Gravitational waves in the third run of Advanced Virgo and LIGO

Tito Dal Canton - Gravitational Waves Team, 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

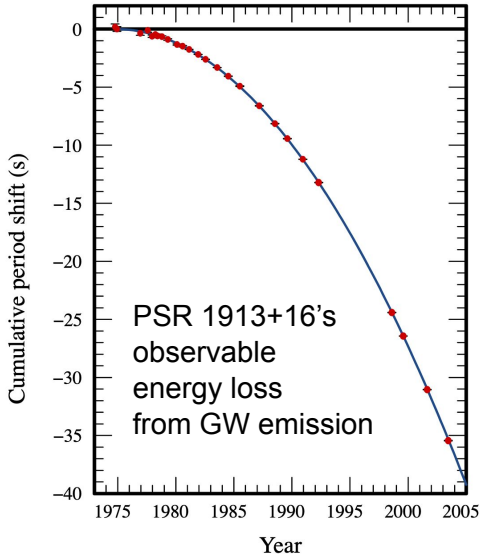
O1, **O2**, **O3**: observing runs of Advanced Virgo/LIGO

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



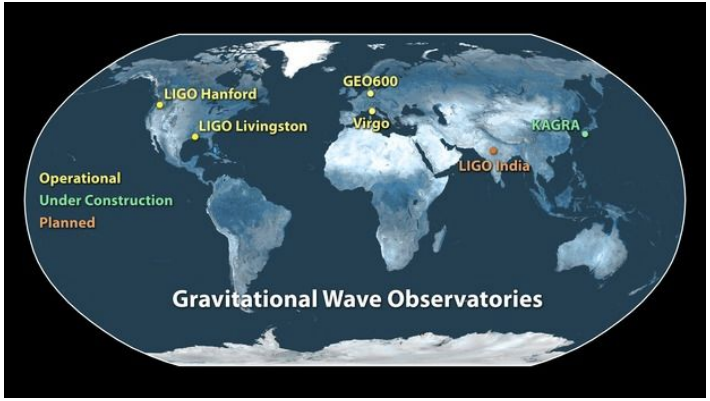
Mass ~ 10 M_{Sun}

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

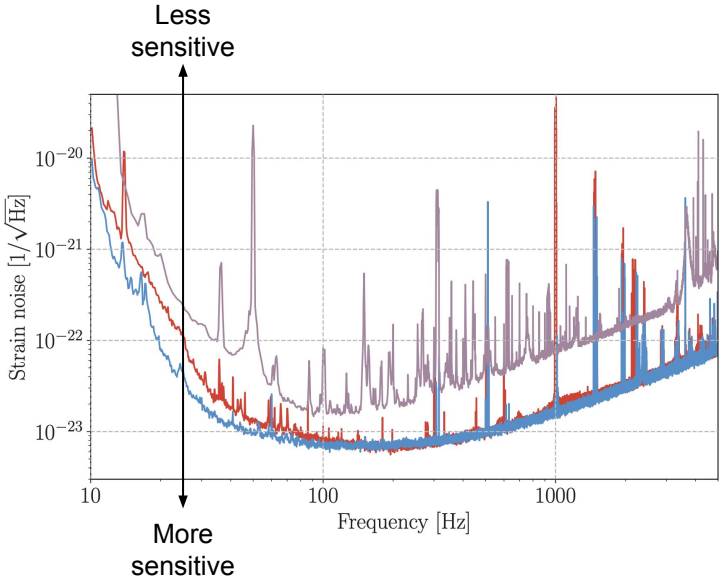
- Shot noise
- Thermal noise
- Seismic noise

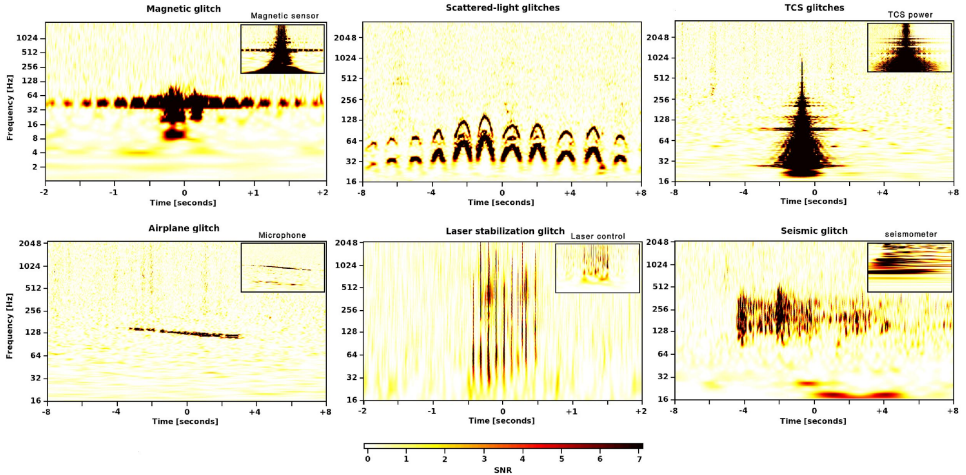
Excess/technical noise

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

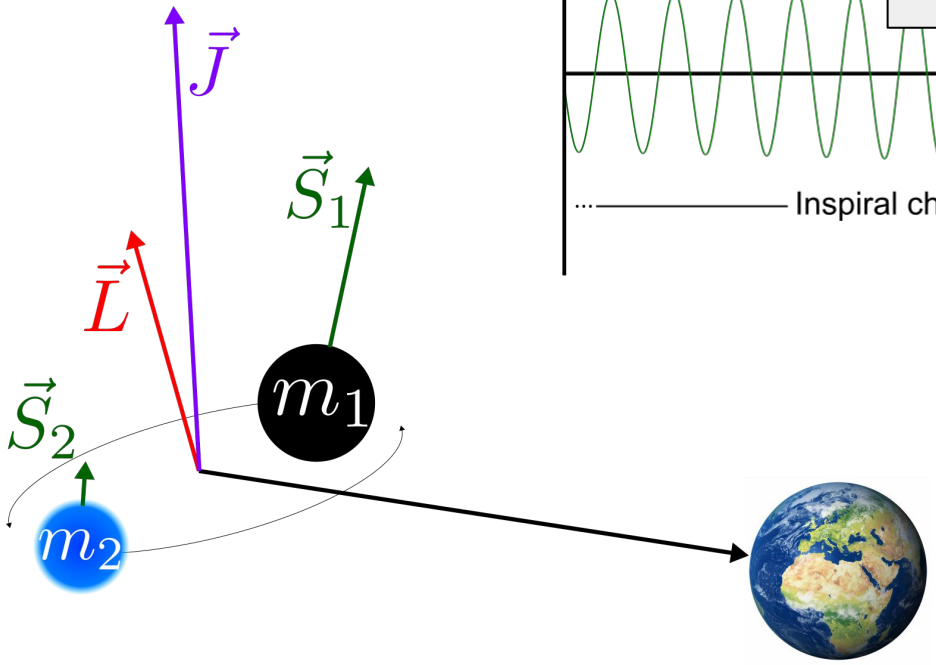
Astrophysical signals

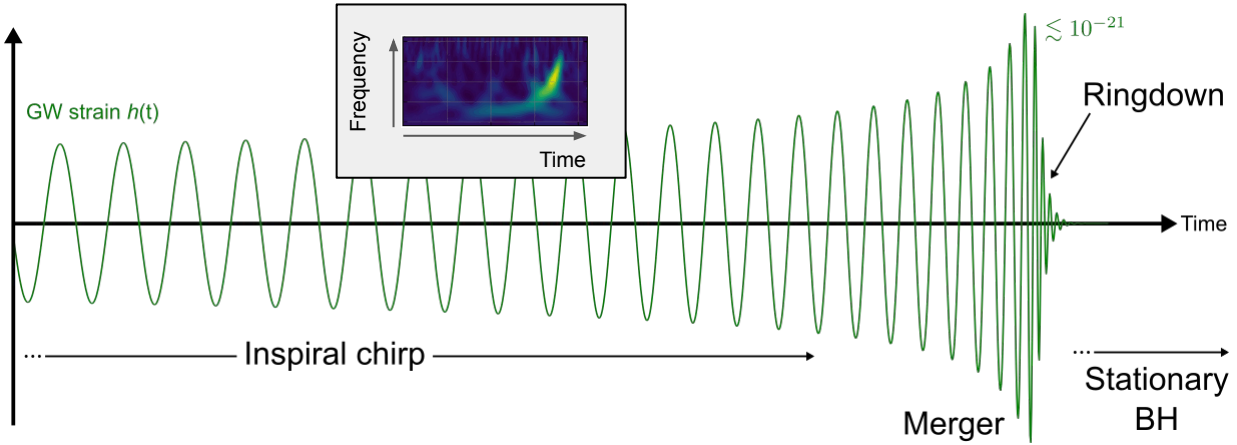
- **Compact binary mergers**
- Core-collapse SN bursts
- Quasi-monochromatic GWs
- Cosmic string bursts
- Stochastic background





Recap of GW astronomy: compact binary mergers



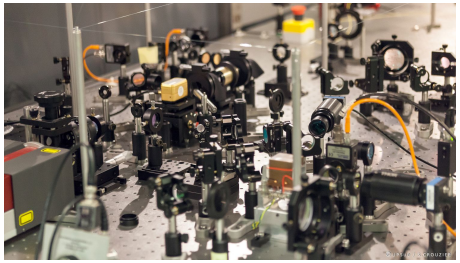


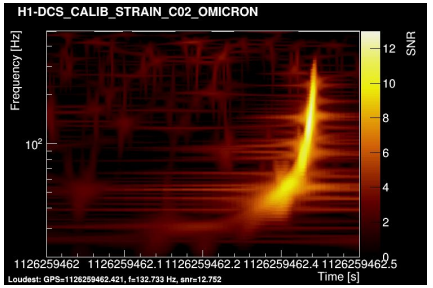
Data analysis challenges:

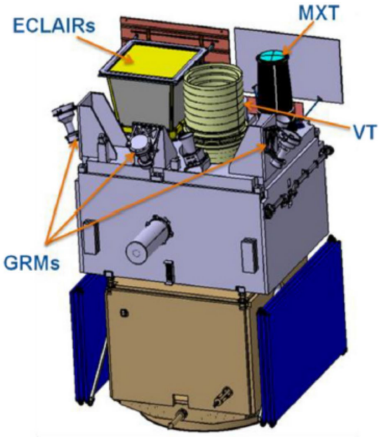
1. Signal detection
   a. Correlation / matched filtering
   b. Time-frequency excess power
2. Parameter estimation
   a. Bayesian formalism

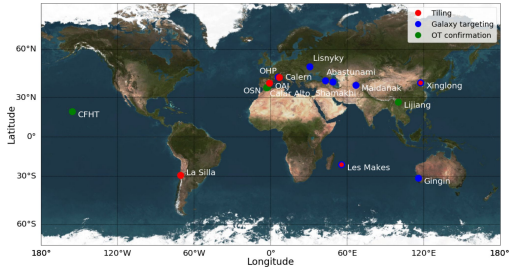
The GW team at IJCLab

- 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

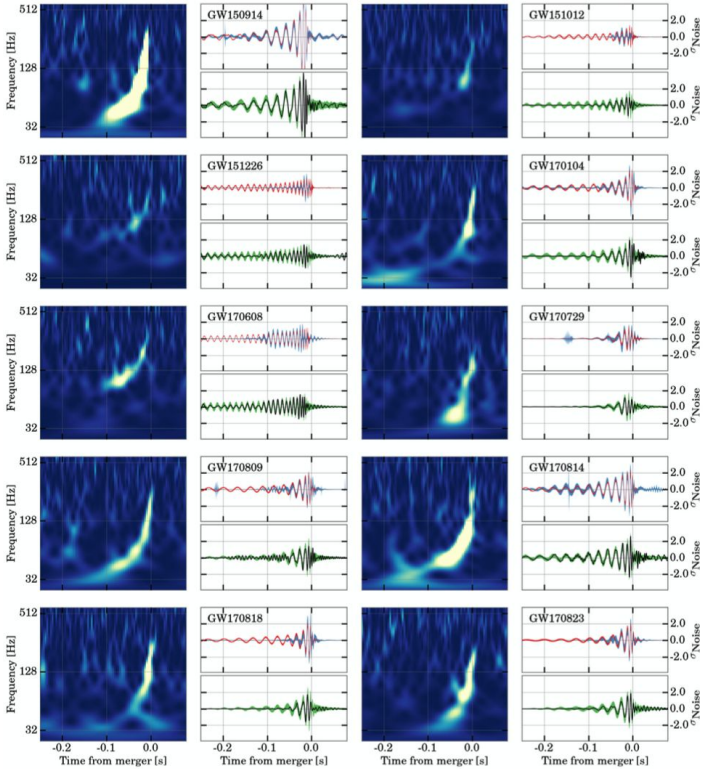
10 stellar-mass BH mergers

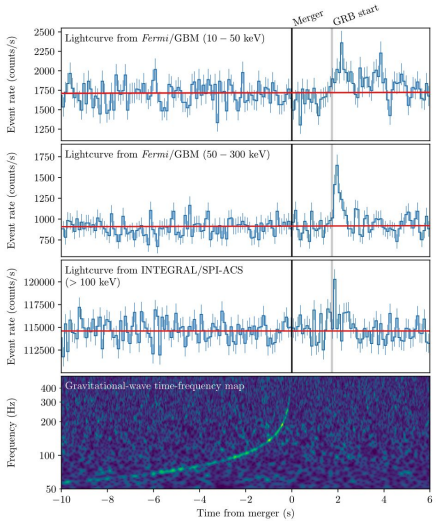
One NS merger

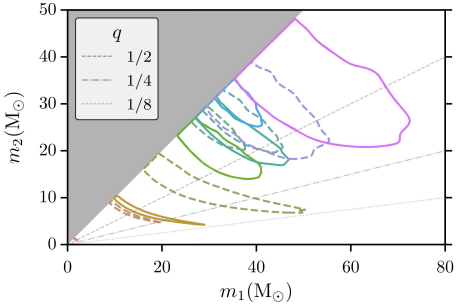
Weaker candidates from independent groups

"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)

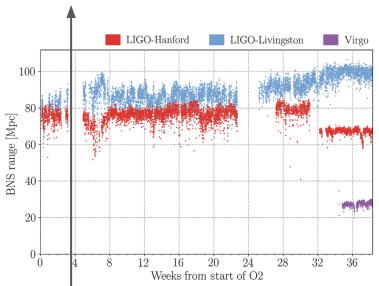
- Increased laser power
- Squeezed light
- Reduction of technical noise

Virgo improvements

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

O2 range

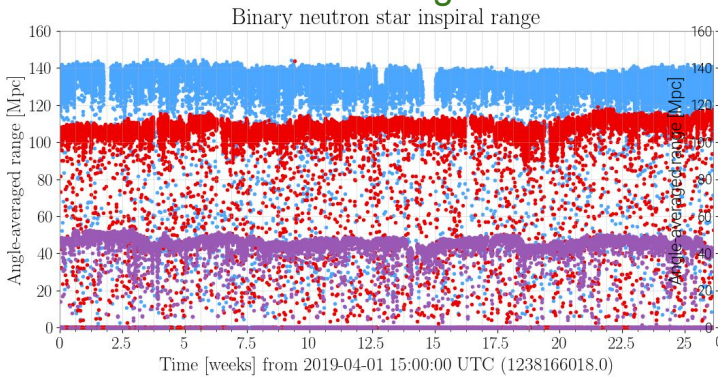
More sensitive



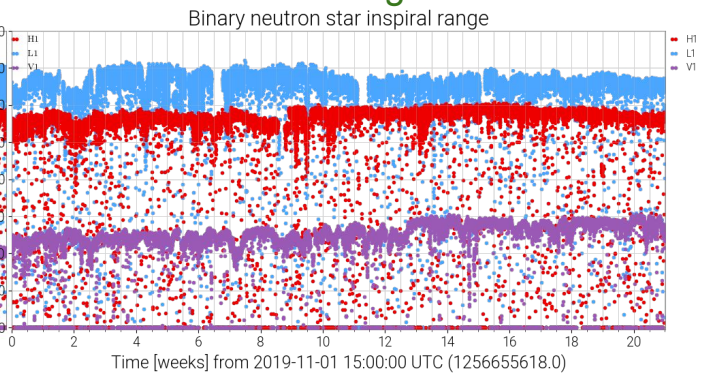
Less sensitive

Detection rate ~ Range^3

O3a range



O3b range



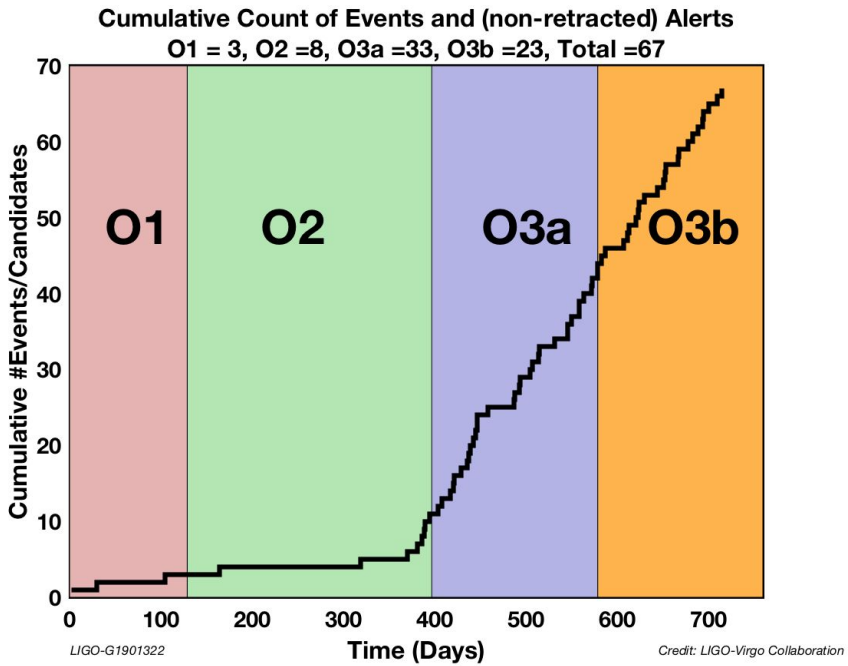
2019-04-01

2019-10
commissioning break

2020-03-27
Early break due to pandemic

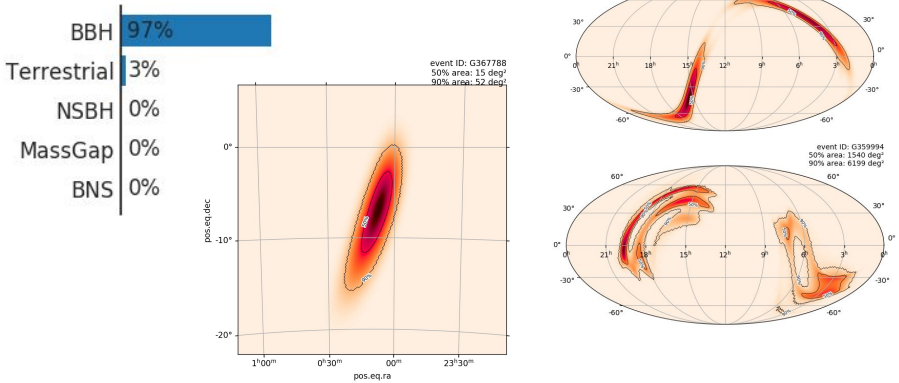
The O3 run of Advanced Virgo and LIGO

Higher detection rate



Public minute-latency alerts

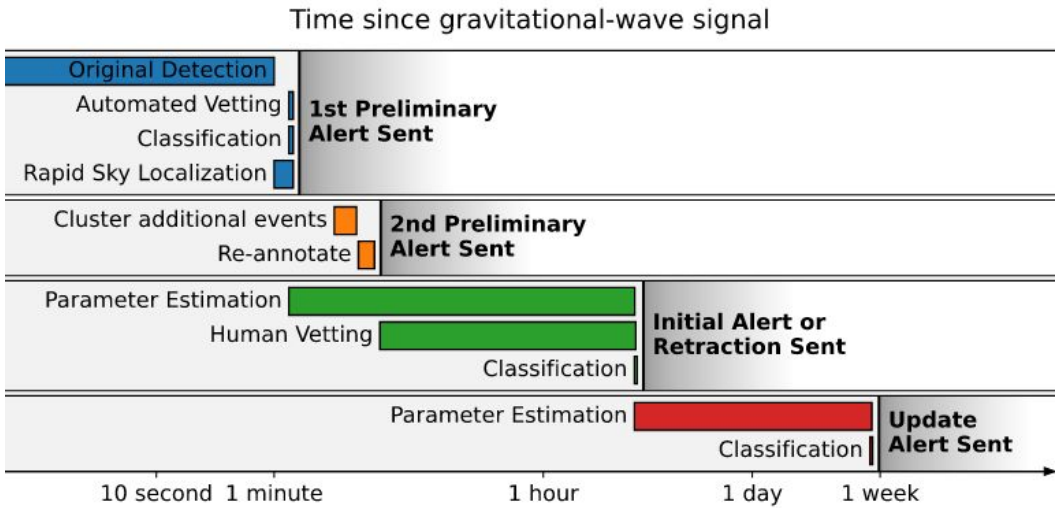
- Automatic notices, human-vetted circulars
- False alarm rate threshold ~ O(1/year)
- Spatial localization, source classification
- https://gracedb.ligo.org
- 56 non-retracted alerts



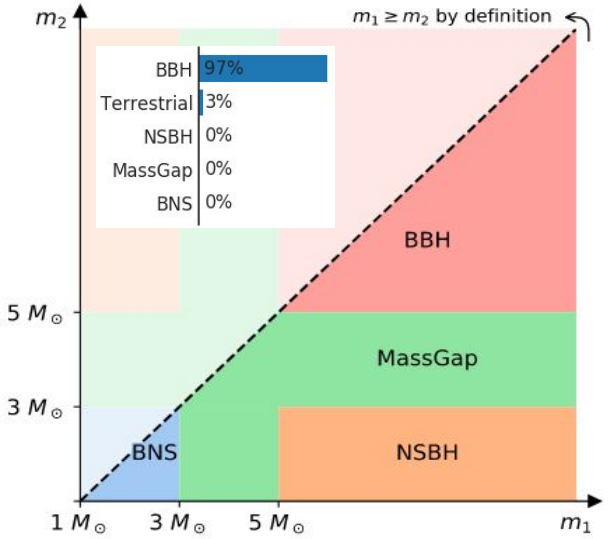
4 published discoveries

The O3 run of Advanced Virgo and LIGO

Public alert distribution timeline

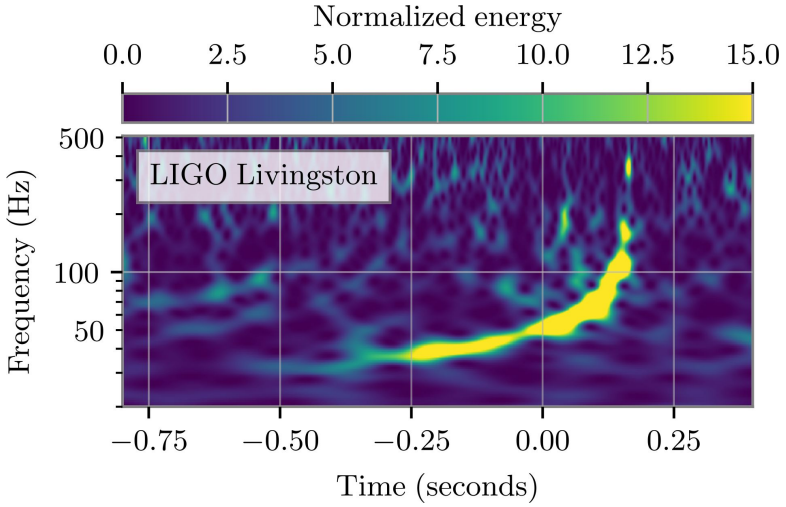


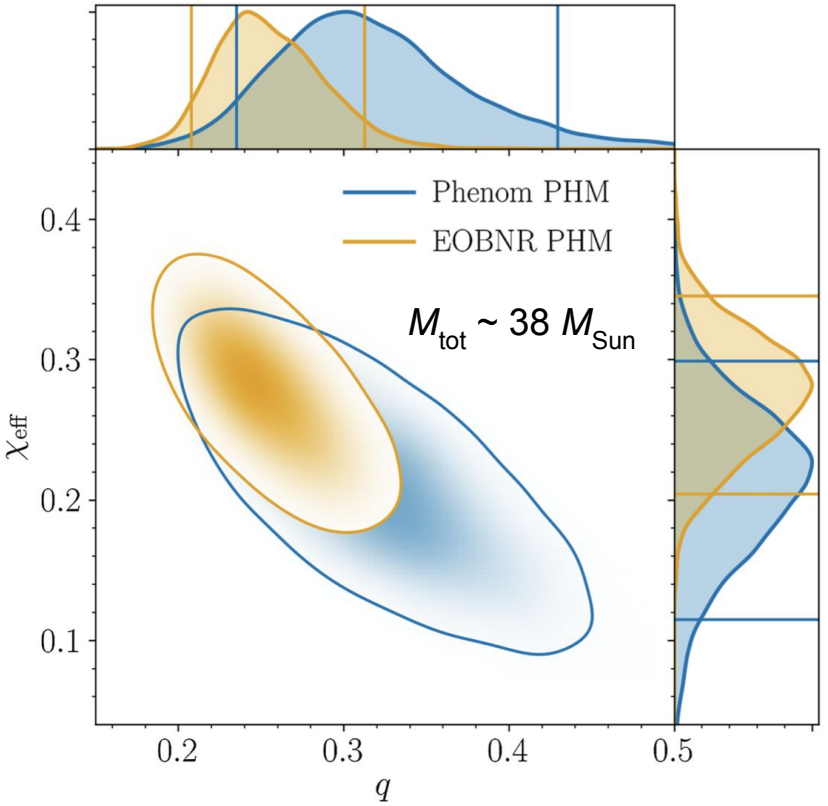
Source classification model



https://emfollow.docs.ligo.org

GW190412: a merger of unequal-mass BHs

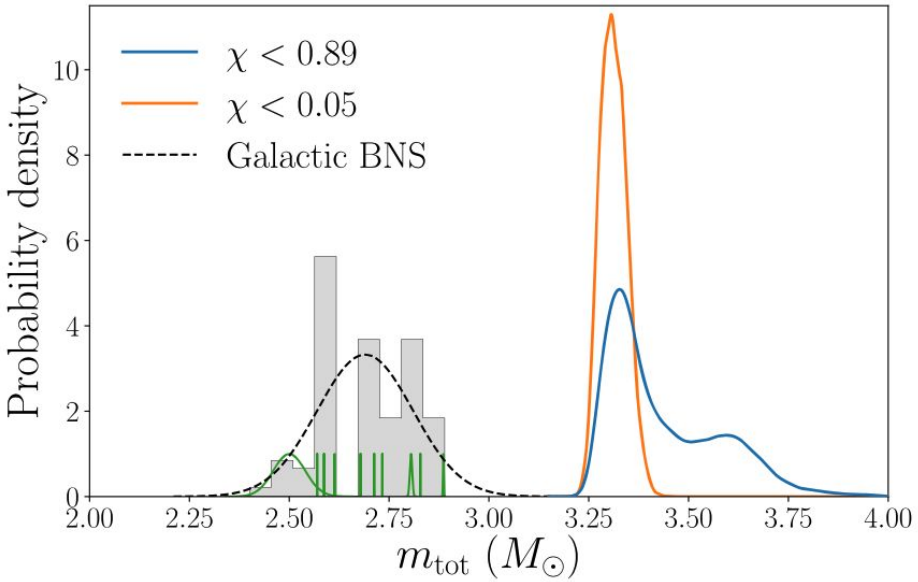




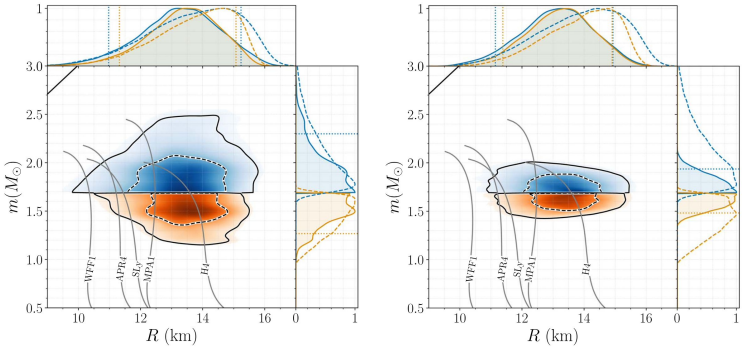
- The merging BH binary population includes unequal-mass binaries
- First observation of GW multipole moments beyond the quadrupole

Phys. Rev. D 102, 043015

GW190425: a merger involving massive NSs

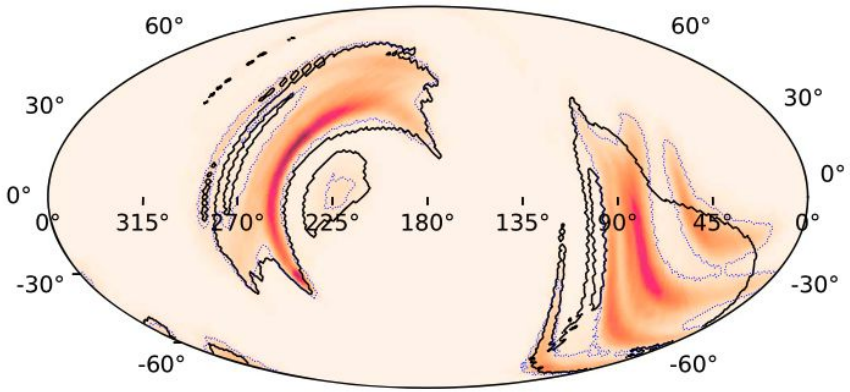


- Probably the second NS merger detected by LIGO and Virgo
- Total mass **incompatible** with known galactic NS binaries
- No evidence for tides; one or both objects may be BHs
- No significant new constraints on NS equation of state

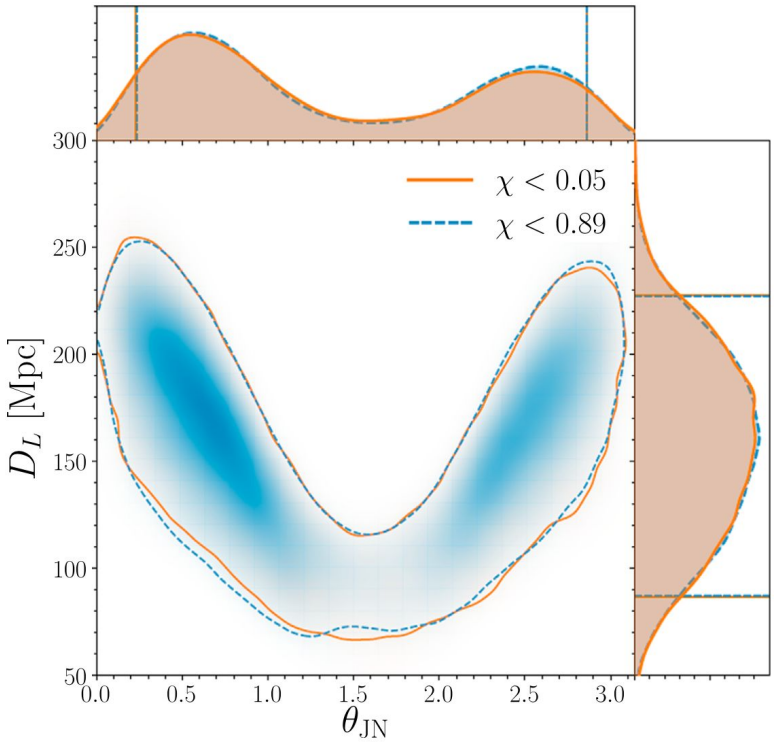


ApJ Letters, 892:L3 (24pp), 2020

GW190425: a merger involving massive NSs

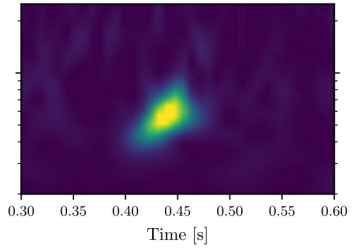


- LIGO-Livingston-only signal with uncertain spatial localization
- 2–5 times farther than GW170817
- Associated GRB in INTEGRAL claimed, not confirmed

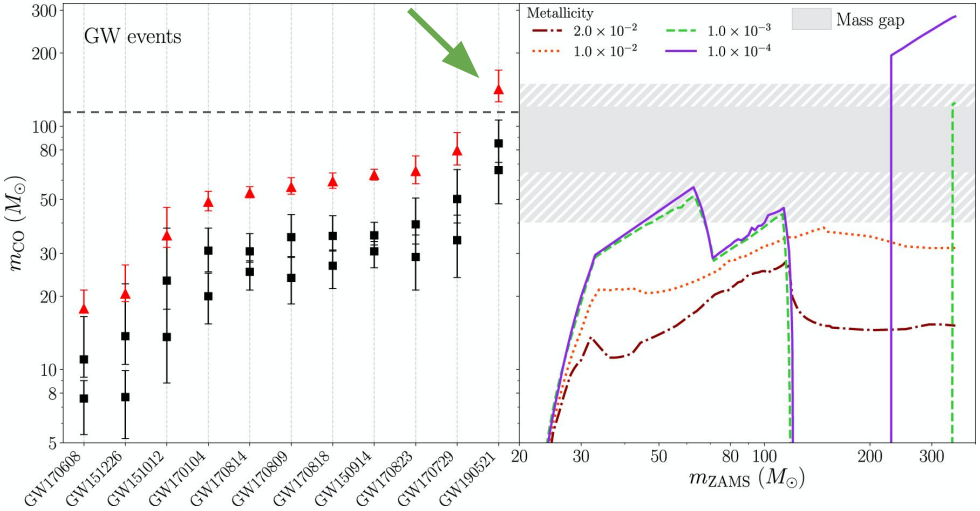


GW190521: a merger of remarkably massive BHs

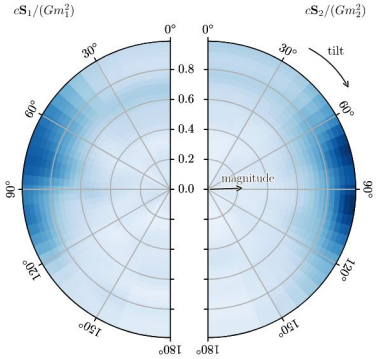
- **Shortest** signal confidently detected so far



- 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**

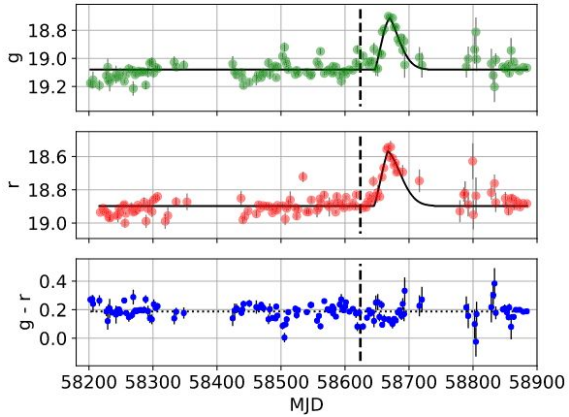


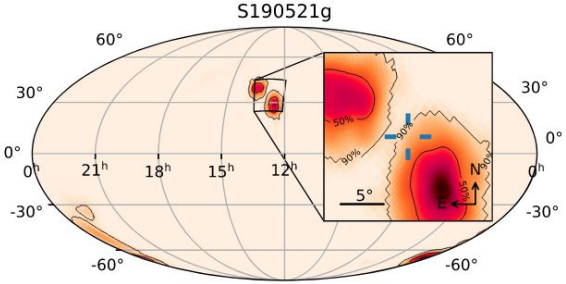
- Possible presence of **orbital eccentricity**
  e.g. Romero-Shaw+ 2020

GW190521: a BH merger in an AGN disk?

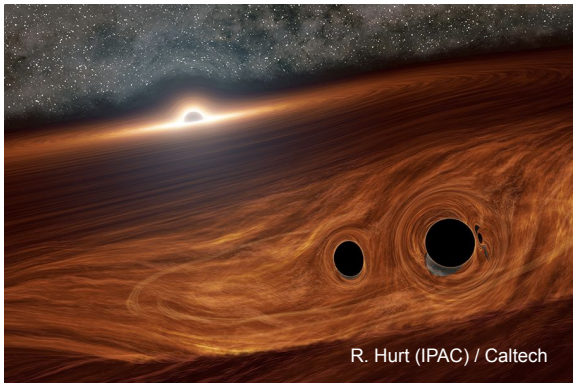
Candidate Electromagnetic Counterpart to the Binary Black Hole Merger Gravitational-Wave Event S190521g*

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]

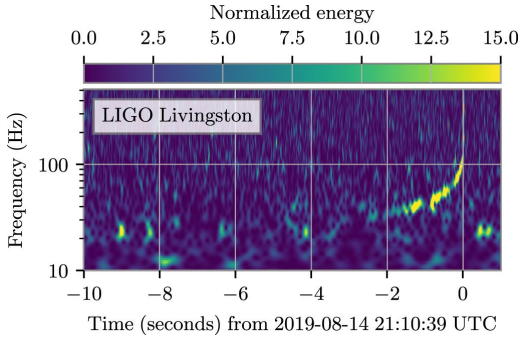


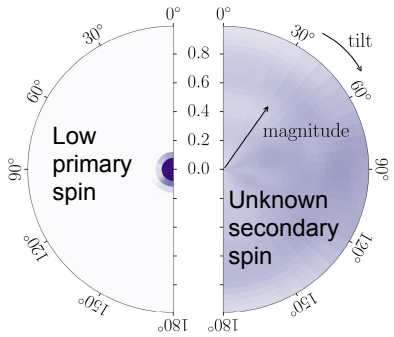


We predict a similar repeat flare in this source when the kicked BBH reencounters the disk on timescale $1.6\ \mathrm{yr}(M_{\mathrm{SMBH}}/10^8\ M_\odot)(a/10^3 r_g)^{3/2}$.

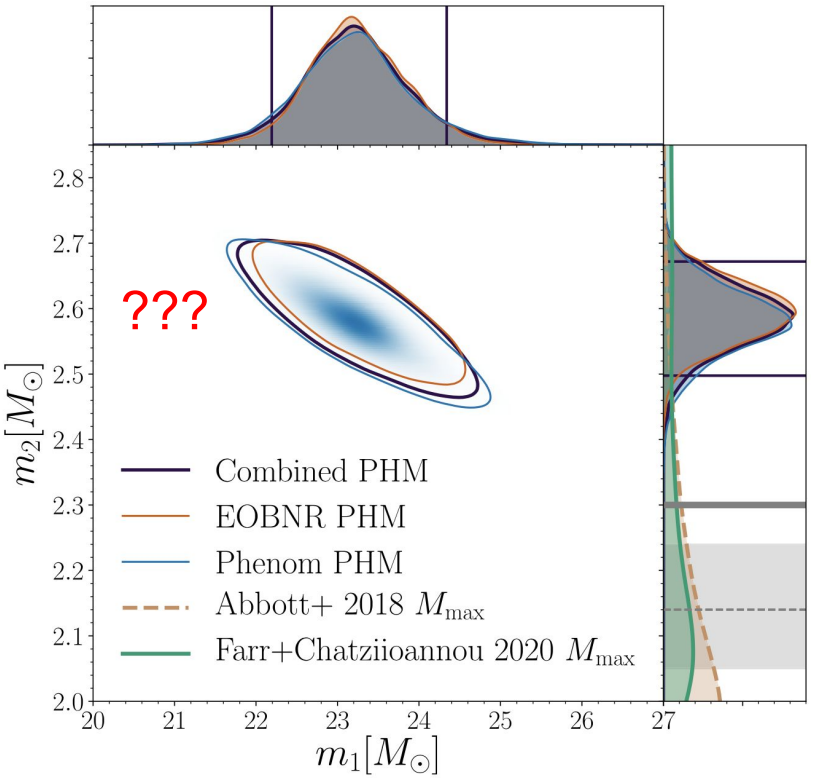


GW190814: the first observed NSBH merger… maybe





- 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

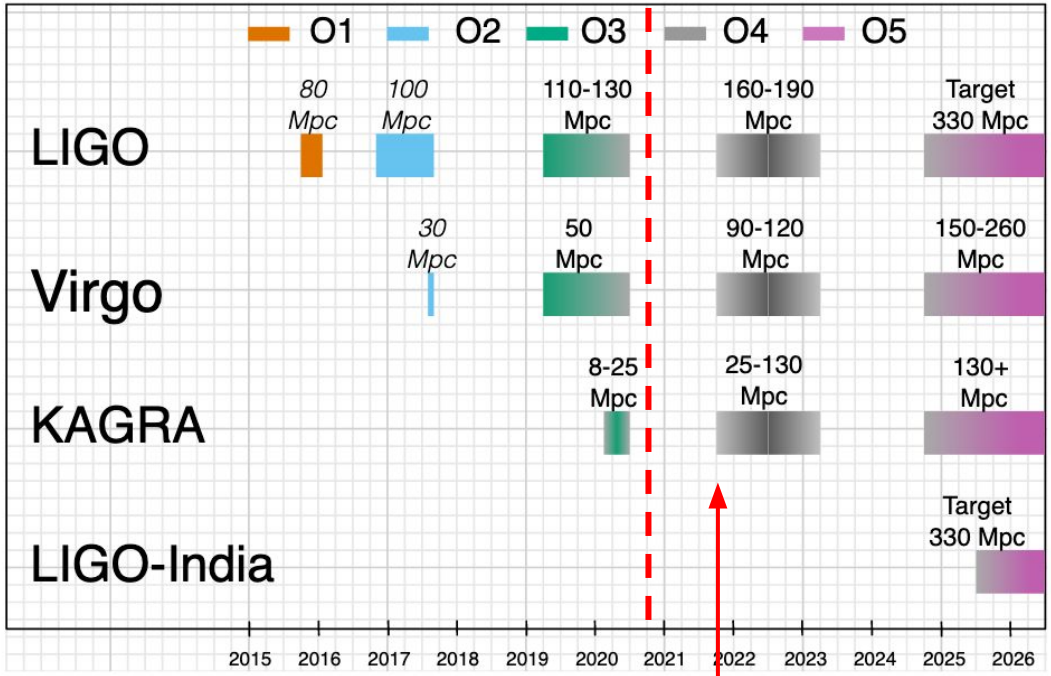
O3 summary: a very successful run!

- 56 public non-retracted alerts
- Four “exceptional events” published so far
  - Probing the extremes of the NS/BH mass distribution
  - Spins? Orbital precession? Orbital eccentricity?
  - No definitive multimessenger discoveries since GW170817
  - Challenges to current formation channels
  - No evidence of violations of general relativity
- Forthcoming publications
  - Full event catalog(s)
  - Inferred properties of the source population
  - Tests of general relativity
  - Targeted GRB followup
  - Updated H_0 estimate, cosmology implications
- Public O3 data release in April and October 2021
- Get data from the GW Open Science Center: www.gw-openscience.org

The future

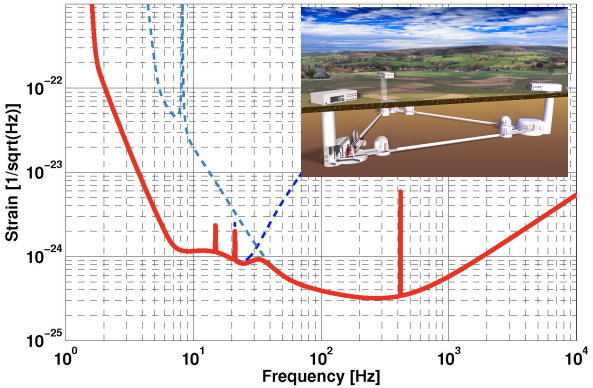
Second-generation detectors

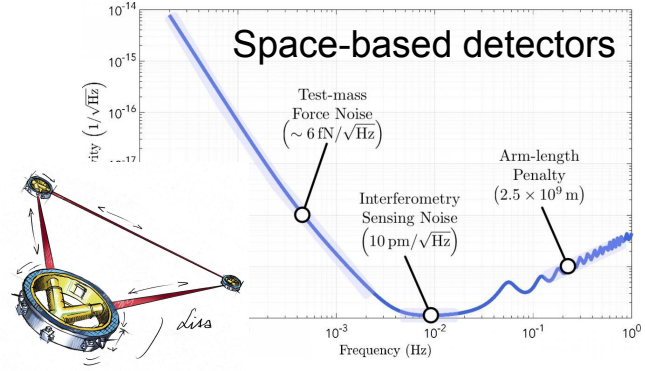
arXiv:1304.0670



Assuming no worldwide pandemics

Third-generation detectors





Thank you!

IJCLab
Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis