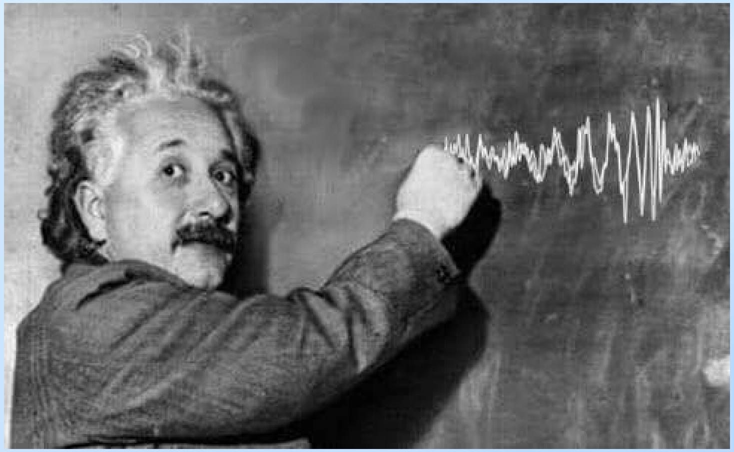
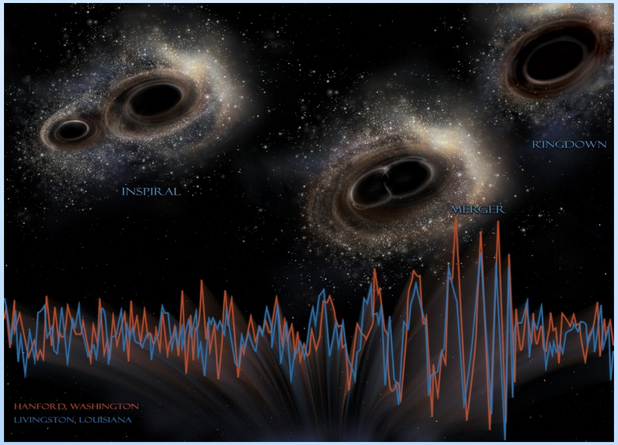
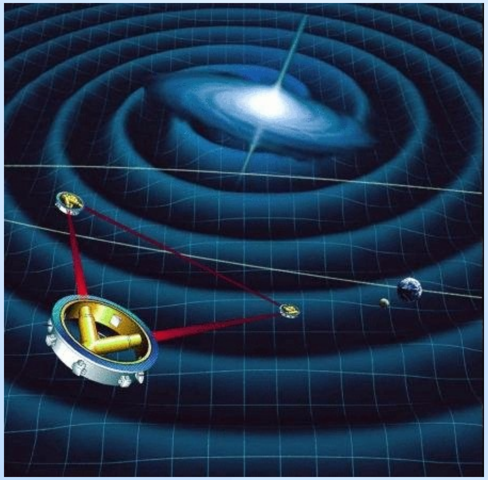






La science future avec les ondes gravitationnelles

Nelson Christensen
Artemis, Observatoire de la Côte d’Azur, Nice

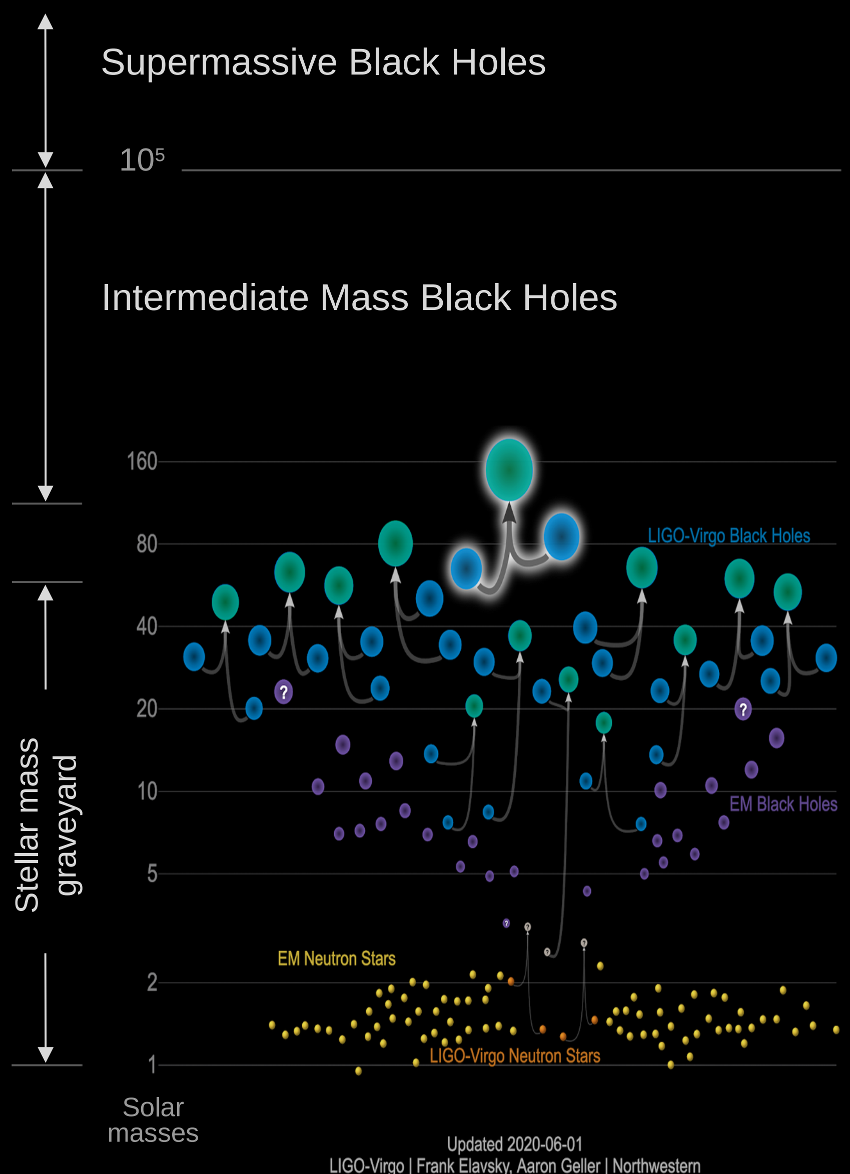
GdR Ondes Gravitationnelles. October 14, 2020

Talk Outline

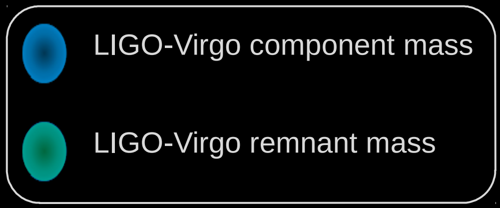
- Past:
  - LIGO-Virgo gravitational-wave detections
  - Beginning of gravitational wave multimessenger astronomy
- Present:
  - Upcoming LIGO-Virgo searches
  - Further gravitational wave detections
  - Scientific implications
- Future:
  - LISA
  - Third generation detectors
  - Atom interferometers
  - Pulsar timing
  - CMB polarizations

In the talk I will try to call out scientific goals based on observations to date, plus goals of future detectors.

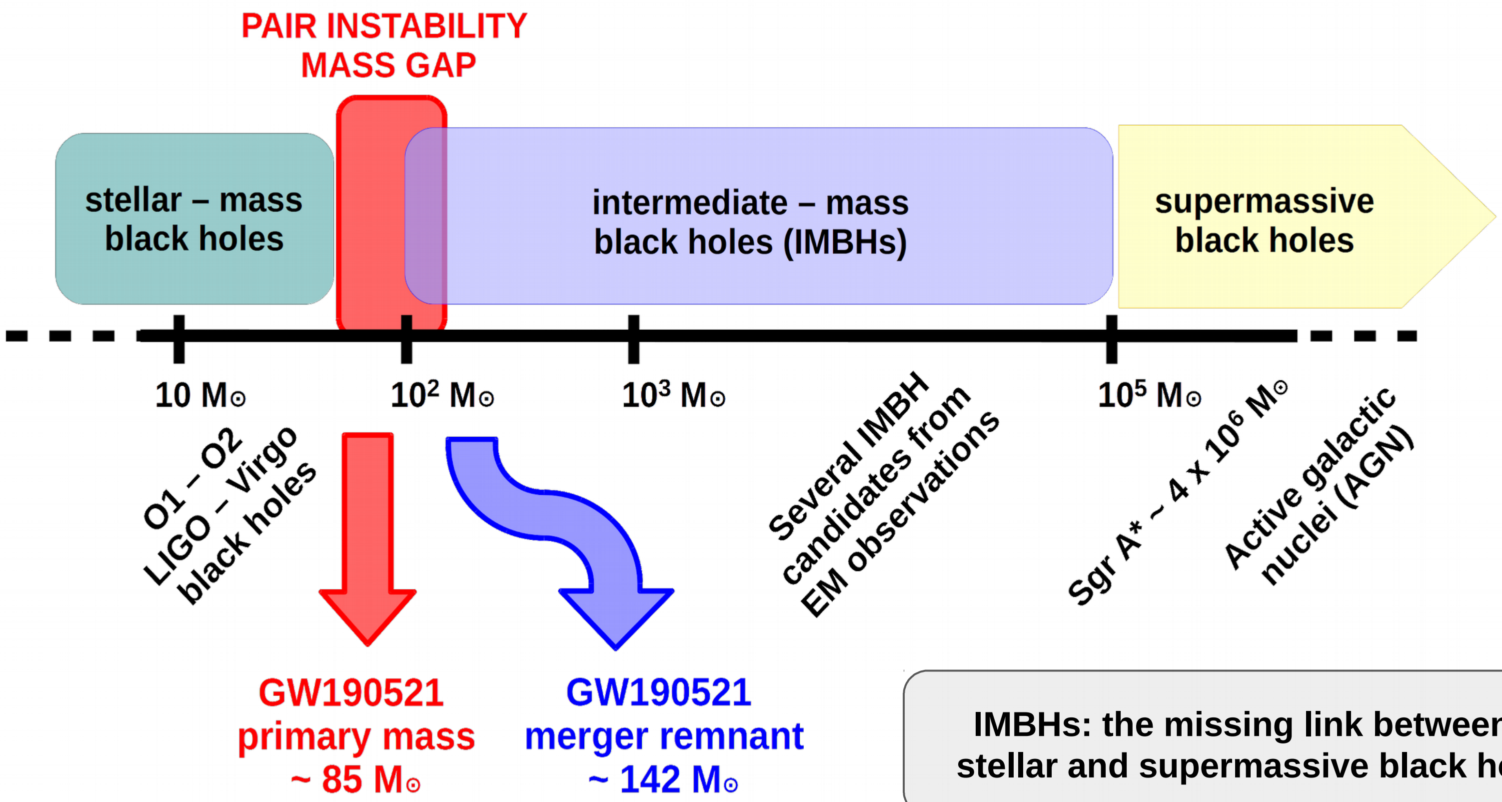
LIGO-Virgo Detections



- So far, LIGO-Virgo have reported 13 binary black hole mergers
- Final remnant mass of GW190521 is well above 100 solar masses, **marking it as the first intermediate mass black hole (IMBH) detected by LIGO-Virgo**
- **The primary mass lies outside of the stellar mass graveyard (> 65 solar masses)**

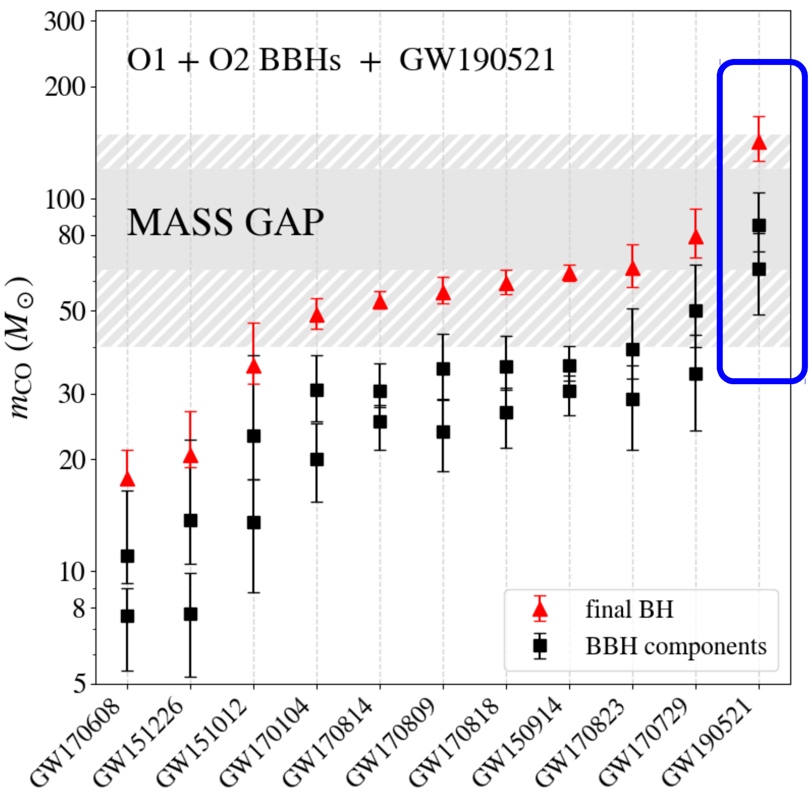


Astrophysical implications



IMBHs: the missing link between
stellar and supermassive black holes

Primary component in the pair-instability (PI) mass gap



Efficient pair production in massive stars drives (pulsational) pair instability:

opens a gap in ~ 65 - 120 M⊙ range

Large uncertainties on mass gap boundaries:

- Nuclear reaction rates, e.g. $^{12}C(\alpha,\gamma)^{16}O$

- Collapse of hydrogen envelope

- Stellar rotation

- Convection model

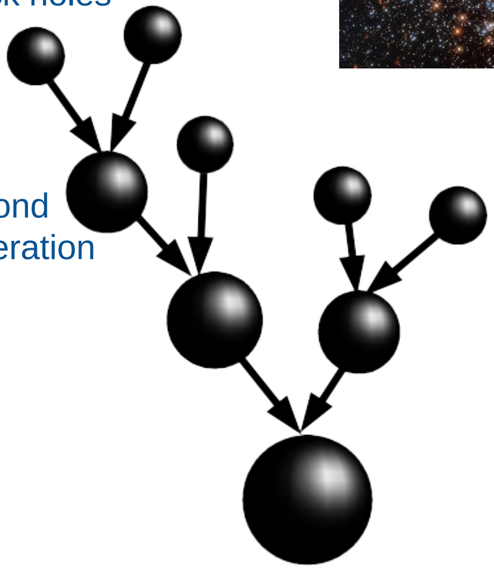
CHALLENGE FOR STELLAR EVOLUTION

Dynamical scenarios: Hierarchical mergers

credit: NASA / ESA / Hubble

First-generation (1g) black holes

Second generation (2g)



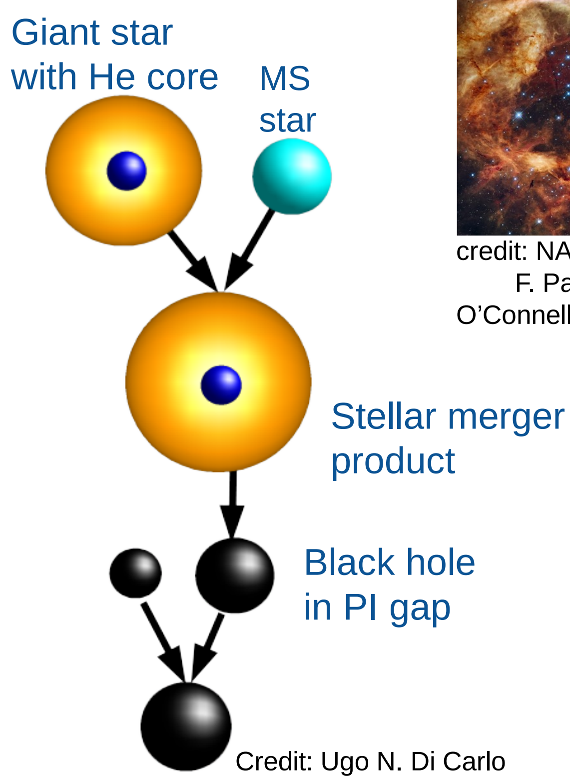
- Multiple mergers of black holes are possible in dense star clusters and galactic nuclei:
  - mass in the PI gap
  - consistent with $\chi_{eff} \sim 0$ and large χ_p
  - uncertain rates

GW170729 final black hole in the PI gap

Results of hierarchical Bayesian inference on a population model depend strongly on assumed properties of 1g mergers

→ no conclusive evidence for GW190521 to be a 2g merger

Dynamical scenarios: Stellar mergers in young star clusters



Credit: Ugo N. Di Carlo

credit: NASA, ESA, F. Paresce, R. O'Connell

- Merger of a massive star with He core and a main sequence (MS) star produces a star with oversized H enveloppe

  It could collapse to a black hole in the PI gap

  In a dense star cluster, the black hole acquires companions dynamically:

  - primary mass in PI gap

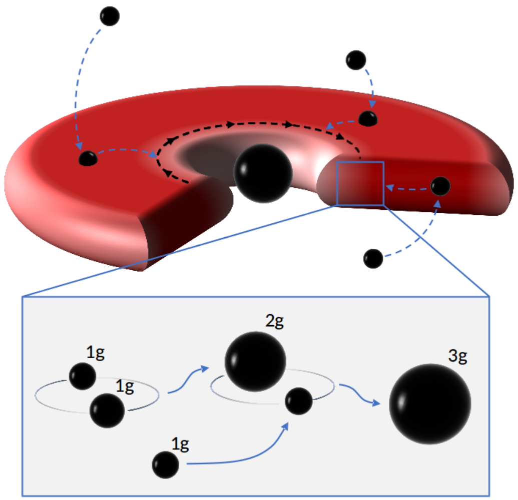
  - consistent with χ_{eff}~ 0 and large χ_p

  - uncertain evolution of stellar collision product

  - rate < 10% of all detectable BBH mergers

Dynamical scenarios: Active galactic nucleus (AGN) disks

Credit: NASA/JPL-Caltech



Credit: Imre Bartos

- Gas torques from AGN disks favor black hole pairing and hierarchical mergers

  - primary mass in PI gap

  - large χ_p

  - uncertain rates

  - predicts an EM counterpart

  Candidate optical counterpart in AGN J124942.3+344929 (Graham et al. 2020)

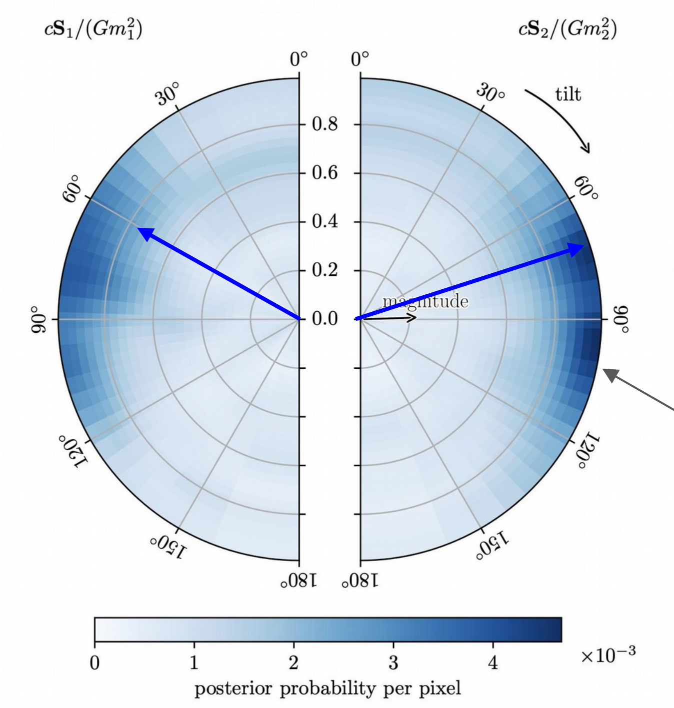
  AGN redshift: z = 0.438

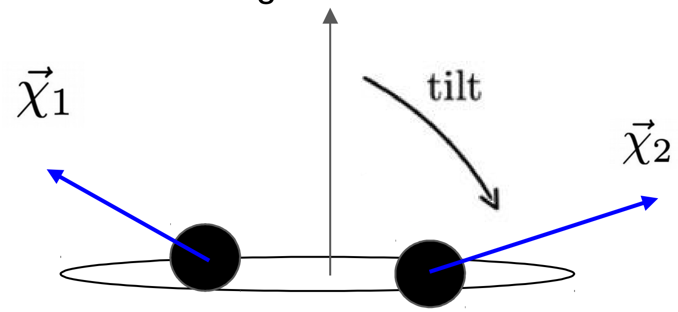
  GW190521 redshift: z = 0.82 (+0.28, -0.34) (90% CI)

Binary black hole formation models will be an important research subject for the future.

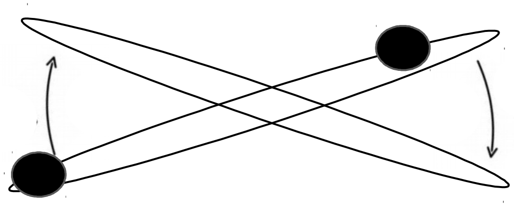
More observations → more information

Spins

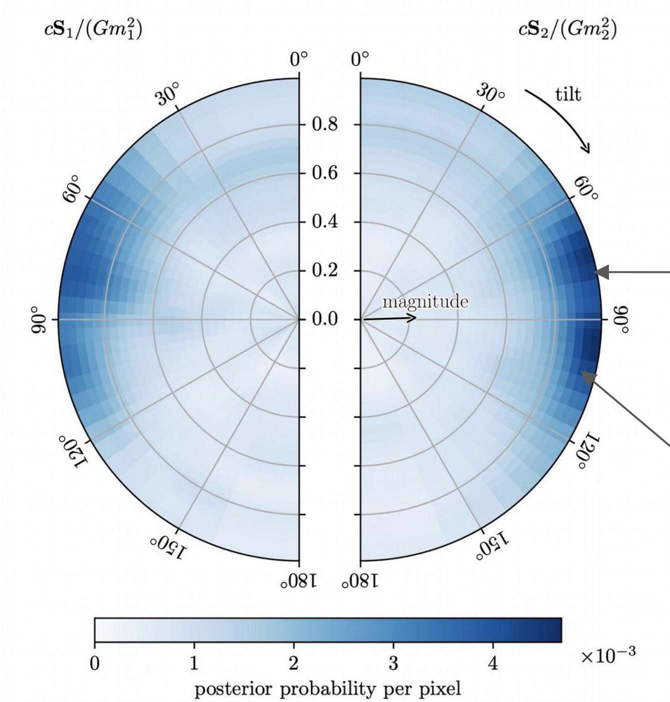




- Spin magnitude $\chi \leq 1$ (cosmic censorship)
- tilt = 0: constant orbital plane
- tilt not 0: orbital precession



Spins GW190521



- Spin magnitudes:

$$\chi_1 = 0.69^{+0.27}_{-0.62} \qquad \chi_2 = 0.73^{+0.24}_{-0.64}$$

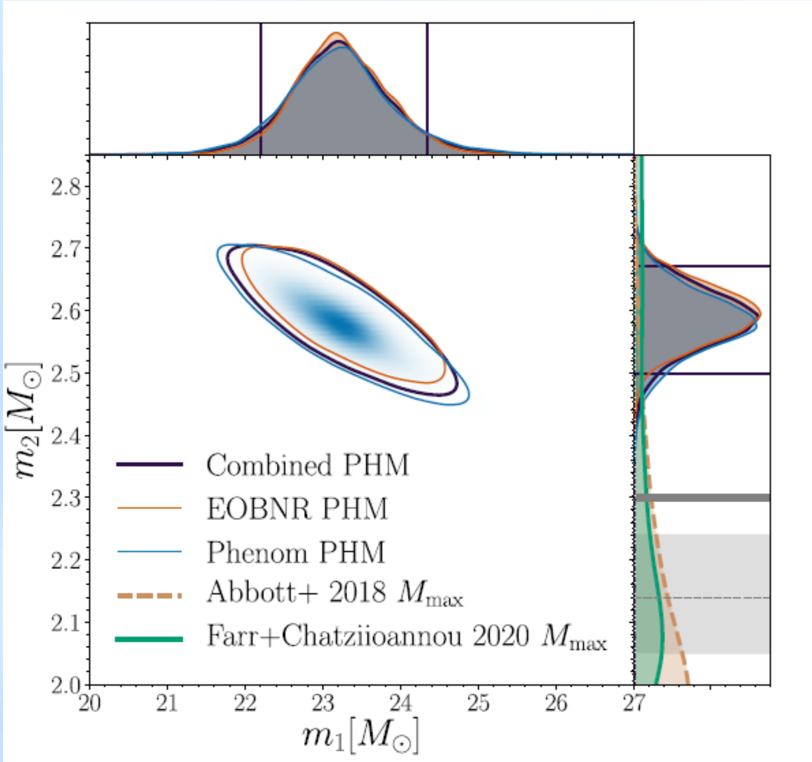
  - Strong support at $\chi_{1,2} = 1$
  - Also at $\chi_{1,2} = 0$

$$P(\text{Spins vs. No-spins}) = 8.3 : 1$$

- Support for misaligned spins

$$P(\text{Precession vs. No-precession}) = 11.5 : 1$$

GW190814 + GW190421: Higher Multiples



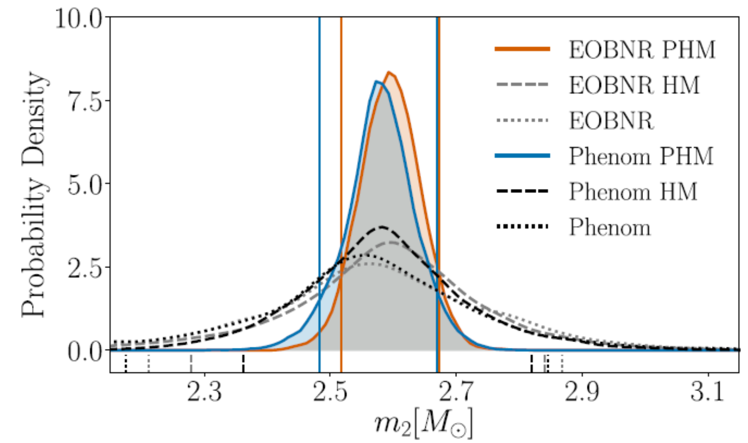


Figure 4. Marginalized posterior distribution for the secondary mass obtained using a suite of waveform models. The vertical lines indicate the 90% credible bounds for each waveform model. The labels Phenom/EOBNR PHM (generic spin directions + higher multipoles), Phenom/EOBNR HM (aligned-spin + higher multipoles), and Phenom/EOBNR (aligned-spin, quadrupole only) indicate the different physical content in each of the waveform models.

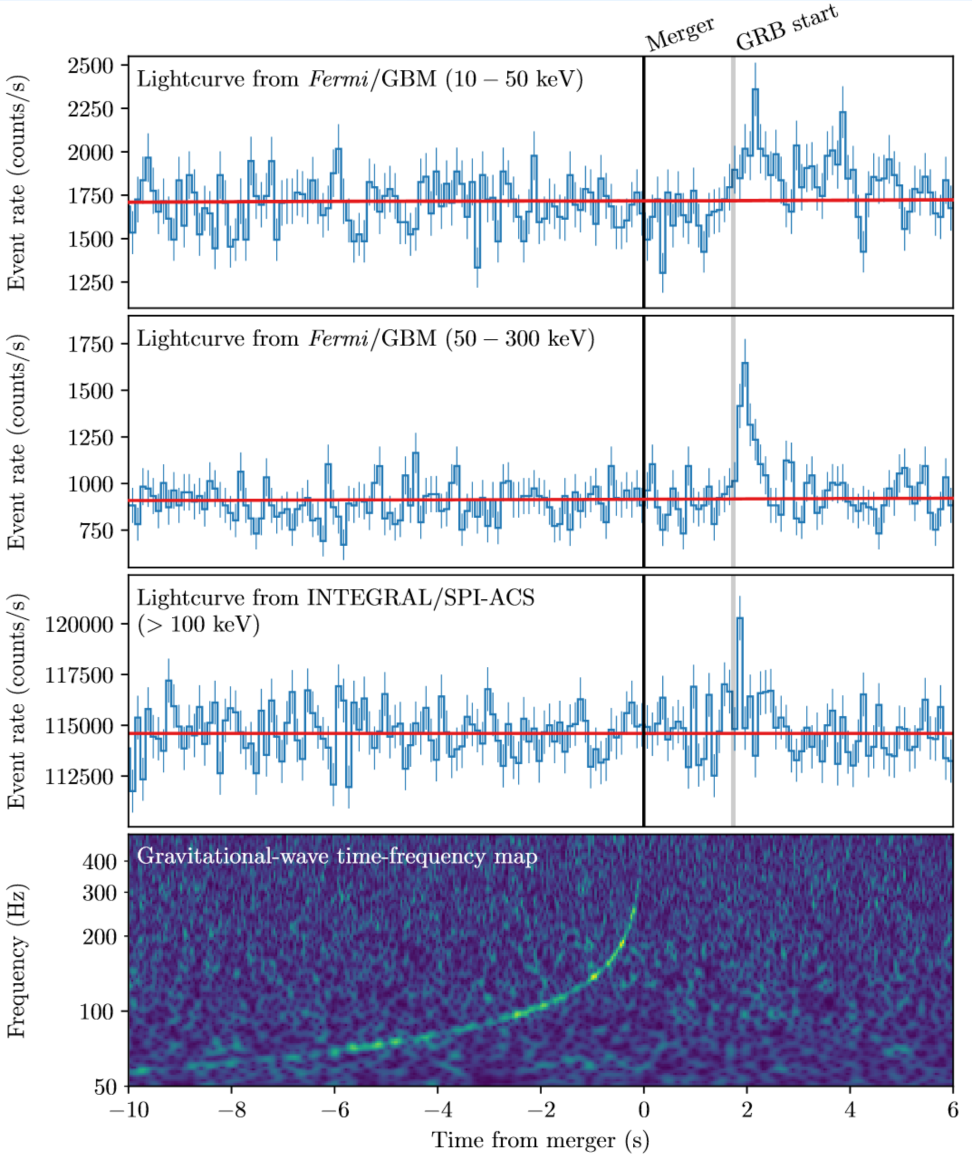
GW190814: “Signal models that exclude higher multipoles or precession do not constrain the secondary mass as well.”

Important For The Future

- Waveform development critical
- Large mass ratios
- Higher order modes
- Spin, precession
- High mass → signal dominated by merger and ringdown
  - In band for only a short time
- Tests of General Relativity from inspiral signal parameters and final black hole mass and spin
- The future will bring many more events, some of which will challenge the waveforms →
  - An important area of research for the future.

GW170817 – The Birth of GW Multi-Messenger Astronomy

17 August 2017



GW170817 – Host Galaxy Found

T_0 + 12 hours :
Alert sent from
1m2H Swope

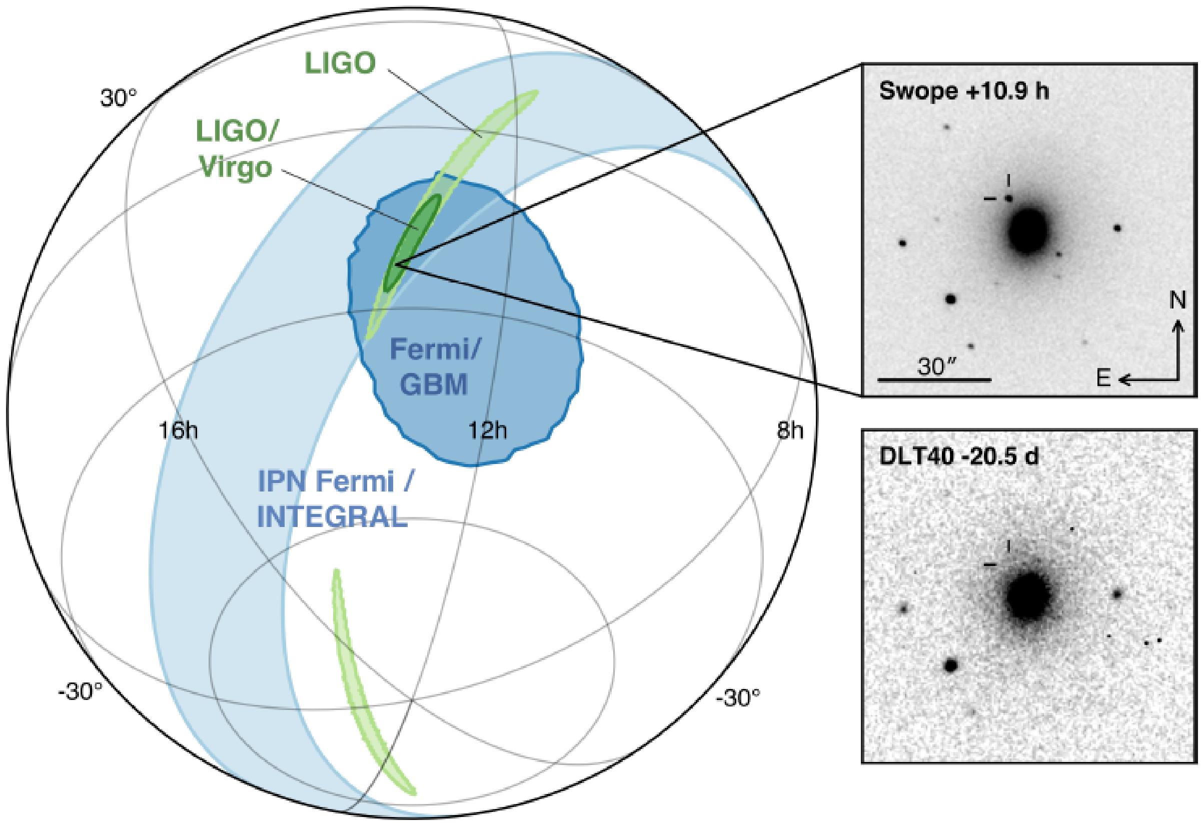
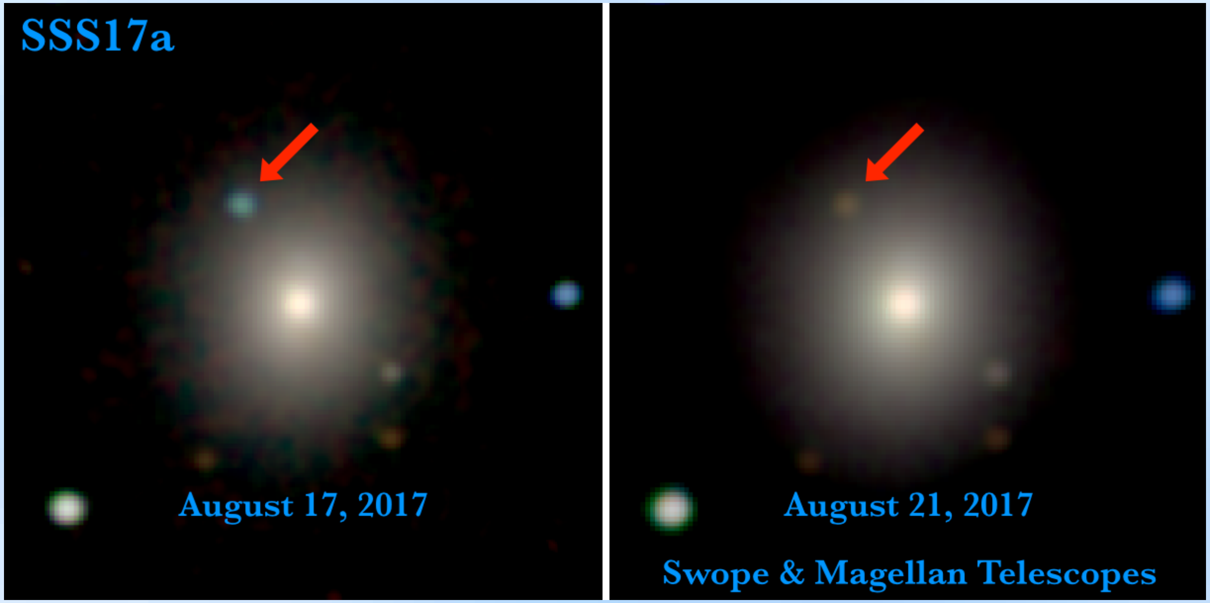
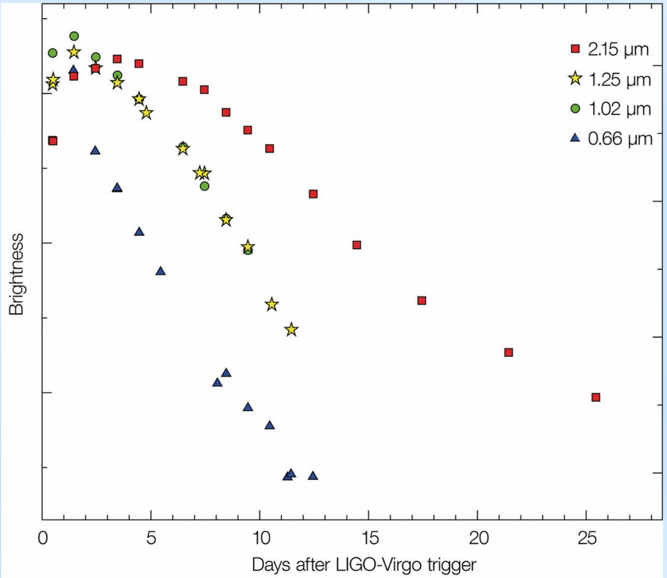


Figure 1. Localization of the gravitational-wave, gamma-ray, and optical signals. The left panel shows an orthographic projection of the 90% credible regions from LIGO (190 deg^2, light green), the initial LIGO-Virgo localization (31 deg^2, dark green), IPN triangulation from the time delay between *Fermi* and *INTEGRAL* (light blue), and *Fermi* GBM (dark blue). The inset shows the location of the apparent host galaxy NGC 4993 in the Swope optical discovery image at 10.9 hours after the merger (top right) and the DLT40 pre-discovery image from 20.5 days prior to merger (bottom right). The reticle marks the position of the transient in both images.

Kilonova





An initially blue signals that fades and turns to red.

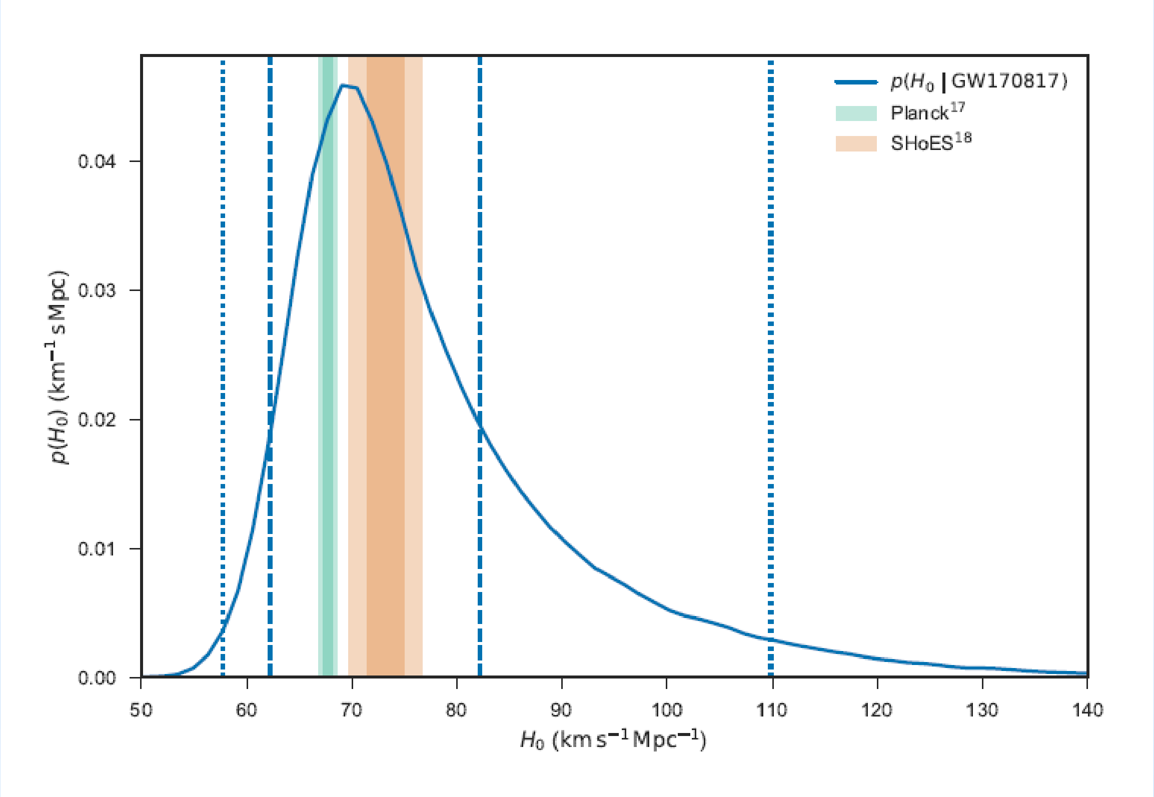
Future -
Rapid follow-up of events a necessity.
For example, GRANDMA network.

There might not be a gamma-ray burst, hence need to directly find kilonova in UV-optical-IR

All that glisters is not gold—
Often have you heard that told.

A New Measurement of the Hubble Constant

We determine the Hubble constant to be $70.0^{+12.0}_{-8.0}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$



“Our measurement combines the distance to the source inferred purely from the gravitational-wave signal with the recession velocity inferred from measurements of the redshift using electromagnetic data.”

Future: More observations and a better estimate of H_0.

Break tension H_0?

Tidal Effects and Equation of State of Nuclear Material

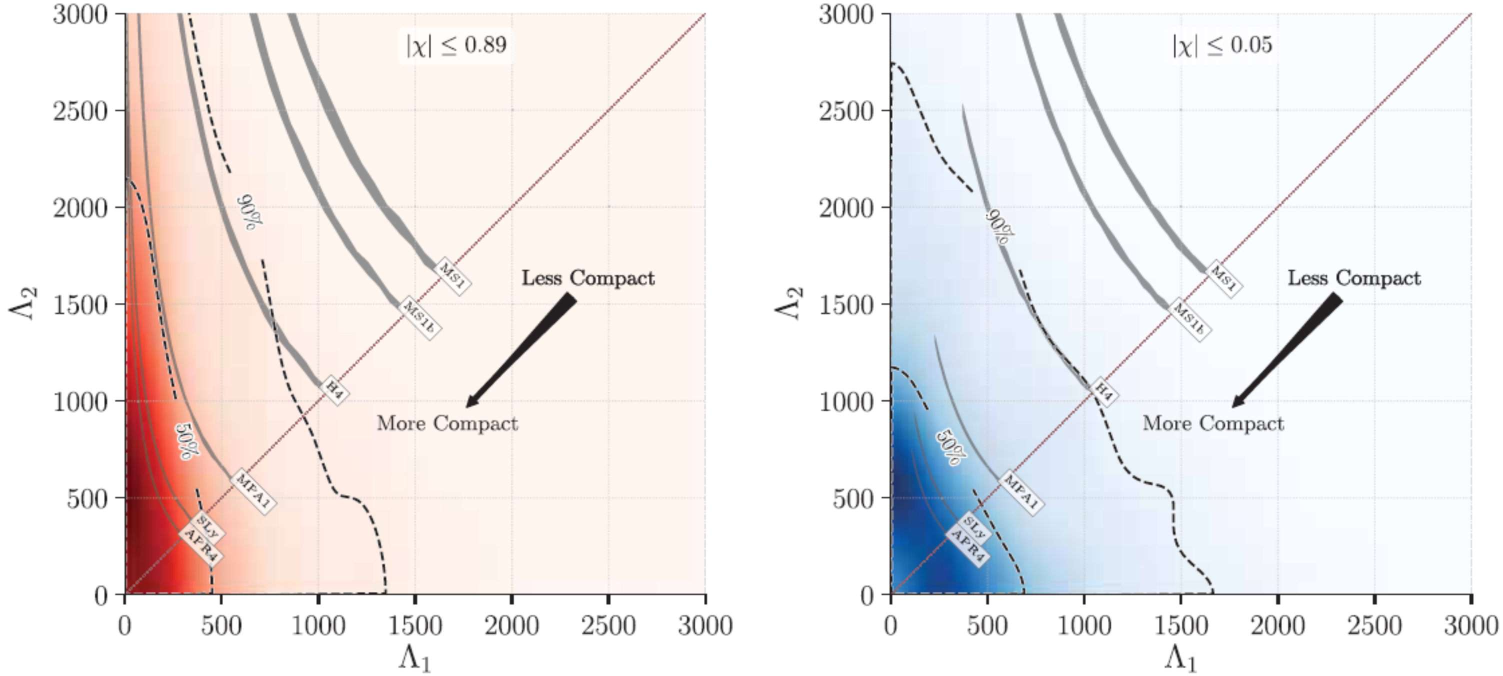


FIG. 5. Probability density for the tidal deformability parameters of the high and low mass components inferred from the detected signals using the post-Newtonian model. Contours enclosing 90% and 50% of the probability density are overlaid (dashed lines). The diagonal dashed line indicates the $\Lambda_1 = \Lambda_2$ boundary. The Λ_1 and Λ_2 parameters characterize the size of the tidally induced mass deformations of each star and are proportional to $k_2(R/m)^5$. Constraints are shown for the high-spin scenario $|\chi| \leq 0.89$ (left panel) and for the low-spin $|\chi| \leq 0.05$ (right panel). As a comparison, we plot predictions for tidal deformability given by a set of representative equations of state [156–160] (shaded filled regions), with labels following [161], all of which support stars of $2.01 M_\odot$. Under the assumption that both components are neutron stars, we apply the function $\Lambda(m)$ prescribed by that equation of state to the 90% most probable region of the component mass posterior distributions shown in Fig. 4. EOS that produce less compact stars, such as MS1 and MS1b, predict Λ values outside our 90% contour.

Future: Important opportunity for nuclear physicists

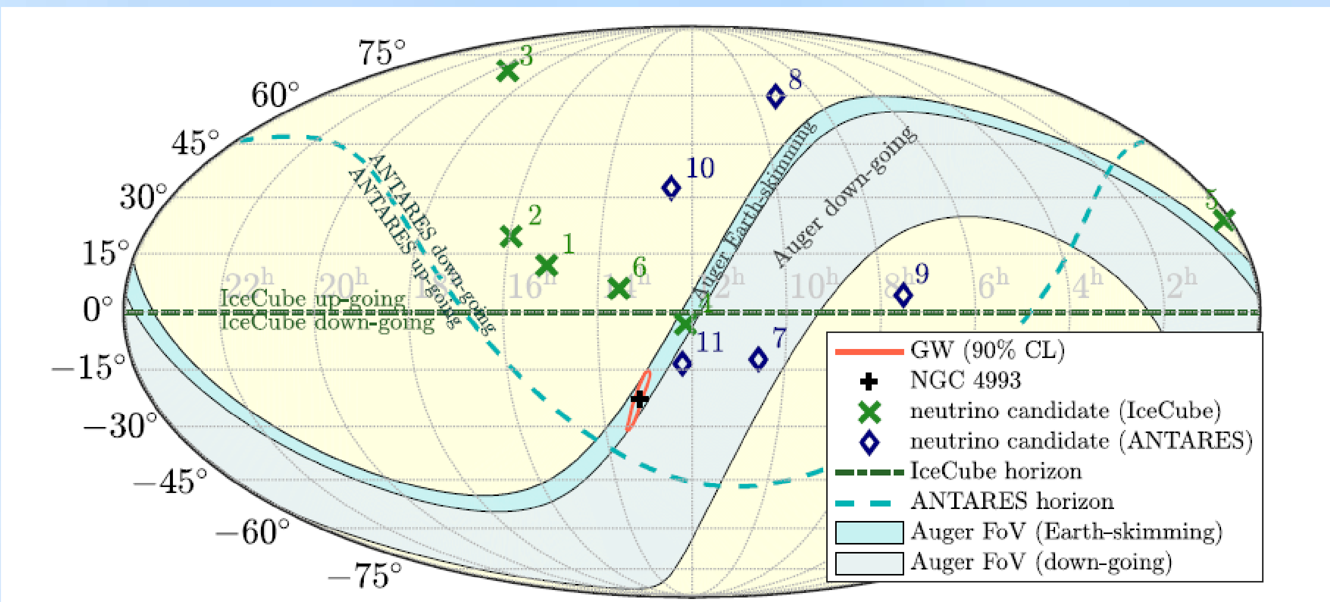
No neutrinos … but we looked!

The Astrophysical Journal Letters, 850:L35 (18pp), 2017 December 1 https://doi.org/10.3847/2041-8213/aa9aed

CrossMark

Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory

ANTARES Collaboration, IceCube Collaboration, The Pierre Auger Collaboration, and LIGO Scientific Collaboration and Virgo Collaboration



"No neutrinos directionally coincident with the source were detected within ±500 s around the merger time. Additionally, no MeV neutrino burst signal was detected coincident with the merger. We further carried out an extended search in the direction of the source for high-energy neutrinos within the 14 day period following the merger, but found no evidence of emission."

Future: Another multi-messenger opportunity.

GW190425 – A Heavy Binary Neutron Star System

Source Properties for GW190425

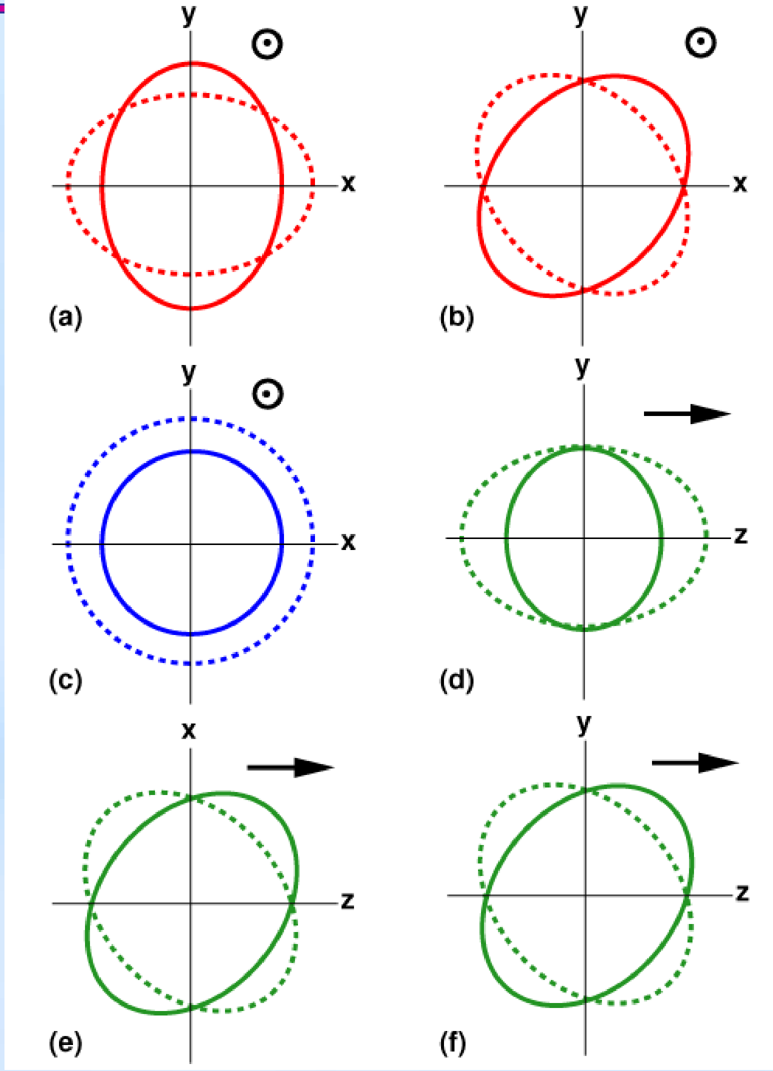
	Low-spin Prior ($\chi < 0.05$)	High-spin Prior ($\chi < 0.89$)
Primary mass m_1	1.60–1.87 $M_\odot$	1.61–2.52 $M_\odot$
Secondary mass m_2	1.46–1.69 $M_\odot$	1.12–1.68 $M_\odot$
Chirp mass $\mathcal{M}$	$1.44^{+0.02}_{-0.02}$ $M_\odot$	$1.44^{+0.02}_{-0.02}$ $M_\odot$
Detector-frame chirp mass	$1.4868^{+0.0003}_{-0.0003}$ $M_\odot$	$1.4873^{+0.0008}_{-0.0006}$ $M_\odot$
Mass ratio m_2/m_1	0.8 – 1.0	0.4 – 1.0
Total mass $m_{\rm tot}$	$3.3^{+0.1}_{-0.1}$ $\mathrm{M}_\odot$	$3.4^{+0.3}_{-0.1} M_\odot$
Effective inspiral spin parameter $\chi_{\rm eff}$	$0.012^{+0.01}_{-0.01}$	$0.058^{+0.11}_{-0.05}$
Luminosity distance $D_{\rm L}$	159^{+69}_{-72} Mpc	159^{+69}_{-71} Mpc
Combined dimensionless tidal deformability $\tilde{\Lambda}$	$\leqslant 600$	$\leqslant 1100$

Source-frame chirp mass 1.44 M and the total mass 3.4 M of system are significantly larger than those of any other known binary neutron star system.

Much to learn about neutron stars.
Need to find kilonova without γ's.

No electromagnetic counterpart signal

Testing General Relativity With GW170814



Clifford Will, Living Reviews in Relativity)

We now have a network of detectors with different orientations (2 LIGO are almost co-aligned, Virgo is not).

Allows the study of polarization of the gravitational waves.

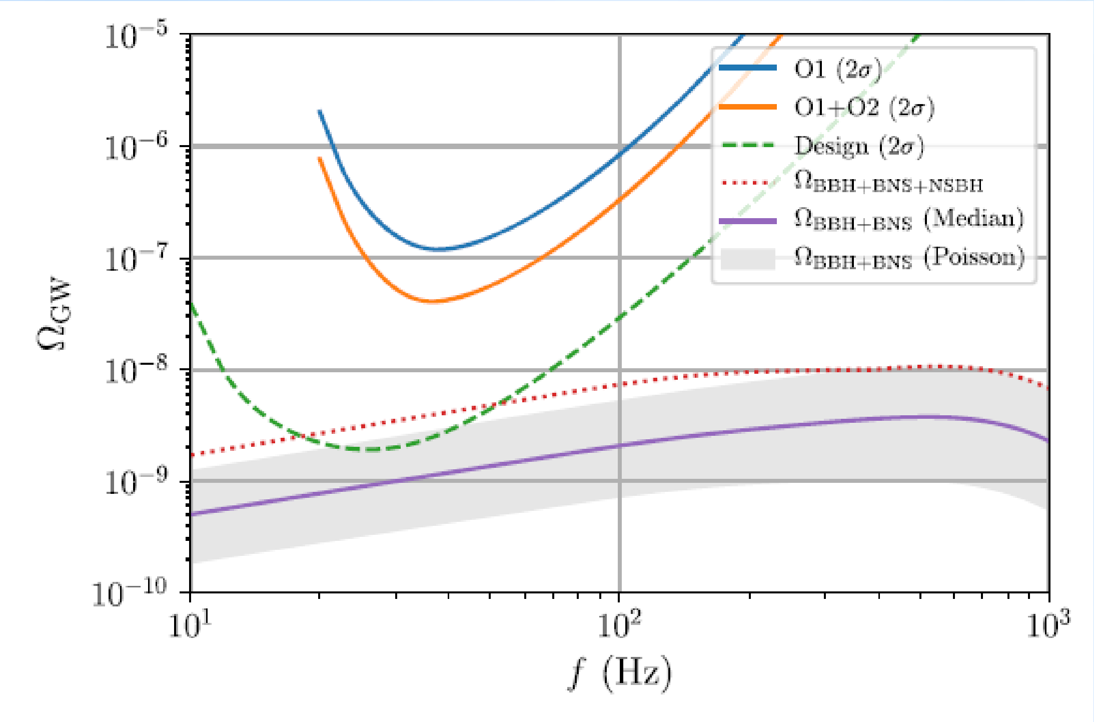
Results favor purely tensor polarization against purely vector and purely scalar.

Tests of GR performed similar to those carried out for the previous confirmed detections — similar results, consistent with the predictions of Einstein's theory.

Post-Newtonian tests, signal consistency, …

World-wide detector network allows for important tests of GR

Implications for a Stochastic Background



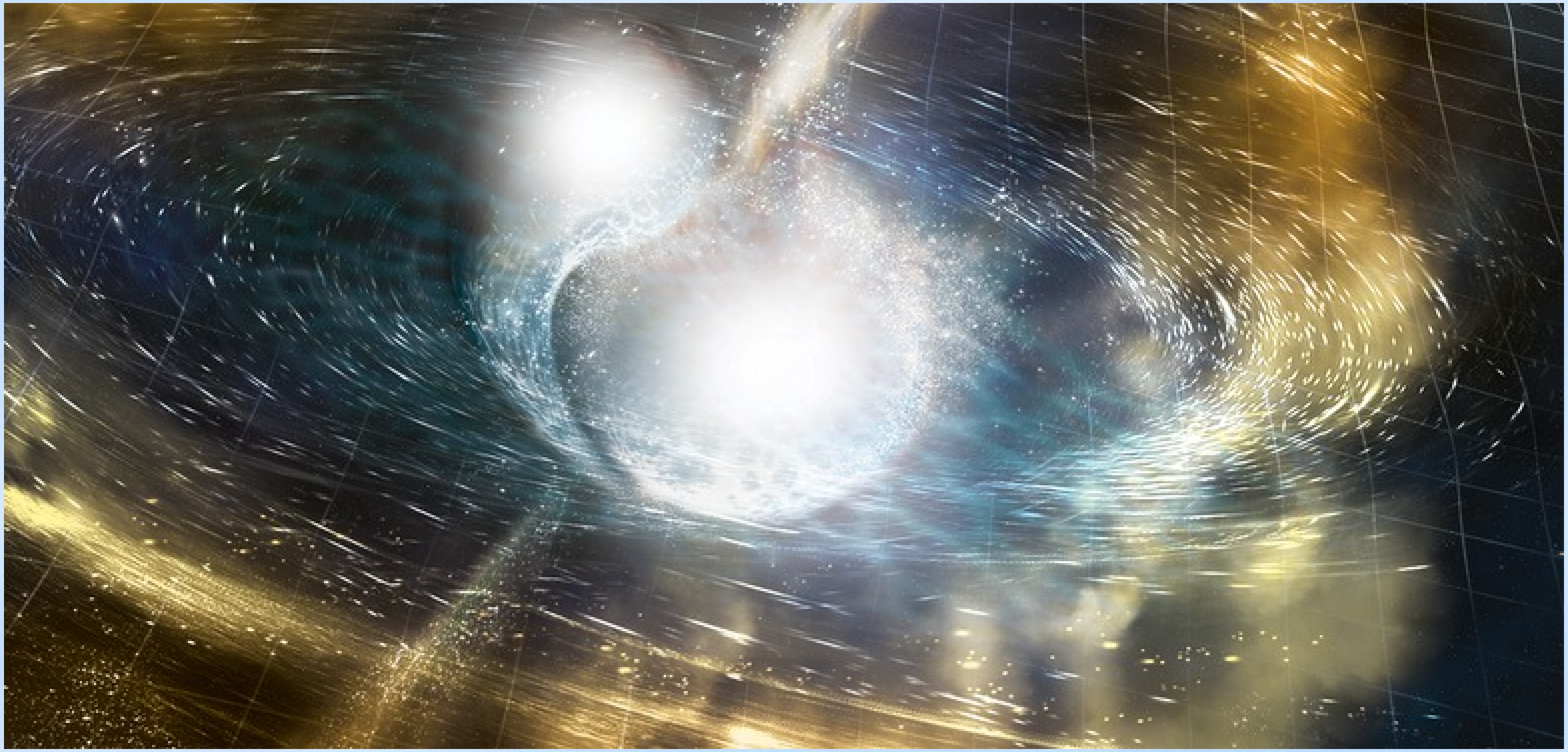
$$\Omega_{GW}(f) = \frac{f}{\rho_c}\frac{d\rho_{GW}}{df},$$

$$\Omega_{GW}(f) = \Omega_{ref}\left(\frac{f}{f_{ref}}\right)^{\alpha},$$

	Uniform prior		Log-uniform prior	
α	O1 + O2	O1	O1 + O2	O1
0	6.0×10^{-8}	1.7×10^{-7}	3.5×10^{-8}	6.4×10^{-8}
2/3	4.8×10^{-8}	1.3×10^{-7}	3.0×10^{-8}	5.1×10^{-8}
3	7.9×10^{-9}	1.7×10^{-8}	5.1×10^{-9}	6.7×10^{-9}
Marg.	1.1×10^{-7}	2.5×10^{-7}	3.4×10^{-8}	5.5×10^{-8}

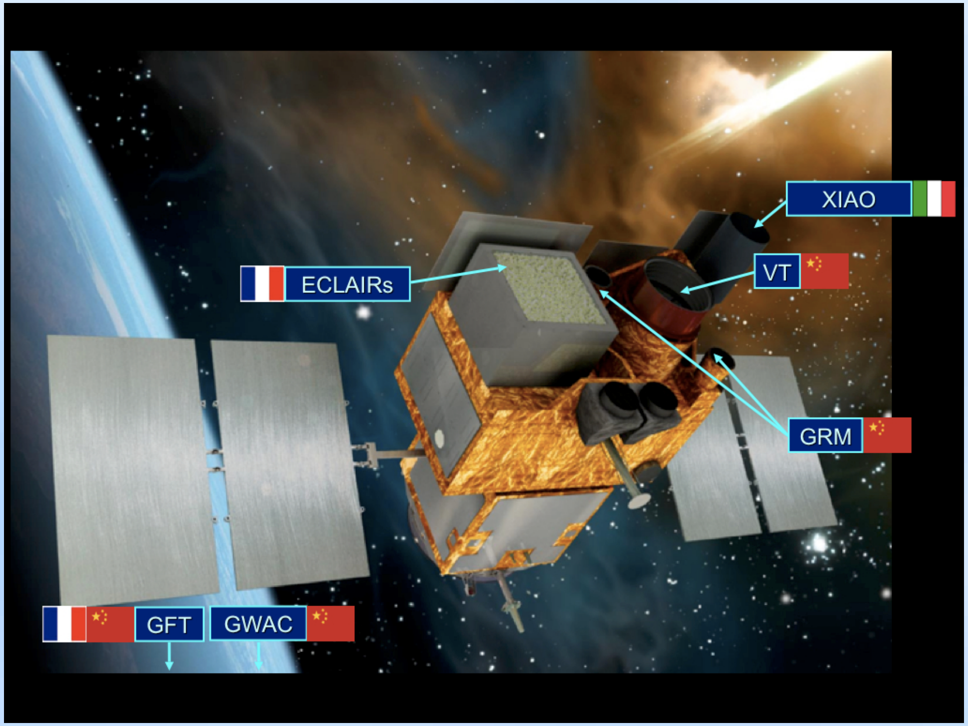
The astrophysically produced stochastic background could be detected in O4 or O5.

What’s Next?



Future – More Multimessenger Astronomy

TAROT-Zadko: optic follow-up.
Calern France, Réunion Island,
Chile, Western Australia
To come? More sites?
GRANDMA network

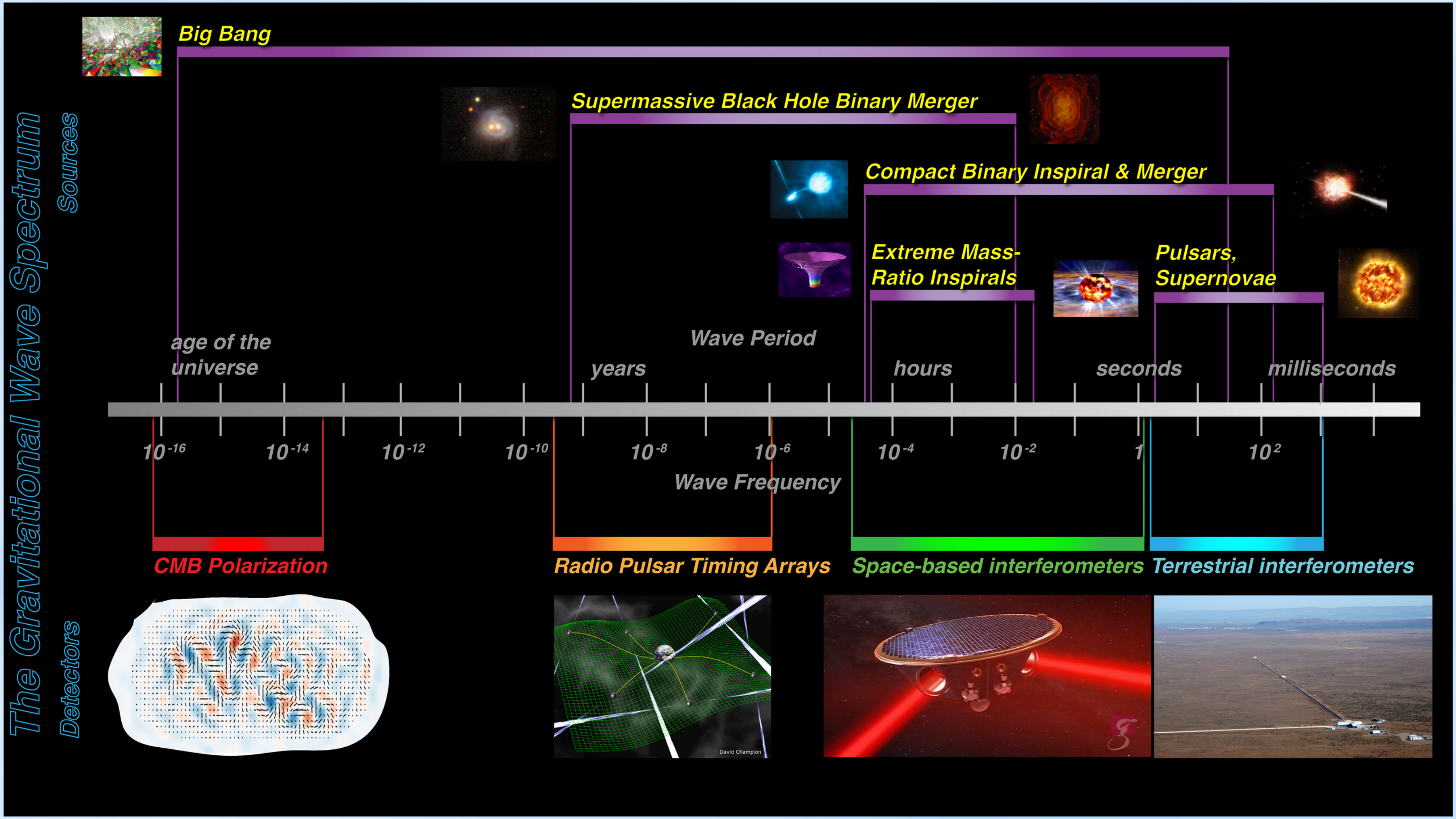


SVOM (Space-based multi-band astronomical Variable Objects Monitor)

France – China.

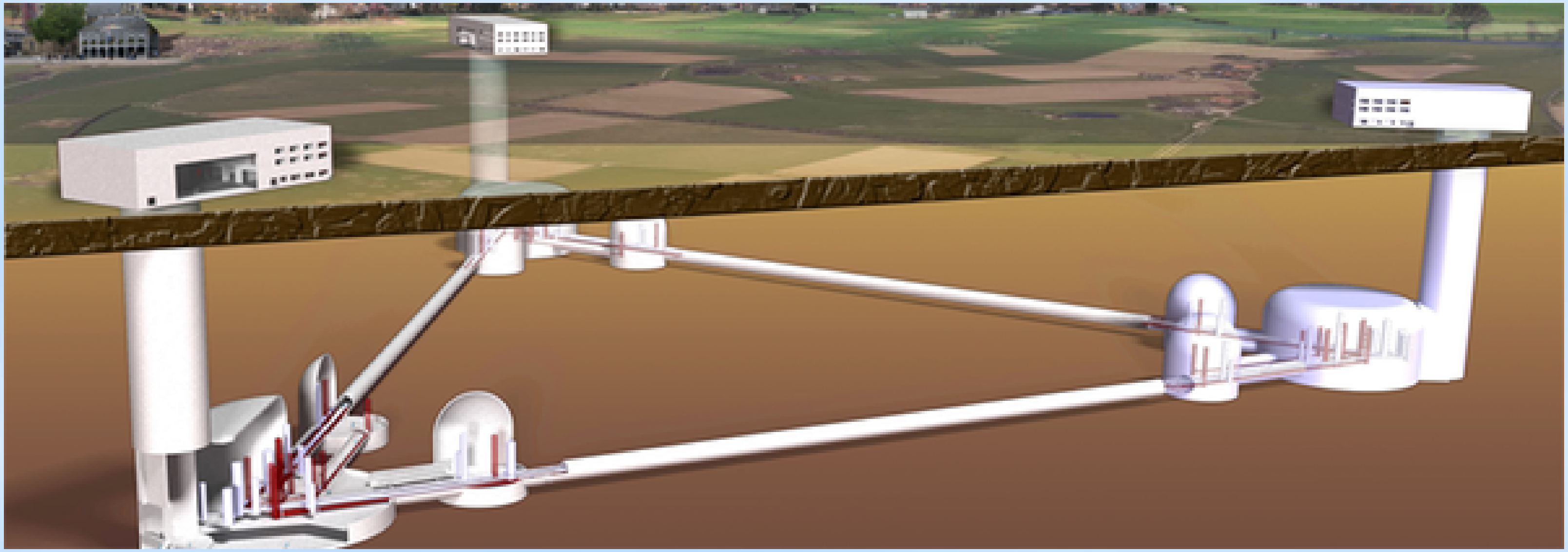
3 – 5 year mission. ~ 2021 launch

Gravitational Wave Spectrum



Third Generation Gravitational Wave Detectors

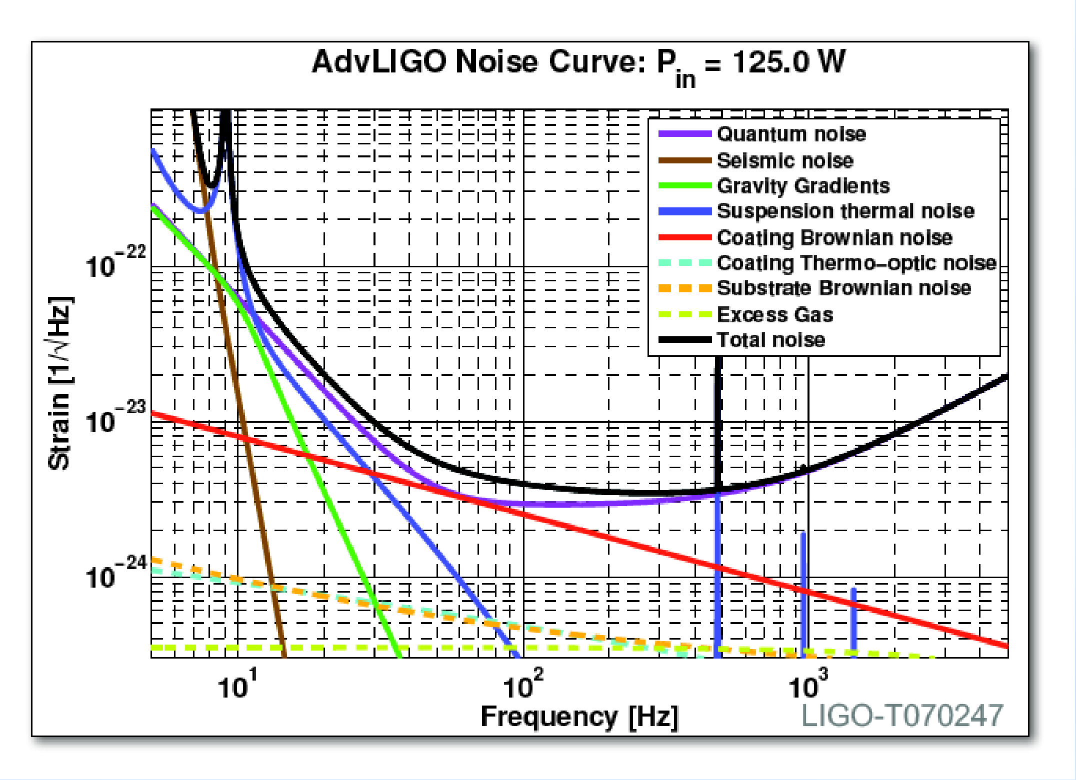
Einstein Telescope



Underground to reduced seismic noise.
10 km arms
Cryogenic mirrors
Lower frequency limit, ~ 1 Hz
10 x better sensitivity than 2nd generation detectors
Farther back in the universe

Noise Sources Limiting the 2G Detectors

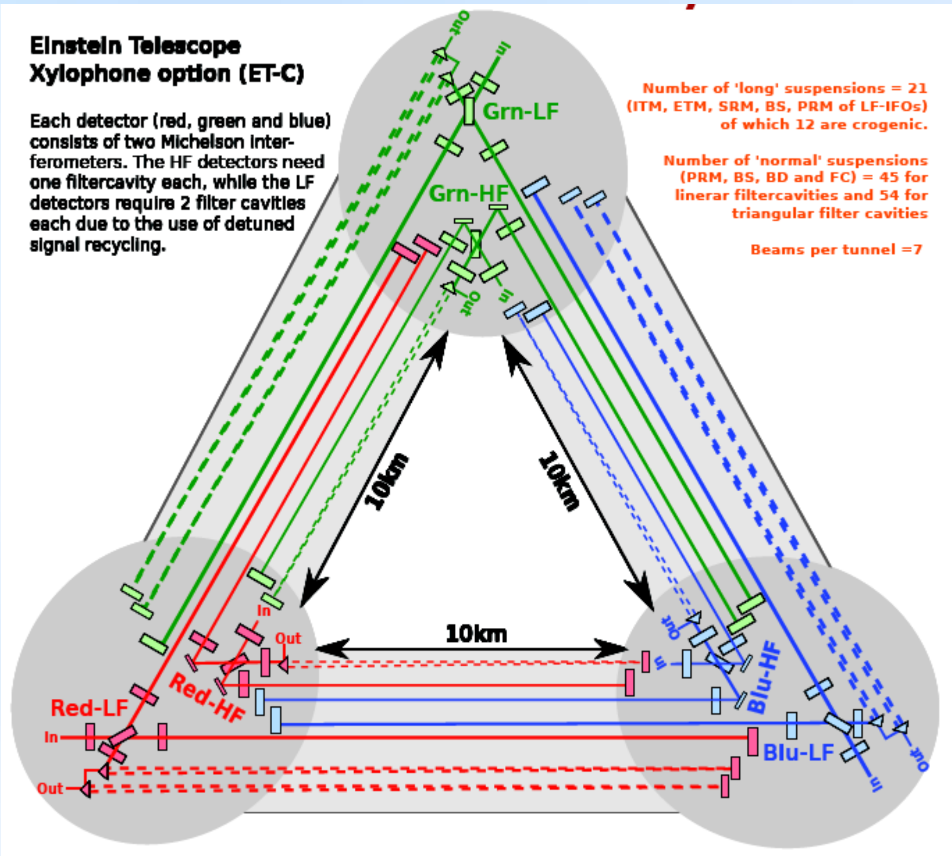
- Quantum noise limits most of the frequency range.
- Coating Brownian noise limits in the range from 50 to 100Hz.
- Below ~15Hz we are limited by ‘walls’ made of Suspension Thermal, Gravity Gradient and Seismic noise.
- And then there are the, often not mentioned, ‘technical’ noise sources which trouble the commissioners so much.

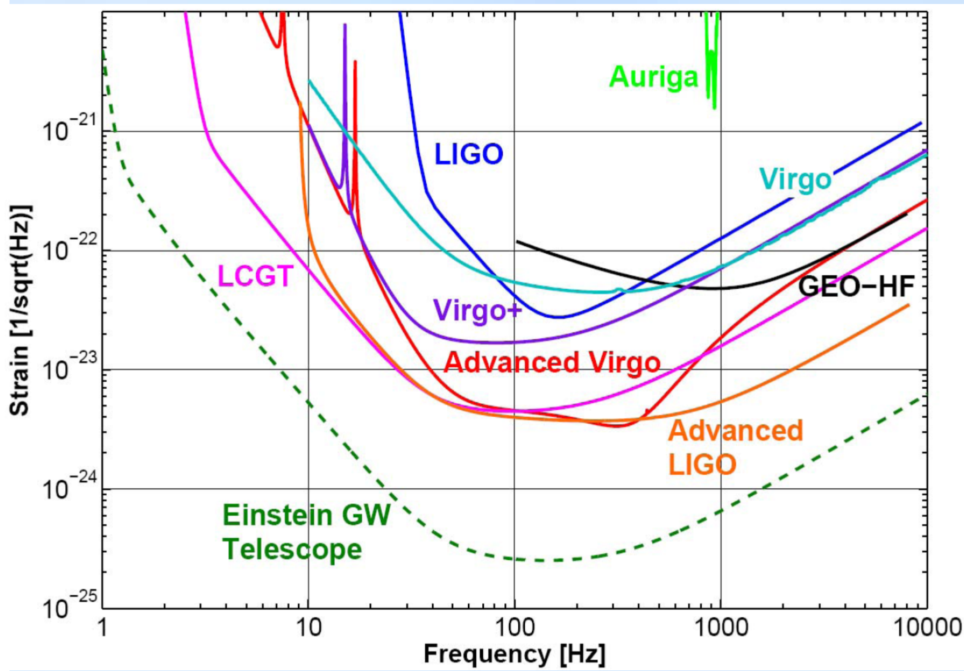


3^{rd} Generation Detectors, To Do List

- Increase arm length, 3km → 10 km: decrease all displacement noises by ~ 3
- Optimizing signal recycling (tuned SR)
- Increase laser power: 125 W to 500 W at IFO input. Reduce shot noise but increase radiation pressure
- Quantum noise suppression: squeezed light
- Increase the beam size → decrease coating Brownian noise
- Cool the test masses: 20 K and decrease Brownian noise
- Longer suspensions: 50 m, 5 stage, corner frequency 0.16 Hz and bring seismic noise wall from 10 Hz down to 1.5 Hz
- Go underground: decrease seismic noise and gravity gradient noise
- Gravity gradient suppression (seismic arrays)
- Heavier mirrors: 42 kg → 120 kg, reduce radiation pressure noise

Einstein Telescope – Very Ambitious Goals



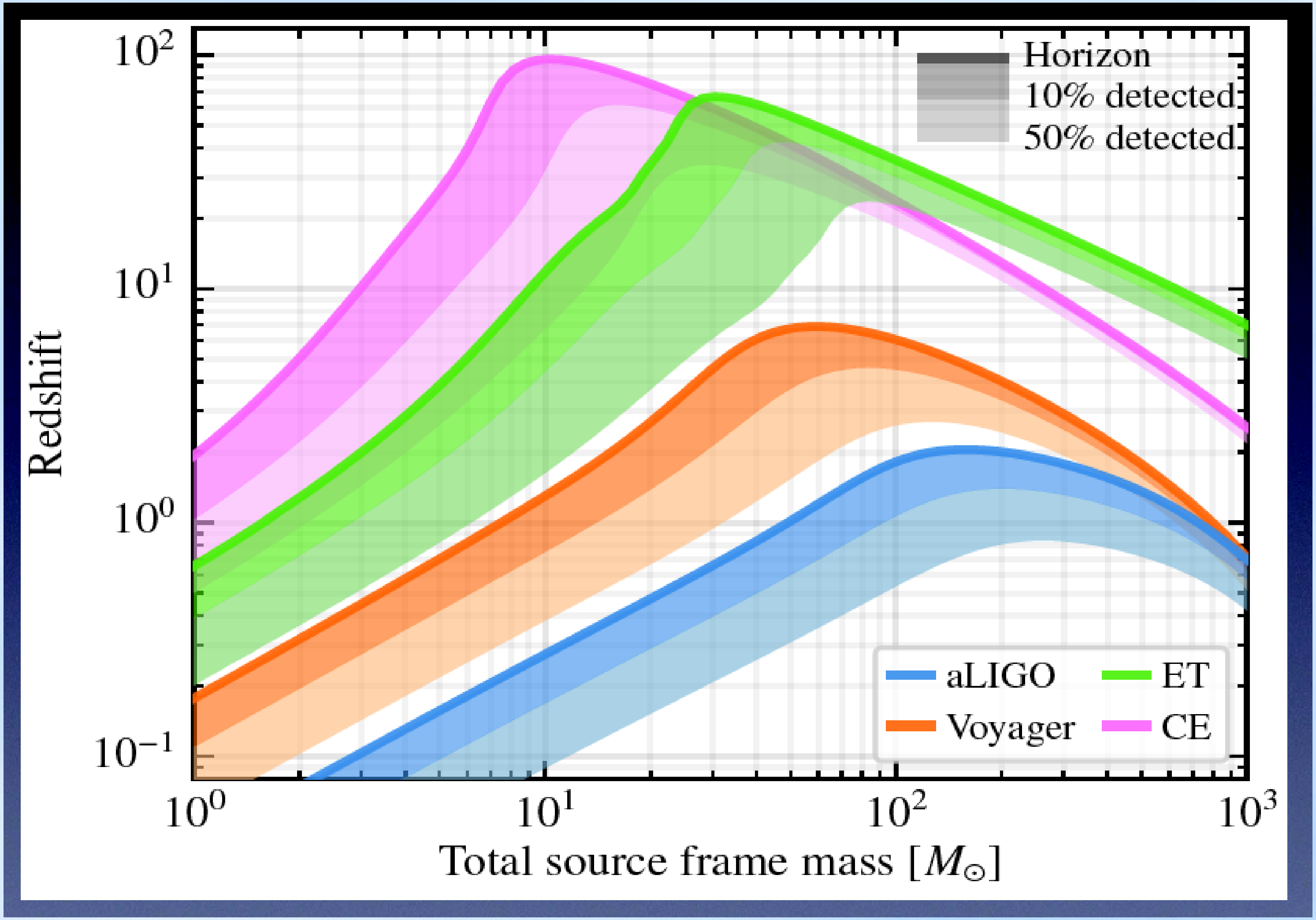


As well, in the US:
LIGO Voyager, 4 km cryogenic
Cosmic Explorer: 40 km interferometer

3G Science

- Advance exploration of extremes of gravity and astrophysics
- Address fundamental questions in physics and astronomy
- Provide insights into most powerful events in the Universe
- Reveal new objects and phenomena
- Try to identify observations that:
  - Will lead to breakthrough science
  - Are uniquely available with gravitational wave observations, possibly in conjunction with EM observations
  - Can only be achieved with the sensitivity of 3rd generation detectors such as Einstein Telescope

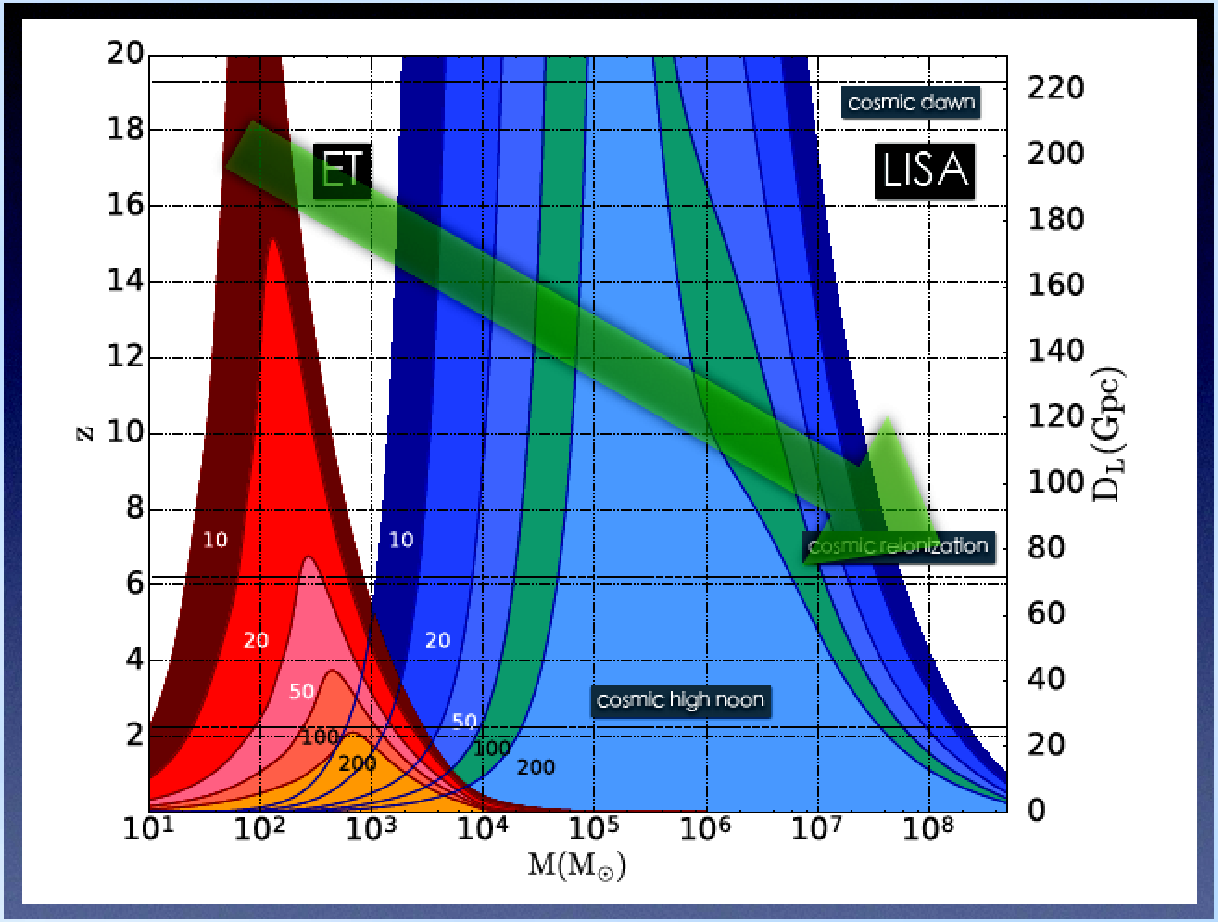
3G Science - Compact Binaries



Credit:
Evan Hall

What is the mass and spin distribution of compact objects through cosmic time?

3G Science - Seed black holes

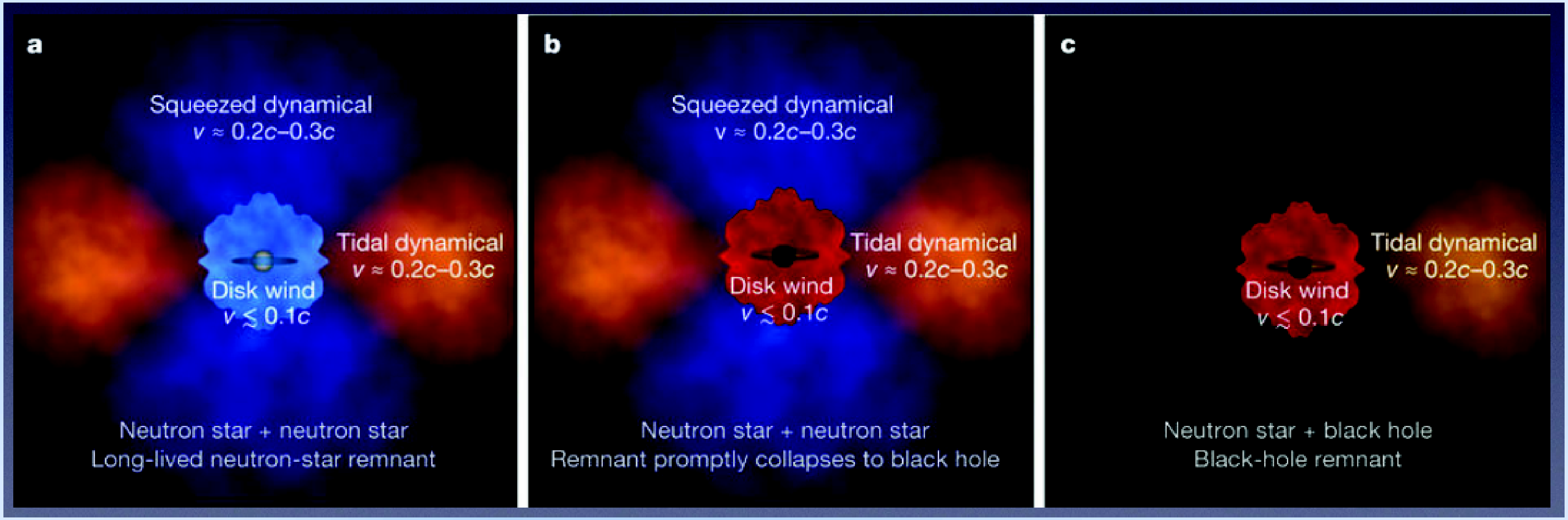


Credit:
Monica Colpi

When and where do the first binary seeds form?

How fast do seed BHs grow hand-in-hand with the growth of cosmic structures?

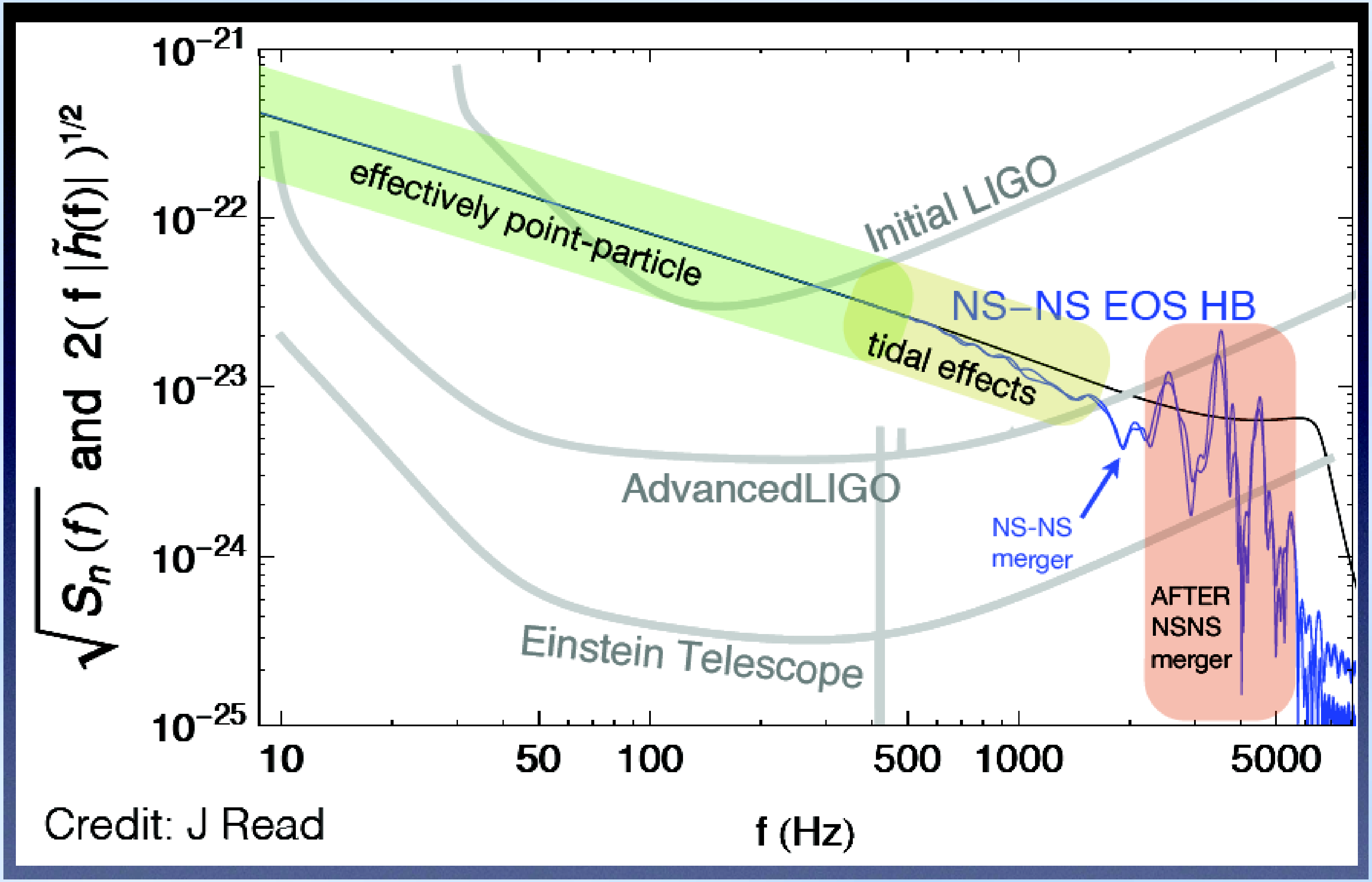
3G Science - Multi-messenger observations



Kasen et al 2017

- What is the contribution of NS-NS and/or NS-BH mergers to r-process elemental production?
- How does this vary with redshift?
- Where in the galaxies do these mergers occur and what does the location tell us?

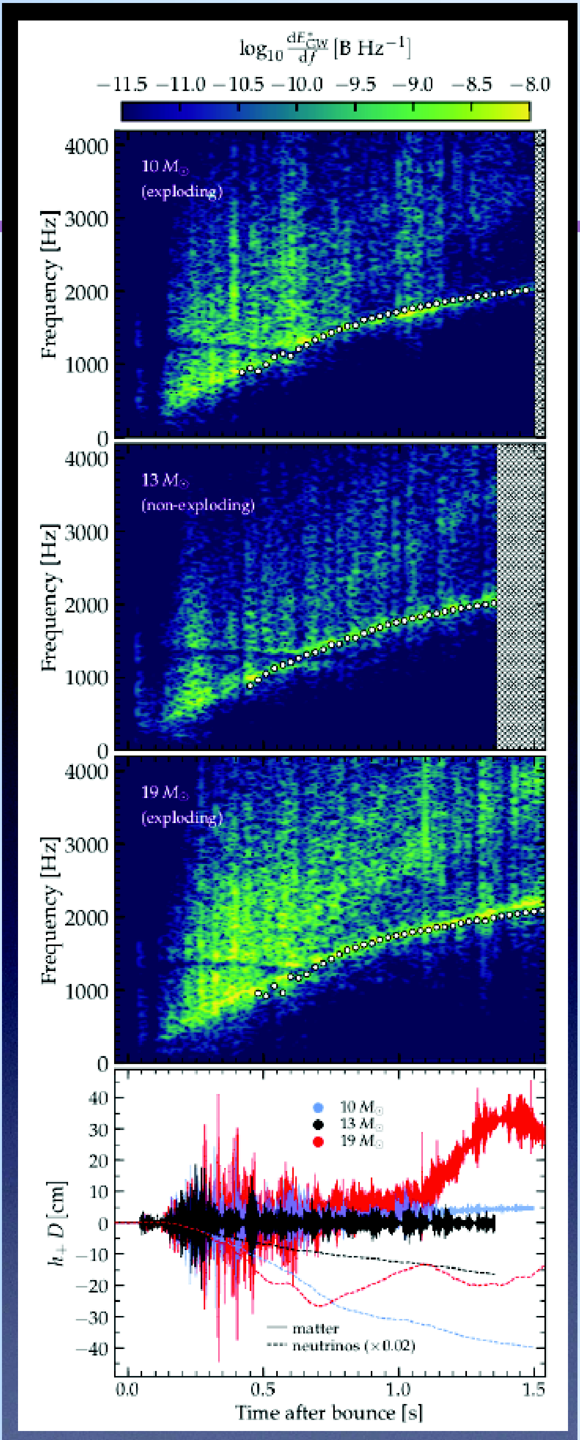
3G Science – Neutron Stars



Neutron star structure from observation of binaries, and continuous waves.

3G Science - Supernovae

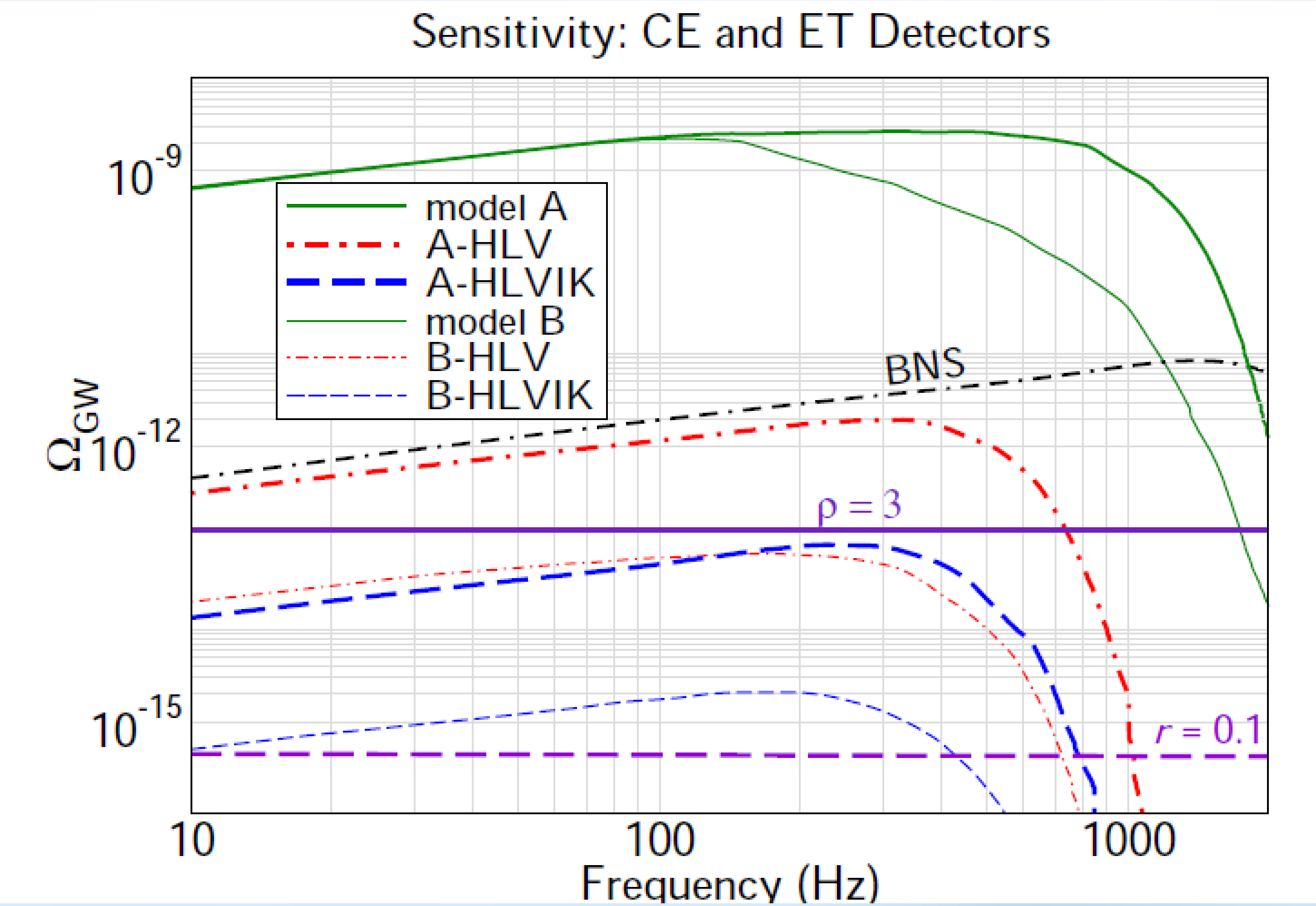
- Can we distinguish the various phases of the supernova explosion?
- Can we determine the nuclear equation of state?
- Can we determine the progenitor mass?



Morozova et al 2018

Third Generation Gravitational Wave Detectors

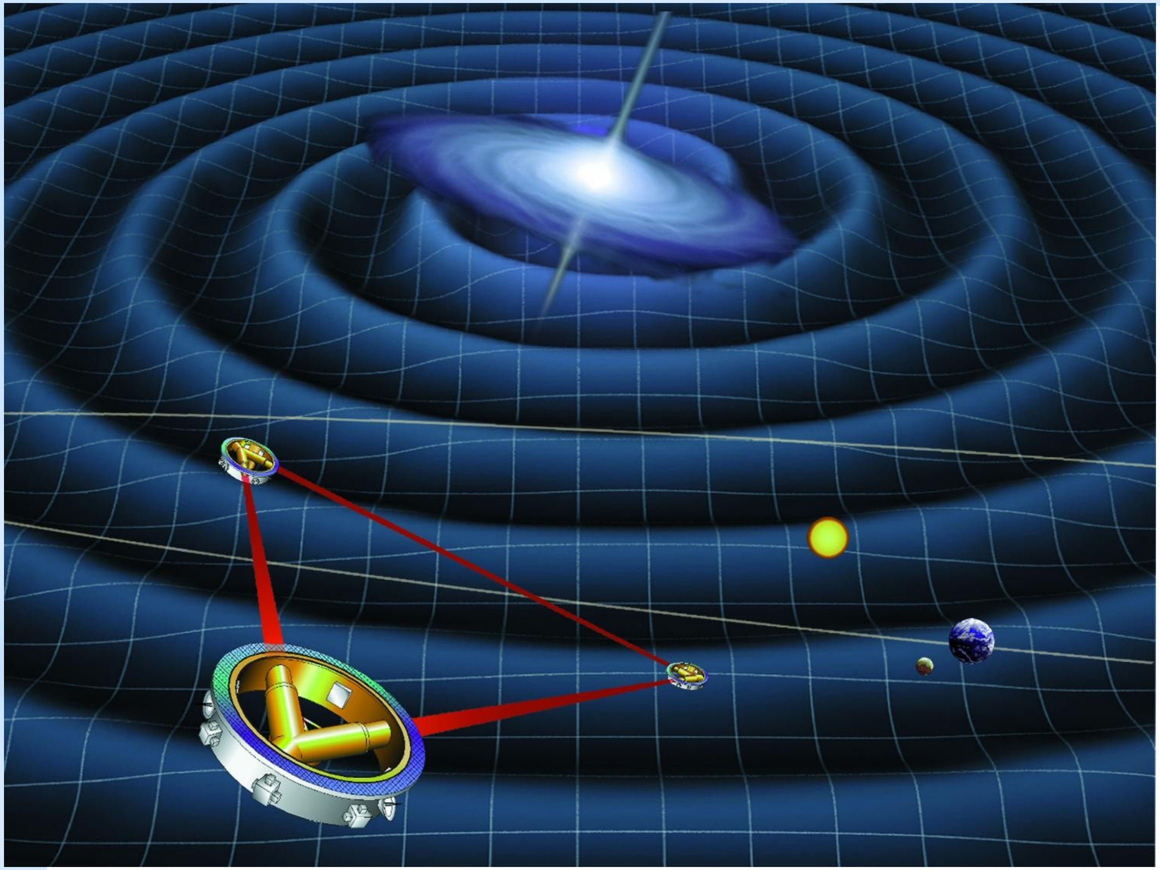
With Einstein Telescope (European) or Cosmic Explorer (US) almost every stellar mass binary black hole merger in the observable universe will be detectable.



BBH confusion background can potentially be subtracted to observe the primordial background at the level of $\Omega_{GW} \sim 10^{-13}$ after five years of observation.

Regimbau et al 2017

Laser Interferometer Space Antenna - LISA



ESA – All Systems GO!

NASA, junior partner

LIGO-Virgo GW events and Lisa Pathfinder success have helped significantly

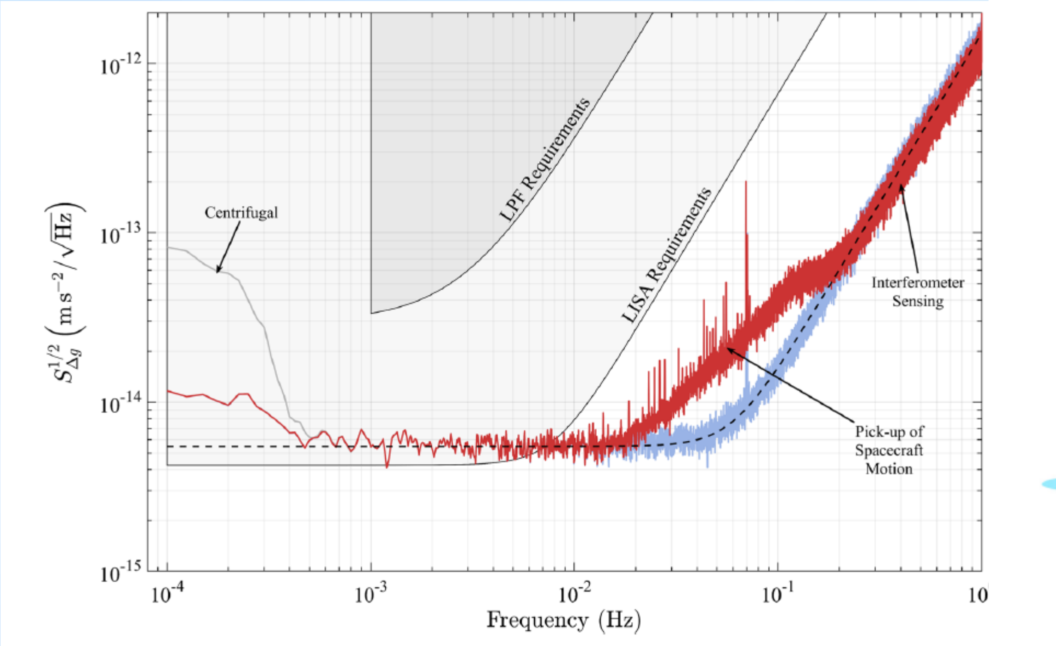
Tremendous activity at present

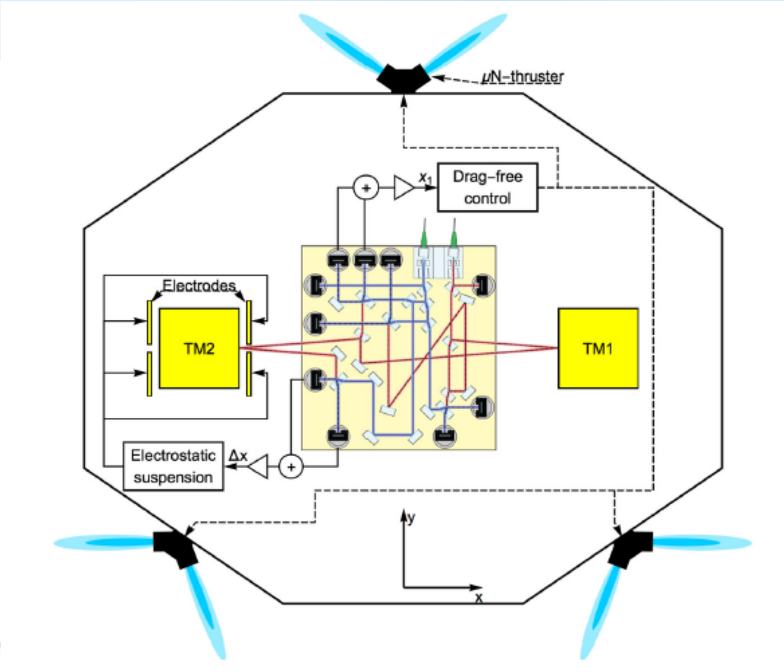
Planned launch 2034

4 year mission → 10 years?

Present plan: 3 Interferometers
2.5 x 10^6 km arm lengths

LISA Pathfinder – Demonstrating LISA Technology



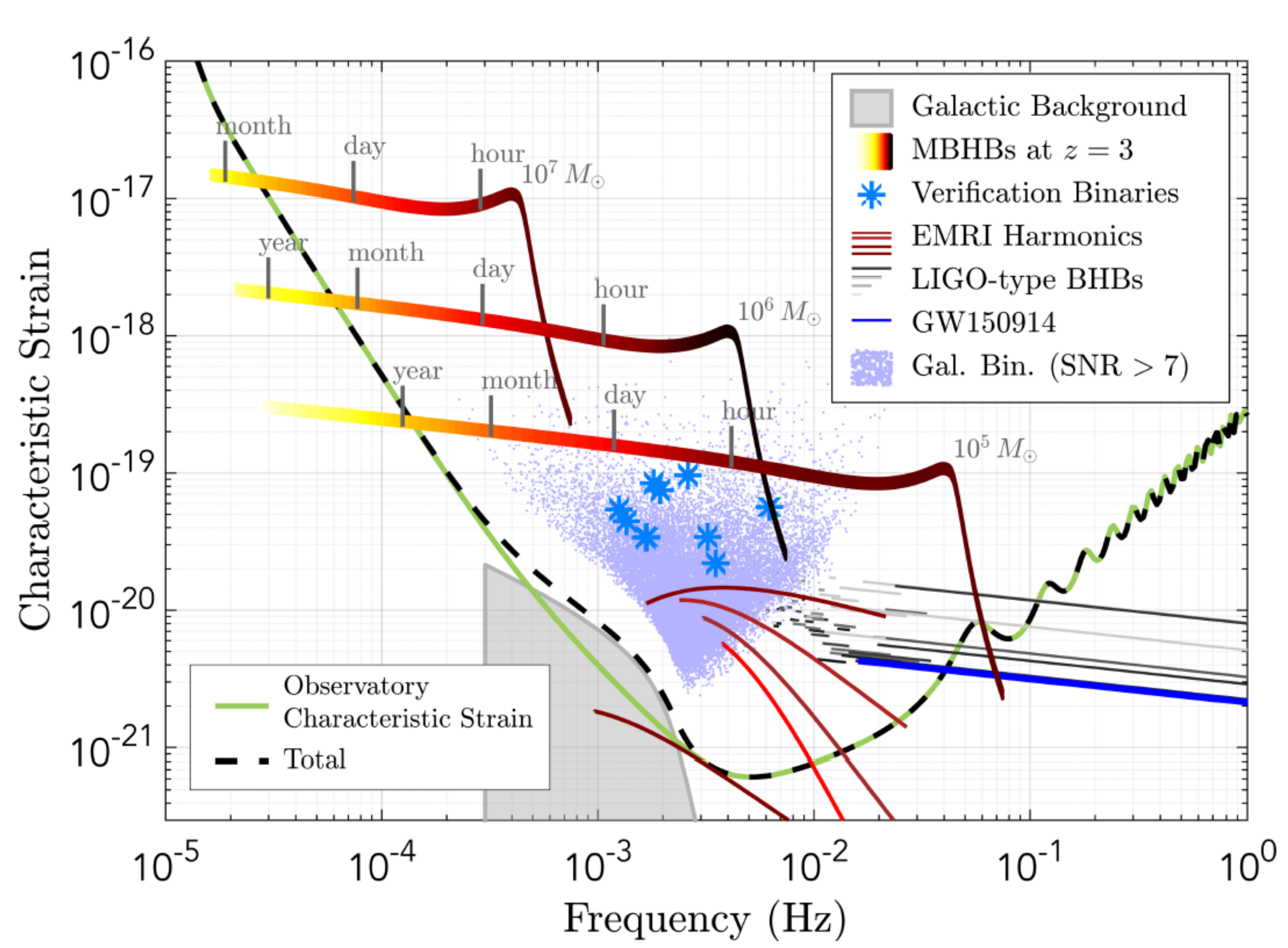


LISA Pathfinder worked! Exceeded requirements. Still, operation was not perfect, and there is lots of experimental work to do before LISA.

A set of cold gas micro-newton thrusters to ensure the spacecraft follows TM1. A second control loop forces TM2 to stay at a fixed distance from TM1 and thus centered in its own electrode housing.

PRL **116**, 231101 (2016)

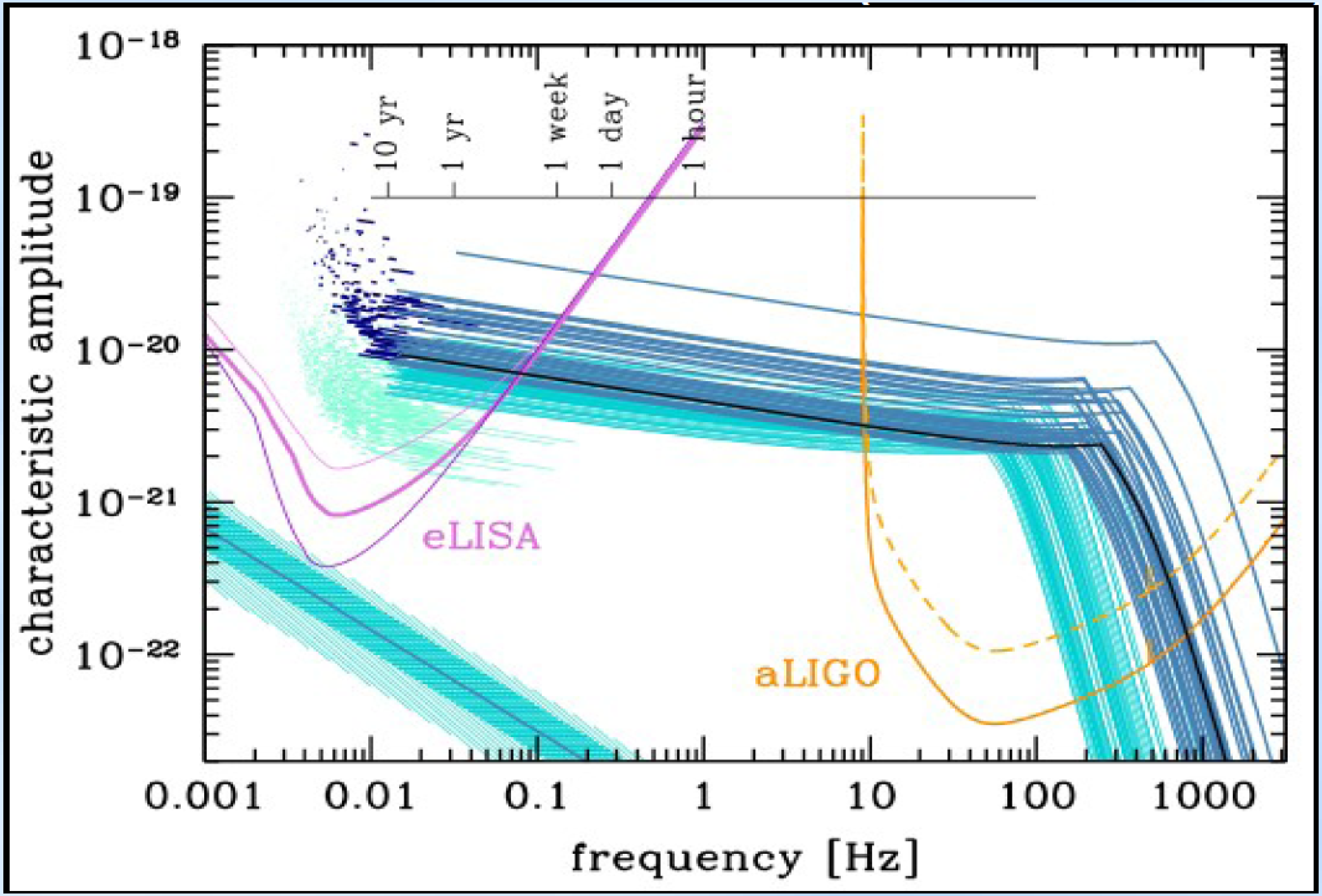
LISA Physics



1702.00786

Characteristic strain amplitude versus frequency (arm length 2.5 x 10^6 km, 1-yr observations).

LISA Physics



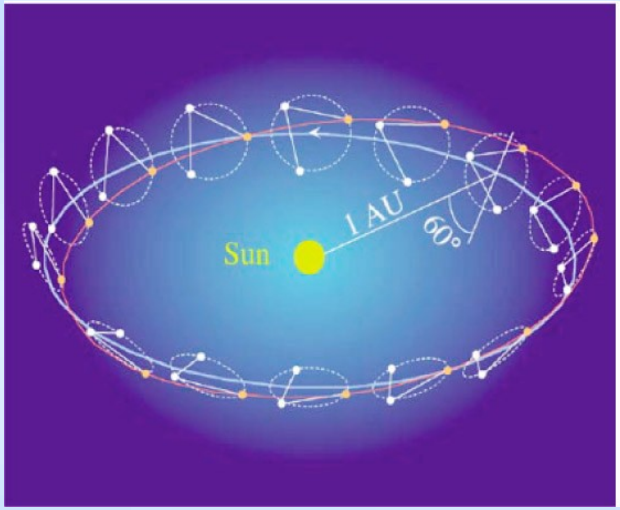
Gravitational wave signals from a heavy stellar black hole binaries. BBH systems can be observed by both LISA and Advanced LIGO – Advanced Virgo.

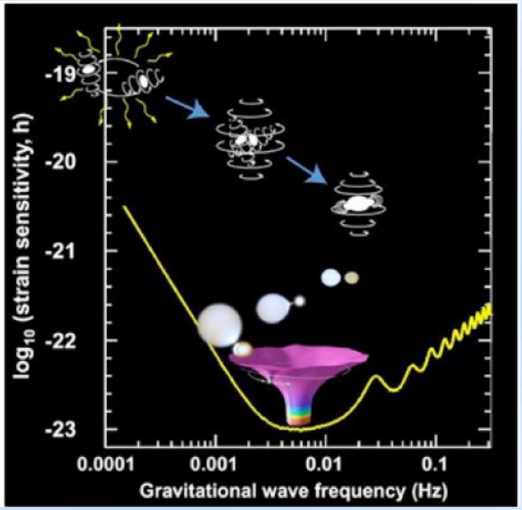
LISA GOAT, A. Sesana

LISA physics

- the nature of gravity
- the fundamental nature of black holes
- black holes as sources of energy
- nonlinear structure formation
- dynamics of galactic nuclei
- formation and evolution of stellar binary systems
- the very early universe
- cosmography (specifically, the cosmic distance scale)

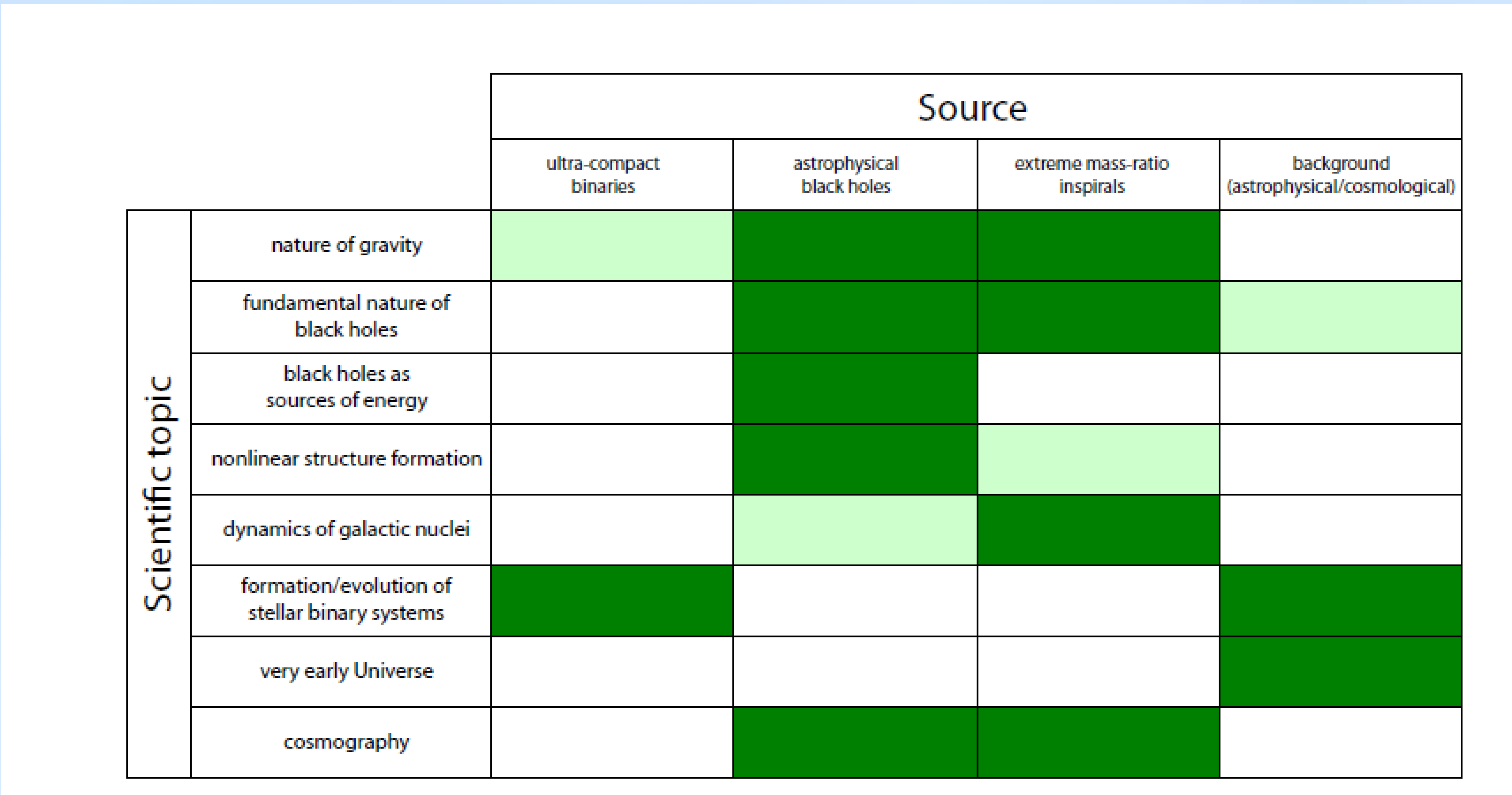
Gravitational Observatory Advisory Team – GOAT (ESA web site)





Testing the Early Universe

- Inflation
- Electro-weak phase transition, or phase transitions related to new physics
- Cosmic strings (phase transitions, topological defects, cosmic superstrings)



LISA – France

- France has the responsibility for ...
  - LISA Data Procession Center
  - Assembly, Integration, Verification, Testing (AIVT)
- Lots of other work in France: astrophysics, cosmology, etc.
- Exciting work ahead!!!!

https://signup.lisamission.org/

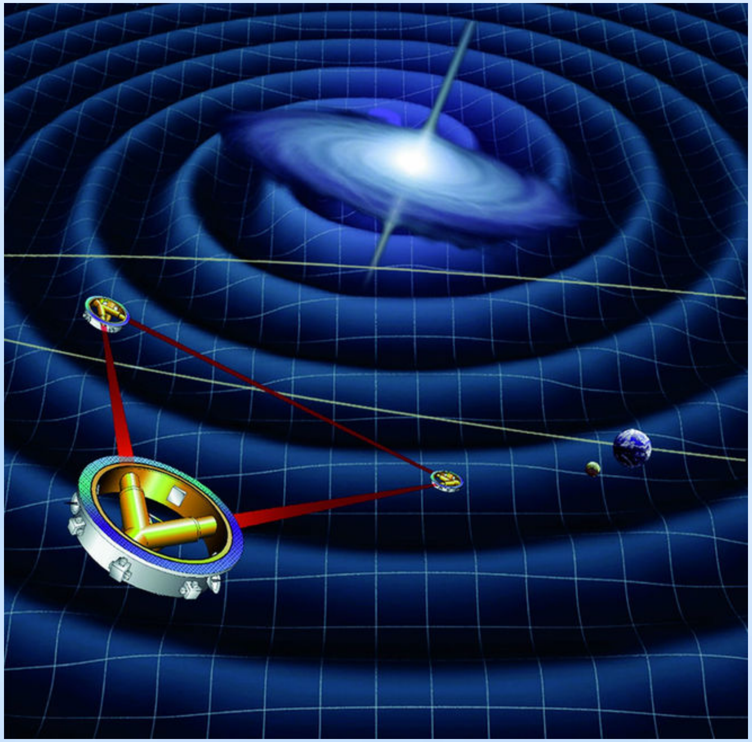
LISA Summary

The LISA project is presently moving forward rapidly.

ESA and NASA see this as a high priority.

A tremendous amount of R&D still needs to be done for LISA, and there is much experimental activity.

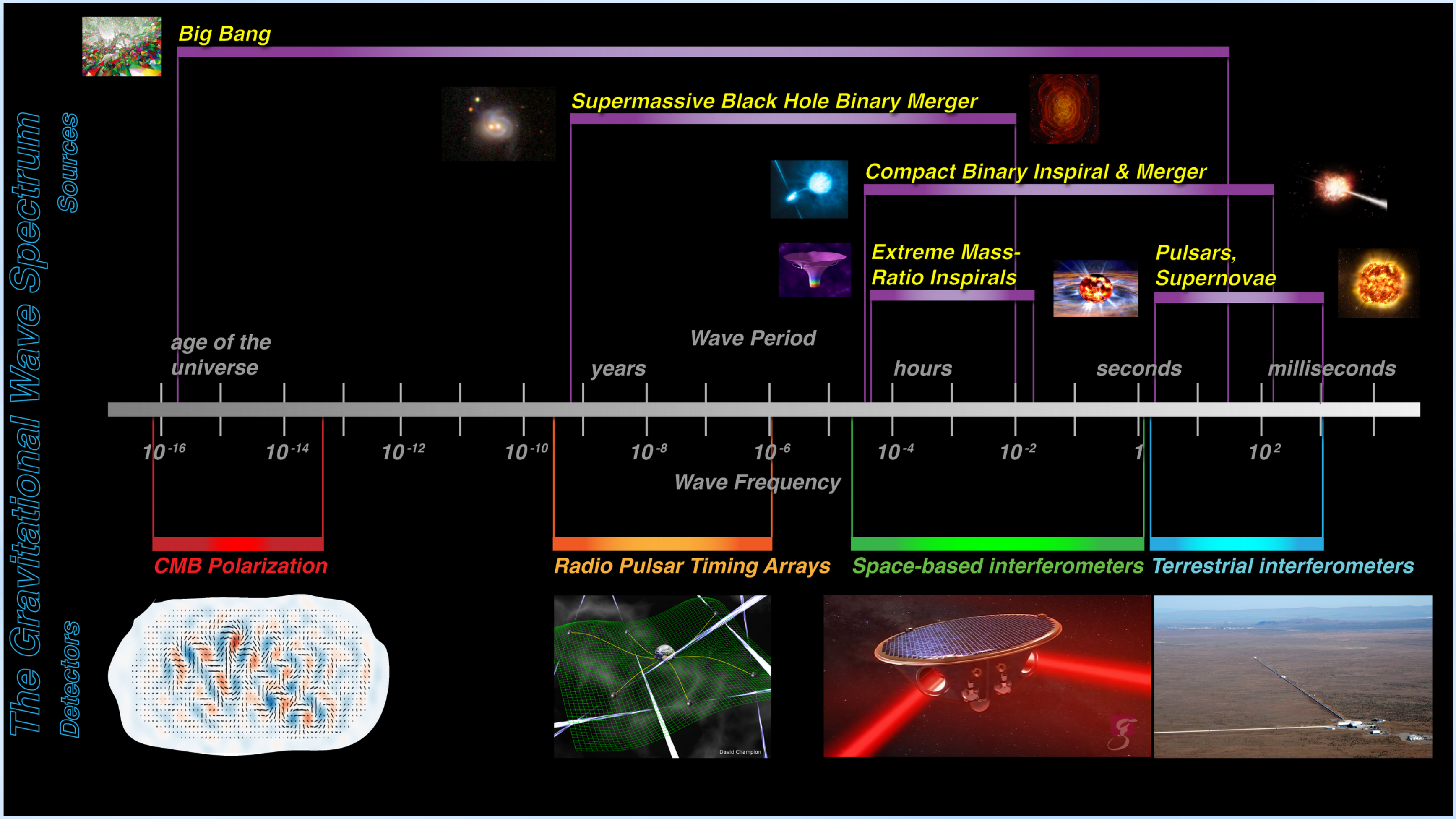
After the LHC, LISA may offer the best opportunity to observe the high energy physics that describes the universe.



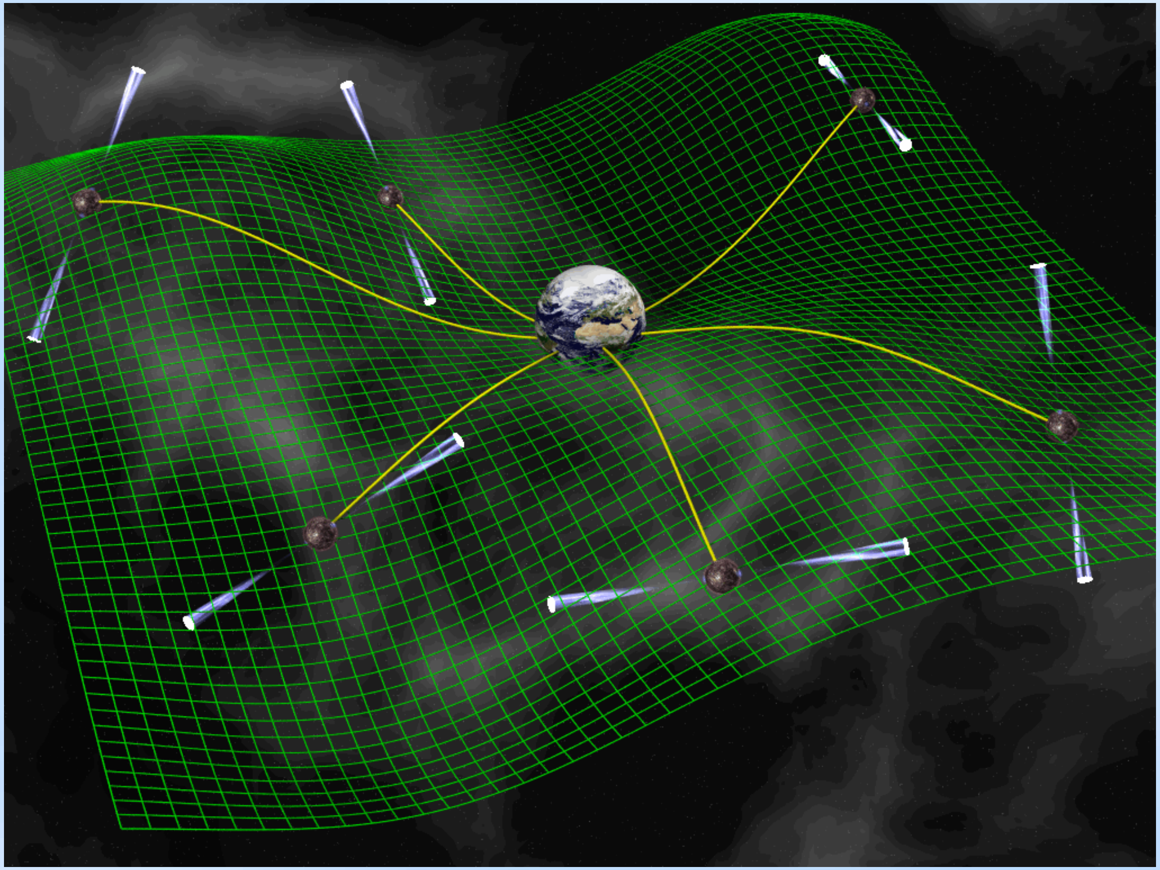
IMBH: Bridge from Stellar Mass to SMBH

- LIGO-Virgo, BBH systens with 100s of solar mass
- Einstein Telescope and Cosmic Explorer, BBH systens with 1000s of solar mass
- LISA, BBH systens with millions of solar mass
- A tremendous opportunity to measure the BBH systems from stellar mass to SMBH
- This can only be done with gravitational wave observations!

Gravitational Wave Spectrum



Pulsar Timing



arXiv:1211.4590

Distant pulsars send regular radio pulses – highly accurate clocks.
A passing gravitational wave would change the arrival time of the pulse.

Numerous collaborations around the world. Interesting upper limits and likely detections in the near future.

NANOGrave 12.5 Data Set – A Hint At ASignal?

The NANOGrav 12.5-year Data Set:
Search For An Isotropic Stochastic Gravitational-Wave Background

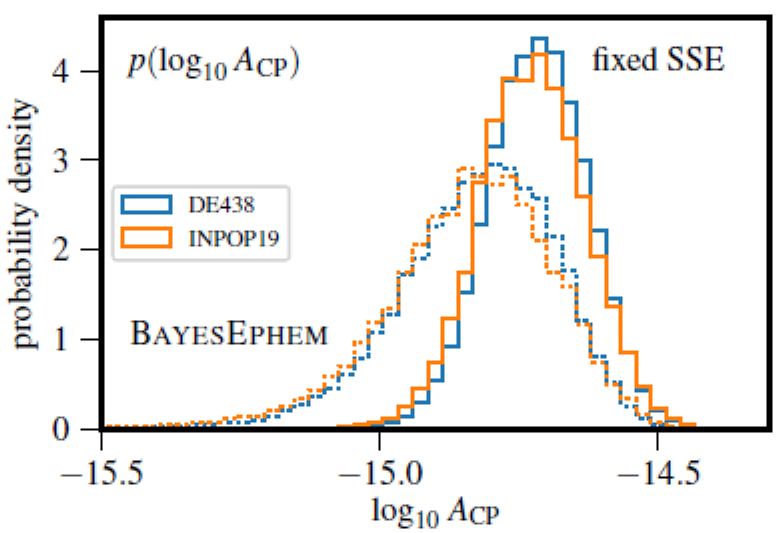


Figure 2. Bayesian posteriors for the ($f_{yr} = 1\mathrm{yr}^{-1}$) amplitude A_{CP} of a common-spectrum process, modeled as a $\gamma = 13/3$ power law using only the lowest five component frequencies. The posteriors are computed for the

First hint of a signal?

Some bias or “red noise”?

Arxiv is hot with theories: SMBHs, primordial BHs, cosmic strings, …

The coming years of pulsar timing observations could see a confirmed observation.

“Our analysis finds strong evidence of a stochastic process, modeled as a power-law, with common amplitude and spectral slope across pulsars.”

arXiv:2009.04496

Pulsar Timing

EPTA
The Radio Telescope Effelsberg in Germany
The Lovell Telescope in the UK,
The Nancay Decimetric Radio Telescope in France
The Sardinia Radio Telescope in Italy
The 14-dish Westerbork Synthesis Radio Telescope in the Netherlands.

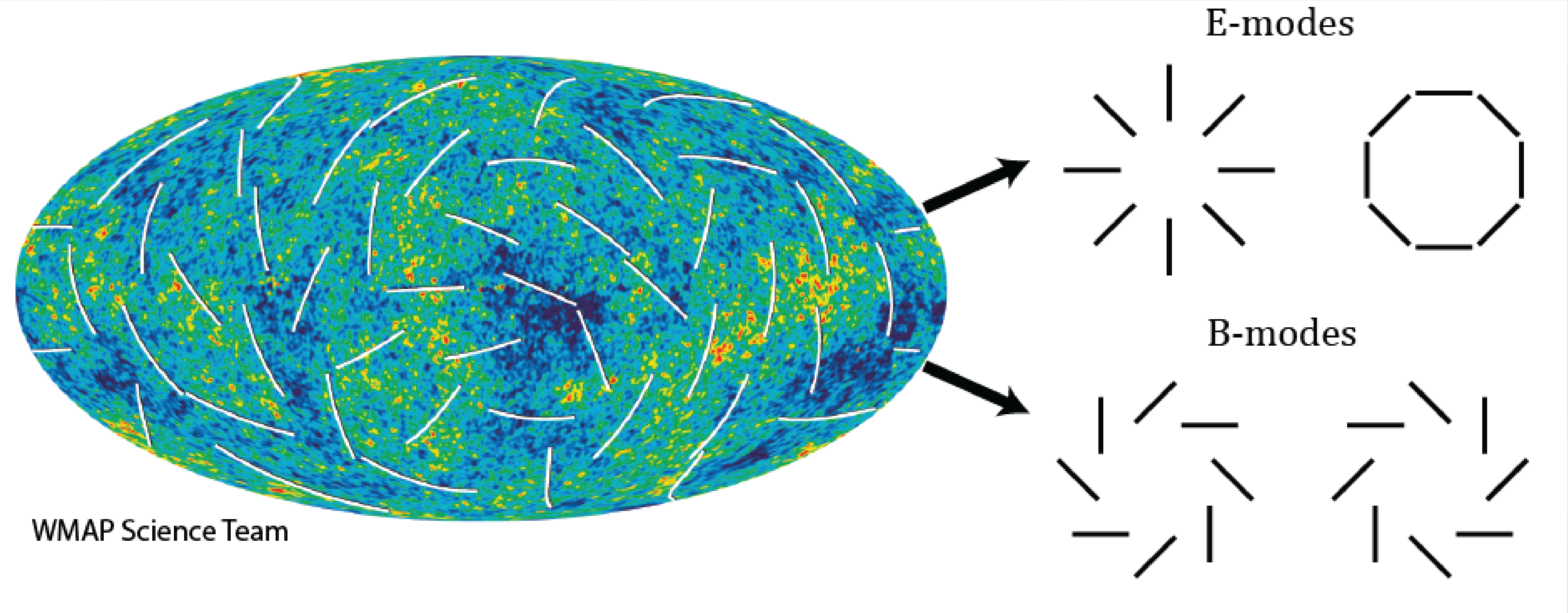
A ~ 3 x 10^{-15} 10^{-7} to 10^{-9} Hz over 18 years

THE WESTERBORK SYNTHESIS RADIO TELESCOPE in the Netherlands brings 14 dishes, each 25 m in diameter, to the European Pulsar Timing Array project. Together, they have an effective diameter of 94 m.

NANOgrav, EPTA, IPTA.

Square Kilometer Arrary – France is Back

Polarization Map of the Cosmic Microwave Background

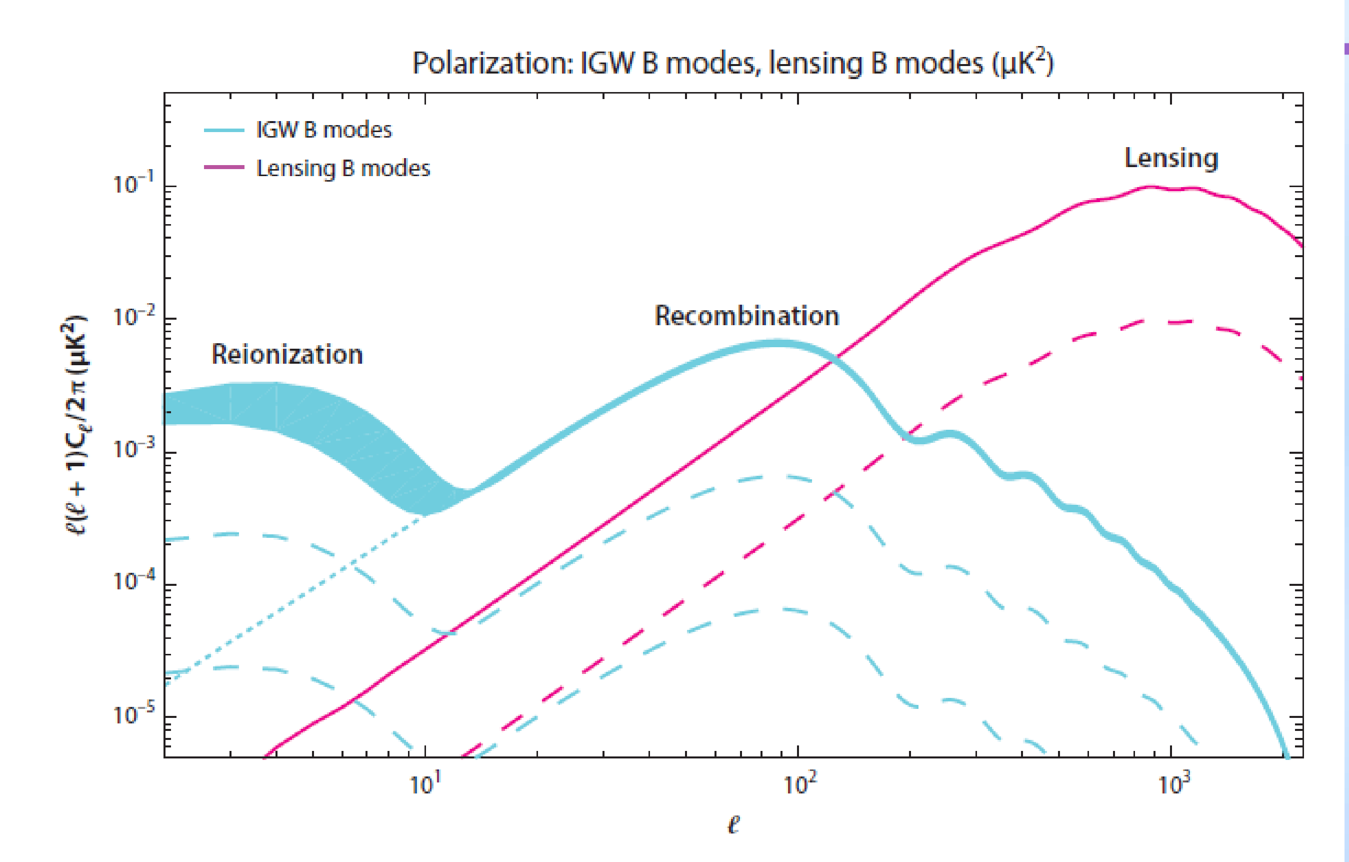


The CMB anisotropy polarization map may be decomposed into curl-free even-parity E-modes and divergence-free odd-parity B-modes.

Gravitational waves in the early universe imparts a “curl” on CMB polarization.
ArXiv:1407.2584

BICEP2, KECK Array, Planck, Atacama

Polarization Map of the Cosmic Microwave Background



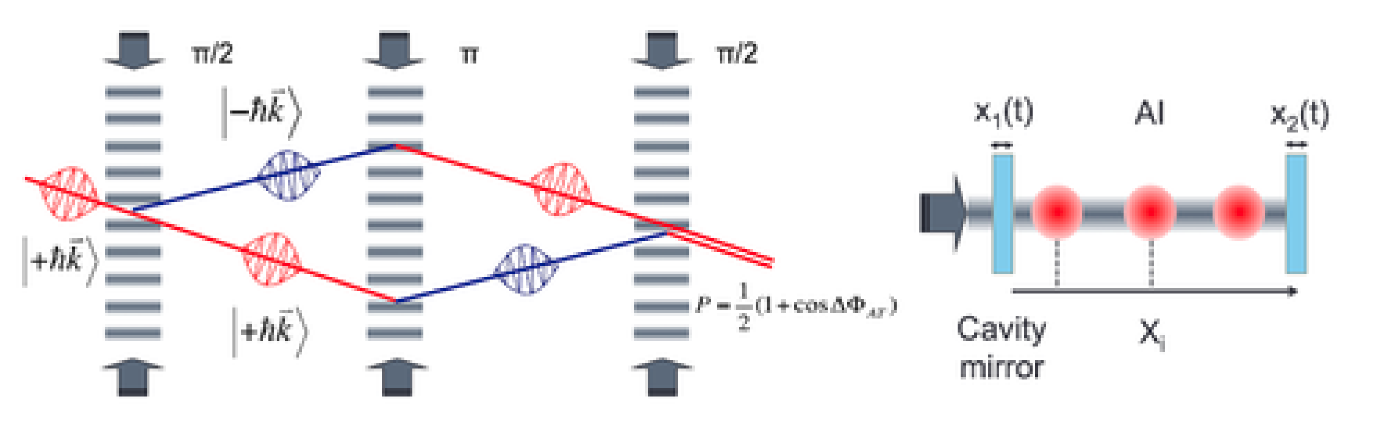
The GW amplitude is often reported as a tensor-to-scalar ratio,

$$r \equiv \frac{\Delta_h^2}{\Delta_{\mathcal{R}}^2} = 16\epsilon \simeq 0.1 \left[\frac{V}{(2 \times 10^{16}\,\mathrm{GeV})^4} \right], \tag{16}$$

where the measured value of $\Delta_{\mathcal{R}}^2$ was used in the last step. The current bound $r \lesssim 0.1$ (Ade et al. 2015a,d) thus provides a slightly stronger constraint on the energy density than the bound from measurement of the scalar amplitude.

M. Kamionkowski and E.D. Kovetz, 2016

Atom Interferometers

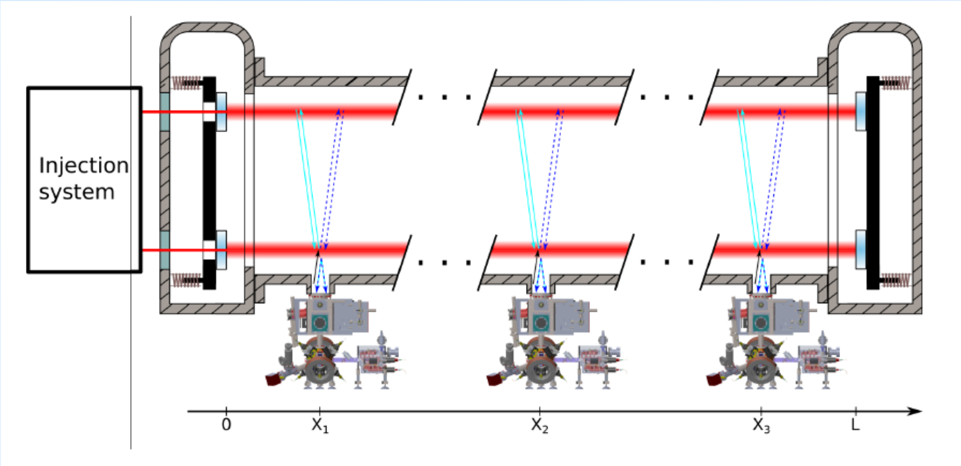


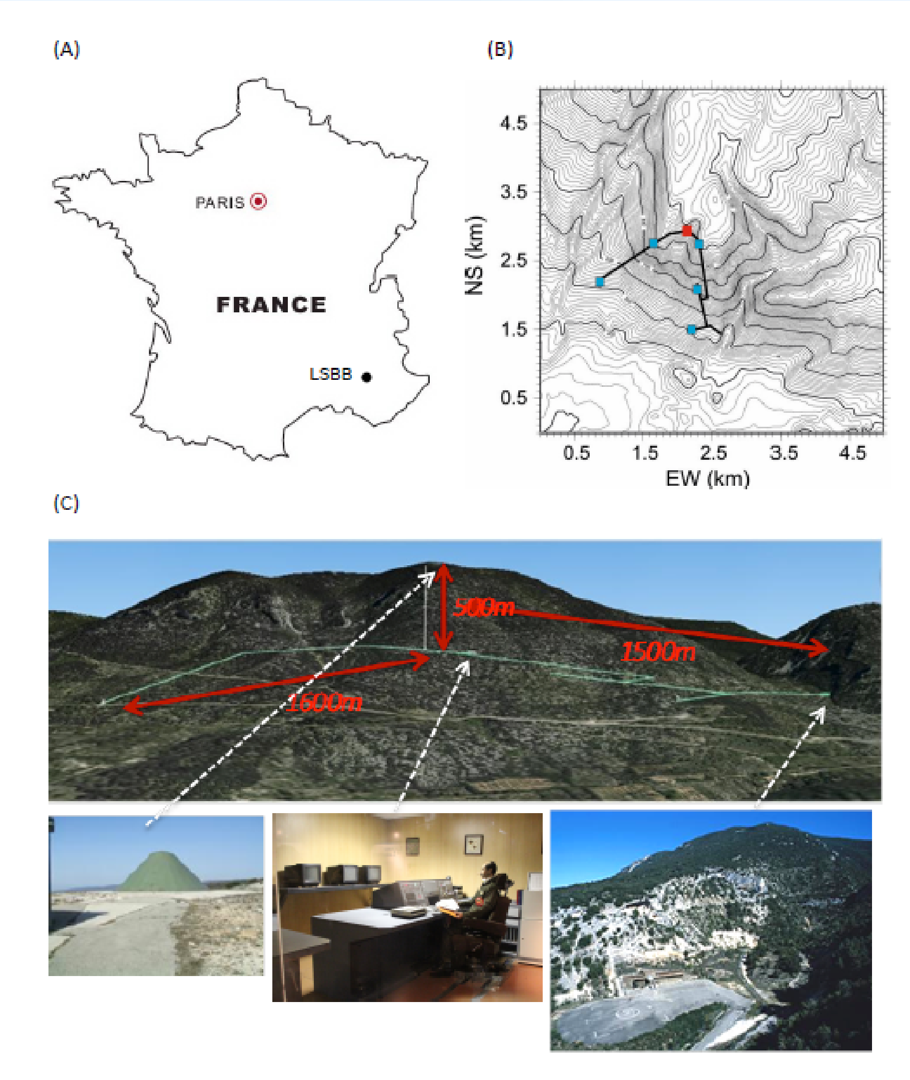
Use a long optical cavity to interrogate atom interferometers.

It may be possible to use this method to build a gravitational wave detector in the 0.1 Hz – 10 Hz band, between LISA and LIGO-Virgo.

Arxiv 1505:07137

MIGA: Matter Wave laser Interferometric Gravitation Antenna



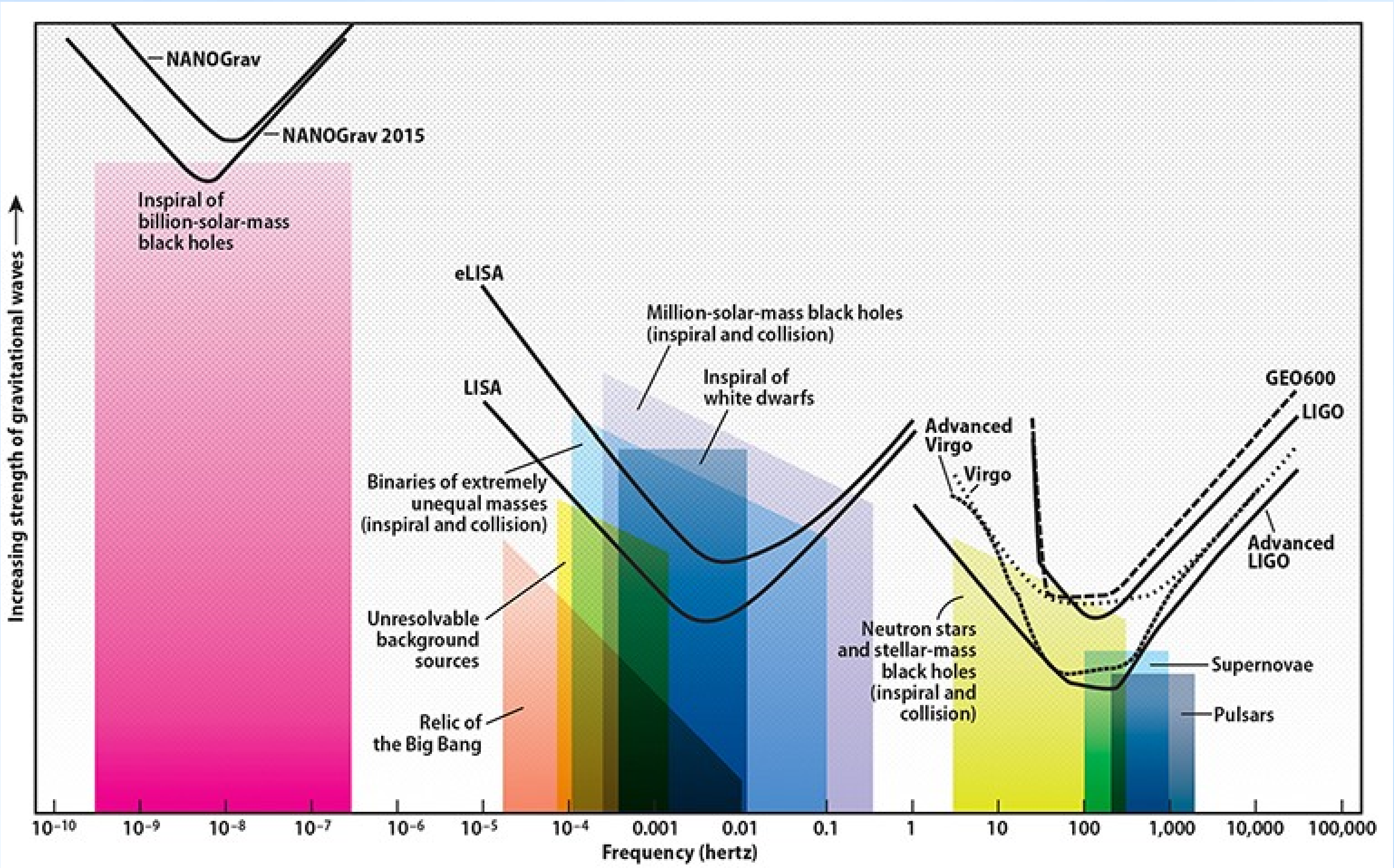


MIGA - 200 m arms

For longterm goals, see,
ELGAR - a European Laboratory for Gravitation and Atom-interferometric Research, arXiv:1911.03701

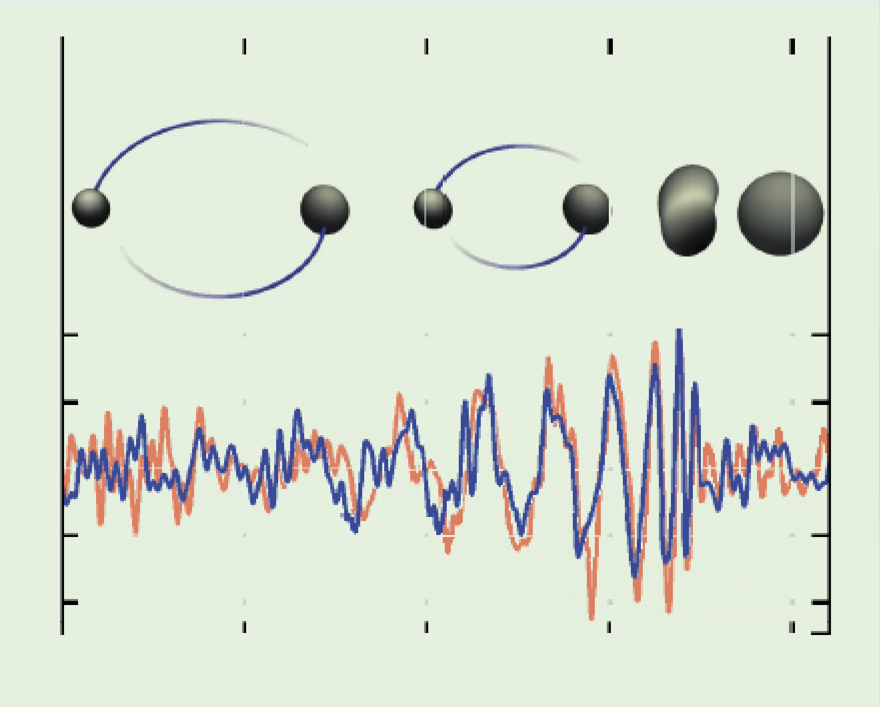
MIGA, a peak strain sensitivity of $2 \cdot 10^{-13}/\sqrt{\mathrm{Hz}}$ at 2 Hz. arXiv:1703.02490

Gravitational Wave Spectrum



Atom interferometric detectors would fill a critically important region of the GW spectrum. Between LISA and LIGO-Virgo

Conclusion on Gravitational Waves



A new window on the universe has opened.

We are just beginning!

The Results

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

GW190521 – Biggest BBH System Yet

GW190521: A Binary Black Hole Merger with a Total Mass of 150 $M_\odot$

R. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 30 May 2020; revised 19 June 2020; accepted 9 July 2020; published 2 September 2020)

On May 21, 2019 at 03:02:29 UTC Advanced LIGO and Advanced Virgo observed a short duration gravitational-wave signal, GW190521, with a three-detector network signal-to-noise ratio of 14.7, and an estimated false-alarm rate of 1 in 4900 yr using a search sensitive to generic transients. If GW190521 is from a quasicircular binary inspiral, then the detected signal is consistent with the merger of two black holes with masses of 85^{+21}_{-14} $M_\odot$ and 66^{+17}_{-18} $M_\odot$ (90% credible intervals). We infer that the primary black hole mass lies within the gap produced by (pulsational) pair-instability supernova processes, with only a 0.32% probability of being below 65 $M_\odot$. We calculate the mass of the remnant to be 142^{+28}_{-16} $M_\odot$, which can be considered an intermediate mass black hole (IMBH). The luminosity distance of the source is $5.3^{+2.4}_{-2.6}$ Gpc, corresponding to a redshift of $0.82^{+0.28}_{-0.34}$. The inferred rate of mergers similar to GW190521 is $0.13^{+0.30}_{-0.11}$ $\mathrm{Gpc^{-3}\,yr^{-1}}$.

DOI: 10.1103/PhysRevLett.125.101102

Formation of an Intermediate Mass Black Hole

Progenitor in pair instability supernova mass gap