Gravitational waves in the third run of Advanced Virgo and LIGO

Tito Dal Canton - IJCLab

Overview

1. Recap of GW astronomy
2. IJCLab GW team
3. Status of GW astronomy before the O3 run
4. Results from the O3 run
5. The future

GW: gravitational wave

NS: neutron star

BH: black hole

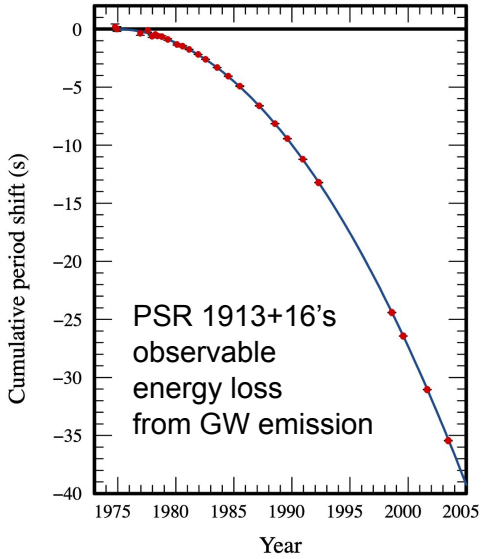
O1, **O2**, **O3**: observing runs of Advanced Virgo/LIGO

Recap of GW astronomy: GW theory

Einstein field equations
Flat, empty spacetime
Weak metric perturbation h_{ij}

→

Wave equation for h_{ij}
Speed of light
Two polarization states



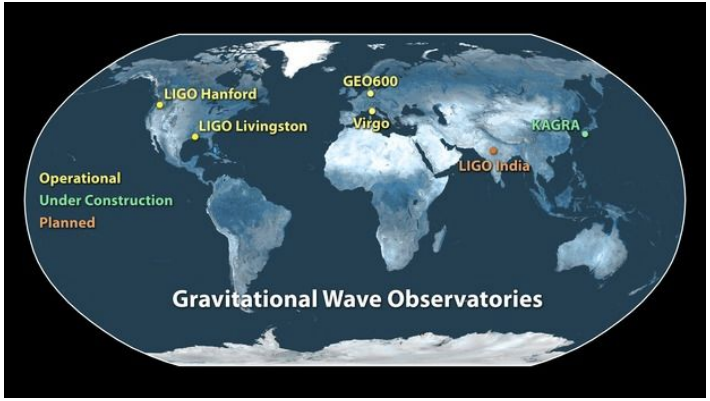
Mass ~ 10 M_{Sun}

Time-varying mass quadrupole Q

r ~ 100 Mpc

$$h_{ij} \sim \frac{G}{c^4}\frac{\ddot{Q}}{r} \sim 10^{-21}$$

Recap of GW astronomy: detectors



Recap of GW astronomy: detector data

Fundamental noise

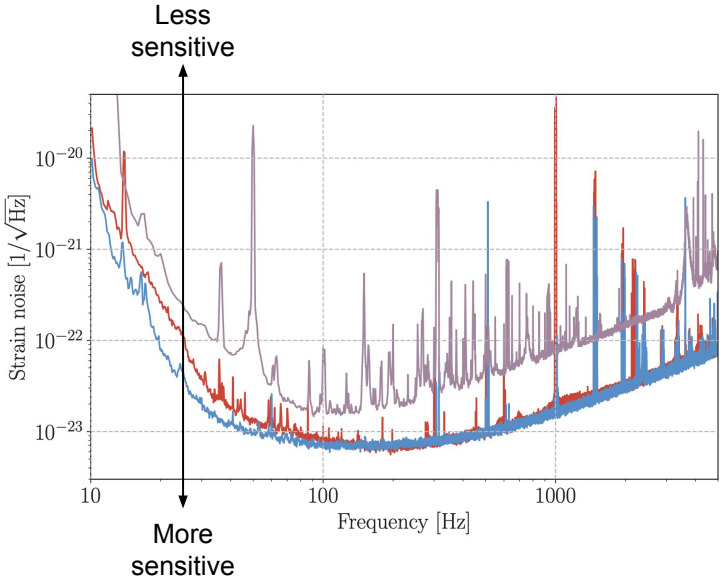
- Shot noise
- Thermal noise
- Seismic noise

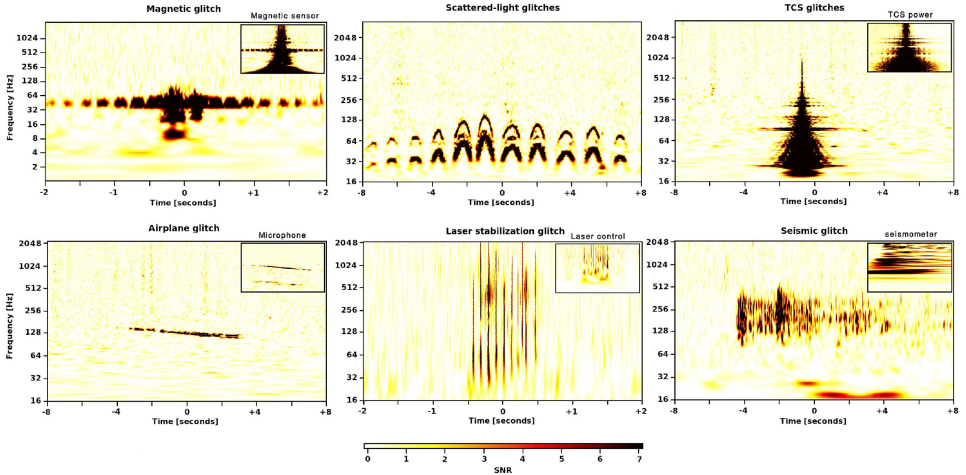
Excess/technical noise

- Saturation glitches
- Scattered light
- Whistles
- Blip glitches
- Lines

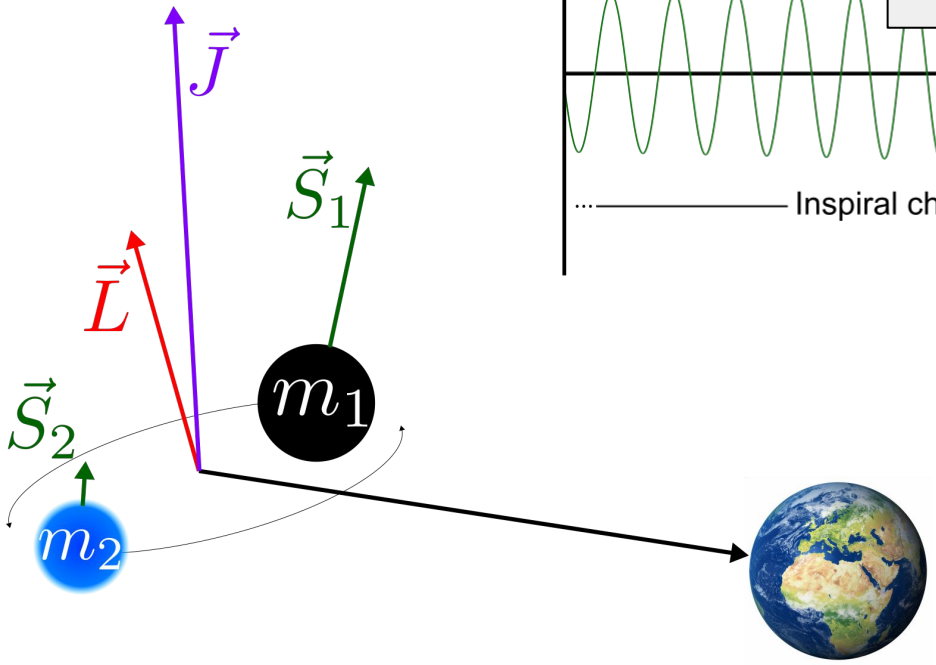
Astrophysical signals

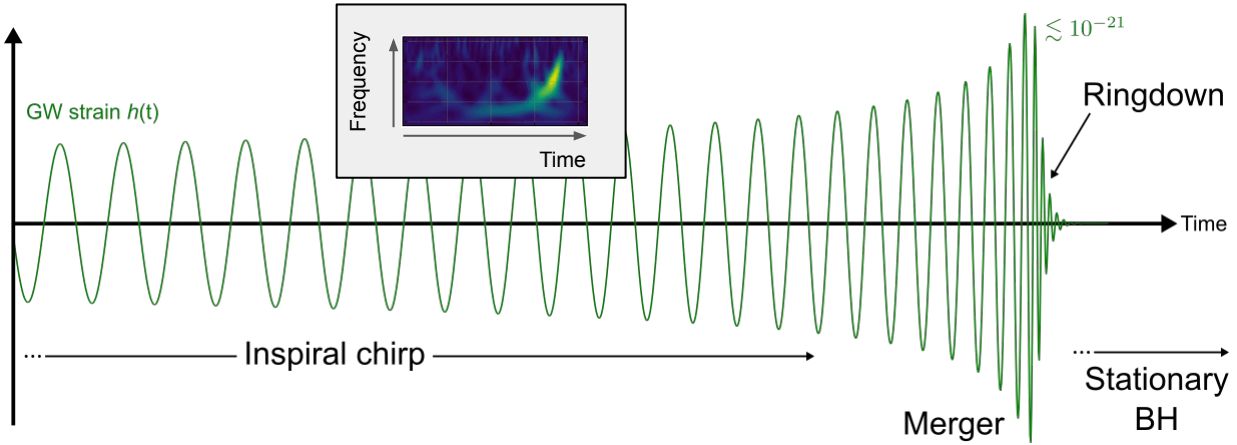
- **Compact binary mergers**
- Core-collapse SN bursts
- Quasi-monochromatic GWs
- Cosmic string bursts
- Stochastic background





Recap of GW astronomy: compact binary mergers



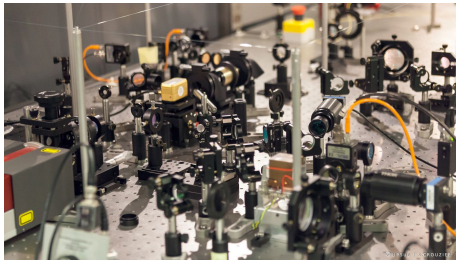


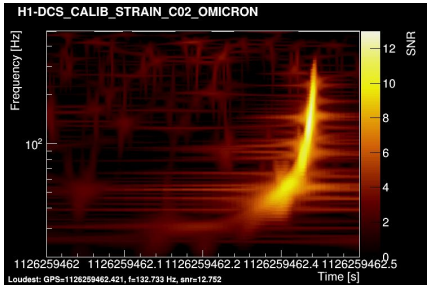
Data analysis challenges:

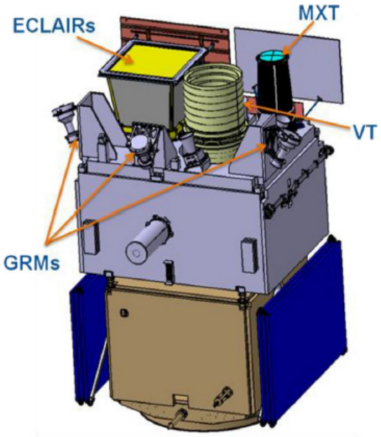
1. Signal detection
   a. Correlation / matched filtering
   b. Time-frequency excess power
2. Parameter estimation
   a. Bayesian formalism

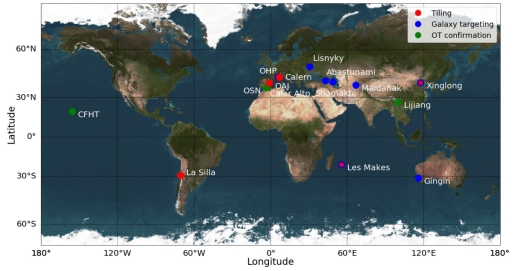
The GW team at IJCLab

- Improving Virgo's sensitivity using squeezed light (CALVA)
- Virgo detector characterization and data quality investigations
- Analysis of LIGO/Virgo data to search for compact binaries and cosmic strings
- Electromagnetic counterparts to GW events (SVOM, GRANDMA, Fermi/GBM)









GW astronomy before the O3 run

Abbott+ 2019, PRX

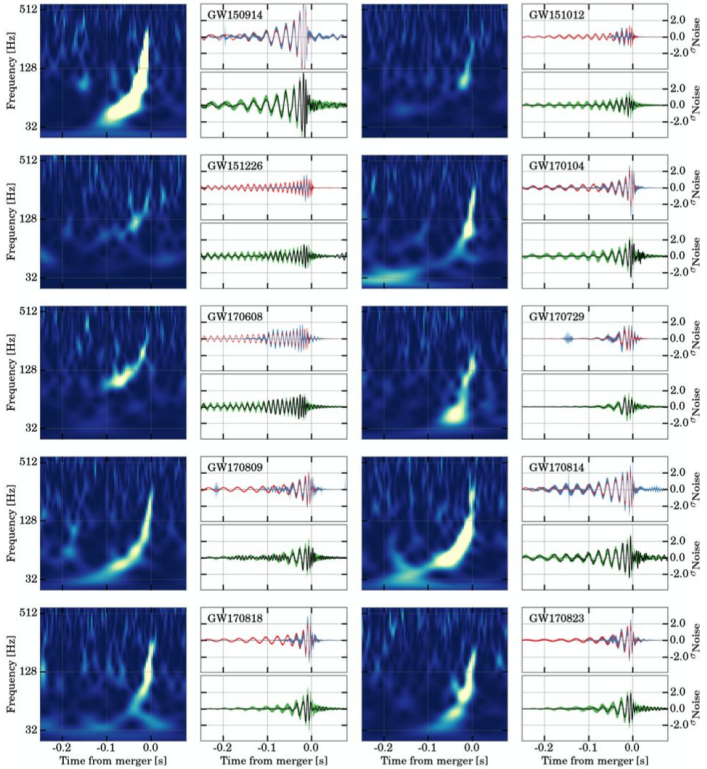
10 stellar-mass BH mergers

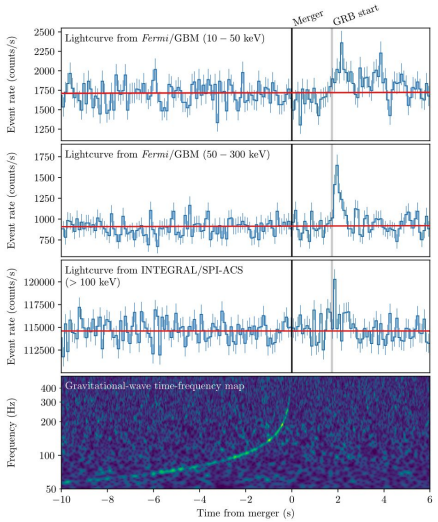
One NS merger

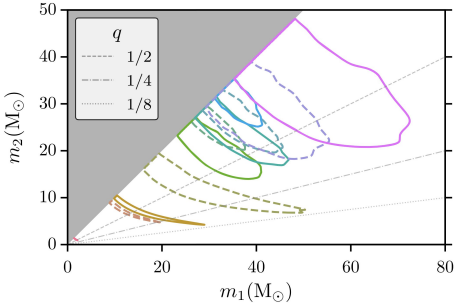
Weaker candidates from independent groups

"Wishlist"

- NSBH mergers
- Intermediate-mass BHs
- Unequal-mass binaries
- Large spins
- Tilted spins
- (and much more…)







The O3 run of Advanced Virgo and LIGO

LIGO improvements

Phys. Rev. D 102, 062003 (2020)

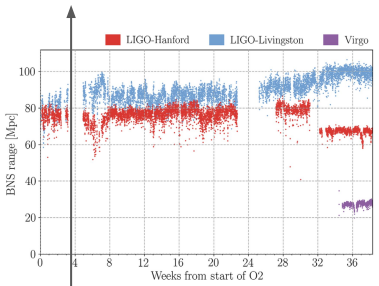
- Increased laser power
- Squeezed light
- Reduction of technical noise

Virgo improvements

- Increased laser power
- Squeezed light
- Reduction of technical noise
- Restored fused silica suspensions

O2 range

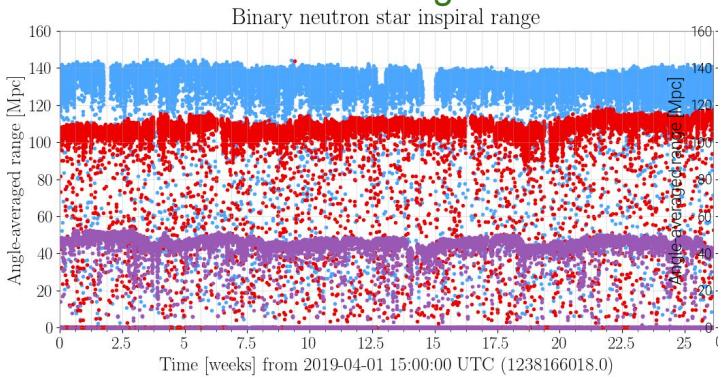
More sensitive



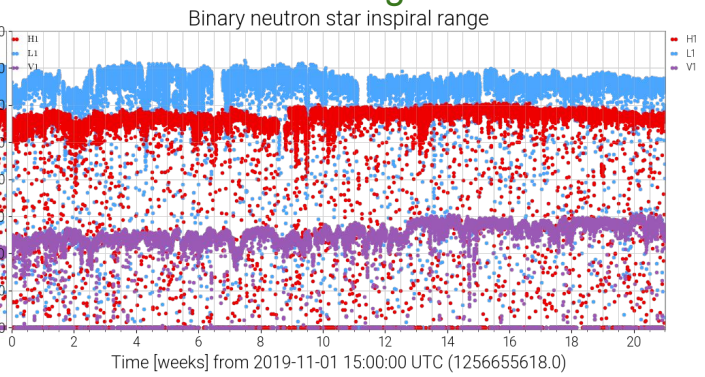
Less sensitive

Detection rate ~ Range^3

O3a range



O3b range



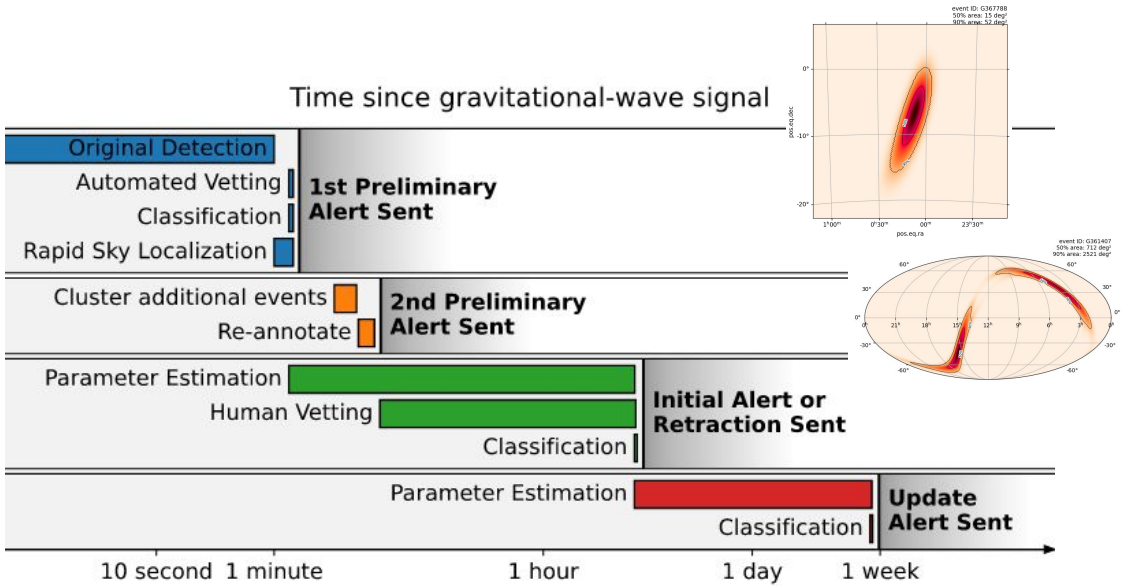
2019-04-01

2019-10
commissioning break

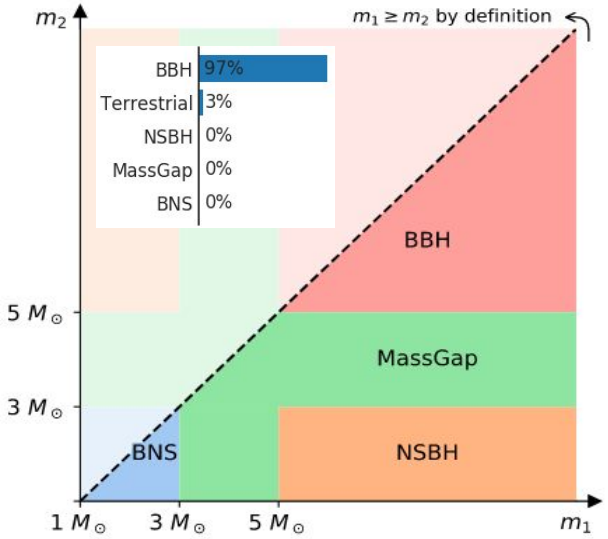
2020-03-27
Early break due to pandemic

The O3 run of Advanced Virgo and LIGO

Public minute-latency alerts



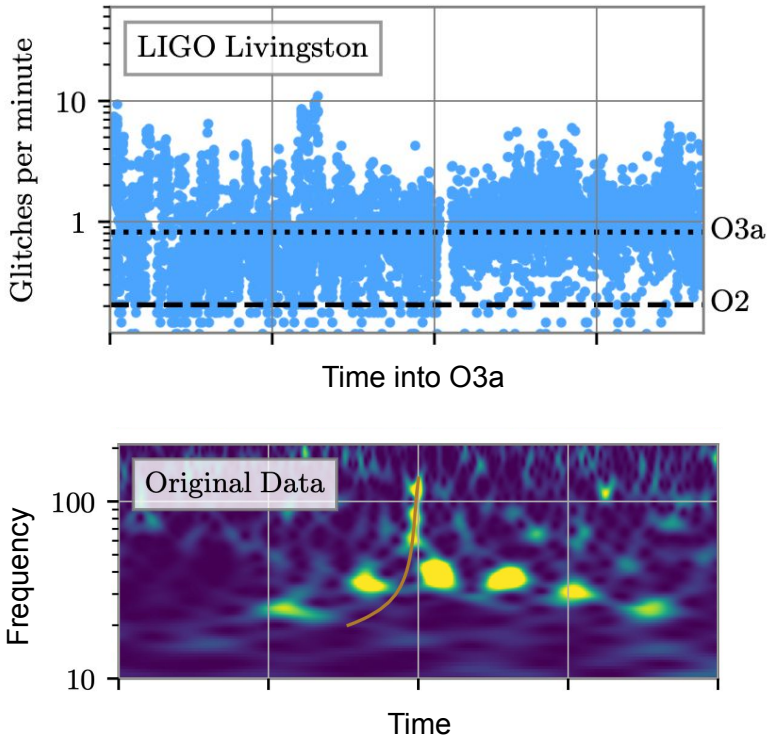
Source classification



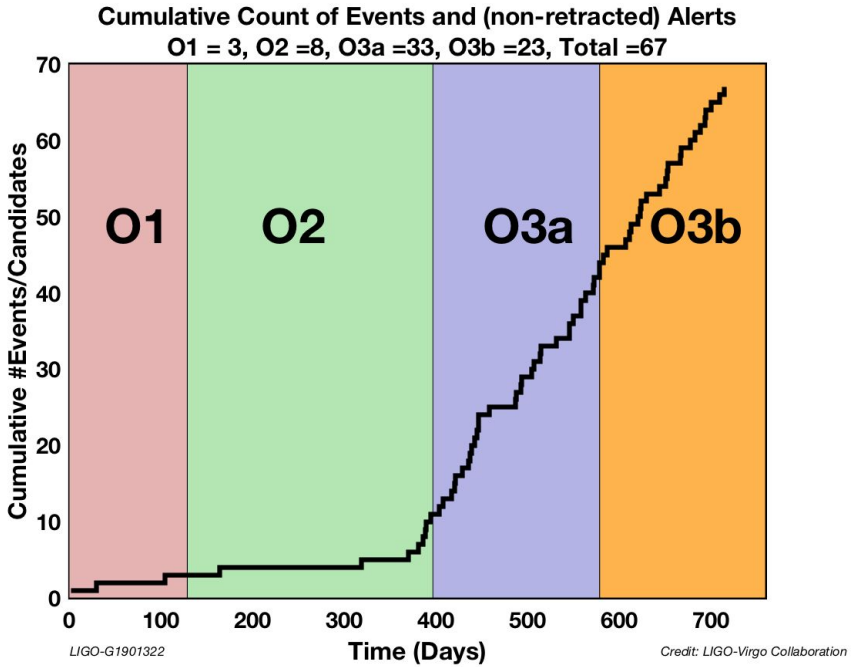
https://gracedb.ligo.org – https://emfollow.docs.ligo.org

The O3 run of Advanced Virgo and LIGO

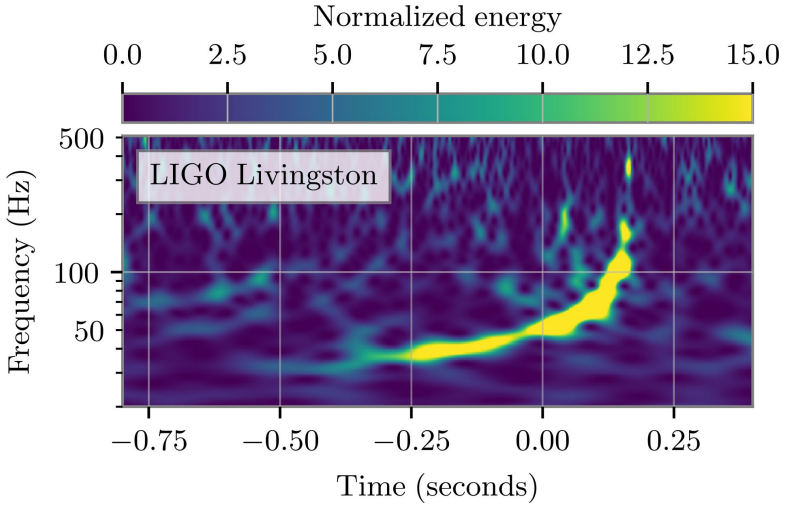
Challenging data analysis

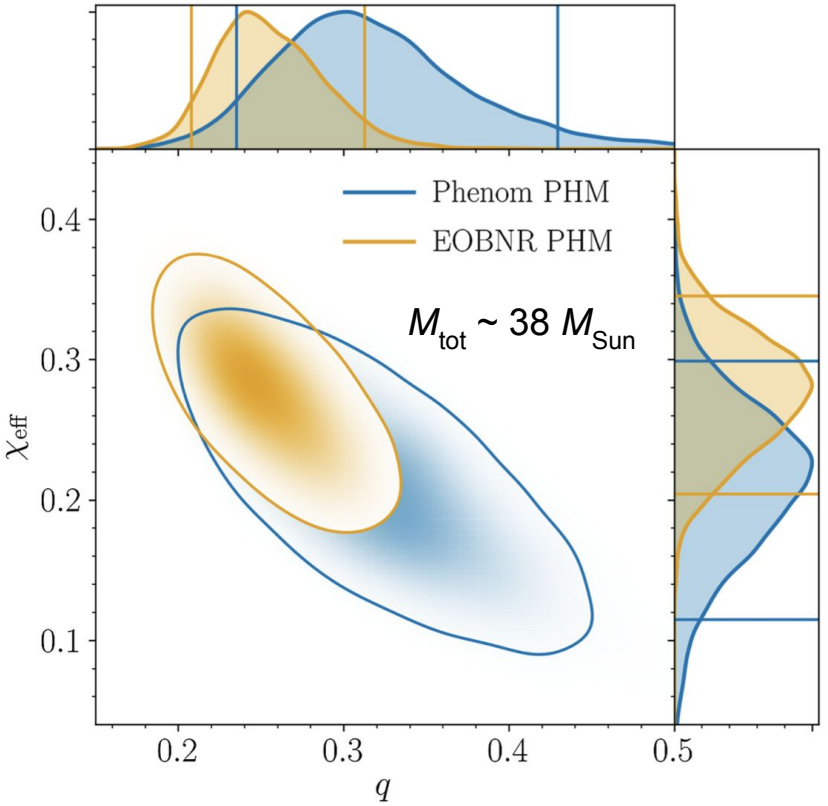


Higher detection rate



GW190412: a merger of unequal-mass BHs

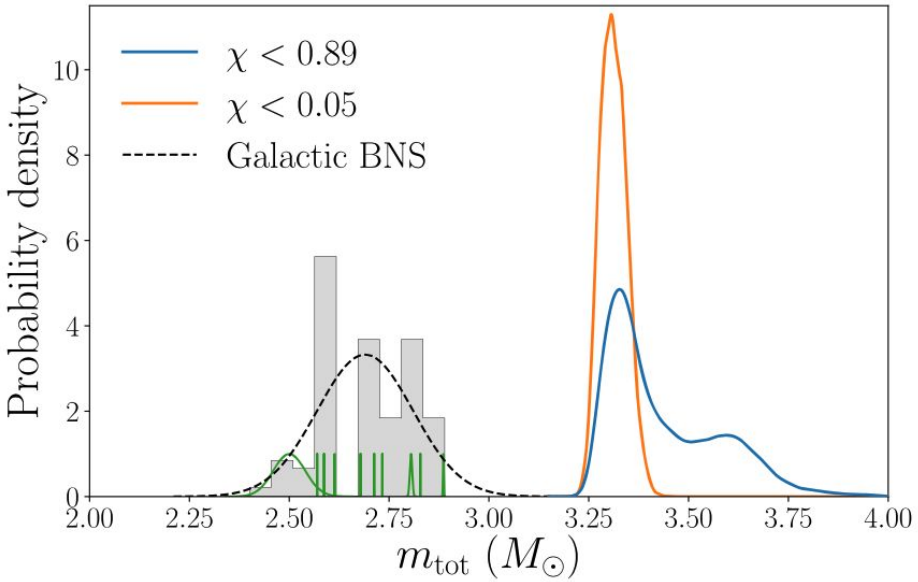




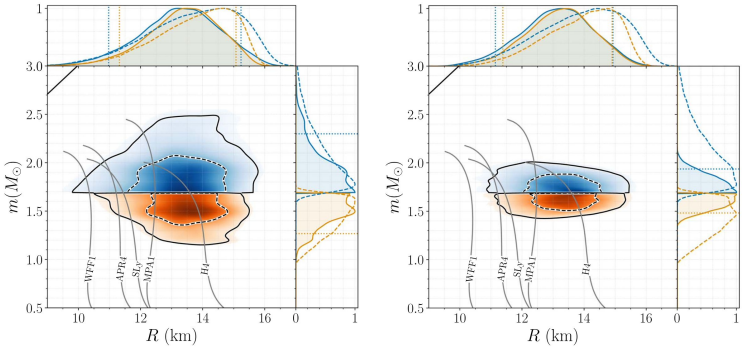
- The merging BH binary population includes unequal-mass binaries
- First observation of GW multipole moments beyond the quadrupole

Phys. Rev. D 102, 043015

GW190425: a merger involving massive NSs

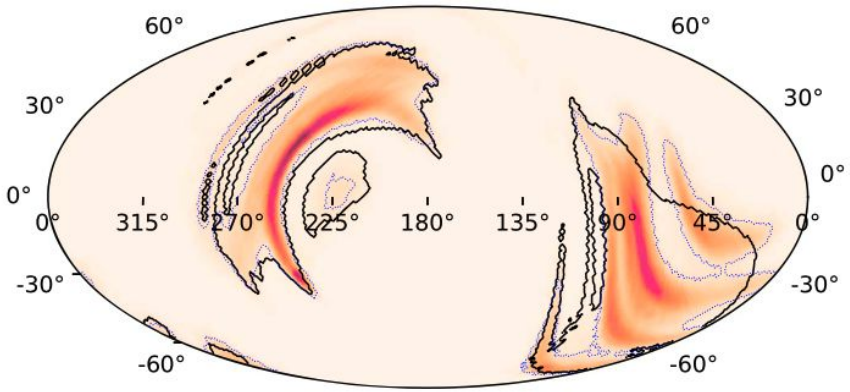


- Probably the second NS merger detected by LIGO and Virgo
- Total mass **incompatible** with known galactic NS binaries
- No evidence for tides; one or both objects may be BHs
- No significant new constraints on NS equation of state

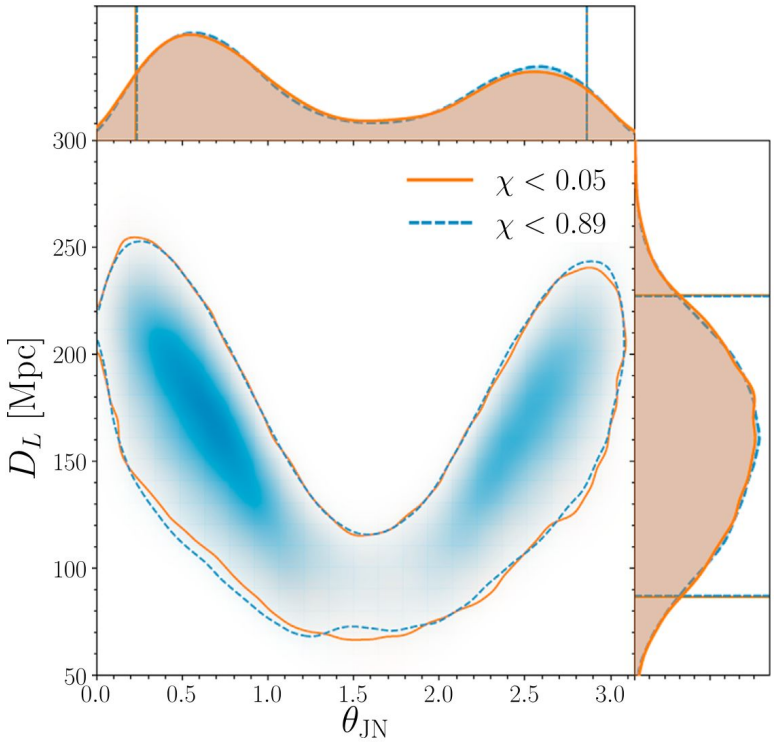


ApJ Letters, 892:L3 (24pp), 2020

GW190425: a merger involving massive NSs

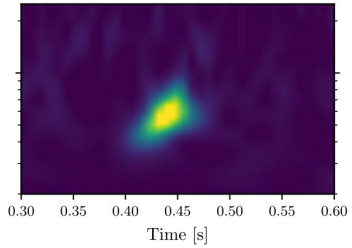


- LIGO-Livingston-only signal with uncertain spatial localization
- 2–5 times farther than GW170817
- Associated GRB in INTEGRAL claimed, not confirmed

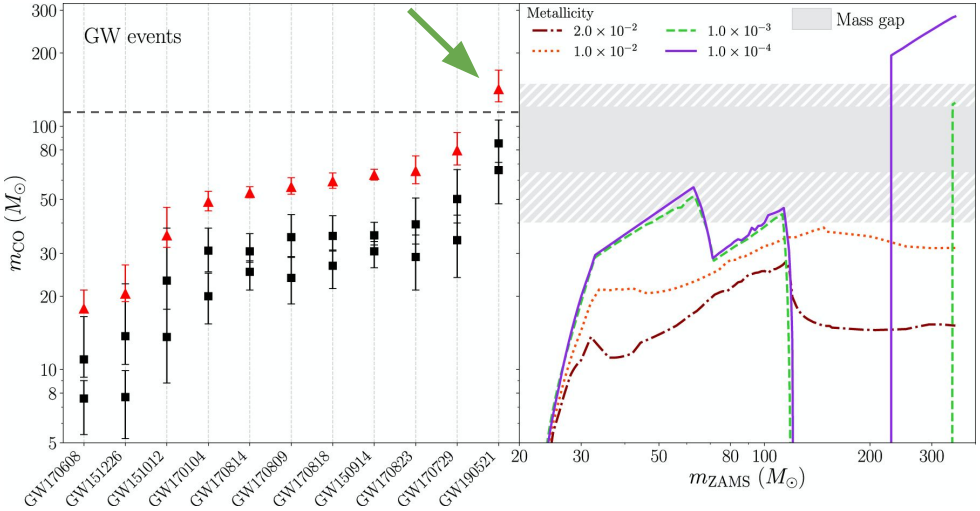


GW190521: a merger of remarkably massive BHs

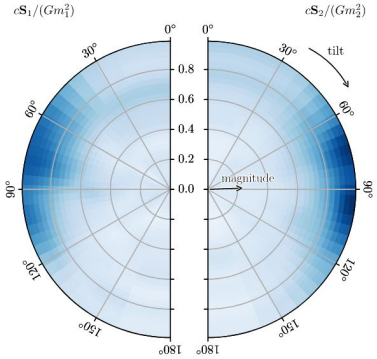
- **Shortest** signal confidently detected so far



- Remnant object is an **intermediate mass** BH
- Heavier progenitor BH in **pair-instability mass gap**



- Evidence for **very large spins, spin misalignment** and **orbital precession**

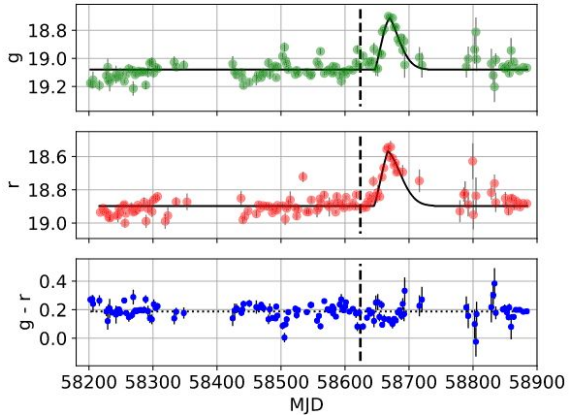


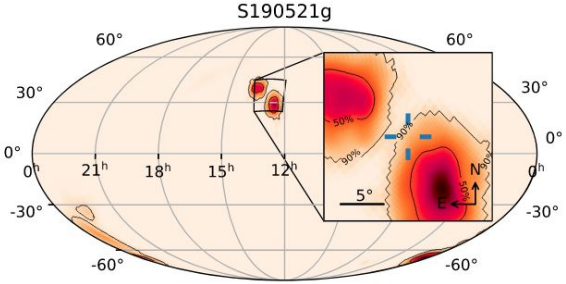
- Possible presence of **orbital eccentricity**
  e.g. Romero-Shaw+ ApJL 2020

GW190521: a BH merger in an AGN disk?

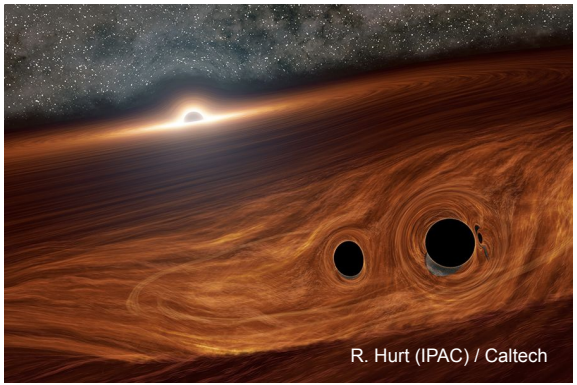
Candidate Electromagnetic Counterpart to the Binary Black Hole Merger Gravitational-Wave Event S190521g*

M. J. Graham,[1,†] K. E. S. Ford,[2,3,4] B. McKernan,[2,3,4] N. P. Ross,[5] D. Stern,[6] K. Burdge,[1] M. Coughlin,[7,8] S. G. Djorgovski,[1] A. J. Drake,[1] D. Duev,[1] M. Kasliwal,[1] A. A. Mahabal,[1] S. van Velzen,[9,10] J. Belecki,[11] E. C. Bellm,[12] R. Burruss,[11] S. B. Cenko,[13,14] V. Cunningham,[9] G. Helou,[15] S. R. Kulkarni,[1] F. J. Masci,[15] T. Prince,[1] D. Reiley,[11] H. Rodriguez,[11] B. Rusholme,[15] R. M. Smith,[11] and M. T. Soumagnac[16,17]

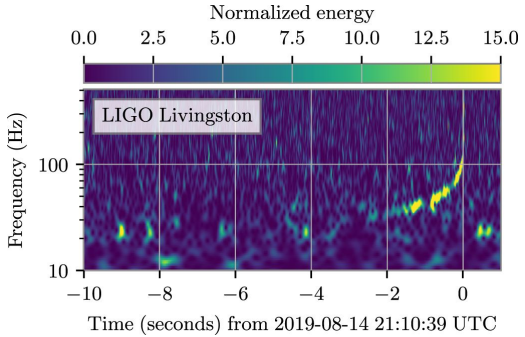


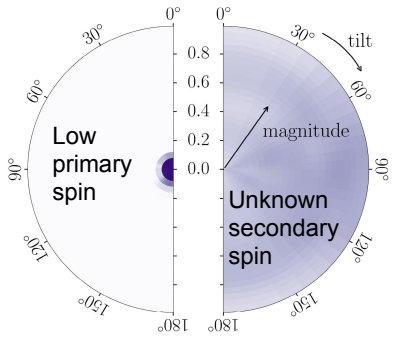


We predict a similar repeat flare in this source when the kicked BBH reencounters the disk on timescale $1.6\ \mathrm{yr}(M_{\mathrm{SMBH}}/10^8\ M_\odot)(a/10^3 r_g)^{3/2}$.

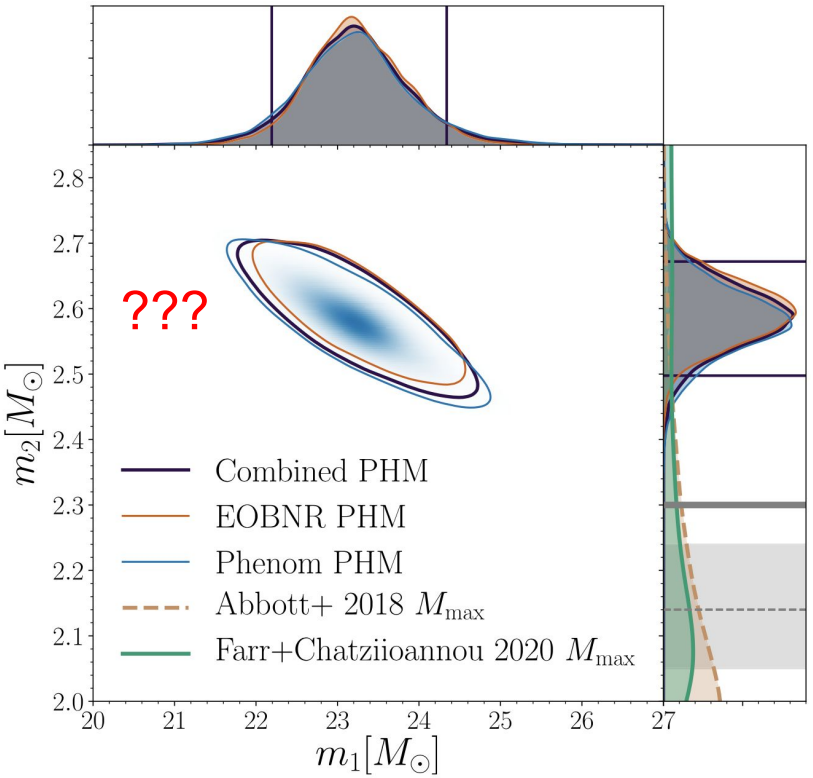


GW190814: the first observed NSBH merger… maybe





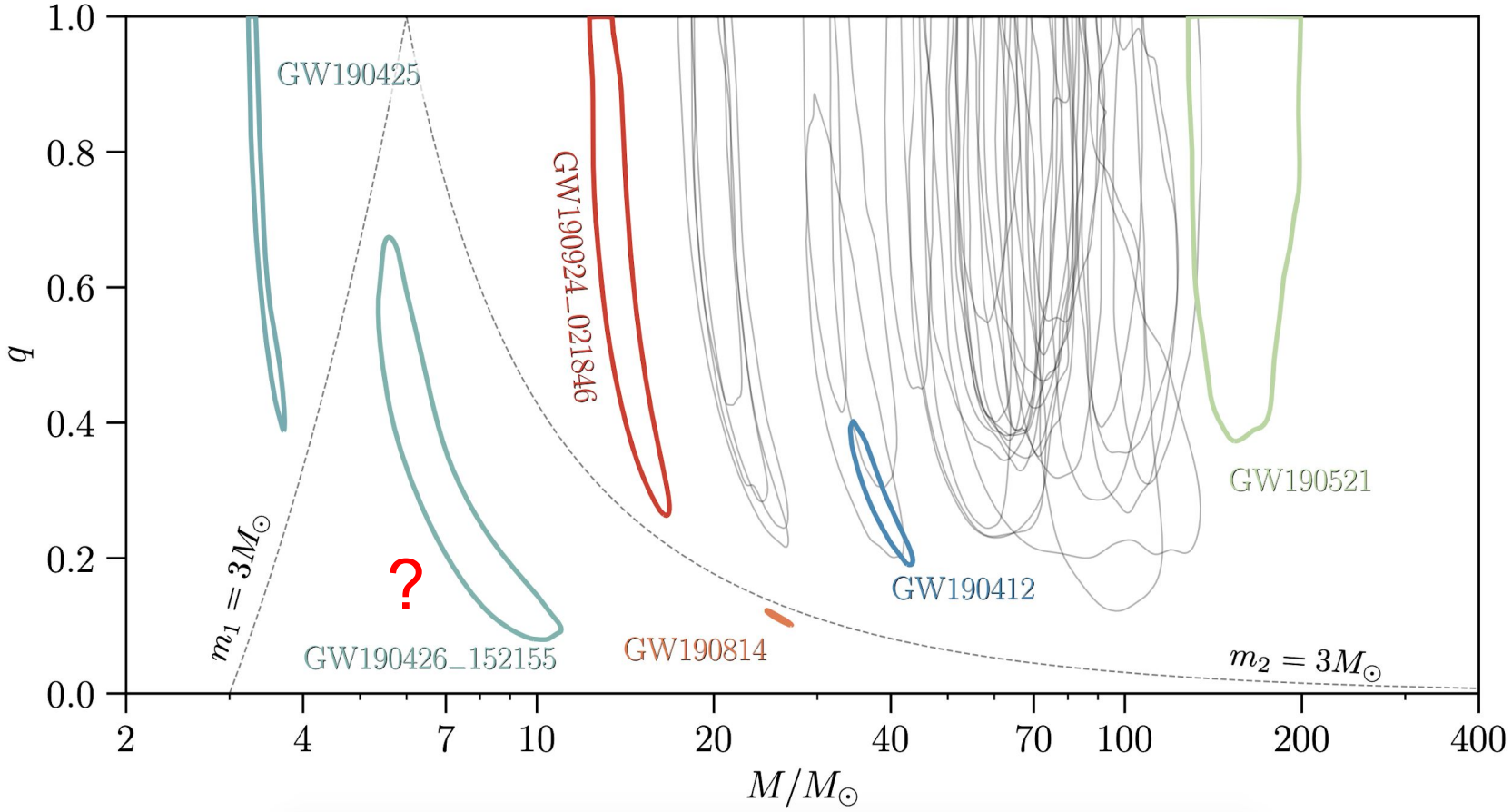
- Secondary object is either the **lightest black hole** or the **heaviest neutron star** ever discovered in a compact binary
- Estimates of max possible NS mass favor the first hypothesis
- The combination of masses, mass ratio, and rate is challenging to explain



ApJ Letters, 896:L44 (20pp), 2020

Group picture from the first half of O3

arXiv:2010.14527



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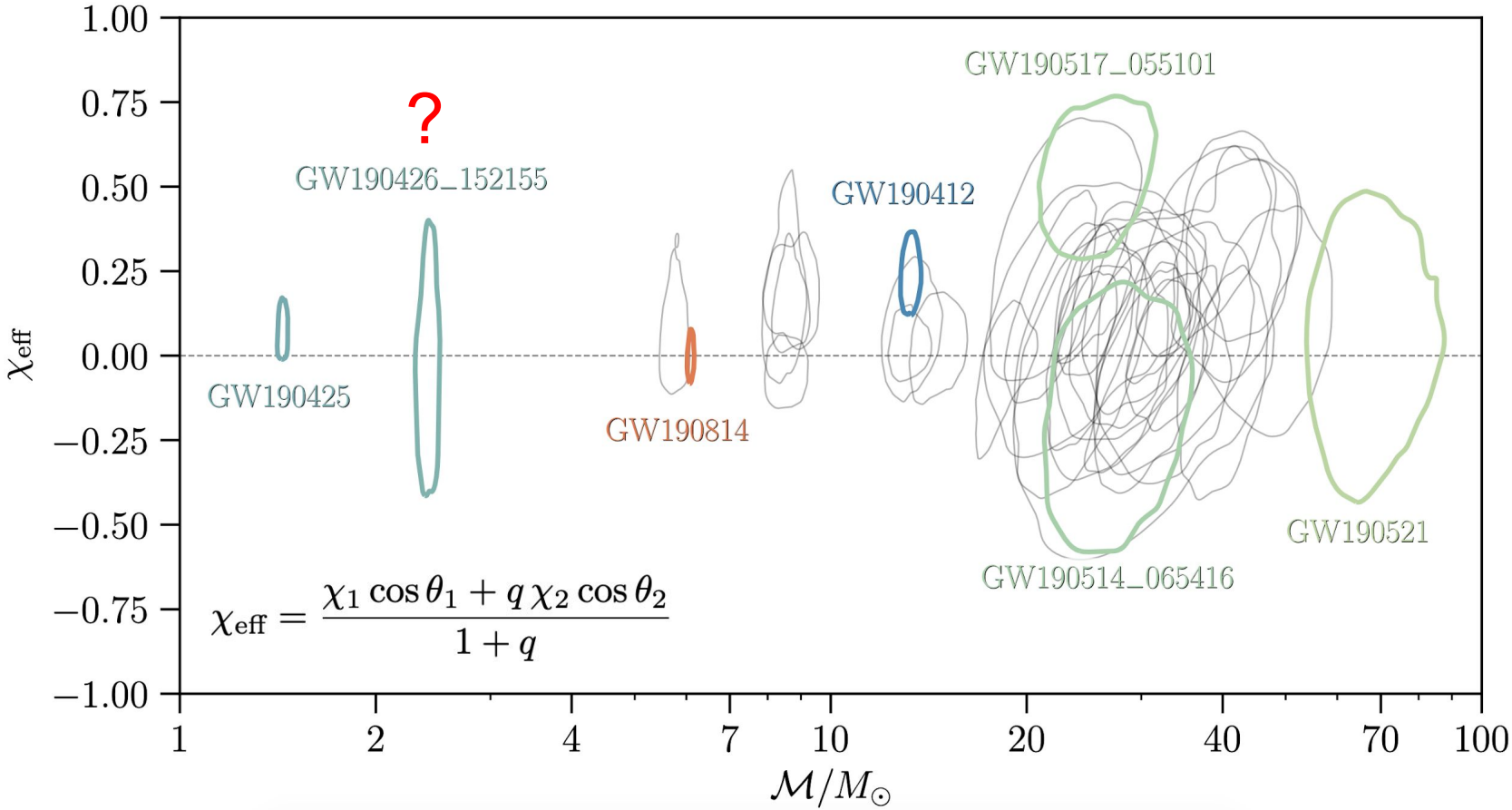
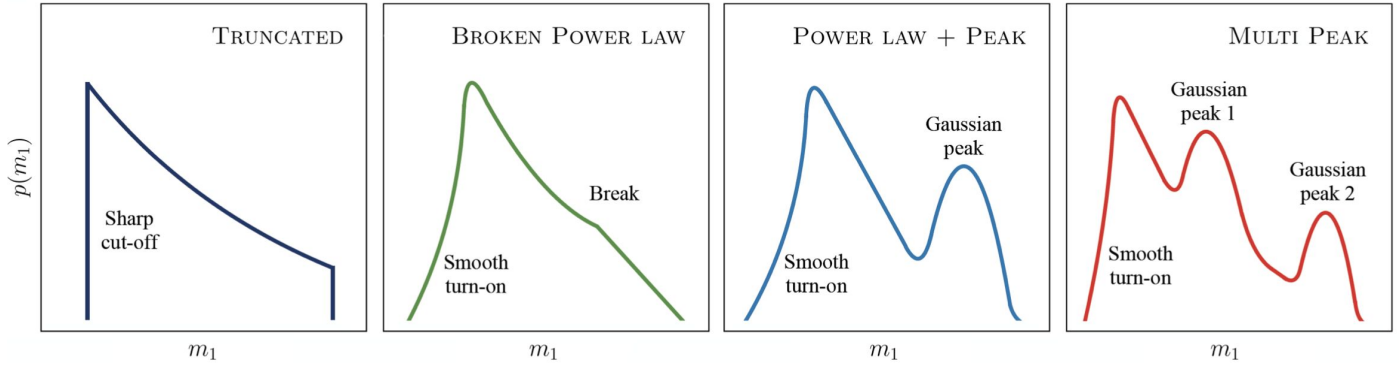


Updated inference of the BBH population

arXiv:2010.14533

Mass distribution models



Spin distribution models

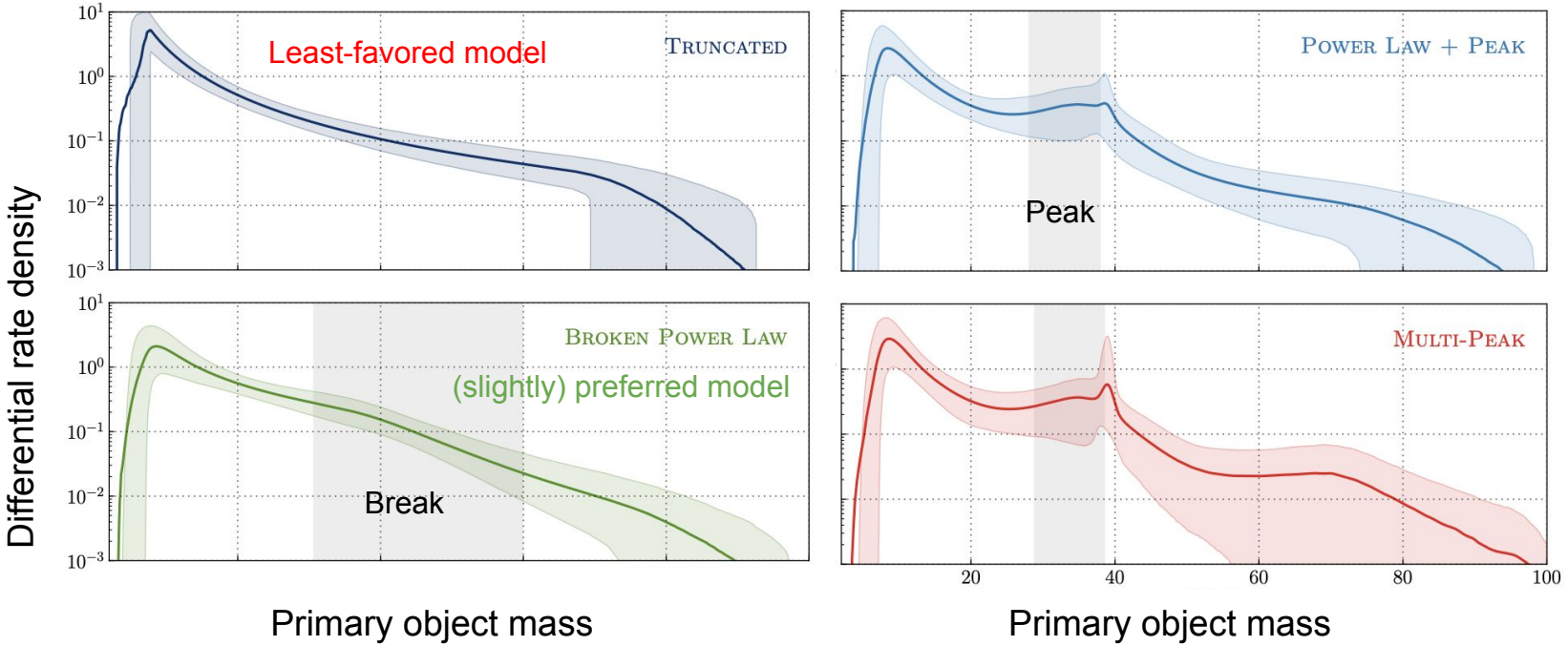
- Independently-drawn magnitude and tilt angle for each component
- Effective and precession spins as a bivariate Gaussian
- Two-population model

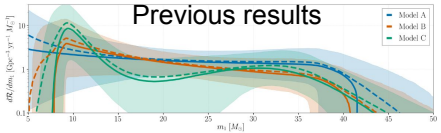
Redshift evolution models

- Merger rate independent from redshift
- Merger rate as a power law in 1+*z*

Updated inference of the BBH population

arXiv:2010.14533

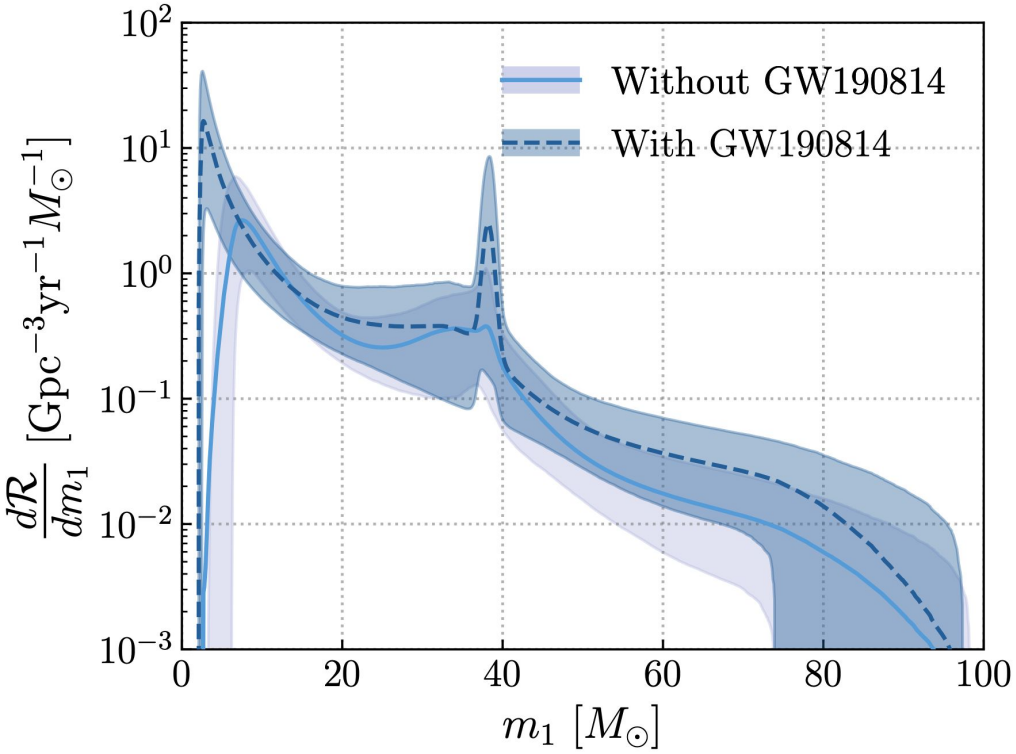




Feature at ~40 M_{Sun} and lack of mergers between NSs and BHs

Updated inference of the BBH population

arXiv:2010.14533

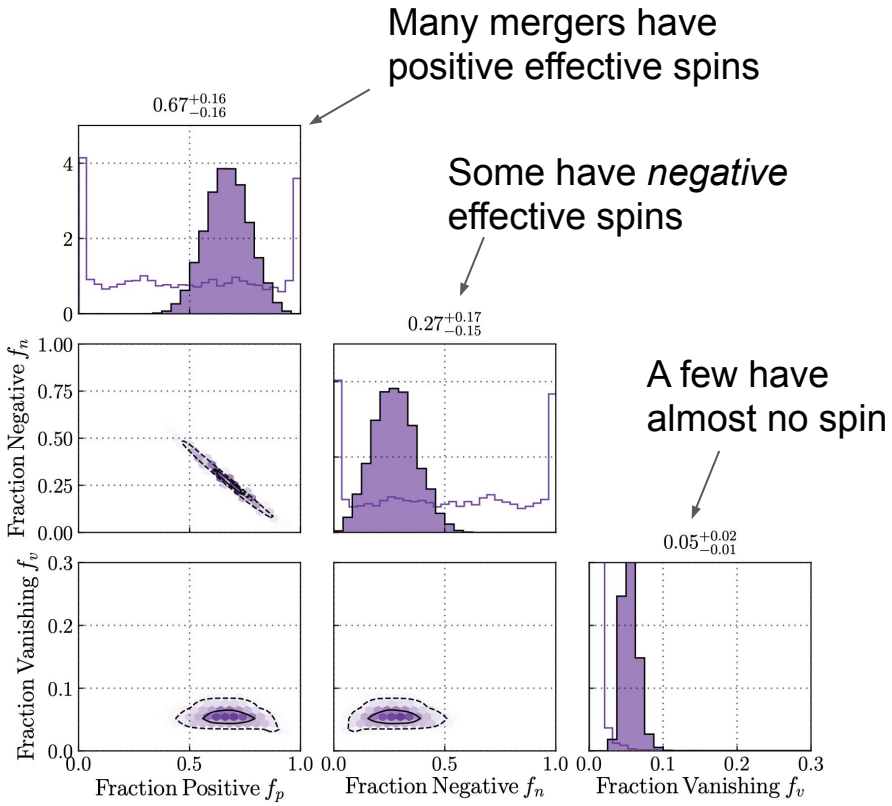


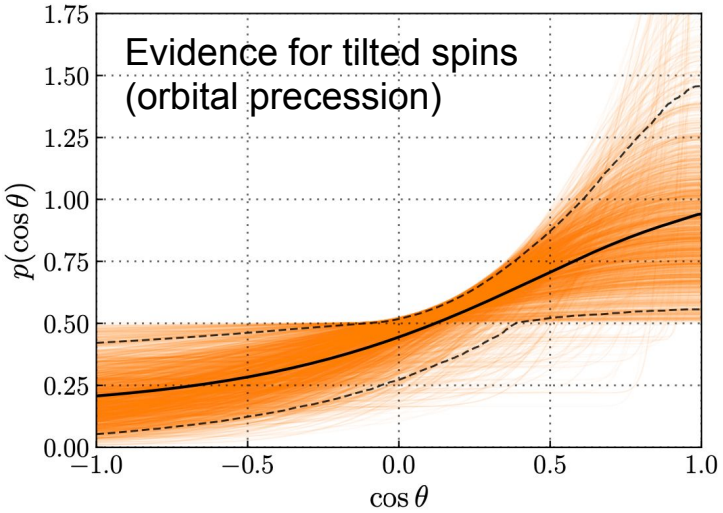
GW190814 is a “special case”, difficult to explain with these models.

More complicated models may eventually fit the entire catalog consistently.

Updated inference of the BBH population

arXiv:2010.14533

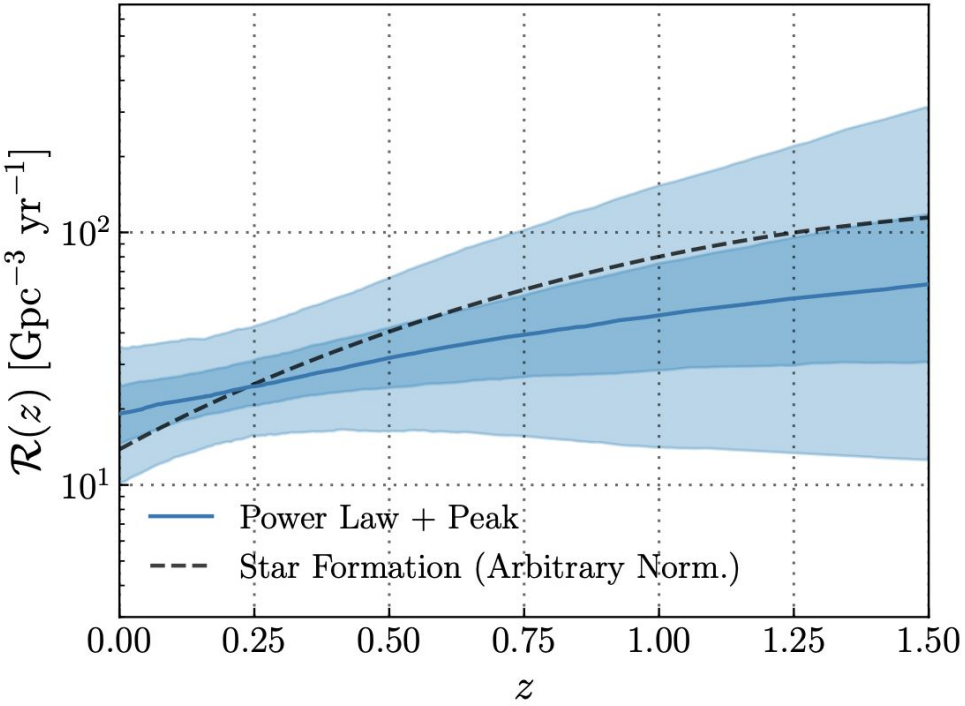




No evidence so far for correlations between mass and spin properties, or sub-populations

Updated merger rates

arXiv:2010.14533



$$\mathcal{R}_{\rm BNS} = 320^{+490}_{-240}\ {\rm Gpc}^{-3}\ {\rm yr}^{-1}$$

$$\mathcal{R}_{\rm BBH} = 23.9^{+14.9}_{-8.6}\ {\rm Gpc}^{-3}\ {\rm yr}^{-1}$$

If you believe GW190814 is an NSBH merger:

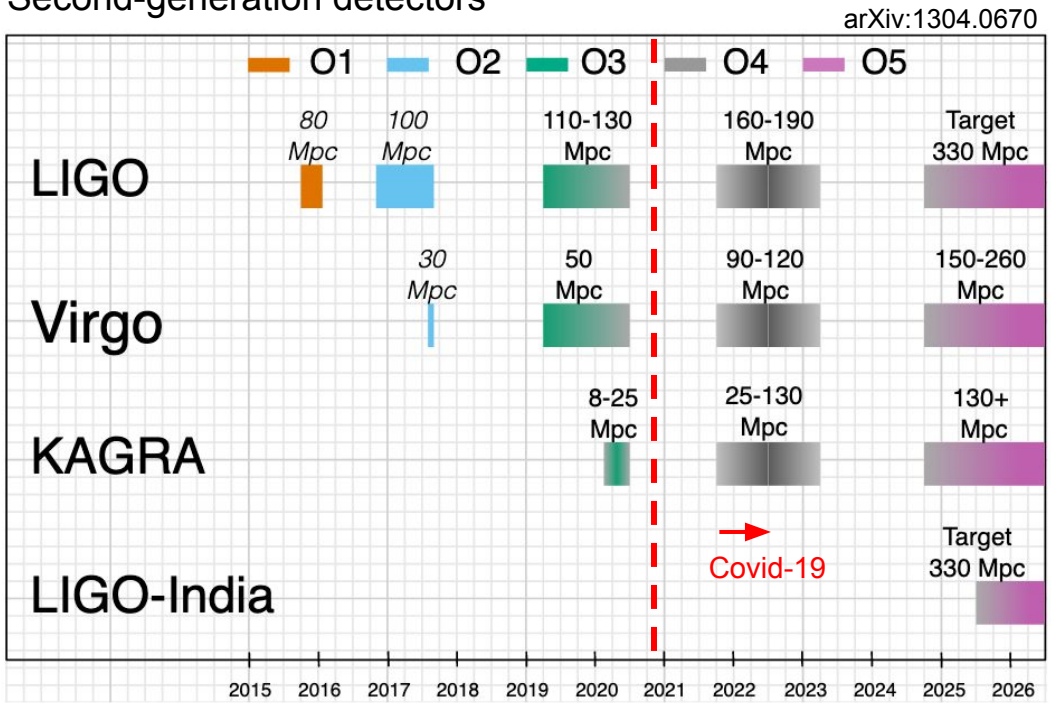
$$7^{+16}_{-6}\ {\rm Gpc}^{-3}\ {\rm yr}^{-1}$$

O3 summary: a challenging but successful run

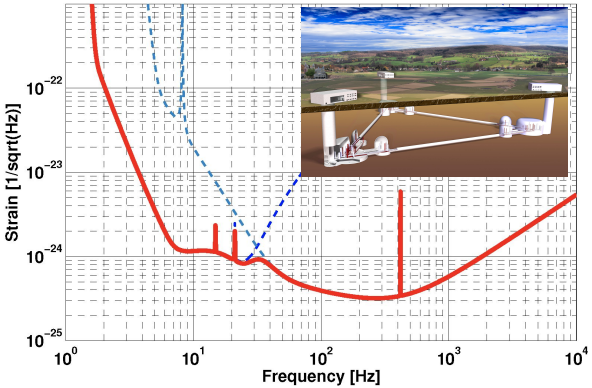
- 56 public non-retracted candidates from the whole run
- 39 published events (four “exceptional” ones) from the first half
  - Probing the extremes of the NS/BH mass distribution
  - Evidence for spins and orbital precession, *maybe* orbital eccentricity
  - Origin of these systems still elusive – current binary formation channels are challenged
  - No evidence of violations of general relativity
  - No definitive multimessenger discoveries since GW170817
- Forthcoming publications
  - Results from the second half of O3
  - Final analyses of O3 and updated astrophysical implications
- Public O3 data release in April and October 2021
- Get data from the GW Open Science Center: www.gw-openscience.org

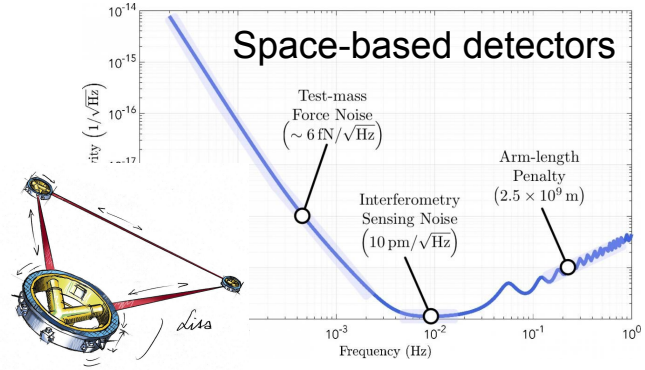
The future

Second-generation detectors



Third-generation detectors





Thank you!

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