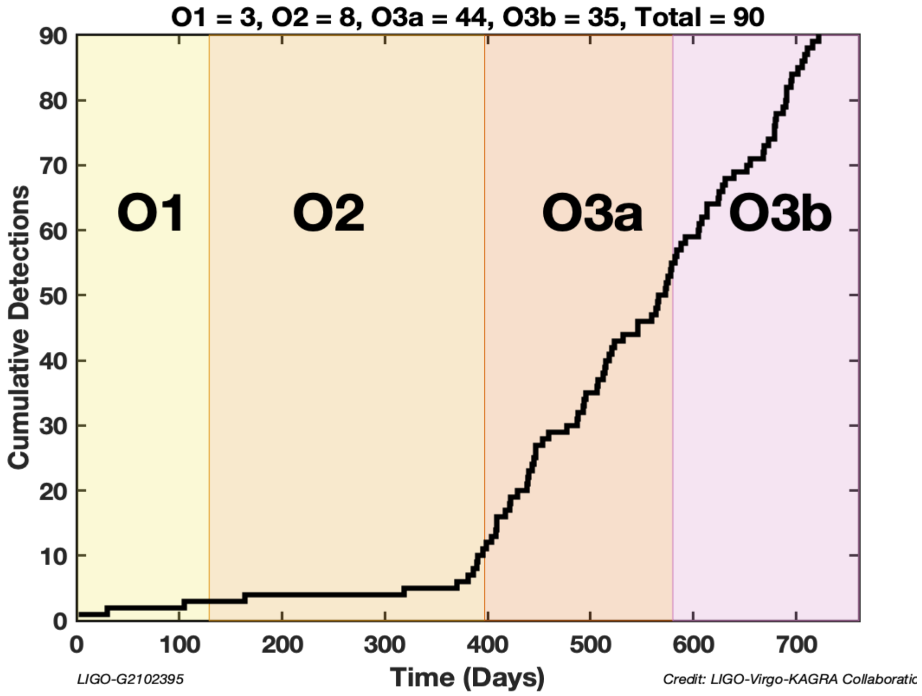
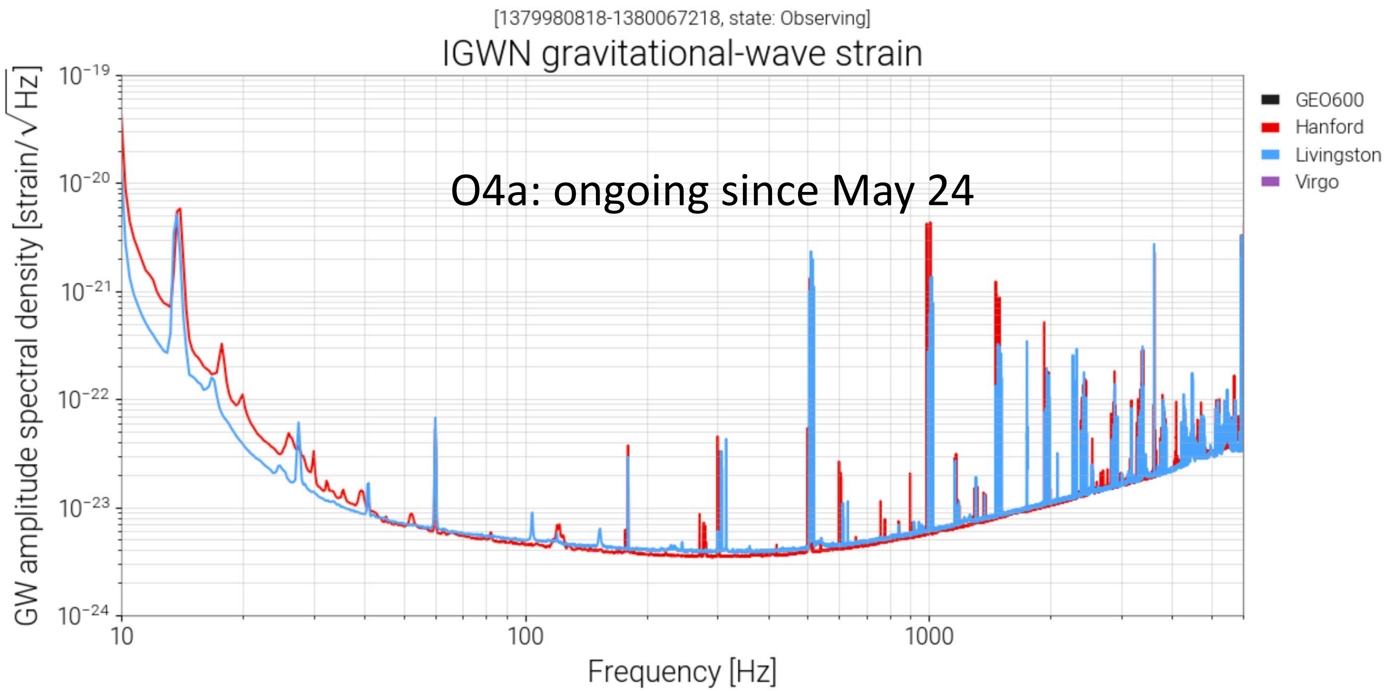
Current GW measurement results and plans

Sascha Husa, Institute of Space Sciences, Barcelona

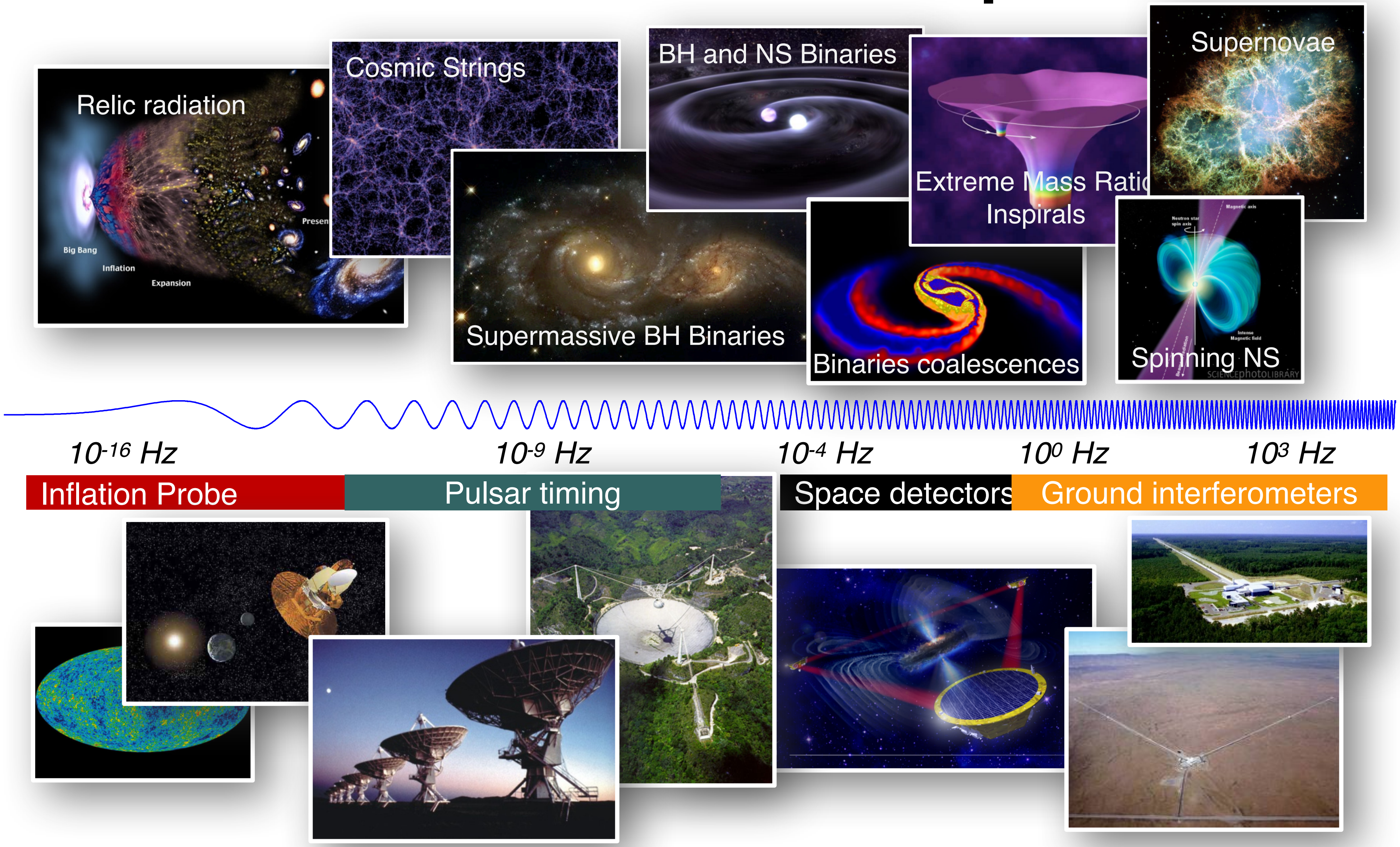




L International Meeting on Fundamental Physics and XV CPAN days - 5/10/2023

CSIC
Institute of Space Sciences
EXCELENCIA MARÍA DE MAEZTU
EUROPEAN UNION
EUROPEAN REGIONAL DEVELOPMENT FUND
A WAY TO MAKE EUROPE
IEEC
Institut d'Estudis Espacials de Catalunya
UIB Universitat de les Illes Balears
IAC3 Institute of Applied Computing & Community Code.

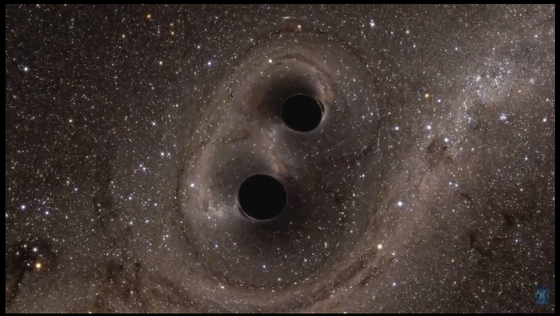
Gravitational Wave Spectrum

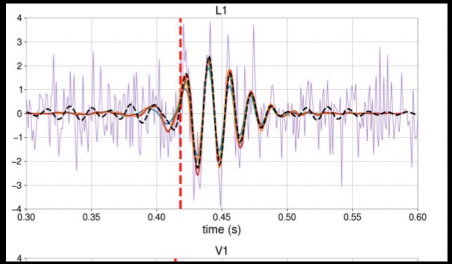


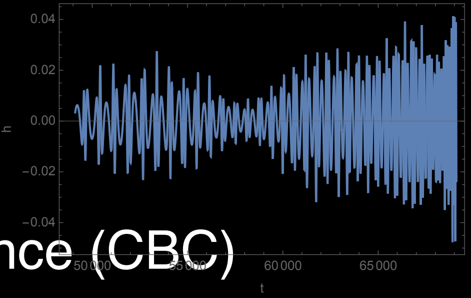
Types of Gravitational Wave Signals & Sources

MATCHED FILTER

TRANSIENT

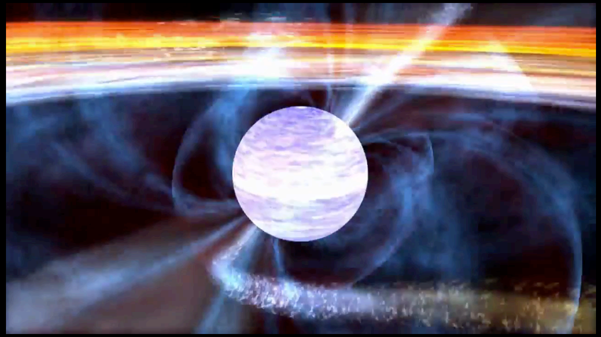


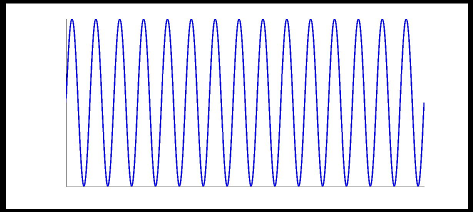




compact binary coalescence (CBC)

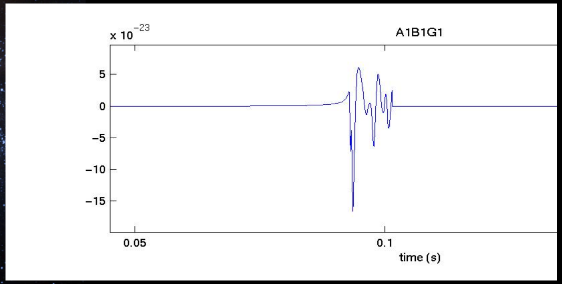
PERSISTENT



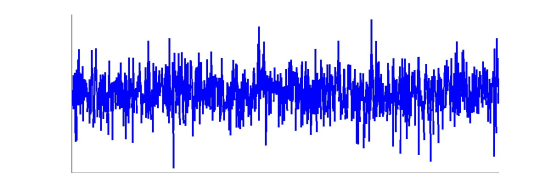


Asymmetric neutron stars

UNMODELED



BURSTS
core collapse supernovae, the unknown



STOCHASTIC BACKGROUND
Cosmological origins, superposition of unresolved signals

Types of Gravitational Wave Signals & Sources

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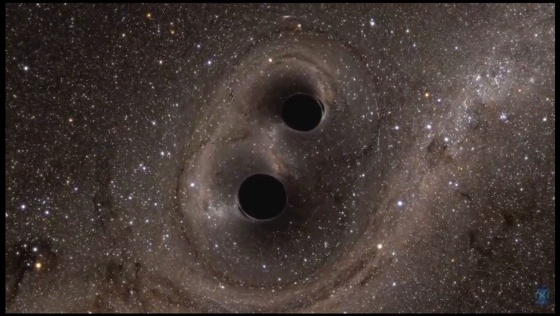

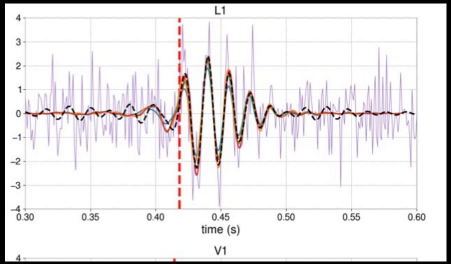

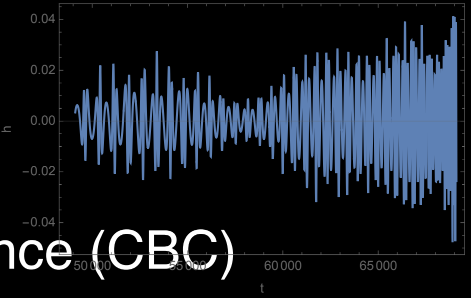

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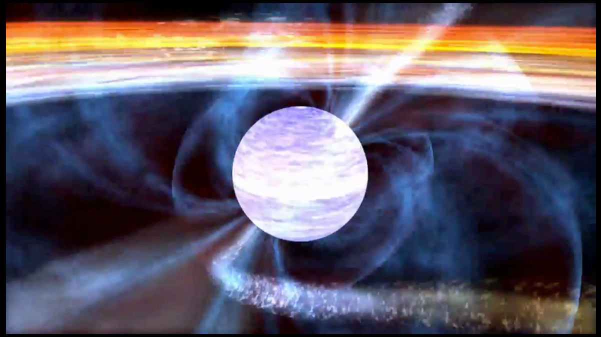

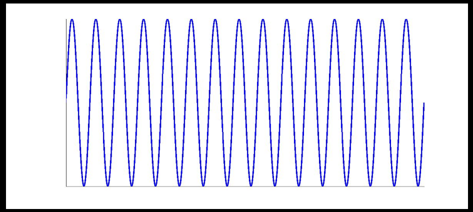

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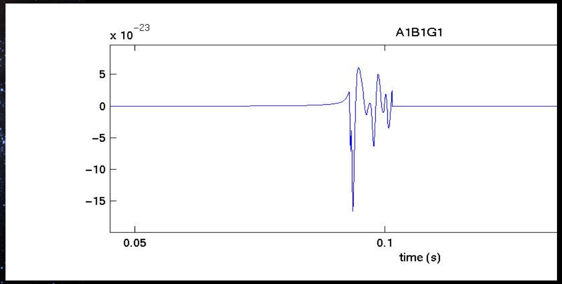

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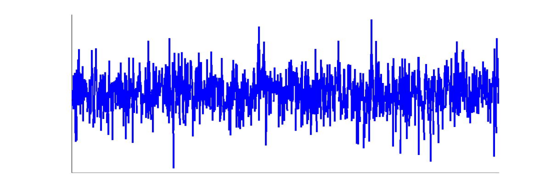

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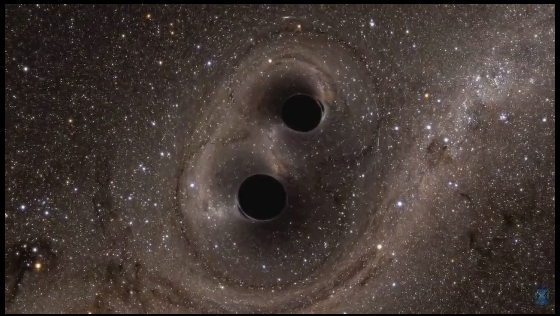

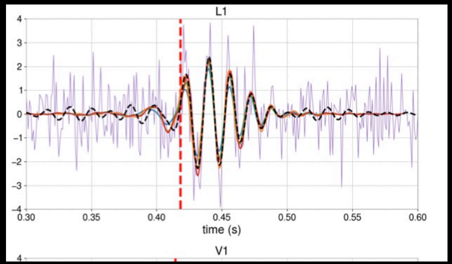

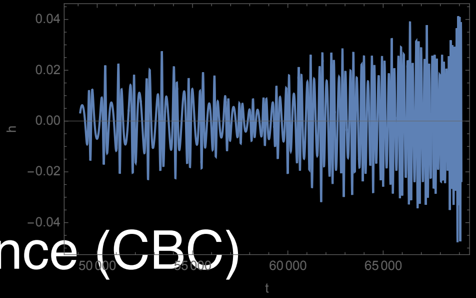

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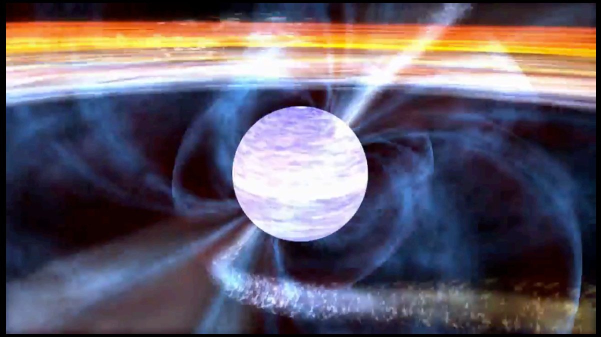

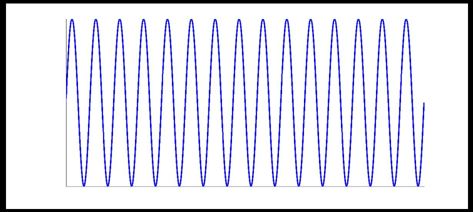

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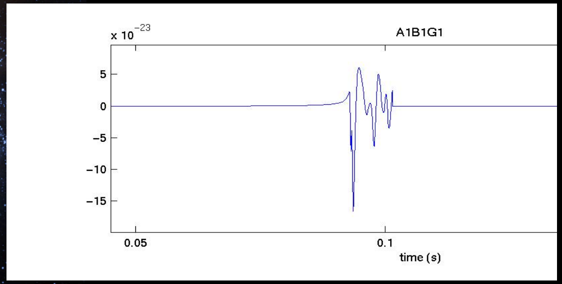

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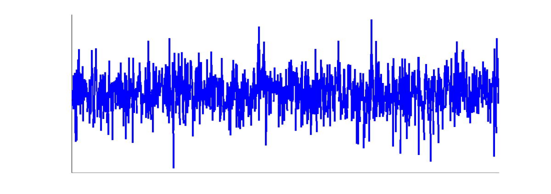

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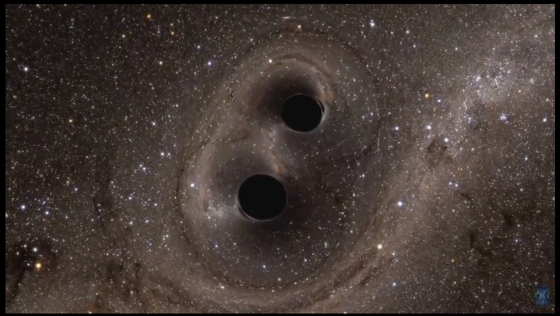

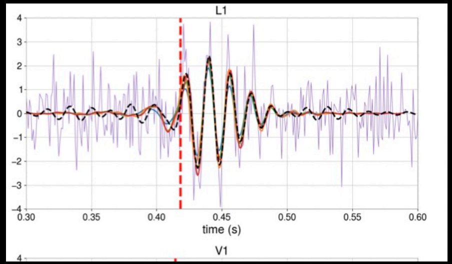

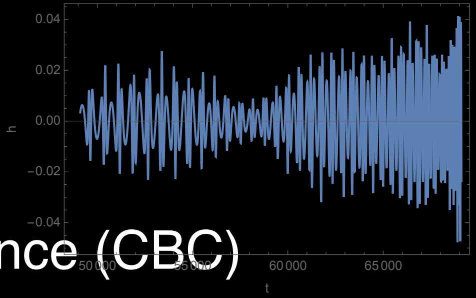

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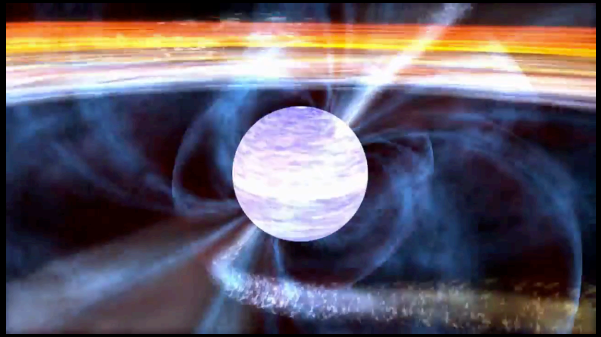

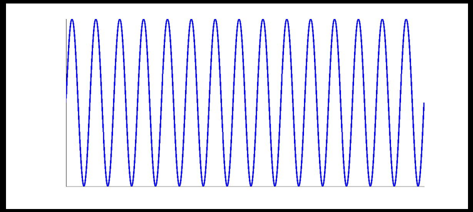

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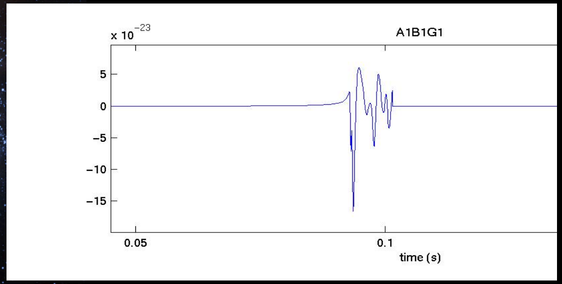

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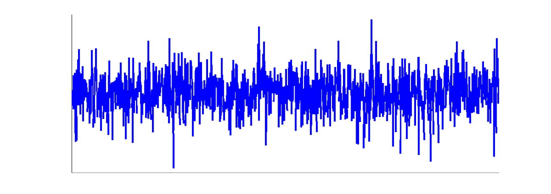
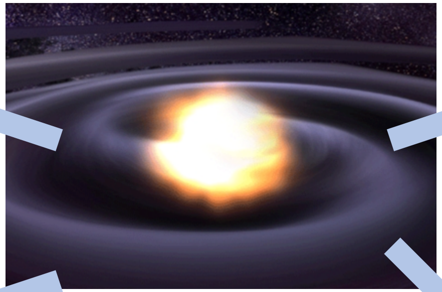


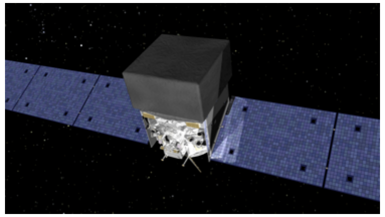
STOCHASTIC BACKGROUND
Cosmological origins, superposition of unresolved signals

Multi-messenger astronomy

Merger involving a NS, SN or accretion disk of a MBHB for LISA or ???

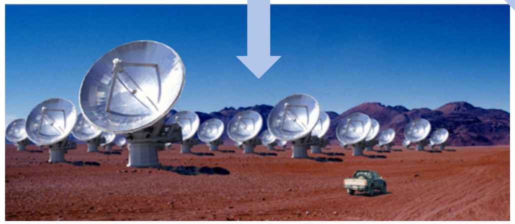
Gravitational Waves



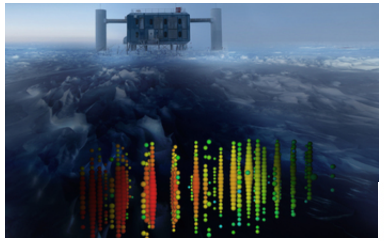


X/γ-rays

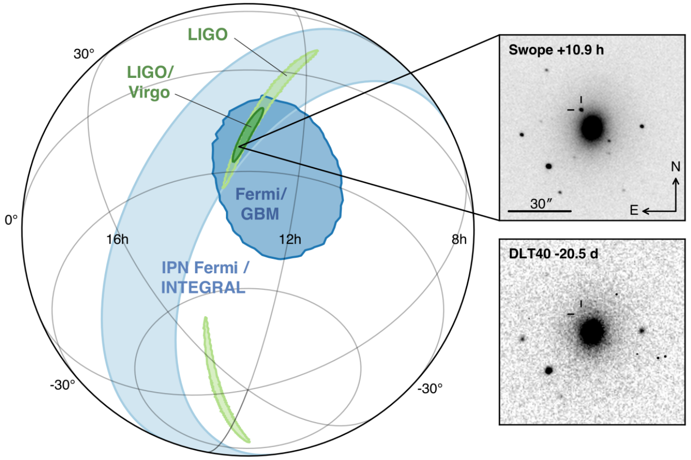
Visible/Infrared Light



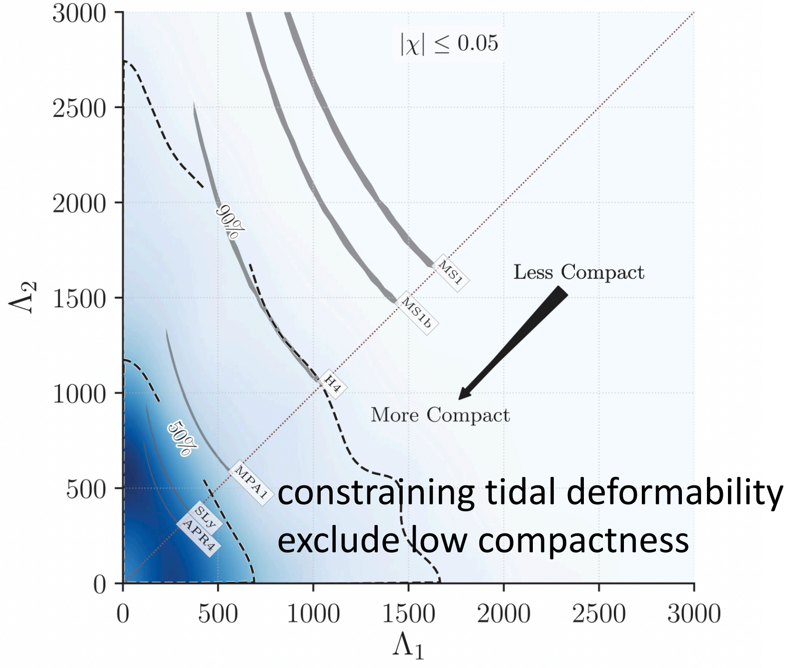
Radio Waves



Neutrinos



GW170817: LVC, PRL 119, 161101 (2017)



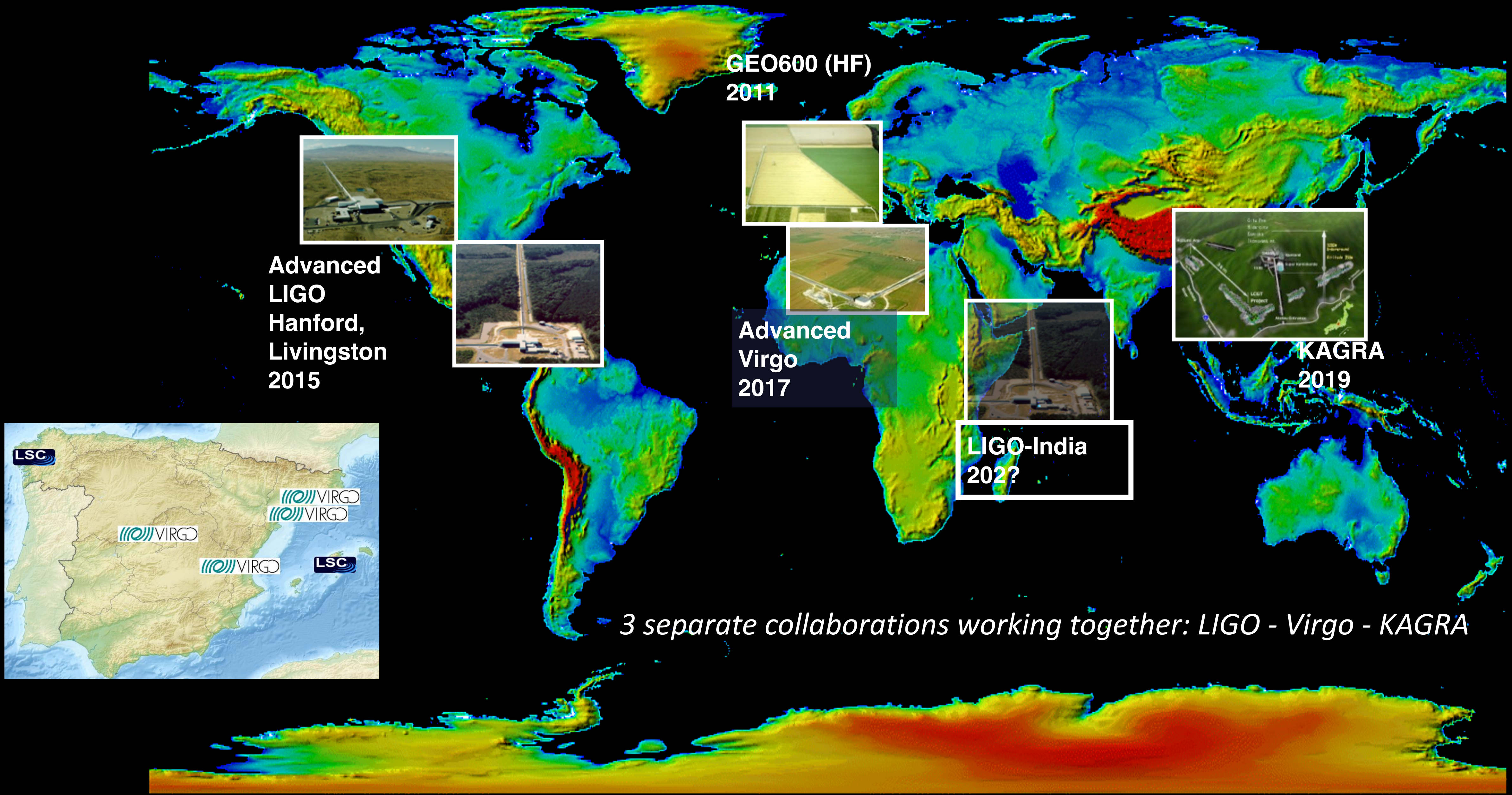
constraining tidal deformability
exclude low compactness

GW170817 breakthrough

"Multi-Messenger Observations of a Binary Neutron Star Merger"
B. Abbott et al., ApJL 848 (2017)
59-page letter
> 3000 authors,
~70 collaborations

Important contributions from Spanish groups: INTEGRAL, AGILE, Fermi-LAT, DES, Vinrouge, Master, ePESSTO, TOROS, Red Global BOOTES, VLT, HAWK, Chandra, Gemini, Pierre Auger, ANTARES, EURO VLBI, …

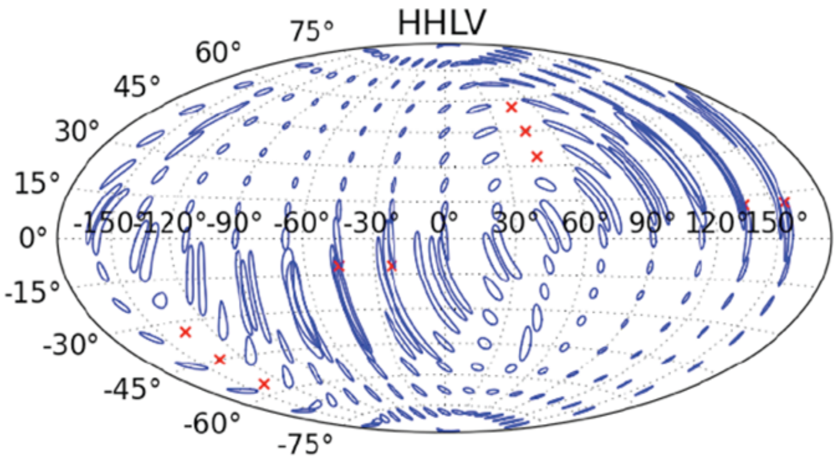
The growing network of advanced GW detectors



3 separate collaborations working together: LIGO - Virgo - KAGRA

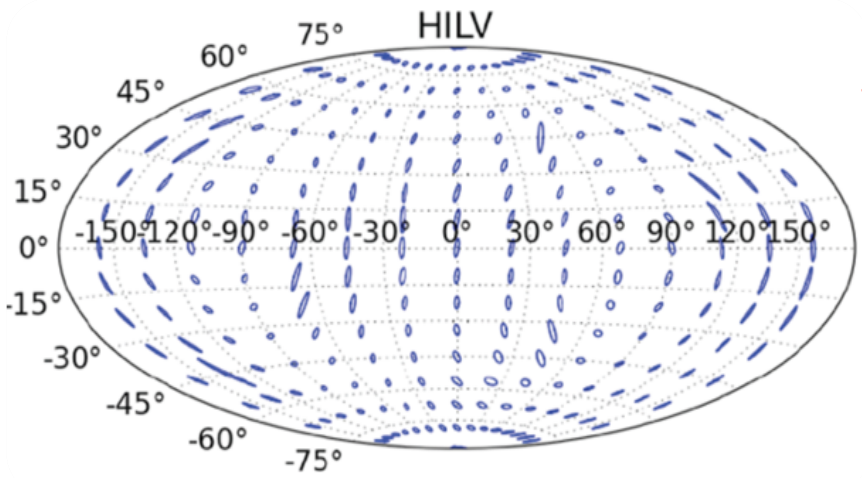
Detector networks

- Larger community! Shared experience and best practices!
- Improved duty cycle - catch rate events like supernovae!
- Much better sky location -> locate counterparts!   e.g. addition LIGO India (instead of 2nd Hanford detector):

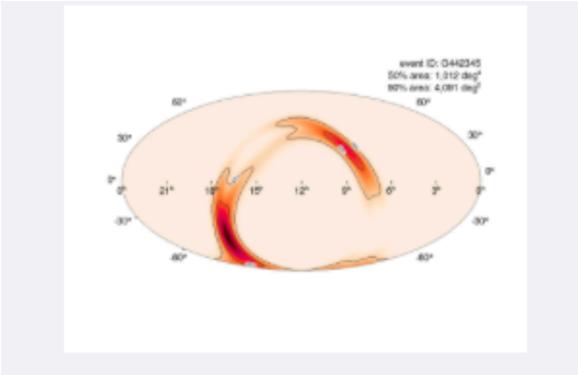


Fairhurst 2011

Red crosses denote regions where the network has blind spots



Currently only LIGO taking science data in O4a.



- Increased signal to noise ratio: Coherently sum signals from multiple detectors
- Improved detection confidence
    - Multi-detector coincidence greatly reduces false alarm rate
    - Improved source reconstruction - Inverse problem" requires 3 non-aligned detectors
    - Better measurement of both polarizations (and possible non-GR polarisations)

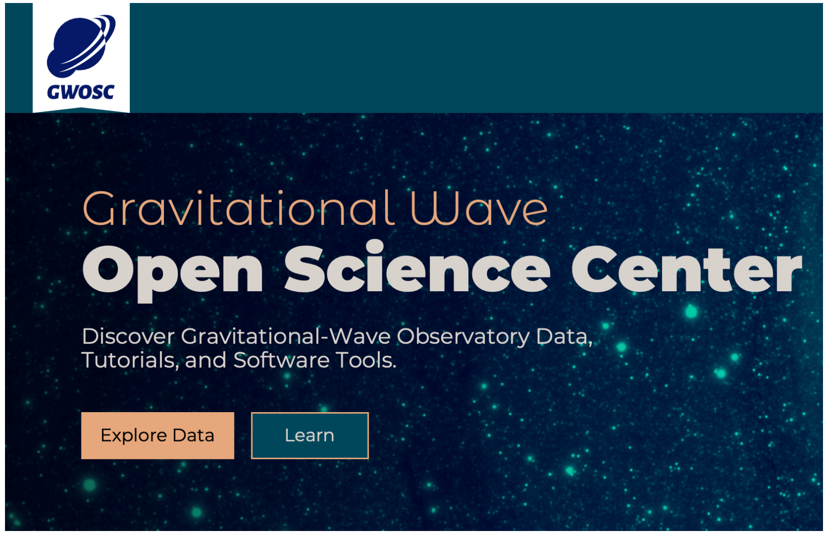
Also important: concurrent operation of GW and EM/Neutrino Detectors, Especially for space missions.

Open Science: open code + open data + community updates

- Community updates: ligo.org | www.virgo-gw.eu | gwcenter.icrr.u-tokyo.ac.jp
  - LIGO magazine: www.ligo.org/magazine
  - OpenLVKEM: wiki.gw-astronomy.org/OpenLVEM

    community forum on multi-messenger observations
    Town hall meetings, detector updates, alerts, … ; recordings available.

- Public alerts: GraceDB
- Open source code: LIGO algorithms C library + many python packages + …
  - Code is reviewed + open source before the analysis
  - All results and papers are reviewed separately
- Open data https://dcc.ligo.org/public/0009/M1000066/029/Data_Management_Plan-v29.pdf
  - Gravitational Wave Open Science Center at https://gwosc.org
  - Public detector logbooks
  - arXiv:2302.03676: “Open data from the third observing run of LIGO, Virgo, KAGRA and GEO”
  - Annual Open Data Workshops, documentation + codes via GWOSC
  - https://ask.igwn.org - GW community forum

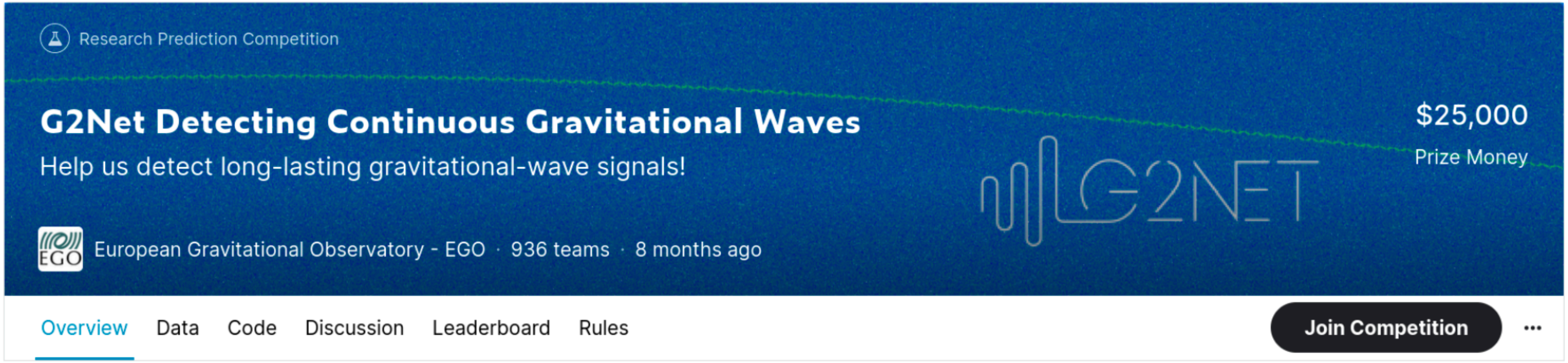


“Let others work for you …” - Kaggle competitions

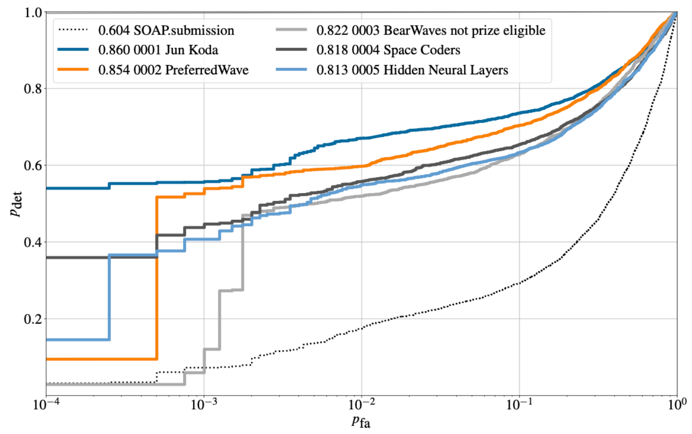
- **Rodrigo Tenorio (UIB),** Michael J. Williams, Chris Messenger (U. of Glasgow) :

  Kaggle competition to detect continuous wave signals in a mock data set

- -> Rodrigo’s talk in RENATA session on Tuesday -> interested people talk to Rodrigo



Comparison metric (AUC-ROC) was selected amongst the ones available in Kaggle.



- Competition lasted for 3 months and attracted ~ 1000 participants
- Total prize of $25,000, to be split amongst top three submissions.
- No definitive ML solution in sight.
- Solutions involve a rich variety of approaches.

From O3 to O5 - concrete plans for O5 in place

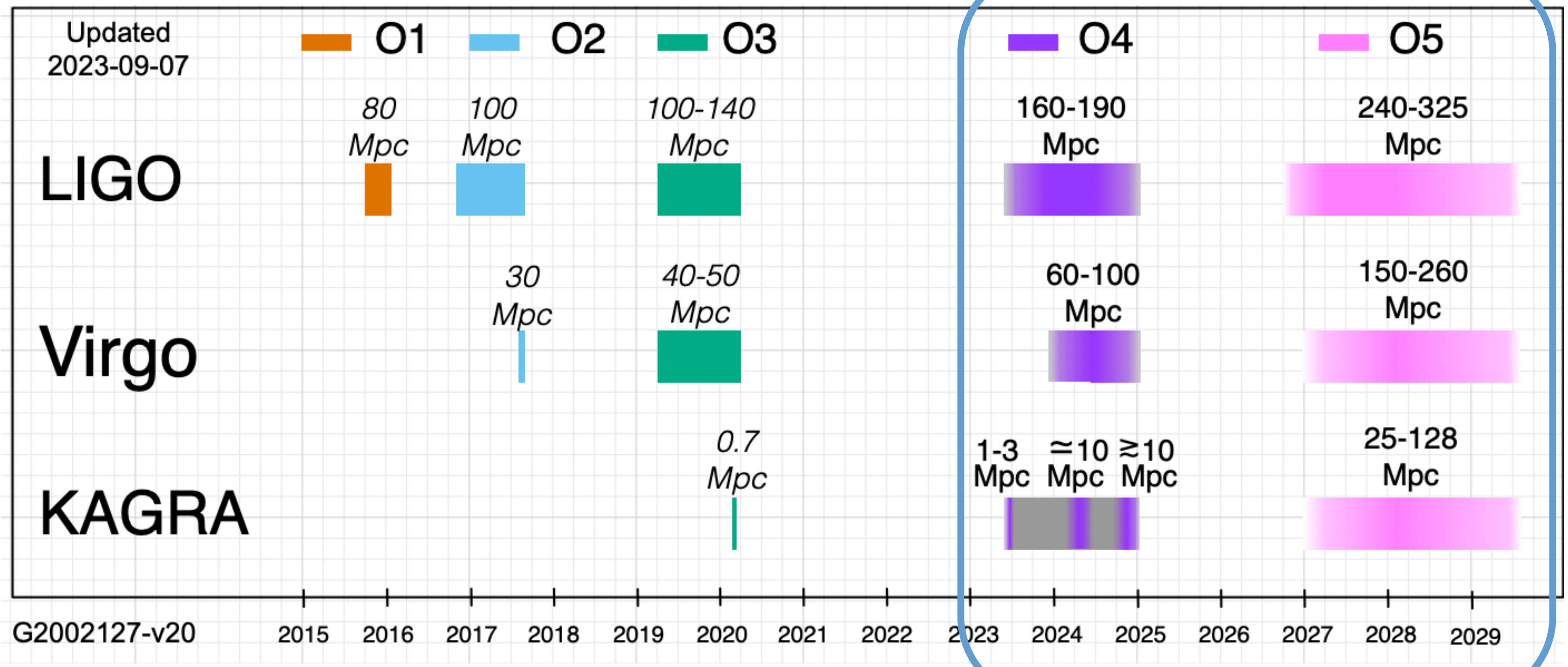
LIGO-Virgo-KAGRA observing scenarios: LRR23,3 (2020) and arXiv:1304.0670 (last update 24/11/2020)

On-going upgrades toward O5 - Advanced LIGO+ ("A+")/adVirgo+ in two main steps:

O4: frequency-dependent squeezing, higher laser power, many baffles to minimize stray light noise, new test masses/new coating, …

O5: improved mirror coatings, higher laser power, …

—> also Mario's Talk in RENATA Session



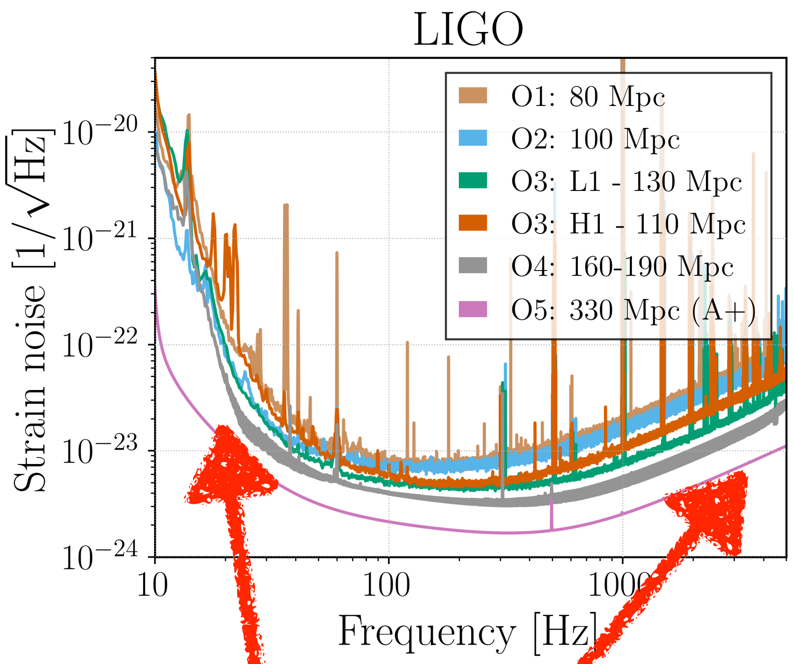
BNS inspiral range:

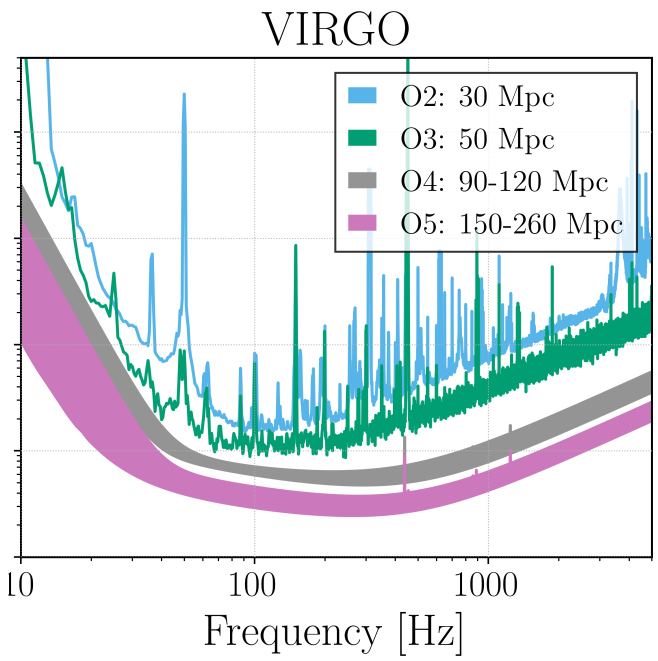
$1.4 + 1.4\ M_\odot$

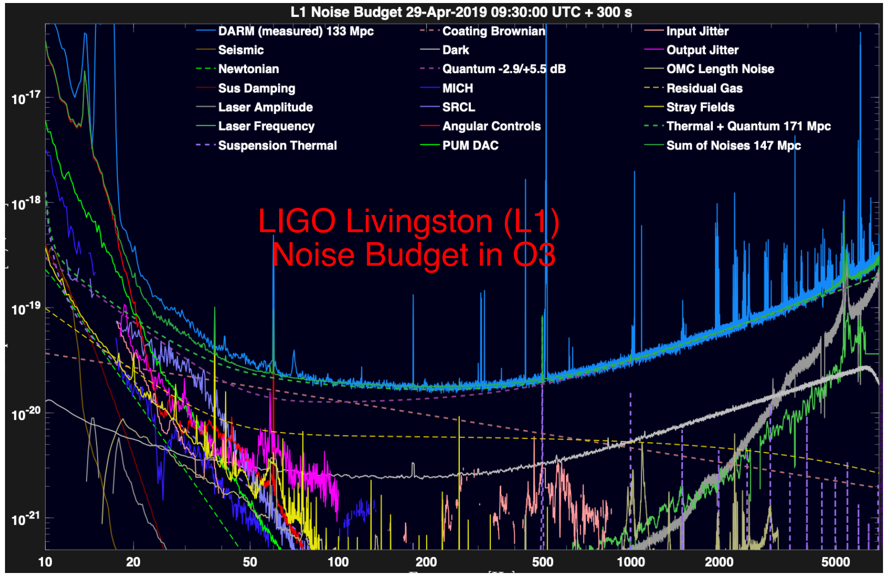
@ SNR=8.

Sensitivity across observation runs

LIGO-Virgo-KAGRA observing scenario: Living Reviews in relativity





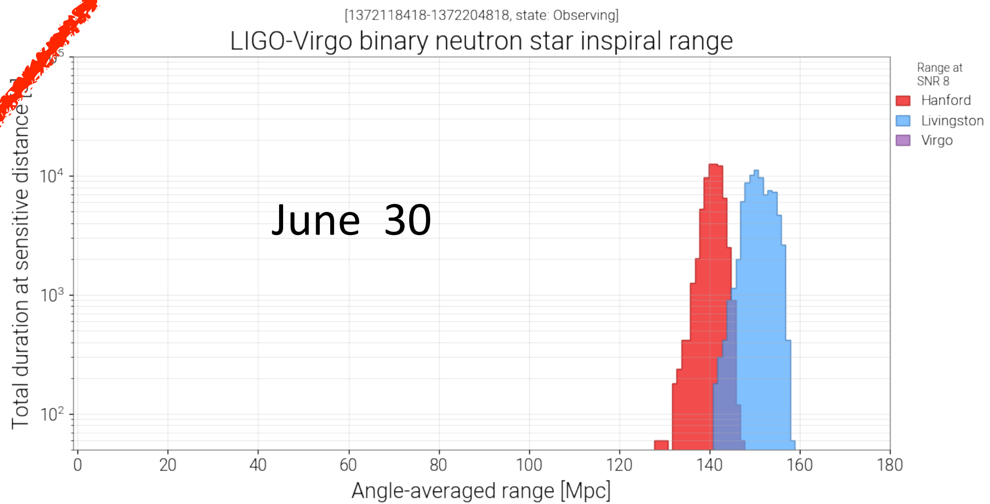


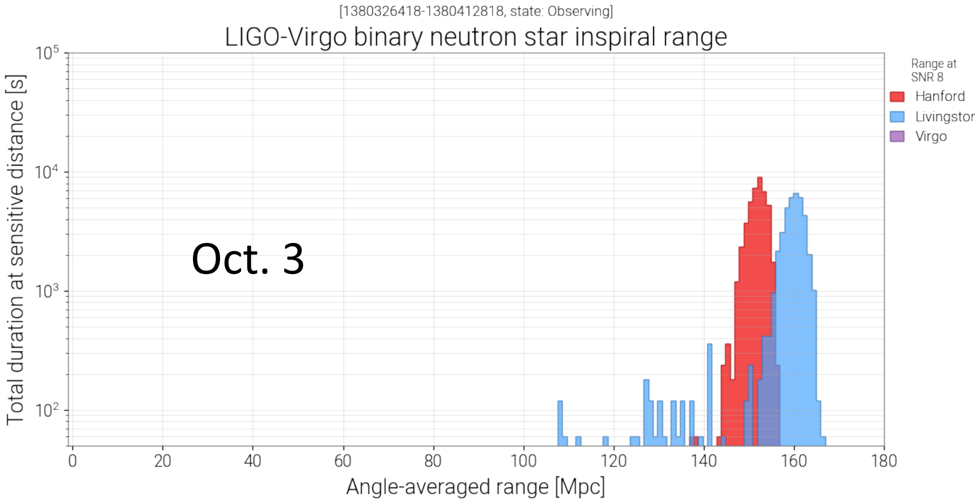
O4 sensitivity is slowly improving

https://gwosc.org/detector_status/today

High mass

Low mass





Post O5: A$^\#$, Virgo_nEXT

For both LIGO and Virgo post-O5 study teams develop further upgrade plans.

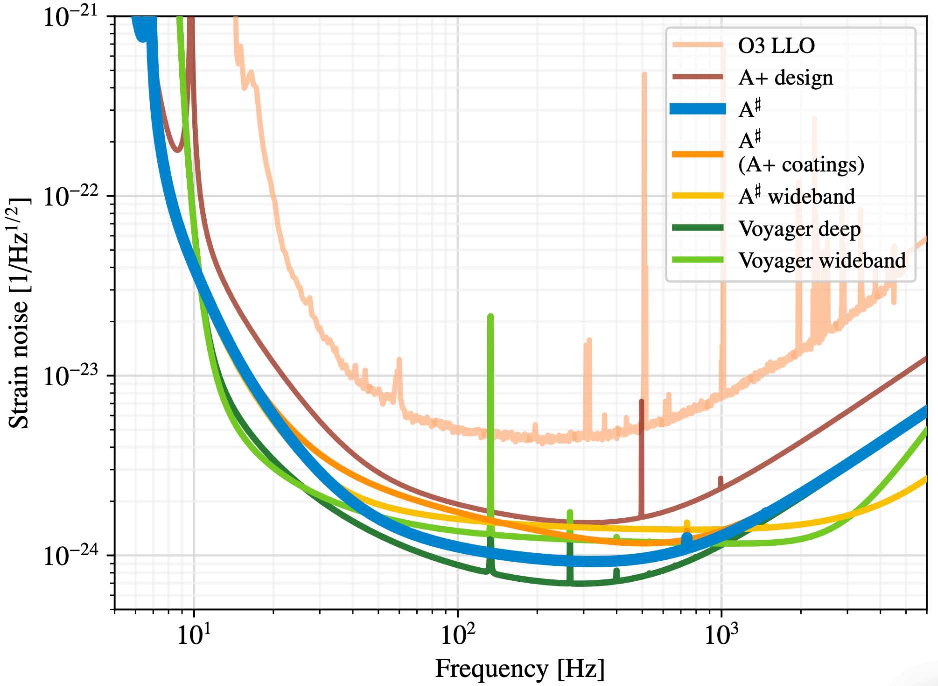
A$^\#$: Test mass 40 kg -> 100 kg, arms laser power x2 -> 1.5 MW

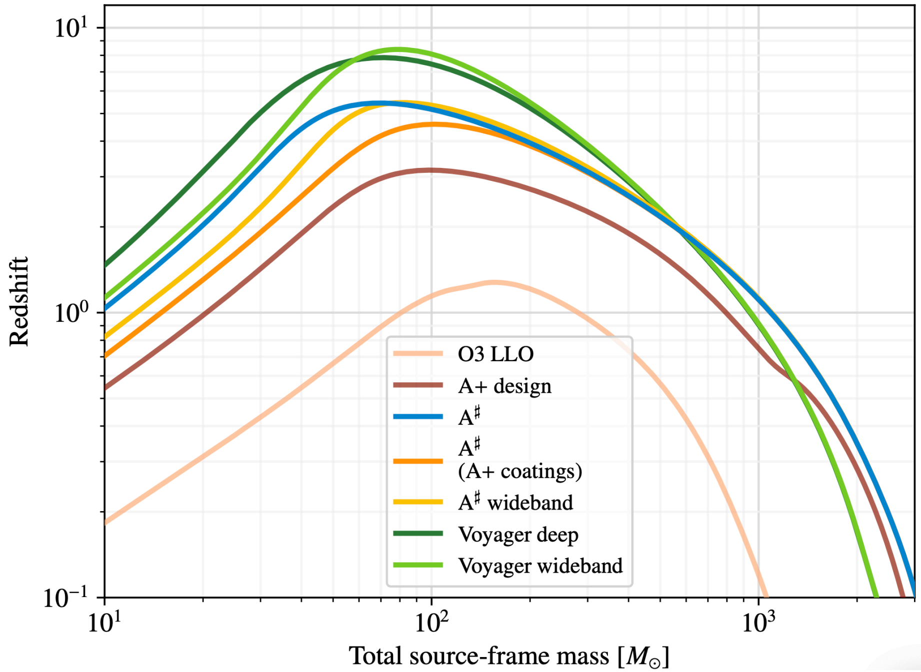
More ambitious LIGO post-O5 plan: Voyager 123K.

https://dcc.ligo.org/public/0183/T2200287/002/T2200287v2_PO5report.pdf

Configuration	Annual Detections		
	BNS	NSBH	BBH
A+	135^{+172}_{-78}	24^{+34}_{-16}	740^{+940}_{-420}
A$^\sharp$	630^{+790}_{-350}	100^{+128}_{-58}	2100^{+2600}_{-1100}
A$^\sharp$ (A+ coatings)	260^{+320}_{-140}	45^{+60}_{-27}	1150^{+1450}_{-640}
A$^\sharp$ Wideband (A+ coatings)	200^{+250}_{-110}	40^{+54}_{-25}	970^{+1220}_{-540}
Voyager Deep	1280^{+1610}_{-710}	190^{+240}_{-110}	3100^{+3900}_{-1700}
Voyager Wideband	730^{+920}_{-410}	129^{+165}_{-74}	2300^{+2900}_{-1300}

Table 5: Plausible range of number of detections in a calendar year observing run for each class of binary. Ranges are based on the central 90 % credible intervals on astrophysical rates from O3 [28].





Some configurations: minutes of pre-merger warning time and detectability of BNS post-merger

Configuration	Range [Mpc] BNS	Range [Mpc] BBH	t_{early} [min]	z_{max}	Post-Merger $\rho_{pm}^{(10)}$	Post-Merger $\rho_{pm}^{(max)}$
O3 LLO	130	1200	0.3	1.3	0.4	0.6
July 2022 LLO	120	1200	0.5	1.5	0.3	0.5
A+	350	2600	2.7	3.2	1.4	2.0
A+ Wideband	290	2300	3.7	3.5	2.2	2.6
A$^\sharp$	600	3700	6.2	5.4	2.7	3.7
A$^\sharp$ (A+ coatings)	440	3000	6.1	4.6	2.7	3.4
A$^\sharp$ Wideband	490	3300	6.8	5.5	4.8	5.6
A$^\sharp$ Wideband (A+ coatings)	400	2900	6.7	4.7	4.8	5.5
Intermediate Voyager	670	3900	4.8	6.5	2.5	3.7
Voyager Deep	780	4100	9.0	7.9	2.8	4.1
Voyager Wideband	630	3800	9.3	8.4	5.2	5.9
STO	690	4000	10.1	7.6	2.7	3.7
A$^\sharp$ 655 m SEC	450	3100	6.7	5.3	3.4	5.1
A$^\sharp$ 12 km folded arms	530	3400	9.9	6.4	8.5	9.7

O4: started May 24 2023

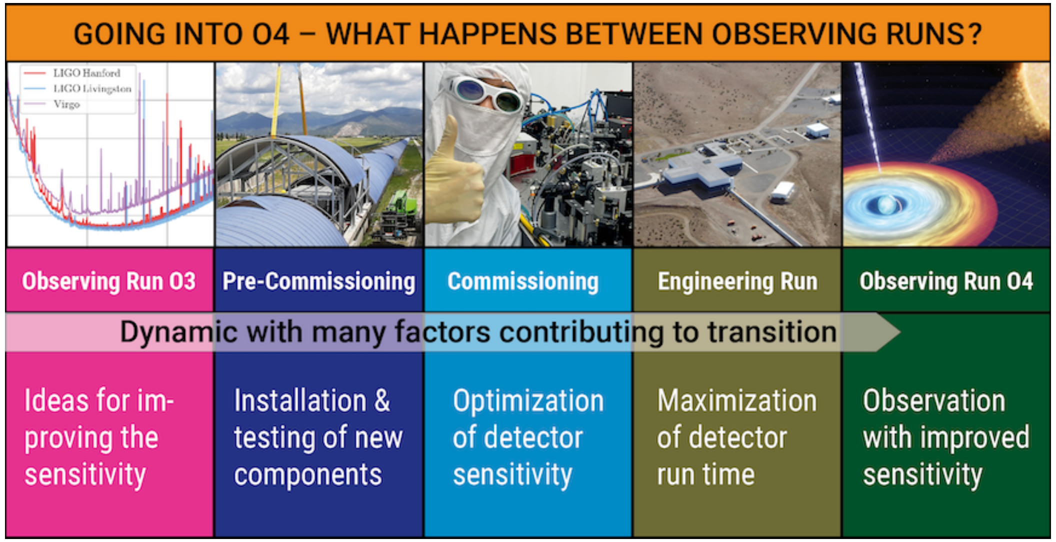
- **Planned: 20 calendar months**

  including ~ 2 months commissioning/maintenance breaks.

- **Currently only LIGO in observation mode**
  - Virgo: commissioning to improve sensitivity, will join in February/March [Mario update Tue]
  - KAGRA returned to commissioning to improve sensitivity after 4 weeks in O4a on June 21. Plans to restart in 2024 with higher sensitivity.

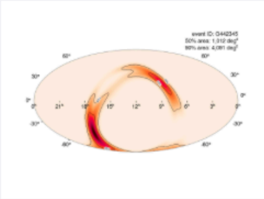
- **Detector status**
  - https://online.igwn.org
  - https://gwosc.org/detector_status/today

- **Events:** gracedb.ligo.org/superevents/public/O4



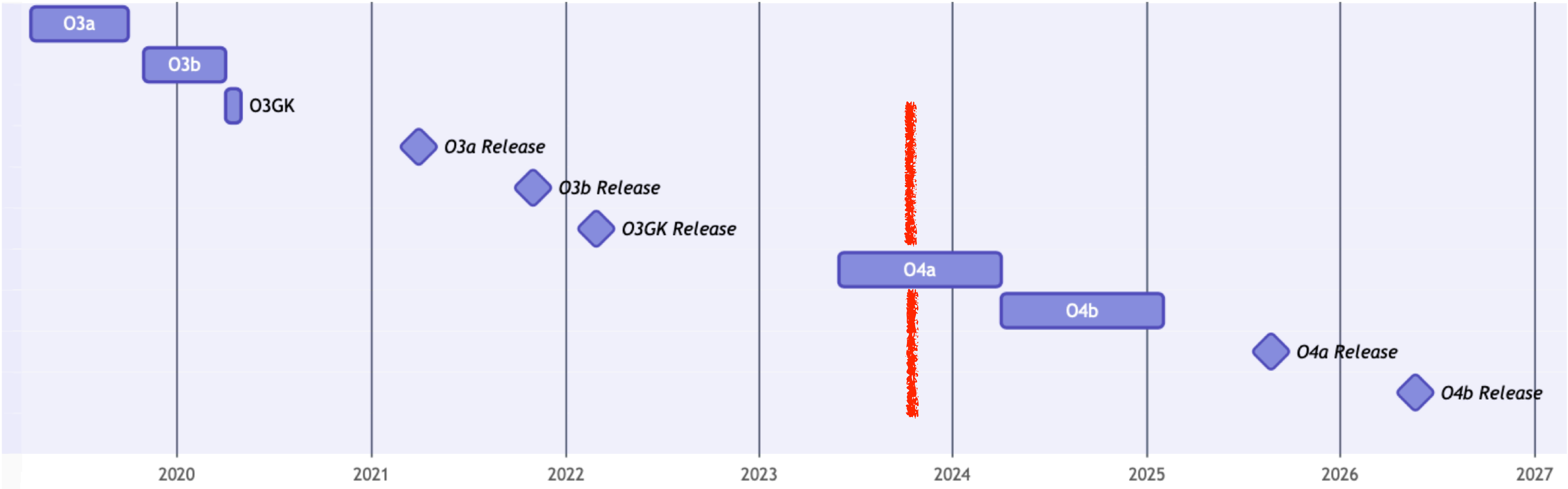
[Image credit: LIGO/Virgo/KAGRA]

- LHO and LLO observing with good availability.
- LHO sensitivity improved to BNS range = 145-150 Mpc.
- LLO operating at BNS range of 150-160 Mpc.
- Ongoing work to increase duty cycle + sensitivity.
- **Next detectors update by Oct. 15.**

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR	Comments
S231001aq	BBH (>99%)	Yes	Oct. 1, 2023 14:02:20 UTC	GCN Circular Query Notices | VOE		1 per 6.3814 years	

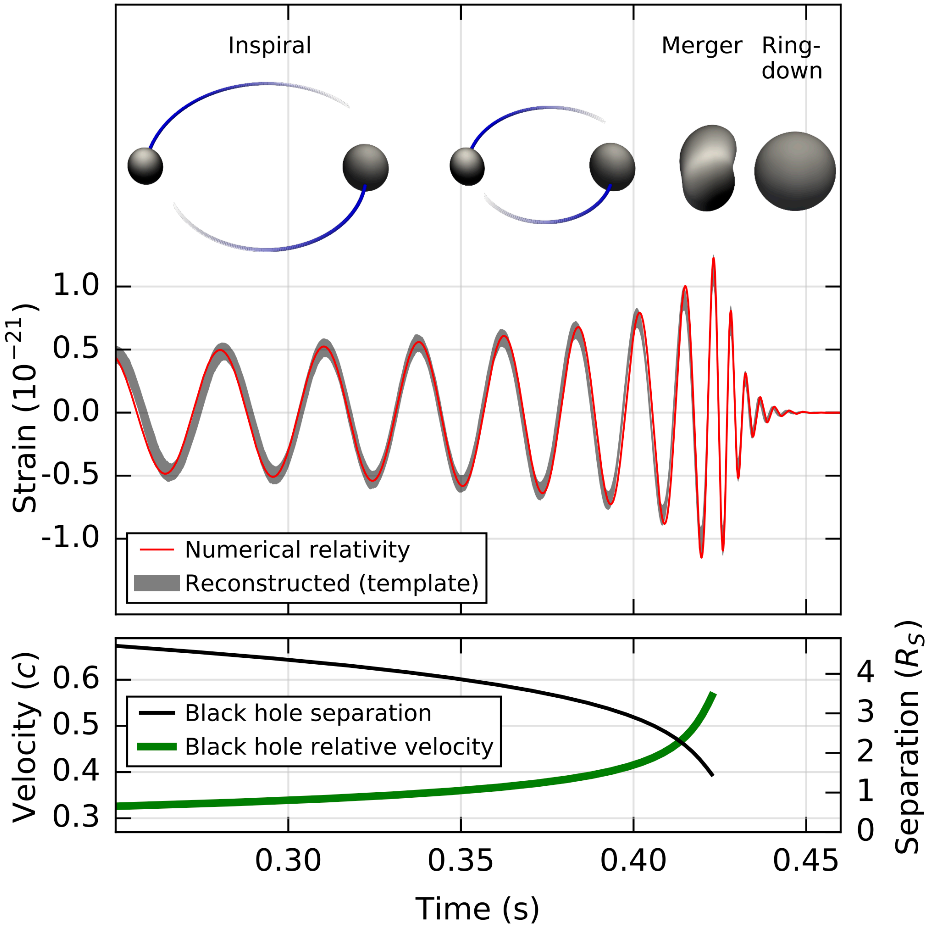
O4 data release plan

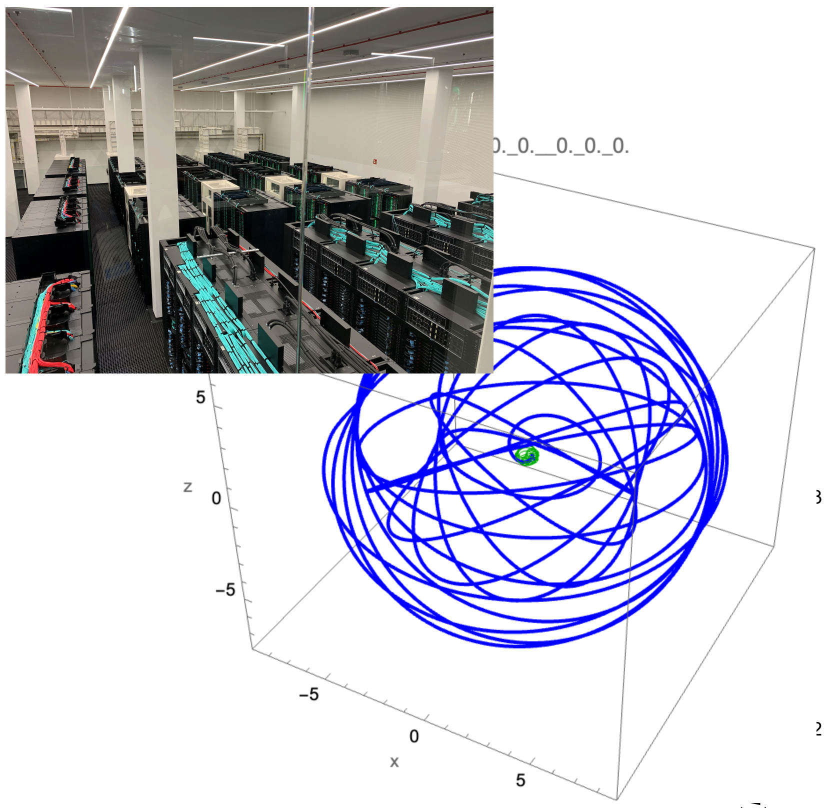
- **2 O4 data releases planned**
  - O4 Data Release A: the first 10 months of O4 data (M1-M10) at the end of Month 27, i.e. 2025-08-23.
  - O4 Data Release B: M11-M20 at the end of M36, i.e. 2026-05-23.
  - Unexpected delays can occur - scientific community will be informed.



https://dcc.ligo.org/public/0009/M1000066/029/Data_Management_Plan-v29.pdf

CBC: Need perturbative approaches + numerical relativity to model signals

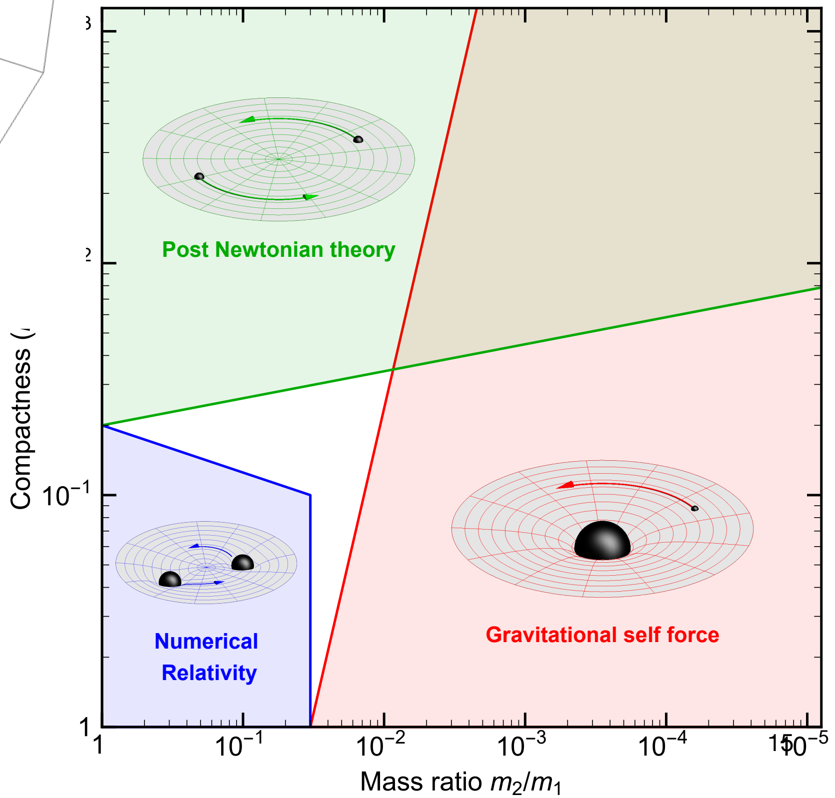




Numerical relativity:
Solve Einstein equations with FD or spectral methods.

~ 10^5 core hours/coalescence

For CBC: possible since 2005



Inspiral: Post-Newtonian expansion in v/c
Breaks down for the last orbits
Recent progress $(v/c)^8$ nonspinning- Blanchet, ….

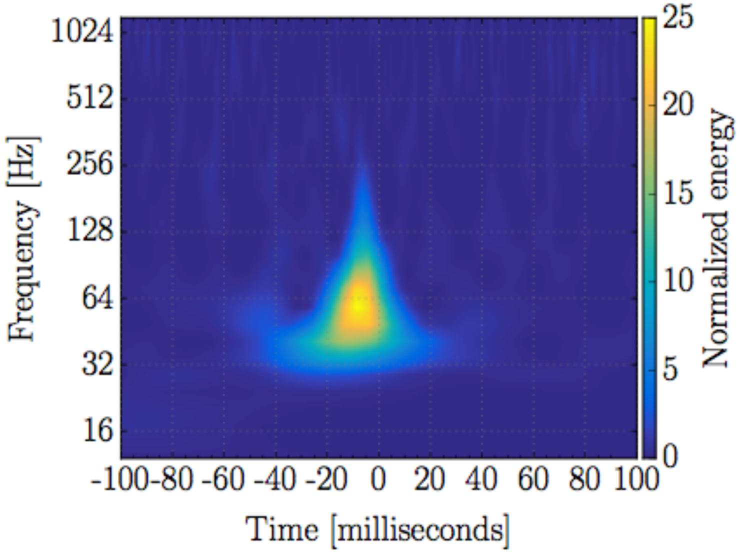
Self-force: expansion in mass ratio

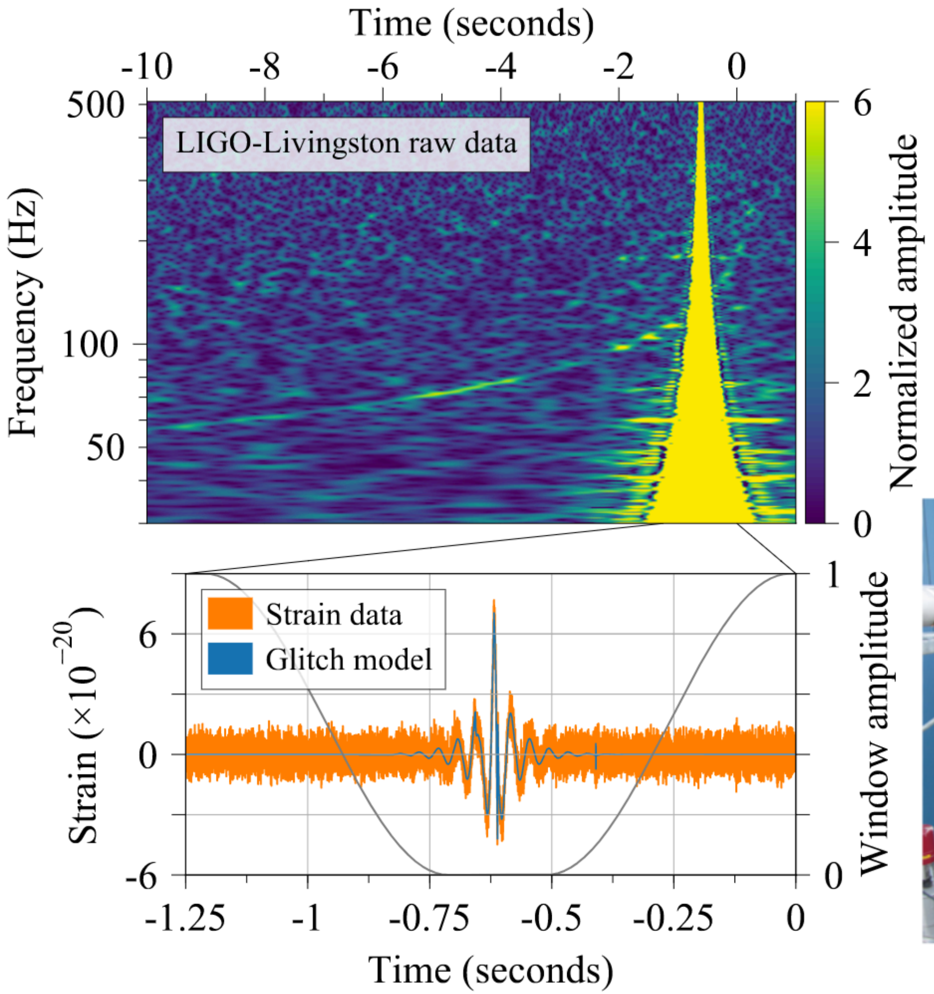
Recent breakthrough for second order.

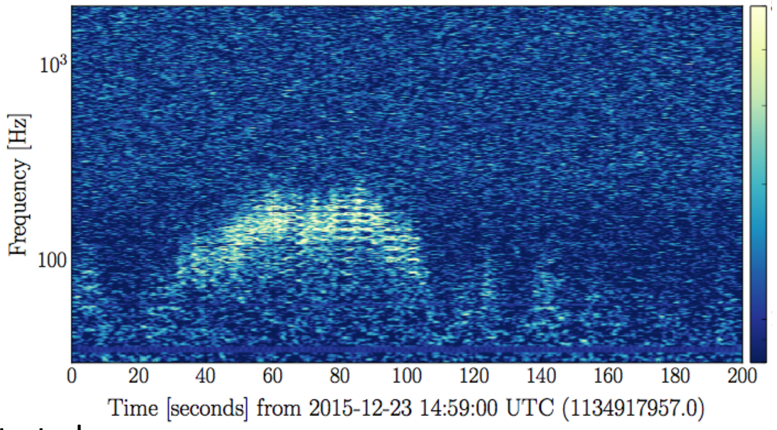
Put it all together: EOB (AEI+), Phenom (UIB+)

Data is non-stationary, not Gaussian!

Also need to model noise, including non-gaussian artefacts = glitches.
DetChar & calibration groups are essential for ensuring data quality.







B.P Abbott et al.
CQG (2018)

Citizen science + ML: gravityspy.org

Observations so far: last catalog GWTC-3 (GW transients)

90 signals detected, 67-76 with sufficient confidence for population studies.

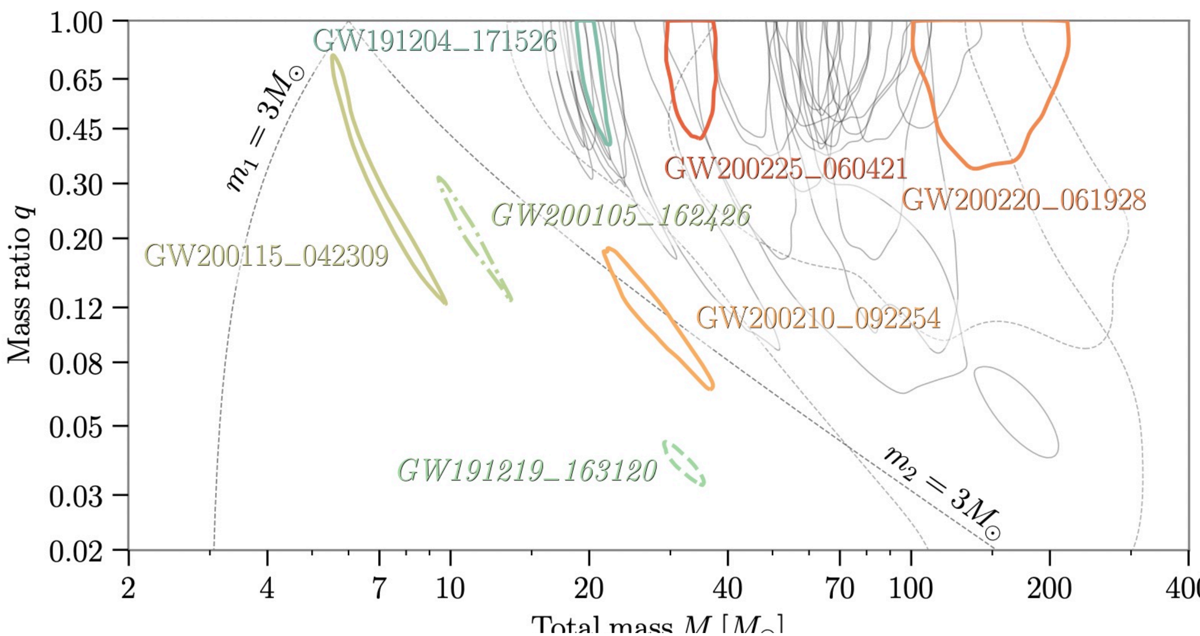
Redshift up to ~ 0.9.

- 63 BBH (first discovered in O1)
- 2 NS-NS (first discovered in O2)
- 2 BH-NS (first discovered in O3)

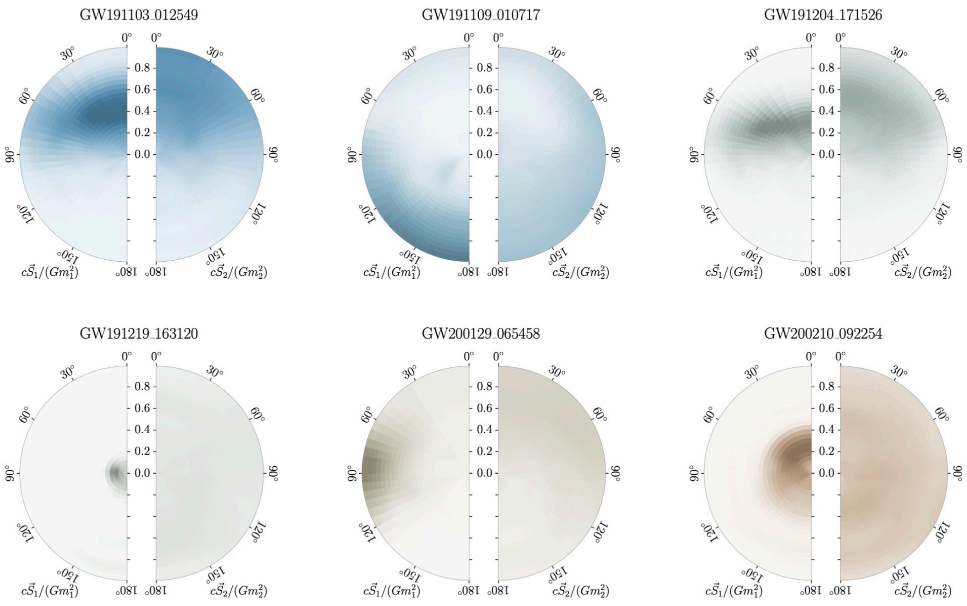
Still large uncertainties in masses, spins, sky location, identification of NS in binary:

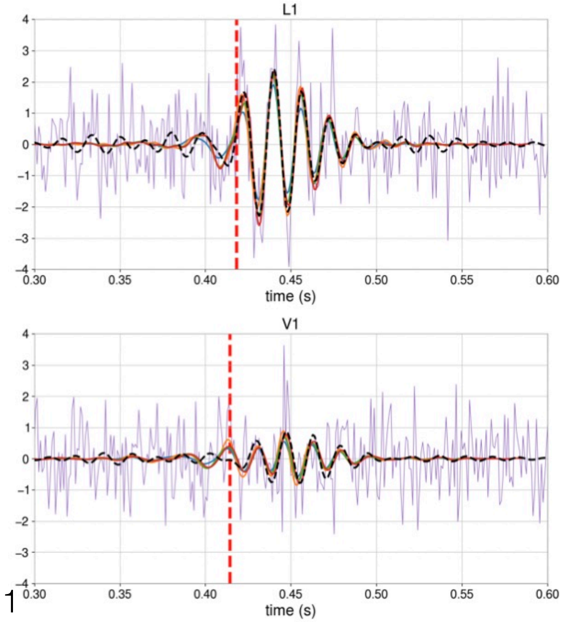
Absence of EM counterpart: use m ≦ 3 M$_\odot$.

- Limited detector sensitivity: SNR ≲ 30
- Deficient waveform models
- High mass: Short signals



LIGO+Virgo +KAGRA: arXiv:2111.03606 *GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run*





GW190521, From Estellés+21

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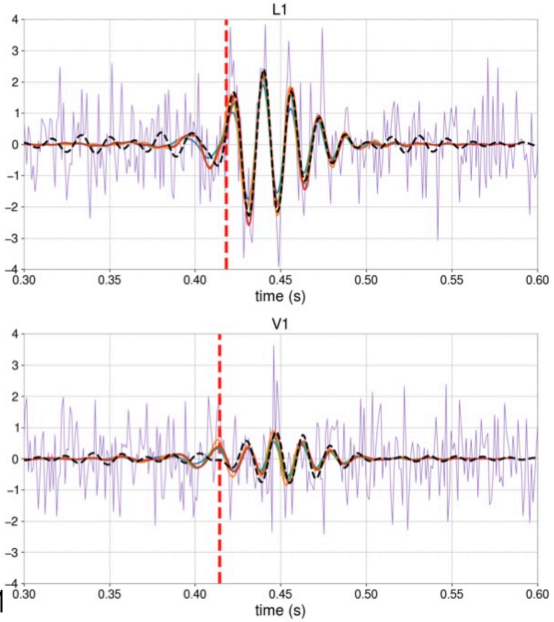
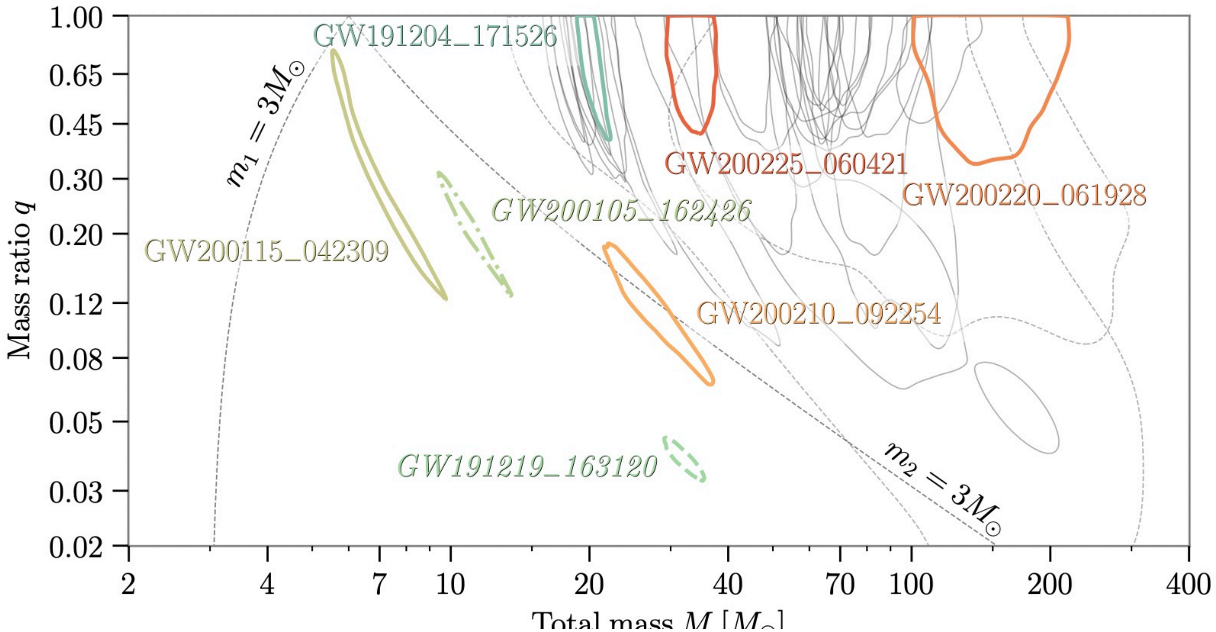
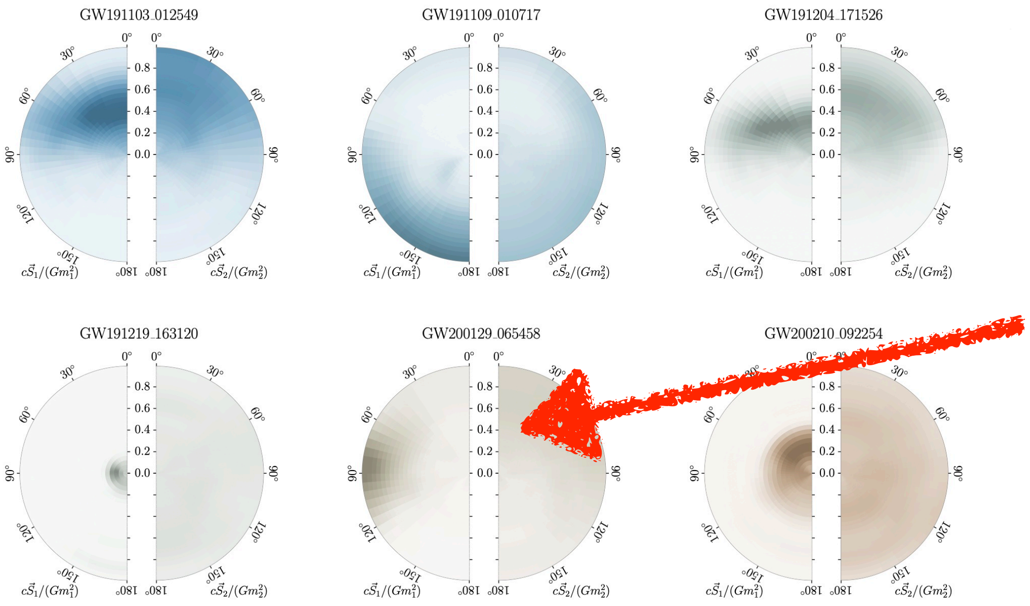


GW190521, From Estellés+21



LIGO+Virgo +KAGRA: arXiv:2111.03606 *GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run*



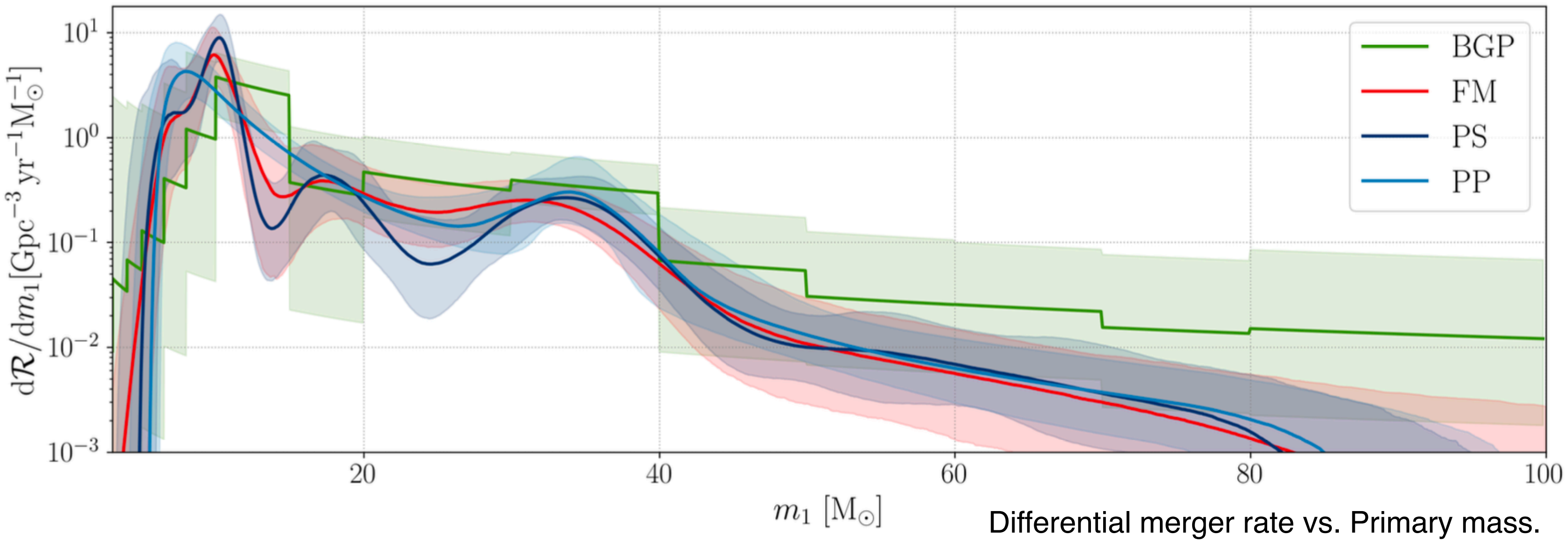
Glitch?

Payne+ '22

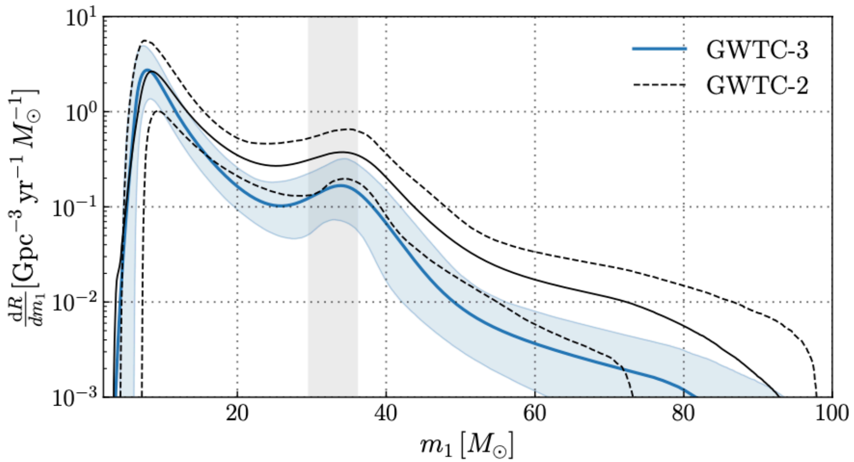
Population & rates

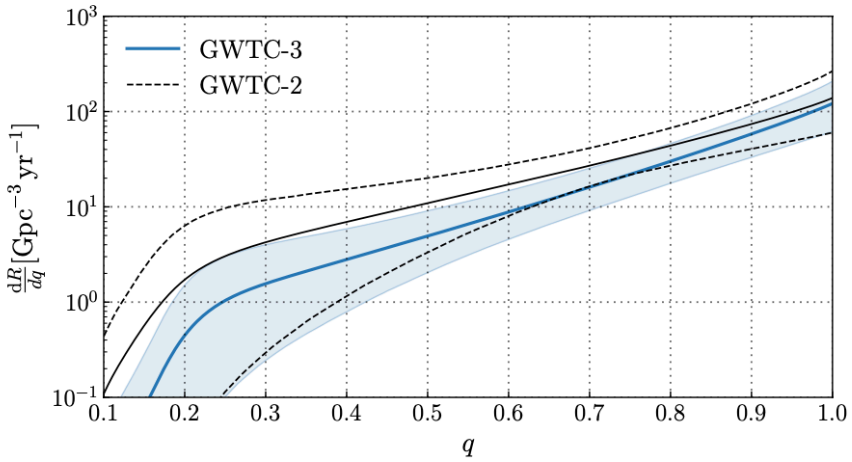
LIGO+Virgo+KAGRA
arXiv:2111.03634
The population of merging compact binaries inferred using gravitational waves through GWTC-3

- Structure emerges in the population, follow trends suggested by GWTC-2.



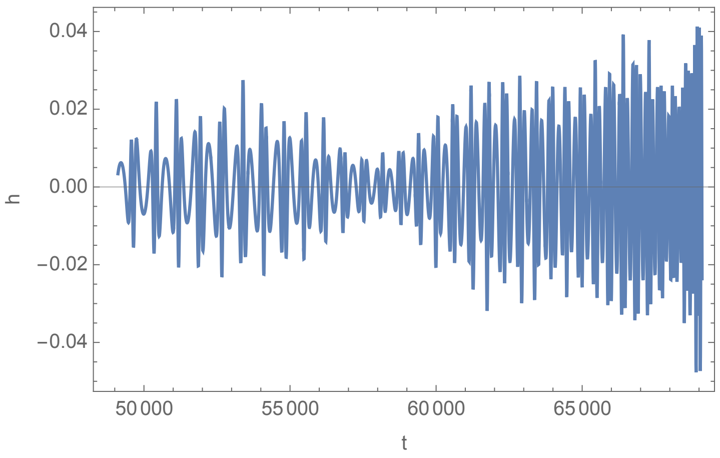
Differential merger rate vs. Primary mass.





Spins and orbital eccentricity are important markers for BH formation channels

- not yet good at modelling generic waveforms:



Cosmology

LIGO+Virgo+KAGRA:arXiv:2111.03604v2
Constraints on the cosmic expansion history from GWTC–3

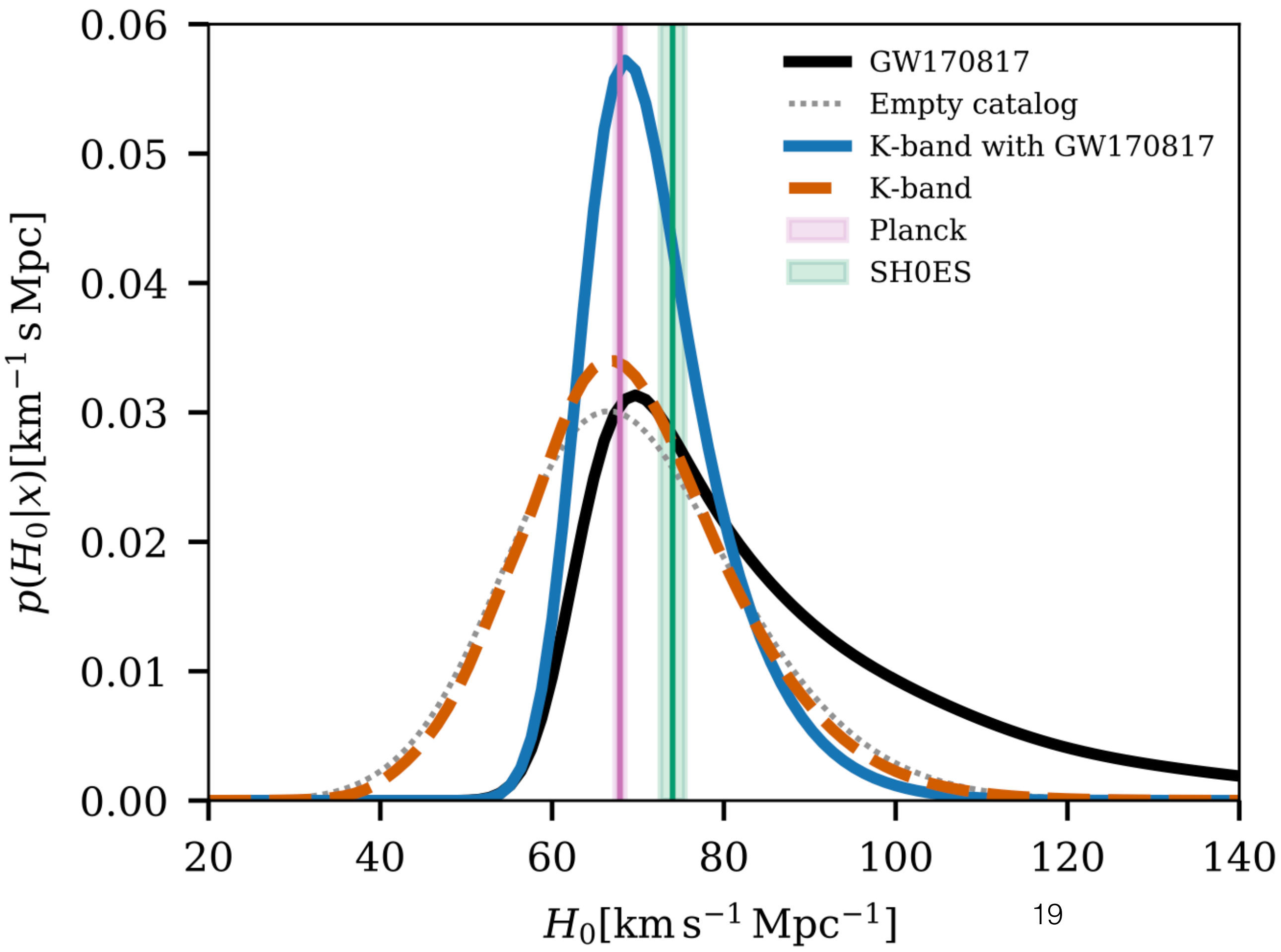
Track expansion history of the universe:

Want distance (from GWs) and redshift (not from individual GW events, unless EM counterpart)!

Redshifted events appear like higher mass events!

2 methods to determine redshift for BBH:

- fix the source population properties and infer the cosmological parameters using statistical galaxy catalog.
- joint fit of cosmological parameters and the source population properties of BBHs without using galaxy catalog



No evidence for deviations from general relativity.

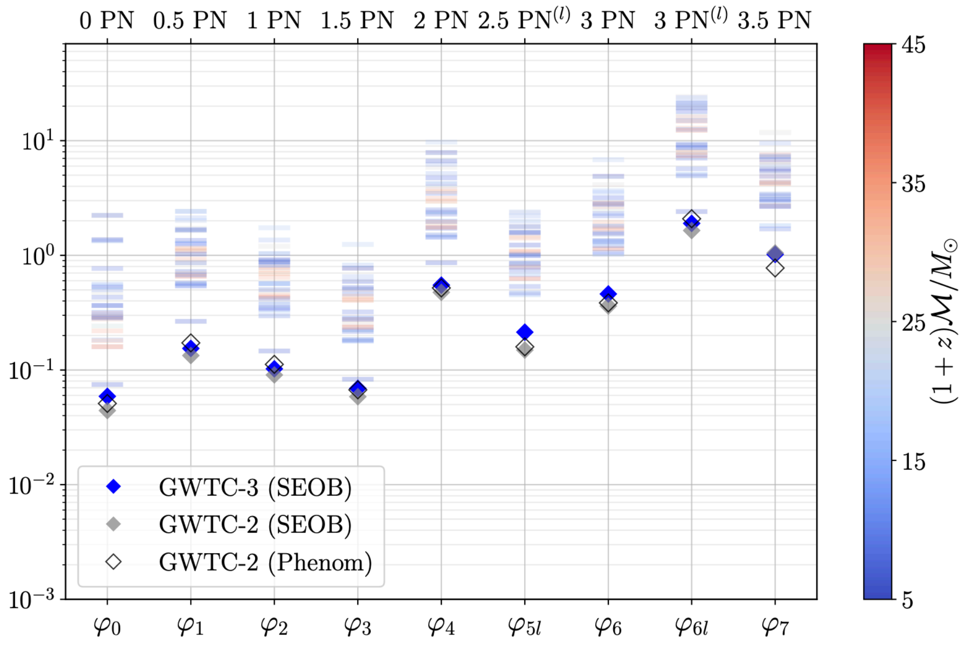
LVK: arXiv:2112.06861; Ghosh for the LVK: Summary of Tests of General Relativity with GWTC-3

Types of tests:

- specific theory: specific GR effects (speed of light); specific non-GR theory
- theory agnostic: consistency test with signal portions; parameterised tests to constrain beyond-GR parameters

Observations

- Residuals from best-fit waveforms consistent with noise
- Consistency of parameters from inspiral and merger-ringdown
- No evidence for deviations for PN coefficients predicted by GR
- Consistency with no dispersion of GWs and massless graviton
- BH spin-induced quadrupole moments consistent with Kerr values
- Ringdown frequencies and damping times consistent with GR
- No detection of echoes
- No evidence for pure scalar or pure vector polarizations
- New bound on mass of graviton —>



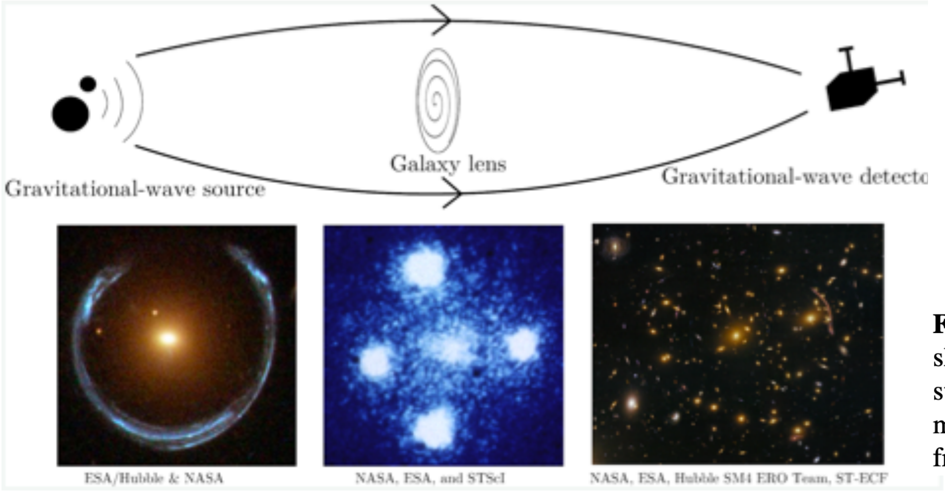
$$m_g \leq 1.27 \times 10^{-23}\, eV/c^2$$

Are any O3 CBC detections gravitationally lensed?

Abbott et al.arXiv:2304.08393

Search for GW magnification, multi-image, and microlensing signatures.

Not yet, but soon.



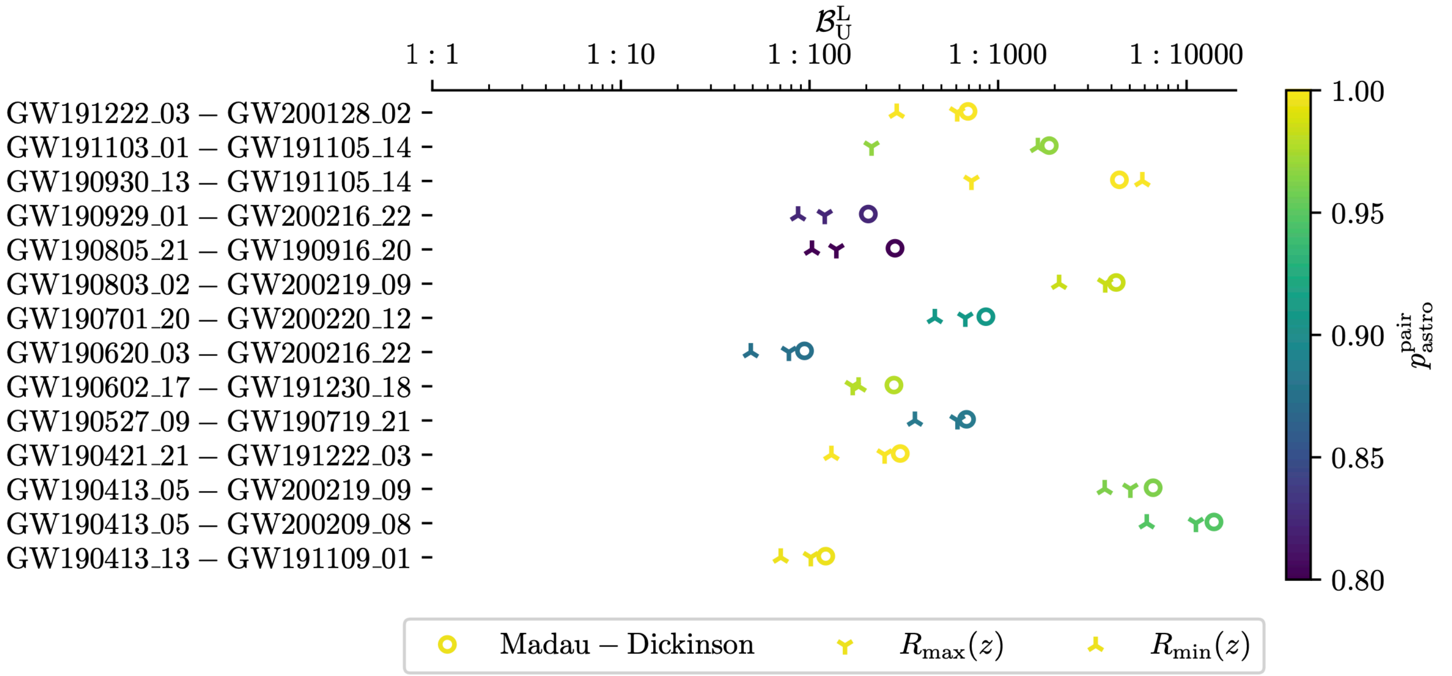


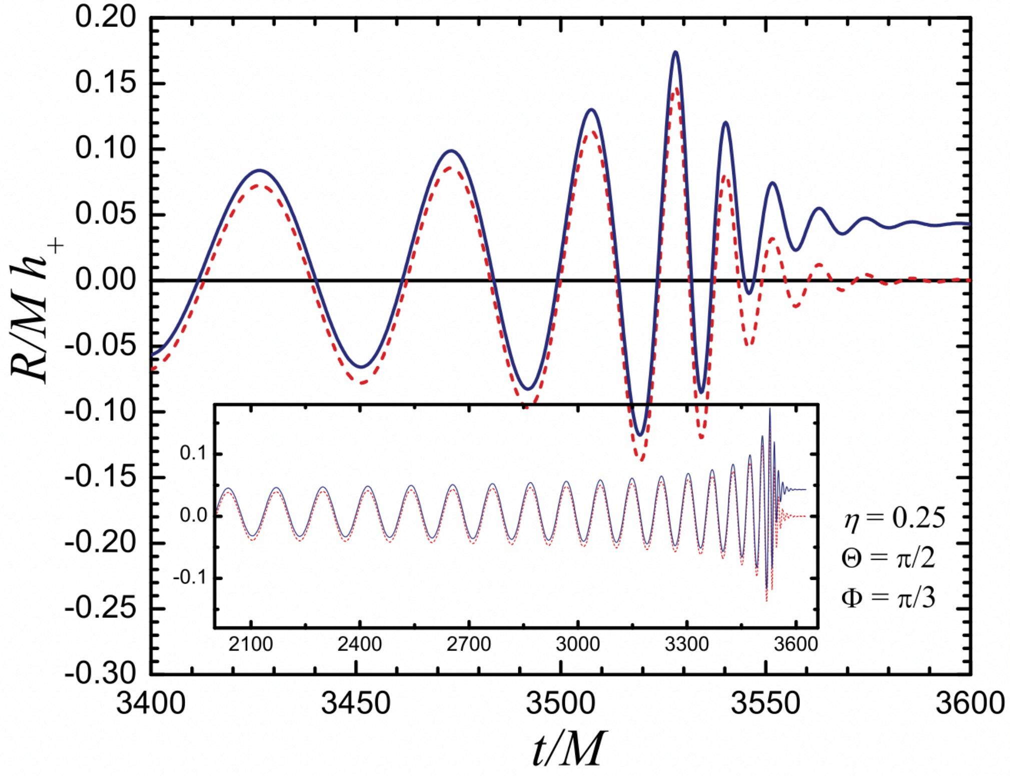
Figure 2. Bayes factors $\mathcal{B}^{\mathrm{L}}_{\mathrm{U}}$ from `hanabi` for the highest-ranked multiple-image candidate pairs. As a check on the robustness of our results, we show the Bayes factors calculated using three different merger rate density models, namely the fiducial model tracking the Madau–Dickinson star-formation rate (Madau & Dickinson 2014), and also the $R_{\min}(z)$ and $R_{\max}(z)$ model introduced in Abbott et al. (2021a). The color for each marker represents the value of $p^{\mathrm{pair}}_{\mathrm{astro}}$ for each pair, which is the probability that both of the signals from a pair are of astrophysical origins and not from terrestrial sources.

Also not yet, but soon: Gravitational Wave Memory

- Early 1970s: GWs generated by unbound binary creates persistent physical change to metric -> **linear memory**

- Christodoulou 91:
  nonlinear memory effect also results from unbound radiation pulse.

  main effect: l=2, m=0 harmonic (m=0: non-oscillatory, except ringdown to BH remnant)



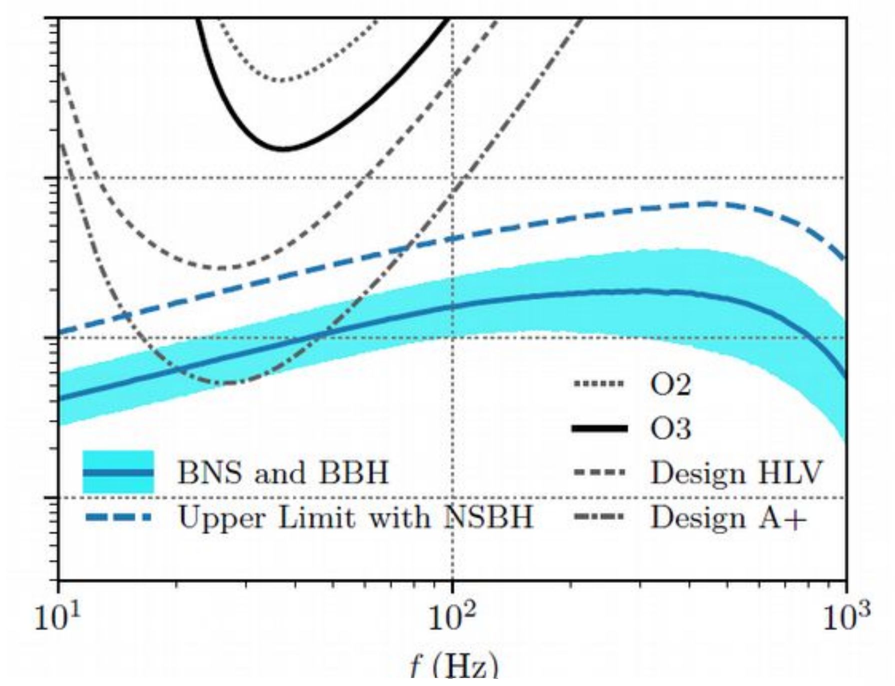
- **Compute memory via BMS group**: fix BMS frame for NR simulations [Mitman+, PRD 104, 2021]
- **Memory is related to "soft" black hole hair - relevant for resolving BH information paradox.**

Searches for isotropic GW background in LV O3 data

Abbott et al. PRD 104, 022004 (2021)

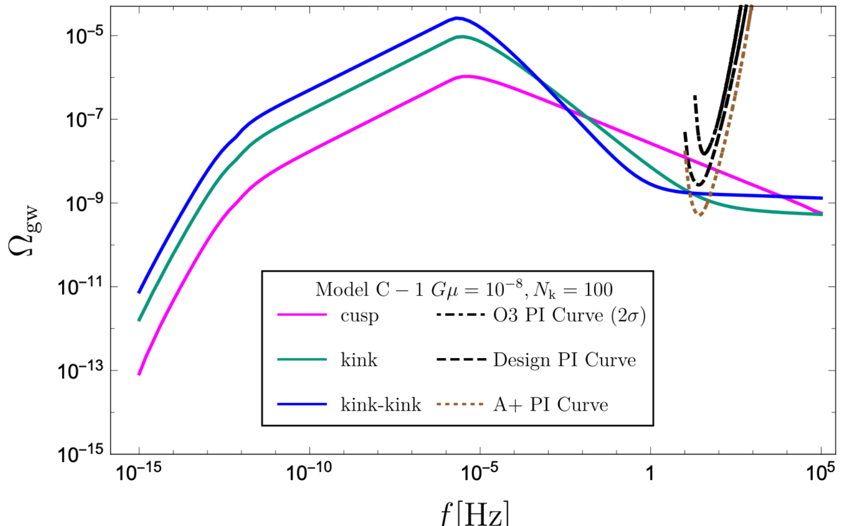
astrophysical or cosmological background

- **no significant evidence for a GW background**
- up to date most stringent limits on strength of background (upper limits improved previous bounds by about a factor of 6.0 for a flat background)



Cosmic Strings PRL 126, 241102 (2021)

- Stochastic GW background energy density => upper limits on cosmic string tension Gμ for 2 cosmic string loop distribution models.
- Tempted searches for cusps, kinks and, for the first time, kink-kink collisions -> no detections



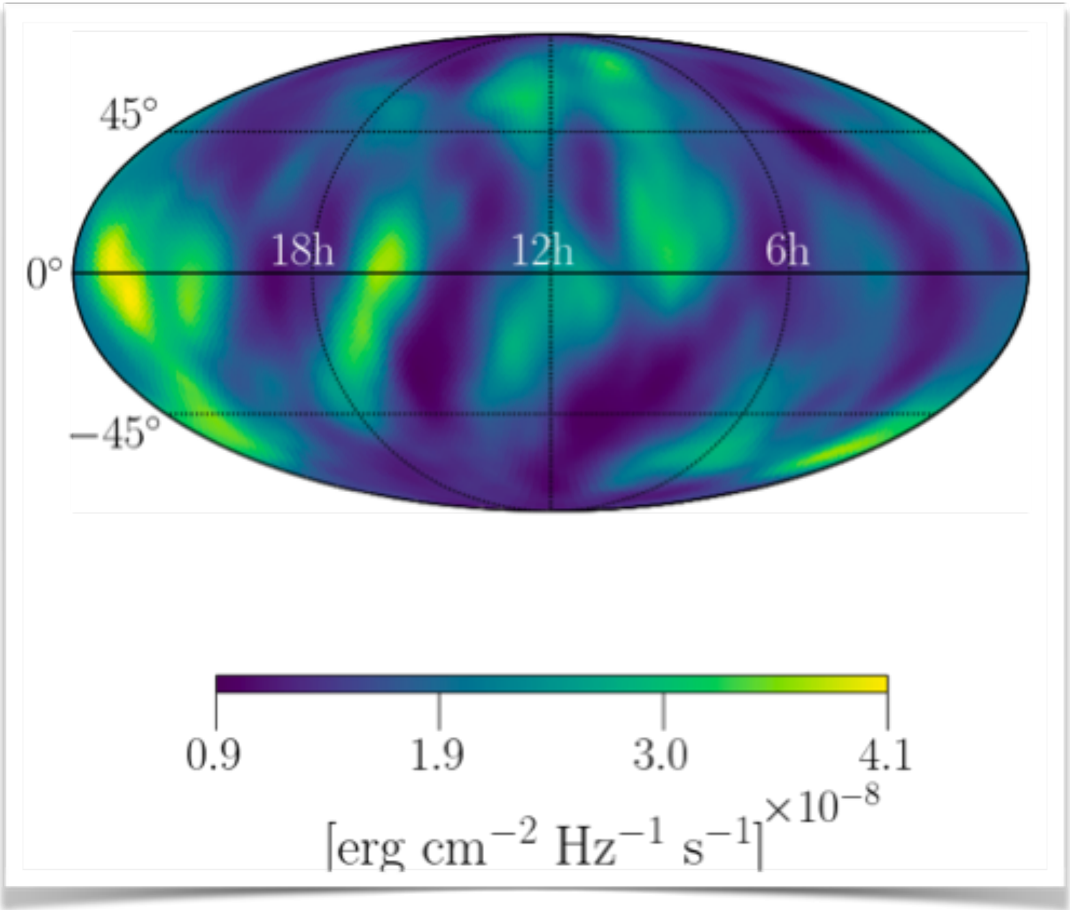
Search for anisotropies in the GW background

Abbott et al. Phys. Rev. D 104, 022005 (2021)

Search for anisotropic GW background (direction-dependent features)

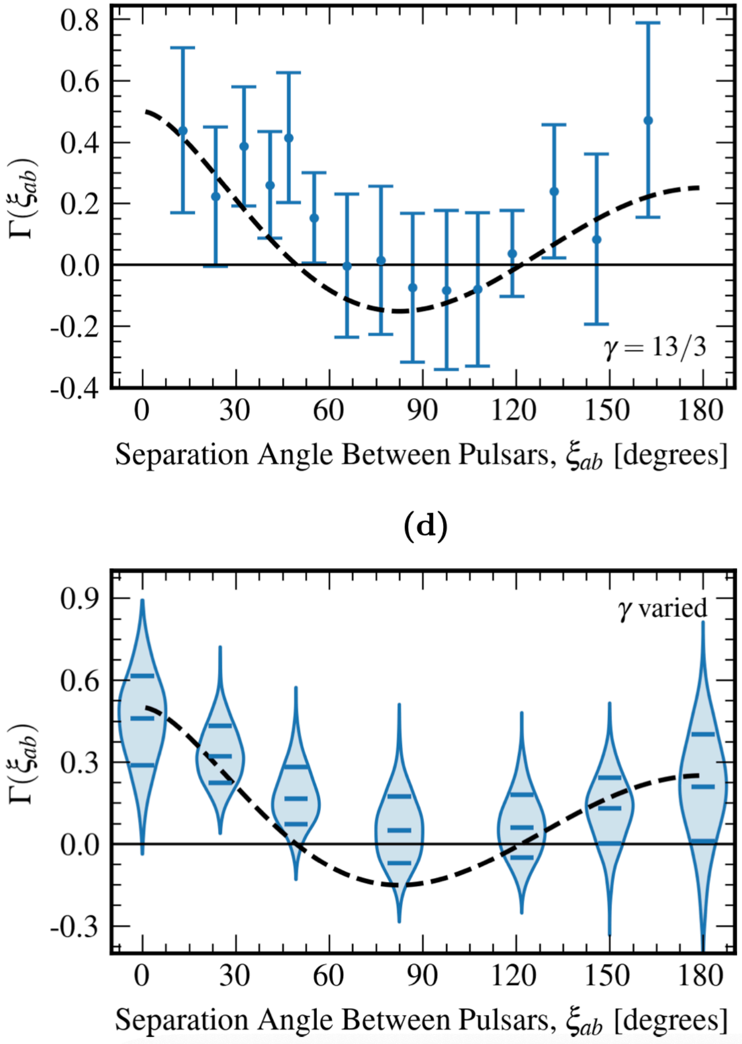
- No significant evidence for audible frequency GW background.

- Upper limits set on the strength of GW background in every direction in the sky



June: Discovery of stochastic GW background by PTAs

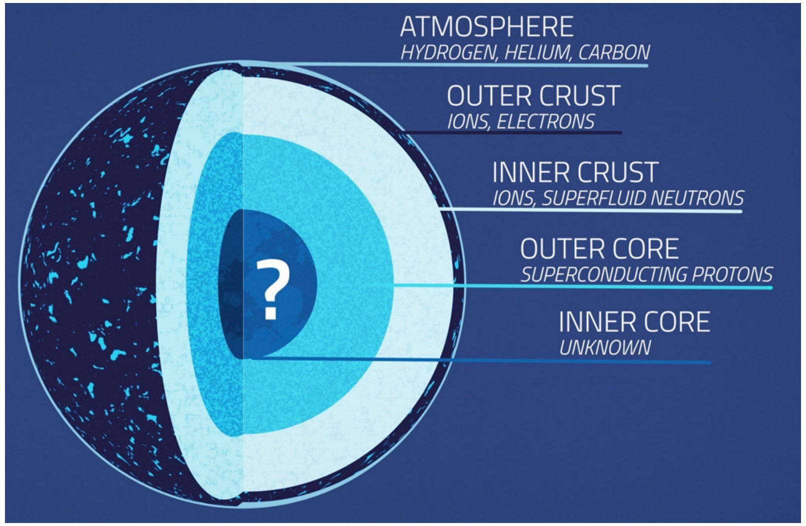
- Collective announcement of **“first evidence”** for nHz stochastic background of GWs
- **Separate analyses** from NANOGrav, European PTA, Indian PTA, Parkes PTA, Chinese PTA
  - Several separate papers from different collaborations released together.
- **Future: Joint analysis** is foreseen to further improve significance and other results.
- Most likely source: SMBH binaries
- Other explanations/contributions possible.

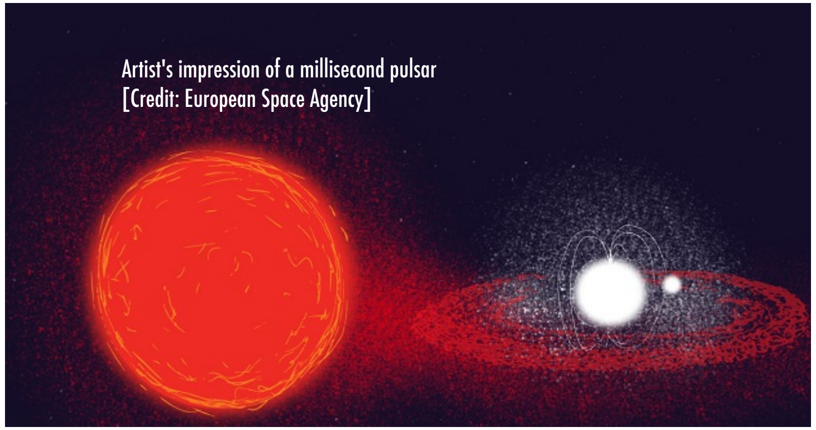


Evidence for Hellings-Down curve from NANOGrav

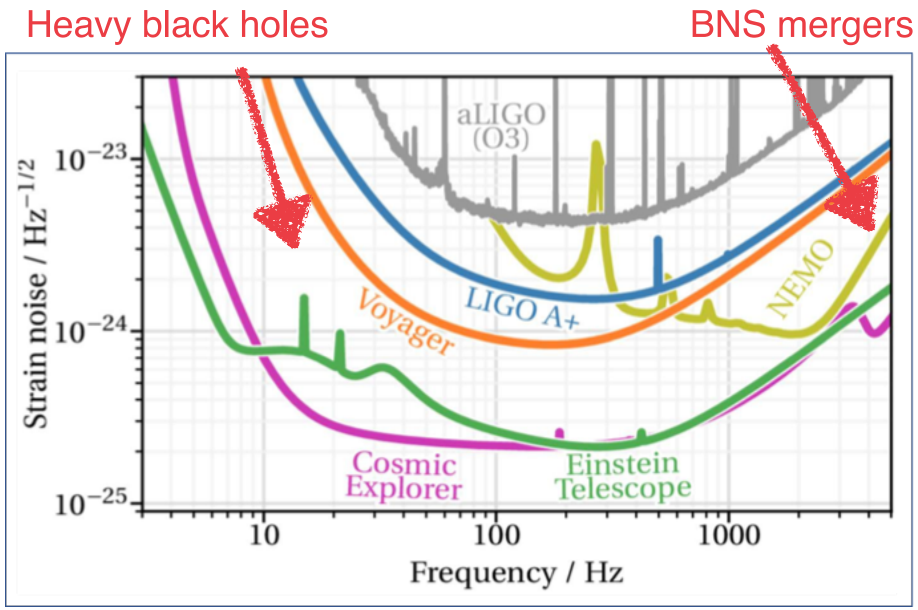
Continuous gravitational waves

- **E.g. from deformed rapidly rotating NSs may be the next major discovery - so far upper limits on NS ellipticity, boson clouds around BHs, PBH.**
    - **->** Talk of Rodrigo Tenorio in Tue RENATA session.
    - Alicia Sintes' UIB group one of the leaders in the field.
    - would significantly broaden the field beyond transients.
    - also: multi-messenger
- Longer observed -> more accurate results, even for very weak signals. Very long signals -> cost prohibits optimal matched filtering
- Observing these signals and measuring the ellipticity informs about NS composition and extreme matter.
- Particularly promising: NSs in binaries:
    - Recent progress with UIB GPU code [Covas+Sintes PRL 2020]
- Methods also relevant for
    - post-merger emission from BNS
    - e.g. LISA observation of WD binaries

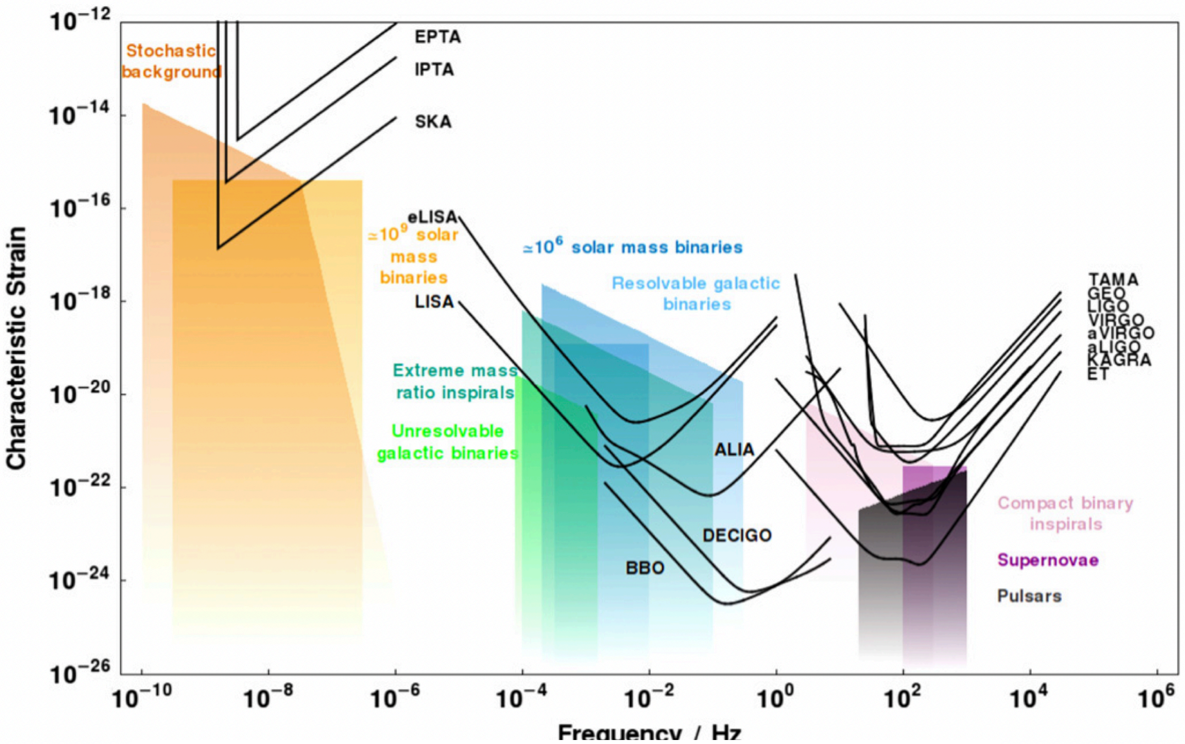




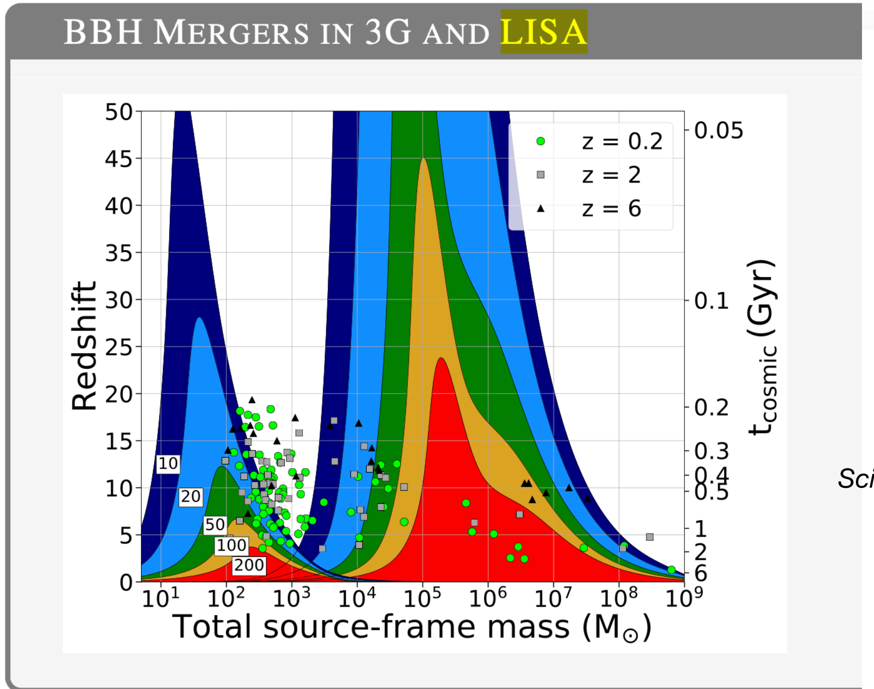
GW detection in Space &



[E.Hall/S.Vitale/MIT]



C J Moore *et al* 2015 *Class. Quantum Grav.* **32** 015014



Science Book: The Next Generation Global Gravitational Wave Observatory

- **3G: hundreds of thousands of BH mergers / year, thousands of EM counterparts**.
- Einstein Telescope included in ESFRI roadmap 2021.
    - **-> Mario's talk at Tue RENATA session.**
- **LISA: data dominated by signal,** many signals overlapping. analysis: **global fit to all signals+noise**.
- **All methods need to be re-imagined!**

ET Science Case in a nutshell

ASTROPHYSICS

- **Black hole properties**
  - origin (stellar vs. primordial)
  - evolution, demography
- **Neutron star properties**
  - interior structure (QCD at ultra-high densities, exotic states of matter)
  - demography
- **Multi-band and -messenger astronomy**
  - joint GW/EM observations (GRB, kilonova,...)
  - multiband GW detection (LISA)
  - neutrinos
- **Detection of new astrophysical sources**
  - core collapse supernovae
  - isolated neutron stars
  - stochastic background of astrophysical origin

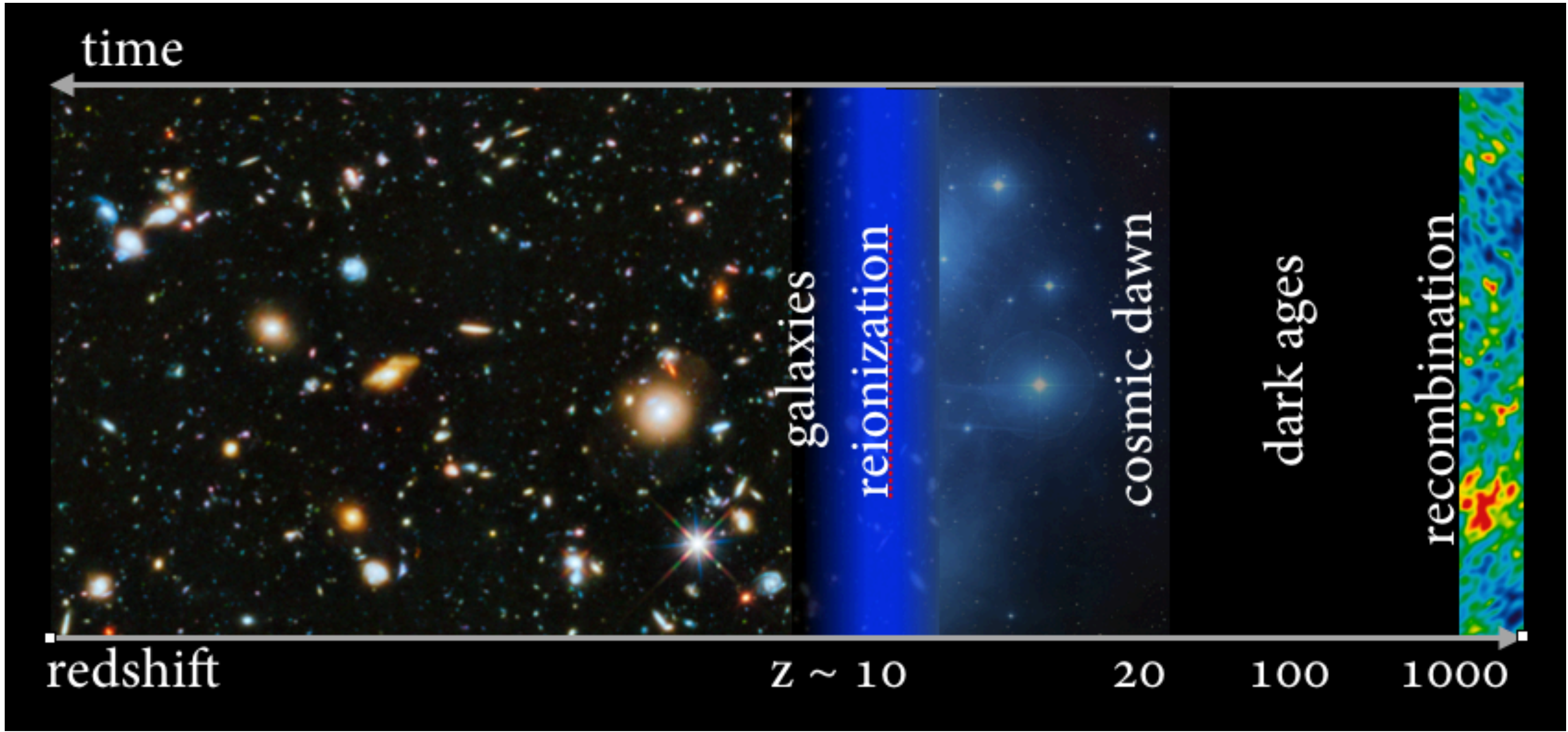
FUNDAMENTAL PHYSICS AND COSMOLOGY

- **The nature of compact objects**
  - near-horizon physics
  - tests of no-hair theorem
  - exotic compact objects
- **Tests of General Relativity**
  - post-Newtonian expansion
  - strong field regime
- **Dark matter**
  - primordial BHs
  - axion clouds, dark matter accreting on compact objects
- **Dark energy and modifications of gravity on cosmological scales**
  - dark energy equation of state
  - modified GW propagation
- **Stochastic backgrounds of cosmological origin**
  - inflation, phase transitions, cosmic strings

Conclusions

- O4 is ongoing - 16 more months of observation - looking forward to new surprises!
- 90 detection published. Waveform modeling is crucial for decoding the signals and understanding the sources.
- Open data for O1 - O3 are available. Wide range of publications from outside the LVK.
- **Bright future ahead** for the field of GW astrophysics, with steady upgrades toward 3G ground based detectors and low frequency space detectors.

LISA, ET, CE will allow us
to observe (essentially)
all mergers of BHs
throughout the universe.
~ mid 2030s
Many opportunities to further
strengthen Spanish involvement.



A Detector parameters

Parameter	Units	A+	A$^\sharp$	iVoy	STO	VoyD	VoyW
Arm power	kW	750	1500	3000	1500	4000	4000
Laser wavelength	µm	1	1	2	1	2	2
Test mass material		Silica	Silica	Silicon	Silica	Silicon	Silicon
Temperature	K	295	295	123	295	123	123
Test Mass	kg	40	100	200	200	200	200
Total susp. mass	kg	120	400	520	520	520	520
Final stage susp. length	cm	60	60	80	80	80	80
Total susp. length	m	1.6	1.6	1.6	1.6	1.6	1.6
Observed squeezing	dB	7	10	9	10	9	9
Rayleigh wave suppression	dB	0	6	6	20	20	20
Test Mass Coatings		A+	AlGaAs	Ta/aSi/SiO_2	AlGaAs	aSi	aSi
Horiz. susp. pt. at 1 Hz	pm/$\sqrt{\text{Hz}}$	10	10	10	0.1	0.1	0.1
Final susp. stage blade		None	None	Aluminum	Silica	Silicon	Silicon
ETM beam radius	cm	6.2	5.5	8.0	5.5	8.4	8.4
ITM beam radius	cm	5.3	4.5	5.2	4.5	5.9	5.9
Cavity stability $g_i g_e$		0.83	0.71	0.62	0.71	0.73	0.73
Transverse mode spacing	kHz	32.5	30.7	29.6	30.7	31.0	31.0
Filter cavity linewidth	Hz	48	42	28	30	36	13
Arm finesse		450	450	3100	450	2000	2000
SRM transmission	%	32.5	32.5	4.6	32.5	9.2	1.1
Arm length	m	3995	3995	3995	3995	3995	3995
Filter cavity length	m	300	300	300	300	300	300
SEC length	m	55	55	55	55	55	55
RT arm cavity loss	ppm	75	75	20	75	20	20
RT filter cavity loss	ppm	40	30	10	20	10	10
RT SEC loss	ppm	3000	500	500	500	500	500
Exc. gas damp.		2.0	2.6	2.5	3.1	2.5	2.5
Diffusion time	µs	800	1500	1400	2300	1400	1400

Table 6: Defining parameters of detectors (aSi: amorphous silicon; AlGaAs: aluminum gallium arsenide; RT: round trip). The parameters needed to reach these squeezing levels are given in Table 2. Detailed coating parameters are given in Table 8. The excess gas damping is the squeezed film enhancement to residual gas damping as described in [48] and calculated in LIGO-T0900582. As described in Appendix A of [48], the details of the sticking time for molecules in the TM/ERM gap depend on the mirror temperature and the AR coating's sticking energy. These are not well characterized for our amorphous oxides at 123 K, and so while we expect the squeezed film damping to be less for Voyager, we use the standard room temperature formula as a conservative upper limit for now.

GWTC Catalog - GW transients

- Cumulative set of GW transients maintained by the LIGO/Virgo/KAGRA collaboration.
- Online GWTC contains confidently-detected events from multiple data releases.
- Periodic updates, and may not contain recently published events.
  - GWTC-1: O1 + O2 - 11 confident detections + marginal triggers
  - GWTC-2: O3a - 39 detections
  - GWTC-2.1: O3a reanalysis with new calibration and other updates + marginal triggers
  - GWTC-3: O3b + previous - 35 confident detections + marginal triggers
- all available events - periodically updated.
- Previous catalog versions archived on zenodo.

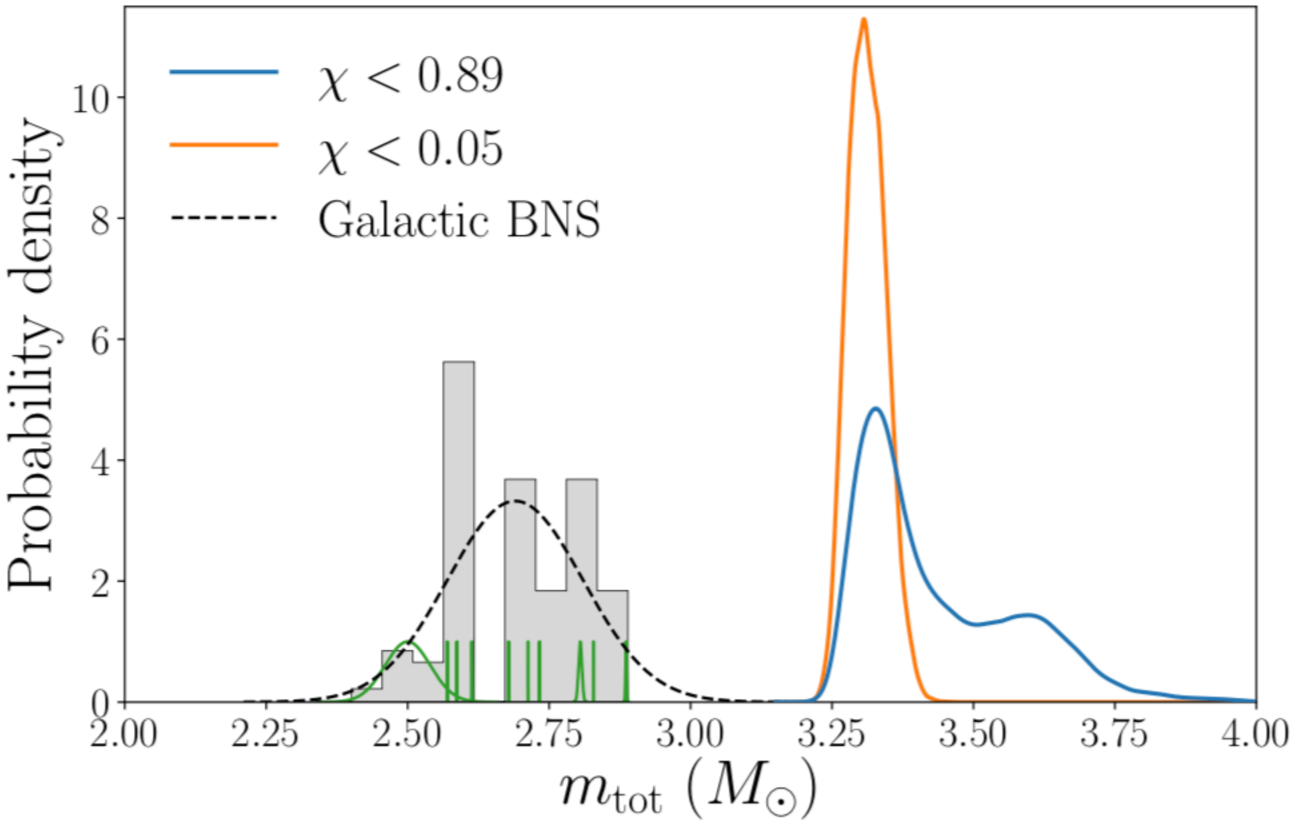
Marginal trigger:

p_astro <= 50%

- Mostly BBH - # BNS # NSBH.
- How do we know which one it is?
- Observables: intrinsic - extrinsic - EOS

https://dcc.ligo.org/public/0009/M1000066/029/Data_Management_Plan-v29.pdf

GW190425



m_1	m_2	m_{tot}
$1.6 - 2.5\,\mathrm{M}_\odot$	$1.1 - 1.7\,\mathrm{M}_\odot$	$\sim 3.4\,\mathrm{M}_\odot$

A massive binary neutron star merger

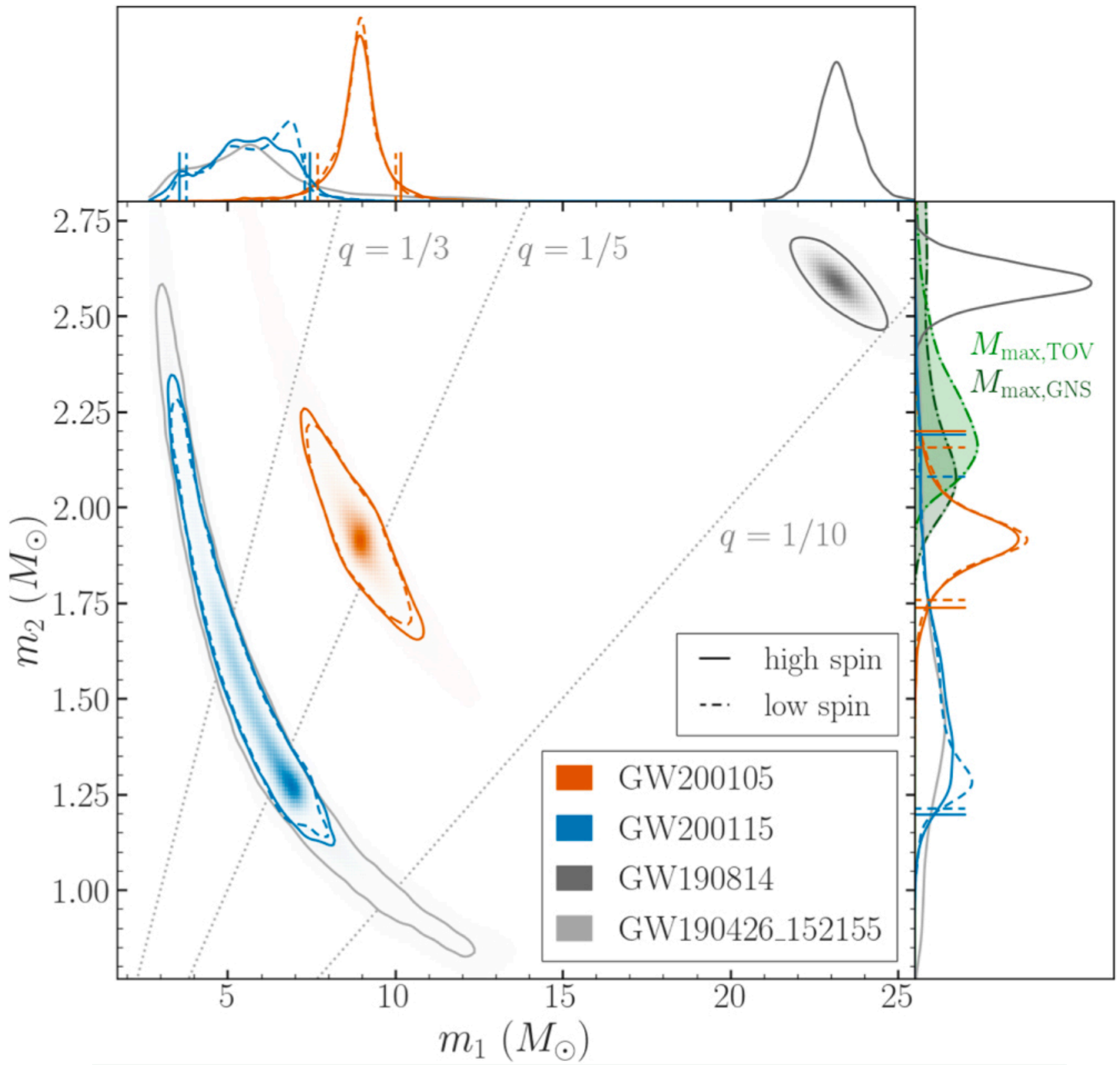
Abbott et al. ApJ Lett. 896, L44 (2020)

- Both component masses < 3 $M_\odot$
- No EM counterpart
- Total mass larger than any known BNS (5σ from mean of Galactic BNS)
- Initial sky map had a 90% credible region of 10,200 deg² at luminosity distance of 159^{+69}_{-72} Mpc

May indicate population of short period BNSs invisible to radio pulsar surveys

The possibility that one or both binary components are black holes cannot be ruled out

GW200105 & GW200115



	m_1	m_2
GW200105	$\sim 8.9\,M_\odot$	$\sim 1.9\,M_\odot$
GW200115	$\sim 5.7\,M_\odot$	$\sim 1.5\,M_\odot$

Observation of Gravitational Waves from Two Neutron Star-Black Hole Coalescences

Abbott et al. ApJ Lett. 915, L5 (2021)

- First detections of neutron star-black hole systems
- No EM counterpart observed (as expected)
- Luminosity distances 280 and 300 Mpc

- GW200115: preference for spin to be anti-aligned with orbital angular momentum
- Some of the most expensive parameter estimation runs done by UIB group on MareNostrum

LIGO-Virgo-KAGRA Collaboration

roster.ligo.org

LIGO Scientific Collaboration (LSC)

143 groups ~ 1495 members ~ 1008 authors ~ 714 FTEs

Virgo

36 groups ~140 institutions ~800 members ~450 authors

MOUs of individual groups with GEO, LIGO or Virgo. GEO is part of LIGO.

MOUs between collaborations.

IGWN: International Gravitational Waves observatory Network - rtd.igwn.org

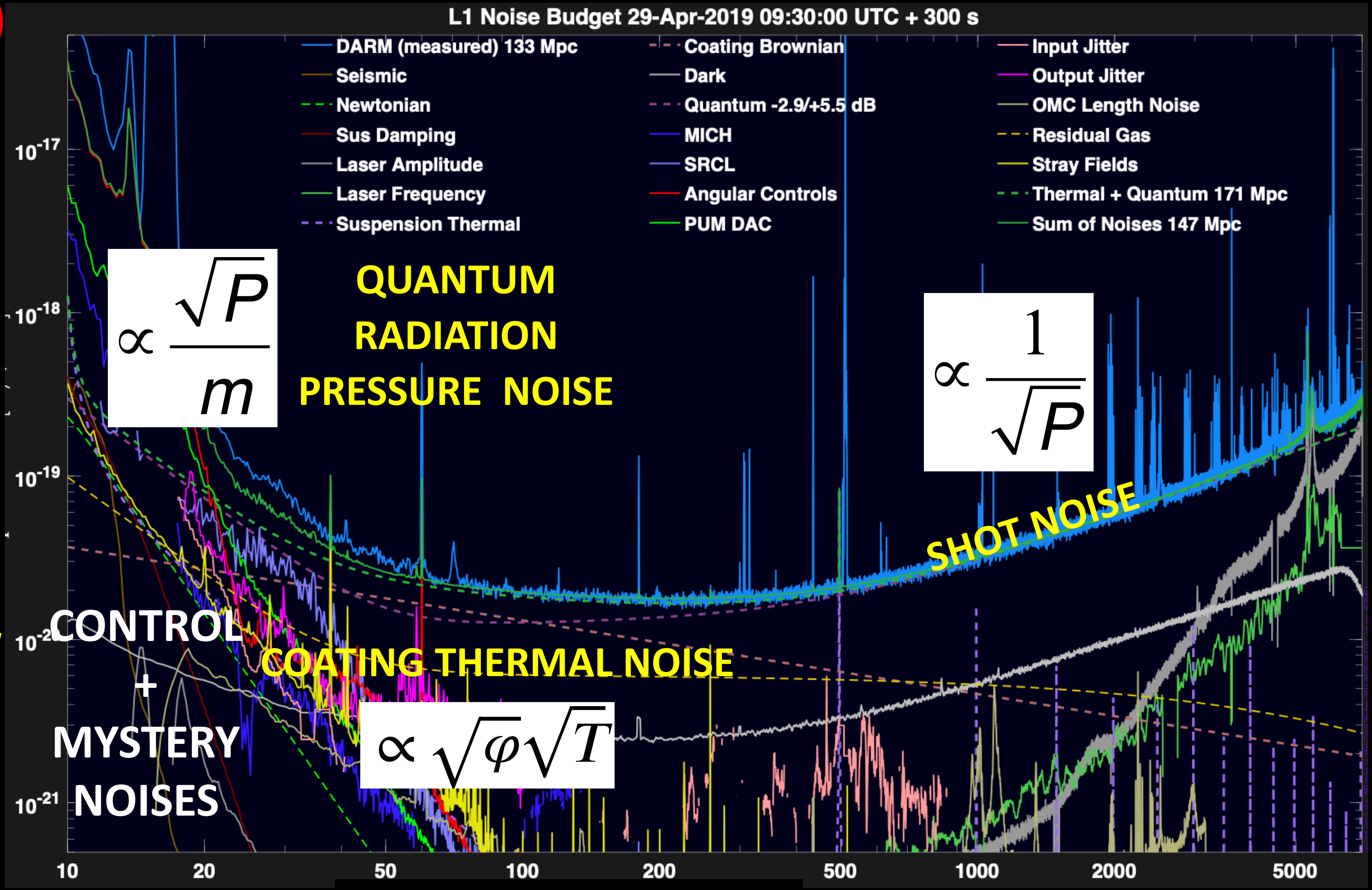
- Coordination effort aimed at jointly discussing computing policy, management, and architecture issues of LIGO-Virgo-KAGRA.
- Software "backbone": conda - gitlab - mattermost - high throughput computing | HTCondor - OSG

O3 01/04/2019-27/03/2020

LIGO Livingston (L1) Noise Budget in O3

Displacement (m/√Hz)

S E I S M I C W A L L



Frequency (Hz)

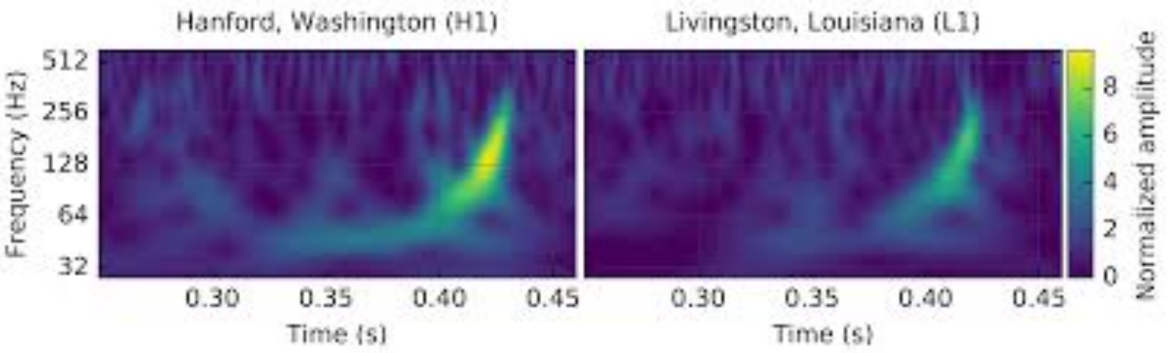
P: laser power in the arms

m: mirror mass

T: mirror temperature

φ: mechanical loss of mirror coating

Data analysis methods

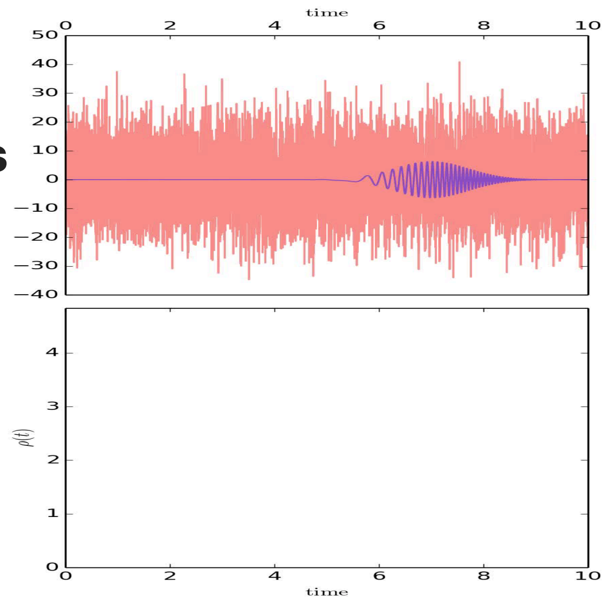


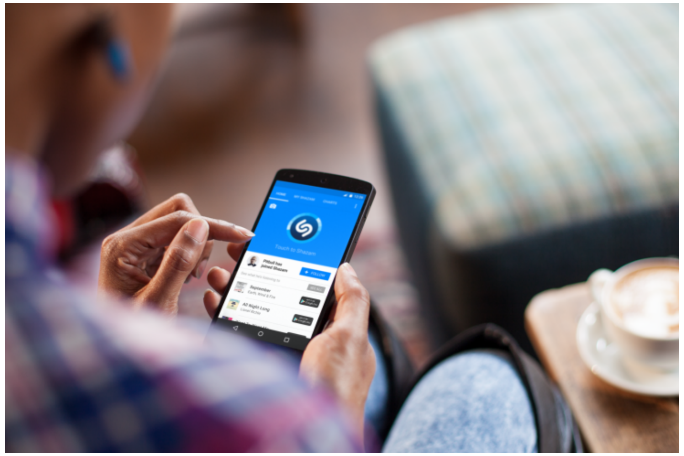
- **Un-modeled searches:**
  Time-frequency pattern recognition, optionally tuned to waveform models.

- **Modeled signals: matched filtering:**
  optimal analysis using accurate waveform models as signal templates.

$$\langle h_1, h_2 \rangle = \max_{\phi_0, t_0} 4\Re \int_{f_1}^{f_2} \frac{\tilde{h}_1(f)\, \tilde{h}_2^*(f)}{S_n(f)}\, df$$

- **Machine learning**
  - e.g. neural networks trained on accurate waveform models





- **Injection/recovery studies for astrophysical rates** with accurate waveform models

- **Searches can be**
  - all sky/all time
  - directed or triggered, e.g. known pulsar, GRB, supernova

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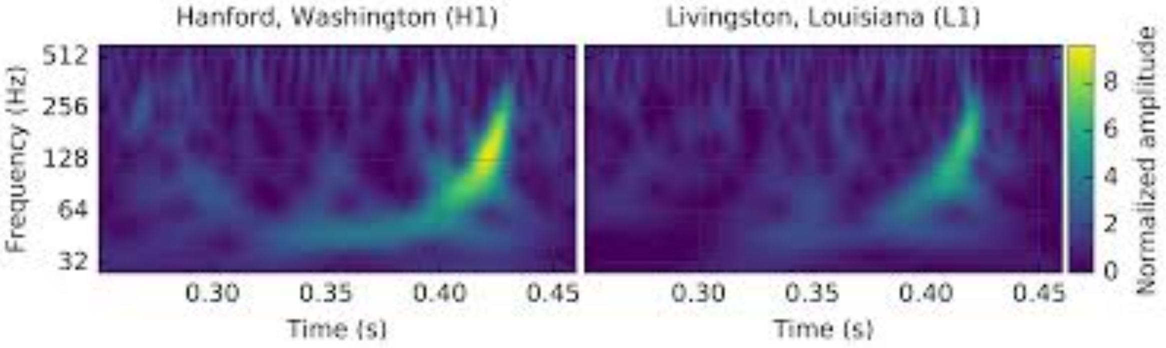

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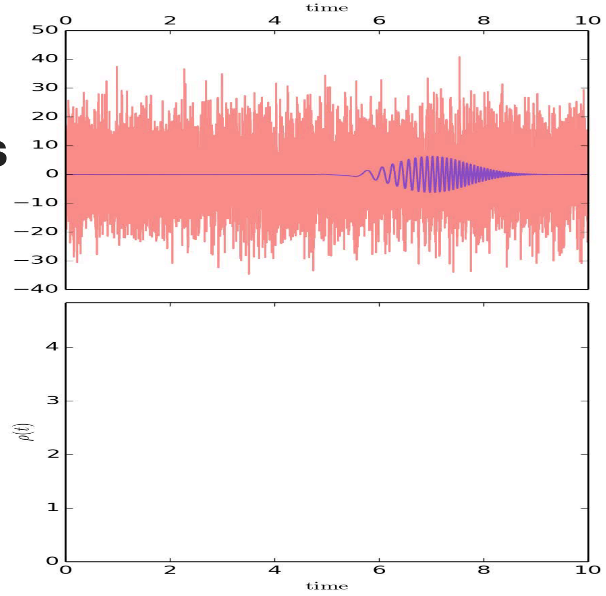

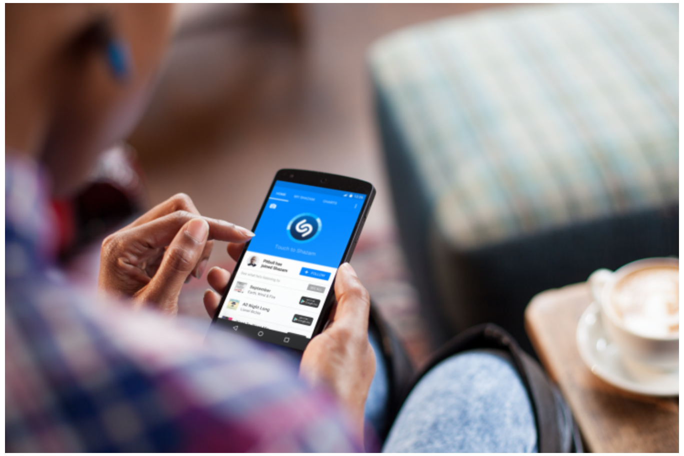

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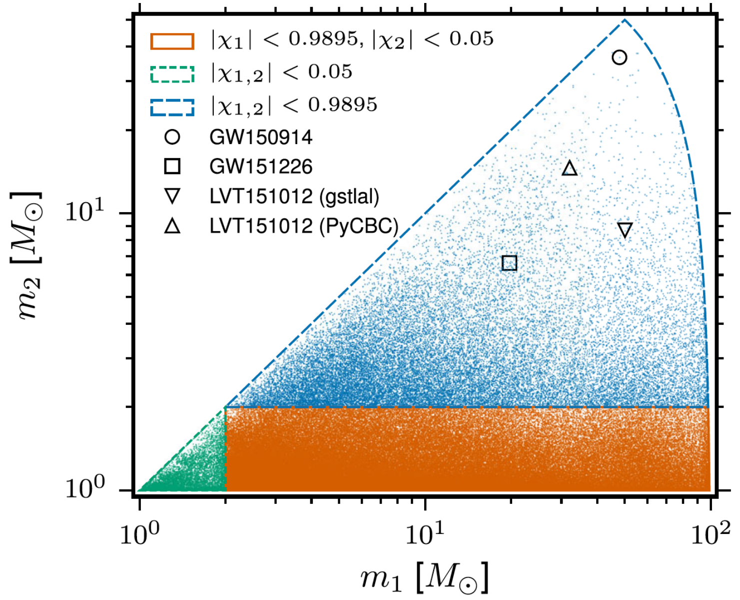
2-step LVK CBC workflow: searches + PE

- **Searches -> detection:**
  statistical evidence of seeing a signal above background,
- Matched filter with fixed template bank / unmodeled / neural networks
  - Separate background from noise, estimate background, online + offline
  - Standard SNR value for detection: SNR ~ 8
    - Sub-threshold triggers are also analysed!
  - More signal parameters -> higher false alarm rate
    - Currently neglect precession, eccentricity, higher modes for matched filter searches
- **Bayesian parameter estimation:** continuously vary templates with random walks in parameter space, using nested sampling, MCMC etc. **+ ML**

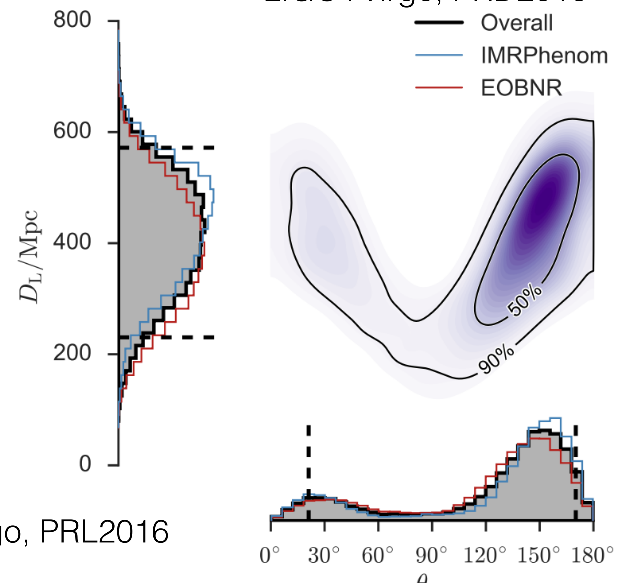
  ML breakthrough: use importance sampling
  - But: non-gaussian noise can not always be neglected, especially for short high mass signals

LISA data to be dominated by (overlapping) signals, not noise:

- Data analysis workflow is expected to be quite different.



LIGO+Virgo, PRD2016



LIGO+Virgo, PRL2016