Particle Physics and Quantum Technology (QTFP)

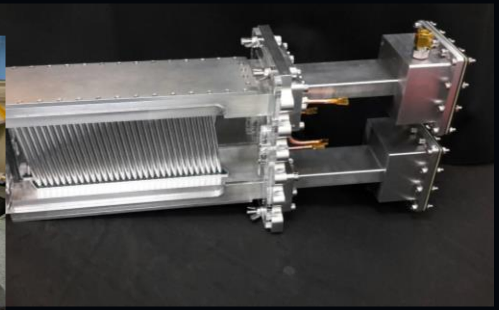
Themis Bowcock

UNIVERSITY OF LIVERPOOL

CERN

Physics Beyond Colliders

Preamble



- Personal views (not representing UK or quantum community)
- Thanks to many especially Ian Shipsey
  - *Reference talk to HEP Forum in Durham Nov 2020 (and slides)*
- Key elements of science case including
  - Atom interferometry network in UK
  - Making a measurement of neutrino mass
  - Ref. Oliver Buchmuller this meeting
  - and Ruben Saakyan UK HEP Forum

UK Research and Innovation

Quantum Technology Fundamental Physics

Great time to be a fundamental physicist…

Modified from slide by F. Gianotti

Higgs boson and EWSB

- ❑ m_H natural or fine-tuned ?
  → if natural: what new physics/symmetry?
- ❑ does it regularize the divergent $V_L V_L$ cross-section at high $M(V_L V_L)$? Or is there a new dynamics ?
- ❑ elementary or composite Higgs ?
- ❑ is it alone or are there other Higgs bosons ?
- ❑ origin of couplings to fermions
- ❑ coupling to dark matter ?
- ❑ does it violate CP ?
- ❑ cosmological EW phase transition

Quarks and leptons:

- ❑ why 3 families ?
- ❑ masses and mixing
- ❑ *CP* violation in the lepton sector
- ❑ matter and antimatter asymmetry
- ❑ baryon and charged lepton number violation

Physics at the highest E-scales:

- ❑ how is gravity connected with the other forces ?
- ❑ do forces unify at high energy ?

Dark matter:

- ❑ composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ..
- ❑ one type or more ?
- ❑ only gravitational or other interactions ?

Neutrinos:

- ❑ *ν* masses and and their origin
- ❑ what is the role of *H*(125) ?
- ❑ Majorana or Dirac ?
- ❑ *CP* violation
- ❑ additional species → sterile *ν* ?

The two epochs of Universe's accelerated expansion:

- ❑ primordial: is inflation correct ?
  which (scalar) fields? role of quantum gravity?
- ❑ today: dark energy (why is Λ so small?) or gravity modification ?

Our scope is broad

Many tools:

accelerator,

non-accelerator

cosmological

Why a new programme in UK?

- Describe (briefly) how we got involved
  - one of many paths for PP groups
- Give a brief description of UK's QFTP Programme
  - International context
  - Pointers to resources
- "Reflections"
  - What happens next?
  - Choices for the community, conflicts and opportunities
- Summary

The arc … to be continued

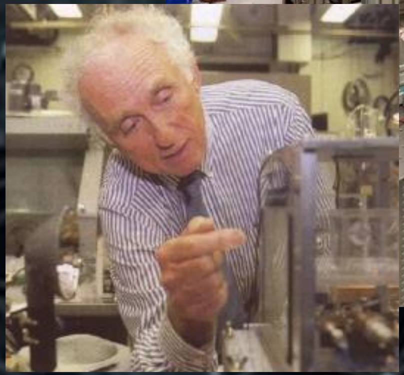
- At Liverpool (in the PP group) in 2011

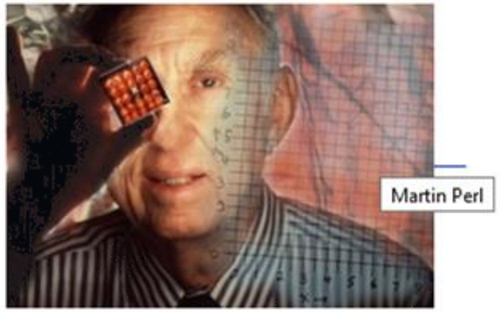
"We aim to find out the nature of dark energy. Is it an energy field, is it a fluid, or some other phenomenon we have never thought about?

Jon Coleman (ex BaBar)

Build an atom interferometer to attack this question within the PP group

FUNDING NOT READILY AVAILABLE!!!





Published:
December 1, 2011
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Nobel Laureate Martin Perl joins University as Visiting Professor

Martin Perl

Nobel Laureate, Professor Martin Perl, has accepted a Visiting Professorship at the University.

Professor Perl won the 1995 Nobel Prize for Physics for the discovery of the tau lepton particle, an elementary particle similar to the electron. He spent his career at the University of Michigan and the Stanford Linear Accelerator Center (SLAC) and currently serves on the board of advisors of Scientists and Engineers for America.

Professor Perl is collaborating with Dr Jonathan Coleman, a Royal Society Research Fellow in the University's **Department of Physics**, on an experiment to detect dark energy, previously only seen through cosmological and astronomical observations. The research aims to investigate the nature of dark energy in the laboratory.

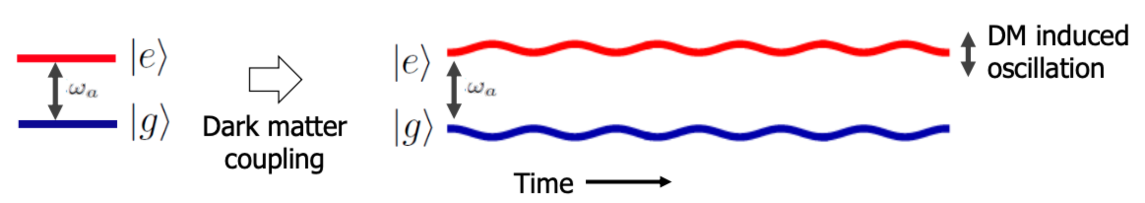
Dr Coleman said: "The 2011 Nobel Prize in Physics was awarded for the unexpected discovery that the visible universe is expanding in time – in contrast to the previous assumption that while the size of the universe will continue to expand, the rate of expansion will slow down. This acceleration phenomenon is called dark energy – a term to describe something we know something is driving the expansion.

"We aim to find out the nature of dark energy. Is it an energy field, is it a fluid, or some other phenomenon we have never thought about?"

See AION talk

- Atoms as de Broglie waves in quantum superposition of states
- Large wavepacket separation to increase sensitivity to:
  - Ultralight dark matter (10^{-22} eV – 10^{-14} eV)
  - Mid-band gravitational waves (30 mHz – 10 Hz)

- DM Affects fundamental constants (m_e and α), altering atomic energy level separation



- Same configuration used for gravitational wave measurements

One of many examples: so why quantum?

Modified from slide by I. Shipsey

- We are no longer in an era of "no-lose" theorems/strategies
  - SM may hold up to Planck scale?
  - Precision instruments and measurements could play a vital role
- Sensitivity in new regimes
  - E.g. light axion searches
- Simulation and Computing Technology

Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical," Feynman (1981).

QFTP UK

- “The Confluence” – a perfect match

New ways to look at the Universe

Unanswered questions – mysteries

Quantum Sensors for Fundamental Physics and Society Workshop I (2018)

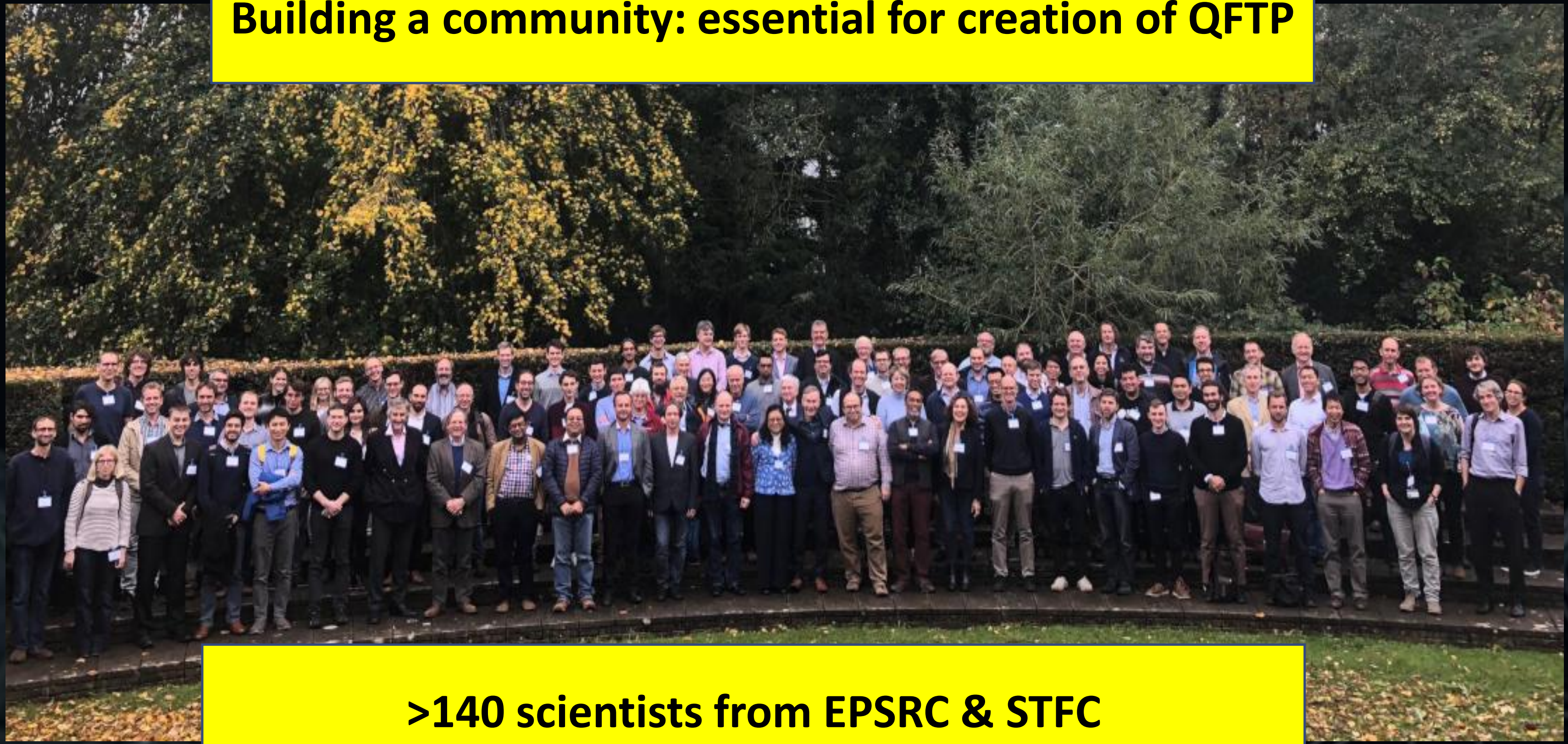
- Four goals
  1. To survey the extraordinary science opportunities and UK capabilities to exploit this science in a world class programnme
  2. To demonstrate to UK funding agencies the immense interest in UK for Quantum Sensors
  3. To build a community around key experiments
  4. To work with STFC/EPSRC to bid for funding to Strategic Priorities Fund

- Kai Bongs (Birmingham)
- Ed Daw (Sheffield)
- John March-Russell (Oxford)
- Ruben Saakyan (UCL)
- … + Liverpool

Ian Shipsey

UK “building the community” % Science Case

Building a community: essential for creation of QFTP



>140 scientists from EPSRC & STFC

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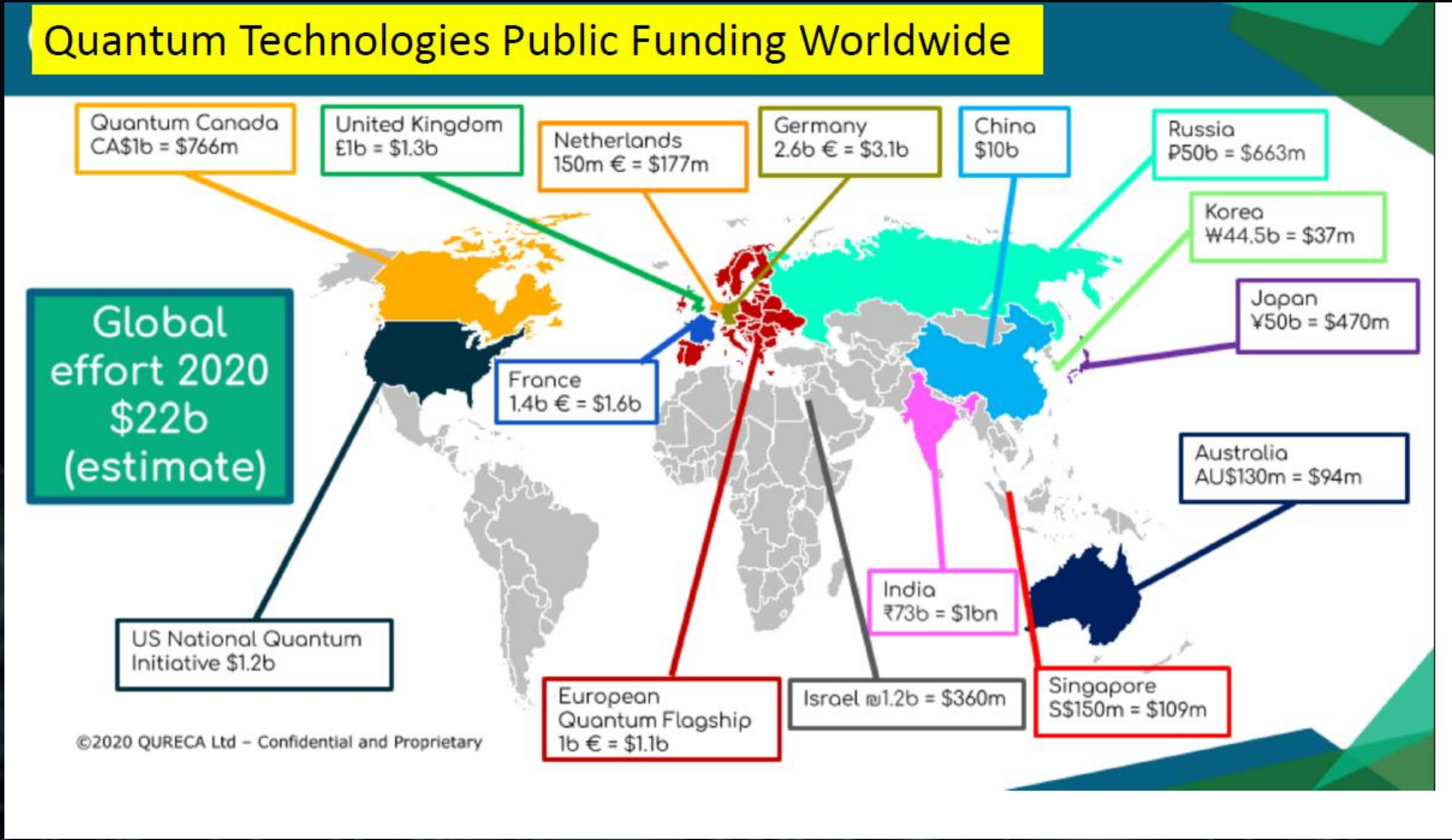
Young Experimentalists

Theorists

Group Leaders

PP and non PP

International Context Funding



Slide by I. Shipsey

US Initiative including QuantiSED

DOE Office of Science High Energy Physics QIS Core Research
QuantISED (Quantum Information Science Enabled Discovery)

The High Energy Physics (HEP) Program Mission is:

To understand how the universe works at its most fundamental level

It is implemented via projects, facilities, and research & technology programs

Science Drivers were identified with community input https://www.usparticlephysics.org/ as

Higgs Boson, Neutrino Mass, Dark Matter, Cosmic Acceleration, and Explore the Unknown

The HEP QuantISED effort explores the universe via interdisciplinary partnerships between HEP and QIS communities through the topics:

A: Cosmos and Qubits

B: Foundational QIS-HEP Theory and Simulation

C: Quantum Computing for HEP

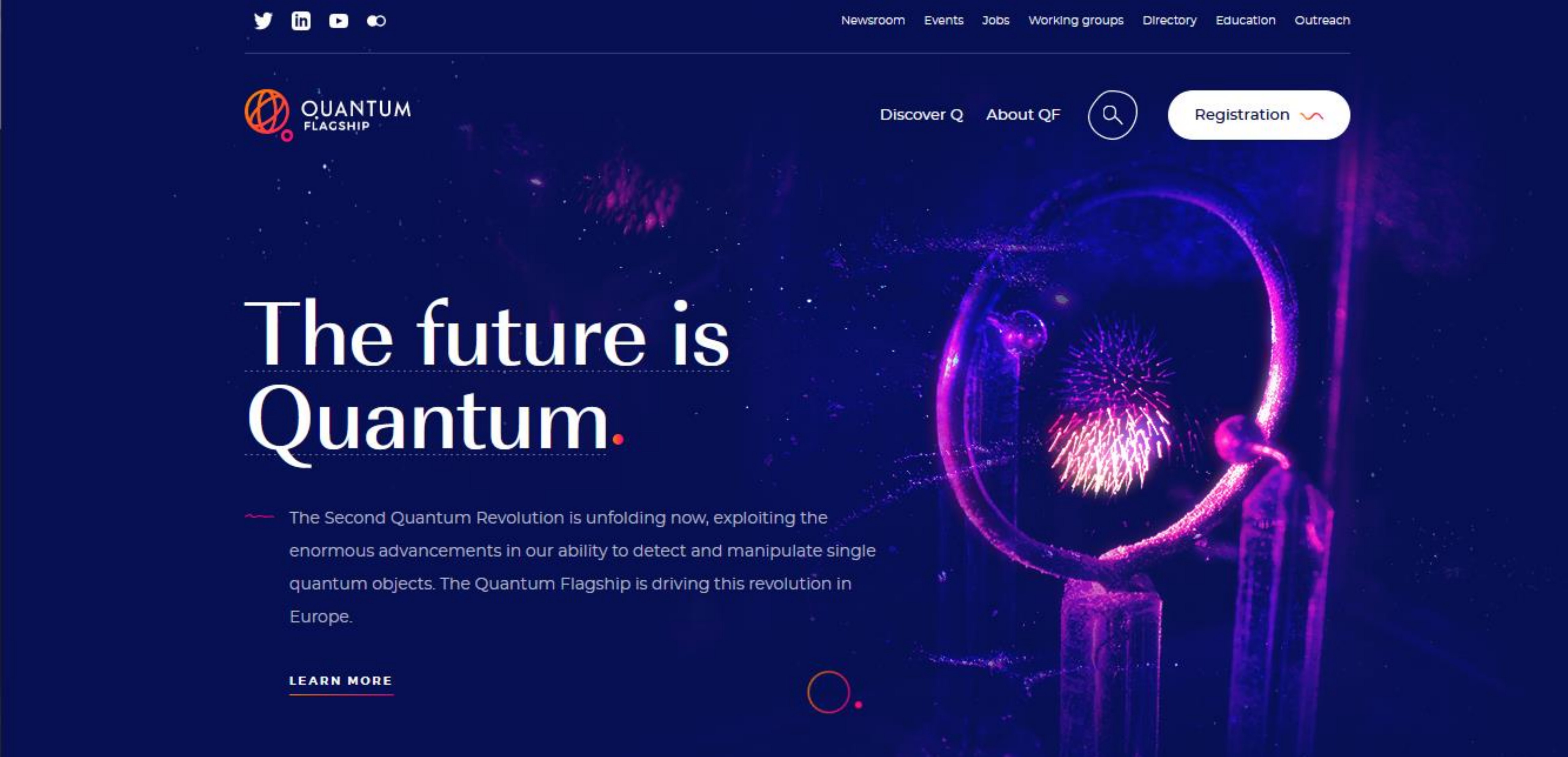
D: QIS-based Quantum Sensors

E: Research Technology for QIST

F: QuantISED (Small) Experiments exploring P5 science drivers using QIS tools & techniques

(QuantISED was publicly competed in 2018 and 2019 and is part of the DOE Office of Science QIS Initiative)
https://science.osti.gov/hep/Research/Quantum-Information-Science-QIS

QuantISED is in many respects the analogue of QTFP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Events
Jobs
Working groups
Directory
Education
Outreach
QUANTUM FLAGSHIP
Discover Q
About QF
Registration
The future is Quantum.
The Second Quantum Revolution is unfolding now, exploiting the enormous advancements in our ability to detect and manipulate single quantum objects. The Quantum Flagship is driving this revolution in Europe.
LEARN MORE

https://qt.eu/

Meanwhile domestic landscape (UK) …

- UK National Quantum Technology Programme

- NQTP vital for QFTP

£40M for Quantum Sensors for Fundamental Physics

- Phase I 2015-2019
- Phase 2 2020-2024

Approx £1B including training, and National Quantum Computing Centre..

NQTP Phase 2. 2019- a non HEP perspective

Further investment into the National Programme

- **Ensuring UK research leadership:** Renewal and refresh of the QT Research Hubs (£94M over 5 years)
- **Commercialisation and industrialisation of QT:** industry led projects to drive innovation and commercialisation (£153M over 6 years, ISCF)
- **Delivering skilled people:** investment in research training (£25M over 5 years)
- **Enhancing national capabilities:** National Quantum Computing Centre to drive development in this new technology and place us at the forefront of this field (£93M over 5 years)
- **Science as a customer of QT:** A focussed research programme aimed at demonstrating how the application of QT will advance the understanding of fundamental physics questions (£40M over 3 years)

Slide credit Sir Peter Knight

An excellent review

IOP Publishing Quantum Sci. Technol. 4 (2019) 040502 https://doi.org/10.1088/2058-9565/ab4346

Quantum Science and Technology

Quantum Technologies for Fundamental Physics funds originated from the Strategic Priorities fund and It is part of the National Quantum Technologies Programme

CrossMark

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PUBLISHED
29 October 2019

PERSPECTIVE

UK national quantum technology programme

Peter Knight and Ian Walmsley
Imperial College London SW72AZ, United Kingdom

Keywords: quantum, imaging, timing, communication, sensors, computing

The bid was made by STFC/EPSRC December 20, 2018. This requested the funding to create the new programme (£40M/ 3 years)

Feedback: The QSFP consortium has been essential to demonstrating the interdisciplinary interest & formation of a community . Without it there would have been no credible bid.

STFC Opportunities Funding had been awarded QSFP to build a community and consortium and to prepare for the call. We supported more than a dozen workshops that facilitated the formation of teams and the development of proto-proposals around key experiments that targeted the new programme, we also hosted a school in January 2020

We also engaged with the international community who gave feedback on our ideas

The call opened 9/19 closed 12/19 many excellent proposals submitted by the community 11 from QSFP and many more not associated with QSFP

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Original Proposals/Workpackages

The Workpackages (WP) are:

WP1
Using Quantum Technology to Search for Low-mass Particles in the Hidden Sector
Participants/Collaborators >
Join this group >

WP2
MaQS (pronounced "Max") Macroscopic quantum superpositions for physics beyond the standard model
WP2 workshop slides >
Participants/Collaborators >
Join this group >

WP3
AION A UK Atom Interferometer Observatory and Network
Join this group >

WP4
Absolute neutrino mass
Participants/Collaborators >
Join this group >

WP5
Quantum Simulators of Fundamental Physics
Participants/Collaborators >
Join this group >

WP6
QSNET Networked Quantum Sensors for Fundamental Physics
Join this group >

WP7
Searches for a Fifth Force and Dark Matter using Precision Atomic Spectroscopy
Join this group >

WP8
Fundamental physics from precision studies of exotic atoms
Participants/Collaborators >
Join this group >

WP9
LIST – Lorentz Invariance Space Test
Participants/Collaborators >
Join this group >

WP10
Quantum sensors for fundamental physics: Collective quantum excitations as quantum sensors
Participants/Collaborators >
Join this group >

WP11
QI: Quantum-enhanced Interferometry for New Physics

RAL Space
NPL National Physical Laboratory
ADMX
Argonne National Laboratory
Fermilab

International Institutions

- CNRS (France)
- Perimeter Institute (Canada)
- U. Bremen (Germany)
- U. British Columbia (Canada)
- U. Frieburg (Canada)
- U. Marseille (France)
- U. Toronto (Canada

Seven areas supported

The Workpackages (WP) are:

WP1

Using Quantum Technology to Search for Low-mass Particles in the Hidden Sector

Participants/Collaborators >
Join this group >

WP3

AION A UK Atom Interferometer Observatory and Network

Join this group >

Oliver

WP4

Absolute neutrino mass

Participants/Collaborators >
Join this group >

Ruben

WP5

Quantum Simulators of Fundamental Physics

Participants/Collaborators >
Join this group >

WP6

QSNET Networked Quantum Sensors for Fundamental Physics

Join this group >

WP11

QI: Quantum-enhanced Interferometry for New Physics

+ QUEST DMC

Quantum Technologies for Fundamental Physics selected proposals: QUEST-DMC + six that were developed by the community activities supported by the STFC Opportunities Award

2nd Quantum Revolutioun ….

The second quantum revolution
Dowling & Milburn 2002
Alain Aspect

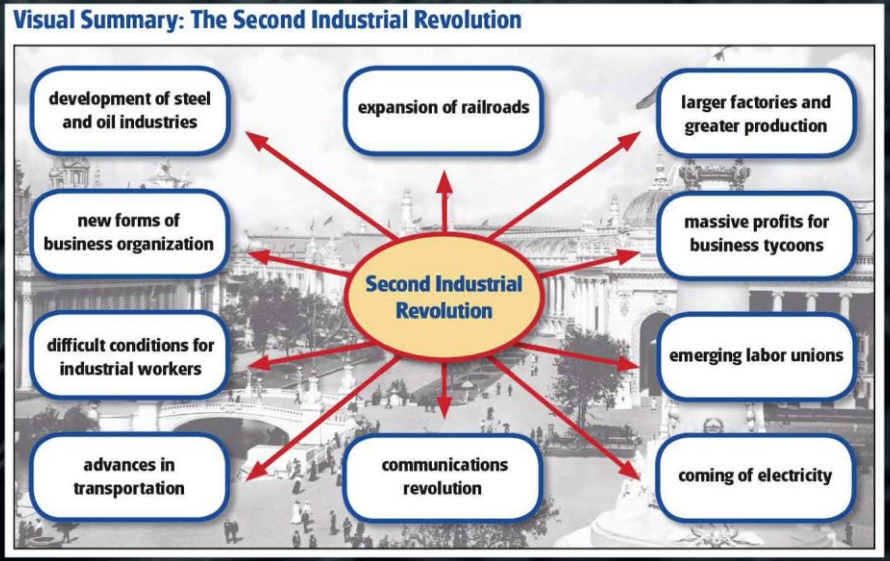
- P

Quantum 1.0[4] These include: laser systems, transistors, semiconductor devices, MRI imagers etc . The UK Defence Science and Technology Laboratory (Dstl) grouped these devices tgat rely on the effects of quantum mechanics.

Second Quantum Revolution "The hallmark of this on is the realization that we humans are no longer passive observers of the quantum world that Nature has given us." - Dowling

First Industrial Revolution: use of steam, interchangeable parts and mass production,

Second Industrial Revolution: railroads, large-scale iron and steel production, machinery in manufacturing, greatly increased use of steam power, telegraph, use of petroleum. Modern organizational methods for operating large scale businesses over vast areas came into use.



Hubs or Distributed

- First Quantum Wave
  - Largely hub based
  - Expensive, “risky” (although note all the successes)
  - Many defence drivers
- 2nd Quantum Wave
  - Much looser confederation – as technology progresses
    - Using rather than heavily R&D
    - Lower technological tariff for excellence
    - Risk transferred to project goals rather then tech.
  - Earlier stage PIs (for creativity and expression)
  - Do the old hubs try and absorb (centres of expertise)

UNIVERSITY OF LIVERPOOL

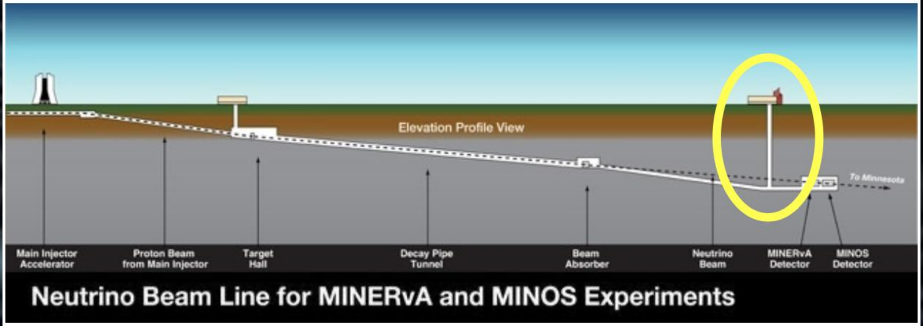
A second call

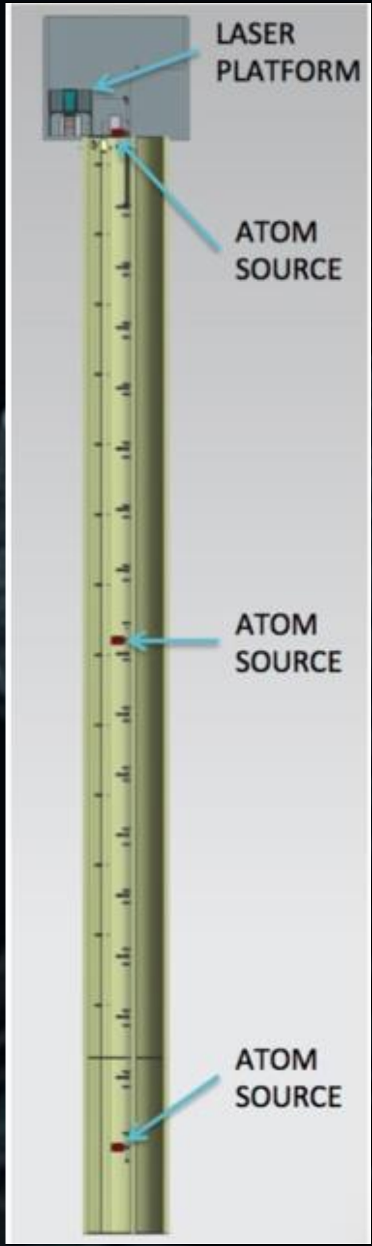
- Community building. Who are the constituents?
- Hub or “dispersed”?
- Is it a threat?
  - Some see it as a possible diversion of funds
  - Others as competitor
- The opportunity?

2021

MAGIS-100 Fermilab

- 100m baseline – MINOS access shaft
- 3 interferometers (2x50m sections)
  - 3 Sr atom sources
  - Differential measurements, GGN
- Sensitivity proportional to baseline L
  - 2L/c ~ gravitational wave signal
- Intermediate step to full scale detector for GWs



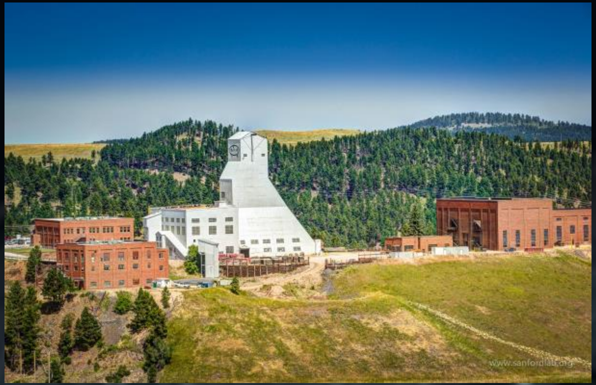


University of Oxford, Northwestern University, University of Cambridge, Johns Hopkins University, University of Liverpool, Stanford, NIU Northern Illinois, Fermilab, UK Research and Innovation, Gordon and Betty Moore Foundation, U.S. Department of Energy

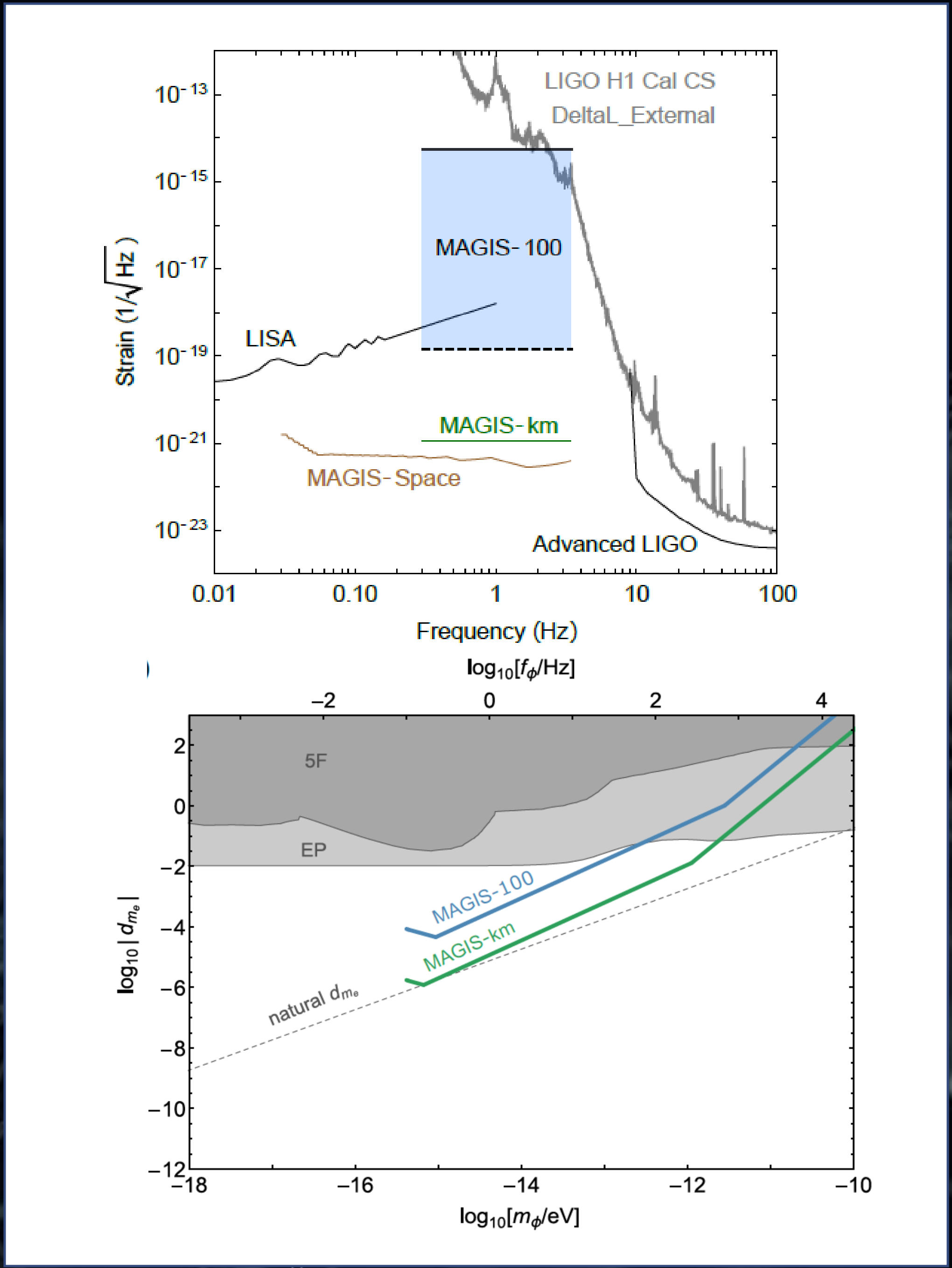
University of Liverpool

MAGIS-1km SURF

- 1km baseline
- Proposed to be built at Homestake mine (SURF)
  - Vertical network of twenty x 50m interferometer sections

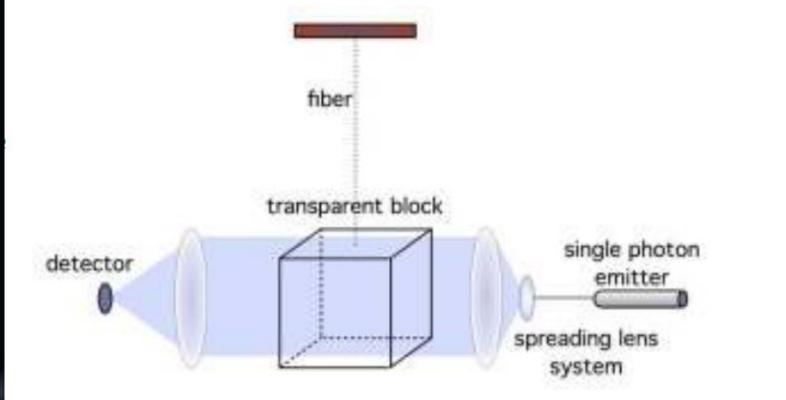


- Increased sensitivity to gravity waves
  - Between ALIGO and LISA
- Towards end of decade

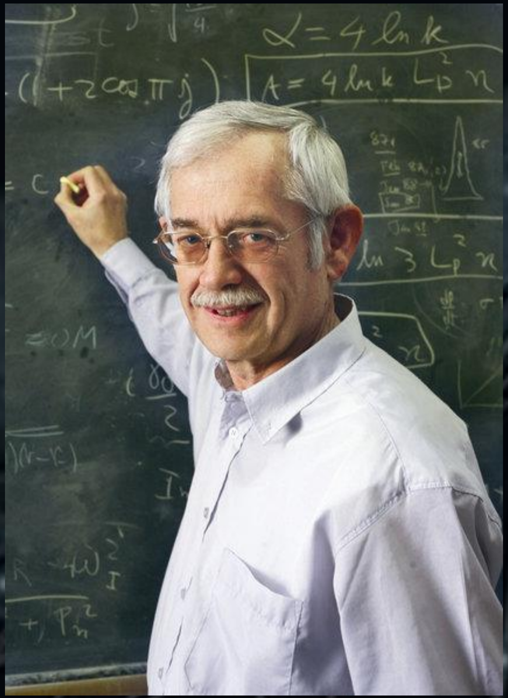


Many other possible ideas e.g.

- Investigating the Planck Scale directly



Jacob Bekenstein's proposed experiment fires a photon through a transparent block to check whether space-time is 'pixellated'.



Discussions (2014) on building experiment to test his proposal

Prototype 2015-2016. Next stage?

Summary

- Quantum can help us answer some of our deepest physics questions
- Cross-over technologies
- Our UK strategy(ies)
- Funding

Questions

- How does our (CERN) facility based community thrive/benefit?
- What are long term implications (historical precedent?)

BACKUP

Quantum Enhanced Superfluid Technologies for Dark Matter and Cosmology, QUEST –DMC

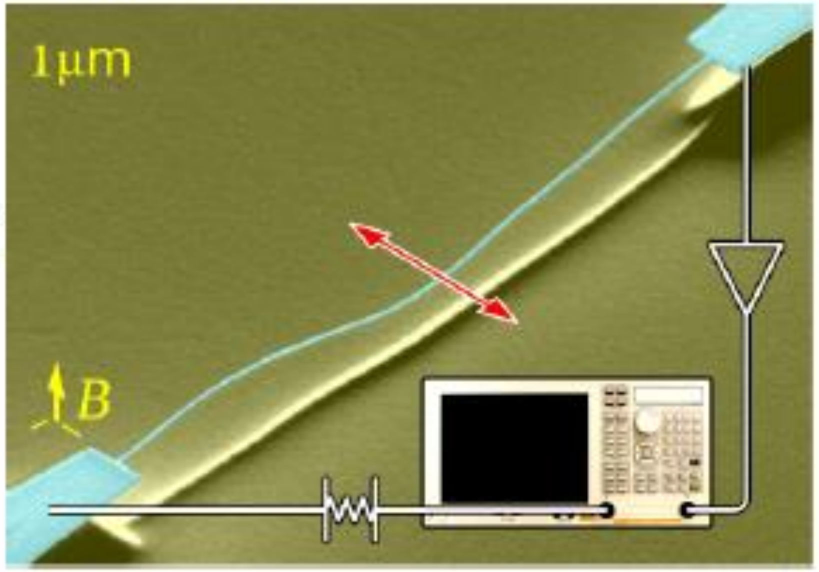
Royal Holloway University of London

Lancaster University

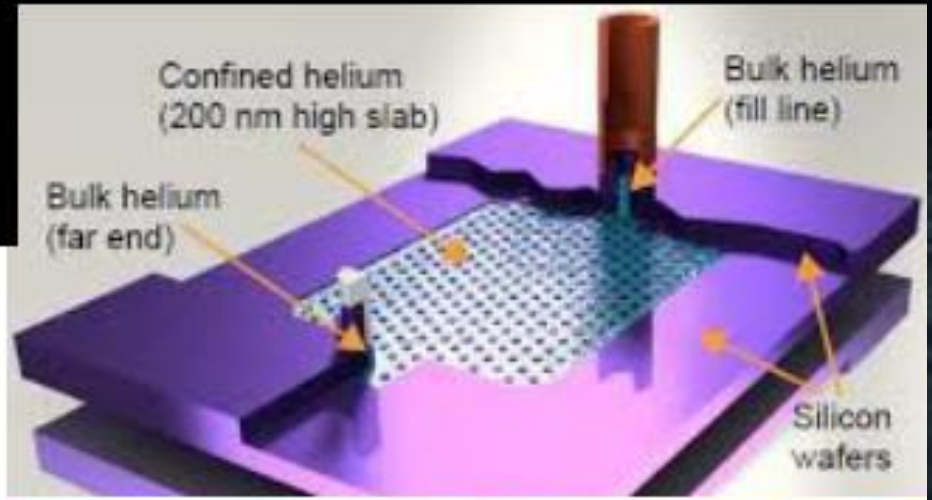
US University of Sussex

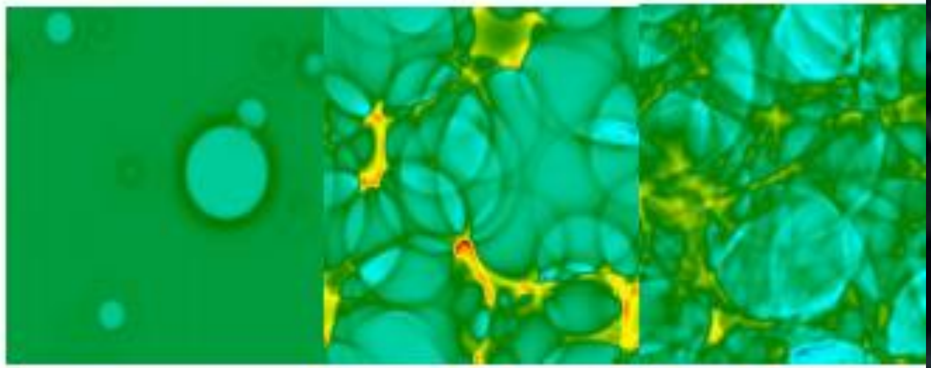
University of Oxford

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



Phase transitions in extreme matte





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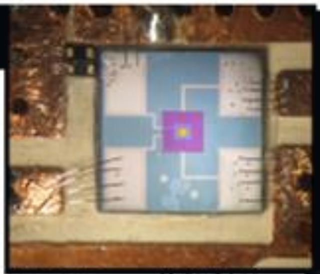
Quantum Sensors for the Hidden Sector

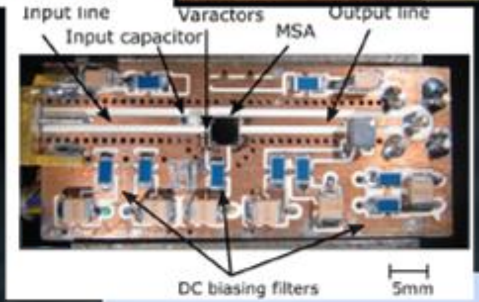
Sheffield, Cambridge, Oxford, RHUL, Lancaster, UCL, NPL, Liverpool

- A search for axions/ALPs using resonant conversion to microwave photons in high magnetic fields
- Initial focus on QCD axion, mass range 25-40μeV
- Collaboration with U.S. Axion Dark Matter eXperiment group, who operate the worlds most sensitive axion search, ADMX.
- **Ambition to build a UK high field (8T) low temperature (10mK) facility at Daresbury.**
- Ed Daw to talk this afternoon.

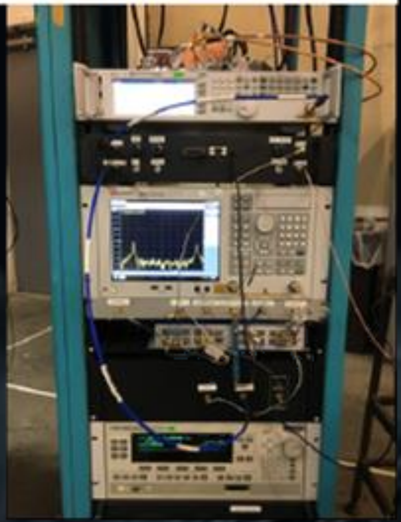
ADMX SQUID washer



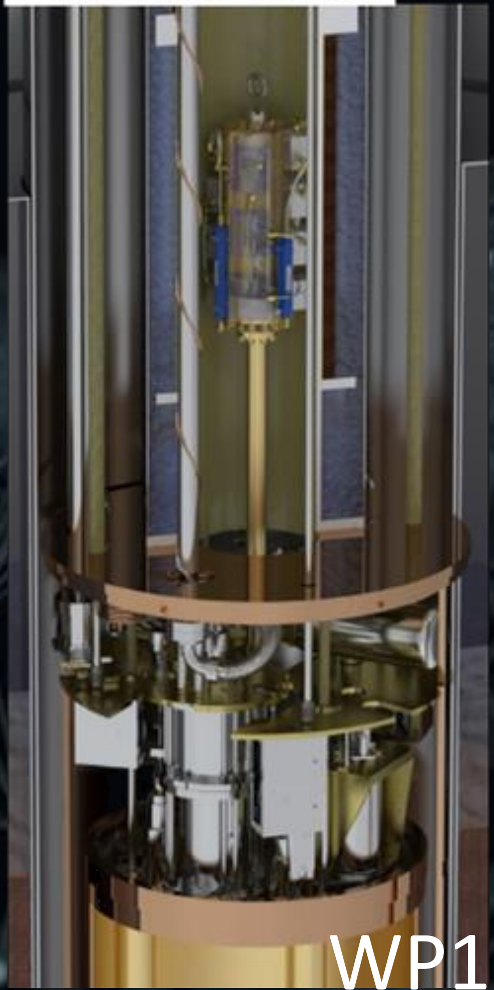
ADMX Microwave SQUID amplifier



Resonant feedback test



ADMX SQUID housing



WP1

Quantum Technologies for Neutrino Mass Consortium

UCL · NPL National Physical Laboratory · Prifysgol Abertawe Swansea University · The University of Warwick · University of Cambridge

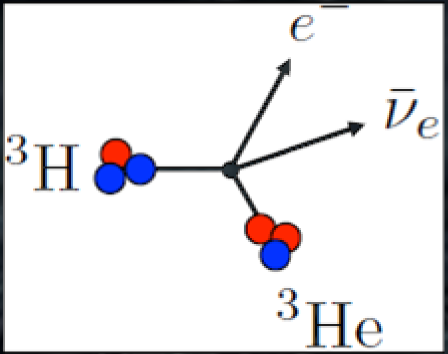
F. Deppisch[1], J, Gallop[2], L. Hao[2], S. Hogan[1], L.Li[3], R. Nichol[1], Y. Ramachers[4], R. Saakyan[1](PI), D. Waters[1], S. Withington[5]

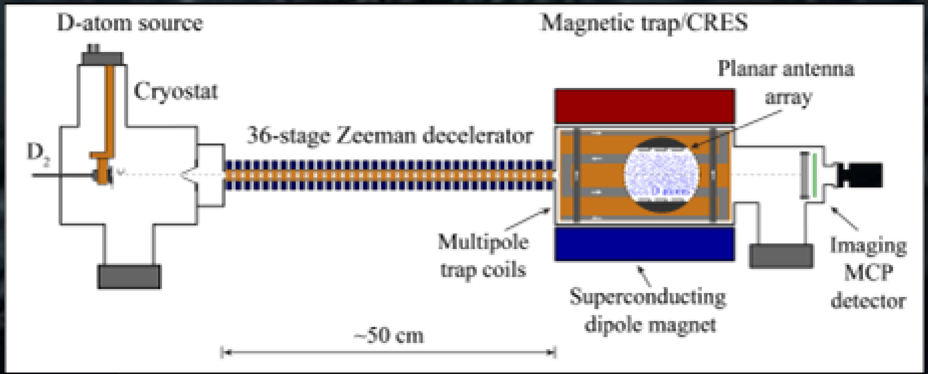
A collaboration of particle, atomic and solid state physicists, electronics engineers and quantum sensor experts

3-yr proposal goal:

Technology demonstration for neutrino mass determination from ^{3}H β-decay

- Trapping ~10^{20} D/T atoms
- B-field mapping with ≲0.1ppm precision
- Quantum limited micro-wave electronics





Ultimate goal:

Neutrino mass measurement at a Tritium facility (e.g. *Culham Centre for Fusion Energy*)

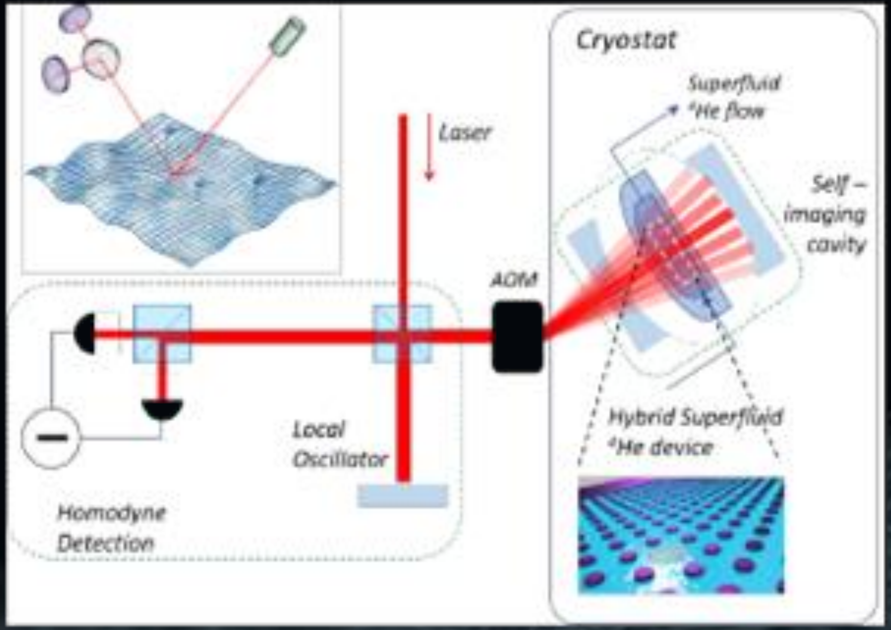
WP4

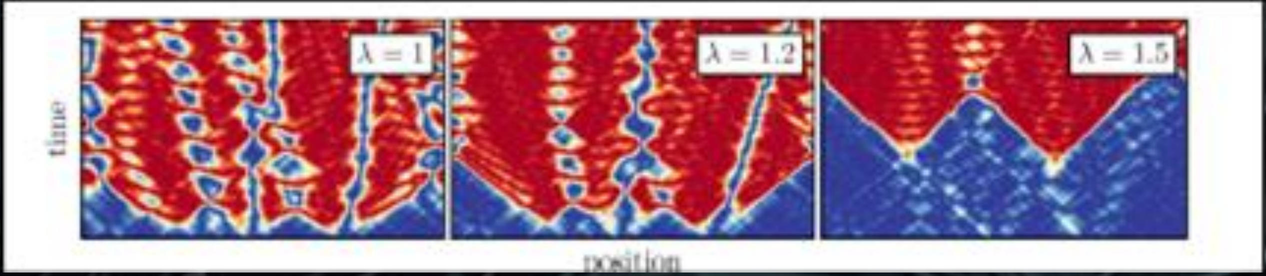
QSimFP Quantum Simulators for Fundamental Physics

Silke Weinfurtner talk

Team:

Carlo F Barenghi (Newcastle),
Thomas Billam (Newcastle),
Ruth Gregory (Durham),
Gregoire Ithier (RHUL),
Zoran Hadzibabic (Cambridge),
Friedrich Koenig (St. Andrews),
Jorma Louko (Nottingham), Ian Moss (Newcastle),
John Owers-Bradley (Nottingham),
Hiranya Peiris (UCL),
Andrew Pontzen (UCL), Xavier Rojas (RHUL),
Pierre Verlot (Nottingham),
Silke Weinfurtner (Nottingham).





Science goals:

- **Quantum vacuum**: perform experiments for quantum simulation of false vacuum decay in an inflationary multiverse setting
- **Quantum black holes**: to perform the first experiments that will allow systematic study of quantum wave-modes around quantised analogue black holes

WP5

A network of clocks for measuring the stability of fundamental constants

G. Barontini, V. Boyer, X. Calmet, M. Chung, N. Fitch, R. Godun, J. Goldwin, V. Guarrera, I. Hill, M. Keller, J. Kronjaeger, H. Margolis, C. Mow-Lowry, P. Newman, L. Prokhorov, B. Sauer, M. Schioppo, M. Tarbutt, A. Vecchio, S. Worm

Slide modified from original by I. Shipsey

The aim of the consortium is to build a community that will achieve unprecedented sensitivity in testing variations of the fine structure constant, α, and the proton-to-electron mass ratio, μ. This in turn will provide more stringent constraints on a wide range of fundamental and phenomenological theories beyond the Standard Model and on dark matter models. The ambition of the QSNET consortium will be enabled by a unique network that connects a number of complementary quantum clocks across the UK

Clock	WP	Variations of fund. Constant
Ion clock Yb^+ (467 nm)	1	α
Atomic clock Sr (698 nm)	1	Stable reference
Atomic clock Cs (32.6 mm)	1	μ
Highly-charged ion clock Cf^{15+} (618 nm)	2	α
Molecular clock CaF (17 μm)	3	μ
Molecular ion clock N_2^+ (2.31 μm)	3	μ

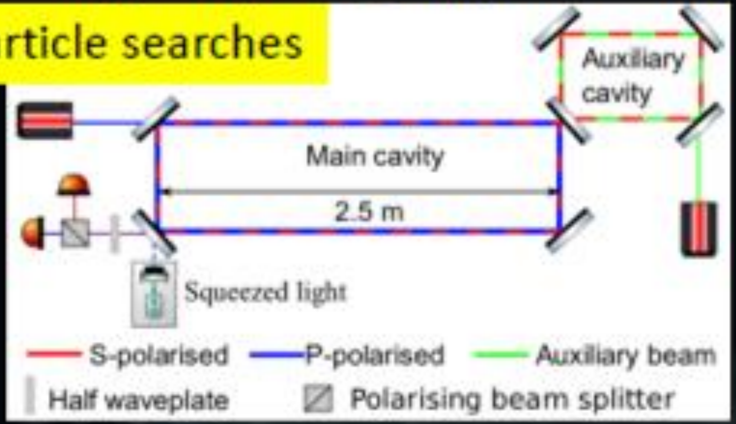
WP6

113

Quantum-enhanced Interferometry

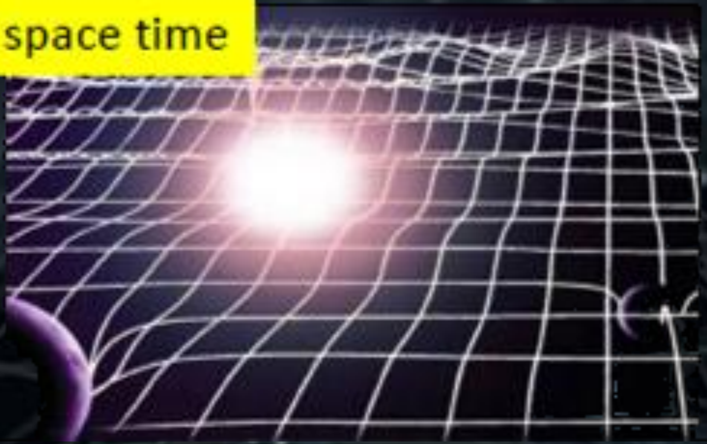
Vincent Boyer (Birmingham), Animesh Datta (Warwick), Katherine Dooley (Cardiff),
Hartmut Grote (Cardiff, PI), Robert Hadfield (Glasgow), Denis Martynov (Birmingham, Deputy PI)
Haixing Miao (Birmingham), Stuart Reid (Strathclyde)

Axion-like particle searches

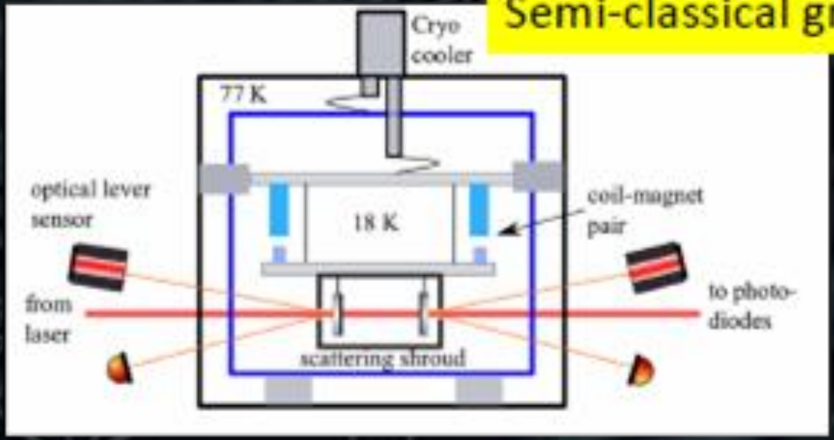


Enhancing ALPS @ DESY

Quantization of space time



Semi-classical gravity



WP11