"The Big Picture"

- The **Big Issues** in fundamental physics

  in astrophysics and cosmology

- The **Big Issues** in Earth Observation

  monitoring climate change

- The **Big Issues** in metrology

  time and space

KING'S College LONDON

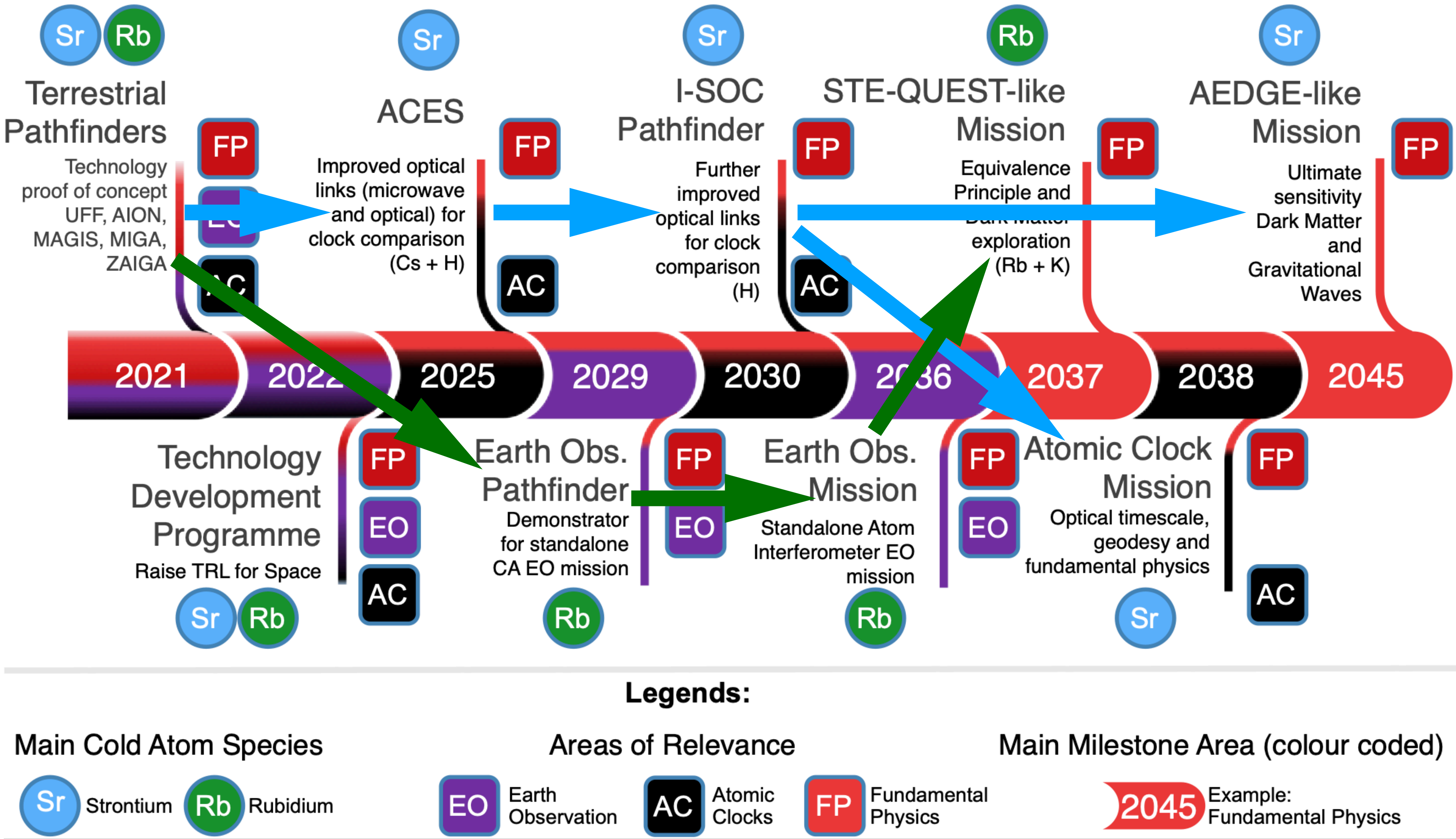
John Ellis

The Big Issues
in Fundamental Physics, Astrophysics & Cosmology

- Successful theories of gravity (general relativity) and quantum mechanics
- But no generally accepted combination
- Would need to modify theory of gravity or quantum mechanics or both
  - Modify gravity: **Violation of Equivalence Principle?**
  - Modify quantum mechanics: **Collapse of wave function?**
- Successful theory of visible matter in the Universe
  - Nature of **dark matter** (30% of density) and **dark energy** (69%)?

Alonso, …, Badurina, …, JE, …, McCabe et al, arXiv:2201.07789

Proposed ESA Road-Map for Cold Atoms in Space

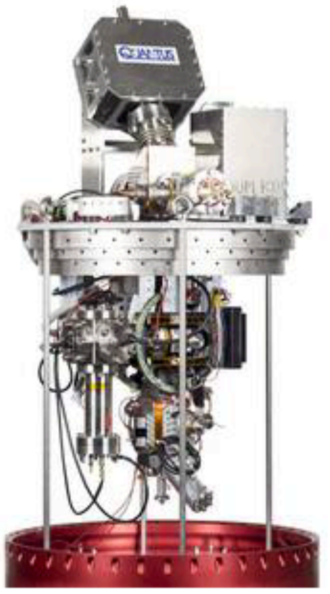


MAIUS Programme

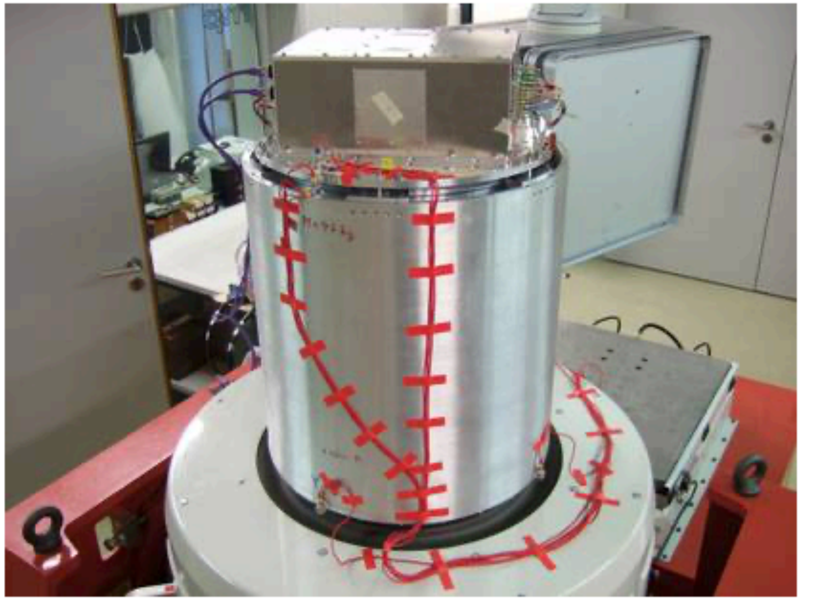
MAIUS-1 Physics Package

Launched in Jan. 2017

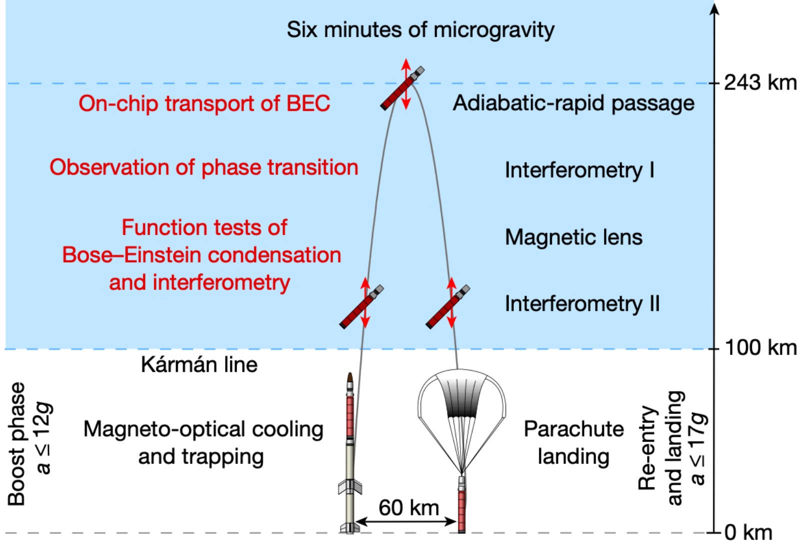
MAIUS-2 to follow in 2023



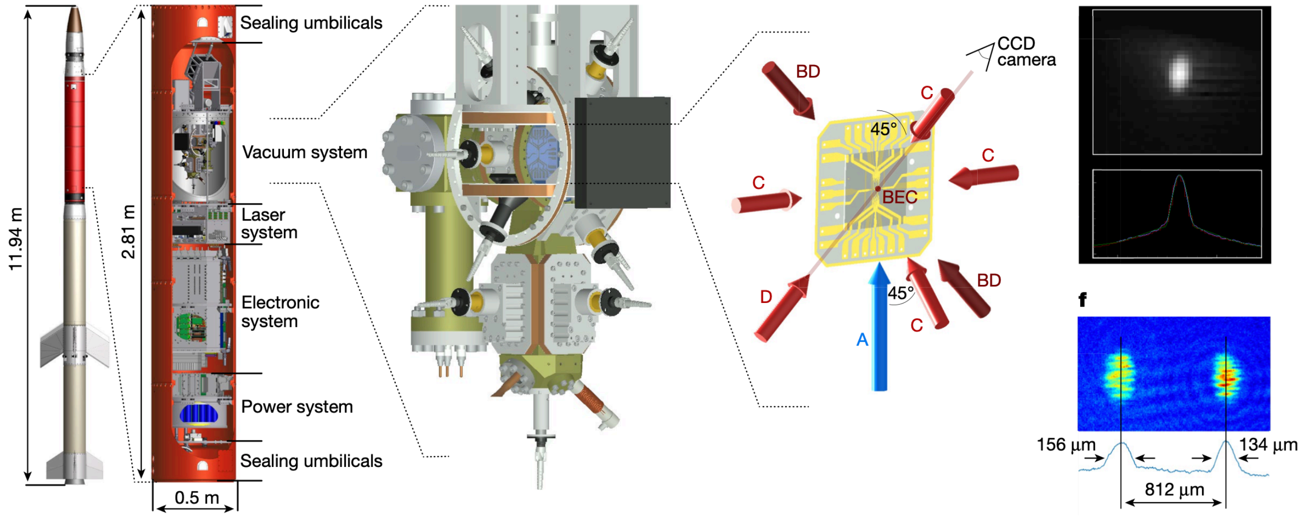
The MAIUS-1 physics package.



The MAIUS-1 laser system and electronics package during a vibrational test at the ZARM shaker facility.

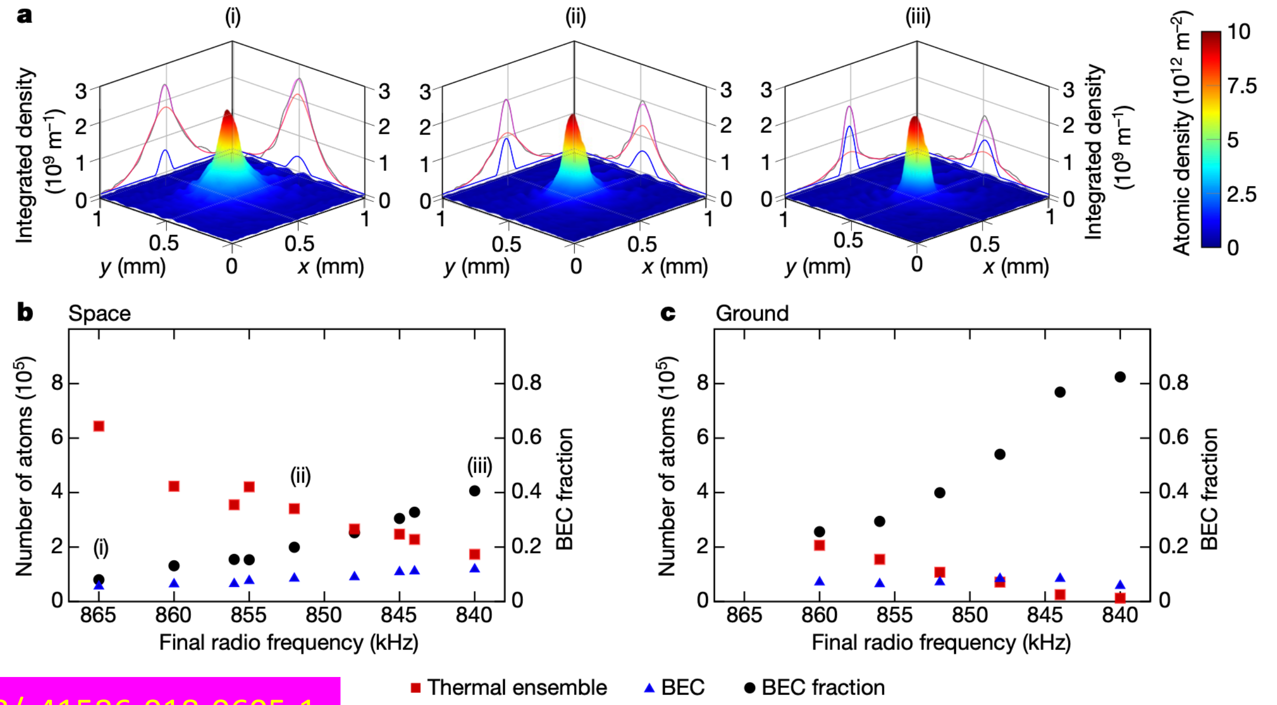


MAIUS-1



Bose-Einstein condensate on a chip

Atoms in BEC in space > on Earth

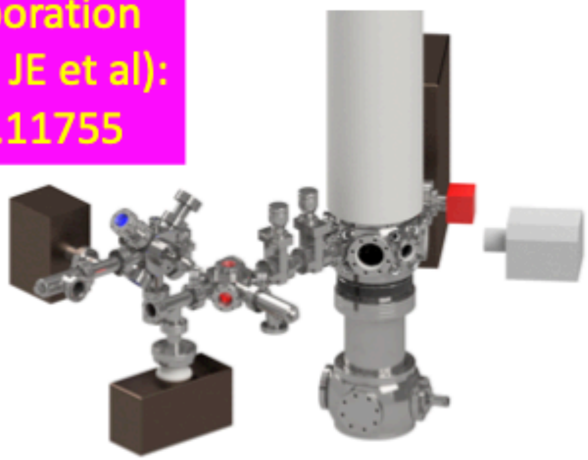


Becker et al, Nature, 2018, https://doi.org/10.1038/s41586-018-0605-1

Planned Site for AION 10m

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

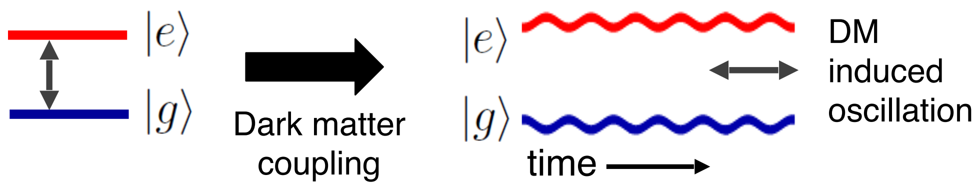
AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755

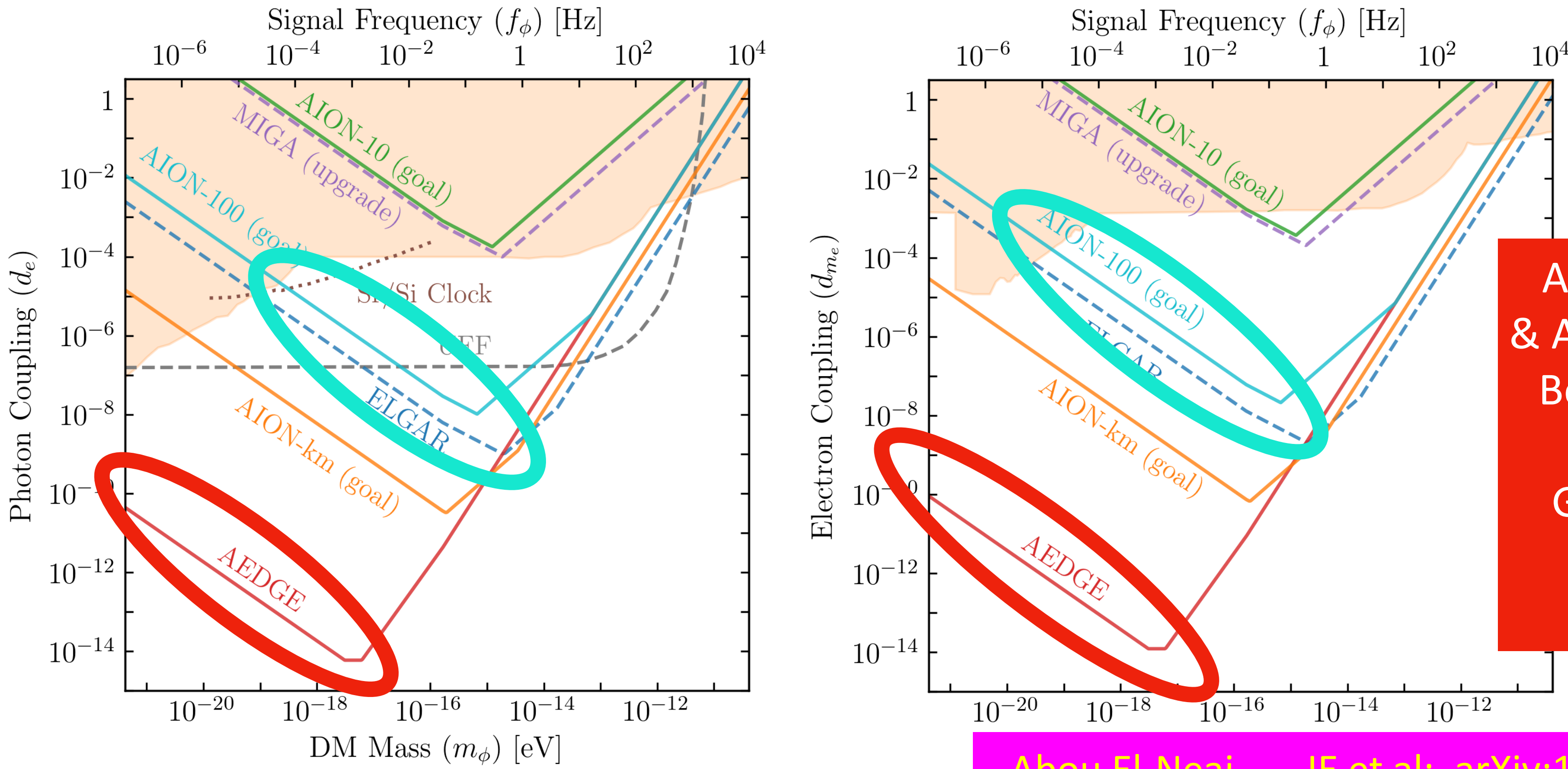


Searches for Ultralight Dark Matter

Linear couplings to gauge fields and matter fermions

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



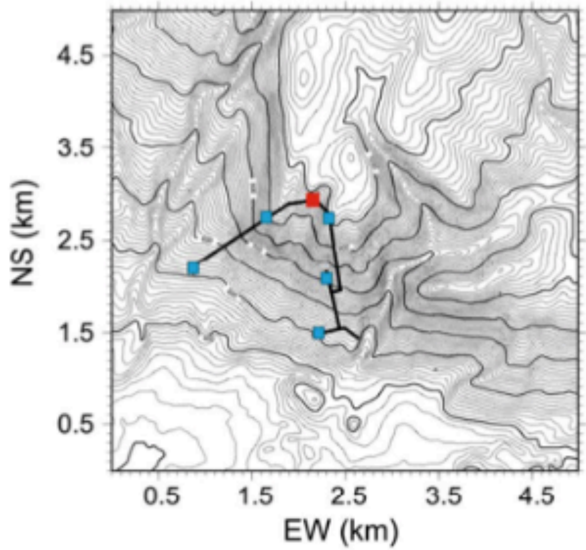


AION-100 & AION-1km: Beware of Gravity Gradient Noise (GGN)

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

The MIGA Large-Scale Atom Interferometer

Under construction in former nuclear bunker



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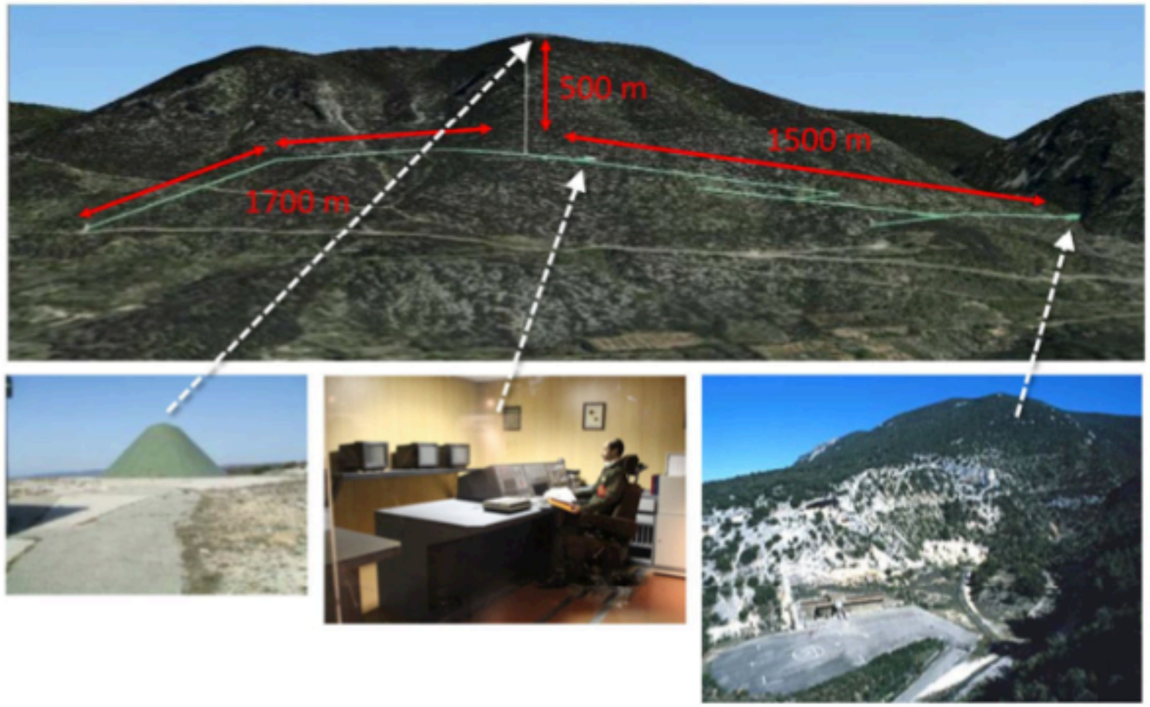
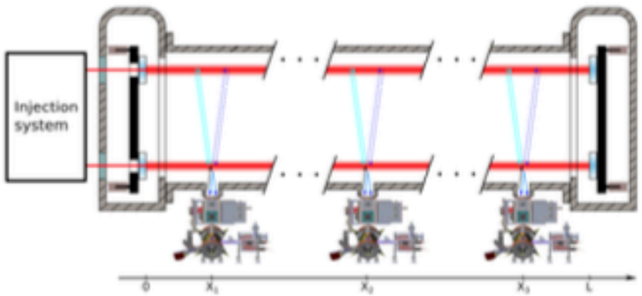


Atomic fountains illuminated by laser beams



ESA Call for M, F-Class Science Missions

call for missions 2021

esa

Call for missions 2021 » Home

- Home
- Briefing meeting
- Phase-1 proposal
- Workshop
- Phase-2 proposal
- Endorsement letters
- Q & A

CALL FOR A MEDIUM-SIZE AND A FAST MISSION OPPORTUNITY IN ESA'S SCIENCE PROGRAMME

Update 3 February 2022: A Q&A page has been added with answers to questions posed after the briefing meeting.

Update 13 January 2022: The presentation from the briefing meeting is available to download here (pdf).

Issue date: 13 December 2021

The ESA Director of Science solicits the scientific community in ESA's Member States for proposals for both a "Fast" mission opportunity (to be launched in the 2030-2031 timeframe) and for a Medium mission opportunity (to be launched around 2037).

The new long-term scientific plan Voyage 2050, for the Science Programme of the European Space Agency (ESA), has been issued in June 2021, following a broad consultation of the scientific community and a peer review process, with final recommendations issued by an independent scientific Senior Committee.

The plan includes three Large (L) missions in selected science themes (Moons of the Giant Planets, From Temperate Exoplanets to the Milky Way, and New Physical Probes of the Early Universe) and a set of Medium (M) and Fast (F) missions.

The definition of the F and M space missions is based on a competitive, peer-reviewed selection process. Even though the Voyage 2050 plan identifies a set of possible themes for the Medium missions, proposals in all fields of space science will be considered, with no prejudice.

DOCUMENTATION

Letter of Invitation from the Director of Science (pdf)

Call for a Medium-size and a Fast mission opportunity in ESA's Science Programme (pdf)

Technical Annex for this Call (pdf)

Voyage 2050 Senior Committee Report (pdf)

Added 13 January 2022:
Presentation from the briefing meeting

Added 3 February 2022:
Q & A page with answers to questions posed after the briefing meeting.

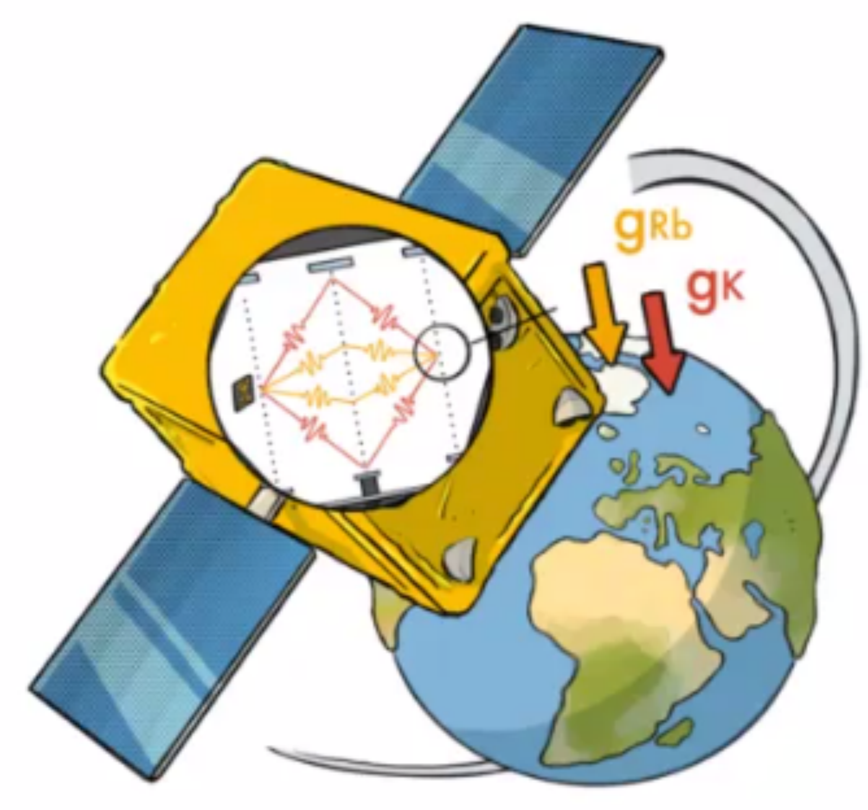
STE-QUEST Phase 1 Proposal

STE-QUEST
Space Time Explorer and QUantum Equivalence principle Space Test

A M-class mission proposal in response to the 2022 call in ESA's science program

Lead proposer: Peter Wolf
SYRTE, Observatoire de Paris-PSL, CNRS, Sorbonne Université, LNE
61 Av. de l'Observatoire, 75014 Paris, France
e-mail: peter.wolf@obspm.fr

February 15, 2022



Core Team:

- Angelo Bassi, Department of Physics, University of Trieste, and INFN - Trieste Section, *Italy*
- Kai Bongs, Midlands Ultracold Atom Research Centre, School of Physics and Astronomy University of Birmingham, *United Kingdom*
- Philippe Bouyer, LP2N, Université Bordeaux, IOGS, CNRS, Talence, *France*
- Claus Braxmaier, Institute of Microelectronics, Ulm University and Institute of Quantum Technologies, German Aerospace Center (DLR), *Germany*
- Oliver Buchmueller, High Energy Physics Group, Blackett Laboratory, Imperial College London, London, *United Kingdom*
- Maria Luisa (Marilu) Chiofalo, Physics Department "Enrico Fermi" University of Pisa, and INFN-Pisa *Italy*
- John Ellis, Physics Department, King's College London, *United Kingdom*
- Naceur Gaaloul, Institute of Quantum Optics, Leibniz University of Hanover, *Germany*
- Aurélien Hees, SYRTE, Observatoire de Paris-PSL, CNRS, Sorbonne Université, LNE, Paris, *France*
- Philippe Jetzer, Department of Physics, University of Zurich, *Switzerland*
- Steve Lecomte, Centre Suisse d'Electronique et de Microtechnique (CSEM), Neuchâtel, *Switzerland*
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- Thilo Schuldt, German Aerospace Center (DLR), Institute of Quantum Technologies, Ulm *Germany*
- Carlos F. Sopuerta, Institute of Space Sciences (ICE, CSIC), Institute of Space Studies of Catalonia (IEEC), *Spain*
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- Lisa Wörner, German Aerospace Center (DLR), Institute of Quantum Technologies, Ulm *Germany*
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Other contributors: Leonardo Badurina, Baptiste Battelier, Matteo Carlesso, Robin Corgier, Sandro Donadi, Gina Kleinsteinberg, Sina Loriani, Dennis Schlippert, Christian Schubert, Christian Struckmann, Jens Grosse, and the numerous colleagues who contributed to the past STE-QUEST proposals.

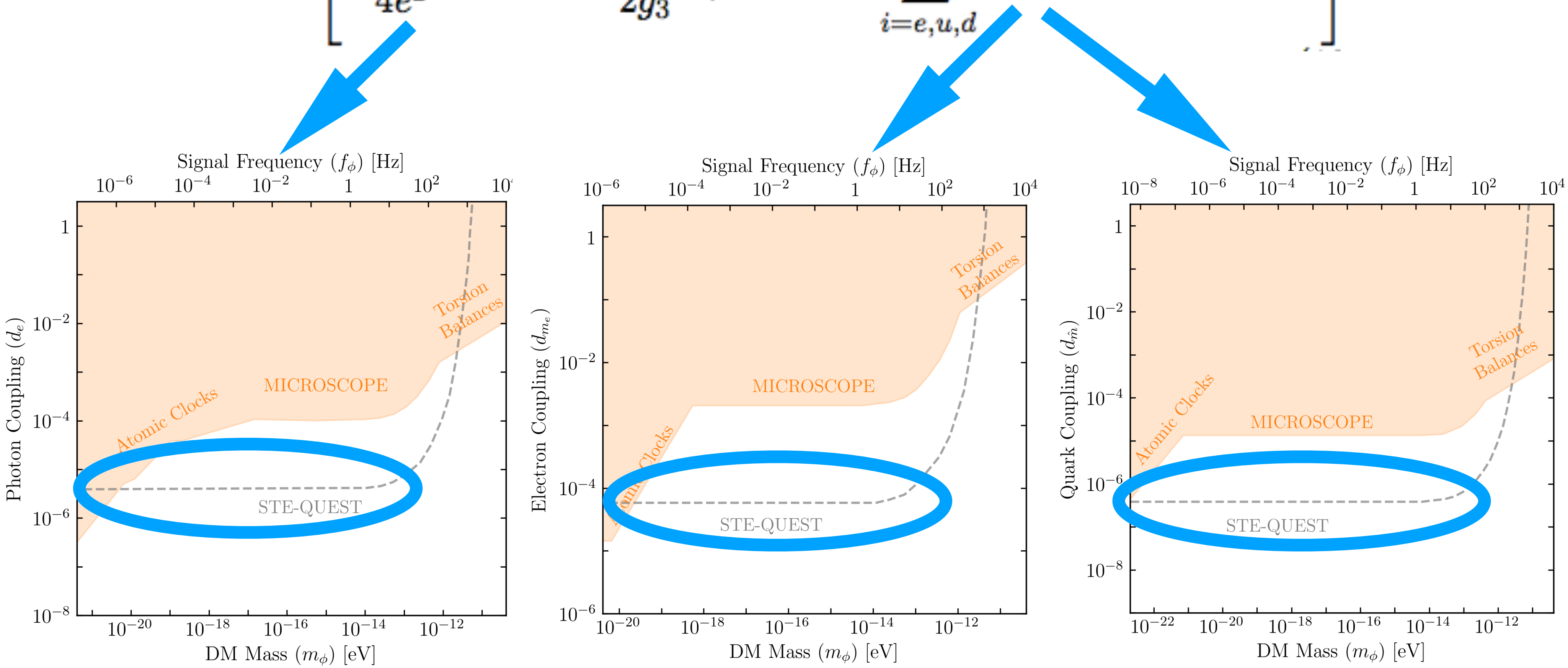
STE-QUEST Science:
Testing the Equivalence Principle

Class	Elements	η	Year [ref]	Comments
Classical	Be - Ti	2×10^{-13}	2008	Torsion balance
	Pt - Ti	1×10^{-14}	2017	MICROSCOPE first results
	Pt - Ti	(10^{-15})	2022+	MICROSCOPE full data
Hybrid	^{133}Cs - CC	7×10^{-9}	2001	Atom Interferometry
	^{87}Rb - CC	7×10^{-9}	2010	and macroscopic corner cube (CC)
Quantum	^{39}K - ^{87}Rb	3×10^{-7}	2020	different elements
	^{87}Sr - ^{88}Sr	2×10^{-7}	2014	same element, fermion vs. boson
	^{85}Rb - ^{87}Rb	3×10^{-8}	2015	same element, different isotopes
	^{85}Rb - ^{87}Rb	3.8×10^{-12}	2020	10 m tower
	^{41}K - ^{87}Rb	(10^{-17})	2037	STE-QUEST
Antimatter	$\bar{H}$ - H	(10^{-2})	2023+	under construction at CERN

Talk by Marilu Chiofalo

STE-QUEST Science:
Searching for Ultralight Dark Matter

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



Talk by Aurélien Hees

STE-QUEST Science:
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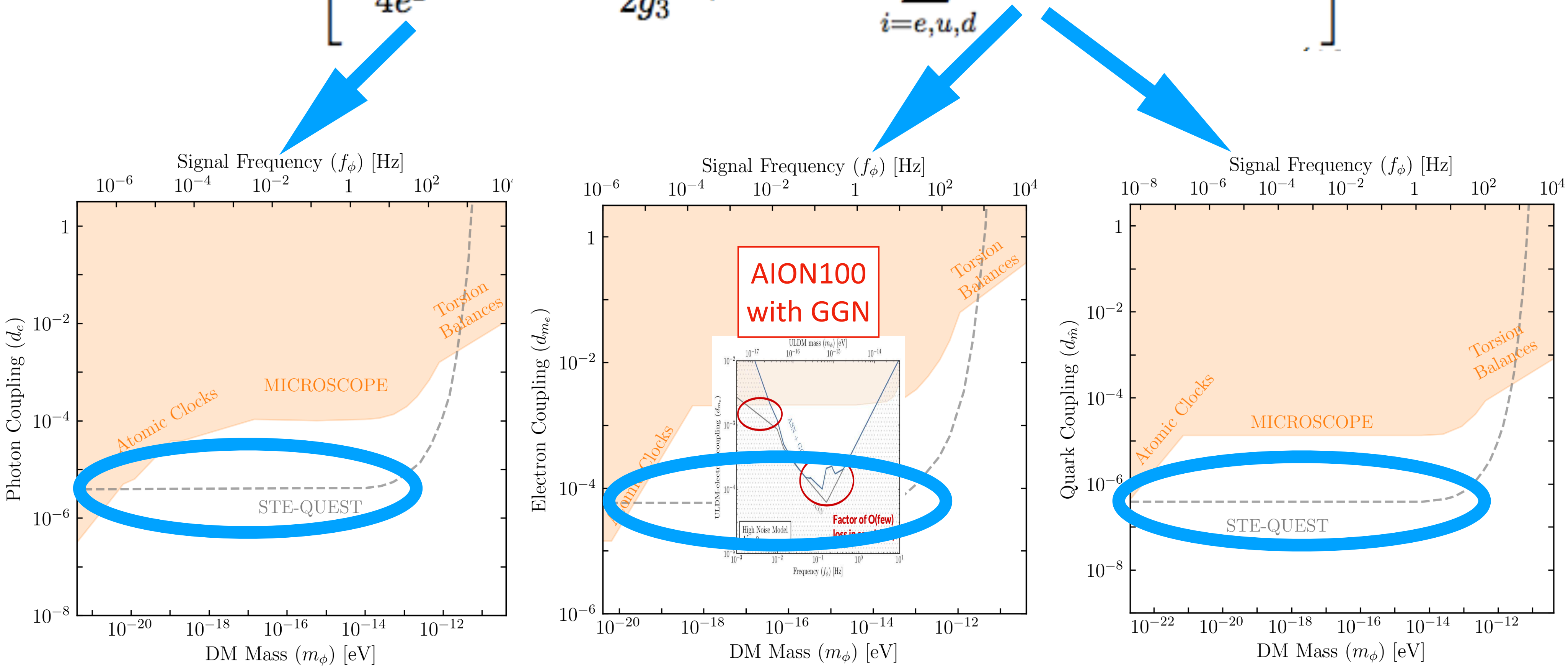

Talk by Aurélien Hees

STE-QUEST Science: Searching for Ultralight Dark Matter

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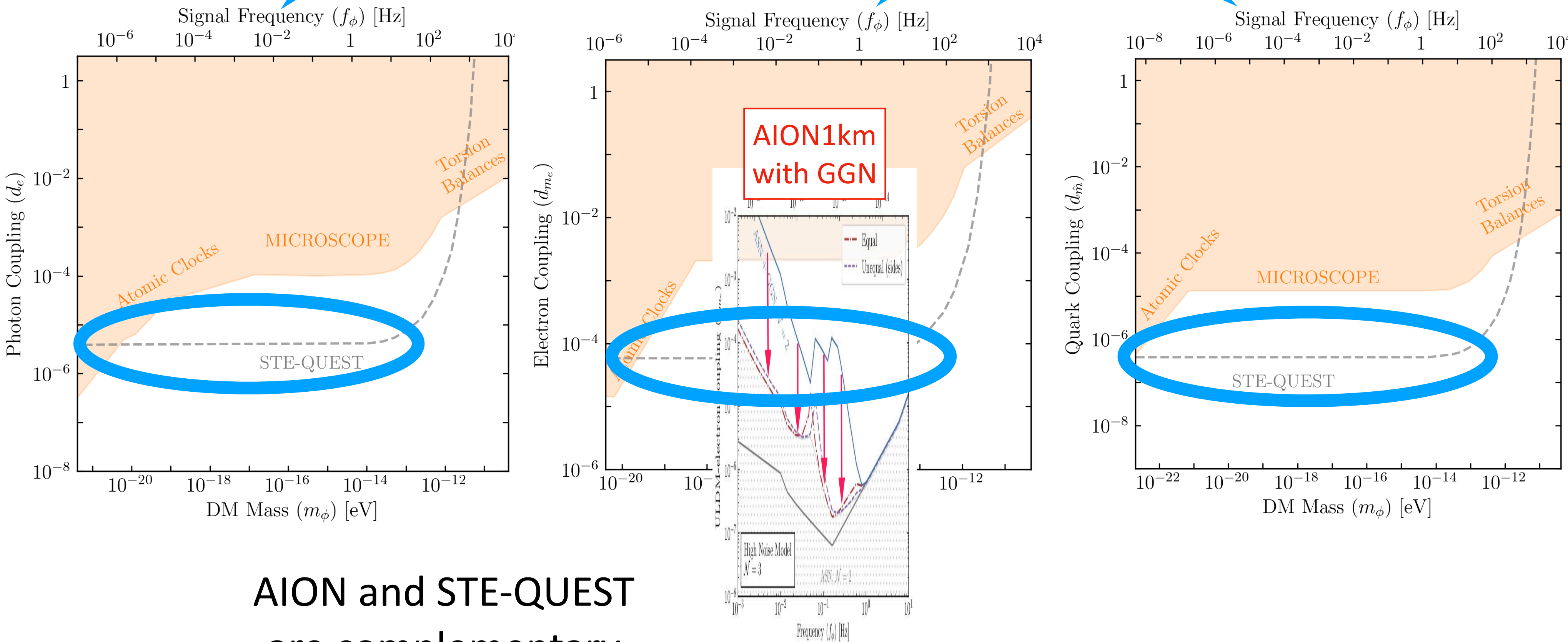


AION and STE-QUEST are complementary

Talk by Aurélien Hees

Wave-Function Collapse?

- Transition from quantum to classical behaviour?
- Black holes: information loss across horizon causes pure states → mixed states

Hawking, 1975

- Non-factorising scattering matrix $\rho_{out} = \$\, \rho_{in} : \$ \neq SS^{\dagger}$
- Non-Hamiltonian evolution: $\partial_t \rho = i[\rho, H] + \mathscr{H} \rho$ due to information loss via microscopic black holes?

JE, Hagelin, Nanopoulos, Olive & Srednicki, 1984

- e.g., 2-state system with equal energies:

$$\rho = \frac{1}{2} \begin{pmatrix} 1 & e^{-\lambda t} \\ e^{-\lambda t} & 1 \end{pmatrix}$$

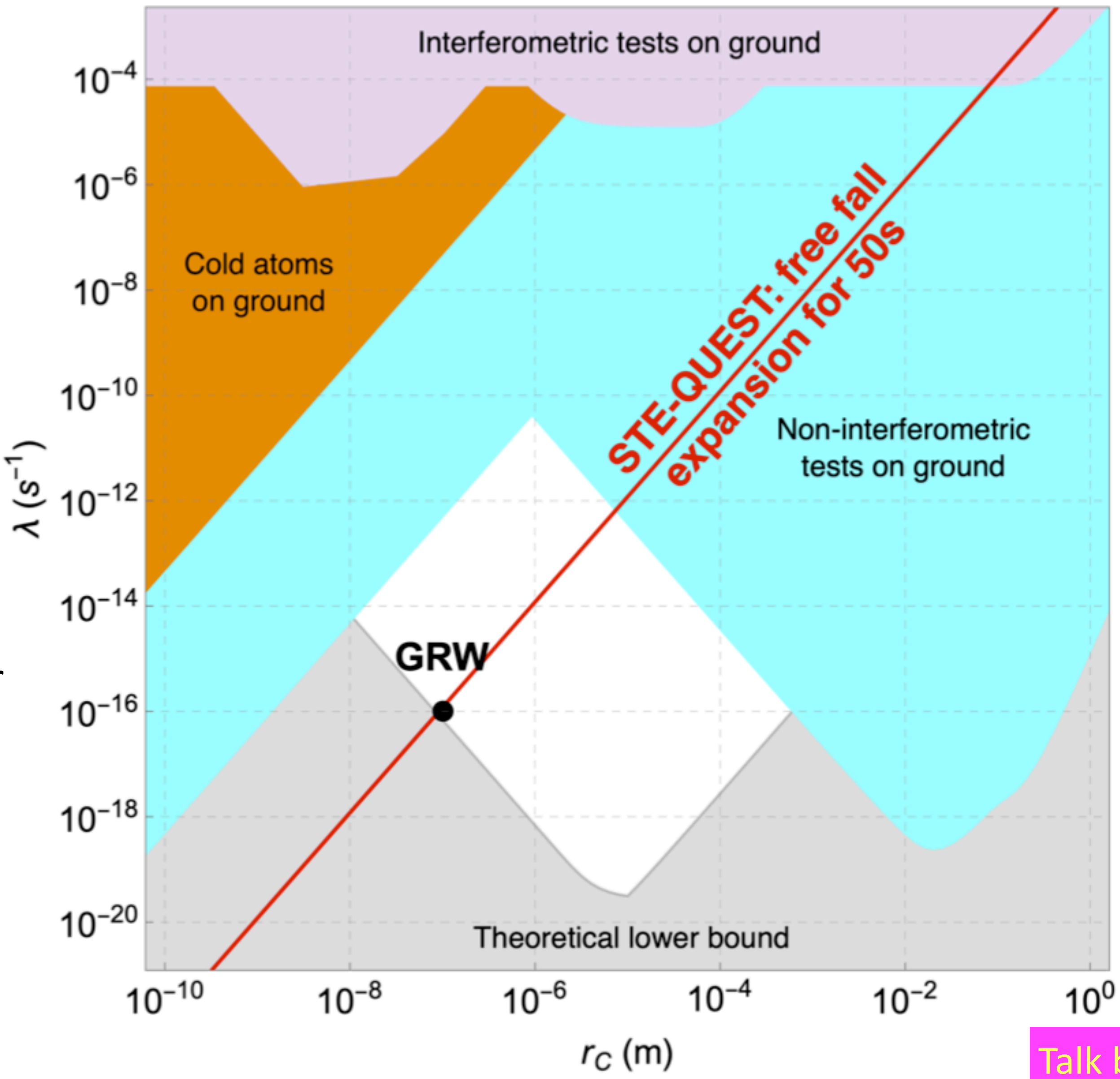
- General parametrisation: $e^{-\frac{d}{r_c}}, e^{-\lambda t}$

Ghirardi, Rimini & Weber, 1986

STE-QUEST Science:
Probe of Quantum Mechanics

Models for
wave-function collapse
parameterised by
time-scale λ
and range r_c

GRW = parameters
proposed by
Ghirardi, Rimini, Weber

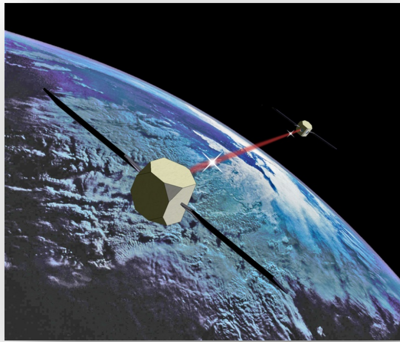


Talk by Matteo Carlesso

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

Beyond LISA

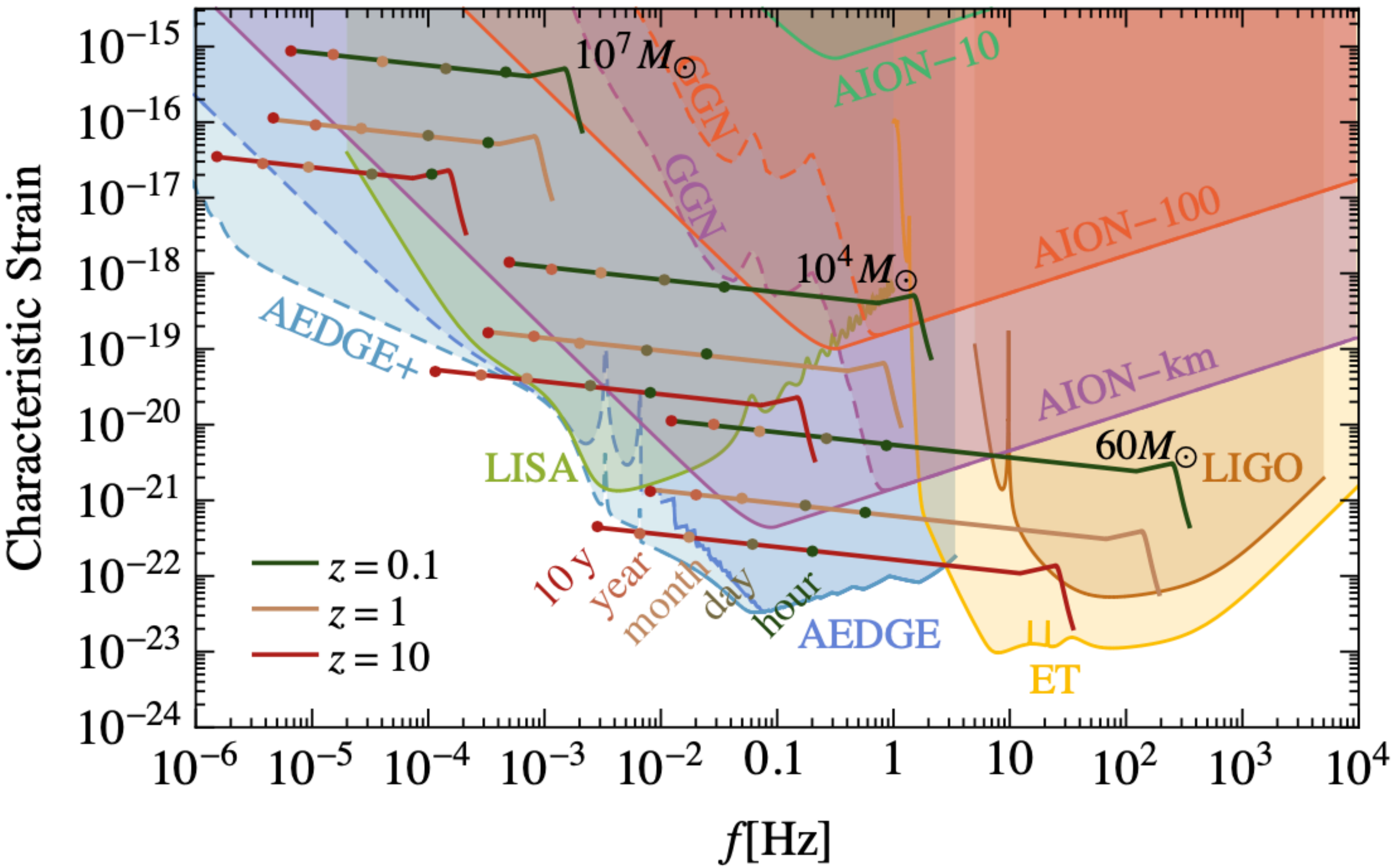
Yousef Abou El-Neaj,[1] Cristiano Alpigiani,[2] Sana Amairi-Pyka,[3] Henrique Araújo,[4] Antun Balaž,[5] Angelo Bassi,[6] Lars Bathe-Peters,[7] Baptiste Battelier,[8] Aleksandar Belić,[5] Elliot Bentine,[9] José Bernabeu,[10] Andrea Bertoldi,[8,*] Robert Bingham,[11] Diego Blas,[12] Vasiliki Bolpasi,[13] 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

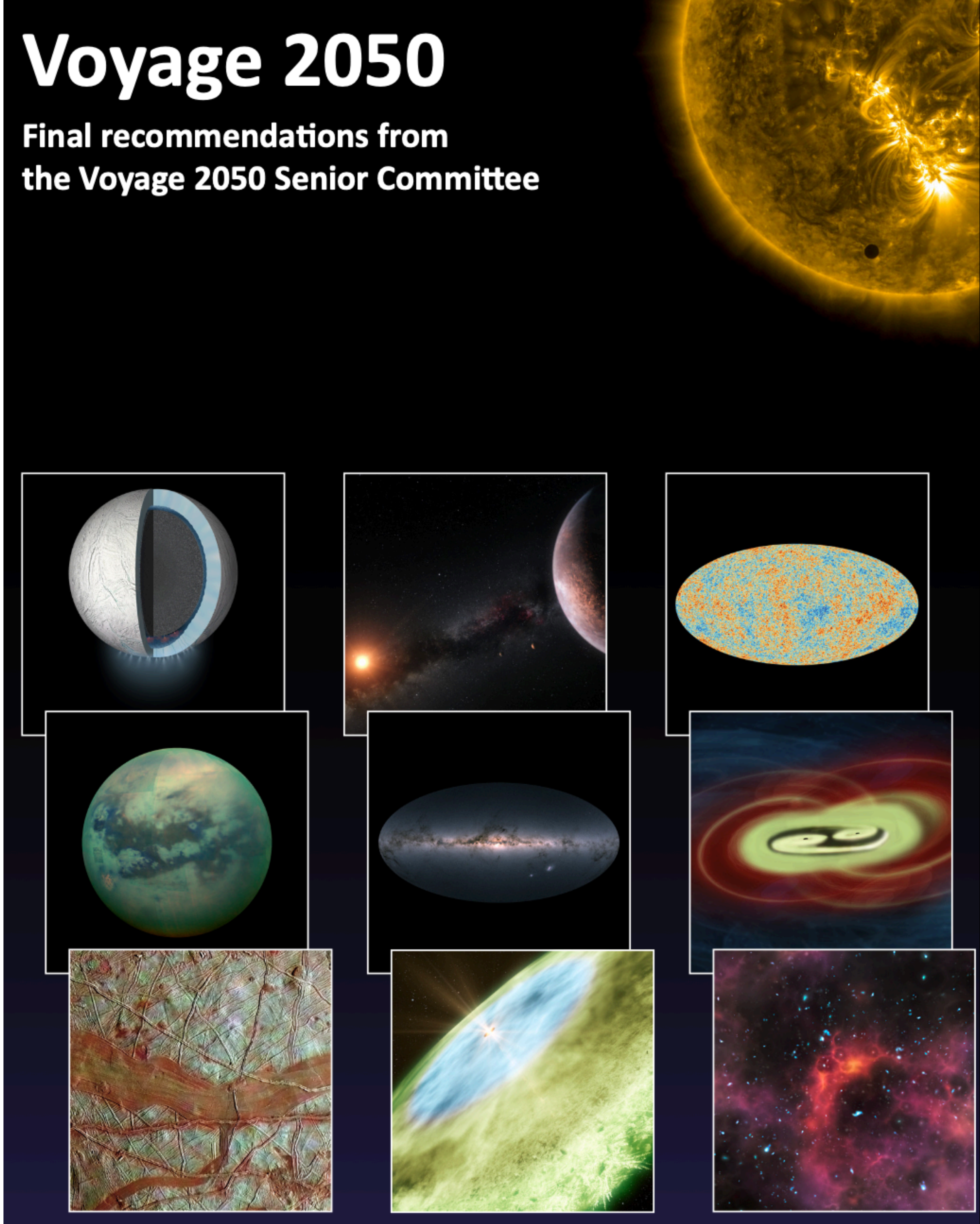
AEDGE: Gravitational Waves from IMBH Mergers



Probe formation of SMBHs

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

Badurina, Buchmueller, JE, Lewicki, McCabe & Vaskonen: arXiv:2108.02468



Large missions:

- Moons of the Giant Planets
- Exoplanets
- New Physical Probes of the Early Universe: Fundamental physics and astrophysics

Possible Medium missions:

- … QM & GR (cold atoms?)

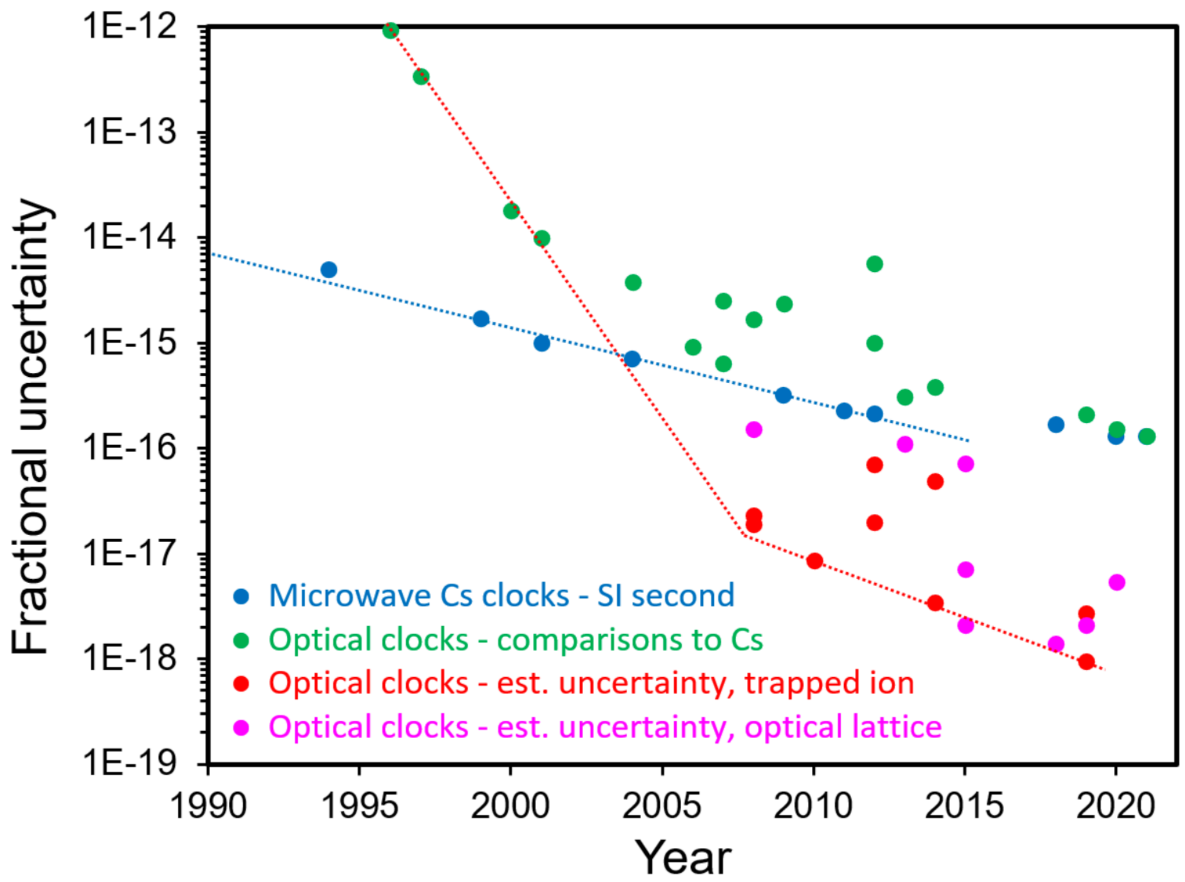
Technology development recommendations for Cold Atom Interferometry

- for gravitational wave detectors in new wavebands …, detectors for dark matter candidates, sensitive clock tests of general relativity, tests of wave function collapse ….
- must reach high technical readiness level, be superior to classical technologies
- start with atomic clocks, on free-flyer or ISS?
- M-mission?

The Big Issues

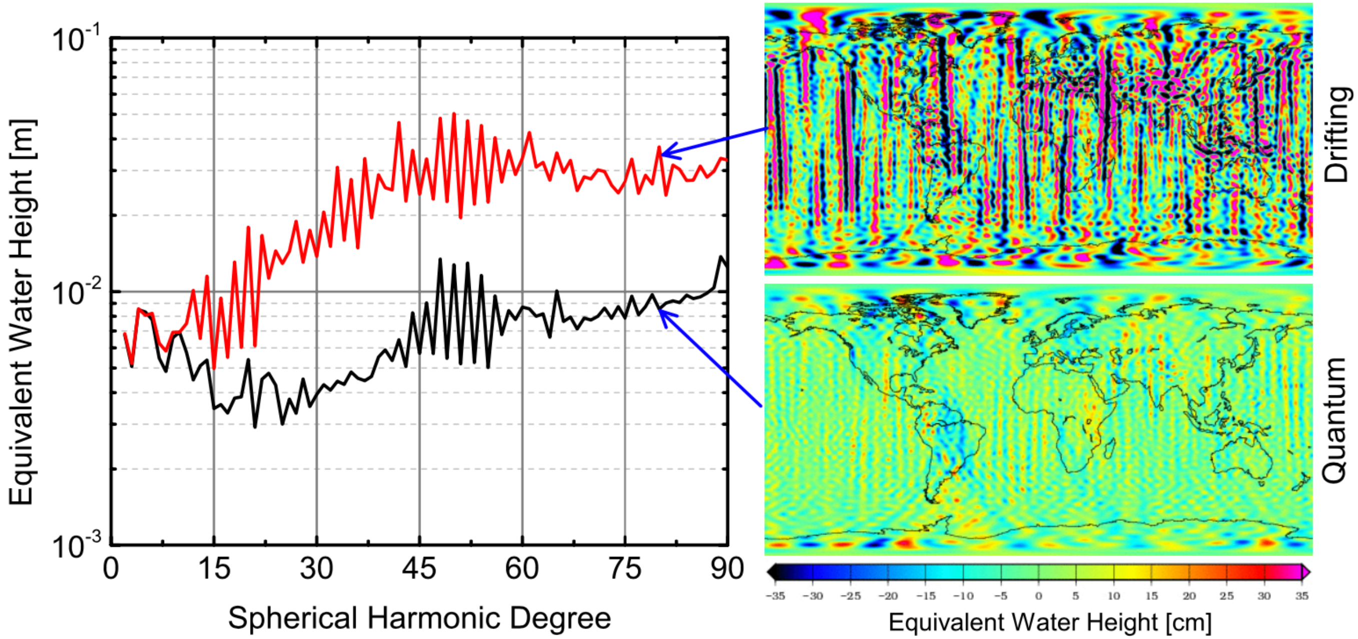
in Metrology

- Next-generation world time standard, 10^{-18} accuracy
  - Optical clocks
- Next-generation geodesy
- Use strontium



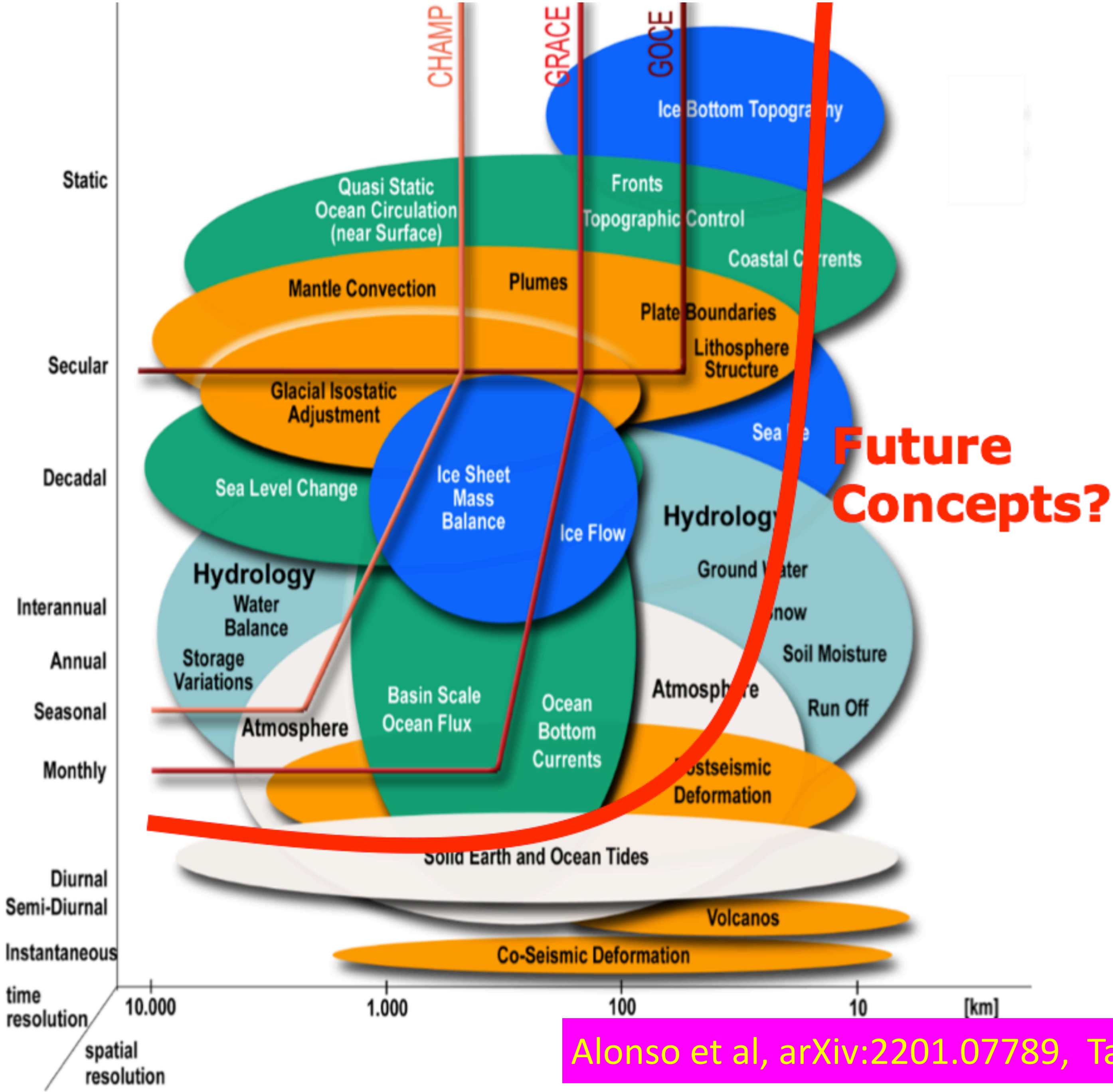
The Big Issues
in Earth Observation

- Measuring changes in Earth's mass distribution
  - e.g., water level rise, ice melting
- Monitor effects of climate change
- Use rubidium



Alonso et al, arXiv:2201.07789, Talk by Olivier Carraz

Cold Atoms in Space: Earth Observation



Alonso et al, arXiv:2201.07789, Talk by Olivier Carraz

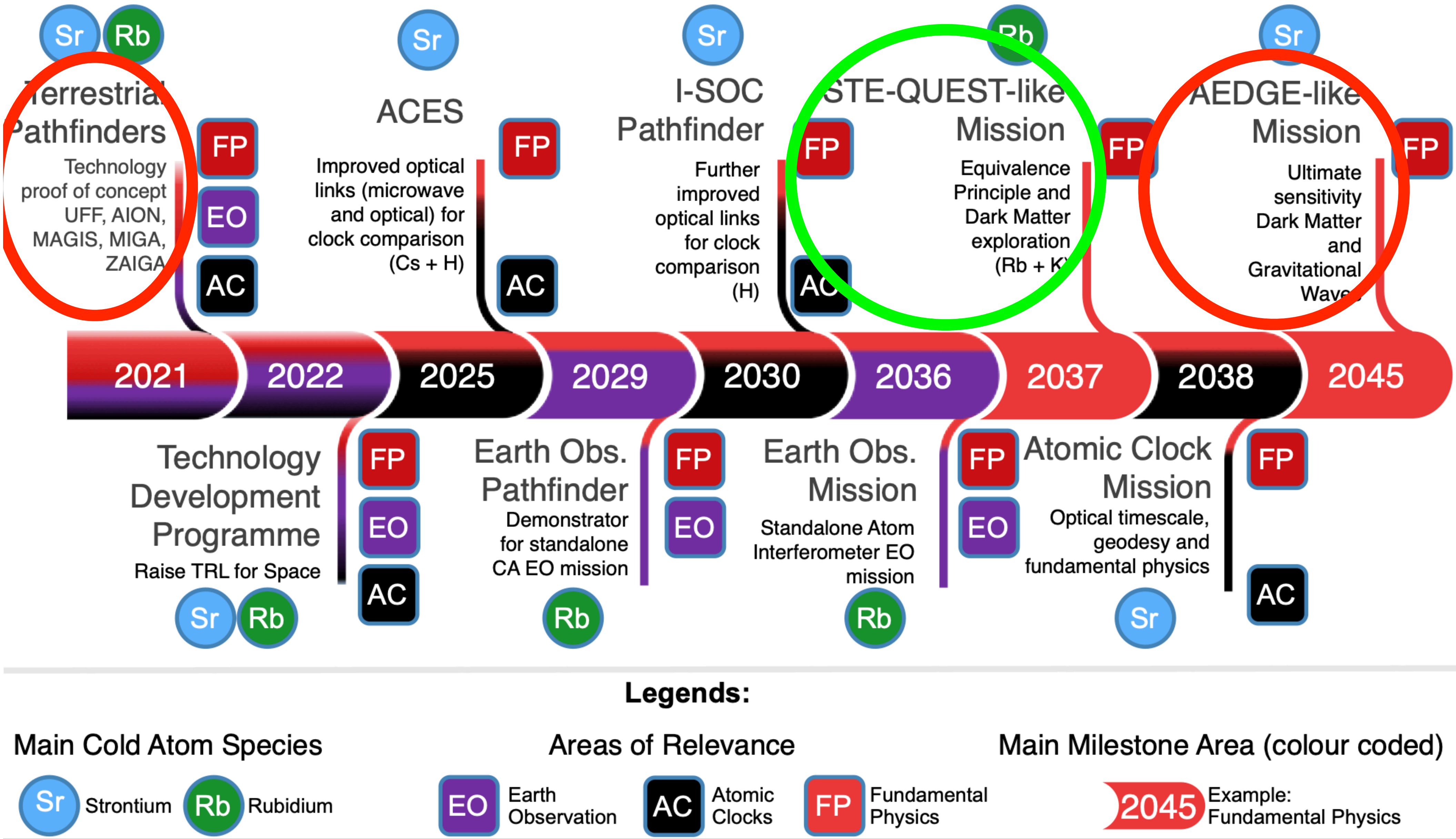
Alonso et al, arXiv:2201.07789

Cold Atoms in Space

- In addition to fundamental physics:
  - Applications to time-keeping and geodesy using strontium atomic clocks accurate to 10^{-18}
  - Next-generation Earth Observation using rubidium, e.g., to monitor changes in water level due to climate change
- Joint proposal for cold atom road-map presented to ESA
- The road-map starts from existing terrestrial cold-atom projects, and progresses via pathfinder projects towards long-term scientific space missions

Alonso et al, arXiv:2201.07789

Proposed ESA Road-Map for Cold Atoms in Space



STE-QUEST 2022: "The Big Picture"

- Broad programme in fundamental science
  - Equivalence Principle (universality of free fall), search for ultralight dark matter, probe collapse of quantum-mechanical wave function
- Compare rubidium and potassium rather than ^{87}Rb and ^{85}Rb
  - Longer lever arm for probes of universality of free fall and the equivalence principle
- Different orbit: circular rather than elliptic
- Significant work since 2014 on cold atoms in space and atom interferometry on Earth
- Commonalities with proposed Earth Observation missions