Gravitational Waves

Literally a world-shaking discovery

Earth expands and contracts by the diameter of an atomic nucleus: 10^{-12} cm

John Ellis

KING'S College LONDON

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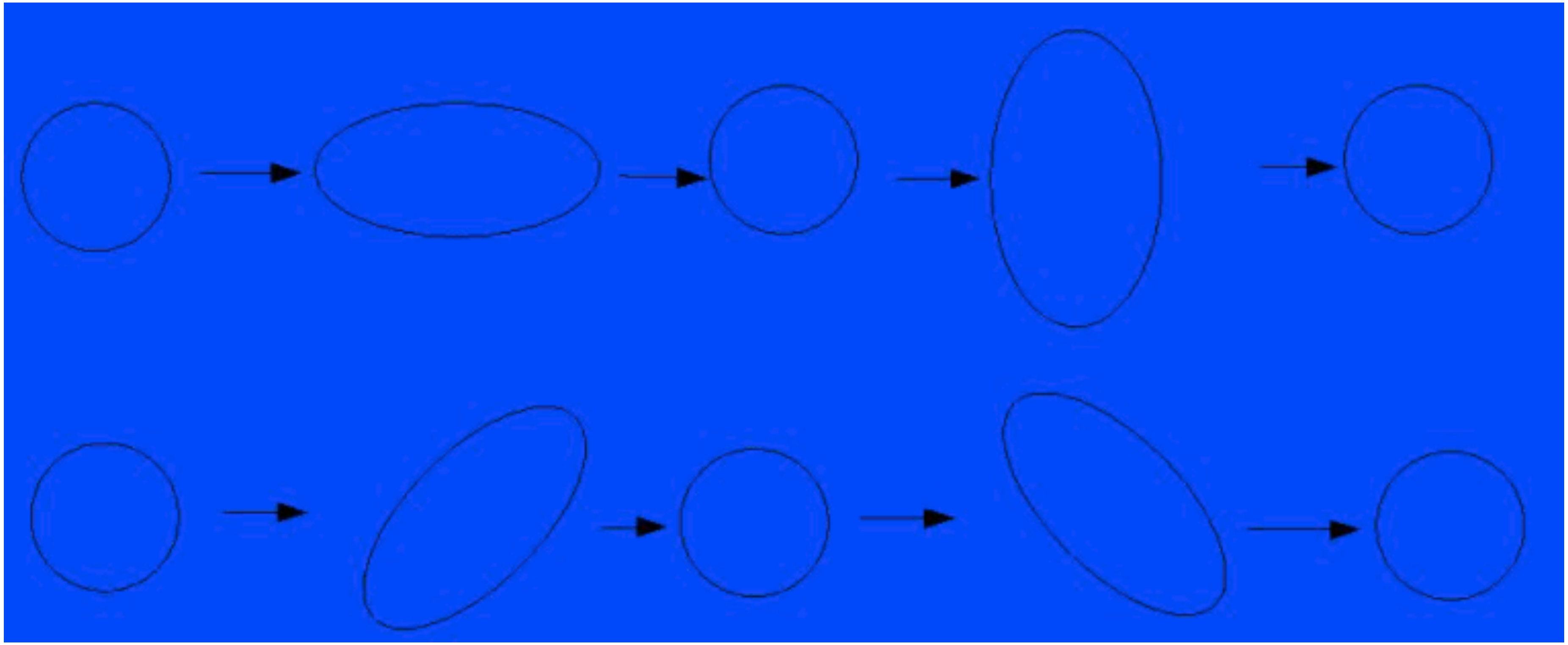

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The GW story so far
Mergers of black holes & neutron stars
Covering the spectrum
The AION & AEDGE projects
GWs from mergers, phase transitions, strings
NANOGrav pulsar timing array & cosmic strings

Gravitational Waves

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

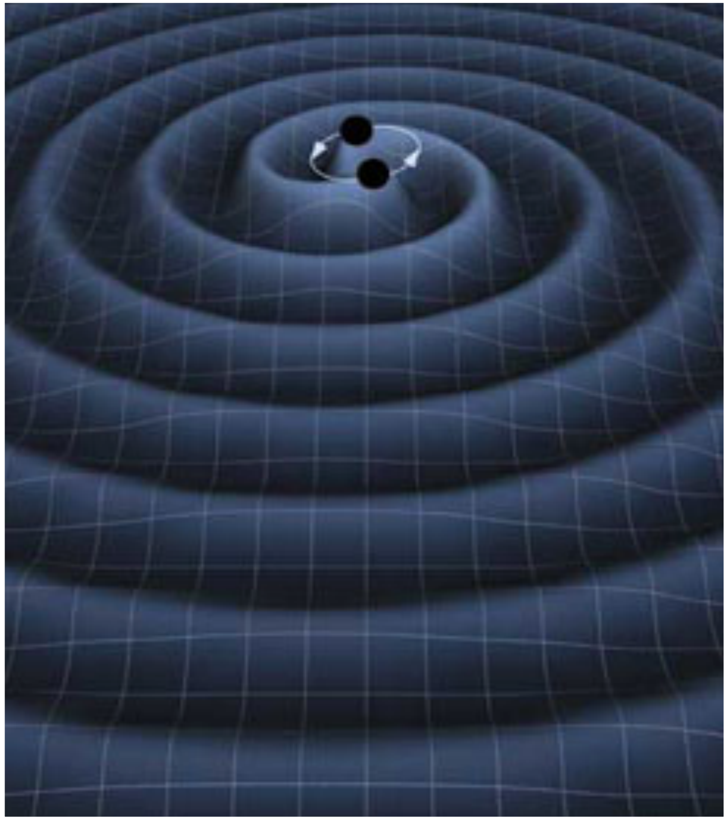
Näherungsweise Integration der Feldgleichungen der Gravitation.

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 … aus denselben Gründen … in der speziellen Relativitätstheorie. Unter »erster Näherung« ist d… verstanden, daß die durch die Gleichung

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

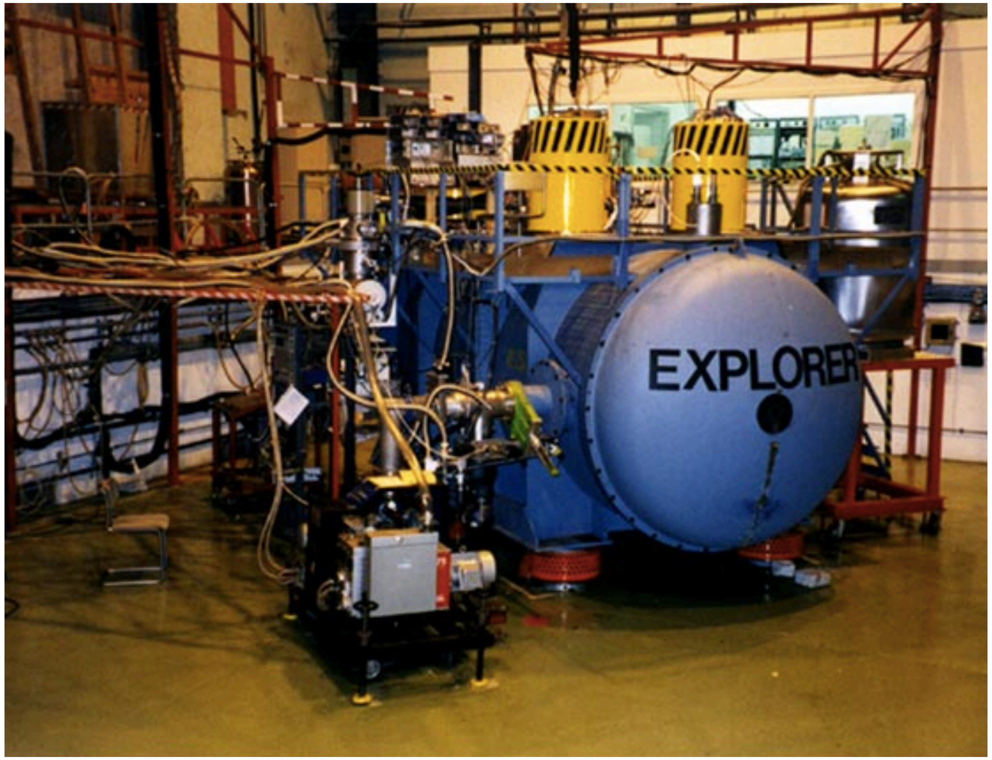
Albert Einstein, *Näherungsweise Integration der Feldgleichungen der Gravitation*, 22.6.Berlin 1916

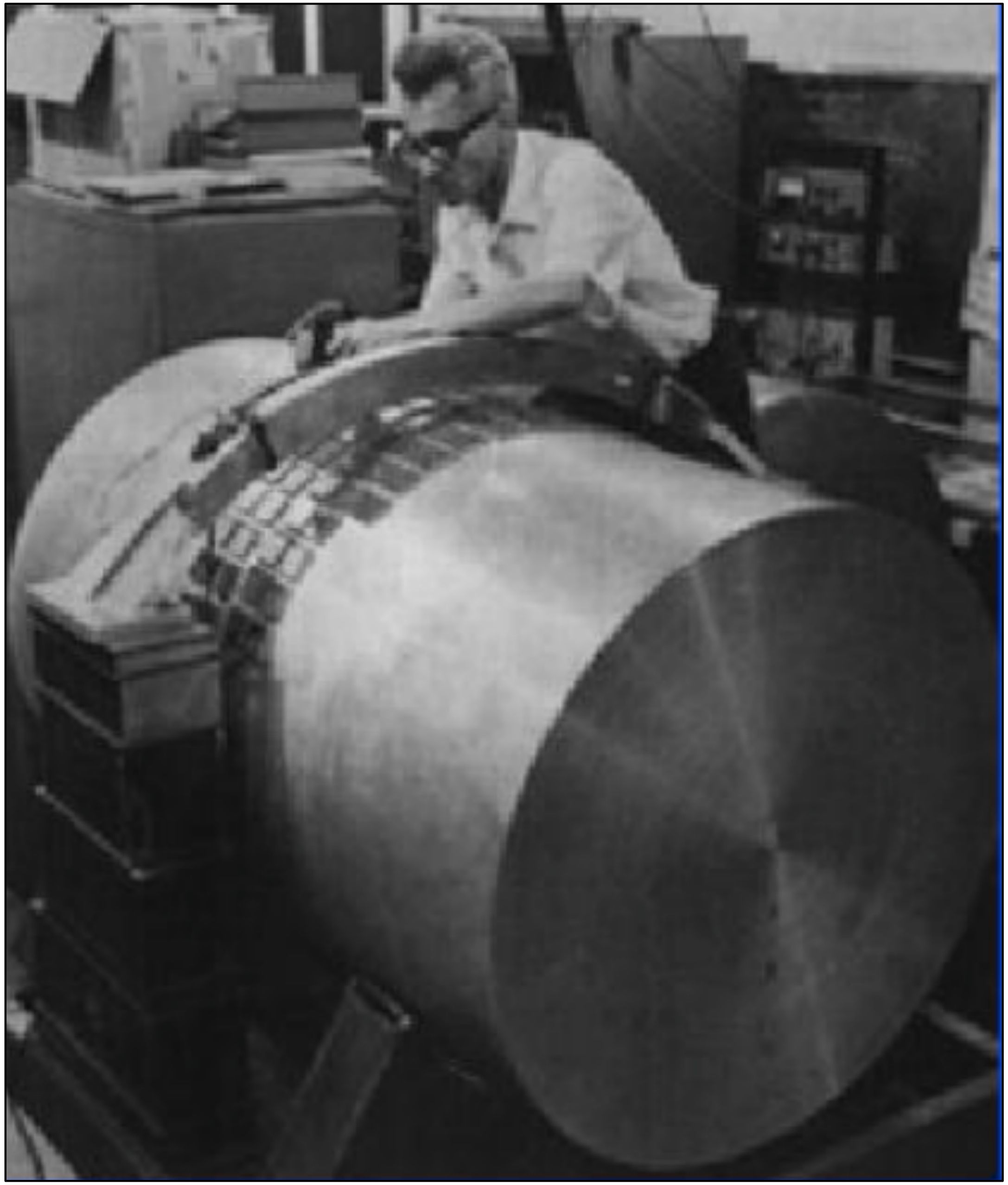


- Tried to retract prediction in 1936!

First Attempts at Detection

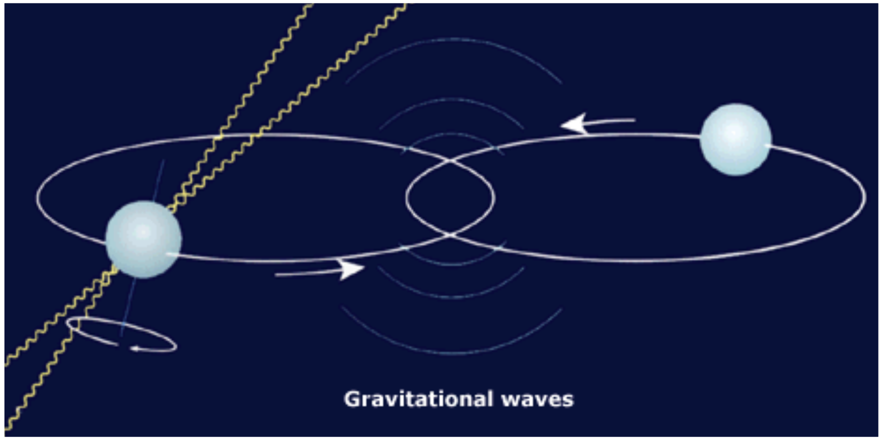
- 1970s: Metal bars (Joseph Weber)
- Also Explorer at CERN

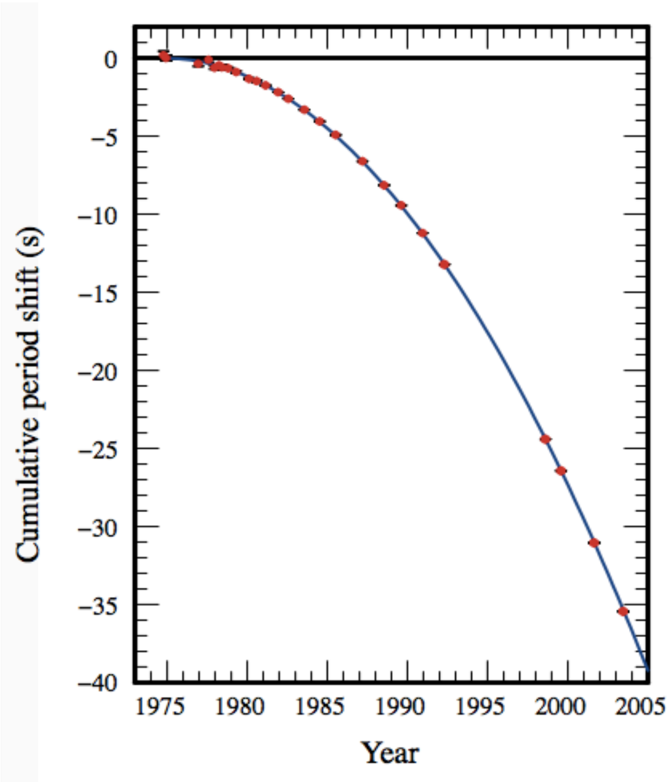




Indirect Detection

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



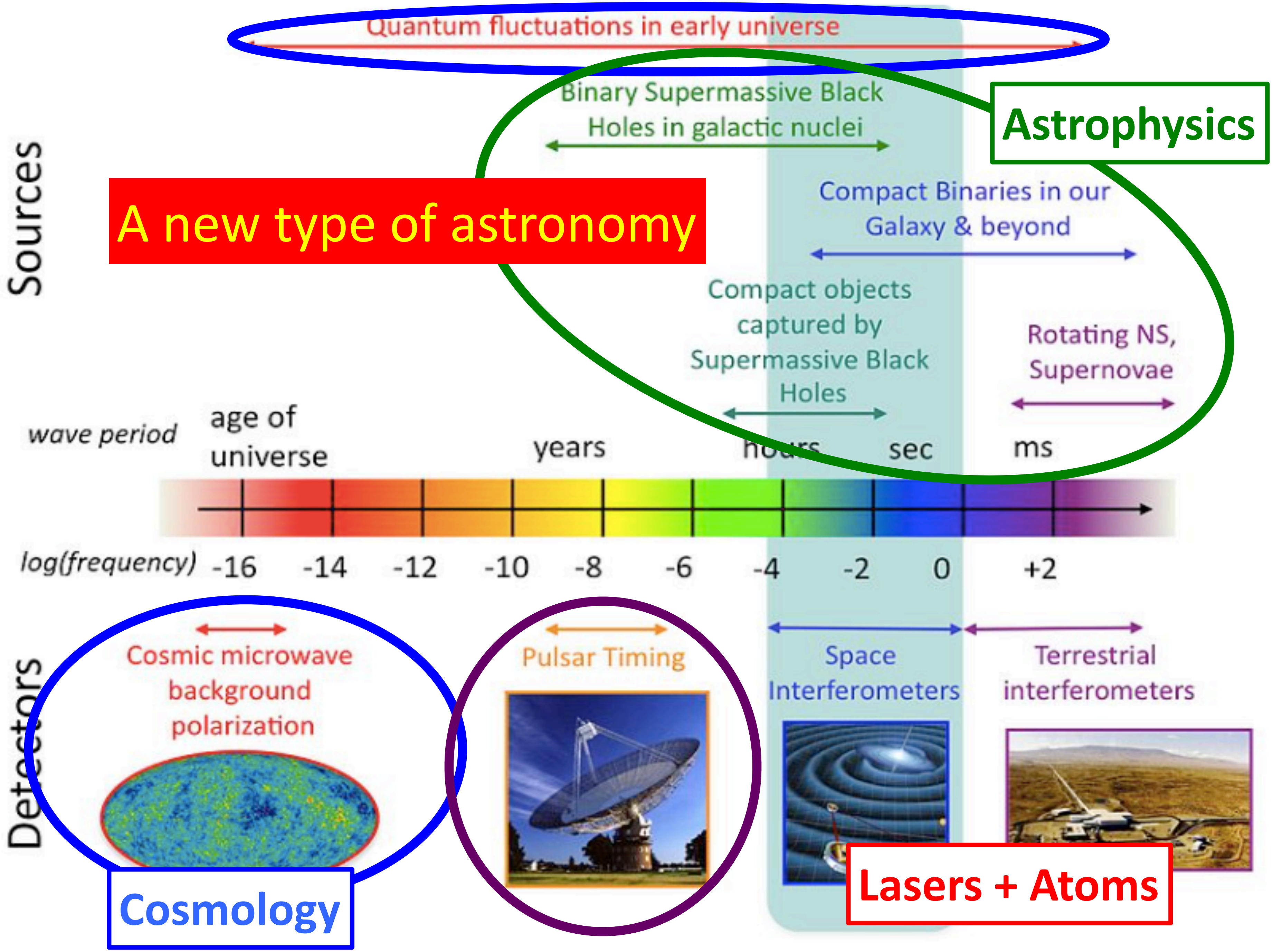


for years

agreement with Einstein

Nobel Prize 1993

Gravitational Wave Spectrum

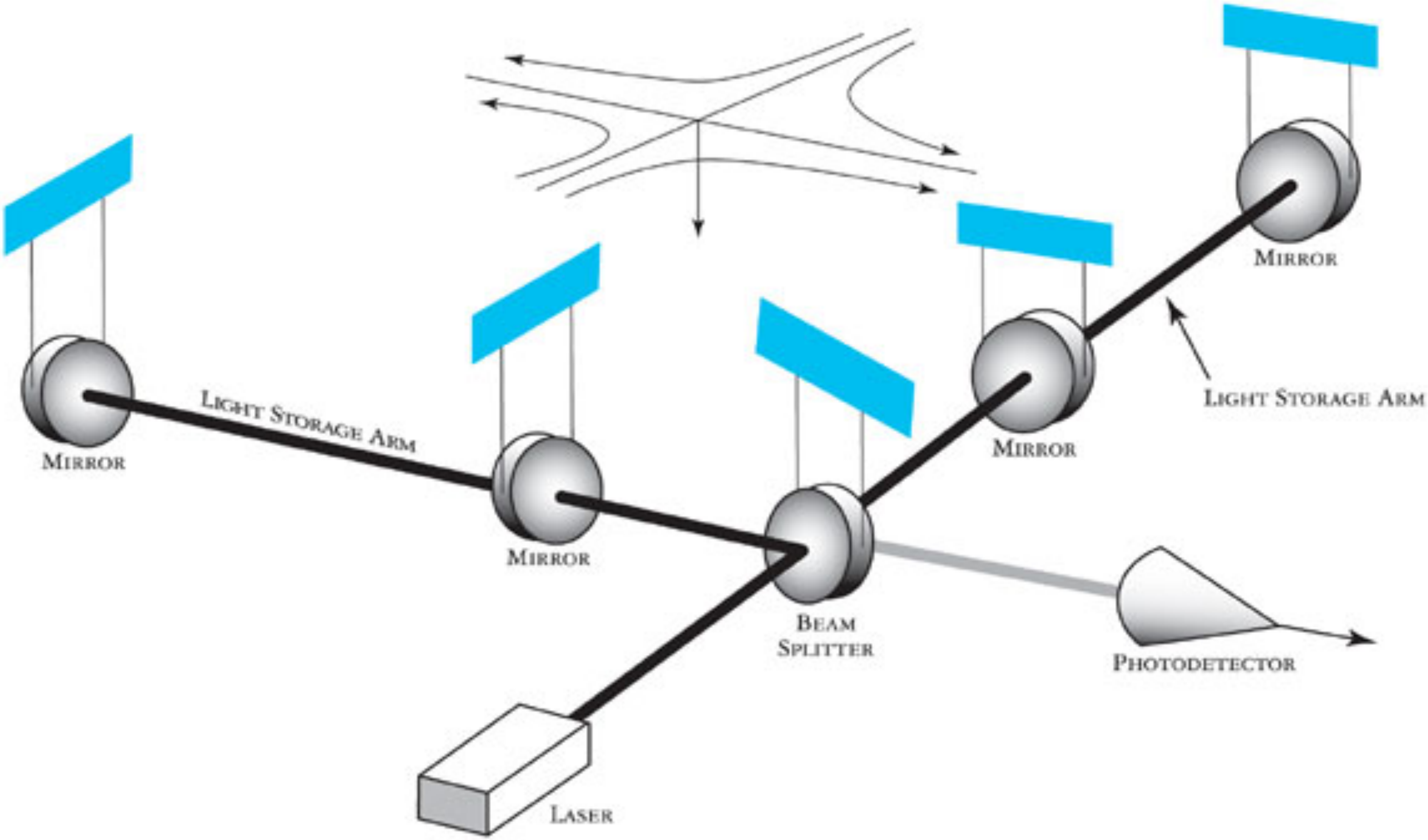


Direct Discovery of Gravitational Waves

- Measured by the LIGO experiment in 2 locations

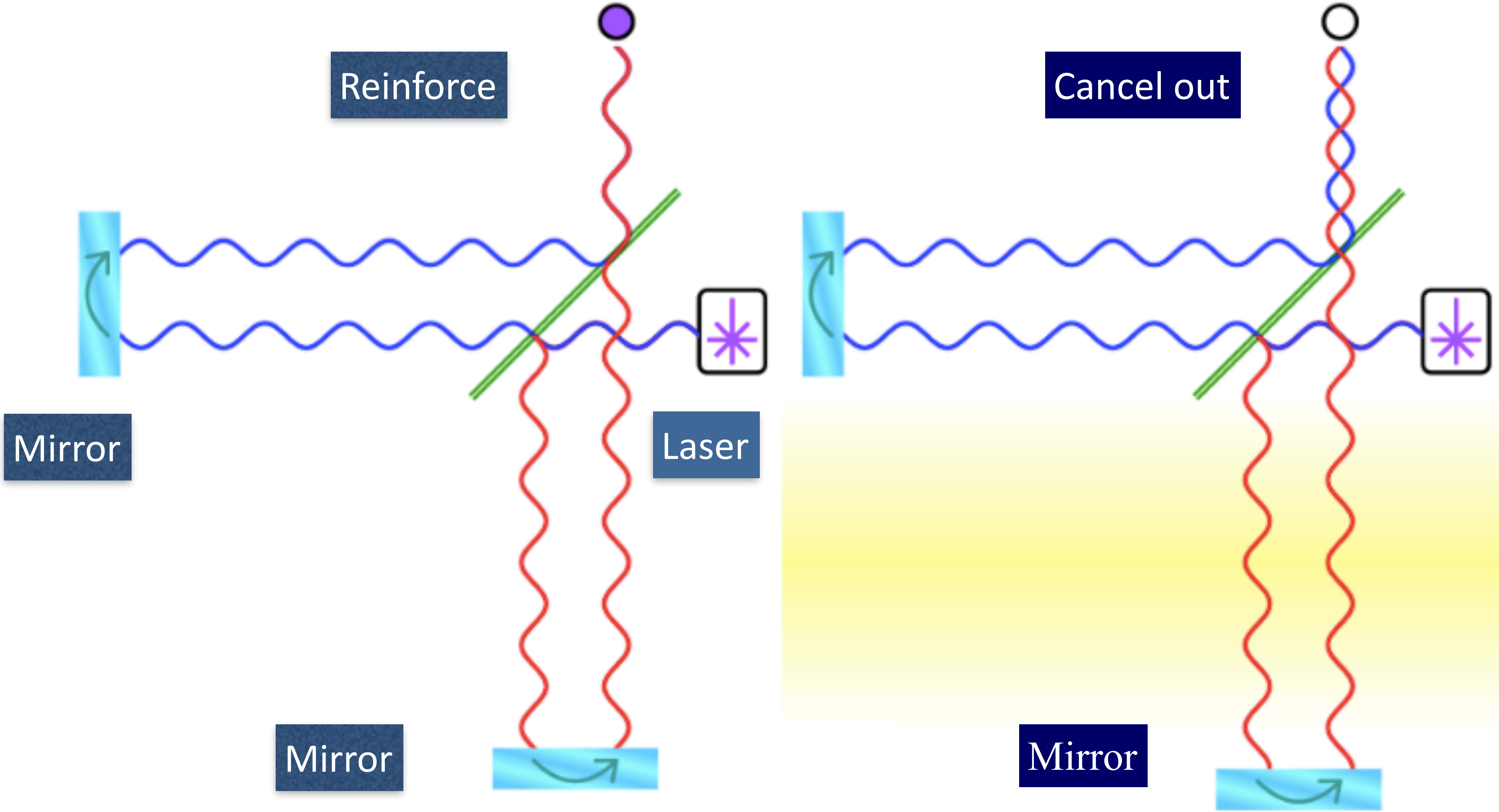
LIGO experiment

- Interference between 2 laser beams measures the expansion and contraction of space



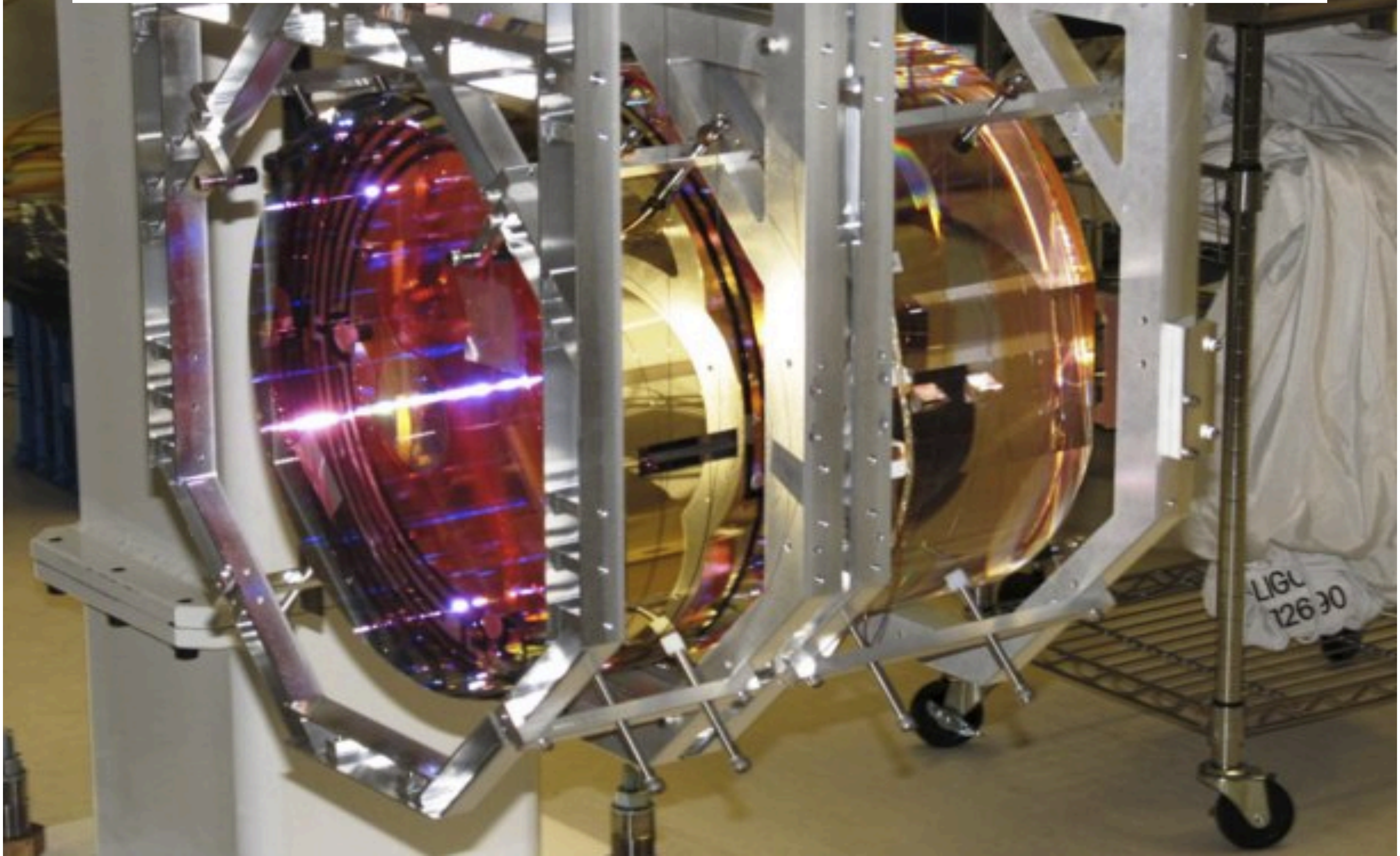
Principle of Laser Interferometer

Interference between 2 laser beams measures the expansion and contraction of space

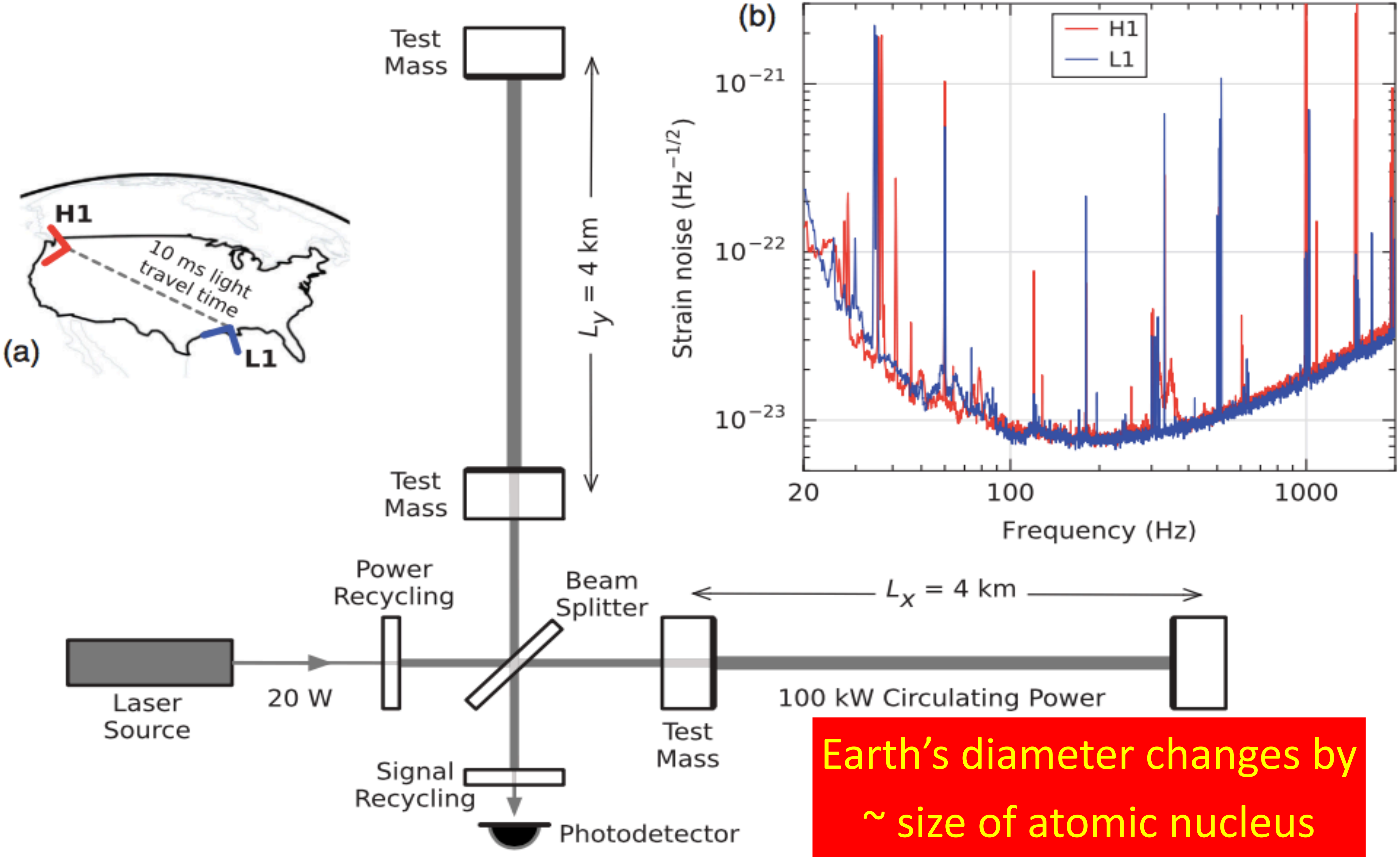


Installing LIGO Experiment

LIGO Experimental Apparatus



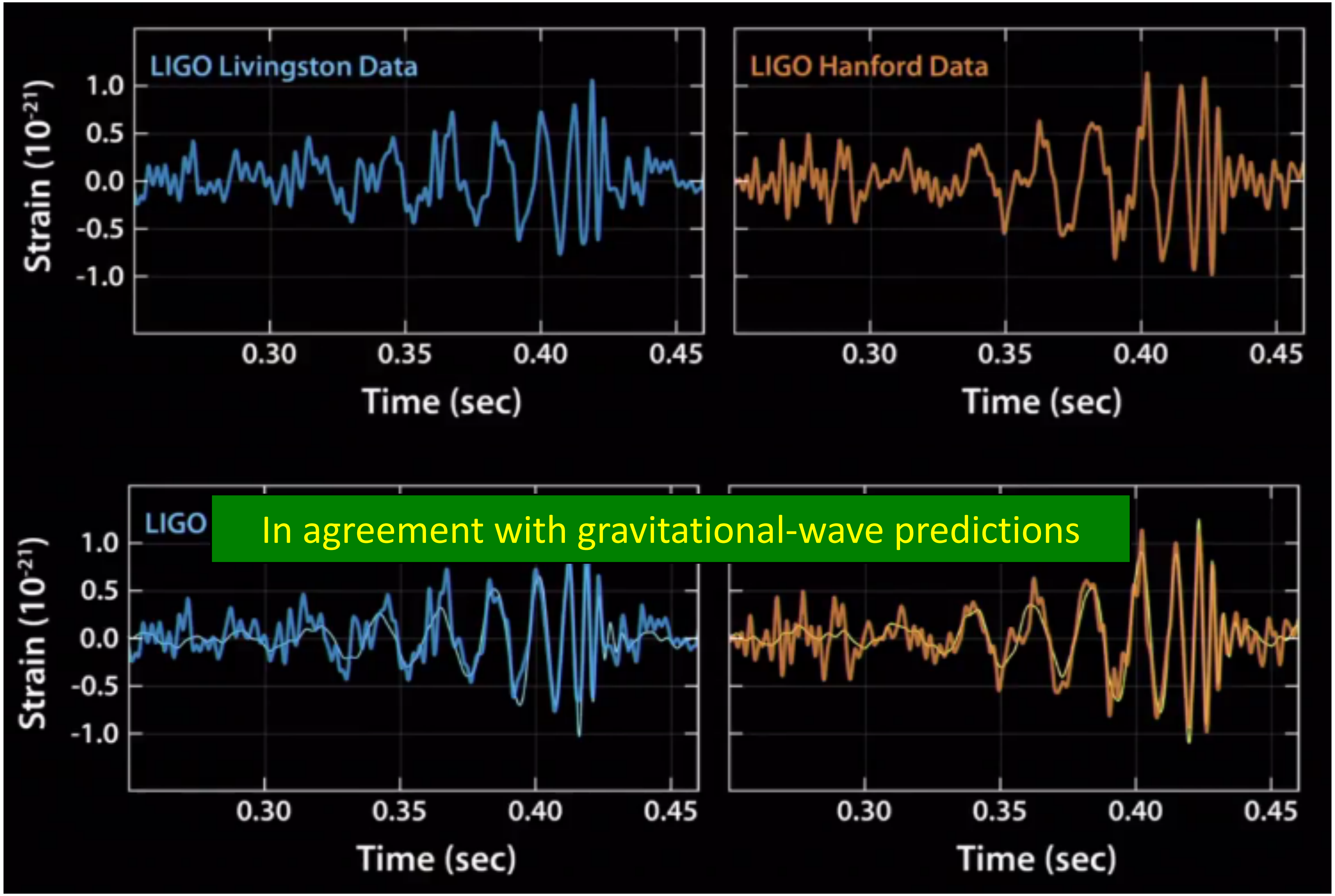
LIGO Layout & Sensitivity



Earth's diameter changes by ~ size of atomic nucleus

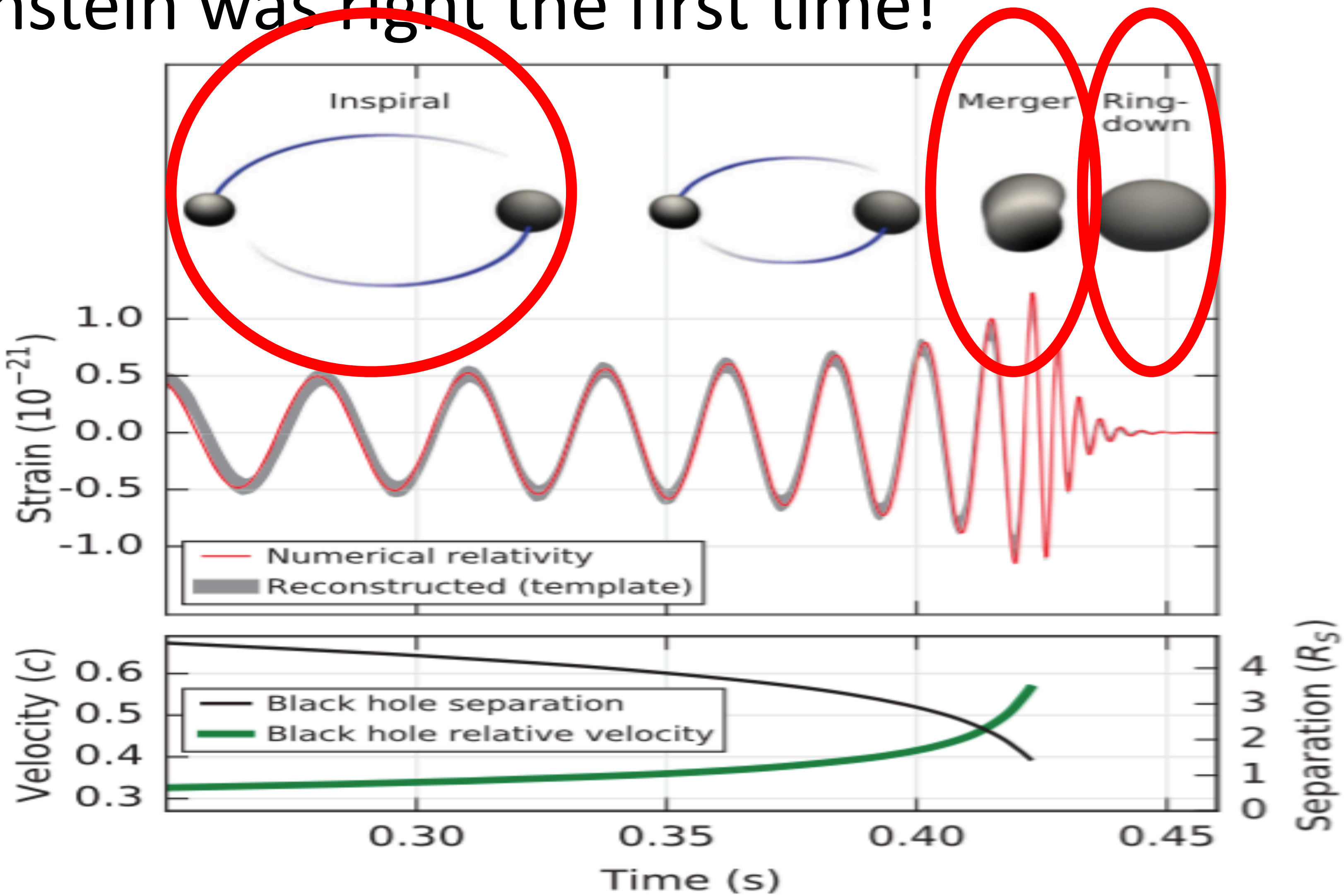
What was observed

- **Very similar signals in the 2 detectors**



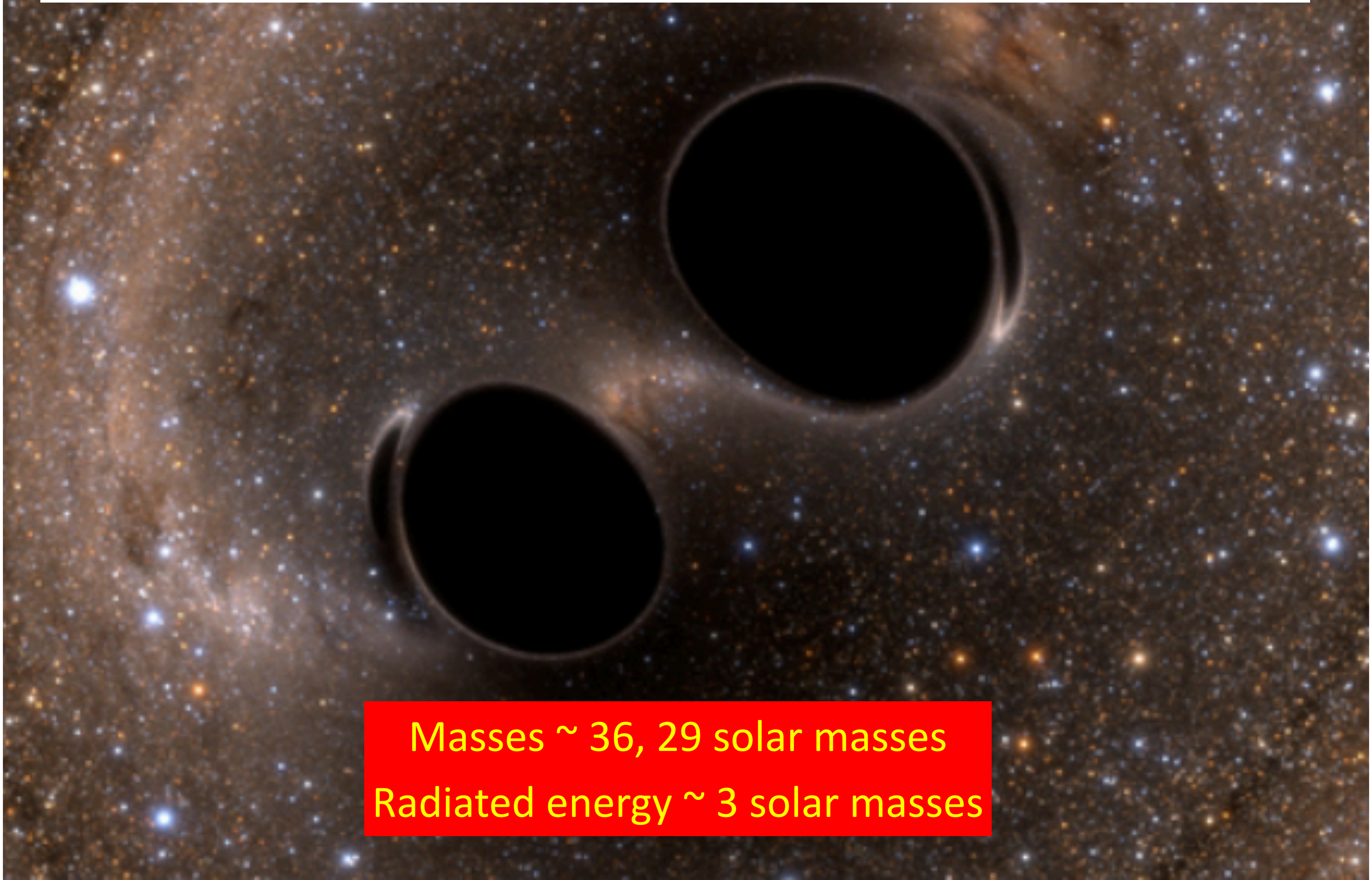
Fusion of two massive black holes

- Einstein was right the first time!



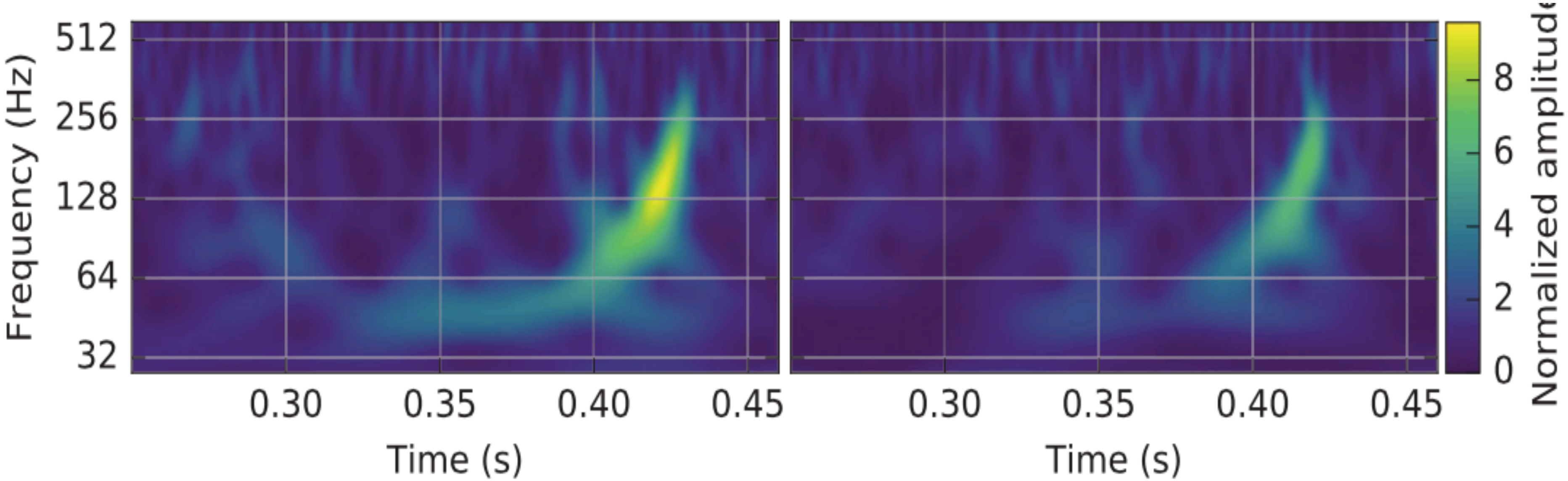
- A new way to study the Universe

Fusion of two massive black holes



The Gravitational Chirp …

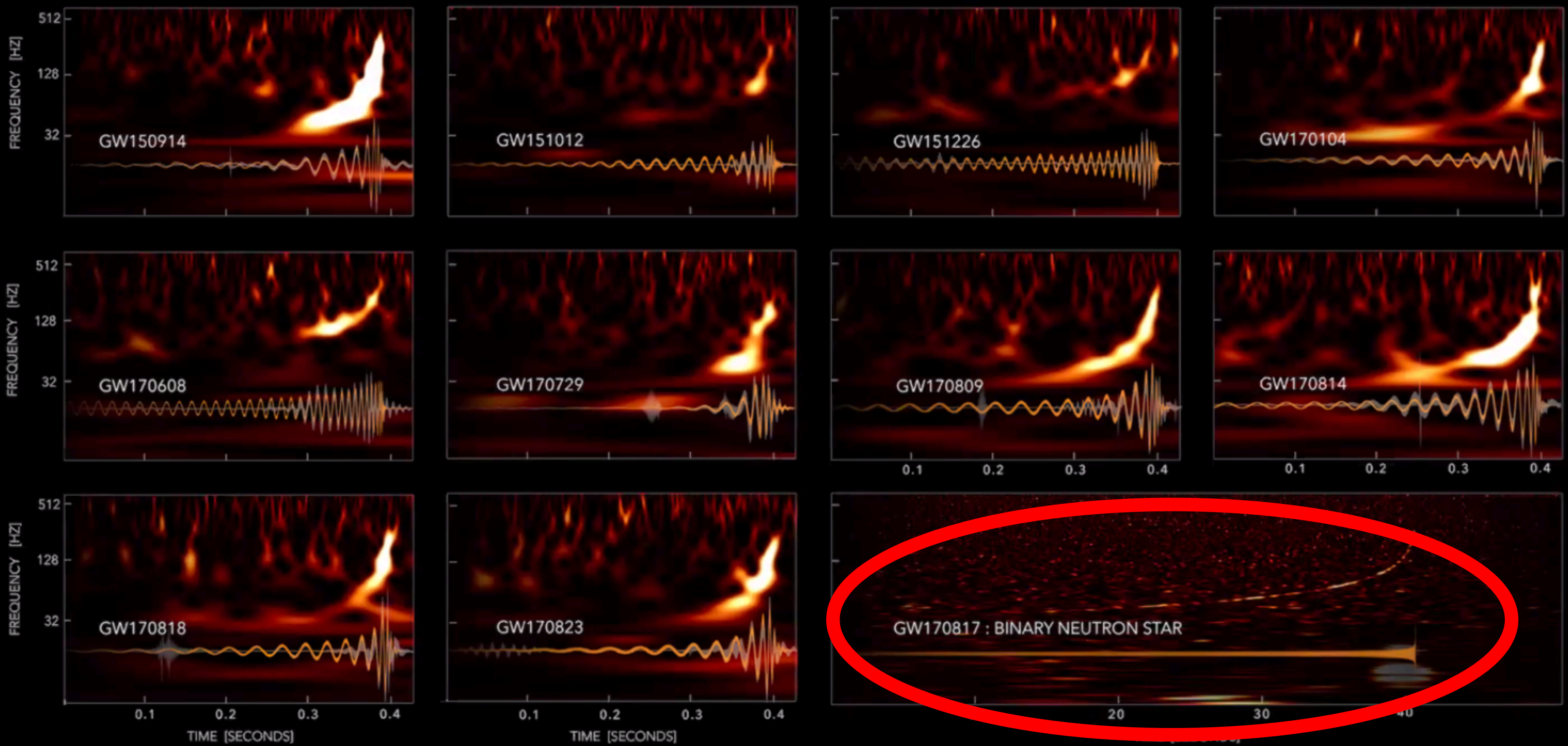
- … heard around the world



- Frequency increases with time during inspiral
- Followed by ringdown of combined black hole
- Graviton mass < $10^{-27} \times$ mass of electron LIGO
- Waves of different frequencies have same speed

JE, Mavromatos & Nanopoulos, arXiv:1602.04764

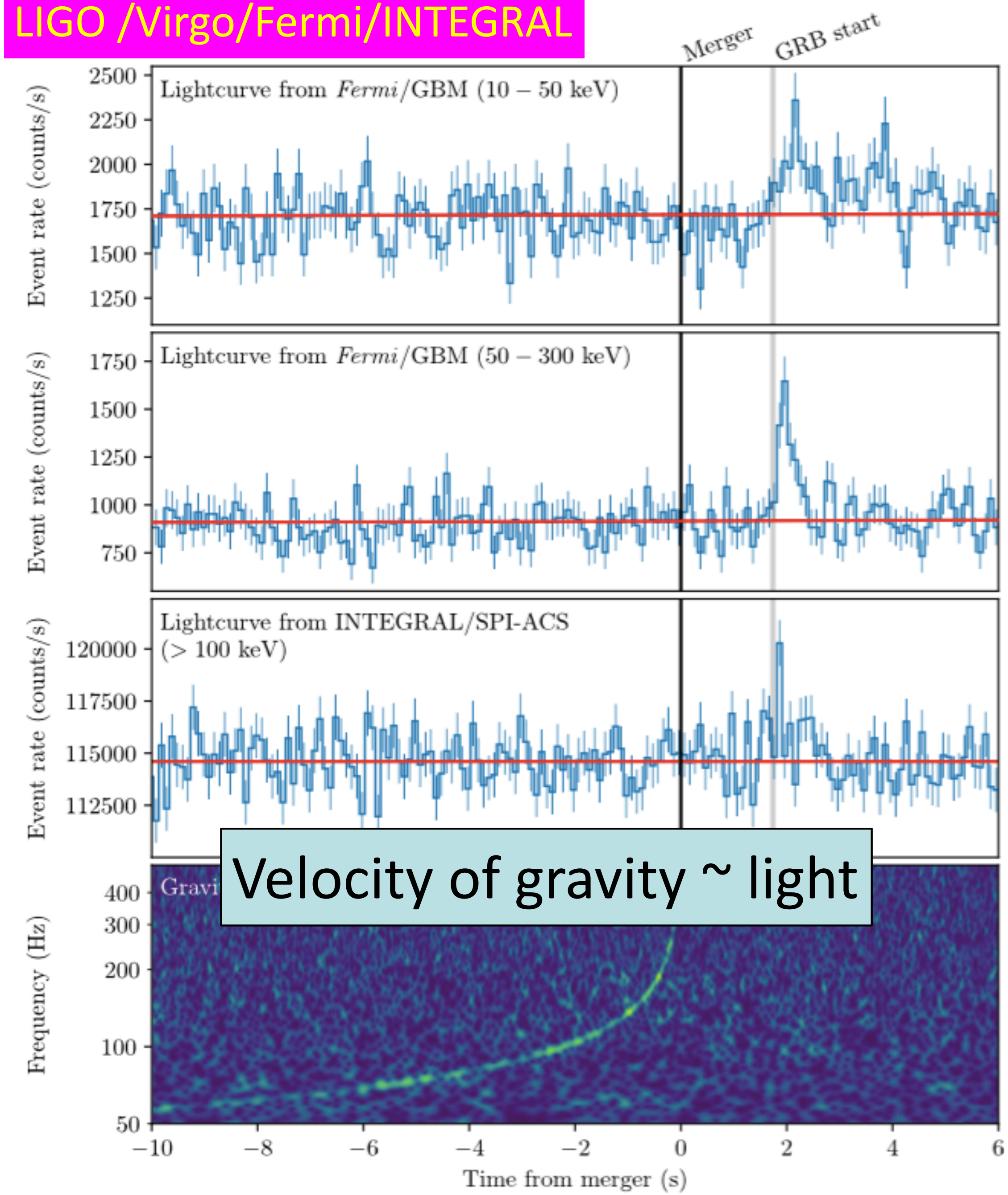
Mergers Measured in First LIGO/Virgo Observation Period



Binary neutron star merger: electromagnetic counterpart

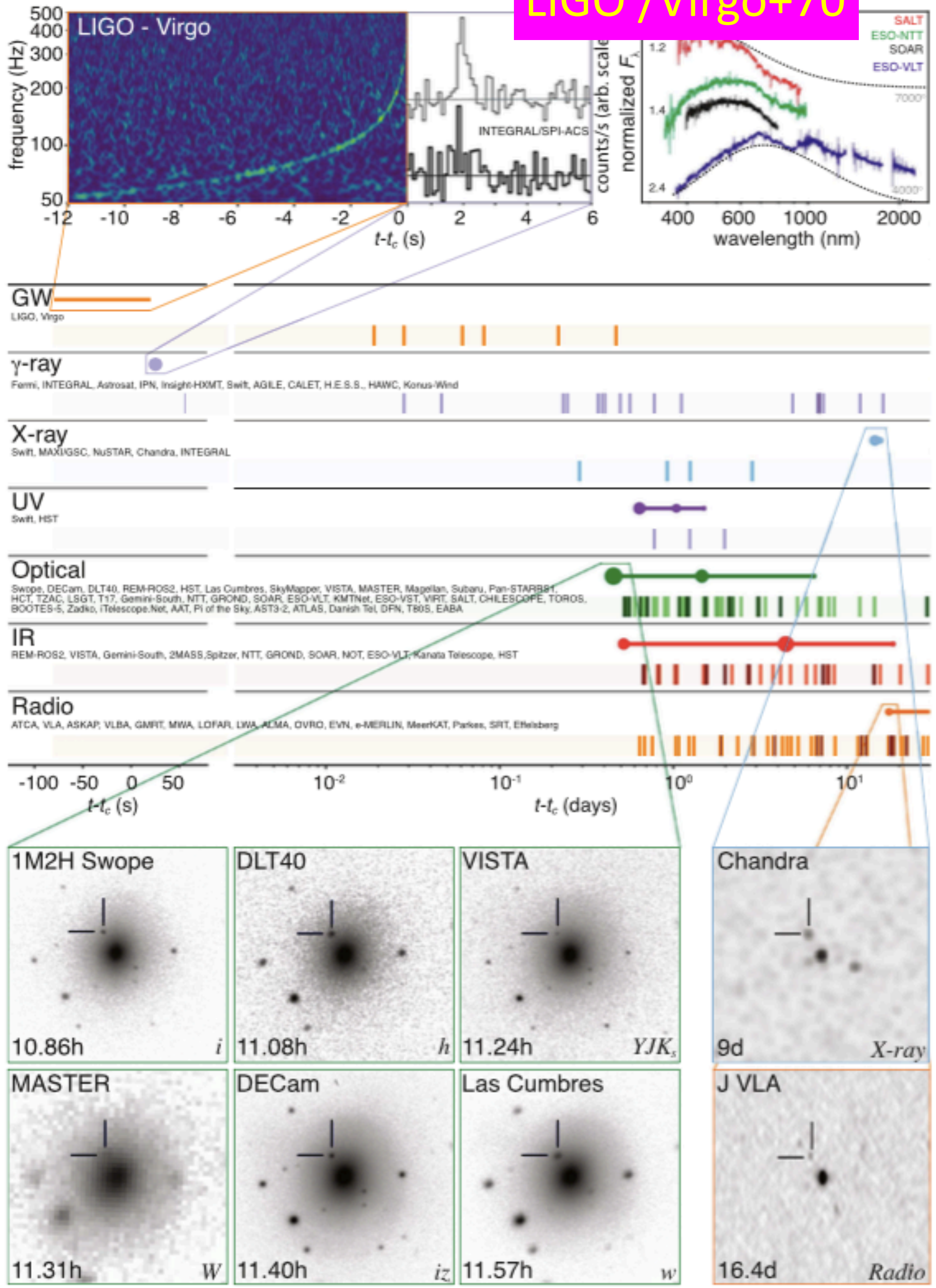
Observations of Neutron Star Merger

LIGO /Virgo/Fermi/INTEGRAL

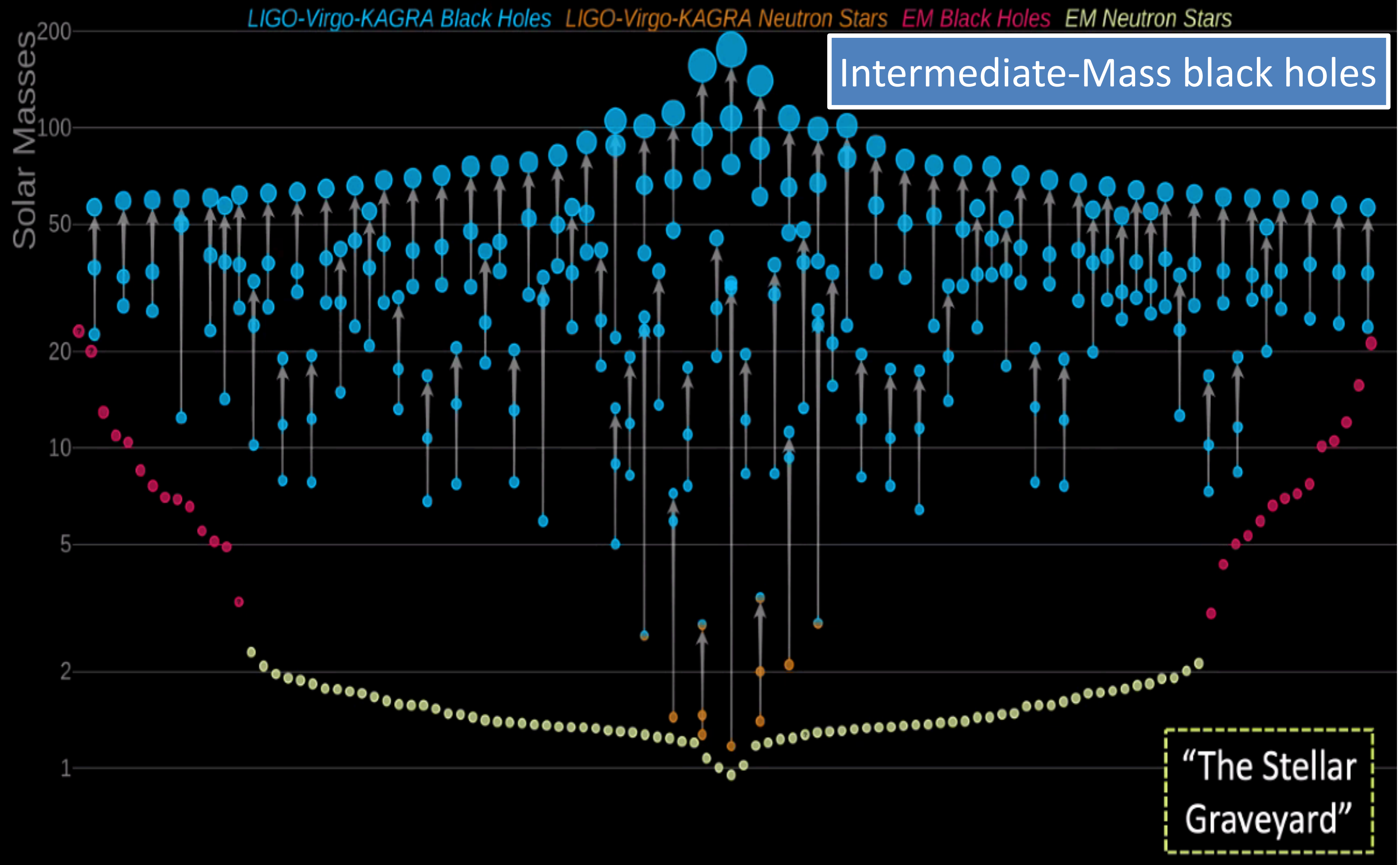


Velocity of gravity ~ light

LIGO /Virgo+70

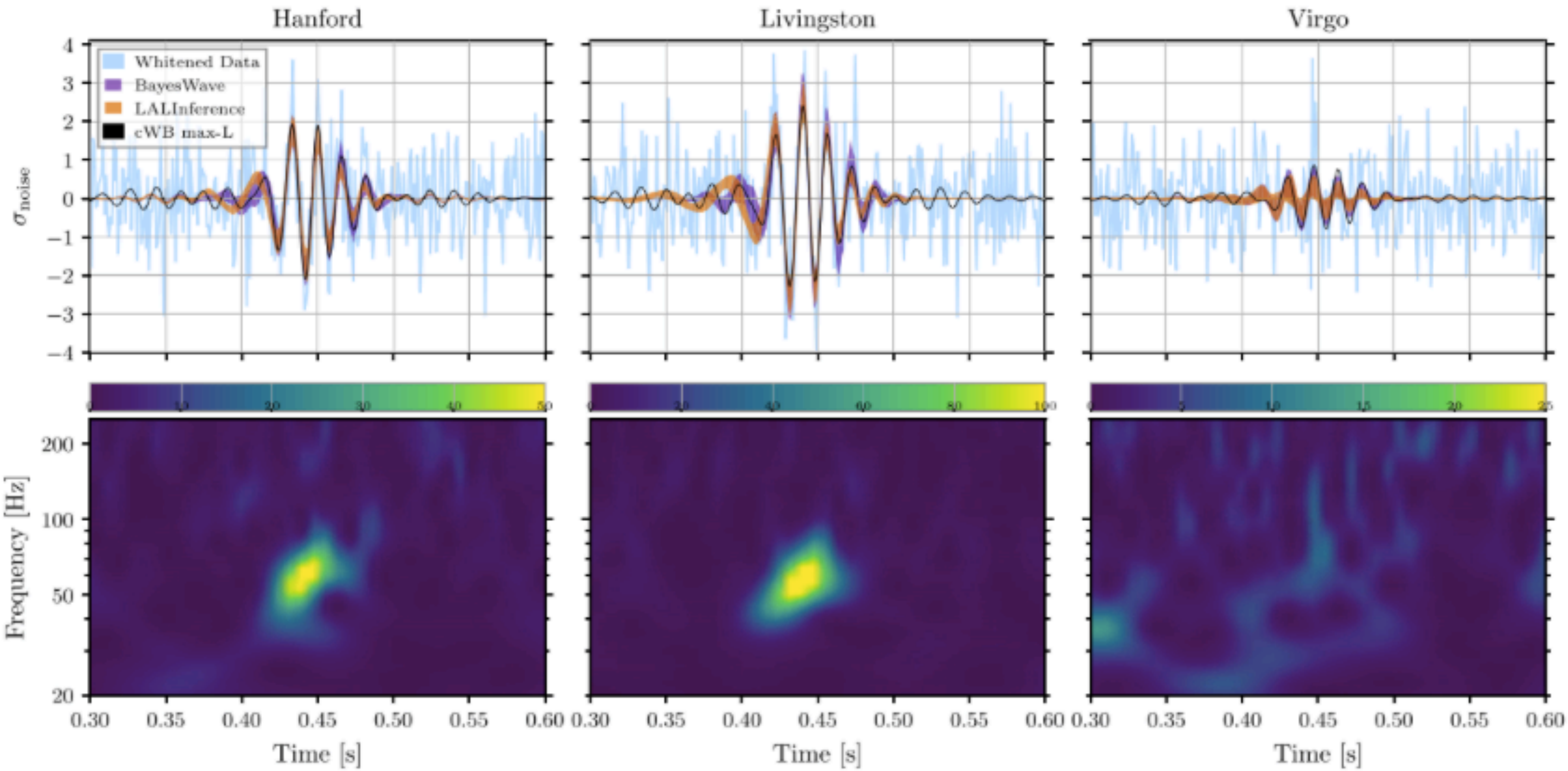


LIGO/Virgo/KAGRA Black Hole, Neutron Star Masses



LIGO & Virgo Collaborations: arXiv:2009.01075, 01190

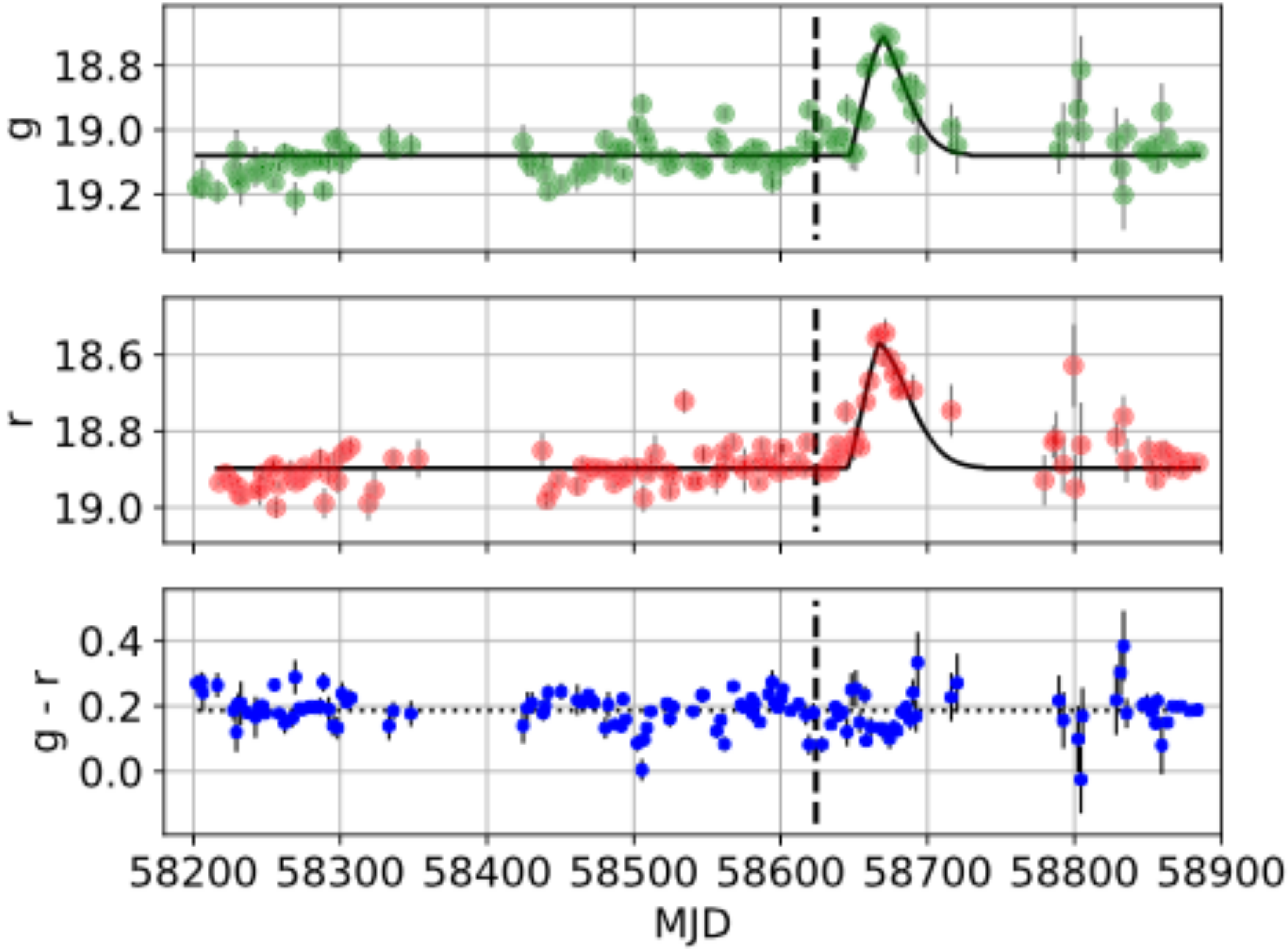
GW190521 – a Bang not a Chirp



Triple measurement of merger of heaviest black holes seen so far

Graham et al.: arXiv:2006.14122

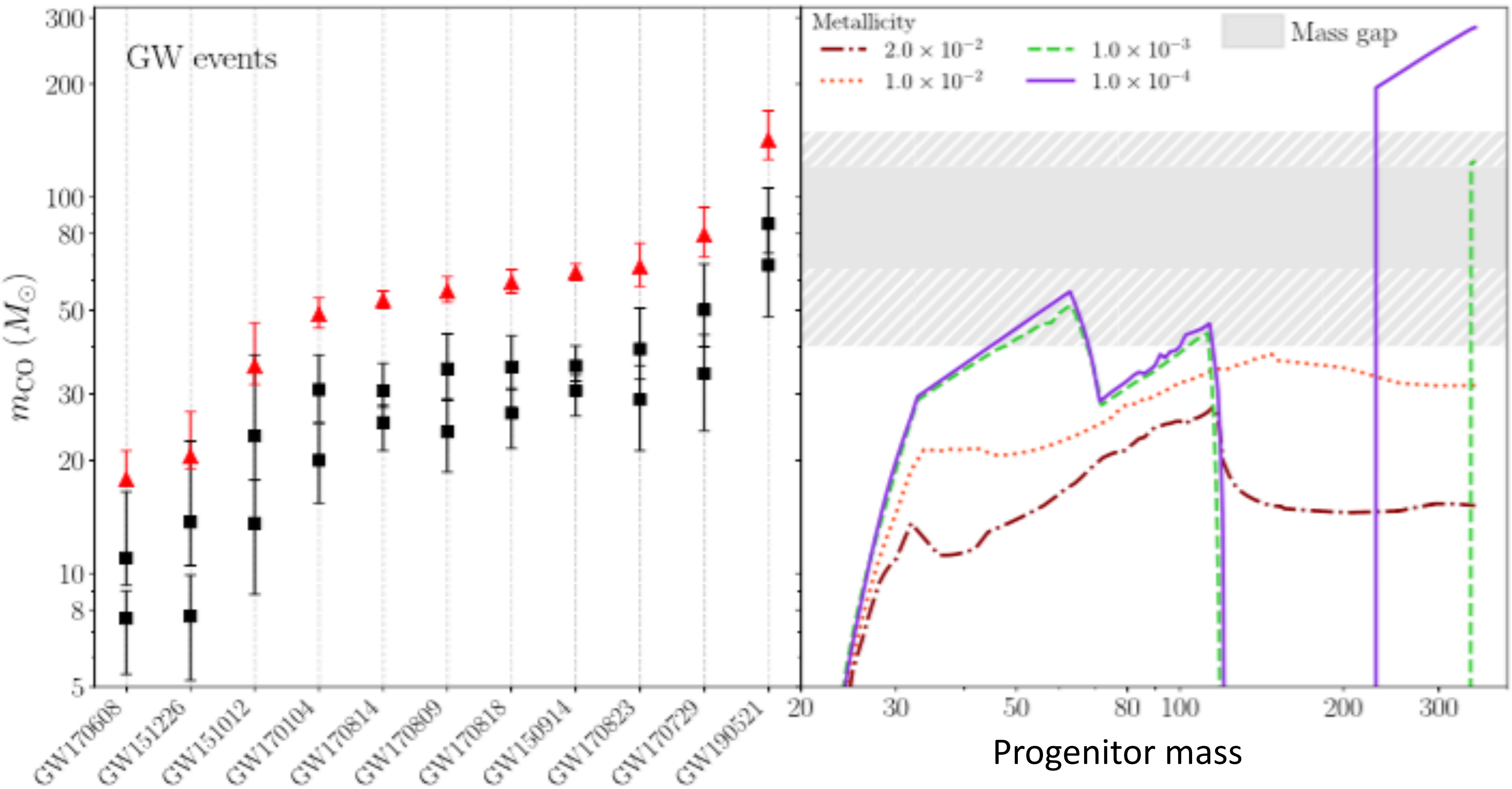
Optical Counterpart?



Optical flash detected with Zwicky Transient Facility
Due to “shake-up” of gas clouds in AGN accretion disk by GW emission?

LIGO & Virgo Collaborations: arXiv:2009.01075, 2009.01190

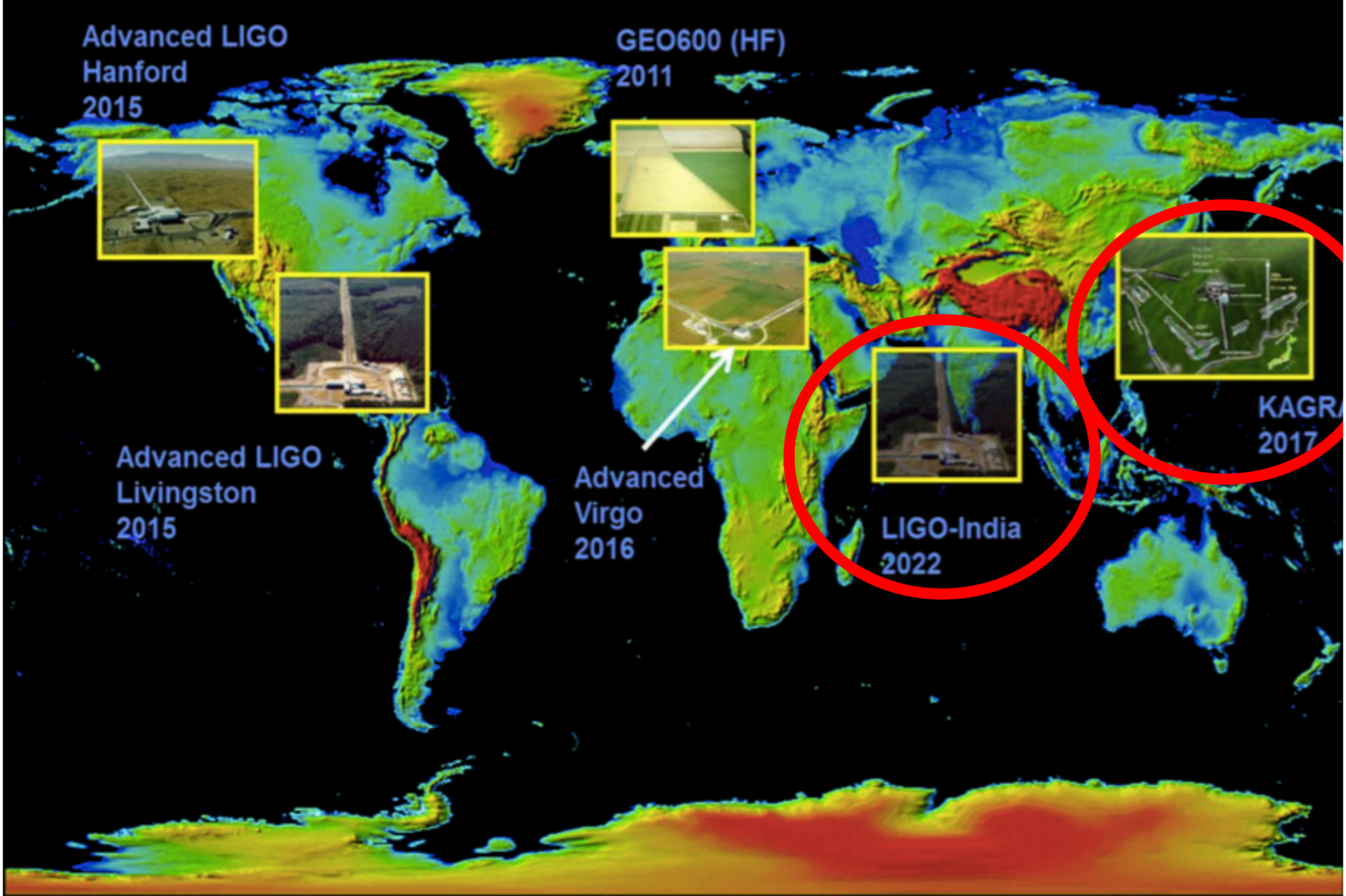
Predicted Mass Gap



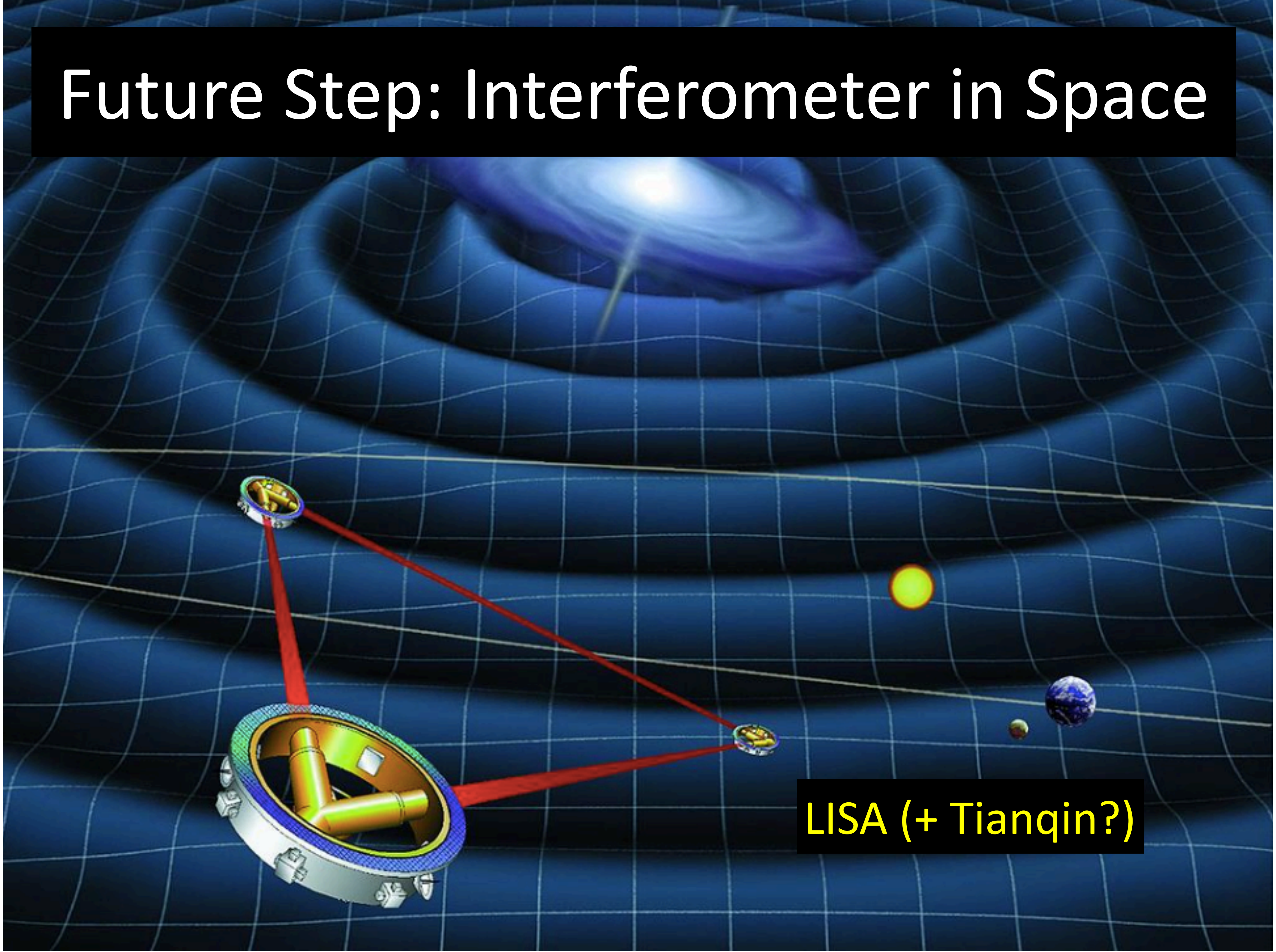
Standard stellar evolution ➔ no black holes between ~70, 120 solar masses

Previous mergers? Primordial black holes? BSM physics to fill in mass gap?

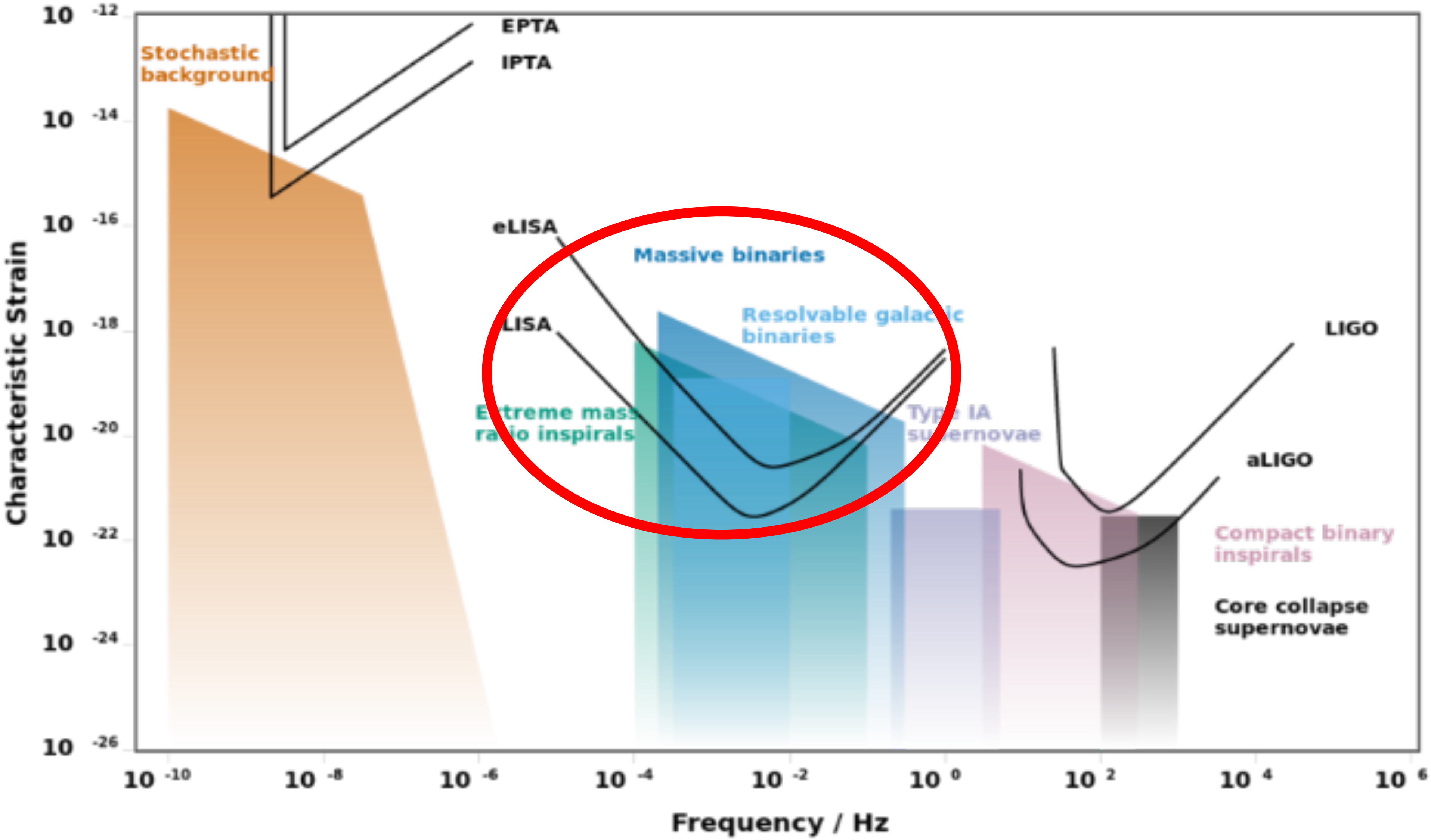
Ground-Based GW Detectors



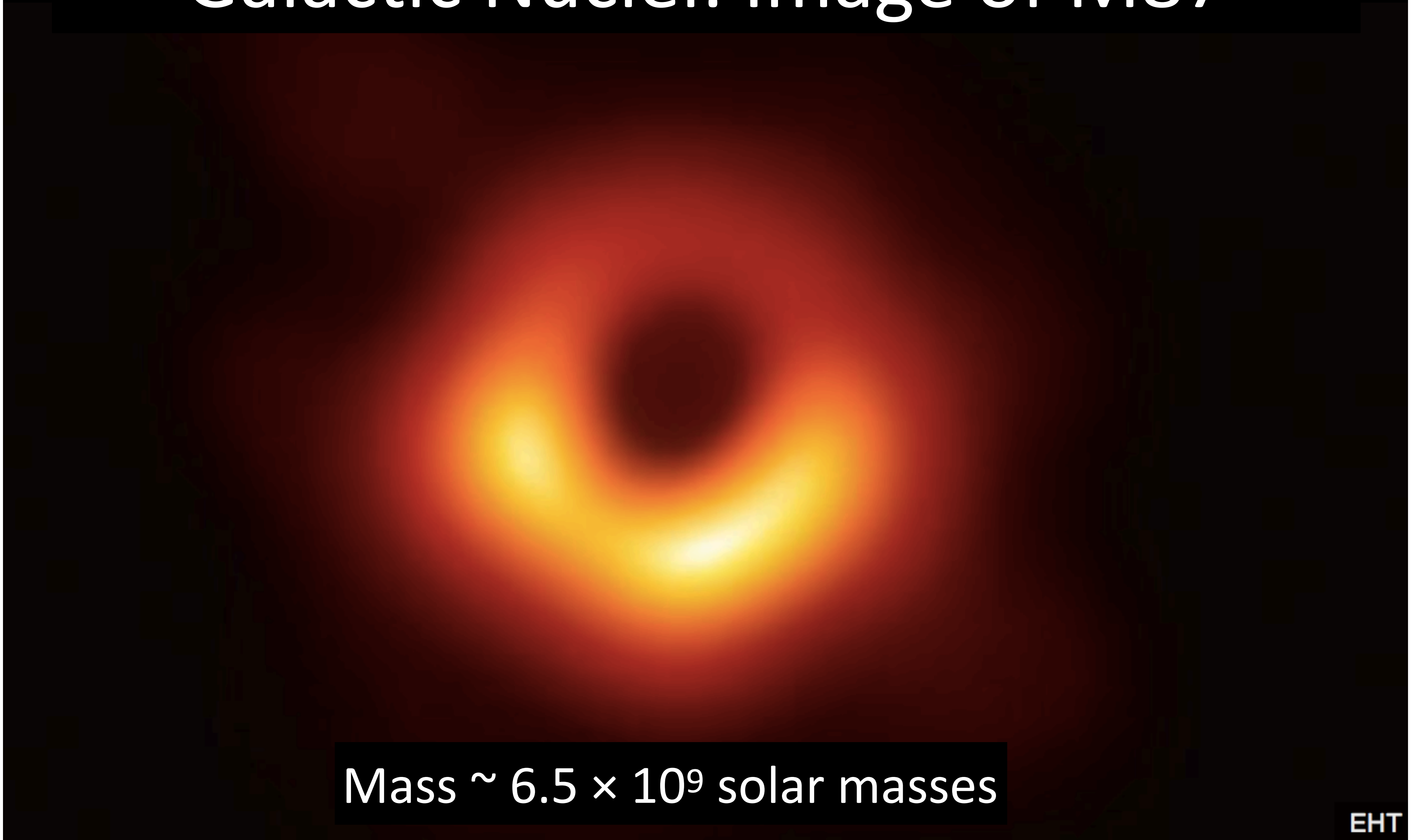
Future Step: Interferometer in Space



Gravitational Wave Landscape

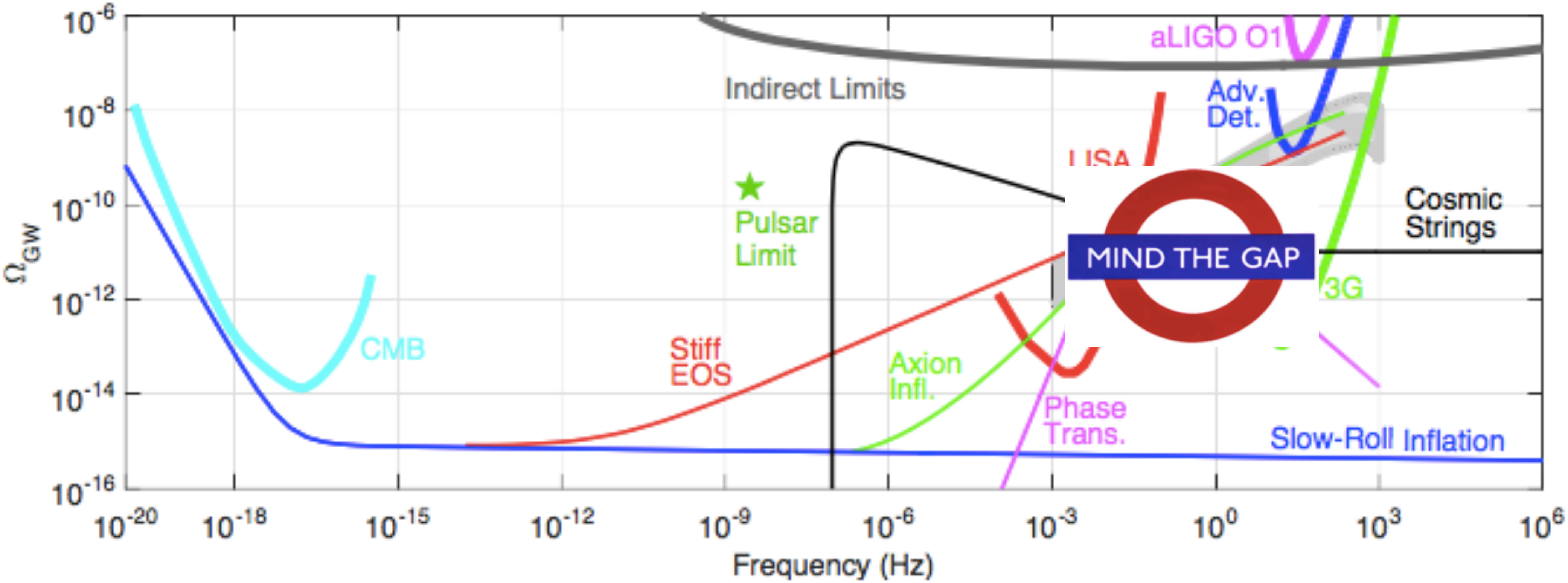


Supermassive Black Holes in Active Galactic Nuclei: Image of M87



Mass ~ 6.5×10^9 solar masses

Gravitational Wave Spectrum

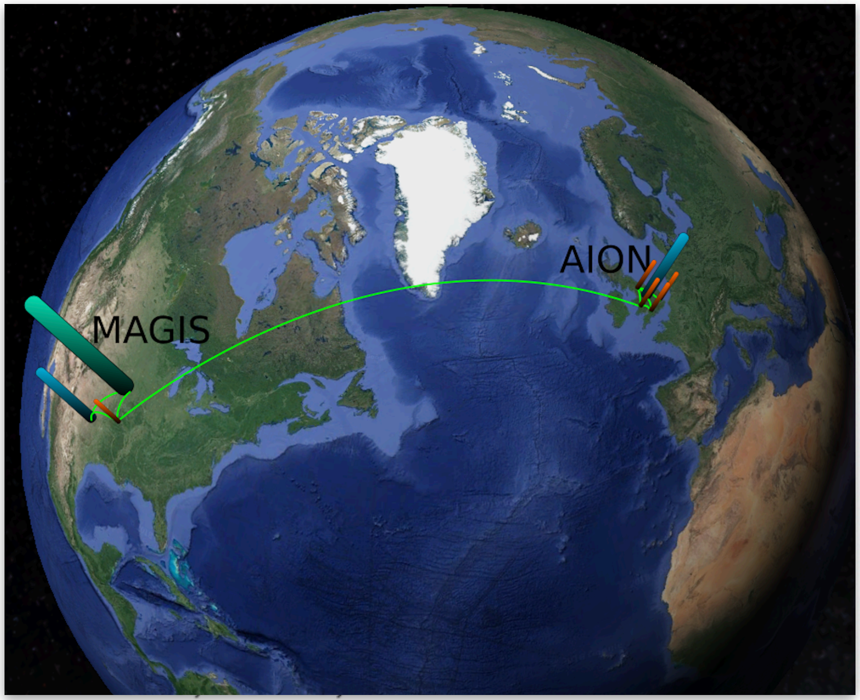


- Gap between ground-based optical interferometers & LISA
  - Formation of supermassive black holes (SMBHs)?
  - Electroweak phase transition? Cosmic strings?
- Gap between LISA & pulsar timing arrays (PTAs)

AION Collaboration

L. Badurina[1], S. Balashov[2], E. Bentine[3], D. Blas[1], J. Boehm[2], K. Bongs[4], D. Bortoletto[3], T. Bowcock[5], W. Bowden[6,*], C. Brew[2], O. Buchmueller[6], J. Coleman[5], G. Elertas, J. Ellis[1,&], C. Foot[3], V. Gibson[7], M. Haehnelt[7], T. Harte[7], R. Hobson[6,*], M. Holynski, 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]

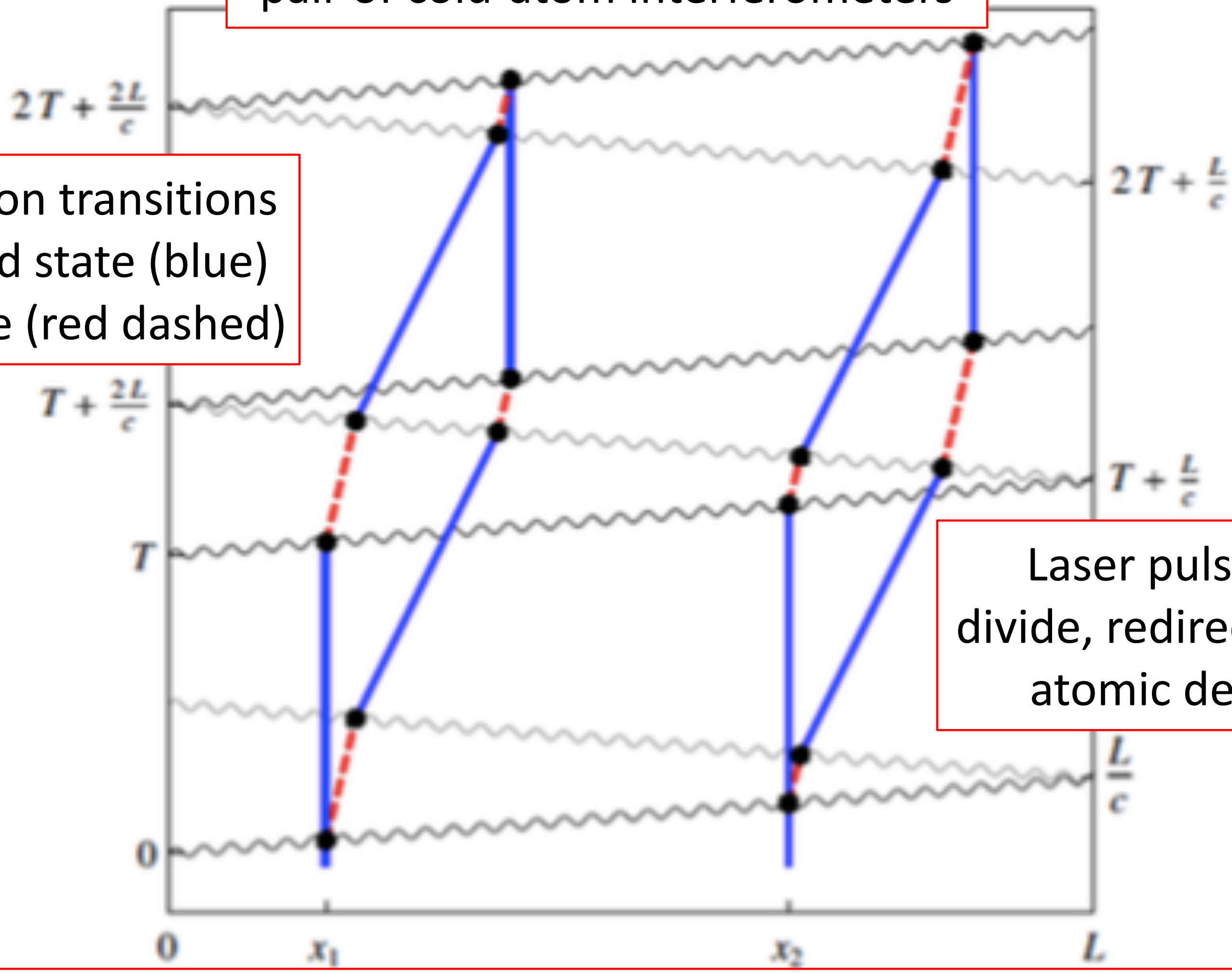
[1]Kings College London, [2]STFC Rutherford Appleton Laboratory, [3]University of Oxford, [4]University of Birmingham, [5]University of Liverpool, [6]Imperial College London, [7]University of Cambridge



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

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

Beyond LISA

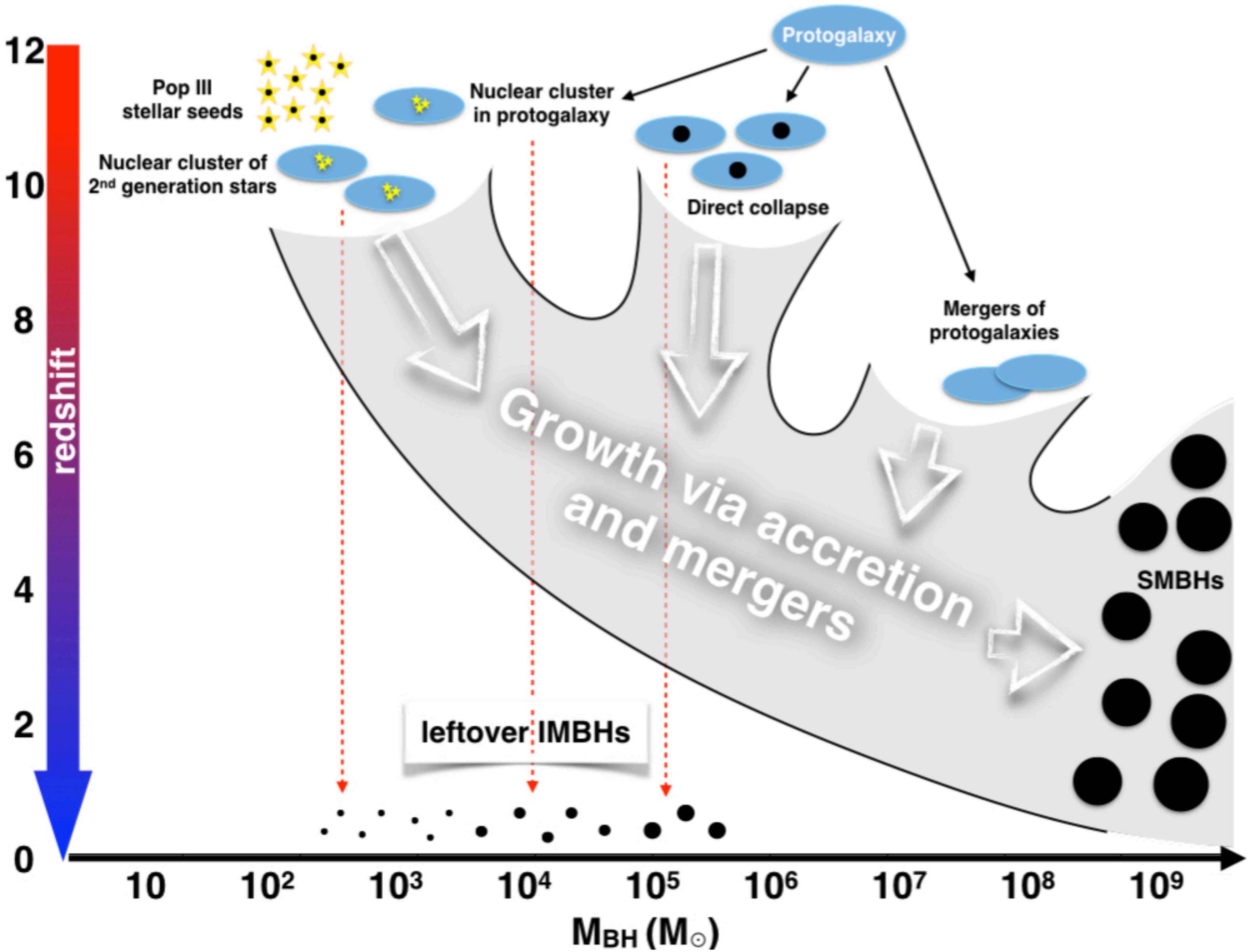
Yousef Abou El-Neaj,[1] Cristiano Alpigiani,[2] Sana Amairi-Pyka,[3] Henrique Araújo,[4] Antun Balaž,[5] Angelo Bassi,[6] Lars Bathe-Peters,[7] Baptiste Battelier,[8] Aleksandar Belić,[5] Elliot Bentine,[9] José Bernabeu,[10] Andrea Bertoldi,[8,*] Robert Bingham,[11] Diego Blas,[12] Vasiliki Bolpasi,[13]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

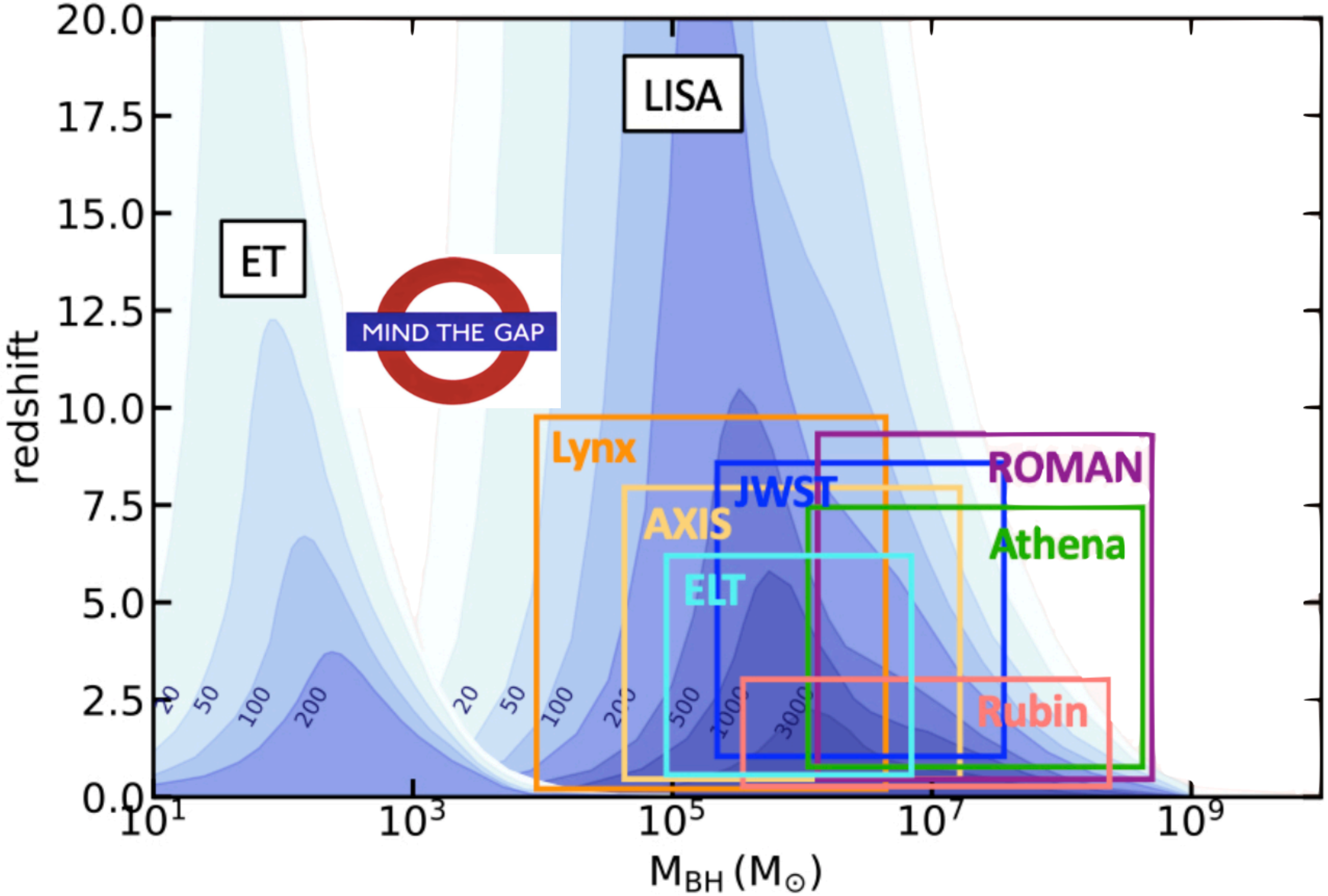
Abou El-Neaj, ..., JE et al: arXiv:1908.00802

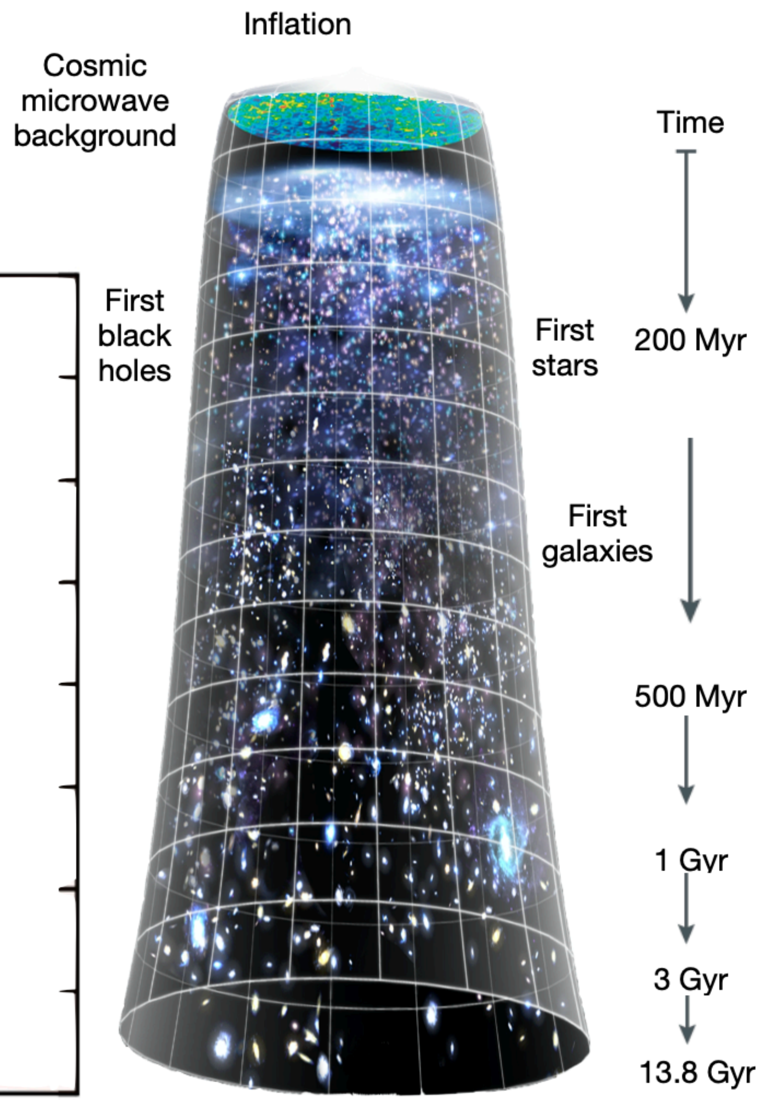
How to Make a Supermassive BH?

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



How to Observe Mergers of Massive BHs?

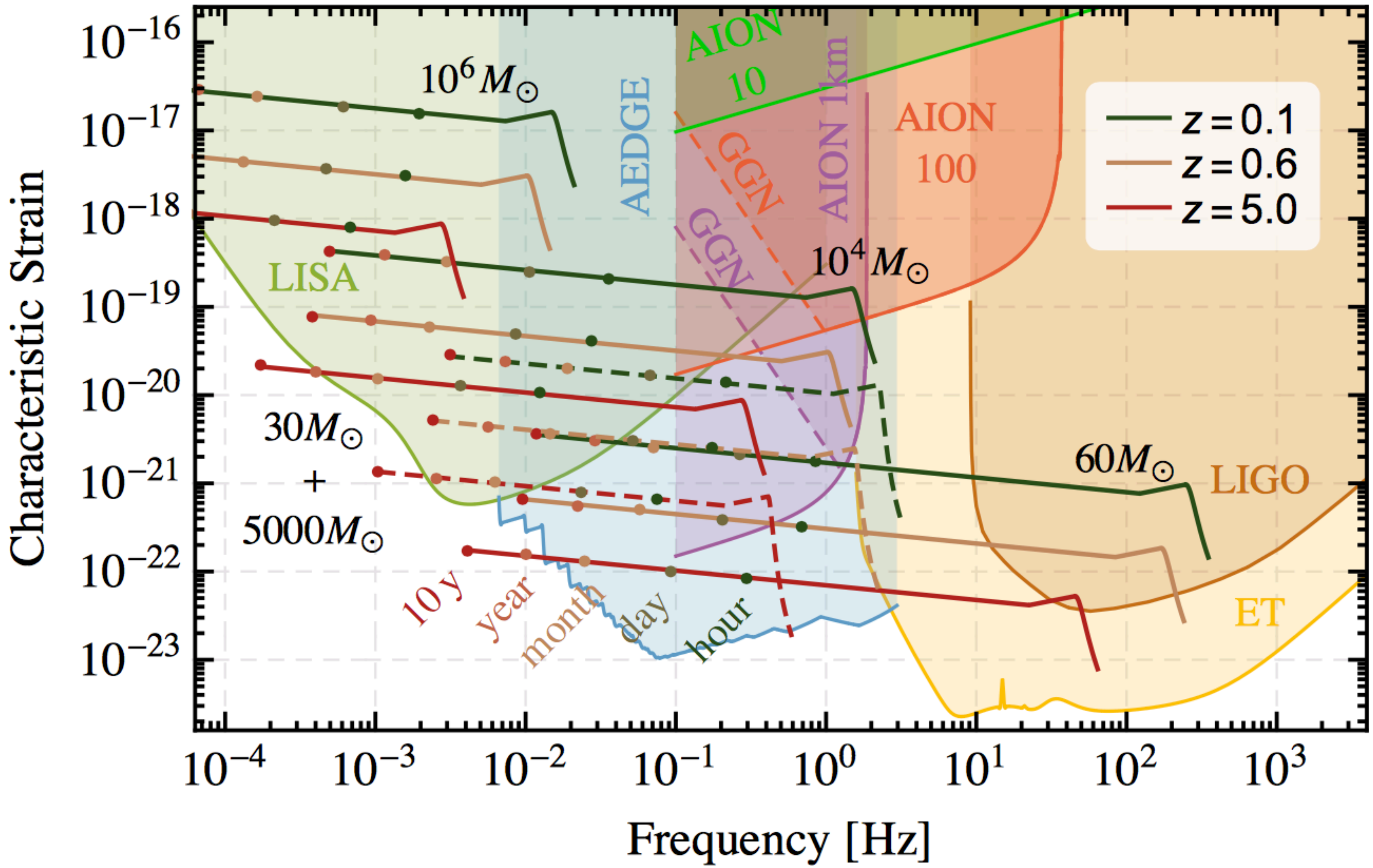




Volonteri, Habouzit & Colpi, arXiv:2110.10175

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

Gravitational Waves from IMBH Mergers

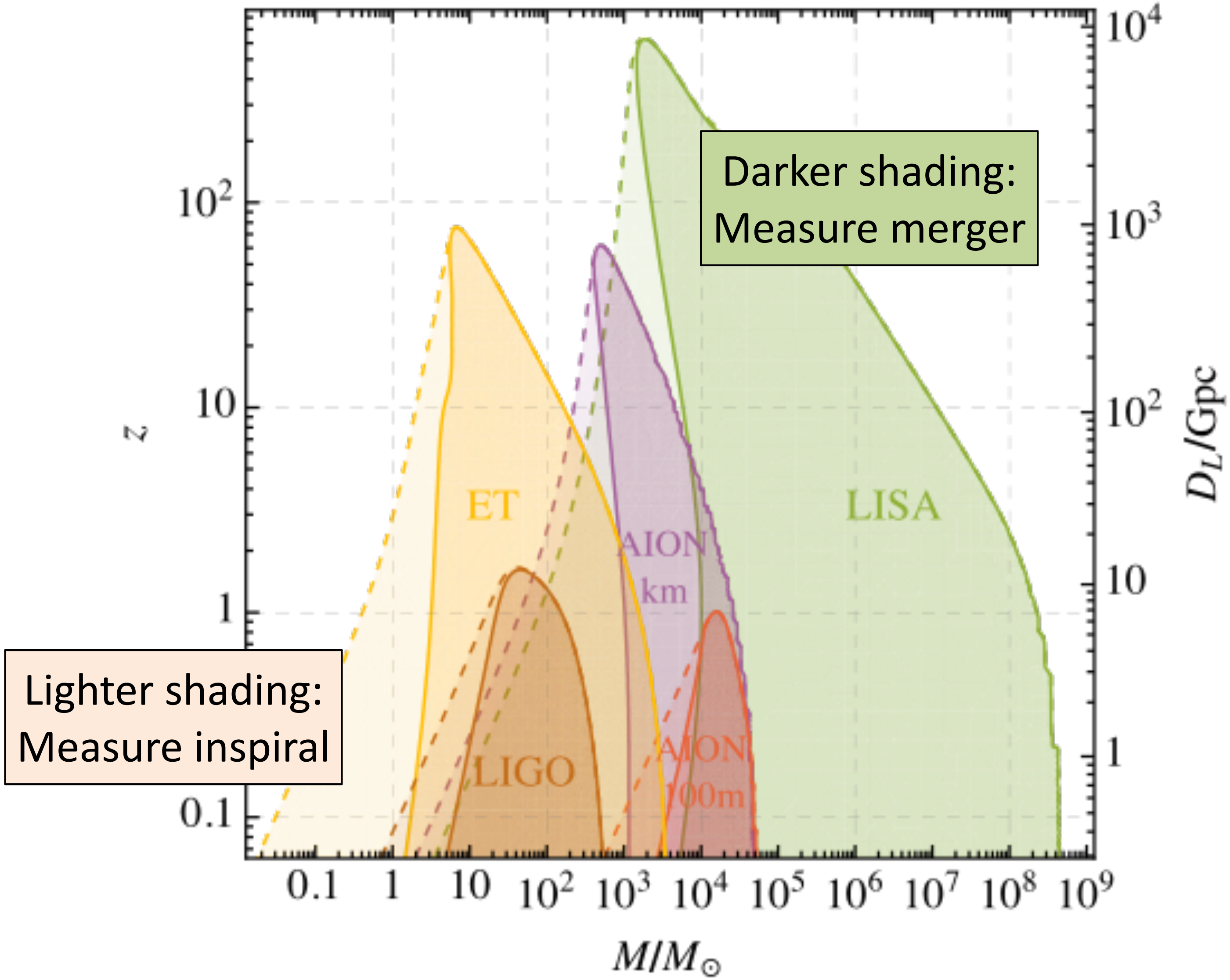


Probe formation of SMBHs

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

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

GWs from IMBH Mergers: SNR = 8

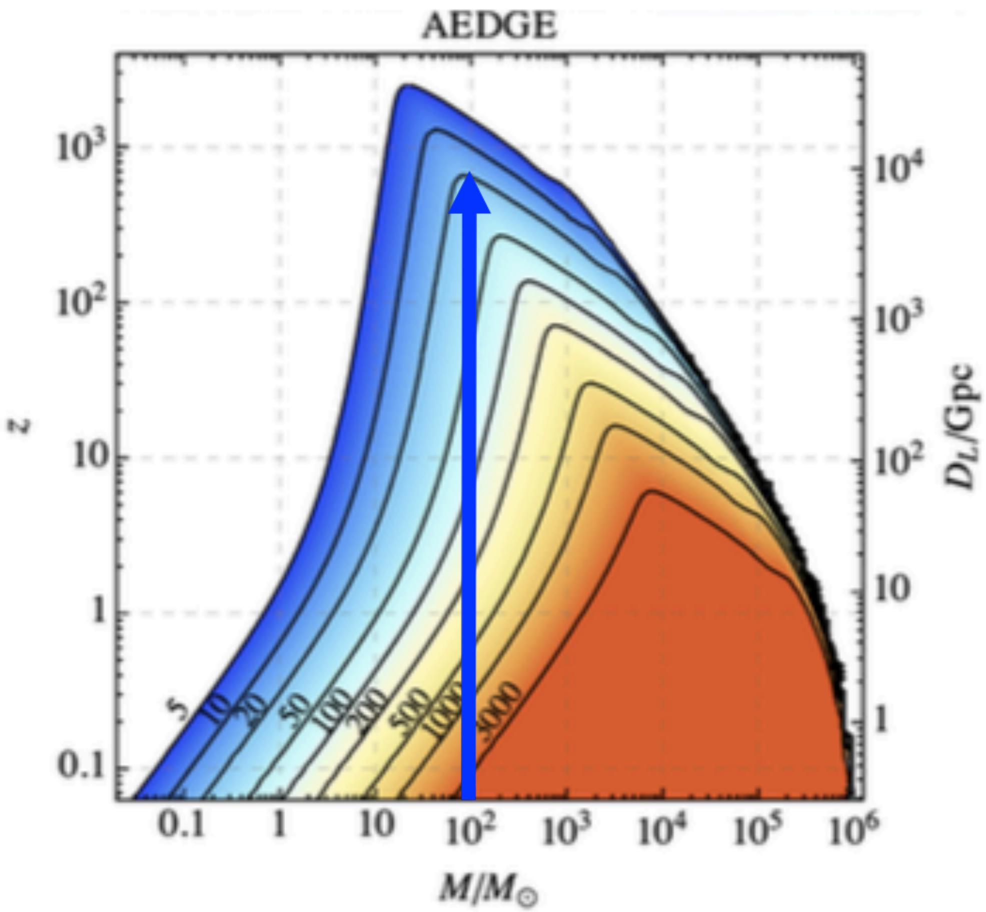


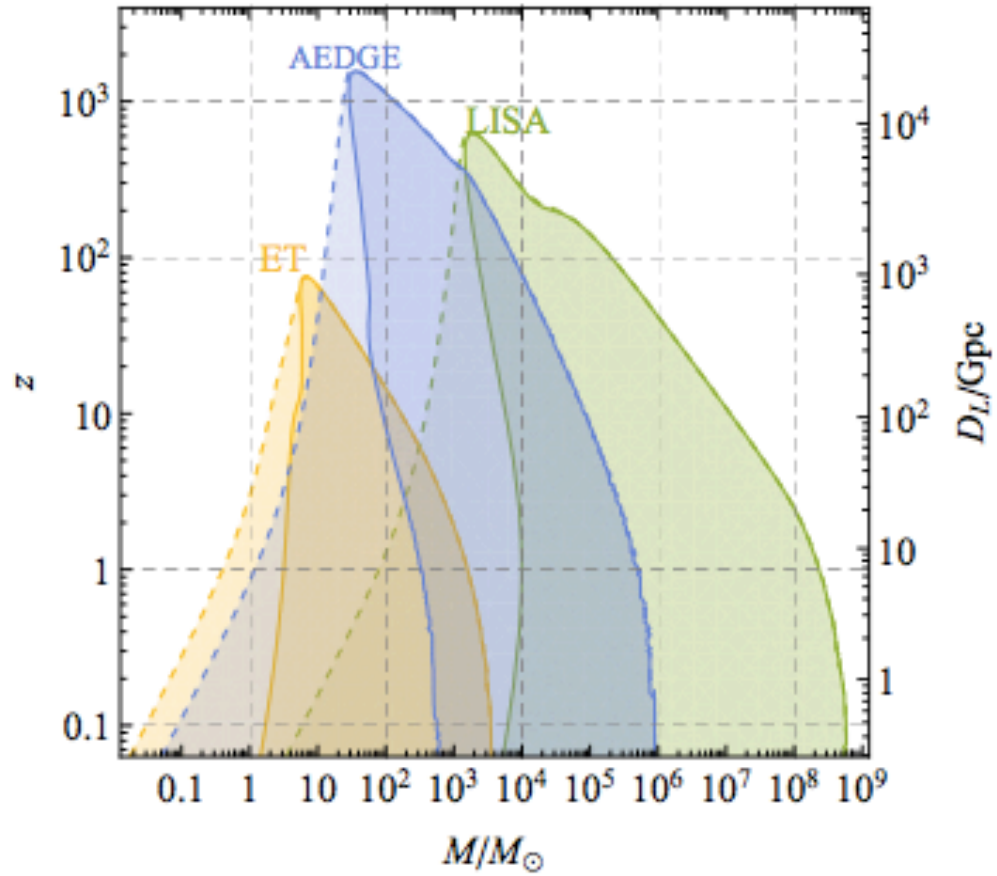
AION complementary to LIGO, Einstein Telescope (ET)

Operation before LISA

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

Gravitational Waves from IMBHs





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

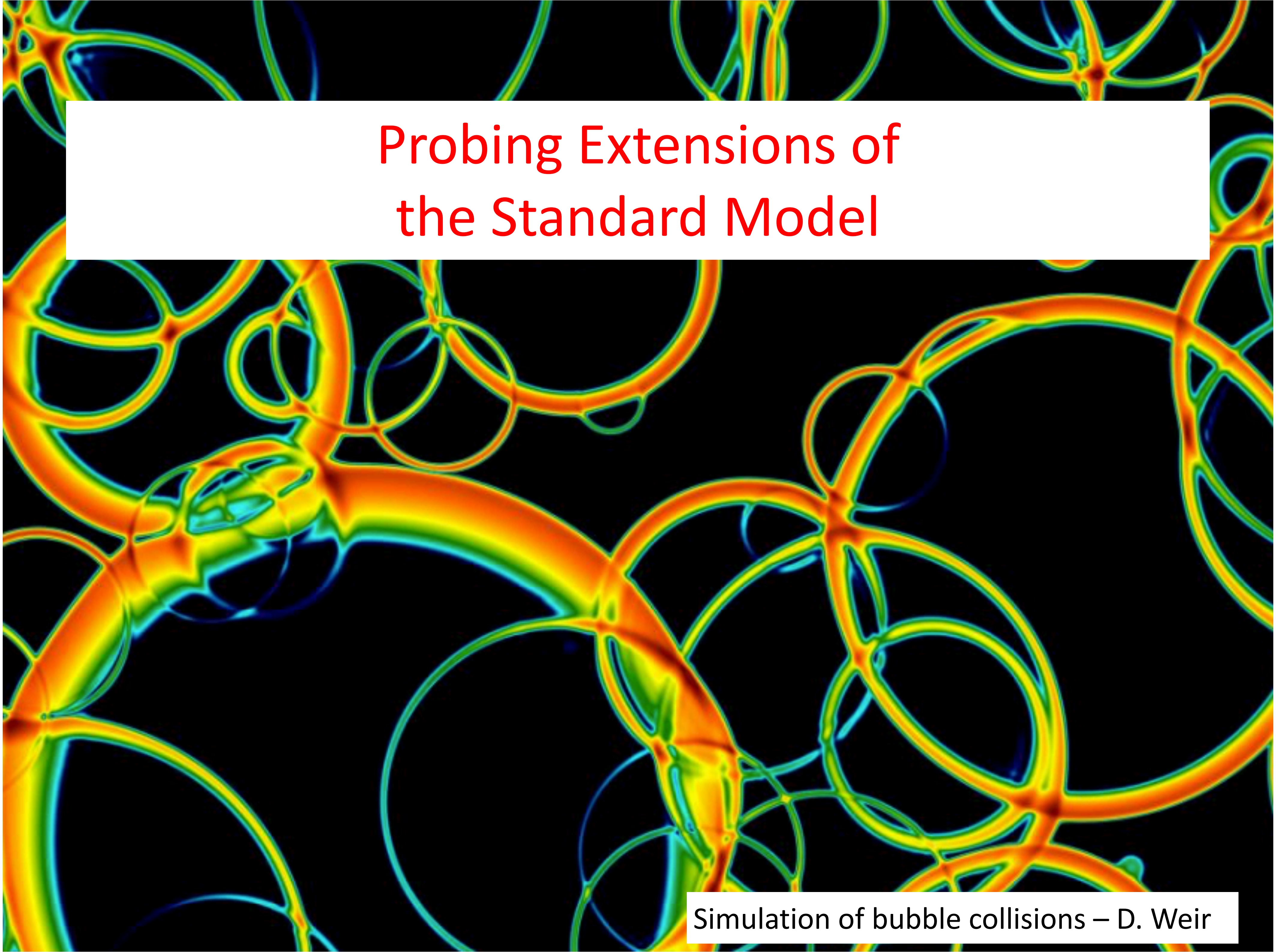
with SNR 1000 out to z ~ 10

Lighter shades: inspiral

Darker shades: merger + ringdown

Complementarity + synergy

Probing Extensions of the Standard Model



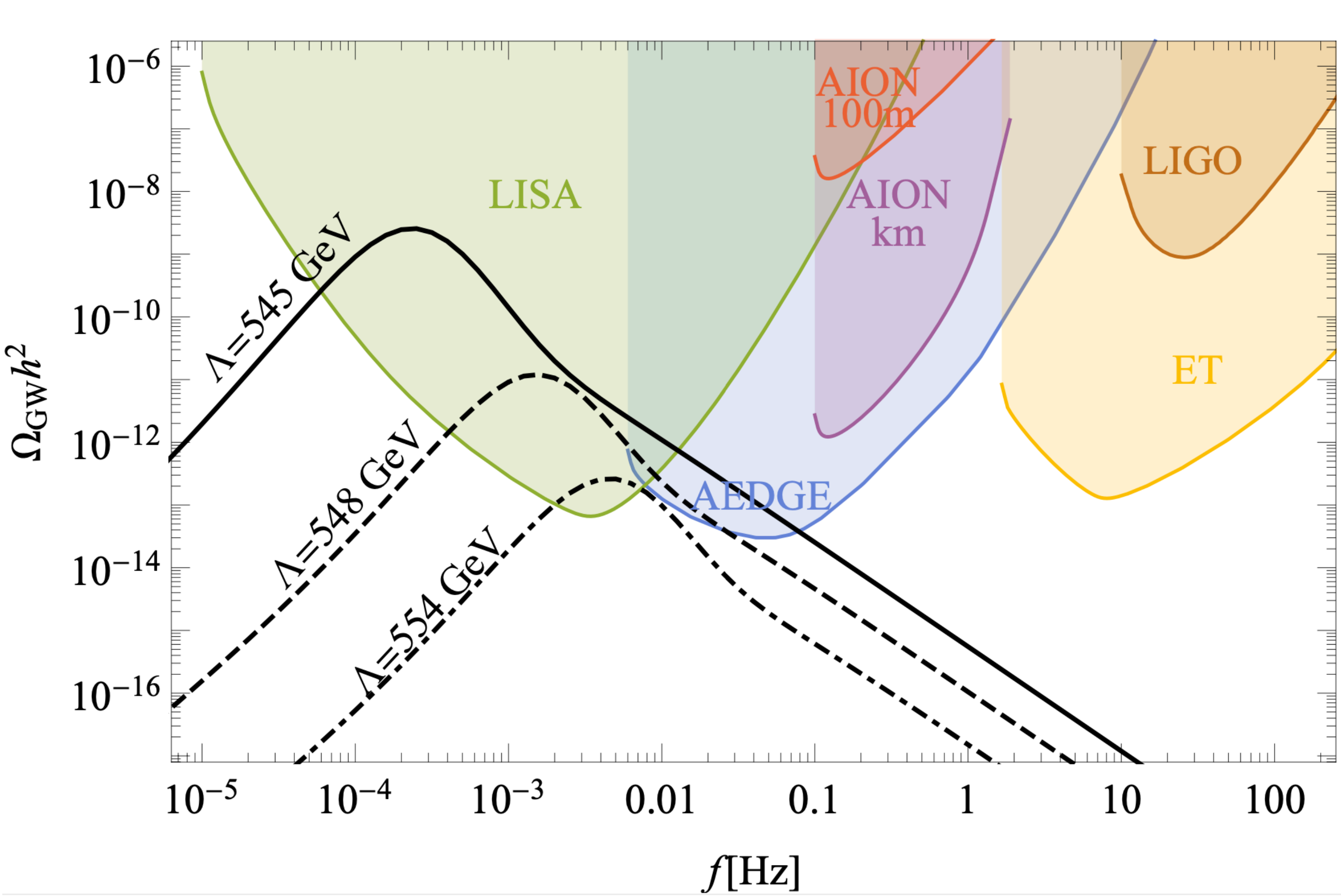
Simulation of bubble collisions – D. Weir

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

GW Signal in H^6 Model

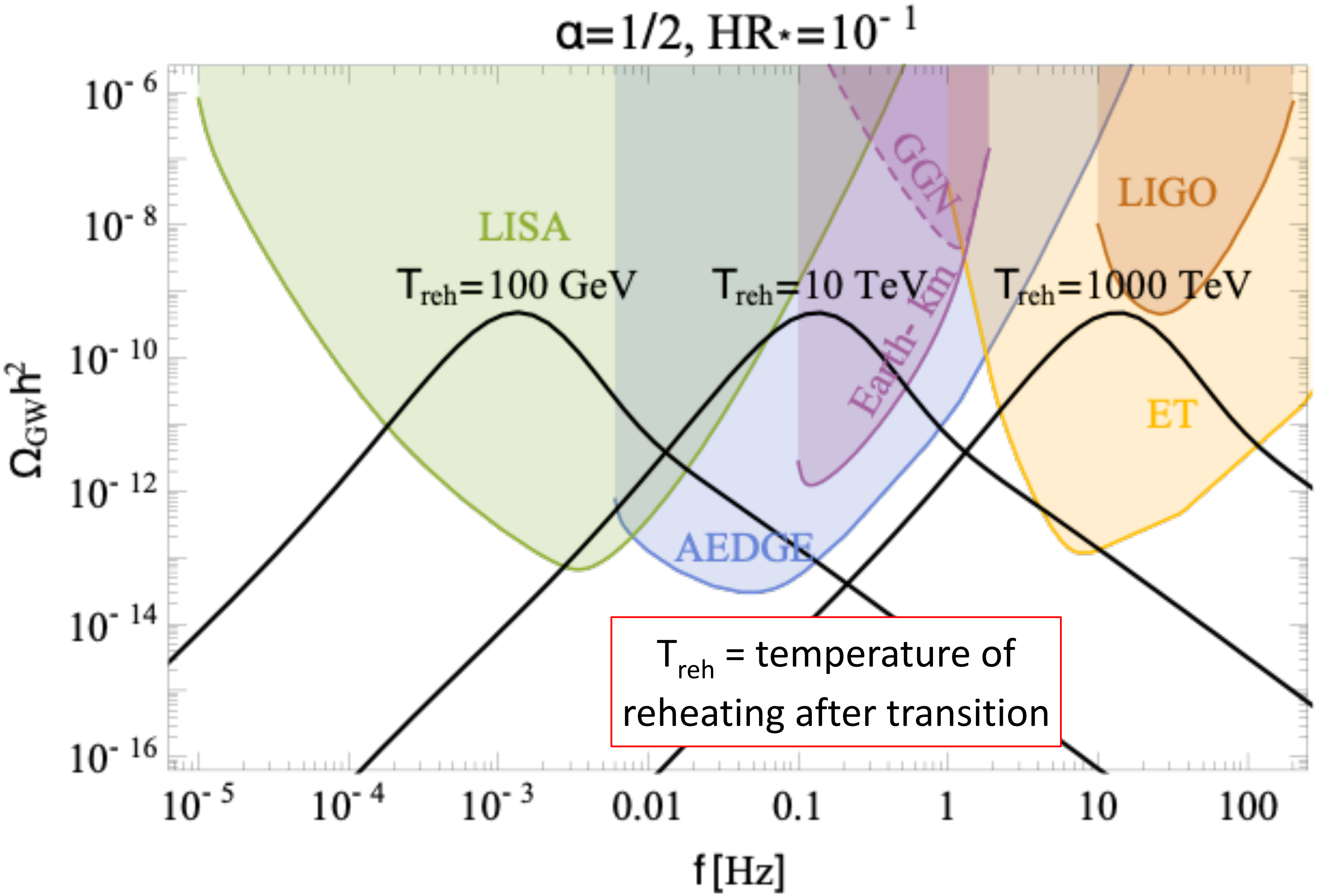
- Strongest signal for which percolation is assured



- AEDGE and LISA sensitivities very similar

JE, Lewicki, No & Vaskonen, arXiv:1903.09642

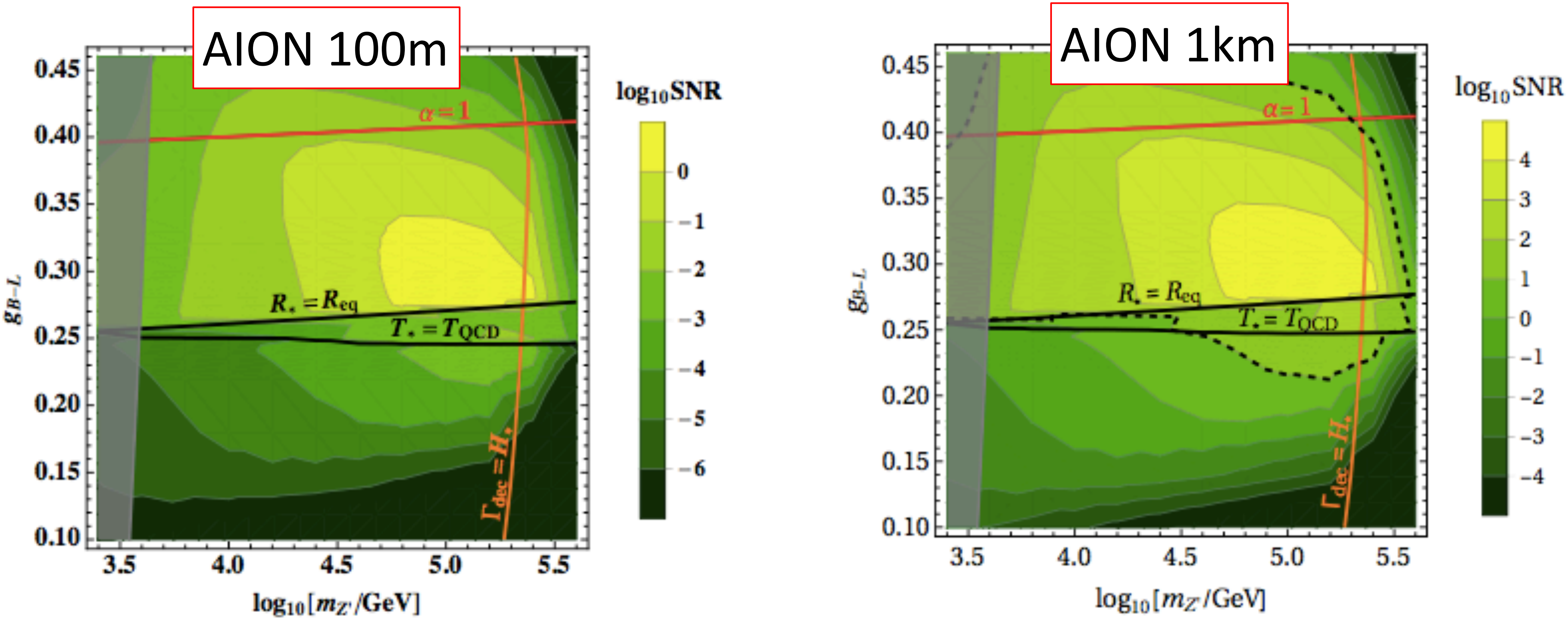
Gravitational Waves from $U(1)_{B-L}$ Phase Transition



T_{reh} = temperature of reheating after transition

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

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



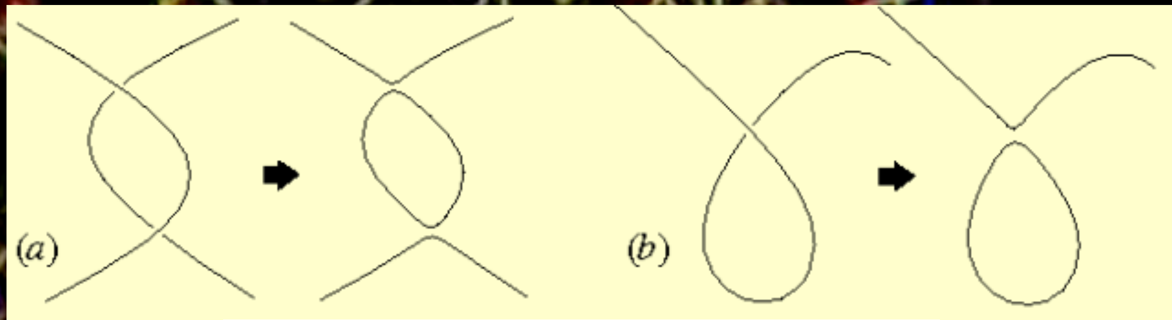
Discovery of GW possible with AION 1km

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

JE, Lewicki, No & Vaskonen, arXiv:1903.09642

Probing Cosmic Strings

Hint from the NANOGrav pulsar timing array?

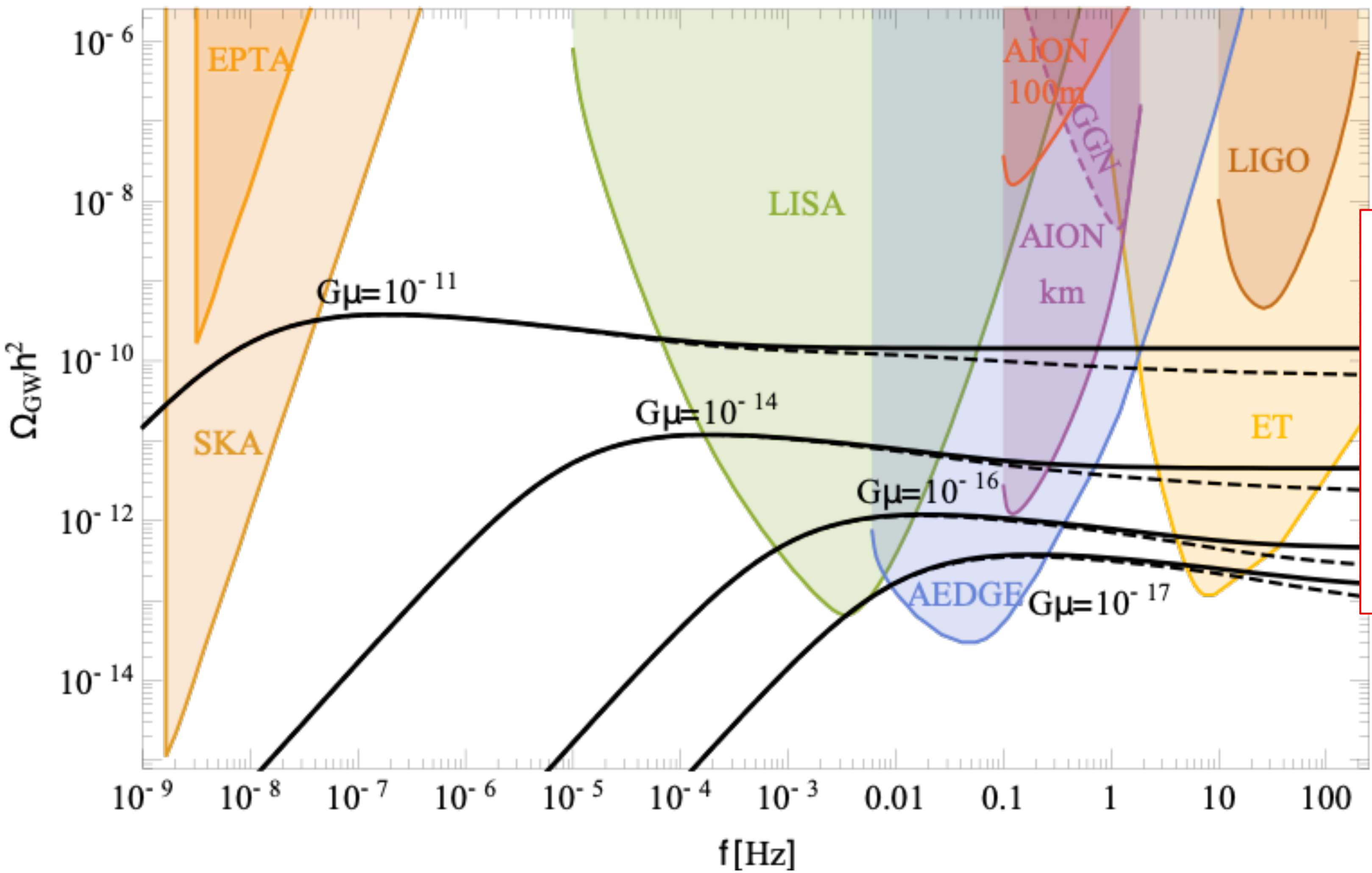


GW emission from string loops

Simulation of cosmic string network – Cambridge cosmology group

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

Gravitational Waves from Cosmic Strings



Effect of change in degrees of freedom In SM

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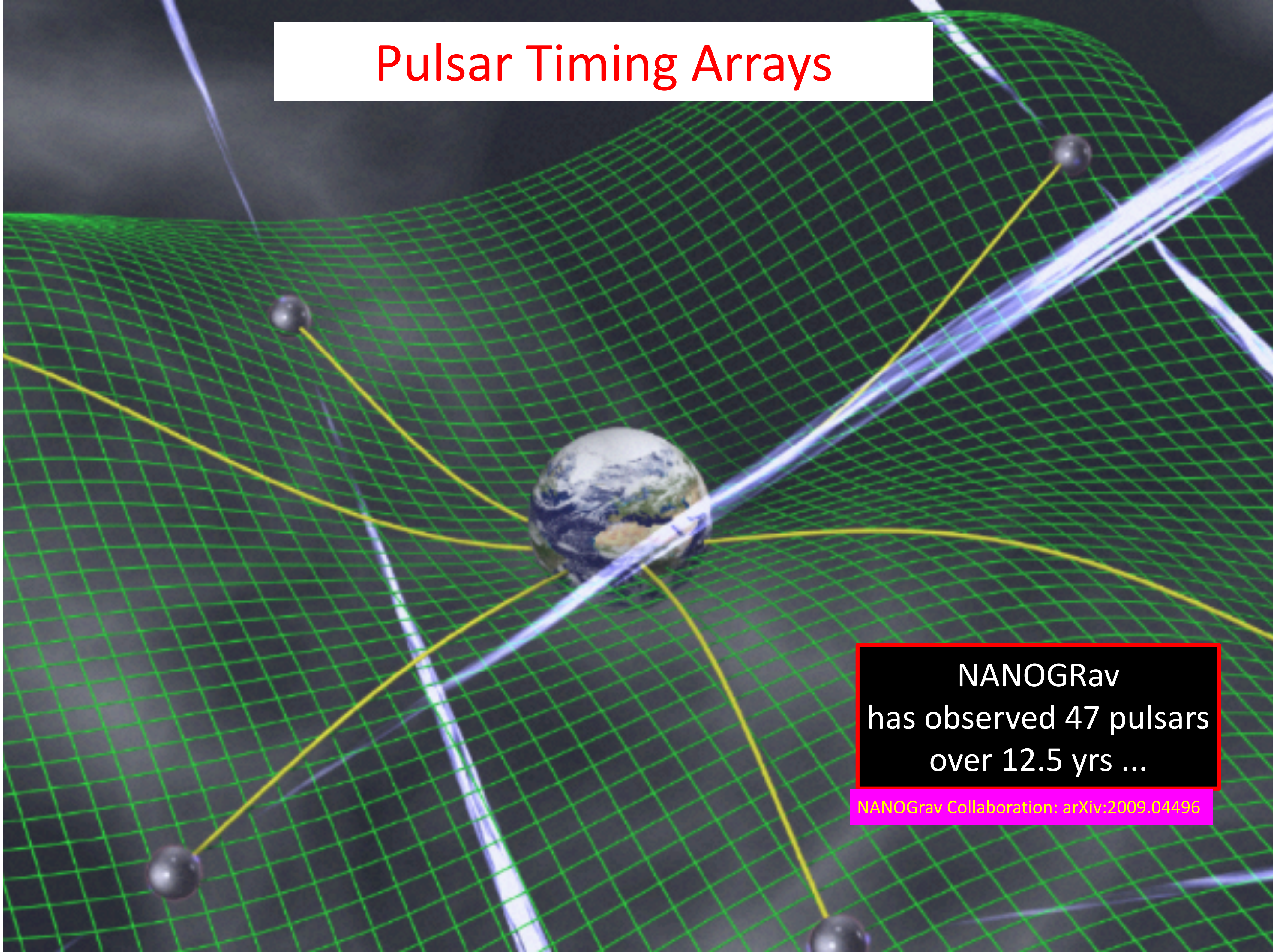
- - -

Spectrum ~ flat from PTA/SKA to LIGO/ET

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

Pulsar Timing Arrays



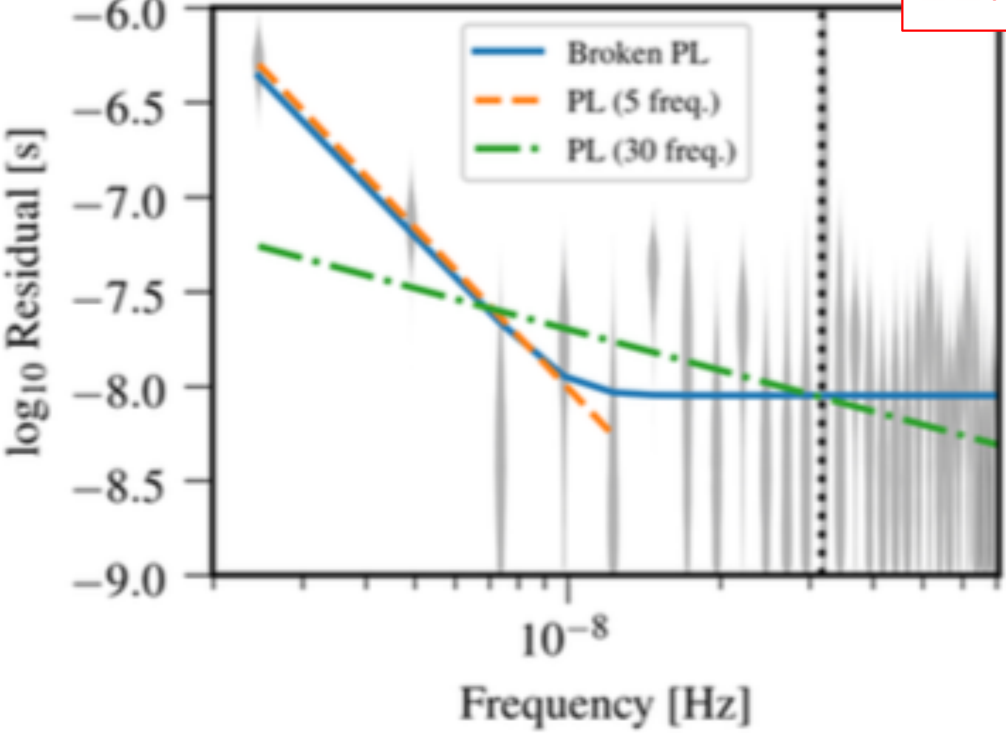
NANOGRav
has observed 47 pulsars
over 12.5 yrs ...

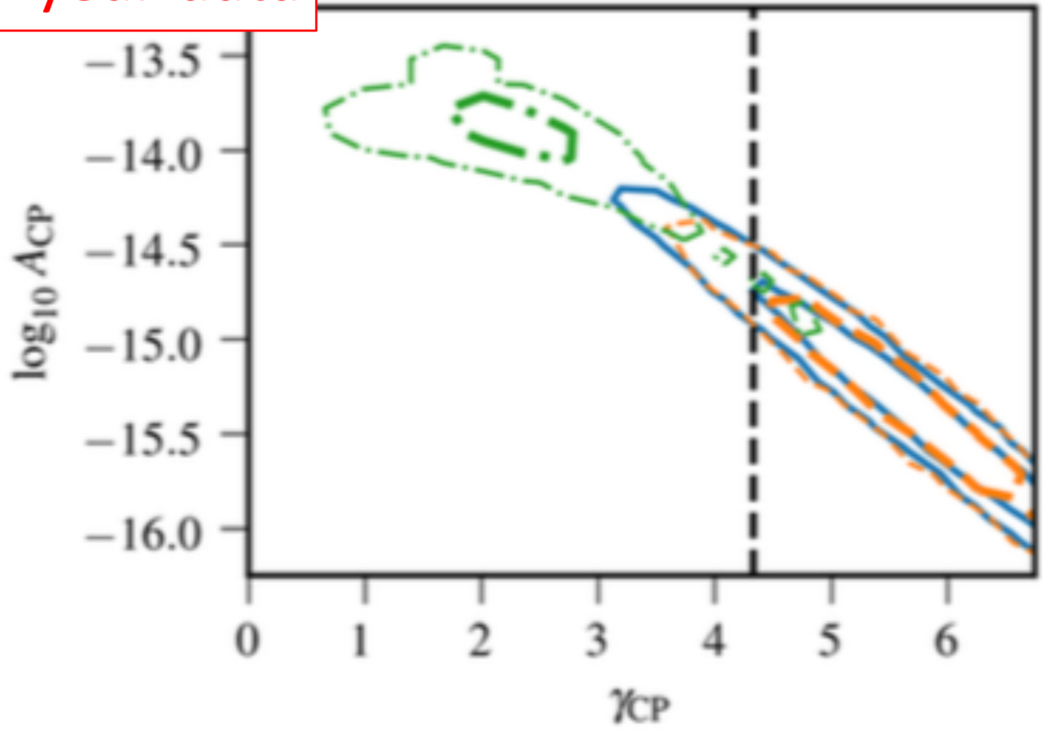
NANOGrav Collaboration: arXiv:2009.04496

NANOGrav Collaboration: arXiv:2009.04496

Pulsar Timing Data from NANOGrav

12.5-year data





NANOGrav reports
"strong evidence for a stochastic common-spectrum process"
at frequencies < 10^{-8} Hz
No dipole or quadrupole signal detected

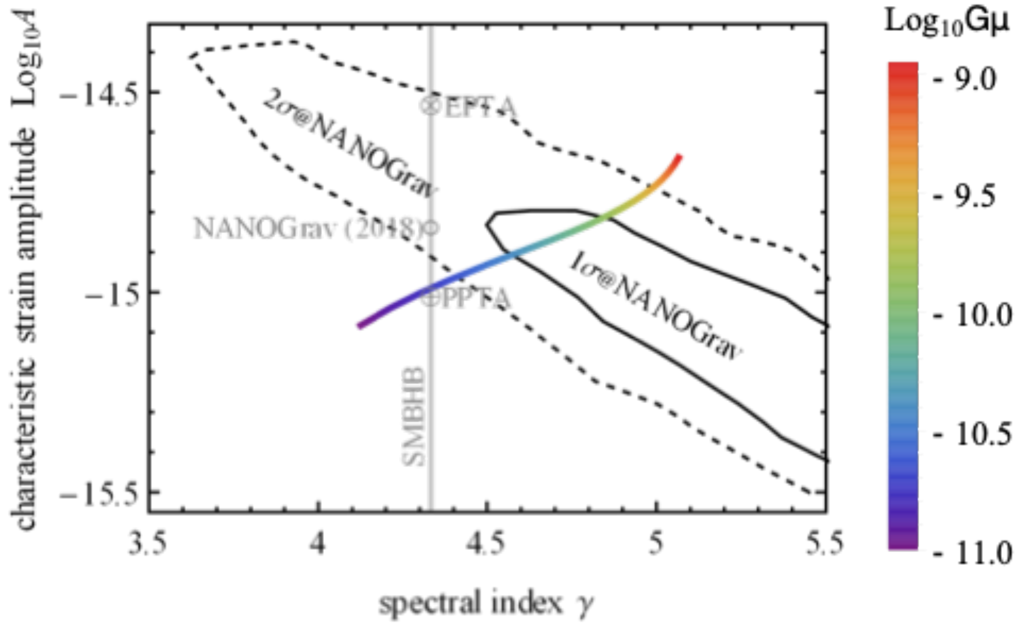
Fits to amplitude of signal
Focus on simple power law
Amplitude A ~ 10^{-15}
Slope γ ~ 5

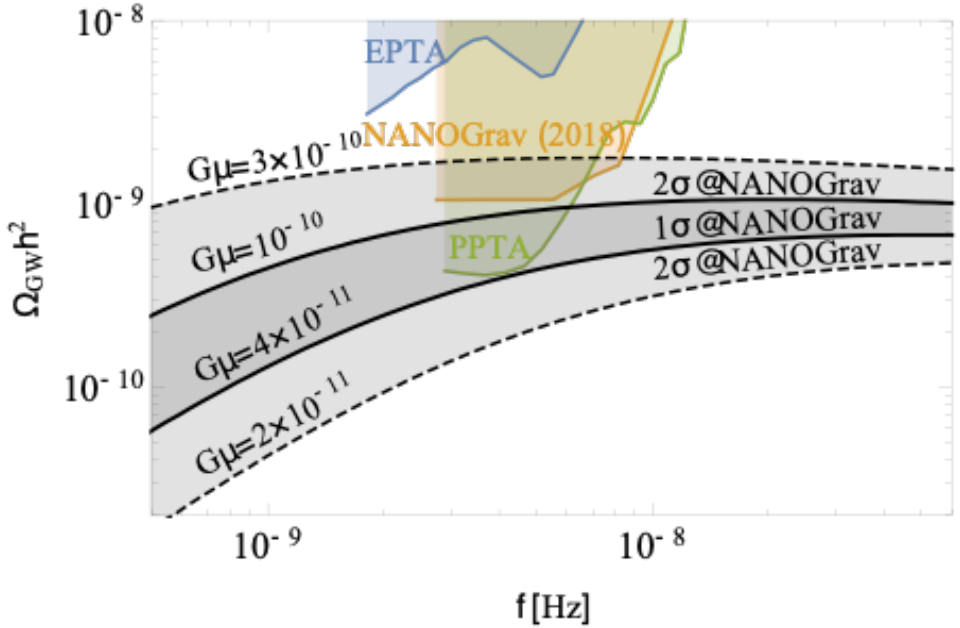
Default model

Vertical dashed line: simple model of mergers of supermassive BHs

JE & Lewicki: arXiv:2009.06555

Cosmic String Interpretation of NANOGrav



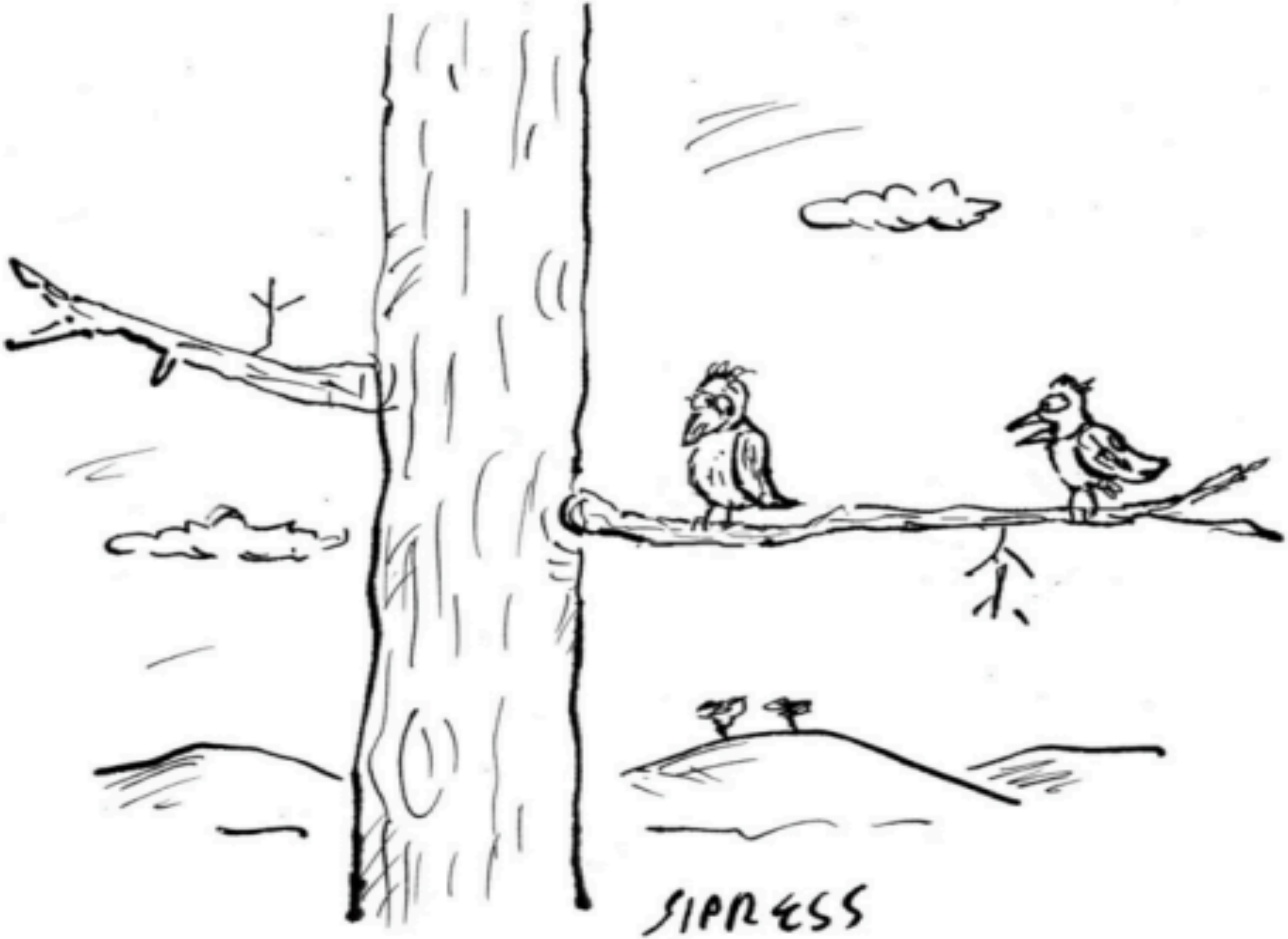


"Rainbow curve"
is cosmic string prediction as a
function of the cosmic string tension Gμ
Vertical line is naïve SMBH merger prediction
Previous PTA upper limits for
this value of γ

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

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
- AION offers a programme for exploring deci-Hz GW based on atom interferometry (IMBHs, 1st-order phase transitions, …)
- AEDGE is a concept for a space mission that would complement, and have synergies with, other future GW experiments
- Hint of cosmic strings from NANOGrav pulsar timing array?
- Atom interferometry could also explore the nature of DM
- Other possible opportunities in fundamental physics, astrophysics and cosmology have been identified, but not yet explored in detail
- **Unique interdisciplinary science!**



Was that you I heard just now, or was it two black holes colliding?