Fundamental Physics from Gravitational Waves

The GW spectrum
From LIGO to supermassive black holes (LISA)
Atom interferometers (AION, AEDGE)
GW propagation: graviton mass, Lorentz violation?
GWs from first-order phase transitions
GWs from cosmic strings
Interpreting GW hint from NANOGrav PTA

John Ellis
KING'S College LONDON

Gravitational Waves

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

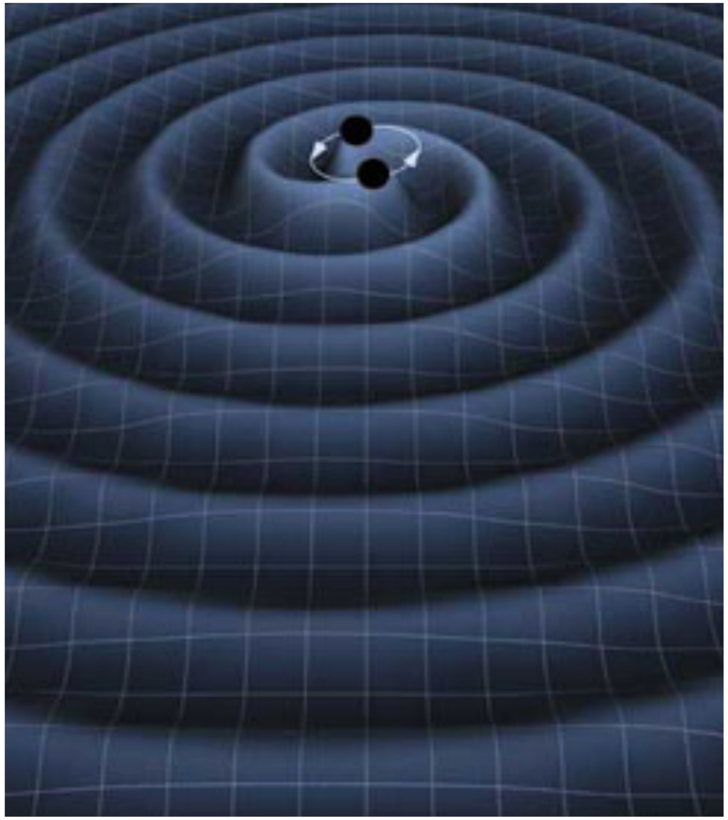
Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

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

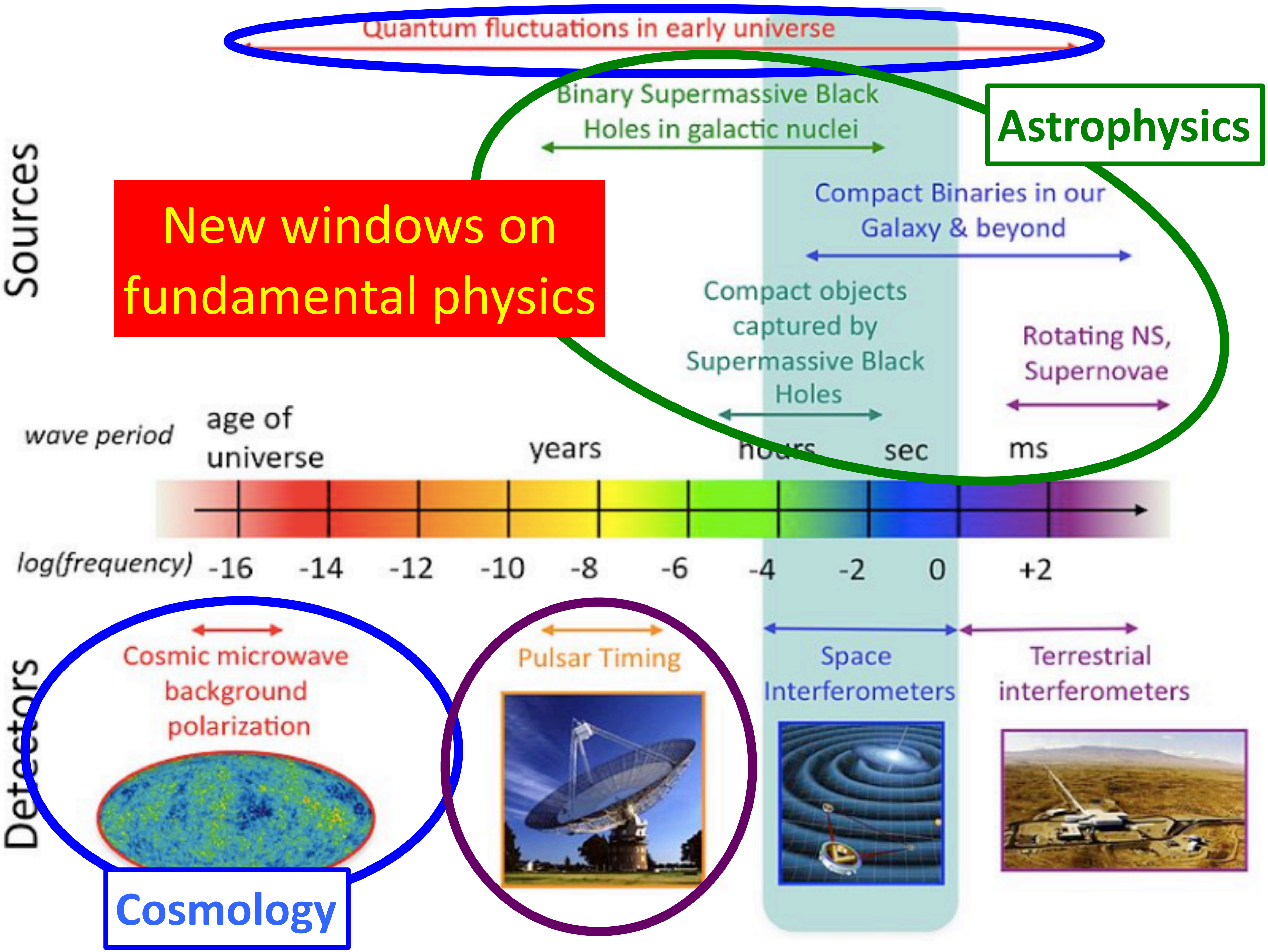
$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu}$$

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



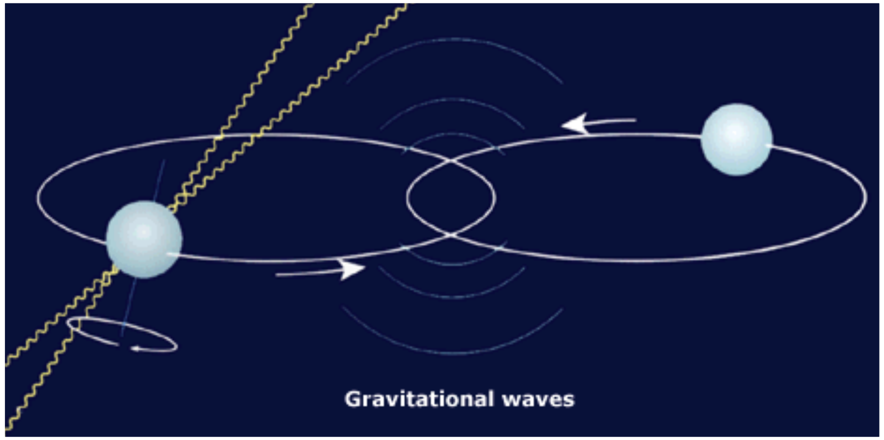
- Tried to retract prediction in 1936!

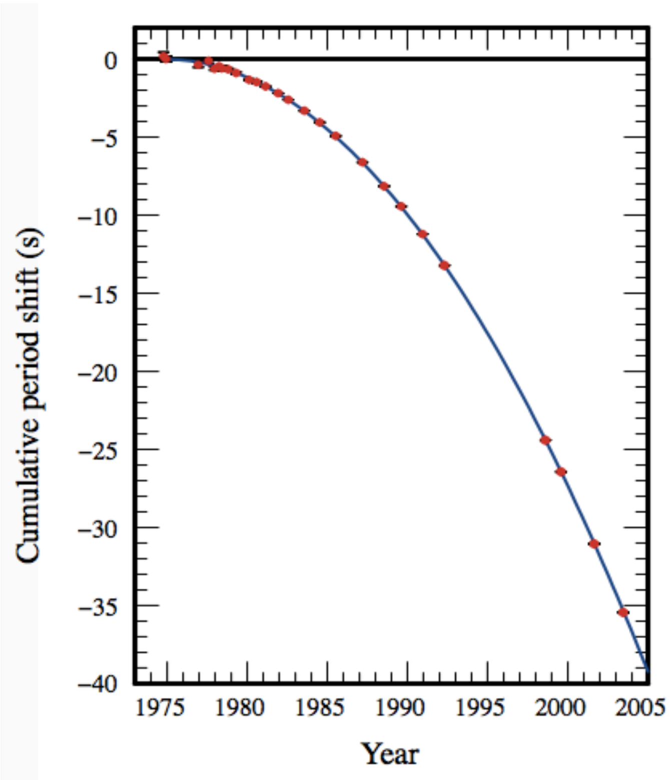
Gravitational Wave Spectrum



Indirect Detection

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





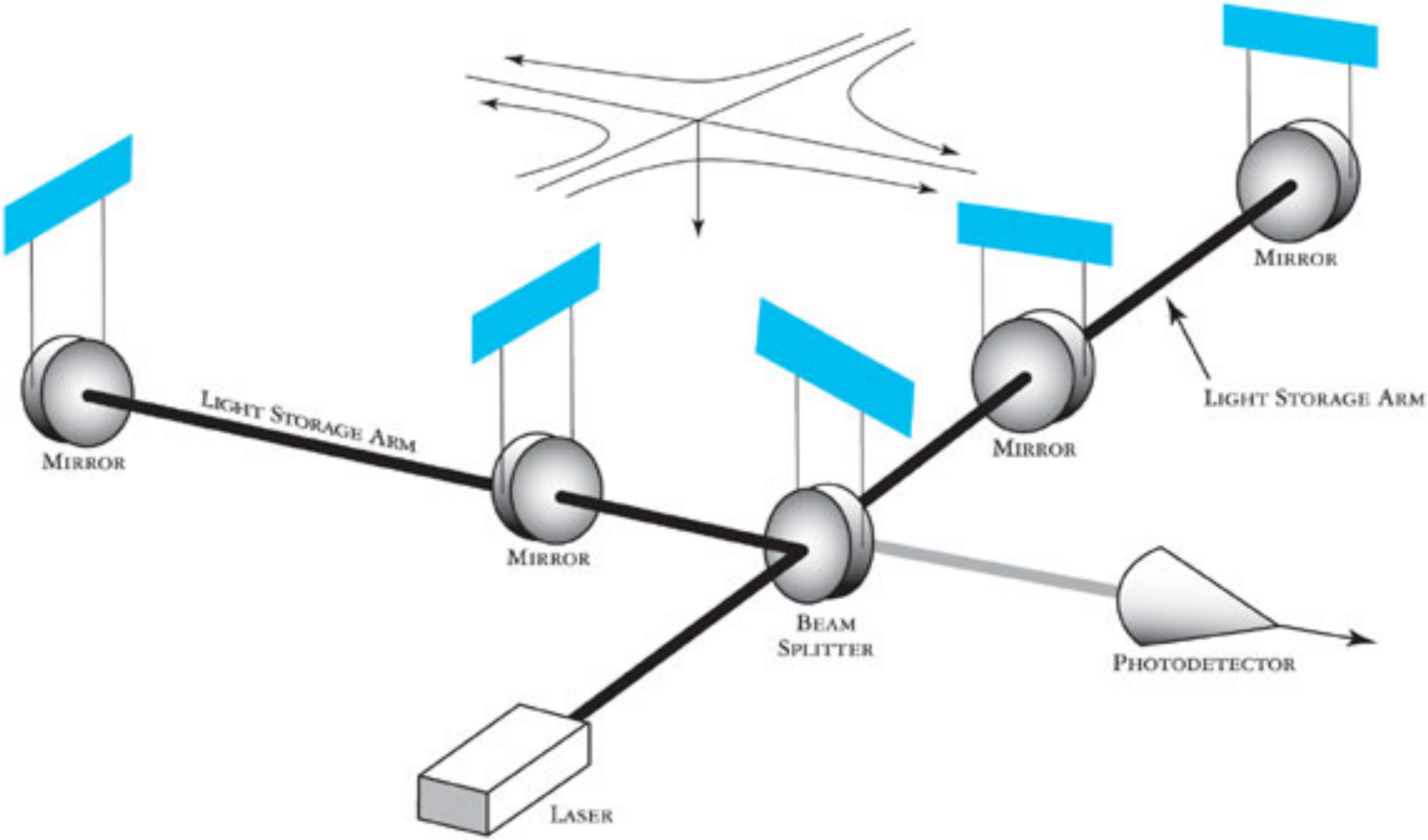
for years

agreement with Einstein

Nobel Prize 1993

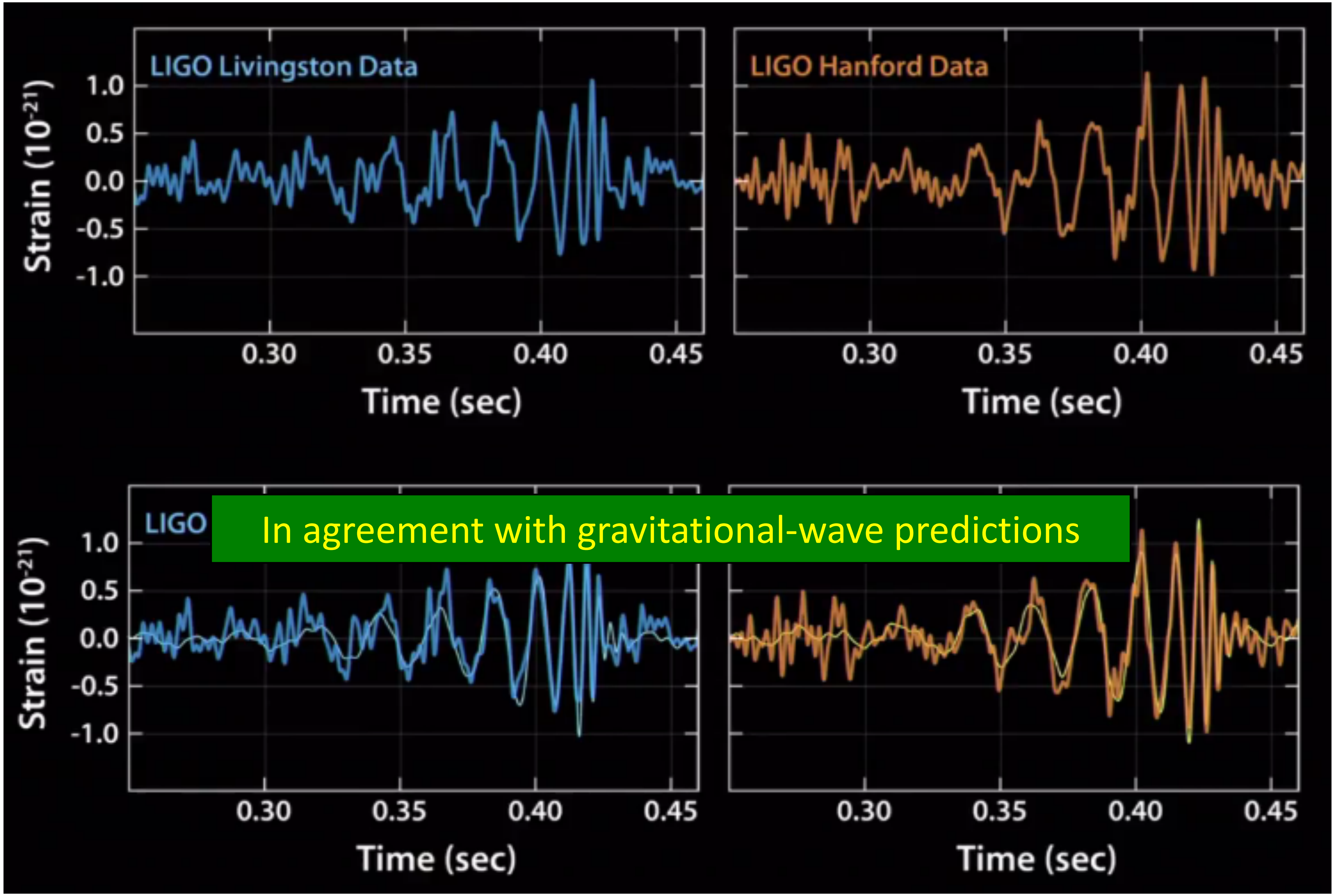
LIGO experiment

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

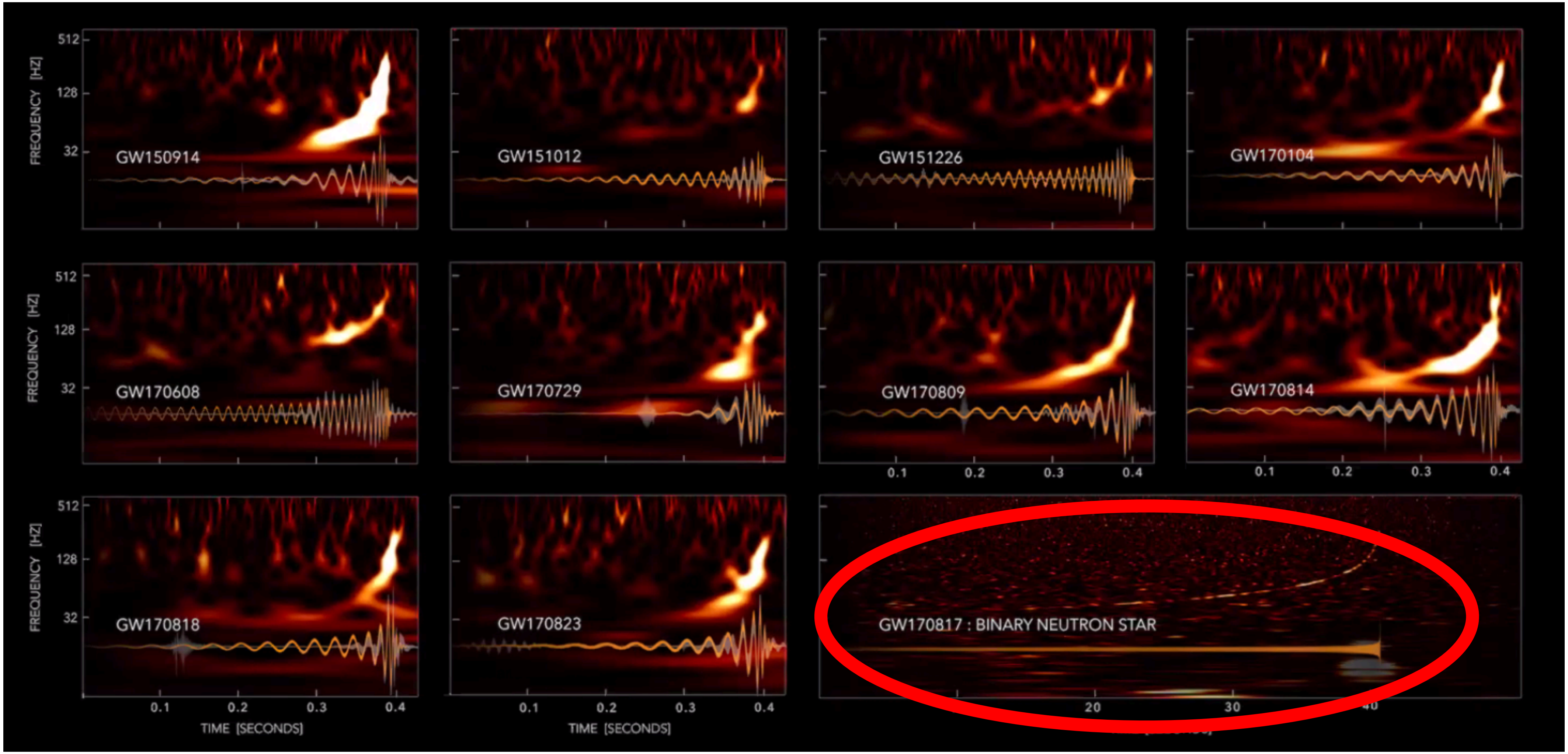


What was observed

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



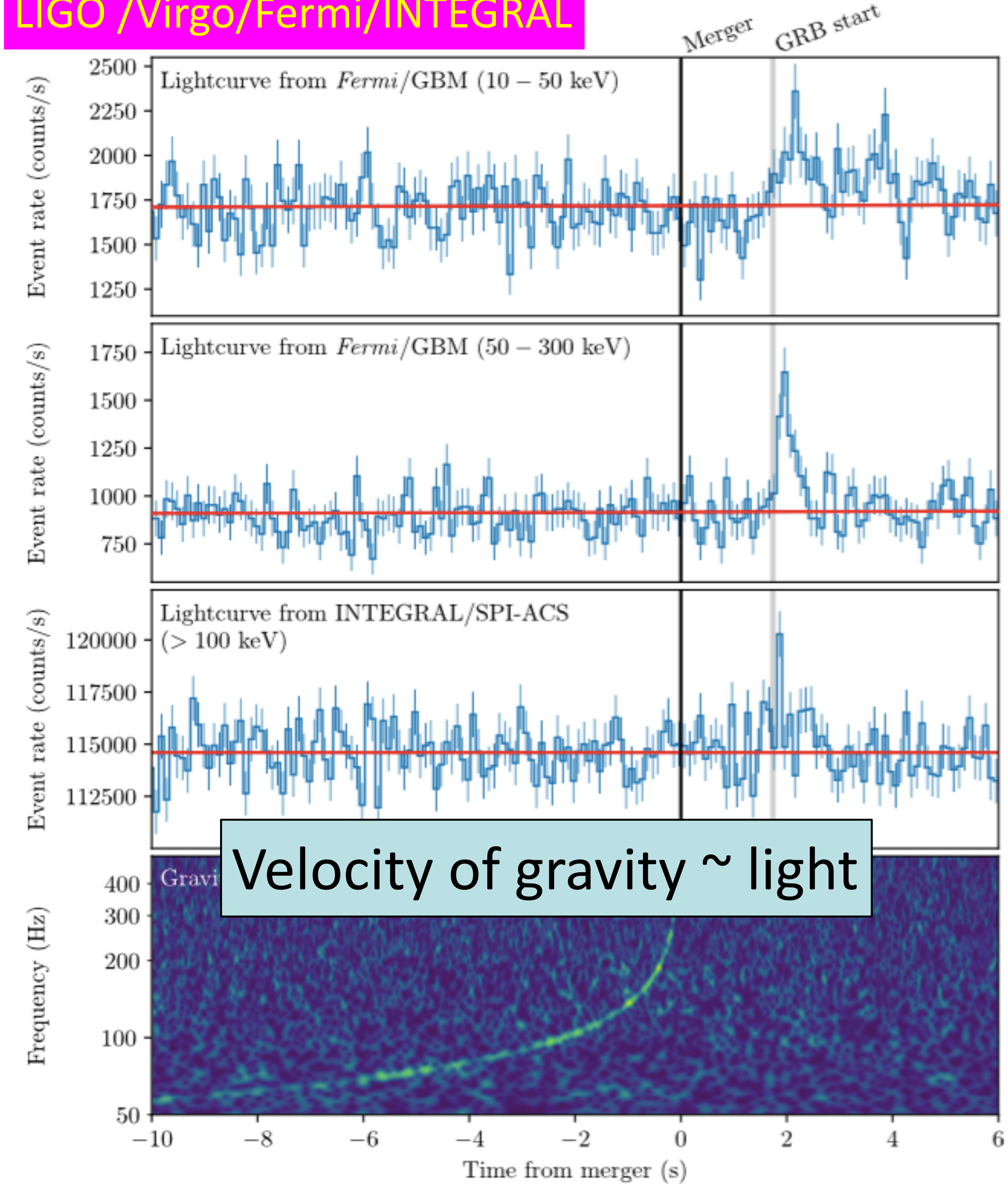
Mergers Measured in First LIGO/Virgo Observation Period



Binary neutron star merger: electromagnetic counterpart

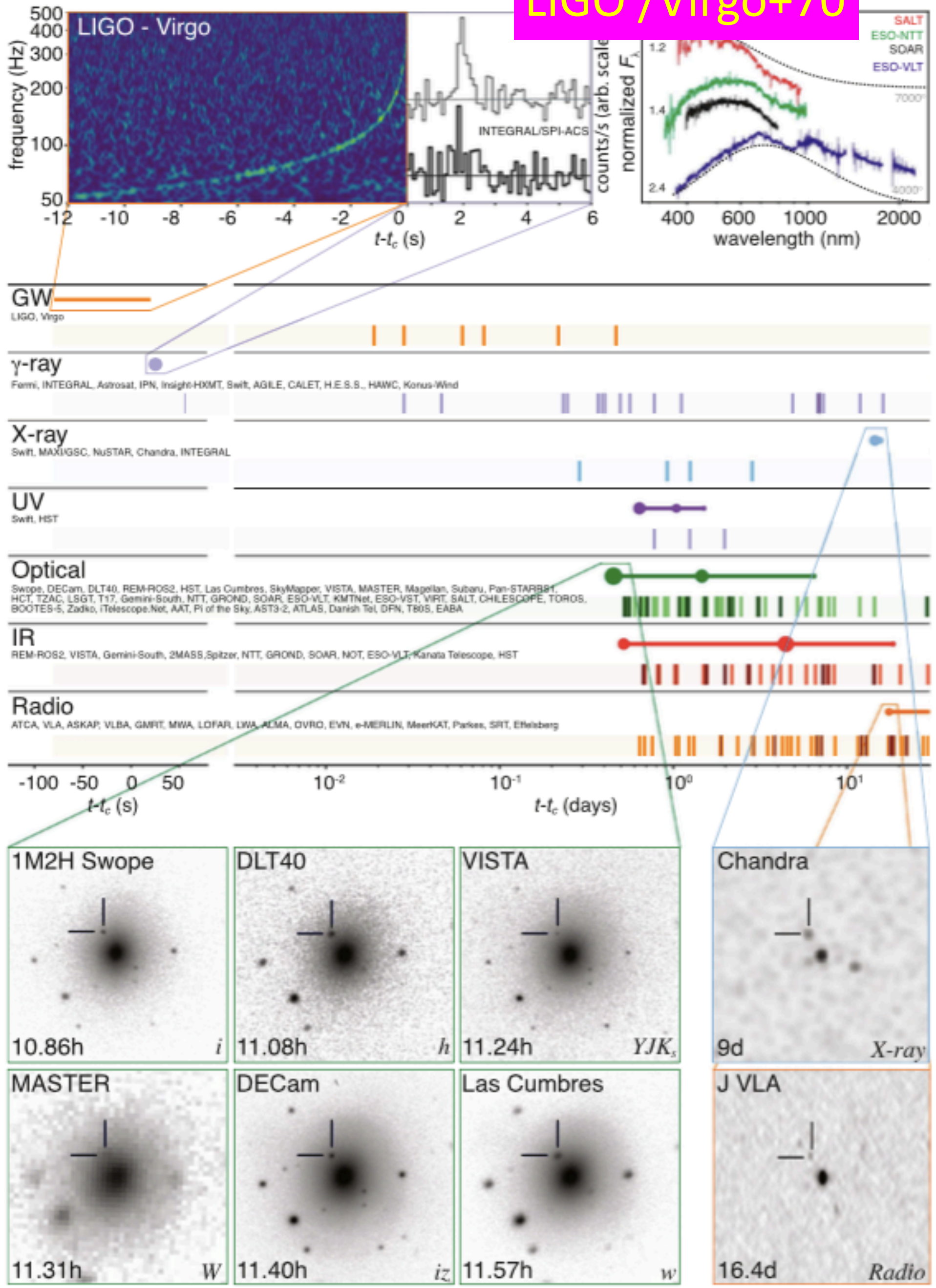
Observations of Neutron Star Merger

LIGO /Virgo/Fermi/INTEGRAL

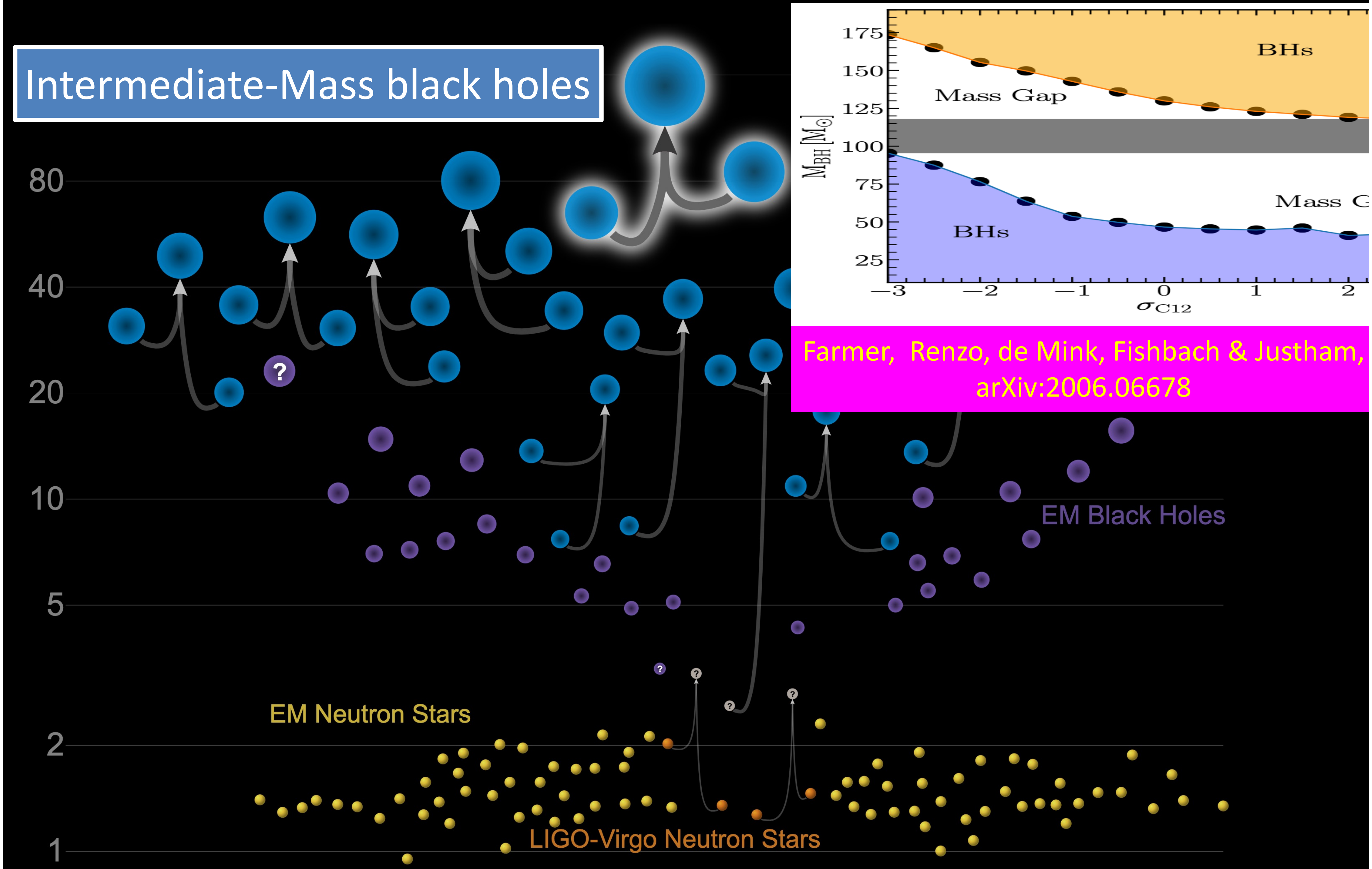


Velocity of gravity ~ light

LIGO /Virgo+70



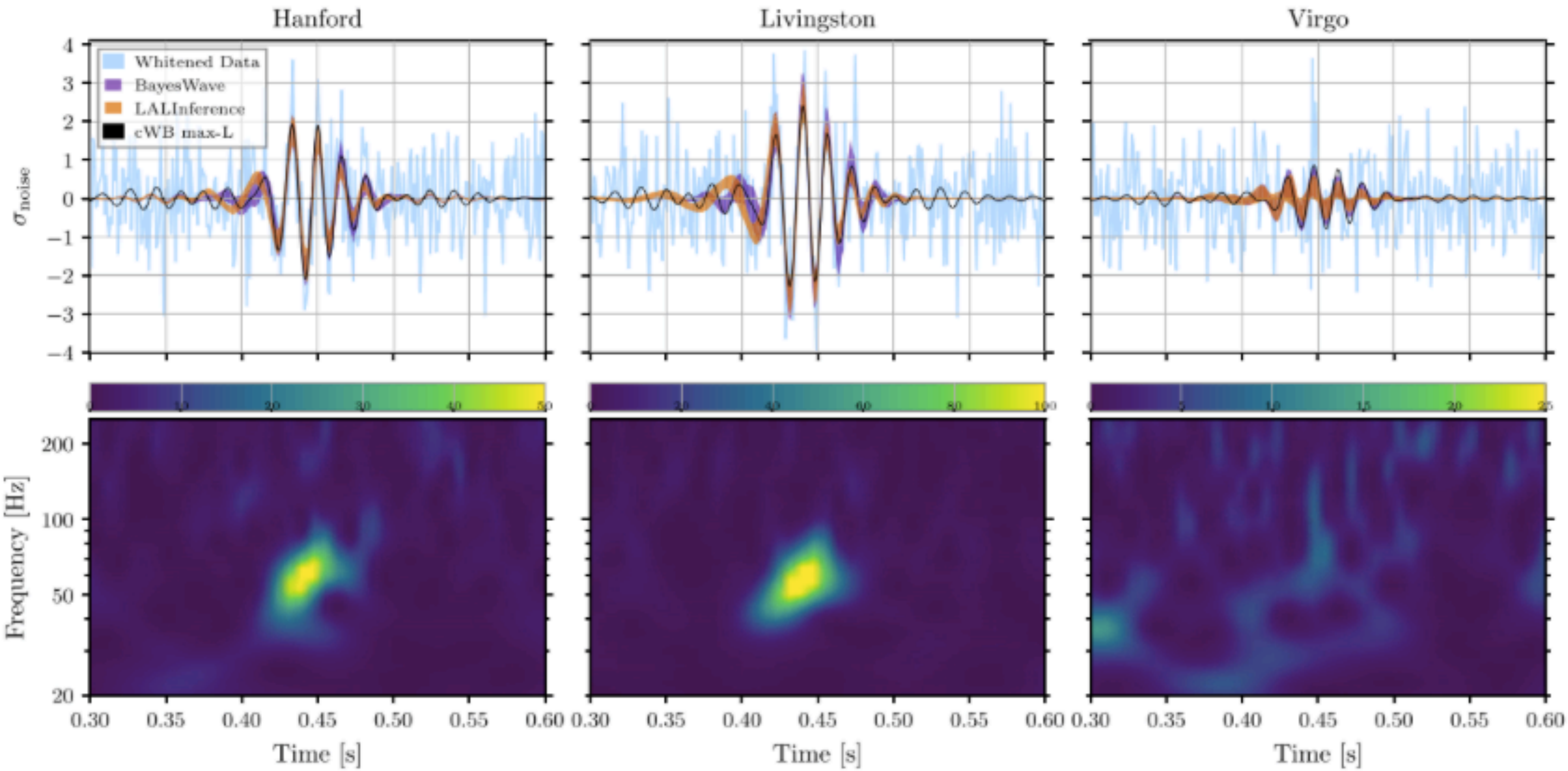
LIGO-Virgo Black Hole & Neutron Star Masses



Farmer, Renzo, de Mink, Fishbach & Justham, arXiv:2006.06678

LIGO & Virgo Collaborations: arXiv:2009.01075, 01190

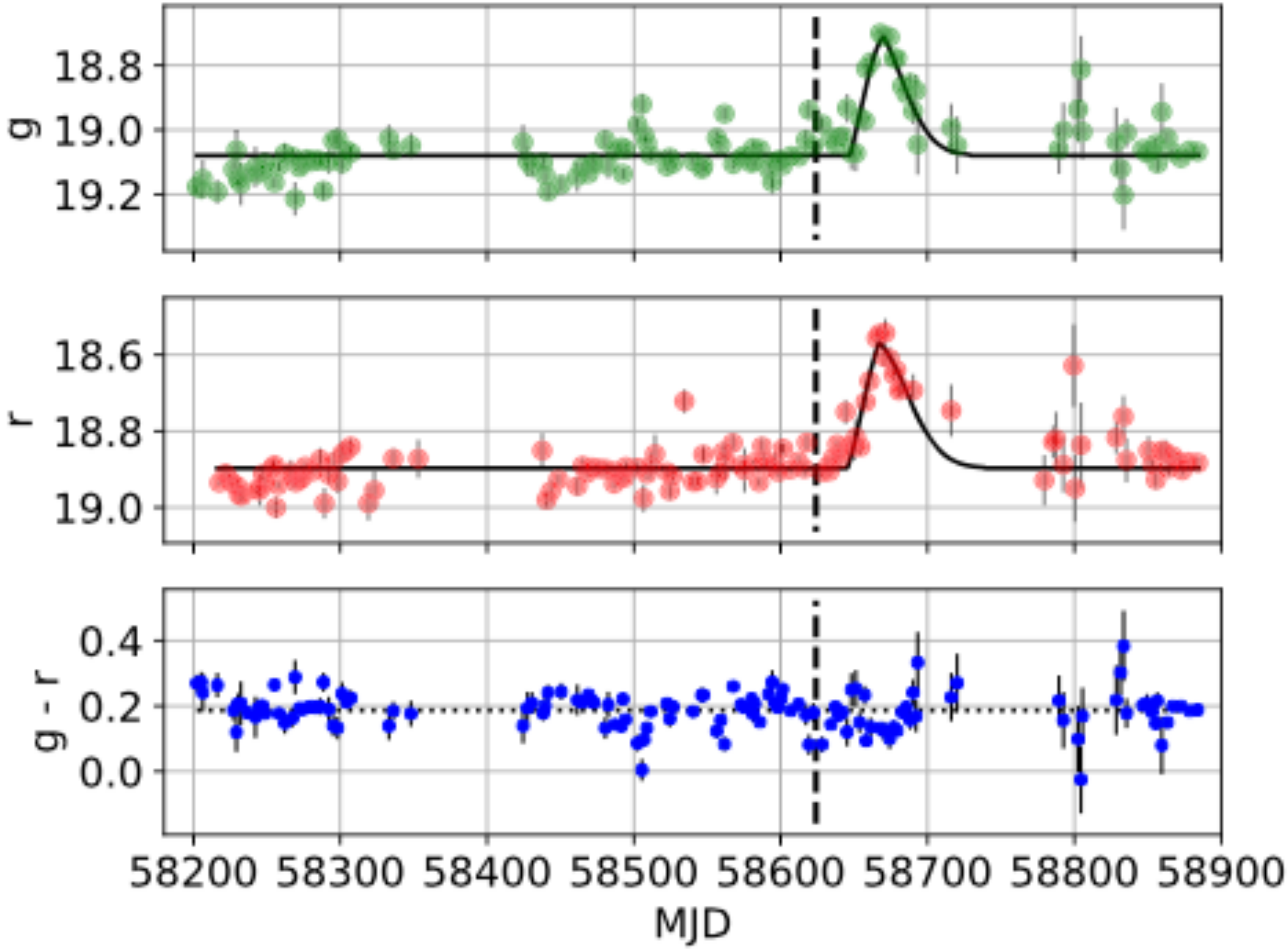
GW190521 – a Bang not a Chirp



Triple measurement of merger of heaviest black holes seen so far

Graham et al.: arXiv:2006.14122

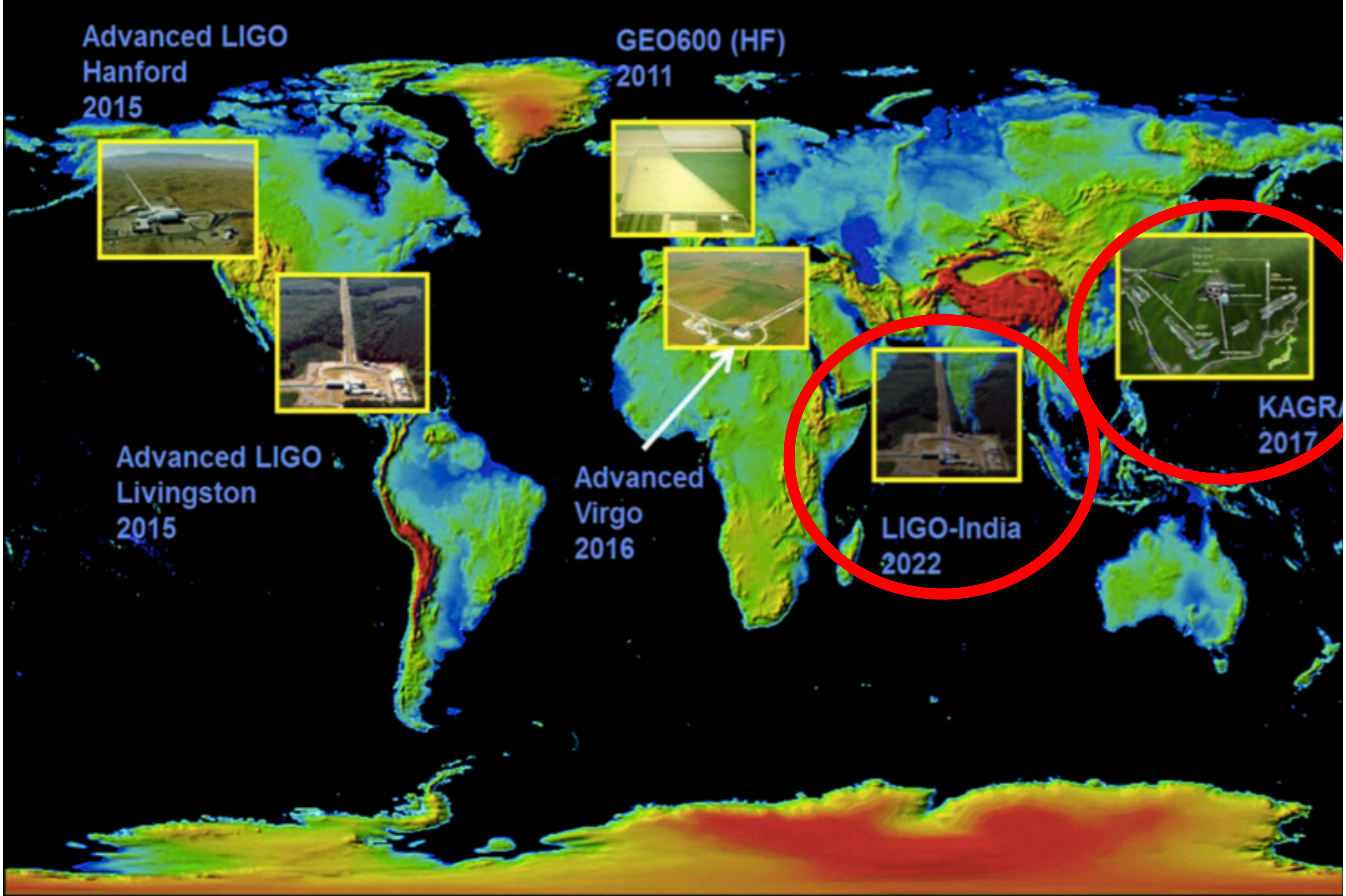
Optical Counterpart?



Optical flash detected with Zwicky Transient Facility

Due to “shake-up” of gas clouds in AGN accretion disk by GW emission?

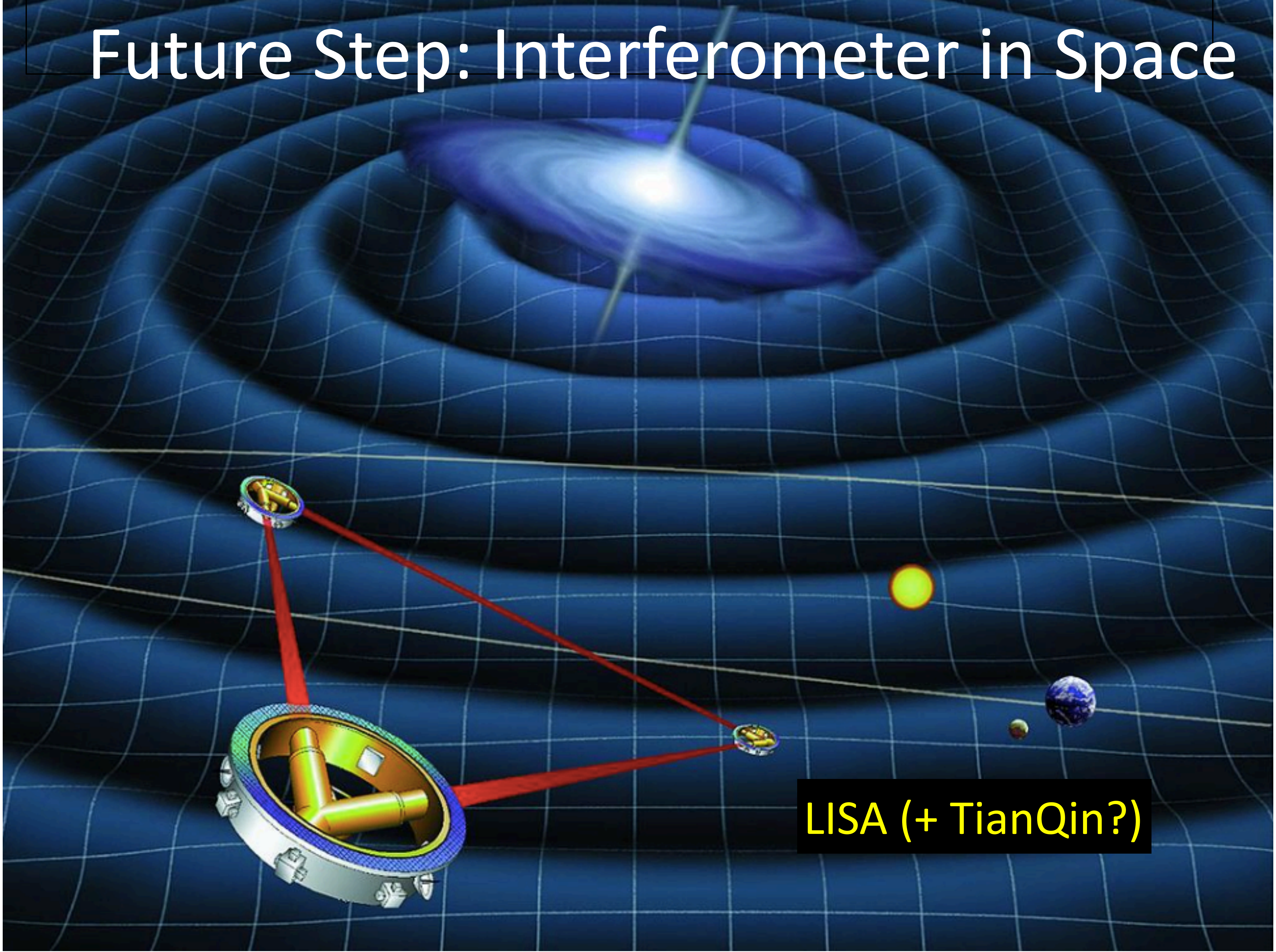
Ground-Based GW Detectors



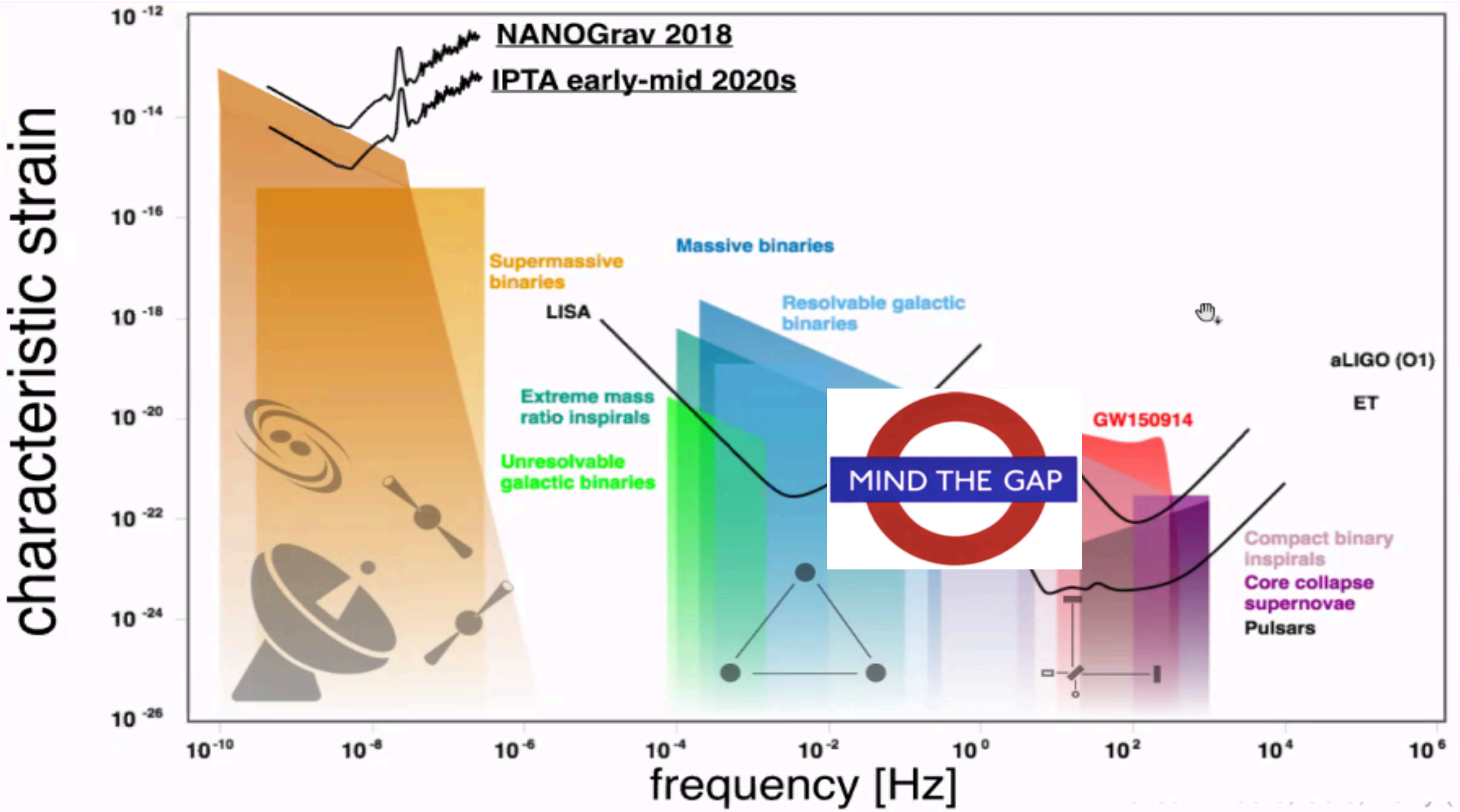
Supermassive Black Holes

M87: mass ~ 6.5×10^9 solar masses

Future Step: Interferometer in Space



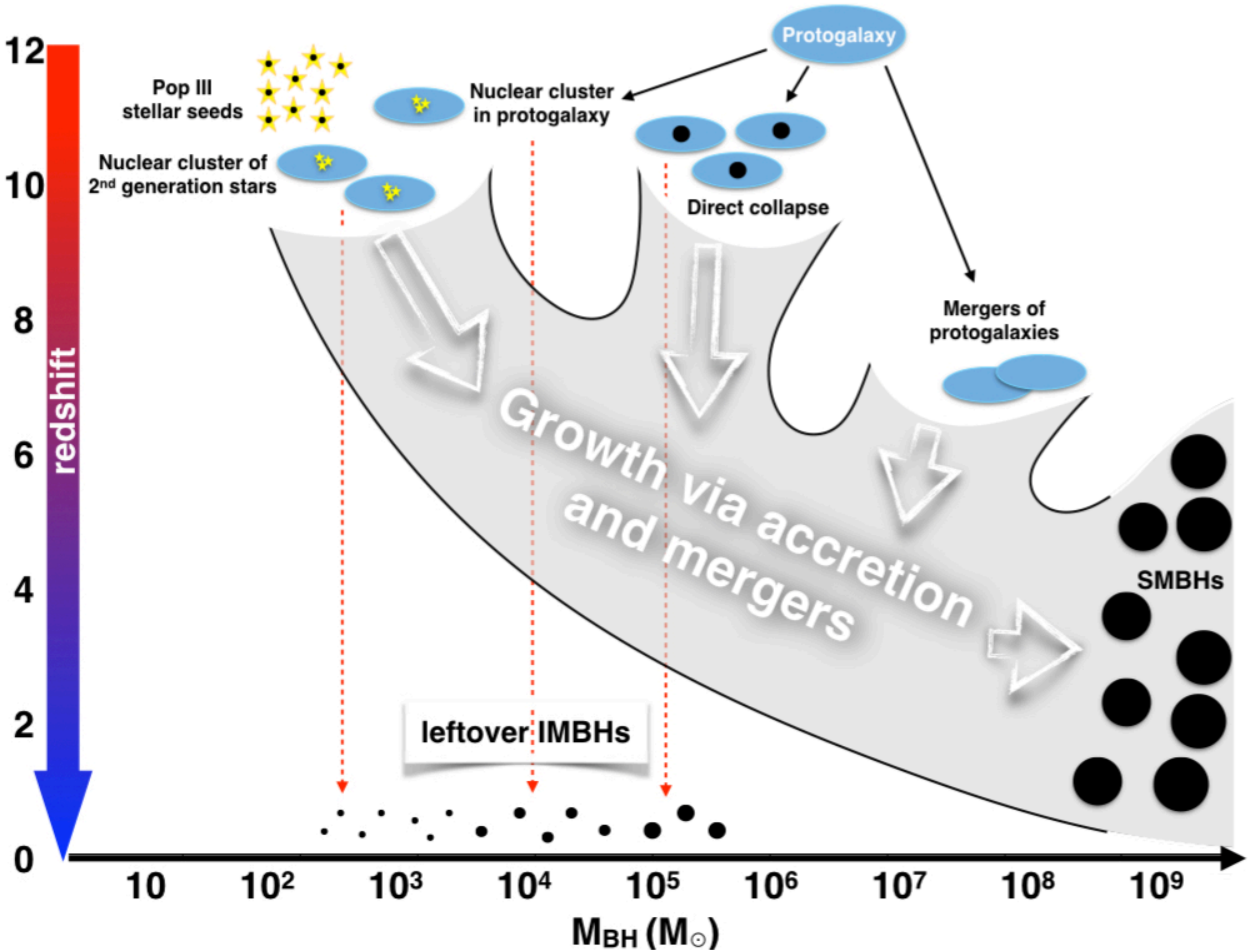
Gravitational Wave Spectrum



- 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)

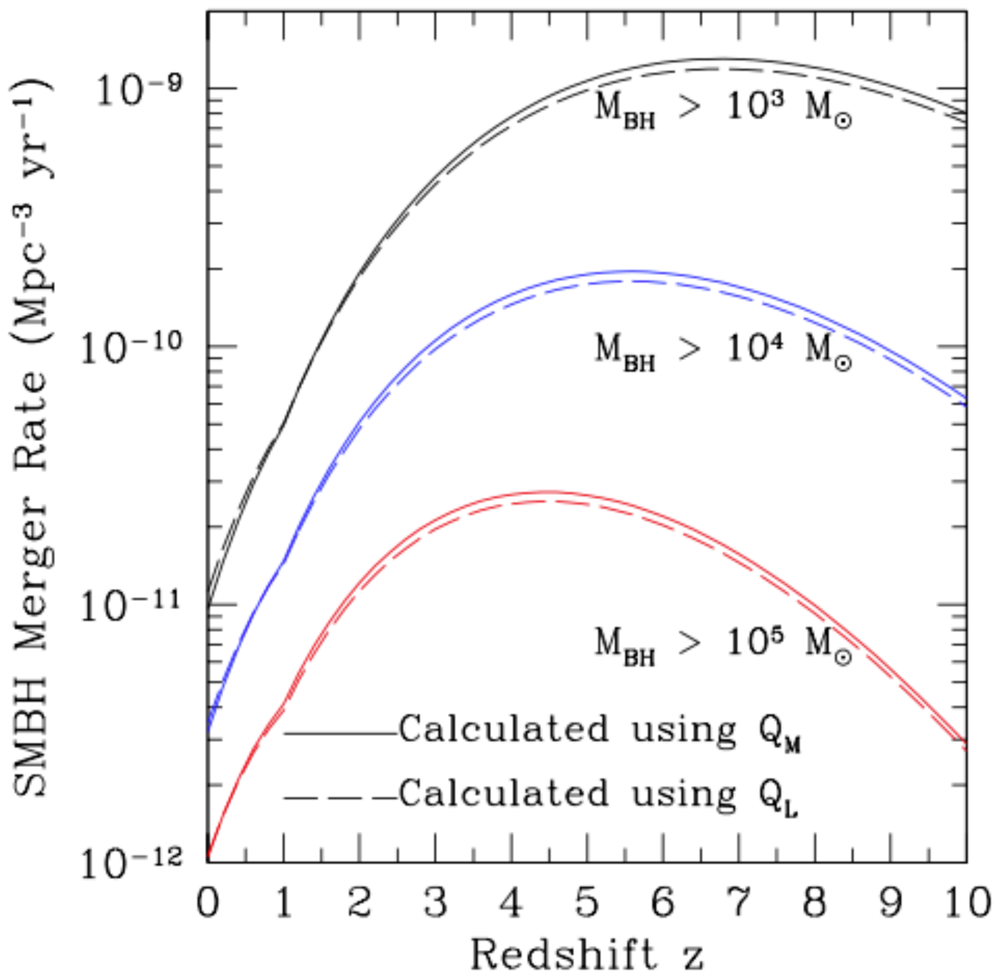
How to Make a Supermassive BH?

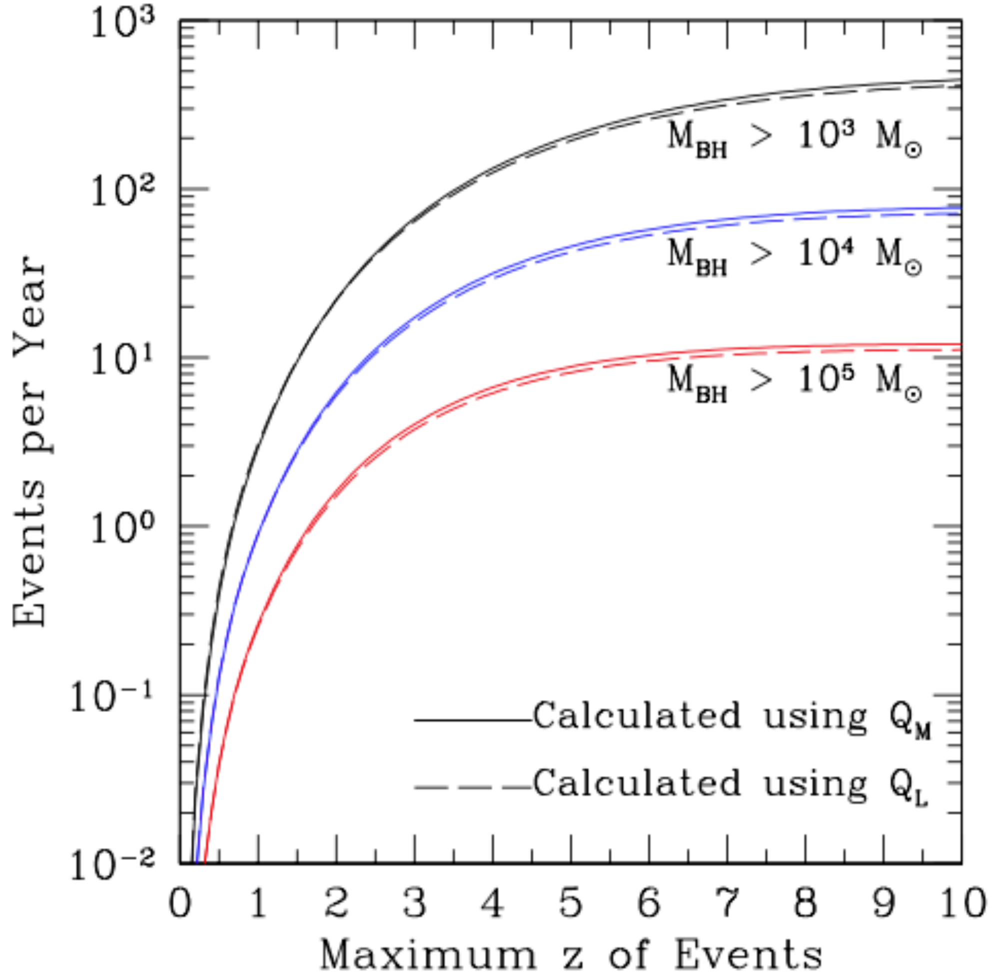
SMBHs from mergers of intermediate-mass BHs (IMBHs)?



How to Make a Supermassive BH?

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

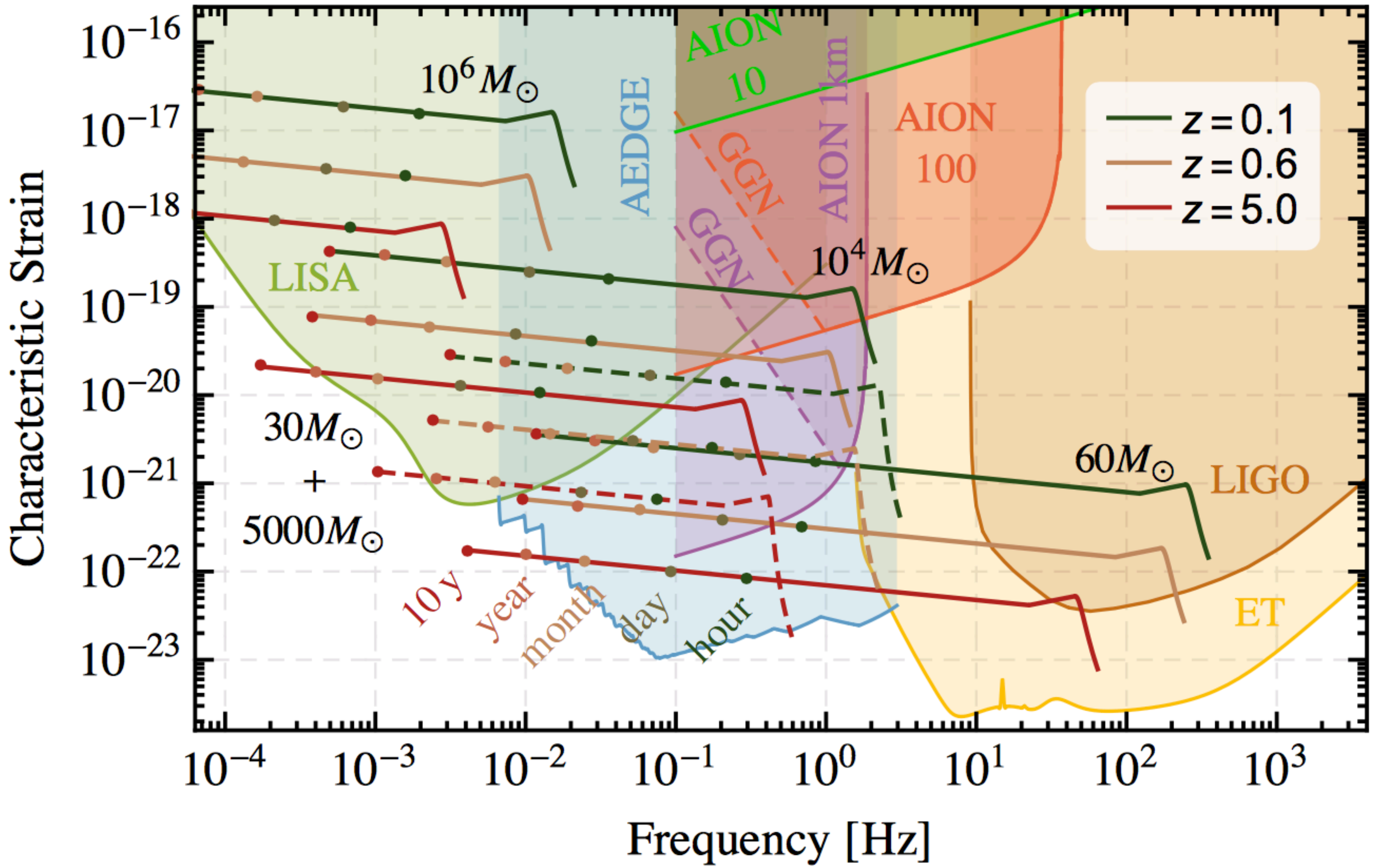




Erickcek, Kamionkowski & Benson, astro-ph/0604281

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

Gravitational Waves from IMBH Mergers



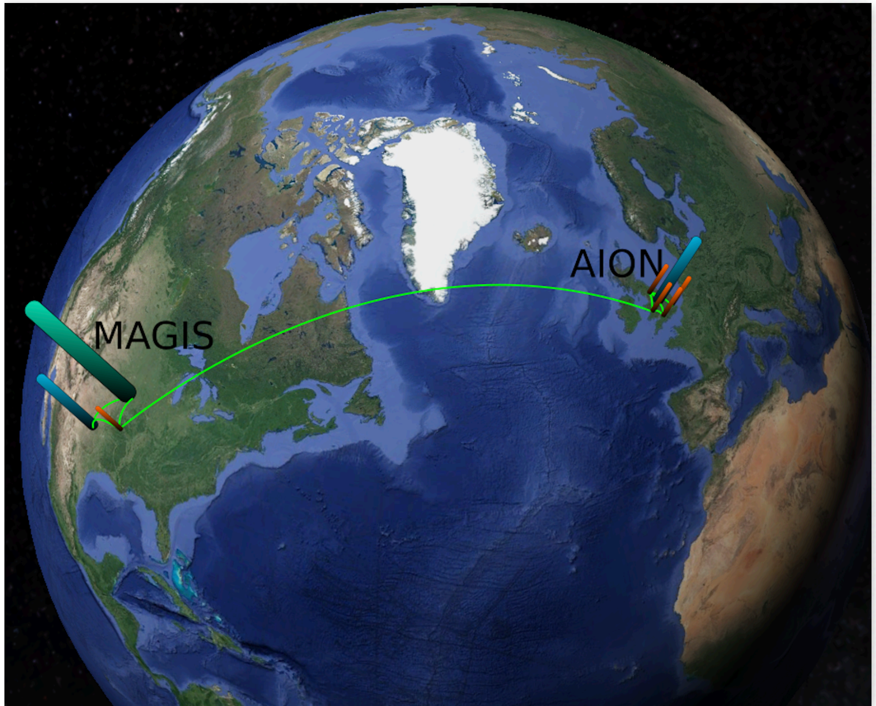
Probe formation of SMBHs

Synergies between GW experiments (LIGO, AION, LISA), test GR

AION Collaboration

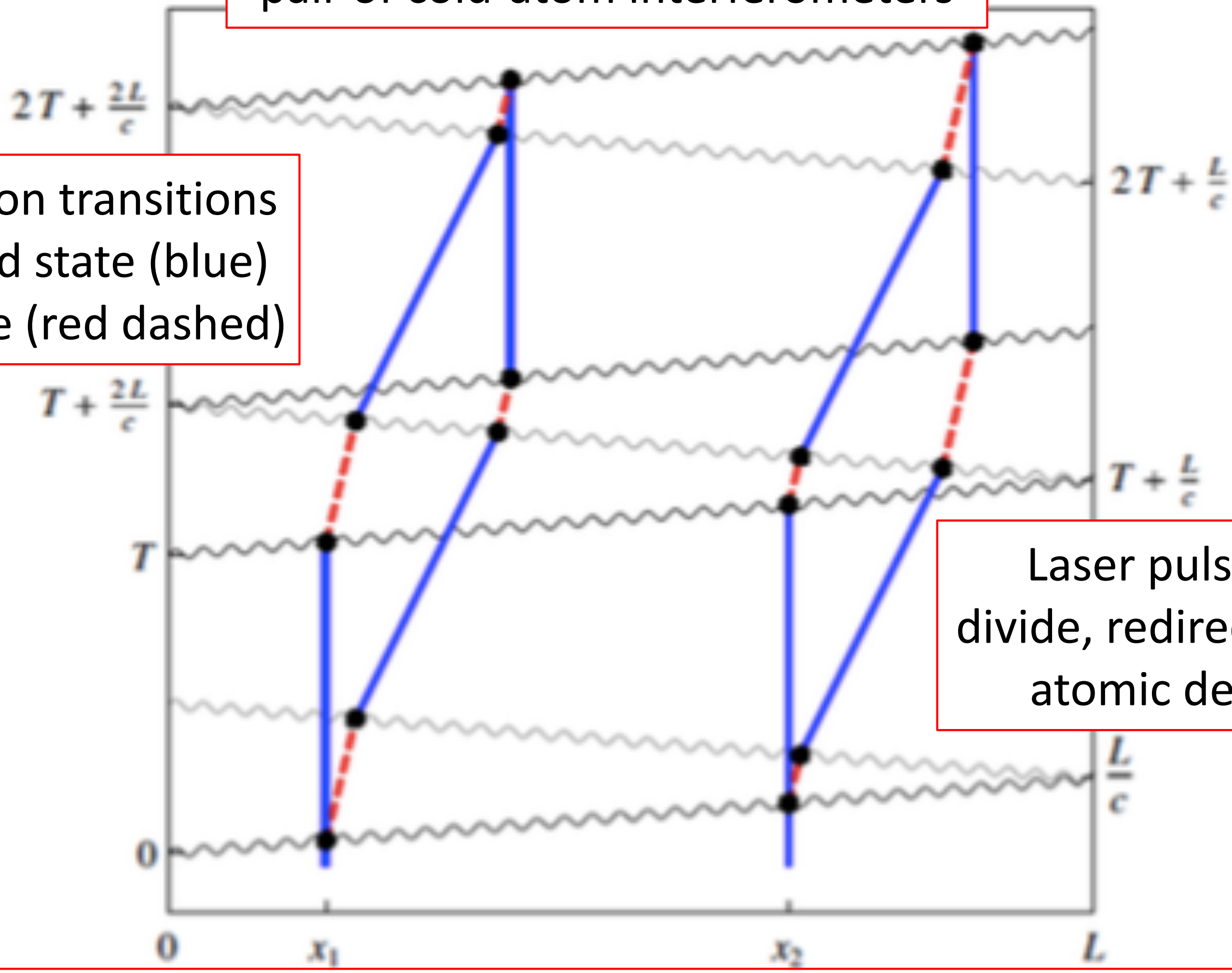
L. Badurina[1], S. Balashov[2], E. Bentine[3], D. Blas[1], J. Boehm[2], K. Bongs[4], D. Bortoletto[3], T. Bowcock[5], W. Bowden[6,*], C. Brew[2], O. Buchmueller[6], J. Coleman[5], G. Elertas, J. Ellis[1,&], C. Foot[3], V. Gibson[7], M. Haehnelt[7], T. Harte[7], R. Hobson[6,*], M. Holynski, A. Khazov[2],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

AION – Staged Programme

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

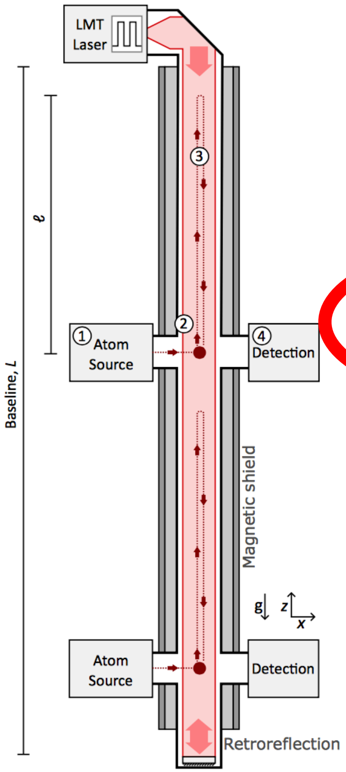
Initial funding from UK STFC

- 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

AION Design Parameters

Table 1. *List of basic parameters: length of the detector L; interrogation time of the atom interferometer T_{int}; phase noise $\delta\phi_{\text{noise}}$; 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]	$\delta\phi_{\text{noise}}$ $[1/\sqrt{\text{Hz}}]$	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

Initial targets and final goals

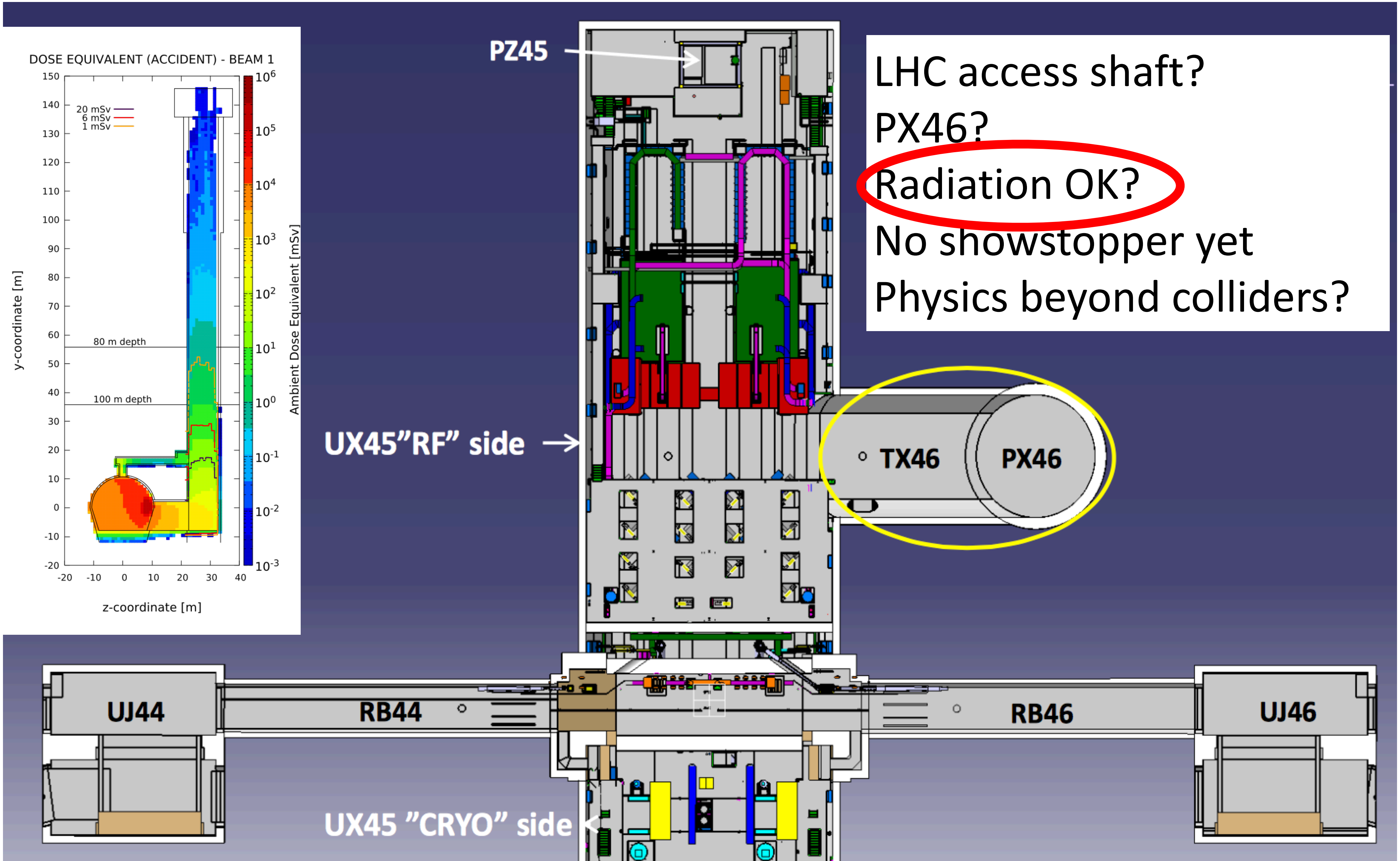
AION Collaboration (Badurina, ..., JE et al): arXiv:1911.11755

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 in UK … or CERN?



LHC access shaft?

PX46?

Radiation OK?

No showstopper yet

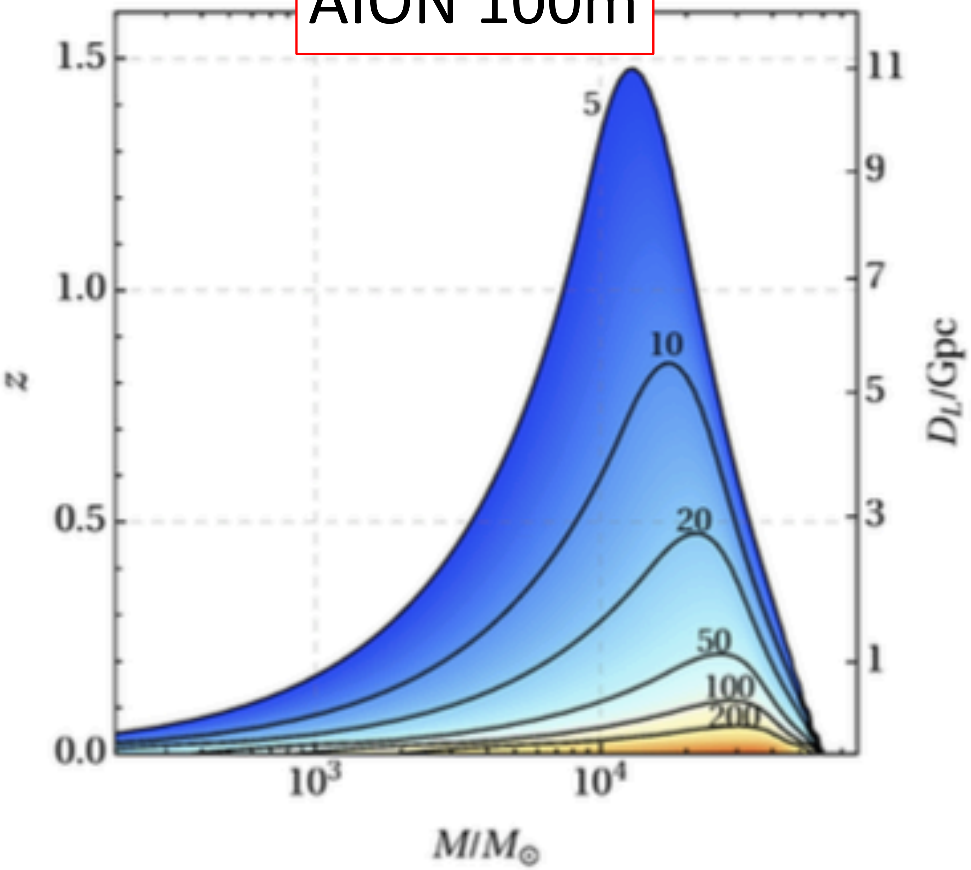
Physics beyond colliders?

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

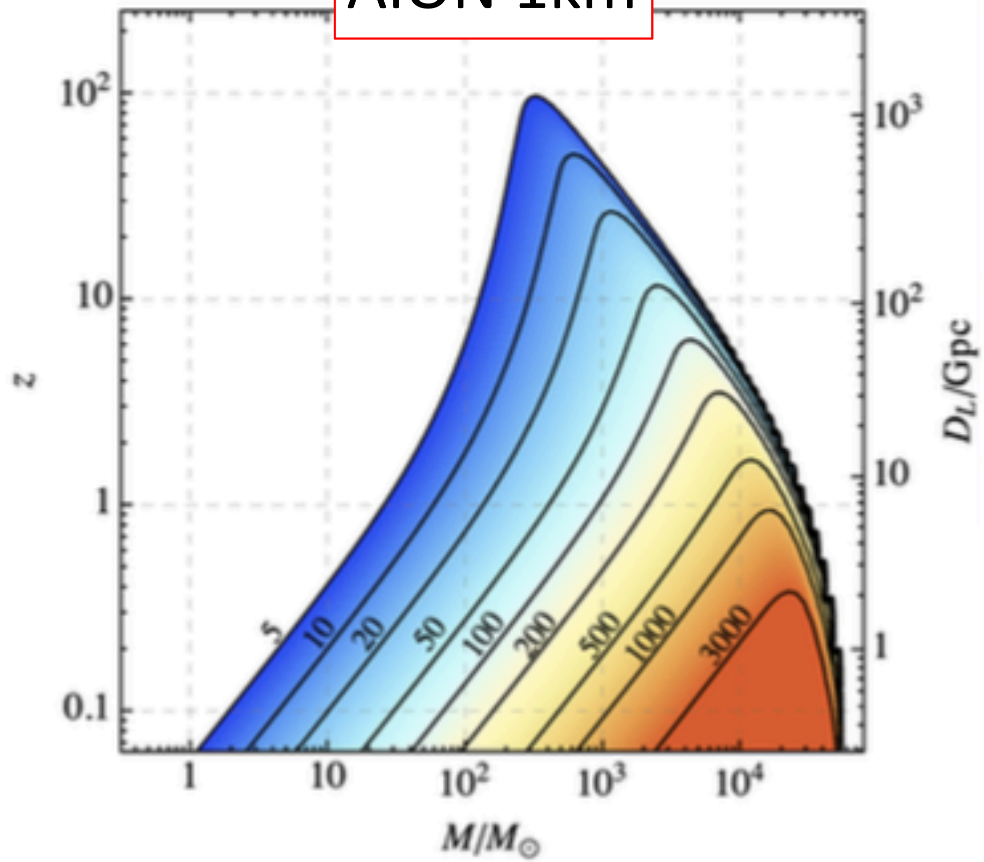
AION GW SNR from IMBH Mergers

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

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

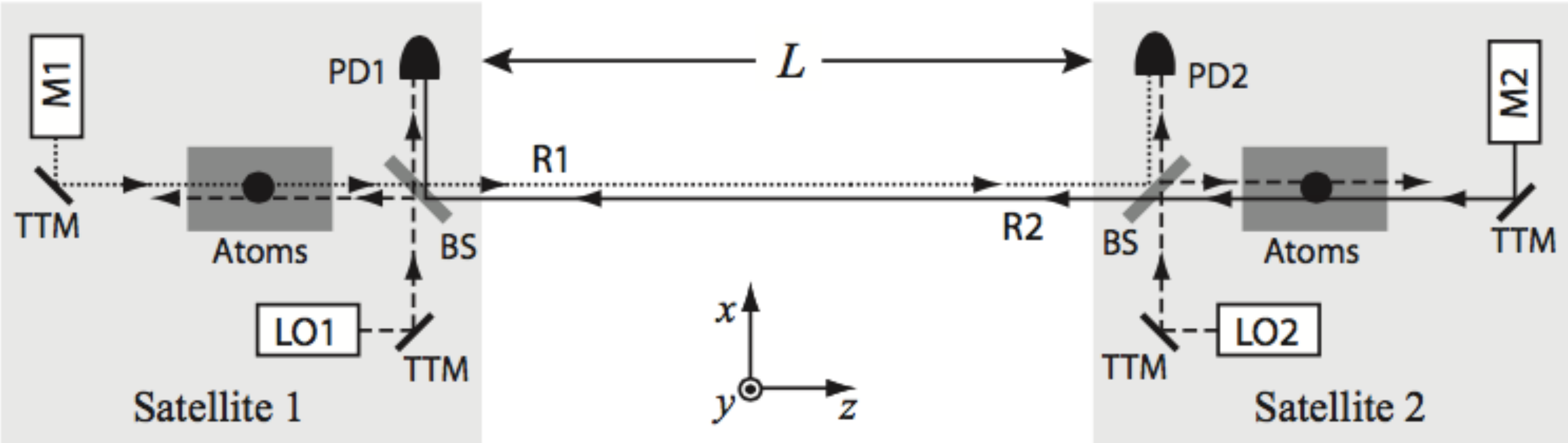
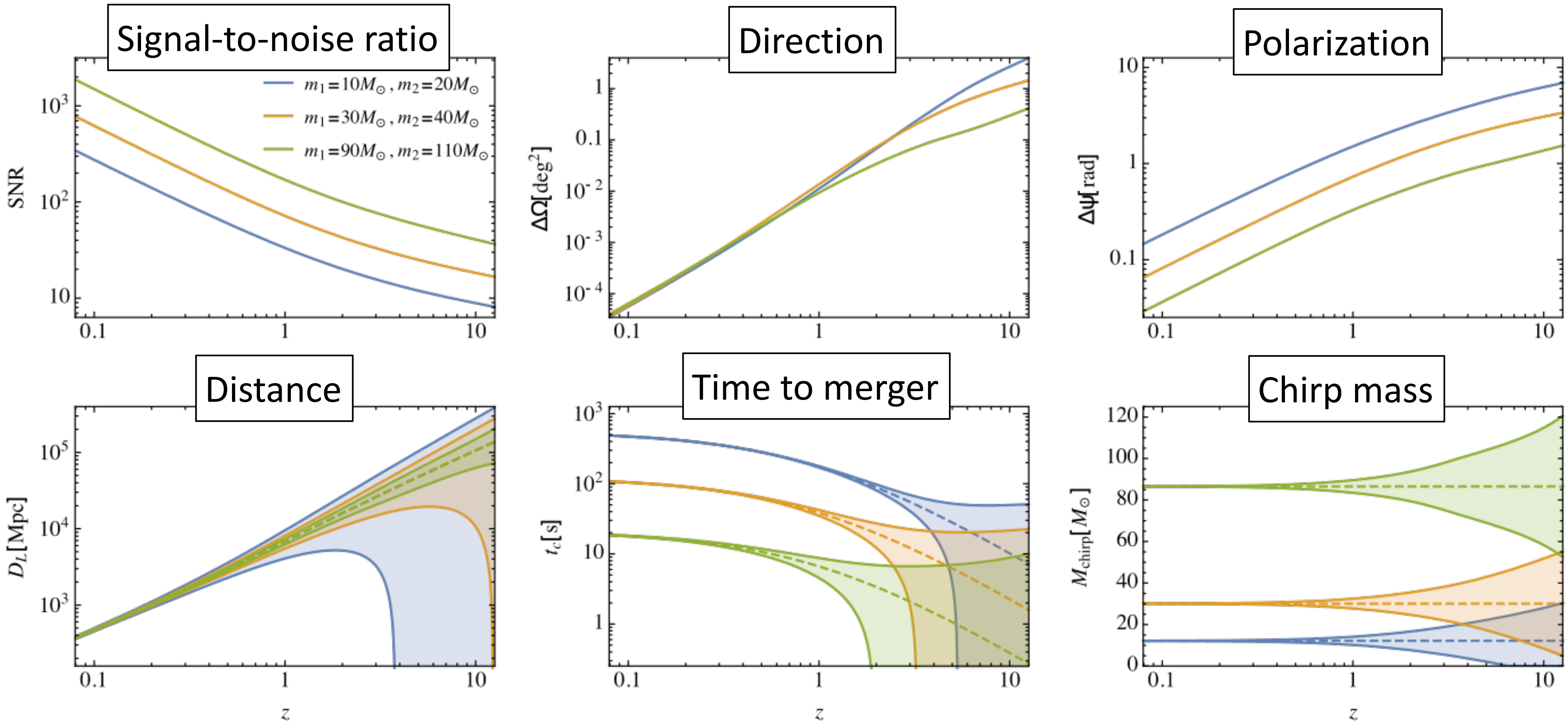


Table 1. List of basic parameters of strontium atom interferometer designs for AEDGE and a benchmark 1-km terrestrial experiment using similar technologies: length of the detector L; interrogation time of the atom interferometer $T_{\rm int}$; phase noise $\delta\phi_{\rm noise}$; and the total number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

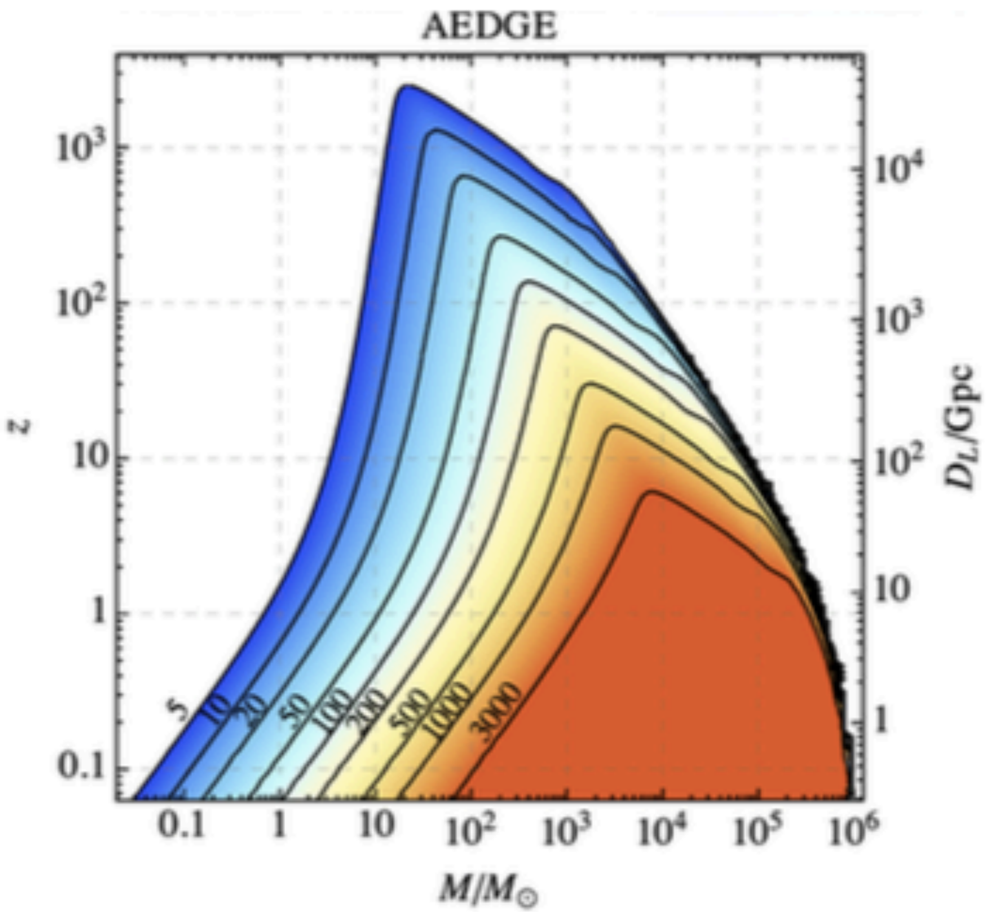
AEDGE: Abou El-Neaj, …, JE et al: arXiv:1908.00802

Possible AEDGE Measurements

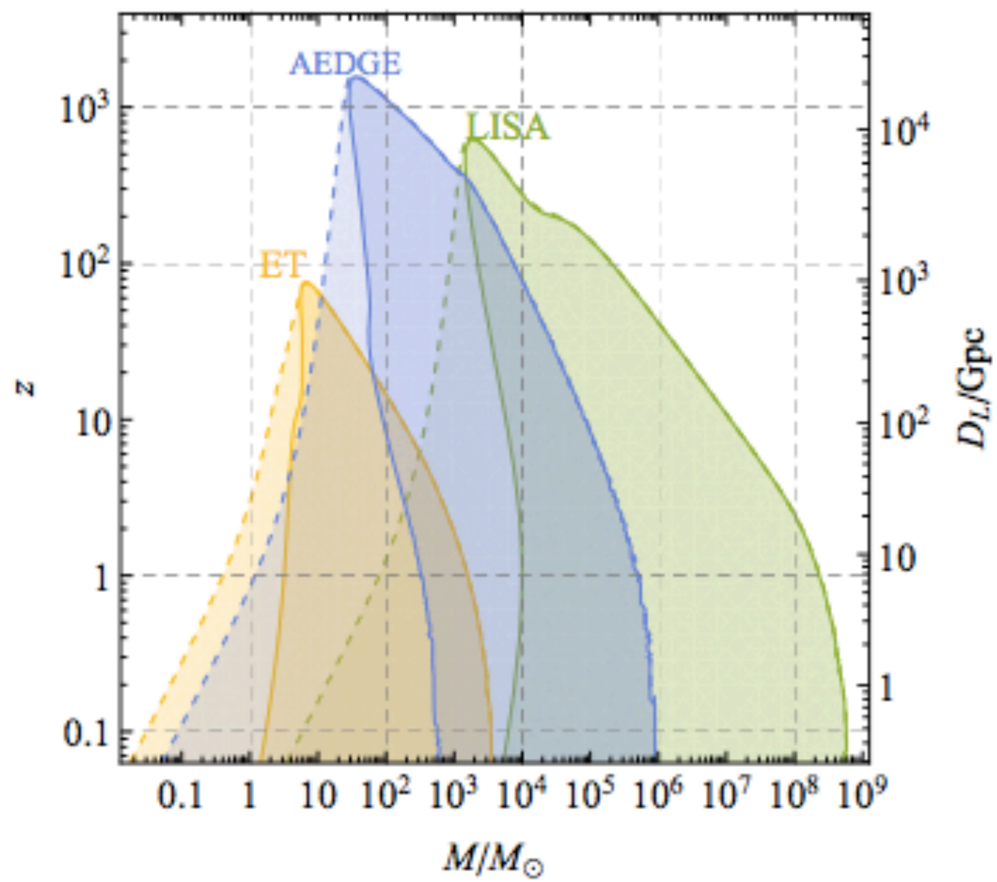


AEDGE: Abou El-Neaj, ..., JE et al: arXiv:1908.00802

Gravitational Waves from IMBHs

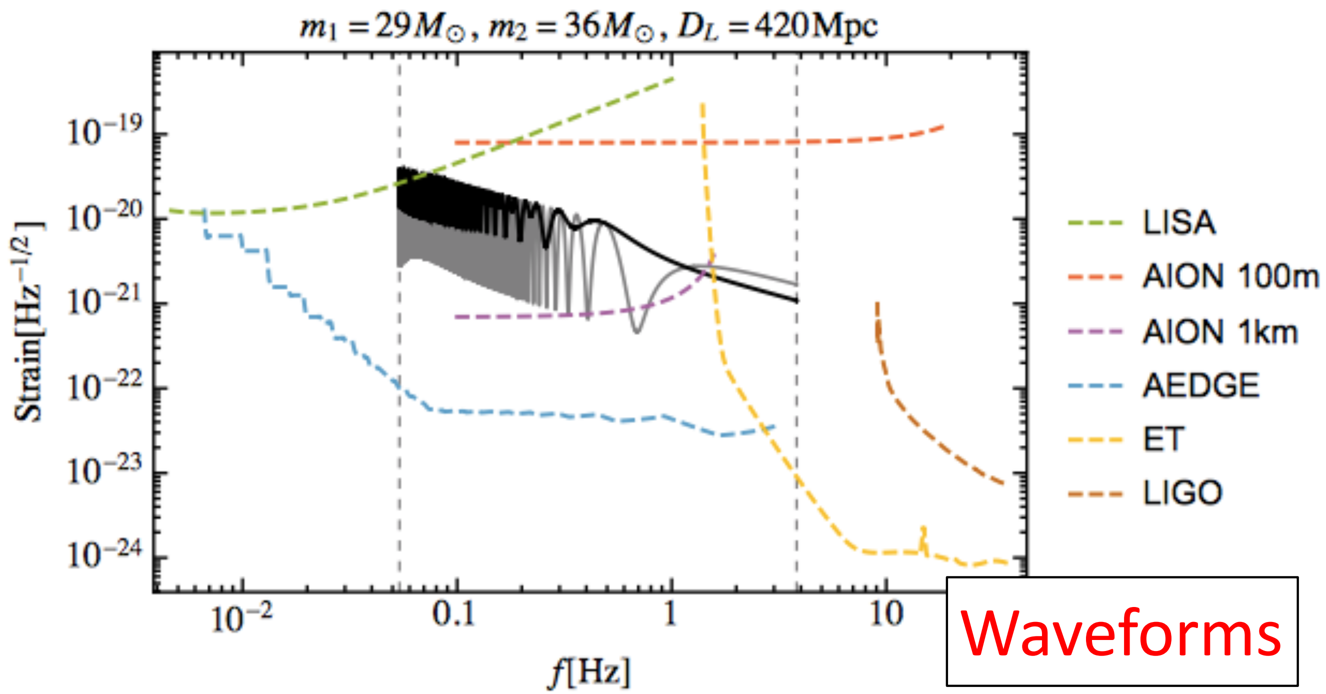


Detect mergers of ~ 10^4 solar-mass BHs
with SNR 1000 out to z ~ 10,
Mergers of ~ 10^3 solar-mass BHs
with SNR 100 out to z ~ 100



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

Constraints on Graviton Mass



Waveforms

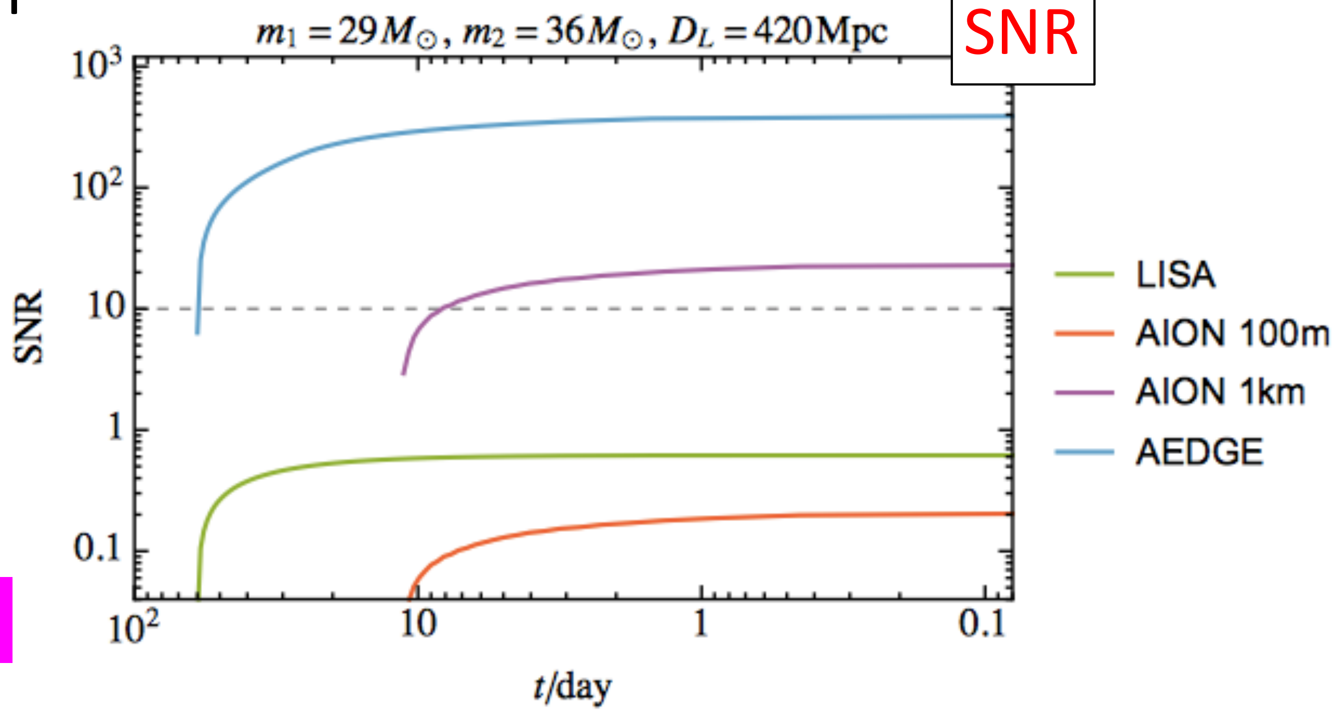
LIGO/Virgo: arXiv:2010.14529

- Current LIGO/Virgo limit: 1.76 × 10^{-23} eV
- Future sensitivity with LIGO/Virgo-like event?

  Longer observations
- With merger of heavier BHs?

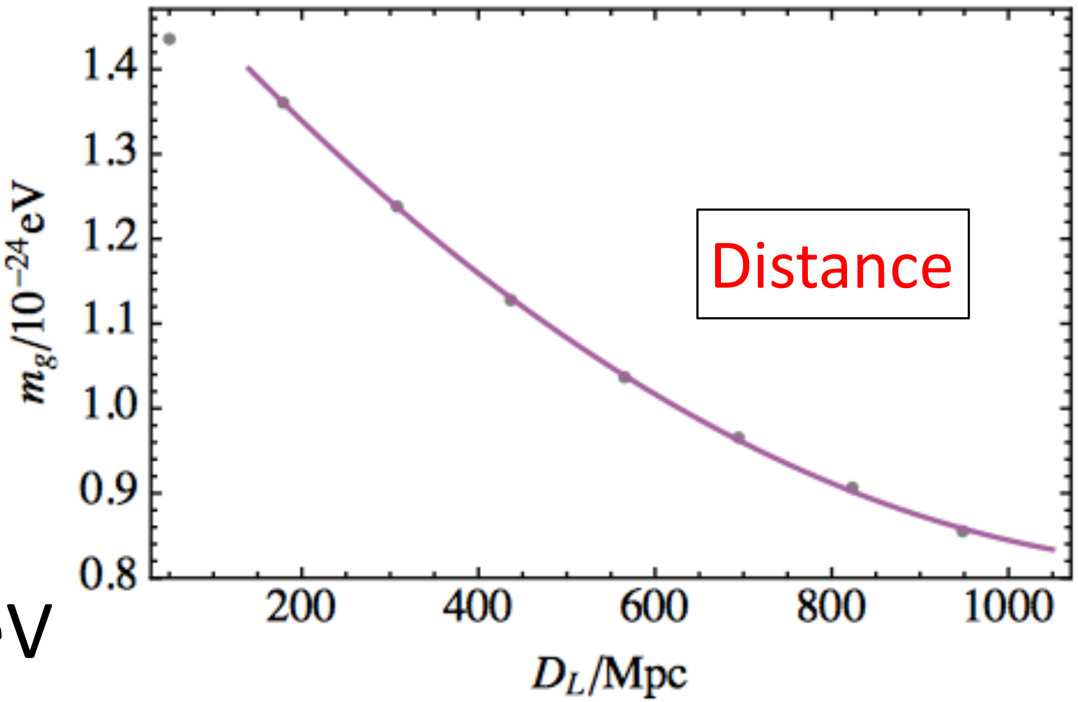
  Lower frequencies

SNR

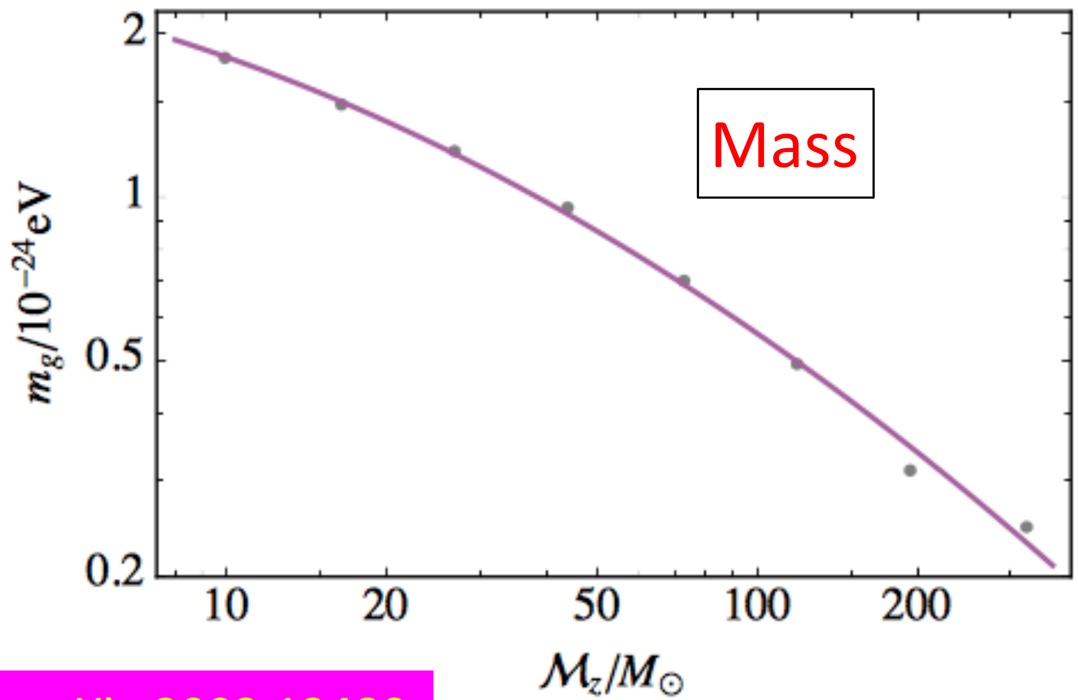


JE & Vaskonen: arXiv:2003.13480

Constraints on Graviton Mass



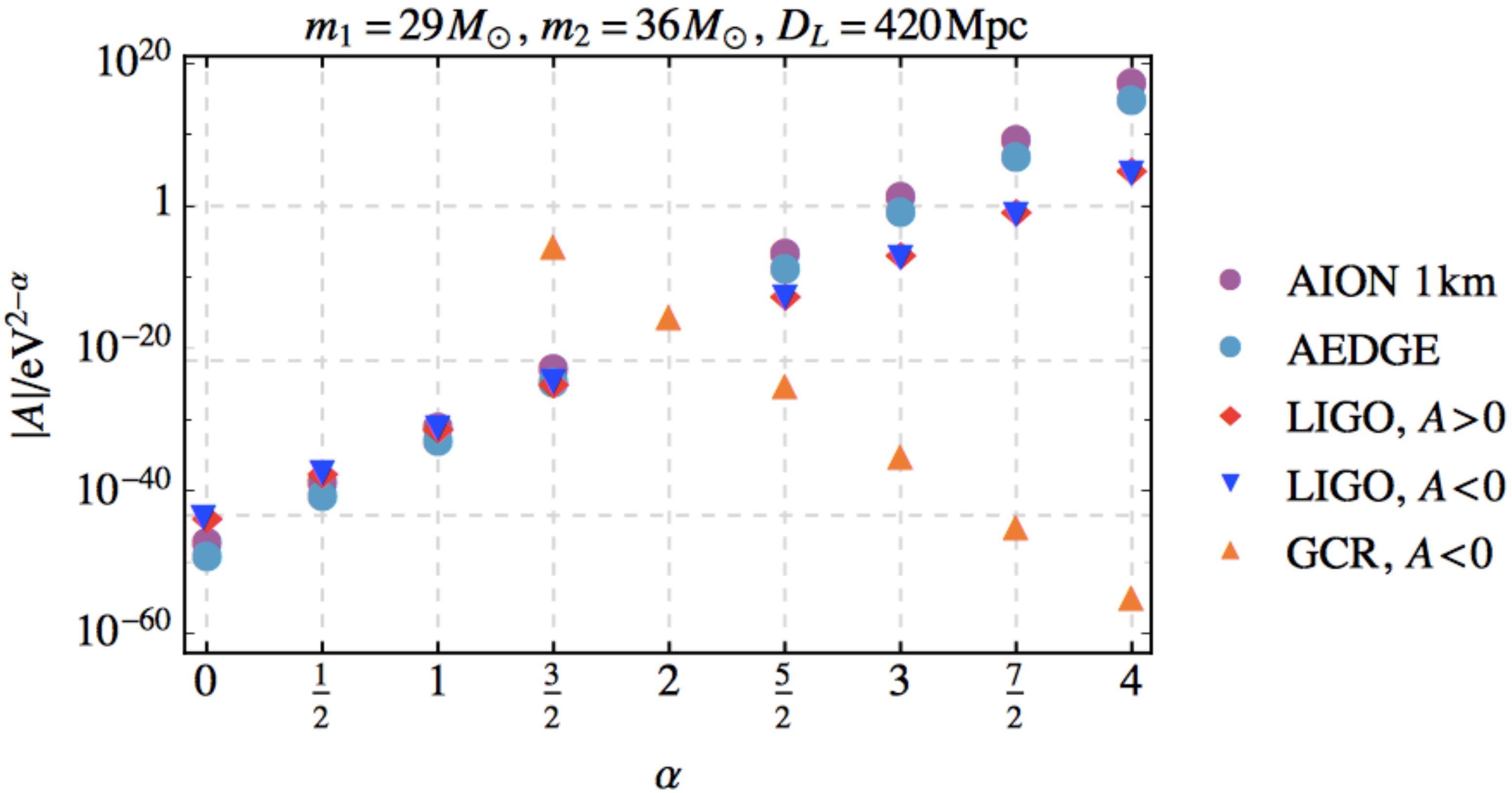
- LIGO/Virgo: <1.76 × 10^{-23} eV
- AION 1-km: sensitive to 10^{-24} eV with LIGO/Virgo-like event
- Sensitive to 2 × 10^{-25} eV with heavier BHs
- AEDGE: 8 × 10^{-27} eV with BHs 5600 + 4400 solar masses



JE & Vaskonen: arXiv:2003.13480

Lorentz Violation

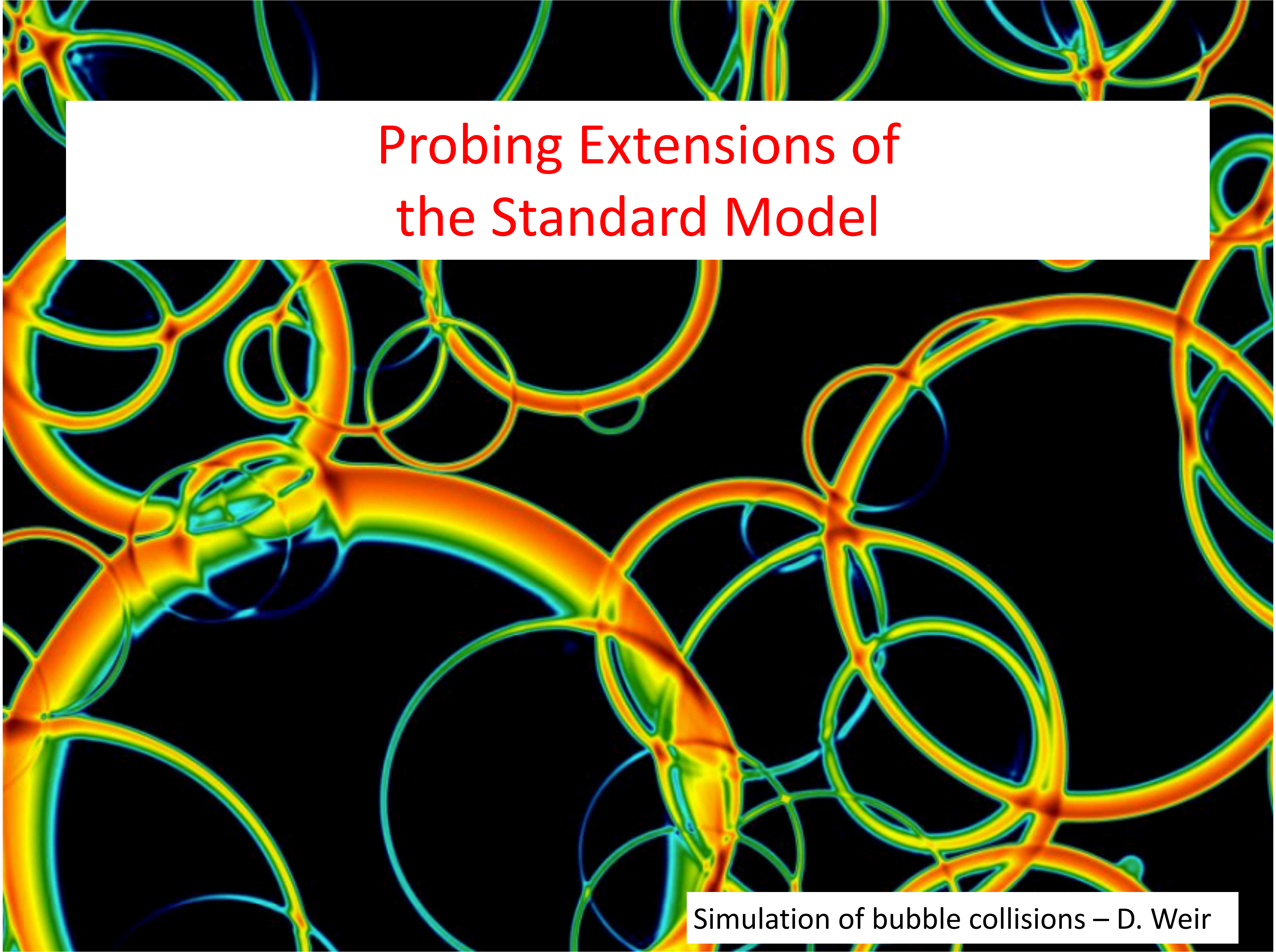
- Modified dispersion relation: $E^2 = p^2 + Ap^\alpha$



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

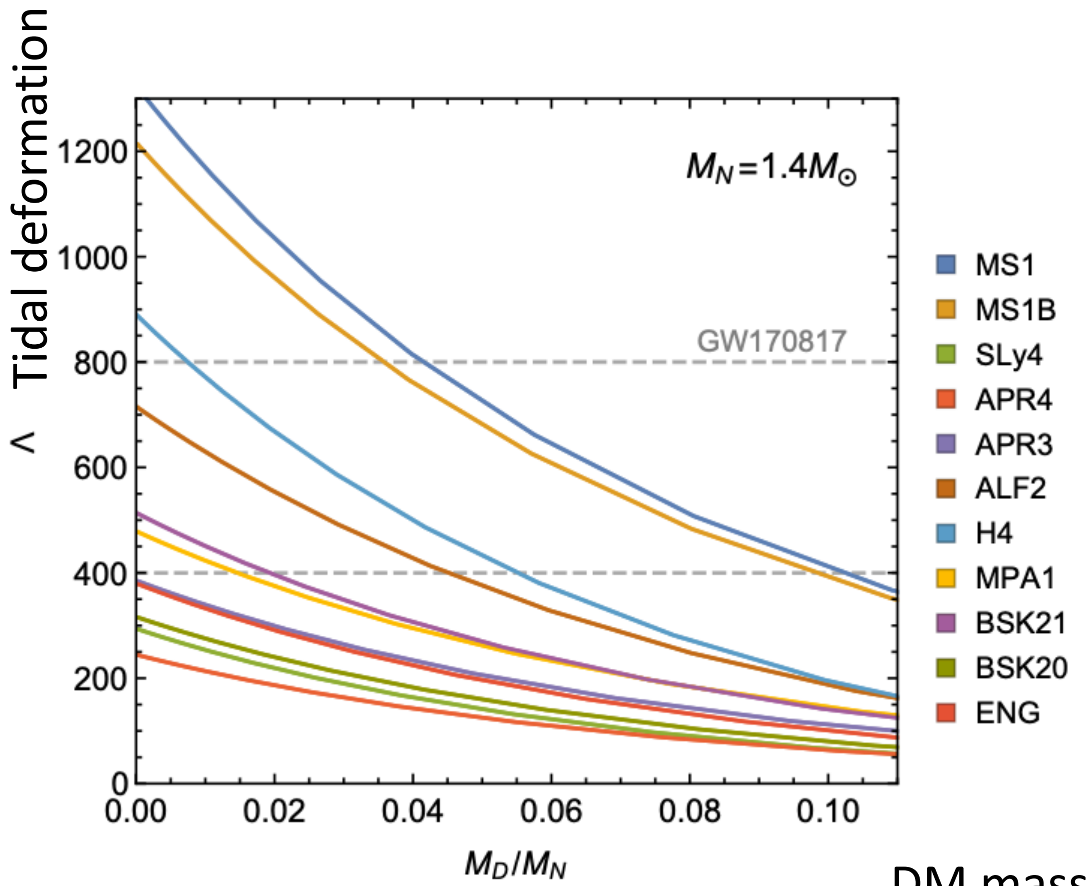
JE & Vaskonen: arXiv:2003.13480

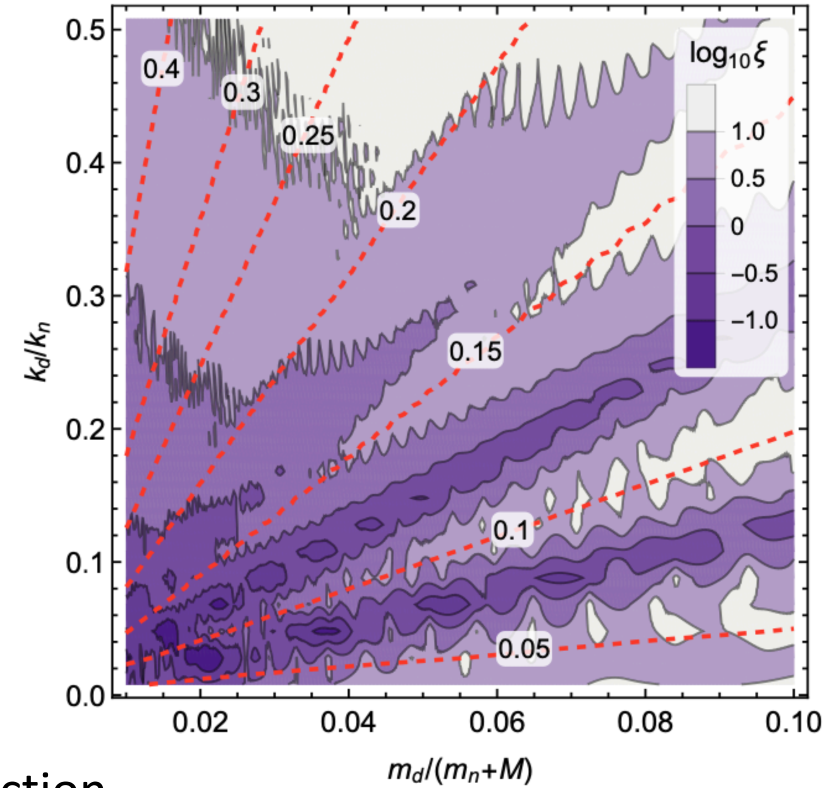
Probing Extensions of the Standard Model



Simulation of bubble collisions – D. Weir

Dark Matter Effects in Neutron-Star Mergers?





DM mass fraction

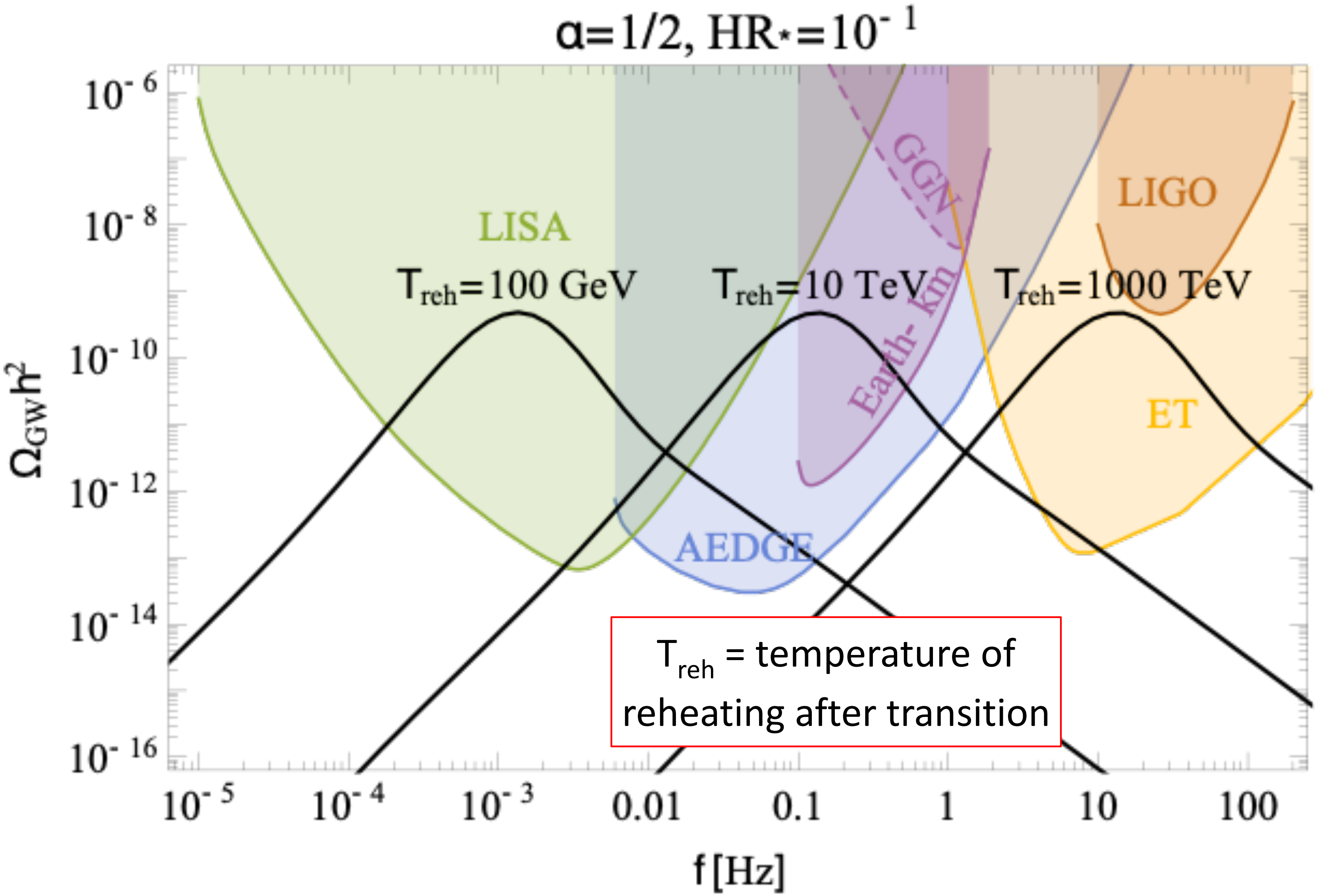
(Very) large DM fraction could have measurable effect on equation of state, give additional feature in GW spectrum

JE, Hektor, Hütsi, Kannike, Marzola, Raidal & Vaskonen: arXiv:1710.05540, arXiv:1804.01418

GWs from a First-Order Phase Transition

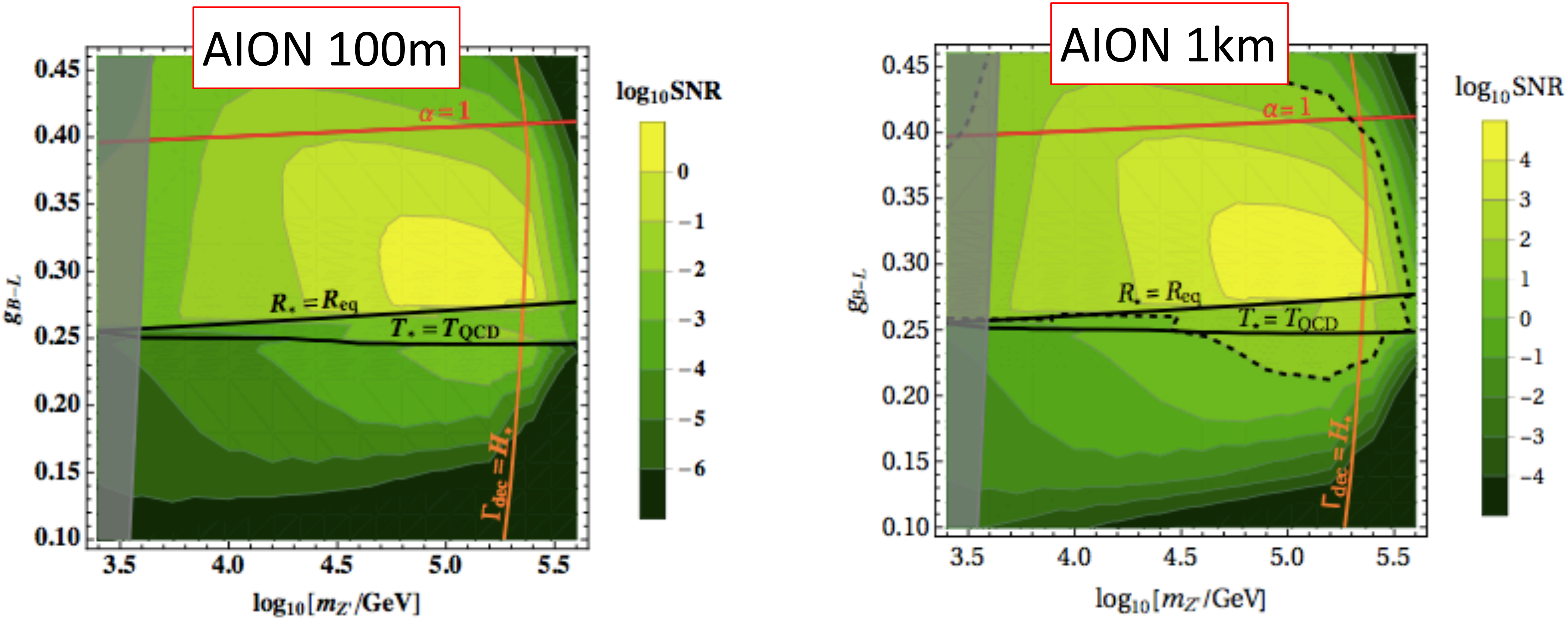
- Transition by percolation of bubbles of new vacuum
- Bubbles grow and collide
- Possible sources of GWs:
  - Bubble collisions
  - Turbulence and sound waves in plasma
- Models studied:
  - Standard Model + H^6/Λ^2 interaction
  - Standard Model + $U(1)_{B-L}$ Z'
- These also have prospective collider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

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



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

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



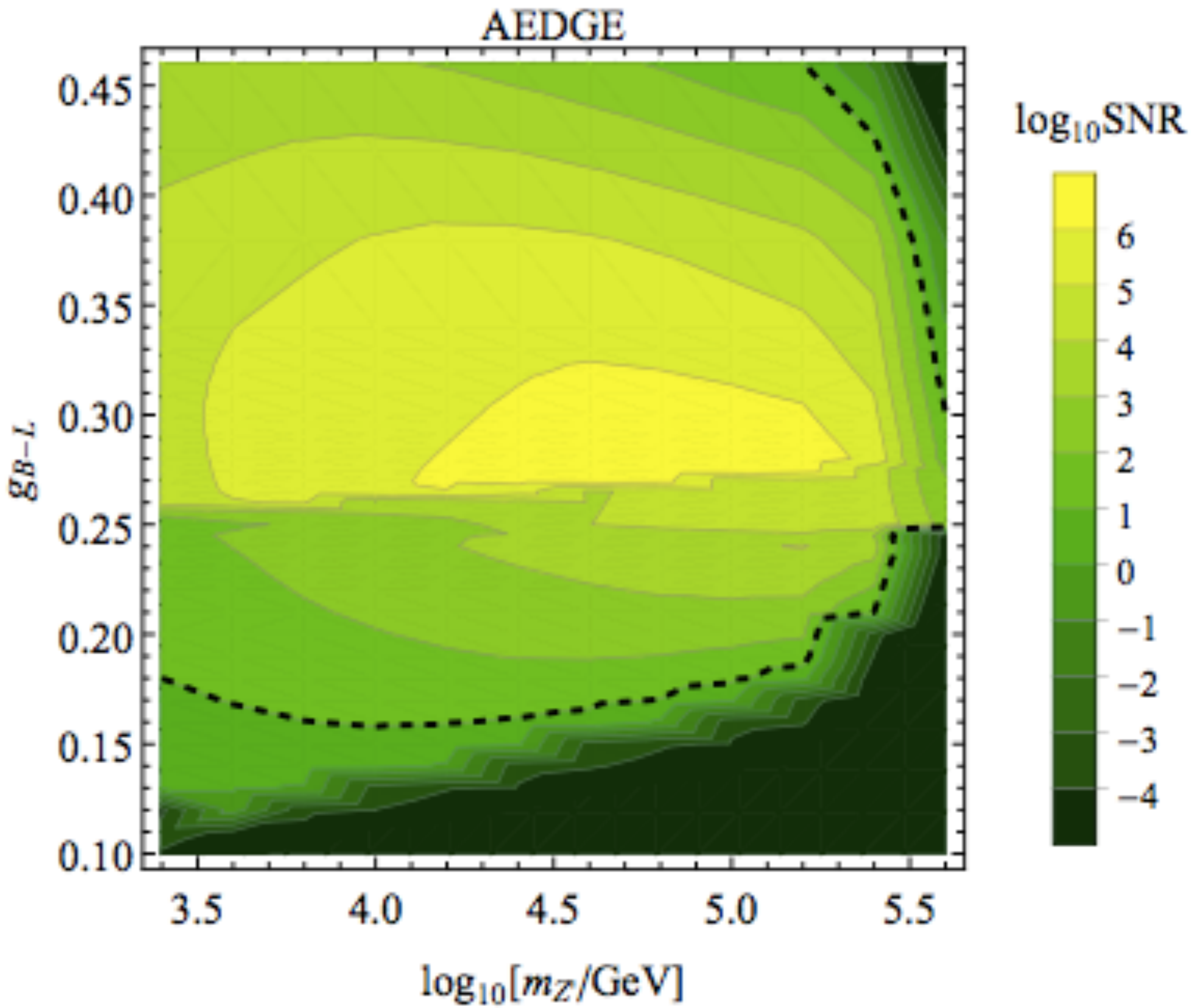
Discovery of GW possible with AION 1km

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

JE, Lewicki, No & Vaskonen, arXiv:1903.09642

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

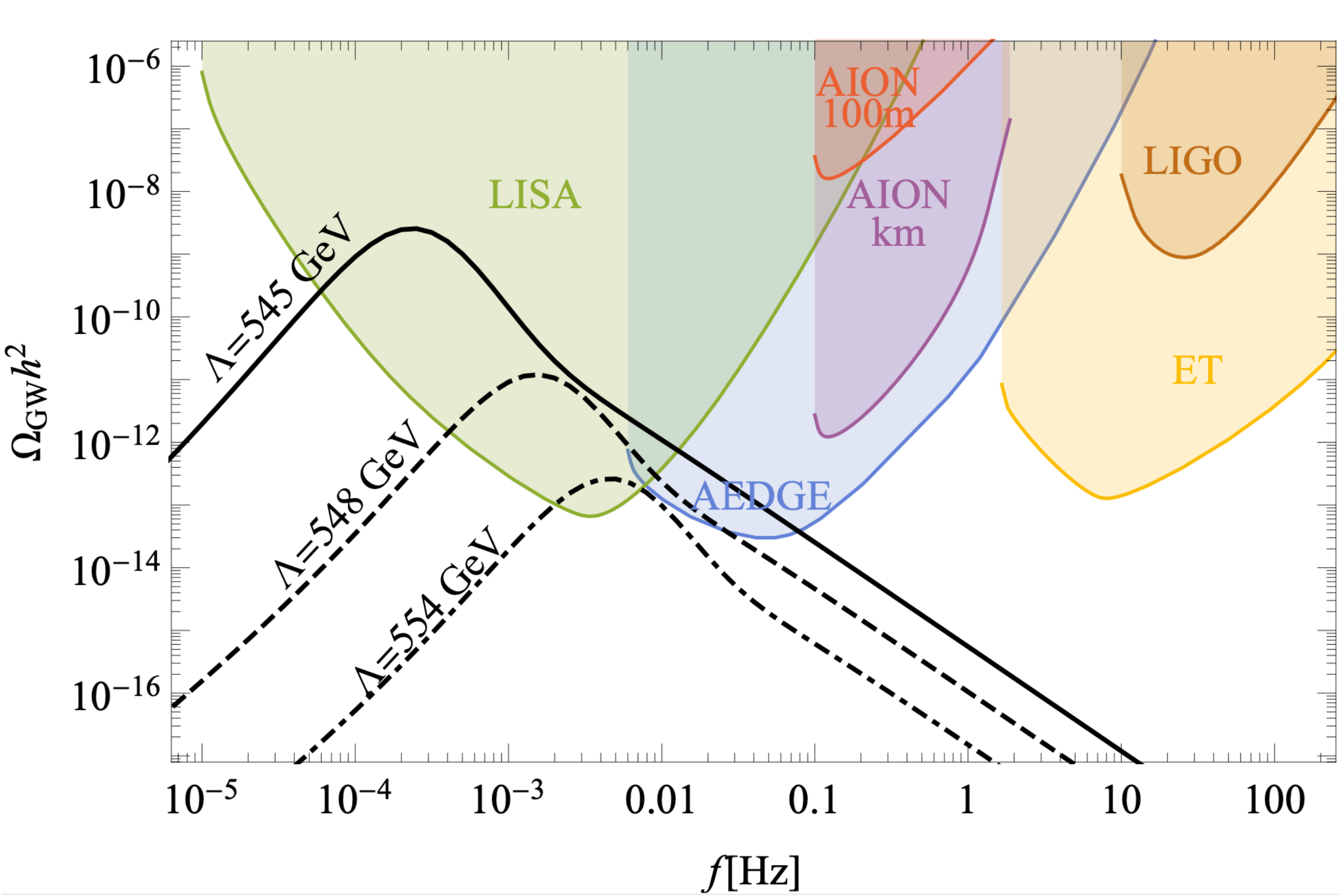
Sensitivity to $U(1)_{B-L}$ Z’



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

GW Signal in H^6/Λ^2 Model

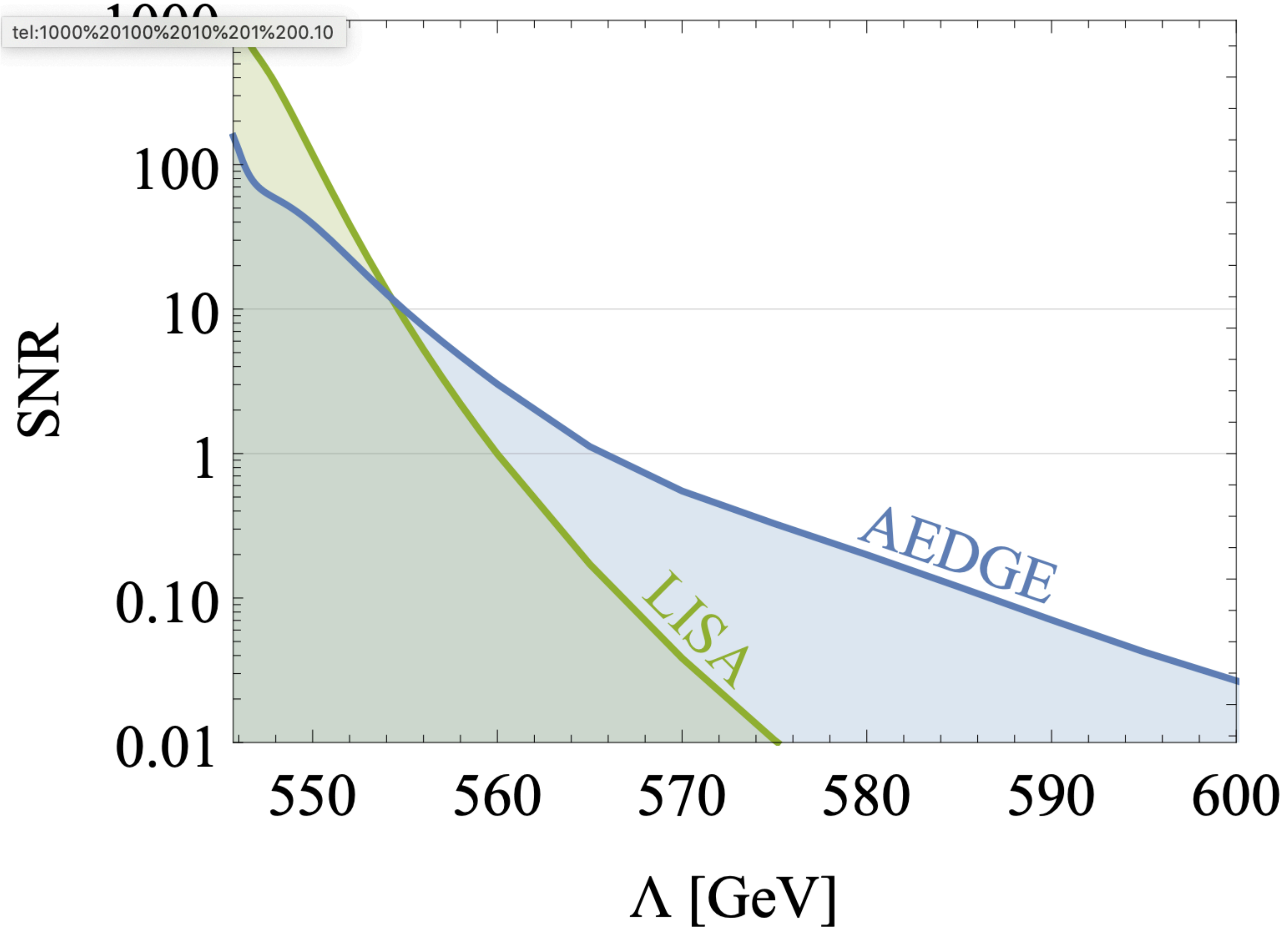
- Strongest signal for which percolation is assured



- AEDGE and LISA sensitivities very similar

JE, Lewicki, No & Vaskonen, arXiv:1903.09642

Gravitational Wave Sensitivity to Scale of H^6/Λ^2 Interaction

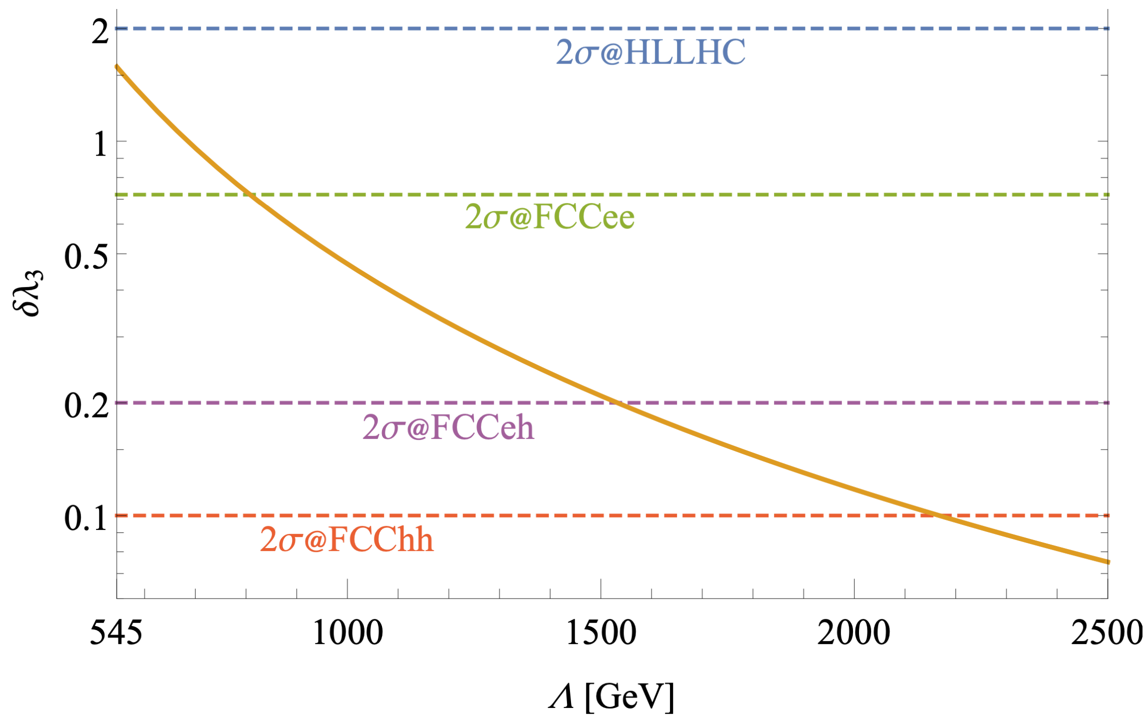


Gravitational wave sensitivity to Λ

JE, Lewicki & No, arXiv:1809.08242

Modification of Triple-H Coupling

- Current LHC data insensitive to H^6/Λ^2 coupling
- Future collider sensitivity via modification of triple-Higgs coupling λ_3

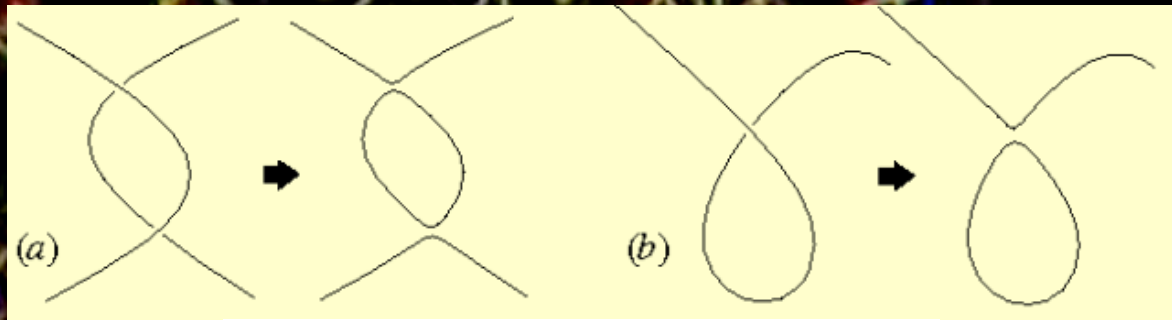


Collider sensitivity will be > gravitational waves

JE, Lewicki & No, arXiv:1809.08242

Probing Cosmic Strings

Hint from the NANOGrav pulsar timing array?

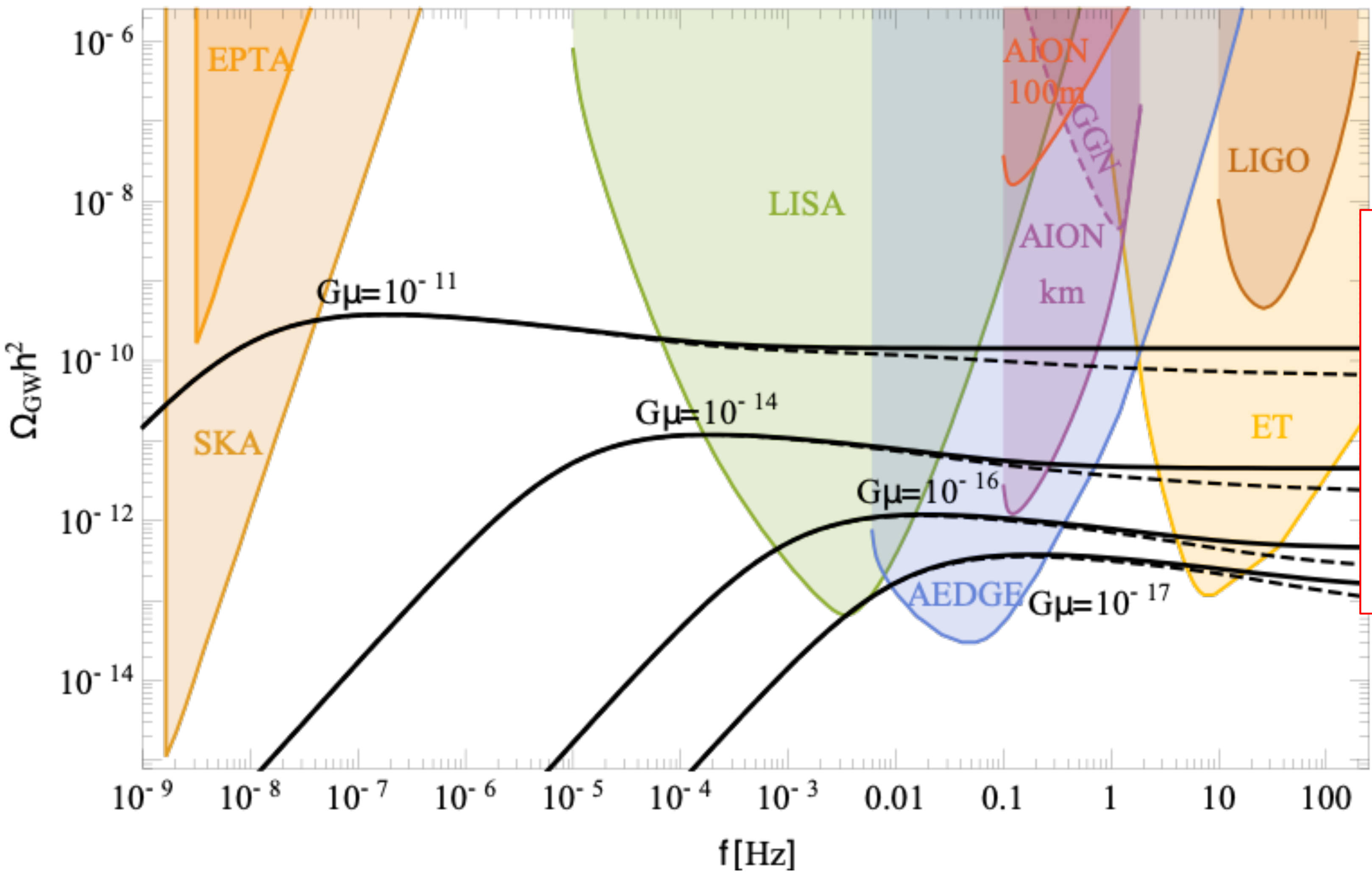


GW emission from string loops

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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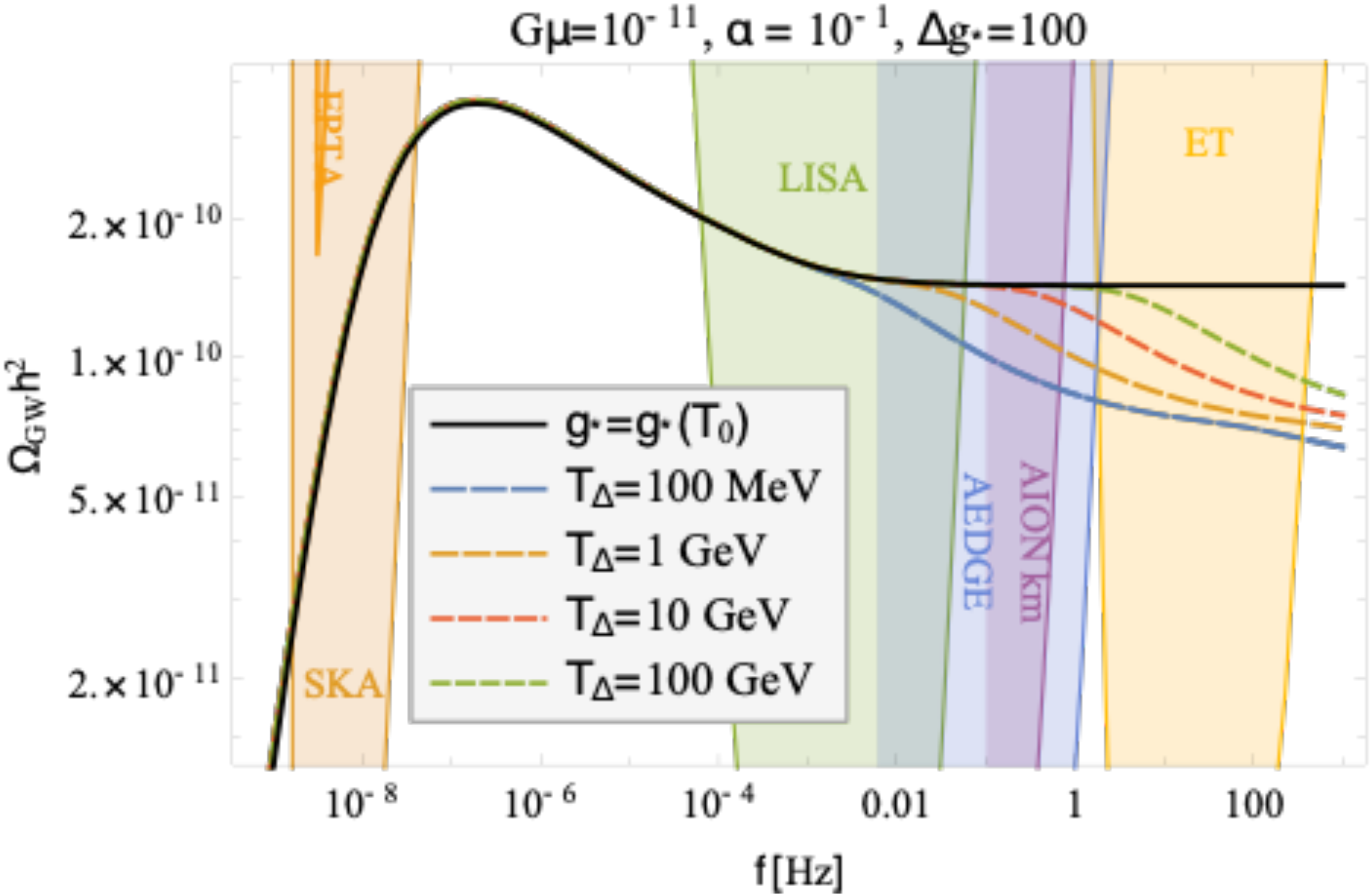
- - -

Spectrum ~ flat from PTA/SKA to LIGO/ET

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

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

Gravitational Waves from Cosmic Strings

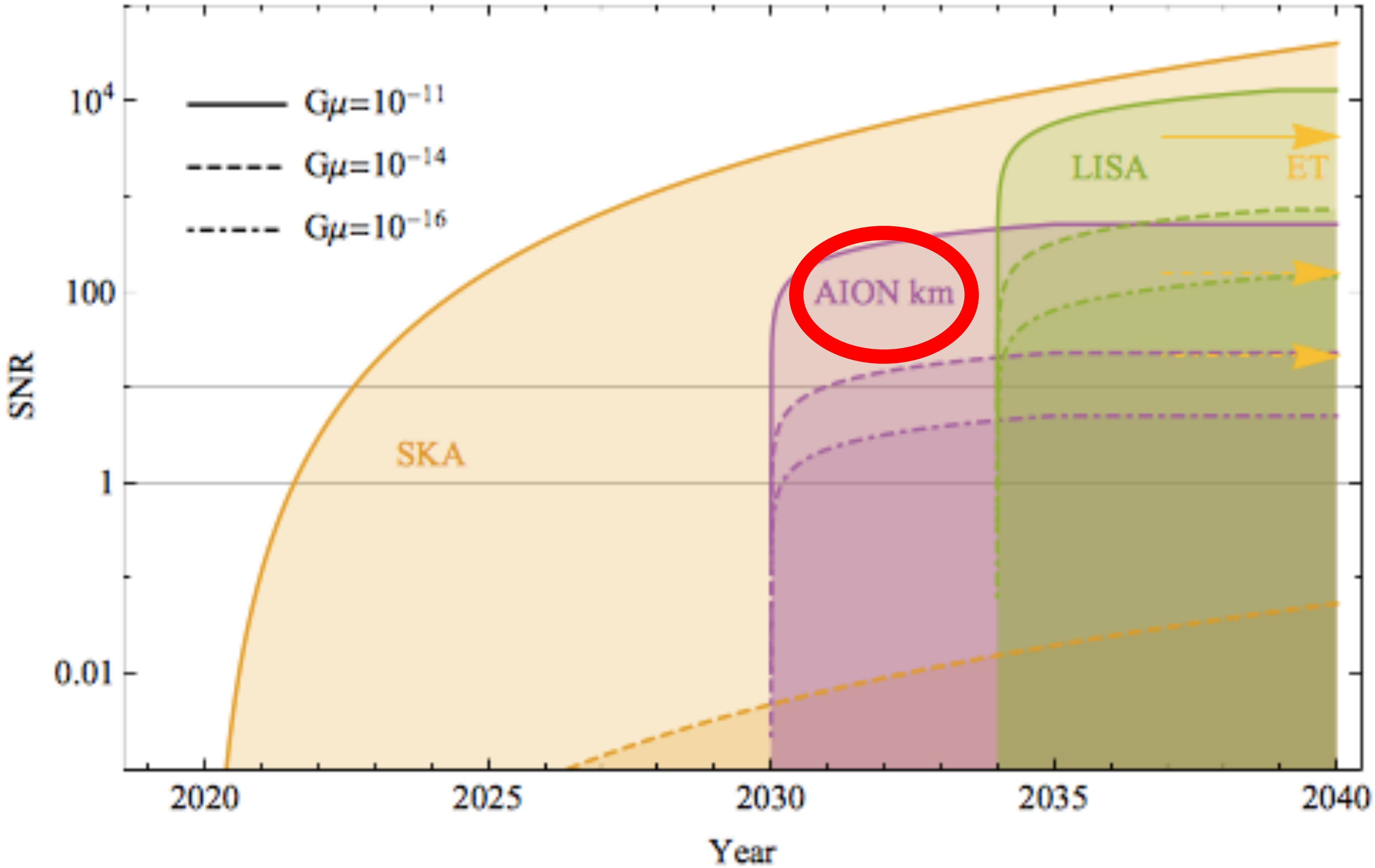


Sensitive to changes in # of degrees of freedom

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

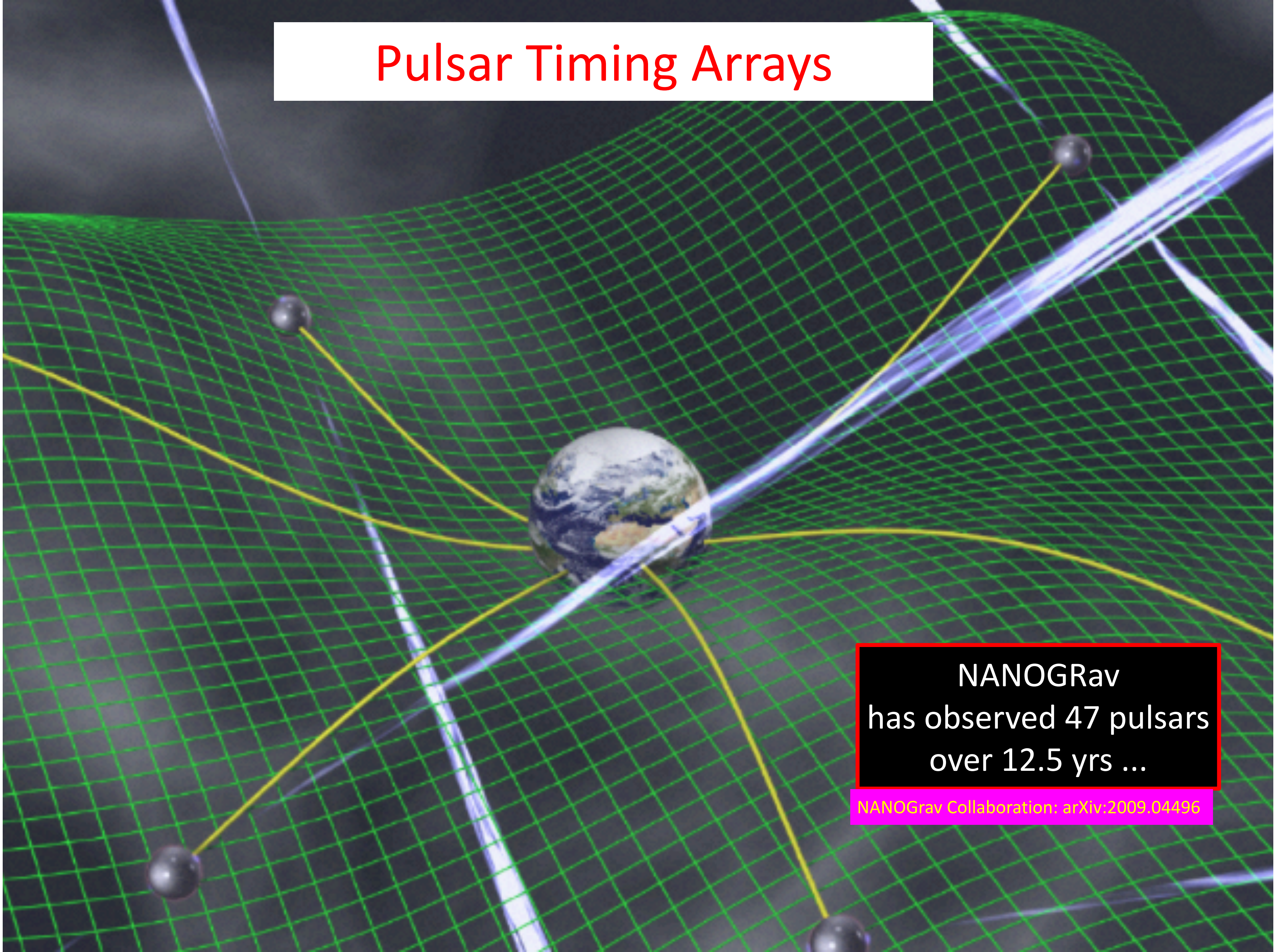
Probe expansion history of early universe

Perspectives for Future Experiments



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

Pulsar Timing Arrays



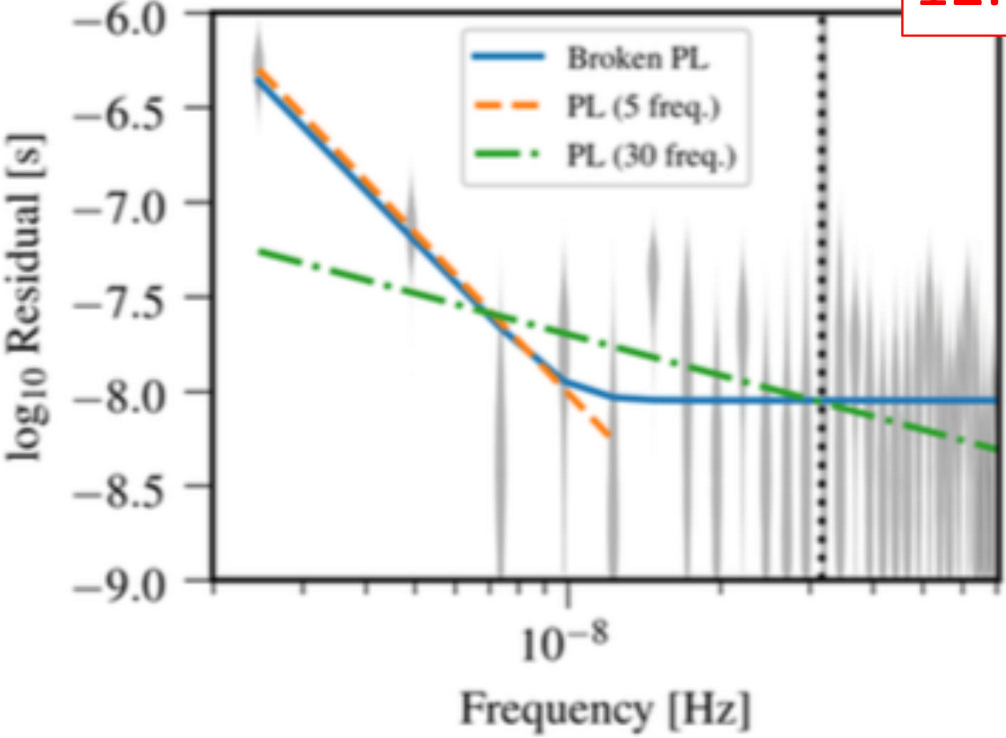
NANOGRav
has observed 47 pulsars
over 12.5 yrs ...

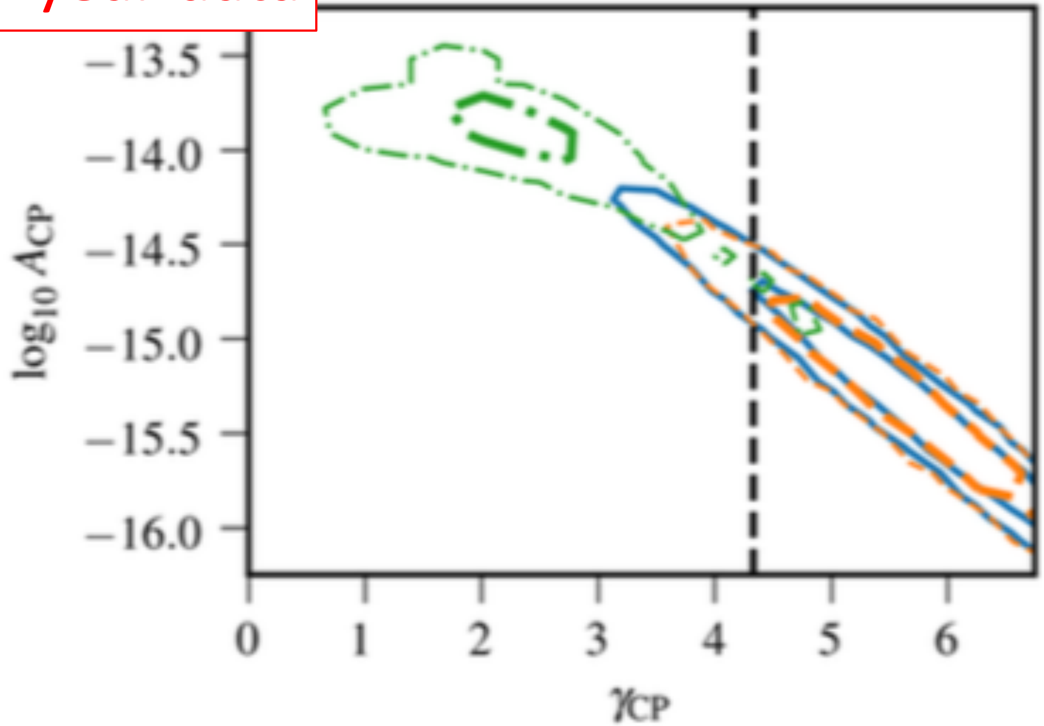
NANOGrav Collaboration: arXiv:2009.04496

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

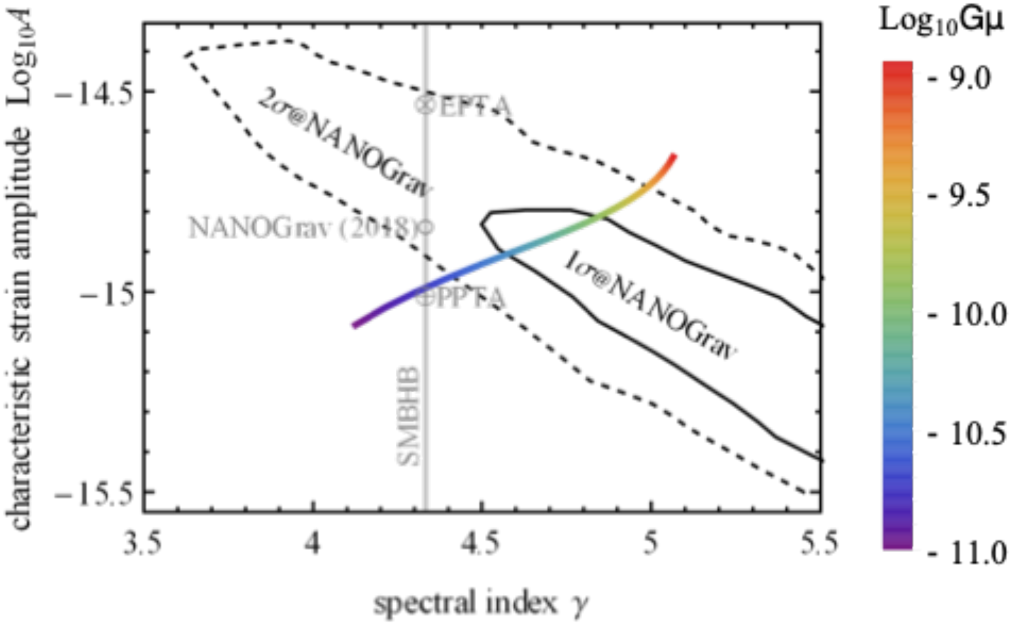
Fits to amplitude of signal
Focus on simple power law
Amplitude A ~ 10^{-15}
Slope γ ~ 5

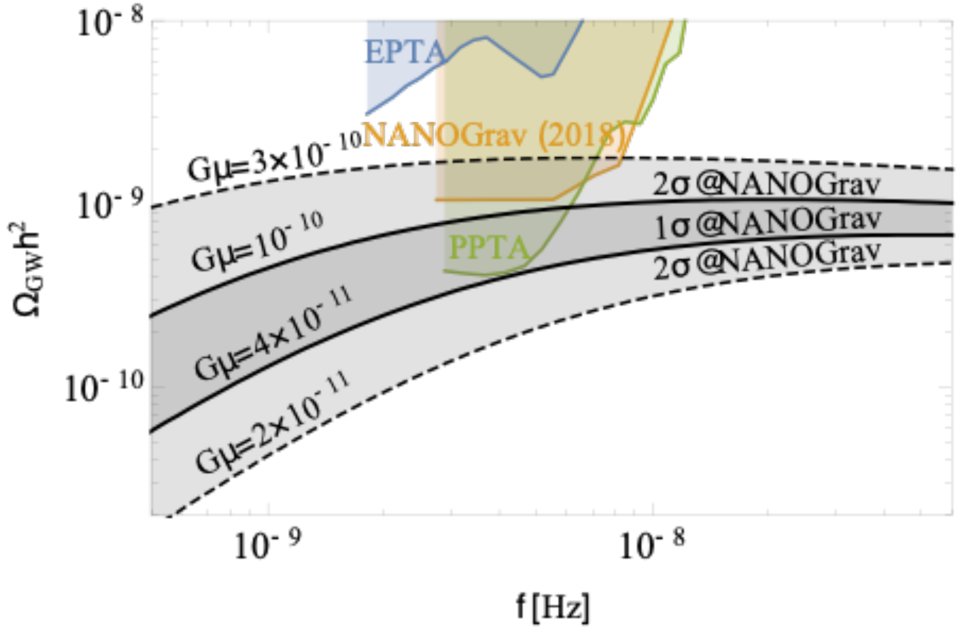
Default model

Vertical dashed line: simple model of mergers of supermassive BHs

JE & Lewicki: arXiv:2009.06555

Cosmic String Interpretation of NANOGrav



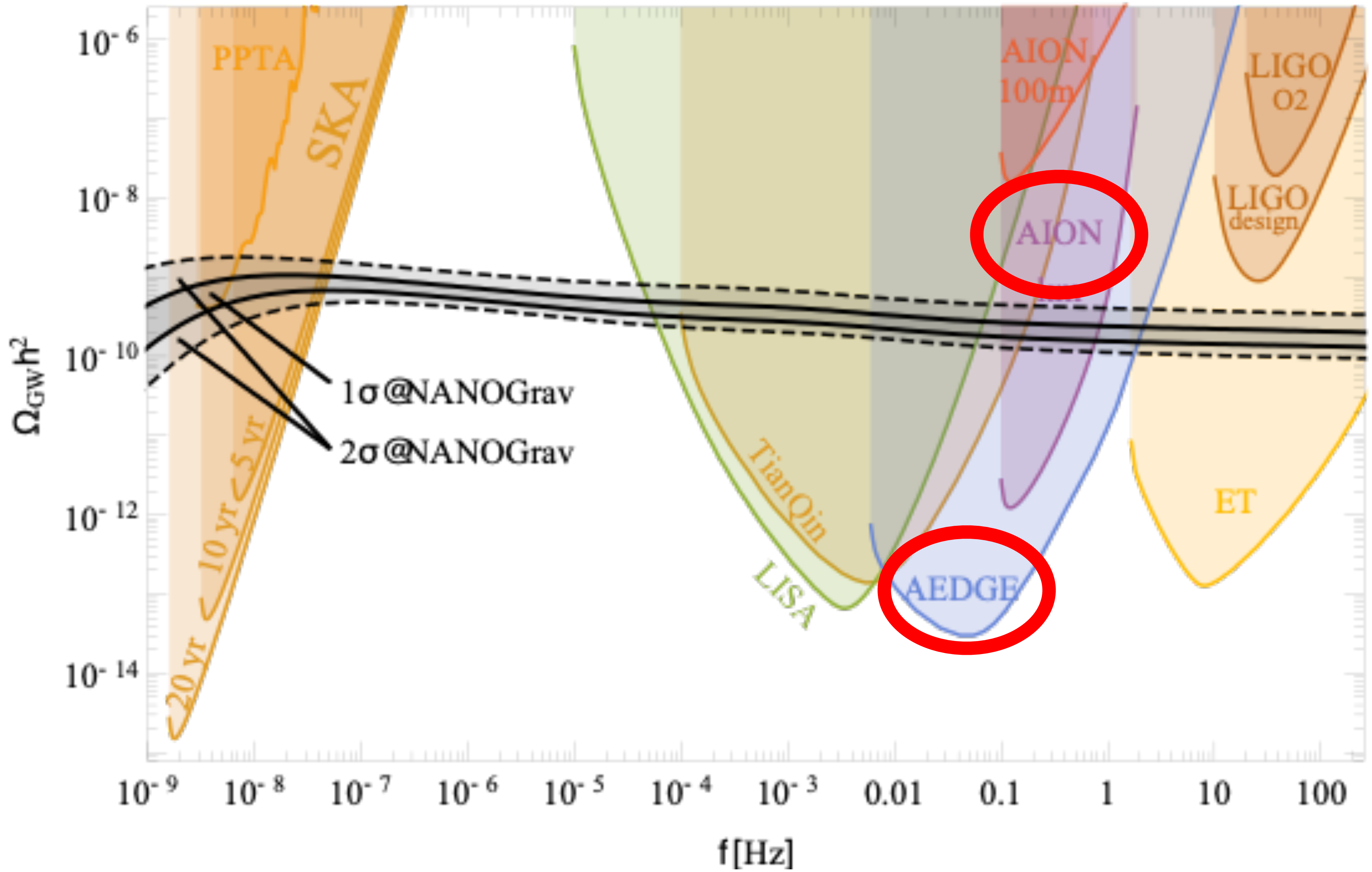


"Rainbow curve"
is cosmic string prediction as a
function of the cosmic string tension Gμ
Vertical line is naïve SMBH merger prediction
Previous PTA upper limits for
this value of γ

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

JE & Lewicki: arXiv:2009.06555

Cosmic String Interpretation of NANOGrav

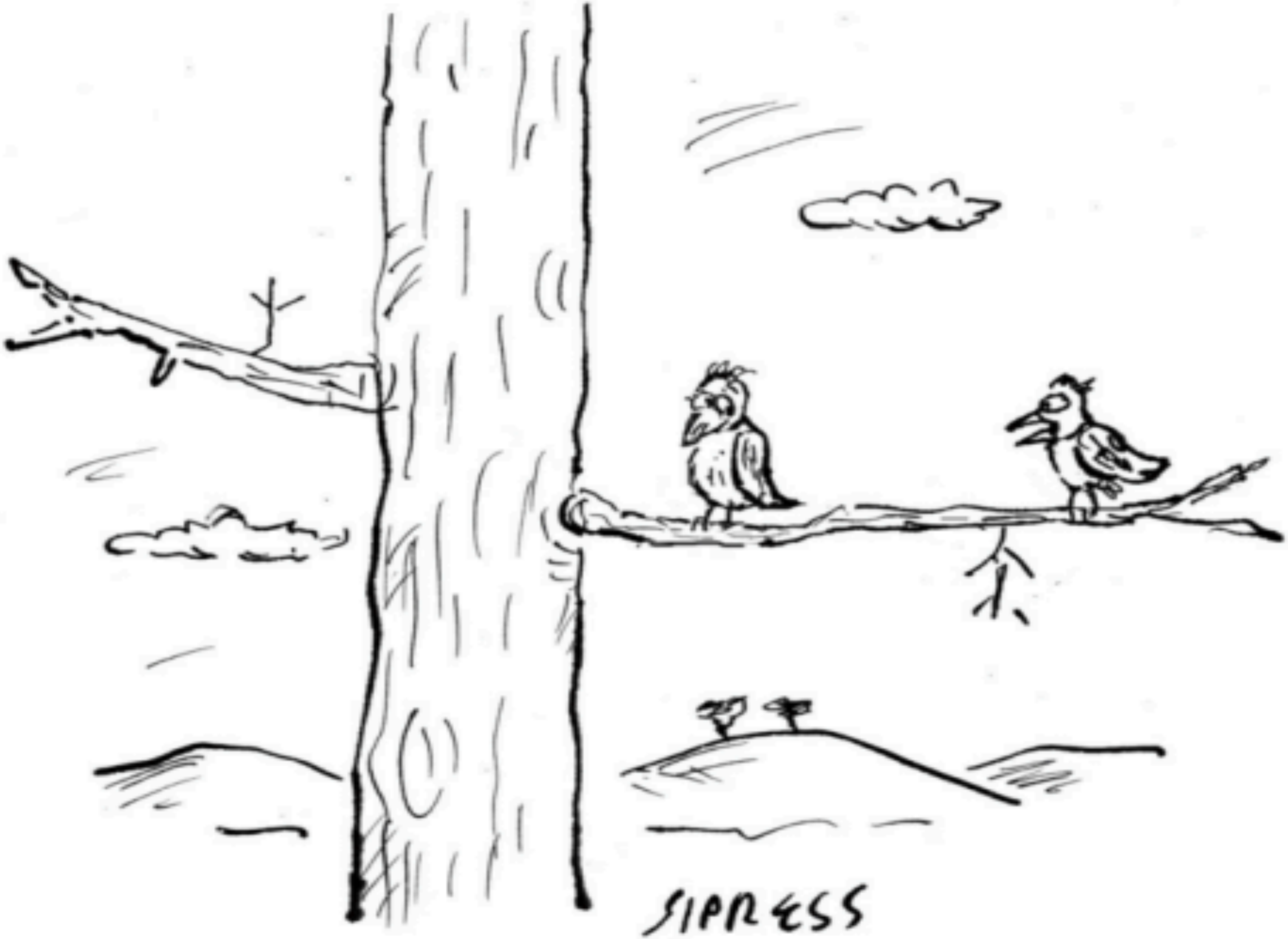


Cosmic string prediction can be tested in several upcoming experiments (not LIGO)

See also Blasi, Vrdar & Schmitz: arXiv:2009.06607v2

Fundamental Physics
Beyond Gravitational Waves

- Atom interferometers can search for ultralight dark matter
- High-precision measurement of the gravitational redshift, probes of Bell inequalities and the equivalence principle
- Probing fundamental "constants", chameleons, dark energy
- Fundamental (≠ environmental) decoherence?
- …..



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