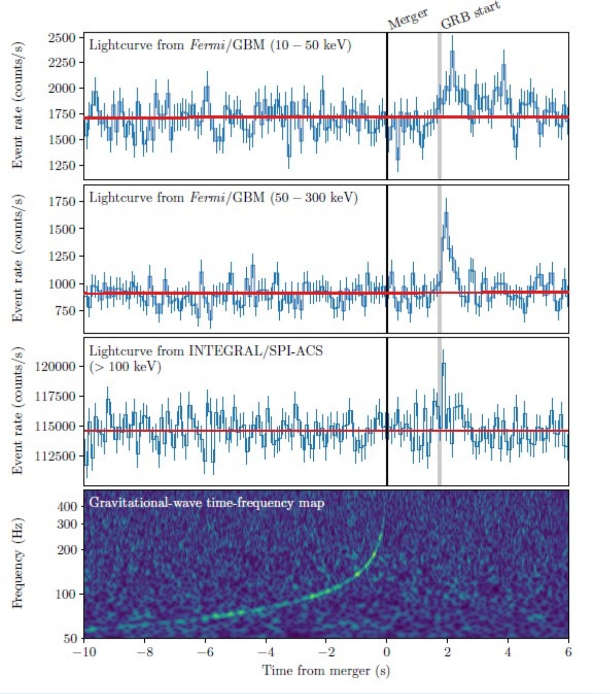
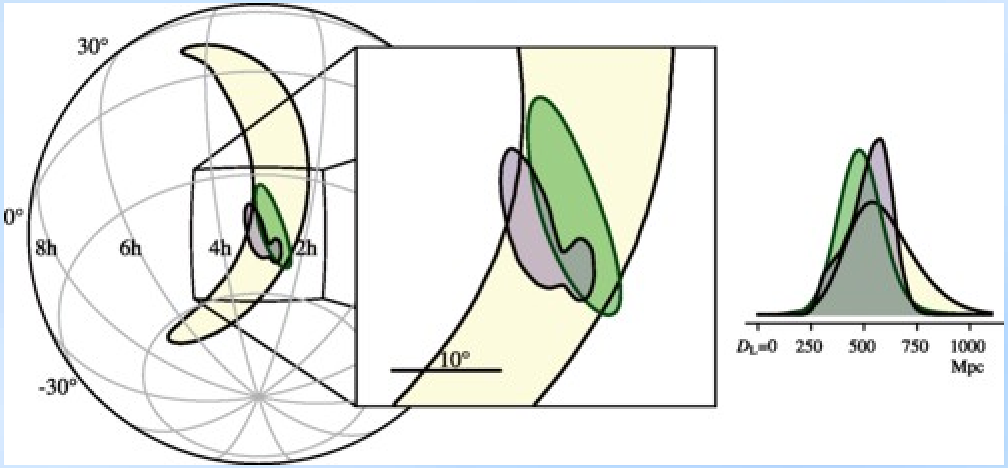




# Gravitational Waves: Now and in the Future

Nelson Christensen, Artemis

Observatoire de la Côte d’Azur, Nice

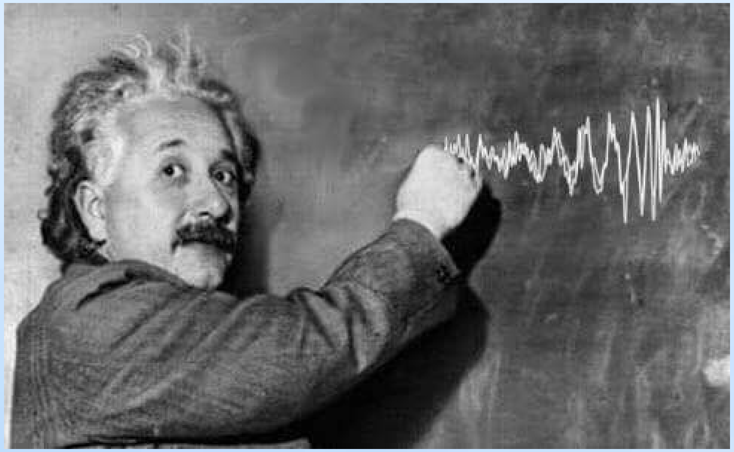
October 21, 2024 Blois

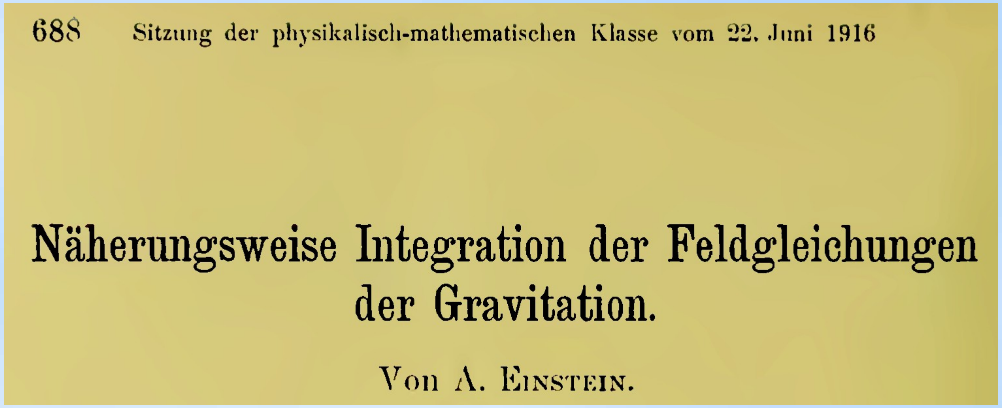
# General Relativity

1915: Einstein’s Theory of General Relativity

1916: Einstein paper on linear approximation to general relativity with multiple applications, including gravitational waves.

1918: On gravitational waves: emission (quadrupole), polarizations, they carry energy, etc



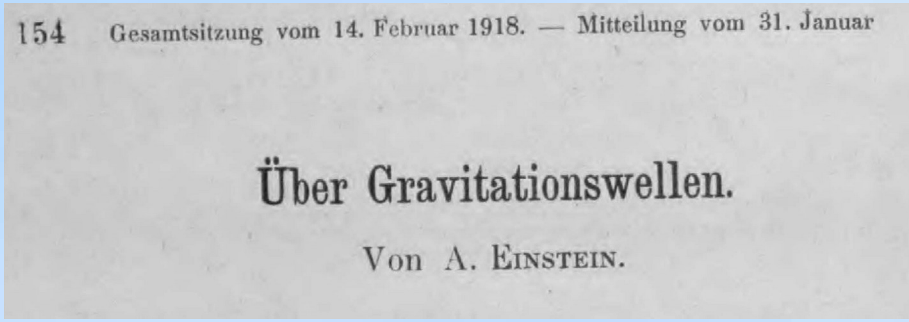


688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Approximative Integration of the Field Equations of Gravitation



154 Gesamtsitzung vom 14. Februar 1918. — Mitteilung vom 31. Januar

Über Gravitationswellen.

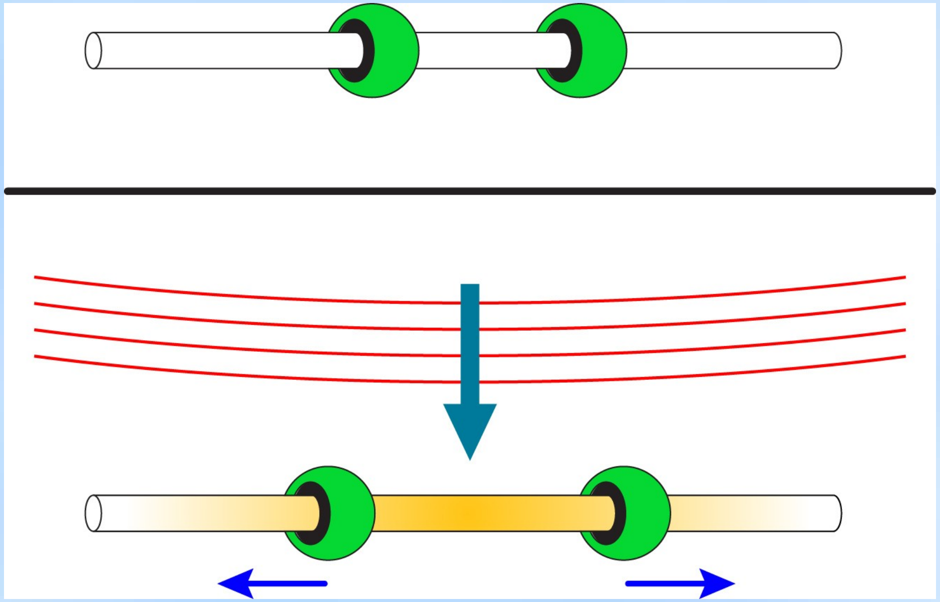
Von A. Einstein.

On Gravitational Waves

# Are Gravitational Waves Real?

Continued debate on whether gravitational waves really exist up until 1957 Chapel Hill conference.

Felix Pirani paper and presentation: relative acceleration of particle pairs can be associated with the Riemann tensor. The interpretation of the attendees was that non-zero components of the Riemann tensor were due to gravitational waves.



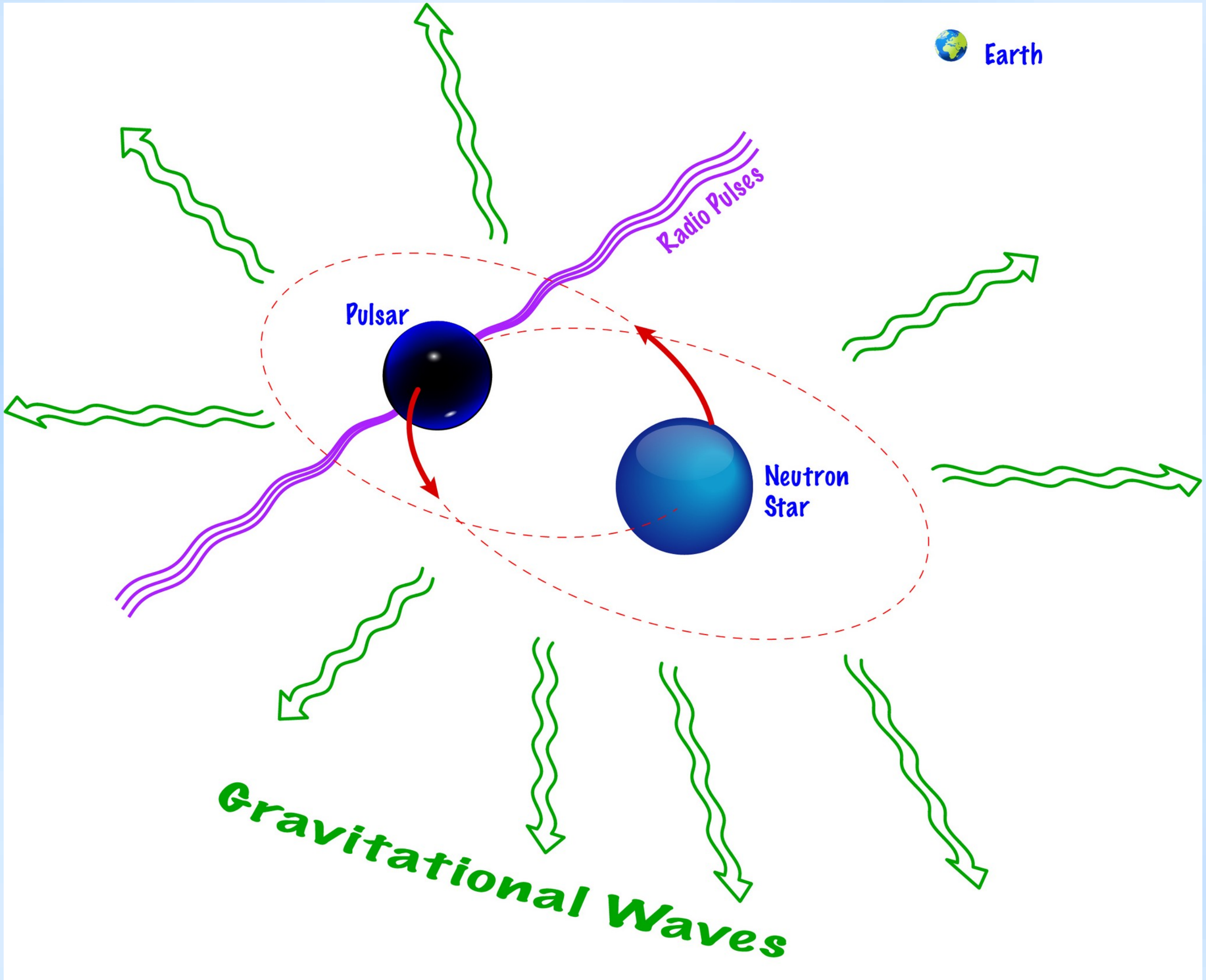
Sticky bead (Felix Pirani, Richard Feynman, Hermann Bondi)

Joe Weber of  the University of Maryland, and from this inspiration started to think about gravitational wave detection.

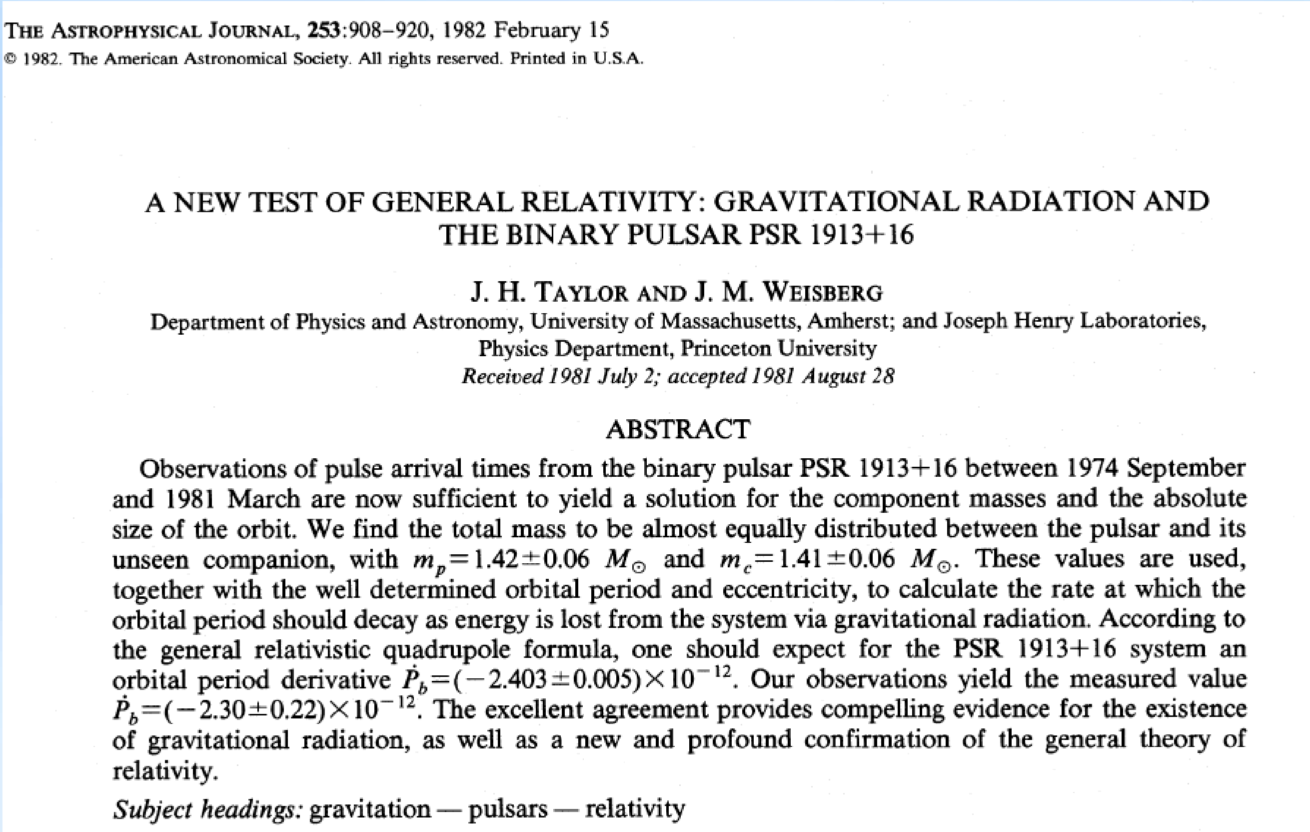
# Binary Pulsar PSR 1913+16

M1 = 1.438 $M_o$
M2 = 1.390 $M_o$
8 hour orbit
Orbit decays by
3mm per orbit.

Discovered in
1974 by Russell
Hulse and
Joseph Taylor,
then at
University
Massachusetts.



# First Proof That Gravitational Waves Exist - 1982



THE ASTROPHYSICAL JOURNAL, **253**:908–920, 1982 February 15

## A NEW TEST OF GENERAL RELATIVITY: GRAVITATIONAL RADIATION AND THE BINARY PULSAR PSR 1913+16

J. H. TAYLOR AND J. M. WEISBERG
Department of Physics and Astronomy, University of Massachusetts, Amherst; and Joseph Henry Laboratories,
Physics Department, Princeton University

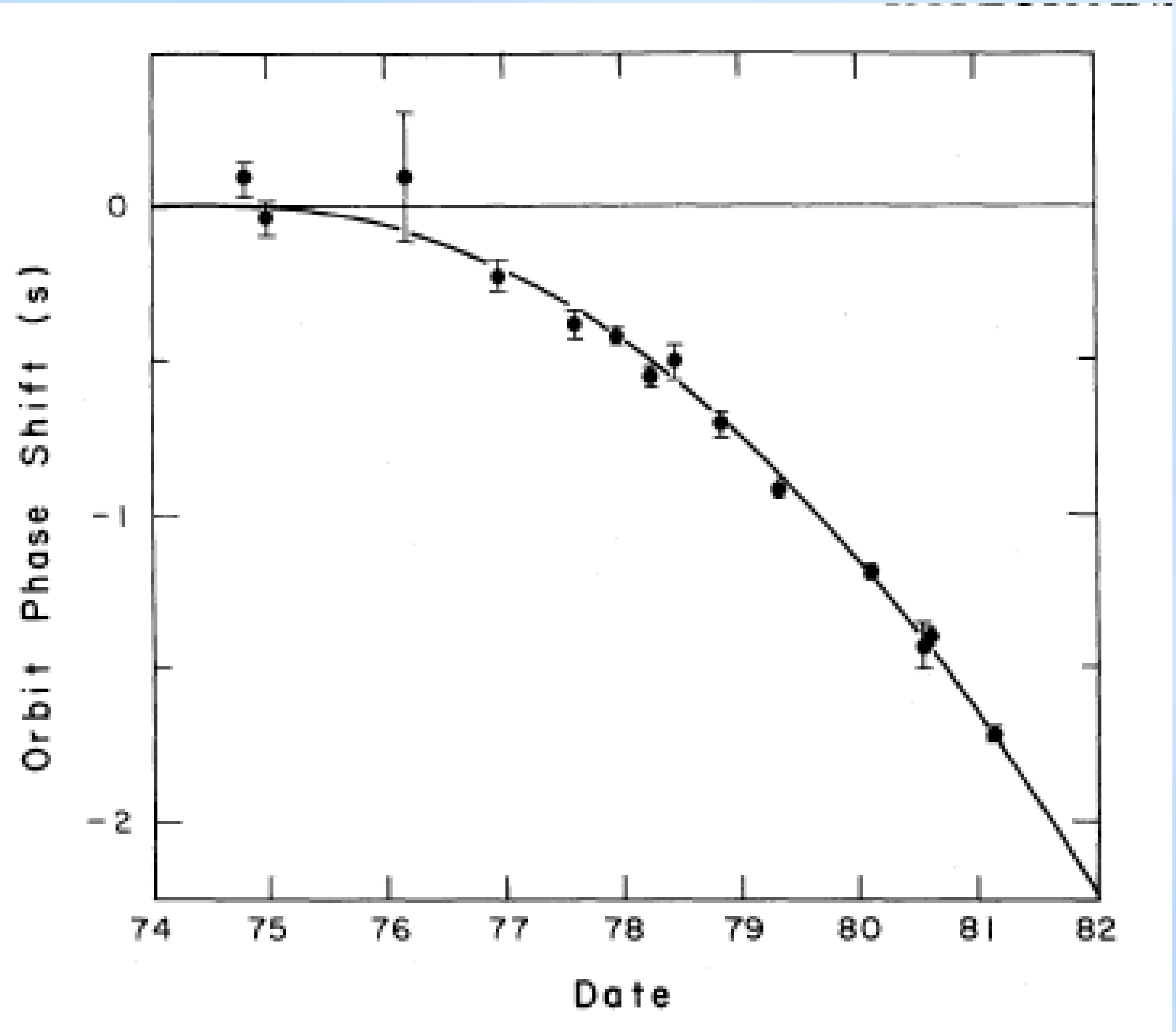
*Received 1981 July 2; accepted 1981 August 28*

### ABSTRACT

Observations of pulse arrival times from the binary pulsar PSR 1913+16 between 1974 September and 1981 March are now sufficient to yield a solution for the component masses and the absolute size of the orbit. We find the total mass to be almost equally distributed between the pulsar and its unseen companion, with $m_p = 1.42 \pm 0.06\ M_\odot$ and $m_c = 1.41 \pm 0.06\ M_\odot$. These values are used, together with the well determined orbital period and eccentricity, to calculate the rate at which the orbital period should decay as energy is lost from the system via gravitational radiation. According to the general relativistic quadrupole formula, one should expect for the PSR 1913+16 system an orbital period derivative $\dot{P}_b = (-2.403 \pm 0.005) \times 10^{-12}$. Our observations yield the measured value $\dot{P}_b = (-2.30 \pm 0.22) \times 10^{-12}$. The excellent agreement provides compelling evidence for the existence of gravitational radiation, as well as a new and profound confirmation of the general theory of relativity.

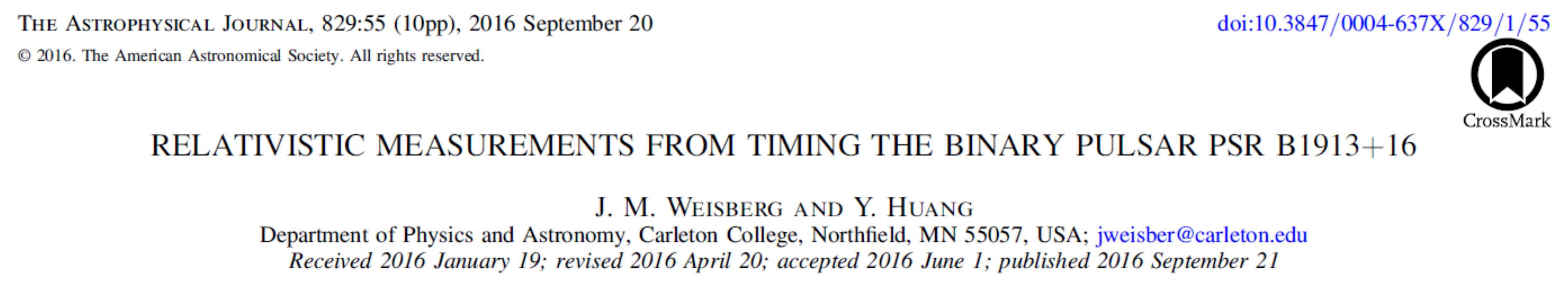
*Subject headings:* gravitation — pulsars — relativity

# Gravitational Wave Proof



Taylor and Weisberg, 1982

# Binary Pulsar Studies Continue

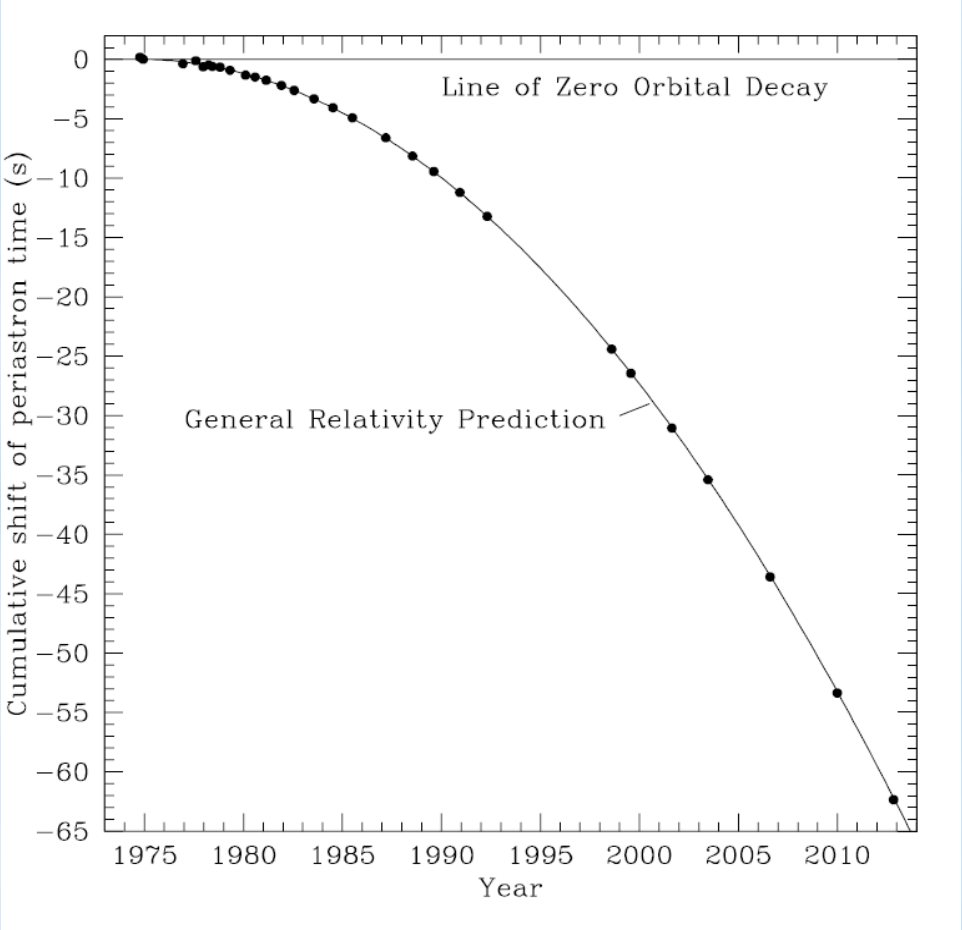


THE ASTROPHYSICAL JOURNAL, 829:55 (10pp), 2016 September 20
doi:10.3847/0004-637X/829/1/55

## RELATIVISTIC MEASUREMENTS FROM TIMING THE BINARY PULSAR PSR B1913+16

J. M. WEISBERG AND Y. HUANG
Department of Physics and Astronomy, Carleton College, Northfield, MN 55057, USA; jweisber@carleton.edu

*Received 2016 January 19; revised 2016 April 20; accepted 2016 June 1; published 2016 September 21*



“The points, with error bars too small to show, represent our measurements”

# Advanced LIGO – Advanced Virgo Network


LIGO Lab/Virgo

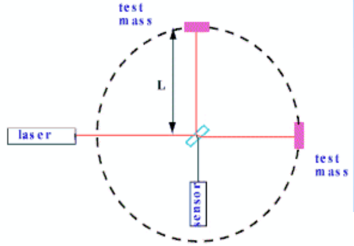
LIGO, Livingston,
Louisiana, USA
4 km

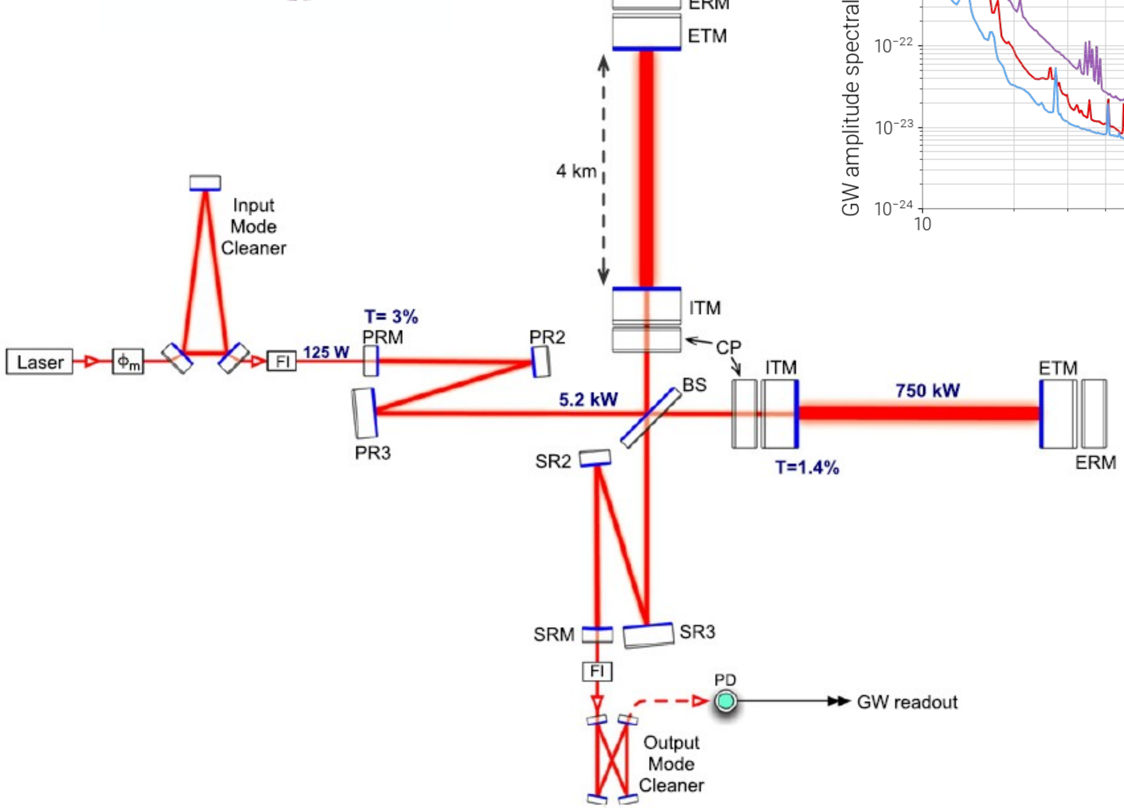
LIGO, Hanford,
Washington, USA
4 km

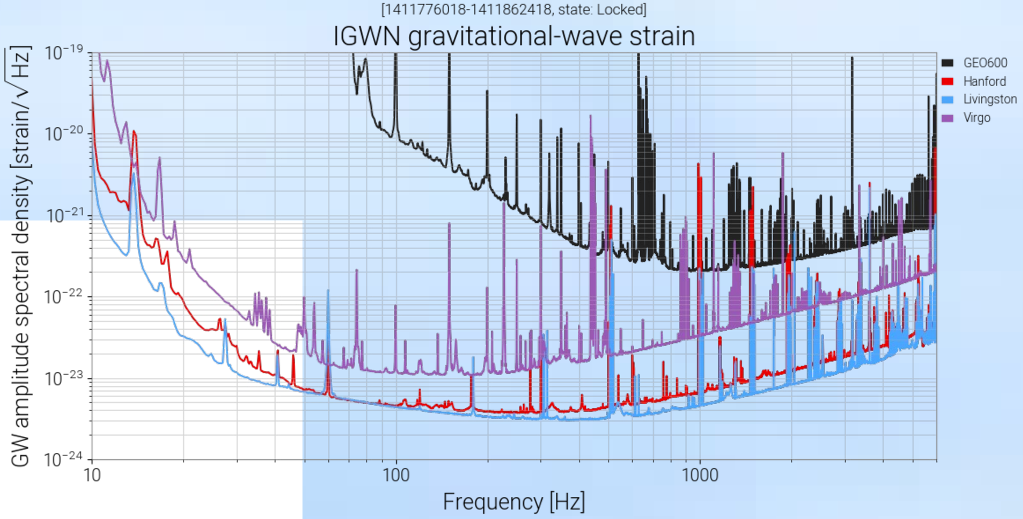
Virgo, Cascina,
Pisa, Italy
3 km

Three observing runs so far completed
O4 2023, 24 months in duration
+ KAGRA (3 km, underground, cryogenic mirrors) in Japan

# The Detectors



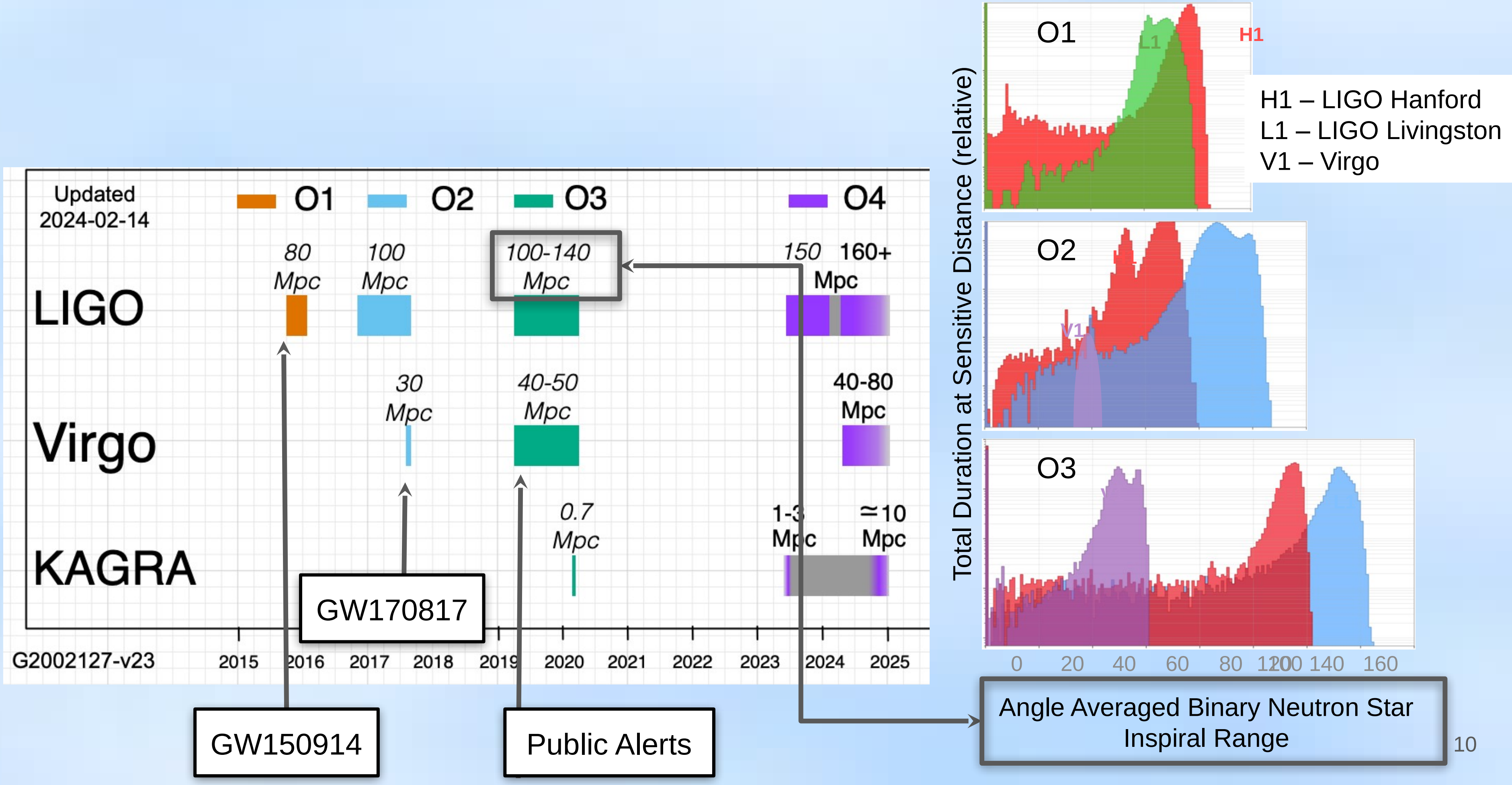




Recent O4 sensitivities

Advanced LIGO 4 km arms
Advanced Virgo 3 km

# Observing runs



H1 – LIGO Hanford
L1 – LIGO Livingston
V1 – Virgo

GW150914

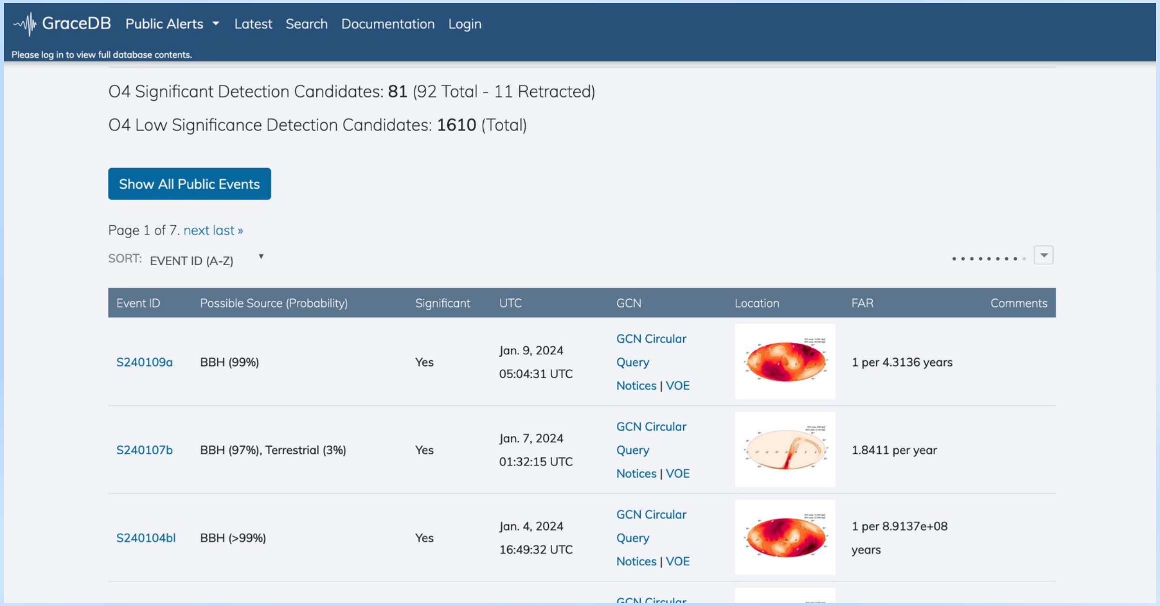
GW170817

Public Alerts

Angle Averaged Binary Neutron Star Inspiral Range

# The fourth observing run (O4)

- O4a: 24 May 2023 – 16 Jan 2024, LIGO and KAGRA for 1 month
- O4b: 10 April 2024 – Feb 2025, LIGO and Virgo
- O4c: Up to 9 June 2025
- Binary detection rates
  - O3 ~ 1 / 5 days
  - O4 ~ 1 / (2.8 days)
- Improved public alerts
  - Localization
  - Classification
  - Latency
  - Early-warning
  - Low-significance
- Improved sensitivity
  - > 150Mpc BNS range



Please log in to view full database contents.

O4 Significant Detection Candidates: **81** (92 Total - 11 Retracted)

O4 Low Significance Detection Candidates: **1610** (Total)

Page 1 of 7. next last »

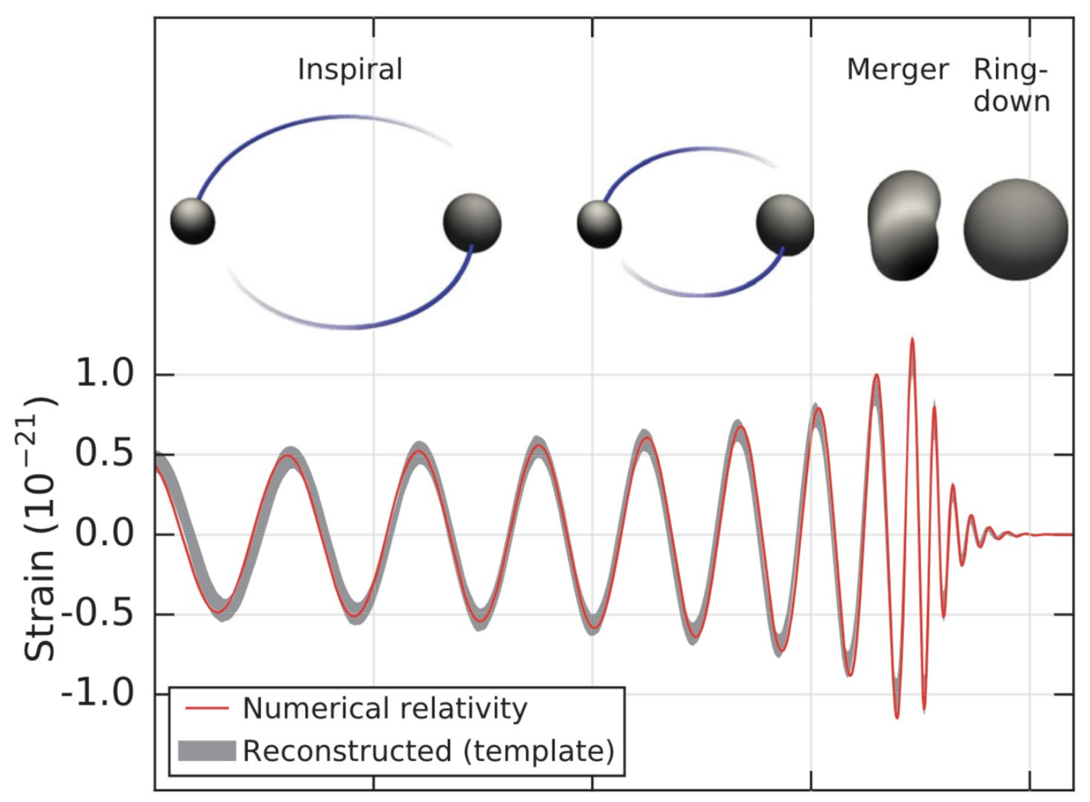
SORT: EVENT ID (A-Z)

| Event ID | Possible Source (Probability) | Significant | UTC | GCN | Location | FAR | Comments |
|---|---|---|---|---|---|---|---|
| S240109a | BBH (99%) | Yes | Jan. 9, 2024<br>05:04:31 UTC | GCN Circular<br>Query<br>Notices \| VOE | | 1 per 4.3136 years | |
| S240107b | BBH (97%), Terrestrial (3%) | Yes | Jan. 7, 2024<br>01:32:15 UTC | GCN Circular<br>Query<br>Notices \| VOE | | 1.8411 per year | |
| S240104bl | BBH (>99%) | Yes | Jan. 4, 2024<br>16:49:32 UTC | GCN Circular<br>Query<br>Notices \| VOE | | 1 per 8.9137e+08 years | |

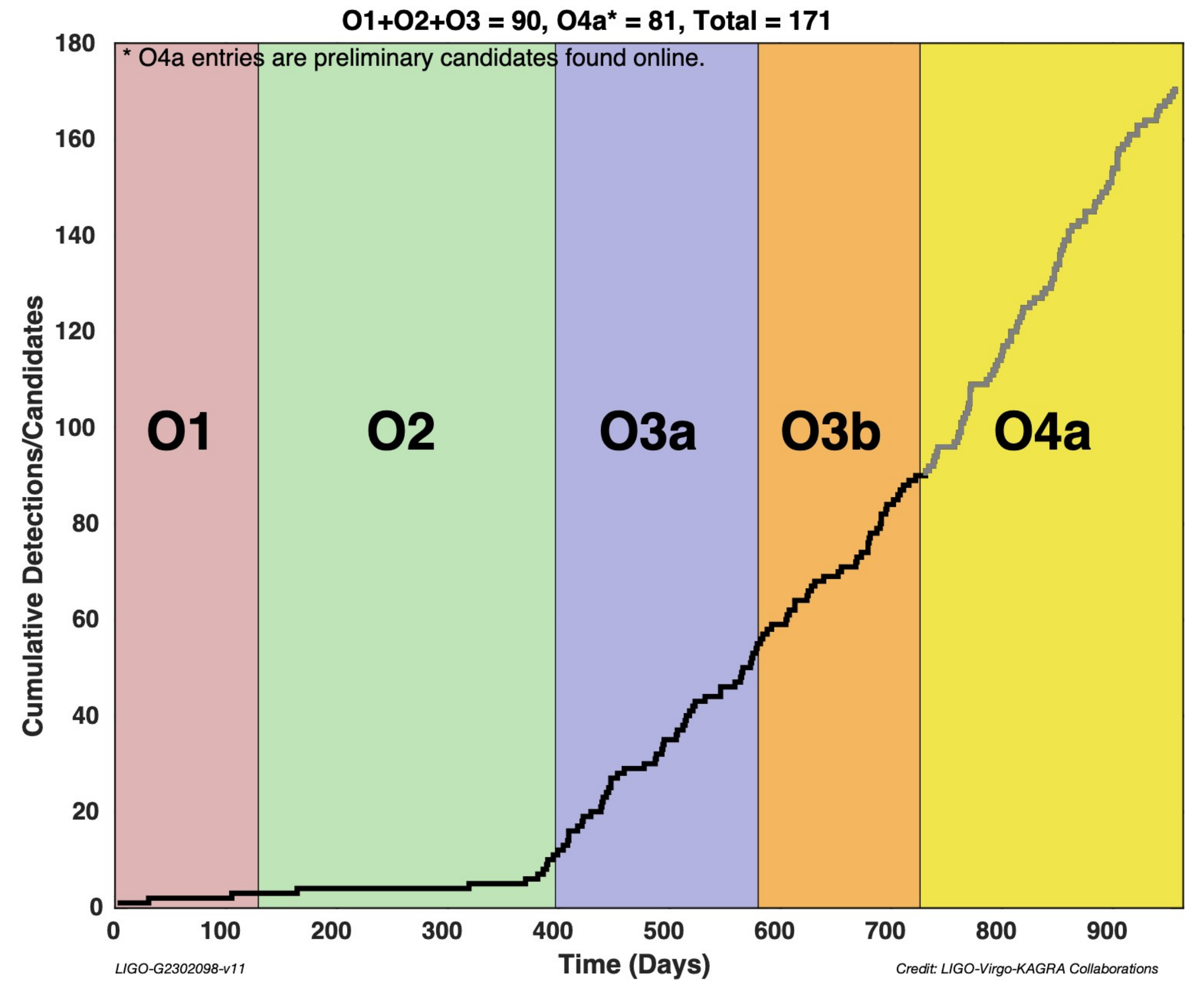
# Compact object mergers

Pairs of stellar-mass black holes, neutron stars, or a stellar-mass black hole and neutron star

$$h_{ij} \sim \frac{4GM}{c^4}\frac{v^2}{r}$$

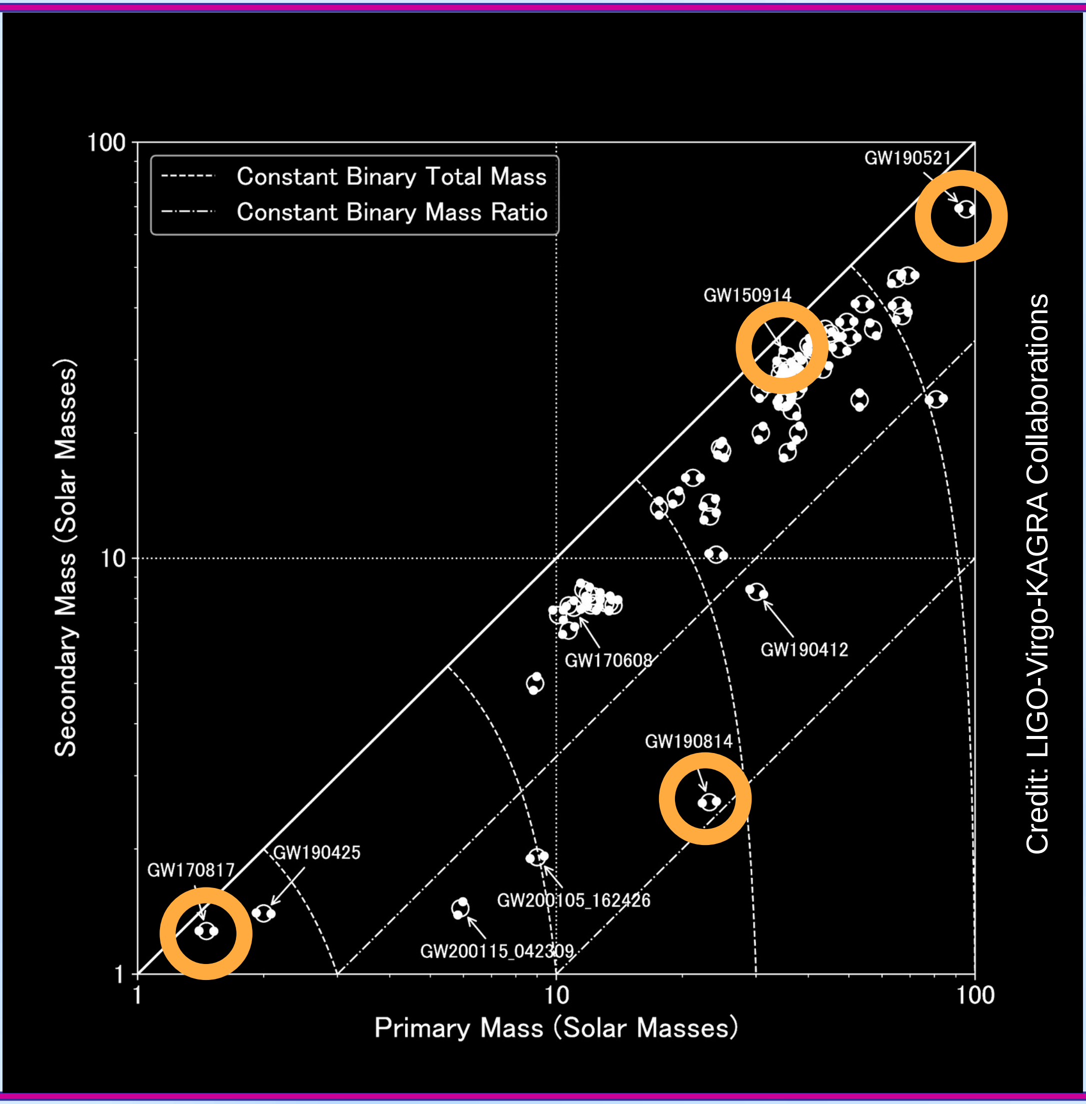


# Detections versus time observing



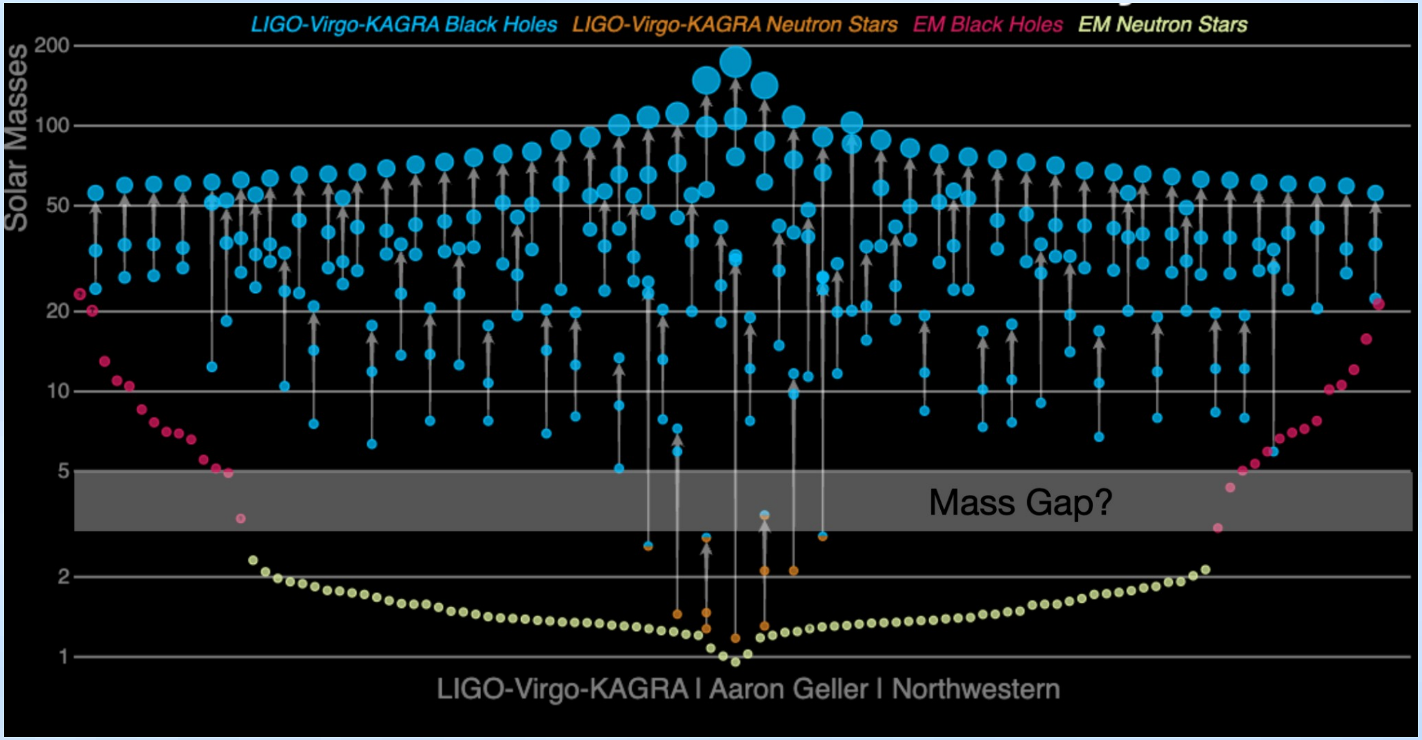
# Previous Important Detections

- GW150914
    - First astrophysical source
    - Binary black holes exist
- GW170817
    - Binary neutron star mergers are gamma-ray burst progenitors
- GW190521
    - Black holes exist in pair instability mass gap
- GW190814
    - Compact objects exist with masses between 2-5 Msun



Credit: LIGO-Virgo-KAGRA Collaborations

# LIGO-Virgo Measure of Compact Binary Mass Distributions



O3 – April 2019 to March 2020. Stopped early due to Covid.

Catalog of 90 events for O1+O2+O3

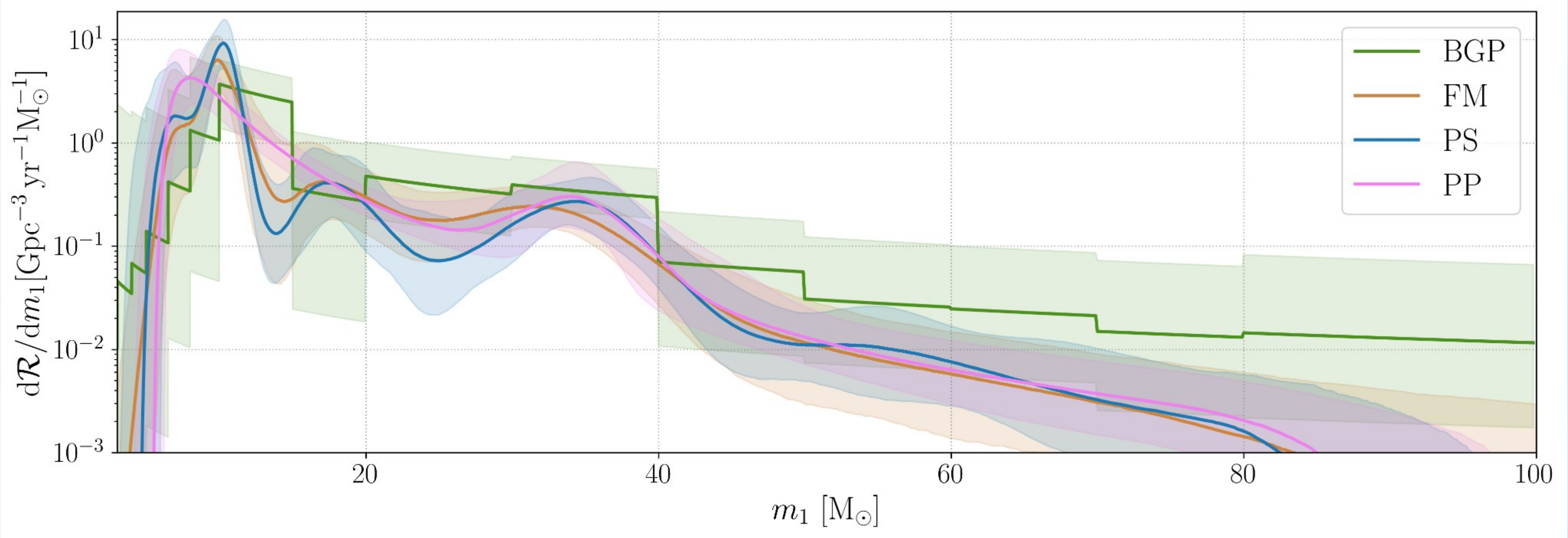
Culmative catalog

2 binary neutron star mergers

At least 2 NS-BH events

Majority of events are binary black holes

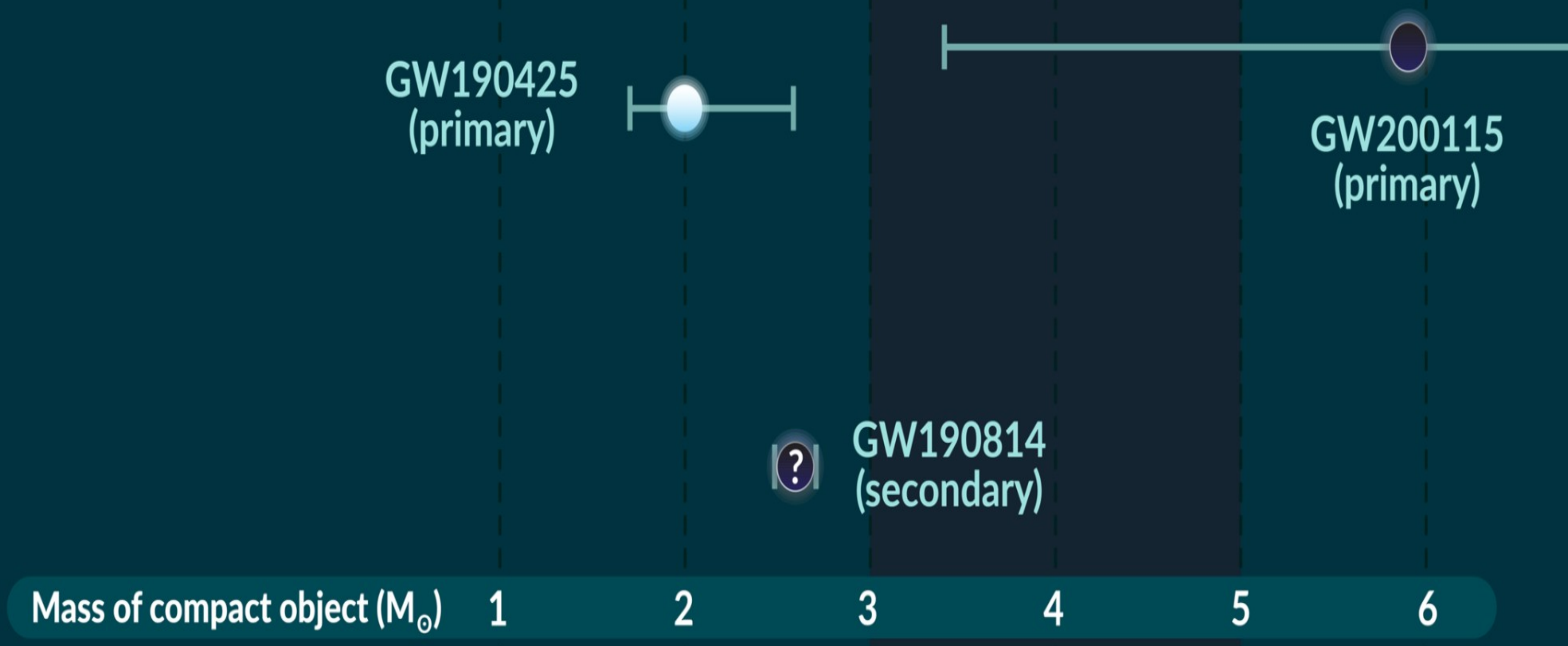
# Populations



Merger rate density as a function of primary mass using 3 non-parametric models compared to the power-law+peak (pp) model.

# FILLING THE MASS ⟷ GAP

*with observations of compact binaries from gravitational waves*

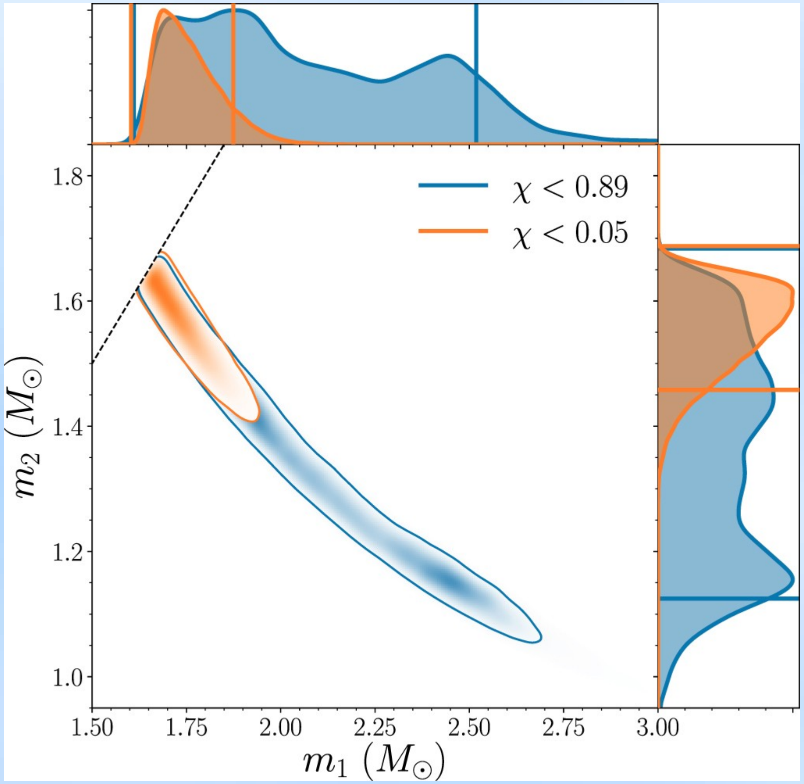


Includes components of compact binary mergers detected with a False Alarm Rate (FAR) of less than 0.25 per year

Figure credit: Shanika Galaudage / Observatoire de la Côte d'Azur

# Interesting O3 Events - GW190425

- 2nd binary neutron star observation
- Total Mass ~ 3.4 M⊙
  - $M_1 = 1.61 – 2.52$ M⊙
  - $M_2 = 1.12 – 1.68$ M⊙
- Heaviest binary neutron star system
- No EM counterpart observed, 159 Mpc
- GW170817 Total Mass ~ 2.74 M⊙
- Heaviest neutron star known from EM observations (PSR J0740+6620) M ~ 2.05–2.24



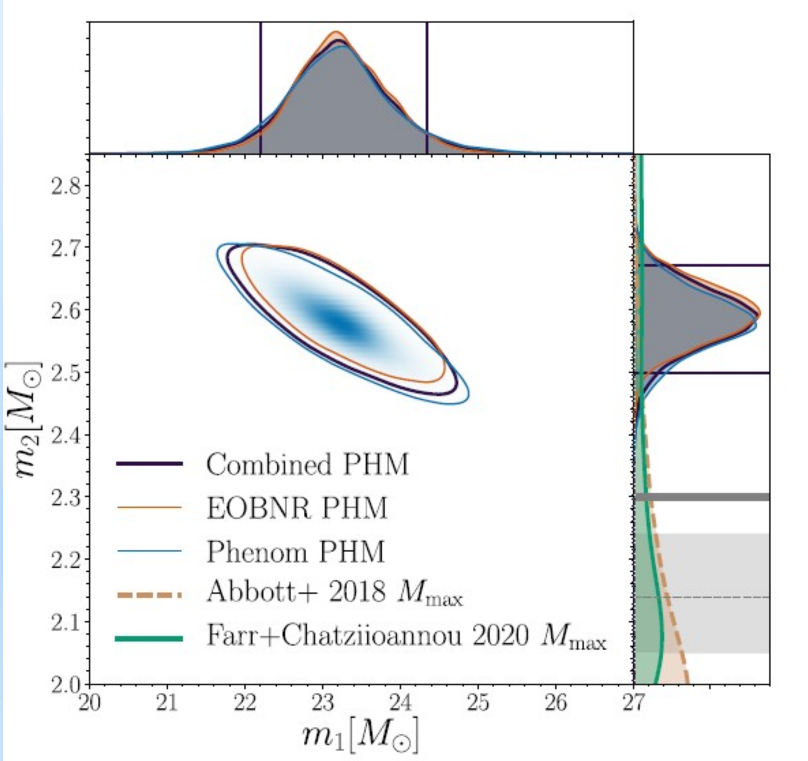
# Interesting O3 Events - GW190814

- Another unequal compact binary merger
- $M_1 \sim 23\ M_\odot$ , $M_2 \sim 2.50 – 2.67\ M_\odot$
- What is $M_2$?
  - A very large neutron star?
  - A very small black hole?

  - Above the heaviest known neutron star, MSP J0740+6620
  - Below the typical masses of black holes detected indirectly through EM observations.

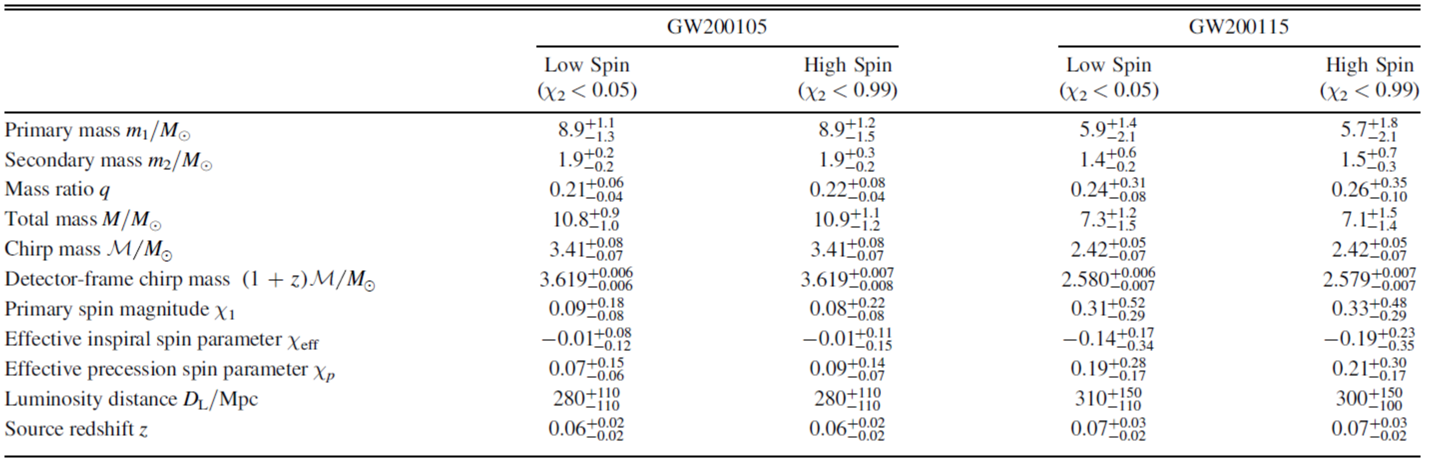
  - Mass is compatibles with remnant of a binary neutron star merger

- GW190814 poses a challenge for our understanding of the population of merging compact binaries

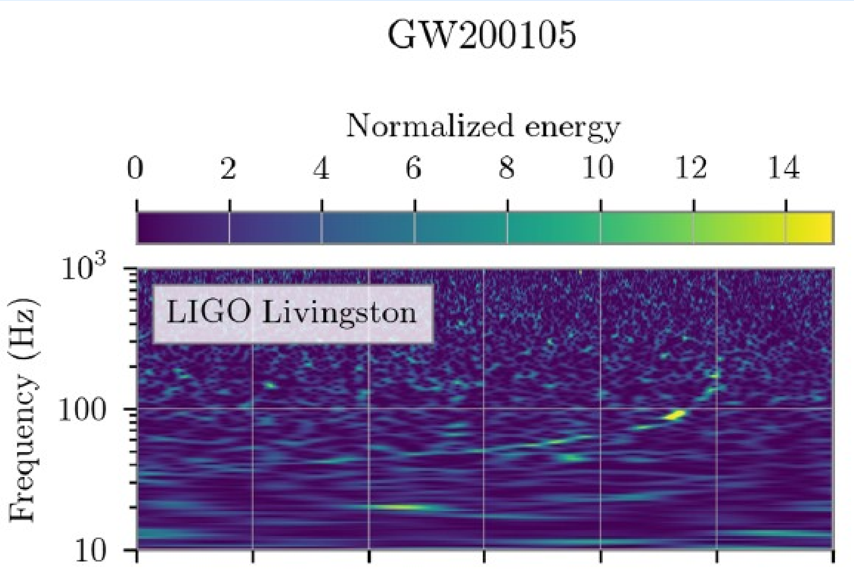


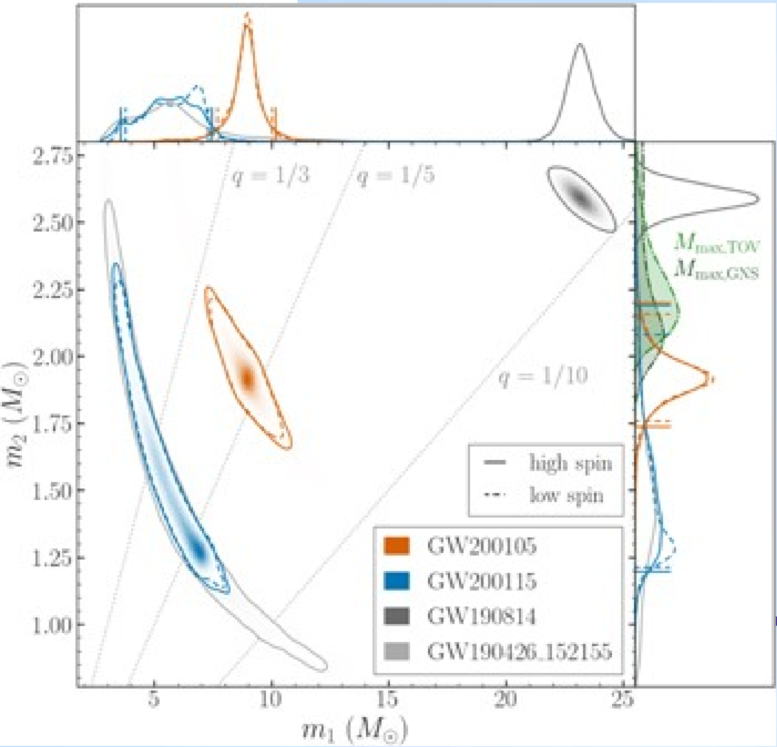
GW190814: “Signal models that exclude higher multipoles or precession do not constrain the secondary mass as well.”

# Interesting O3 Events – NS + BH Binaries



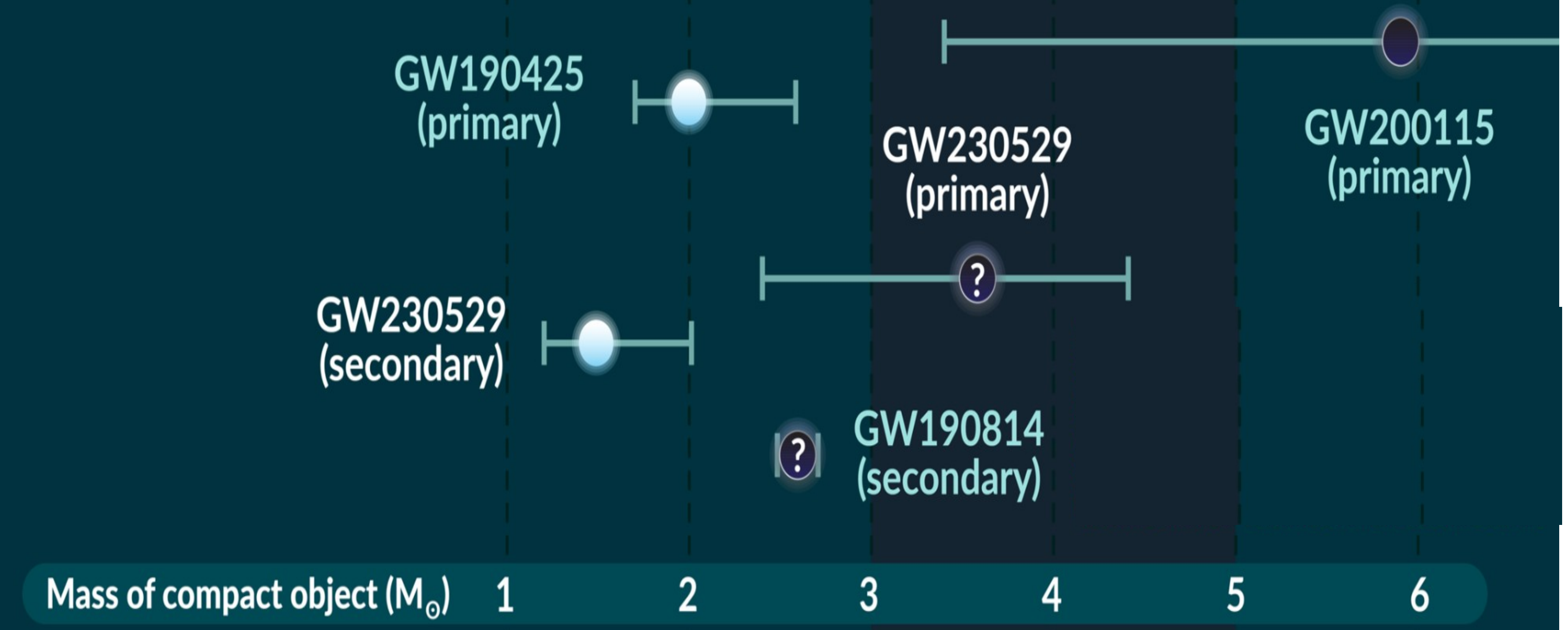
| | GW200105 | | GW200115 | |
|---|---|---|---|---|
| | Low Spin ($\chi_2 < 0.05$) | High Spin ($\chi_2 < 0.99$) | Low Spin ($\chi_2 < 0.05$) | High Spin ($\chi_2 < 0.99$) |
| Primary mass $m_1/M_\odot$ | $8.9^{+1.1}_{-1.3}$ | $8.9^{+1.2}_{-1.5}$ | $5.9^{+1.4}_{-2.1}$ | $5.7^{+1.8}_{-2.1}$ |
| Secondary mass $m_2/M_\odot$ | $1.9^{+0.2}_{-0.2}$ | $1.9^{+0.3}_{-0.2}$ | $1.4^{+0.6}_{-0.2}$ | $1.5^{+0.7}_{-0.3}$ |
| Mass ratio $q$ | $0.21^{+0.06}_{-0.04}$ | $0.22^{+0.08}_{-0.04}$ | $0.24^{+0.31}_{-0.08}$ | $0.26^{+0.35}_{-0.10}$ |
| Total mass $M/M_\odot$ | $10.8^{+0.9}_{-1.0}$ | $10.9^{+1.1}_{-1.2}$ | $7.3^{+1.2}_{-1.5}$ | $7.1^{+1.5}_{-1.4}$ |
| Chirp mass $\mathcal{M}/M_\odot$ | $3.41^{+0.08}_{-0.07}$ | $3.41^{+0.08}_{-0.07}$ | $2.42^{+0.05}_{-0.07}$ | $2.42^{+0.05}_{-0.07}$ |
| Detector-frame chirp mass $(1+z)\mathcal{M}/M_\odot$ | $3.619^{+0.006}_{-0.006}$ | $3.619^{+0.007}_{-0.008}$ | $2.580^{+0.006}_{-0.007}$ | $2.579^{+0.007}_{-0.007}$ |
| Primary spin magnitude $\chi_1$ | $0.09^{+0.18}_{-0.08}$ | $0.08^{+0.22}_{-0.08}$ | $0.31^{+0.52}_{-0.29}$ | $0.33^{+0.48}_{-0.29}$ |
| Effective inspiral spin parameter $\chi_{\rm eff}$ | $-0.01^{+0.08}_{-0.12}$ | $-0.01^{+0.11}_{-0.15}$ | $-0.14^{+0.17}_{-0.34}$ | $-0.19^{+0.23}_{-0.35}$ |
| Effective precession spin parameter $\chi_p$ | $0.07^{+0.15}_{-0.06}$ | $0.09^{+0.14}_{-0.07}$ | $0.19^{+0.28}_{-0.17}$ | $0.21^{+0.30}_{-0.17}$ |
| Luminosity distance $D_L$/Mpc | $280^{+110}_{-110}$ | $280^{+110}_{-110}$ | $310^{+150}_{-110}$ | $300^{+150}_{-100}$ |
| Source redshift $z$ | $0.06^{+0.02}_{-0.02}$ | $0.06^{+0.02}_{-0.02}$ | $0.07^{+0.03}_{-0.02}$ | $0.07^{+0.03}_{-0.02}$ |





# FILLING THE MASS ↔ GAP

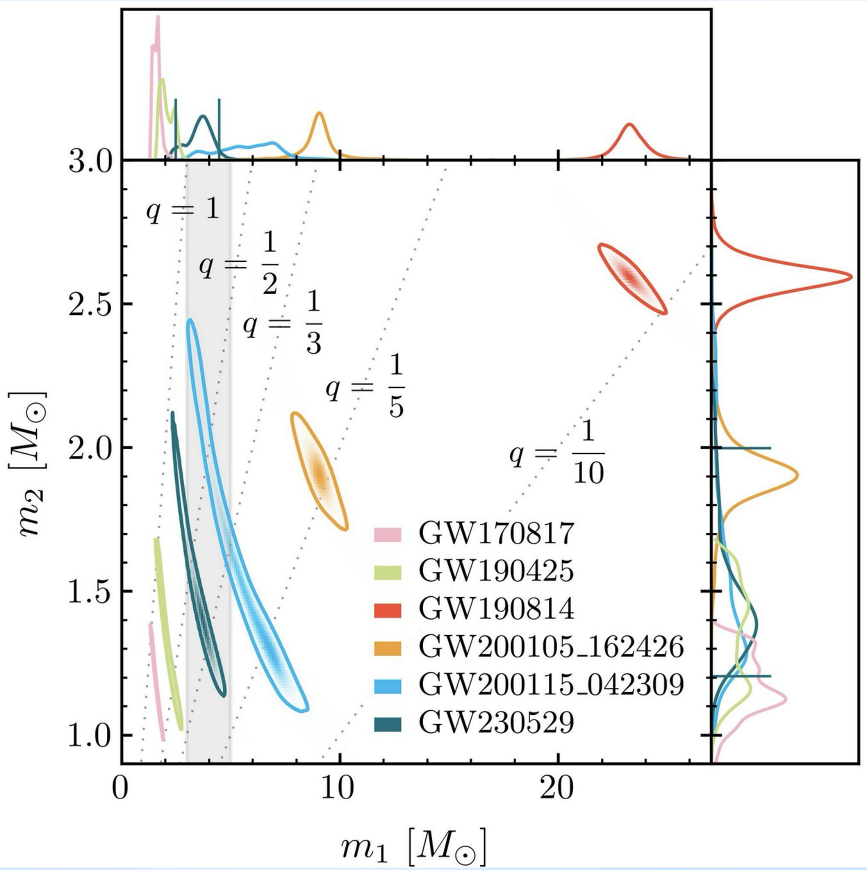
*with observations of compact binaries from gravitational waves*



Includes components of compact binary mergers detected with a False Alarm Rate (FAR) of less than 0.25 per year

Figure credit: Shanika Galaudage / Observatoire de la Côte d'Azur

# GW230529

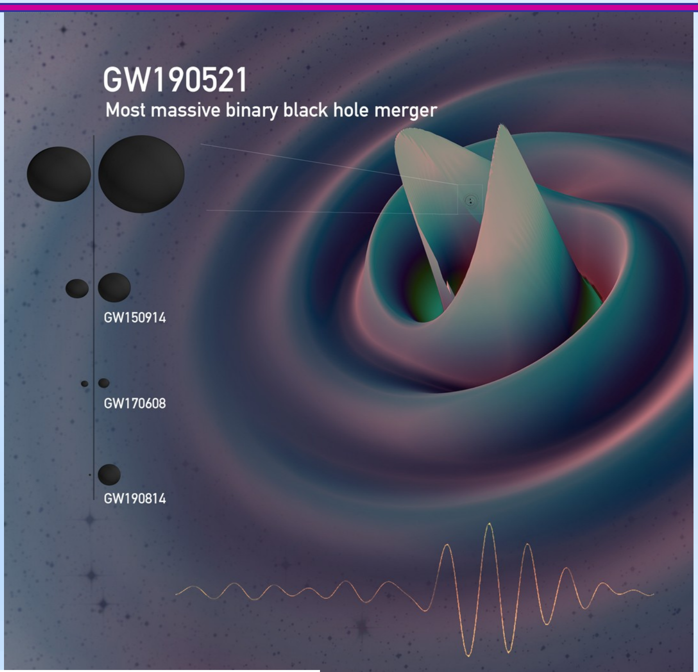


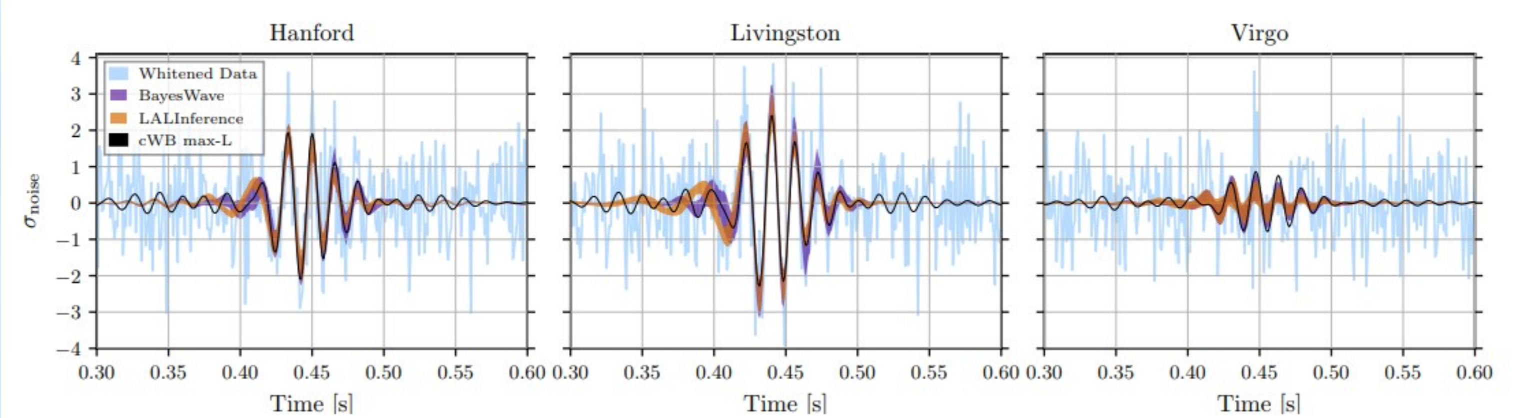
| | |
|---|---|
| Primary mass $m_1/M_\odot$ | $3.6^{+0.8}_{-1.2}$ |
| Secondary mass $m_2/M_\odot$ | $1.4^{+0.6}_{-0.2}$ |
| Mass ratio $q = m_2/m_1$ | $0.39^{+0.41}_{-0.12}$ |
| Total mass $M/M_\odot$ | $5.1^{+0.6}_{-0.6}$ |
| Chirp mass $\mathcal{M}/M_\odot$ | $1.94^{+0.04}_{-0.04}$ |
| Detector-frame chirp mass $(1+z)\mathcal{M}/M_\odot$ | $2.026^{+0.002}_{-0.002}$ |
| Primary spin magnitude $\chi_1$ | $0.44^{+0.40}_{-0.37}$ |
| Effective inspiral-spin parameter $\chi_{\mathrm{eff}}$ | $-0.10^{+0.12}_{-0.17}$ |
| Effective precessing-spin parameter $\chi_{\mathrm{p}}$ | $0.40^{+0.39}_{-0.30}$ |
| Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$ | $201^{+102}_{-96}$ |
| Source redshift $z$ | $0.04^{+0.02}_{-0.02}$ |

LIGO-Virgo-KAGRA COllaboration
ApJ Lett 970:L34 (39pp), 2024 August 1

# Interesting O3 Events - GW190521

- The GW signal is consistent with a BBH merger source, with total mass of **150 $M_\odot$** .
  - $M_1 \sim 85\ M_\odot$ , $M_2 \sim 66\ M_\odot$, $M_{final} \sim 142\ M_\odot$
  - 5.3 Gpc, z ~ 0.82; age of universe was 6.7 Gyr
- System had large spin in orbital plane → precession
- The final merged (remnant) black hole is an **Intermediate Mass Black Hole (IMBH)**.
- The more massive of the two BHs in binary is ~ 85 $M_\odot$ , **in the Pair Instability Supernova mass gap**.
- It may itself be the result of a previous BBH merger.

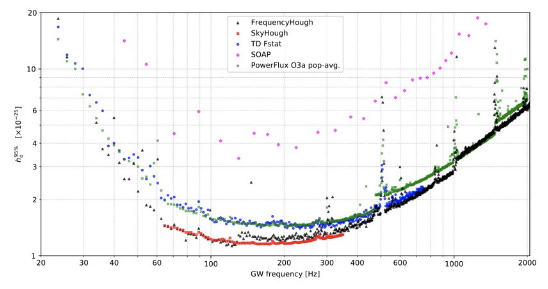




# Many other observational results

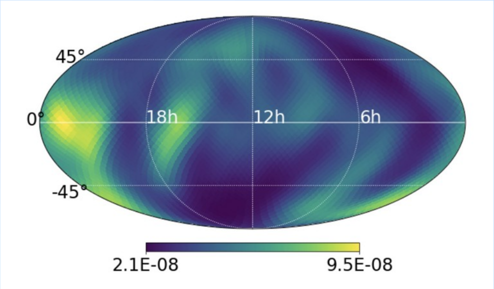
Limits on waves from pulsars

Phys. Rev. D 106, 102008 (2022)



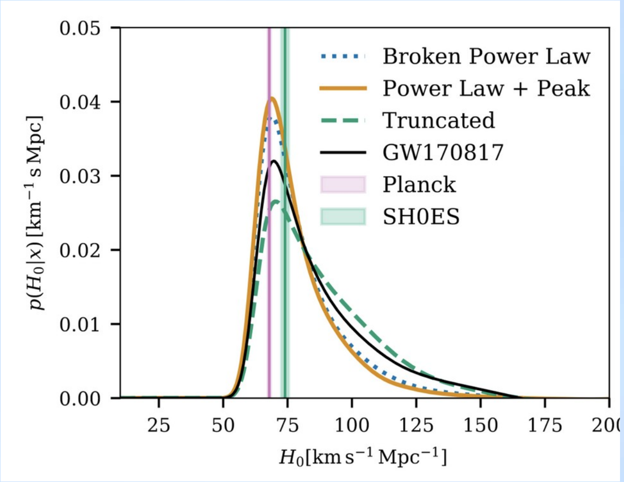
Stochastic background limits

Phys. Rev. D 105, 122002 (2022)



Hubble constant measurements

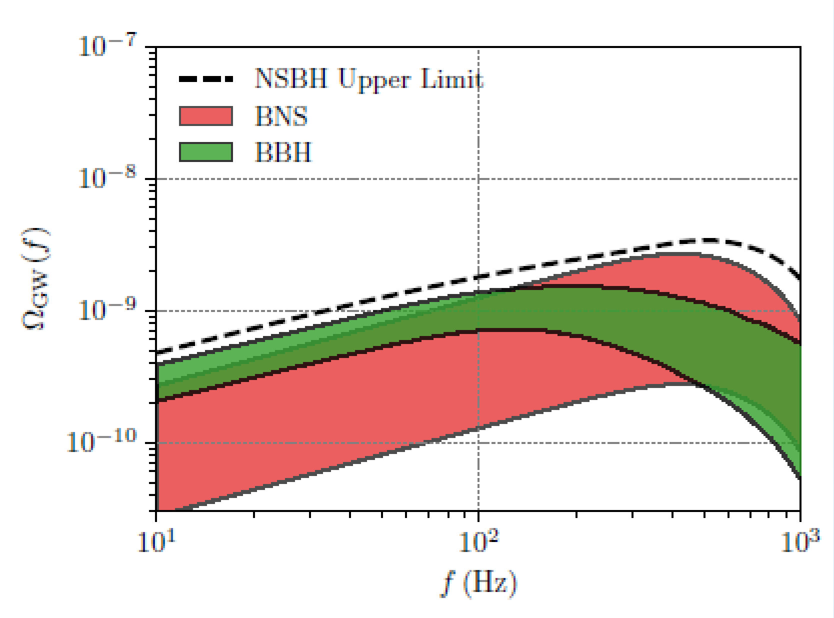
Astrophys. J. 949, 76 (2023)



And much more!

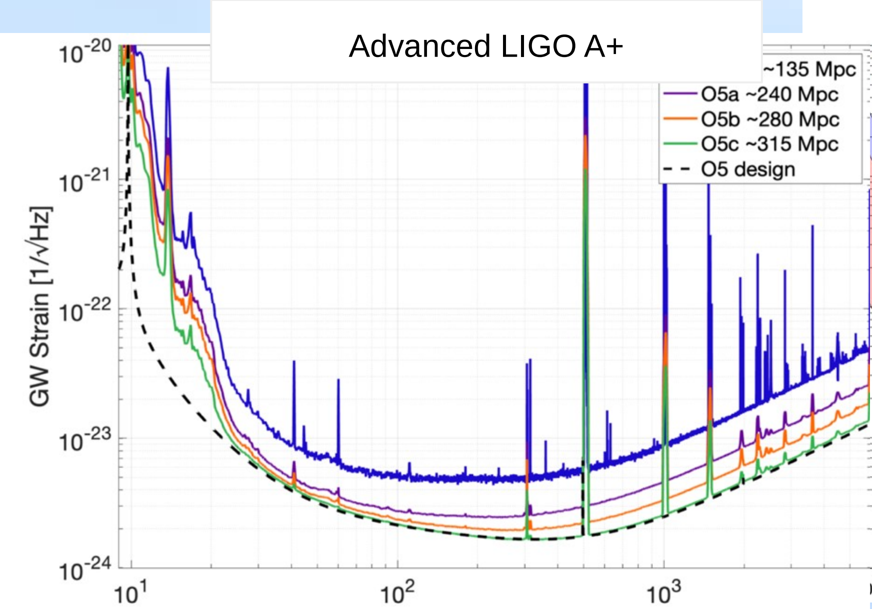
# Stochastic Gravitational-Wave Background

- Upper limit on normalized energy density $\Omega_{GW} < 5.8 \times 10^{-9}$ at 25 Hz
- Approaching level of stochastic background binary produced by compact binary mergers over the history of the universe
- Ultimate goal is to detect a stochastic background from early Universe
    - Astrophysical sources obscure this signal

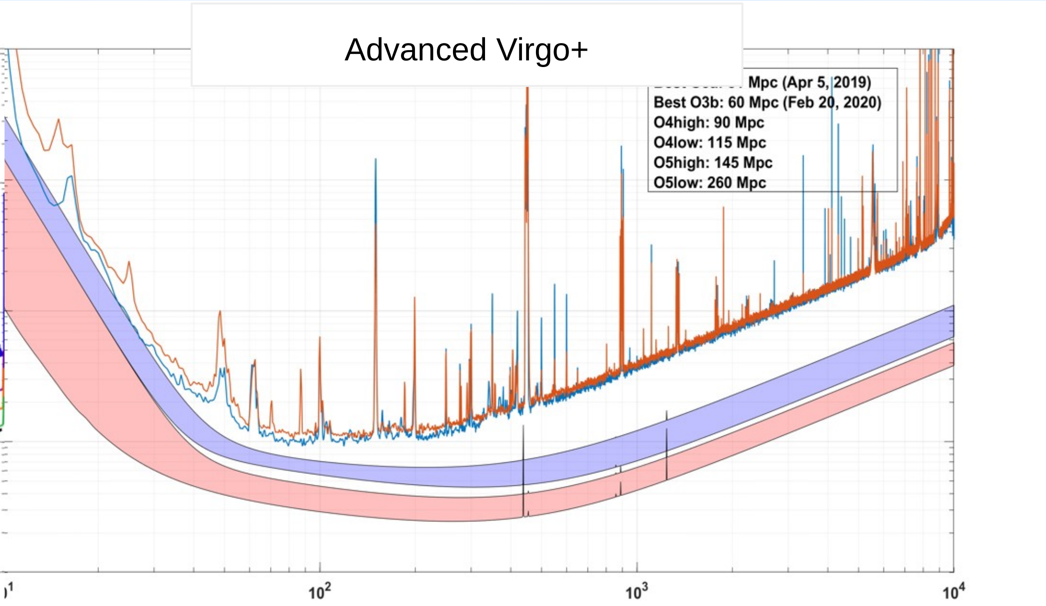


# Towards O5

Advanced LIGO A+



Advanced Virgo+



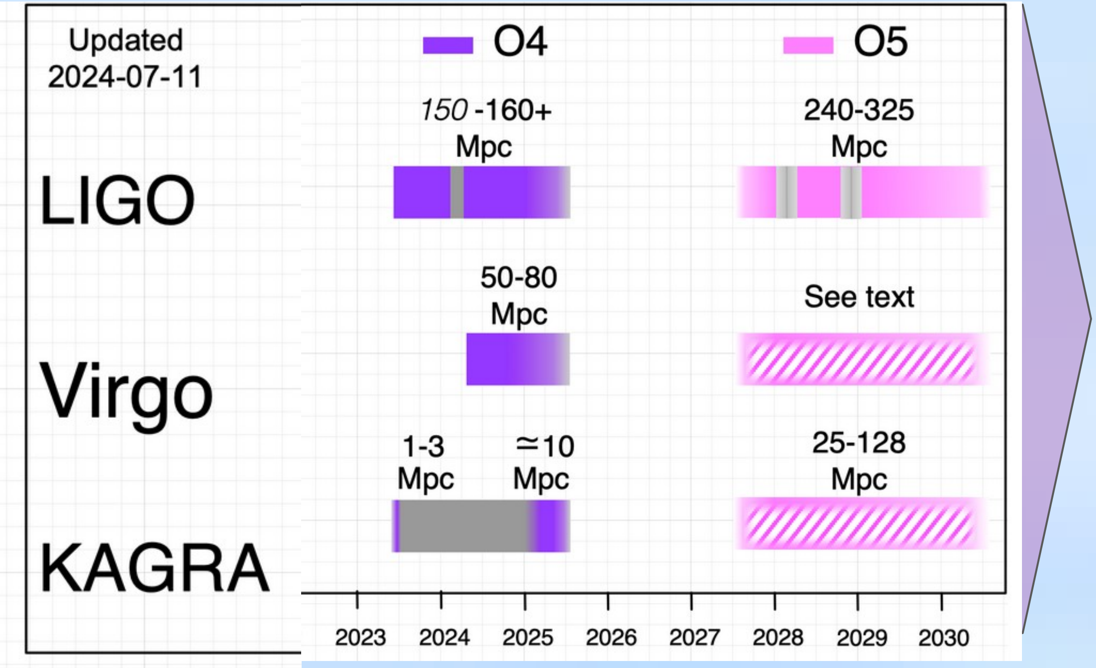
Full Power in the arm cavities: 750 kW
Frequency-dependent Squeezing* level of 6 dB
Test Masses with 2x lower coating thermal noise

KAGRA will continue to work towards 130Mpc goal in O5

# O5 Observing run

LIGO-Virgo-KAGRA anticipate observing to dovetail with next generation facilities

- Current thinking
  - Start is paced by upgrades after O4: 2 years gap.
  - Intersperse commissioning and observations
- Binary detection rates
  - O3 ~ 1 / 5 days
  - O4 ~ 1 / (2.8) days
  - O5 ~ 3 / day
- Other science
  - Improved SNR
  - New sources?



https://observing.docs.ligo.org/plan/

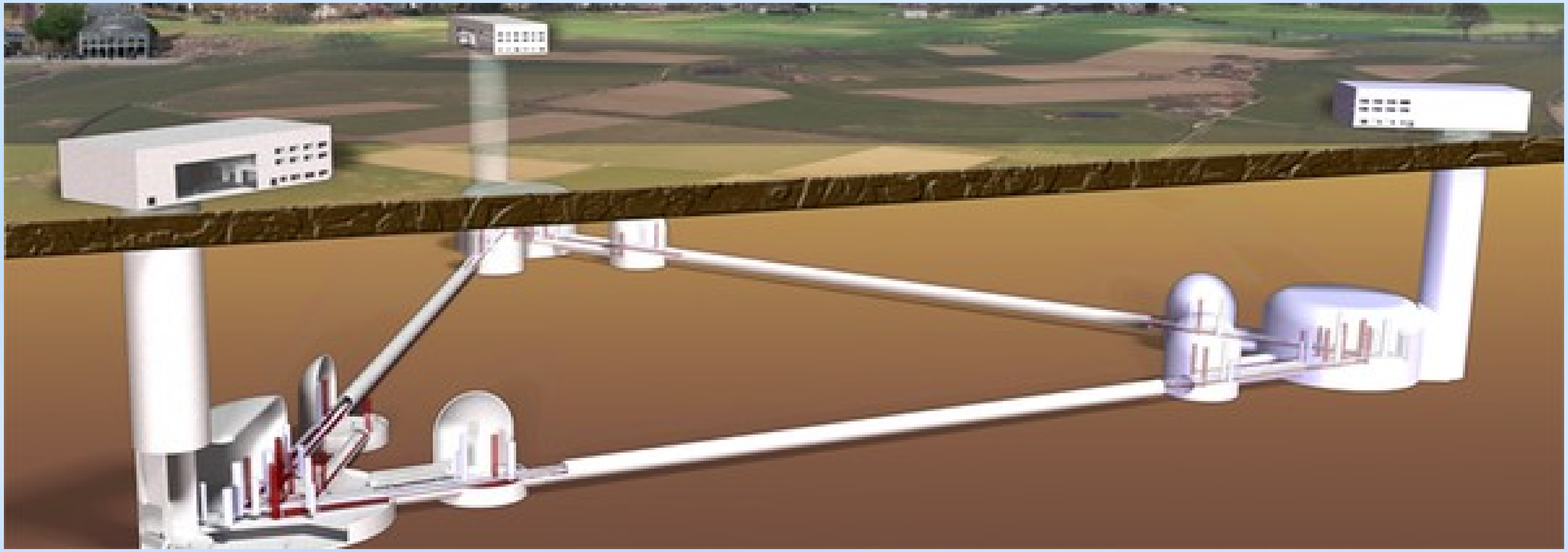
# Early 2030s

- LIGO Aundha Observatory (LAO) is to be constructed in India and operated as part of the LIGO network in the 2030s.
- A$^{\#}$: targeted improvements to the LIGO detectors
  - Achieve close to a factor of 2 amplitude sensitivity improvement with larger test masses, better seismic isolation, improved mirror coatings, higher laser power, better squeezing …
  - Begin observing at the end of 2031 and observe for several years.
  - A$^{\#}$ an engine for observational science and a pathfinder for next-generation technologies.

- Virgo has scoped similar improvements, called VirgoNEXT, with similar timetable. KAGRA is focused on reaching its current target.

# Third Generation Gravitational Wave Detectors

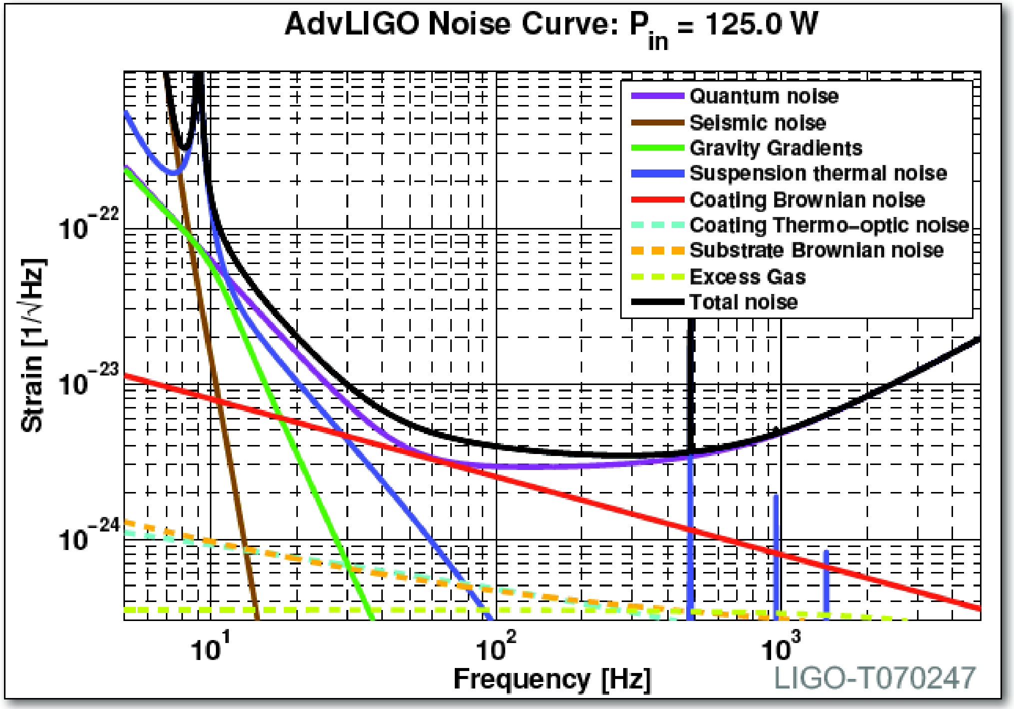
Einstein Telescope



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
ESFRI Roadmap 2021

# Noise Sources Limiting the 2G Detectors

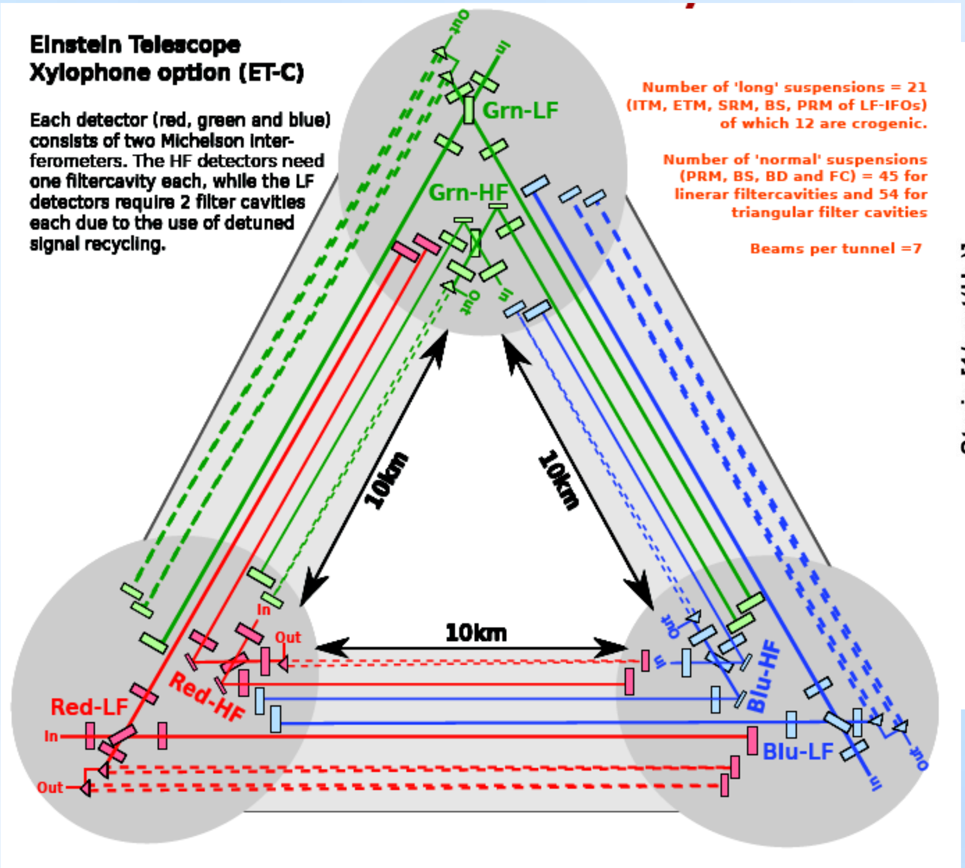
- Quantum noise limits most of the frequency range.
- Coating Brownian noise limits in the range from 50 to 100Hz.
- Below ~15Hz we are limited by ‘walls’ made of Suspension Thermal, Gravity Gradient and Seismic noise.
- And then there are the, often not mentioned, ‘technical’ noise sources which trouble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



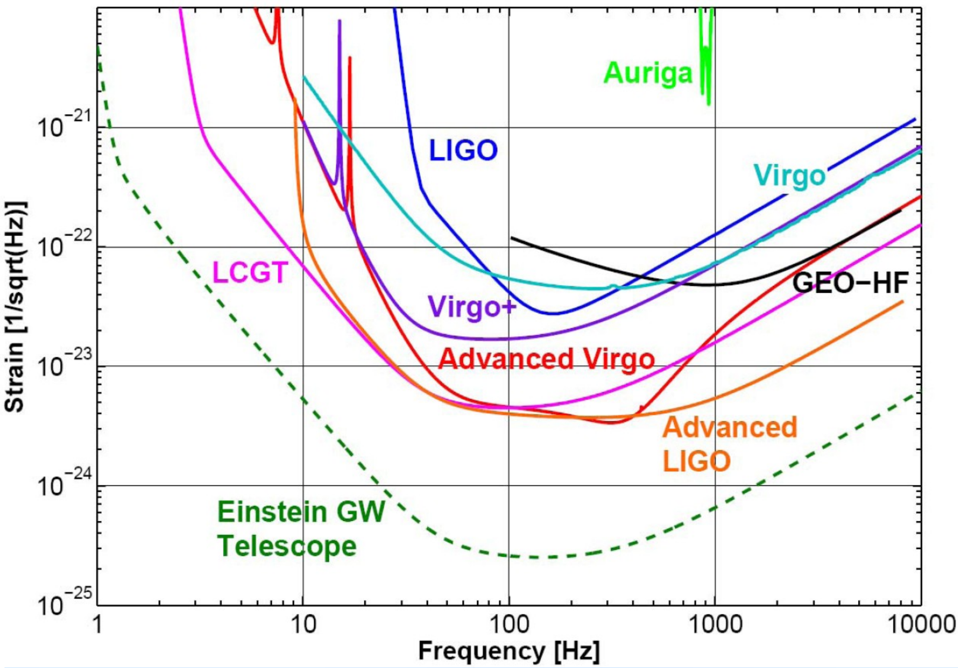
**Einstein Telescope Xylophone option (ET-C)**

Each detector (red, green and blue) consists of two Michelson interferometers. The HF detectors need one filtercavity each, while the LF detectors require 2 filter cavities each due to the use of detuned signal recycling.

Number of 'long' suspensions = 21 (ITM, ETM, SRM, BS, PRM of LF-IFOs) of which 12 are crogenic.

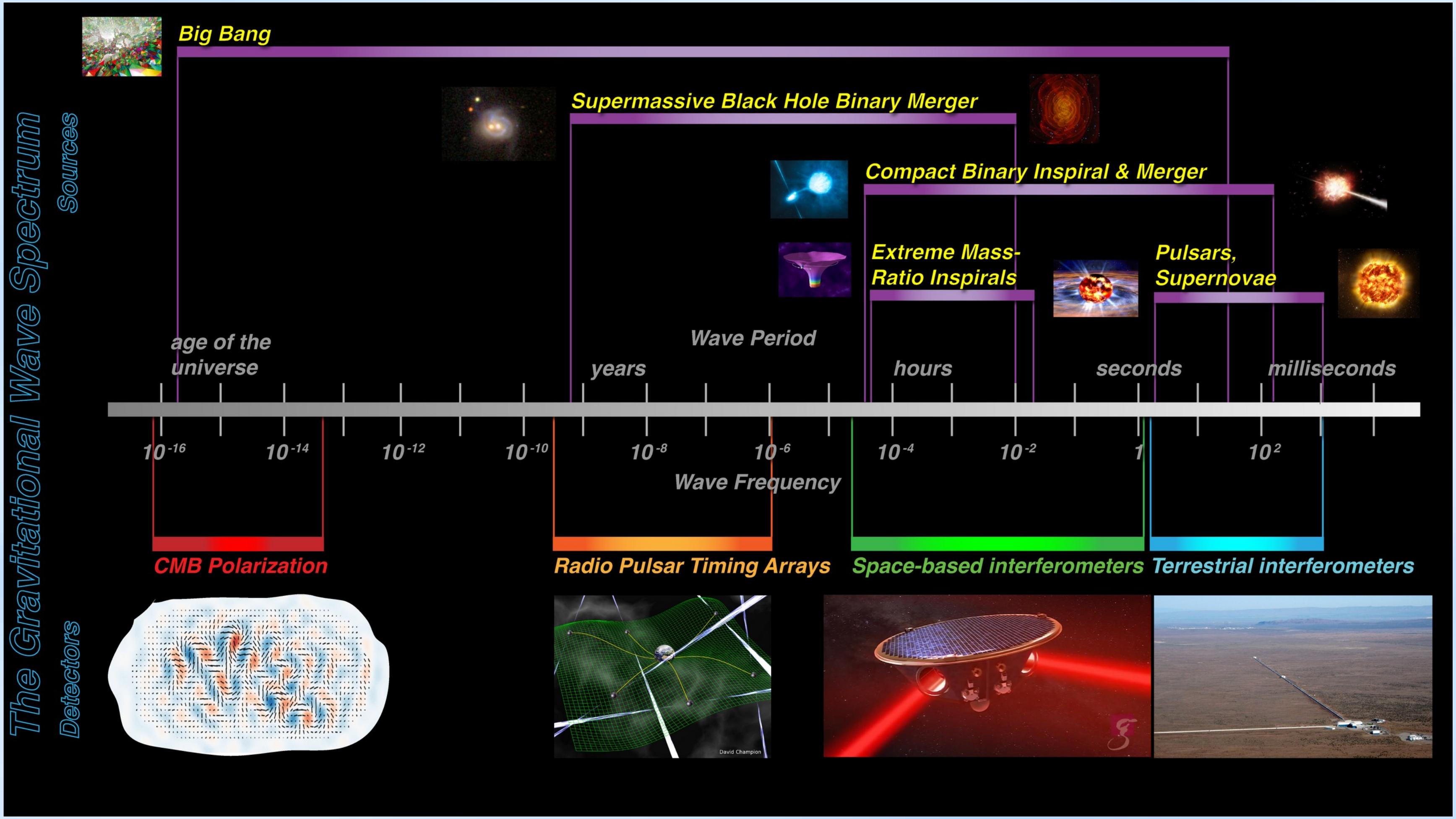
Number of 'normal' suspensions (PRM, BS, BD and FC) = 45 for linerar filtercavities and 54 for triangular filter cavities

Beams per tunnel =7

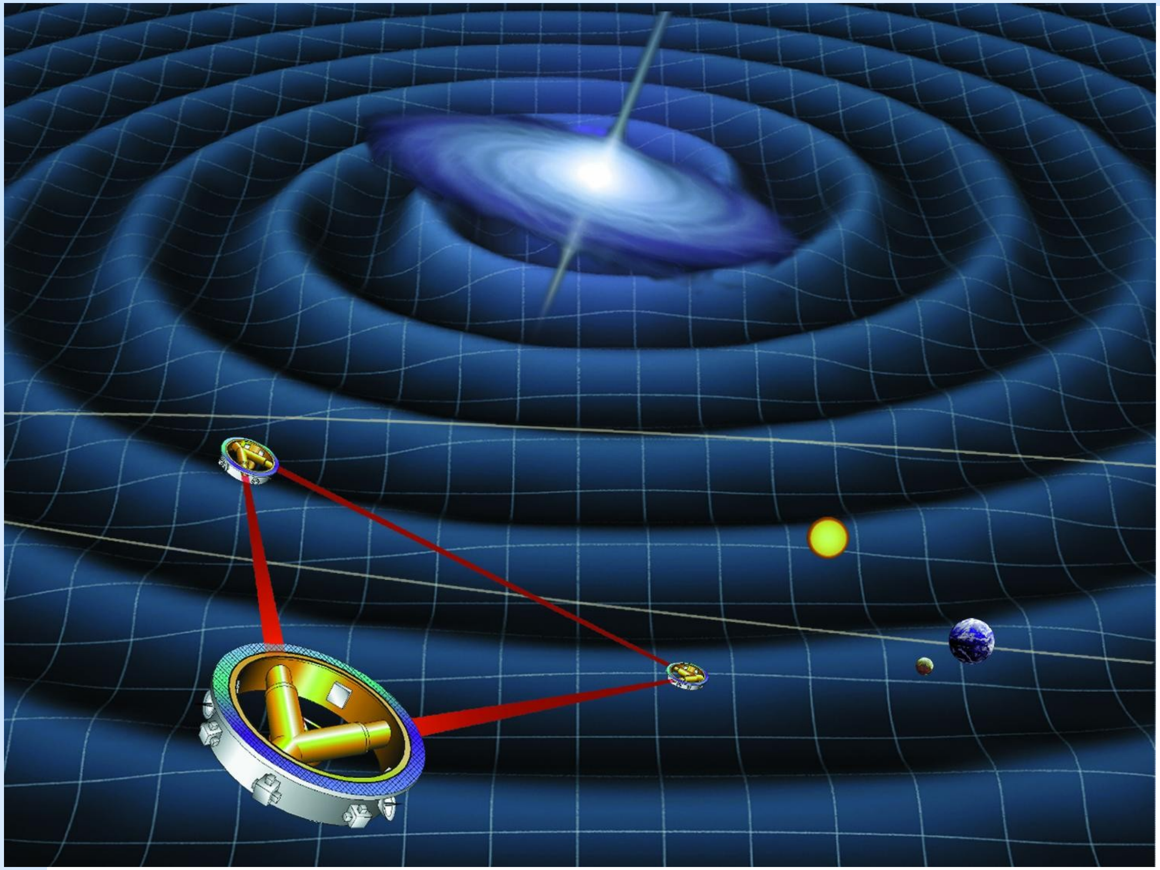


As well, in the US:
LIGO Voyager, 4 km cryogenic
Cosmic Explorer: 20 + 40 L-shape km interferometer

# Gravitational Wave Spectrum



# Laser Interferometer Space Antenna - LISA



ESA – All Systems GO!

Mission accepted 2024

Planned launch 2035

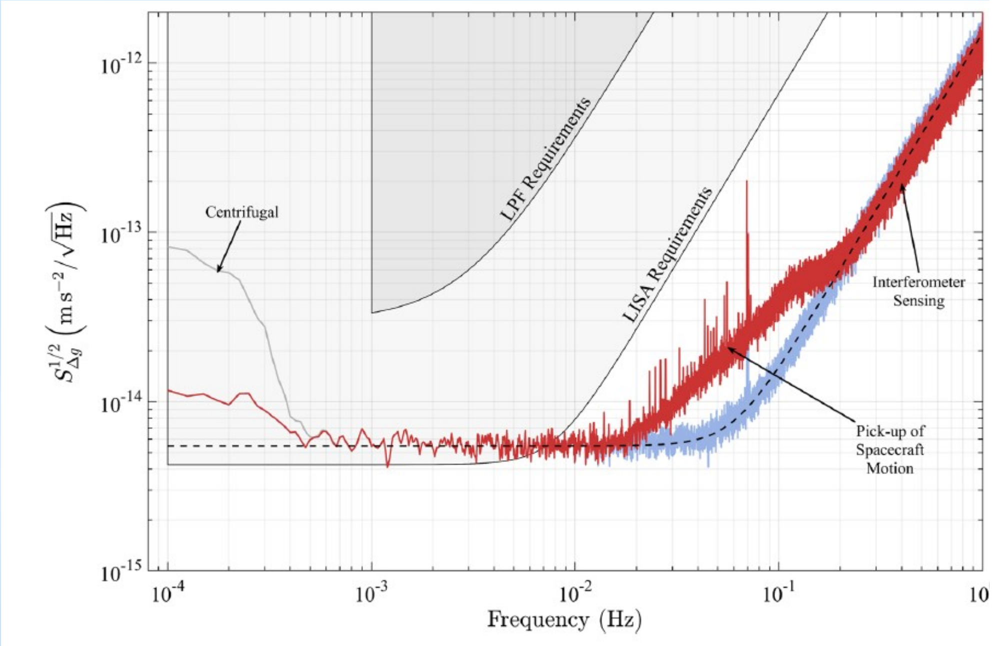
NASA as a junior partner

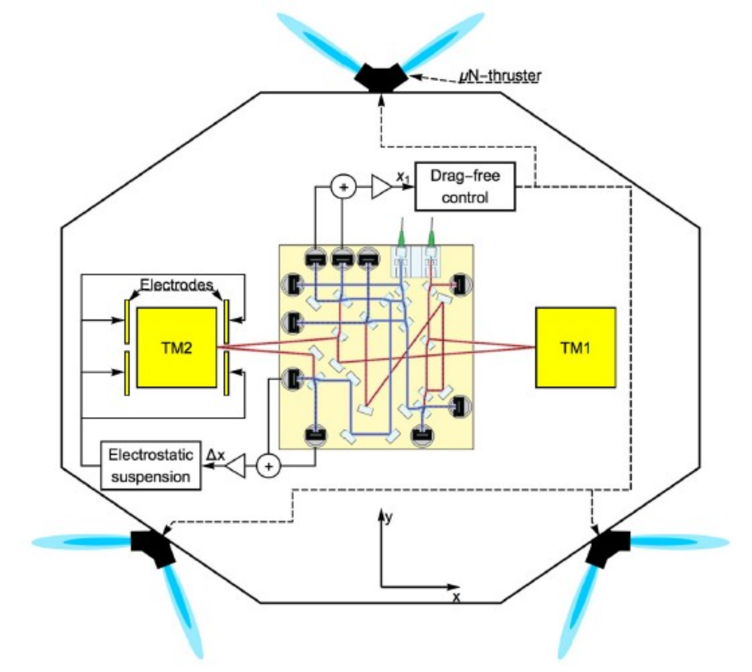
LIGO-Virgo GW events and Lisa Pathfinder success have helped significantly

Tremendous activity at present

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

# LISA Pathfinder – Demonstrating LISA Technology



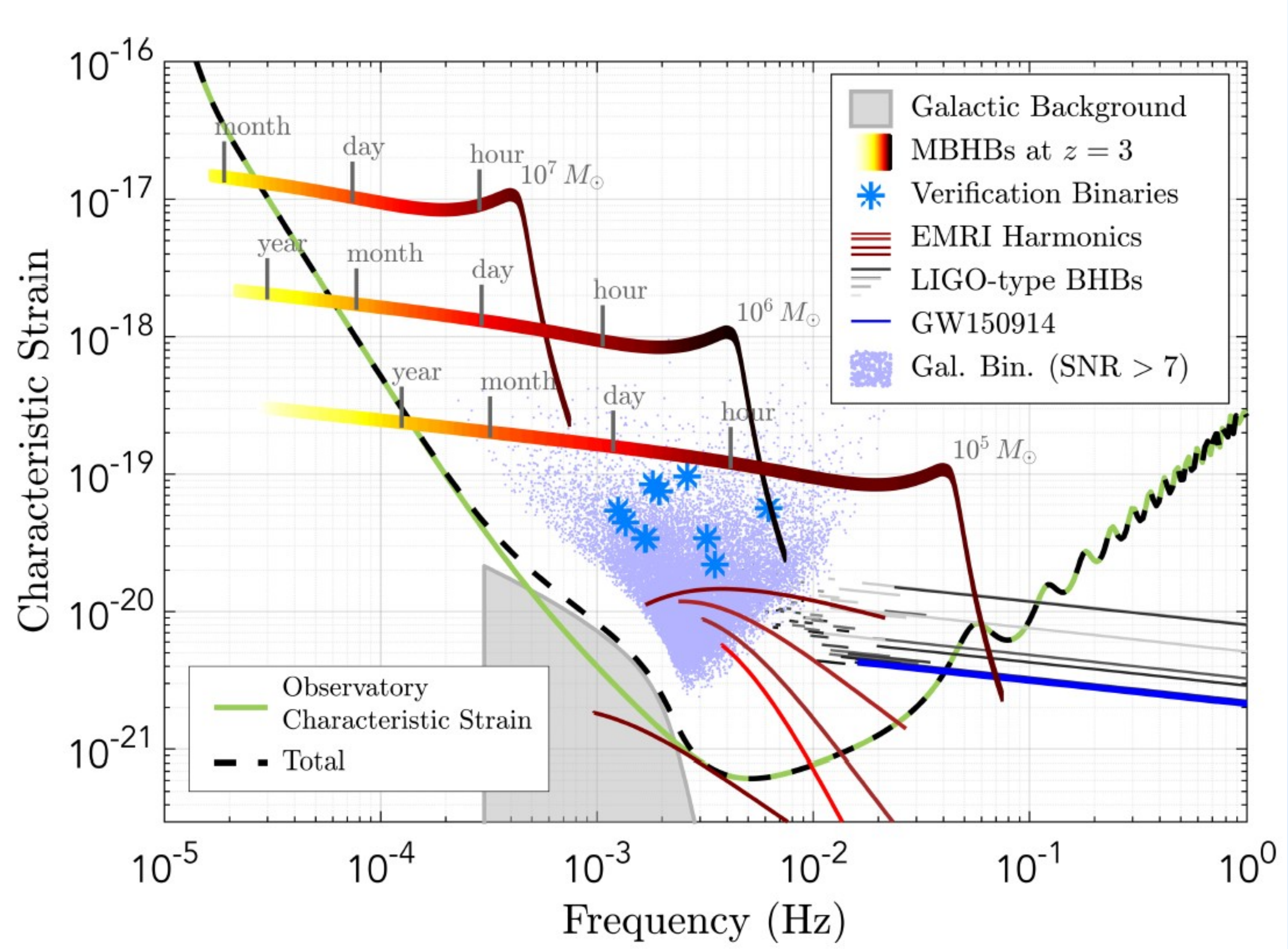


LISA Pathfinder worked! Exceeded requirements. Still, operation was not perfect, and there is lots of experimental work to do before LISA.

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



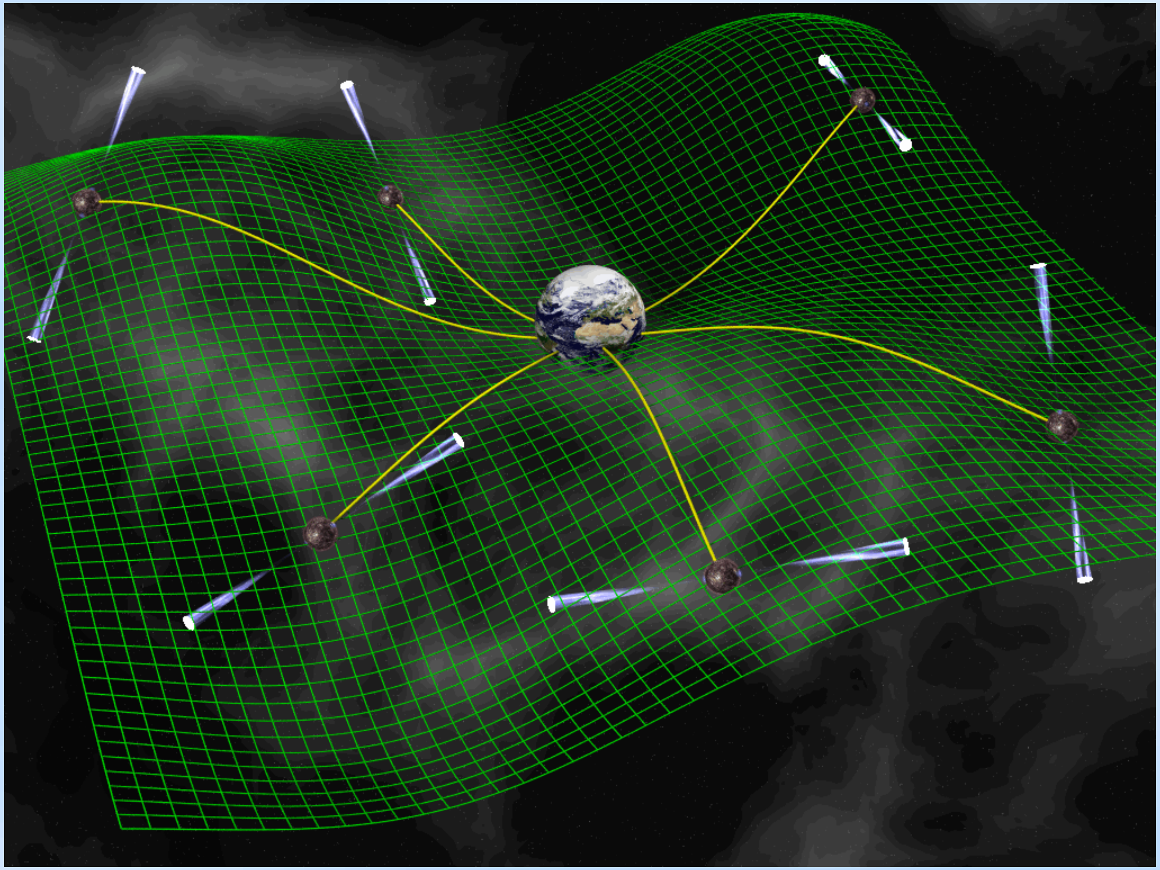
1702.00786

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

# 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!

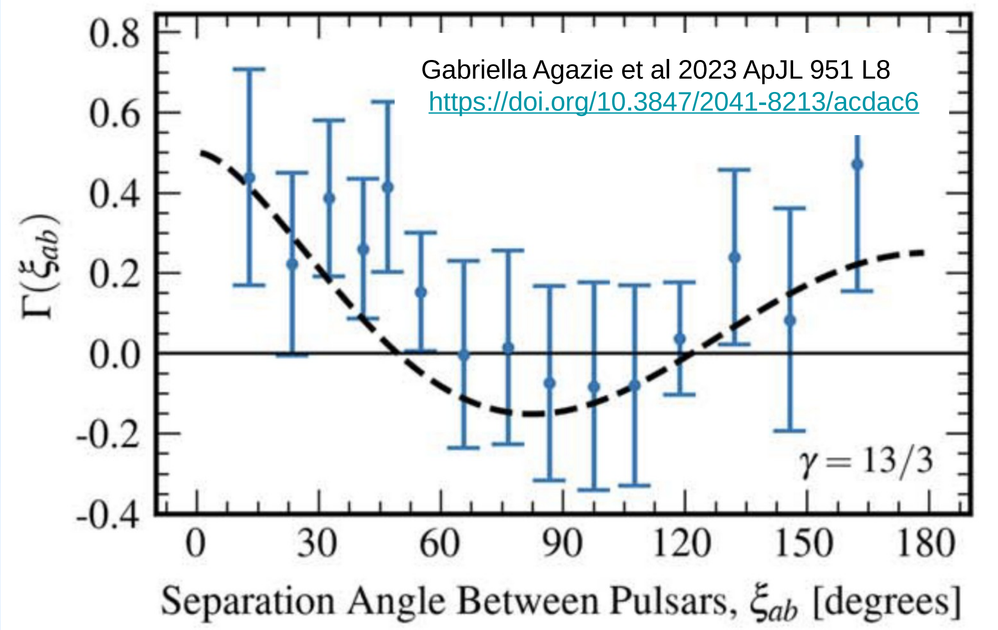
# Pulsar Timing



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. Nano-Hz band.

# Recent Pulsar Timing Observations



Gabriella Agazie et al 2023 ApJL 951 L8
https://doi.org/10.3847/2041-8213/acdac6

Hellings-Downs interpulsar correlations from a gravitational-wave background.

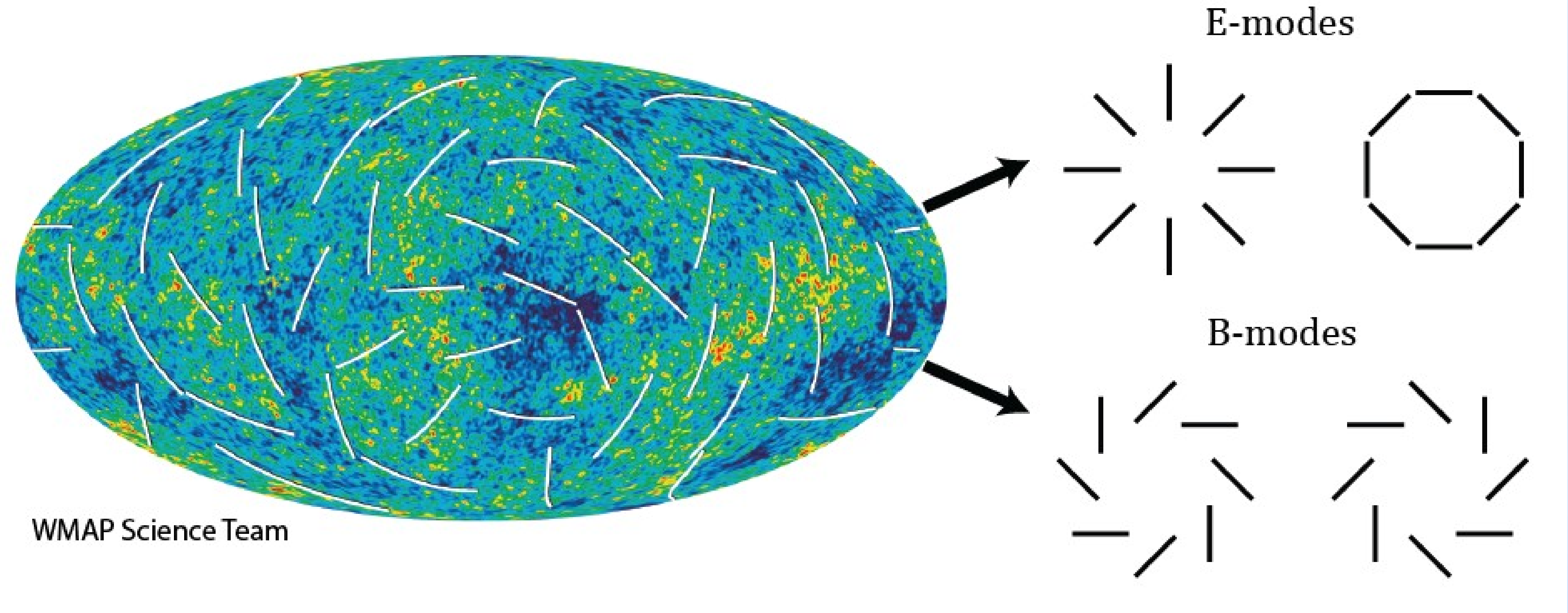
- Bayesian analysis ~ 3 sigma
- Frequentist analysis ~ 3.5 - 4 sigma

Possibly background from supermassive black hole binaries.

- NANOGrav - G. Agazie et al 2023 ApJL 951 L8
- PPTA - D. J. Reardon et al 2023 ApJL 951 L6
- EPTA and InPTA - J. Antoniadis et al. A&A, to appear
- CPTA - H. Xu et al 2023 Res. Astron. Astrophys. 23 075024

See upcoming talk by Stas Babak!

# Polarization Map of the Cosmic Microwave Background

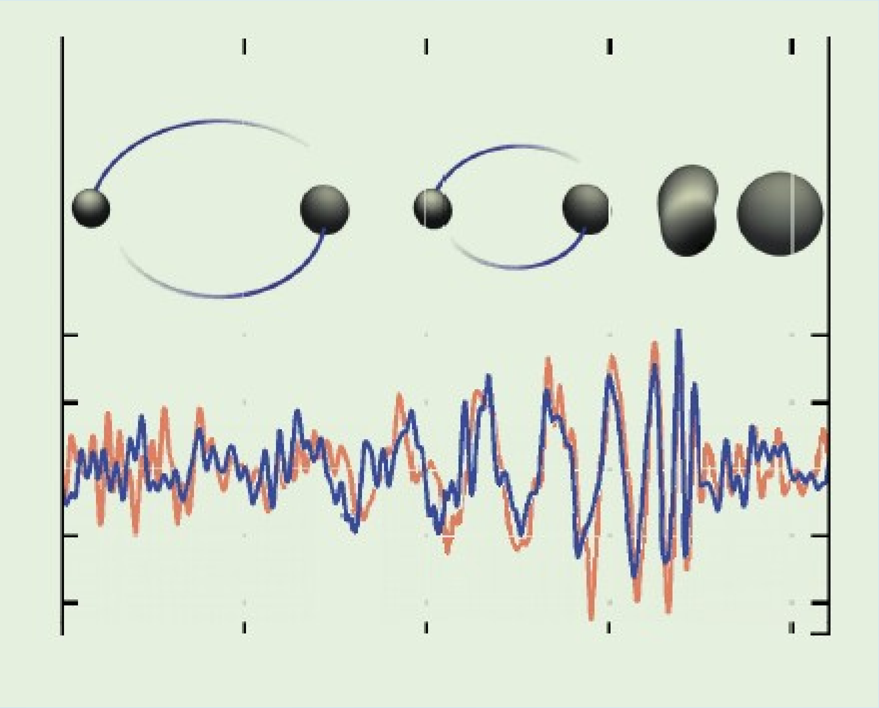


The CMB anisotropy polarization map may be decomposed into curl-free even-parity E-modes and divergence-free odd-parity B-modes.

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

BICEP2, KECK Array, Planck, Atacama

# Conclusion on Gravitational Waves



A new window on the universe has opened.

We are just beginning!

# GW170817 – The Birth of GW Multi-Messenger Astronomy

17 August 2017