TESSERACT

The TESSERACT Project for Sub-GeV Dark Matter Detection

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LBNL/UC Berkeley

Rencontres de Blois 2022
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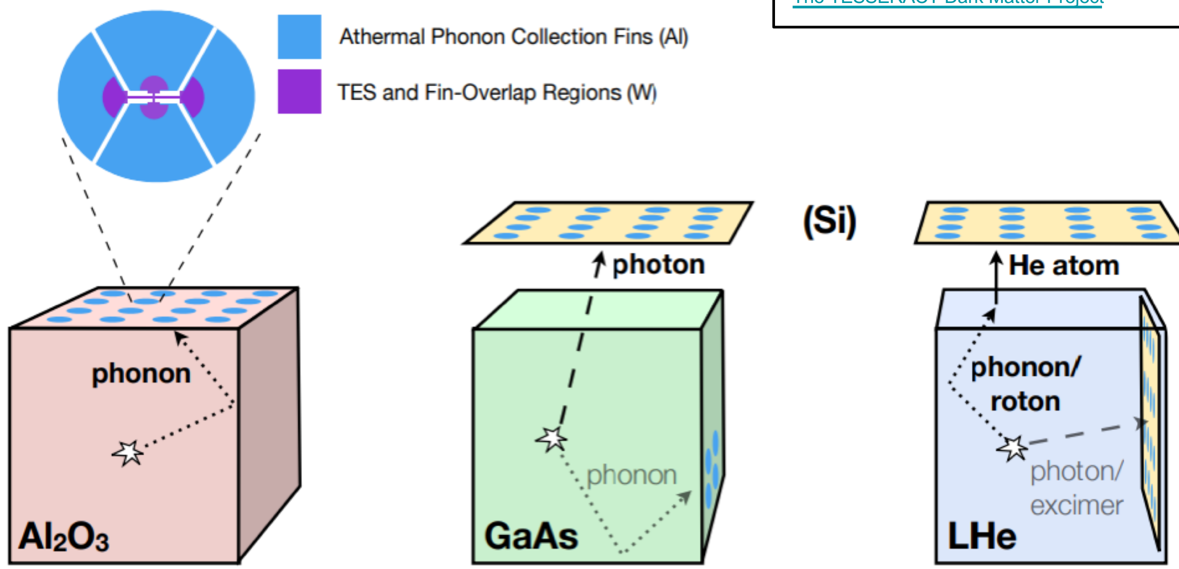
The TESSERACT project (part of the DMNI suite)

Transition Edge Sensors with Sub-Ev Resolution And Cryogenic Targets

- 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 institutions
- Includes SPICE (polar crystals) and HeRALD (superfluid helium).

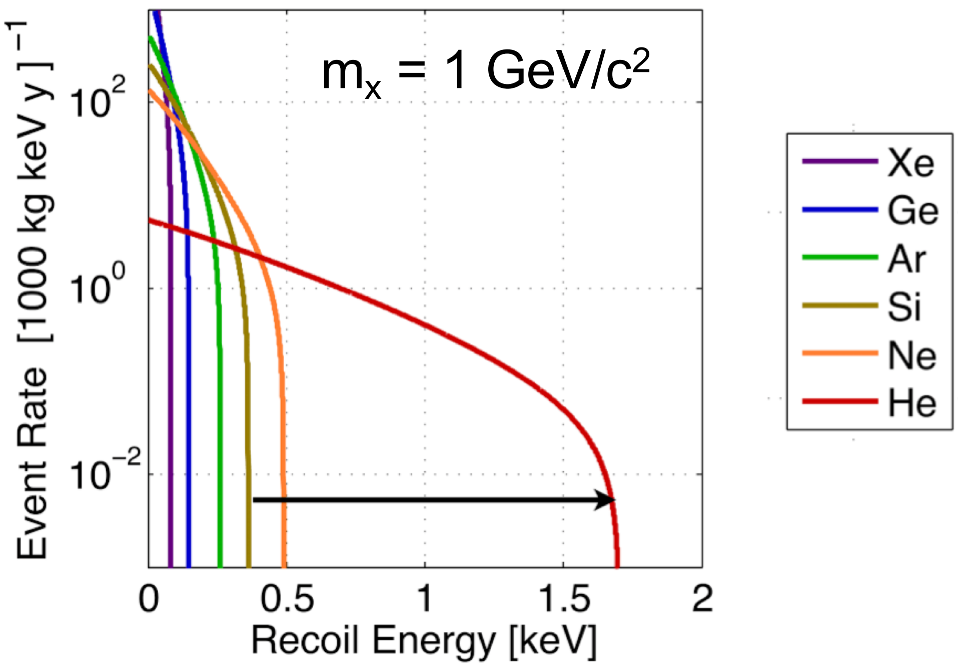
Snowmass2021 - Letter of Interest
The TESSERACT Dark Matter Project

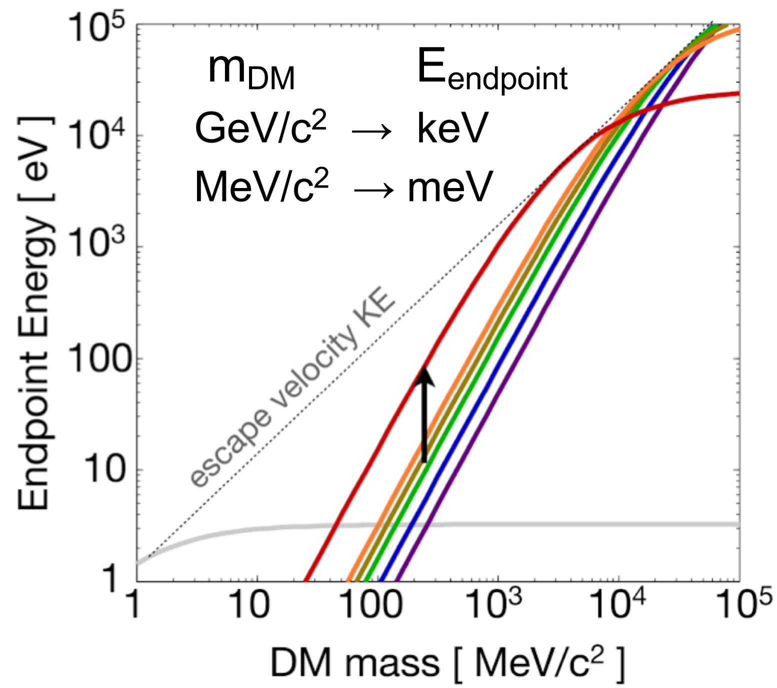


Light baryonic target nuclei for NRDM

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)

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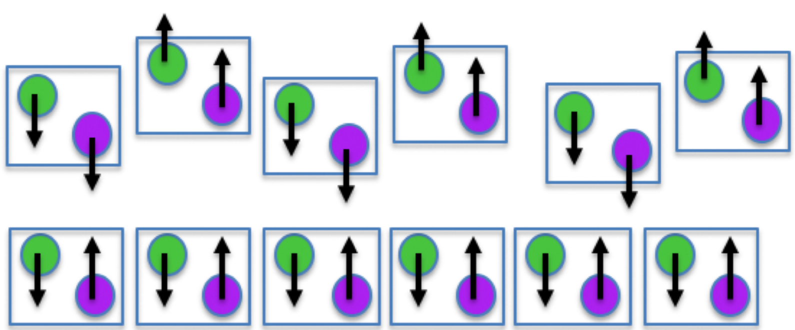
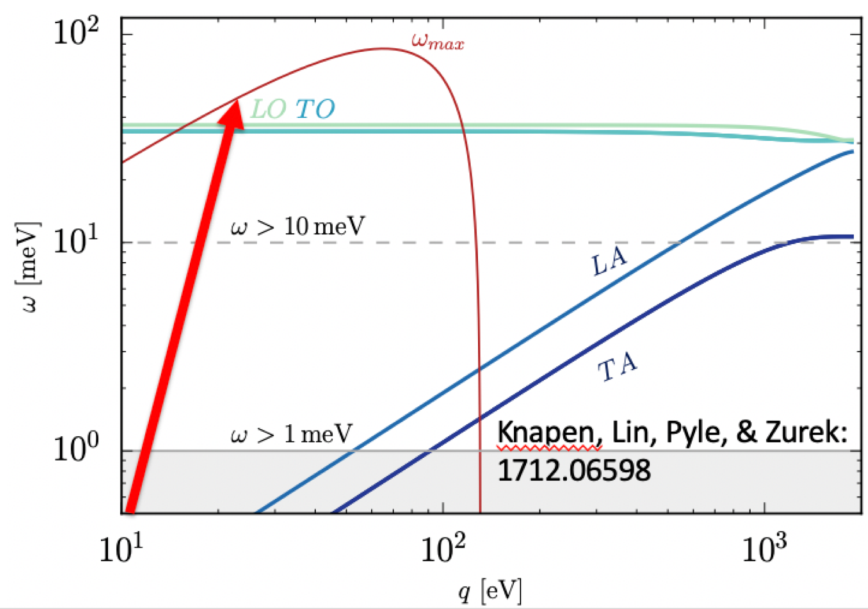
Coherent Excitations for ERDM

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

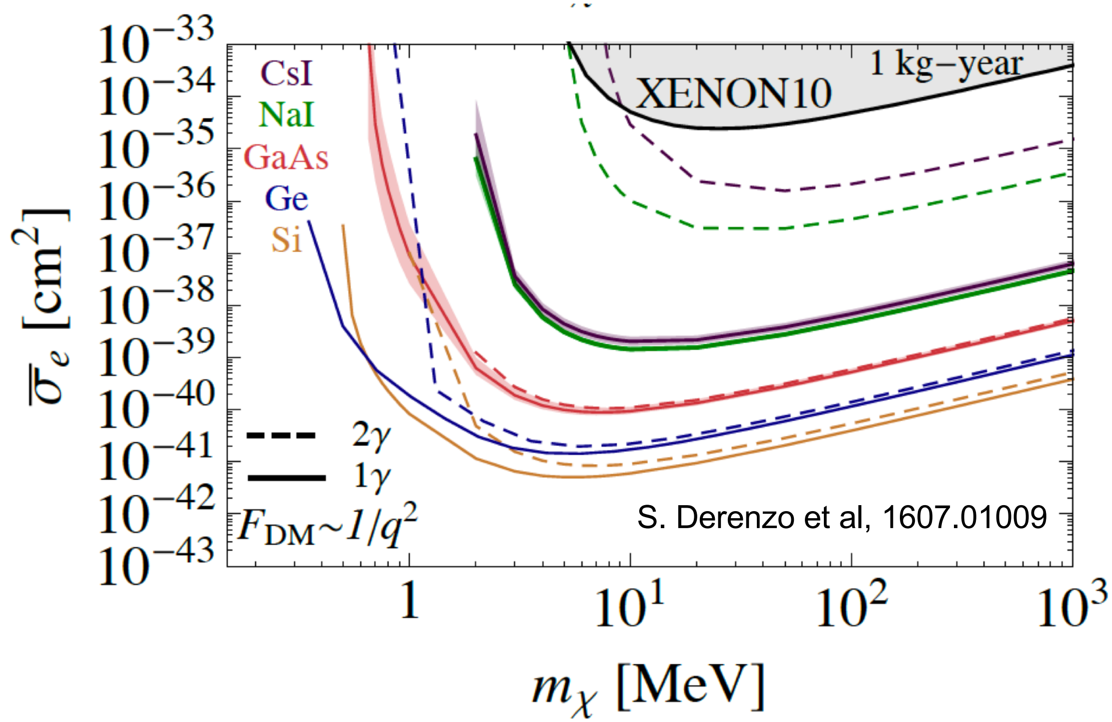
Low bandgaps:

- 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.



Substantial backgrounds seen at low energies, across experiments

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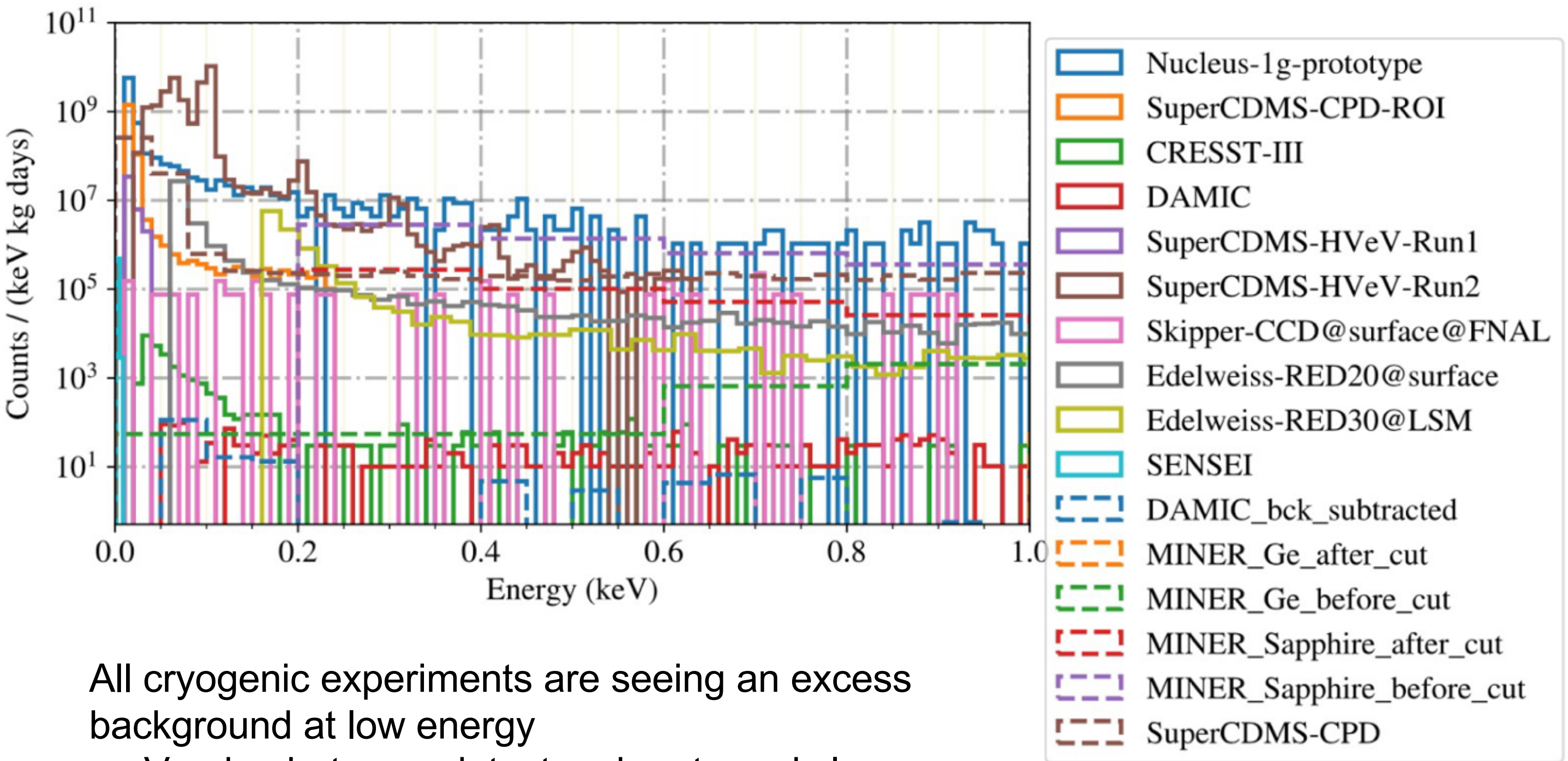
EXCESS workshop, see: https://indico.cern.ch/event/1013203/
See summary by J. Billard and R. Strauss



All cryogenic 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

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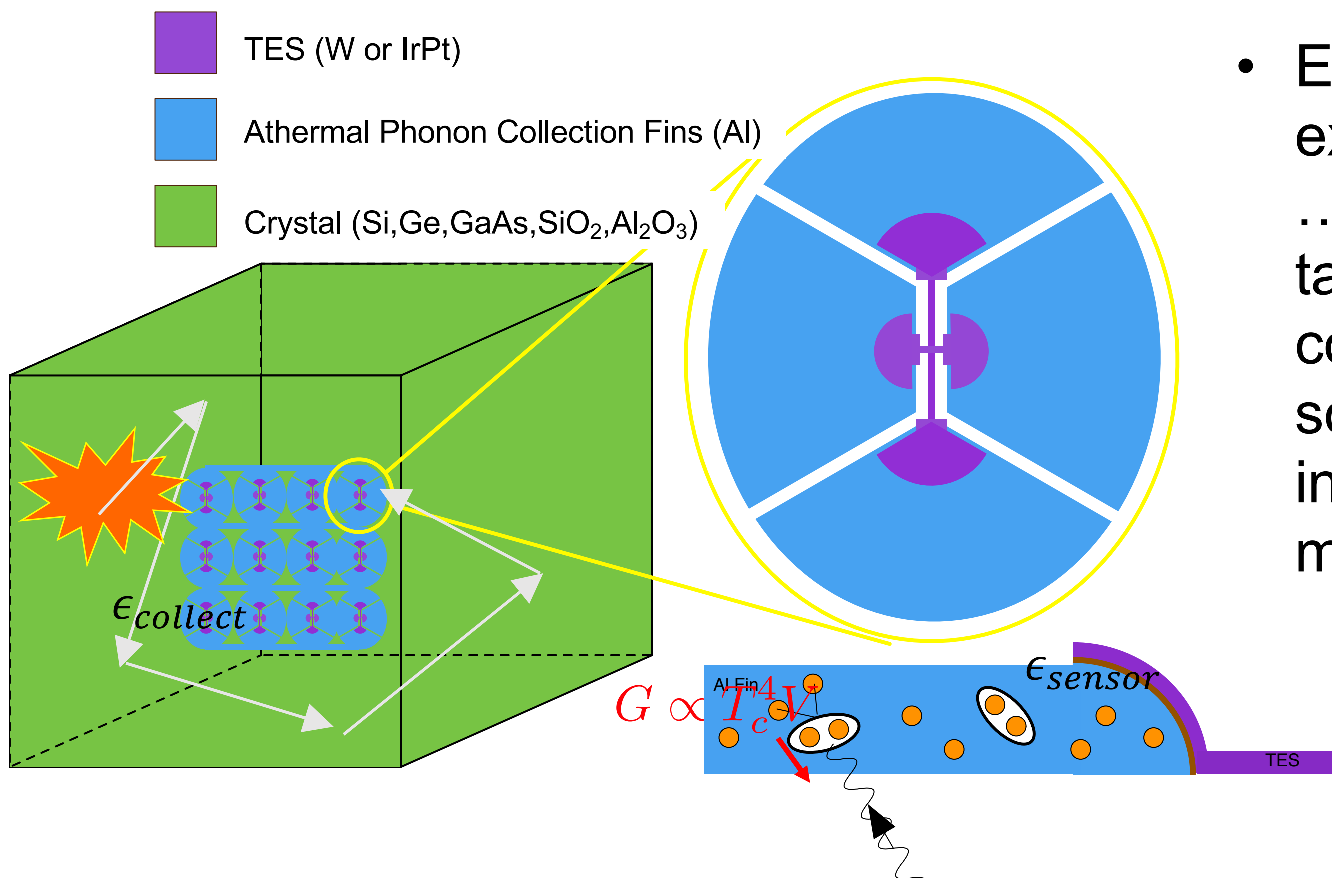
Athermal Phonon Detectors



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

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

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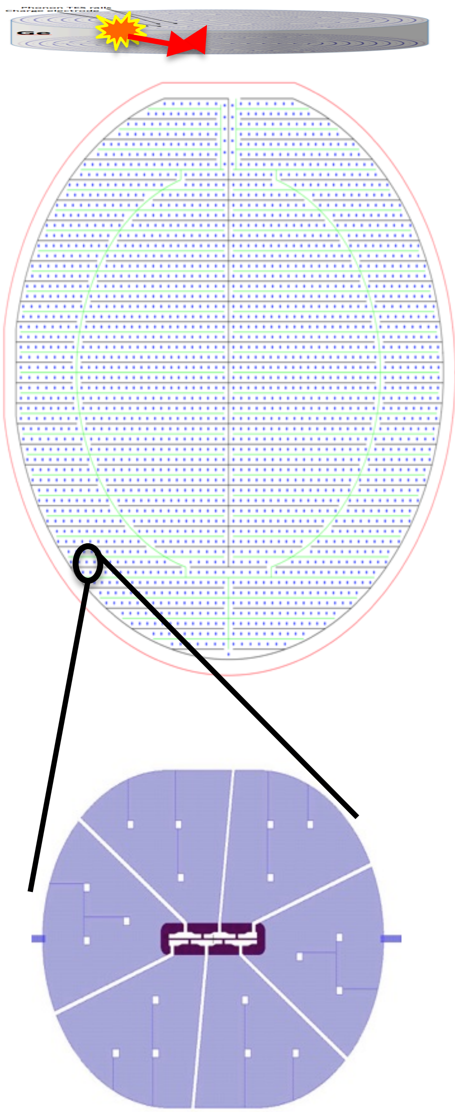
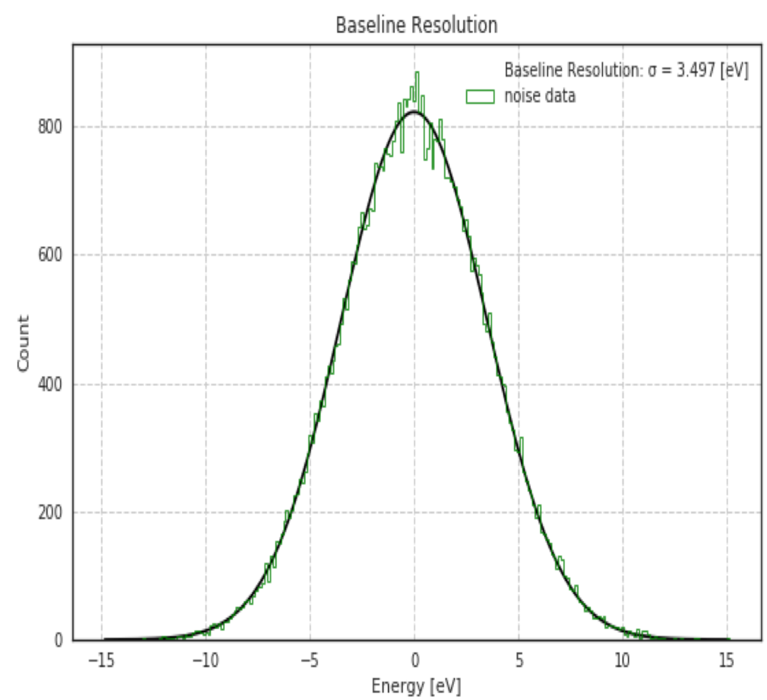
Recent Progress: Large Area Photon Calorimeters



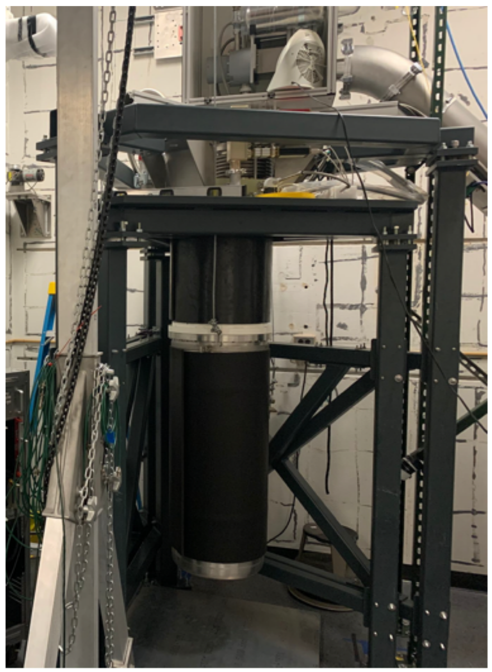
- 3” diameter 1mm thick Si wafer (45.6 cm^2)
- Distributed athermal phonon sensors
  - Athermal Phonon collection time estimated to be ~20us
  - 2.5% sensor coverage
- Tc= 41.5mK
- **17% Athermal Phonon Collection Efficiency**
- **Measured Baseline σ_E =3.5 ± 0.25 eV**



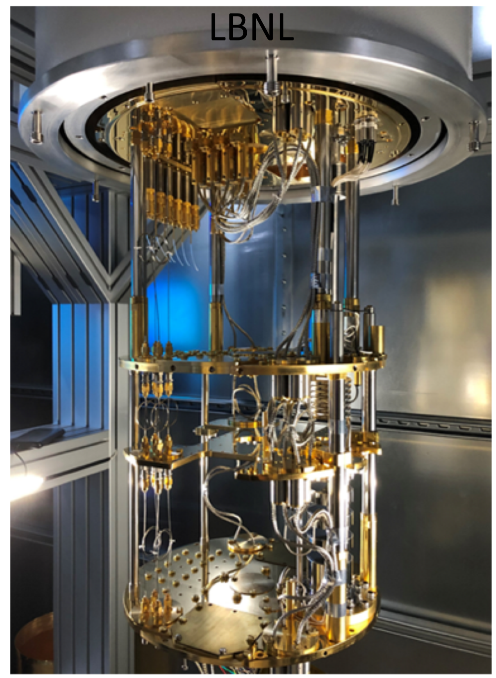
TESSERACT testbeds

Leiden MNK126-500
McKinsey Group @ UCB

CryoConcept UQT-B 200
Pyle Group @ UCB



BlueFors LD-400
Detector Group @ LBNL



CryoConcept HEXADRY UQT-B 400
Hertel Group @ UMass

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Detector Performance Specifications

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

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-γ)	**35 meV** (optical phonon)
$0.1\times1\times1\,cm^2$ Ge-based photon sensor	2.3 eV	300 meV	12 meV
$0.1\times1\times1\,cm^3$ 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 $\epsilon_{collectHe}\times g_{He}$			
$0.1\times4\times4$ cm Si-based He evaporation sensor	6.7 eV	900 meV	38 meV

TES Development

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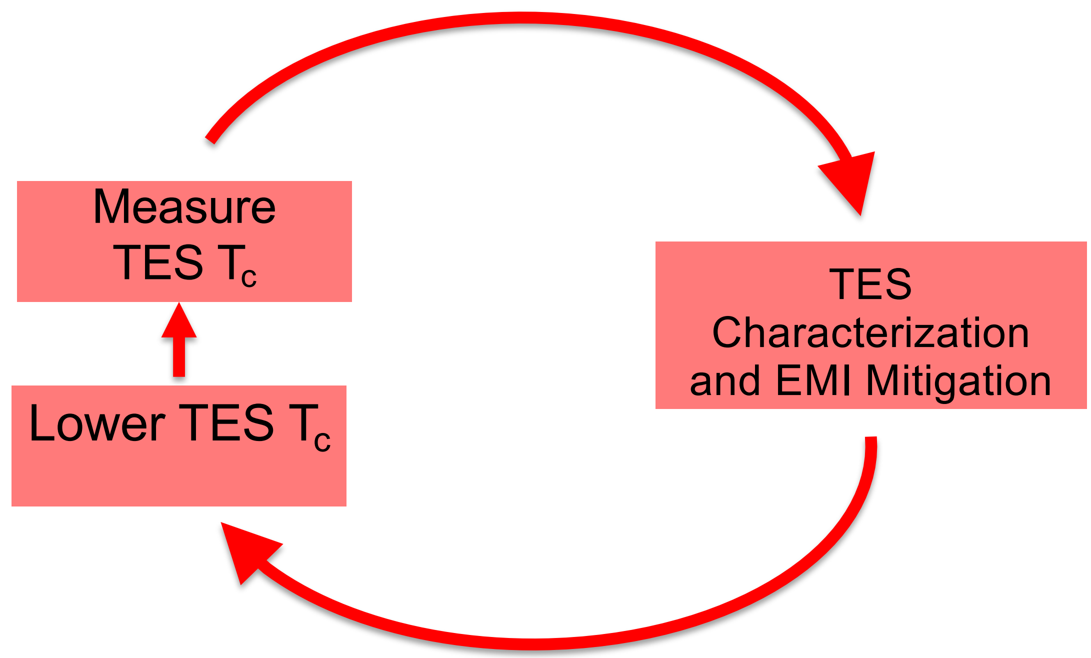
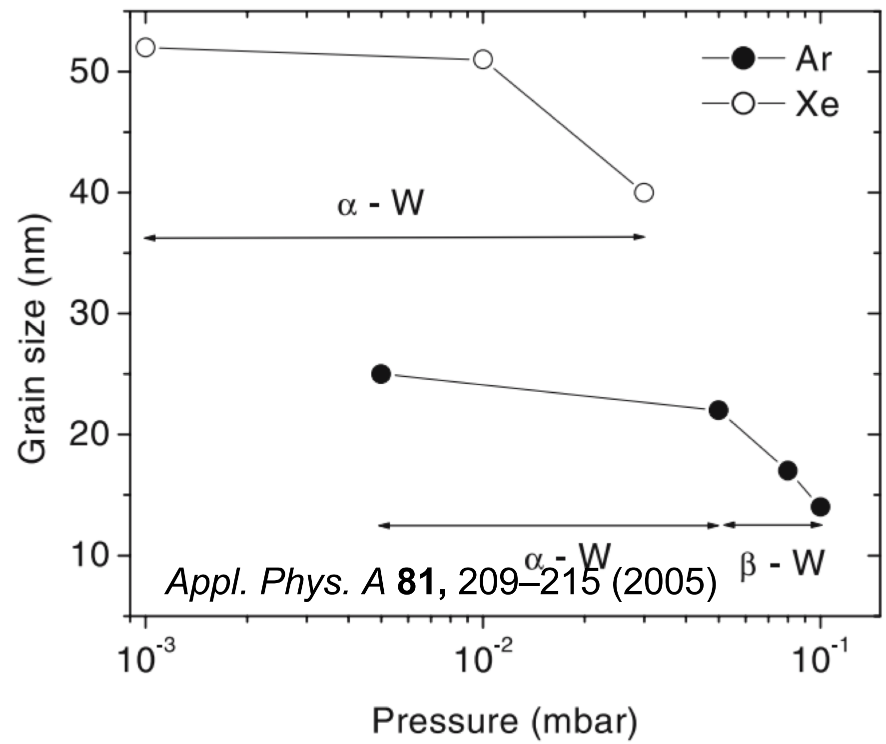
Major R&D goal: Develop ultra sensitive TES

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



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

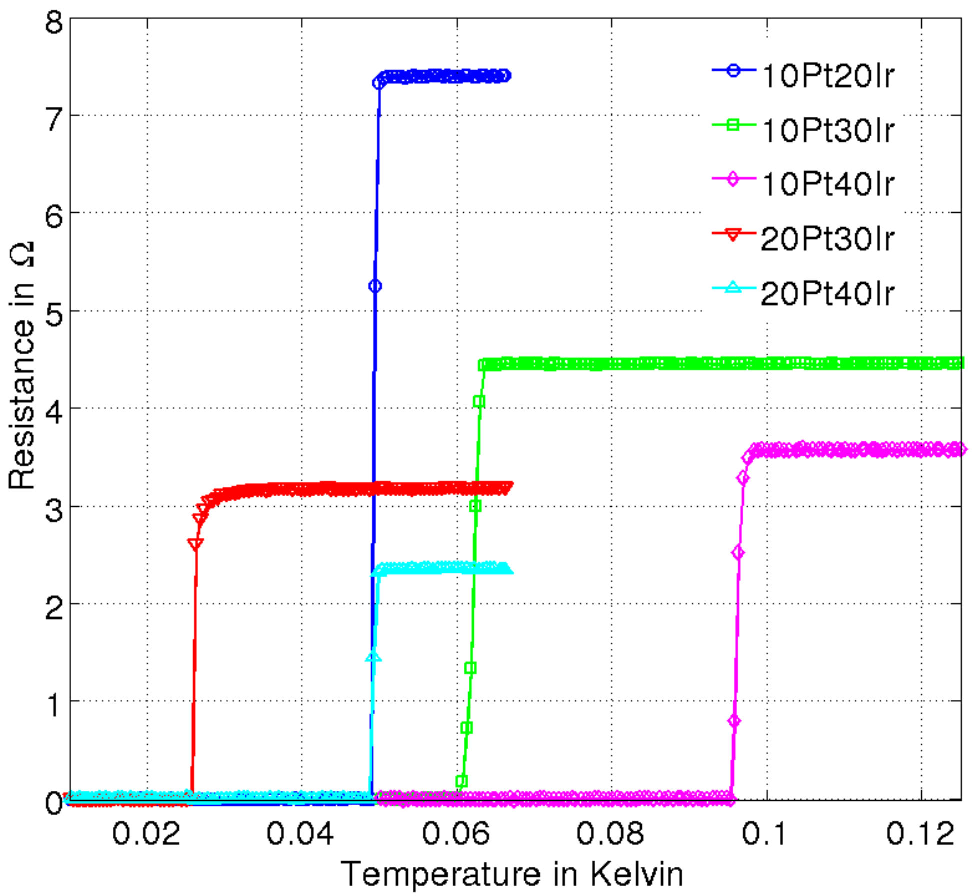


Appl. Phys. A **81,** 209–215 (2005)

- Year 1 TESSERACT Progress: Produced W film with T_c= 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: Sub-ev Polar Interactions Cryogenic Experiment

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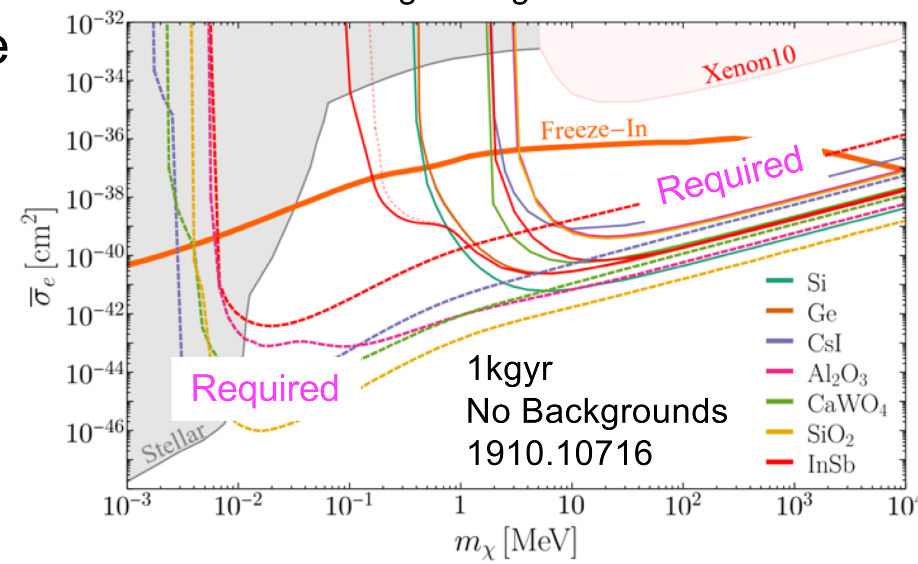
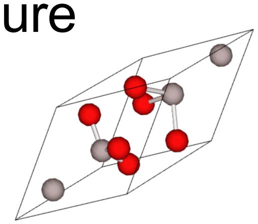
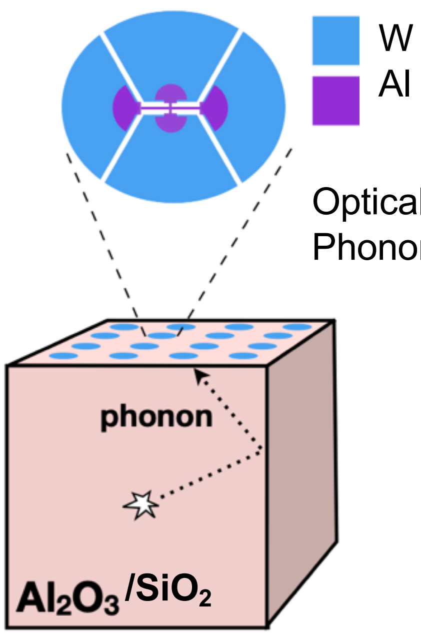
- In ionic crystals, optical phonons are oscillating electric dipoles!
- Very large coupling to photons (black in the IR)… Very large coupling to the dark photons
- 1712.06598
- 10-1000gyr exposure

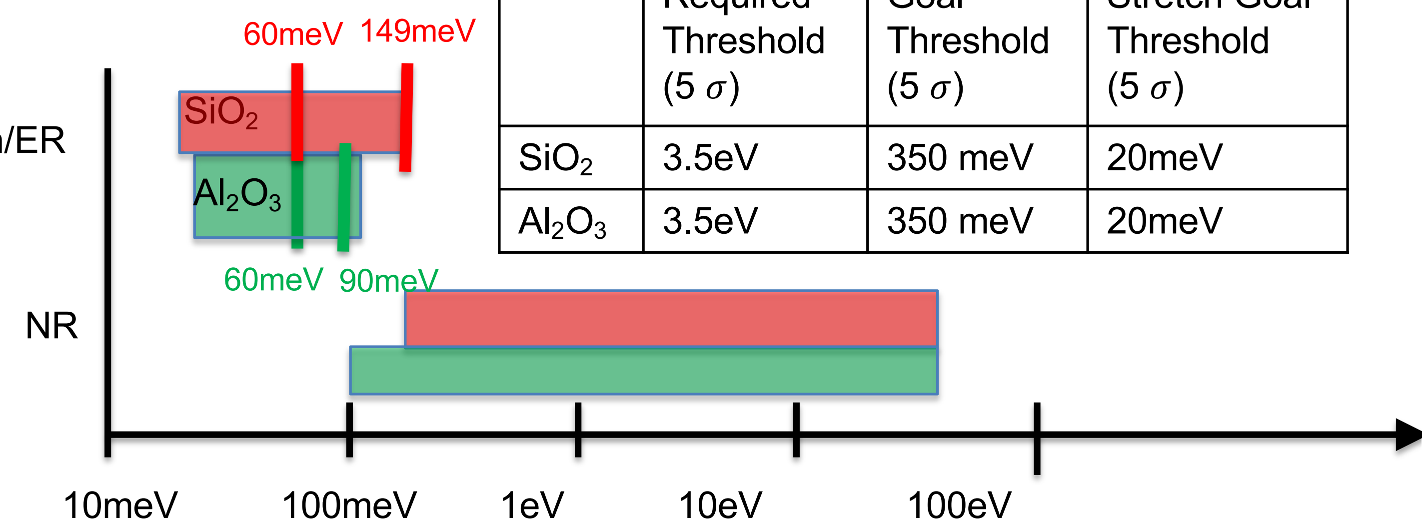
Scattering via Light Dark Photon







	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

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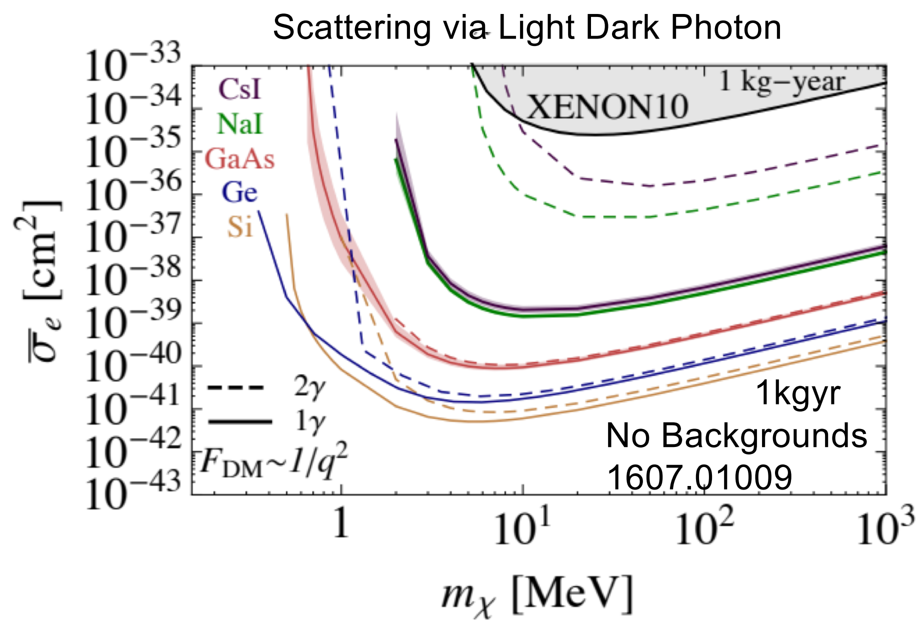
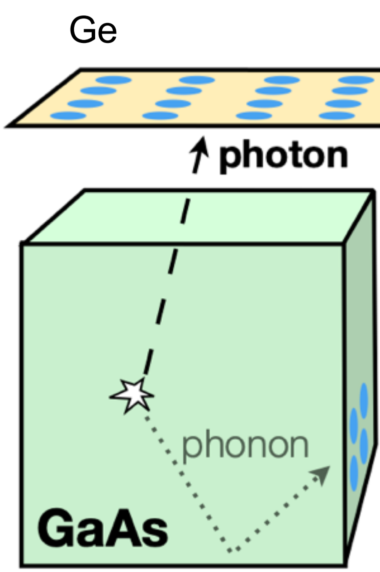
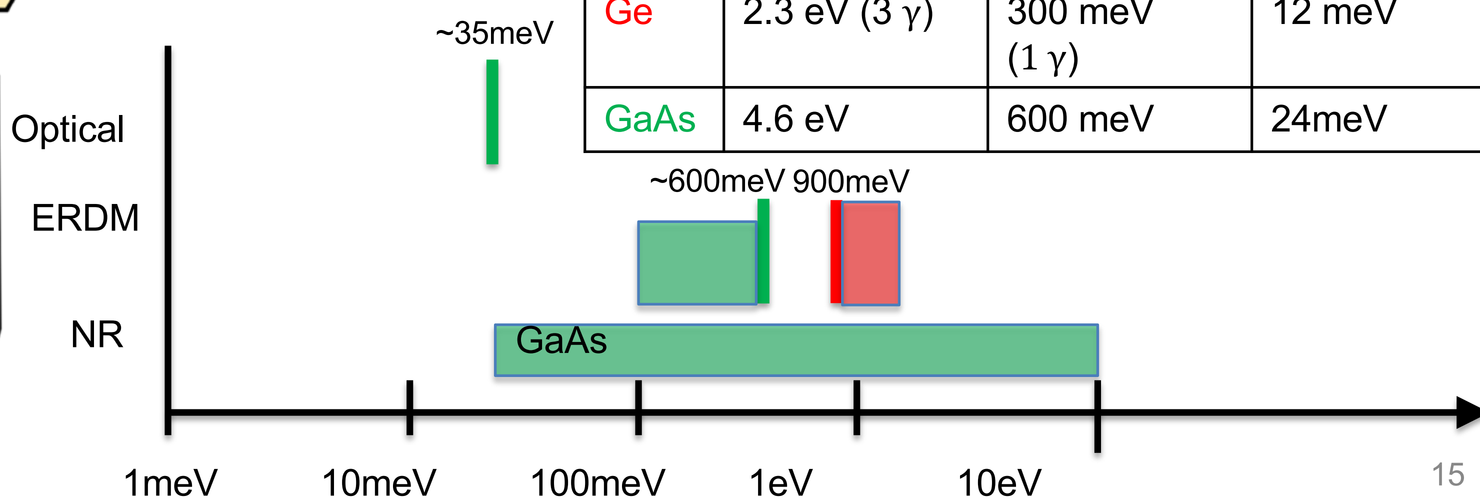
- GaAs has very high scintillation yield (1802.09171)
- 10-1000 gyr exposure
- Notice GaAs has worse background free reach than both Si and Ge! It's actually even worse than this because this doesn't include quantum efficiency suppression
- However, GaAs has background control:
  - 2 photon coincidence 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

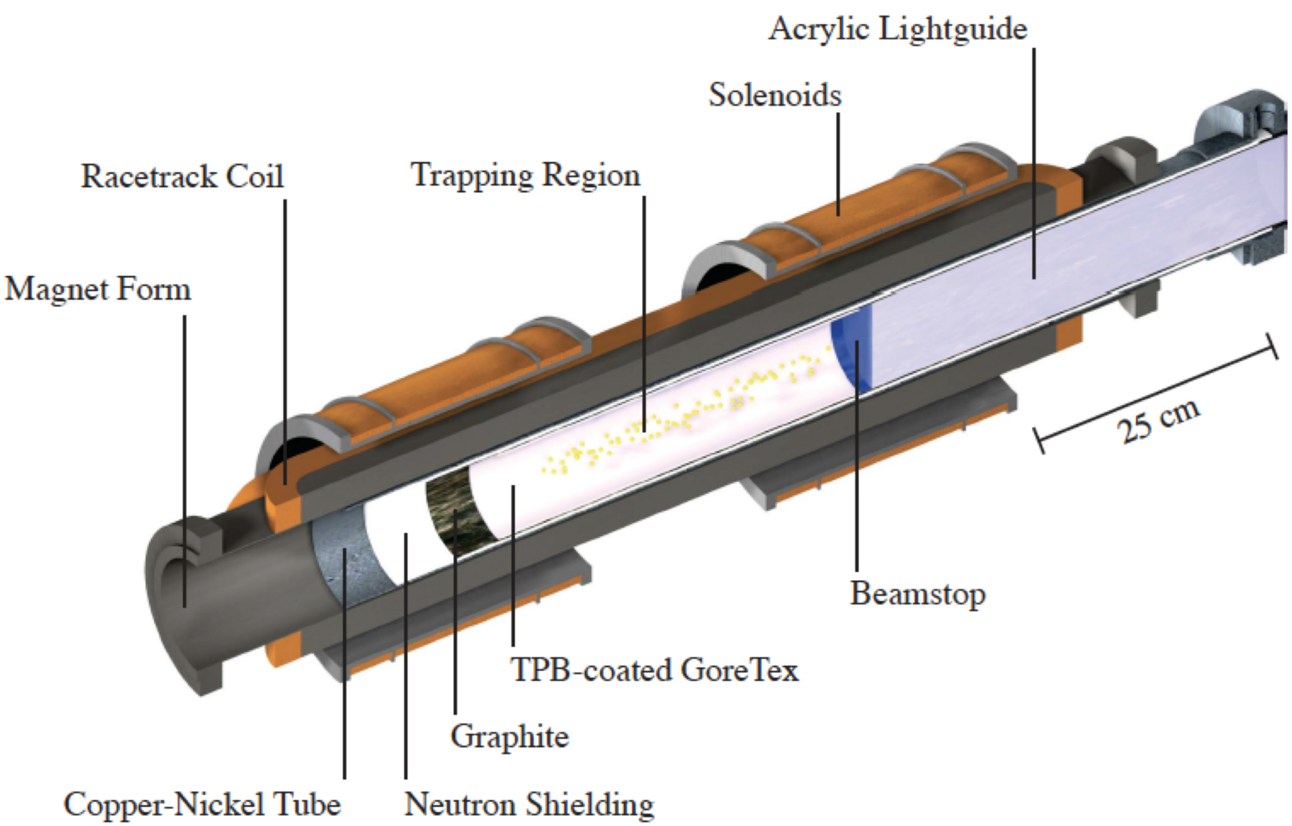




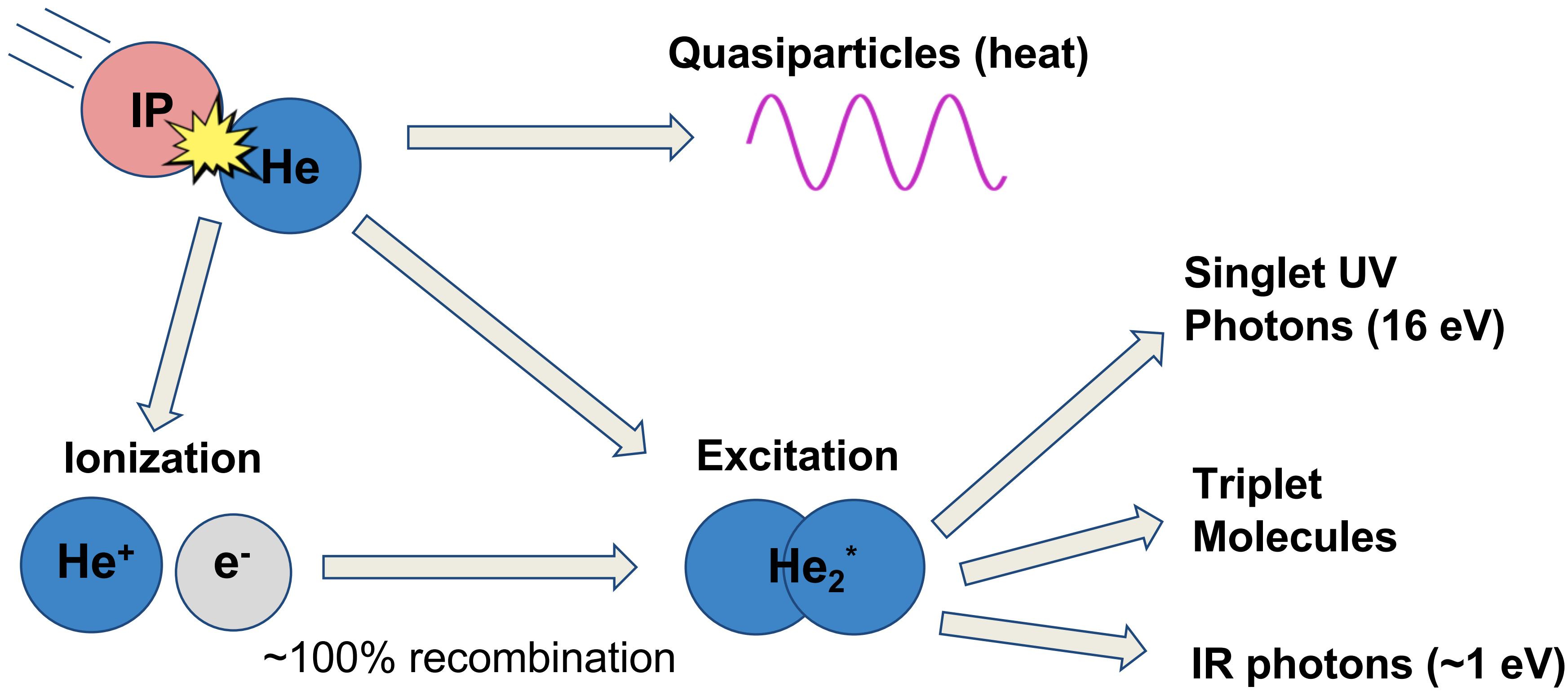
Superfluid helium-4 as a detector material

- 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).



Recoils in Helium (generic incident particle IP)



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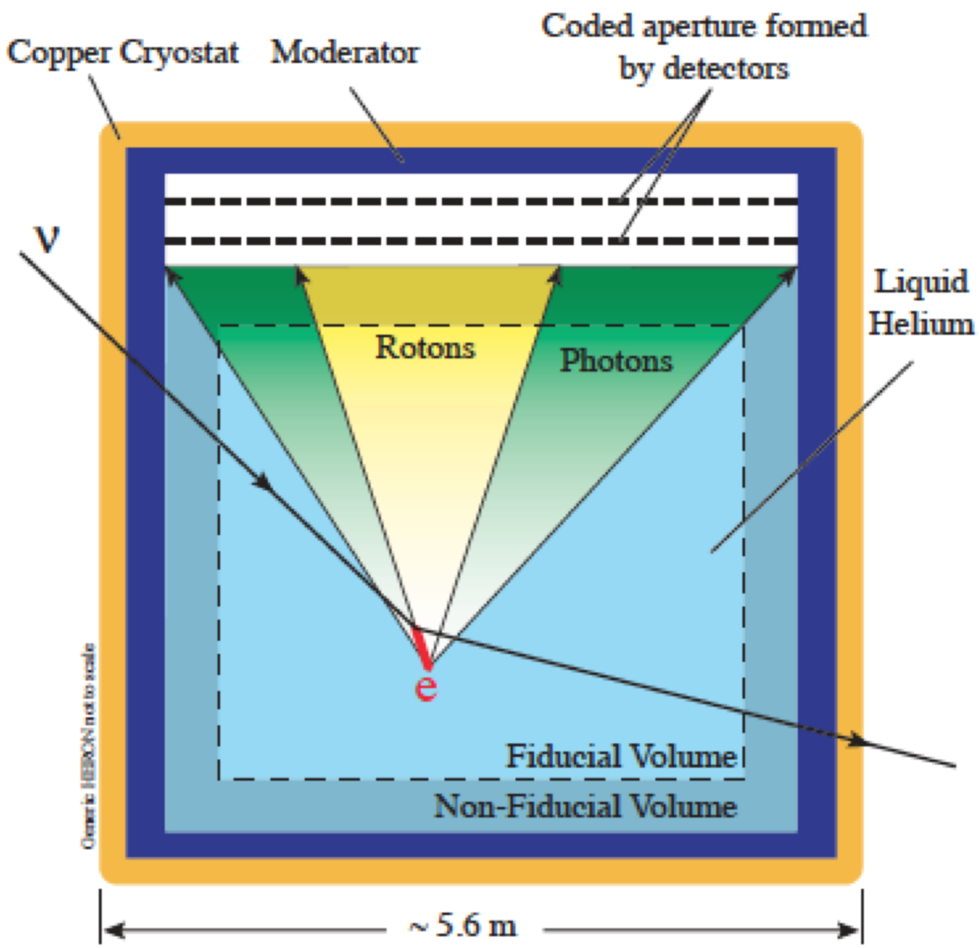
Superfluid helium-4 as a detector material

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)

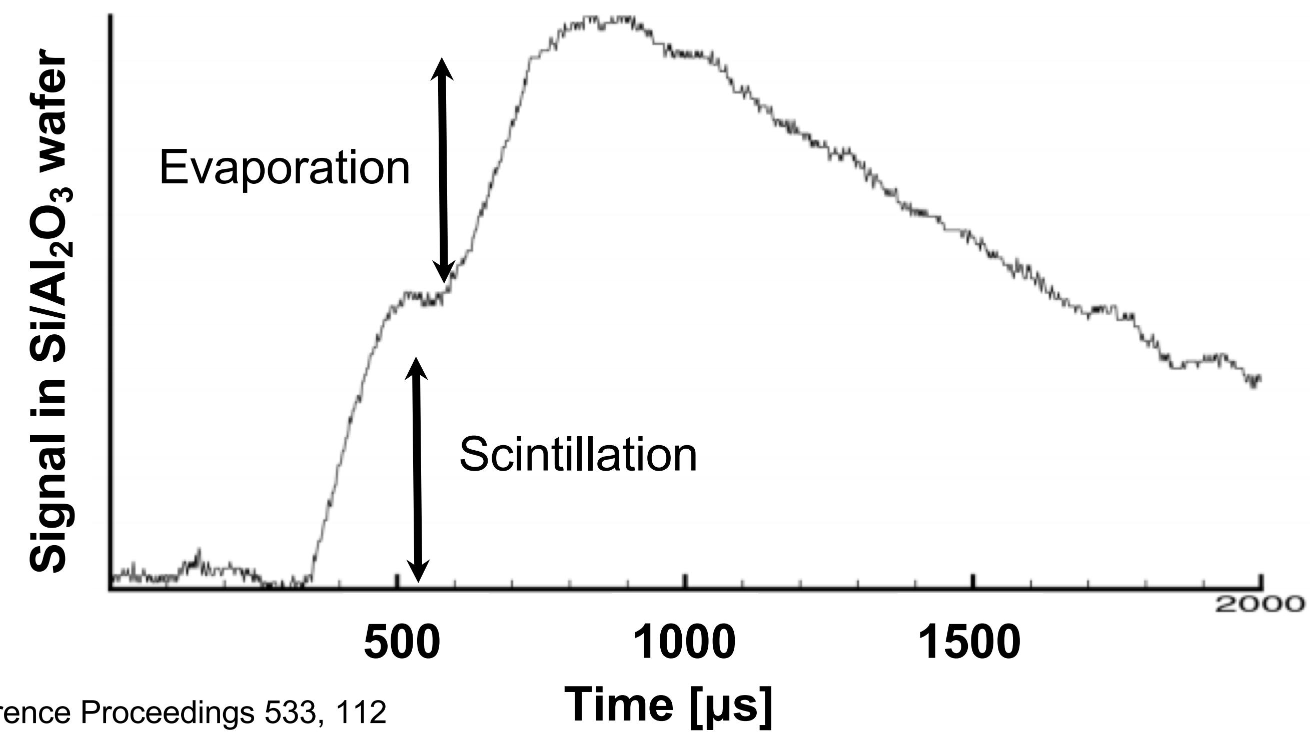


Previous work by HERON

HERON: proposed *pp* neutrino observatory

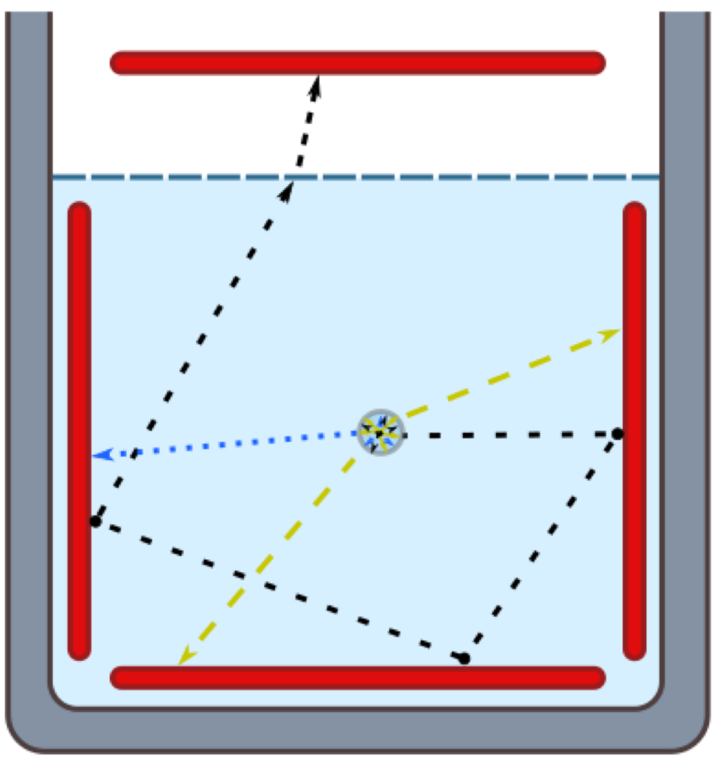
R&D at right shows simultaneous detection of photons and rotons

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.

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

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

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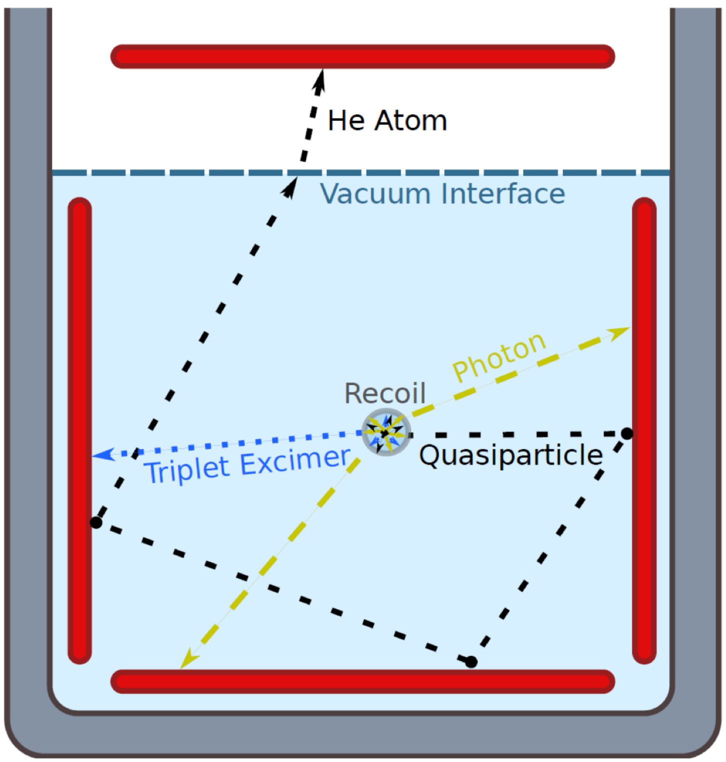
HeRALD concept and sensitivity paper
[PhysRevD.100.092007]



- Operated at ~20-50 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)

Quasiparticles in ^{4}He

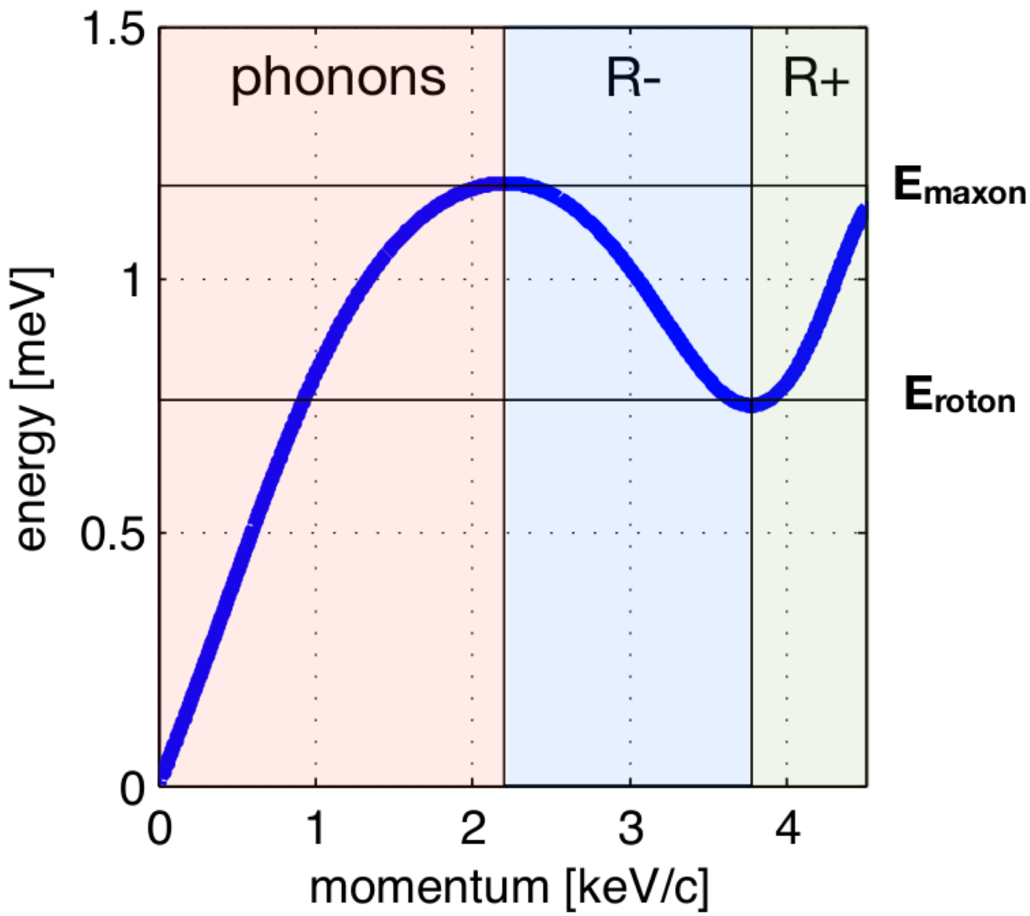
Quasiparticles: collective excitations in superfluid helium

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

An eV scale recoil produces thousands of quasiparticles!



Detecting Quasiparticle Signal

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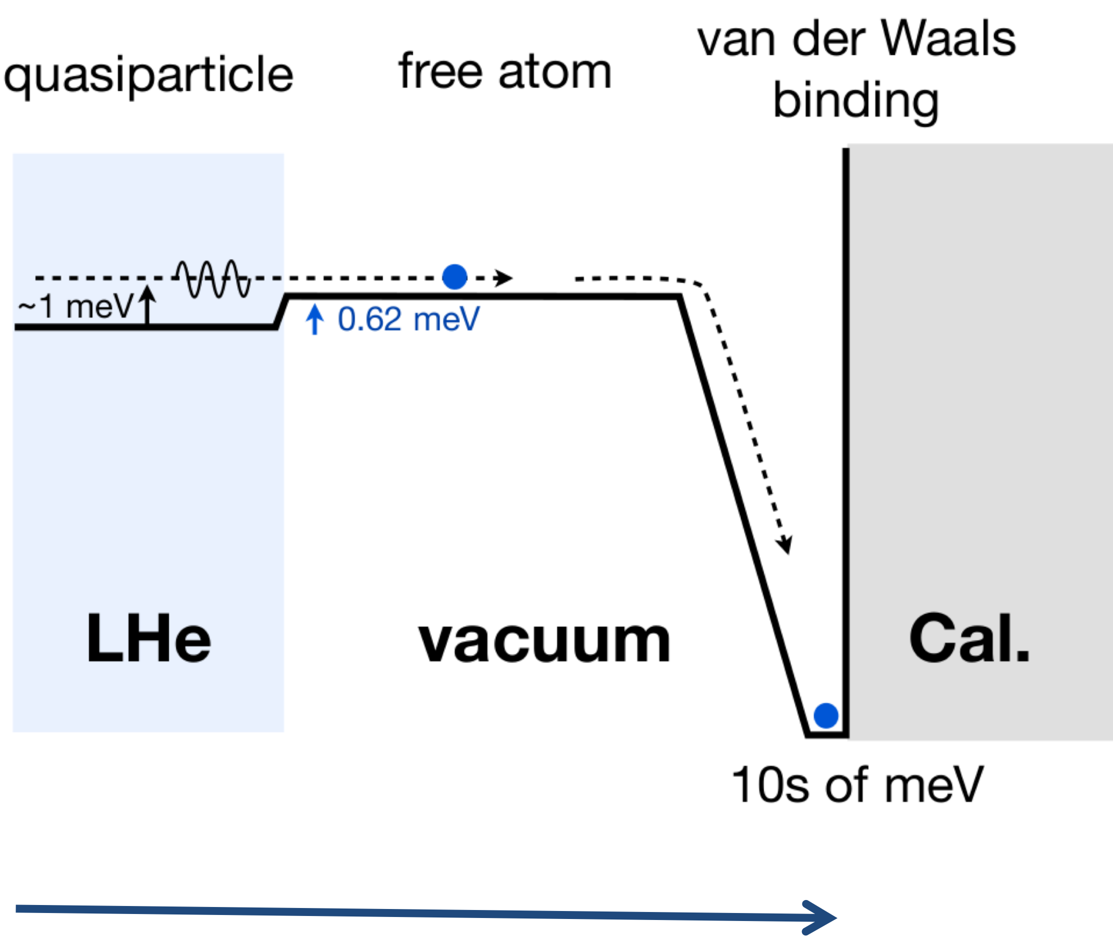
Binding energy between helium and solid amplifies signal

1 meV recoil energy → up to 40 meV detectable energy

Thermal energy negligible (μeV)

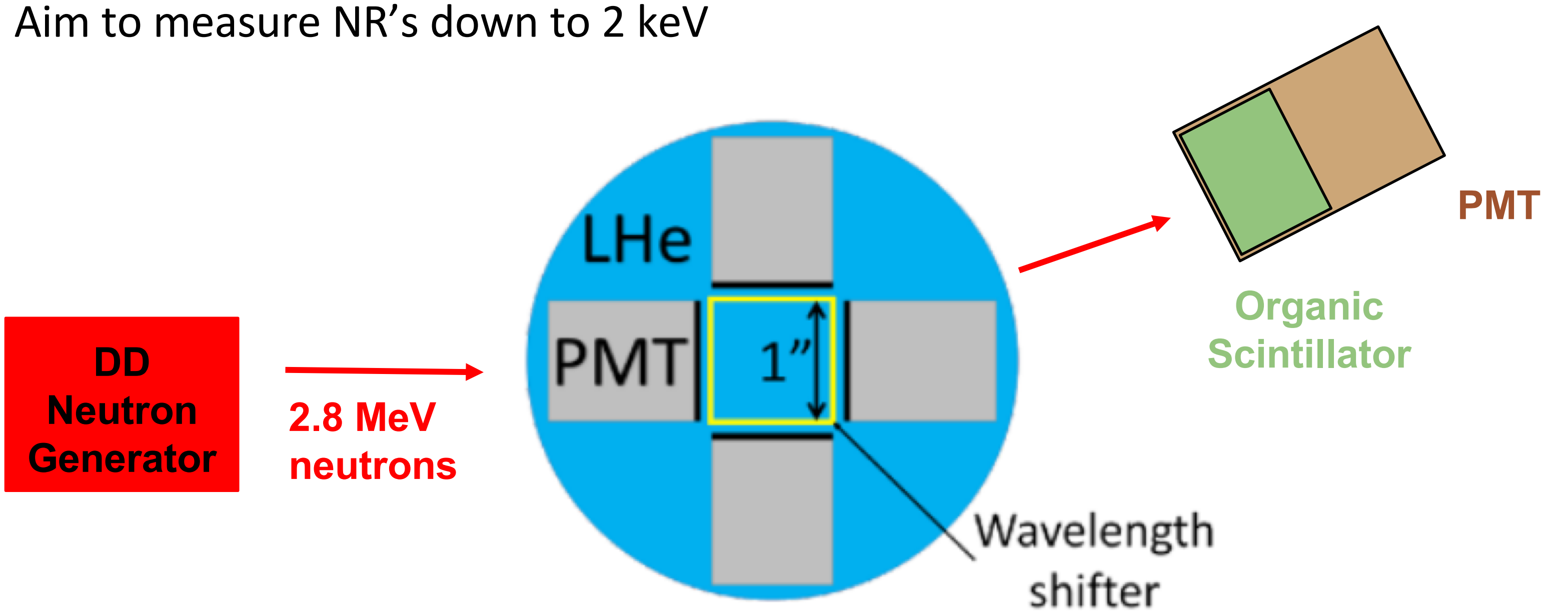
Film burner to remove helium from calorimeter



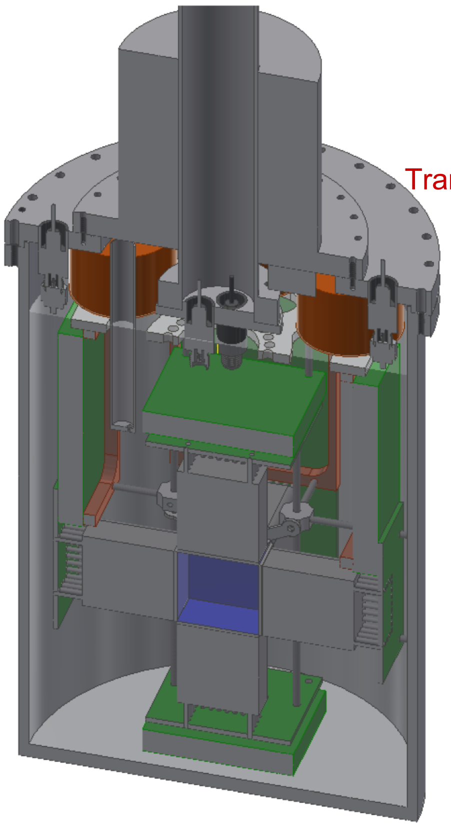
A one-way process, providing heat signal gain!

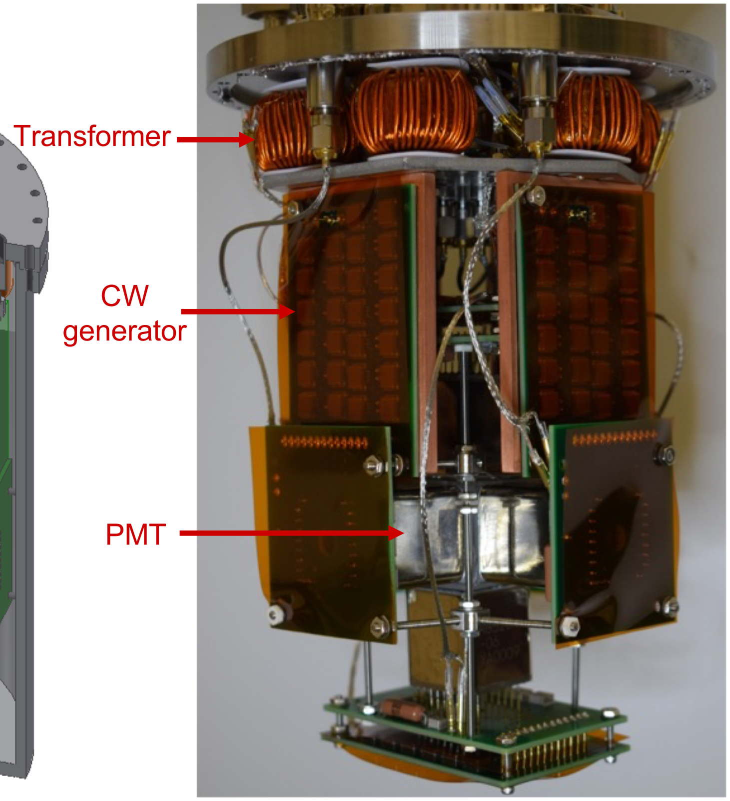
Measurement of Nuclear Recoil Light Yield in Superfluid ^{4}He

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



Light yield measurement of superfluid He-4

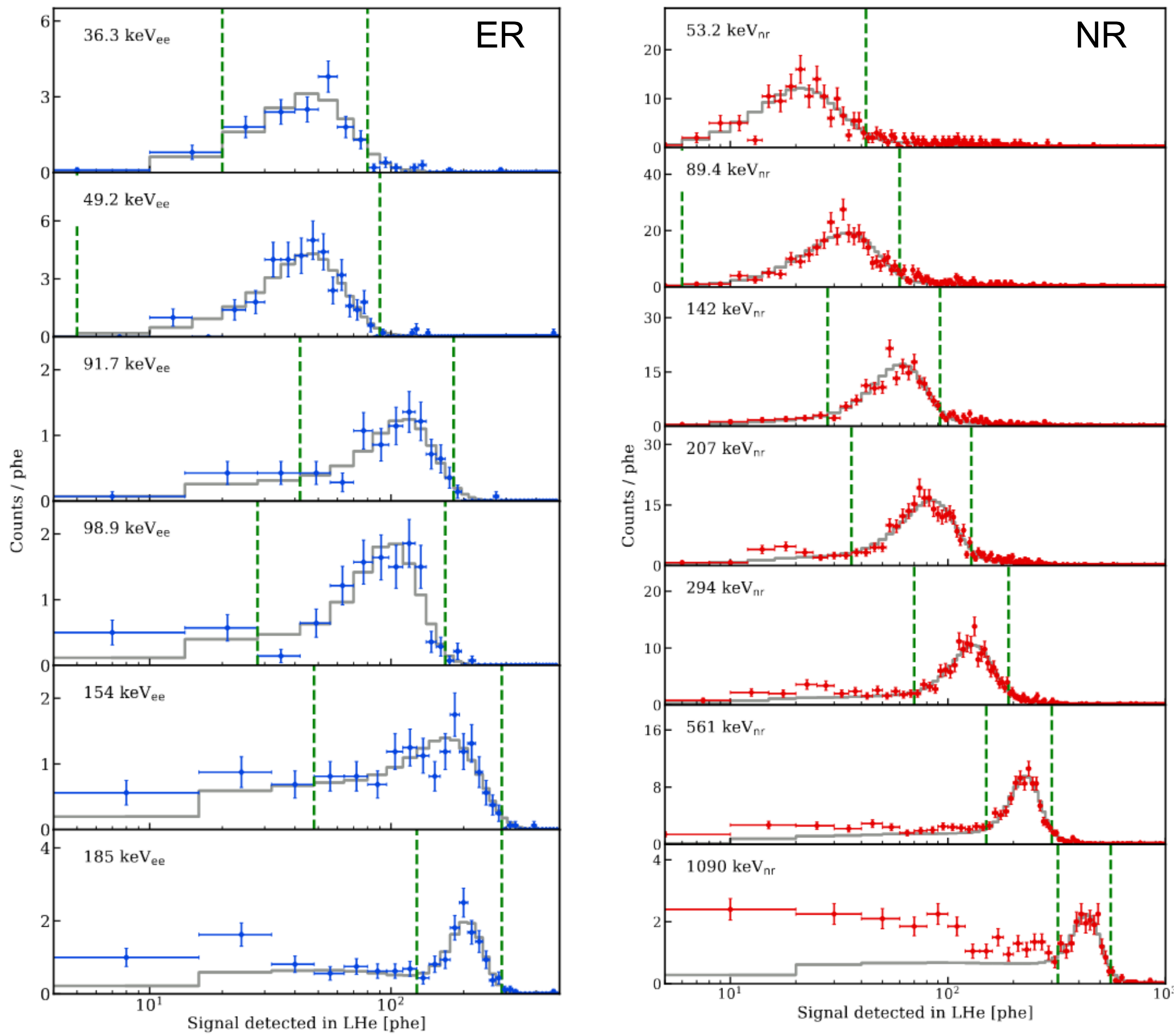




- Data taken at 1.75K
- Cockcroft–Walton (CW) generator
  - No voltage divider for PMT
  - No resistive heat
  - Suitable for down to ~mK
- High light yield
  - ~1.1 PE/keV_{ee}

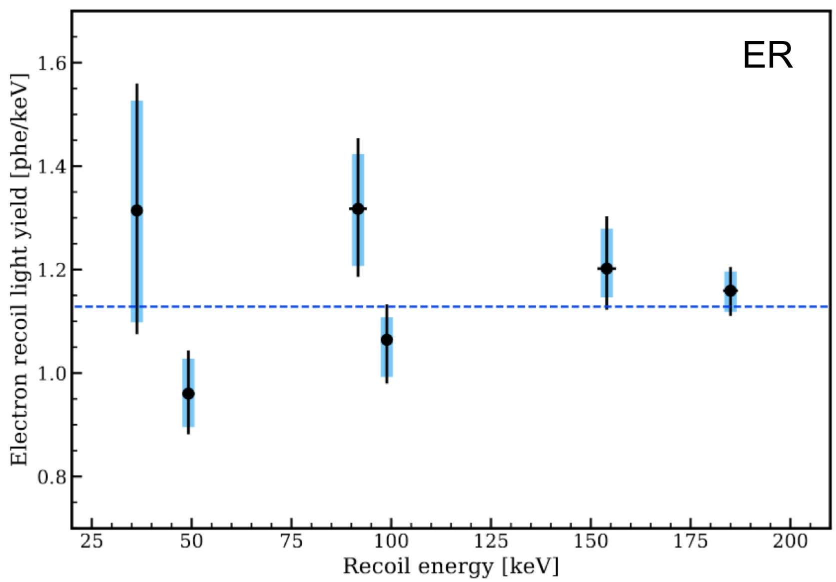
Light yield measurement of superfluid He-4

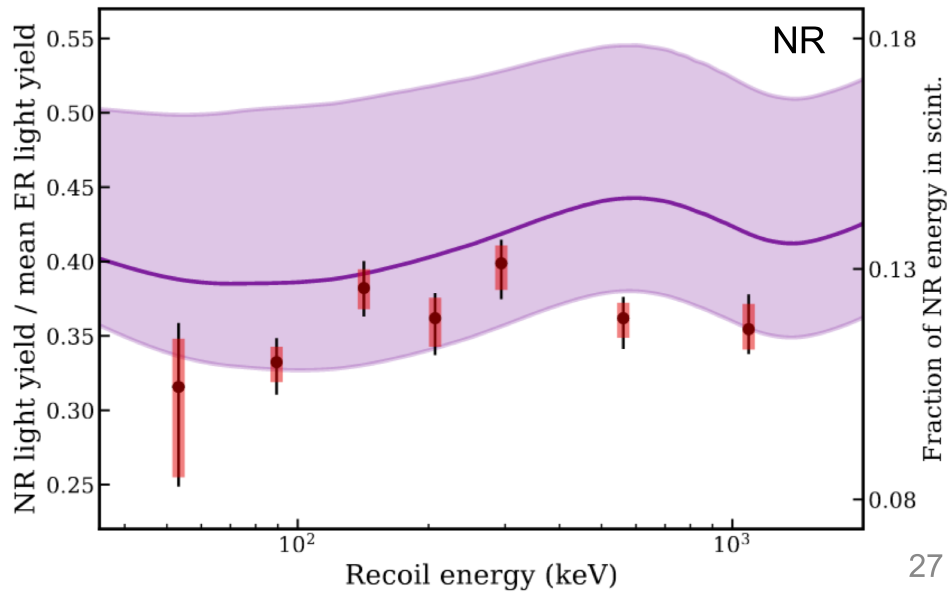
- ➢ Data selection cuts
  - ○ Time of flight
  - ○ Pulse shape discrimination (LS detector)
  - ○ Deposited Energy (NaI detector)
- ➢ Fit data with MC sims



Light yield measurement of superfluid He-4

- **(arXiv:2108.02176, accepted to Phys. Rev. D**
- First measurement of LHe scintillation in tens of keV.
- 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





SbBe source with iron filter

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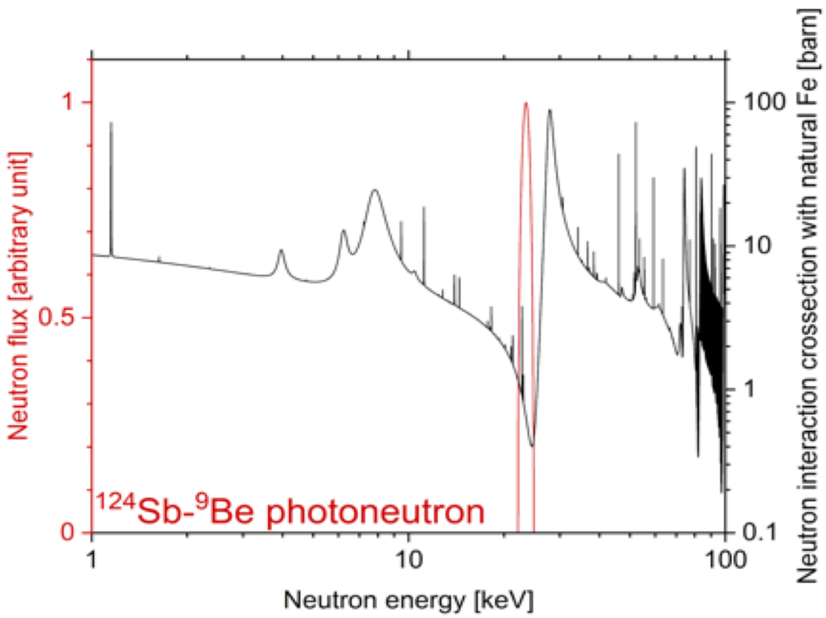
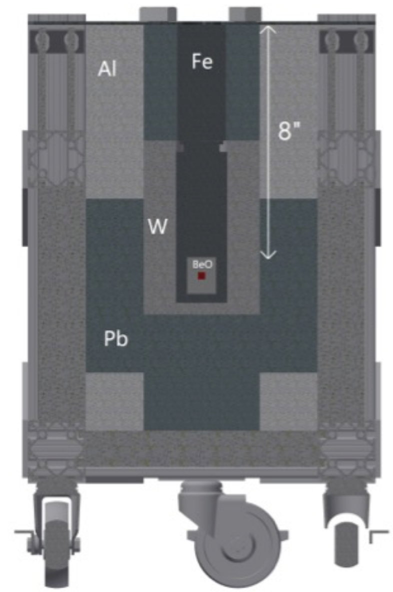
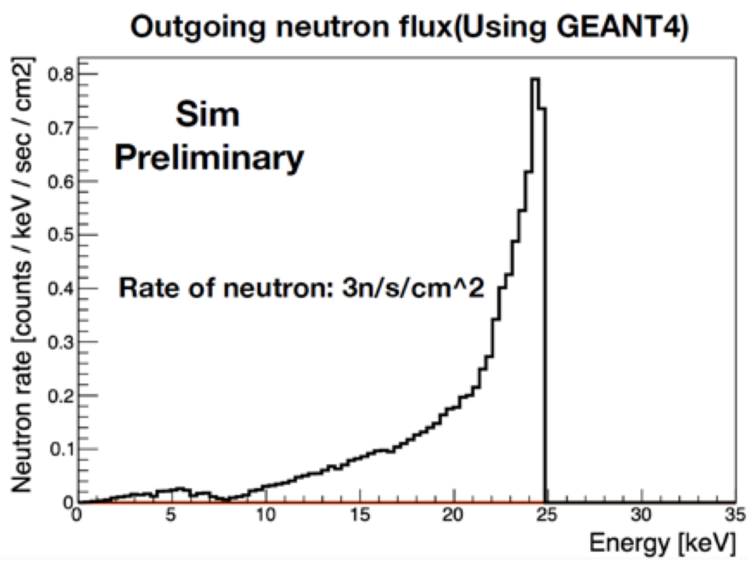






- 24 keV photo-neutron from ^{124}Sb-^{9}Be
- Iron cross-section dip at 24 keV neutrons
- 1-GBq Sb produced in nuclear reactor
- Currently being characterized

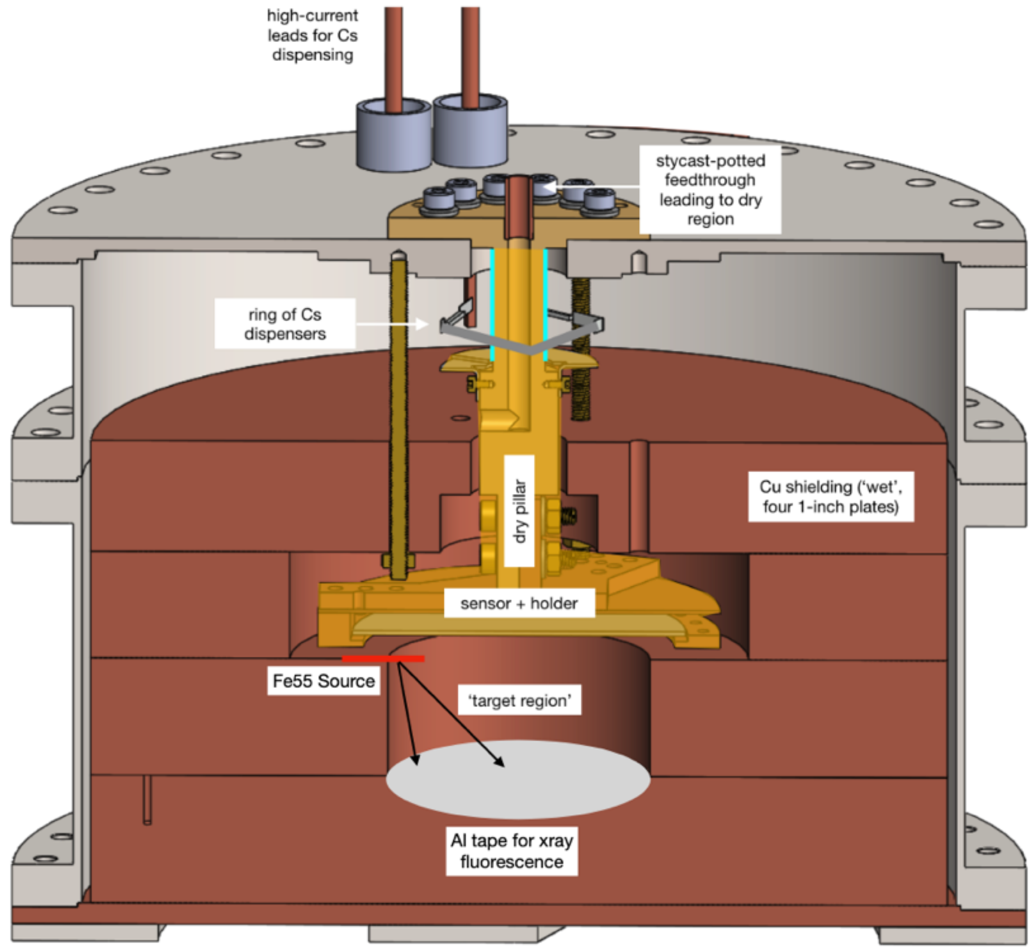
Progress on Superfluid Helium

First TESSERACT measurements of quantum evaporation signals in liquid helium, done at U Massachusetts (group of S Hertel).

Superfluid 4He covers all surfaces of a closed container. Do not want this on calorimeter!

- Preserve adsorption gain
- Empirically: superfluid on calorimeter degrades performance
- Superfluid 4He does not wet Cs, deposit a ring of Cs between helium target and calorimeter

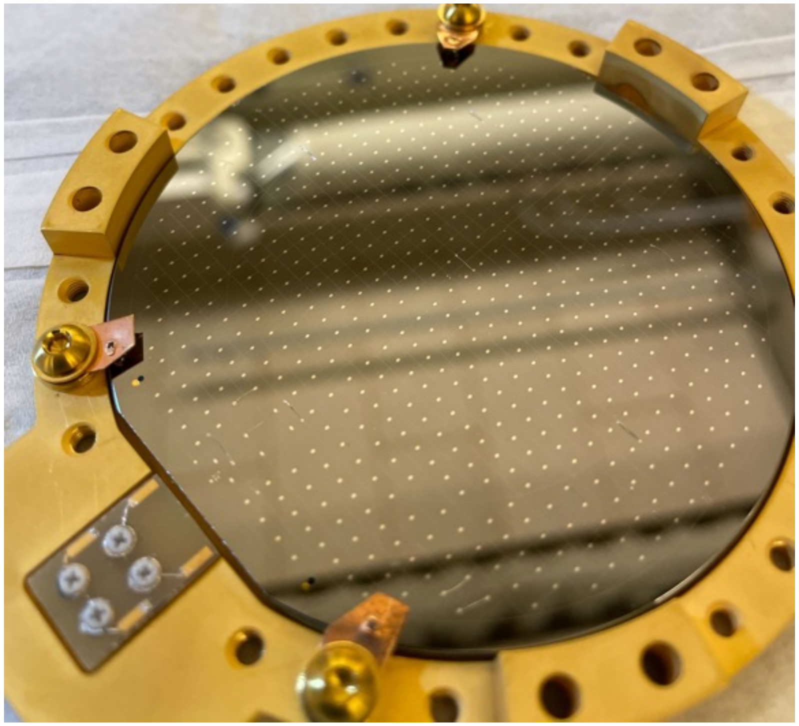
Ketola, Wang, Hallock PRL 68, 201 (1992)

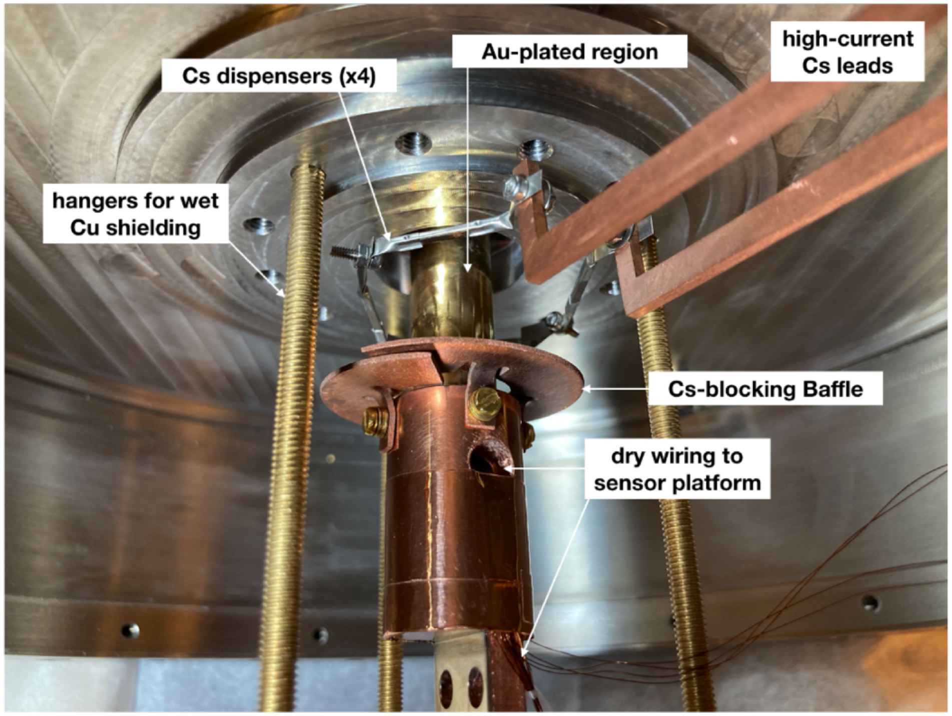


Progress on Superfluid Helium

TESSERACT detector running at UMass (group of S. Hertel), with 55 mK critical temperature and 3 eV resolution.

The Cs film stopper: success!
Deposit Cs in situ below 100 K
Au-plated Cu substrate





Progress on Superfluid Helium

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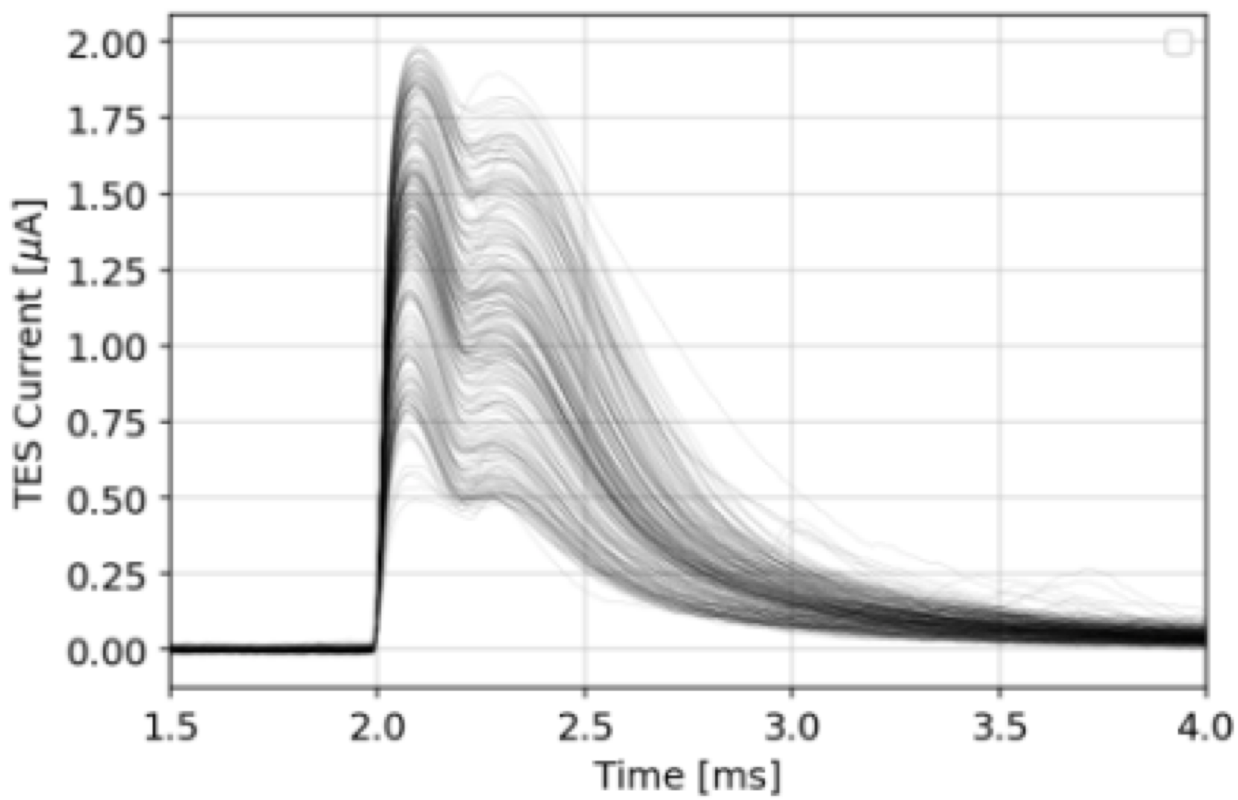
First TESSERACT measurements of quantum evaporation signals in liquid helium, done at U Massachusetts (group of S Hertel). Excitation with Fe-55 x-rays and Al x-ray fluorescence.

First pulse: prompt scintillation. Second pulse: quantum evaporation.
ANALYSIS ONGOING



Progress on Superfluid Helium

Superfluid He detector being designed in Berkeley based on Cs-based film blocking

Will be first operated at LBNL using existing dilution refrigerator

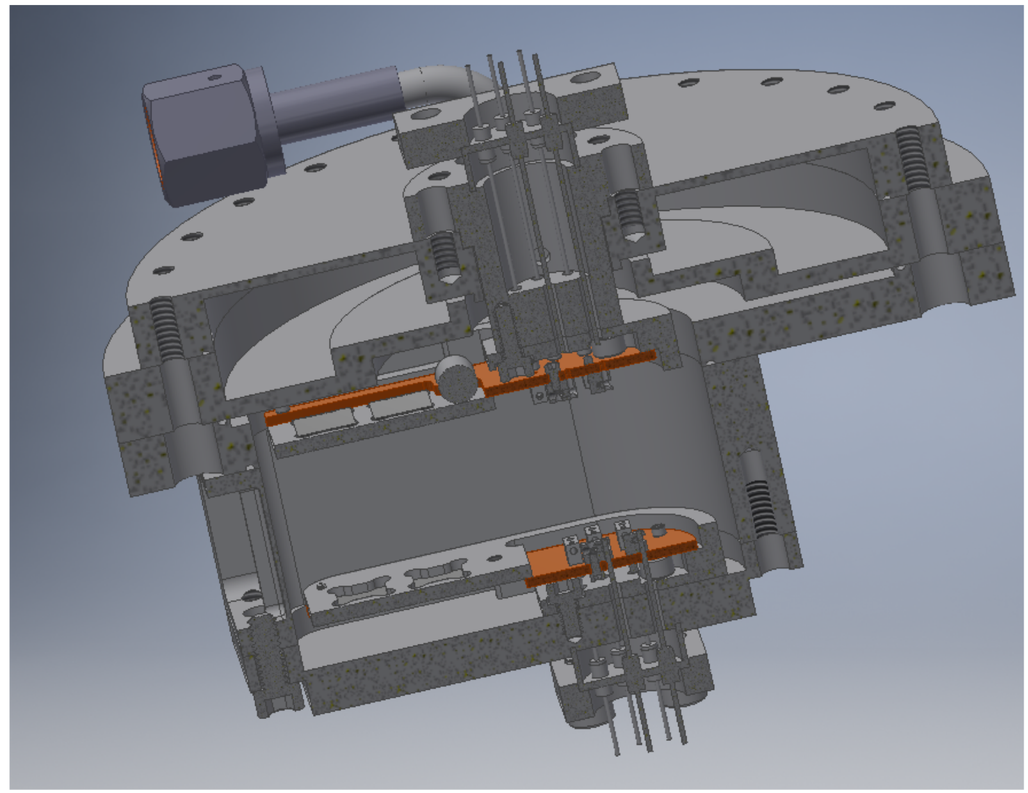
in^3 of active liquid helium

Will use very latest TES-based detectors, with < 1 eV resolution

Calibrations to be performed using x-rays, gamma-rays, and new SbBe 24 keV neutron beam (UCB)

Prototype for future TESSERACT detectors

Investigate heat-only backgrounds – are they eliminated by using LHe?



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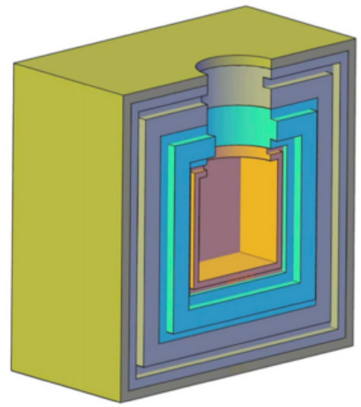
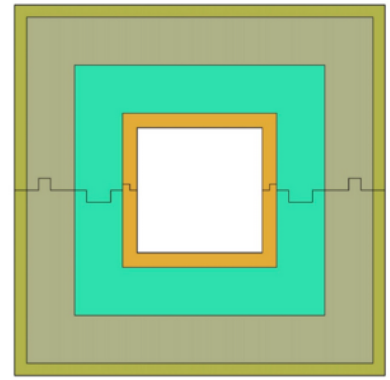
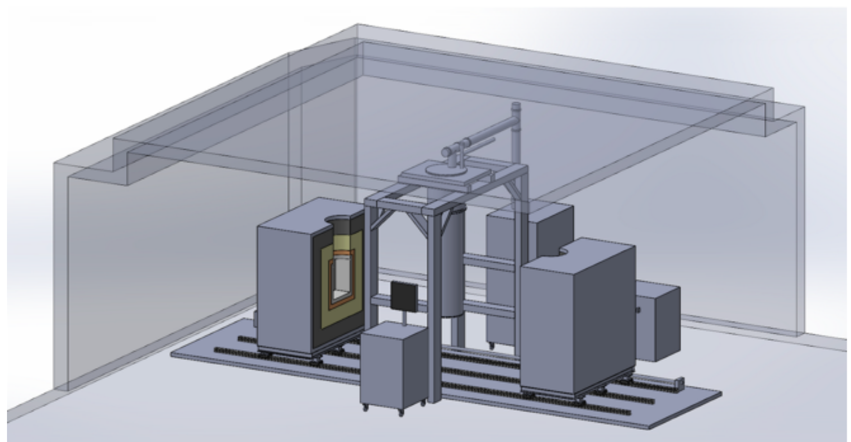
Progress on Shielding Design

The experiments will be operated in an underground laboratory (not yet chosen). 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.

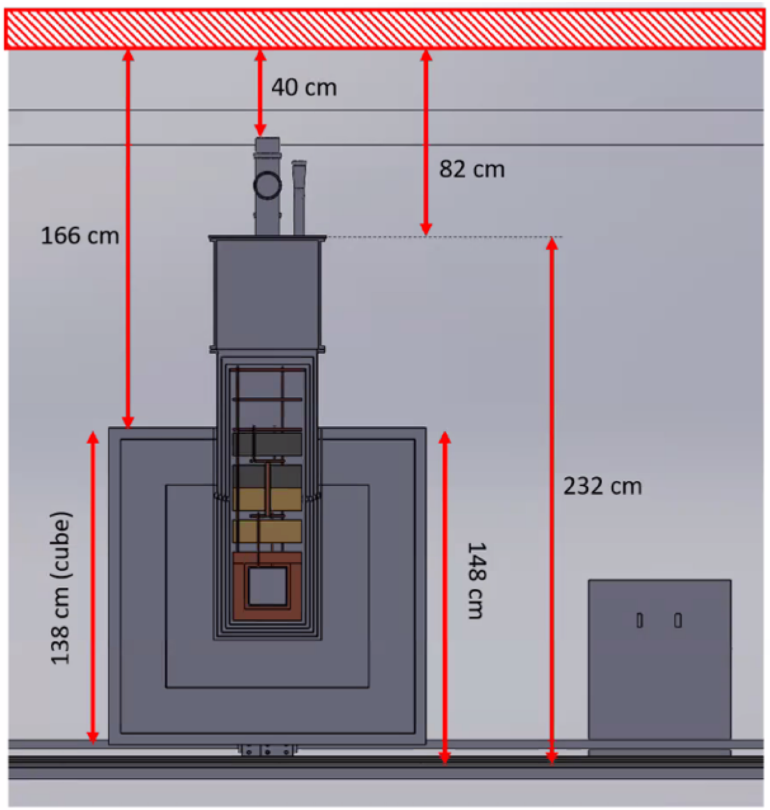


Significant emphasis on vibrational and EM noise suppression. Substantial R&D effort is being devoted to reducing these instrumental backgrounds, and this R&D will feed into the engineering design.

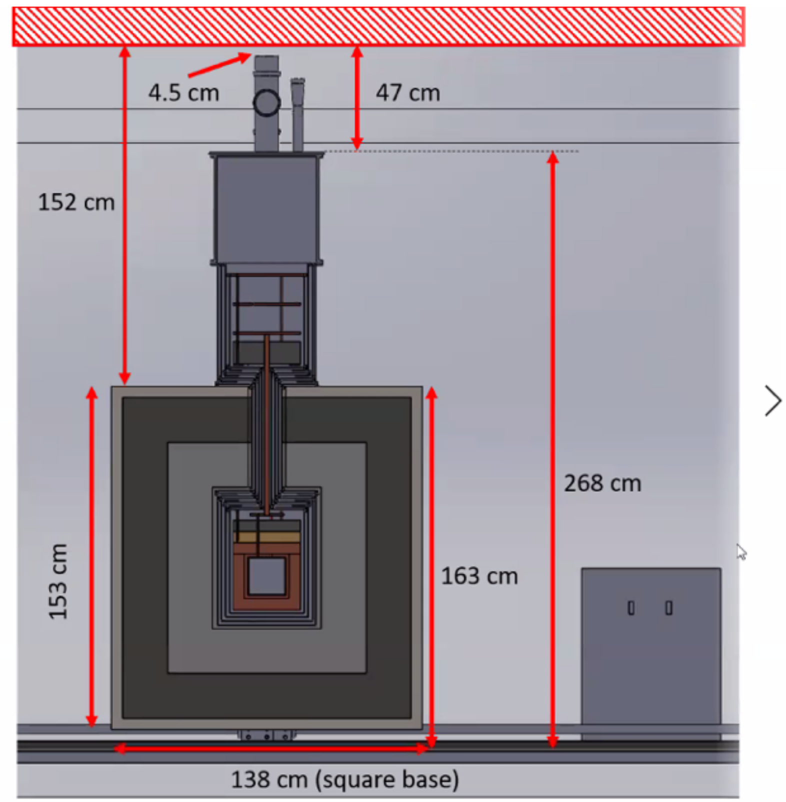
Progress on Shielding Design

Two shielding designs were studied, to understand engineering and radioactive background tradeoffs. Both designs were simulated using GEANT. The cylindrical design has a simpler cryostat, but simulations showed a gamma-ray background that was a factor 10 too high because of gamma rays and neutrons coming down the gaps between cryogenic layers.

Cylindrical design

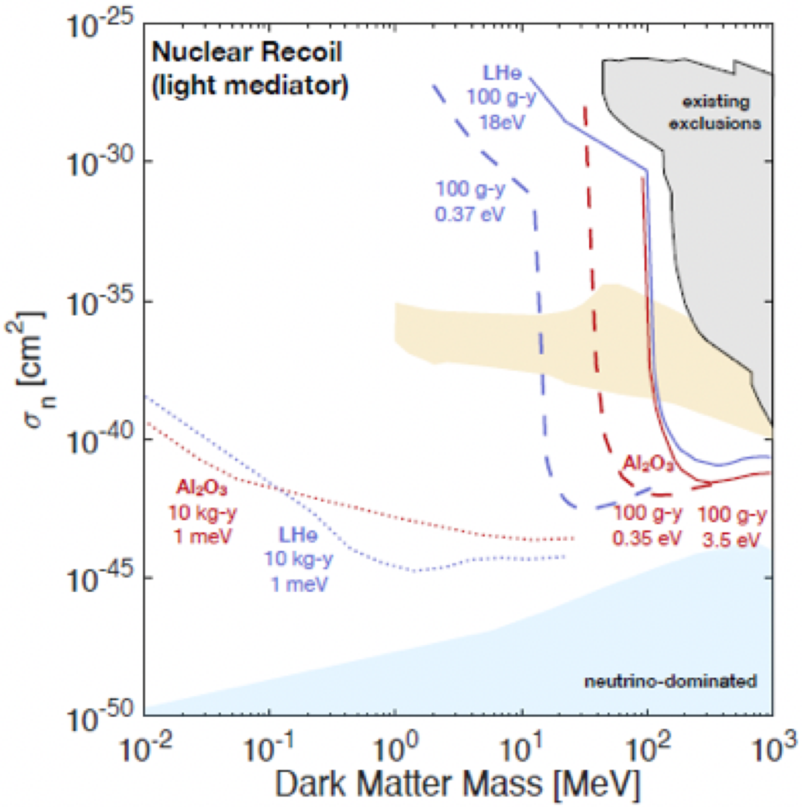


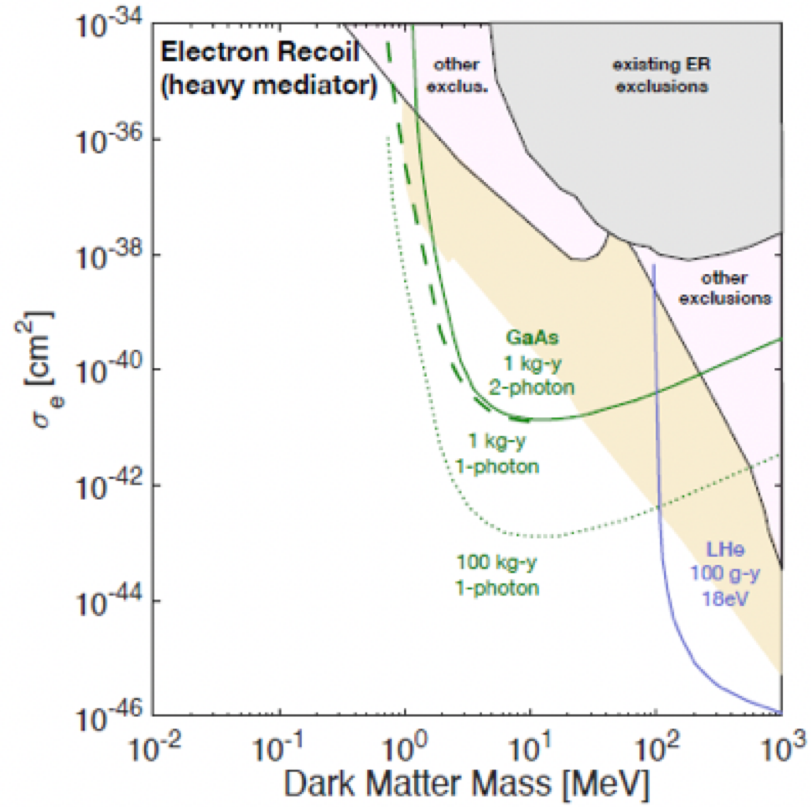
Nested cryostat design



SPICE and HeRALD - projected sensitivity

Snowmass2021 - Letter of Interest
[The TESSERACT Dark Matter Project]





SPICE and HeRALD - projected sensitivity

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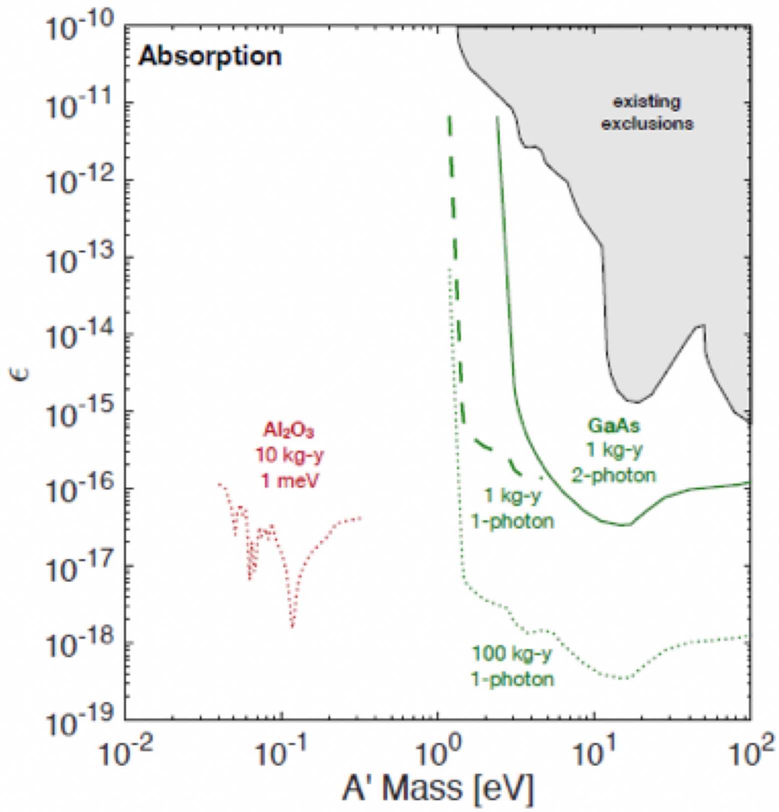

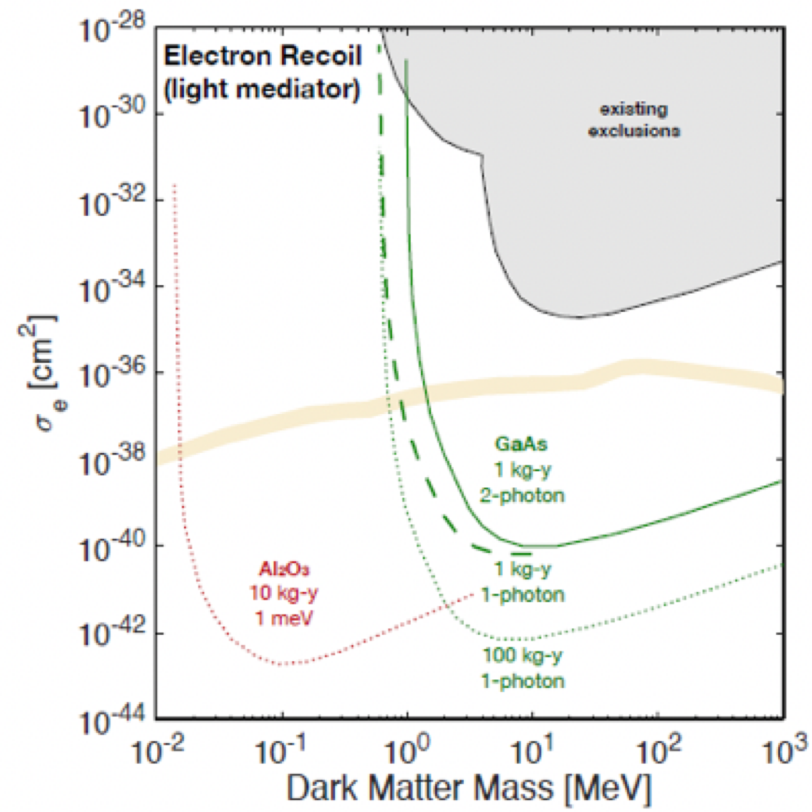

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Summary

- TESSERACT is developing different targets for DM searches
- DM targets include polar crystals (SPICE) and superfluid helium (HeRALD).
- R&D has begun on TES, athermal phonon sensors, and coupling these to multiple targets. First R&D accomplishments have already been achieved!
- First R&D results on superfluid helium light yield, SbBe neutron beam.
- In parallel, TESSERACT design, engineering, and project management is ramping up
- Discussions ongoing with underground laboratories.

Backup