Cold Atom Probes of Fundamental Science

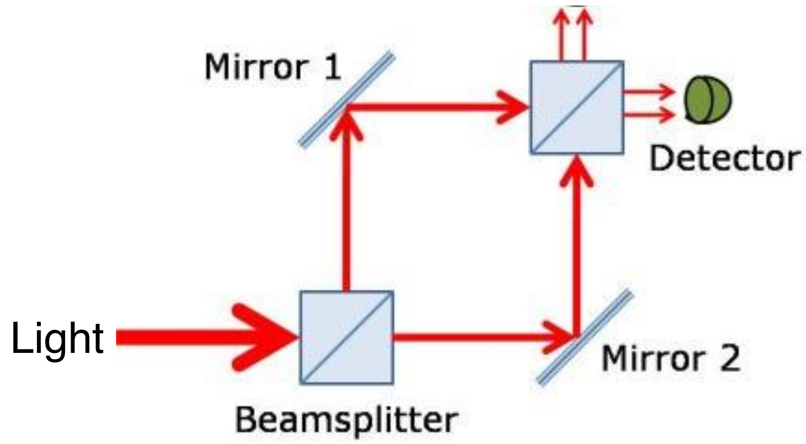
- Ultralight Dark Matter
- Gravitational Waves
- Quantum Mechanics

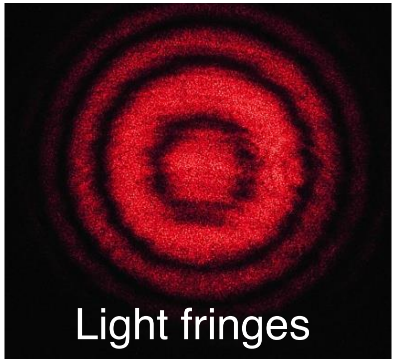
KING'S College LONDON

John Ellis

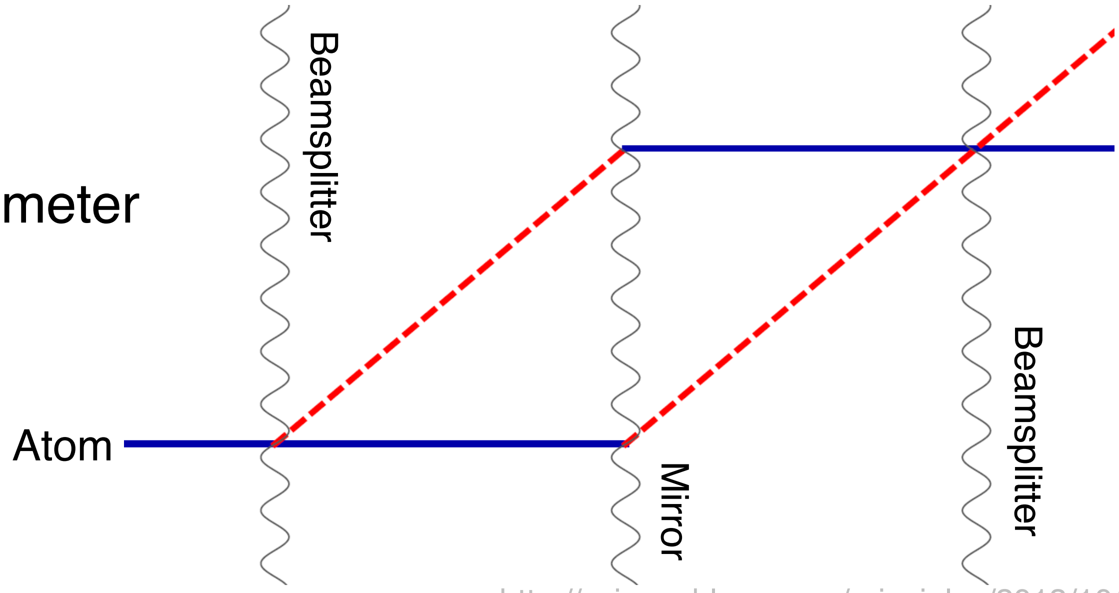
Principle of Atom Interferometry

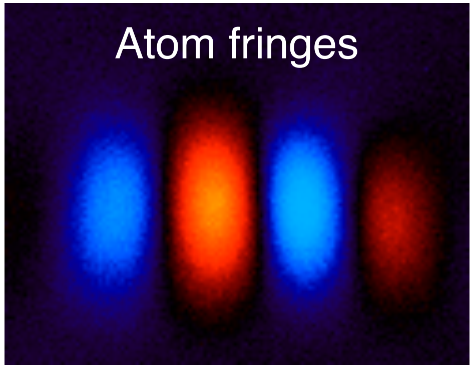
Light interferometer





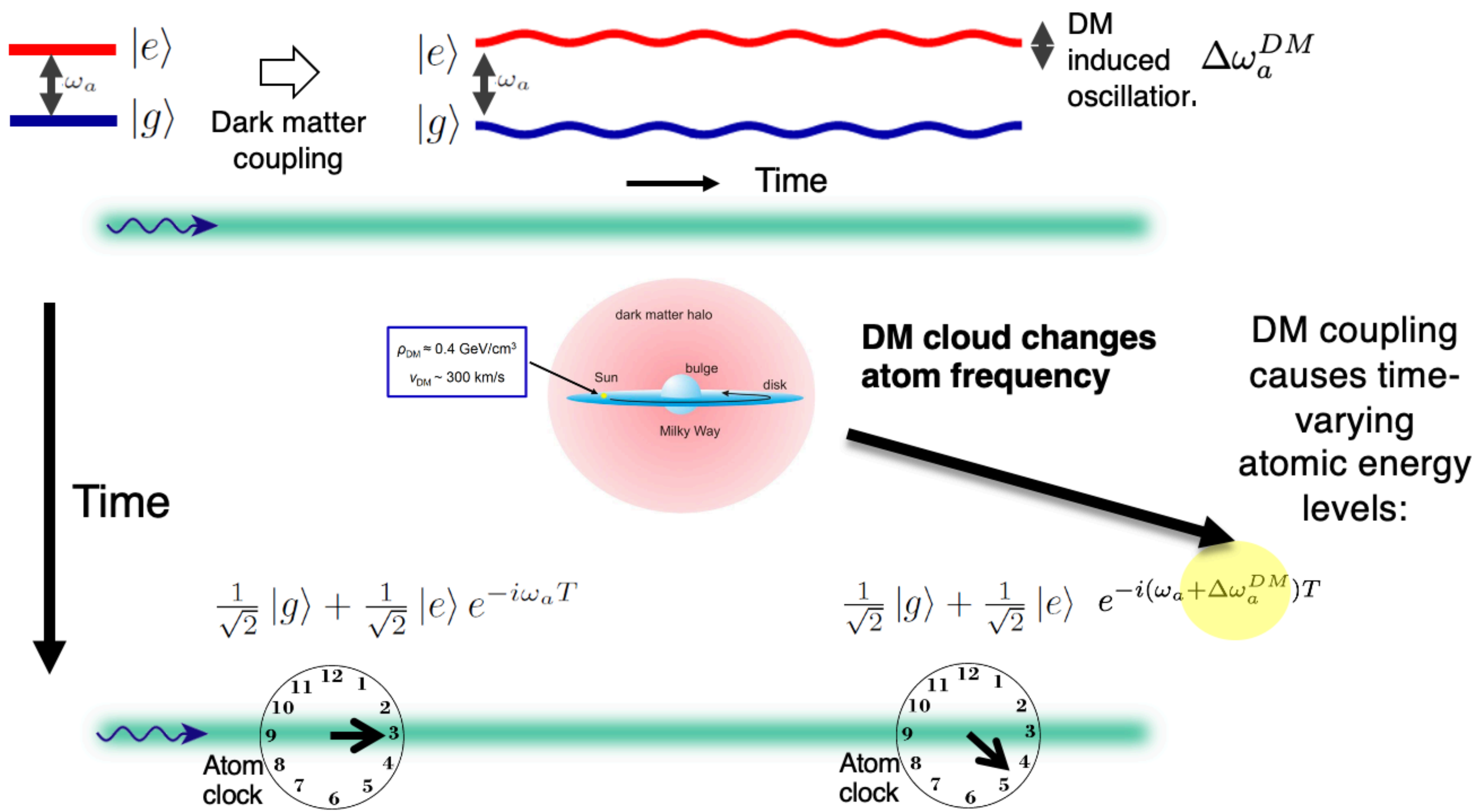
Atom interferometer





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

Effect of Dark Matter on Atom Interferometer



Effect of Gravitational Wave on Atom Interferometer

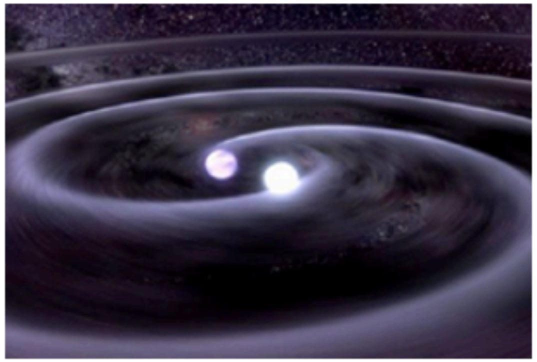
$|e\rangle$

ω_a

$|g\rangle$

$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle \qquad \frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle$$

Time

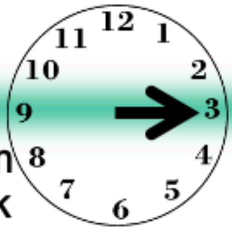


GW changes light travel time

$\Delta T \sim hL/c$

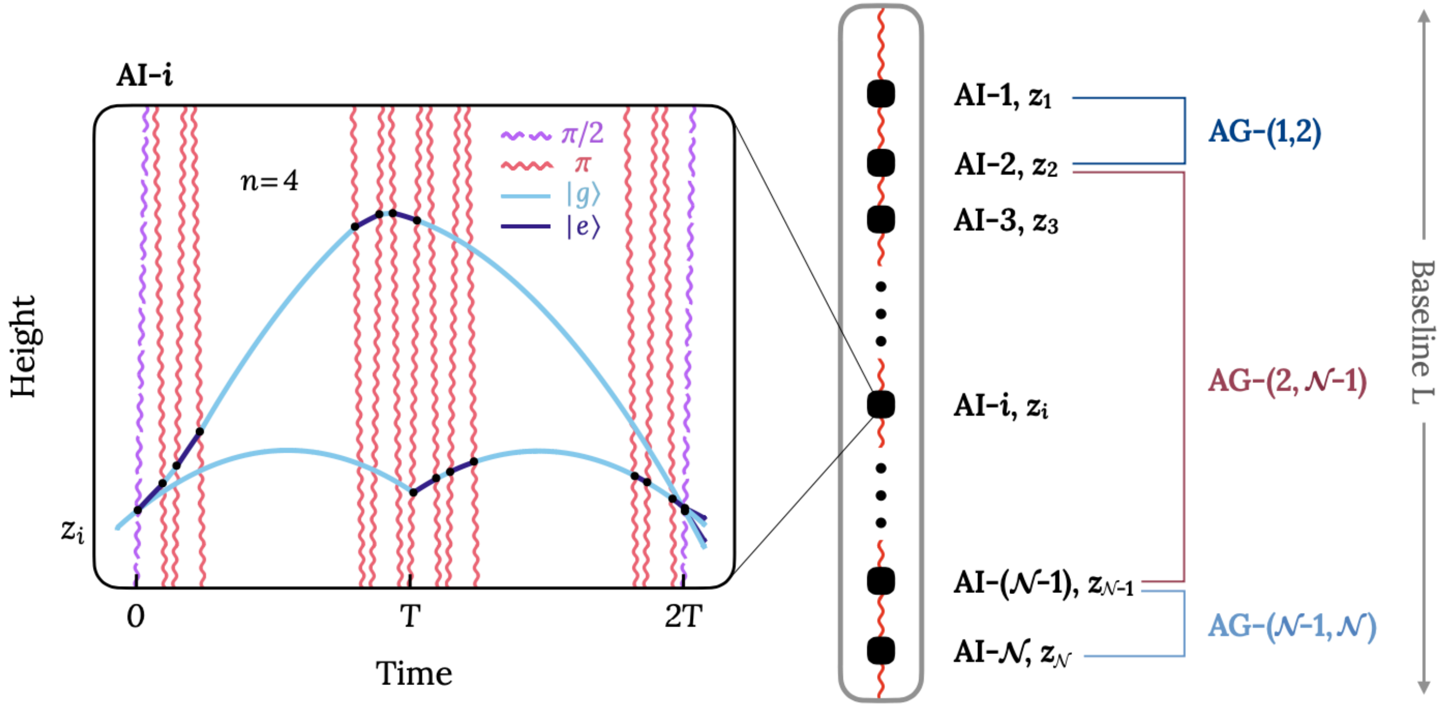
$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle\, e^{-i\omega_a T} \qquad \frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle\, e^{-i\omega_a (T+\Delta T)}$$

Atom clock



Atom clock

Atomic Multi-Gradiometer

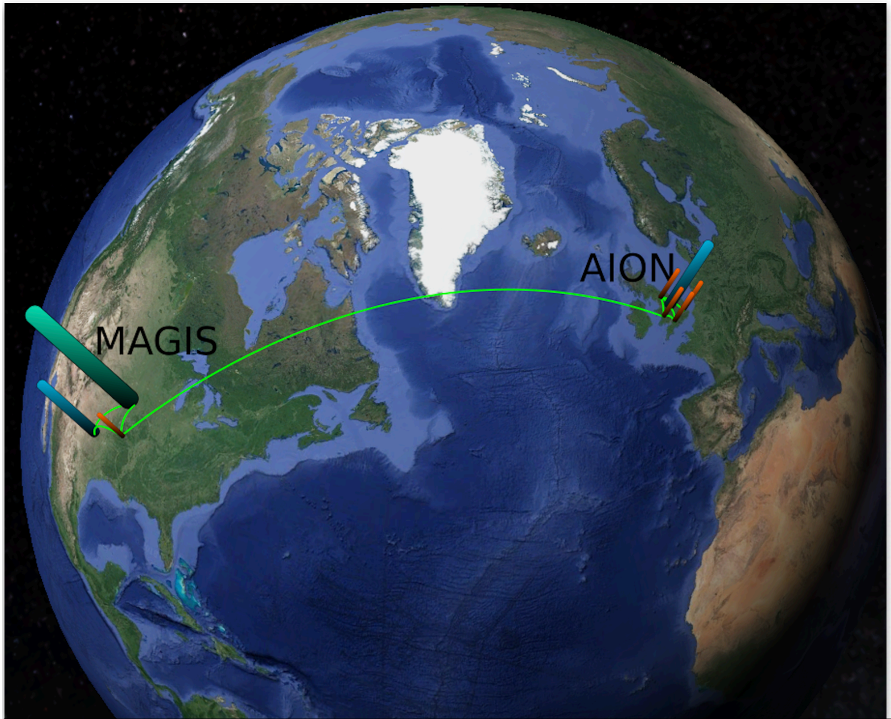


Multiple atomic interferometers in the same vertical shaft, manipulated with same laser beam.
Eliminate laser noise, minimize gravity gradient noise.

AION Collaboration

L. Badurina[1], S. Balashov[2], E. Bentine[3], D. Blas[1], J. Boehm[2], K. Bongs[4], A Beniwal[1], D. Bortoletto[3], T. Bowcock[5], W. Bowden[6,*], C. Brew[2], O. Buchmueller[6], J. Coleman[5], J. Carlton, 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[5], 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



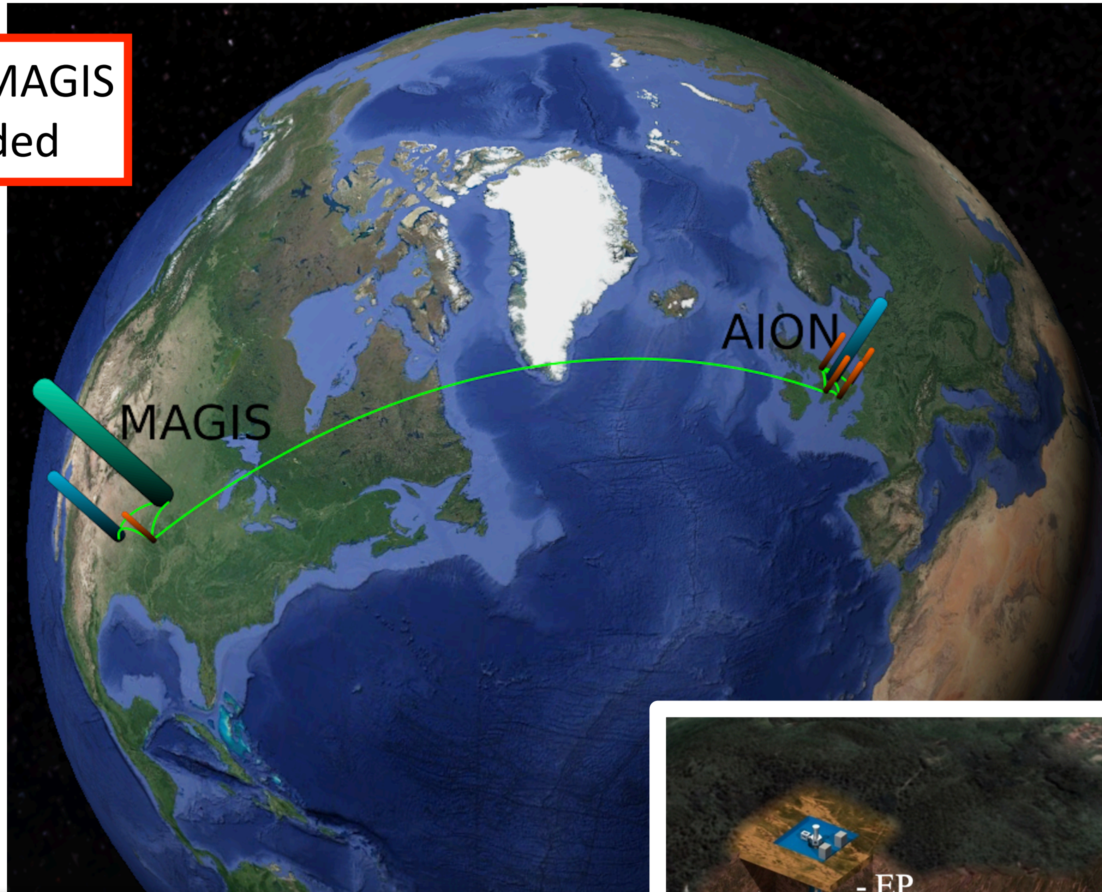
Network with MAGIS project in US

MAGIS Collaboration (Abe et al): arXiv:2104.02835

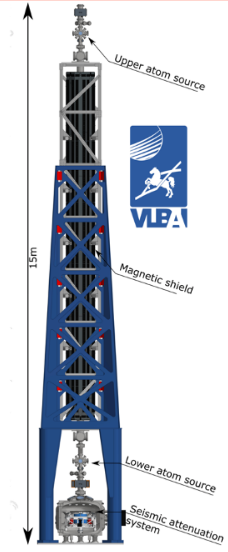
Atom Interferometer Observatory &

Network

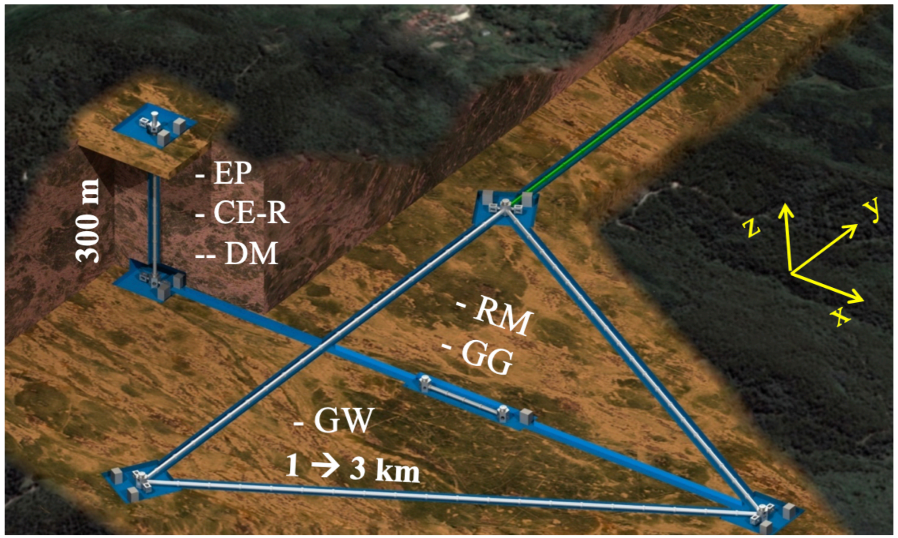
Partnership with MAGIS could be extended



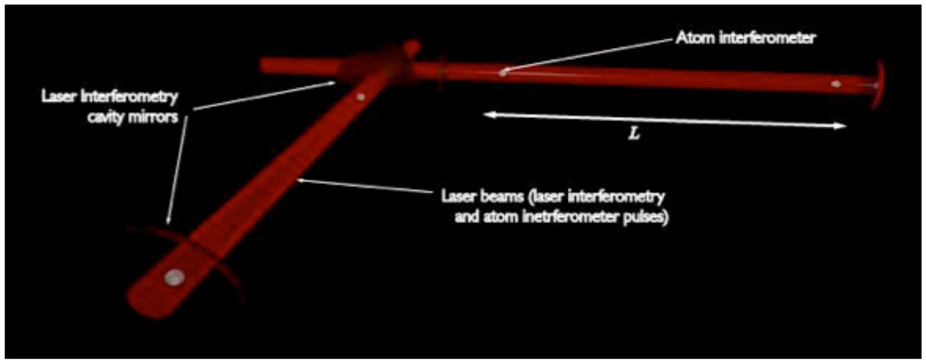
VLBAI (Germany)



ZAIGA (China)



MIGA (France)



AION – Staged Programme

AION

- AION-10: Stage 1 [year 1 to 3]
  - 1 & 10 m Interferometers & site investigation 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]

Workshop @ CERN, March 13/14, 2023

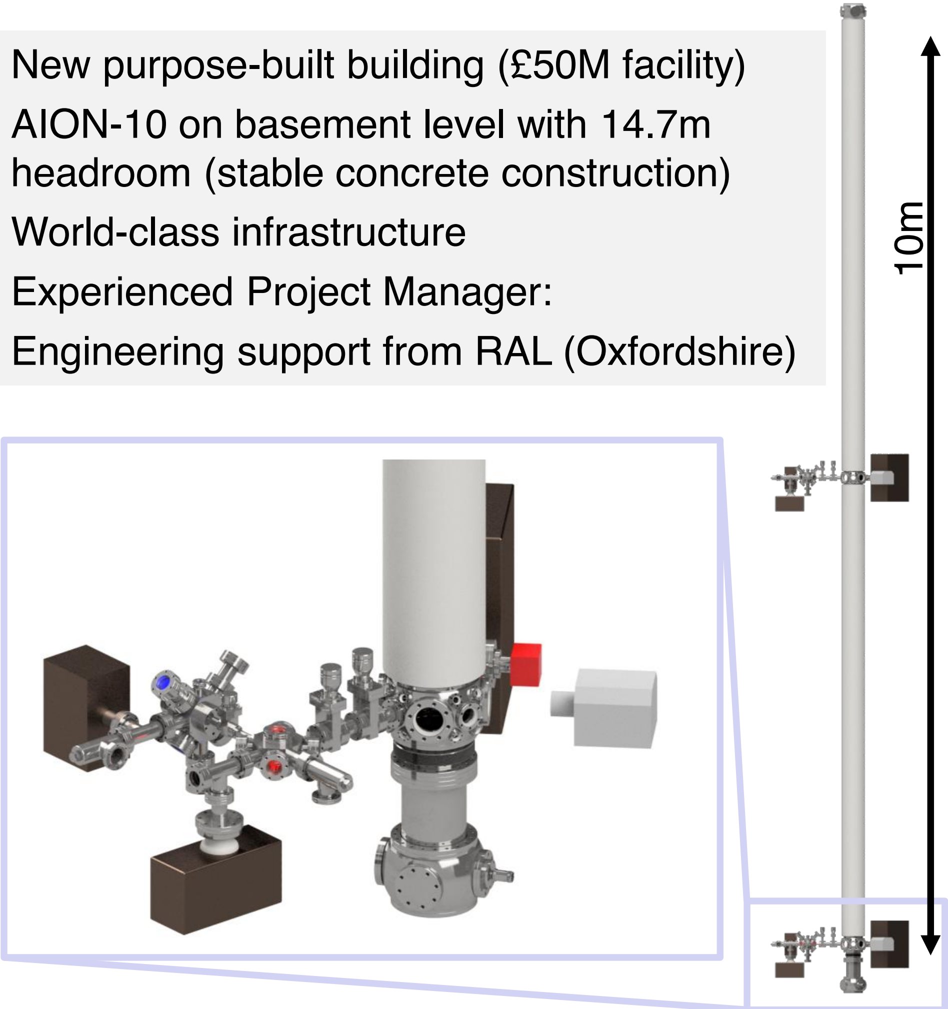
  - Operating AION-100 and planning for 1 km & beyond
- AION-SPACE (AEDGE): Stage 4 [after AION-km]
  - Space-based version

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

Planned Location of AION-10m

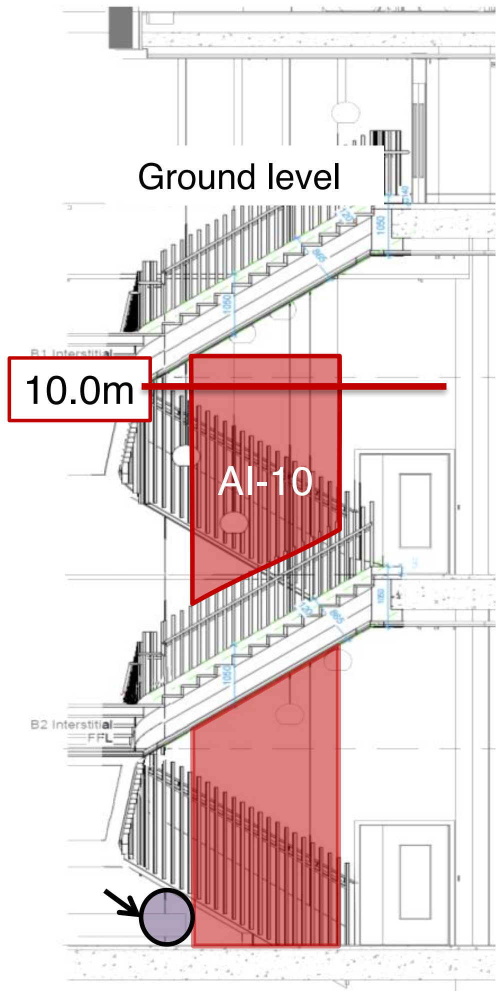
AION-10 @ Beecroft building, Oxford Physics

- New purpose-built building (£50M facility)
- AION-10 on basement level with 14.7m headroom (stable concrete construction)
- World-class infrastructure
- Experienced Project Manager:
- Engineering support from RAL (Oxfordshire)



Laser lab for AION

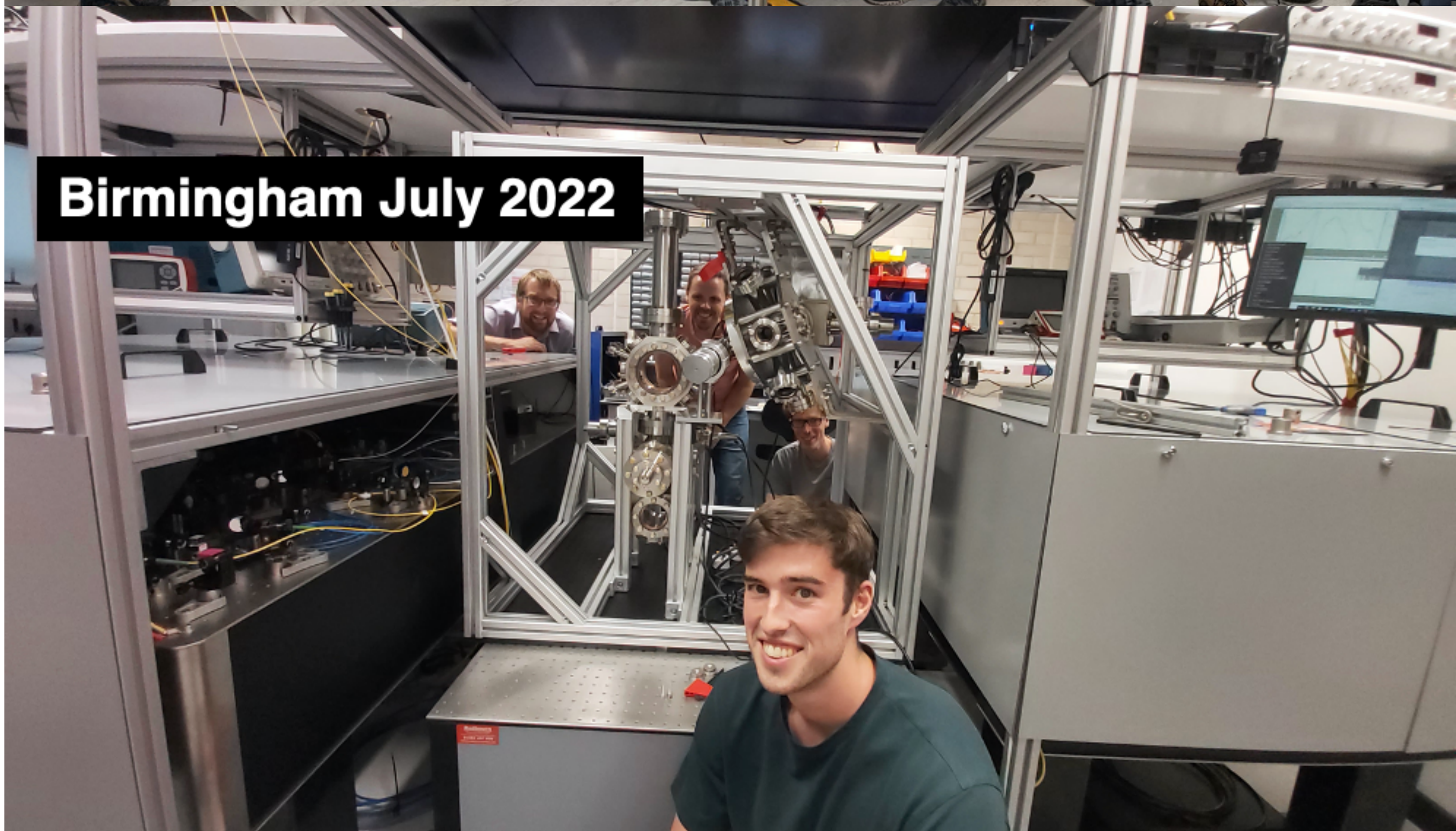
vibration criterion, VC-G = 10nm@10Hz. Temperature (22±0.1)° C




Cambridge July 2022


Oxford October 2022

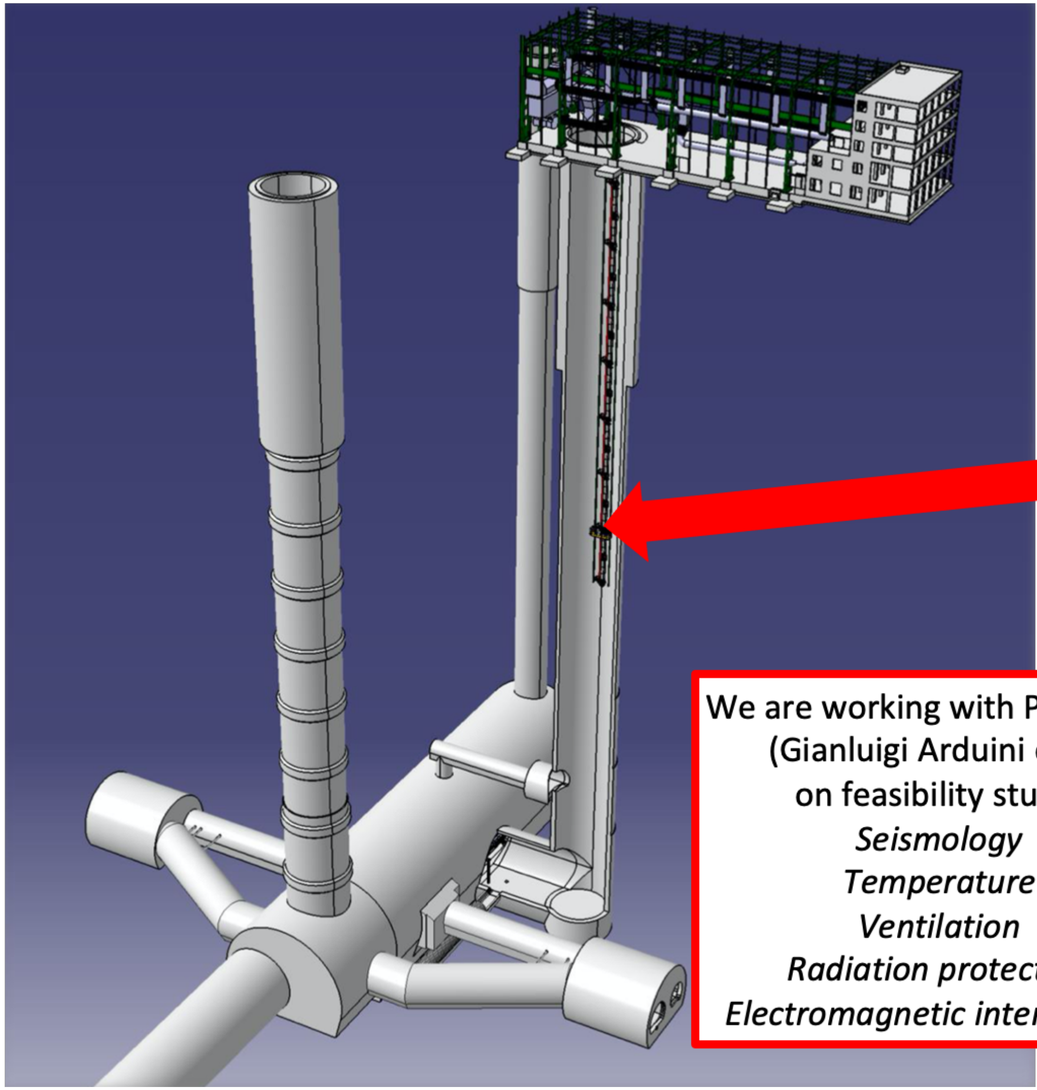
AION


Birmingham July 2022

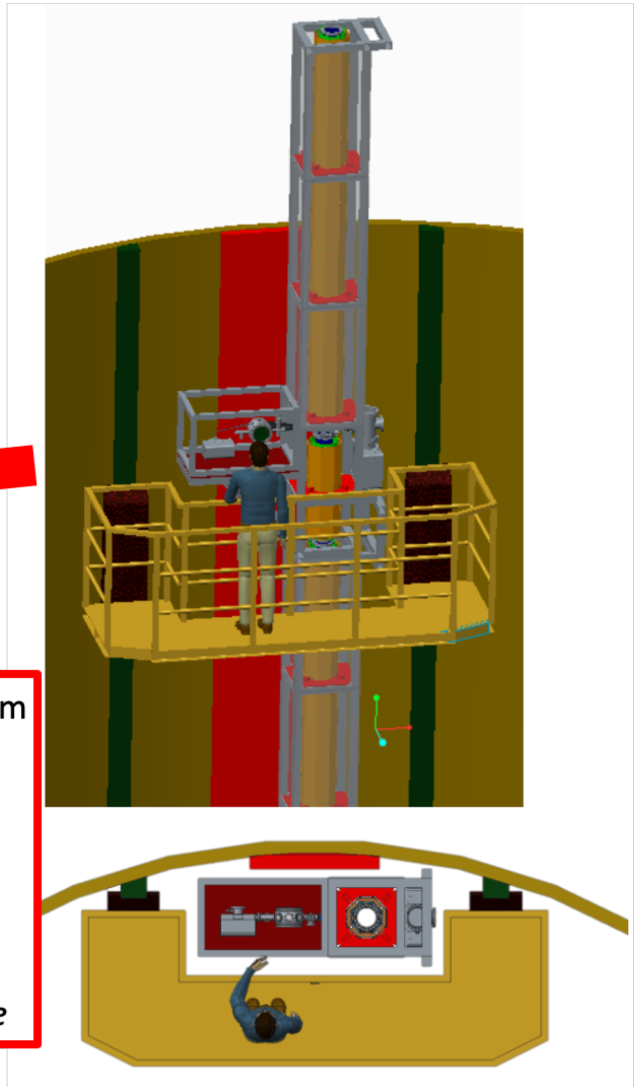

Imperial July 2022

Possible CERN Location of AION-100m

General view of LHC Point 4



Possible layout in PX46 shaft



We are working with PBC Team
(Gianluigi Arduini et al)
on feasibility study:
Seismology
Temperature
Ventilation
Radiation protection
Electromagnetic interference

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

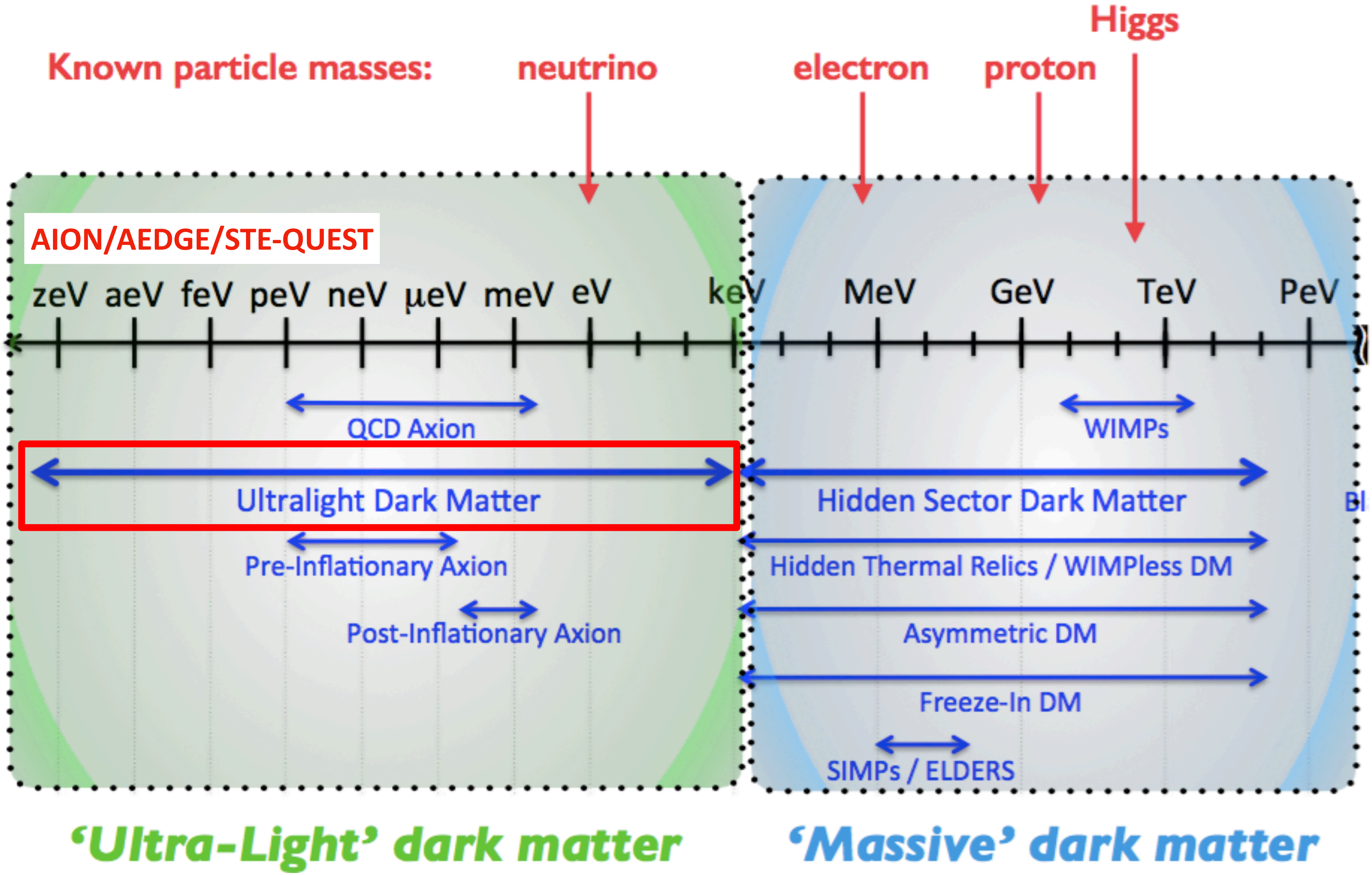
Beyond LISA

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

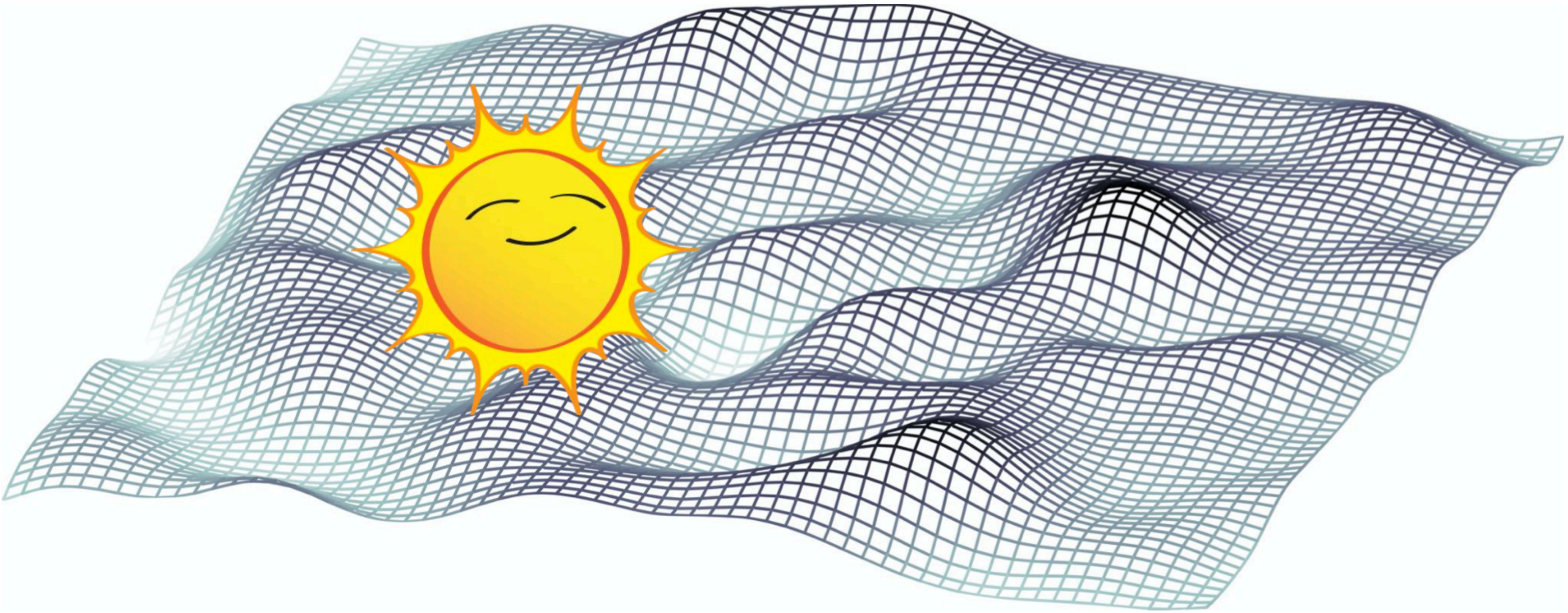
Abou El-Neaj, …, JE et al: arXiv:1908.00802

Search for Ultralight Dark Matter



Ultralight Dark Matter

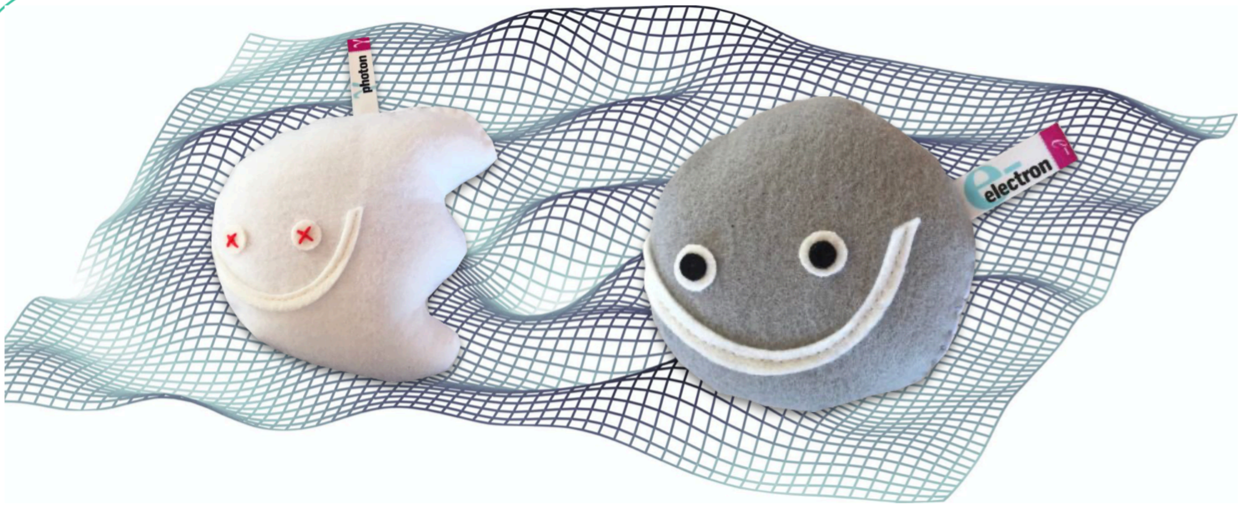
A scalar ULDM $\phi(\mathbf{x}, t)$ field would be present throughout the Solar System



The wavelength depends on the ULDM mass: $\lambda \sim 10^8\,\mathrm{km}\left(\frac{10^{-15}\,\mathrm{eV}}{m_\phi}\right)$

Ultralight Dark Matter

Interactions with the ULDM field lead to oscillations in fundamental 'constants'



Time-dependent electron mass:

$$m_e(t,\mathbf{x}) = m_e\left[1+\frac{d_{m_e}}{M_{\rm Pl}}\phi(t,\mathbf{x})\right]$$

Time-dependent electromagnetic fine structure constant:

$$\alpha(t,\mathbf{x}) = \alpha\left[1+\frac{d_e}{M_{\rm Pl}}\phi(t,\mathbf{x})\right]$$

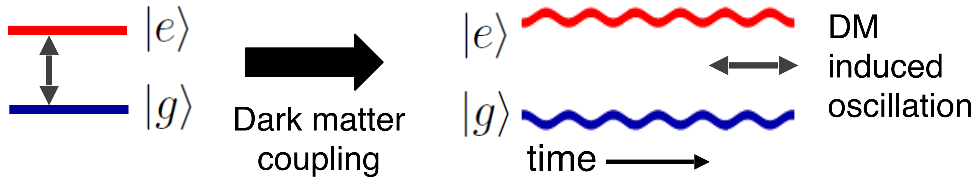
Tiny oscillations induced in transition energies:

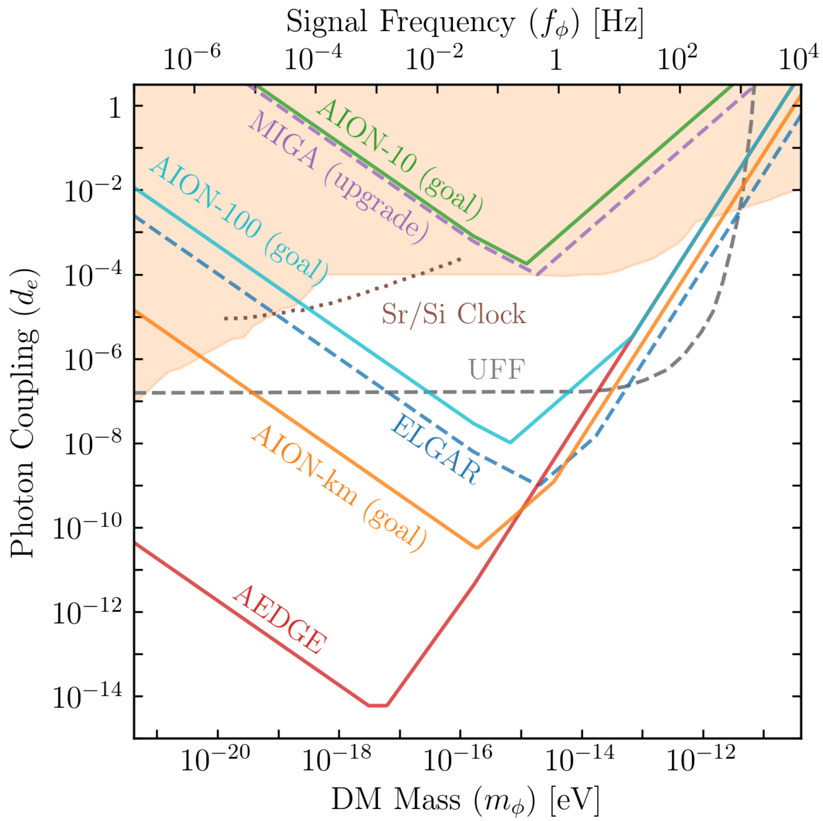
$$\frac{\delta\omega_{\rm Sr}}{\omega_{\rm Sr}} = \frac{\sqrt{2\rho_{\rm DM}}}{m_{\rm DM}}\frac{(d_{m_e}+\xi d_e)}{M_{\rm Pl}}\cos(m_{\rm DM}t)$$

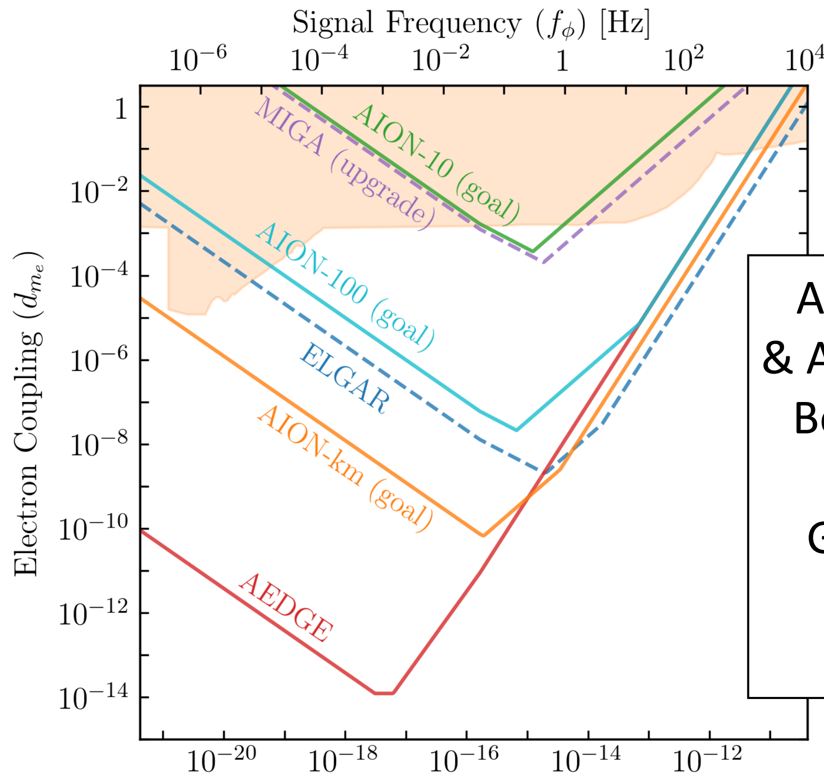
Searches for Ultralight Dark Matter AION

Linear couplings to gauge fields and matter fermions

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







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

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

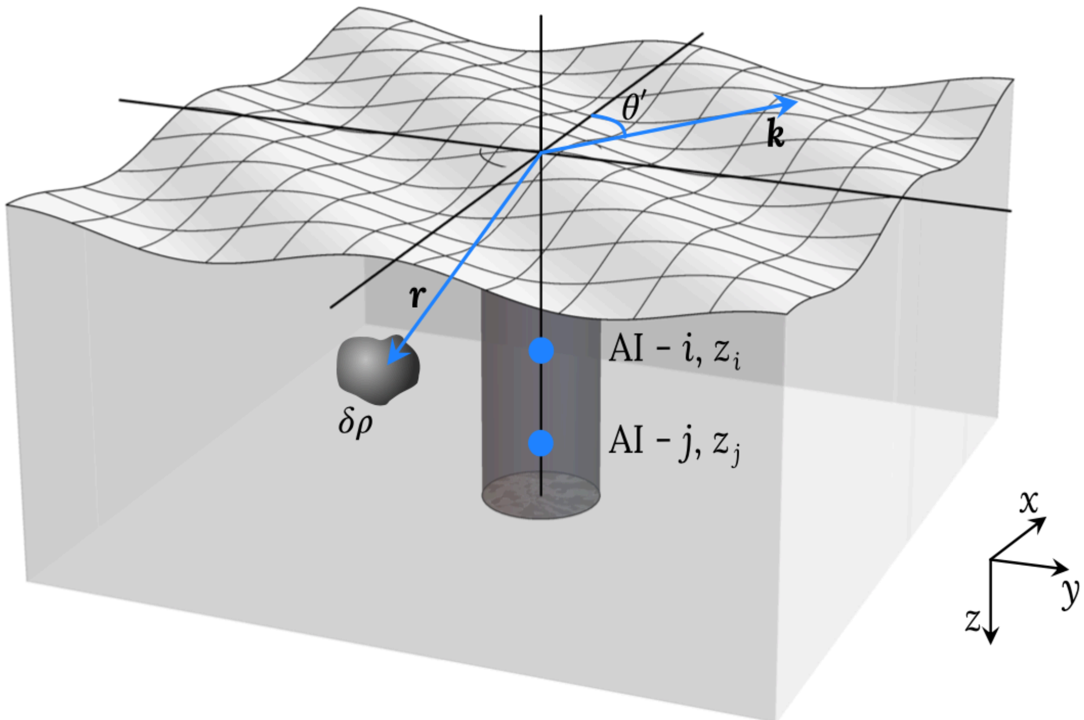
Gravity Gradient Noise

Seismic waves on the surface (Rayleigh waves) change the gravitational field experienced by the atoms and lead to a phase shift

$$\Phi_{\mathrm{Rayleigh}} = \left(\widetilde{A}e^{-qkz_0} + \widetilde{B}e^{-kz_0}\right)\xi_V \cos(\omega T + \Theta)$$

$$\widetilde{A}, -\widetilde{B} \propto \frac{\sin\left(\frac{\omega T}{2}\right)^2}{\omega^2}$$

We consider the simplest scenario:
Isotropic sourcing around the shaft,
single geological stratum present
(so only the fundamental Rayleigh mode)

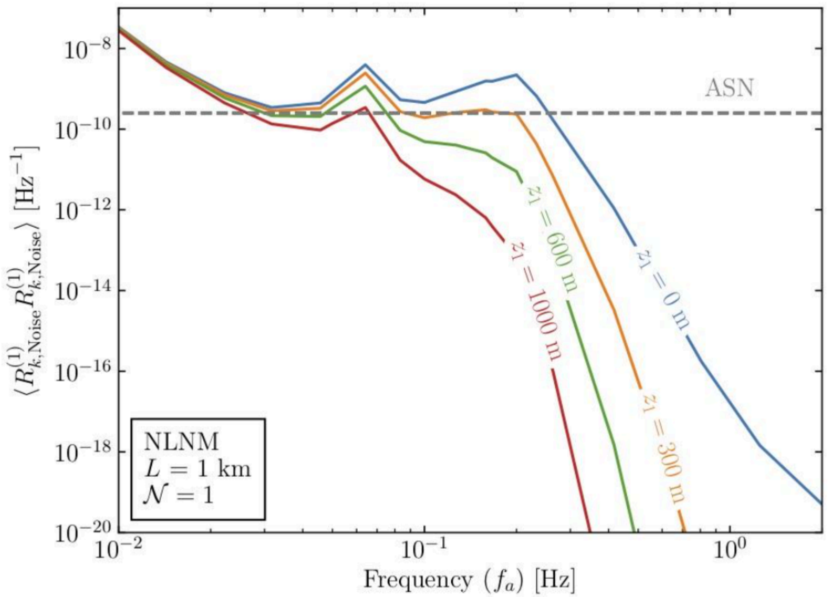


Badurina, Gibson, McCabe & Mitchell, *in preparation*

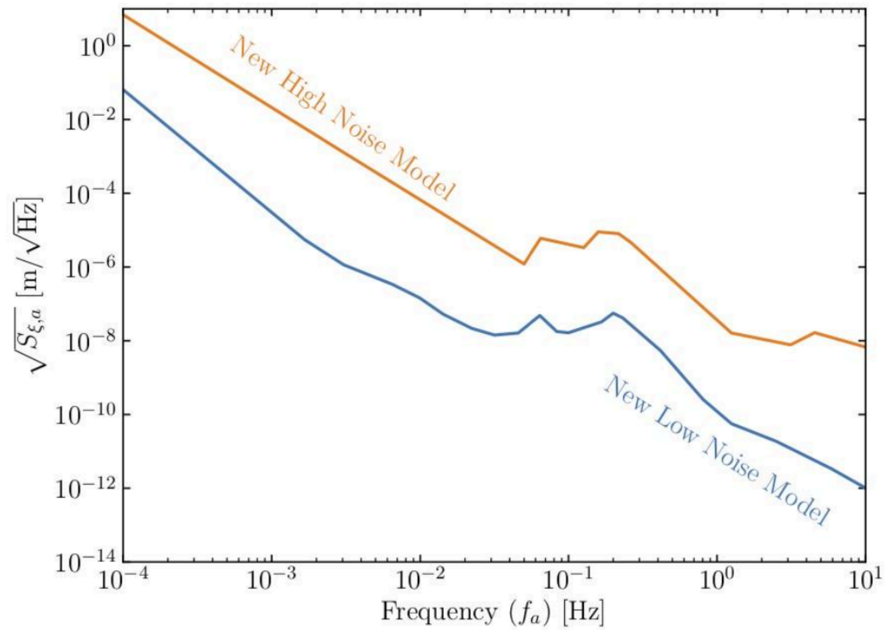
Gravity Gradient Noise

$$\Phi_{\text{Rayleigh}} = \left(\widetilde{A}e^{-qkz_0} + \widetilde{B}e^{-kz_0}\right)\xi_V \cos(\omega T + \Theta)$$

Exponential suppression and frequency dependence



Vertical displacement (Rayleigh distributed)

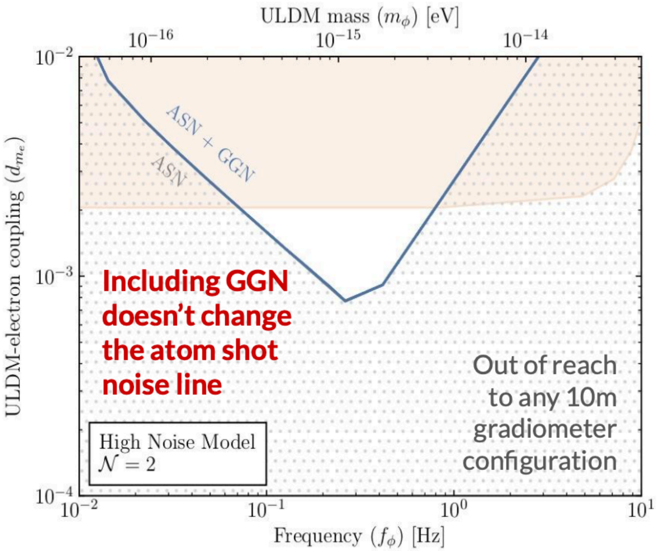


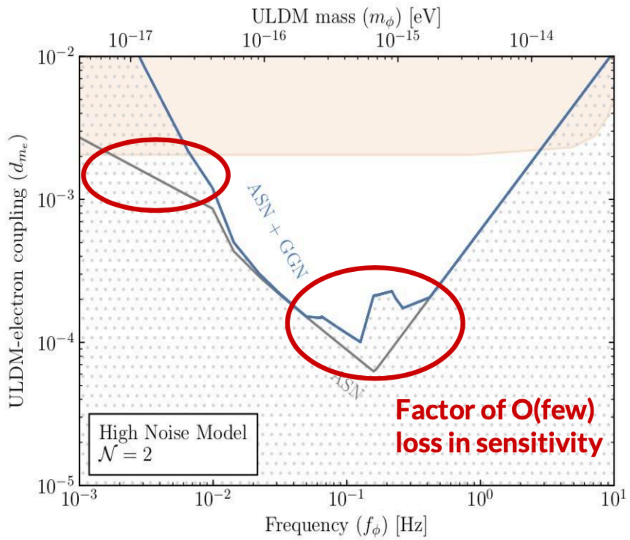
Badurina, Gibson, McCabe & Mitchell, *in preparation*

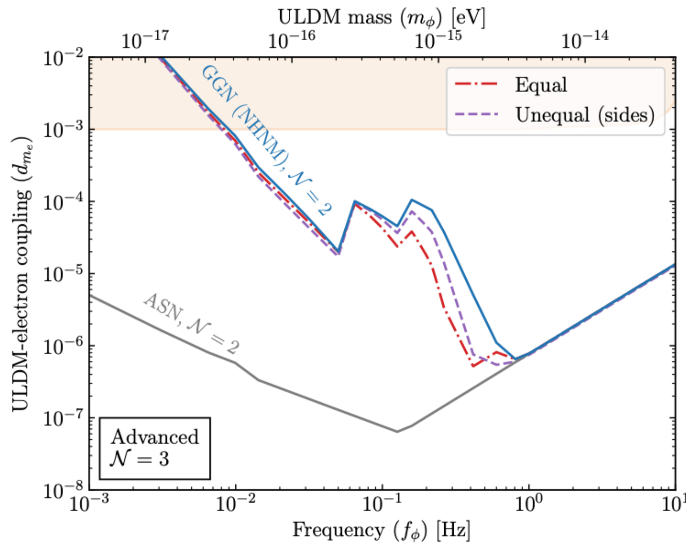
Gravity Gradient Noise

AION

Unimportant for AION-10	Not large for AION-100	Important for AION-1km



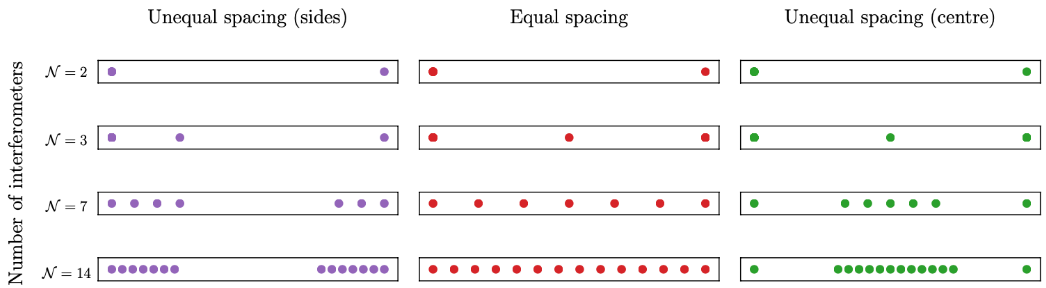




Design	L [m]	T [s]	n	$\Delta z_{\max}$ [m]	N_{atom}	Δt [s]	T_{int} [s]
Intermediate	100	1.4	1000	85	10^8	1.5	10^8
Advanced	1000	1.7	2500	970	10^{10}	1.0	10^8

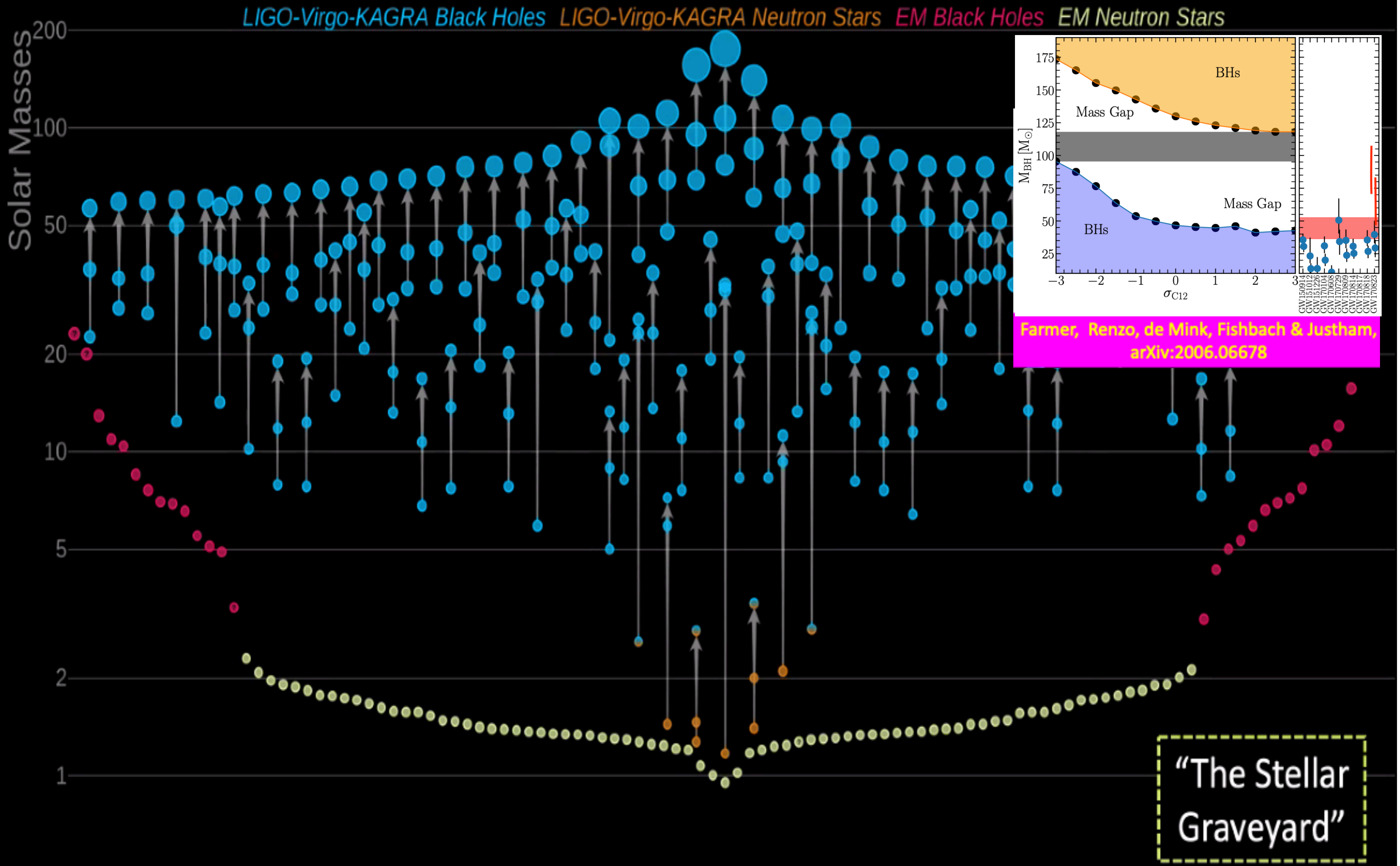
AION-100 & AION-1km:

Mitigate Gravity Gradient Noise (GGN) with multiple gradiometers

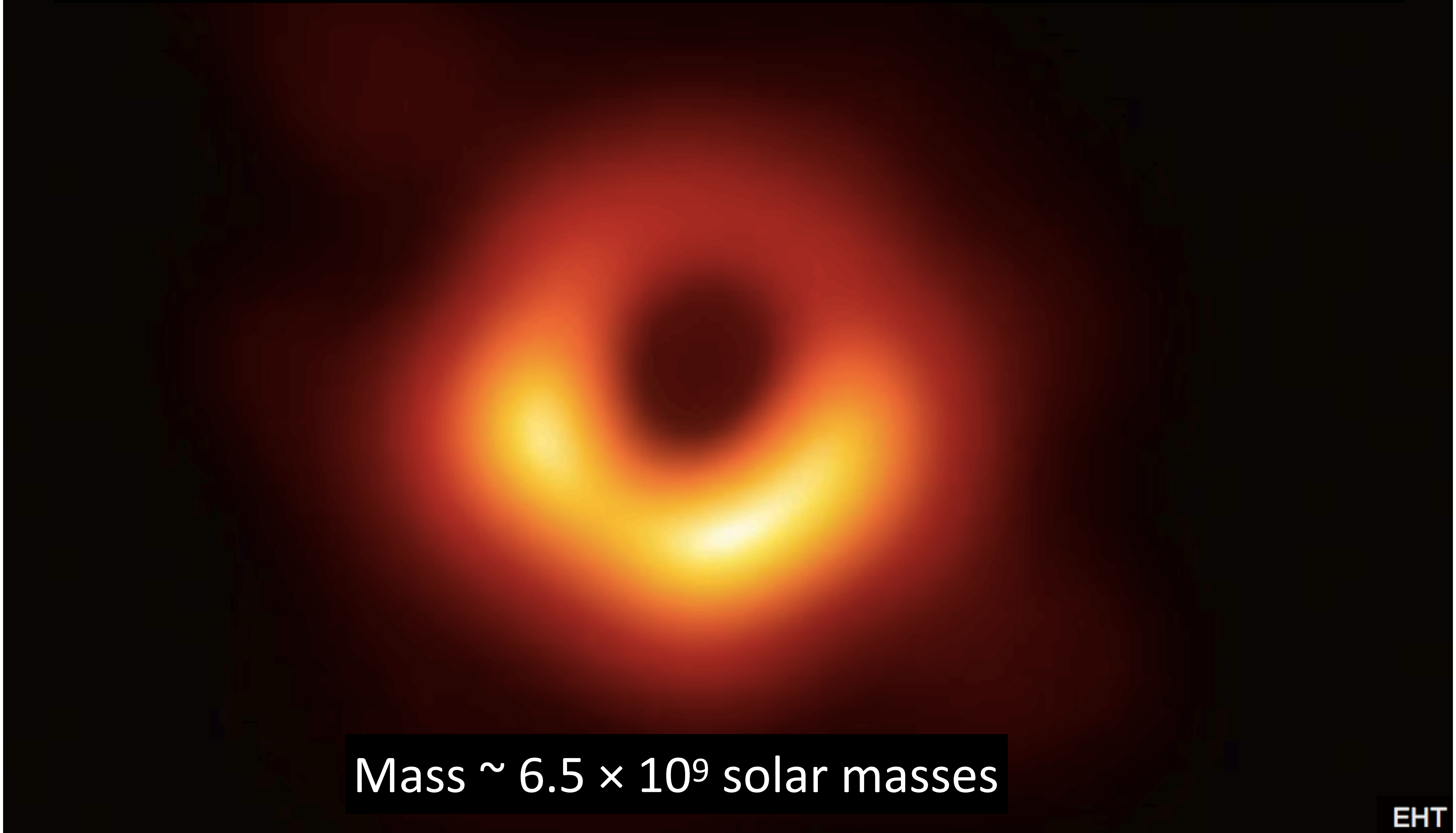


Badurina, Gibson, McCabe & Mitchell, *in preparation*

LIGO-Virgo-KAGRA Black Hole & Neutron Stars



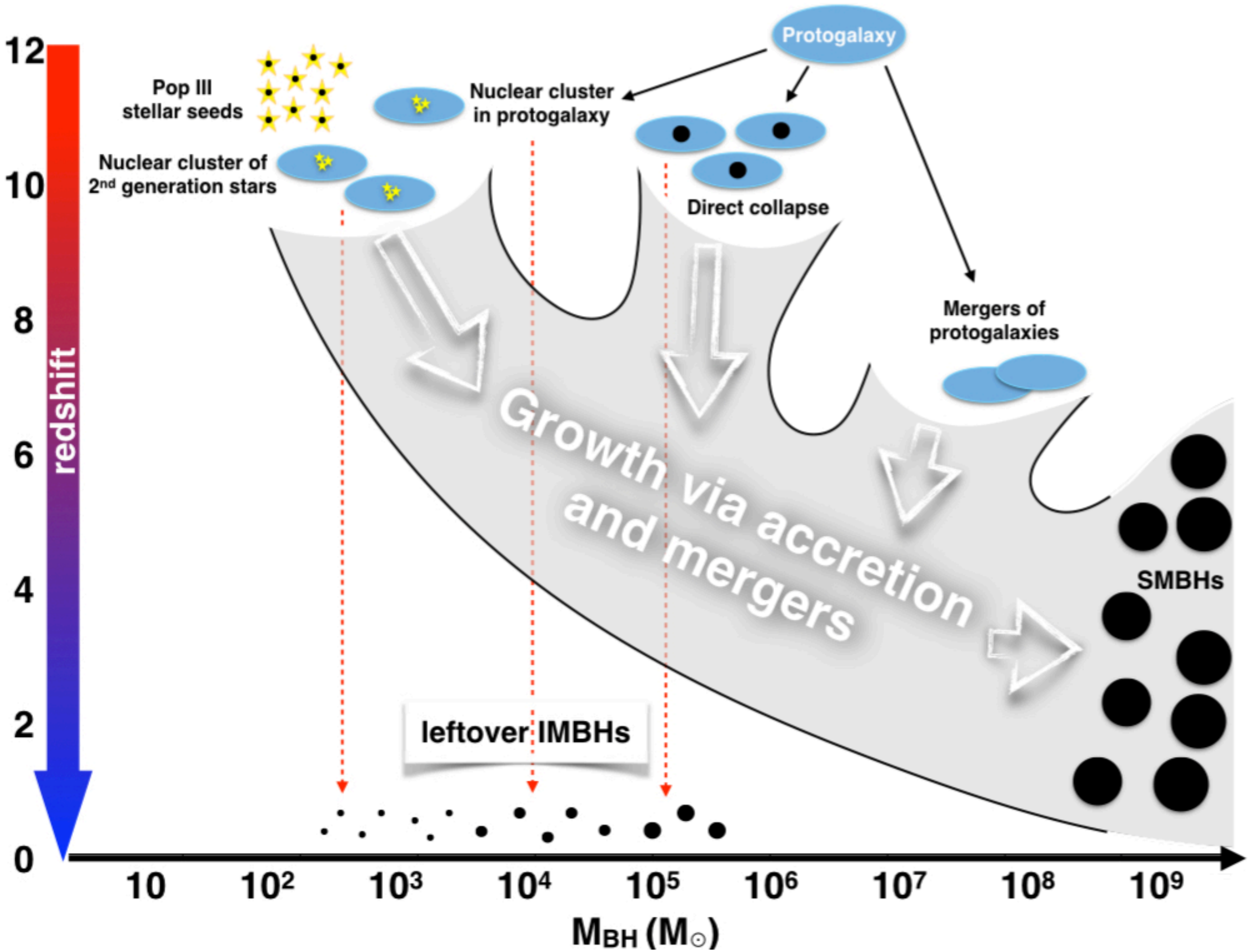
Supermassive Black Holes in Active Galactic Nuclei: Image of M87



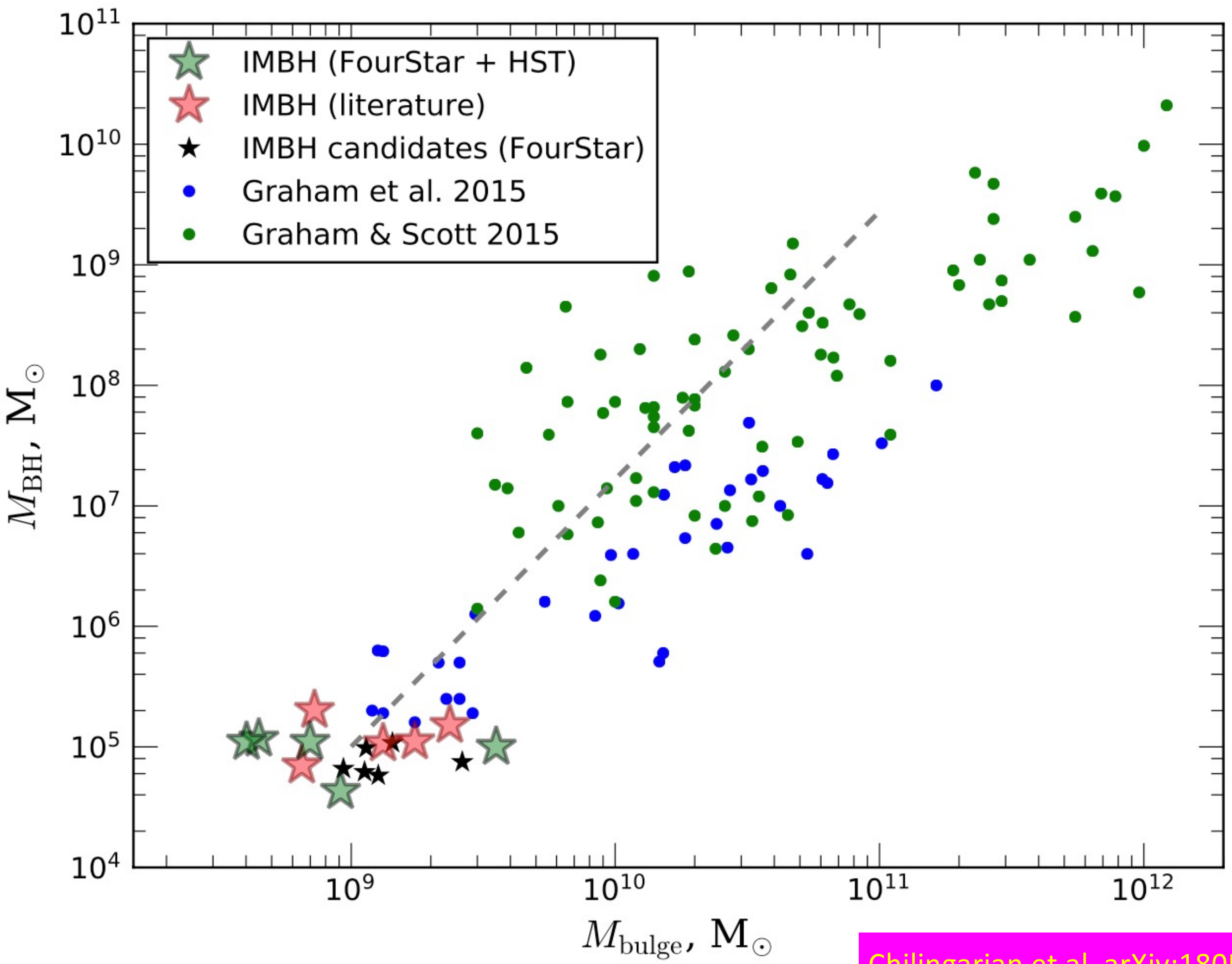
Mass ~ 6.5×10^9 solar masses

How to Make a Supermassive BH?

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

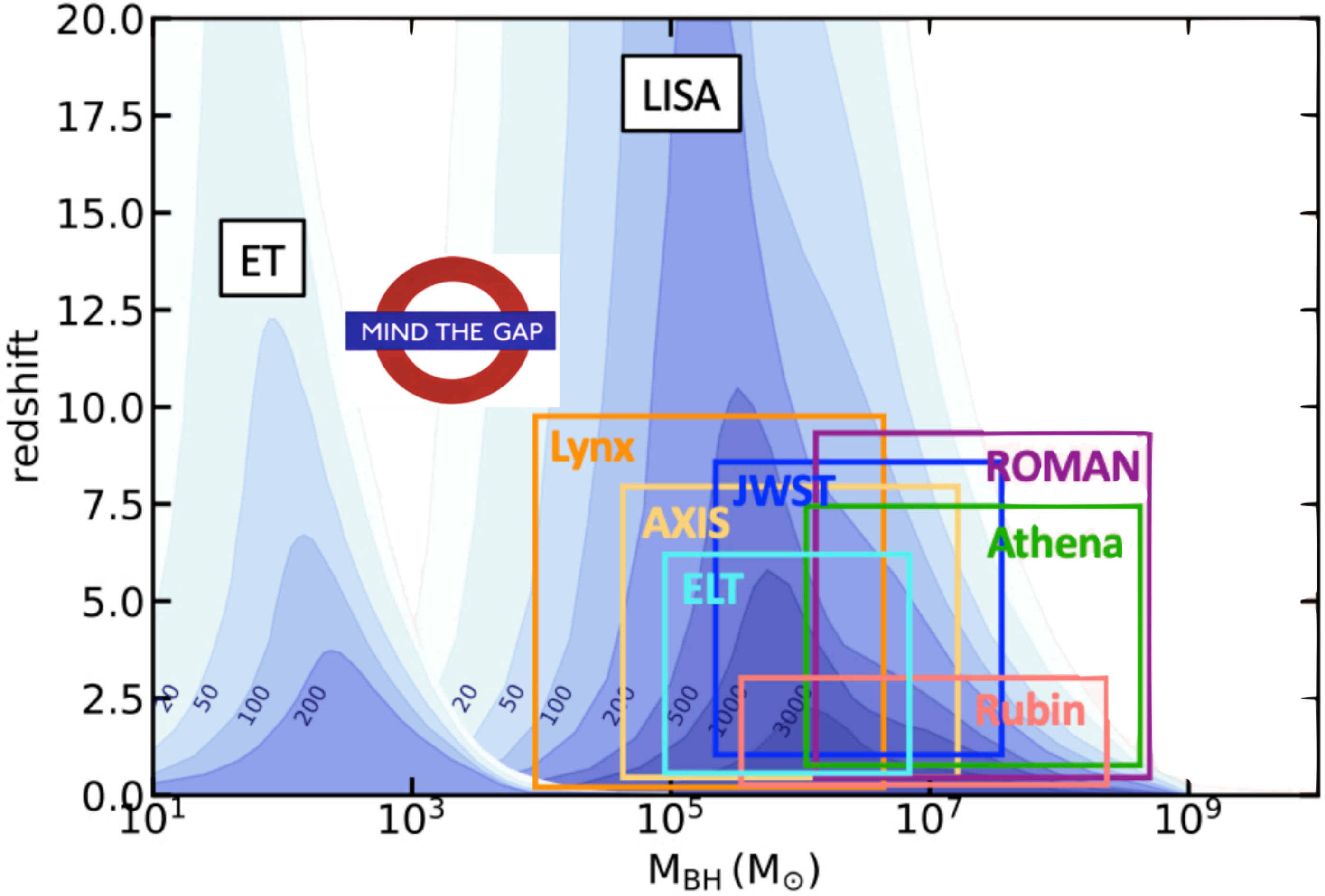


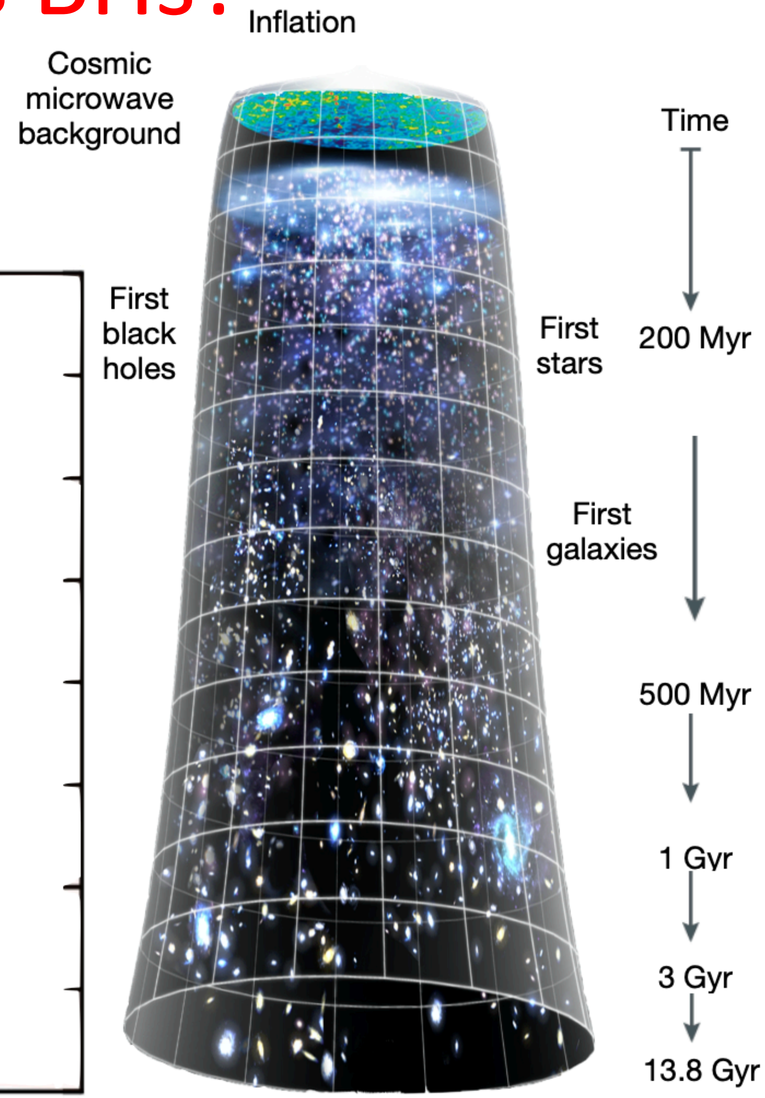
Intermediate Mass Black Holes Identified as Low-Luminosity Active Galactic Nuclei



Chilingarian et al, arXiv:1805.01467

How to Observe Mergers of Intermediate Mass BHs?



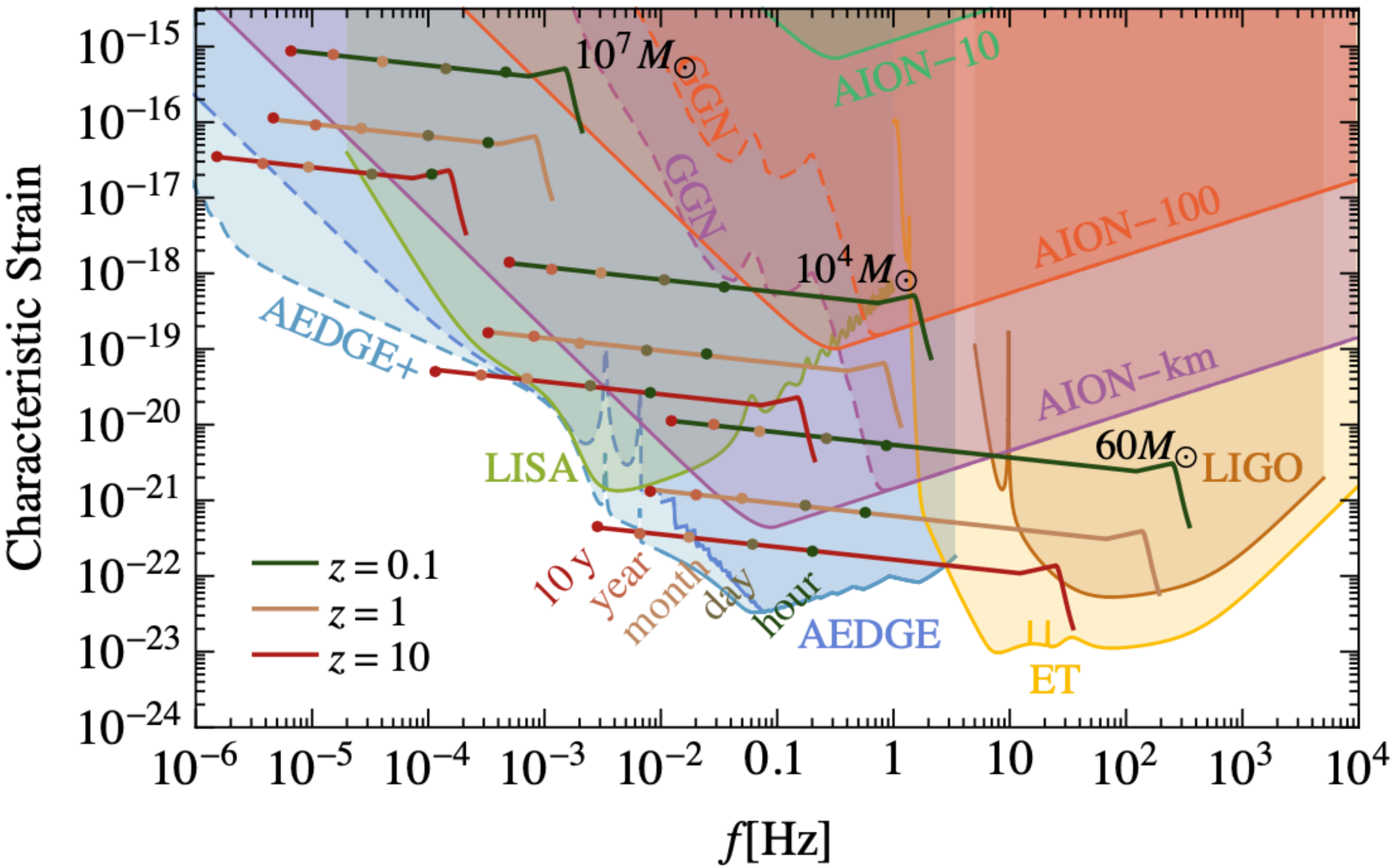


Volonteri, Habouzit & Colpi, arXiv:2110.10175

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

AION

Gravitational Waves from IMBH Mergers



Probe formation of SMBHs

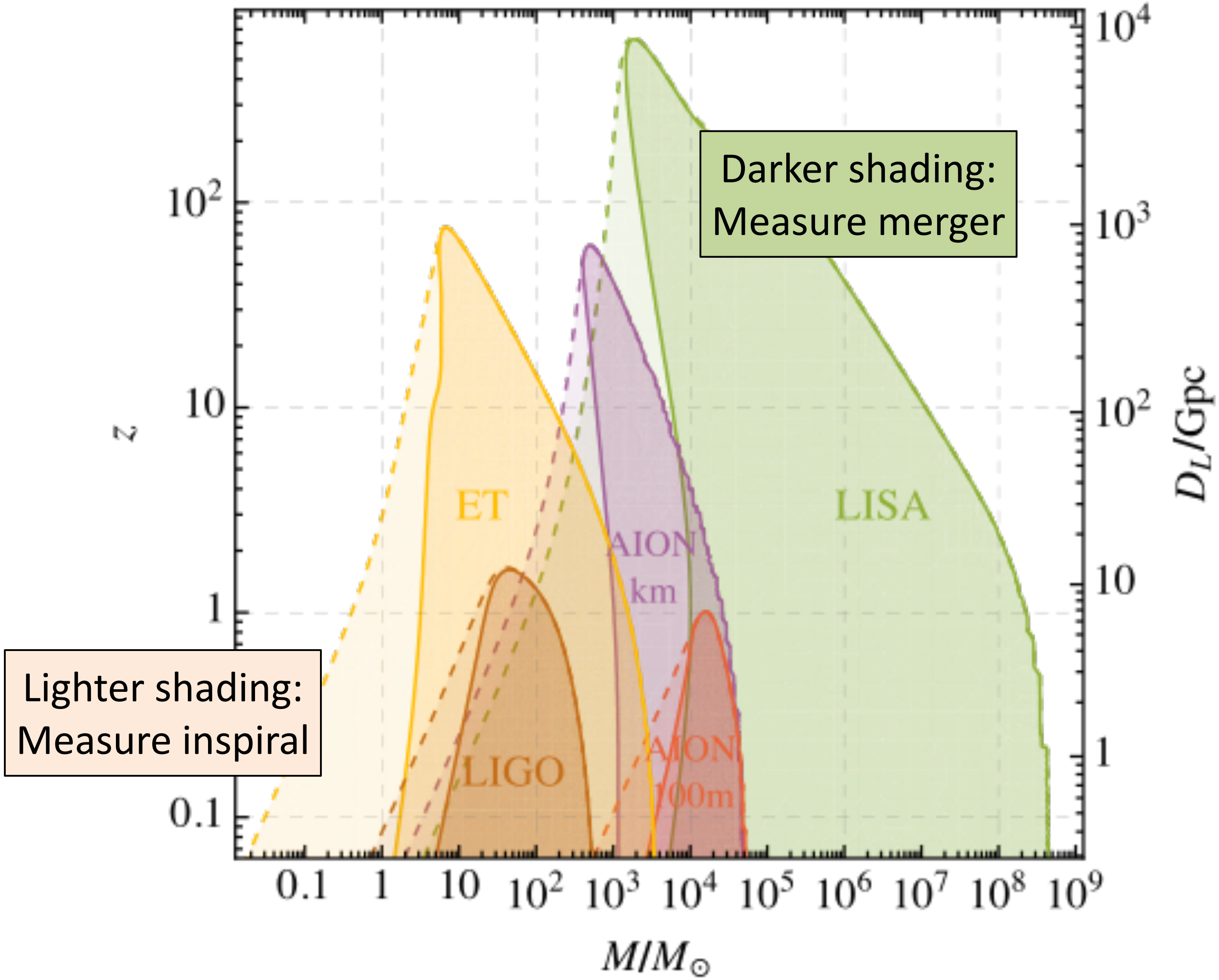
Synergies with other GW experiments (LIGO, LISA), test GR

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

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

GWs from IMBH Mergers: SNR = 8

AION

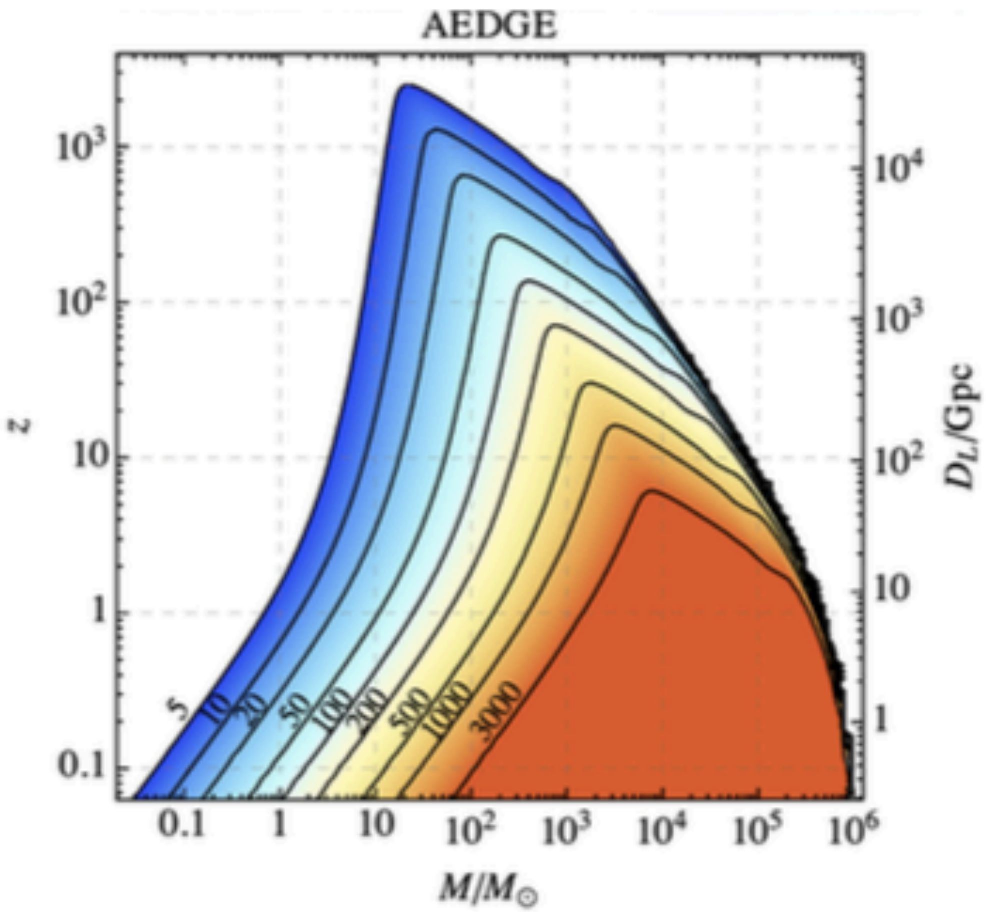


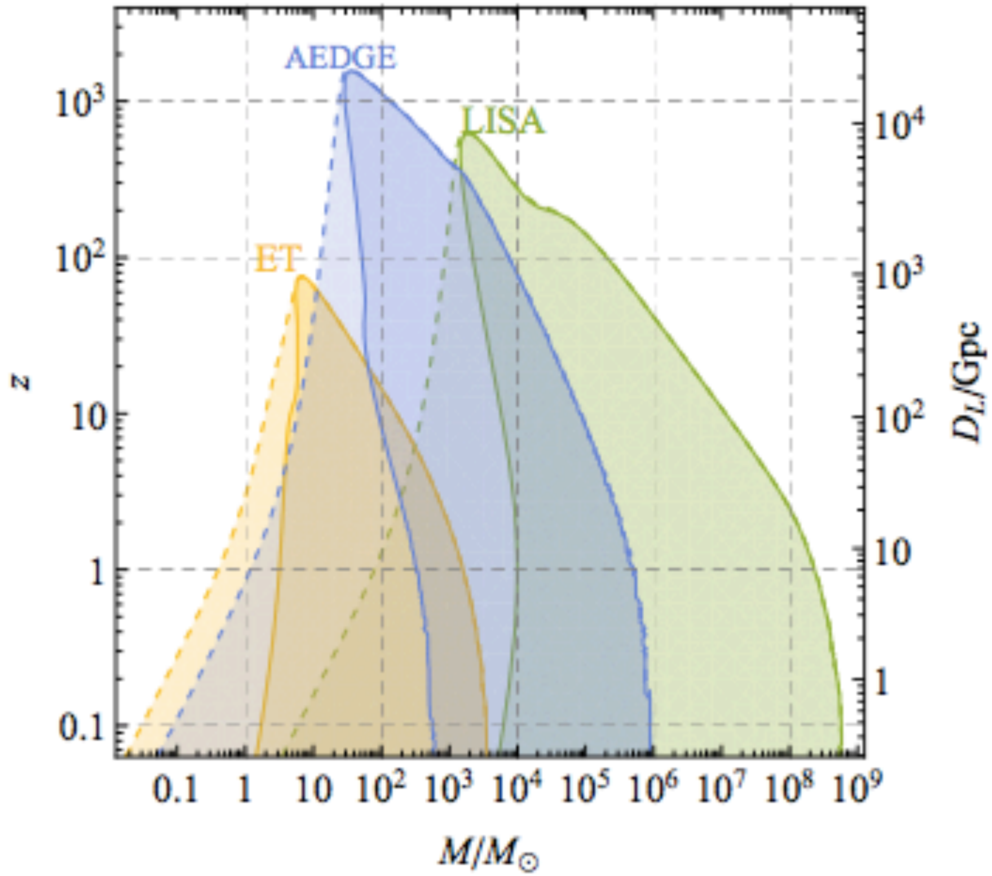
AION complementary to LIGO, Einstein Telescope (ET)

Operation before LISA

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

Gravitational Waves from IMBHs





Probe BHs in 10^2 solar-mass gap out to z ~ 10^3

Mergers of ~ 10^3 solar-mass BHs out to z > 10^2

Detect mergers of ~ 10^4 solar-mass BHs

with SNR 1000 out to z ~ 10

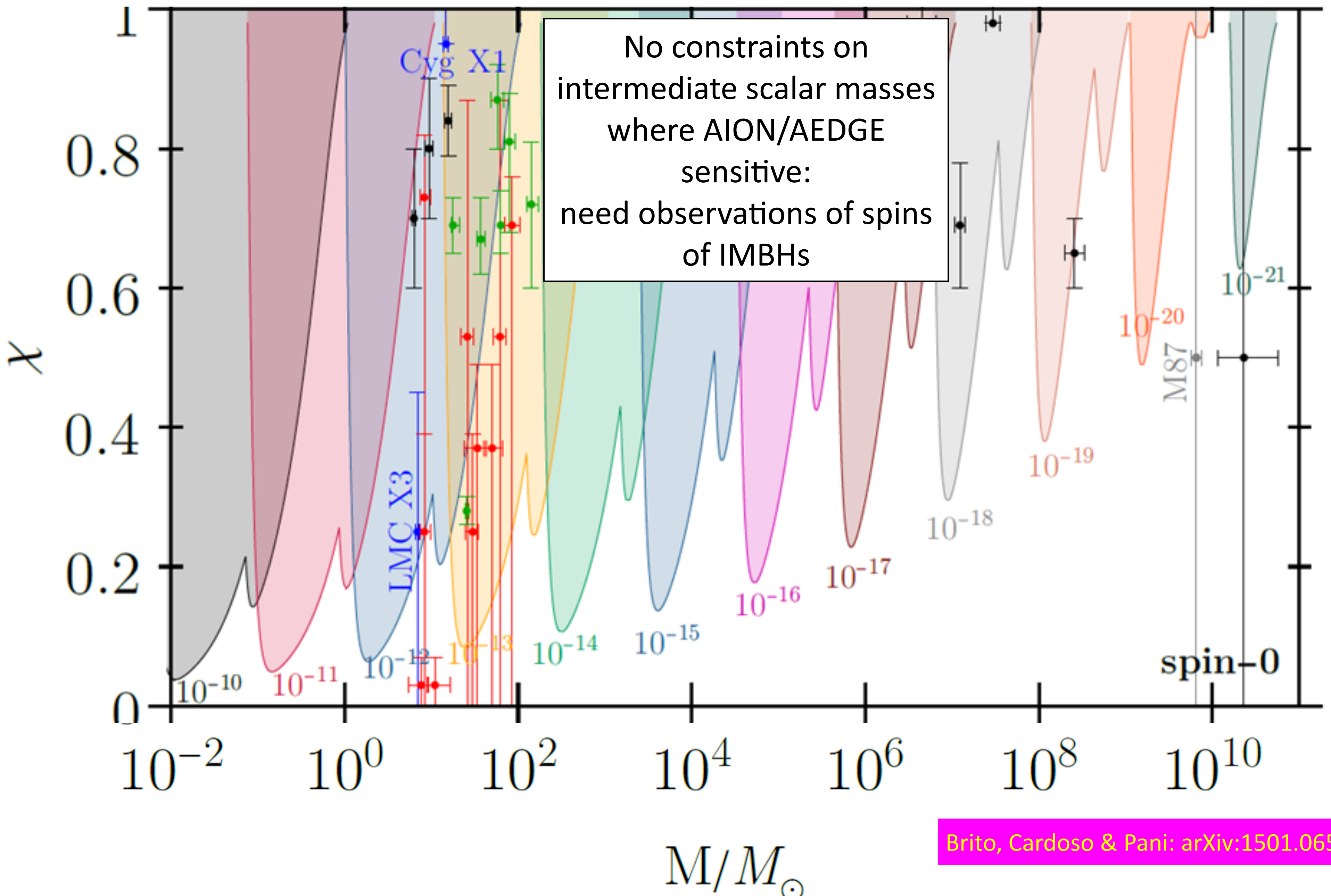
Lighter shades: inspiral

Darker shades: merger + ringdown

Complementarity + synergy

Black Hole Superradiance

Boson emission may cause spin-down of black holes (if self-interactions weak)

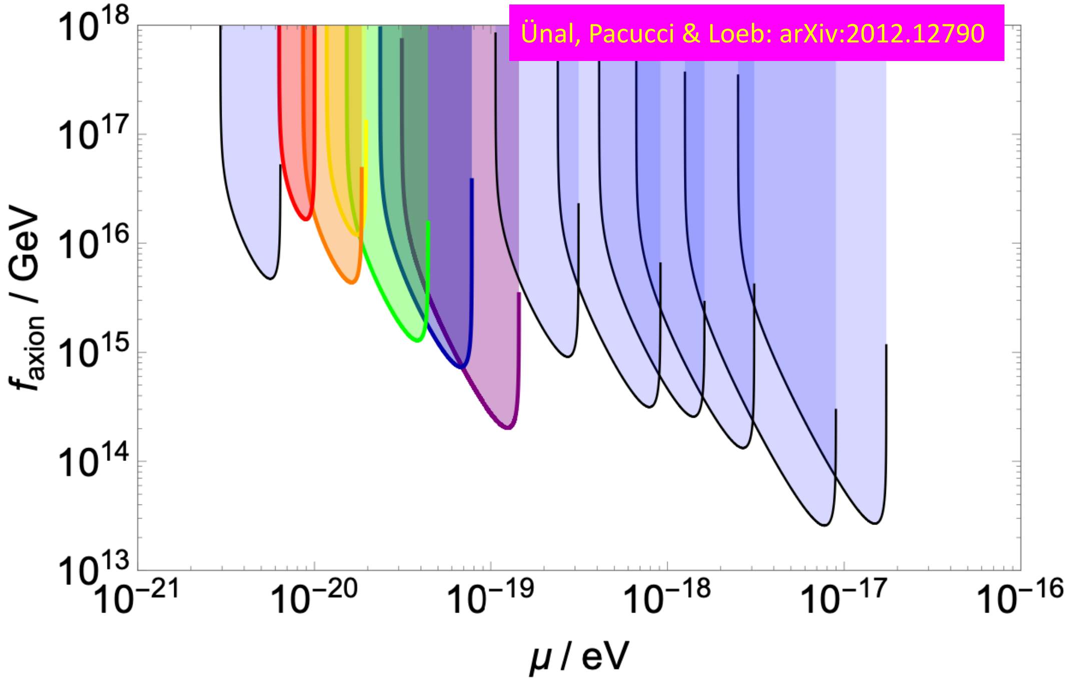


Brito, Cardoso & Pani: arXiv:1501.06570

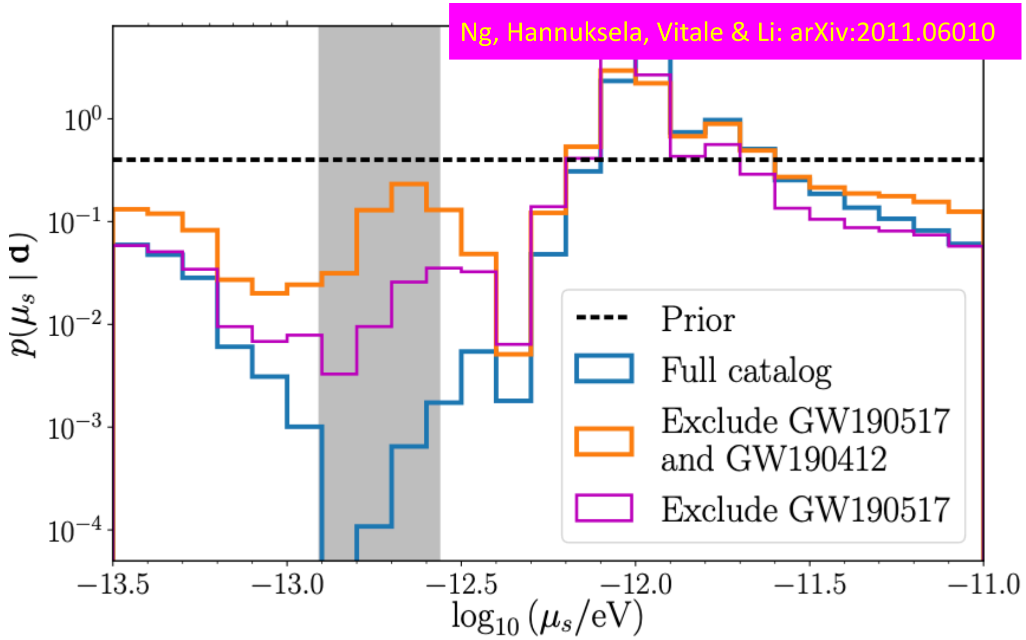
Black Hole Superradiance

Boson emission causes spin-down of black holes (if self-interactions weak)

AGNs constrain masses $< 2 \times 10^{-17}$ eV

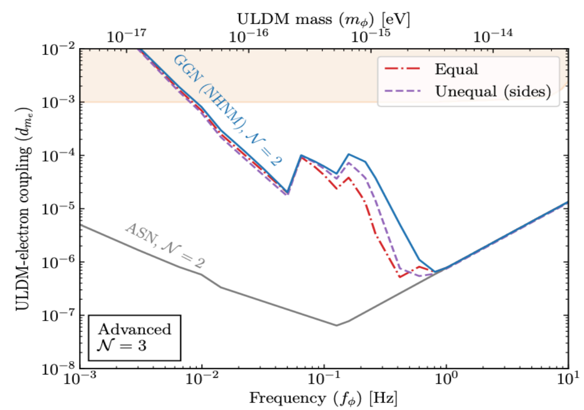


LIGO constrains masses $> 3 \times 10^{-14}$ eV



Object	$M/10^6 M_\odot$	a
[1] 1H0707-495	3 ± 1	> 0.97
[2] IRAS13224–3809	6.3	> 0.987
[3] MRK 335	14.2 ± 3.7	> 0.91
[4] Mrk 110	25.1 ± 6.1	> 0.89
[5] NGC 4151	$45.7^{+5.7}_{-4.7}$	> 0.9
[6] Ark 120	118 ± 16	> 0.85
[7] 1H0419-577	~ 340	> 0.96
M87	$\sim 6.5 \times 10^3$	0.9 ± 0.1

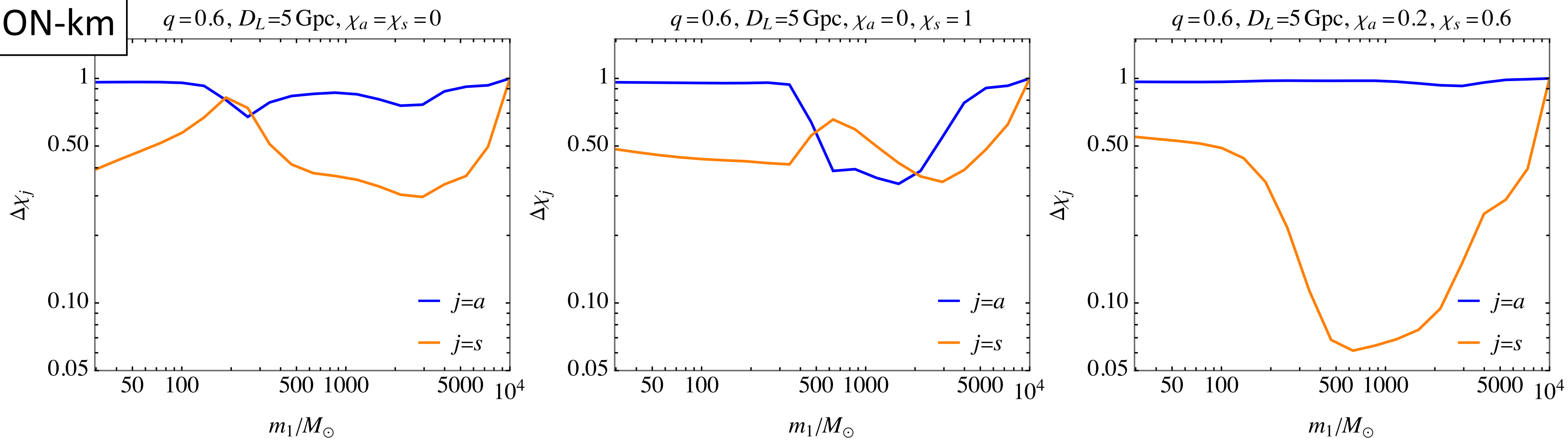
No constraints on intermediate scalar masses where AION/AEDGE sensitive: would need observations of spins of IMBHs



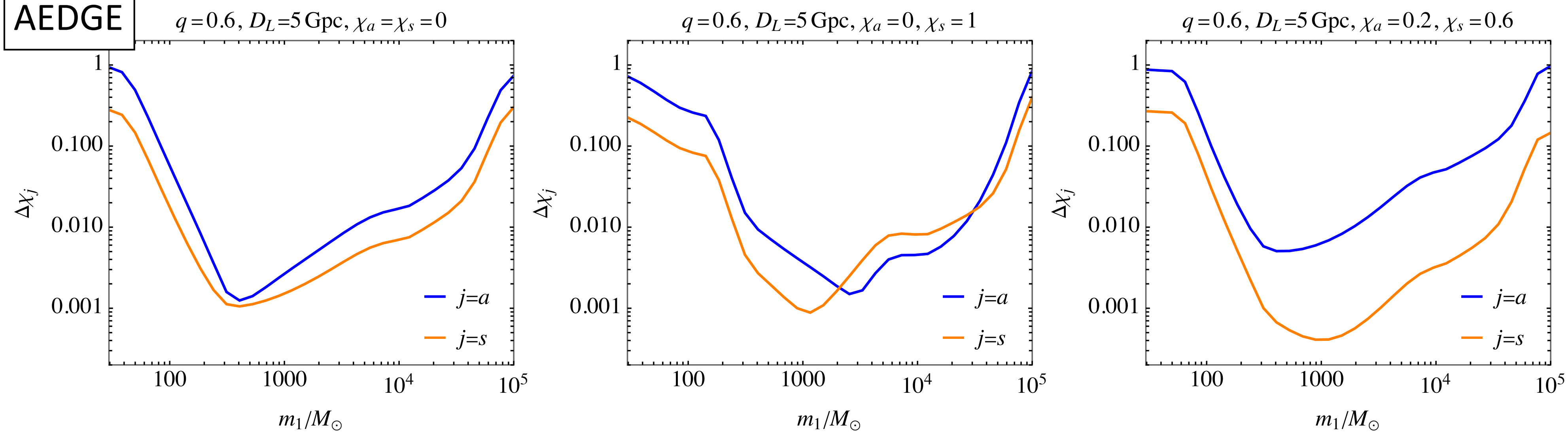
Prospective Spin Measurements with AION-km, AEDGE

JE & Vaskonen: *in preparation*

AION-km

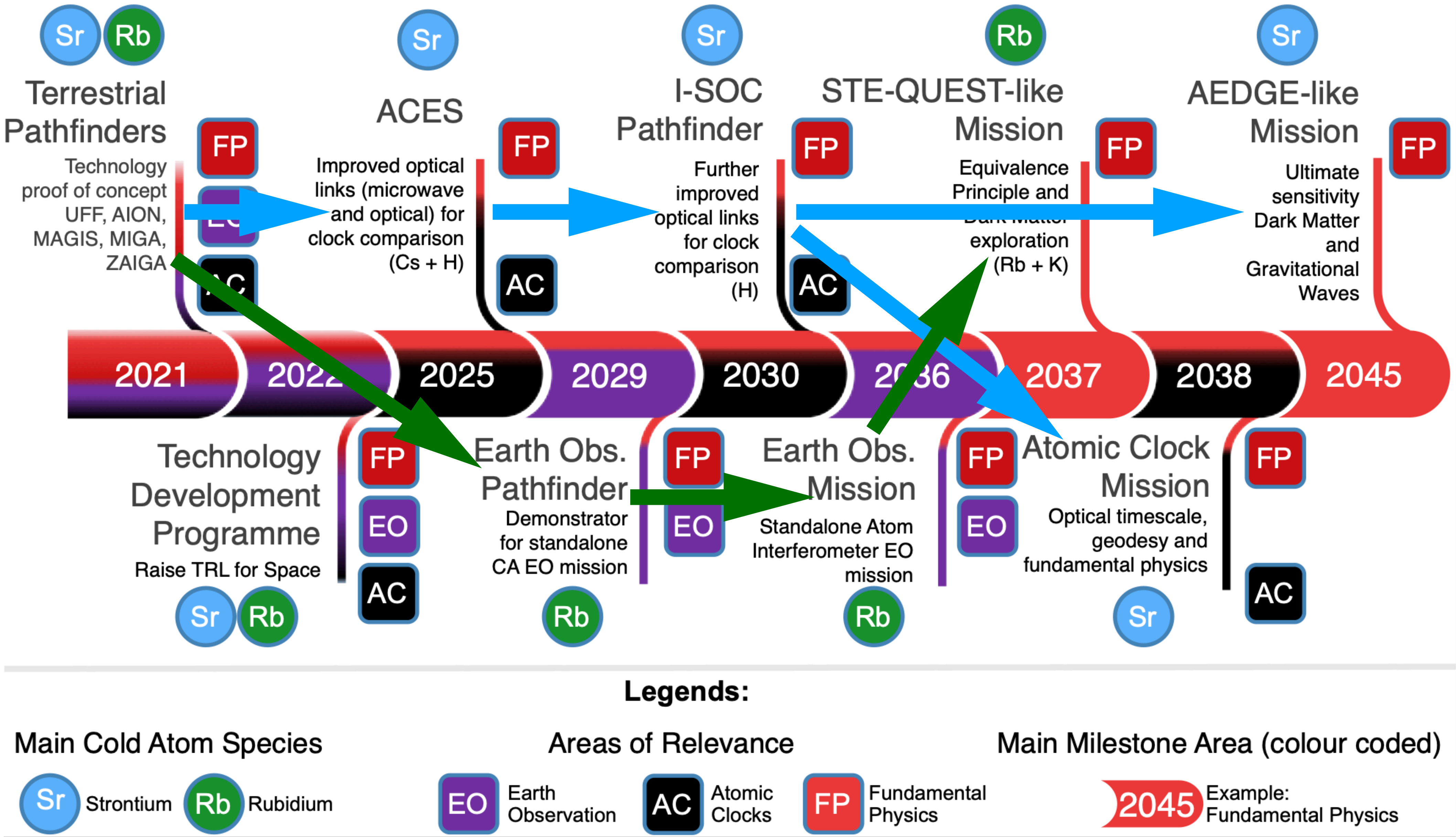


AEDGE



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

Proposed ESA Road-Map for Cold Atoms in Space



ESA Call for
M, F-Class Science Missions

call for missions 2021

esa

- 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 Proposal

Compare free fall of clouds of Rb and K

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
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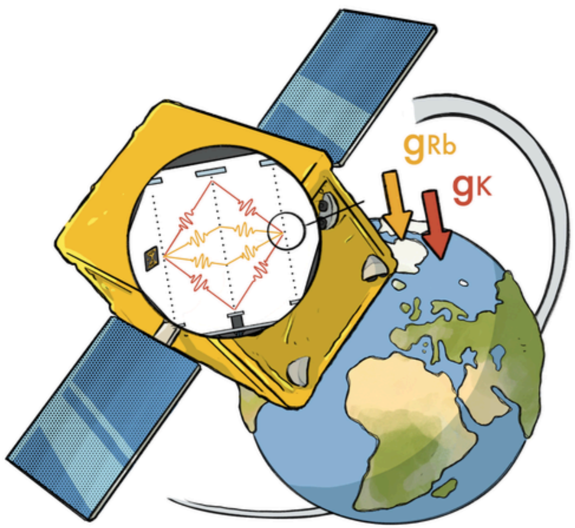
June 28, 2022



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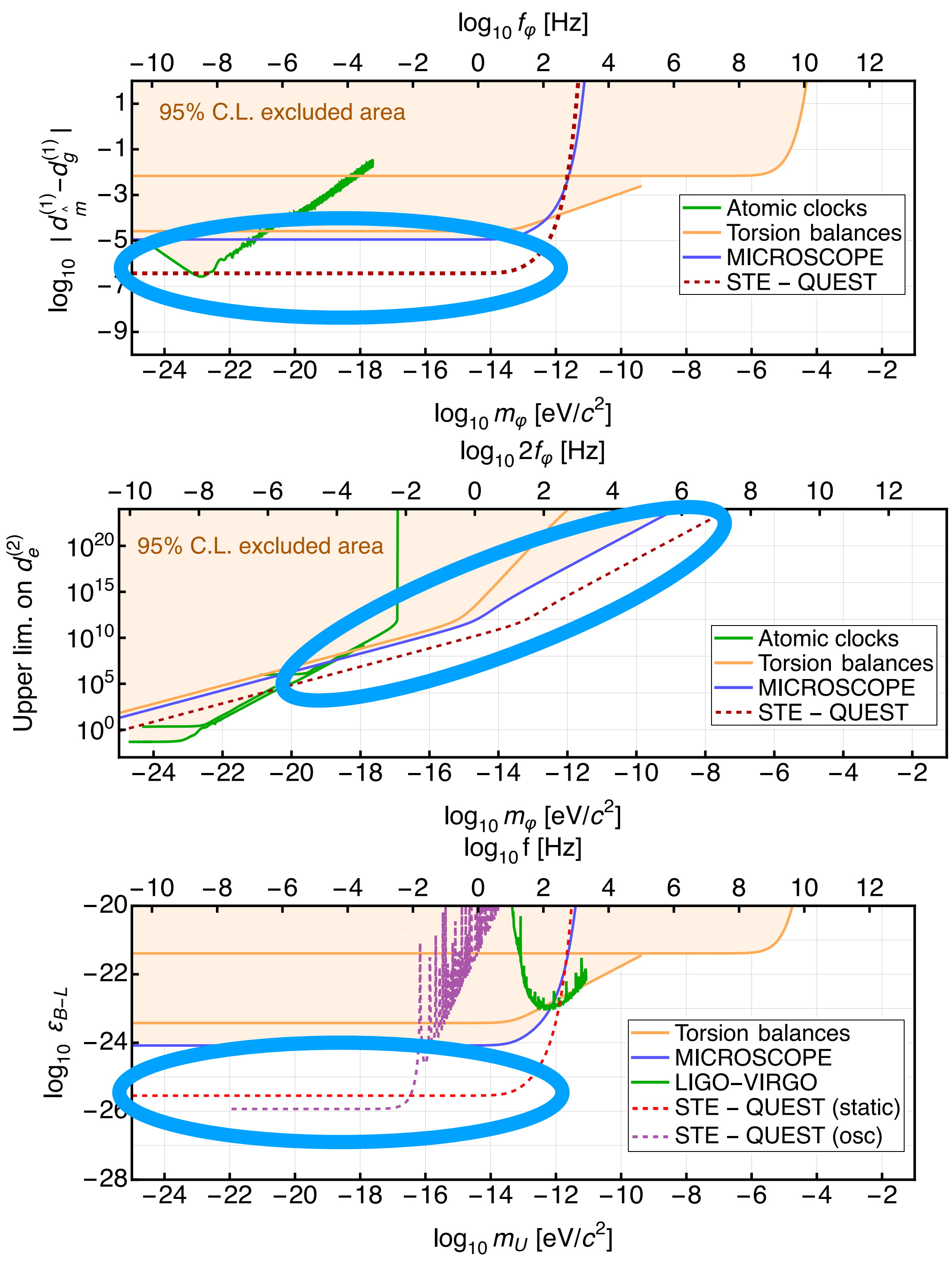
Testing the Equivalence Principle

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	$(-1.5 \pm 2.7) \times 10^{-15}$	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	$\bar{\mathrm{H}}$ - H	(10^{-2})	2023+	under construction at CERN

MICROSCOPE Collaboration, PRL 129, 121102, 2022

STE-QUEST Science: Searching for Ultralight Dark Matter



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:

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

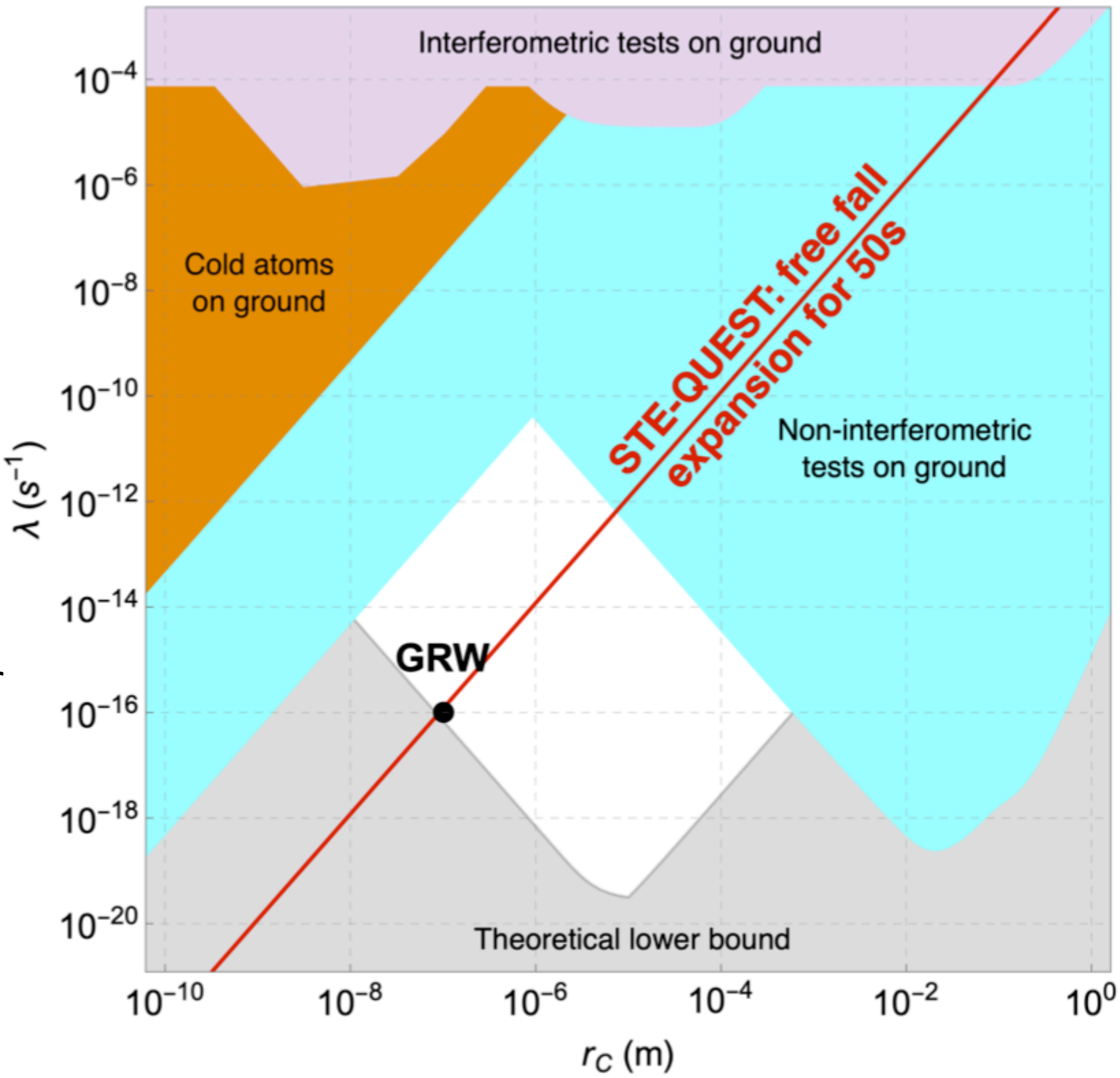
- General parametrisation: $e^{-\frac{d}{r_c}}, e^{-\lambda t}$

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



STE-QUEST Science Programme

Probe the boundaries of our fundamental theories
and the interfaces between them