Probing Sub-GeV Dark Matter with Superfluid Helium: The HeRALD Experiment

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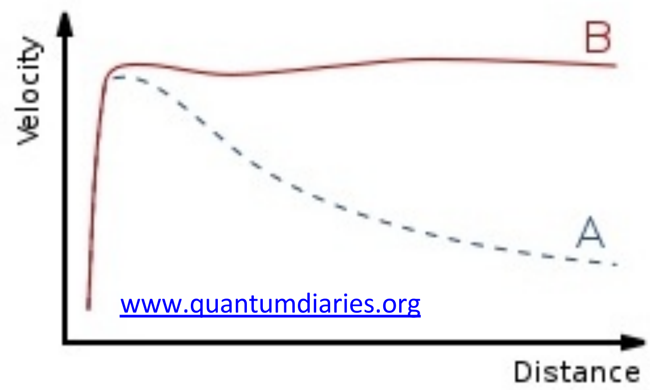
Evidence for Dark Matter

Galaxy rotation curves



The cosmic microwave background

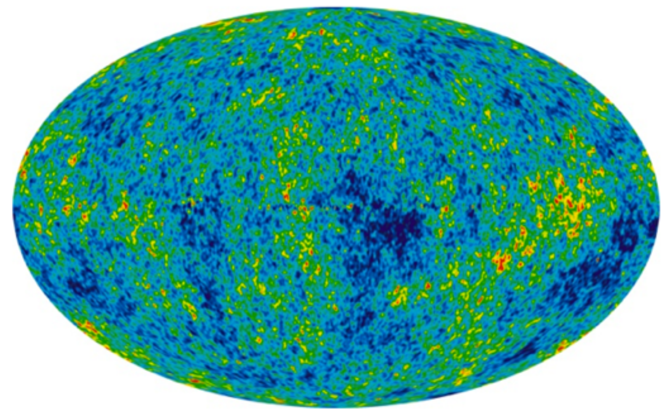
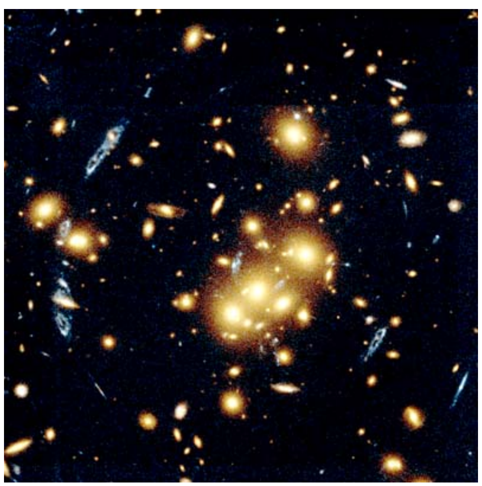


Image: ESA and the Planck collaboration

Gravitational lensing

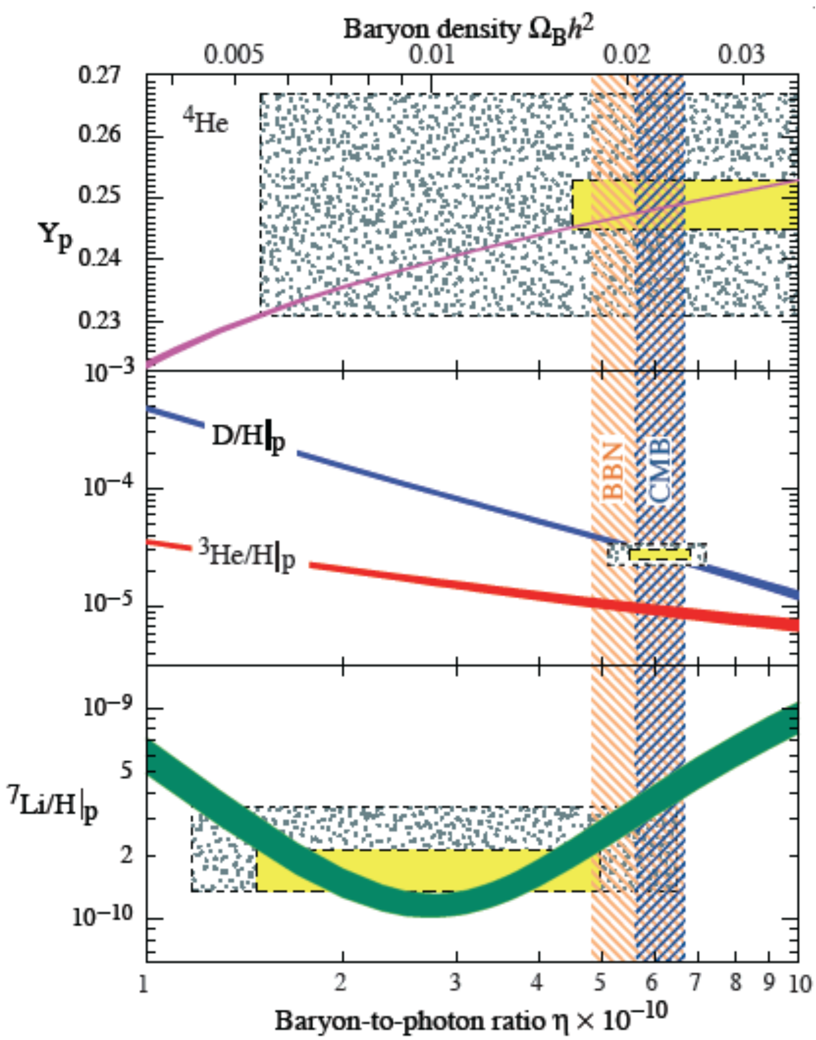


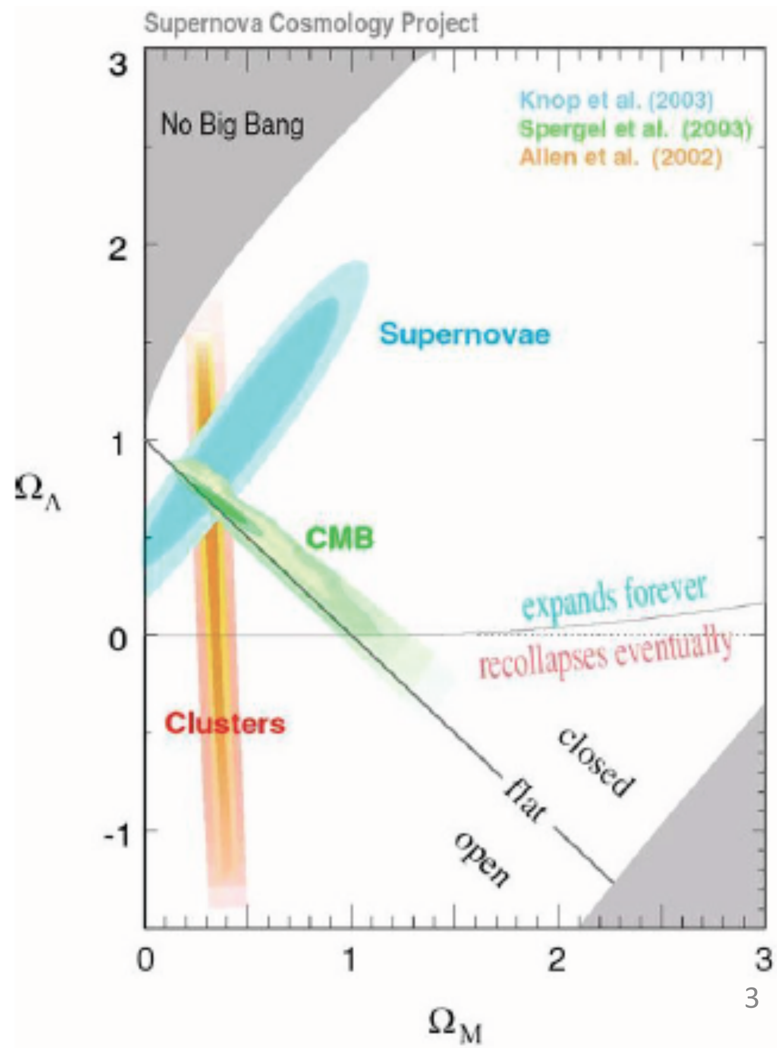
Colley, Turner, Tyson, and NASA

- 27% of the energy composition of the universe
- Properties:
- Stable and electrically neutral
- Non-baryonic
- Non-relativistic
- Estimated local density: $0.3 \pm 0.1 \mathrm{GeV \cdot cm^{-3}}$
- Candidates: WIMPs, axions, dark photons,...

Evidence for Dark Matter

Nucleosynthesis determines the density of baryons at early times; the amount of baryonic matter required is far smaller than the total quantity of matter.

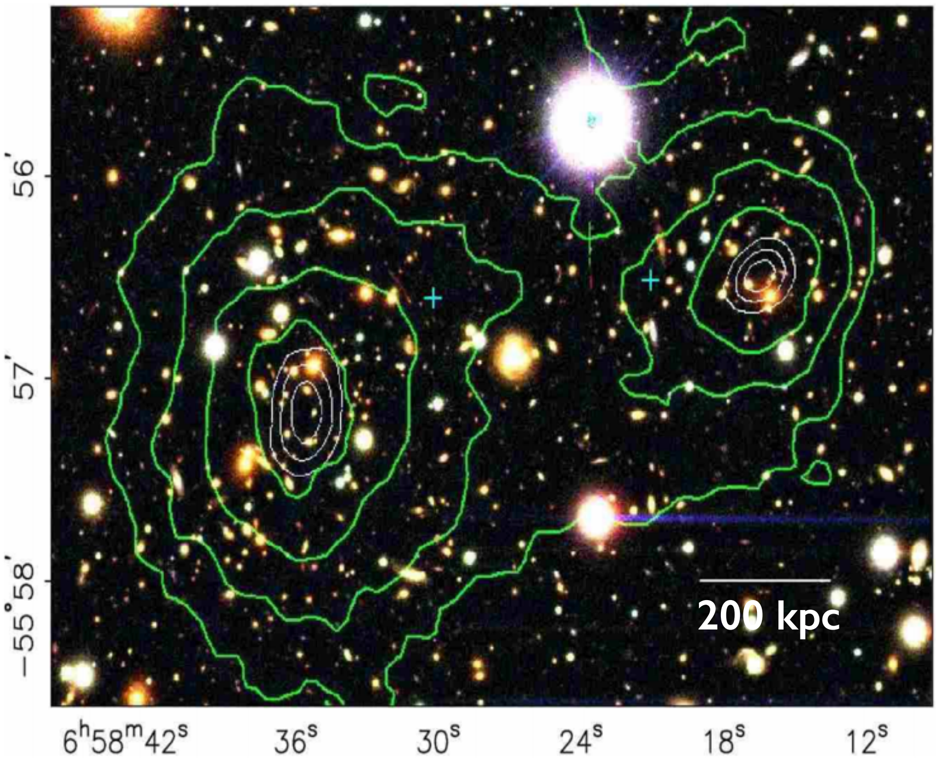




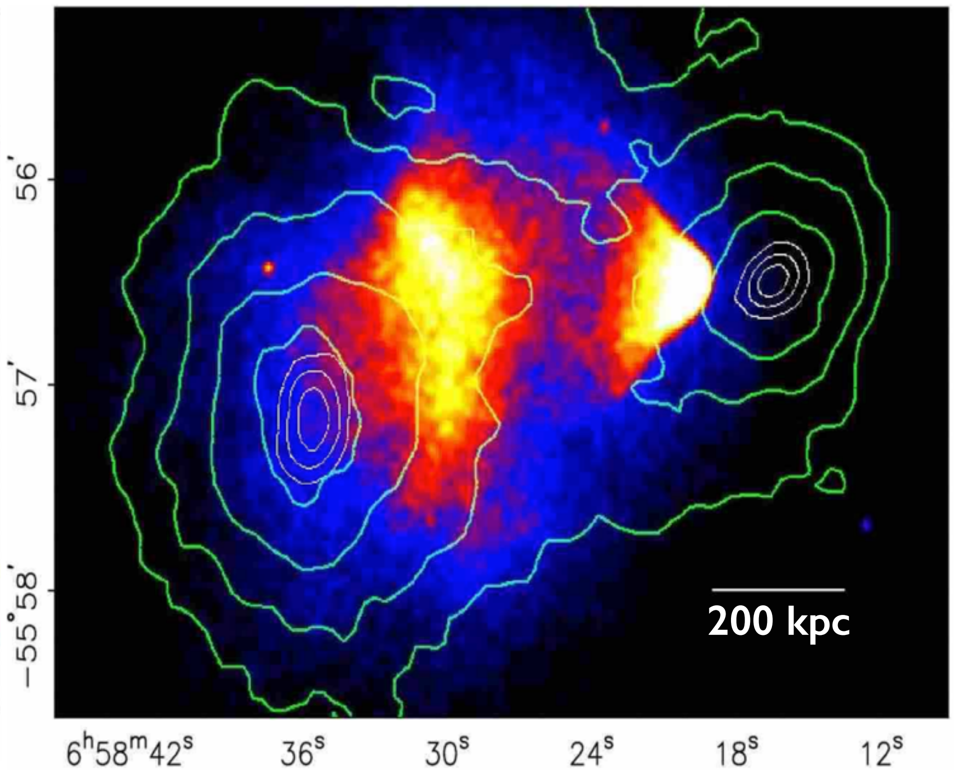
Evidence for Dark Matter

The Bullet Cluster (and similar astrophysical objects) exhibit *spatial separation* between its ordinary matter and its dominant gravitationally-interacting mass.

This is difficult to achieve with models that don't include dark matter.



Mass contours from lensing



Chandra x-ray image of hot plasma

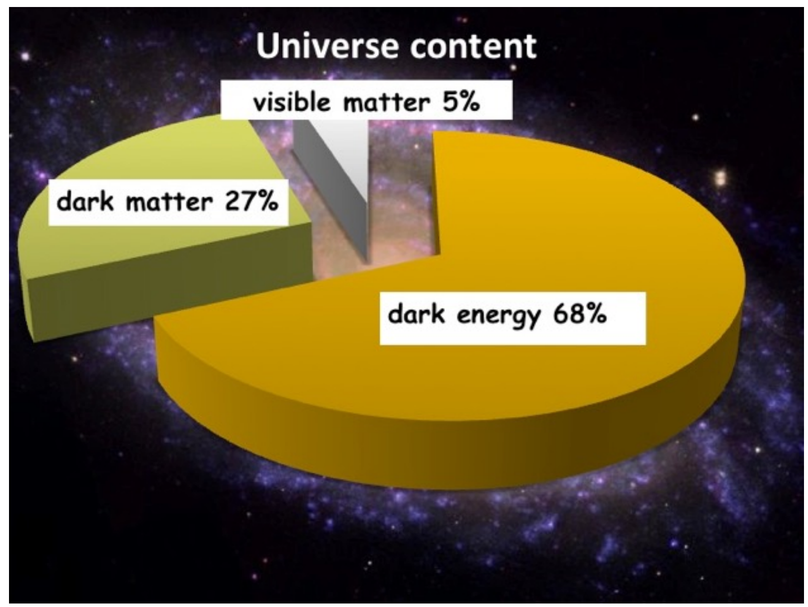
Composition of the Universe

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.

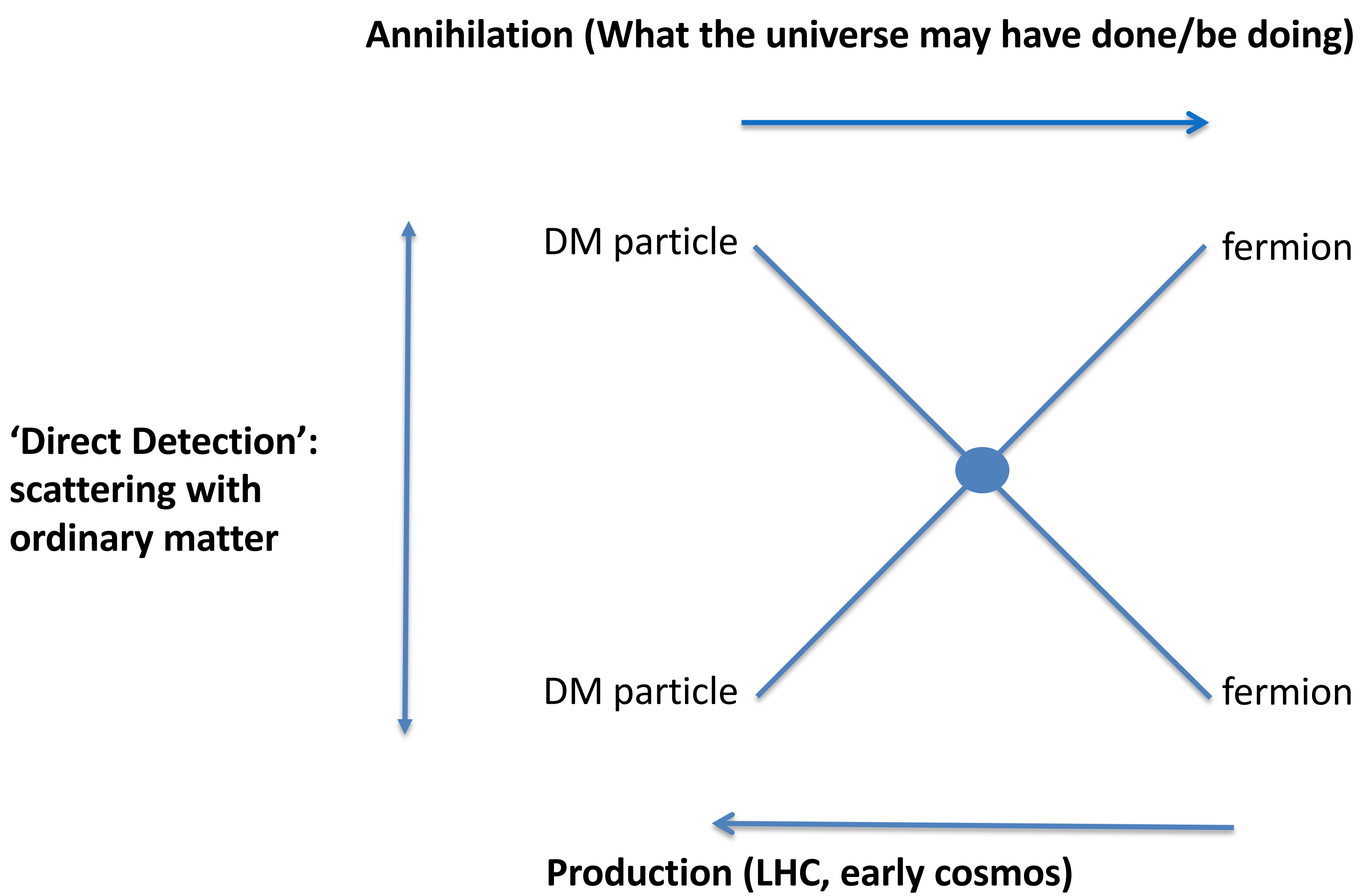
Discovery of the fundamental interactions and mass of the dark matter would likely provide important clues about the physics beyond the Standard Model.

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



Weakly Interacting Massive Particles (WIMPs)

A new particle that only very weakly interacts with ordinary matter could form Cold Dark Matter

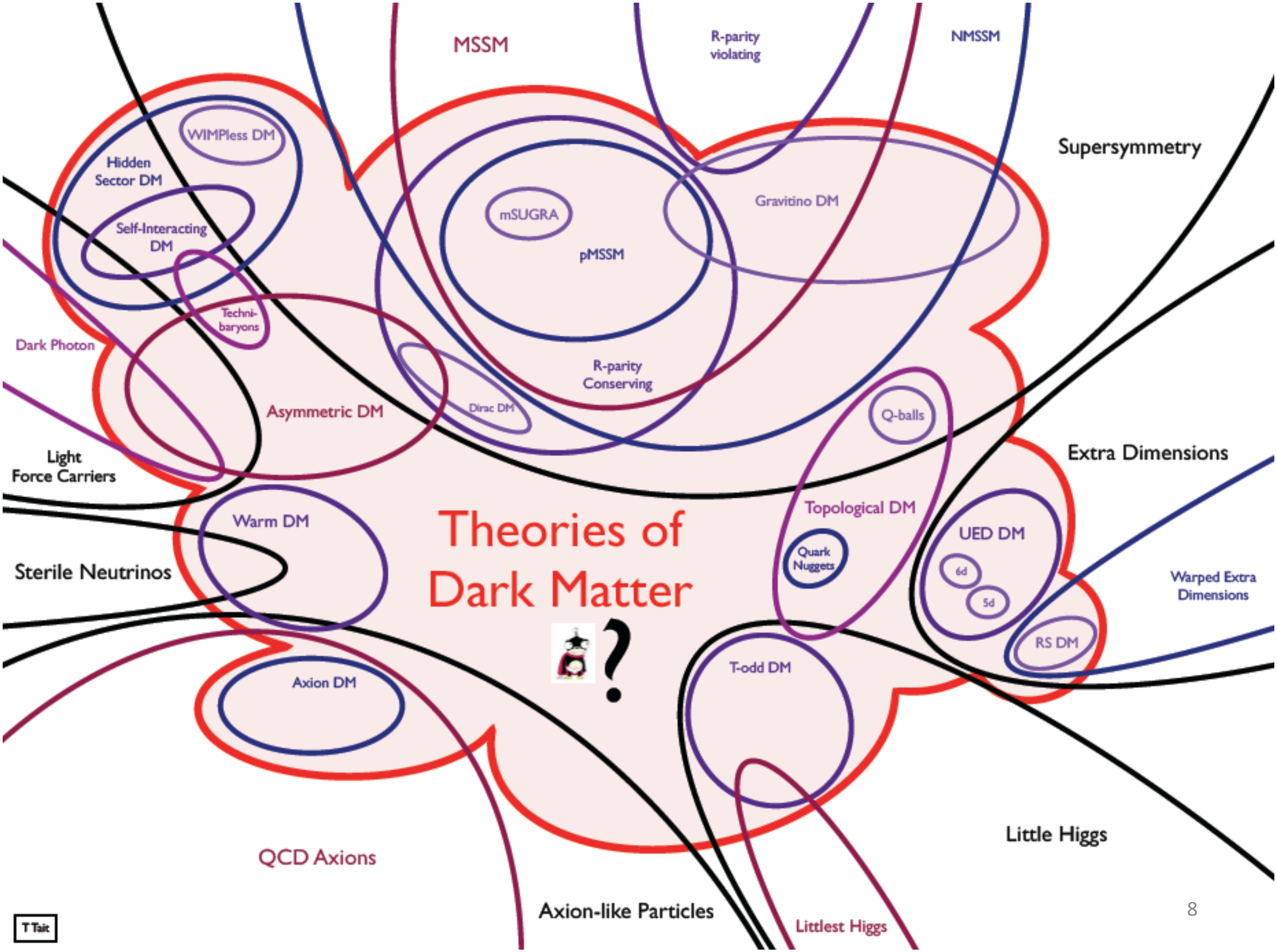
- Formed in massive amounts in the Big Bang.
- Non-relativistic freeze-out. Decouples from ordinary matter.
- Would exist today at densities of about $1000/m^3$.

Supersymmetry provides a natural candidate – the neutralino.

- Lowest mass superposition of photino, zino, higgsino
- Mass range from the proton mass to thousands of times the proton mass.
- Wide range of cross-sections with ordinary matter, from 10^{-40} to 10^{-50} cm^2.
- Charge neutral and stable!

Universal Extra Dimensions: predicts stable Kaluza-Klein (KK) particles

- Similar direct detection properties as neutralino
- Distinguishable from neutralinos at accelerators



MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
mSUGRA
pMSSM
Gravitino DM
Techni-baryons
Dark Photon
R-parity Conserving
Asymmetric DM
Dirac DM
Q-balls
Light Force Carriers
Extra Dimensions
Topological DM
Warm DM
Theories of Dark Matter
UED DM
Quark Nuggets
6d
5d
Warped Extra Dimensions
Sterile Neutrinos
RS DM
?
T-odd DM
Axion DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

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:

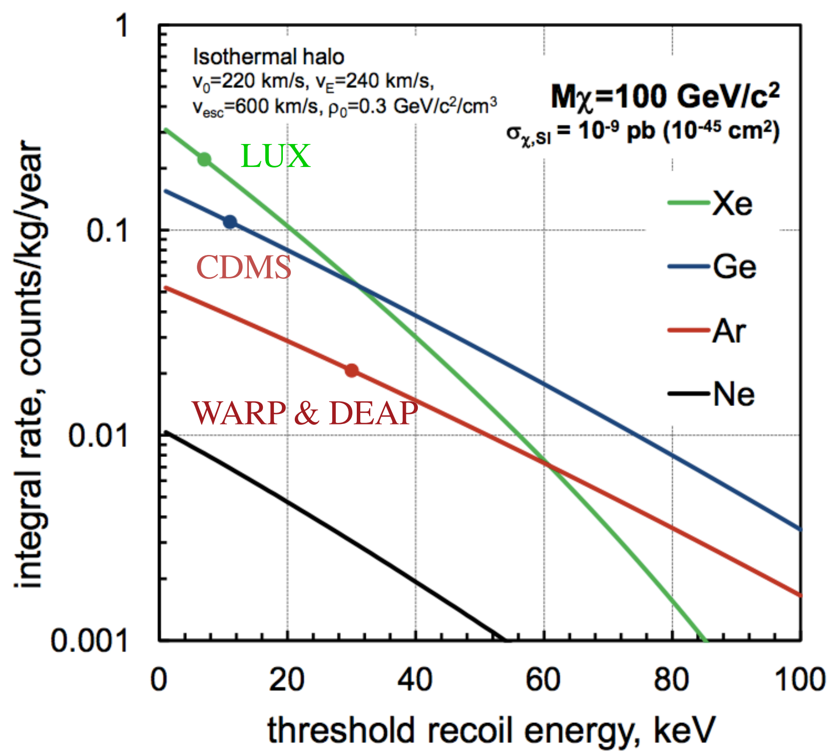
•Low radioactivity

•Deep underground laboratory

•Low energy threshold

•Gamma ray rejection

•Scalability



Dark matter detection

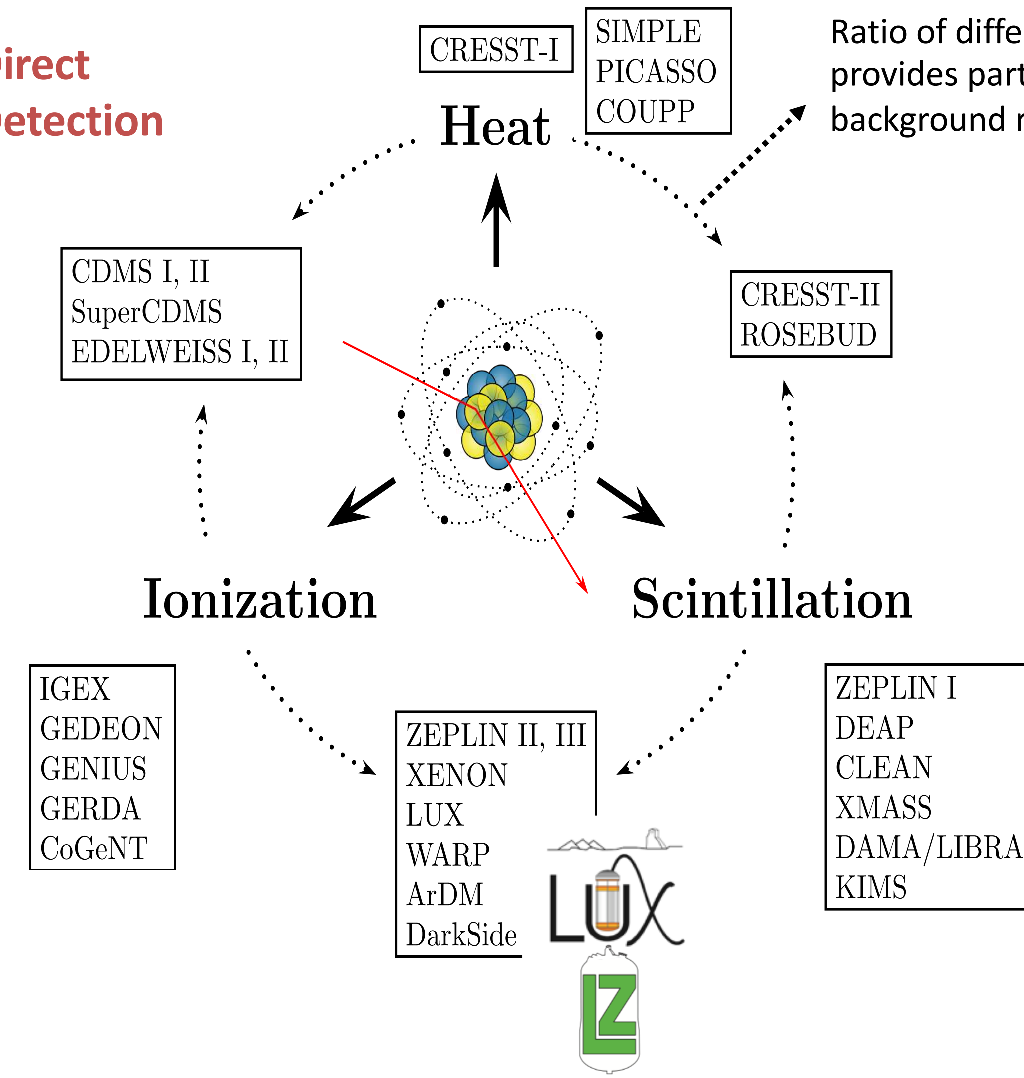
Indirect Detection

- Fermi-LAT
- VERITAS
- HAWC
- DES
- HESS
- MAGIC

Production

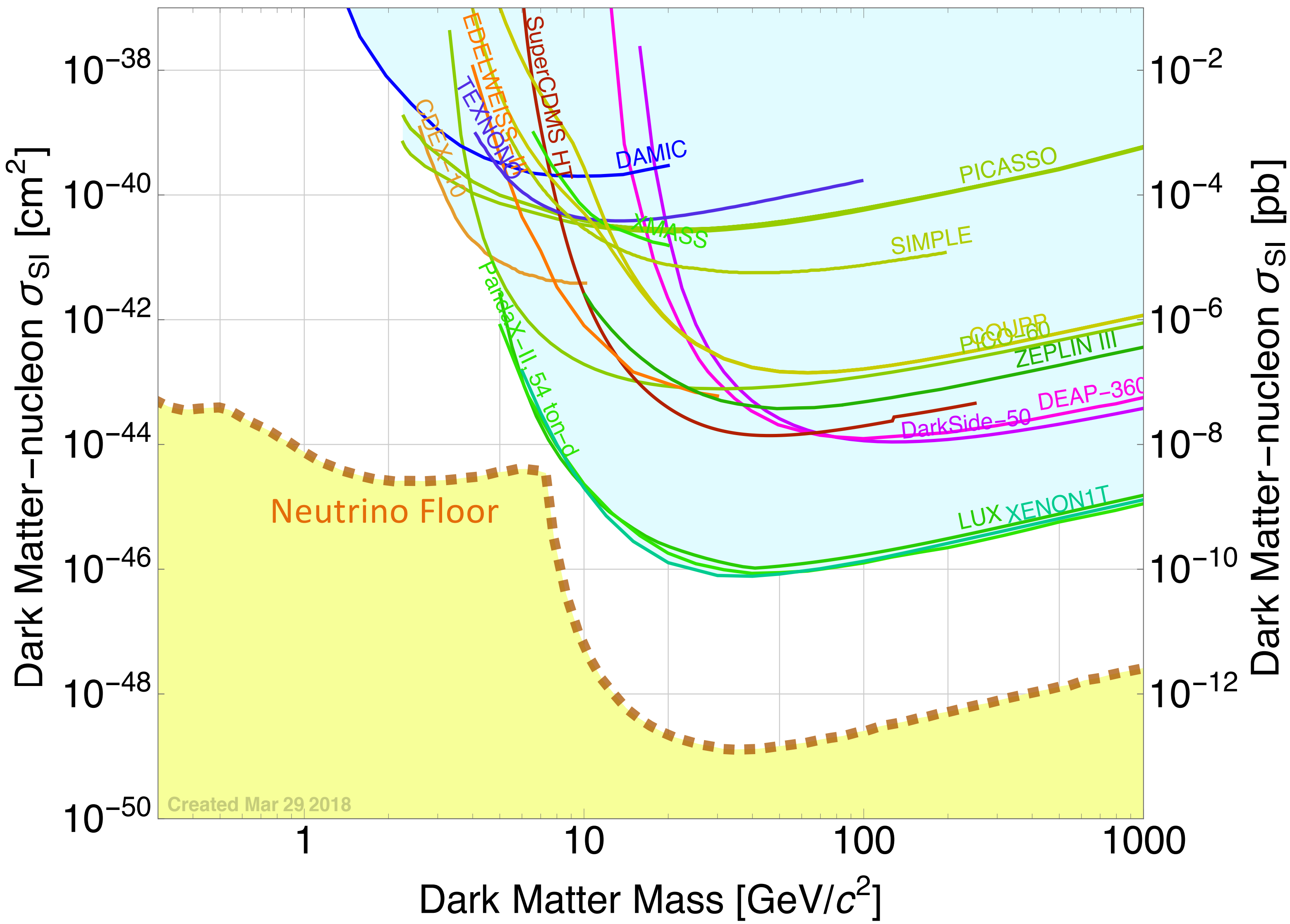
- Collider experiments
- LHC
  - ATLAS, CMS

Direct Detection

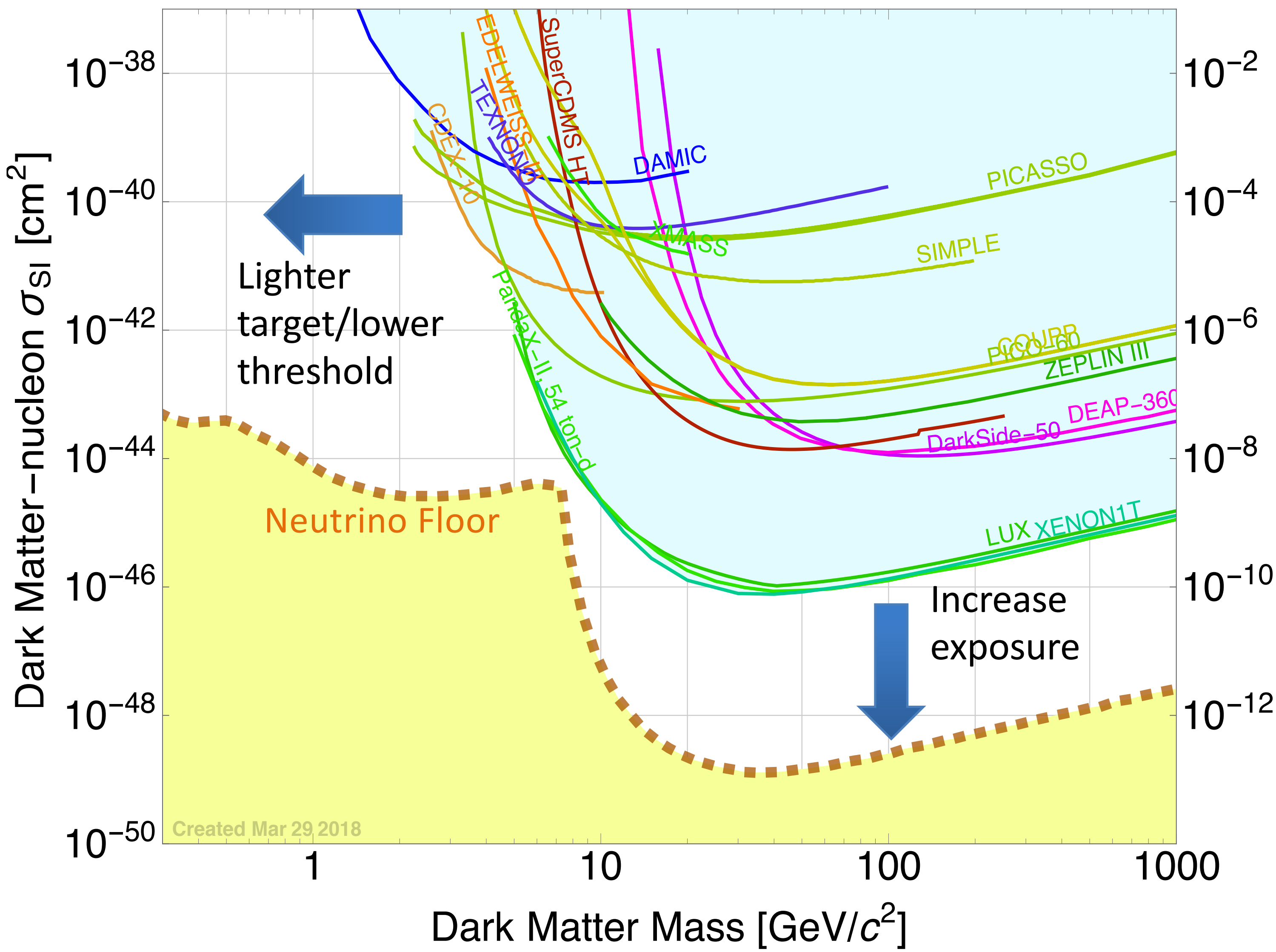


Ratio of different signals provides particle ID & background rejection

Dark Matter Nuclear Recoils: Current Landscape



Dark Matter Nuclear Recoils: Future Directions

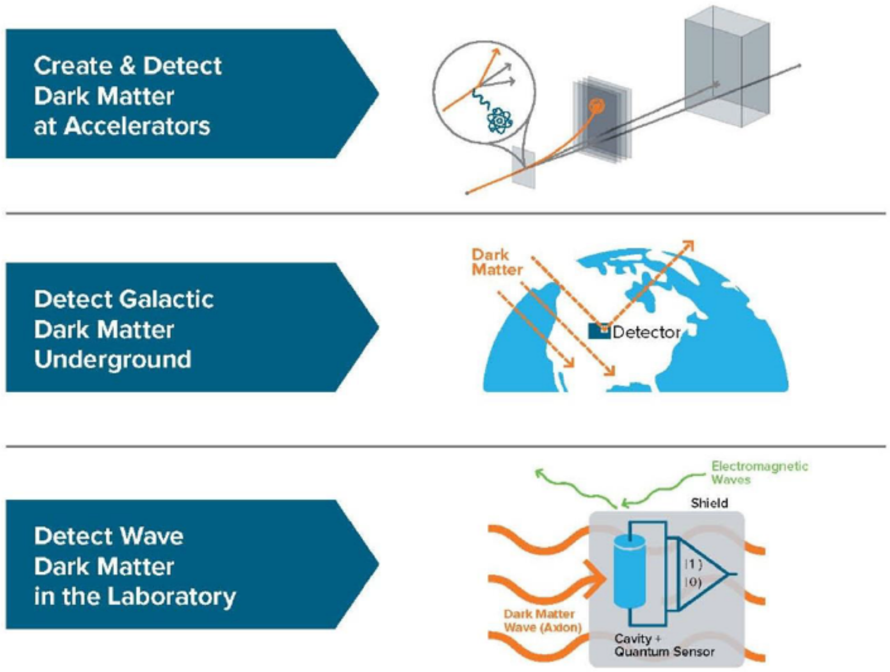


US DOE High Energy Physics Basic Research Needs Study for Dark Matter Small Projects

- Workshop held in Washington DC, Oct 15-18.
- Resulted in a report to the Dept of Energy

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.”*



TESSERACT

The “Basic Research Needs for Dark-Matter Small Projects New Initiatives” report reviews the strong theoretical motivation for searching for particle Dark Matter (DM) in the mass range below the proton mass, continuously down to small fractions of an eV.

The TESSERACT **(Transition Edge Sensors with Sub-EV Resolution and Cryogenic Targets)** project is designed to address Principal Research Direction 2 identified in this report: **Detect individual galactic DM particles below the proton mass through interactions with advanced, ultra-sensitive detectors.**

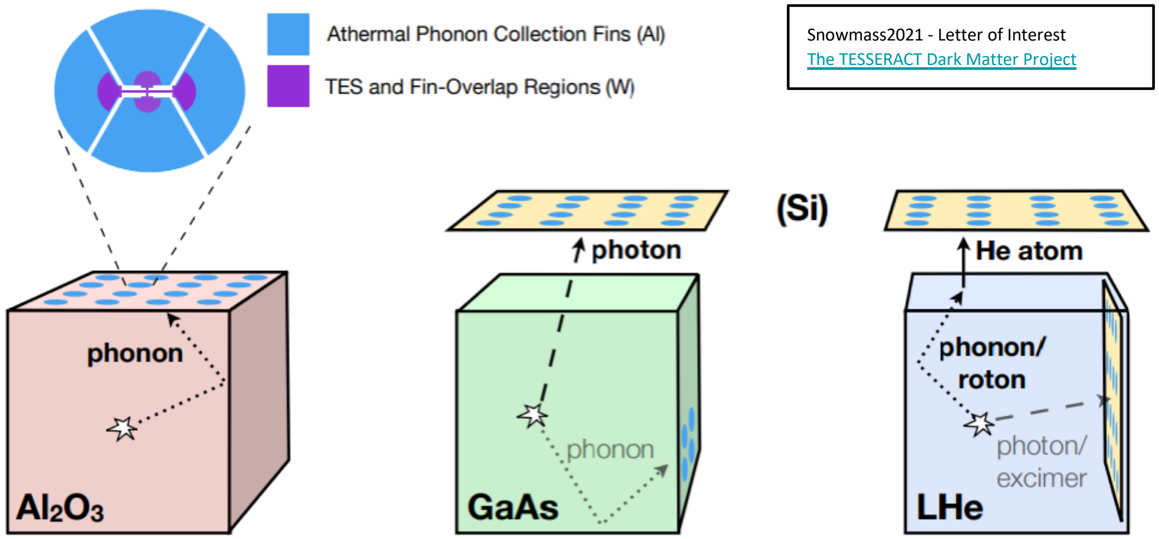
TESSERACT will deliver the shielding, cryogenics, calibration tools, detectors, and project management necessary to perform the HeRALD and SPICE experiments, which will be sensitive to both nuclear recoil interacting DM (NRDM) and electron recoil interacting DM (ERDM).

Both NRDM and ERDM-sensitive detectors are called out in the BRN as scientifically important. TESSERACT has broad scientific impact, but also very deep impact due to a) its extremely low energy thresholds, enabling searches for extremely low-mass dark matter, and b) its many means of reducing backgrounds, enabling searches to low cross-sections.

TESSERACT project

- Managed by LBNL
- 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



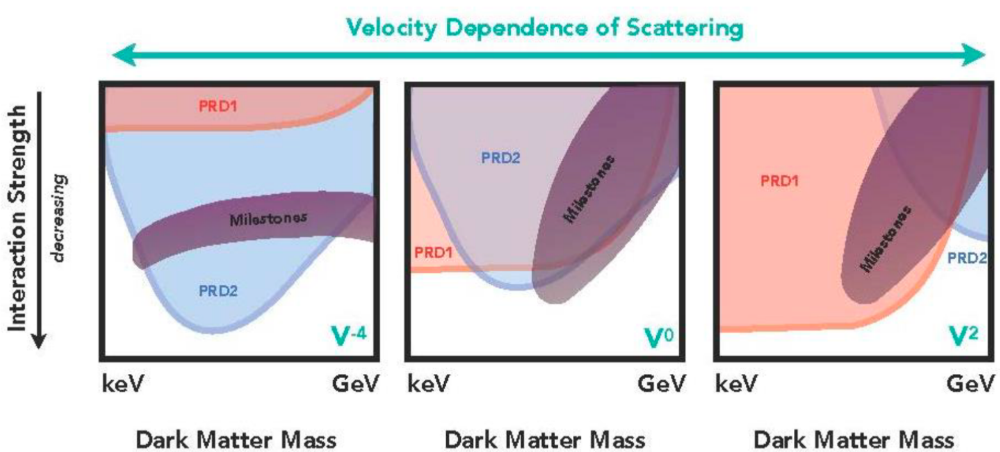
Complementarity with accelerator-based experiments

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:

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



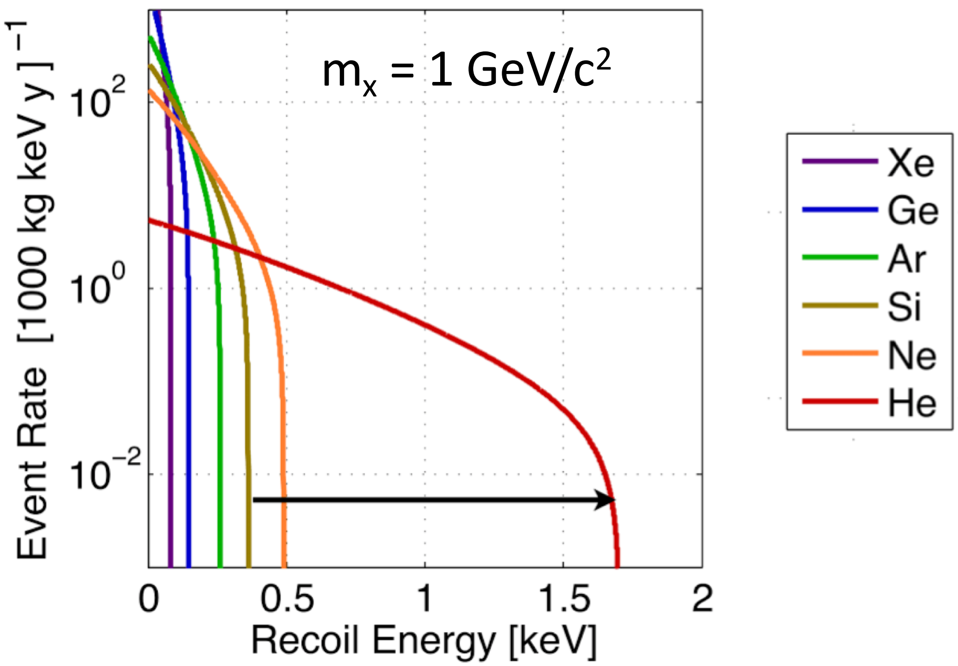
Direct detection: DM flux enhanced for low mass DM

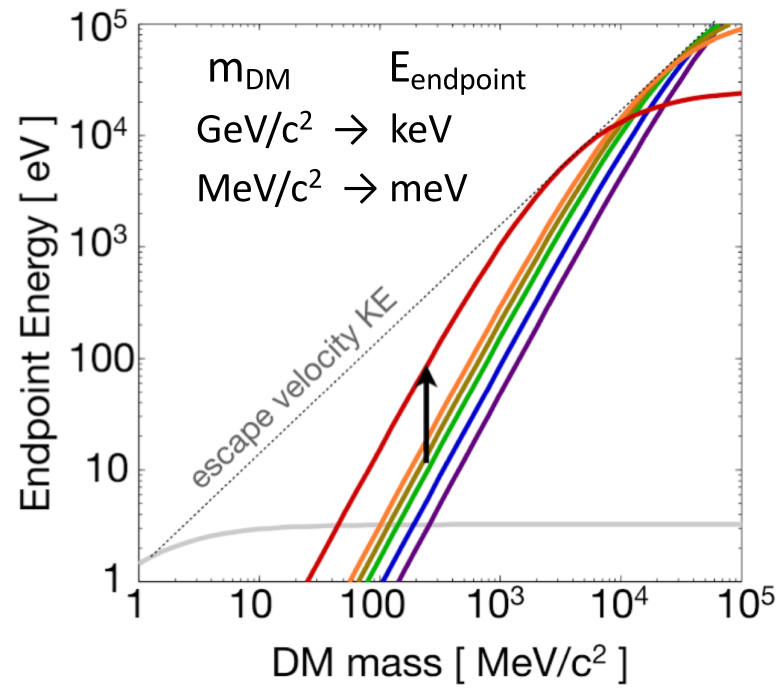
$$R = \sigma n_{DM} N_{exp}$$
$$= \sigma \frac{\rho_{DM}}{M_{DM}} N_{exp}$$

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





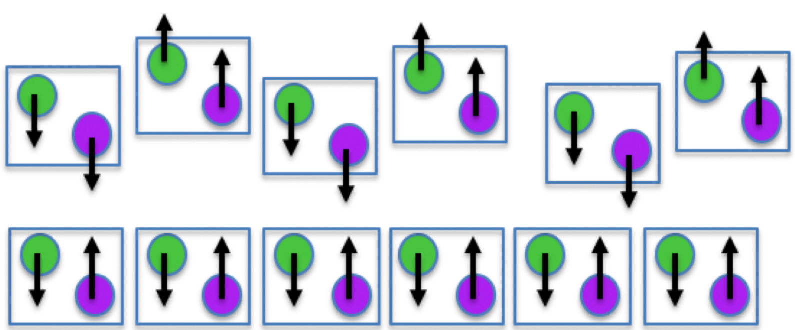
Superfluid helium has significant additional advantages

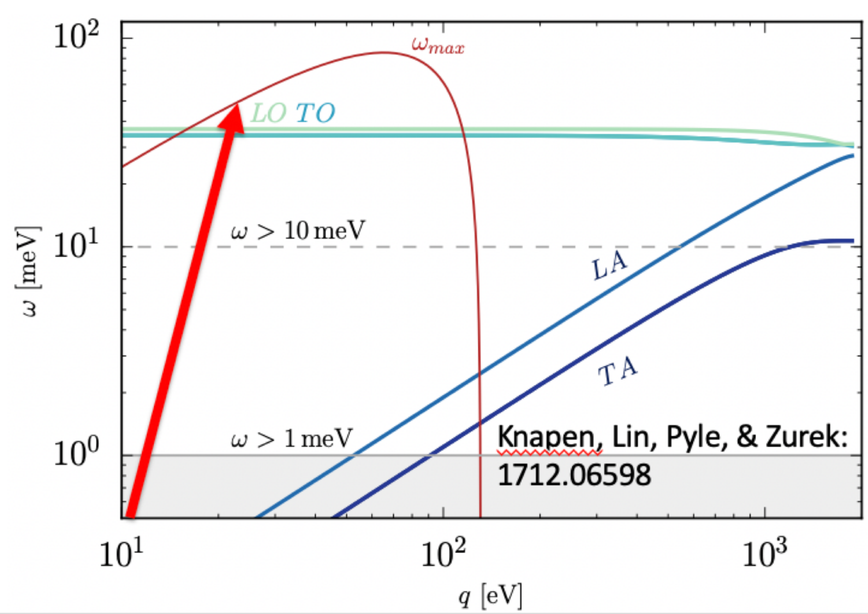
- Quantum evaporation signal gain
- Multipixel background rejection through requiring coincidence
- Multiple signal channels (rotons, phonons, scintillation, triplet excimers)

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.
- To maximize sensitivity to these electro-magnetically coupled DM models, we have chosen to use Al2O3 and SiO2 as target materials.





Low Bandgaps for ERDM

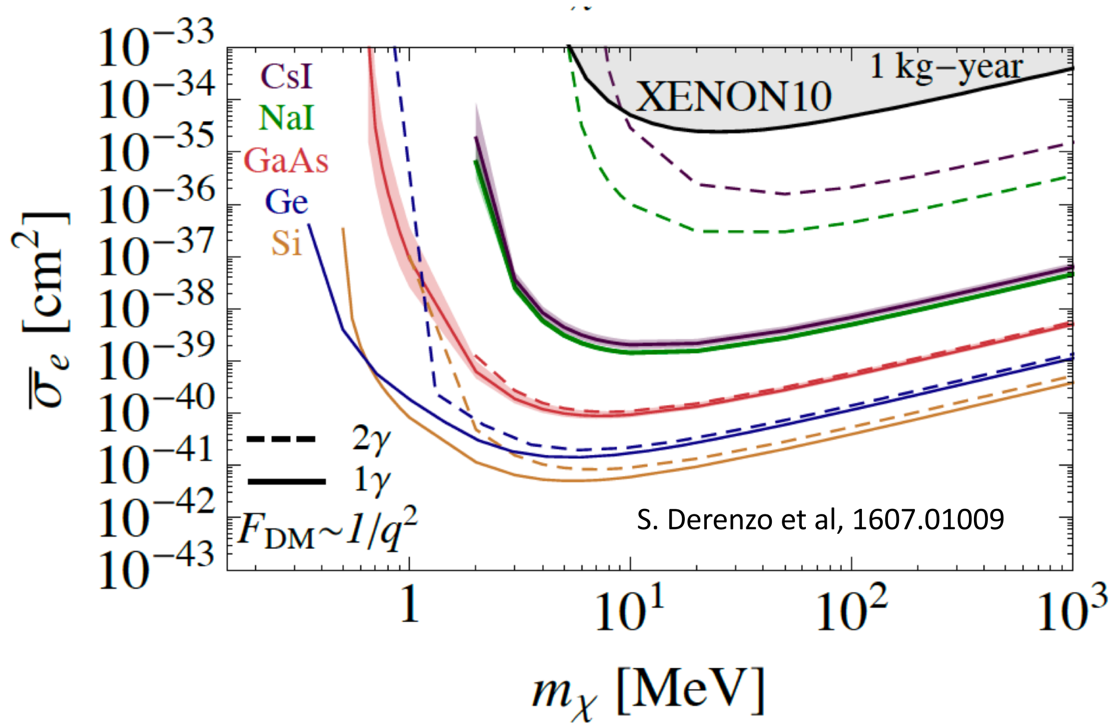
Low bandgaps:

- 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 we 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.

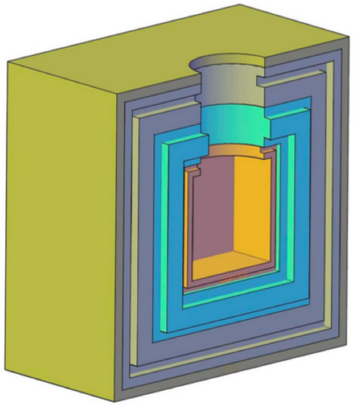


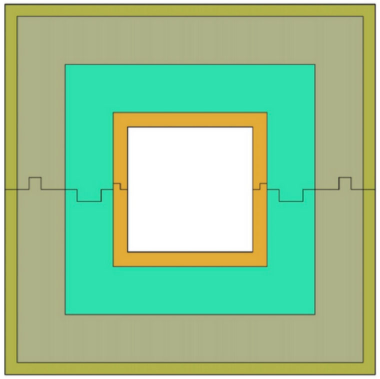
Progress on Shielding Design

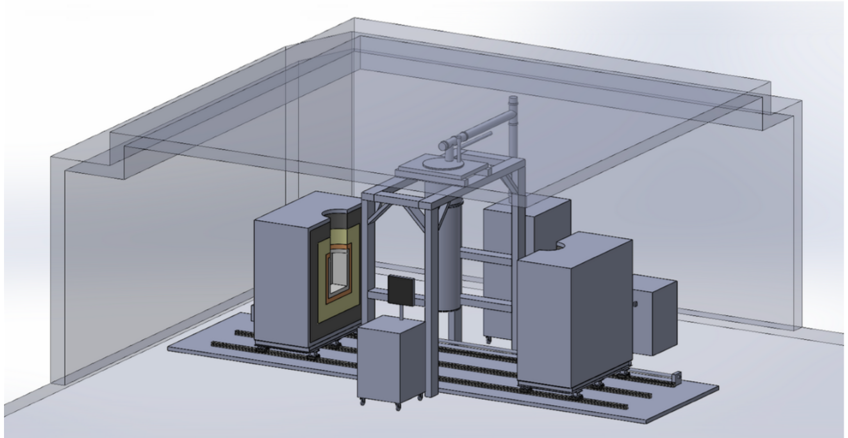
The experiments will be operated in an underground laboratory. Discussions are just beginning with underground labs.

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.







- **Science goal:**
    - Direct detection of particle-like sub-GeV dark matter
    - Sensitive to a wide variety of dark matter interaction modes
        - dark photon-phonon interactions
        - electron scattering
        - nuclear scattering / absorption

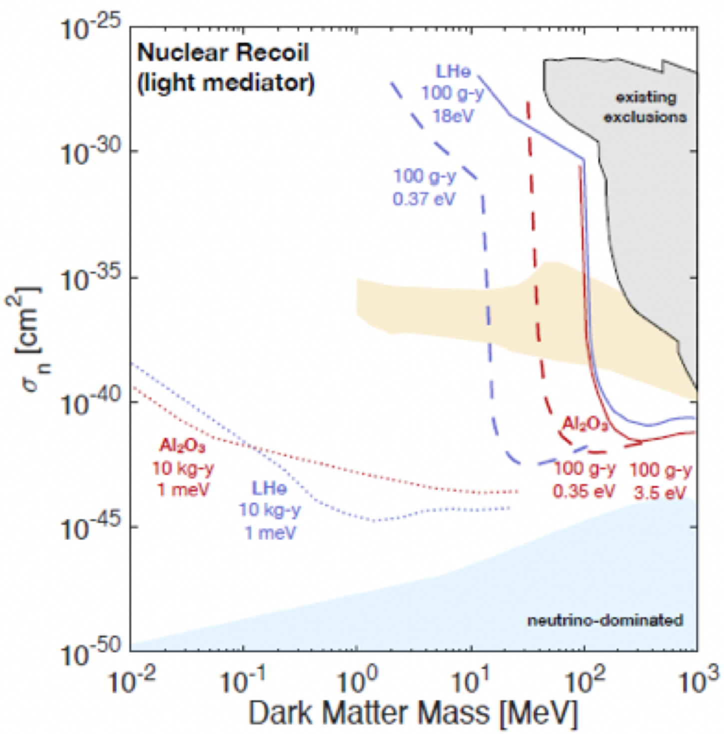
- **Technology: Transition Edge Sensors (TESs)**
    - Athermal phonon readout for fast signals, decreased noise
    - Shared engineering on shielding design, vibrational isolation, electromagnetic interference, TES readout electronics
    - Multiple targets, each under zero electric field. Sapphire, Silica, Gallium arsenide, Superfluid helium

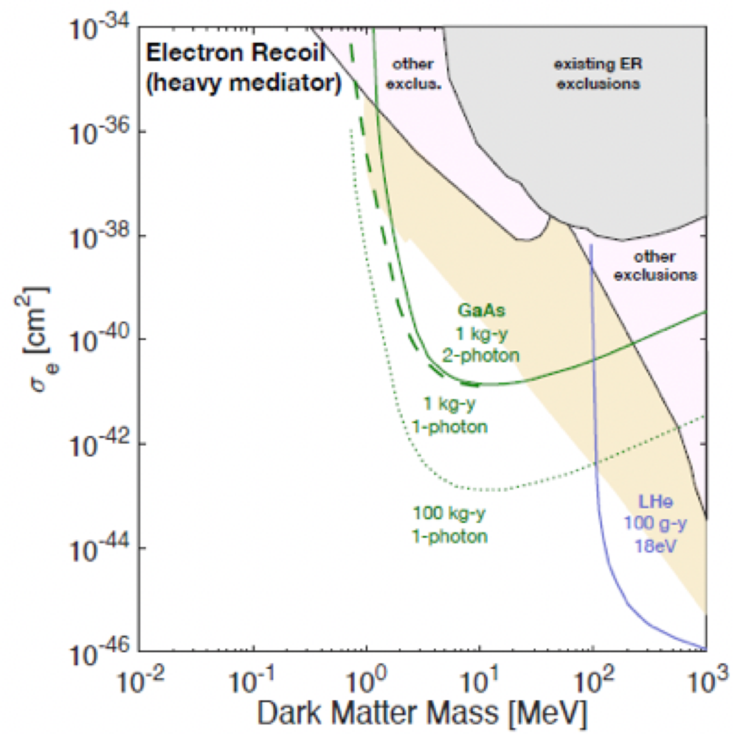
- **R&D:** Couple TES to different targets, test detector signal and background, calibrate target material response.

- **Schedule: Project planning stage:** 5 years, FY20-FY24
    - Project planning stage: 2020-2024
    - Fabrication: 24 months beginning 2025-2026
    - Operations: Beginning 2027

SPICE and HeRALD - projected sensitivity

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





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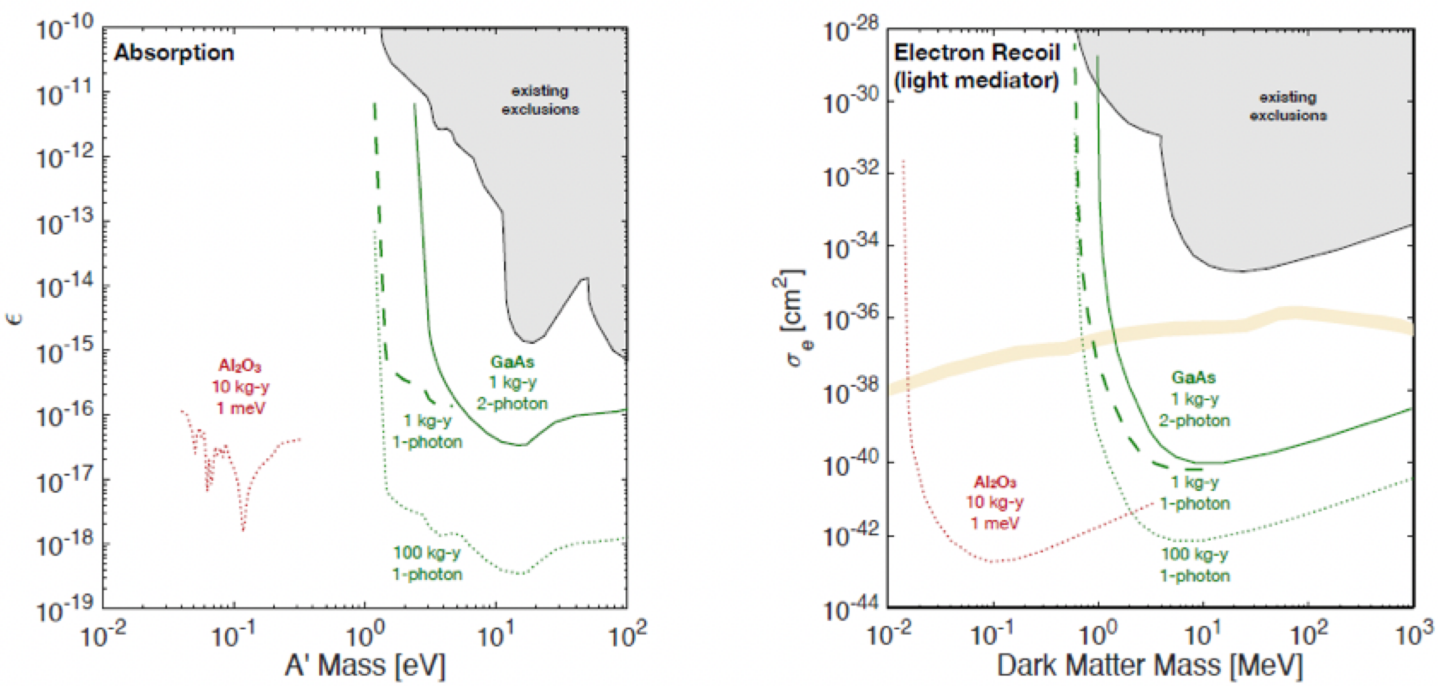
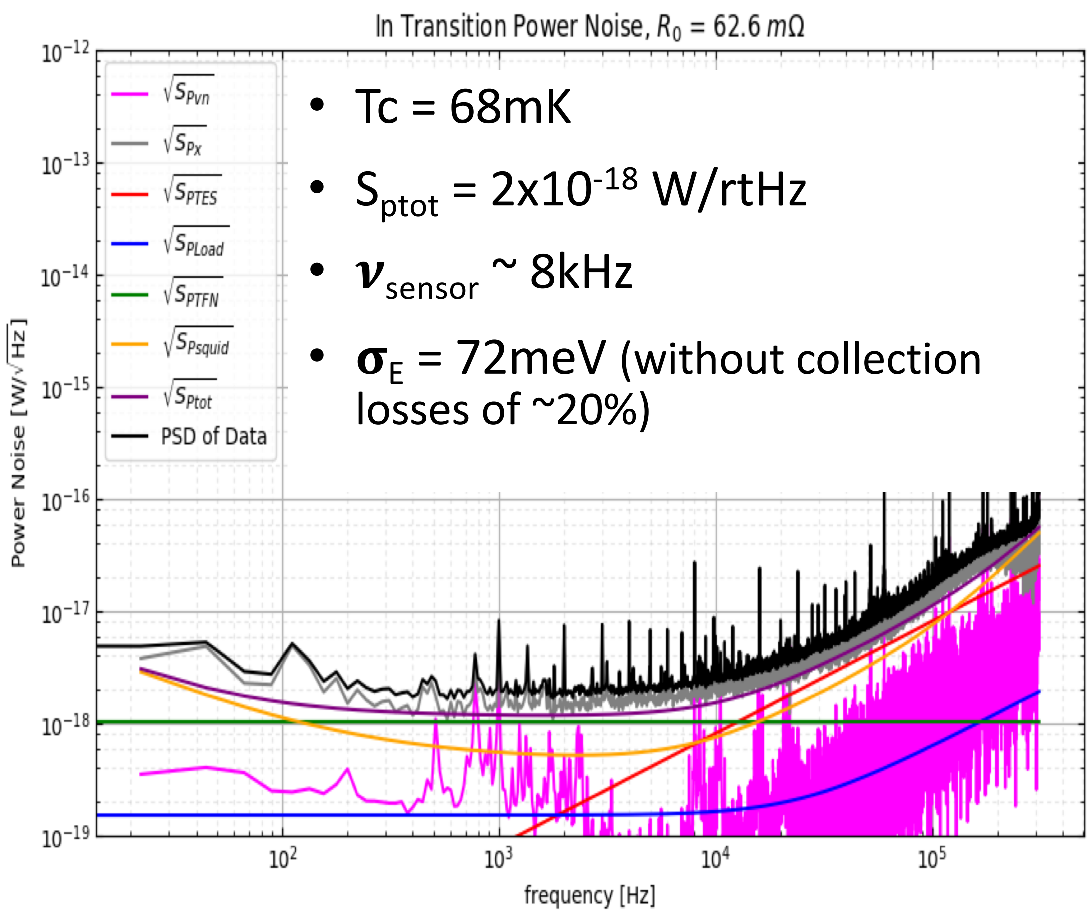
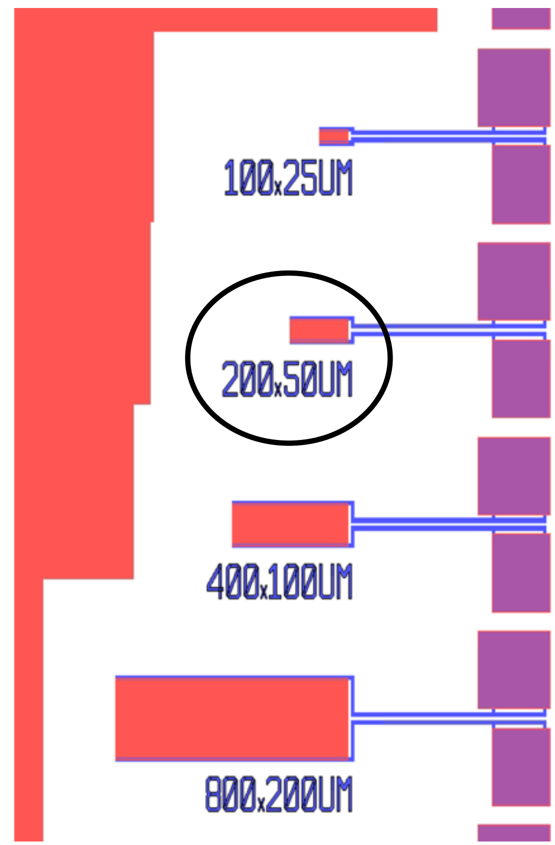


Recent Progress:
TES R&D from M. Pyle et al.

Light Mass Dark Matter Experimental Driver: Energy Threshold

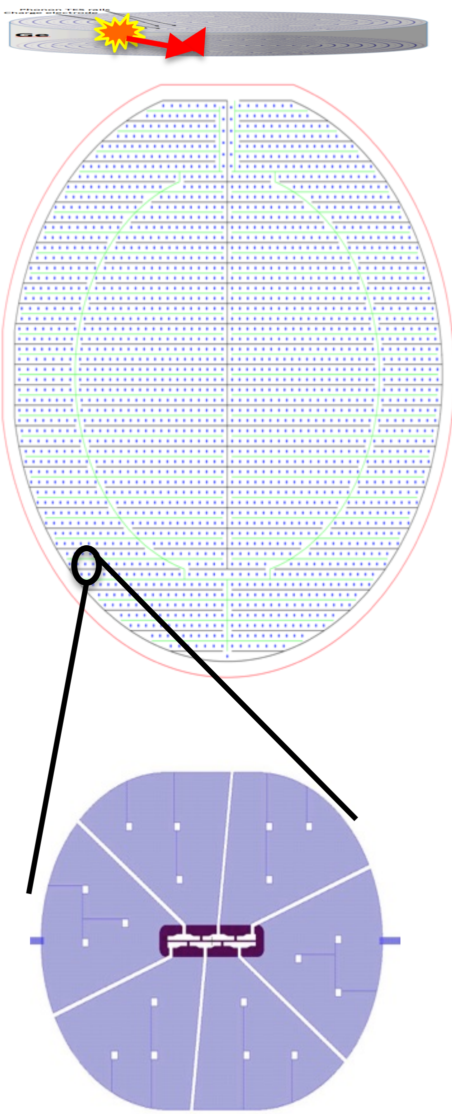


- Tc = 68mK
- S_{ptot} = 2×10^{-18} W/rtHz
- ν_{sensor} ~ 8kHz
- σ_E = 72meV (without collection losses of ~20%)

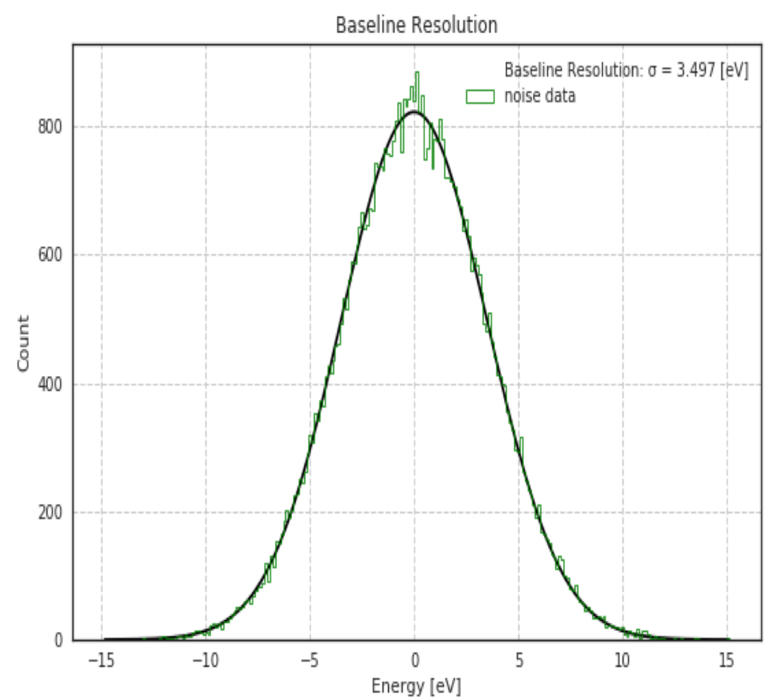


- Environmental noise pickup not problematic for > 100meV experimental applications
- Measured sensitivity with x1.4 of theoretical sensitivity

Recent Progress: Large Area Photon Calorimeters

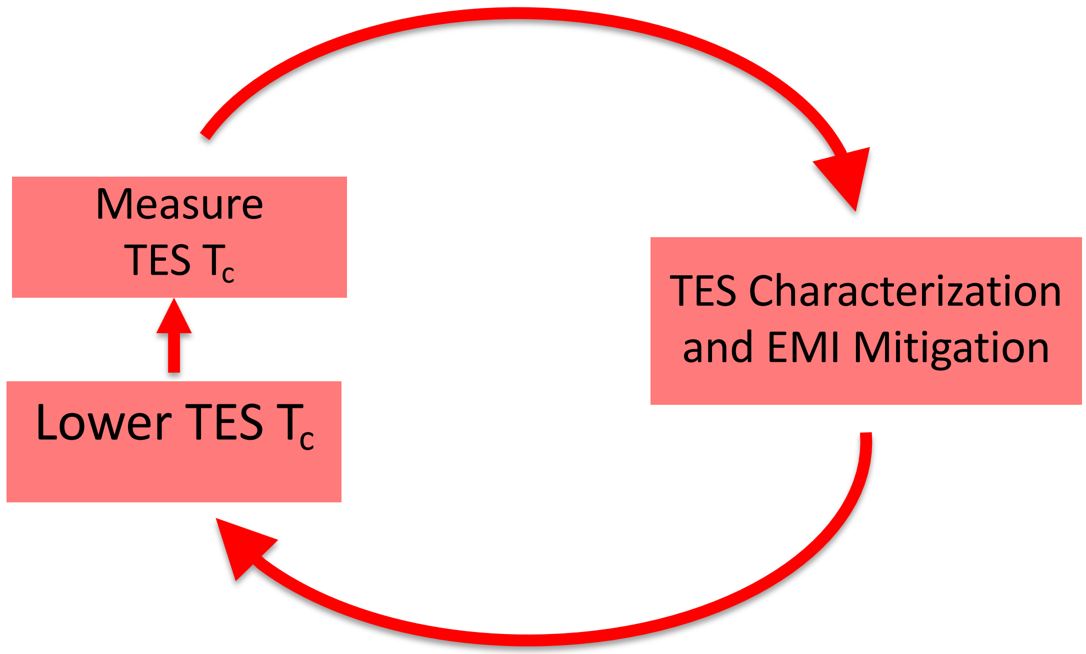


- 3" diameter 1mm thick Si wafer (45.6 cm^2)
- Distributed athermal phonon sensors
  - Athermal Phonon collection time estimated to be ~20us
  - 2.5% sensor coverage
- Tc= 41.5mK
- **17% Athermal Phonon Collection Efficiency**
- **Measured Baseline σ_E =3.5 ± 0.25 eV**



Major R&D goal: Develop ultra sensitive TES

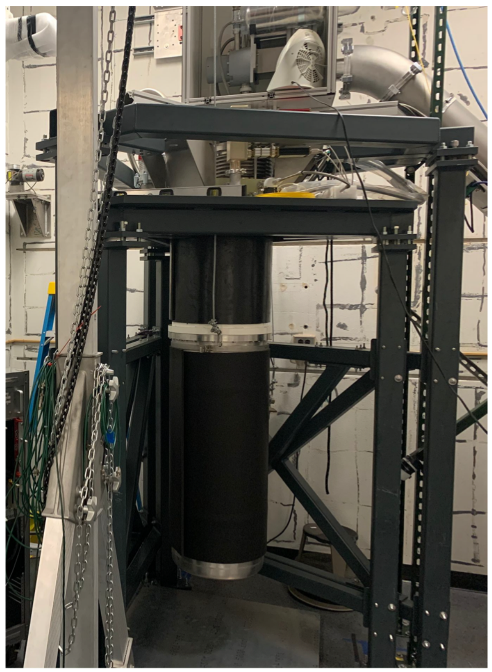
Work ongoing on fabrication (TAMU and ANL) and testing (UC Berkeley, LBNL, UMass)



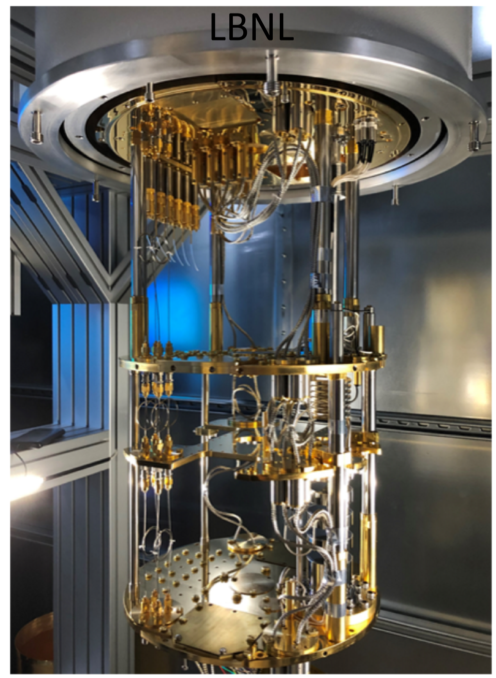
SPICE/HeRALD testbeds

Leiden MNK126-500
McKinsey Group @ UCB

CryoConcept UQT-B 200
Pyle Group @ UCB



BlueFors LD-400
Detector Group @
LBNL

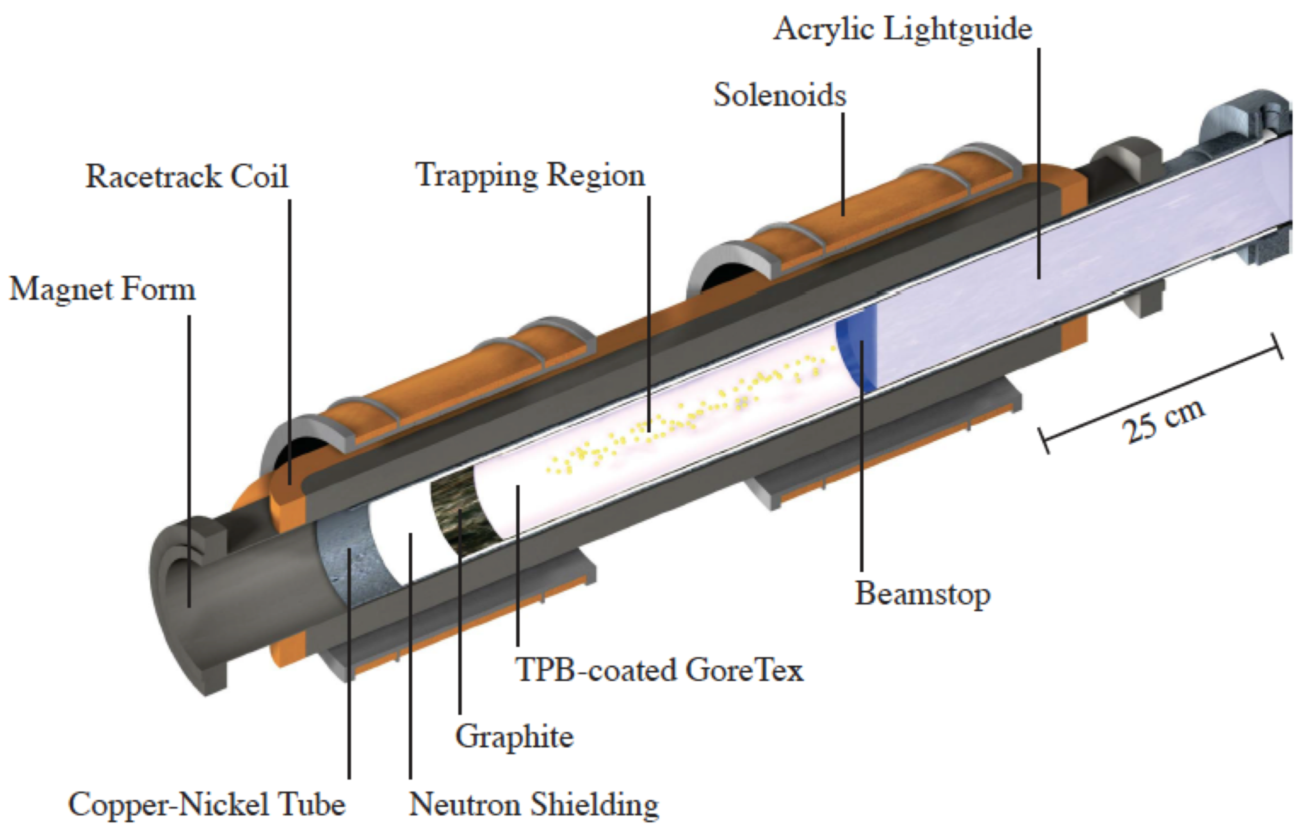


CryoConcept HEXADRY
UQT-B 400
H

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).

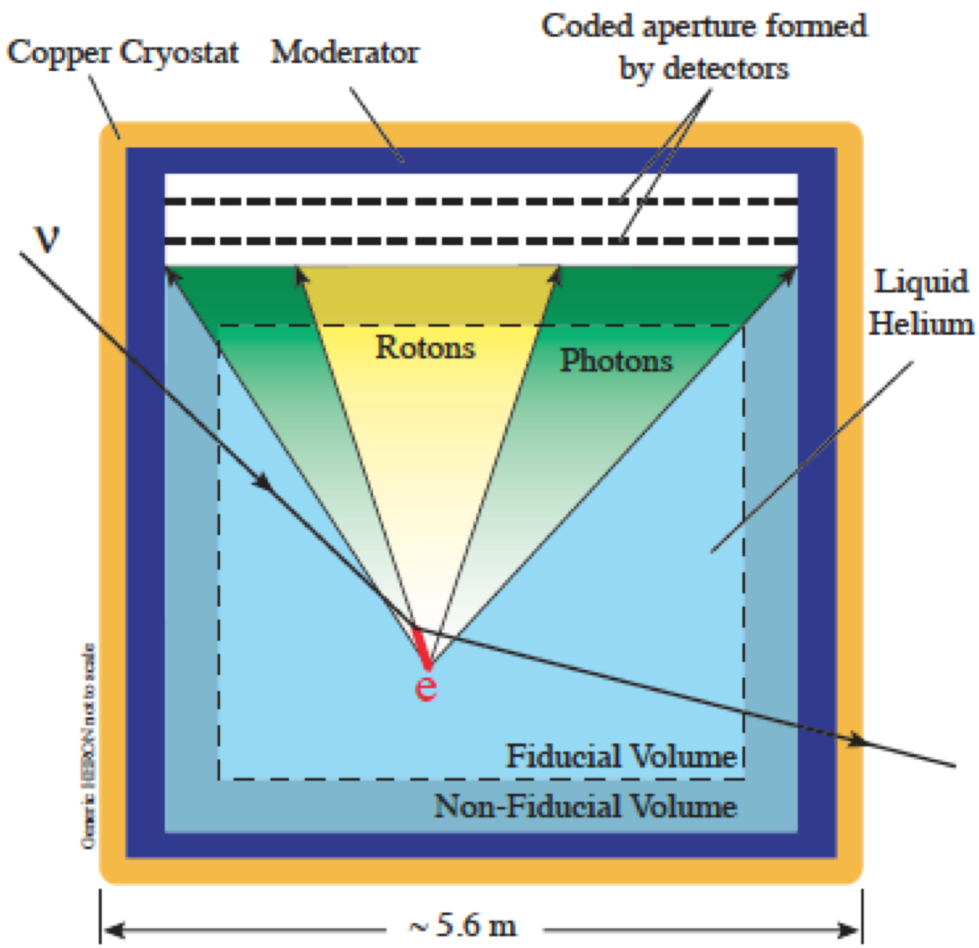


Superfluid helium-4 as a detector material

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).

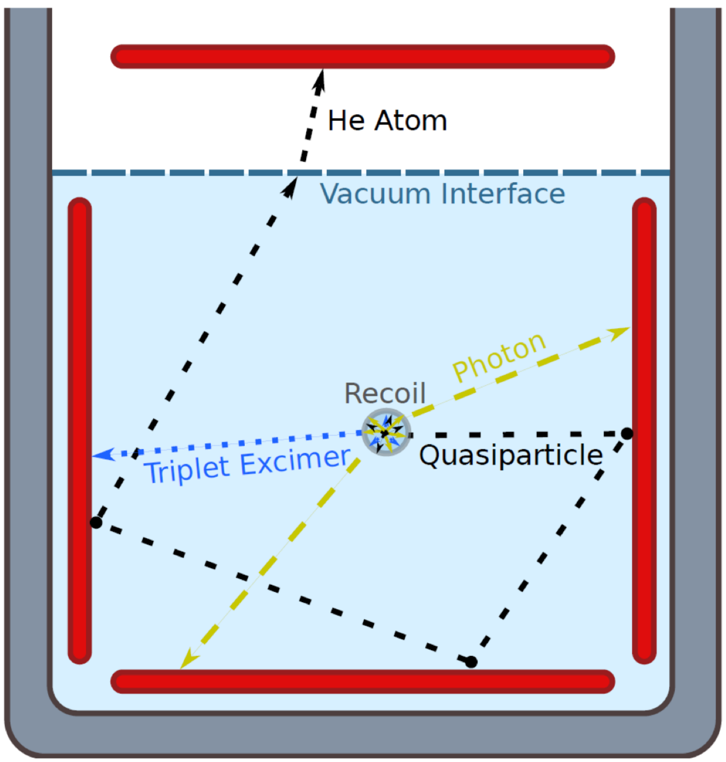
Two signal channels, heat and light. Both measured with a bolometer array.

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



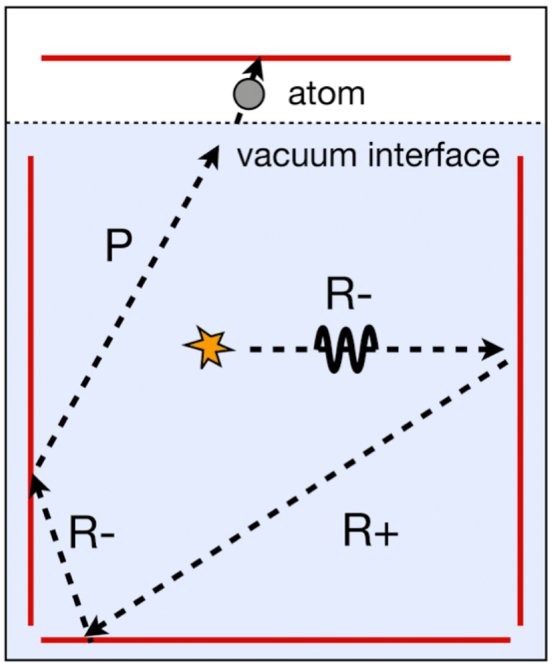
Helium **R**oton **A**pparatus for **L**ight **D**ark matter (HeRALD)

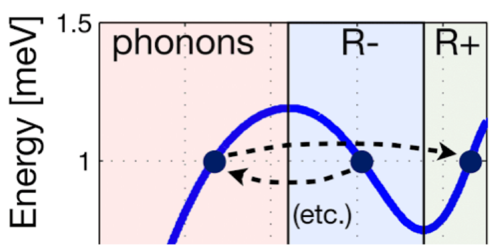
HeRALD concept and sensitivity paper
PhysRevD.100.092007

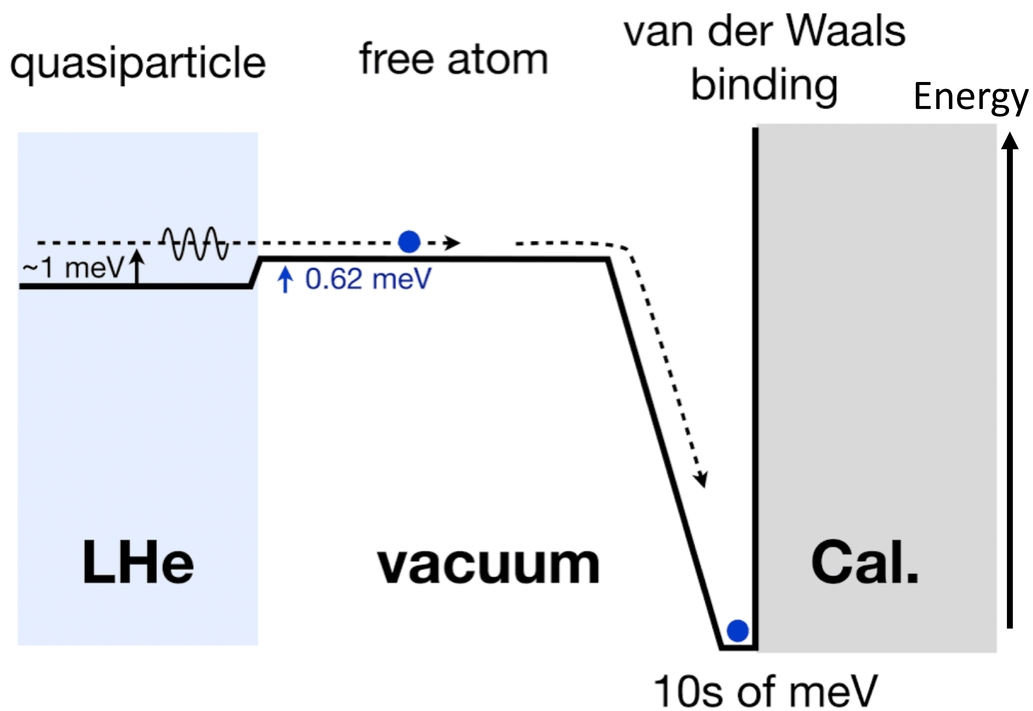


- Operated at ~30-50 mK
- Calorimeters with TES readout
  - submerged in liquid
    - Detect **UV photons**, **triplet molecules** and **IR photons**
  - suspended in vacuum
    - Detect UV photons, IR photons and **He atoms** (evaporated by quasiparticles)

Quasiparticle readout - Quantum evaporation of helium atom

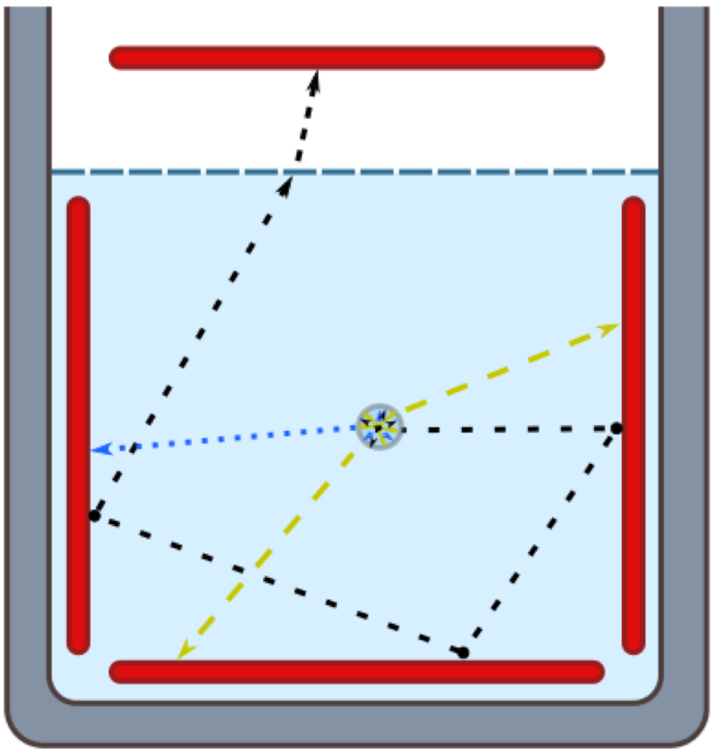






- ➢ 1 meV roton energy becomes up to 40 meV observable
  - × 40 amplification
  - Graphene-fluorine surface

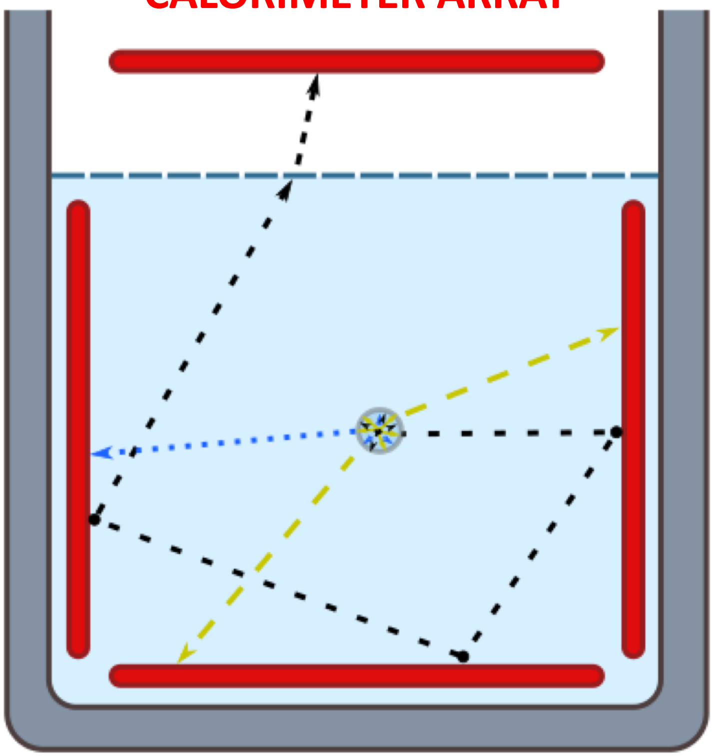
Superfluid Helium as a Dark Matter Target



Advantages of He-4

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

Proposed Detector: HeRALD



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

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

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

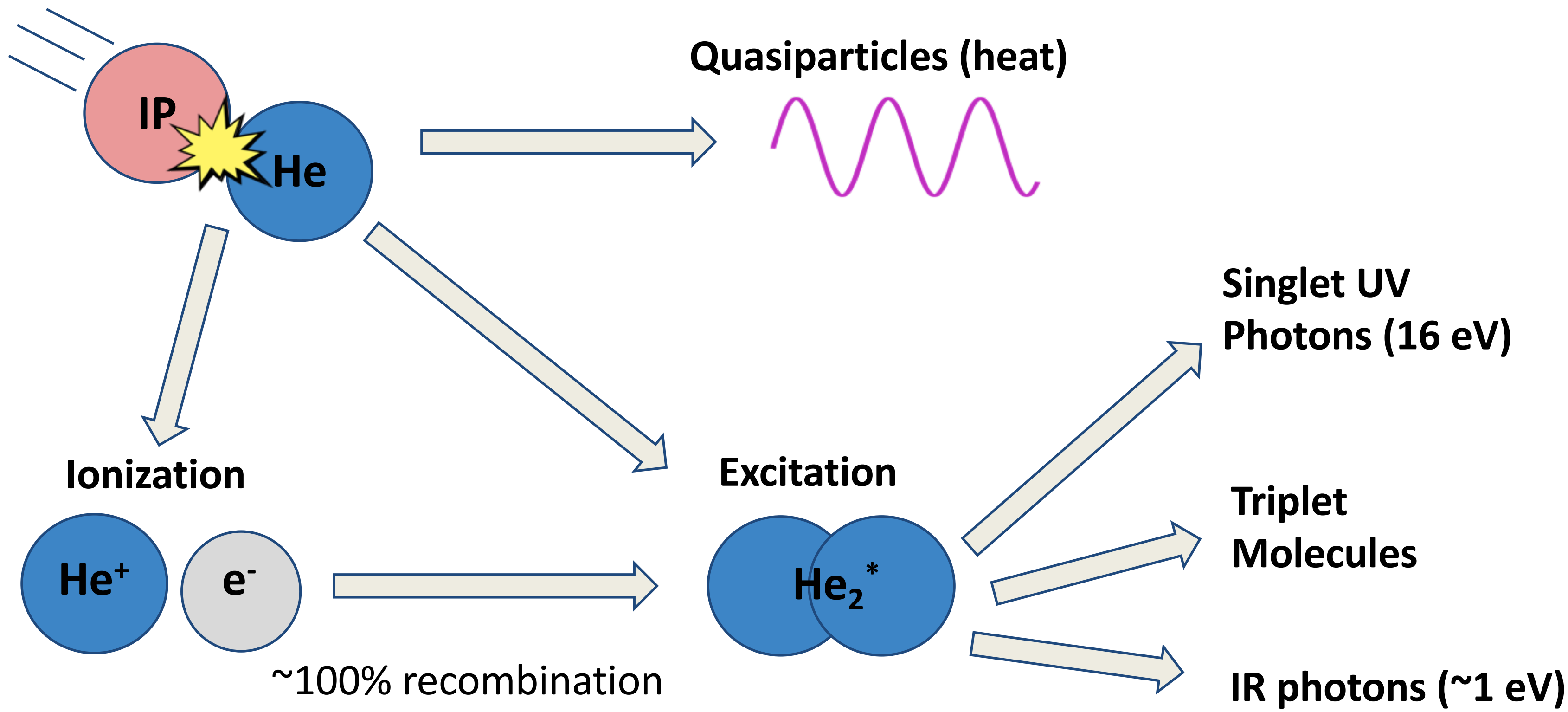
- Detect UV photons, triplet excimers, IR photons

Vacuum layer between helium and 6th TES array

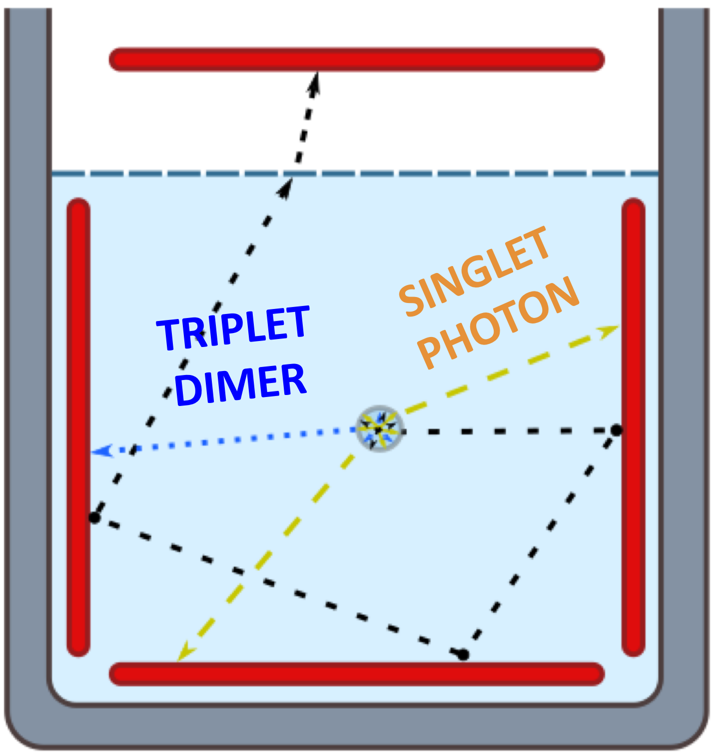
- Detect quasiparticles via quantum evaporation

arXiv:1810.06283

Recoils in Helium (generic incident particle IP)



Detecting Excimer Signal



Singlet decay (16 eV)

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

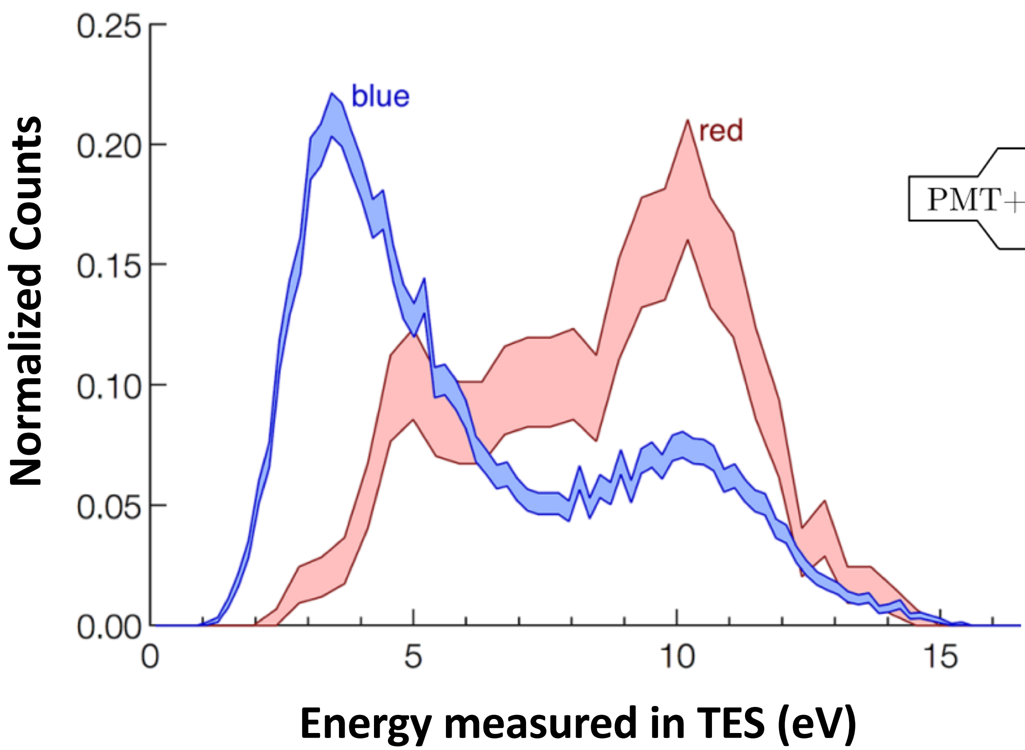
Triplet decay (16 eV)

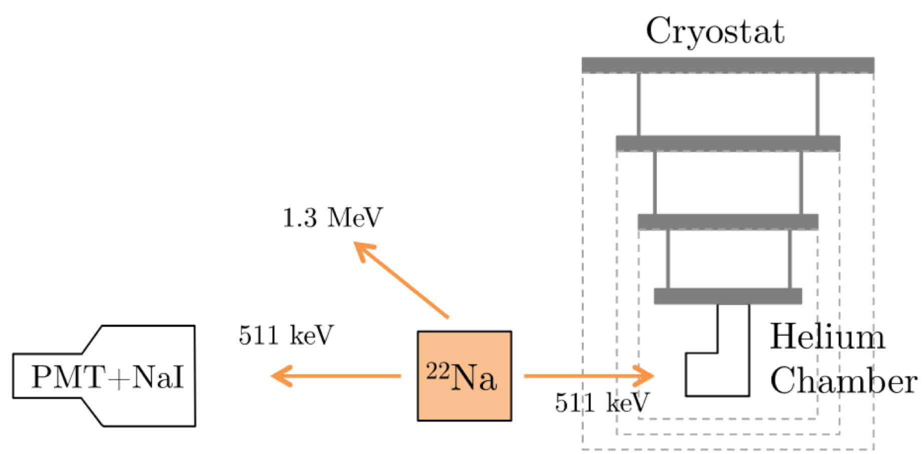
- Lifetime of 13 seconds (McKinsey et al, Phys Rev A **59**, 200 (1999).
- Helium dimer molecule travels ballistically at speed ~1-10 m/s, measured by calorimeter after **few ms**

IR (~1 eV)

Detecting Excimer Signal

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





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

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

Singlets from TES coincident with PMT; triplets from only TES

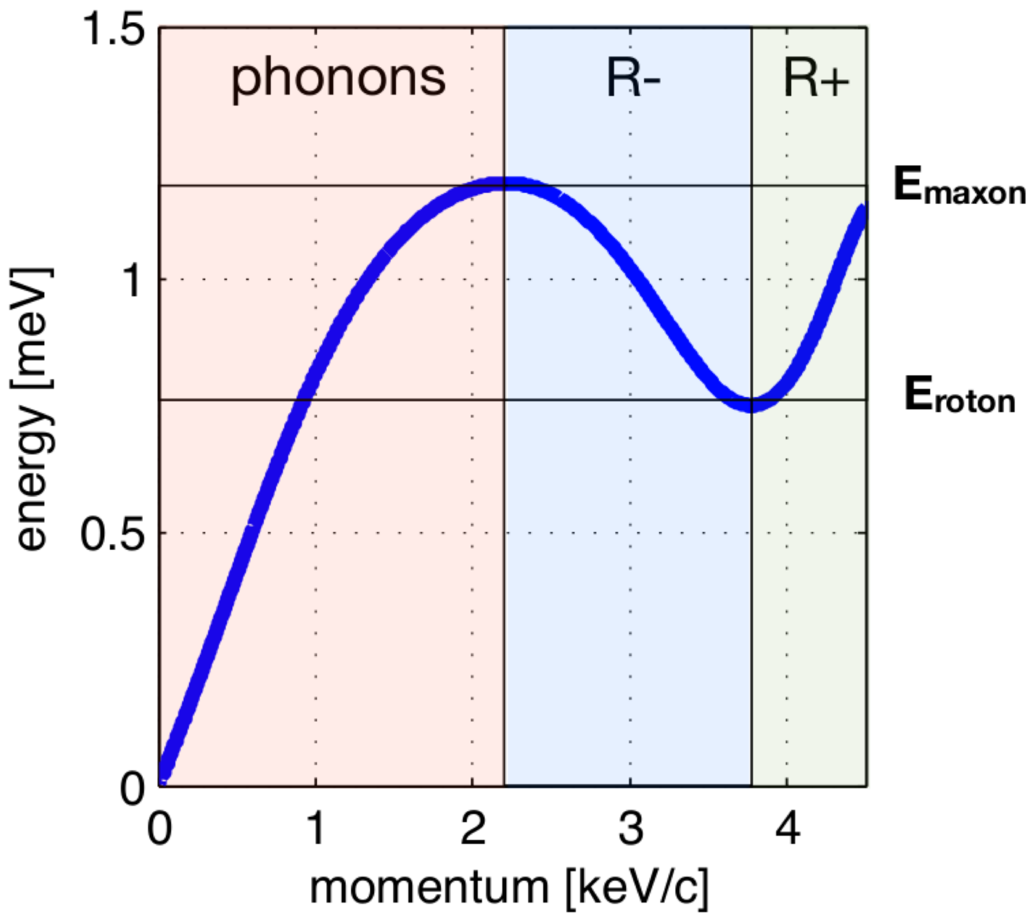
Quasiparticles in ^{4}He

Quasiparticles: collective excitations in superfluid helium

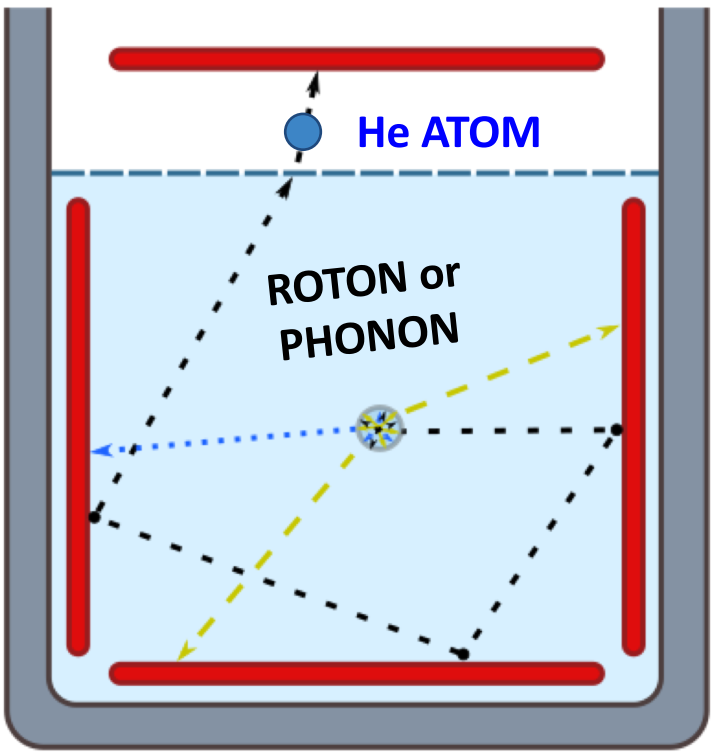
Long-lived, speeds of ~100 m/s

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

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



Detecting Quasiparticle Signal



Recoils produce ~0.8 meV phonons and rotons

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

Transmission of quasiparticles into the wall suppressed by Kapitza resistance

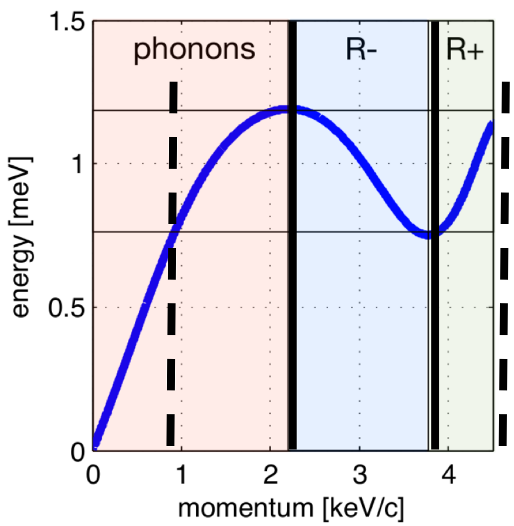
Quantum evaporation of a helium atom into vacuum, followed by energy deposit on top TES

Quasiparticle Propagation

In ^{4}He bulk, quasiparticles move freely

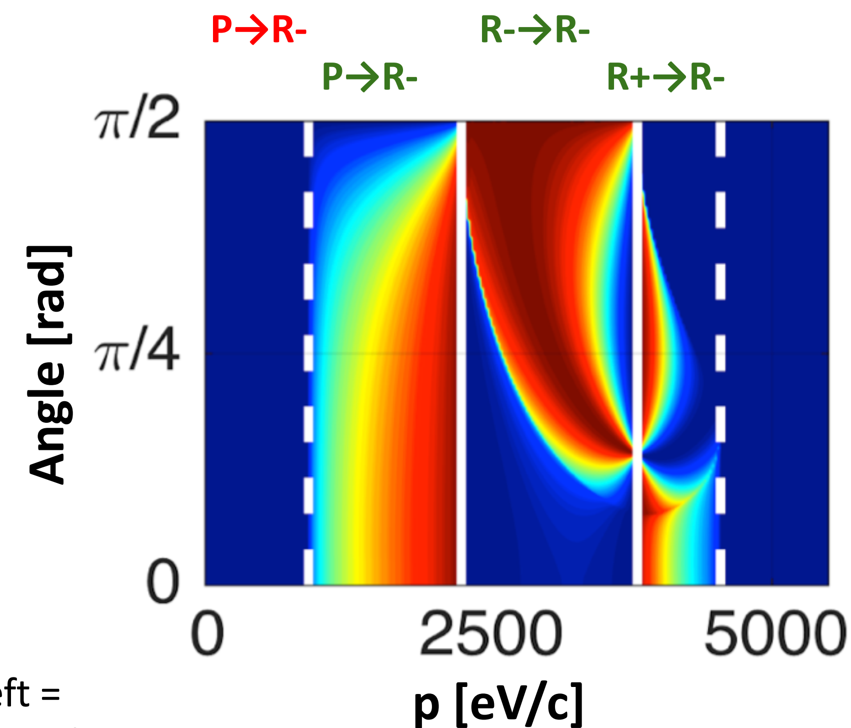
At interface, can be transmitted, reflected, or transformed (if E conserved)

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



Note:
Black lines at left =
White lines at right

Reflection as R-
(allowed; forbidden)



Quasiparticle Propagation

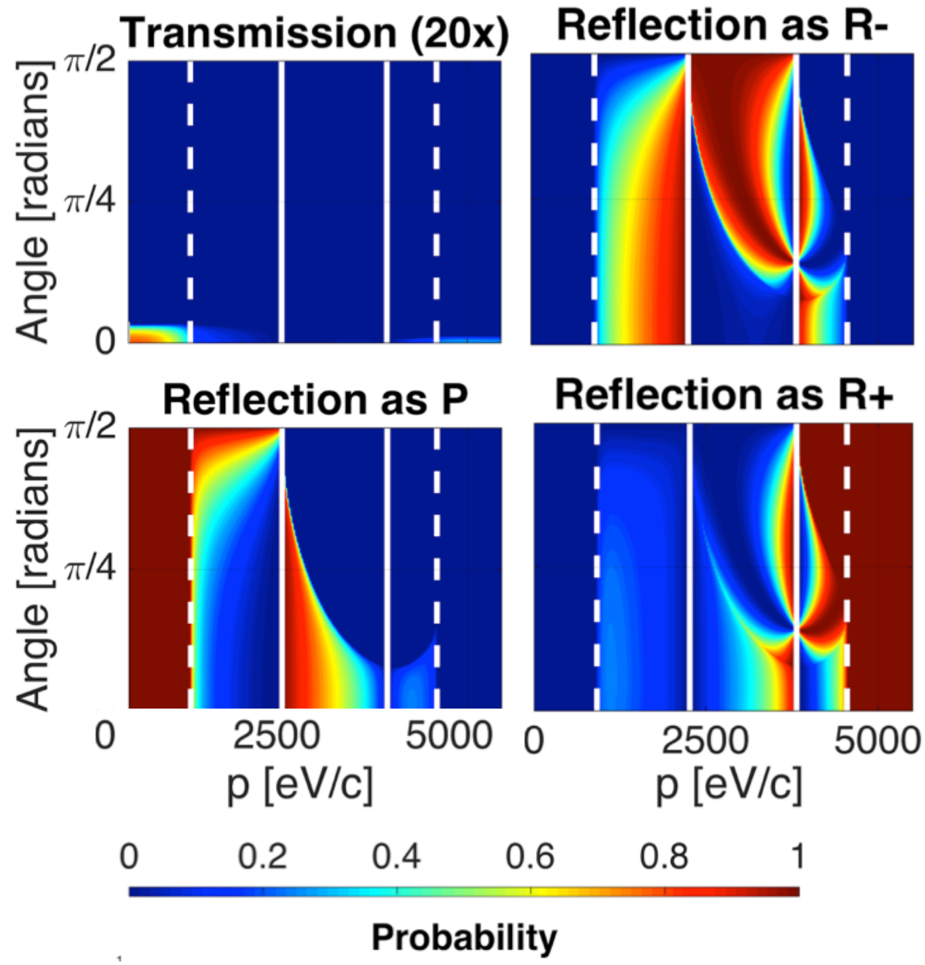
Simulated all reflection/transmission probabilities †

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)*.

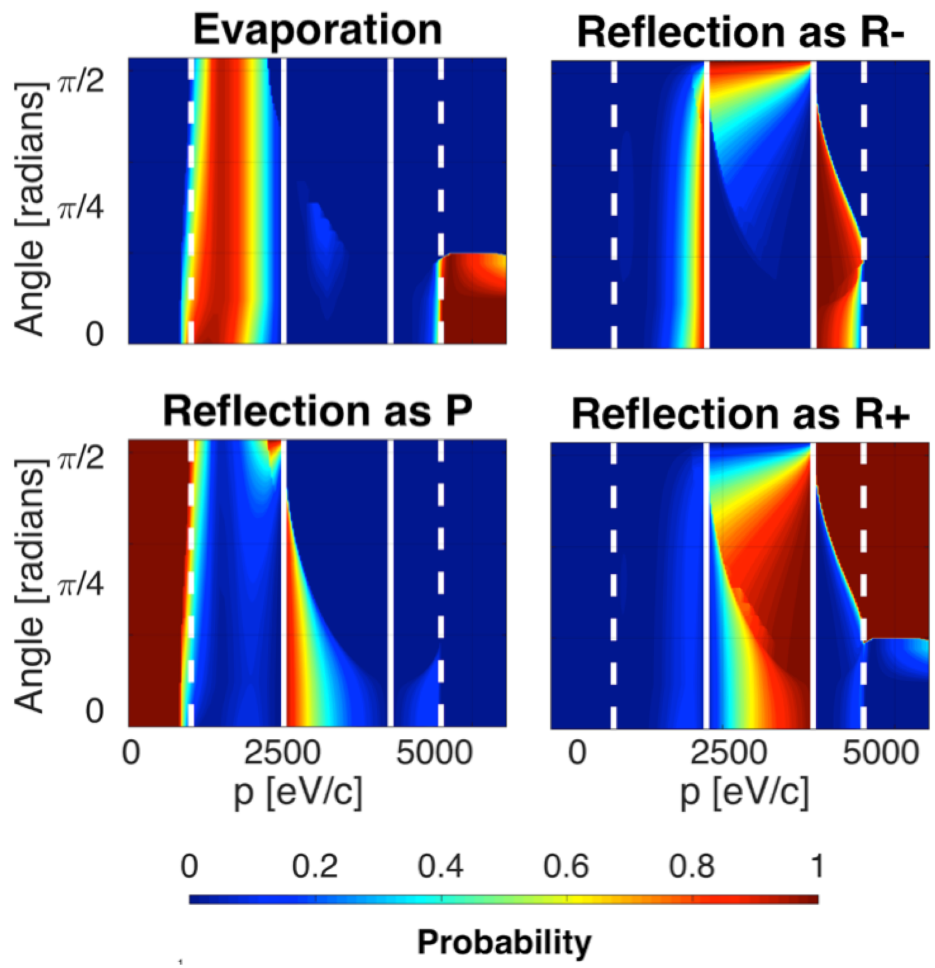
Helium-Solid Interface



Quasiparticle Propagation

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

Helium-Vacuum Interface



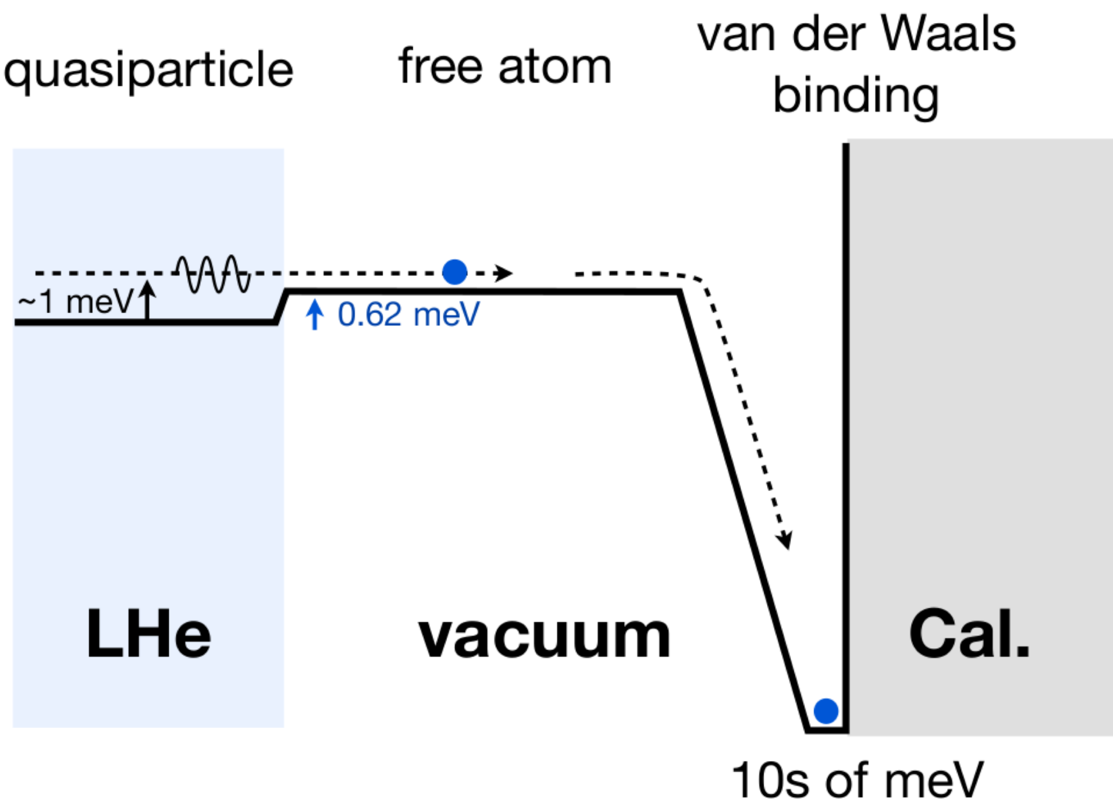
Detecting Quasiparticle Signal

Binding energy between helium and solid amplifies signal

1 meV recoil energy → up to 40 meV detectable energy

Thermal energy negligible (μeV)

Film burner to remove helium from calorimeter

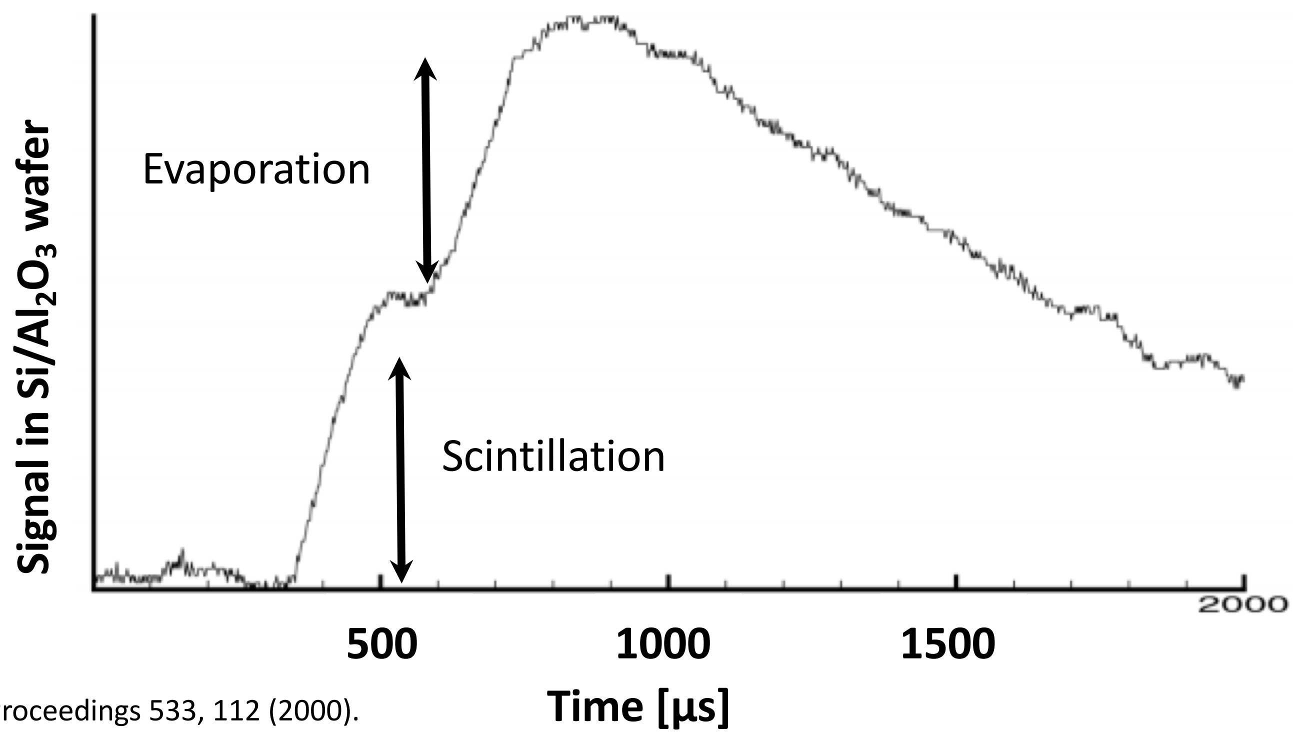


Previous work by HERON

HERON: proposed *pp* neutrino observatory

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

Achieved 300 eV threshold at 30 mK

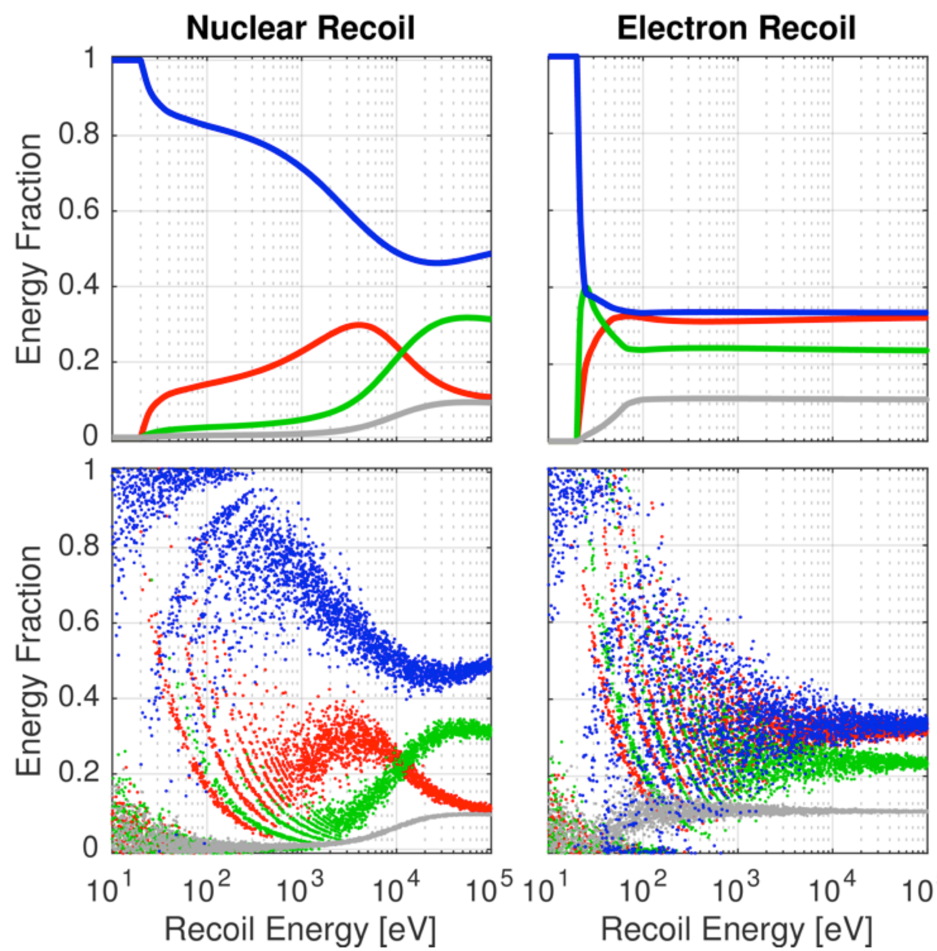


Source: J. S. Adams et al. AIP Conference Proceedings 533, 112 (2000).
Also see: J. S. Adams et al. Physics Letters B 341 (1995) 431-434.

Energy Partitioning

Means

Simulated Poisson Statistics



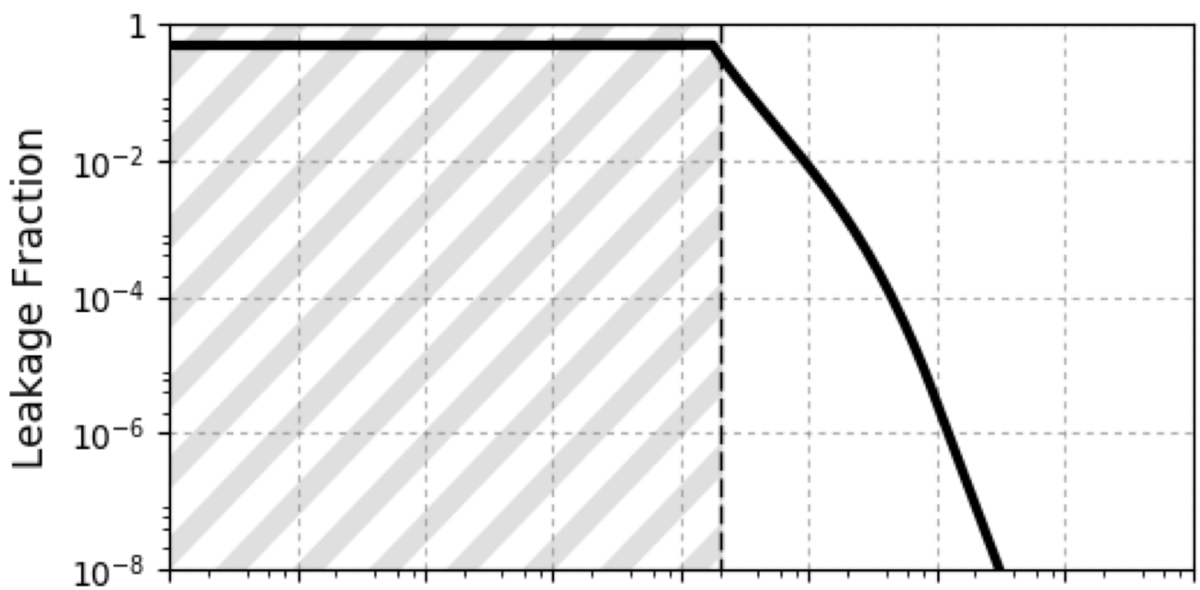
Discrimination

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

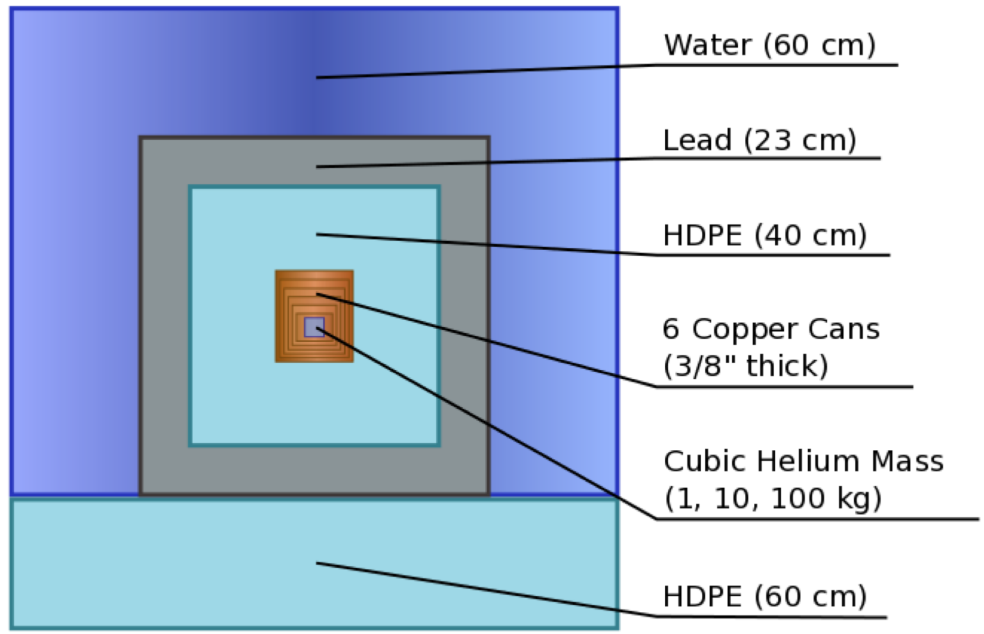
ER acceptance at 50% NR acceptance



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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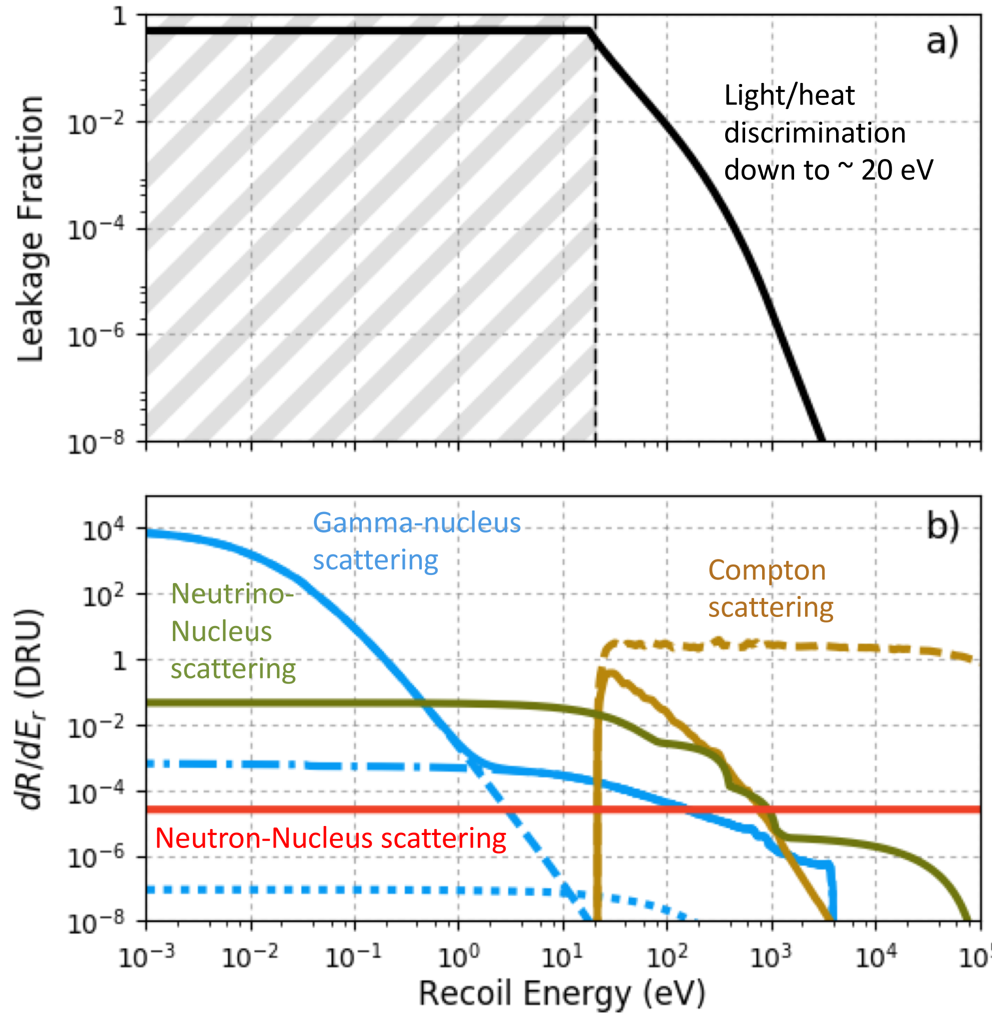
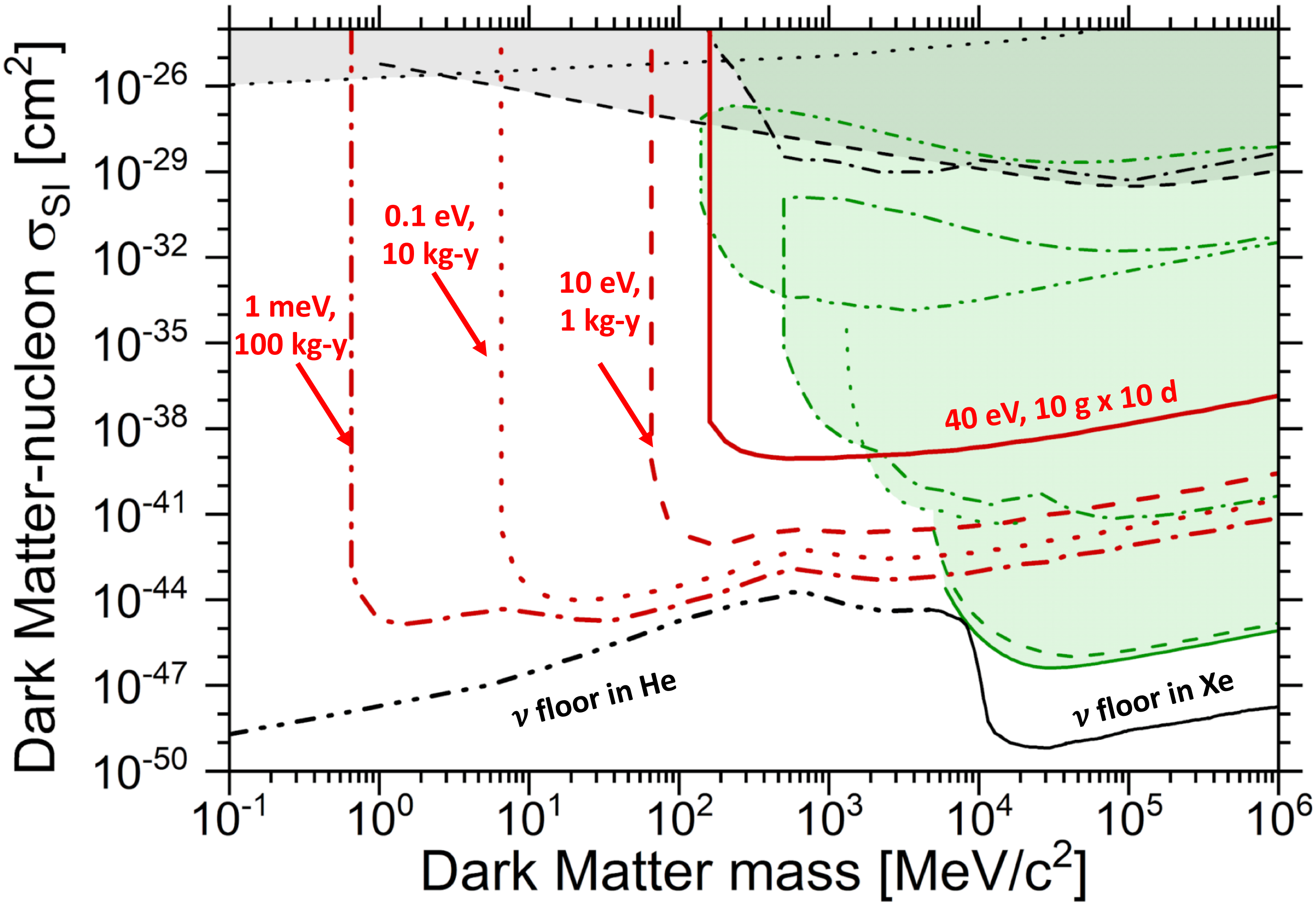
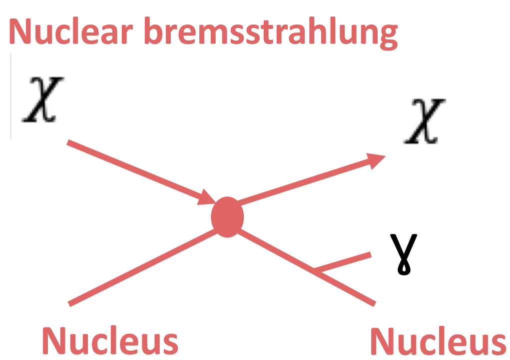
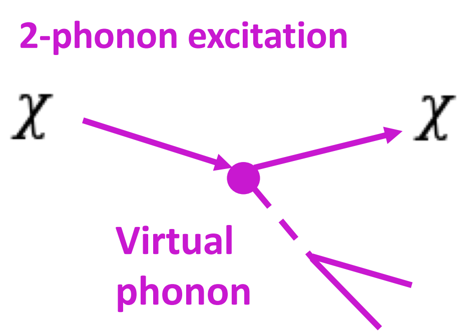


Projected Sensitivity

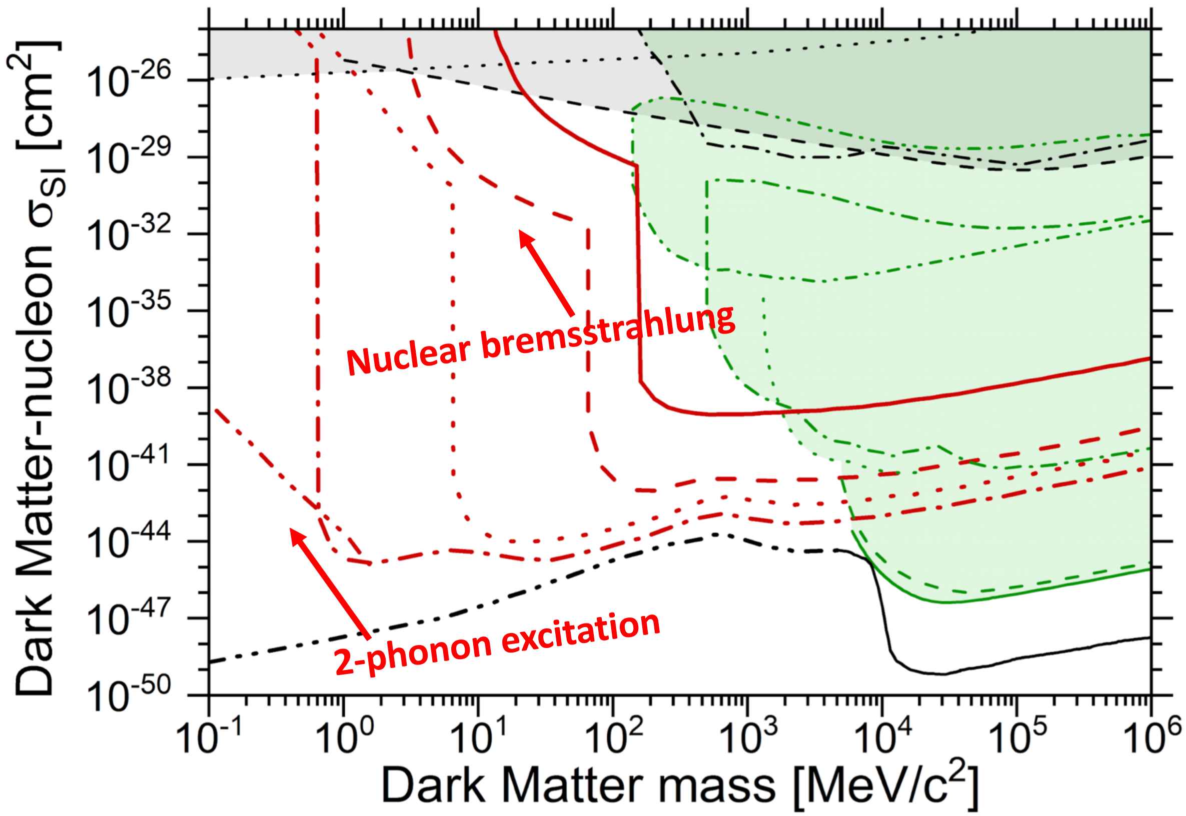


Extending Sensitivity



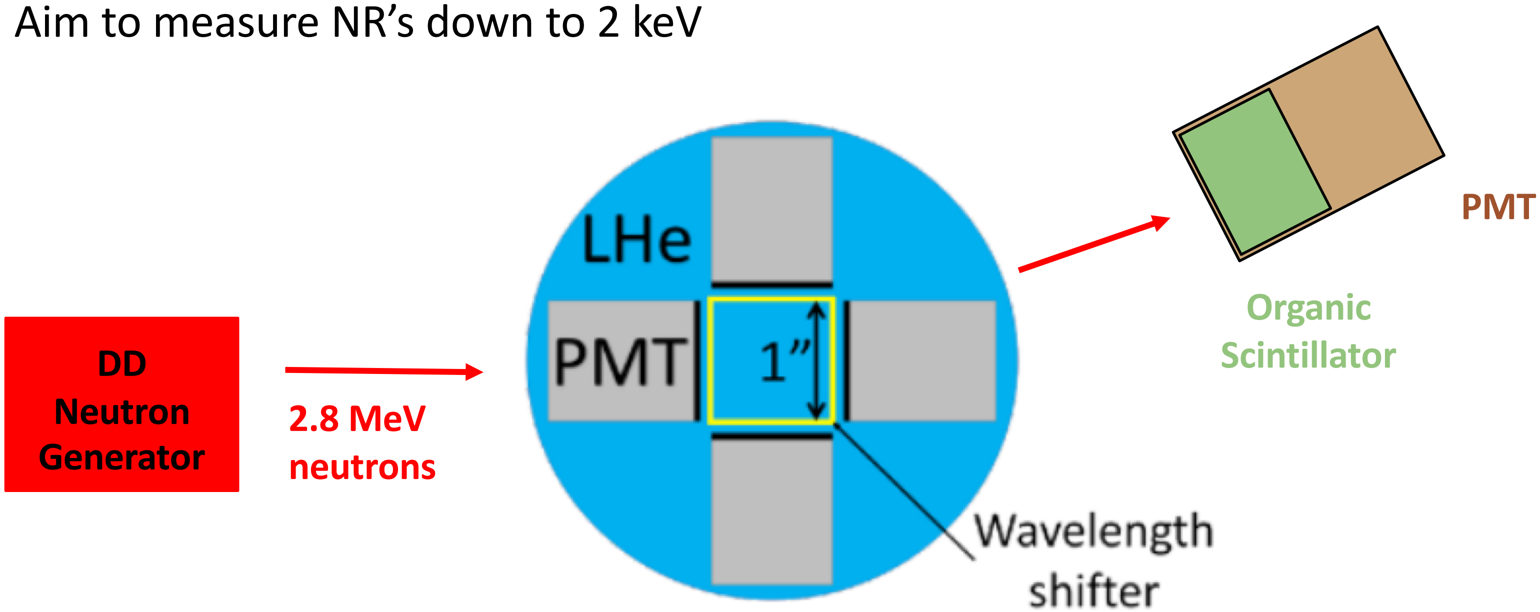


See: *C. McCabe. Phys. Rev. D 96, 043010 (2017).*
C. Kouvaris and J. Pradler. Phys. Rev. Lett. 118, 031803 (2017)
K. Schutz and K. M. Zurek. Phys. Rev. Lett. 117, 121302 (2016)

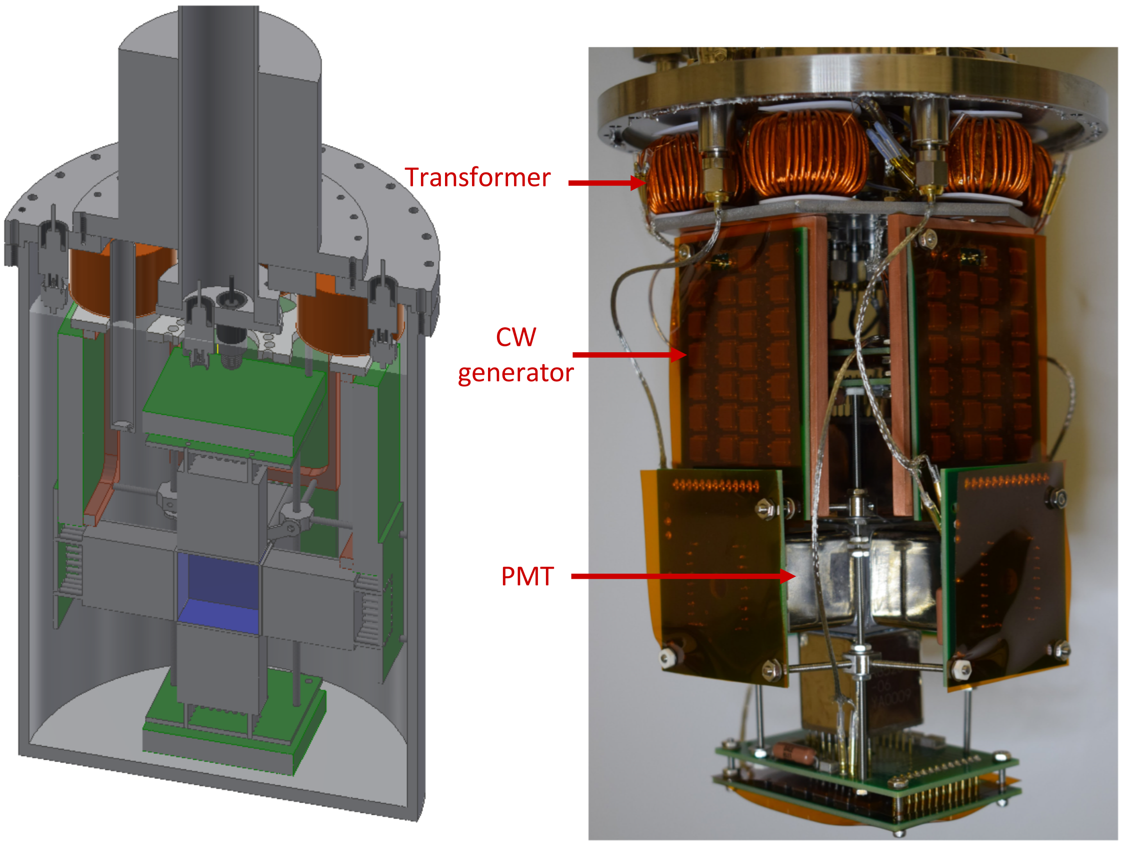


Measurement of Nuclear Recoil Light Yield in Superfluid ^{4}He

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



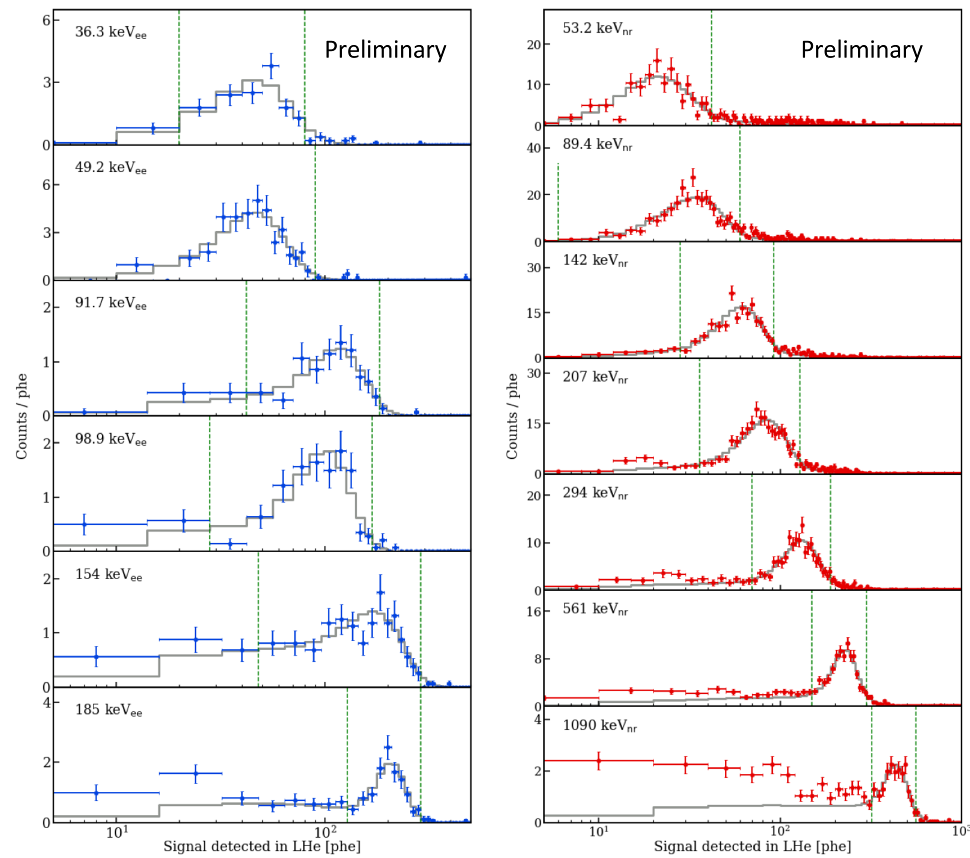
Light yield measurement of superfluid He-4



- ➢ 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}

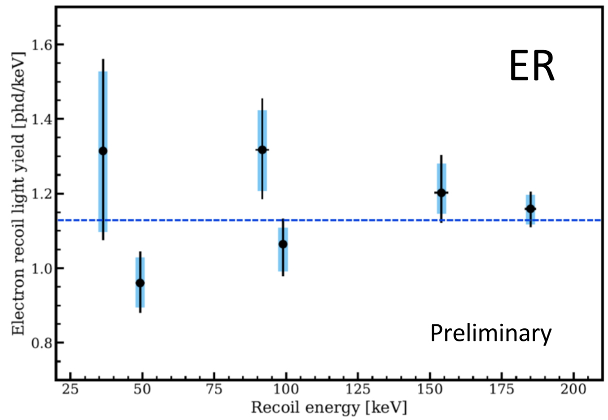
Light yield measurement of superfluid He-4

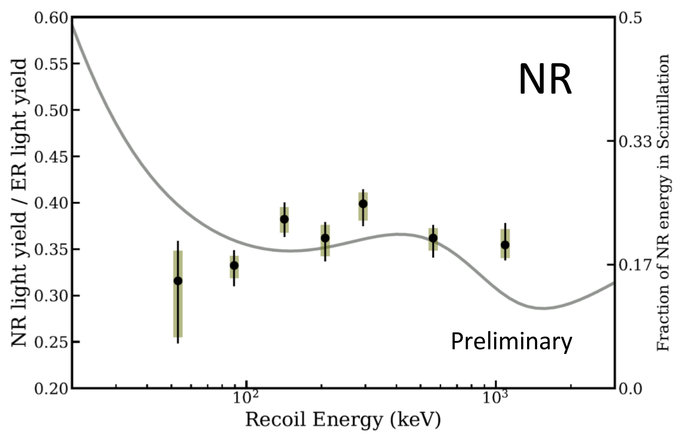
- Data selection cuts
  - Time of flight
  - Pulse shape discrimination (LS detector)
  - Deposit Energy (NaI detector)



- Fit data with MC sims

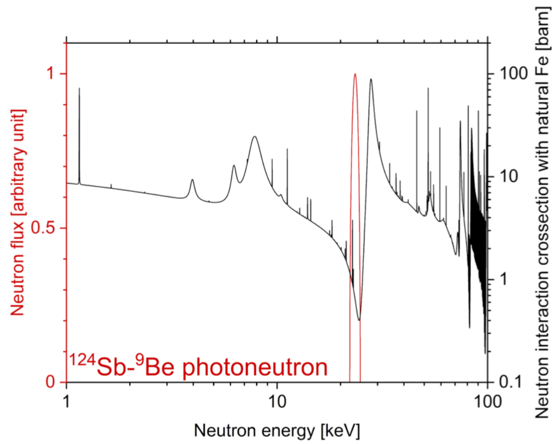
Light yield measurement of superfluid He-4

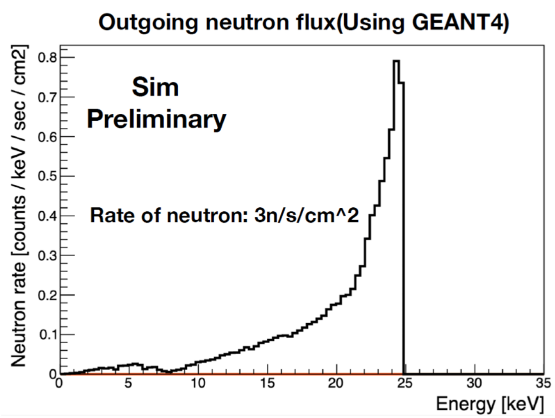


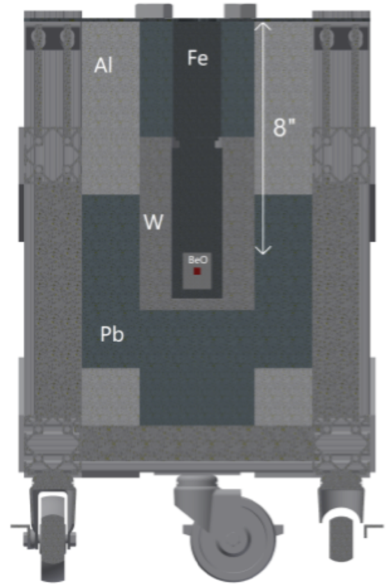


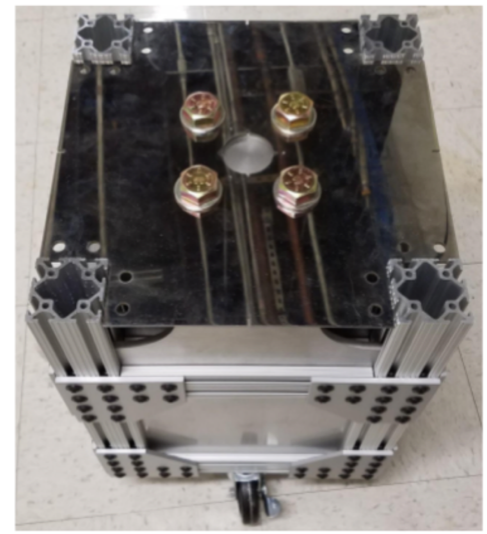
- First measurement of LHe scintillation in tens of keV. Publication draft nearly complete.
- ER yield relatively flat (as expected)
- NR yield agrees with pre-defined model
- Working on lower energy (keV) measurements
  - ER: Compton scattering from Co-57 source
  - NR: SbBe with iron filter

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

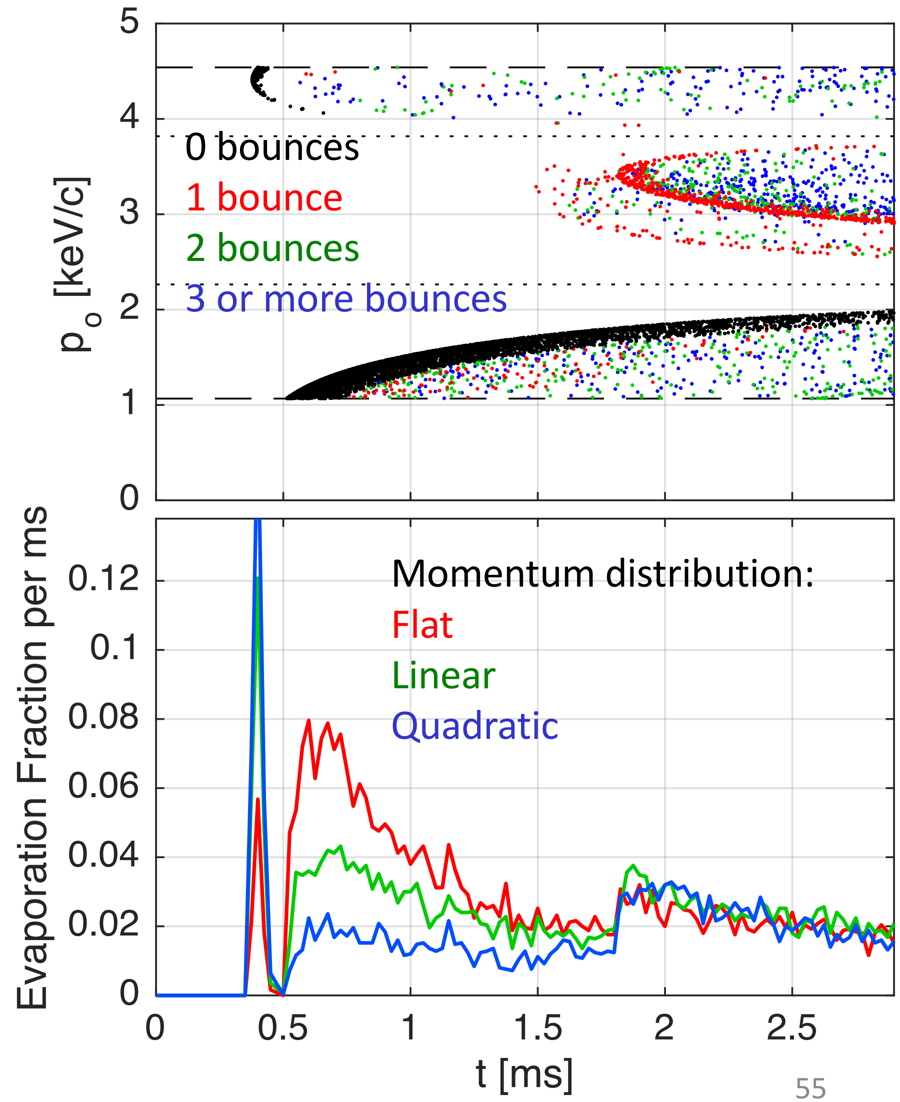
Discrimination without electronic excitations?

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

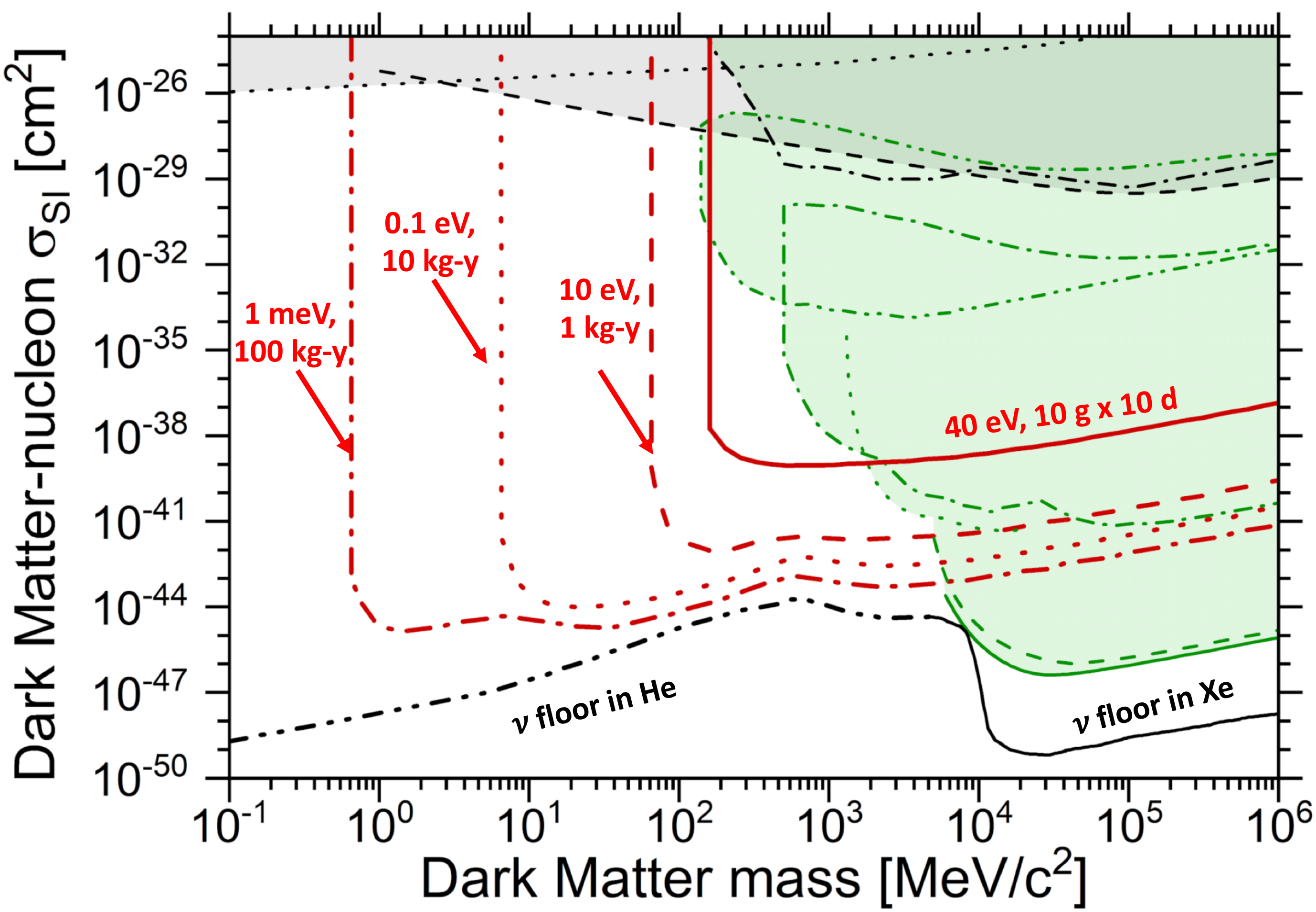
How to get particle identification without electronic excitations?

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

Pulse-shape discrimination looks plausible!



Projected Sensitivity



Summary

- TESSERACT is developing different targets for DM search.
- DM targets include polar crystals (SPICE) and superfluid helium (HeRALD)
- R&D is just beginning on TES, athermal phonon sensors, coupling these to multiple targets, and calibration. R&D will ramp down by 2023
- First R&D results on superfluid helium light yield, SbBe neutron beam.
- In parallel, TESSERACT design, engineering, and project management is ramping up, should end pre-project phase by 2024. Project would begin in 2025.