Quantum Technologies for Fundamental Physics

Programme Overview

•••

RECFA visit to UK
Royal Society, London

Ruben Saakyan (UCL)

13-Sep-2024

QTFP is part of National Quantum Technology Programme

- New strategic initiative created with £40M from Strategic Priorities Fund in 2019
- Awarded to EPSRC and STFC with STFC administering the programme
- **Primary purpose** : Exploit, develop, customise and refine latest advances in quantum technologies to address greatest scientific mysteries in fundamental physics

Programme Scope:

Quantum Technologies for Fundamental Physics	
Fundamental physics	**Quantum technologies**
Covering: • Quantum science • Astronomy • Particle physics & astrophysics • Nuclear physics	Including but not limited to: • Quantum computing and simulation • Quantum sensing and timing • Quantum imaging • Quantum communication • Quantum components.
Including topics such as: • The search for dark matter • Macroscopic quantum effects • Quantum simulators • Searches for violations of fundamental symmetries of nature • Gravitational effects • Quantum observatory • Neutrino mass studies	

QTFP funded 7 large consortia in 2020 until Mar'2025 (Wave 1)

Followed by 17 smaller projects in 2022

In this presentation:

- Summarise objectives and contributions of UK consortia
- Provide insights into group dimensions, funding and challenges
- Review international links, discuss progress against programme objectives
- Highlight challenges and limitations

Focus on overarching programme and 7 Consortia

Key Facts

Indicator	Value
QTFP Award	£40M, 2021 - ***Mar'2025***)
Number of projects funded	24 (7 Consortia in Call 1, 17 smaller projects in Call 2)
Number of research organisations	29
Number of people	250 (PI, Co-I, RA, Tc, Eng, PhD students)
Publications	~50
International Links	26 links across 9 countries. Collaboration Agreements: AION-MAGIS, QSHS-ADMX, QUEST_DMC-HERALD, QTNM-Project 8
Engagement activities	25 activities including 9 international events
Community building	Feb 2023 event, 190 registrants, 120 attended

QTFP projects

Source: Mid-Term review of QTFP

QTFP Consortia

Over 200 academics, senior researchers, early-career scientists, engineers, technicians and doctoral students

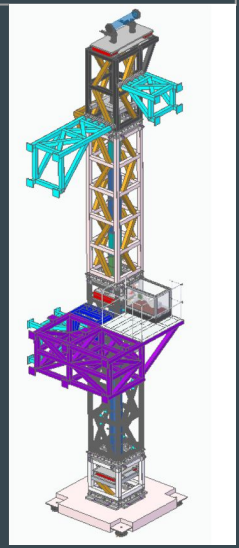
- AION, atom interferometer observatory and network. Gravitational waves, dark matter
- Quantum Interferometry (QI), space-time quantisation, dark matter
- Quantum Technologies for Neutrino Mass (QTNM), measure absolute neutrino mass
- Quantum Sensors for the Hidden Sector (QSHS), wave-like dark matter, axions
- Quantum Simulations for Fundamental Physics (QSimFP), early universe and dark matter
- Quantum Sensors Network (QSNET), variations of fundamental constants
- QUEST-DMC, superfluid technologies for dark matter and cosmology.

Atom Interferometry Observatory and Network

Consortium	Personnel	Funding	Scope
Imperial, Birmingham, Cambridge, Kings, Liverpool, Oxford, RAL PI. Prof. O. Buchmueller	50, even split between STFC/EPSRC. Acad/RA/PhD/Eng = 34%/34%/22%/10%	£7.2M initial, £12M overall	Construct a series of advanced atom interferometers to explore dark matter, detect gravitational waves and test fundamental physics through high-precision measurements.

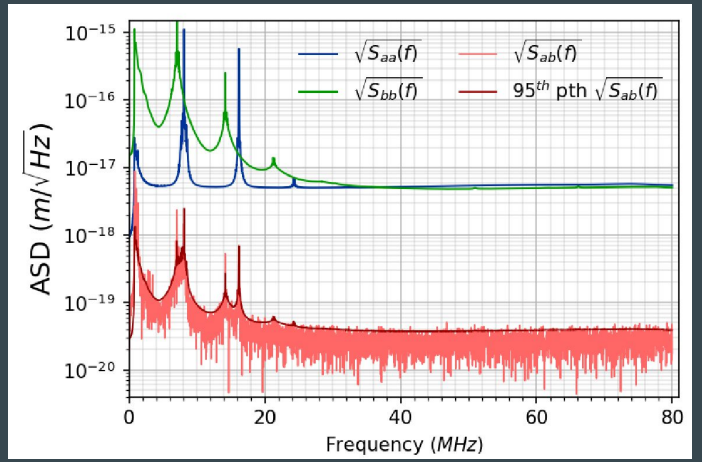
UK-US partnership between AION and MAGIS

- Large scale particle physics production methods to build “quantum lab” capacity.
- 5 Ultra-cold Sr Labs, more than doubled ultra-cold Sr R&D capacity in the UK and increased by 25% worldwide
- 22 publications including in Phys Rev D, EPJ etc



Quantum Interferometry for New Physics

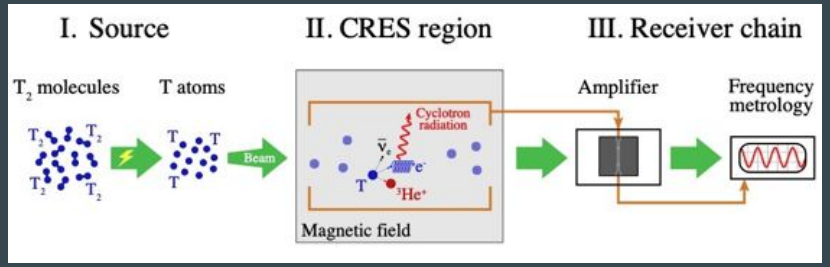
- Novel searches for DM and axion-like particles: LIDA, ALPS II
- Searches for signatures of quantum gravity: QUEST, CRYO-BEAT
- Quantum Tech: squeezed light and TES single photon detection
- Most displacement sensitive table-top interferometer worldwide
- PI is also co-spokesperson of international ALPS Collaboration



Consortium	Personnel	Funding	Scope
Cardiff, Birmingham, Glasgow, Strathclyde, Warwick PI: Prof. H. Grote	26, 6 academics, 8 RAs, 10 PhD-st, 2 Eng.	£5M. Some other funds from Leverhulme, Welsh HERC.	Develop novel interferometers and squeezed light techniques to explore space-time quantisation and dark matter

Quantum Technologies for Neutrino Mass

Consortium	Personnel	Funding	Scope
UCL, Oxford, Cambridge, NPL, Warwick, Swansea, QMUL PI: Prof. R. Saakyan	25, 9 academics, 3 senior researchers, 7 RAs, 3 grad-st, 3 Eng/Tech 50/50 Quantum/PP	£4M	Neutrino mass measurement from atomic ^{3}H β-decay via Cyclotron Radiation Emission Spectroscopy using latest advances in quantum technologies



Current project QTFP Wave 1, 2021-2025

- **Quantum** noise limited microwave **sensors** at TRL7/8 for CRES at ~18GHz ✅
- 3D B-field mapping with ≲1 μT precision, using H-atoms as **quantum sensors** (Rydberg Magnetometry), 1D ✅
- Production and confinement of H-atoms, ≥ 10^{12} cm^{-3} 10^{10} cm^{-3} ✅

7 publications on work since 2021

Phased Approach:

CRESDA0 → **CRESDA-Tritium** → **100 meV** → **50 meV** → ***O*(10 meV)**

current

Future: e.g. Culham Centre for Fusion Energy

Consortium agreement with Project 8 Collaboration.

Quantum Sensors for Hidden Sector

Consortium	Personnel	Funding	Scope
Sheffield, Oxford, Lancaster, UCL, RHUL, NPL PI: Prof. E. Daw	35, 15 academ/senior, 7 RAs, 7 PhD-st, 6 Eng 50/50 Q-electronics/Astropart. physics	£4.7M + £0.9M for test facility	Search for halo axion dark matter. Significantly extended mass range compared to "traditional" axion searches.

- Dilution fridge and magnet procured, reached 8.5 mK
- First resonant cavity cool-down imminent
- Magnetic shield delivered, soon to be integrated
- Close collaboration with **ADMX** (US Axion Dark Matter Search)
- Current ADMX sidecar cavity searching for axions at ~20 μeV supplied by **QSHS**
- 31 publications associated with consortium

Quantum Simulators for Fundamental Physics

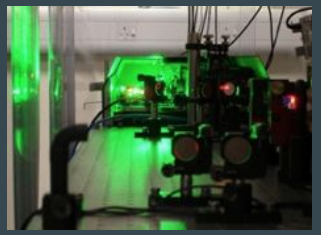
Consortium	Personnel	Funding	Scope
Nottingham, Cambridge, KCL, UCL, RHUL, Newcastle, St Andrews PI: Prof. S. Weinfurtner	27 QTFP funded, 50-50 QT-FP split	£5M	Quantum Simulations of Black Holes and Early Universe processes.

1+1-Dimensional Black Hole Simulator

- Fibre-optical solitons
- Quantum Light Detectors
- **Black Hole Spectral Stability**

2+1-Dimensional Black Hole Simulator

- Biggest Quantum Vortex Flows
- Off-axis Holography Detectors
- **Black Hole Bound states and Instabilities**



2+1-Dim. False Vacuum Decay Simulator

- Ultracold-atoms in optical box traps
- Biggest Potassium Condensate
- First-order Relativistic Phase-Transitions

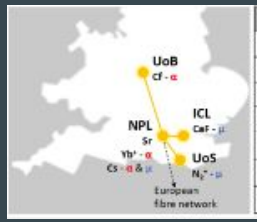
2+1-Dimensional Black Hole Simulator

- State-of-the-art nanotechnology facilities
- Superconducting microwave micro-structures
- Quantum Fields Dynamics & Quantised Rotation

- 28 publications including Nature, Editor suggestions
- Outreach events in schools, artist in residence
- Patent application

Quantum Sensors Network

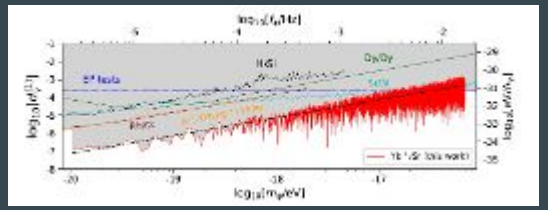
Consortium	Personnel	Funding	Scope
Birmingham, Sussex, Imperial, NPL PI: Prof. G. Barontini	21, 10 academics and senior researchers, 7 RAs, 4 PhD-st. Mostly AMO community	£4M	Search for variations of SM fundamental constants using a network of clocks

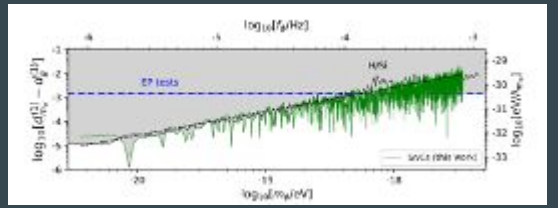


Clock	Kα	Kμ
Yb^+ (467 nm)	-5.95	0
Sr (698 nm)	0.06	0
Cs (32.6 mm)	2.83	1
CaF (17 μm)	0	0.5
N_2^+ (2.31 μm)	0	0.5
Cf^{15+} (618 nm)	47	0
Cf^{17+} (485 nm)	-43.5	0

TRL

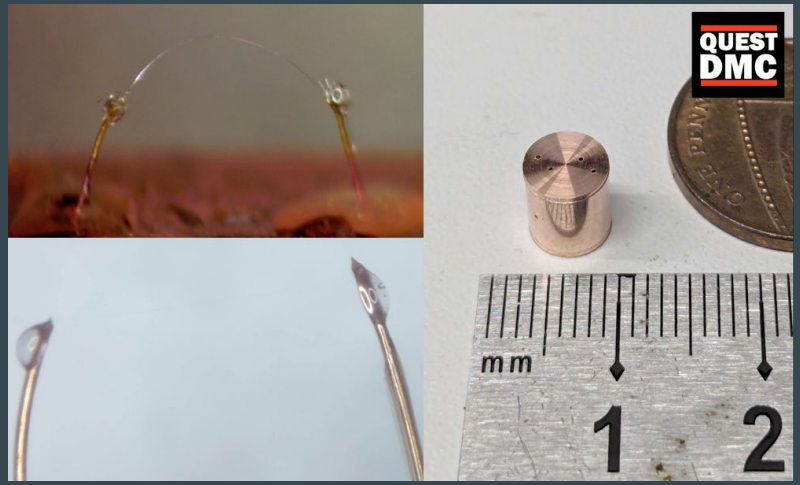
- World-leading constraints on ultra-light dark matter, New J. Phys. 25 9, 093012 (2023)
- First compact electron beam ion trap in UK
- First cryogenic vacuum system to trap and cool highly charged ions in UK
- Sideband cooling for molecular ions and quantum logic spectroscopy
- 10 papers, 2 thesis





Quantum Enhanced Superfluid Technologies for Dark Matter and Cosmology

Consortium	Personnel	Funding	Scope
RHUL, Oxford, Lancaster, Sussex PI: Prof. A. Casey	33, 14 faculty, 8 RAs, 8 PhD-st, 3 Eng/Tech	£3.4M Wave 1 + £1.6M extensions and equipment	Using superfluid Helium-3 to search for light dark matter particles and to investigate phase transitions that simulate early universe



4.5um (top) and 450nm (bottom) nanowire detectors for broken Cooper pairs in superfluid Helium-3. Cylindrical container for the helium and nanowire sensors.

4 publications

Need to expand infrastructure to underground facilities – Boulby connection

Mid-Term Review (2023) and QTFP Science Review (2024)

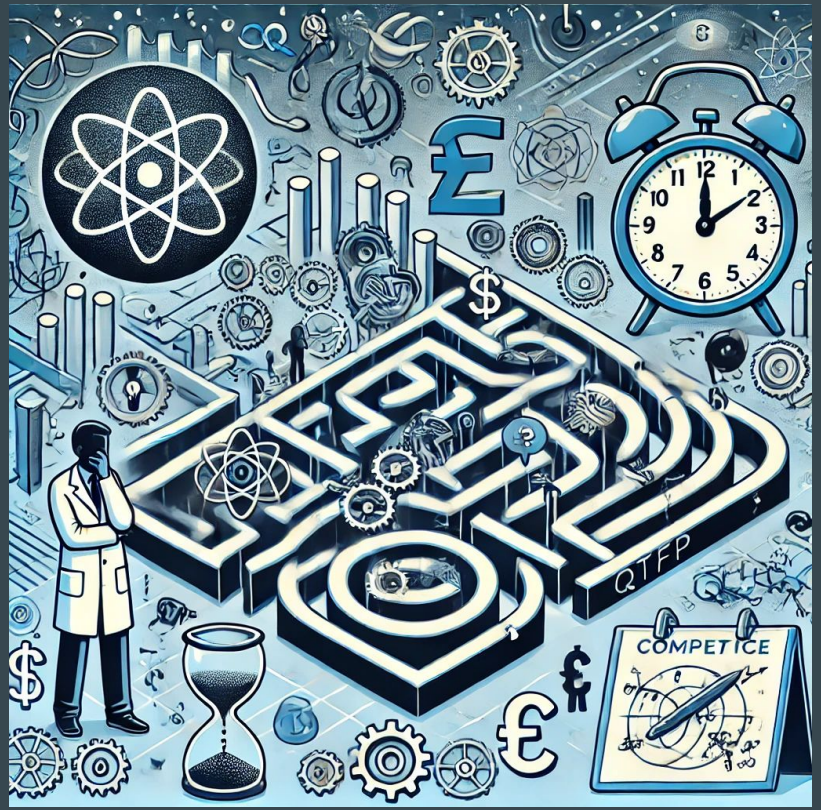
Commissioned by STFC

- High standard and transformational in some aspects
- Industry connection → quantum economy (Oxford Instruments, Bluefors, Low Noise Factory, ...)
- World-leading results in some cases.
- Community building has been exemplary.
- Have done well with attracting and training ECR. Maintaining support for ECR will be crucial for future phases.
- Lack of clear vision for future of the Programme and sustainability of funding is biggest concern.

Findings.

- UK has set the standard with QTFP but it will require a concerted effort to maintain that lead.

Difficulties and Limitations



- *All Consortia identified the absence of a mid- to long-term funding strategy as the primary challenge and limitation of the programme.*
- *It hinders forward planning, jeopardises our competitive advantage, and poses a risk to the retention of top early-career researchers.*
- *In Aug'2024 STFC suggested a way forward for continuation of QTFP beyond Mar'2025*
- *This is very welcome. But uncertainties over amount and duration of future funding, along with the lack of flexibility in carrying forward existing funds, continue to be problematic.*
- *Sustainability of QTFP funding and its place in STFC strategy and core programme are still main concerns.*

Extra

Mid-Term Review.
Progress against Programme Objectives.

1. Build up a new scientifically and technically productive community in the area of quantum technologies for fundamental physics based in the UK – ✅ (see key indicators, slide 4, and Science Review, slide 13

2. Position the UK as a first rank nation in the scientific exploitation of quantum technology for physics applications, delivering high-impact scientific results and pushing existing quantum technologies to their limits – ✓ Too early for science breakthroughs (Wave 1) but strong international interest and in some areas world-leading results in demonstrating key QT.

3. Perform an active role in the NQTP widening the take up of quantum technology throughout the science research base in the UK, and acting as a pipeline of both talent and early stage technology – ✓ for pipeline of talent, new methods with wider applications

4. Create opportunity for new patents and products as a result of developing new or improved equipment that will be needed to support the scientific work programme – ✓ new patents, developments and products, world-leading in some cases