Atomic Sensors:

from the Desktop to the Universe

Activities in Europe and beyond:

Quantum sensors for fundamental physics in the UK

Axions, q. gravity, dark matter, varying "constants", m_ν , …

AION atom interferometer project

MIGA project in France

ELGAR proposed project in Europe

AEDGE proposed space mission

Ultralight dark matter, gravitational waves, …

Other space missions: STE-QUEST, …

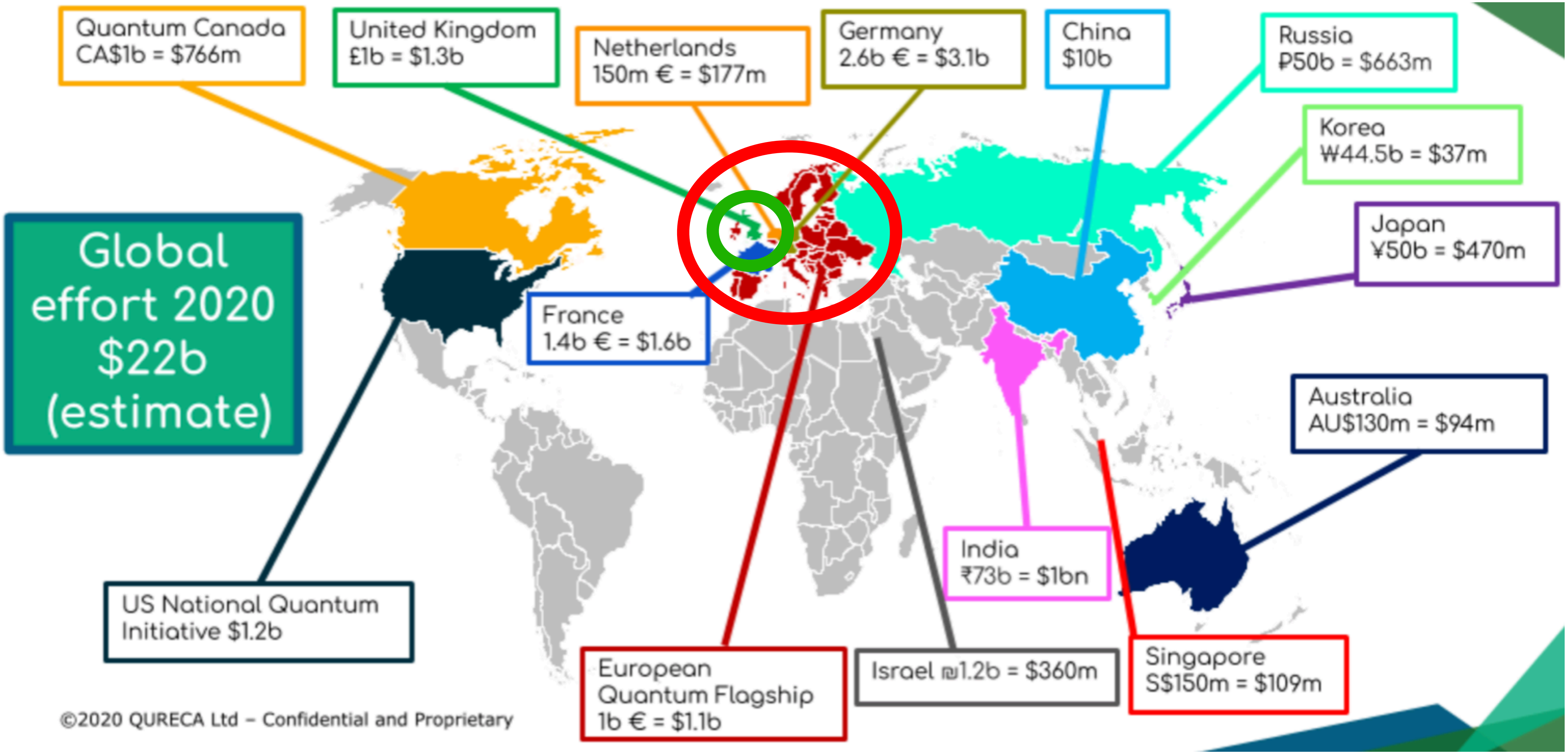
Equivalence principle, quantum correlations, …

ESA Voyage 2050 programme

John Ellis

KING'S College LONDON

Quantum Science & Technology Programmes

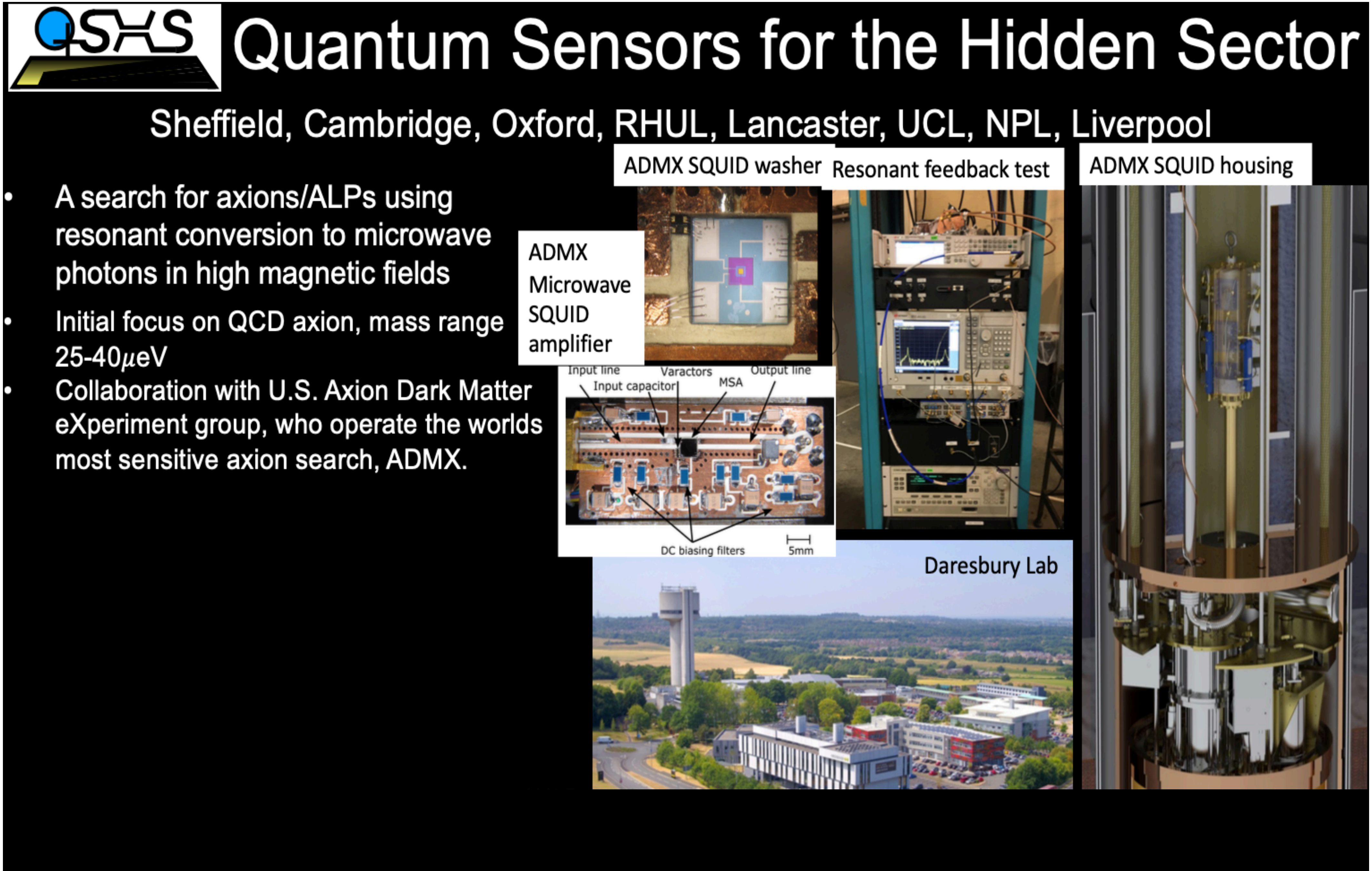


UK National Quantum Technology Programme

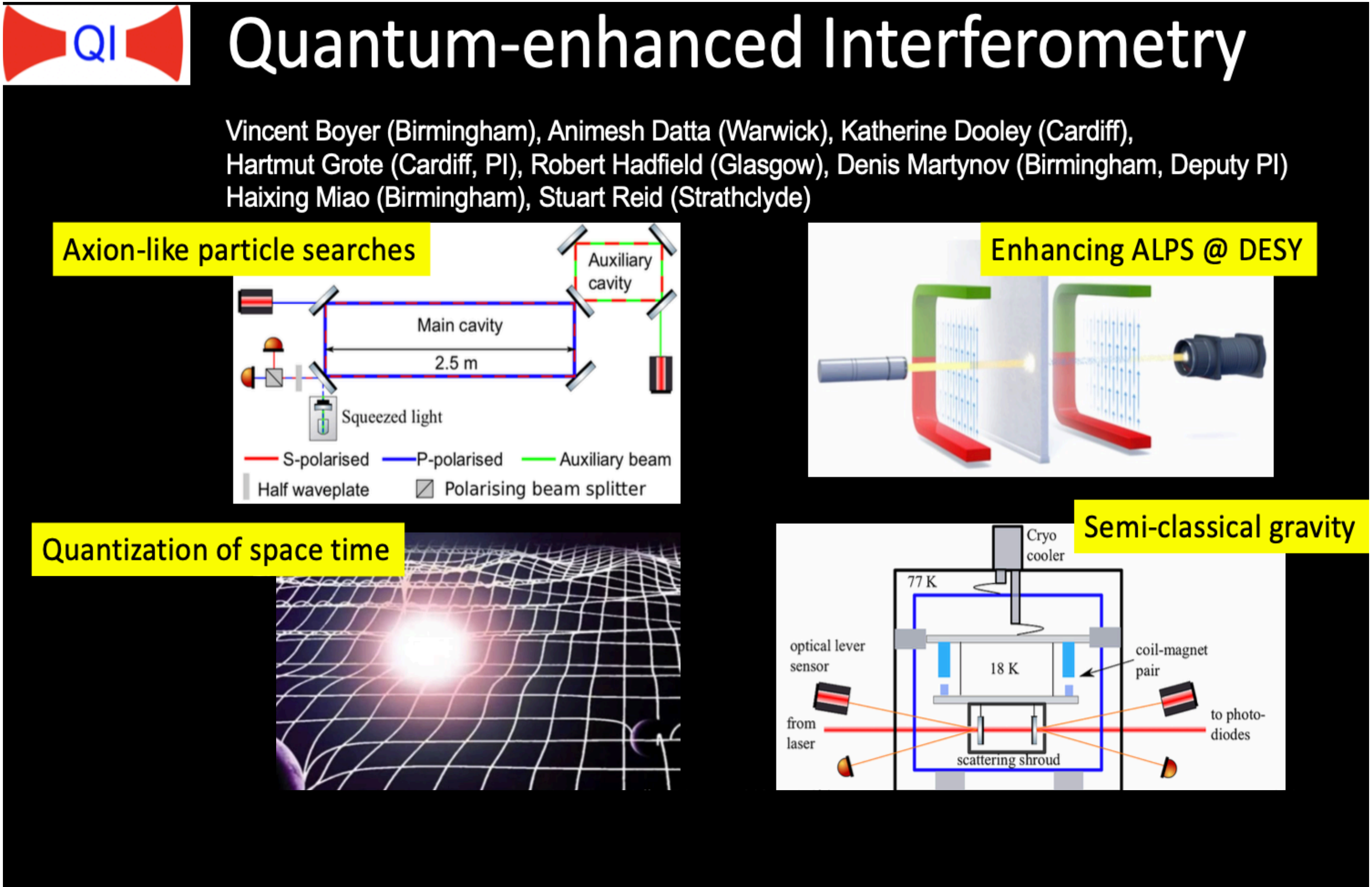
- *Phase 1 2015-2019, Phase 2 2020-24 (total investment Phase 1+2= £1B)*
- *Phase 2 investments:*
  - *Industry led projects to drive innovation and commercialisation of QT (£173m over 6 years)*
  - Renewal of the QT Research Hubs (£94m over 5 years)
  - Research training portfolio (£25m over 5 years)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

Seven samurai …

Quantum Sensors for the Hidden Sector

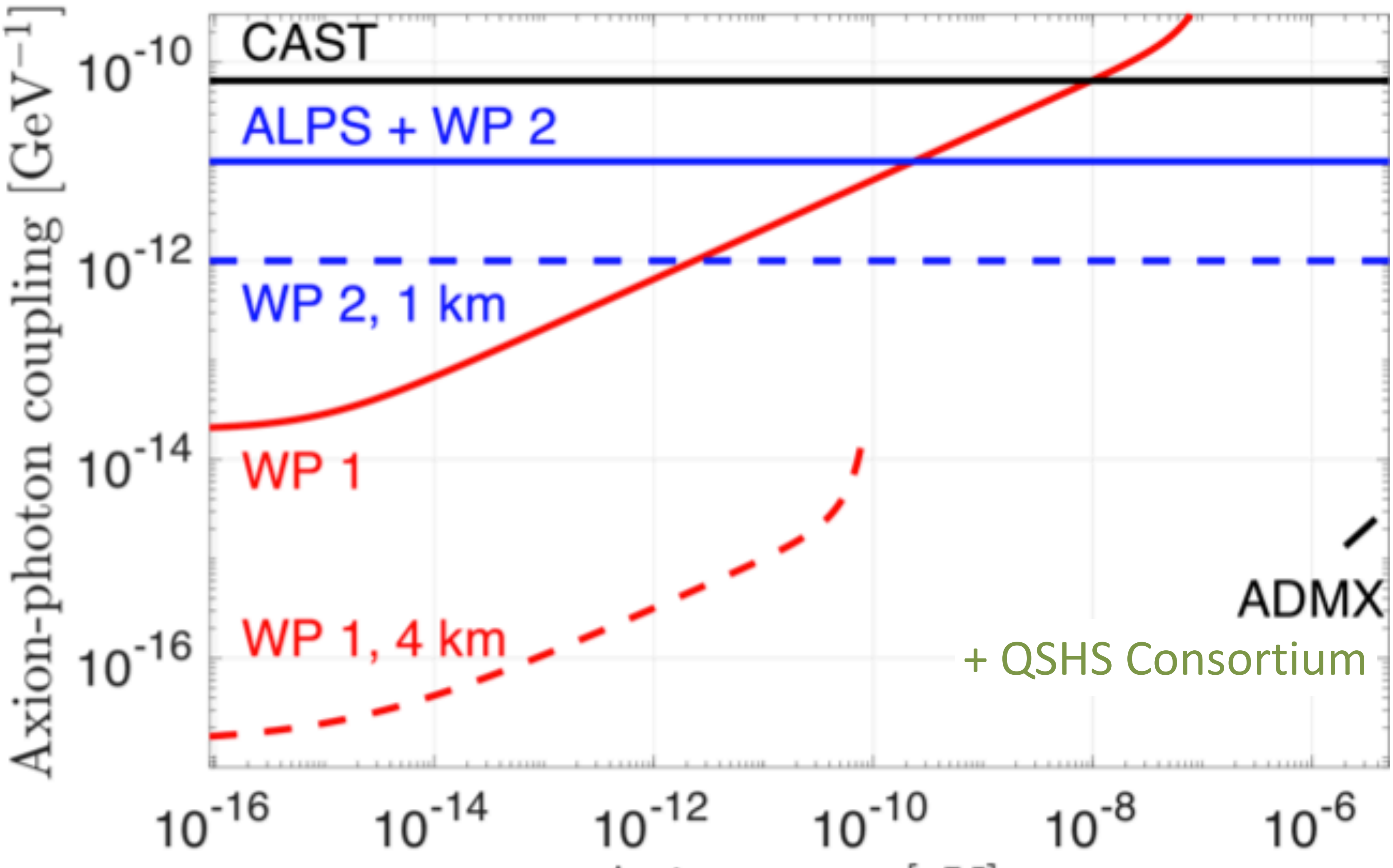


Quantum-Enhanced Interferometry



Quantum Technologies for Fundamental Physics:

Axion-Like Particles



QI Consortium

Clock Network to Measure Stability of Fundamental Constants

A network of clocks for measuring the stability of fundamental constants

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

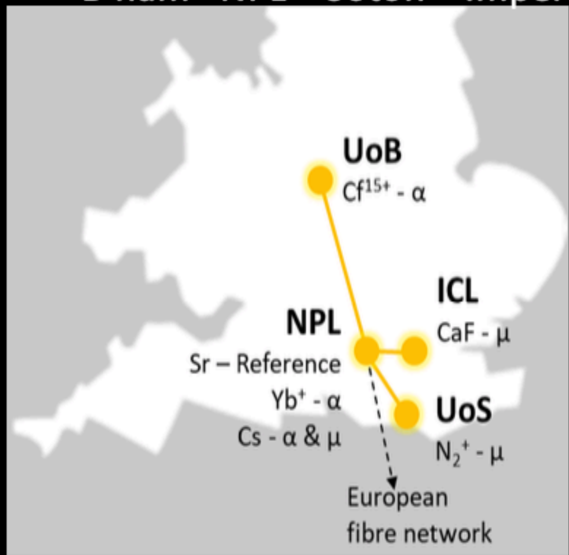
QT Hubs
- Sensors & timing
- Communications
- Computing & simulation

7 international institutions

B'ham NPL Soton Imperial

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

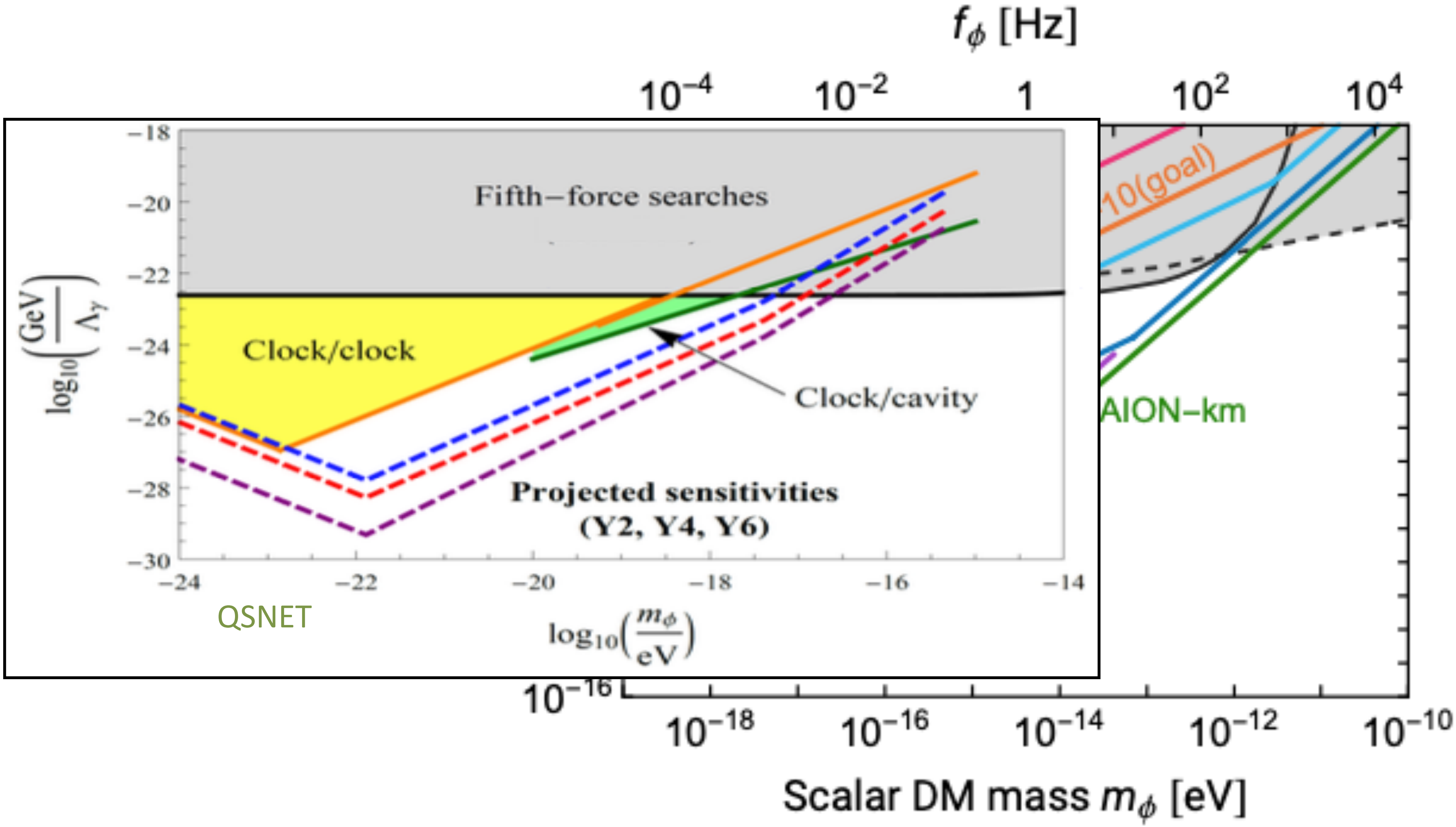
Clock	WP	Variations of fund. Constant
Ion clock Yb^+ (467 nm)	1	α
Atomic clock Sr (698 nm)	1	**Stable reference**
Atomic clock Cs (32.6 mm)	1	μ
Highly-charged ion clock Cf^{15+} (618 nm)	2	α
Molecular clock CaF (17 μm)	3	μ
Molecular ion clock N_2^+ (2.31 μm)	3	μ



e Giovanni Barontini talk
UK HEP Forum

Quantum Technologies for Fundamental Physics:

Ultralight Scalar Dark Matter Searches



Quantum-Enhanced Superfluid Technologies for Data Matter & Cosmology

Quest-DMC

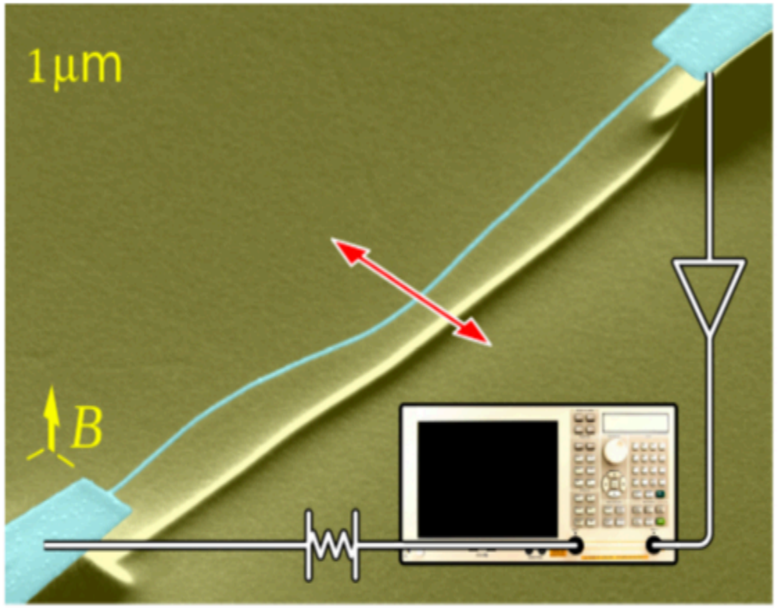
Royal Holloway University of London

Lancaster University

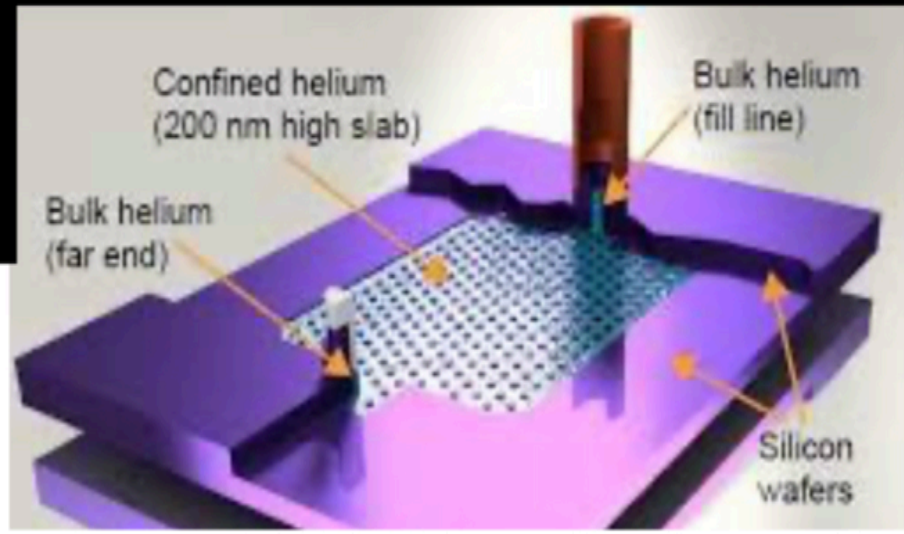
University of Sussex

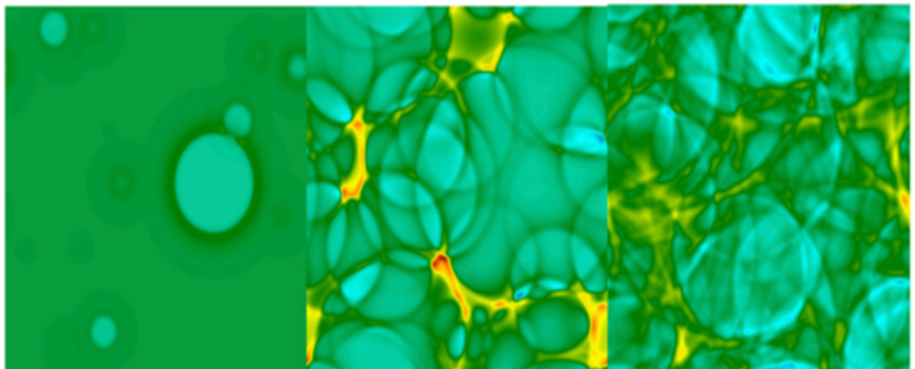
University of Oxford

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



Phase transitions in extreme matter





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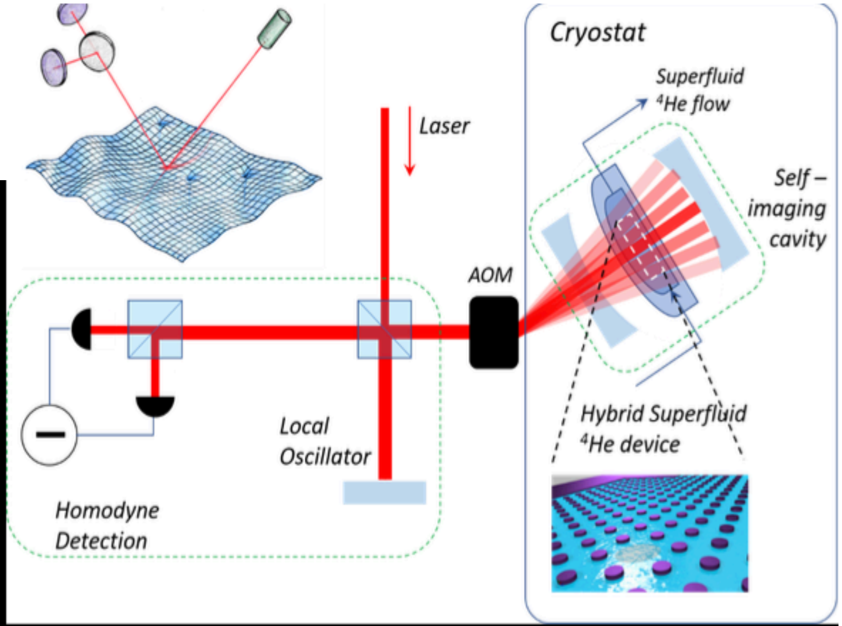
Quantum Simulators for Fundamental Physics

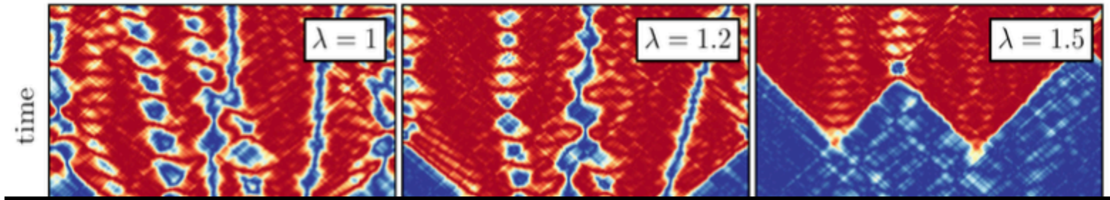
QSimFP



Team:

Silke Weinfurtner talk
At UK HEP Forum

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



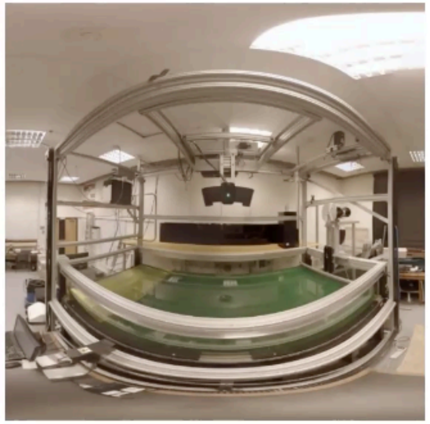
Science goals:

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

Pathways to quantum black hole experiment

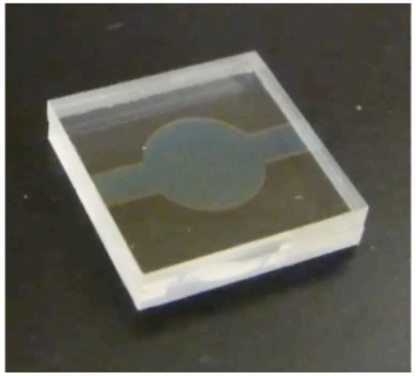
Only assumption: a quantum black hole exhibits quantised angular momentum

Classical angular momentum
Classical surface waves



Quantised angular momentum
Classical relativistic ripplons

Quantised angular momentum
Quantum relativistic ripplons



Classical spacetime
Classical relativistic fields

Quantum spacetime
Classical relativistic fields

Quantum spacetime
Quantum relativistic fields

Quantum Technologies for Neutrino Mass Consortium

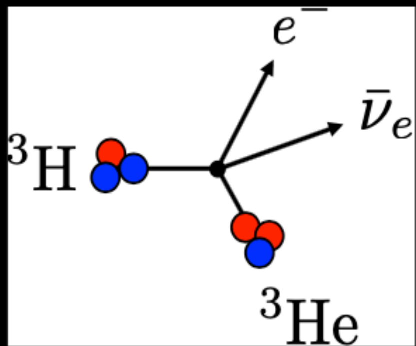
F. Deppisch[1], J, Gallop[2], L. Hao[2], S. Hogan[1], L.Li[3], R. Nichol[1], Y. Ramachers[4], R. Saakyan[1](PI), D. Waters[1], S. Withington[5]

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

3-yr proposal goal:

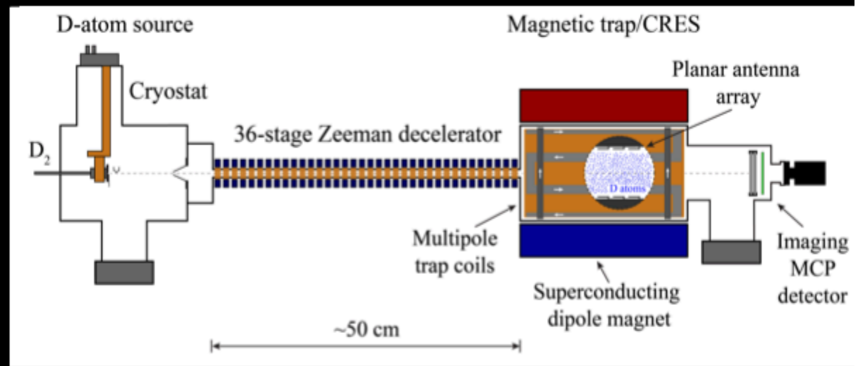
Technology demonstration for neutrino mass determination from ^{3}H $\boldsymbol{\beta}$-decay

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



Ultimate goal:

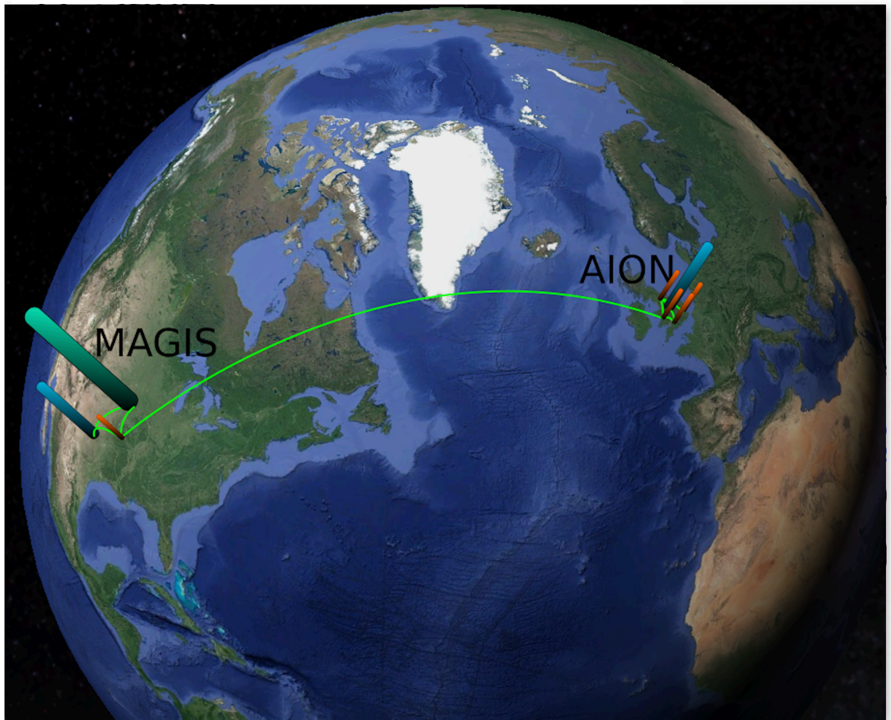
Neutrino mass measurement at a Tritium facility (e.g. *Culham Centre for Fusion Energy*)

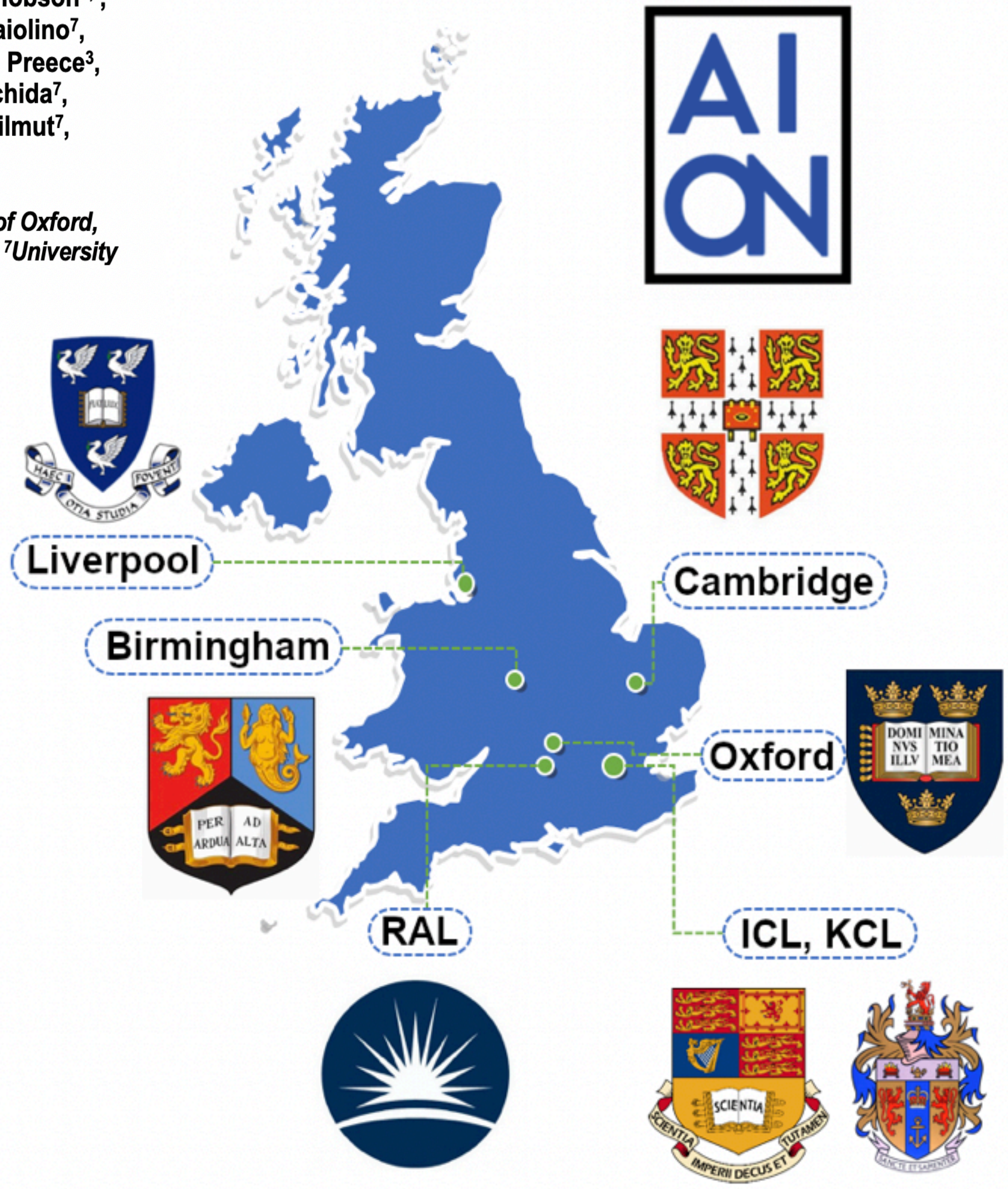


AION Collaboration

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

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





Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755

AION: an atom interferometer observatory and network

Abstract. We outline the experimental concept and key scientific capabilities of AION (Atom Interferometer Observatory and Network), a proposed experimental programme using cold strontium atoms to search for ultra-light dark matter, to explore gravitational waves in the mid-frequency range between the peak sensitivities of the LISA and LIGO/Virgo/ KAGRA/INDIGO/Einstein Telescope/Cosmic Explorer experiments, and to probe other frontiers in fundamental physics. AION would complement other planned searches for dark matter, as well as probe mergers involving intermediate-mass black holes and explore early-universe cosmology. AION would share many technical features with the MAGIS experimental programme, and synergies would flow from operating AION in a network with this experiment, as well as with other atom interferometer experiments such as MIGA, ZAIGA and ELGAR. Operating AION in a network with other gravitational wave detectors such as LIGO, Virgo and LISA would also offer many synergies.

Network with sibling MAGIS project in US

MAGIS Collaboration (Abe et al): arXiv:2104.02835

AION – Staged Programme

- AION-10: Stage 1 [year 1 to 3]
  - 1 & 10 m Interferometers & Site Development for 100m Baseline

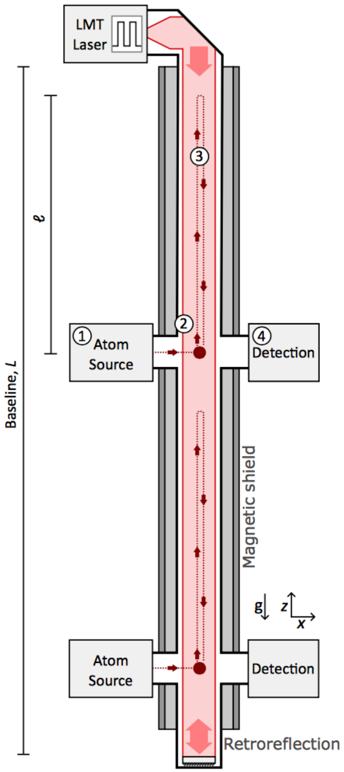
Initial funding from UK STFC

- AION-100: Stage 2 [year 3 to 6]
  - 100m Construction & Commissioning
- AION-KM: Stage 3 [> year 6]
  - Operating AION-100 and planning for 1 km & Beyond
- AION-SPACE (AEDGE): Stage 4 [after AION-KM]
  - Space-based version

AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755

AION Design Parameters

Table 1. *List of basic parameters: length of the detector L; interrogation time of the atom interferometer T_{int}; phase noise $\delta\phi_{\rm noise}$; and number of momentum transfers LMT. The choices of these parameters largely determine the sensitivities of the projection scenarios. It should be noted that at a 100m detector it will be conceptually possible to increase the interrogation time of the atom interferometer beyond 1.4 sec.*

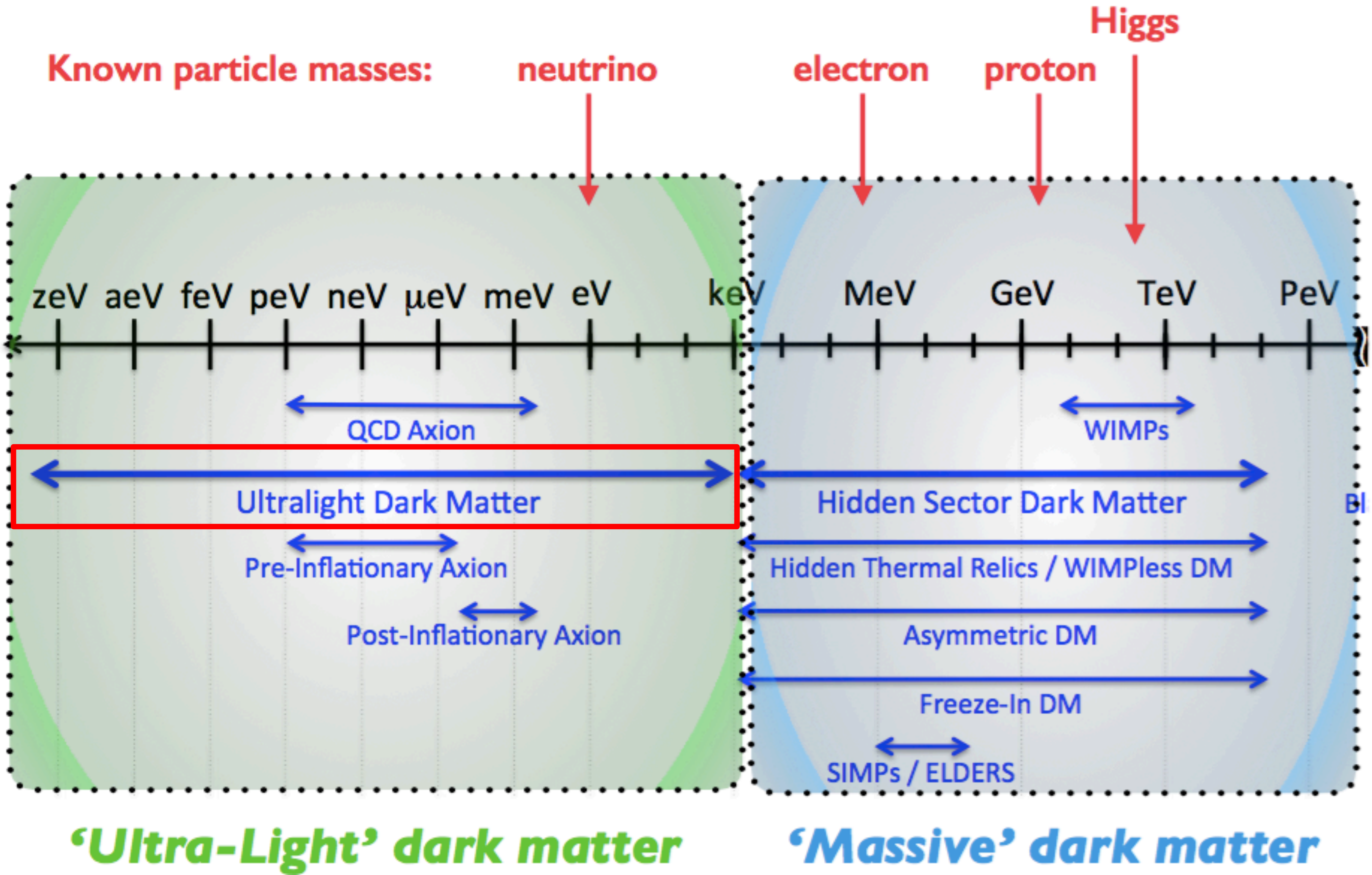


Sensitivity Scenario	L [m]	T_{int} [sec]	$\delta\phi_{\rm noise}$ $[1/\sqrt{\rm Hz}]$	LMT [number n]
AION-10 (initial)	10	1.4	10^{-3}	100
AION-10 (goal)	10	1.4	10^{-4}	1000
AION-100 (initial)	100	1.4	10^{-4}	1000
AION-100 (goal)	100	1.4	10^{-5}	40000
AION-km	2000	5	0.3×10^{-5}	40000

Initial targets and final goals

AION Collaboration (Badurina, ..., JE et al): arXiv:1911.11755

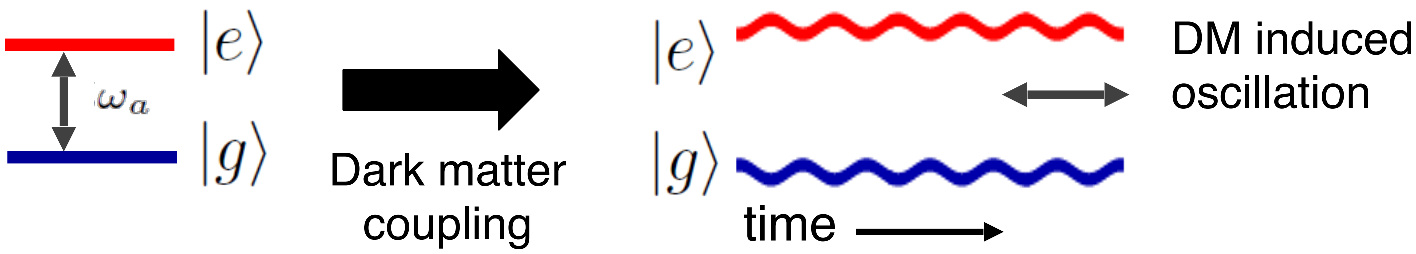
Searches for Light Dark Matter

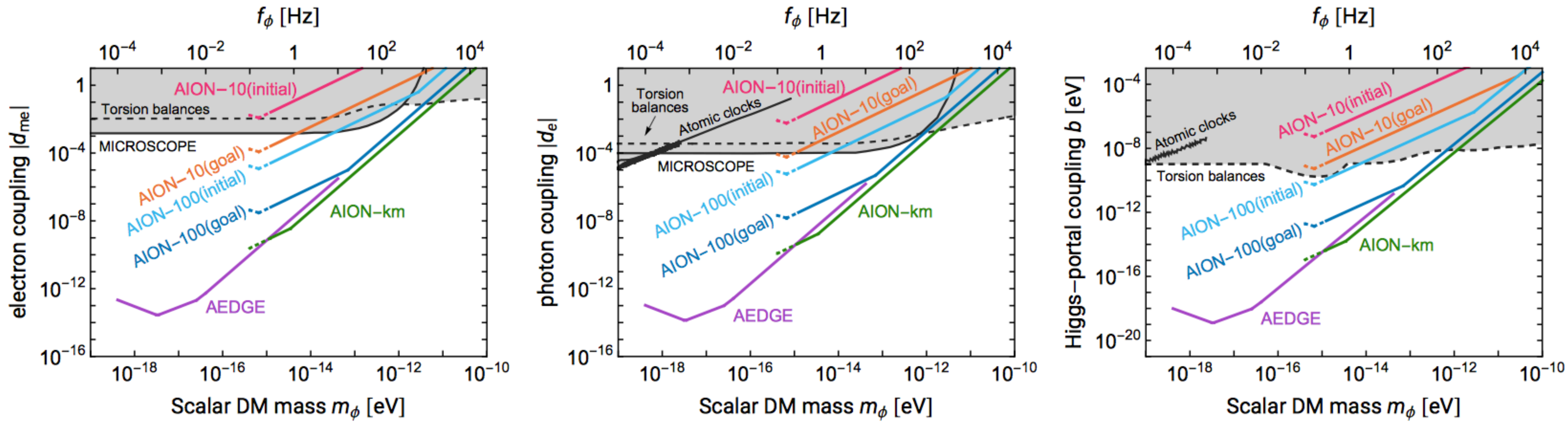


Searches for Light Dark Matter

Linear couplings to gauge fields and matter fermions

$$\mathcal{L}_{\text{int}\phi} = \kappa\phi \left[+\frac{d_e}{4e^2} F_{\mu\nu}F^{\mu\nu} - \frac{d_g \beta_3}{2g_3} F^A_{\mu\nu}F^{A\mu\nu} - \sum_{i=e,u,d} (d_{m_i} + \gamma_{m_i} d_g) m_i \bar{\psi}_i \psi_i \right]$$





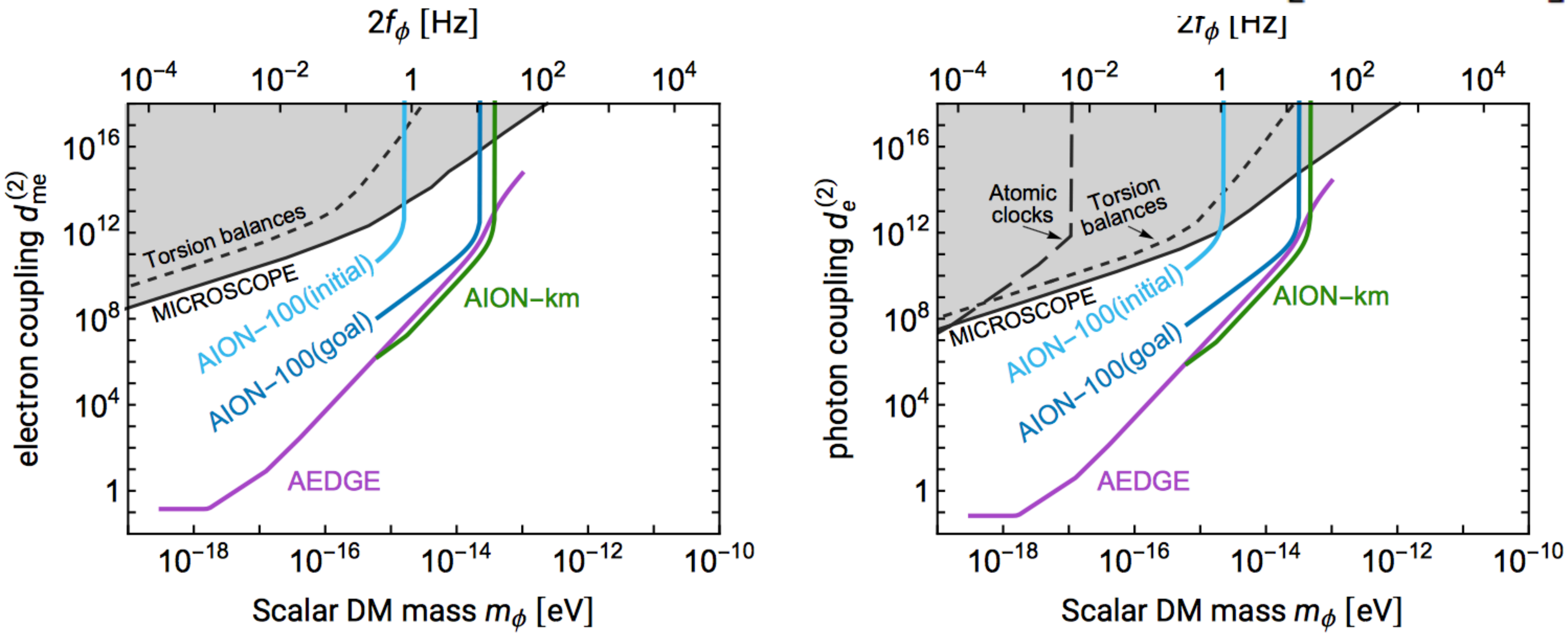
AION Collaboration (Badurina, ..., JE et al): arXiv:1911.11755

AEDGE: Bertoldi, …, JE et al: arXiv:1908.00802

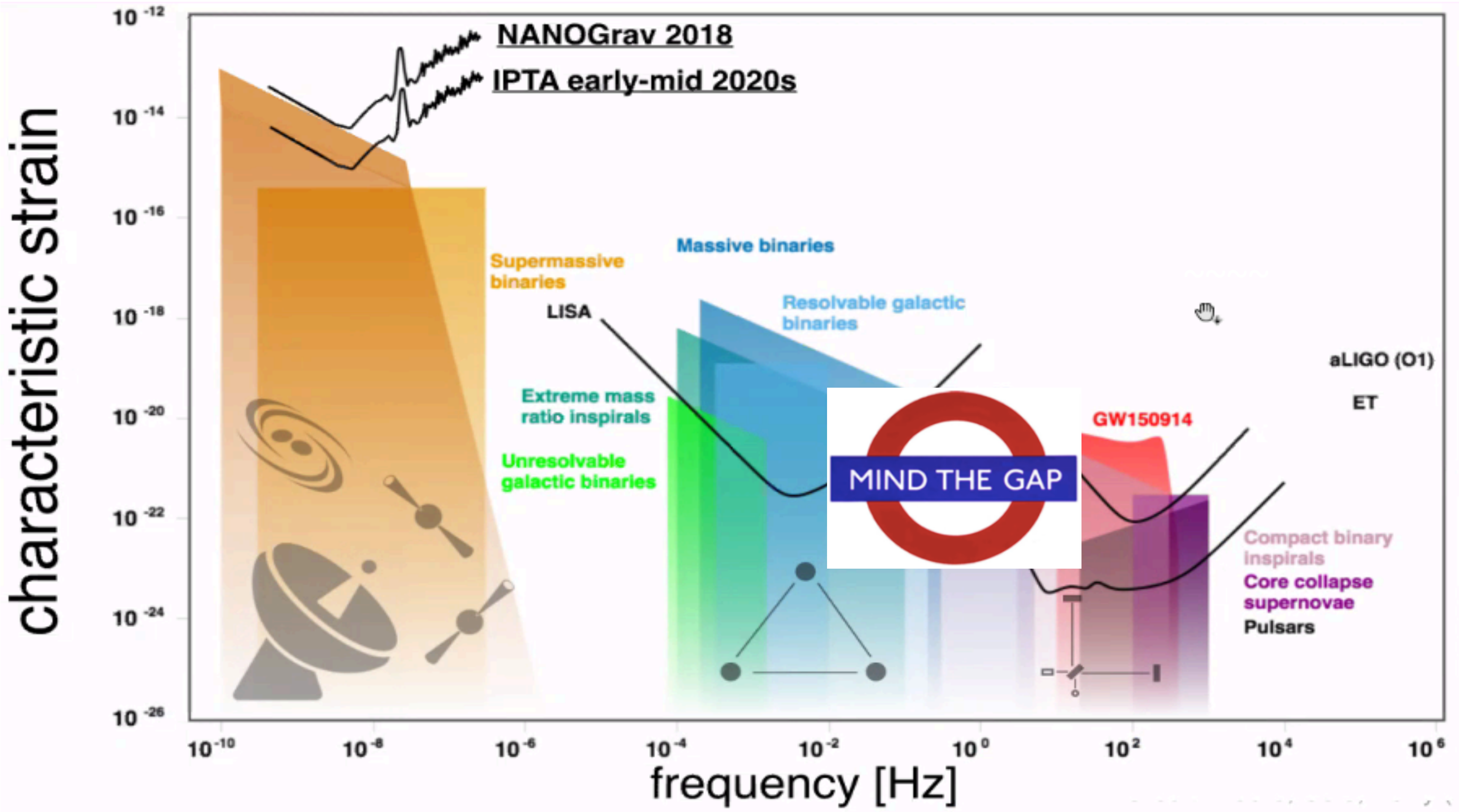
Sensitivities to Quadratic DM Interactions

$$\mathcal{L}^f_{\rm int} = -\sum_{f=e,p,n} m_f \left(\frac{\phi c}{\Lambda'_f}\right)^2 \bar{f} f, \qquad m_f \to m_f \left[1 + \left(\frac{\phi}{\Lambda'_f}\right)^2\right],$$

$$\mathcal{L}^\gamma_{\rm int} = \left(\frac{\phi}{\Lambda'_\gamma}\right)^2 \frac{F_{\mu\nu}F^{\mu\nu}}{4} \qquad \alpha \to \frac{\alpha}{1-(\phi/\Lambda'_\gamma)^2} \simeq \alpha \left[1 + \left(\frac{\phi}{\Lambda'_\gamma}\right)^2\right]$$



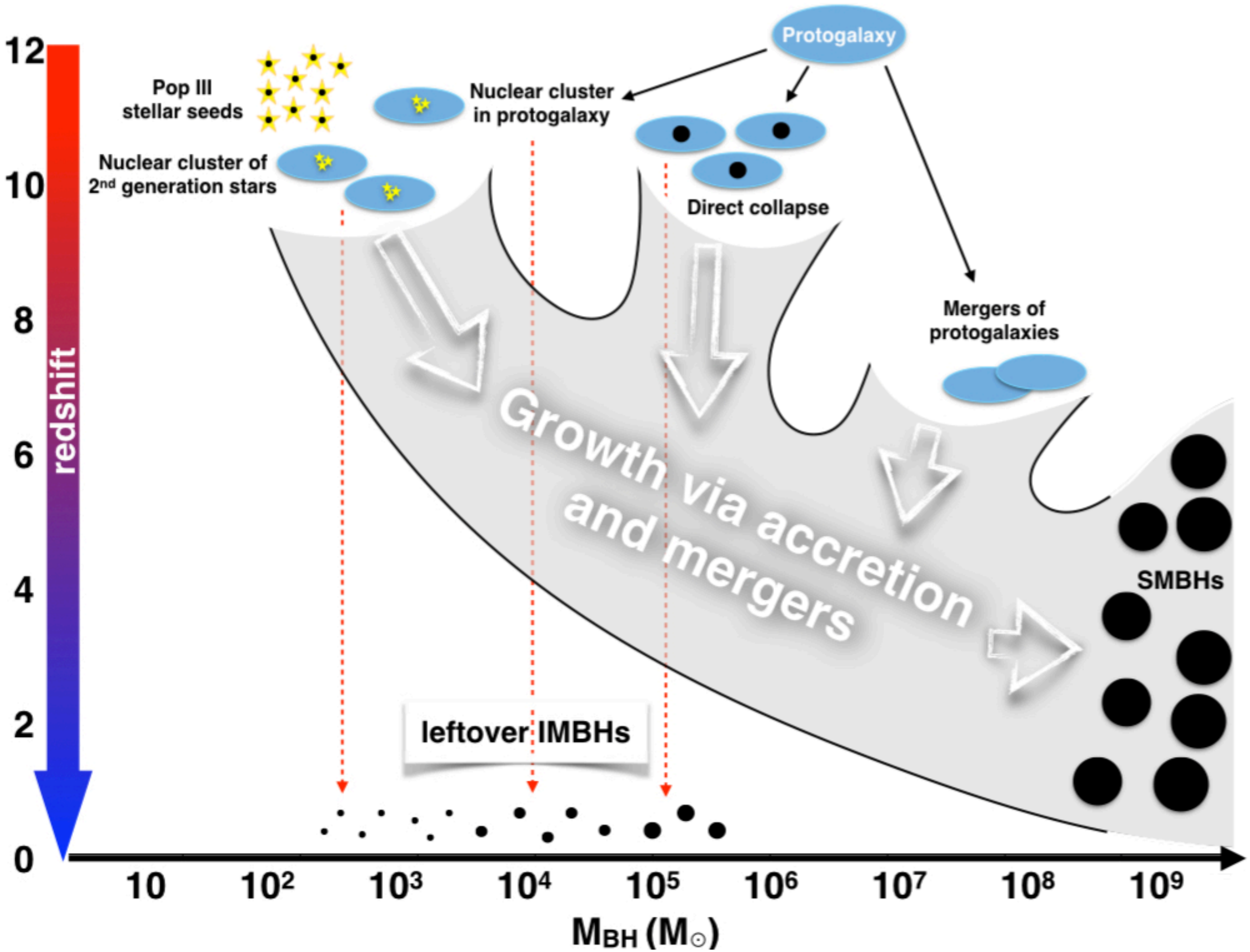
Gravitational Wave Spectrum



- Gap between ground-based optical interferometers & LISA
  - Formation of supermassive black holes (SMBHs)?
  - Electroweak phase transition? Cosmic strings?
- Gap between LISA & pulsar timing arrays (PTAs)

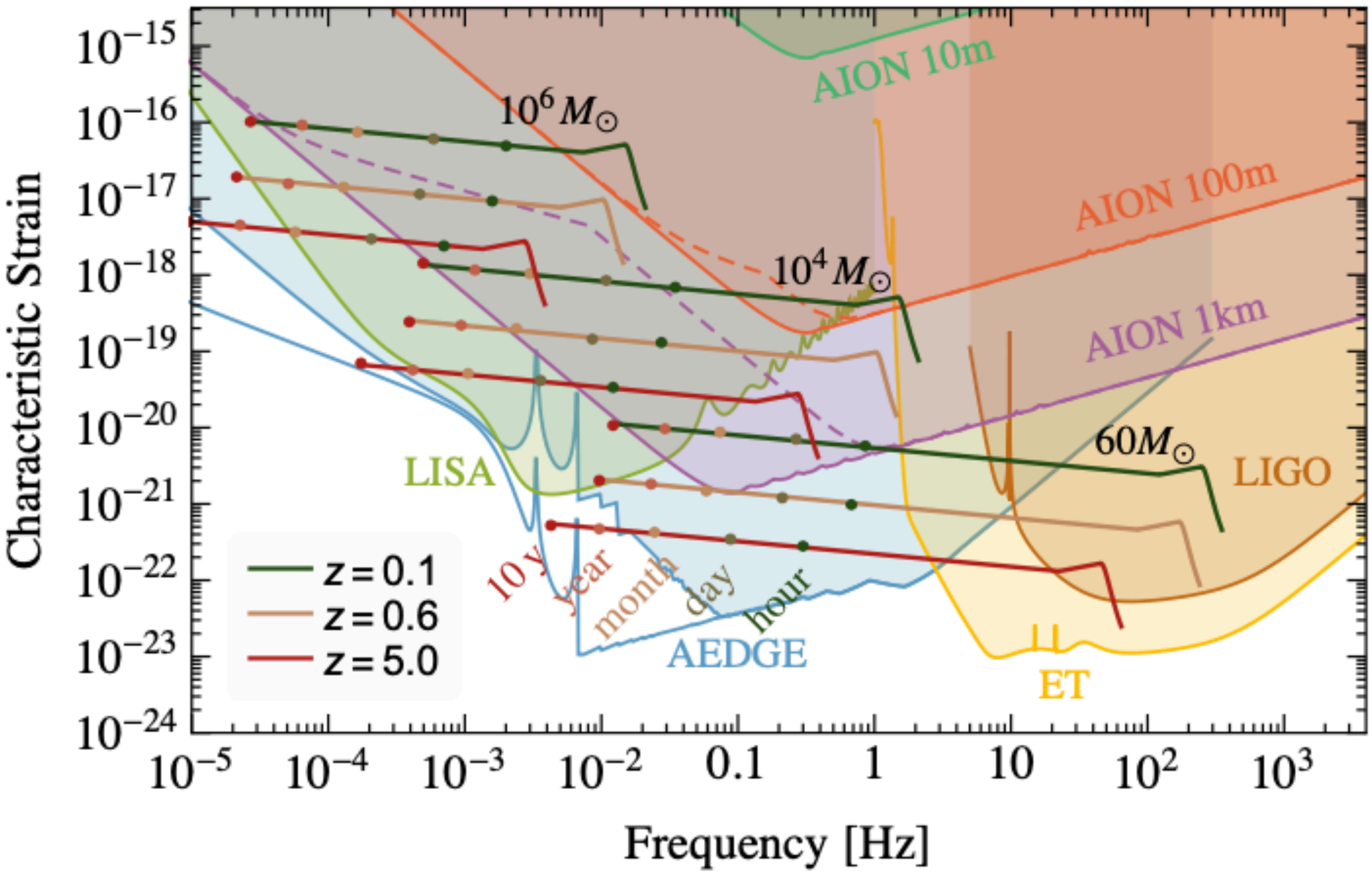
How to Make a Supermassive BH?

SMBHs from mergers of intermediate-mass BHs (IMBHs)?



AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755

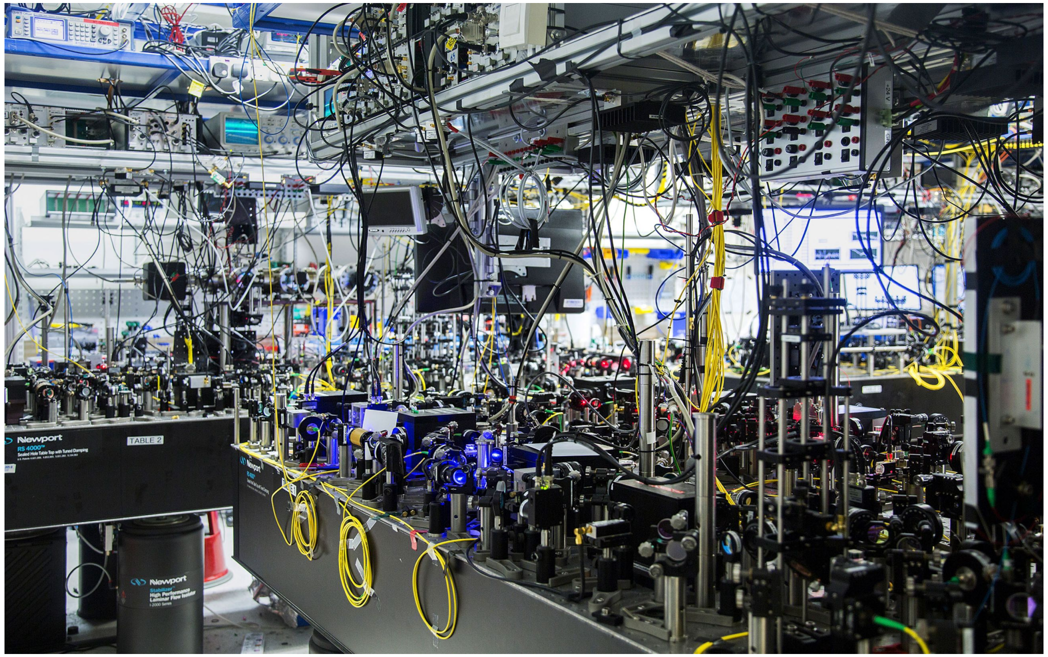
Gravitational Waves from IMBH Mergers



Probe formation of SMBHs

Synergies with other GW experiments (LIGO, LISA), test GR

Ultra-Cold Strontium Laboratories



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

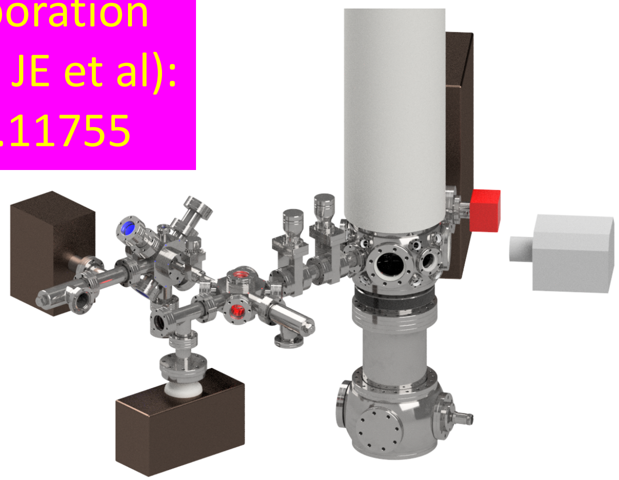
Birmingham, Cambridge, Imperial College, Oxford, and RAL

The laboratories are expected to be operational in autumn 2021.

Planned Site for AION 10m

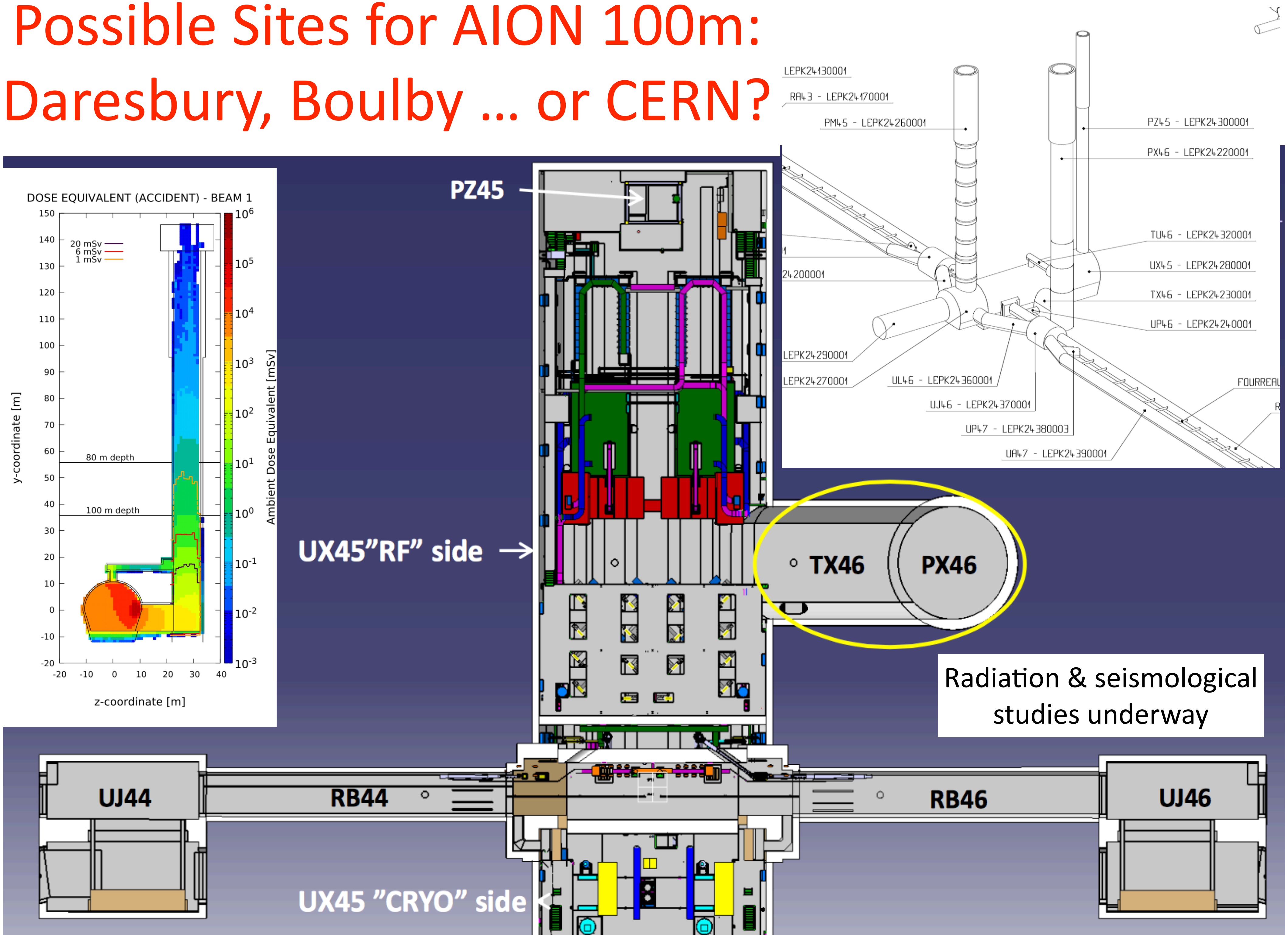
- Oxford Physics Department
- New purpose-built building
  - Low vibration
  - Temperature control
  - Laser laboratory
  - Engineering support

AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755



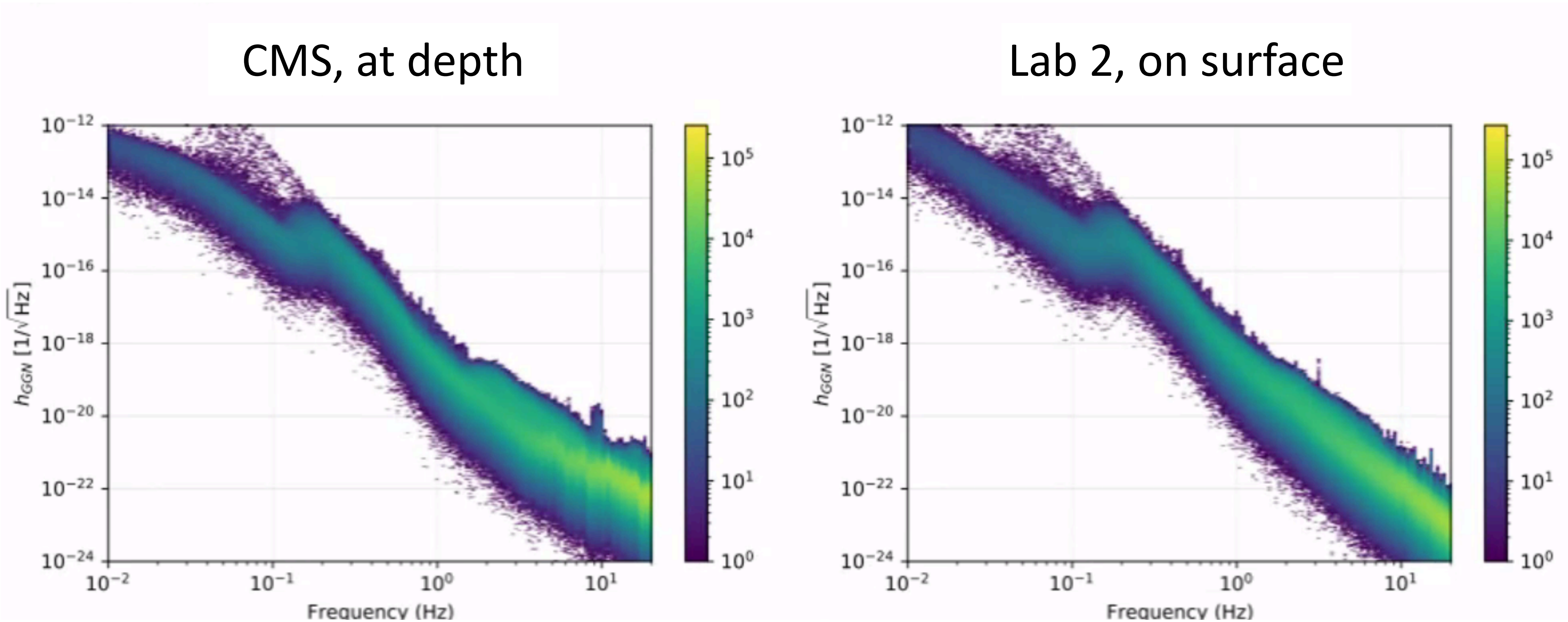
Possible Site for AION 100m (1km?) Boulby Mine STFC Laboratory

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



Radiation & seismological studies underway

Preliminary seismological study: GGN strain at CERN

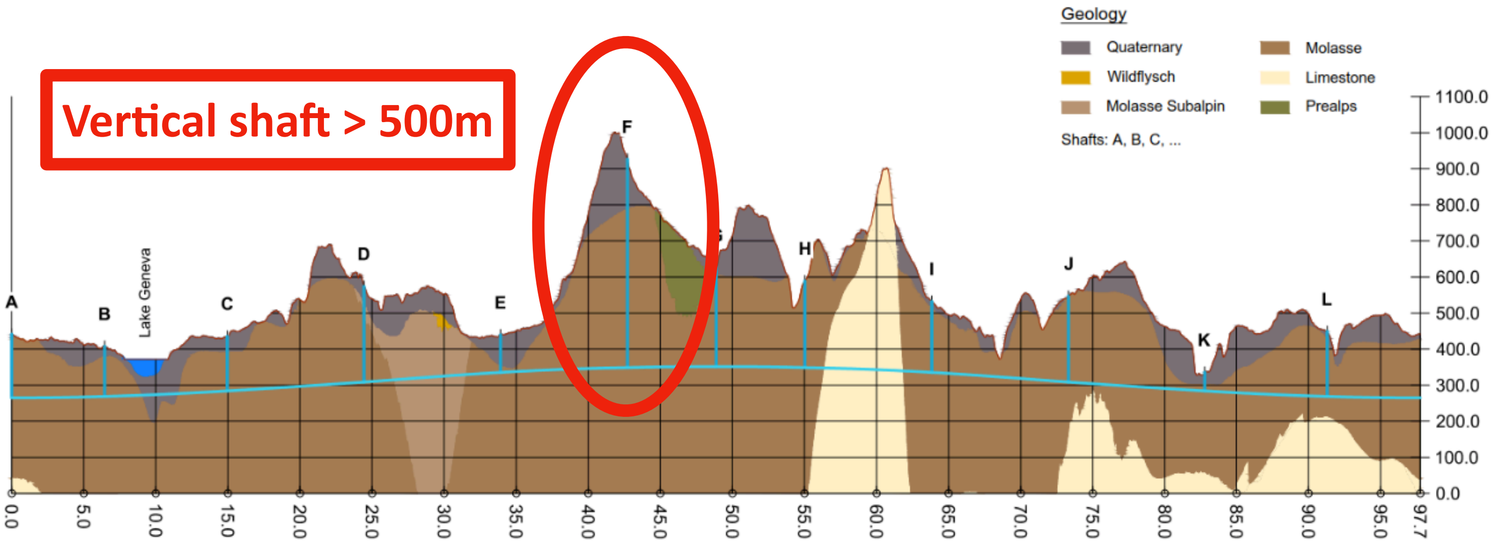


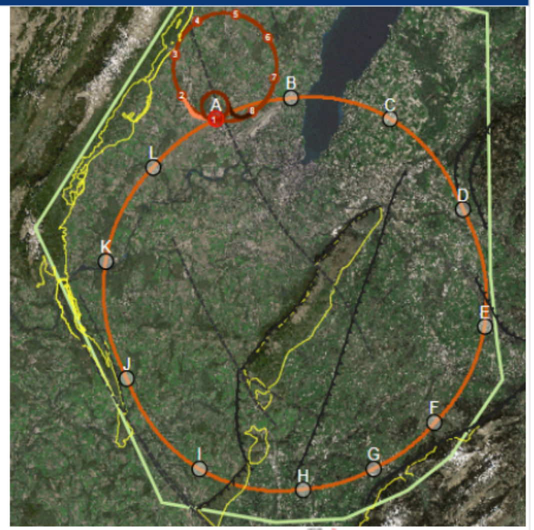
Jeremiah Mitchell, using seismometer data obtained via Michael Guinchard (CERN)

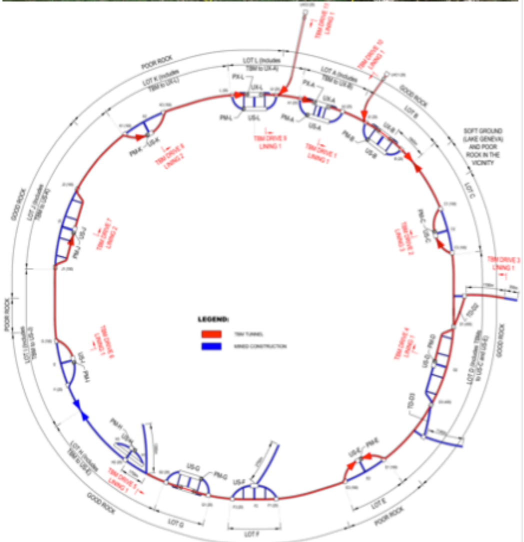
Possible Site for AION-1km?

FCC implementation - footprint baseline

FUTURE CIRCULAR COLLIDER





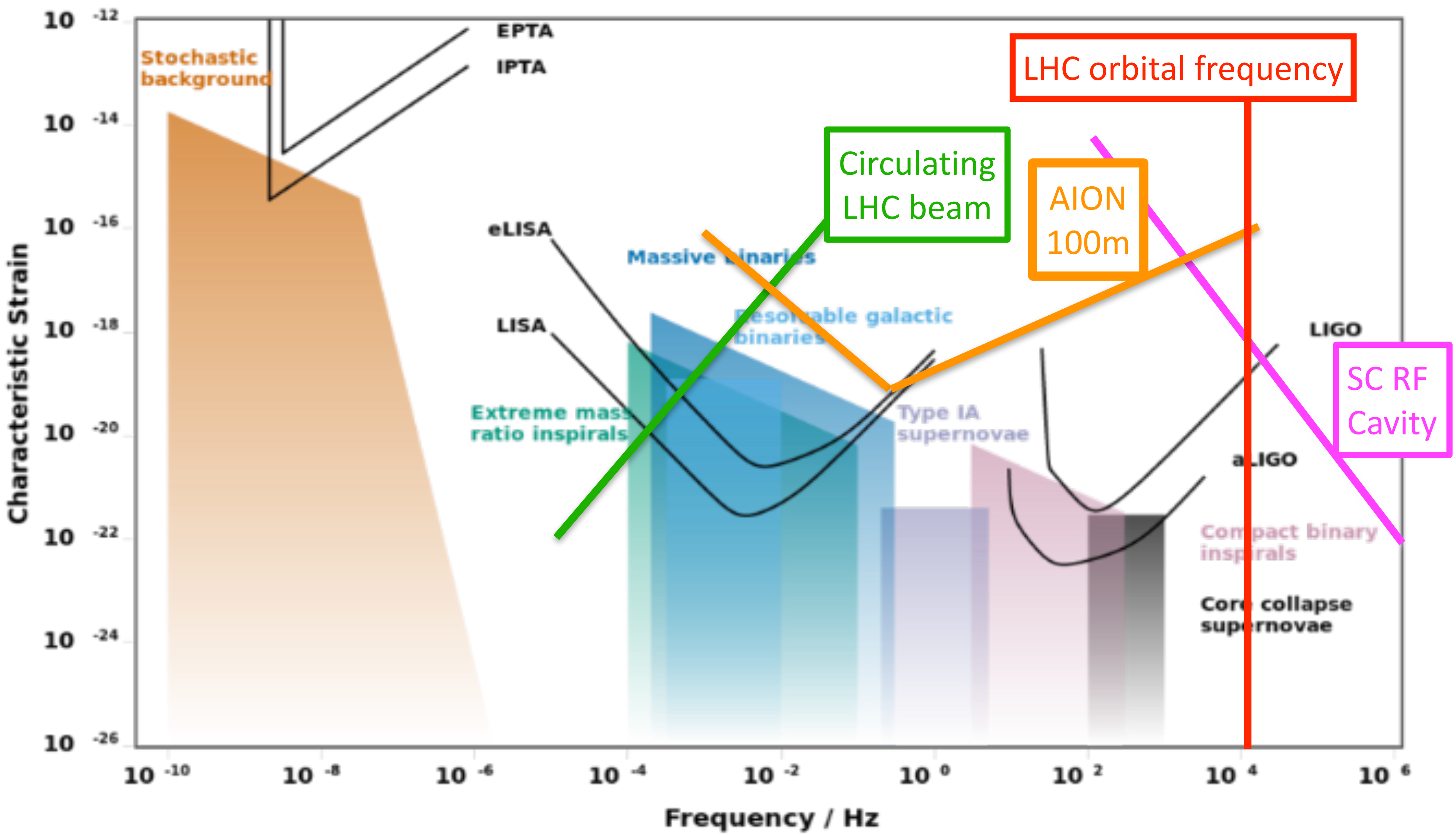


Present baseline position was established considering:

- Molasse rock preferred for tunnelling, avoid limestone with karstic structures
- low risk for construction, fast construction

- **90 – 100 km circumference**
- **12 surface sites with few ha area each**

CERN-Related GW Ideas

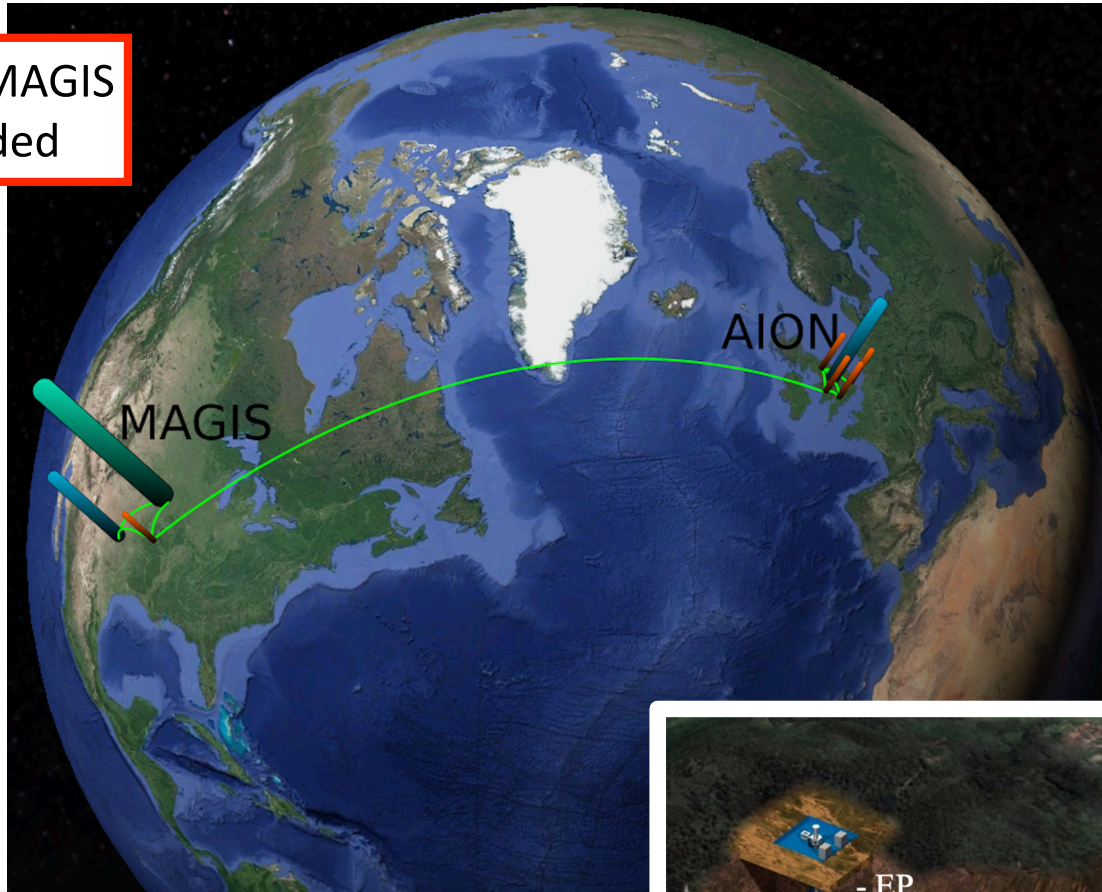


SRGW2021 workshop (Berlin, …, JE et al): arXiv:2105.00992

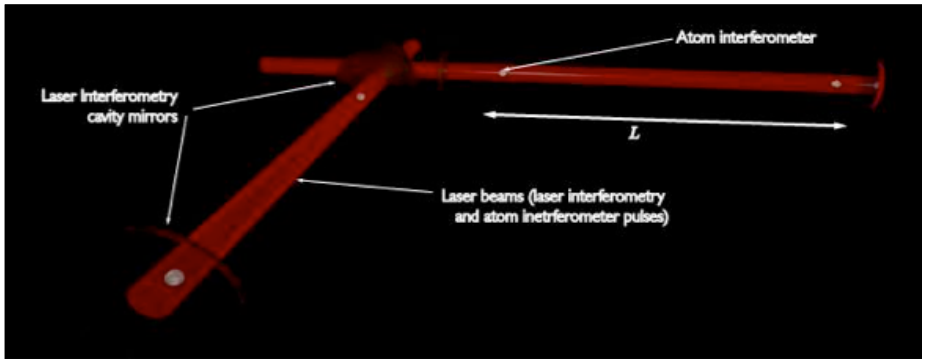
Atom Interferometer Observatory &

Network

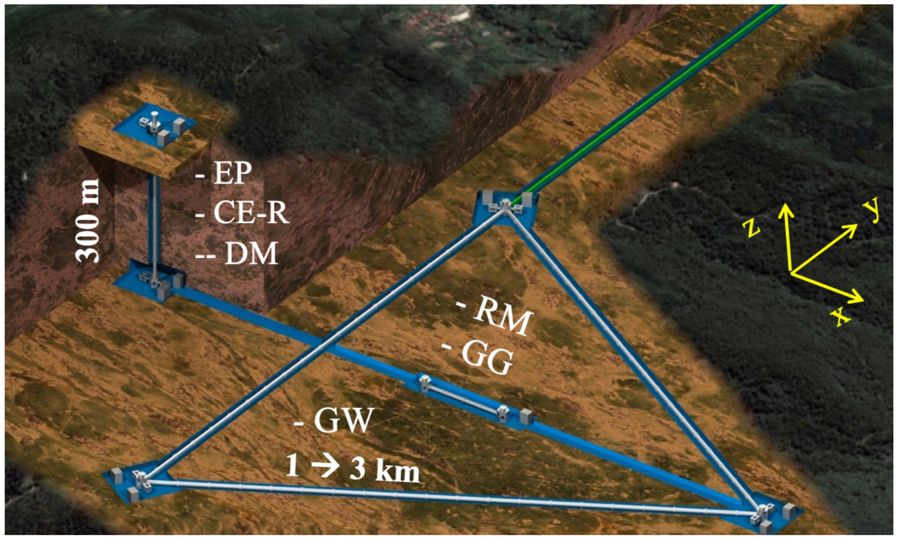
Partnership with MAGIS could be extended



MIGA (France)



ZAIGA (China)



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SCIENTIFIC REPORTS

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Exploring gravity with the MIGA large scale atom interferometer

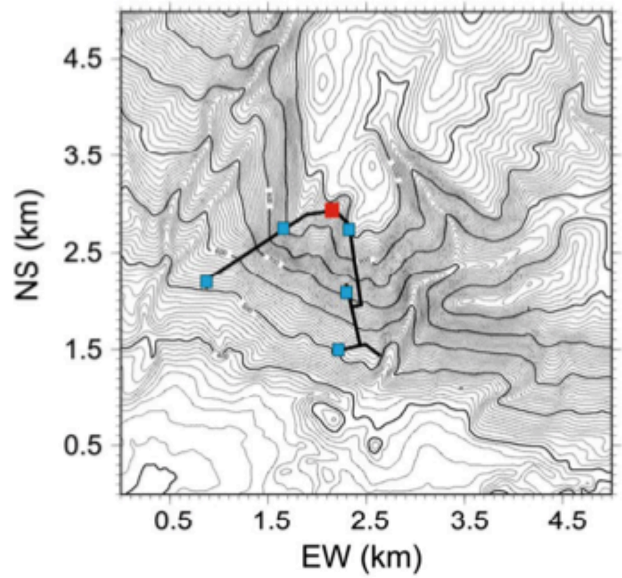
B. Canuel[1,2], A. Bertoldi[1,2], L. Amand[1,3], E. Pozzo di Borgo[1,4], T. Chantrait[1,3], C. Danquigny[1,4], M. Dovale Álvarez[5], B. Fang[1,3], A. Freise[5], R. Geiger[1,3], J. Gillot[1,2], S. Henry[6], J. Hinderer[1,7], D. Holleville[1,3], J. Junca[1,2], G. Lefèvre[1,2], M. Merzougui[1,8], N. Mielec[1,3], T. Monfret[9], S. Pelisson[1,2], M. Prevedelli[10], S. Reynaud[1,11], I. Riou[1,2], Y. Rogister[1,7], S. Rosat[1,7], E. Cormier[1,12], A. Landragin[1,3], W. Chaibi[1,8], S. Gaffet[1,9,13] & P. Bouyer[1,2]

Received: 25 May 2018
Accepted: 8 August 2018
Published online: 14 September 2018

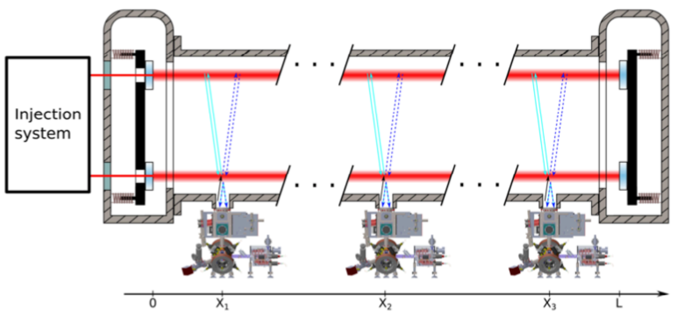
We present the MIGA experiment, an underground long baseline atom interferometer to study gravity at large scale. The hybrid atom-laser antenna will use several atom interferometers simultaneously interrogated by the resonant mode of an optical cavity. The instrument will be a demonstrator for gravitational wave detection in a frequency band (100 mHz–1 Hz) not explored by classical ground and space-based observatories, and interesting for potential astrophysical sources. In the initial instrument configuration, standard atom interferometry techniques will be adopted, which will bring to a peak strain sensitivity of $2 \cdot 10^{-13}/\sqrt{\mathrm{Hz}}$ at 2 Hz. This demonstrator will enable to study the techniques to push further the sensitivity for the future development of gravitational wave detectors based on large scale atom interferometers. The experiment will be realized at the underground facility of the Laboratoire Souterrain à Bas Bruit (LSBB) in Rustrel–France, an exceptional site located away from major anthropogenic disturbances and showing very low background noise. In the following, we present the measurement principle of an in-cavity atom interferometer, derive the method for Gravitational Wave signal extraction from the antenna and determine the expected strain sensitivity. We then detail the functioning of the different systems of the antenna and describe the properties of the installation site.

The MIGA Large-Scale Atom Interferometer

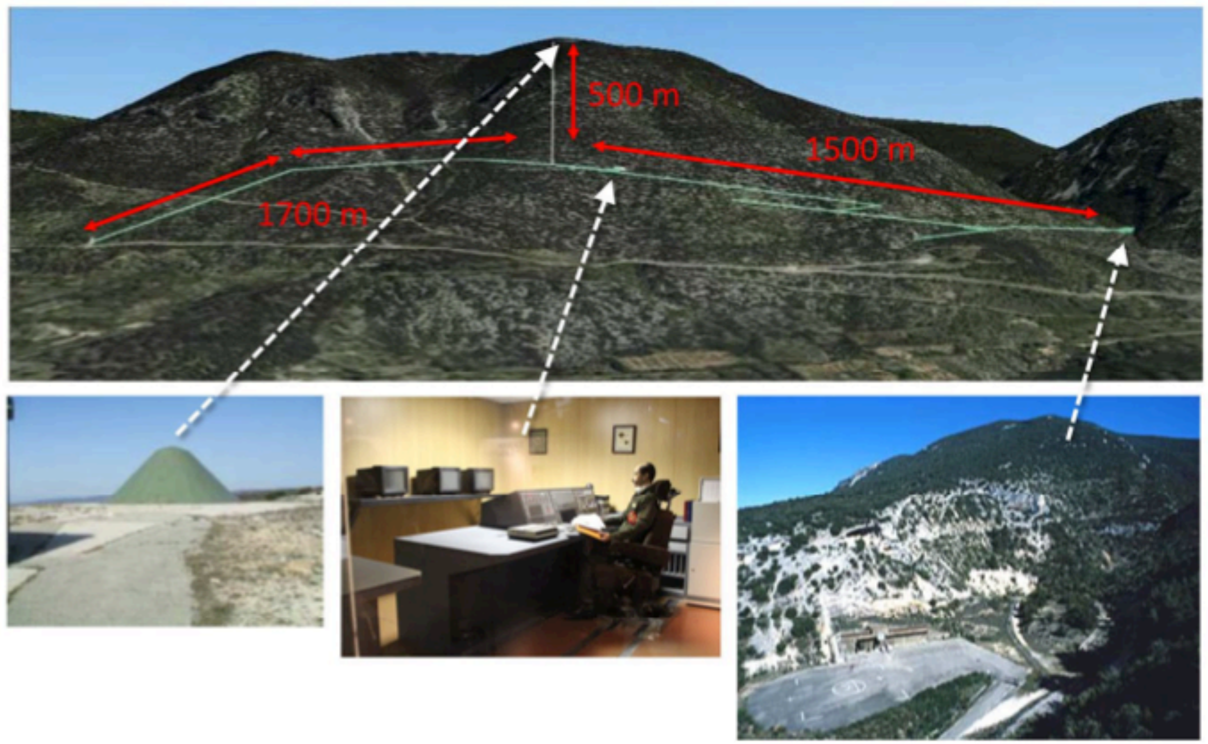
Under construction in former nuclear bunker



Atomic fountains illuminated by laser beams

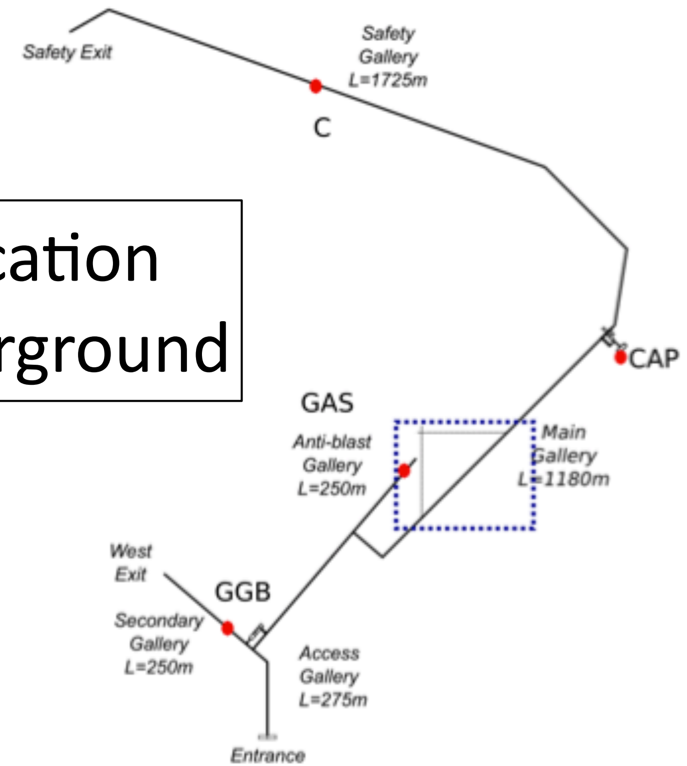


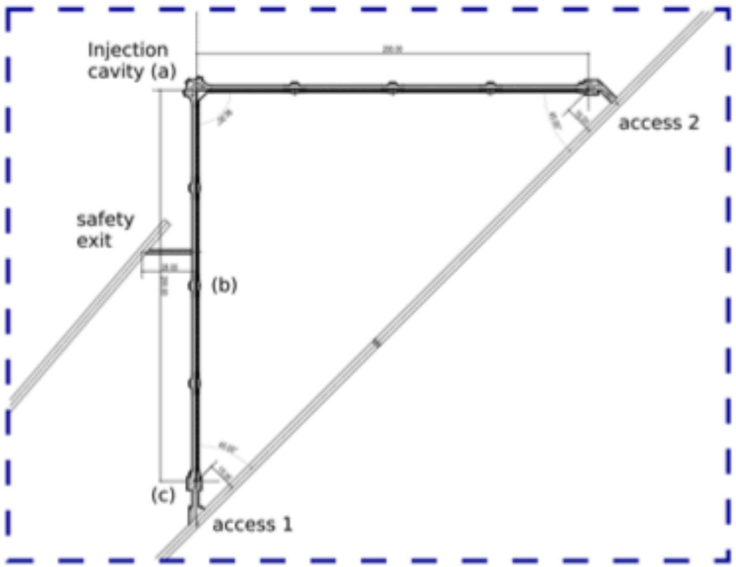
(C)

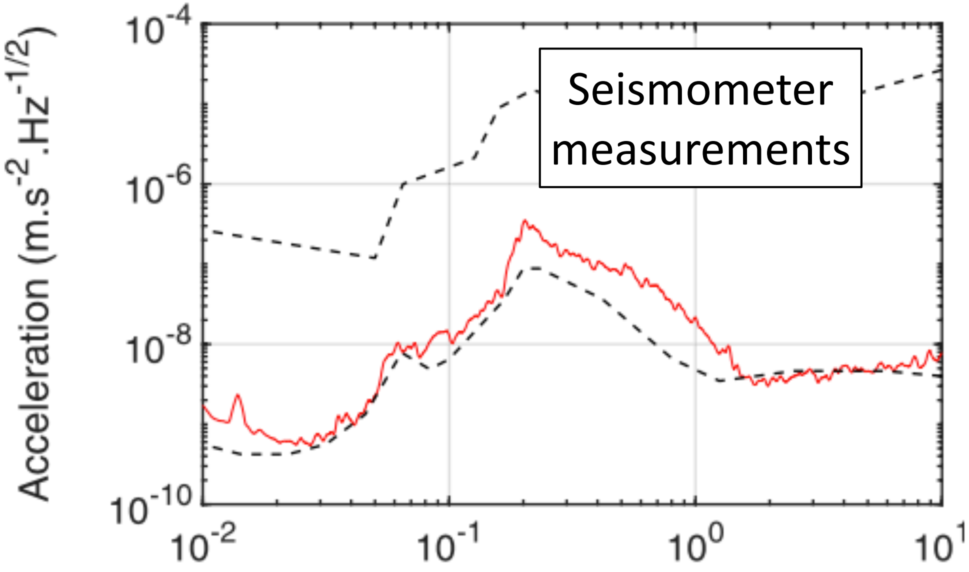


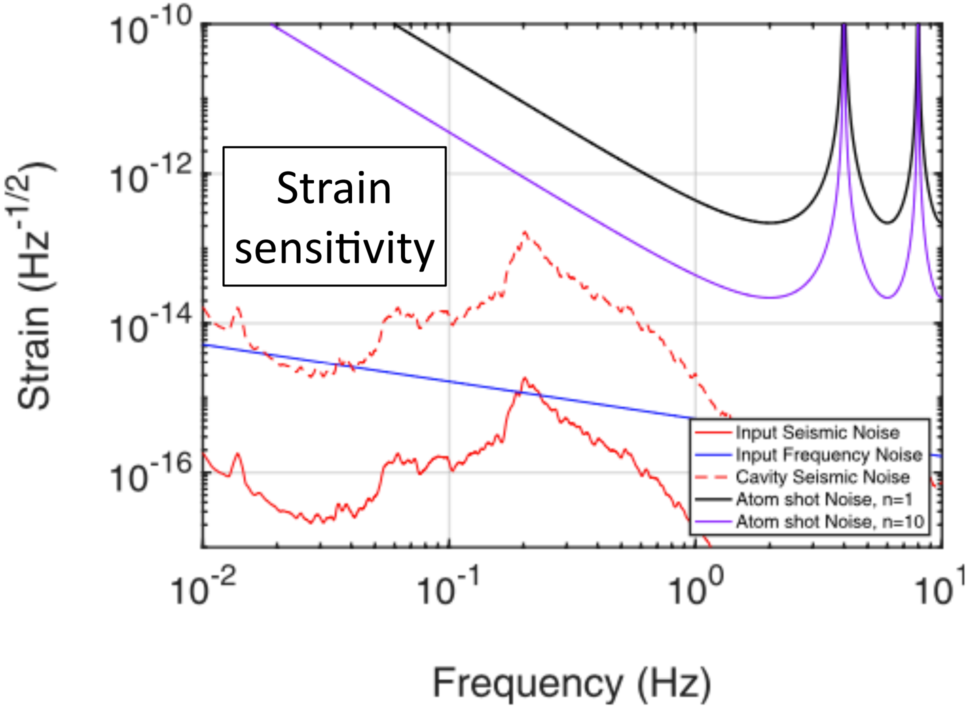
The MIGA Large-Scale Atom Interferometer

Location underground



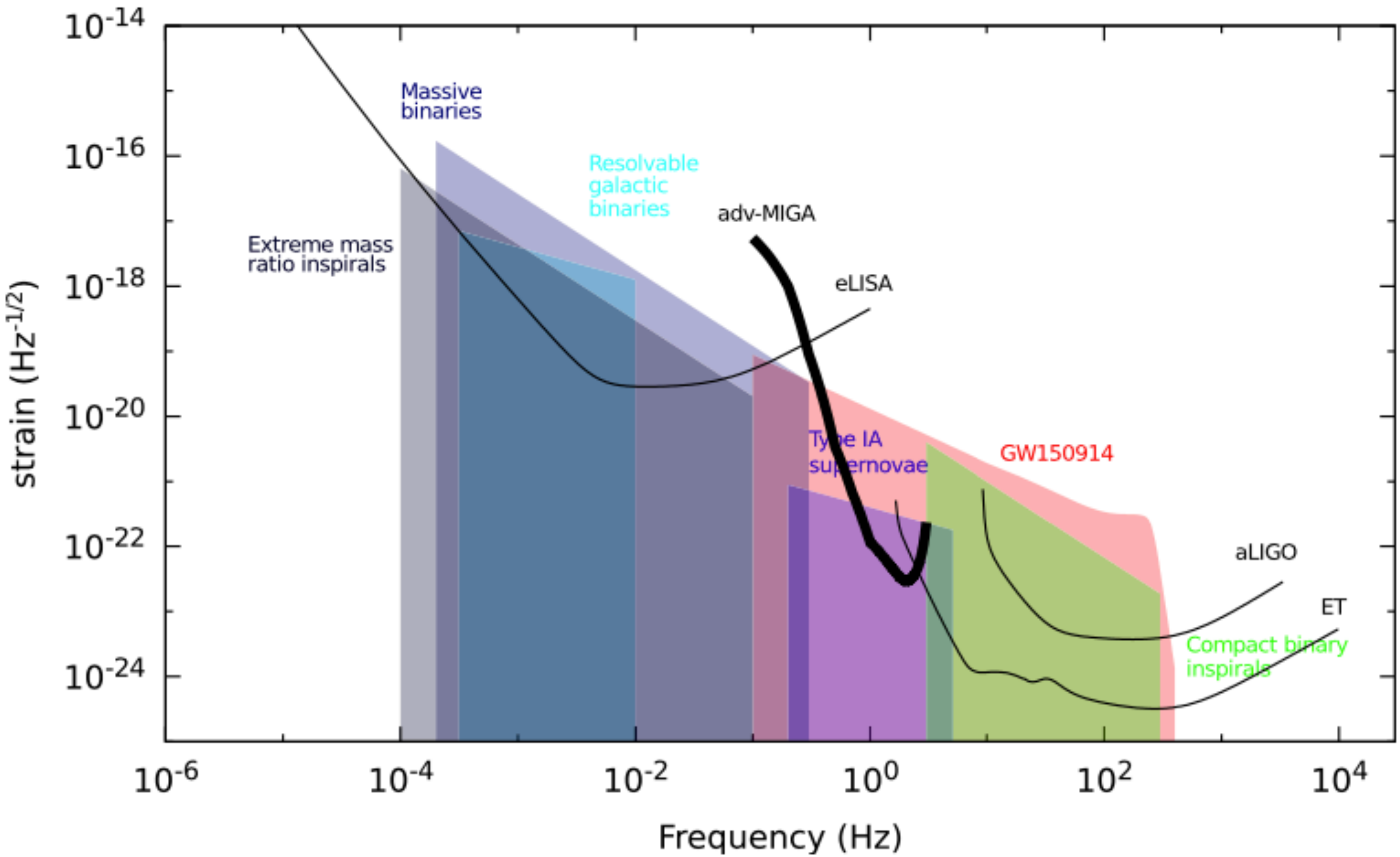






The MIGA Large-Scale Atom Interferometer

Sensitivity to gravitational waves



Next step?

OPEN ACCESS
IOP Publishing
Classical and Quantum Gravity
Class. Quantum Grav. 37 (2020) 225017 (35pp)
https://doi.org/10.1088/1361-6382/aba80e

ELGAR—a European Laboratory for Gravitation and Atom-interferometric Research

B Canuel[1,*], S Abend[2], P Amaro-Seoane[3,4,5,6], F Badaracco[7,8], Q Beaufils[9], A Bertoldi[1], K Bongs[10], P Bouyer[1], C Braxmaier[11,12], W Chaibi[13], N Christensen[13], F Fitzek[2,14], G Flouris[15], N Gaaloul[2], S Gaffet[16], C L Garrido Alzar[9], R Geiger[9], S Guellati-Khelifa[17], K Hammerer[14], J Harms[7,8], J Hinderer[18], M Holynski[10], J Junca[1], S Katsanevas[19], C Klempt[2], C Kozanitis[15], M Krutzik[20], A Landragin[9], I Làzaro Roche[16], B Leykauf[20], Y-H Lien[10], S Loriani[2], S Merlet[9], M Merzougui[13], M Nofrarias[21,22], P Papadakos[15,23], F Pereira dos Santos[9], A Peters[20], D Plexousakis[15,23], M Prevedelli[24], E M Rasel[2], Y Rogister[18], S Rosat[18], A Roura[25], D O Sabulsky[1], V Schkolnik[20], D Schlippert[2], C Schubert[2,31], L Sidorenkov[9], J-N Siemß[2,14], C F Sopuerta[21,22], F Sorrentino[26], C Struckmann[2], G M Tino[27], G Tsagkatakis[15,23], A Viceré[28,29], W von Klitzing[30], L Woerner[11,12] and X Zou[1]

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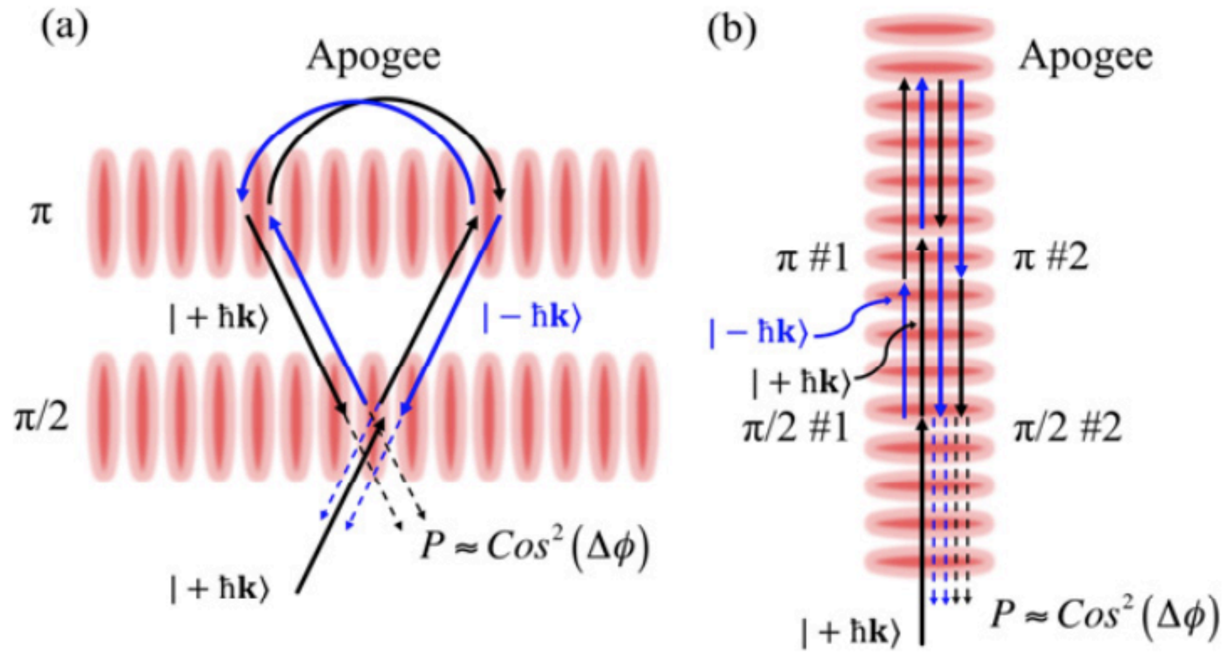
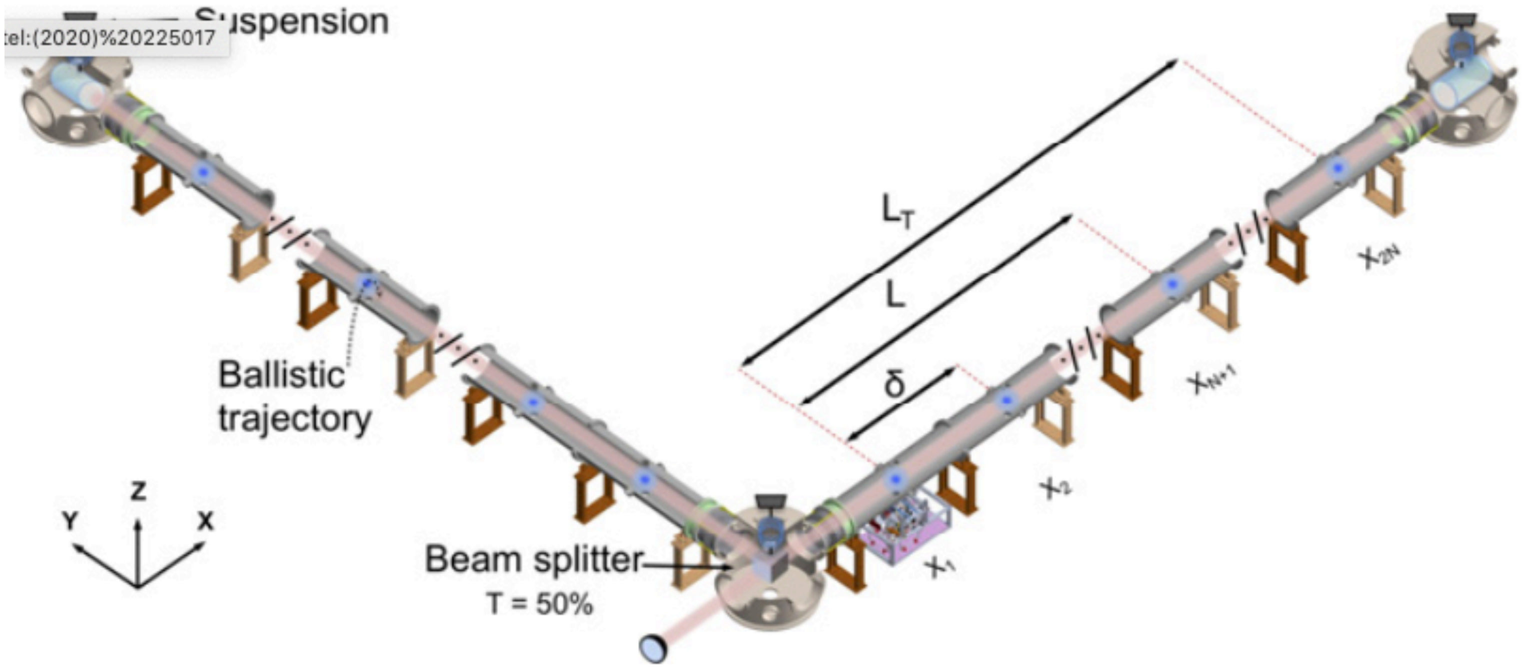
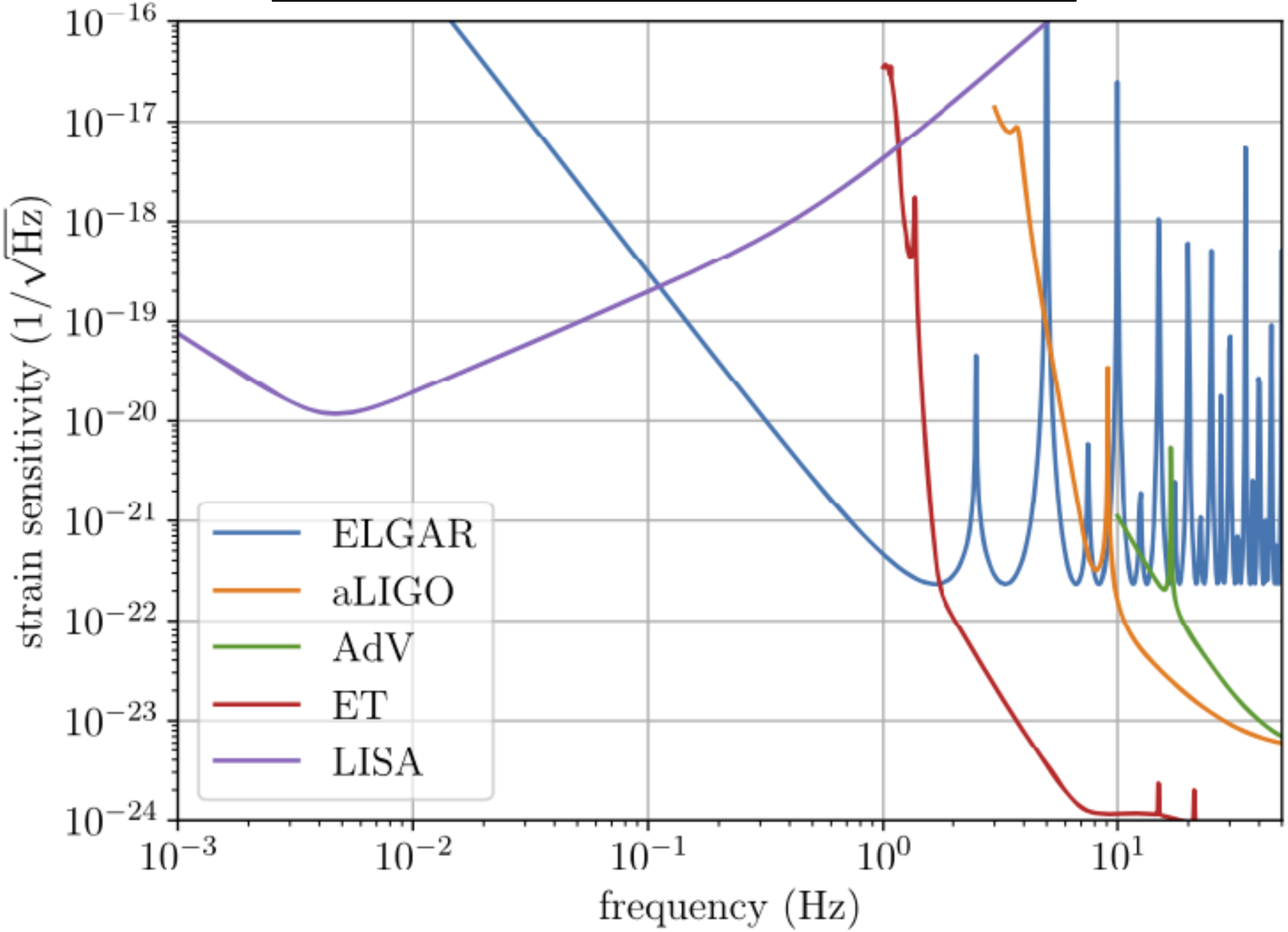
Design for the ELGAR Atom Interferometer





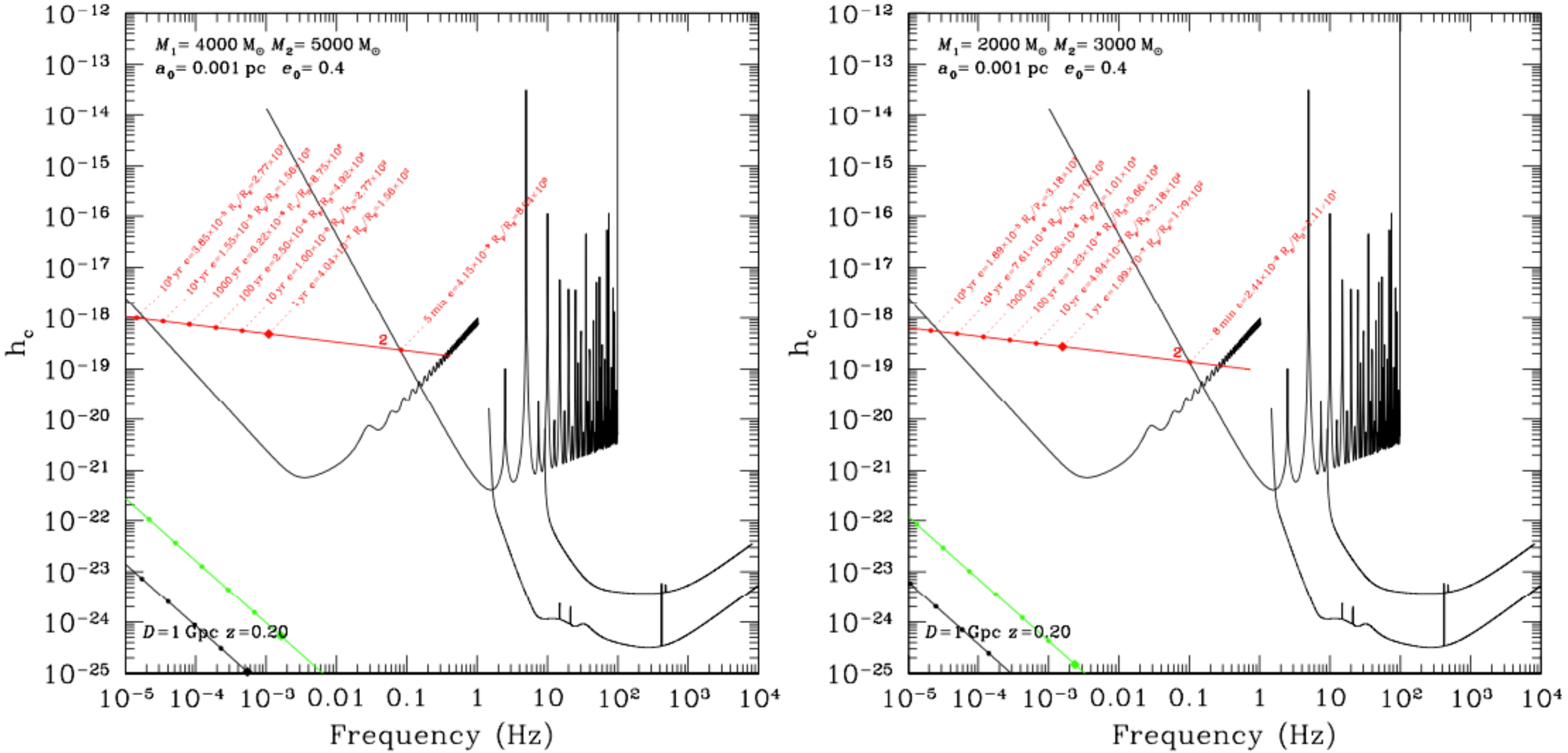
Prospects for the ELGAR Atom Interferometer

Sensitivity to gravitational waves



Prospects for the ELGAR Atom Interferometer

Sensitivity to Intermediate-Mass Black-Hole mergers



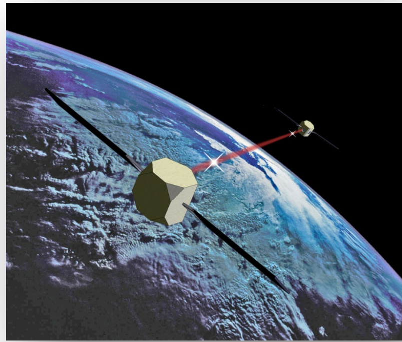
ESA Voyage 2050

“Après-LISA”

Some of the Cold Atom White Papers submitted to ESA in response to its call for input to the Voyage 2050 long-term plan for the ESA Science Programme.

AEDGE:
Atomic Experiment for Dark Matter and Gravity Exploration in Space

Beyond LISA



Yousef Abou El-Neaj,[1] Cristiano Alpigiani,[2] Sana Amairi-Pyka,[3] Henrique Araújo,[4] Antun Balaž,[5] Angelo Bassi,[6] Lars Bathe-Peters,[7] Baptiste Battelier,[8] Aleksandar Belić,[5] Elliot Bentine,[9] José Bernabeu,[10] Andrea Bertoldi,[8,*] Robert Bingham,[11] Diego Blas,[12] Vasiliki Bolpasi,[13] Kai Bongs,[14,*] Sougato Bose,[15] Philippe Bouyer,[8,*] Themis Bowcock,[16] William Bowden,[17] Oliver Buchmueller,[4,@] Clare Burrage,[18] Xavier Calmet,[19] Benjamin Canuel,[8,*] Laurentiu-Ioan Caramete,[20,*] Andrew Carroll,[16] Giancarlo Cella,[21,22] Vassilis Charmandaris,[23] Swapan Chattopadhyay,[24,25] Xuzong Chen,[26] Maria Luisa Chiofalo,[21,22] Jonathon Coleman,[16,*] Joseph Cotter,[4] Yanou Cui,[27] Andrei Derevianko,[28] Albert De Roeck,[29,30,*] Goran Djordjevic,[31] Peter Dornan,[4] Michael Doser,[30] Ioannis Drougkakis,[13] Jacob Dunningham,[19] Ioana Dutan,[20] Sajan Easo,[11] Gedminas Elertas,[16] John Ellis,[12,32,33,*] Mai El Sawy,[34] Farida Fassi,[35] Daniel Felea,[20] Chen-Hao Feng,[8] Robert Flack,[15] Chris Foot,[9] Ivette Fuentes,[18] Naceur Gaaloul,[36] Alexandre Gauguet,[37] Remi Geiger,[38] Valerie Gibson,[39] Gian Giudice,[33] Jon Goldwin,[14] Oleg Grachov,[40] Peter W. Graham,[41,*] Dario Grasso,[21,22] Maurits van der Grinten,[11] Mustafa Gündogan,[3] Martin G. Haehnelt,[42,*] Tiffany Harte,[39] Aurélien Hees,[38,*] Richard Hobson,[17] Bodil Holst,[43] Jason Hogan,[41,*] Mark Kasevich,[41] Bradley J. Kavanagh,[44] Wolf von Klitzing,[13,*] Tim Kovachy,[45] Benjamin Krikler,[46] Markus Krutzik,[3,*] Marek Lewicki,[12,47,*] Yu-Hung Lien,[15] Miaoyuan Liu,[26] Giuseppe Gaetano Luciano,[48] Alain Magnon,[49] Mohammed Mahmoud,[50] Sarah Malik,[4] Christopher McCabe,[12,*] Jeremiah Mitchell,[24] Julia Pahl,[3] Debapriya Pal,[13] Saurabh Pandey,[13] Dimitris Papazoglou,[51] Mauro Paternostro,[52] Bjoern Penning,[53] Achim Peters,[3,*] Marco Prevedelli,[54] Vishnupriya Puthiya-Veettil,[55] John Quenby,[4] Ernst Rasel,[36,*] Sean Ravenhall,[9] Haifa Rejeb Sfar,[29] Jack Ringwood,[16] Albert Roura,[56,*] Dylan Sabulsky,[8,*] Muhammed Sameed,[57] Ben Sauer,[4] Stefan Alaric Schäffer,[58] Stephan Schiller,[59,*] Vladimir Schkolnik,[3] Dennis Schlippert,[36] Christian Schubert,[3,*] Armin Shayeghi,[60] Ian Shipsey,[9] Carla Signorini,[21,22] Marcelle Soares-Santos,[53] Fiodor Sorrentino,[61,*] Yajpal Singh,[14,*] Timothy Sumner,[4] Konstantinos Tassis,[13] Silvia Tentindo,[62] Guglielmo Maria Tino,[63,64,*] Jonathan N. Tinsley,[63] James Unwin,[65] Tristan Valenzuela,[11] Georgios Vasilakis,[13] Ville Vaskonen,[12,32,*] Christian Vogt,[66] Alex Webber-Date,[16] André Wenzlawski,[67] Patrick Windpassinger,[67] Marian Woltmann,[66] Michael Holynski,[14] Efe Yazgan,[68] Ming-Sheng Zhan,[69,*] Xinhao Zou,[8] Jure Zupan[70]

White paper submitted to ESA Voyage 2050 Call

Abou El-Neaj, …, JE et al: arXiv:1908.00802

AEDGE: Abou El-Neaj, ..., JE et al: arXiv:1908.00802

Conceptual Design of Experiment

Two satellites in Medium Earth Orbit

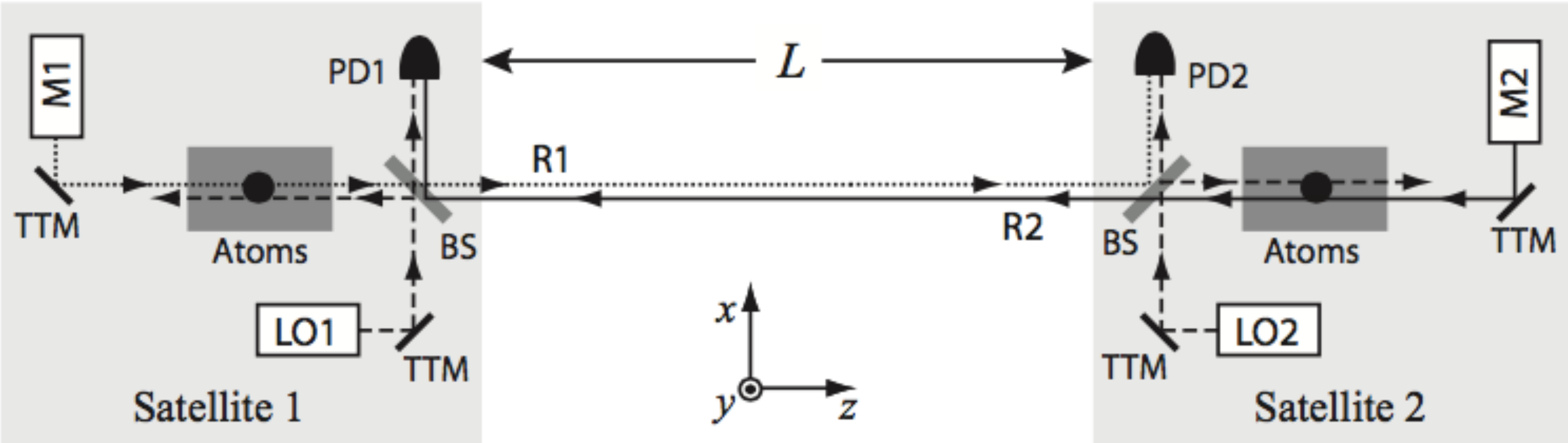
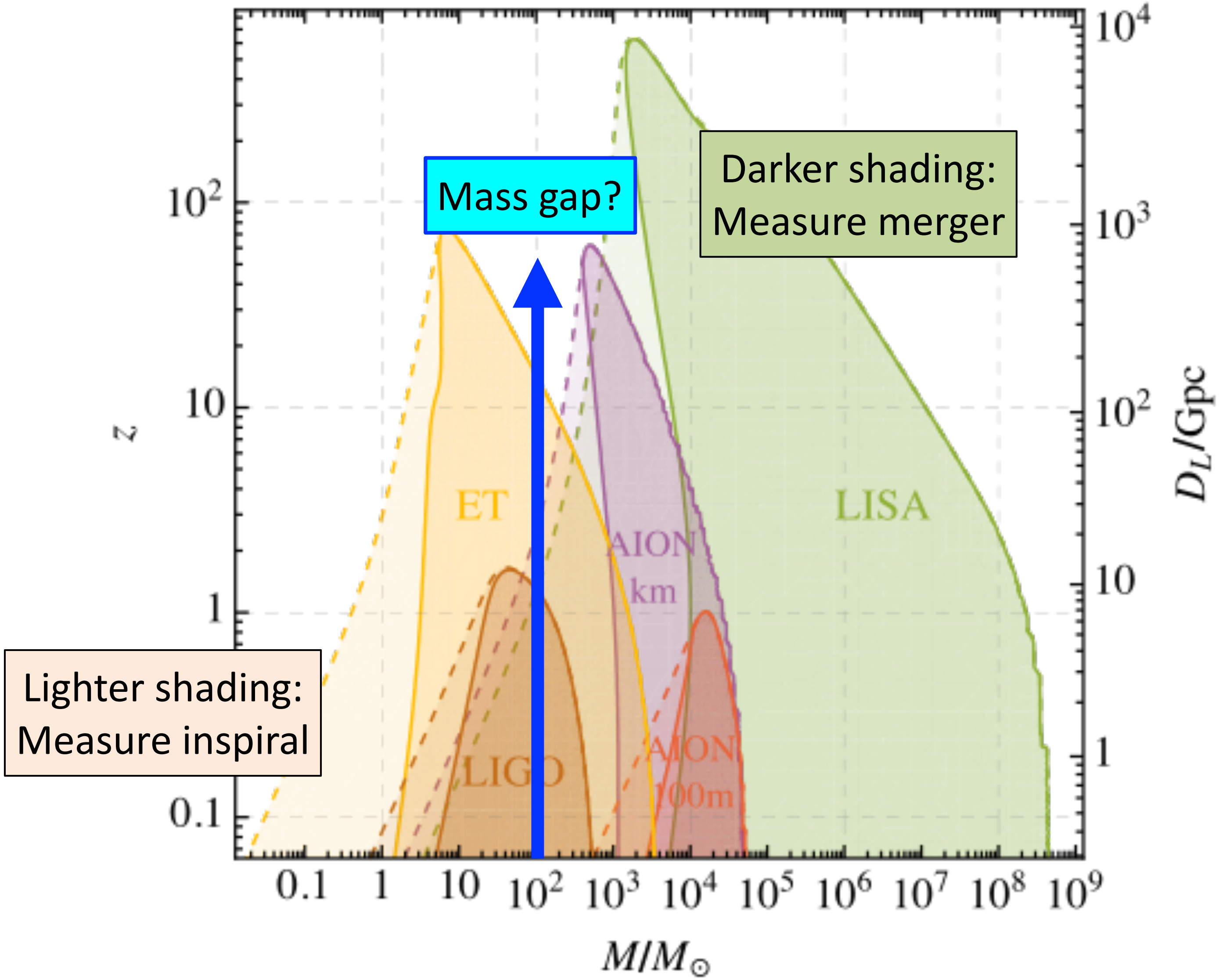


Table 1. List of basic parameters of strontium atom interferometer designs for AEDGE and a benchmark 1-km terrestrial experiment using similar technologies: length of the detector L; interrogation time of the atom interferometer $T_{\rm int}$; phase noise $\delta\phi_{\rm noise}$; and the total number of pulses $n_p^{\rm max}$, where n is the large momentum transfer (LMT) enhancement and Q the resonant enhancement. The choices of these parameters predominately define the sensitivity of the projection scenarios[45].

Sensitivity Scenario	L [m]	$T_{\rm int}$ [sec]	$\delta\phi_{\rm noise}$ $[1/\sqrt{\rm Hz}]$	$n_p^{\rm max} = 2Q(2n-1)+1$ [number]
Earth-km	2000	5	0.3×10^{-5}	40000
AEDGE	4.4×10^7	300	10^{-5}	1000

AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755

GWs from IMBH Mergers: SNR = 8

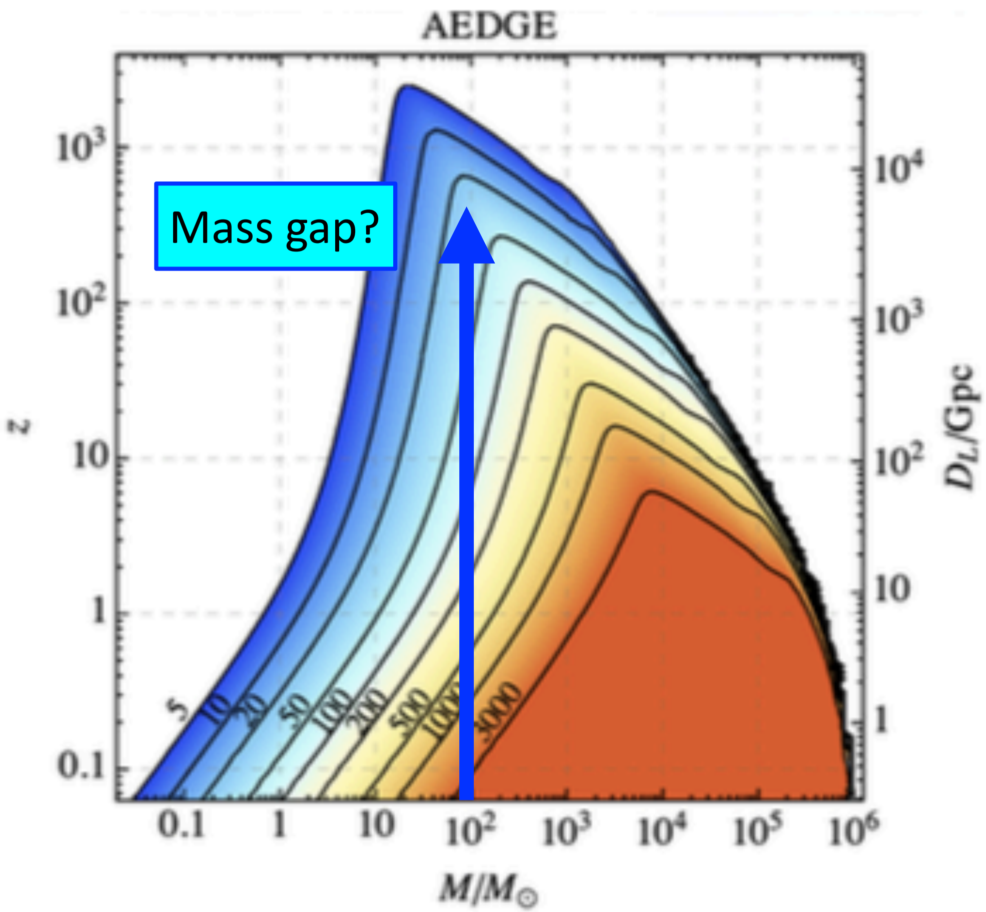


AION complementary to LIGO, Einstein Telescope (ET)

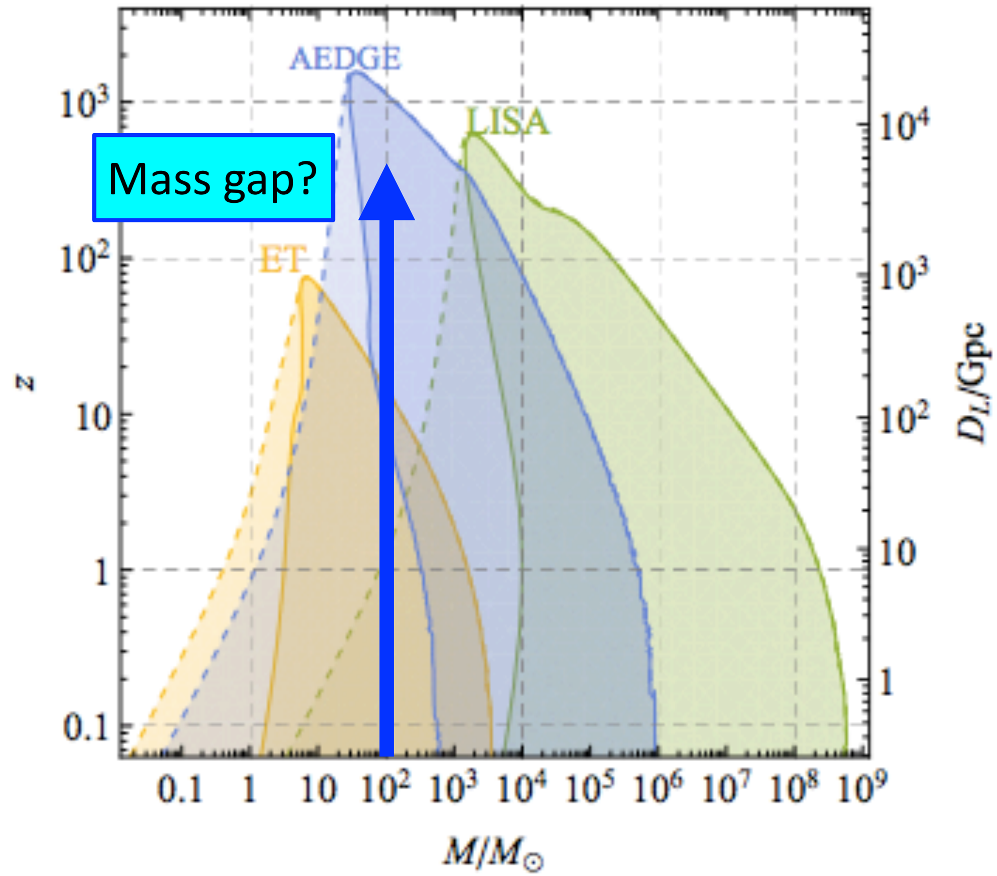
Operation before LISA

AEDGE: Abou El-Neaj, …, JE et al: arXiv:1908.00802

Gravitational Waves from IMBHs



Detect mergers of ~ 10^4 solar-mass BHs
with SNR 1000 out to z ~ 10,
Mergers of ~ 10^3 solar-mass BHs
with SNR 100 out to z ~ 100

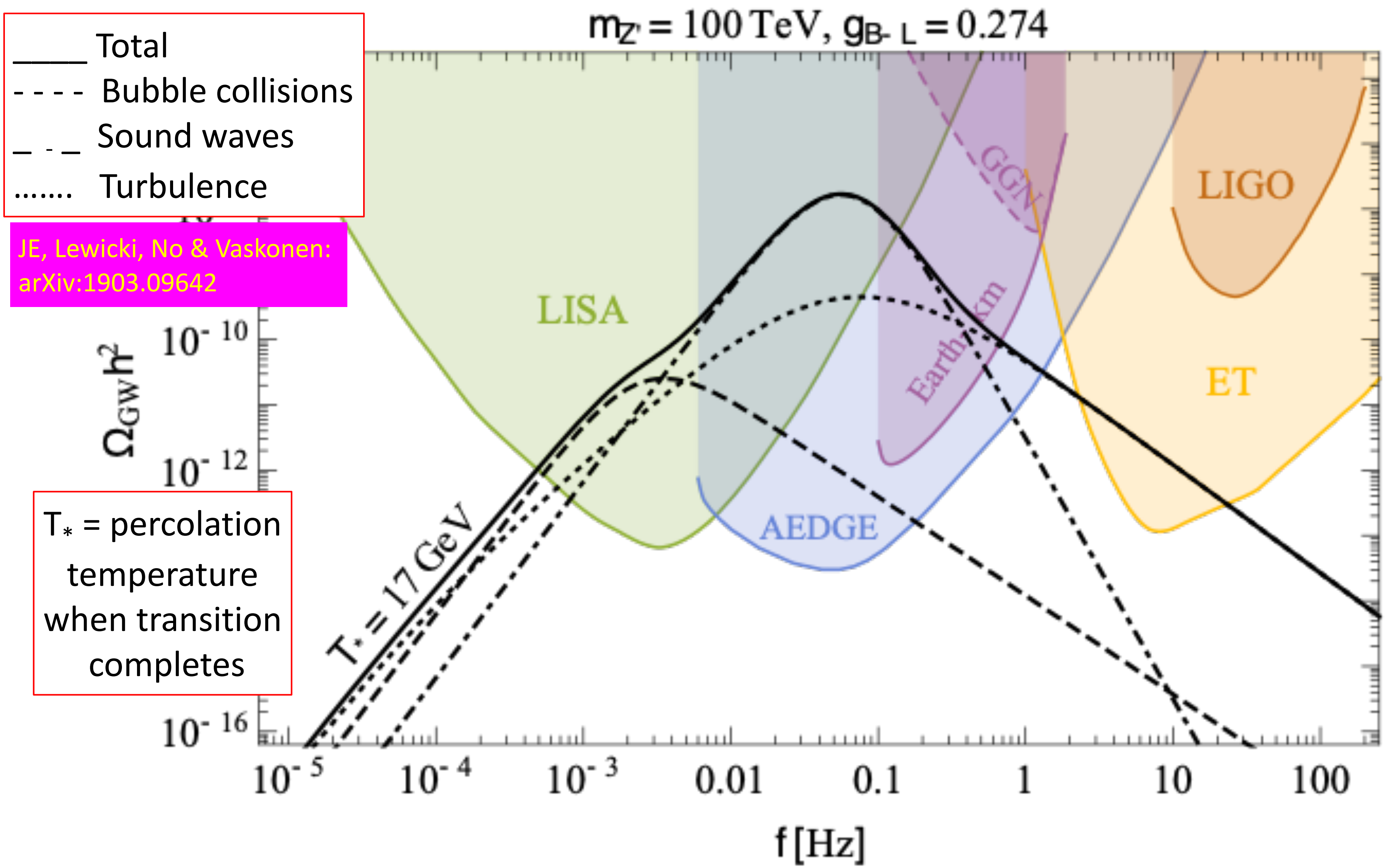


Lighter shades: inspiral
Darker shades: merger + ringdown
Complementarity + synergy

GWs from a First-Order Phase Transition

- Transition by percolation of bubbles of new vacuum
- Bubbles grow and collide
- Possible sources of GWs:
  - Bubble collisions
  - Turbulence and sound waves in plasma
- Models studied:
  - Standard Model + H^6/Λ^2 interaction
  - Standard Model + $U(1)_{B-L}$ Z'
- These also have prospective collider signatures

Gravitational Waves from $U(1)_{B-L}$ Phase Transition

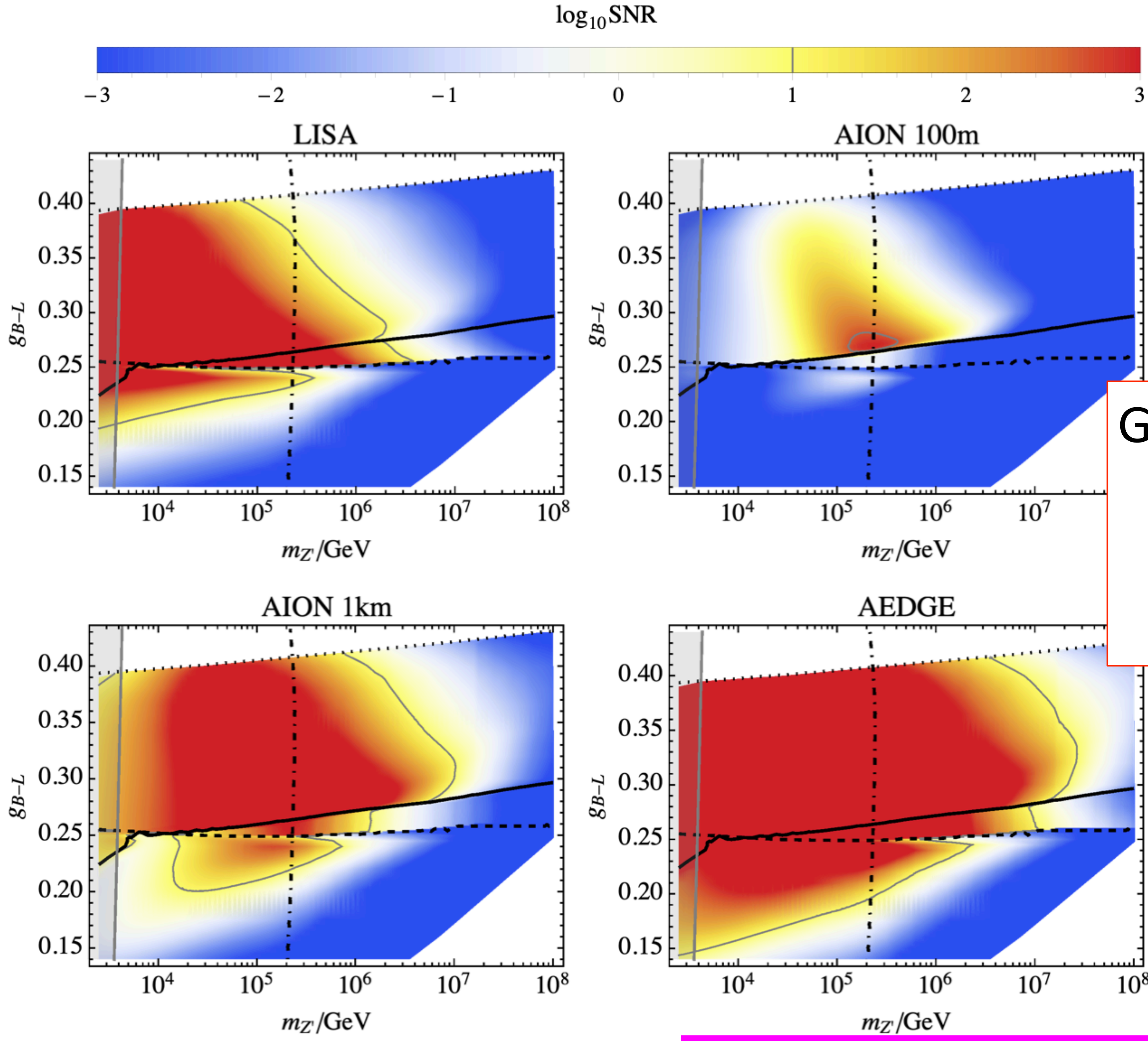


JE, Lewicki, No & Vaskonen: arXiv:1903.09642

T_* = percolation temperature when transition completes

AEDGE: Bertoldi, …, JE et al: arXiv:1908.00802

Sensitivities to $U(1)_{B-L}$ Z'



GW discovery sensitivity far beyond colliders

JE, Lewicki & Vaskonen, arXiv:2007.15586

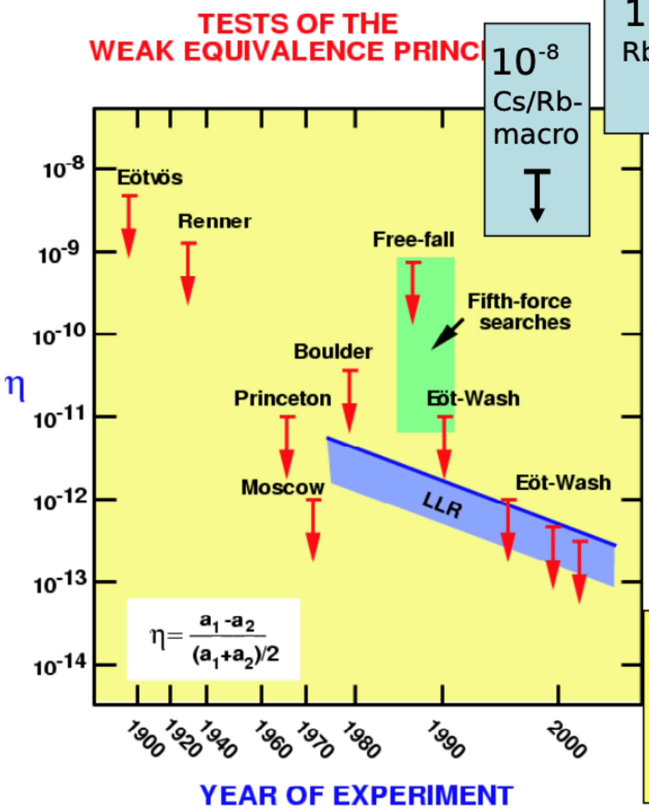
Tests of the Weak Equivalence Principle

10^{-3}
n-macro
COW
1975

10^{-2}
H–Hbar
CERN
2016+

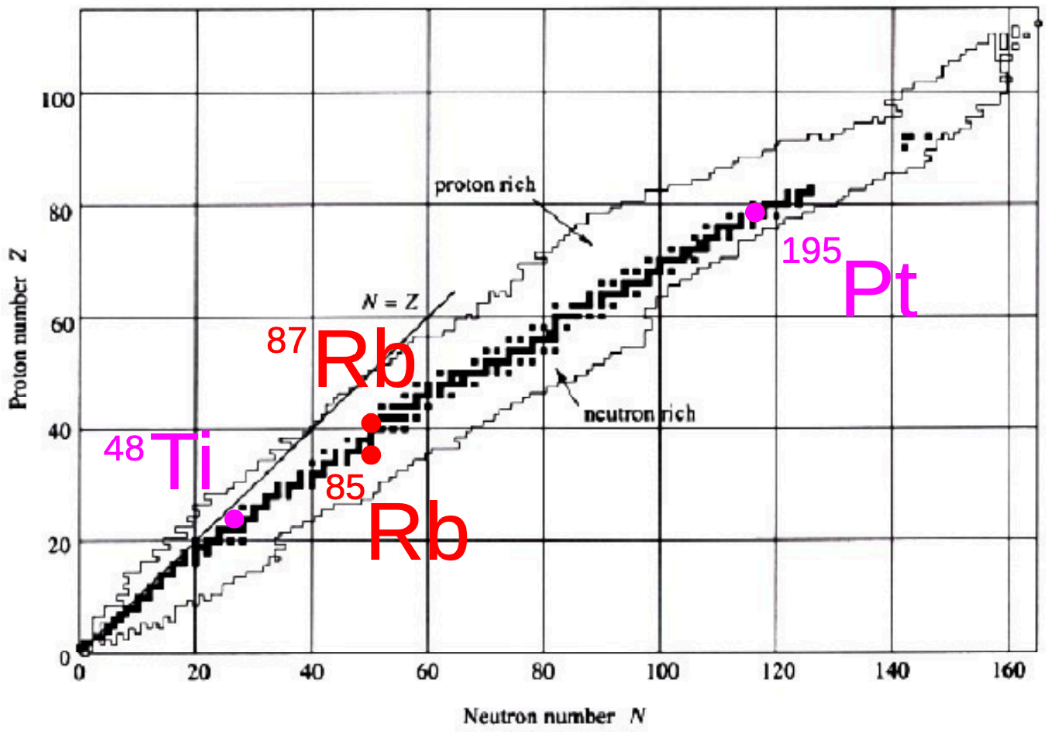
10^{-8}
Cs/Rb-
macro

10^{-7}
Rb–Rb
2004

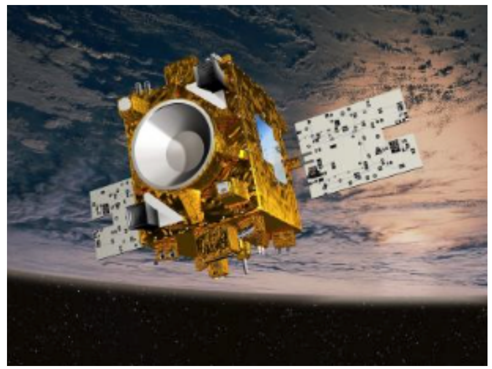


2016
10^{-15}
μ-SCOPE

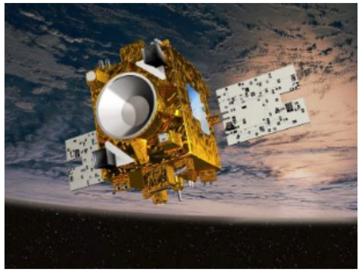
2024
10^{-15}
Rb–Rb
STE-QUEST



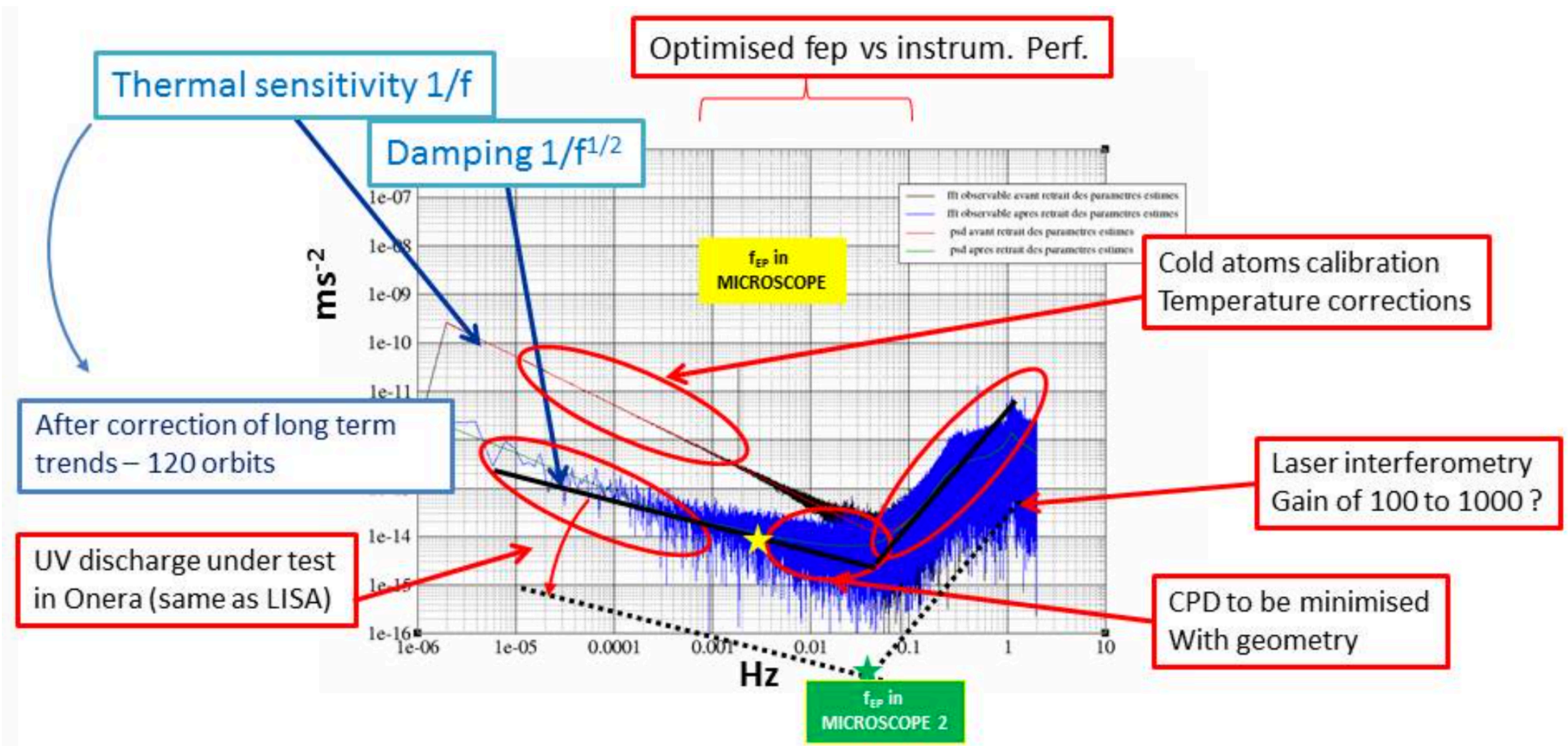
From
Microscope
to
STE-QUEST



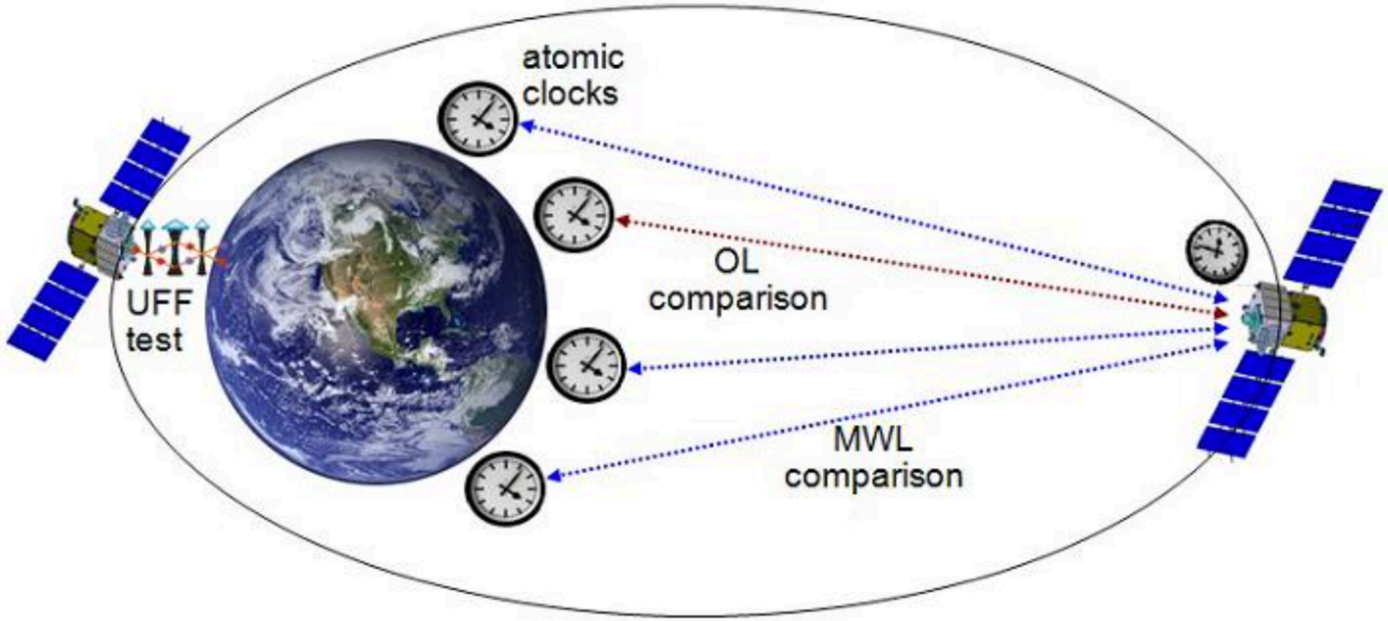
Tests of the Weak Equivalence Principle



Class	Elements	η	Year [ref]	Comments
Classical	Be - Ti	2×10^{-13}	2008 [57]	Torsion balance
	Pt - Ti	1×10^{-14}	2017 [1]	MICROSCOPE first results
	Pt - Ti	(10^{-15})	2019+	MICROSCOPE full data
	$M_A - M_B$	10^{-17}	2035+	Adv. MICROSCOPE, macrsocopic masses M_i TBD
Hybrid	^{133}Cs - CC	7×10^{-9}	2001 [59]	AI and macroscopic corner cube (CC)
	^{87}Rb - CC	7×10^{-9}	2010 [60]	
	$At_A - M_B$	10^{-17}	2035+	Adv. MICROSCOPE, atomic species At_A TBD
Quantum	^{39}K - ^{87}Rb	5×10^{-7}	2014 [61]	different elements
	^{87}Sr - ^{88}Sr	2×10^{-7}	2014 [62]	same element, fermion vs. boson
	^{85}Rb - ^{87}Rb	3×10^{-8}	2015 [63]	same element, different isotopes
	^{85}Rb - ^{87}Rb	(10^{-13})	2020+ [64]	$\geq$ 10 m towers
	^{170}Yb - ^{87}Rb	(10^{-13})	2020+ [65]	
	^{41}K - ^{87}Rb	10^{-17}	2035+	Atom Interferometry mission
Antimatter	$\overline{\text{H}}$ - H	(10^{-2})	2020+ [66, 67]	under construction at CERN

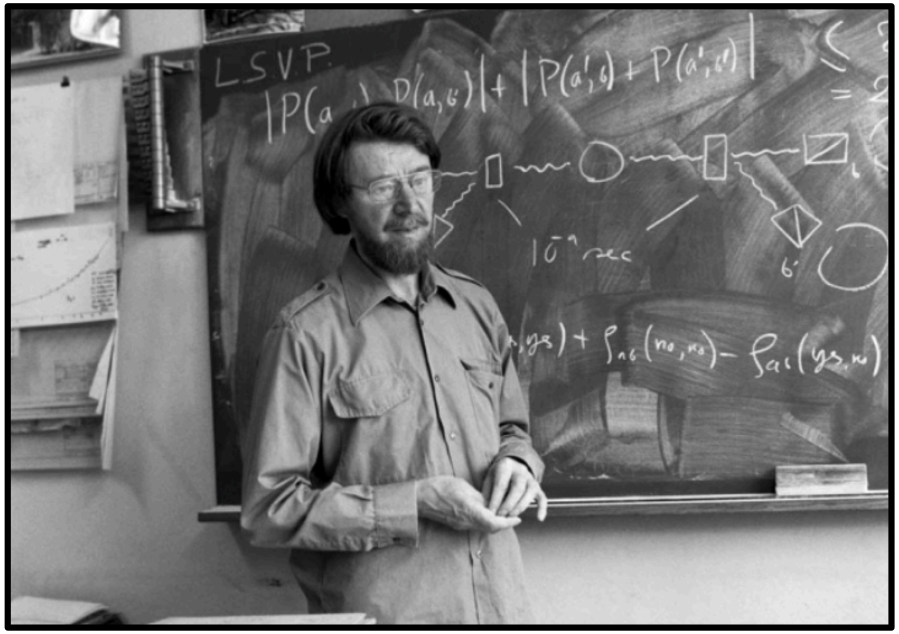


Proposed Space Mission: STE-QUEST



Science Investigation	Measurement Requirement
Weak Equivalence Principle Tests	
Universality of propagation of matter-waves	Test the universality of the free propagation of matter waves to an uncertainty in the Eötvös parameter better than 2×10^{-15}.
Gravitational Red-shift Tests	
Sun gravitational red-shift	Test of the Sun gravitational red-shift effect to a fractional frequency uncertainty of 2×10^{-6}, with an ultimate goal of 5×10^{-7}.
Moon gravitational red-shift	Test of the Moon gravitational red-shift effect to a fractional frequency uncertainty of 4×10^{-4}, with an ultimate goal of 9×10^{-5}.
Earth gravitational red-shift (optional)[a]	Measurement of the Earth gravitational red-shift effect to a fractional frequency uncertainty of 2×10^{-7}.
Local Lorentz Invariance and CPT Tests	
LLI and CPT	Provide significant improvements on the determination of several LLI and CPT parameters of the Lorentz and CPT symmetry violating Standard Model Extension.

Quantum Prophet



- John Bell: CERN 1960/90
- Particle/accelerator physics
- Quantum physics foundations: Bell inequalities
  - "Spooky action at a distance"
- Long-range correlations > classical physics
  - Verified in laboratory experiments (Aspect et al.)
- Destruction if somebody eavesdrops
  - Applications in quantum cryptography, …

"Quantum engineering" to "Quantum cosmology" to "Quantum finance"?

Long-Distance Correlations

- Observed between Geneva & CERN

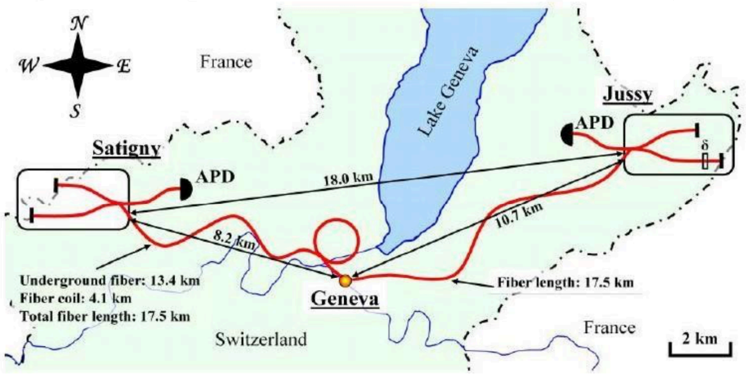
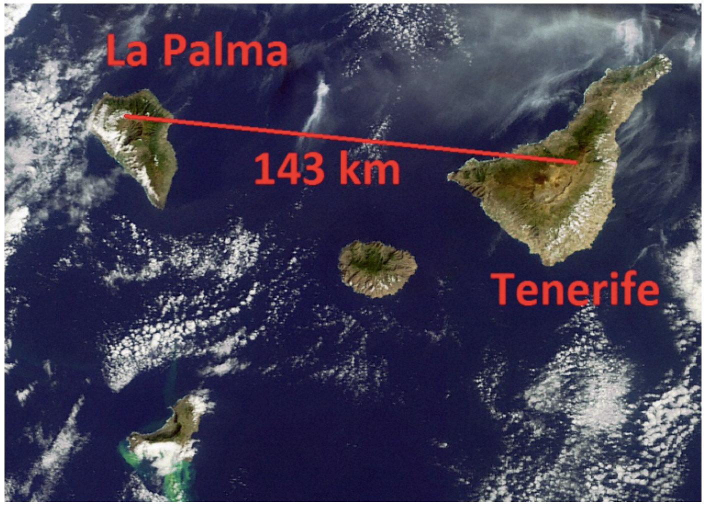
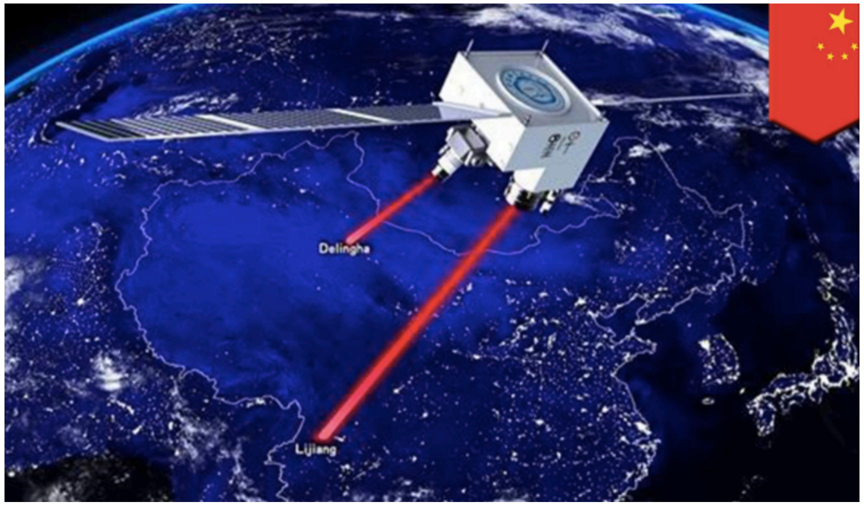


Illustration 1.: Salart et al (2008) Bell-type correlation experiment

- Between Canary Islands > 100km, Chinese satellite > 1000km





- Next step: between Earth & Moon? Correlation > 10^7c

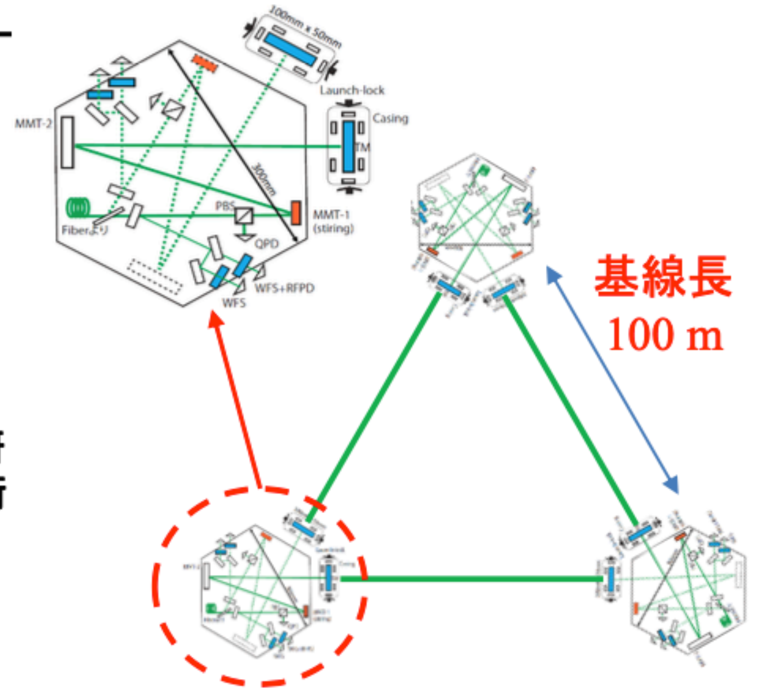
共通様式

フォーメーションフライト(FF)技術の研究
最終報告書

ISAS事業計画No,	研究代表者(所属)	費用(概算でもOK)
3-2-1(例)事務局記入	河野 功 JAXA	10000千円

研究成果のハイライト

・研究目的・GOAL:複数の宇宙機が相互の位置関係を保って飛行するフォーメーションフライト(FF、編隊飛行)技術につき、公募型小型計画ミッション等による技術実証を遂行。
・具体的な成果: FF技術の内、重力波望遠鏡等の宇宙干渉計の実現に必要な超精密FF技術につき、軌道上実証計画を立案、実証システムの概念設計を進め、公募型小型計画ミッション等に採用され、プロジェクト化される事。
・今年度の研究成果:2019年度公募型小型計画に超精密FF技術実証機SILVIA (Space Interferometer Laboratory Voyaging towards Innovative Applications)を提案し、2020年度9月にPre-phase A1b へのPhase upが認められた。これを受け、下半期に、SILVIAのPre-phase A1b、Pre-phase A2の研究スキームの策定、3衛星の展開や捕捉シーケンス等運用シナリオの検討、衛星システムの概念設計、超精密FF制御系と制御アルゴリズムの概念検討、FFシミュレータの検討、ミッション機器のハードウェア技術検討等、技術的実現性確認作業を実施。
・次年度以降の研究計画:SILVIAのPre-phase A1b活動を継続し、開発スキームの目途付けを行い、CML3、TRL3を達成し、Pre-phase A2活動に進む。

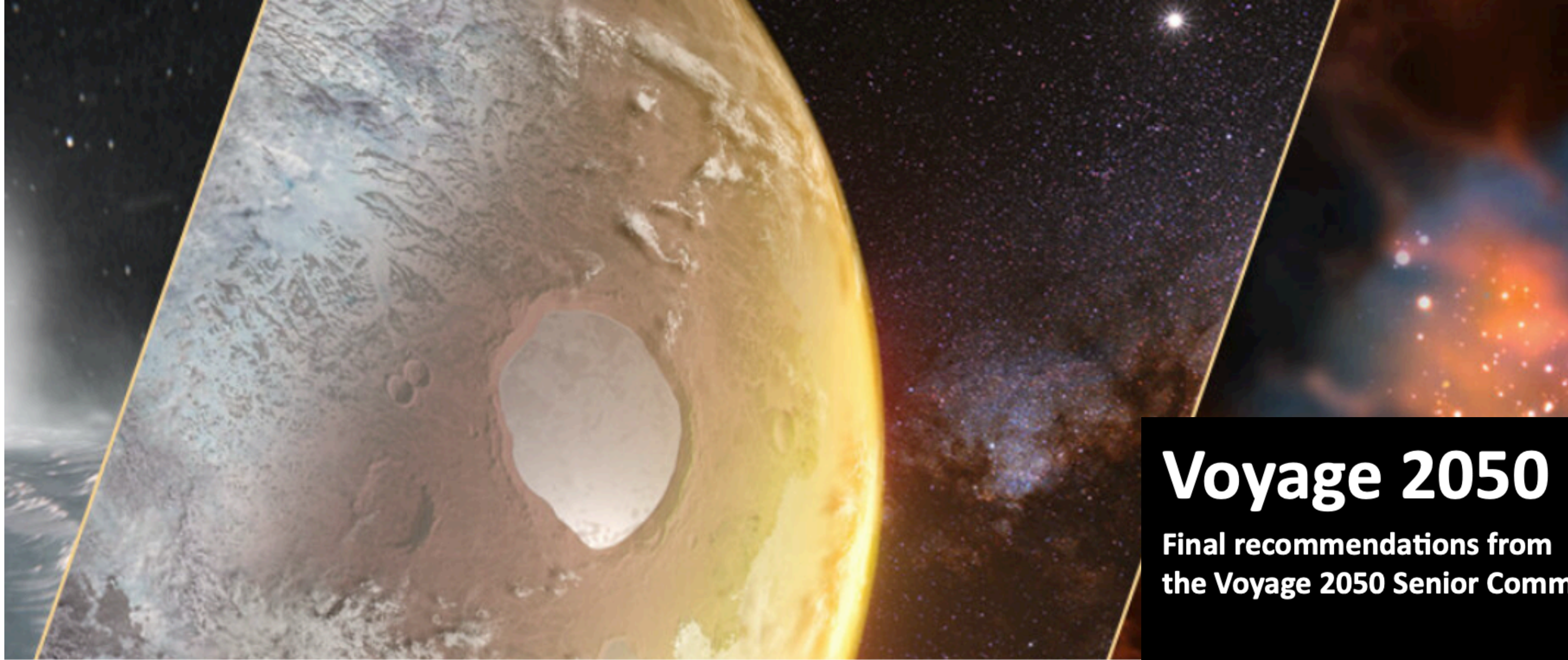


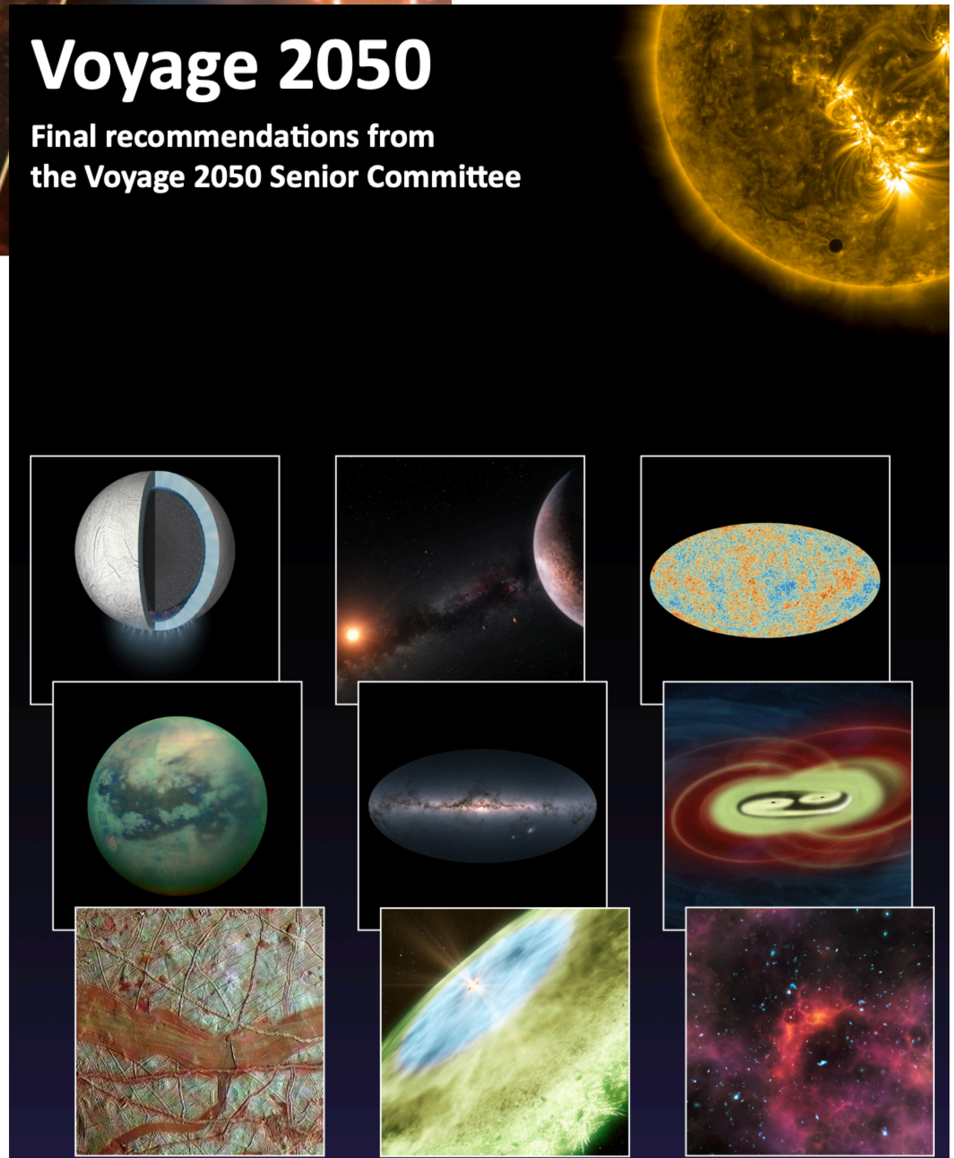
SILVIA衛星の3機フォーメーションのイメージ

成果の社会的意義・価値	成果創出に至る取組・克服状況
「宇宙科学技術ロードマップ」(次ページ)が宇宙科学ミッションとして挙げている「重力波干渉計(望遠鏡)」「赤外線干渉計」等の実現に不可欠な「編隊飛行」(FF:フォーメーションフライト)技術の軌道上実証を行い、技術修得を行うための研究である。	SILVIAを公募型小型計画に提案して、Pre-phase A1b へのPhase upが認められたのを受け、理学者と工学者が緊密に連携してミッション機器との協調制御による超精密FF技術の実現性検討、限られた資金で衛星3機を開発するための開発スキームの検討を重点的に行っている。

上記研究成果に関するエビデンス(査読付き論文、学会発表等)

宇宙科学技術連合講演会(FF WGでオーガナイズドセッションを開催)、DECIGOワークショップなどでFF研究にかかる発表を行った。理学者と工学者が連携してSILVIAを公募型小型計画に提案しPre-phase A1b へのPhase upが認められた。





SCIENCE & EXPLORATION

Voyage 2050 sets sail: ESA chooses future science mission themes

ESA Voyage 2050 Programme

In 2018, the ESA Director of Science established a Senior Committee to identify

- Next three Large missions following JUICE, ATHENA and LISA.
- Possible science themes that could be addressed through Medium missions
- Long-term technology development for ESA Space Science missions beyond Voyage 2050

Large missions:

- Moons of the Giant Planets
- Exoplanets
- New Physical Probes of the Early Universe. Fundamental physics and astrophysics, deploying gravitational wave detectors or precision microwave spectrometers to explore the early Universe at large redshifts.

Possible Medium missions:

- Magnetospheres, plasmas, solar magnetic field & particle acceleration, solar poles, Venus, astrometry, astrospectrometry, ISM, accretion, mapping structure, IGM, QM & GR (cold atoms?)

Possible contributions to international missions:

- Ice giants, NASA observatories, interstellar probe, origins of solar system

Technology development recommendations ->

Technology Development

Cold Atom Interferometry

- must reach TRL 5 or 6, be superior to classical technologies
- start with atomic clocks
- choose single species: recommend strontium
- clock on free-flyer or ISS?
- M-mission with science goals similar to STE-QUEST?
- for gravitational wave detectors in new wavebands …, detectors for dark matter candidates, sensitive clock tests of general relativity, tests of wave function collapse ….

(Also X-rays, technologies for solar system exploration, …)

Comments of ESA Executive

Cold atom interferometry

- … was one of the themes identified in the “Call for new scientific ideas” issued by the Executive in 2016 …. This activity showed that the feasibility of a mission in this field is strictly driven by the lack of maturity of payloads in this area.
- Experiments in this field in laboratories in a number of countries have produced and continue to produce outstanding science results, with an impressive rate of progress. While this is of course a testimonial to the fertility and great promise of the field, it has for this reason proven to be difficult to identify experts that would invest the very significant amount of time and resources that would be necessary to mature and develop viable space payload starting from the very performing but very complex, and often fragile, laboratory experiments.
- The Executive plans nevertheless on the basis of this recommendation to consult again with the interested community, as well as with Member States, to define a possible concrete plan of action in this field.

"Per ardua ad astra"
(Onward and upward)

- We (Oliver Buchmueller, JE, …) are coordinating a two-fold community response

- A letter to ESA's Director of Science, Guenther Hasinger:

    - to raise awareness in ESA that the community is prepared to organise itself and to work actively with ESA as it shapes a roadmap for a Cold Atom technology in space development programme.

- A community workshop in September:

    - to formulate a roadmap for the development programme, which would provide input to ESA on how to structure it and what priorities could be established.

Please let me know of you want to co-sign and/or join the workshop