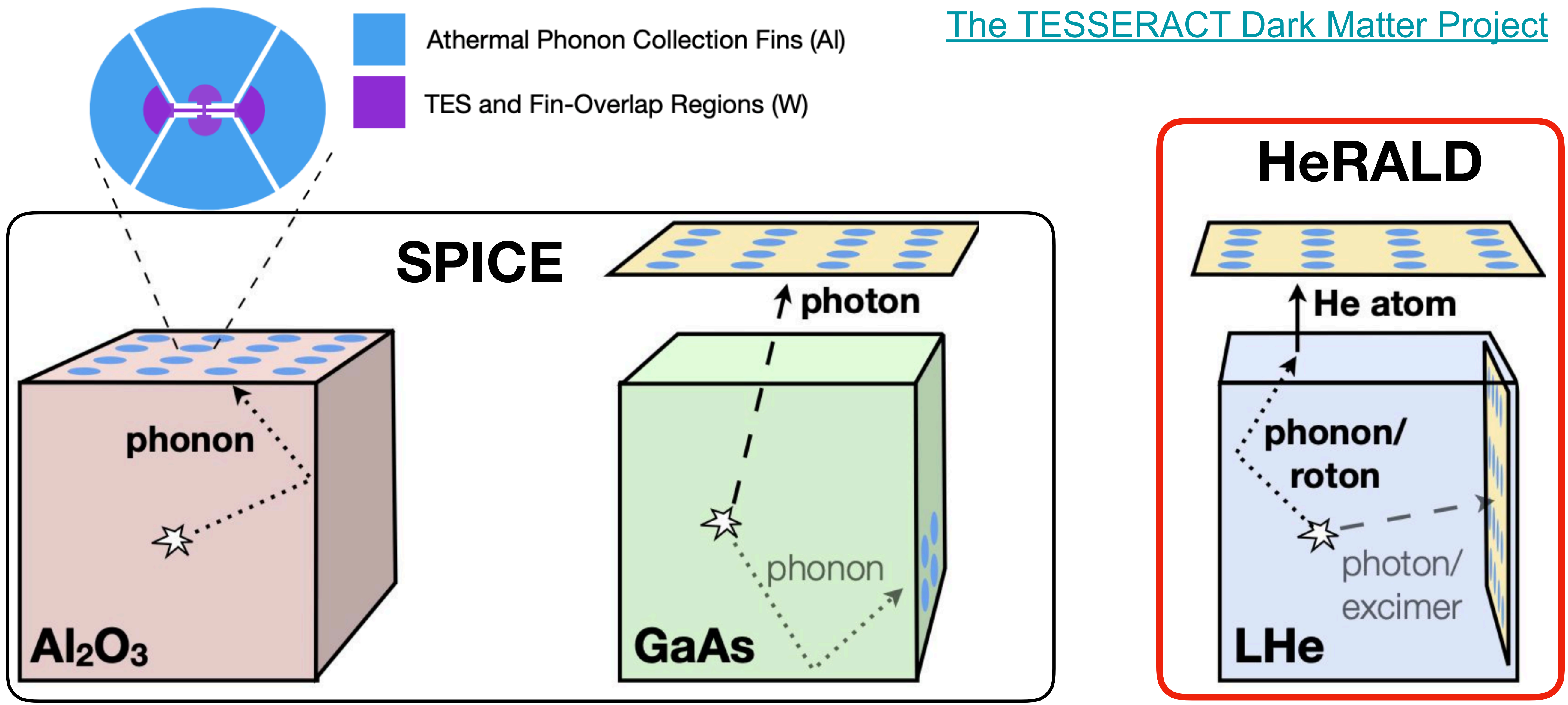
HeRALD: Dark Matter Direct Detection with Superfluid ^4He

Pratyush Patel (University of Massachusetts, Amherst)

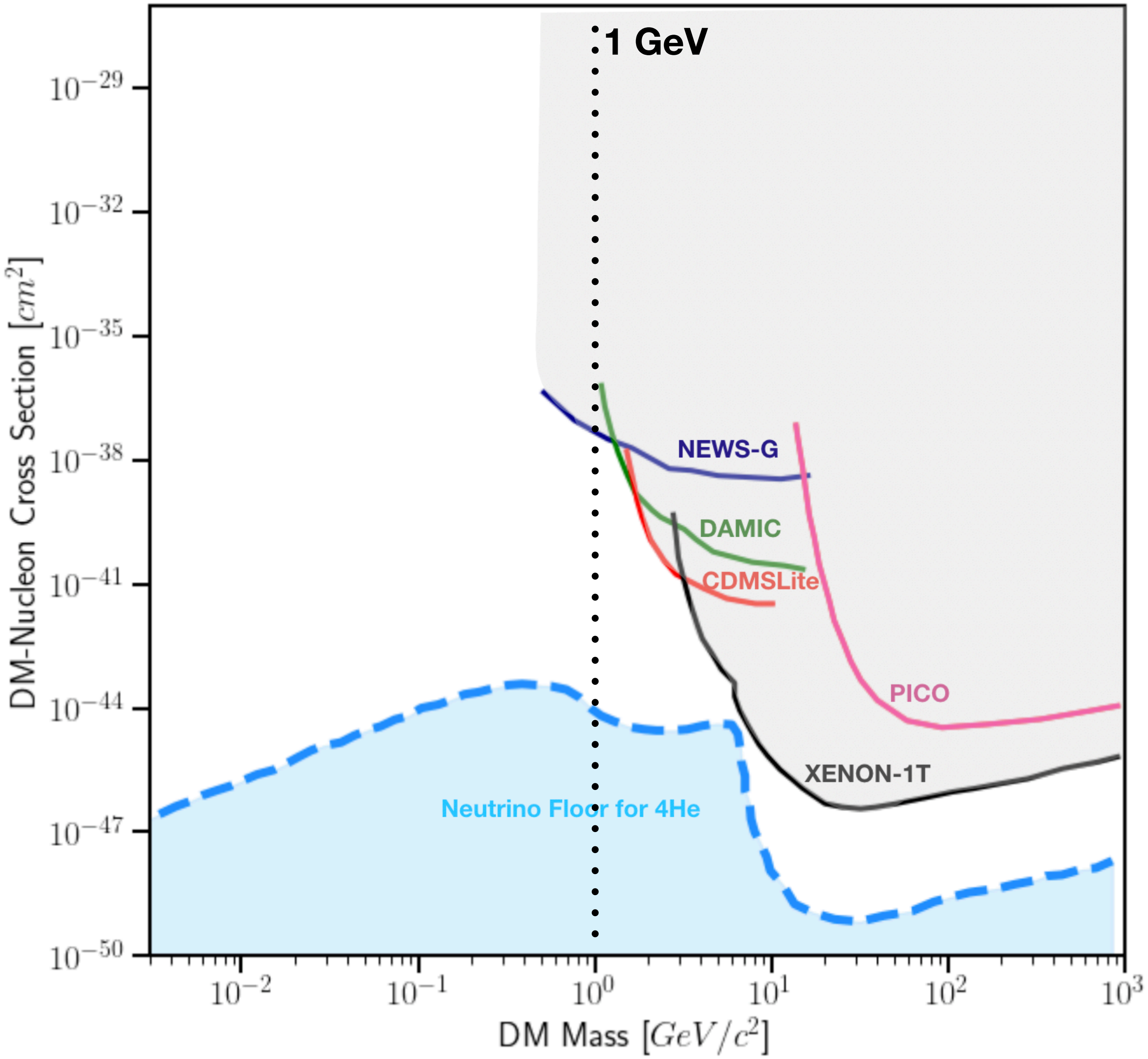
For the SPICE/HeRALD Collaboration

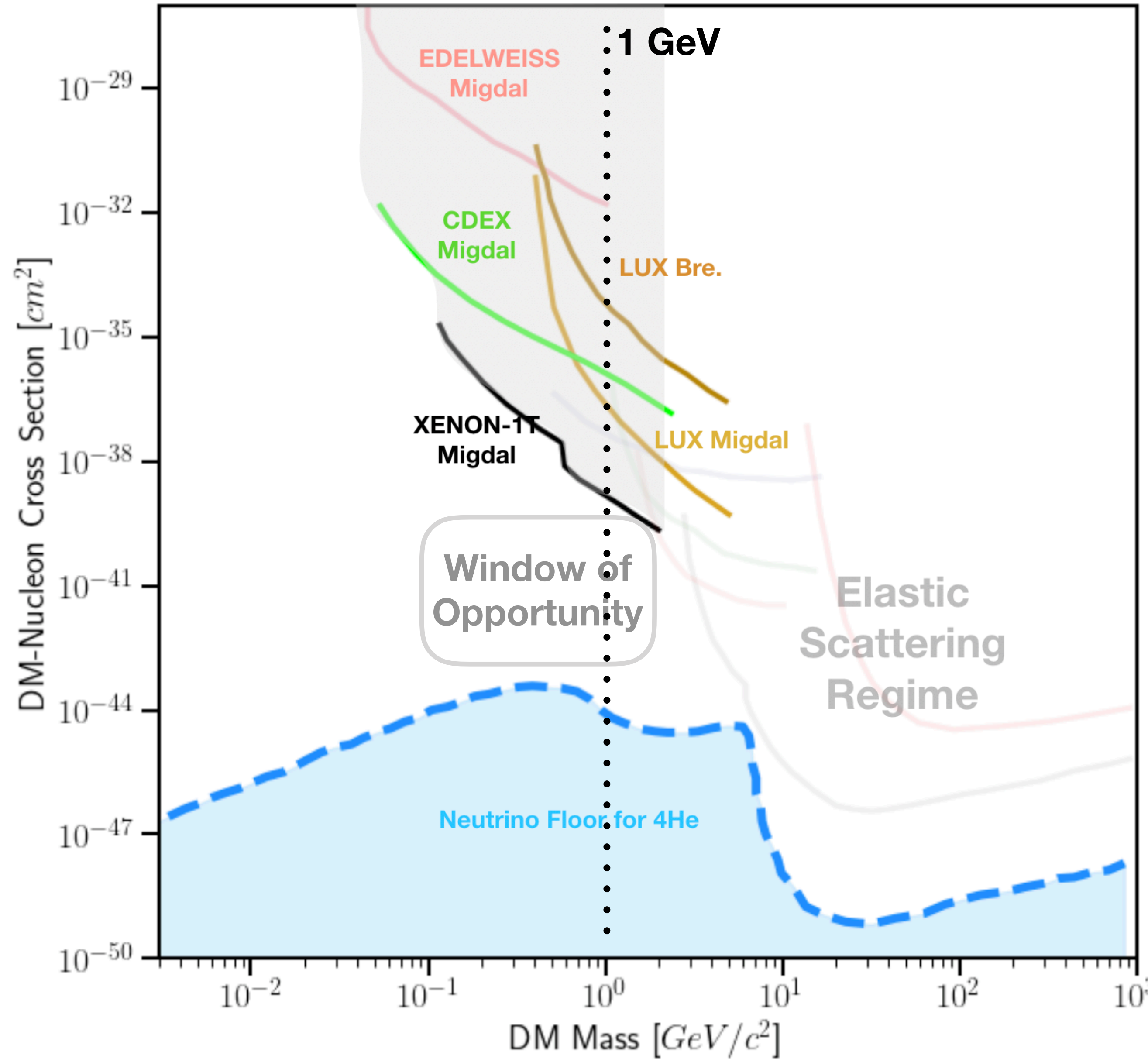
SPICE/HeRALD Collaboration

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



Spin Independent DM-Nucleon search



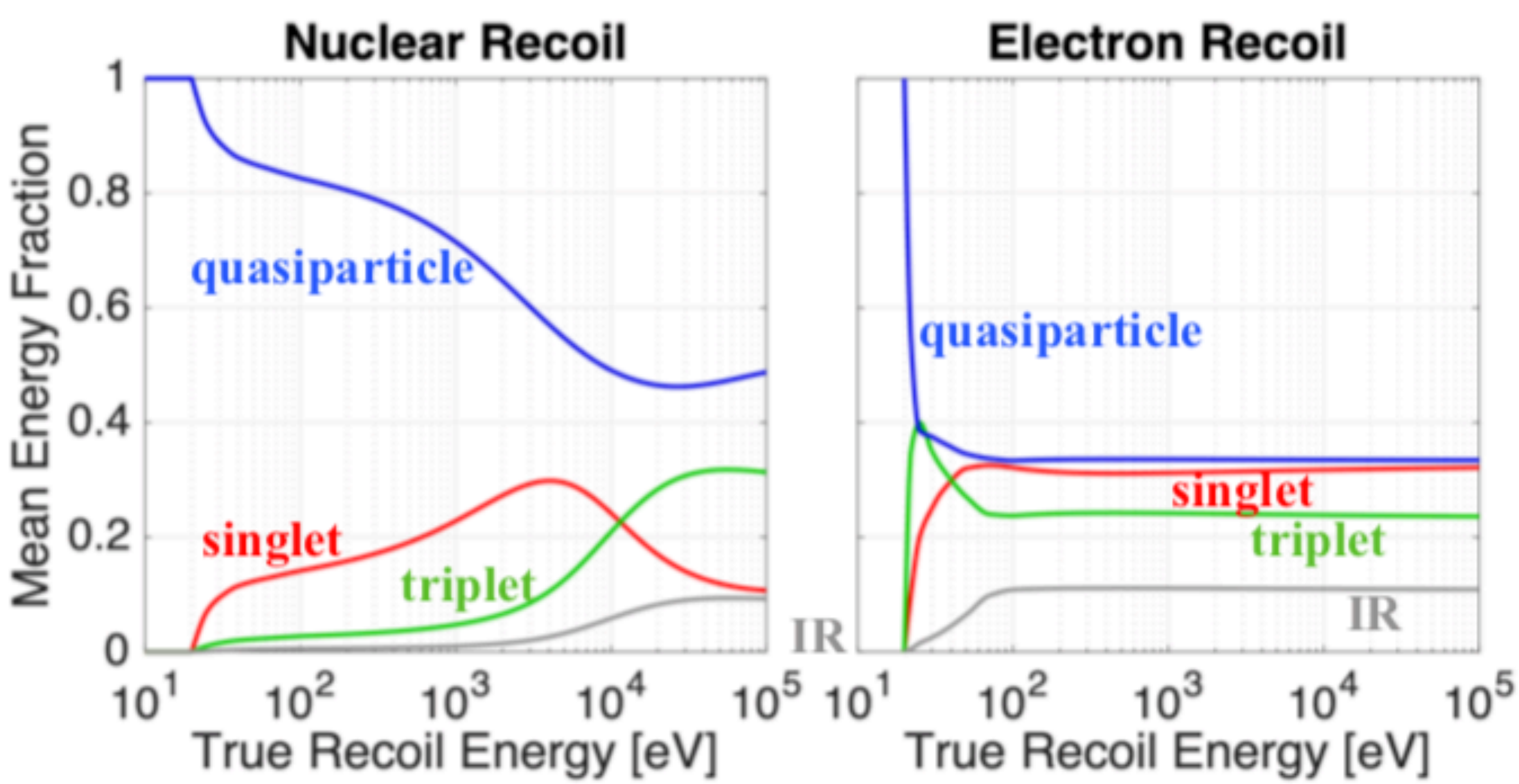


- World leading DM-Nucleon(Spin Independent) limits using different experimental techniques.
- Reach to sub-GeV scale is achieved via second order process like Migdal effect and Bremsstrahlung.
- Probe lower cross-section with upcoming new target materials and technology.

Why Superfluid ^{4}He?

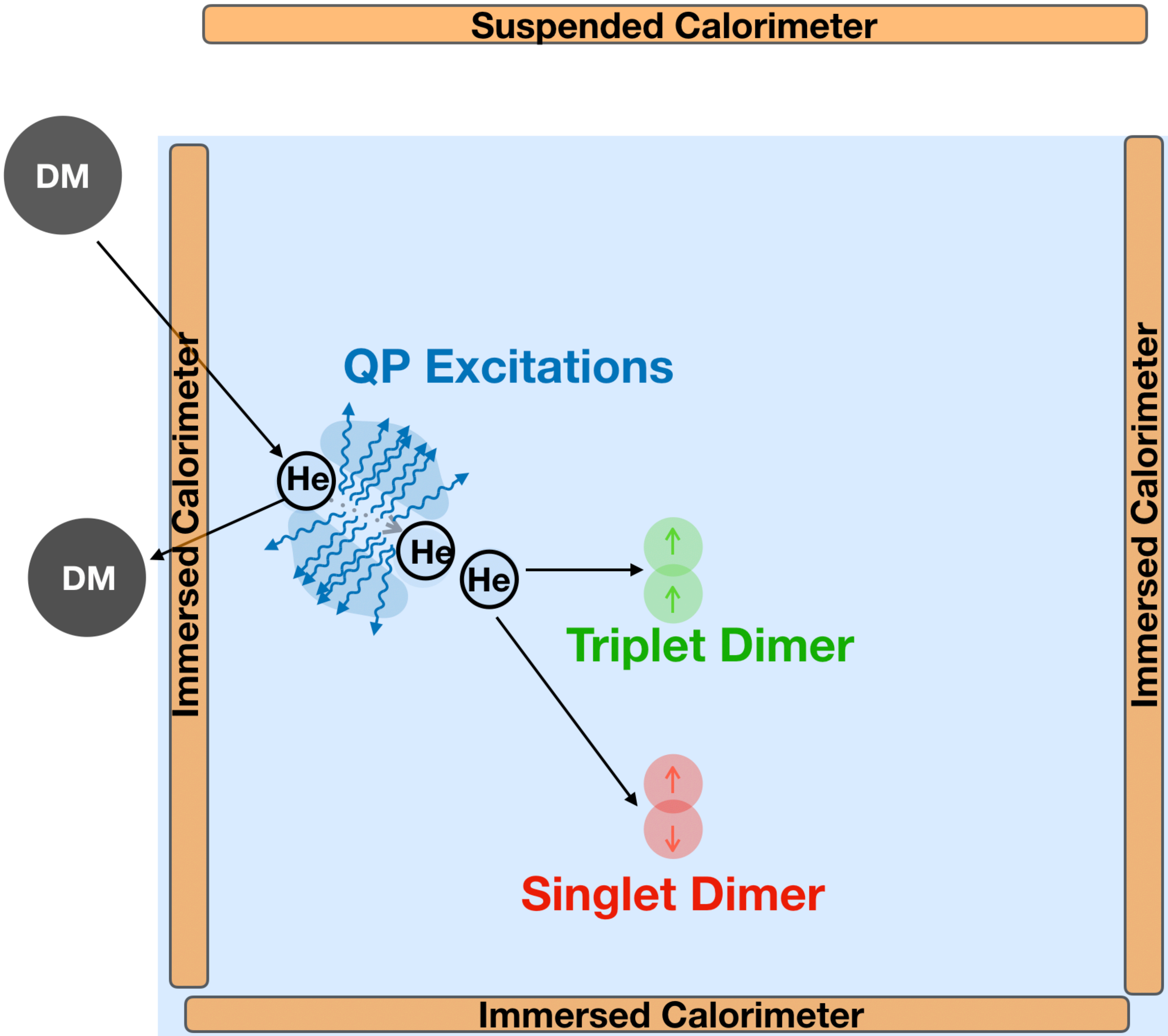
PhysRevD.100.092007

- Chemically pure and liquid at mK temperature
- Multiple excitation signal, enabling NR-ER discrimination
- Free of lattice defect
- < 20eV no ER backgrounds, quasiparticle only regime



^{4}He Excitations channel

PhysRevD.100.092007



Singlet Dimer

- Atomic excitations
- Decays promptly ~ 10ns

Triplet Dimer

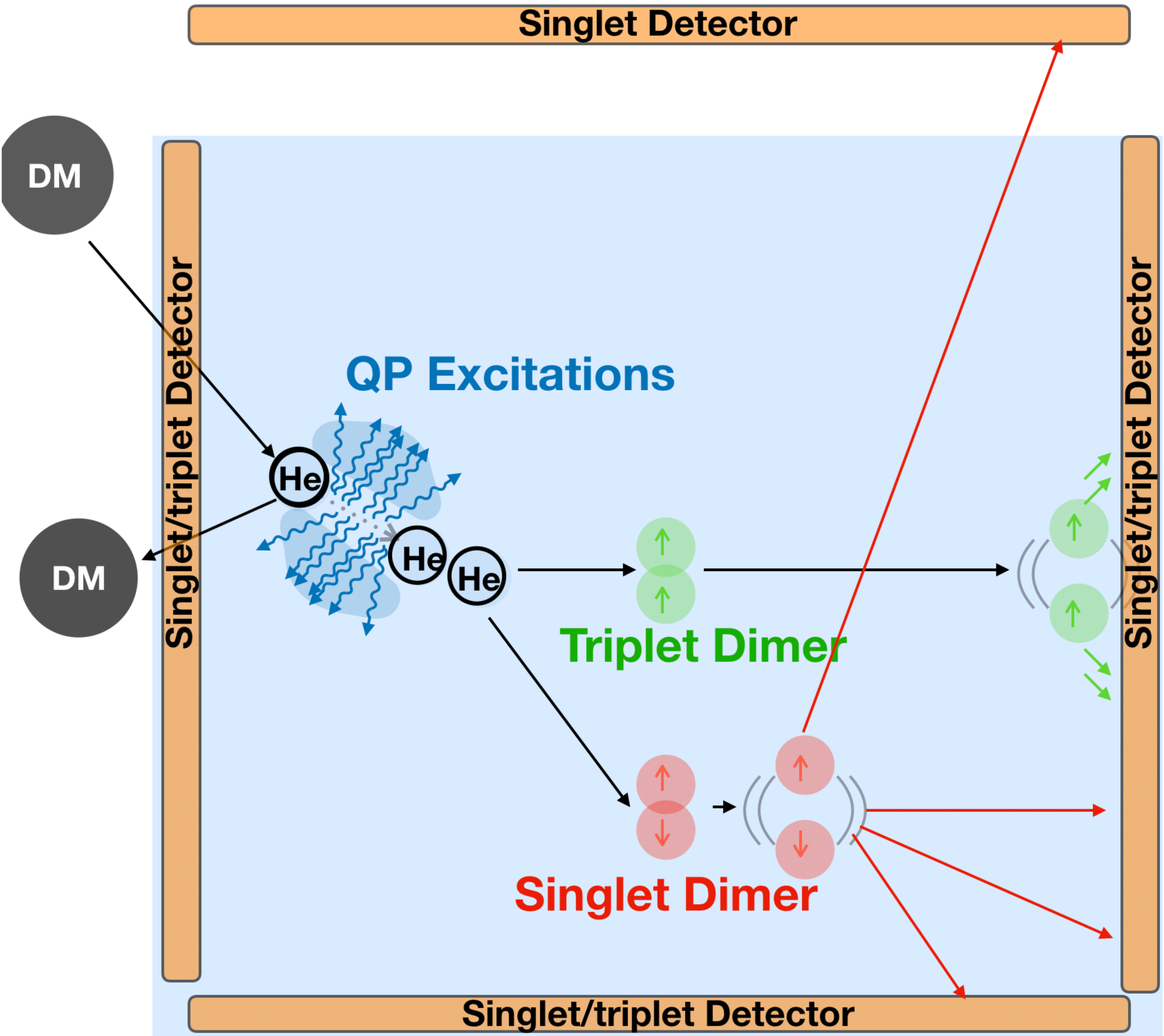
- Atomic excitations
- Long lived dimer ~ 13s, ballistic propagation ~ 10 m/s

Quasiparticle Excitation

- Collective excitations
- Phonons and rotons
  - ✦ Different flavors, different velocity, different boundary crossing/reflecting probabilities

^{4}He Detection channel: Atomic excitations

PhysRevD.100.092007



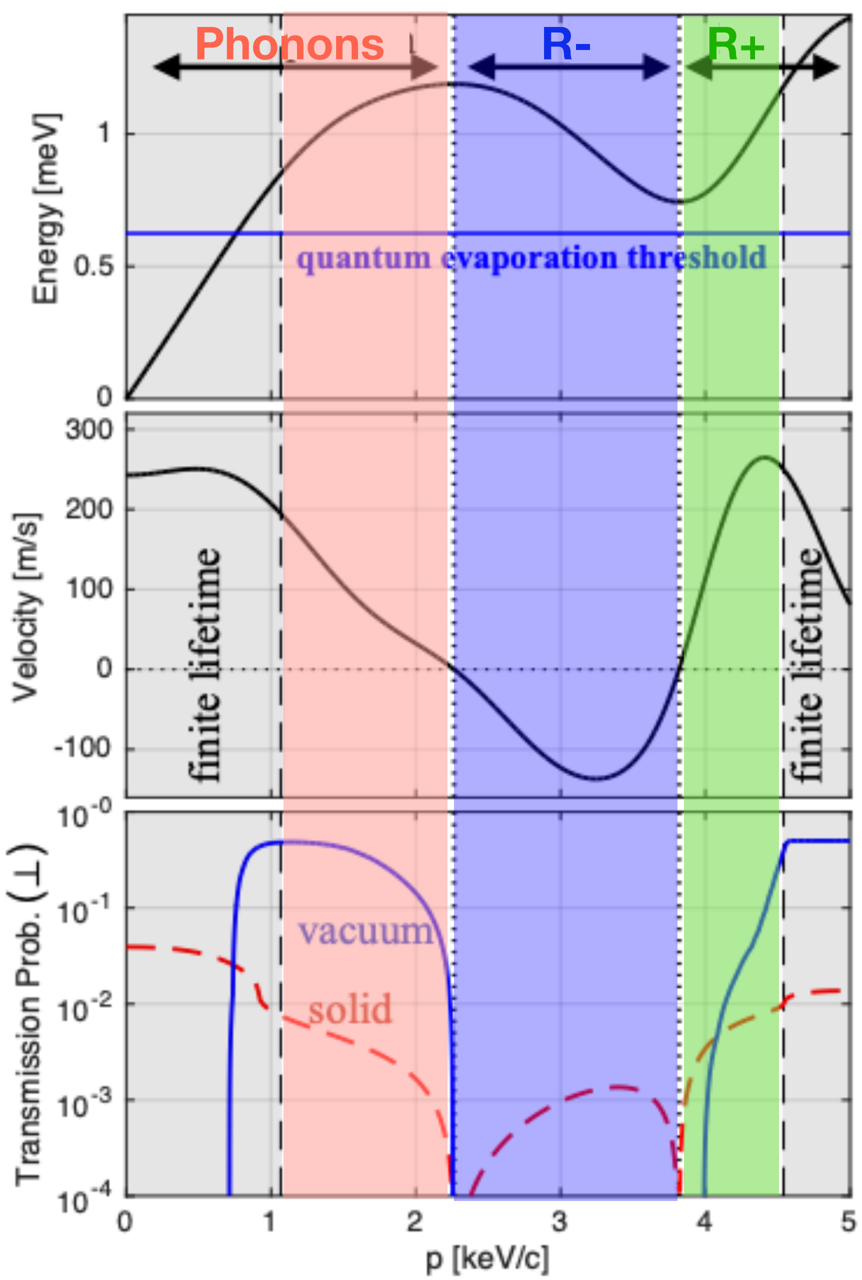
Singlet Dimer

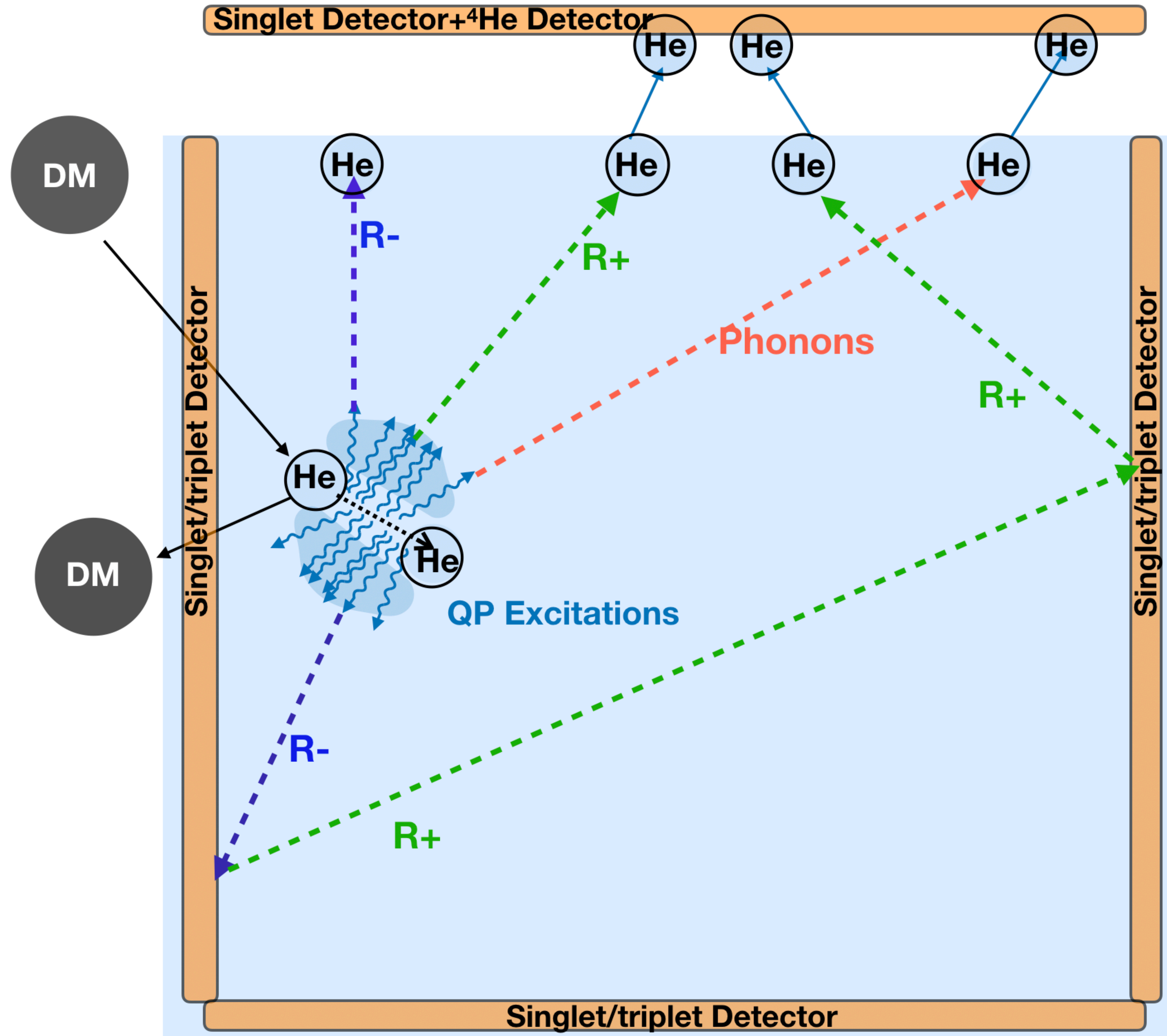
- Decays via Photon emission (16eV)
- Detected via both suspended and immersed calorimeters (ns time scale)

Triplet Dimer

- Decays via quenching at the detector-^{4}He interface (16eV)
- Detected via immersed calorimeters (ms time scale)

4He Detection channel: Collective excitations PhysRevD.100.092007





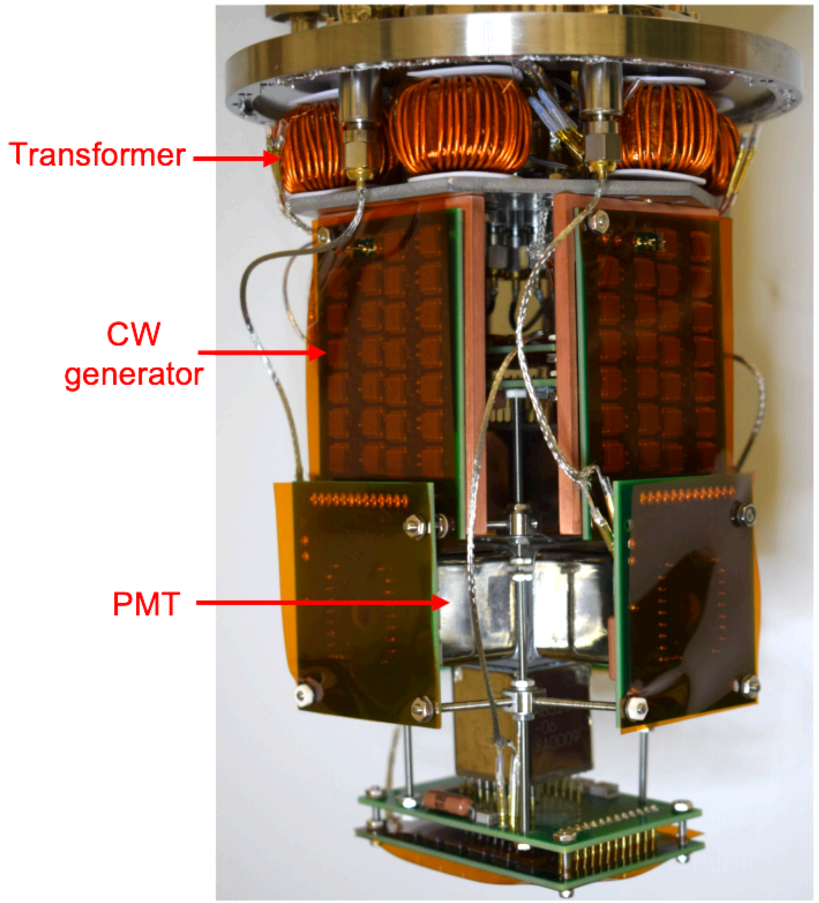
Quasiparticle Detection

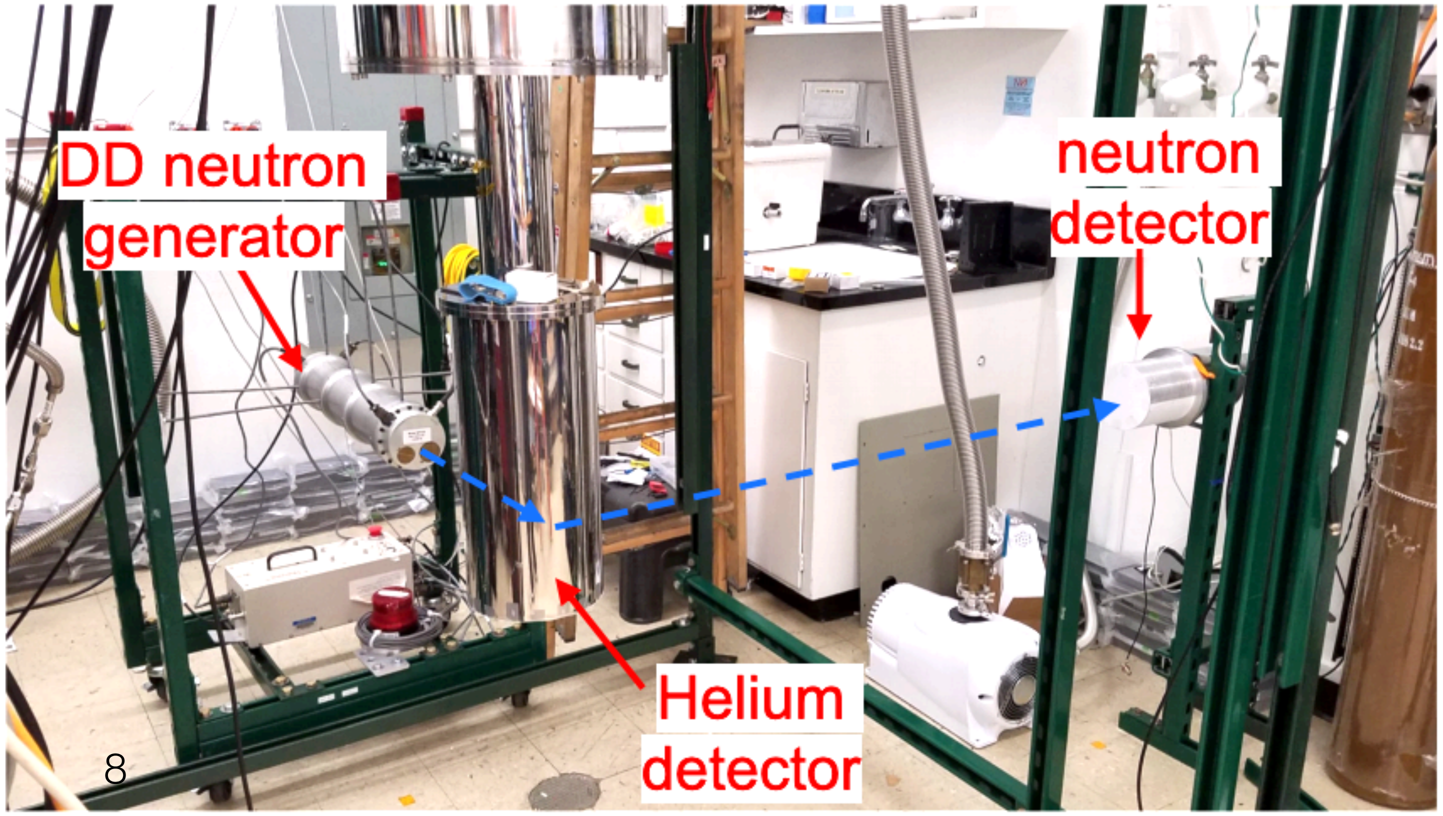
- Detected via Quantum Evaporation of ^{4}He atom at the vacuum-^{4}He interface.
- ^{4}He atom sticking on to detector surface amplifies the signal via adhesion gain.

Scintillation from ER and NR in superfluid ^{4}He: Setup

Data Taking:

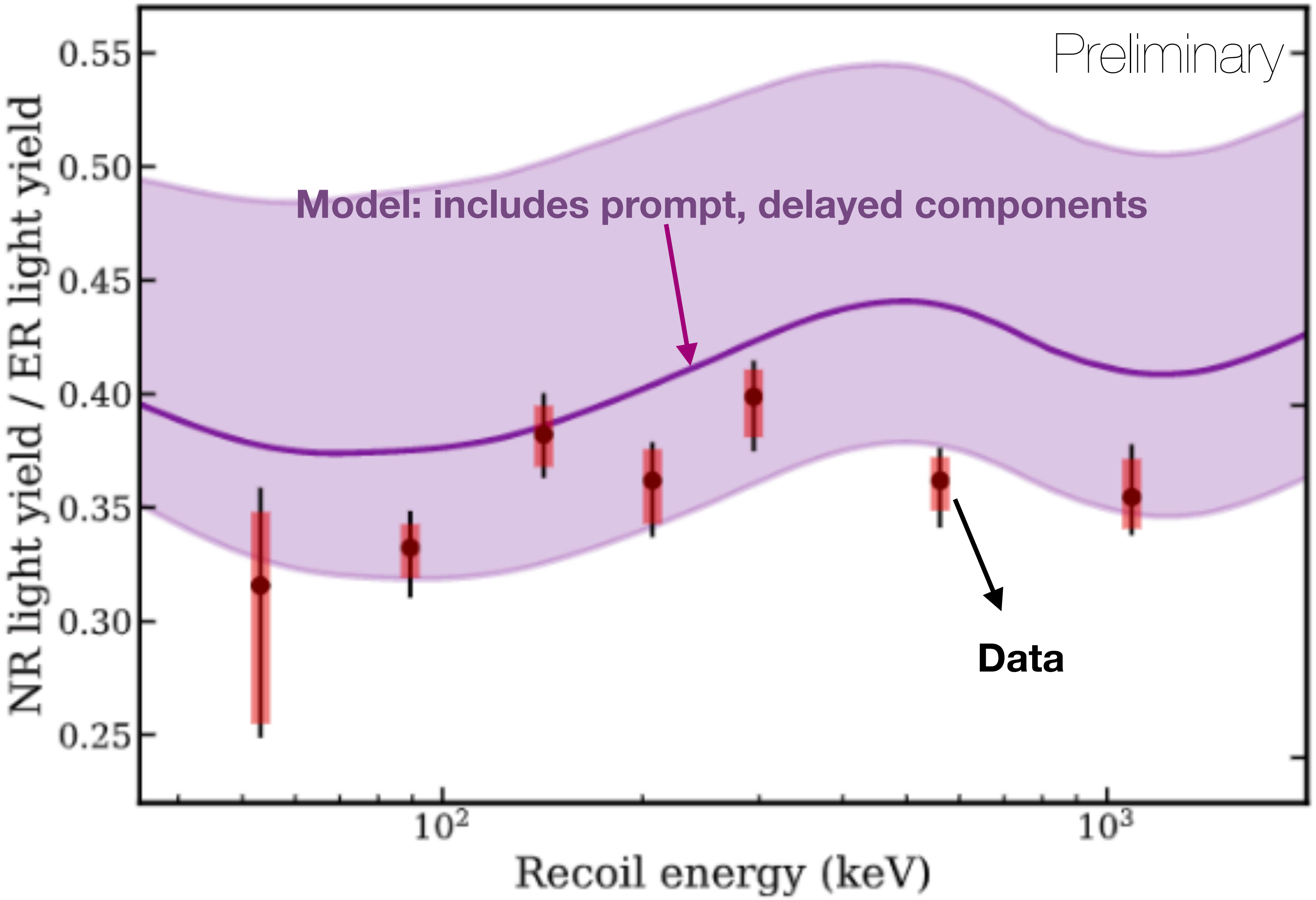
- ER Data: 662 keV ^{137}Cs Source.
  NR Data: 2.8 MeV Neutron, DD fusion neutron generator.
- ^{4}He Temperature: 1.75K
- Quartz panel in front of the PMTs coated with TPB.
- ~30 μs of data taking window, scintillation from triplet will be a constant background signal.



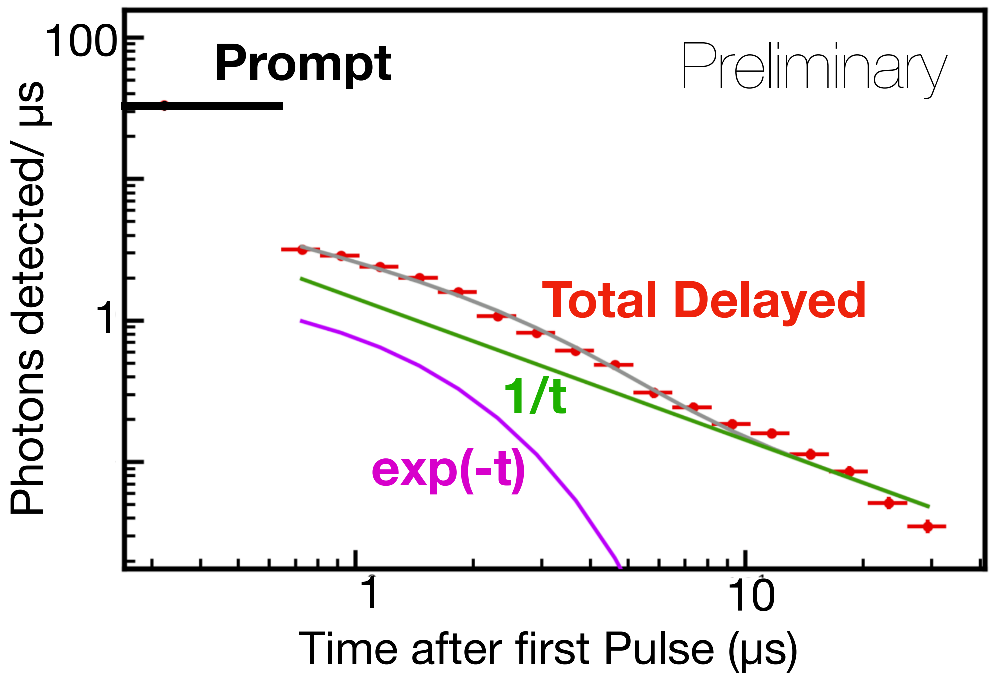


Scintillation from ER and NR in superfluid 4He: Result

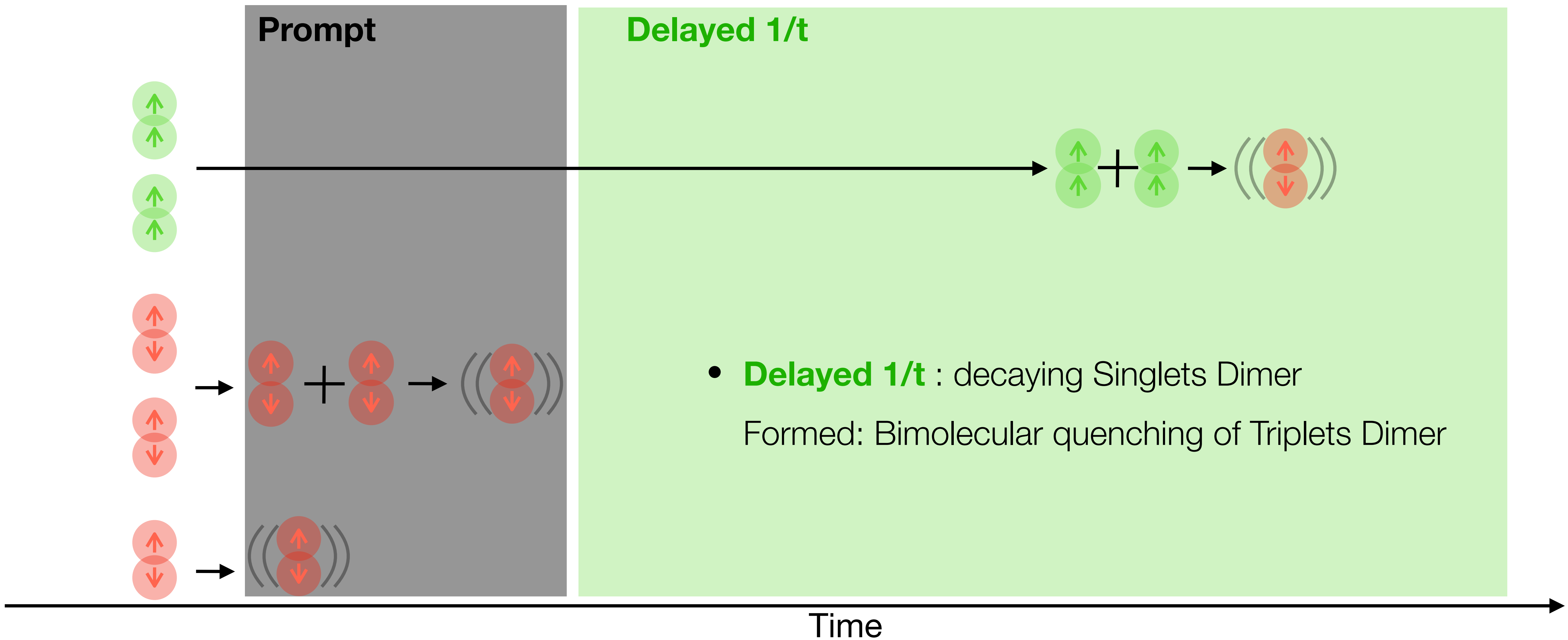
- Agreement with the scintillation model



- Performed timing study of these scintillation



Scintillation from ER and NR in superfluid 4He: Timing Studies



- **Delayed 1/t** : decaying Singlets Dimer

  Formed: Bimolecular quenching of Triplets Dimer

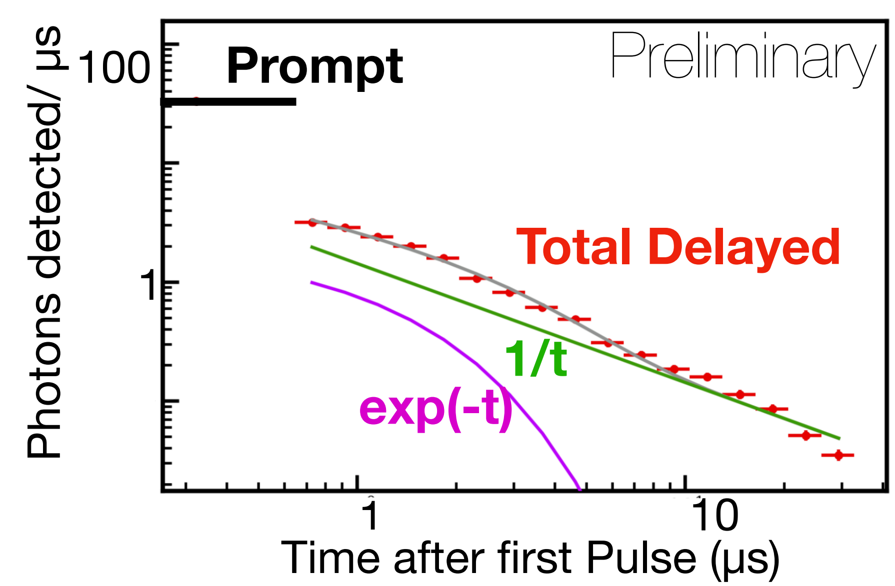
- **Prompt**: decaying

  Singlets Dimer

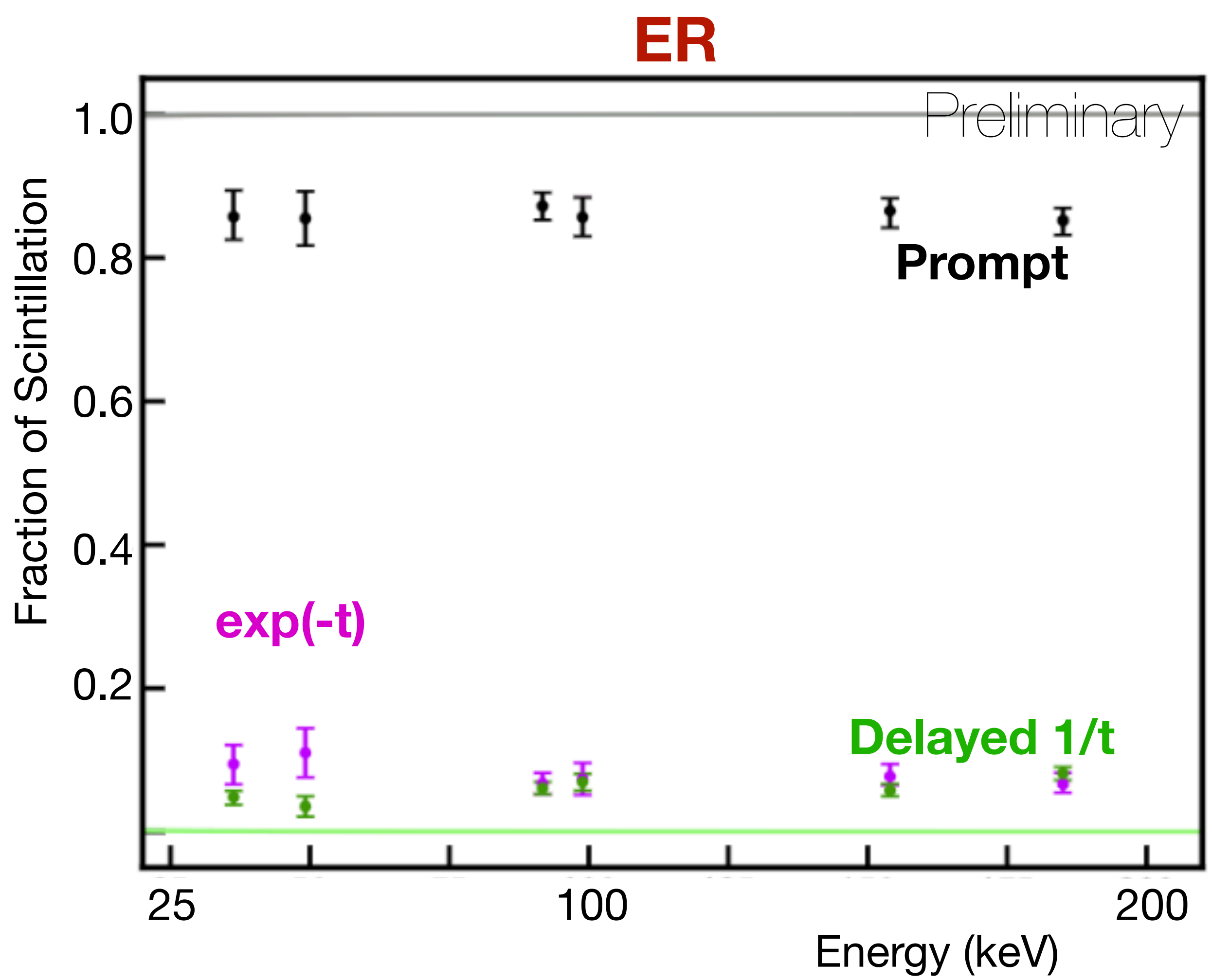
  Formed: Atomic Excitation

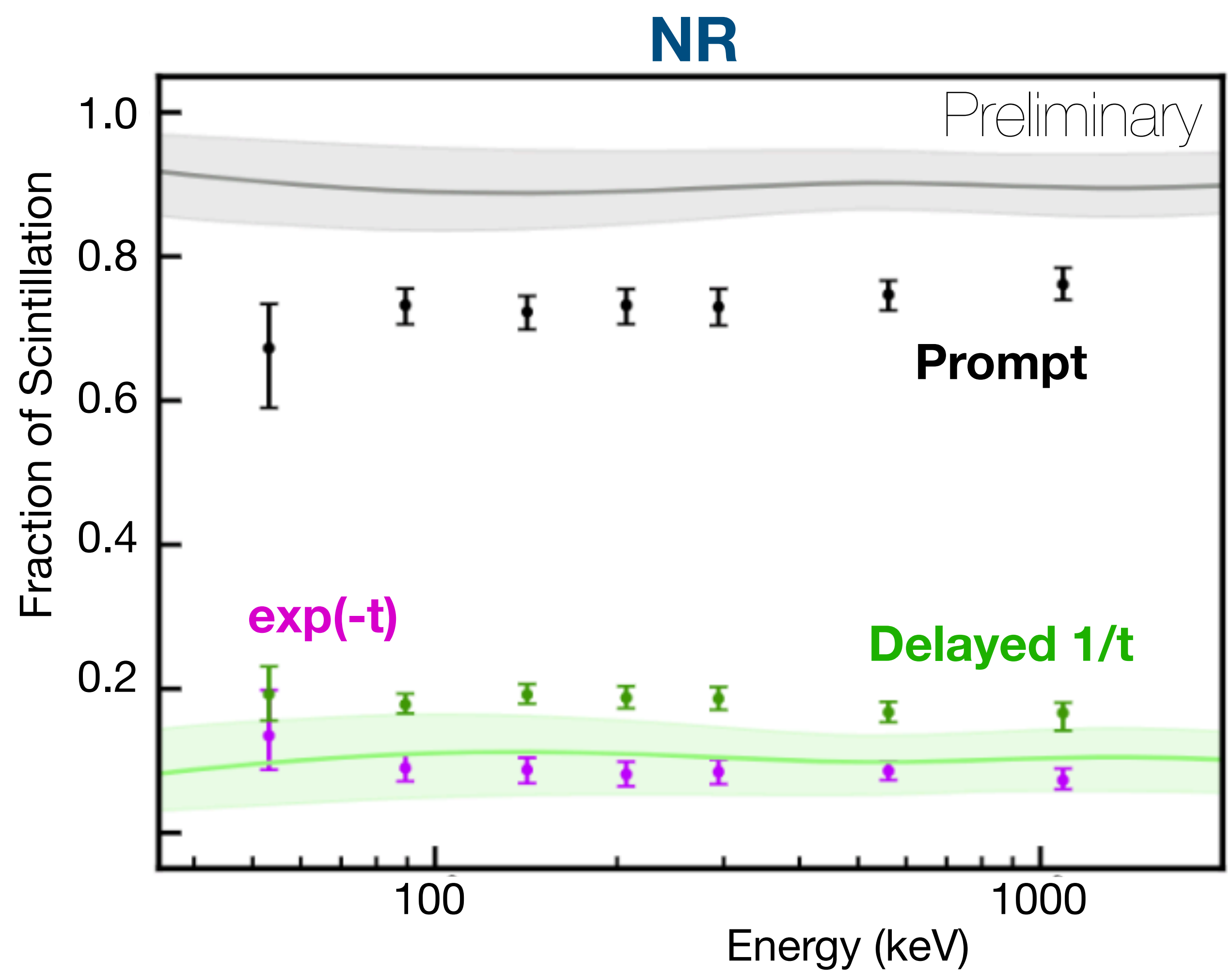
  + Bimolecular quenching

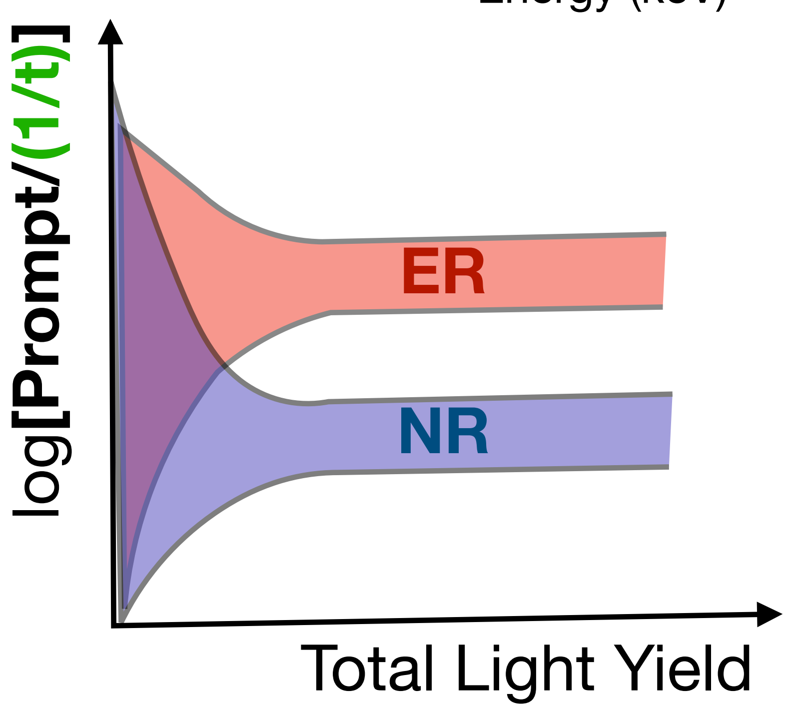
  of Singlets Dimer



Scintillation from ER and NR in superfluid ^{4}He: Timing Studies



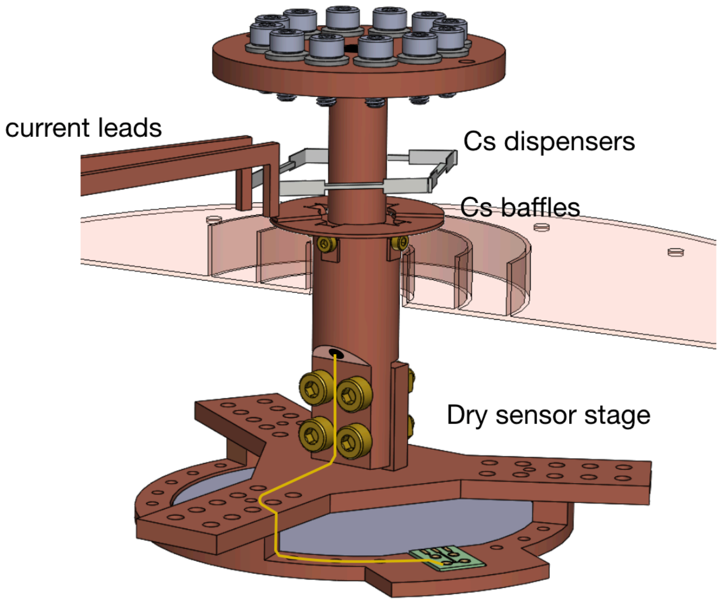




- exp(-t) delayed components similar in both NR and ER
- Ratio of **prompt**/(**1/t delayed** component) is different, potentially to enable NR and ER discrimination

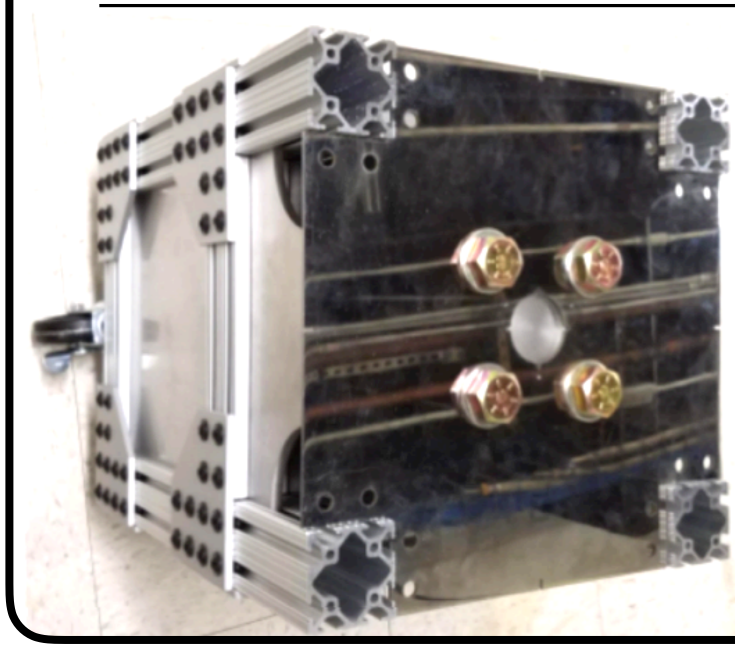
Ongoing Activities at UMass and UC Berkley

Superfluid 4He cell design tested

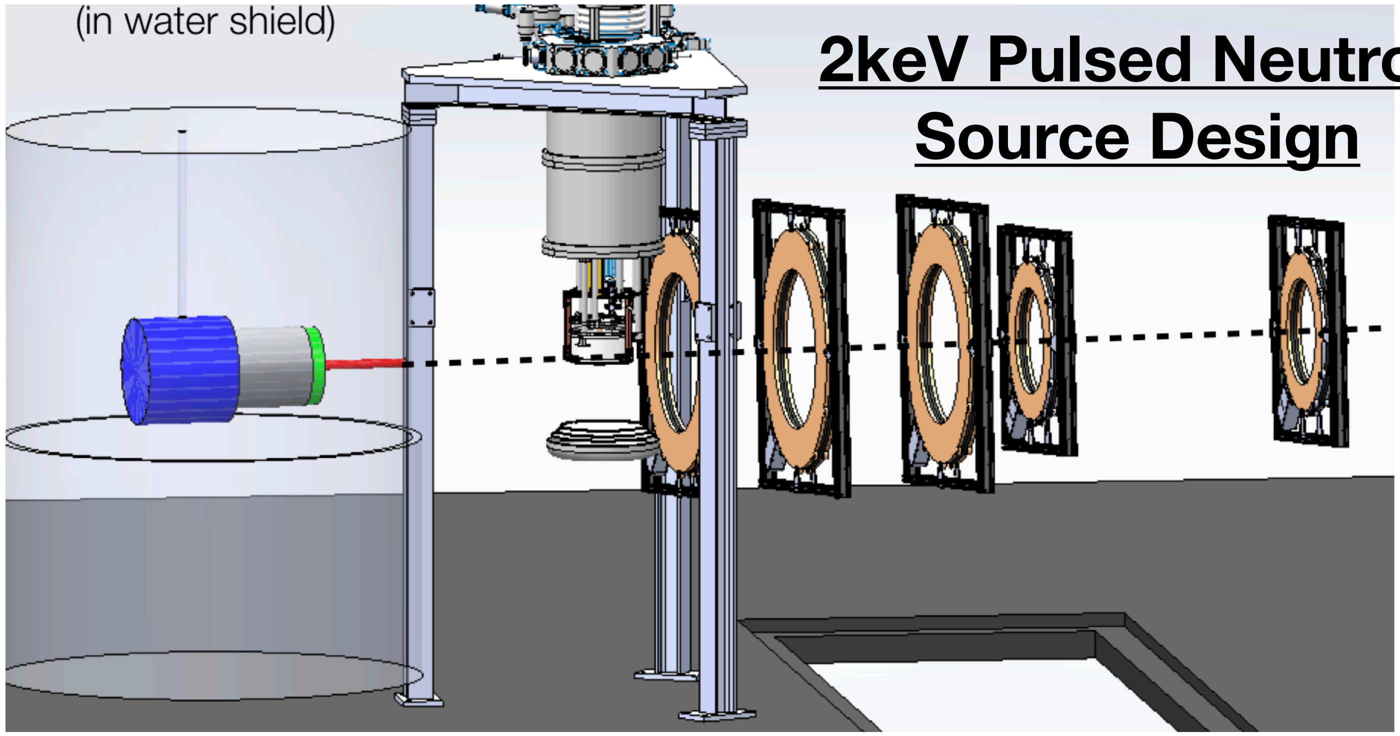


- NR Calibration down to ~20eV: using the Sb-Be and Sc-Filtered DT neutron source with ^{4}He Cell.

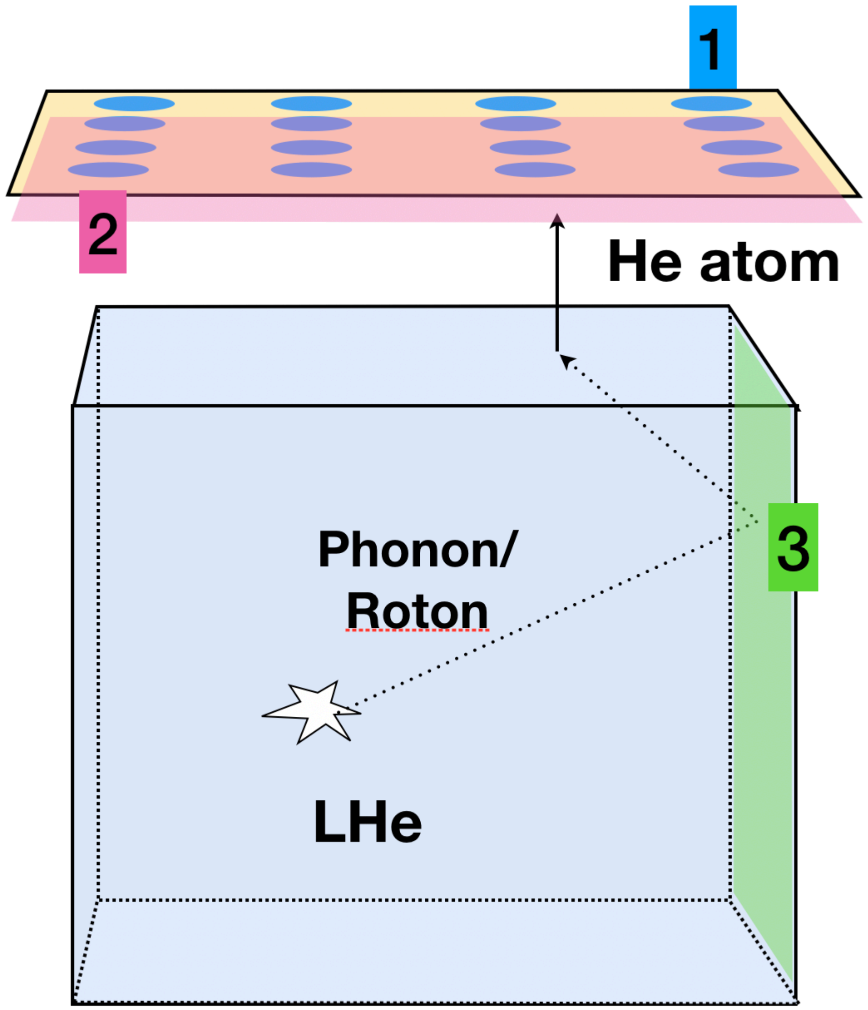
24keV neutron from Sb-Be



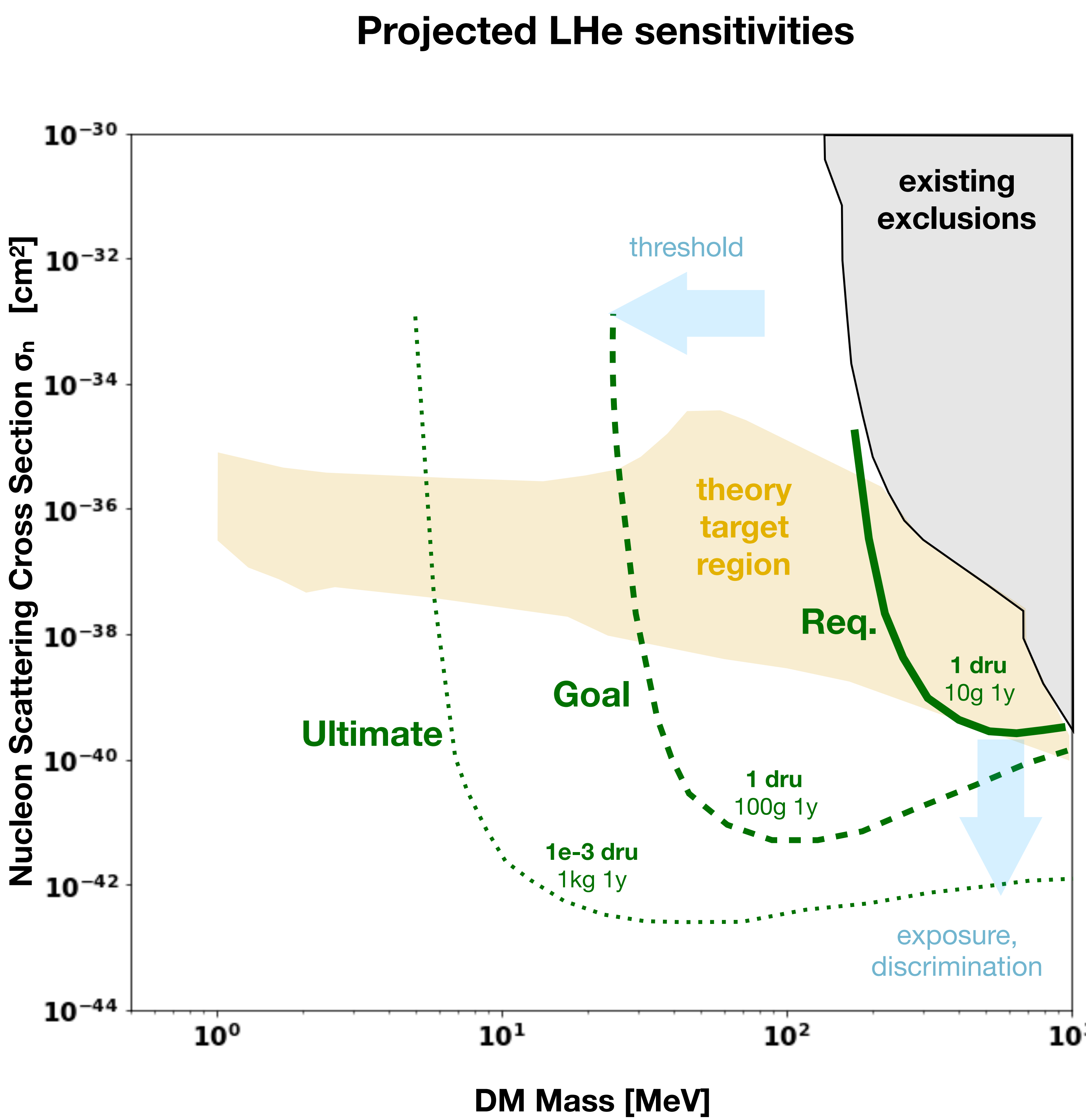
2keV Pulsed Neutron Source Design



Road map for superfluid ^{4}He, quasiparticle excitations regime



1. Lowering threshold of sensors, TES dynamics
2. Increase adhesion gain, coat *Fluro-Graphene* on Si
3. Enhance the reflectivity of QPs, control surface roughness on atomic scales

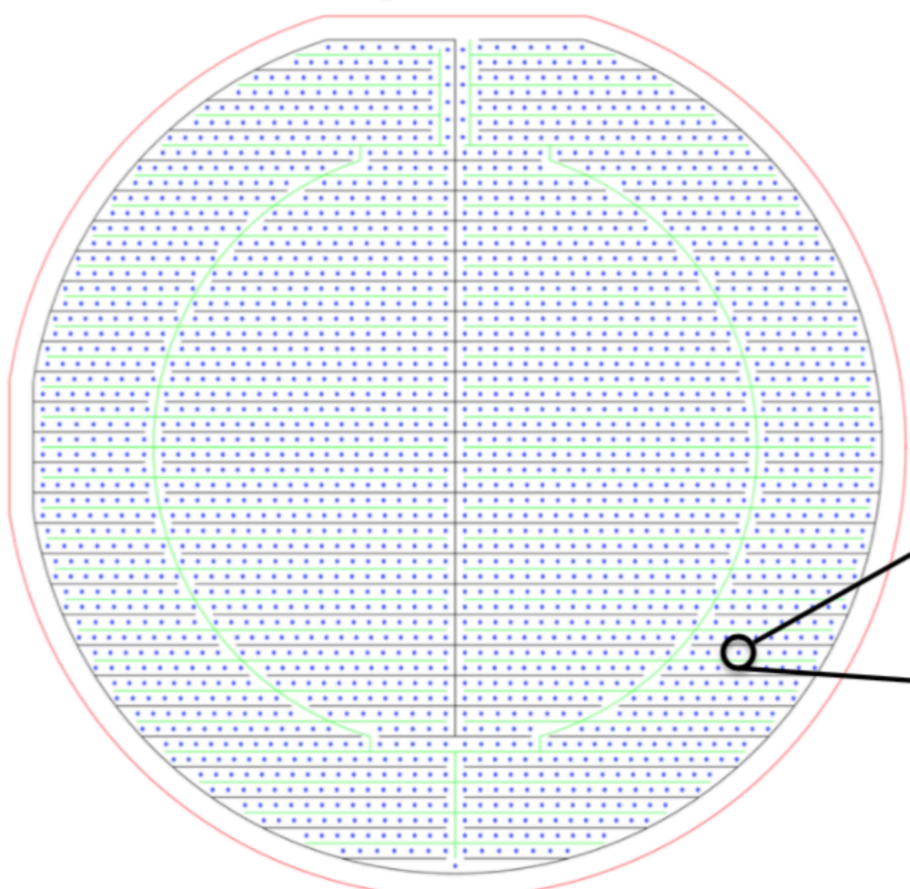


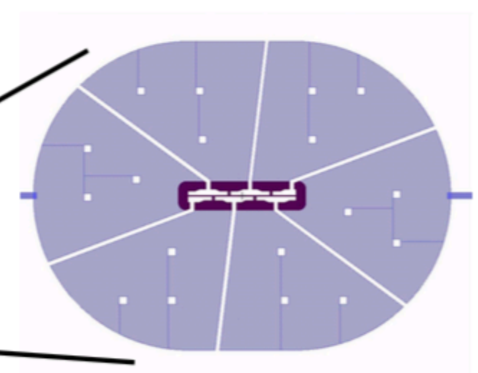
Thank you

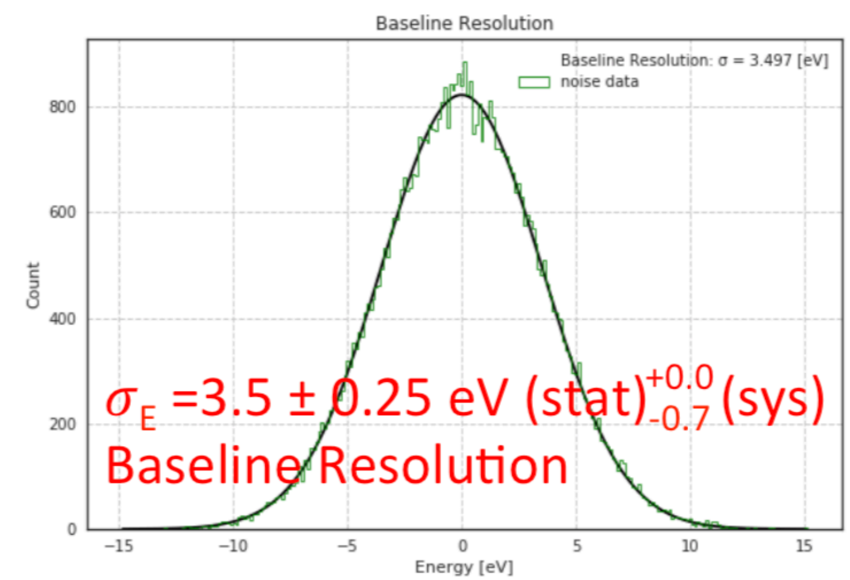
Calorimetry: Slide From Matt Pyle

Large Area Photon Detector: Just Shrink a SuperCDMS detector

- 3” diameter Si wafer (45.6 cm^2)
- 1mm thick
- Distributed athermal phonon sensors minimize phonon collection time (as fast as it can be for its size)
  - Athermal Phonon collection time estimated to be ~20us
  - 2.5% sensor coverage







Quasiparticles Transmission and Reflection Probabilities:

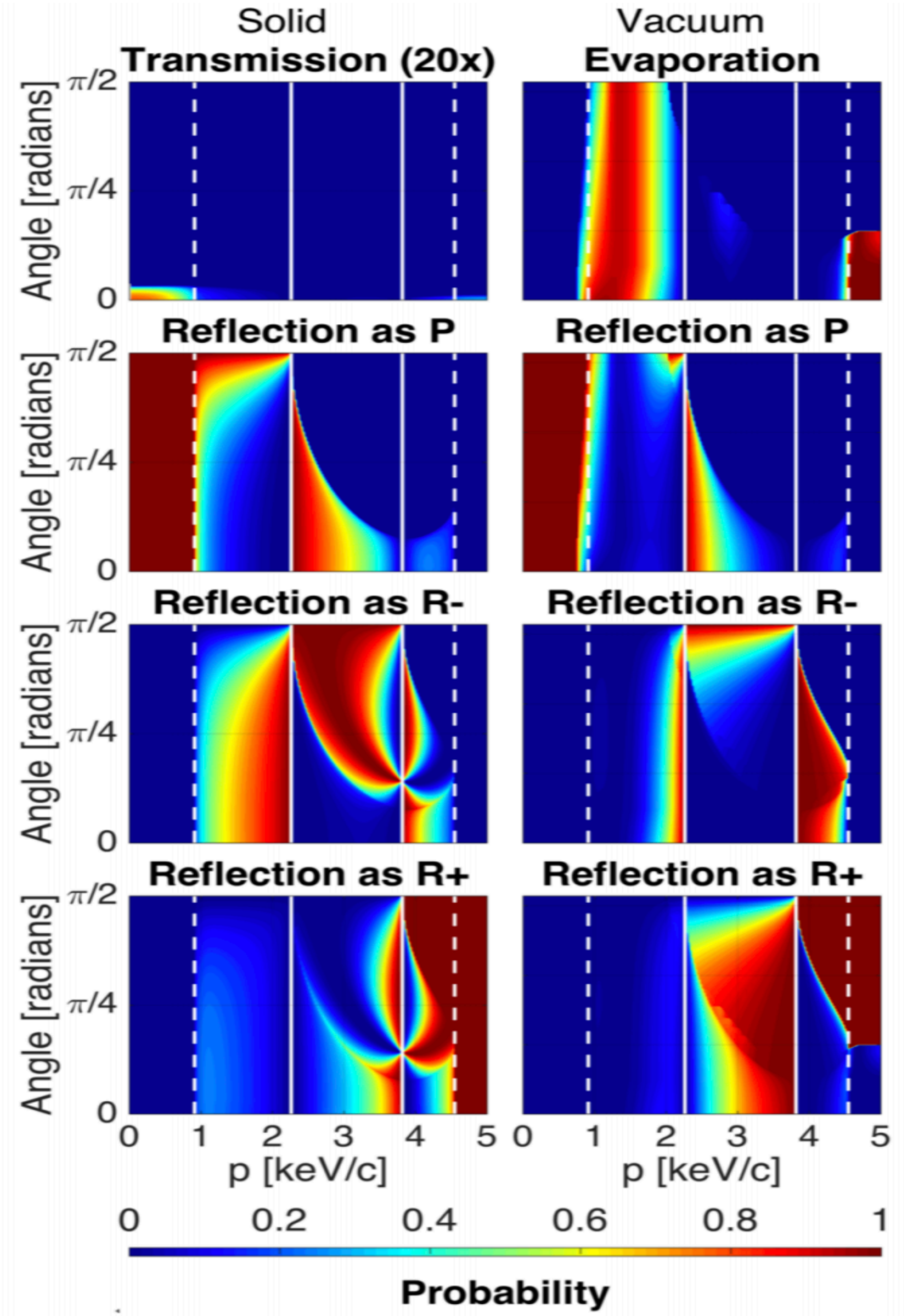
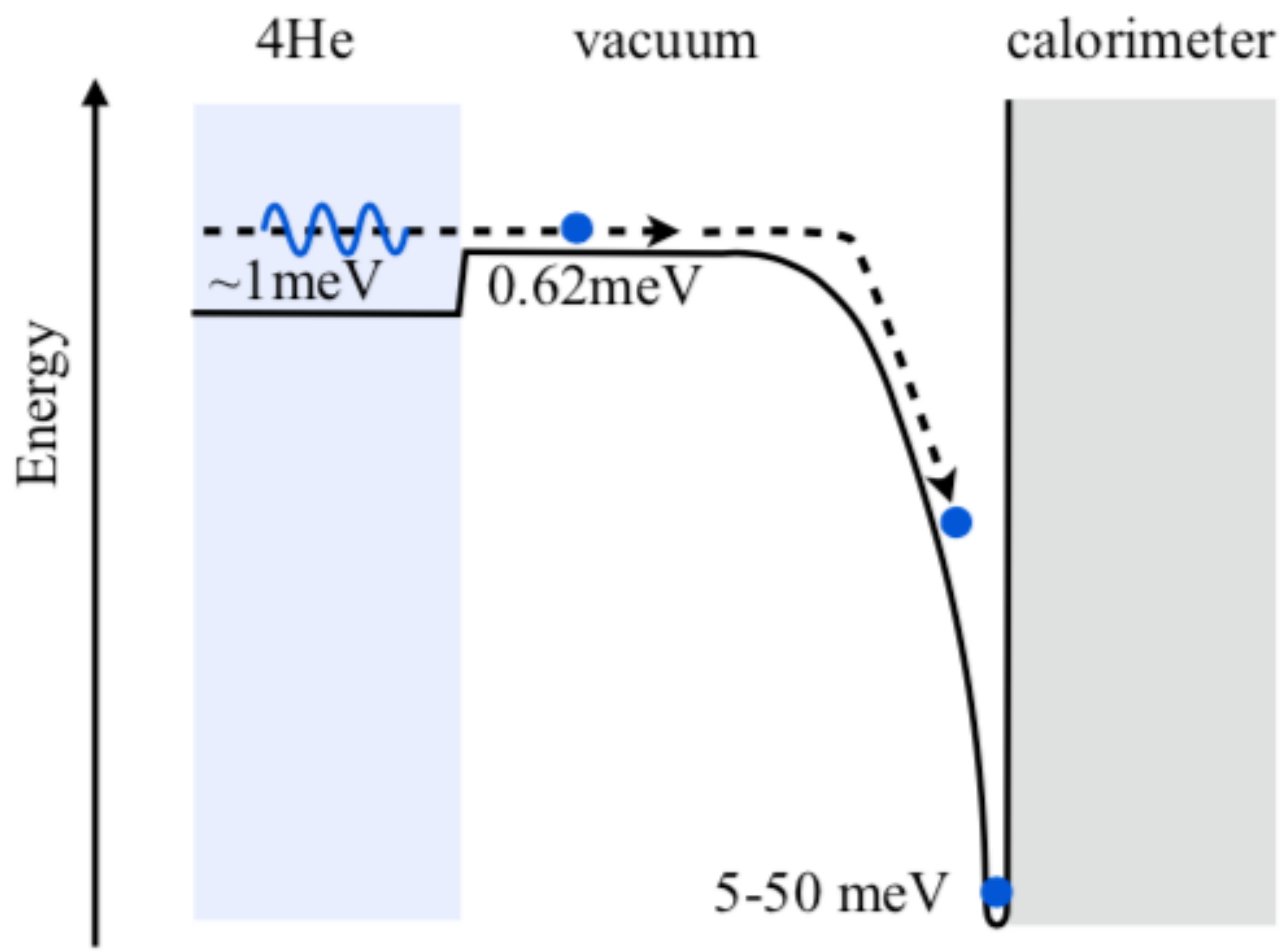
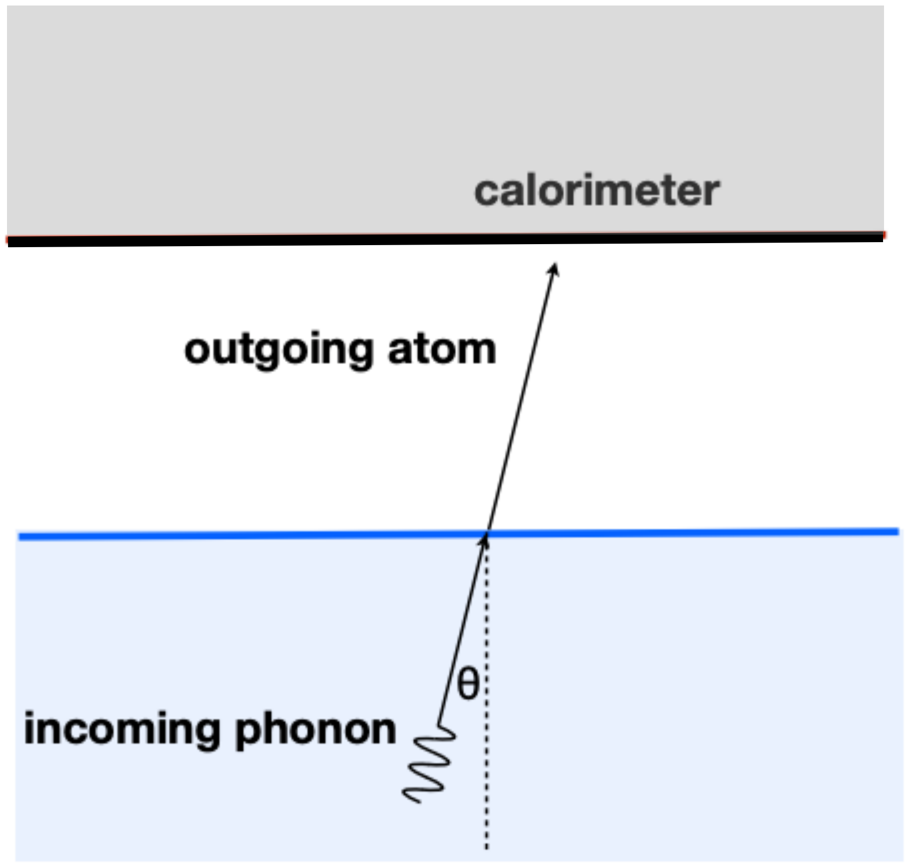


FIG. 4. Quasiparticle transmission and reflection probabilities (per interface interaction) showing dependence on incoming quaiparticle momentum (x axis) and incidence angle (y axis). We combine the quasiparticle reflection description of Tanatarov *et al.* [84] with the evaporation description of Sobnack *et al.* [85]. The transmission probability across the ^{4}He-solid interface (upper left panel) has been multiplied by a factor of 20 here for visibility. The Sobnack *et al.* quantum evaporation probability (upper right panel) has been reduced by a factor of 2 (here and in the Monte Carlo simulation) to better match experiment. Solid white lines indicate the boundaries between phonon, R^-, and R^+ regions. Dashed white lines indicate the boundaries of the momentum range for which the dispersion relation is multivalued in energy.

Quantum Evaporation: Slide From Scott Hertel

- Low transmission probability of QP to other solid, Immersed Calorimeter is inefficient
- Downconversion of the QP to thermal phonons is prevented, enabling Quantum Evaporation.
- Interconversion of QP aids the process of detection via Quantum Evaporation.

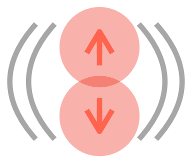




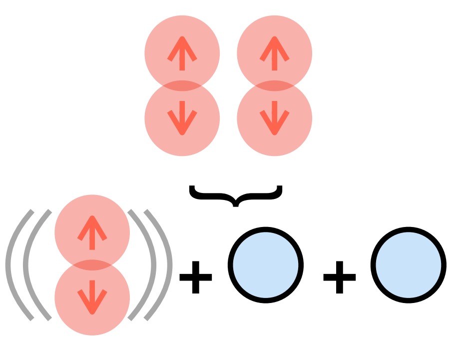
Scintillation from ER and NR in superfluid 4He

Prompt Scintillation < 460ns

From Singlets



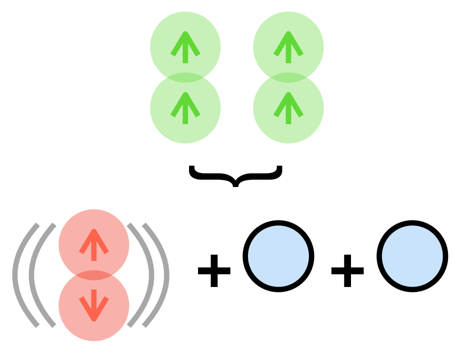
Bimolecular Quenching of Singlets



- Singlet Quenching ~ decreases prompt scintillation
- Quenching ~track density,NR higher track density
- Decrease in prompt scintillation is more in NR

Delayed scintillation ~ 1/t

Bimolecular Quenching of Triplets



- Triplet Quenching ~ increases delayed 1/t scintillation
- Decrease in delayed 1/t scintillation is more in NR

Delayed scintillation ~ exp(-t)

exponential decay

Atomic Singlet+4He-> Singlet?