TESSERACT

Design and testing of a monoenergetic 24 keV neutron source for calibration of low threshold dark matter detectors

Dan McKinsey for the SPICE/HeRALD collaboration
UC Berkeley/LBNL

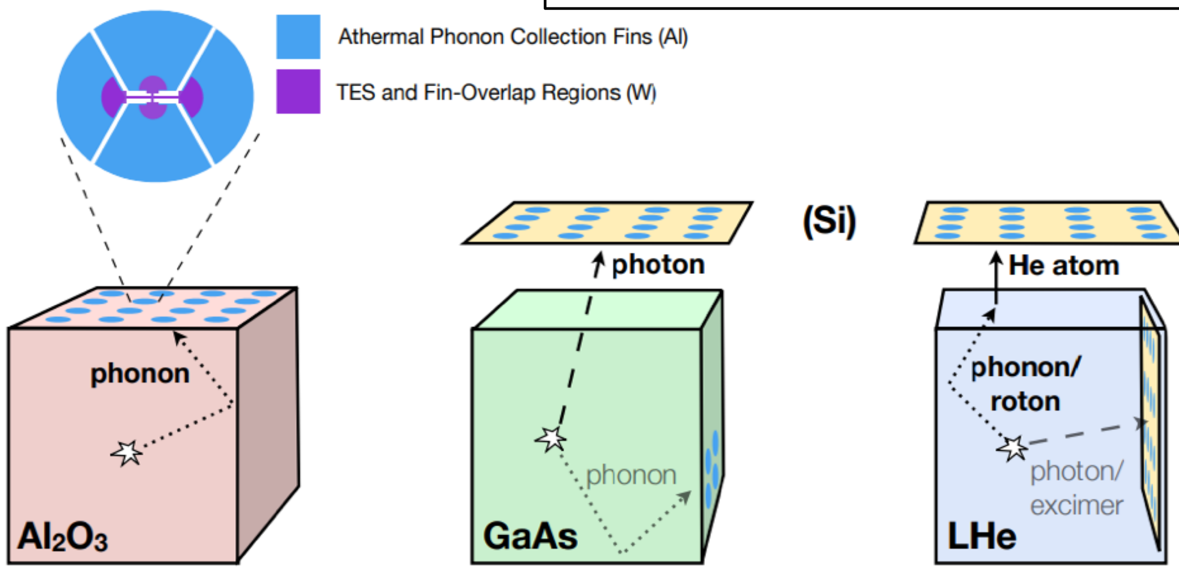
GUINEAPIG Workshop on Light Dark Matter
TRIUMF
September 10, 2022

The TESSERACT project (part of the DMNI suite)

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

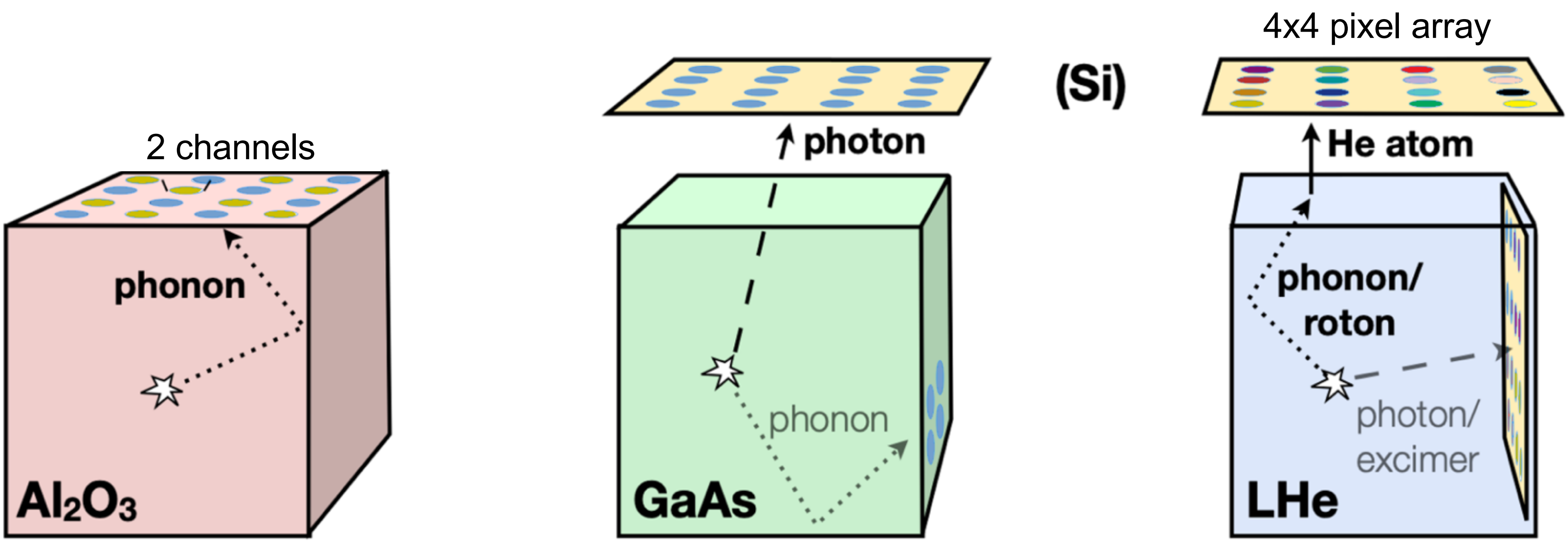
Transition Edge Sensors with Sub-Ev Resolution And Cryogenic Targets

- 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).



Coincidence-based background rejection

SPICE and HeRALD are both designed for instrumental background rejection, in the event low energy backgrounds can't be fully mitigated in a given sensor.



Multi-channel coincidence

Photon+ Phonon Coincidence

He can't have stress + Multi-channel Coincidence

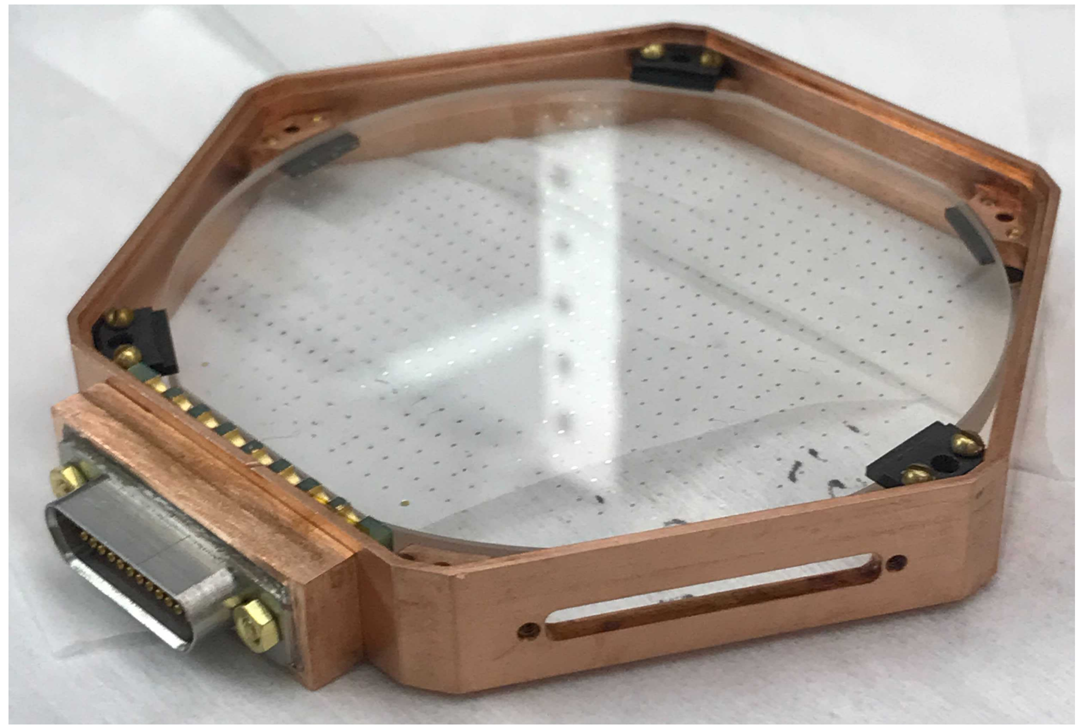
Science goals achievable even with residual micro-stress fracture rate

Sapphire, aka Al_2O_3 (part of SPICE)

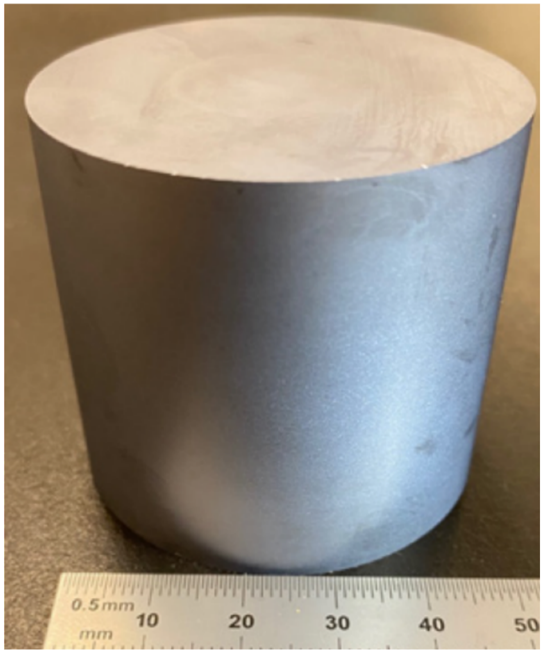
Design driver: Push threshold to single optical phonon scale, 10s of meV

TES fabrication on Sapphire now demonstrated!

Tc too low for current parasitic power levels… (no DM search data yet)

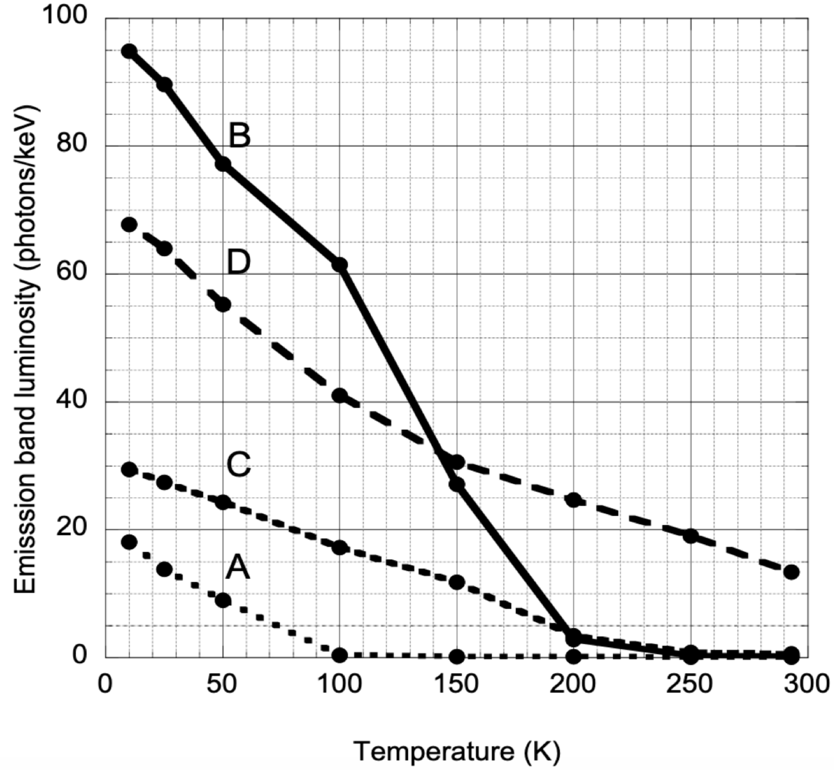


Developing GaAs target



One of the brightest samples of silicon and boron-doped GaAs scintillator tested.

Nucl. Instr. Meth. A989, 164957 (2021)



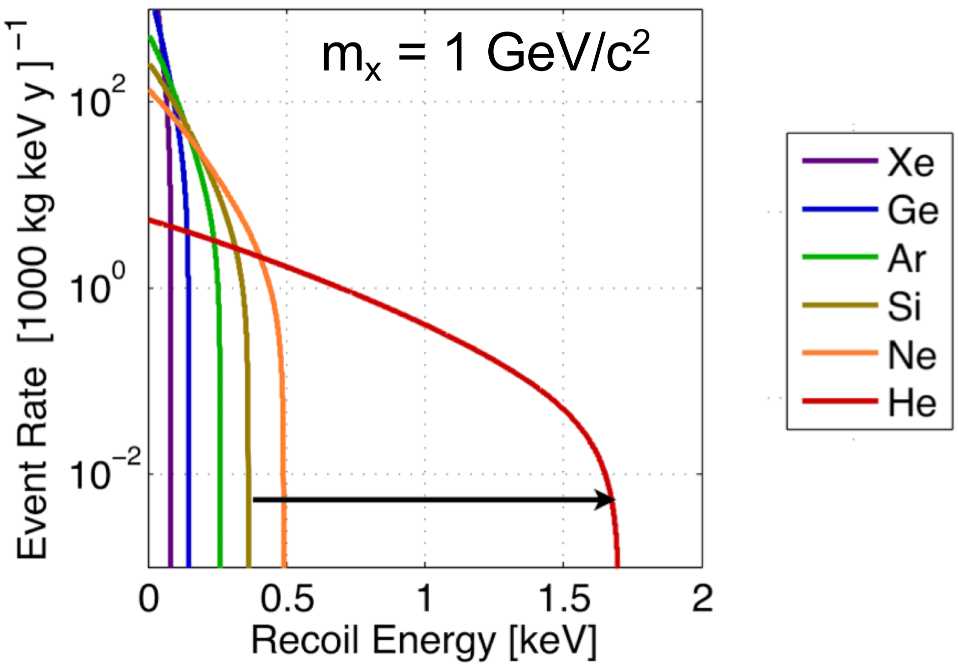
- Measured (+ongoing) the luminosity of 27 GaAs samples at 850, 925, 1075, and 1350 nm.
- Luminosities vary from nearly zero to over 100 photons/keV, radiative decay times range from 200 to 2000 ns

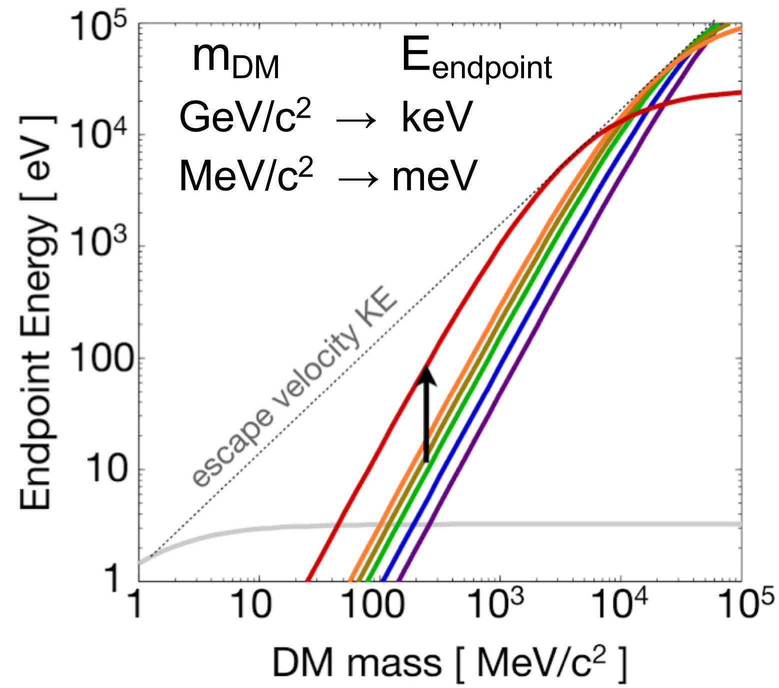
In SPICE, we will detect this scintillation in coincidence with phonon signal, providing ER/NR/instrumental background rejection
In addition, we hope to use phonon signal ratios over multiple TES channels to mitigate surface-localized stress-induced background events

Light baryonic target nuclei for NRDM

With sufficiently low threshold and/or a light target, lower dark matter masses may be probed. NR searches benefit from A^2 or Z^2 scaling of DM cross-sections, generically lower NR backgrounds (neutrons) than ER backgrounds (betas, gammas)

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



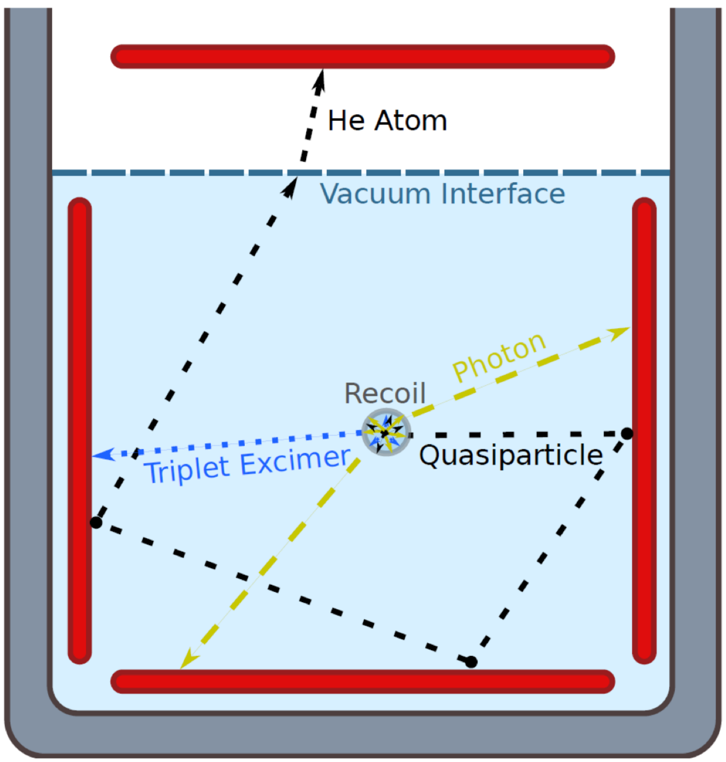


Superfluid helium has significant additional advantages

- Quantum evaporation signal gain
- Multipixel background rejection (including heat-only events!) by requiring coincidence
- Multiple signal channels (rotons, phonons, scintillation) -> ER/NR/instrumental discrimination

Helium Roton Apparatus for Light Dark matter (HeRALD)

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

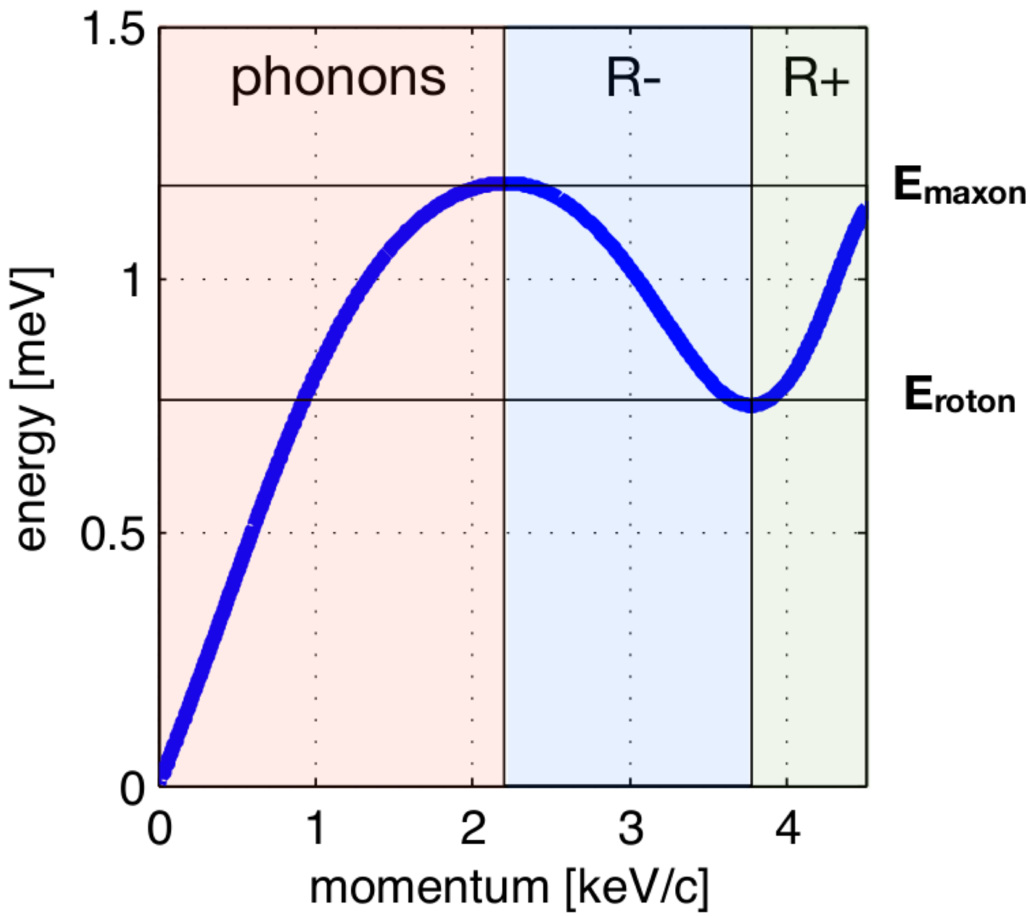
Quasiparticles: collective excitations in superfluid helium

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!



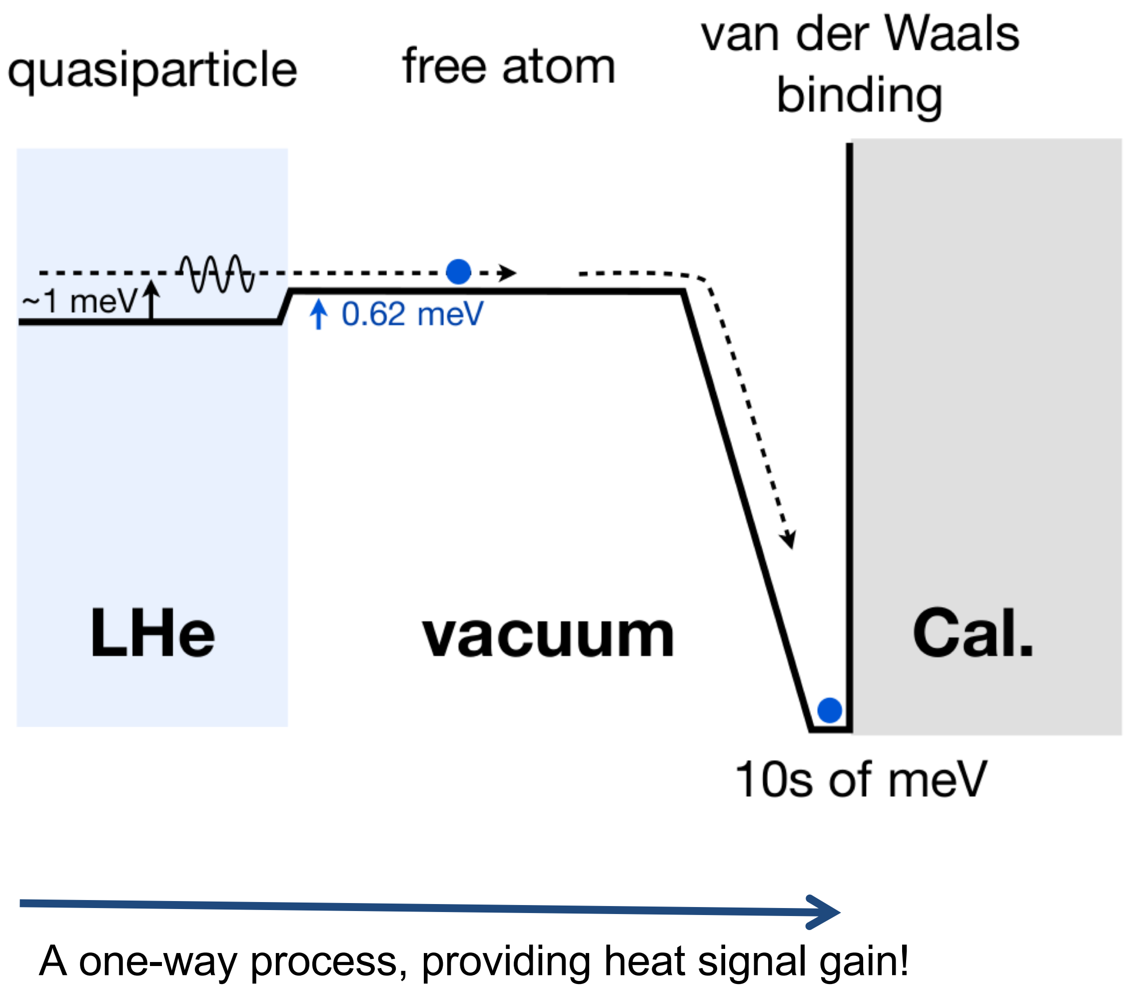
Detecting Quasiparticle Signal

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



TESSERACT

Detector Performance Specifications

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

Sensor Characteristics	**Required**	**Goal**	**Stretch Goal**
TES T_c	40 mK	24 mK	13 mK
Total TES Volume	$[100\times400]\mu m\times40nm$	$[50\times200]\mu m\times40nm$	$[25\times100]\mu m\times40nm$
Bare TES bias power	40fW	780aW	9aW
Bare TES noise σ_{TES}	40 meV	10 meV	1.9 meV
W/Al interface transmission probability $\epsilon_{W/Al}$	10^{-4}	10^{-4}	$5\text{x}10^{-4}$

Target Excitation Efficiencies

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 7σ Recoil Energy Thresholds

Scaled from Si demonstrator (2.6 eV σ_{phonon}) by phonon velocity, mean free path, and sensor area.

1 cm^3 Al_2O_3/SiO_2 (phonon only)	**3.5 eV**	**750 meV**	**24 meV**
1 cm^3 GaAs (phonons GaAs + photons on Ge)	**2.8 eV** (∼ 2−γ)	**900 meV** (1-γ)	**35 meV** (optical phonon)
1 cm^3 GaAs (phonons GaAs + photons on Ge)			
$0.1\times1\times1$ cm^2 Ge-based photon sensor	**1.8 eV** (∼2γ)	**390 meV** (< 1 γ)	12 meV
1 cm^3 GaAs phonon sensor	3.6 eV	770 meV	**24 meV** (∼ 1 OP)
64 cm^3 LHe (evaporation via Si-based sensor)	**16.2 eV**	**0.75 eV**	**24 meV**
includes scaling by $\epsilon_{collectHe}\times g_{He}$			
$0.1\times4\times4$ cm^3 Si-based He evaporation sensor	5.2 eV	750 meV	38 meV

Detector Performance Specifications

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

Sensor Characteristics	Required	Goal	Stretch Goal
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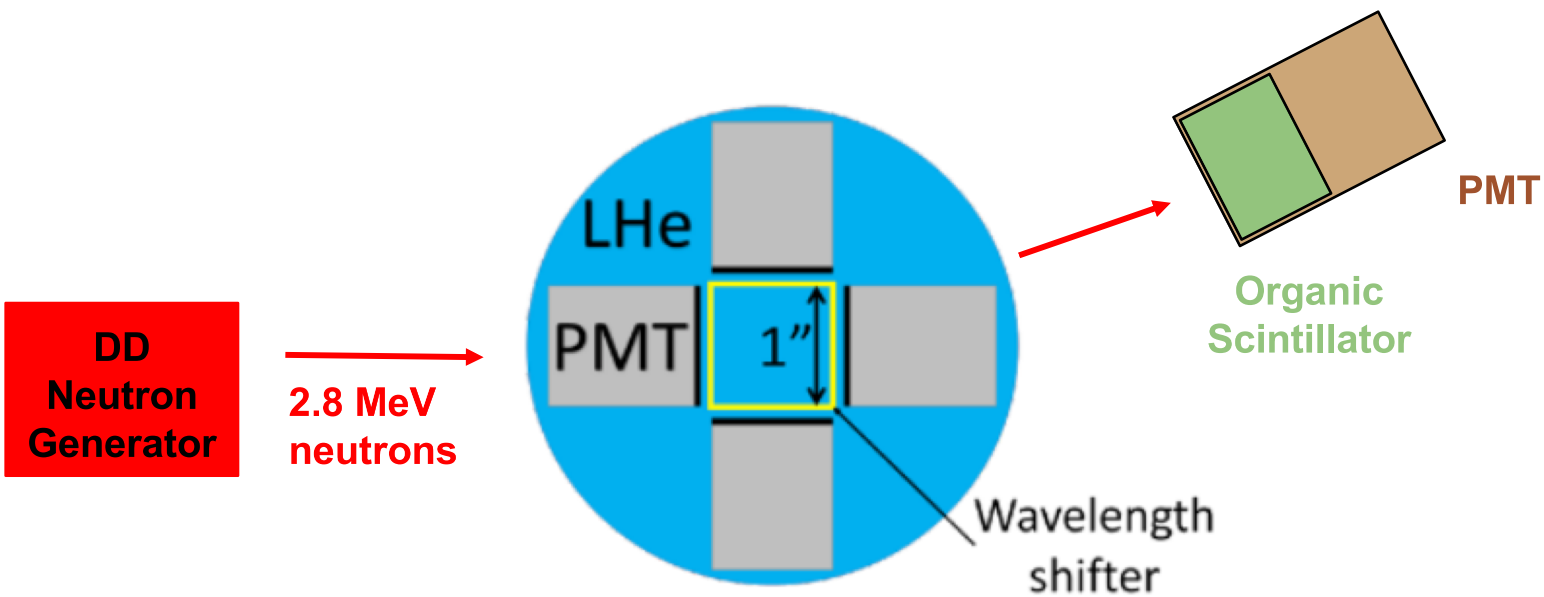
includes scaling by $\epsilon_{collectHe} \times g_{He}$			
0.1×4× 4 cm^3 Si-based He evaporation sensor	5.2 eV		

How to calibrate down to such low energies?

Measurement of NR Light Yield in Superfluid ^{4}He

- First measurement of the liquid ^{4}He nuclear recoil light yield!
- arXiv:2108.02176, Phys. Rev. D 105, 092005 (2022)
- Aim to measure NR's down to ~2 keV



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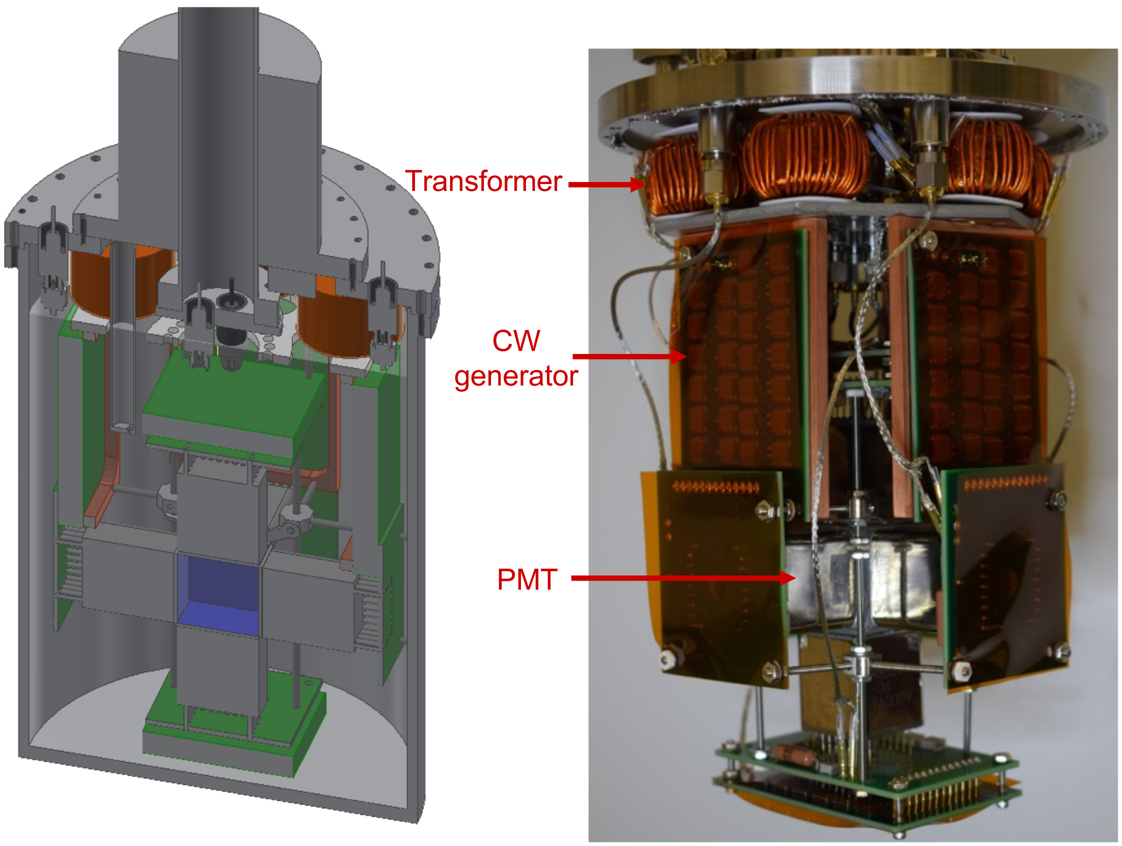
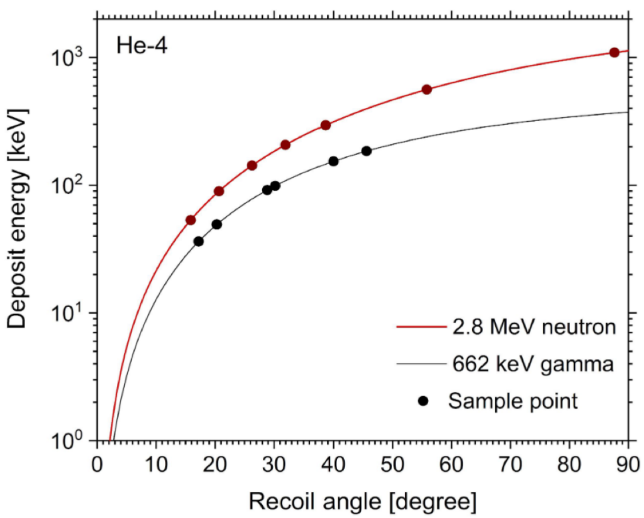
Light yield measurement of superfluid He-4

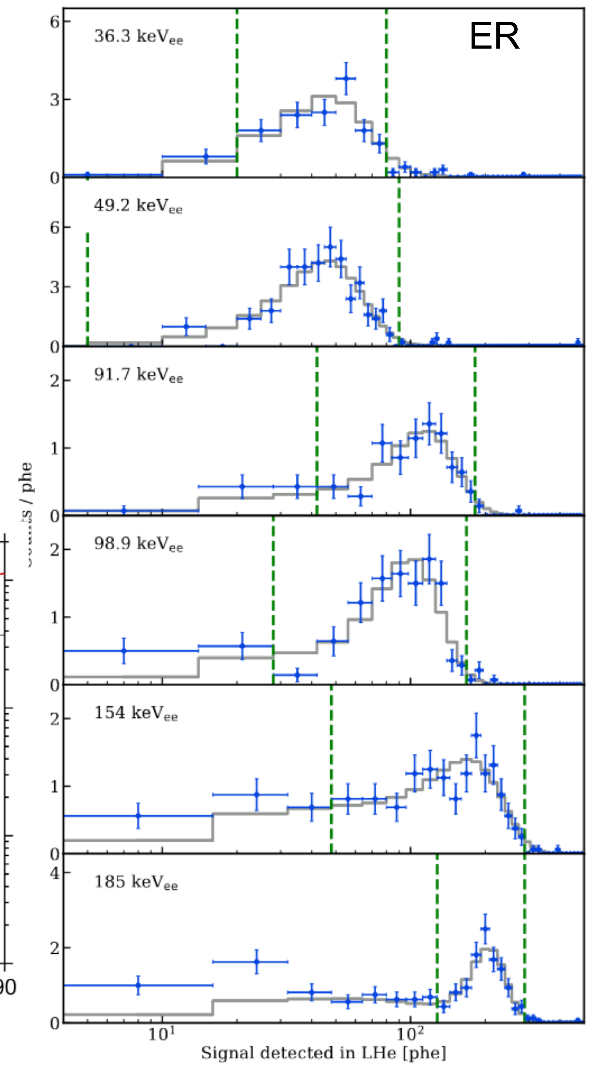


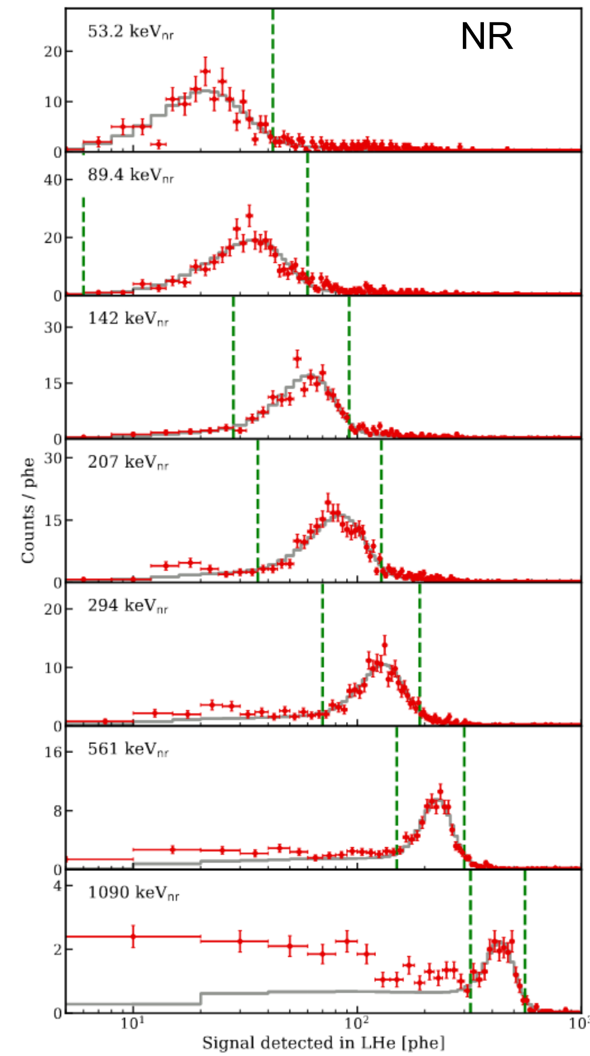
- ➢ Data taken at 1.75K
- ➢ Cockcroft–Walton (CW) generator
  - ○ No voltage divider for PMT
  - ○ No resistive heat
  - ○ Suitable for down to ~mK
- ➢ High light yield
  - ○ ~1.1 PE/keV_{ee}

Light yield measurement of superfluid He-4

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







Light yield measurement of superfluid He-4

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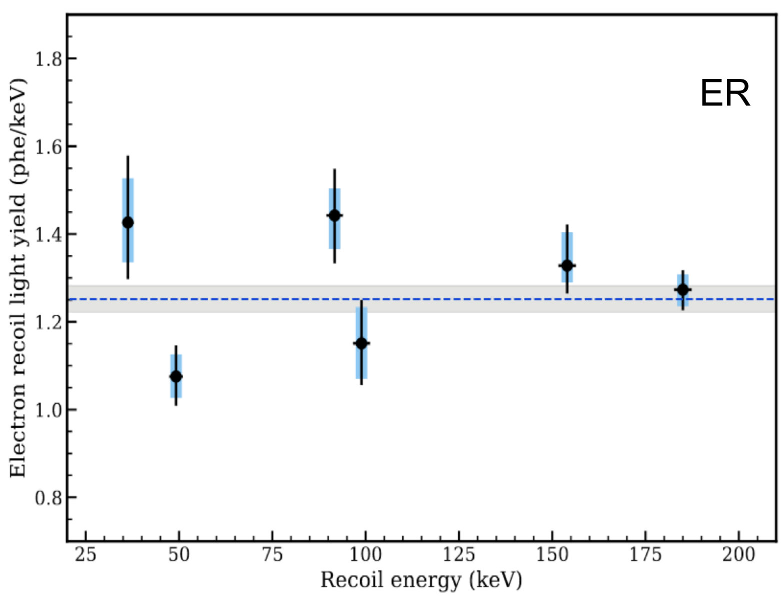
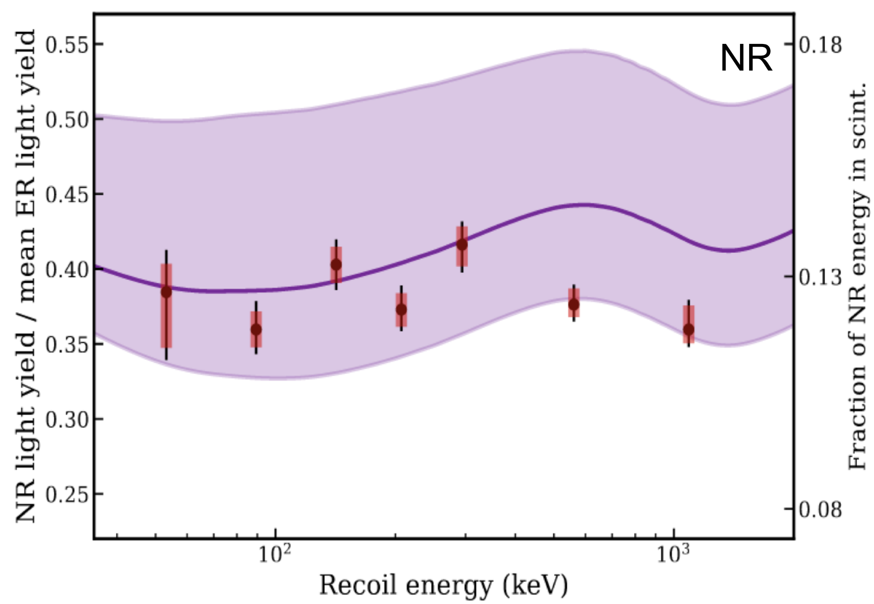
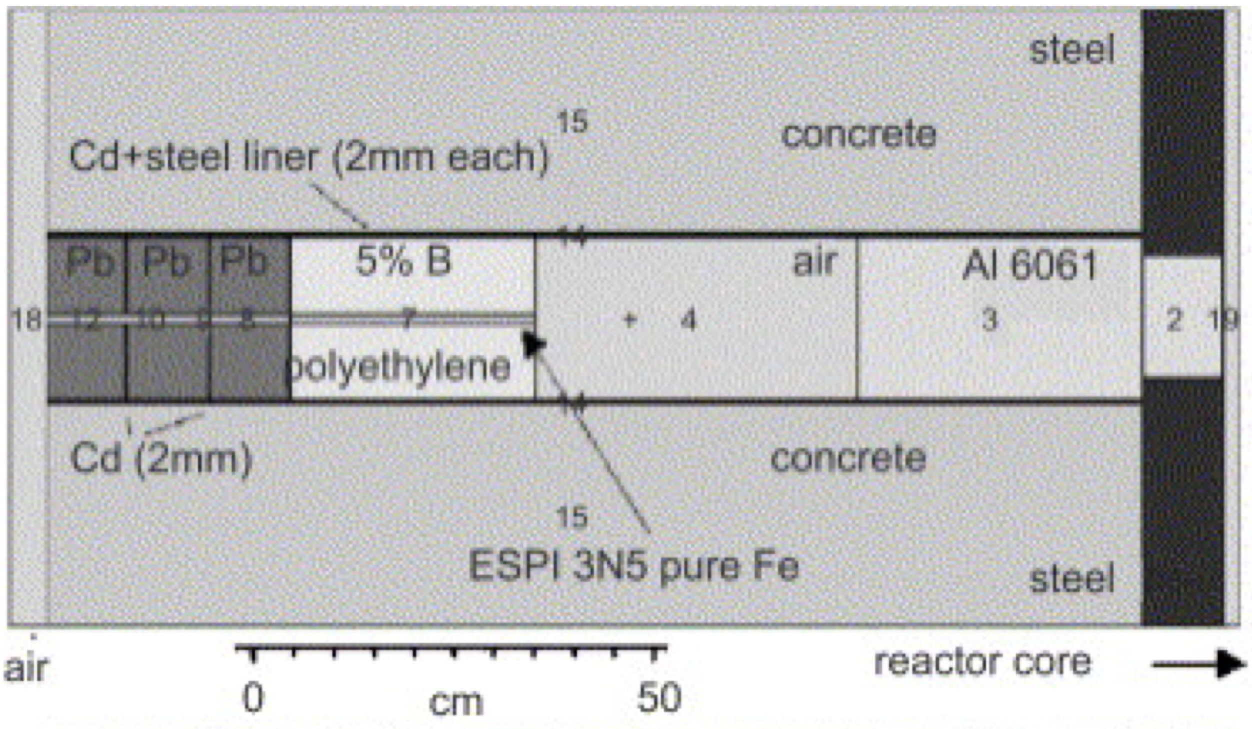
- arXiv:2108.02176, Phys. Rev. D 105, 092005 (2022)
- First measurement of LHe scintillation in tens of keV.
- ER yield relatively flat (as expected)
- NR yield agrees with pre-defined model
- Very high fraction (~13%) of NR energy goes into scintillation!
- How to calibrate at sub-keV energies?





Background - filtered source

- Filter neutrons using a notch in cross section in iron at 24 keV
- Uses moderated reactor neutrons - not portable

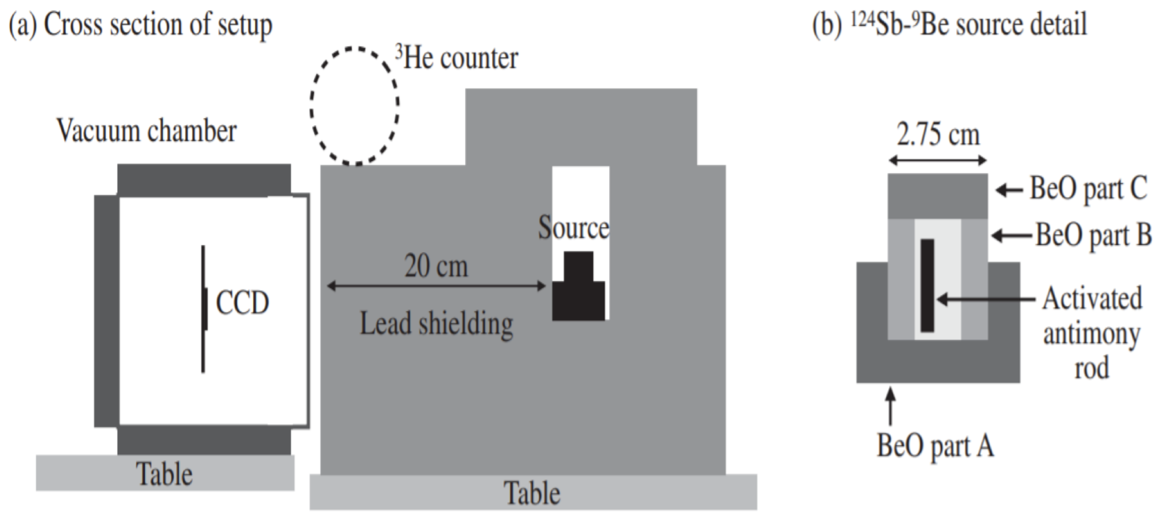


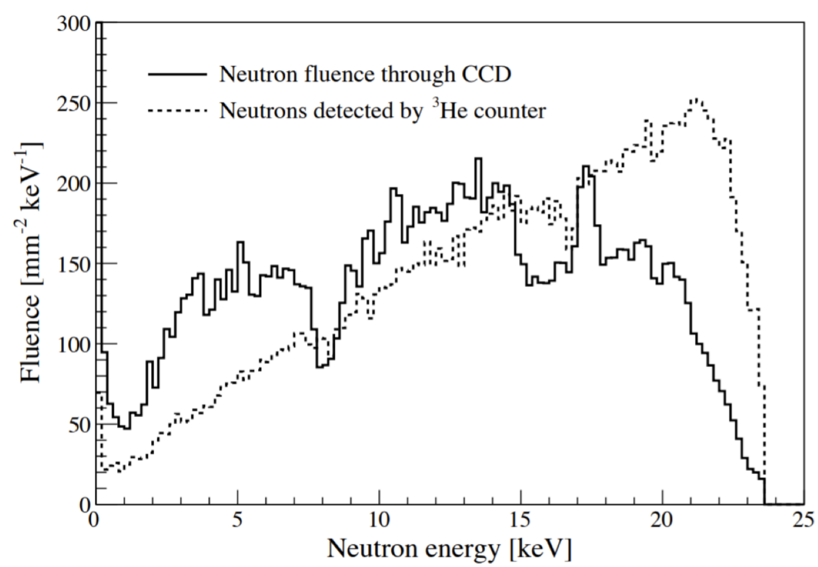
P.S. Barbeau, J.I. Collar, P.M. Whaley, NIMA (2007)

Background - photoneutron source

- ^{9}Be (γ,n) with 1.691 MeV gamma from ^{124}Sb produces 24 keV neutrons
- Lead shielding to reduce gammas - degrades neutron spectrum

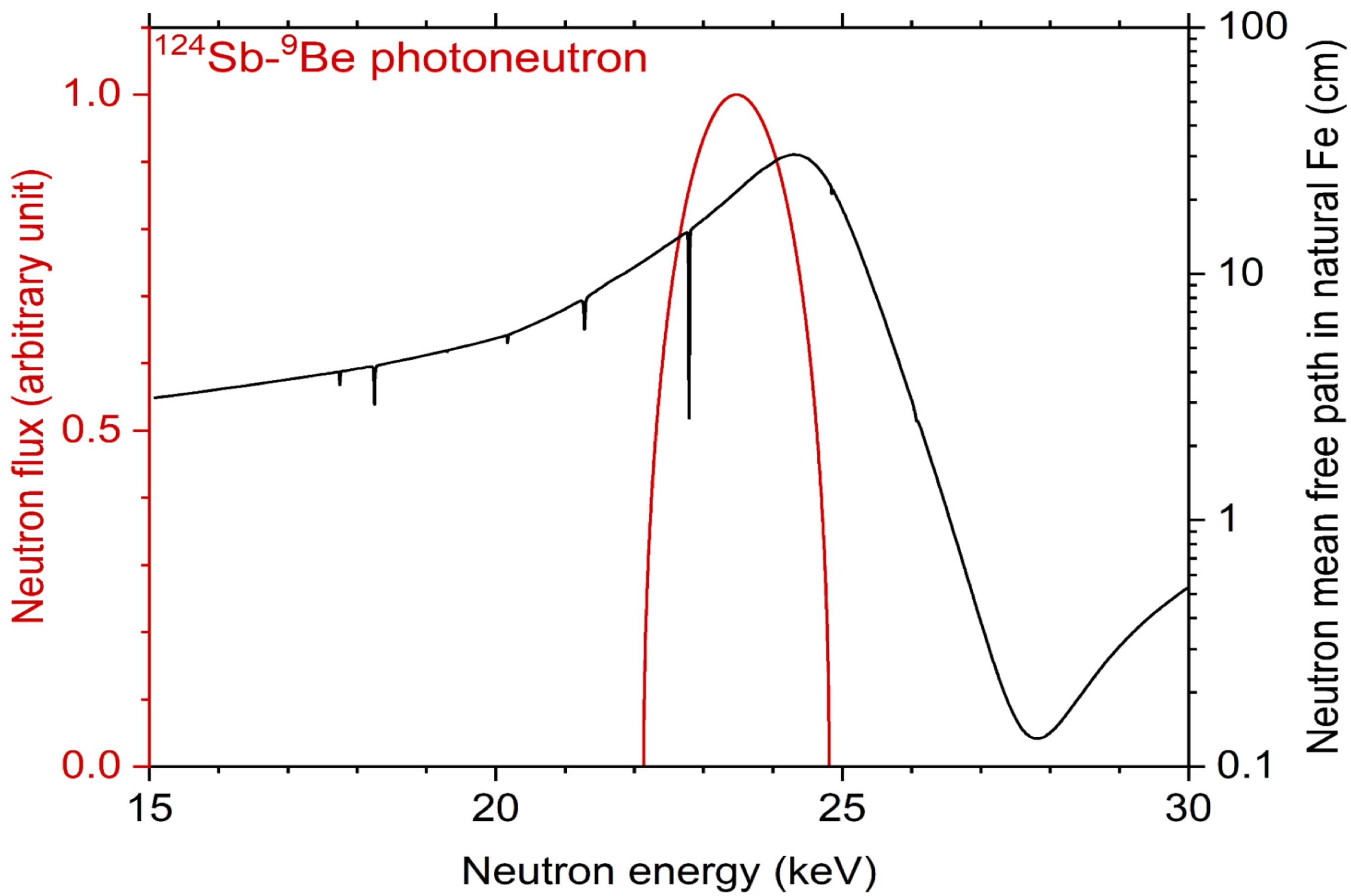
A.E. Chavarria et al., Phys. Rev. D (2016)





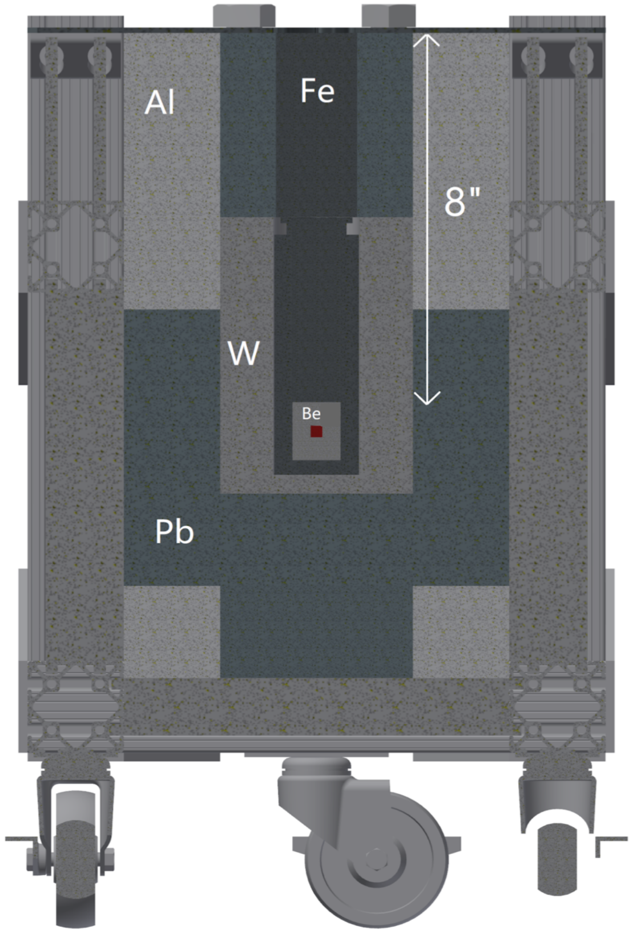
Concept

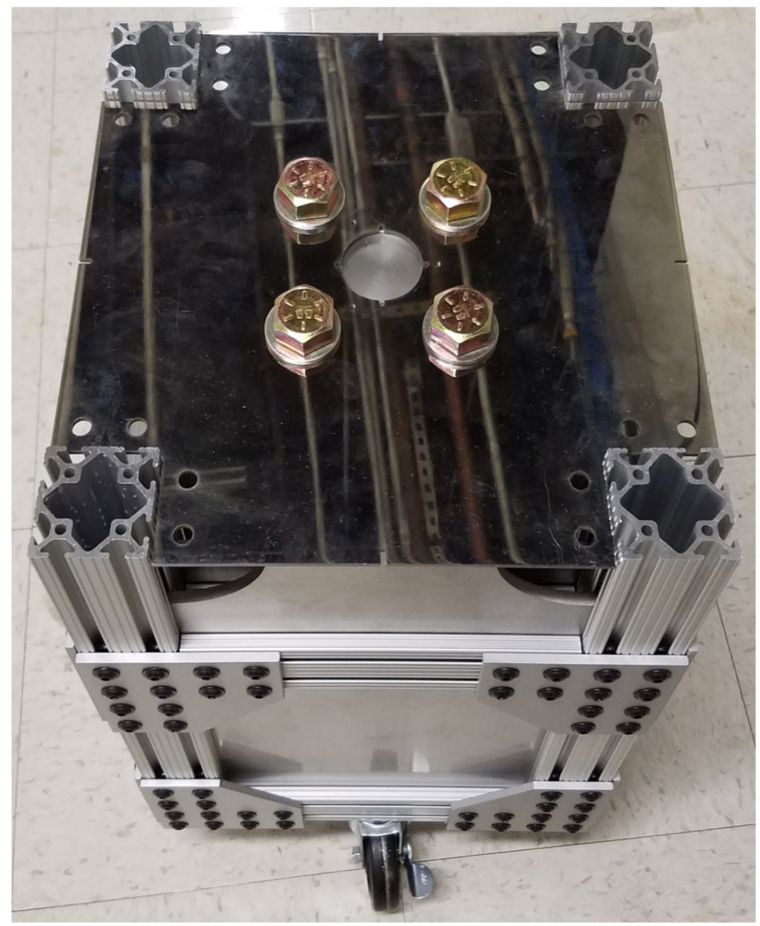
Notch in iron cross section coincides with SbBe photoneutron energy at 24 keV!



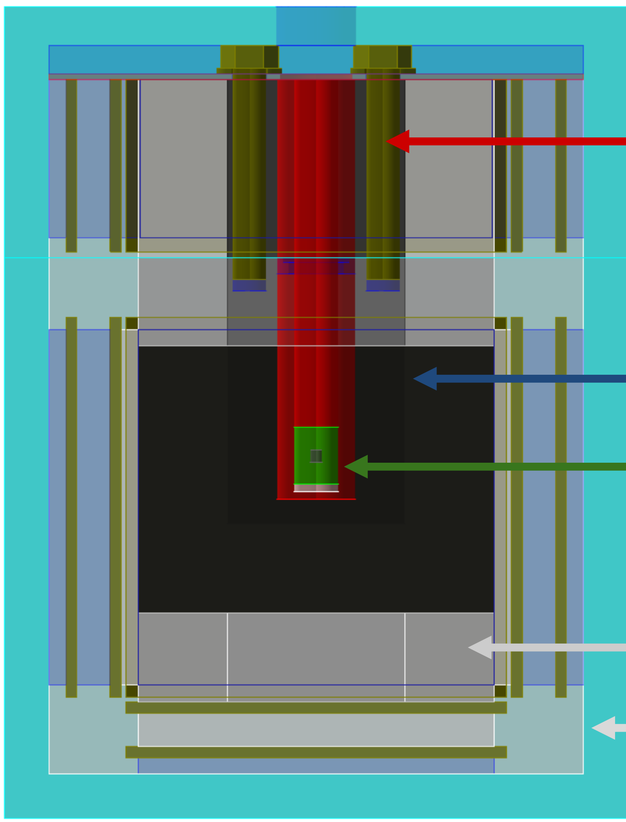
Design

- 1 GBq antimony activated at McClellan research reactor
- Iron rod for monoenergetic 24 keV neutrons along axis





Simulation geometry



Borated PE

Iron

Tungsten/lead shielding

Beryllium metal

Aluminum

Aluminum T-slot (reduced density)

Neutron spectrum

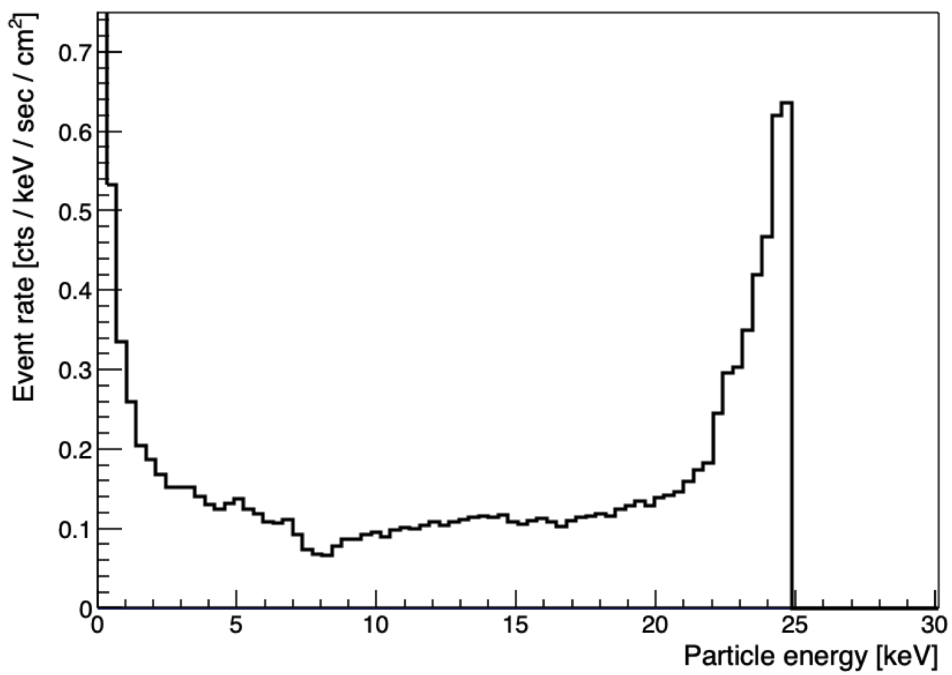
For 1 GBq Sb^{124} source:
3.73 neutrons / sec / cm^2 (> 1 keV)

40% of this flux 20-25 keV

24 keV neutron production rate estimated using:

- 47.57% branching fraction for 1691 keV gamma production in Sb^{124} decays
- ENDF/B-VIII.0 photonuclear cross section of 1.41 mb

379 keV neutrons (not included in plot) expected to be about 3% of total neutron production, before iron filter moderation



Gamma spectrum front face

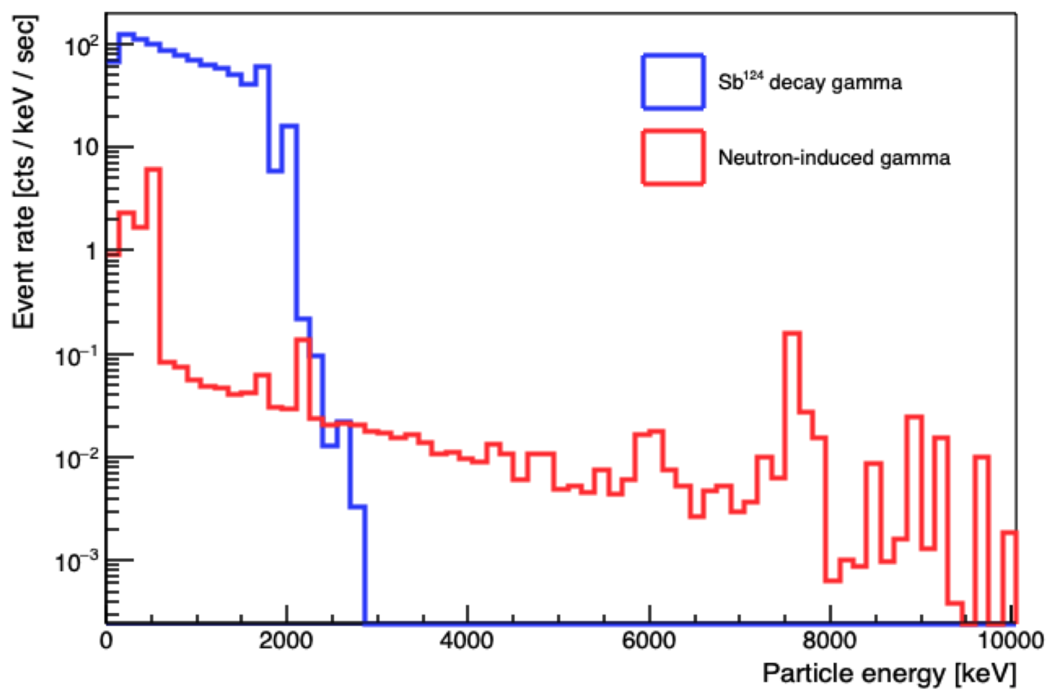
For 1 GBq Sb^{124} source: 111 gammas / sec / cm^2 leaving front of assembly

Only 3 gammas / sec / cm^2 leaving iron filter face

Translates to total rate of 141 kHz gammas leaving front face of source

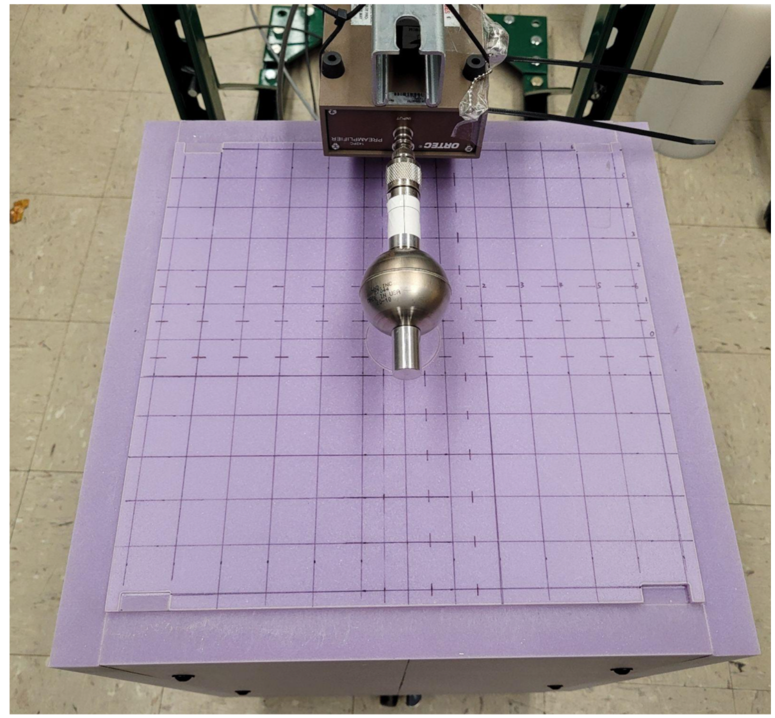
Dominated by Sb^{124} decay gammas < 3 MeV

1% contribution from inelastic/neutron capture gammas extending to higher energies



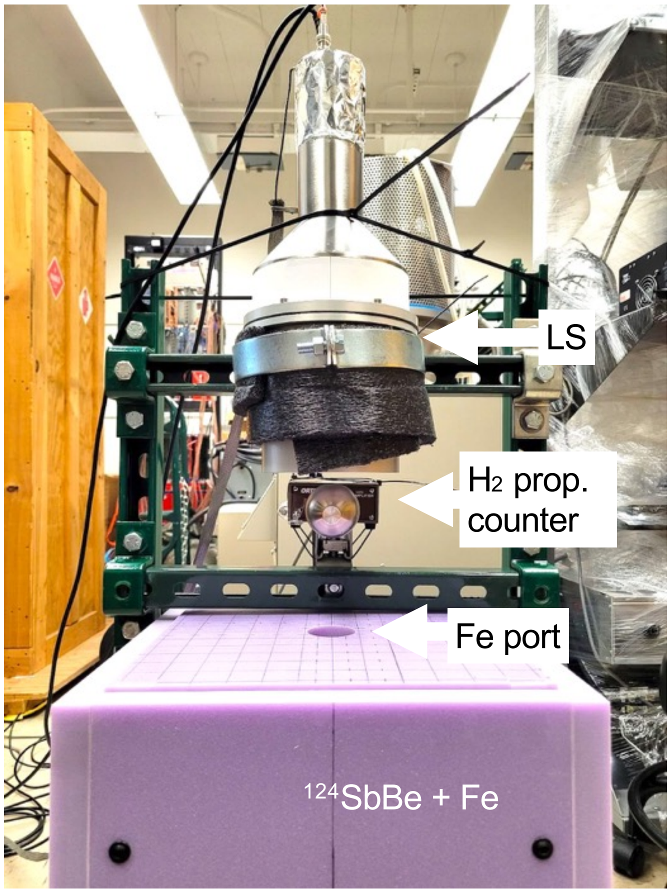
Hydrogen gas proportional counter

- 5 cm diameter sphere of 3 bar hydrogen gas
- Low threshold - kinematic matching
- Flat recoil spectrum for low energy, monoenergetic source - endpoint at incident neutron energy

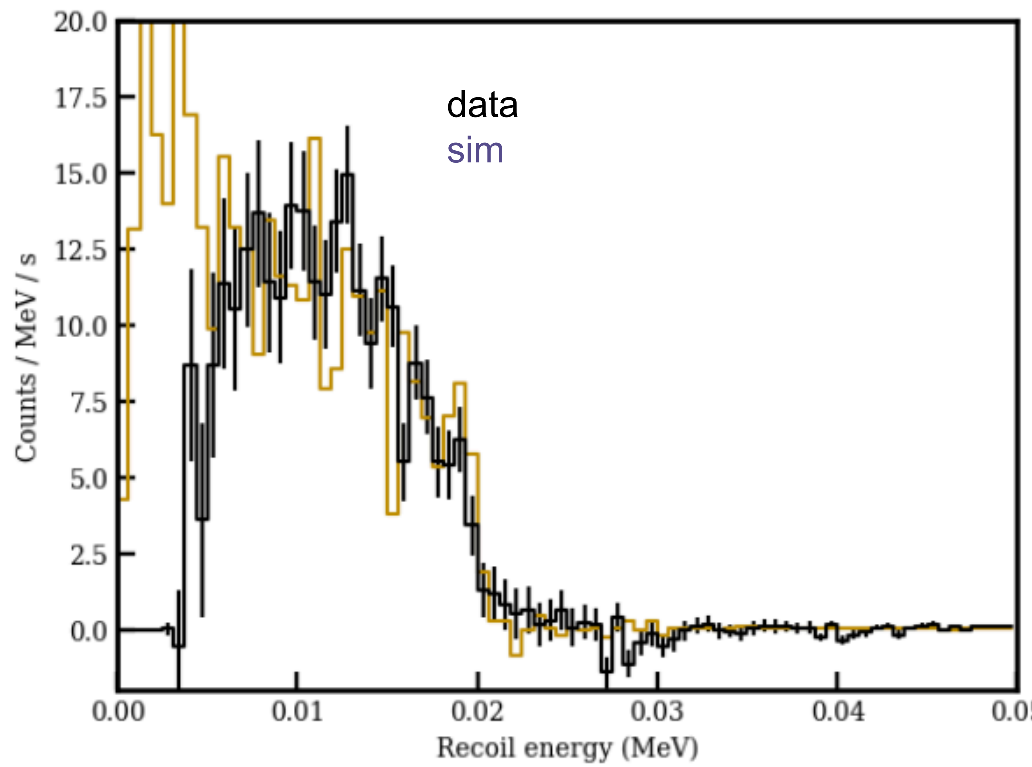


Characterization of Fe-shielded SbBe

Characterization Setup



H_2 prop. counter data
(not requiring LS tag)

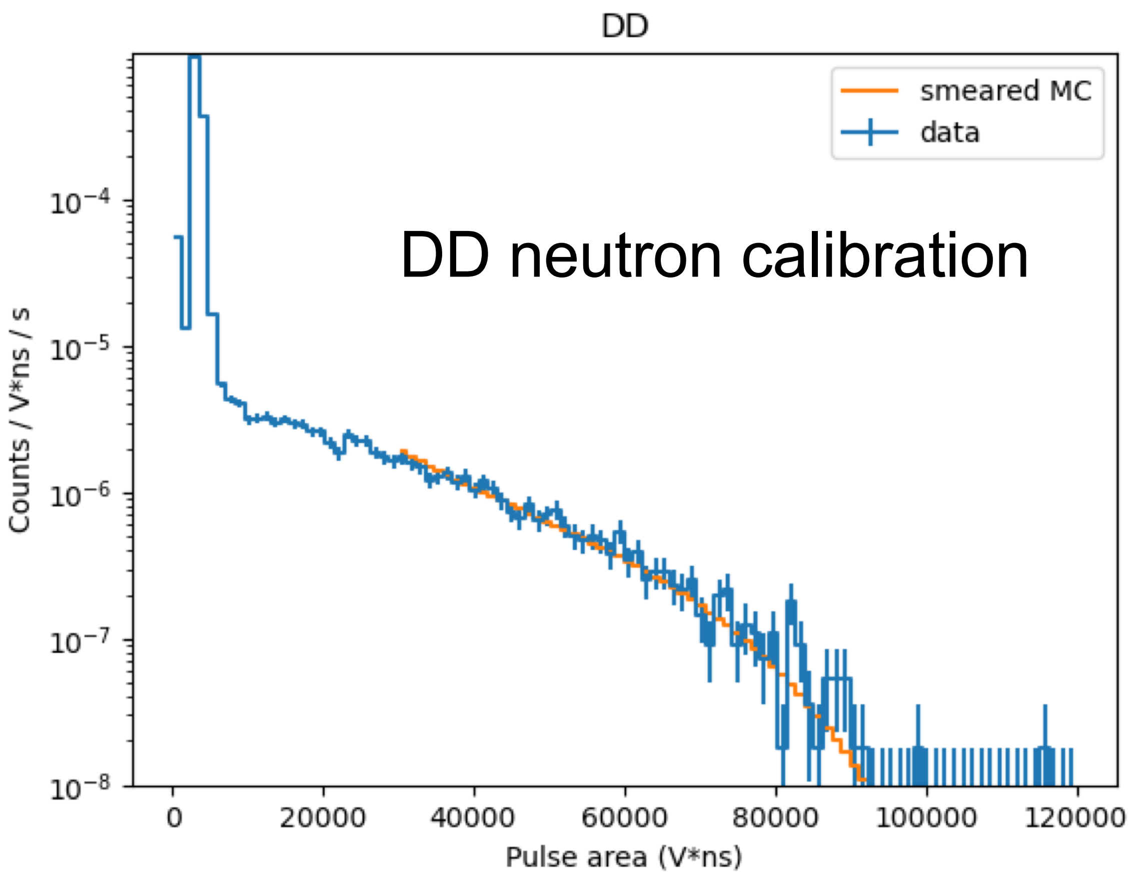


Measured flux of 24keV neutrons is
1.9x higher than expectation from sim

Hydrogen gas proportional counter calibration

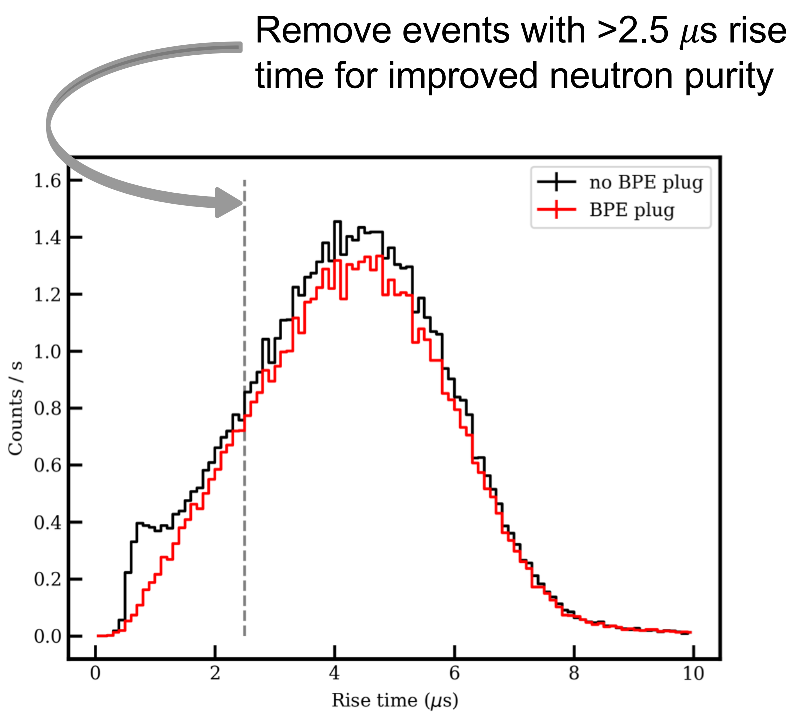
- Tricky to calibrate - gammas interact mainly in detector walls, so no ER peaks

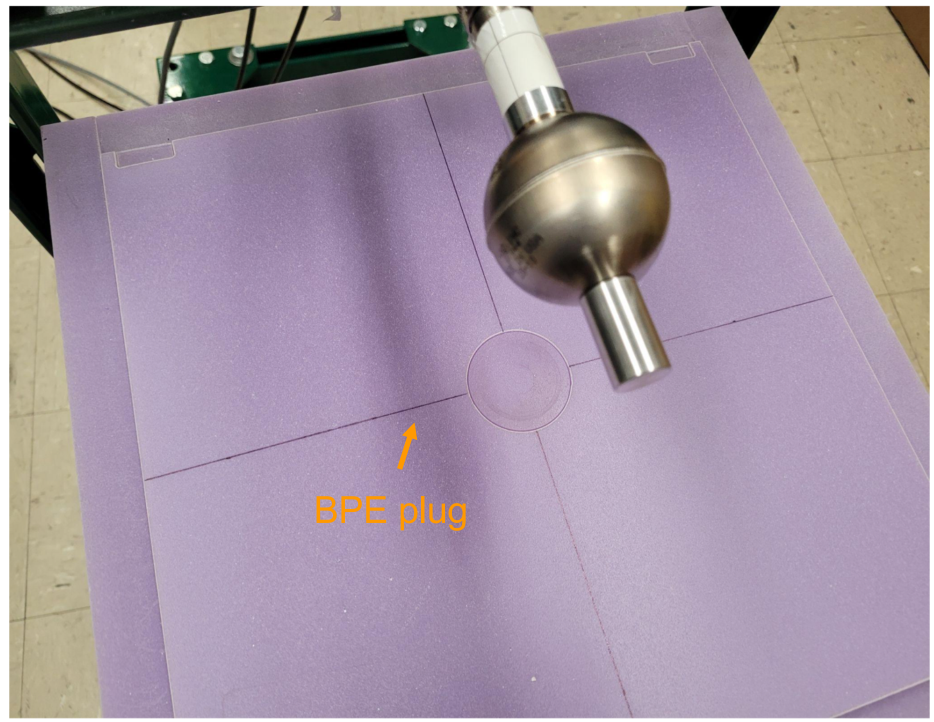
- DD energy of 2.8 MeV well above signal, soft “endpoint” at 800 keV due to detector geometry



Gamma background in proportional counter

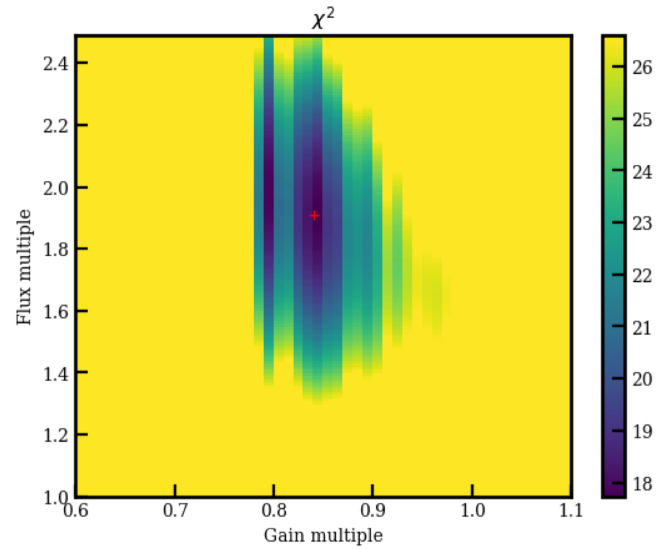
- Use rise time to reduce electron recoils (long track length for betas)
- Gamma-only spectrum from plugged source

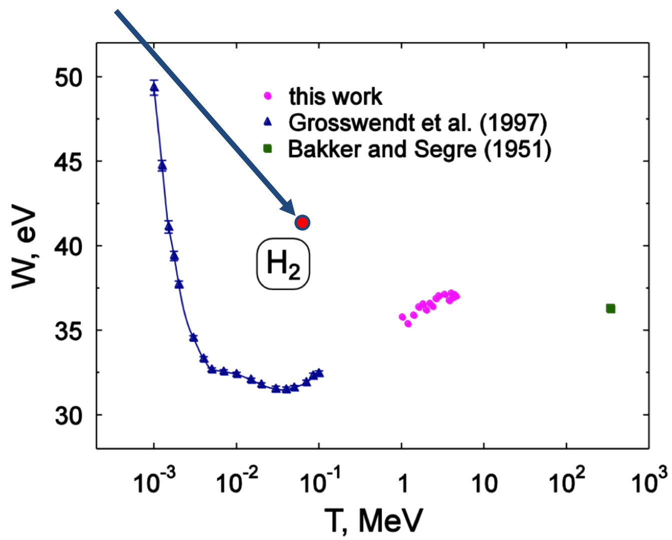




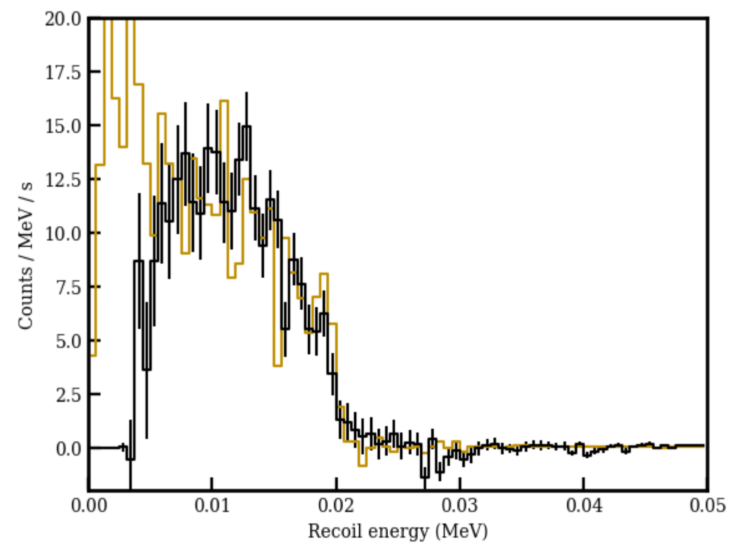
Floating flux and W-value

- Best fit - flux is 1.9x higher in data than sim, and gain is 0.84x calibration from DD
- Literature W-value for protons in hydrogen at >MeV is 36 eV. To explain the discrepancy with DD calibration, W-value at ~20 keV needs to be 36/0.84 = 43 eV



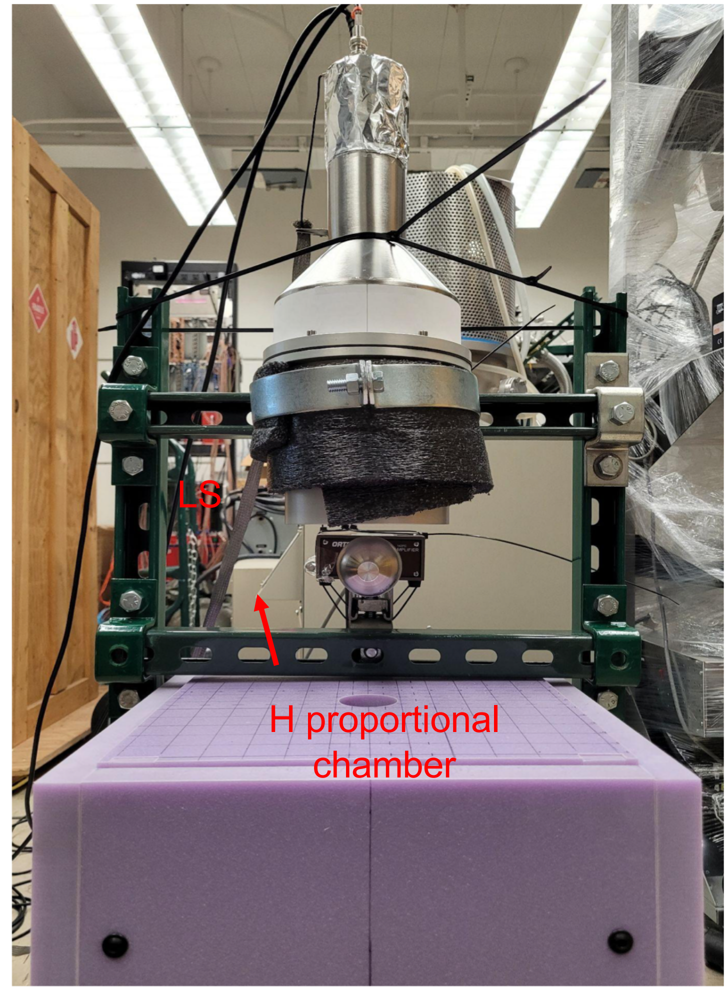


https://arxiv.org/ftp/arxiv/papers/1405/1405.5665.pdf



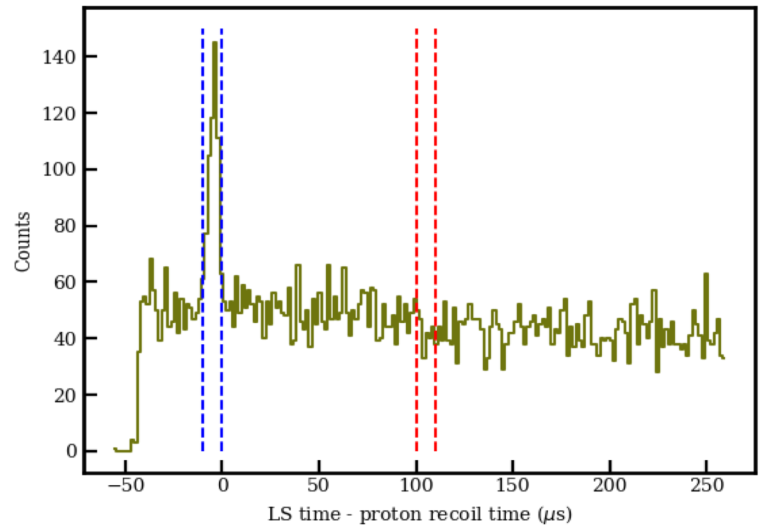
Neutron tagging with liquid scintillator (LS)

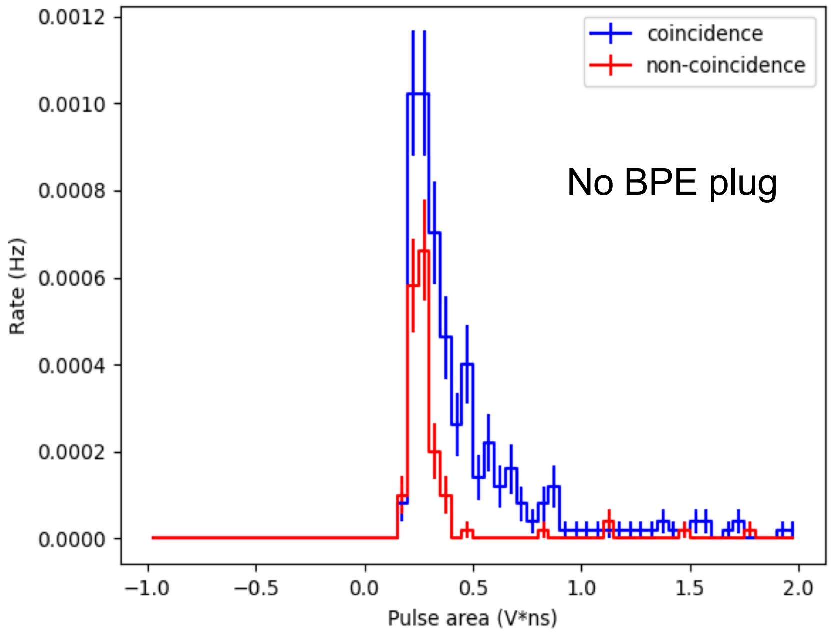
- Do we have a fast backing detector for a scattering experiment with 24 keV neutrons? Try liquid scintillator EJ-301 with high-QE PMT
- C. Awe et al, Phys. Rev. C (2018) measure quenching factor of ~10%, and Eljen estimates ~1 phe/keVee, so expect signal around a couple photoelectrons
- Use coincidence with hydrogen gas proportional counter to look for neutrons in LS
- In coincidence, maximum energy in the H2 proportional chamber drops to 15 keV

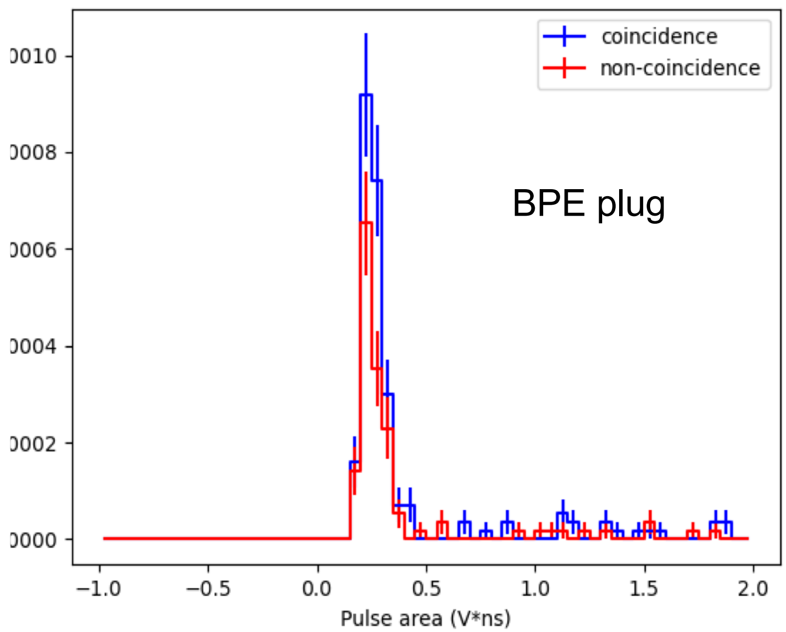


Liquid scintillator neutron tagging

- Excess of small pulses observed in LS in coincidence with proton recoil
- Not observed in plugged source

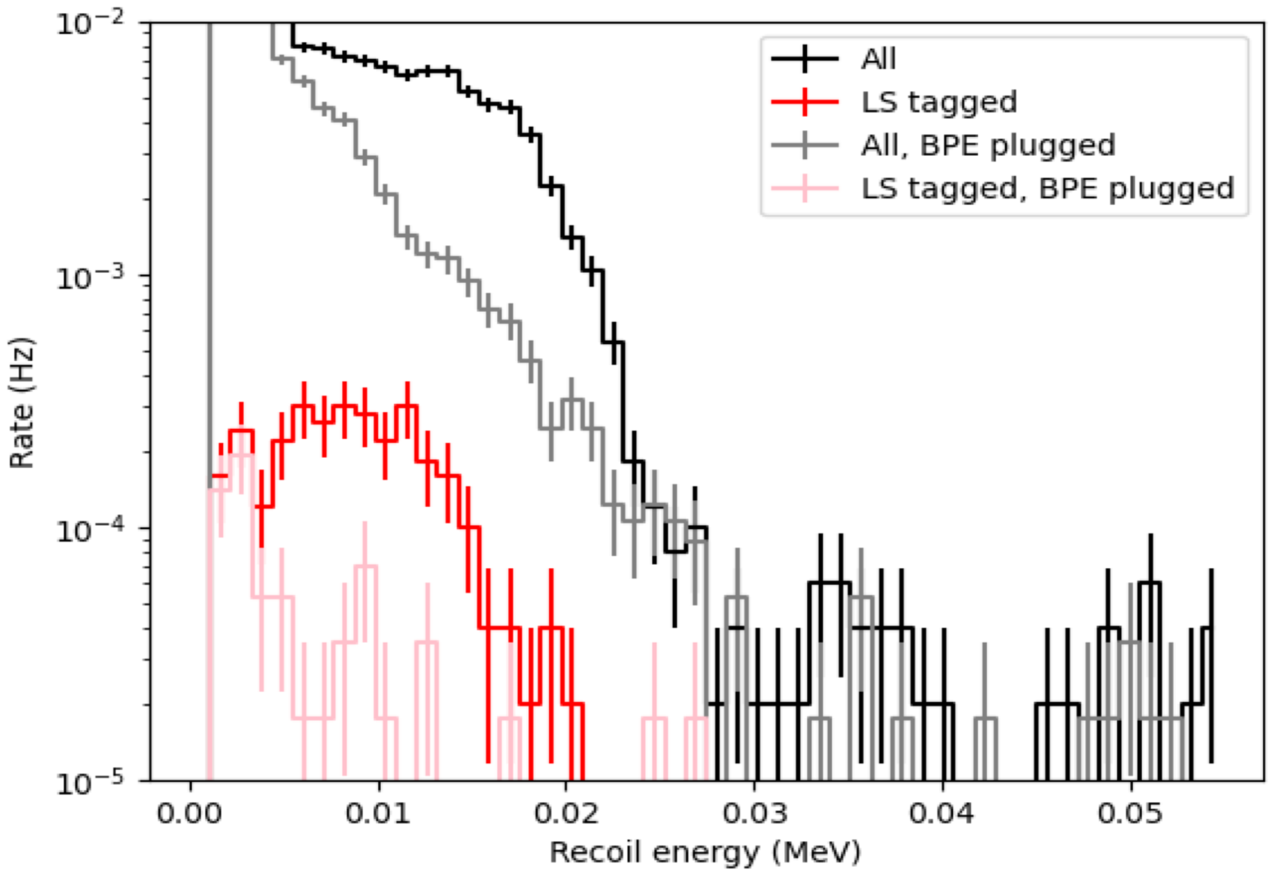






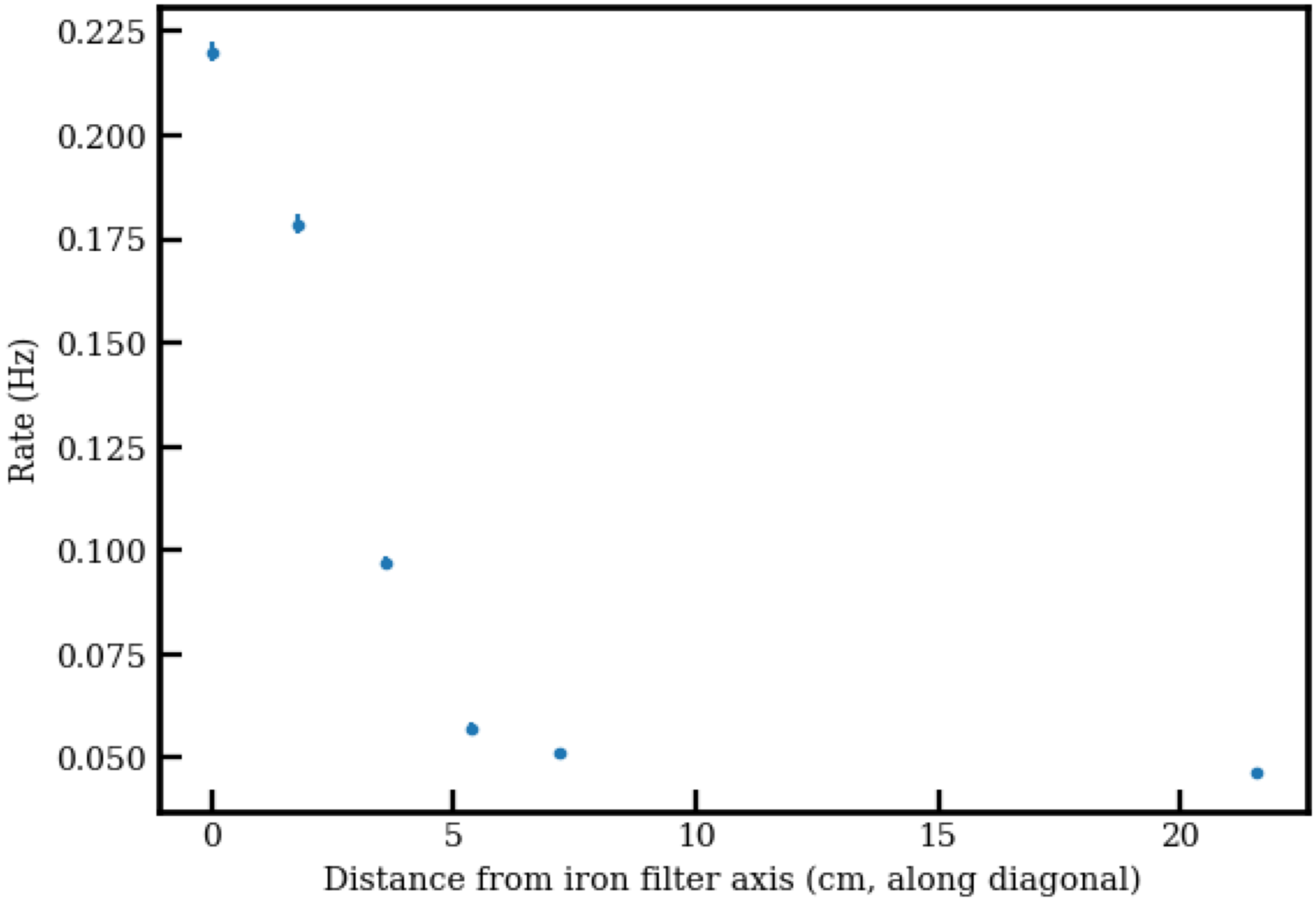
Liquid scintillator neutron tagging efficiency

- Efficiency of ~10% for ~15 keV neutrons
- Allows neutron tagging
- Confirms 24 keV neutron production



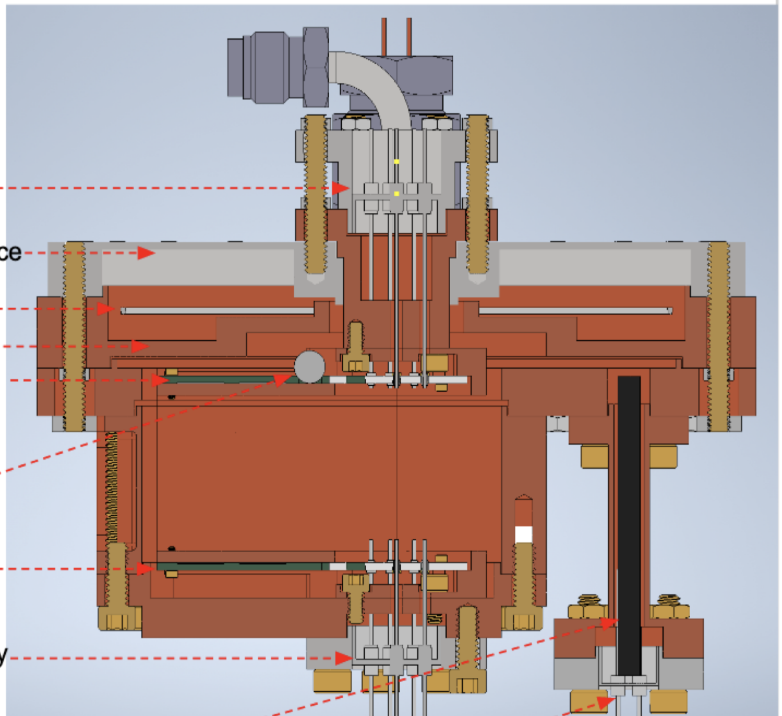
Collimation

- Neutron rate in hydrogen proportional counter decreases quickly away from iron filter axis



Progress on Superfluid Helium

Superfluid He detector (HeRALD 0.2) being designed, based on Cs-based film blocking recently demonstrated at UMass



- Will be first operated at LBNL
- Eight sensors viewing 8 cm^3 LHe
- Will use very latest TES-based detectors, with projected < 1 eV resolution
- Calibrations to be performed using x-rays, gamma-rays, **and new SbBe 24 keV neutron beam**
- Reach single-photon counting regime for LHe scintillation photons using TES
- Measure quantum evaporation yield for low-energy recoils
- Demonstrate detector threshold of <100eV, quantify ER/NR discrimination
- Demonstrate rejection of “heat-only” backgrounds through use of TES coincidence

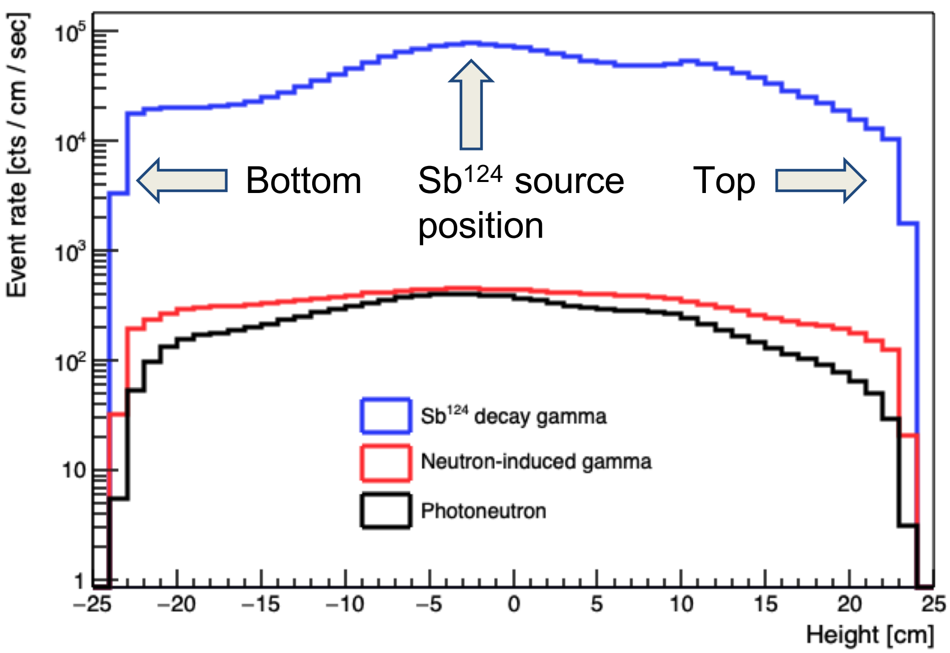
Summary

- TESSERACT is developing different targets for DM searches
- DM targets include polar crystals (SPICE) and superfluid helium (HeRALD).
- First R&D results on superfluid helium light yield, SbBe neutron beam.
- Plans to use SbBe neutron beam for LHe detector calibration

Backup

Rates in other directions

Side radiation flux profile



Gamma flux out the back face is about 3x larger than front

For 1 GBq Sb^{124} source:
The total gamma radiation rate out of the sides of the assembly is 2 MHz

Represents a flux of about 300 gammas / sec / cm^2 on average, with variations of a factor of a few across the face

The total simulated neutron rate leaving the sides and back of the source is 13 kHz

Gamma characterization

- NaI detector
- Neutron/gamma ratio of 0.025 in simulation
- Measured gamma flux is ~half of simulated (could be from uncertainty in source activity)
- Combined with higher measured neutron flux than sims, neutron/gamma ratio may be as high as 0.1