Quantum Technologies for Neutrino Mass

17 members (and growing)

UCL · UNIVERSITY OF CAMBRIDGE · NPL National Physical Laboratory · WARWICK THE UNIVERSITY OF WARWICK · Prifysgol Abertawe Swansea University

Determination of Neutrino Mass with Quantum Technologies

A collaboration of particle, atomic and solid state physicists, electronics engineers and quantum sensor experts

PPTAP Workshop
Cyberspace
3 June 2021

Ruben Saakyan (UCL)

Neutrino oscillations → *$m_\nu \neq 0$* → *Window to New Physics*

Absolute mass not known → complementarity of cosmological observations and **laboratory measurements**

Model independent measurement: electron spectrum near end-point of β-decay

E. Fermi, Z. Phys. 88 (1934) 161

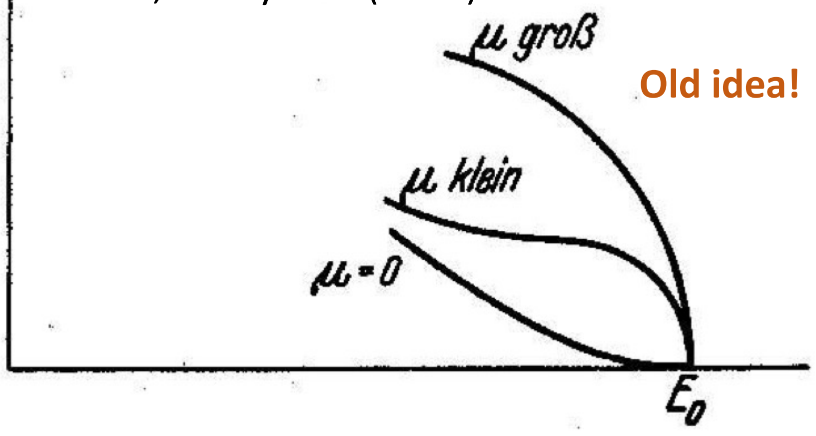
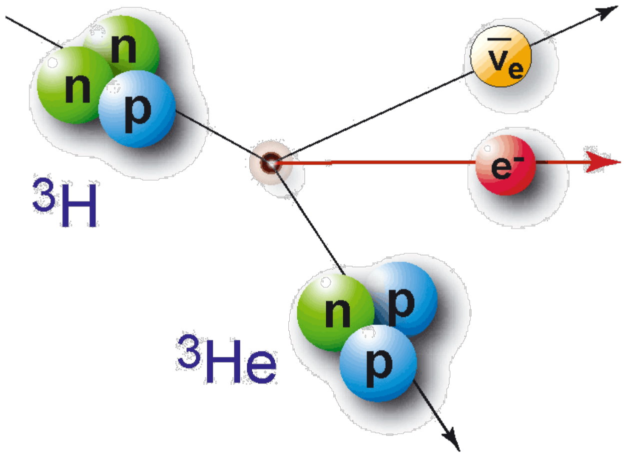
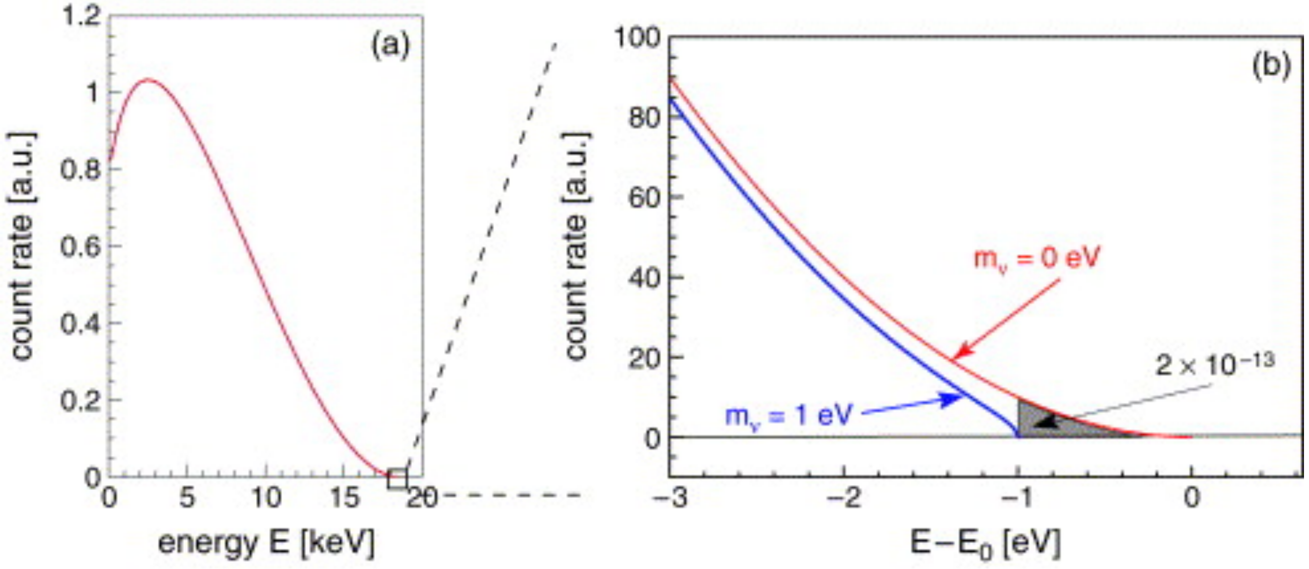


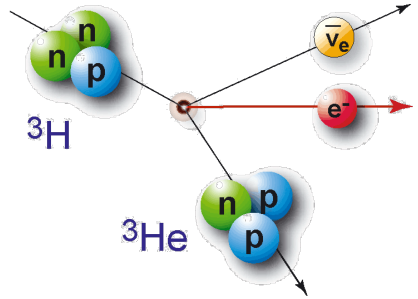
Fig. 1.

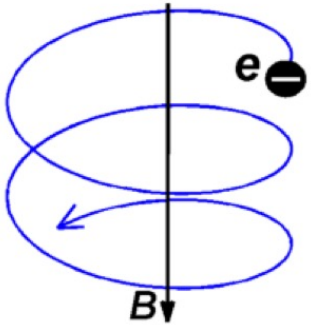
Old idea!



- **Current upper limit, < 0.8 eV (KATRIN)**
- **Lower bound (from ν-oscillations) > 0.009 eV (!)** → ***Requires a "quantum leap" in technology***







Cyclotron Radiation Emission Spectroscopy (CRES)

$$f = \frac{1}{2\pi}\frac{eB}{m_e + E_{\rm kin}/c^2}$$

Challenges:
- ***Atomic tritium***
- ***Sub fW power***
- ***< 1ppm resolution***

<u>Goal</u>: To build on recent **investment** in **quantum sensors** to assess feasibility of an **experiment** capable of a positive **neutrino mass measurement** from **^{3}H *β*-decay** using **CRES** technology.

QTNM is funded for 3 years under the UKRI **QTFP** Programme

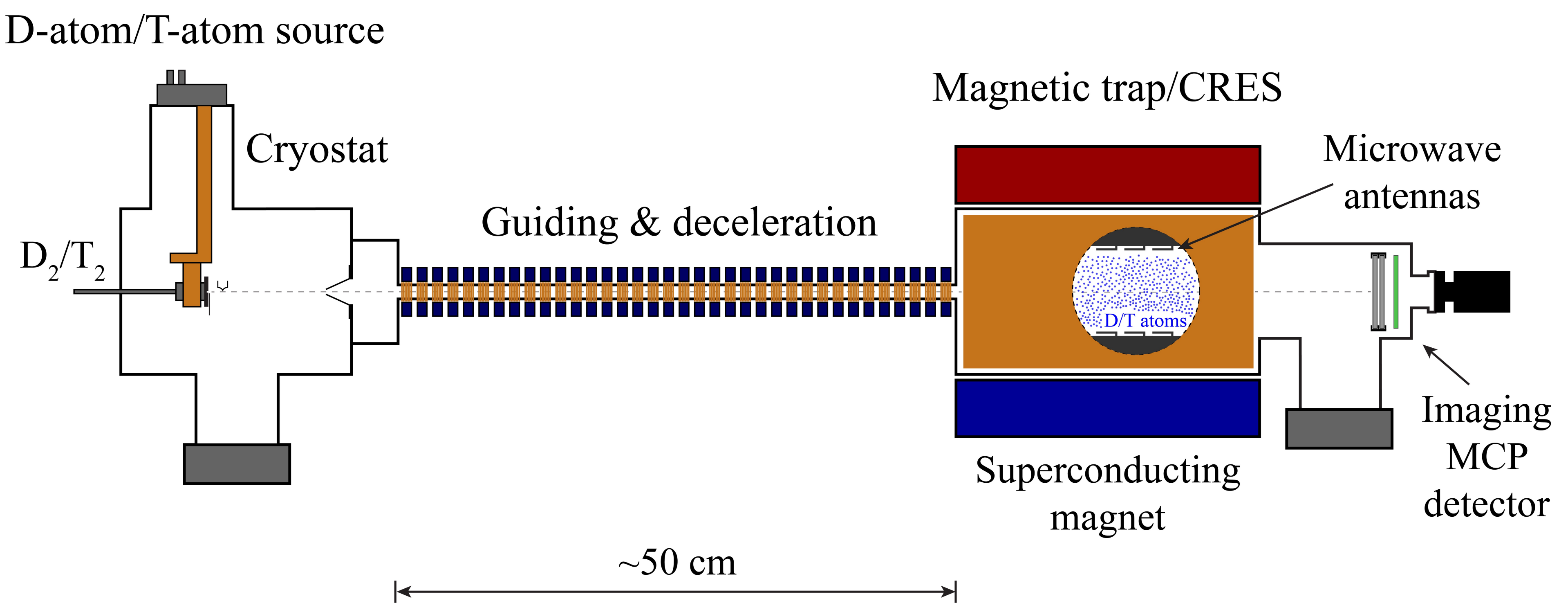
The aim is to build **CRES D**emonstration **A**pparatus, **CRESDA**, based on Deuterium-atoms but “Tritium-ready”

CRESDA

- D/T *atomic source*
  D/T atoms cooling and *confinement*
- D/T atoms as *quantum sensors* for 3D *B-field uniformity* mapping at ≤ 0.1ppm
- *Quantum-limited* systems for microwave radiation *detection*

Trap simulations, CRES signal modelling, Sensitivity and scale-up studies

CRESDA. Atomic Source and Atom Confinement.

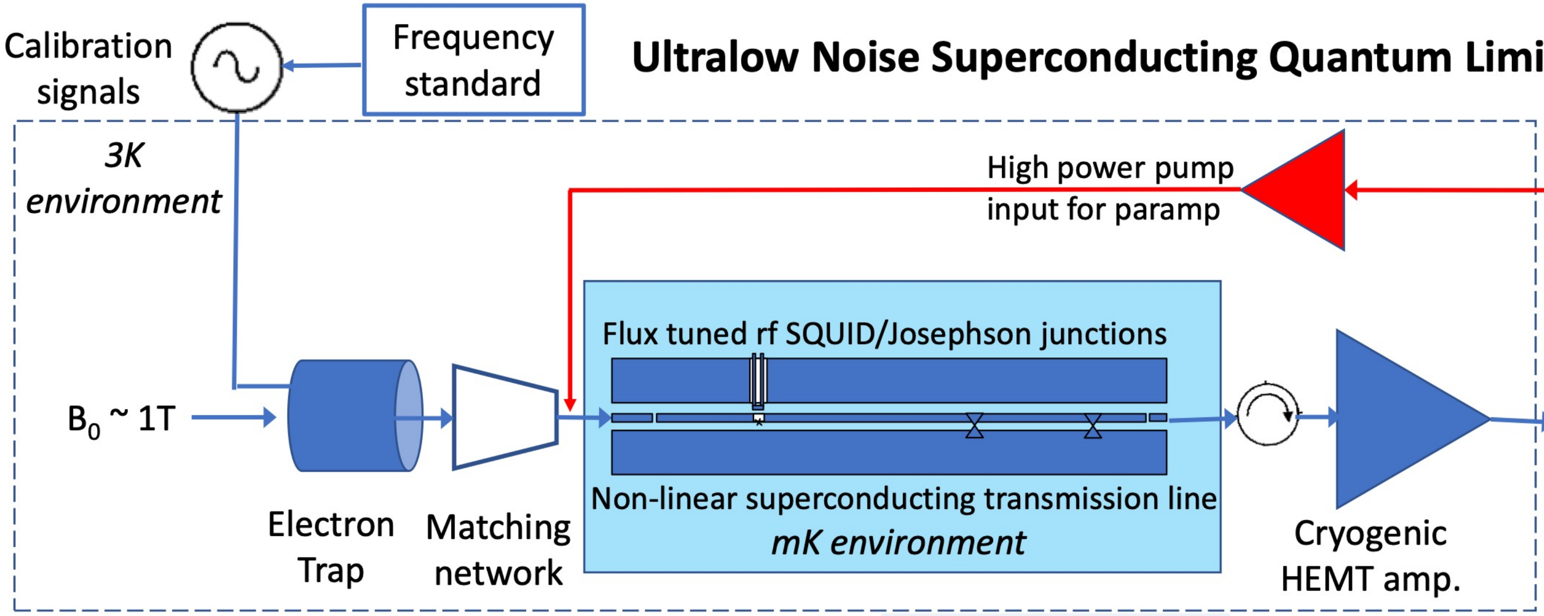


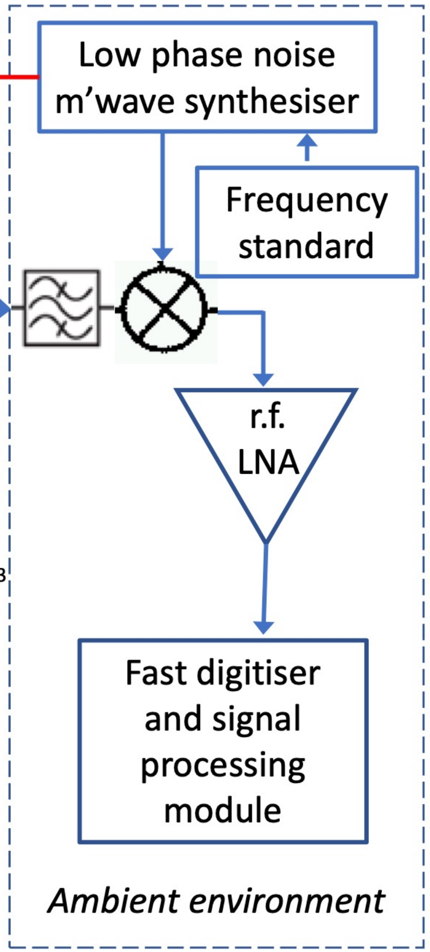
- A number of designs under consideration
- 1L CRES region with ρ~10^{12}-10^{14} cm^{-3}.
- Initially operate with D-atoms, tritium ready.

- Extensive characterisation of confined atoms (density, velocity distributions…)
- B-field mapping with ≤ 0.1ppm using D/T-atoms as quantum sensors
- D_2/T_2 background characterisation

CRESDA. Quantum MW-Spectrometer.

MW signal → Antennas → SQUID or JTWPA preamp → HEMT amp

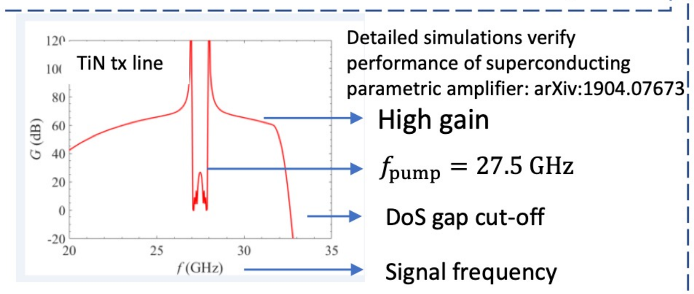


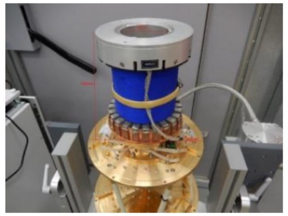


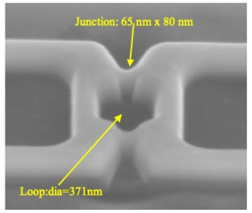
Challenge of millimetre-wave (25-30 GHz) ultra-low-noise amplifiers:

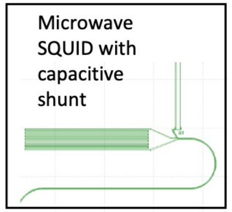
- Push superconducting microwave SQUID amplifiers up in frequency
- Push superconducting parametric amplifiers down in frequency
- High gain quantum-limited noise performance possible

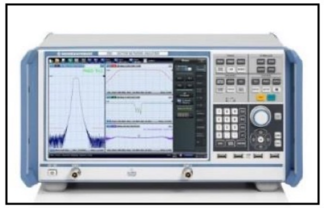
Draws heavily on major investments by funding agencies in establishing superconducting device processing and measurement labs



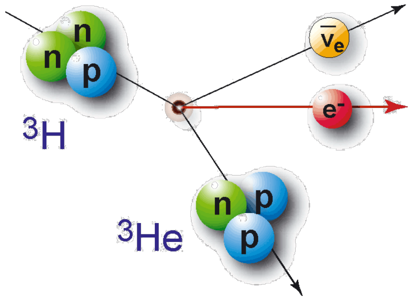








QTNM Future Outlook

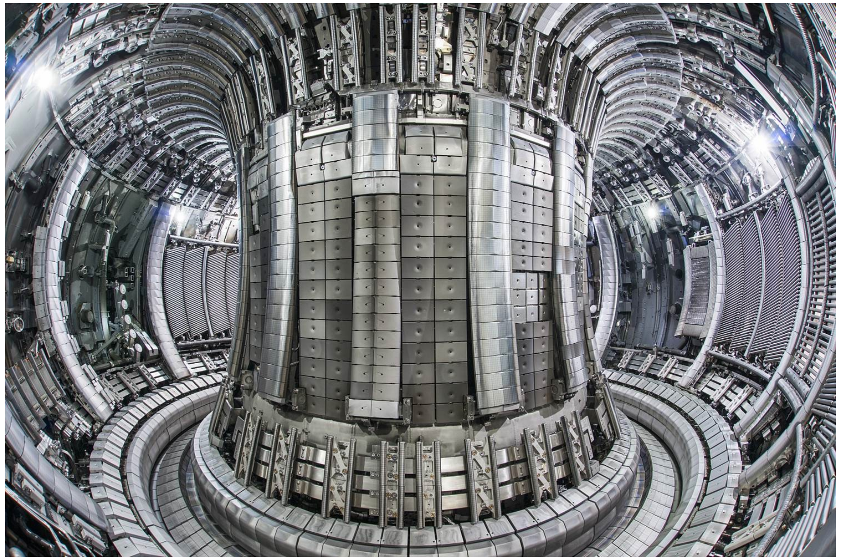


A (*VERY*) tentative timeline

- Current project: 2021-2024
  - Technology demonstration with Deuterium which is Tritium ready

- Next step. 2025-2029
  - Moving CRESDA to a Tritium facility (strong engagement with Culham)
  - Tritium phase demonstration
  - *O*(eV) sensitivity

- ”Ultimate” international project > 2029
  - Consolidate technological breakthroughs (QTNM, Project-8, …) to build and operate a detector with a phased sensitivity: 100 meV ⇨ 50 meV ⇨ 10 meV plus sterile neutrino programme



CCFE
CULHAM CENTRE FOR FUSION ENERGY

Quantum Simulators for Fundamental Physics

QSimFP

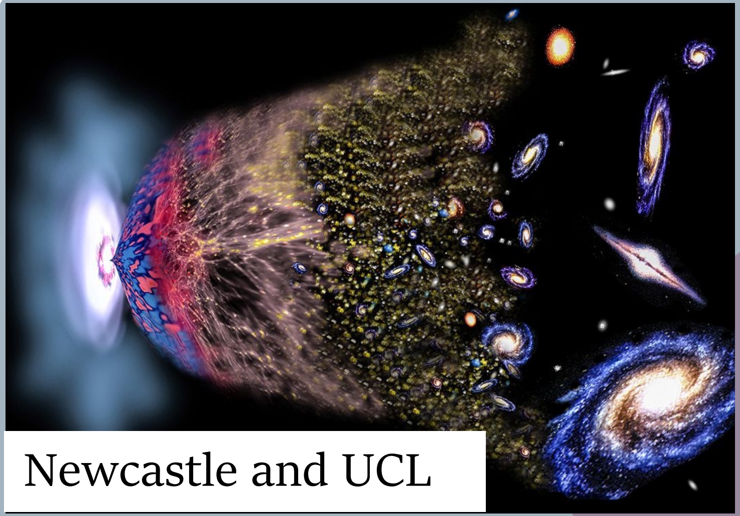
- St Andrews
- Newcastle
- KCL
- Nottingham
- Cambridge
- UCL
- RHUL

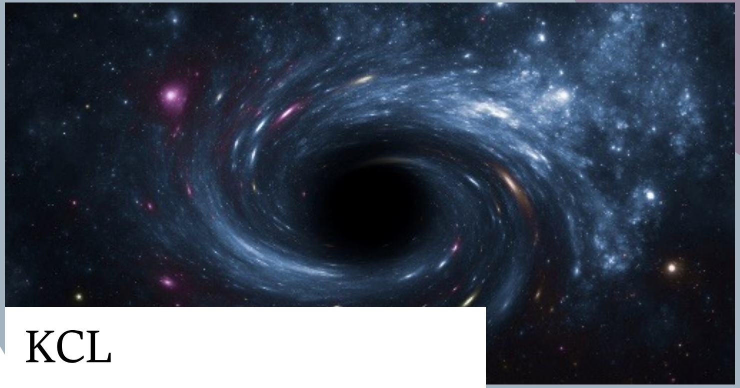
PI:
Silke Weinfurtner (Nottingham)

Representatives:
Zoran Hadzibabic (Cambridge)
Ruth Gregory (KCL)

15 Investigators
7 UK Research Organisations
6 External Partners (Austria, Canada, Germany)

Vision

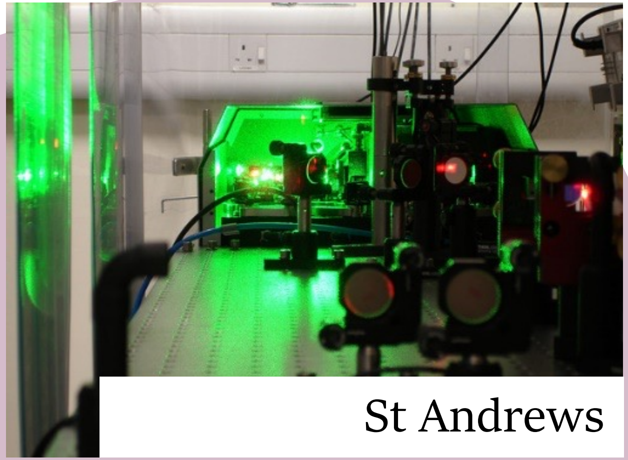

Newcastle and UCL

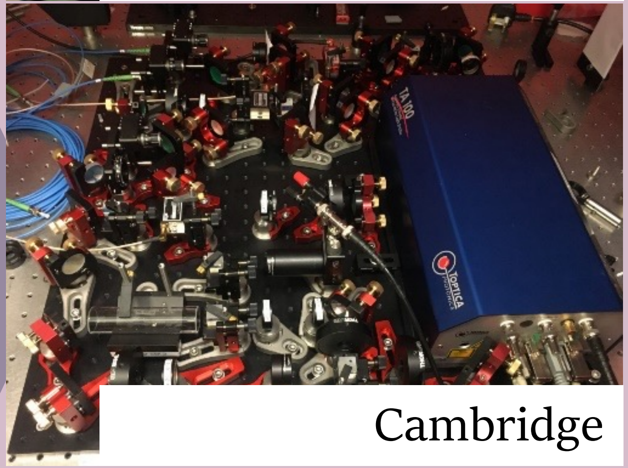

KCL

QSimFP

Quantum Vacuum:
- False Vacuum Decay

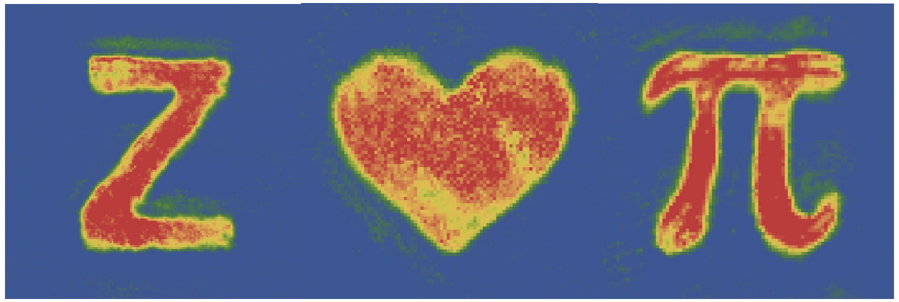
Quantum Black Hole:
- Black hole ring-down


St Andrews

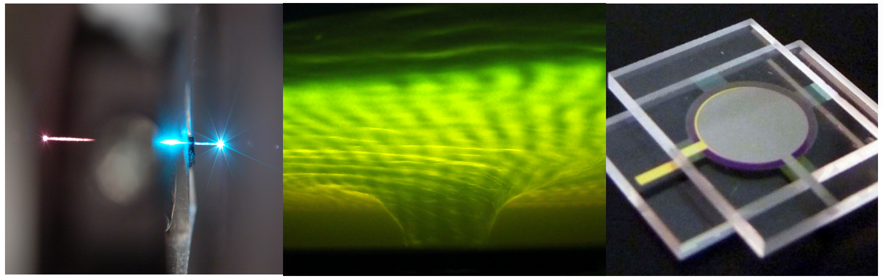

Cambridge


Nottingham and RHUL

ZH, Science 347 (2015)
ZH, Nature 563 (2018)
ZH, Science 366 (2019)

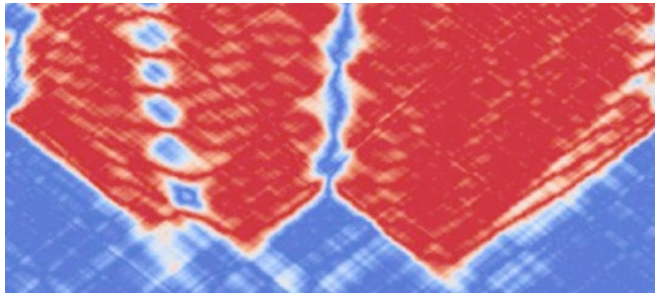


Quantum Science & Technology

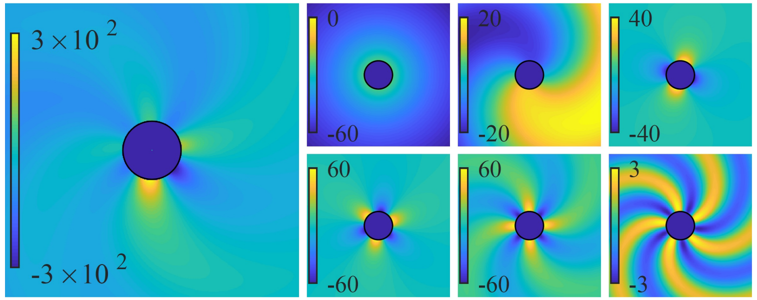


FK, Science 319 (2008)
SW, Nature Physics 13 (2017)
XR, PRB 91 (2015)

HP+SW, JHEP 07 (2018)
HP+AP+SW, PRL 123 (2019)
HP+AP+SW, JHEP 10 (2019)
TB+RG+IM, PRD 100 (2019)



Fundamental Physics



SW, PRL 121 (2018)
SW, J. Fluid Mech. 857 (2018)
SW, PRL 125 (2020)
JL+SW, PRL 125 (2020)

QSimFP

In 3 years:

- Versatile FVD simulator, first results on seeded FVD
- Two types of versatile QBH simulators, first QBH ringdown results
- UK takes international leadership

Next stage - more science to come:

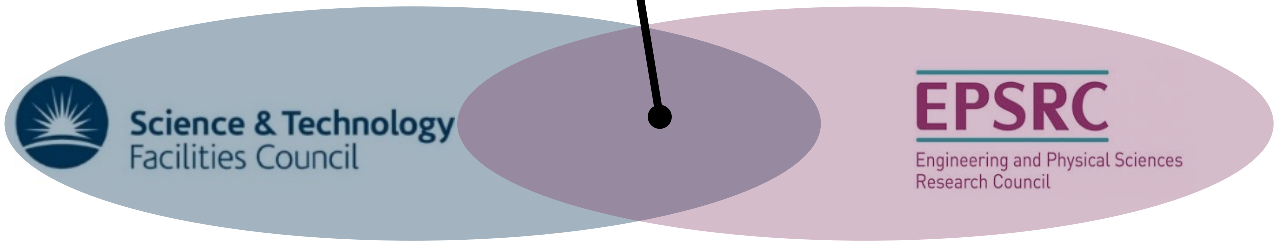
- Equipment and network in place
- Operational and networking costs needed
- Driving new areas of fundamental physics research

QSimFP

- St Andrews
- Newcastle
- KCL
- Nottingham
- Cambridge
- UCL
- RHUL

External partners
- J. Braden (CA)
- M. Johnson (CA)
- J. Schmiedmayer (AU)
- R. Schuetzhold (DE)
- Pierre Verlot (FR)
- W.G. Unruh (CA)

Gravity simulators
Silke Weinfurtner
(PI, Nottingham)



Cosmology & black holes
- Ruth Gregory
- Jorma Louko
- Ian Moss
- Hiranya Peiris
- Andrew Pontzen

Ultracold atoms
- Thomas Billam
- Zoran Hadzibabic

Superfluids & optomechanics
- Carlo Barenghi
- Anthony Kent
- John Owers-Bradley
- Xavier Rojas
- Viktor Tsepelin

Quantum circuits
- Gregoire Ithier

Quantum optics
- Friedrich Koenig

Our consortium

Quantum-Enhanced Interferometry for New Physics

University of Birmingham

D. Martynov

H. Miao

V. Boyer

University of Warwick

Dr. A. Datta

Cardiff University

H. Grote (PI)

K. Dooley

University of Glasgow

R. Hadfield

University o

S. Reid

- 8 investigators from 5 UK institutions
- 8 project partners (UK quantum hubs, MIT, Caltech, NIST, Fermilab, DESY, Max Planck)

Goals

Quantum Enhanced Interferometry for two fundamental physics questions:

- Dark matter (2 experiments)
- Observational signatures of quantized gravity (2 experiments)

Quantum technologies:

- Squeezed light
- TES (transition edge sensor)

Unifying technology:

- Interferometry with extreme performance optical coatings

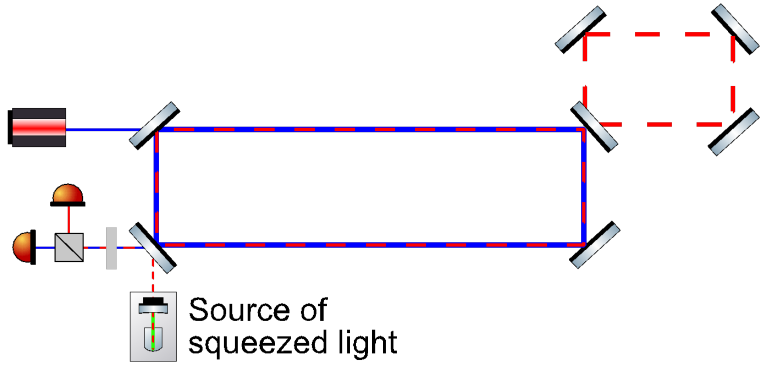
Experiments

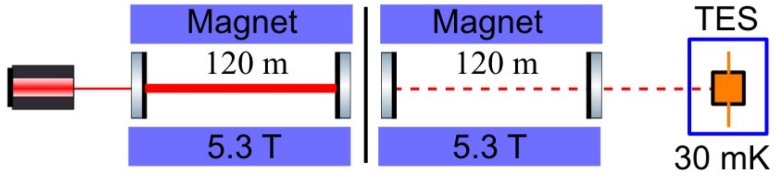
Experiment 1: Axions in the galactic halo

- An ‘interferometry haloscope’ (PRD 101, 095034)
- Axions with masses from 10^{-16} eV up to 10^{-8} eV

Experiment 2: Light-shining-through-wall (collab.)

- Making and detecting axion-like particles
- Transition edge sensor with background $<10^{-6}$/s

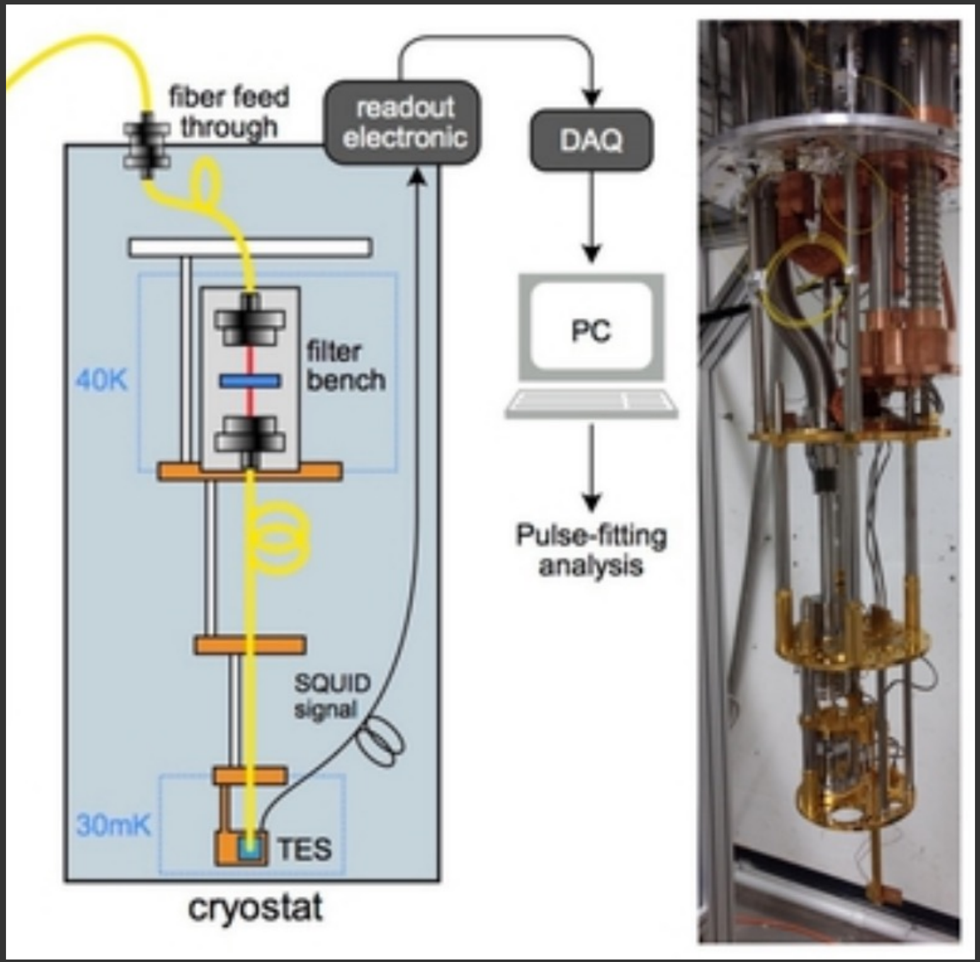




ALPS II at DESY

ALPS II magnet string installed at DESY.
Copyright DESY / M.Mayer

Single photon detector
(noise of less than one photon in 10 days)



R. H. Hadfield Nat. Photon 3 696 (2009)
A. Lita et al. Optics Express 16 3032 (2008)
A. Lita et al. Proc. SPIE 7681 (2010)

Experiments

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Experiment 2: Light-shining-through-wall (collab.)

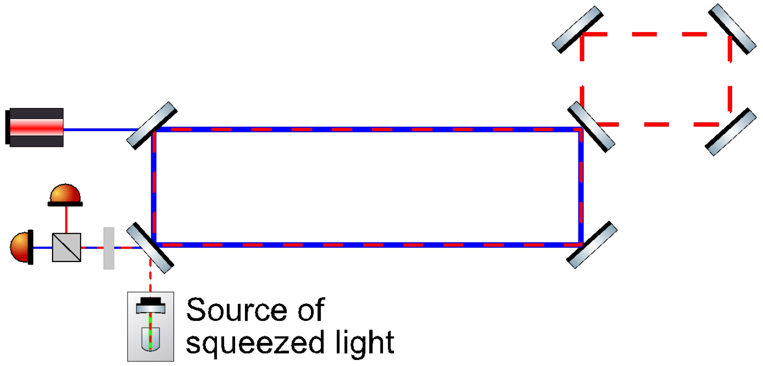
- Making and detecting axion-like particles
- Transition edge sensor with background $<10^{-6}$/s

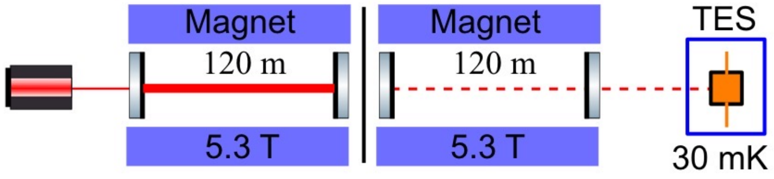
Experiment 3: Quantisation of space-time

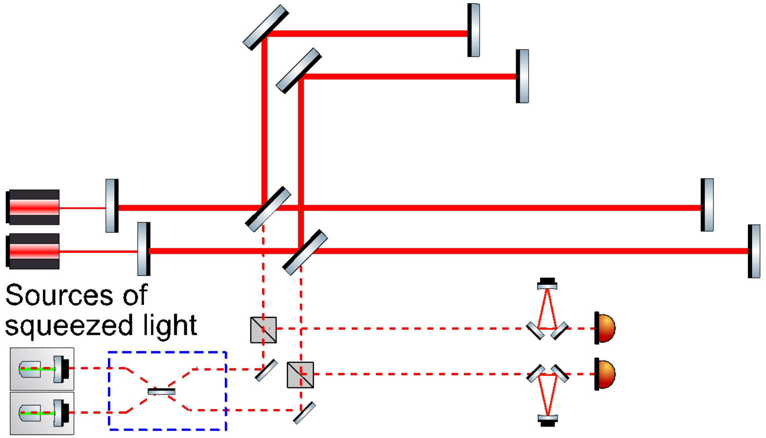
- Testing ideas on quantization of space-time
- Sensitivity of 2×10^{-19} m/rt(Hz) above 1 MHz

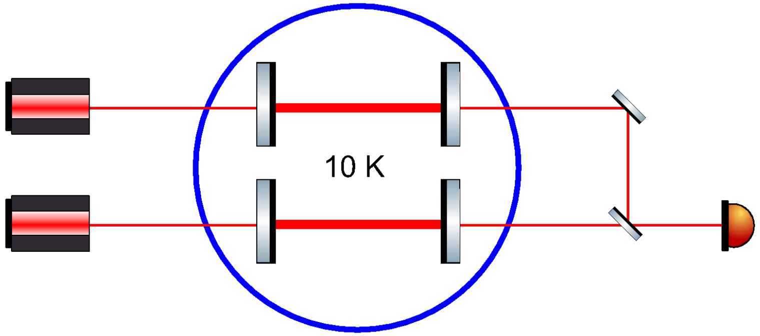
Experiment 4: Semiclassical gravity

- Testing semiclassical gravity predictions
- Expect to confirm or rule out









Experiment 3

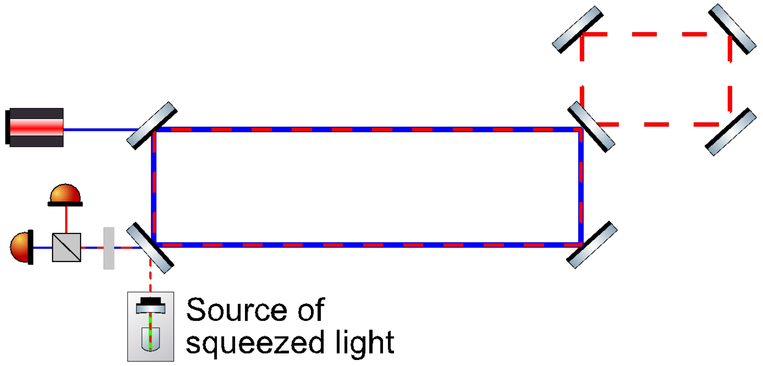
First lock of 2m cavity

Left to right:
Lorenzo Aiello
Aldo Ejlli
Sander Vermeulen
Alasdair James
William Griffiths

Outlook

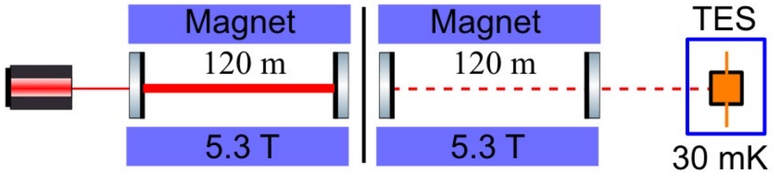
Experiment 1: Axions in the galactic halo

- Scalable to km-scale facilities



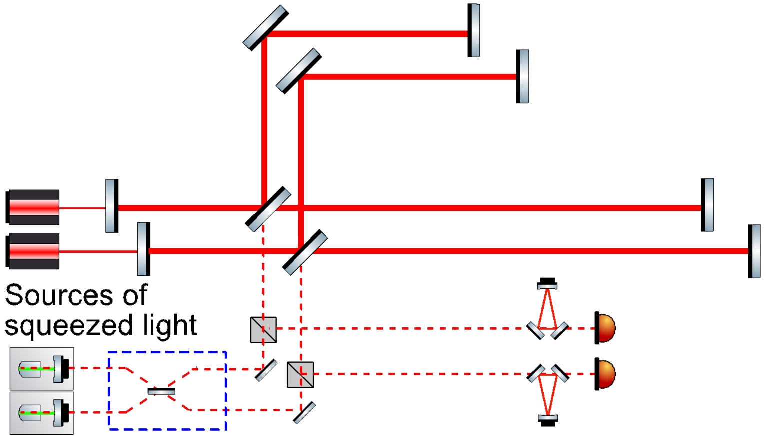
Experiment 2: Light-shining-through-wall (collab.)

- Scalable to km-scale
- Transition edge sensor for future dark matter searches



Experiment 3: Quantisation of space-time

- Scalable and reconfigurable for different geometries (CQG 38, 085008)
- Advanced squeezing schemes



Experiment 4: Semiclassical gravity

- Testbed for more quantum-gravity exploration using interferometry (arXiv 2104.04414)