Probing Sub-GeV Dark Matter with Superfluid Helium-4

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UC Berkeley Physics 290E

Outline

1. Dark Matter and Direct Detection
2. Proposed ^{4}He Detector
3. Backgrounds
4. Backgrounds and Projected Sensitivity

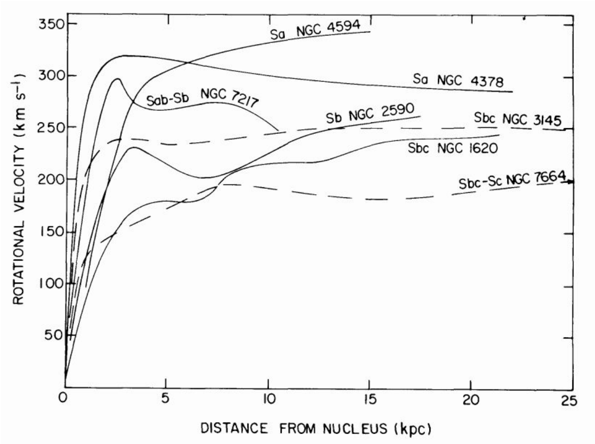
Dark Matter

- Vast evidence for non-luminous **dark matter** in the universe
- Strong impact on astrophysics and cosmology

Bullet Cluster

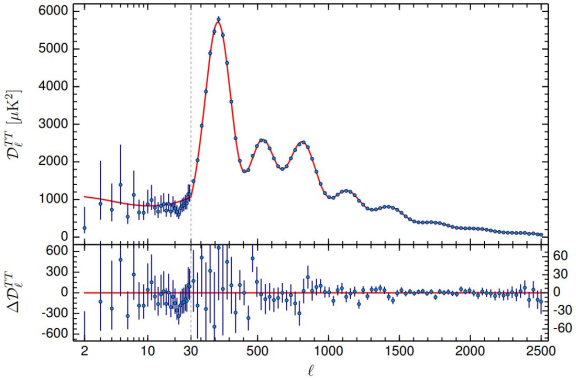
X-ray: NASA/CXC/CfA/ M. Markevitch et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al.
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.

Galactic Rotation Curves



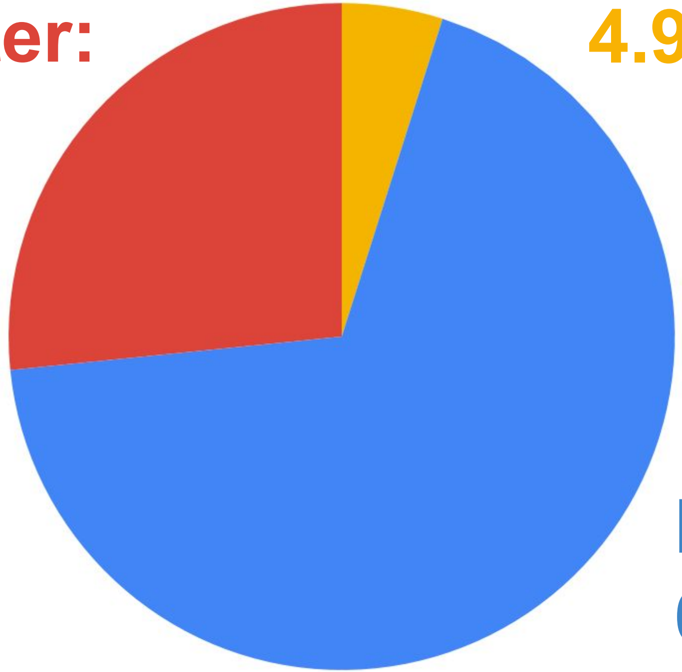
Rubin et al. Astrophys. J. 225:L107-L111 (1978).

Cosmic Microwave Background



Planck Collaboration. A&A 594, A13 (2016).

Composition of the Universe



- Thermal production in early universe
- Relics remain today, via some mechanism (often assumed freeze-out)

Source: Planck Collaboration. A&A 594, A13 (2016).

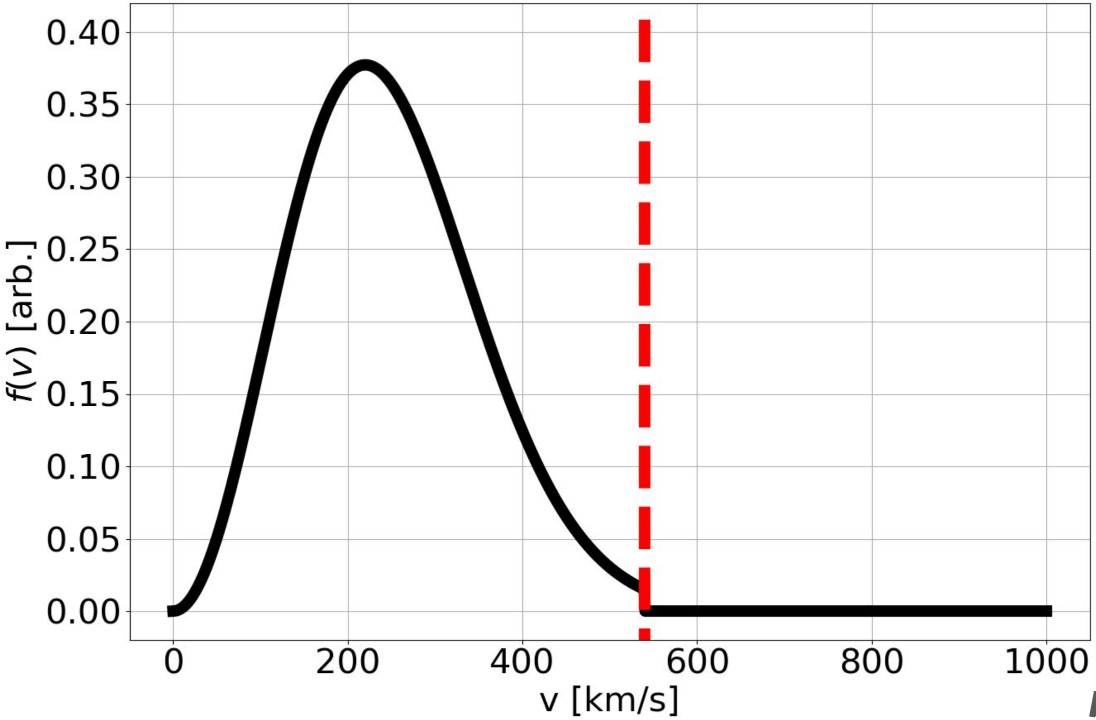
Dark Matter in our Galaxy

- Galactic "halo" of dark matter: approximately Maxwell-Boltzmann distribution

  v_0 = 220 km/s

  Cutoff v_{escape} = 540 km/s

- ρ_{DM} = 0.3 GeV/cm^3



Dark Matter as a Particle

- Particle nature of dark matter? Interactions with normal matter?
- Requires physics beyond the Standard Model
- Popular candidate: Weakly Interacting Massive Particle (WIMP)
  - Massive particle at the electroweak scale (GeV - TeV)
  - Many theory candidates, e.g. LSP in SUSY
  - “WIMP miracle”: current DM density explained by weak-scale mass and cross-section

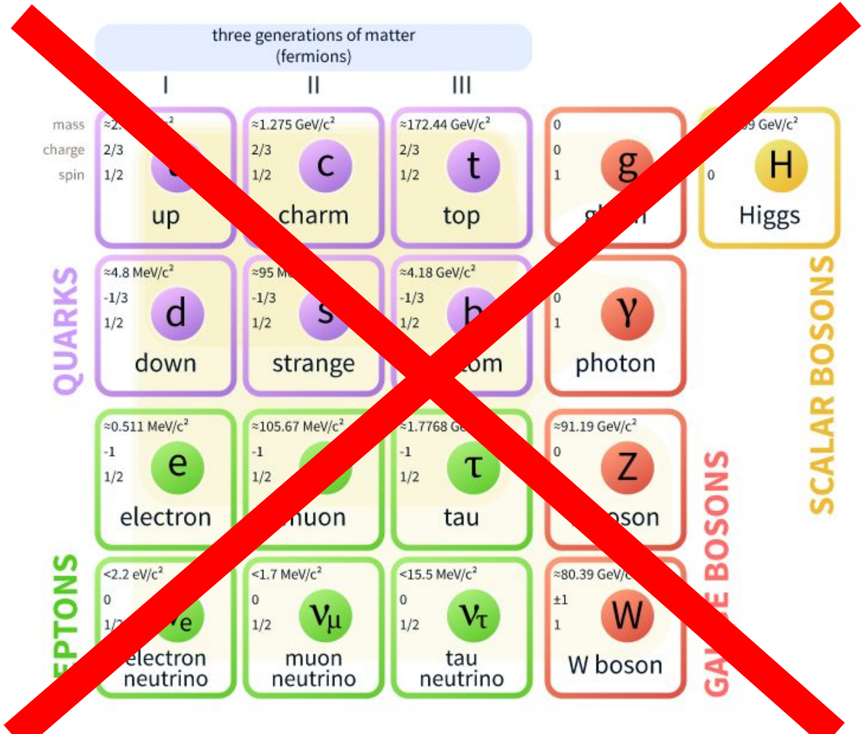
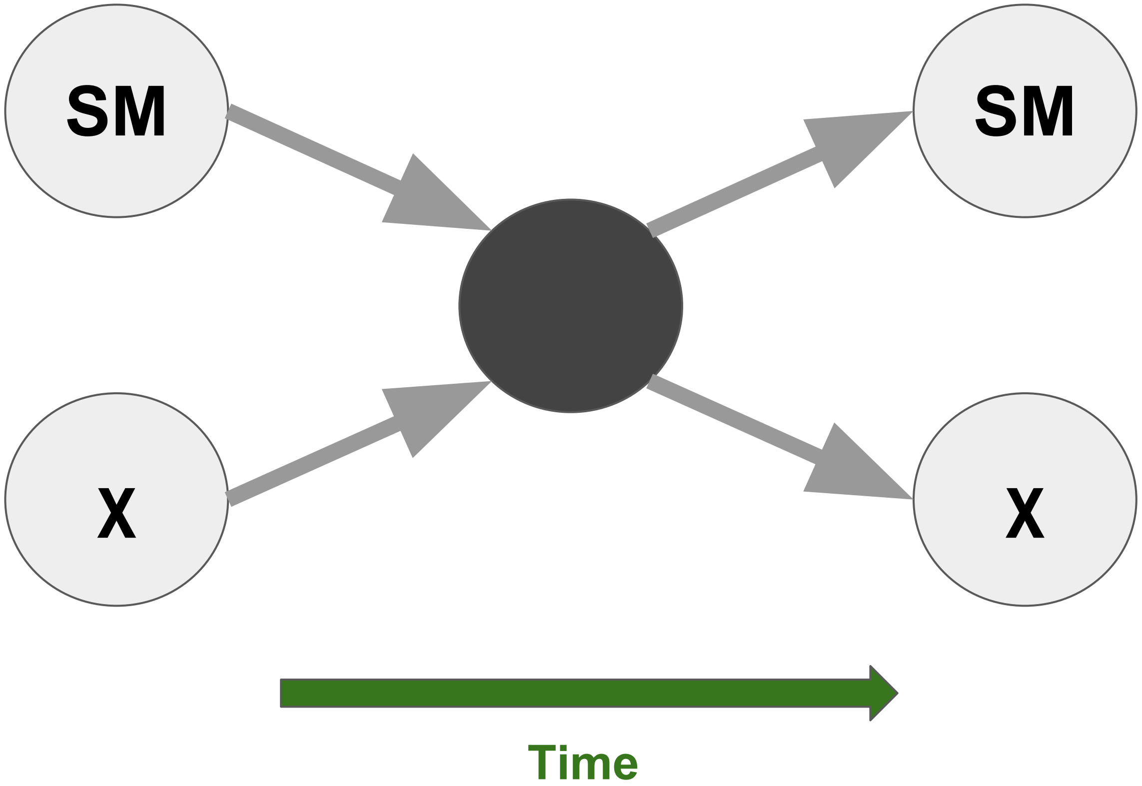


Image from Wikipedia:Standard Model

Dark Matter Direct Detection



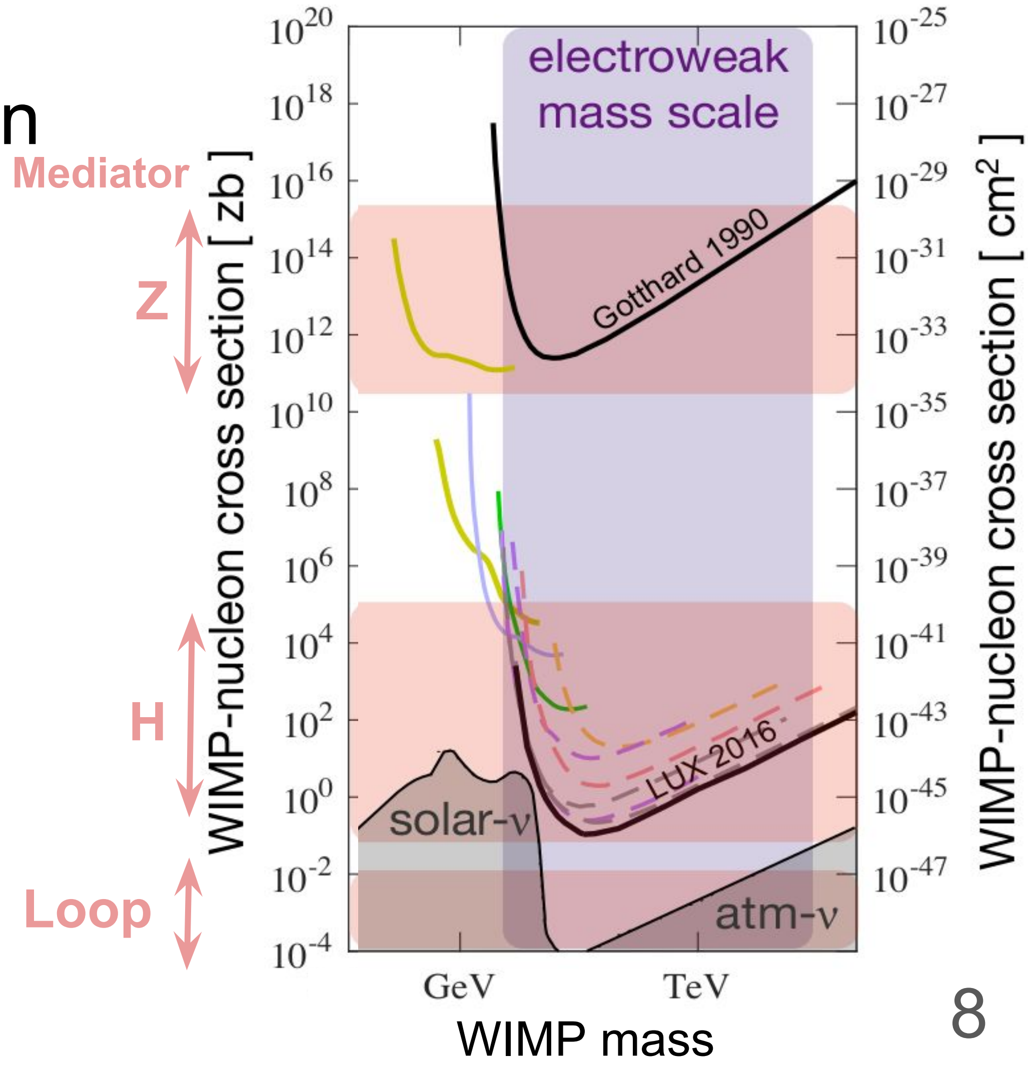
Status of Direct Detection

Decades-long campaign to probe WIMP dark matter (Lee-Weinberg limit: m > 2 GeV)

Issues:

1) Approaching the “neutrino floor”, a challenging background to overcome

2) Assumption of electroweak-scale physics--worth keeping?



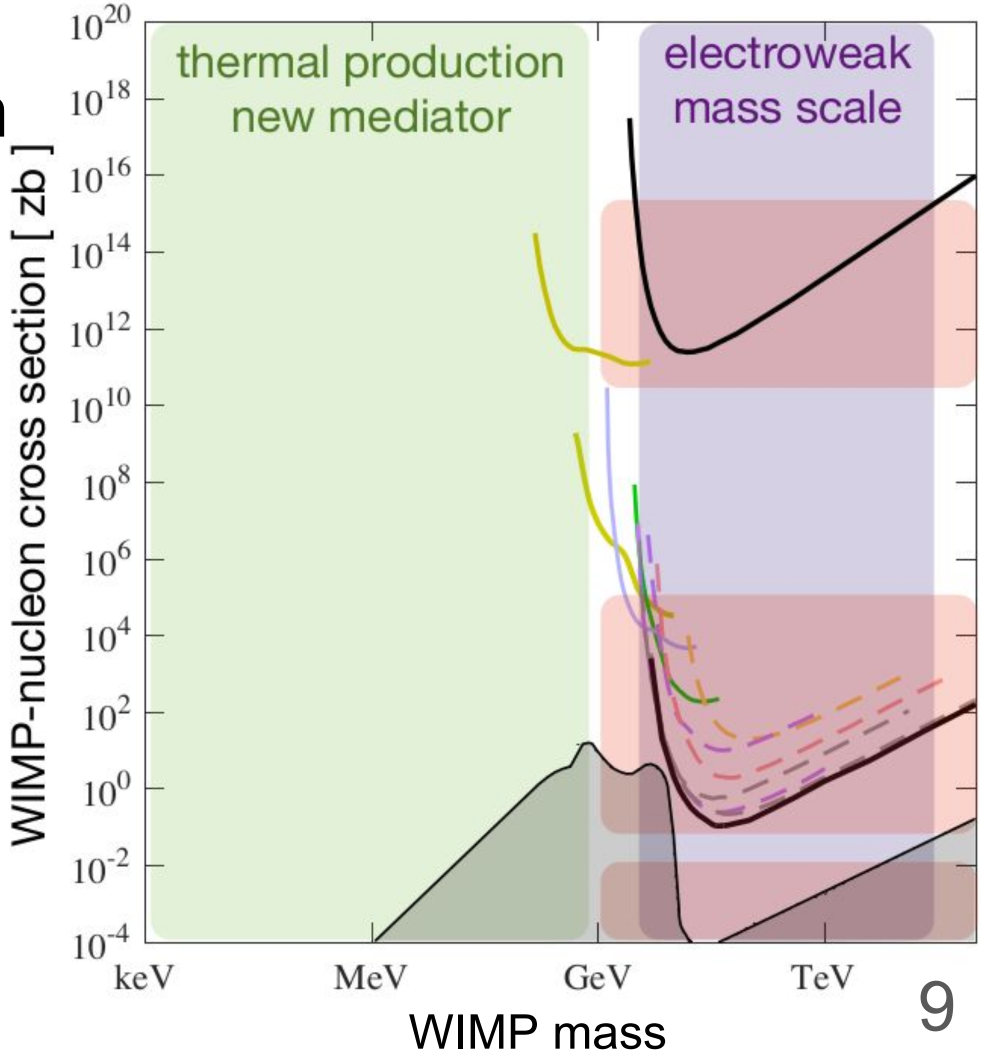
Status of Direct Detection

Solution: expand the field!

Keep assumption of thermal production; allows DM masses down to few keV

Loosen restrictions on mediator

What target allows us to explore these masses?

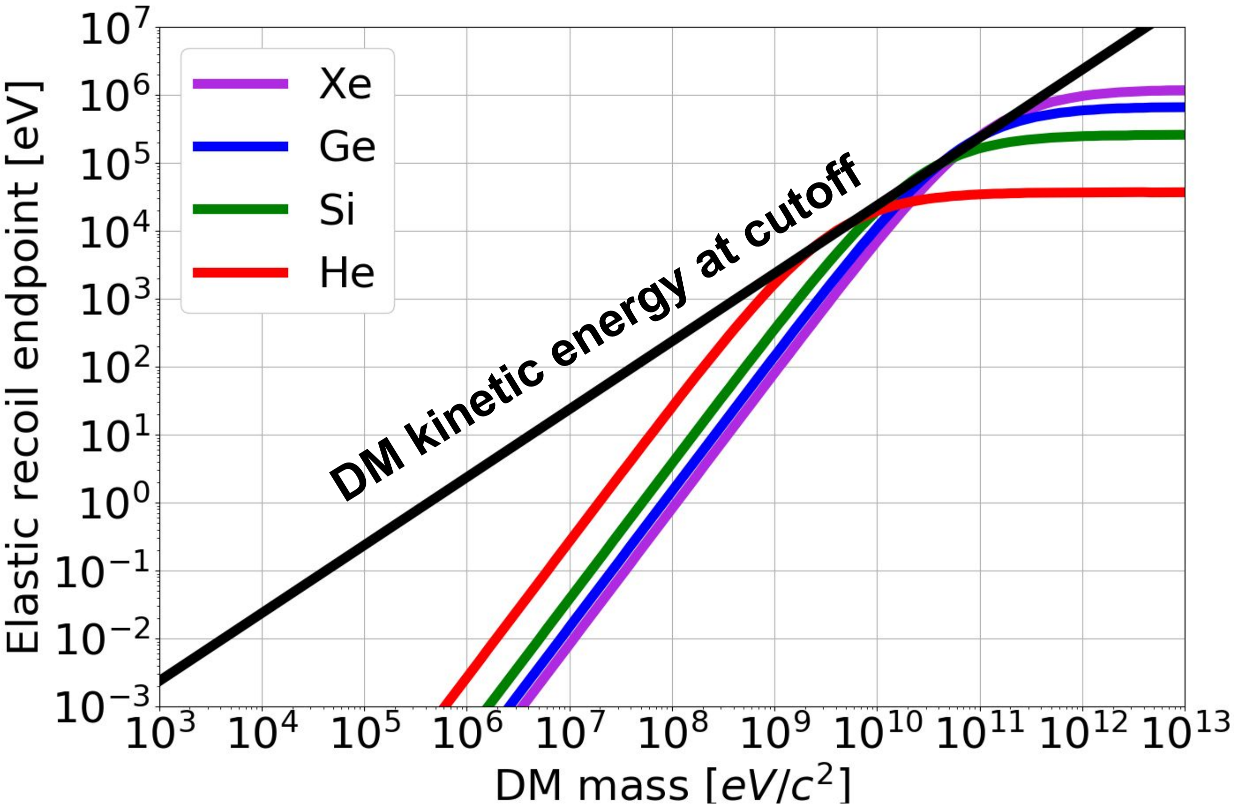


Dark Matter Kinematics

Max kinetic energy carried by dark matter is
$KE_{max} = ½\, m_{DM}\, v_{escape}^2$

Transferred inefficiently to target unless $m_{DM} \approx m_{target}$

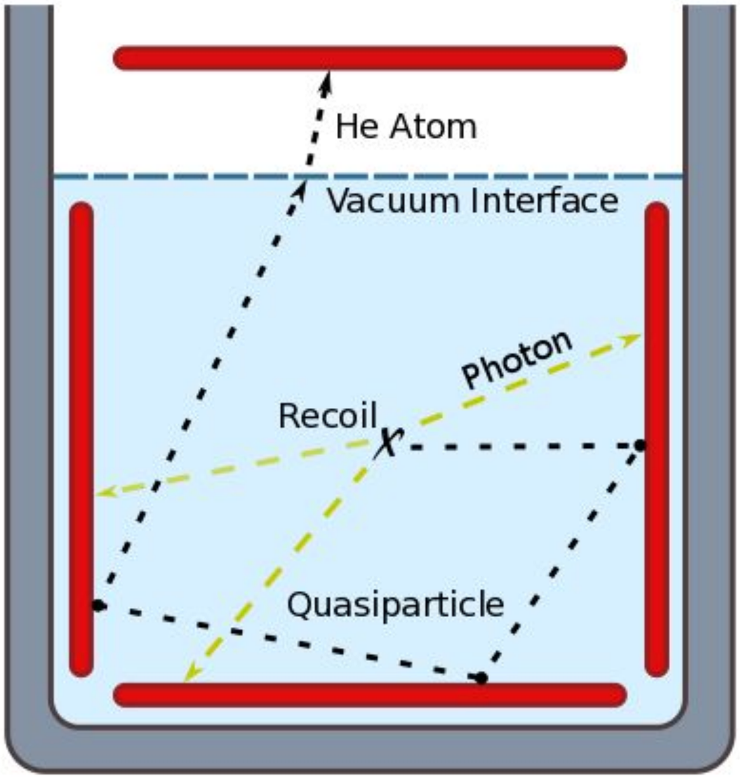
To probe MeV-scale dark matter, we need:
1) Light target
2) Ability to access meV recoil energies



HELIUM!

Outline

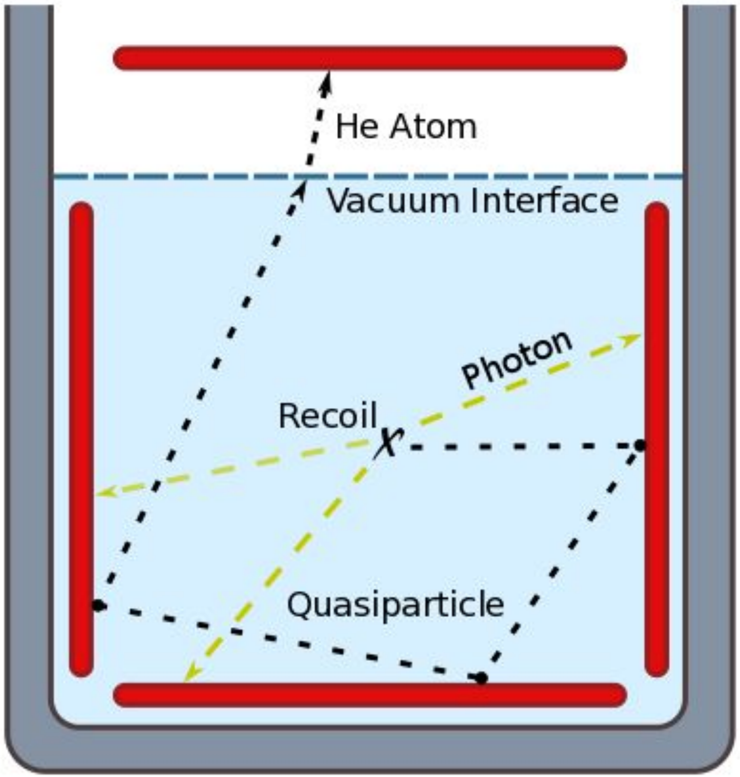
Superfluid Helium as a Dark Matter Target



He-4 meets all the requirements plus:

- Cheap
- Easy to purify
- Intrinsically radiopure
- Remains liquid/superfluid down to absolute zero
- Monolithic, scalable
- Calorimetry for signal readout

Proposed Detector



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

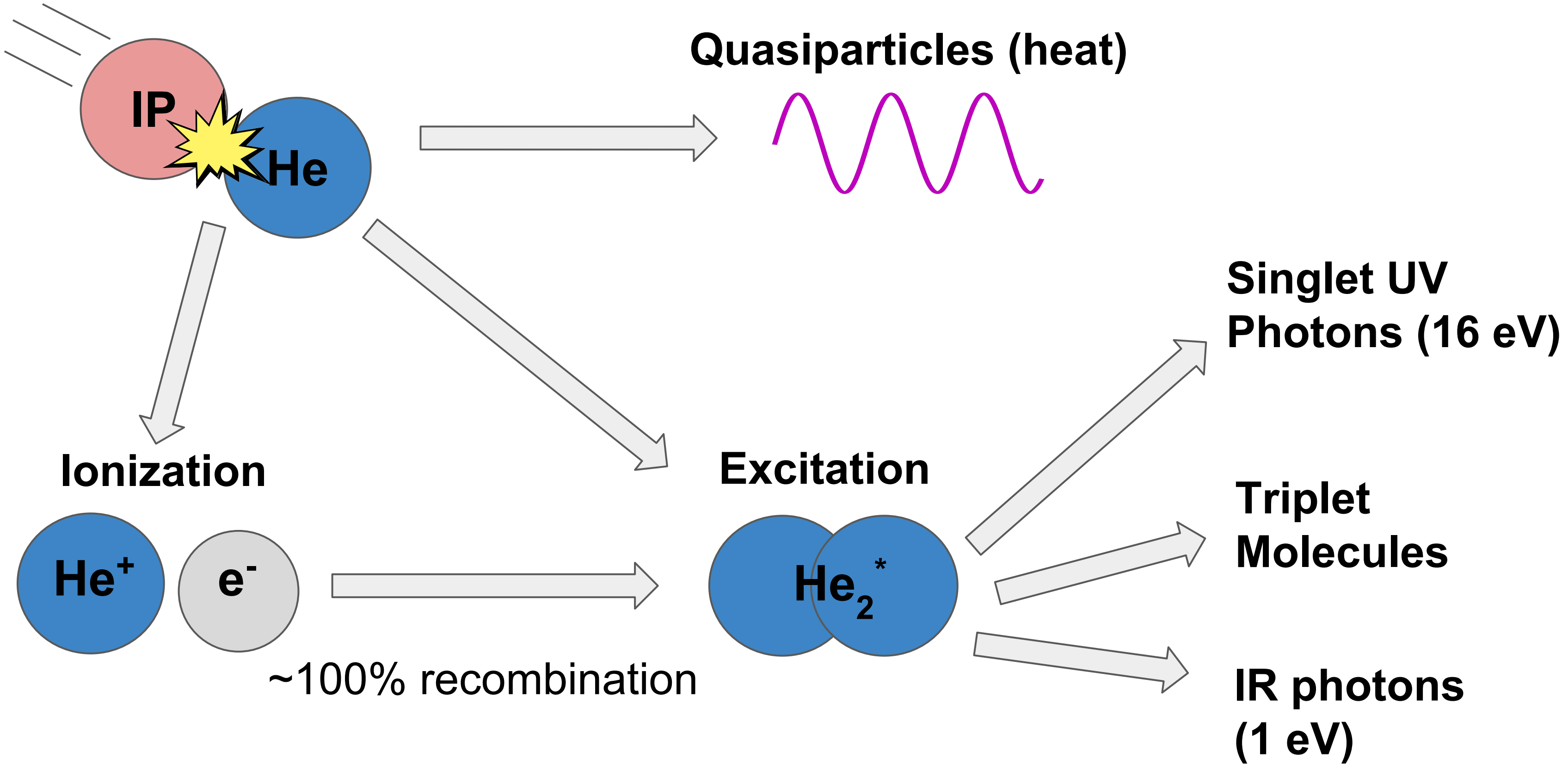
5 transition-edge sensor (TES) arrays on walls, adjacent to helium

- Detect UV photons, triplet excimers, IR photons

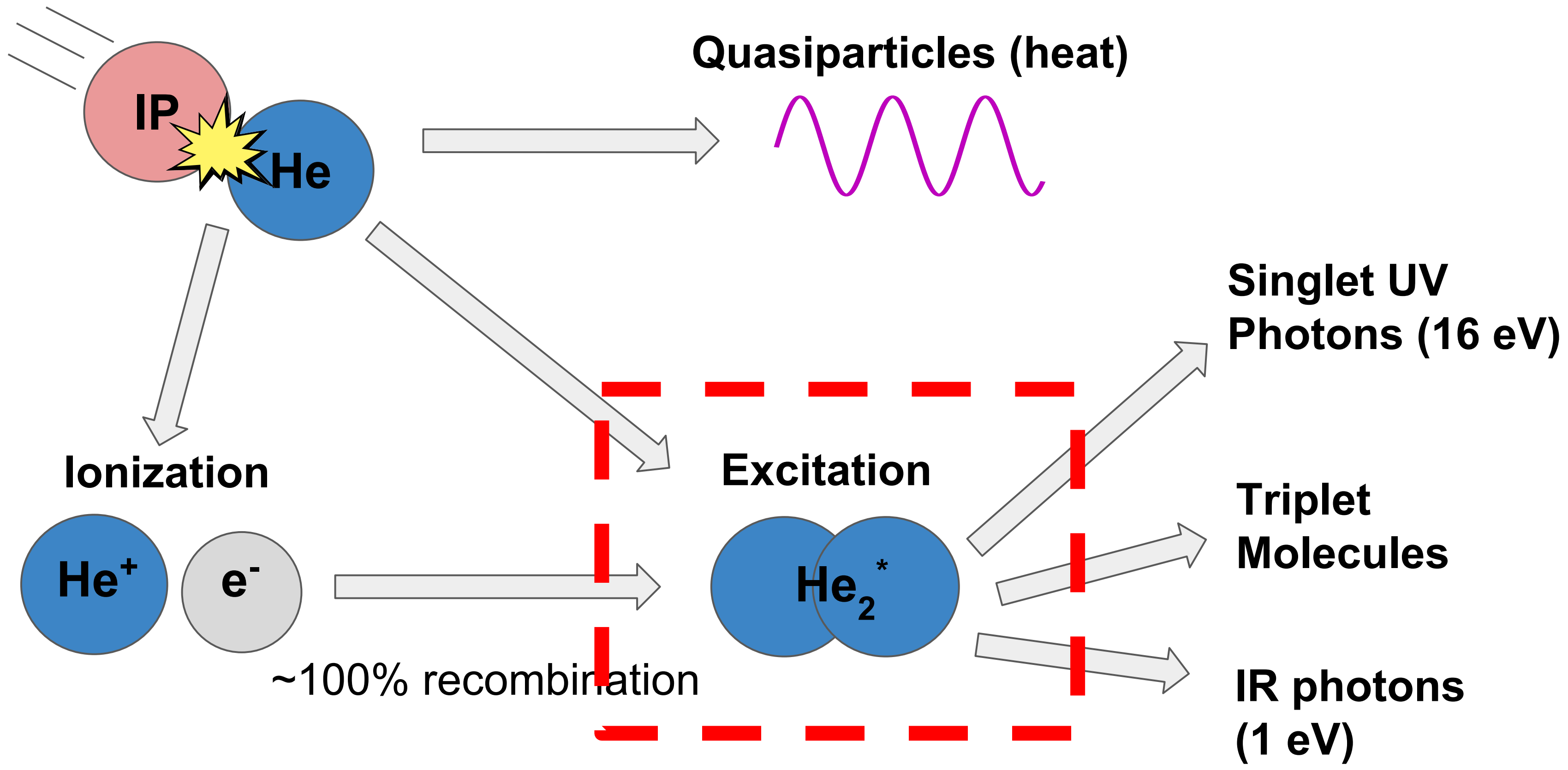
Vacuum layer between helium and 6th TES array

- Detect quasiparticles via quantum evaporation

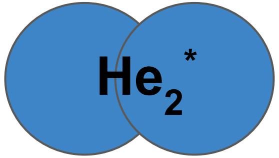
Recoils in Helium (generic incident particle IP)

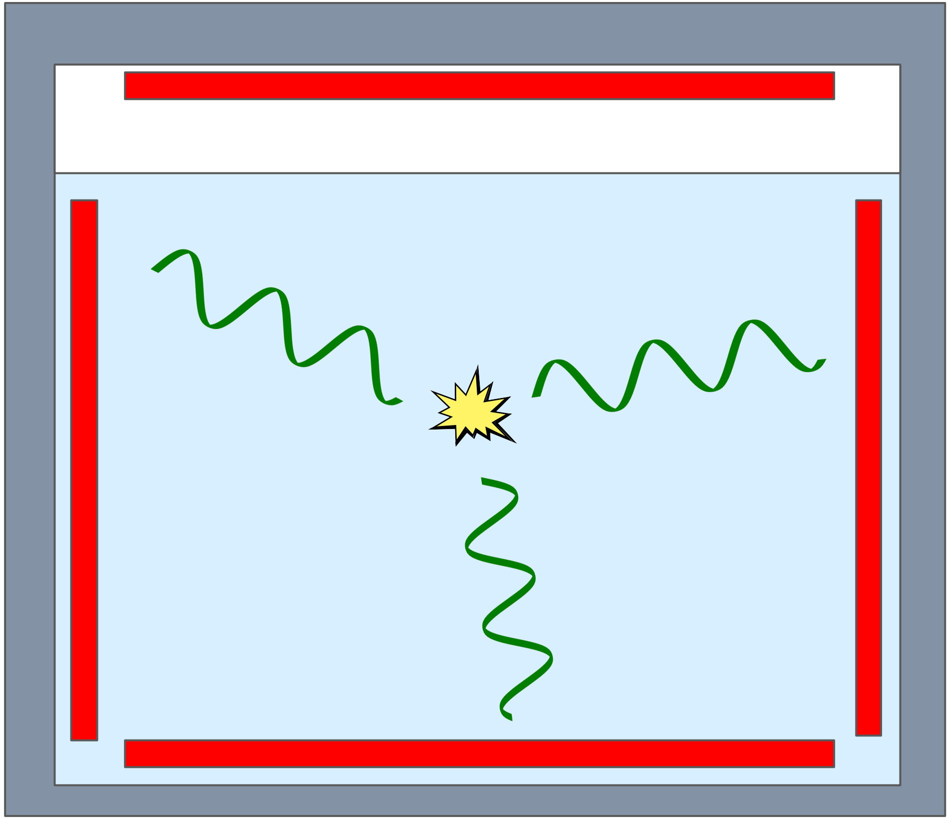


Recoils in Helium (generic incident particle IP)



Detecting Excimer Signal





Singlet decay

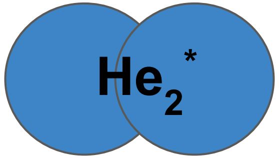
- Half-life of few ns
- 16 eV photon

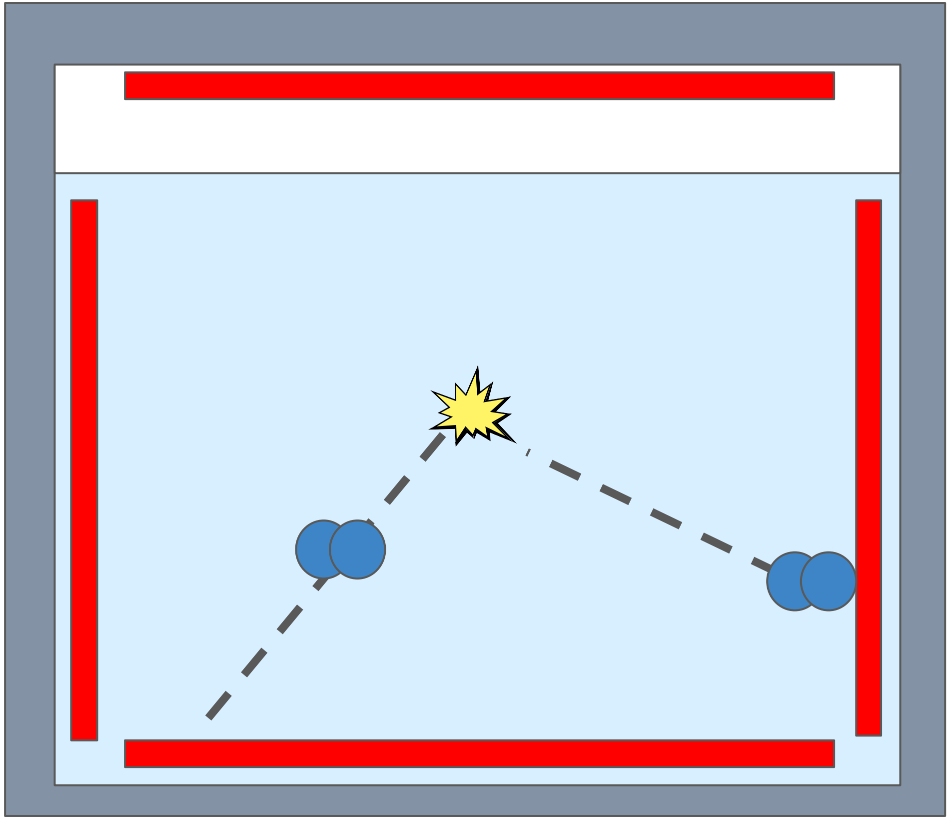
Hits detector walls on ns timescale

Detected directly by TES

Calorimetry possible because of large Kapitza resistance

Detecting Excimer Signal





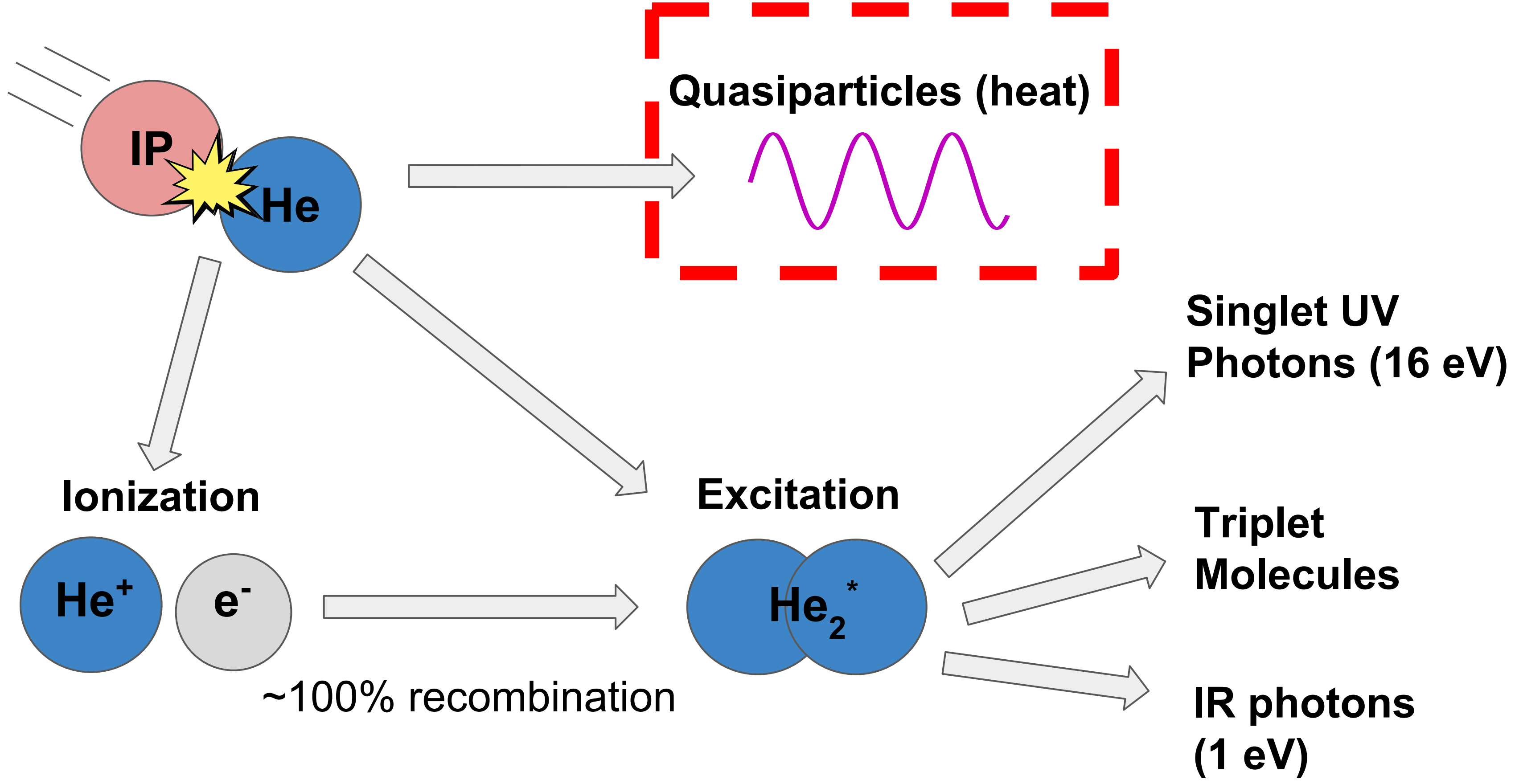
Triplet decay

- Half-life of 13 seconds
- 16 eV photon (but too slow for our detector)

Helium dimer molecule travels ballistically, detected by TES on few ms timescale

Also some IR from higher excitations, 1 eV

Recoils in Helium (generic incident particle IP)



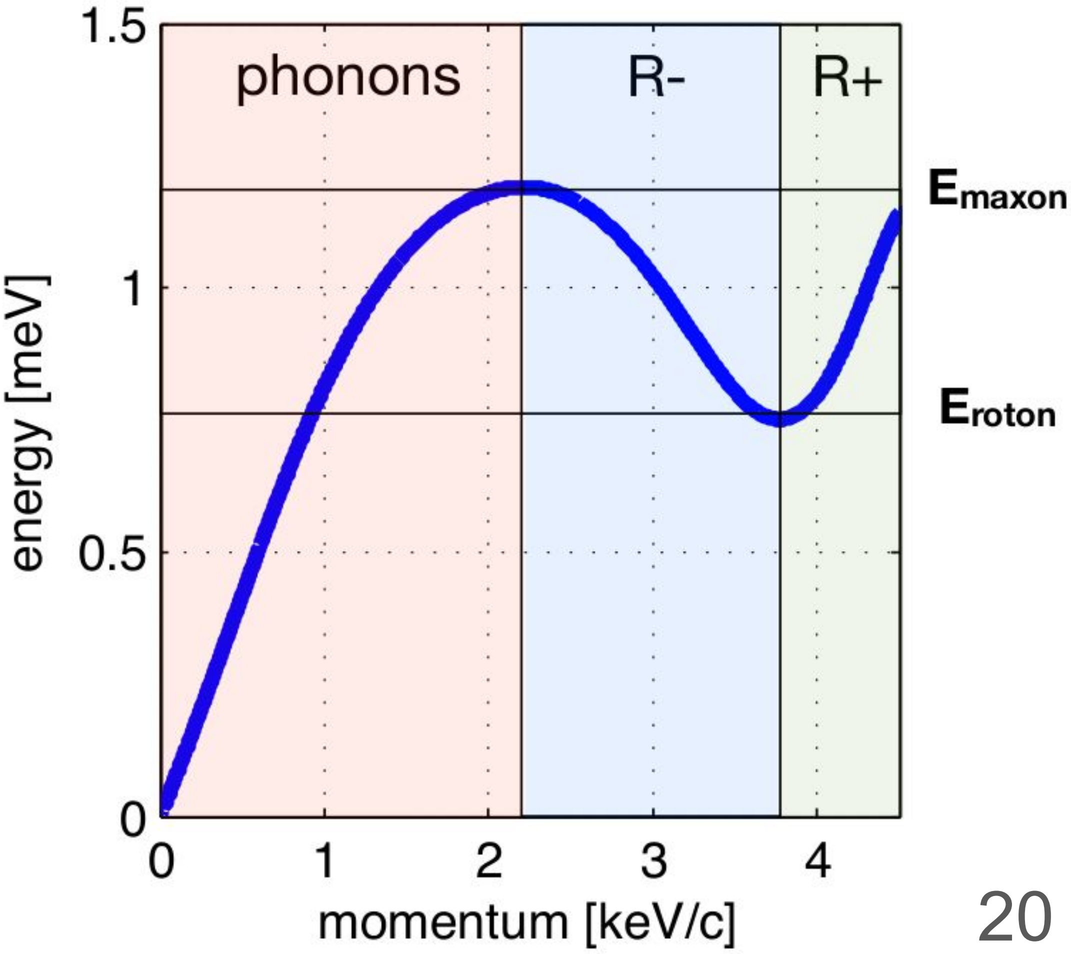
Quasiparticles in ^{4}He

Quasiparticles: collective excitations in superfluid helium

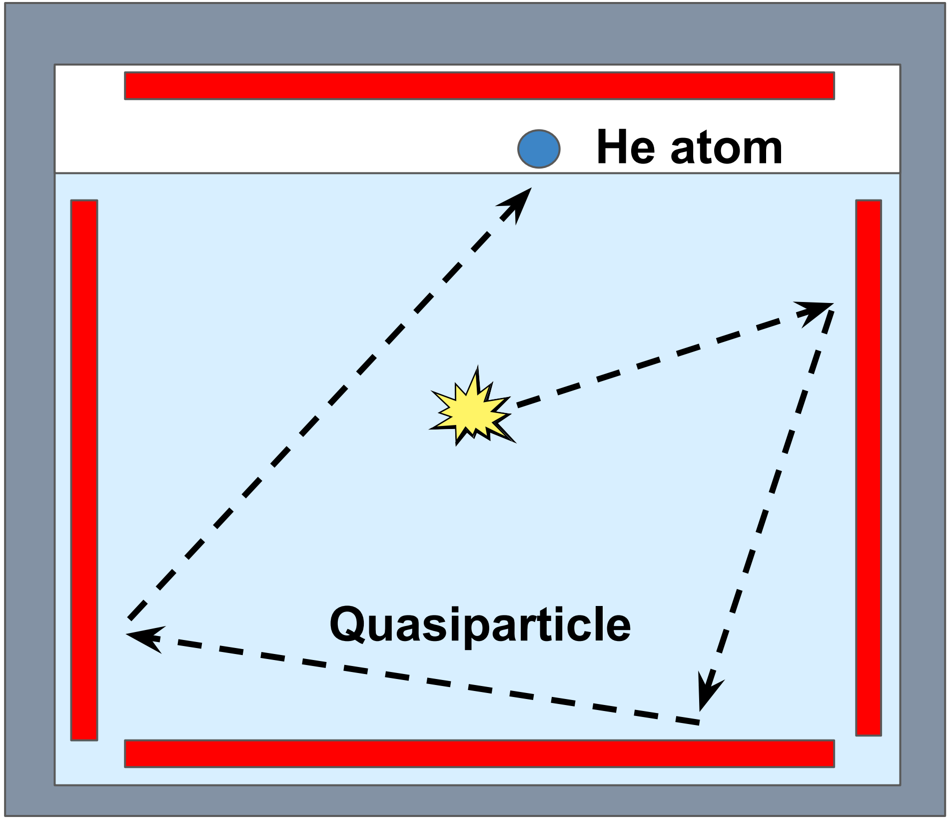
Long-lived

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

At interface, can transform from one type to another (i.e. **P** ↔ **R-** ↔ **R+**) if $E_{roton} < E_{quasiparticle} < E_{maxon}$



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 is suppressed by Kapitza resistance

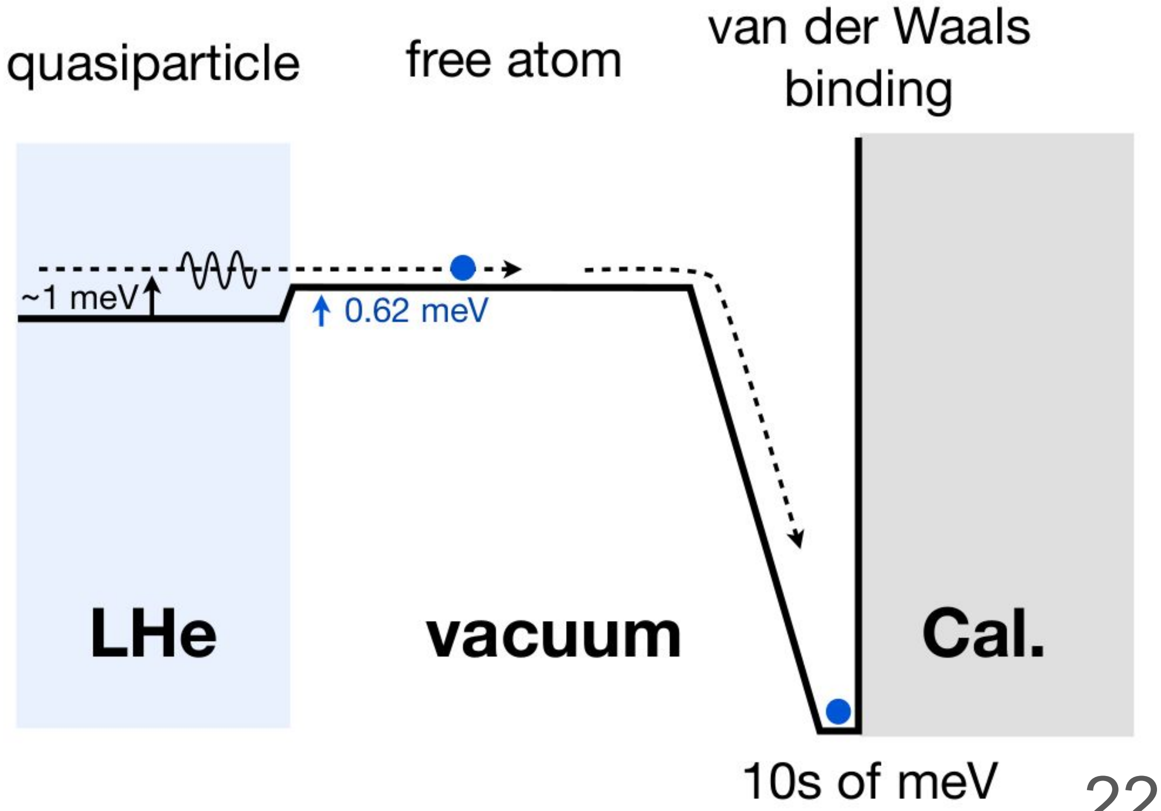
Quantum evaporation of a helium atom into vacuum, followed by energy deposit on top TES

Detecting Quasiparticle Signal

Binding energy between helium and solid will amplify signal

1 meV recoil energy → up to 40 meV detectable energy

Film burner to remove helium from calorimeter



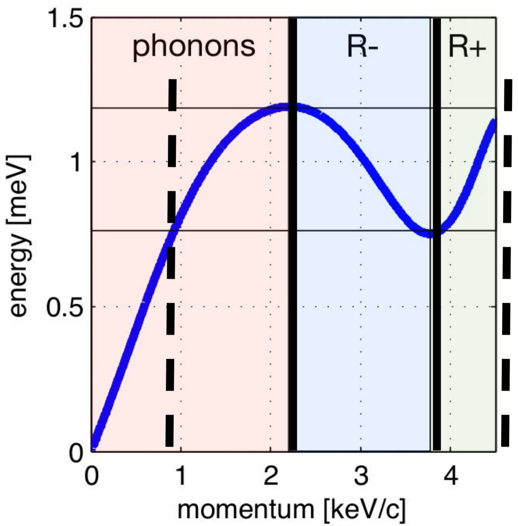
Outline

Quasiparticle Propagation

In ^{4}He bulk, quasiparticles move freely

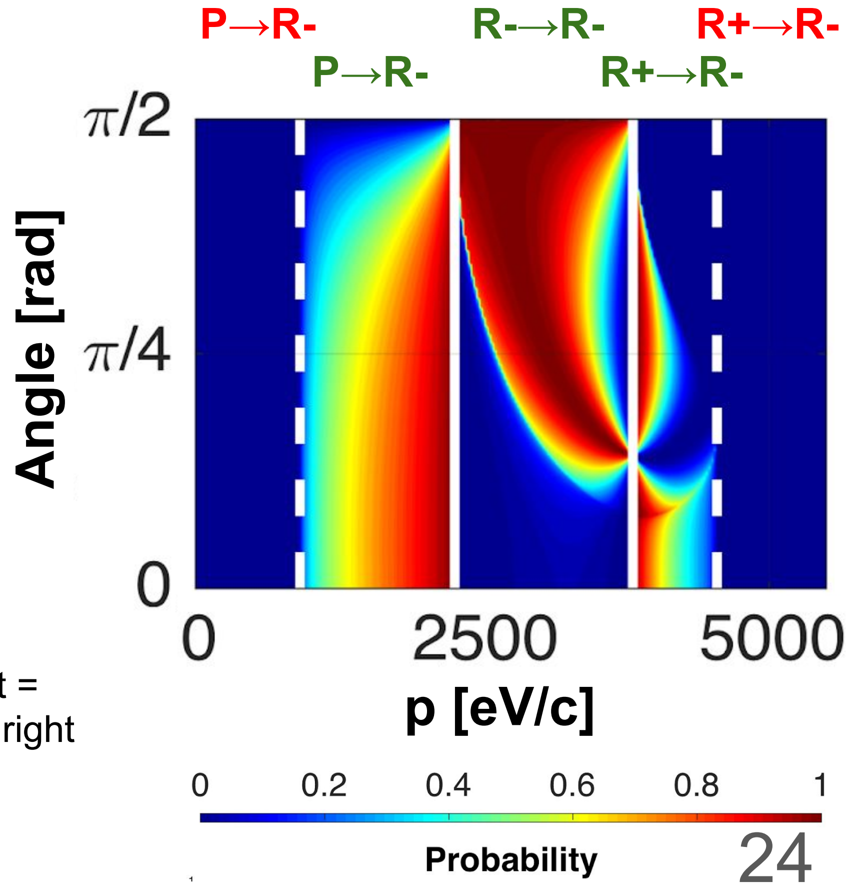
At interface, can be transmitted, reflected, or transformed (if E conserved)

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)

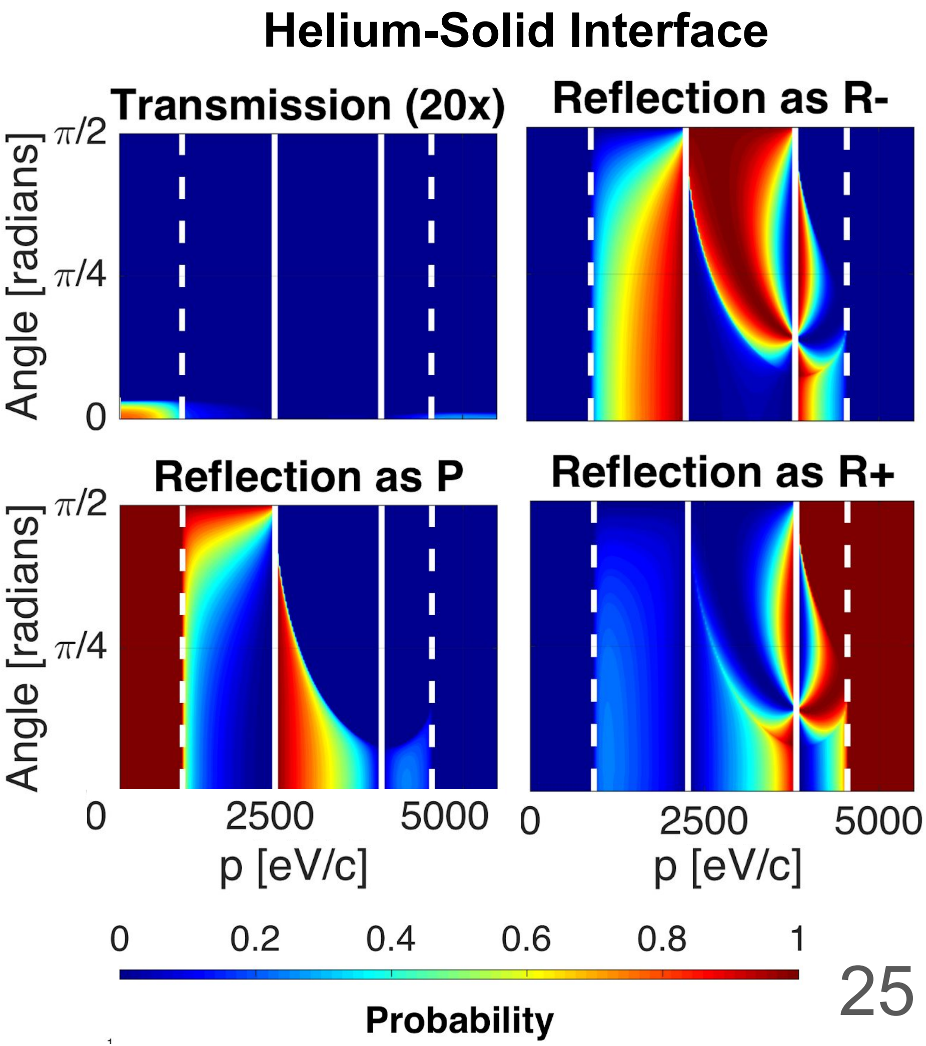


Quasiparticle Propagation

Simulated all reflection/transmission probabilities †

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

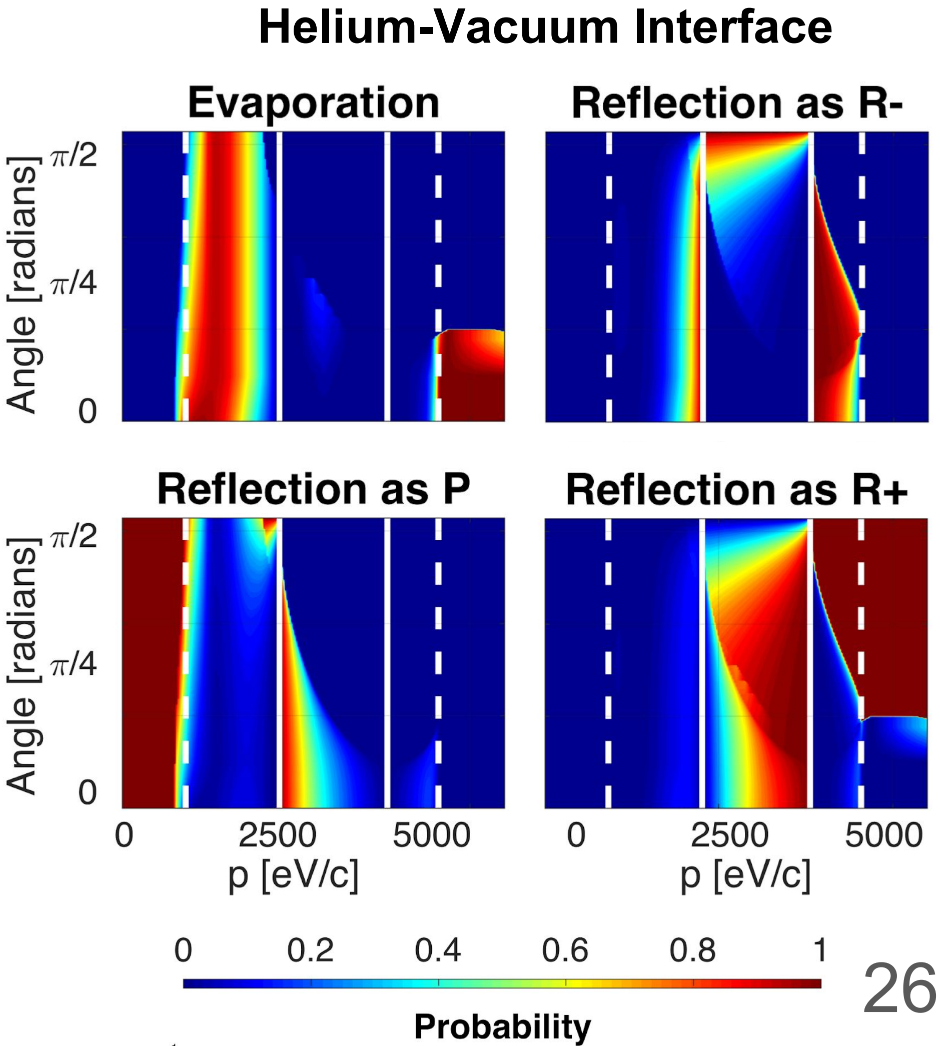
Reflection as same flavor most likely, but significant chance of changing flavor



† Probabilities based on calculations in *Phys. Rev. B* ***77****, 174510 (2008)*.

Quasiparticle Propagation

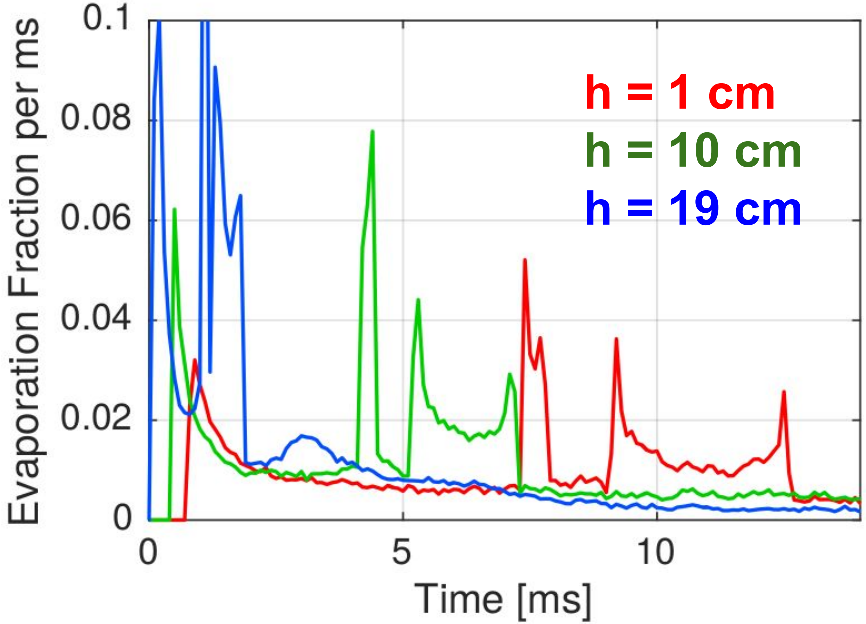
At helium-vacuum interface, transmission (quantum evaporation) is most likely for phonons



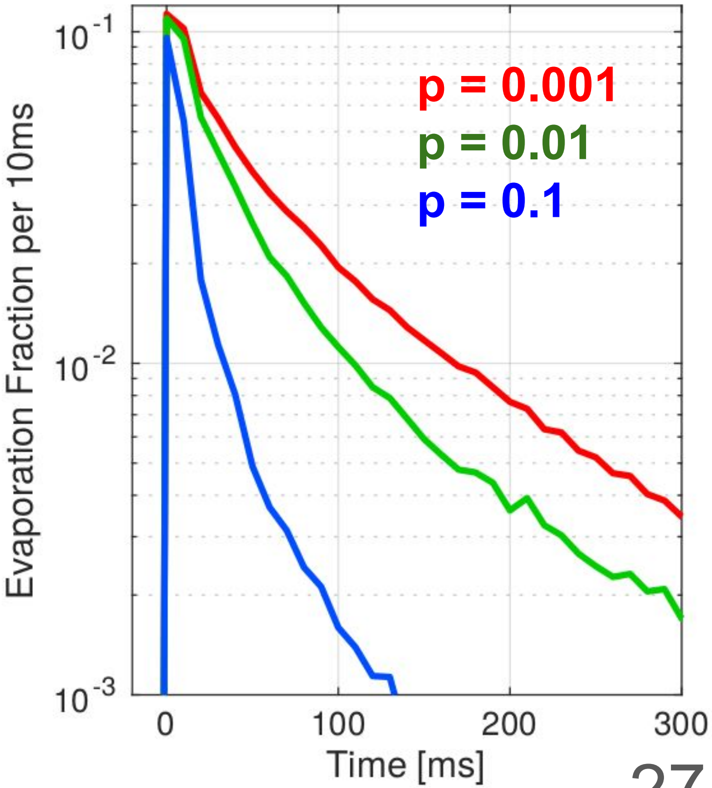
Quantum Evaporation

Simulated pulses from evaporation

Vary height of recoil (h = 20 cm at top of detector)



Vary quasiparticle loss probability

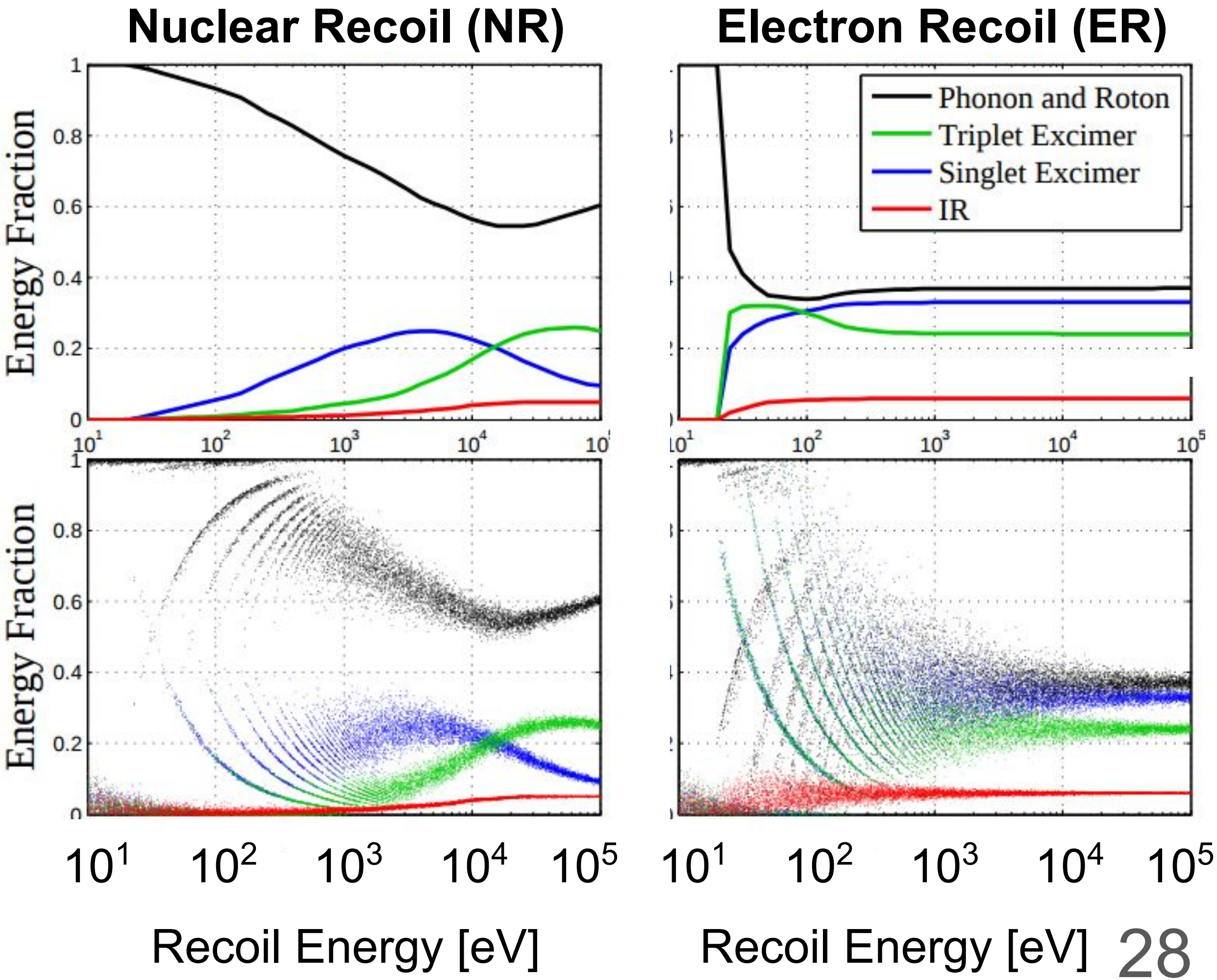


Energy Partition

Means

From G. Seidel, unpublished; Extrapolated below 100 eV

Poisson Fluctations



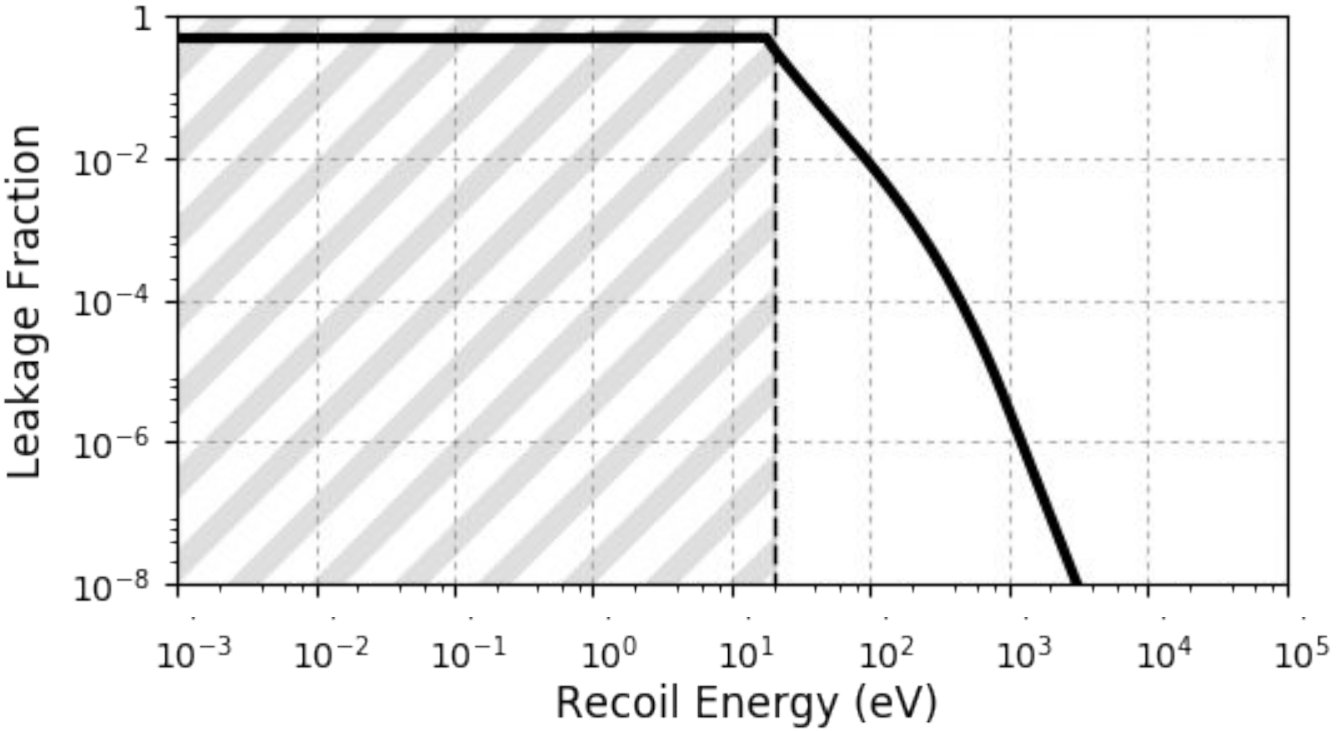
Discrimination

Signal is NR; backgrounds are dominated by ER

Discriminate between ER and NR by using ratio of energy in each channel

Cannot discriminate light/phonon ratio below 20 eV, but superb discrimination above 500 eV

ER acceptance at 50% NR acceptance



Outline

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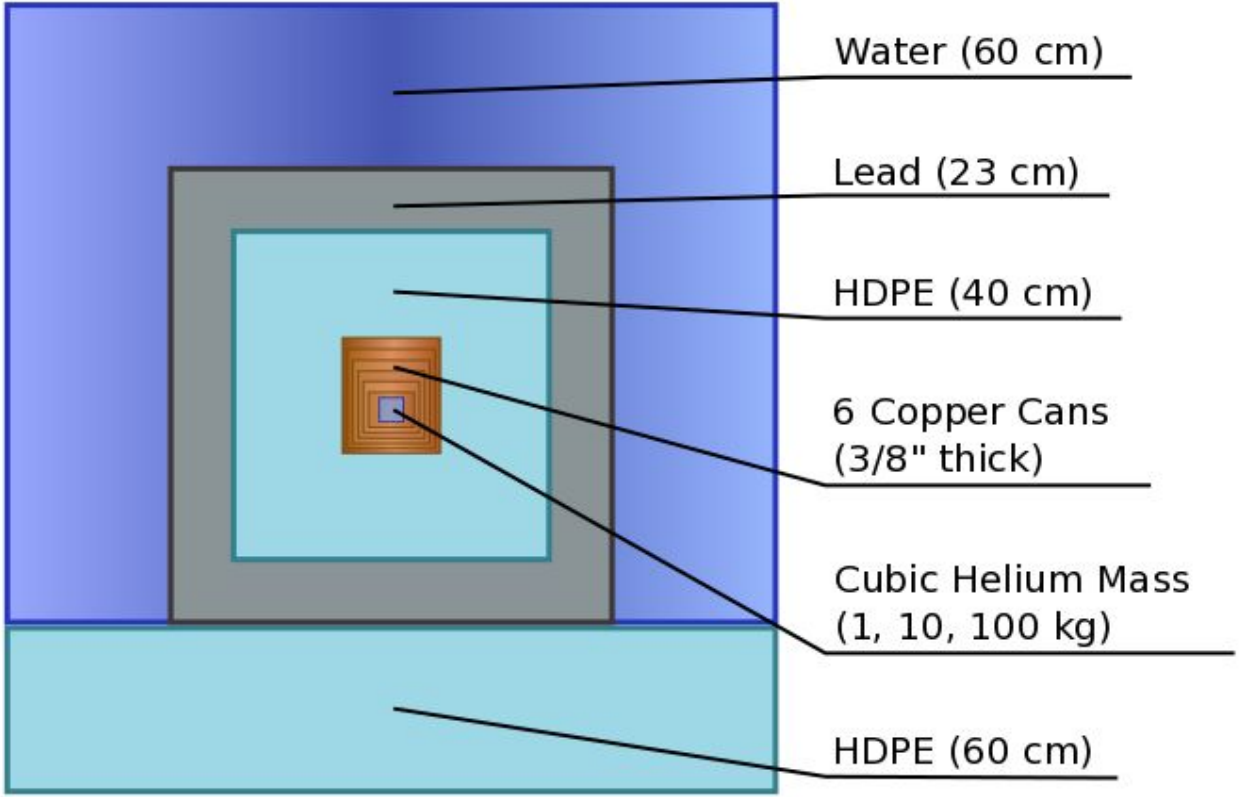
3. Simulations
4. Backgrounds and Projected Sensitivity

Backgrounds

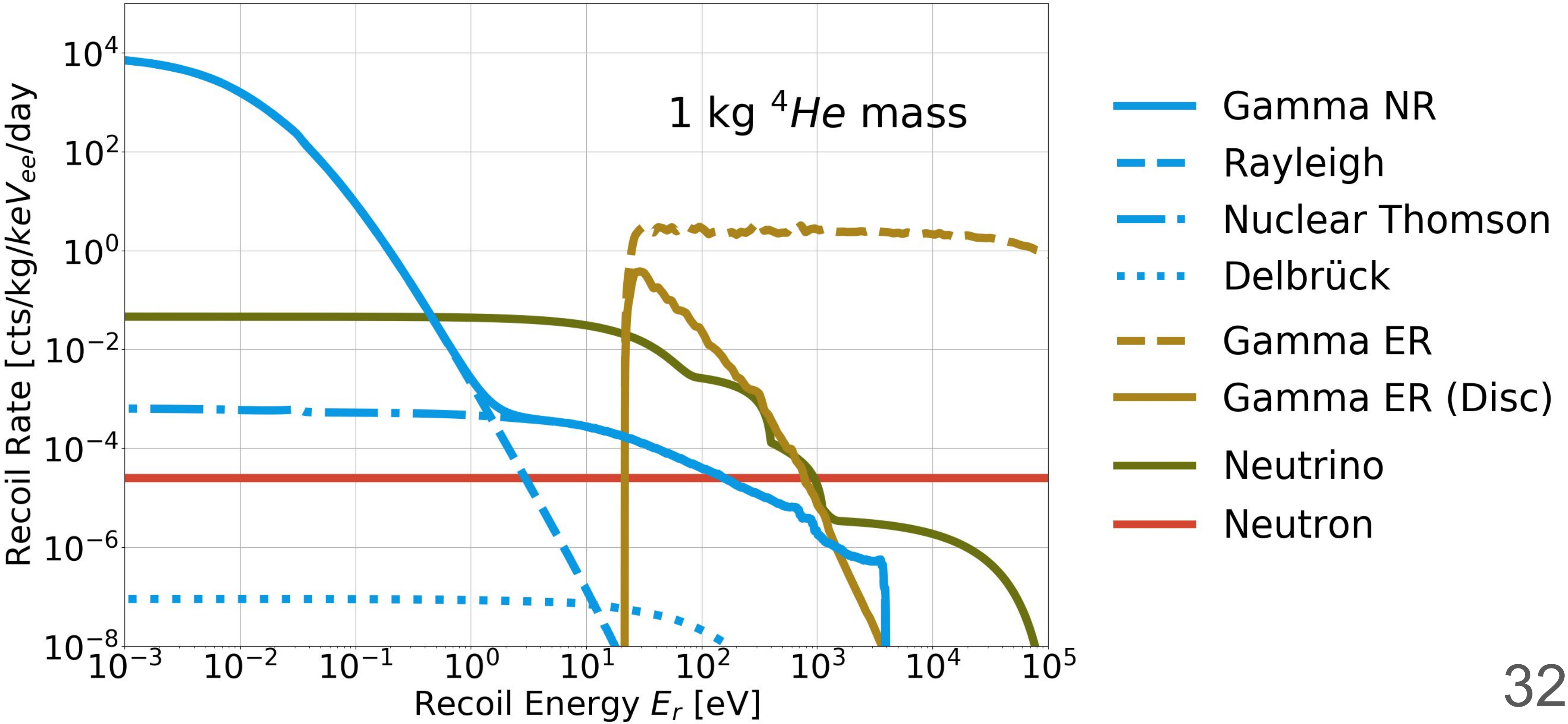
Shielding based on SuperCDMS SNOLAB projections †

Deep underground



† *Phys. Rev. D 95, 082002 (2017)*

Backgrounds



Projected Sensitivity

Red: Projected sensitivity of superfluid ^{4}He detector

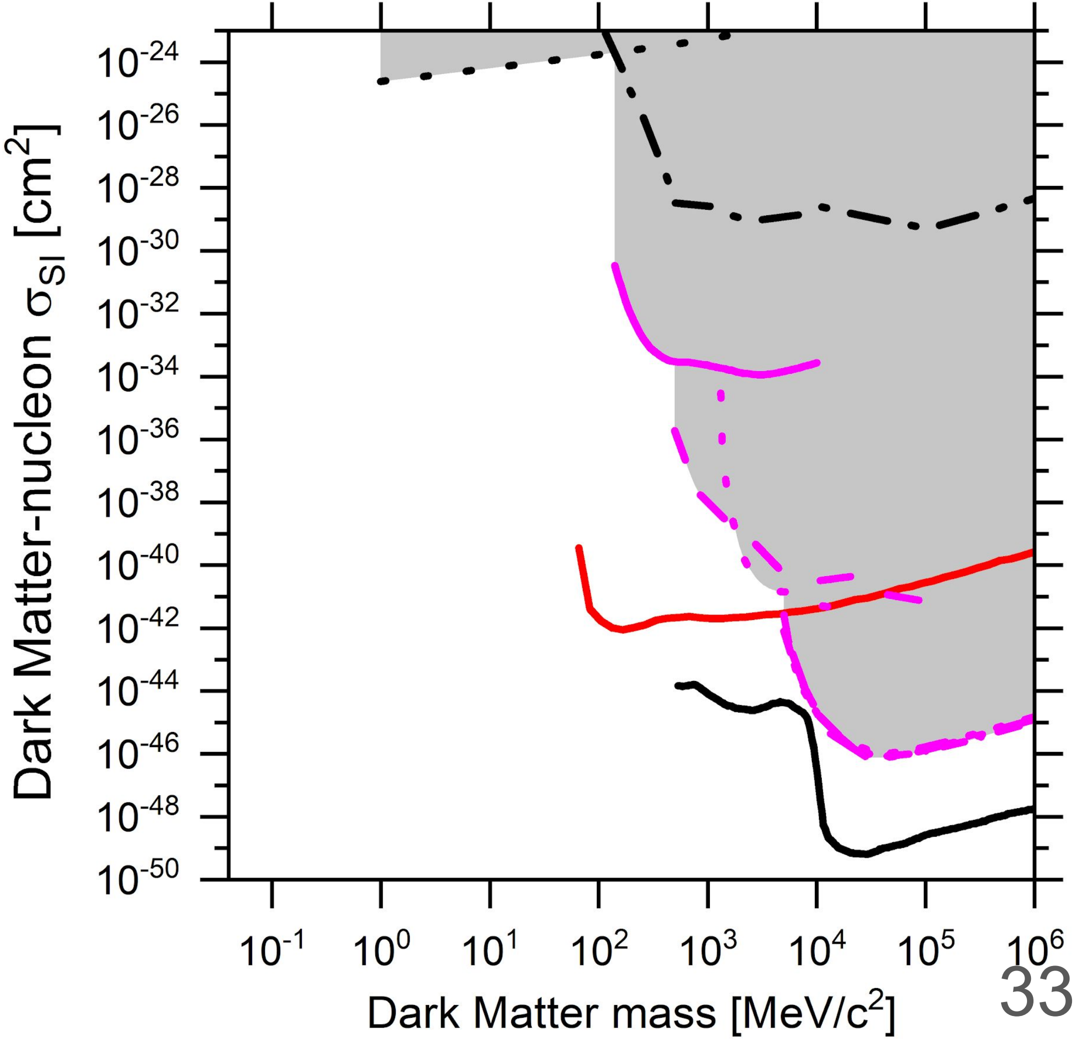
- 10 eV recoil threshold
- 1 kg-yr exposure
- “Shovel-ready”; existing technology

Black Solid: Neutrino floor in Xe

Grey Shaded: Currently excluded parameter space

Black Dashed: Excluded by CMB measurements and XQC

Magenta: Excluded by standard NR experiments

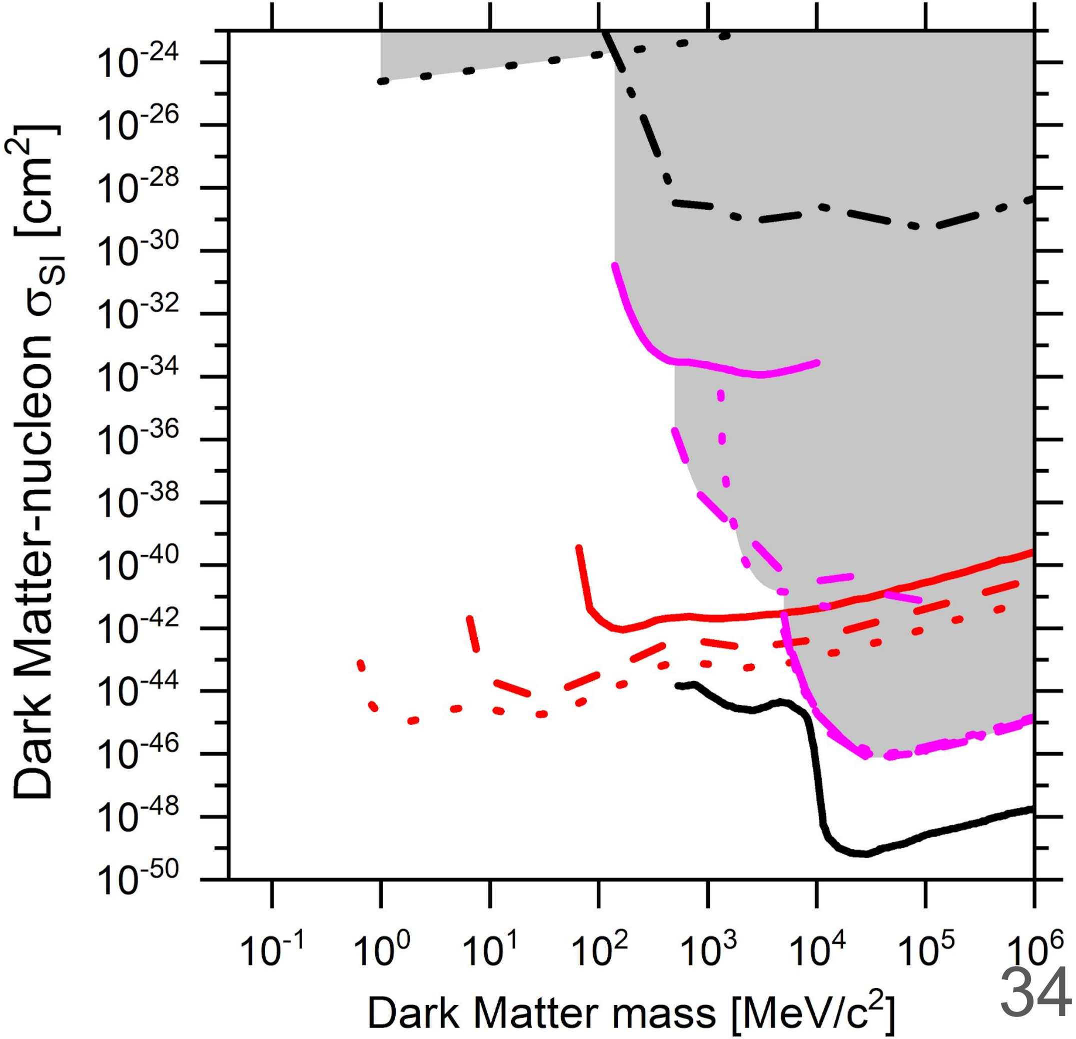


Projected Sensitivity

Red Dashed: Two more generations of superfluid ^{4}He detector

- 100 meV recoil threshold;
  10 kg-yr exposure;
  Requires extra R&D

- 1 meV recoil threshold;
  100 kg-yr exposure;
  Theoretical minimum
  (Single evaporated atom)

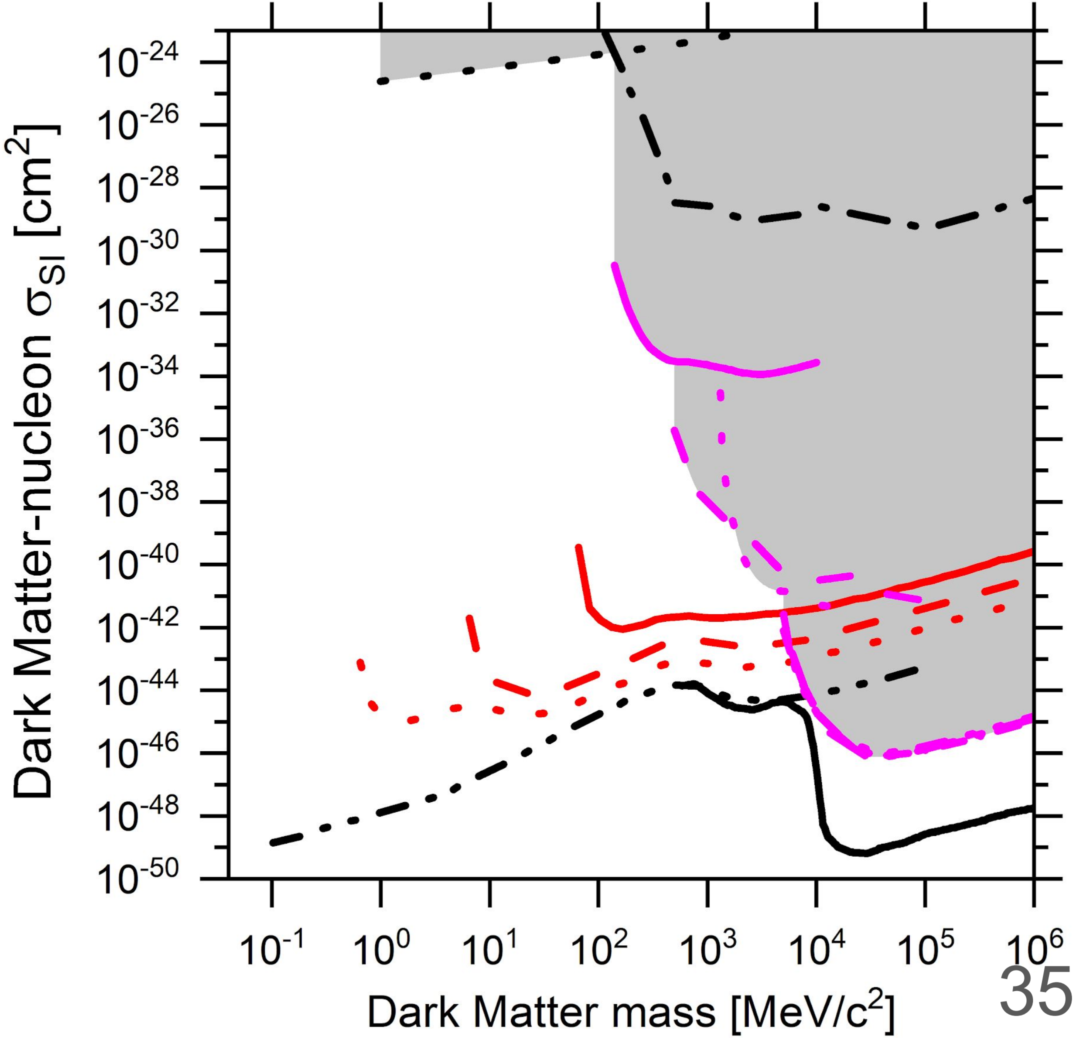


Projected Sensitivity

Black Dashed: Extended neutrino floor to ~100 keV

Used coherent interactions of solar neutrinos with helium

Dominated by *pp* and ^{7}Be neutrinos

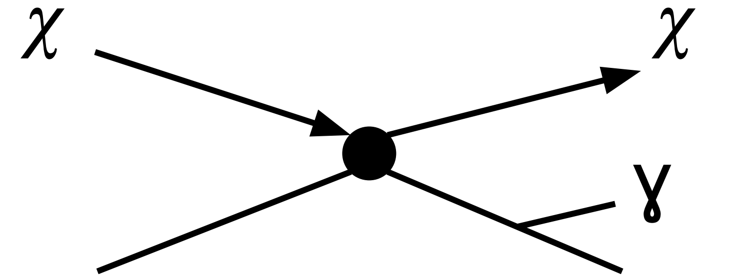


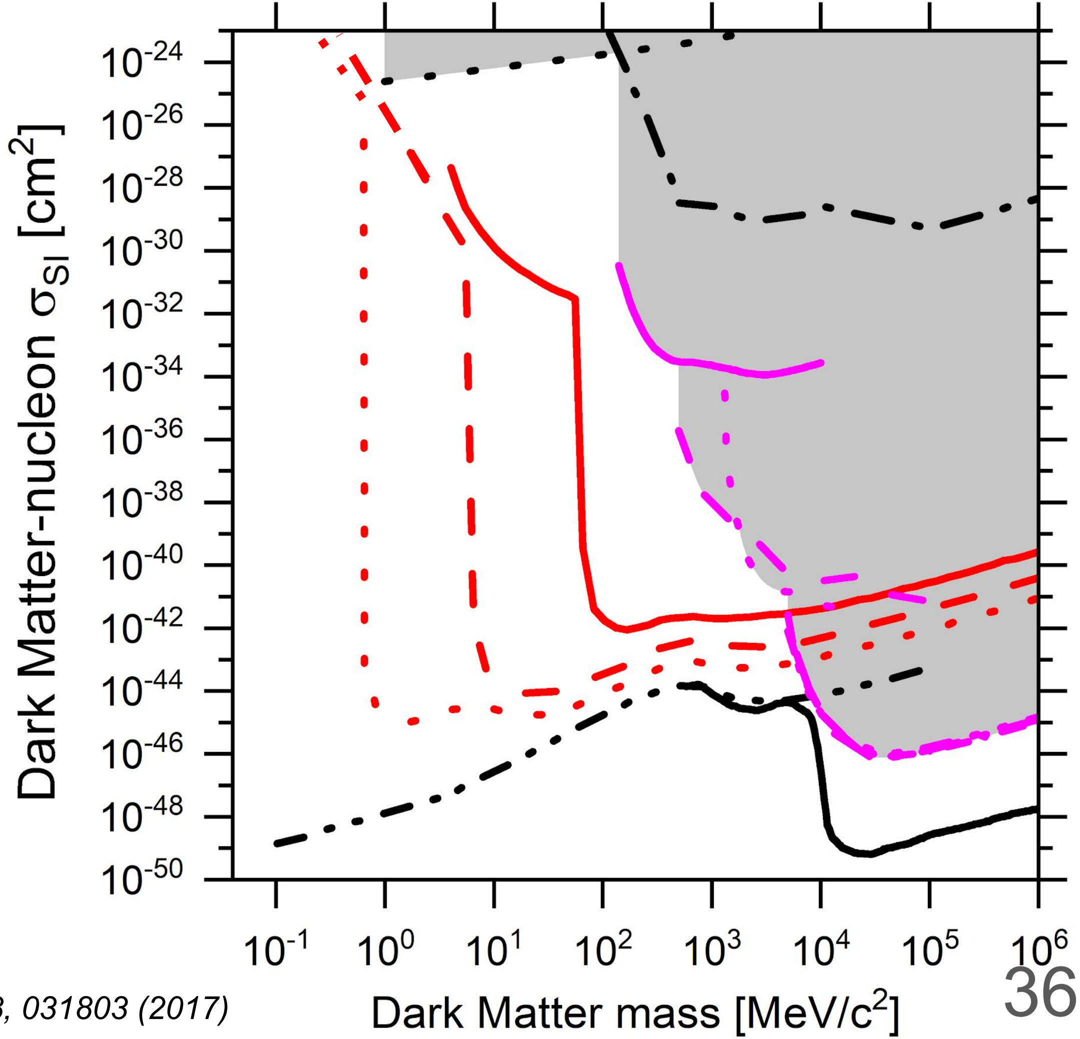
Projected Sensitivity

Red Extension: Nuclear bremsstrahlung signal

Nucleus de-excites, releasing photon of arbitrarily low energy

Phase space suppression



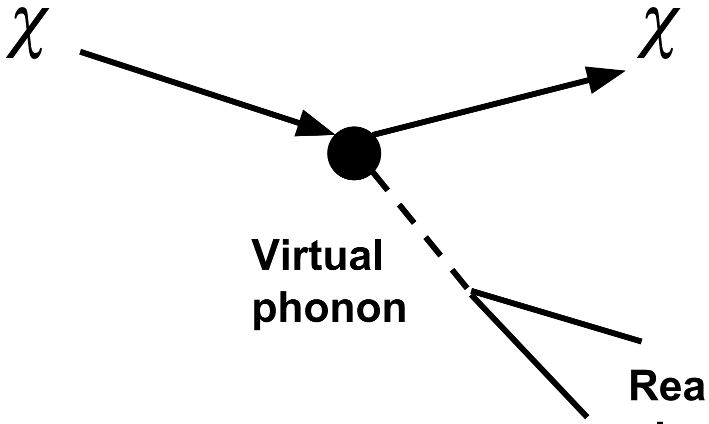


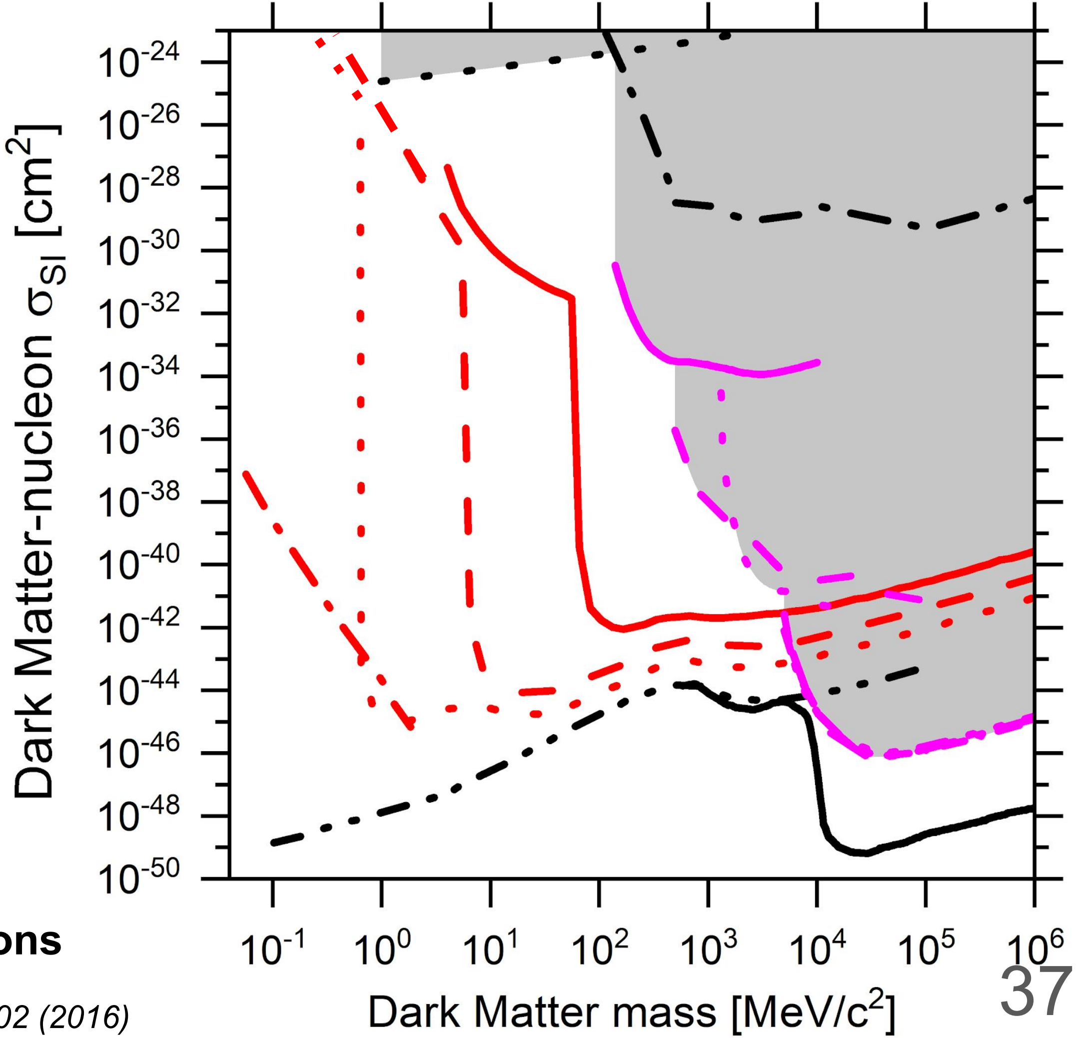
See: C. McCabe. Phys. Rev. D 96, 043010 (2017).
C. Kouvaris and J. Pradler. Phys. Rev. Lett. 118, 031803 (2017)

Projected Sensitivity

Red Dot-Dashed: Two-Phonon Excitation

Access to lowest DM masses





K. Schutz and K. M. Zurek. Phys. Rev. Lett. 117, 121302 (2016)

Projected Sensitivity

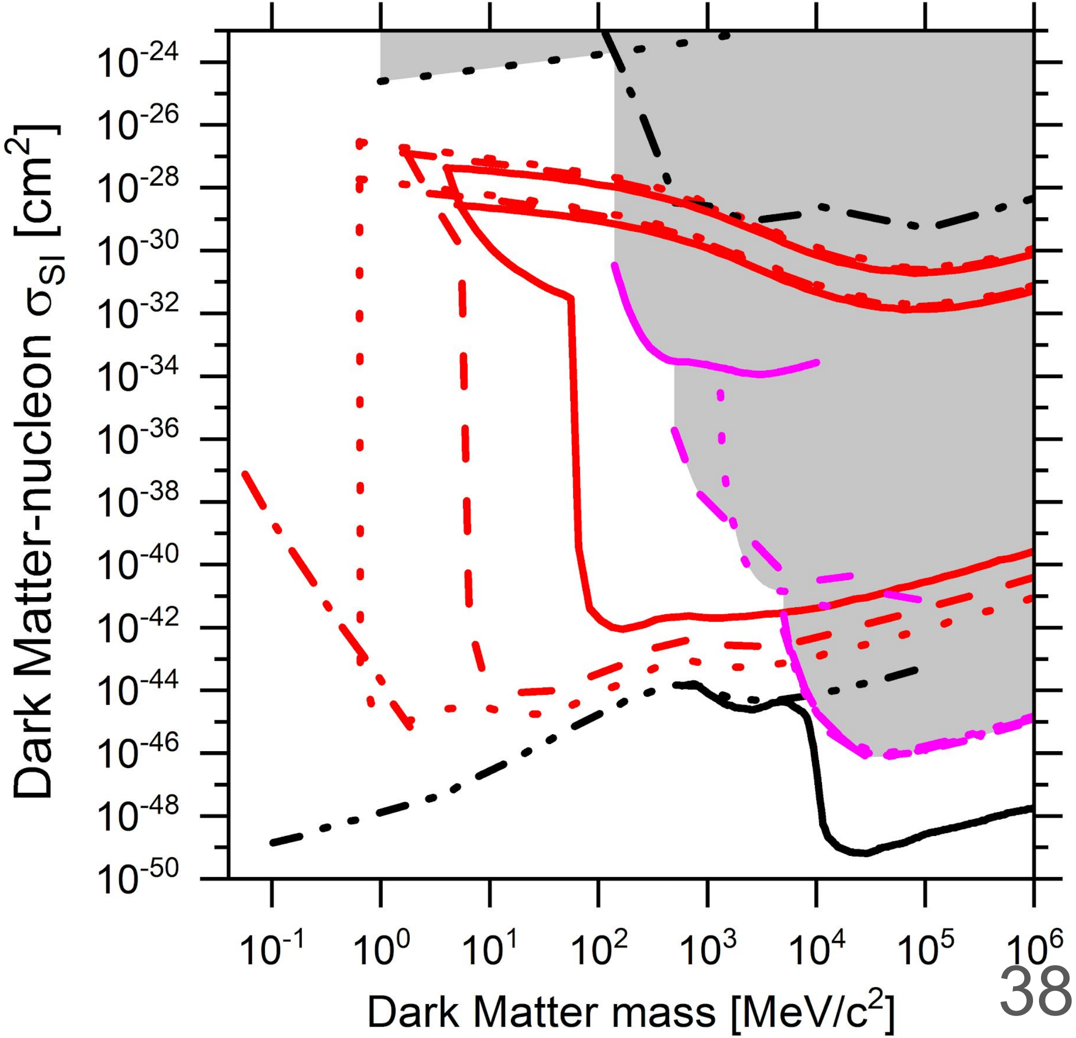
Red Upper Curves: Earth Shielding

If **σ** is high, DM can scatter in the Earth and lose kinetic energy → below experiment threshold

Upper limits on sensitivity for facilities at 100 m and 1478 m underground

v-cleus operated above ground, XQC above atmosphere

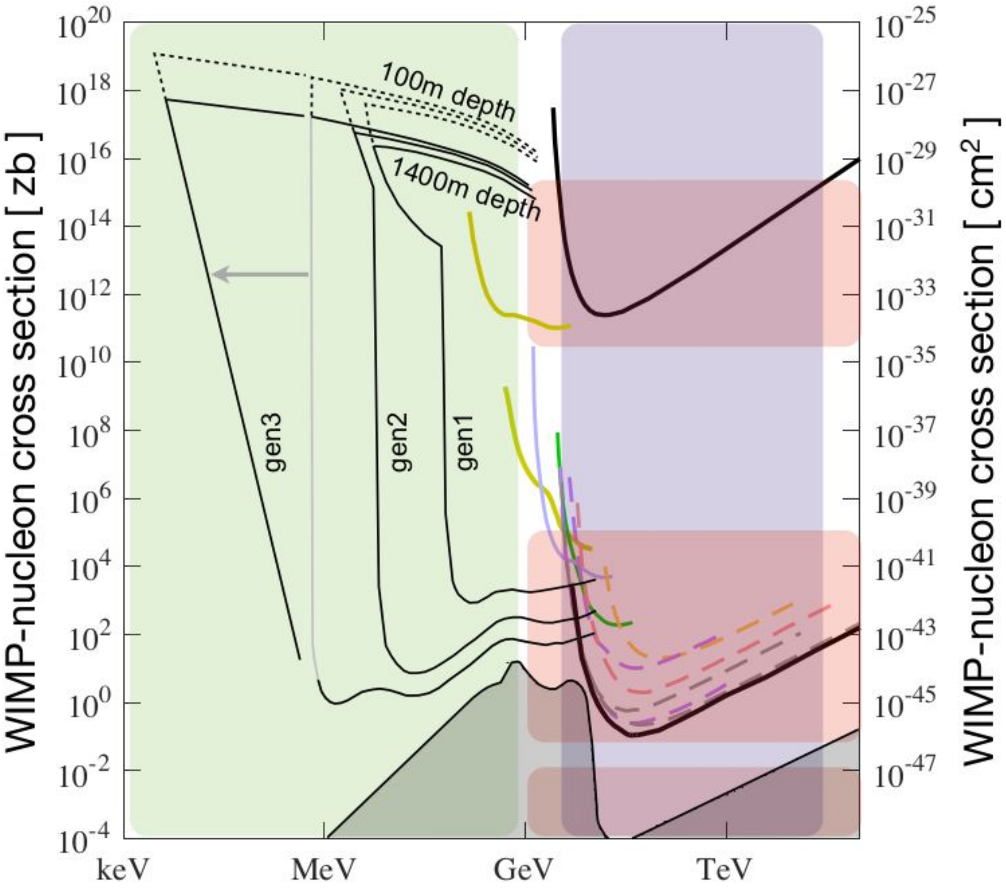
Considering doing a surface run



T. Emken et al. Phys. Rev. D 96, 015018 (2017)

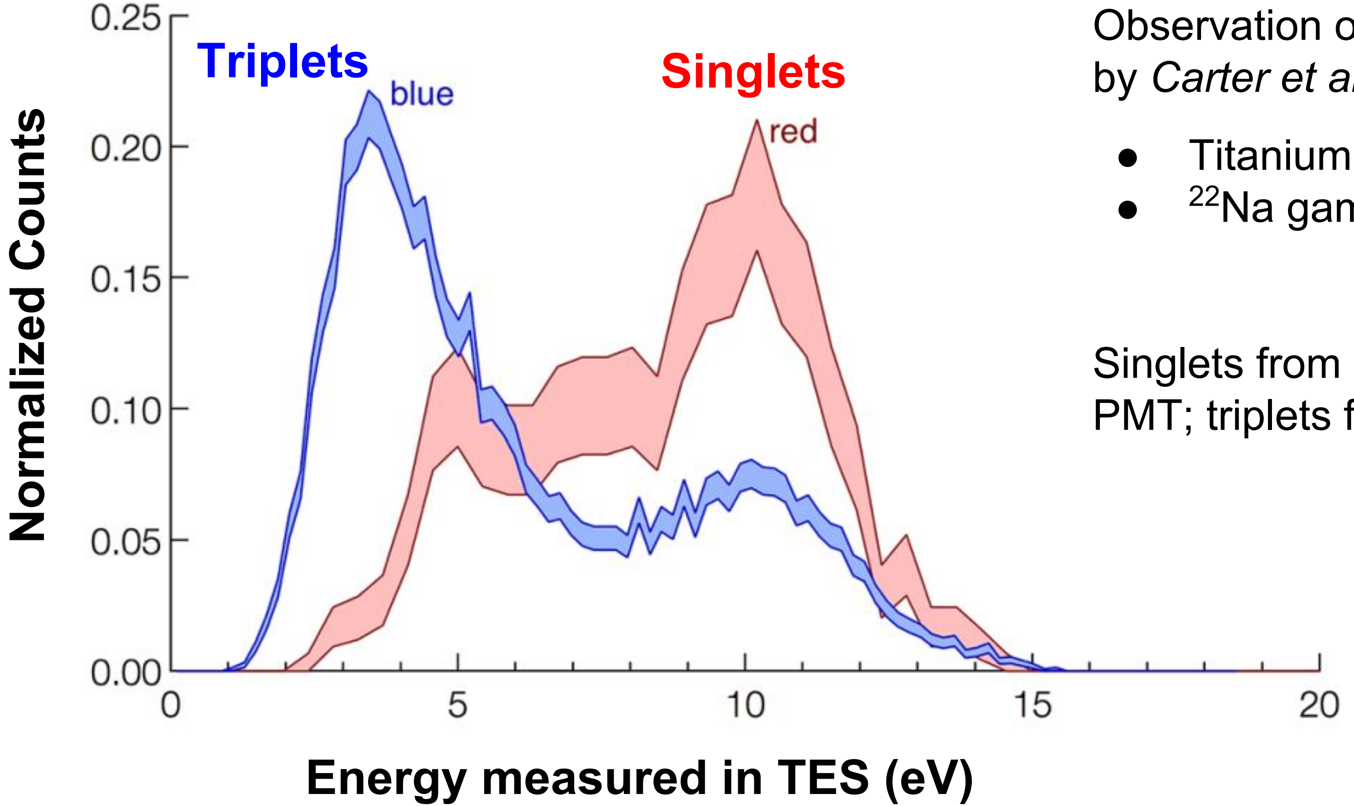
Conclusion

- Superfluid ^4He offers a cheap, practical, and powerful target for probing new dark matter interactions
- Existing technology (HERON; advancements in calorimetry by CDMS, CRESST, etc.)



Backup Slides

Detecting Excimer Signal



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

- Titanium TES in 100 mK ^{4}He bath
- ^{22}Na gamma source

Singlets from TES coincident with PMT; triplets from only TES

Carter et al.J Low Temp Phys (2017) 186:183–196

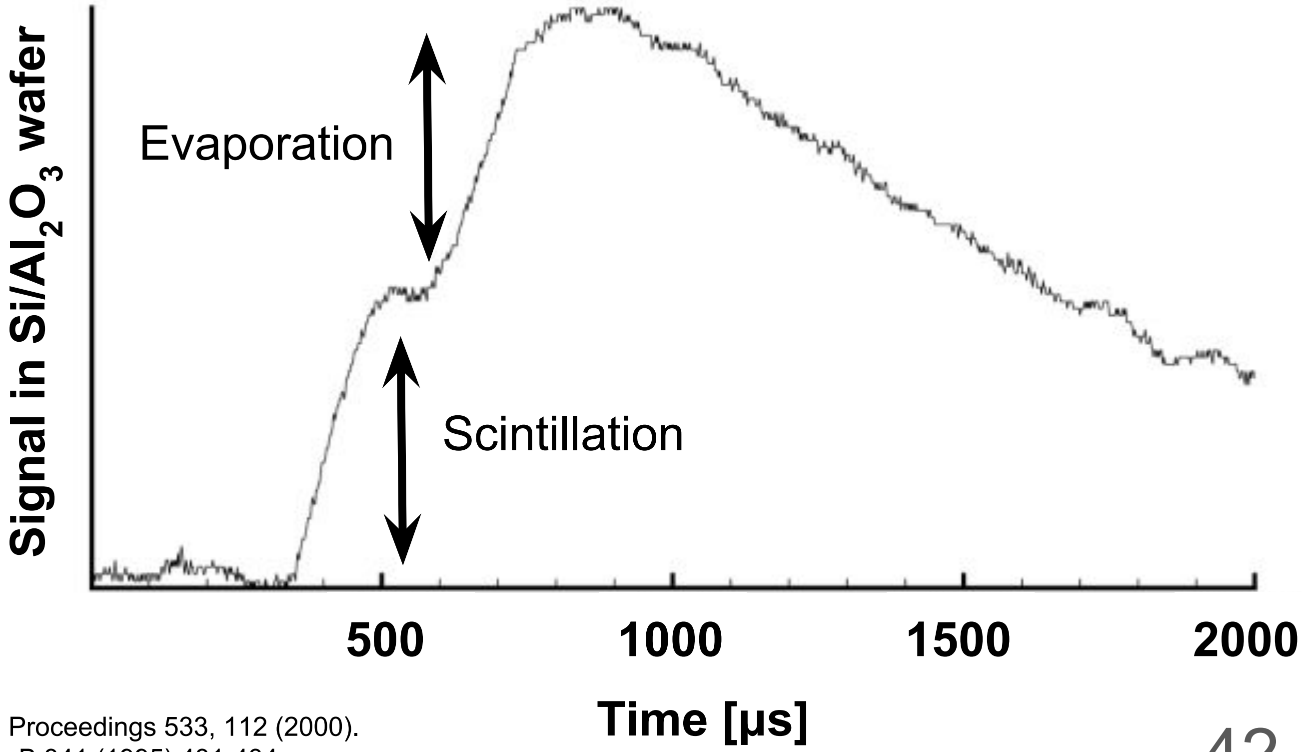
Previous work by HERON

HERON: proposed *pp* neutrino observatory

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

Achieved 300 eV threshold at 30 mK

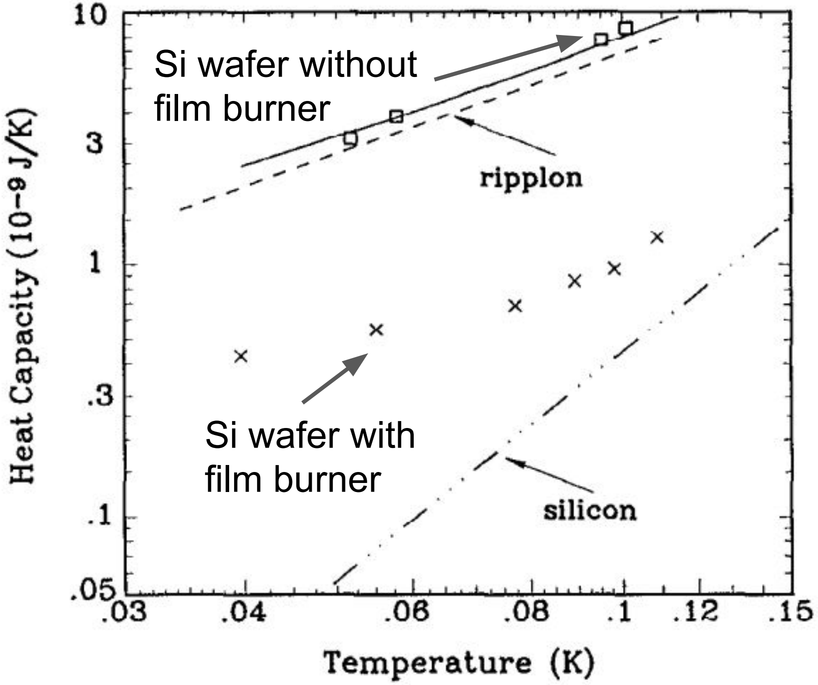
364 keV electron pulse



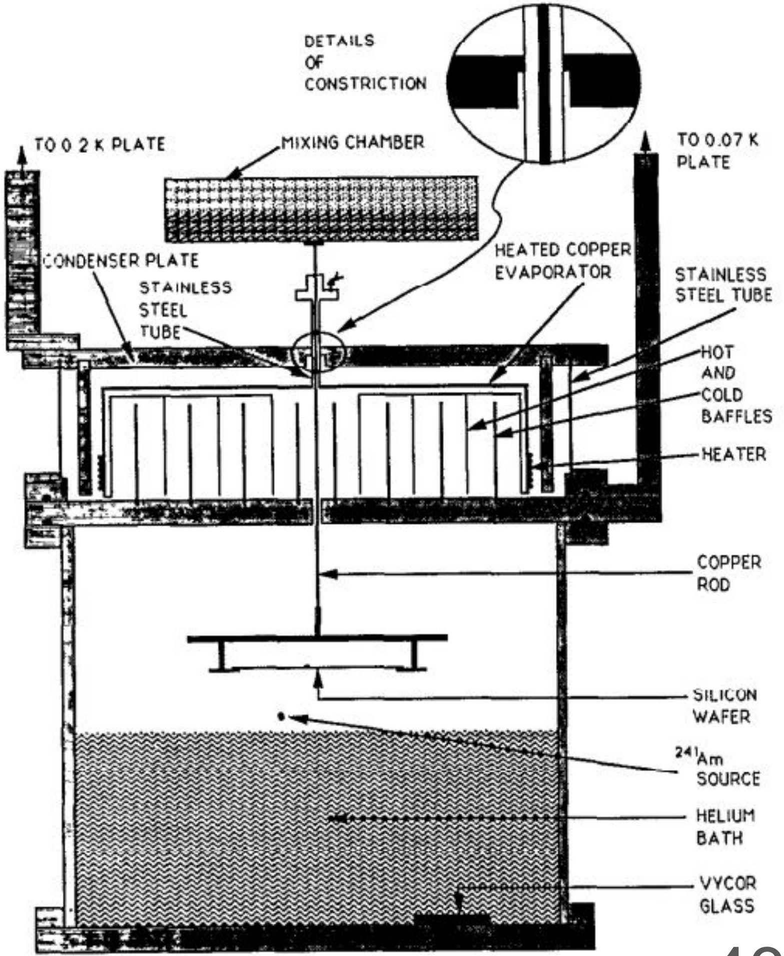
Source: J. S. Adams et al. AIP Conference Proceedings 533, 112 (2000).
Also see: J. S. Adams et al. Physics Letters B 341 (1995) 431-434.

Previous work by HERON

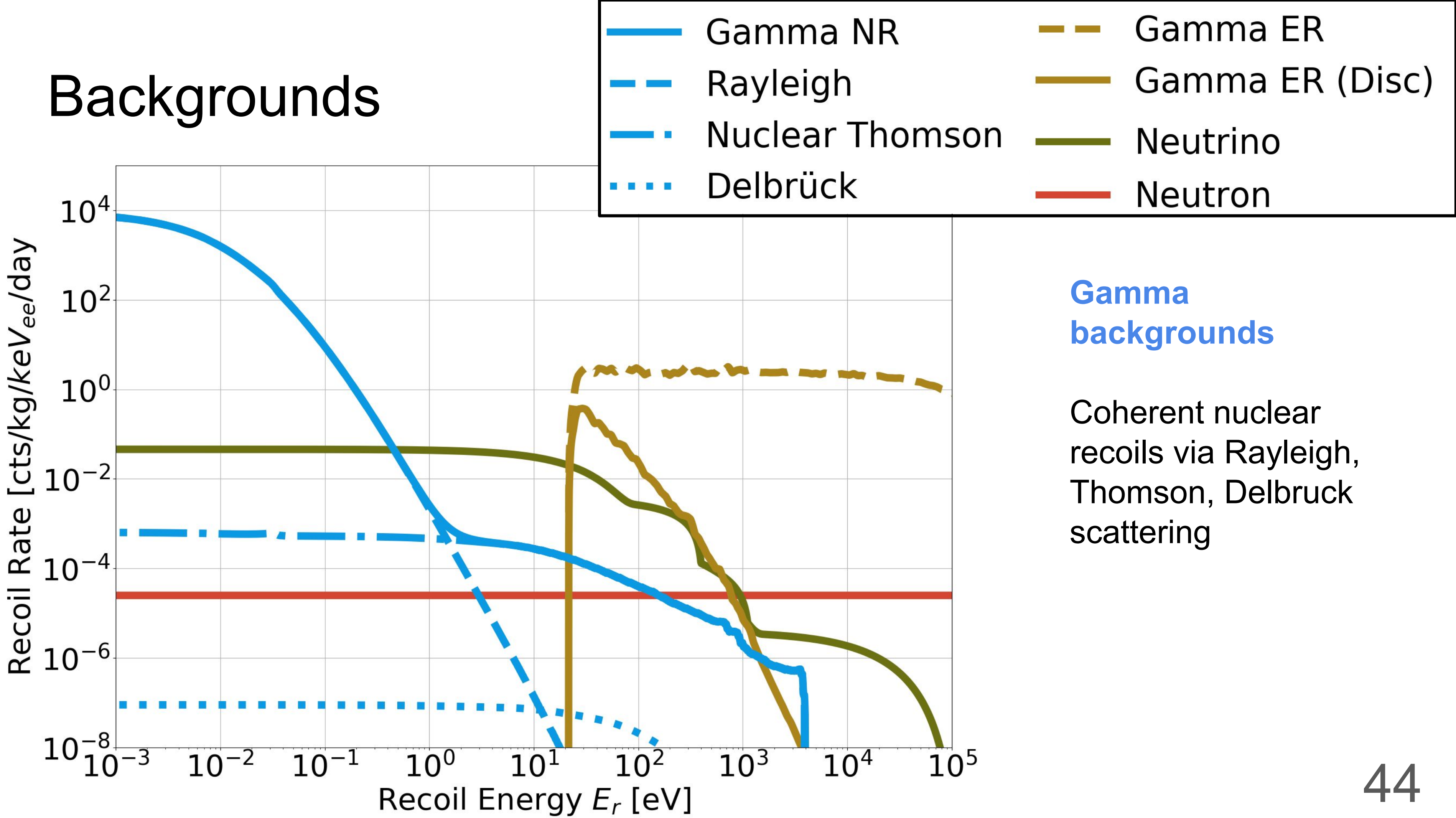
Successful operation of film burner



R. Torii et al. Review of Scientific Instruments 63, 230 (1992).



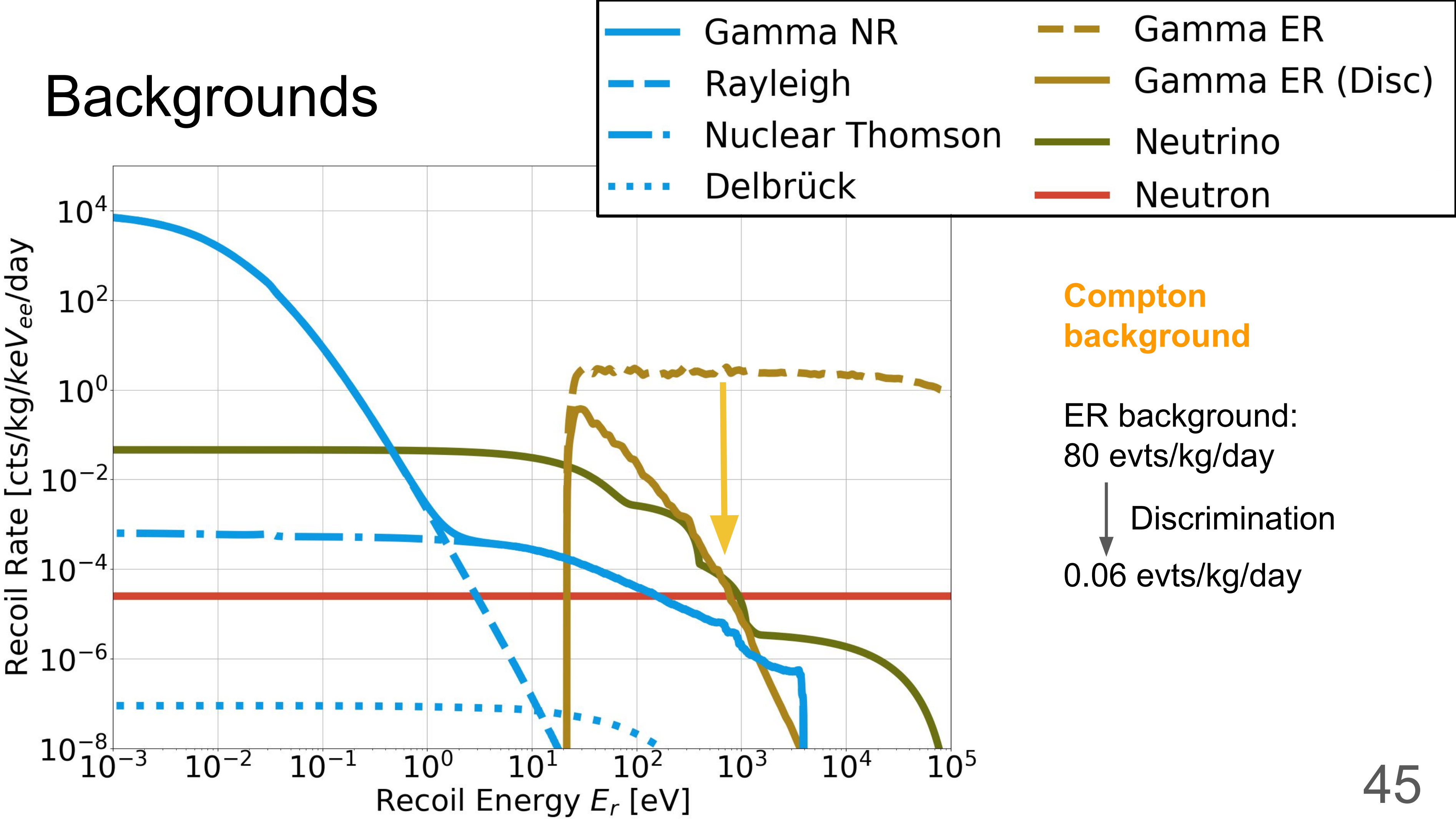
Backgrounds



Gamma backgrounds

Coherent nuclear recoils via Rayleigh, Thomson, Delbruck scattering

Backgrounds



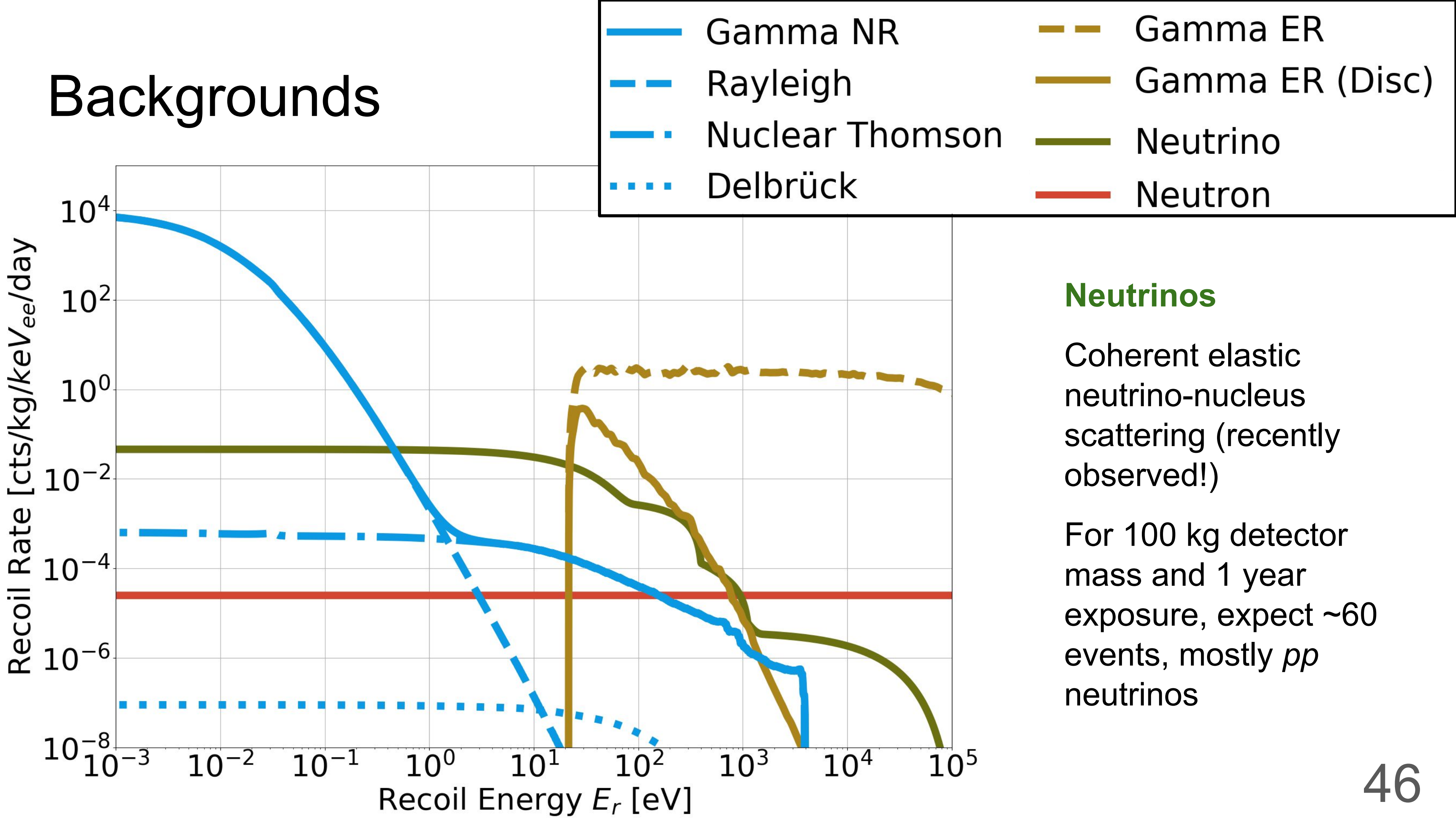
Compton background

ER background:
80 evts/kg/day

Discrimination

0.06 evts/kg/day

Backgrounds

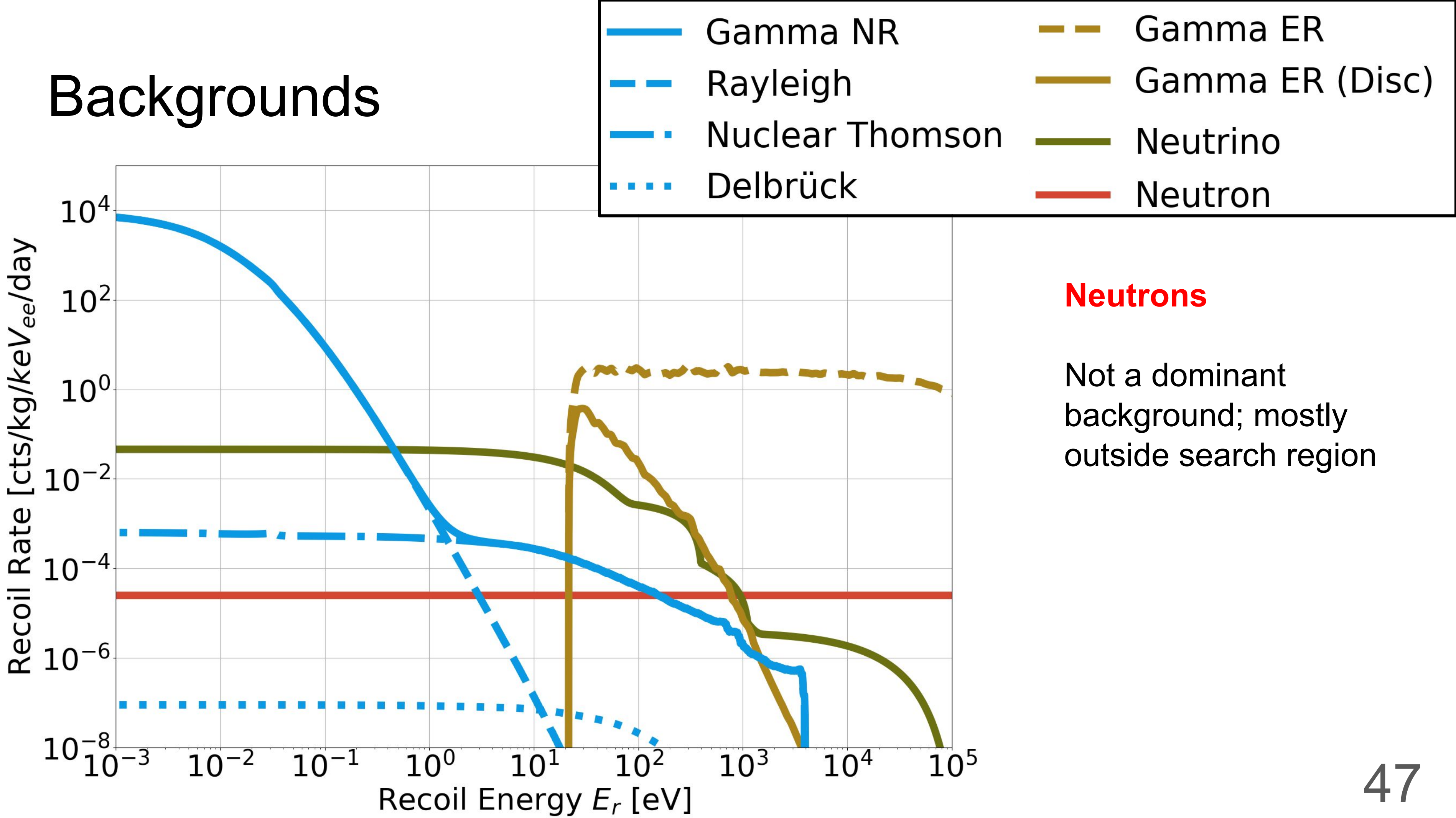


Neutrinos

Coherent elastic neutrino-nucleus scattering (recently observed!)

For 100 kg detector mass and 1 year exposure, expect ~60 events, mostly *pp* neutrinos

Backgrounds



Neutrons

Not a dominant background; mostly outside search region