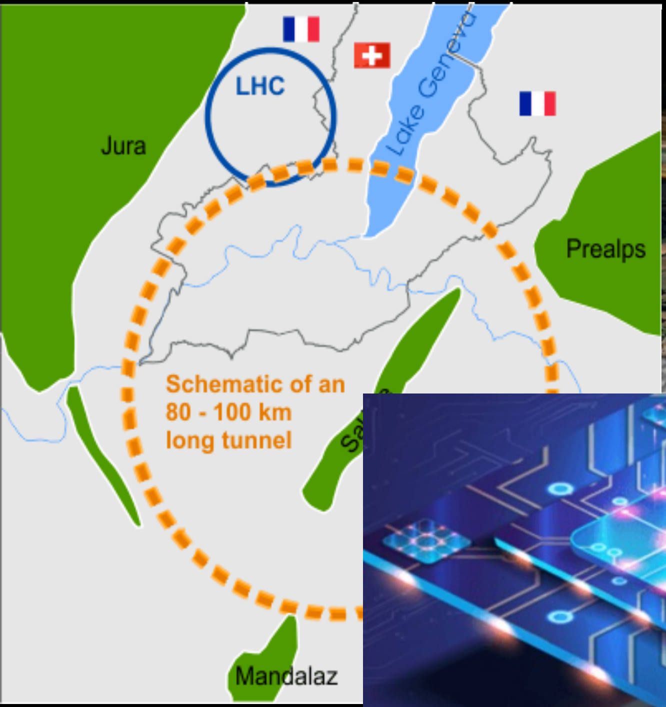
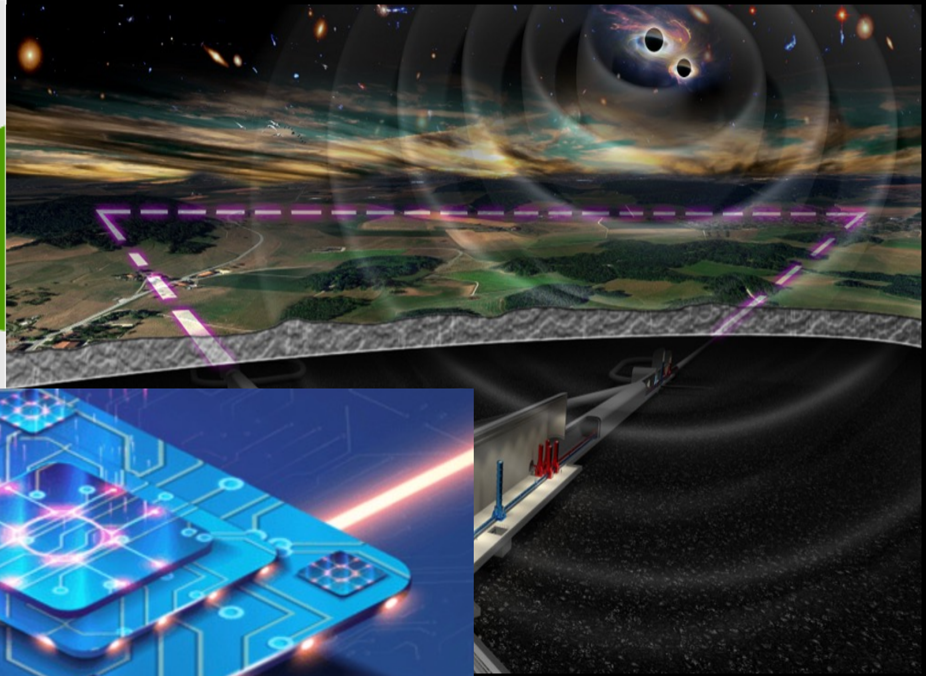
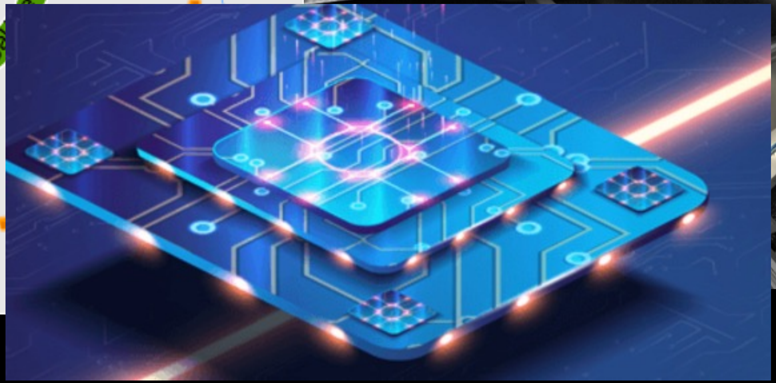
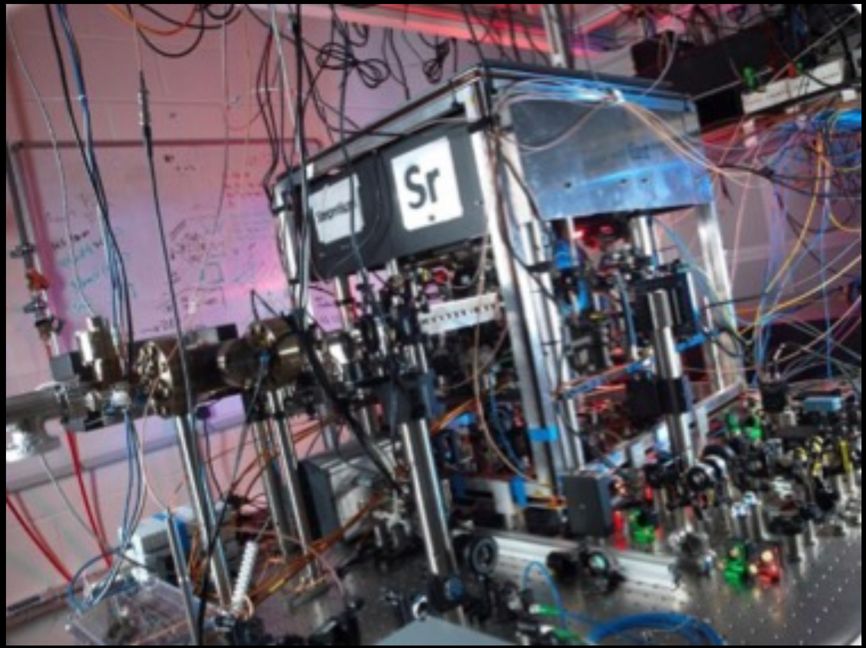
Quantum Technologies for Fundamental Physics

The Science & The Quantum Technologies Landscape









Ian Shipsey,
Oxford University
(on behalf of the seven QTFP projects)

PPAP Community Meeting
Manchester, September, 2022

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

Outline

- QTFP
- The Science
- Quantum Revolution 2.0
- Quantum & particle physics
- The Seven QTFP Projects
- Future

QTFP is a new strategic initiative within the National Quantum Technology Programme created with £40M from the UKRI Strategic Priorities Fund in 2019 awarded to EPSRC and STFC with STFC administering the programme.

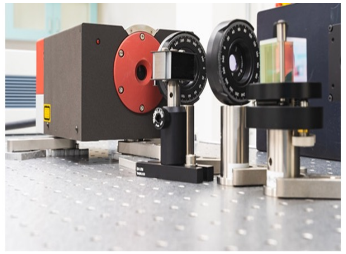
The primary purpose of QTFP is to enable advanced quantum technologies, innovated and demonstrated during the last 5-10 years to be developed, customised and refined to enable major advances in understanding of some of the greatest scientific mysteries in particle physics, particle astrophysics, cosmology and other areas of fundamental physics

There are seven QTFP projects. Funding commenced in February, 2021 for up to 41 months. QTFP currently comprises 101 faculty and scientists, 66 post docs, 11 Engineers and technicians, 5 administrative staff and 32 PhD students (the students are funded from other sources). Each project has built its own collaboration, including formal working agreements with some of the best overseas scientific teams

QTNM QI QSNET QSHS AION QUEST DMC QSimFP

QI

Quantum-enhanced Interferometry for new physics

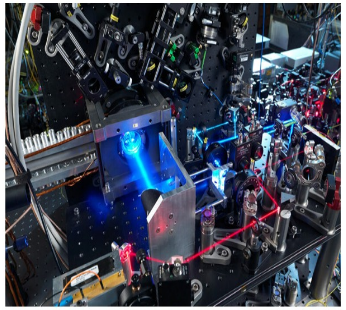


Principal investigator: Harmut Grote

Using quantum technologies we can now explore new fields of physics, seeking answers to long-standing questions like "what is dark matter?" and "is space-time quantised?"

QSNET

A network of clocks for measuring the stability of fundamental constants



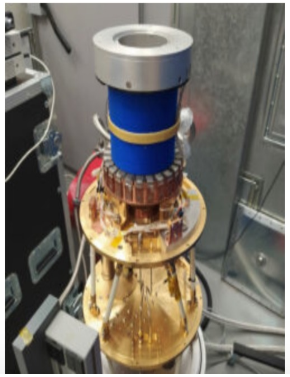
Strontium optical lattice clock experiment

Principal investigator: Giovanni Barontoni

Using quantum technology we can now network ultra-advanced atomic clocks to investigate the origin of dark matter and dark energy, which constitute 95% of the universe, but have so far eluded any detection.

QTNM

Determination of absolute neutrino mass using quantum technologies



Principal investigator: Ruben Saaykan

The QTNM project aims to harness recent breakthroughs in quantum technologies to solve one of the most important outstanding challenges in particle physics – determining the absolute mass of neutrinos.

QSHS

Quantum sensors for the hidden sector

Principal investigator: Ed Daw

Amplifiers operating at the quantum limit are essential for probing the astrophysics of the hidden sector. With this technology, we could solve the dark matter problem.

AION

A UK atom interferometer observatory and network

Principal investigator: Oliver Buchmuller

Using ultracold strontium atom interferometers as quantum sensors to tackle open questions in fundamental physics, such as the nature of dark matter, the existence of new fundamental interactions, and novel sources of gravitational waves.

QUEST DMC

Quantum enhanced superfluid technologies for dark matter and cosmology

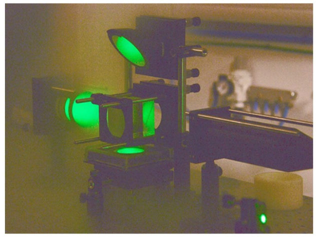
Nuclear demagnetisation experiment

Principal investigator: Andrew Casey

Combining Quantum Technology with ultralow temperatures we can now search for dark matter in a mass regime that is strongly motivated by theory, but inaccessible using current techniques.

QSimFP

Quantum simulators for fundamental physics

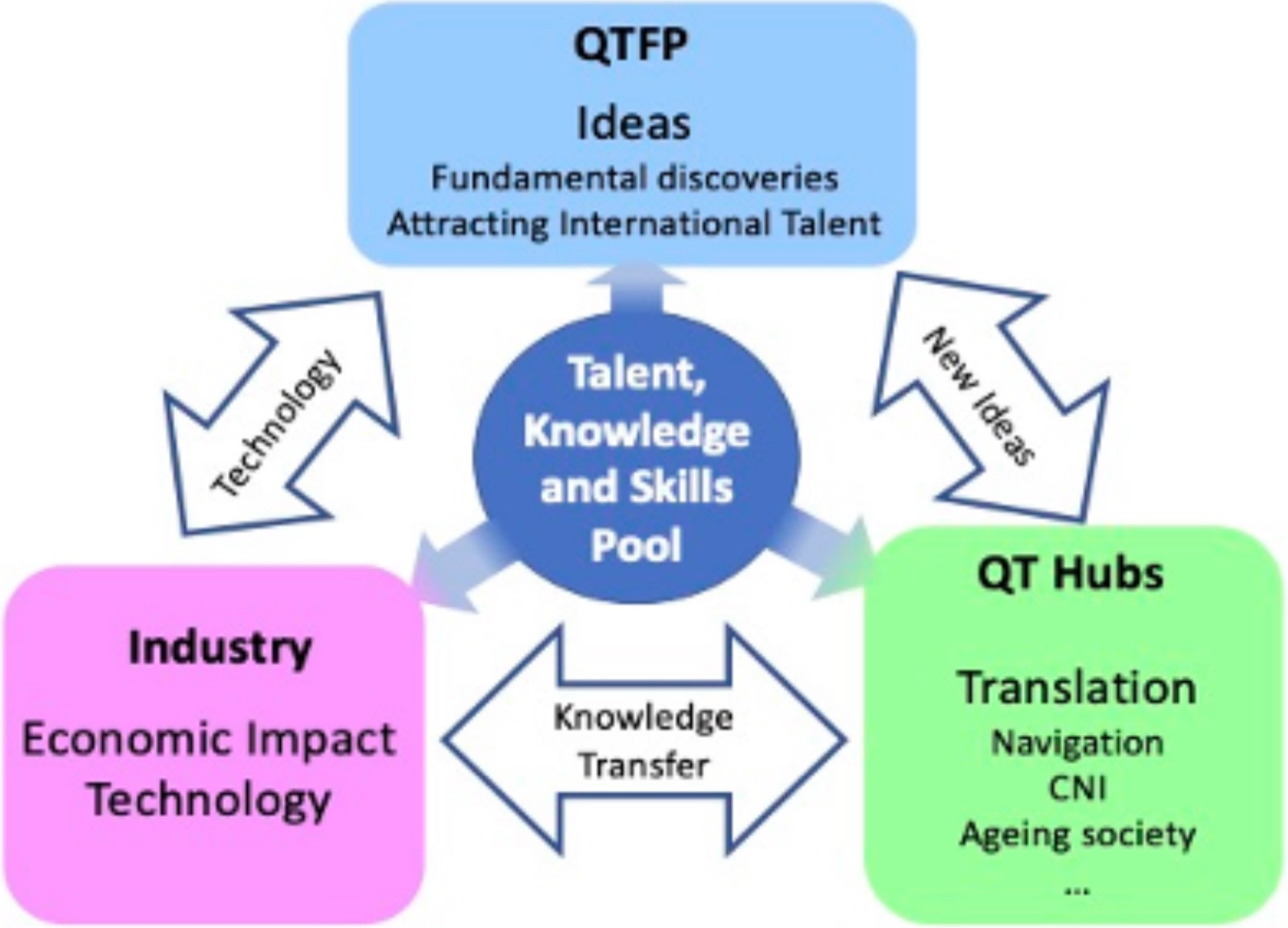


Principal investigator: Silke Weinfurtner

Using a novel high-precision interferometric scheme to observe the surface dynamics of quantum fluids, we will elucidate unifying features of quantum phenomena around rotating black holes and rotating fluid flows.

•**76 partnerships** between QTFP institutions and international institutions, 4 UK-US QTFP consortia level agreements and many institution to institution collaborations.

Fig. 2 – International groups collaborating with QTFP: UK Organizations (yellow), and International Partners of QSimFP (orange), QI (red), QSNET (purple), QSHS (green), QTNM (turquoise), AION (brown) and QUEST-DMC (gray).


QTFP
Ideas
Fundamental discoveries
Attracting International Talent
Technology
New Ideas
Talent, Knowledge and Skills Pool
Industry
Economic Impact
Technology
Knowledge Transfer
QT Hubs
Translation
Navigation
CNI
Ageing society
...

https://uknqt.ukri.org

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https://uknqt.ukri.org/our-programme/qtfp/›

Quantum Technologies for Fundamental Physics

Quantum Technologies for Fundamental Physics (QTFP) is a £40 million Strategic Priorities Fund (SPF) programme that aims to transform our approach to understanding the universe and its evolution.

The QTFP programme aims to demonstrate how quantum technologies can be utilised to investigate key fundamental physics questions such as the search for dark matter, the nature of gravity and measurements of the quantum properties of elementary particles, thus ensuring the UK remains a first rank nation in the physics and quantum communities around the world.

QTNM

QI

QSNET

QSHS

AION

QUEST DMC

QSimFP

Seven projects have been funded under this programme:

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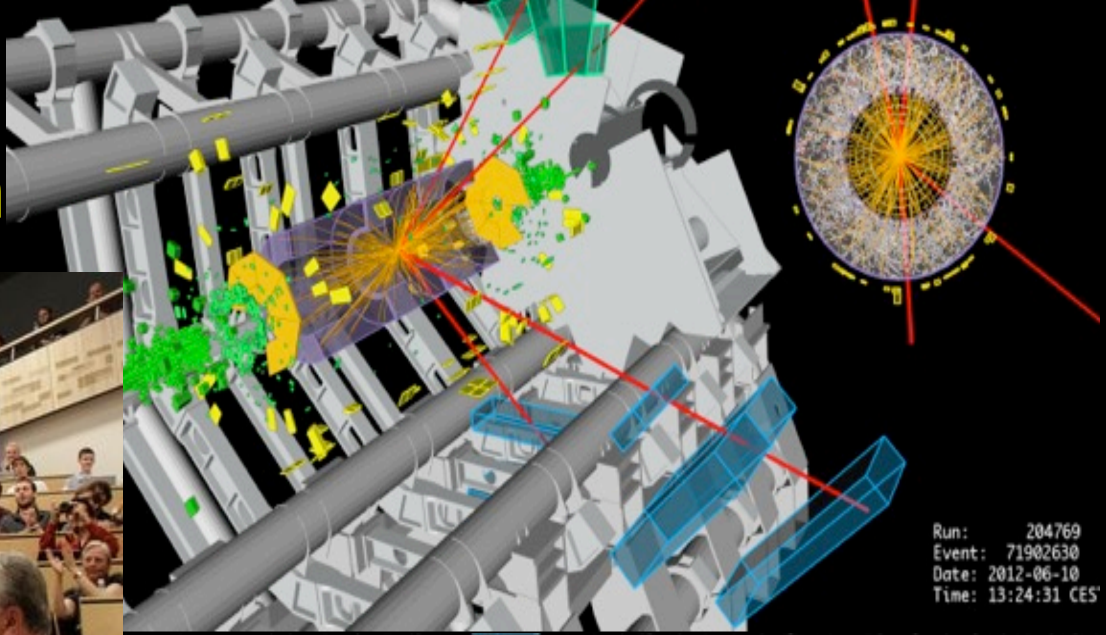
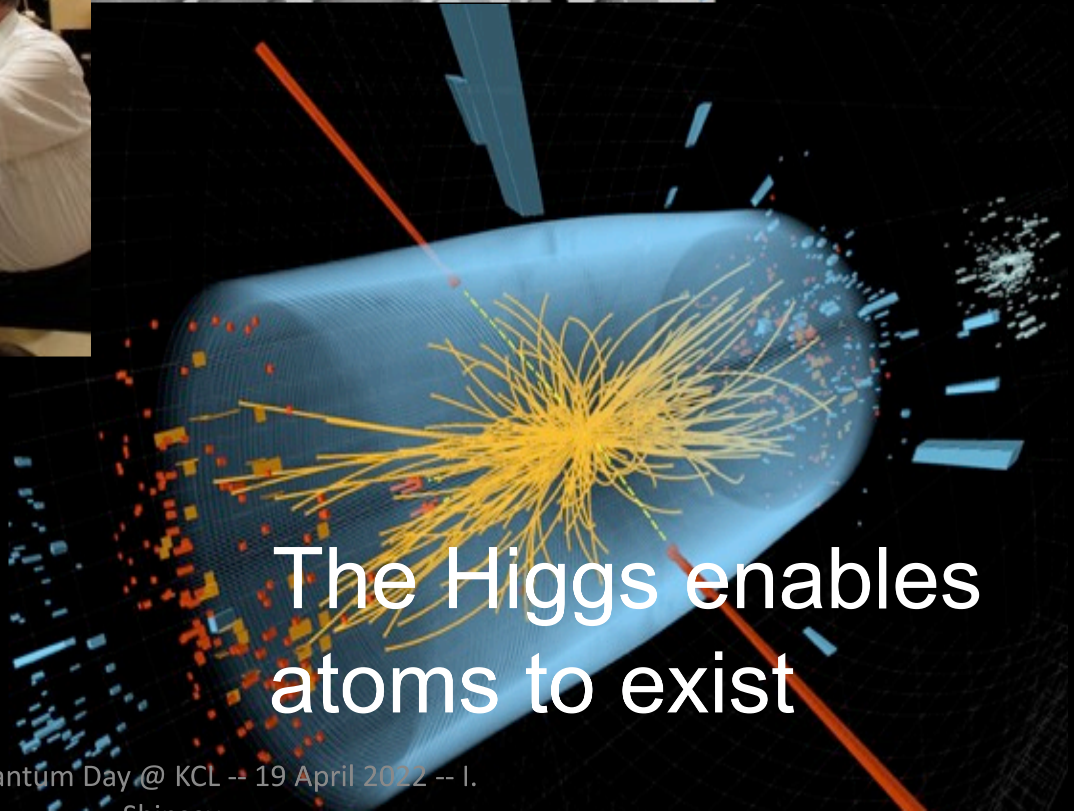
2012.7.4

discovery of Higgs boson





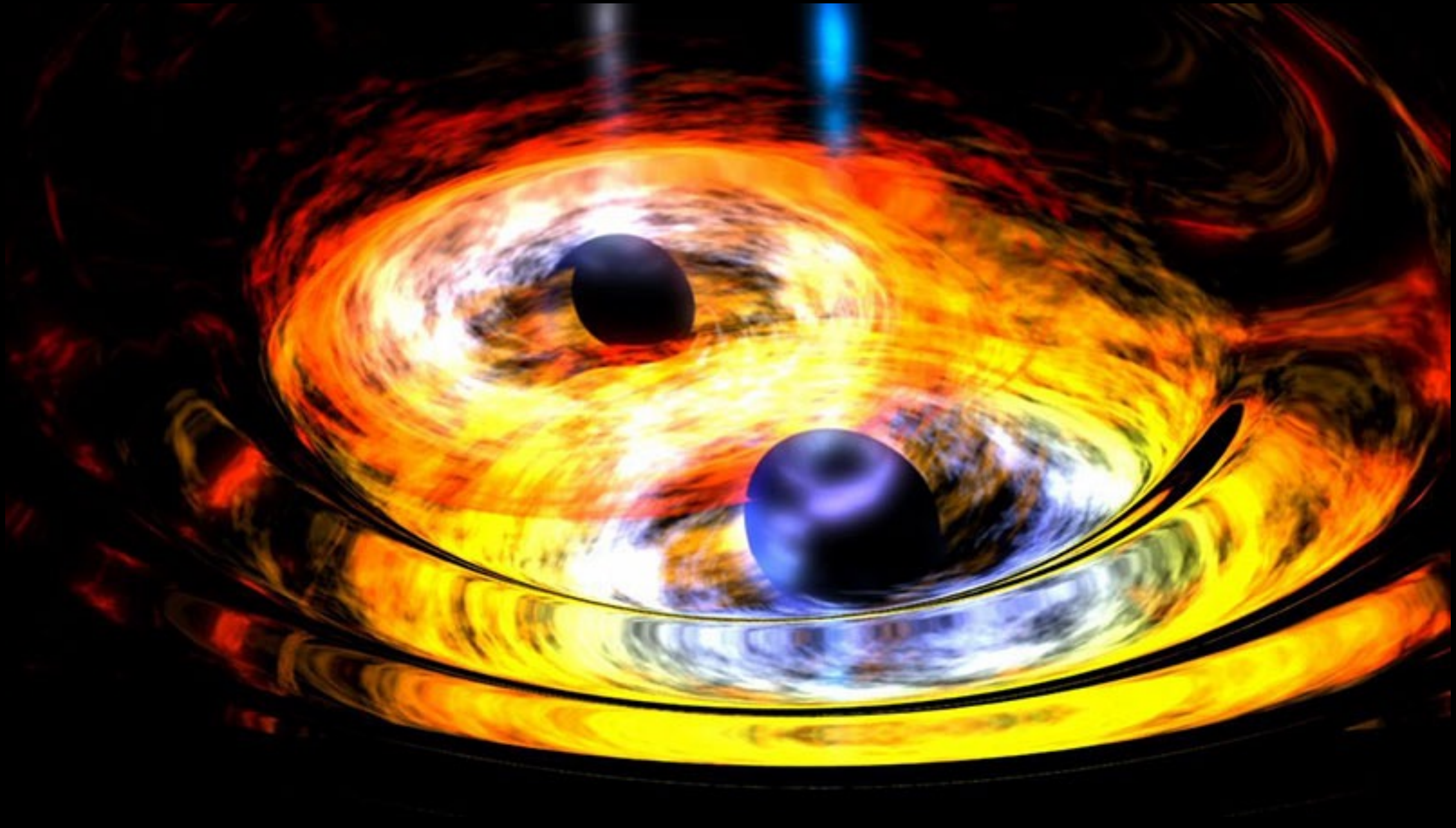
The Higgs enables atoms to exist

theory : 1964

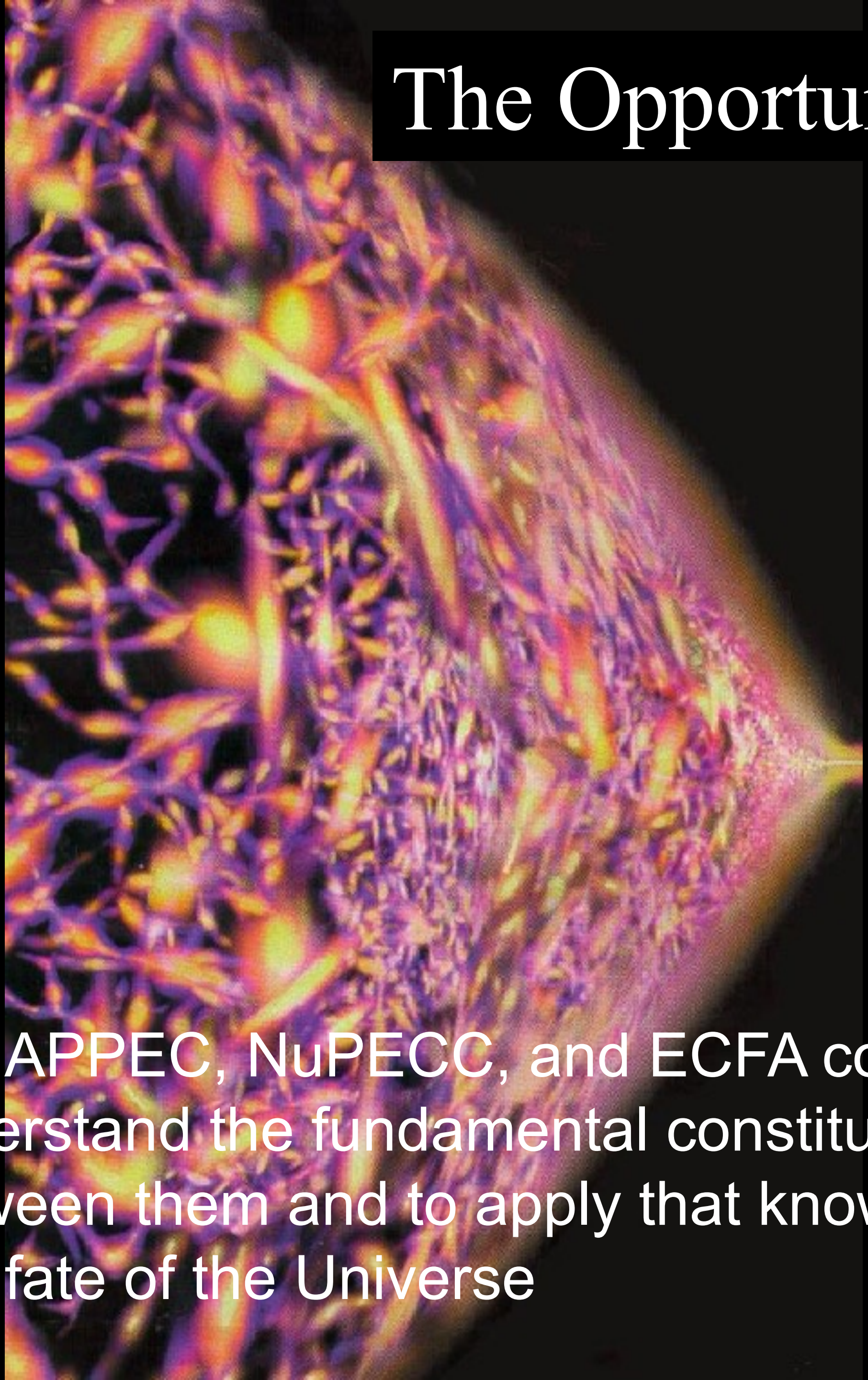
design : 1984

construction : 1998

Detection of gravitational waves
LIGO February, 2016

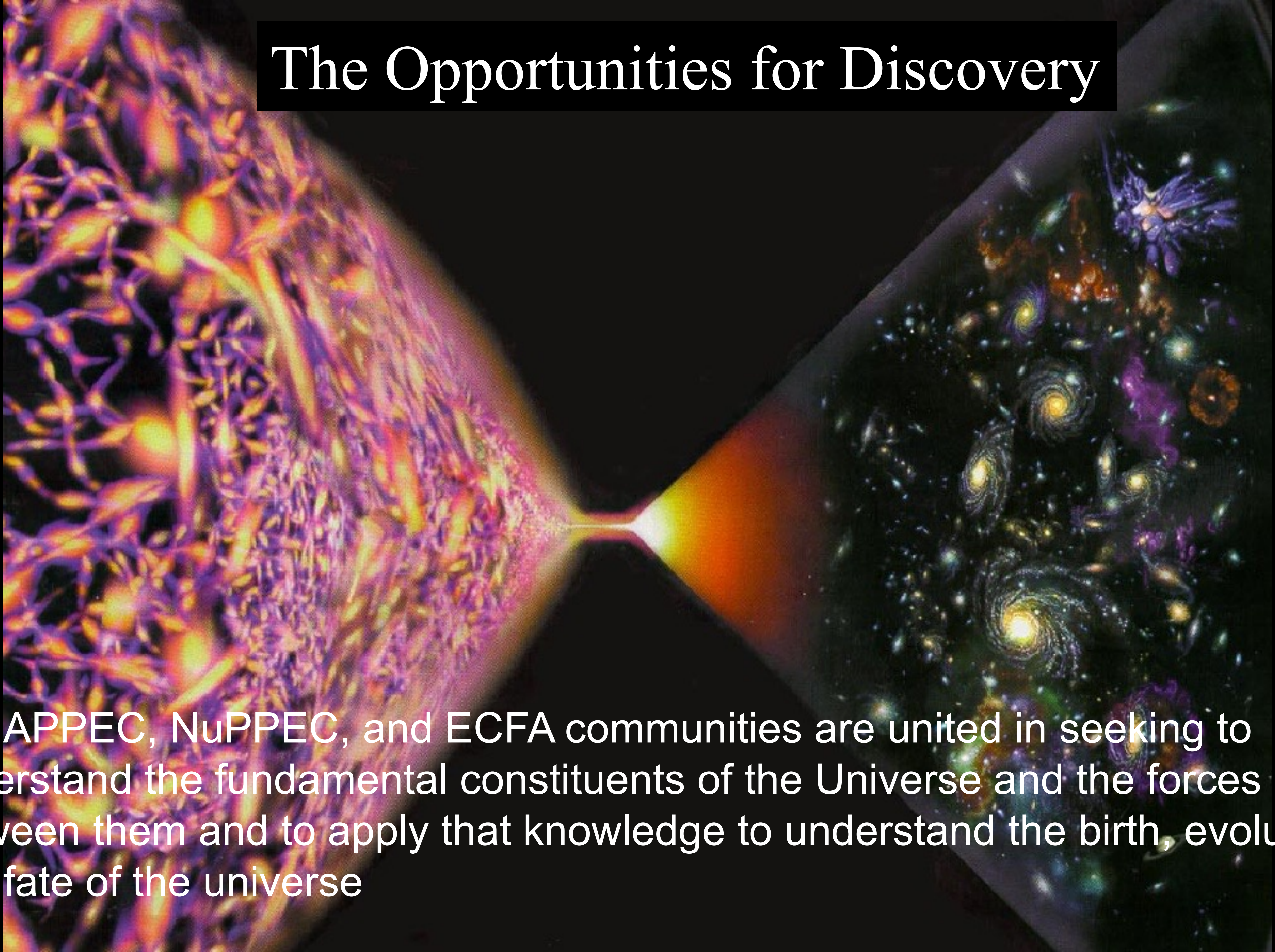


The Opportunities for Discovery



The APPEC, NuPECC, and ECFA communities are united in seeking to understand the fundamental constituents of the Universe and the forces between them and to apply that knowledge to understand the birth, evolution and fate of the Universe

The Opportunities for Discovery



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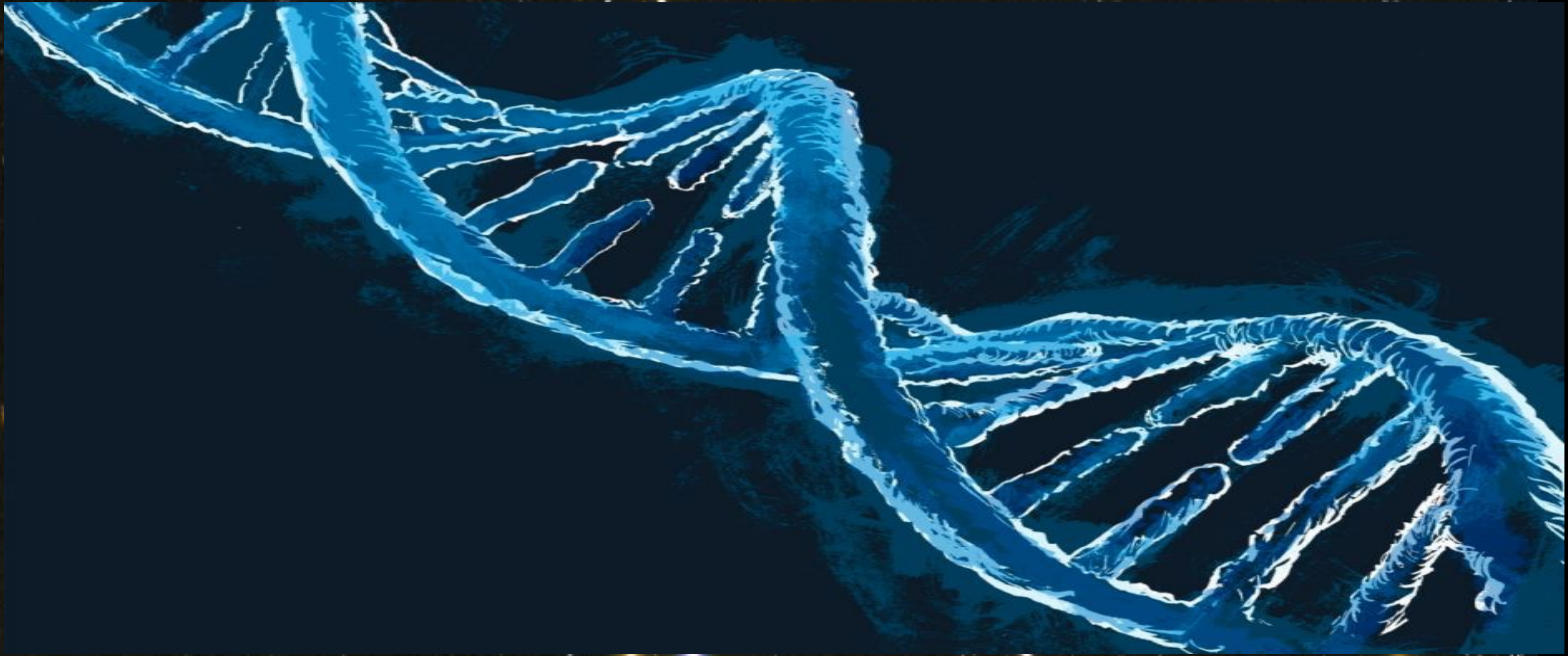
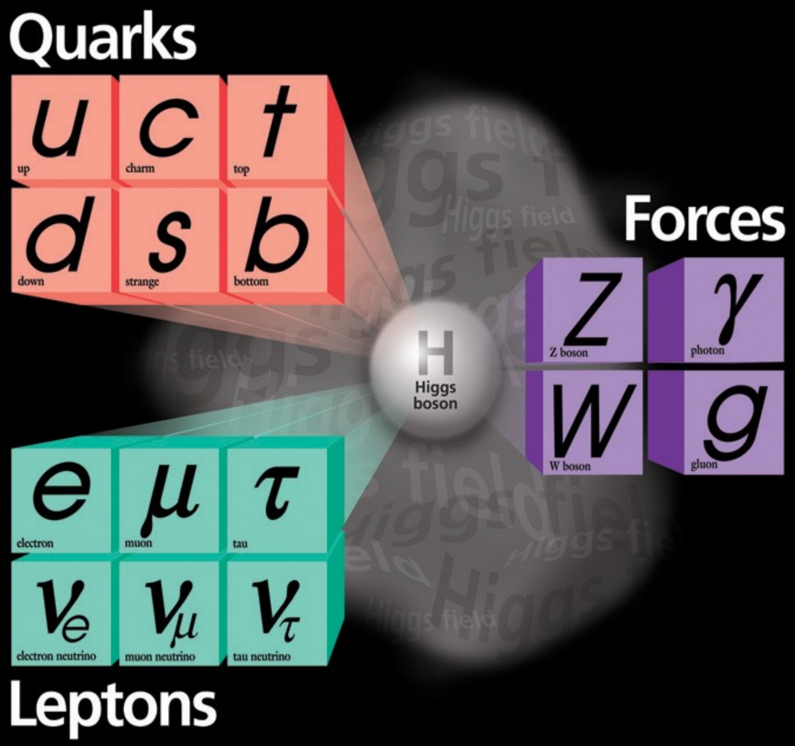
BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

Our communities have revolutionized human understanding of the Universe – its underlying code, structure and evolution

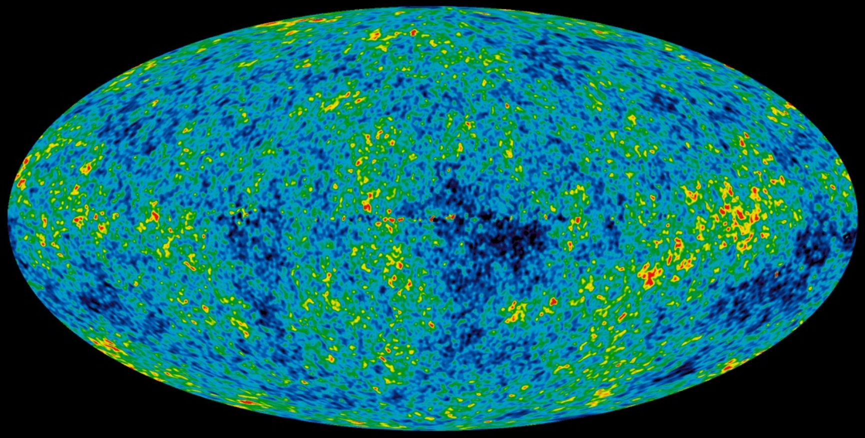


BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

Particle Standard Model



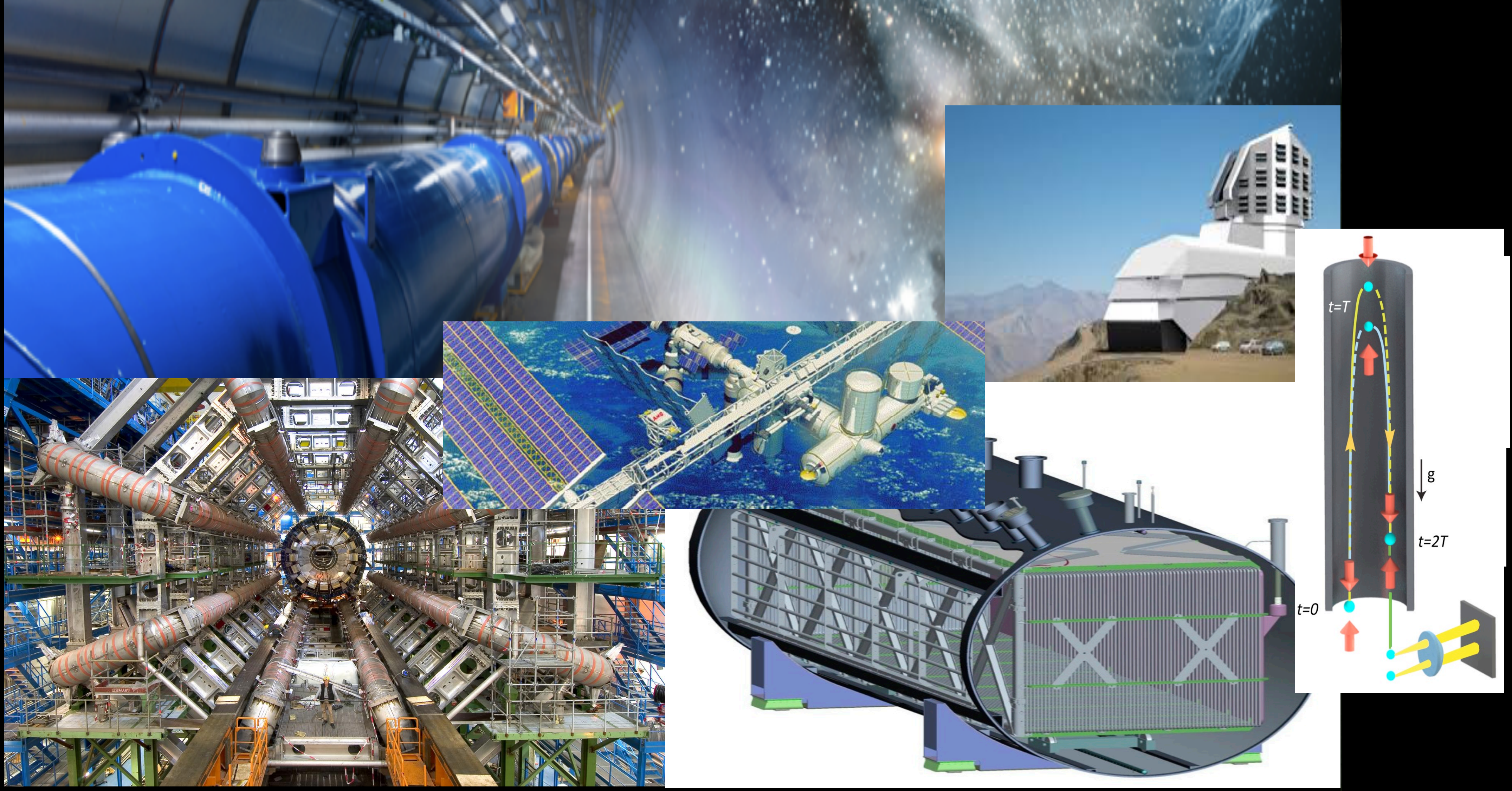
Cosmology Standard Model



Λ_{CDM}

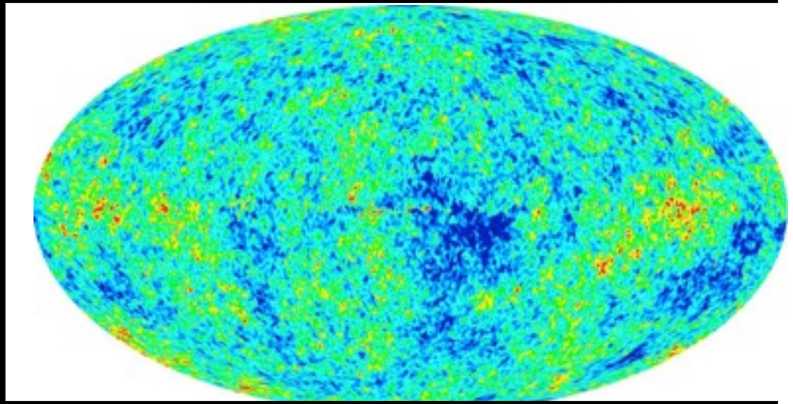
……enabled by instrumentation

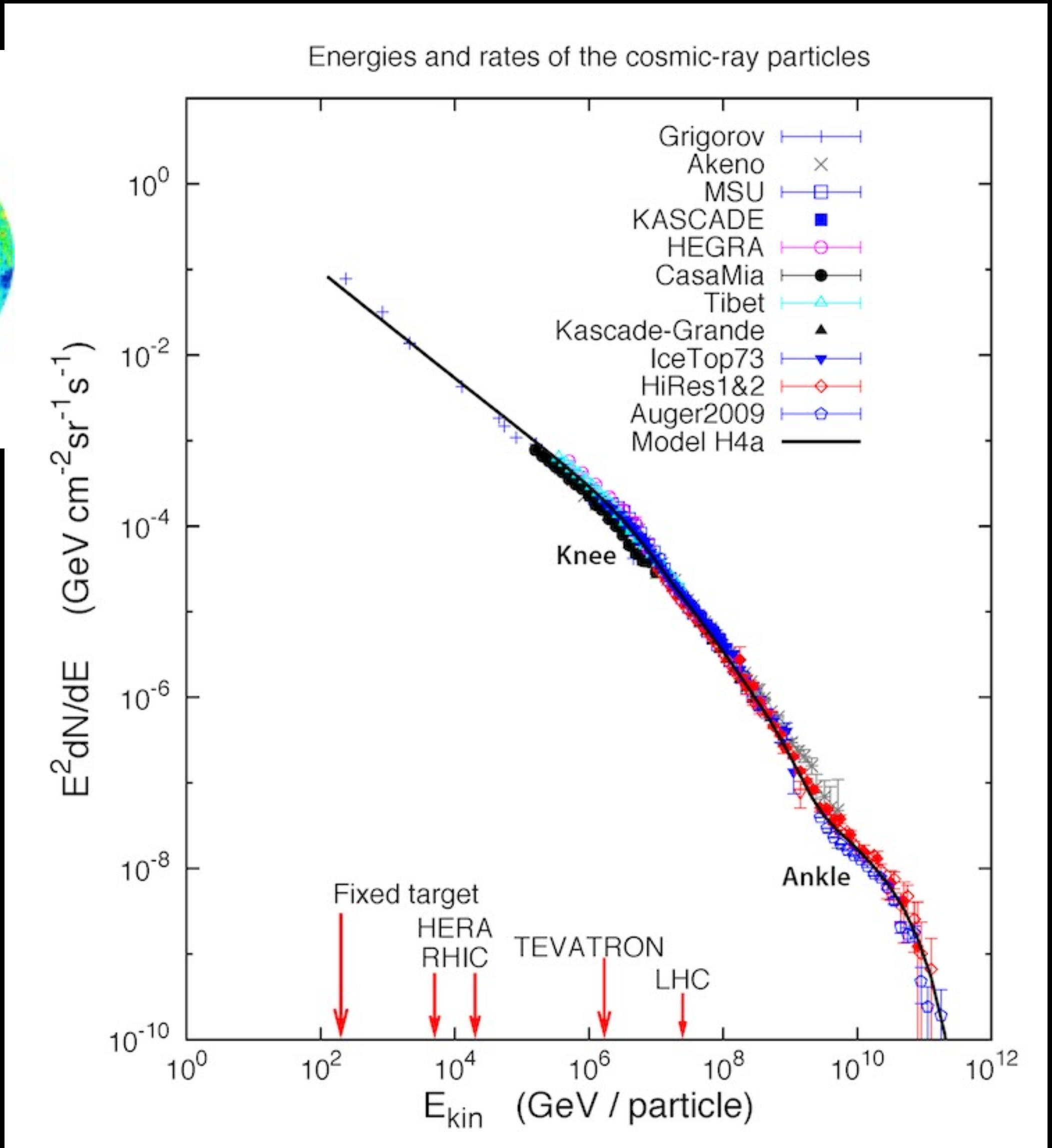
APPEC
ECFA
NuPECC



Our APPEC/ECFA/NuPECC scope is broad and we deploy many tools; accelerator, non-accelerator, astrophysical & cosmological observations all have a critical role to play

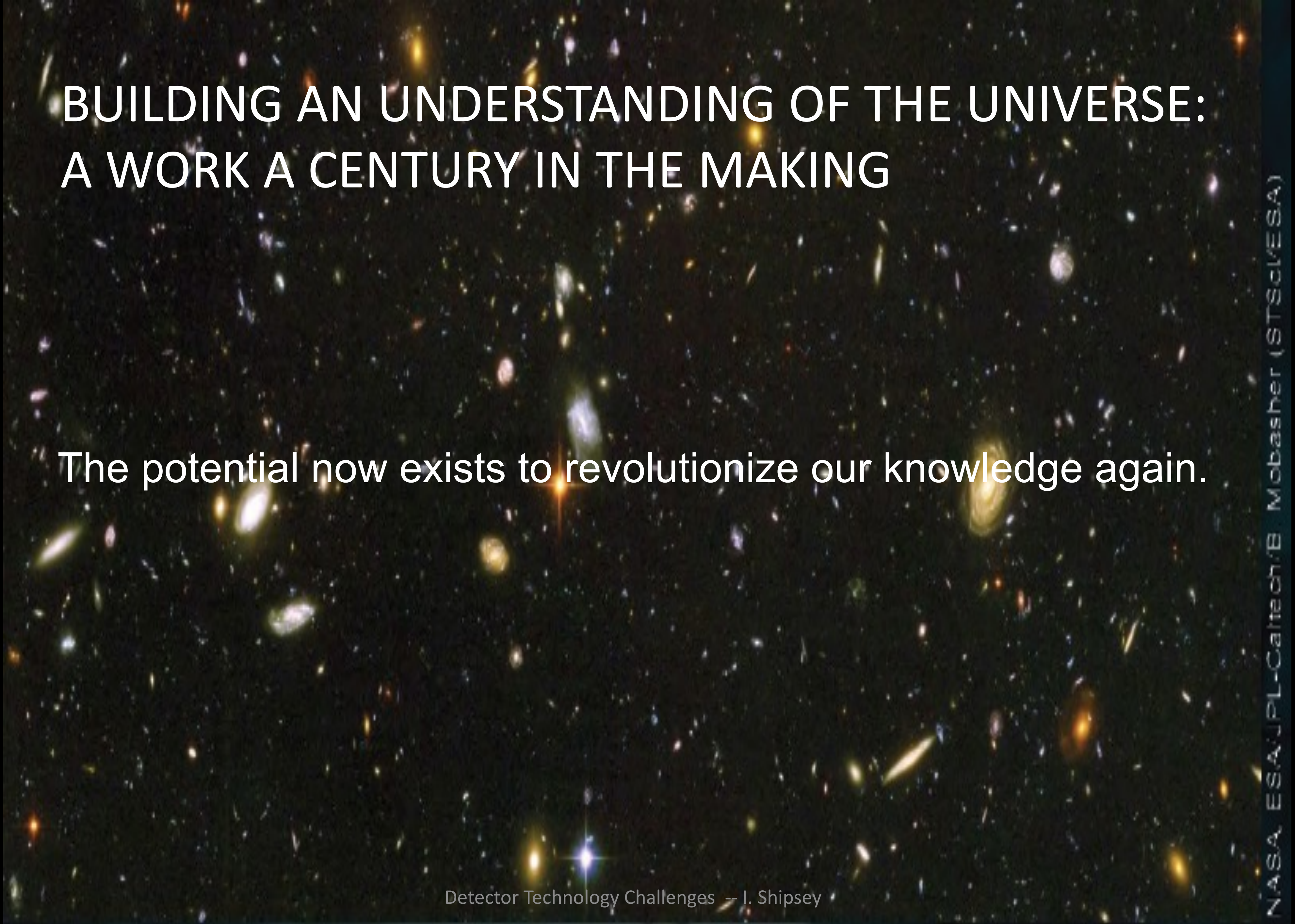
Detect & Measure over 24 orders of magnitude





A Rich Spectrum of Technologies Developed by our Community

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



The potential now exists to revolutionize our knowledge again.

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

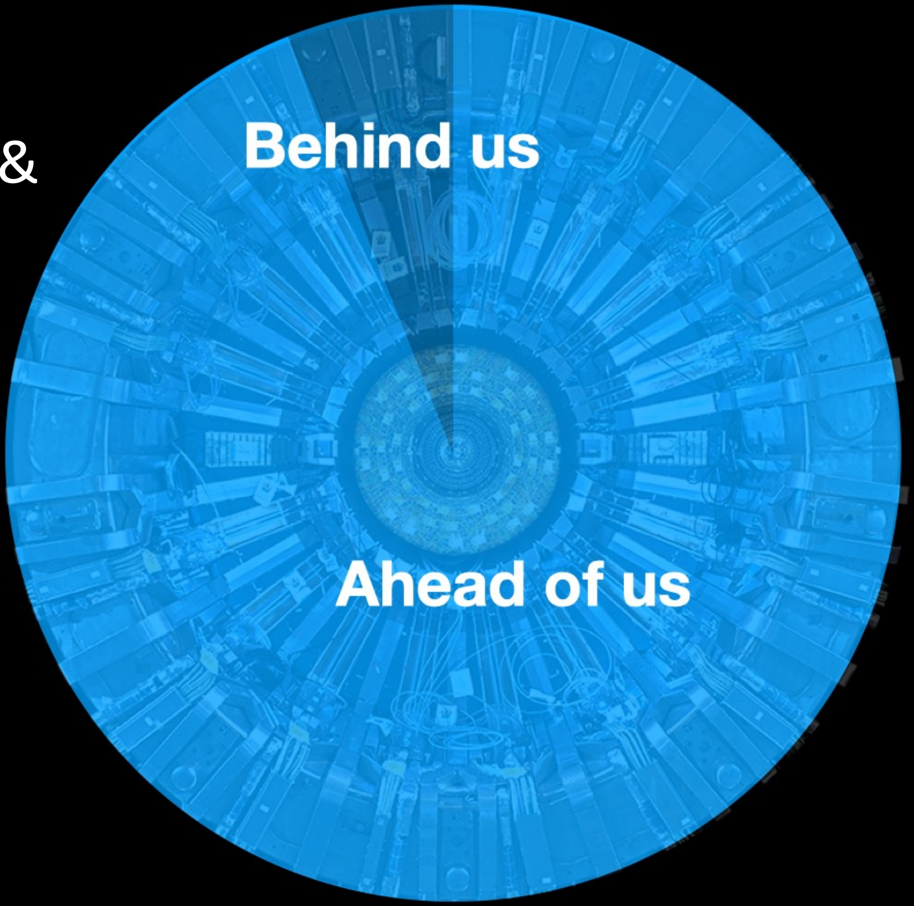
The mystery of Gravity

How do quarks and gluons give rise to the properties of nuclei
The mystery of the origin and engine of high energy cosmic particles

Multiple theoretical solutions – experiment must guide the way

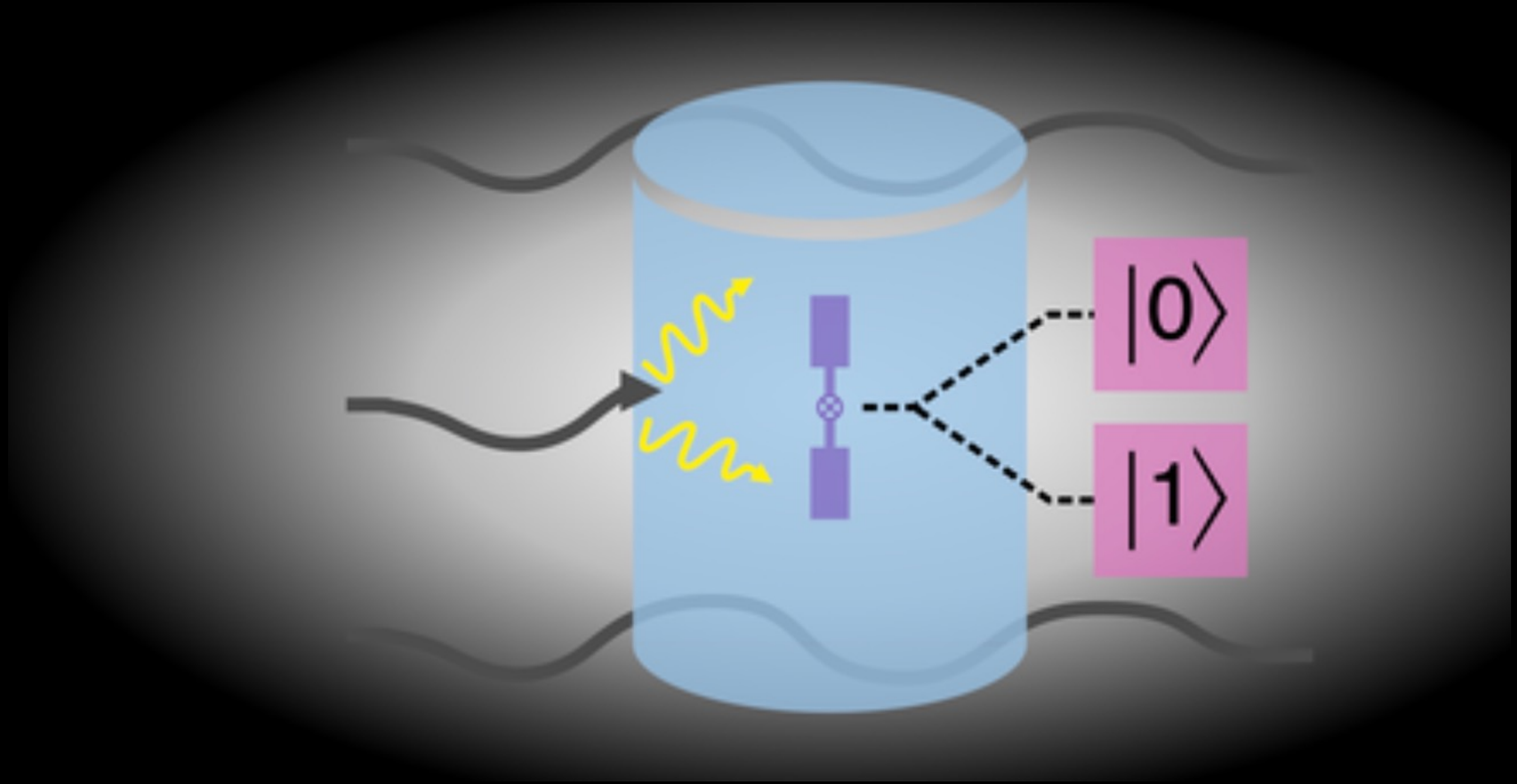
We are very much in a data driven era for which we need new tools!

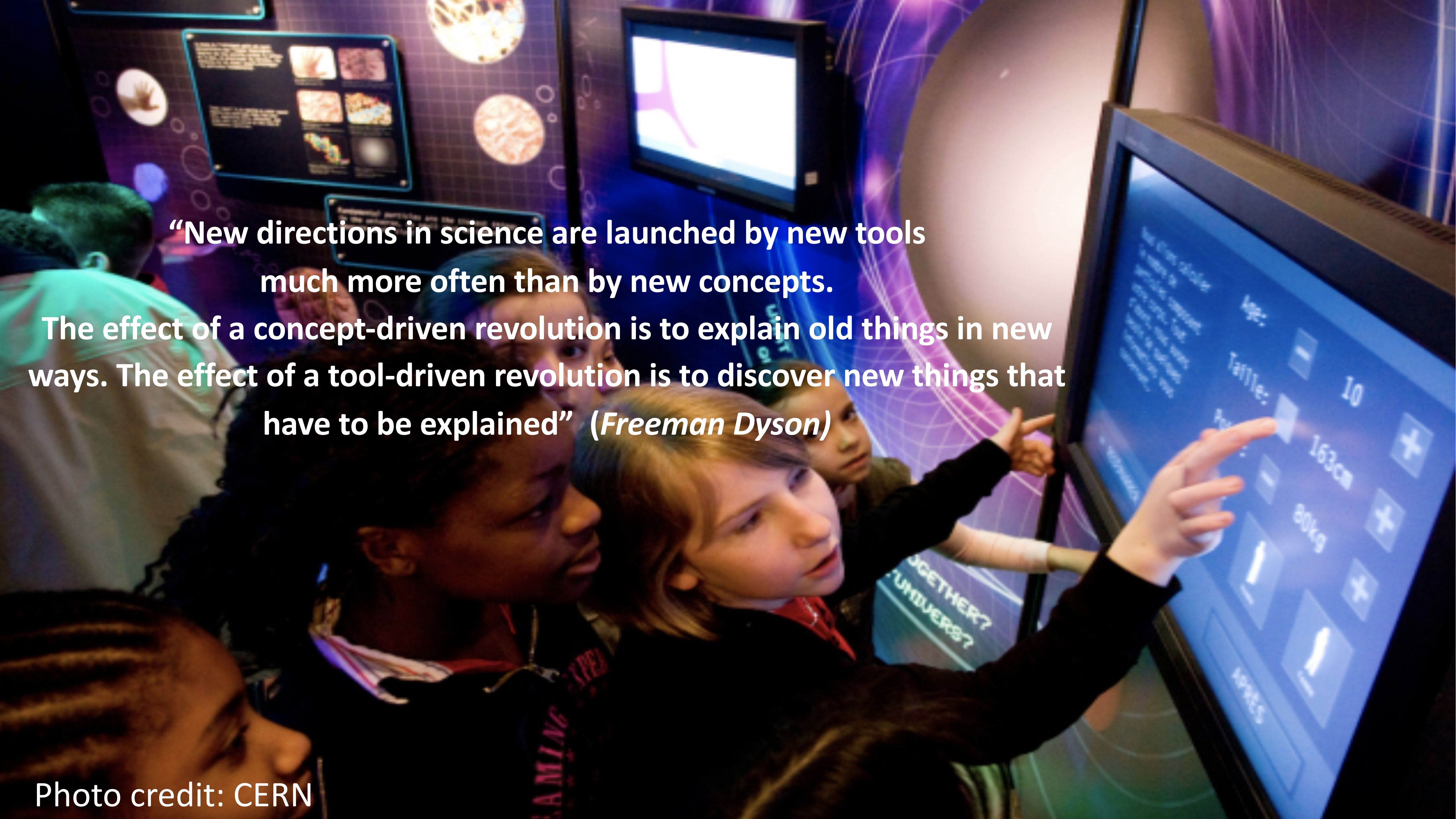
New tools:
e.g. the HL-LHC upgrades &
later FCC-ee/hh etc.



Only ~4% of the complete LHC/ HL-LHC data set
has been delivered to date
There is every reason to be optimistic that
an important discovery could come at any time

New tools e.g. Qubits as cameras





"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)*

Photo credit: CERN

“Measure what is measurable, and make measurable what is not so” (*Galileo Galilei*)

Photo credit: CERN

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	
AGS BNL (1960)	π N interactions	
FNAL Batavia (1970)	Neutrino Physics	
SLAC Spear (1970)	ep, QED	
ISR CERN (1980)	pp	
PETRA DESY (1980)	top quark	
Super Kamiokande (2000)	Proton Decay	
Telescopes (2000)	SN Cosmology	

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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
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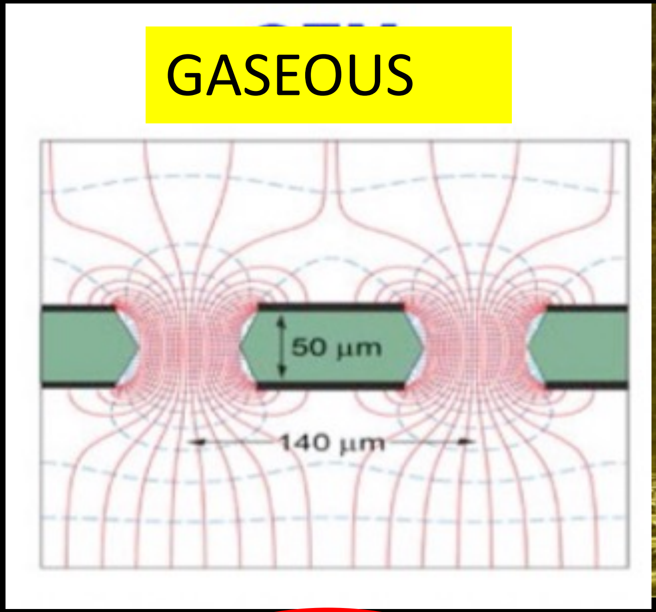
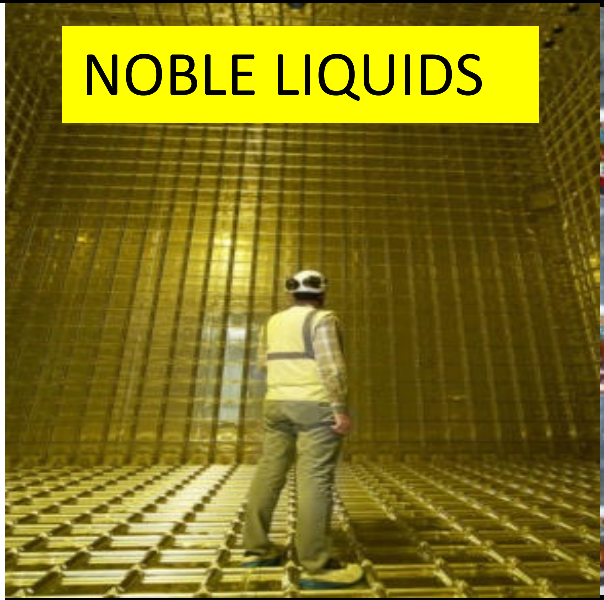
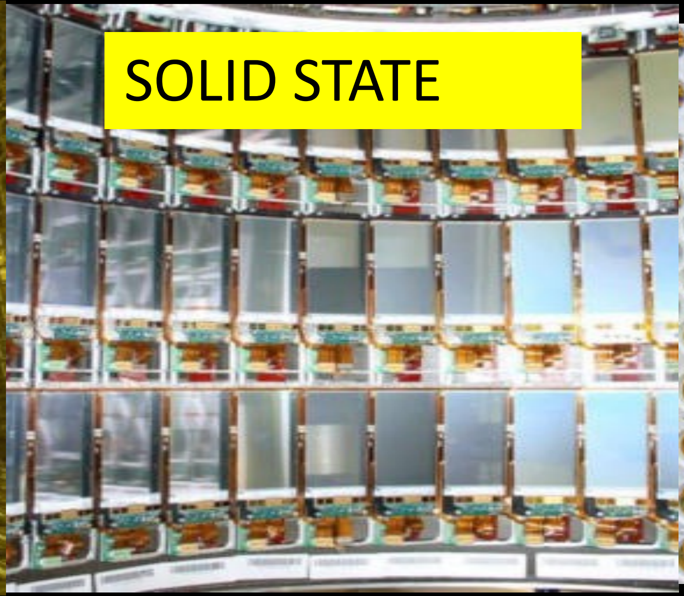
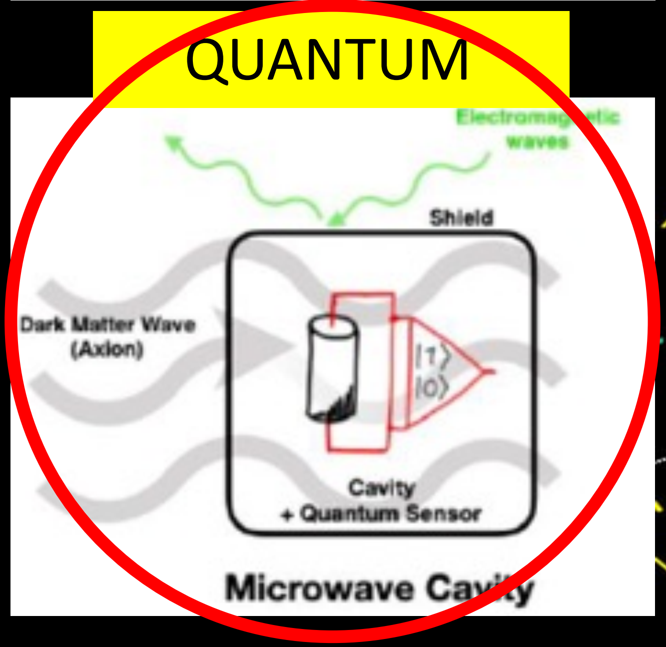
precision instruments are key to discovery when exploring new territory

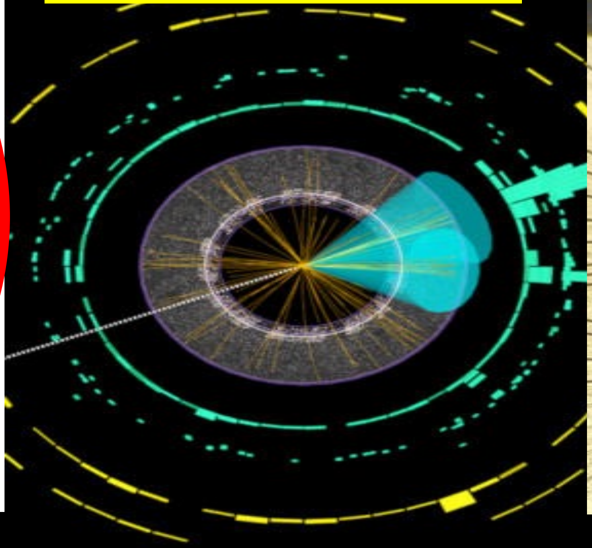
Technology Classification for the ECFA R&D Roadmap

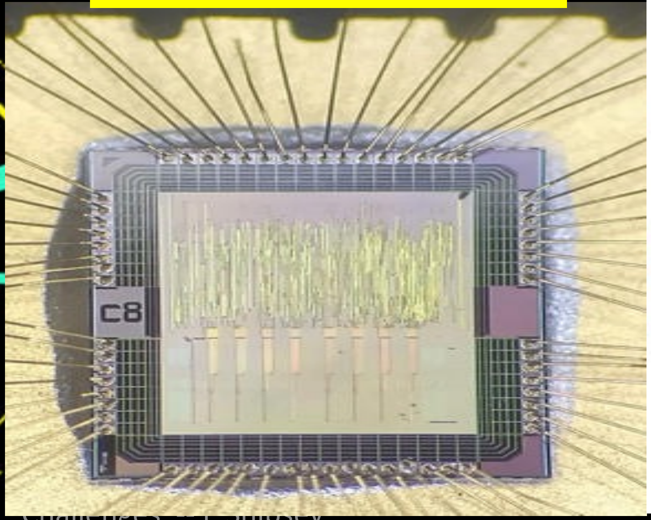


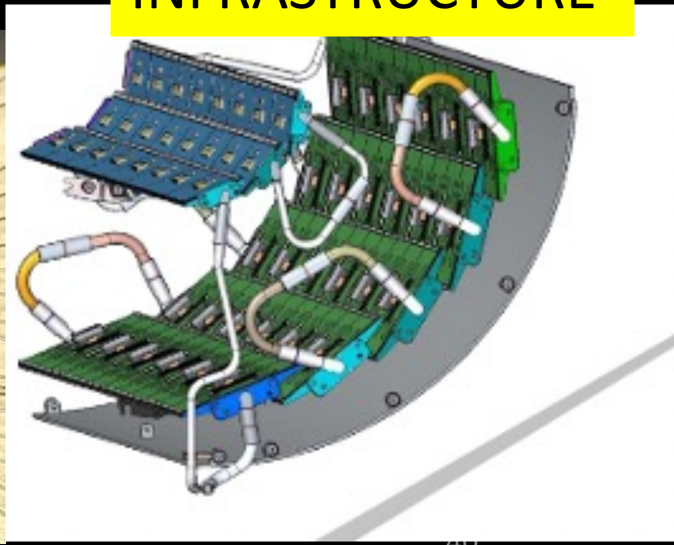












quantum sensors register a change of quantum state caused by the interaction with an external system:

- transition between superconducting and normal-conducting
- transition of an atom from one state to another
- change of resonant frequency of a system (quantized)

Then, ***a "quantum sensor" is a device, the measurement (sensing) capabilities of which are enabled by our ability to manipulate and read out its quantum states***.

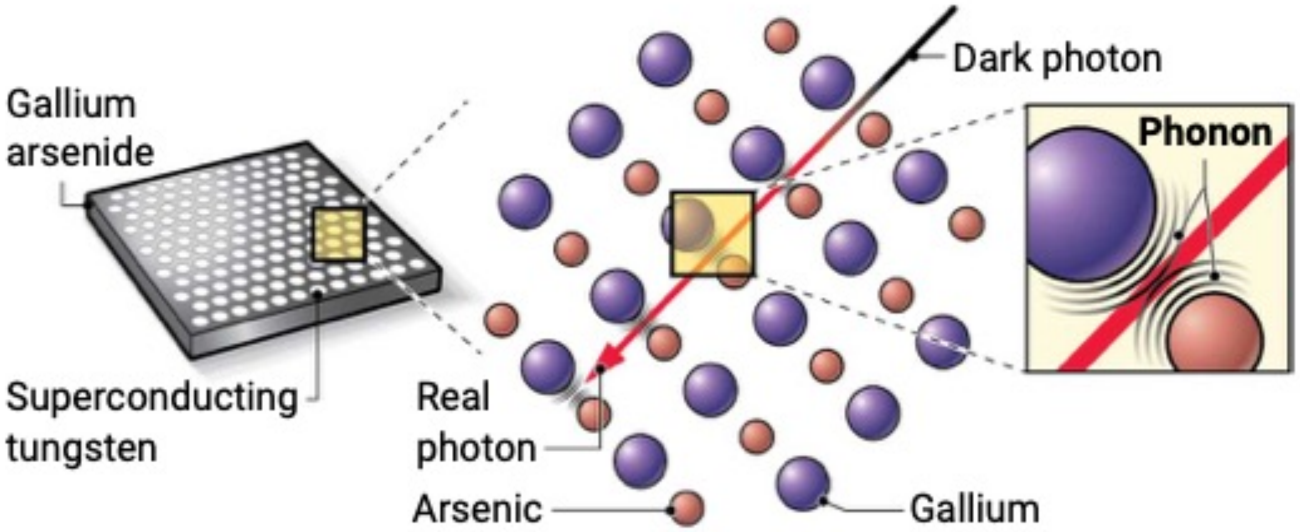
and because the commensurate energies are very low, unsurprisingly, quantum sensors are ideally matched to low energy (particle) physics;

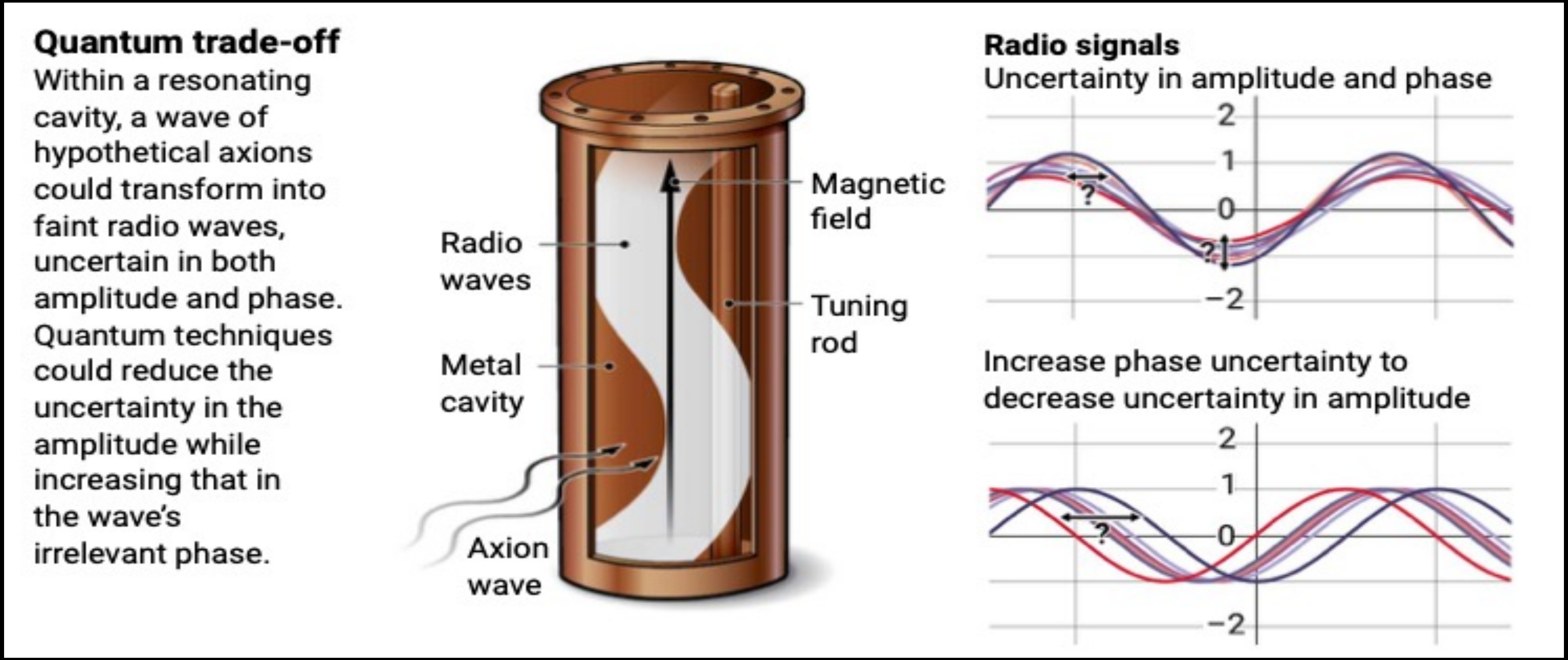
Particles and waves

Quantum detectors include devices that can detect a single quantum, such as a photon, and devices that exploit a quantum trade-off to measure one variable more precisely at the cost of greater uncertainty in another.

Just one click

A dark matter candidate called a dark photon could morph into an ordinary photon that would trigger a quantized vibration in a crystal. The vibration, or phonon, would warm superconducting heat sensors on the crystal.

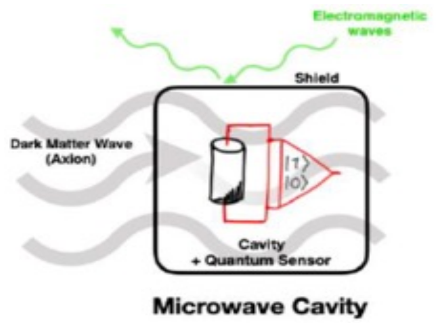



Quantum trade-off
Within a resonating cavity, a wave of hypothetical axions could transform into faint radio waves, uncertain in both amplitude and phase. Quantum techniques could reduce the uncertainty in the amplitude while increasing that in the wave's irrelevant phase.
Radio waves
Metal cavity
Axion wave
Magnetic field
Tuning rod
Radio signals
Uncertainty in amplitude and phase
2
1
0
−2
?
Increase phase uncertainty to decrease uncertainty in amplitude
2
1
0
−2
?

Quantum and emerging technologies

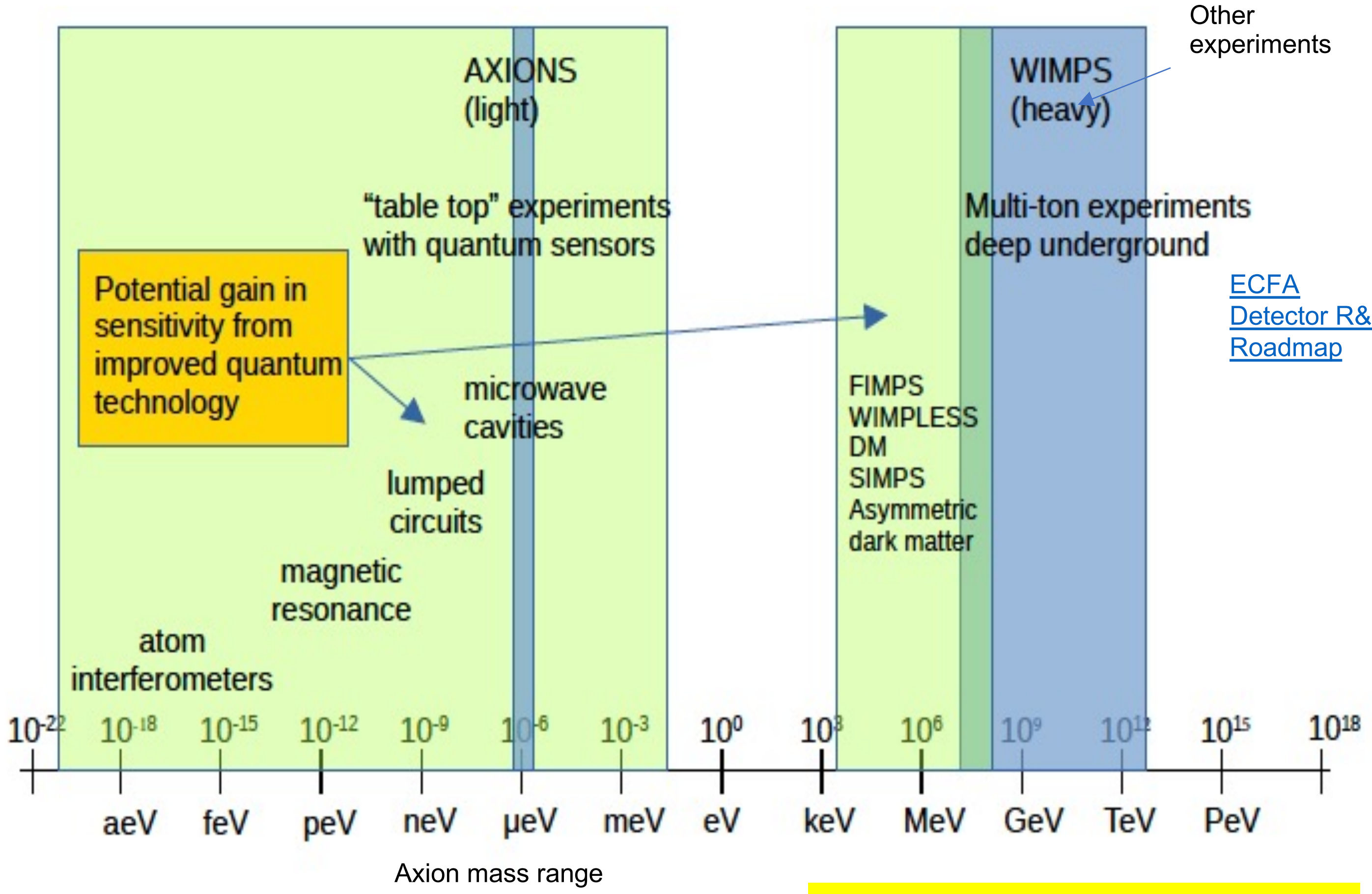
- **Quantum Technologies are a rapidly emerging area** of technology development to study fundamental physics
- The ability to engineer quantum systems to improve on the measurement sensitivity holds great promise
- **Many different sensor and technologies being investigated**: clocks and clock networks, spin-based, superconducting, optomechanical sensors, atoms/molecules/ions, atom interferometry, …
- Several initiatives started at CERN, DESY, FNAL, US, UK, …

QUANTUM TECHNOLOGY INITIATIVE



S. Golawa

Example: potential mass ranges that quantum sensing approaches open up for Axion searches



ECFA Detector R&D Roadmap

Blue: now
Light green: with quantum

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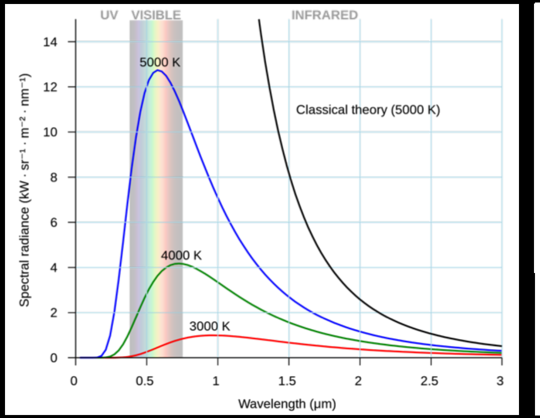
While quantum sensors are not new they have suddenly become prominent and this is due both to technological advances & to greater appreciation in the world for quantum mechanics

Quantum 1.0



Blackbody Radiation

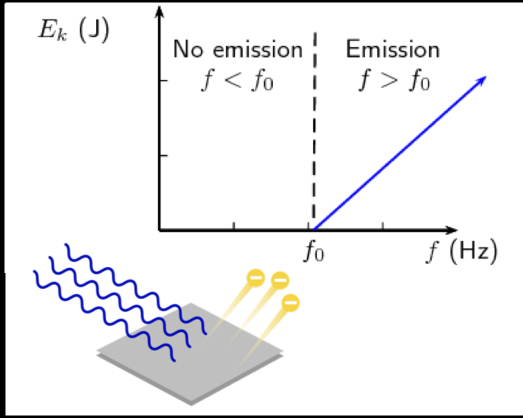
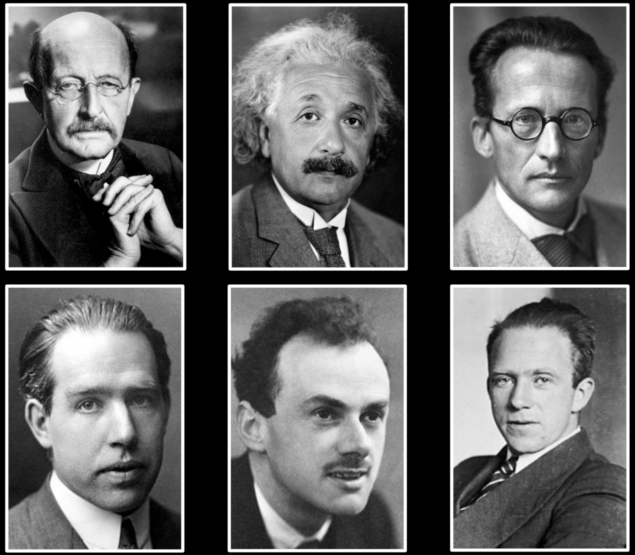
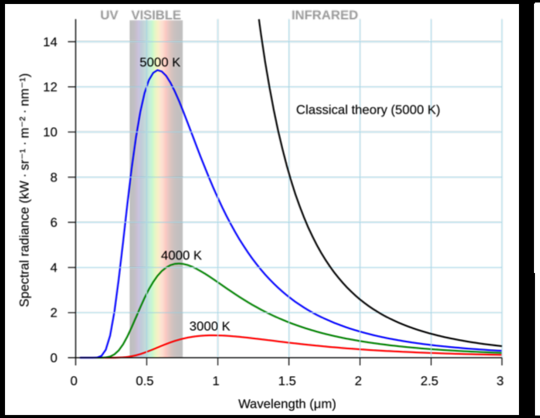


Photo-electric Effect

Quantum Mechanics



Quantum 1.0



Blackbody Radiation

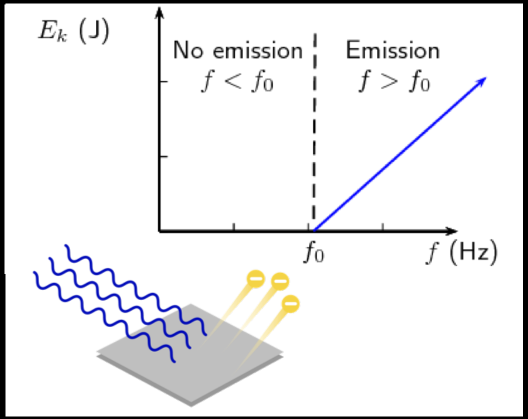
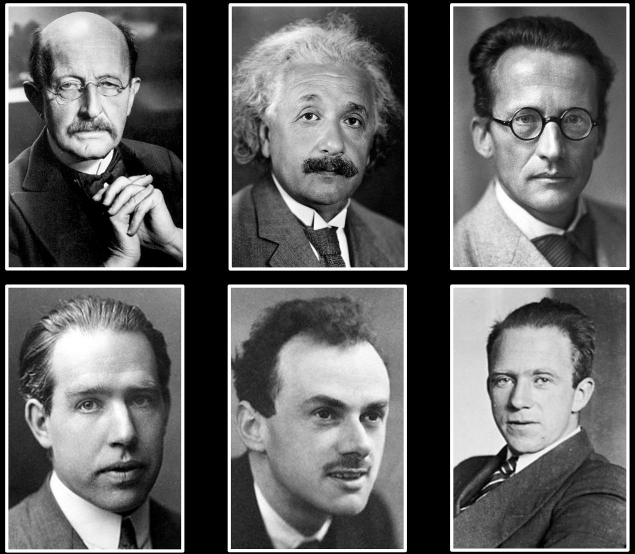


Photo-electric Effect

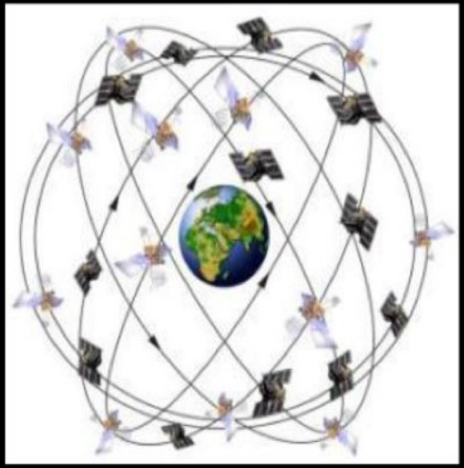
Quantum Mechanics



Exascale Computing

Laser Technology

Magnetic Resonance Imaging



Global Positioning System

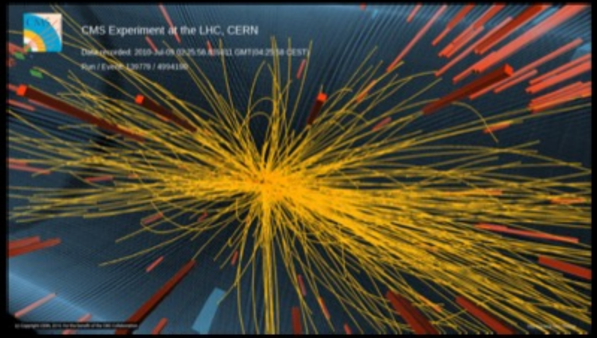
Quantum 1.0


09:41
100 %
mercredi
7
Mail
Calendrier
Photos
Appareil photo
Plans
Horloge
Météo
Wallet
Notes
Rappels
Bourse
Vidéos
iBooks
iTunes Store
App Store
Domicile
Santé
Réglages
Téléphone
Safari
Messages
Musique

Quantum 2.0

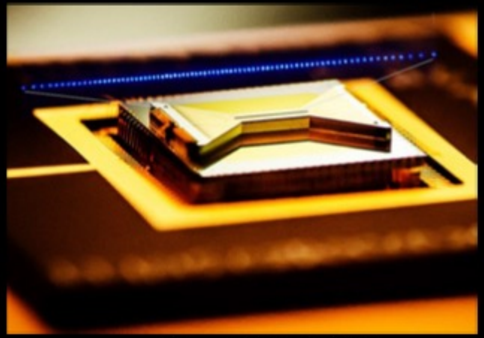
The First Quantum Revolution: exploitation of quantum matter to build devices
Second Quantum Revolution: engineering of large quantum systems with full control of the quantum state of the particles, e.g. entanglement

AI, ML on Quantum annealer



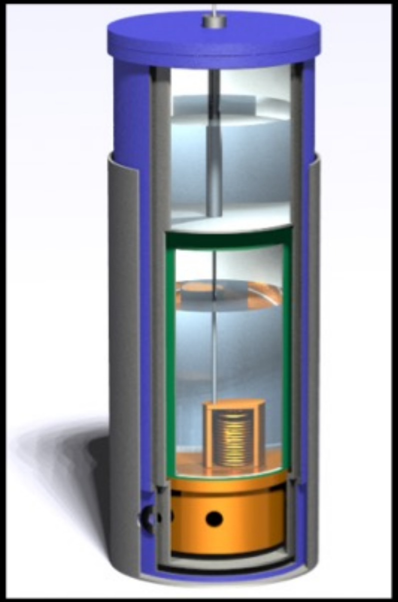
Nature 550 (2017) 375

IonQ >60-qubit



arXiv:1902.10171

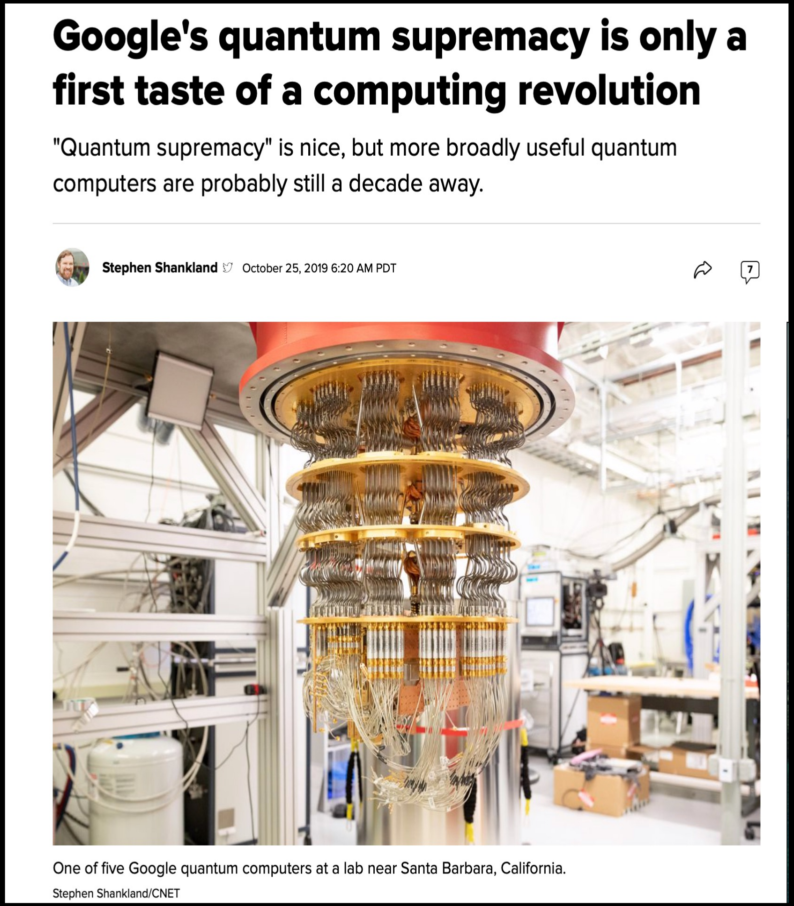
Atomic clocks



Nature (564) 87 (2018)

Quantum 2.0

The First Quantum Revolution: exploitation of quantum matter to build devices
Second Quantum Revolution: engineering of large quantum systems with full control of the quantum state of the particles, e.g. entanglement



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

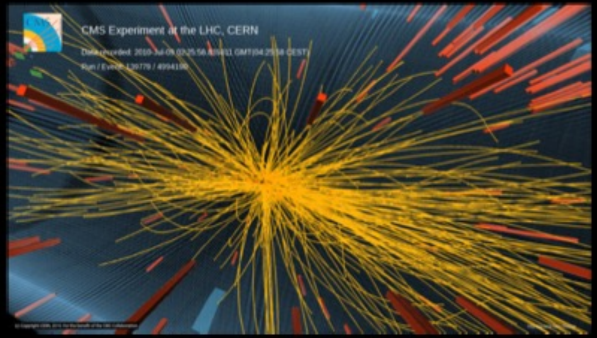
"Quantum supremacy" is nice, but more broadly useful quantum computers are probably still a decade away.

Stephen Shankland October 25, 2019 6:20 AM PDT

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

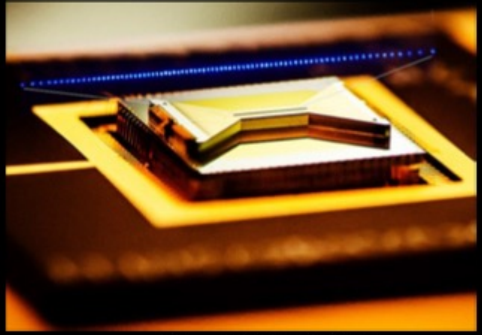
Stephen Shankland/CNET

AI, ML on Quantum annealer



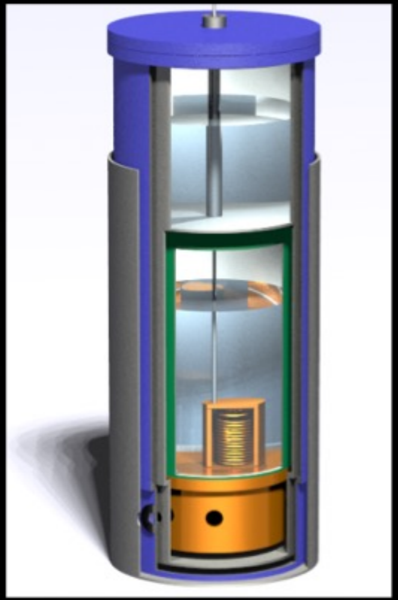
Nature 550 (2017) 375

IonQ >60-qubit



arXiv:1902.10171

Atomic clocks



Nature (564) 87 (2018)

Quantum 2.0

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Photos
Appareil photo
Plans
Horloge
Météo
Wallet
Notes
Rappels
Bourse
Vidéos
iBooks
iTunes Store
App Store
Domicile
Santé
Réglages
Téléphone
Safari
Messages
Musique

"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

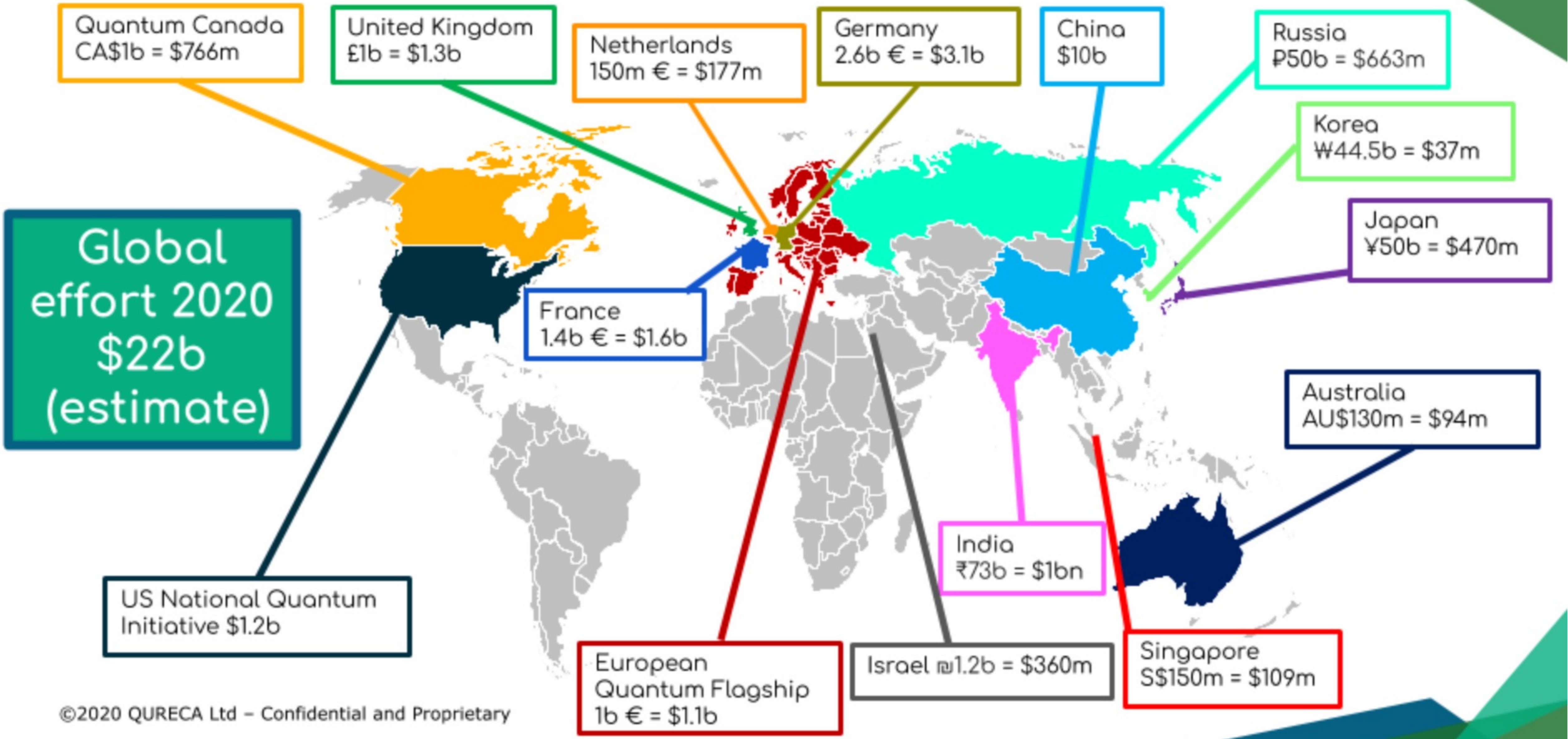
Quantum Liquid Crystals

Quantum Mind Interface

Quantum enabled searches for dark matter

Quantum Gravity

Quantum Technologies Public Funding Worldwide



£1bn UK National Quantum Technology Programme Pillars

2019

UKRI Engineering and Physical Sciences Research Council

QT Hubs, Training and Skills, CDTs
£360M

Translating research into applications

Industry-pick up points

UKRI Innovate UK

IUK, ISCF, Industry
£450M

Prototypes

Products

Spin-offs

Department for Business, Energy & Industrial Strategy

NPL National Physical Laboratory

Quantum Metrology Institute
£30M

Standards

Validation

GCHQ [dstl] Ministry of Defence

Other
£80M

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

£1bn UK National Quantum Technology Programme Pillars

2020

UKRI Science and Technology Facilities Council | UKRI Engineering and Physical Sciences Research Council

Quantum Technologies for Fundamental Physics (QTFP)
£40M

New Ideas

Attracting worldwide talent

Internationally leading science across 7 projects

National Quantum Computing Centre
£93M

UKRI Engineering and Physical Sciences Research Council

QT Hubs, Training and Skills, CDTs
£360M

Translating research into applications

Industry-pick up points

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GCHQ | dstl | Ministry of Defence

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£80M

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

Quantum Technologies and Particle Physics

- The nature of dark matter
- The earliest epochs of the universe at temperatures >> 1TeV
- The existence of new forces
- The violation of fundamental symmetries
- The possible existence of dark radiation and the cosmic neutrino background
- The possible dynamics of dark energy
- The measurement of neutrino mass
- Tests of the equivalence principle
- Tests of quantum mechanics
- A new gravitational wave window to the Universe:
  - LIGO sources before they reach LIGO band
  - Multi-messenger astronomy: optimal band for sky localization
  - Cosmological sources

Quantum Technologies and Particle Physics

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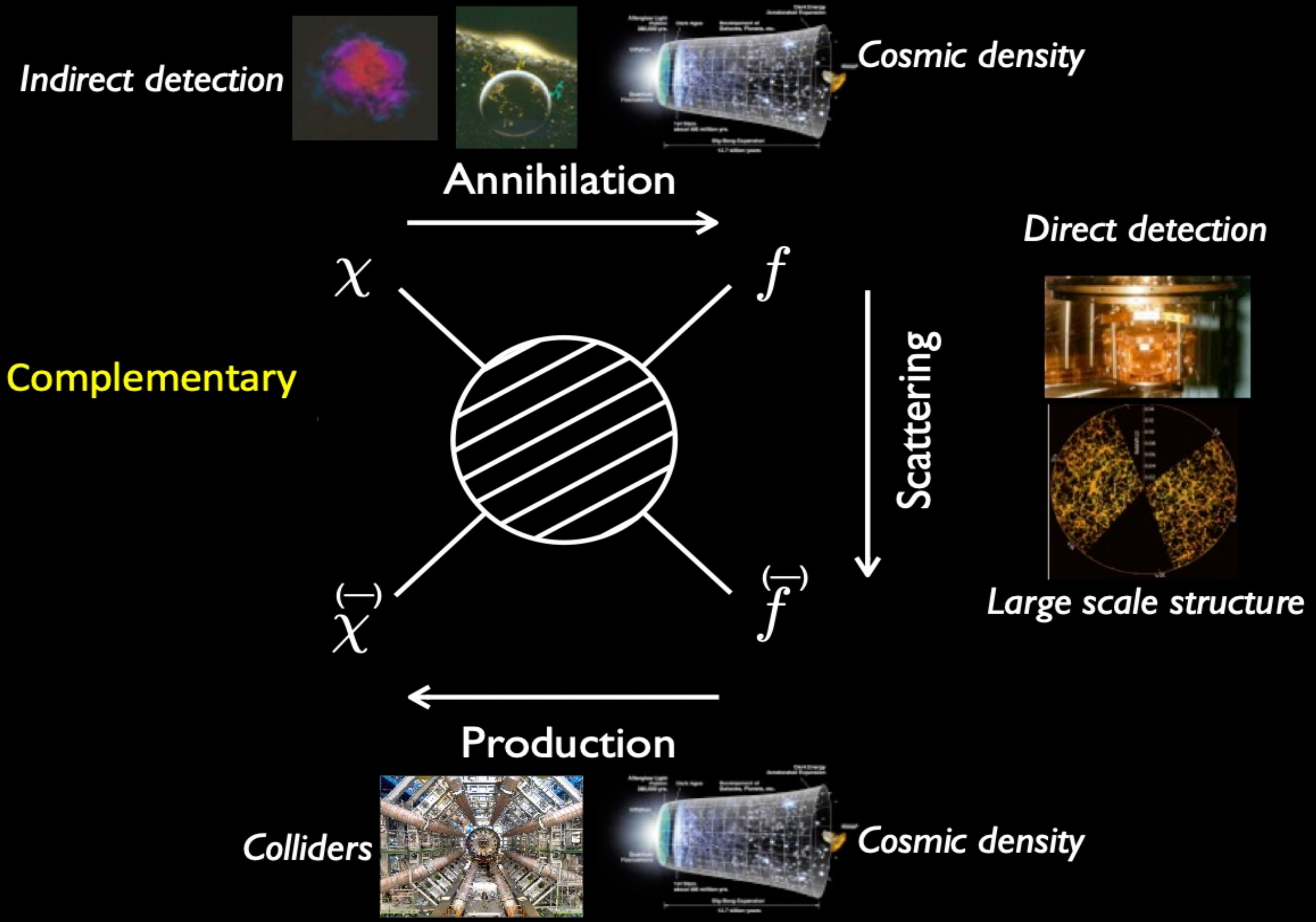
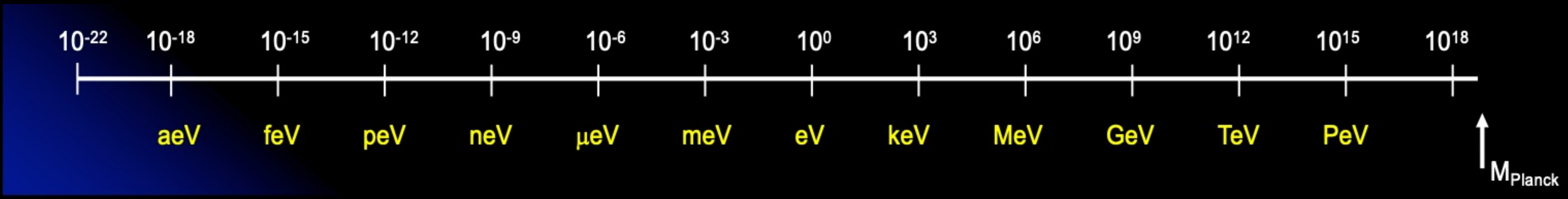
Dark Matter Experimental approaches

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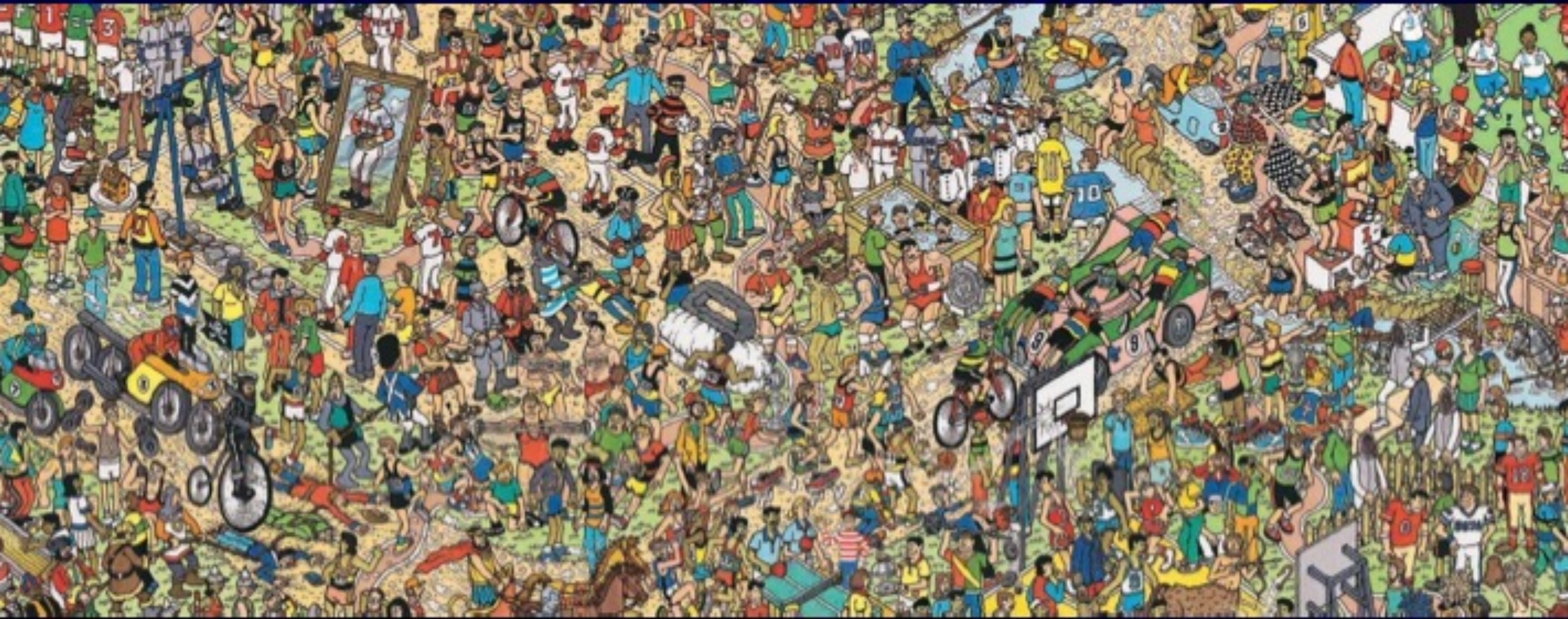
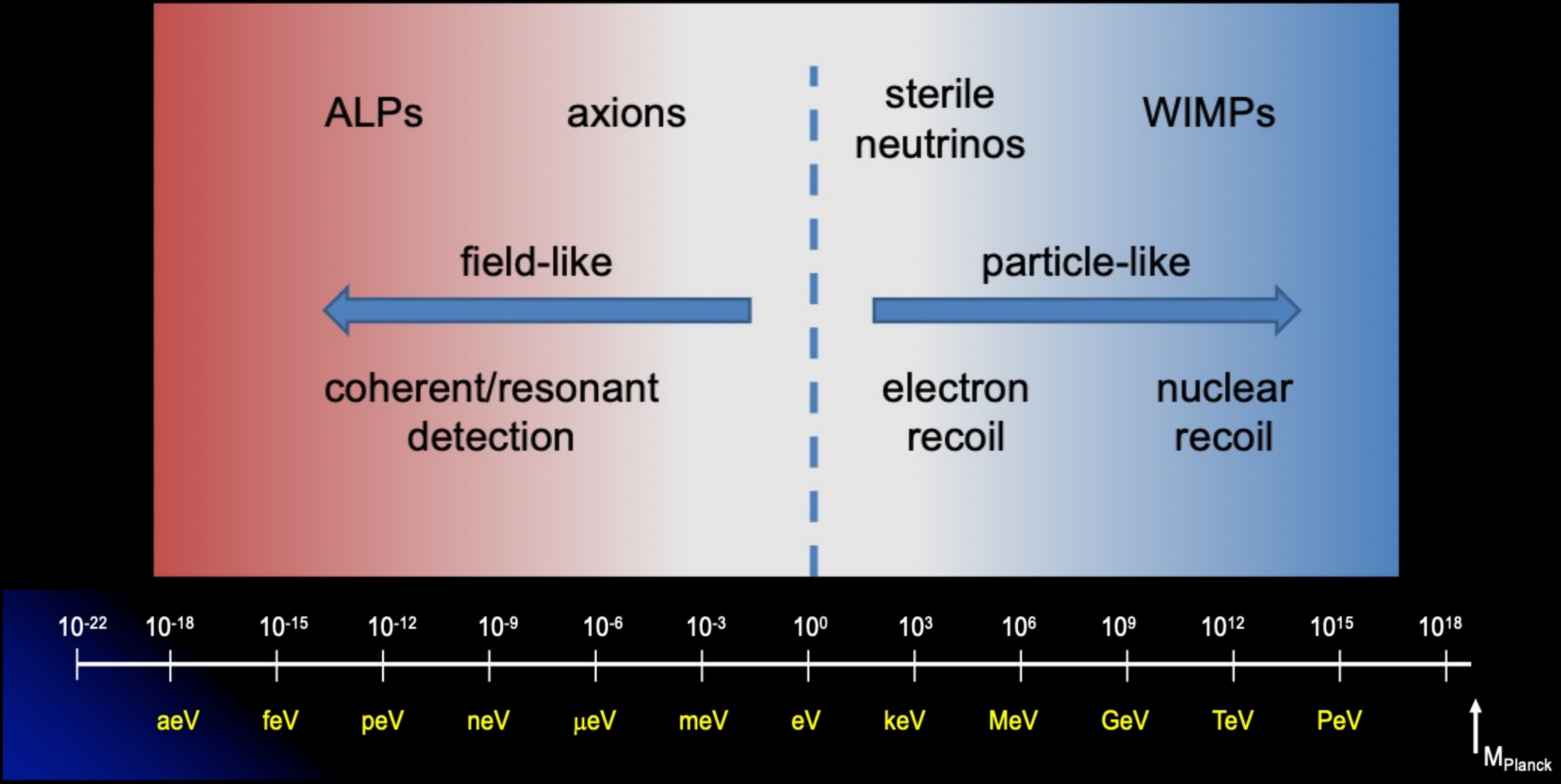
peV
neV
μeV
meV
eV
keV
MeV
GeV
TeV
PeV
MPlanck

Possible Dark Matter Masses

~90 orders of magnitude

10^{-21}eV | eV | GeV | PeV | M_{Planck} | kg | 10^{50}eV | $M_{☽}$ | $M_{\odot}$




ALPs
axions
sterile neutrinos
WIMPs
field-like
particle-like
coherent/resonant detection
electron recoil
nuclear recoil
10-22
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10-12
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neV
μeV
meV
eV
keV
MeV
GeV
TeV
PeV
MPlanck

Dark Matter Search Strategy

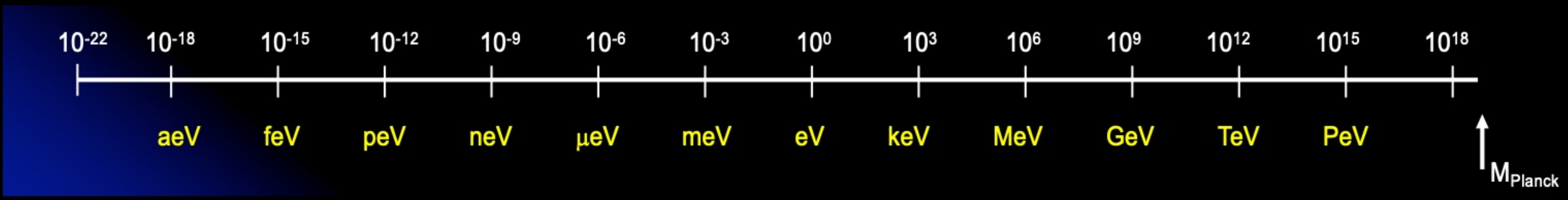
The two theoretically best-motivated candidates:

AXIONS (light)

"table top" expts with quantum sensors

WIMPS (heavy)

Multi-ton expts deep underground



Elements of String Theory

Extra Dimensions

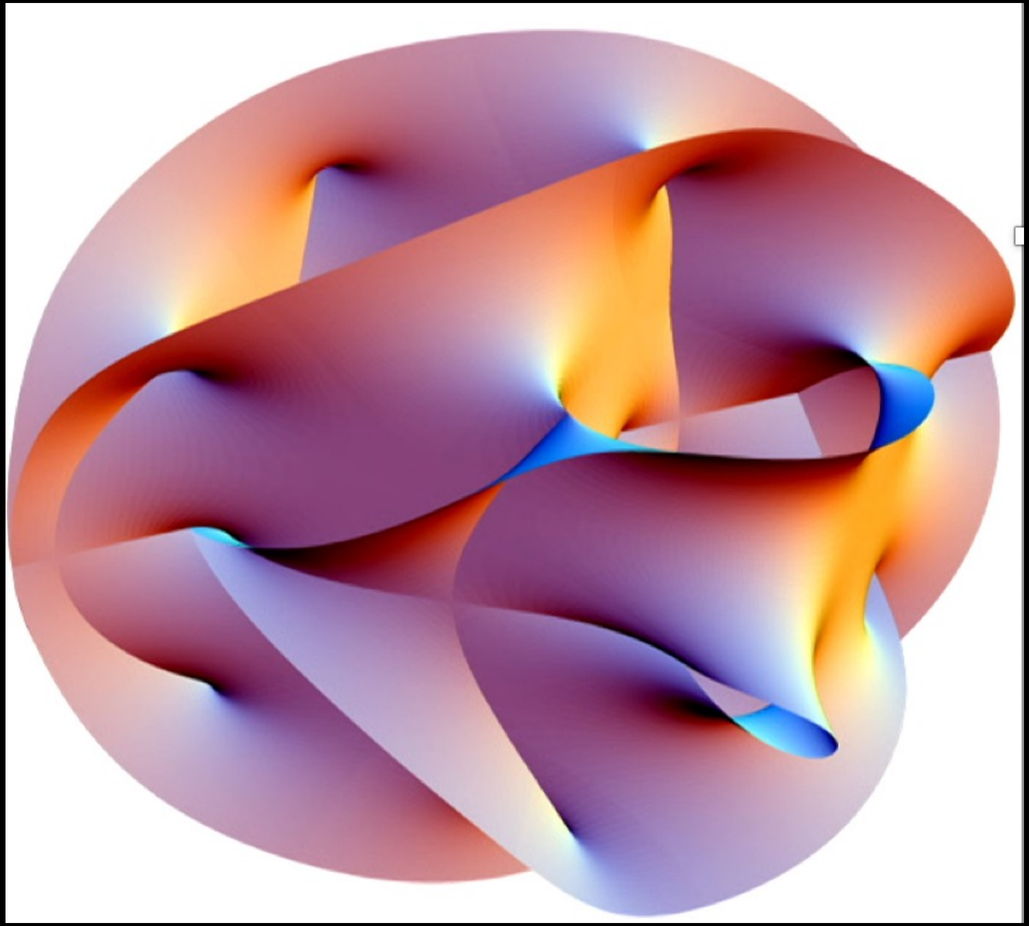
Gauge Fields

Topology

Give rise to a plenitude of Universes

A Plenitude of Massless Particles

Compactification Naturally Gives Rise to Massless Particles



In the presence of non-trivial topology
Non-trivial gauge configurations can carry no energy
Resulting in 4D massless particles

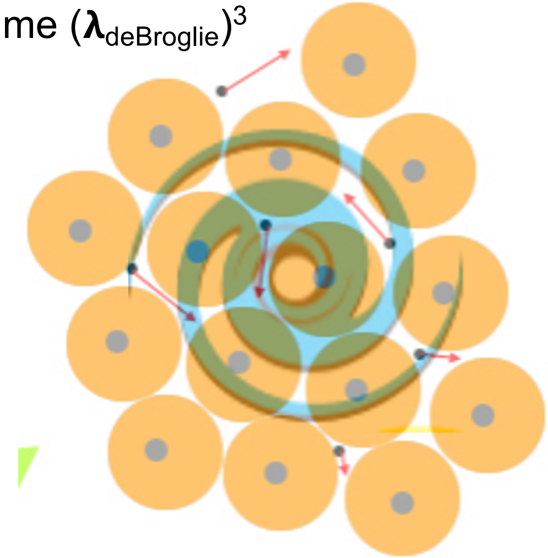
Based on a slide
by Mina Arvanitaki

Summary

	New Particle	Comes from	Couples to
Spin zero CP odd	Axion and Axion Like Particles	Topology of Extra Dimensions	Spin and Mass density, Light in a background field
Spin zero CP even	Dilatons, Moduli, radion	Geometry of Extra Dimensions	Mass density, Fundamental constants
Spin one	Dark Photons	Topology of Extra Dimensions	Mixes with the photon

Low mass dark matter generically takes the form of classical bosonic sine waves

Fermions: 1 DM particle per mode volume ($\lambda_{deBroglie}$)^3



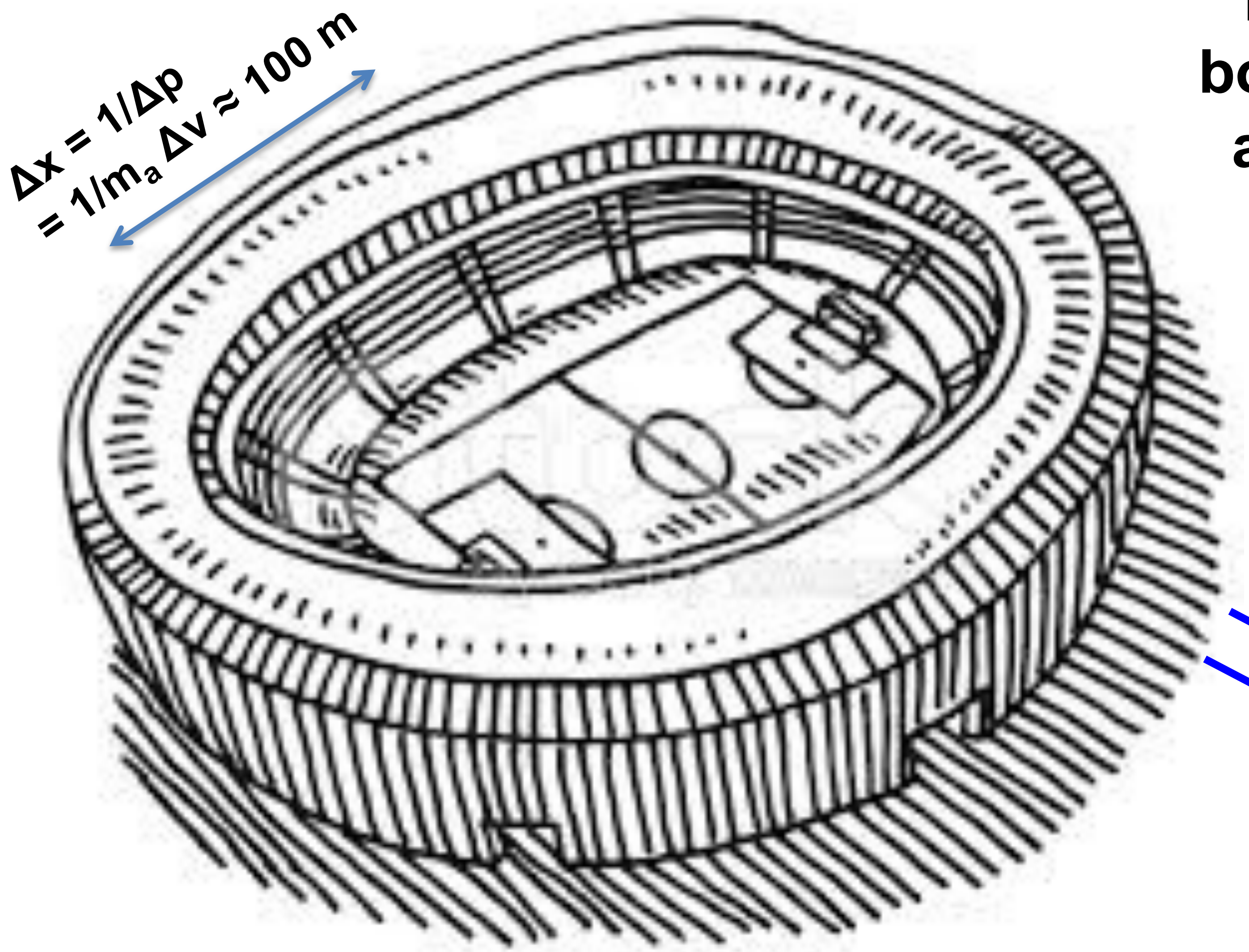
For **mass < 70 eV**, Pauli exclusion principle causes dark matter clumps to swell up to be larger than the size of the smallest dwarf galaxies. (Randall, Scholtz, Unwin 2017)

→ If lower mass, dark matter must be coherent bosonic sine waves with **macroscopic mode occupation number >>1**

Not billiard balls.

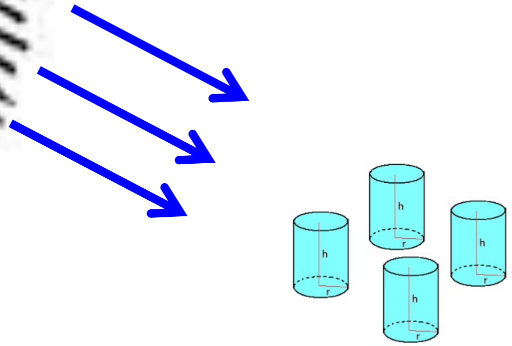
Need coherent wave detector.

e.g. 10^{-5} eV = GHz dark matter



Non-relativistic bosonic DM is like a slow CW laser with $f=m_a/2\pi$

$v \approx \Delta v \approx 300$ km/s (galactic escape velocity)



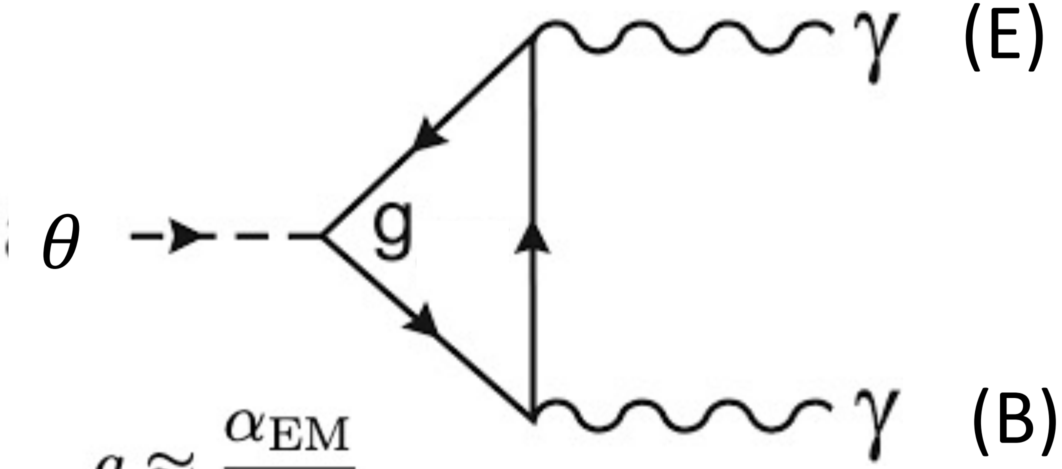
Football stadium-sized regions of coherently oscillating **classical sine waves** slowly drifting through detectors. Mean DM occupation number **$N>10^{22}$ per mode.**

Accumulate oscillatory signals in various kinds of laboratory oscillators which are weakly coupled to the DM wave

Signal strength is independent of m_a, f_a

Wave amplitude and hence signal strength depends only on local dark matter density ρ_a !

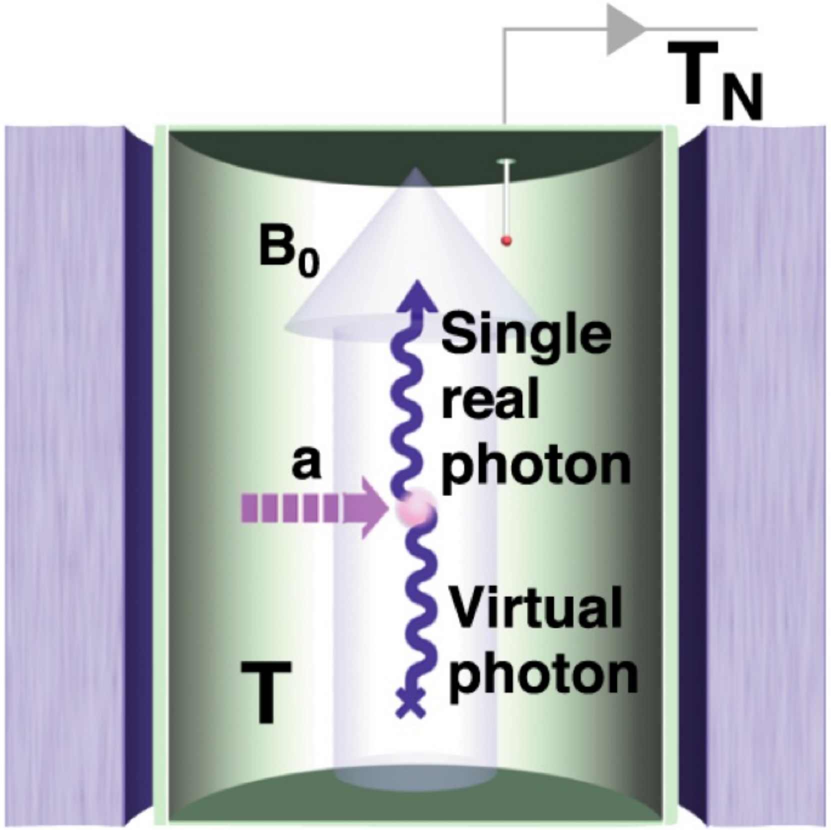
Experimental goal:
Determine frequency of the signal and hence the axion mass



$$g \approx \frac{\alpha_{EM}}{4\pi}$$

The Dark Matter Haloscope:
Classical axion wave drives RF cavity mode

Pierre Sikivie,
Sakurai Prize 2019



- In a constant background B_0 field, the oscillating axion field acts as an exotic, space-filling current source

$$\vec{J}_a(t) = -g\theta\vec{B}_0 m_a e^{im_a t}$$

which drives E&M via Faraday's law:

$$\vec{\nabla} \times \vec{H}_r - \frac{d\vec{D}_r}{dt} = \vec{J}_a$$

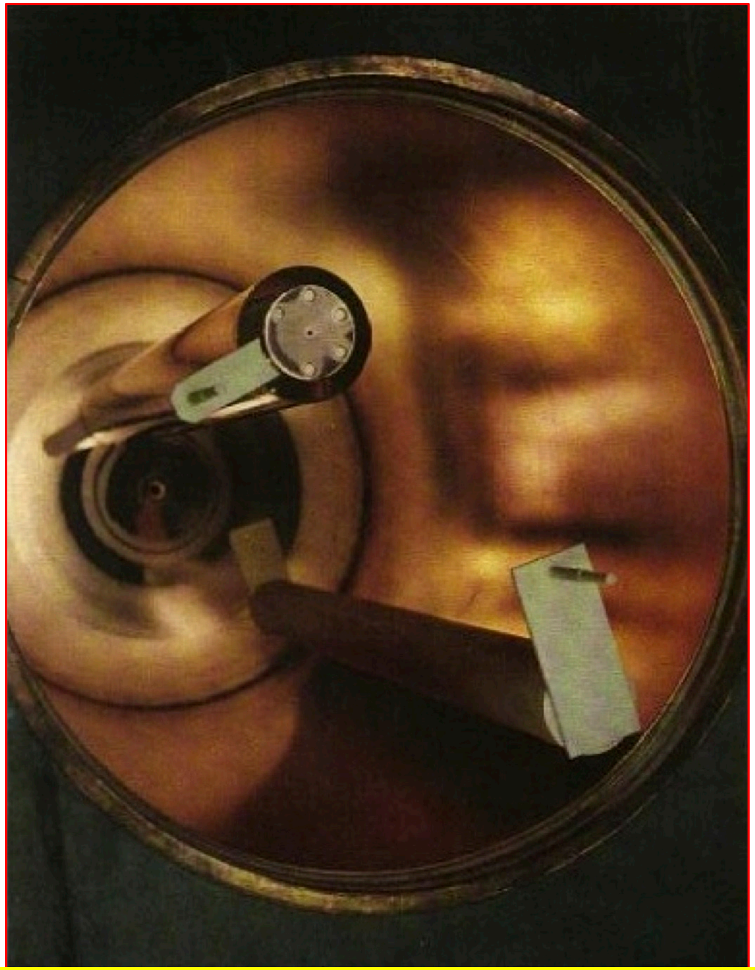
- Periodic cavity boundary conditions extend the coherent interaction time **(cavity size ≈ 1/m_a)** → the exotic current excites standing-wave RF fields.

A spatially-uniform cavity mode can **optimally** extract power from the dark matter wave

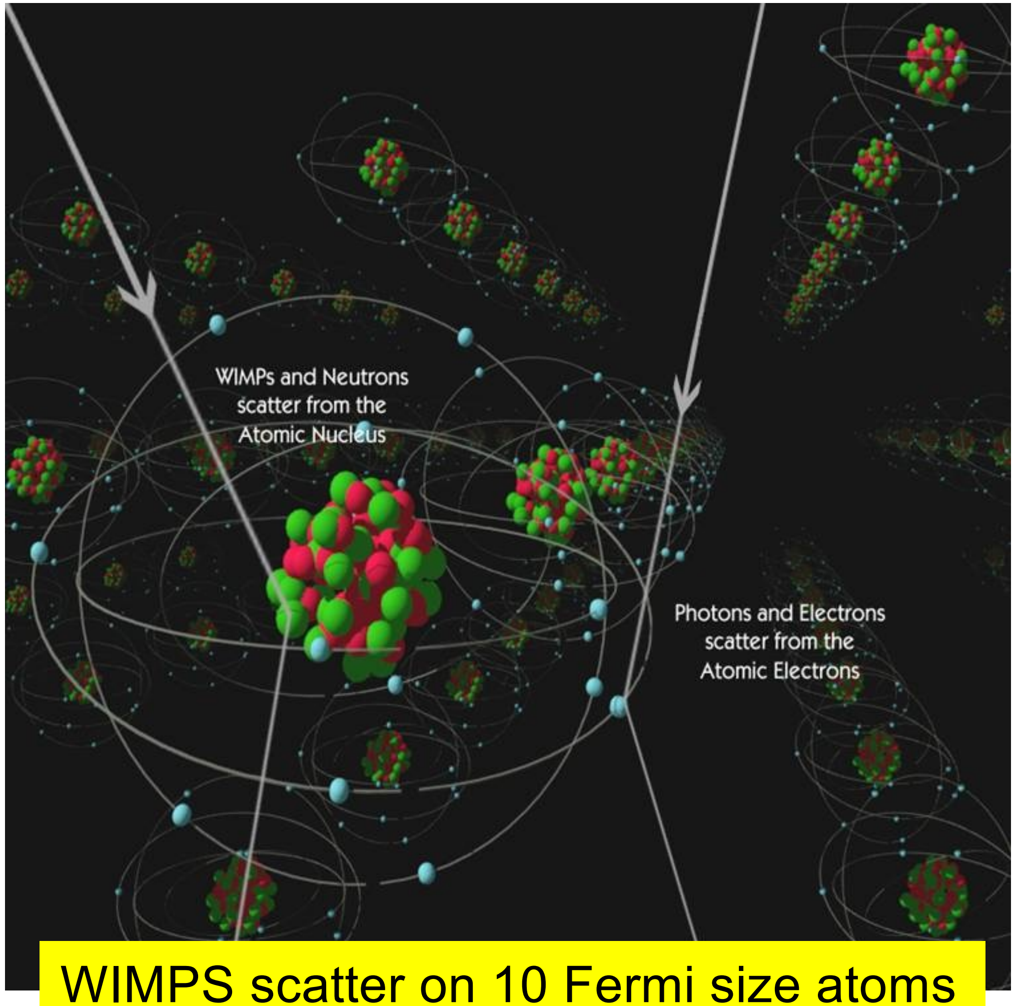
$$P_a(t) = \int \vec{J}_a(t) \cdot \vec{E}_r(t)\, dV$$

Axions vs WIMPs:

Resonant scattering requires size of scattering target = 1/(momentum transfer)



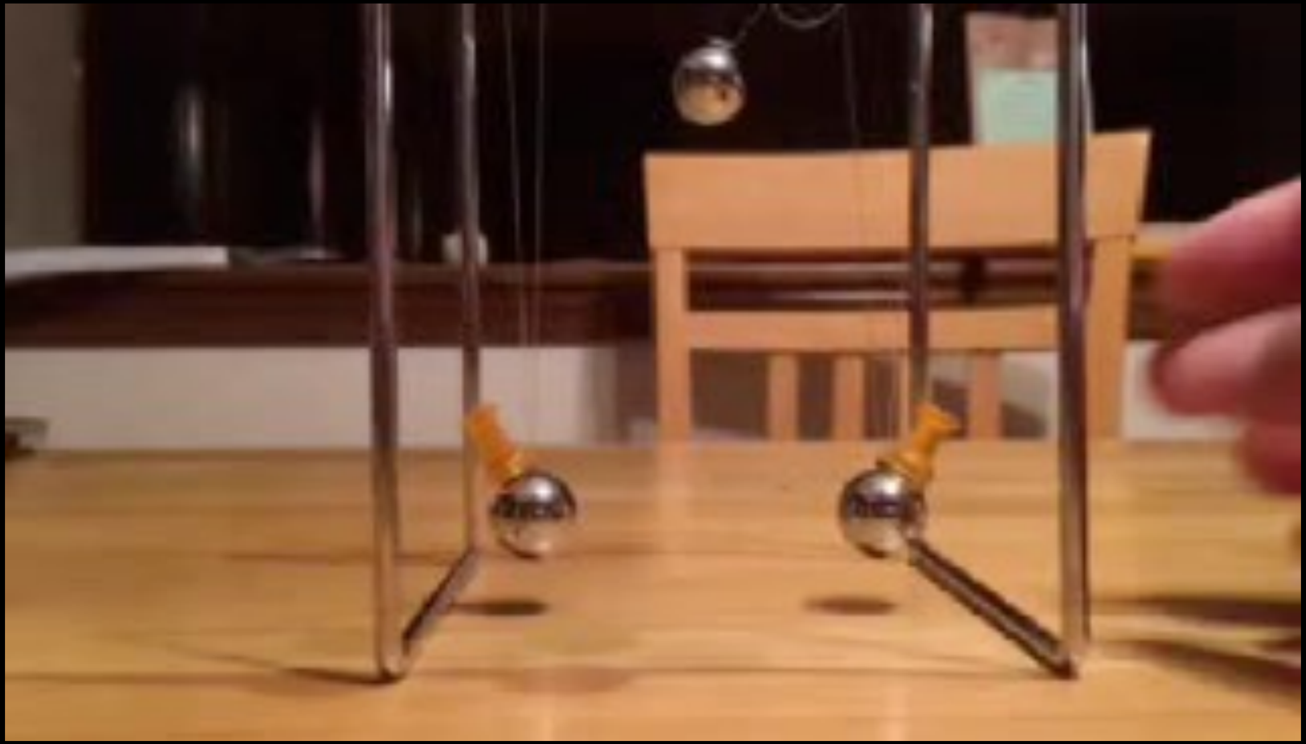
4 μeV mass axions scatter on 50cm size microwave cavities



WIMPS scatter on 10 Fermi size atoms

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

Detection oscillator



Axion wave

Weak coupling -- takes many swings to fully transfer the wave amplitude.
In real life, Q = number of useful swings is limited by coherence time.

2017: 30-year axion R&D program culminates in first sensitivity to DFSZ axions

PRL 120, 151301 (2018)

ADMX at U.Washington,
FNAL = DOE lead lab

Operate an ultrasensitive radio in a cold, RF-shielded box to tune in to the axion broadcast.

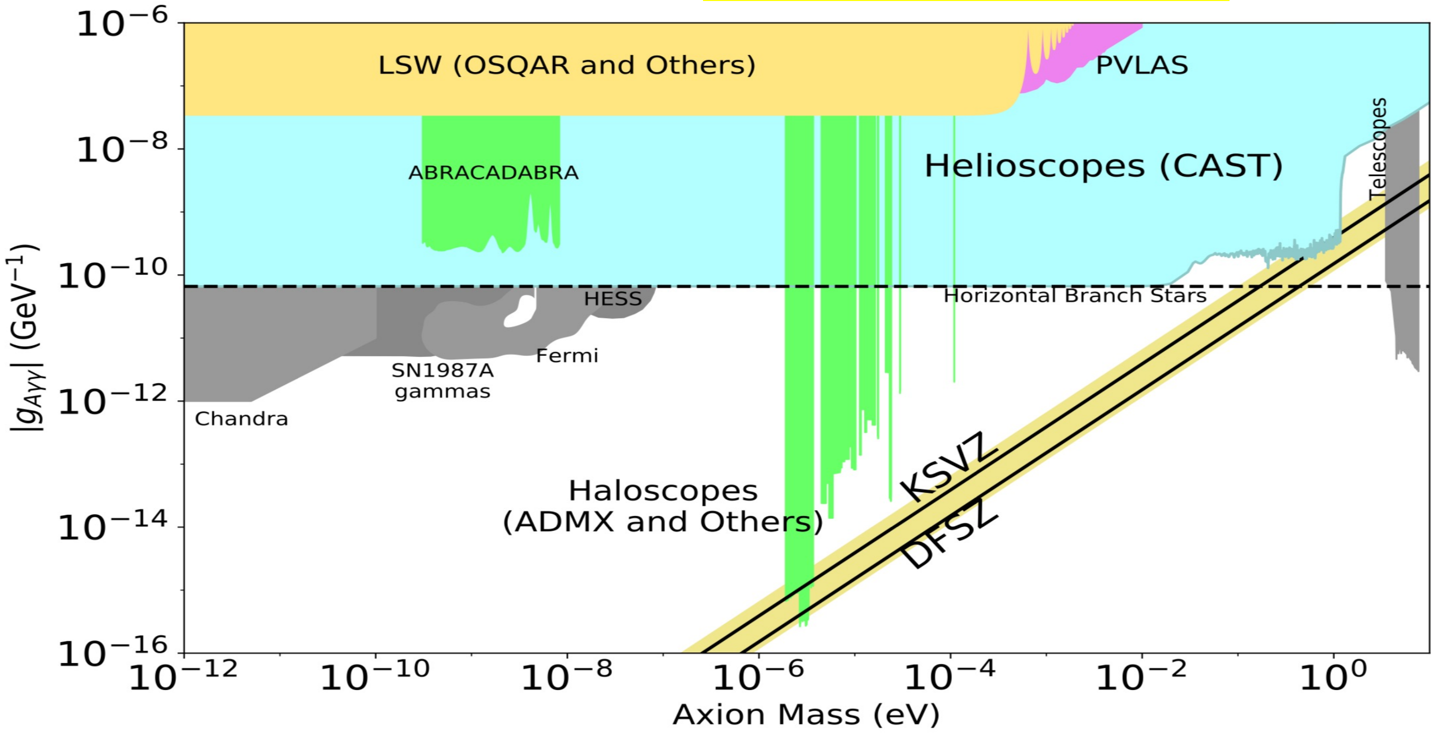


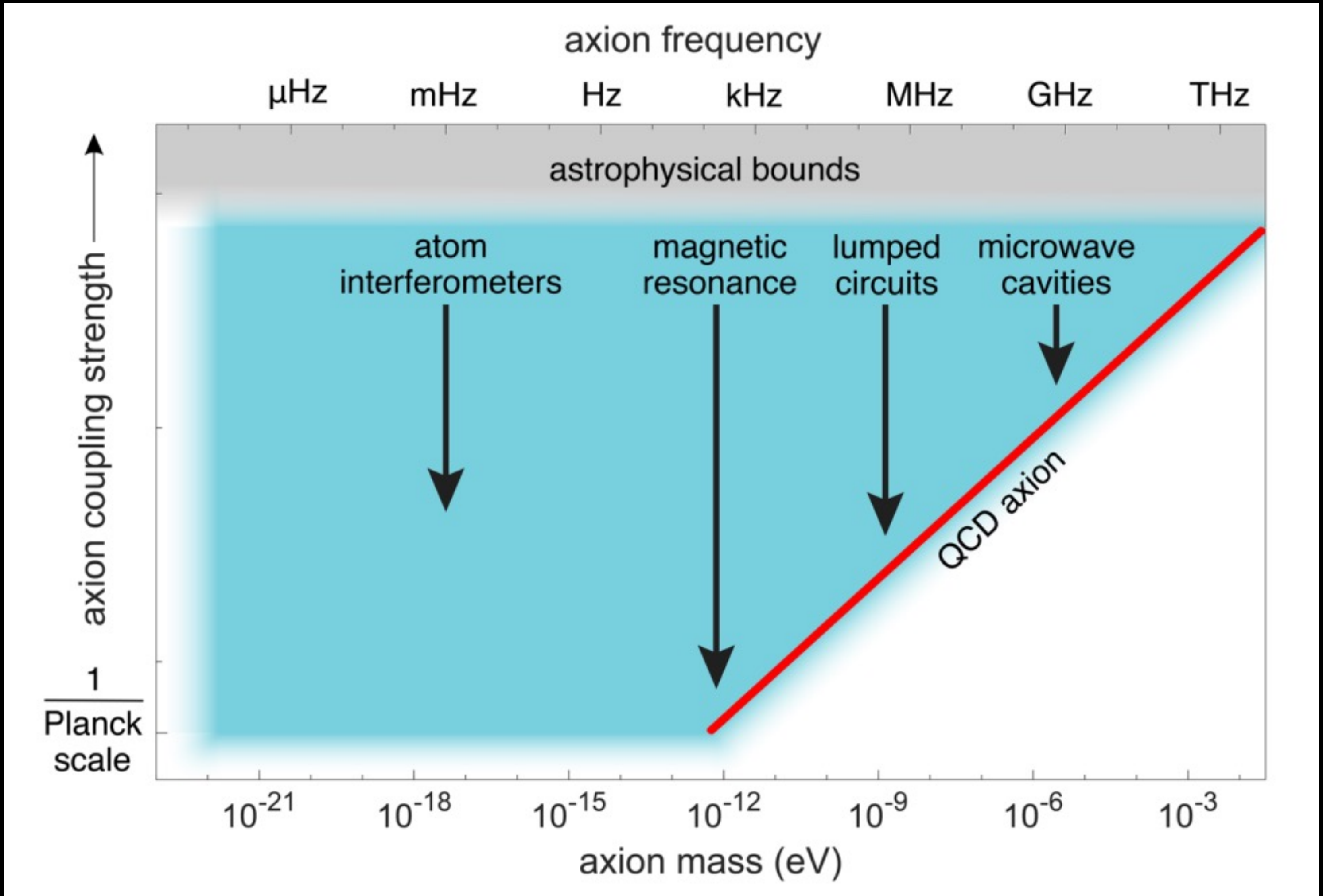
Figure 91.1: Exclusion plot for ALPs as described in the text.

Look for "spontaneous" emission from local axion dark matter into the empty cavity mode.

Signal power level = 10^{-23} W

Need 15 minutes integration per radio tuning to beat thermal noise power at 500 mK.

Parameter Space for General Axion Dark Matter

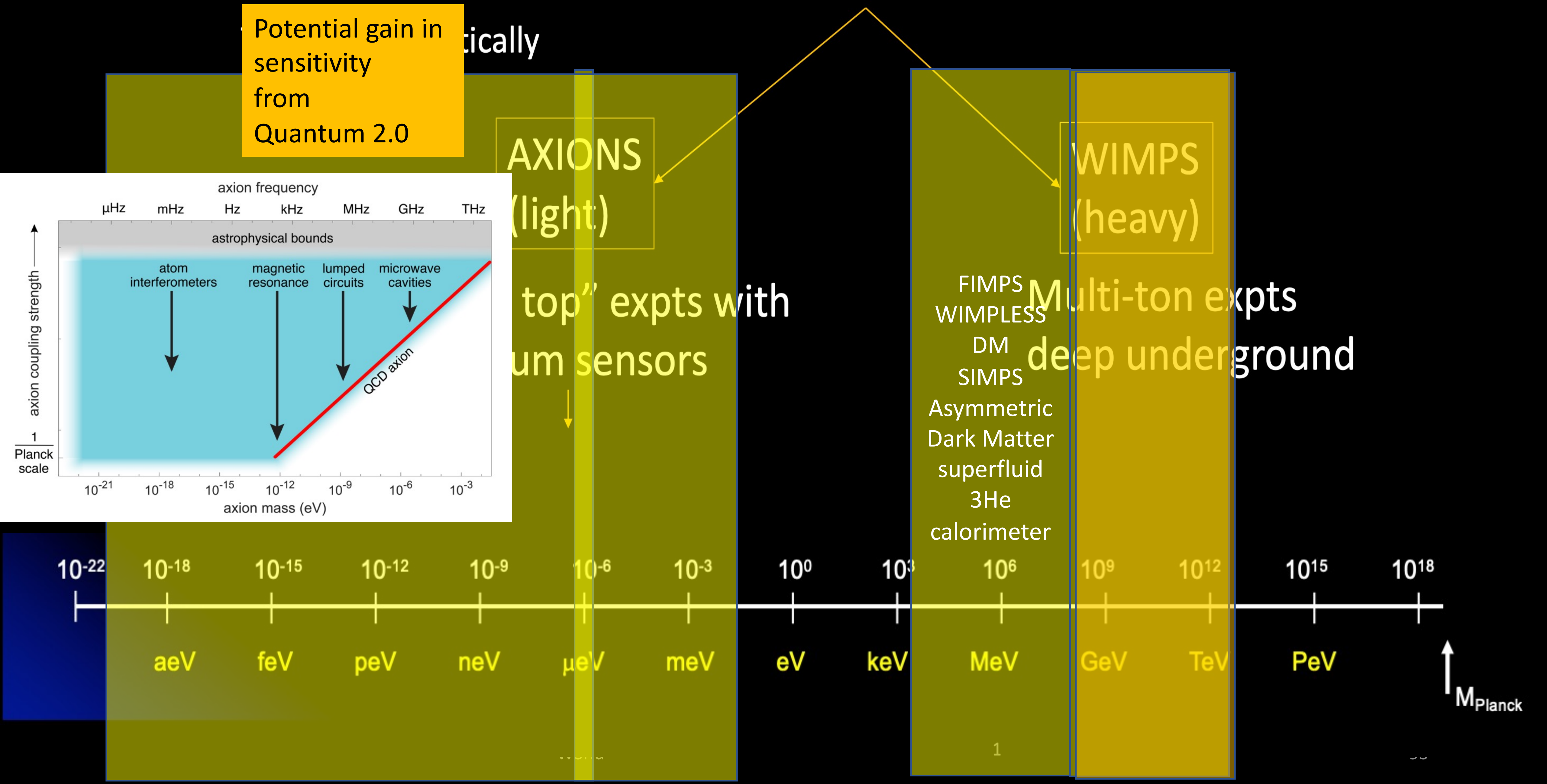


DOE HEP BRN
For Dark Matter
Small Projects
New Initiatives

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

A wide variety of quantum enhanced technologies are important

Dark Matter Search Strategy



TODAY

Dark Matter Search Strategy

The two theoretically best-motivated candidates:

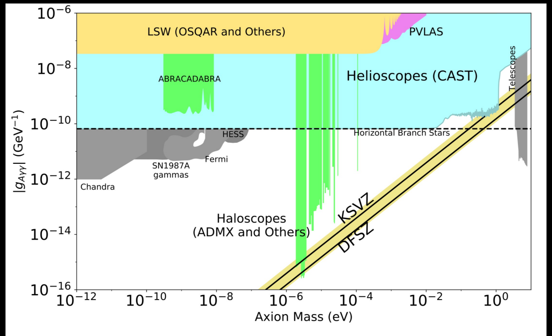
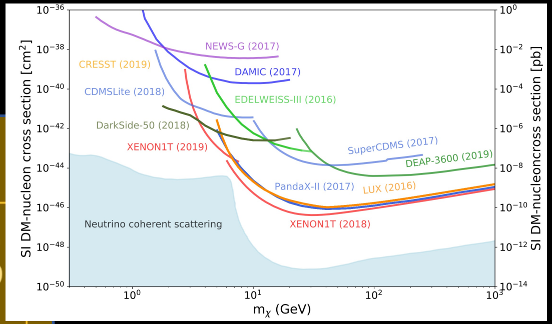


Figure 91.1: Exclusion plot for ALPs as described in the text.

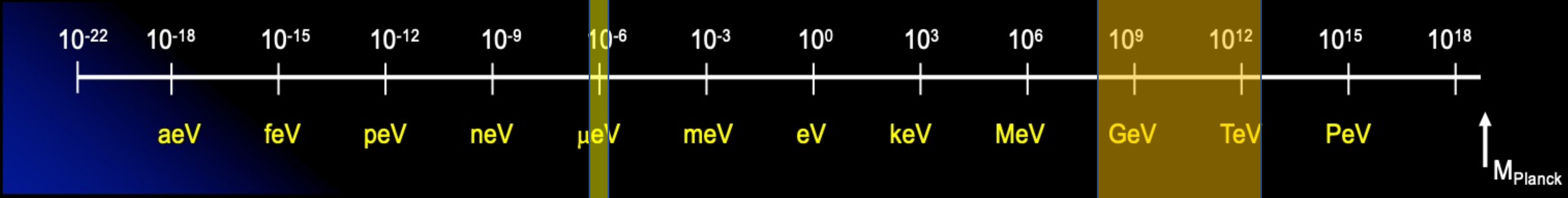
AXIONS (light)

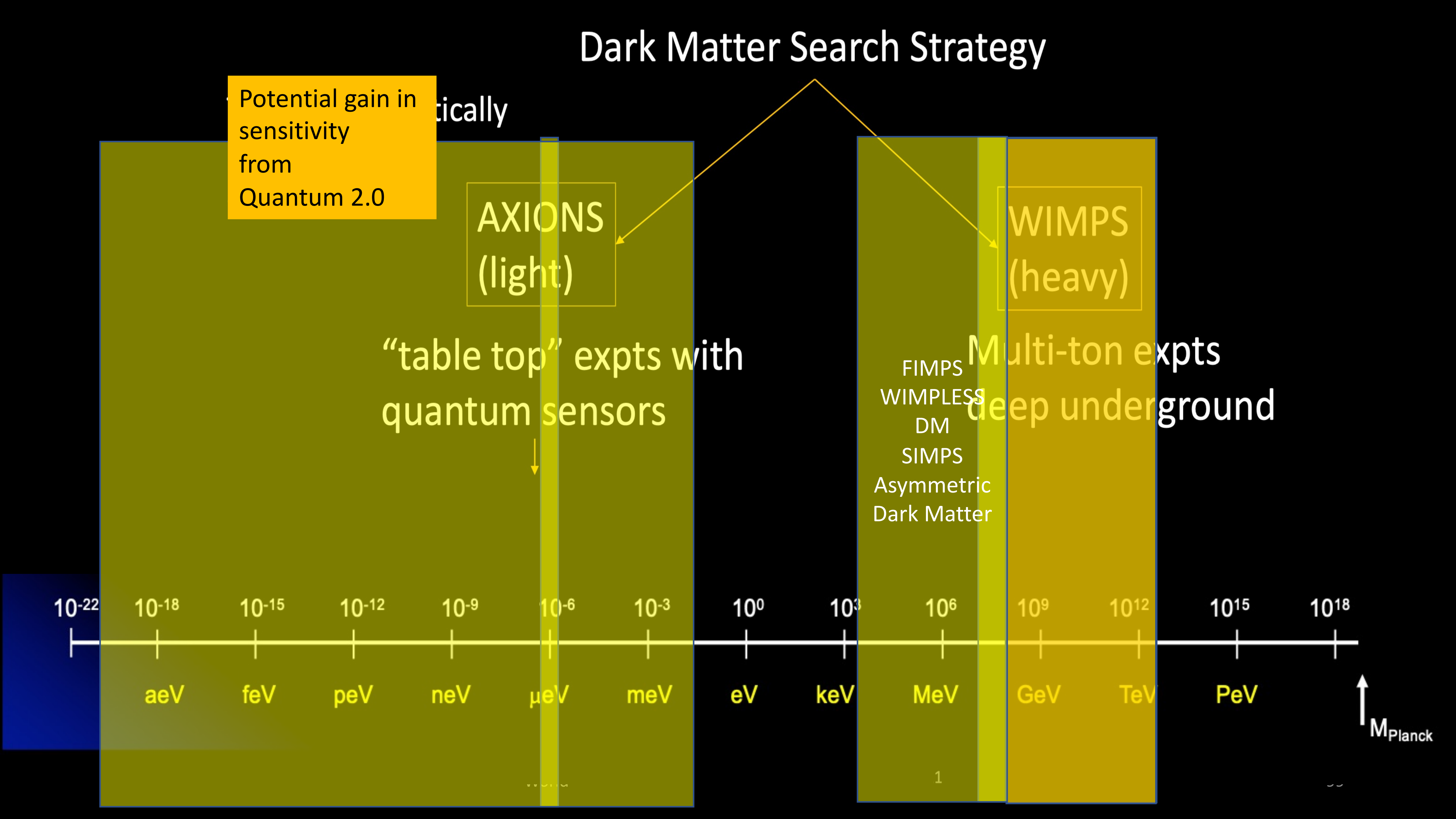
"table top" expts with quantum sensors

WIMPS (heavy)



Multi-ton expts deep underground





Dark Matter Search Strategy
Potential gain in sensitivity from Quantum 2.0
tically
AXIONS (light)
WIMPS (heavy)
"table top" expts with quantum sensors
Multi-ton expts deep underground
FIMPS
WIMPLESS DM
SIMPS
Asymmetric Dark Matter
10-22
10-18
10-15
10-12
10-9
10-6
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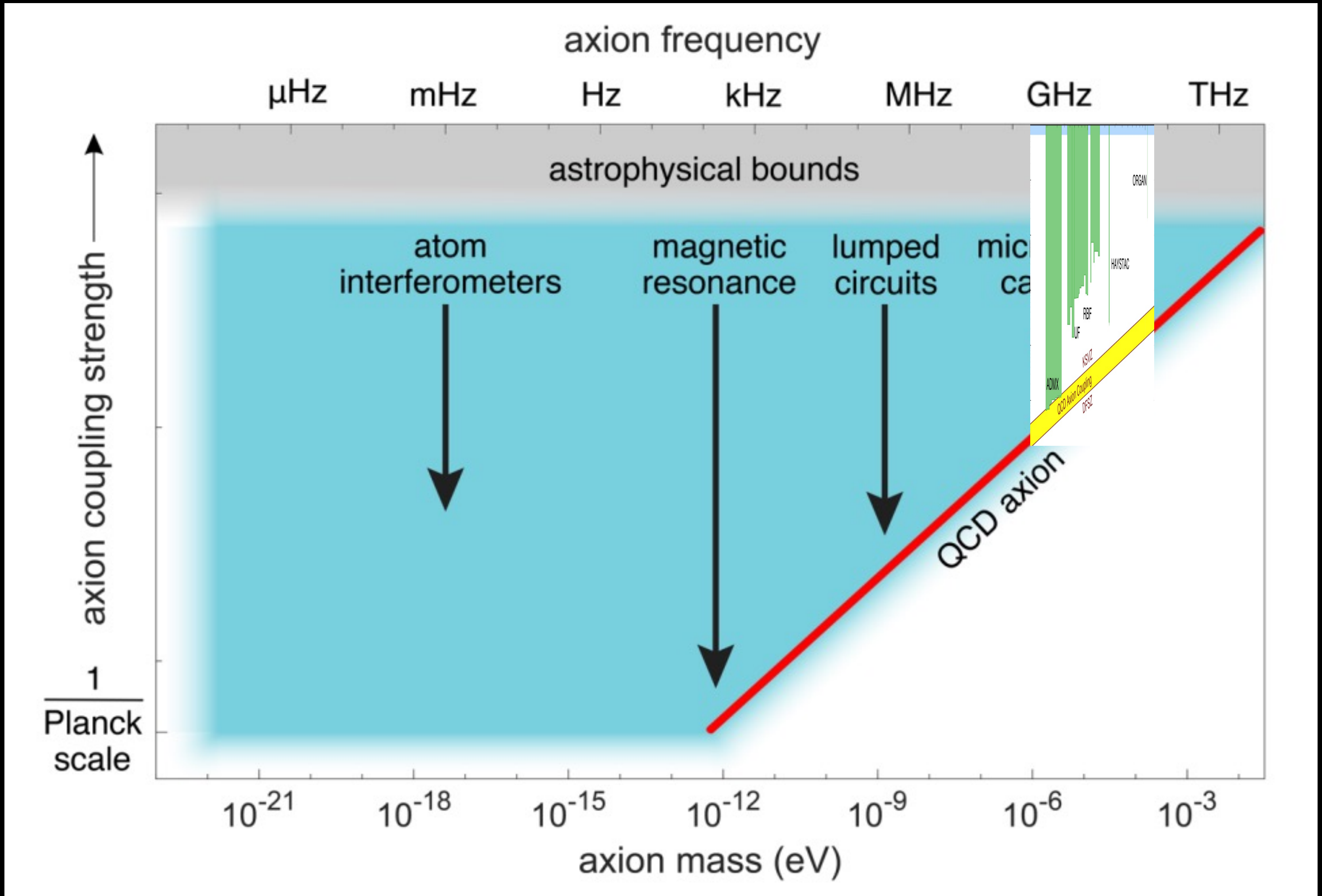
PeV
MPlanck
1

Parameter Space for General Axion Dark Matter



- Covering 1 – 10 GHz at DFSZ limit will take ~20,000 yrs at quantum limit, with one 9 Tesla magnet (K. Lehnert, Oxford Workshop http://www.physics.ox.ac.uk/confs/quantum2018/index.asp, HAYSTAC)

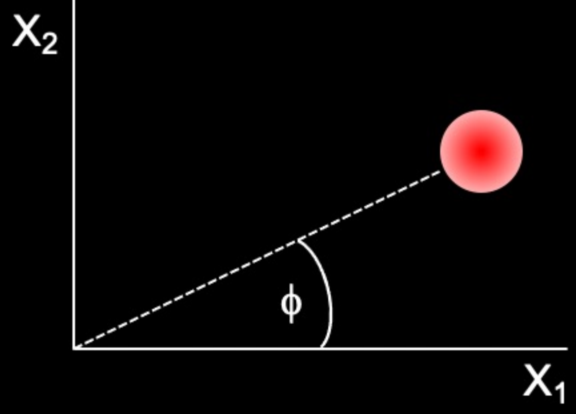
Standard Quantum Limit

- Standard Quantum Limit: A measurement repeated N times or with N independent particles is a binomial distribution ≈ Gaussian distribution
  - Measurement precision scales as $1/\sqrt{N}$
- Fundamental limit set by Heisenberg Uncertainty Principle: $\Delta E\ \Delta t\ \geq\ \hbar/2$

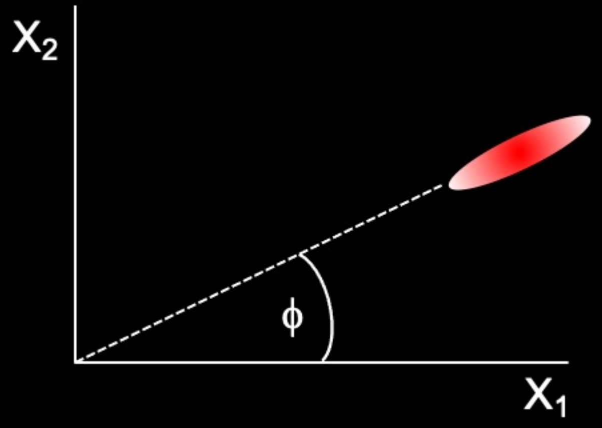
$$x(t) = X_1(t)\cos(\omega t) + X_2(t)\sin(\omega t)$$

- The Standard Quantum Limit can be evaded using quantum correlations:
  - Photon counting
  - Squeezing
  - Backaction evasion
  - Entanglement
  - Cooling
  - Quantum Non-Demolition (QND)

- Noise squeezing is possible as long as uncertainty area is preserved.

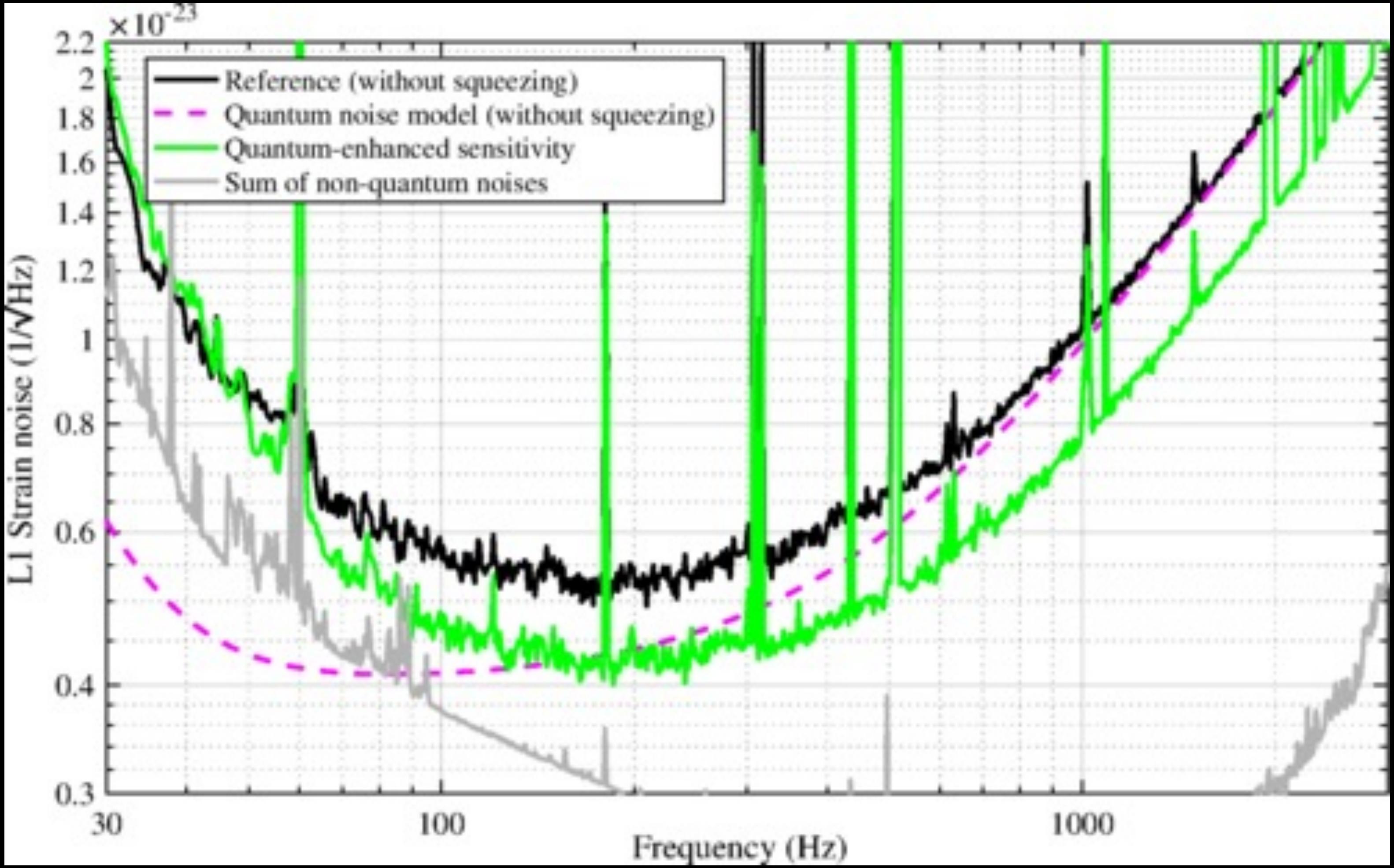


Coherent Spin State



Squeezed Spin State

LIGO: Quantum enhanced sensing-Squeezed light for improved sensitivity



https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.123.231107
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.123.231108

Axion Detectors and the Current Landscape

SUPERCONDUCTING QUANTUM ELECTRONICS:
- SQUIDs
- Josephson Parametric Amplifiers
- Travelling Wave Parametric Amplifiers
- Bolometers
- Qubits / QuBit arrays

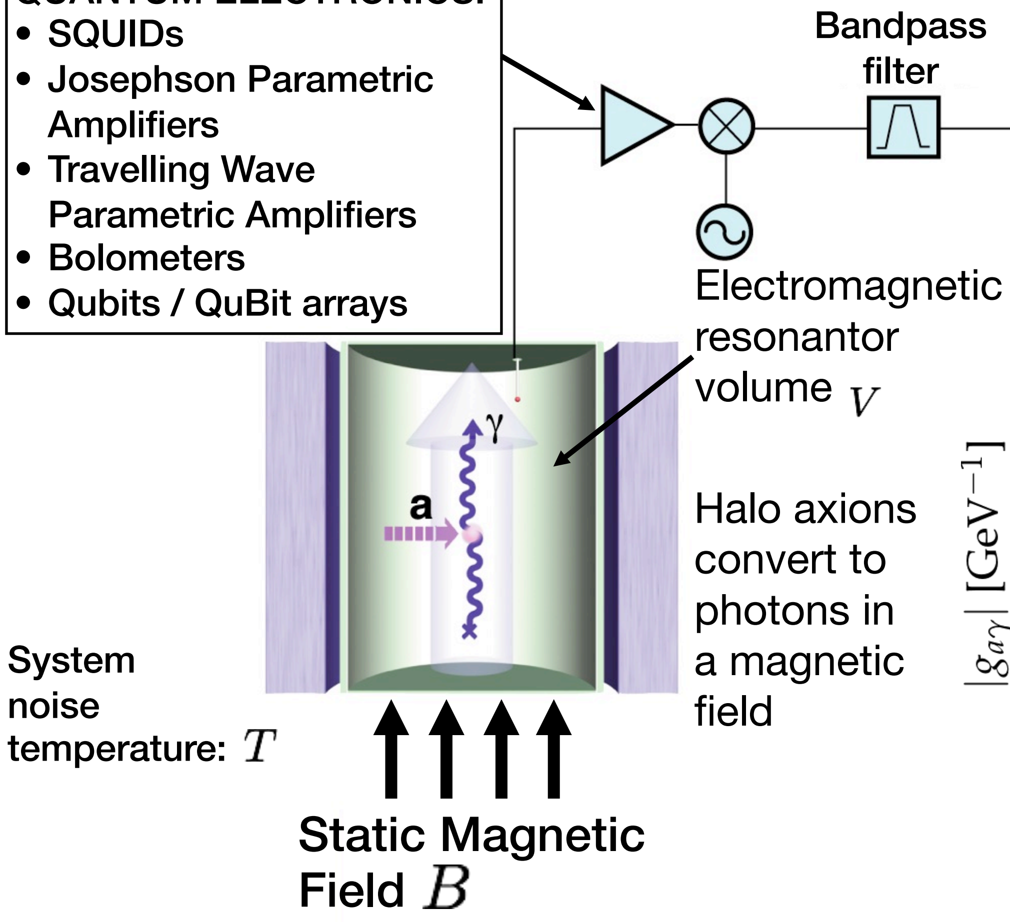
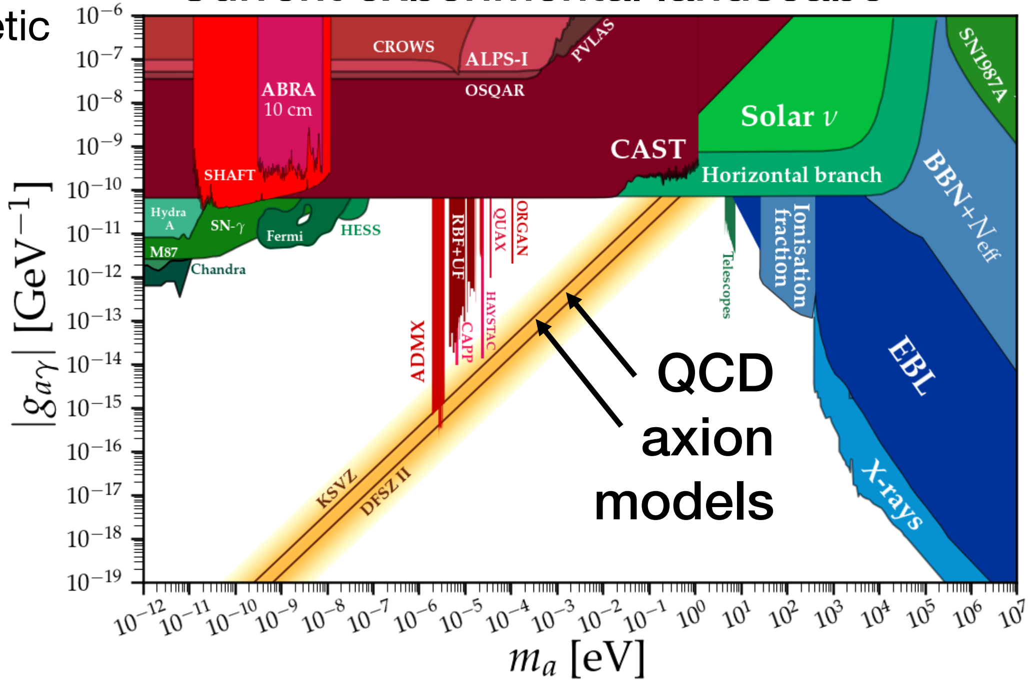


Figure of merit for detector sensitivity: $\frac{B^2 V}{T}$

Current experimental landscape

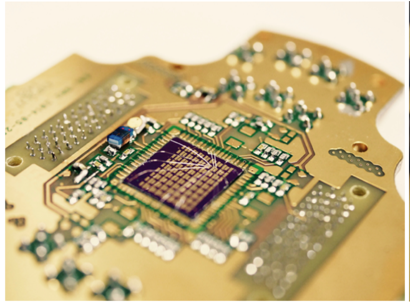


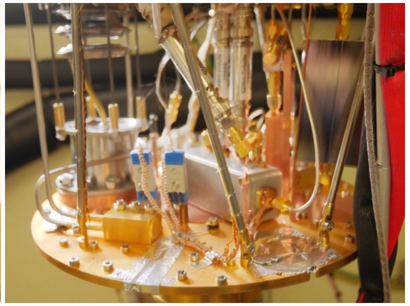
- Non resonant experiments have broad mass coverage, but insensitive to QCD axions
- Resonant experiments much more sensitive. ADMX is the only experiment to have probed a broad range of existing axion models. However, mass coverage too slow. Can speed up: 1. By using a new generation of quantum electronics; 2. By using a larger, higher field magnet; 3. Using multiple resonators in parallel.

Quantum Electronics for QSHS

Josephson parametric amplifiers (JPAa) / Travelling wave parametric amplifiers (TWPAs)

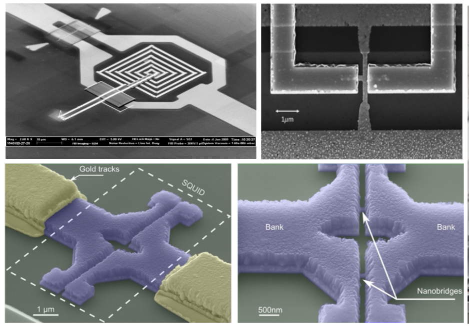
Lancaster University · Royal Holloway University of London · University of Oxford

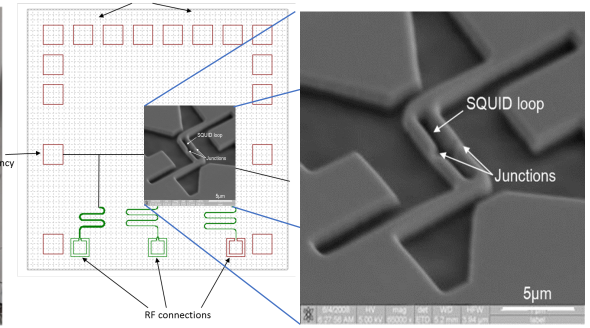




SLUG loaded SQUID amplifiers

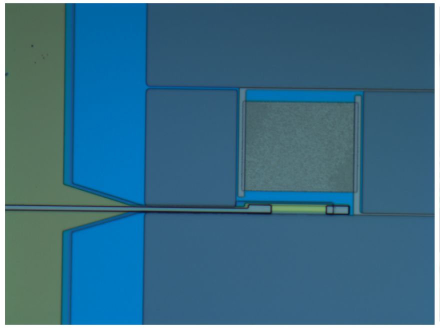
UCL · NPL National Physical Laboratory

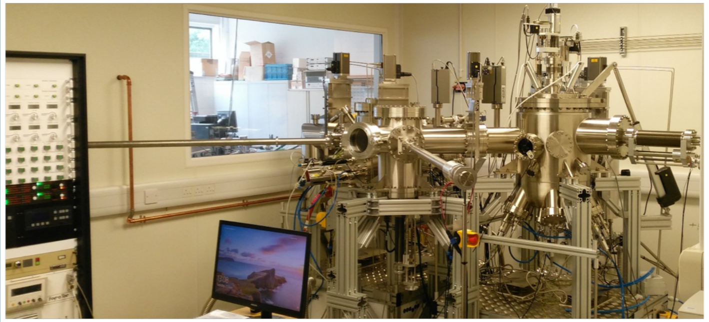




Cryogenic bolometer arrays

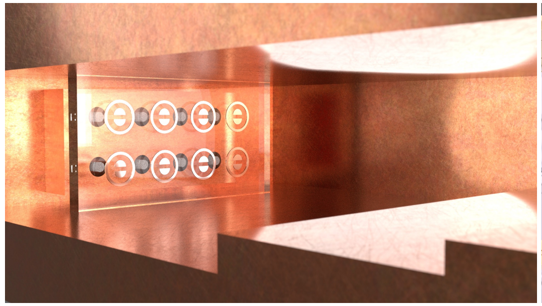
University of Cambridge

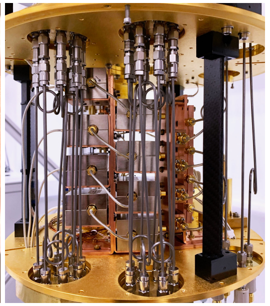


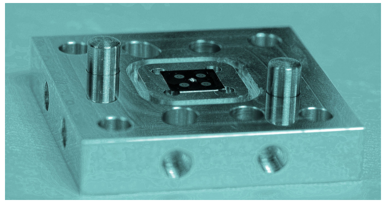


Qubit arrays

University of Oxford · Royal Holloway University of London





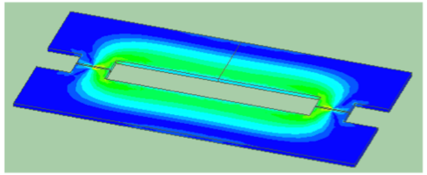


Progress

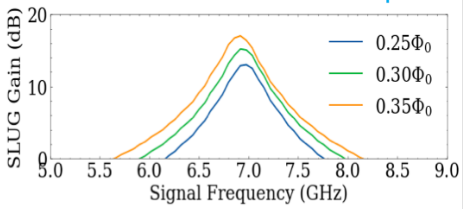
First SLUG loaded SQUID devices fabricated by the NPL/UCL group, Nov/Dec 2021. Currently under test.

NPL National Physical Laboratory
UCL

Ansys Maxwell – simulated inductance / capacitance of SLUG loop



Python – simulated frequency-dependent gain of SLUG amplifier

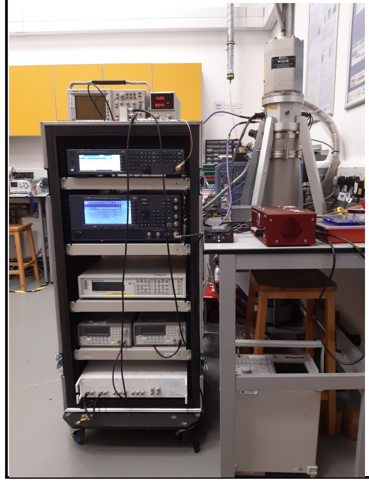


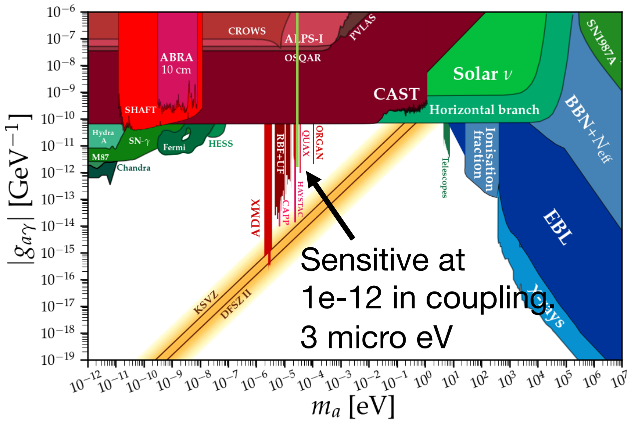
Proteox MX with 8T, 20cm bore magnet ordered from Oxford Instruments.
Delivery expected Autumn 2023.
10mK base Temperature.

QSHS PI Daw with similar fridge at Oxford.

4m high lab space for the 20cm prototype at Sheffield

Preliminary sensitivity to 3e-5 micro eV using the 3K test stand at NPL.





Future Plans

QSHS Phase 1 (current STFC Support)

- Install and commission fridge and magnet at Sheffield
- Run 1 with a single cavity at around 5GHz, first untuned, then with a tuning rod. Start with a HEMT amplifier.
- Establish sensitivity to axion dark matter, extrapoloate to projected sensitivity at lower noise, larger volume.
- Develop 4 varieties of quantum electronics.

maybe during phase 1

- Deploy and test Quantum Electronics
- Run 2, with quantum electronics, measure revised noise temperature, search for axions, again around 5GHz.

QSHS phase 2 requires support.

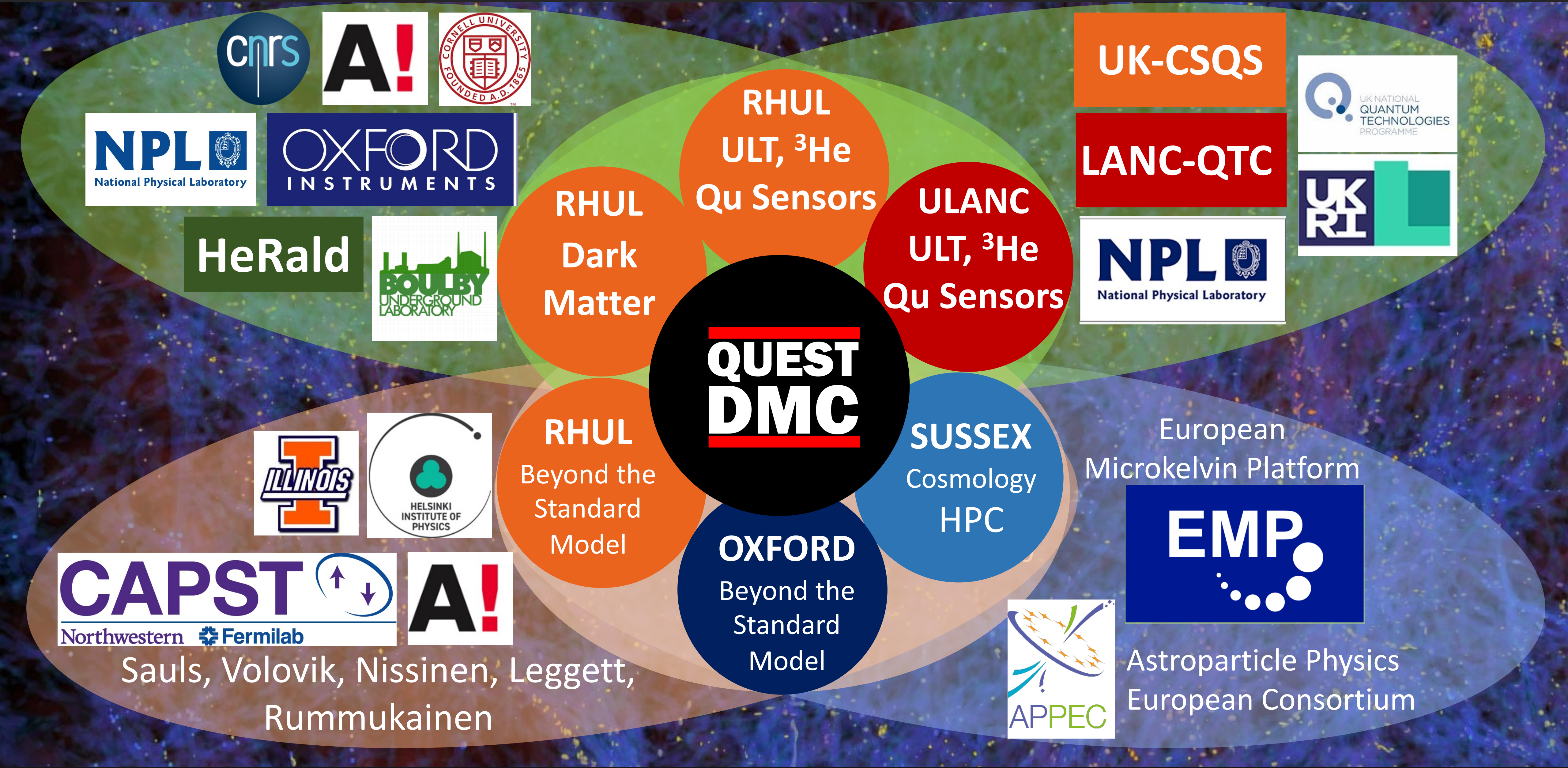
- Develop and test resonant feedback and improved resonators in collaboration with ADMX.
- Study possible cosmic ray backgrounds.
- Engineering design for a UK scaled up national facility.

Two fundamental open questions in cosmology

- **In WP1:** What is the nature of Dark Matter?
- **In WP2:** How did the early universe evolve?

Linked through requirement of beyond-standard model physics and the internationally unique experimental approach of combining quantum sensors with ^{3}He at ultralow temperatures.

QUEST – DMC *Ecosystem*



Implementation of current quantum sensors, operated in new regime at ultralow temperatures, and new sensors co-designed for fundamental physics

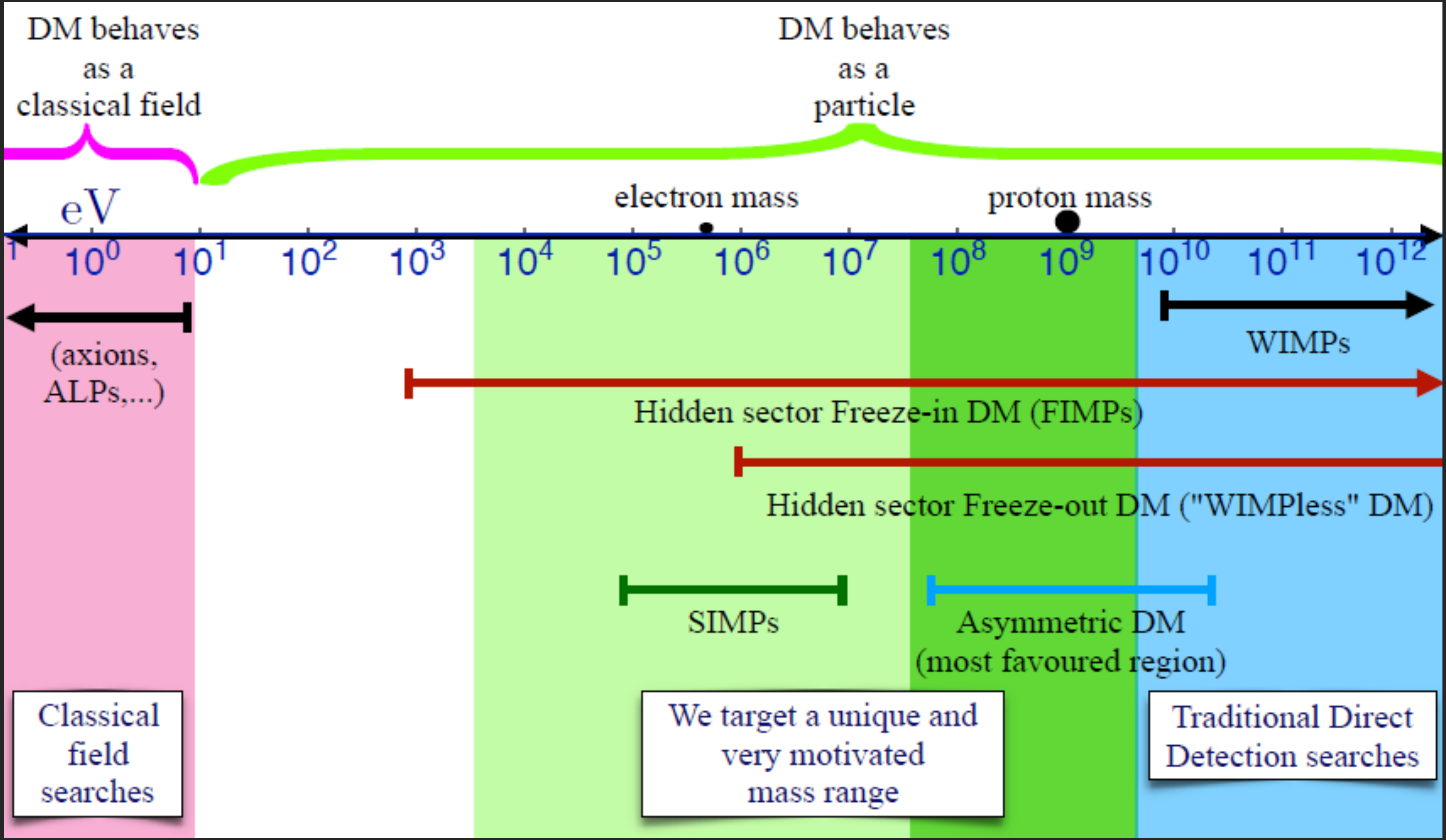
Quantum Enhanced Superfluid Technologies for Dark Matter and Cosmology, QUEST –DMC

Superconducting Devices:

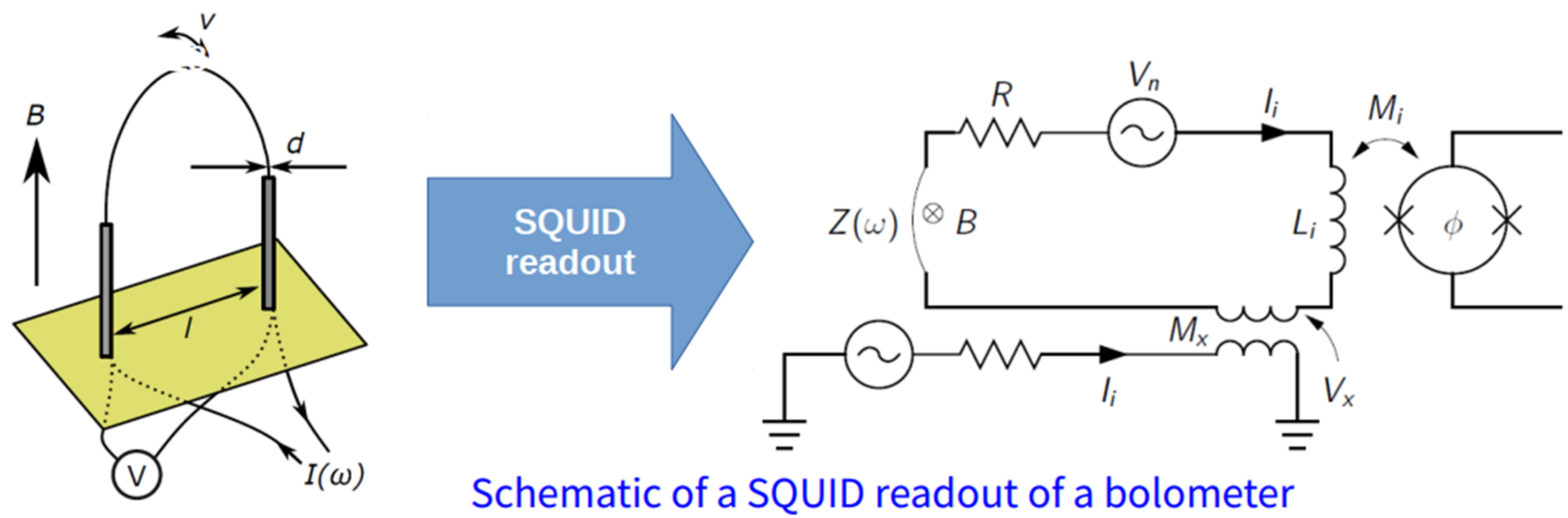
- SQUIDs
  - Coupled to Nano-electro-mechanical systems (NEMs) WP1
  - For NMR WP2
- Transition Edge Sensors to detect ionisation channel WP1
- HyQUIDs to replace SQUID
- Josephson Parametric Amplifiers (2nd generation ionisation channel)
- Transmon Qubit coupled to NEMs beam to address multiple bolometers

Potentially Operating at ULT or remotely coupled to experiment

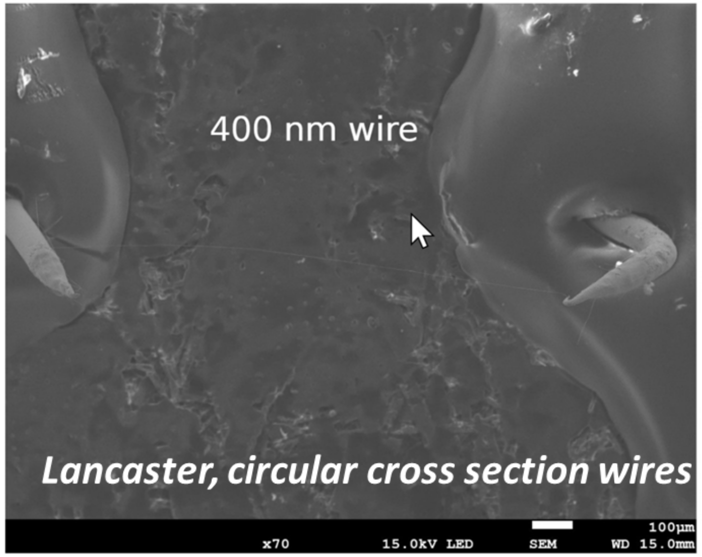
• **In WP1: What is the nature of Dark Matter?**



Merging existing state-of-art tech to achieve beyond 10 eV resolution



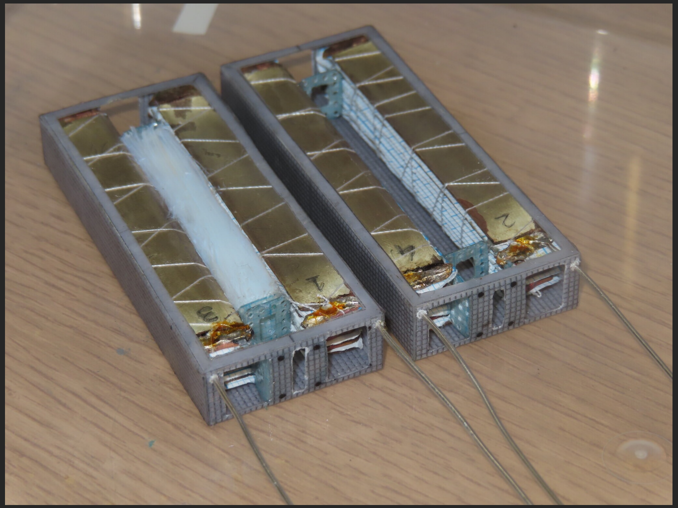
Schematic of a SQUID readout of a bolometer



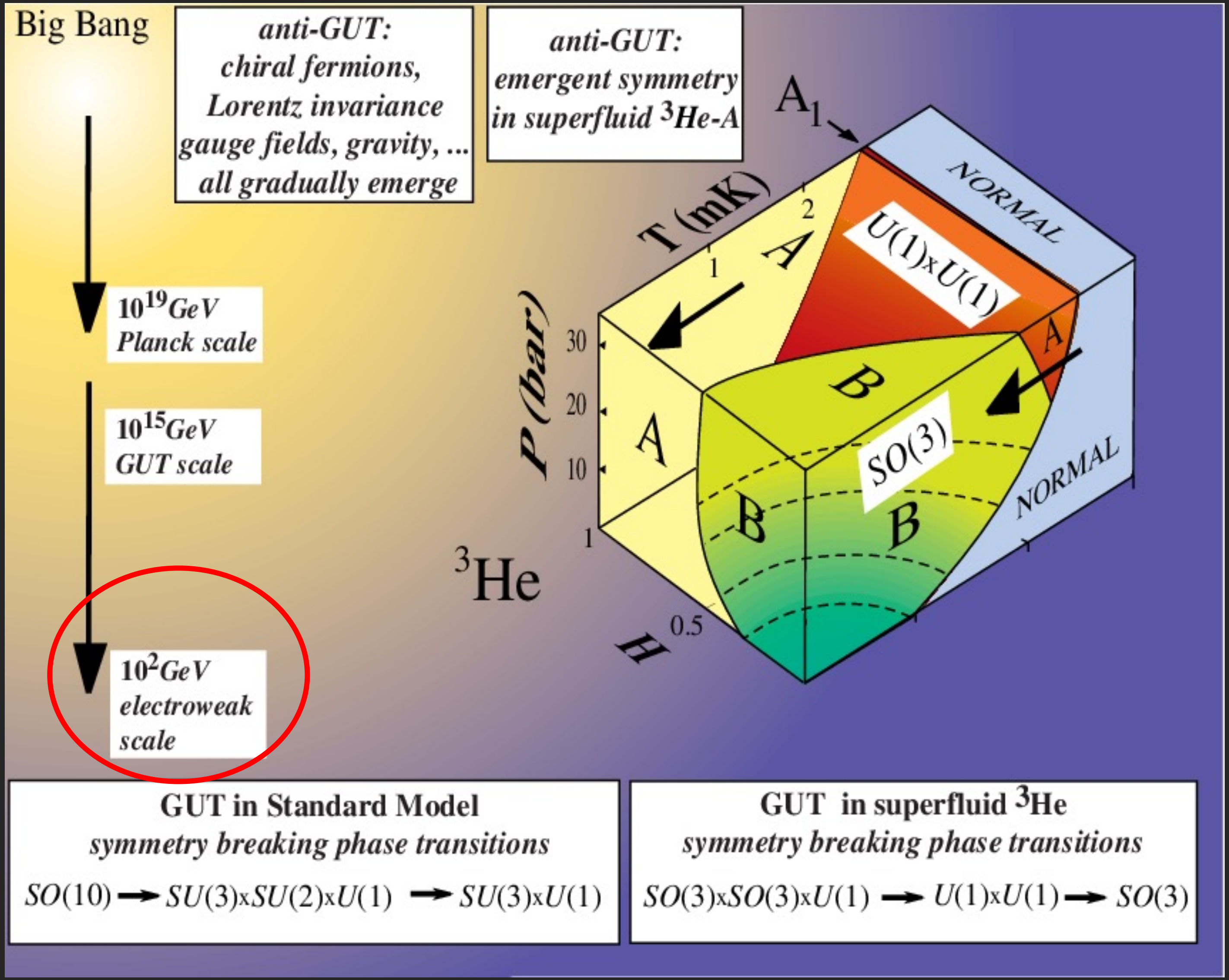
Lancaster, circular cross section wires

Andreev Reflection in Superfluid ^{3}He: A Probe for Quantum Turbulence D.I. Bradley, A.M. Guénault, R.P. Haley, G.R. Pickett, and V. Tsepelin, Annual Review of Condensed Matter Physics 2017 8:1, 407-430

2-stage SQUID amplifier (PTB) IEEE Trans. Appl. Supercond. 17 (2007)



WP2: Phase transitions in extreme matter



Precise control of Quantum analogue system, Superfluid ^{3}He & dynamics of phase transitions *open gravitational wave window to physics beyond the Standard Model in the early universe*

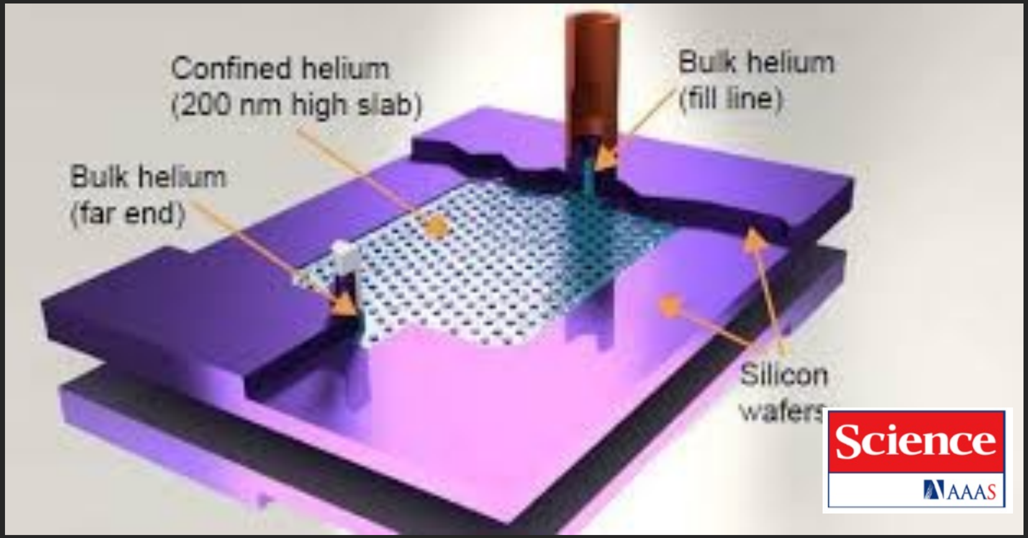
Solve the nucleation puzzle in ^{3}He

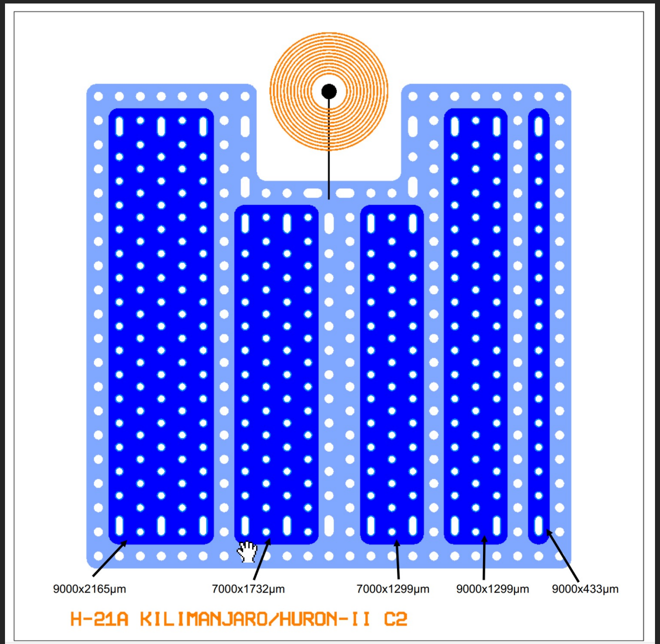
Engineer phase transitions between superfluid ^{3}He phases of distinct symmetry

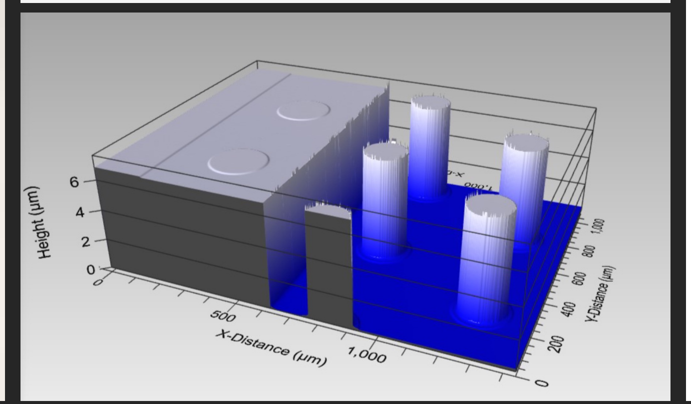
Confinement

Phase Diagram of the Topological Superfluid ^{3}He Confined in a Nanoscale Slab Geometry

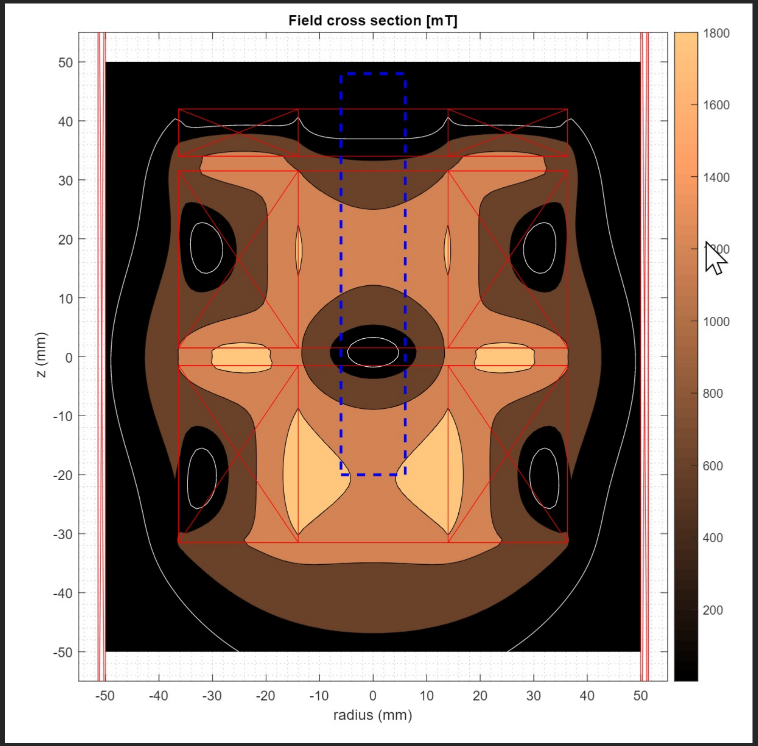
L. V. Levitin,[1] R. G. Bennett,[1*] A. Casey,[1] B. Cowan,[1] J. Saunders,[1†] D. Drung,[2] Th. Schurig,[2] J. M. Parpia[3]





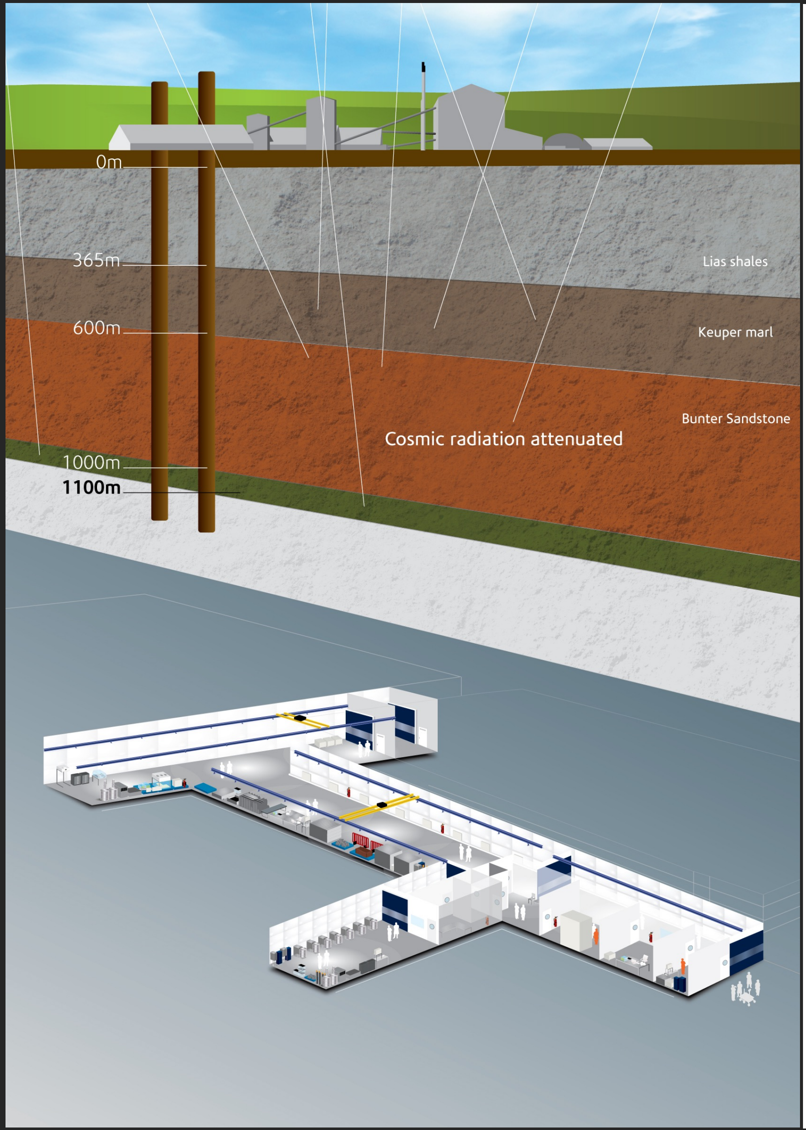


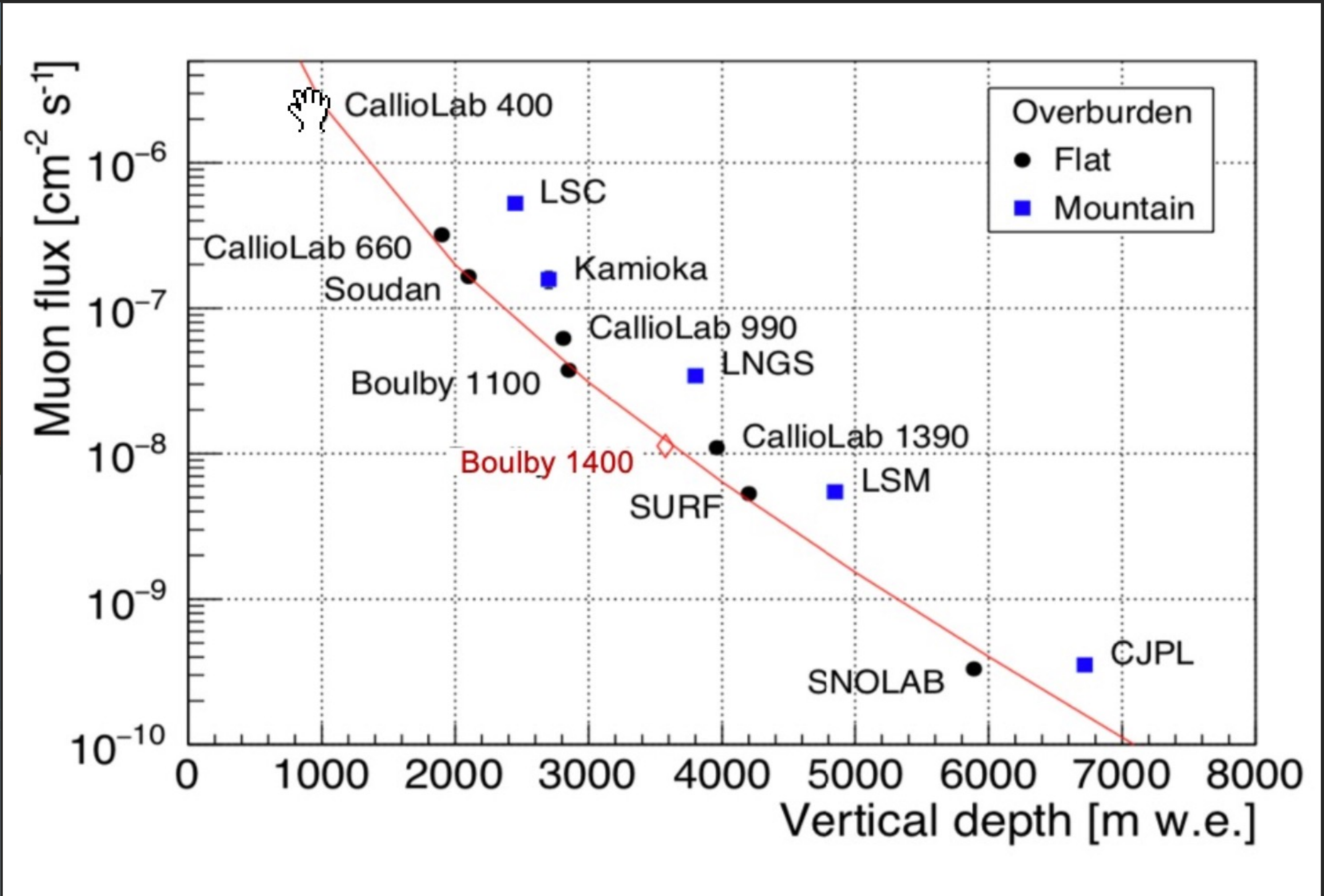
Magnetic Field



Quantum sensors to probe the nucleation and dynamics of transition, control the free energy landscape with tuning parameters.

Future Prospects: ULT Underground





Quantum-Enhanced Interferometry (QI) For New Physics

[redacted]

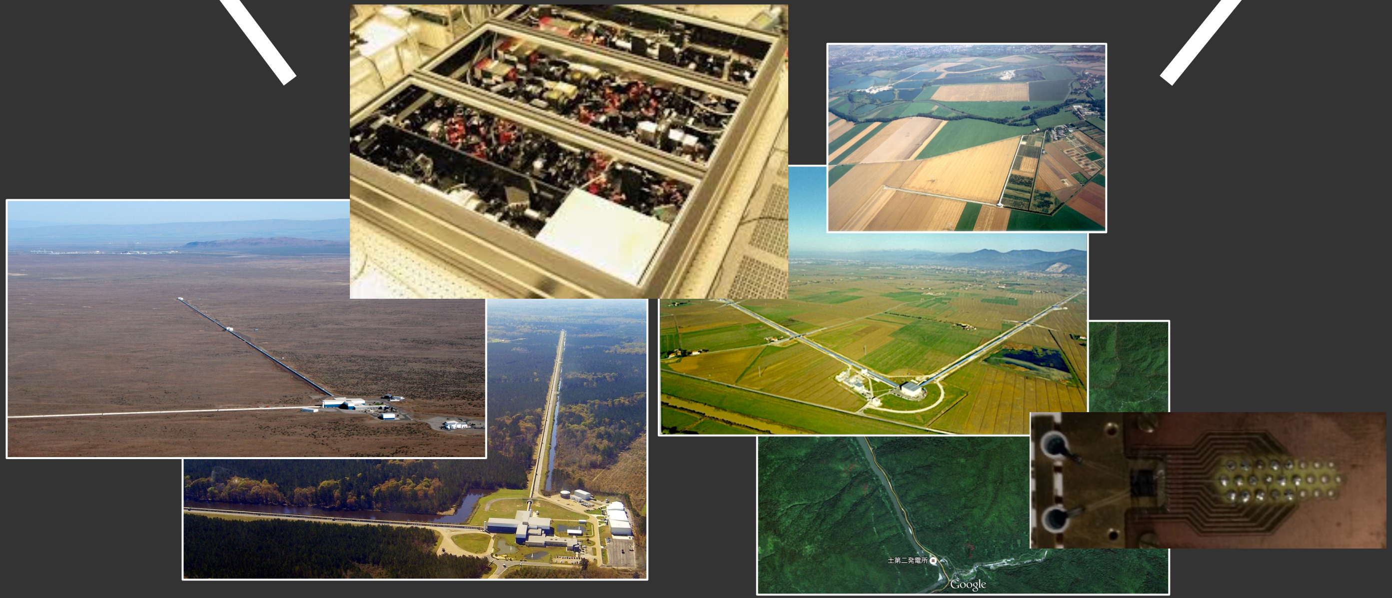
[redacted]

Quantum-Enhanced Interferometry (QI) For New Physics

QI

Dark Matter

Quantum Gravity



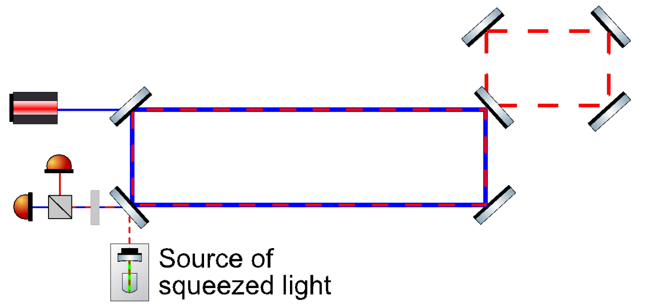
Work Packages

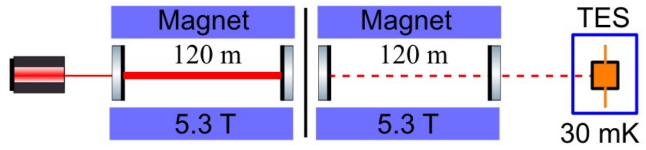
WP 1: Axions in the galactic halo

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

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

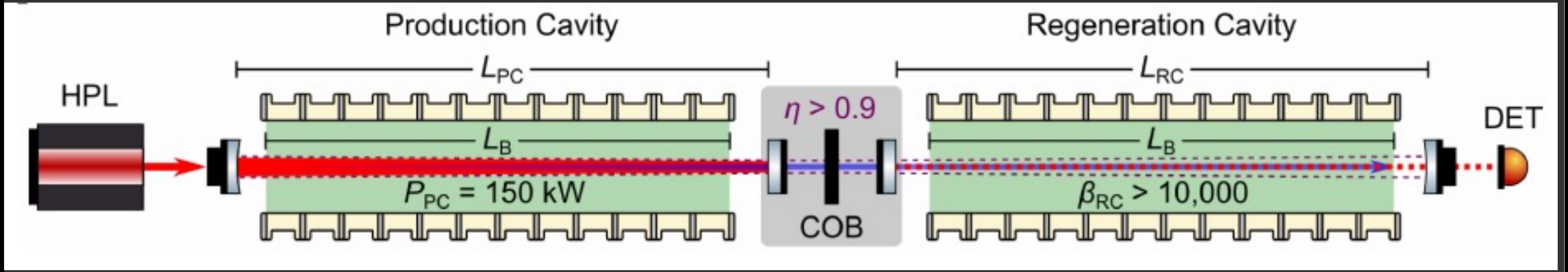
- Making and detecting axion-like particles
- Transition edge sensor with background $<10^{-6}$/s





WP1

ALPS @ DESY, Germany



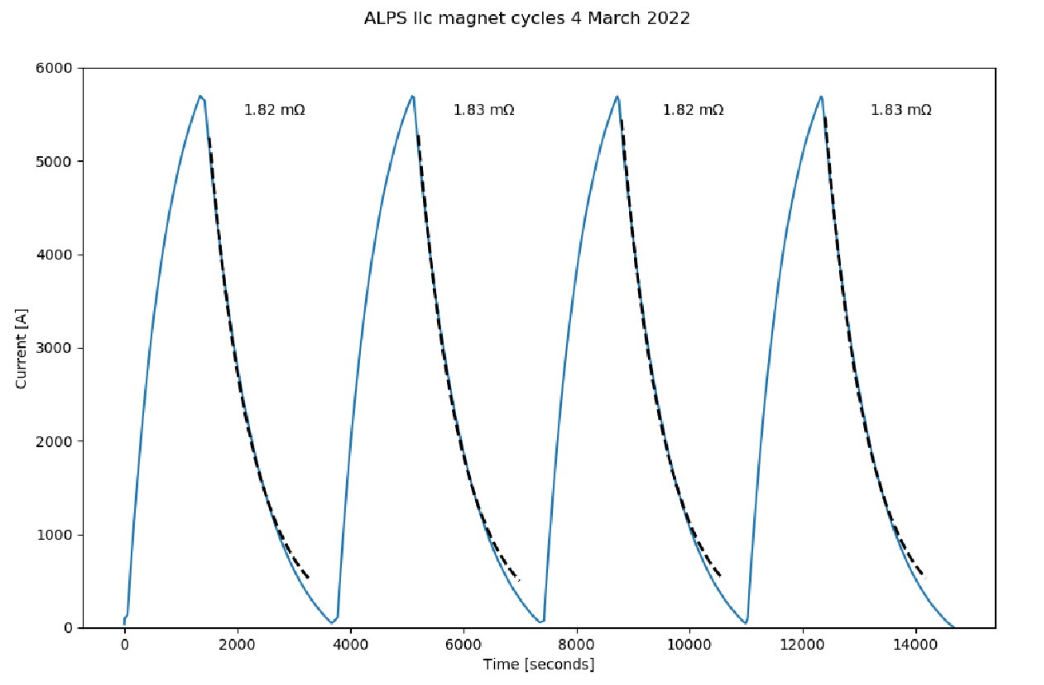
arXiv:2009.14294

- International collaboration (DESY, U Florida, AEI Hannover, Mainz, Cardiff)
- Under construction in former HERA accelerator tunnel at DESY
- WP2 contribution: improved TES and ALPS commissioning

ALPS II at DESY

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

Successful magnet test:
current cycling.



Work Packages

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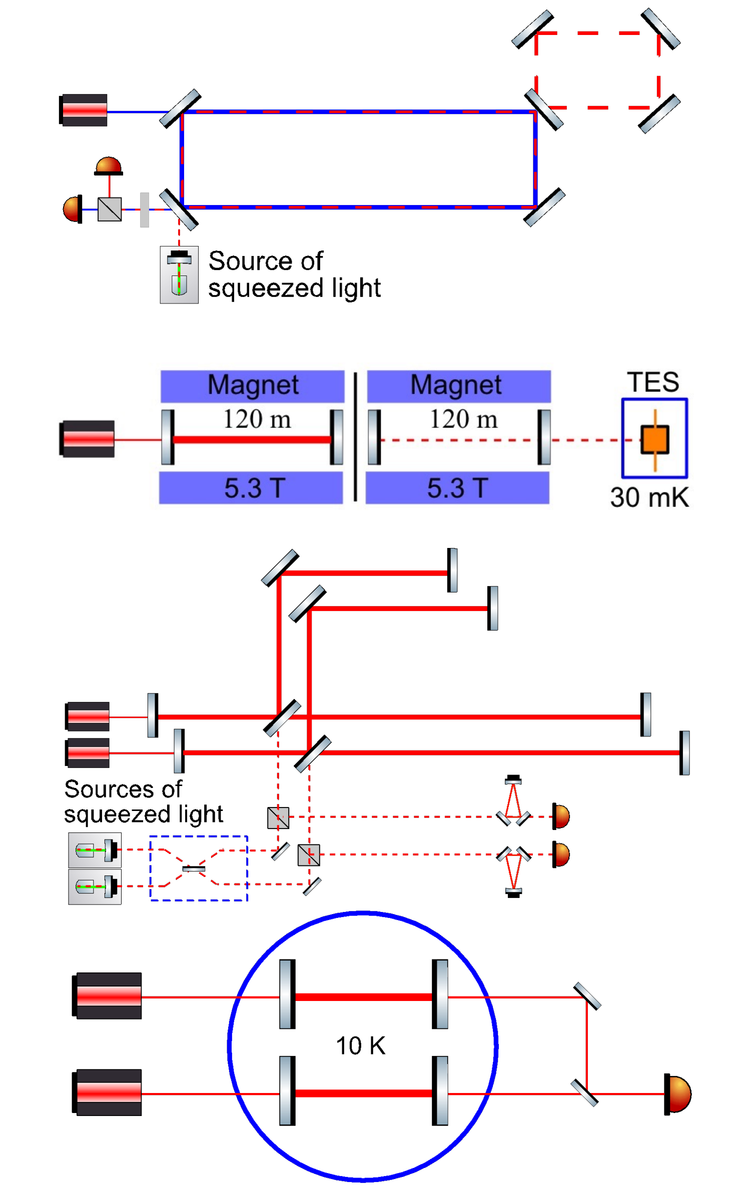
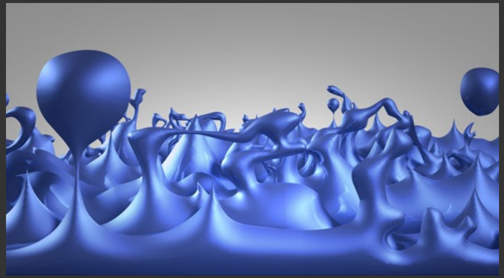
WP 2: Light-shining-through-wall (collab.)
- Making and detecting axion-like particles
- Transition edge sensor with background $<10^{-6}$/s

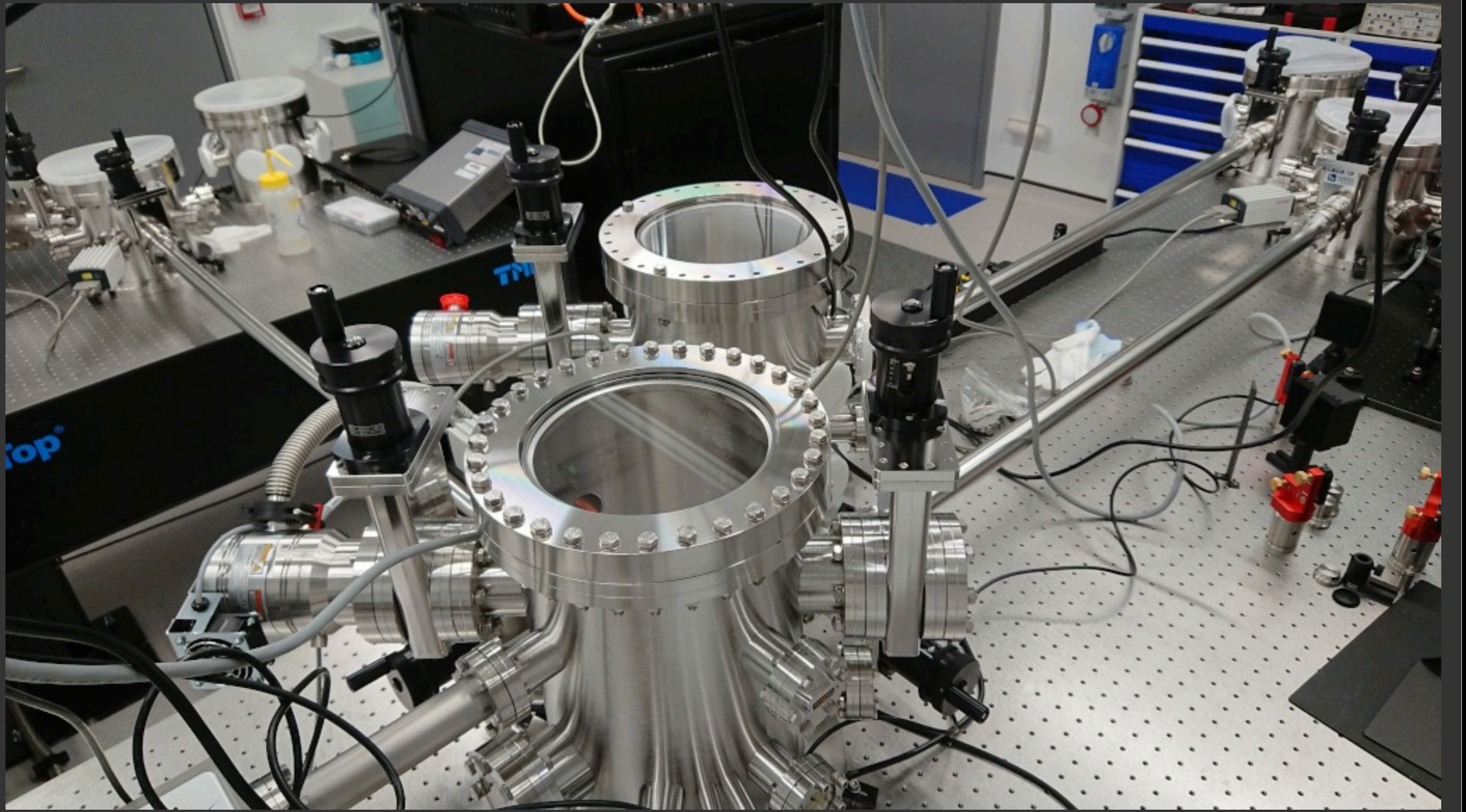
WP 3: Quantisation of space-time
- Testing ideas on quantization of space-time
- Sensitivity of 2×10^{-19} m/rt(Hz) above 1 MHz

WP 4: Semiclassical gravity
- Testing semiclassical gravity predictions
- Test-bed for other forms of possible quantum/gravity interaction experiments

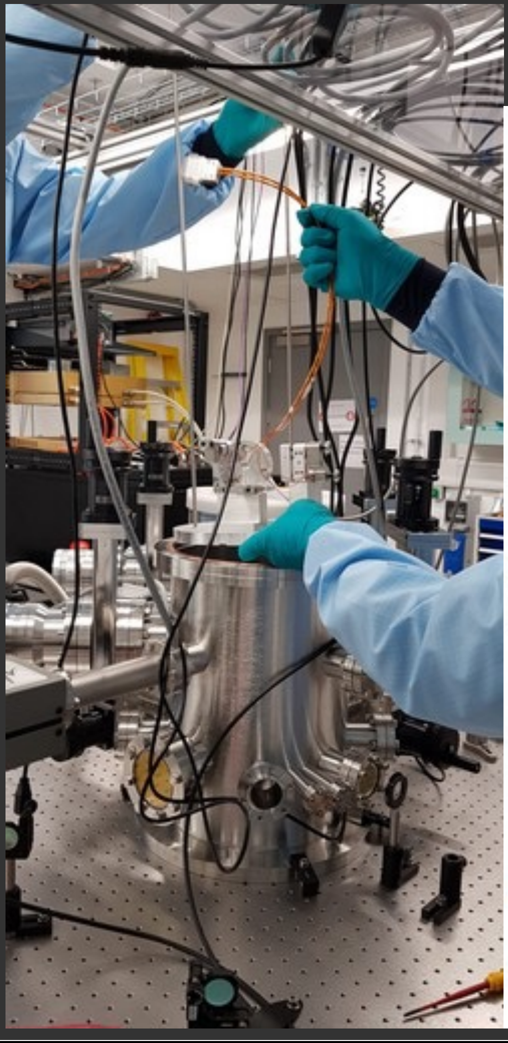


WP3: Quantization of Space-Time

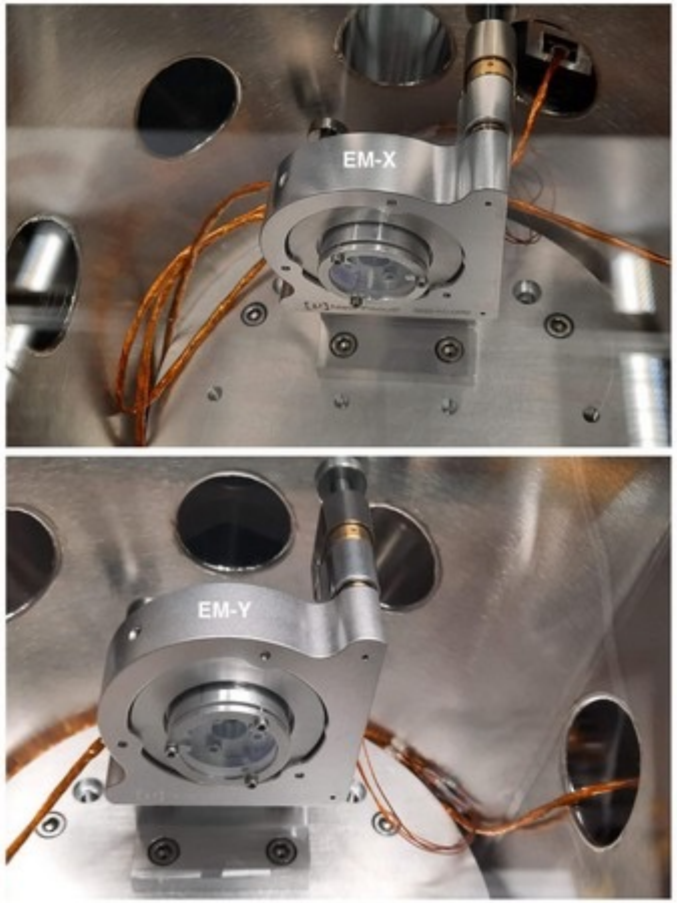




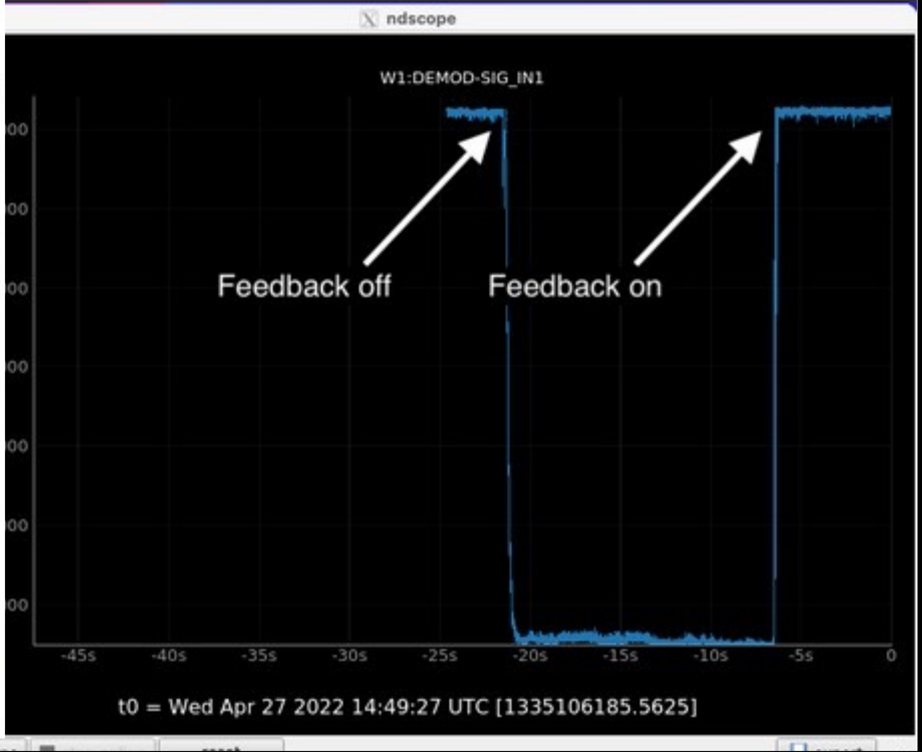
WP3: Quantization of Space-Time



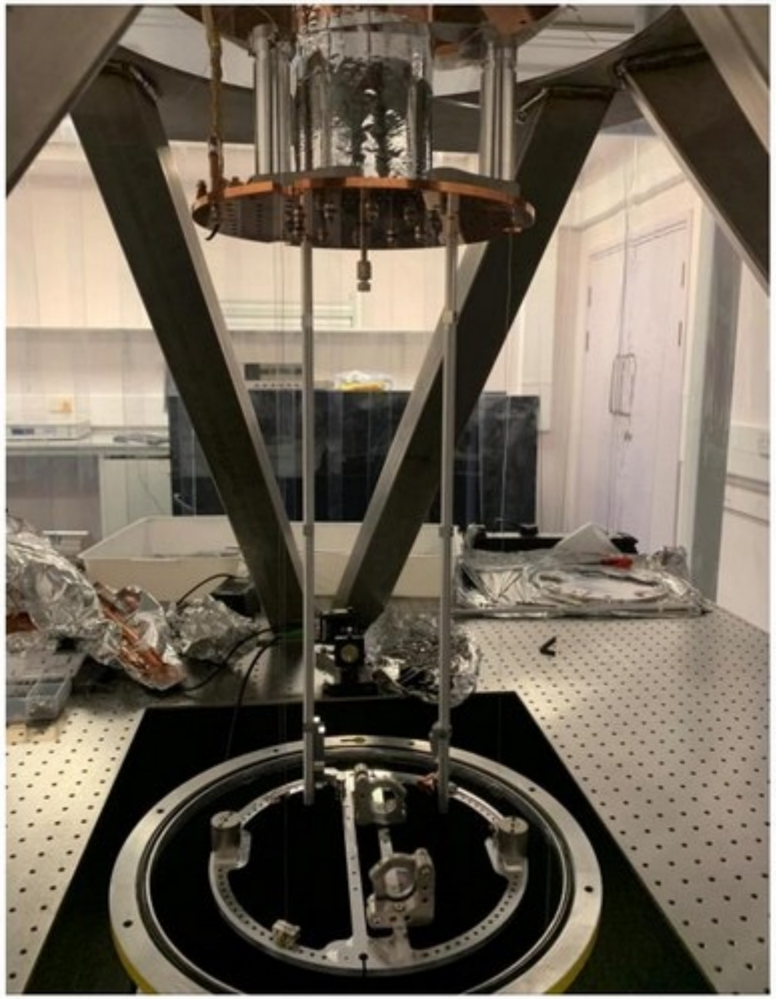
Optics installed (1st IFO)



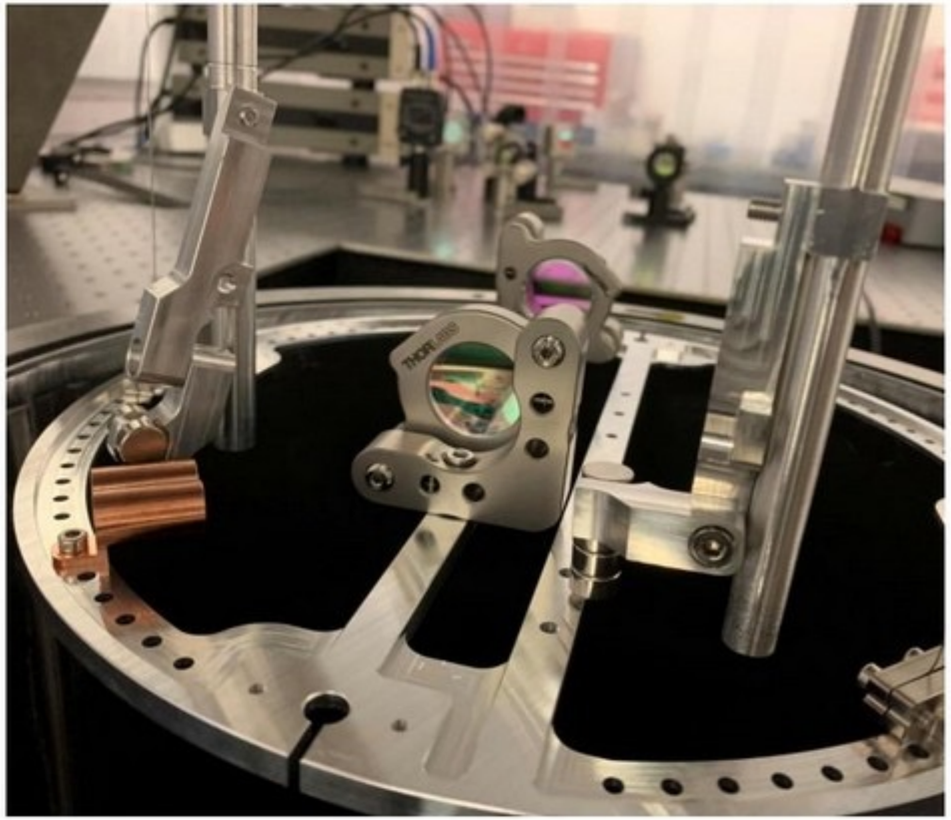
Michelson interferometer locked with
Dither modulation scheme



WP4: Semiclassical Gravity



Simplified suspension version for locking commissioning



Quantum Technologies

- Squeezed states of light
  - Quantum 2.0, enhancing quantum limited interferometers
- Single Photon Detectors
  - Facilitating single photon detection with ~100kW pump fields

Optical coating facility + R&D

National Manufacturing Institute Scotland

EPOC
extreme performance in optical coatings

University of Strathclyde Glasgow

University of the West of Scotland UWS

University of Glasgow

Gooch & Housego

HELIA PHOTONICS

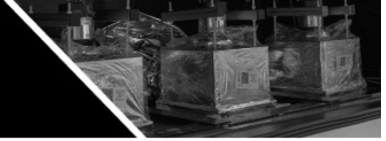
First several optics coated in dedicated facility
(shared use for QI)

Optics for WP's 1,3,4

Progress being made on all WPs, eager to see results!

Neutrinos

QTNM



Quantum Technologies for Neutrino Mass

On behalf of the QTNM Consortium

NPL National Physical Laboratory

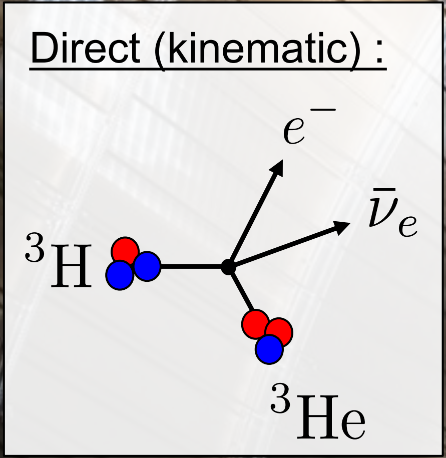
UNIVERSITY OF CAMBRIDGE

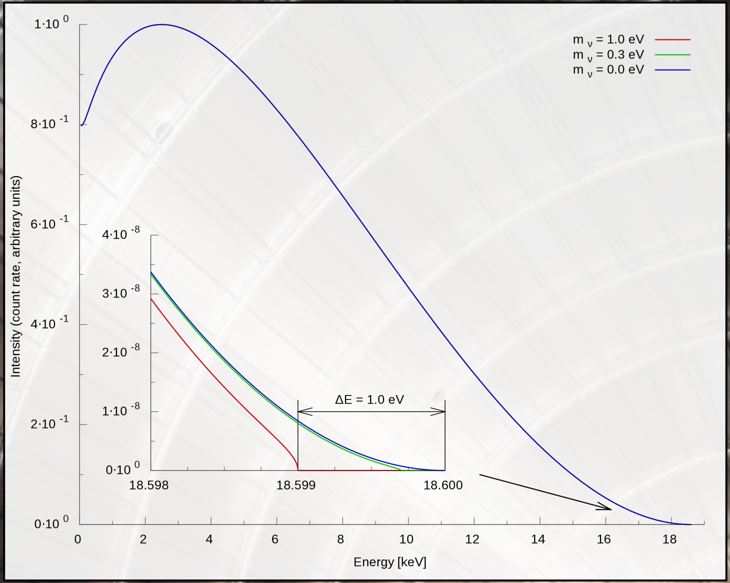
UCL

THE UNIVERSITY OF WARWICK

Prifysgol Abertawe Swansea University

Direct Neutrino Mass Measurement

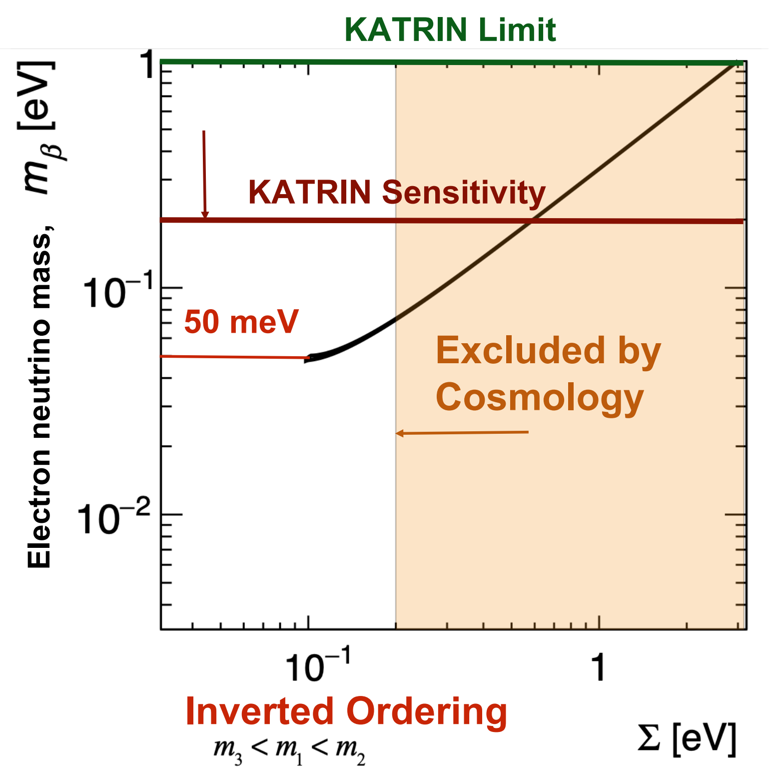


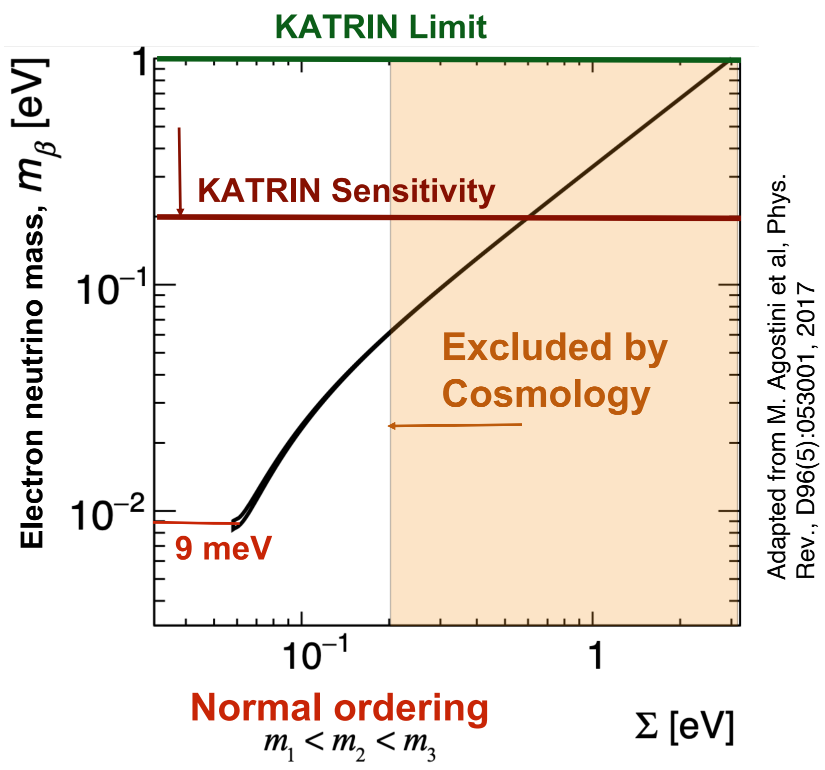


KATRIN (2022)

$$m_\nu < 0.8 \text{ eV } (90\% \text{ C.L.})$$

Direct Neutrino Mass Measurement





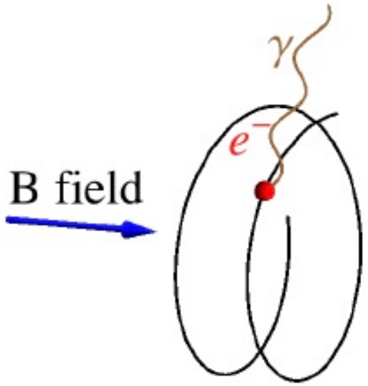
- Powerful constraints from cosmology but cannot replace **lab measurements.**
- Kinematic" measurement of β-decay spectrum is the **only model independent method.**
- Two clear sensitivity goals: **50 meV** for **I.O.** and **9 meV** for **N.O.**

Goal of next generation experiments.

"Guaranteed" observation if reached.

CRES

A. Schawlow: “Never measure anything but frequency!”



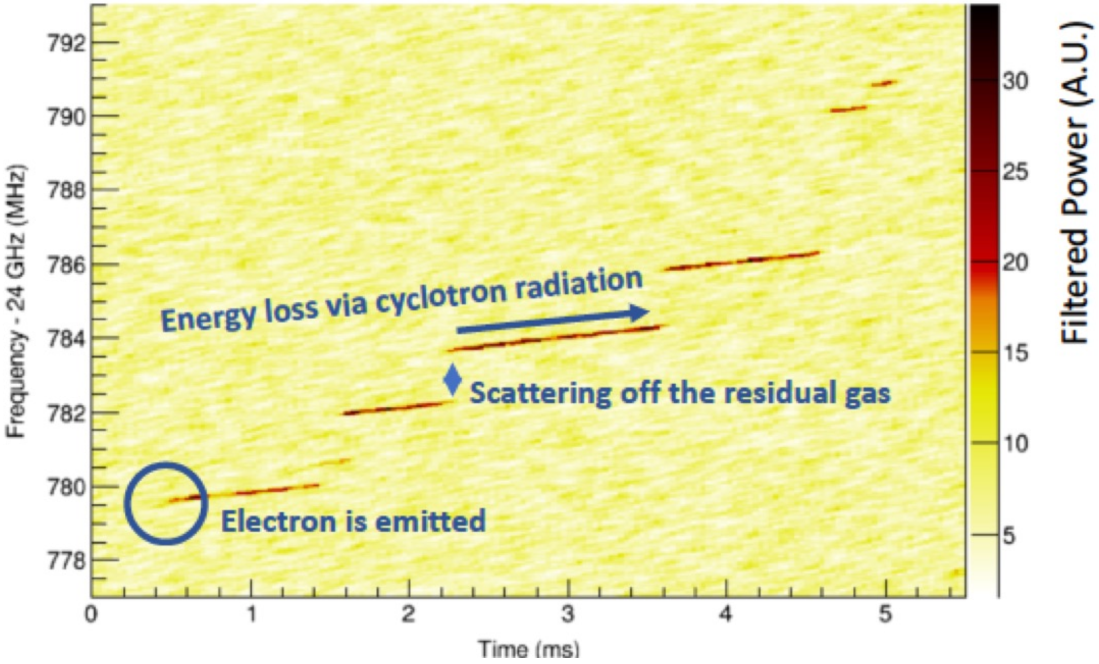
Cyclotron **R**adiation **E**mission **S**pectroscopy

(Monreal and Formaggio, Phys. Rev. D 80 2009)

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

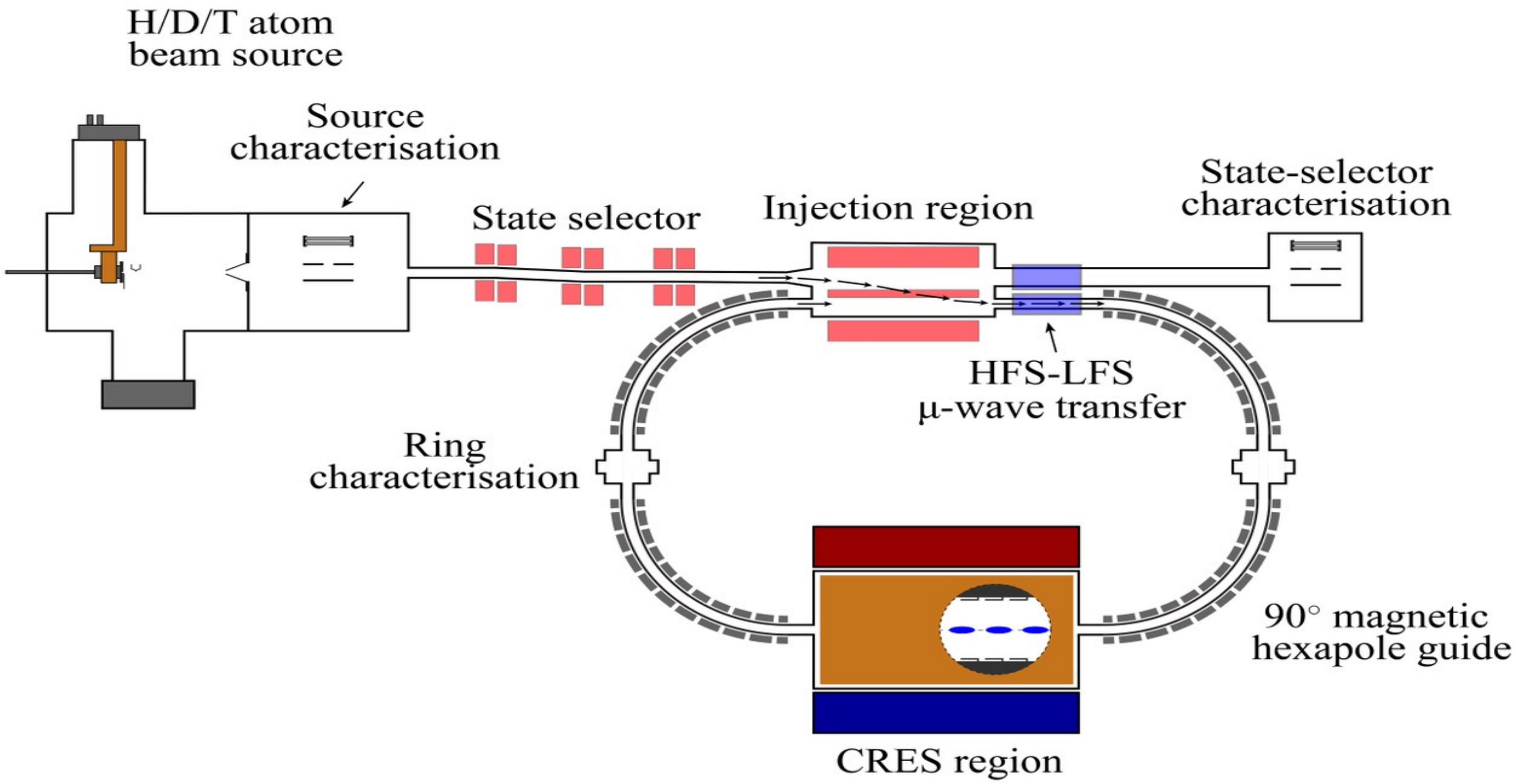
≈ 27 GHz for 18.6 keV and 1 Tesla.

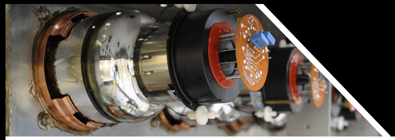
Project-8 (2015)



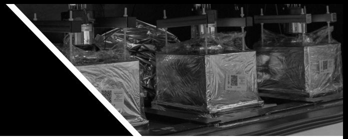
QTNM-CRESDA

- Novel atomic source and delivery system together with characterisation.
- Quantum-limited microwave detection system in CRES region.
- High-precision B-field mapping.
- Software, simulations & sensitivity studies.





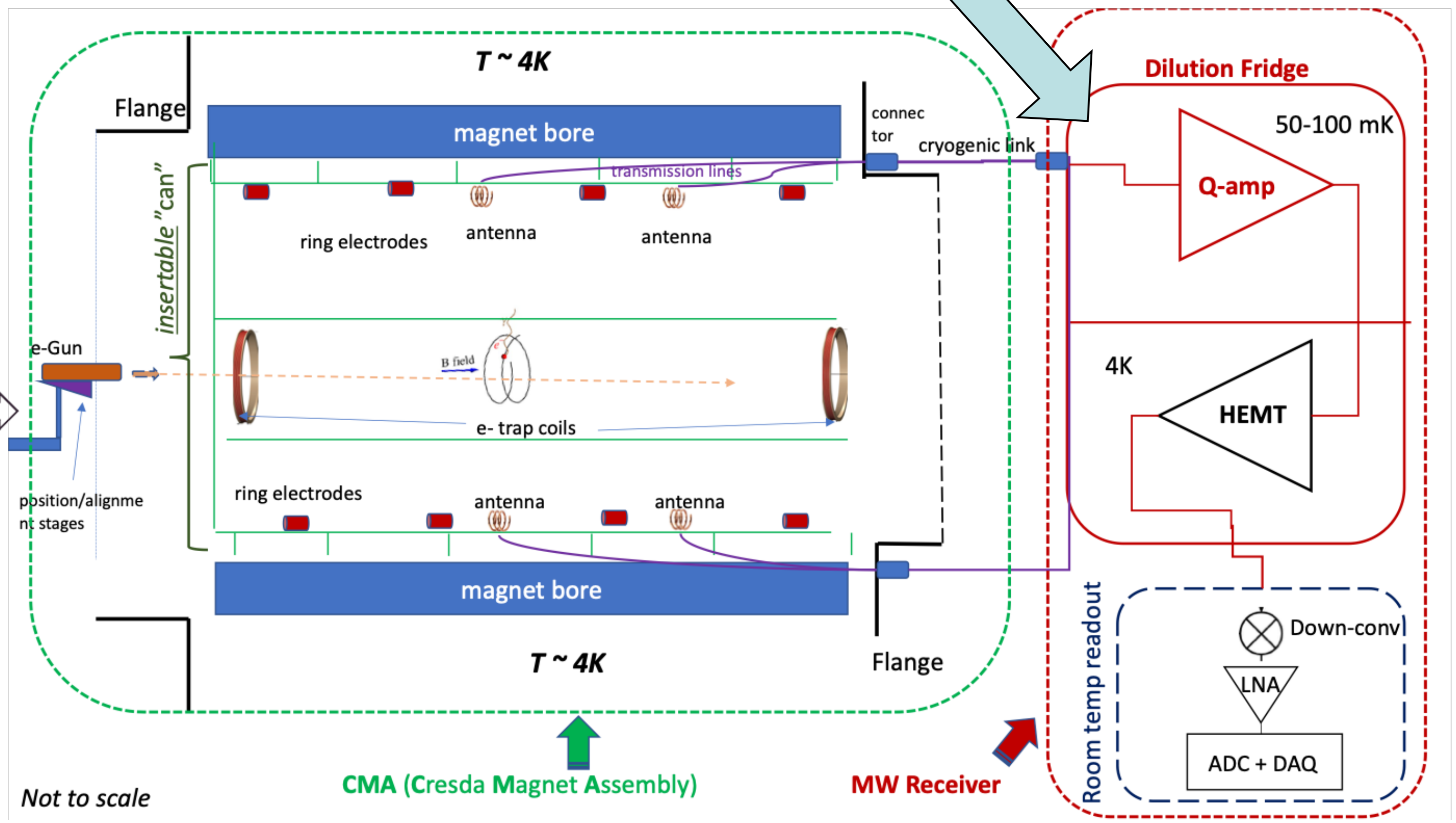
CRES Magnet Assembly



Quantum pre-amplifier options:

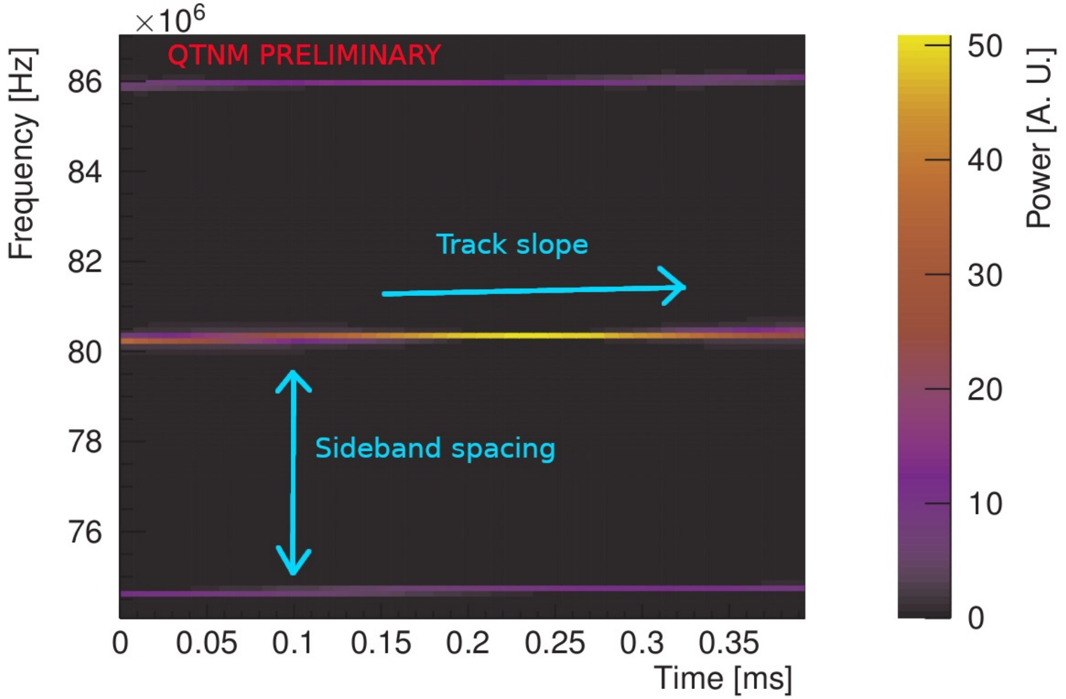
- Parametric Amplifiers
- Superconducting Low-Inductance Undulatory Galvanometer (SLUG)

Source of (10-20 keV electrons to simulate Tritium β-decay



QTNM : Recent Progress

- End-to-end simulation stack including electron motion, CRES emission & detection, noise injection, down-mixing and signal extraction.
- Magnetic trap simulations guiding magnet procurement. Antenna characterisation.
- TWPA development and analysis (Zhao & Withington 2021, 2022).
- Laboratory and facility preparations @ UCL, NPL, Cambridge.
- First in-person collaboration meeting In June 2022 @UCL



mK cooler - Bluefors

- mK cooler installed in NPL AQML lab & tested June 2022

Blufors dry dilution fridge operating at ***15 mK*** *with* ***2T*** *magnet*

VNA operating frequency up to ***40 GHz***

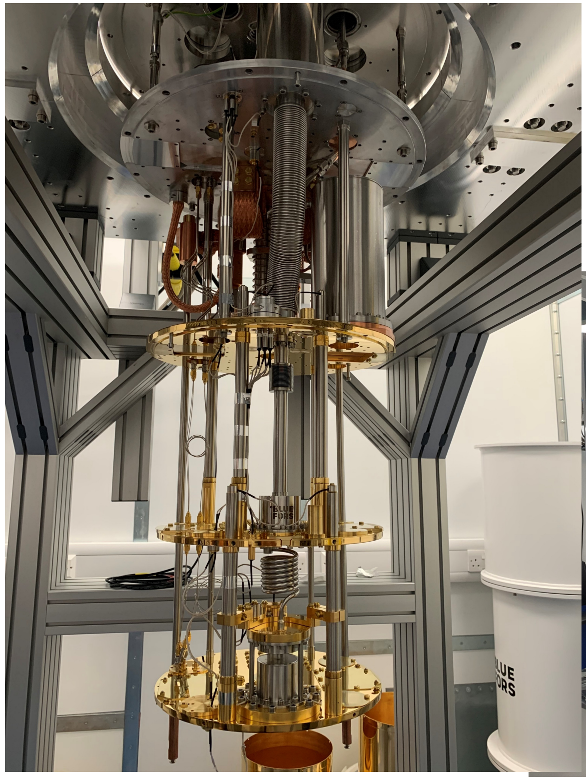
Low noise amplifiers: broadband and narrow-band up to 30 GHz

AWG 2.5 GS/s sample rate

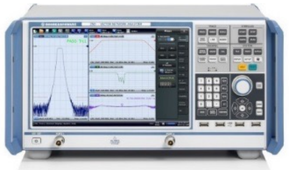
This system could provide a test-bed to evaluate and develop prototype systems for a future ultimate quantum limited detector experiments for quantum technology, digital, advanced instrument and fundamental physics (e.g. Neutrino mass measurements).

National Physical Laboratory

NPL AQML Lab



mK cooler insert



Vector Network Analyser, up to 40GHz

mK cooler installed inside screen room

Community Links

QTNM Consortium

UNIVERSITY OF CAMBRIDGE

UCL

THE UNIVERSITY OF WARWICK

Prifysgol Abertawe
Swansea University

NPL
National Physical Laboratory

University Groups
Particle Physics
Atomic Physics
Theory
Quantum Technology
Electrical Engineering

National Laboratories
Quantum Technology
Cryogenics
Metrology

- Joint CM attendance.
- Consortium Agreement.

- Advice & consultation.
- Preparation for future phases.

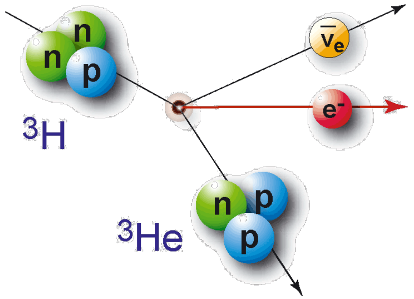
International Partners

PROJECT 8

National Centres

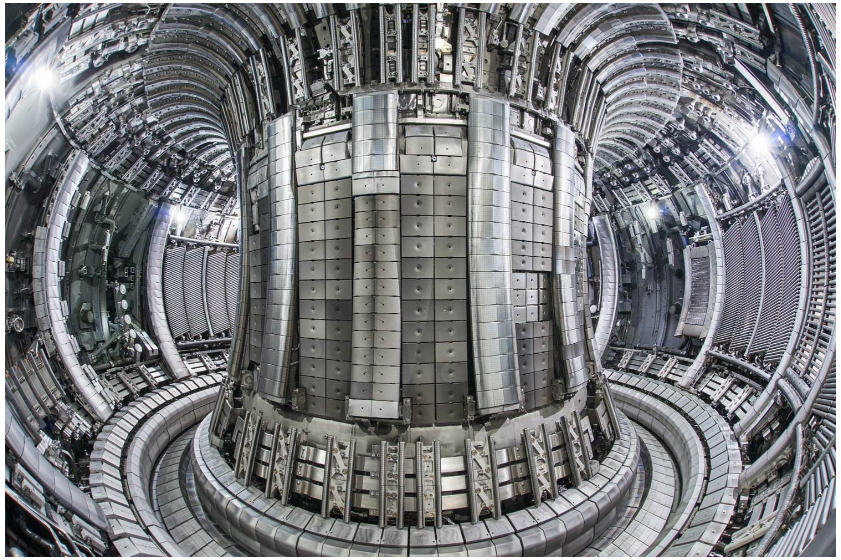
CCFE
CULHAM CENTRE FOR FUSION ENERGY

QTNM Future Outlook



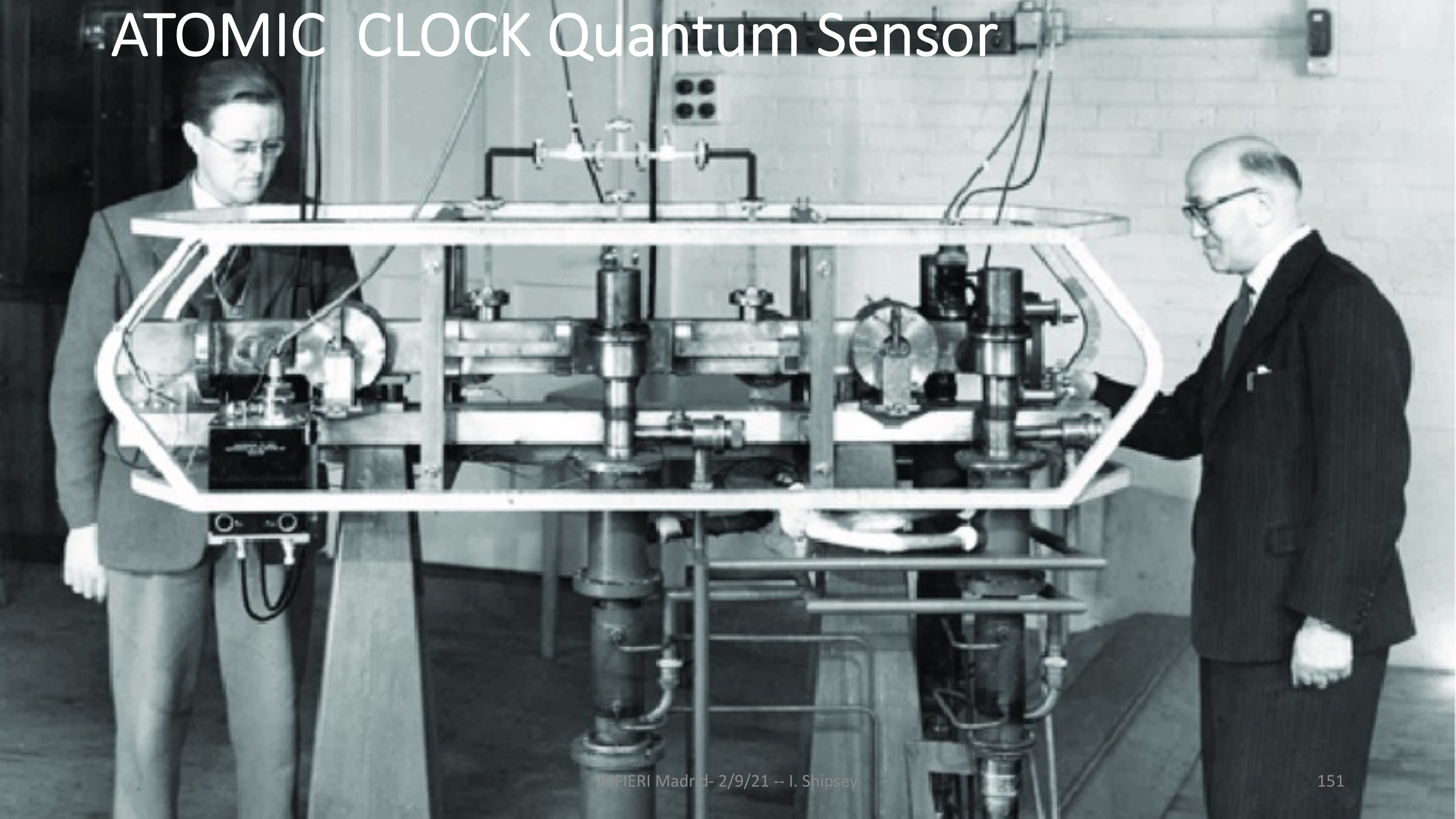
A (*VERY*) tentative timeline

- Current project: 2021-2024
  - Technology demonstration with Deuterium which is Tritium ready
- Next step. 2025-2029
  - Moving CRESDA to a Tritium facility (strong engagement with Culham)
  - Tritium phase demonstration
  - *O*(eV) sensitivity
- ”Ultimate” international project > 2029
  - Consolidate technological breakthroughs (QTNM, Project-8, …) to build and operate a detector with a phased sensitivity: 100 meV ⇨ 50 meV ⇨ 10 meV plus sterile neutrino programme

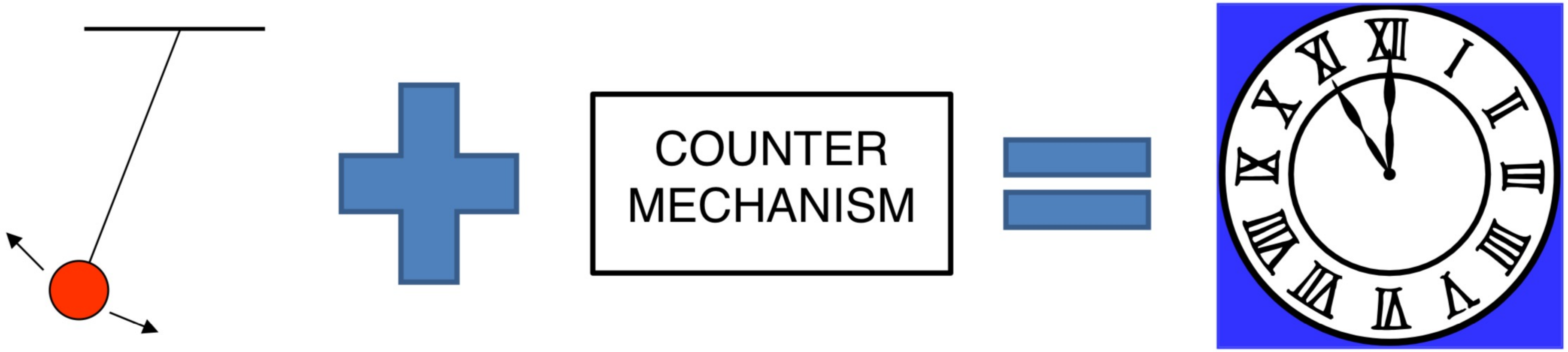


CCFE
CULHAM CENTRE FOR FUSION ENERGY

ATOMIC CLOCK Quantum Sensor

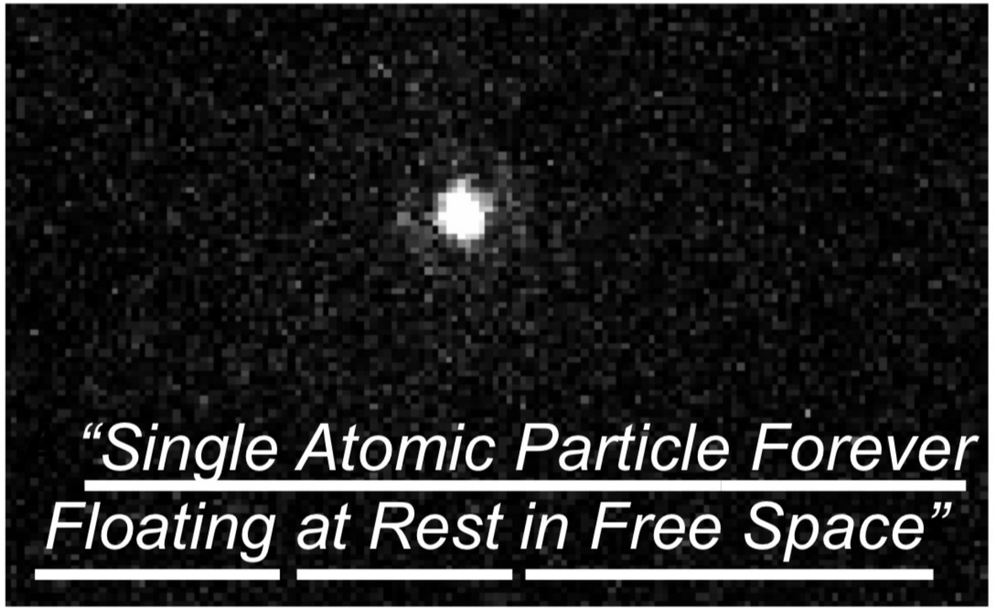


Clocks and oscillators



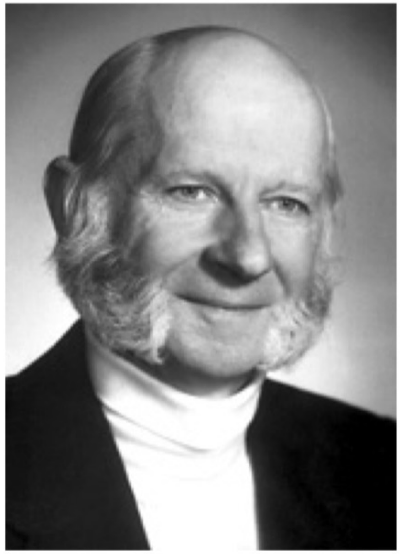
OSCILLATOR	COUNTER MECHANISM
Earth rotation	Sundial
Pendulum Swing	Clock Gears and Hands
Quartz Crystal Vibration	Electronic Counter
Cesium Atomic Vibration	Microwave Counter

Trapped Atomic Ions



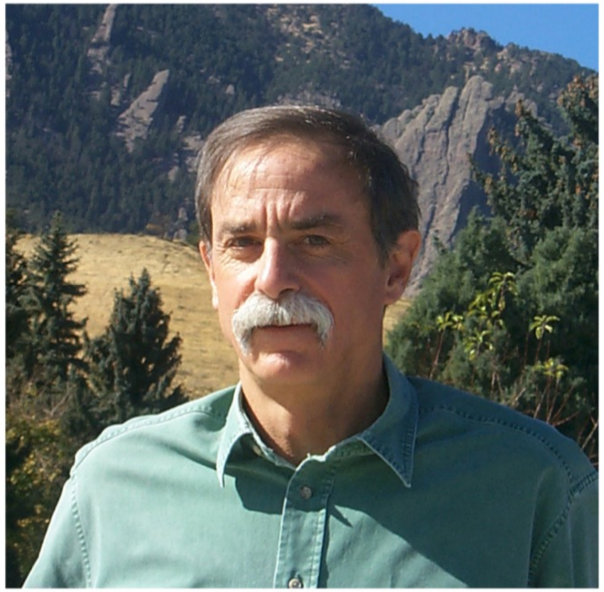
- Quantum-limited experiments
- Long interaction times
- Small relativistic shifts
- Small perturbation from EM fields

Predicted resolution of 1×10^{-18}



Hans Dehmelt

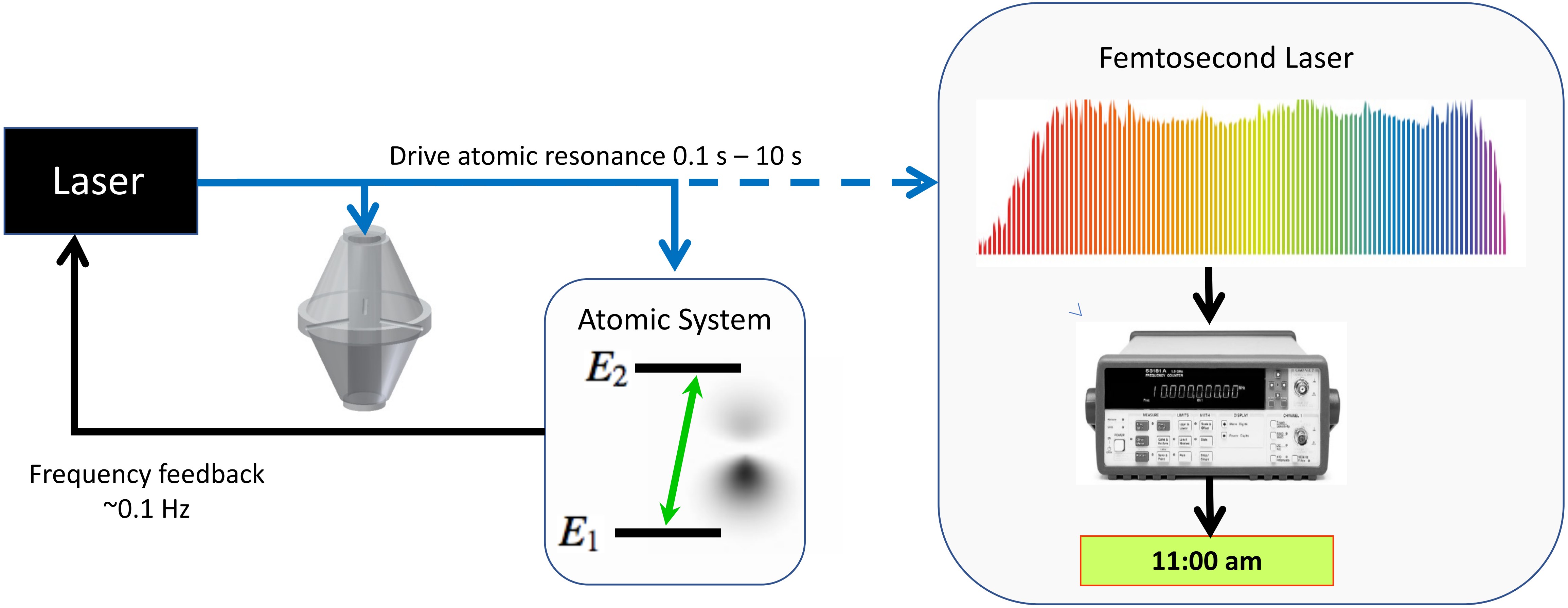
Hans Dehmelt 1988 *Phys. Scr.* **1988** 102



+ Strong, controllable interactions between ions

Slide credit: David Hume

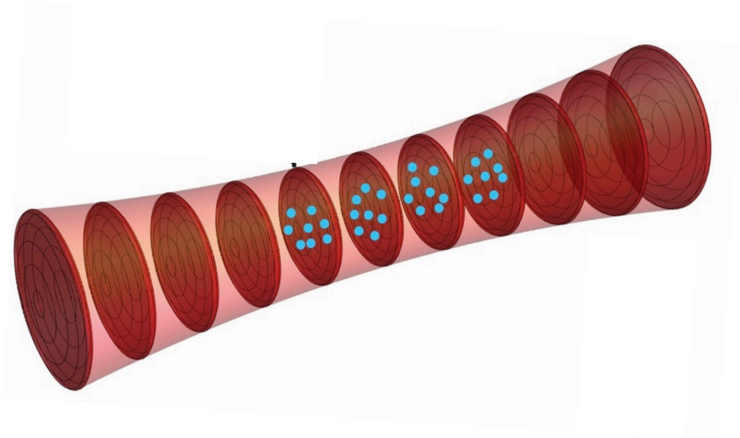
Principle of Optical Clocks



Clock frequency: $f_0 = \frac{E_2 - E_1}{h}$ $\approx 10^{15}$ Hz

Slide credit: David Hume

Optical Lattice Clocks and Trapped Ion Clocks



- Magic wavelength optical lattice
- Typically, 1000s of atoms
- Laser cooled to uK temperatures
- Dominant systematics: blackbody radiation, lattice light shifts

More atoms = higher stability

- RF Paul trap
- Typically, single ions
- Can be cooled to ground state
- Dominant systematics: 2nd-order Doppler, blackbody radiation

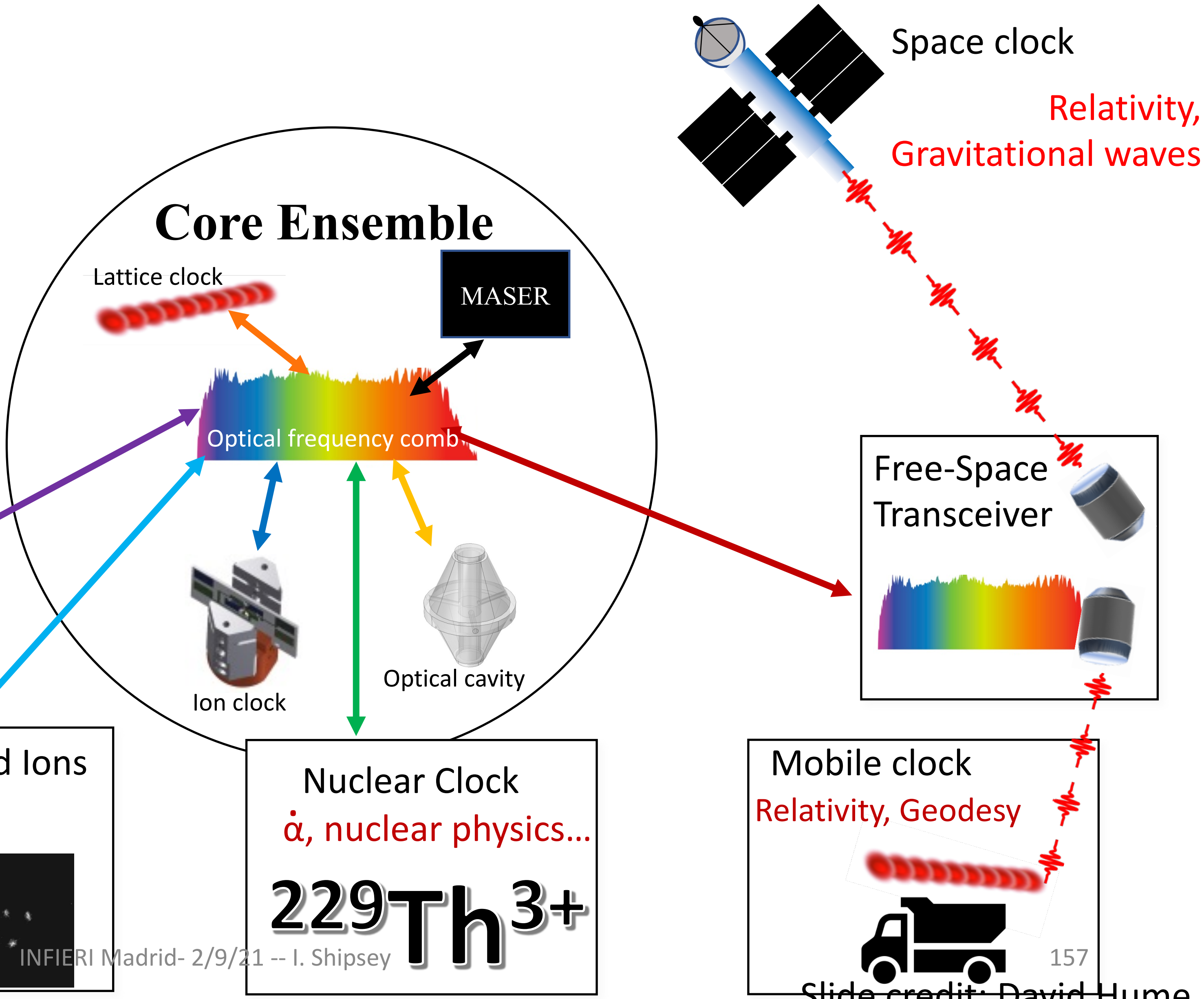
Applicable to any ionic species

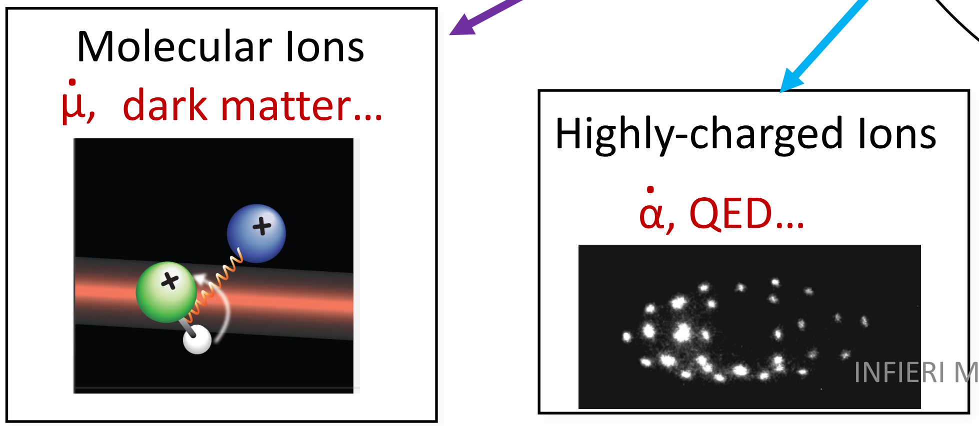
Slide credit: David Hume

An Atomic Observatory for Fundamental Physics

<u>Features:</u>

- Broad science reach
  - QED, fundamental constants, relativity, dark matter, gravitational waves…
- Modular and extensible
- Core ensemble based on proven technology
- Science modules (local or remote) connected via fiber optic or free-space links





Slide credit: David Hume

QSNET

A network of clocks for measuring the stability of fundamental constants

Giovanni Barontini

Birmingham NPL Sussex Imperial

Background

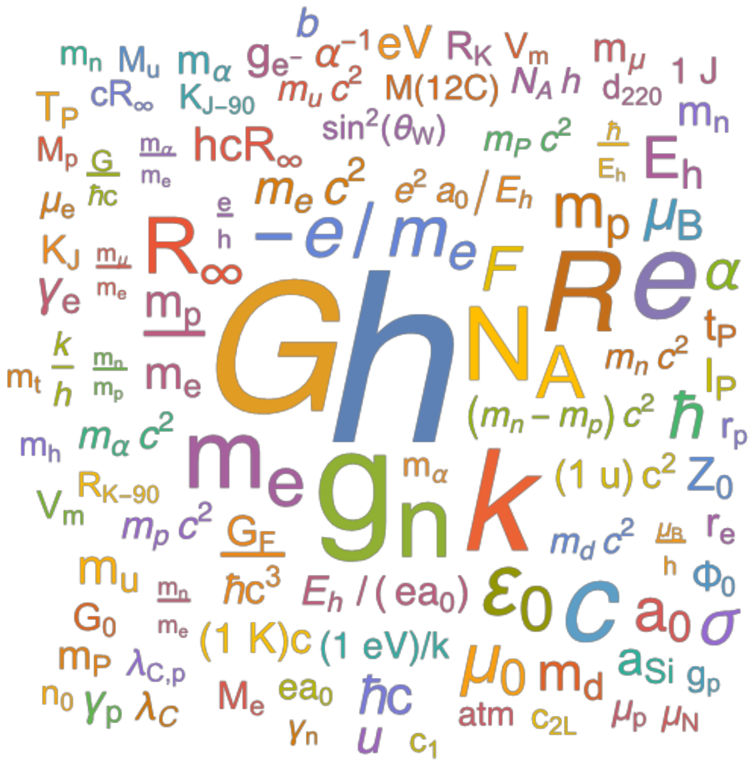
- The Standard Model and ΛCDM are very successful theories but…

- The ΛCDM model postulates that 95% of the energy content of the universe is dark matter and dark energy. Their exact nature is unknown. Only the remaining 5% is described by the SM.

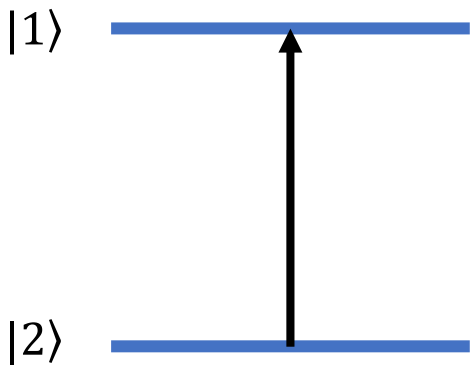
- Both models have several parameters, supposed to be immutable, called fundamental constants.

- Challenging this central assumption could be the key to solving the dark matter and dark energy enigmas

- Any variations of fundamental constants would give us evidence of revolutionary new physics



Sensitive probes

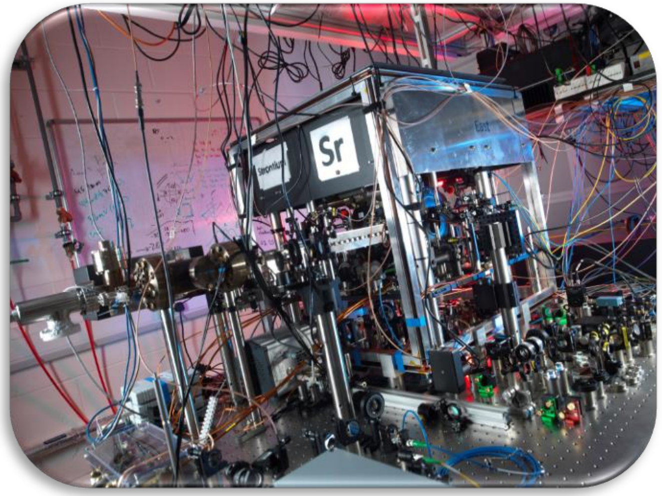


- All atomic and molecular energy spectra depend on the fundamental constants of the Standard Model
- Spectroscopy lends itself to measure variations of:

α

$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c} \qquad \mu = \frac{m_p}{m_e}$$

- Atomic an molecular spectra can be measured with extreme precision using atomic clocks

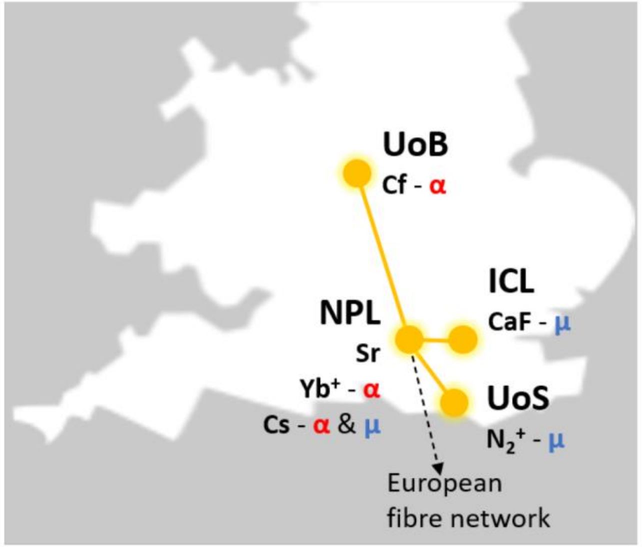


- Stability and accuracy at the 10^{-18} level

The QSNET project

- **Search for variations of fundamental constants of the Standard Model, using a network of clocks**

- A unique network of clocks chosen for their different sensitivities to variations of **α** and **μ**



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

- The clocks will be linked, essential to do clock-clock comparisons

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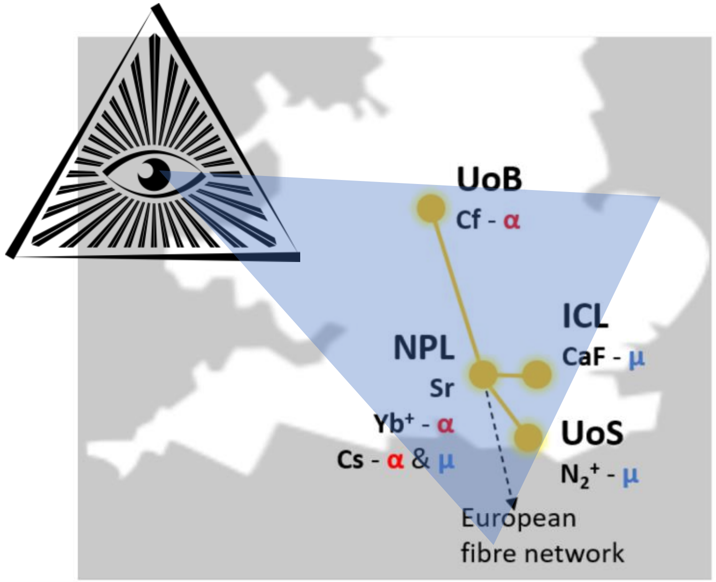

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The network approach

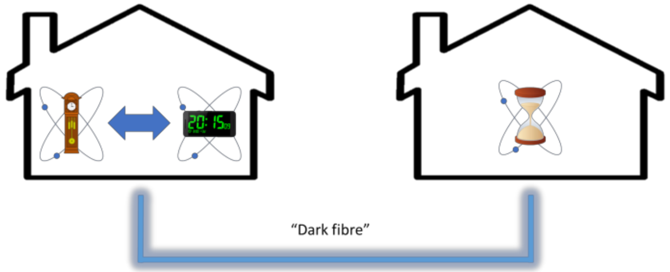
- Optimally exploit existing expertise. No single institution has the range of expertise required to run a sufficiently large and diverse set of clocks

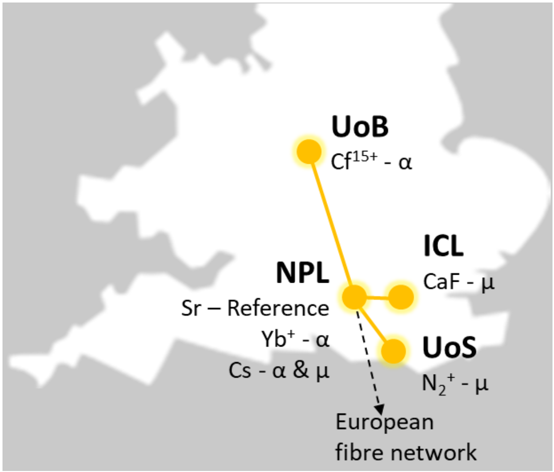
- Sensors with similar sensitivities and different systematics are necessary to confirm any measurements and reject false positives

- Networks enable probing of space-time correlations

- The possibility of detecting transient events such as topological defects in dark matter fields or oscillations of dark matter

- A new versatile and expandable national infrastructure with possible further applications in and beyond fundamental physics.

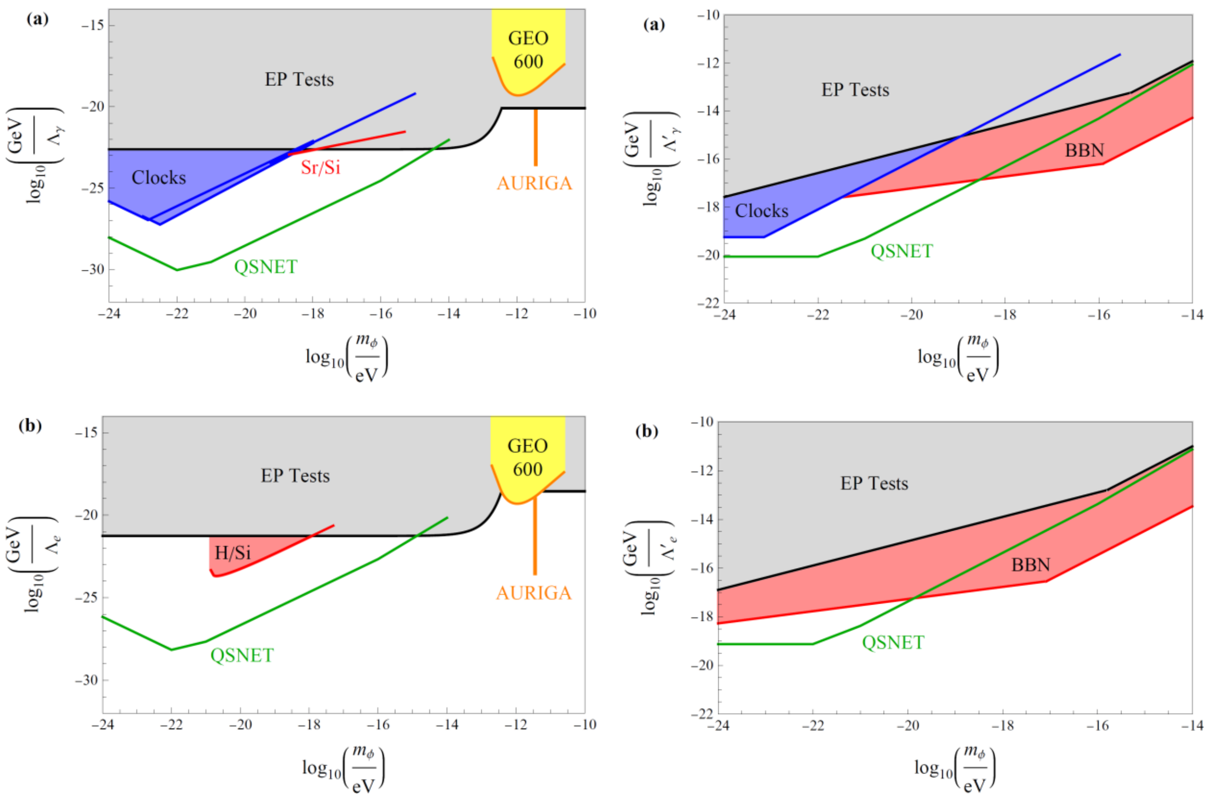




Phenomenology [EPJ QT 9, 12 (2022)]

Improve by orders of magnitude the sensitivity to:

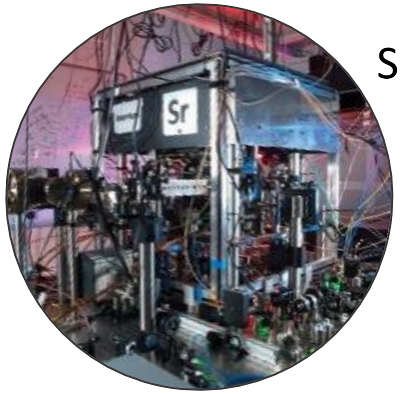
- Light scalar dark matter
- Dark energy fields like Quintessence
- A generic hidden sector scalar field
- Kaluza-Klein and Dilaton fields
- DM Solitons
- Cosmic strings
- DM Domain walls
- DM kink solutions
- Violation of fundamental symmetries
- Tests of grand unification theories
- Tests of quantum gravity



Progress, NPL

- Improved robustness and automation of optical clock operation, to record longer time series of frequency data
- Expect constraints on α and μ to exceed the current state-of-the-art before the end of Phase 1
- μ-sensitive ratio (Sr / H-maser) has revealed better stability and wider frequency range than previously published results

Yb^+



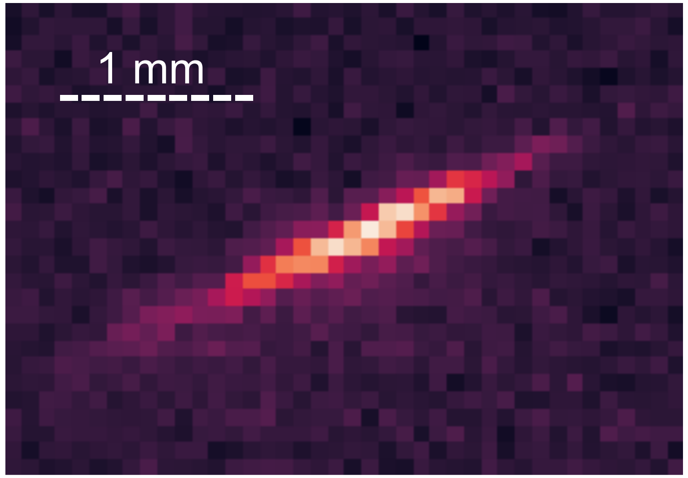
Sr

Cs

Progress, Imperial

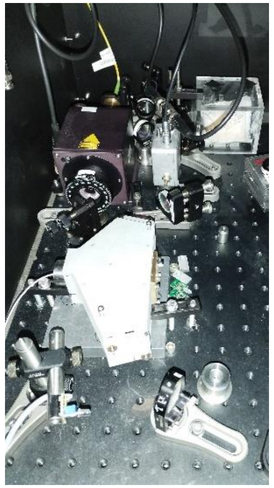
- Idea: clock based on vibrational transition in a molecule, sensitive to m_e / m_p
- Recent breakthrough: have trapped CaF molecules in a 1D optical lattice
- Laser systems for the clock are currently being developed

Ultracold CaF in a 1D lattice



Progress, Sussex

- Spectroscopy lasers setup finished
- Successful loading of nitrogen in to ion trap by REMPI
- Development of novel ionisation laser in progress
- Development of novel quantum logic spectroscopy in progress

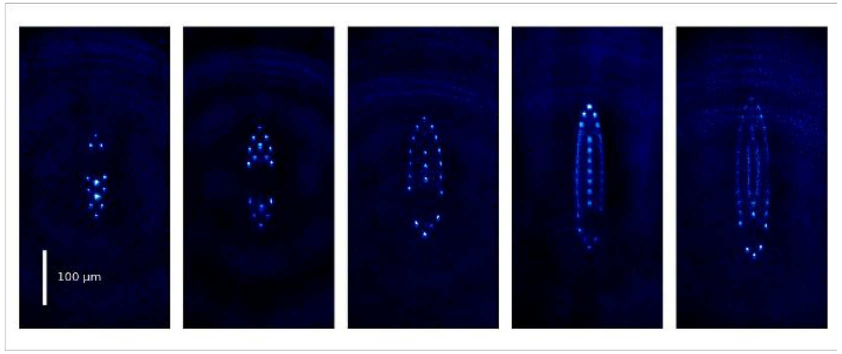


Progress, Birmingham

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

- Realisation of a compact Electron Beam Ion Trap (cEBIT) for highly charged ions of Cf

- Characterisation of a superconducting Paul trap for singly charged and highly charged ions



- Realisation of a ultra-low vibration cryogenic vacuum system for trapping ofhighly charged ions

Progress, Theory

- Derived model independent bounds on the masses of singlet dark matter. X. Calmet and F. Kuipers, Phys. Lett. B 814 (2021), 136068. This is directly relevant to searches with clocks and interferometers. (Major press coverage)

- Discovered that quantum gravity leads to a quantum pressure for black holes, first calculation of quantum gravitational corrections to BHs entropy from first principles. X. Calmet and F. Kuipers, Phys. Rev. D 104 (2021) no.6, 066012.(Major press coverage)

- Solution to Hawking information paradox using the concept of macroscopic superposition and quantum hair X. Calmet and S. D. H. Hsu, Phys. Lett. B 827 (2022), 136995, EPL 139 (2022) no.4, 49001; X. Calmet, R. Casadio, S. D. H. Hsu and F. Kuipers, Phys. Rev. Lett. 128 (2022) no.11, 111301. (Major press coverage)

- Shown that quantum gravity rules out singlet scalar dark matter discovery with clocks or interferometers. Searches should focus on charged scalar dark matter/dim 6 operators. X. Calmet and N. Sherrill, Universe 8 (2022) no.2, 103

- Sussex/NPL paper in progress with new theoretical and data analysis frameworks applied to new data. We are obtaining the best limits on the parameters space of, e.g., ultra light dark matter to date.

Goals for Phase 1

1. New constraints on $\Delta\mu/\mu$ on timescales from 10-1000 s, targeting $4x10^{-15}$ at 1000 s
2. Measure $\Delta\alpha/\alpha$ on fast timescales targeting $1x10^{-17}$ at 1000 s, exceeding current state of-the-art sensitivity
3. Realization of a Cf^{15+} and Cf^{17+} cEBIT
4. Measure the N_2^+ clock transition
5. Quantify the impact of the new limits on unified models and dark matter models
6. Load CaF molecules in optical lattices and identify the clock transition
7. Using available data, provide first tests of model-independent parametrization for variations of fundamental constants and theoretical bounds on dark matter masses.

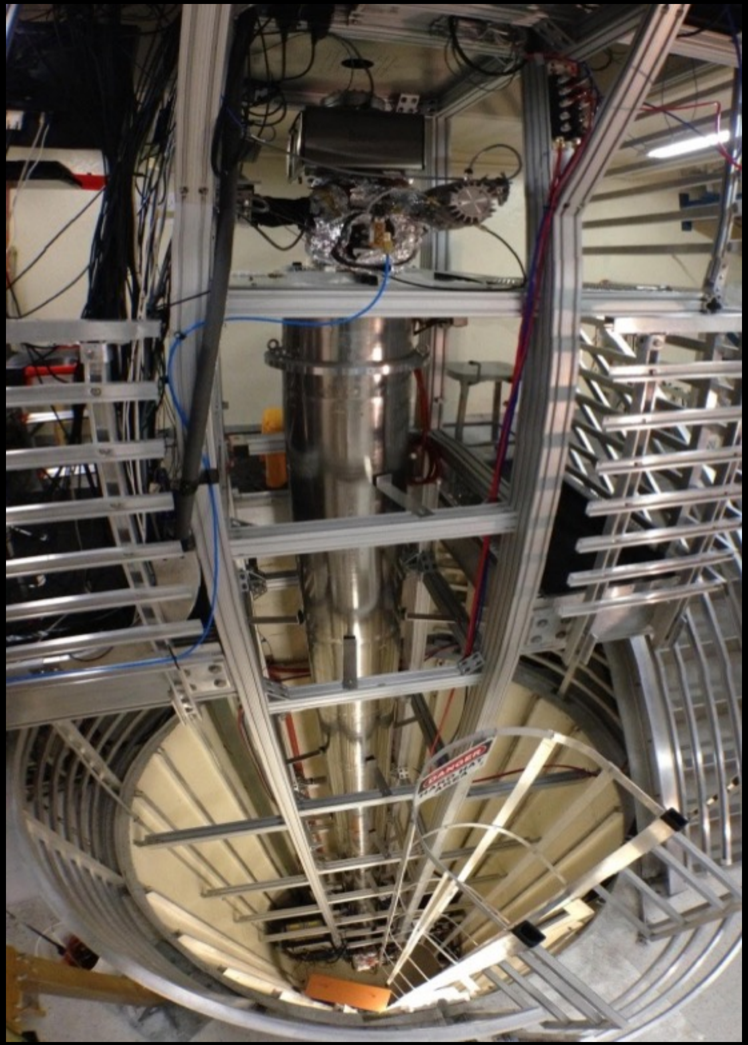
Beyond Phase 1

- Connect the clocks via fibre links and run clock/clock comparison campaigns
- Achieve the projected sensitivity of QSNET [EPJ QT 9, 12 (2022)]
- Detection of variations of fundamental constants. If no variation is detected, improved limits on variations of α and μ and evaluation of impact on models beyond the Standard Model
- Extend the network nationally and internationally to other clocks and other sensing modalities
- Development of quantum correlations between the nodes of the network to enhance sensitivity

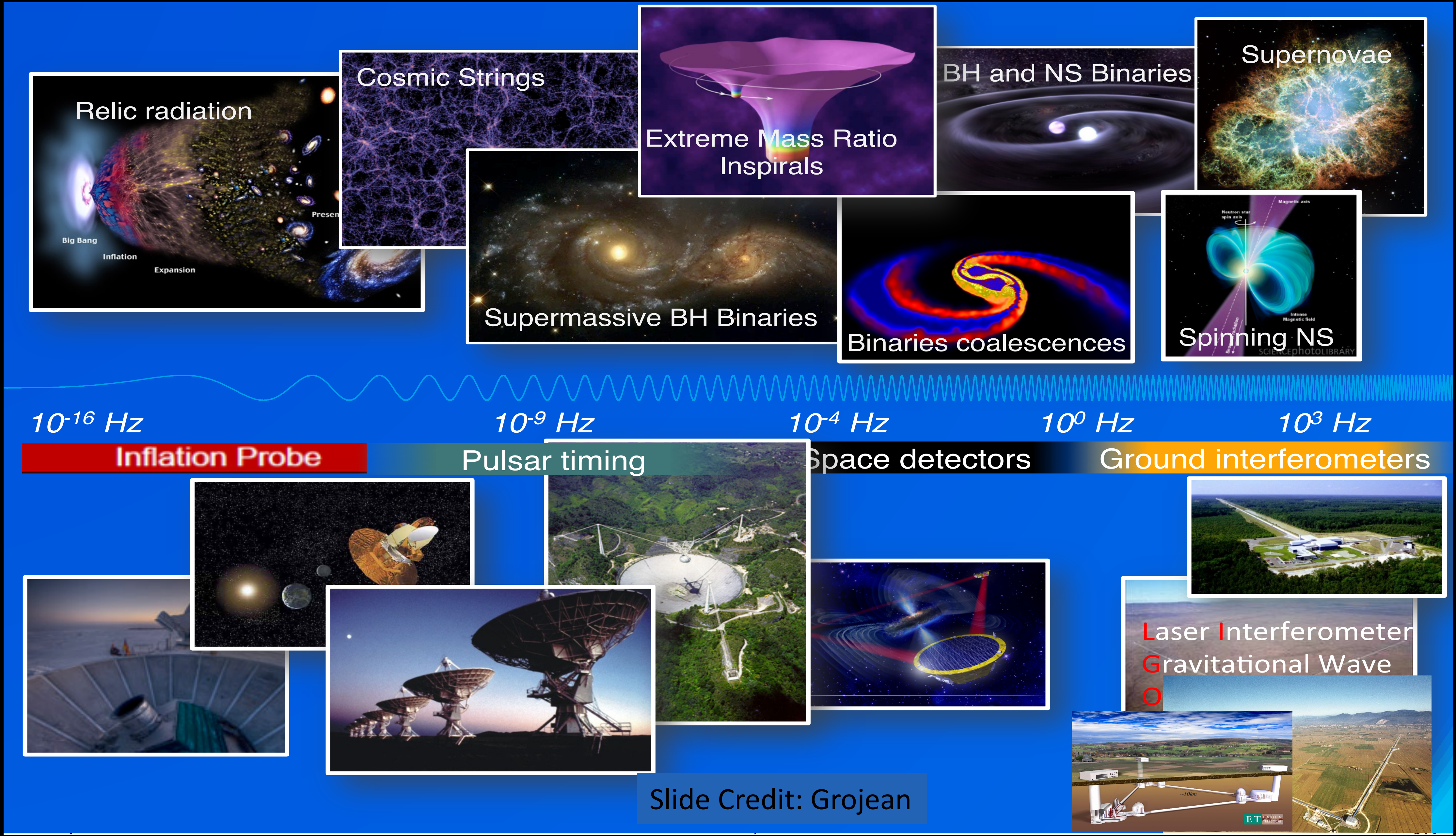
Possible funding routes:

- **QTFP Phase 2!**
- UKRI Infrastructure fund, a national dark fibre infrastructure (example in figure)
- International collaborations
- EPSRC program grant

Atom Interferometry

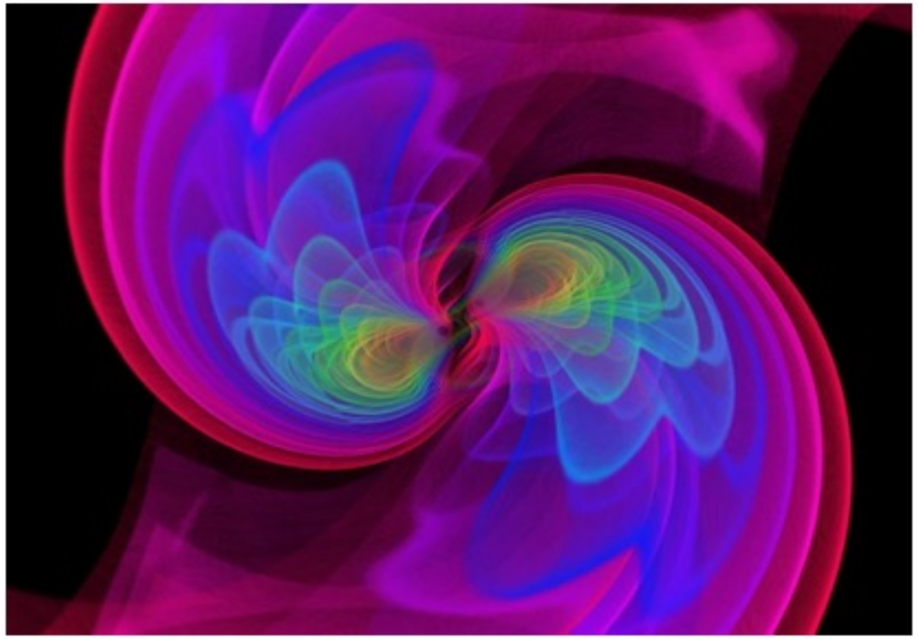


Gravitational Waves: Cosmology and Astrophysics

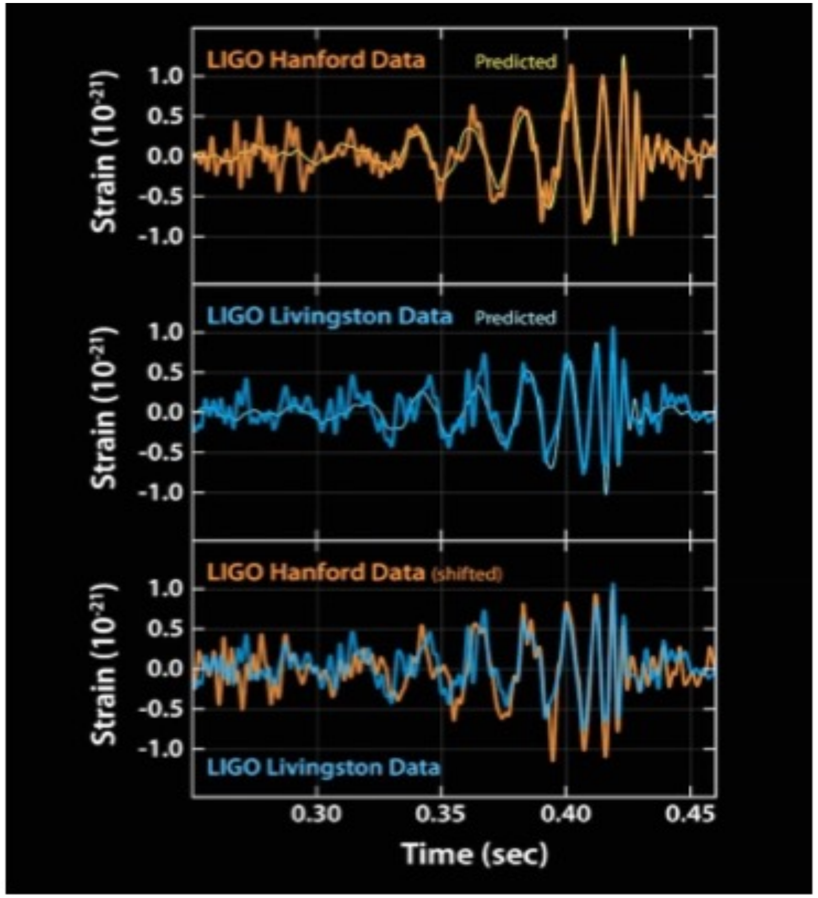


The pictures that shook the world

GW150914



1.3 billion years later on earth



Slide Credit: Grojean

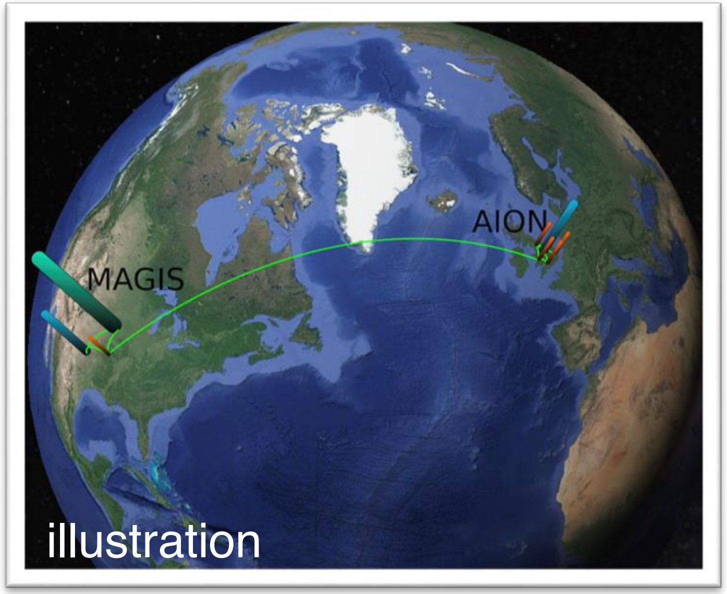
what did it teach us?

- never give up against strong background when you know you are right
- $m_g < 10^{-22}$ eV ($c_g - c_\gamma < 10^{-17}$. GRB observed together with GW with the same origin?)
- no spectral distortions: scale of quantum gravity > 100 keV

The AION Project

A UK Atom Interferometer Observatory and Network
to explore Ultra-Light Dark Matter and Mid-Frequency Gravitational Waves.

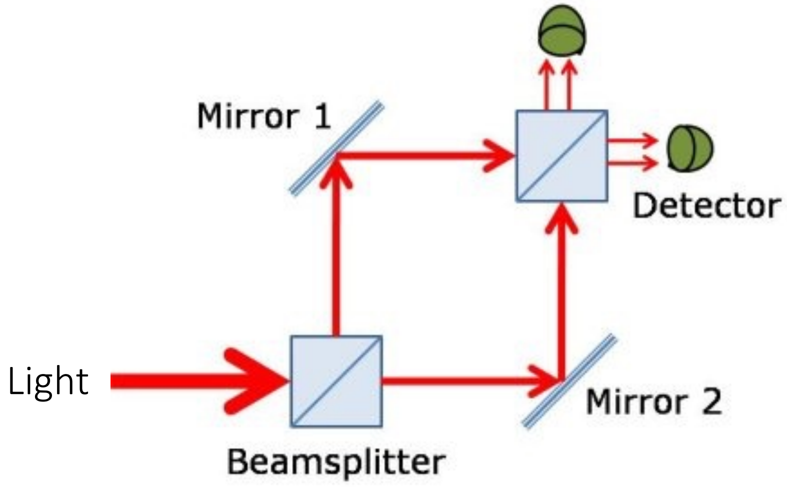
O. Buchmueller, Imperial College London

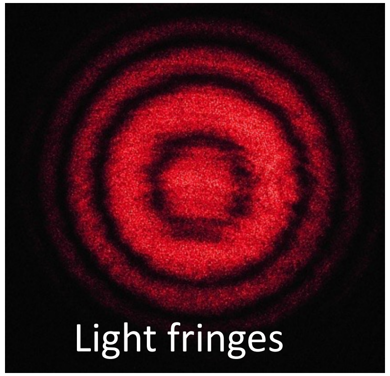


Project executed in national partnership with **UK National Quantum Technology Hub in Sensors and Timing, Birmingham, UK,** and international partnership with **The MAGIS Collaboration and The Fermi National Laboratory, US**

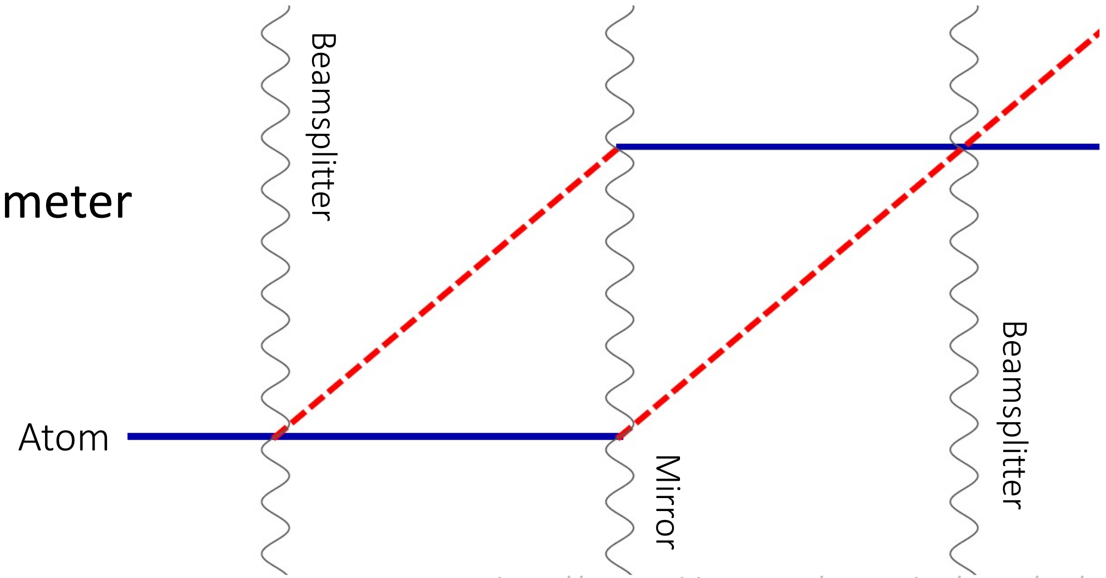
Light vs. Cold Atoms: Atom Interferometry

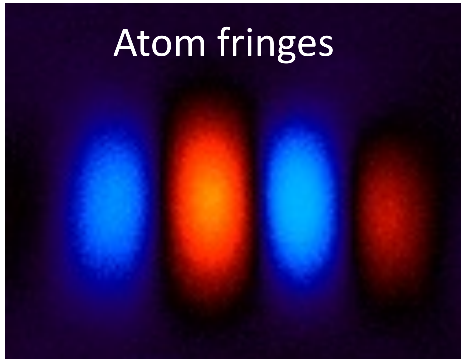
Light interferometer





Atom interferometer

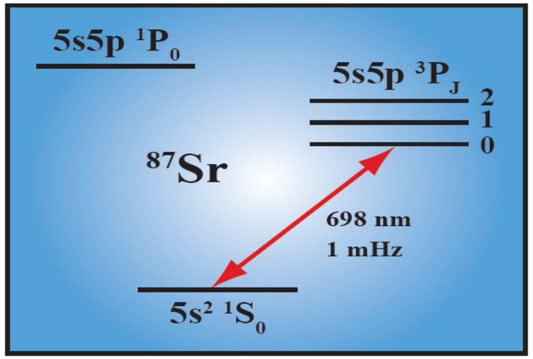




Courtesy of Jason Hogan!

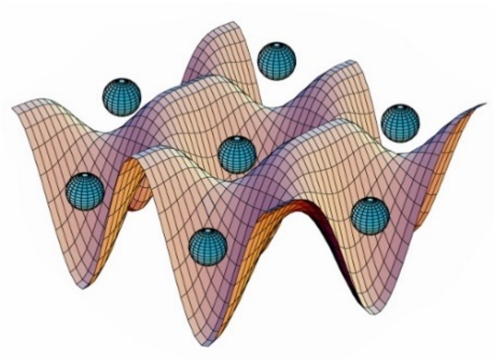
http://scienceblogs.com/principles/2013/10/22/quantum-erasure/
http://www.cobolt.se/interferometry.html

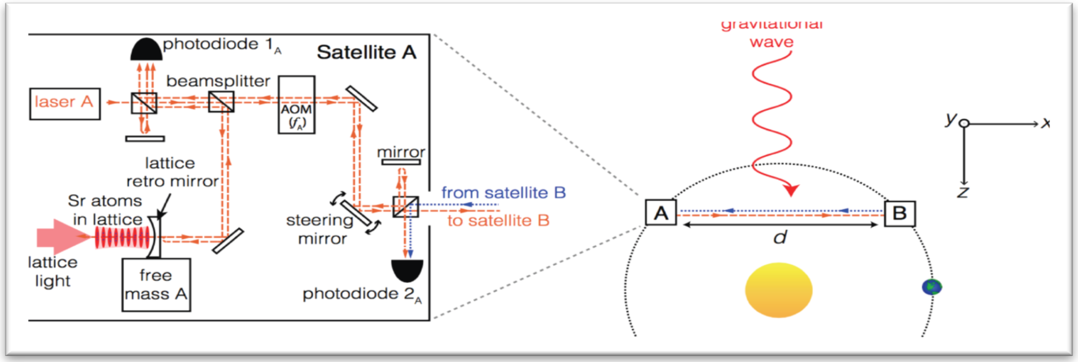
Atomic clocks and atom interferometers



- How can we leverage the incredible gains in stability and accuracy of clocks for fundamental physics?
- Atomic clocks and interferometers offer the potential for gravitational wave detection in an unexplored frequency range
- Development of new "clock" atom interferometer inertial sensors based on narrow optical transitions

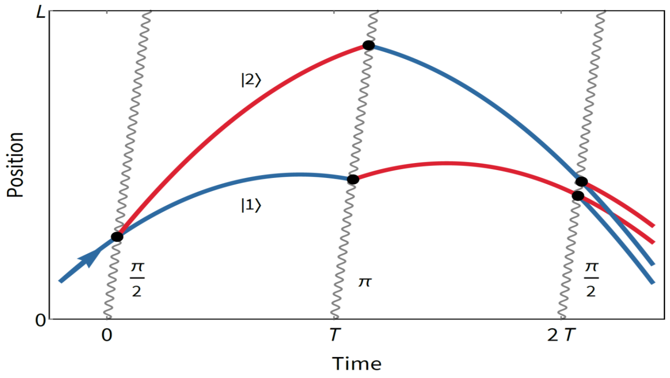
Optical lattice clocks

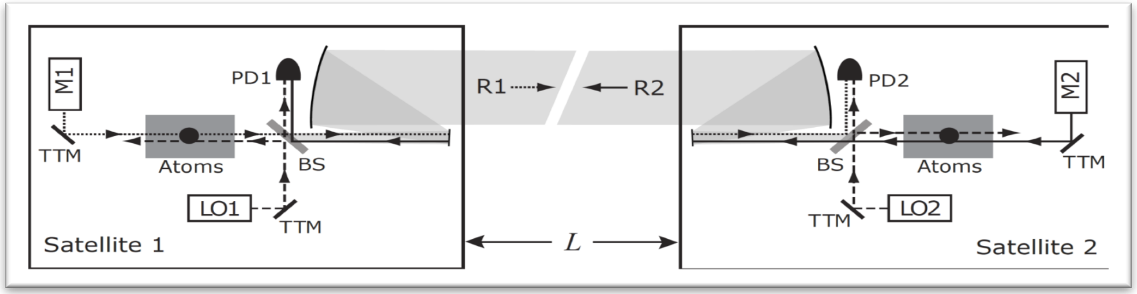




Kolkowitz et al., PRD 2016

Atom interferometers





Hogan et al., PRA 2016

Slide credit: Jason Hogan

AION and MAGIS concept

Matter wave **A**tomic **G**radiometer **I**nterferometric **S**ensor

Passing gravitational waves cause a small modulation in the distance between objects. Detecting this modulation requires two ingredients:

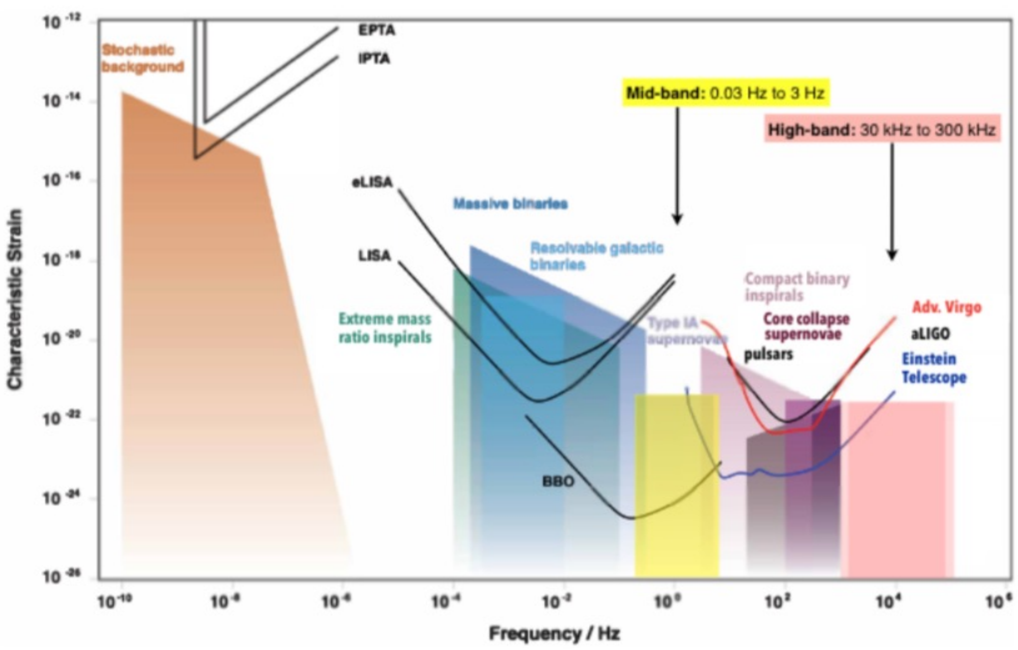
1. **Inertial references**
   - Freely-falling objects, separated by some baseline
   - Must be insensitive to perturbations from non-gravitational forces
2. **Clock**
   - Used to monitor the separation between the inertial references
   - Typically measures the time for light to cross the baseline, via comparison to a precise phase reference (e.g. a clock).

In AION and MAGIS atoms play both roles

Atom as "active" proof mass: Atomic coherence records laser phase, avoiding the need of a reference baseline – **single baseline** gravitational wave detector.

Slide credit: Jason Hogan

Long baseline atom interferometry science



Mid-band gravitational wave detection

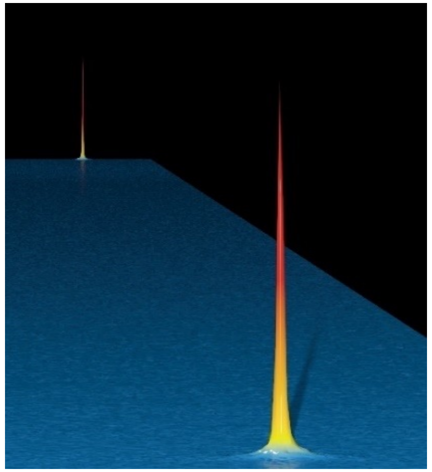
- LIGO sources before they reach LIGO ban
- Multi-messenger astronomy: optimal band for sky localization
- Cosmological sources

Ultralight wave-like dark matter probe

- Mass $<10^{-14}$ eV (Compton frequency in ~Hz range)
- Scalar- and vector-coupled DM candidates
- Time-varying energy shifts, EP-violating new forces, spin-coupled effects

Tests of quantum mechanics at macroscopic scales

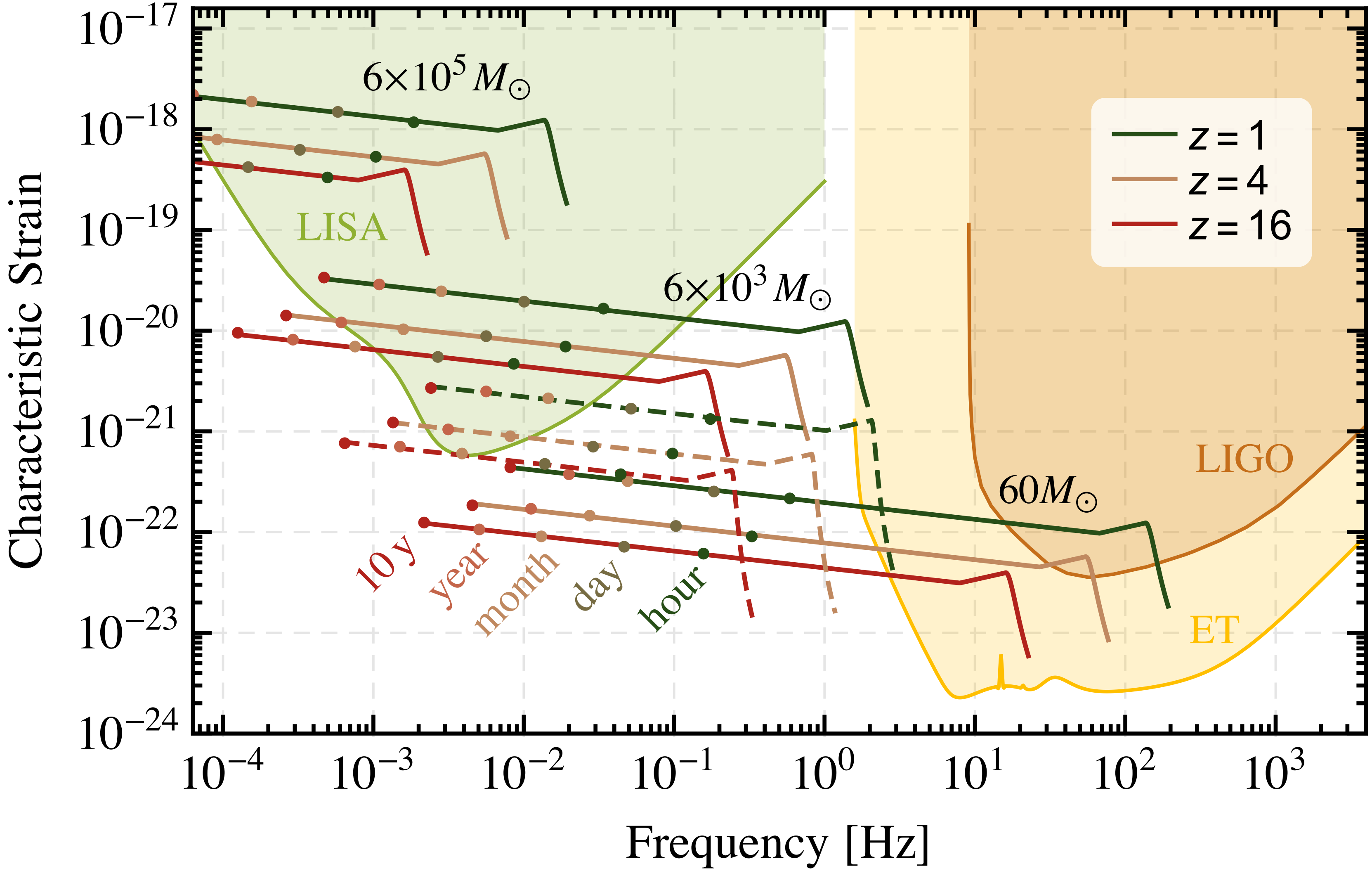
- Meter-scale wavepacket separation, duration of seconds
- Decoherence, spontaneous localization, non-linear QM, …



Rb wavepackets separated by 54 cm

Slide credit: Jason Hogan

Pathway to the GW Mid-(Frequency)



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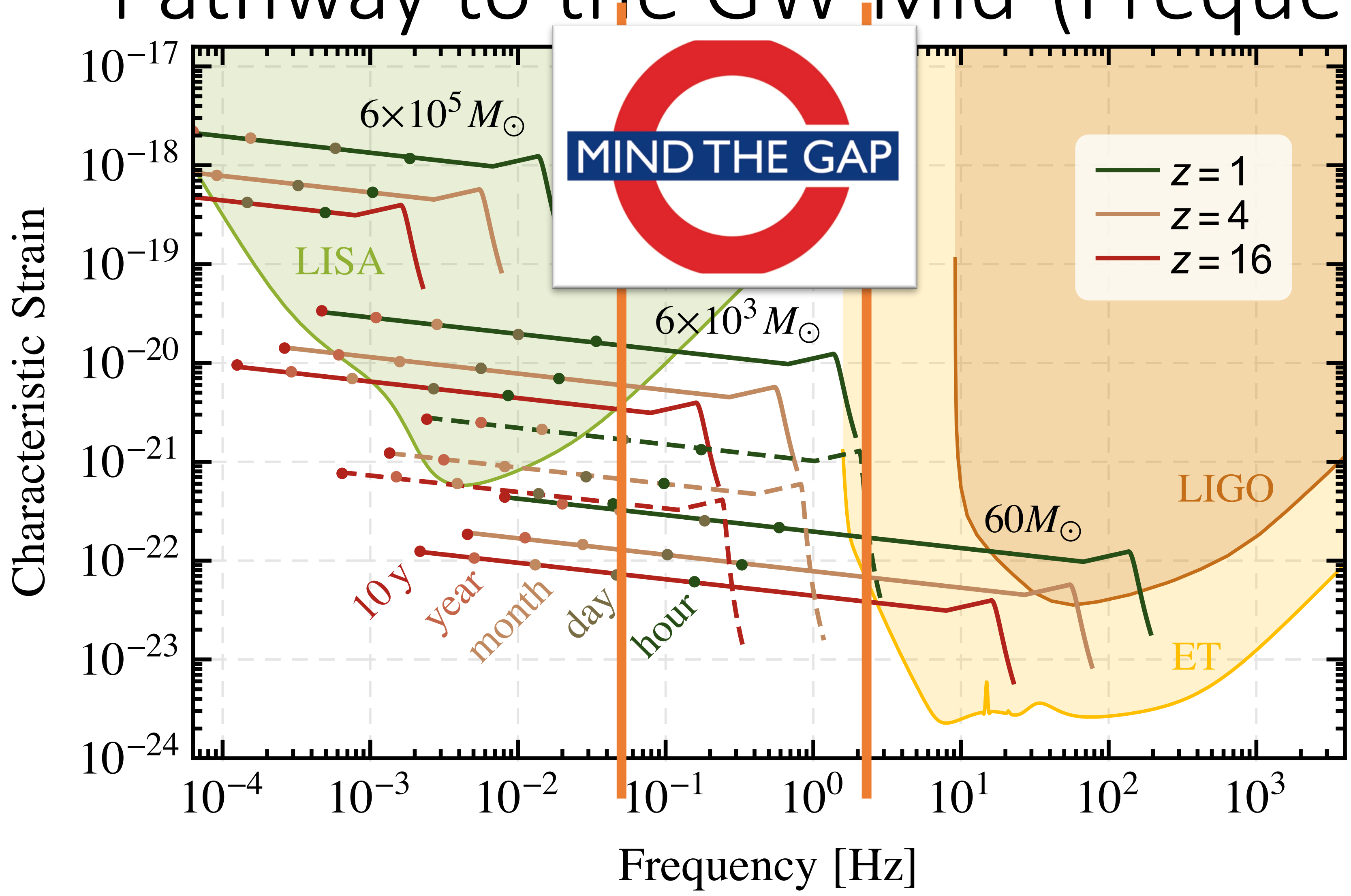
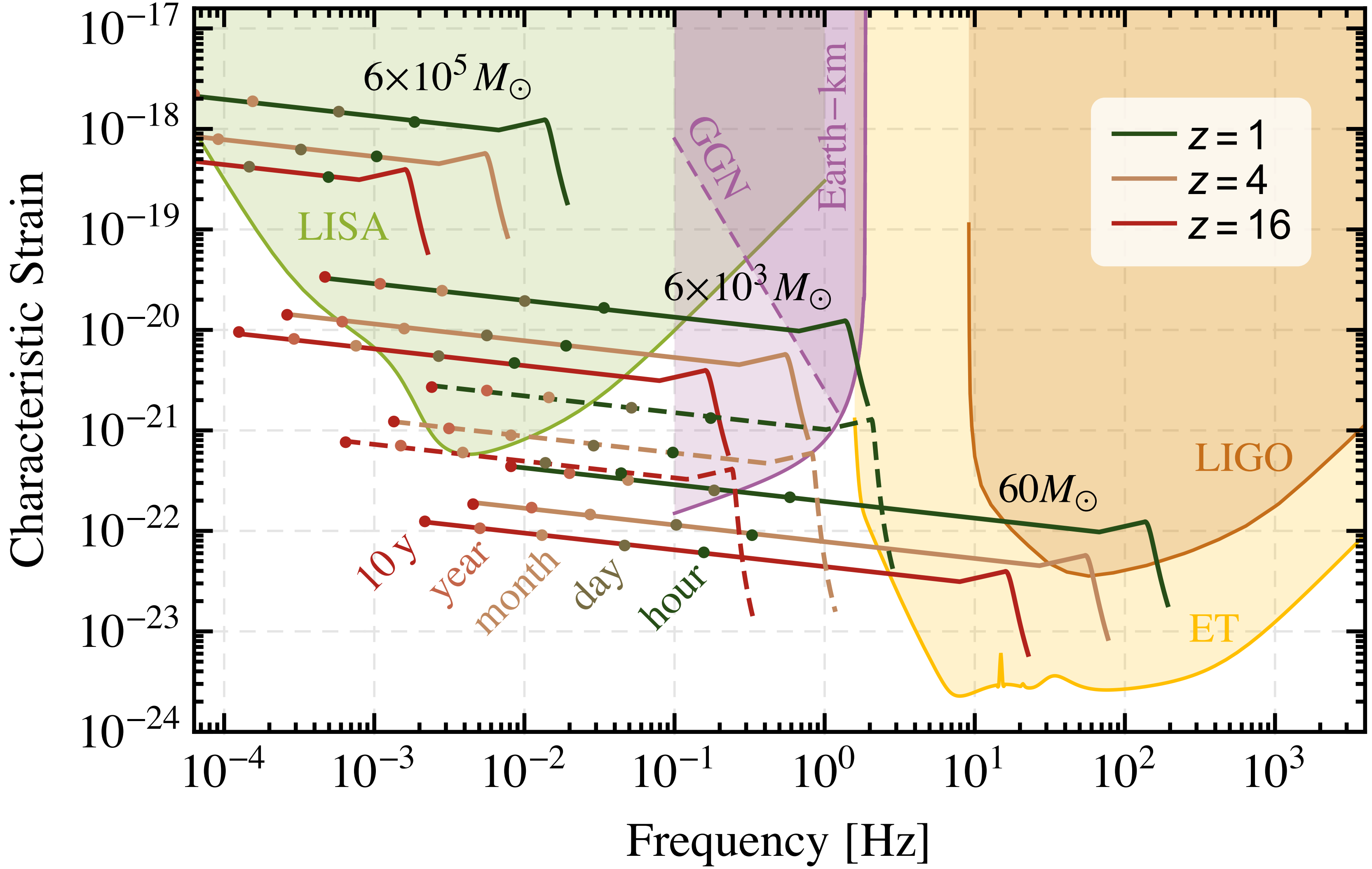


Mid-band science

- Detect sources BEFORE they reach the high frequency band [LIGO, ET]
- Optimal for sky localization: predict when and where events will occur (for multi-messenger astronomy)
- Search for Ultra-light dark matter in a similar frequency [i.e. mass] range

Mid-Band currently NOT covered

AION: Pathway to the GW Mid-(Frequency)



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AION:
Terrestrial detectors can start filling this gap

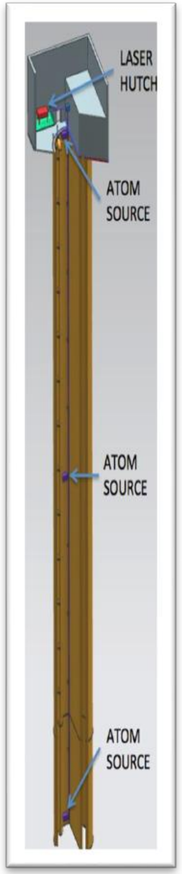
The AION Programme consists of 4 Stages

- **Stage 1:** to build and commission the 10 m detector, develop existing technology and the infrastructure for the 100 m.
- **Stage 2:** to build, commission and exploit the 100 m detector and carry out a design study for the km-scale detector.
  - AION was selected in 2018 by STFC as a high-priority medium-scale project.
  - AION will work in equal partnership with MAGIS in the US to form a "LIGO/Virgo-style" network & collaboration, providing a pathway for UK leadership.

L ~ 10m

L ~ 100m

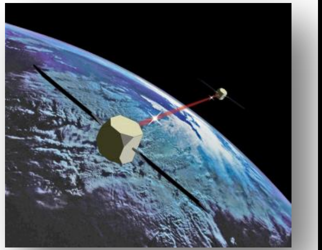
***Stage 1 is now funded with about £10M by the QTFP Programme and other sources* and Stage 2 could be placed at national facility in Boulby or Daresbury (UK), possibly also at CERN (France/Switzerland).**



- **Stage 3:** to build a kilometre-scale terrestrial detector.

L ~ 1km

- **Stage 4**: long-term objective a pair of satellite detectors (thousands of kilometres scale) [AEDGE proposal to ESA Voyage2050 call]
  - AION has established science leadership in AEDGE, bringing together collaborators from European and Chinese groups (e.g. MIGA, MAGIA, ELGAR, ZAIGA).



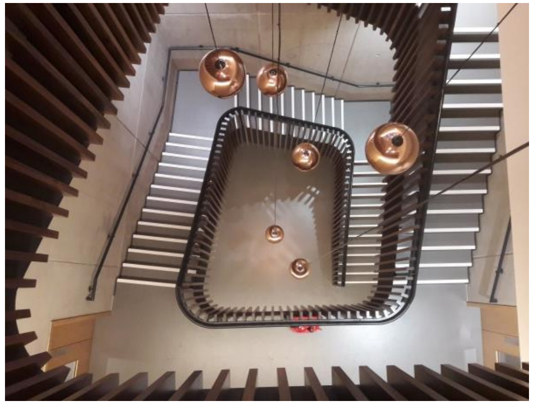
Stage 3 and 4 will likely require funding on international level (ESA, EU, etc) and AION has already started to build the foundation for it.

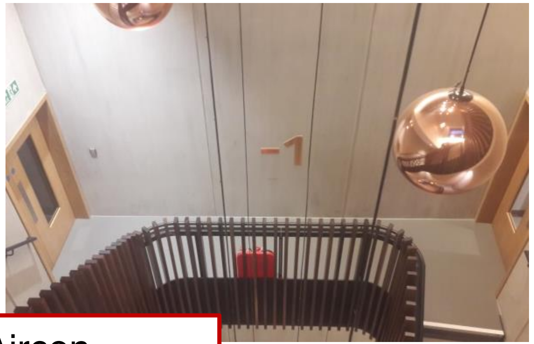
AION Collaboration Days in Oxford: Fall 2021

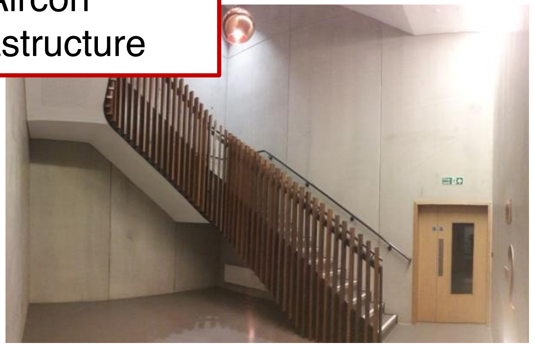
AION Collaboration Days in Oxford: Fall 2021

Ratio of Cold Atom : Particle/Fundamental Physics people is 1:1

Beecroft building, Oxford Physics







Ultralow vibration
- All plant isolated
- Thick concrete walls

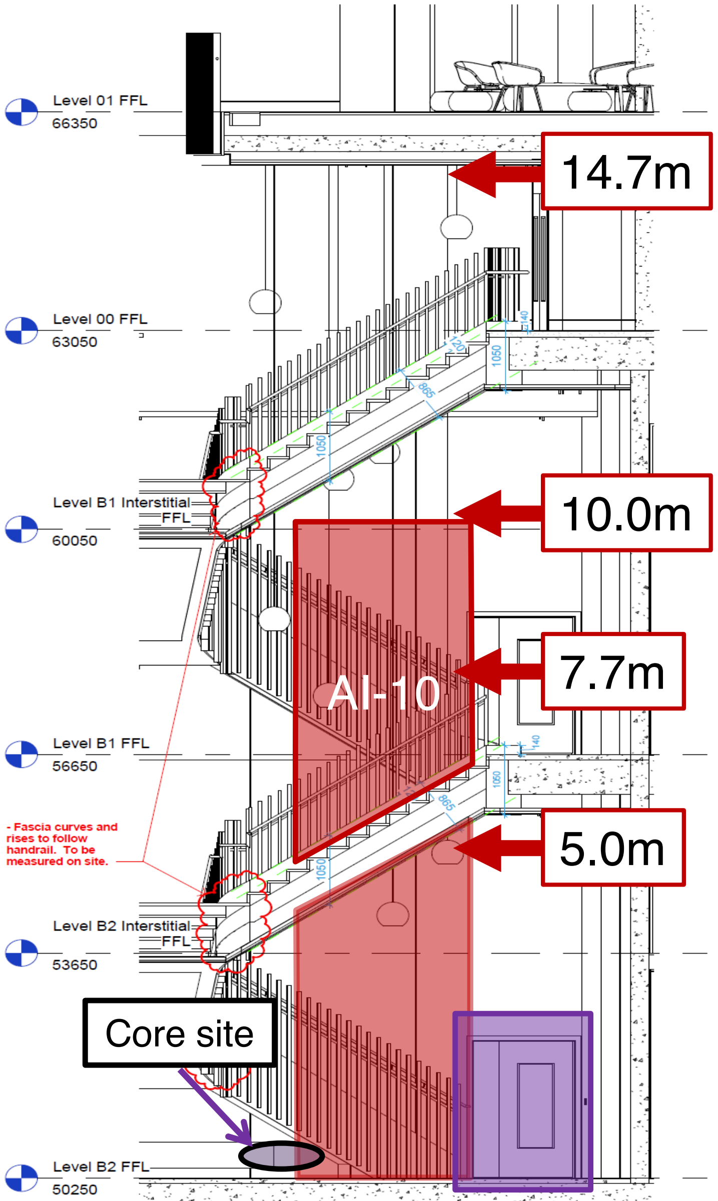
Adjacent laser lab reserved for AION use
- keel slabs
- $\pm 0.1^{\circ}$C stability
- Isolated mains

Vertical space
- 12m basement to ground floor
- 14.7m floor to ceiling

Stairwell is **not** a fire escape route.

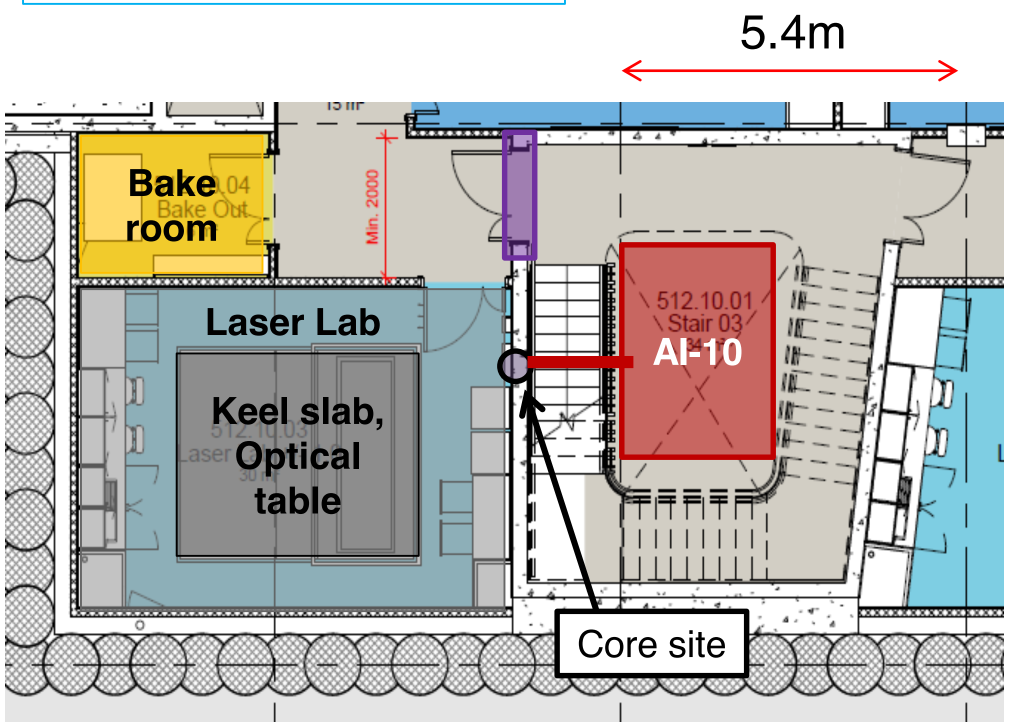
Bakeout room and cleanroom nearby

Beecroft building, Oxford Physics



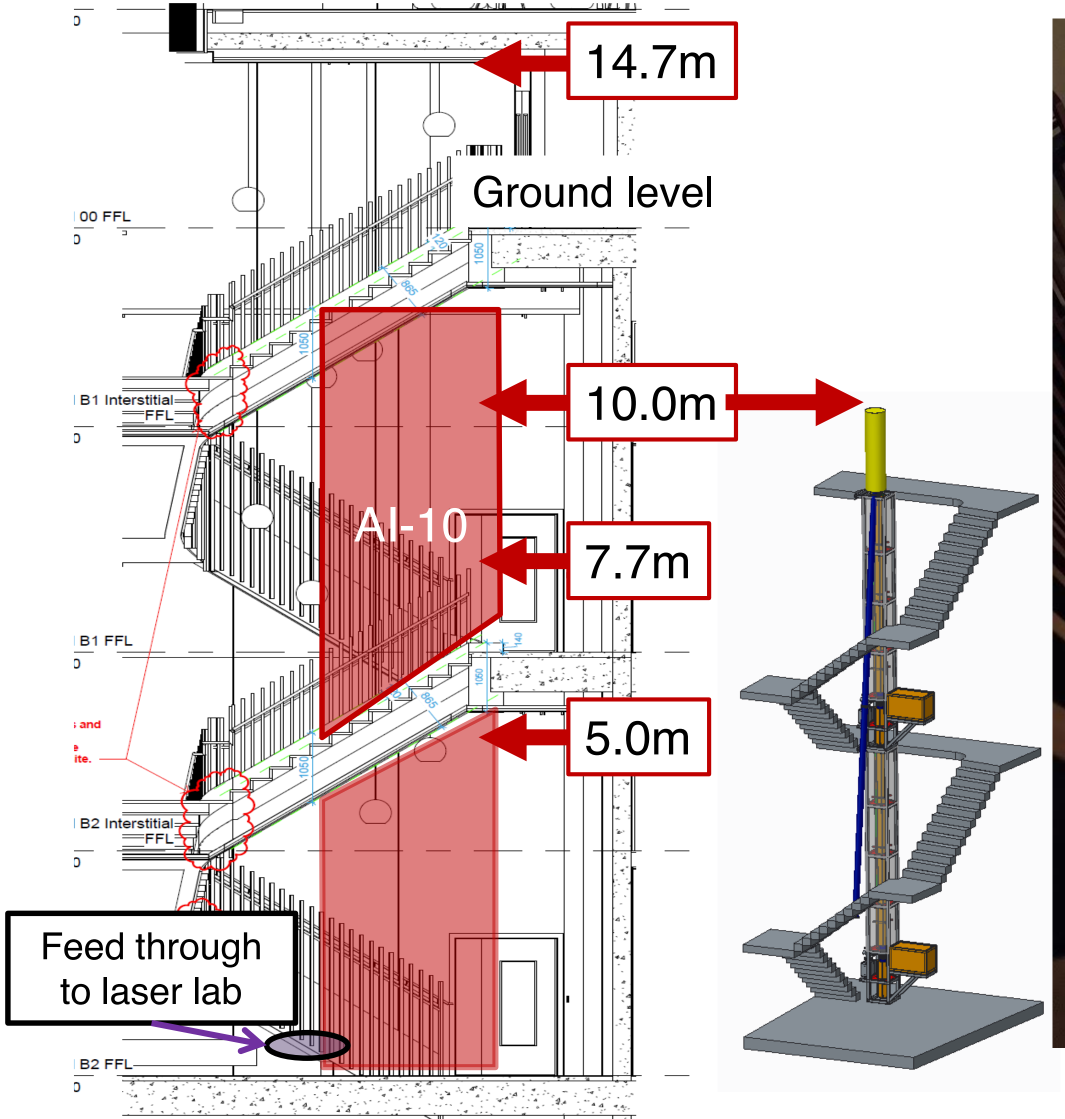
← Side view

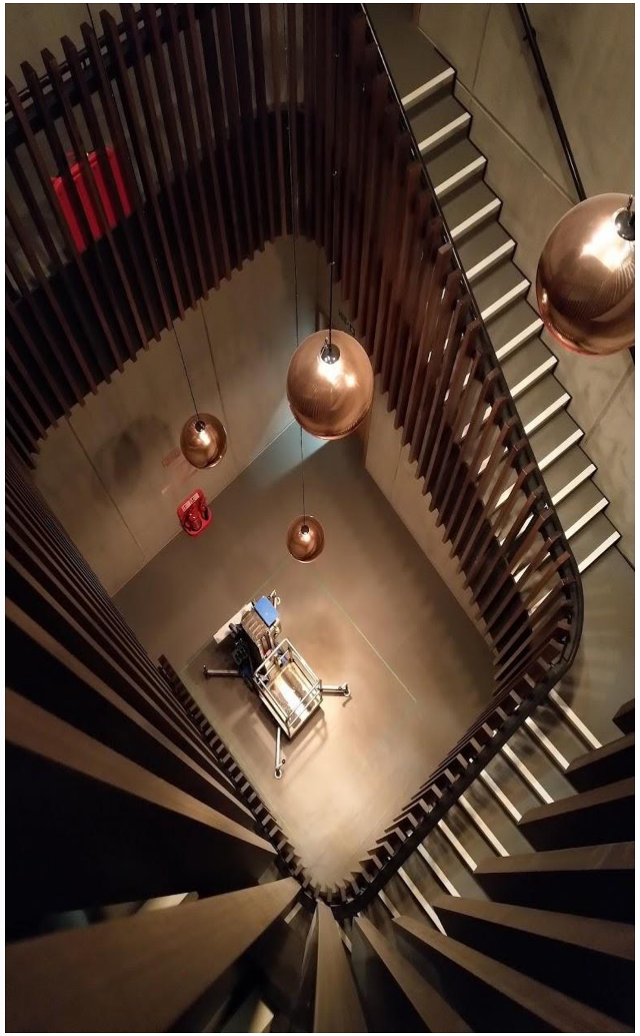
↓ Plan view



AION-10 site: Beecroft building, Oxford Physics

Beecroft building – brand new, low-vibration laser lab and concrete stairwell



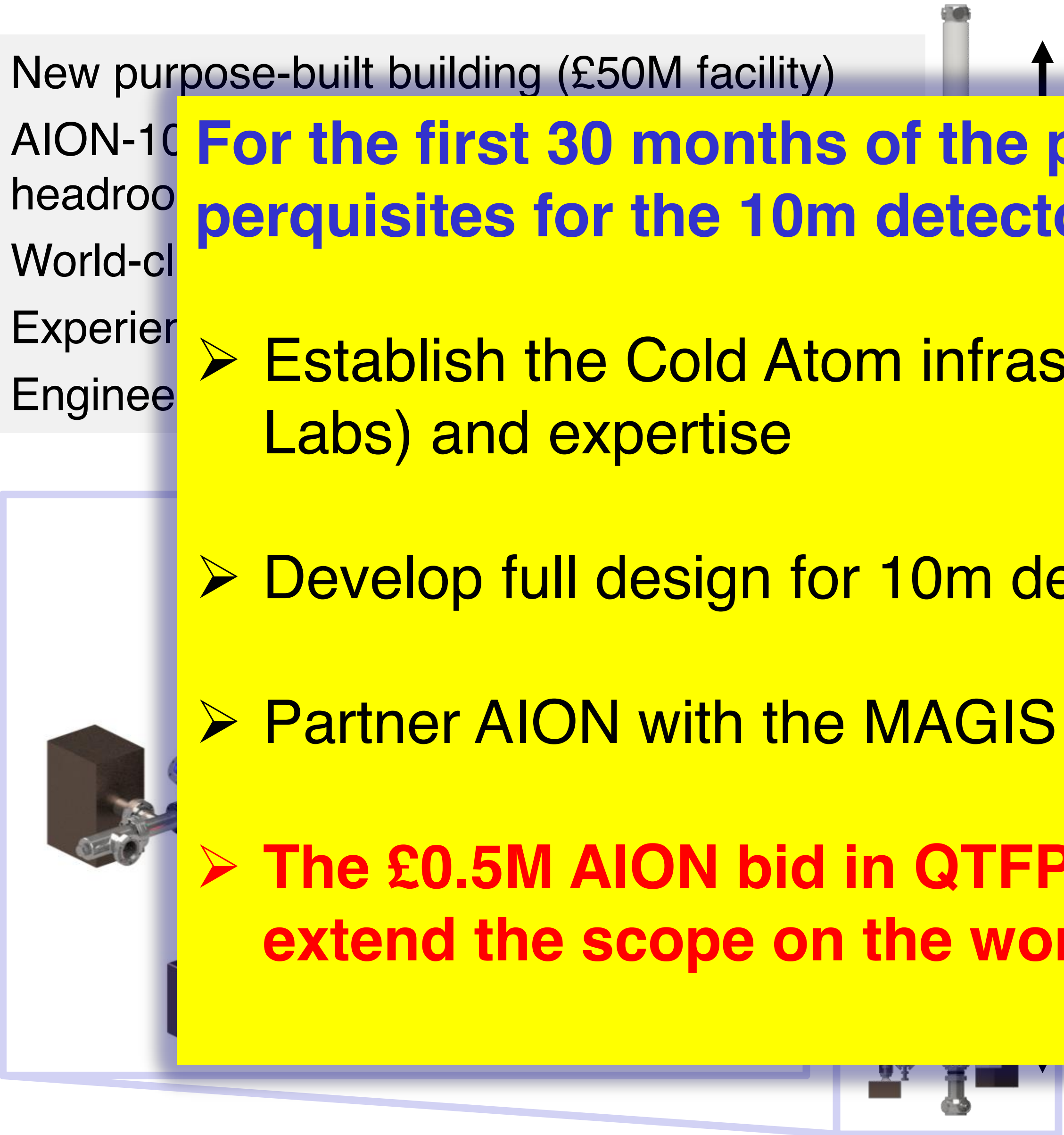


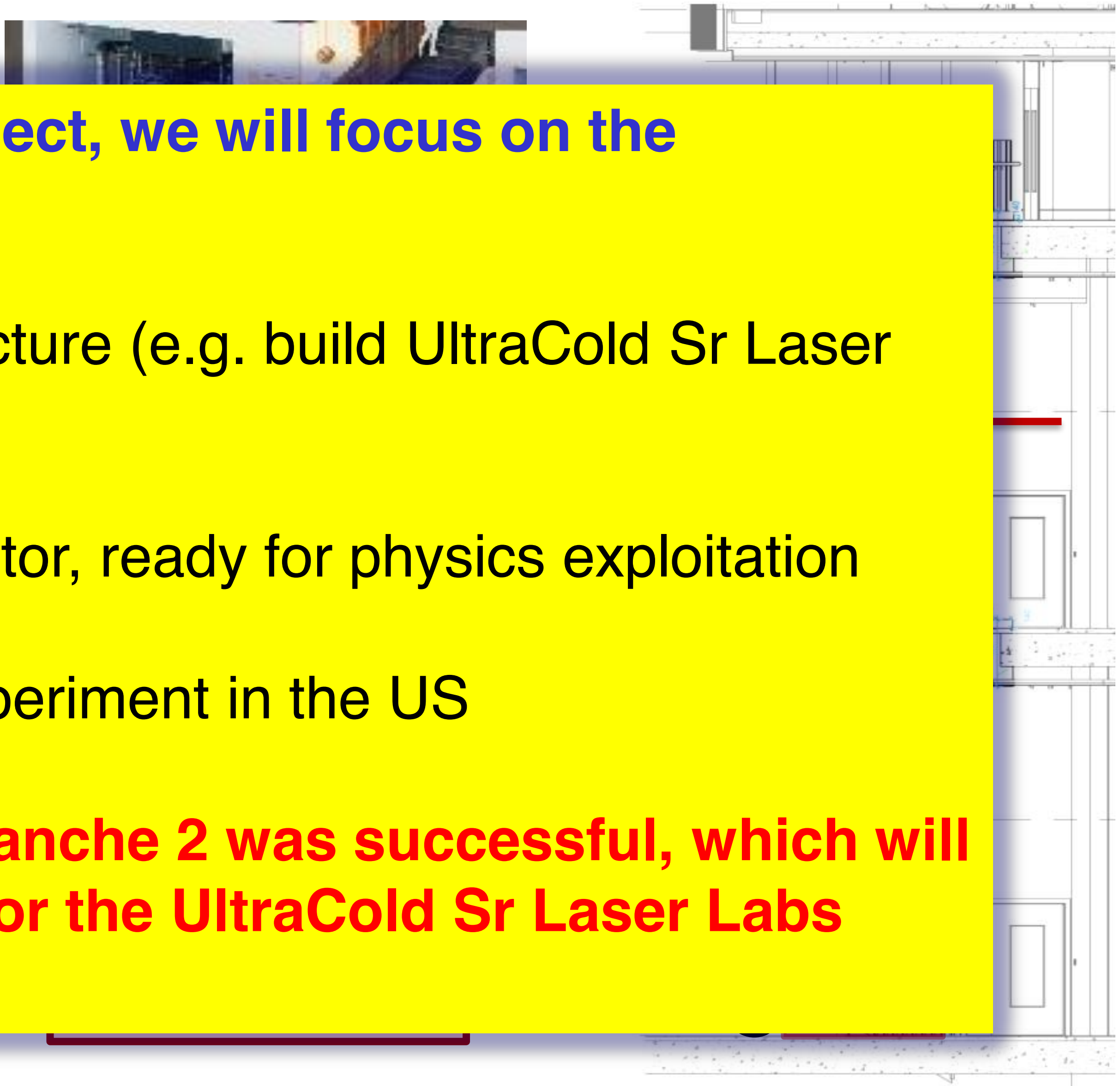
Conceptual Design AION10

- Process of defining what the requirements need to cover, and put numbers to these, has started
- Initial list of top-level requirements put forward and being worked on,
- Principal focus so far has been on stability characteristics (and defining tower length and
- Proper engineering design effort to go into a conceptional design and associated CDR will go hand in hand with underlying scientific discussions reflected in design requirements.
- Currently identifying what is achievable with resources and time now available

AION-10 @ Beecroft building, Oxford Physics

- New purpose-built building (£50M facility)
- AION-1(
  headroo
- World-cl
- Experier
- Enginee

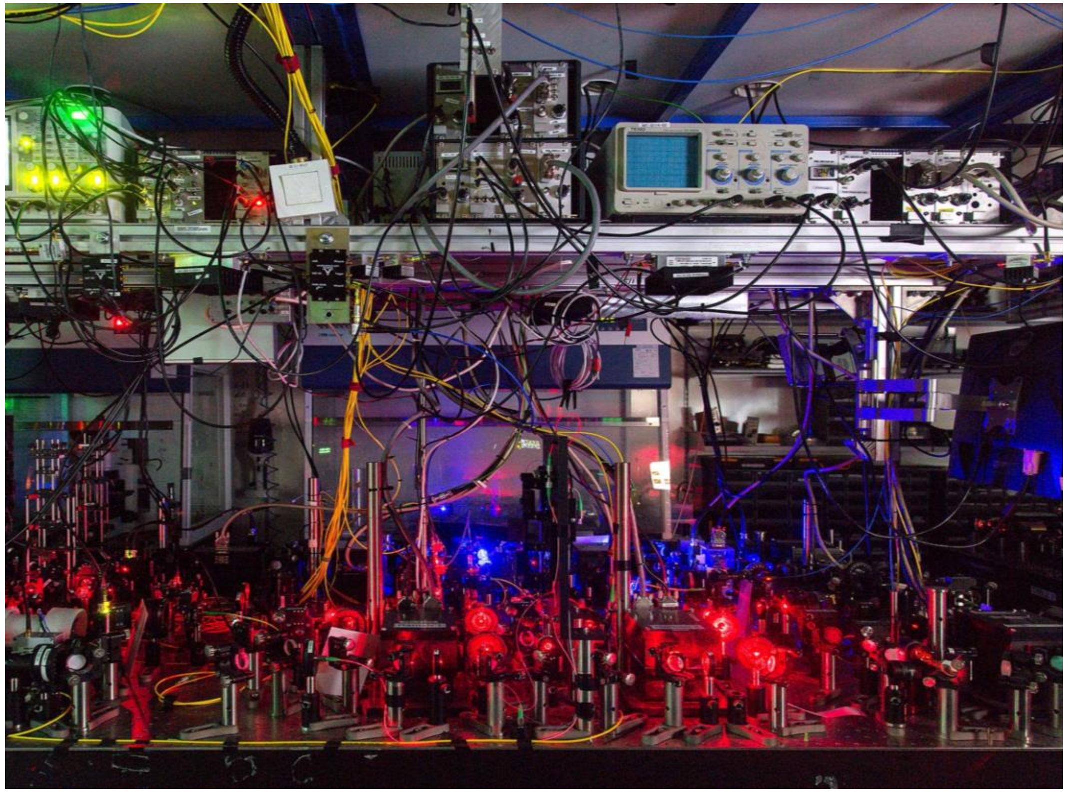


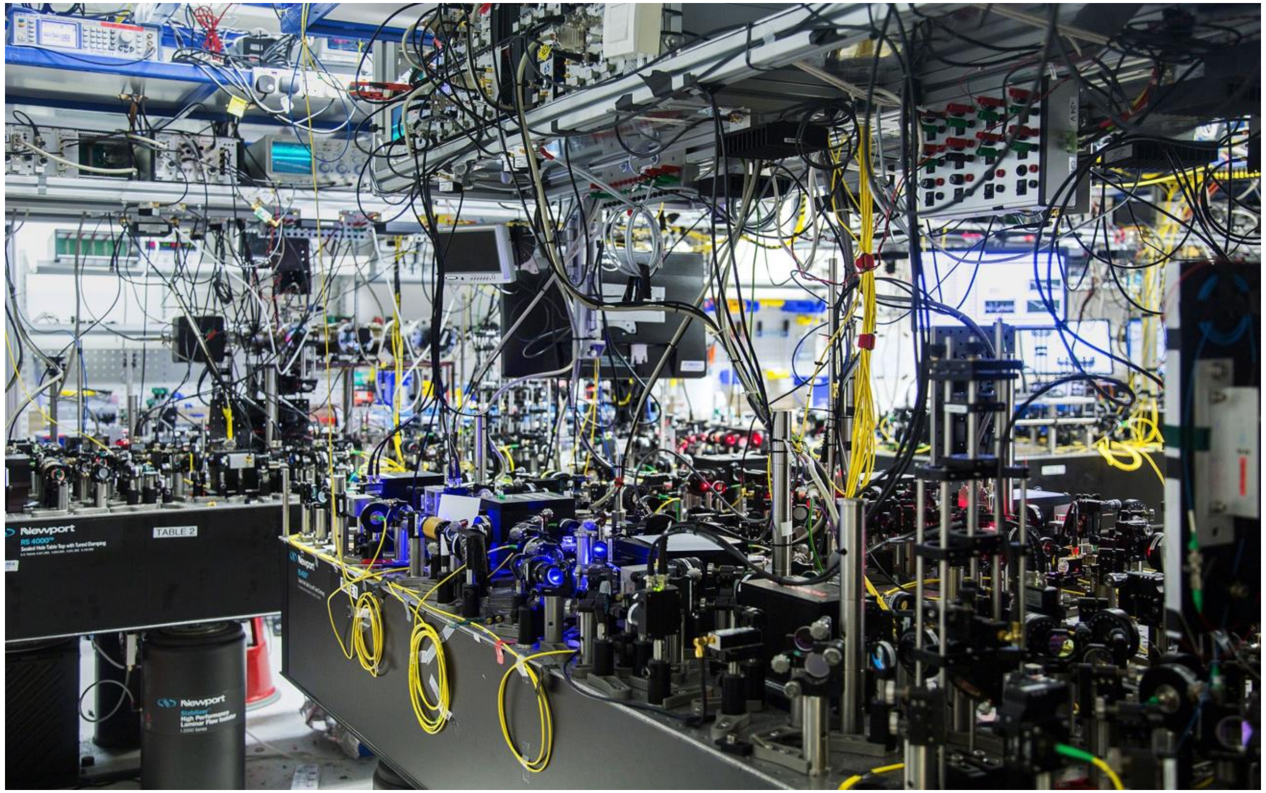


For the first 30 months of the project, we will focus on the perquisites for the 10m detector:

- ➢ Establish the Cold Atom infrastructure (e.g. build UltraCold Sr Laser Labs) and expertise
- ➢ Develop full design for 10m detector, ready for physics exploitation
- ➢ Partner AION with the MAGIS experiment in the US
- ➢ **The £0.5M AION bid in QTFP Tranche 2 was successful, which will extend the scope on the work for the UltraCold Sr Laser Labs**

AION: Ultra-Cold Strontium Laboratories in UK





To push the state-of-the-art single photon Sr Atom Interferometry, the AION project builds dedicated Ultra-Cold Strontium Laboratories in:

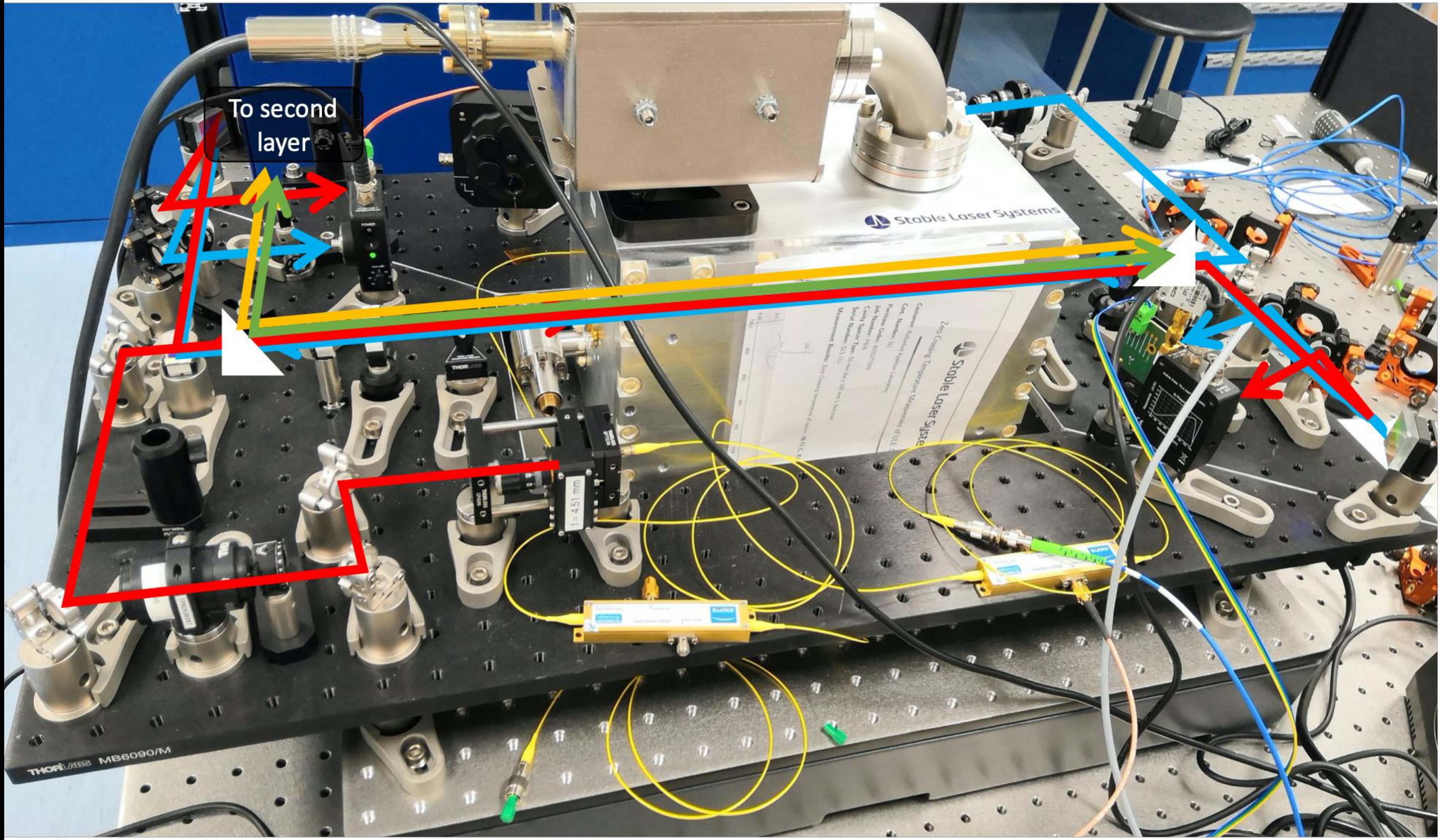
Birmingham, Cambridge, Imperial College, Oxford, and RAL

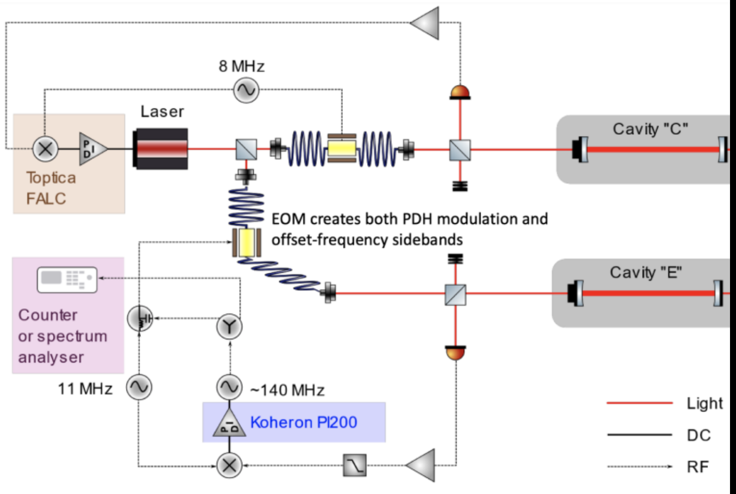
The laboratories are expected to be fully operational in fall 2022.


Cambridge July 2022
Imperial July 2022
Birmingham July 2022
On the way:
Oxford September 2022
RAL October 2022

Institute	Deliverable
Oxford (WP2)	High flux cold atom source development and demonstration of interferometry with two clouds (integration of all other WP deliverables into one system).
Imperial (WP3)	Cavity QND measurement realisation for Strontium atoms.
Cambridge (WP4)	Transport, cooling and atom optics development including parallel cloud preparation and advanced cooling (decompression and delta-kick).
Birmingham (WP5)	LMT (large momentum transfer) development on 689nm transition
RAL (co-WP3)	Aiding Imperial in WP3 developments

Laser Stabilisation Work in RAL (WP3)

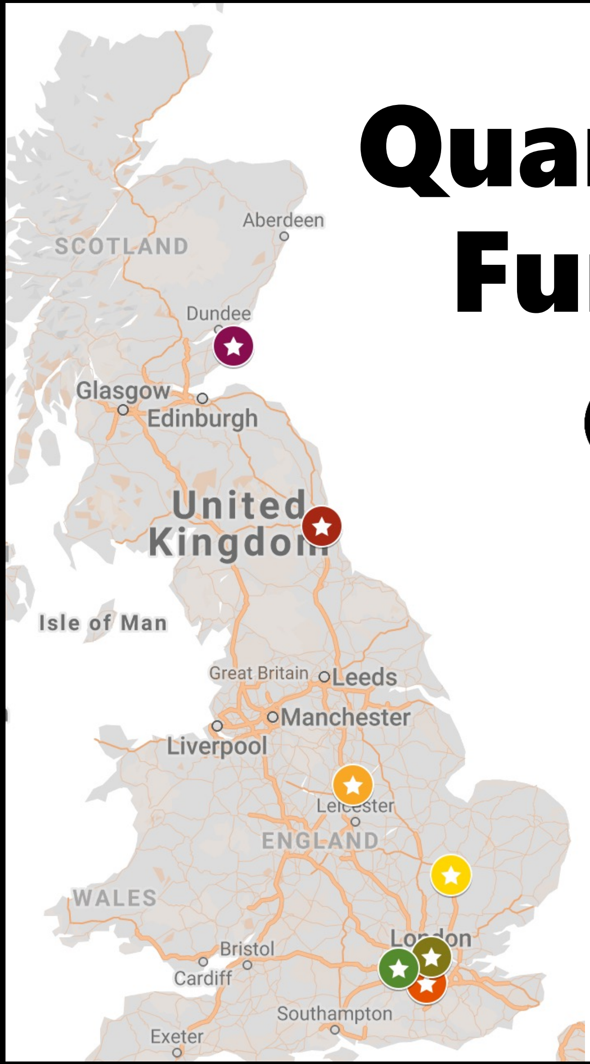




- The work at the LS system has been progressing very well, and all five LS systems have been built at RAL.
- The systems are now deployed at the five AION Labs and are now undergoing commission.

AION Related Publications (so far)

- ➢ AtomECS: Simulate laser cooling and magneto-optical traps (X. Chen, M. Zeuner, U. Schneider, C.J. Foot, T. L. Harte, E. Bentine) [arXiv:2105.06447]
- ➢ High-fidelity atom optics with polychromatic light pulses (S. Lellouch, O. Ennis, R. Haditalab, M. Langlois, M. Holynski) [Patent pending]
- ➢ Refined Ultra-Light Scalar Dark Matter Searches with Compact Atom Gradiometers (L. Badurina, D. Blas, C. McCabe) [arXiv:2109.10965]
- ➢ Prospective Sensitivities of Atom Interferometers to Gravitational Waves and Ultralight Dark Matter (L. Badurina, O. Buchmueller, J. Ellis, M. Lewicki, C. McCabe, M. Lewicki) [arXiv:2108.02468]
- ➢ Cold Atoms in Space: Community Workshop Summary and Proposed Road-Map (I. Alonso, L. Badurina, O. Buchmueller, J. Coleman, G. Elertas, J. Ellis, C. McCabe, ...)[arXiv:2201.07789]
- ➢ Snowmass 2021: Quantum Sensors for HEP Science - Interferometers, Mechanics, Traps, and Clocks (D. Carney, ..., J. Ellis et al) [arXiv:2203.07250]



Quantum Simulators for Fundamental Physics

QSimFP

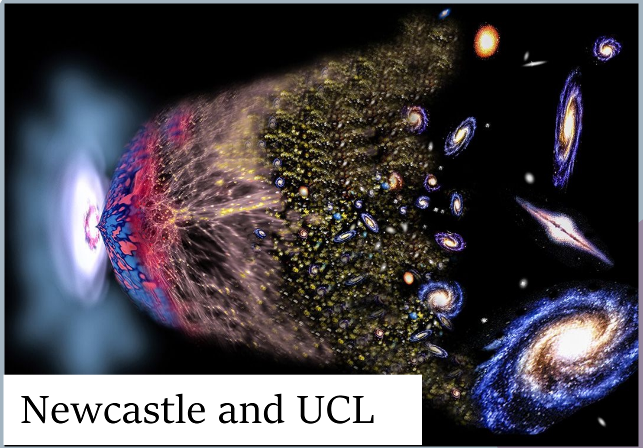
- St Andrews
- Newcastle
- KCL
- Nottingham
- Cambridge
- UCL
- RHUL

PI:
Silke Weinfurtner (Nottingham)

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

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

Vision

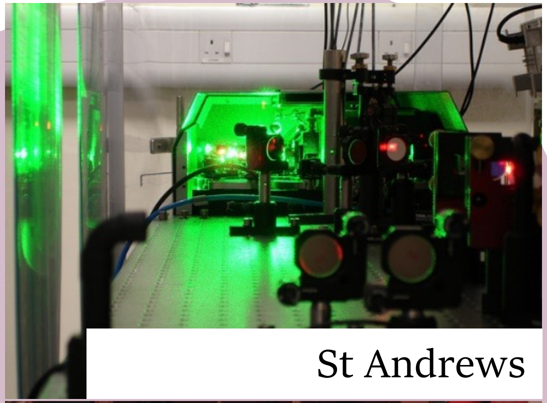

Newcastle and UCL

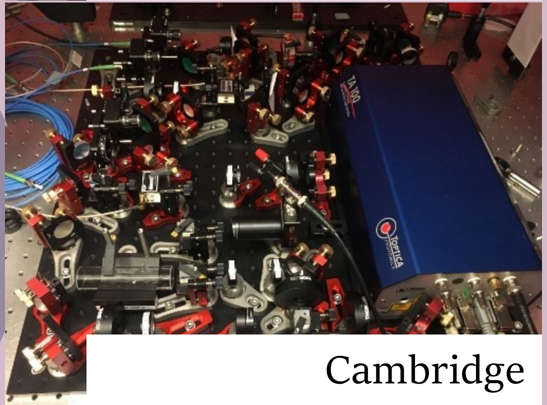

KCL

QSimFP

Quantum Vacuum:
- False Vacuum Decay

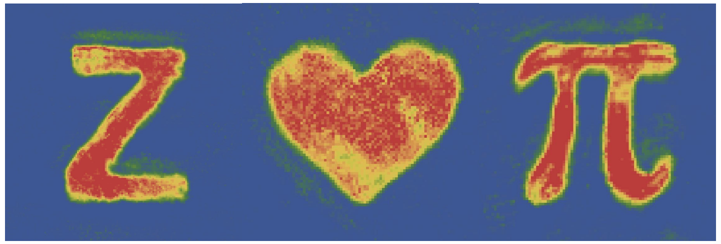
Quantum Black Hole:
- Black hole ring-down


St Andrews

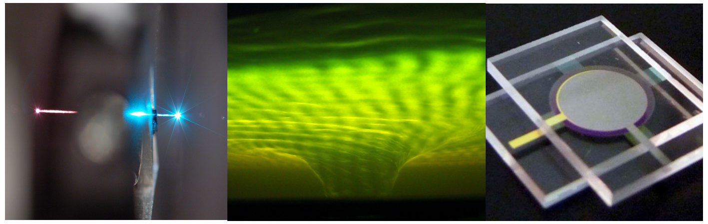

Cambridge


Nottingham and RHUL

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

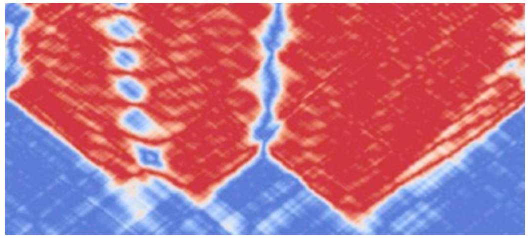


Quantum Science & Technology

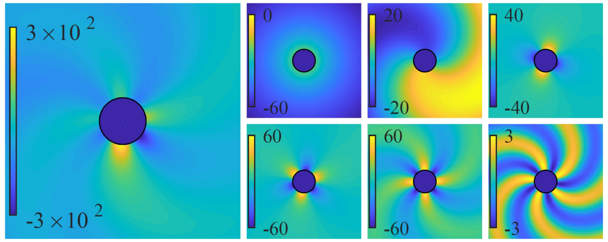


FK, Science 319 (2008)
SW, Nature Physics 13 (2017)
XR, PRB 91 (2015)

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



Fundamental Physics



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

QSimFP

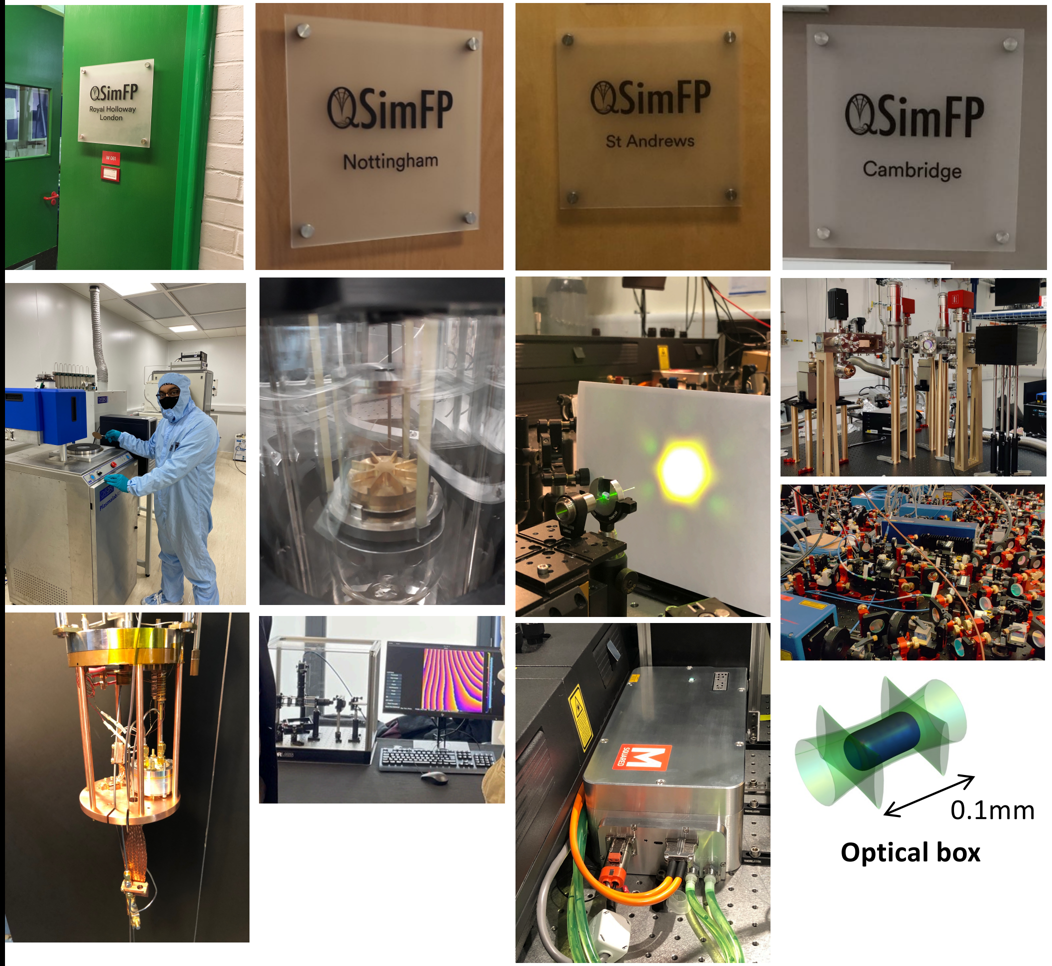
In 3 years:

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

Next stage - more science to come:

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

QSimFP



Optical box

Experimental setups constructed and now benchmarked:

- Ultra-cold atoms system (Cambridge)
- Quantum optics (St. Andrews)
- Superfluid opto-mechanics (Nottingham)
- Superfluid nanofabrication (Royal Holloway London)
- Patent application Oct 2022:
  - Off-axis holography technique to detect fluid interfaces at room and ultra-low temperatures

QSimFP

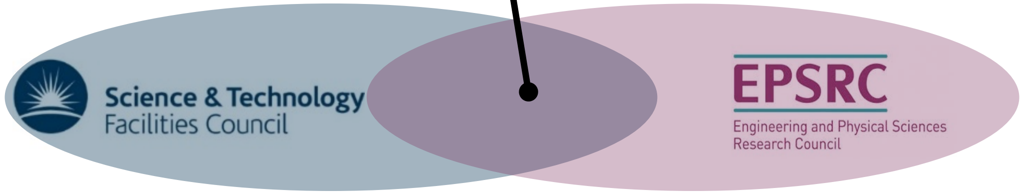
- St Andrews
- Newcastle
- KCL
- Nottingham
- Cambridge
- UCL
- RHUL

Early Career Researchers
- 7 PDRA
- 10 PhD students

Supporting staff
- 2 Project Managers
- 1 Technician

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

Gravity simulators
Silke Weinfurtner
(PI, Nottingham)



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

Ultracold atoms
- Thomas Billam
- Zoran Hadzibabic

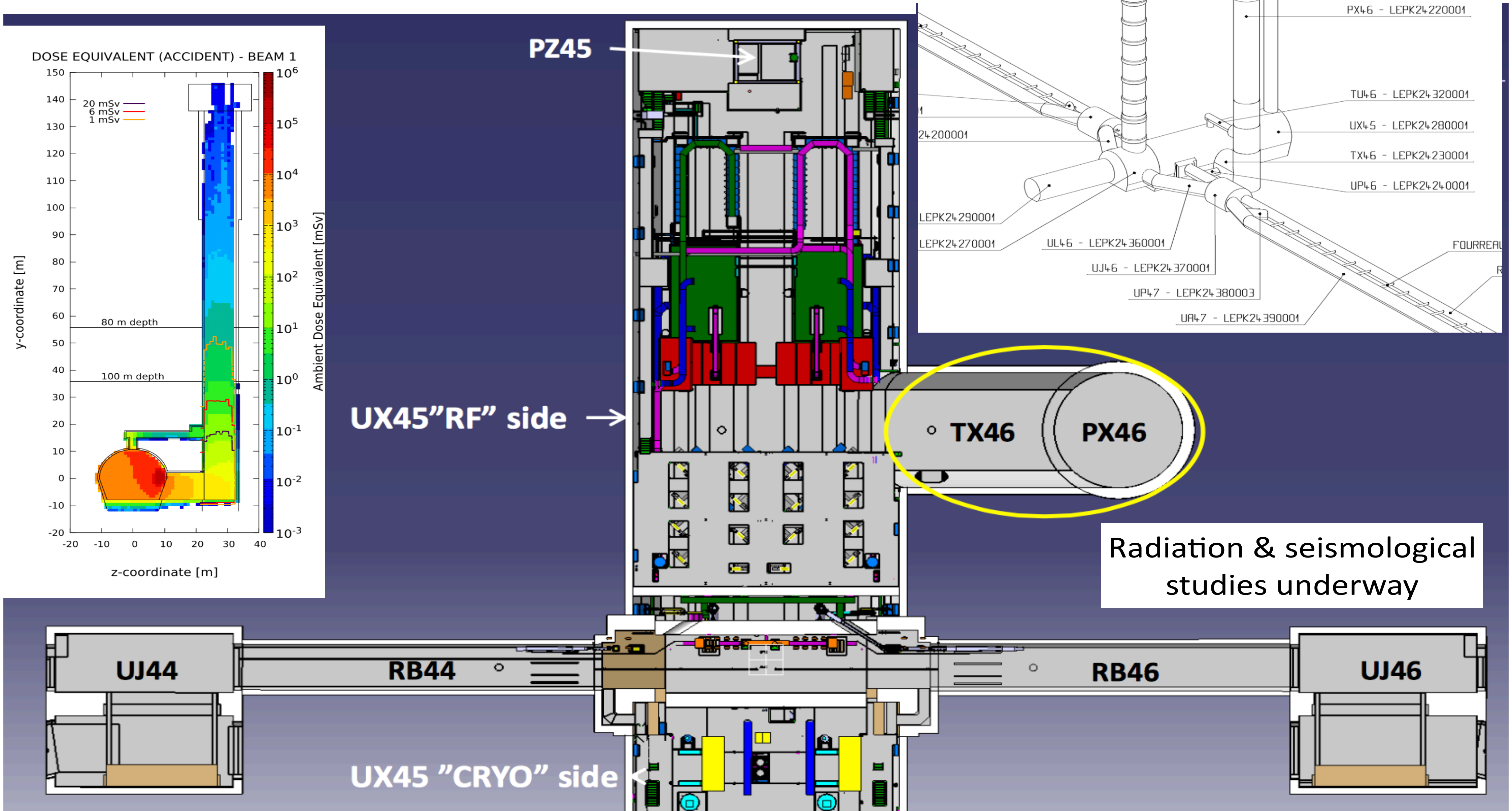
Superfluids & optomechanics
- Carlo Barenghi
- Anthony Kent
- John Owers-Bradley
- Xavier Rojas
- Viktor Tsepelin

Quantum circuits
- Gregoire Ithier

Quantum optics
- Friedrich Koenig

Possible Site for AION 100m (1km?) Boulby Mine STFC Laboratory

Possible Sites for AION 100m: Daresbury, Boulby … or CERN?



Radiation & seismological studies underway

@ CERN: PBC, large low energy physics community…

https://indico.cern.ch/event/1002356/ PBC technology annual workshop 2021 (focus on quantum sensing)
https://indico.cern.ch/event/1057715/ PBC technology mini workshop: superconducting RF (Sep. 2021)

Initial experiments with quantum sensors world-wide
→ rapid investigation of new phase space

→ scaling up to larger systems, improved devices
→ expanding explored phase space

⟶ particles, atoms, ions, nuclei: tests of QED, symmetries

⟶ atomic interferometers: DM searches

⟶ RF cavities: axion searches

Can quantum sensors be used in traditional high energy physics?

typically not obvious, given that most detectors rely on detecting the product of many interactions between a particle and the detector (ionization, scintillation, Cerenkov photons, …)

handful of ideas that rely on quantum devices, or are inspired by them, but do not necessarily use them as quantum detectors per se, but rather their properties to enhance / permit measurements that are more difficult to achieve otherwise

main focus on tracking / calorimetry / timing

closely related: nanostructured materials
→ Frontiers of Physics, M. Doser et al., 2022

these are not developed concepts, but rather the kind of approaches one might contemplate working towards

very speculative!

Michael Doser
EP Seminar
13/5/2022

Metamaterials, 0 / 1 / 2-dimensional materials (quantum dots, nanolayers)

ultra-fast scintillators based on perovskytes

chromatic calorimetry (QDs)

active scintillators (QCL, QWs, QDs) 5.3.6 *

GEMs (graphene)

Atoms, molecules, ions

Rydberg TPC's 5.3.5 *

Spin-based sensors

helicity detectors 5.3.3 *

* https://cds.cern.ch/record/2784893

Michael Doser
EP Seminar
13/5/2022

Quantum Technologies and Particle Physics

- The nature of dark matter
- The earliest epochs of the universe at temperatures >> 1TeV
- The existence of new forces
- The violation of fundamental symmetries
- The possible existence of dark radiation and the cosmic neutrino background
- The possible dynamics of dark energy
- The measurement of neutrino mass
- Tests of the equivalence principle
- Tests of quantum mechanics
- A new gravitational wave window to the Universe:
    - LIGO sources before they reach LIGO band
    - Multi-messenger astronomy: optimal band for sky localization
    - Cosmological sources

Most recent European Strategies

the large …

weblink

2017-2026 European Astroparticle Physics Strategy

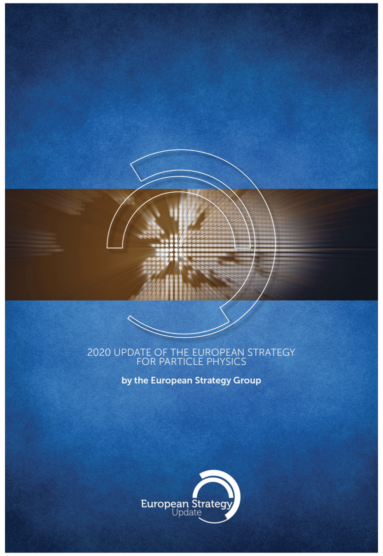
… the connection …

weblink

Long Range Plan 2017 Perspectives in Nuclear Physics

… the small

weblink



2020 Update of the European Particle Physics Strategy

Are community driven strategies outlining our ambition to address compelling open questions

Guidance for funding authorities to develop resource-loaded research programmes

Most recent European Strategies

the large … | … the connection … | … the small

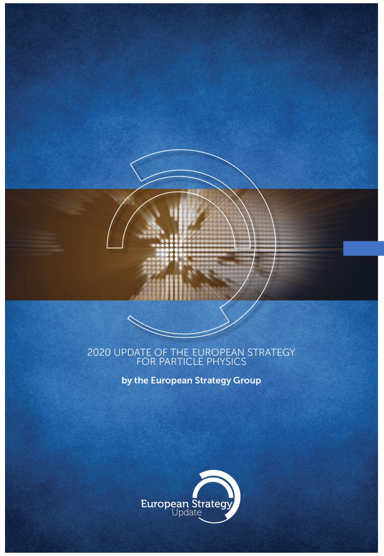
weblink

2017-2026 European Astroparticle Physics Strategy

weblink

Long Range Plan 2017 Perspectives in Nuclear Physics

weblink

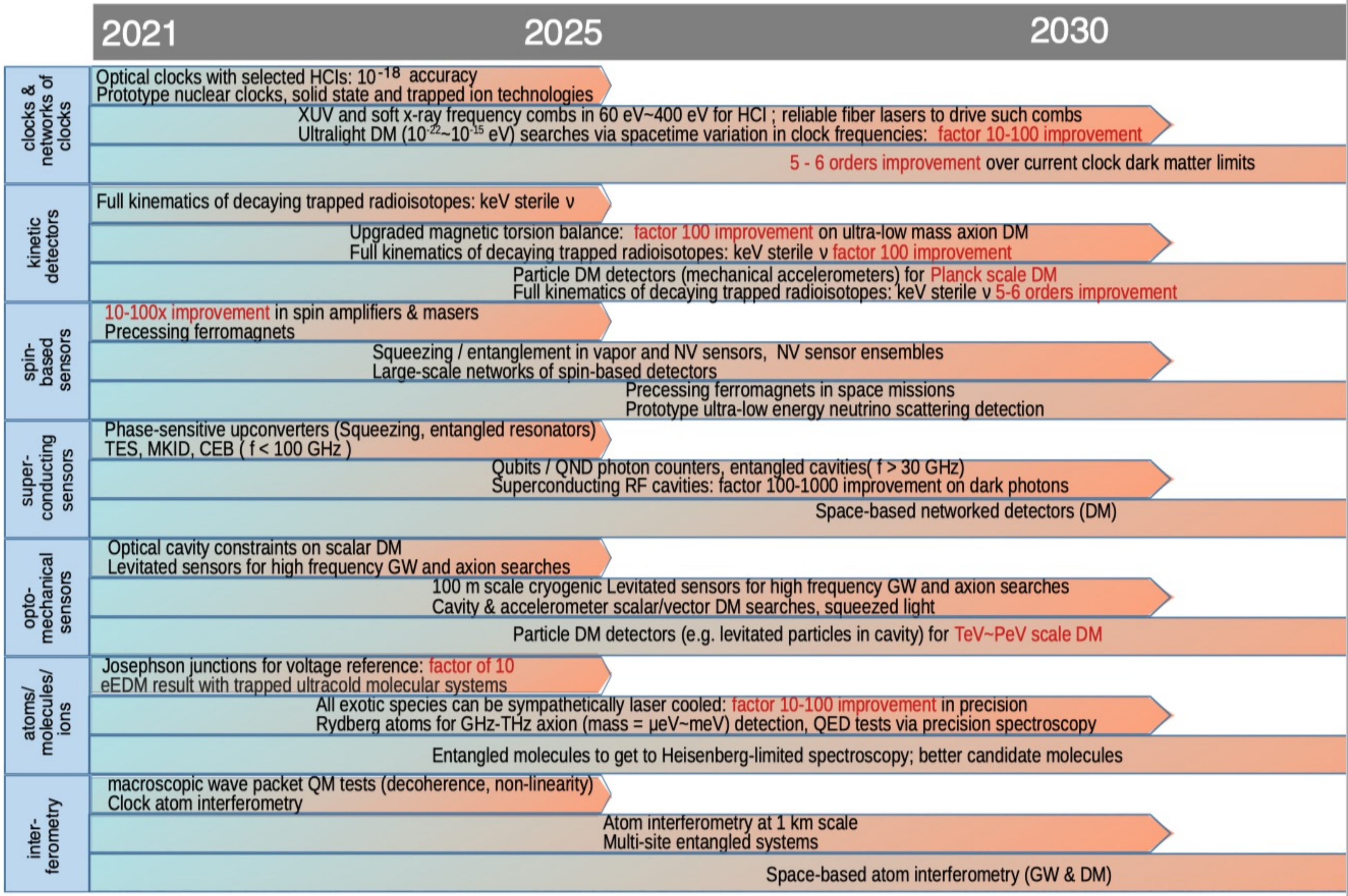


2020 Update of the European Particle Physics Strategy

ECFA Detector R&D Roadmap

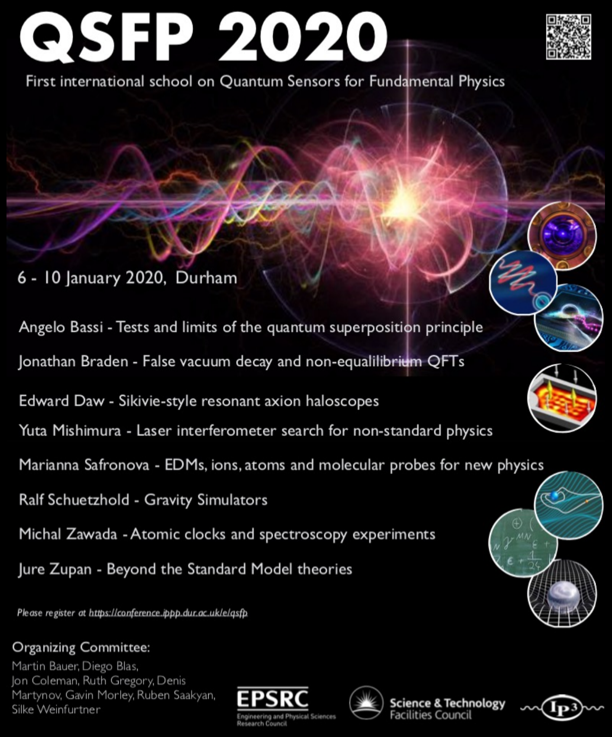
In line with the RECFA R&D roadmap, it makes sense to consider a quantum-sensing R&D program that brings together the following strands:

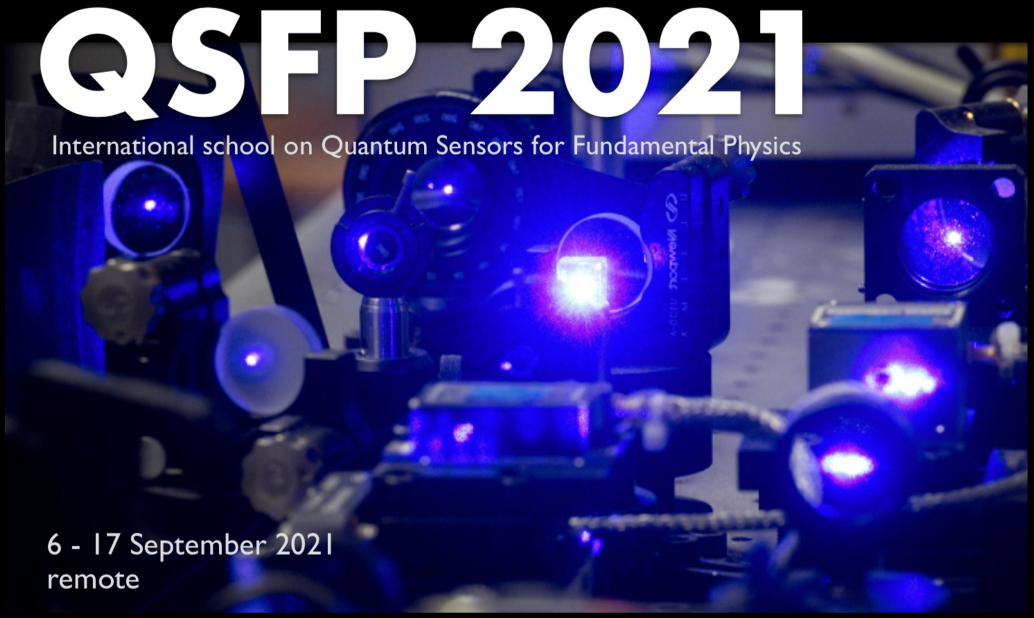
- Clocks and clock networks 5.3.1
- Kinetic detectors 5.3.2
- Spin-based sensors 5.3.3
  Superconducting sensors 5.3.3
- Optomechanical sensors 5.3.4
- Atoms/molecules/ions 5.3.5
  Atom interferometry 5.3.5
- Metamaterials, 0/1/2D-materials
  Quantum materials 5.3.6



also for HEP!

Education : The QTFP School





Paolo Agnes - Detection of light particle dark matter

Andrei Derevianko - Atomic clocks and laser spectroscopy

Aaron Chou - Axions and axion detection

Jason Hogan - Atom interferometry and gravitational wave detection

Thierry Lasserre - Neutrinos and quantum sensors

Jörg Schmiedmayer - Quantum simulators

Henrik Ulbricht - Quantum sensor tests of quantum mechanics

Organizing Committee:

Giovanni Barontini , Martin Bauer,
Oliver Buchmüller, Ed Daw, John Ellis,
Hartmut Grote, Jocelyn Monroe,
John March-Russell, Rubin Saakyan,
Ian Shipsey, Silke Weinfurtner

Please register at

EPSRC Engineering and Physical Sciences Research Council · Science & Technology Facilities Council · Ip3

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

Next school Jan 23 Cambridge
Lead by Tiffany Hart
Registration opening very soon

THE EUROPEAN STRATEGY UPDATE CALLED FOR A DETECTOR R&D ROADMAP – QUANTUM SENSORS IS A KEY AREA

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 (September, 2020) 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

THERE IS EXCITING SCIENCE AHEAD

STFC & Quantum

There is a clear intention to pursue quantum – the word appears 25 times in the recently relased 3-year Strategic Delivery Plan, including:

•Invest £15 million, in partnership with EPSRC, to complete the first phase of the Quantum Technology for Fundamental Physics programme, explore opportunities for international collaboration, and plan for the next phase. “

•The UKRI infrastructure fund is a target of opportunity for sme of the QTFP projects


"The greater danger for most of us lies not in setting our aim too high and falling short; but in setting our aim too low, and achieving our mark" *(Michelangelo)*

Aim high or we will not realize the potential of our field, discovery will be stalled and we betray ourselves and the next generation.

Photo credit: Michael Hoch/CERN

Acknowledgements

Many thanks to all 7 QTFP projects

And to the following two groups for valuable discussions whilst preparing this talk:

Laura Baudis, Daniela Bortoletto, Michael Campbell, Paula Collins, Garret Cotter, Sijbrand de Jong, Marcel Demarteau, Michael Doser, Francis Halzen, Roxanne Guenette, Jim Hinton, Stefan Hild, Andreas Huangs, Marek Lewitowicz, Jocelyn Monroe, Gerda Neyens, Samaya Nissanke and many more.

Mina Arvanitaki, Themis Bowcock, Chip Brock, Oliver Buchmueller, Nathaniel Craig, Marcel Demarteau, Savas Dimopoulos, Michael Doser, Gerry Gabrielse, Andrew Geraci, Peter Graham, Joanne Hewett, Rafael Lang, David Hume, Jason Hogan, John March-Russell, Hitoshi Murayama, Marianna Safronova, Alex Sushkov, Chris Tully, Stafford Withington & the UK Quantum Technologies for Fundamental Physics Program