UK Research
and Innovation

QT
FP

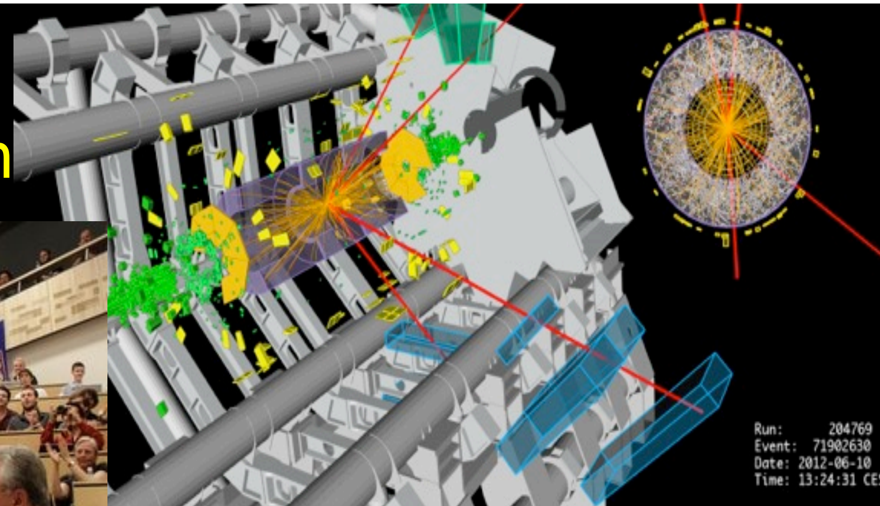
Quantum Technologies for Fundamental Physics

The Science & The Quantum Technologies Landscape

Ian Shipsey

2012.7.4

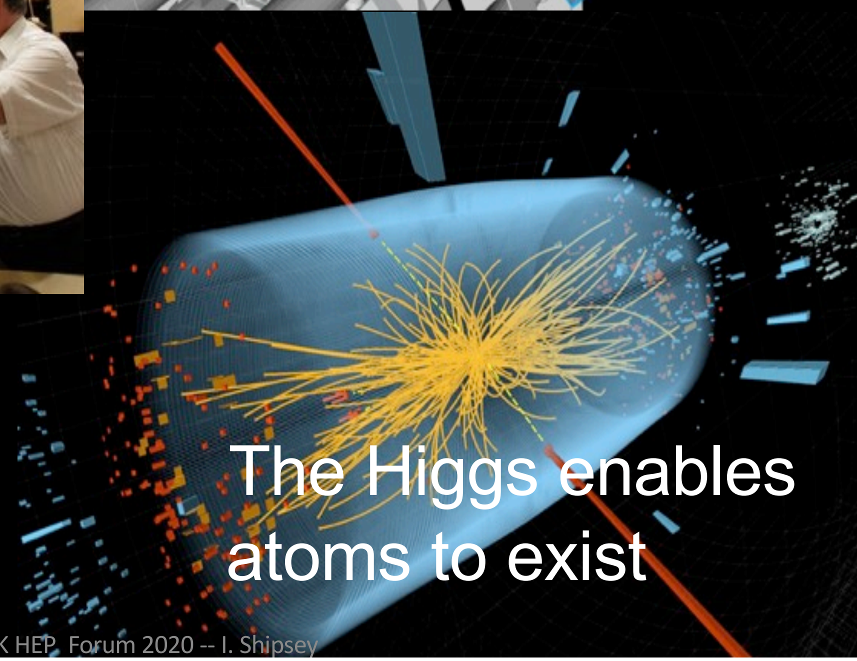
discovery of Higgs boson



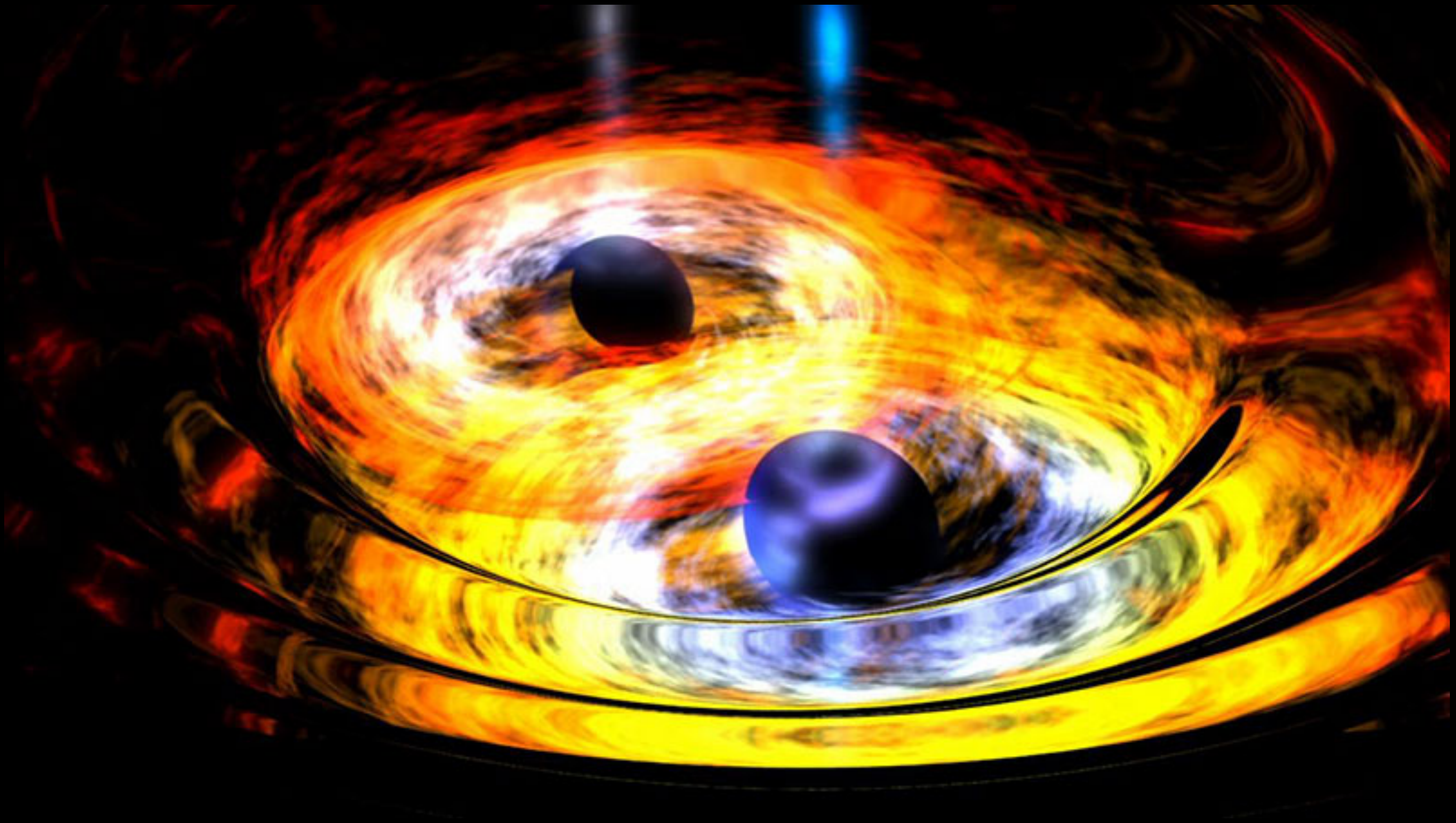
theory：1964

design：1984

construction：1998



Detection of gravitational waves
LIGO February, 2016



Opportunities for Discovery

Many mysteries to date go unanswered including:

The mystery of the Higgs boson

The mystery of Neutrinos

The mystery of Dark Matter

They mystery of Dark Energy

The mystery of quarks and charged leptons

The mystery of Matter – anti-Matter asymmetry

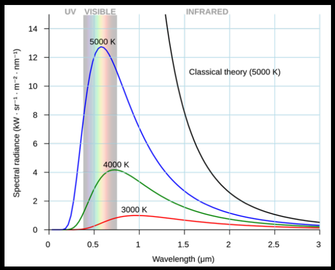
The mystery of the Hierarchy Problem

The mystery of the Families of Particles

The mystery of Inflation

The mystery of Gravity

Quantum 1.0



Blackbody Radiation

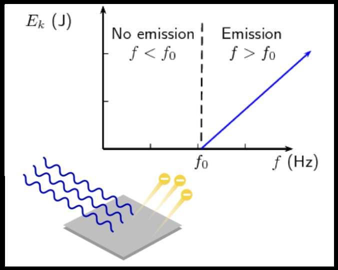
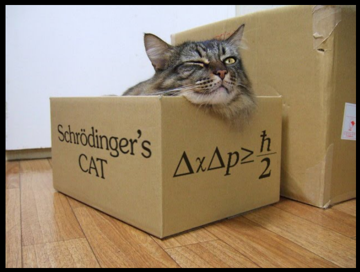
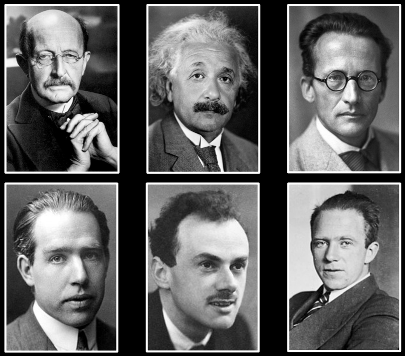


Photo-electric Effect



Quantum Mechanics



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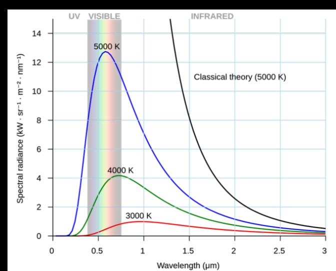

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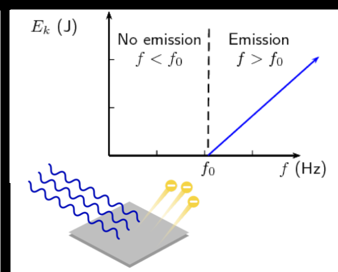

Photo-electric Effect

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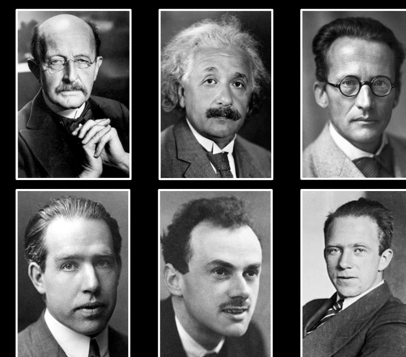
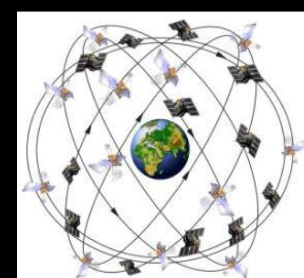


Exascale Computing

Laser Technology

Magnetic Resonance Imaging



Global Positioning System

Quantum 2.0

- There is a growing realization that we are at the dawn of the Second Quantum Revolution.
- **First Quantum Revolution**: exploitation of the quantum nature of matter to build devices
- **Second Quantum Revolution**: engineering of large quantum systems;
  control of full quantum system at the individual level

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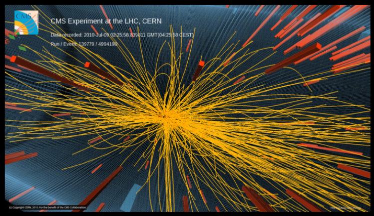
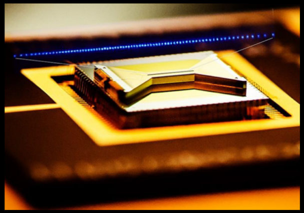
AI, ML on Quantum annealer



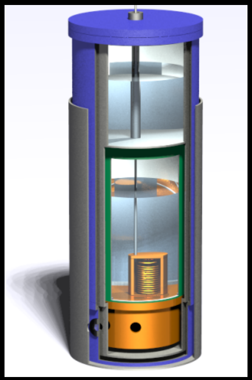
Nature 550 (2017) 375

IonQ >60-qubit



arXiv:1902.10171

Atomic clocks



Nature (564) 87 (2018)

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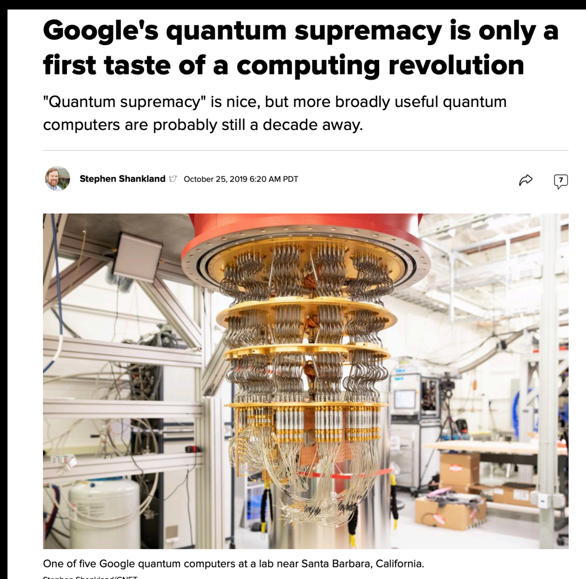


Google's quantum supremacy is only a first taste of a computing revolution

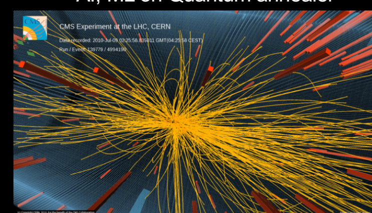
"Quantum supremacy" is nice, but more broadly useful quantum computers are probably still a decade away.

Stephen Shankland October 25, 2019 6:20 AM PDT

One of five Google quantum computers at a lab near Santa Barbara, California.

Stephen Shankland/CNET

AI, ML on Quantum annealer



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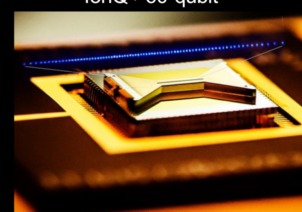

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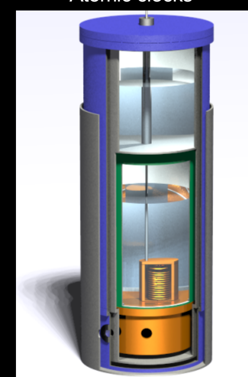


Nature (564) 87 (2018)

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

You can approximate nature with a simulation on a classical computer, but Feynman wanted a quantum computer that offers the real thing, a computer that "will do exactly the same as nature,"

What if?

Quantum Internet

Quantum Artificial Neural Network

Quantum Liquid Crystals

Quantum Mind Interface

Quantum enabled searches for dark matter

Quantum Gravity

The Confluence

Quantum technologies offer new ways to look at the universe

The Confluence

Particle Physics has many
unanswered questions

The Confluence

A perfect match

Building a science case: essential for creation of QTFP

The Confluence

A perfect match at a perfect time!

Building a science case: essential for creation of QTFP

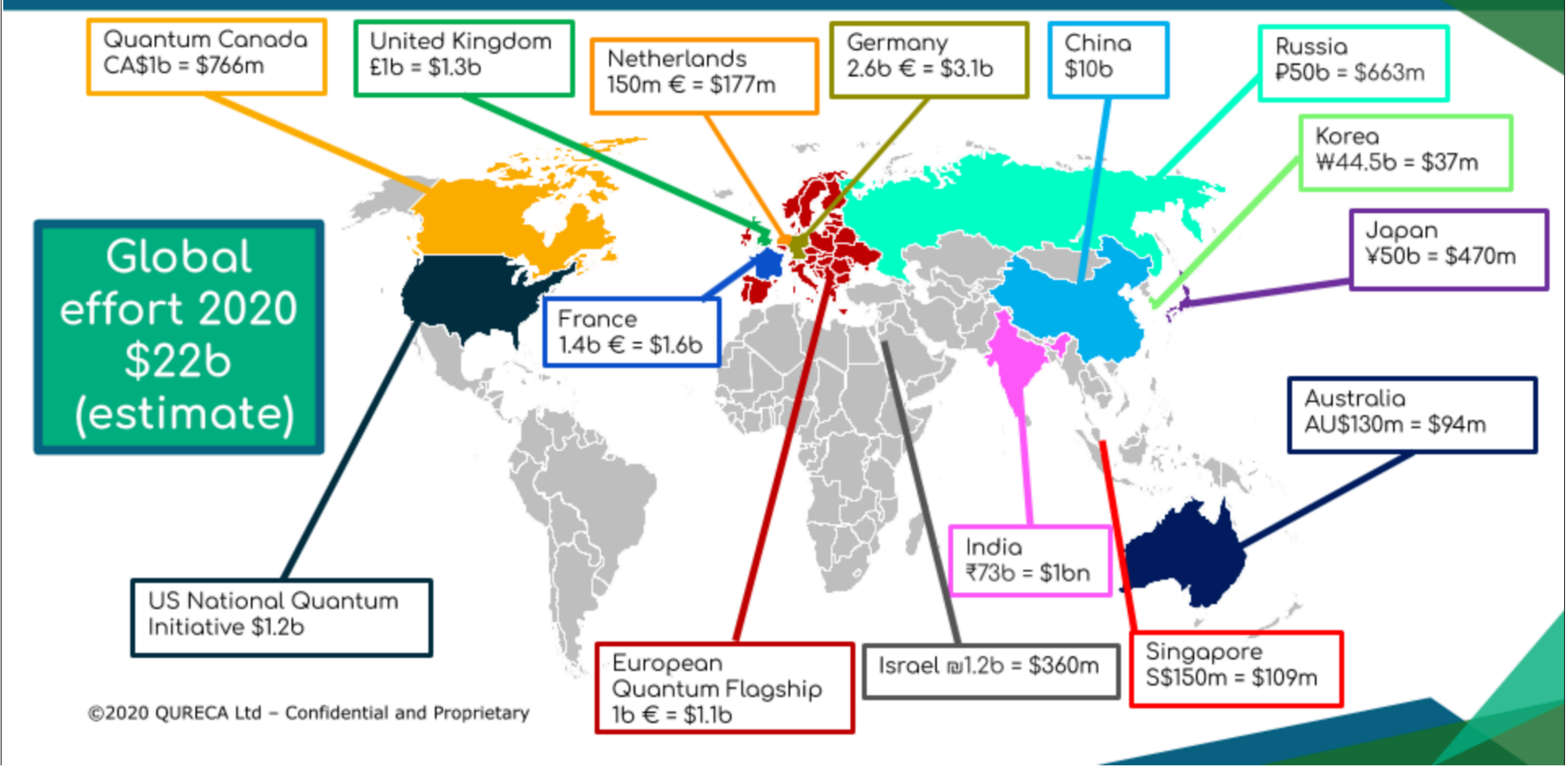
More on the science case later in this talk

Building a community: essential for creation of QTFP

Quantum Sensors for Fundamental Physics Community Workshop October 2018 Oxford
>140 from EPSRC & STFC in attendance

More on community later in this talk

Quantum Technologies Public Funding Worldwide



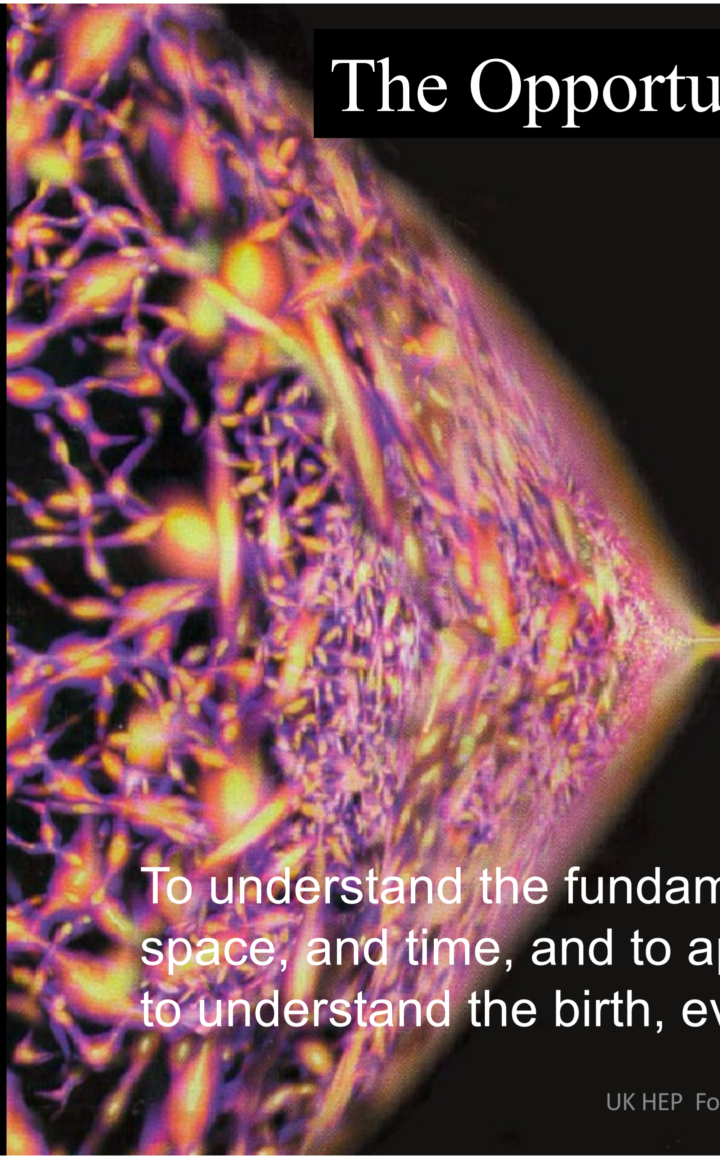
UK National Quantum Technology Program (NQTP)

- *Phase 1 2015-2019, Phase 2 2020-24 (total investment Phase 1+2= £1B)*
- *Phase 2 investments:*
  - *Industry led projects to drive innovation and commercialisation of QT (£173m over 6 years)*
  - Renewal of the QT Research Hubs (£94m over 5 years)
  - Research training portfolio (£25m over 5 years)
  - Quantum Sensors for Fundamental Physics programme (£40m over 4 years)
  - National Quantum Computing Centre to drive development in this new technology and place us at the forefront of this field (£77m over 5 years)

NQTP essential for creation of QTFP

More on NQTP later in this talk

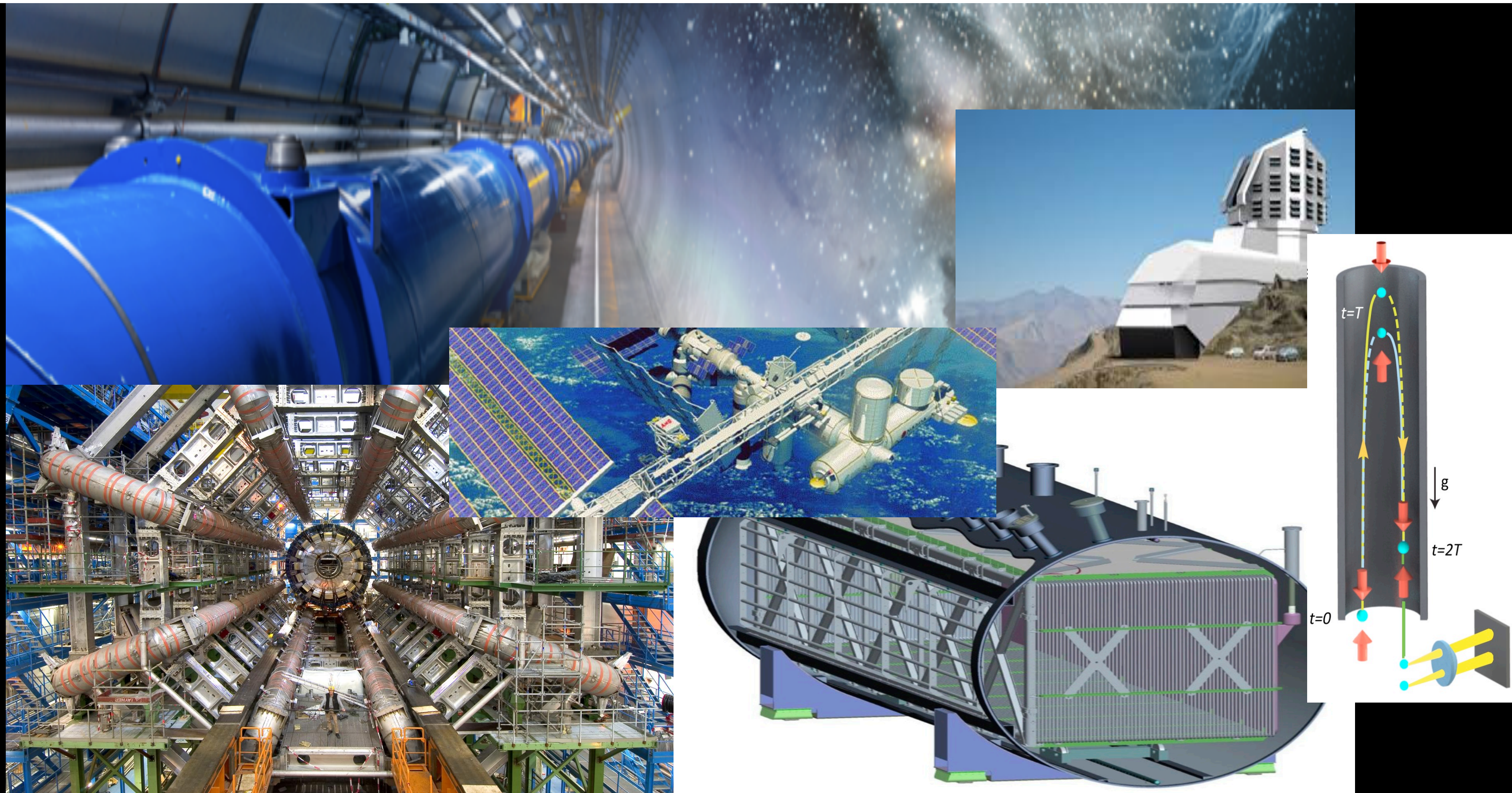
The Opportunities for Discovery



To understand the fundamental nature of energy, matter, space, and time, and to apply that knowledge to understand the birth, evolution and fate of the universe

The Opportunities for Discovery

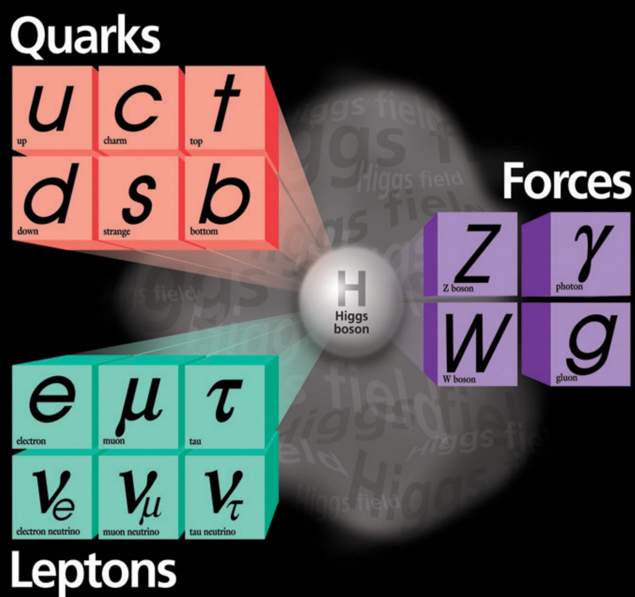
To understand the fundamental nature of energy, matter, space, and time, and to apply that knowledge to understand the birth, evolution and fate of the universe



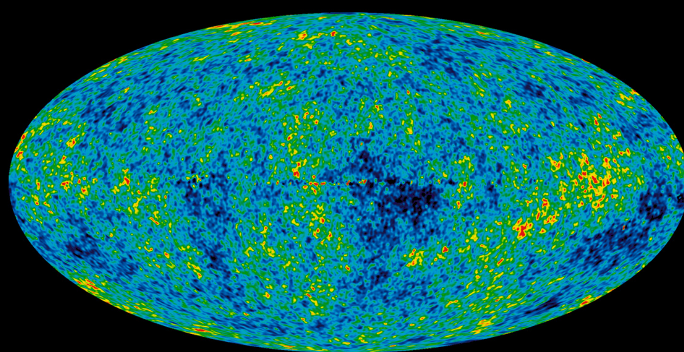
Our scope is broad and we use many tools: accelerator, non-accelerator & cosmological observation*s* all have a critical role to play

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

Particle Standard Model



Cosmology Standard Model



Λ_{CDM}

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

…..that are highly predictive and have been rigorously tested in some cases to 1 part in 10 billion

Quantity	Value	Standard Model	Pull	Dev.
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1	0.0
Γ_Z [GeV]	2.4952 ± 0.0023	2.4961 ± 0.0010	−0.4	−0.2
$\Gamma(\mathrm{had})$ [GeV]	1.7444 ± 0.0020	1.7426 ± 0.0010	—	—
$\Gamma(\mathrm{inv})$ [MeV]	499.0 ± 1.5	501.69 ± 0.06	—	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	84.005 ± 0.015	—	—
σ_{had}[nb]	41.541 ± 0.037	41.477 ± 0.009	1.7	1.7
R_e	20.804 ± 0.050	20.744 ± 0.011	1.2	1.3
R_μ	20.785 ± 0.033	20.744 ± 0.011	1.2	1.3
R_τ	20.764 ± 0.045	20.789 ± 0.011	−0.6	−0.5
R_b	0.21629 ± 0.00066	0.21576 ± 0.00004	0.8	0.8
R_c	0.1721 ± 0.0030	0.17227 ± 0.00004	−0.1	−0.1
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01633 ± 0.00021	−0.7	−0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.4	0.6
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5	1.6
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1034 ± 0.0007	−2.6	−2.3
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0739 ± 0.0005	−0.9	−0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1035 ± 0.0007	−0.5	−0.5
$\bar{s}_\ell^2(A_{FB}^{(0,q)})$	0.2324 ± 0.0012	0.23146 ± 0.00012	0.8	0.7
	0.23200 ± 0.00076		0.7	0.6
	0.2287 ± 0.0032		−0.9	−0.9
A_e	0.15138 ± 0.00216	0.1475 ± 0.0010	1.8	2.1
	0.1544 ± 0.0060		1.1	1.3
	0.1498 ± 0.0049		0.5	0.6
A_μ	0.142 ± 0.015		−0.4	−0.3
A_τ	0.136 ± 0.015		−0.8	−0.7
	0.1439 ± 0.0043		−0.8	−0.7
A_b	0.923 ± 0.020	0.9348 ± 0.0001	−0.6	−0.6
A_c	0.670 ± 0.027	0.6680 ± 0.0004	0.1	0.1
A_s	0.895 ± 0.091	0.9357 ± 0.0001	−0.4	− 0.4

Quantity	Value	Standard Model	Pull	Dev.
m_t [GeV]	173.4 ± 1.0	173.5 ± 1.0	−0.1	−0.3
M_W [GeV]	80.420 ± 0.031	80.381 ± 0.014	1.2	1.6
	80.376 ± 0.033		−0.2	0.2
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0398 ± 0.0003	0.0	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064 ± 0.0001	0.0	0.0
$Q_W(e)$	-0.0403 ± 0.0053	-0.0474 ± 0.0005	1.3	1.3
$Q_W(\mathrm{Cs})$	-73.20 ± 0.35	-73.23 ± 0.02	0.1	0.1
$Q_W(\mathrm{Tl})$	-116.4 ± 3.6	-116.88 ± 0.03	0.1	0.1
τ_τ [fs]	291.13 ± 0.43	290.75 ± 2.51	0.1	0.1
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	$(4511.07 \pm 0.77) \times 10^{-9}$	$(4508.70 \pm 0.09) \times 10^{-9}$	3.0	3.0

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

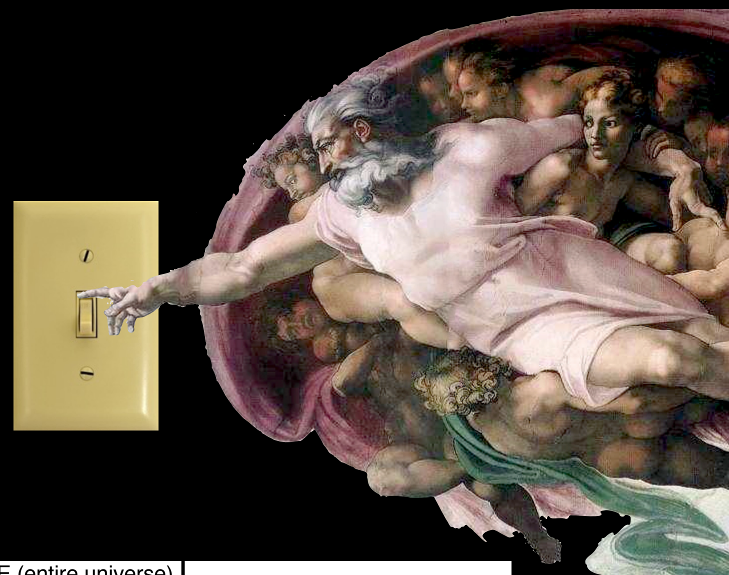
BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

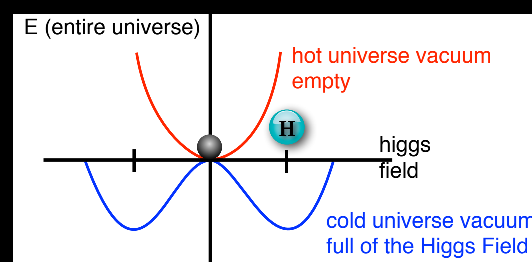
- The potential exists now to revolutionize our knowledge again.
- Despite the huge successes, there are deep and fundamental mysteries that are unanswered and for which following traditional methods of exploration and new quantum sensing methods combine to form the optimal approach.

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

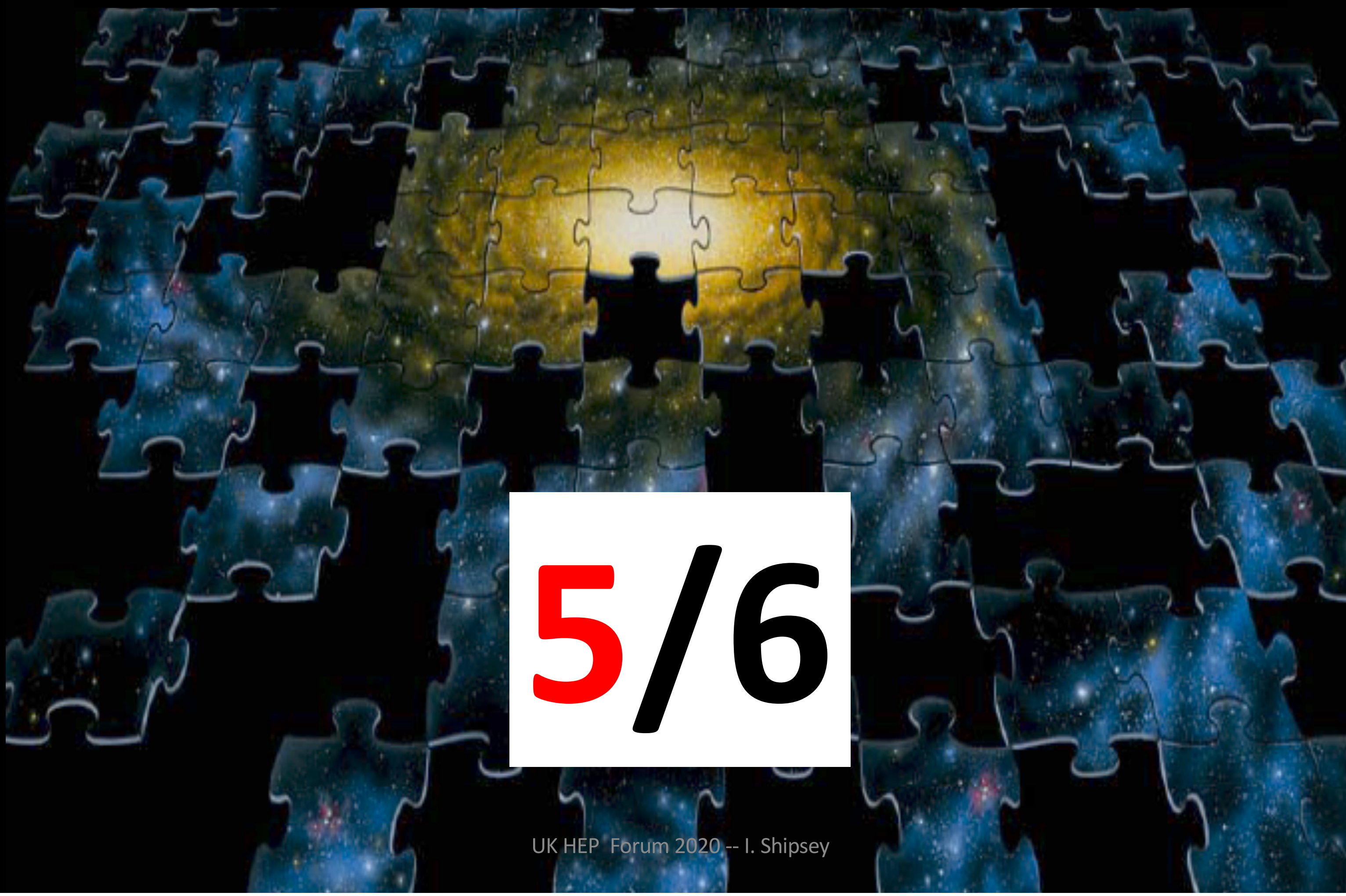
Mystery: The Higgs

That Spin 0 Boson
Changes Everything

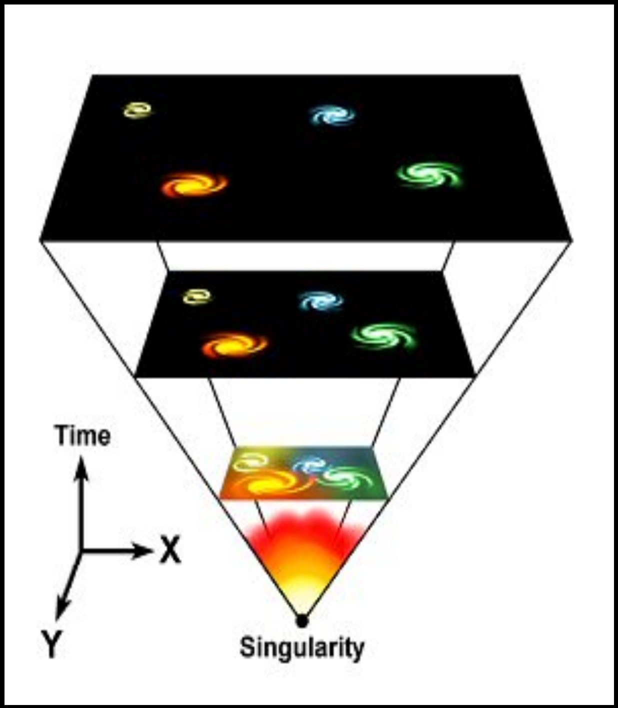




Mystery: Dark Matter



Mystery: Dark Energy



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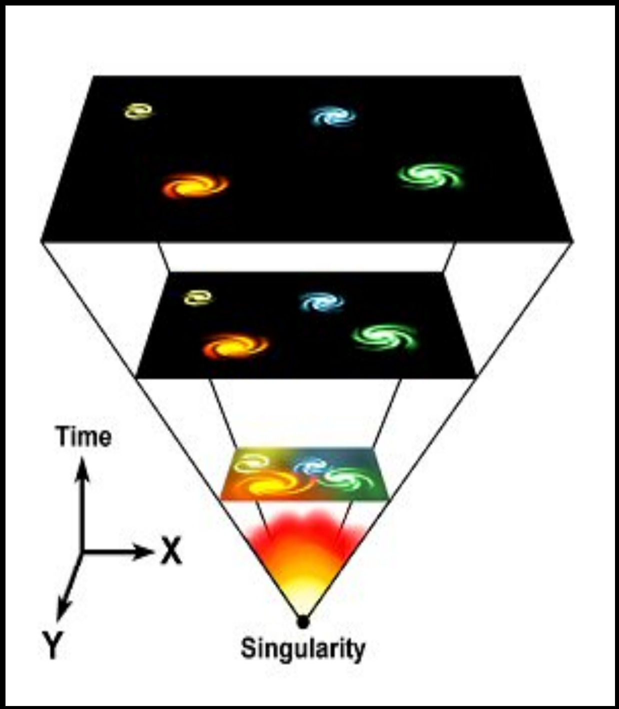


What we know: just the tip of the iceberg.

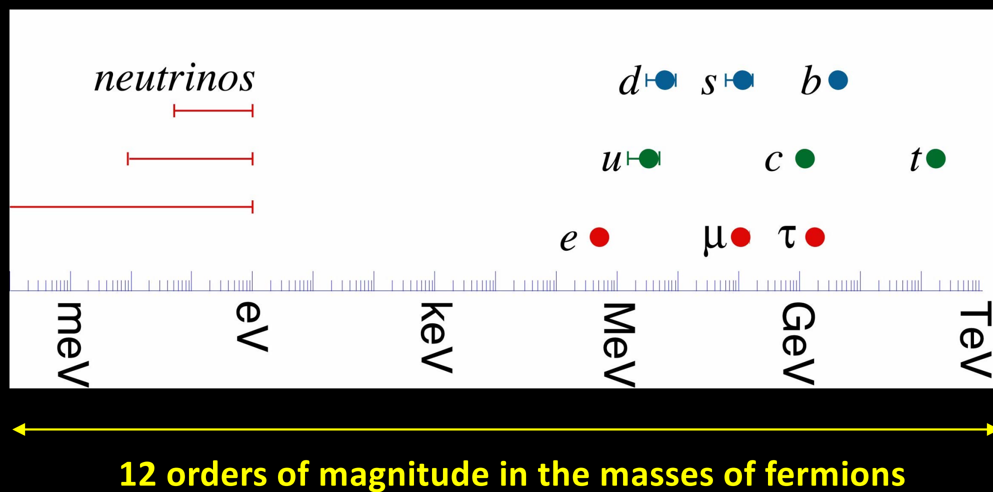
Mystery: how did matter survive the birth of the universe?

Matter	anti-Matter
1,000,000,001	1,000,000,000

The baryon asymmetry of the Universe

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

Mystery: Why are there so many types of particles?

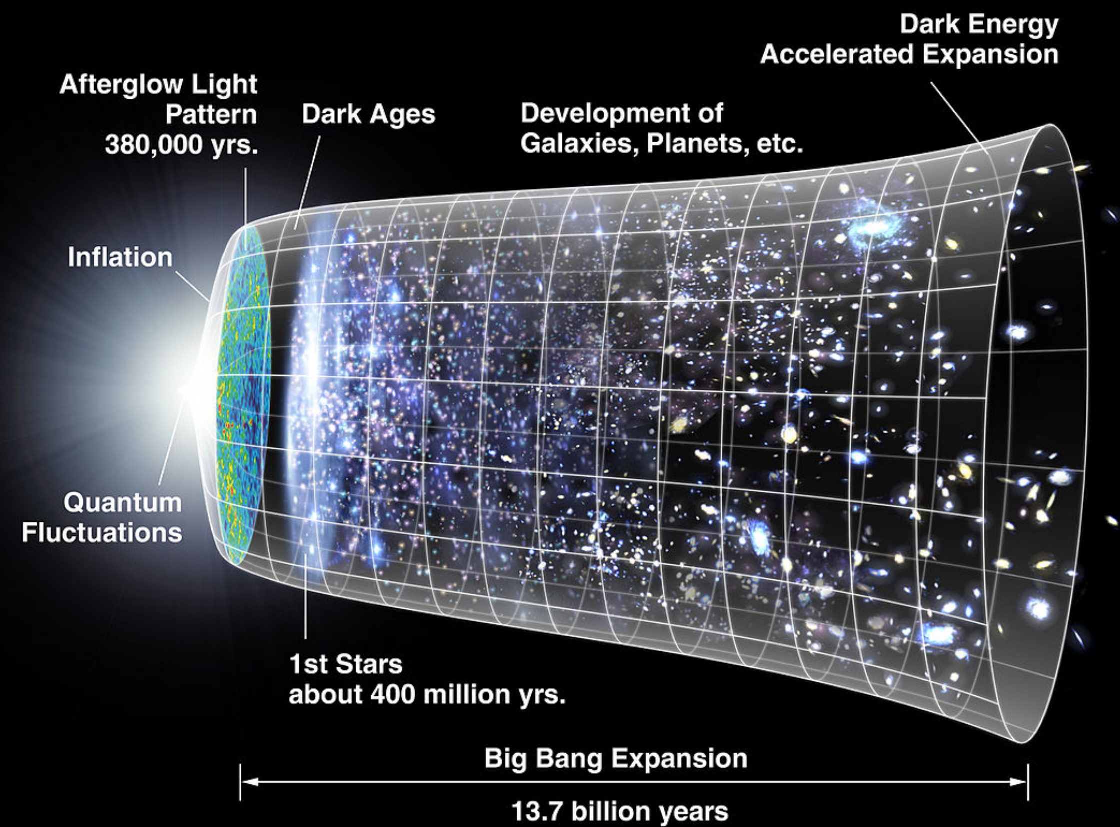


Why do the particles have such a large range of masses?

Why does the pattern of particles repeat three times?

Why do neutrinos have mass at all (in the Standard Model they are massless)?

Mystery: What powered cosmic inflation?



Based on an original slide by F. Gianotti

Outstanding Questions in Particle Physics *circa* 2011

EWSB
- ❑ Does the Higgs boson exist?

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 ?

Based on an original slide by F. Gianotti

Outstanding Questions in Particle Physics *circa* 2020

… there has never been a better time to be a particle physicist!

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

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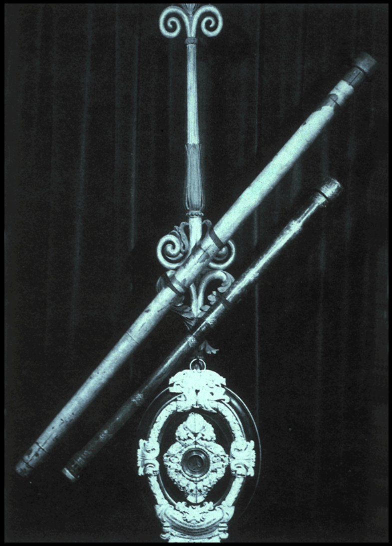
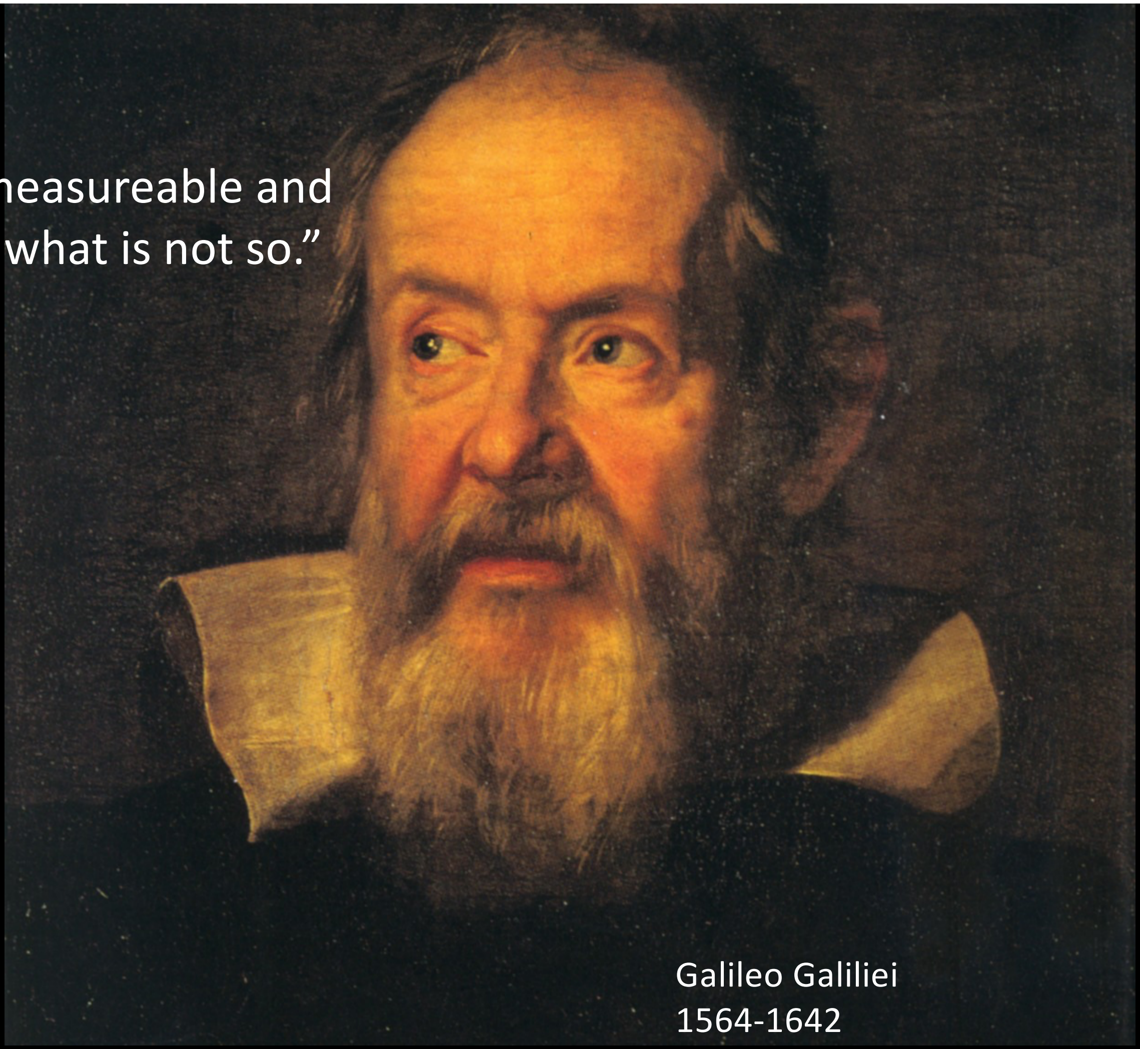
We are in a data driven era

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





Galileo Galiliei
1564-1642

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

precision instruments are key to discovery when exploring new territory

Science progresses by experimentation, observation, and theory

Nobody would have predicted that slight irregularities
in black body radiation would have led to an entirely
new conception of the world in terms of quantum theory

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That pondering the constancy of the speed of light would have led to $E= mc^2$

That special relativity and quantum mechanics would have led to anti-matter

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That pondering the constancy of the speed of light would have led to $E= mc^2$

That special relativity and quantum mechanics would have led to anti-matter

Experiments that explore uncharted territory, or study phenomena we do not understand with greater precision, lead to a deeper understanding of nature, the global particle physics program (& science generally) does that.

A special time in particle physics

After the establishment of quantum mechanics and general relativity
The next ~90 years have been spent exploring the consequences

Now in the last several years we have entered an era without no-lose theorems (i.e. the Standard Model could be consistent up to the Planck Scale) an era that is data driven, similar to 1850 before Planck had interpreted the black body radiation, and Einstein had formulated Special and General Relativity

Discoveries in particle physics

Based on an original slide by S.C.C. Ting

Facility	Original purpose, Expert Opinion	Discovery with Precision Instrument
P.S. CERN (1960)	π N interactions	Neutral Currents -> Z,W
AGS BNL (1960)	π N interactions	Two kinds of neutrinos Time reversal non-symmetry charm quark
FNAL Batavia (1970)	Neutrino Physics	bottom quark top quark
SLAC Spear (1970)	ep, QED	Partons, charm quark tau lepton
ISR CERN (1980)	pp	Increasing pp cross section
PETRA DESY (1980)	top quark	Gluon
Super Kamiokande (2000)	Proton Decay	Neutrino oscillations
Telescopes (2000)	SN Cosmology	Curvature of the universe Dark energy

precision instruments are key to discovery when exploring new territory

The Confluence

- Quantum Information Science:
  - Promises, through control of quantum properties, to go beyond the Standard Quantum Limit and deliver ultimate precision;
  - Enables novel, cost-effective approaches complementary to traditional HEP approaches;

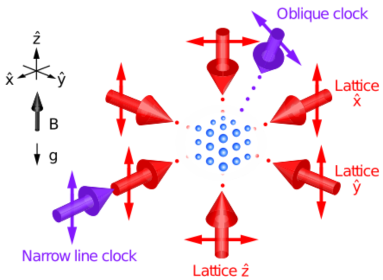
The Confluence

- High Energy Physics
  - In need of new ideas and more sensitive instrumentation;
  - Needs precision data to guide the way.

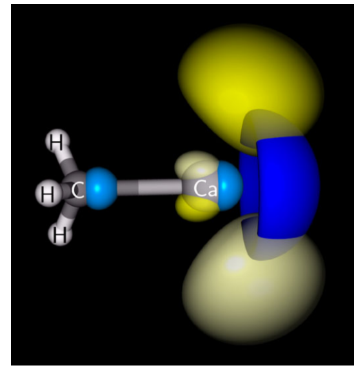
The Confluence

A perfect match at a perfect time!

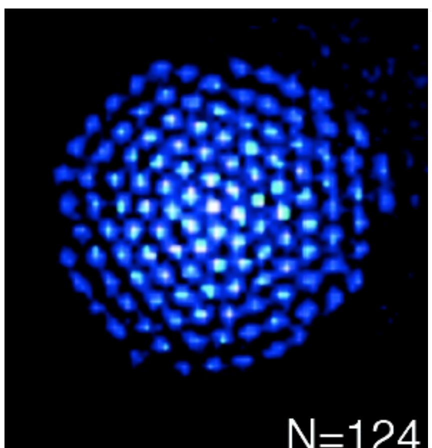
Experimental Systems



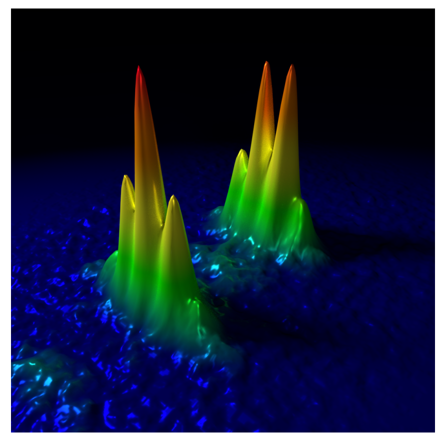
Atoms in an Optical Lattice/Cavity



Molecules

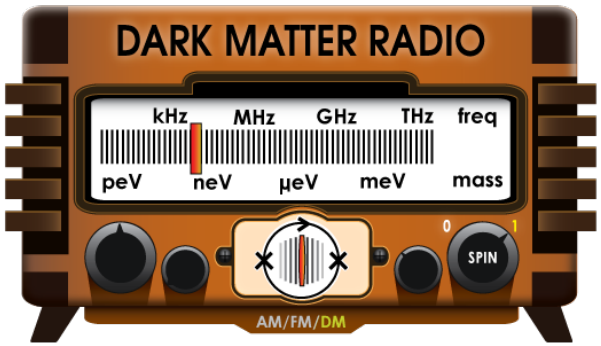


Trapped Ions

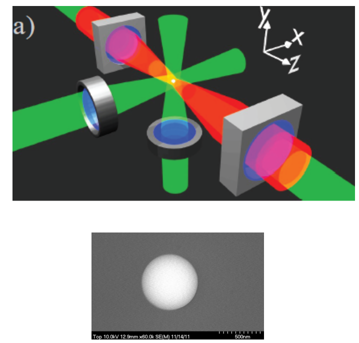


Atom Interferometers

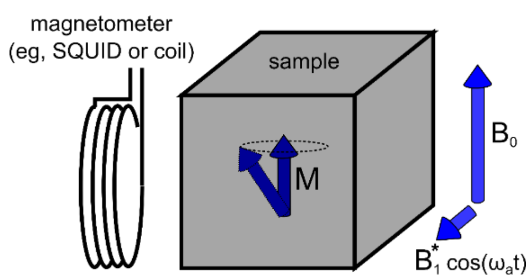
Experimental Systems, continued…



Superconducting Circuits



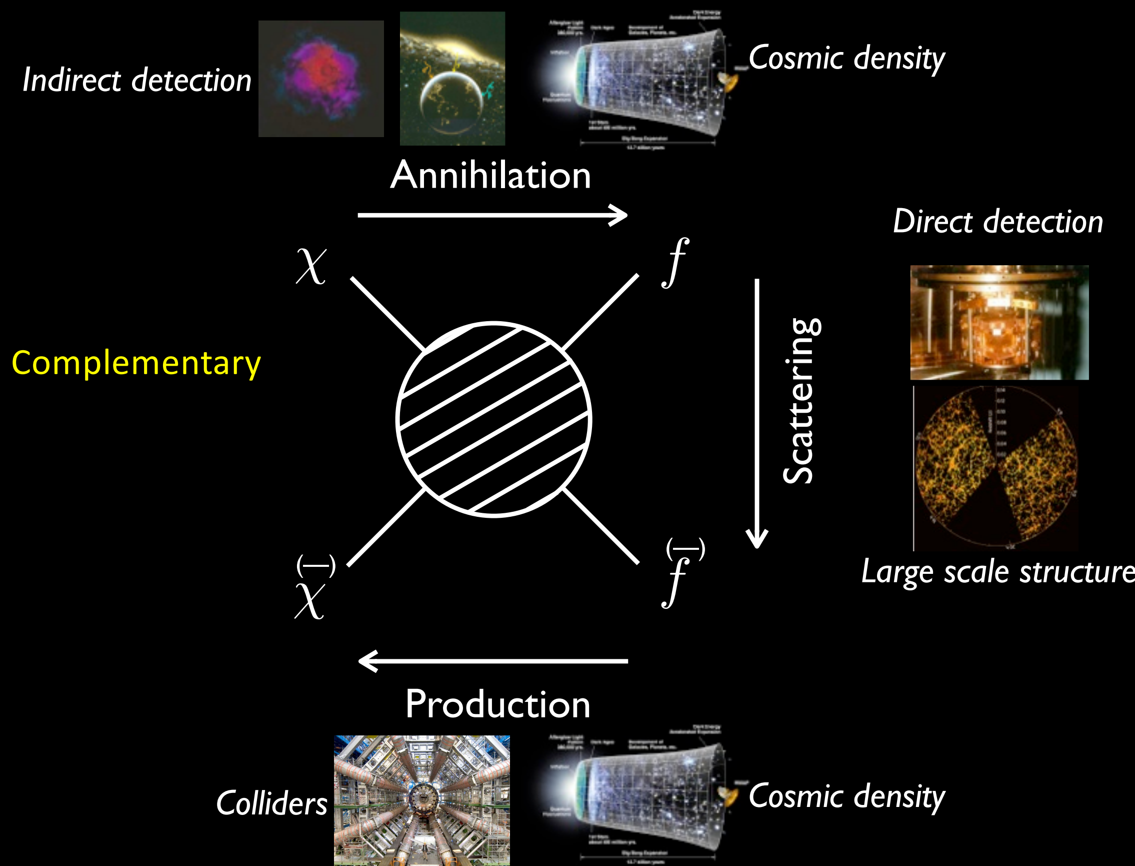
Nanomechanical Resonators



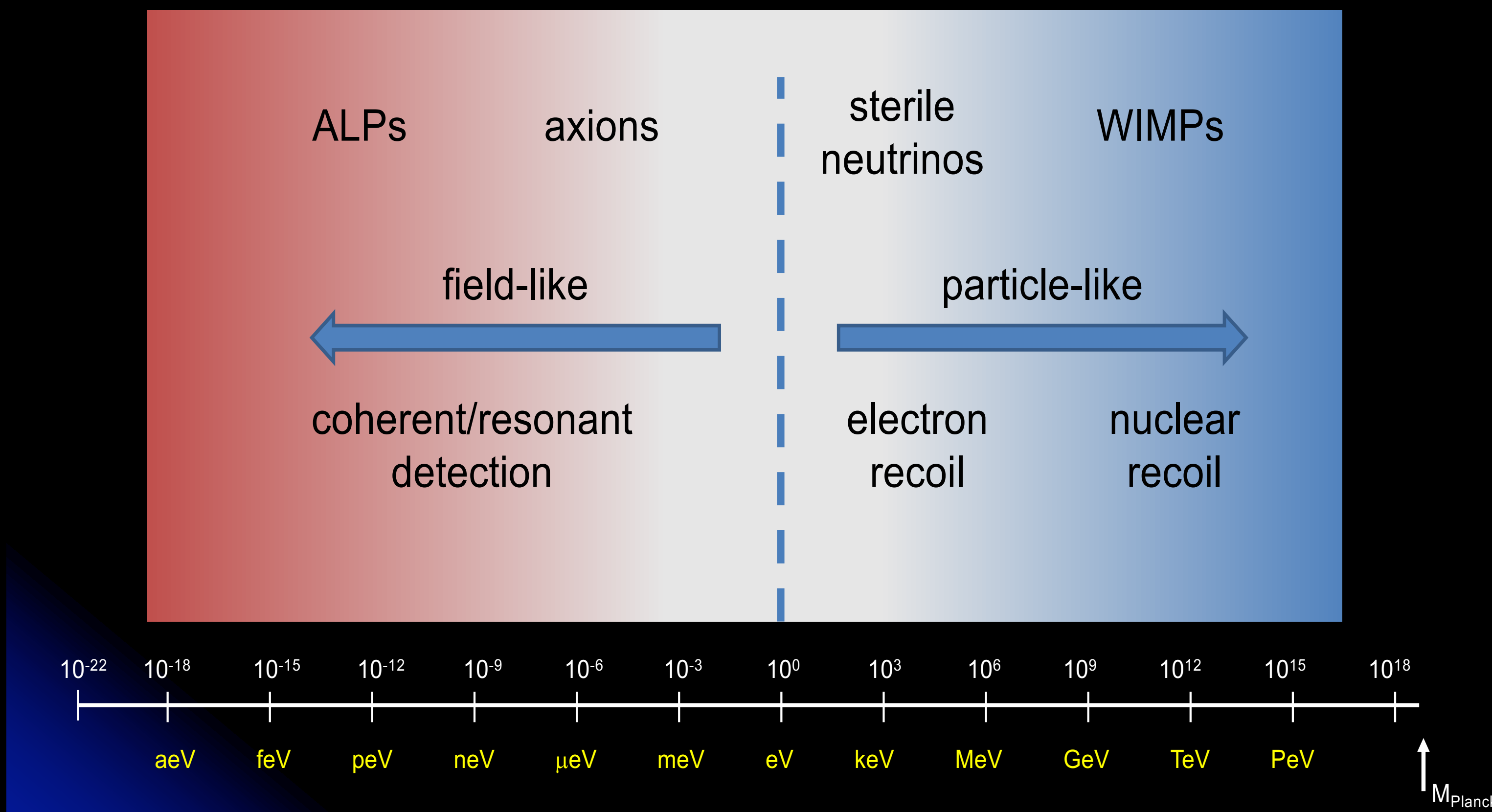
NMR

Commercial Quantum Annealer

Dark Matter Experimental approaches



Dark Matter Searches



Quantum Technologies open a new frontier on field-like dark matter

Dark Matter Search Strategy

"table top" experiments
with quantum sensors

AXIONS
(light)

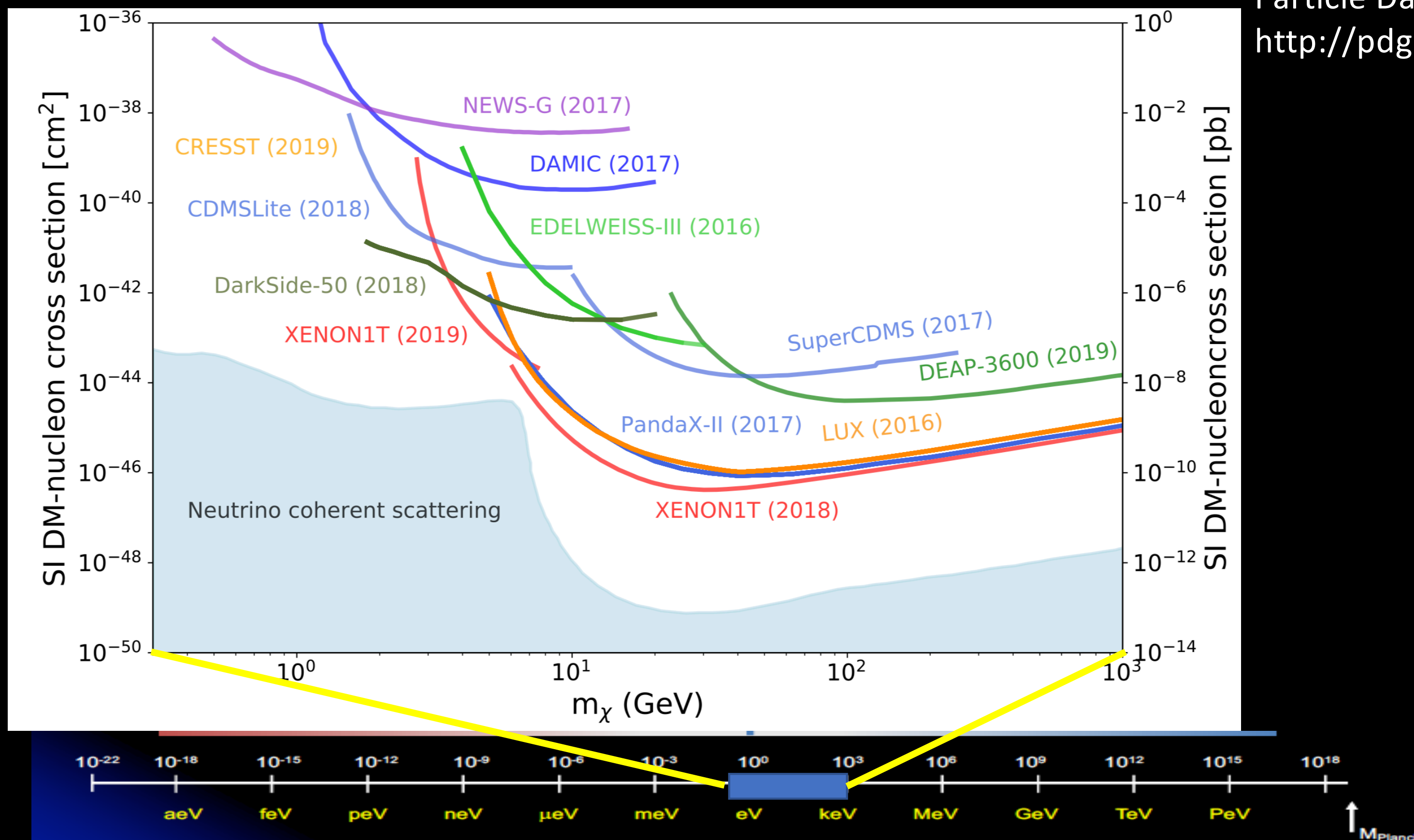
Multi-ton experiments
deep underground

WIMPS
(heavy)

The two theoretically best-motivated candidates

WIMP Dark Matter Searches

Particle Data Group, 2020
http://pdg/lbl/gov



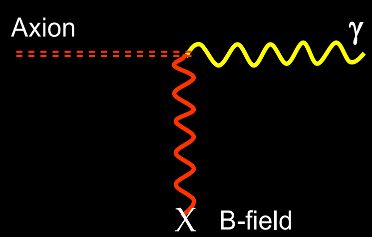
An oscillator (resonance) detector can accumulate the weak interactions of light dark matter over many "swings"

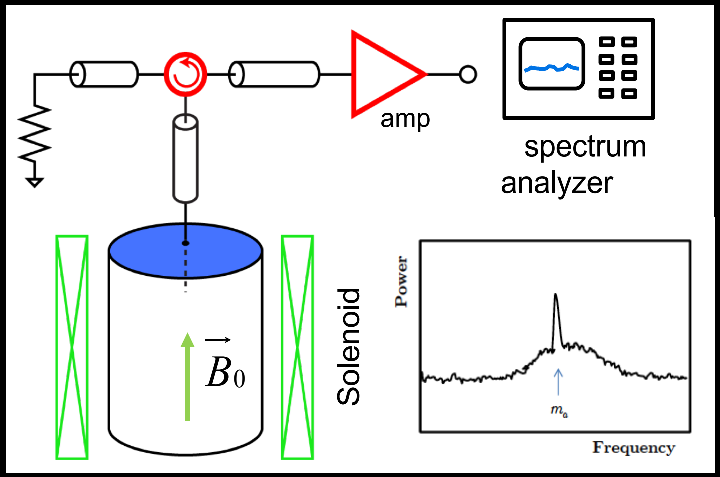
Detection oscillator

Axion wave

Cavity based searches

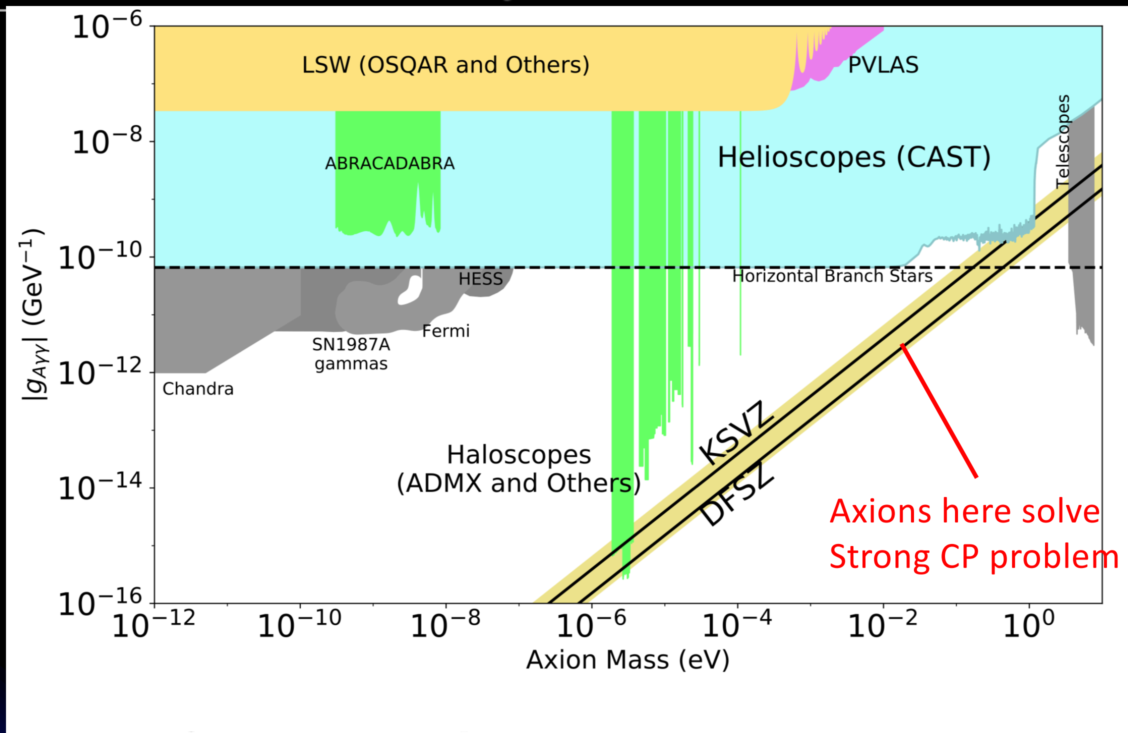
- Axions convert to microwave photons in external magnetic field (Primakov effect)





- Need to tune the cavity over a large frequency range.
- The axion to photon conversion power is very small.
- Long integration times: scanning rate $\frac{df}{dt} \sim g_{a\gamma\gamma}^4 \frac{1}{T^2} B^2$

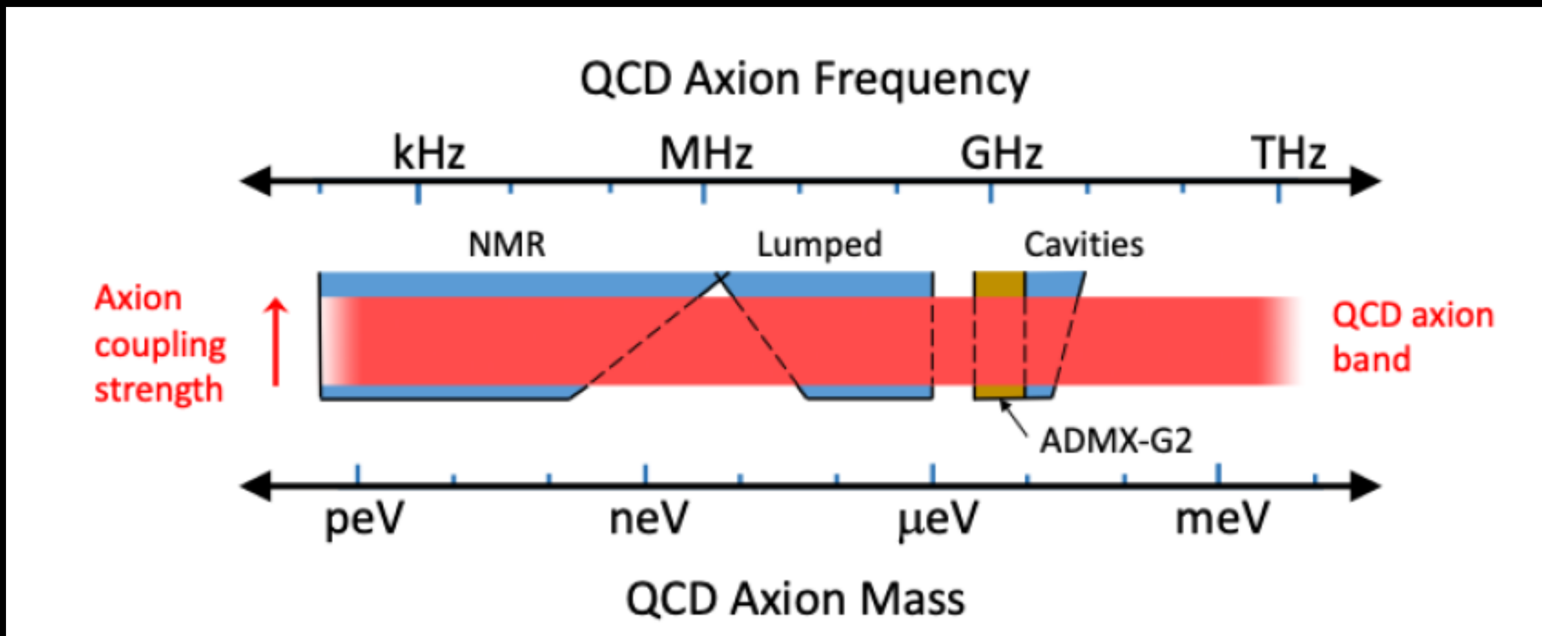
Cavity-Based Searches



Particle Data Group, 2020
http://pdg/lbl/gov

- Most recent results start excluding the 'QCD axion' region over narrow mass window

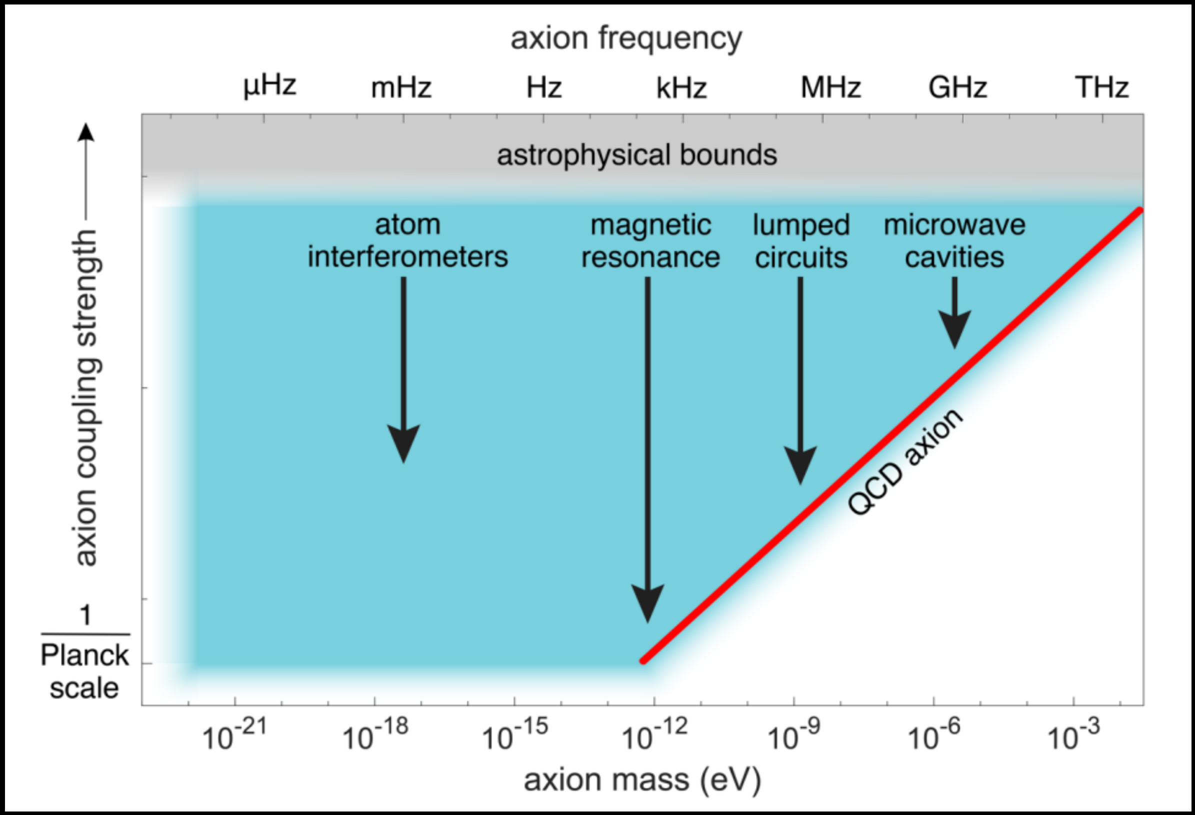
Parameter Space for QCD Axion Dark Matter



Graph: DOE OHEP BRN for Dark Matter Small Projects New Initiatives

3 highly complementary techniques
Need to exploit QCD and electromagnetic coupling of QCD axion to explore full mass range
For the general axion the techniques have broader overlapping mass ranges and therefore (crucially) a discovery by one can be confirmed by another
Greater sensitivity and gaps can be closed by going beyond the standard quantum limit (blue band in figure)

Parameter Space for General Axion Dark Matter



DOE HEP BRN
For Dark Matter
Small Projects
New Initiatives

By general axion I mean any light scalar with suppressed couplings to the standard model

23-25 March 2017:

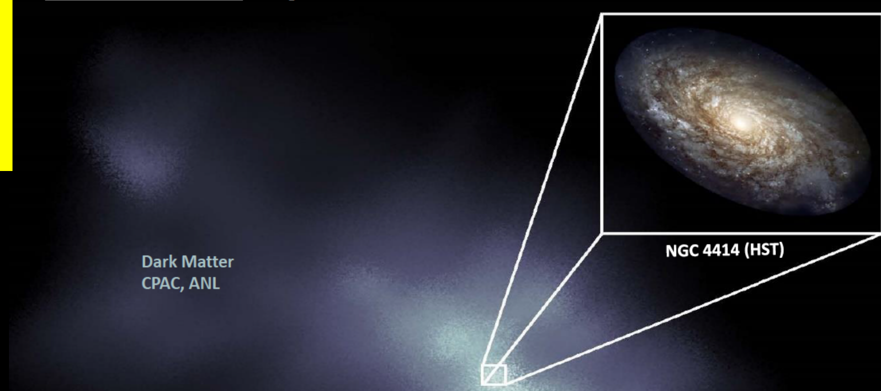
"U.S. Cosmic Visions: New Ideas in Dark Matter" workshop, focusing "… on the science case for additional new small-scale projects in dark-matter science that complement the G2 program …" Comprehensive (exhaustive) report.

14 July 2017:

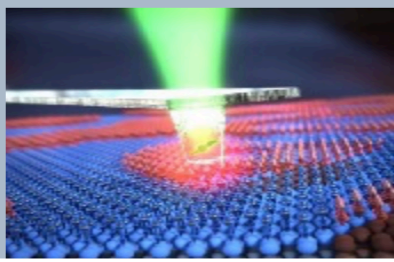
Cosmic Visions Report published (1707.04591). 113 pages. 254 signatories from 112 Institutions (US, Australia, Austria, Canada, Denmark, Germany, Israel, Italy, Japan, Korea, Russia, Switzerland, Taiwan, UK).

Basic Research Needs (BRN) Study for Dark-Matter Small Projects
(preliminary report to HEPAP 30 November 2018)

Increased awareness of the promising application of quantum sensing as one way to the search for dark matter is widespread



APS-DPF Coordinating Panel for Advanced Detectors Interdisciplinary workshop



Workshop on Quantum Sensing

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

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

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

, Malcolm Boshier (LANL), Marcel Demarteau (ANL, co-chair)
Maurice Garcia-Sciveres (LBNL) Salman Habib (ANL), Hannes
Irwin (Stanford), Akito Kusaka (LBNL), Joe Lykken (FNAL),
phael Pooser (ORNL), Sergio Rescia (BNL), Ian Shipsey (Oxford,
co-chair), Chris Tully (Princeton).

the first workshop dedicated to **Quantum Sensors for High Energy Physics**, which was influential (and cited in the House Science and Technology Report) in the creation of the US DOE **QS-HEP** program QuantISED for which funds were first awarded in August 2018.

arXiv:1803.11306v1 [hep-ex]

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

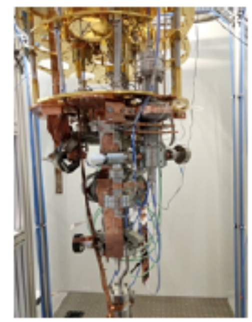
B: Foundational QIS-HEP Theory and Simulation

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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Legislation — Examples: hr5, sres9, "health care"

MORE OPTIONS

Home > Legislation > 115th Congress > H.R.6227

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H.R.6227 - National Quantum Initiative Act

115th Congress (2017-2018)

LAW Hide Overview ✖

Sponsor: Rep. Smith, Lamar [R-TX-21] (Introduced 06/26/2018)

Committees: House - Science, Space, and Technology | Senate - Commerce, Science, and Transportation

Committee Meetings: 06/27/18 10:00AM

Committee Reports: H. Rept. 115-950

Latest Action: 12/21/2018 Became Public Law No: 115-368. (TXT | PDF) (All Actions)

Roll Call Votes: There has been 1 roll call vote

Tracker:

Introduced > Passed House > Passed Senate > Resolving Differences > To President > **Became Law**

More on This Bill

Constitutional Authority Statement

CBO Cost Estimates [1]

Subject — Policy Area:

Science, Technology, Communications

View subjects »

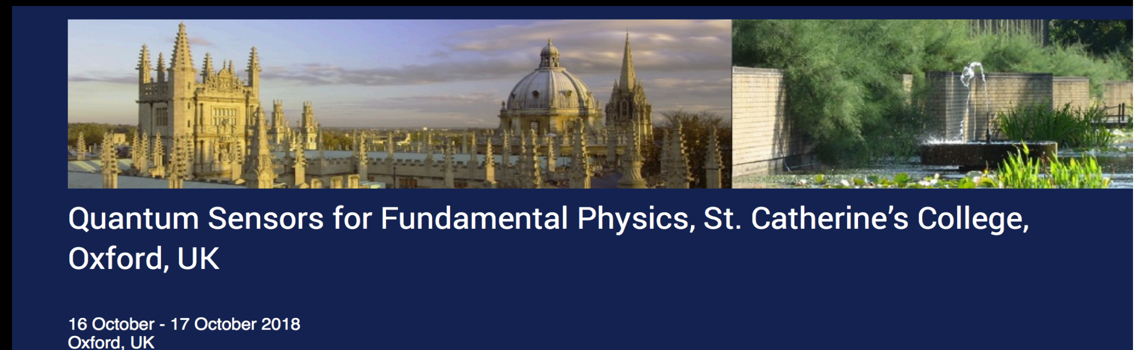
Submission of staging proposal Quantum Sensors for Fundamental Physics to STFC Opportunities Call June 2018 Principal Investigators (45)

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 subsequently ~200 total (open to all)

Quantum Sensors for Fundamental Physics Workshop October 2018 Oxford
>140 from EPSRC & STFC in attendance

Quantum Sensors for Fundamental Physics and Society- Workshop #1



The workshop had 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 STFC, EPSRC and UKRI the immense interest in the UK in QSFP

#3 To begin to build a community around key experiments that would be funded by a future programme

#4 To work with STFC and EPSRC on the bid for funding from the UKRI Strategic Priorities Fund for a future programme.

Quantum Technologies for Fundamental Physics

Strategy

- Focus on the science
- Targets SPF Funding cross-council interdisciplinary
- Exploit existing STFC & EPRSC expertise and infrastructure
- Enable the STFC community to engage with Quantum Information Science and Quantum Technology
- Landscape:
  - the National Quantum Technology Programme
  - The international picture of rapidly increasing interest and investment
- Collaborative R&D funding streams
- Builds a new community (AMO, CMP, QIS, Particle, Cosmology, Astro)
- Opportunities if funded to attract to the UK and train young scientists in a multidisciplinary area

Quantum Technologies for Fundamental Physics

Benefits

- 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
- This is a genuinely new *interdisciplinary* partnership between STFC, EPSRC and other partners
- - enabled by and well-matched to the UKRI era.

Quantum Sensors for Fundamental Physics

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


QSFP
UK Institutions
Partners
International Institutions
Workpackages
QSFP Organization
Quantum Sensors for Fundamental Physics
Welcome to the home page of the Quantum Sensors for Fundamental Physics consortium.
The consortium consists of 32 UK institutions, 7 international institutions and five partners.

Partners

QSFP

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

QSFP UK Institutions Partners International Institutions **Workpackages** QSFP Organization

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

QS FP

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search

Home / Funding / Research Grants / Funding opportunities / Quantum Technologies for Fundamental Physics (QTFP) Programme

Quantum Technologies for Fundamental Physics (QTFP) Programme

STFC and EPSRC invite applications for research consortia to apply for funding as part of the Quantum Technologies for Fundamental Physics (QTFP) programme. This is a new programme which, building on the investments of the National Quantum Technology Programme, aims to demonstrate how the application of quantum technologies will advance the understanding of fundamental physics questions.

The programme has total funds of up to £40m. The majority of funding (c. £36 million) will be allocated to this research call, which is looking to fund up to seven projects at upwards of £2 million each (at 80% fEC). Applicants wishing to submit a proposal for a large award (>£5 million) should discuss this with STFC (contact details below) ahead of the submission.

This research call is for research consortia, i.e. joint proposals with a common research programme from groups of researchers in more than one organisation. Successful applications will require interdisciplinary research teams comprising researchers from both the fundamental physics and quantum technology communities.

The call will be open to all individuals and organisations eligible for UKRI funding. PSREs are asked to contact the office to check if they are eligible. Grants will commence on 1 May 2020 and end no later than 30 September 2023. Successful projects will be expected to show tangible outcomes and results within the lifespan of the funding.

Latest News

October 24, 2019
STFC technicians awarded prestigious new Institute of Physics Technician Award

October 24, 2019
UK research challenges Martian ice theory

October 23, 2019
21 today! Edinburgh's UK Astronomy Technology Centre celebrates 21 years of world class engineering excellence

Share this page

Application process

Applicants must complete an Intention to Submit (ItS) form by 16.00 on 31 October 2019. The ItS will not be formally assessed. The ItS stage will allow STFC to evaluate fit to call scope and allow early consideration of potential reviewers and panel members. Applicants that do not register their intent to submit before the deadline will be ineligible for the call.

Full proposals must be submitted via the research council's Joint Electronic Submissions (Je-S) system by 16.00 on 3 December 2019.

Full details of the call, including the application process, eligibility requirements, assessment process and criteria are provided in the QTFP call document.

Call documents

- QTFP call document (PDF 220KB)
- QTFP equality and inclusion impact assessment (PDF 123KB)

Key dates

(please note all dates marked * are subject to change):

Deadline for Intention to Submit	16.00, 31 October 2019
Deadline for full proposals	16.00, 3 December 2019
Full proposal postal peer review	December 2019 – January 2020*
Deadline for PI response	w/c 10 February 2020*
Panel meeting	March 2020*

Downselect concluded April 2020
successful projects informed

Contact

Rachel Reynolds, QTFP Programme Manager, tel: 01793 44 2832
Ed Mansfield, Assistant Programme Manager, tel: 01793 44 2162
Email: QTFP@stfc.ukri.org

QUEST DMC

QSFP | UK Institutions | Partners | International Institutions | Workpackages | QSFP Organization

WP1

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

Participants/Collaborators ›
Join this group ›

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Absolute neutrino mass

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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

QS FP

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

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

PERSPECTIVE

UK national quantum technology programme

Peter Knight and Ian Walmsley

Imperial College London SW72AZ, United Kingdom

OPEN ACCESS

PUBLISHED
29 October 2019

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

NQTP Phase 1 – 2014 to 2019

Focus

- A **five-year £270M programme** announced by the UK government in the 2013 Autumn Statement which started in April 2014.
- To exploit the potential of quantum science and develop a portfolio of emerging technologies with the potential to benefit the UK..
- Industry, government and academia working together to create opportunities for UK wealth creation. Partners: Department for **Business Energy and Industrial Strategy, EPSRC, Innovate UK, Dstl, National Physical Laboratory, GCHQ**
- Four main application areas: (1) quantum sensors and metrology, (2) quantum imaging, (3) quantum secured communications, (4) quantum computing and simulation
- "The vision is to create a coherent government, industry and academic quantum technologies community that gives the UK a world-leading position in the emerging multi-billion-pound new quantum technology markets, and to substantially enhance the value of some of the biggest UK-based industries."

Slide credit Sir Peter Knight

Four main application areas

- Quantum sensors and metrology-navigation, gravity mapping, timing
- Quantum imaging-gas sensing, imaging round corners, imaging through fog/rain/snow, brain imaging
- Quantum secured communications-post quantum security
- Quantum computing and simulation-potential to solve complex problems beyond the capabilities of conventional supercomputing

UK National Quantum Technology Hub Sensors and Metrology

QUANTIC
The UK Quantum Technology Hub in Quantum Enhanced Imaging

QUANTUM COMMUNICATIONS HUB

NQIT Networked Quantum Information Technologies

Slide credit Ian Walmsley

NQTP Phase 2 – 2019 onwards

Evolution of the National Programme

- Increasing emphasis on **innovation and industrially** led activity
- **Growing** the National Programme including bringing in new partners and evolving the governance structure
- Widening **awareness, understanding and uptake** of quantum technologies in government, industry and academia.

Slide credit Sir Peter Knight

NQTP Phase 2 – 2019 onwards

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

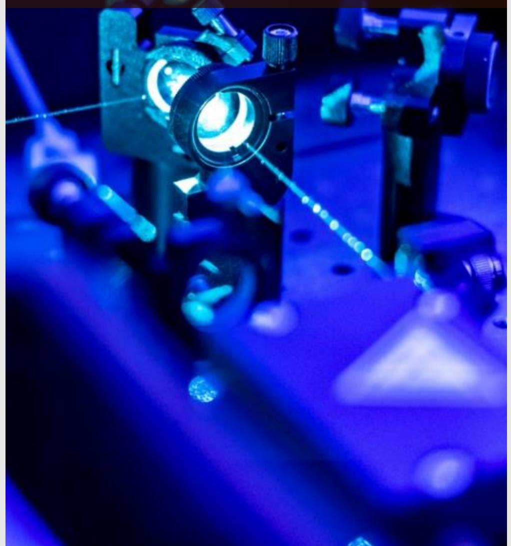
National Quantum Computing Centre

£93m over 5 years

4 key work streams:

- NISQ demonstrator hardware platforms
- Quantum software, algorithm & applications
- High performance, scalable qubit technology
- Roadmap towards universal fault-tolerant quantum computing

Technology



Initial platform focus:

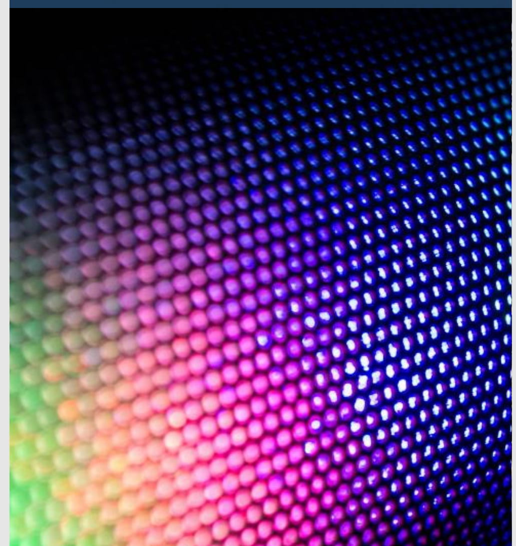
- Superconducting qubits
- Trapped ions

Near term roadmap complete

Long term outlook published

First call for partnership projects Q4-2020

Engagement



Formal NQCC launch Q3-2020:

- Strategic Intent published
- Website launched
- Gov & Policy engagement

Quantum Readiness developing

- Applications work stream
- Access to prototypes

Growing UK research, supply chain and industry eco-system

Facility

Facility located at Harwell Campus in Oxfordshire:

- **Design freeze – Q4-2020**
- Site clearance – by Q2-2021
- Construction – from Q3-2021
- Facility handover – Q1-2023

Strategic Intent

UK NATIONAL
QUANTUM
TECHNOLOGIES
PROGRAMME

A new strategic vision for the next 10 years

An evolved vision to create a 'quantum enabled economy', in which quantum technologies:

- are an integral part of the UK's digital backbone and advanced manufacturing base;
- unlock innovation across sectors to drive growth and help build a thriving and resilient economy and society and;
- contribute significant value to the UK's prosperity and security.

To achieve this, we aim to make the UK:

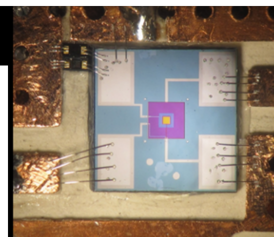
- a global centre of excellence in quantum science and technology development;
- the 'go-to' place for quantum companies or for global companies to locate their quantum activities, and;
- a preferred location for investors and global talent.

Quantum Sensors for the Hidden Sector

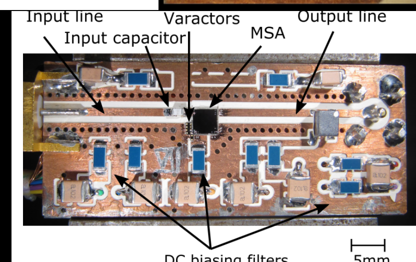
Sheffield, Cambridge, Oxford, RHUL, Lancaster, UCL, NPL, Liverpool

- 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.

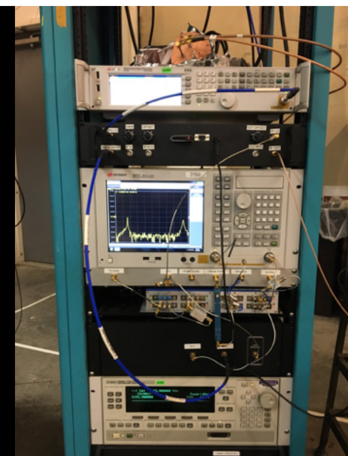
ADMX SQUID washer

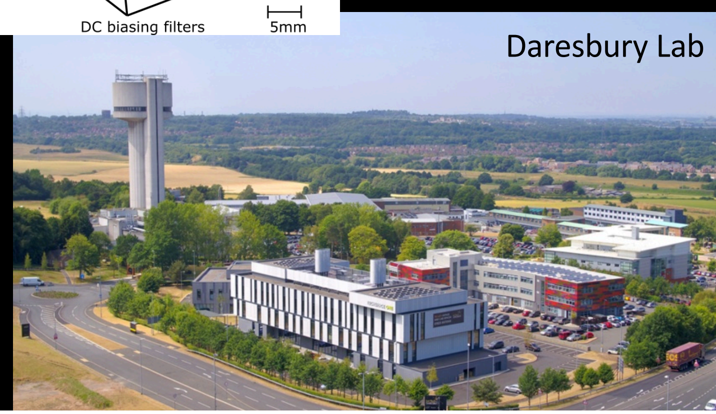


ADMX Microwave SQUID amplifier

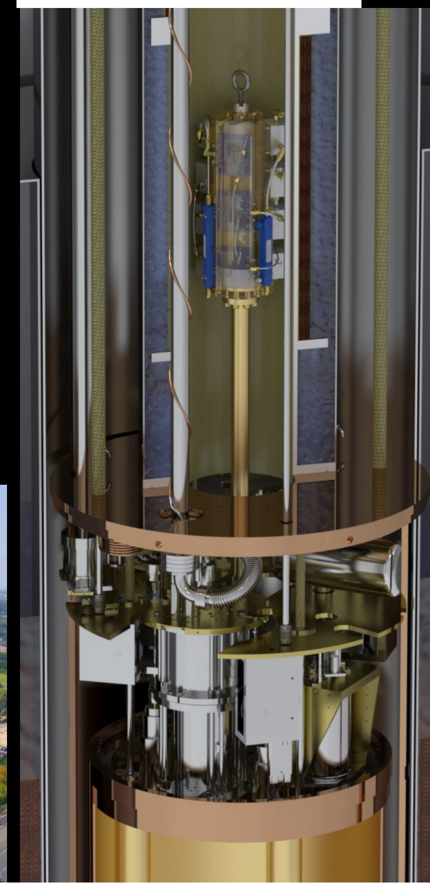


Resonant feedback test



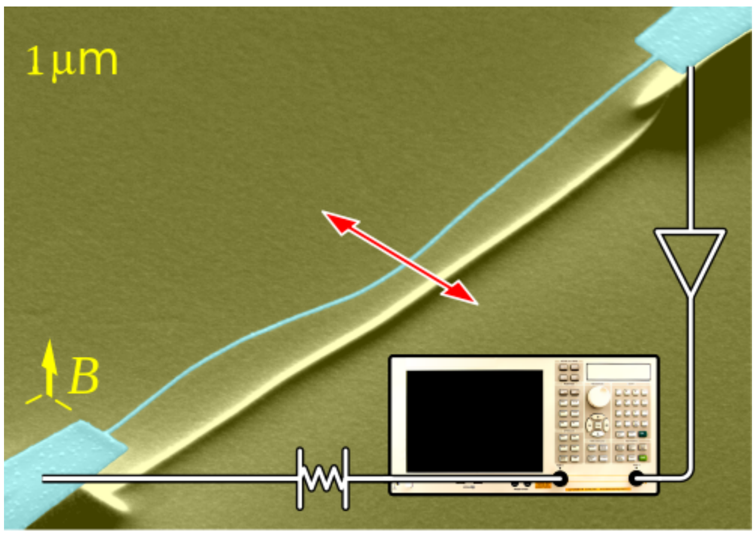


ADMX SQUID housing

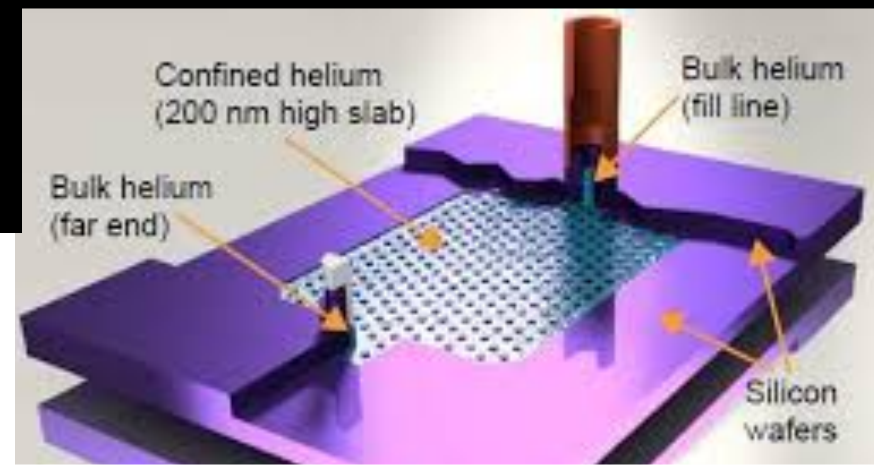


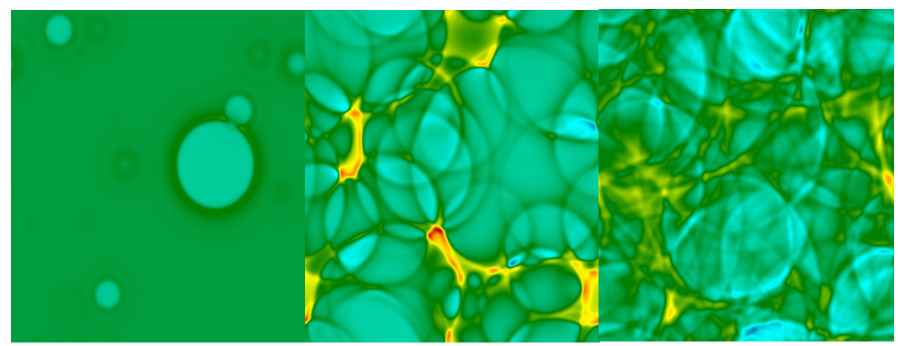
Quantum Enhanced Superfluid Technologies for Dark Matter and Cosmology, QUEST –DMC

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



Phase transitions in extreme matter





UK HEP Forum 2020, 9-11 November 2020, See Andrew Casey's talk

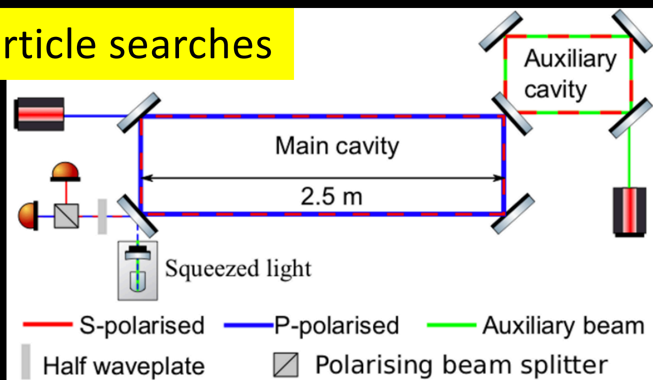
Core Team

Experimental	Theory
Dr. Samuli Autti	**Prof. Mark Hindmarsh (Leading WP2)**
Dr. Andrew Casey	Prof. Stephan Huber
Prof. Richard Haley	Prof. John March-Russell
Dr. Petri Heikkinen	Dr. Stephen West
Dr. Sergey Kafanov	
Prof. Jocelyn Monroe (Leading WP1)	
Dr. Jonathan Prance	
Dr. Xavier Rojas	
Prof. John Saunders	
Dr. Michael Thompson	
Dr. Viktor Tsepelin	
Dr. Dmitry Zmeev	
Dr. Vladislav Zavyalov	

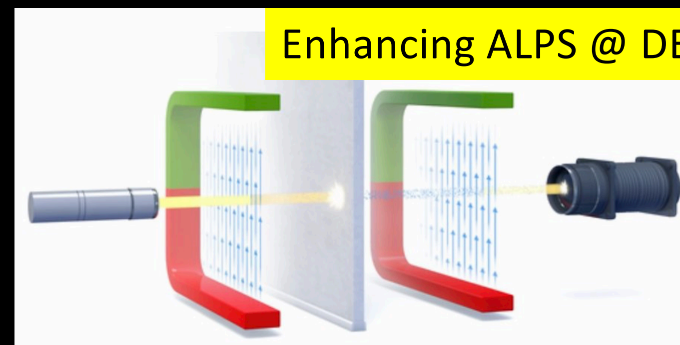
Quantum-enhanced Interferometry

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)

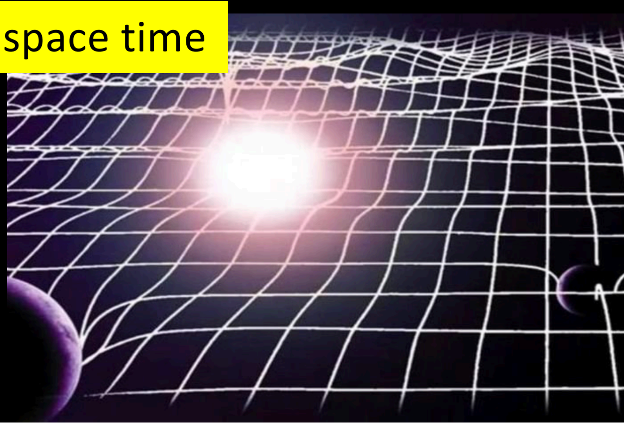
Axion-like particle searches



Enhancing ALPS @ DESY

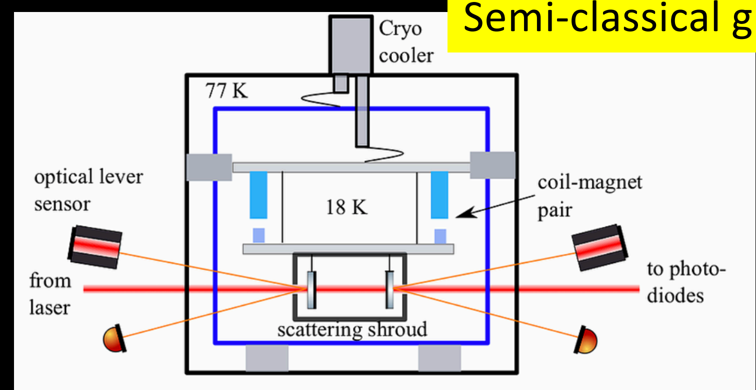


Quantization of space time



See Hartmut Grote talk

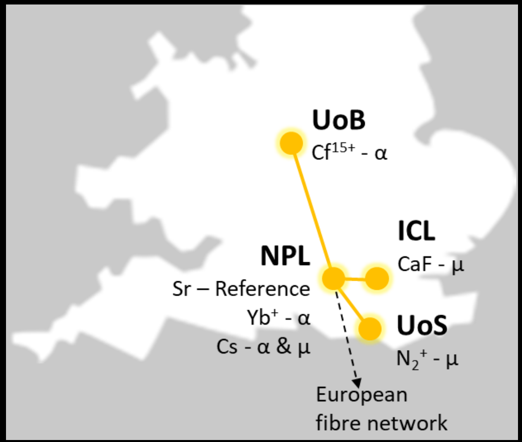
Semi-classical gravity



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

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**

See Giovanni Barontini talk

The AION Project

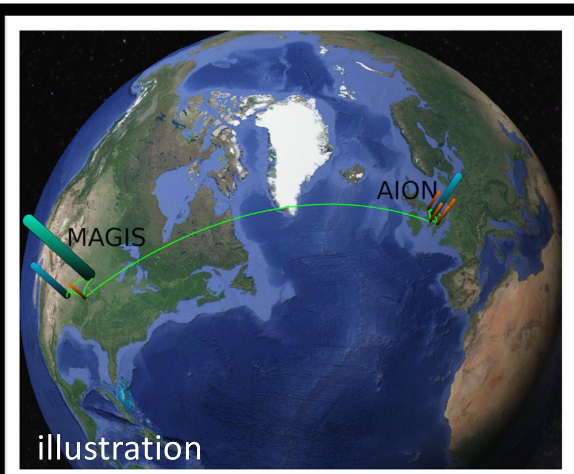
A UK Atom Interferometer Observatory and Network

to explore Ultra-Light Dark Matter and Mid-Frequency Gravitational Waves.

Oliver Buchmueller talk

L. Badurina[1], S. Balashov[2], E. Bentine[3], D. Blas[1], J. Boehm[2], K. Bongs[4], D. Bortoletto[3], T. Bowcock[5], W. Bowden[6,*], C. Brew[2], O. Buchmueller[6], J. Coleman[5], G. Elertas[5], J. Ellis[1,$,&], C. Foot[3], V. Gibson[7], M. Haehnelt[7], T. Harte[7], R. Hobson[6,*], M. Holynski[4], A. Khazov[2], M. Langlois[4], S. Lellouch[4], Y.H. Lien[4], R. Maiolino[7], P. Majewski[2], S. Malik[6], J. March-Russell[3], C. McCabe[1], D. Newbold[2], R. Preece[3], B. Sauer[6], U. Schneider[7], I. Shipsey[3], Y. Singh[4], M. Tarbutt[6], M. A. Uchida[7], T. V-Salazar[2], M. van der Grinten[2], J. Vossebeld[4], D. Weatherill[3], I. Wilmut[7], J. Zielinska[6]

[1]Kings College London, [2]STFC Rutherford Appleton Laboratory, [3]University of Oxford, [4]University of Birmingham, [5]University of Liverpool, [6]Imperial College London, [7]University of Cambridge



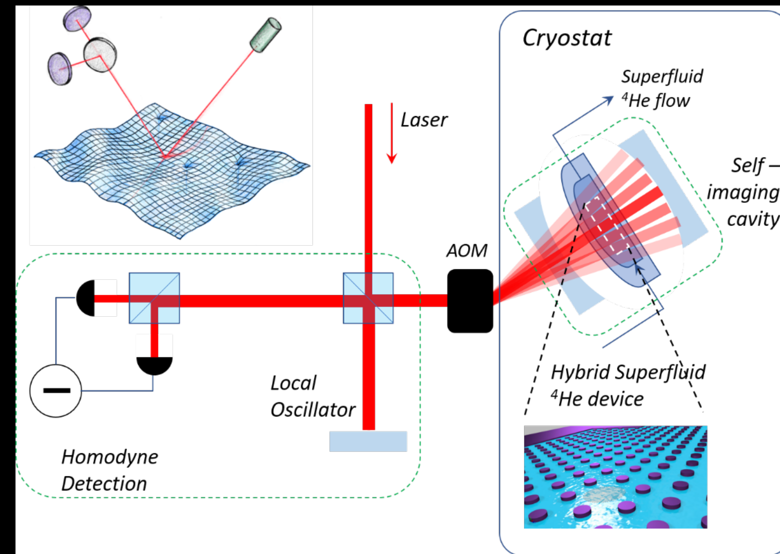
Project executed in national partnership with **UK National Quantum Technology Hub in Sensors and Timing, Birmingham, UK,** and international partnership with **The MAGIS Collaboration and The Fermi National Laboratory, US**

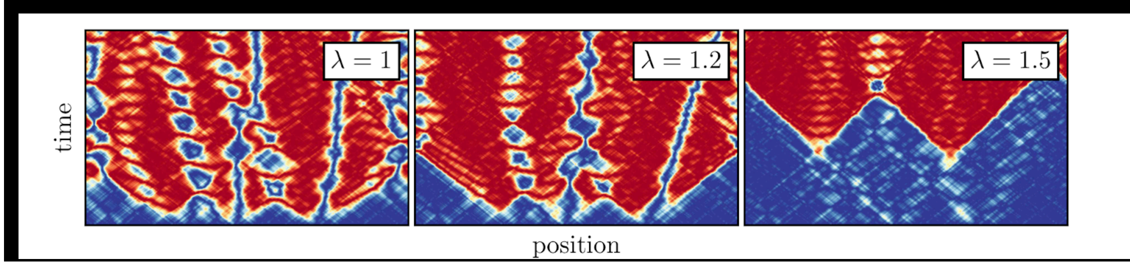
QSimFP Quantum Simulators for Fundamental Physics

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

Quantum Technologies for Neutrino Mass Consortium

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

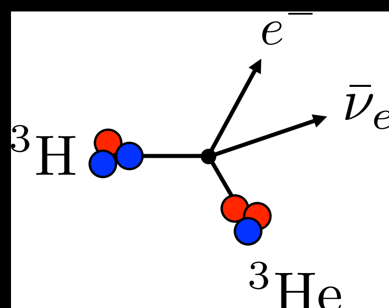
F. Deppisch[1], J, Gallop[2], L. Hao[2], S. Hogan[1], L.Li[3], R. Nichol[1], Y. Ramachers[4], R. Saakyan[1](PI), D. Waters[1], S. Withington[5]

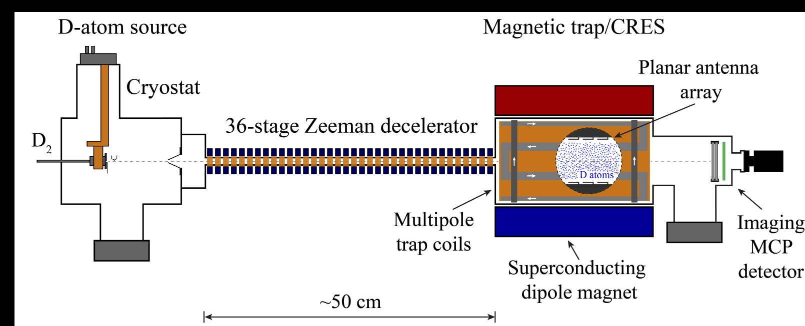
A collaboration of particle, atomic and solid state physicists, electronics engineers and quantum sensor experts

3-yr proposal goal:

Technology demonstration for neutrino mass determination from ^{3}H $\boldsymbol{\beta}$-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*)

Ruben Saakyan talk

The QTFP community comprising the 7 projects are in the process of forming a QTFP Community Committee (two members from each project). The CC will organize the annual (or semi-annual) Community workshops where the 7 projects can present their progress, challenges and future plans. In addition, it will invite people to present new ideas as well as to cover international research happening elsewhere. There will also be an online community platform to share information, best practice and to generally help each other, and an annual school likely aligned with YETI.

To further deepen our relationship with the sensing hub we are exploring common Events

Community Committee
QSHS Ed Daw & Stafford Withington
QI Hartmut Grote & Denis Martynov
QSimFP Silke Weinfurtner & tbd
AION Oliver Buchmueller & tbd
QUEST-DMC Jocelyn Monroe (tbc)
& Mark Hindmarsh (tbc)
QTNM Rubin Saakyan &tbd
QSNET Giovanni Barontini & tbd
Ian Shipsey

School Committee
QSHS Ed Daw
QI Hartmut Grote
QSimFP Silke Weinfurtner
AION Oliver Buchmueller
QUEST-DMC Jocelyn Monroe (tbc)
QTNM Rubin Saakyan
QSNET Giovanni Barontini
Martin Bauer John Ellis Ian Shipsey

THE EUROPEAN STRATEGY UPDATE CALLED FOR A DETECTOR R&D ROADMAP – A TASKFORCE ON QUANTUM SENSORS & OTHER INNOVATIVE TECHNOLOGIES IS ONE OF NINE

CERN HAS A NASCENT QUANTUM PROGRAMME

FERMILAB HAS BEEN CHOSEN AS A DOE QUANTUM SCIENCE CENTER

THE FIRST DOE REVIEW OF THE FUTURE OF THE US NATIONAL INSTRUMENTAITON PARTICLE PHYISCS RESEARCH PROGRAMME HAS IDENTIFED AN AMBITIOUS PROGRAMME OF QUANTUM SENSOR RESEARCH

QUANTUM TECHNOLOGIES FOR PARTICLE PHYSICS WILL BE A PROMINENT PLAYER FOR THE NEXT SEVERAL DECADES

THE ESSENTIAL INGREDIENTS THAT HAVE MADE QTFP POSSIBLE ARE:

- COMPELLING SCIENCE
- QUANTUM REVOLUTION 2.0
- THE NATIONAL QUANTUM TECHNOLOGY PROGRAM
- A STRONG COMMUNITY

AWARD LETTERS WILL SOON BE WITH THE PROJECTS
THERE IS EXCITING SCIENCE AHEAD