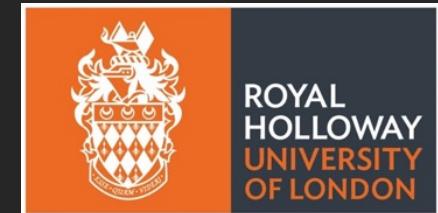




QUEST-DMC: LOW MASS DARK MATTER SEARCH WITH HELIUM-3

ELIZABETH LEASON – ON BEHALF OF QUEST-DMC COLLABORATION

TAUP 2023, 31.08.2023



QUANTUM ENHANCED SUPERFLUID TECHNOLOGIES FOR DARK MATTER AND COSMOLOGY, QUEST-DMC



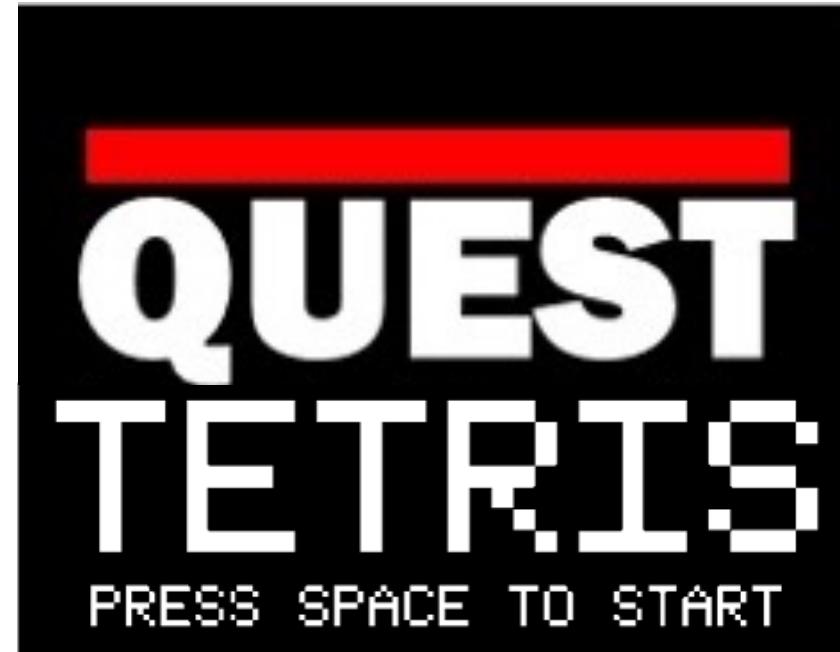
1. Detection of sub-GeV dark matter with a quantum-amplified superfluid ^3He calorimeter

2. Phase transitions in extreme matter, relevant to cosmology and gravitational wave production



Engineering and
Physical Sciences
Research Council

Science and
Technology
Facilities Council 2



TARGET

DETECTION

READOUT

3

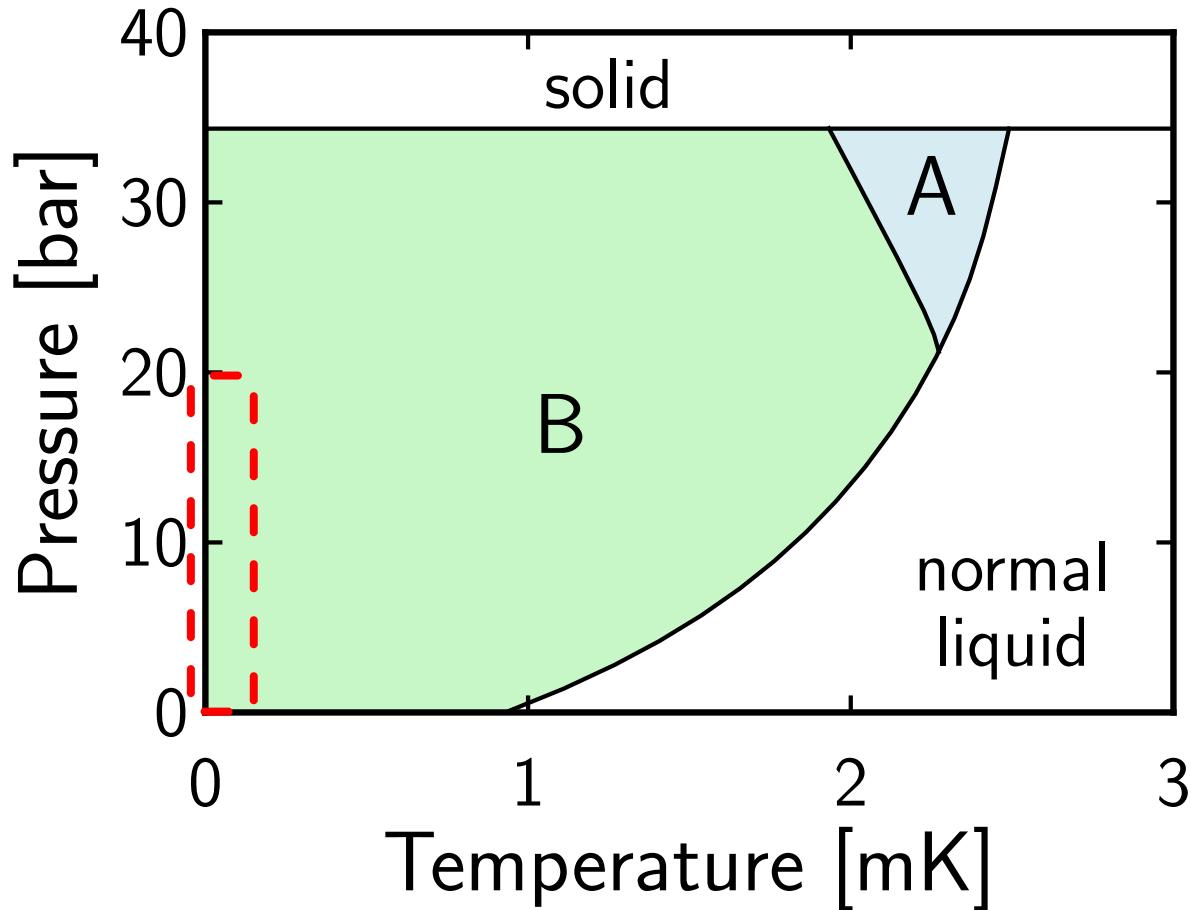


TARGET

DETECTION

READOUT

SUPERFLUID HELIUM 3



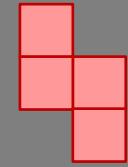
- Fermion – superfluidity from Cooper pairs of ^3He atoms
- B-phase at $\sim 100\mu\text{K}$
- Thermal excitation produces quasiparticles (QPs) – broken Cooper pairs
- Small superfluid gap $\Delta \sim 10^{-7}\text{eV}$

TARGET

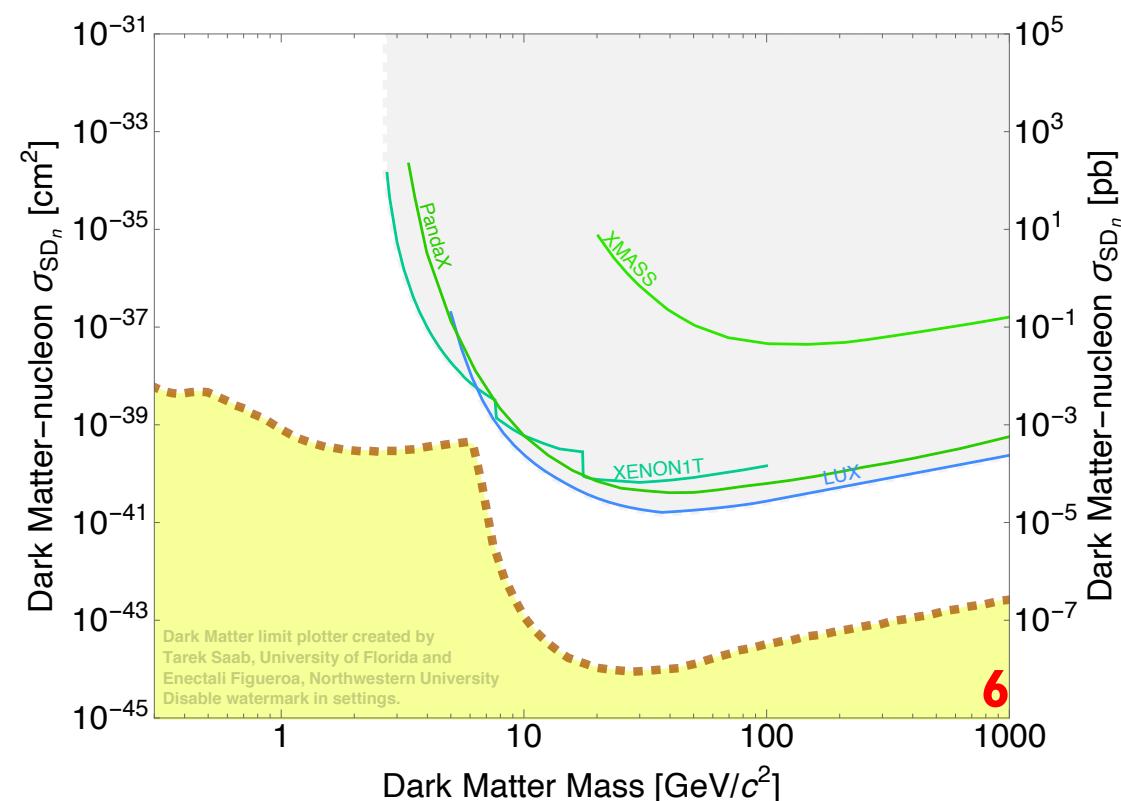
DETECTION

READOUT

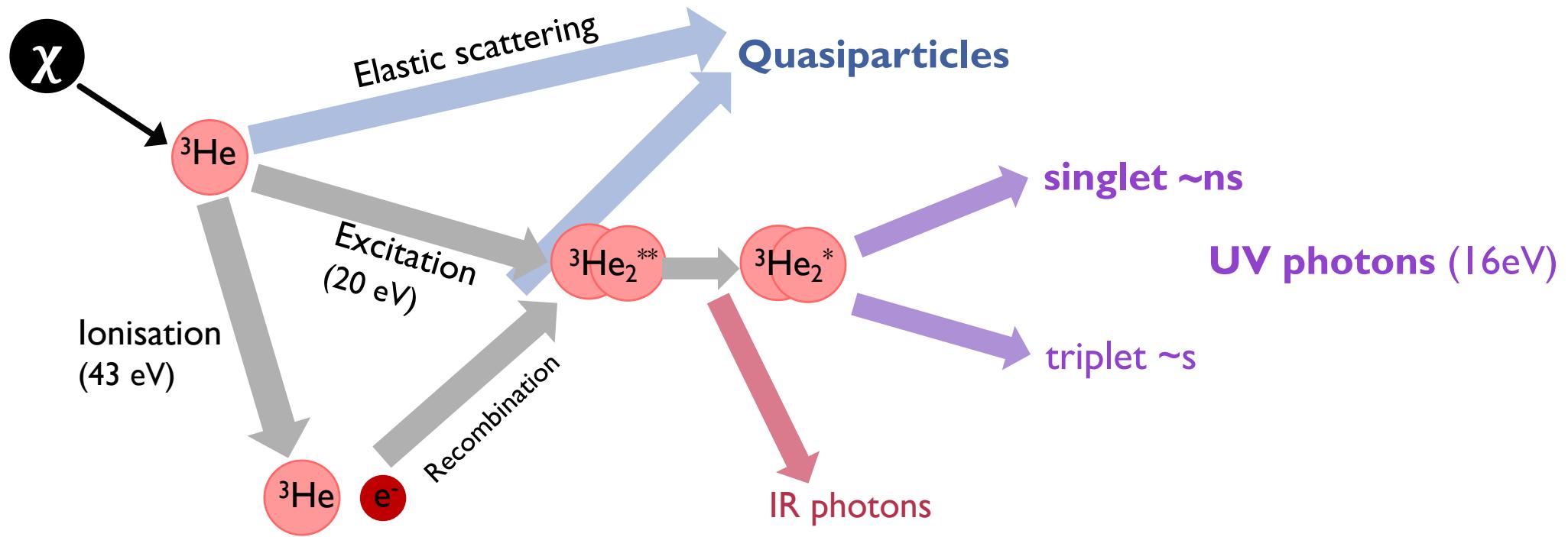
SPIN DEPENDENT INTERACTIONS



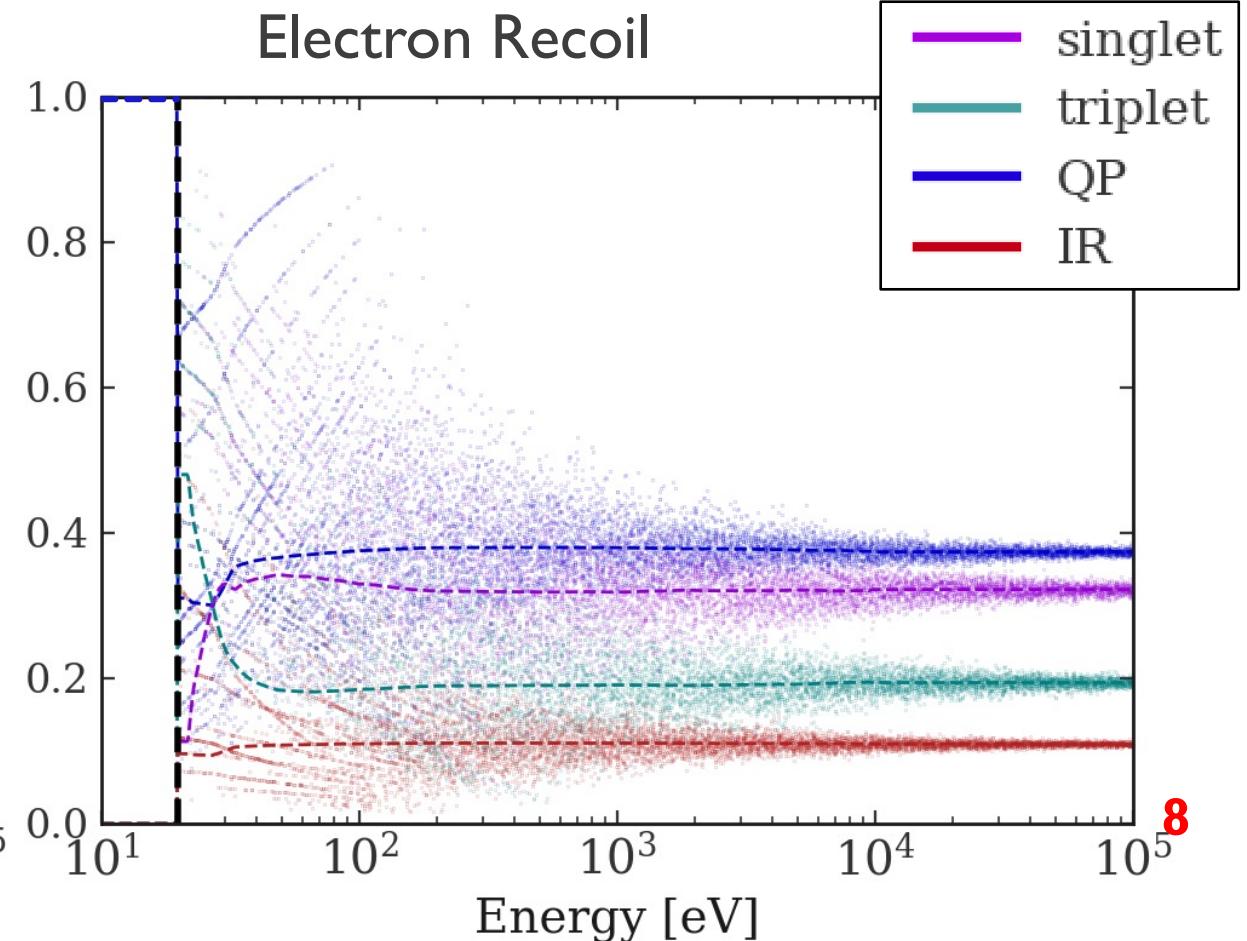
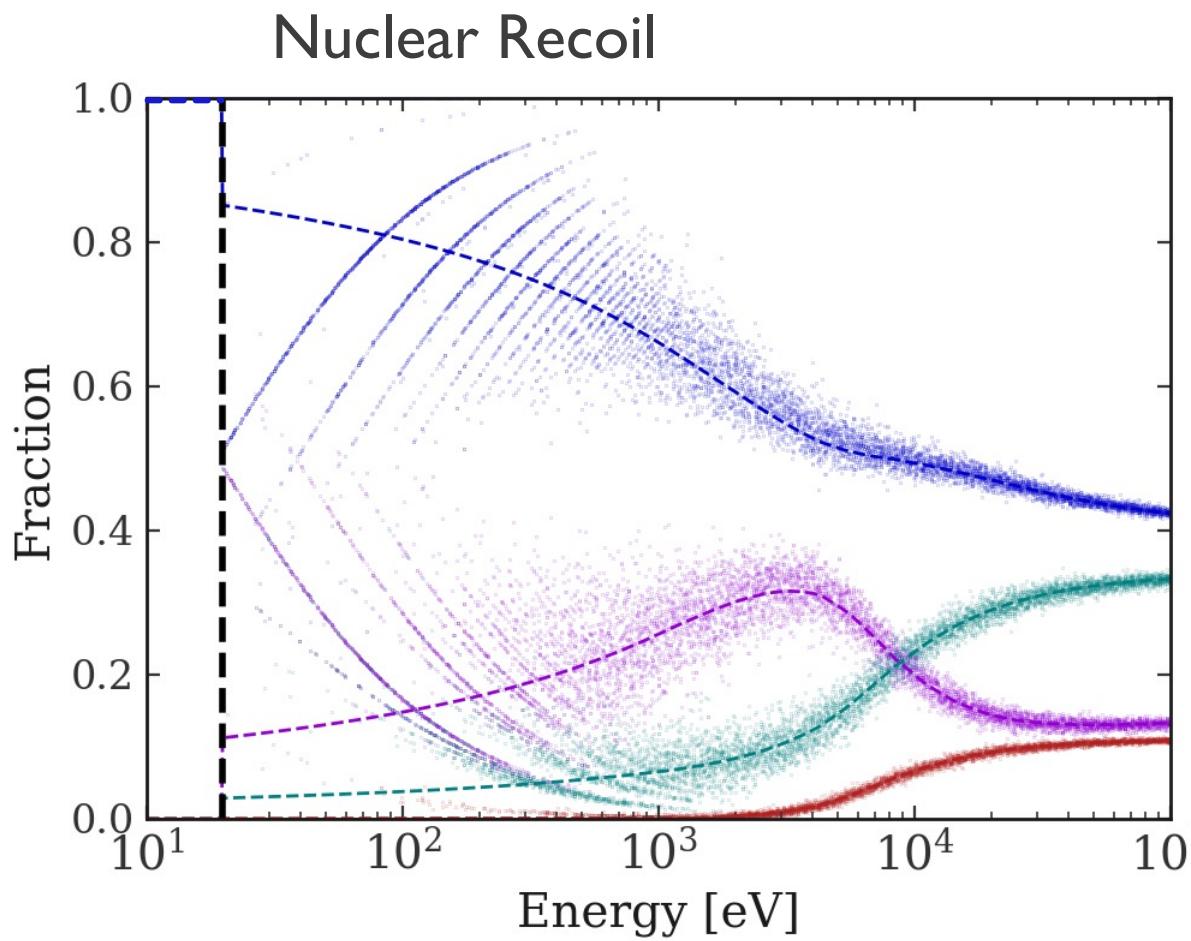
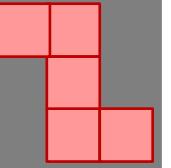
1. **Spin independent** - coherent scattering with all nucleons, vector or scalar couplings, cross section scales with atomic mass number
 2. **Spin dependent** – axial vector interaction couples to nuclear spin, requires uneven total angular momentum (unpaired nucleon)
- ✓ ${}^3\text{He}$ can test WIMP-neutron interaction
 - ✓ Low mass nucleus – kinematic matching with light dark matter $E_R \propto \frac{M_X}{M_N + M_X}$

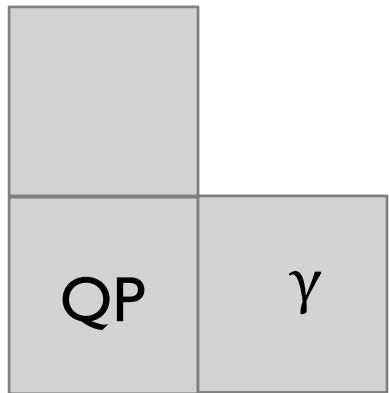


SIGNAL CHANNELS



${}^3\text{He}$ ENERGY PARTITIONING





TARGET

DETECTION

READOUT

QUEST EXPERIMENT

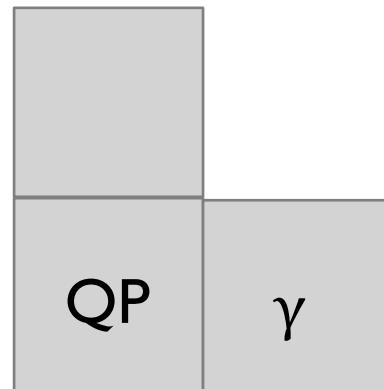
I. Quasiparticles (heat) –
bolometry using vibrating
nanowires immersed in
superfluid
 ^3He cell

Previous bolometer work
[LT.Proc.\(1996\)](#),
[NIMA,455,544-563\(2000\)](#),
[NIMA,574,264-271\(2007\)](#)

TARGET

DETECTION

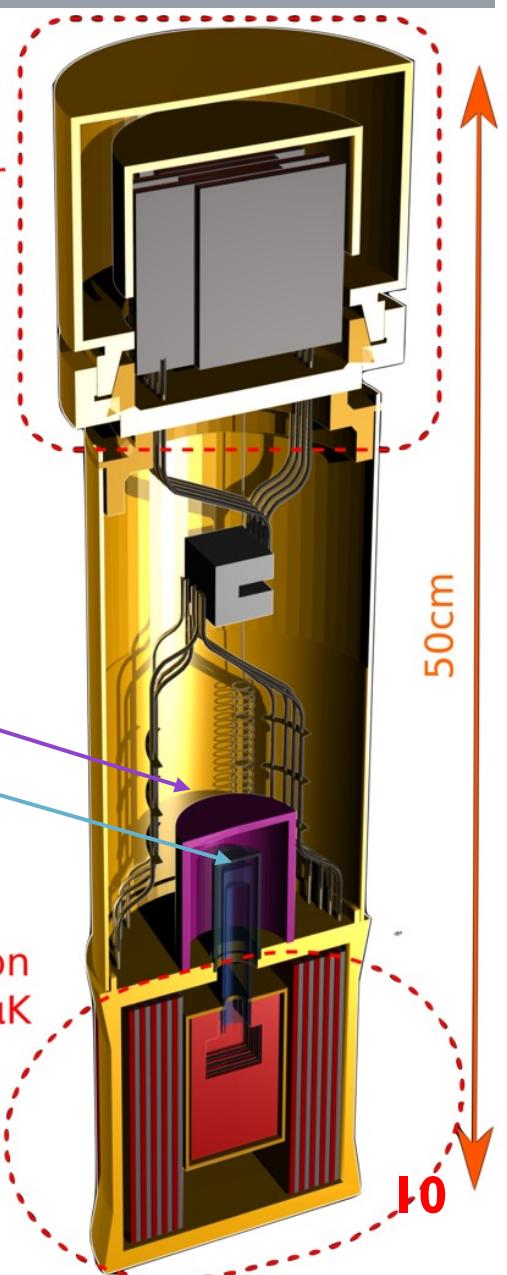
2. Scintillation photons
(light) – photon
detectors above the ^3He
target



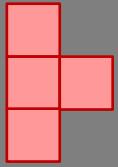
Mixing chamber
at 2mK

Photon detector
Bolometer cells

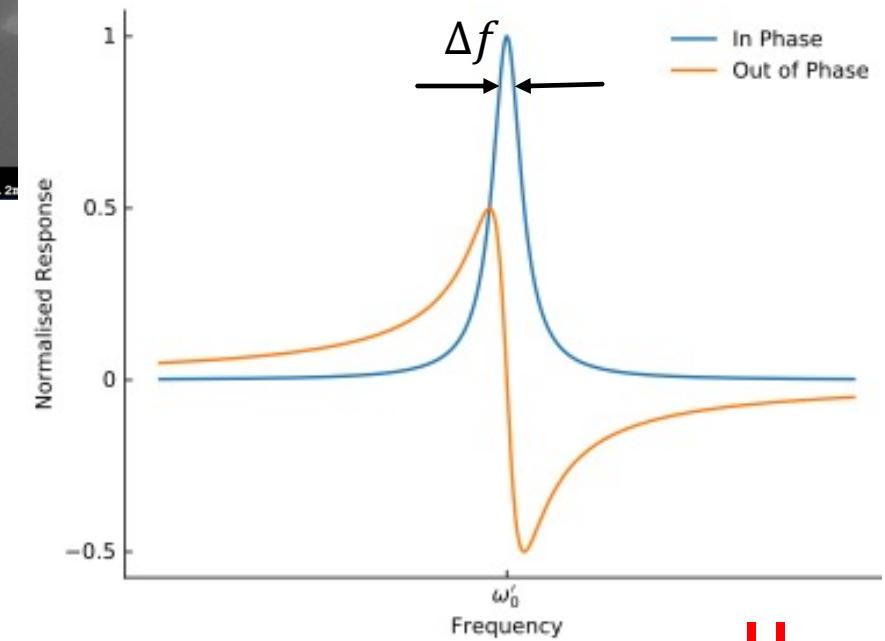
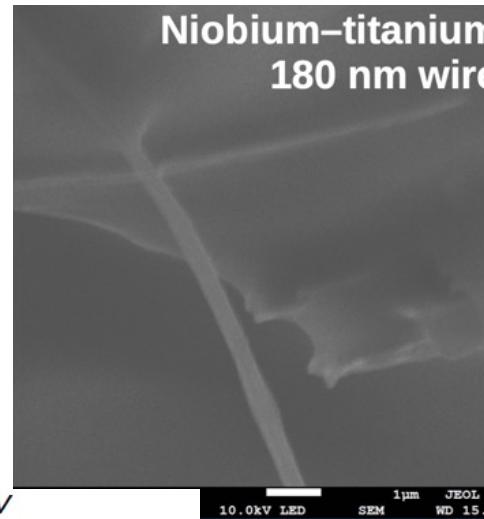
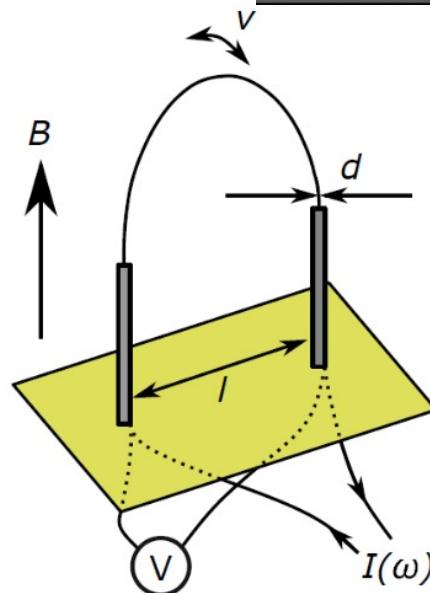
Copper
demagnetisation
stage at $<100\mu\text{K}$



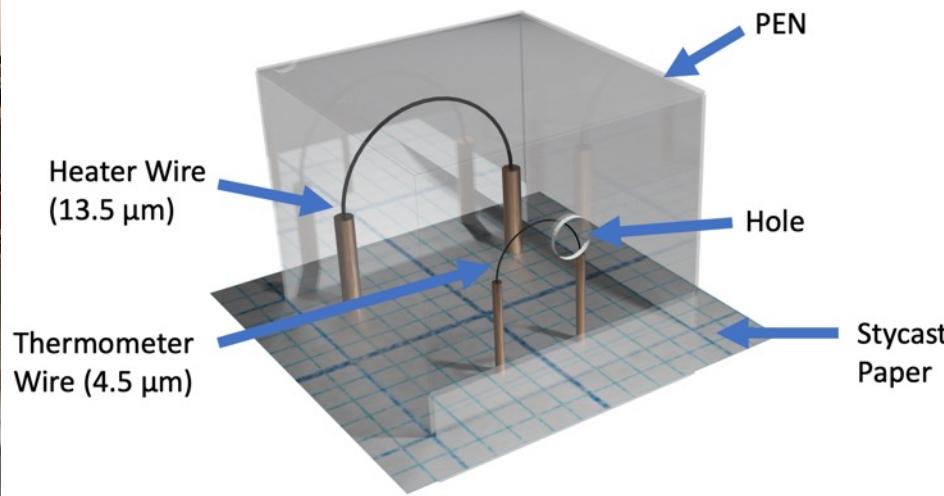
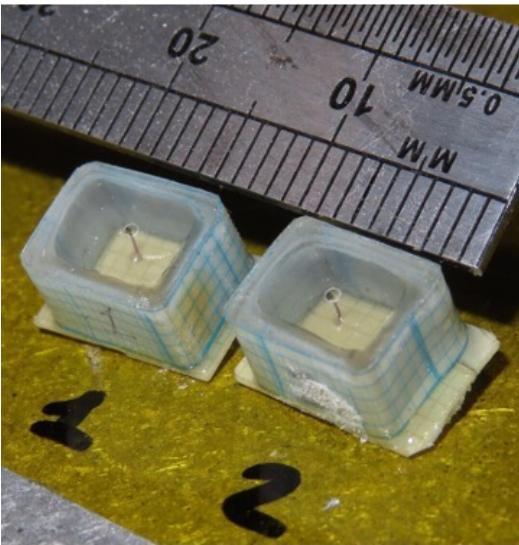
BOLOMETRY



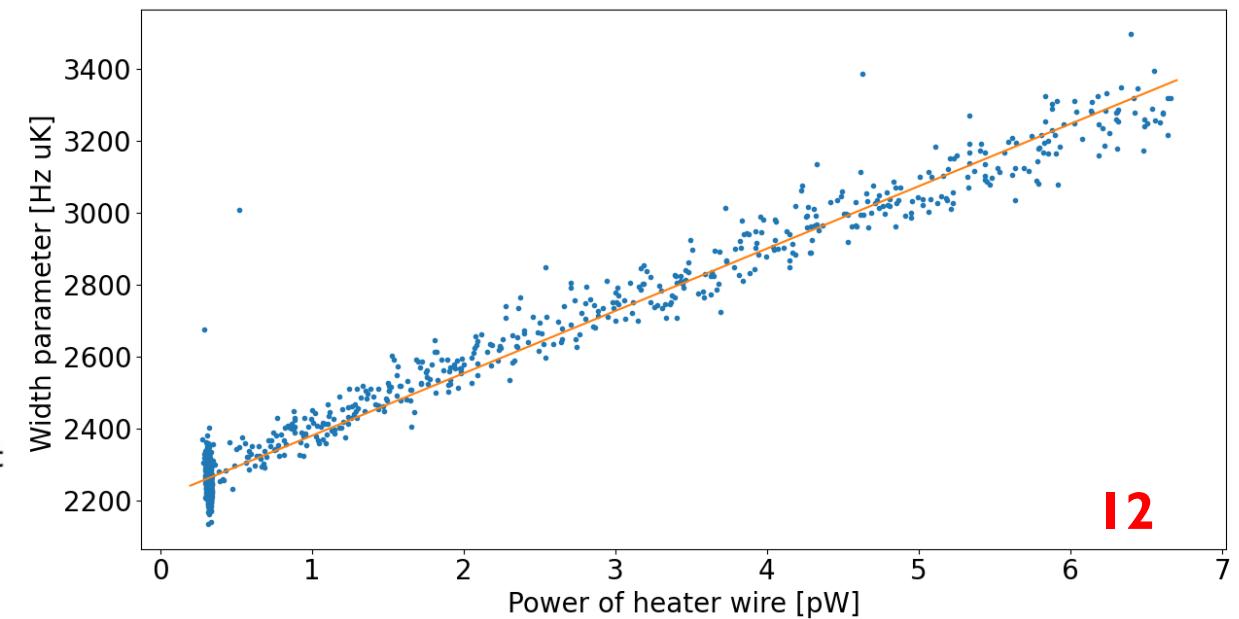
- Vibrating nanowire resonator, driven by AC current in vertical B field
- Damping force from QP collisions
- Energy from variation of resonance width:
$$\Delta Q = \alpha(T_0, P)\Delta(\Delta f)$$
- Amplified by Andreev scattering



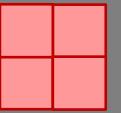
BOLOMETER CALIBRATION



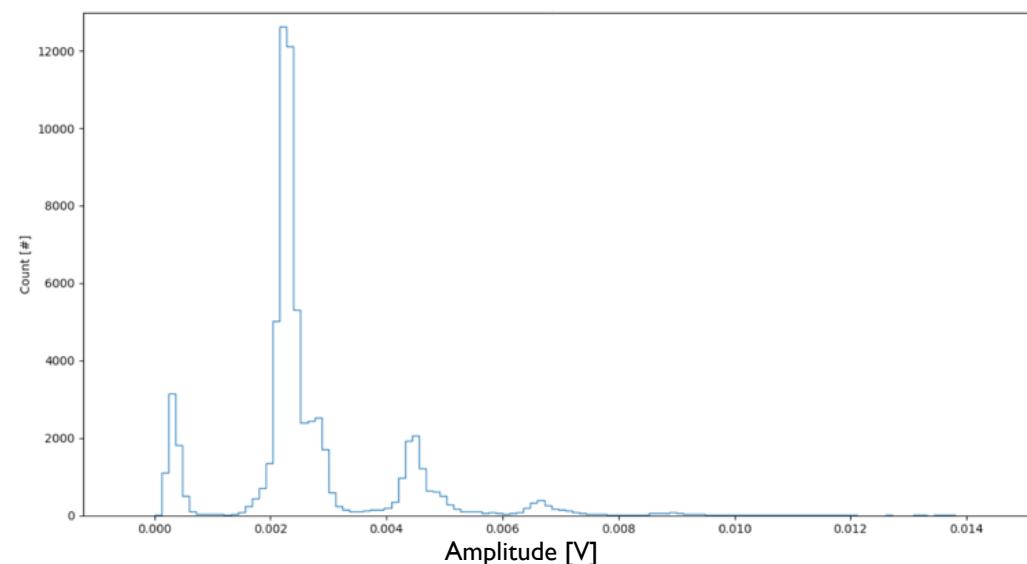
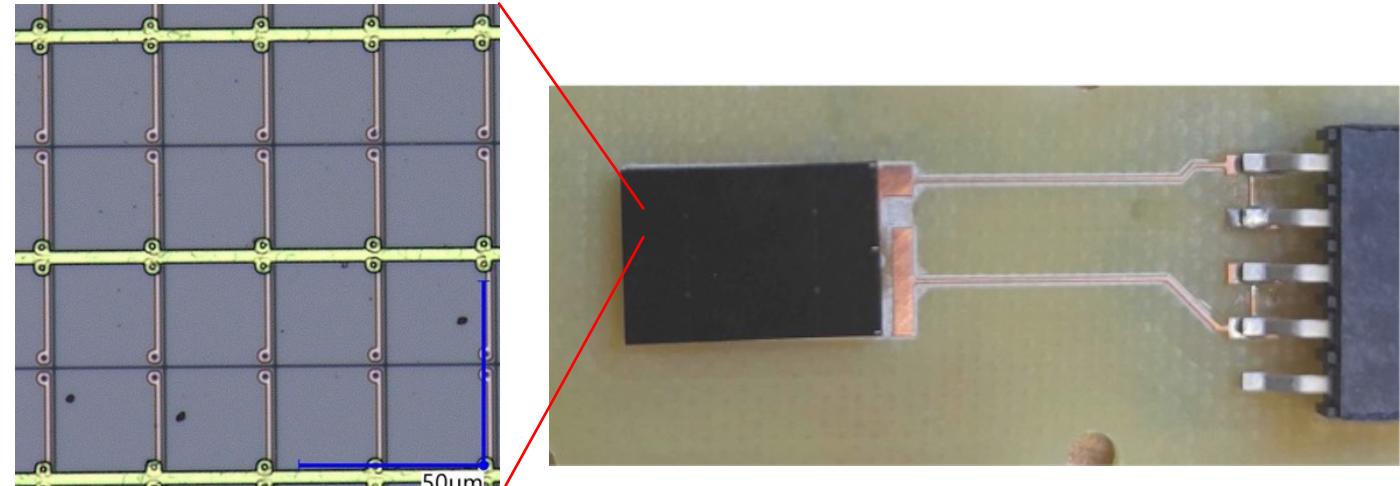
- Bolometer calibration campaign – two bolometers with (4.5 μm) thermometer wire and (13.5 μm) heater wire
- Change in width of thermometer wire vs (known) injected heater power to find calibration coefficient: $P = K(\Delta f - \Delta f_0)T$



PHOTON SENSING WITH SIPMS

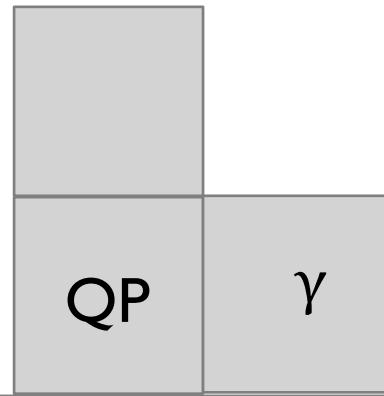


- High gain and single photo-electron resolution
- Wavelength shift to NUV
- *Successful test of device feasibility at 4K - FBK NUV LF SIPMs [A.Ferri et al. JINST 11 P03023(2016)]*





TARGET



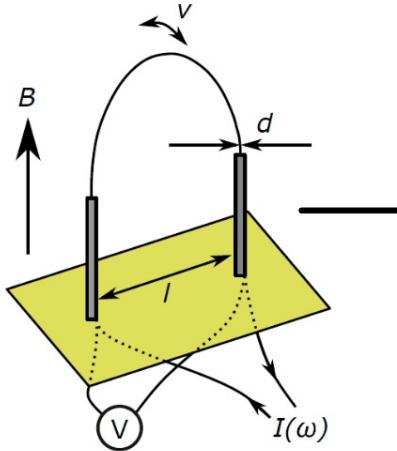
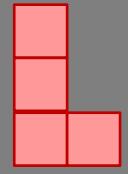
DETECTION



READOUT

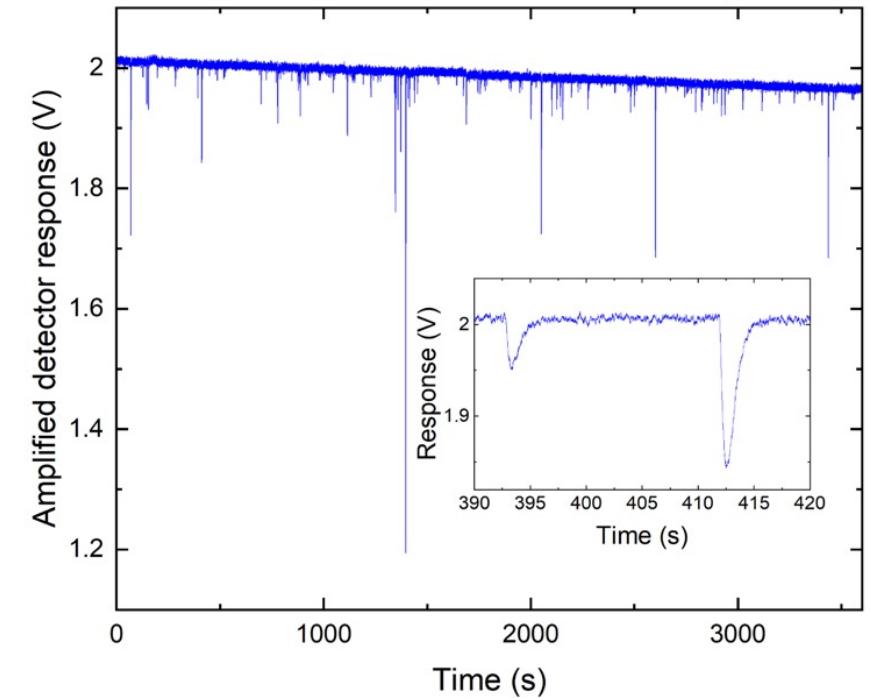
14

BOLOMETER READOUT



Cold preamplifier:
• Transformer
• SQUID circuit

Lockin amplifier

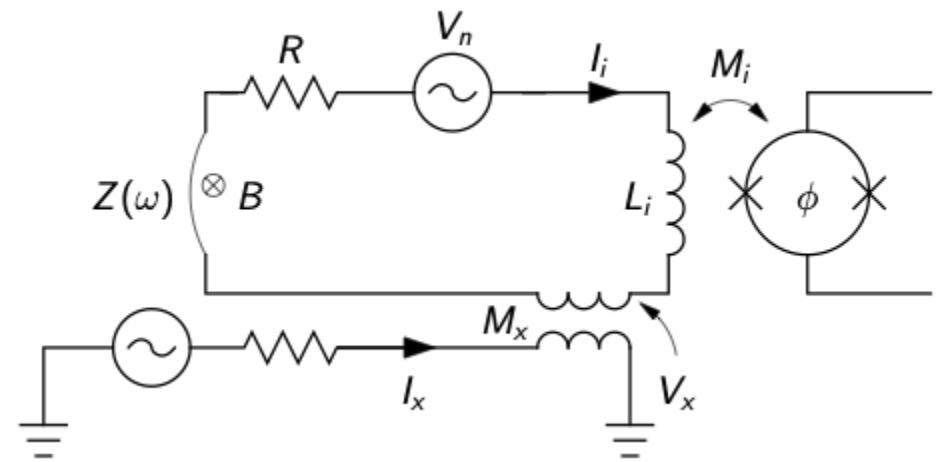
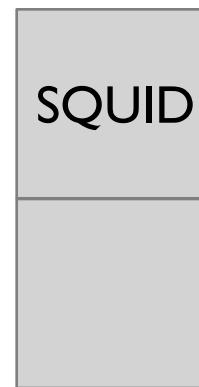
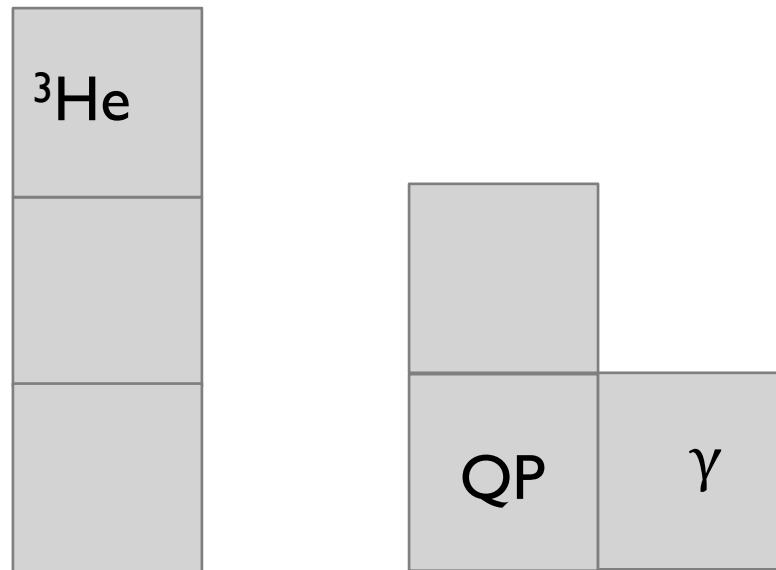


Readout induced voltage on nanowire:

- Conventional method – cold transformer plus lockin

Data from $4.5\mu\text{m}$ wire, $T=125\mu\text{K}$

- Reduce noise – SQUID readout circuit
- SQUID current sensor connected to lockin amplifier using room temperature flux locked loop electronics
- Tested in vacuum at 4.2K



TARGET

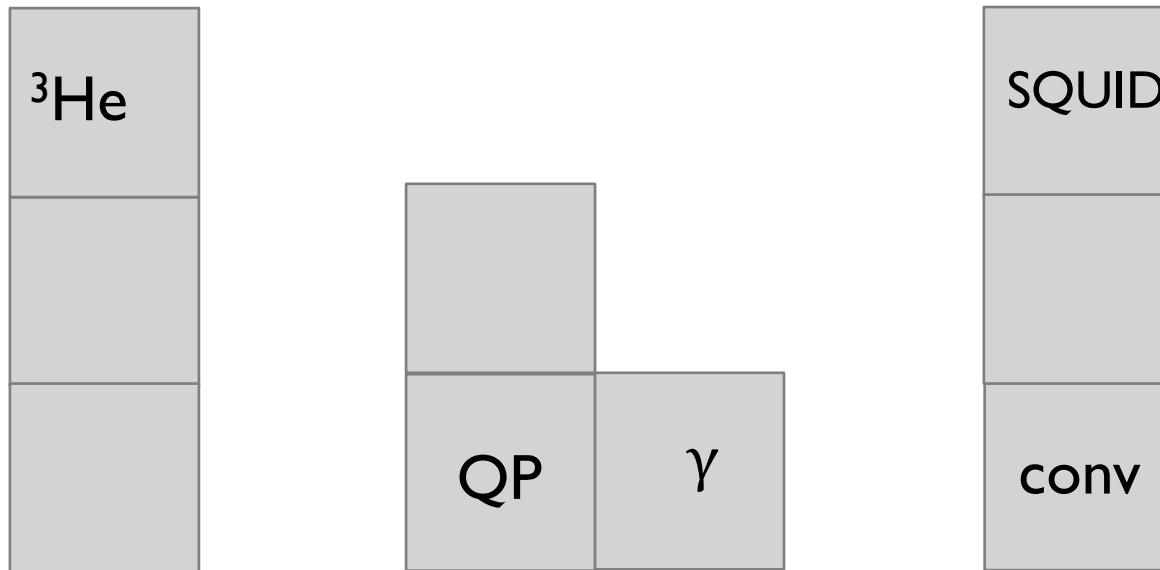
DETECTION

READOUT

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SIMULATION



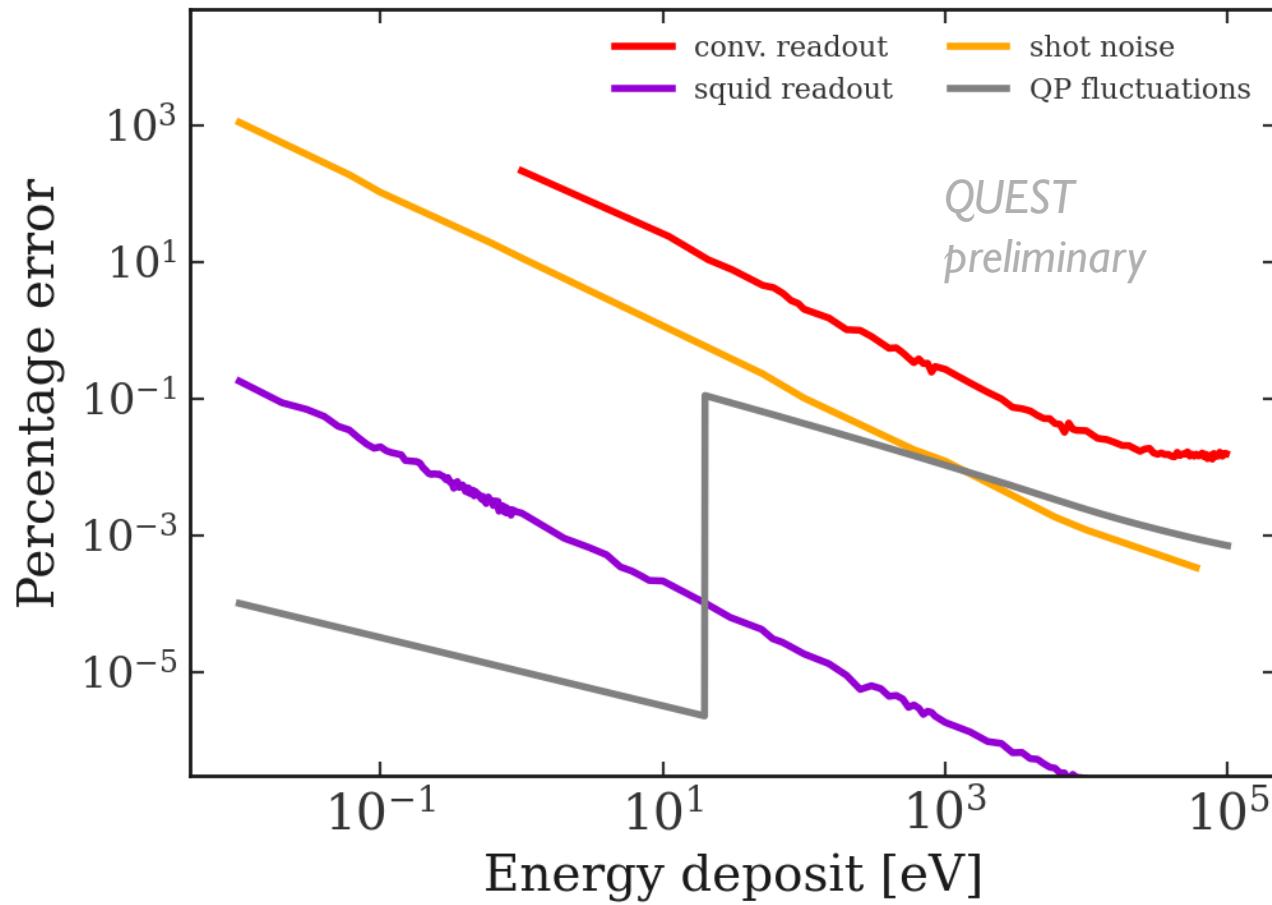
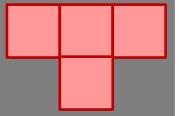
TARGET

DETECTION

READOUT

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ENERGY MEASUREMENT UNCERTAINTY



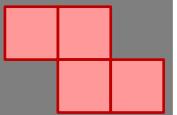
- Quasiparticle (QP) production fluctuations
- Readout noise – **conventional** vs **SQUID**
- **Shot noise** – fluctuations on incident QPs

Nuclear recoil energy thresholds:

- **Conventional readout:** 39 eV
- **SQUID readout:** 0.71 eV

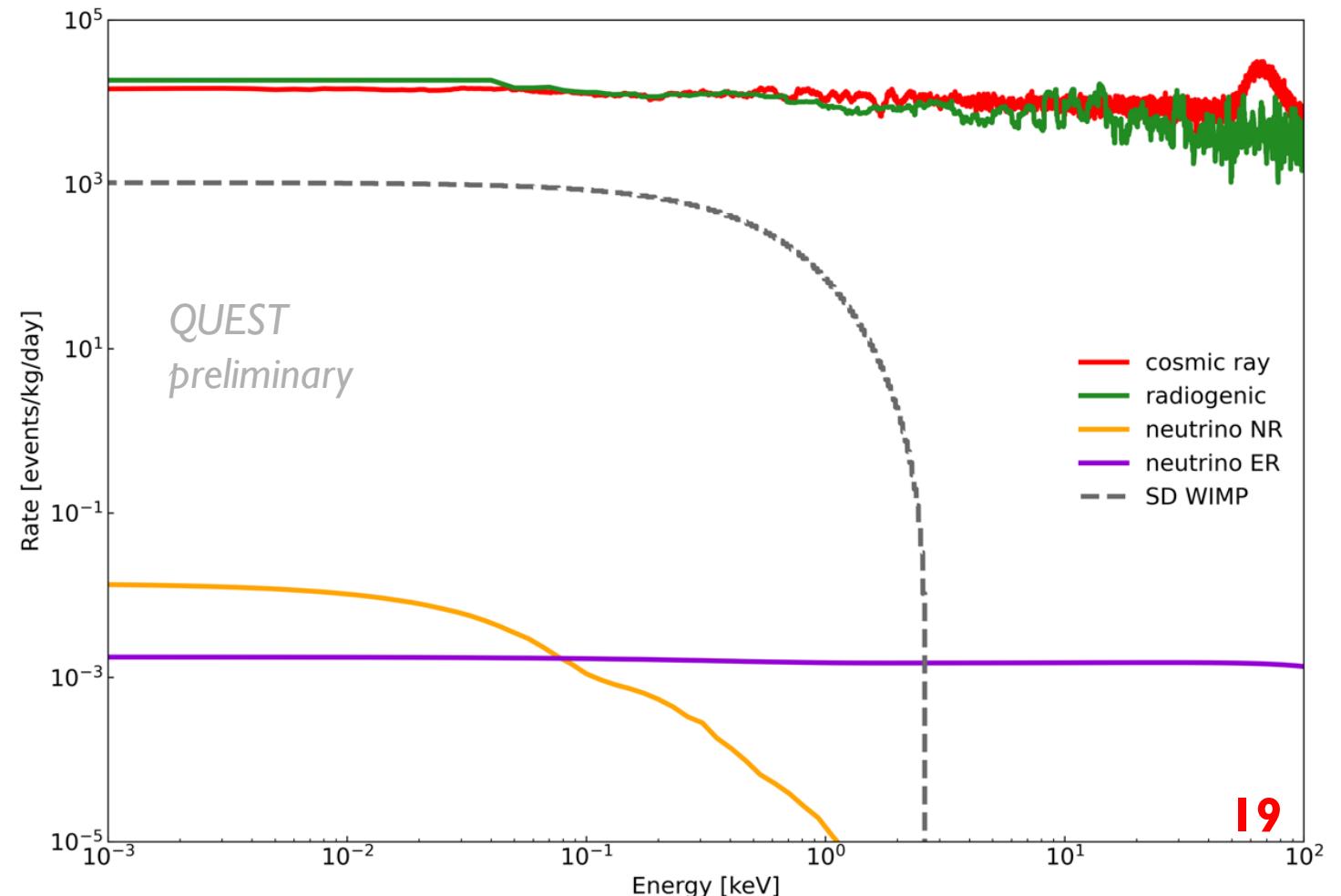
[400nm diameter wire at 0.12 T/Tc]

EXPECTED BACKGROUNDS

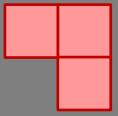


Background	Events/cell/day [0-10keV]
Cosmic rays	3.31
Radiogenic	2.61
PP neutrino	4.76e-7
CN neutrino	2.01e-9

- Cosmic rays - CRY + Geant4, no shielding and 90% veto efficiency
- Radiogenic - material screening and Geant4



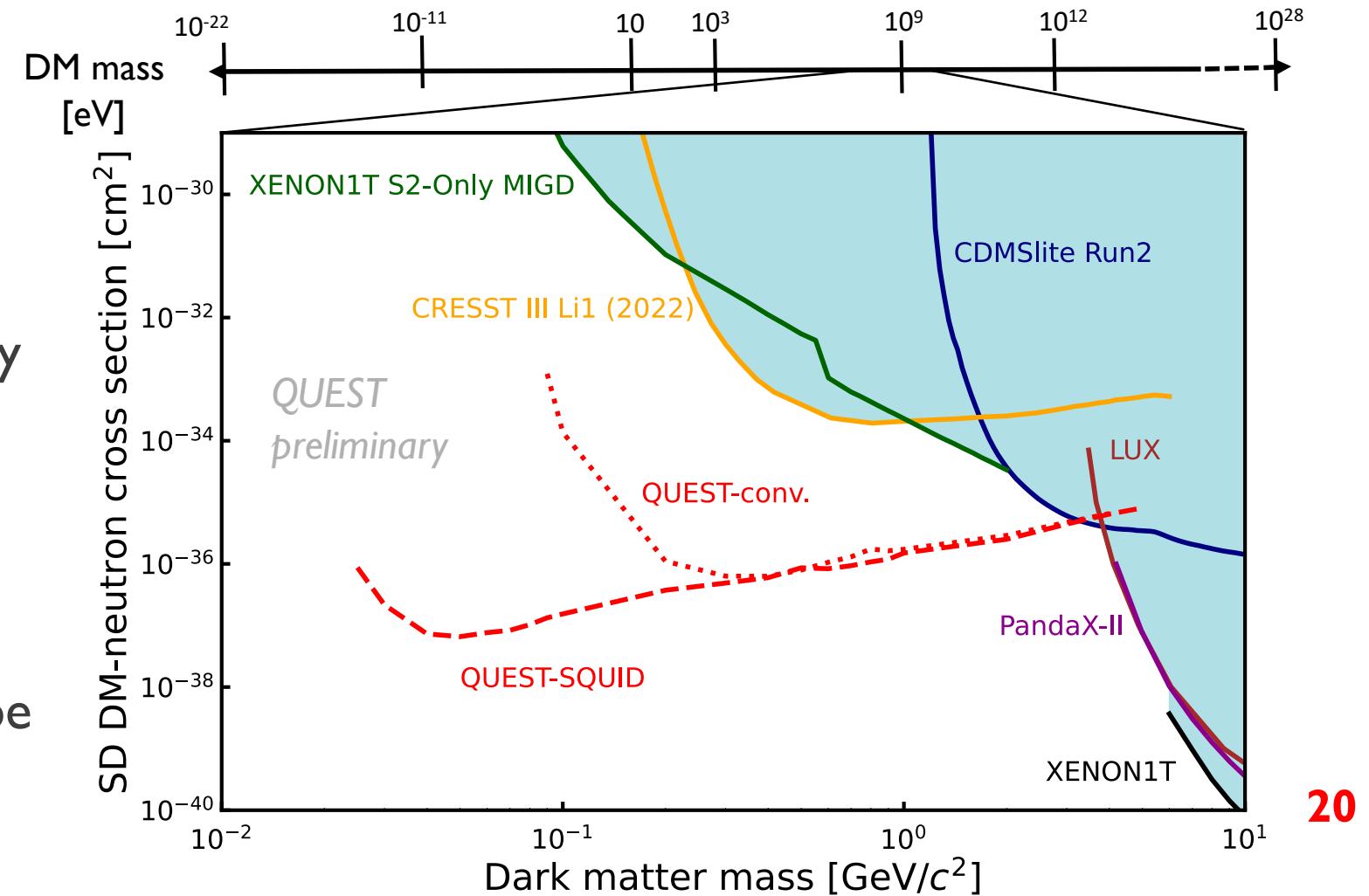
DARK MATTER SENSITIVITY



Spin dependent sensitivity projection for:

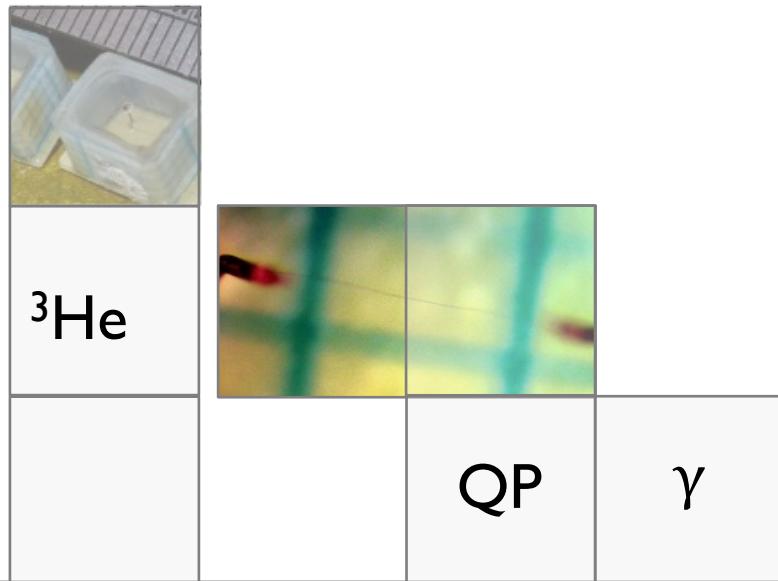
- 5 x 0.3 cm³ cells
- 6 month run with 50% duty cycle
- QP detection only

Profile likelihood ratio with systematics: background rates, energy scale and galactic escape velocity.



Proof of concept:

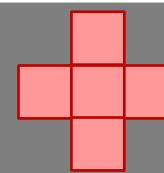
- bolometer operation and calibration
- simulation and analysis software



TARGET

DETECTION

READOUT



21

Proof of concept:

- bolometer operation and calibration
- simulation and analysis software

Ongoing:

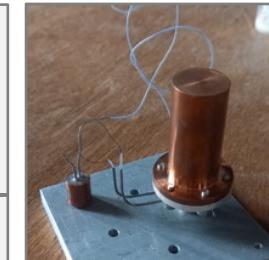
- SQUID readout
- photon sensors



^3He



SQUID

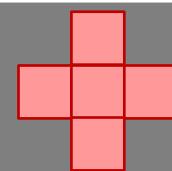


conv

TARGET

DETECTION

READOUT



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Proof of concept:

- bolometer operation and calibration
- simulation and analysis software

Ongoing:

- SQUID readout
- photon sensors



^3He

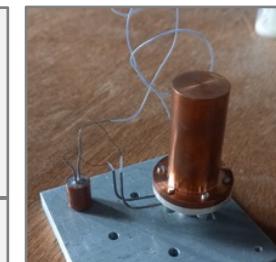


QP



γ

SQUID

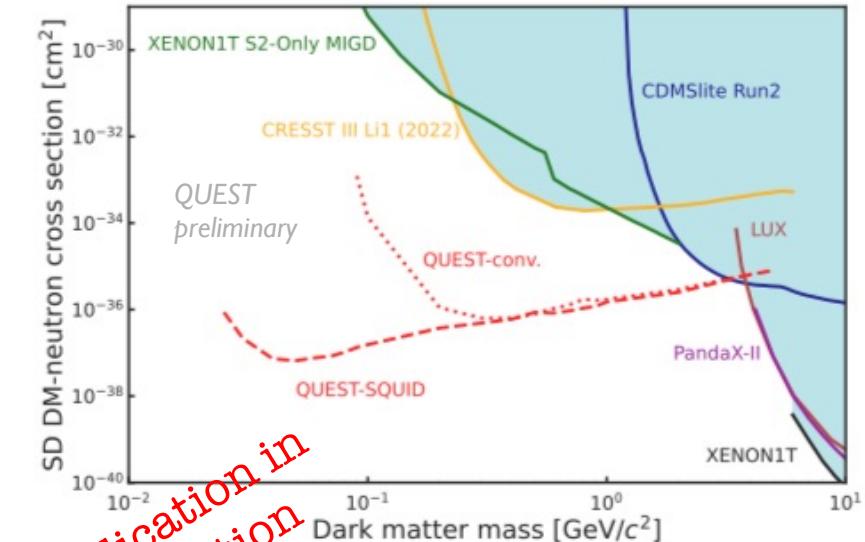


conv

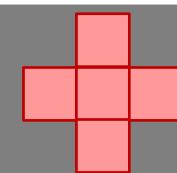
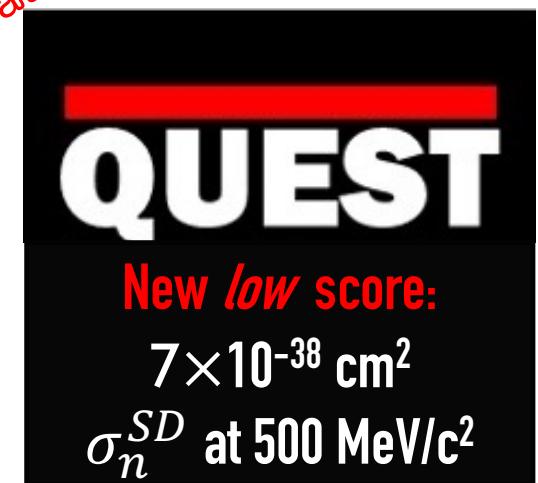
TARGET

DETECTION

READOUT



Publication in
preparation



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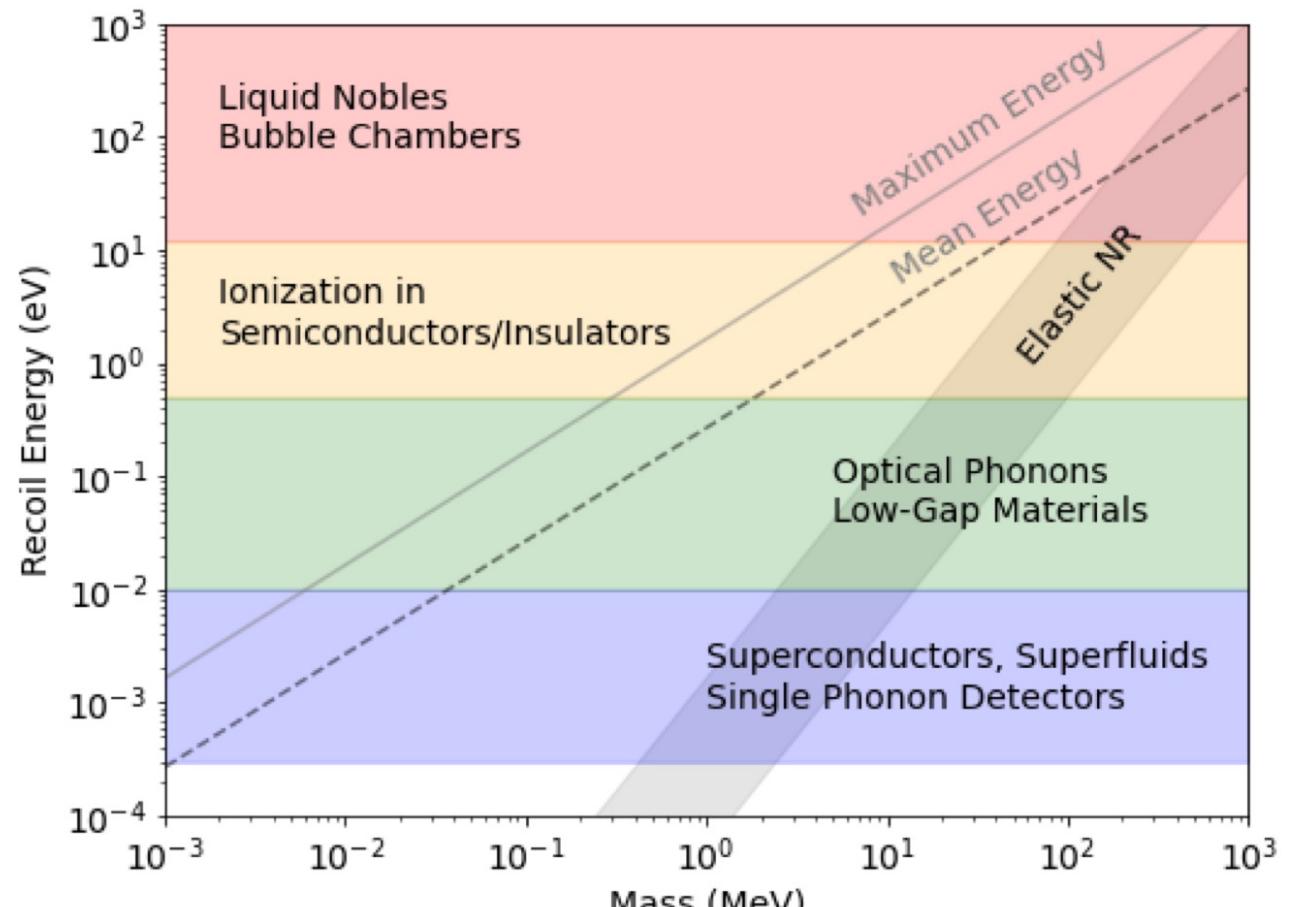
BACKUP SLIDES

LOWER THRESHOLDS

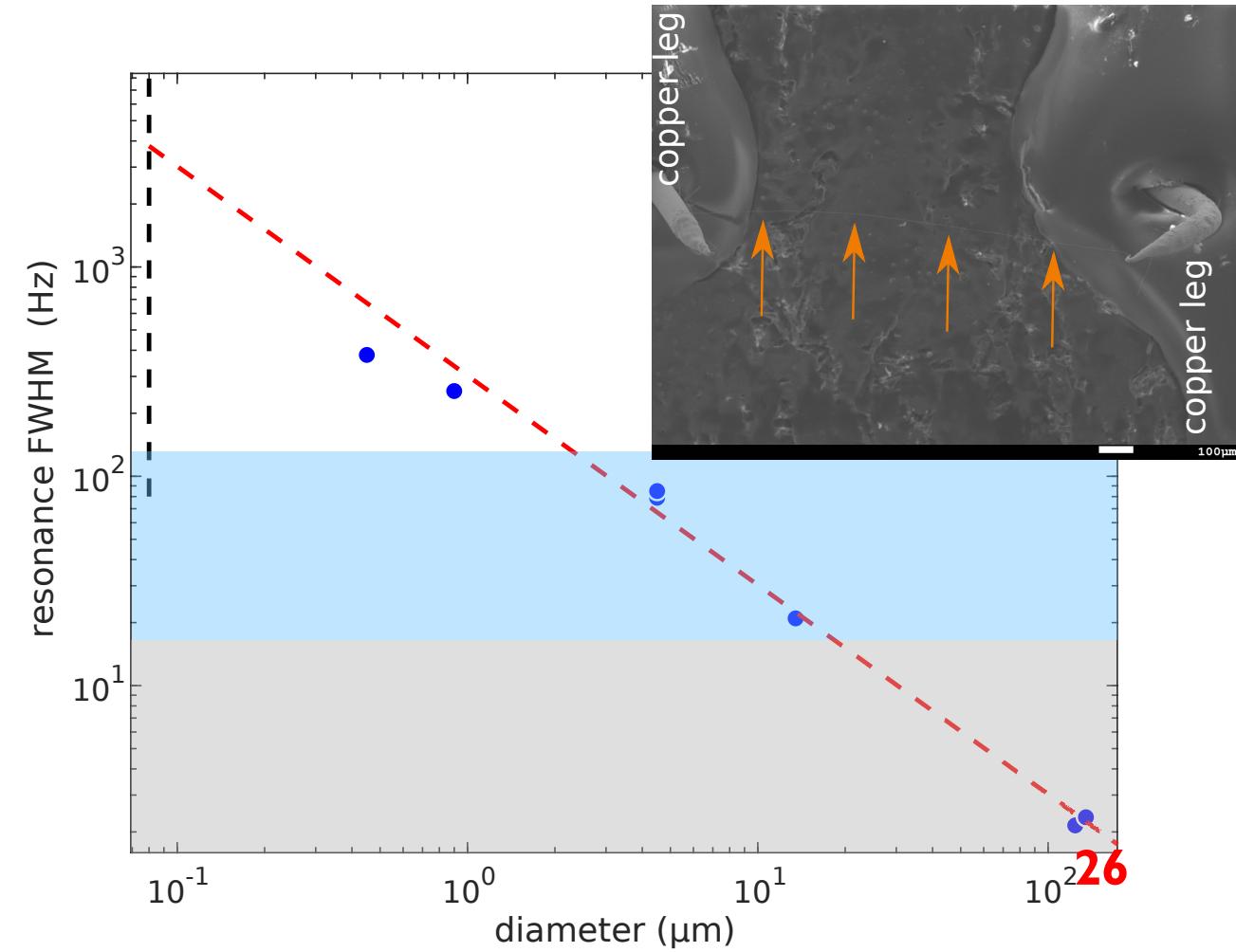
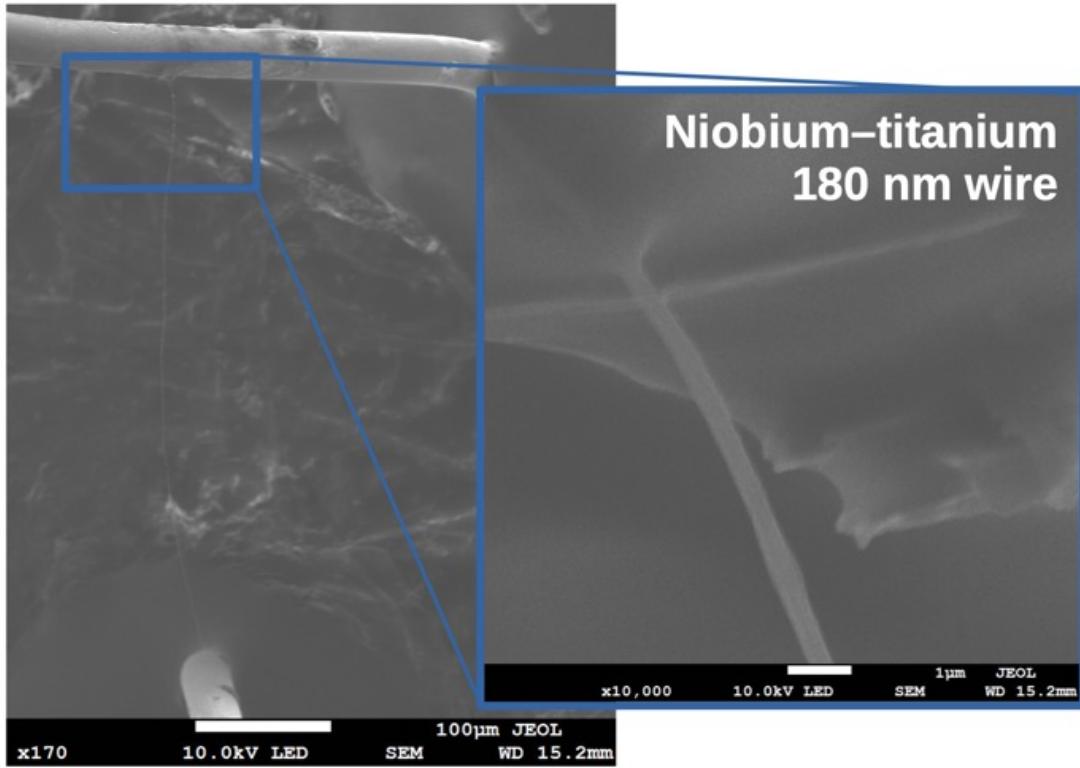
Quanta production:

- $\sim 10\text{eV}$ Xe, Ar ionisation
- $\sim 1\text{eV}$ semiconductor gap Ge, Si
- $\mu\text{eV} - \text{meV}$ collective excitations doped semiconductors, superconductors

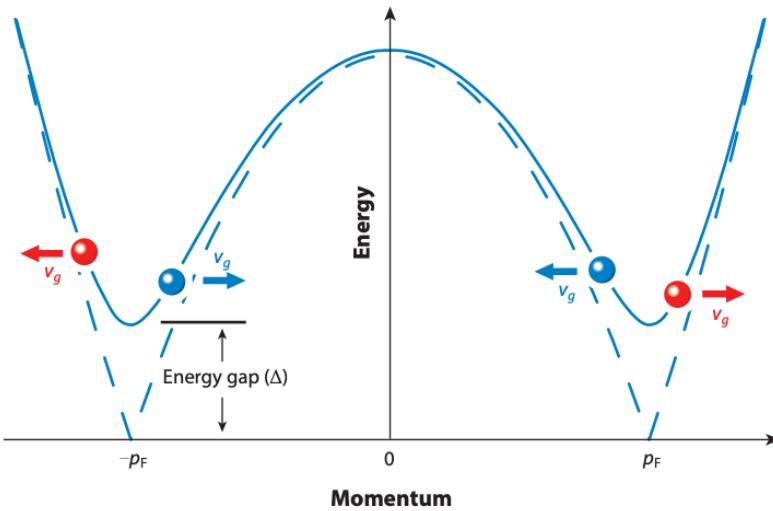
New proposals to bridge gap between DM scattering and resonant cavity experiments



NANOWIRES

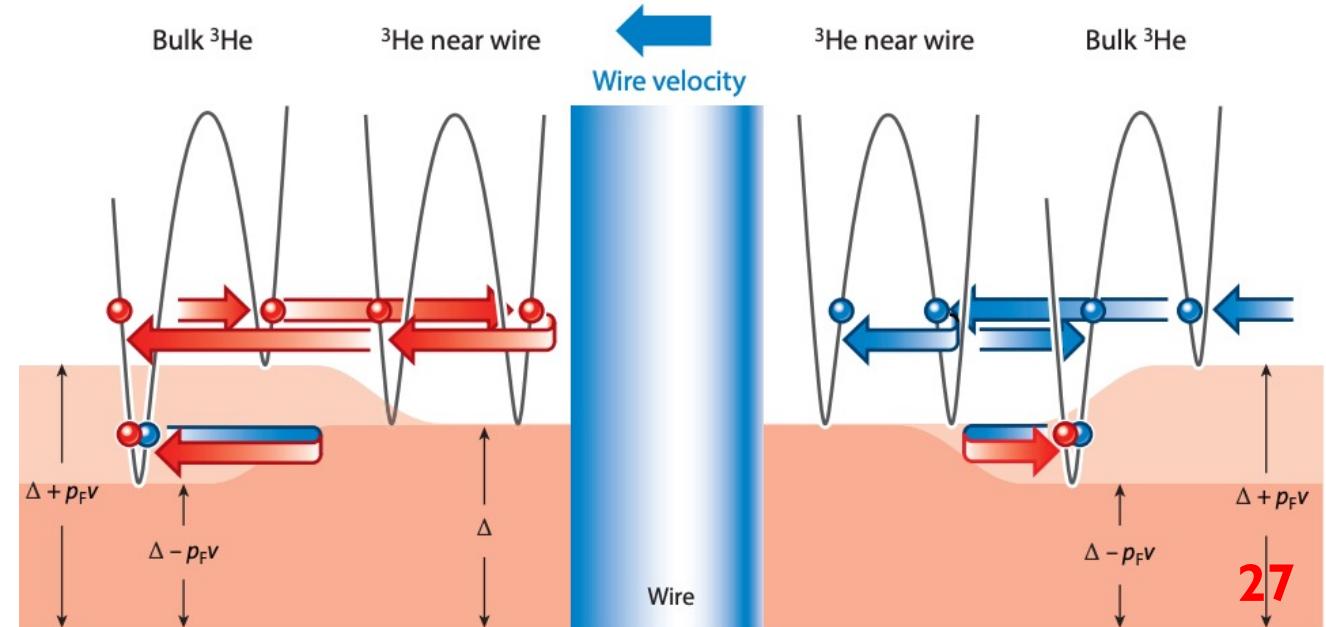


ANDREEV SCATTERING



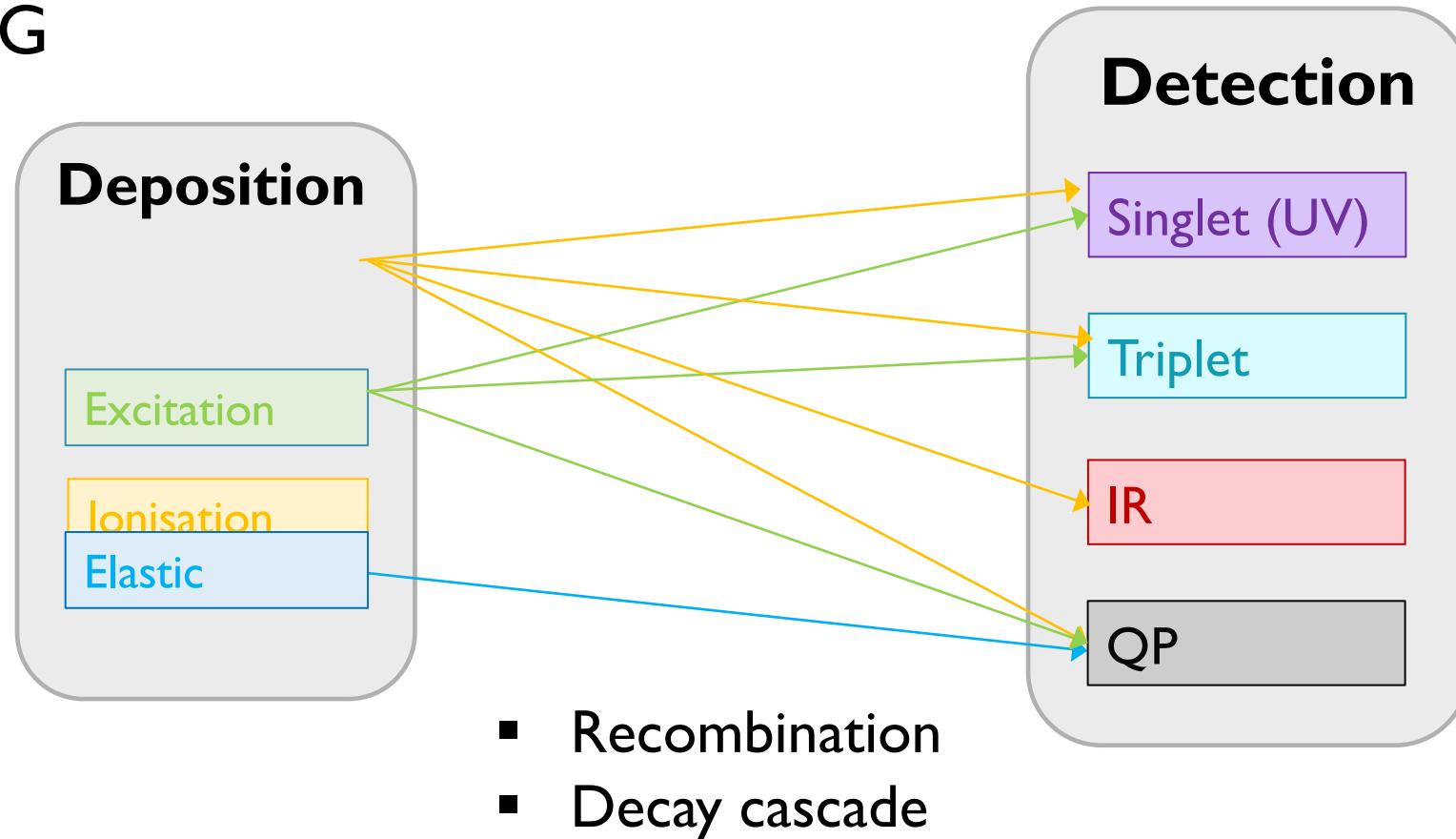
- Quasiparticle dispersion curve , with energy minima at the Fermi momentum.
- Group velocity (slope) parallel to momentum for particles and antiparallel for holes. Becomes zero at p_F , so in some scattering process particle drops to min then moves up other side of curve as a hole, with velocity reversed but momentum same.

- Fluid flow and relative motion of an object can increase/decrease the gap.
- Only quasiparticles from in front and quasiholes from behind can transfer momentum $|2p_Fv|$, increasing the damping.

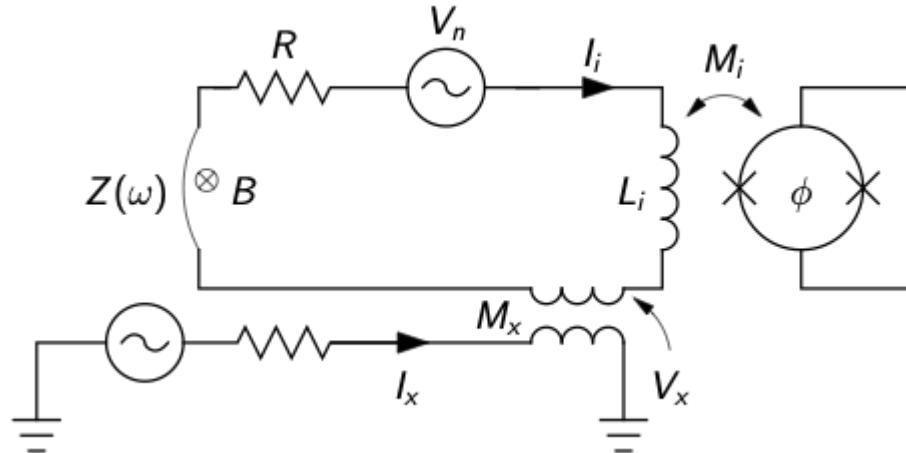
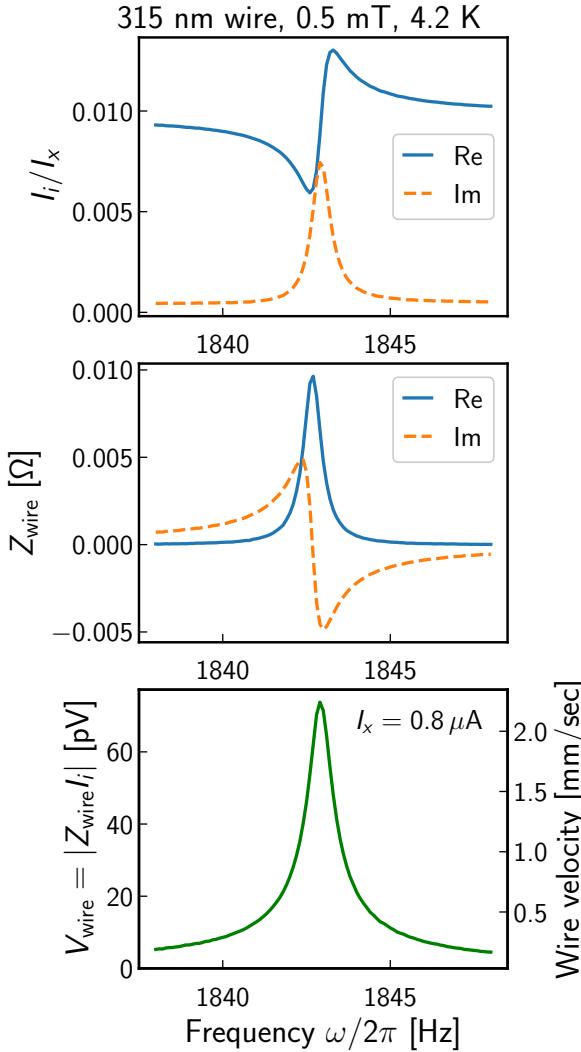


PARTITIONING

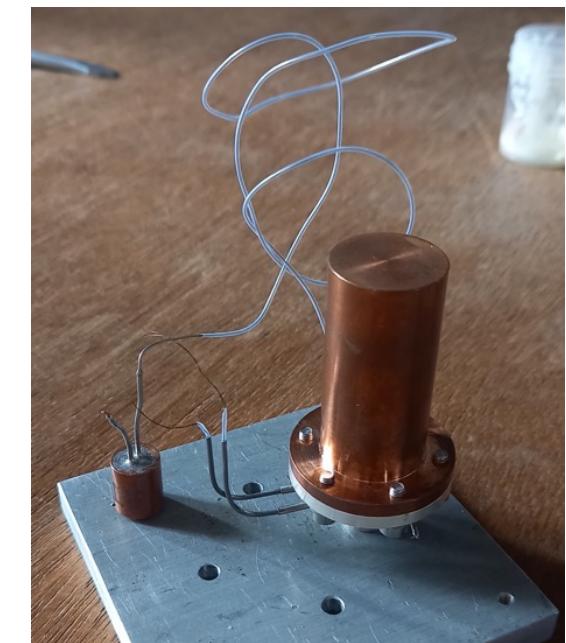
- Nuclear quenching
- Ionisation and excitation cross sections



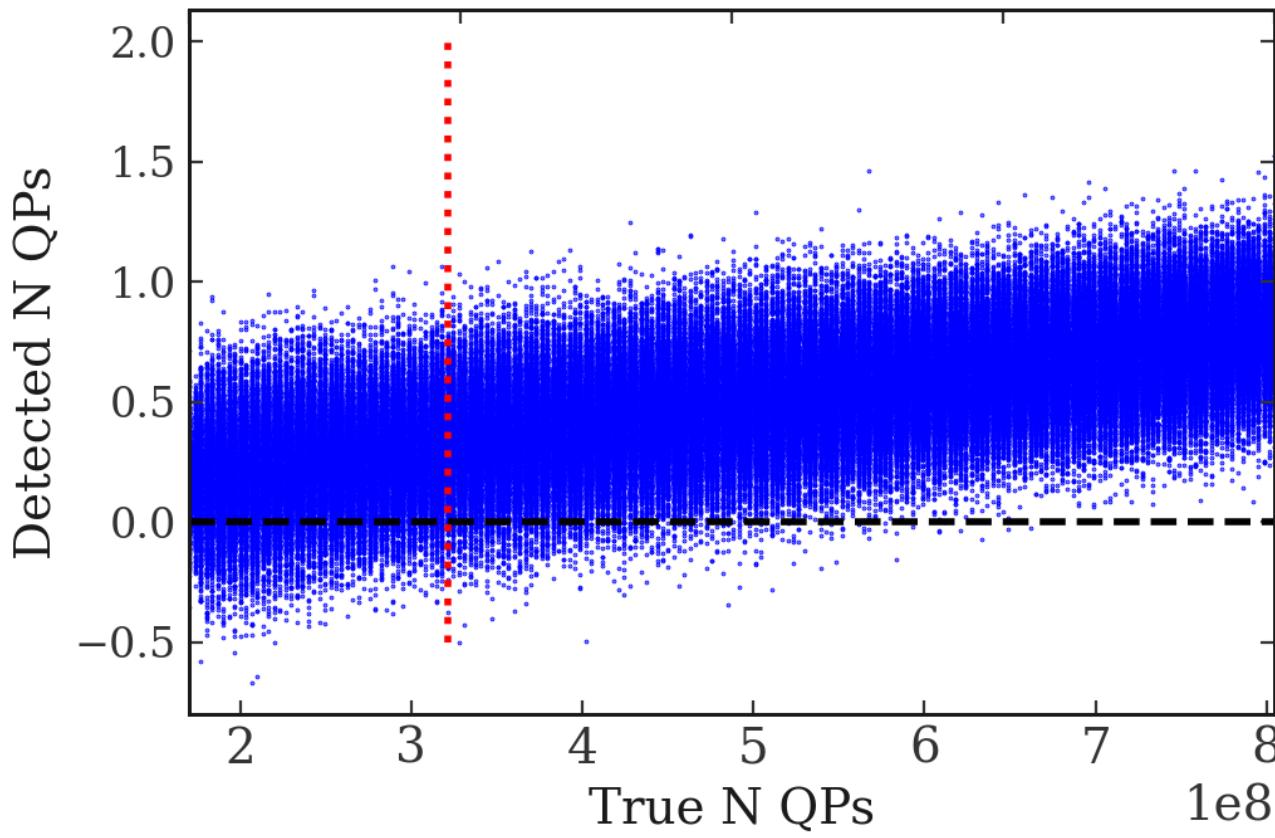
SQUID READOUT SCHEME



- Voltage excitation is applied via a transformer with mutual inductance M_x . SQUID current sensor detects current I_i flowing through the wire with impedance $Z(f)$, contact resistance R , and SQUID input coil L_i .
- Readout scheme tested with 315nm wire in vacuum at 4.2K
- Planned test with 400nm wires



EXPECTED ENERGY THRESHOLD



Resolution at threshold – 95% confidence energy > zero.

- Conventional readout: 39 eV
- Squid readout reduces noise, so resolution is dominated by shot noise.
- Squid readout: 0.71 eV

HELIUM SEARCHES

