES R&D from M. Pyle et al.

Light Mass Dark Matter Experimental Driver:
Energy Threshold

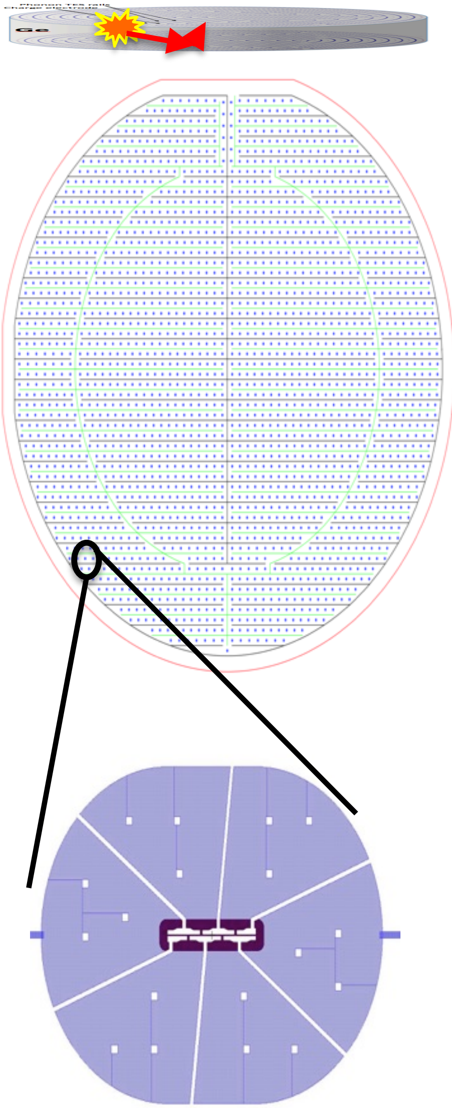


- Tc = 68mK
- S_{ptot} = 2x10^{-18} W/rtHz
- ν_{sensor} ~ 8kHz
- σ_E = 72meV (without collection losses of ~20%)

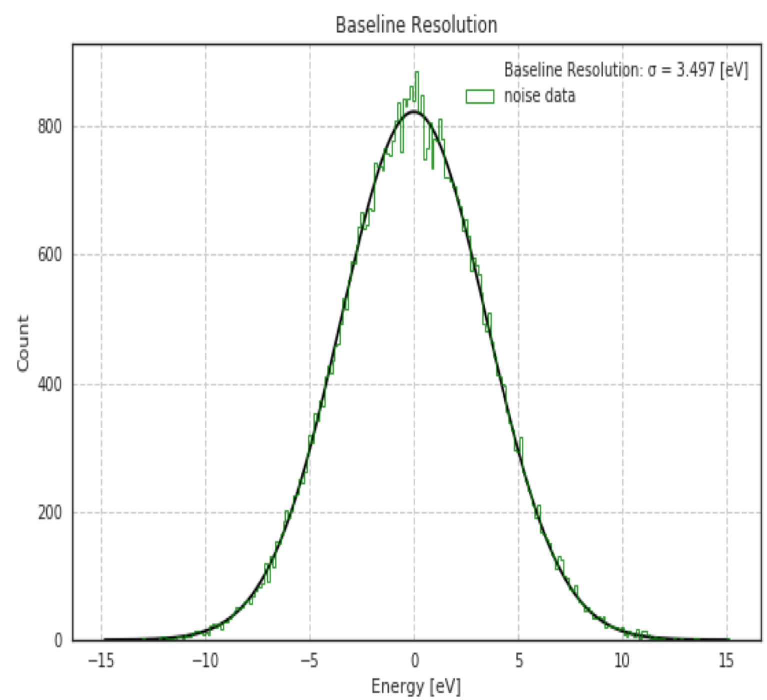


- Environmental noise pickup not problematic for > 100meV experimental applications
- Measured sensitivity with x1.4 of theoretical sensitivity

Recent Progress: Large Area Photon Calorimeters



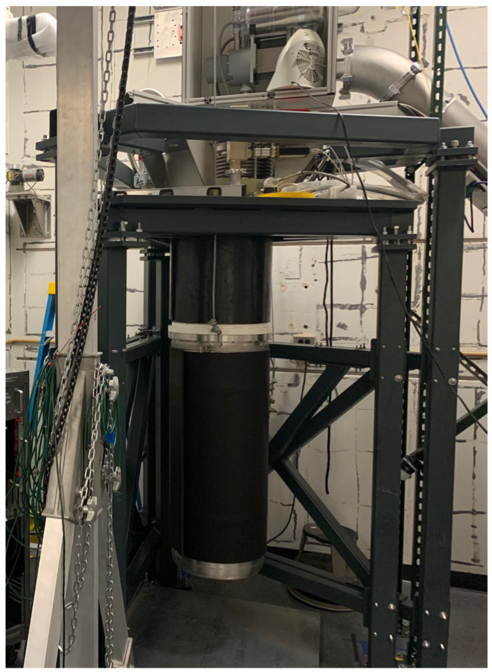
- 3” diameter 1mm thick Si wafer (45.6 cm^2)
- Distributed athermal phonon sensors
  - Athermal Phonon collection time estimated to be ~20us
  - 2.5% sensor coverage
- Tc= 41.5mK
- **17% Athermal Phonon Collection Efficiency**
- **Measured Baseline σ_E =3.5 ± 0.25 eV**



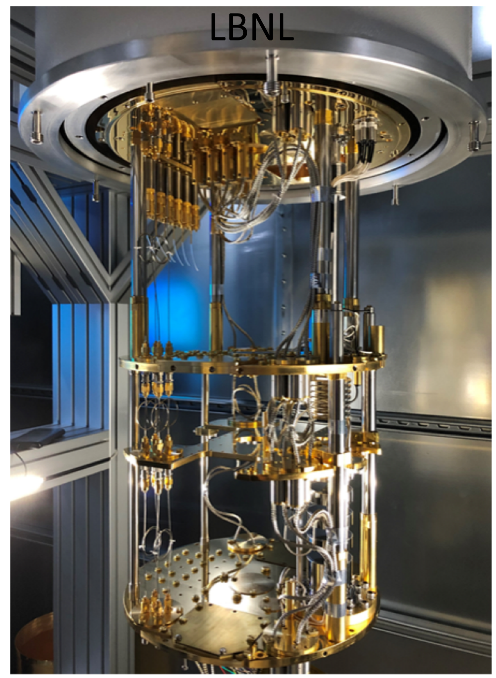
SPICE/HeRALD testbeds

Leiden MNK126-500
McKinsey Group @ UCB

CryoConcept UQT-B 200
Pyle Group @ UCB



BlueFors LD-400
Detector Group @ LBNL

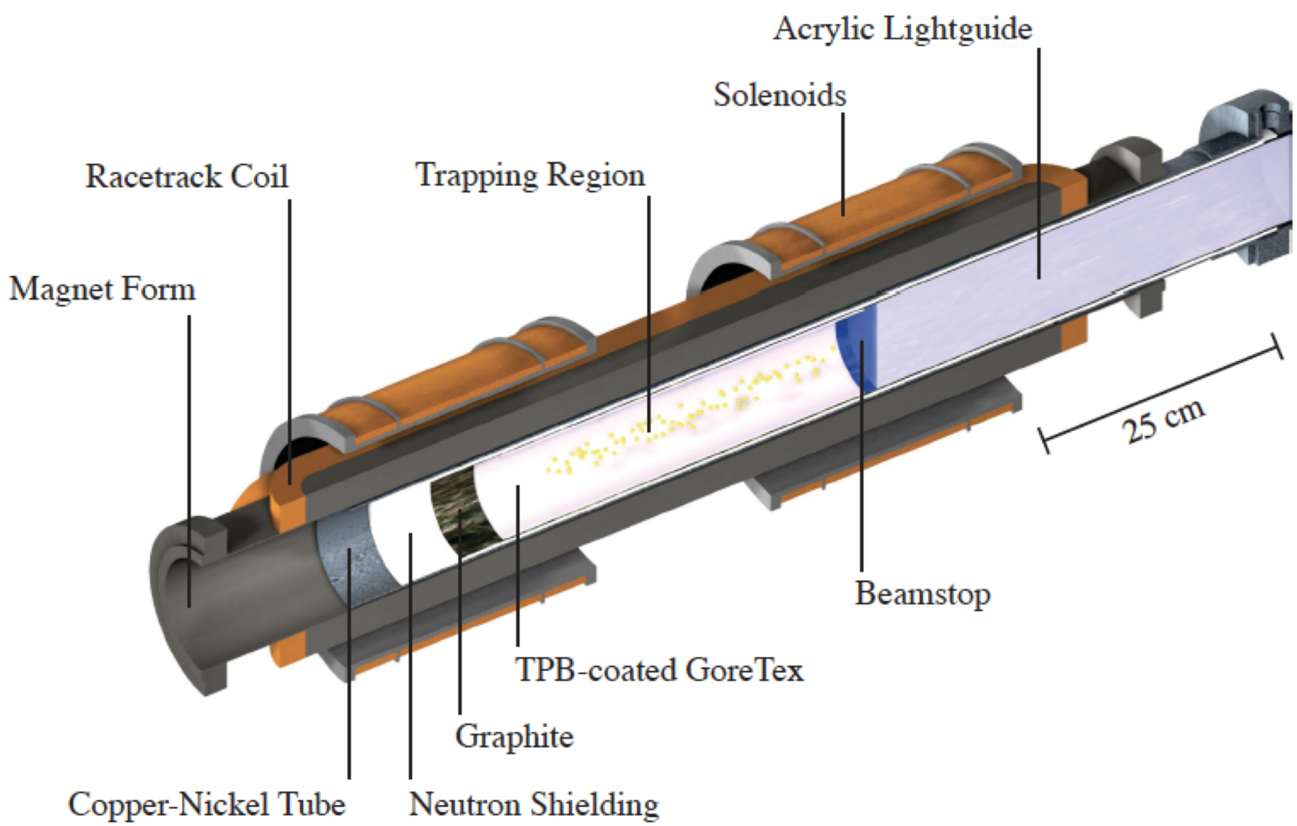


CryoConcept HEXADRY
UQT-B 400
H

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).

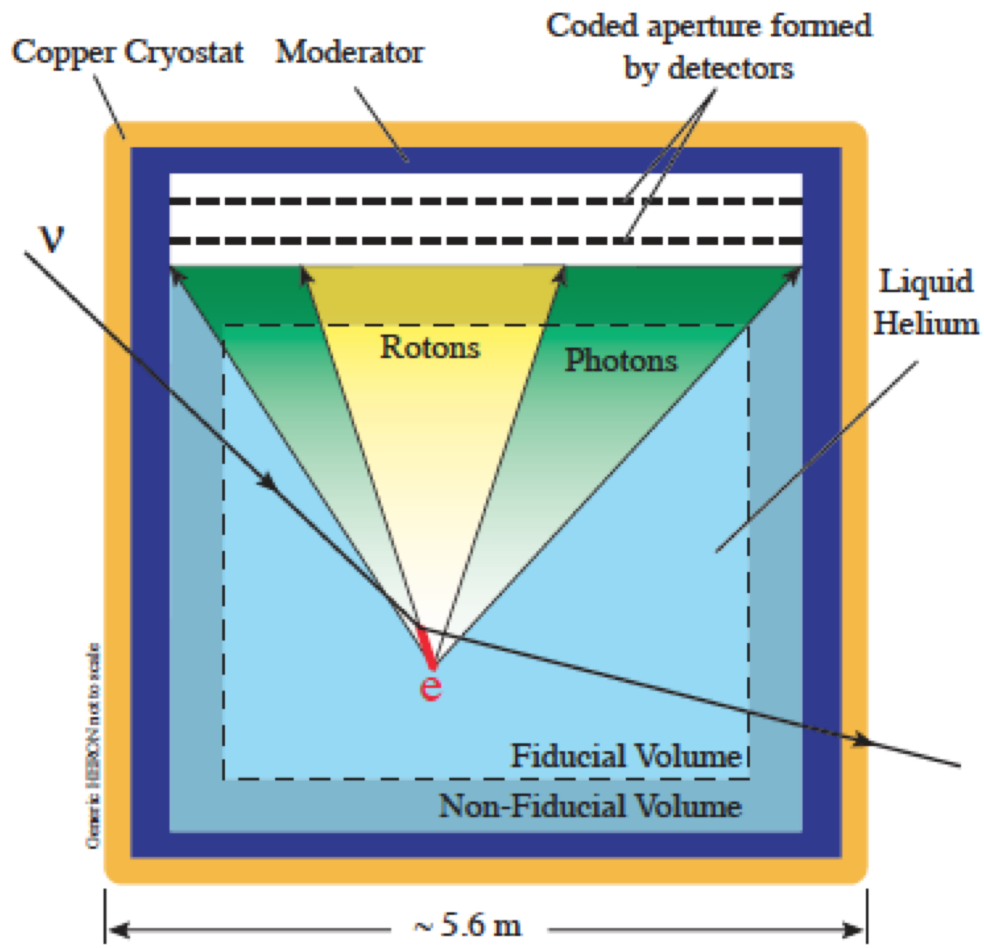


Superfluid helium-4 as a detector material

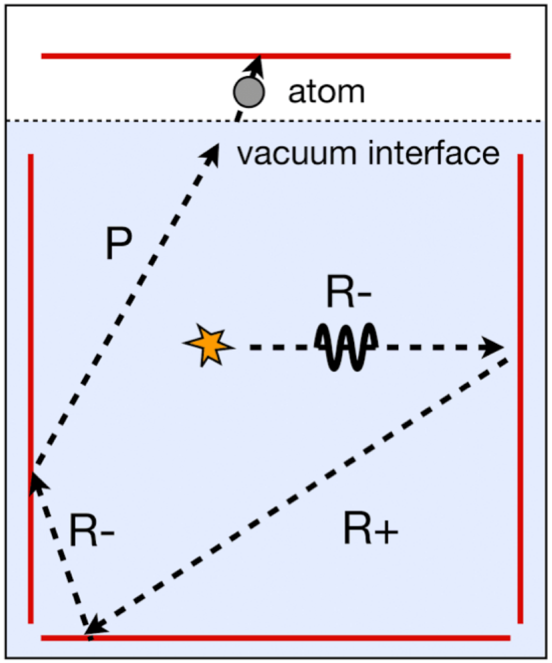
Proposed for measurement of pp solar neutrino flux using roton detection (HERON): R.E. Lanou, H.J. Maris, and G.M. Seidel, Phys. Rev. Lett. **58**, 2498 (1987).

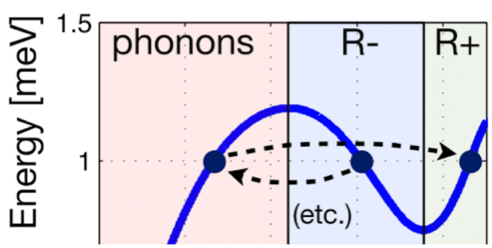
Two signal channels, heat and light. Both measured with a bolometer array.

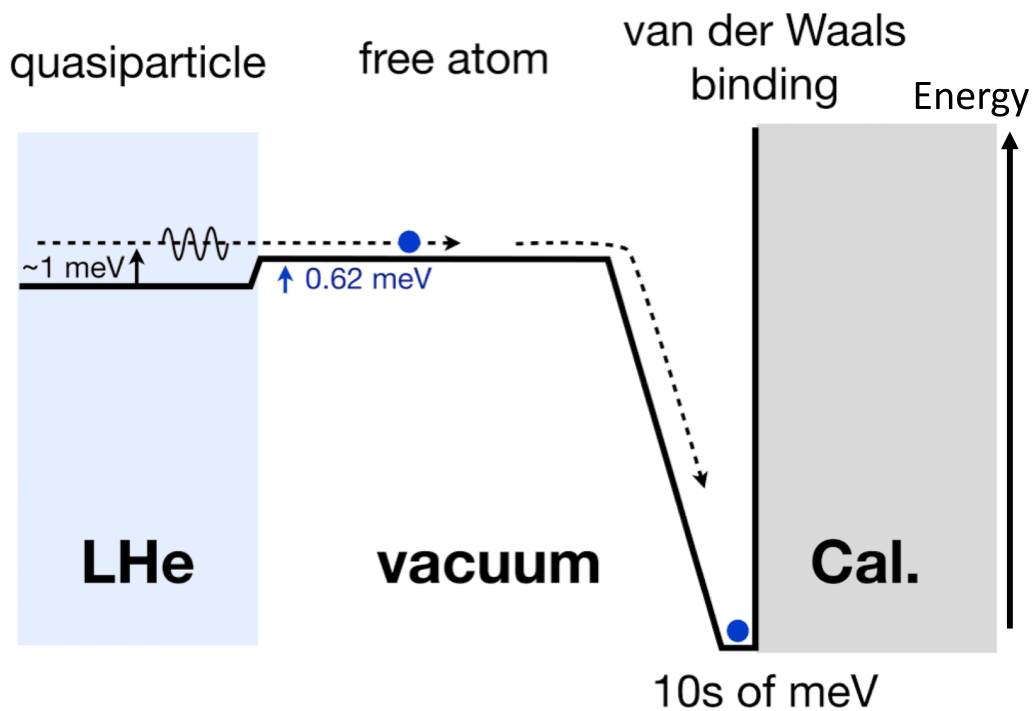
Also, “HERON as a dark matter detector?” in “Dark Matter, Quantum Measurement” ed Tran Thanh Van, Editions Frontieres, Gif-sur-Yvette (1996)



Quasiparticle readout - Quantum evaporation of helium atom

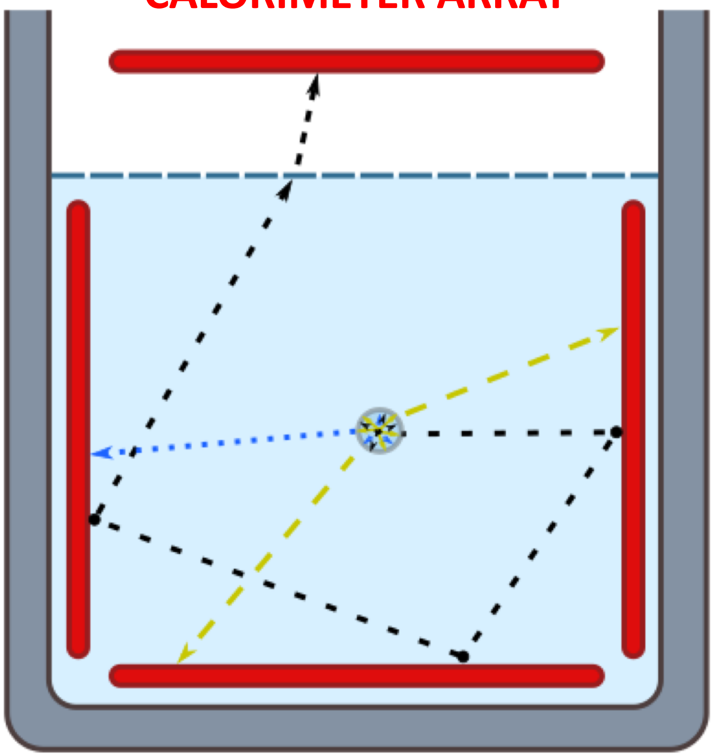






- 1 meV roton energy becomes up to 40 meV observable
  - × 40 amplification
  - Graphene-fluorine surface

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)

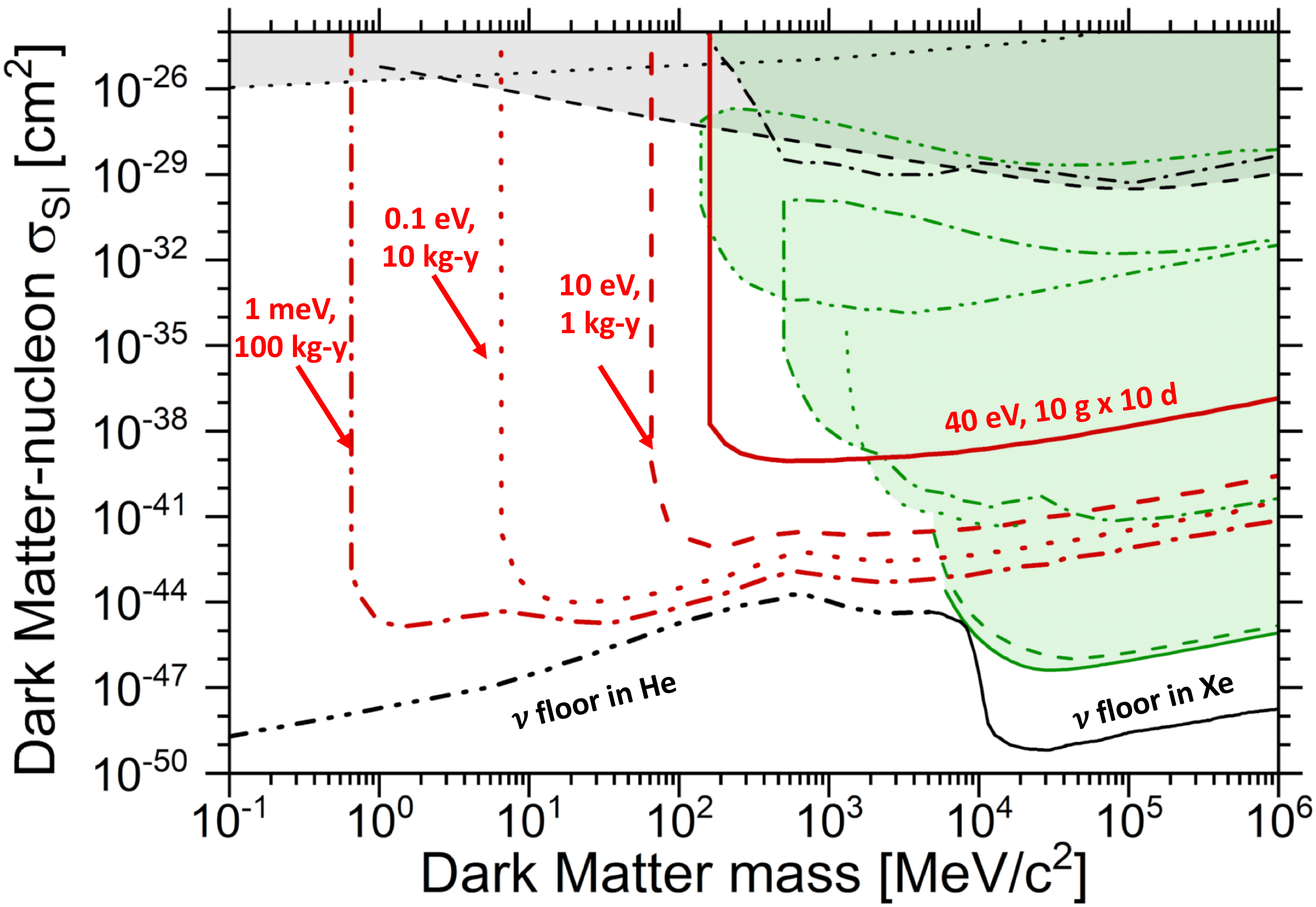
- Detect UV photons, triplet excimers, IR photons

Vacuum layer between helium and 6th TES array

- Detect quasiparticles via quantum evaporation

arXiv:1810.06283

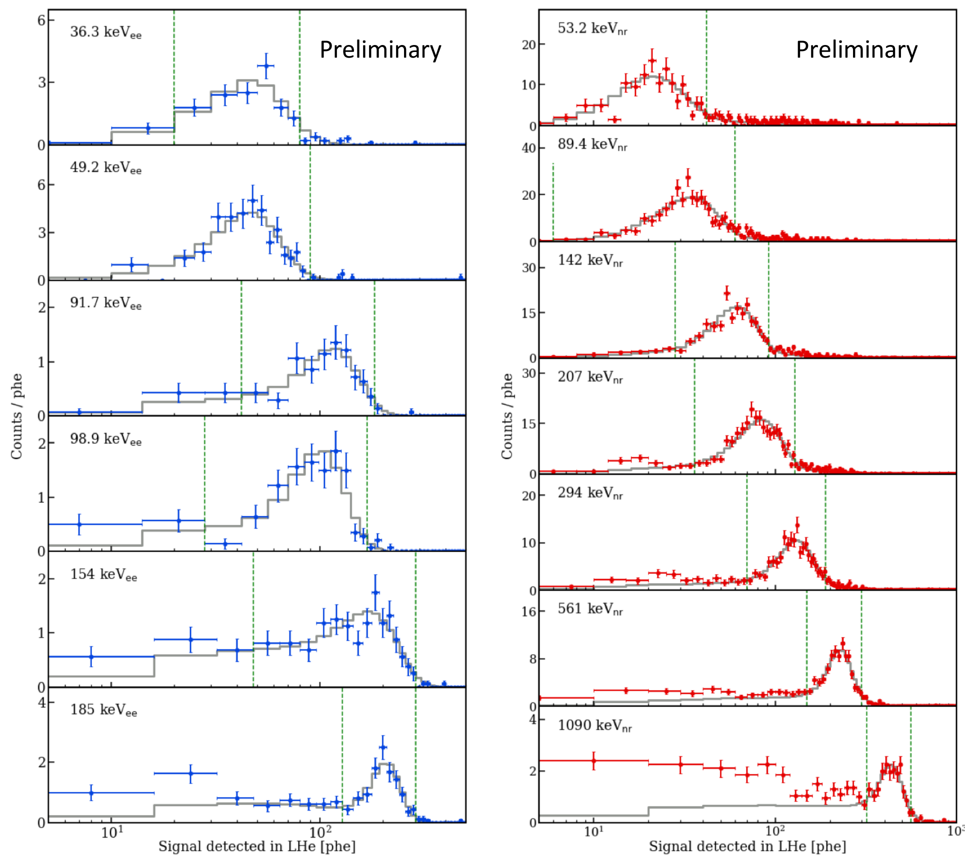
Projected Sensitivity



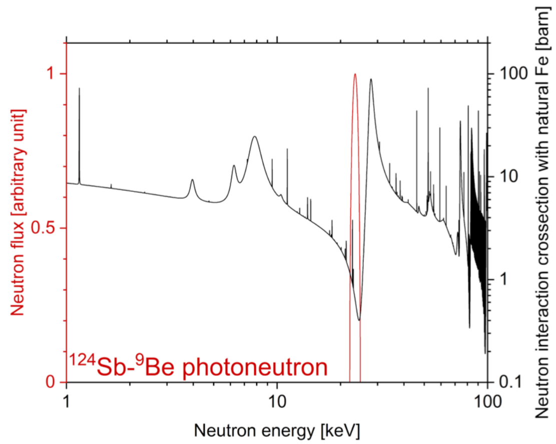
Light yield measurement of superfluid He-4

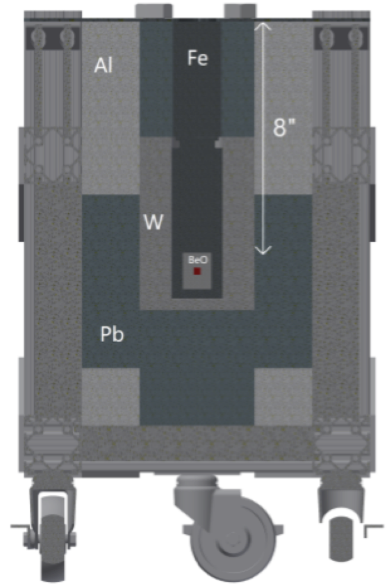
- Data selection cuts
  - Time of flight
  - Pulse shape discrimination (LS detector)
  - Deposit Energy (NaI detector)

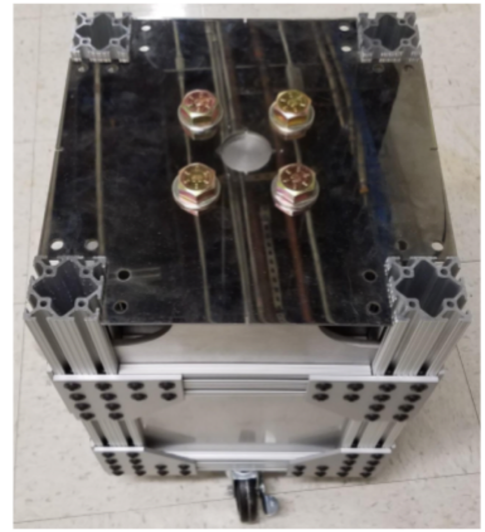
- Fit data with MC sims

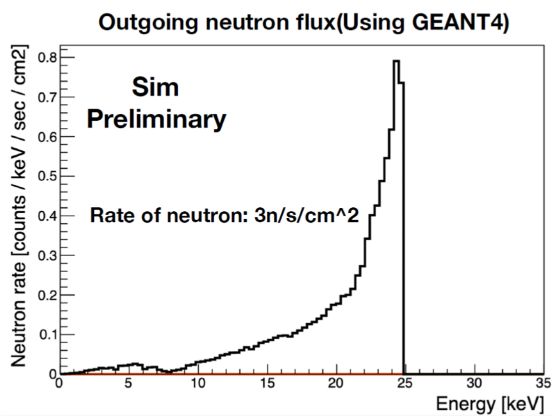


SbBe source with iron filter





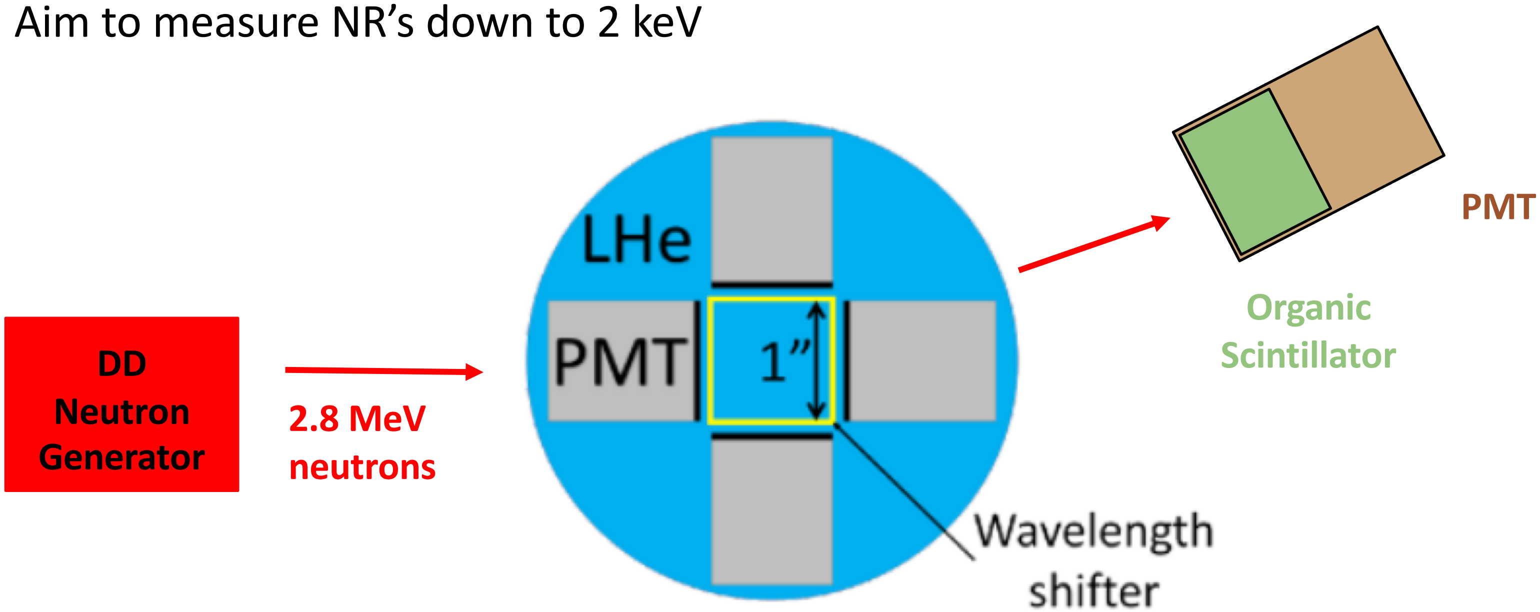




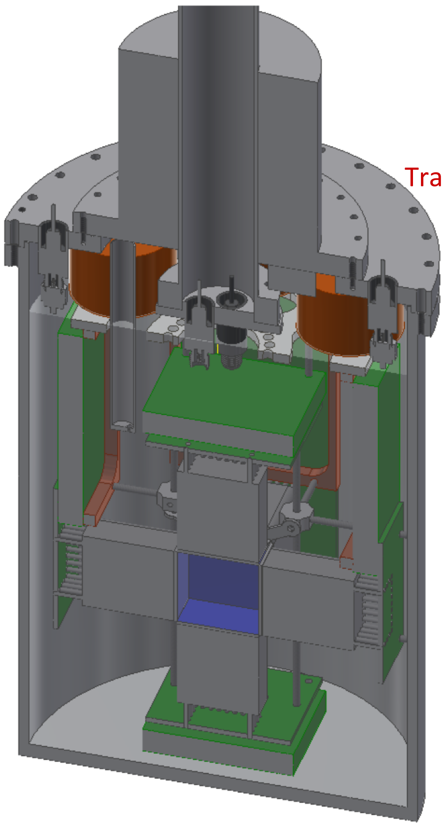
- 24 keV photo-neutron from ^{124}Sb-^{9}Be
- Iron cross-section dip at 24 keV neutrons
- 1-GBq Sb produced in nuclear reactor
- Currently being characterized

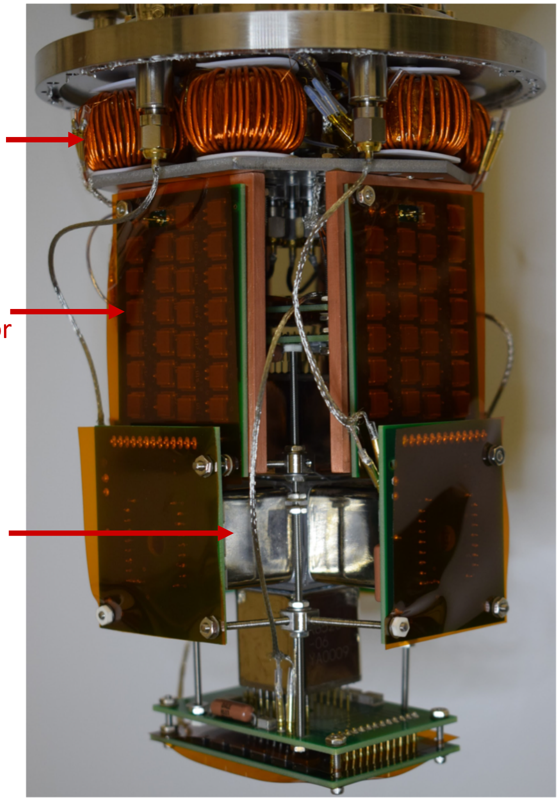
Measurement of Nuclear Recoil Light Yield in Superfluid ^{4}He

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



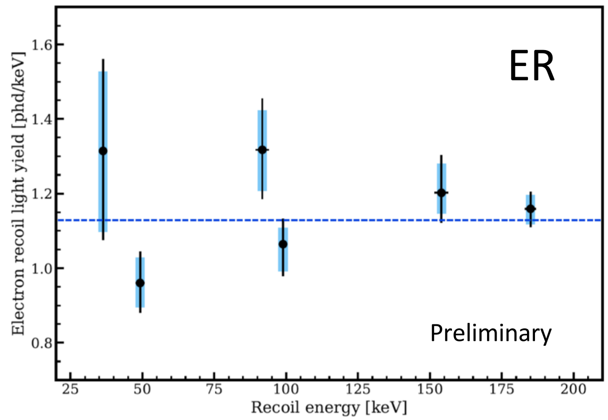
Light yield measurement of superfluid He-4

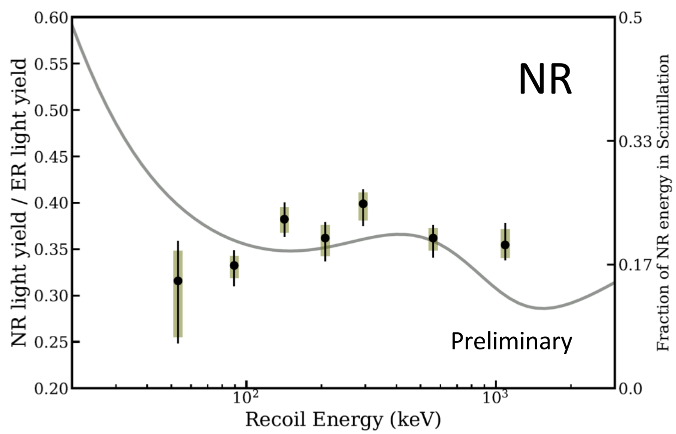




- ➢ Data taken at 1.75K
- ➢ Cockcroft–Walton (CW) generator
  - No voltage divider for PMT
  - No resistive heat
  - Suitable for down to ~mK
- ➢ High light yield
  - ~1.1 PE/keV_{ee}

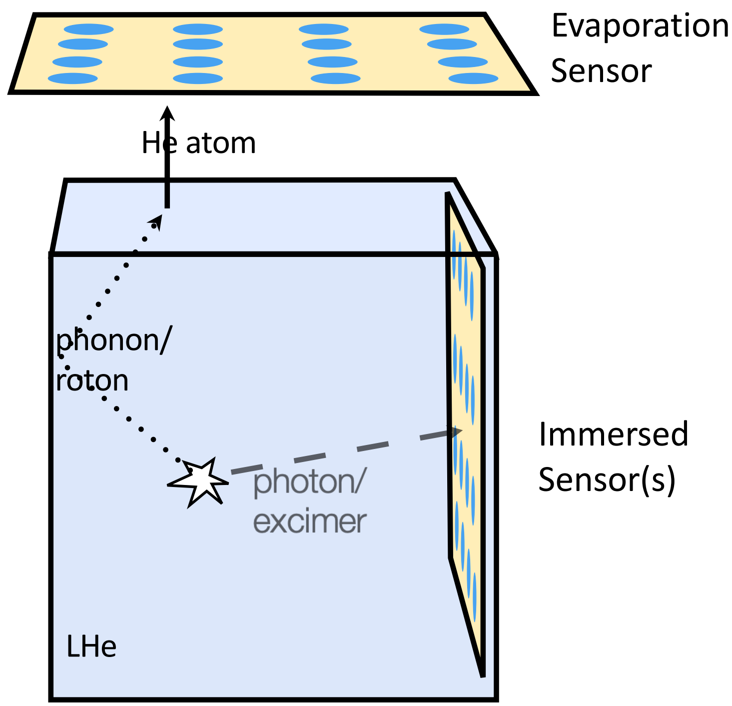
Light yield measurement of superfluid He-4





- First measurement of LHe scintillation in tens of keV. Publication draft nearly complete.
- ER yield relatively flat (as expected)
- NR yield agrees with pre-defined model
- Working on lower energy (keV) measurements
  - ER: Compton scattering from Co-57 source
  - NR: SbBe with iron filter

Basic LHe layout … and LHe motivation



1. Nuclear Recoil using low-mass target

(For a given threshold, sensitivity to a lower DM mass)

2. ER backgrounds greatly suppressed

Many gammas simply pass through

High ER discrimination power above ~100eV
(using scintillation/excimers)

No possibility of ER background below 20eV
(first excited levels of He atom)

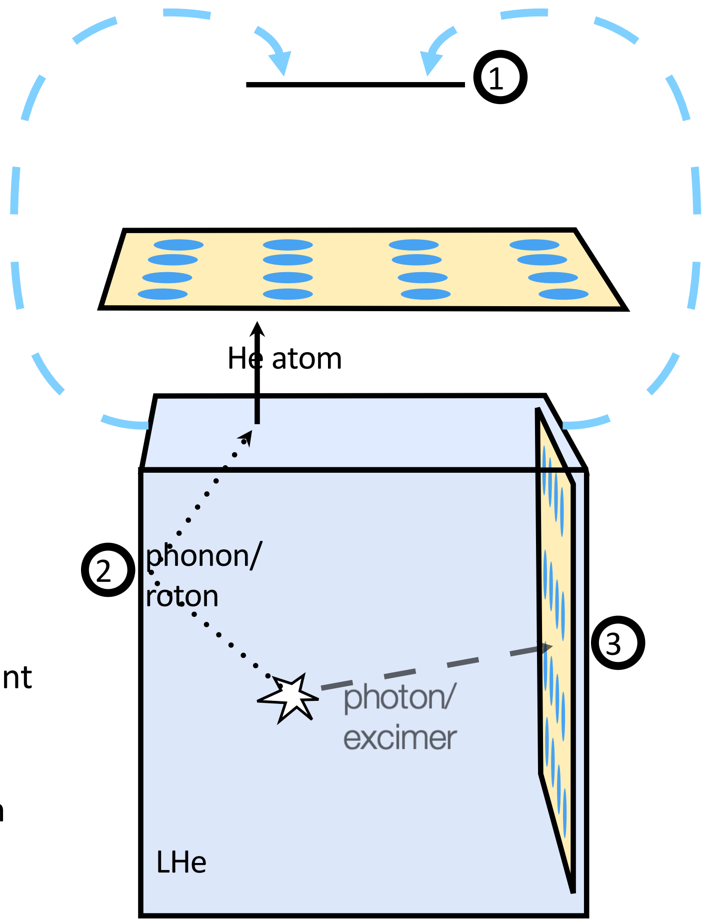
3. Technological Complementarity vs. SPICE

Phonons/rotons long-lived at relatively high energies

Single phonon/roton excitations can only cross vacuum gap if above a specific threshold (0.6meV)

Signal gain through atomic van der Waals attraction

LHe Detector R&D topics



1: Film Stopping

Largely covered by separate funds

Evaporation sensor must stay 'dry'

Requires stopping the film, ideally using a method with zero heatload

2: Phonon/Roton Reflectivity at Immersed Surfaces

wbs 1.3.2

Existing work suggests a few-percent evaporation eff. ("$\varepsilon_{collect}$")

Likely loss via transmission or 1→n downconversion at walls

Significant motivation to study and minimize these losses (sets LHe detector threshold)

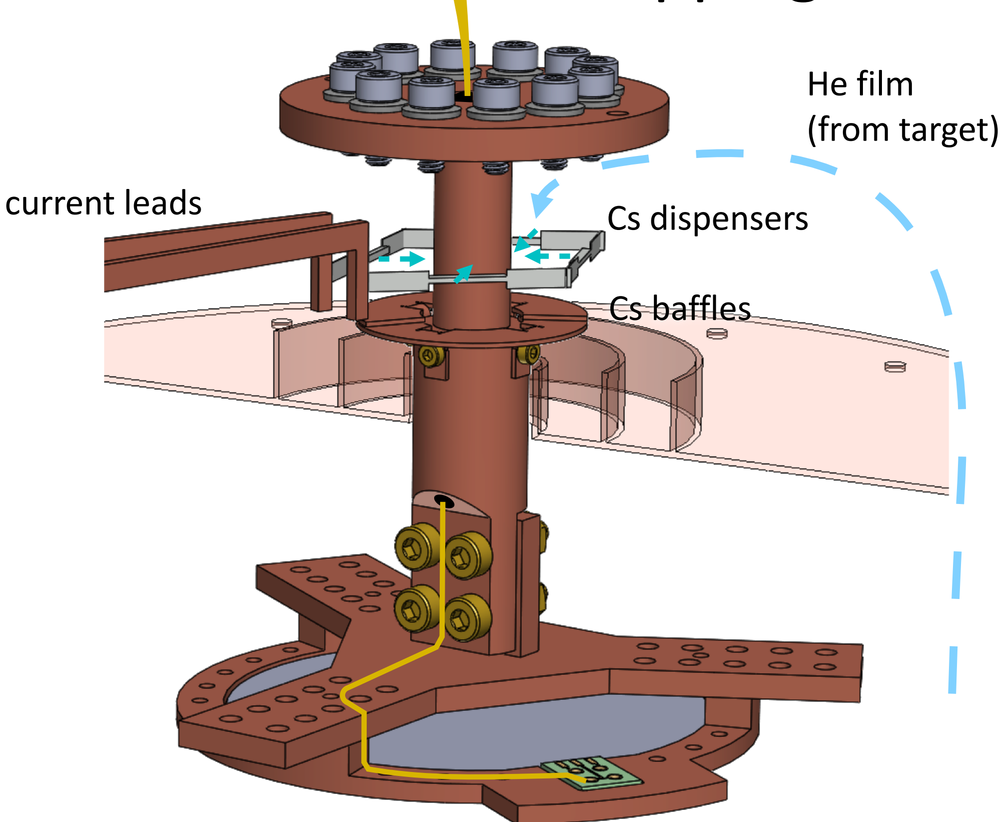
3: Testing of Immersed Sensors

wbs 1.3.3

Tagging scintillation photons (and triplet excimer exciations) could be greatly aided by "4pi" coverage

Immersed large-area sensors largely untested

related R&D: film stopping



Cs dispensers

The Cs strategy

Well-demonstrated by multiple groups that unoxidized Cs is not wetted by He film flow

Unoxidized: requires in-situ deposition

Commercial SAES Cs dispensers available
Previously shown to stop film flow

Accomplishments in Year 1:

Initial Cs evaporation tests in bell jar
-gained experience with current settings
-saw deposition pattern, geometry

New holder incorportating Cs surface
-Designed for CPD-style sensor, but sensor portion can be swapped out
-Fabricated (now at plating vendor)
-Includes eccosorb EMI filter (inside the central column)

Looking forward to initial tests soon
Then either a v2 or build a second for UCB

wbs 1.4.3 : ERDM Photon Calibration

Method 1: Optical Photon Absorption

Laser at room temperature
Fiber optic coupling (with IR-blocking filters)

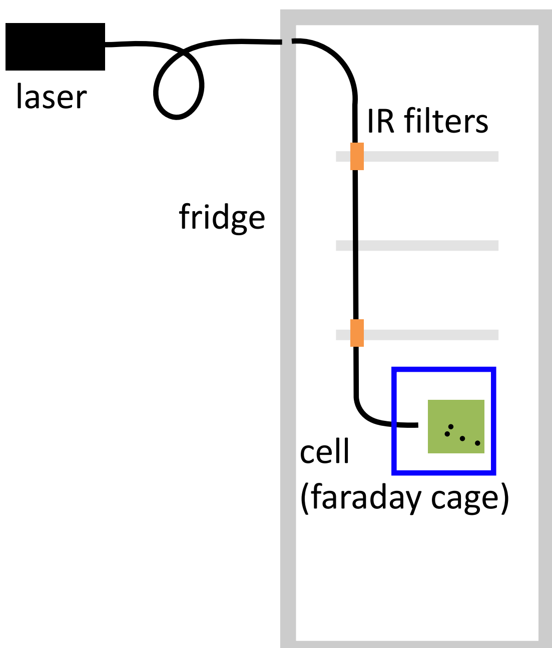
To achieve penetration, wavelength should be similar to band gap

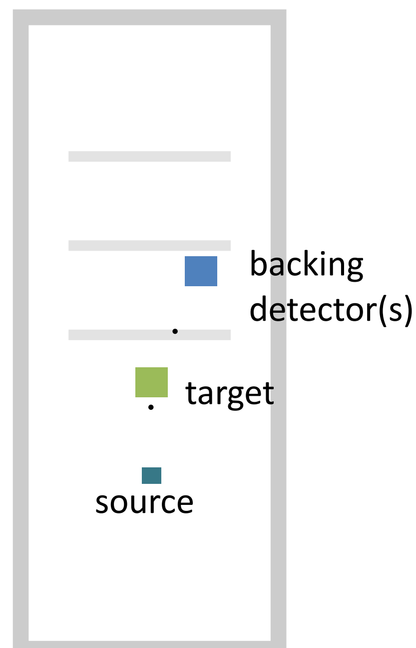
Well-practiced method, will commision at UCB in coming year

Method 2: X-ray Compton Scattering

keV-scale X-ray source
- Fe55 or similar
- within fridge vacuum
- well-practiced method

Backing detector to measure scattering angle
- also within fridge vacuum





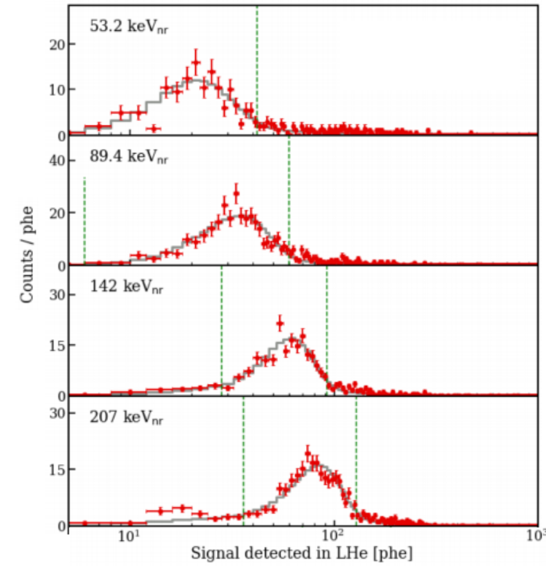
wbs 1.4.1 : NRDM Neutron Calibration

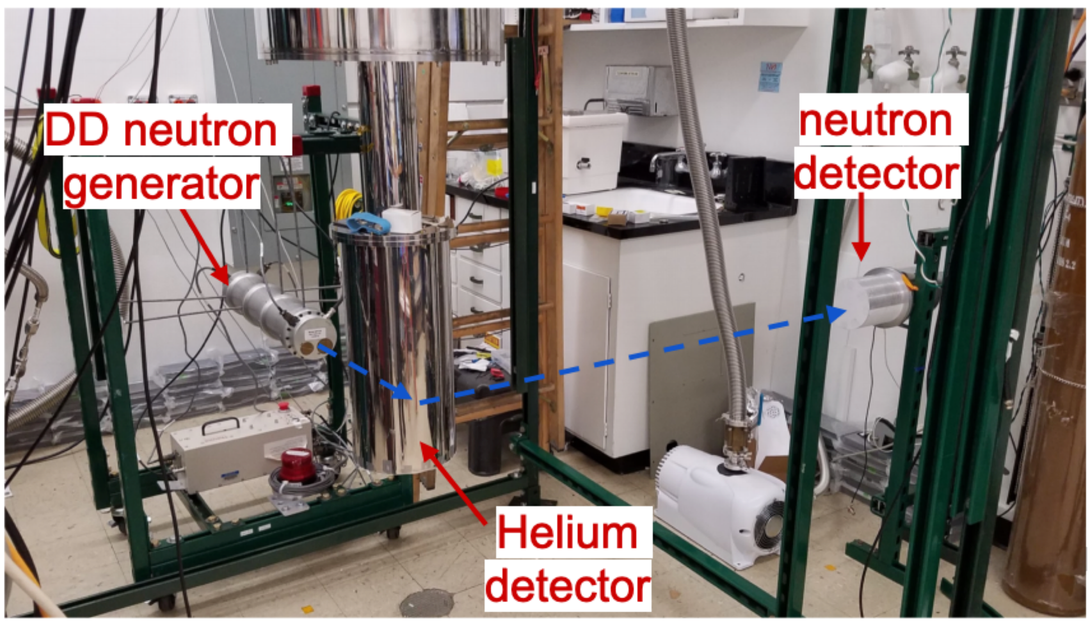
Source 1: DD neutrons, 2.8 MeV

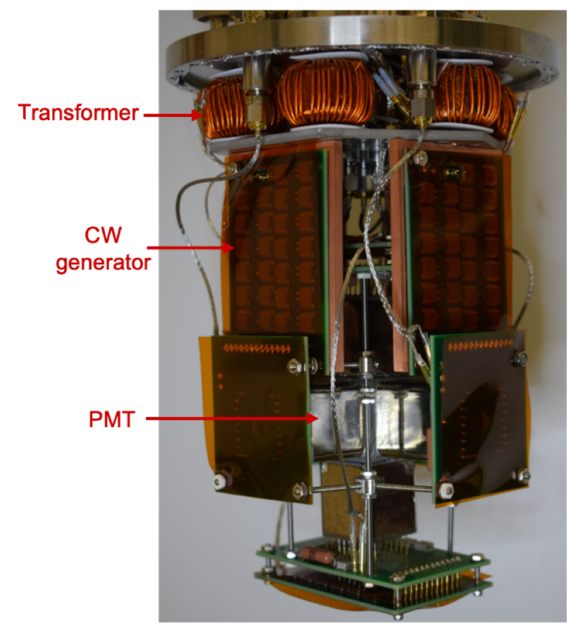
Relatively high-energy neutrons

Useful for measuring NR light yield at keV recoil energies

Recent LHe work at UCB out for publication soon.
Lowest scattering energy: ~53keV (never before measured in LHe)





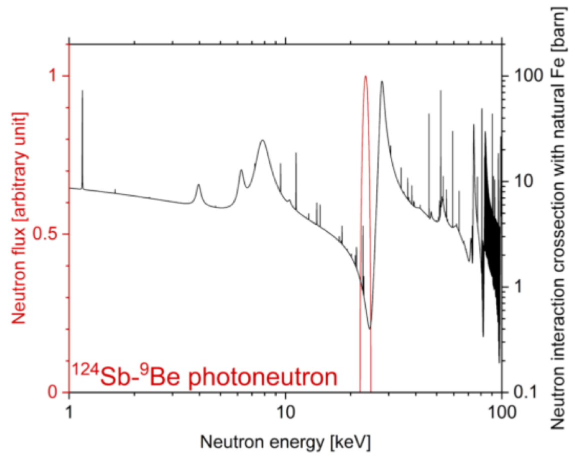


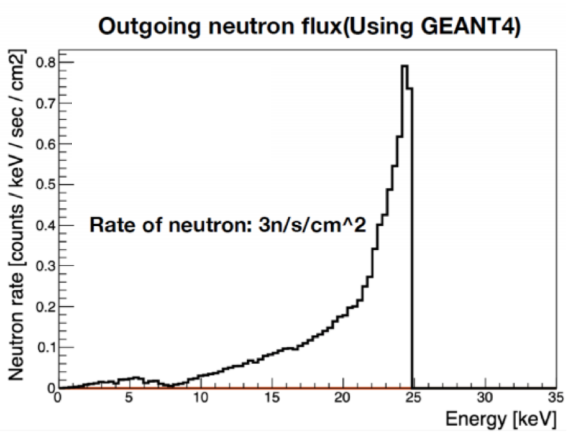
wbs 1.4.1 : NRDM Neutron Calibration

Source 2: SbBe photoneutrons with Fe shield

SbBe produces 24keV neutrons, but with large gamma background

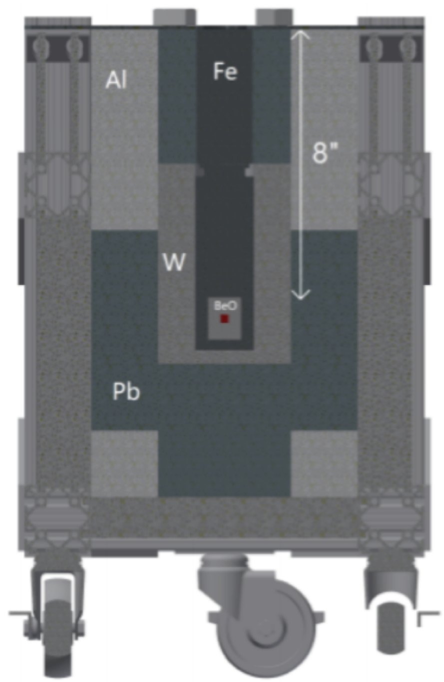
Coincidence: Fe has deep 'dip' in neutron cross section at same energy

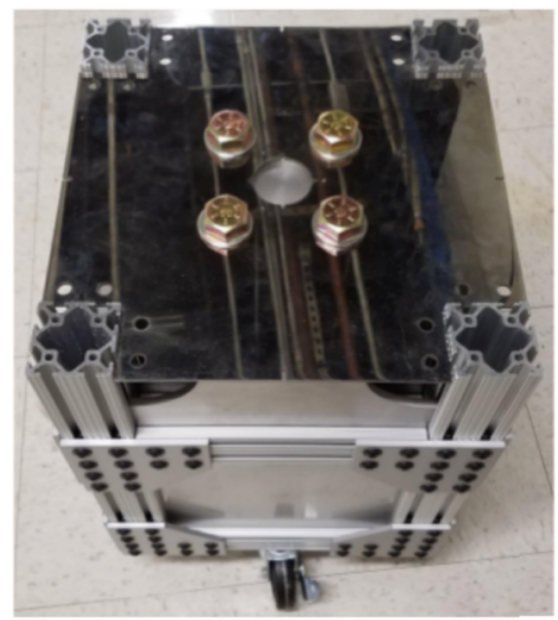




1 GBq of Sb has been produced at Davis Reactor, and assembled into Fe-shielded source, below.

Neutron flux, spectrum characterization ongoing.





wbs 1.4.1 : NRDM Neutron Calibration

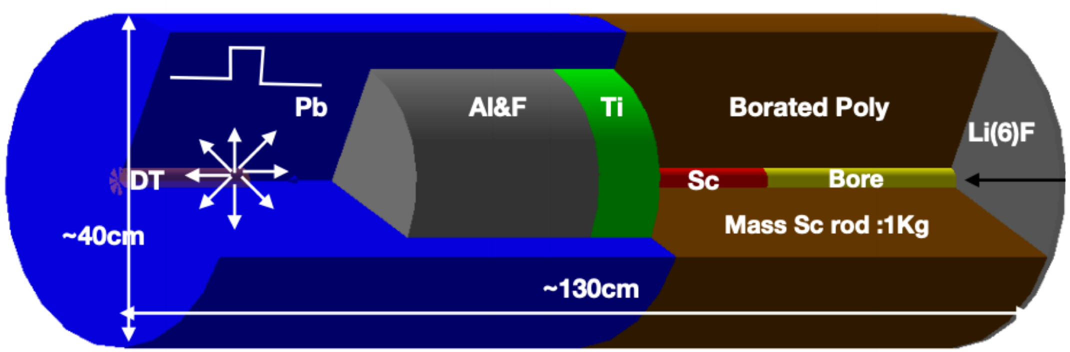
Source 3: DT neutrons, moderated and filtered using Sc

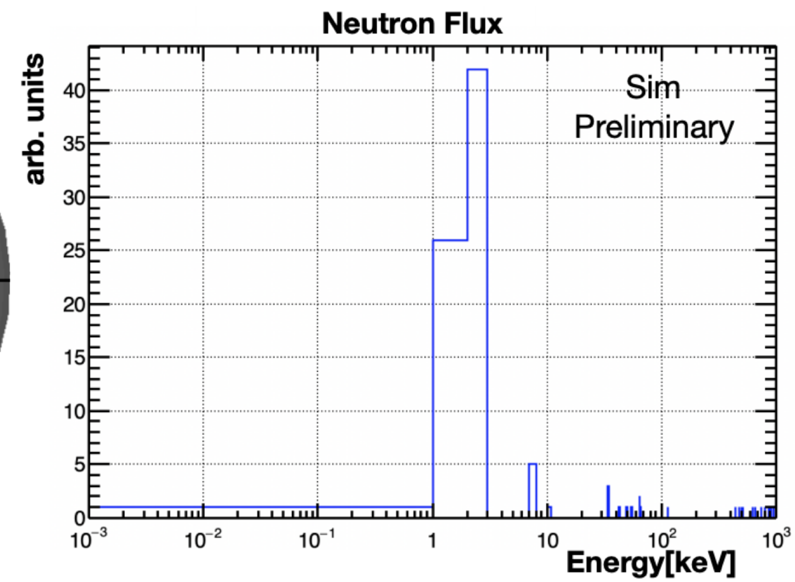
Filtering takes advantage of similar notches, starting with a high-flux 'white' spectrum

Well-practiced at reactors, somewhat novel to apply to a portable DT generator

Sc provides lowest-energy practical 'filtering notch' at 2keV
    Fe filter at 24keV also practical

Moderator/filter assembly has been designed and optimized in Geant





wbs 1.4.1 : NRDM Neutron Calibration

Backing detectors tuned to keV neutrons

Measuring the scattering angle is key to the method

keV-energy neutrons are too low for backing detectors based on scattering…

… but awkwardly high in energy for backing detectors based on neutron capture.
(capture takes significant time, and also leads to significant inefficiencies)

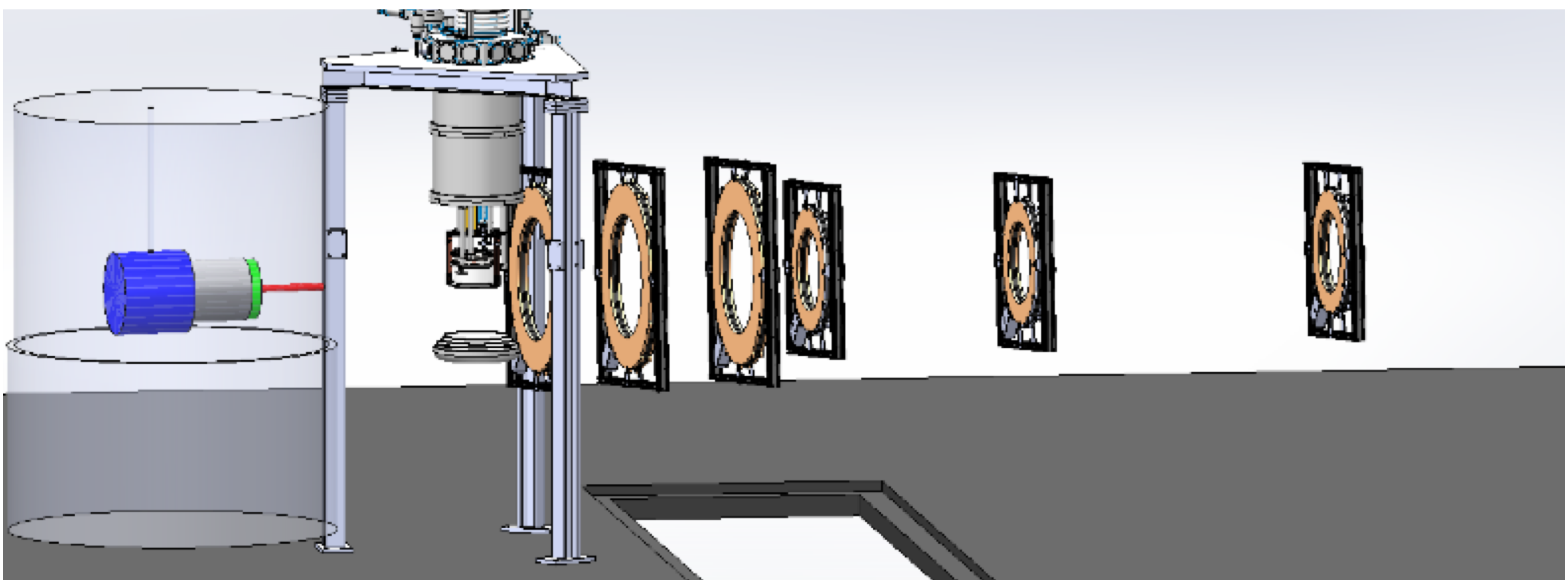
Have now optimized a backing detector in geant, and now characterizing the first test prototype.

[photos]

wbs 1.4.1 : NRDM Neutron Calibration

Putting source and backing detectors together

UMass TF may become a more general low-energy neutron scattering TF, not just LHe.



wbs 1.4.2 : NRDM Gamma Calibration

An alternative to neutrons

This is a very novel approach, but our initial simulation studies have revealed great promise.

MeV-scale gamma undergoing Rayleigh scattering : an eV-scale atomic recoil

Progress to date is tabulating the relative ratio of coherent scattering to Compton scattering at higher energies, understanding ideal gamma energy ranges, angle ranges, etc.

Possibility to extend NRDM calibrations to even lower energies than Sc filter neutrons