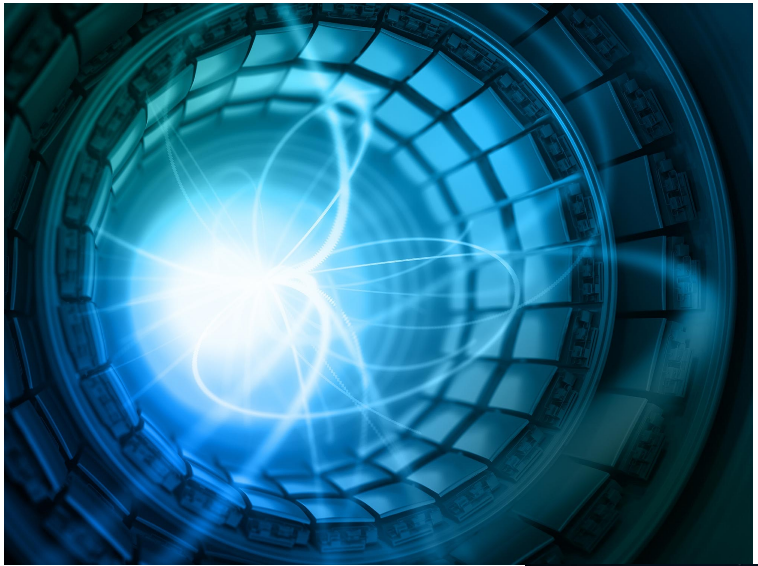
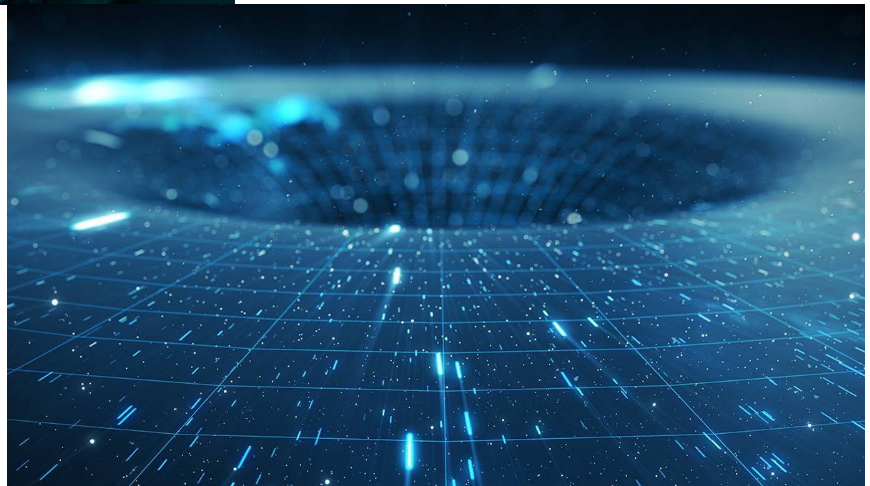


Quantum Technologies for Neutrino Mass, Black Holes and the Early Universe

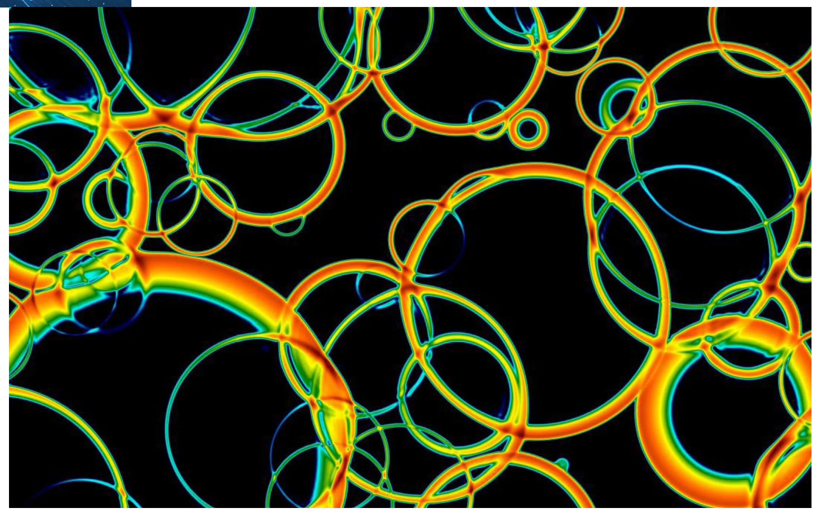


UCL

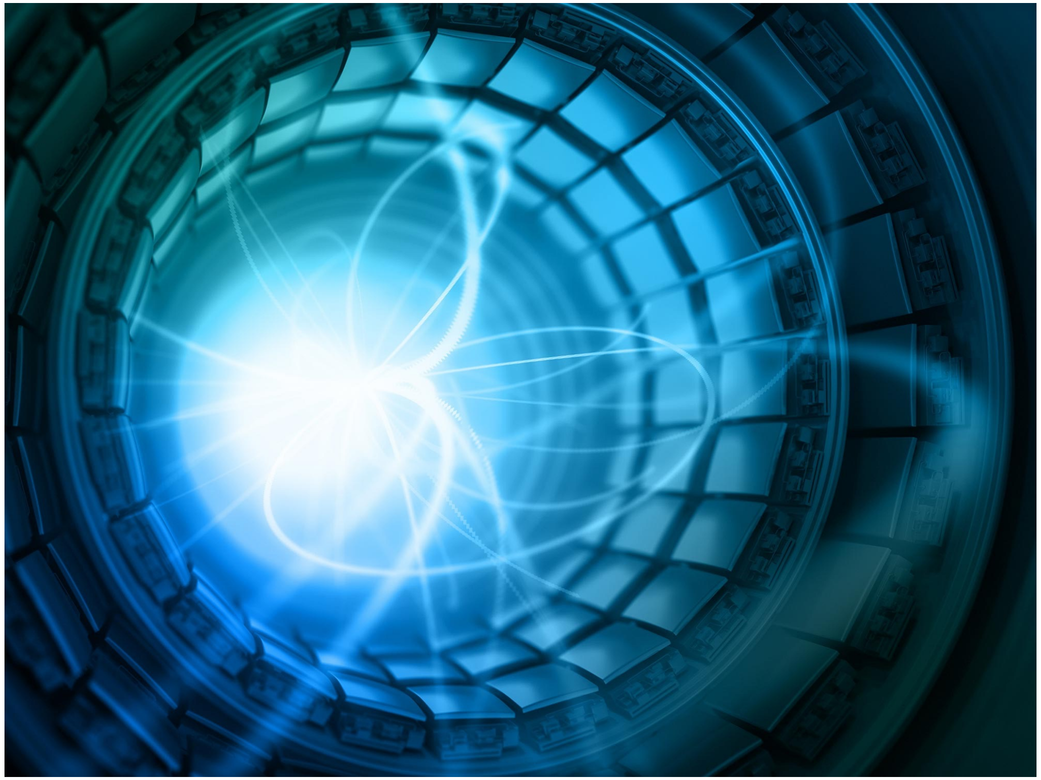
David Waters

ECFA-UK Meeting

24th September 2024



QTNM
Quantum Technologies for Neutrino Mass



Vision: build a demonstrator apparatus for determining neutrino mass via CRES from tritium β-decay

QTNM Consortium

UCL

UNIVERSITY OF CAMBRIDGE

WARWICK
THE UNIVERSITY OF WARWICK

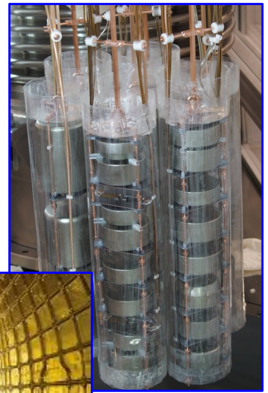
Prifysgol Abertawe
Swansea University

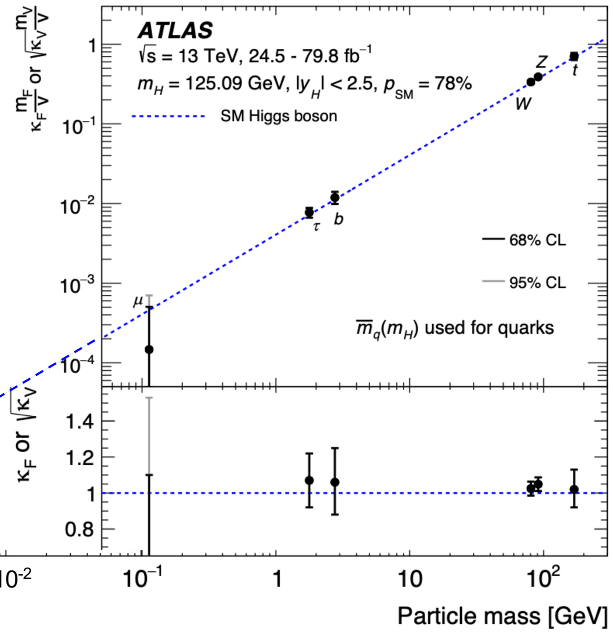
Queen Mary
University of London

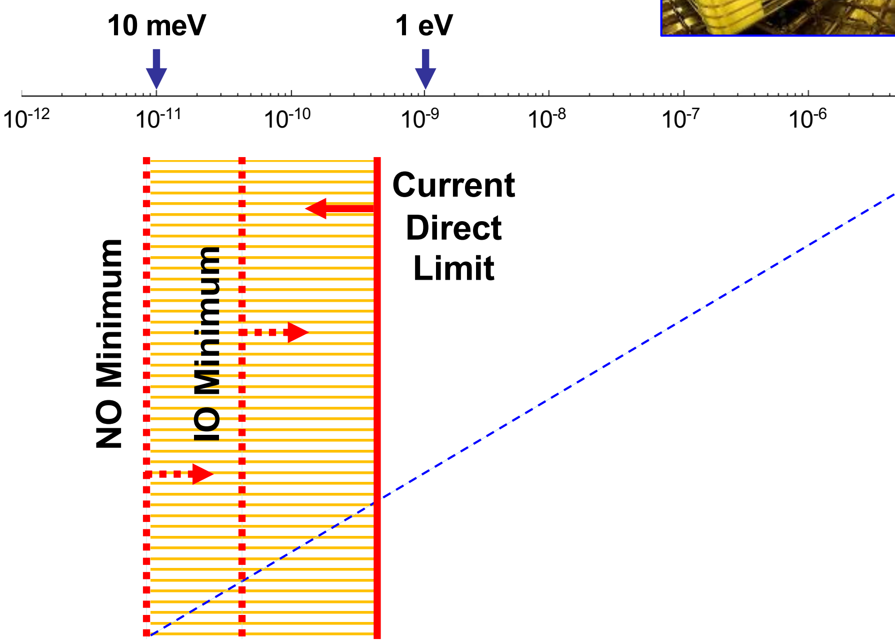
UNIVERSITY OF OXFORD

NPL
National Physical Laboratory

- The nature of neutrino mass – the same mechanism as other fermions, or not?
- How do the neutrino eigenstates mix and is there an asymmetry between neutrinos and anit-neutrinos?

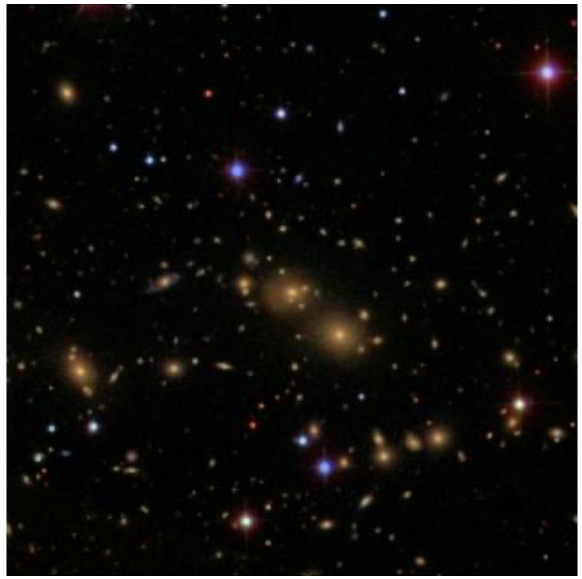


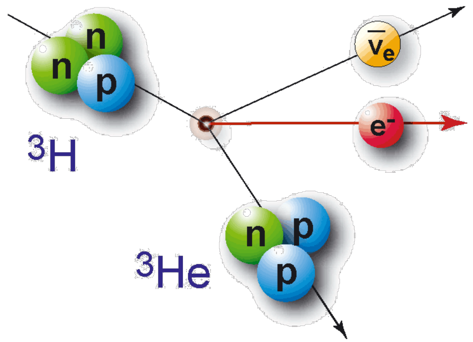




“Electron” neutrino mass

- The most abundant fermion in the universe.
- Neutrino mass from cosmology.





$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X' + \underbrace{e^{-} + \bar{\nu}_e} $$

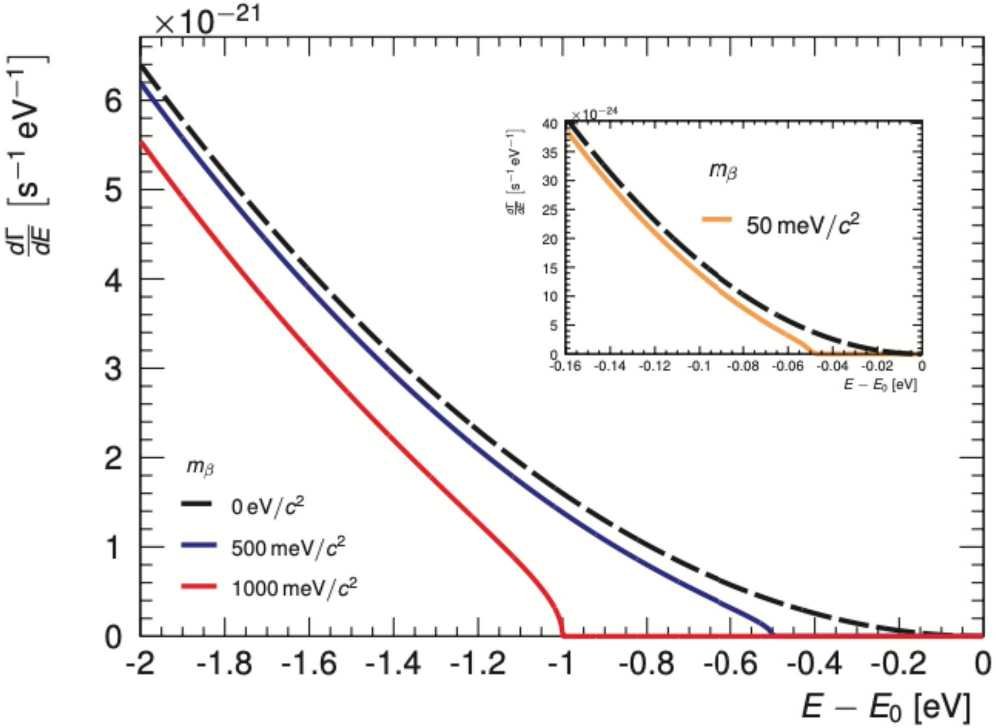
$$ Q - E_e^{\max} \approx m_\nu c^2 $$

- Isotope? Simple atomic state & nuclear transition, low-Q : tritium.
- Atomic or molecular?

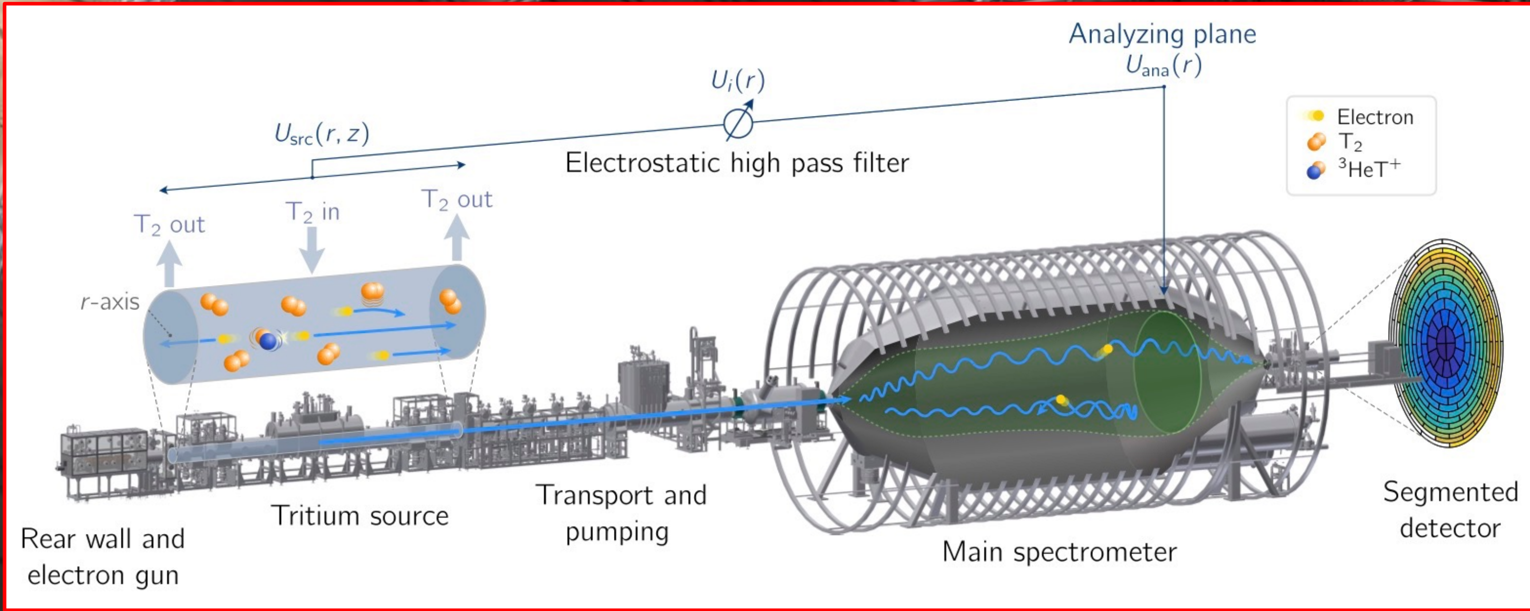
- Effective electron neutrino mass:

$$ m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \, m_i^2} $$

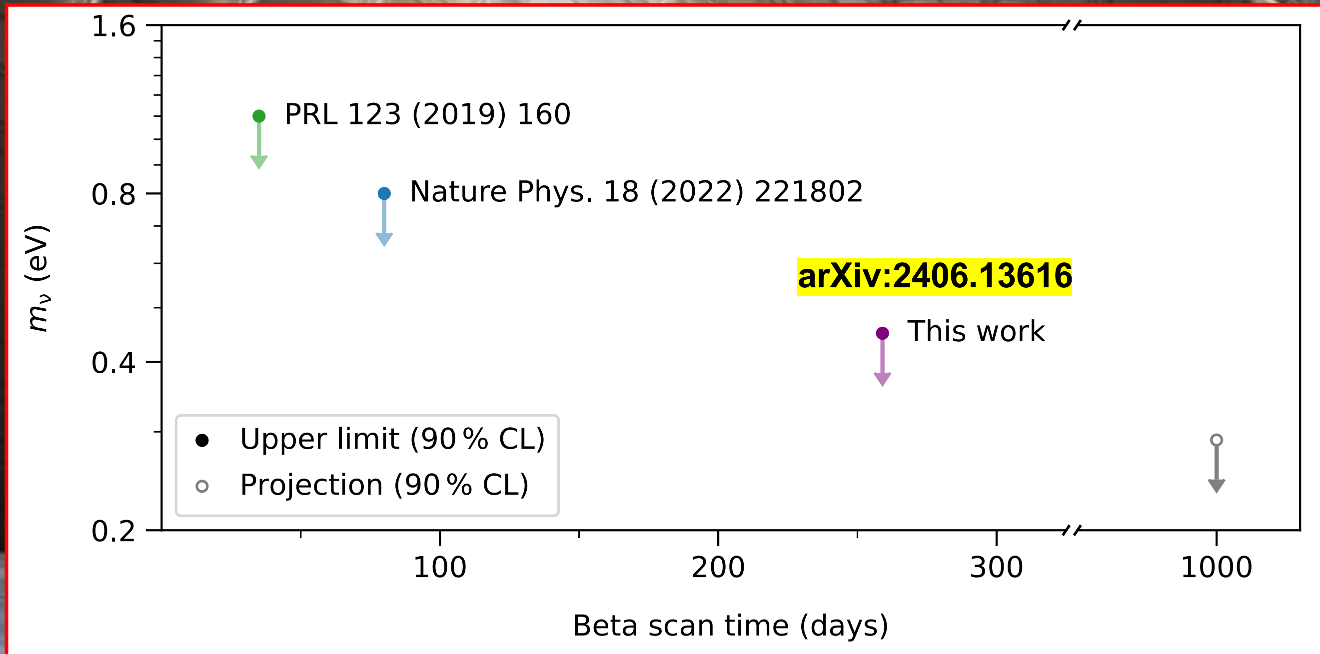
- Sensitive to mass eigenvalues and ordering.
- A tiny fraction of the total decay spectrum is sensitive to the neutrino mass.
- Integral vs. differential spectrum reconstruction.



KATRIN

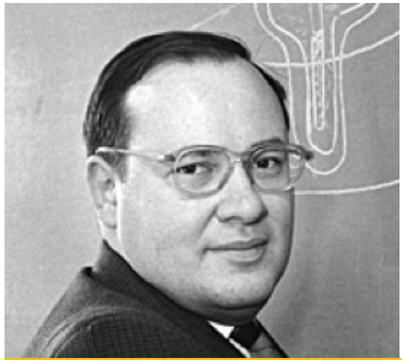


Analyzing plane
$U_{ana}(r)$
$U_i(r)$
$U_{src}(r, z)$
Electrostatic high pass filter
T_2 out
T_2 in
T_2 out
r-axis
Electron
T_2
$^3HeT^+$
Rear wall and electron gun
Tritium source
Transport and pumping
Main spectrometer
Segmented detector

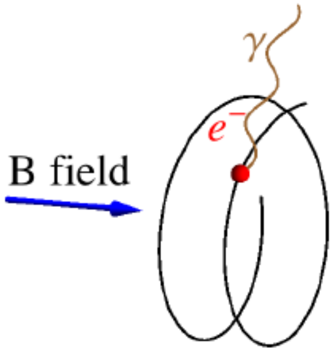


1.6
0.8
0.4
0.2
m_ν (eV)
PRL 123 (2019) 160
Nature Phys. 18 (2022) 221802
arXiv:2406.13616
This work
Upper limit (90 % CL)
Projection (90 % CL)
100
200
300
1000
Beta scan time (days)

Cyclotron Emission Radiation Spectroscopy



A. Schawlow: "Never measure anything but frequency!"



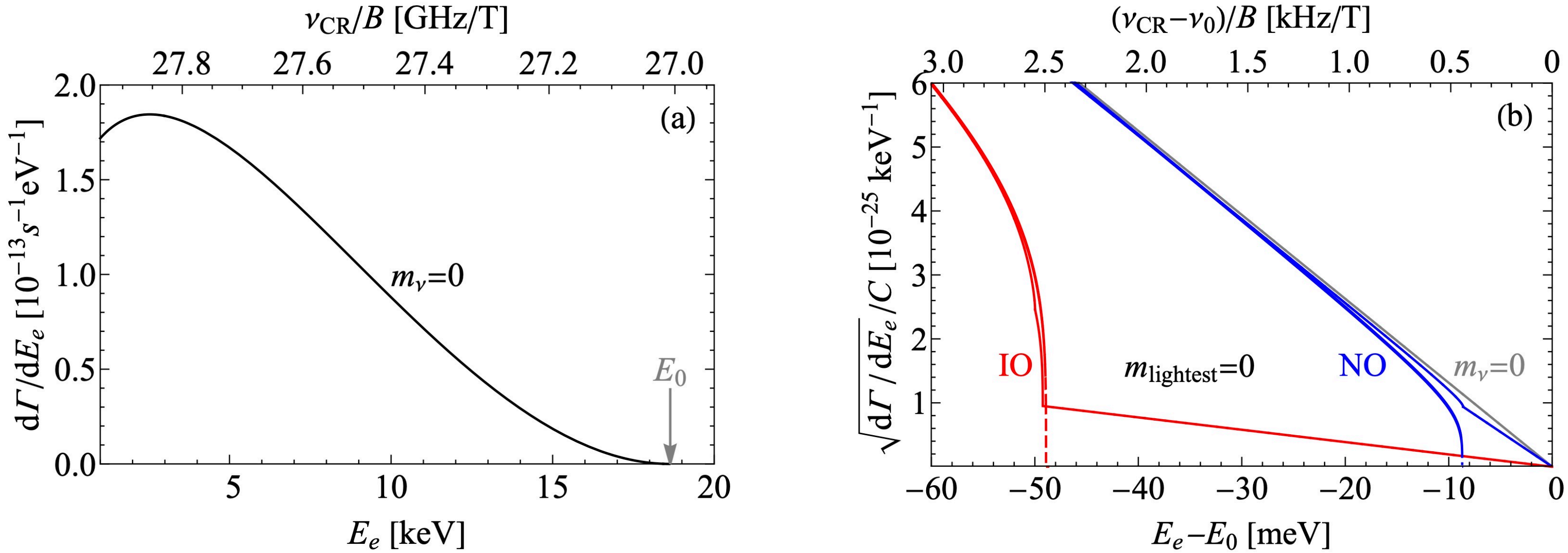
(Monreal and Formaggio, 2009)

$$power = \frac{1}{4\pi\epsilon_0}\frac{2}{3}\frac{e^4}{m_e^2 c}B^2\left(\gamma^2 - 1\right)$$

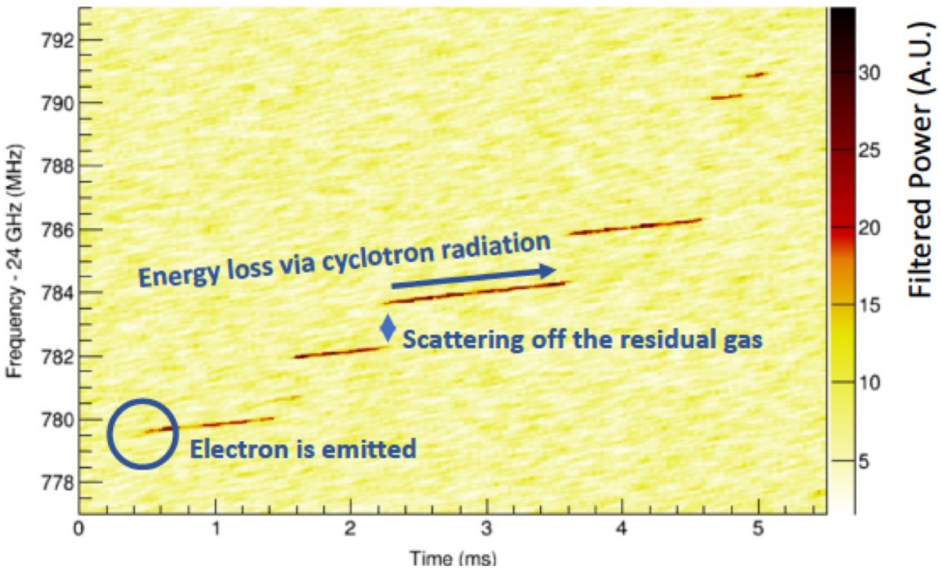
Mildly relativistic at end-point:

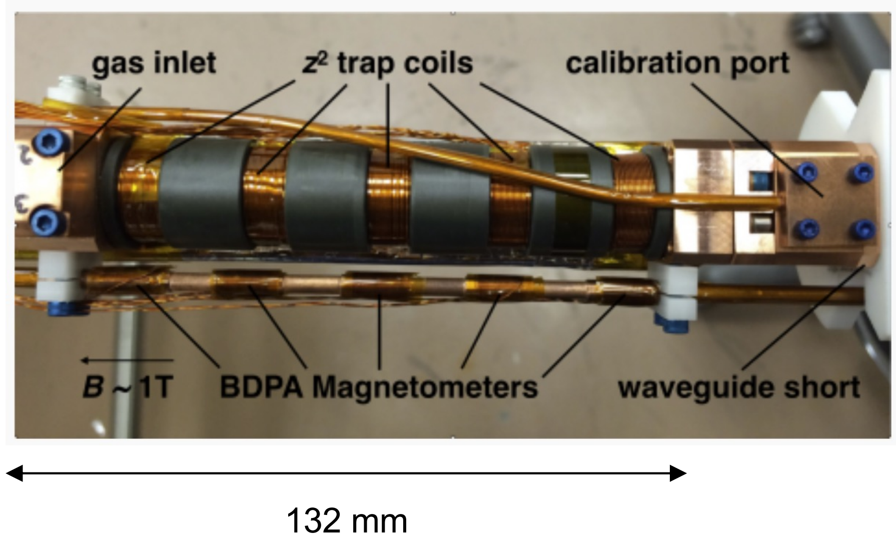
$$\gamma = 1.0364 \quad \Rightarrow p \approx 1 \text{ fW @1 T}$$

Frequency: $\nu_{CR} = \frac{1}{2\pi}\frac{eB}{m_e + E_{\text{kin}}/c^2}$



Project 8

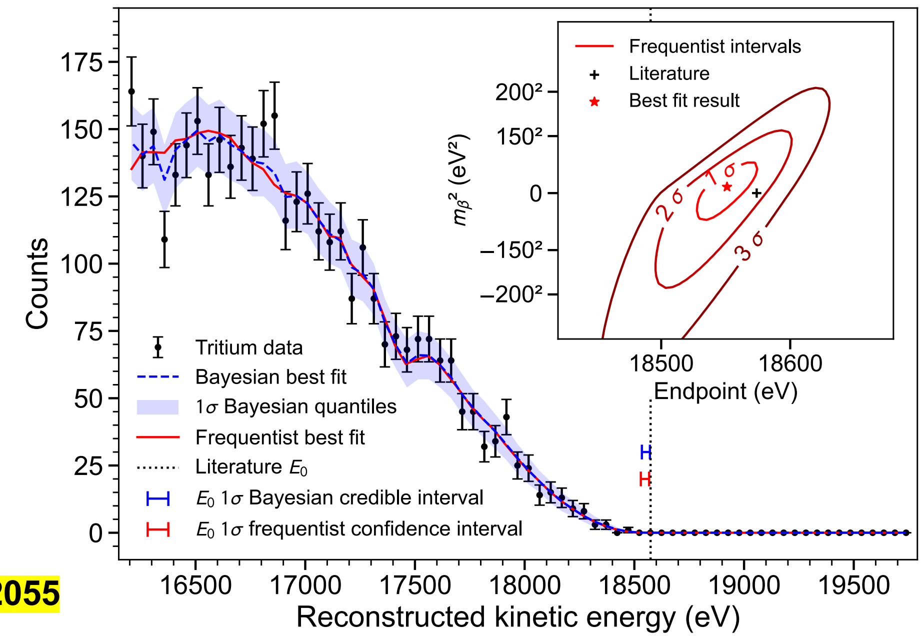




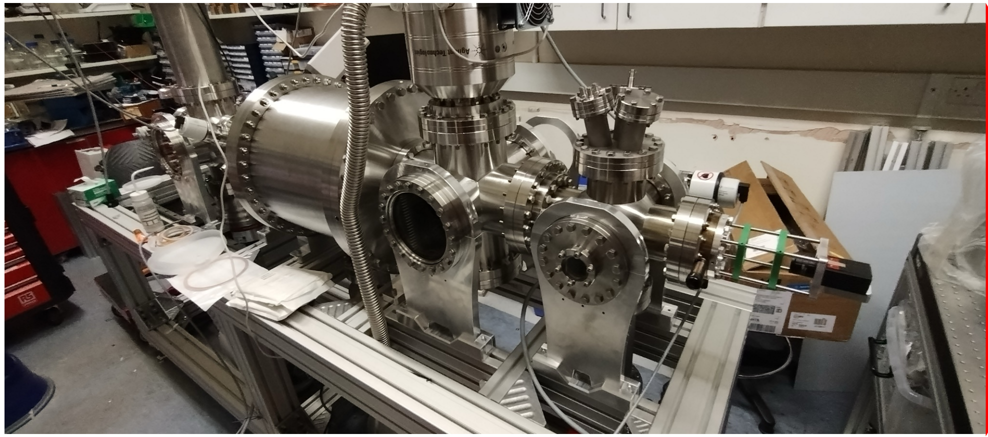
PROJECT 8

- Energy resolution : 1.7 eV (^{83m}Kr)
- Volume × efficiency = 1.2 mm^3
- T_2 density ~ 8 × 10^{10} cm^{-3} (molecular)
- 82 days run time
- m_β < 155 eV (90% C.L.)

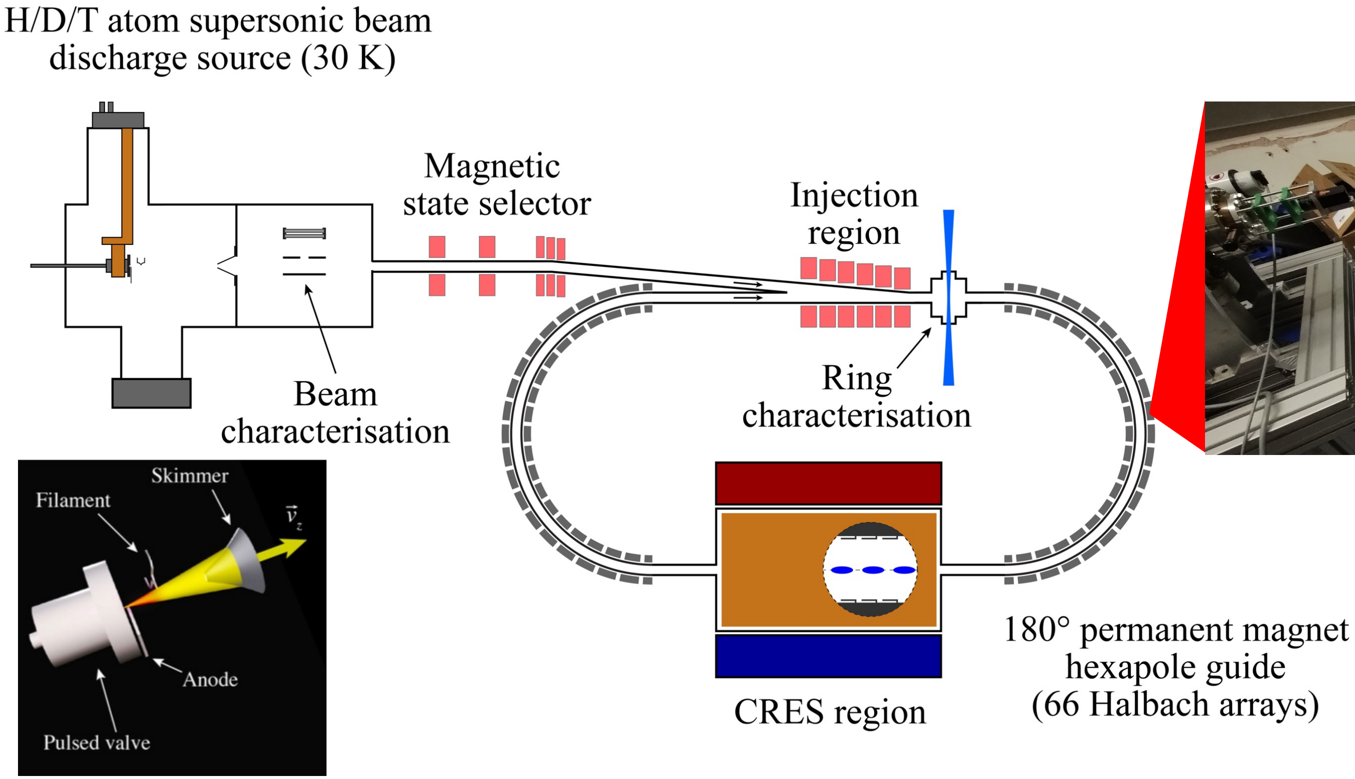
arXiv:2303.12055

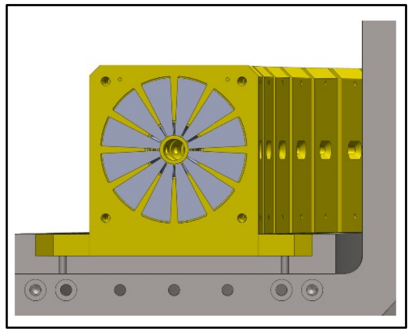


QTNM at a Glance 1/2

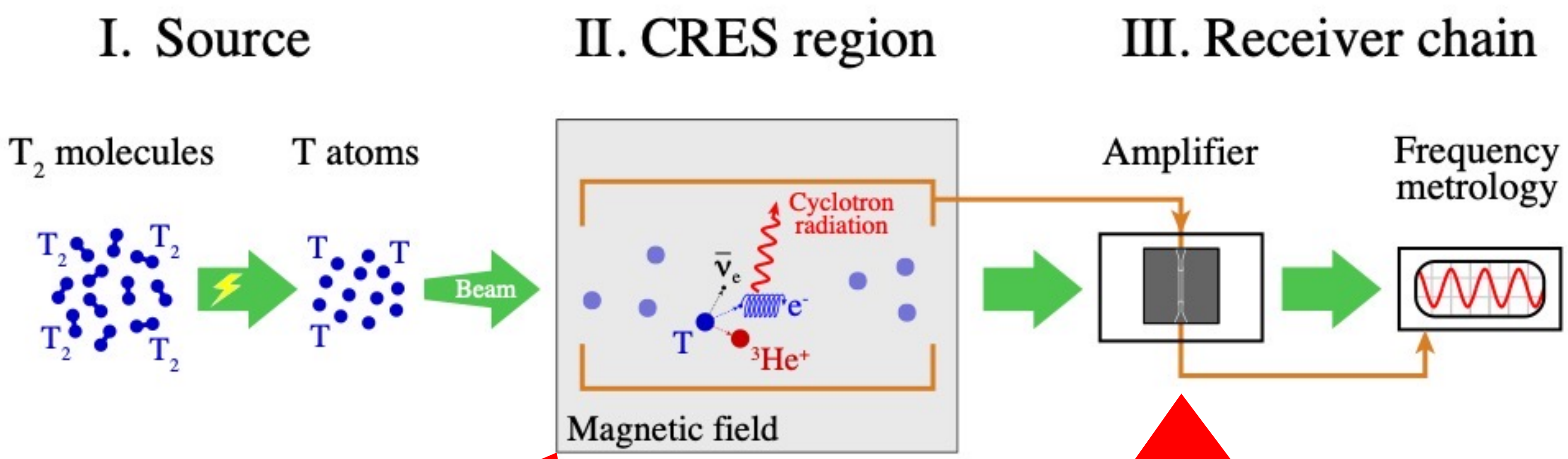


- Atomic source with high number density – aiming for 10^{12} cm^{-3}.
- Supersonic beams with low internal temperature suitable for guiding/trapping.
- Detailed investigation of atom formation and beam dynamics.

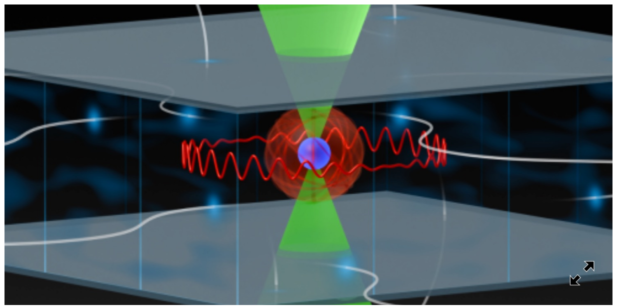




QTNM at a Glance 2/2

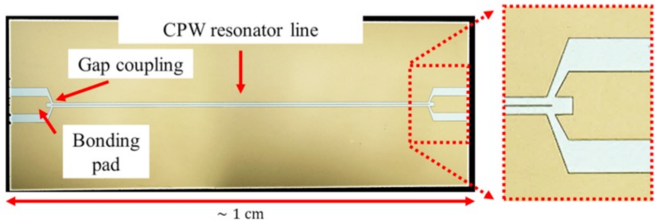


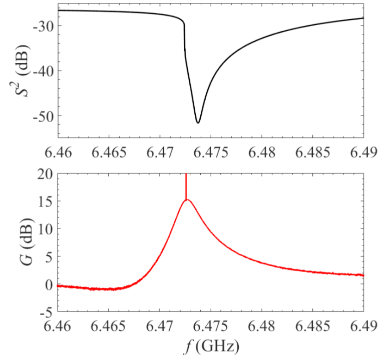
- Magnetic field calibration and mapping will be vital for energy resolution.
- Demonstrated ~1μT absolute precision using novel atomic techniques.



Absolute static-field magnetometry, magnetic gradiometry, and vector electrometry with circular Rydberg atoms PRA 107 (2023)

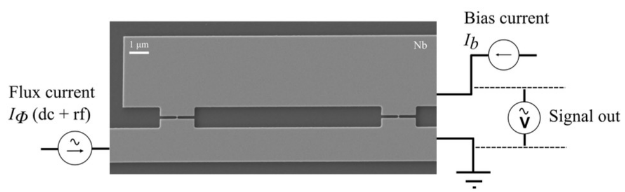
Superconducting Kinetic Inductance Para-Amp

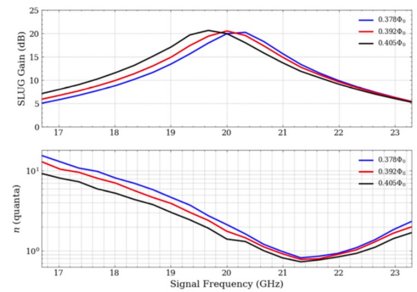




Zhao et al., Supercond. Sci. Technol. 36 (2023)

Superconducting Low-inductance Undulatory Galvanometer



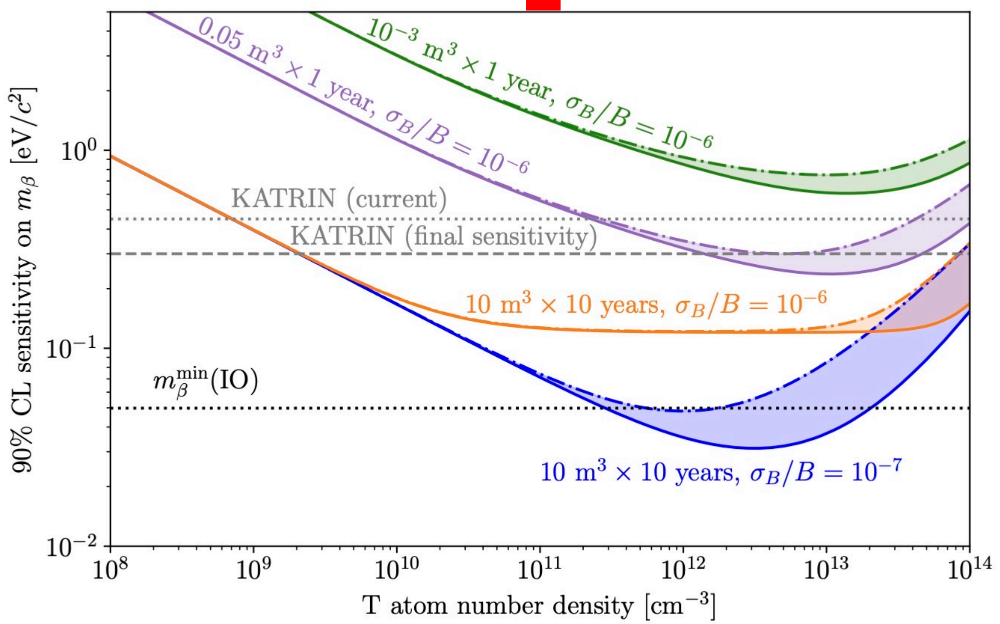


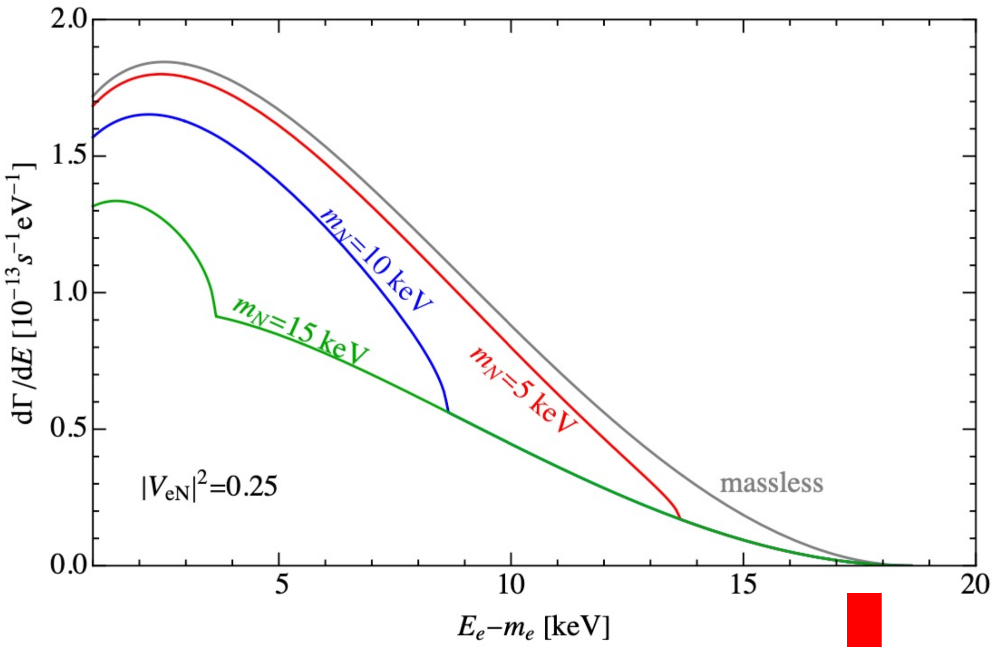
Chapman et al., IEEE Superconductivity 34 (2024)

Sensitivity Studies

- Neutrino mass sensitivity for different exposures and experimental parameters.
- Quantify the requirements to reach 50 meV sensitivity → an order of magnitude beyond current constraints (KATRIN) and fully covering the IO region.
- Is there a pathway towards a guaranteed measurement down to 9 meV?

[publication in preparation]





- BSM physics programme using the whole spectrum → advantage of CRES technique.

Sensitivity of future tritium decay experiments to New Physics **JHEP03 144 (2023)**

International Partnership

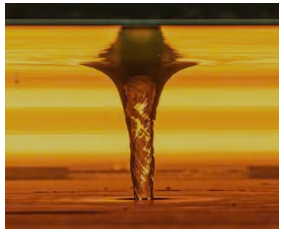
- Consortium agreement between QTNM and Project-8.
- Very successful exchange programme.
- The best technologies from both projects will come together for a large-scale experiment.
- Putting the UK on the map as a potential host site.

Quantum Simulators : Big Picture

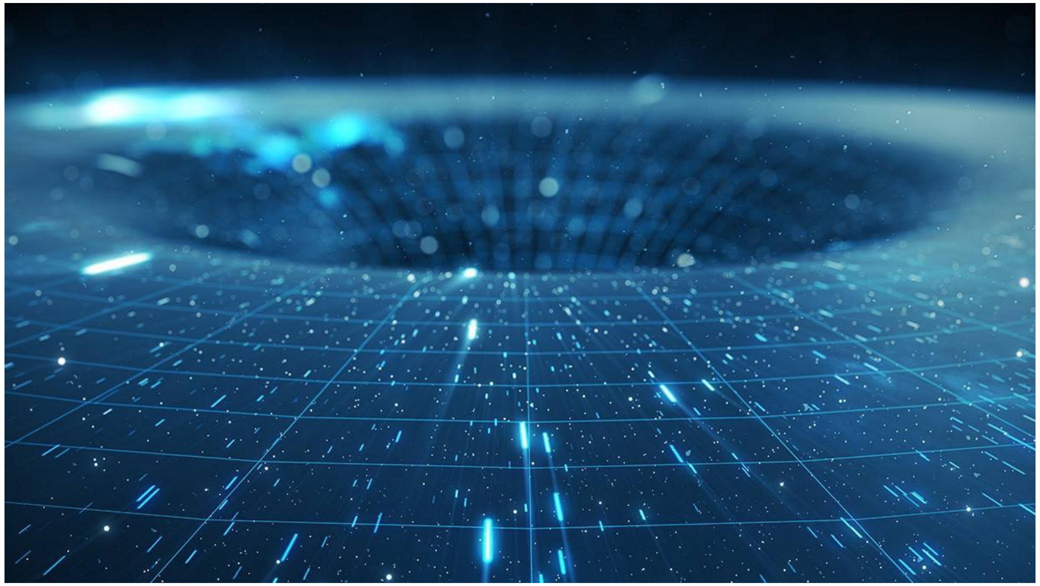
- Mapping between systems (e.g. at Lagrangian level)
- Non-linear systems, difficult to model.
- May be confounding laboratory factors (boundary conditions, noise sources).

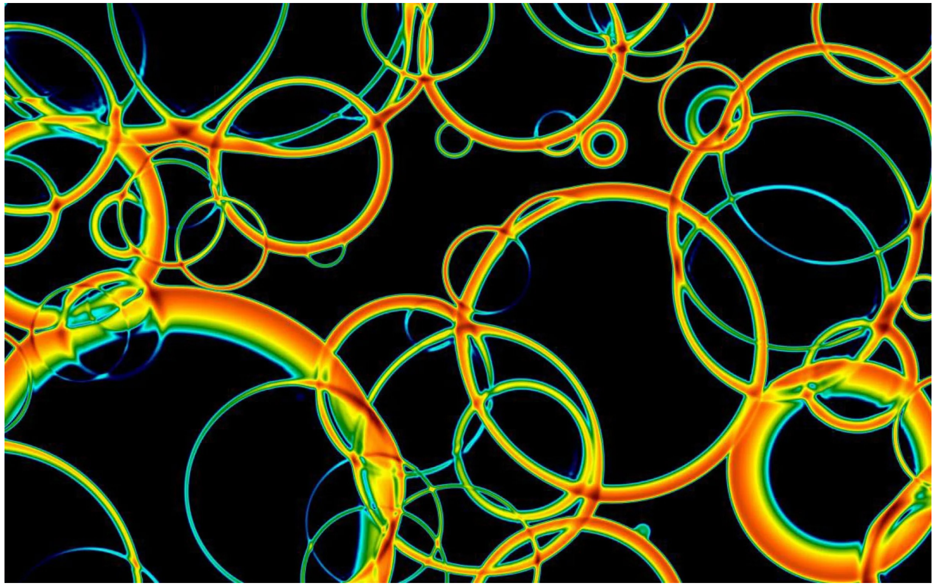
Astrophysical System

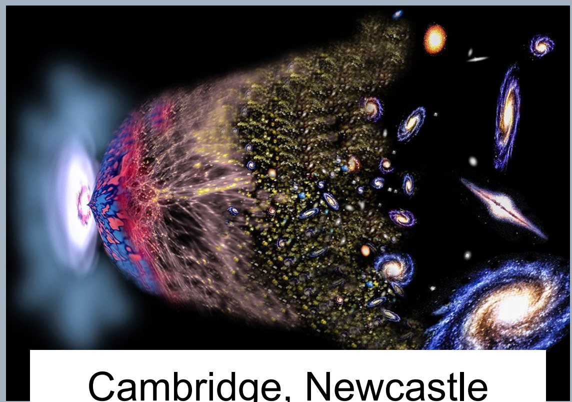
Laboratory Analogue



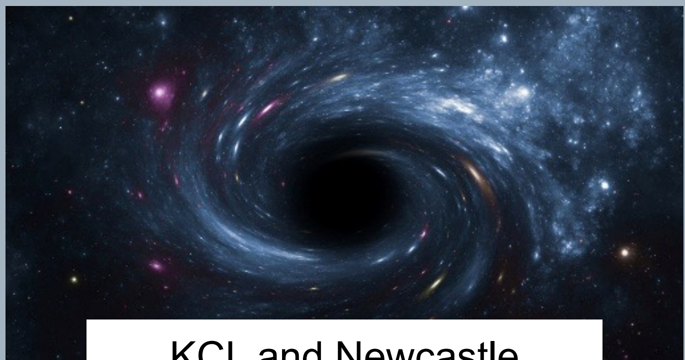
- Laboratory measurements of system properties.
- Test physics understanding and modelling/simulations.
- Confidence in applying those models to astrophysical and/or cosmological systems.







Cambridge, Newcastle and UCL

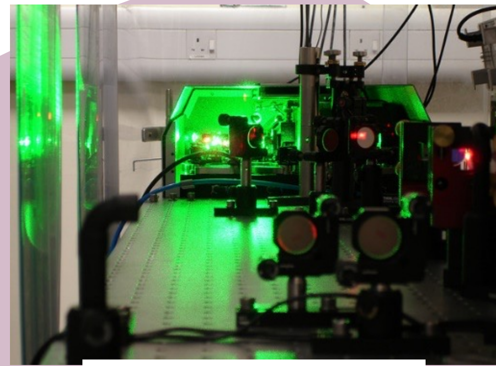


KCL and Newcastle

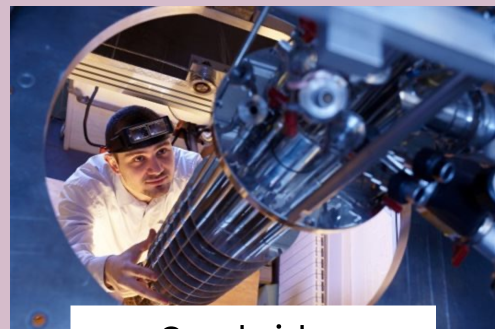
QSimFP

Quantum Vacuum:
False Vacuum Decay

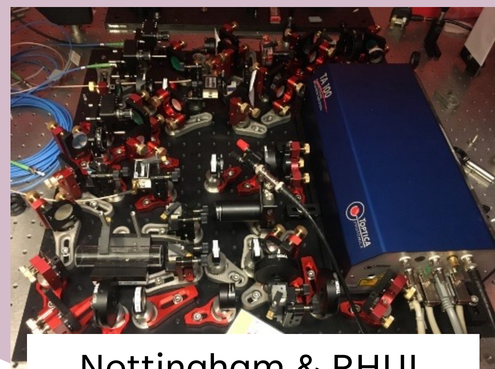
Quantum Black Hole:
Black hole ring-down



St Andrews

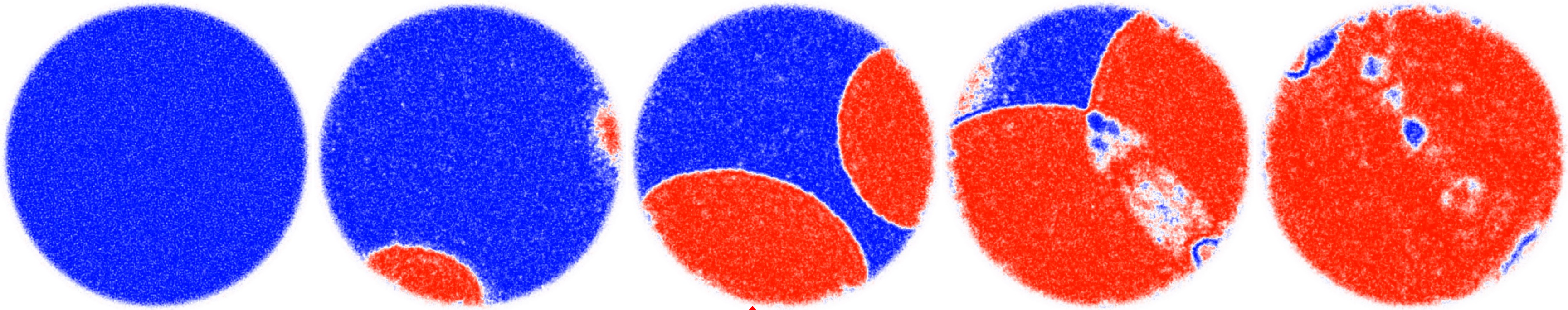


Cambridge



Nottingham & RHUL

UCL/Cambridge/Durham/Newcastle

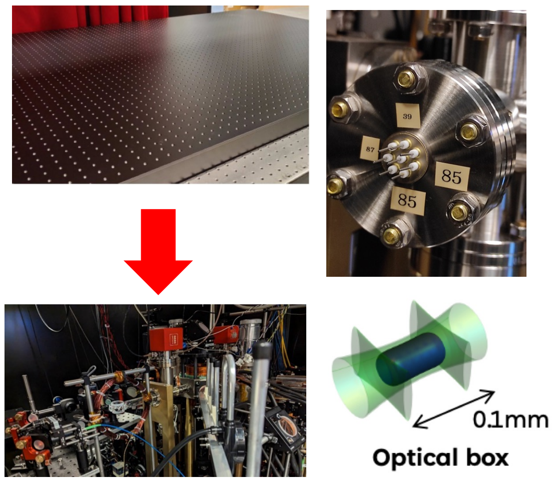


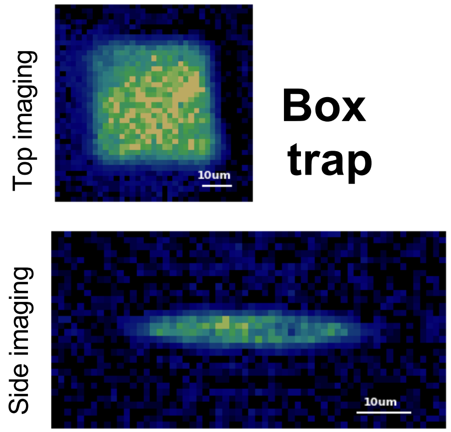
arXiv:2311.02156

Hyperfine states of bosonic condensates $^{39}K/^{41}K$

- Numerical simulations with realistic treatment of atoms, experimental boundary and initial conditions.
- Modelling of optimal trapping potential for experiment, capitalising Cambridge's box-trap.
- Identification of magnetic field stability requirements for Cambridge experiments.

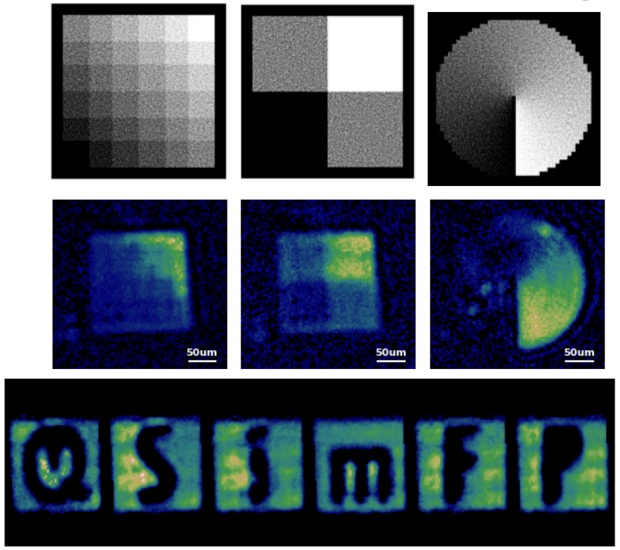
Cambridge Experiments



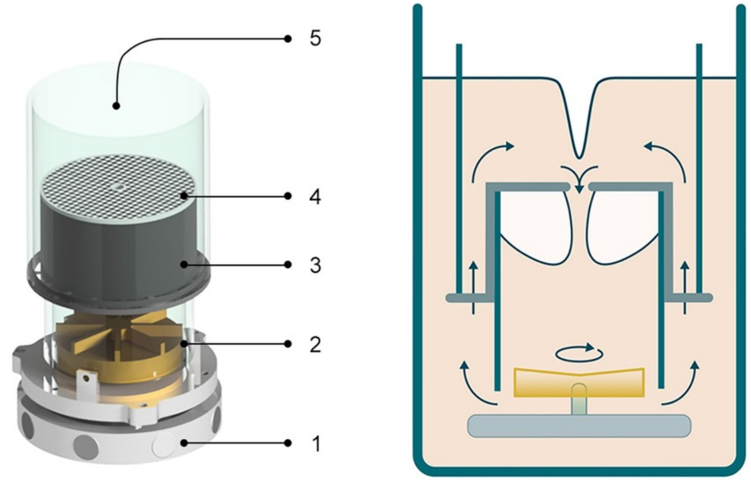


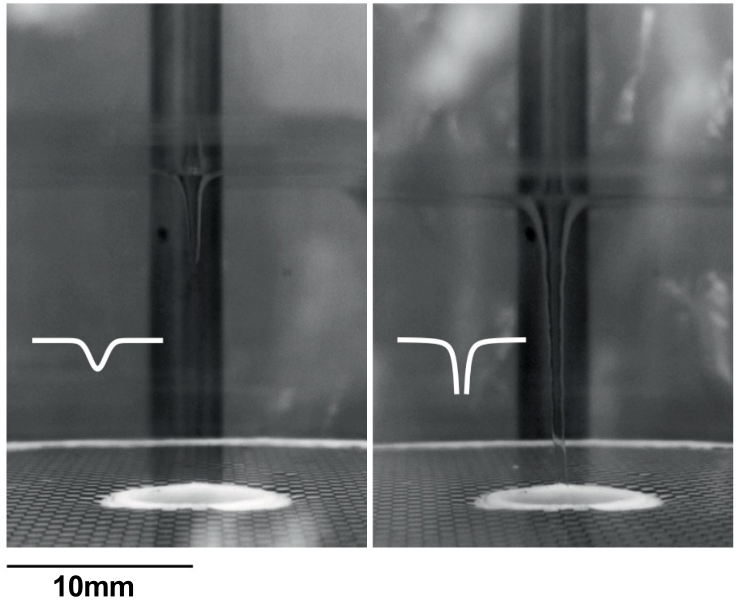
Box trap

DMD potential shaping



Quantum vortex of superfluid ^{4}He

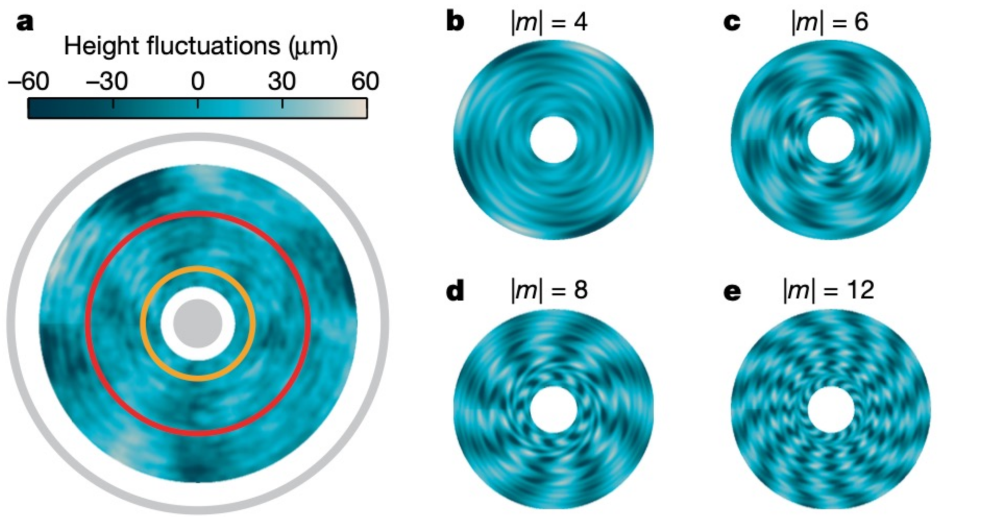




Rotating curved spacetime signatures from a giant quantum vortex

Nature 628 (2024)

- Acoustic & surface wave excitations on irrotational quantum vortex → analogy with fields on a curved spacetime → black-hole physics.
- Spectroscopy and wave analysis of the surface.
- Challenge models with experimental data.

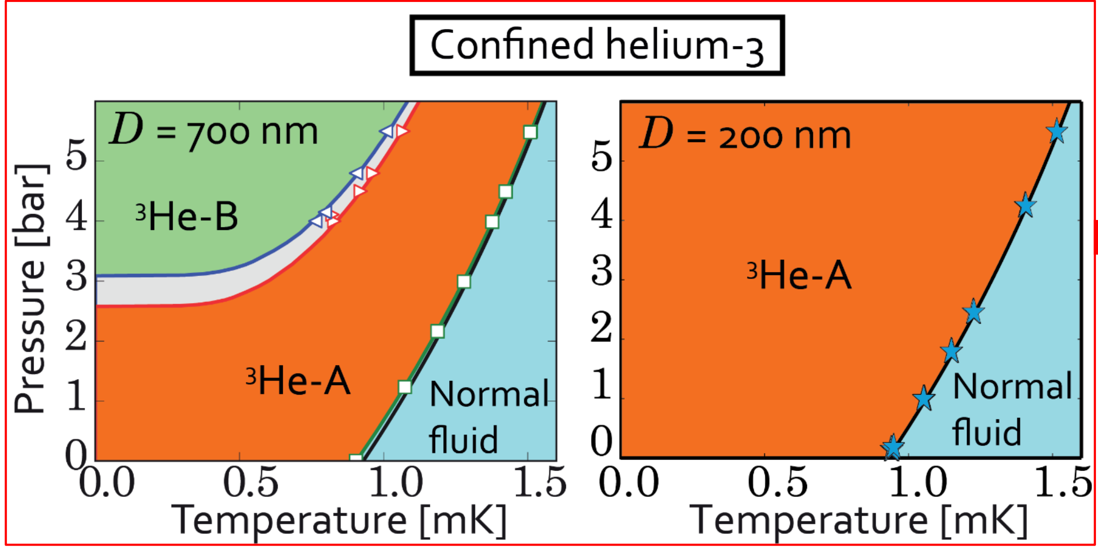


QSimFP Consortium

Facilities

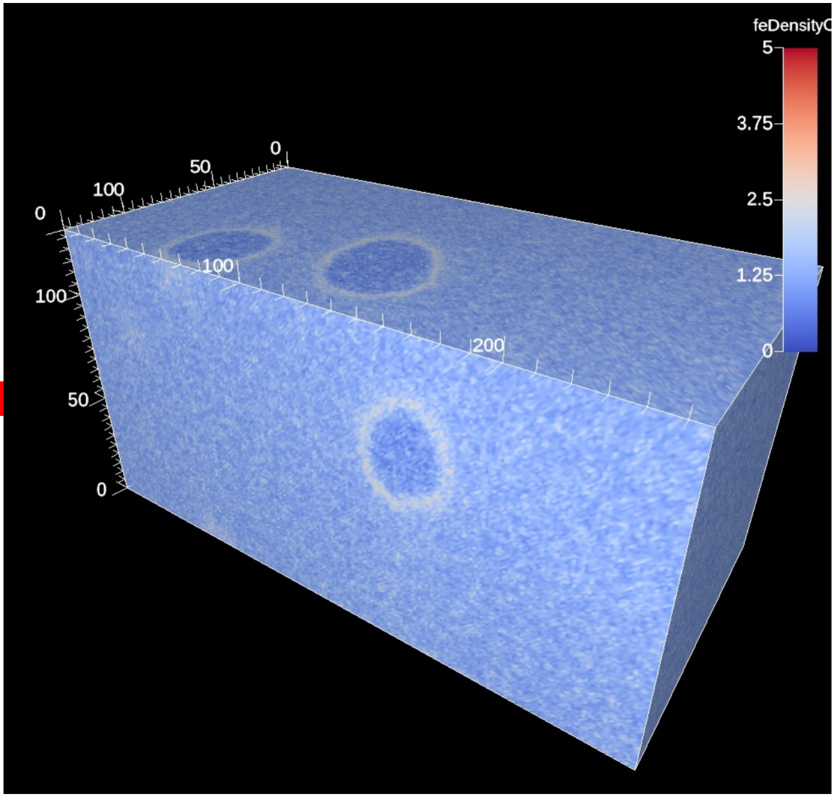
- 27 QTFP funded researchers + 48 partners.
- 50/50 split between quantum technology and fundamental physics experts.
- Important international partners: Perimeter Institute, Canada, Germany, Austria.
- A rich engagement programme.

Quantum Simulators (Quest-DMC)



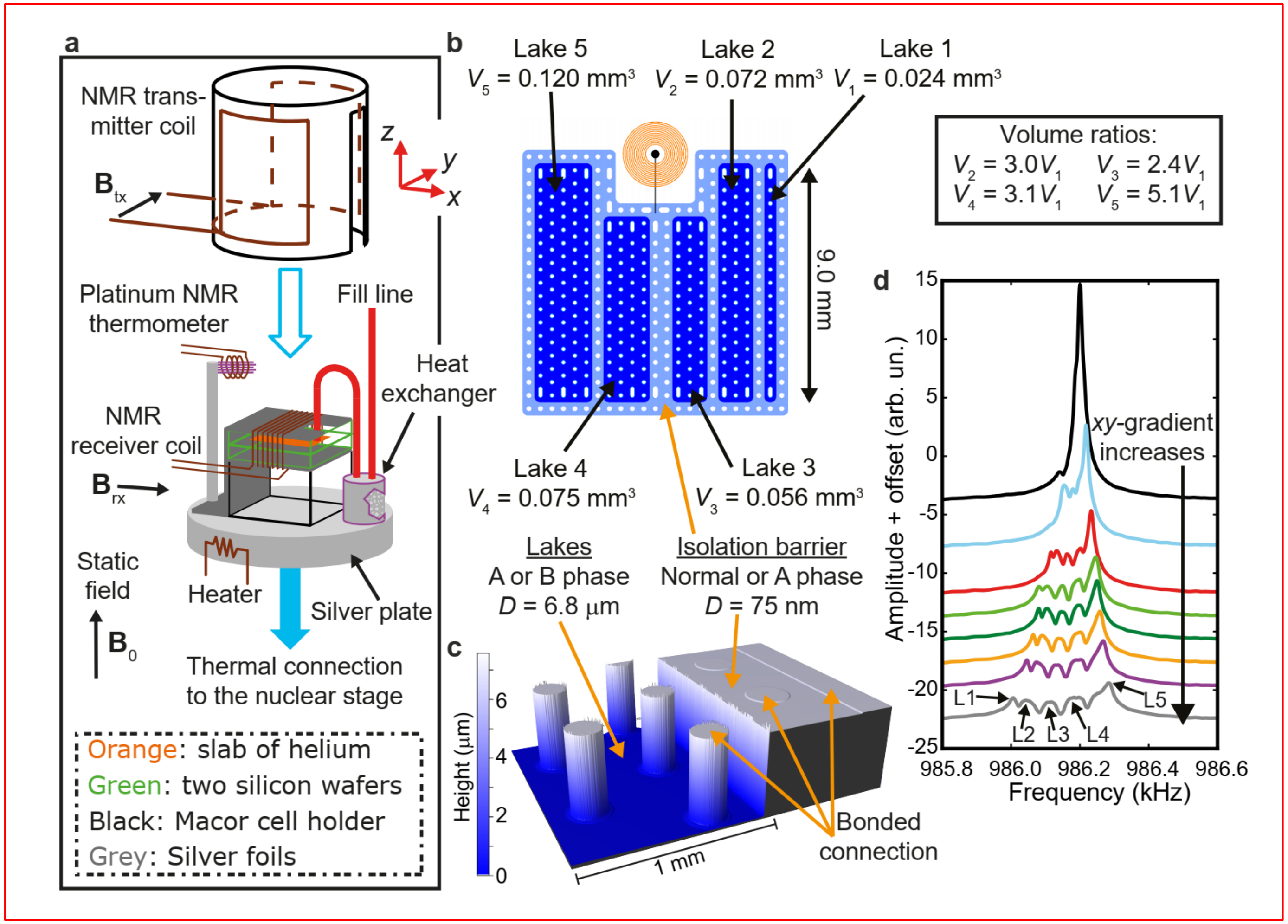
- Superfluid ^{3}He phase diagram → in particular the transition between ^{3}He-A and ^{3}He-B

Described in Science 340 (2013)



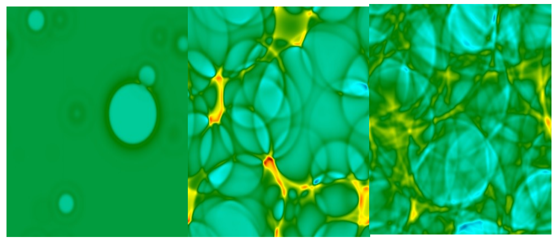
- Simulation of phase changes in liquid helium.
- Nucleation : intrinsic, extrinsic (e.g. radiation induced, surface imperfections).
- A model for phase changes in the early universe.

Quantum Simulators (Quest-DMC)



Superfab

- A new cryogenic platform established and characterized for studying phase transition in superfluid ^{3}He.



Nanofluidic platform for studying the first-order phase transitions in superfluid helium-3

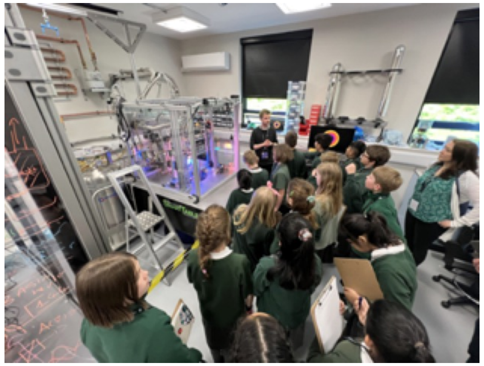
arXiv:2401.06079

Broader Impacts

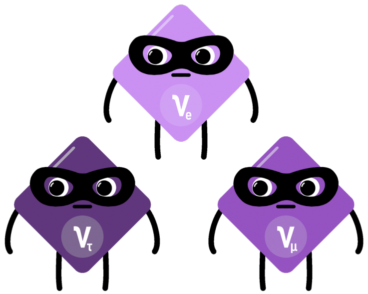
Academic

- Techniques applied to other experiments/research-areas:
  - Precision tests (e.g. using Rydberg positronium for anti-gravity tests).
  - High-precision magnetometry & electrometry.
  - Underpinning theoretical work across all of the topics presented here.
- Many contributions to summer & winter schools in UK and internationally.

Outreach

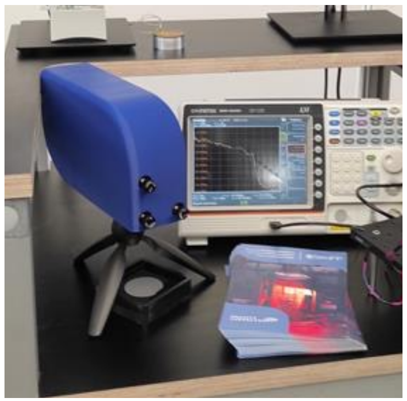


School visit: to a quantum simulator lab.

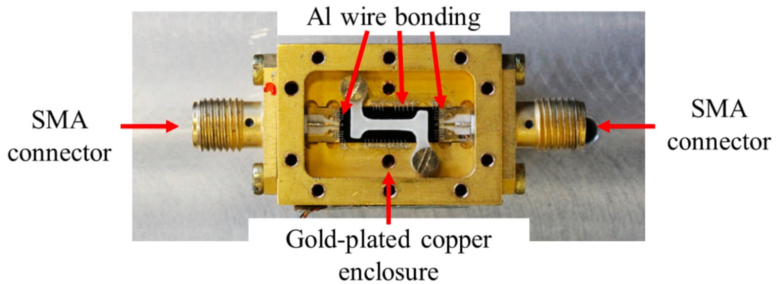


Teaching material: neutrino physics lesson plans and associated materials for schools.

Industry

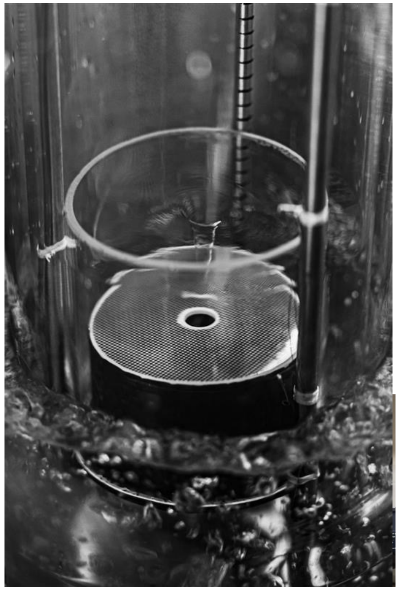


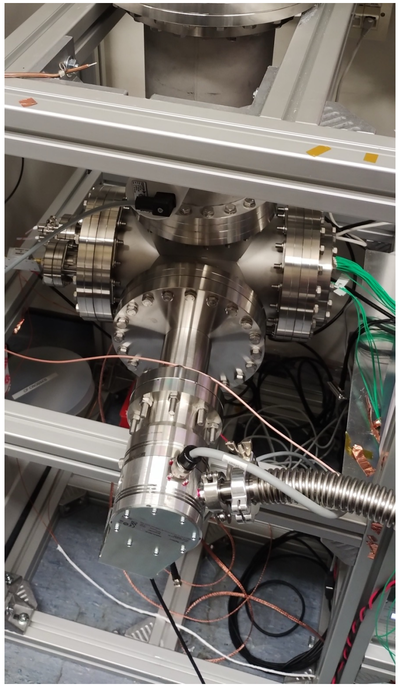
Patent Application: fluid surface optical measurements (developed for quantum vortex experiments).



Para-amps: reliable fabrication of thin-film (NbN) para-amps for quantum electronics.

Perspectives





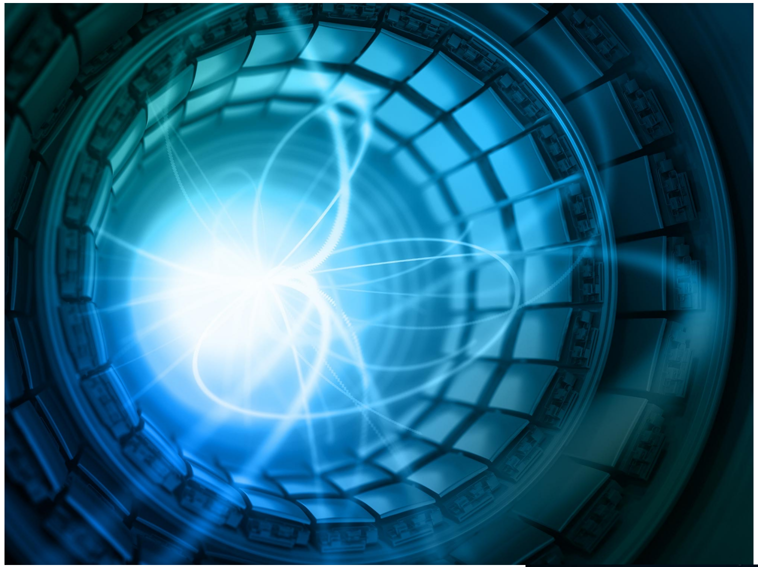
Common successes of QTNM and Quantum Simulations:

- Science!
- Creation of new inter-disciplinary research communities.
- Capacity building in the UK : new labs and experiment-theory collaborations.
- Great platforms for early career researchers to gain skills in QT and related areas, as well as for public engagement.

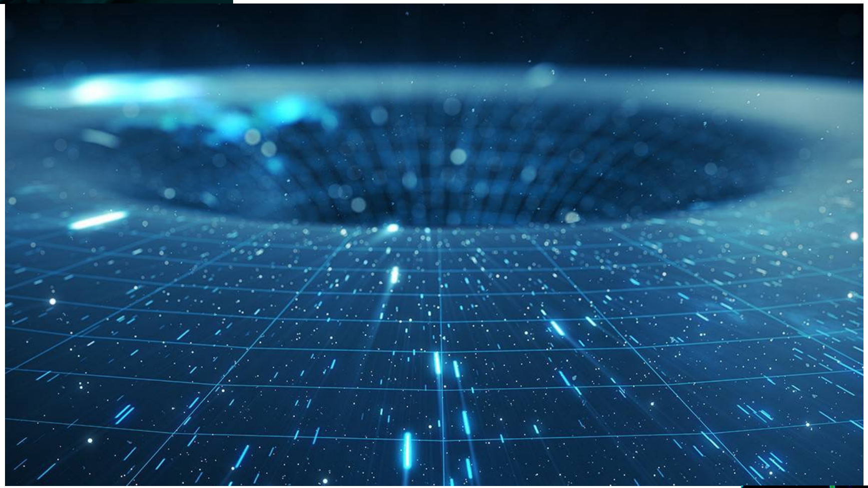
Future Directions

- **QTNM**
  - Exploit the CRES Demonstration Apparatus, and further demonstrate the unique technologies we have developed.
  - Tritium runs in a second phase, with ~eV scale neutrino mass sensitivity.
  - Deepen the partnership with Project-8, defining a pathway to 40 meV.
- **Quantum Simulations**
  - Exploit the platforms that have been successfully constructed across the country. Develop new partnerships (e.g. MIT).
  - Experimental innovations : higher dimensionality (2+1 → 3+1); seeded FVD.
  - Theoretical innovations : new simulation tools, perhaps using QCs.

Very exciting scientific prospects for both areas in future phases of QTFP.



Thank You!



Big thanks for material and discussions:

Silke Weinfurtner (Nottingham University)

Andrew Casey (RHUL)

Ruben Saakyan (UCL)

Seb Jones (UCL)