

# Probing Sub-GeV Dark Matter with Superfluid Helium-4

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SLAC Experimental Seminar

**Berkeley**  
UNIVERSITY OF CALIFORNIA

**UMASS**  
**AMHERST**

On behalf of:

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and Daniel McKinsey

# Outline

1. Overview of Dark Matter
2. Direct Detection
3. Proposed  $^4\text{He}$  Detector
4. Detector Simulations
5. Expected Backgrounds
6. Projected Sensitivity

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# Dark Matter

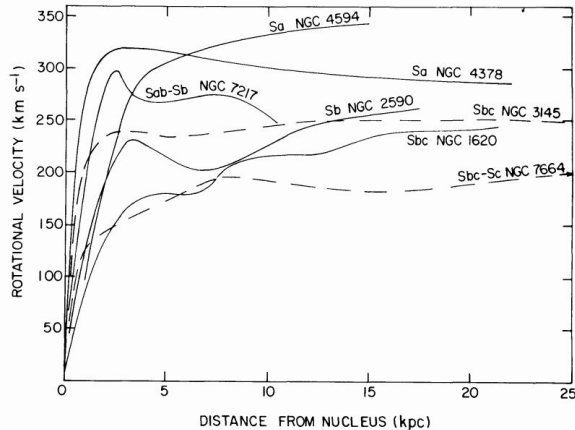
- Vast evidence for non-luminous **dark matter** in the universe
- Strong impact on astrophysics and cosmology

## Bullet Cluster



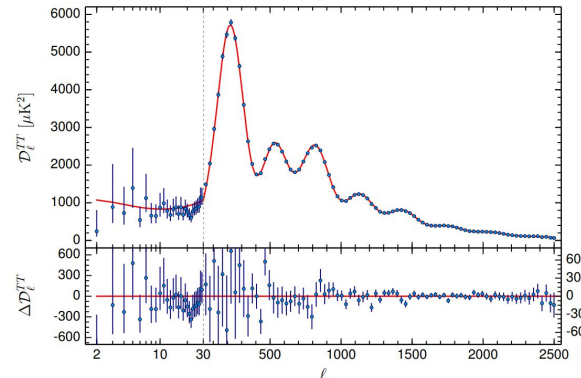
X-ray: NASA/CXC/CfA/ M. Markevitch et al.;  
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al.  
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.

## Galactic Rotation Curves



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

## Cosmic Microwave Background



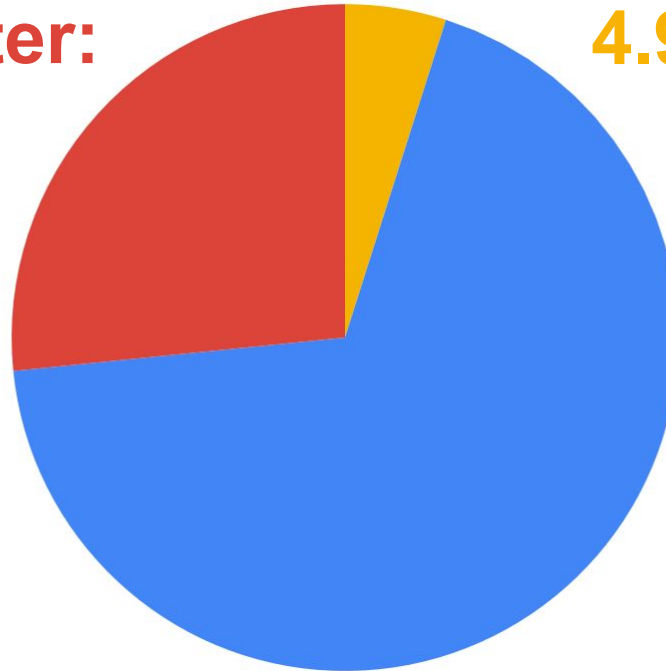
Planck Collaboration. A&A 594, A13 (2016).

# Composition of the Universe

**Dark Matter:  
26.6%**

**Normal Matter:  
4.9%**

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



**Dark Energy:  
68.5%**

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

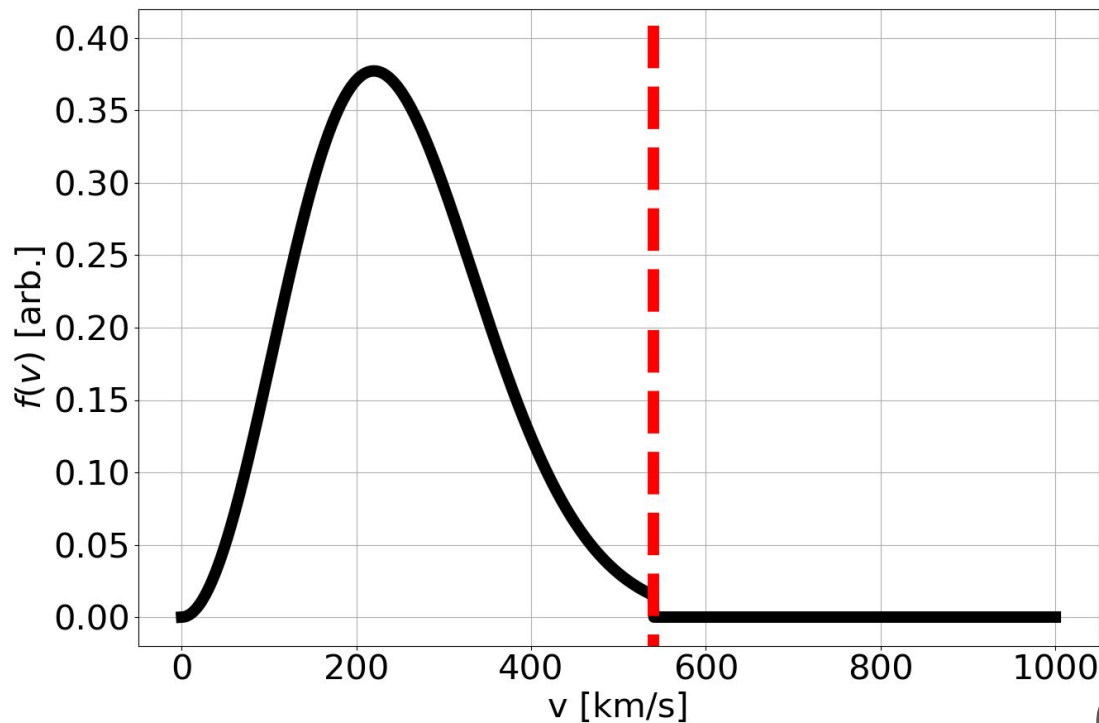
# Dark Matter in our Galaxy

- Galactic “halo” of dark matter: approximately Maxwell-Boltzmann distribution

$$v_0 = 220 \text{ km/s}$$

$$\text{Cutoff } v_{\text{escape}} = 540 \text{ km/s}$$

- $\rho_{\text{DM}} = 0.3 \text{ GeV/cm}^3$



# 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

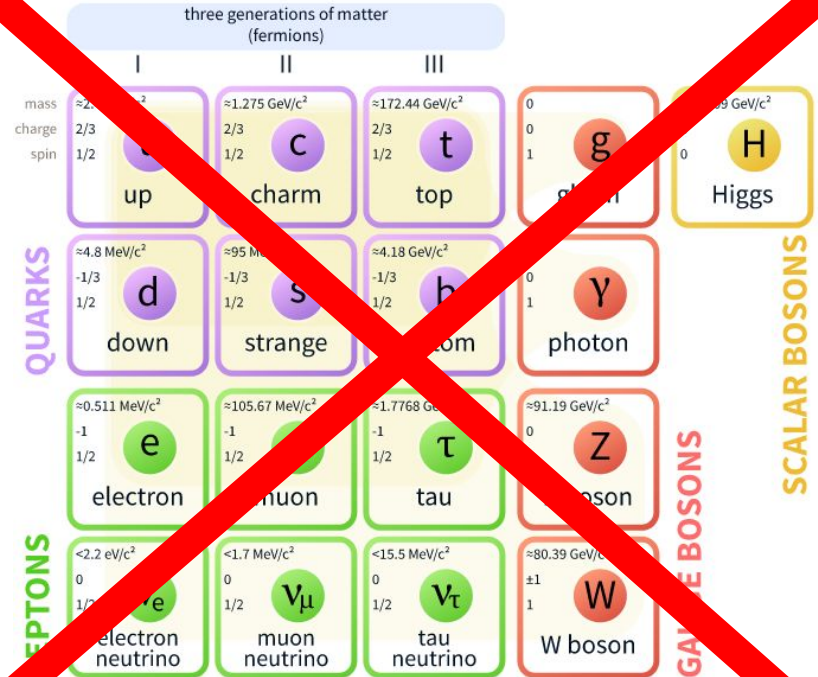


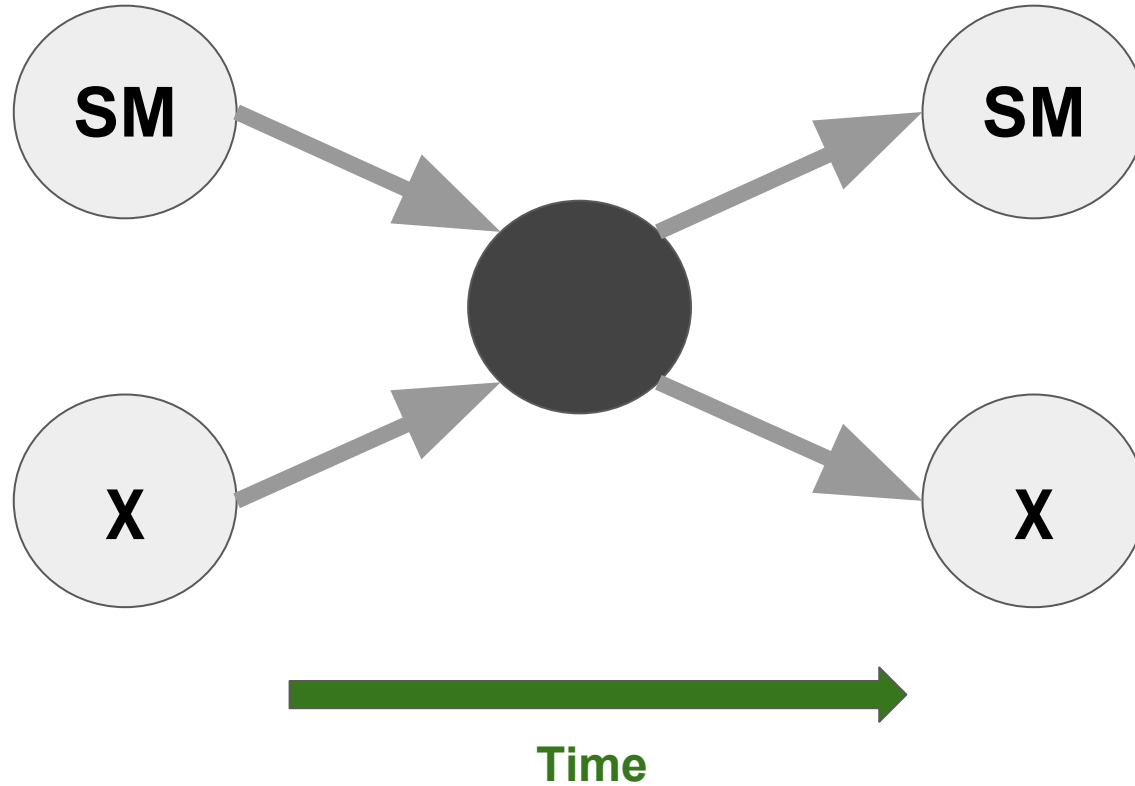
Image from Wikipedia:Standard Model

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# Dark Matter Direct Detection



# Status of Direct Detection

Leading limits:

LUX, PANDAX-II, XENON1T  
SuperCDMS  
CRESST-II  
CRESST nu-cleus surface experiment

Upcoming:

LUX-ZEPLIN  
SuperCDMS SNOLAB

Decades-long campaign to probe WIMP dark matter (Lee-Weinberg limit:  $m > 2 \text{ GeV}$ )

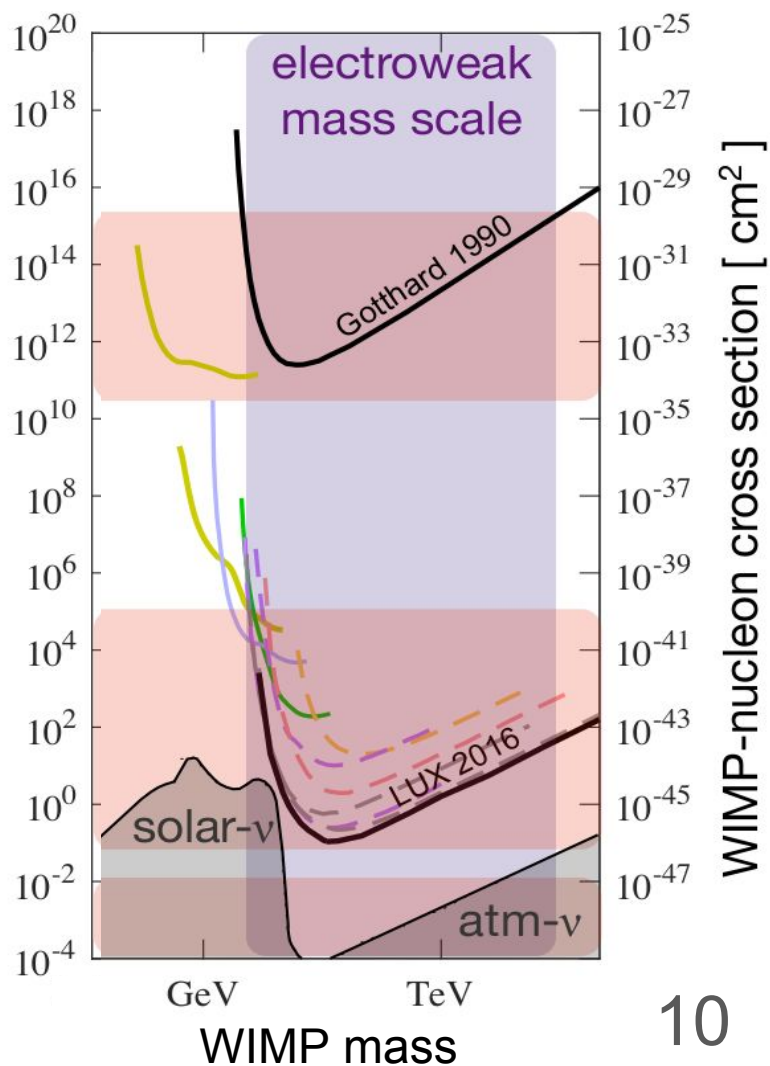
Mediator

Z

H

Loop

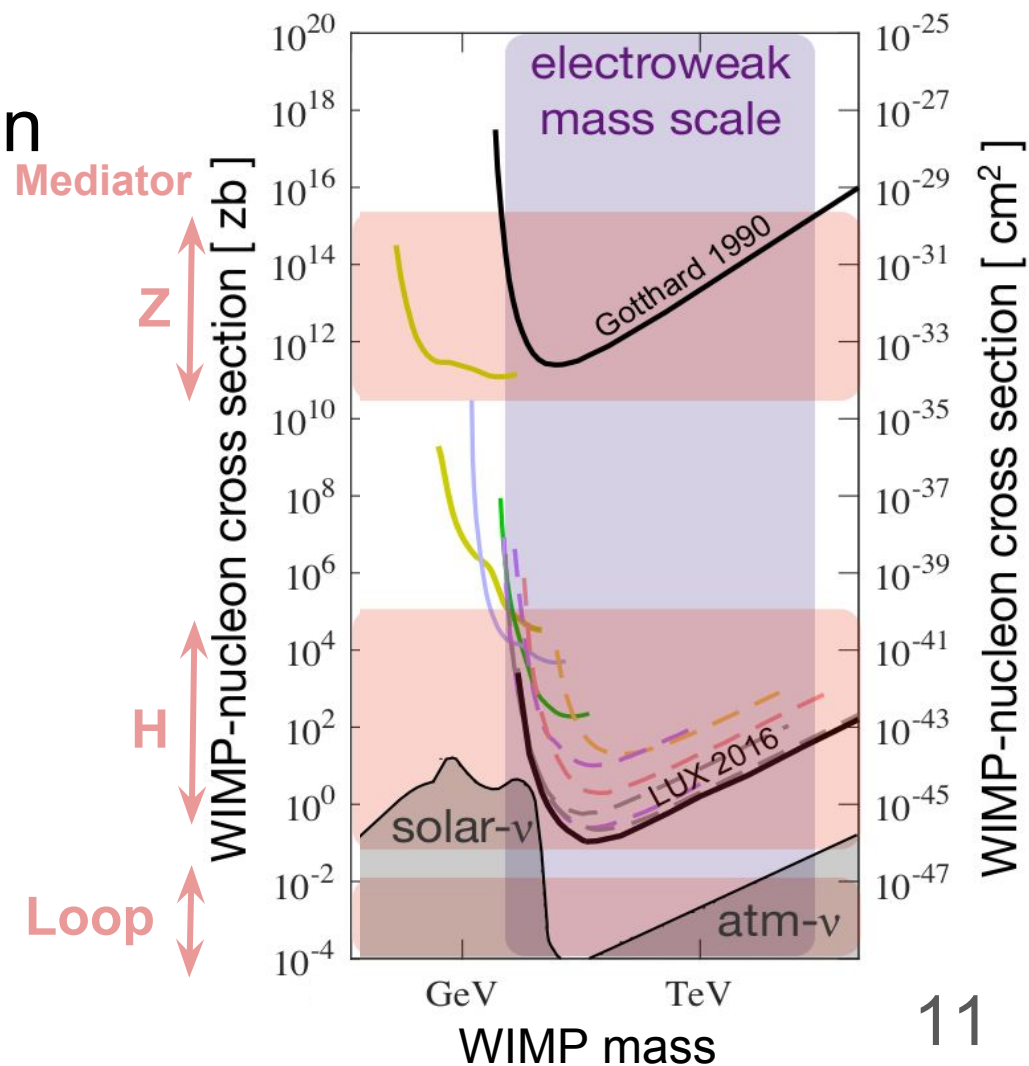
WIMP-nucleon cross section [zb]



# Status of Direct Detection

Issues:

- 1) Approaching the “neutrino floor”, a challenging background to overcome
- 2) Assumption of electroweak-scale physics--worth keeping?



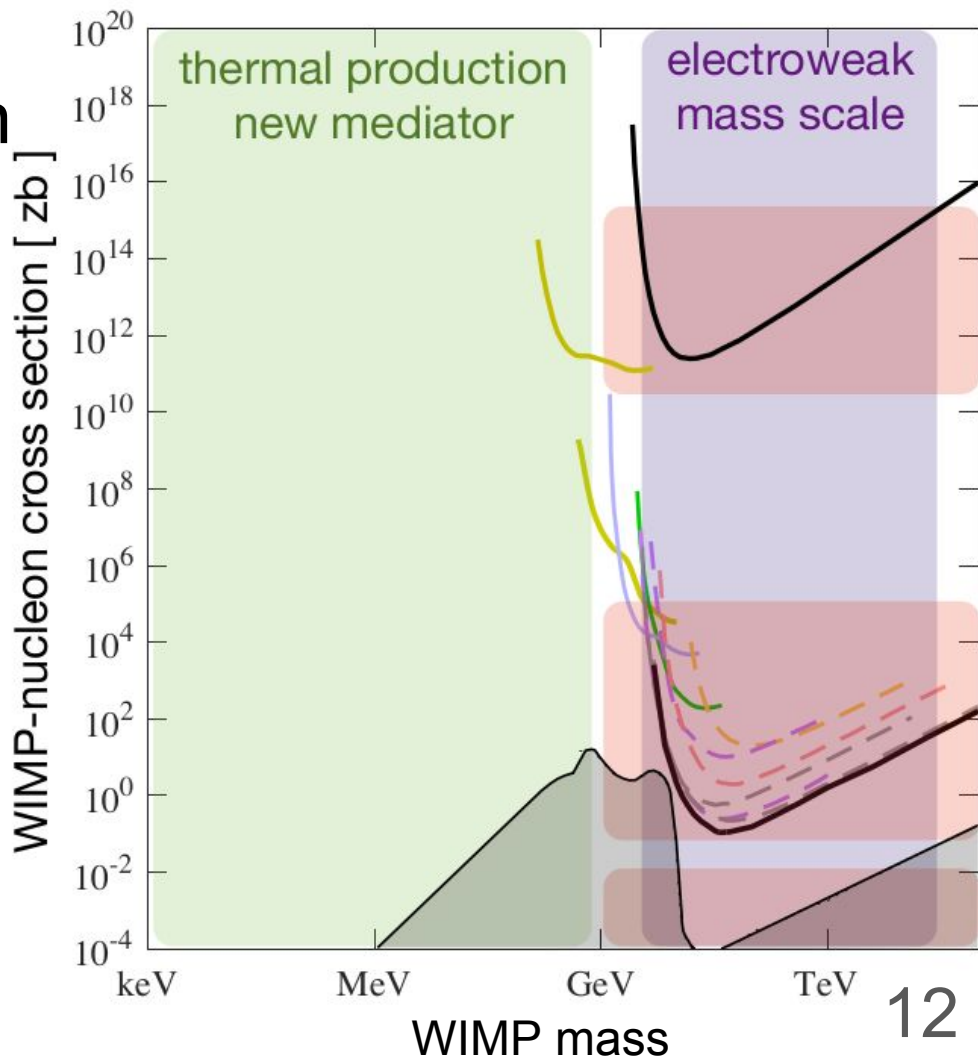
# Status of Direct Detection

**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

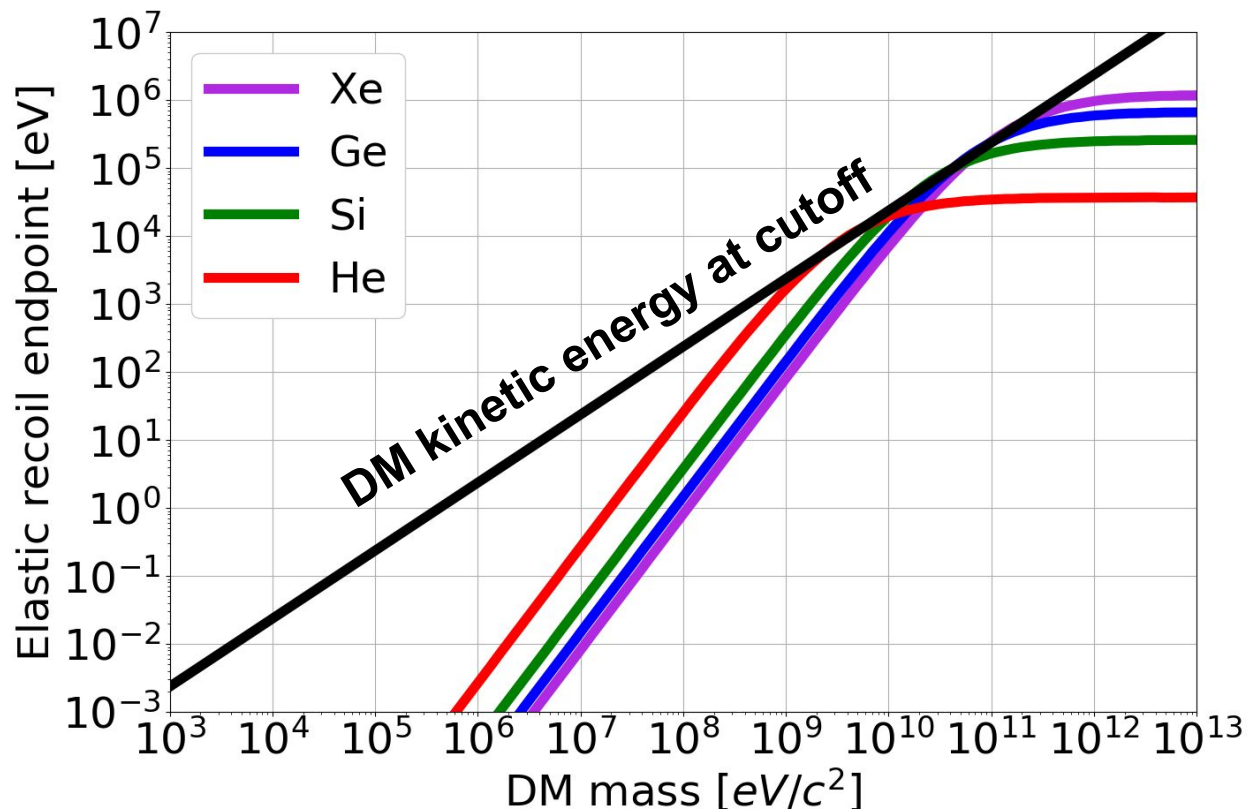
Max kinetic energy carried by dark matter is

$$KE_{\max} = \frac{1}{2} m_{\text{DM}} v_{\text{escape}}^2$$

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

To probe MeV-scale dark matter, we need:

- 1) Light target
- 2) Ability to access meV recoil energies



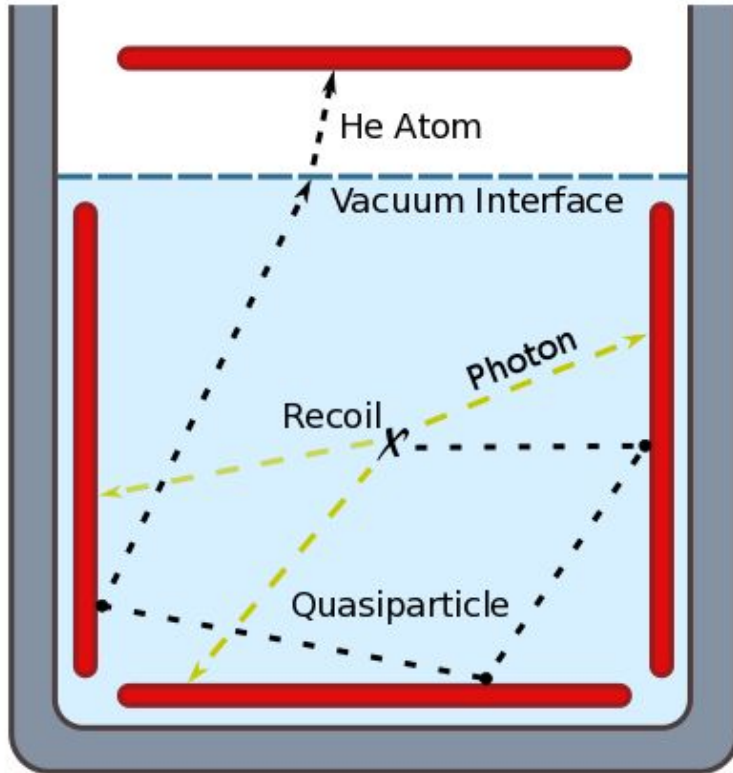
**HELIUM!**



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# Superfluid Helium as a Dark Matter Target

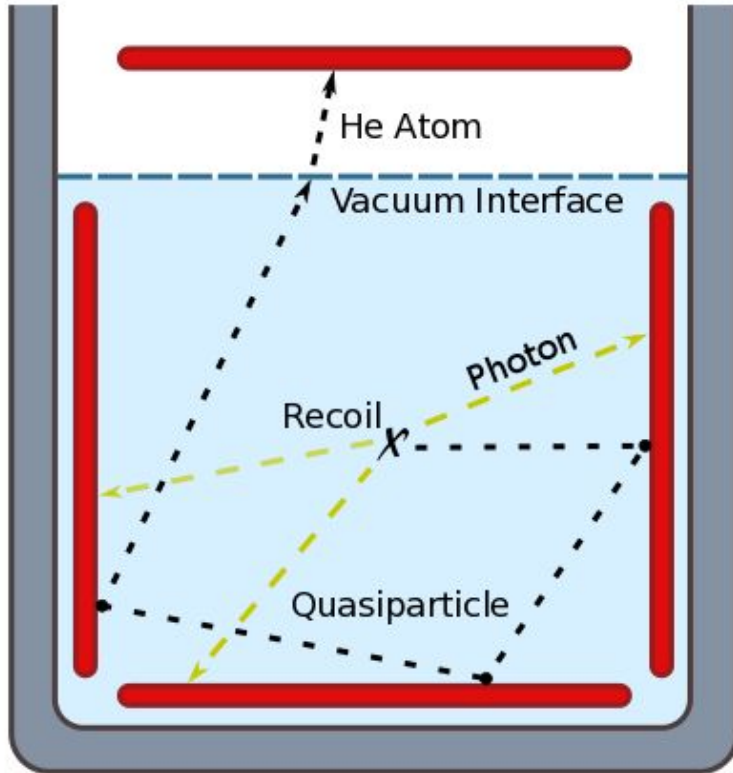


He-4 meets all the requirements plus:

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



# Proposed Detector



$O(1 \text{ kg})$  cubic mass of helium, operated at  $\sim 50$  mK, in dilution refrigerator

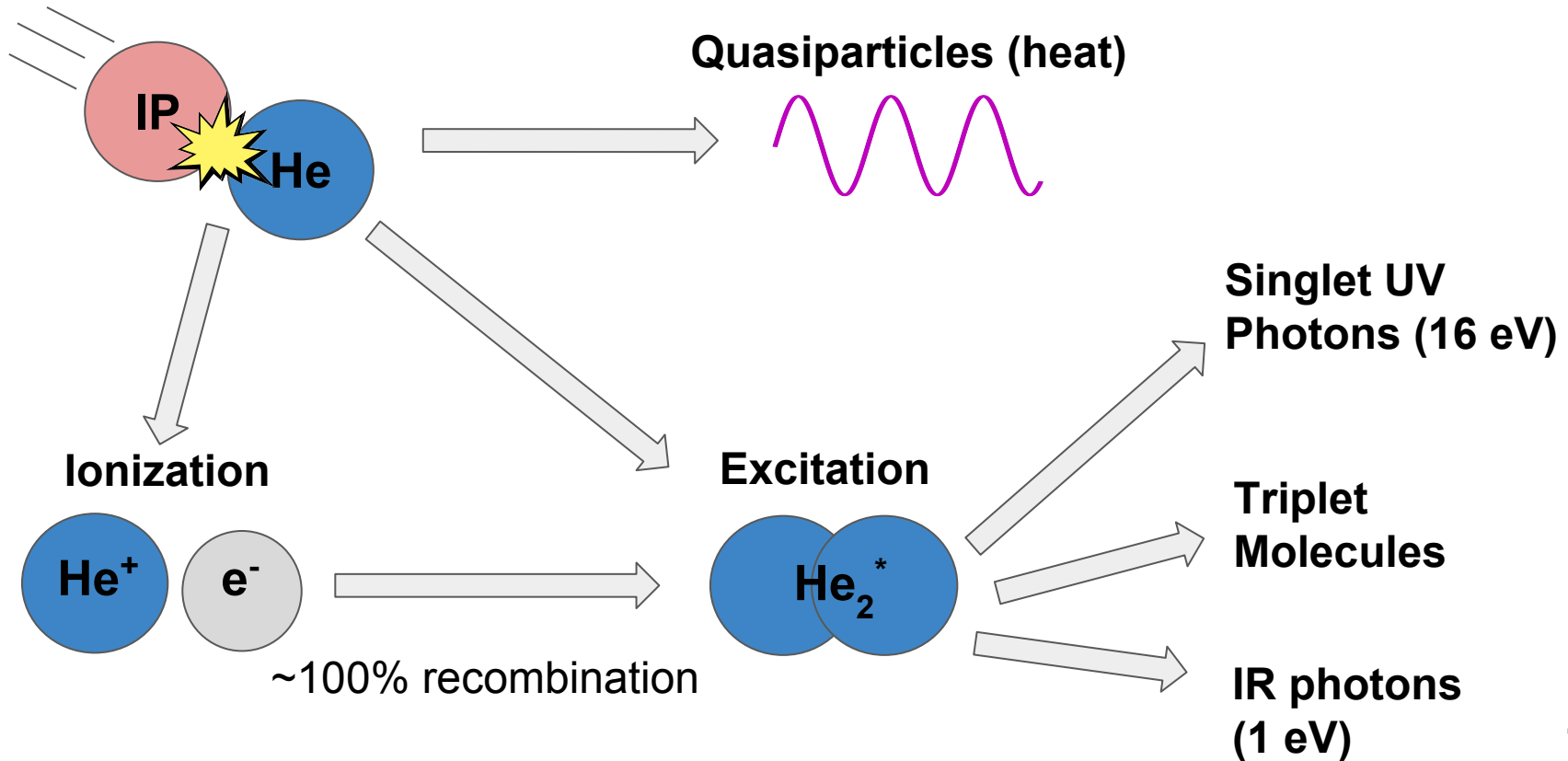
5 transition-edge sensor (TES) arrays on walls, adjacent to helium

- Detect UV photons, triplet excimers, IR photons

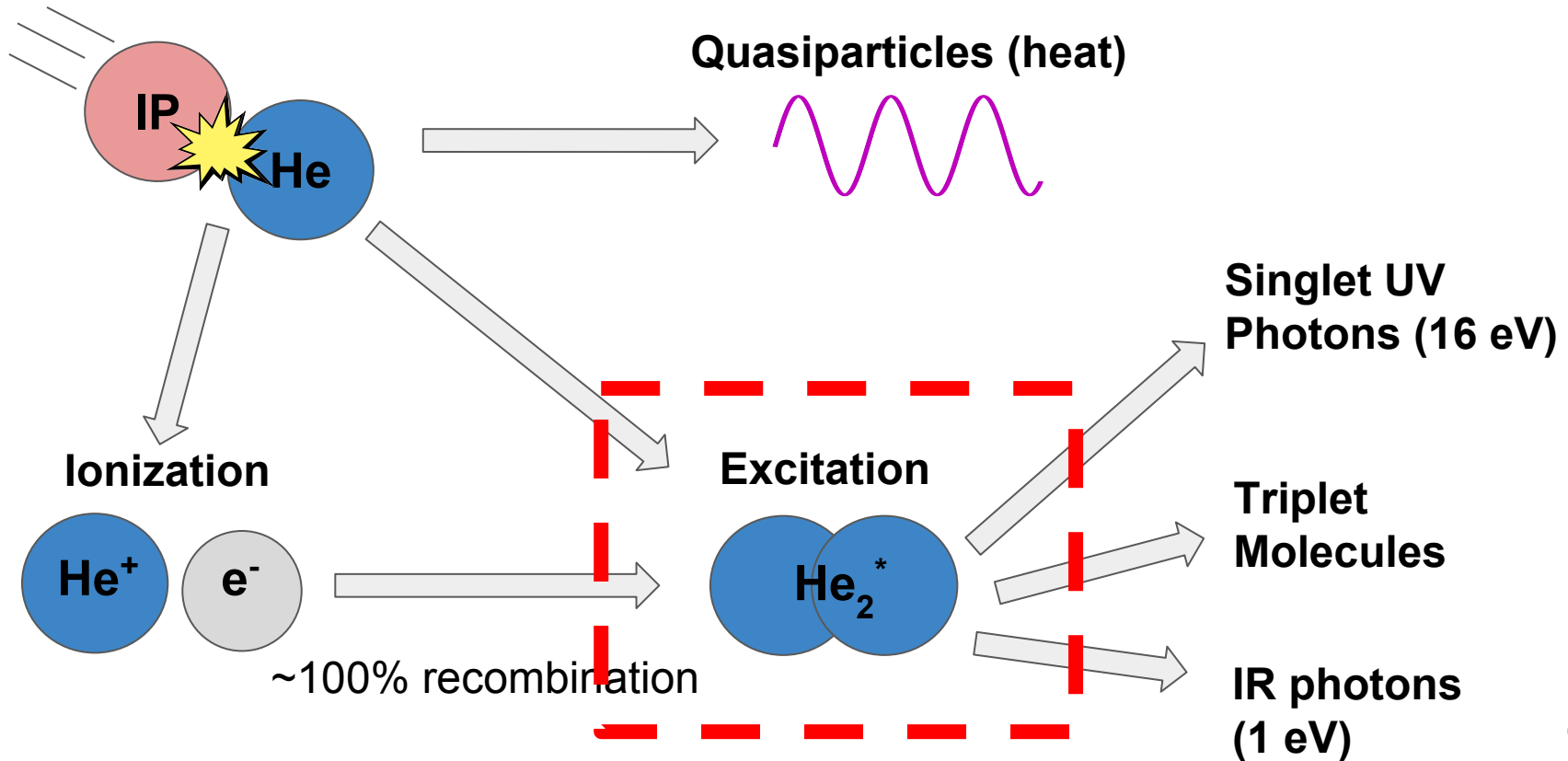
Vacuum layer between helium and 6th TES array

- Detect quasiparticles via quantum evaporation

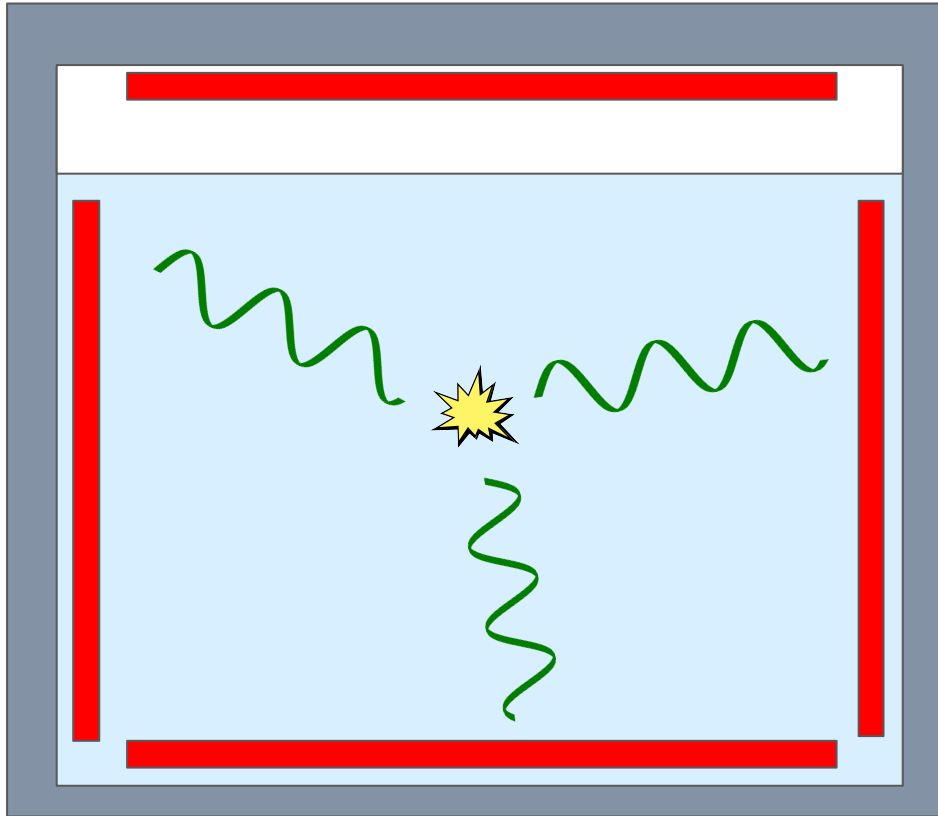
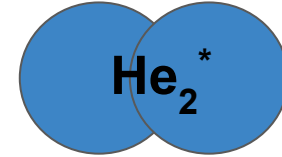
# Recoils in Helium (generic incident particle IP)



# Recoils in Helium (generic incident particle IP)



# Detecting Excimer Signal



Singlet decay

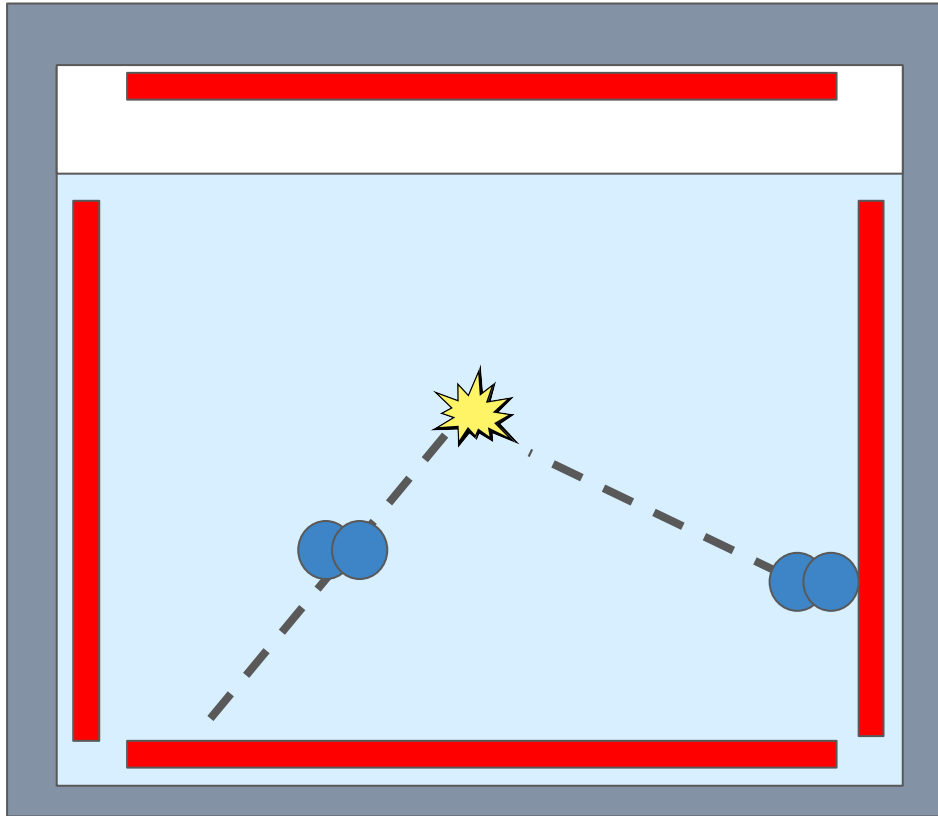
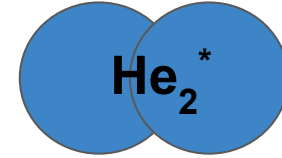
- Half-life of few ns
- 16 eV photon

Hits detector walls on ns timescale

Detected directly by TES

Calorimetry possible because of large Kapitza resistance

# Detecting Excimer Signal



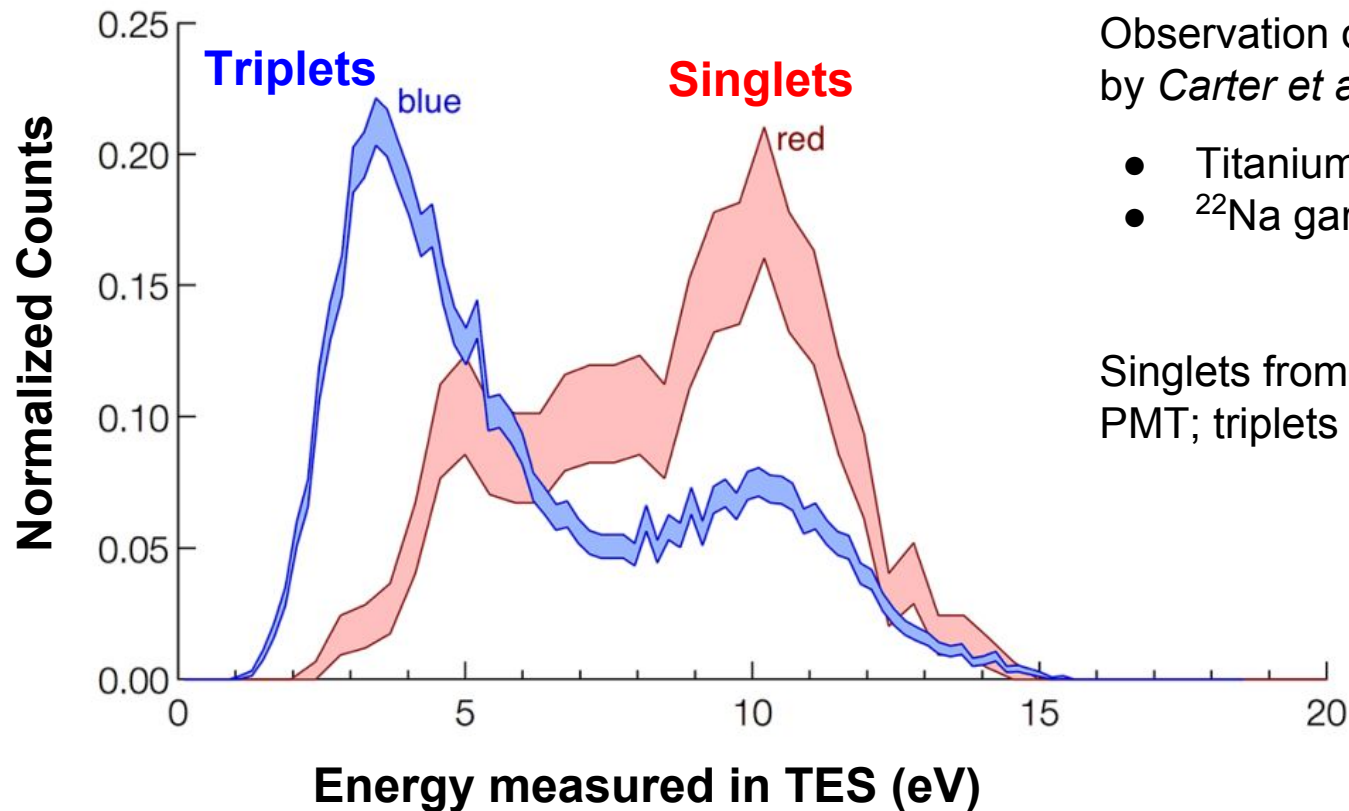
## Triplet decay

- 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

# Detecting Excimer Signal

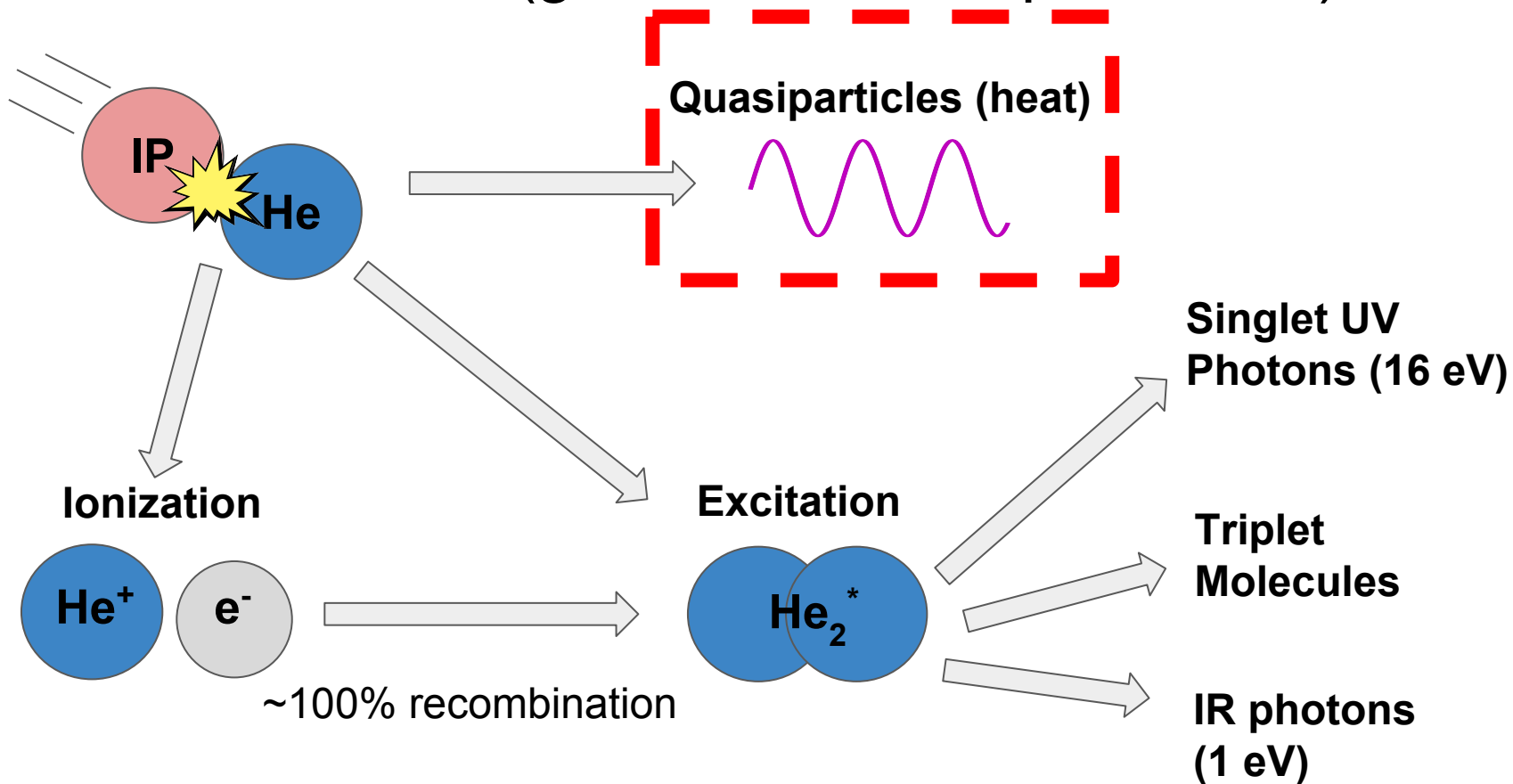


Observation of singlet/triplet excimers by *Carter et al.*

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

Singlets from TES coincident with PMT; triplets from only TES

# Recoils in Helium (generic incident particle IP)



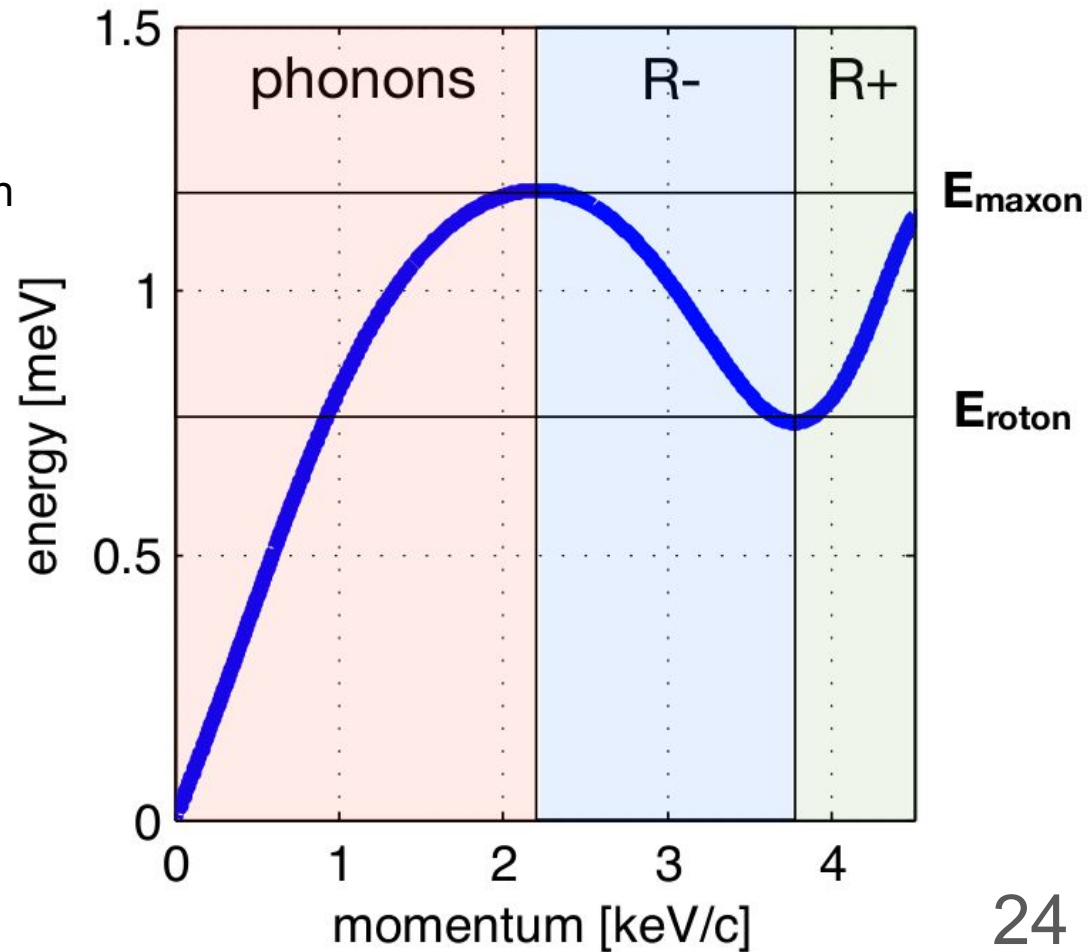
# Quasiparticles in $^4\text{He}$

Quasiparticles: collective excitations in superfluid helium

Long-lived

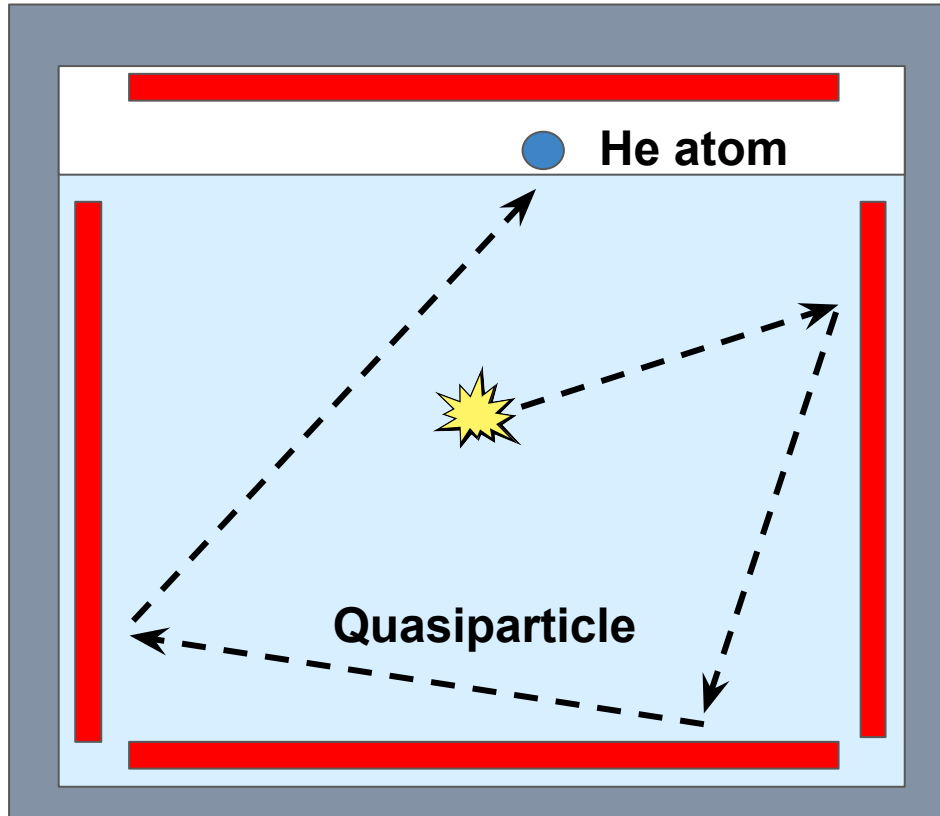
Classified based on momentum:  
Phonons, R- rotons, R+ rotons  
(roton  $\approx$  high-momentum phonon)

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





# Detecting Quasiparticle Signal



Recoils produce  $\sim 0.8$  meV phonons and rotons

Propagate ballistically, bounce around the detector (few ms)

Transmission of quasiparticles into the wall is suppressed by Kapitza resistance

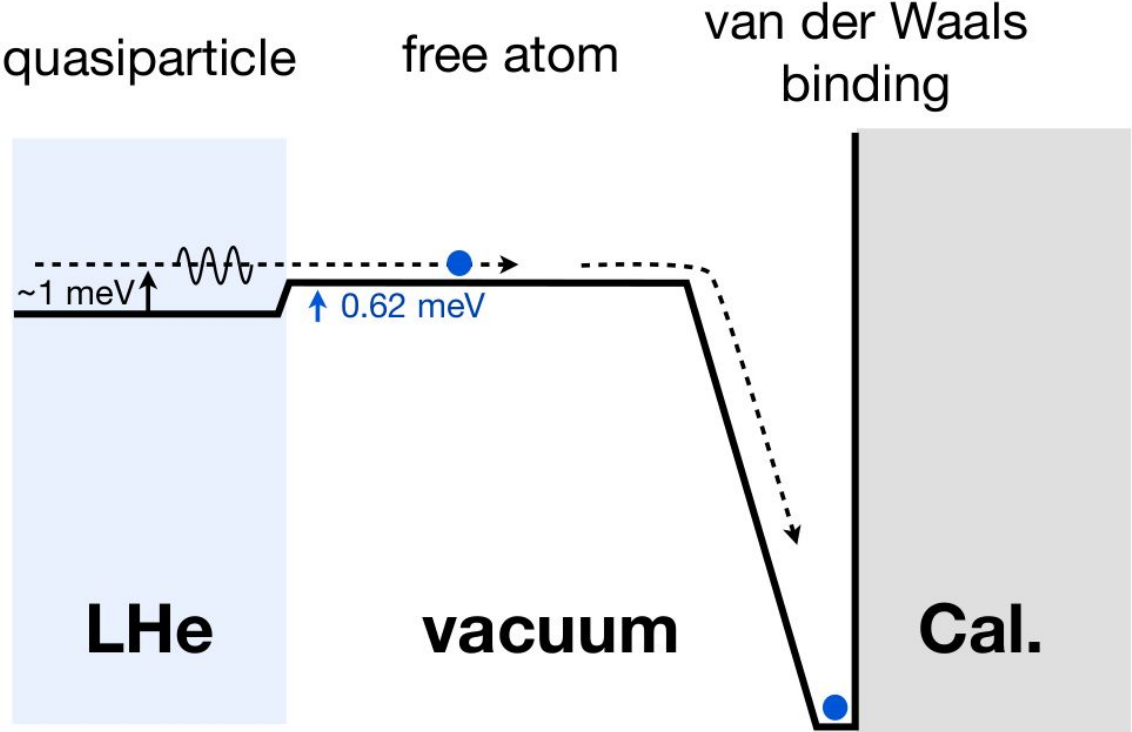
Quantum evaporation of a helium atom into vacuum, followed by energy deposit on top TES

# 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



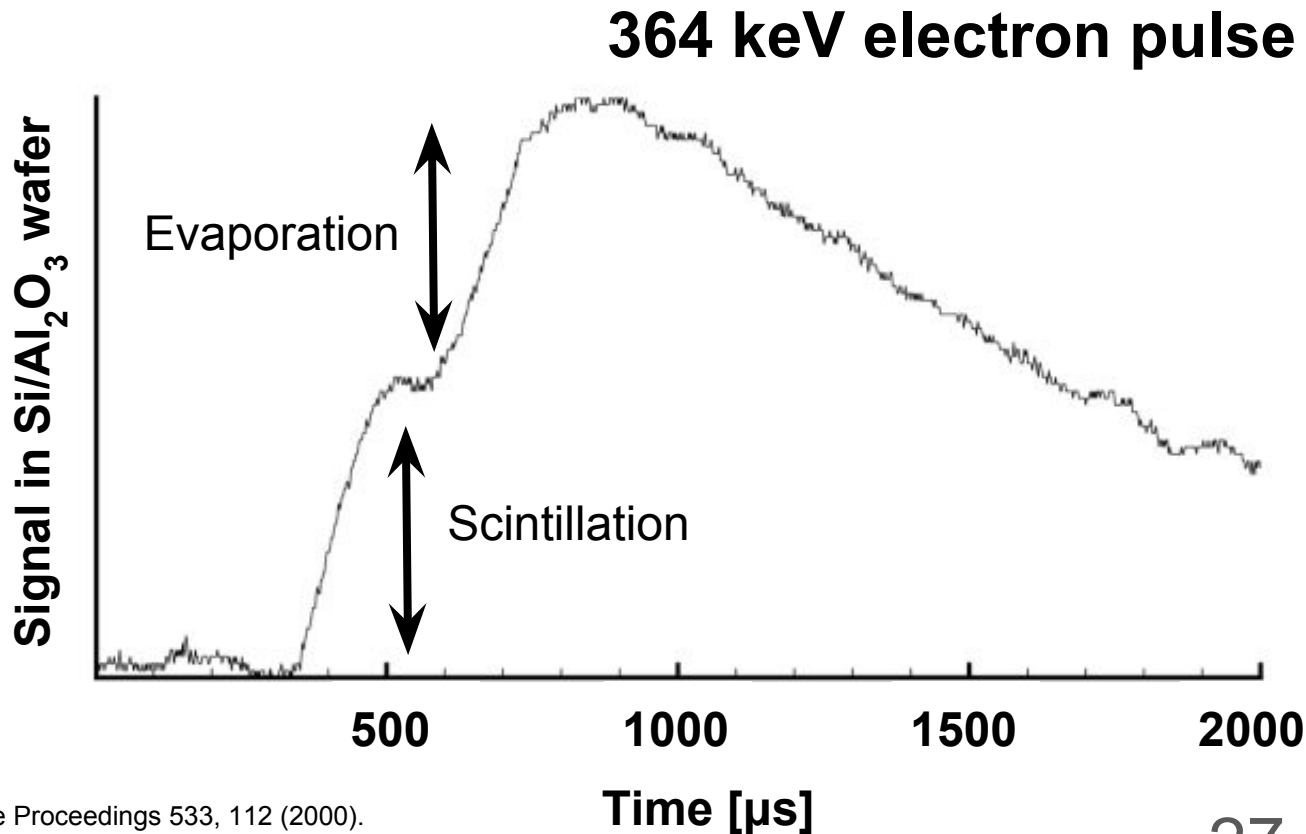
10s of meV

# Previous work by HERON

HERON: proposed  $pp$  neutrino observatory

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

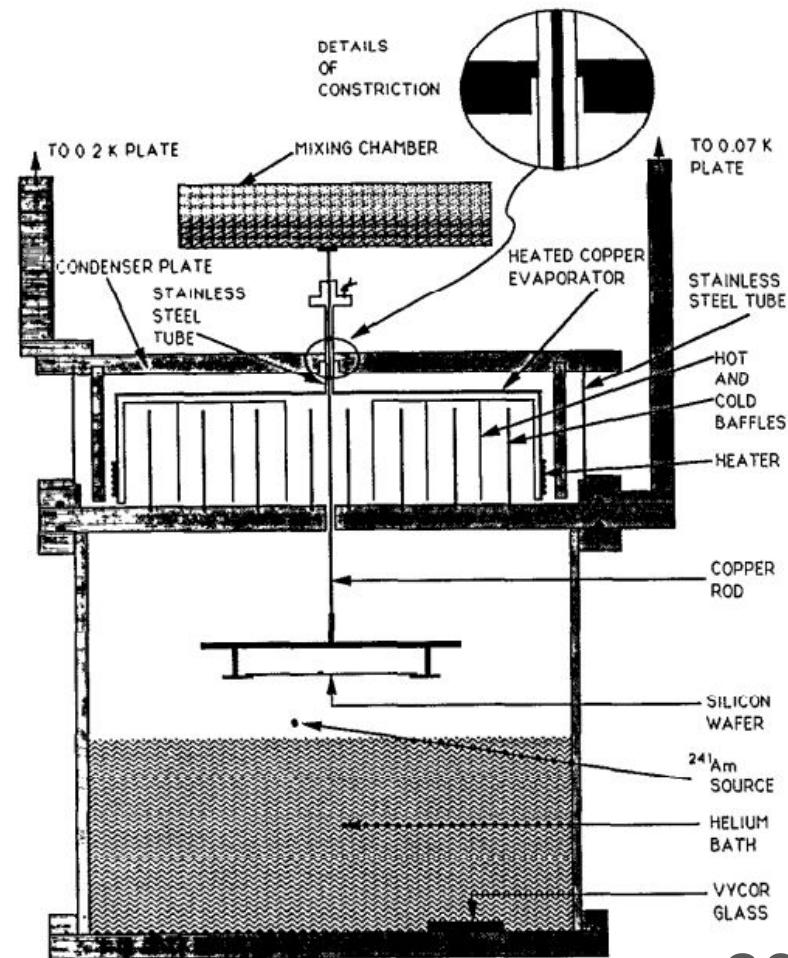
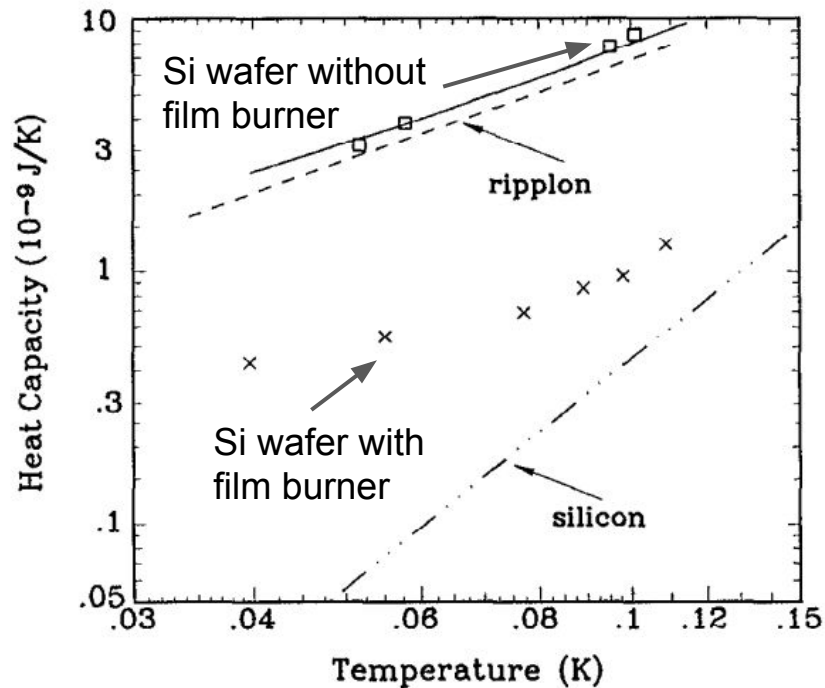
Achieved 300 eV threshold at 30 mK



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.

# Previous work by HERON

Successful operation of film burner



# Outline

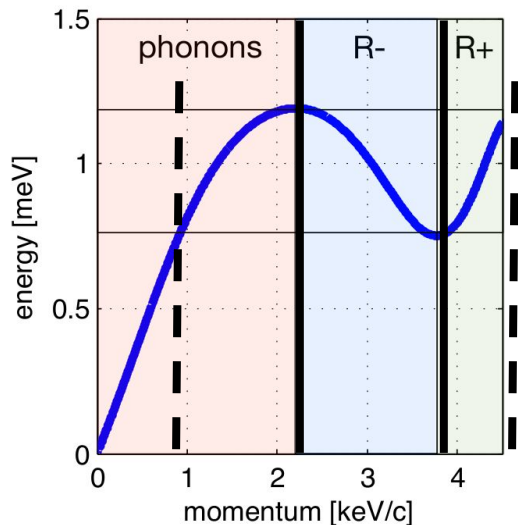
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# Quasiparticle Propagation

In  $^4\text{He}$  bulk, quasiparticles move freely

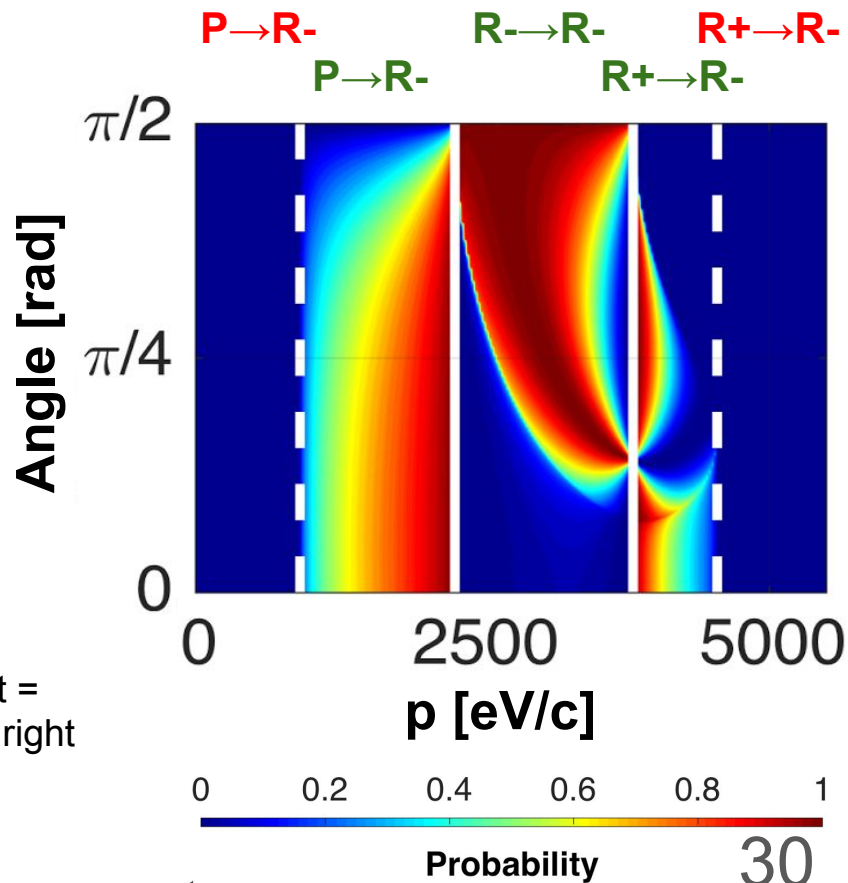
At interface, can be transmitted, reflected, or transformed (if E conserved)

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)



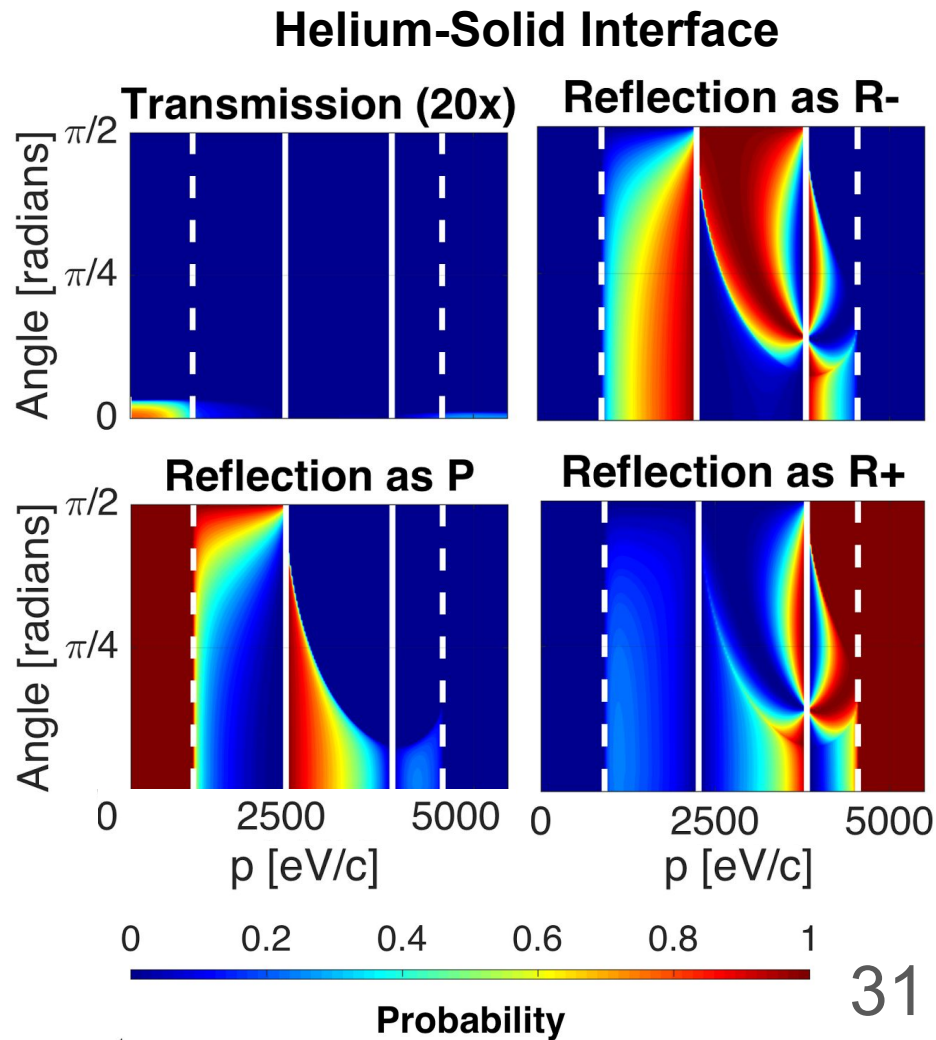
# Quasiparticle Propagation

Simulated all reflection/transmission probabilities †

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

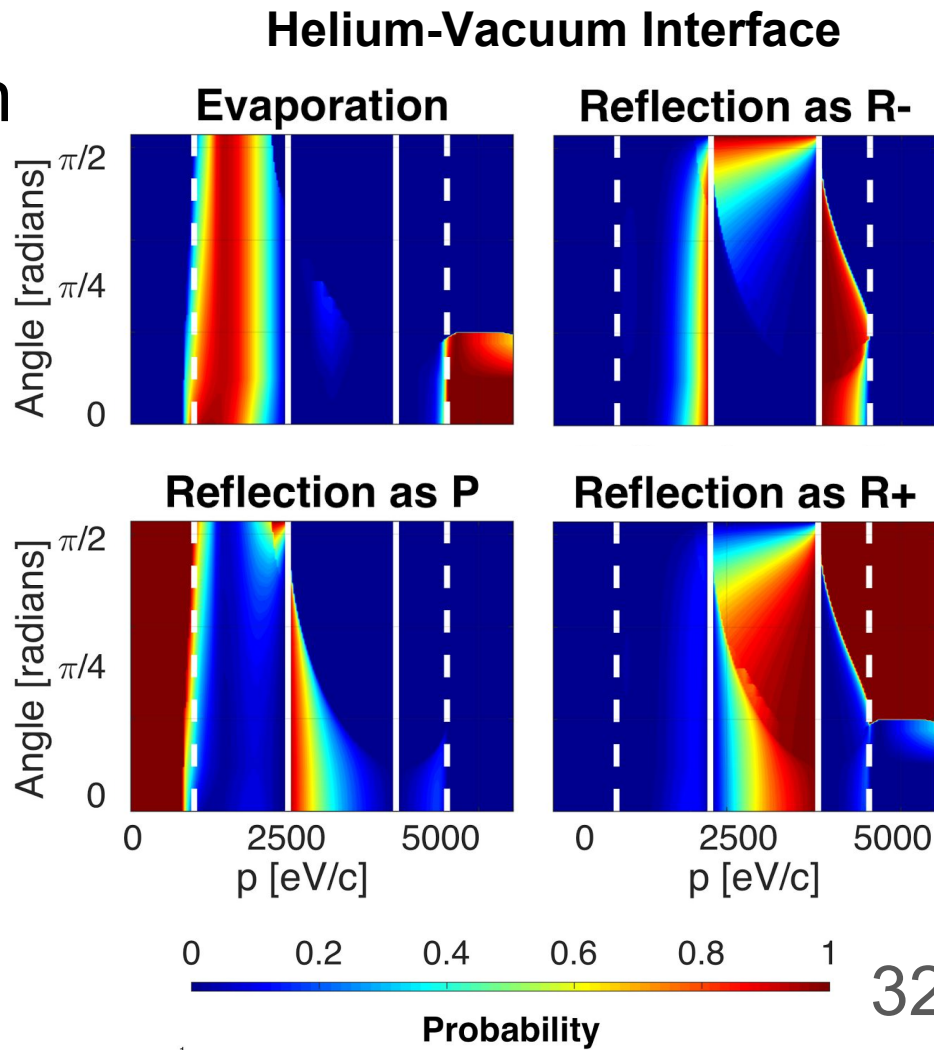
Reflection as same flavor most likely, but significant chance of changing flavor

† 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



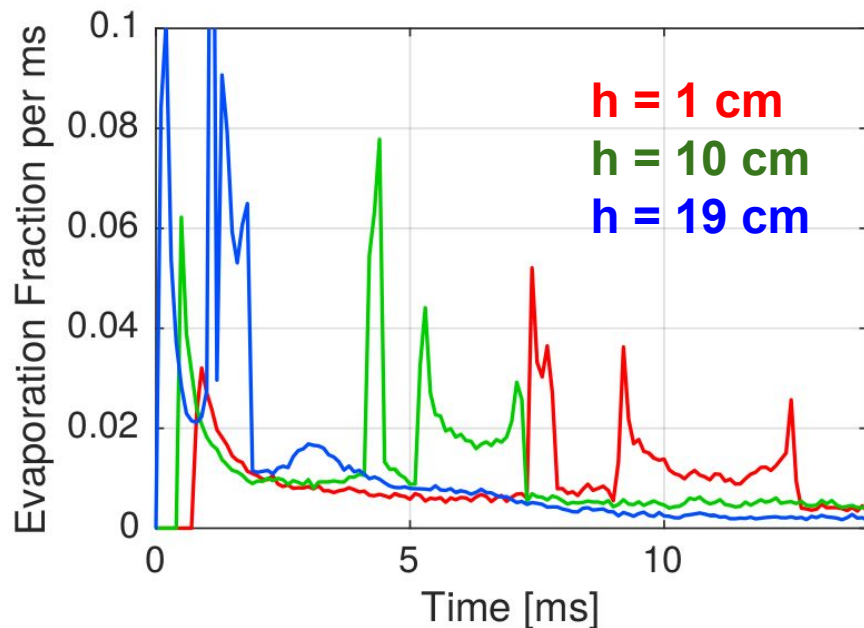


# Quantum Evaporation

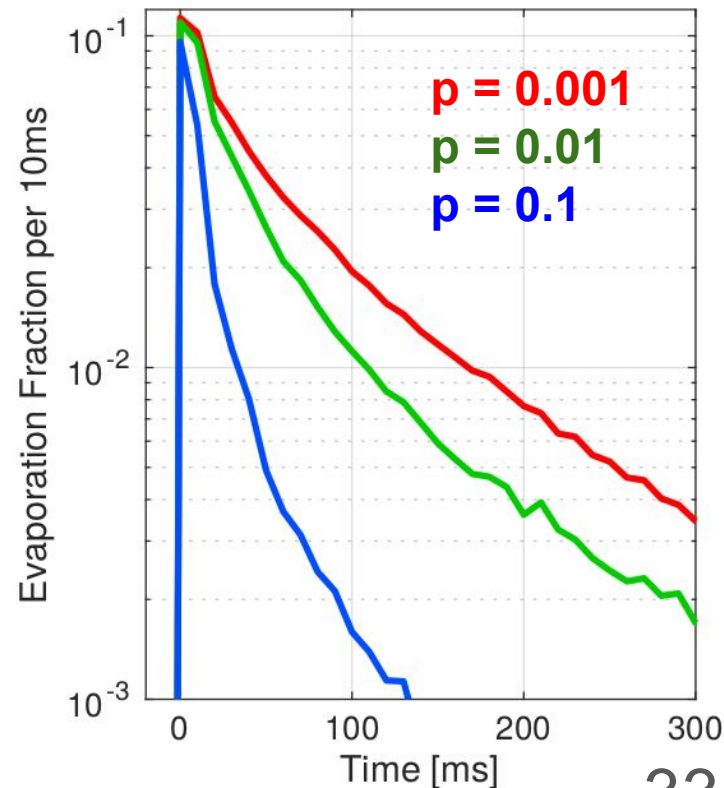
Simulated pulses from evaporation



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



Vary quasiparticle loss probability

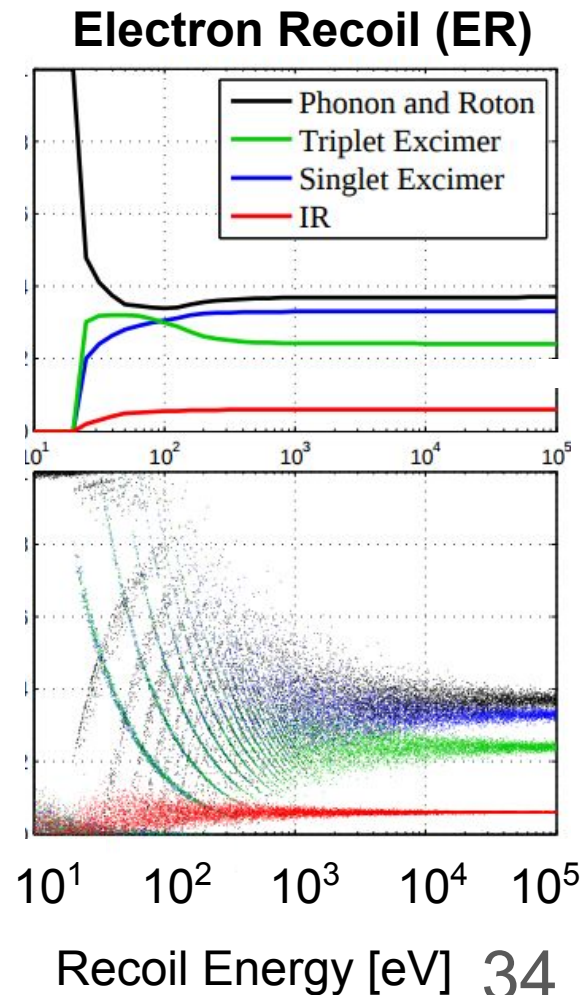
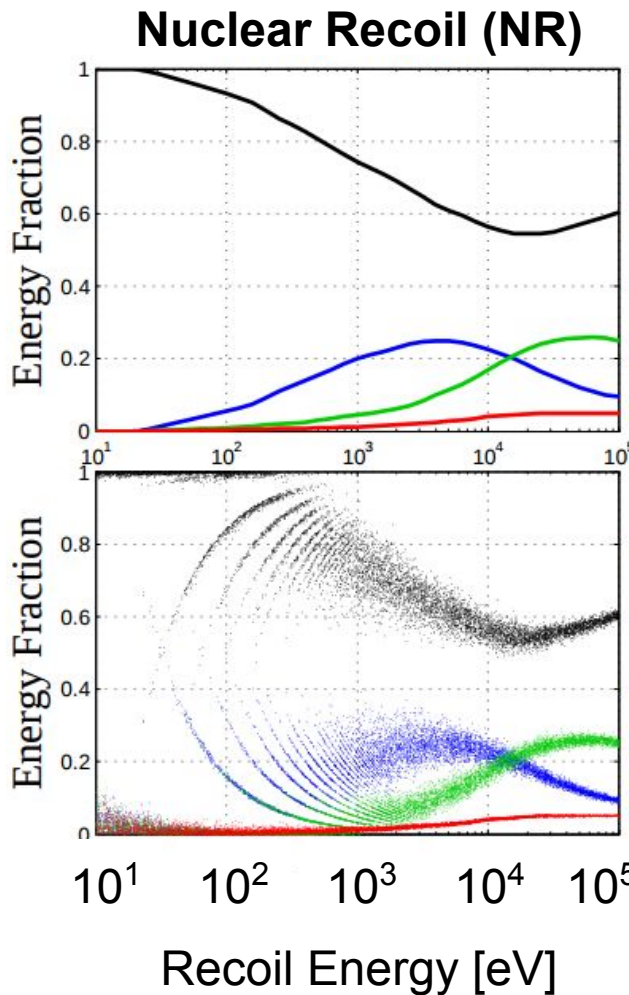


# Energy Partition

## Means

*From G. Seidel,  
unpublished;  
Extrapolated below  
100 eV*

## Poisson Fluctuations



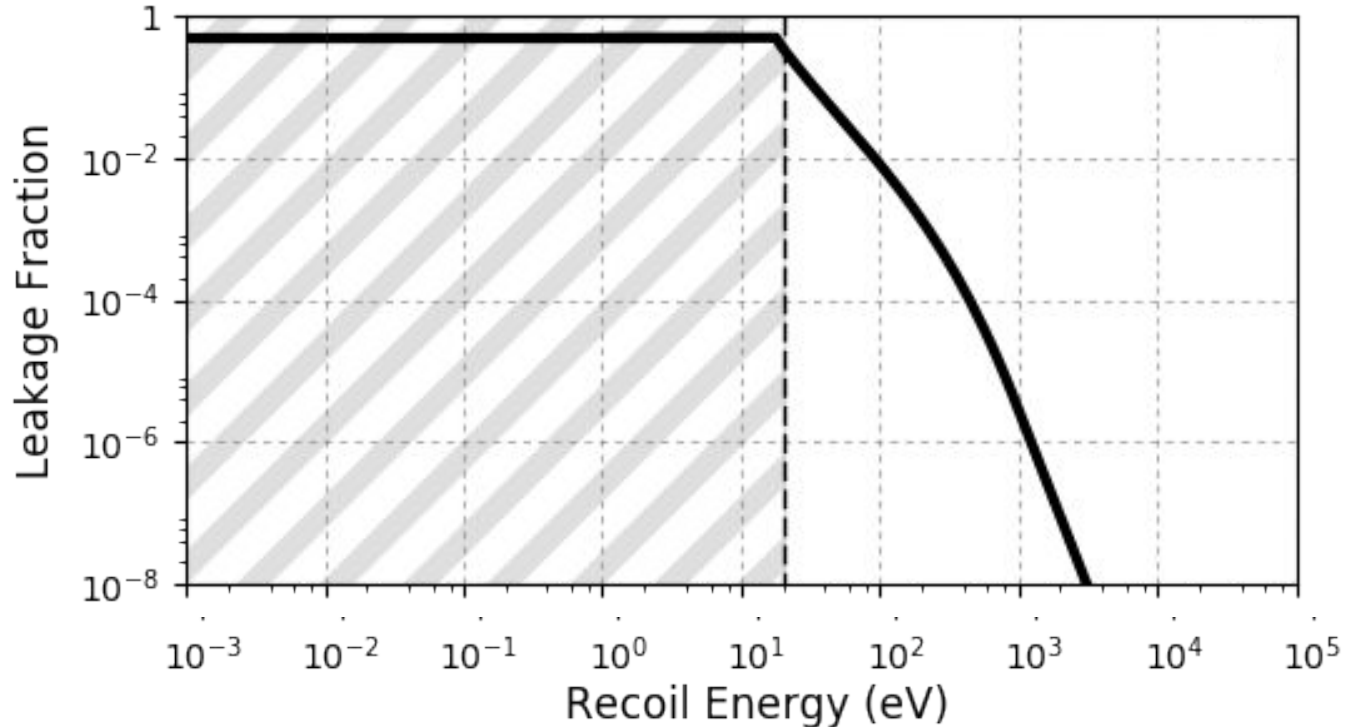
# Discrimination

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



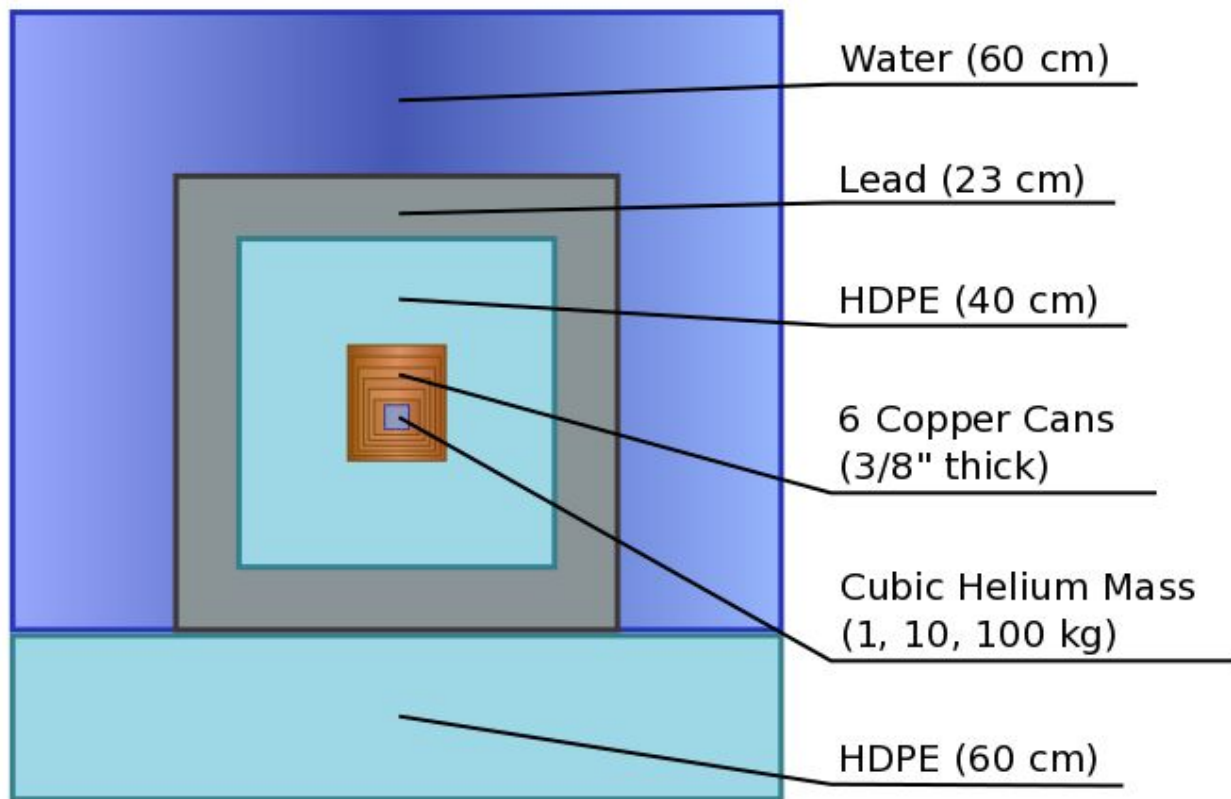
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# Backgrounds

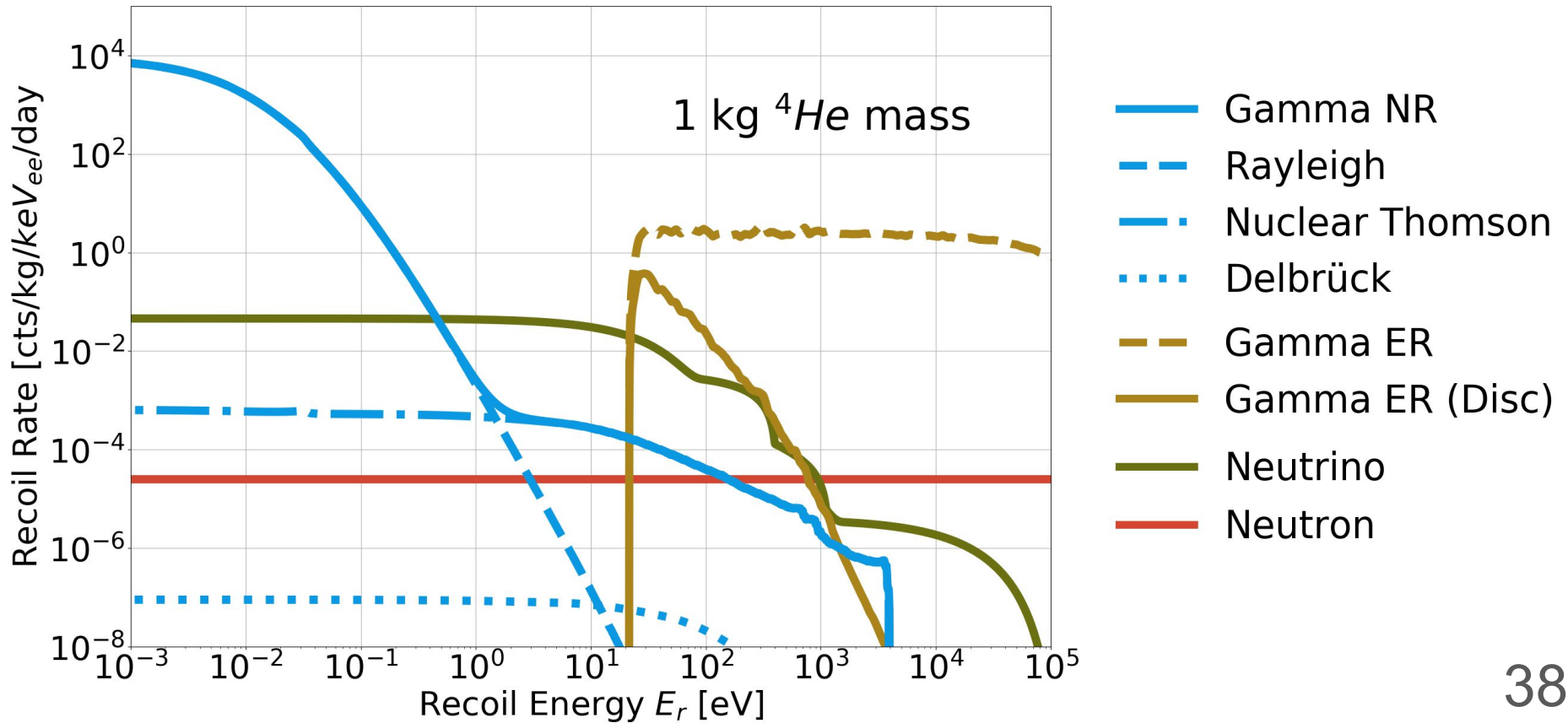
Shielding based on  
SuperCDMS SNOLAB  
projections †

Deep underground

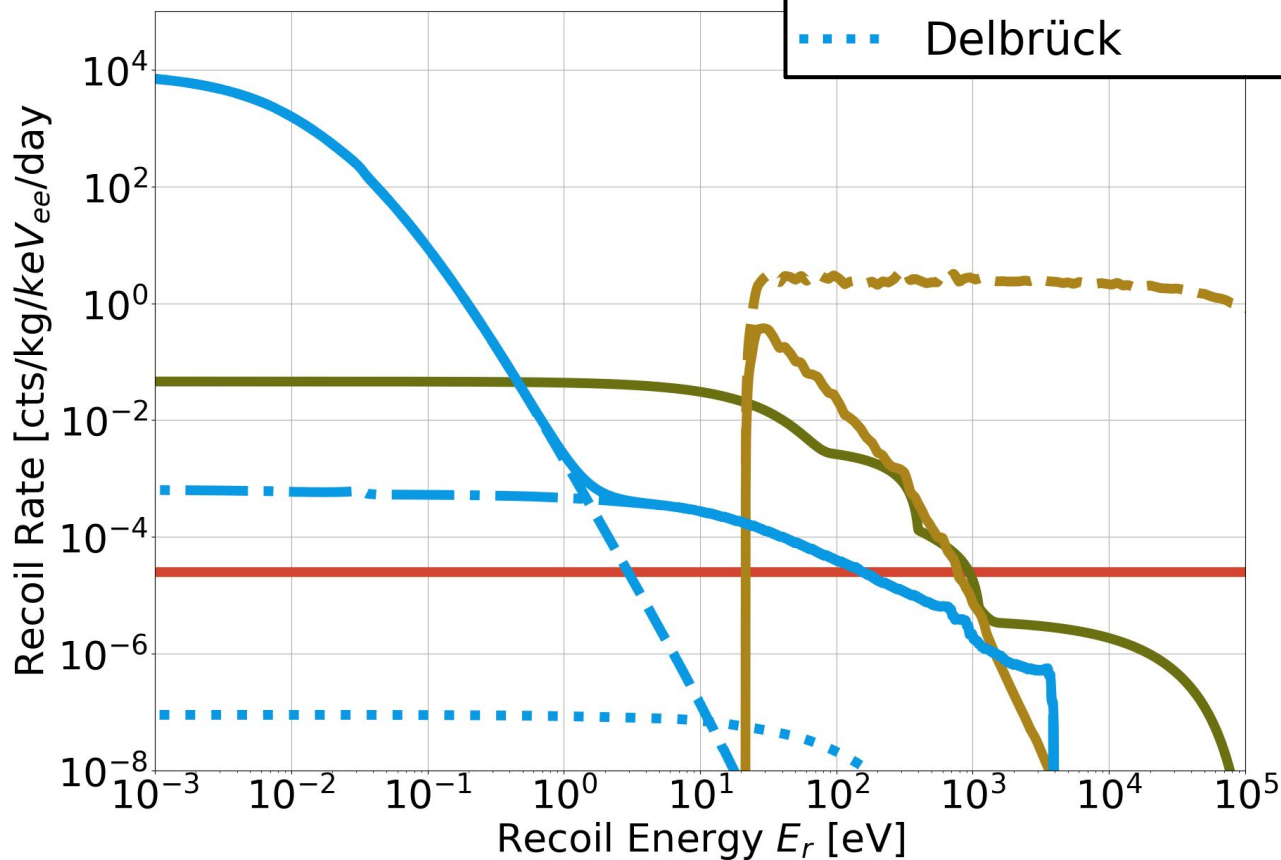


† *Phys. Rev. D* 95, 082002 (2017)

# Backgrounds



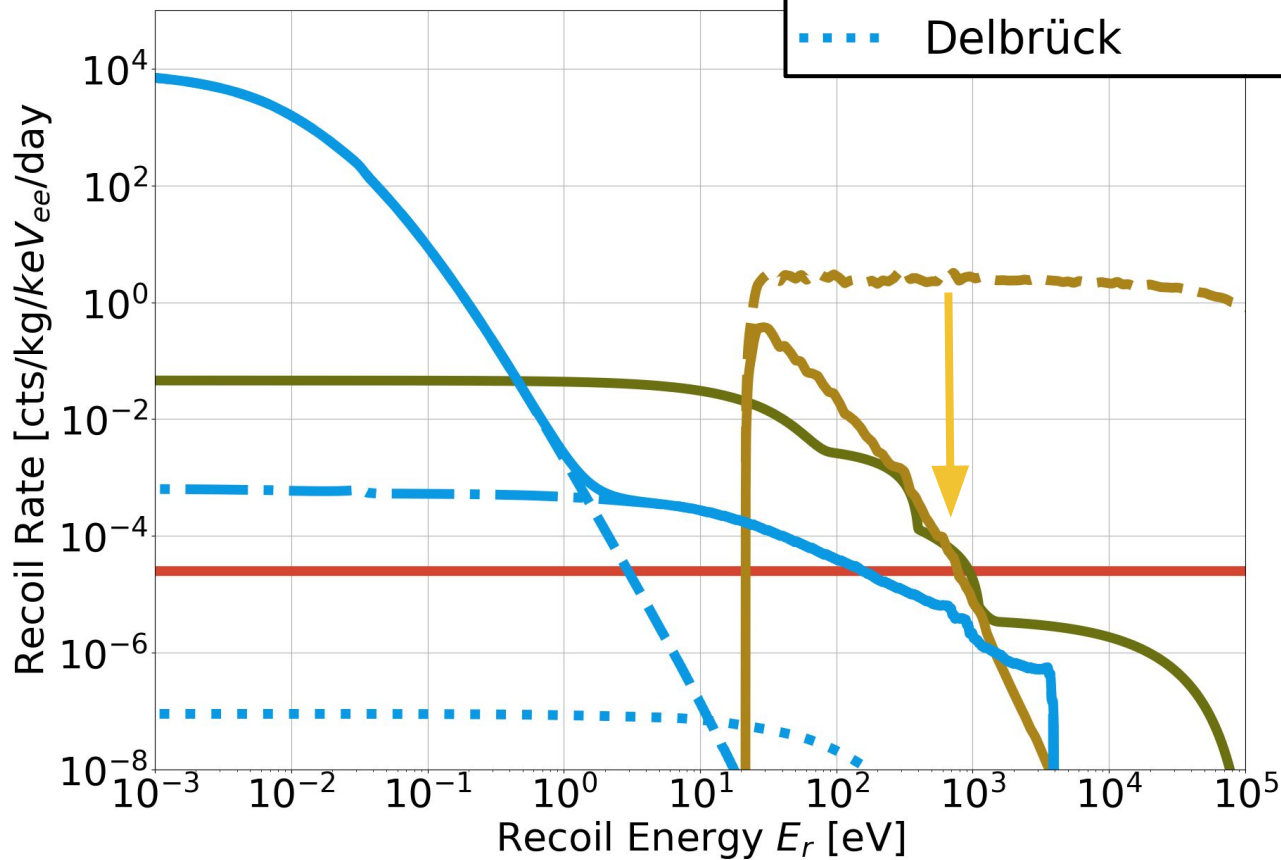
# Backgrounds



**Gamma  
backgrounds**

Coherent nuclear  
recoils via Rayleigh,  
Thomson, Delbruck  
scattering

# Backgrounds



**Compton  
background**

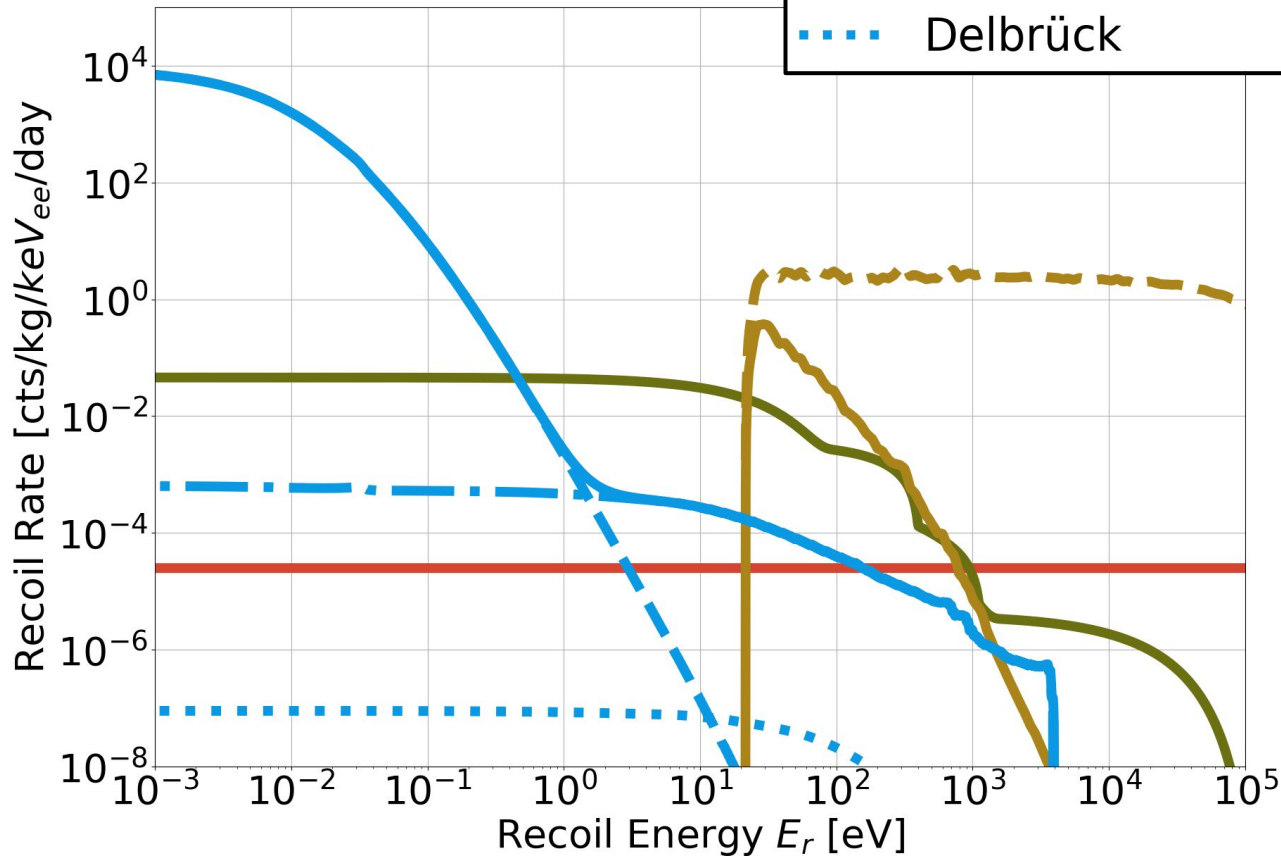
ER background:  
80 evts/kg/day

↓ Discrimination

0.06 evts/kg/day



# Backgrounds

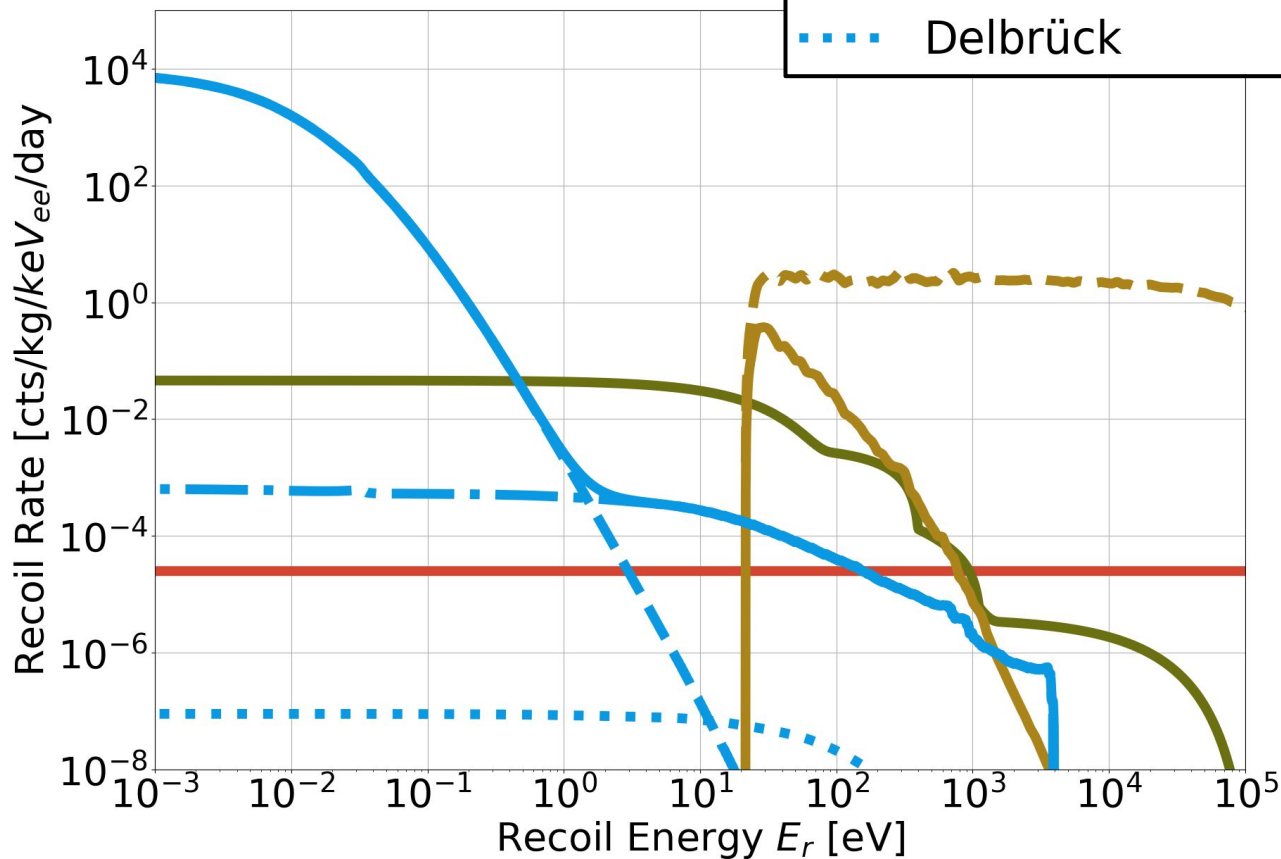


## Neutrinos

Coherent elastic neutrino-nucleus scattering (recently observed!)

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

# Backgrounds



Gamma NR  
Rayleigh  
Nuclear Thomson  
Delbrück

Gamma ER  
Gamma ER (Disc)  
Neutrino  
Neutron

## Neutrons

Approximately  
SuperCDMS SNOLAB  
projections

Not a dominant  
background; mostly  
outside search region

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# Projected Sensitivity

**Red:** Projected sensitivity of superfluid  $^4\text{He}$  detector

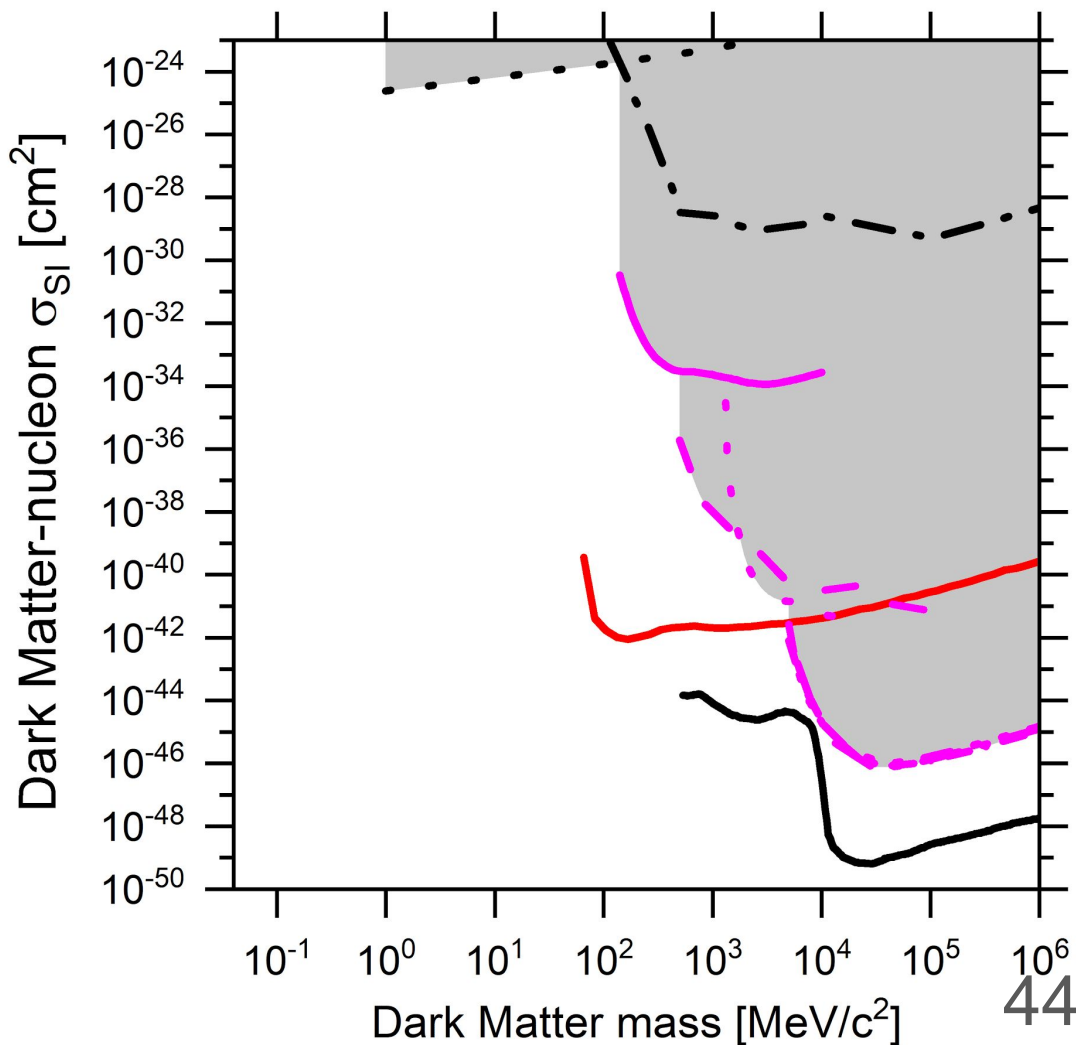
- 10 eV recoil threshold
- 1 kg-yr exposure
- “Shovel-ready”; existing technology

**Black Solid:** Neutrino floor in Xe

**Grey Shaded:** Currently excluded parameter space

**Black Dashed:** Excluded by CMB measurements and XQC

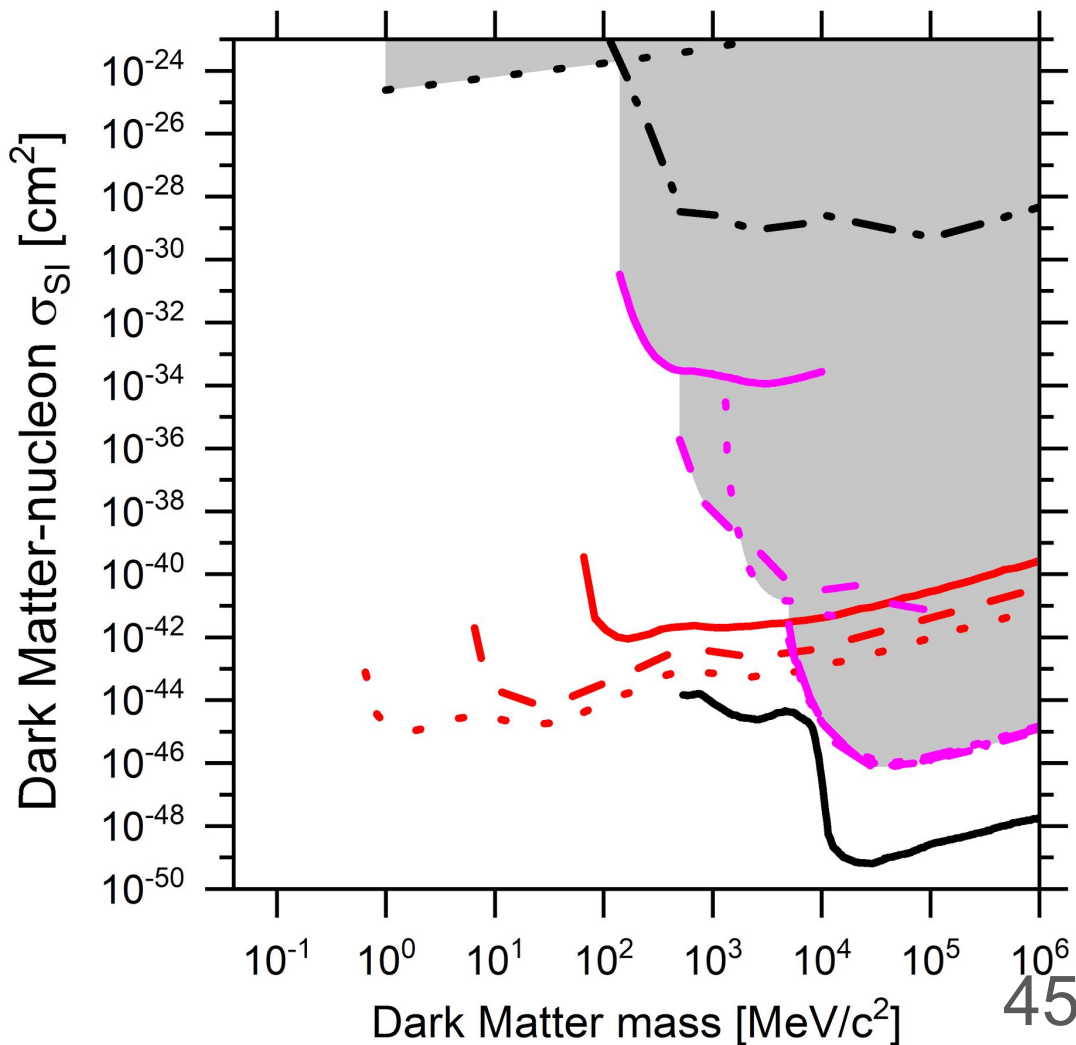
**Magenta:** Excluded by standard NR experiments



# Projected Sensitivity

**Red Dashed:** Two more generations of superfluid  $^4\text{He}$  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)

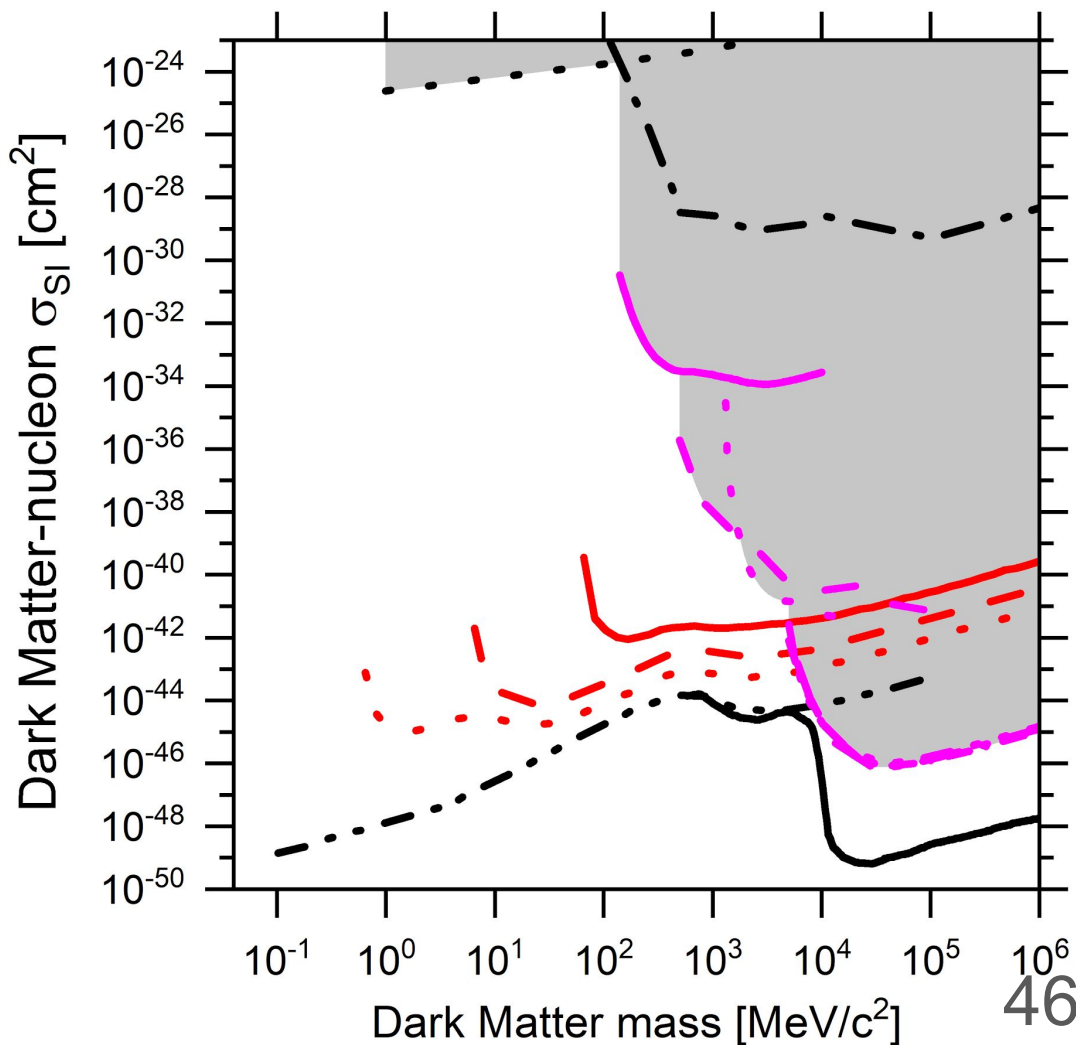


# Projected Sensitivity

**Black Dashed:** Extended neutrino floor to  $\sim 100$  keV

Used coherent interactions of solar neutrinos with helium

Dominated by  $pp$  and  ${}^7\text{Be}$  neutrinos

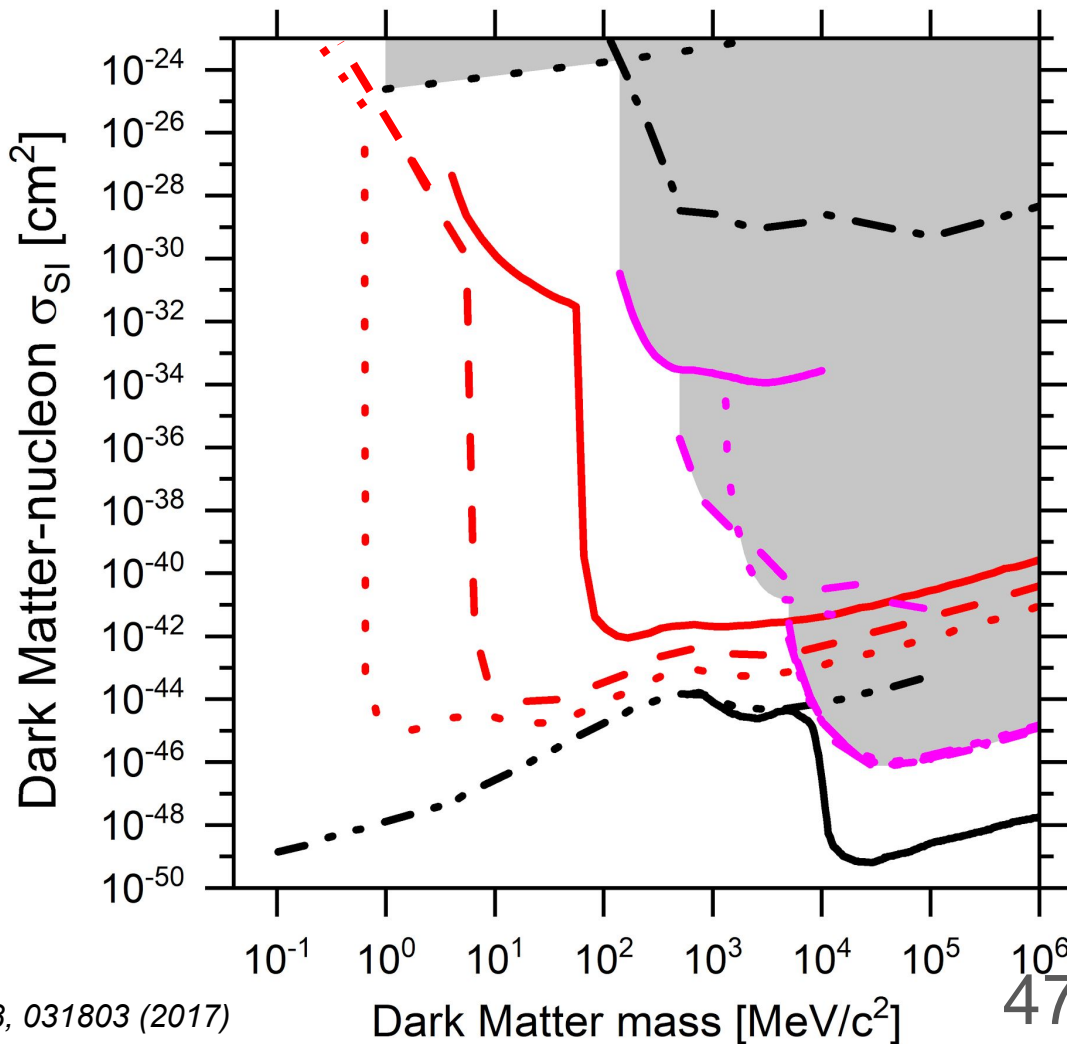
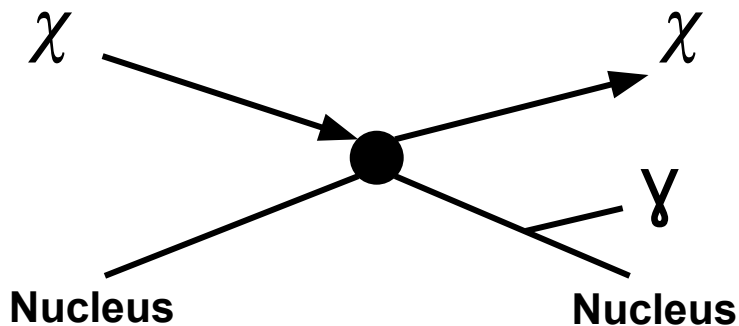


# Projected Sensitivity

**Red Extension:** Nuclear bremsstrahlung signal

Nucleus de-excites, releasing photon of arbitrarily low energy

Phase space suppression

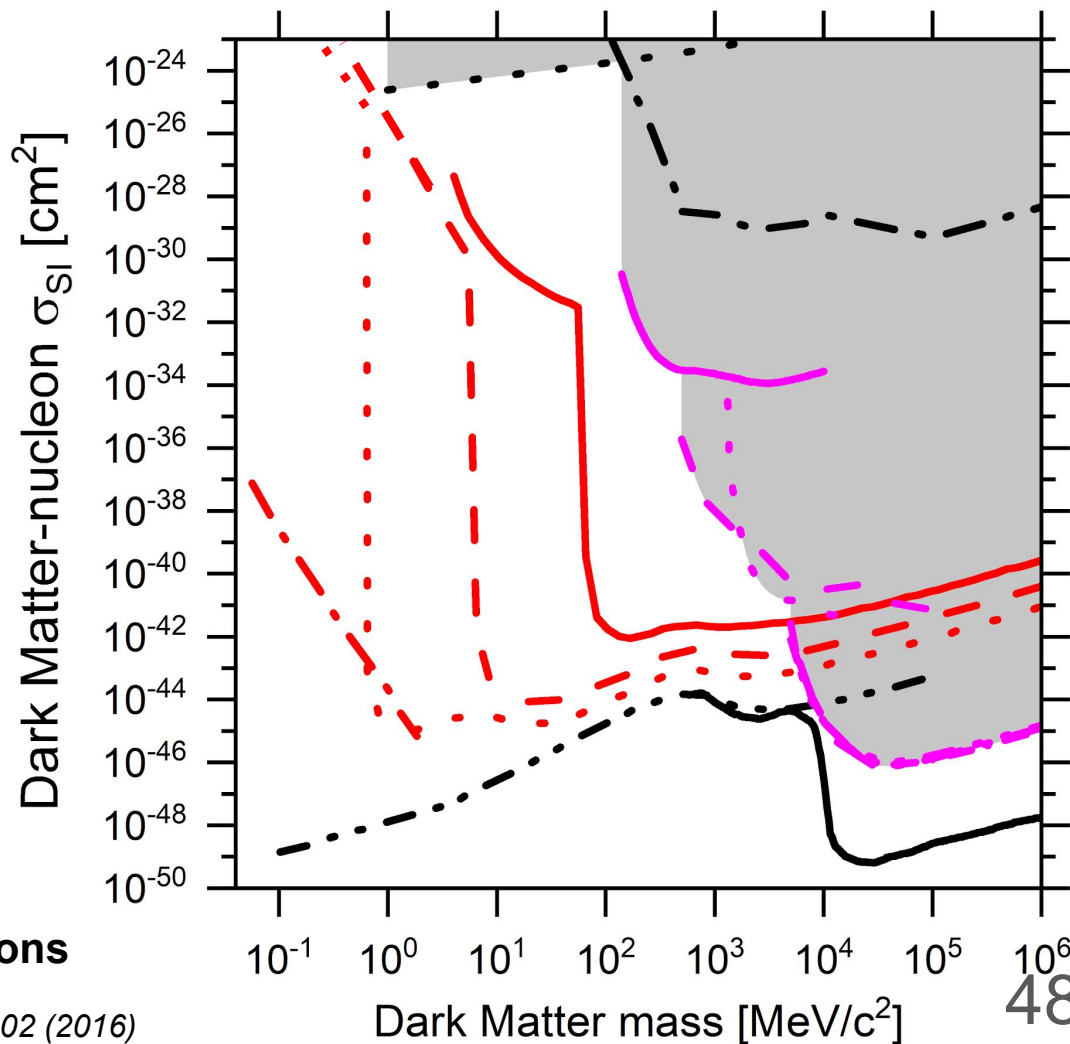
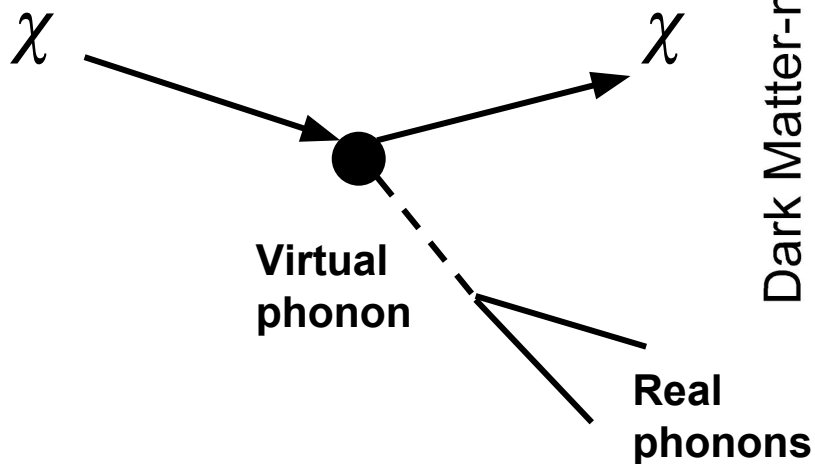


See: C. McCabe. *Phys. Rev. D* 96, 043010 (2017).  
C. Kouvaris and J. Pradler. *Phys. Rev. Lett.* 118, 031803 (2017)

# Projected Sensitivity

**Red Dot-Dashed:** Two-Phonon Excitation

Access to lowest DM masses





# Projected Sensitivity

**Red Upper Curves:** Earth  
Shielding

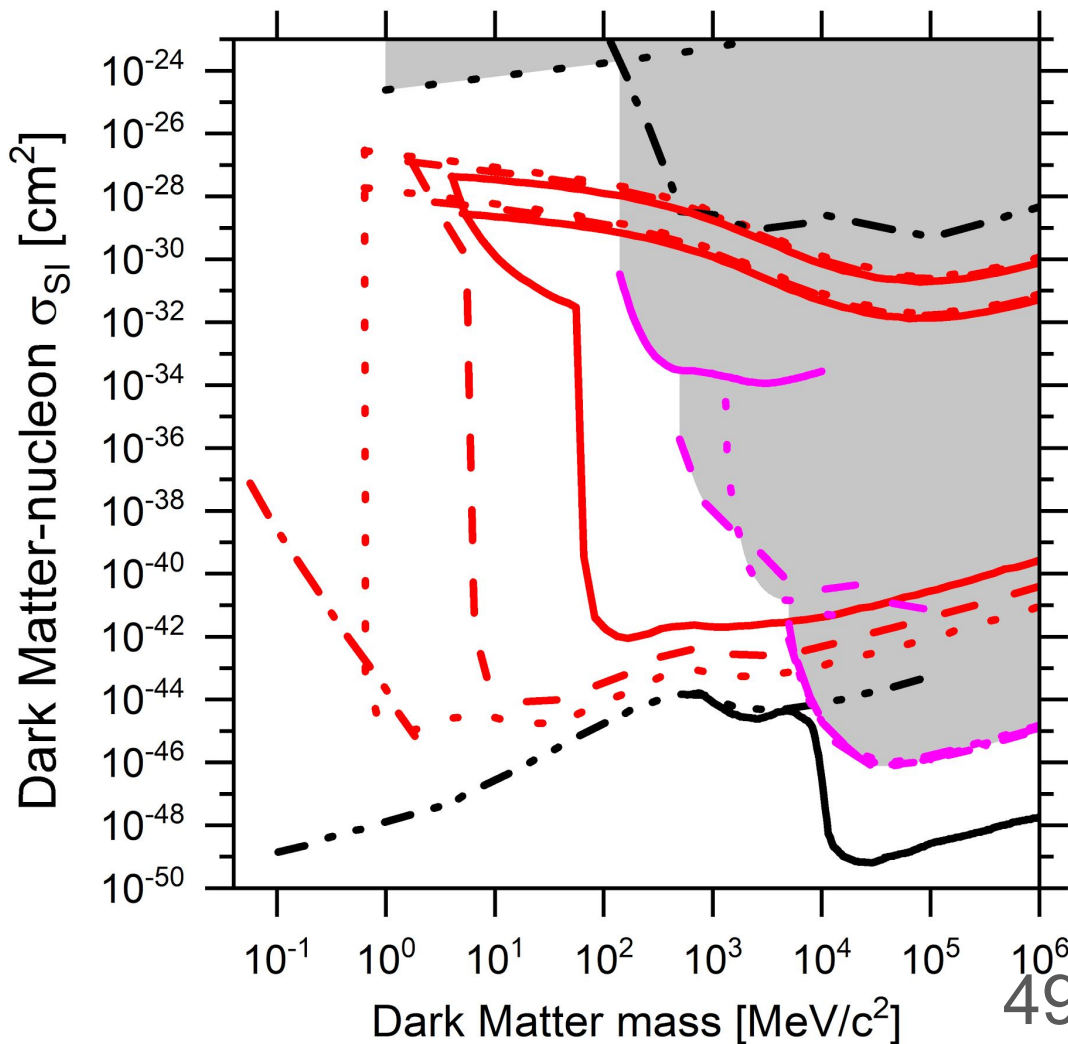
If  $\sigma$  is high, DM can scatter in the  
Earth and lose kinetic energy  $\rightarrow$   
below experiment threshold

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)*



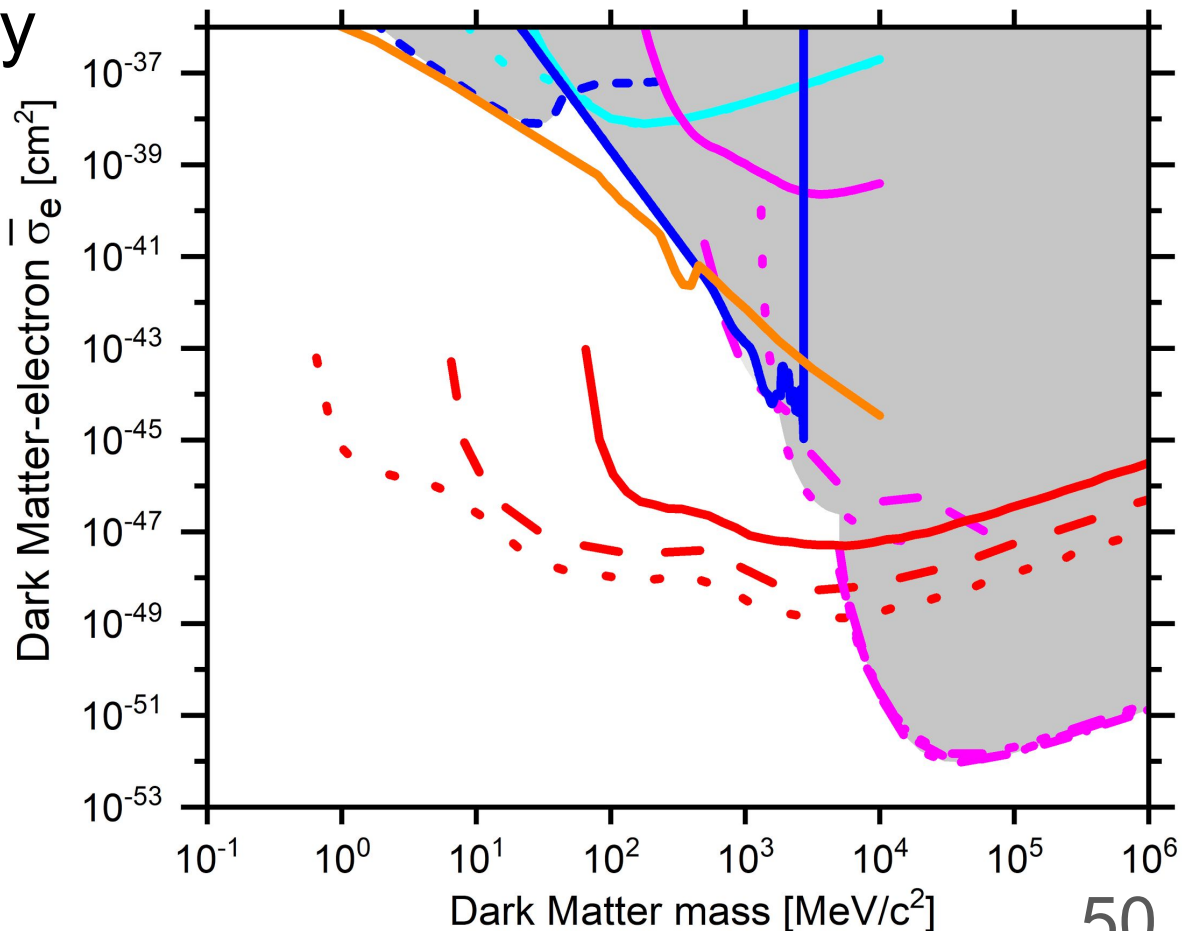
# Projected Sensitivity

**Other force carriers: dark photon**

Additional U(1) symmetry in dark sector, kinetic mixing with EM field

Heavy vector particle can be mediator for DM-nucleus scattering

DM-nucleon + DM-electron scattering both allowed; equal coupling



# Projected Sensitivity

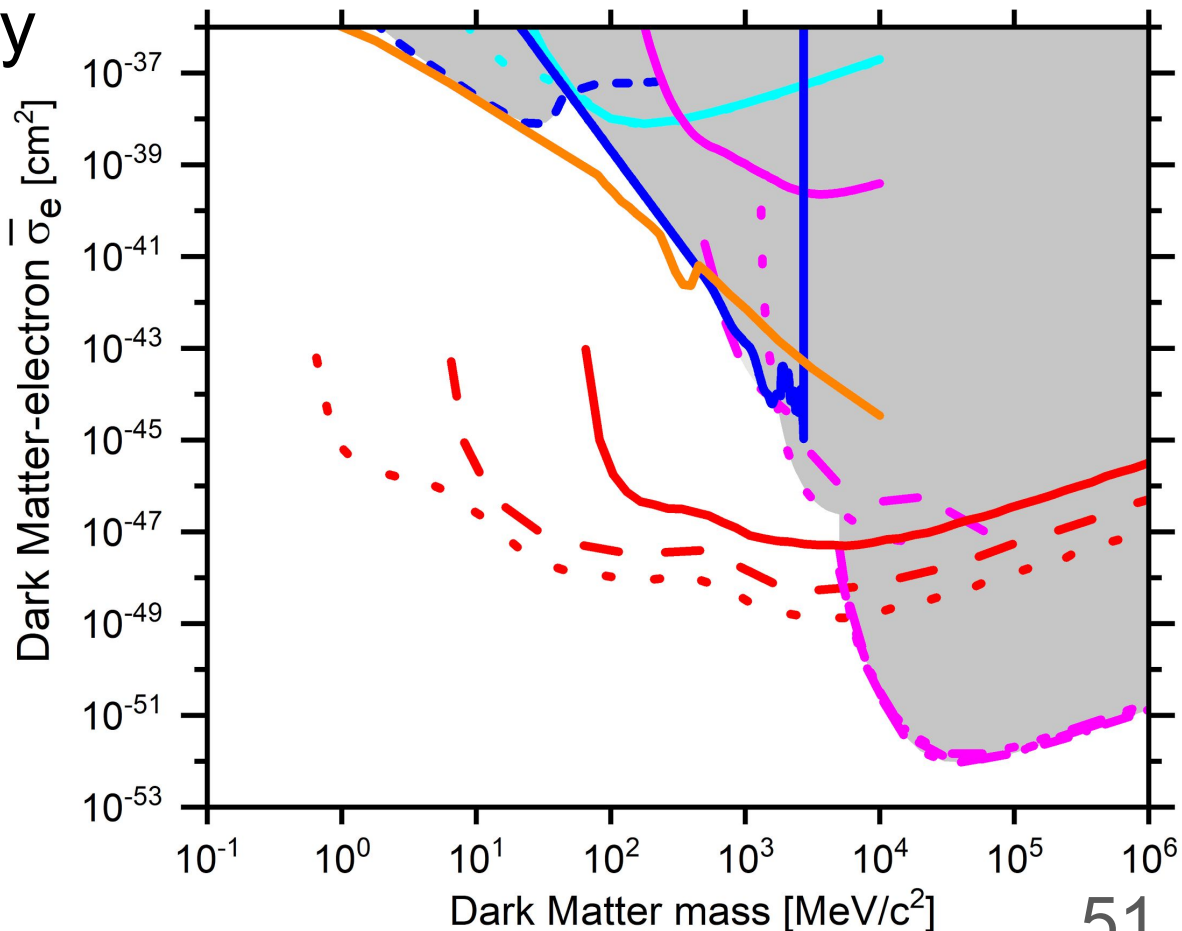
**Red:** Three generations of superfluid  $^4\text{He}$  detector

**Grey Shaded:** Currently excluded parameter space

**Magenta:** Excluded by standard NR experiments

**Cyan:** Direct constraints on  $\sigma_e$  by XENON10/100

**Blue:** Indirect constraints by BaBar, E137, LSND



# Conclusion

- Superfluid  $^4\text{He}$  offers a cheap, practical, and powerful target for probing new dark matter interactions
- Existing technology (HERON; advancements in calorimetry by CDMS, CRESST, etc.)
- Paper in progress...stay tuned!

