Searching for Ultralight Dark Matter and Gravitational Waves

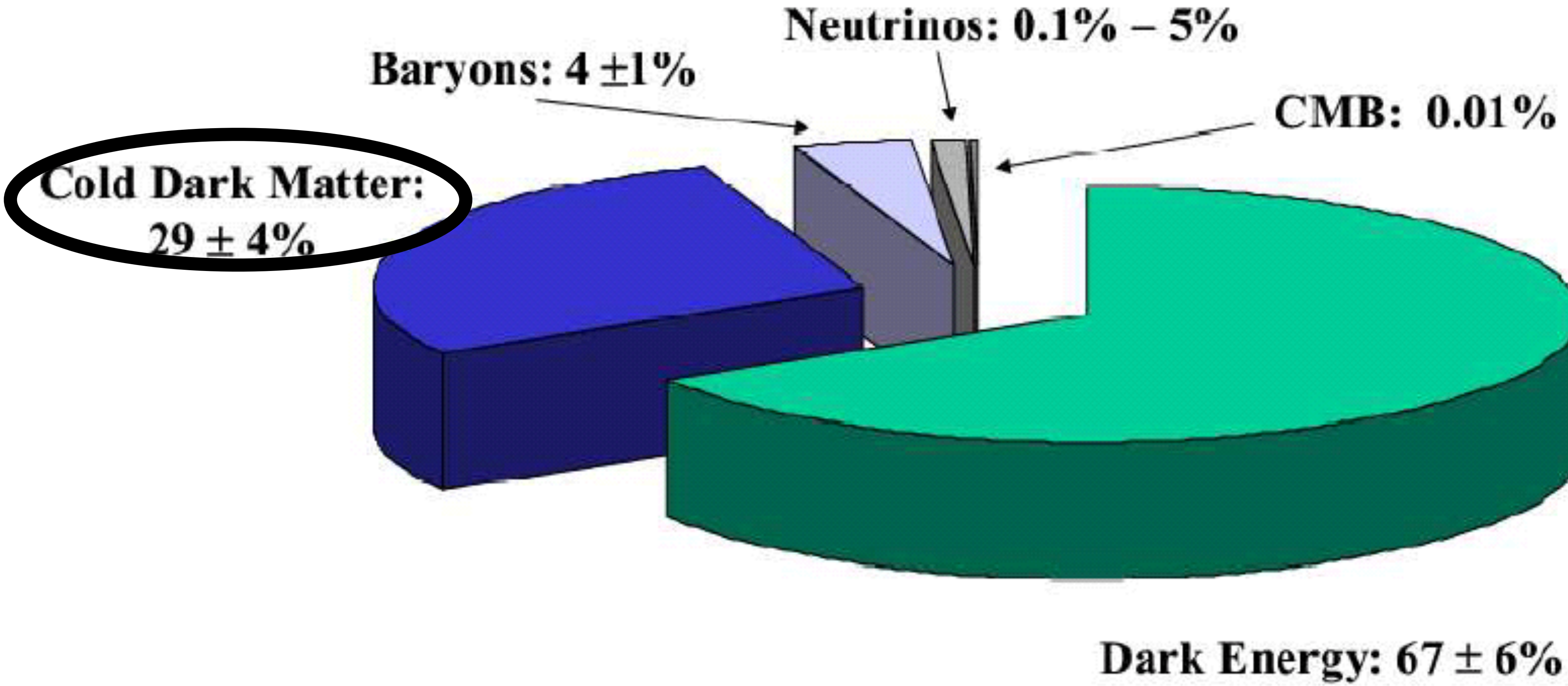
with Atom Interferometers

Recap on Dark Matter and Gravitational Waves
Quantum Sensors for Fundamental Physics projects
Focus on AION project
Search for ultralight dark matter
Gravitational Wave science opportunities
Vision for atom interferometry in space

John Ellis

KING'S College LONDON

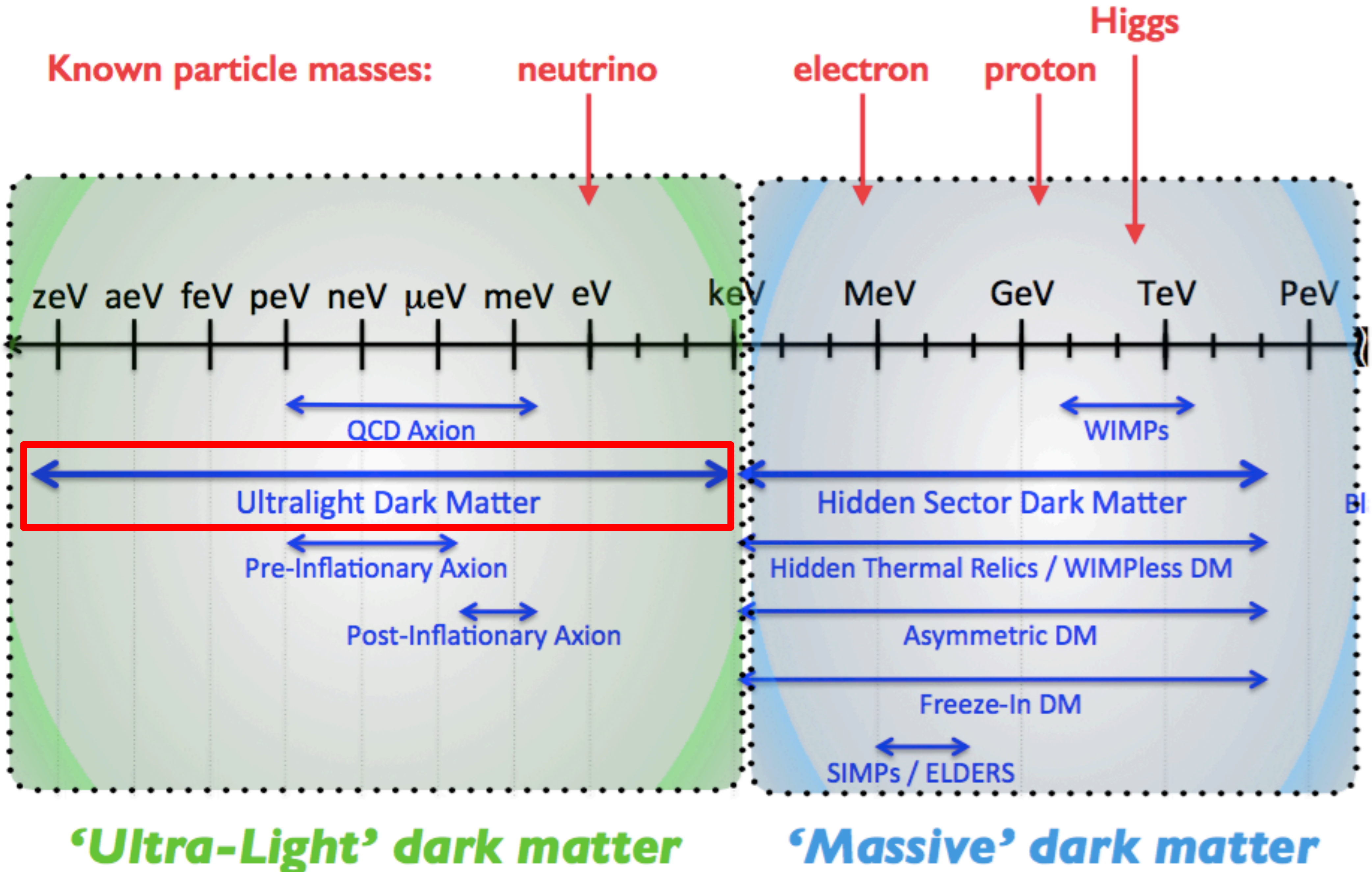
Strange Recipe for a Universe



The 'Standard Model' of the Universe

indicated by astrophysics and cosmology

Search for Ultralight Dark Matter



Gravitational Waves

- General relativity proposed by Einstein 1915
- He predicted gravitational waves in 1916

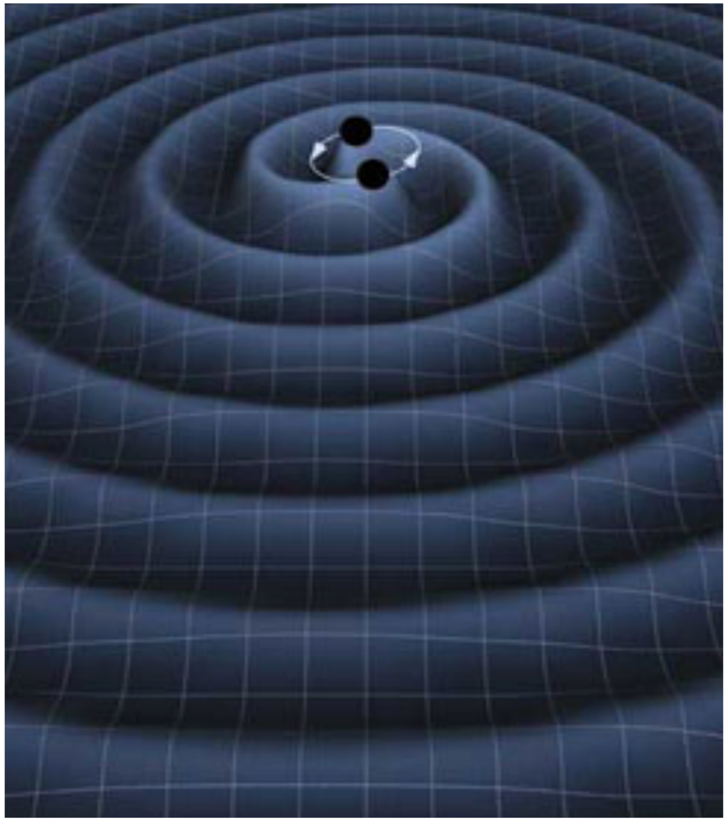
Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Prob… auf dem Gebiete der Gravitationstheorie kann man sich damit begn… die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich… Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen… in der speziellen Relativitätstheorie. Unter »erster Näherung« ist d… verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu}$$

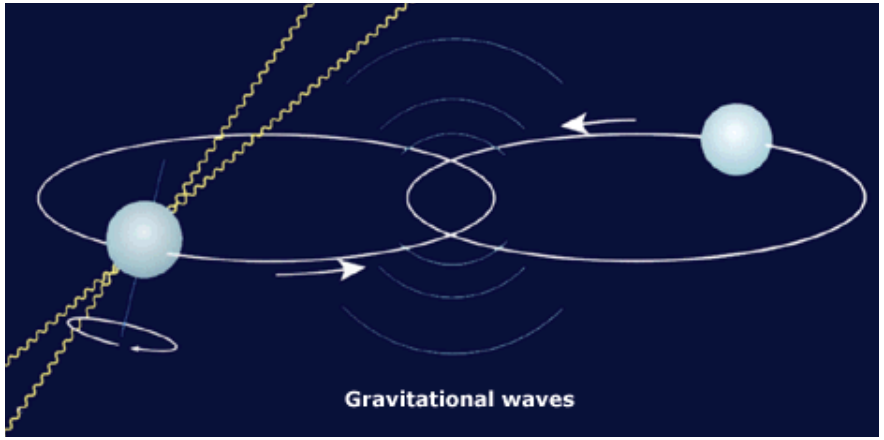
Albert Einstein, *Näherungsweise Integration der Feldgleichungen der Gravitation*, 22.6.Berlin 1916

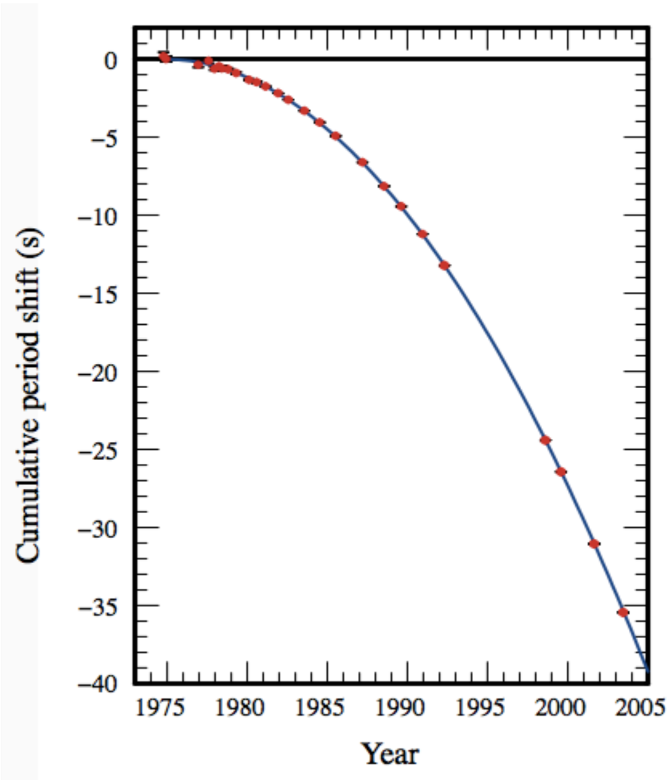


- Tried to retract prediction in 1936!

Indirect Detection

- Binary pulsar discovered 1974 (Hulse & Taylor)
- Emits gravitational waves
- Change in orbit measured



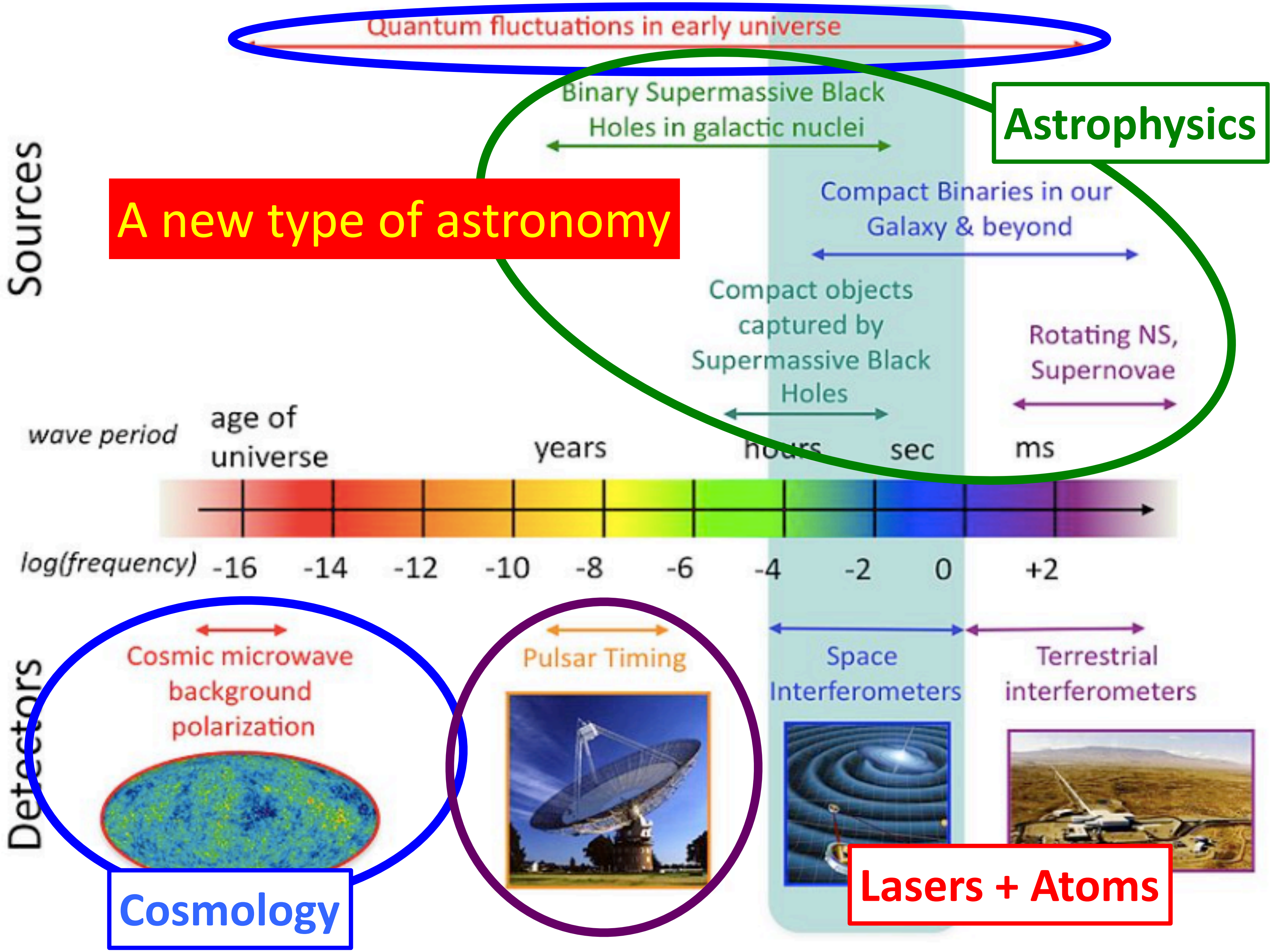


for years

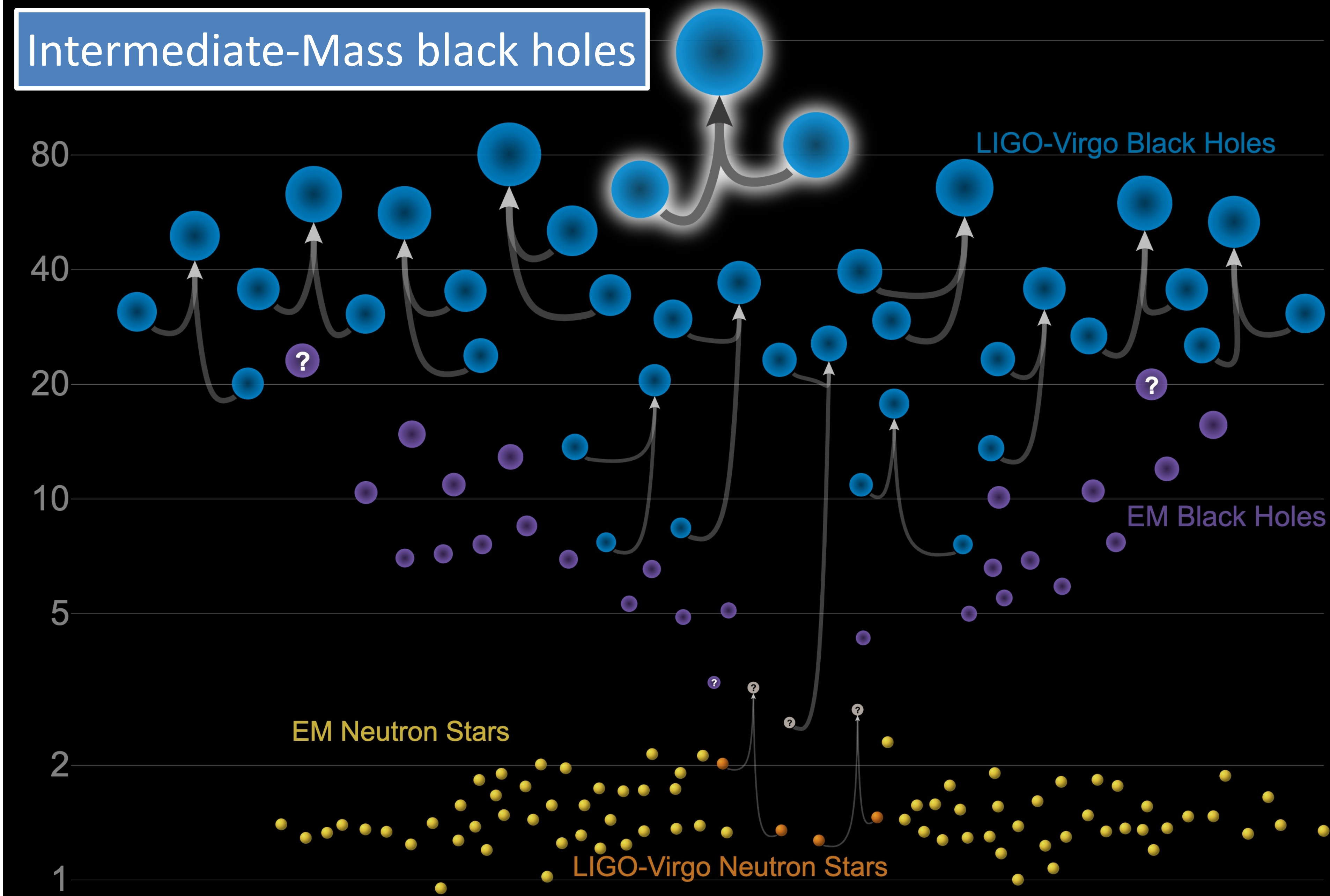
Perfect agreement with Einstein

Nobel Prize 1993

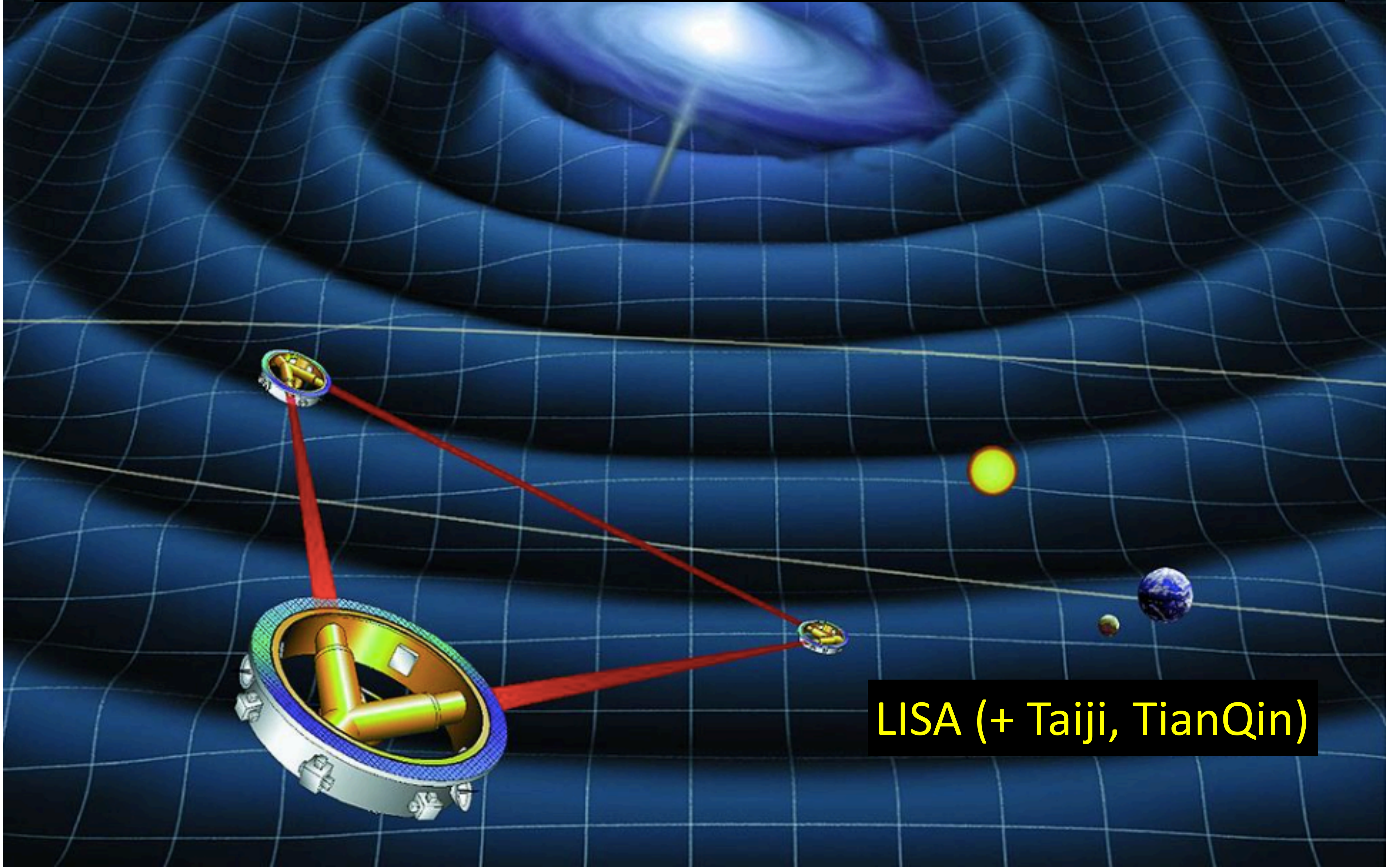
Gravitational Wave Spectrum



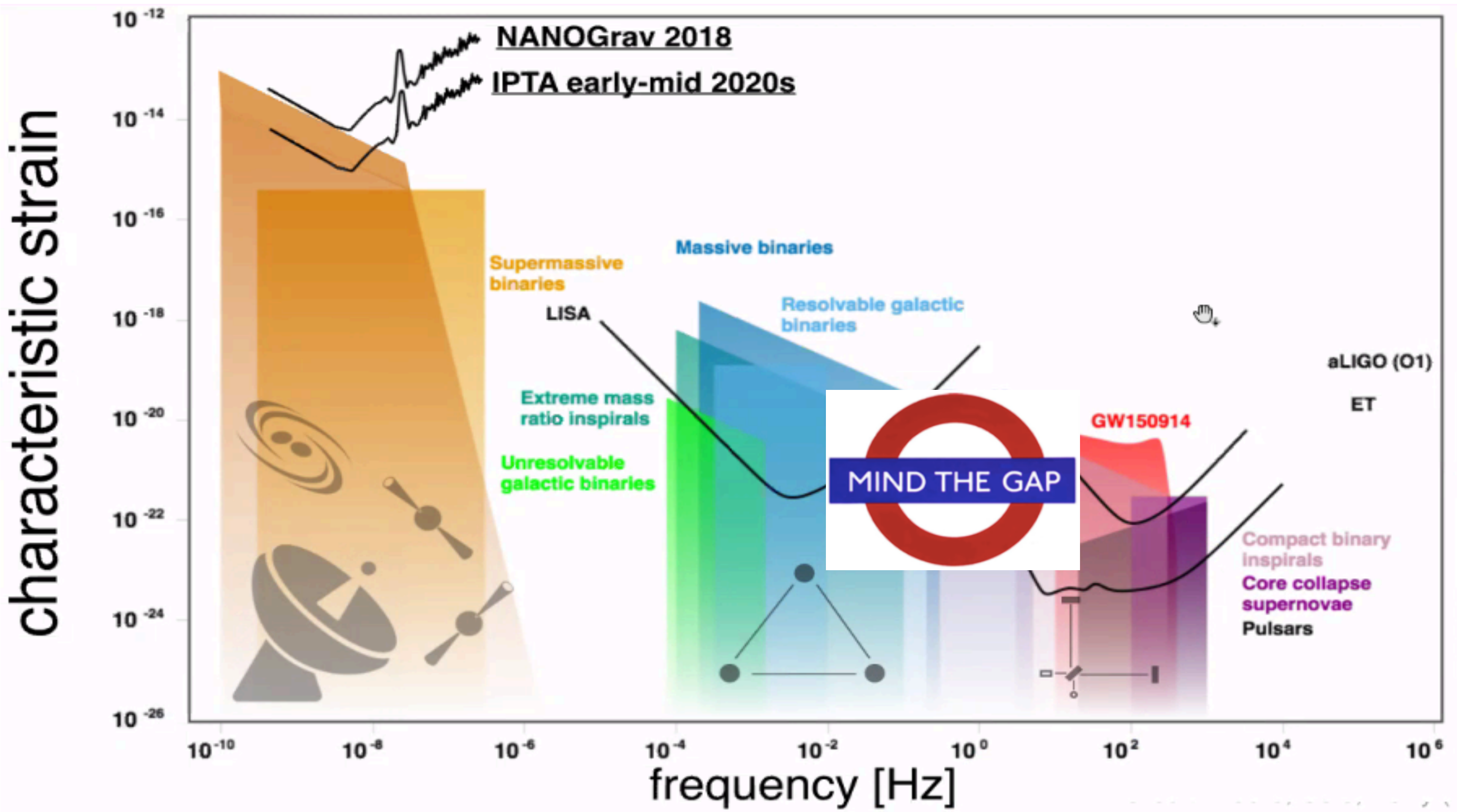
LIGO-Virgo Black Hole & Neutron Star Masses



Future Step: Interferometer in Space

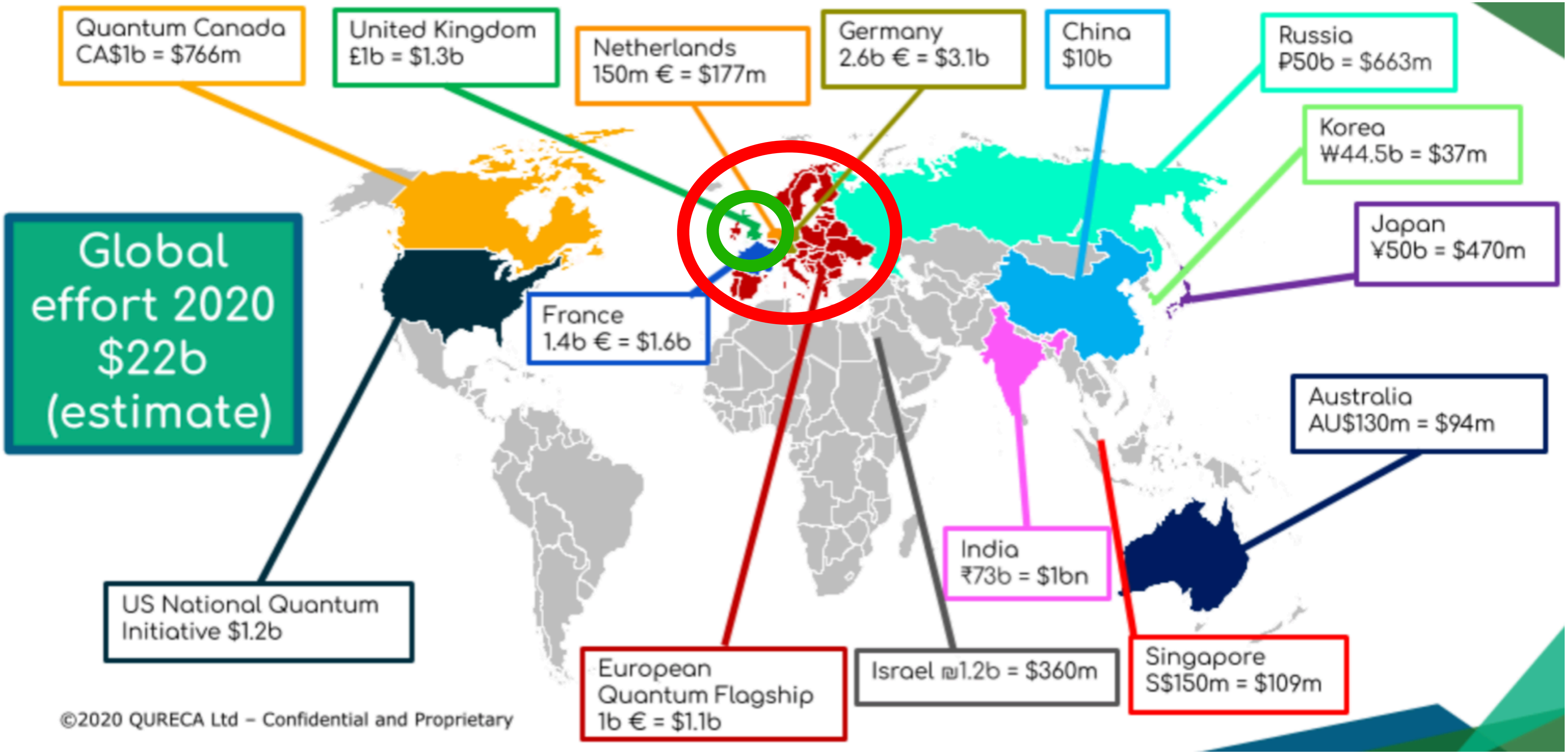


Gravitational Wave Spectrum



- 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)

Quantum Science & Technology Programmes



UK National Quantum Technology Programme

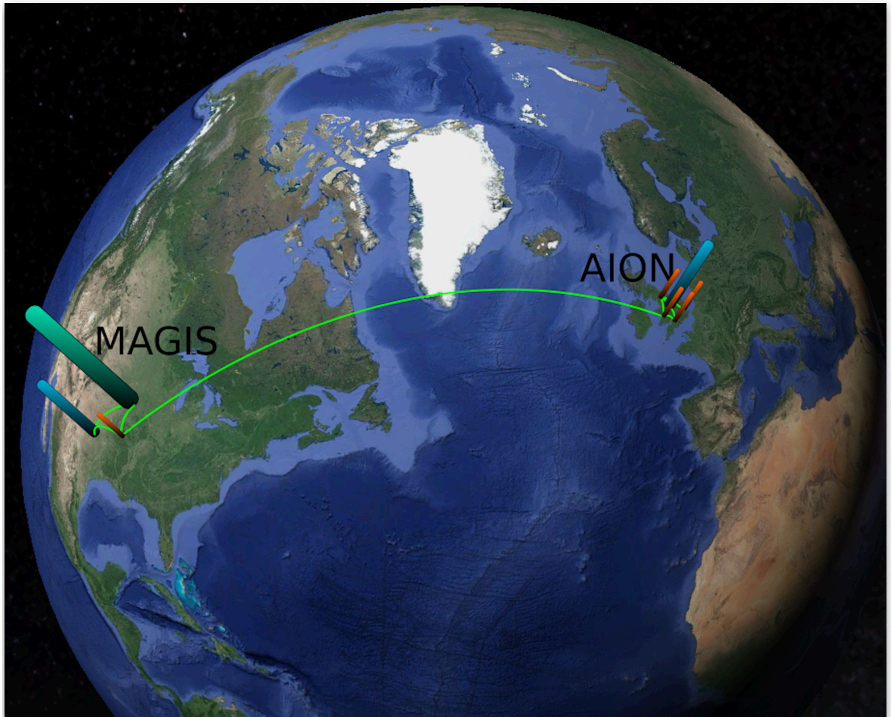
- *Phase 1 2015-2019, Phase 2 2020-24 (total investment Phase 1+2= £1B)*
- *Phase 2 investments:*
  - *Industry led projects to drive innovation and commercialisation of QT (£173m over 6 years)*
  - Renewal of the QT Research Hubs (£94m over 5 years)
  - Research training portfolio (£25m over 5 years)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

Seven samurai …

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],
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

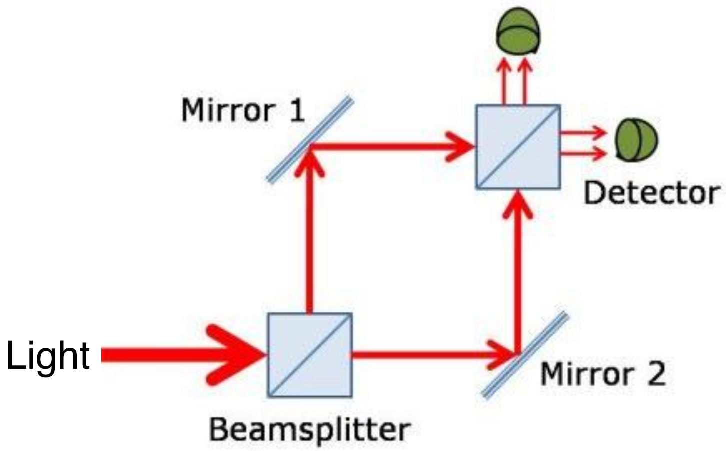


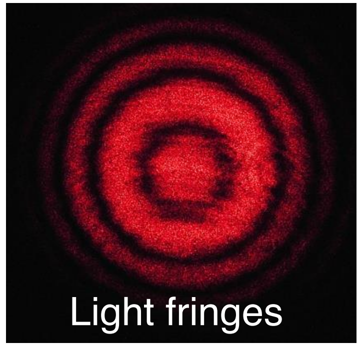
Network with MAGIS project in US

MAGIS Collaboration (Abe et al): arXiv:2104.02835

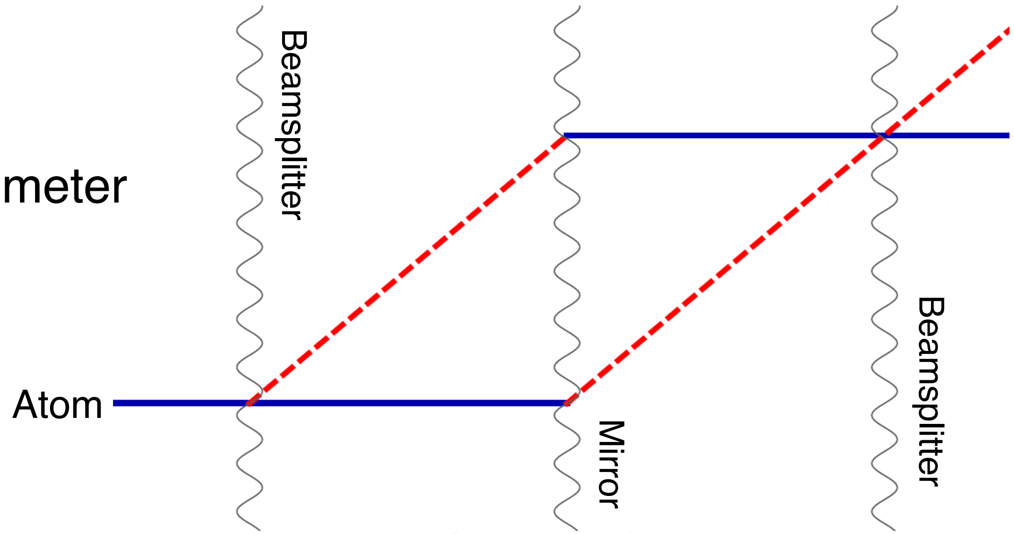
Principle of Atom Interferometry

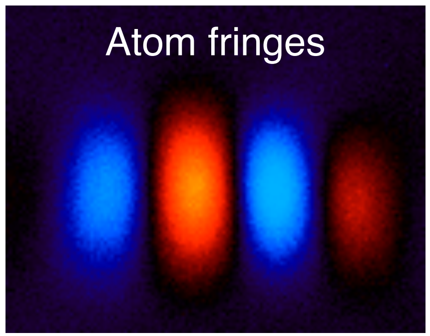
Light interferometer





Atom interferometer





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

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

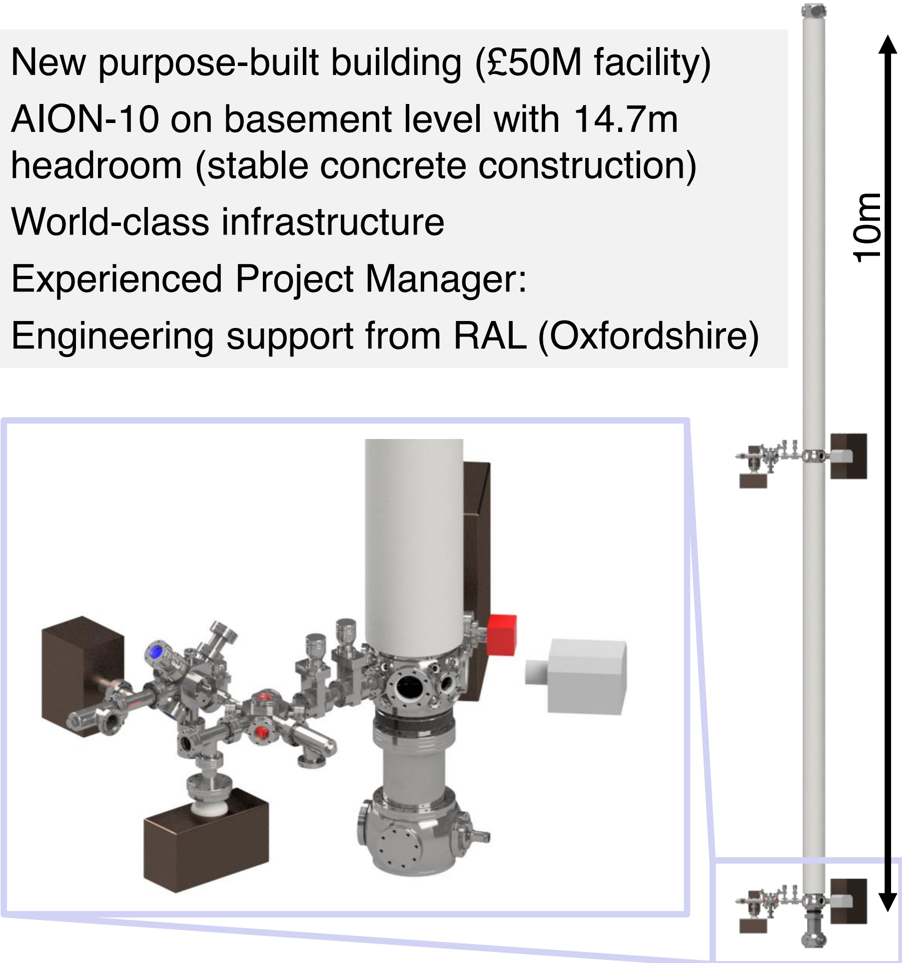
- AION-100: Stage 2 [year 3 to 6]
  - 100m Construction & commissioning
- AION-KM: Stage 3 [> year 6]
  - Operating AION-100 and planning for 1 km & beyond
- AION-SPACE (AEDGE): Stage 4 [after AION-km]
  - Space-based version

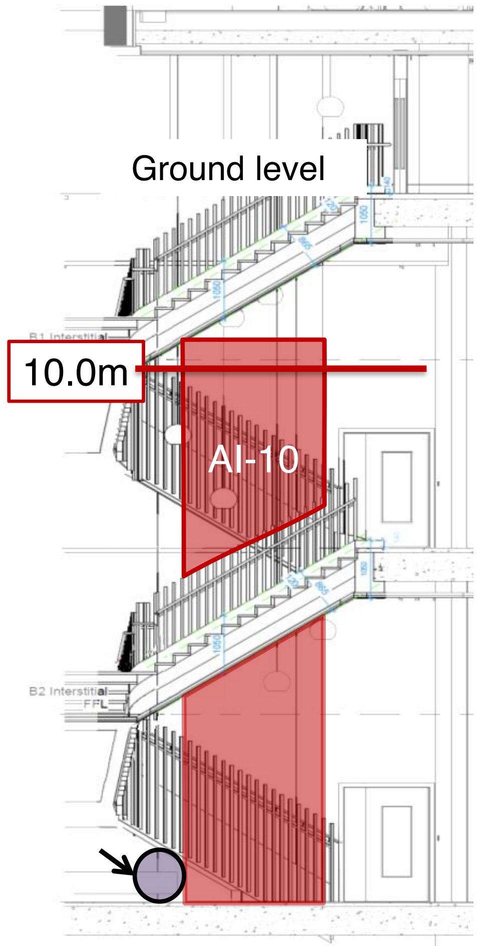
AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755

Planned Location of AION-10m

AION-10 @ Beecroft building, Oxford Physics

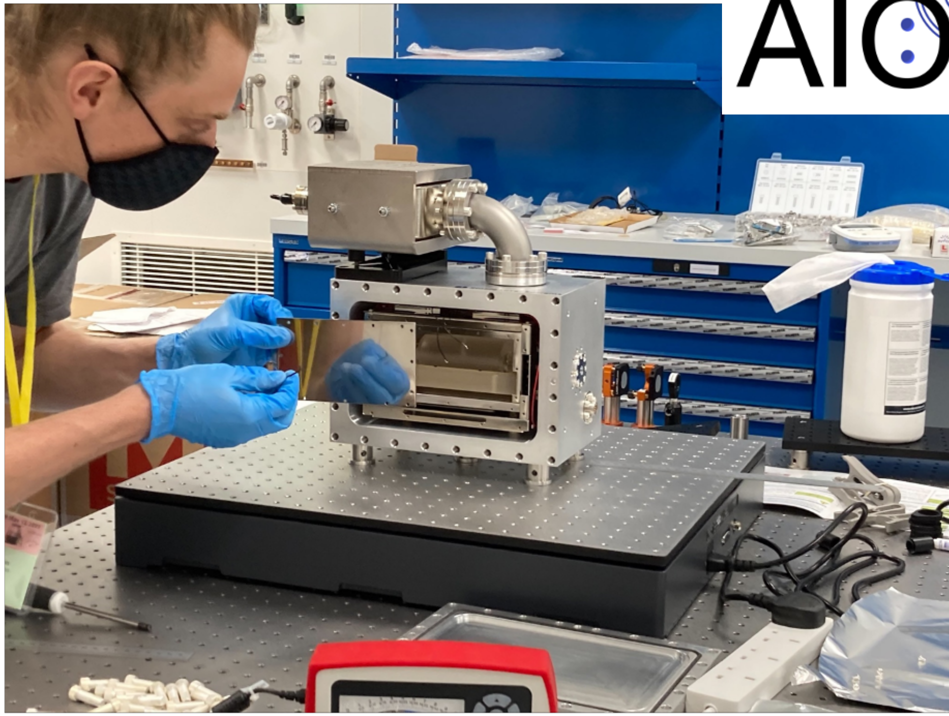
- New purpose-built building (£50M facility)
- AION-10 on basement level with 14.7m headroom (stable concrete construction)
- World-class infrastructure
- Experienced Project Manager:
- Engineering support from RAL (Oxfordshire)

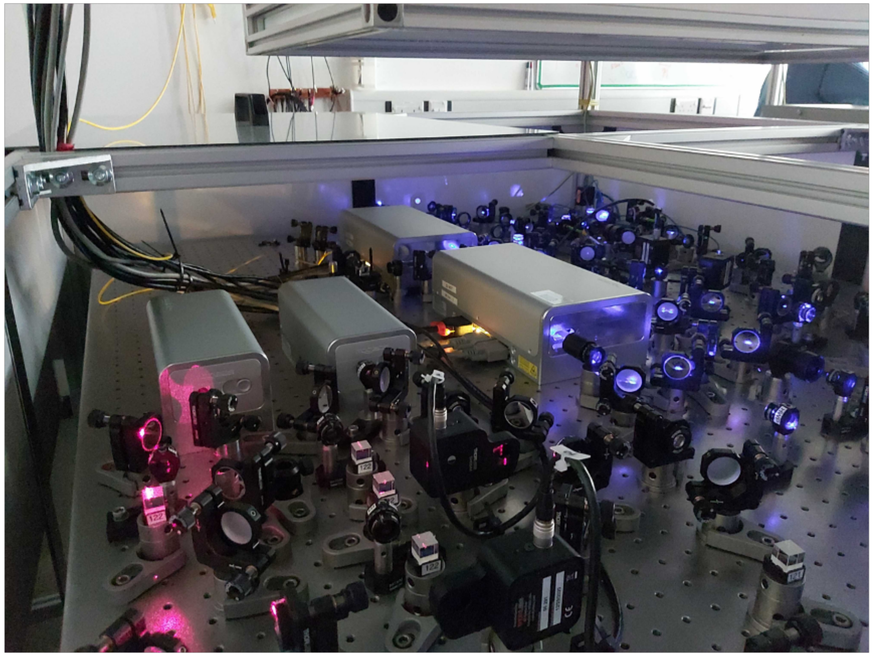


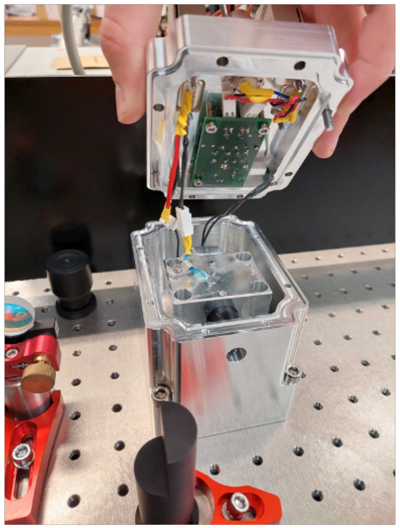


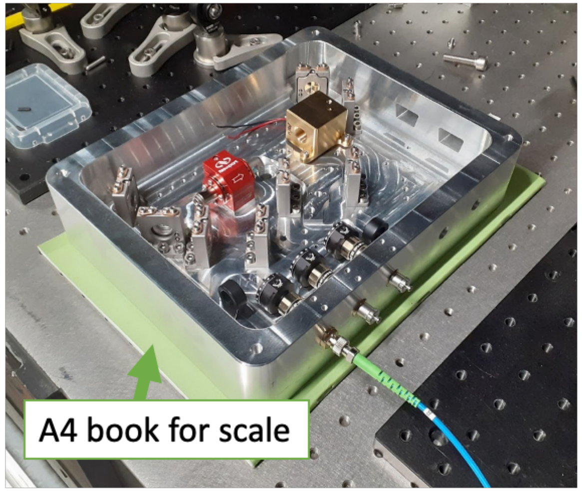
Planned Location of AION-10m

Laboratory Equipment


Imperial College London/Rutherford Appleton Laboratory
(Dr Richard Hobson)


University of Birmingham

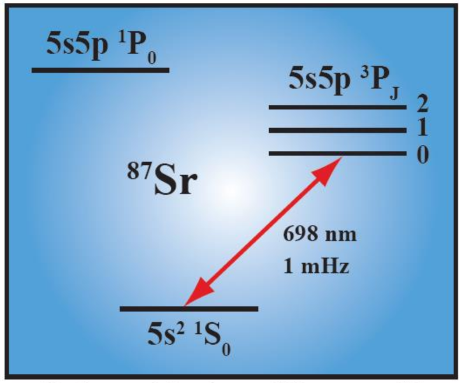

University of Cambridge



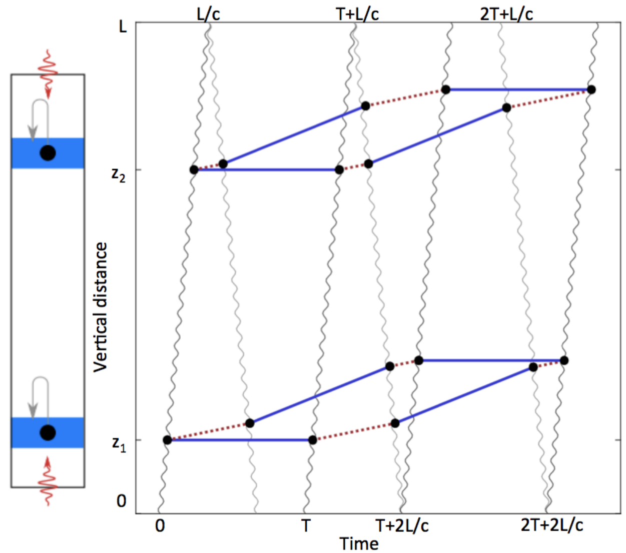
University of Oxford

AION Design Objectives

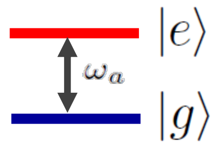
Hybrid "clock accelerometer"



Clock transition in candidate atom ^{87}Sr



Clock: measure light travel time ➜ remove laser noise with *single baseline*



Excited state phase evolution:

$$\Delta\phi \sim \omega_A \, (2L/c)$$

Two ways for phase to vary:

$\delta\omega_A$	*Dark matter*
$\delta L = hL$	*Gravitational wave*

Sensitivity Scenario	L [m]	T_{int} [sec]	$\delta\phi_{\text{noise}}$ [$1/\sqrt{\text{Hz}}$]	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

Used for sensitivity projections

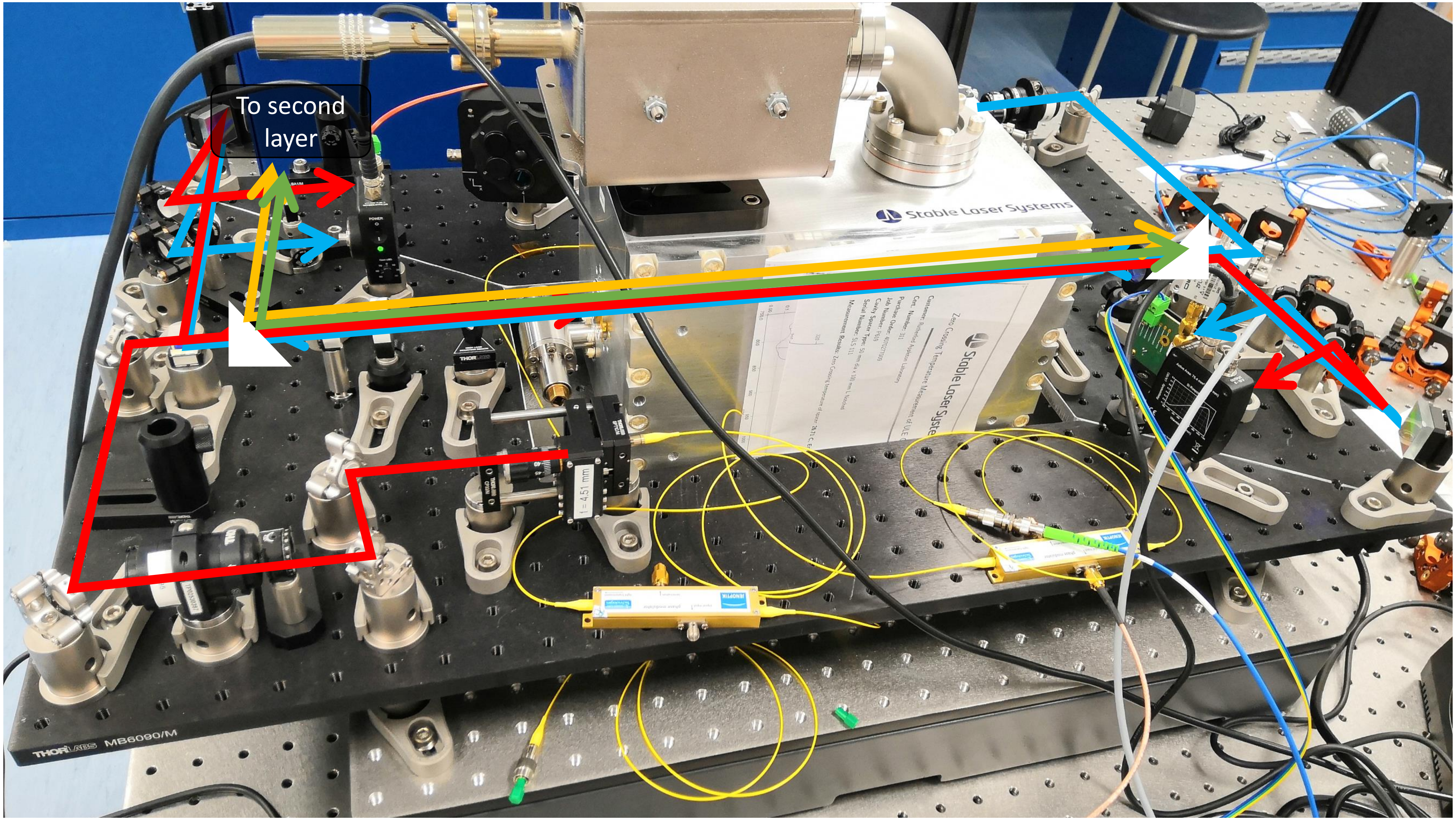
For ultimate sensitivity we need to push each basic parameter by ~O(10).

The project aims to demonstrate in funding period e.g.

- LMT: ~1000 hbar*k
- Squeezing ~ 20dB for > 1e6 Atoms

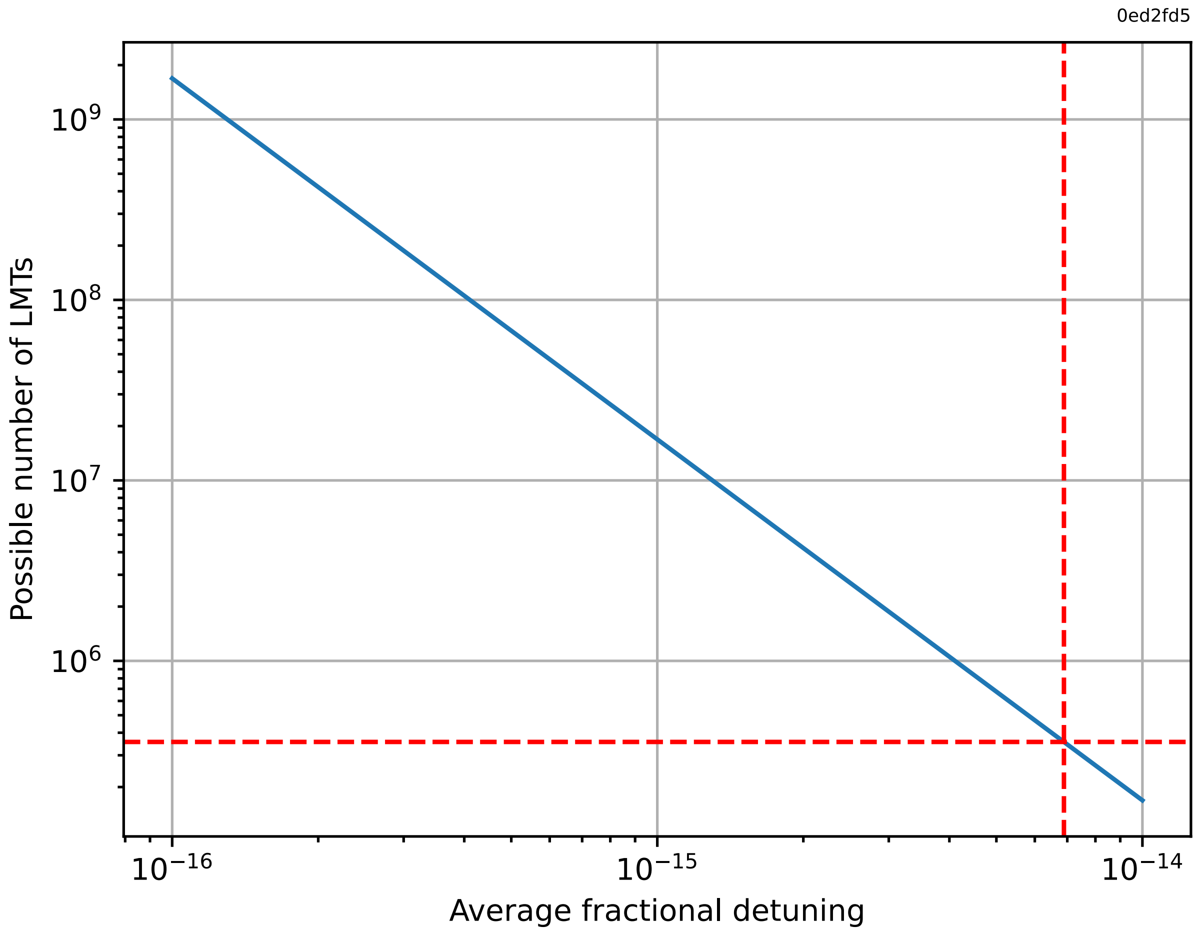
Laser Stabilisation

AION



Laser Stabilisation

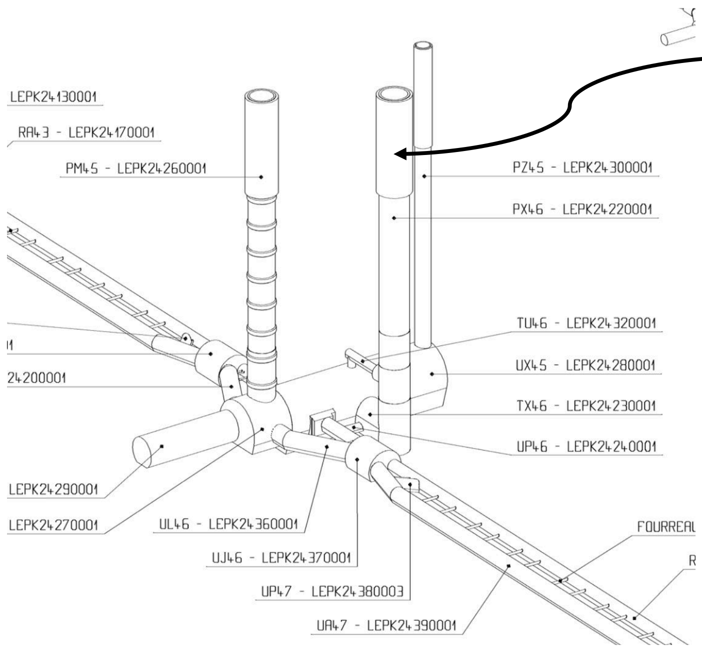
How useful is 7×10^{-15} ?



- Plot shows the possible number of LMTs assuming
  - A Rabi frequency of 8 kHz
  - A desired contrast of 90%
  - That the laser is detuned throughout the atoms' flight by the amount shown
- At a 3 Hz linewidth, that's $n_{max} = 350\,000$

Exceeds science objective by large margin

Possible CERN Location of AION-100m



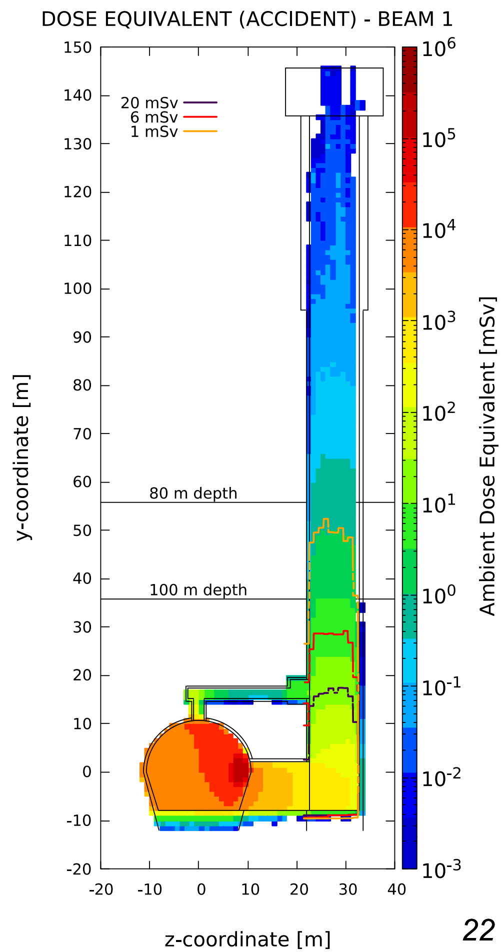
PX46 – P4 Support shaft

Lengths 143m

D = 10.10m

➢ **Ideal basic parameters for AION100**

First radiation studies are also Looking promising but more work is needed to determine if PX46 could be a valid option for AION 100.



Other site options that are currently investigated are the ***national facility in Boulby and Daresbury (UK).***

We are working with PBC Team (Gianluigi Arduini et al) on feasibility study:

Seismology

Temperature

Ventilation

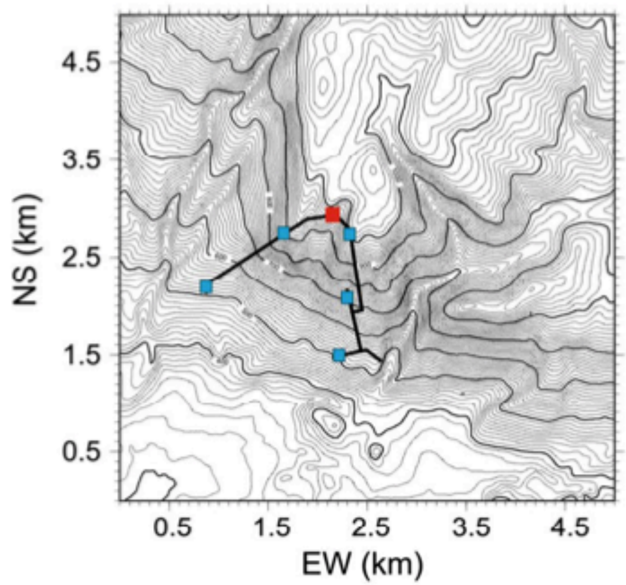
Radiation protection

Electromagnetic interference

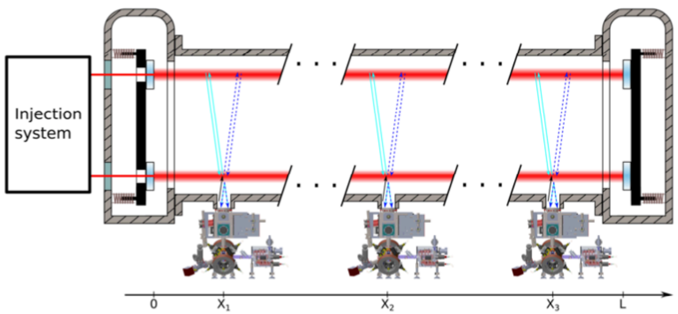
Kincsö Balazs, Angelo Infantino

The MIGA Large-Scale Atom Interferometer

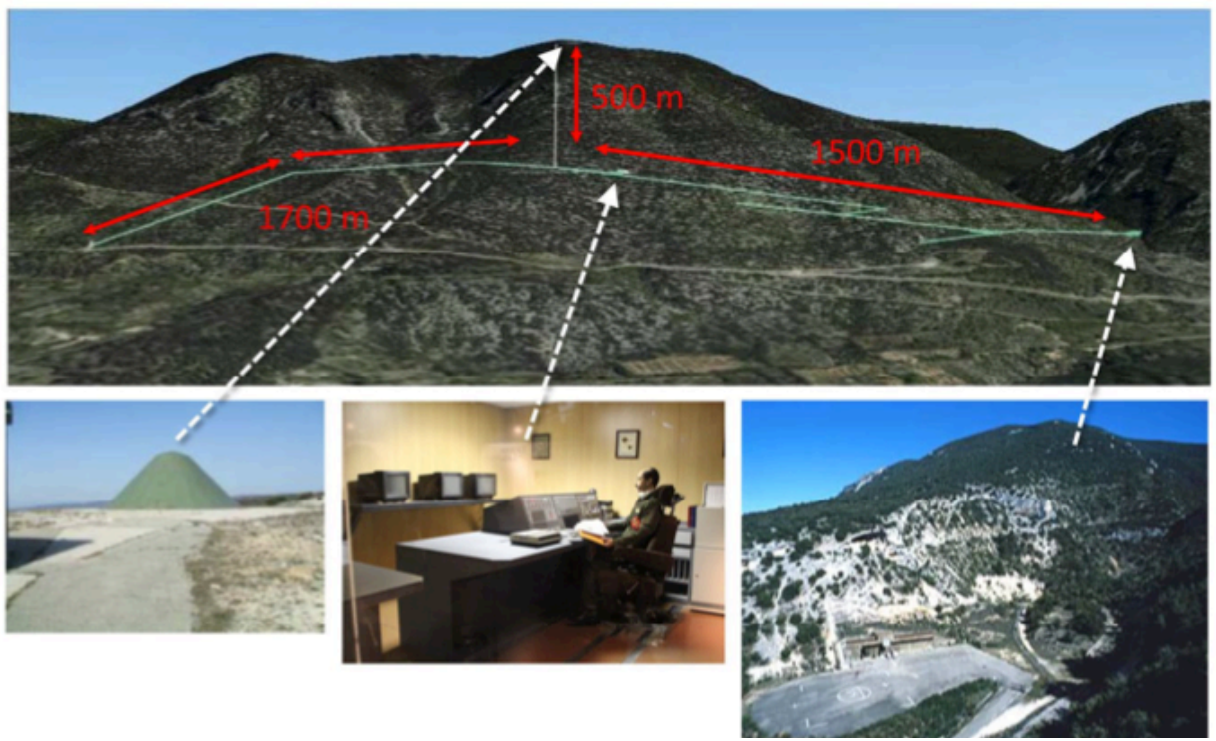
Under construction in former nuclear bunker



Atomic fountains illuminated by laser beams

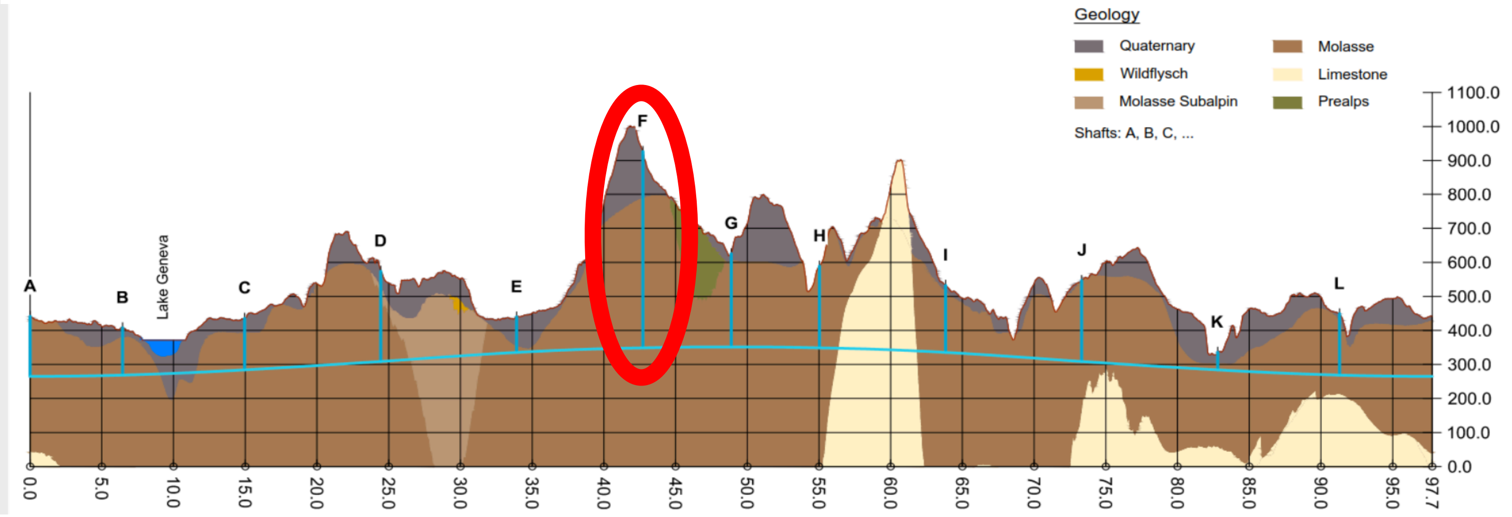


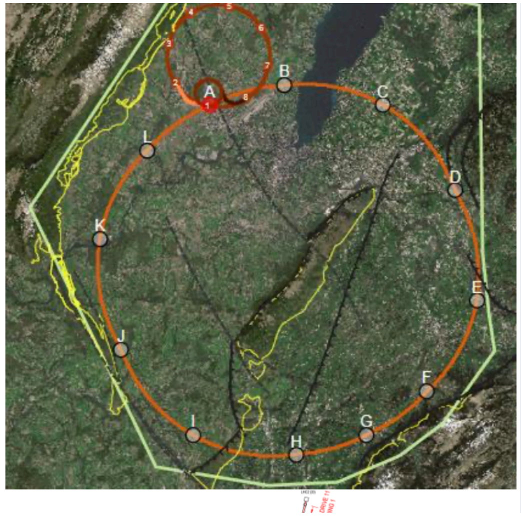
(C)



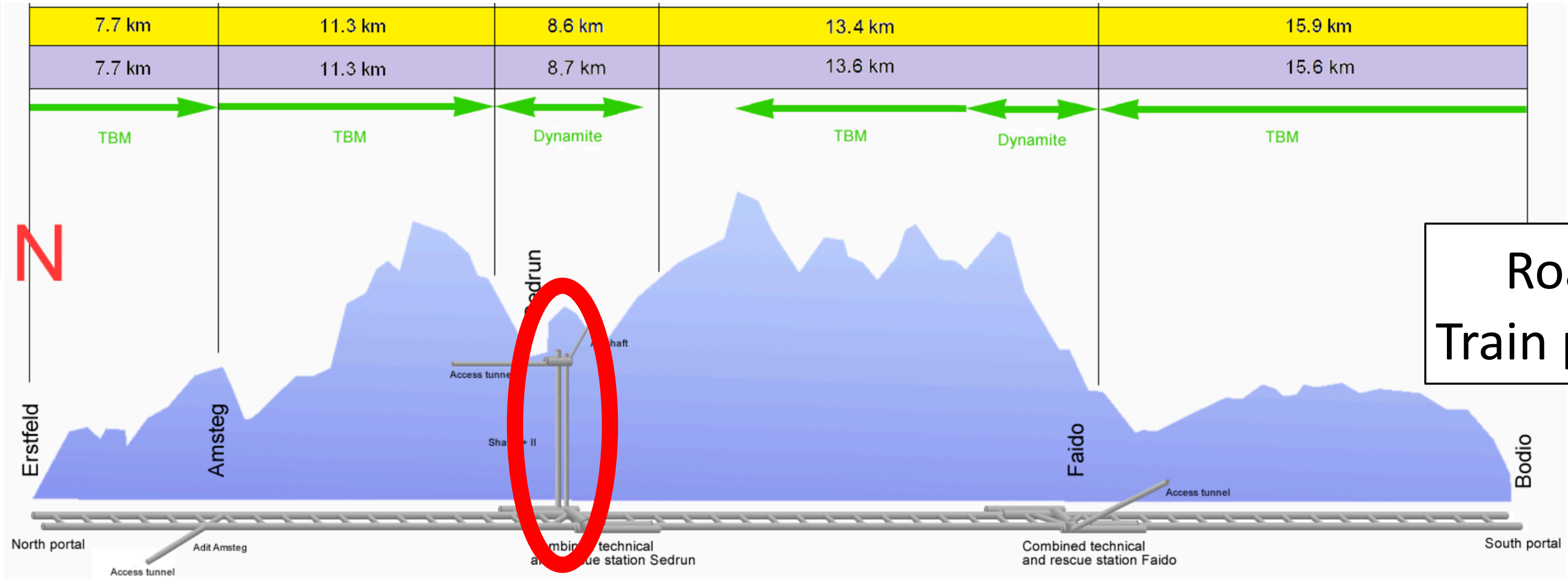
Following step?

FCC Layout has > 500m Vertical Shaft





Gotthard Base Tunnel has Two 800m Vertical Shafts



Road access at top

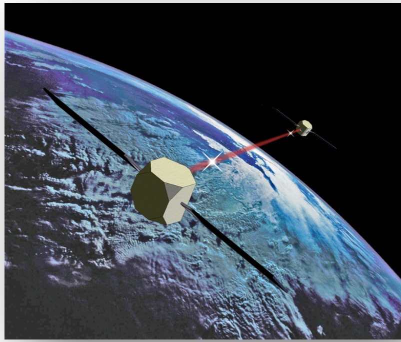
Train platform at bottom

And then?

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 Space Experiment

Two satellites in Medium Earth Orbit

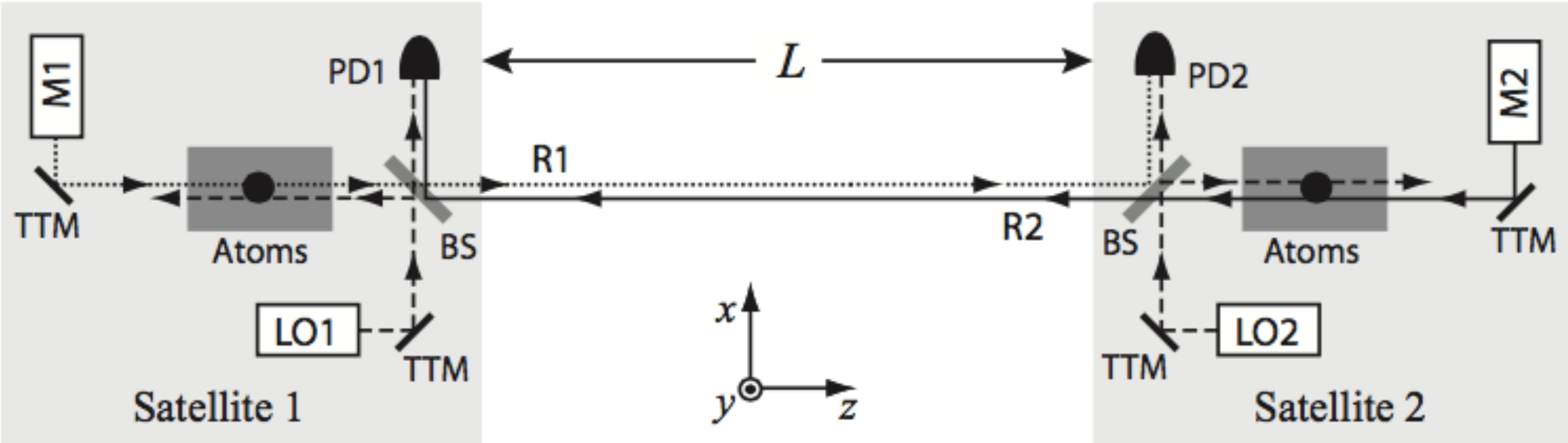
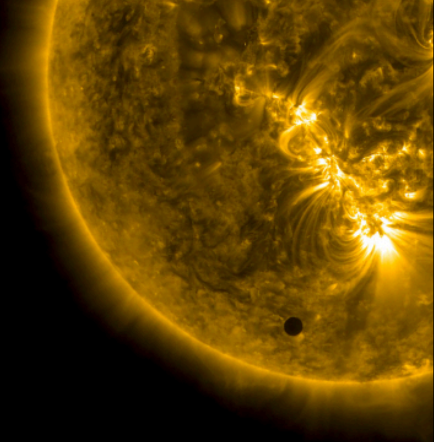


Table 1. List of basic parameters of strontium atom interferometer designs for AEDGE and a benchmark 1-km terrestrial experiment using similar technologies: length of the detector L; interrogation time of the atom interferometer $T_{\rm int}$; phase noise $\delta\phi_{\rm noise}$; and the total number 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

Voyage 2050

Final recommendations from the Voyage 2050 Senior Committee



Large missions:

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

Possible Medium missions:

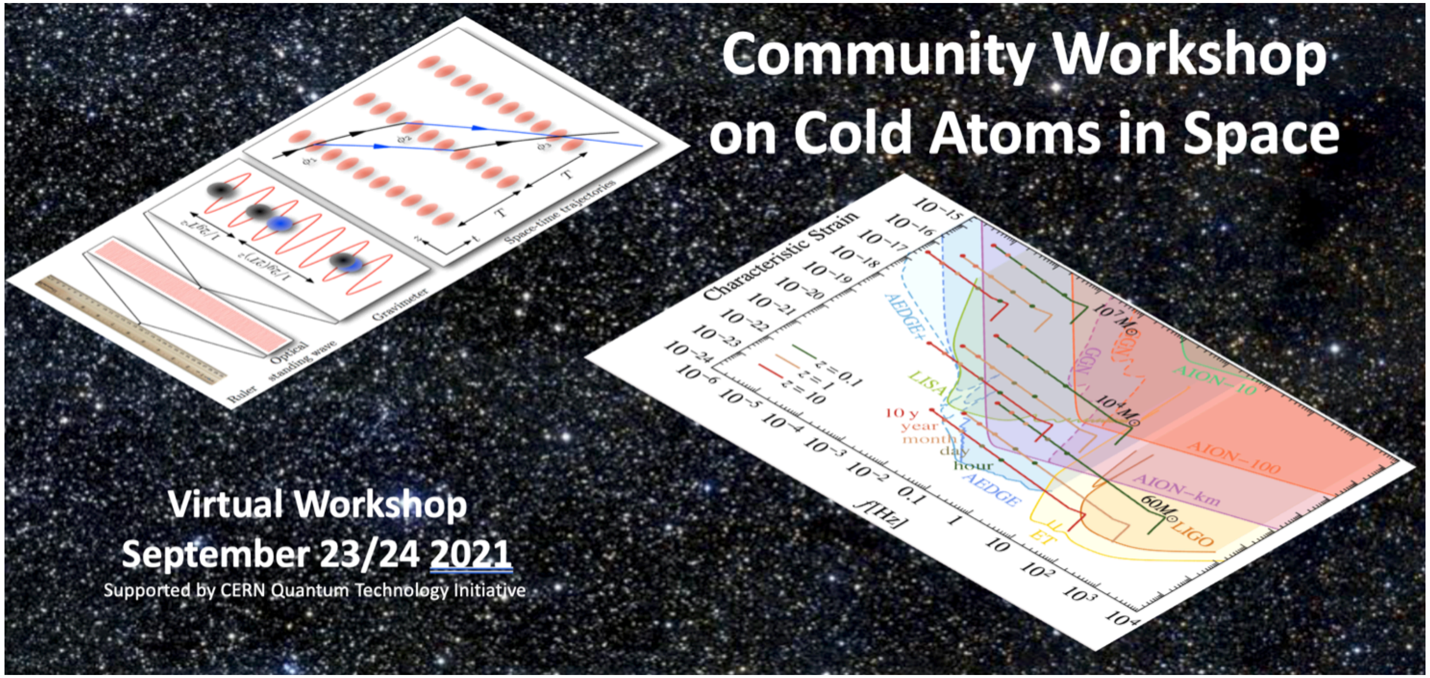
- … QM & GR (cold atoms?)

Technology development recommendations for Cold Atom Interferometry

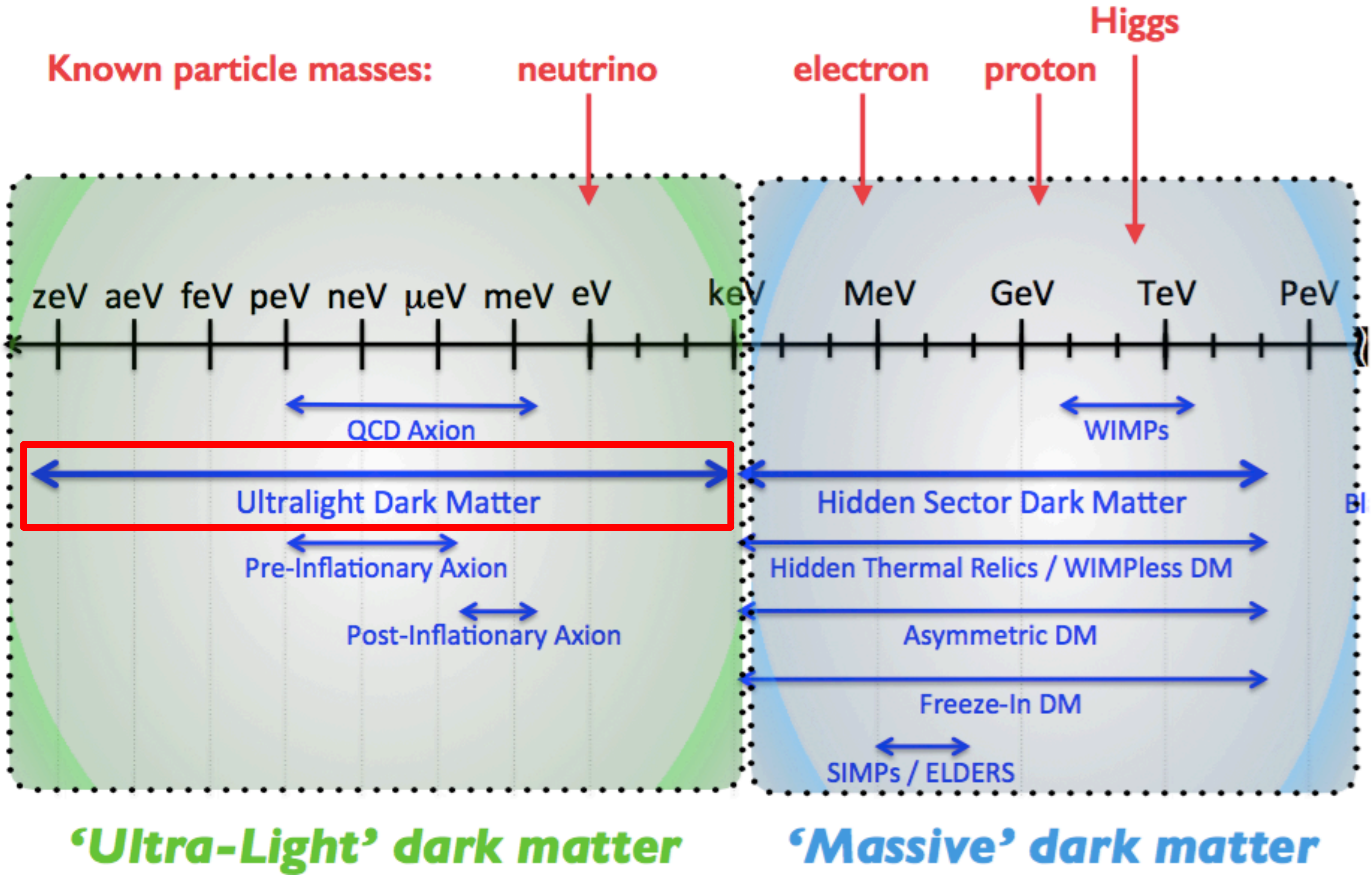
- for gravitational wave detectors in new wavebands …, detectors for dark matter candidates, sensitive clock tests of general relativity, tests of wave function collapse ….
- must reach high technical readiness level, be superior to classical technologies
- start with atomic clocks, on free-flyer or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

“Per audacia ad astra”

- Letter sent to ESA’s Director of Science, Guenther Hasinger:
  - to underline that the community is prepared to work actively with ESA as it shapes a roadmap for developing Cold Atom technology for space.
- Cold Atom community virtual workshop September 23/24:
  - to formulate a roadmap for the development programme



Search for Ultralight Dark Matter

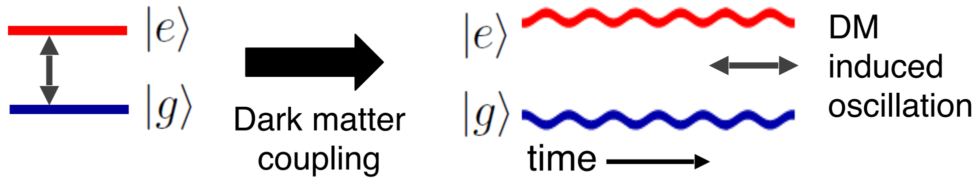


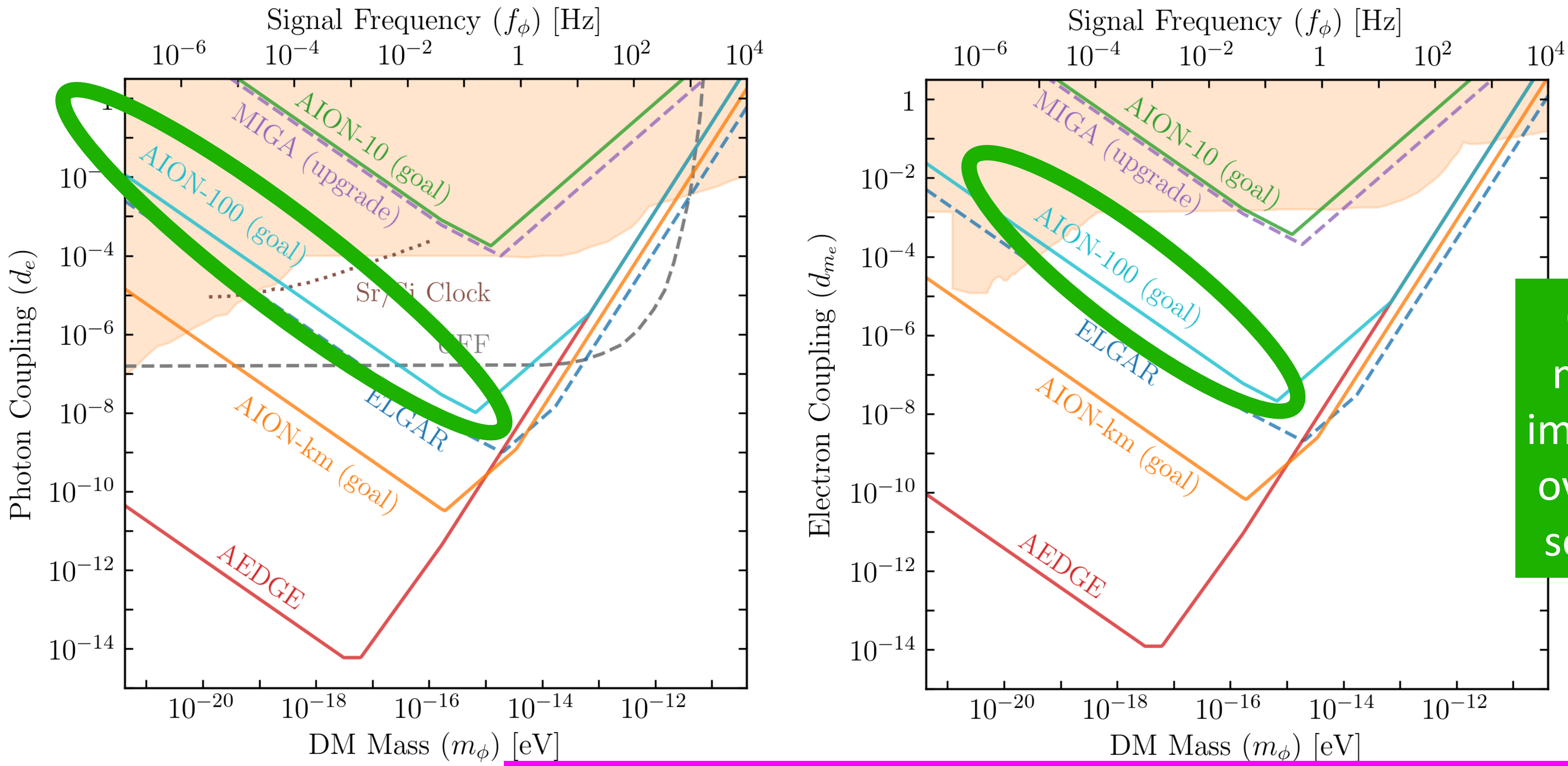
Searches for Light Dark Matter

AION

Linear couplings to gauge fields and matter fermions

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





Orders of magnitude improvement over current sensitivities

AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755; Badurina, Buchmueller, JE, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

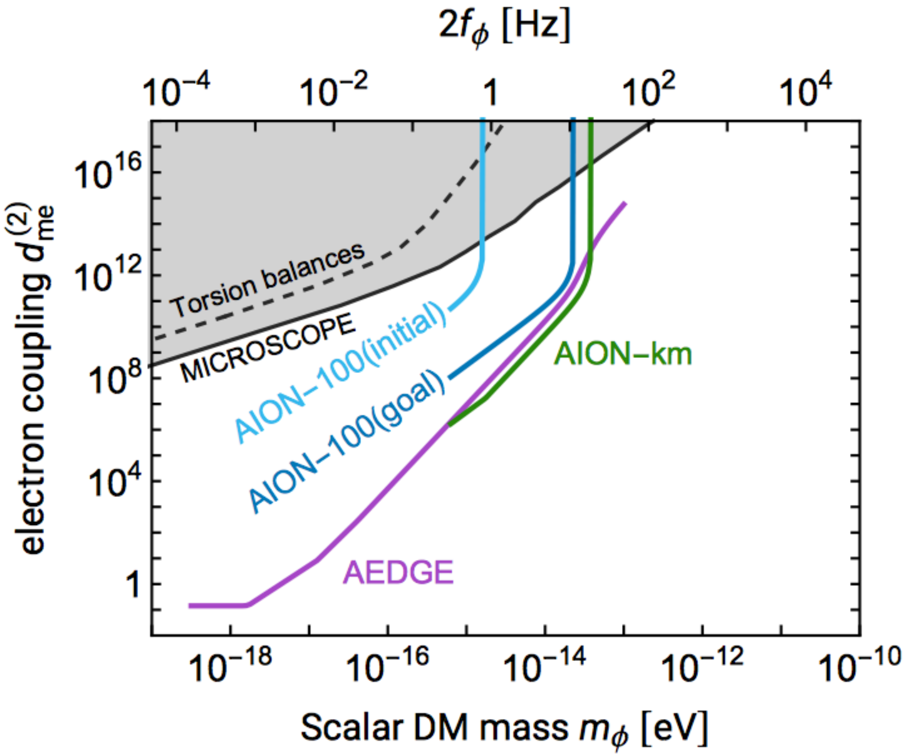
AEDGE: Bertoldi, …, JE et al: arXiv:1908.00802

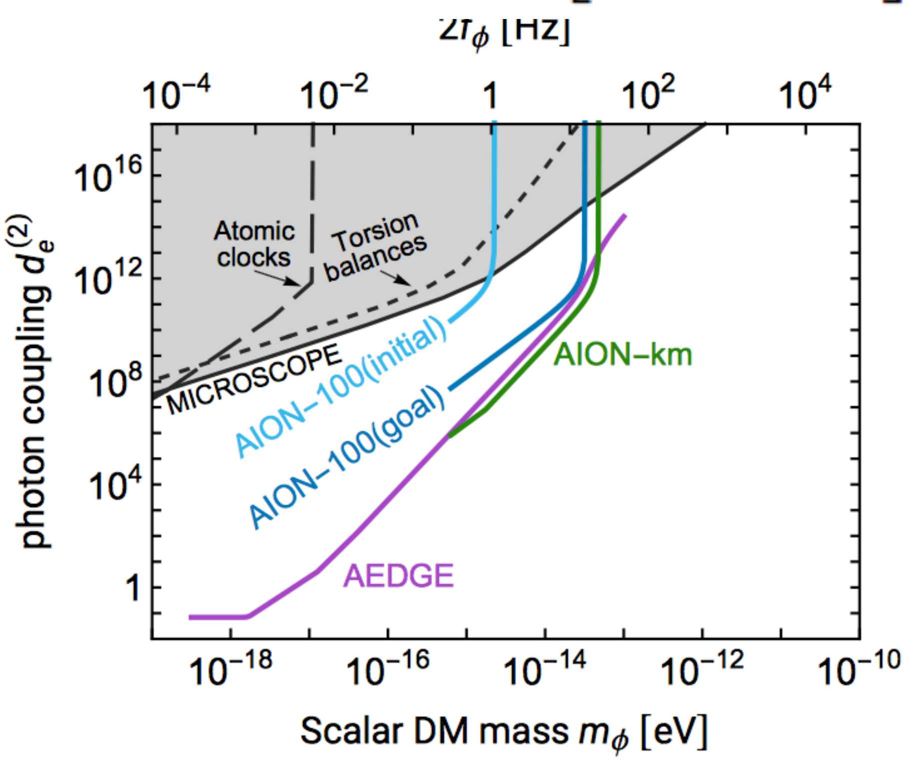
Sensitivities to Quadratic DM Interactions

AION

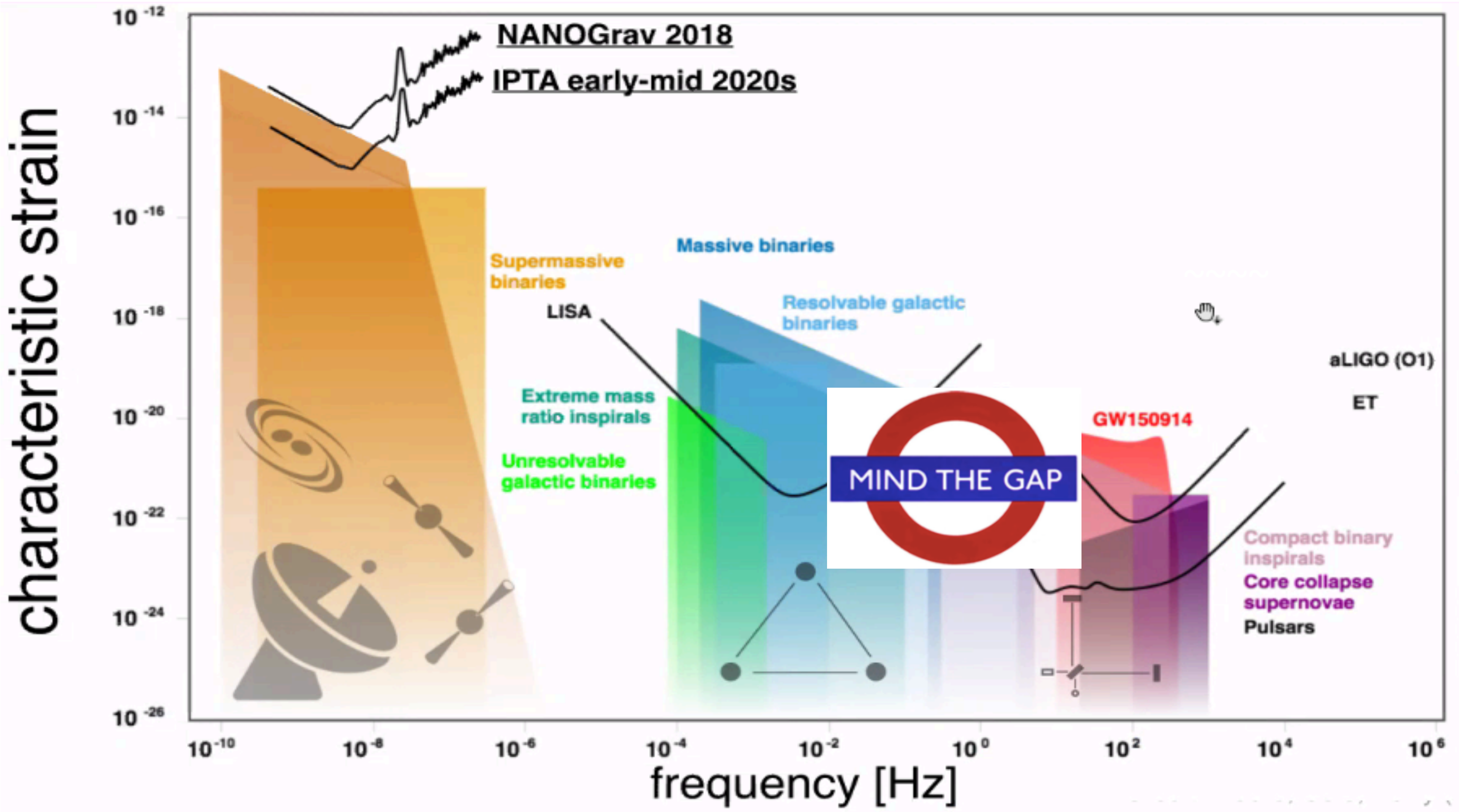
$$\mathcal{L}_{\text{int}}^{f} = -\sum_{f=e,p,n} m_f \left(\frac{\phi c}{\Lambda'_f}\right)^2 \bar{f} f, \qquad m_f \to m_f \left[1 + \left(\frac{\phi}{\Lambda'_f}\right)^2\right],$$

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





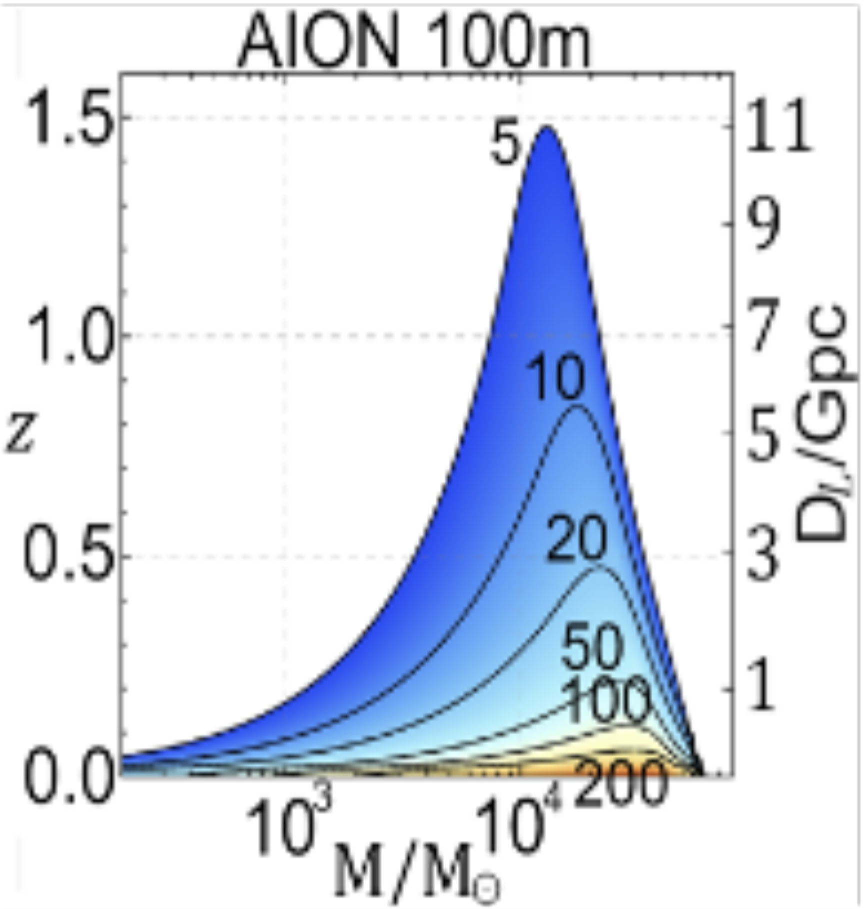
Gravitational Wave Spectrum



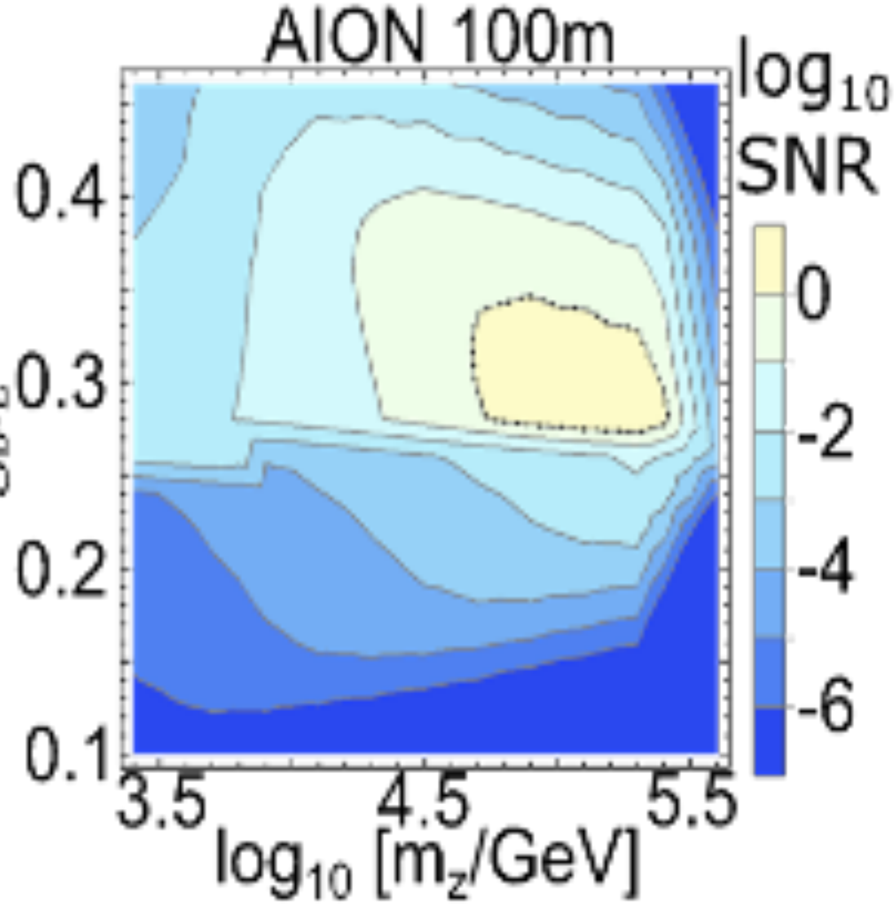
- Gap between ground-based optical interferometers & LISA
  - Formation of supermassive black holes (SMBHs)?
  - Electroweak phase transition? Cosmic strings?

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

SNRs for Gravitational Waves in AION-100



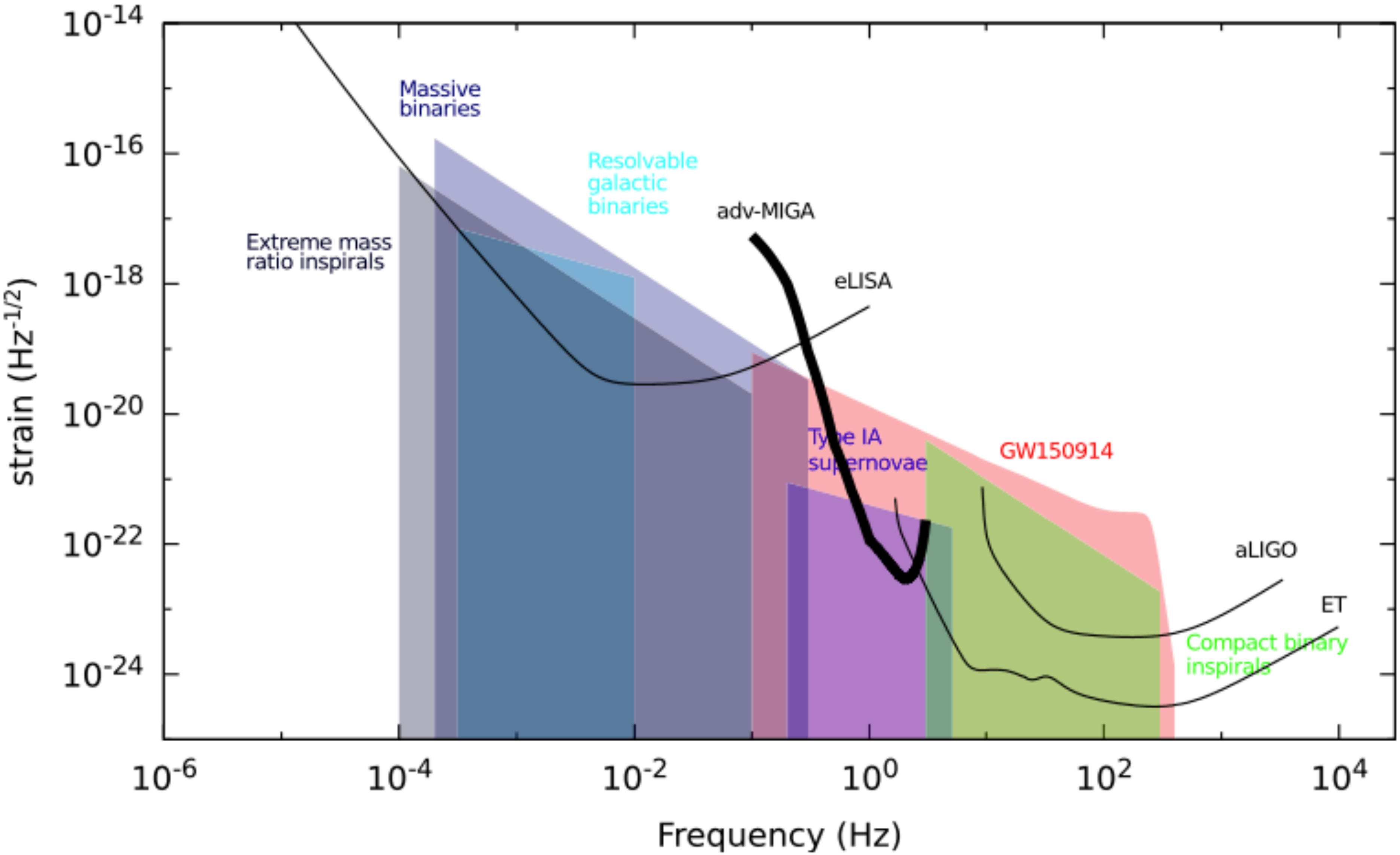
SMBH mergers



Cosmological U(1) phase transition

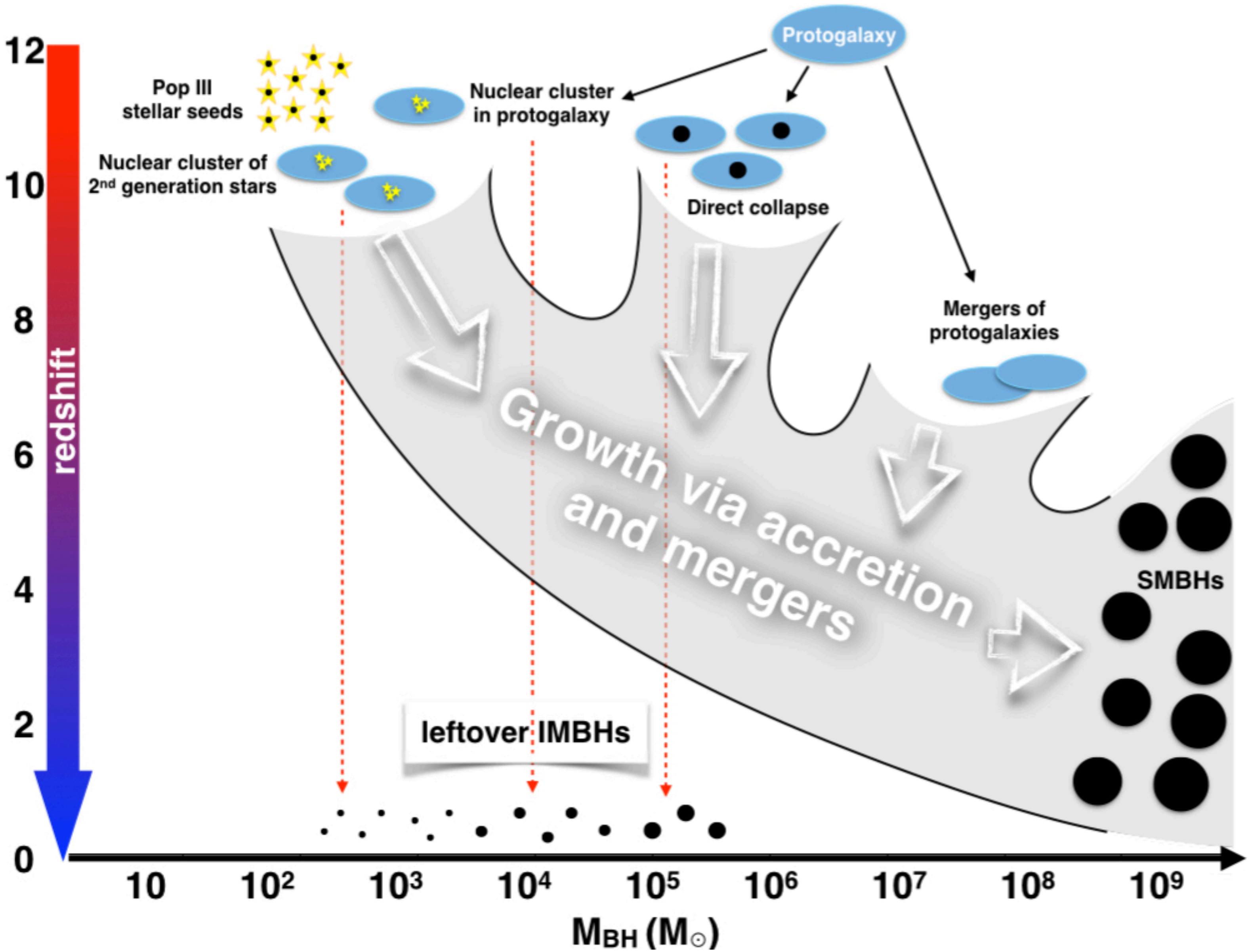
The MIGA Large-Scale Atom Interferometer

Sensitivity to gravitational waves



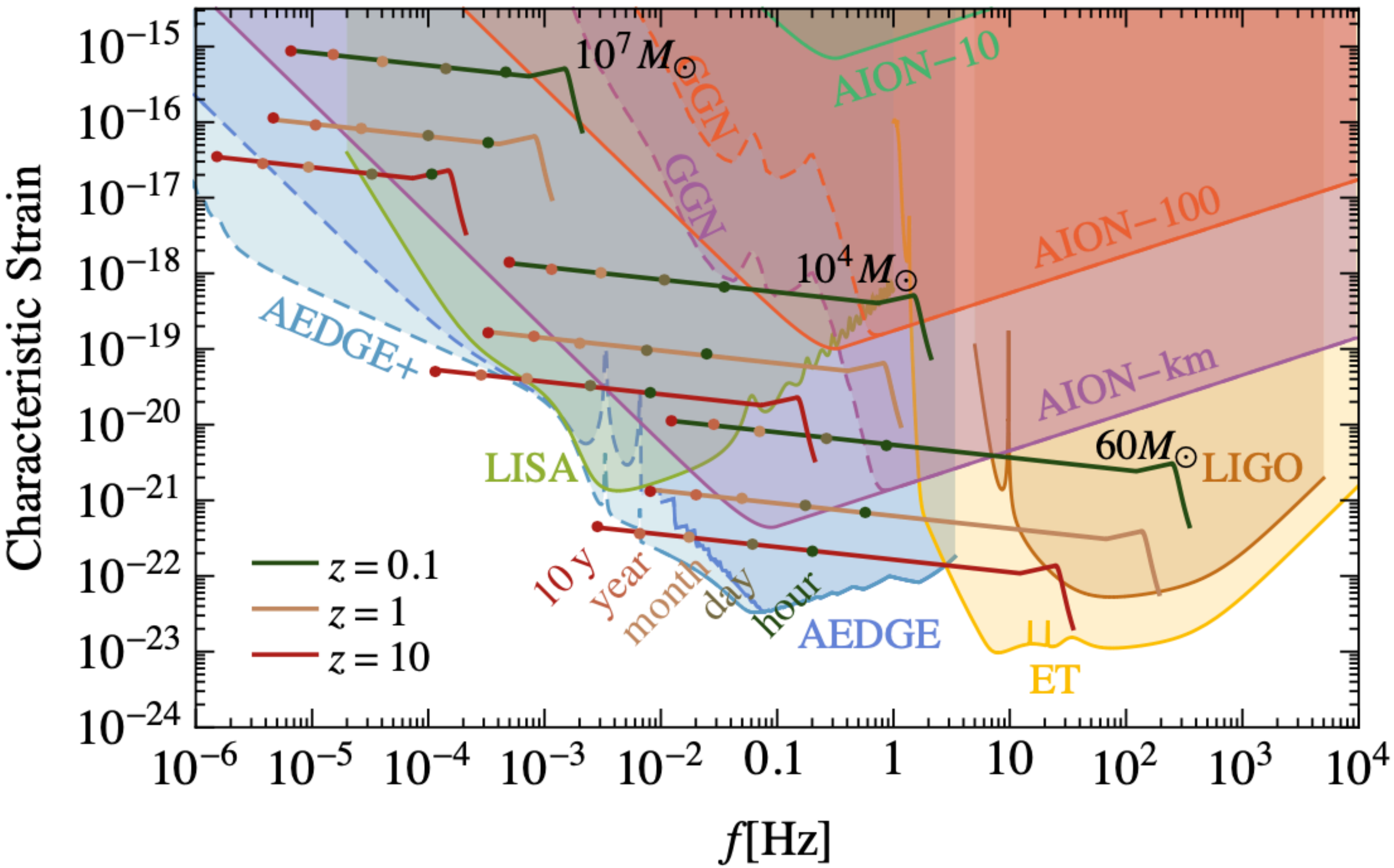
How to Make a Supermassive BH?

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

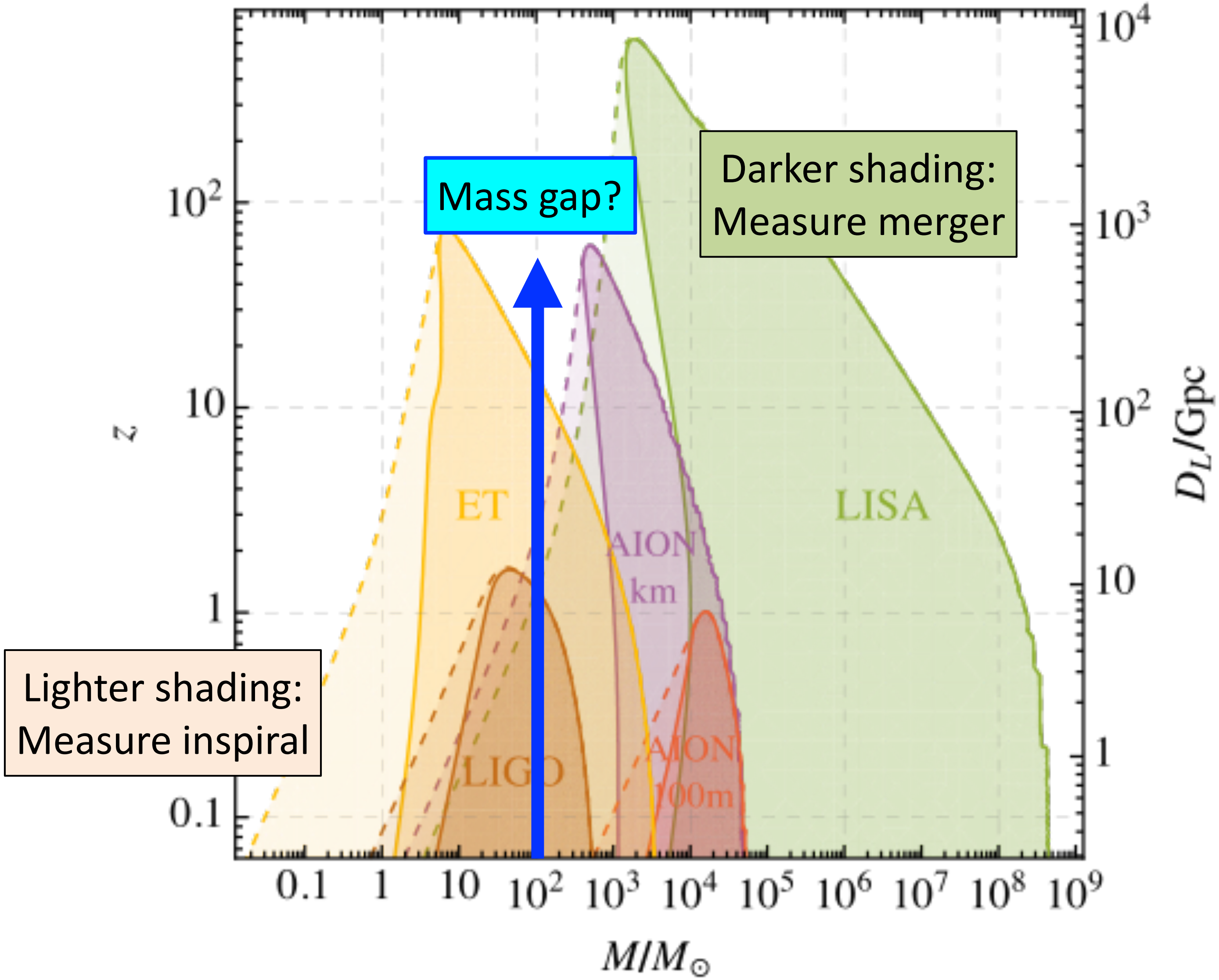
Synergies with other GW experiments (LIGO, LISA), test GR

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



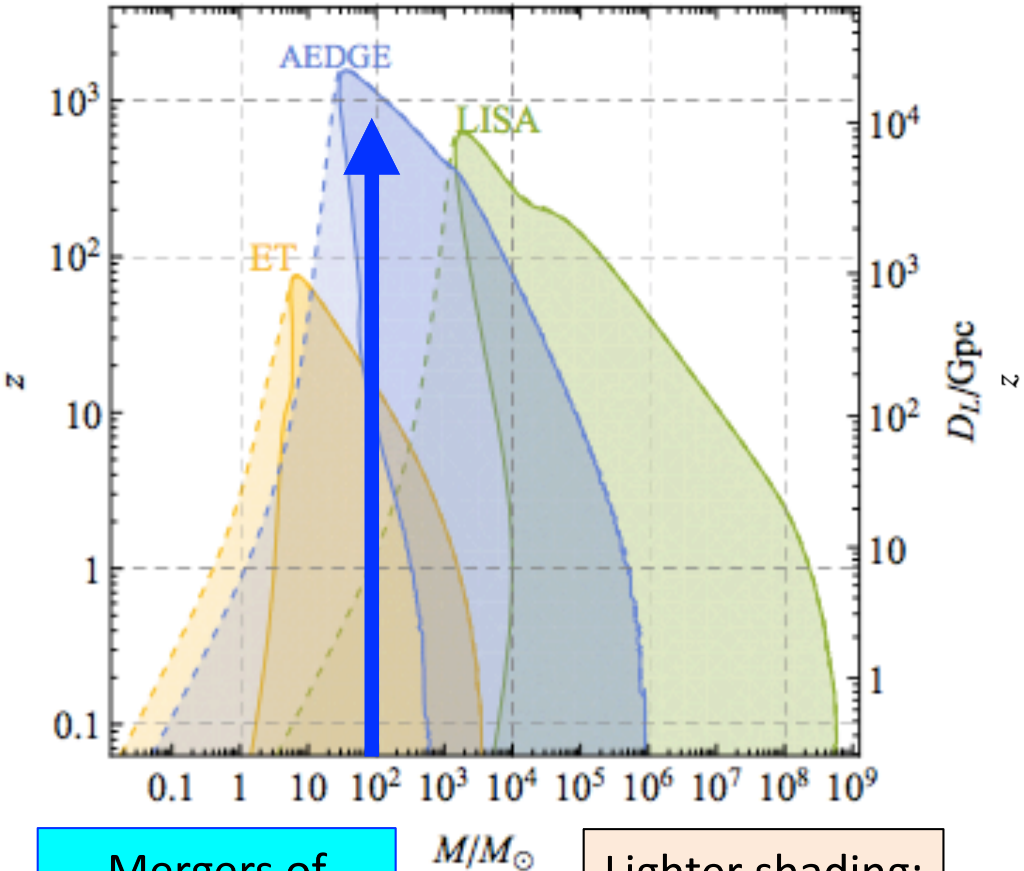
AION complementary to LIGO, Einstein Telescope (ET)

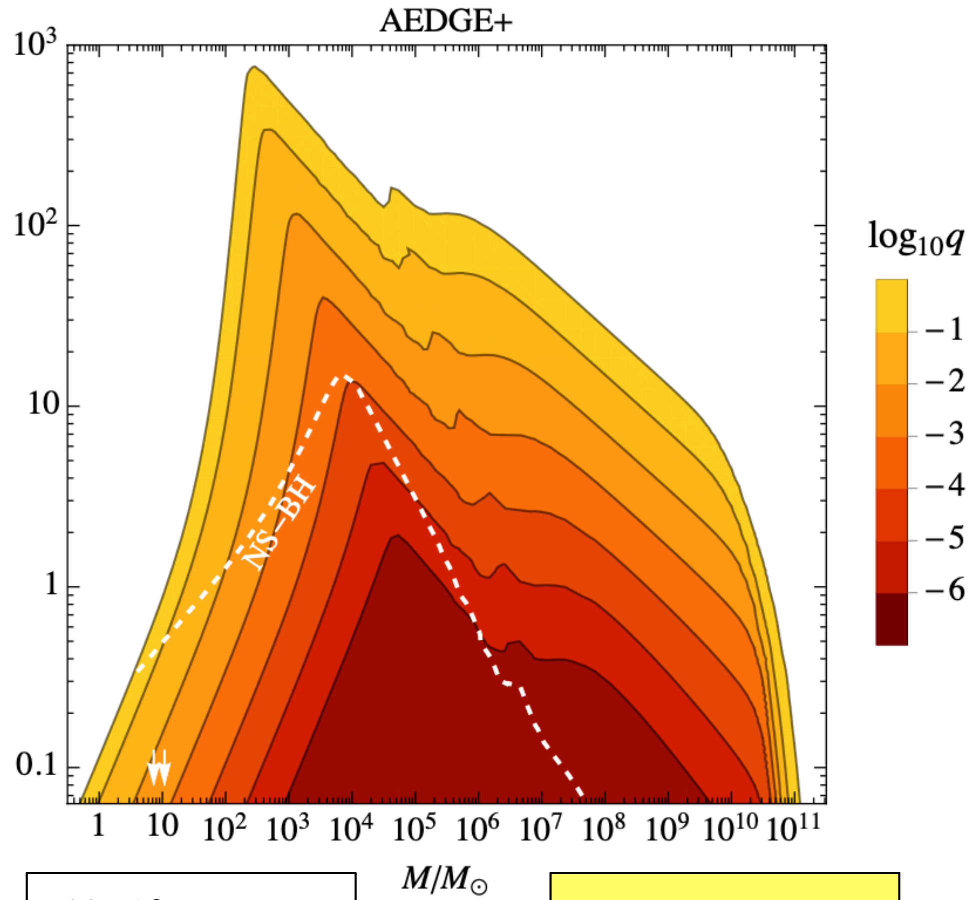
Operation before LISA

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

GWs from IMBH, BH-NS Mergers

AION





Mergers of BHs in mass gap

Lighter shading: Measure inspiral

BH-NS mergers out to large z

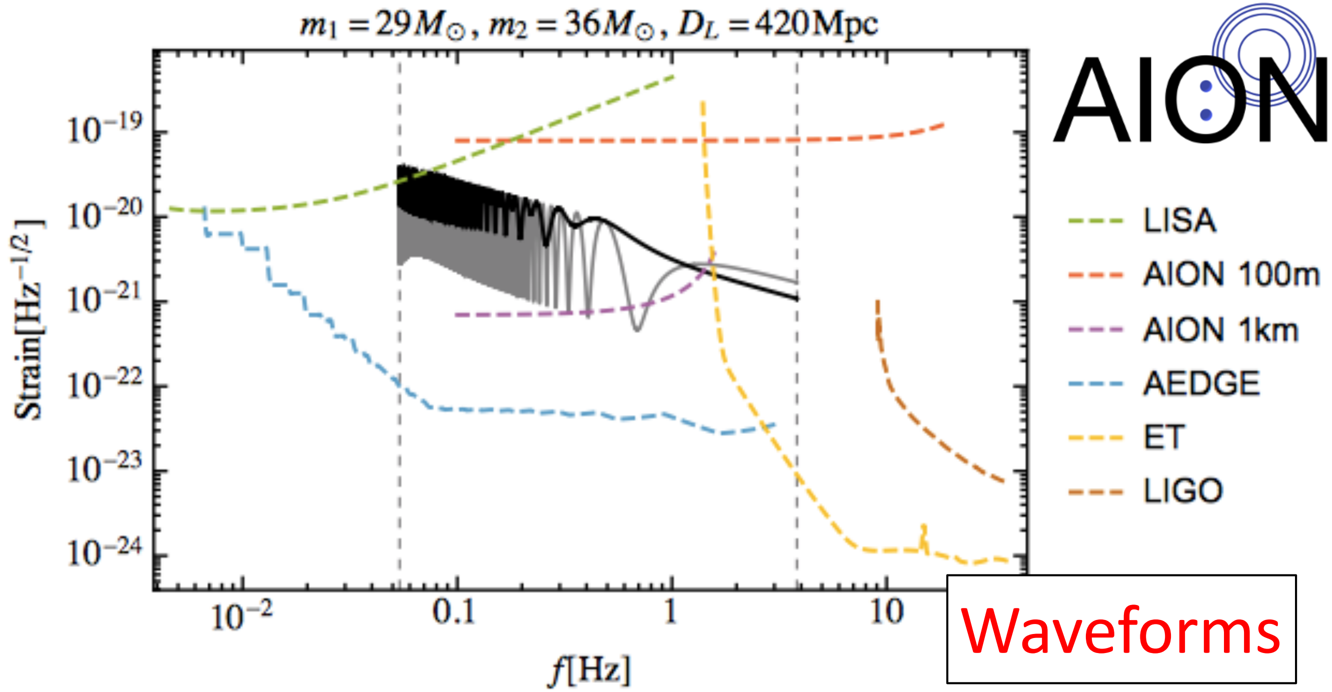
Detect ultramassive BH

AEDGE complementary to LIGO, LISA, Einstein Telescope (ET)

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

Constraints on Graviton Mass

AION

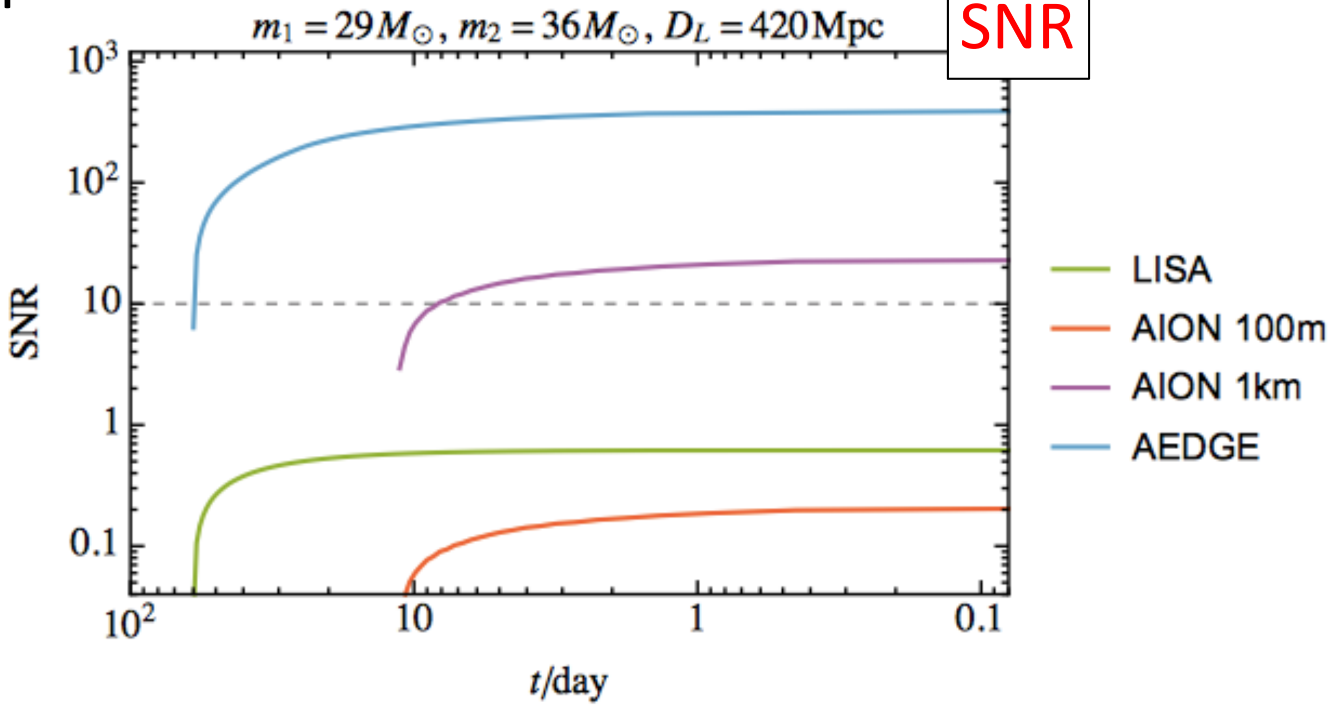


Waveforms

LIGO/Virgo: arXiv:2010.14529

- Current LIGO/Virgo limit: 1.76 × 10^{-23} eV
- Future sensitivity with LIGO/Virgo-like event?
  Longer observations
- With merger of heavier BHs?
  Lower frequencies

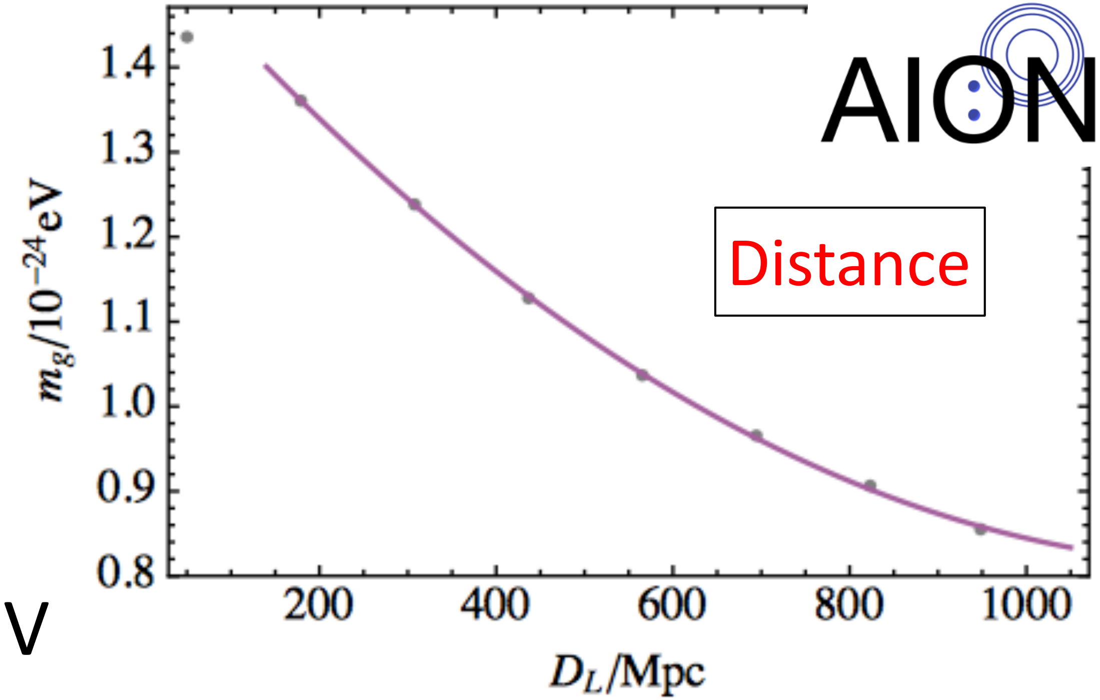
SNR

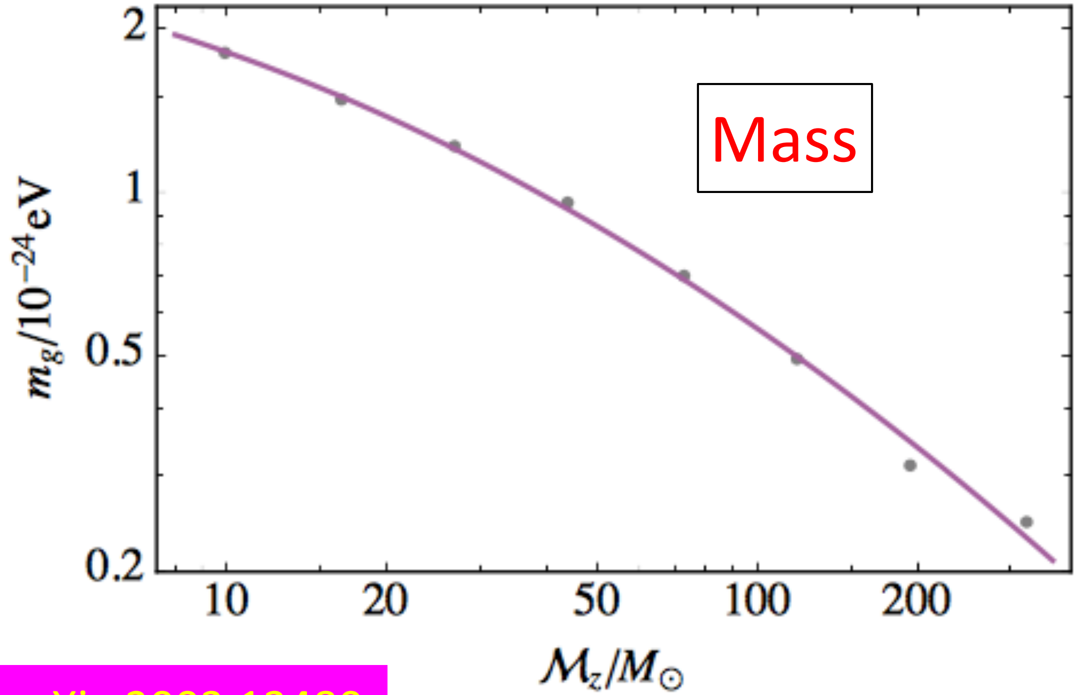


JE & Vaskonen: arXiv:2003.13480

Constraints on Graviton Mass

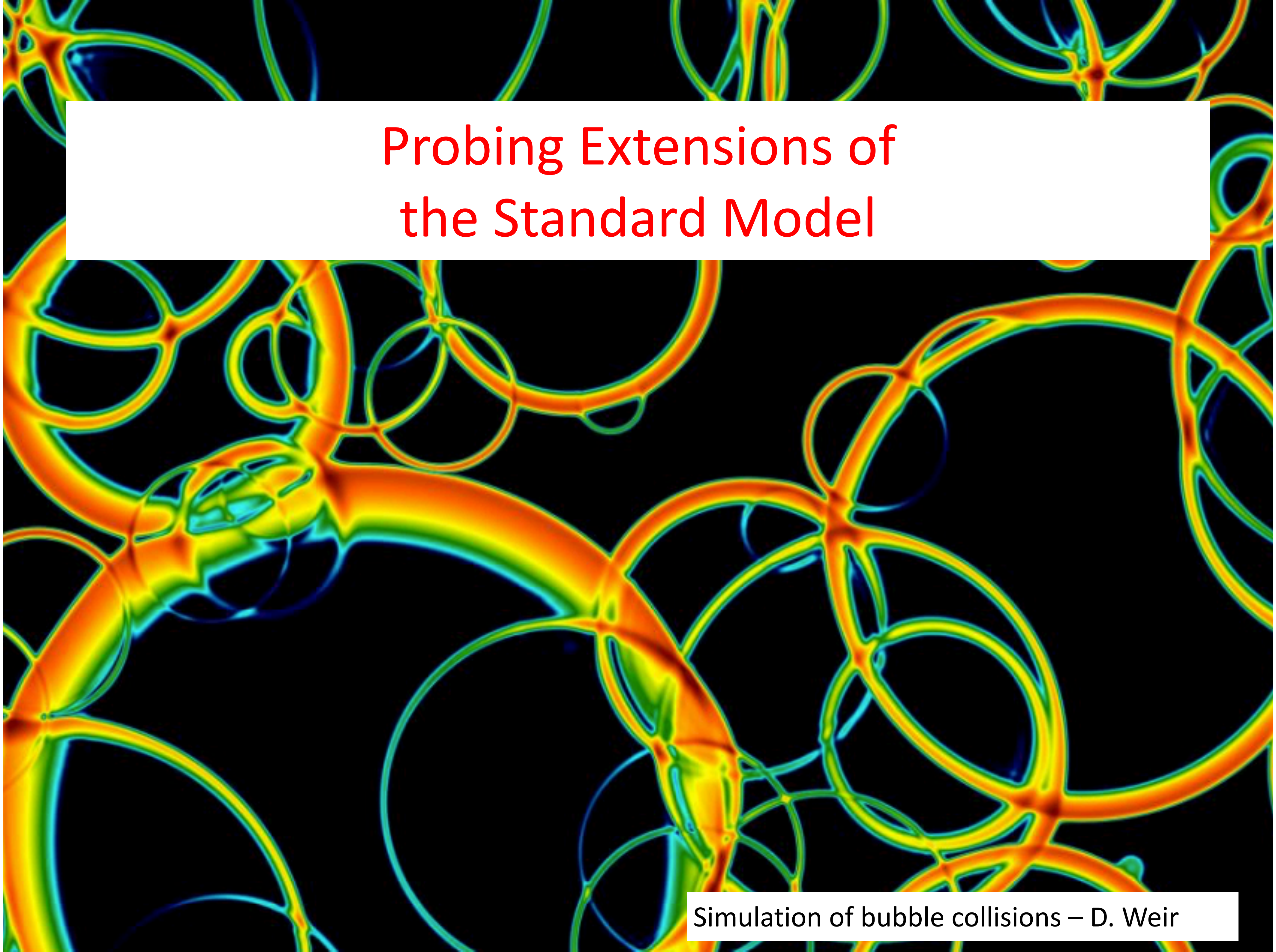
- LIGO/Virgo: <1.76 × 10^{-23} eV
- AION 1-km: sensitive to 10^{-24} eV with LIGO/Virgo-like event
- Sensitive to 2 × 10^{-25} eV with heavier BHs
- AEDGE: 8 × 10^{-27} eV with BHs 5600 + 4400 solar masses





JE & Vaskonen: arXiv:2003.13480

Probing Extensions of the Standard Model



Simulation of bubble collisions – D. Weir

GWs from a First-Order Phase Transition

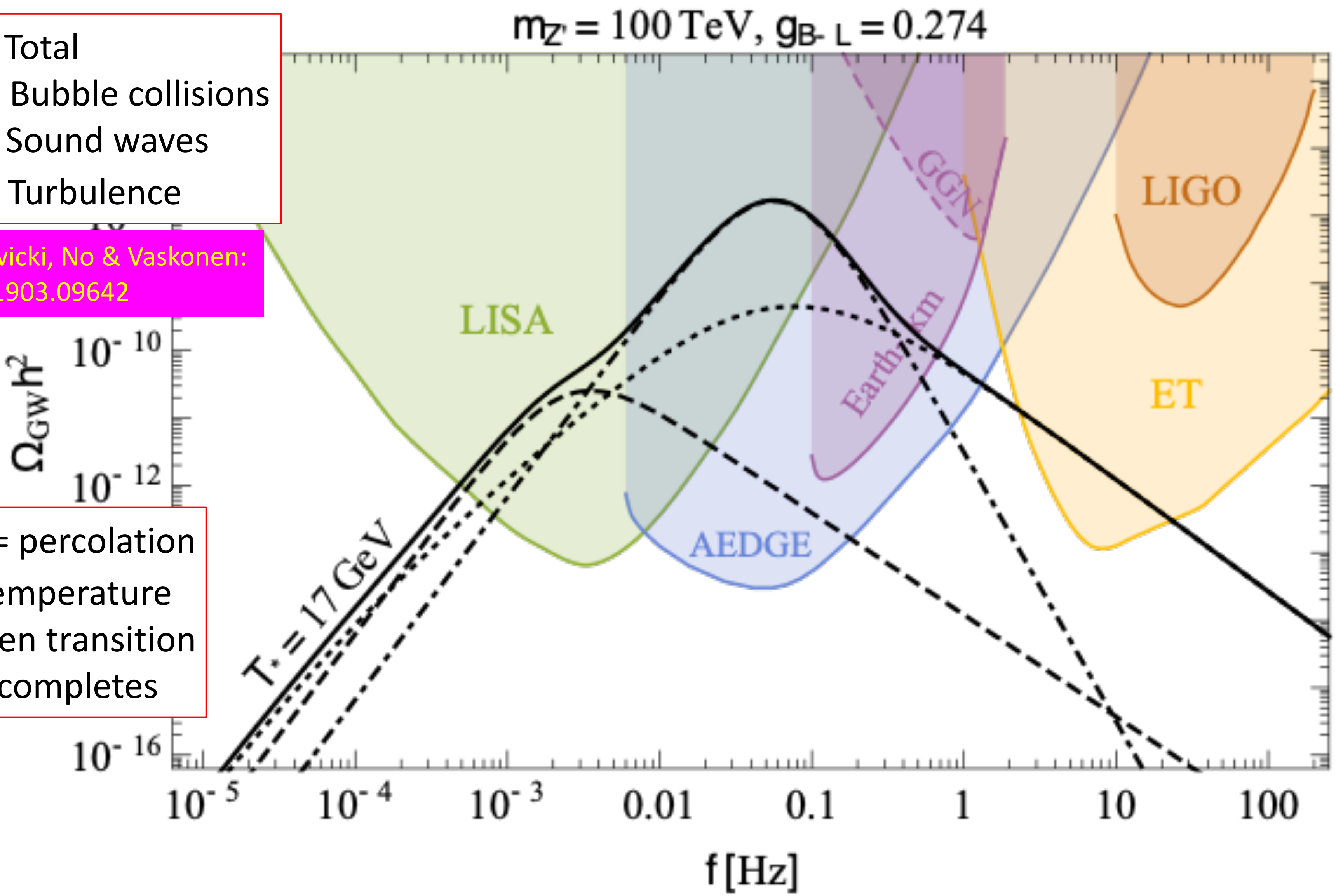
- Transition by percolation of bubbles of new vacuum
- Bubbles grow and collide
- Possible sources of GWs:
  - Bubble collisions
  - Turbulence and sound waves in plasma
- Models studied:
  - Standard Model + H^6/Λ^2 interaction
  - Standard Model + $U(1)_{B-L}$ Z’
- These also have prospective collider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

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

AION

_____ Total
- - - - Bubble collisions
_ - _ Sound waves
……. Turbulence

JE, Lewicki, No & Vaskonen: arXiv:1903.09642

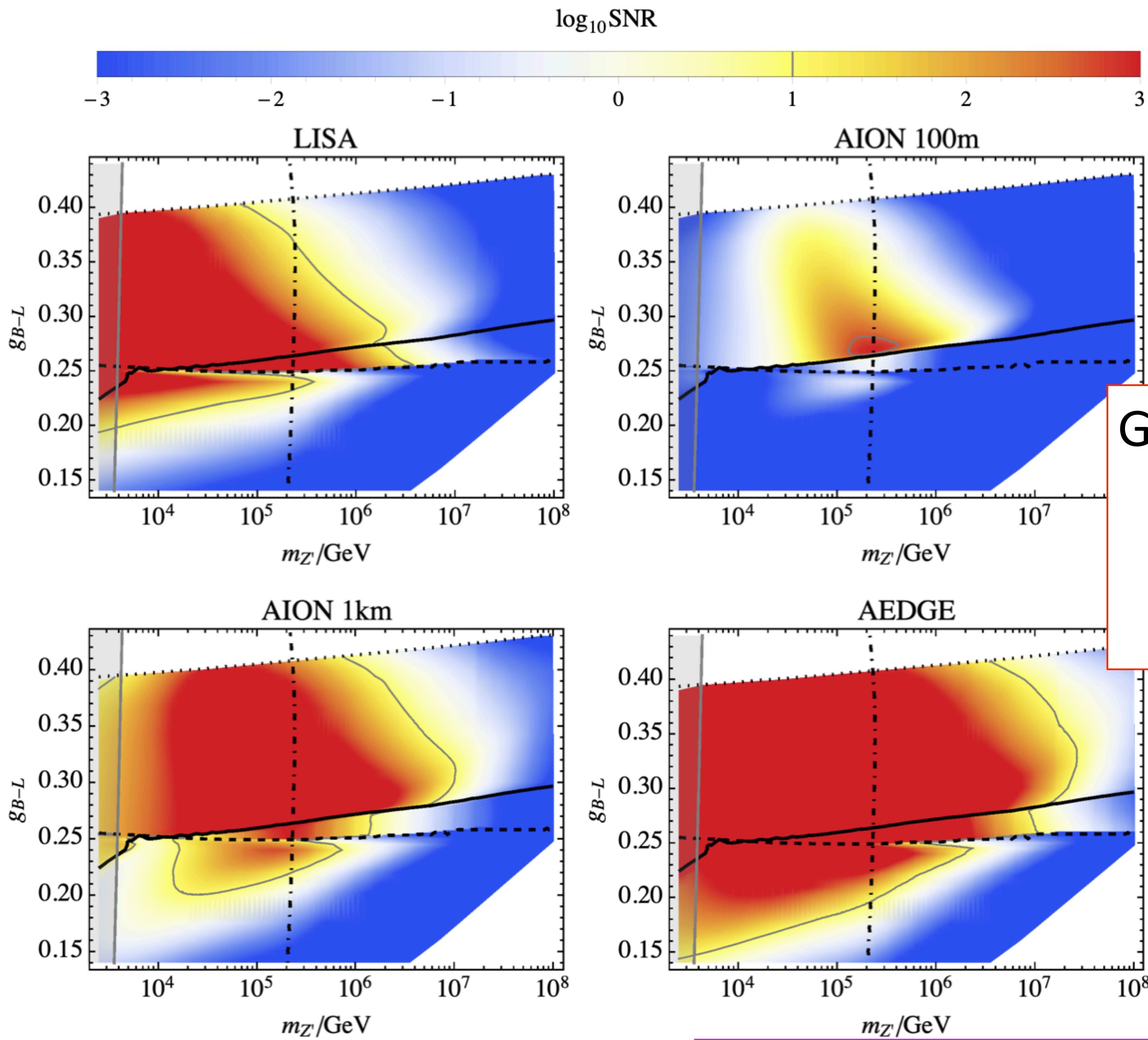


T* = percolation temperature when transition completes

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

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

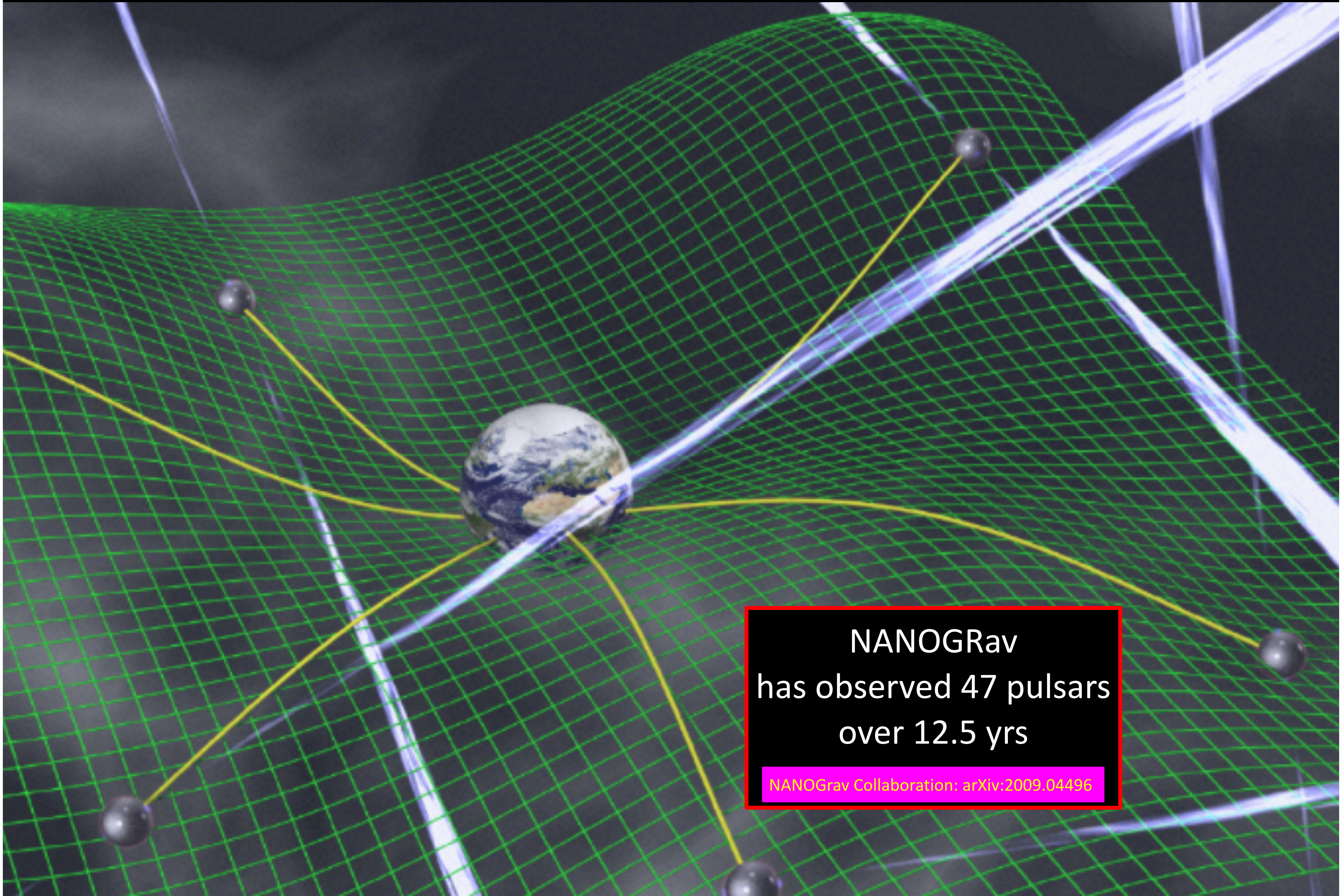
AION



GW discovery sensitivity far beyond colliders

JE, Lewicki & Vaskonen, arXiv:2007.15586

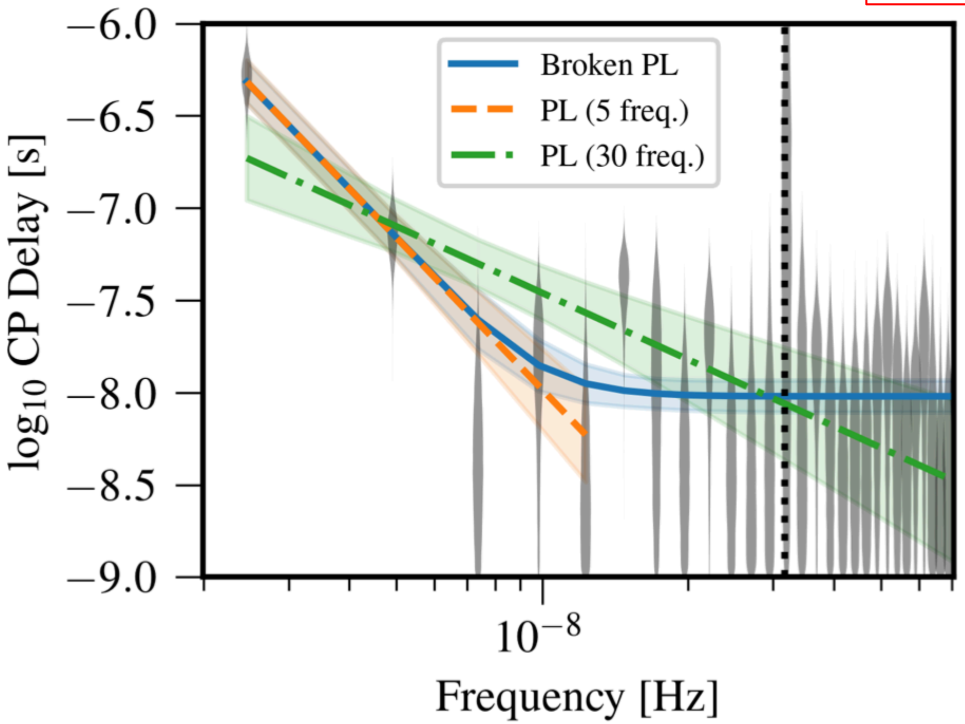
Pulsar Timing Arrays

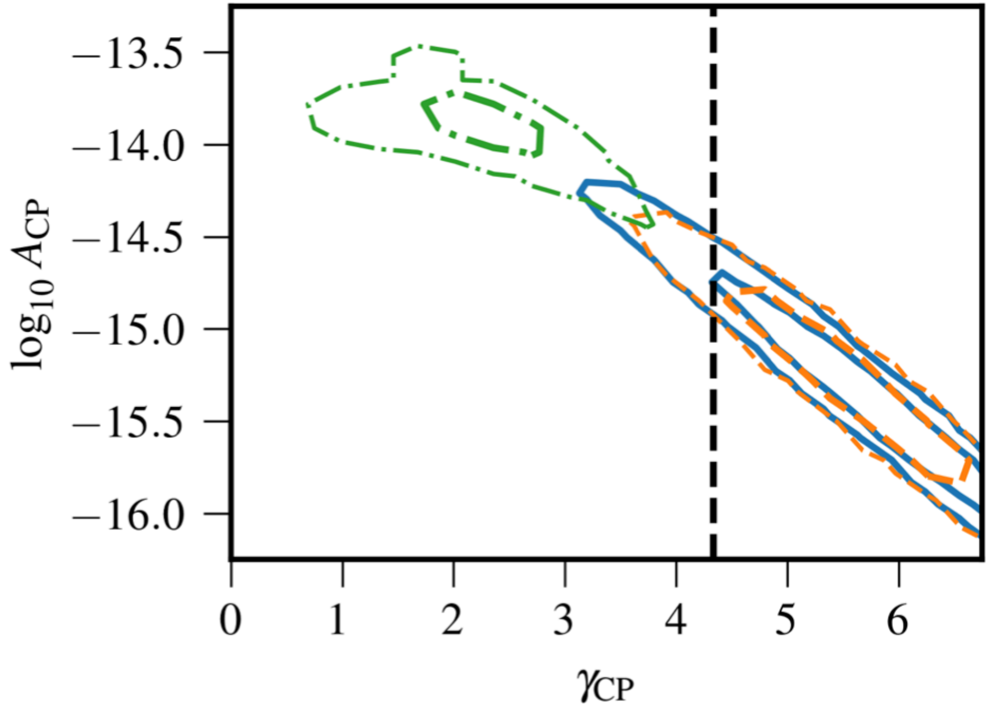


NANOGrav Collaboration: arXiv:2009.04496

Pulsar Timing Data from NANOGrav

12.5-year data





"Strong evidence for a stochastic common-spectrum process" at frequencies < 10^{-8} Hz

No dipole or quadrupole signal detected

Focus on simple power law

Amplitude A ~ 10^{-15}

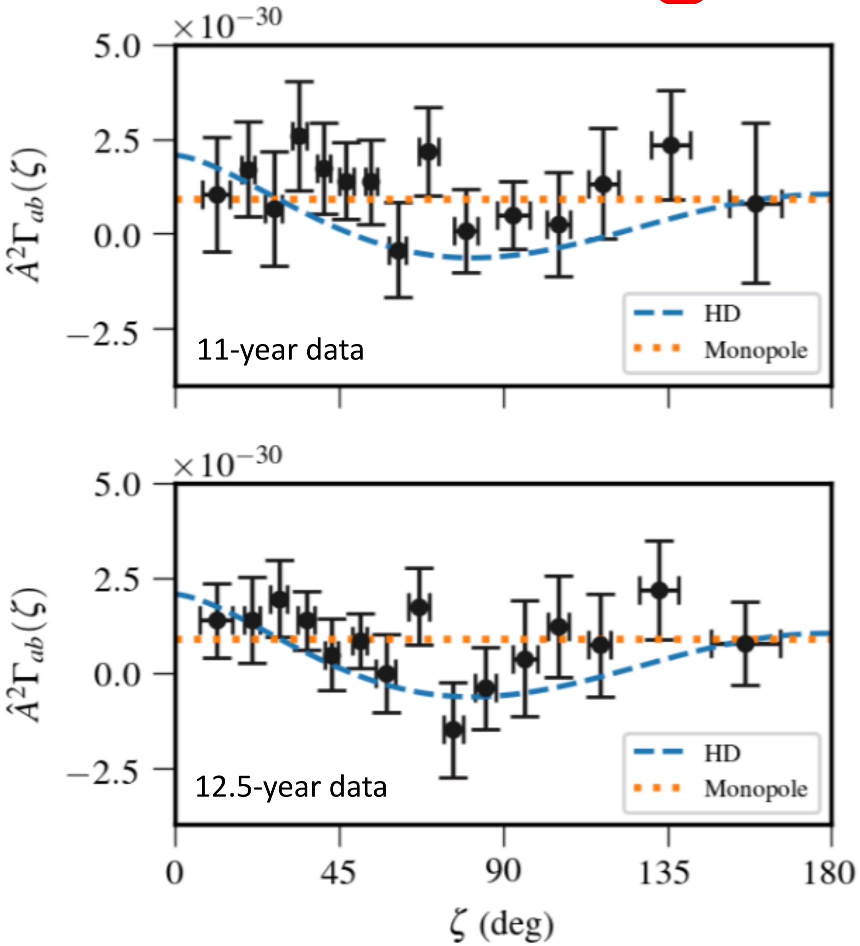
Slope γ ~ 5

Vertical dashed line: mergers of supermassive BHs

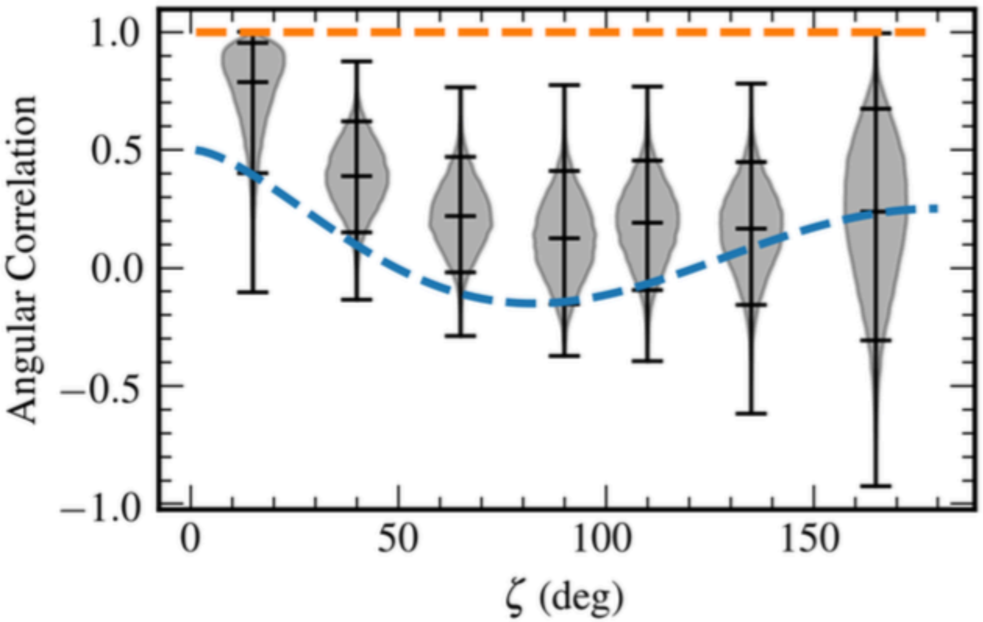
"the amplitude … may imply that the black hole mass function is underestimated, specifically when extrapolated from observations of the local supermassive black hole population"

NANOGrav Collaboration: arXiv:2009.04496

Pulsar Timing Data from NANOGrav



Improved treatment
of intrinsic pulsar red noise
in 12.5-yr data
compared to 11-yr data



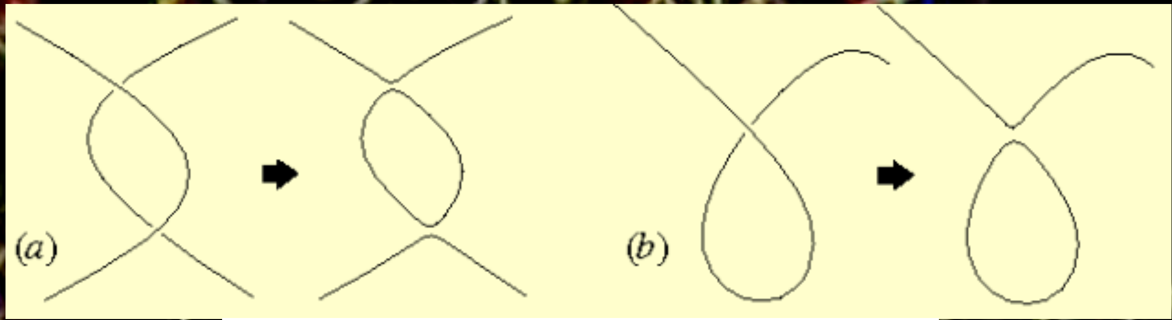
Average angular
distribution of
cross-correlated power
with 11- & 12.5-year data

Reconstruction of
inter-pulsar
angular correlations

Monopole vs HD = angular correlation expected for GWs

Probing Cosmic Strings

Hint from the NANOGrav pulsar timing array?

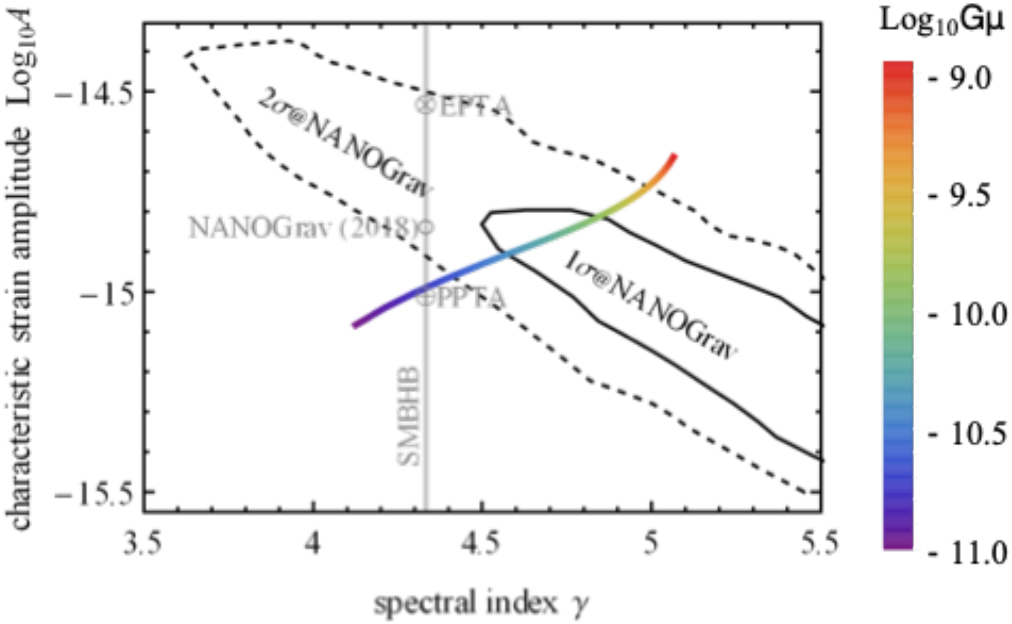


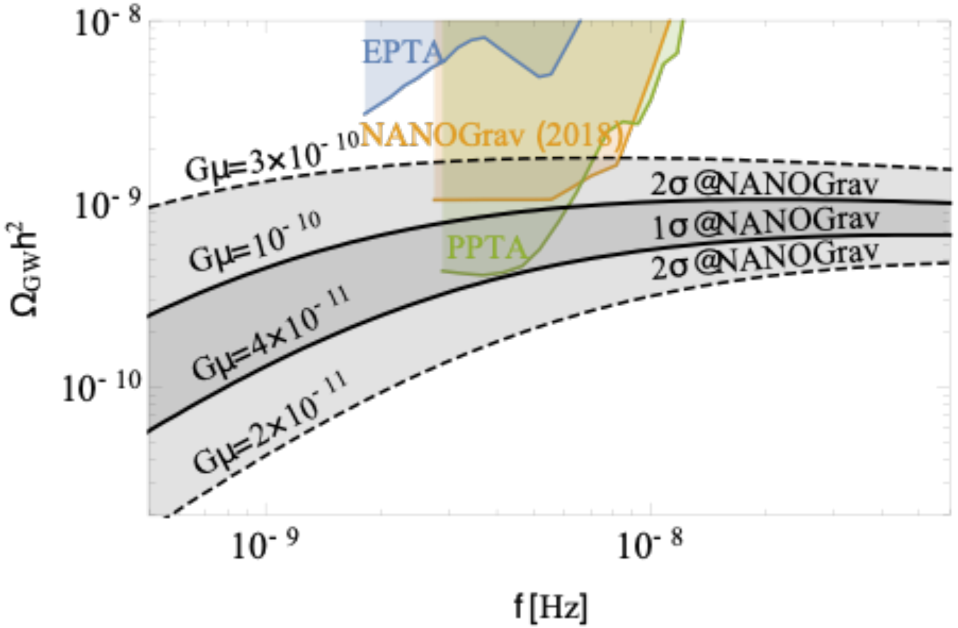
GW emission from string loops

Simulation of cosmic string network – Cambridge cosmology group

JE & Lewicki: arXiv:2009.06555

Cosmic String Interpretation of NANOGrav





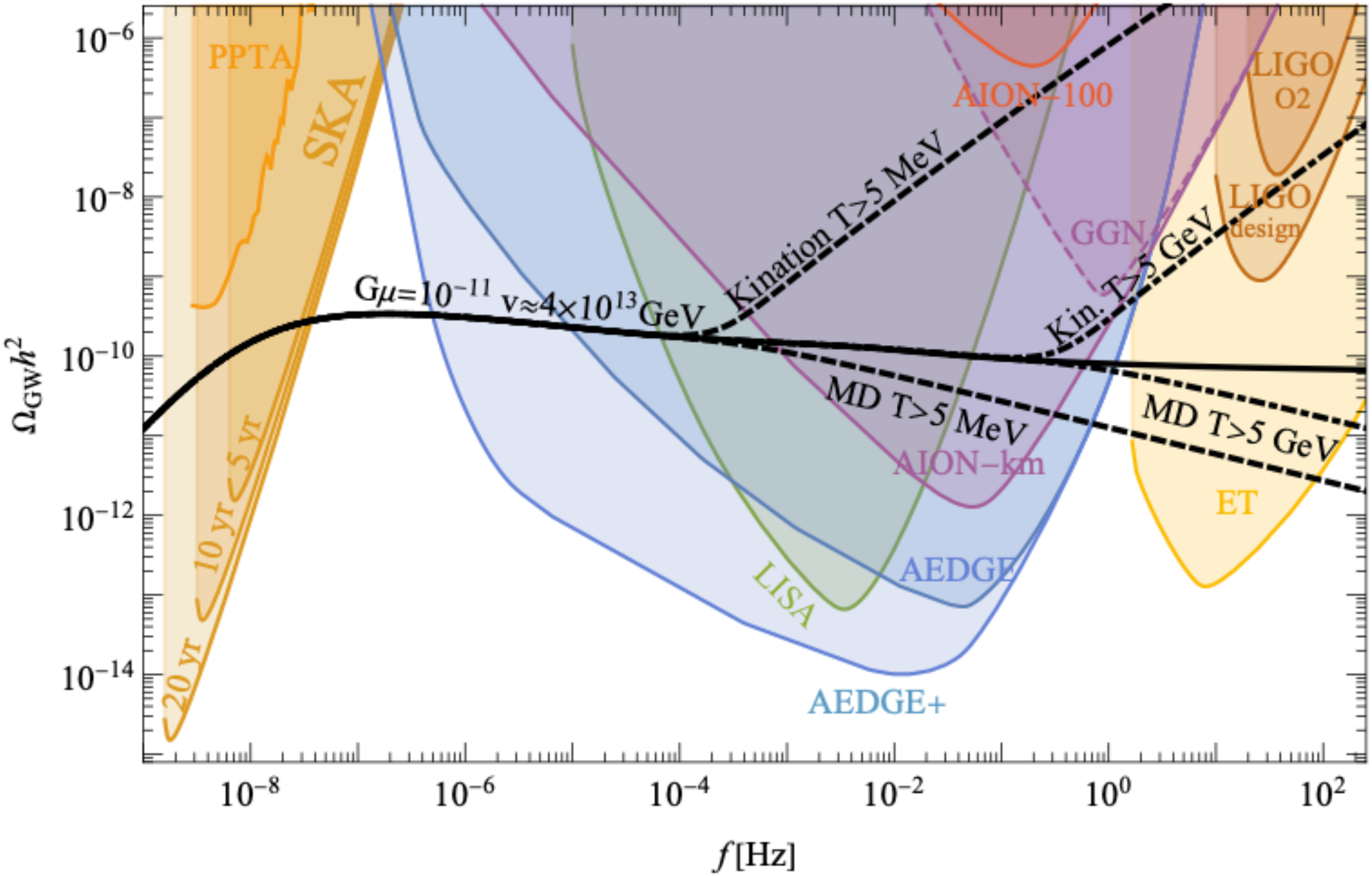
"Rainbow curve"
is cosmic string prediction as a
function of the cosmic string tension Gμ
Vertical line is SMBH merger prediction
Previous PTA upper limits for
this value of γ

Fits to NANOGrav signal
at 1σ (68%), 2σ (95%) levels
Compared to previous
upper limits
(previous NANOGrav superseded)

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

AION

Gravitational Waves from Cosmic Strings



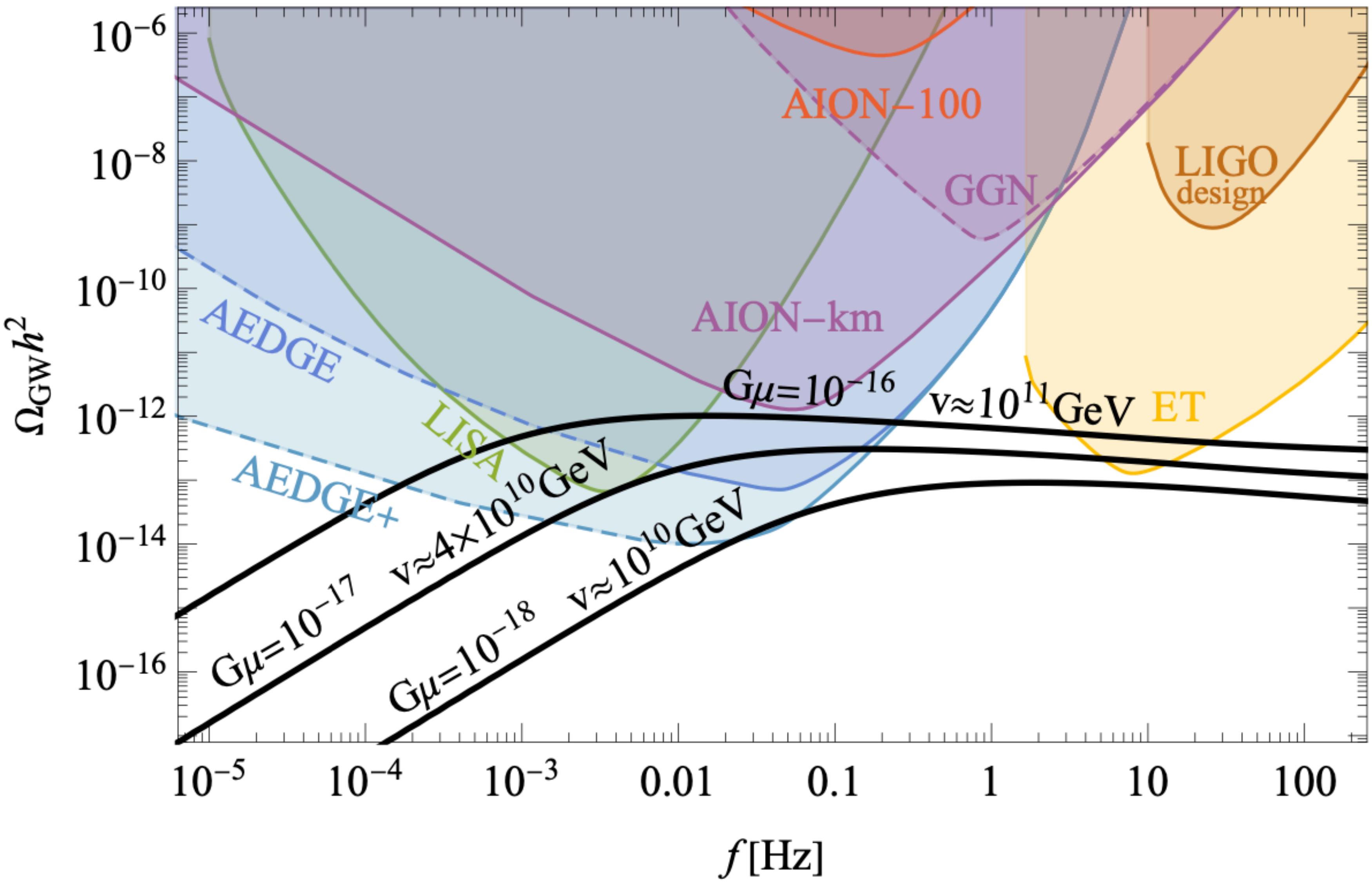
Effects of modified expansion: Kination, Matter Dominance

Spectrum ~ flat from PTA/SKA to LIGO/ET

Tension $G\mu < 10^{-11}$ from PTA limit

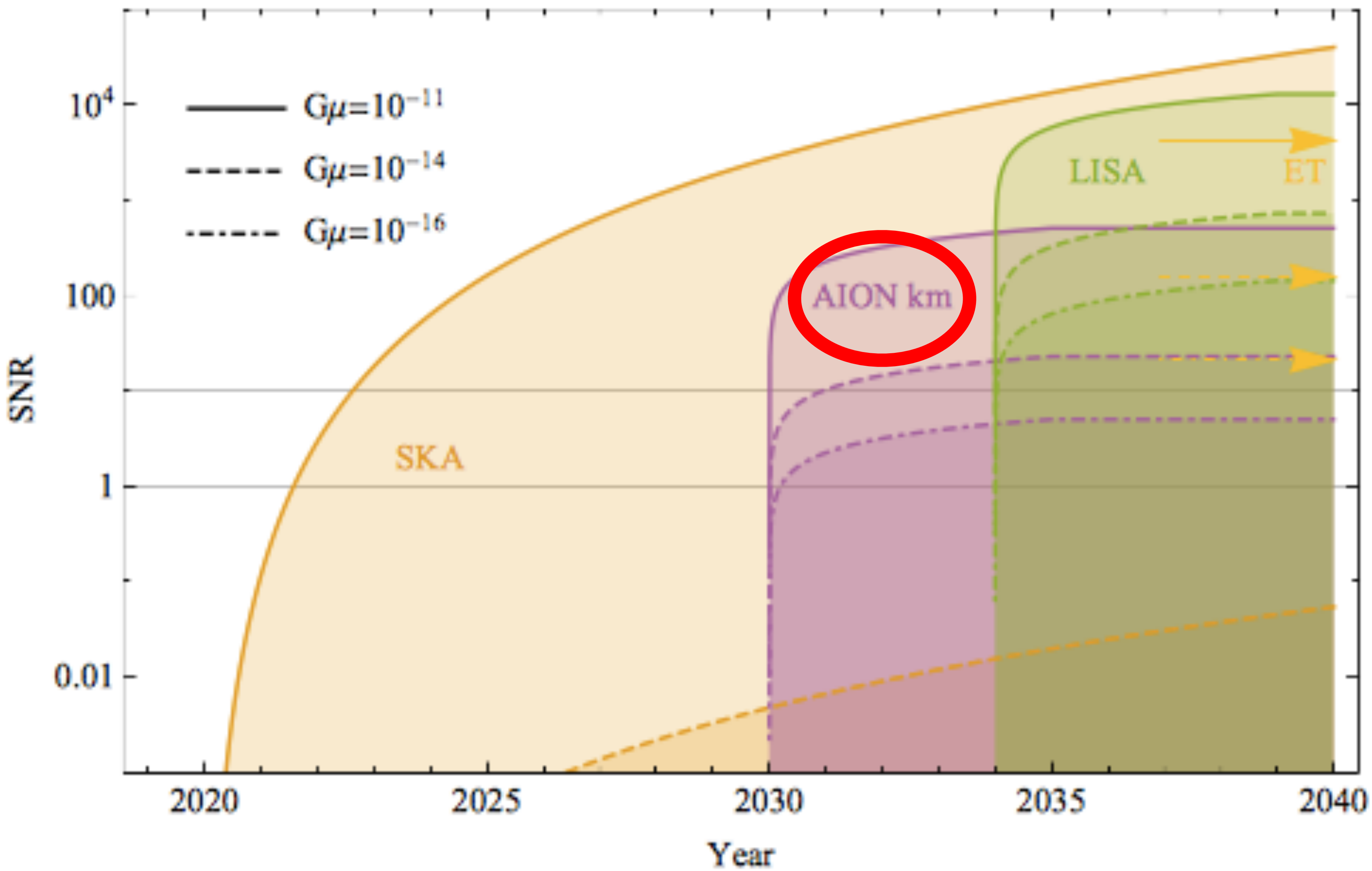
Badurina, Buchmueller, JE et al: arXiv:2108.02468

Gravitational Waves from Cosmic Strings



Different experiments sensitive to different values of cosmic string tension

Perspectives for Future Experiments



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

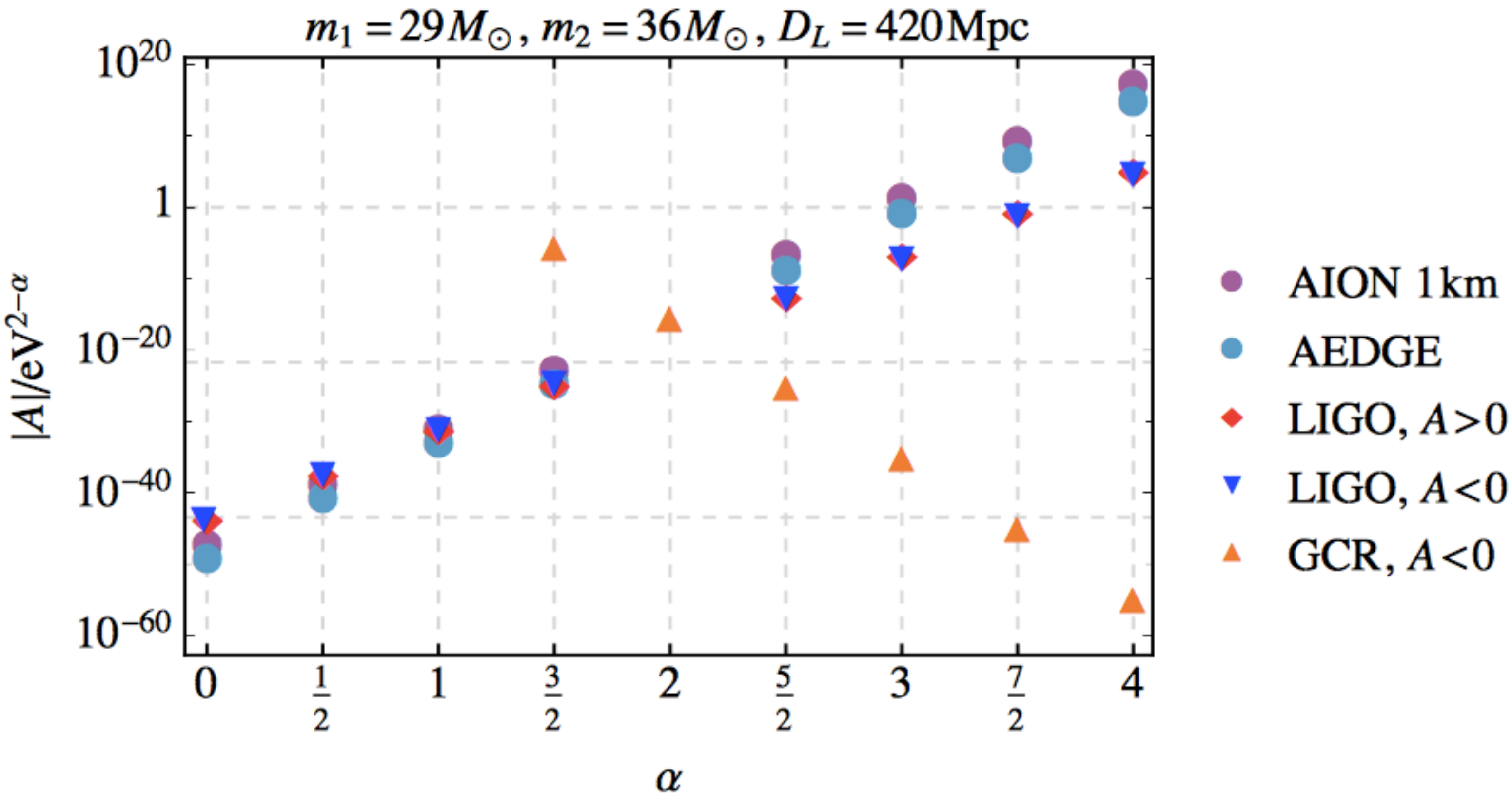
Explore Beyond Dark Matter & GWs

- High-precision measurement of the gravitational redshift, probes of Bell inequalities and the equivalence principle
- Probing fundamental “constants”, chameleons, dark energy
- Detecting astrophysical neutrinos?
- Long-range fifth forces?
- Lorentz violation?
- Fundamental ($\neq$ environmental) decoherence?
- …..

Lorentz Violation

AION

- Modified dispersion relation: $E^2 = p^2 + Ap^\alpha$



- AION 1-km: sensitivity 10 × LIGO for α = ½
- AEDGE: sensitivity 1000 × LIGO for α = ½

JE & Vaskonen: arXiv:2003.13480

Summary

AION

- Experience with electromagnetic waves shows the advantages of making astronomical observations in a range of different frequencies, and the same is expected to hold in the era of gravitational astronomy
- Many opportunities to search for new fundamental physics
- Hint of cosmic strings from NANOGrav pulsar timing array?
- AION offers a programme for exploring deci-Hz GW based on atom interferometry (IMBHs, 1^{st}-order phase transitions, …)
- AEDGE is a concept for a space mission that would complement, and have synergies with, other future GW experiments
- Other possible opportunities in fundamental physics, astrophysics and cosmology have been identified, but not yet explored in detail
- **Unique interdisciplinary science!**