Probing Gravitational Waves and Dark Matter with Atom Interferometry

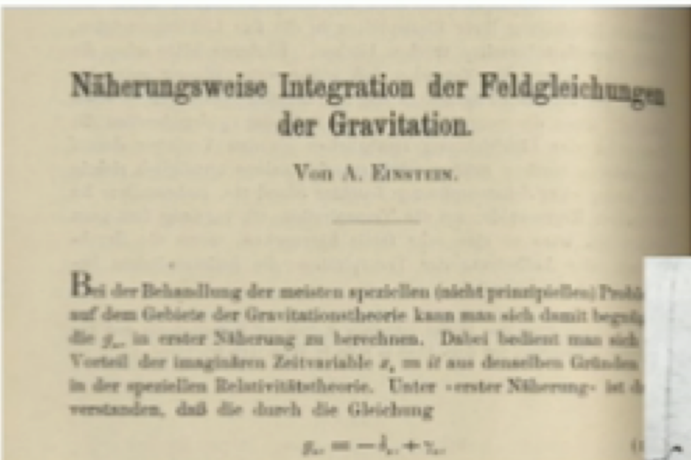
The GW story so far
The gap in the spectrum
The AION project
AION science: GWs from mergers, phase transitions, strings
AEDGE: proposal for atom interferometer in space
Searches for ultralight dark matter, etc.

John Ellis

KING'S College LONDON

Gravitational Waves

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

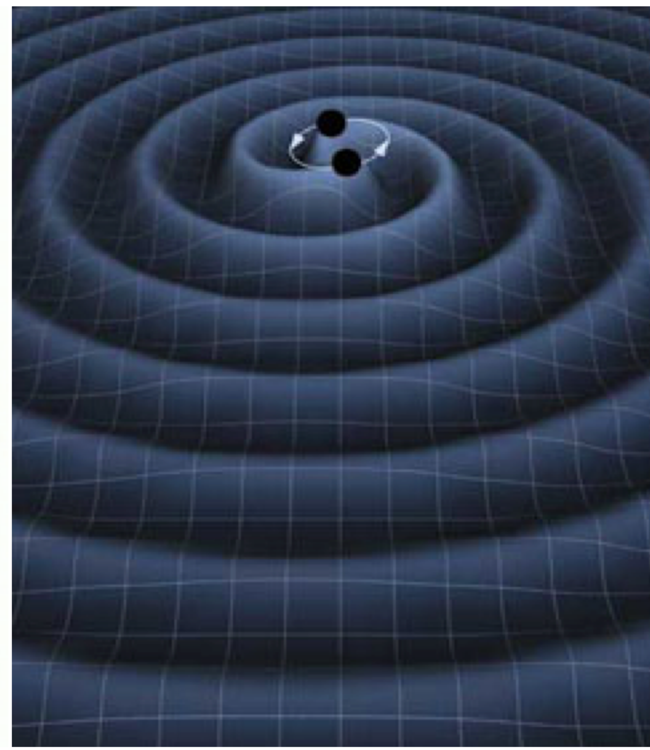

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probl… auf dem Gebiete der Gravitationstheorie kann man sich damit begnü… 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

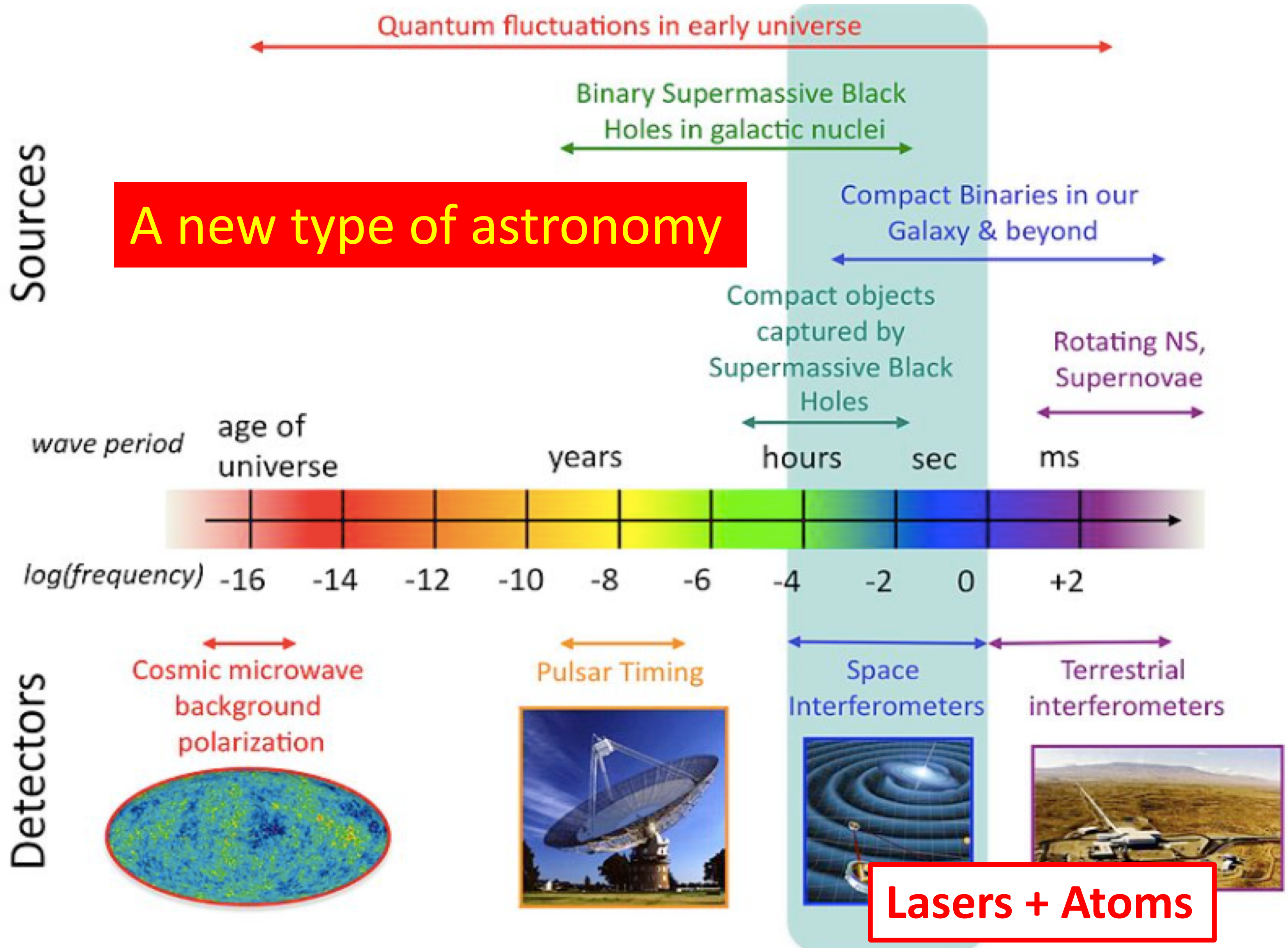
$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu}$$

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



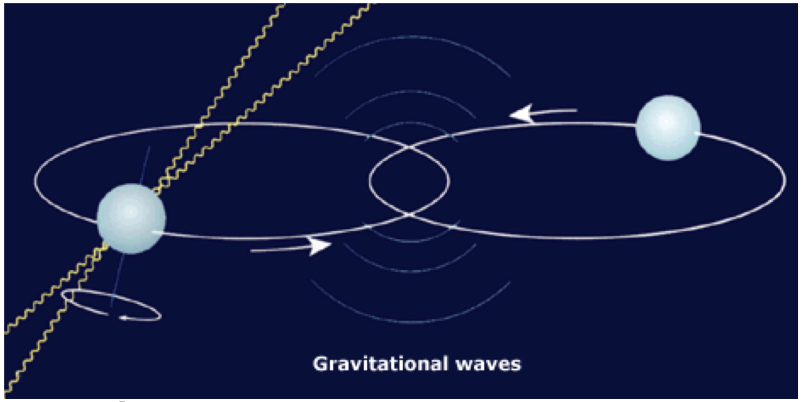
- Tried to retract prediction in 1936!

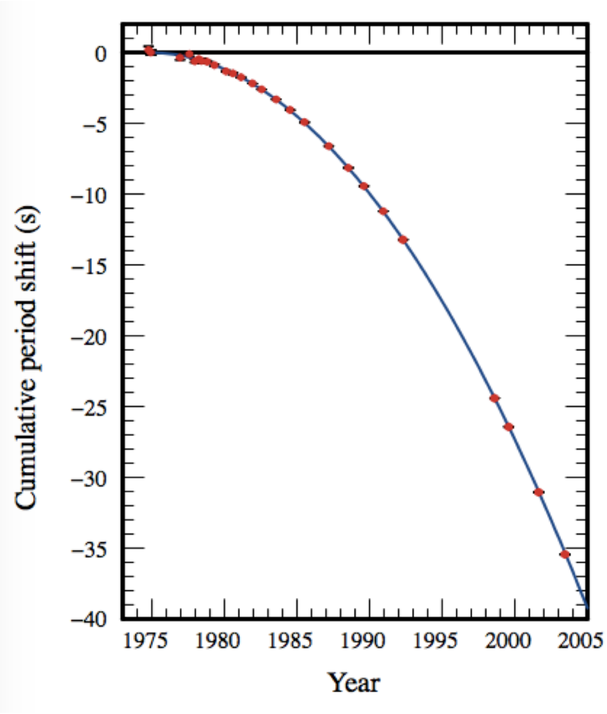
Gravitational Wave Spectrum



Indirect Detection

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

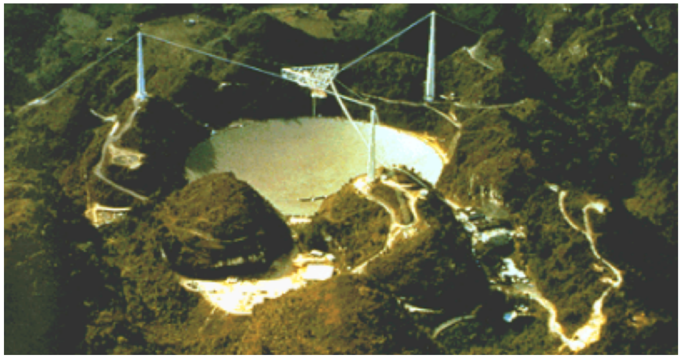




for years

agreement with Einstein

Nobel Prize 1993



Direct Discovery of Gravitational Waves

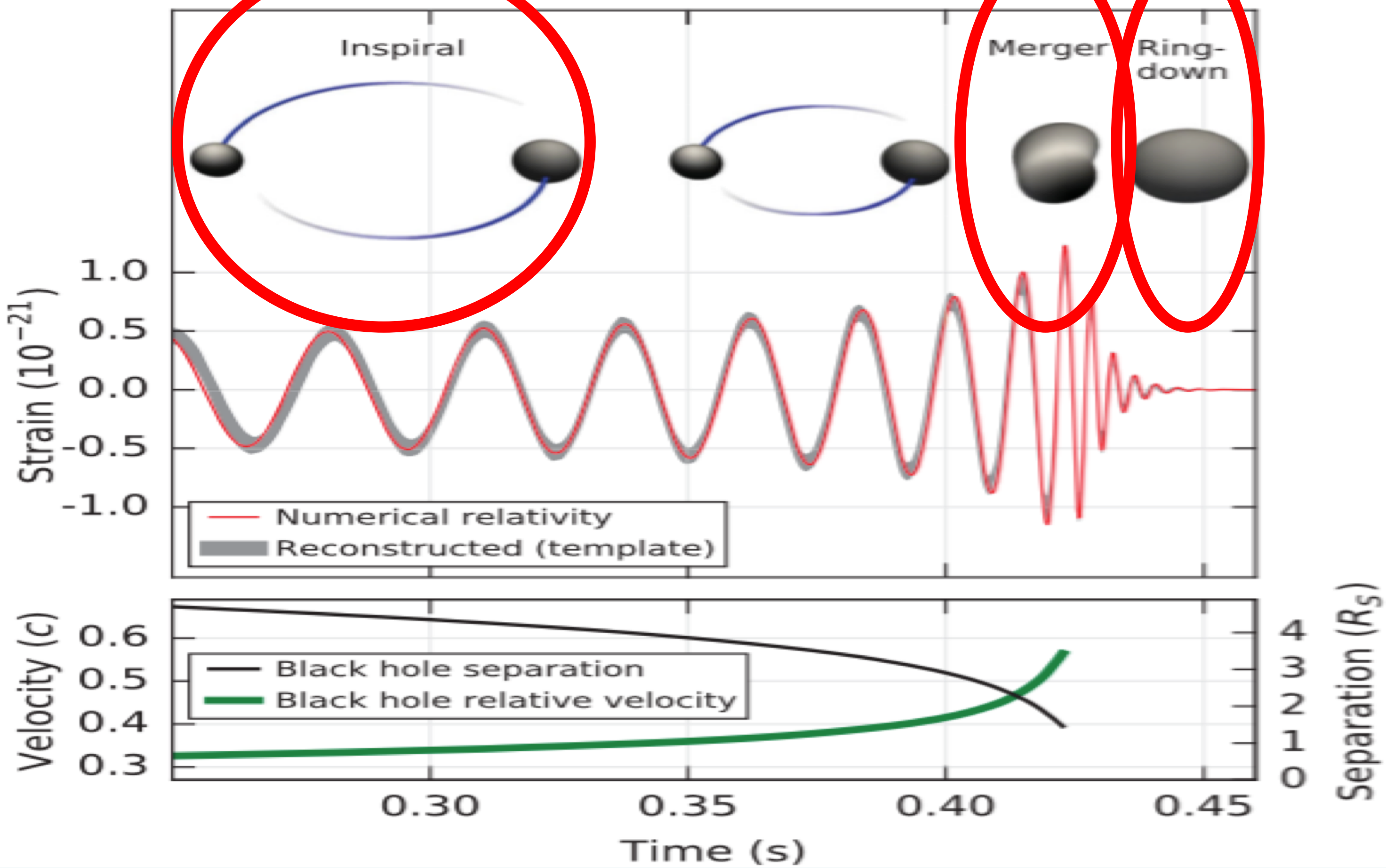
- Measured by the LIGO experiment in 2 locations

Mergers Measured in First LIGO/Virgo Observation Period

Binary neutron star merger: electromagnetic counterpart

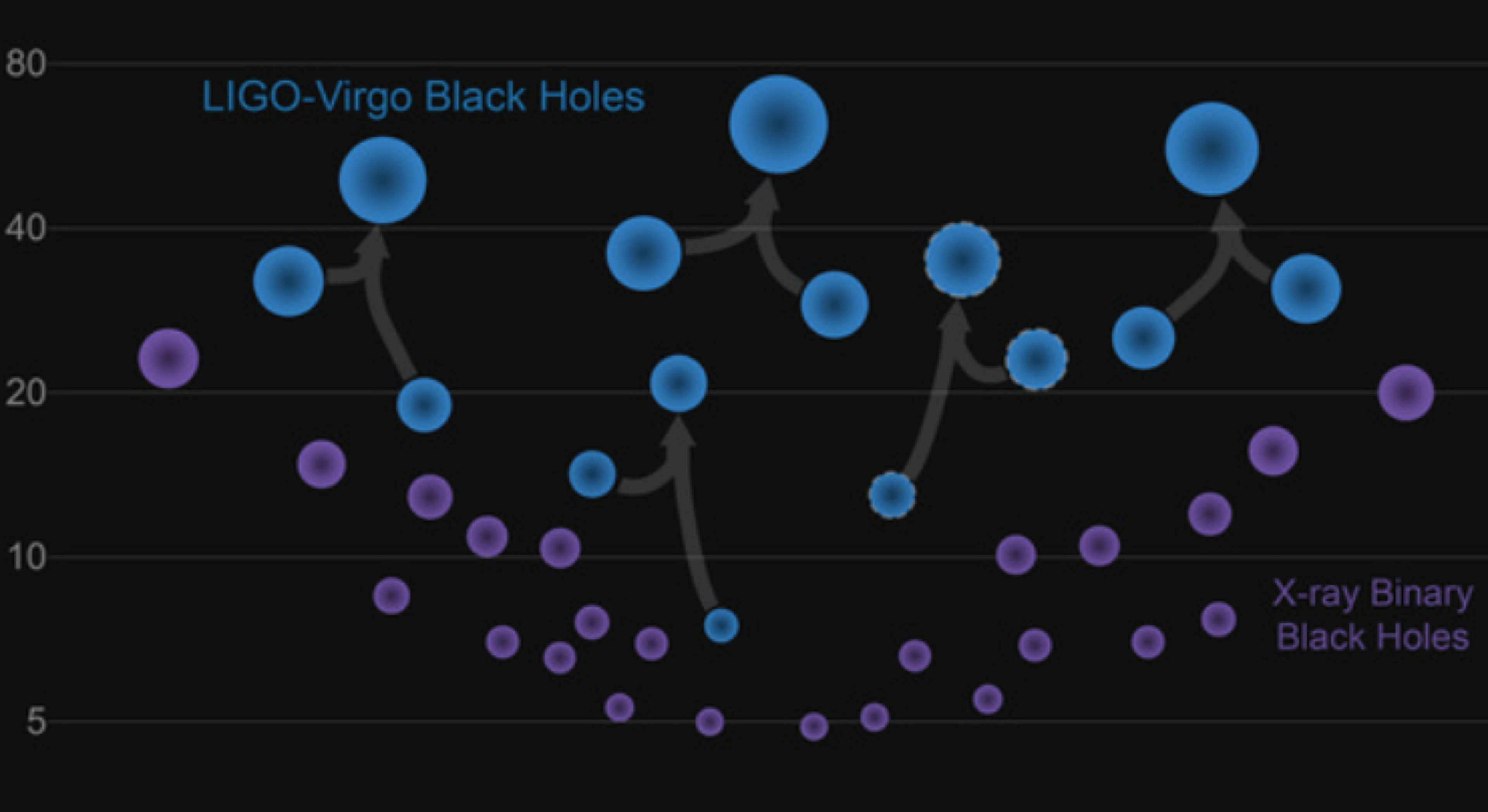
Fusion of two massive black holes

- Einstein was right the first time!

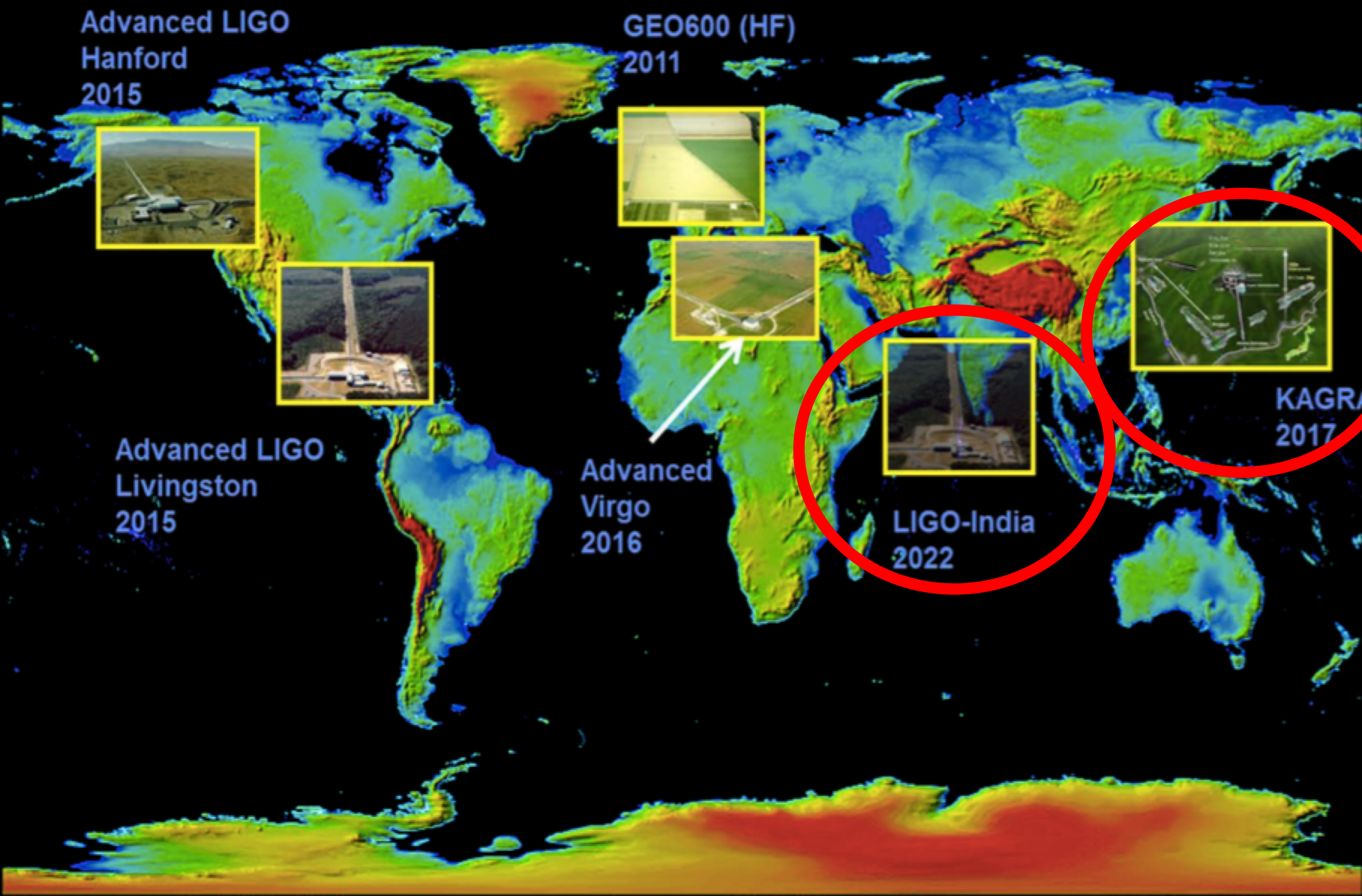


- A new way to study the Universe

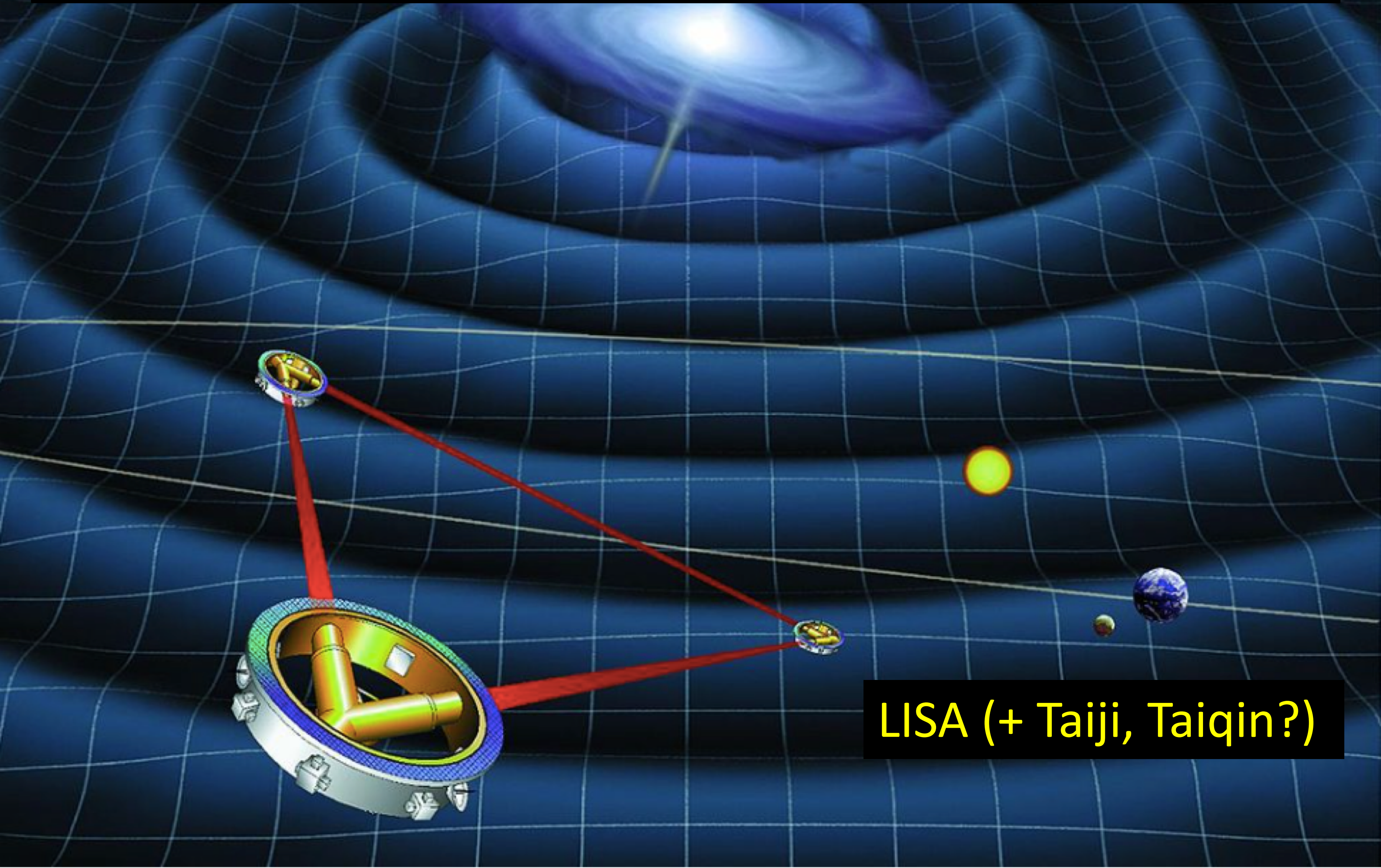
Masses of Black Holes Deduced from Measured Mergers



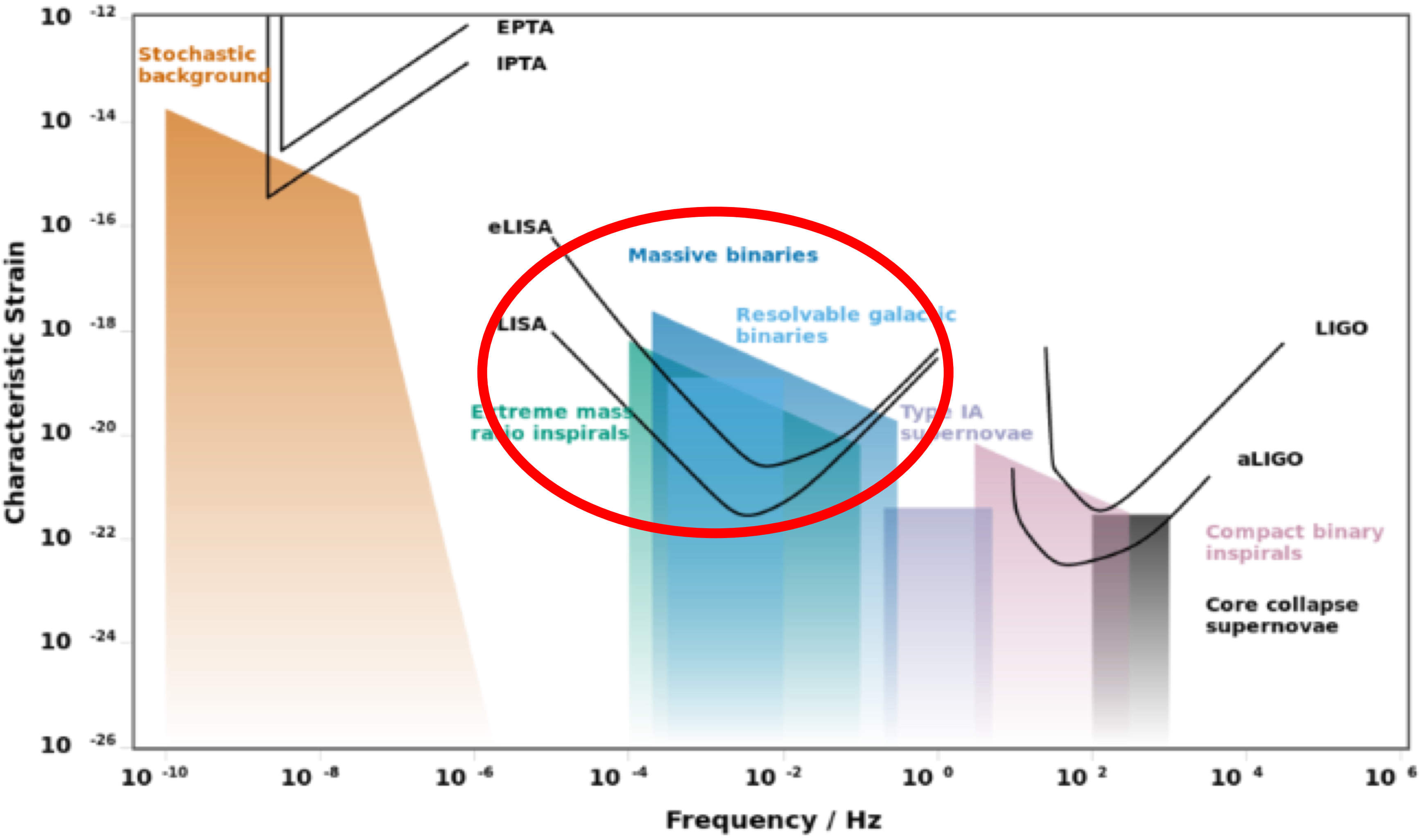
Ground-Based GW Detectors



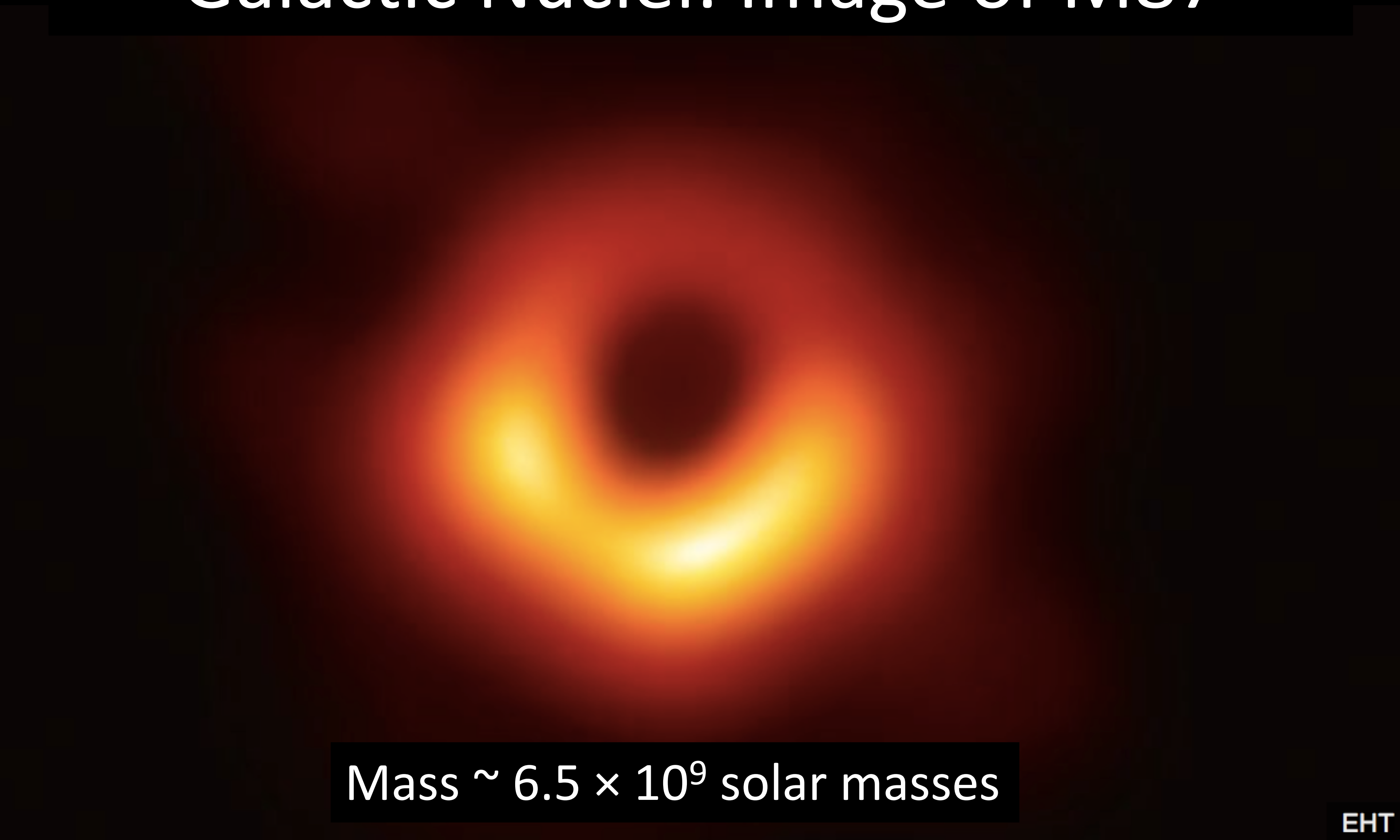
Future Step: Interferometer in Space



Gravitational Wave Landscape

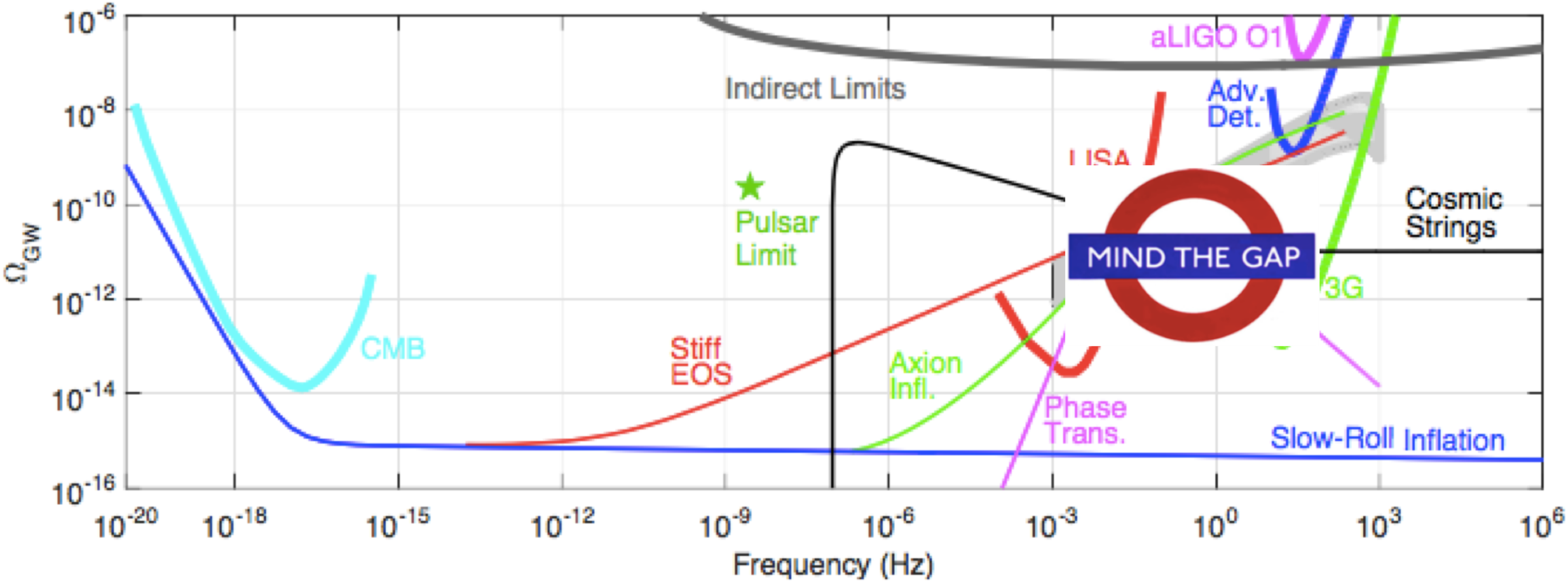


Supermassive Black Holes in Active Galactic Nuclei: Image of M87



Mass ~ 6.5×10^9 solar masses

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)

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Quantum Science Program

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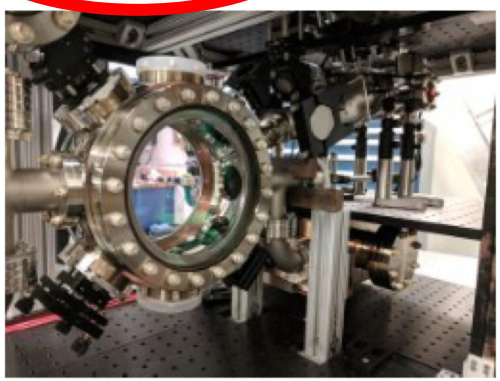
MAGIS-100



Fermilab seeks to host MAGIS-100 — the 100-meter Matter-wa Gradiometer Interferometric Sensor — which will test quantum macroscopic scales of space and time.

The laboratory is developing a sensitive prototype detector tha precisely measure properties of the cosmos.

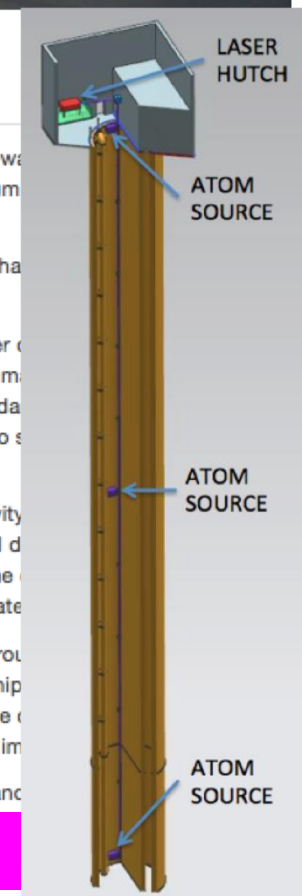
One of these is dark matter. Physicists have offered a number o models describing dark matter, a mysterious substance that m quarter of the universe. Some of these models suggest that da made of ultralightweight particles. MAGIS-100 will be used to s particular those that predict varying atomic energy levels.

A longer-term goal for MAGIS-100 is to establish the sensitivity technique to gravitational waves in the frequency range around 1 hertz, where there are few existing or proposed d waves, predicted by Einstein a century ago but discovered for the first time only in 2015, are ripples in space-time accelerating masses, such as stars and galaxies. MAGIS-100 creates atom matter waves in superposition separate

The MAGIS-100 prototype would make use of an existing vertical shaft on the Fermilab site that leads to undergrou will perform precision quantum measurements using clouds of ultracold falling atoms, whose phases can be manip using lasers, aiding in the test for lightweight dark matter particles. The length of the 100-meter drop expands the technology by about a factor of 10 and provides opportunities for significant advances in the systematics of this im

MAGIS-100 combines the unique physical features of the Fermilab site with the laboratory expertise in vacuum and

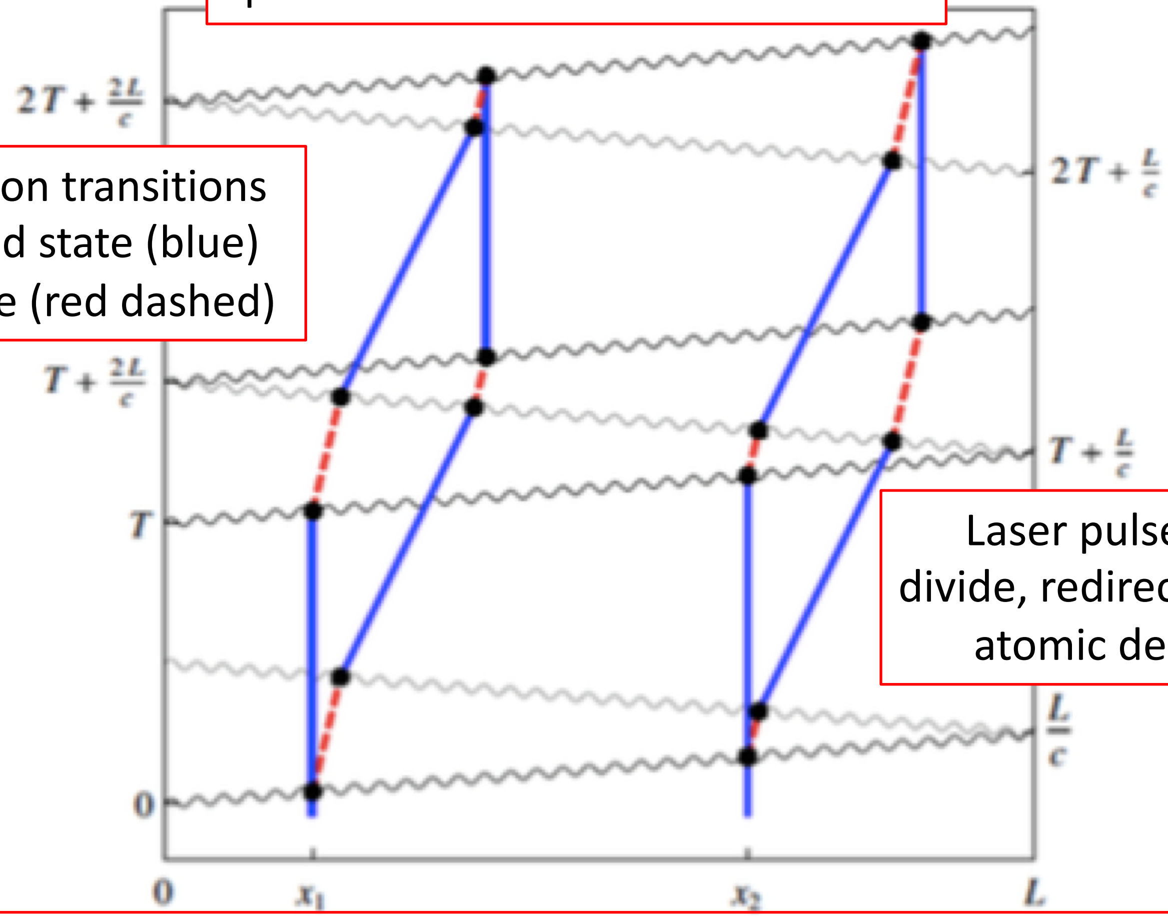
MAGIS Collaboration (Coleman et al): arXiv:1812.00482



Principle of Atom Interferometry

Space-time diagram of operation of pair of cold-atom interferometers

Use single-photon transitions between ground state (blue) and excited state (red dashed)



Laser pulses (wavy lines) divide, redirect, and recombine atomic de Broglie waves

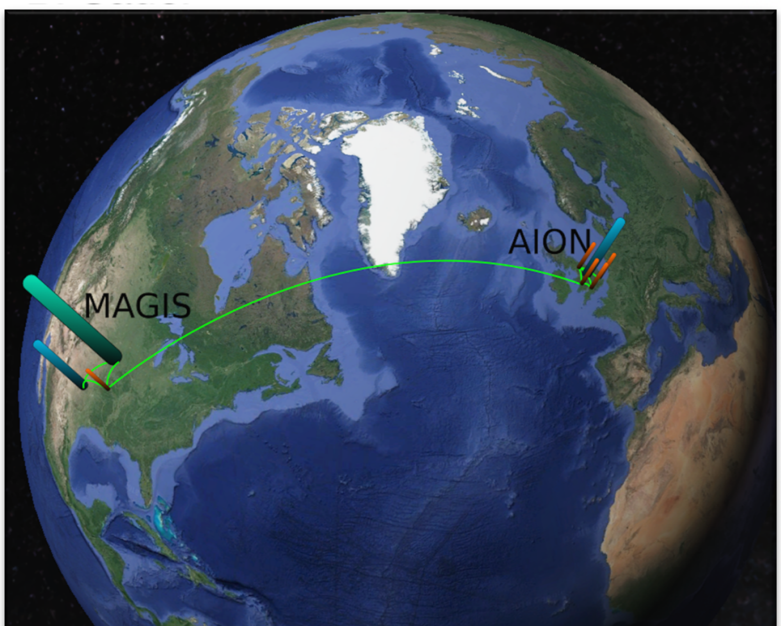
Interference patterns sensitive to modulation of light travel time caused by GWs

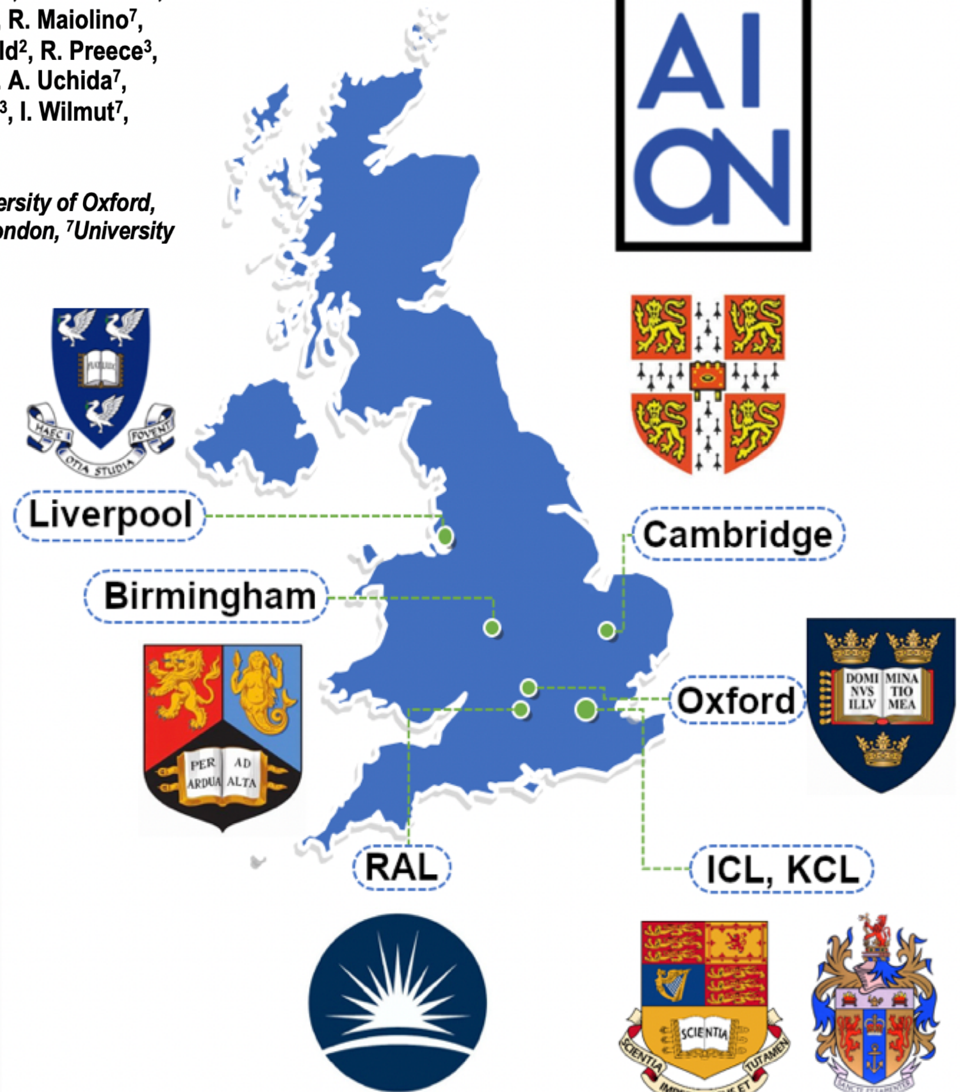
AION Collaboration

The AION Core Team

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





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

AION

An Atom Interferometer Observatory and Network (AION) for the exploration of Ultra-Light Dark Matter and Mid-Frequency Gravitational Waves

ABSTRACT: We outline the experimental concept and key scientific capabilities of AION (Atom Interferometer Observatory and Network), a proposed UK-based 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 in the US, 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 (Coleman et al): arXiv:1812.00482

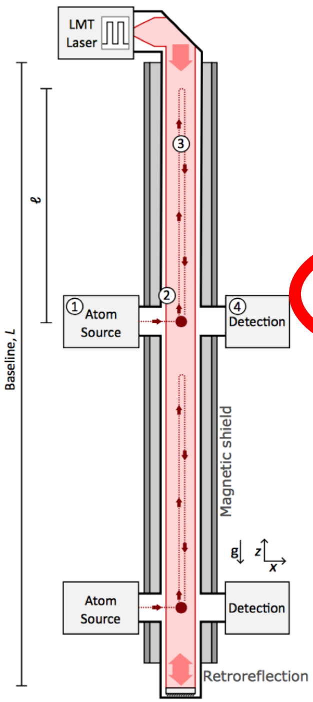
AION – Staged Programme

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

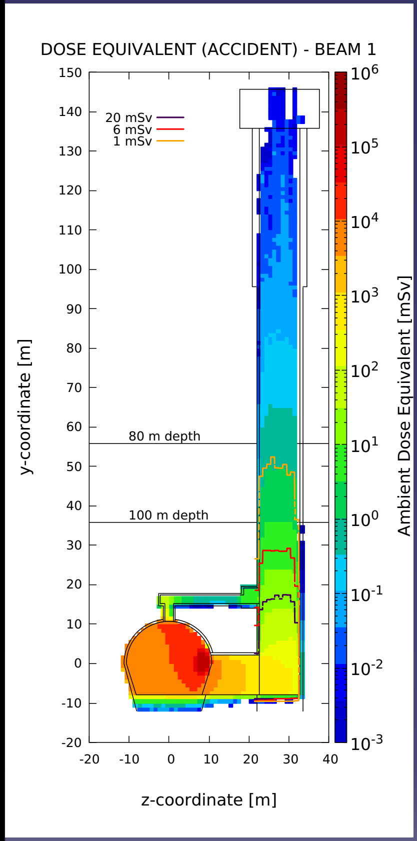
AION Collaboration (Badurina, ..., JE et al): arXiv:1911.11755

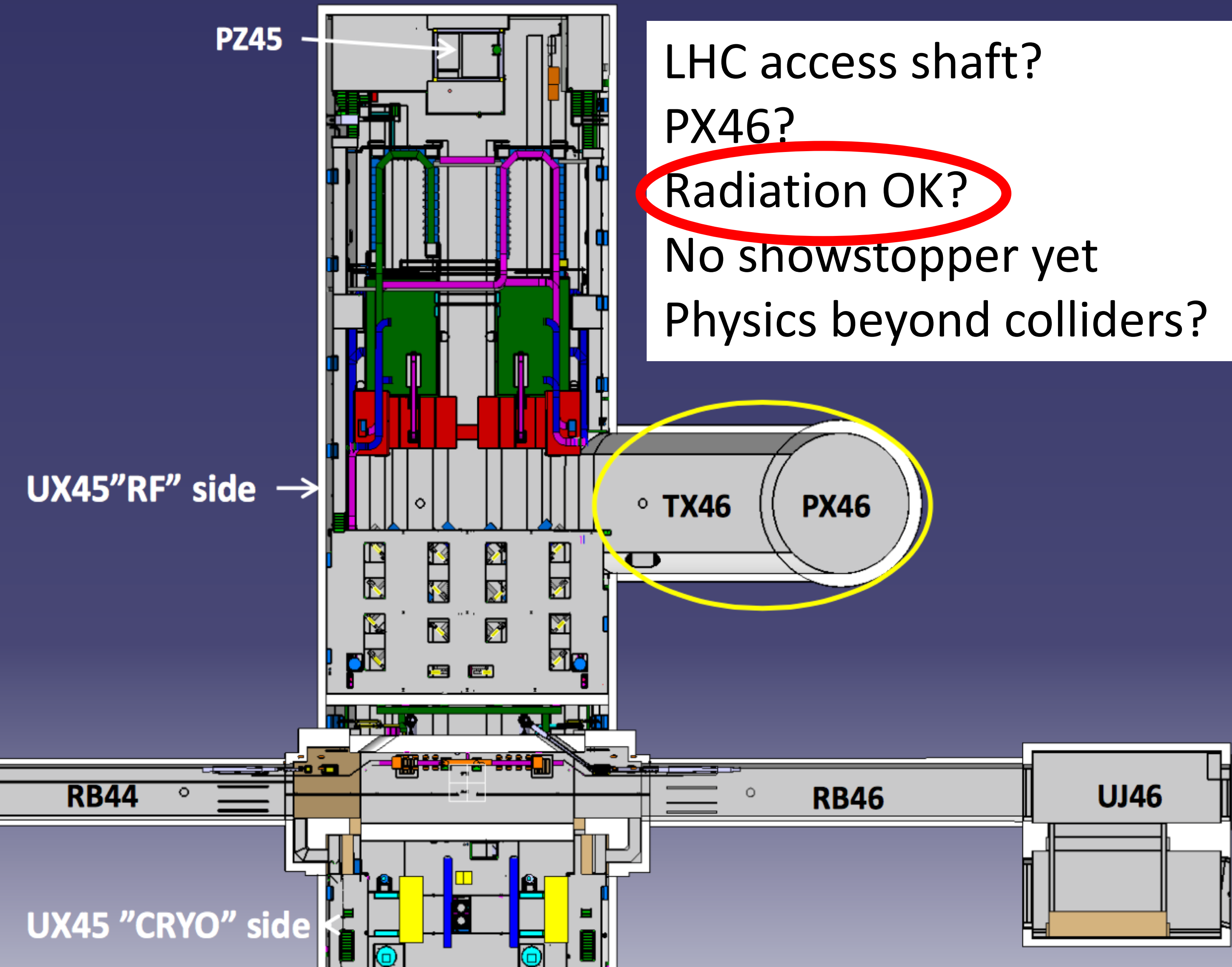
Planned Site for AION 10m

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





LHC access shaft?

PX46?

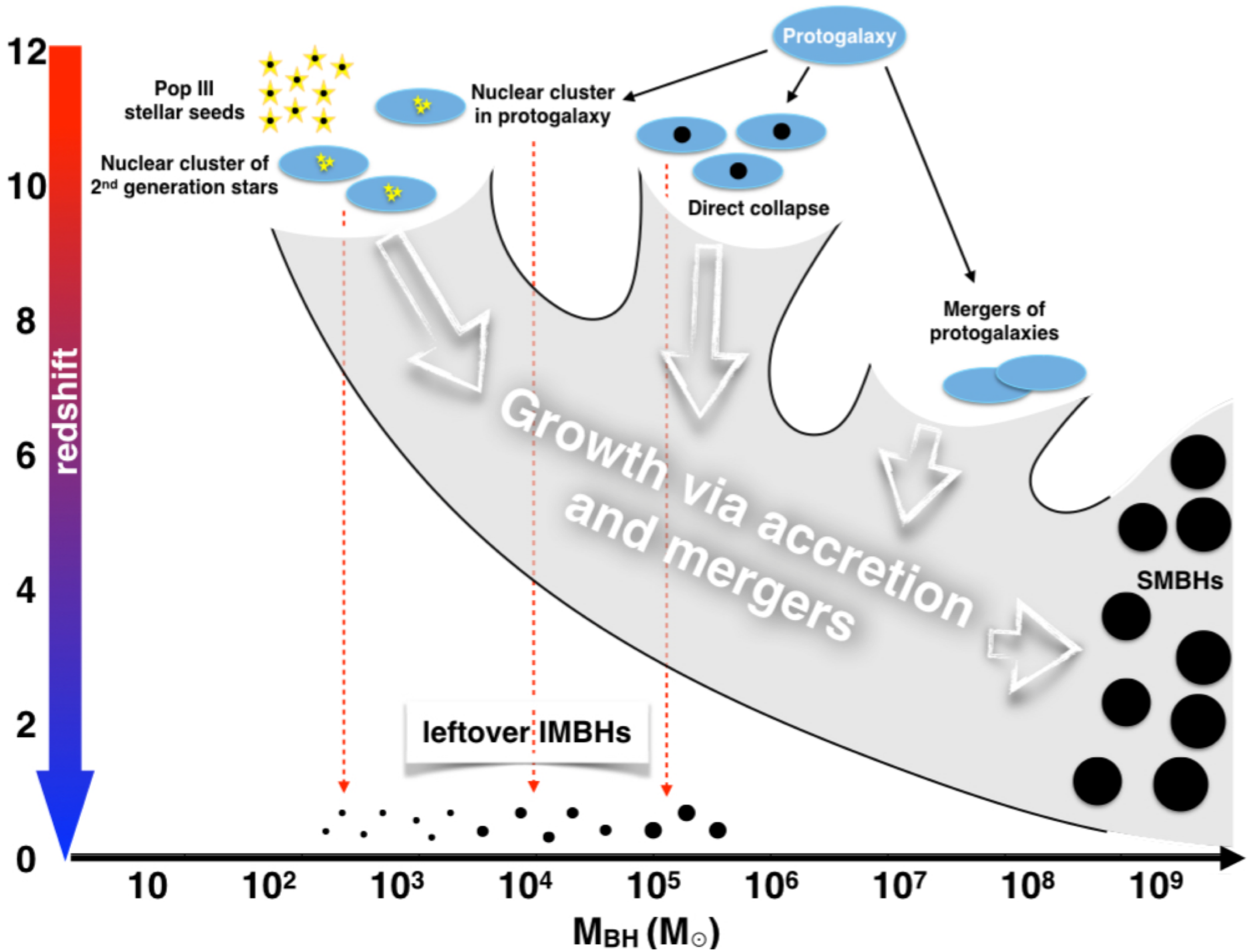
Radiation OK?

No showstopper yet

Physics beyond colliders?

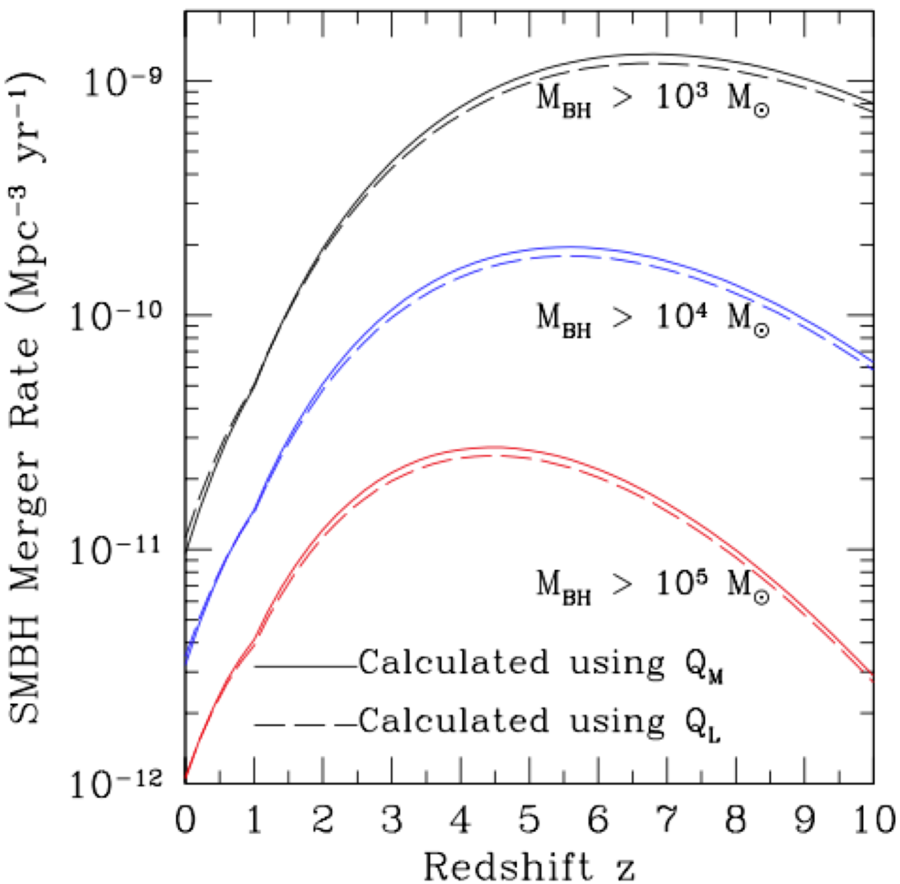
How to Make a Supermassive BH?

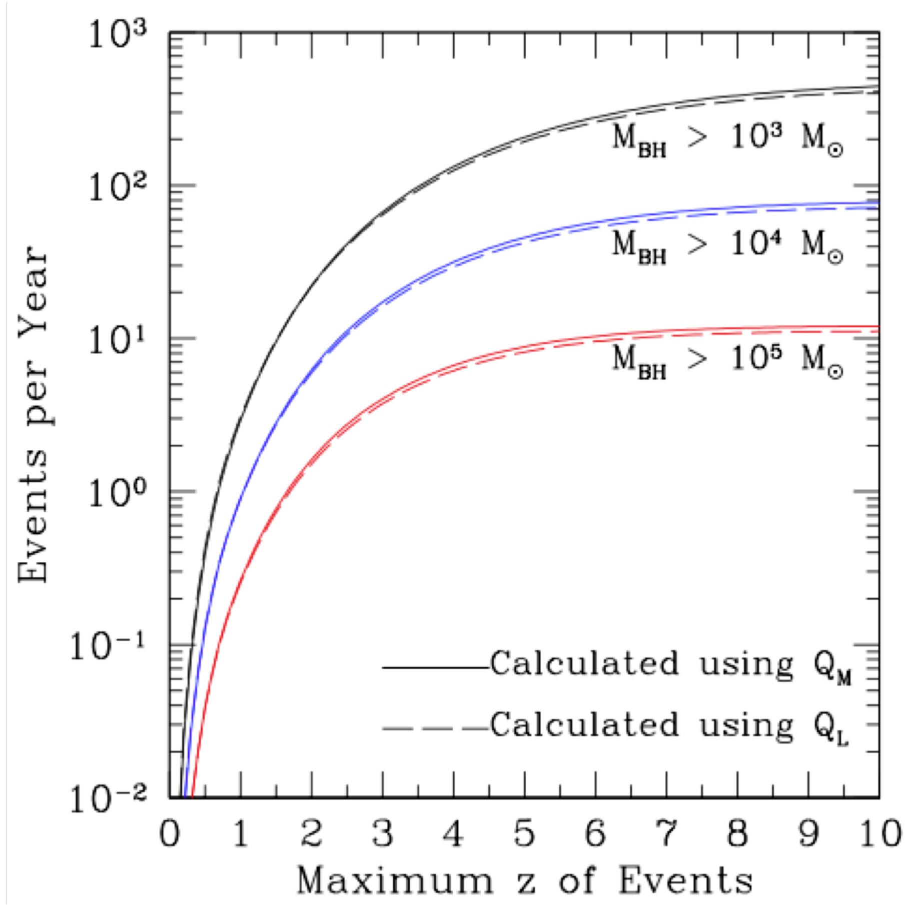
SMBHs from mergers of intermediate-mass BHs (IMBHs)?



How to Make a Supermassive BH?

- SMBHs from mergers of intermediate-mass BHs (IMBHs)?
- Estimated merger rates: most at $z < 10$

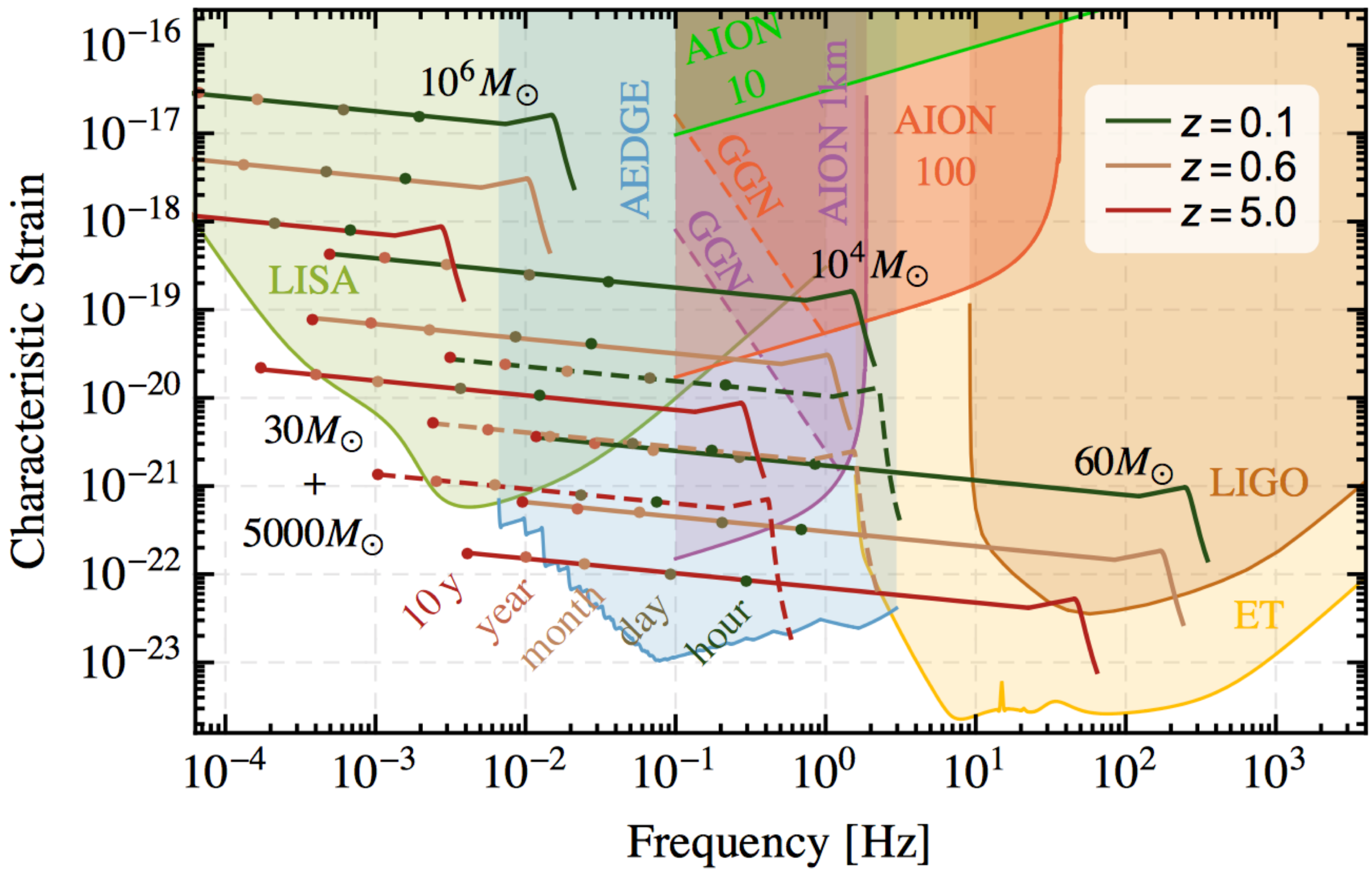




Erickcek, Kamionkowski & Benson, astro- ph/0604281

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

Gravitational Waves from IMBH Mergers



Probe formation of SMBHs

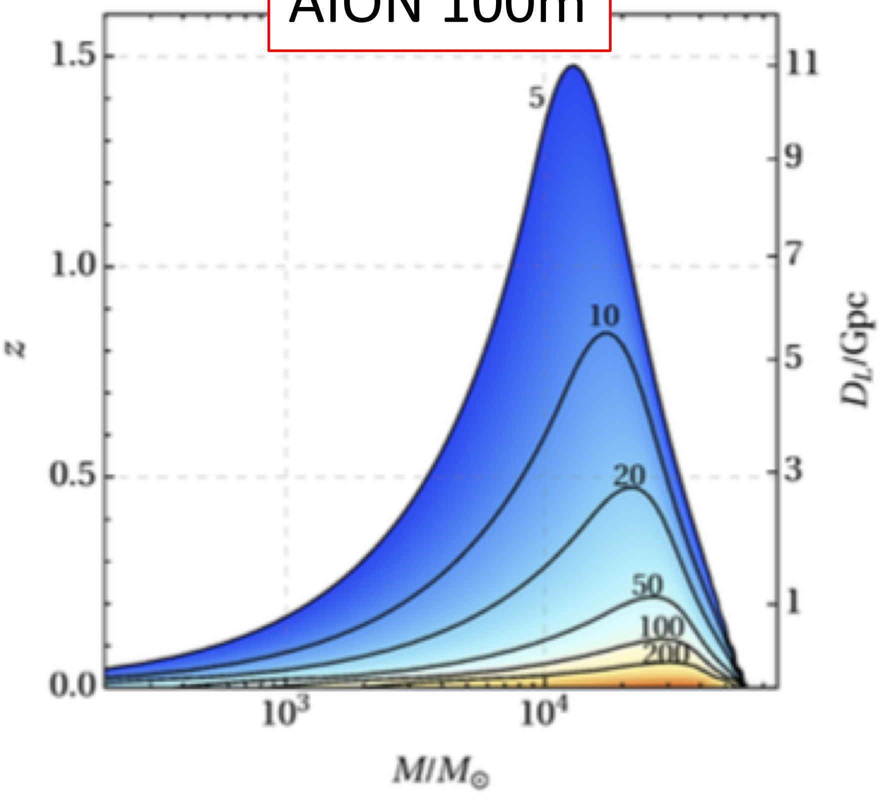
Synergies with other GW experiments (LIGO, LISA), test GR

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

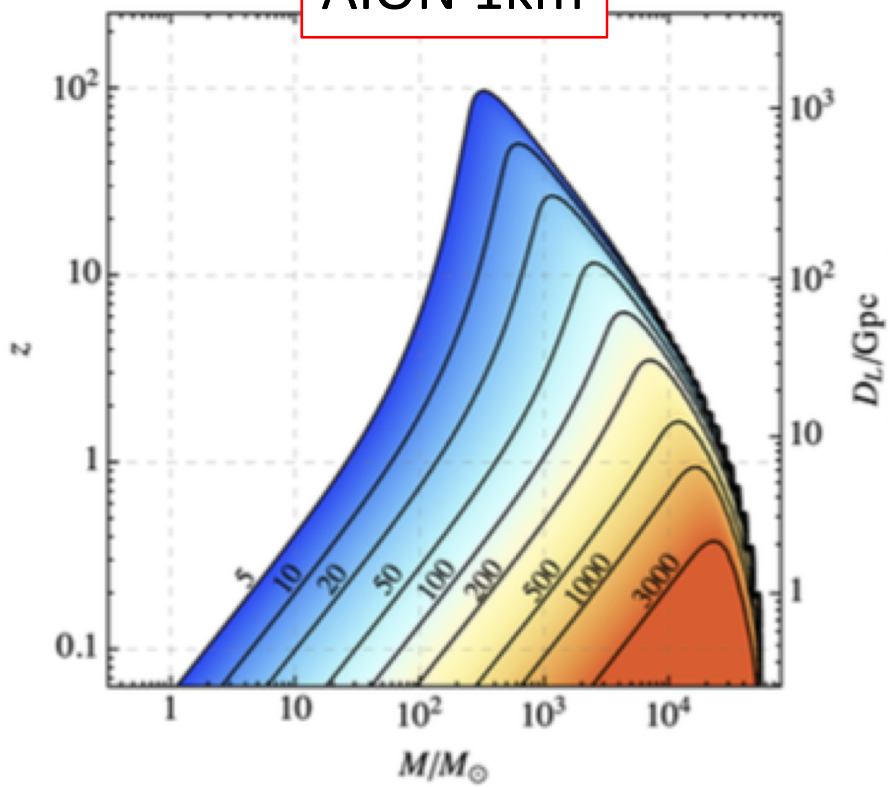
AION GW SNR from IMBH Mergers

Map assembly of SMBHs

AION 100m



AION 1km

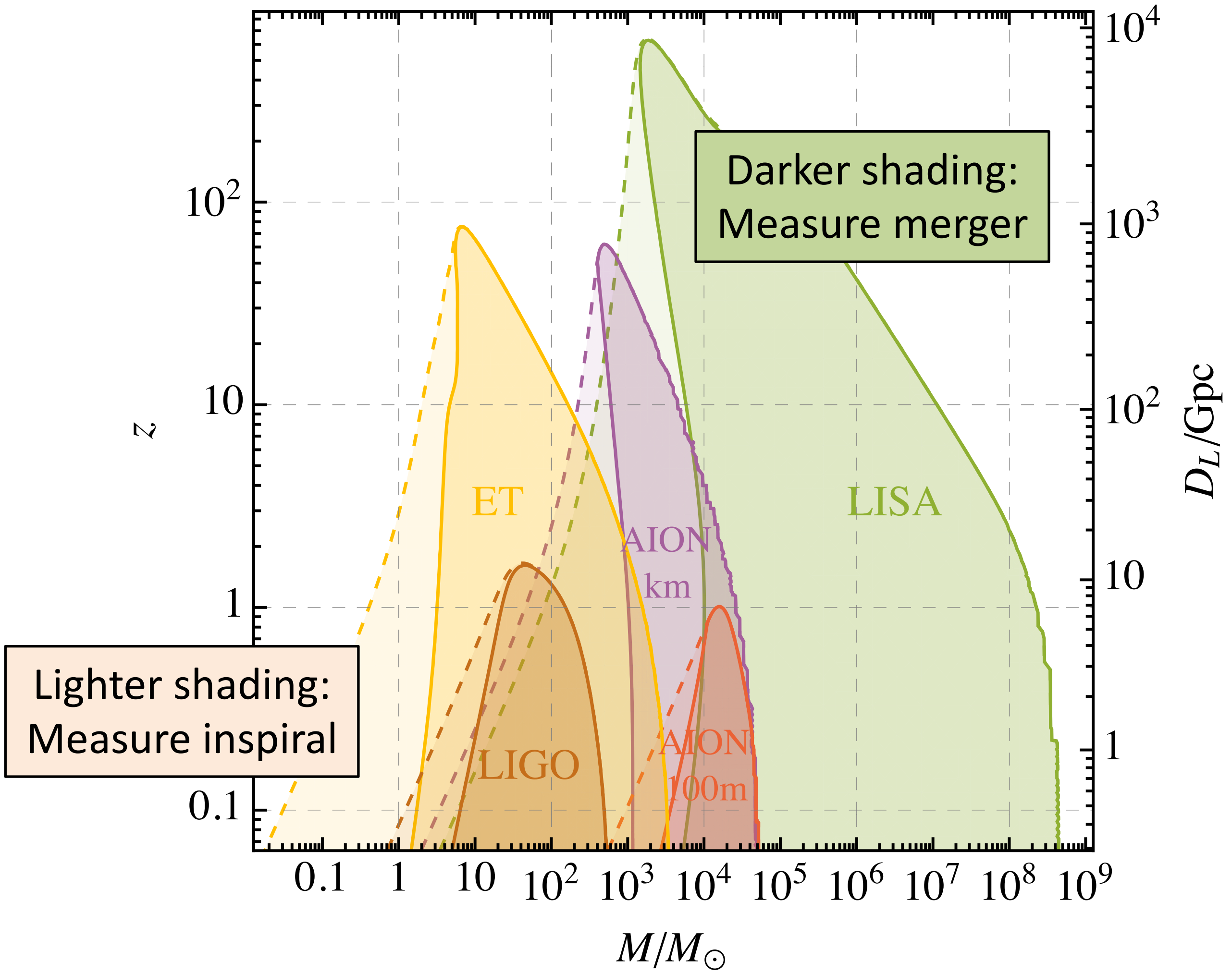


SNR > 5 out to z > 1
for masses ~ 10^4 solar

SNR > 10 out to z ~ 10
for masses ~ 10^3 solar

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

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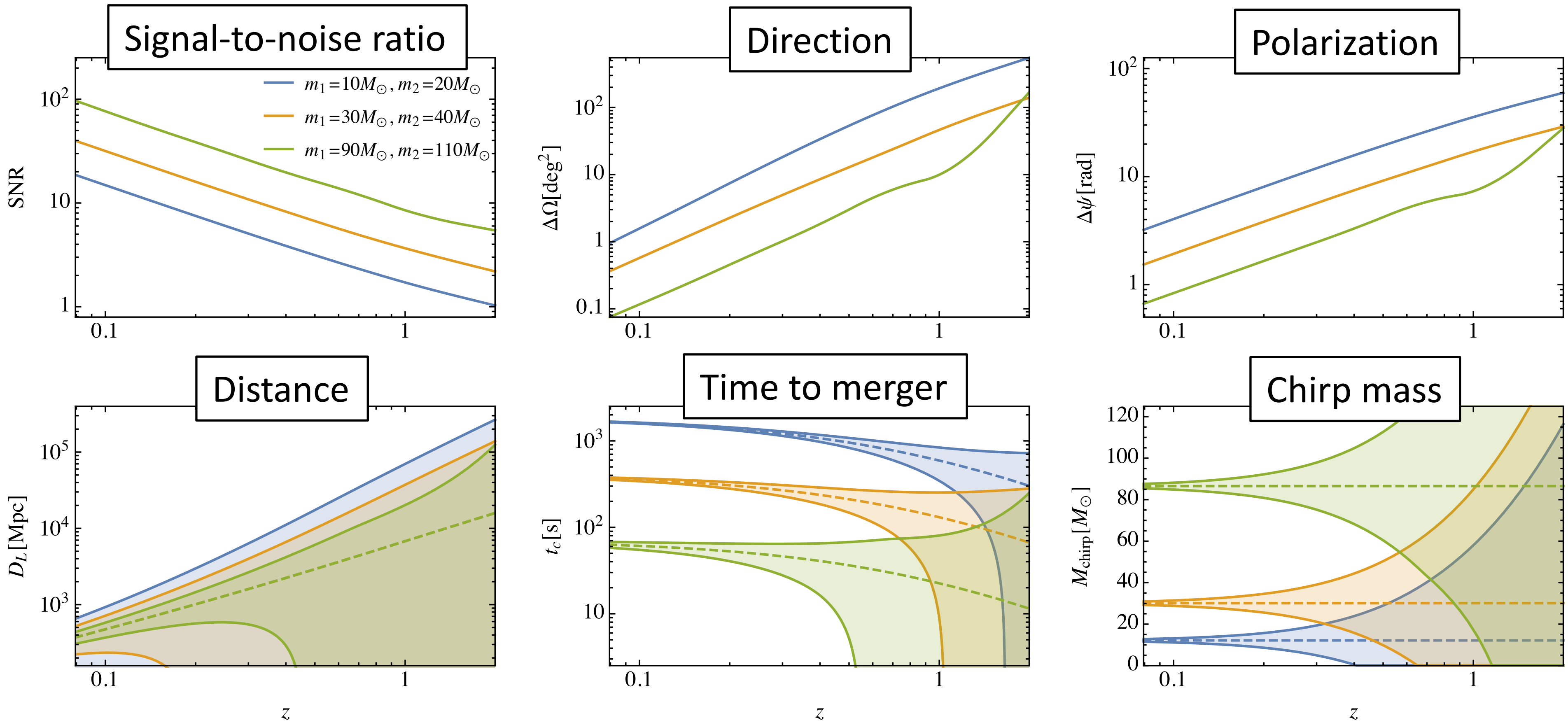
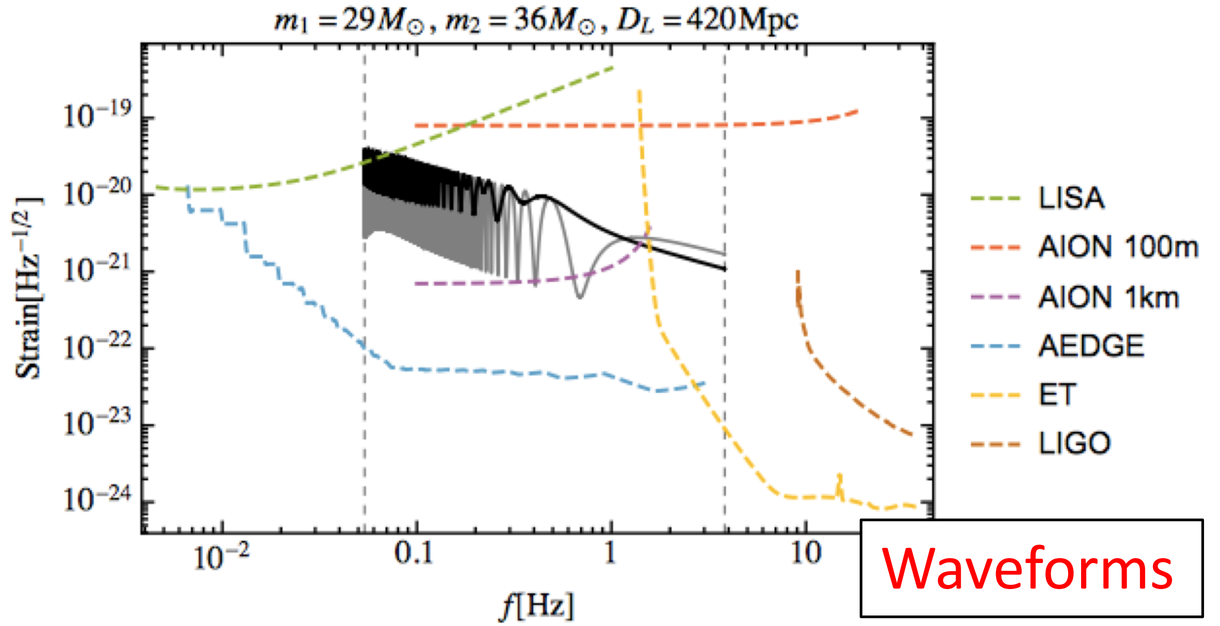
Possible AION-km Measurements



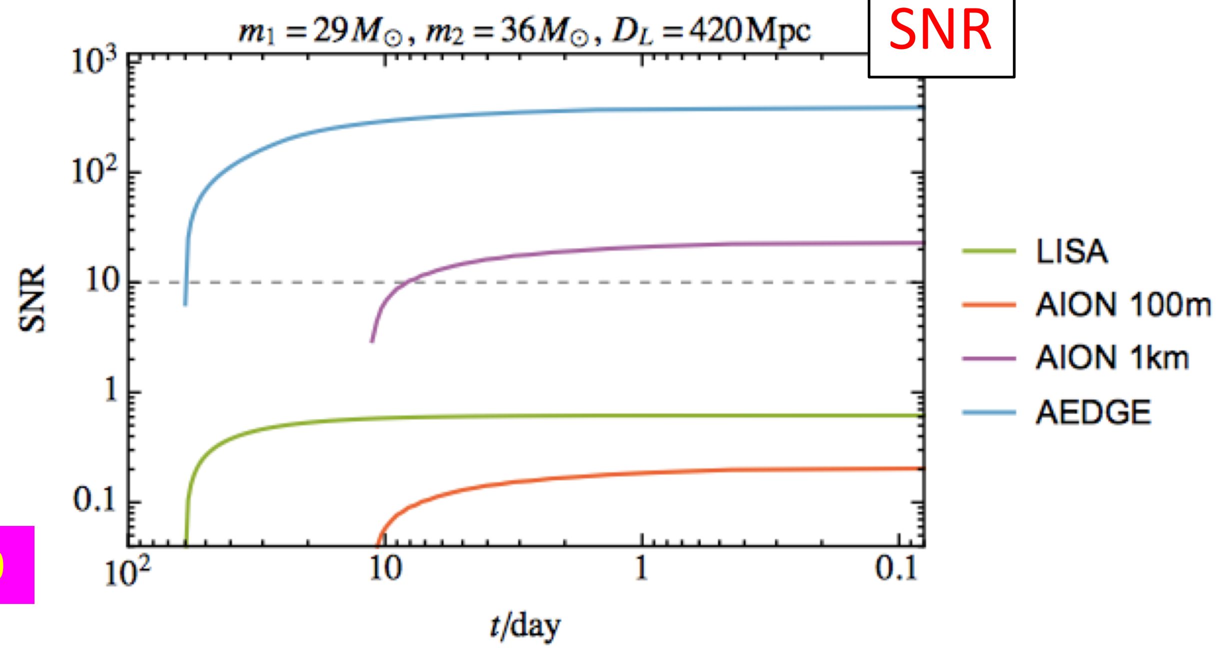
Constraints on Graviton Mass



Waveforms

- Current LIGO/Virgo limit: 4.7 × 10^{-23} eV
- Sensitivity with LIGO/Virgo-like event?
  Longer observations
- With merger of heavier BHs?
  Lower frequencies

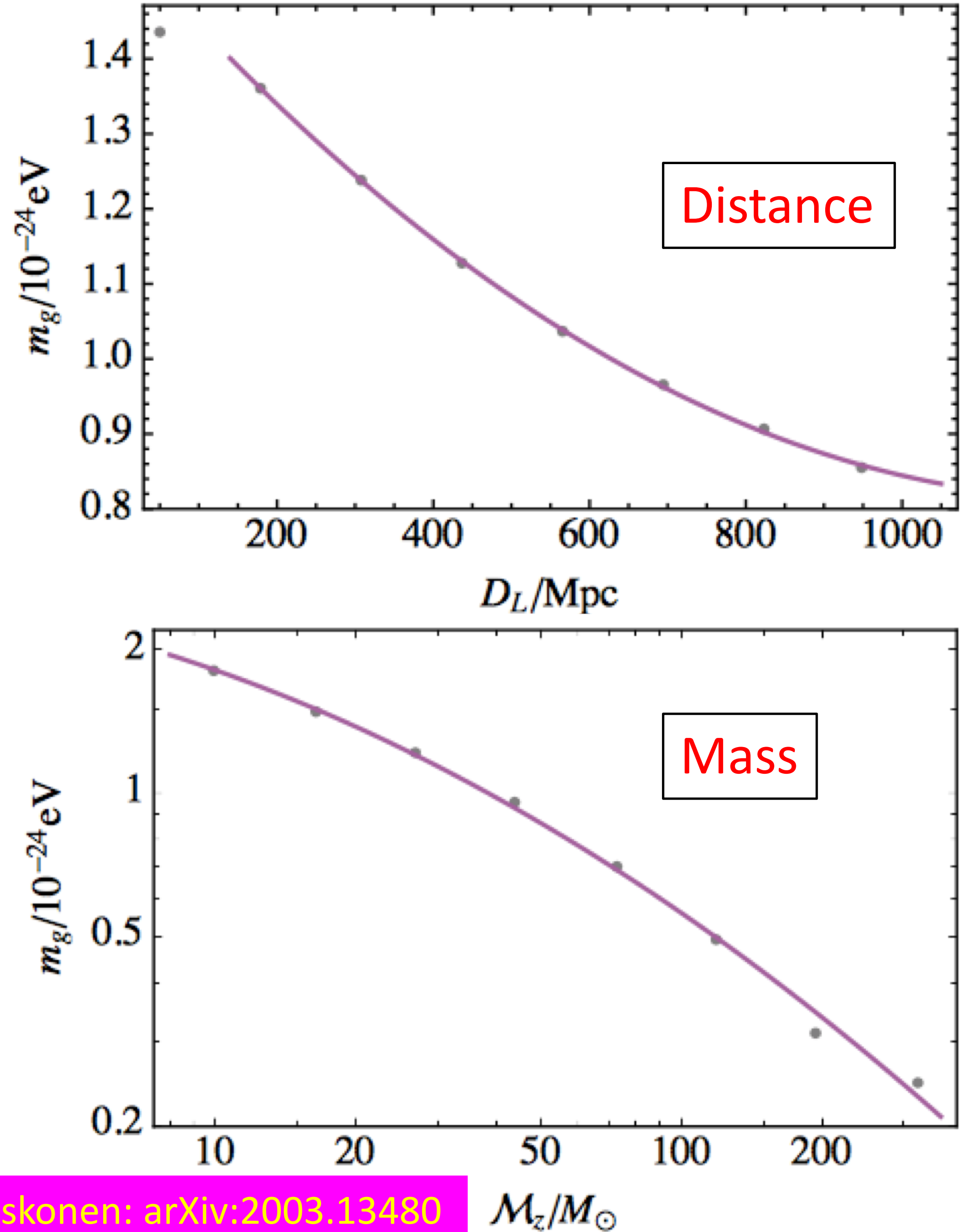
SNR



JE & Vaskonen: arXiv:2003.13480

Constraints on Graviton Mass

- AION 1-km:
- 10^{-24} eV with LIGO/Virgo-like event
- 2×10^{-25} eV with heavier BHs
- AEDGE:
- Order of magnitude more sensitive



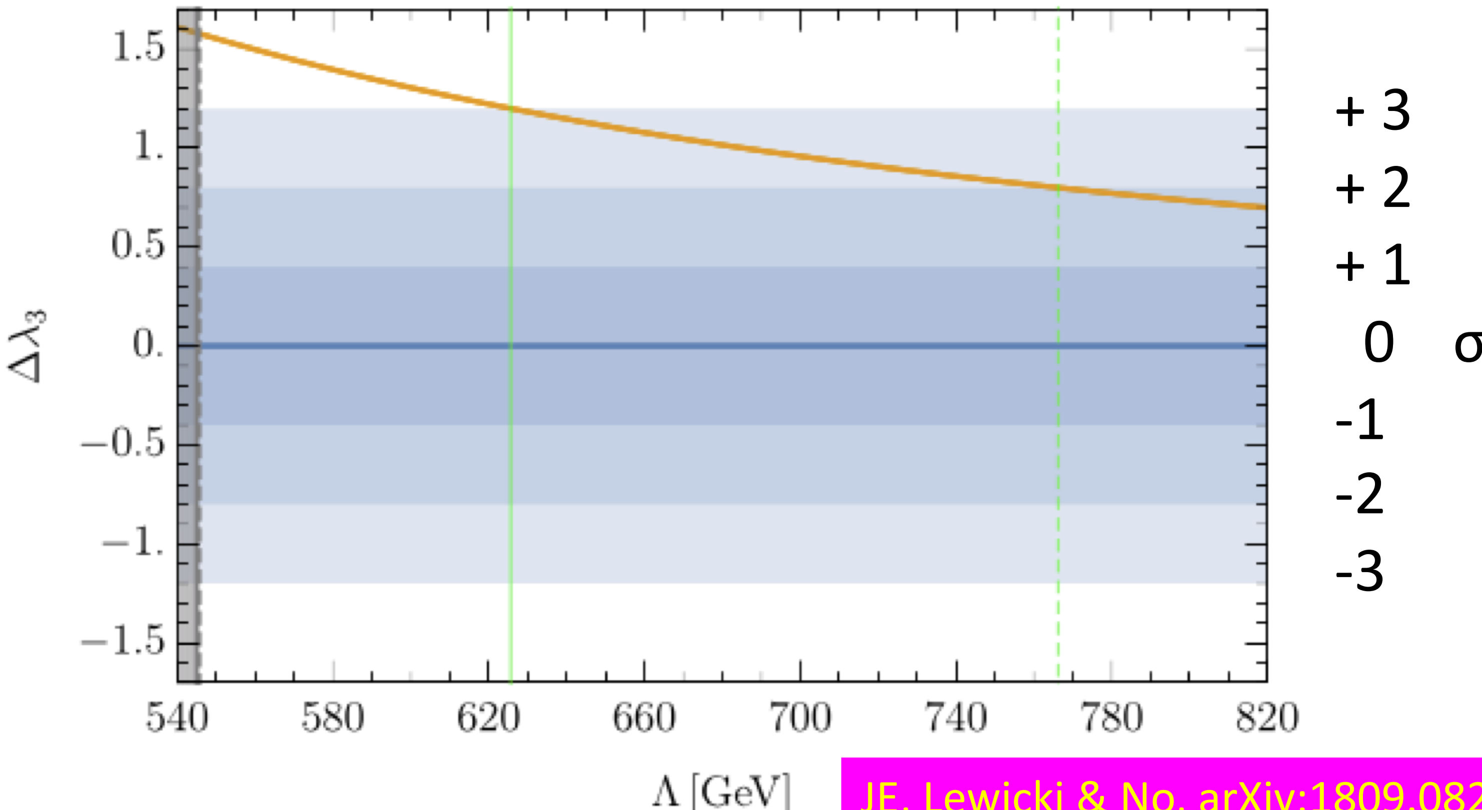
JE & Vaskonen: arXiv:2003.13480

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

Modification of Triple-H Coupling

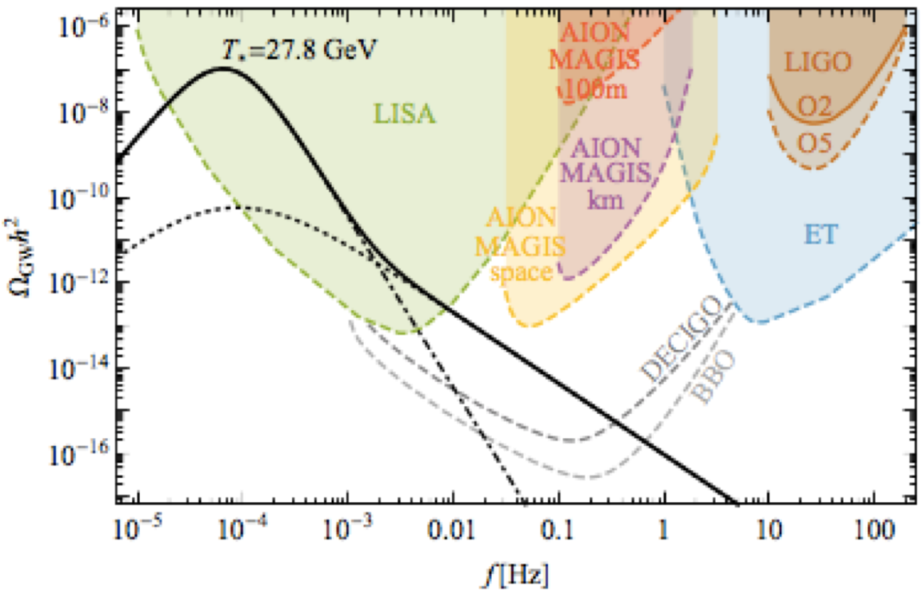
- Current LHC data insensitive to H^6/Λ^2 coupling
- Sensitivity at HL-LHC though modification of triple-Higgs coupling λ_3



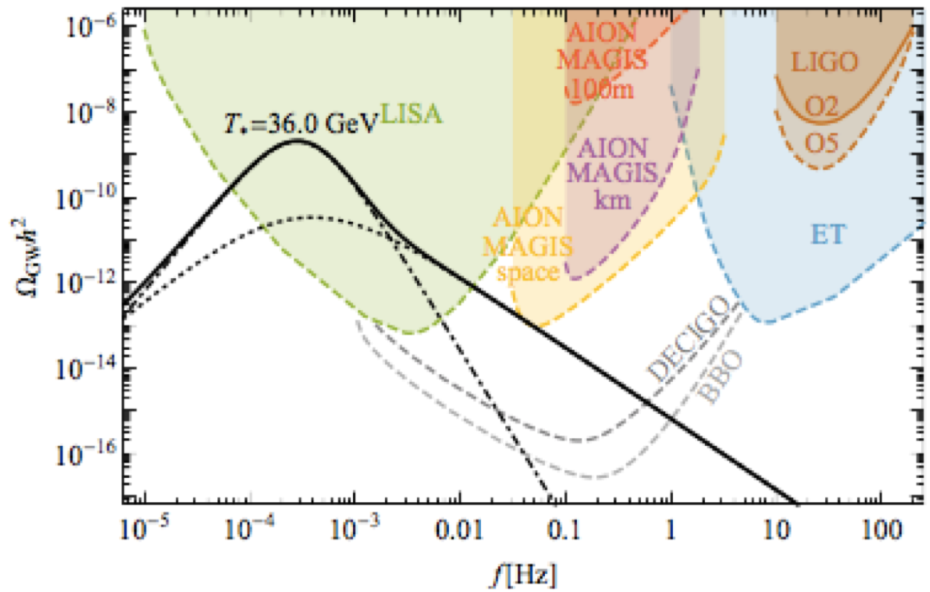
JE, Lewicki & No, arXiv:1809.08242

GW Signal in H^6 Model

- Examples with different percolation temperatures



Strongest signal not excluded
by lack of percolation



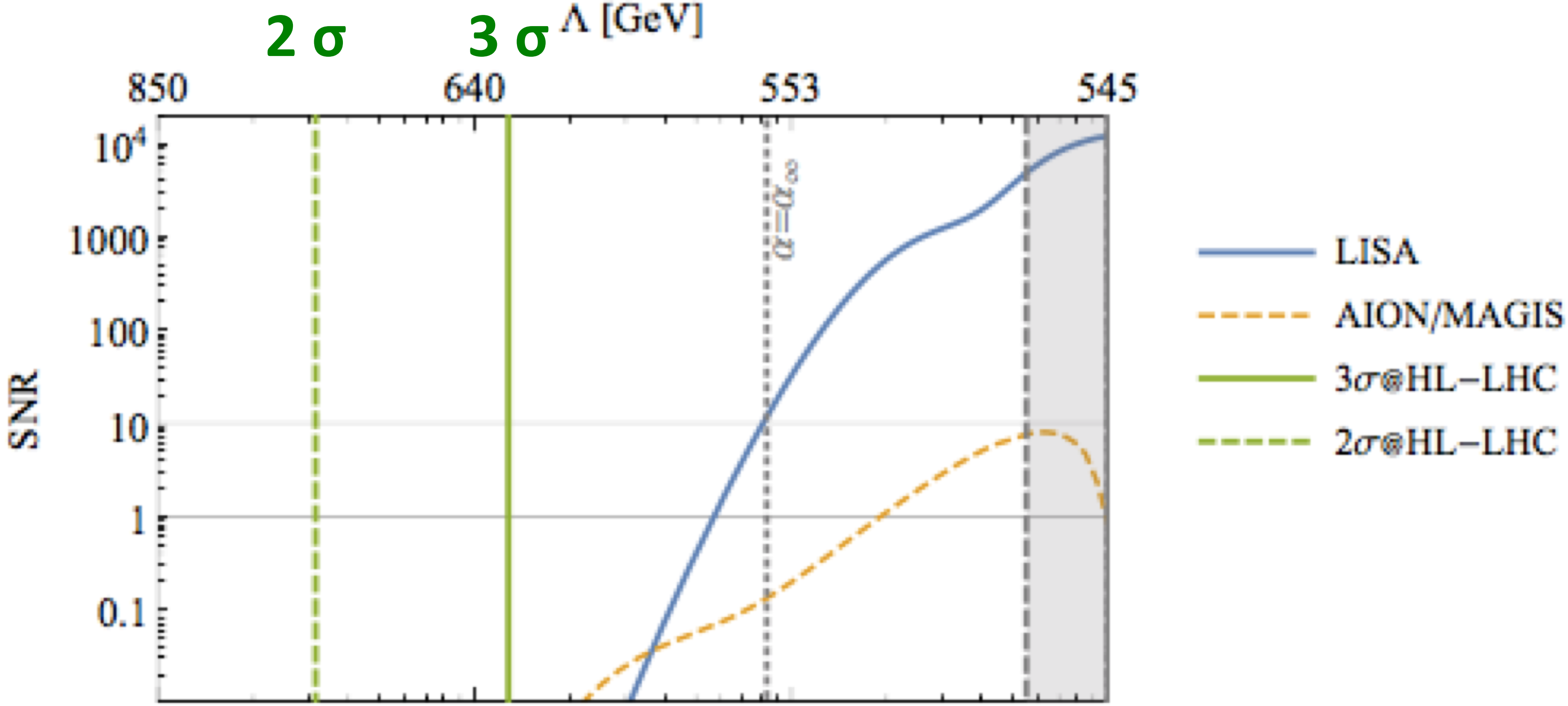
Strongest signal for which
percolation is assured

- Low percolation temperature ~ strong transition ~ small Λ ~ detectable at HL-LHC

JE, Lewicki, No & Vaskonen, arXiv:1903.09642

Gravitational Waves vs HL-LHC

HL-LHC sensitivity:



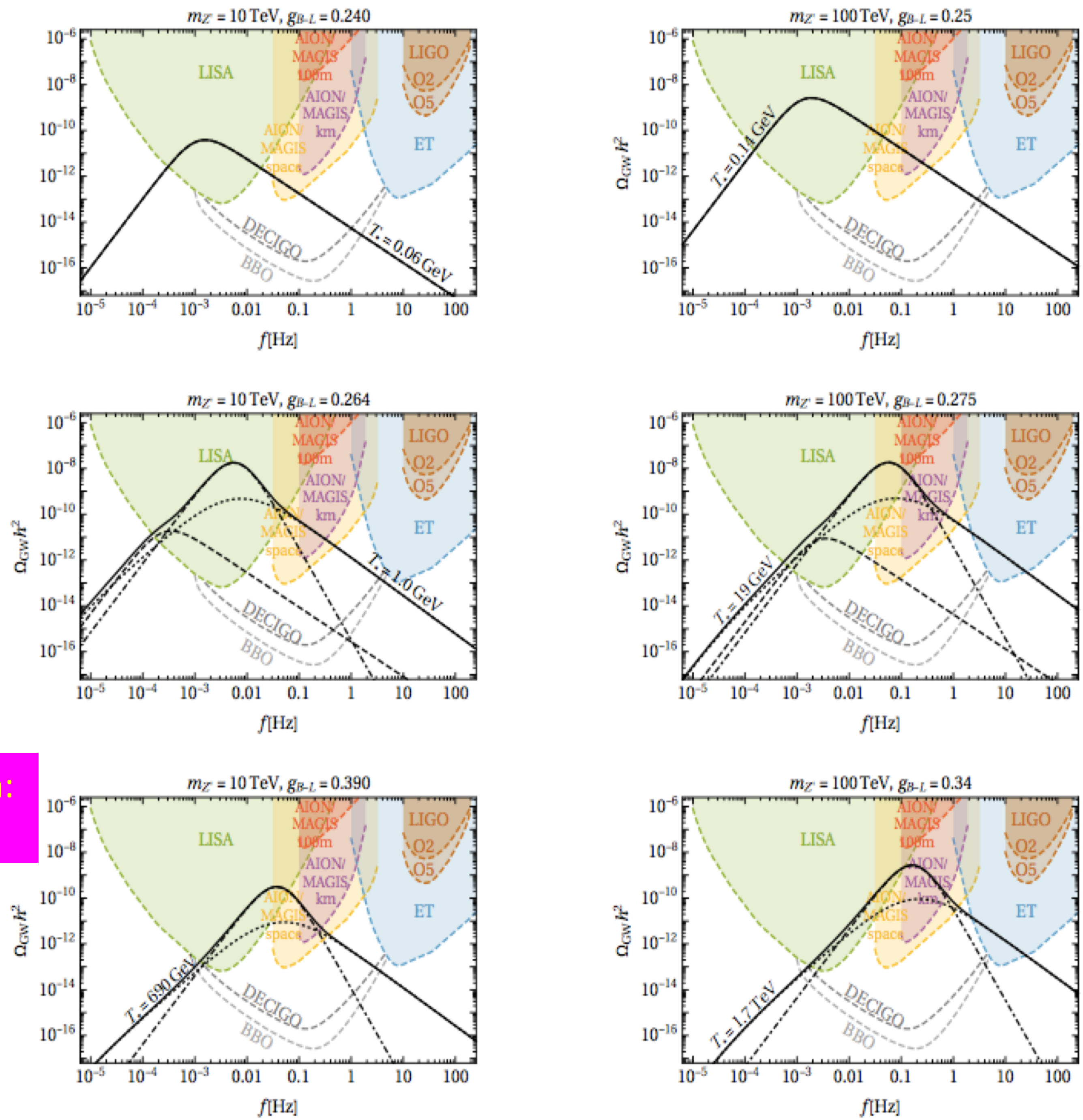
Could see both GWs and collider signature
Latter has greater sensitivity in this case

JE, Lewicki & No, arXiv:1809.08242

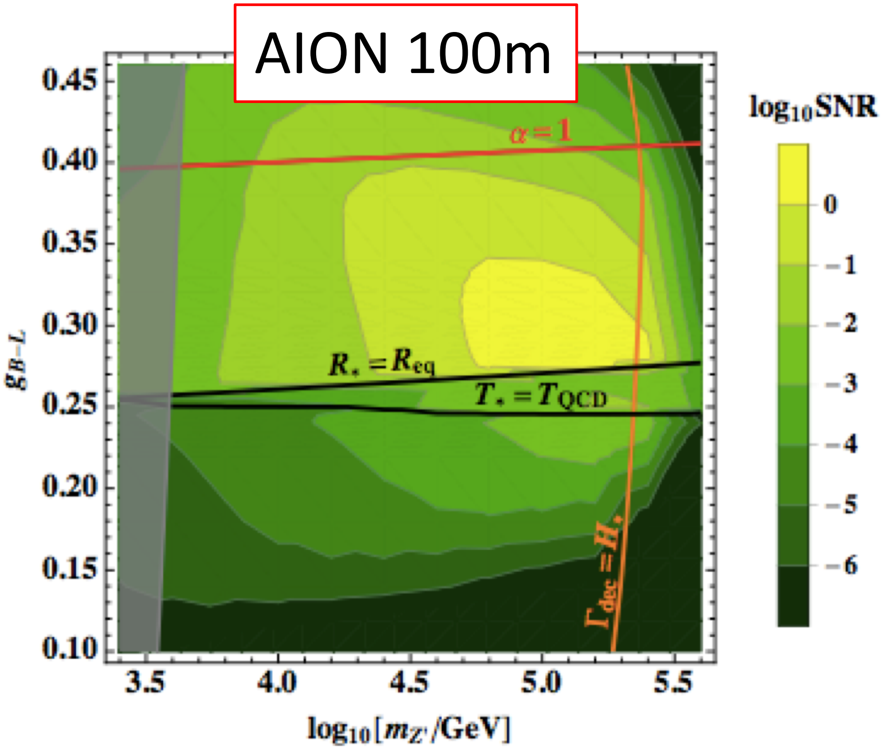
GW Signal in U(1)$_{B-L}$ Model

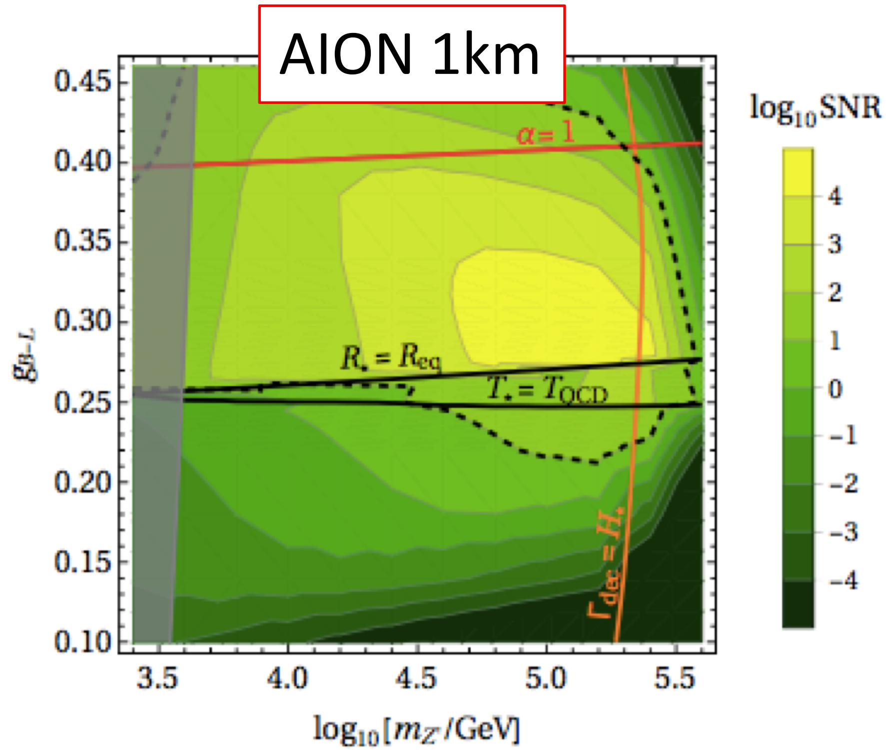
_____ Total
- - - - Bubble collisions
_ - _ Sound waves
……. Turbulence

JE, Lewicki, No & Vaskonen: arXiv:1903.09642



AION GW SNR in $U(1)_{B-L}$ Model





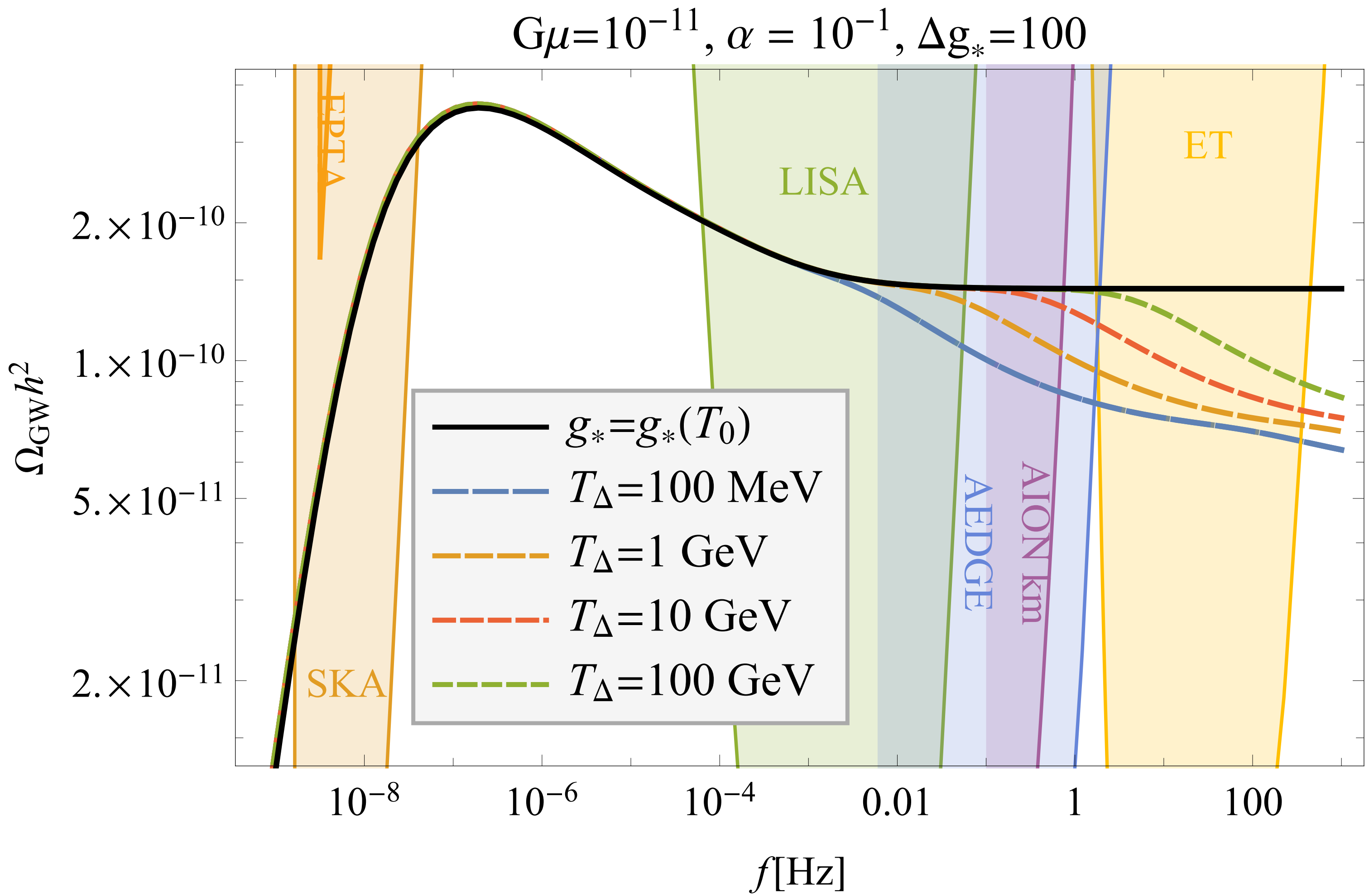
Discovery of GW possible with AION 1km

Above red line: transition before vacuum energy dominates
Right of orange line: period of matter domination

JE, Lewicki, No & Vaskonen, arXiv:1903.09642

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

Gravitational Waves from Cosmic Strings



Sensitive to changes in # of degrees of freedom

1% measurement of spectrum = Δ# d.o.f. = 2

Probe expansion history of early universe

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

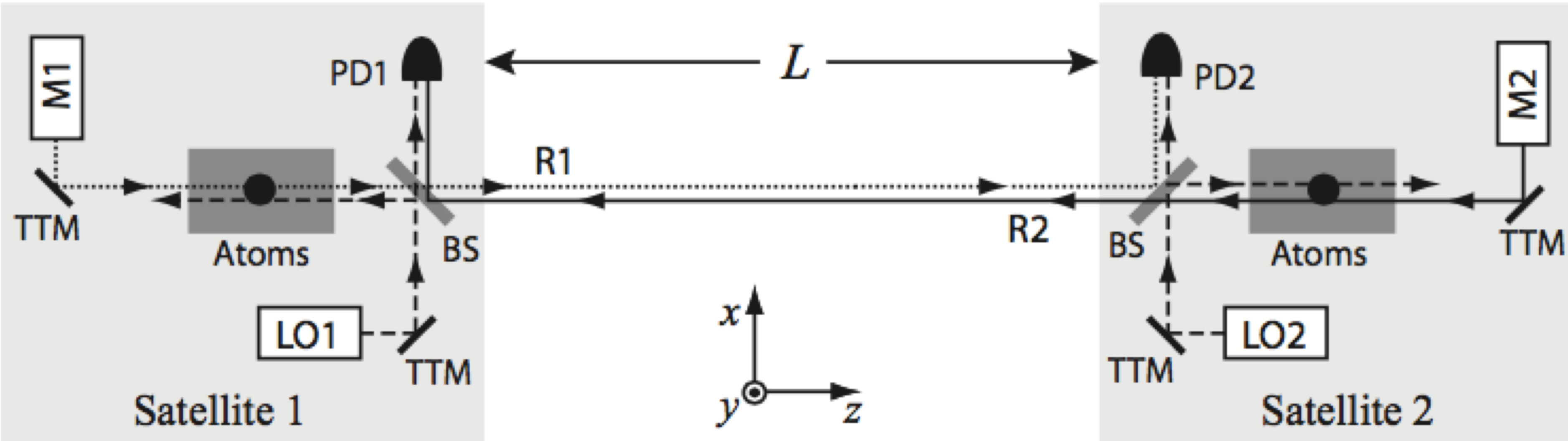
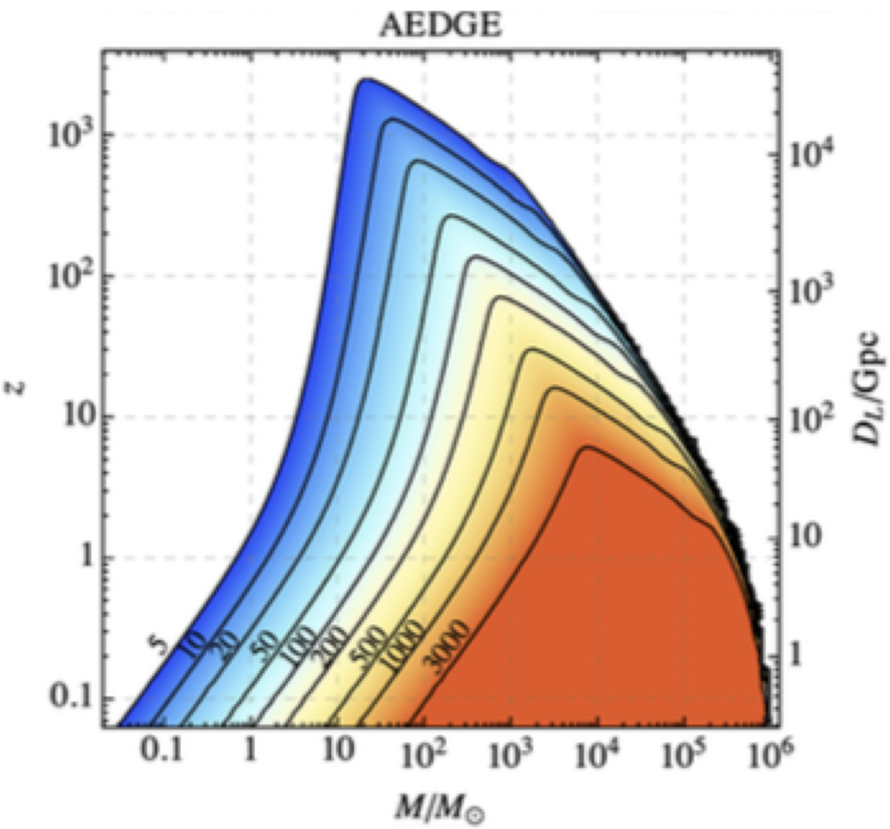


Table 1. List of basic parameters of strontium atom interferometer designs for AEDGE and a benchmark 1-km terrestrial experiment using similar technologies: length of the detector L; interrogation time of the atom interferometer T_{int}; phase noise $\delta\phi_{\text{noise}}$; and the total number of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

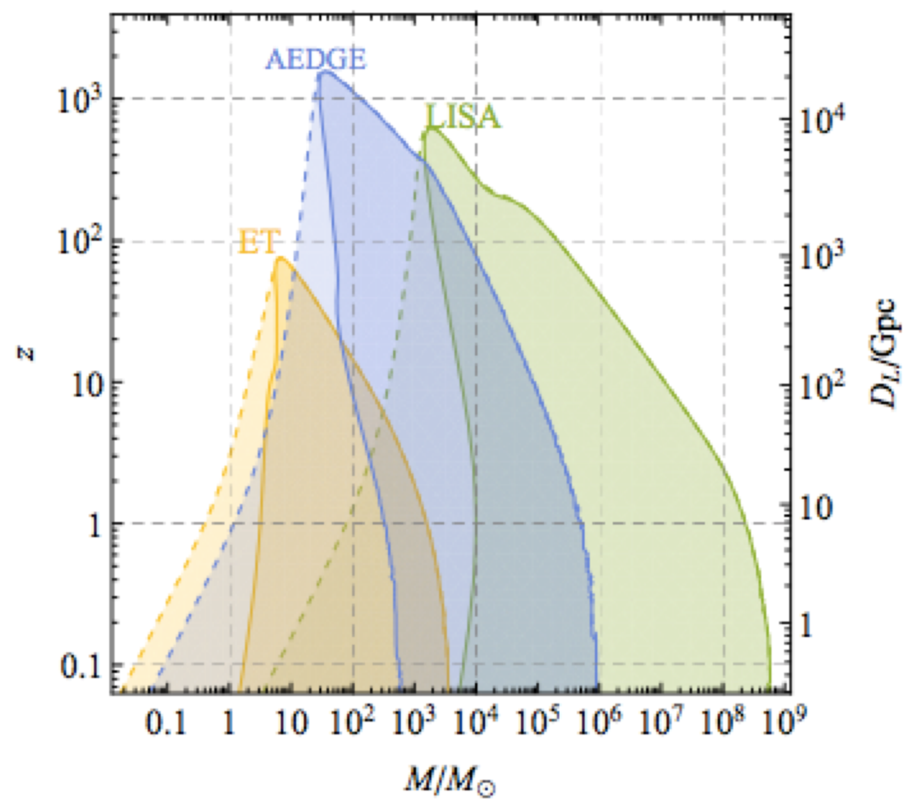
Sensitivity Scenario	L [m]	T_{int} [sec]	$\delta\phi_{\text{noise}}$ $[1/\sqrt{\text{Hz}}]$	$n_p^{\text{max}} = 2Q(2n-1)+1$ [number]
Earth-km	2000	5	0.3×10^{-5}	40000
AEDGE	4.4×10^7	300	10^{-5}	1000

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

Gravitational Waves from IMBHs



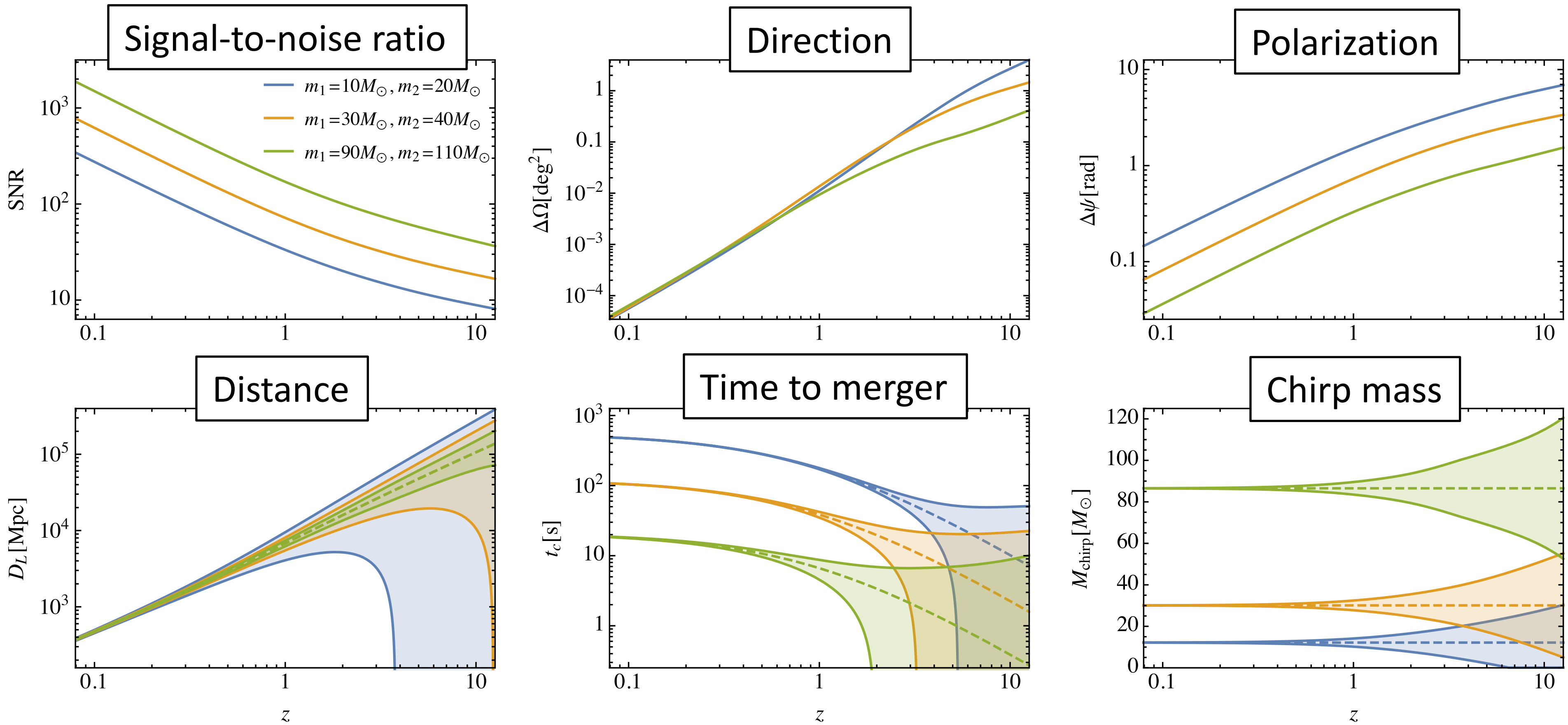
Detect mergers of ~ 10^4 solar-mass BHs
with SNR ≳ 1000 out to z ~ 10,
Mergers of ~ 10^3 solar-mass BHs
with SNR ≳ 100 out to z ≳~ 100



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

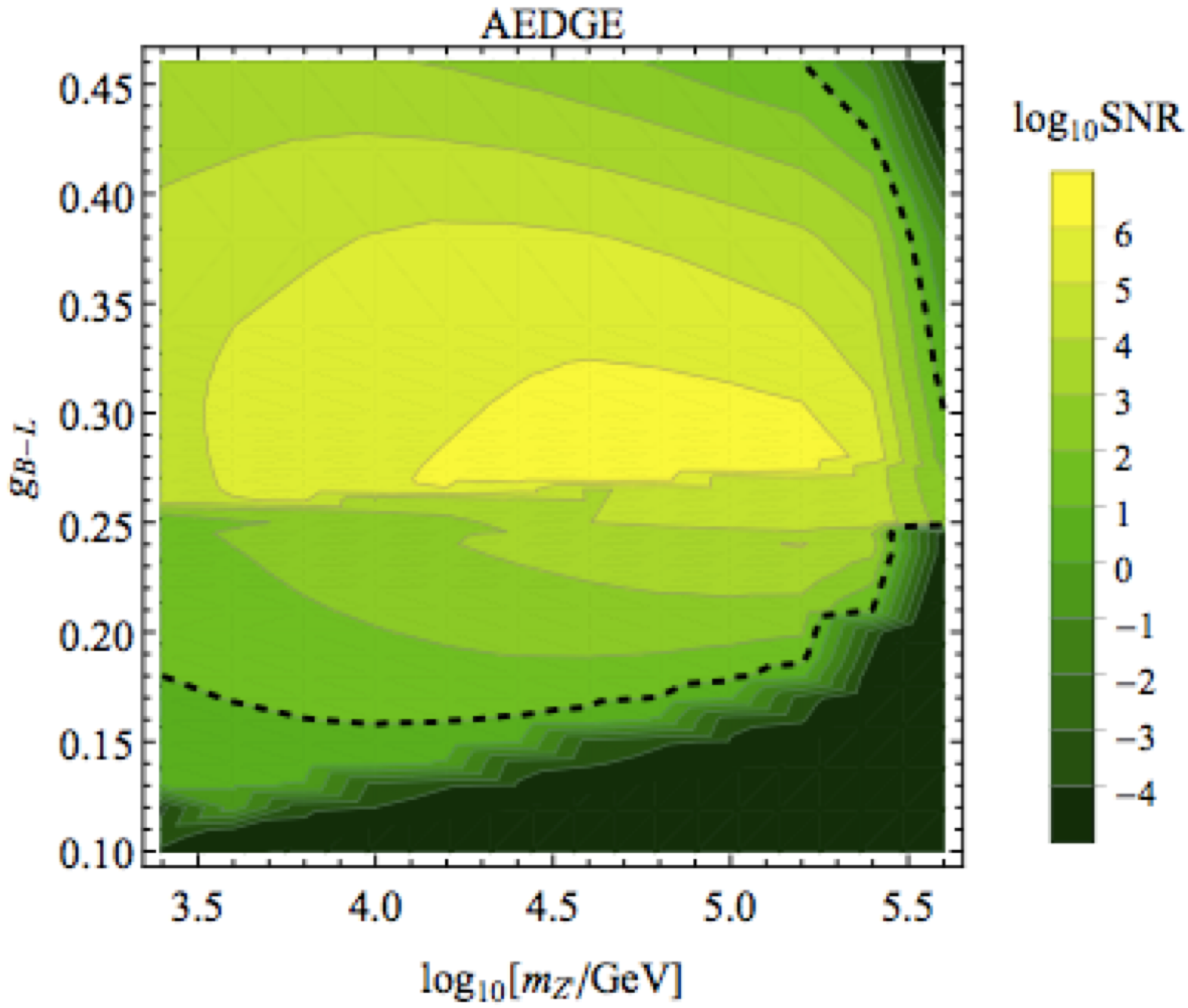
AEDGE: Abou El-Neaj, ..., JE et al: arXiv:1908.00802

Possible AEDGE Measurements



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

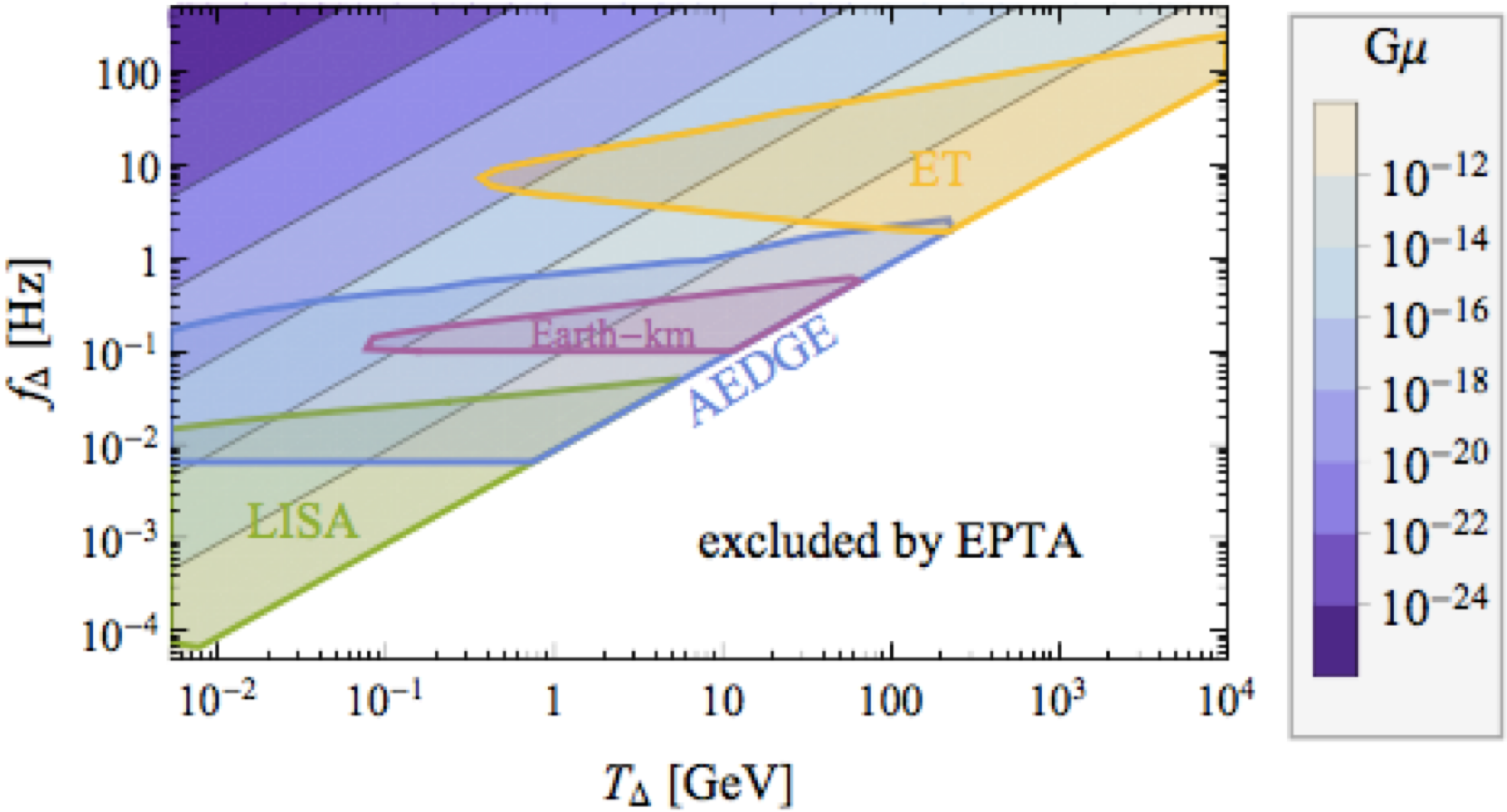
Sensitivity to $U(1)_{B-L}$ Z'



GW discovery sensitivity beyond $m_{Z'}$ = 100 TeV

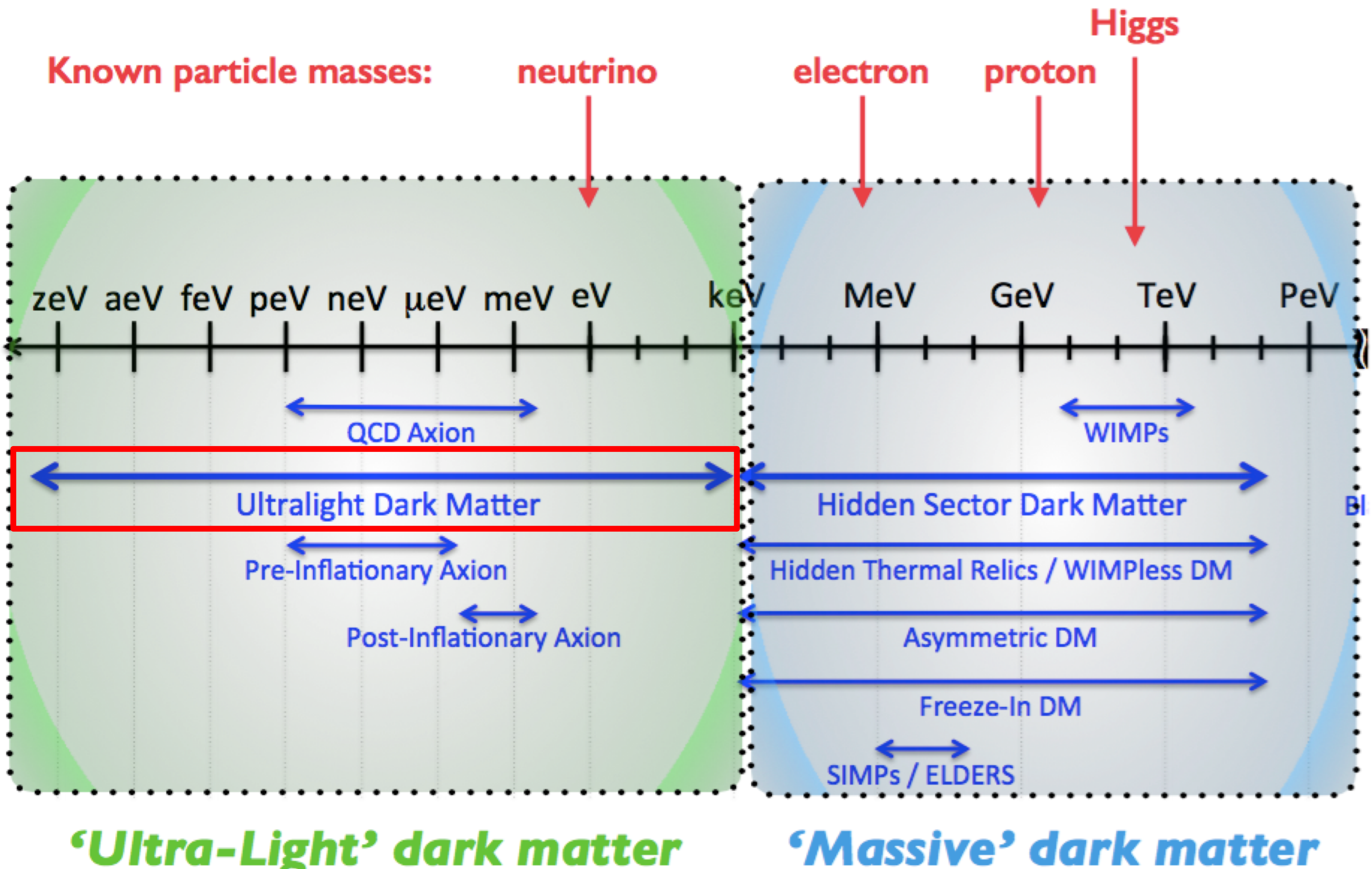
AEDGE: Bertoldi, ..., JE et al: arXiv:1908.00802

Gravitational Waves from Cosmic Strings



Different experiments sensitive to different temperatures when # d.o.f. changes

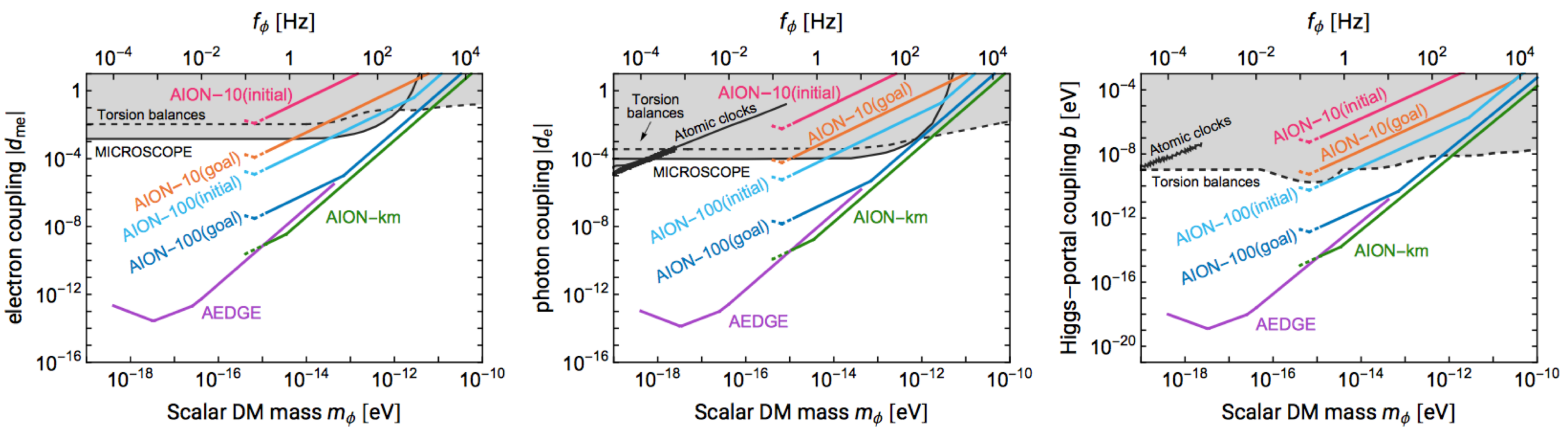
Searches for Light Dark Matter



Searches for Light Dark Matter

Linear couplings to gauge fields and matter fermions

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



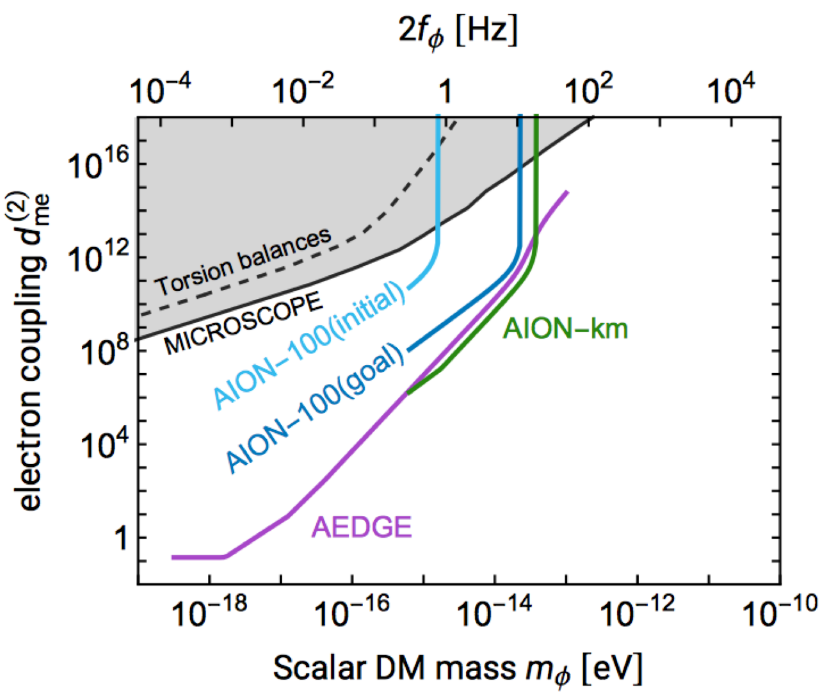
AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755

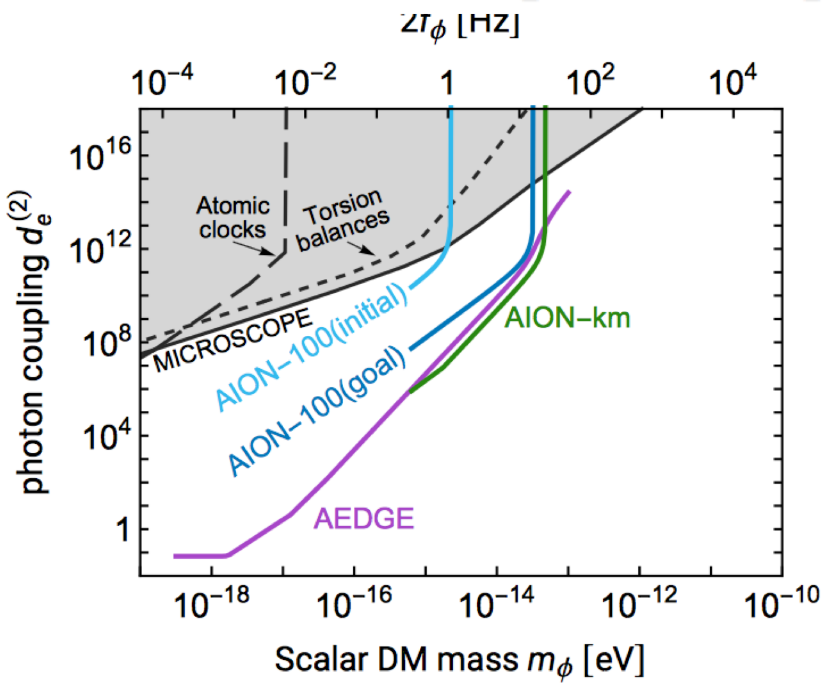
AEDGE: Bertoldi, …, JE et al: arXiv:1908.00802

Sensitivities to Quadratic DM Interactions

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

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



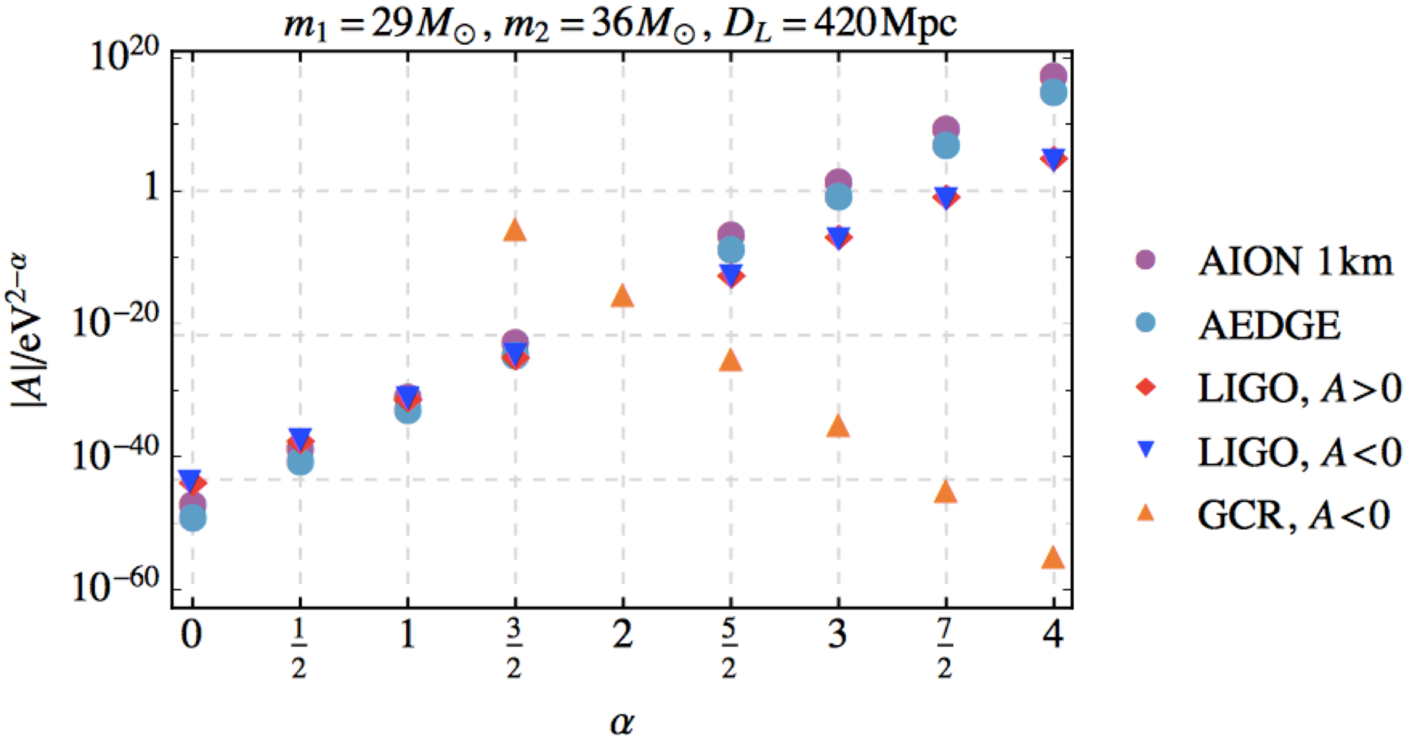


Explore Beyond Dark Matter & GWs

- 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 (≠ environmental) decoherence?
- …..

Lorentz Violation

- 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

- 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
- MAGIS/AION offer 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
- Atom interferometry could also explore the nature of DM
- Other possible opportunities for MAGIS/AION/AEDGE in fundamental physics, astrophysics and cosmology have been identified, but not yet explored in detail
- **Unique interdisciplinary science!**