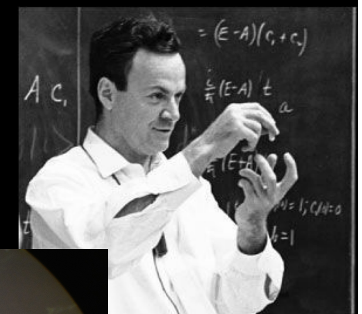
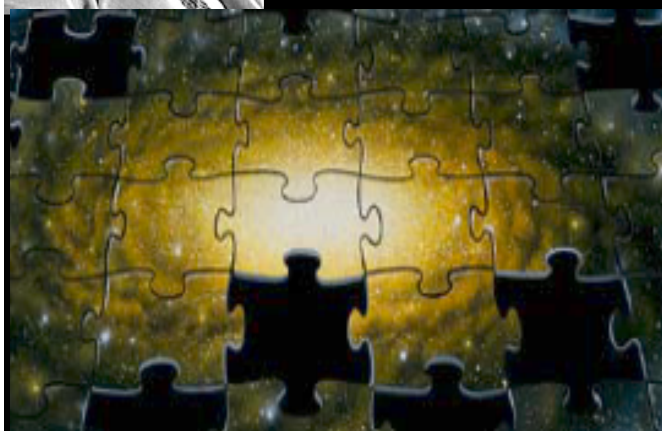
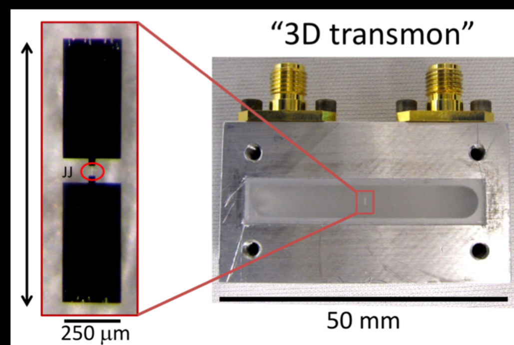
Quantum Sensors for Fundamental Physics

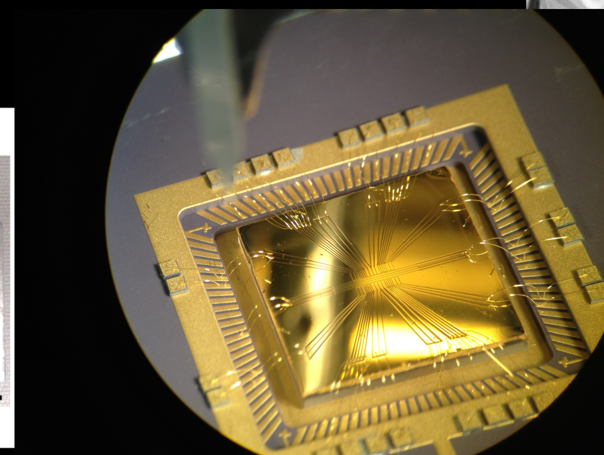


WELCOME!

Ian Shipsey, Oxford







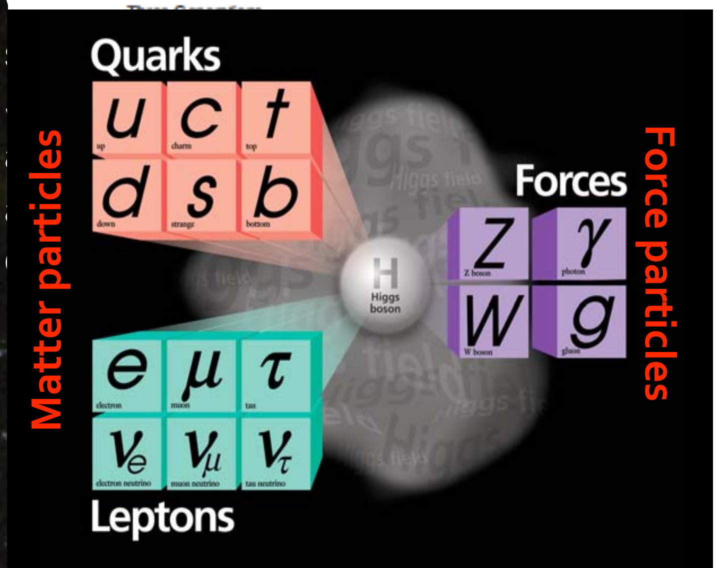
Initial Institutions: Birmingham Bristol Cambridge Edinburgh Glasgow Imperial Liverpool Manchester Oxford Sheffield Sussex UCL Warwick (+ many since)

Partners:

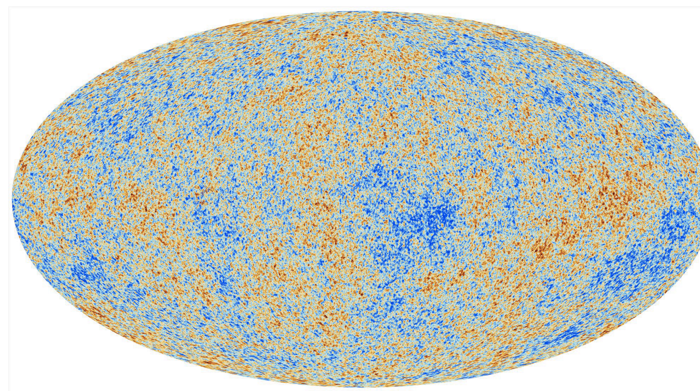
RAL Space | NPL National Physical Laboratory | ADMX | Argonne National Laboratory | Fermilab | SLAC

BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

- **PARTICLE STANDARD MODEL**



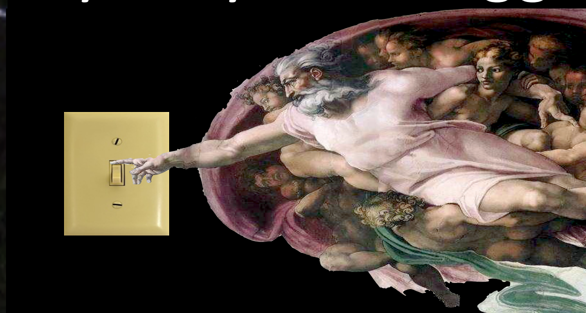
- **COSMOLOGY STANDARD MODEL**



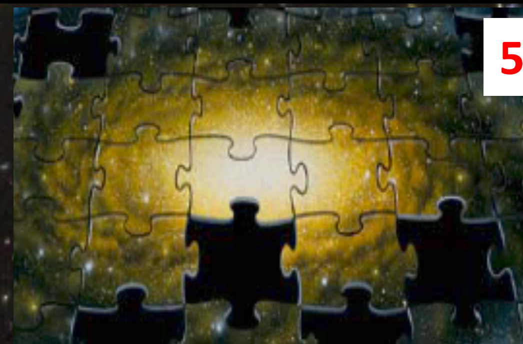
NASA, ESA, JPL-Caltech/B. Mobasher (STScI/ESA)

THE POTENTIAL NOW EXISTS TO REVOLUTIONIZE OUR KNOWLDEGE AGAIN

Mystery: The Higgs

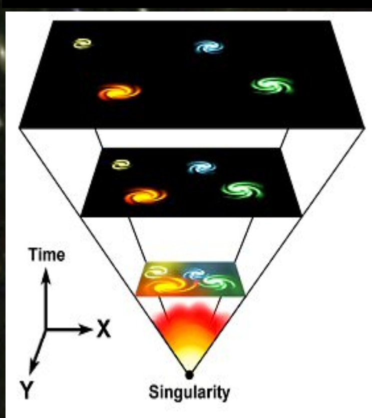


Mystery: Dark Matter



5/6

Mystery: Dark Energy



70% of the universe

Mystery: Why are there so many types of particles?

Mystery: how did matter survive the birth of the universe?

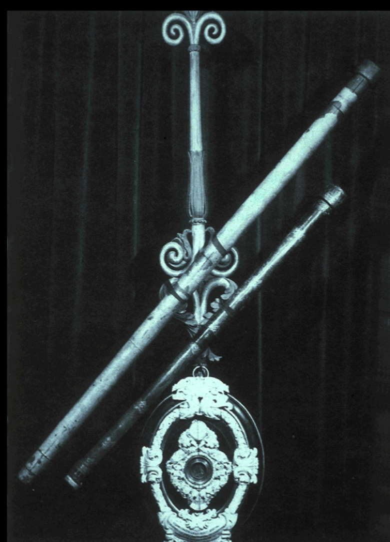
Mystery: What powered cosmic inflation?

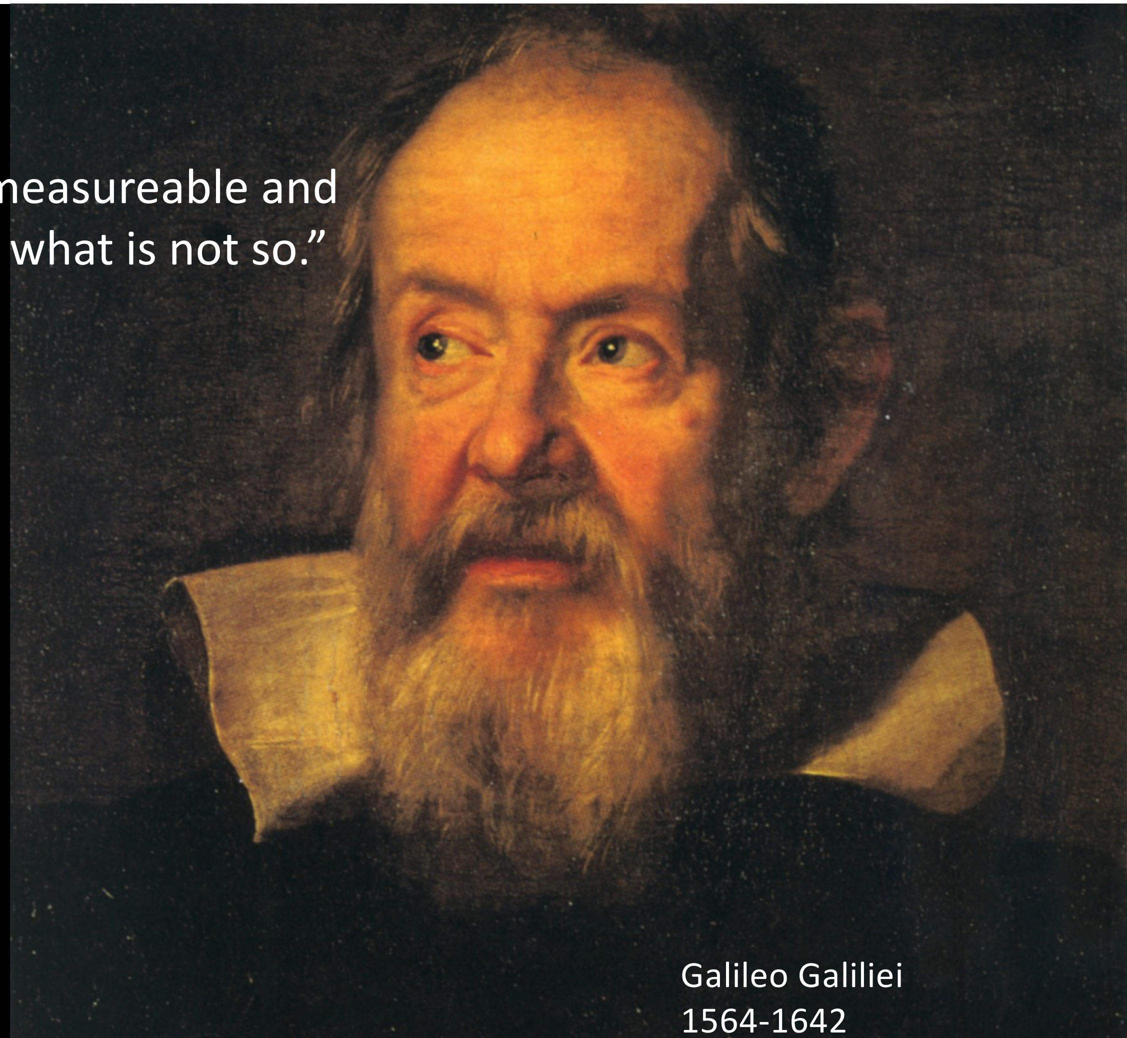
Mystery: What is gravity?

NASA, ESA, JPL-Caltech/B. Mobasher (STScI/ESA)

We are in a data driven era

“Measure what is measureable and make measureable what is not so.”





Galileo Galiliei
1564-1642

Accelerators

Telescopes & Satellites & interferometers

Multi-ton experiments deep underground

“Table Top” Experiments with Quantum Sensors

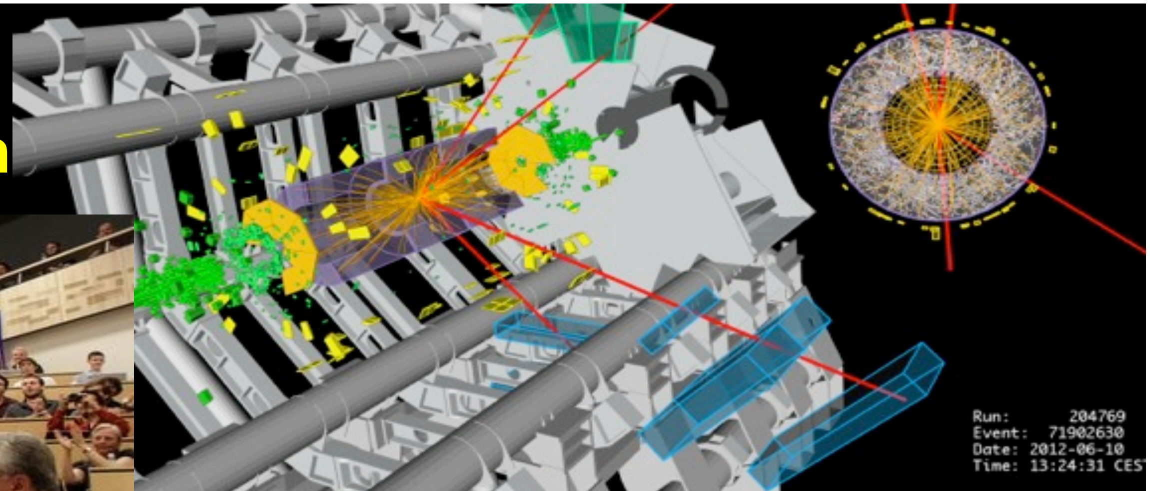
2012.7.4

discovery of Higgs boson

theory：1964

design：1984

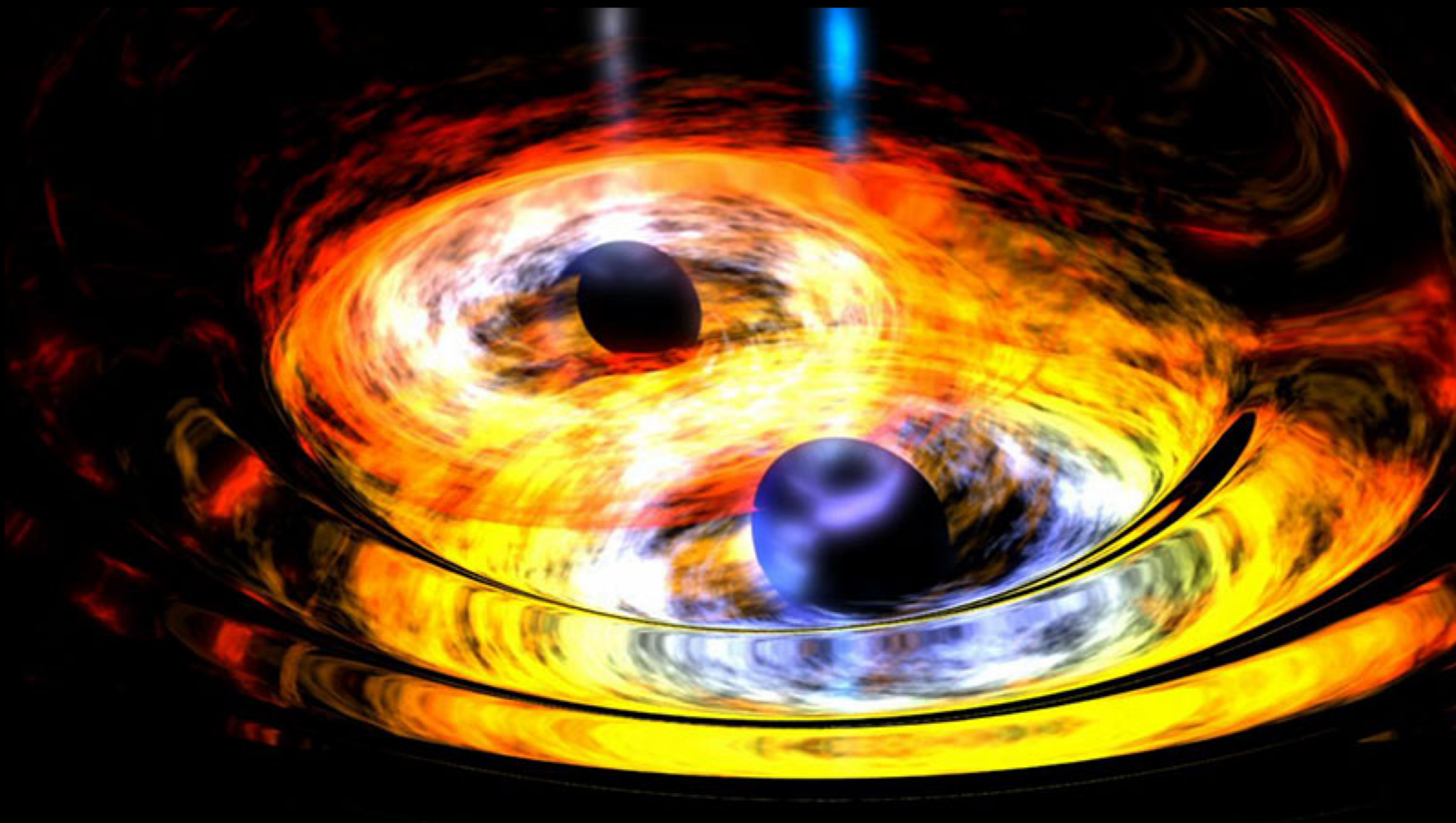
construction：1998



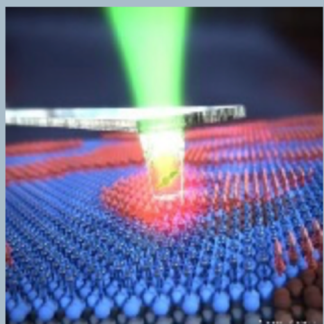
The Higgs enables atoms to exist

Murayama

The discovery of gravitational waves




Mystery: Dark Matter
The most likely next big discovery will be dark matter
5/6



Workshop on Quantum Sensing

12-14 December 2017
Argonne, Building 240
US/Central timezone

The US experience

Autumn 2017
no programme
in QSFP

https://indico.fnal.gov/event/ANLHEP1246/

Support

stezak@anl.gov

Registration is Closed

The Coordination Panel for Advanced Detector R&D of the American Physical Society Division of Particles and Fields is organizing a workshop on "**Quantum Sensing for High Energy Physics**" at Argonne National Laboratory on December 12–14, 2017.

The ultra-precise measurements of quantum phenomena offer opportunities to devise powerful new probes of nature relevant to the mission of particle physics. This workshop seeks to identify approaches and techniques in the domain of quantum sensing that can be utilized by future HEP applications to further the scientific goals of High Energy Physics as outlined by the P5 report. The workshop will have a one day pedagogical introduction to fundamental quantum principles and how they are harnessed in various technologies, followed by two days of in-depth exploration of intersections with and potential applications for particle physics. The conclusions of the workshop will be summarized in a white-paper report that will capture the opportunities.

Scientific Organizing Committee
Karl van Bibber (UCB)
Malcolm Boshier (LANL)
Marcel Demarteau (ANL, co-chair)
Matt Dietrich (ANL)
Maurice Garcia-Sciveres (LBNL)
Salman Habib (ANL)
Hannes Hubmayr (NIST)
Kent Irwin (Stanford)
Akito Kusaka (LBNL)
Joe Lykken (FNAL)
Mike Norman (ANL)
Raphael Pooser (ORNL)
Sergio Rescia (BNL)
Ian Shipsey (Oxford, co-chair)
Chris Tully (Princeton)

arXiv:1803.11306v1 [hep-ex]

Quantum Sensing
for
High Energy Physics

Report of the first workshop to identify approaches and techniques in the domain of quantum sensing that can be utilized by future High Energy Physics applications to further the scientific goals of High Energy Physics.

Organized by the Coordinating Panel for Advanced Detectors of the Division of Particles and Fields of the American Physical Society

March 27, 2018

Karl van Bibber (UCB), Malcolm Boshier (LANL), Marcel Demarteau (ANL, co-chair) Matt Dietrich (ANL), Maurice Garcia-Sciveres (LBNL) Salman Habib (ANL), Hannes Hubmayr (NIST), Kent Irwin (Stanford), Akito Kusaka (LBNL), Joe Lykken (FNAL), Mike Norman (ANL), Raphael Pooser (ORNL), Sergio Rescia (BNL), Ian Shipsey (Oxford, co-chair), Chris Tully (Princeton).

articulated the case for a US DOE Office of High Energy Physics funded quantum sensors programme

FYI
SCIENCE POLICY NEWS FROM AIP
Bulletin

Number 65: May 29, 2018

Science Committee Seeks to Launch a National Quantum Initiative

The House Science Committee plans to introduce a bill next month that would create a 10-year National Quantum Initiative aimed at increasing America's strategic focus on quantum information science and technology development.

Agencies already seeking to ramp up QIS spending

According to the 2016 NSTC report, the federal government was spending about $200 million per year on basic and applied research in QIS at that time. NSF and the DOE Office of Science are among the agencies that have since sought to increase their QIS spending. In their budget proposals for fiscal year 2019, NSF requested $30 million for a new "Quantum Leap" initiative and the Office of Science requested $105 million for QIS across five of its six major program areas. The office also allocated a portion of the large budget increase it received in fiscal year 2018 to QIS, as shown in the table below.

This program has now been created
Proposals have submitted and selected

Reports from workshops convened by the Office of Science to guide its investments are an indicator of the interest in QIS within these disciplinary communities. For instance, a workshop report published this March on potential applications of quantum sensors in high energy physics expresses confidence that a quantum sensor initiative could enable a *"new style"* of experiments that do not rely on large particle accelerators and *"dramatically reshape"* a significant portion of the field.

The Quantum Sensors for HEP awards https://science.energy.gov/~/media/78921BDAD1894BBF9A686A2125C3B3C0.ashx

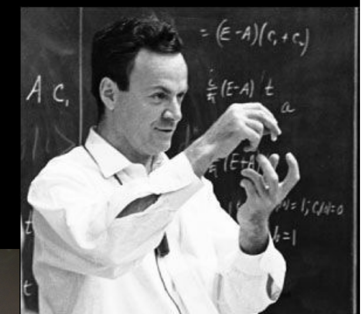
PI	Award Title	Institution	Institution Address
Spiropulo, Maria	Quantum Communication Channels for Fundamental Physics (QCCFP)	California Institute of Technology	Pasadena, CA
Kruczenski, Luis Martin	Quantum Information in a strongly interacting quantum simulator: from gauge/string theory duality to analogue black holes	Purdue University	West Lafayette, IN
Bousso, Raphael	The Geometry and Flow of Quantum Information: From Quantum Gravity to Quantum Technology	The Regents of University of California	Berkeley, CA
Walsworth, Ronald	Towards Directional Detection of WIMP Dark Matter using Spectroscopy of Quantum Defects in Diamond	Smithsonian Institute /Smithsonian Astrophysical Observatory	Cambridge, MA
Gadway, Bryce	Dipolar molecule emulator of lattice gauge theories: experiment and theory	Board of Trustees of the University of Illinois	Champaign, IL
Balantekin, Akif	Quantum-enhanced detection of dark matter and neutrinos	Board of Regents of the University of Wisconsin System, operating as University of Wisconsin-Madison	Madison, WI
Meurice, Yannick	Foundations of Quantum Computing for Gauge Theories and Quantum Gravity	University of Iowa	Iowa City, IA
Hubeny, Veronika	Entanglement in String Theory and the Emergence of Geometry	Regents of the University of California, Davis	Davis, CA
Berggren, Karl	Bosonic Dark Matter Search Using Superconducting Nanowire Single-Photon Detectors	Massachusetts Institute of Technology	Cambridge, MA
Sushkov, Alexander	Quantum system engineering for a next-generation search for axion dark matter	Trustees of Boston University	Boston, MA

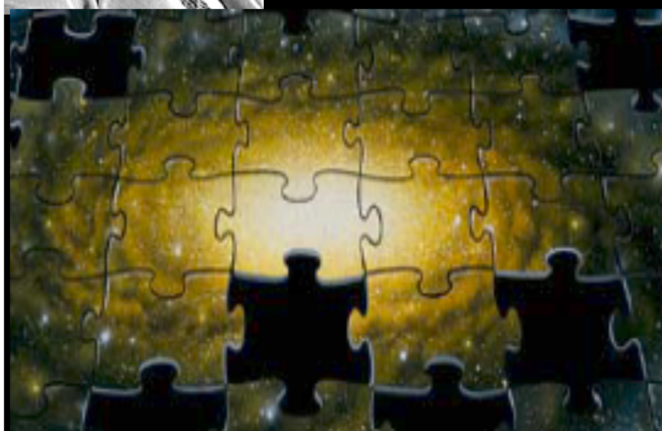
Ice, Lauren	Particle Track Pattern Recognition via Content-Addressable Memory and Adiabatic Quantum Optimization	The Johns Hopkins University	Baltimore, MD
Thaler, Jesse	Quantum Algorithms for Collider Physics	Massachusetts Institute of Technology	Cambridge, MA
Love, Peter	Towards practical quantum simulation for High Energy Physics	Tufts University	Boston, MA
Harlow, Daniel	Algebraic Approach Toward Quantum Information in Quantum Field Theory and Holography	Massachusetts Institute of Technology	Cambridge, MA
Spiropulo, Maria	Quantum Machine Learning and Quantum Computation Frameworks for HEP (QMLQCF)	California Institute of Technology	Pasadena, CA
		National Lab Awards	
Garcia-Sciveres, Maurice	Quantum Sensors HEP-QIS Consortium	Lawrence Berkeley National Lab	Berkeley, CA
Siddiqi, Irfan	FPGA-based quantum control for HEP simulations with qutrits	Lawrence Berkeley National Lab	Berkeley, CA
Bauer, Christian	Unravelling the quantum structure of QCD in parton shower Monte Carlo generators	Lawrence Berkeley National Lab	Berkeley, CA
Gray, Heather	Quantum Pattern Recognition for High Energy Physics	Lawrence Berkeley National Lab	Berkeley, CA
Irwin, Kent	Quantum Sensors for Light-Field Dark Matter Searches	SLAC NATIONAL ACCELERATOR LABORATORY	Menlo Park,CA
Irwin, Kent	The Dark Matter Radio: A Quantum-Enhanced Dark Matter Search	SLAC NATIONAL ACCELERATOR LABORATORY	Menlo Park,CA

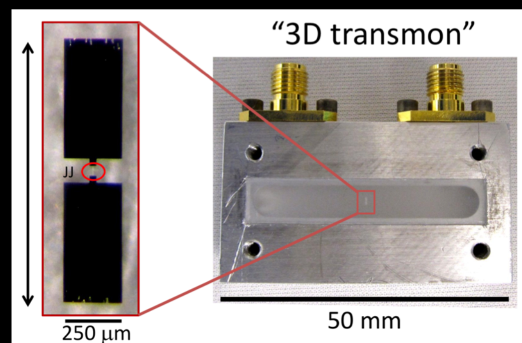
Schleier-Smith, Monika	Holographic Quantum Simulation with Atomic Spins and Photons	SLAC NATIONAL ACCELERATOR LABORATORY	Menlo Park,CA
Chou, Aaron	Quantum Metrology Techniques for Axion Dark Matter Detection	Fermilab	Batavia IL
Carena, Marcela	Quantum Information Science for Applied Quantum Field Theory	Fermilab	Batavia IL
Romanenko, Alexander	Ultra-High Q Superconducting Accelerator Cavities for Orders of Magnitude Improvement in Qubit Coherence Times and Dark Sector Searches	Fermilab	Batavia IL
Estrada, Juan	Skipper-CCD: new single photon sensor for quantum imaging	Fermilab	Batavia IL
Perdue, Gabriel	HEP ML and Optimization Go Quantu/Quantum Machine Learning and Optimization	Fermilab	Batavia IL
Habib, Salman	Quantum-Enhanced Metrology with Trapped Ions for Fundamental Physics	Argonne National Laboratory	Lemont, IL
Demarteau, Marcellinus	Search for bosonic Dark Matter using Magnetic Tunnel Junction Arrays	Argonne National Laboratory	Lemont, IL
Bhattacharya, Tanmoy	Quantum Computing for Quantum Field Theories and Chiral Fermions	Los Alamos National Laboratory	Los Alamos, NM
Gupta, Rajan	Quantum Computing for Neutrino-Nucleus Dynamics	Los Alamos National Laboratory	Los Alamos, NM
Yoon, Boram	Quantum Machine Learning Enhancing Lattice QCD Calculations of Matrix Elements for Beyond the Standard Model Physics Search	Los Alamos National Laboratory	Los Alamos, NM
Sornborger, Andrew	Disentangling Quantum Entanglement: A Machine Learning Approach to Decoherence, Quantum Error Correction, and Phase Transition Dynamics	Los Alamos National Laboratory	Los Alamos, NM
		National Labs - Collaborative Awards	
Siddiqi, Irfan	The Geometry and Flow of Quantum Information: From Quantum Gravity to Quantum Technology	Lawrence Berkeley National Lab	Berkeley, CA

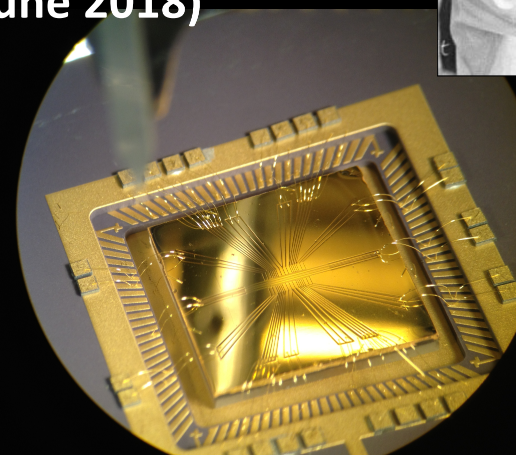
These are multi-year awards, year 1 $15M

The UK timeline
Quantum Sensors for Fundamental Physics staging proposal to STFC Opportunities Call
Targeting UKRI Strategic Priorities Funding (June 2018)









Initial Institutions: Birmingham Bristol Cambridge Edinburgh Glasgow Imperial Liverpool Manchester Oxford Sheffield Sussex UCL Warwick (+ many since)

Partners:

RAL Space, NPL National Physical Laboratory, ADMX, Argonne National Laboratory, Fermilab, SLAC

Submission of staging proposal to STFC Opportunities Call June 2018 Principal Investigators (45)

Birmingham: Newman QCD / DIS / Forward instrumentation. **Nikolopoulos** Light Dark Matter / Higgs
Bristol: Goldstein Collider physics/instrumentation. **Velthuis** Instrumentation.
Cambridge: Withington Quantum sensors. **Gibson** Flavour physics.
Edinburgh: Muheim Flavour physics, instrumentation. **Murphy** Dark matter, nuclear physics.
Glasgow: Buttar Energy Frontier. **Doyle** Energy Frontier. **Eklund** Flavour Physics. **Hammond** Quantum enhanced gravity sensors. **O'Shea** Quantum Sensors.
Imperial: Araujo Dark Matter/Instruments. **Buchmueller** Energy frontier/BSM/DarkMatter. **Hall** Energy frontier/Instruments. **Hassard** Instruments/Technology Transfer. **Sauer and Tarbutt** EDM/Atom Interferometry/ultracold. **Vacheret** Neutrino/DarkMatter/Instruments. **Vanner** Quan. Optomechanics.
Liverpool: Coleman Atom Interferometry. **Bowcock** EDMs/instrumentation/Quantum Foam. **Burdin** Dark Matter. **Rompotis** Muons/Relic neutrinos.
NPL*: Gill Ultra-stable lasers & optical clocks. **Green** Space & Earth observation. **Hao** SQUIDS & microwave cryo-resonators. **Lewis** Quantum sensor technology.
Manchester: Lancaster Precision muon physics.
Oxford: Bortoletto Higgs/BSM/instrumentation. **Konoplev** Adv. acceleration techniques. **Kraus** Dark Matter. **March-Russell and Randall $** BSM Theory. **Shipsey** Higgs/muons/dark energy/instruments.
Sheffield & ADMX: Daw Axions/ other dark sector searches. **Ryaka** * (ADMX Collaboration & U. Wash.)
Sussex: Calmet Gravity/Cosmology/Foundations. **Dunningham** Interferometry in curved spacetime. **Griffith** EDM, magnetic sensors. **Keller** e/p mass ratio & quantum technology.
UCL: Flack Tests of quantum mechanics. **Ghag** Dark Matter. **Hesketh** Precision Muon Physics. **Nichol** Neutrinos osc. & astrophysical. **Saakyan** $0\beta\beta\nu$ /proton therapy. **Waters** $0\beta\beta\nu$.
Warwick: Barker Neutrino oscillation physics. **Datta** Quant. sensors for DM/gravity waves/testing macroscopic QM. **Morley** Dev. Quant. sensors/tests of quant. gravity**. Ramachers** $0\beta\beta\nu$ detector dev.

Additional PIs since ~140 @ this meeting (open to all)

Quantum Sensors for Fundamental Physics

- Targets SPF Funding cross-council interdisciplinary
- Builds a community (AMO CMP QIS Particle Cosmology Astro
- Focus on the science
- Partner with leading QIS expertise (EPSRC community)
- Exploit existing STFC expertise and infrastructure
- Enable the larger STFC community to engage with QIS
- Collaborative R&D funding streams
- Opportunities to attract and train young scientist in a multidisciplinary area

FUNDED

BEECROFT LOW VIBRATION LABORATORIES
(EXAMPLE OF EXISTING RESOURCE)

1ST DILUTION REFRIGERTATOR (SC QUBITS)

the programme we envisage will support experiments at various UK and international sites

Quantum Sensors for Fundamental Physics

Why is this good for all the partners?

The exciting science will benefit all the partners involved: universities, labs & hubs

Leverage the current Hubs to bring state of the art sensors to this new application.

There will likely be a tension between performance and "manufacturability" but the Phase II Hubs should be able to deliver research to push performance, and additional support for user communities from STFC that could feed into and benefit from the Hubs activity

Why is this good match to the SPF?

This would be a genuinely new partnership between STFC EPSRC and other partners
- so plays well to the UKRI era.

Quantum Sensors for Fundamental Physics
Statement to UKRI Executive Board 9/2018

Quantum Sensors for Fundamental Physics

Over the past five years thanks to the investment in the national Quantum programme rapid advances have been made in quantum technology, computing and metrology in the UK. These tools are now at a stage which could allow them to be used, and further developed, in fundamental science. Despite the potential, quantum sensing methods are not currently widely used in research in fundamental physics undertaken in the STFC and EPSRC communities. Several targets for exploration exist including the search for dark matter, gravitational wave research, tests of gravity, searches for a possible time variation in the fundamental constants of nature, test of fundamental symmetries with greatly improved sensitivity, many-body physics, and other areas.

Quantum Sensors for Fundamental Physics
Statement to UKRI Executive Board 9/2018

This SPF activity would bring together the STFC and EPSRC communities to tackle these challenges and provide the opportunity to utilise these new methods. This work will be inherently interdisciplinary combining the UKs world leading physics community with the equally ground breaking quantum information scientists. This programme will align to the governments science priorities as this exciting area of research would allow for the creation of a programme capable of attracting the globally best creative, original, young experimentalists and theorists. In addition this would allow the UK to retain its position as a partner of choice in this area.

The programme will deliver:

- Collaborative R&D funding streams
- Opportunities to attract and train young scientist in a multidisciplinary area

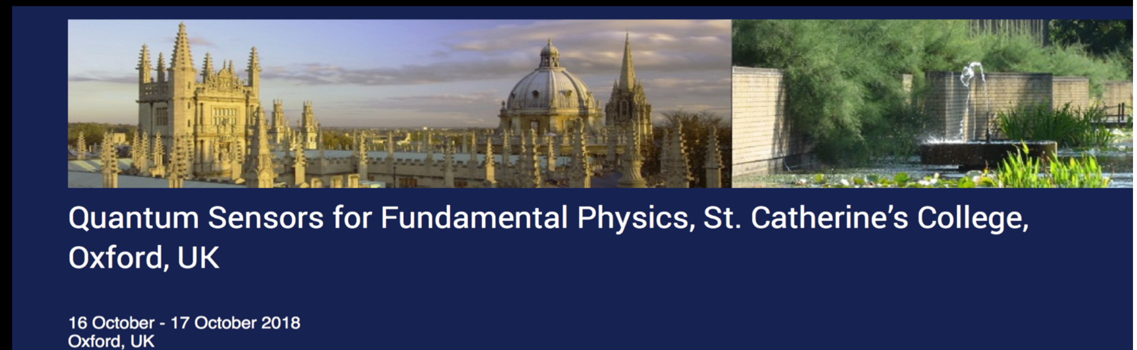
Quantum Sensors for Fundamental Physics and Society- Next Steps

The expected timeline is that the submission into SPF wave 2 will be made by STFC/EPSRC in mid-December. This will request the funding to create the QSFP programme.

If the SPF bid is successful in gaining the funding for a QSFP programme it will commence from the 2nd or 3rd quarter of 2019.

The community will bid into this programme

Quantum Sensors for Fundamental Physics and Society- Next Steps



The workshop has four goals

#1 To survey the extraordinary science opportunities and UK capabilities to exploit this science in a world-class programme

#2 To demonstrate to UKRI the immense interest in the UK in QSFP

#3 To begin to form teams around key experiments that would be funded by QSFP

#4 To work with STFC and EPSRC on the QSFP bid. On Day 2 there will be an overview of the Quantum Programme by Liam Blackwell (EPSRC) and the Strategic Priorities Fund by Jason Green (STFC) and the questions will be introduced that need answers for the bid. Then at the end of the day there will be a Town Hall with an opportunity to help formulate answers.

Summary

In the US the QSFP interface area acts as a major attractor for creative, original young experimentalists and theorists. We believe this will be true in the UK as well. The programme will be world-leading, and highly complementary to the US programme and those of other nations

In this competitive area it is important to quickly develop the community that can launch the proposed programme. To do this expeditiously it will build on expertise, selected existing activities within the UK and exploitation of existing resources.

As the EPSRC, STFC and Space communities come together we anticipate entirely new and exciting science will emerge.

Instrumentation: The Great Enabler

"New directions in science are launched by new tools much more often than by new concepts.

The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained"

Freeman Dyson