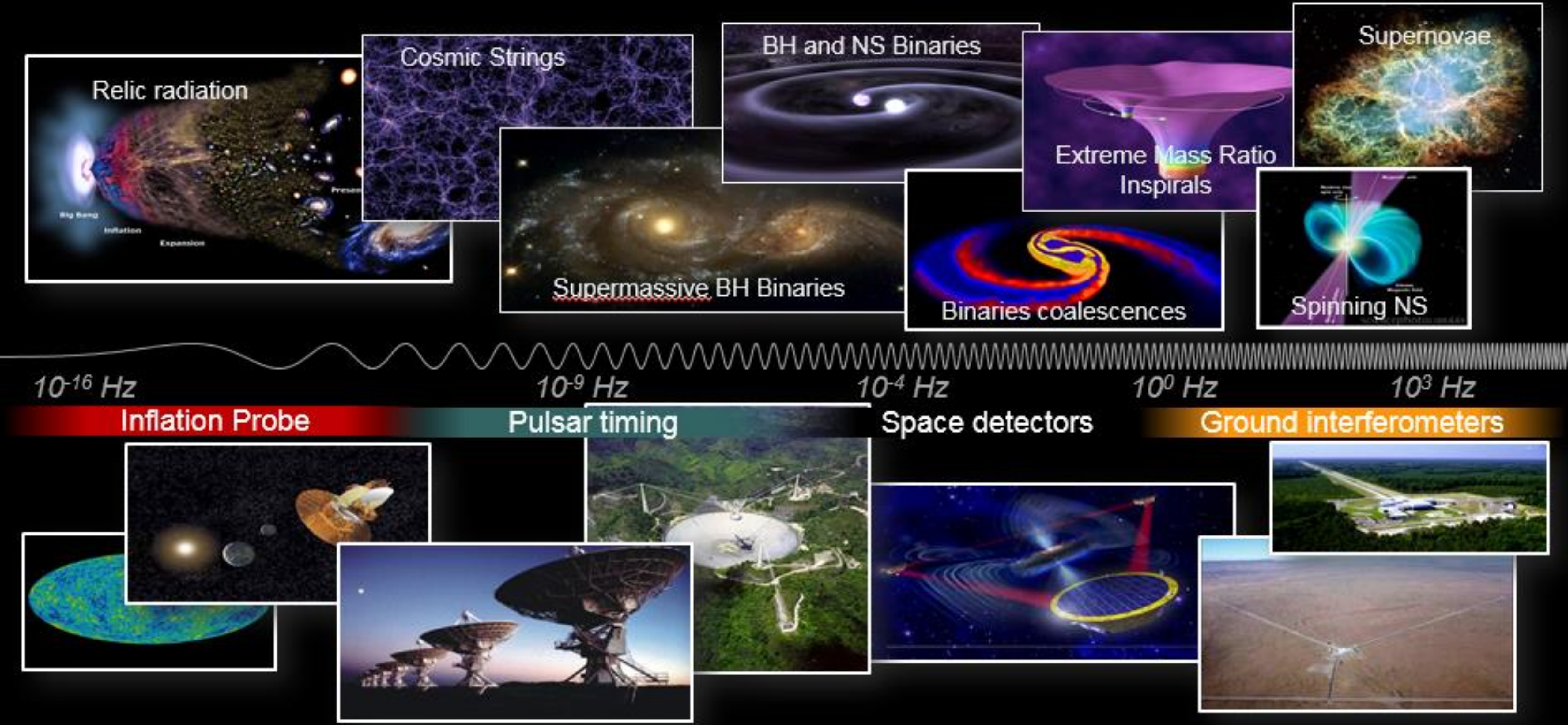
Gravitational Waves (UK)

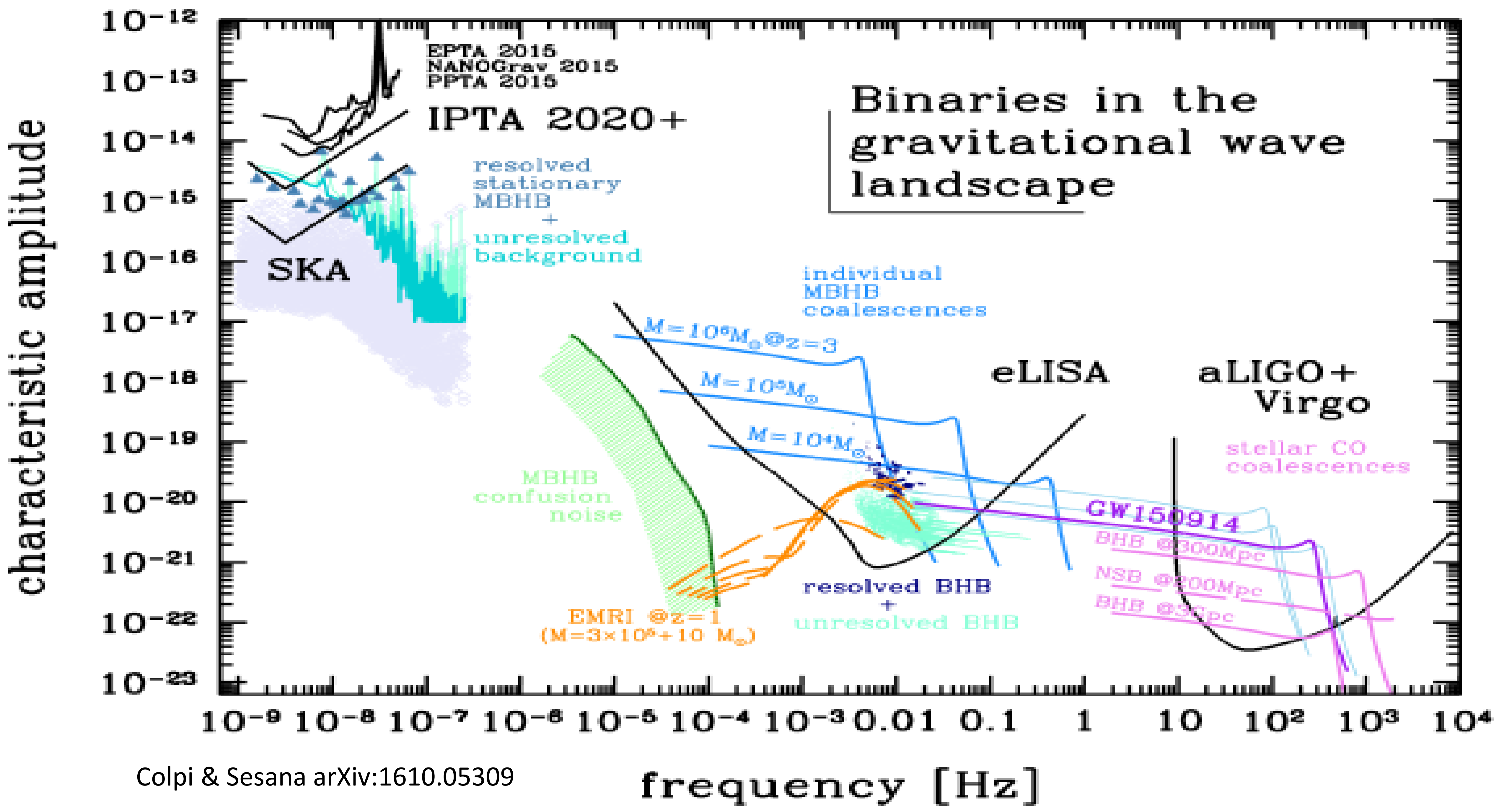
T. J. Sumner

Imperial College London

University of Florida

The GW Spectrum





Colpi & Sesana arXiv:1610.05309

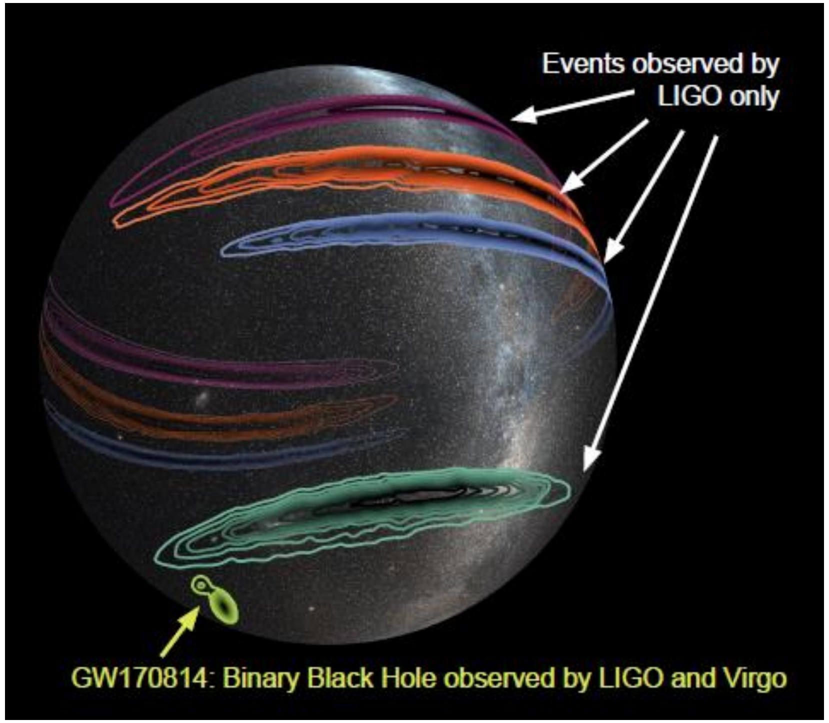
Gravitational Wave Astronomy

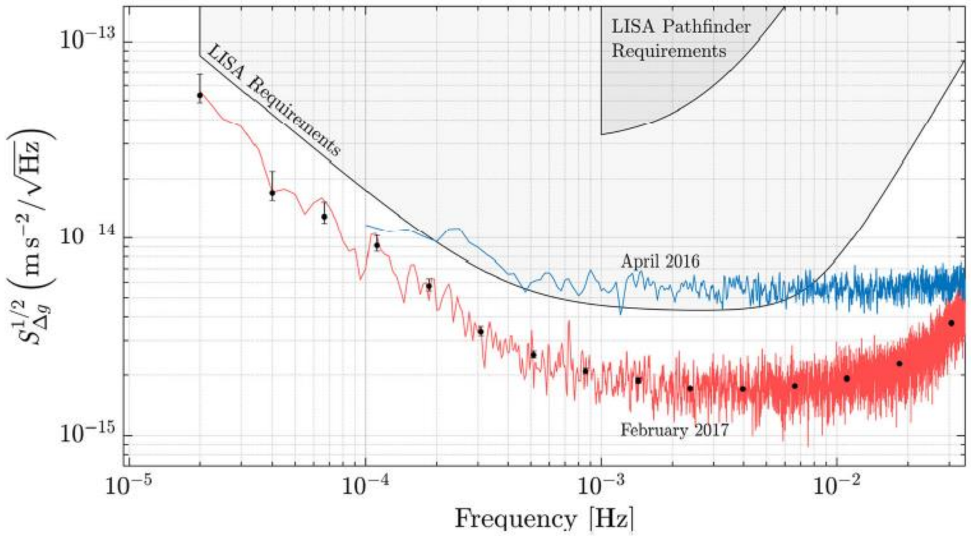
UK GW effort

- UK: Long history of leadership in GW instrumentation and analysis;
- UK made major contributions to Advanced LIGO and LISA Pathfinder (enabling hardware, innovative ideas, leading search groups and analysis
- Faculty expansion in Glasgow, Birmingham, Cardiff (new experimental group), Portsmouth (new group)

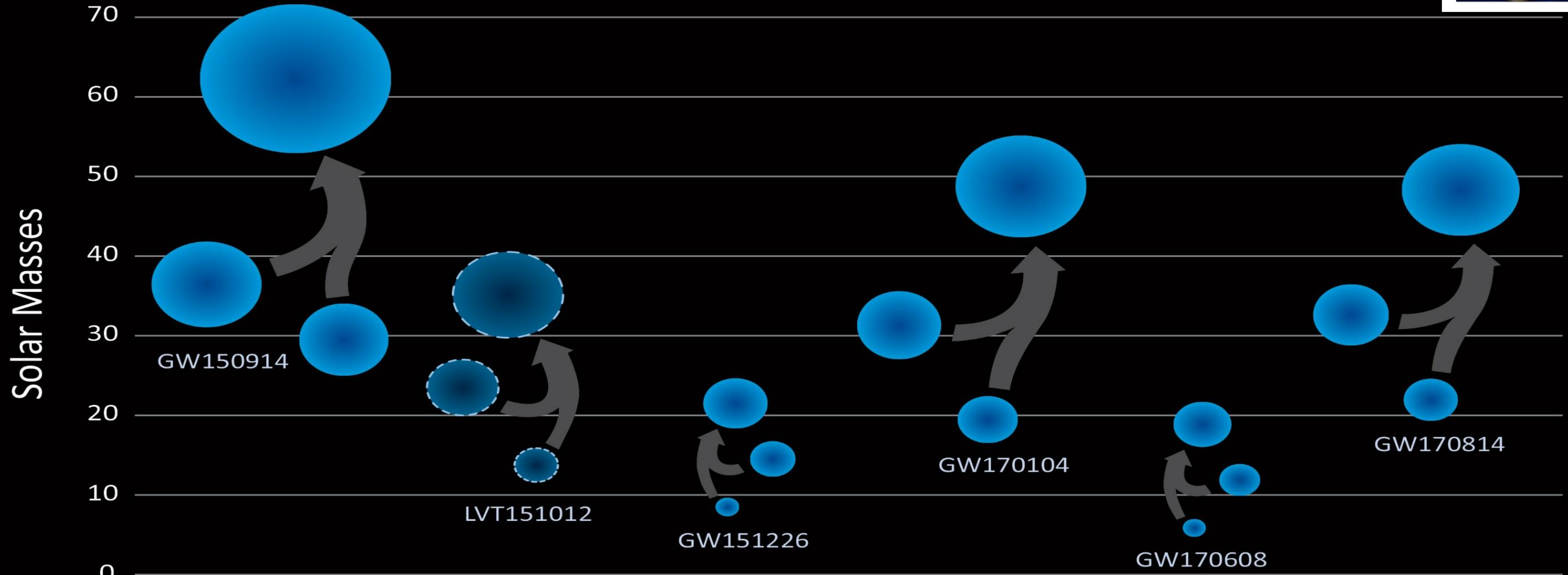
Latest science operations

- Adv. LIGO completed 2nd run (O2: Nov 2016 – Aug 2017)
- Adv. Virgo joined network in Aug 2017, allowing localisation of sources via triangulation
- LISA Pathfinder completed main mission and one extension (May 2016 – July 2017)





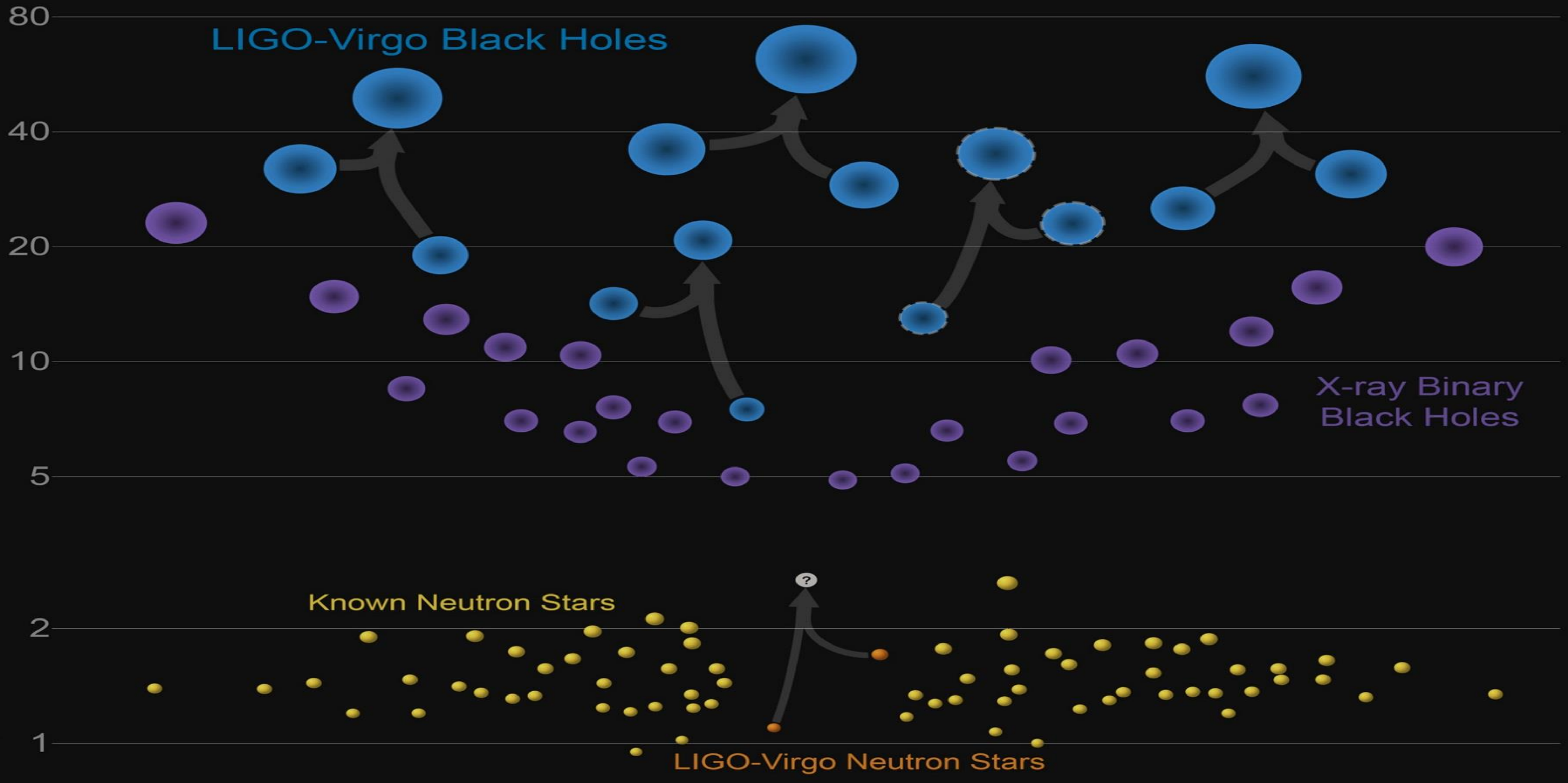
Black Holes of Known Mass



LIGO/VIRGO

Masses in the Stellar Graveyard

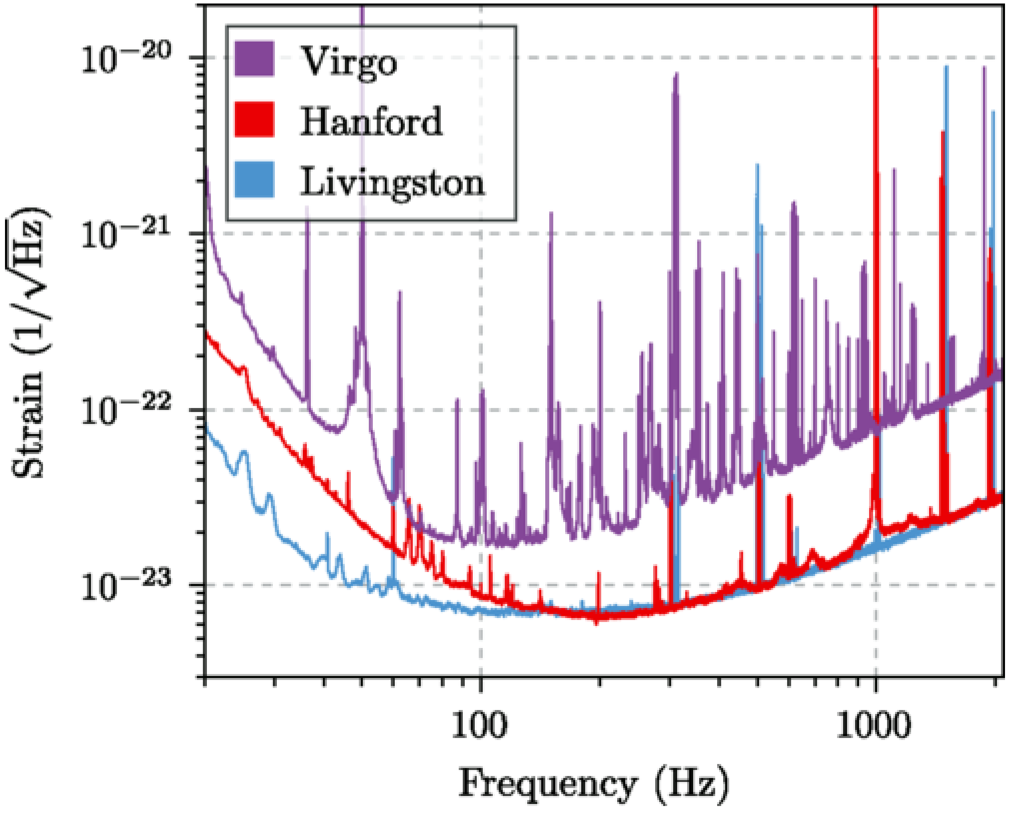
in Solar Masses

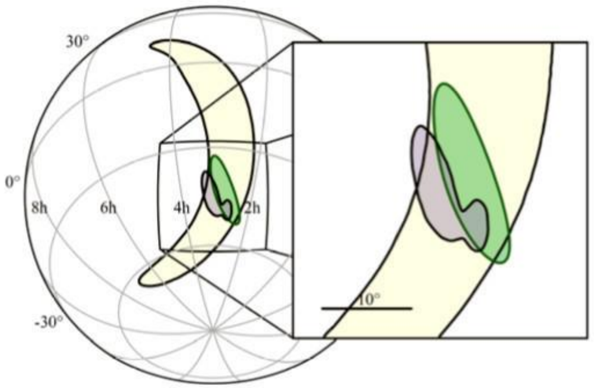


Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate FAR/yr^{-1}	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\sigma$	$> 5.3\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathcal{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_{\mathrm{f}}^{\mathrm{source}}/\mathrm{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_{f}	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s}^{-1})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600

Primary black hole mass m_1	$30.5^{+5.7}_{-3.0} M_\odot$
Secondary black hole mass m_2	$25.3^{+2.8}_{-4.2} M_\odot$
Chirp mass $\mathcal{M}$	$24.1^{+1.4}_{-1.1} M_\odot$
Total mass M	$55.9^{+3.4}_{-2.7} M_\odot$
Final black hole mass M_f	$53.2^{+3.2}_{-2.5} M_\odot$
Radiated energy $E_{\rm rad}$	$2.7^{+0.4}_{-0.3} M_\odot c^2$
Peak luminosity $\ell_{\rm peak}$	$3.7^{+0.5}_{-0.5} \times 10^{56}$ erg s^{-1}
Effective inspiral spin parameter $\chi_{\rm eff}$	$0.06^{+0.12}_{-0.12}$
Final black hole spin a_f	$0.70^{+0.07}_{-0.05}$
Luminosity distance D_L	540^{+130}_{-210} Mpc
Source redshift z	$0.11^{+0.03}_{-0.04}$

Abbott, B et al., PRL, 119, 141101 (2017)





Gravitational wave source localisation.

Yellow : Localisation obtained using two LIGO detectors only.

Green : Localisation obtained using all three detectors LIGO and Virgo, from real-time fast analysis.

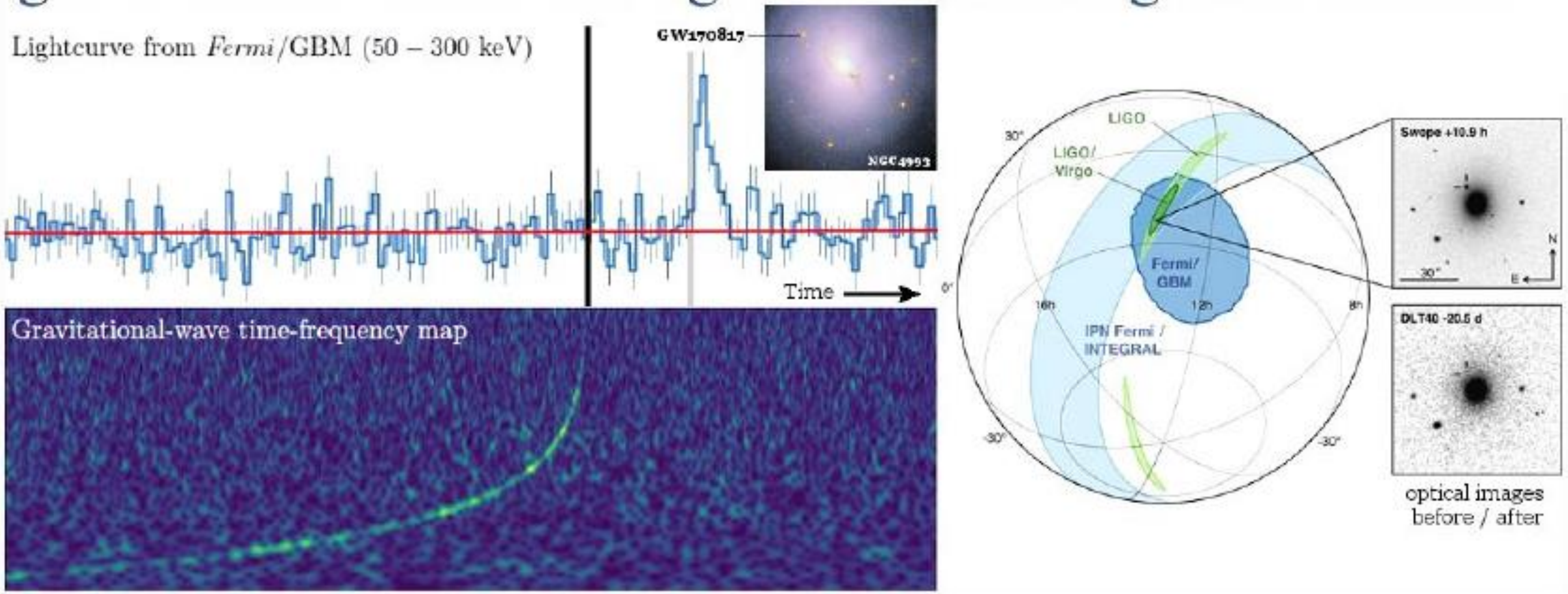
Mauve: Localisation obtained after more powerful post-analysis

(c) collaboration LIGO-Virgo

Science Highlights

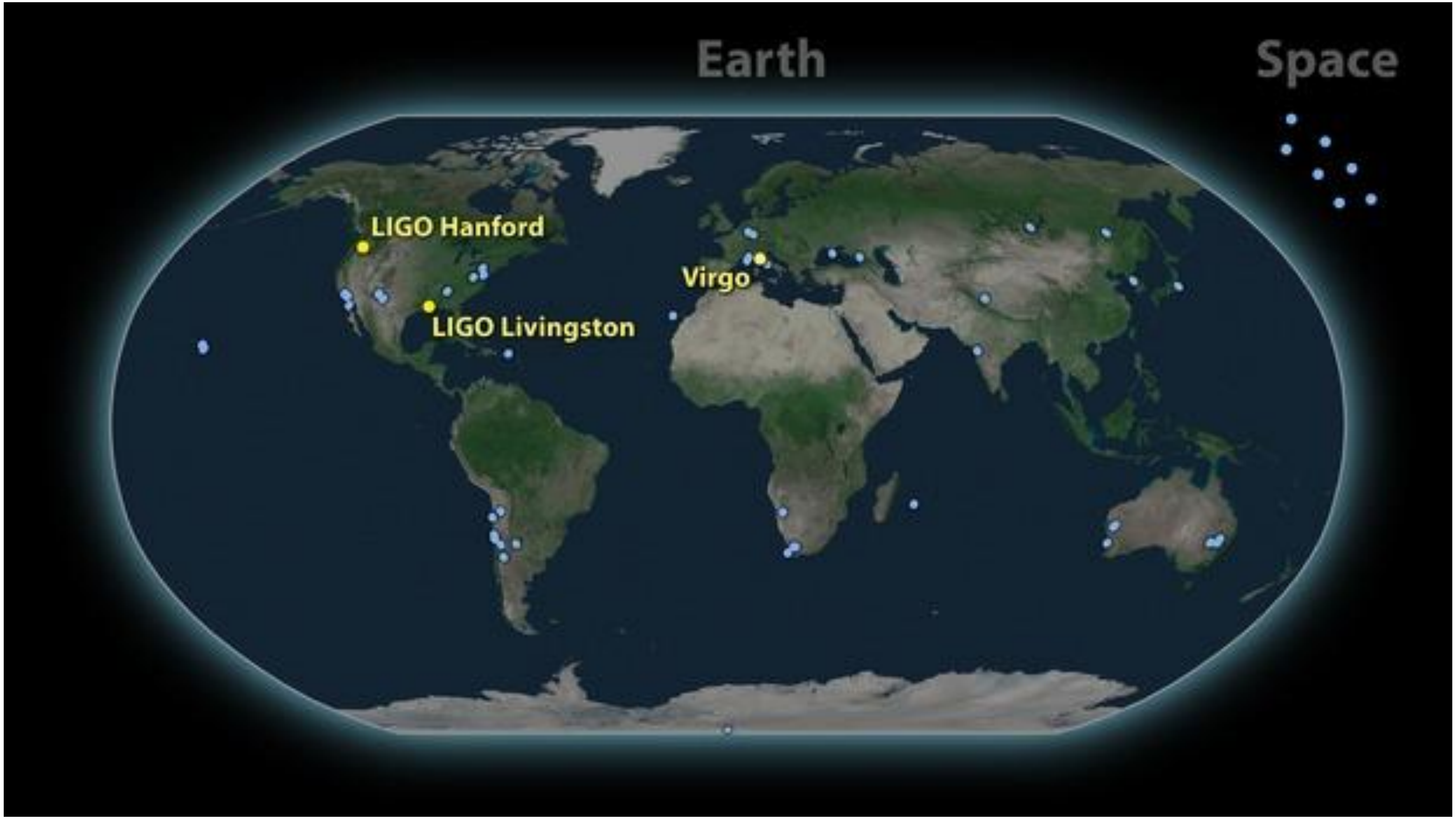
- A new class of high-mass black-hole binary
- ‘Standard’ GR template provides good fit
- Masses of progenitor BHs (~15%)
- Mass of final BH (~10%)
- Final mass spin (~10%)
- Energy loss (~15%)
- Distance (~30%) – NO COUNTERPARTS
- Power output (~25%)
- 12-213 BH-BH mergers Gpc^{-3}/year
- [Re-energised primordial black holes as dark matter]

LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars

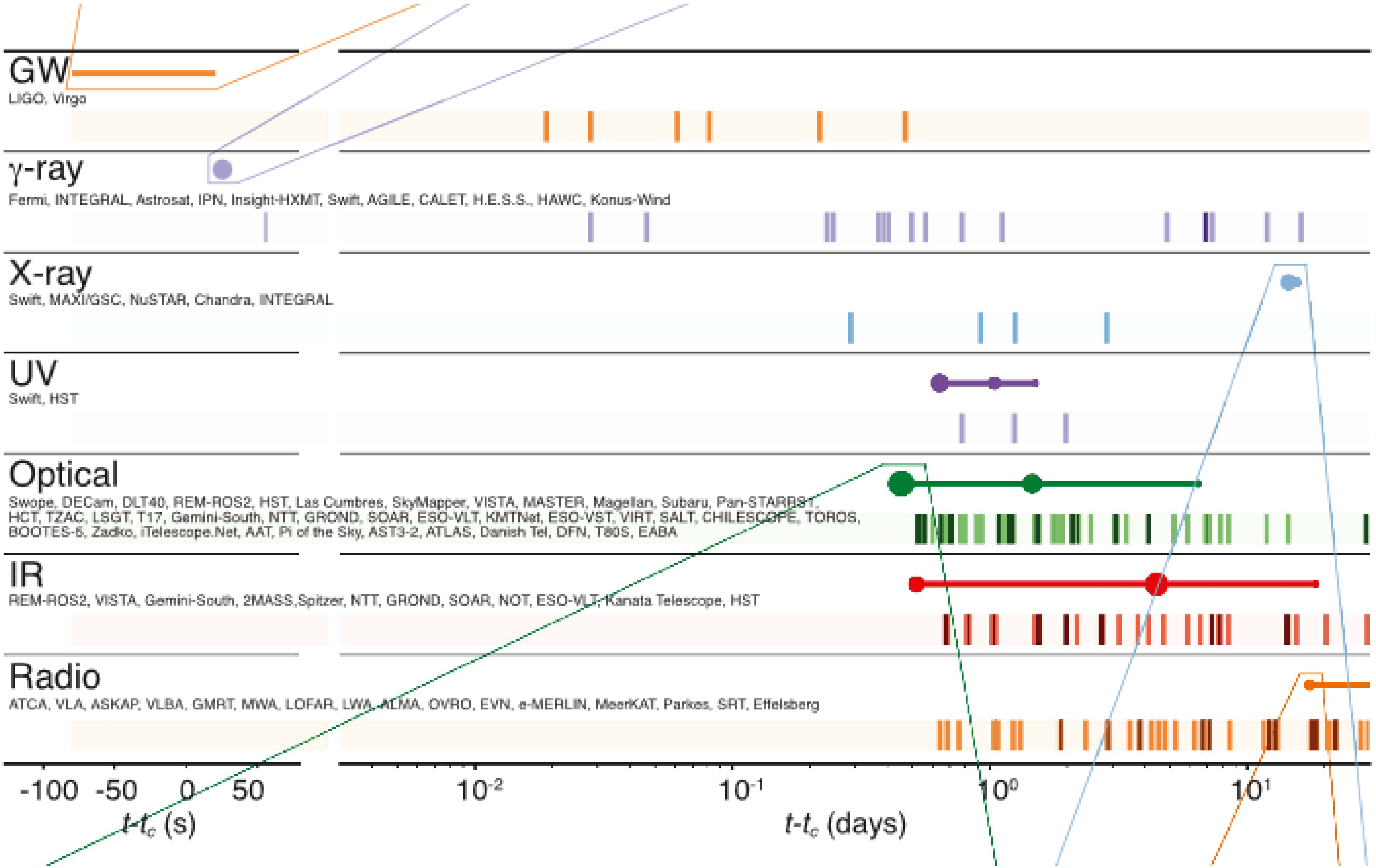


- Multi-messenger astronomy!
- Observed GW from matter
- Evidence for link between BNS and some sGRB
- Tight constraint of speed of GW
- Setting constraint on EOS of neutron stars
- Good sky localisation allowed finding optical counter part and identification of host galaxy.
- Many telescopes around the globe and in space joined observation campaign.
- Enabled observation of kilonova.

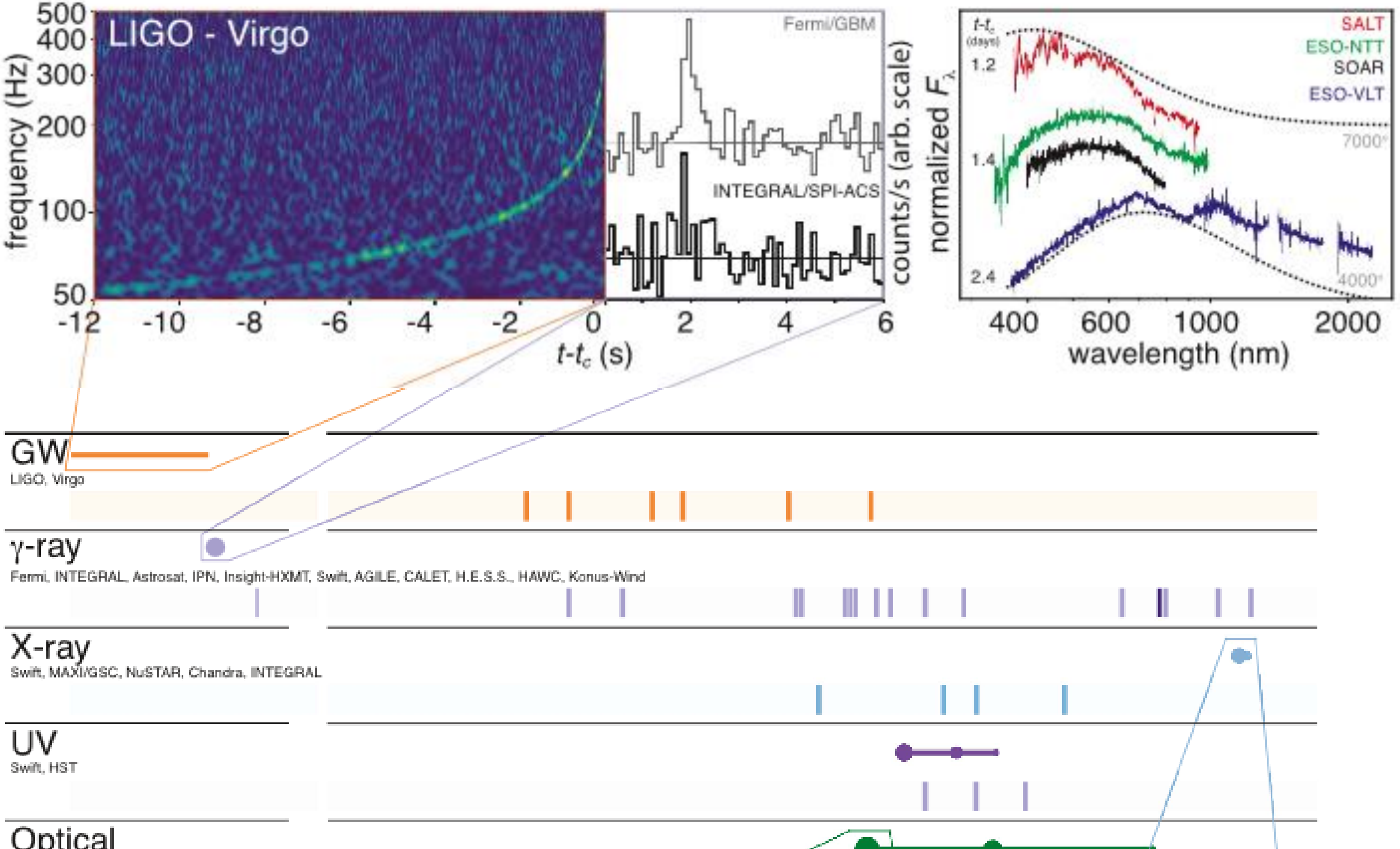
8



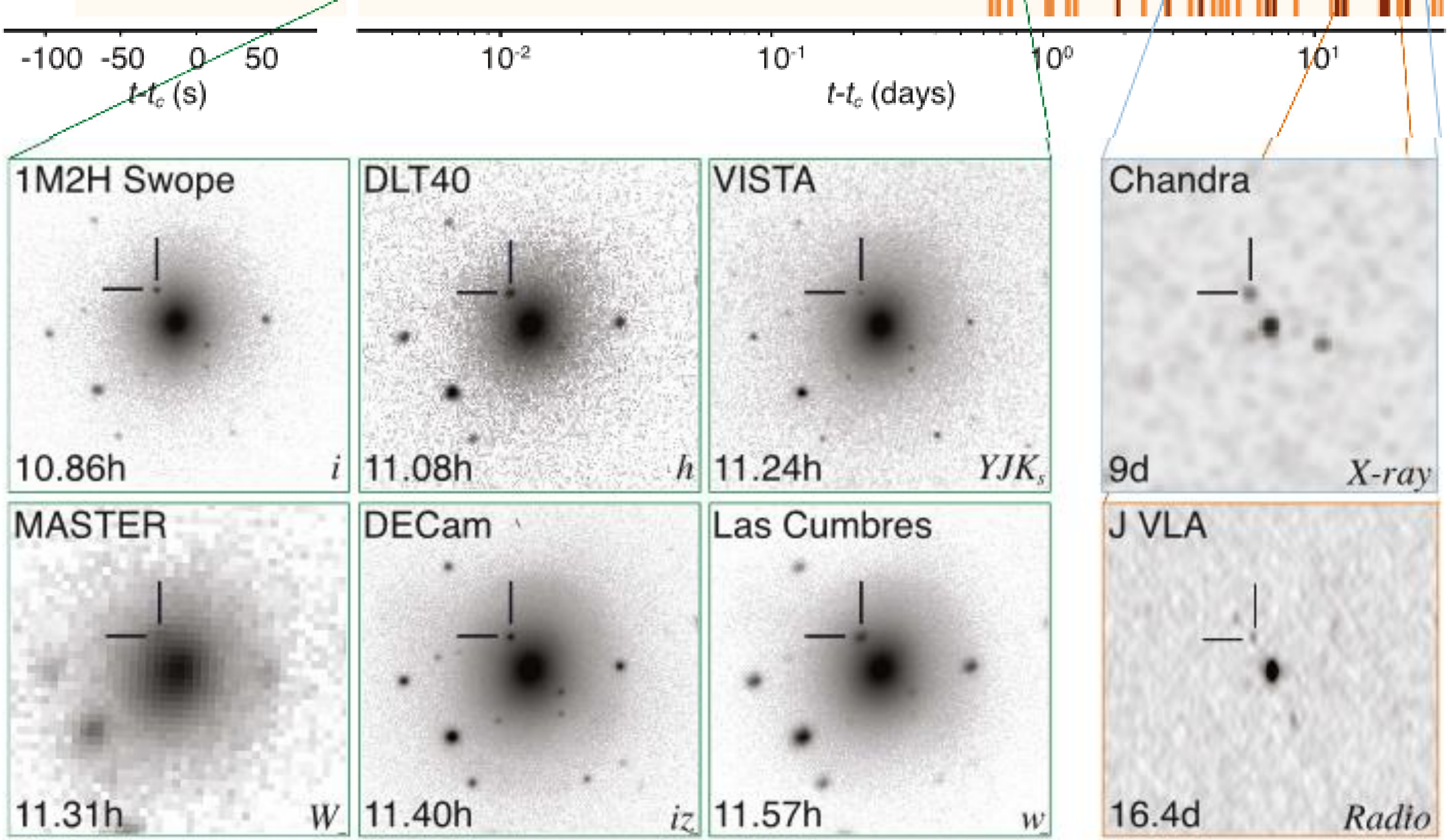
A global multi-messenger observation – gw, gamma, opt, ir, radio from 70 observatories



Abbott, B et al., AJL, 848;L12 (2017)

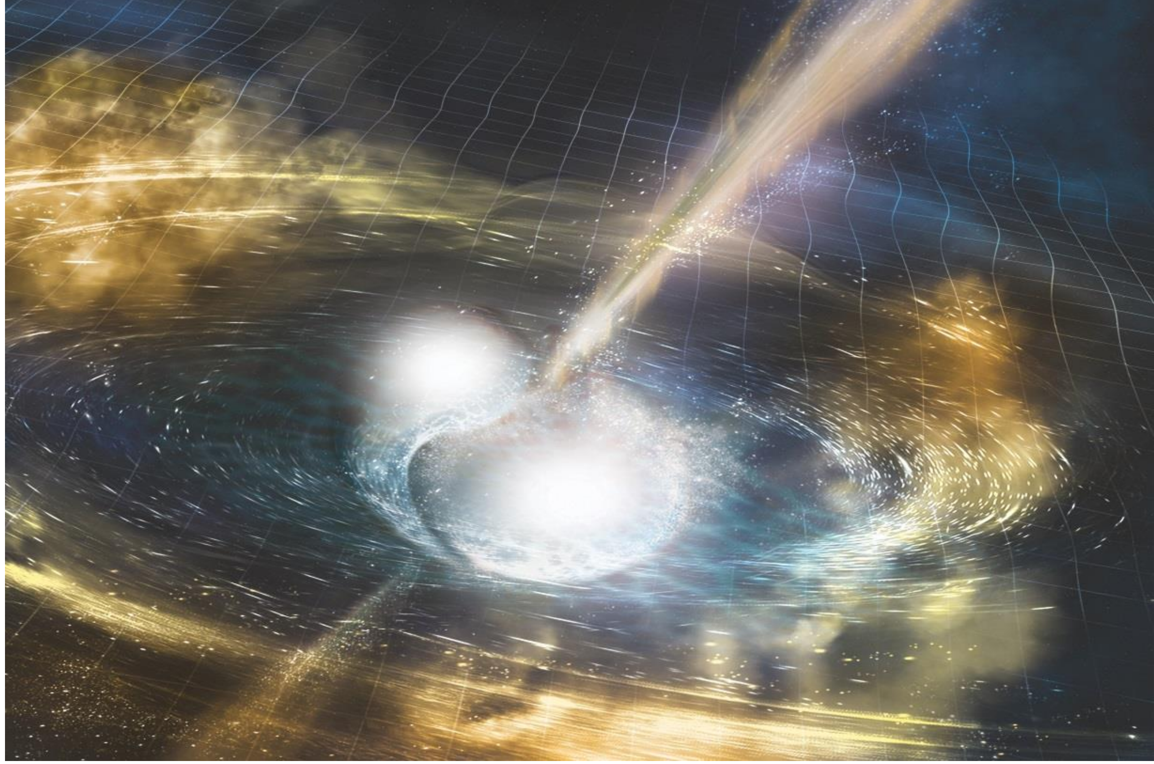


LIGO - Virgo
frequency (Hz)
t-t_c (s)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
normalized F_λ
wavelength (nm)
SALT
ESO-NTT
SOAR
ESO-VLT
7000°
4000°
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical

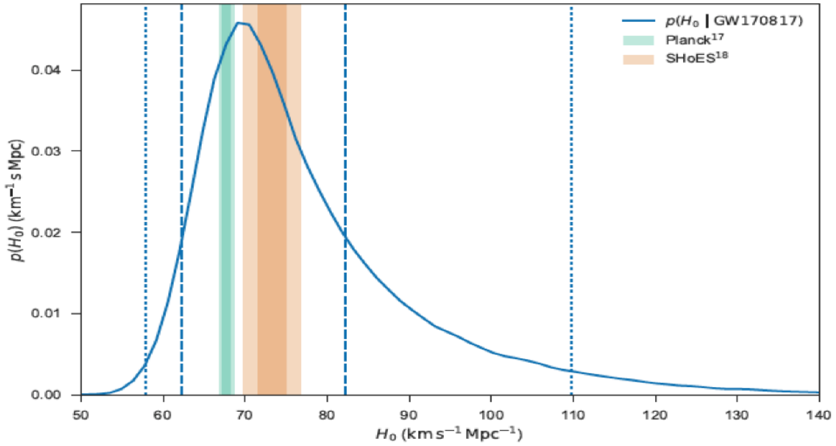

-100
-50
0
50
t-t_c (s)
10^-2
10^-1
10^0
10^1
t-t_c (days)
1M2H Swope
10.86h
i
DLT40
11.08h
h
VISTA
11.24h
YJKs
Chandra
9d
X-ray
MASTER
11.31h
W
DECam
11.40h
iz
Las Cumbres
11.57h
w
J VLA
16.4d
Radio

Key Results

- GW luminosity distance 43.8 +2.9/-6.9 Mpc.
- GW SNR 32.4
- GW Primary M_1 was 1.36-2.26 M_{solar}
- GW Primary M_2 was 0.86-1.36 M_{solar}
- GW chirp mass 1.188 +.004/-.002 M_{solar}
- GW Primary $M_1 + M_2$ was 2.82 +0.47/-.09 M_{solar}
- GW-GRB delay 1.74 +/- 0.05s
  - $|\Delta c|/c < 3 \times 10^{-15}$
  - Competitive limits on Lorentz violations
  - EP for GW vs EM – new limit
- Counterpart in NGC4993 at ~40 Mpc (41.1+/-5.8)
- Binary Neutron Star merger producing
  - a sGRB
  - Kilonova (seen in optical, ultraviolet and ir)
  - Delayed x-rays and radio from environment
- Consistent Ho (70+12/8 km/s/Mpc)



NSF/LIGO/Sonoma State University/A. Simonnet



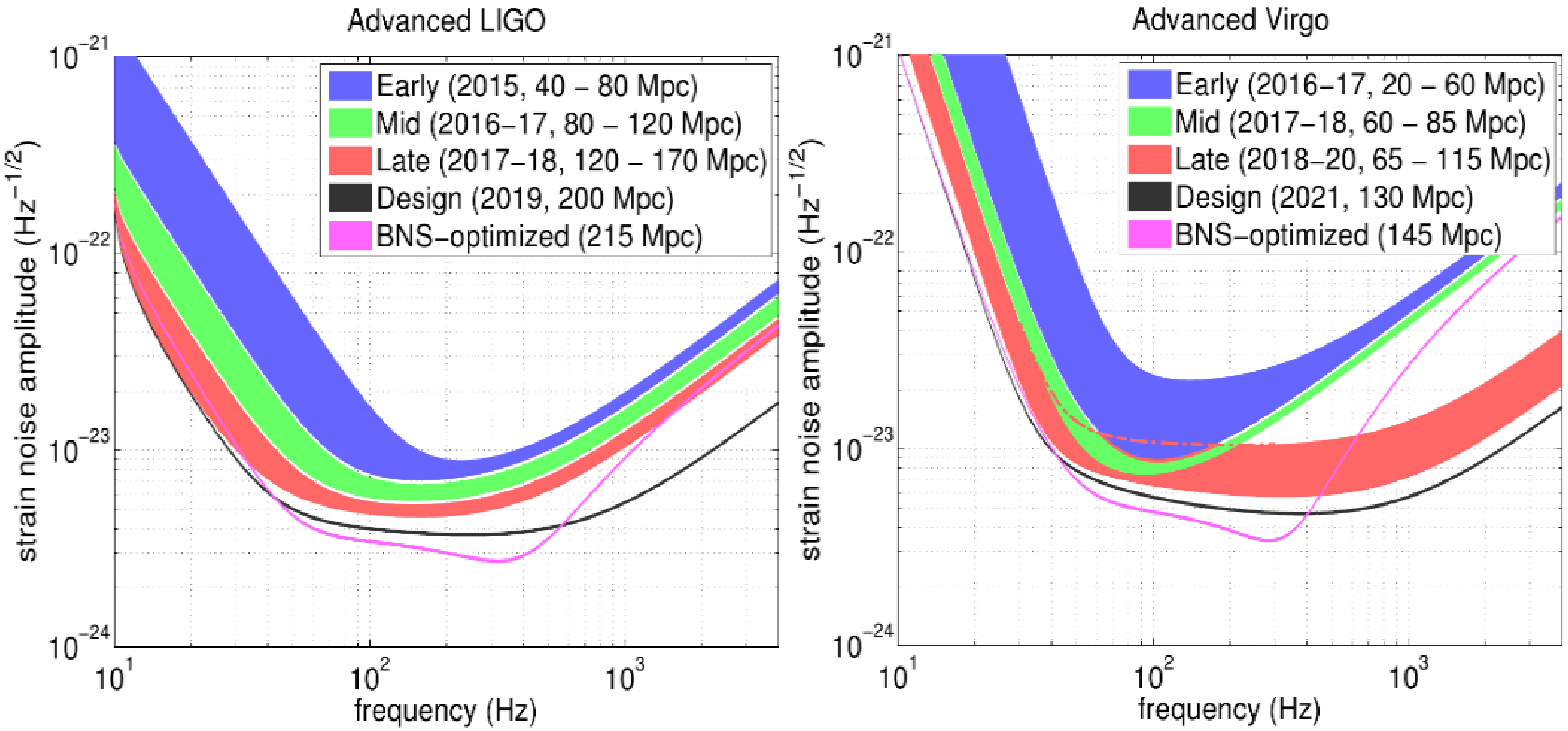
Gravitational Wave Astronomy

Adv. LIGO and Adv. Virgo to start ~1 year long O3 run late in 2018

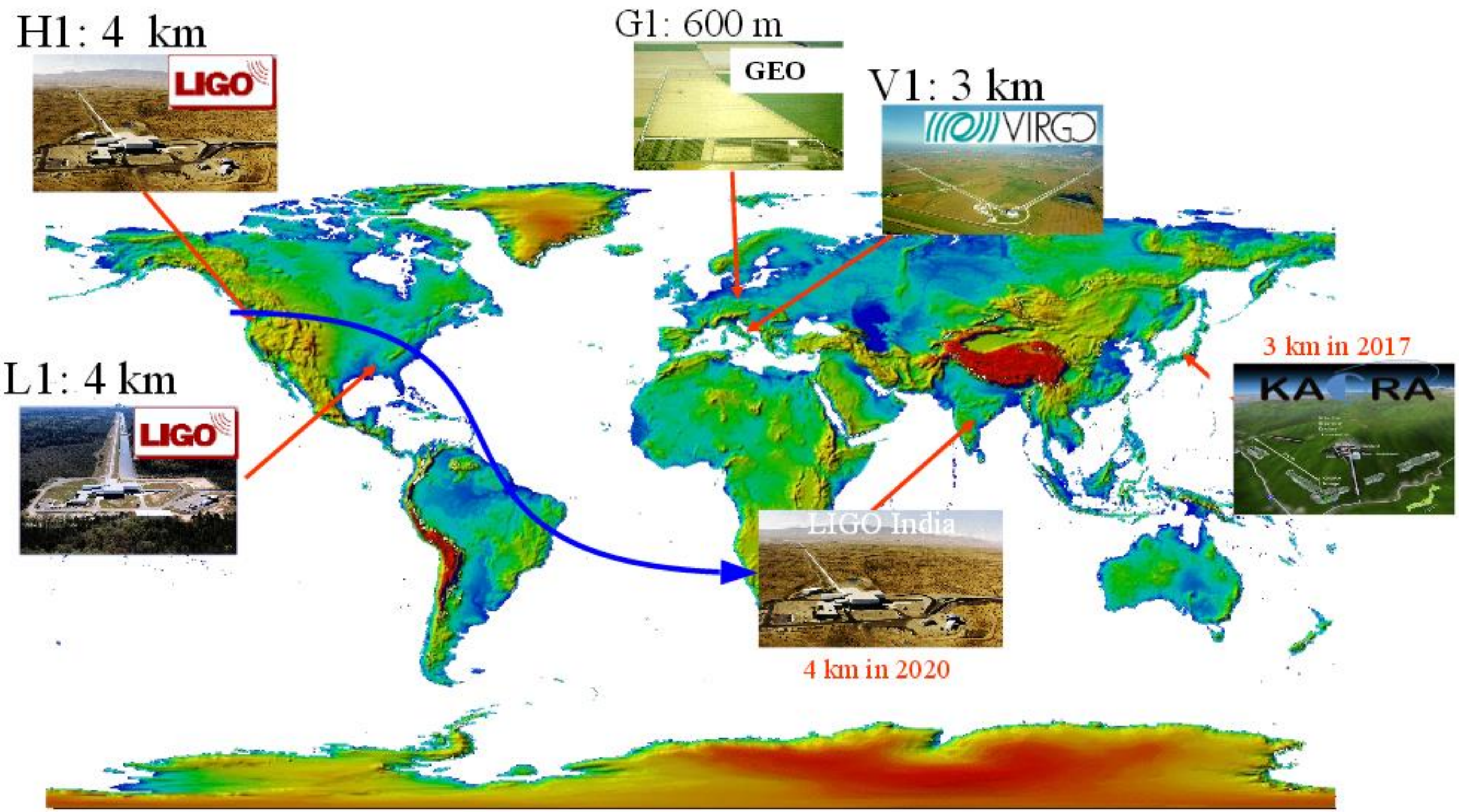
- LIGO with NS-NS 'reach' of ~120 Mpc (was ~70 Mpc in O2), Virgo ~65 Mpc;
- What can we expect from O3? Best guesses:
  - Binary Black Holes: Several per month to several per week
  - Binary Neutron stars: 1 to 10 in the year-long run
  - NSBH: N=0 not ruled out in any scenario, most give ~50% N>0
- Japanese KAGRA detector expected to join as fourth detector towards the end of O3;

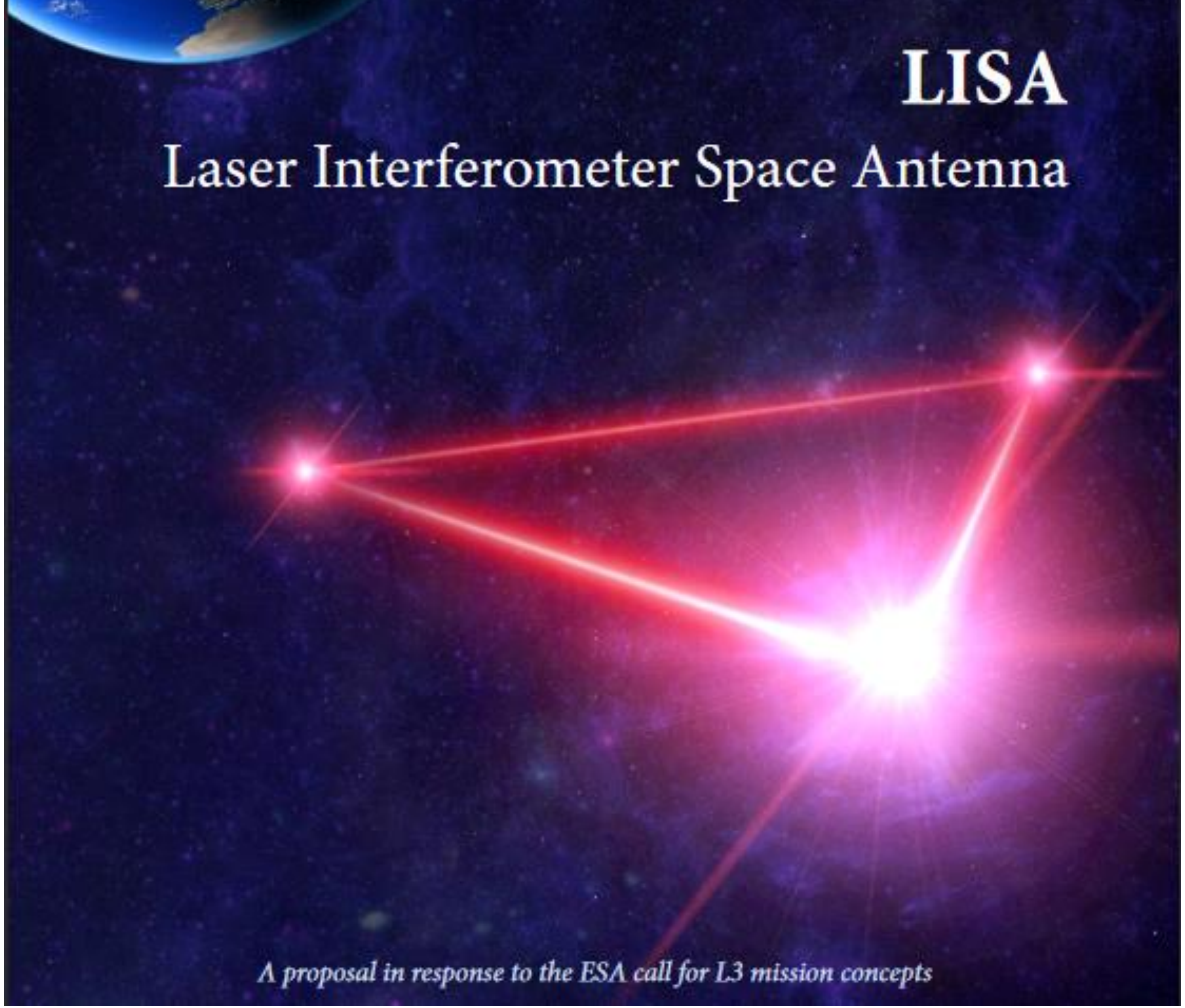
Plans for upgrading GW observatories

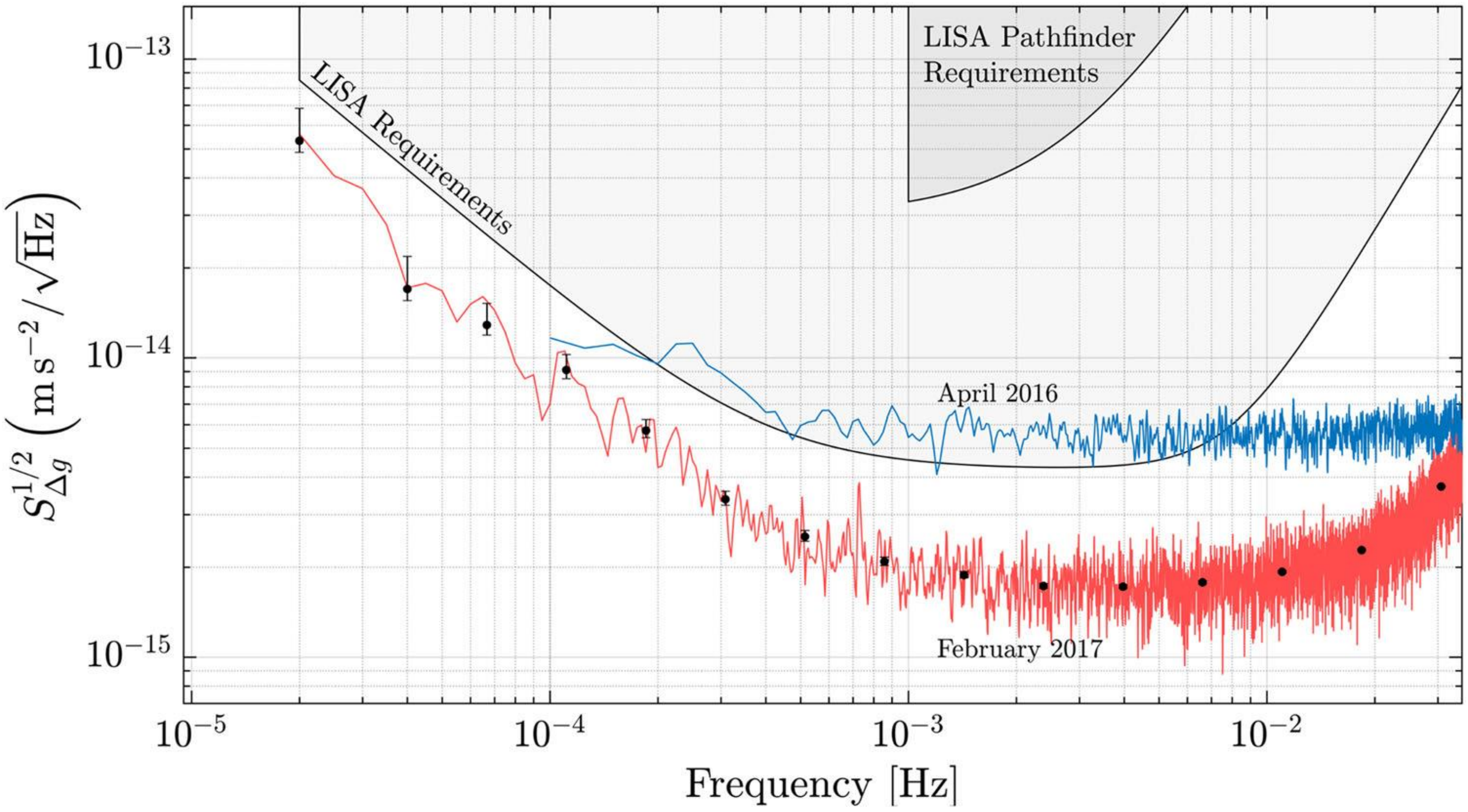
- Work underway on maximising performance of advanced detectors in their infrastructures (Strong UK contribution to research towards Advanced LIGO upgrades)
- UK current Chair of Gravitational Wave International Committee (GWIC) coordinates work on 3G detectors: Einstein Telescope (in Europe), Cosmic Explorer (in US)
- **Space-based GW** (complementary in signal frequency + obtainable science) pushed forward in parallel: LISA was selected in June 2017 for L3 mission (~2034).



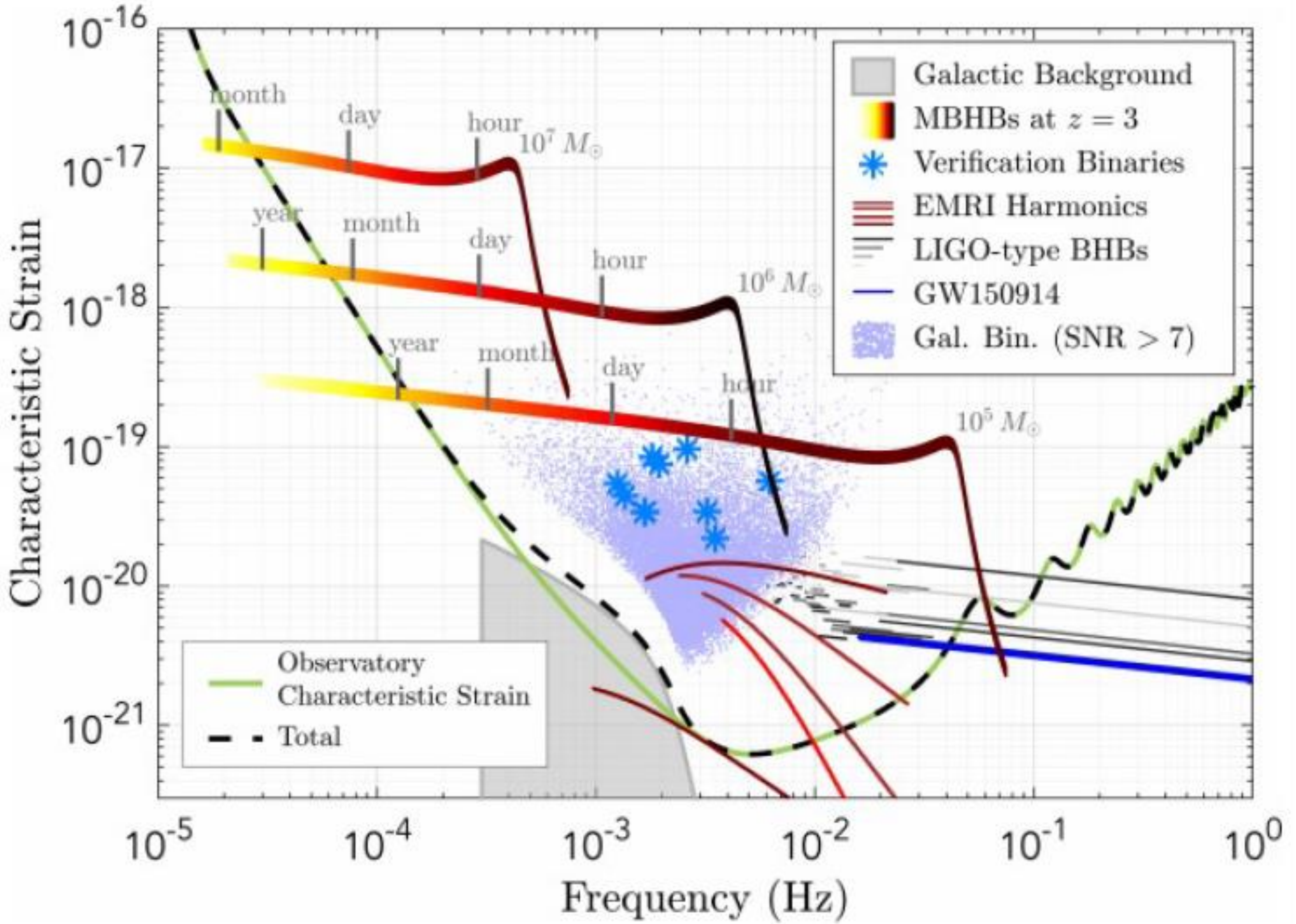
distance x 10 → volume x 10^3


H1: 4 km
LIGO
G1: 600 m
GEO
V1: 3 km
VIRGO
L1: 4 km
LIGO
3 km in 2017
LIGO India
4 km in 2020

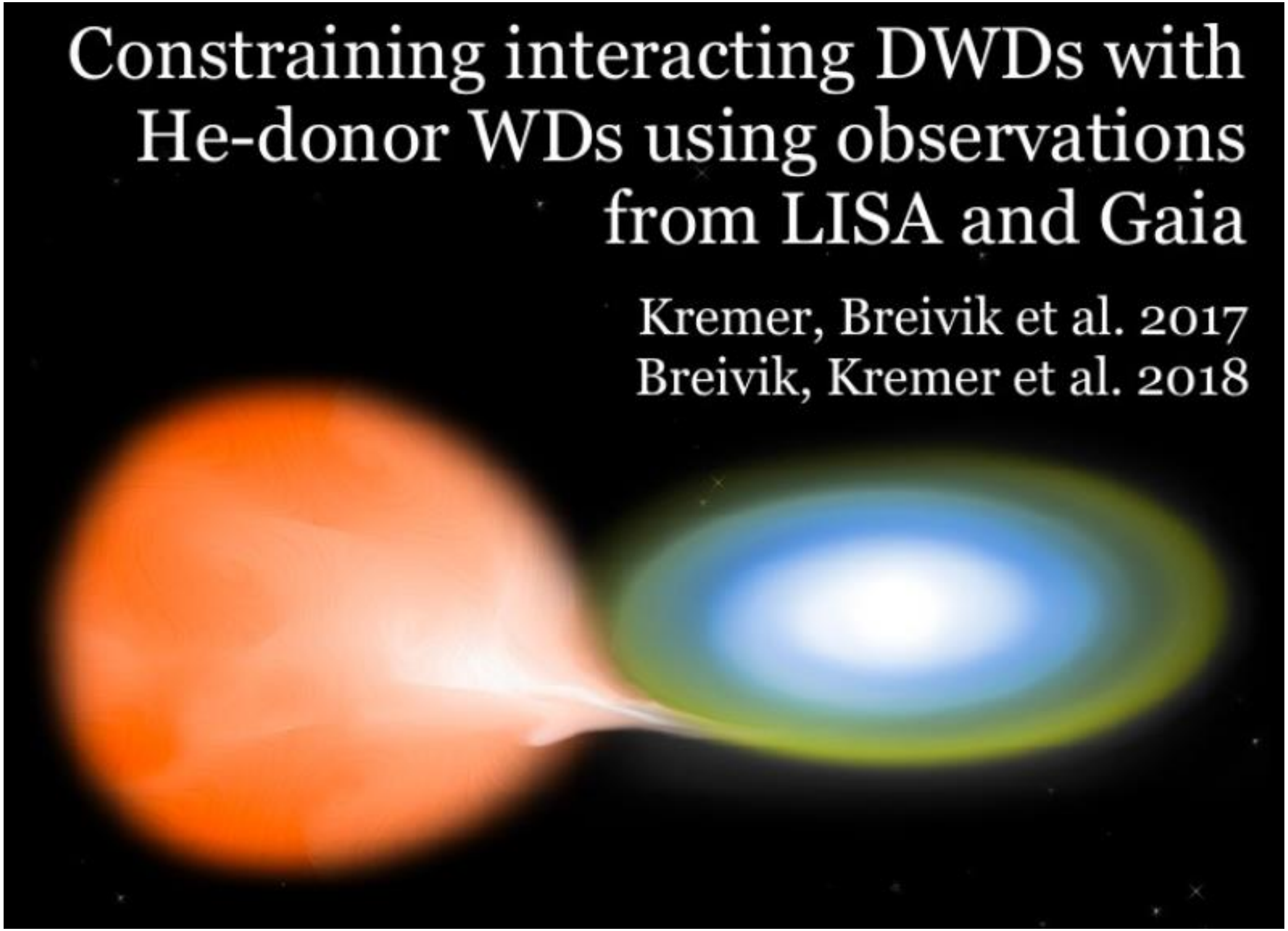

LISA
Laser Interferometer Space Antenna
A proposal in response to the ESA call for L3 mission concepts

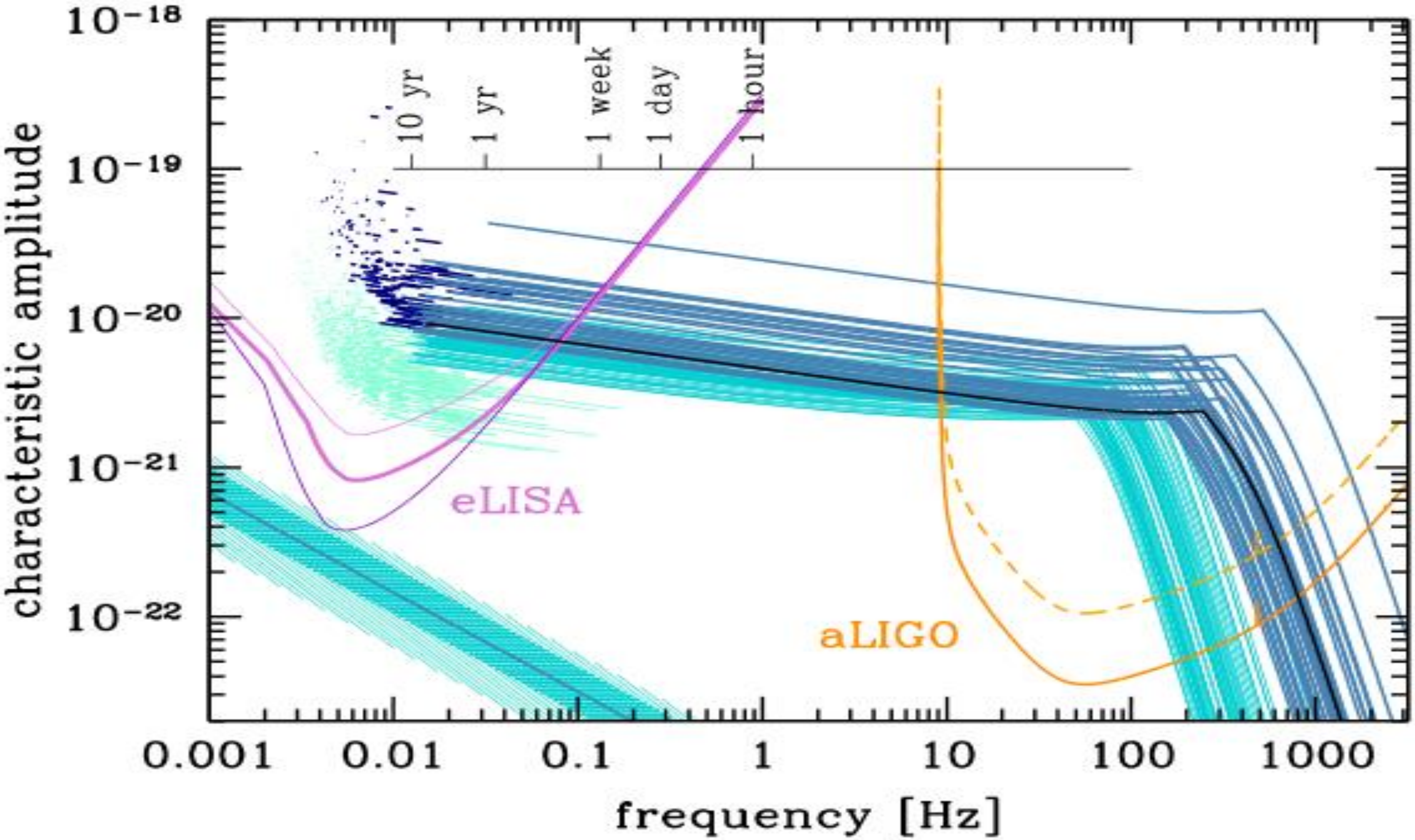

LISA Pathfinder Requirements
LISA Requirements
April 2016
February 2017
10^{-13}
10^{-14}
10^{-15}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
Frequency [Hz]
$S_{\Delta g}^{1/2}\left(\mathrm{m\,s^{-2}}/\sqrt{\mathrm{Hz}}\right)$


PHYSICAL REVIEW LETTERS
Articles published week ending 10 JUNE 2016
Published by
American Physical Society
APS physics
Volume 116, Number 23



Galactic Background
MBHBs at $z = 3$
Verification Binaries
EMRI Harmonics
LIGO-type BHBs
GW150914
Gal. Bin. (SNR > 7)
Observatory Characteristic Strain
Total
month
day
hour
$10^7 M_\odot$
year
month
day
hour
$10^6 M_\odot$
year
month
day
hour
$10^5 M_\odot$
Characteristic Strain
Frequency (Hz)
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}

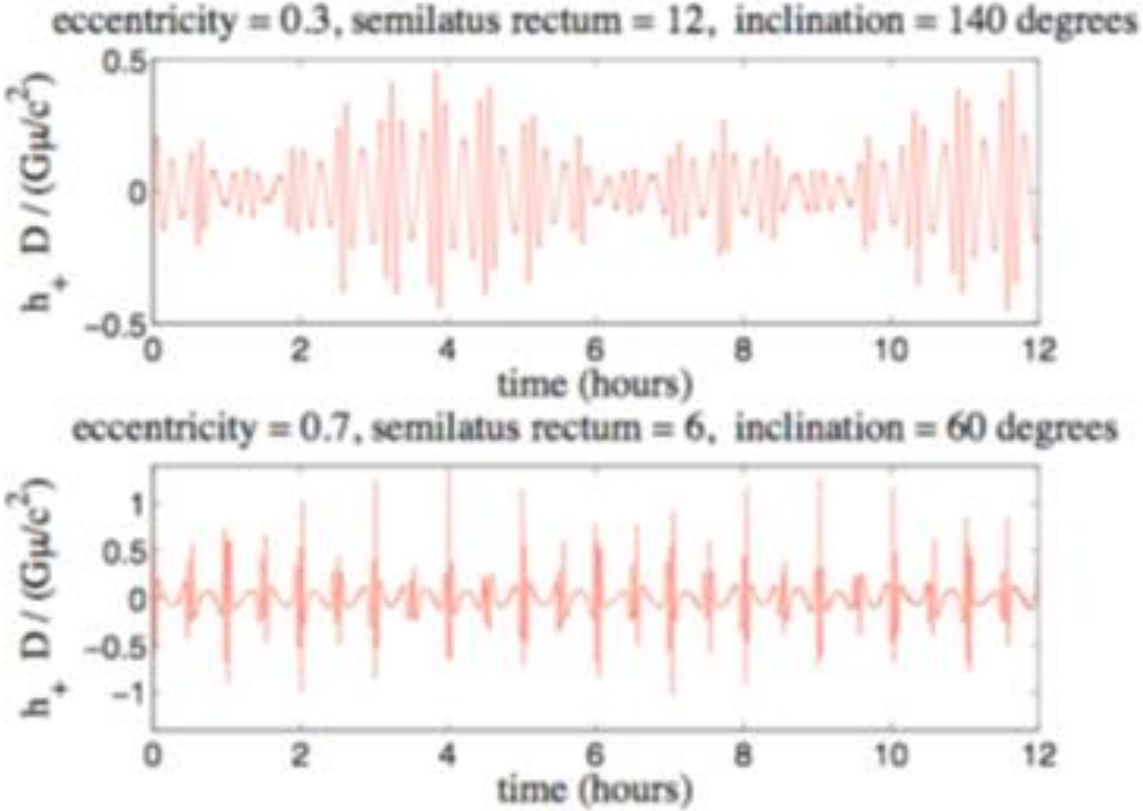

Constraining interacting DWDs with He-donor WDs using observations from LISA and Gaia
Kremer, Breivik et al. 2017
Breivik, Kremer et al. 2018

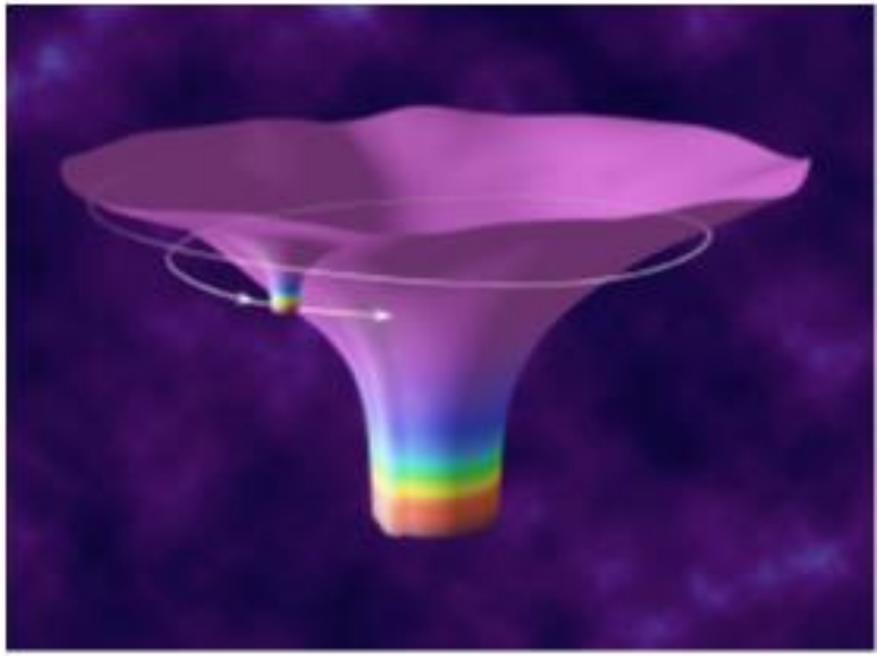


characteristic amplitude
frequency [Hz]
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
0.001
0.01
0.1
1
10
100
1000
10 yr
1 yr
1 week
1 day
1 hour
eLISA
aLIGO

Confronting GR

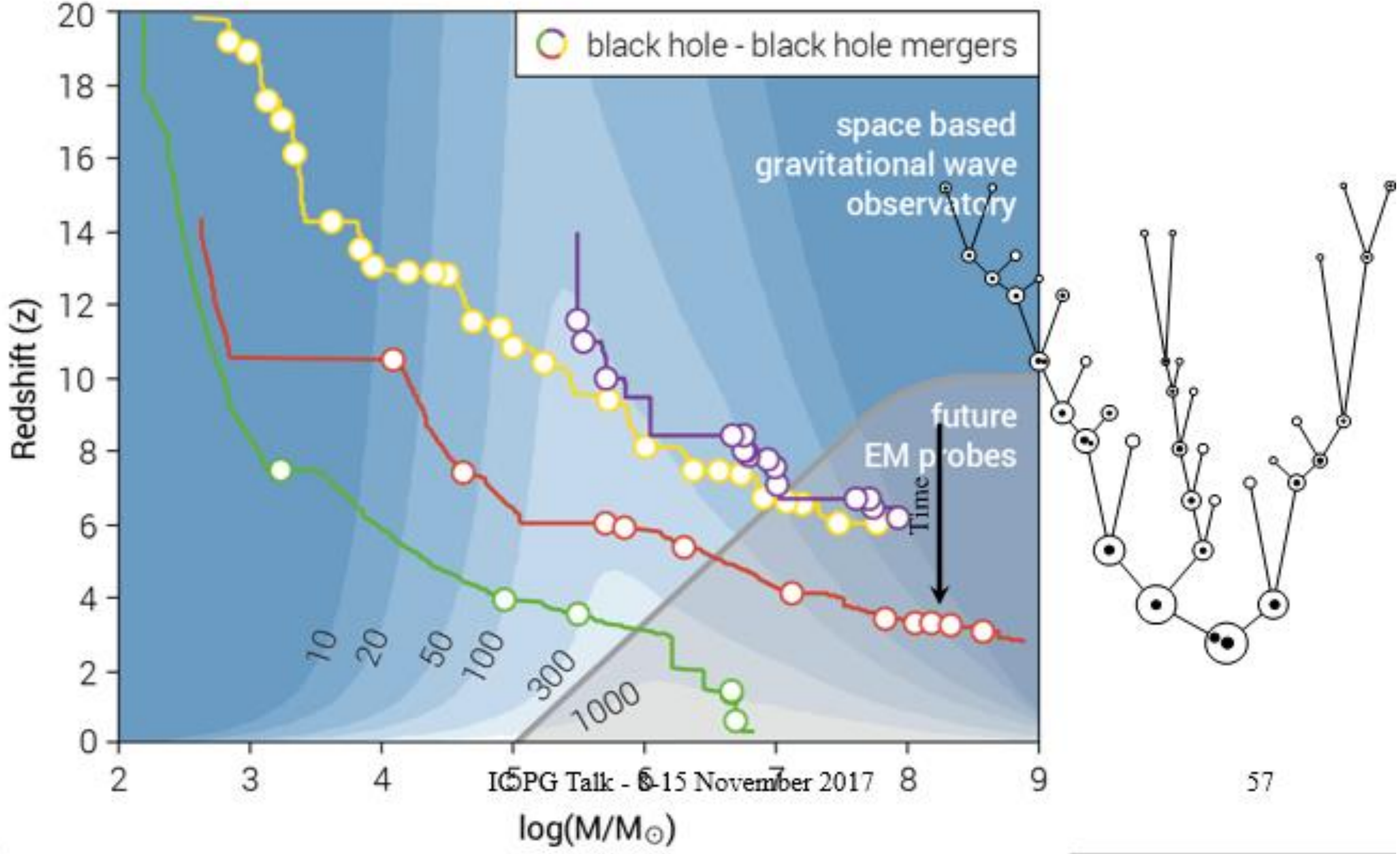
- Extreme Mass Ratio In-spirals

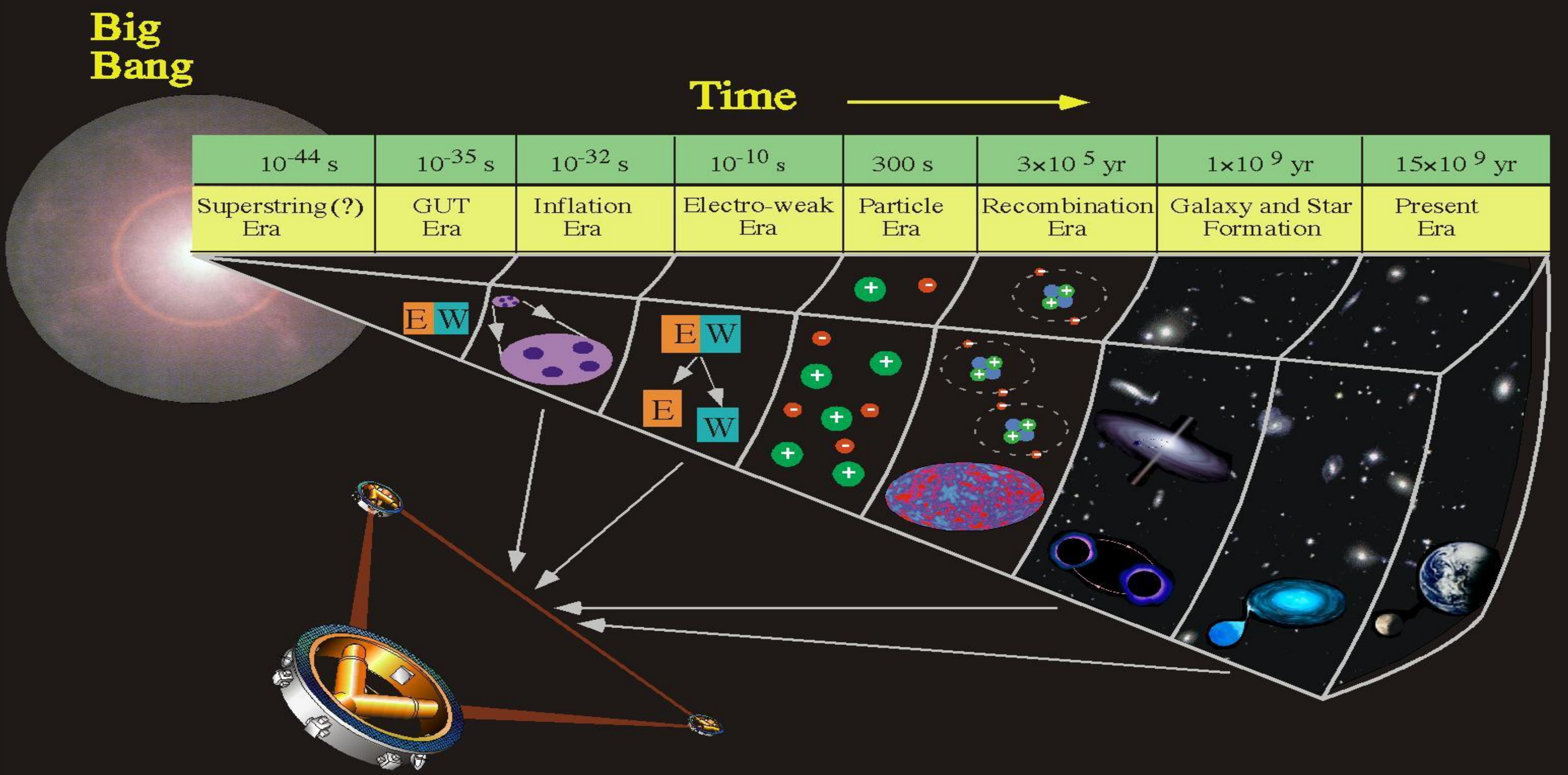




ΔM_2 to 10^{-2} to 10^{-4}

All galaxy mergers cross eLISA band





Big Bang
Time
10^{-44} s
10^{-35} s
10^{-32} s
10^{-10} s
300 s
3×10^{5} yr
1×10^{9} yr
15×10^{9} yr
Superstring (?) Era
GUT Era
Inflation Era
Electro-weak Era
Particle Era
Recombination Era
Galaxy and Star Formation
Present Era
E W
E W
E
W

Schedule Dates

Event	From	To	Status
Phase 0 for instrument contributions	**2017-JUL**	**2017-NOV**	**Done**
Mission Definition Review (MDR)	**2017-NOV-27**		**Done**
Phase A (mission **& instruments**)	2018-APR	2019-DEC	
Mission Consolidation Review (MCR)	2019-FEB	2019-MAR	
Mission Formulation Review (MFR)	2019-OCT	2019-DEC	
Adoption	<=2024		
Implementation (Phase B2/C/D)	8.5-9 years		
Launch			
Transfer & Commissioning	2.5 years		
Operations	4 years		
Extension (TBD)	6 years		10 years total of science

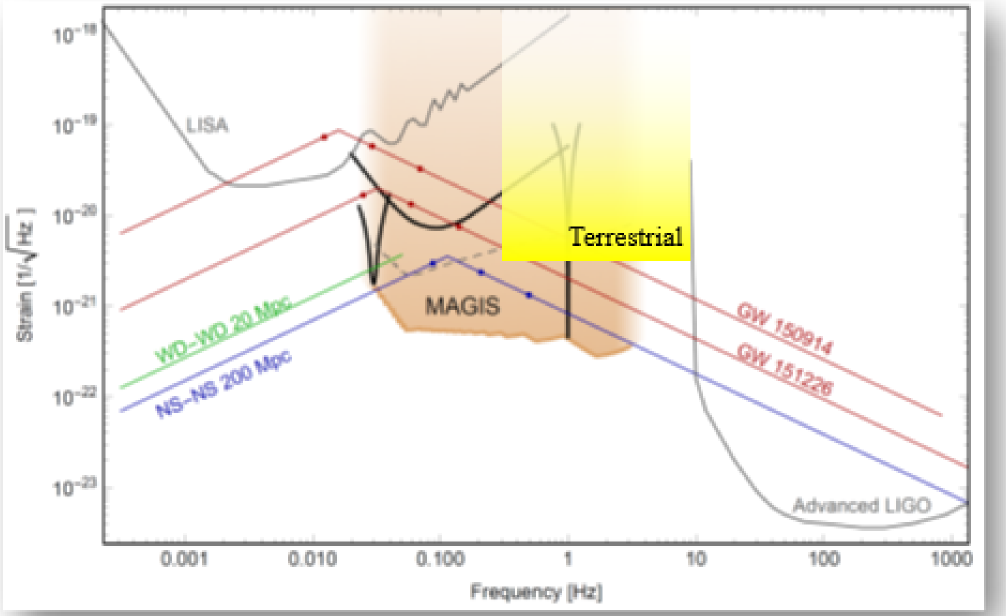
Future Plans – Other Opportunities

http://www.fnal.gov/pub/science/particle-physics/quantum/#magis

Mid-band Gravitational Wave Detection with Quantum Sensors: MAGIS-100

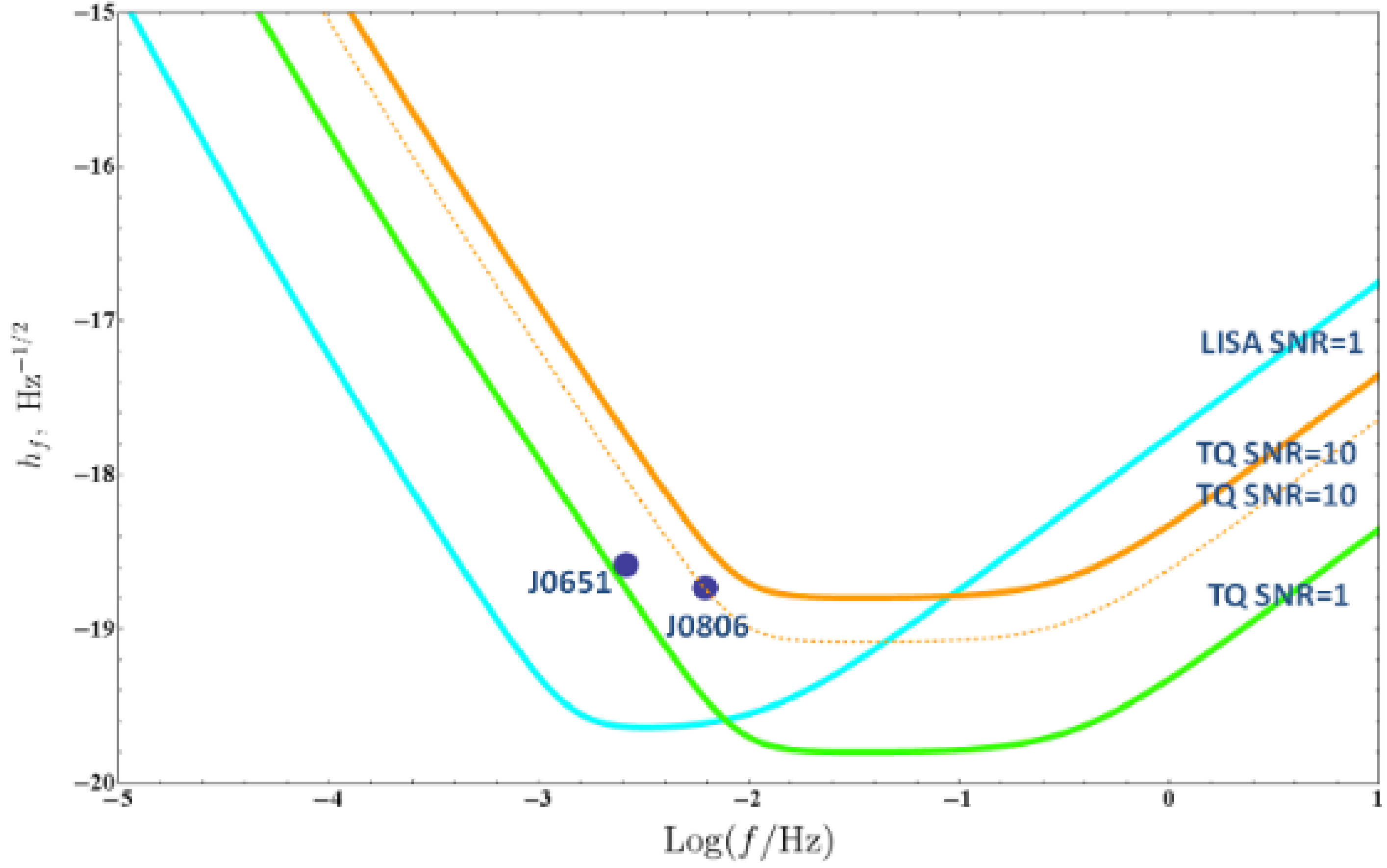
- 100m quantum sensor at Fermilab using atom-interferometry
- Based in the vertical NUMI access shaft
- Test-bed for 1km device (in yellow), at Homestake
- Also sensitive to tests of **axion dark matter**
- and Macroscopic tests of Quantum Mechanics

Atom Interferometry



- Stanford U.
- FNAL
- U.C. Berkeley
- NIU
- U. Liverpool

Future Plans – Other Opportunities

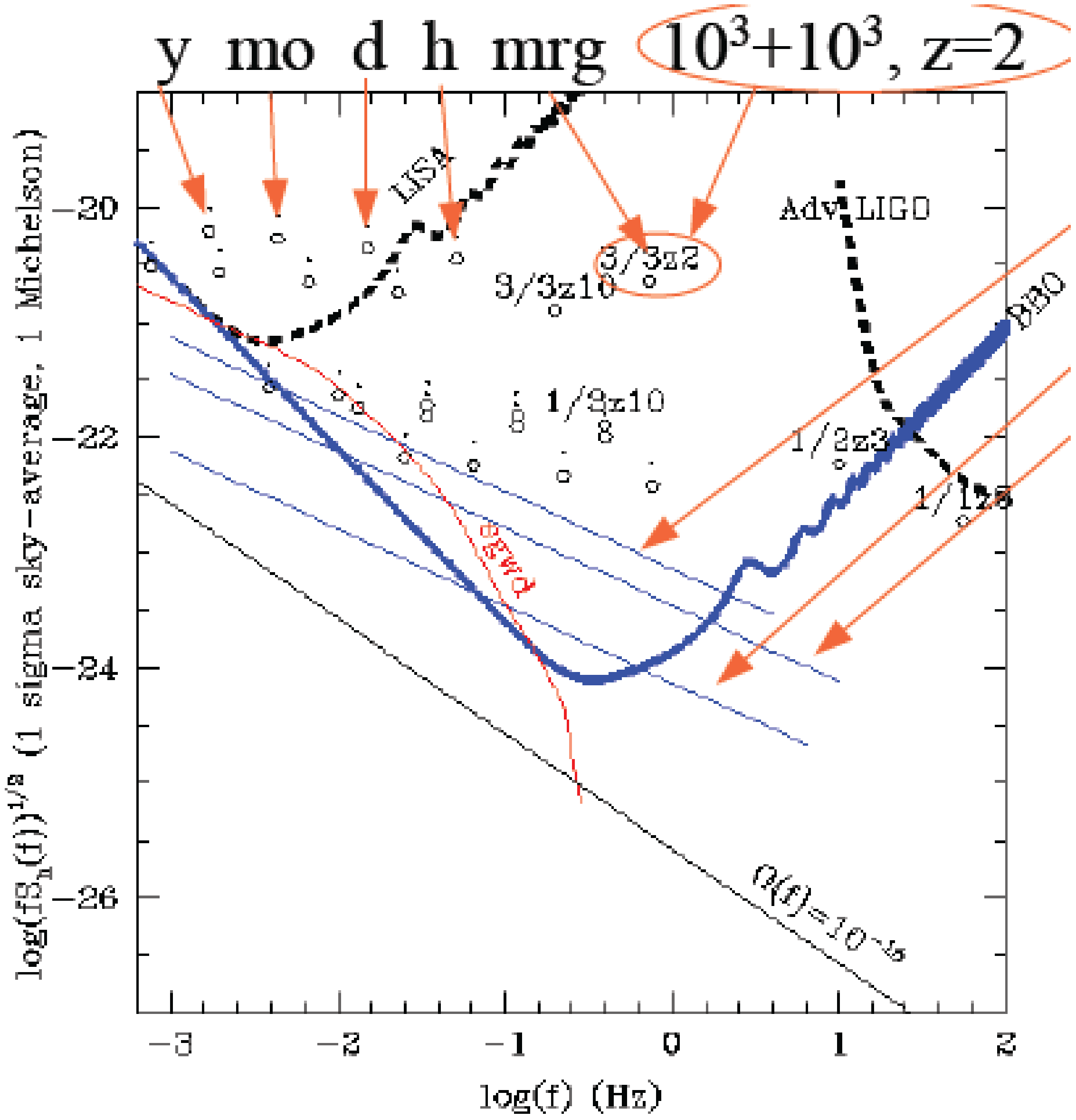


TianQin Chinese Space Observatory
- LISA-like shorter arms

Luo, J et al., CQG 33 (2016)

Some UK groups hosting PhDs and RAs from China

Future Plans – Other Opportunities



Big Bang Observer (BBO)
- Multi-LISA very short arm

Phinney S + LIST, inc UK (2004)

Main funding routes for UK groups

ALIGO – STFC
ET – EU?
LISA – UKSA [– already closed for further applications 20 years before launch!]

Growing discipline, with faculty hiring, in stagnant environment, but

GCRFs – STFC

- UK-India ground-based collaboration
- UK-China ground and space based collaborations

UK Involvement

Advanced LIGO/Virgo

Birmingham
Cardiff
Edinburgh
Glasgow
Kings College
Manchester
Sheffield
Southampton
Strathclyde
West Scotland

Multi-messenger (NSB observations)

Bath
Cambridge
Leeds
Leicester
Liverpool
Liverpool John M
MSSL (UCL)
Nottingham
Oxford
Portsmouth
St. Andrews
Surrey
Sussex
UCL
Warwick

+LIGO (UK)

LISA Pathfinder (2004-2017)

Birmingham
Glasgow
Imperial
[MSSL] ALL FOUR GROUPS PRODUCED FLIGHT H/W

LISA

(consortium snapshot – application process ongoing)

Birmingham
Edinburgh
Glasgow ONLY H/W group left !!
Imperial
Leicester
+
+
+

Since 1997, when LISA was first proposed to ESA, it has attracted 140 publications/year. By launch it will be >5000 for an experiment about to start!