Gravitational waves: where we are

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RICAP 24

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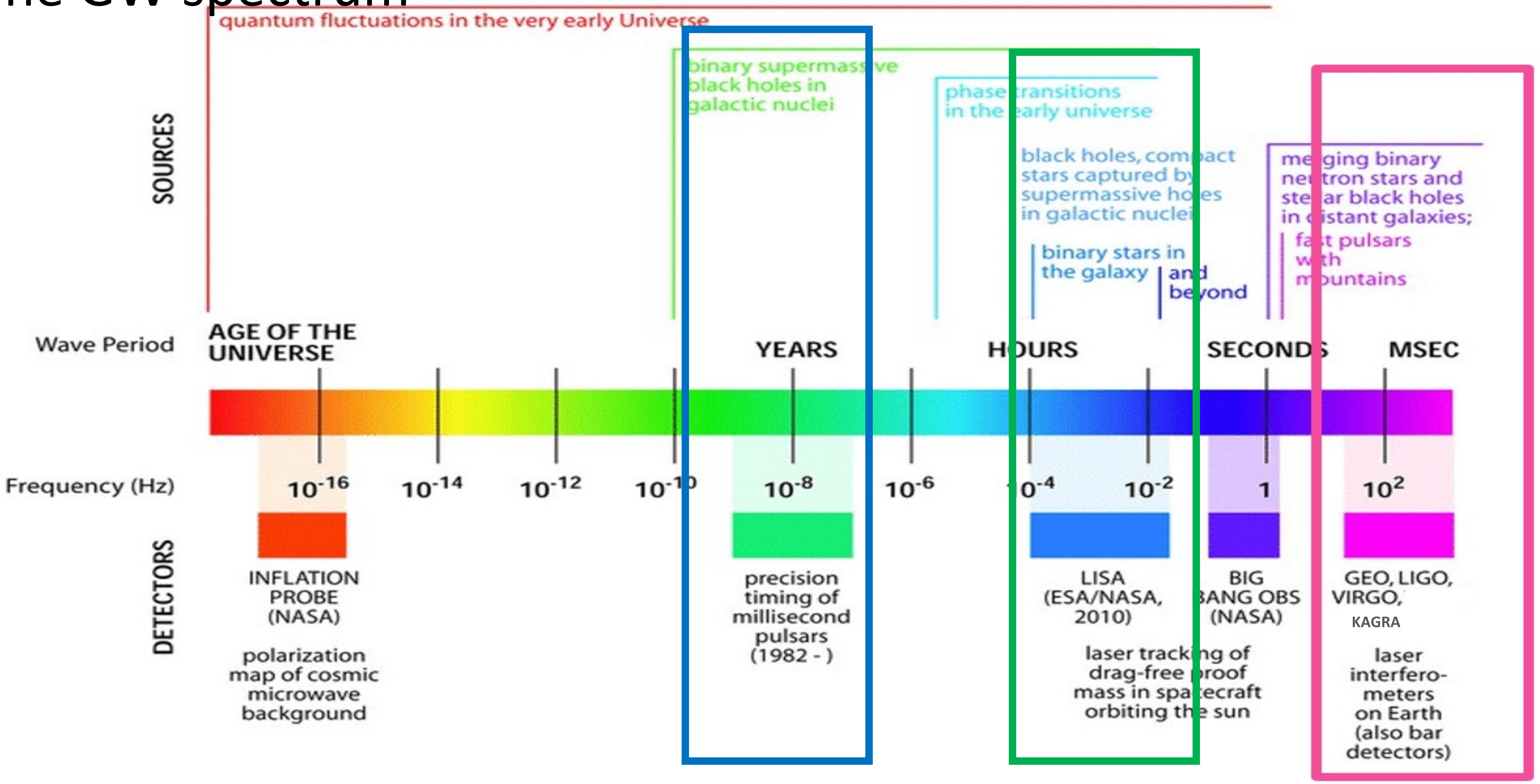
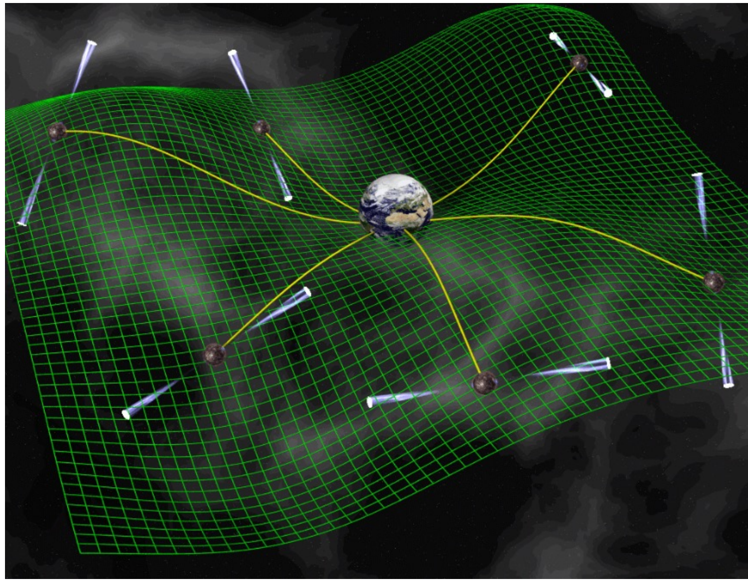
The GW spectrum



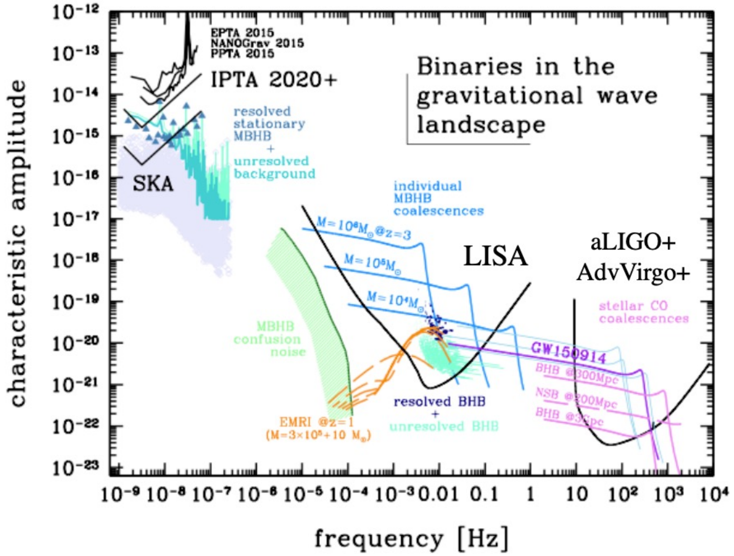
The success of PTA - Pulsar Timing Array

See the M. Falxa's presentation: Wednsday parallel session of this conference

- A Pulsar Timing Array (PTA) exploits the rotational stability of a sample of the rapidly spinning "recycled" pulsars to detect GWs in the frequency range 10^{-7} - 10^{-9} Hz.
- The radio wave emitted by the pulsar and received on the Earth probes the distance between these two bodies in a similar way of the light bouncing between two mirrors set at a enormous distance.
- By analysing the timing signals emitted by an array of pulsars, it is possible to probe the space metric on distances of the order of parsec and detect GWs.
- PTAs is sensitive to GW emitted by supermassive black holes in the early stage of their inspirals and study the population of supermassive black holes binaries in the universe



Courtesy of David J. Champion.



Courtesy of Alberto Sesana.

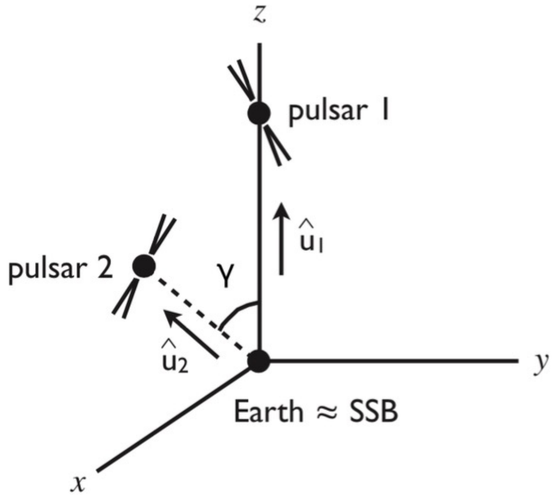
The Hellings and Downs signature

Hellings, R.W.; Downs, G.S. "*Upper limits on the isotropic gravitational radiation background from pulsar timing analysis*". Astrophysical Journal Letters. 265: L39–L42. (1983)

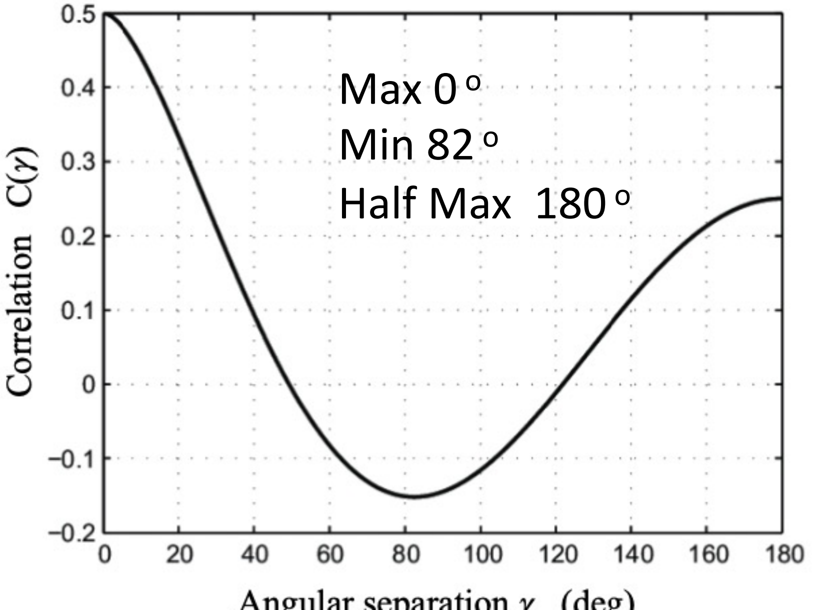
- The solar system barycenter (SSB) and a rotating super stable pulsar in our galaxy are the opposite ends of the radio travel path in space, perturbed by GWs and monitored by the radio-observers on Earth

- We consider <u>several pairs of pulsars (an array)</u>.
  - A GW stochastic background produces a distinctive correlation between **pairs** pulsars.
  - The correlation function C (called the Hellings and Down curve) depends on the angular separation γ of the pulsar of pair.

- The signal from a stochastic GW background will be correlated across the sightlines of pulsar pairs, while that from the other noise processes will not!



$$C(\gamma) = \frac{3}{2}\left[\frac{1-\cos\gamma}{2}\log\left(\frac{1-\cos\gamma}{2}\right) - \frac{1}{6}\,\frac{1-\cos\gamma}{2} + \frac{1}{3}\right]$$



Max 0 °
Min 82 °
Half Max 180 °

reported similar findings with a -significance

IPTA - International pulsar timing array

European PTA

+

North American
Nanohertz Observatory for GW

+

Parks PTA (Australia)

+

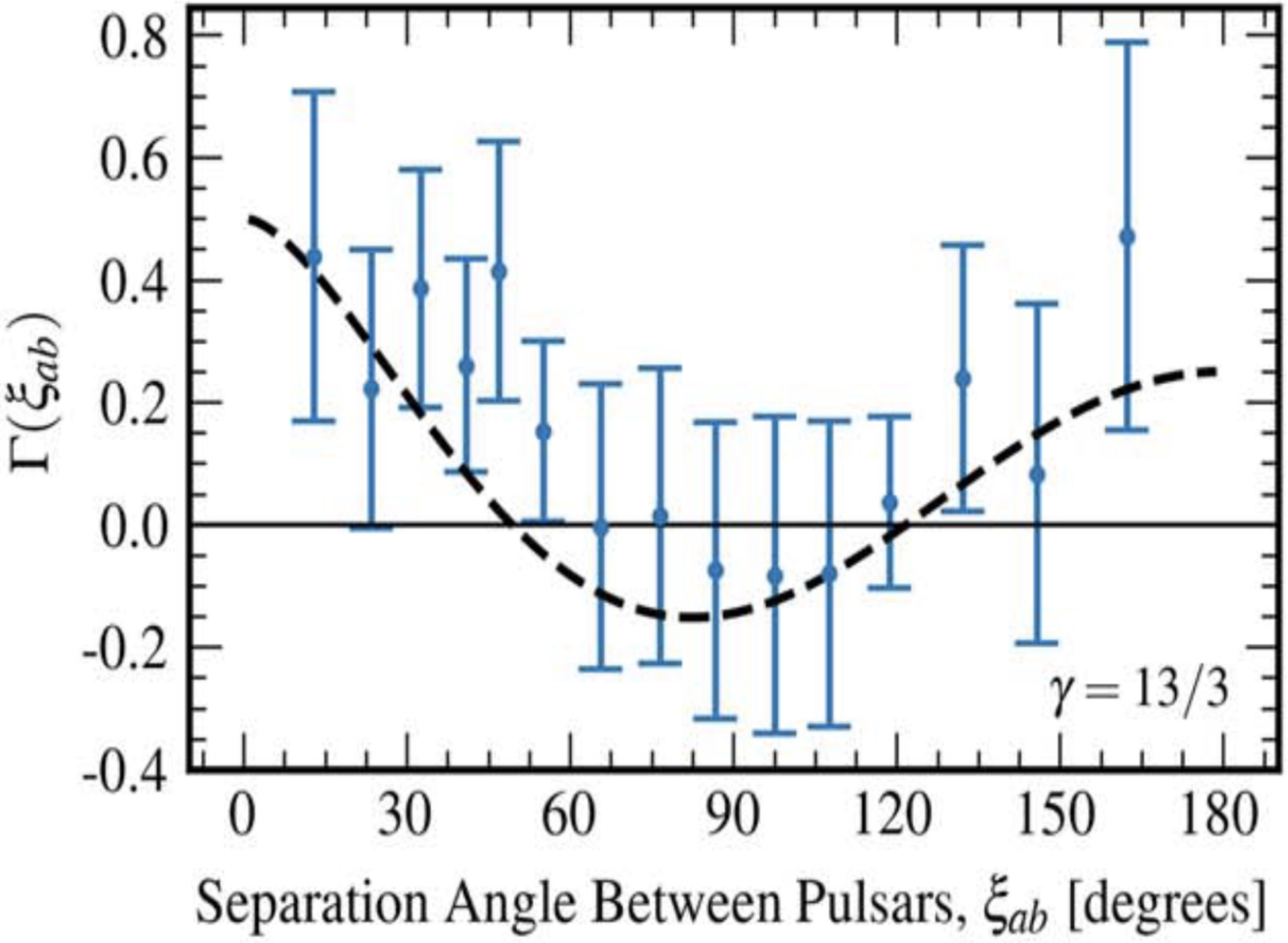
Indian PTA

=

+ Chinese PTA + MeerKAT PTA

- 2020 NANOGrav collaboration (12.5 years data - 68 pulsars): evidence for a stochastic process with common strain amplitude and spectral index across all pulsars
- June 2023 IPTA announce: evidence for a GW stochastic background.
  - ➢ NANOGrav provided a first measurement of the Hellings-Downs curve
  - ➢ EPTA claims similar result.
  - ➢ Combination of IPTA data should give a 5σ evidence
- CPTA (using FAST) reported a 4.6 σ evidence monitoring 57 pulsars in 41 months

The evidence of stochastic GW around 10^{-8} Hz



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

Hellings-Downs inter-pulsar correlations from a gravitational-wave background.

- Bayesian analysis ~ 3.5 σ
- Frequentist analysis ~ 3.5 - 4 σ

Possibly background from supermassive black hole binaries.

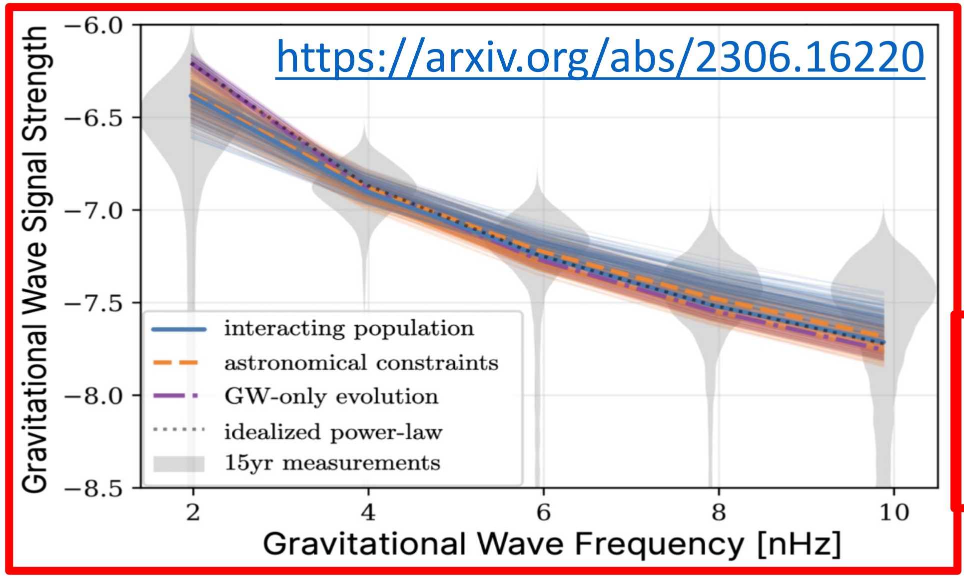
- *NANOGrav - G. Agazie et al 2023 ApJL 951 L8*
- *PPTA - D. J. Reardon et al 2023 ApJL 951 L6*
- *EPTA and InPTA - J. Antoniadis et al. A&A,* 678, A50 (2023)
- *CPTA - H. Xu et al 2023 Res. Astron. Astrophys. 23 075024*

Cosmological or Astrophysical GW background?

Look at the amplitude and shape of the observed GW spectrum

$$\Omega_{GW}(\nu) = \frac{1}{\rho_c}\frac{d\,\rho_{GW}}{d\,log(\nu)} = \frac{\nu}{\rho_c}\frac{d}{d\nu}\rho_{GW} \quad with \quad \rho_c = \frac{3\,c^2 H_o{}^2}{8\pi G}$$

The main suspect: SMBHBs (SuperMassive BBHs) population in the Universe: superposition of unresolved binaries


https://arxiv.org/abs/2306.16220

$$\Omega_{GW}(\nu) = \Omega_\alpha\left(\frac{\nu}{\nu_{ref}}\right)^\alpha$$

GWB spectra from simulated SMBH binary populations that best fit the 15 yr free-spectrum data

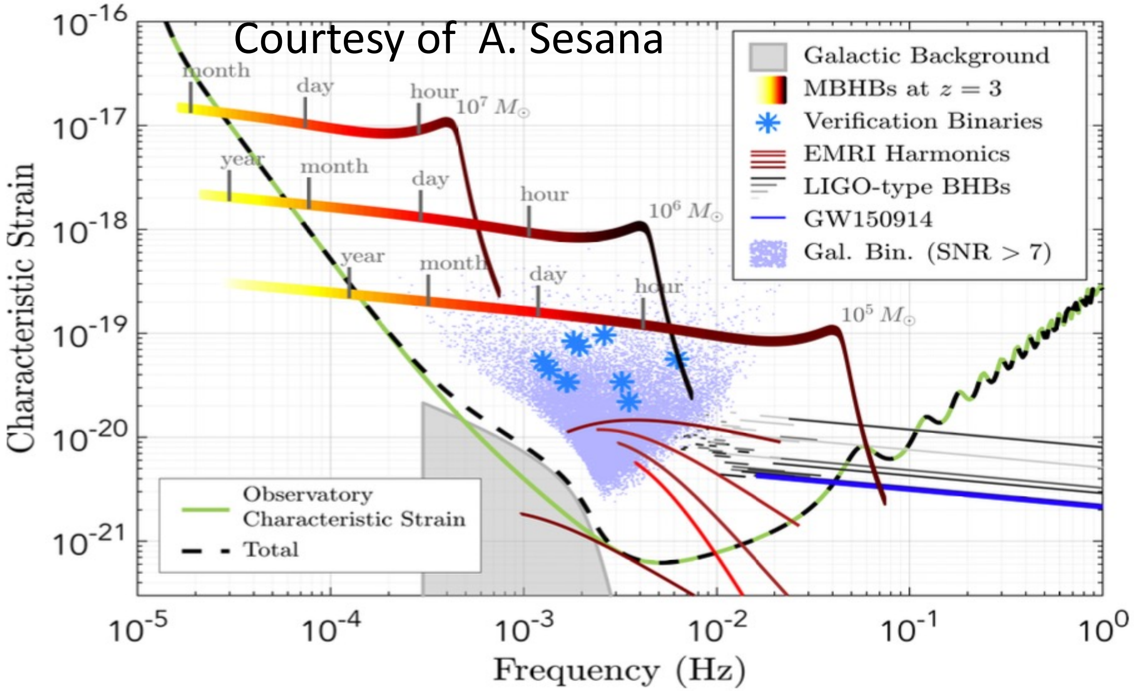
Alternative interpretations Cosmological Background from inflation

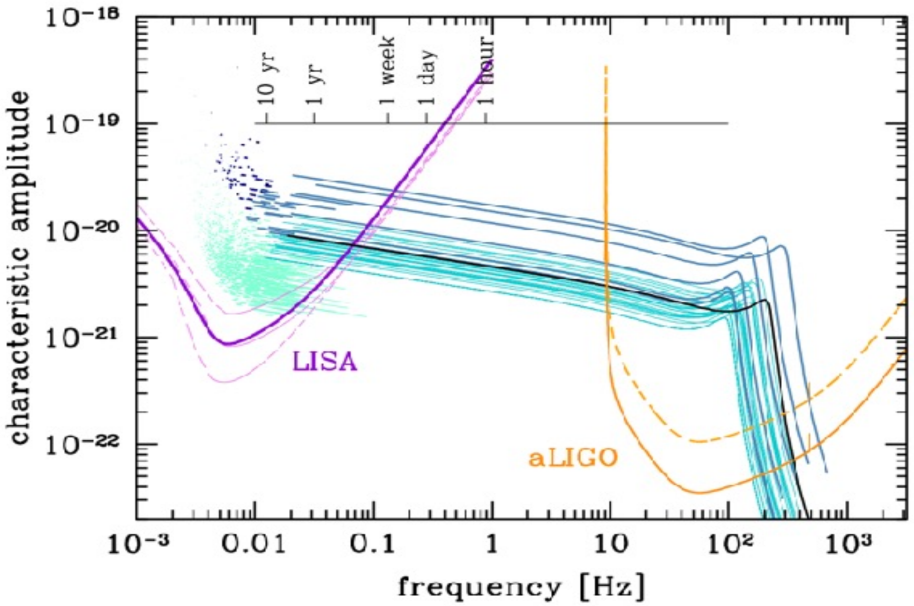
(PRL 132, 171002 (2024)

- Cosmic (super)strings,
- First order Phase Transition,
- Gaussian and non-Gaussian scalar fluctuations,
- Audible axions,

Additional data is required to resolve the GWB origin!

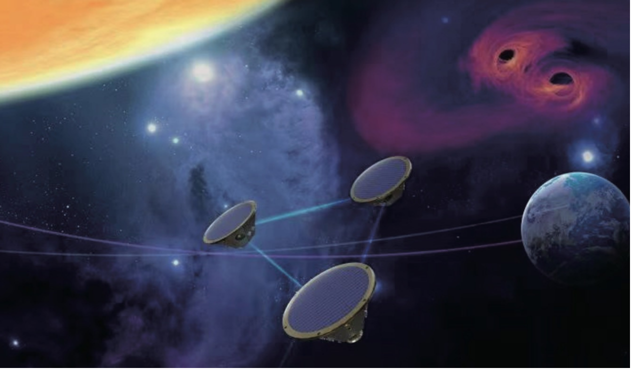
Hunting GW 10^{-4} – 10^{-1} Hz ➔Satellite detectors

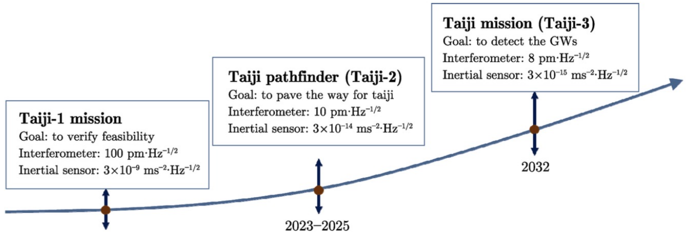

Courtesy of A. Sesana



- The formation and the evolutions of the compact binary stars in the Milky Way
- Trace the origin, growth and merger history of Massive BHs
- Probe the dynamics of dense nuclear clusters using extreme mass ratio Inspirals
- Understand the astrophysics of stellar mass black holes
- Explore the fundamental na- ture of gravity and black holes.
- Probe the rate of expansion of the Universe.
- Understand stochastic GW backgrounds and their implications for the early Universe and TeV-scale particle physics
- Search for GW bursts and unforeseen sources.

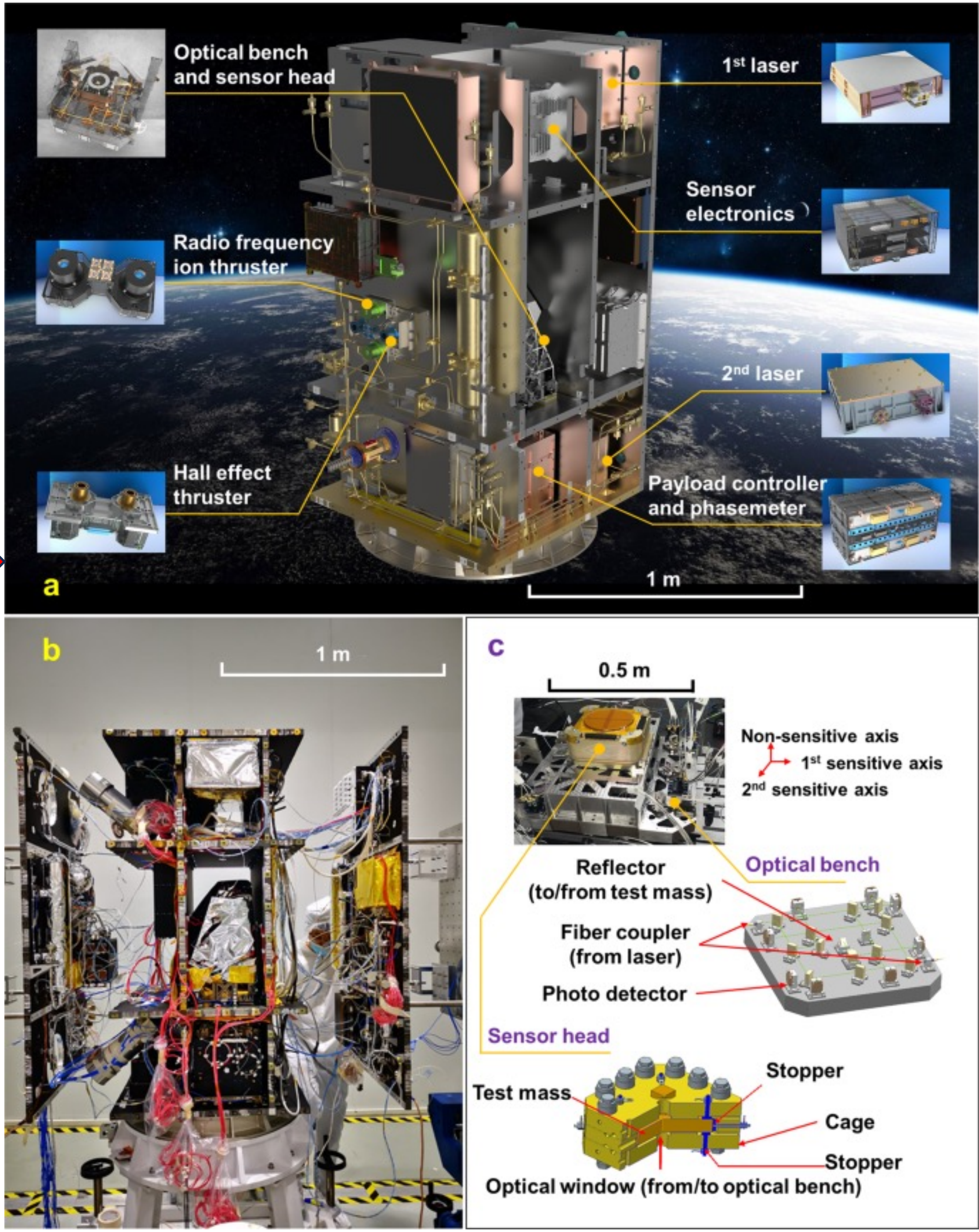
Taiji





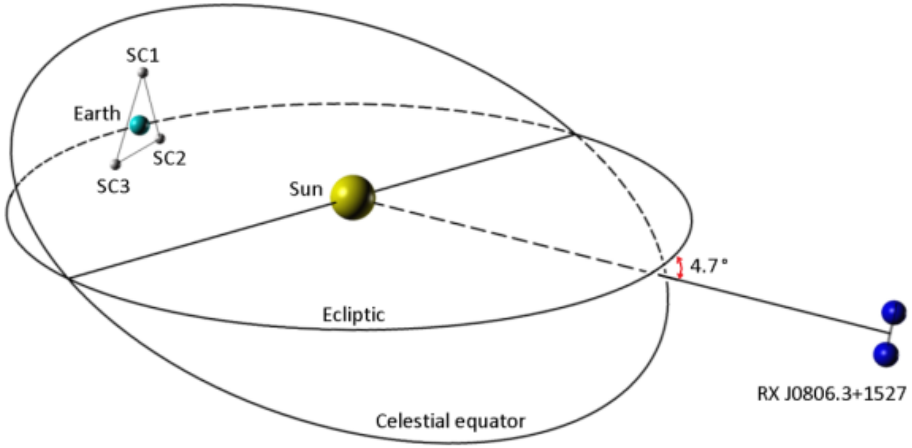
Chinese space gravitational wave detection, 3 step mission (Chin. Acad. Science, Beijing):

- Taiji-1, devoted to prepare the manufacturing technology of the payload. Approved on 30 August 2018 and set to fly on 31 August 2019. Successful test of the optical metrology system and the drag-free control system
- Taiji-2: two satellites to demonstrate technology of the inter-satellite laser link . Feasibility successfully finished in 2024 – launch no later than 2030.
- Tajii-3: 3 satellites forming an equilateral triangle in an Earth-like heliocentric orbit. To be launched in the early 2030s



TianQin - 天琴计划

Space-based GW detector developed by two Chinese teams at Sun Yat- Sen University (in Guangzhou) and Huazhong University of Science and Technology (in Wuhan).



A triangle of spacecrafts on a geocentric orbit, which is easily reachable for implementation and operation.

The orbit radius is 10^5 km, yielding an arm of the equilateral triangle $L = \sqrt{3} \cdot 10^5$ km

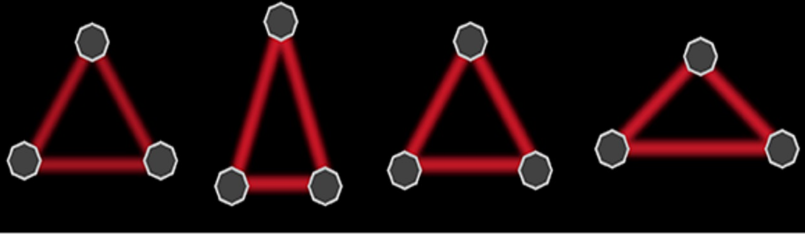
A 4 Step program

- 1: laser ranging technology. Launch in 2018: goal achieved of a laser ranged satellite to the L2 Lagrange point and an Earth station with single-photon sensitivity.
- 2: satellite with inertial sensing. Launch in 2019: goal achieved to test micronewton propulsion, drag-free control and laser interferometry technologies with in-orbit experiments. Measured a residual acceleration of $\sqrt{5} \cdot 10{-}11\ \mathrm{ms}^{-2}\,(\mathrm{Hz})^{1/2}$ at 50 mHz.
- 3: two-satellite mission. Luanche in 2025 to test inter-satellite interferometry and map the gravity field.
- 4: full constellation planned for deployment in 2035

LISA mission

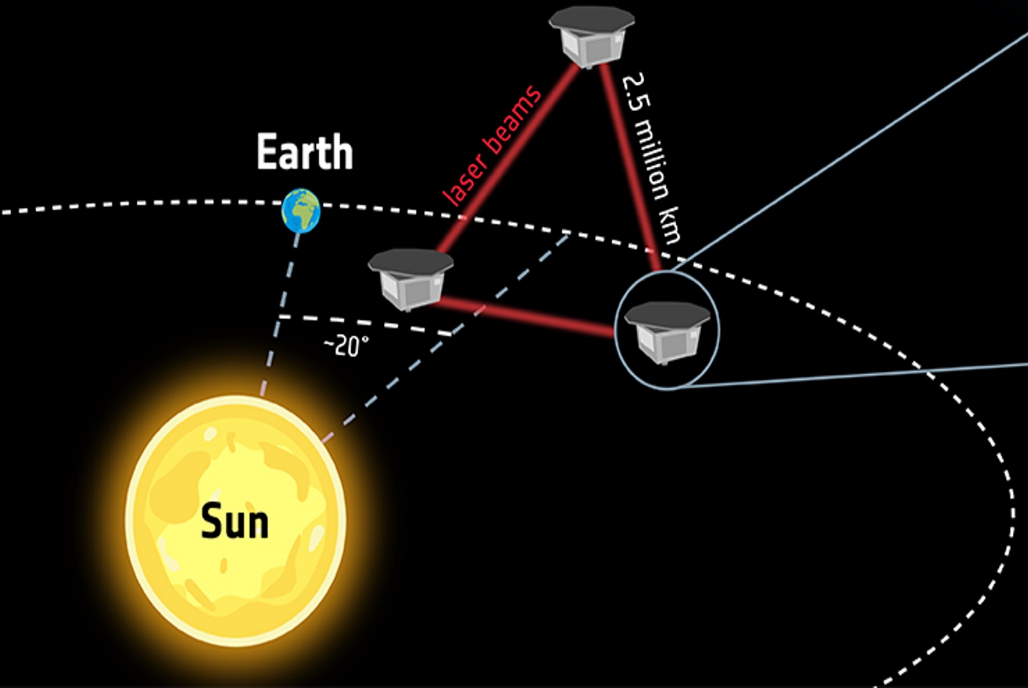
ravitational waves are ripples in spacetime that alter the distances between bjects. LISA will detect them by measuring subtle changes in the distances etween **free-floating cubes** nestled within its three spacecraft.

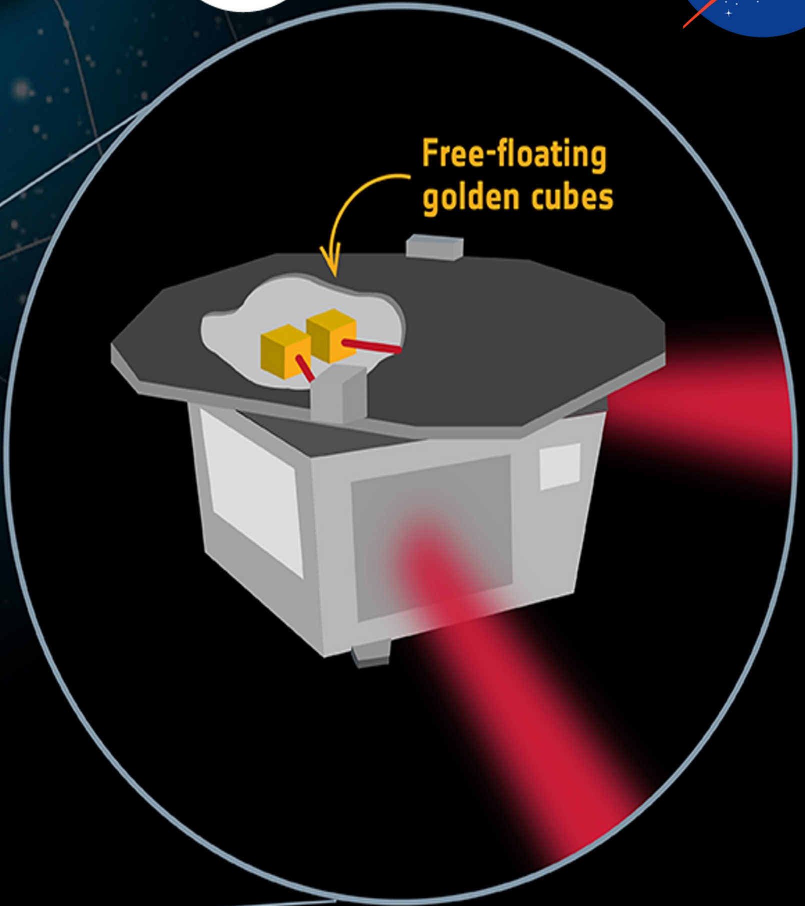
③ **identical spacecraft** exchange **laser beams**. Gravitational waves change the distance between the **free-floating cubes** in the different spacecraft. This tiny change will be measured by the laser beams.



Changes in distances travelled by the laser beams are not to scale and extremely exaggerated

Powerful events such as **colliding black holes** shake the fabric of spacetime and cause gravitational waves

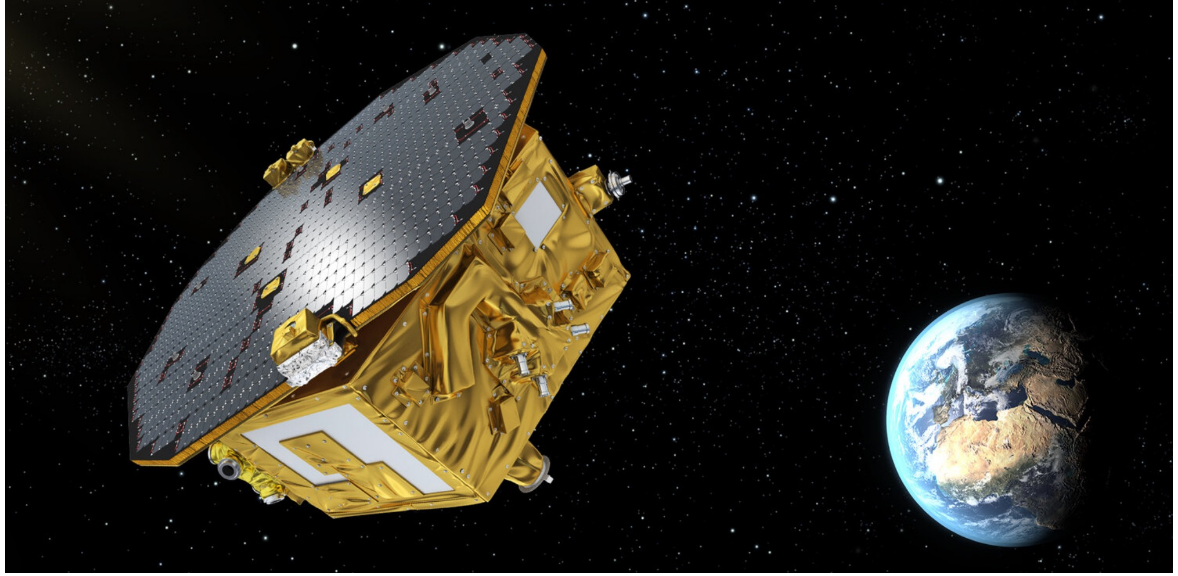




The launch of the three spacecraft is planned for 2035, on an Ariane 6 rocket.

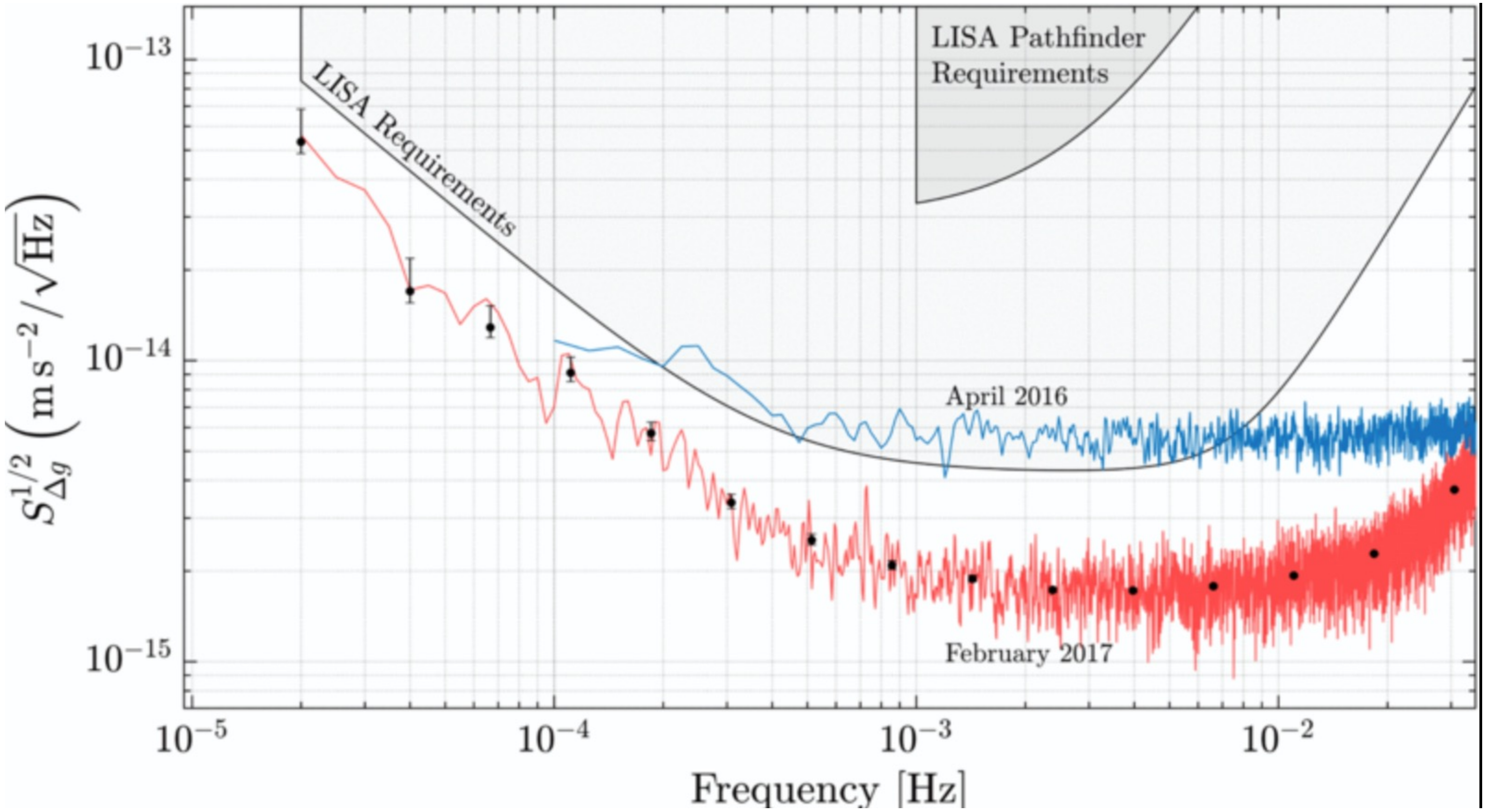
Technological demonstration of LISA pathfinder

Launch 3/12/2015 - Mission End 30/6/2017

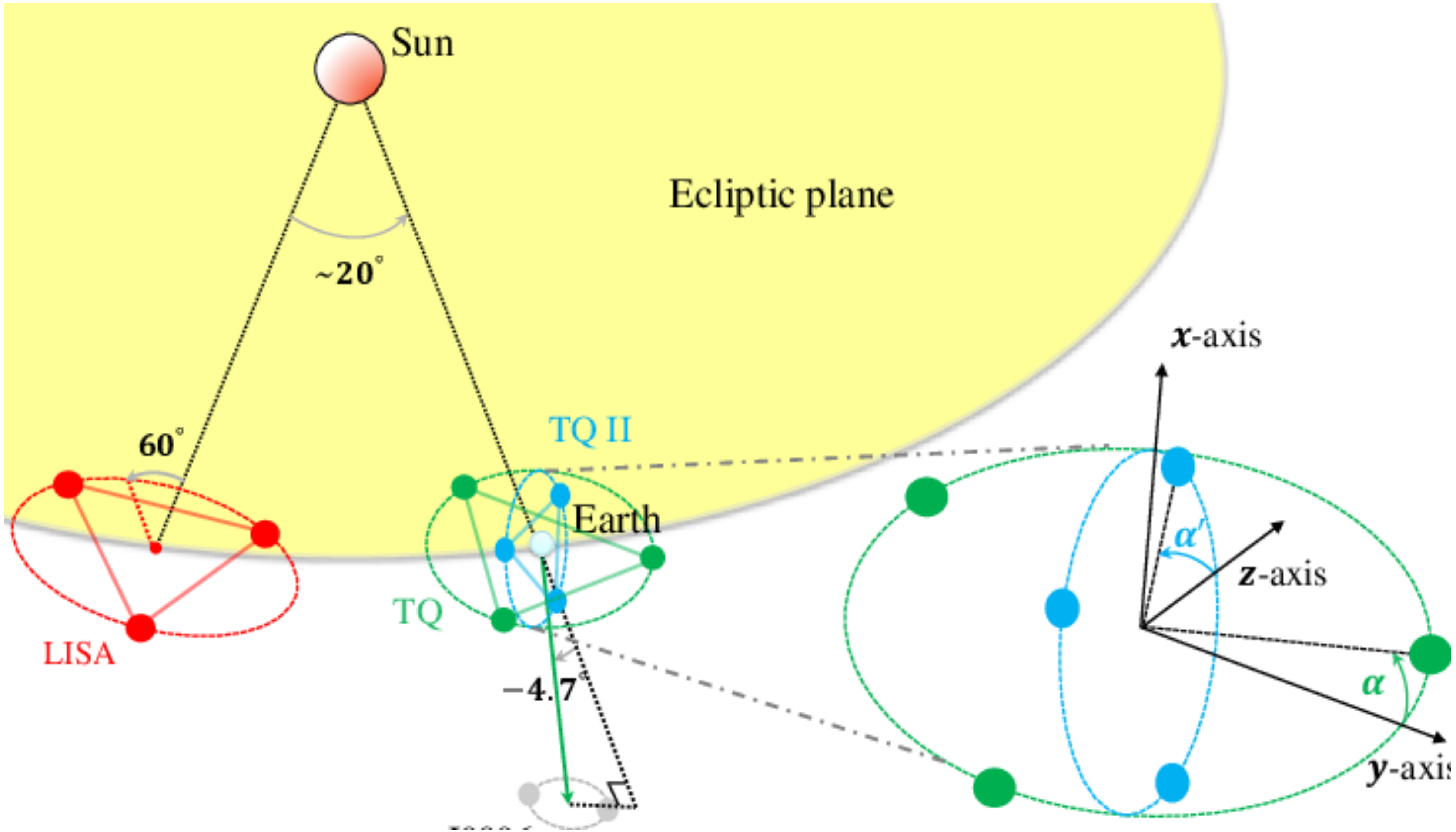


Main techological goals

- drag-free and attitude control in a spacecraft (μN trusters)
- laser interferometry 10^{-12} m resolution at low frequency, in the frequency band 10^{-3} – 3×10^{-2} Hz
- Test of indurance of the different instruments in the space environment



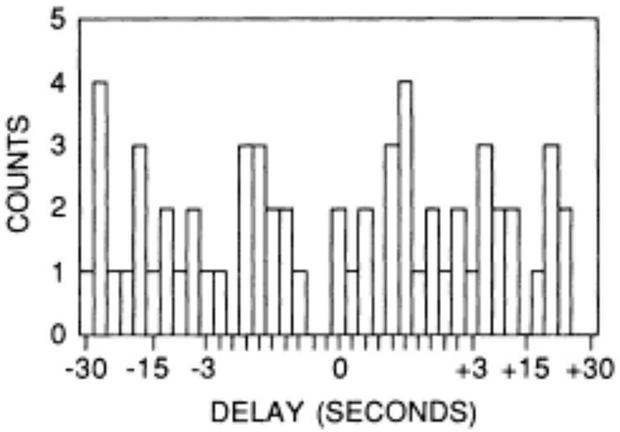
TianQuin and others GW space detectors: different orbits



The GW Detector Network   on the Earth

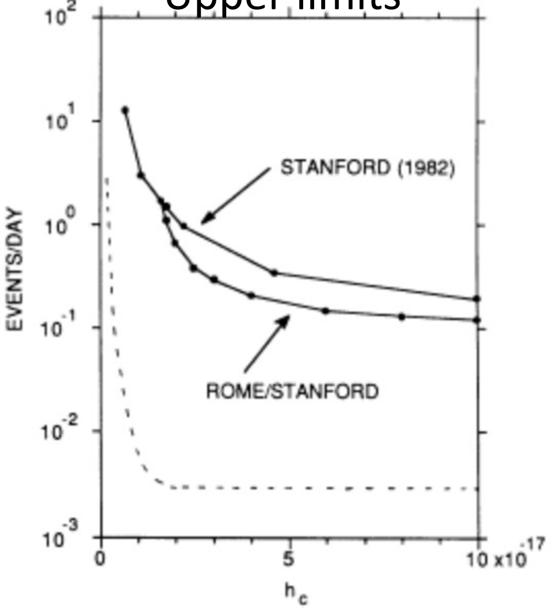
Historical Note
1986: First International Network of GW detectors on the Earth

Amaldi E. et al. (1989), Astron. Astrophys., 216, 325.



Rome-Stanford Time dealy histogram
threshold $h_s = 7.5 \times 10^{-18}$

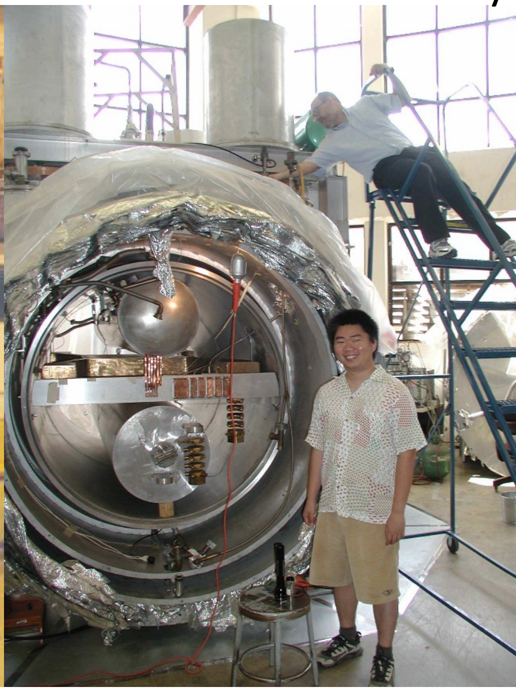
Upper limits



Stanford University

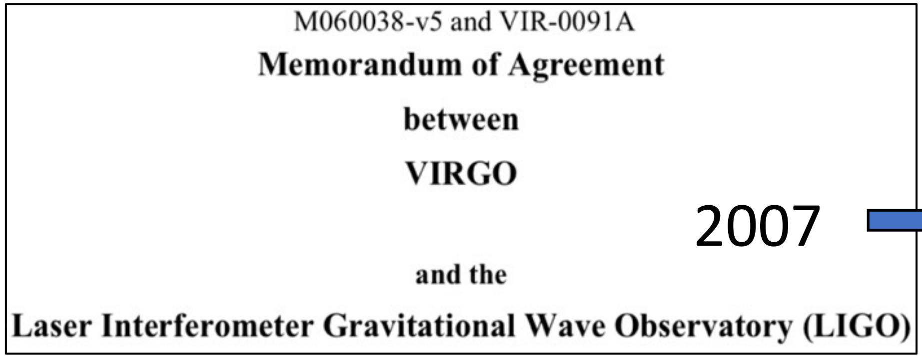
Sapienza University of Rome @ CERN

Louisiana State University



History of the Agreements between GW Collaborations

- 2007: Agreement for joint data analysis ratified between LIGO and the Virgo Collaboration which operates the Virgo interferometer in Cascina, Italy.
- 2019: Agreement for joint data analysis ratified between LIGO, Virgo, and the KAGRA



M060038-v5 and VIR-0091A

Memorandum of Agreement

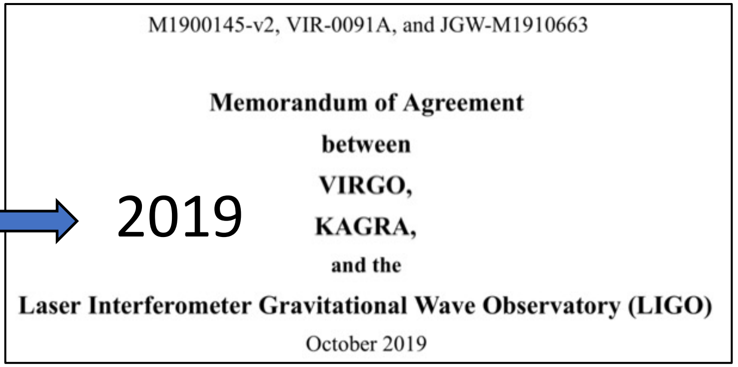
between

VIRGO

and the

Laser Interferometer Gravitational Wave Observatory (LIGO)

2007 → 2019



M1900145-v2, VIR-0091A, and JGW-M1910663

Memorandum of Agreement

between

VIRGO,

KAGRA,

and the

Laser Interferometer Gravitational Wave Observatory (LIGO)

October 2019

LSC (LIGO Scientific collaboration) + Virgo + KAGRA (LVK) membership: ~ 2100 people

Now, we need to move toward a fully unified collaboration:

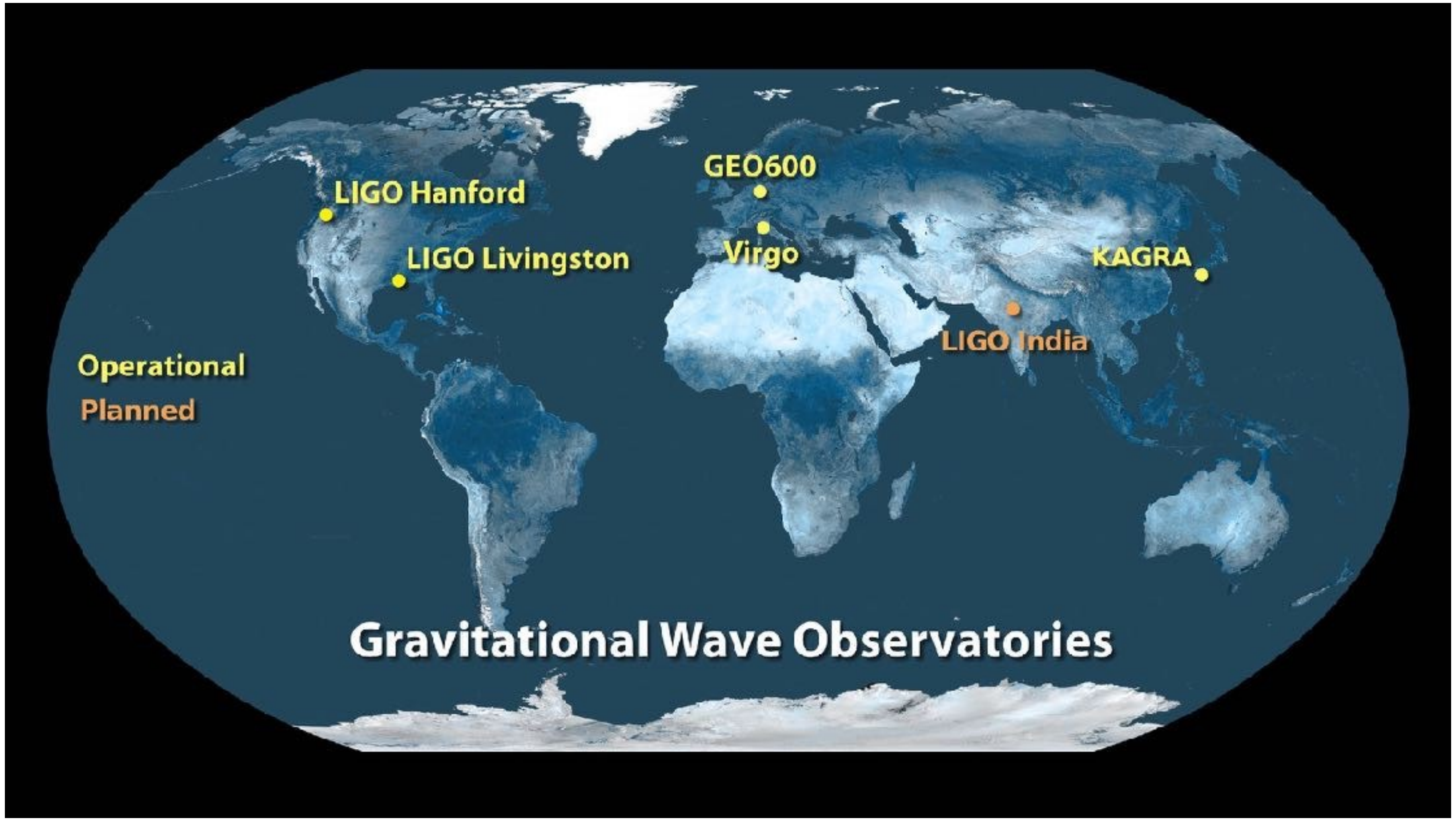
LVK ➔ ***IGWN – International Gravitational Wave Network***

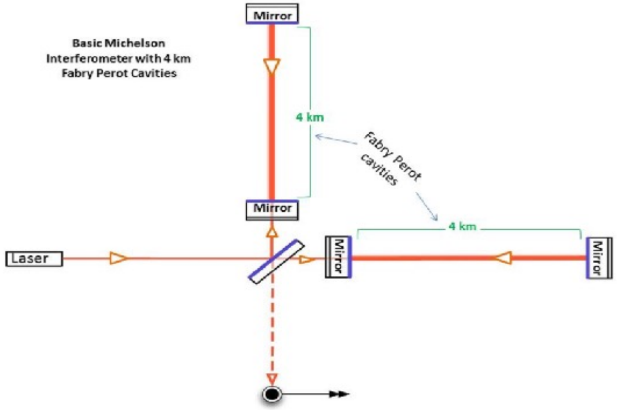
A single organization for equitable and efficient sharing of res sh a single program (and prioritise the scientific goals

- ➢ Elimination of parallel and independe nt, and inefficient) decision-making processes
- ➢ Integration of infrastructu the operations across the network will permit to optimize the available reso

Discussions amog the three collaborations are on going.

The present International network of ground-based GW interferometers





GEO - KAGRA joint run in 2020 (2 weeks)

LIGO and Virgo in science mode

KAGRA: expected to join current observing run later on (operations delayed by earthquake in 2024)

LIGO India ➔ LIGO Aundha ➔ LAO
'Official' schedule to come online in 2030. Detector based on A+ technologies

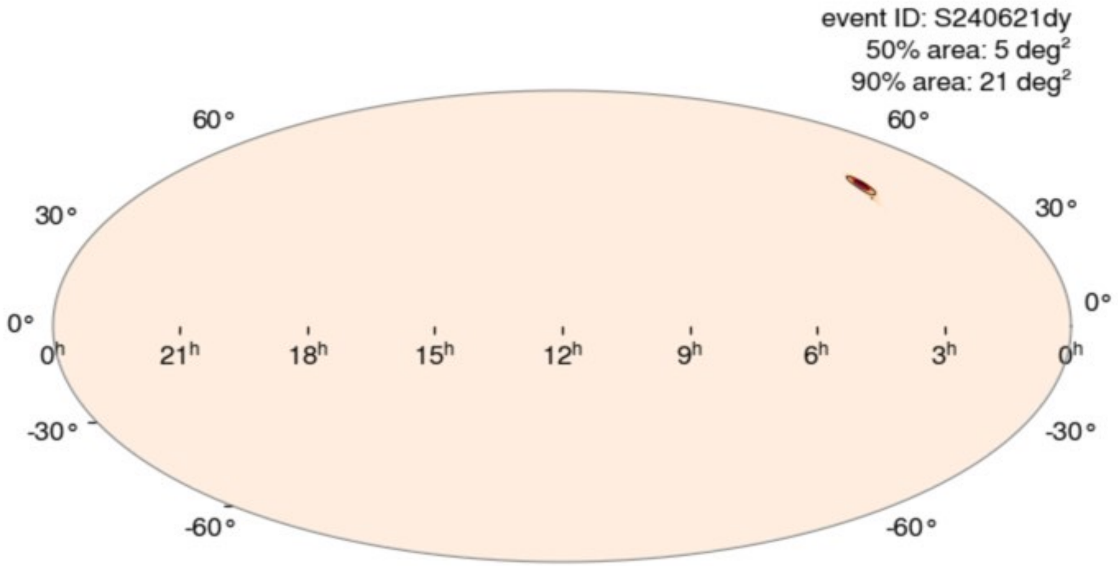
The network is crucial for

- source localisation➔ multimessenger astronomy
- constraints on GW polarisation $h = h_{+c}F_{+} + h_{\times}F_{\times}$

Sky localisation of GW sources

- O4 data taking divided in two chunks:
  - ✓ O4a the two LIGO interferometers (LH) only
  - ✓ O4b the two LIGOs + Virgo (LHV)

- Virgo brings substantial improvement on event localization: in O3b LHV localized GW200208_130117 in a sky area of ~30 deg^2 (comparable to GW170817).



O4b example: **S240621dy**

2024-06-21 19:51:20 UTC

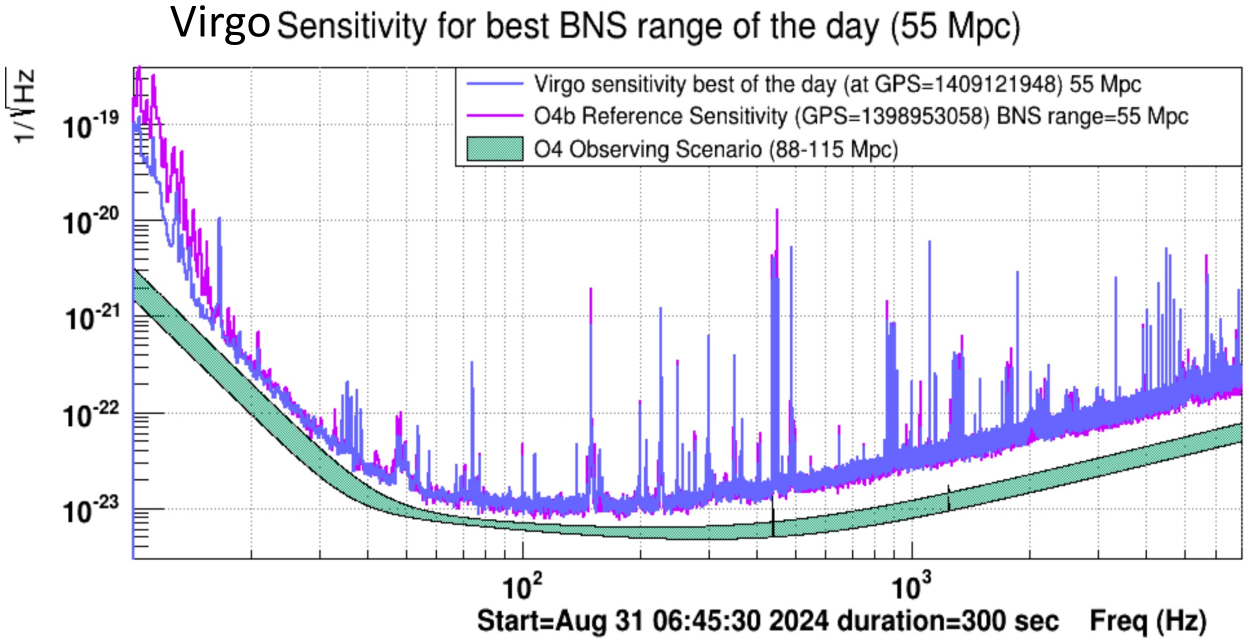
Binary Black Hole event @ 847 Mpc

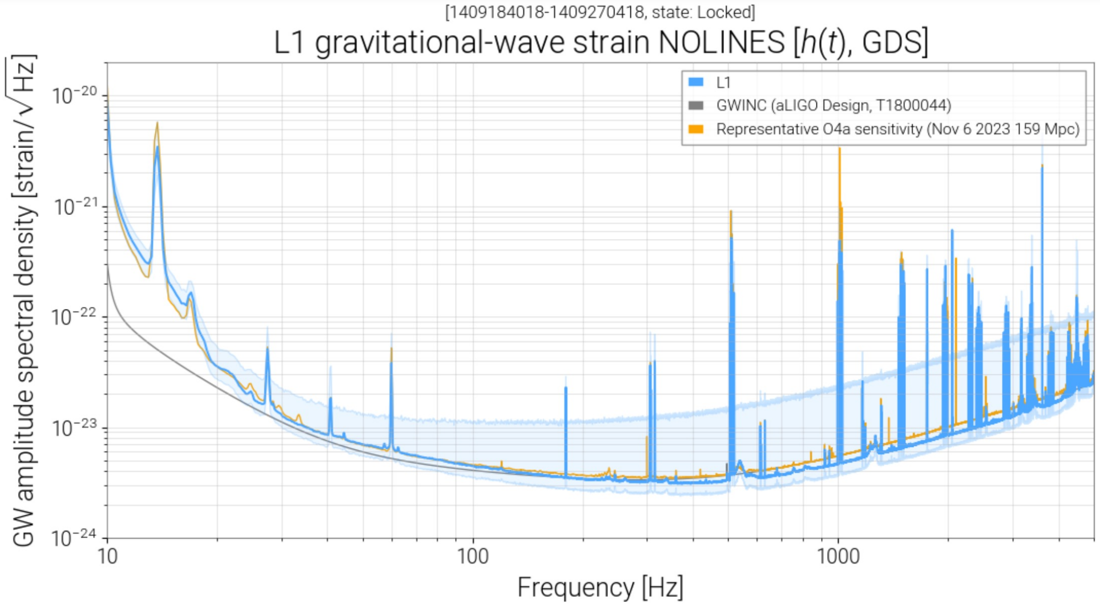
21 deg^2 (90% confidence area)

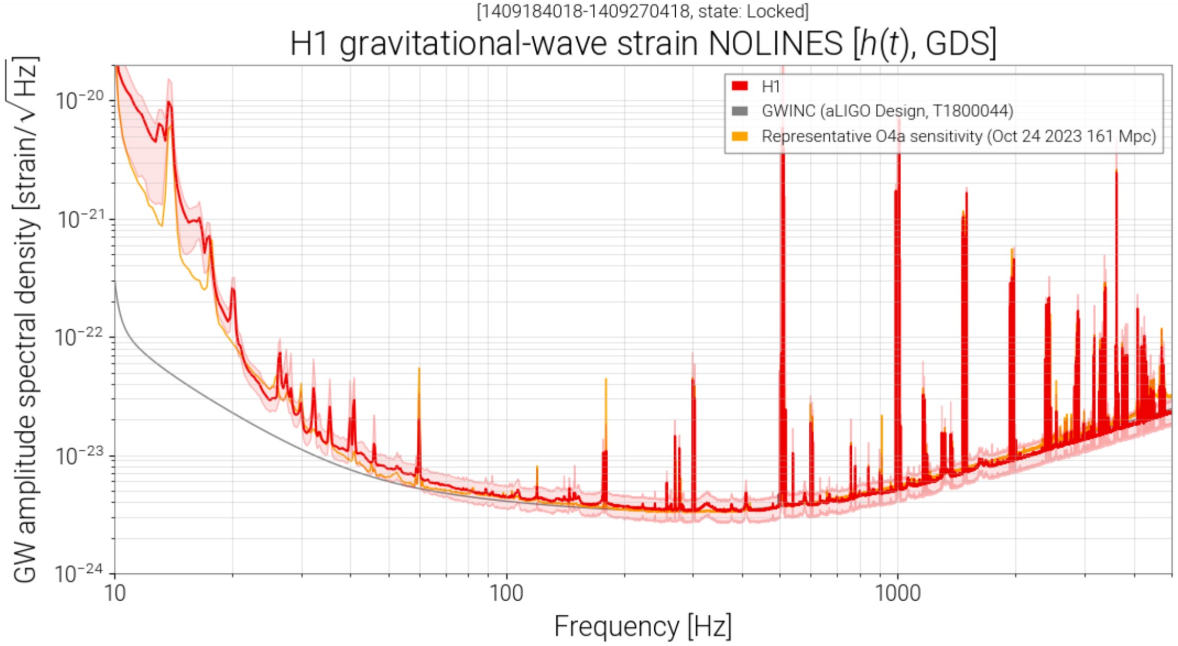
https://gracedb.ligo.org/superevents/S240621dy

Detector sensitivities

Virgo







The sensitivity curve of interferometric detectors corresponds is the minimum detectable (SNR=1) metric tensor perturbation *h(f)* versus the detection frequency *f*.

IGWN detections

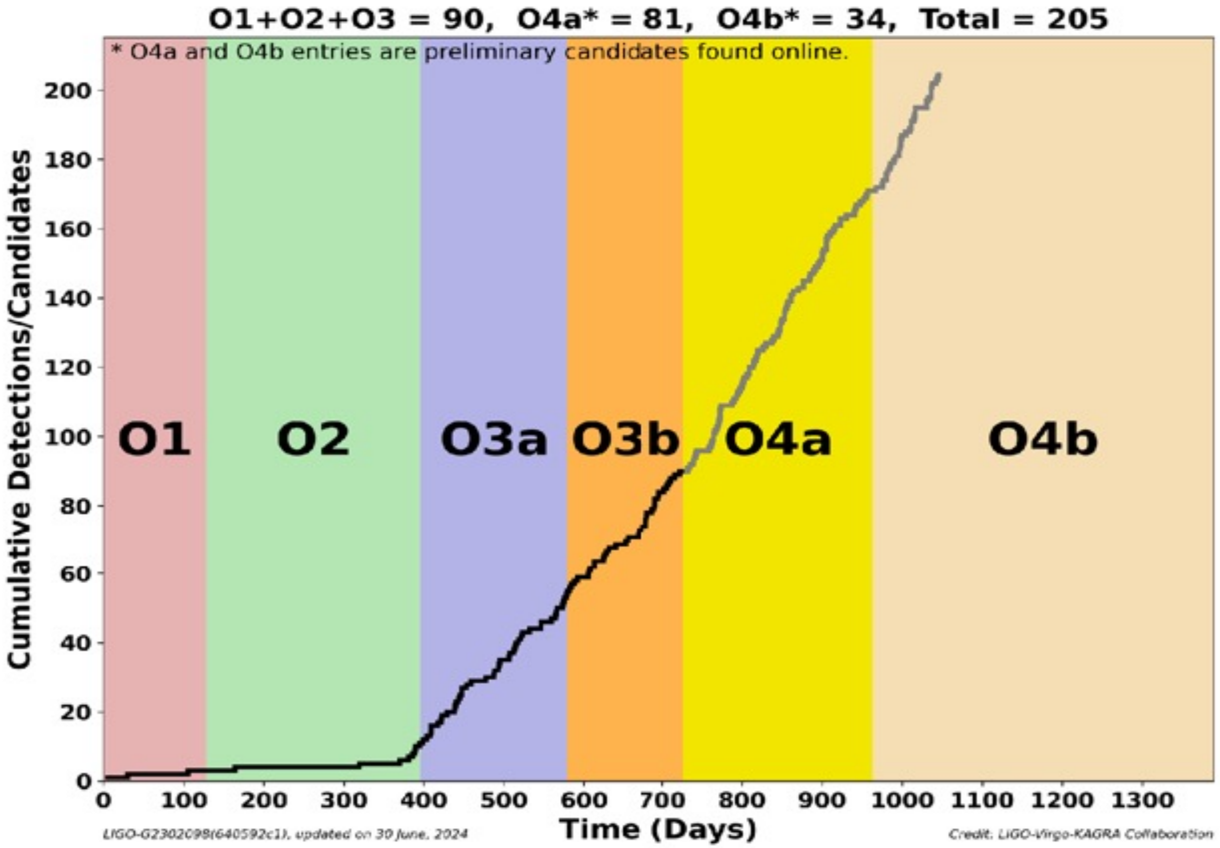
	Data taking period	Number of events
O1	September 12, 2015, January 19, 2016	3
O2	November 30, 2016, August 25, 2017	8
O3	April 1, 2019 September 30, 2019 -------------------------- November 1, 2019 April 20,2020 (premature end due to COVID -19 pandemic)	44+35
O4	May 24, 2023 January 16, 2024 --------------------- April 10, 2024 current	81+(34)

54 ➔up to September 20, 2024

Binary detection rates

- O3 ~ 1 / 5 days
- O4 ~ 1 / (2.8 days)
- O5 ~ 3 / day

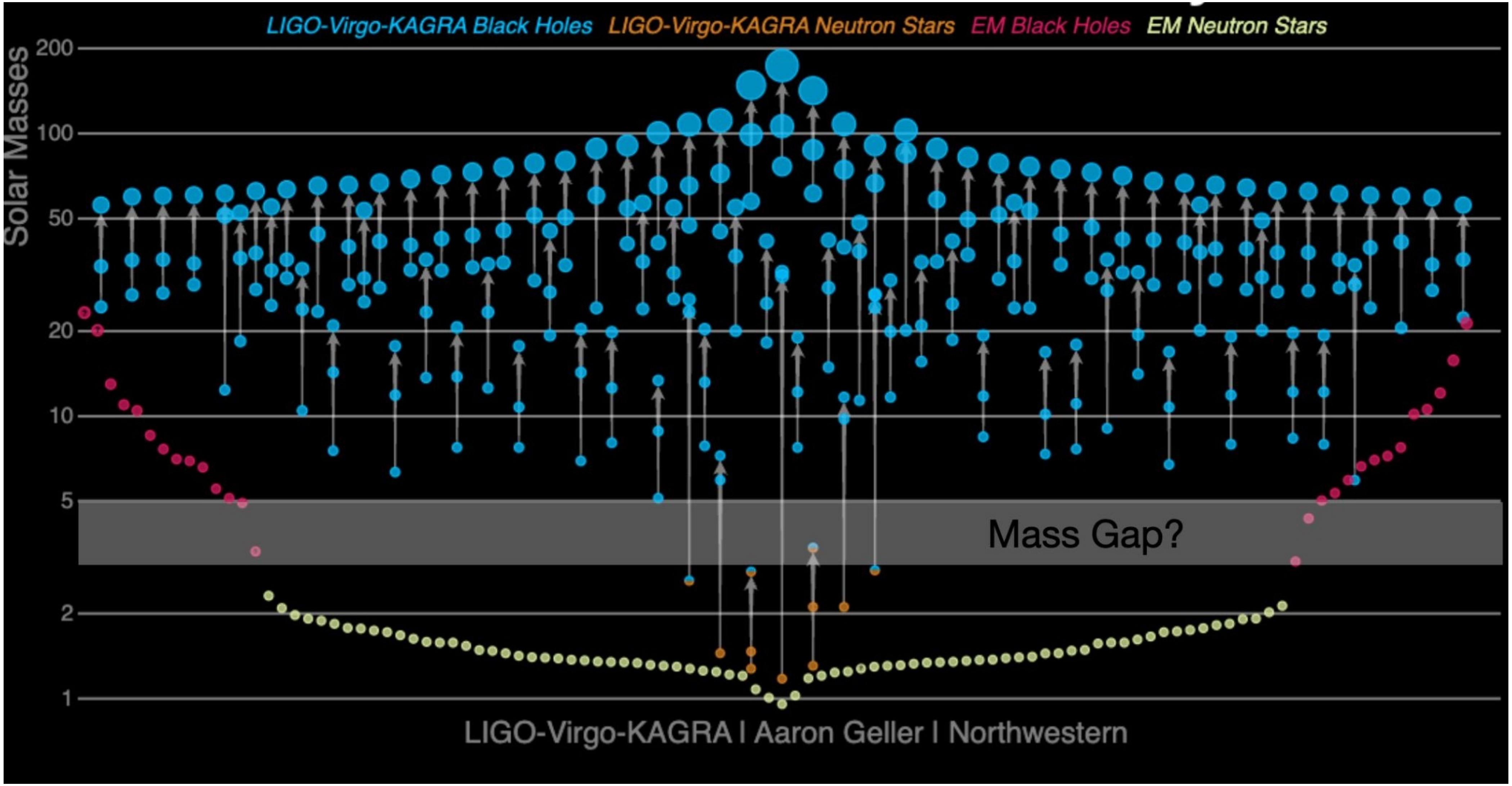
Detections up to June 30, 2024



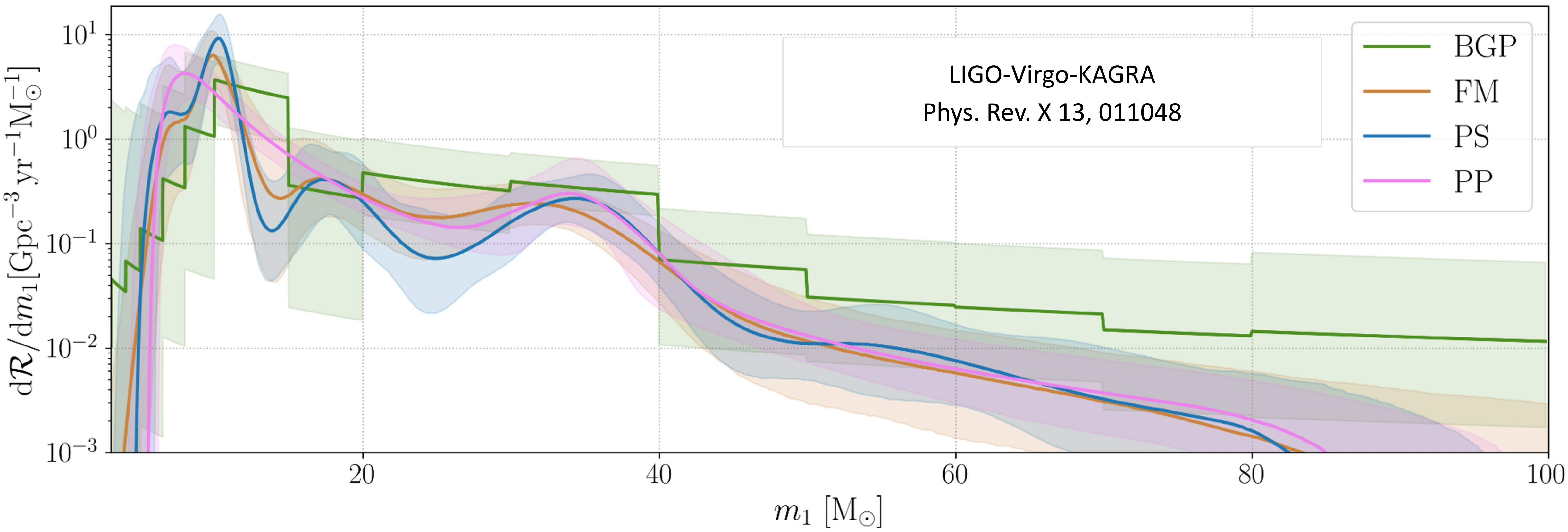
LIGO-G2302098(640592c1), updated on 30 June, 2024

Credit: LIGO-Virgo-KAGRA Collaboration

Masses in the stellar graveyard



From one to many: measuring populations



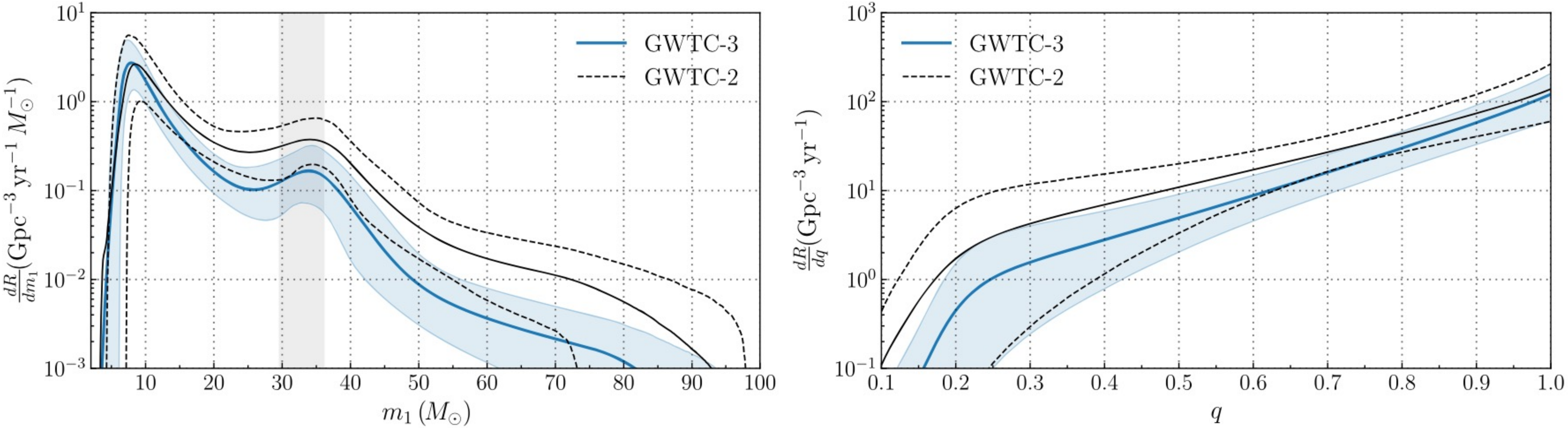
LIGO-Virgo-KAGRA
Phys. Rev. X 13, 011048

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

Phys. Rev. X 13, 011048

BH mass spectrum in the binaries

Differential merger rate as a function of primary mass *m_1* and the mass ratio *q* in the binary system

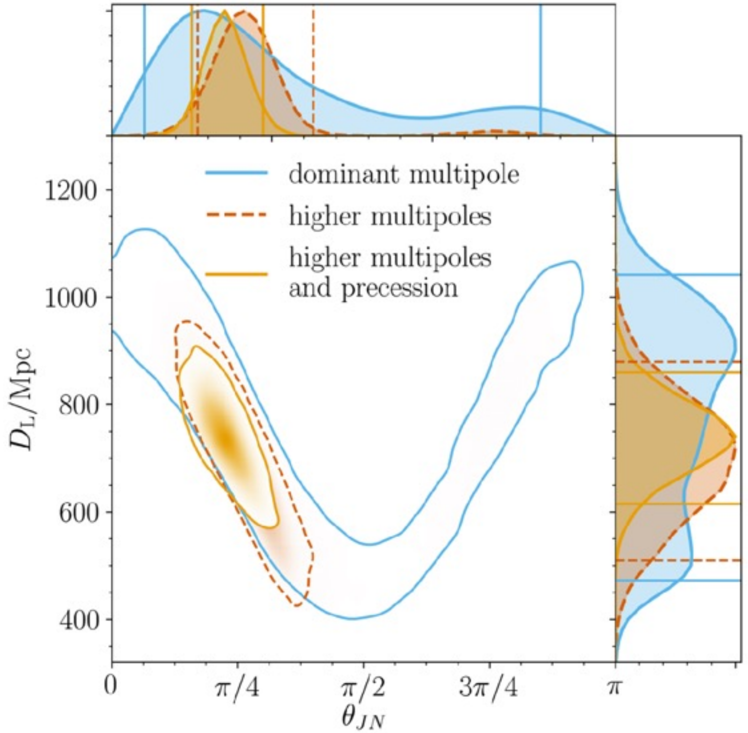


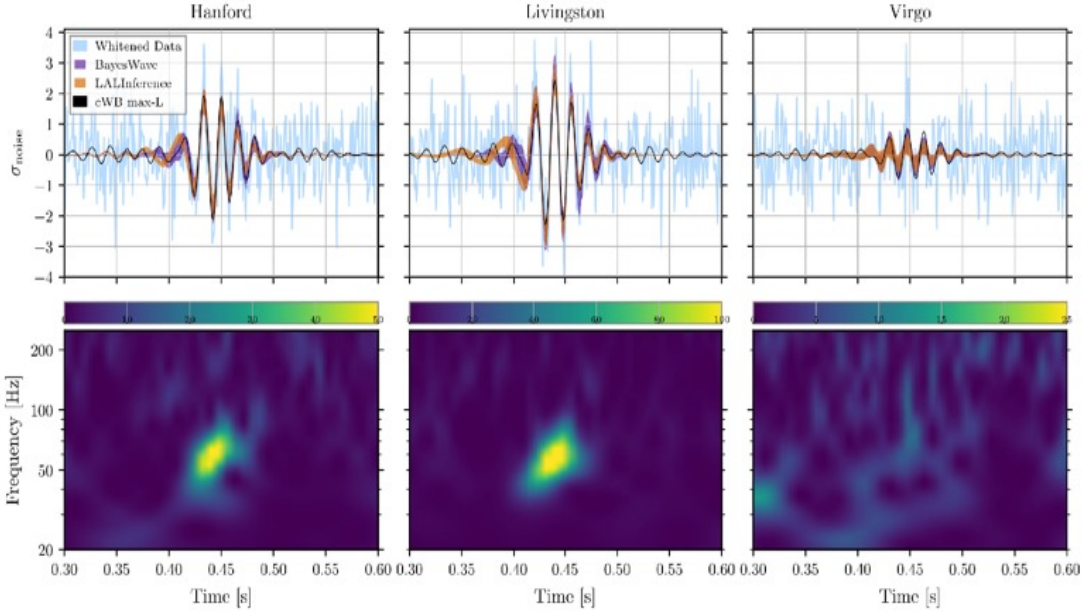
- Mass distribution has substructures
- Mas gap due to air-instability: statistical consistency either with
    - mass gap starting at mass values > 75M⨀),

    or
    - no pair instability gap

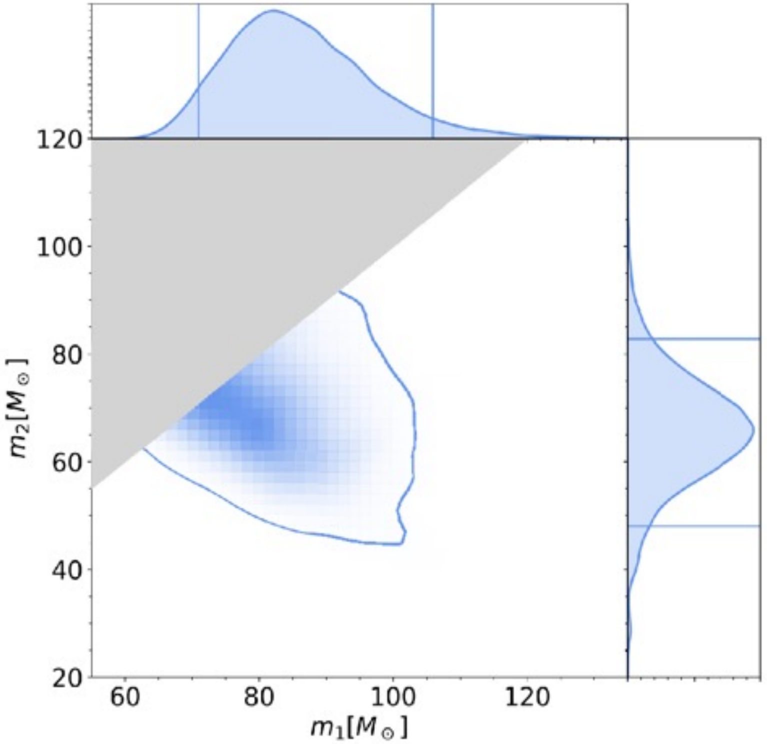
Notable BBH events

GW190412:
First detection of a BBH with clearly unequal masses. PRD 102, 043015 (2020)

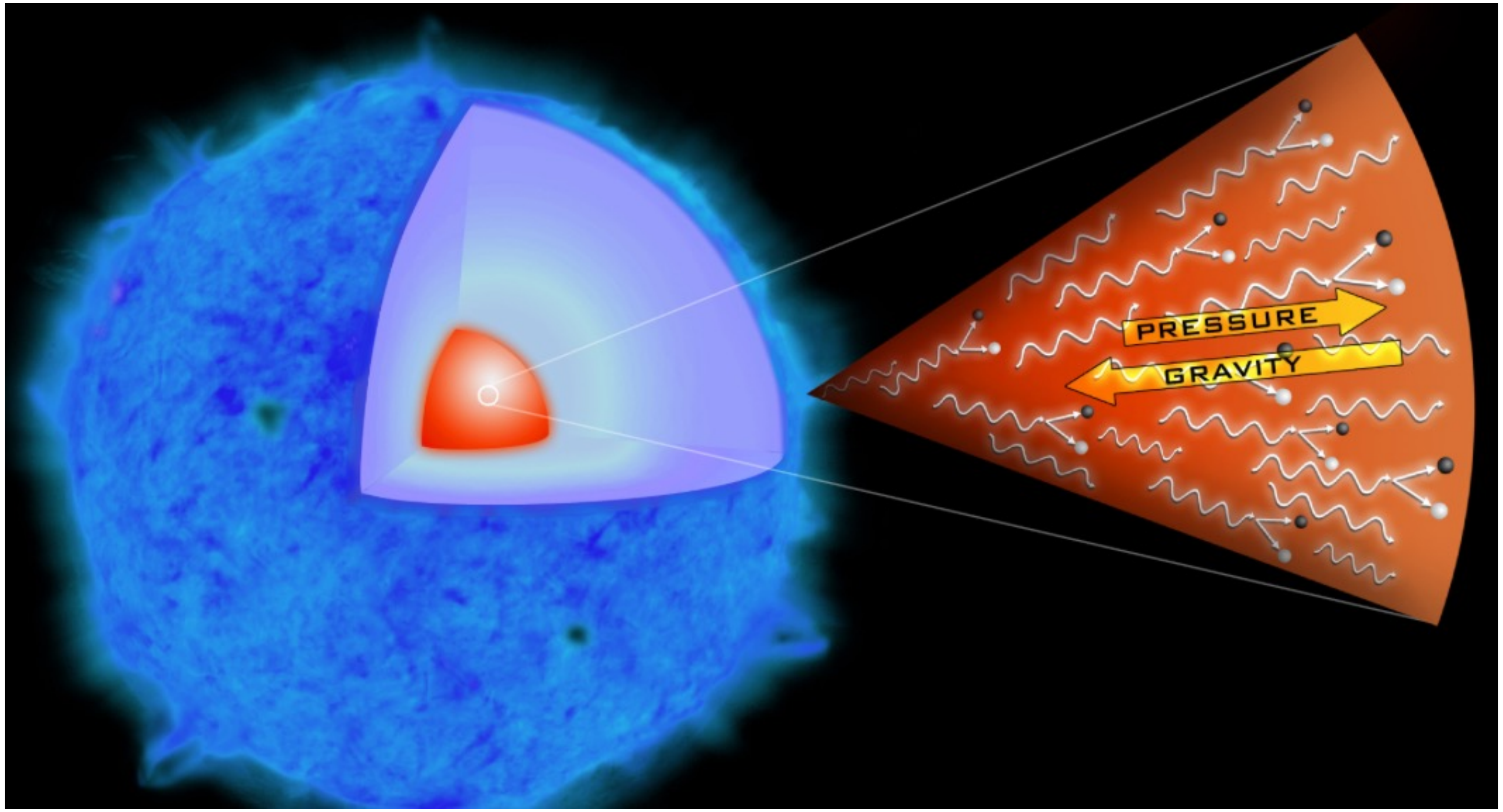




GW190521: high-mass event, very short duration and suppressed inspiral part.
The remnant mass was an intermediate mass BH,
PRL 125, 101102 (2020)



- GW190521
  Black holes exist in pair instability mass gap (130 - 250 $M_{\odot}$)



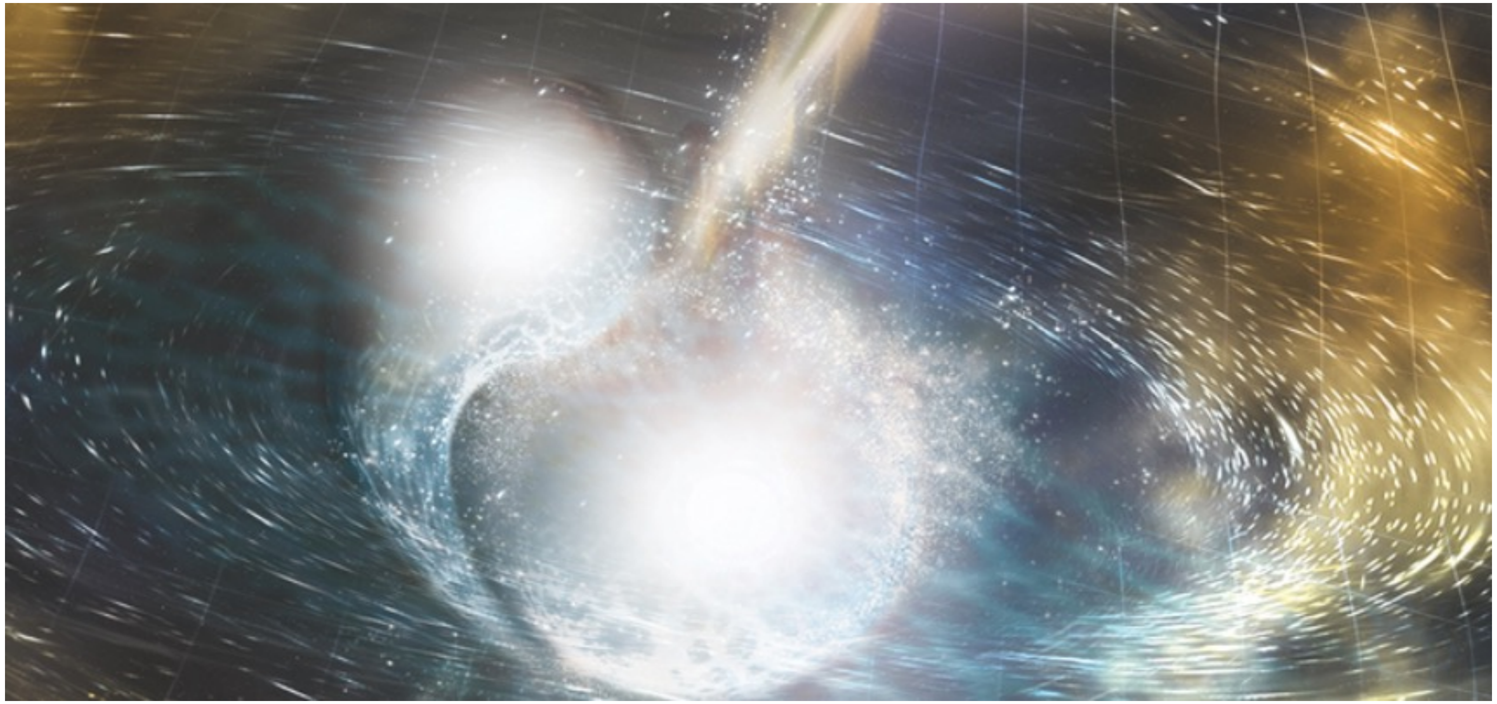
- GW190814
  - Compact objects exist with masses between 2-5 $M_{\odot}$

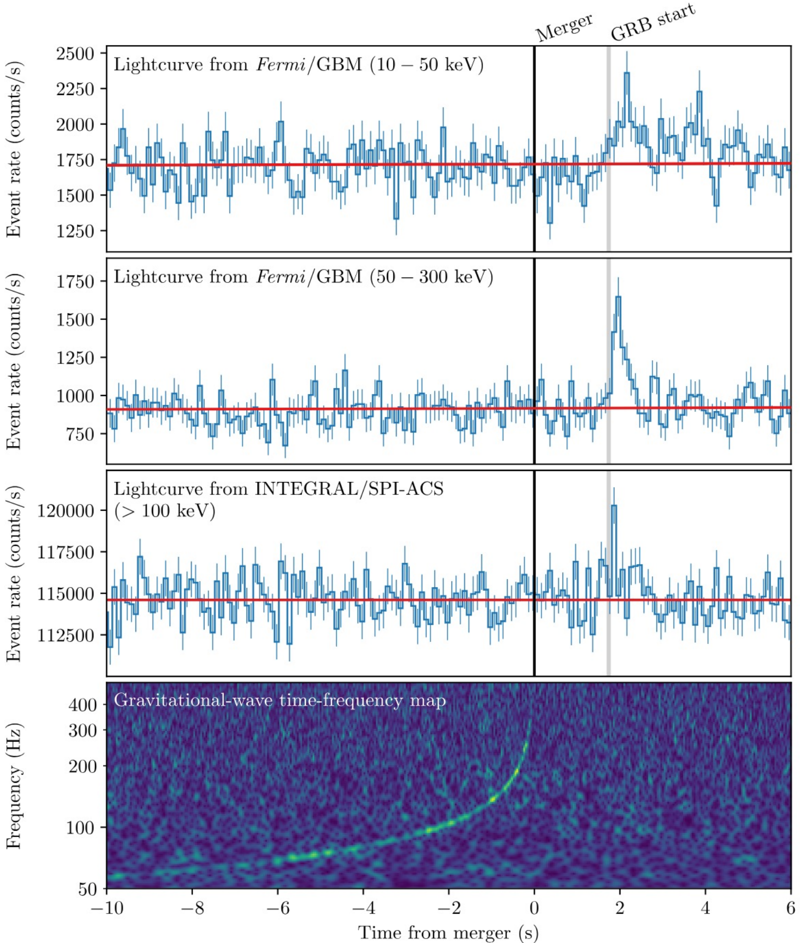
<- ?->

NS and multi-messenger astronomy

Coordinated observation and interpretation of multiple signals: *successful case of GW170817*:

-- Binary NS merger in the galaxy NGC 4993 observed by the LIGO/Virgo collaboration.
-- Fermi Gamma-ray Space Telescope and INTEGRAL observed gamma rays after 1.7 seconds.
-- Optical counterpart SSS17a detected 11 hours later at Las Campanas Observatory,
--Then, observations the Hubble Space Telescope, the Dark Energy Camera, UV Neil Gehrels Swift Observatory, Chandra X-ray Observatory and Karl G. Jansky Very Large Radio Array Radio
-- Non-observation of neutrinos was attributed to the jets being strongly off-axis.





Public alerts https://gracedb.ligo.org/

More details in
[IGWN | Public Alerts User Guide]()

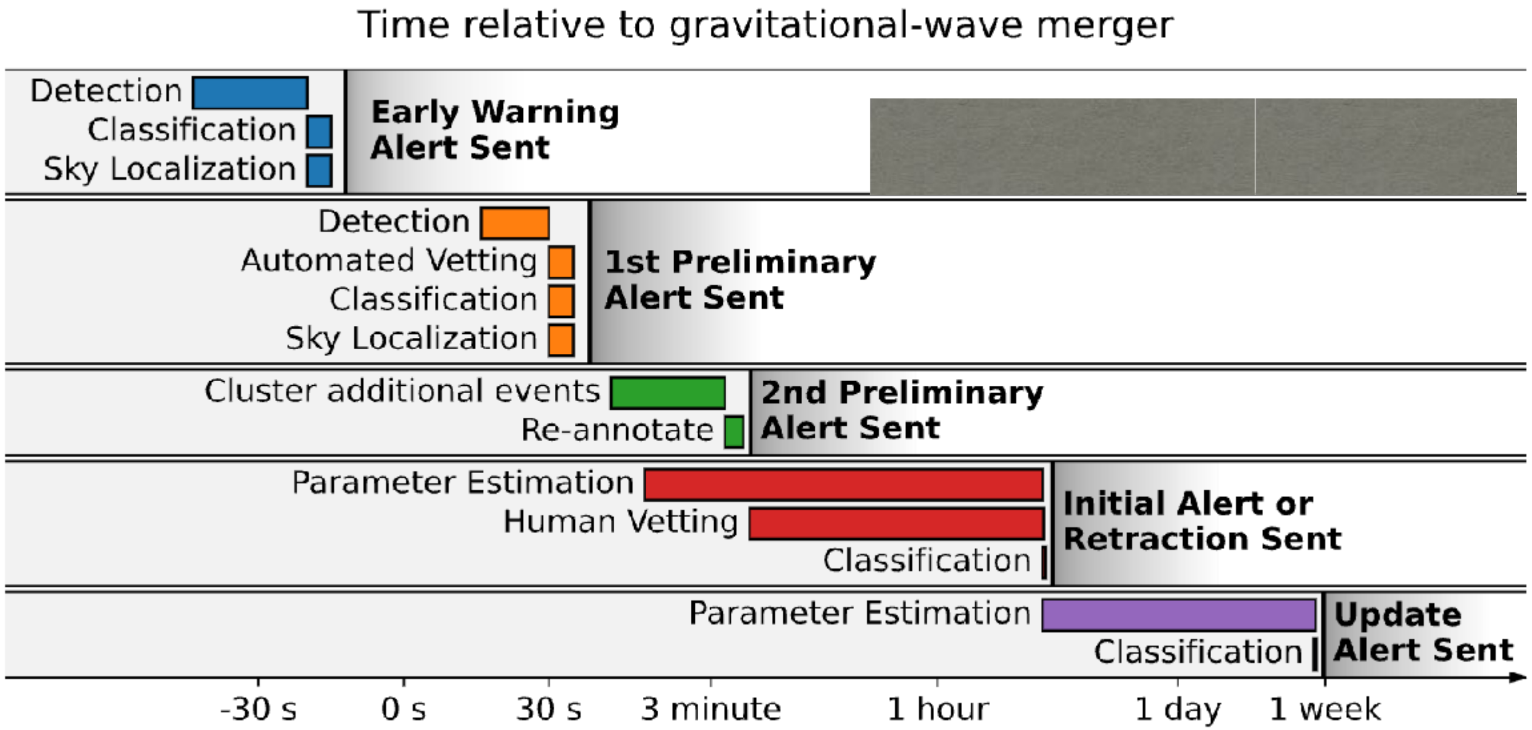
O4 significant candidates 154 *

Retracted events are shown in red

O4 low significant candidates 2302 *

(for an extended multimessenger follow up)

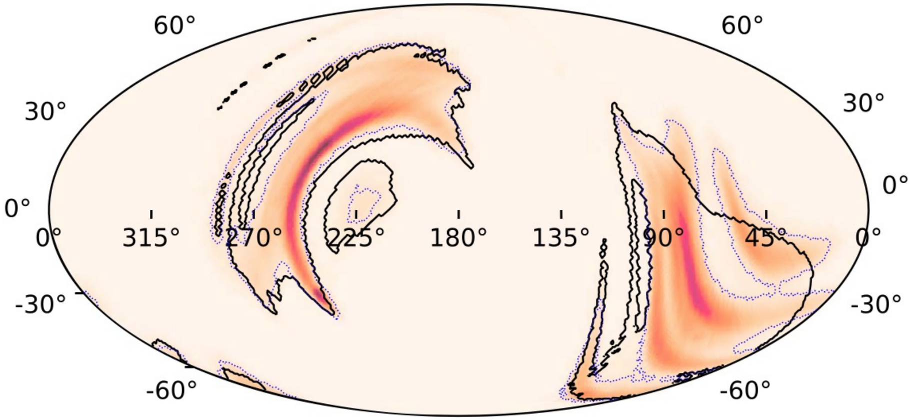
* Numbers recorded on September 1, 2024



- IGWN Alert Contents
  - Notice Types
  - Notice Formats
  - Notice Contents
  - Circular Contents
  - *Not* Included in Alerts
  - Notice Examples
  - Public Annotations

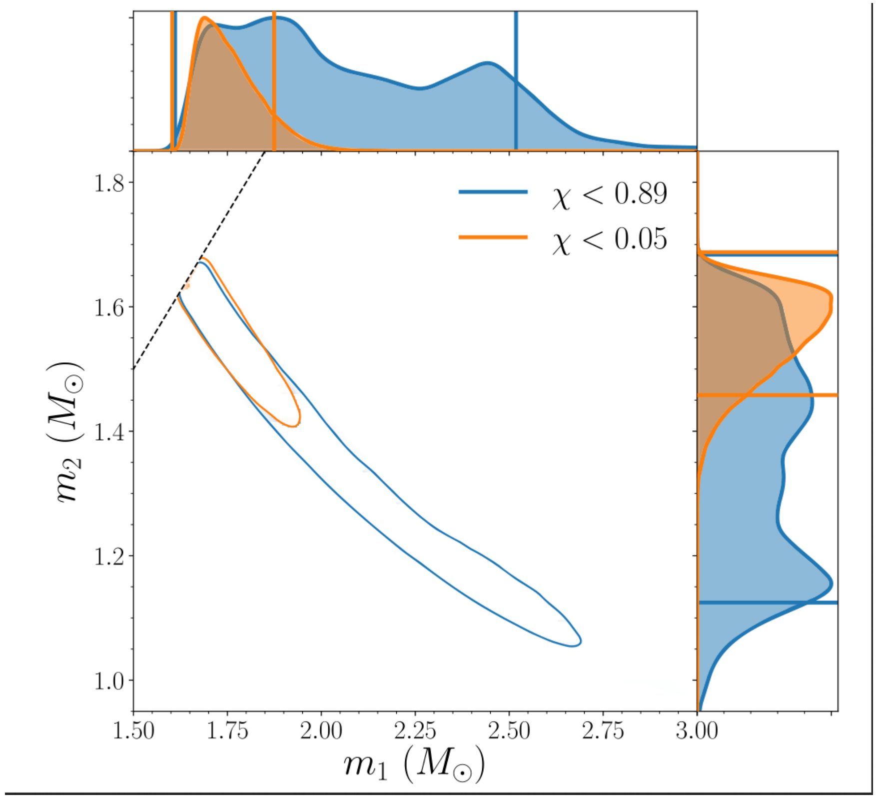
For an alternative way to track the event detections see
Gravitational Wave Treasure Map

Second confident event identified as a BNS merger: GW190425



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 $m_{\rm tot}$	$3.3^{+0.1}_{-0.1}$ 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



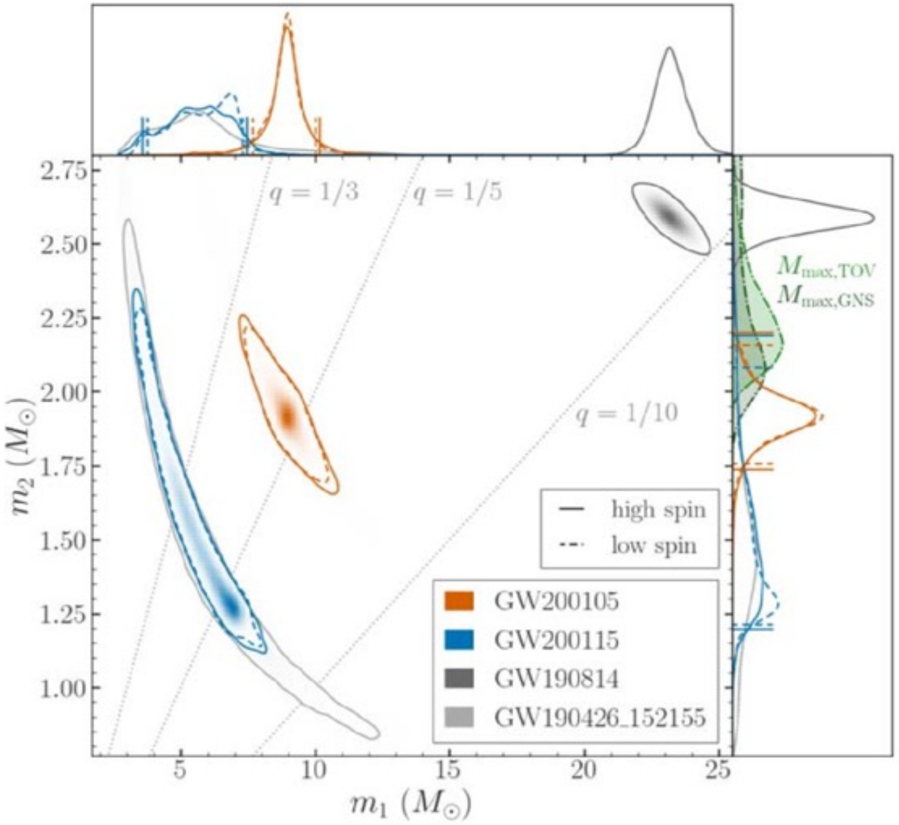
Mainly a single detector event:
SNR LLO 12.5
SNR Virgo 2.5 (below det. treshold 4)

Total mass and chirp mass larger than any known BNS

ApJ L, 892, L3 (2020) L3

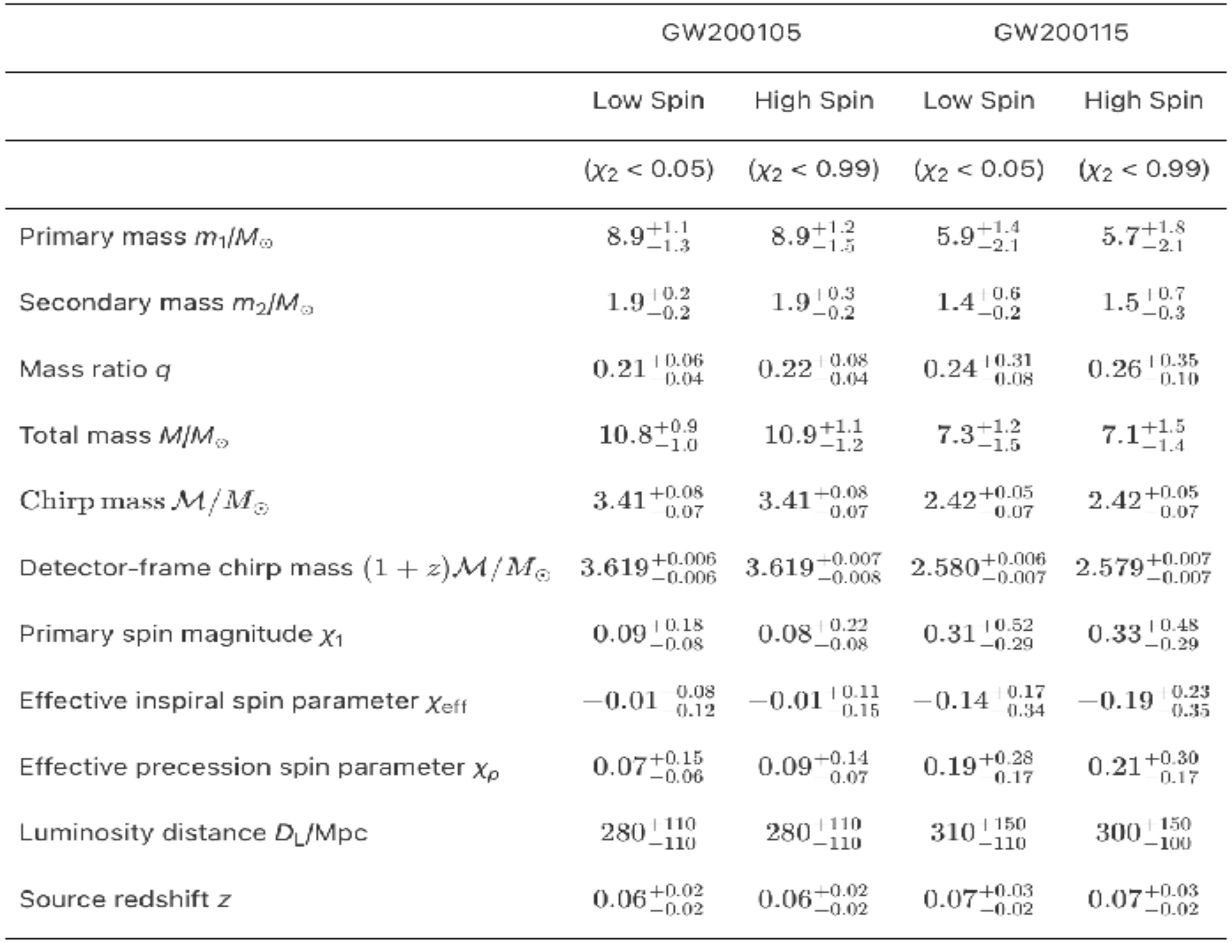
Confident detections of *mixed binaries:* NSBH

GW200105 and GW200115



-- No evidence of tidal effect on NS companion

-- Low-mass BHs, less compact NS and high prograde spins favor tidal disruption



	GW200105		GW200115	
	Low Spin	High Spin	Low Spin	High Spin
	($\chi_2 < 0.05$)	($\chi_2 < 0.99$)	($\chi_2 < 0.05$)	($\chi_2 < 0.99$)
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 χ_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 χ_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 $D_{\rm L}$/Mpc	280^{+110}_{-110}	280^{+110}_{-110}	310^{+150}_{-110}	300^{+150}_{-100}
Source redshift z	$0.06^{+0.02}_{-0.02}$	$0.06^{+0.02}_{-0.02}$	$0.07^{+0.03}_{-0.02}$	$0.07^{+0.03}_{-0.02}$

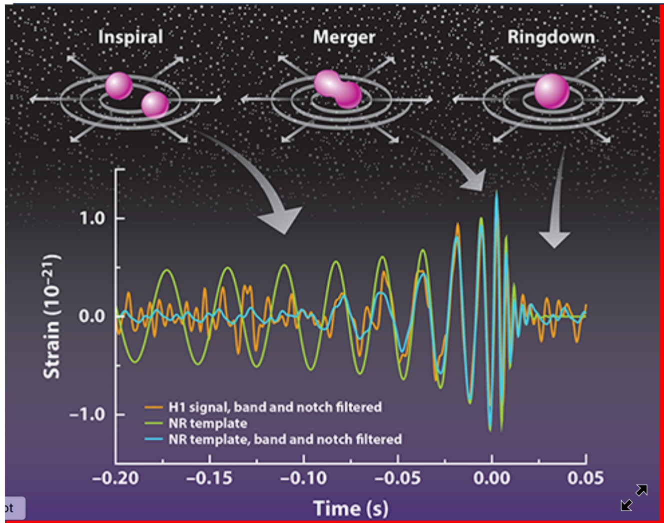
Abbott et al 2021 ApJL 915 L5

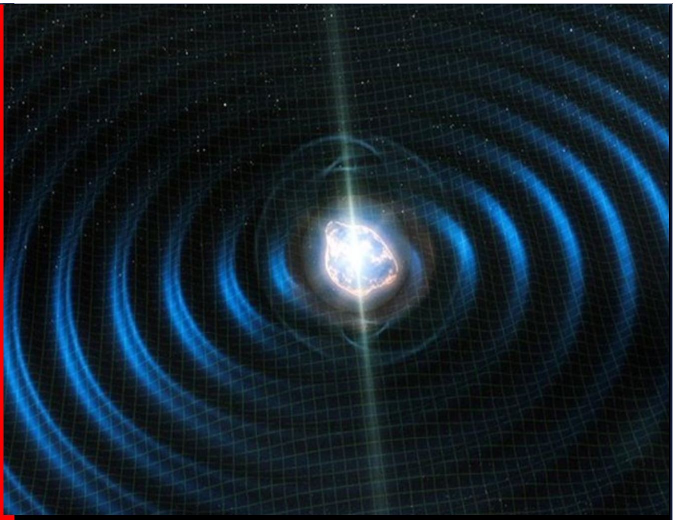
Potential GW sources for the interferometers on the Earth

Short signals

Long signals

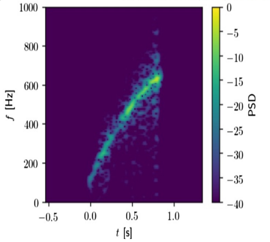
Coalescence of binary systems

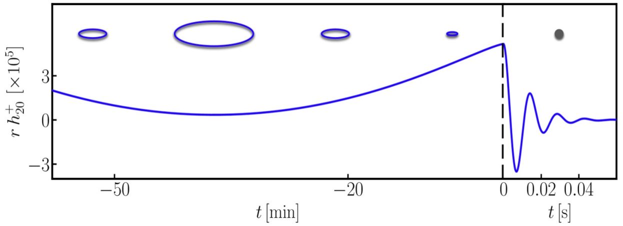


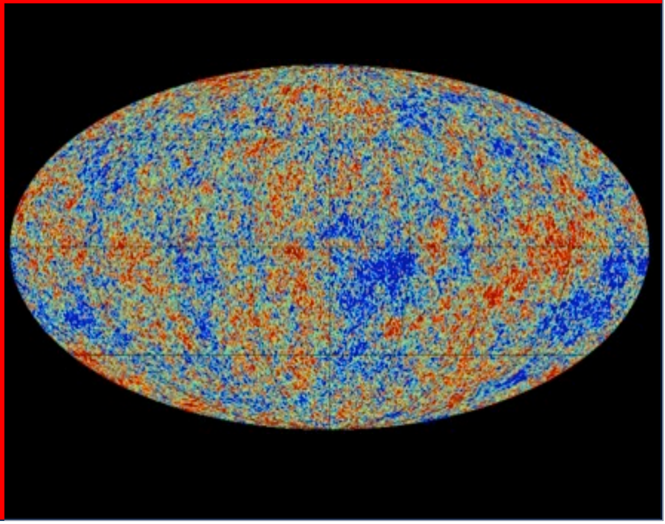


Non-axisymmetric Spinning neutron stars + emission associated to clouds of exotic particles

Core-collapse Supernovae, neutron star excitations, cosmic strings…

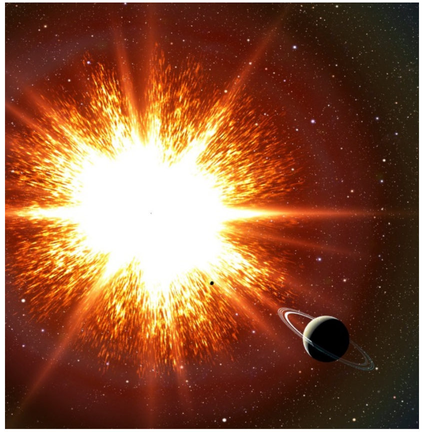






GW stochastic background Unresolved CBCs, Primordial BHs, Cosmological

Hunting a SUPER Multimessenger event: CCSNe

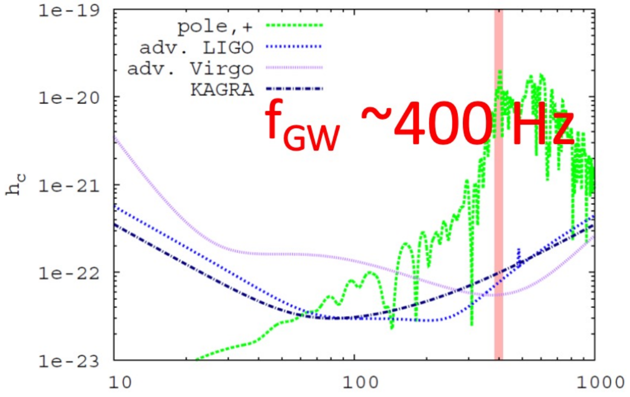


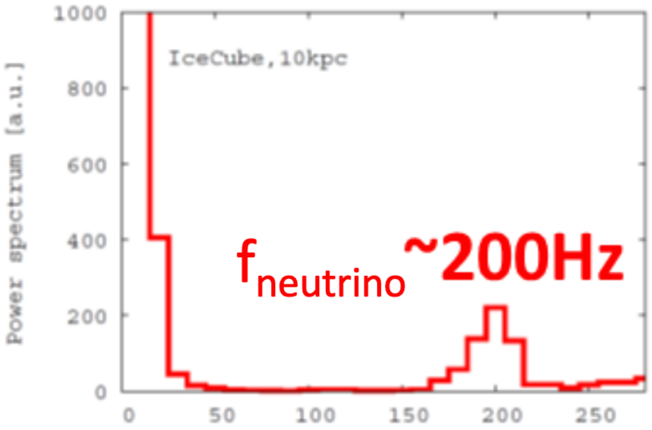
See talk of M. Drago et al. and A. Veutro et al. poster during this conference

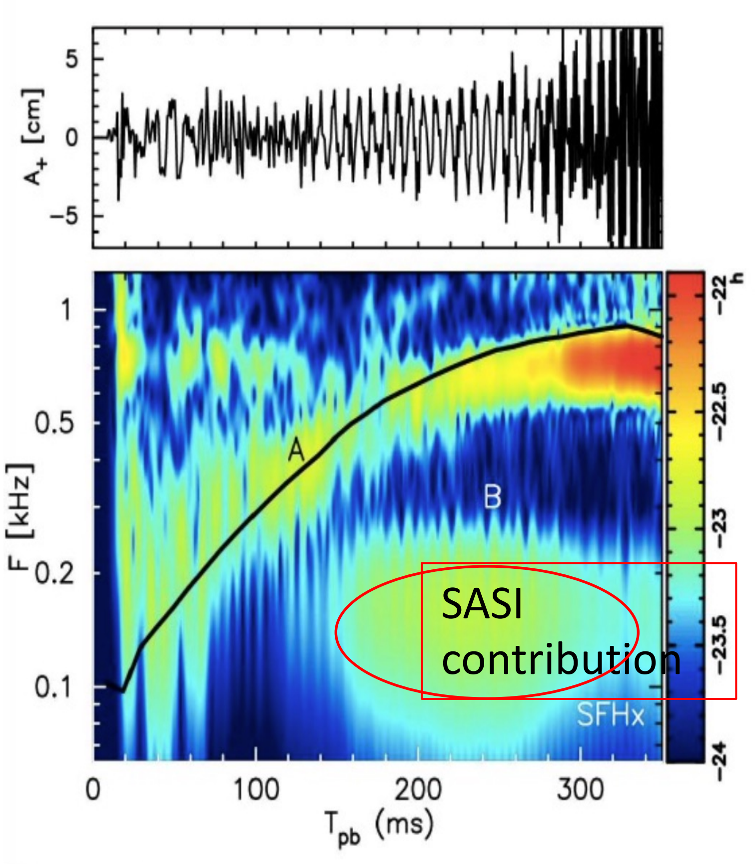
Observation of both neutrinos and gravitational waves from a core-collapse supernova will yield a wealth of information on the explosion mechanism !!!

We will infer fundamental parameters of the system and crucial physics aspects of the process:

- ➢ the structure and angular momentum of the progenitor star,
- ➢ the equation of state of nuclear matter at high densities and low entropies



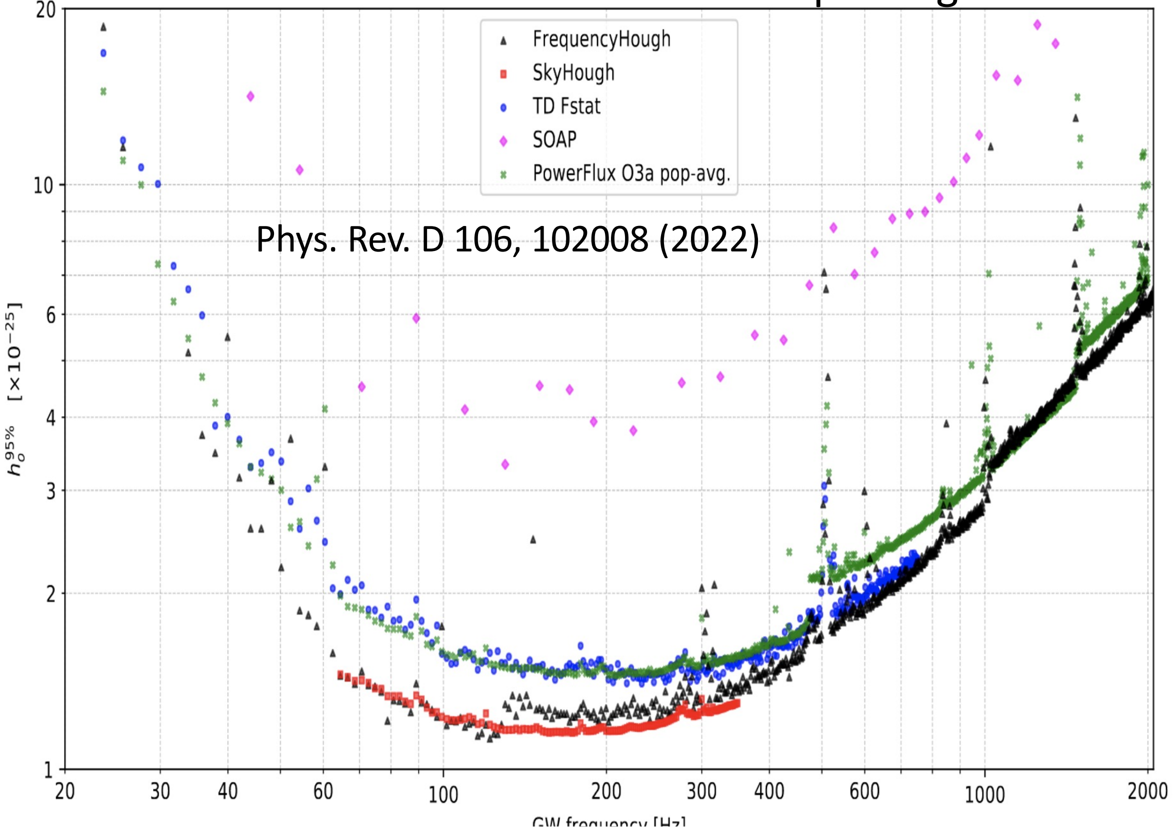




Standing Accretion Shock Instability- SASI mechanism imprinting both ν and GW signals

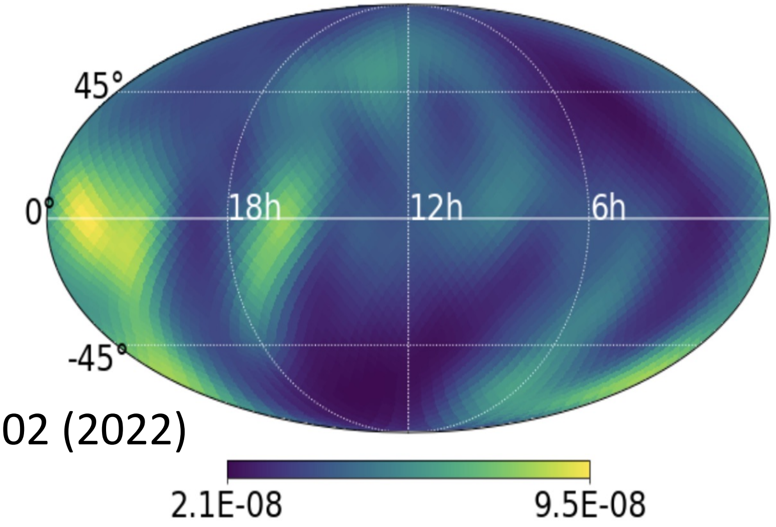
Other results

Limits on the GW emission of isolated spinning neutron stars



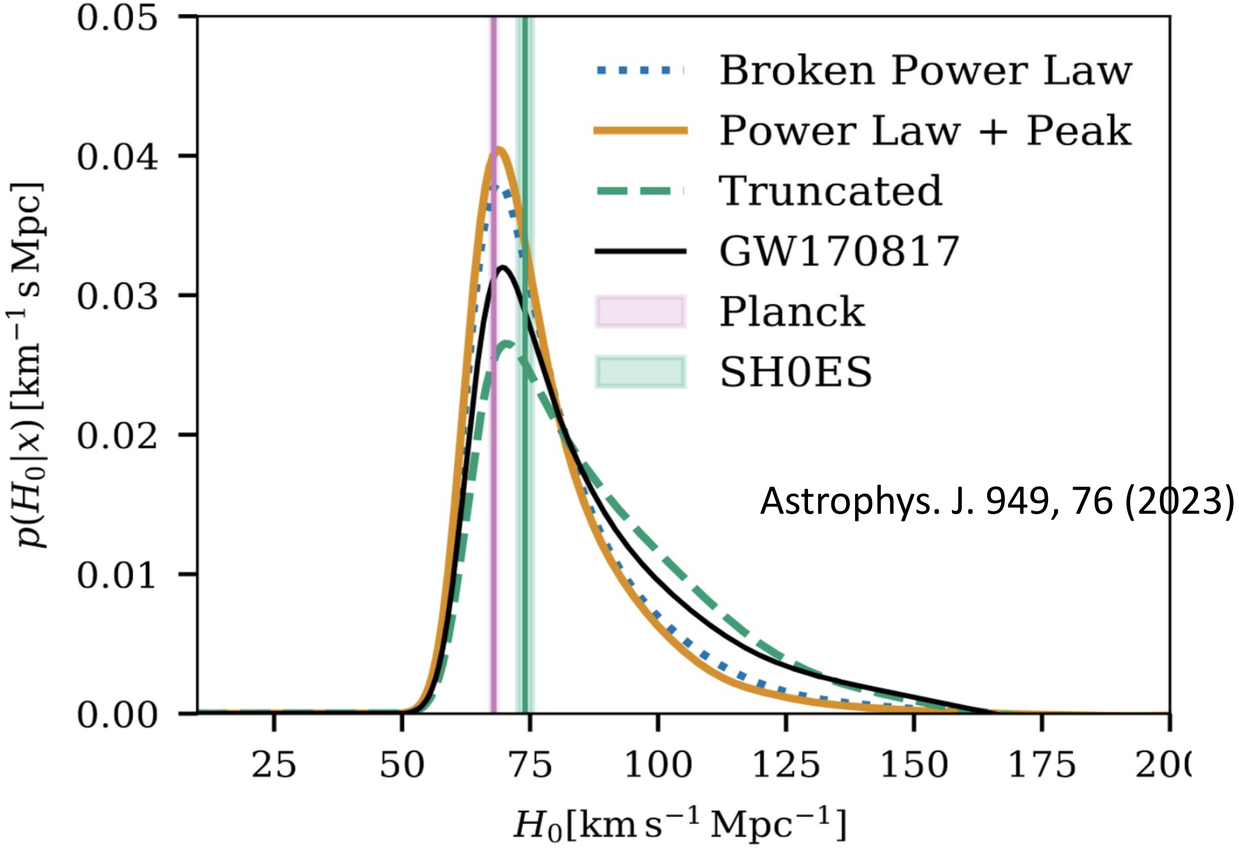
Phys. Rev. D 106, 102008 (2022)

Upper limits on Stochastic background



Phys. Rev. D 105, 122002 (2022)

Hubble-Lemaitre constant: GW measurement



Astrophys. J. 949, 76 (2023)

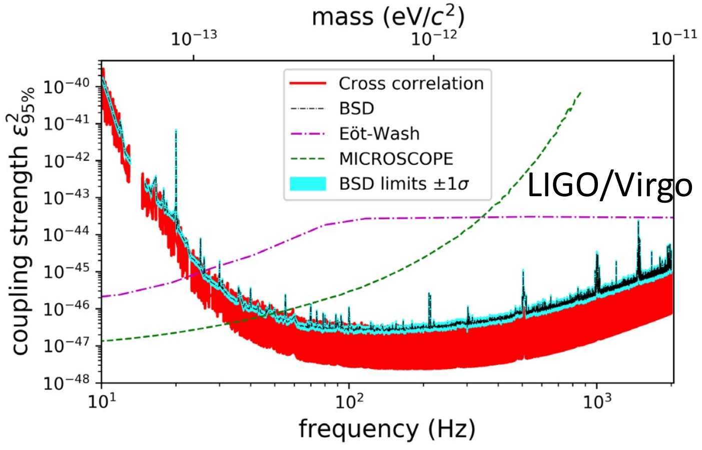
GW interferometers as Dark matter detectors

PRD 105, 063030 (2022) and arXiv:2403.03004 [astro-ph.CO]

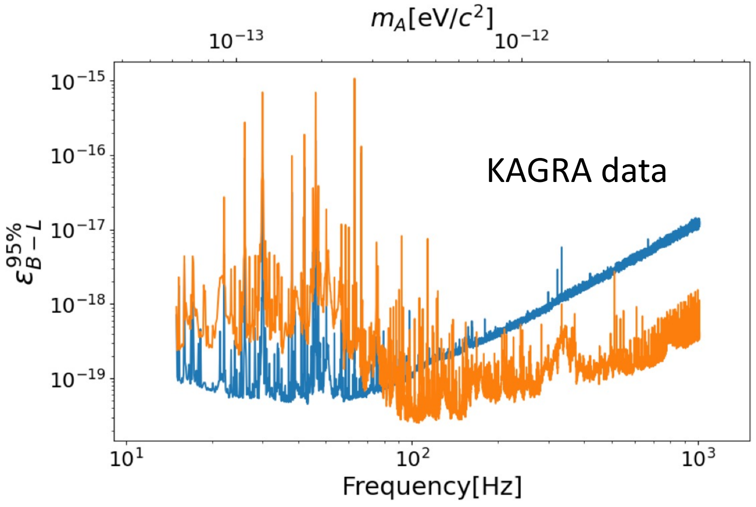
- Dark matter is expected to cause time-dependent oscillations in the mirrors of the interferometers, which would lead to a differential strain on the detector.

Dark photon mass interval $10^{-14} – 10^{-11}$ *eV/c*^{2} ➔ *oscillation frequencies 10 - 2000 Hz,*

- All LIGO-Virgo mirrors are made from fused silica glass
- KAGRA use sapphire for main test mass mirrors and fused silica for other auxiliary mirrors.
- For dark matter coupled to the baryons-leptons number, sapphire mirrors move slightly more than fused silica mirrors because they are slightly more neutron-rich



LIGO/Virgo data



KAGRA data

FIG. 5. 95% upper limit on the $B-L$ gauge coupling constant derived from MICH data (blue line) and PRCL data (orange line). Many narrow peaks observed in lower mass range are due to unknown line artifacts in the lower frequency range.

Conclusions: since 2015 we shine a dark side of the Universe

2015

O1: Gravitational waves from astrophysical sources can be measured.
O1: Binary black hole (BBH) systems exist.

2017

O2: Binary neutron stars (BNS) are progenitors of short gamma ray bursts.
O2: BNS mergers produce kilonovae, which produce heavy elements.
O2: The speed of gravitational waves equals the speed of light.
O2: The Hubble-Lemaître constant can be measured using EM-bright GW ‘sirens’.
O2 – O3: The Hubble-Lemaître constant can be measured using dark GW ‘sirens’.

2019

O3: Black holes with masses in the (pulsational) pair instability gap exist.
O3: Black hole – neutron star systems exist.
O3: Compact objects exist in the 2 – 3 $M_\odot$ mass range.
O1-O3: Astrophysical black holes are Kerr black holes
O1 – O3: General relativity is valid in the high curvature, high field regime.
O1 – O3: Intermediate black holes and stellar mass black holes with mass > 20 $M_\odot$ exist.

2023

Detection of Stochastic Gravitational Wave Background

IGWN CHECKLIST

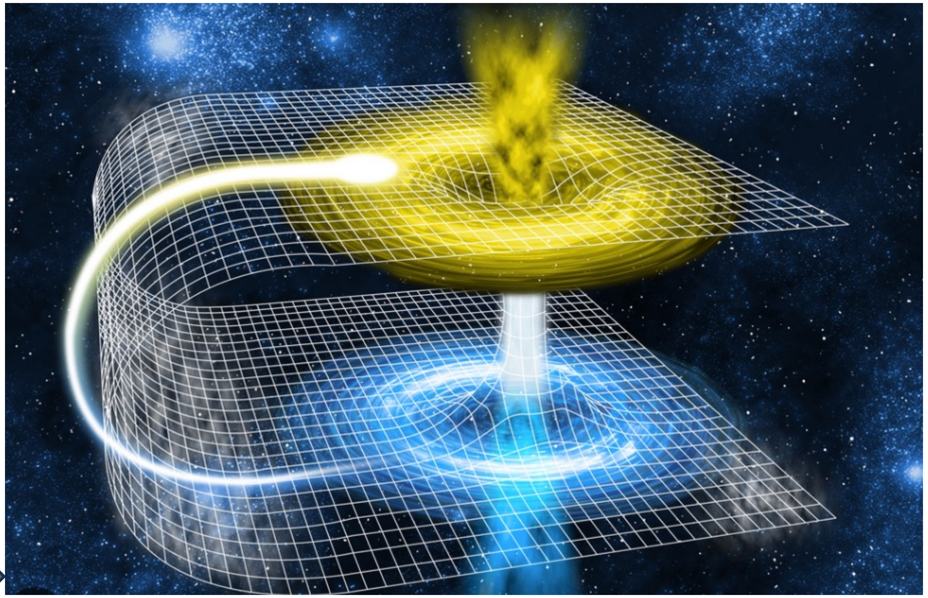
- ☑ BINARY SYSTEM
  - ☑ BLACK HOLES
  - ☑ NEUTRON STARS
    - ☑ WITH EM COUNTER
  - ☑ BH-NS
- ☐ SUPERNOVAE
- ☐ PULSARS
- ☑ STOCHASTIC

Pulsar timing

……..and Serendipidity

RICAP 24

Thanks for the attention and see you in two years



Extra slides

Trading Sensitivity and Observing Time
Compact Binary Detections

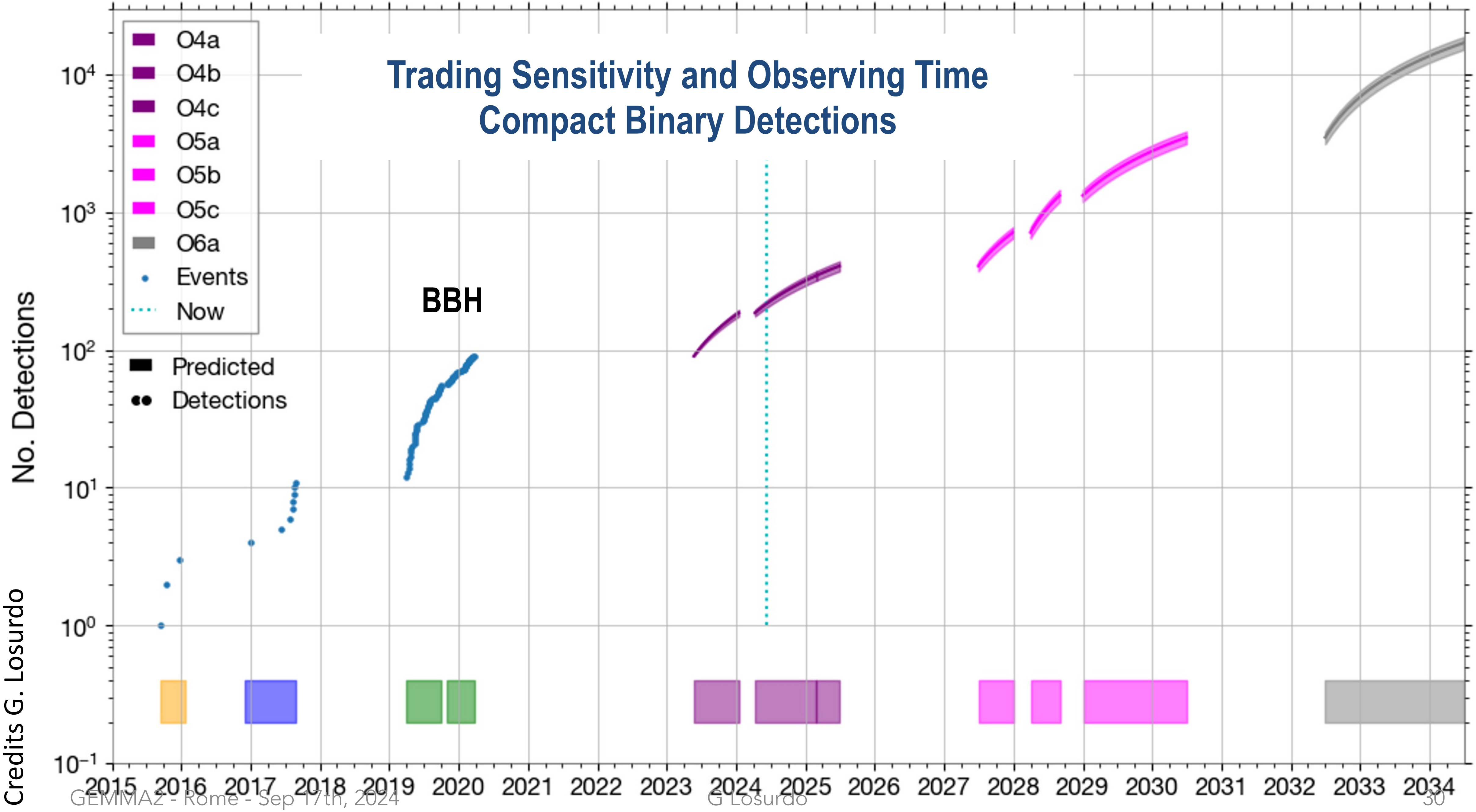
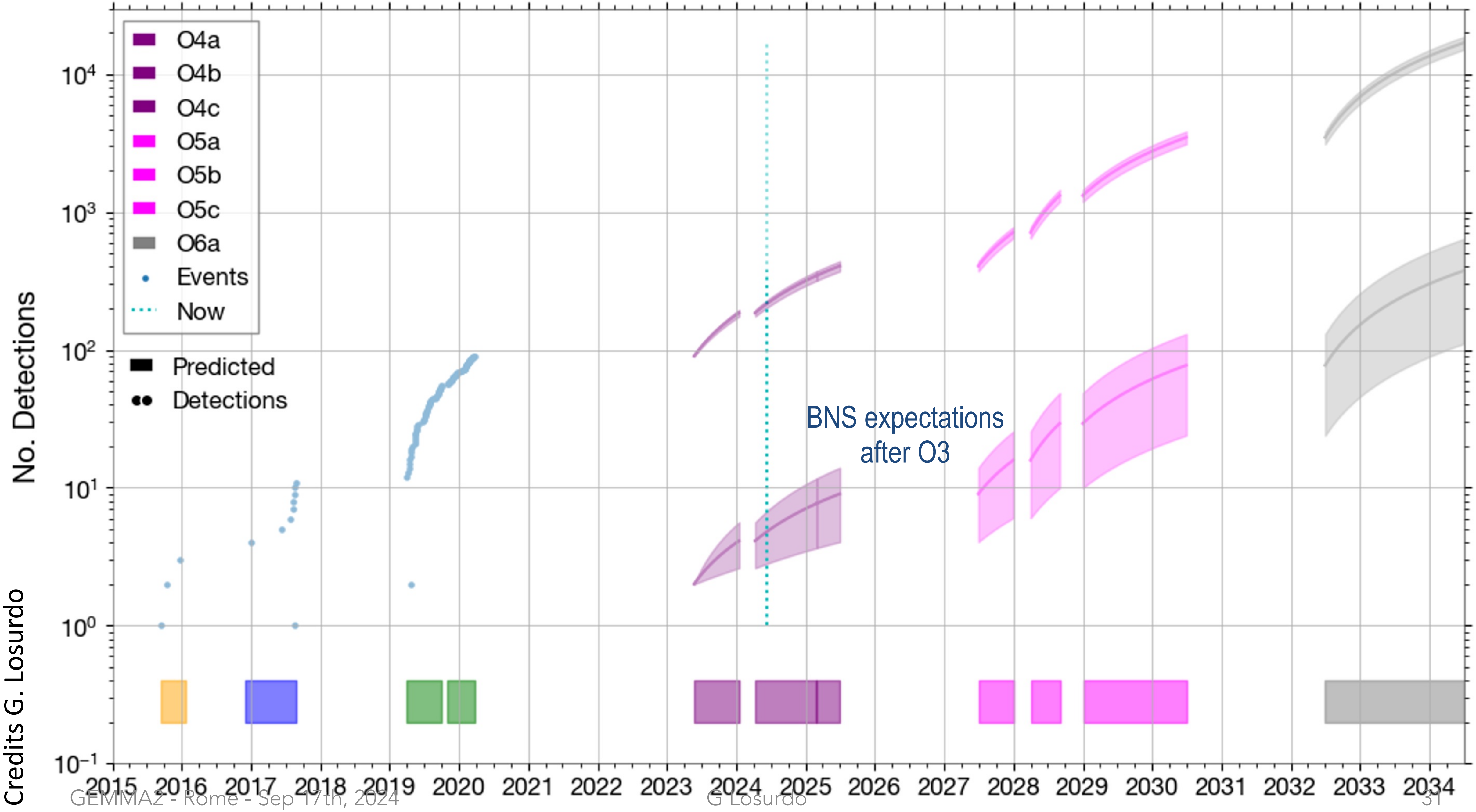


Figure: Amanda Baylor, Cody Messick, PRB

Credits G. Losurdo



BNS expectations after O3

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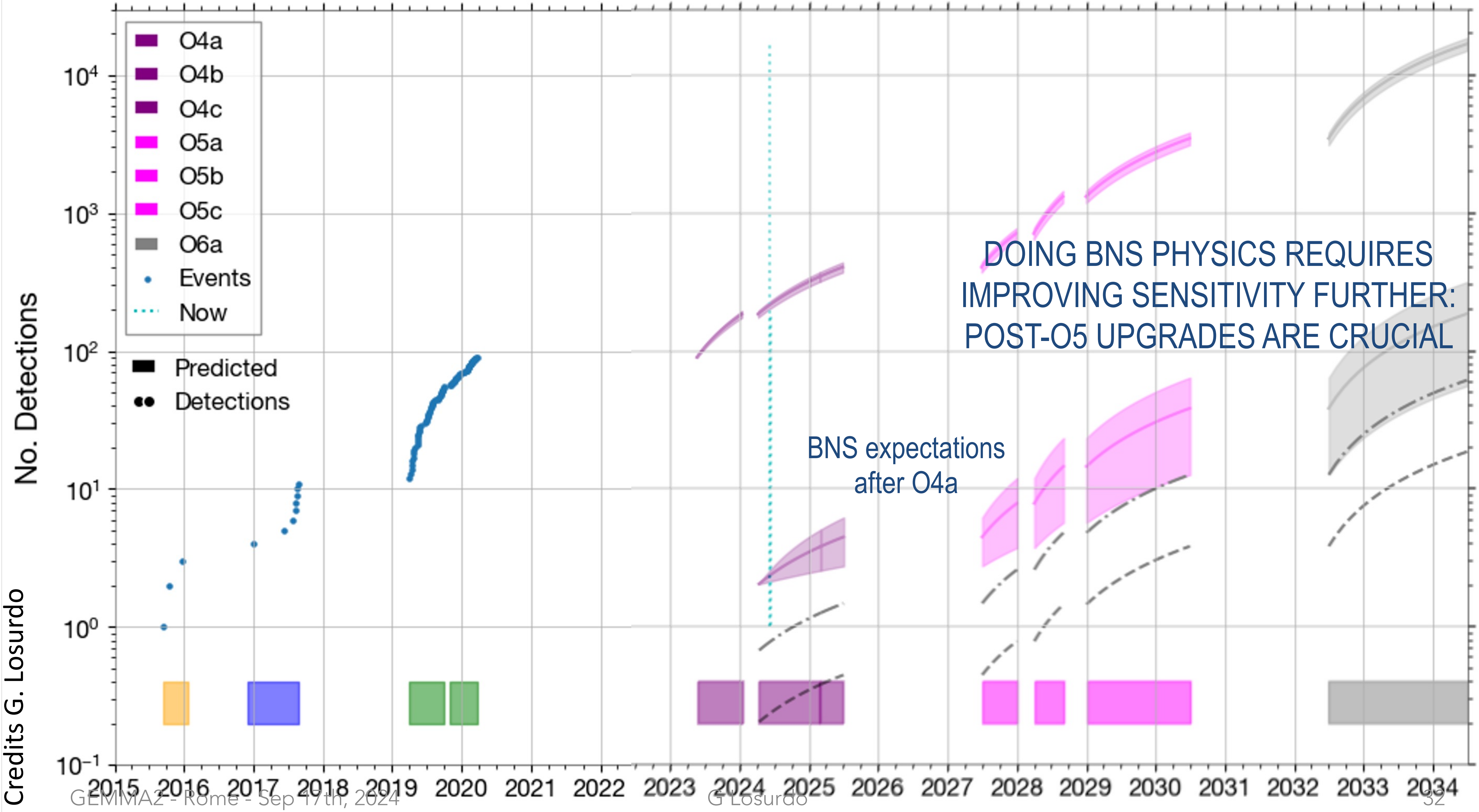
Figure: Amanda Baylor, Cody Messick, PRB



DOING BNS PHYSICS REQUIRES IMPROVING SENSITIVITY FURTHER: POST-O5 UPGRADES ARE CRUCIAL

BNS expectations after O4a

Figure: Amanda Baylor, Cody Messick, PRB

Credits G. Losurdo