LIGO-Virgo Gravitational-Wave Findings So Far, and Current Events

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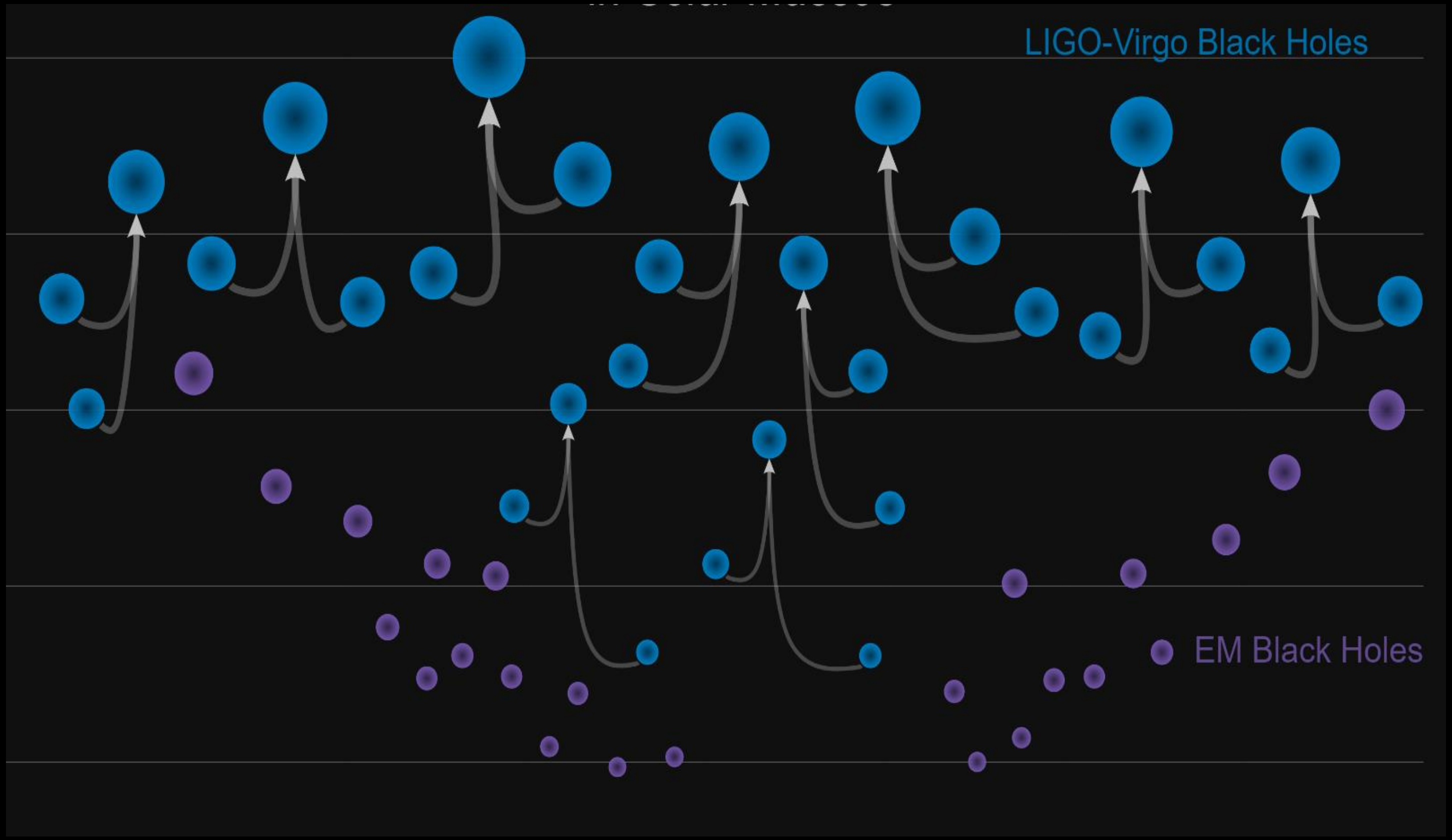
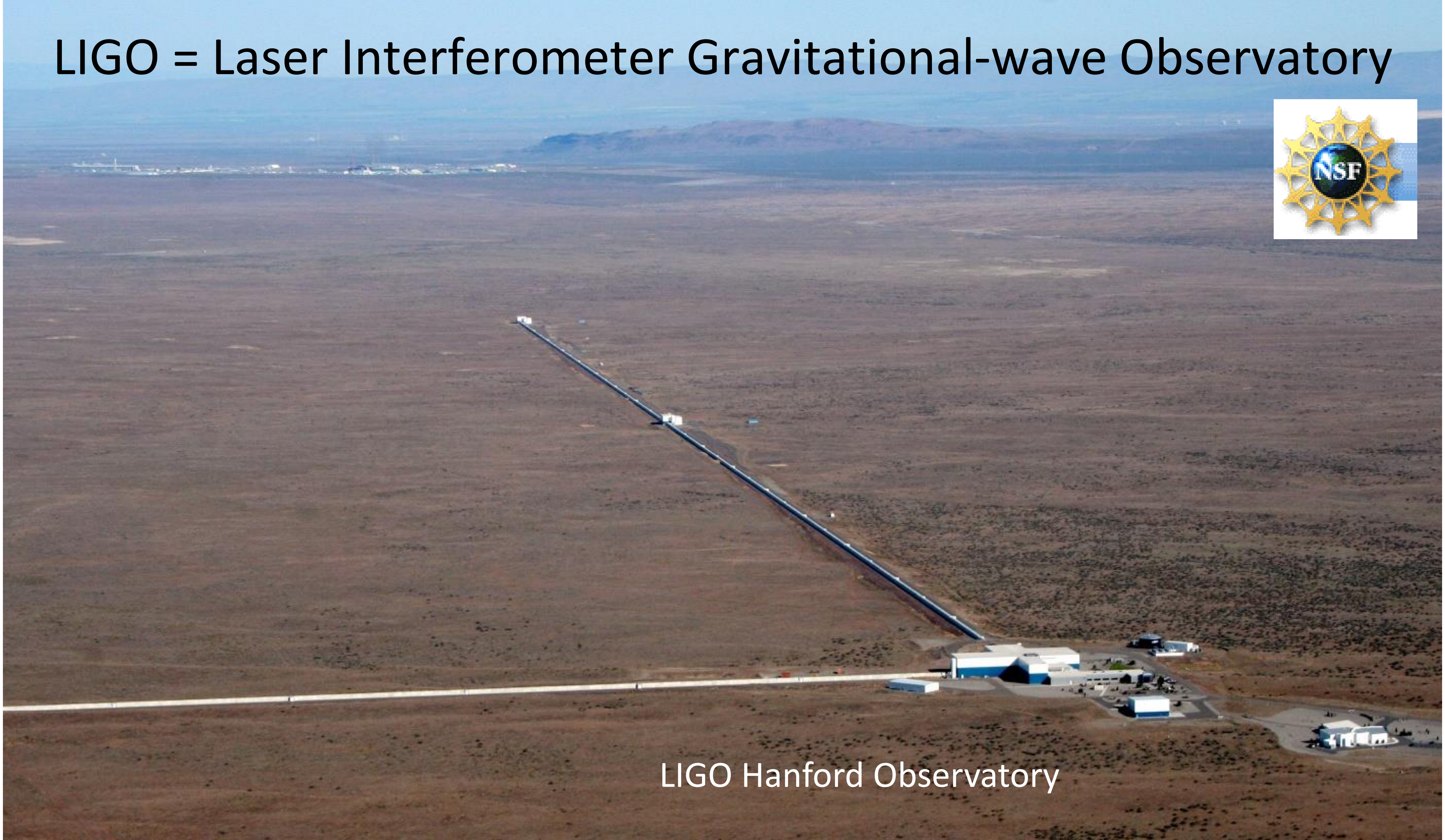


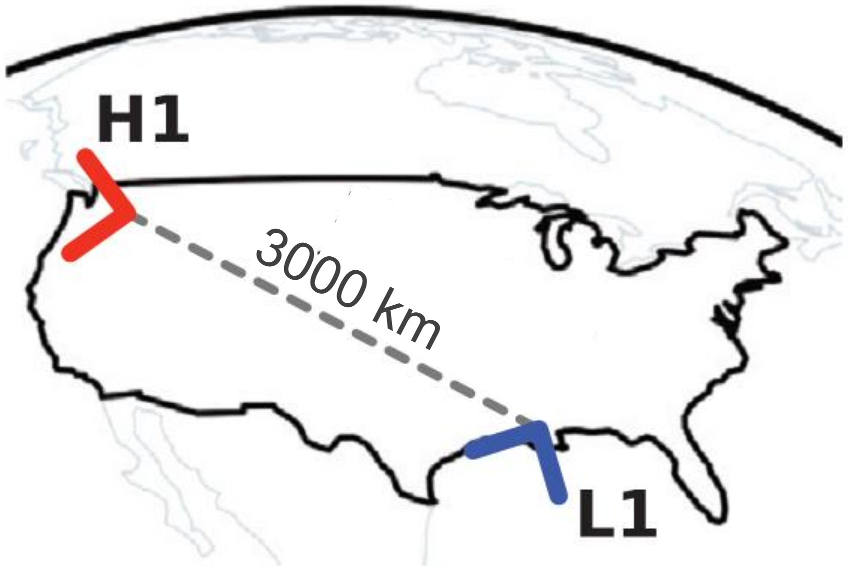
University of Maryland
APS Mid-Atlantic Senior Physicists Group
February 19, 2020

LIGO = Laser Interferometer Gravitational-wave Observatory



LIGO Hanford Observatory

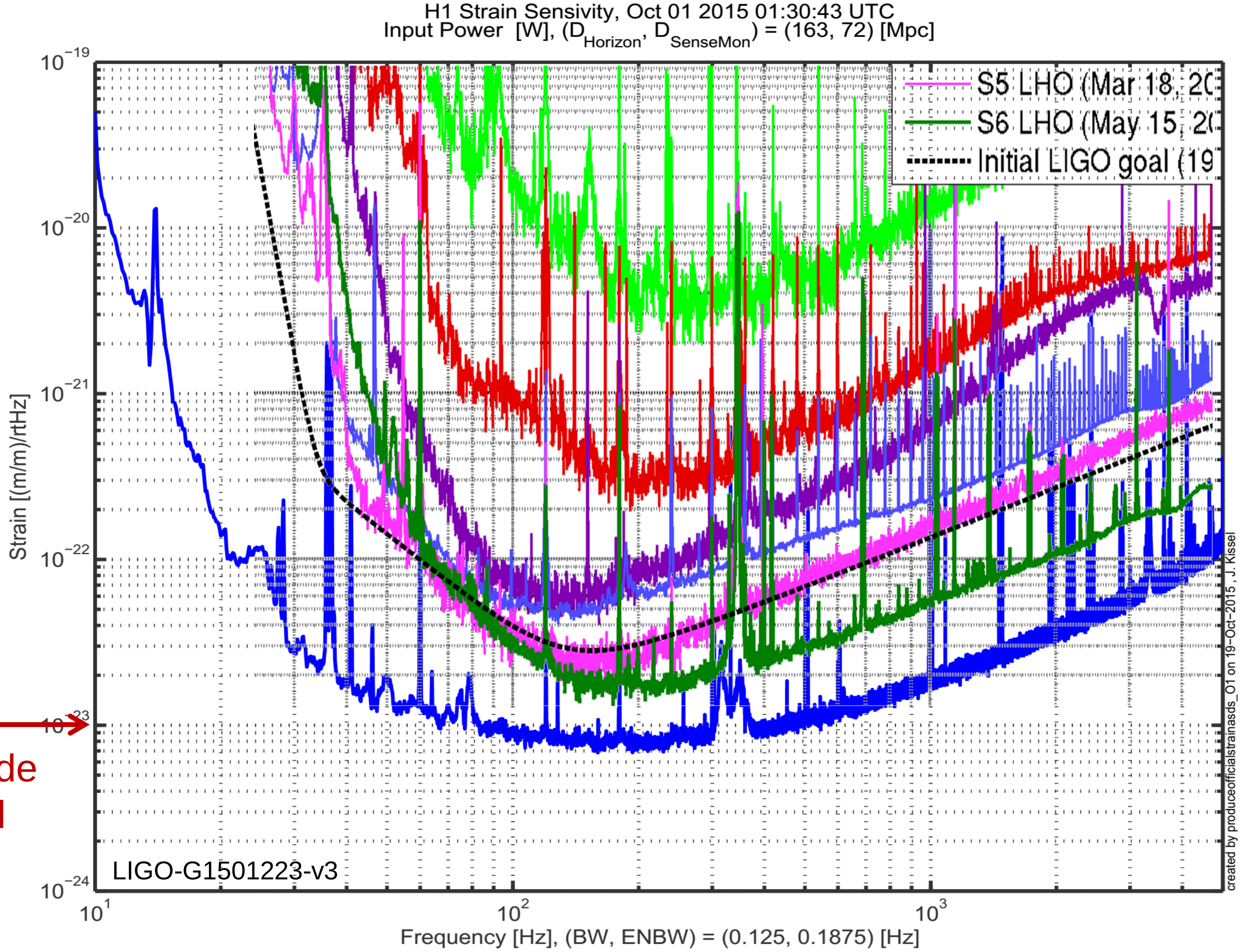
Two LIGO Observatories



Plus the Virgo Observatory in Italy

Having three detectors significantly improves our ability to confidently detect weak sources and to locate them in the sky

Improving detectors over time to reduce the noise level



Initial LIGO (2002-2010)

Advanced LIGO (as of 2015)

10^{-23} amplitude spectral density!

Advanced Detector Observing Runs

O1 — September 12, 2015 to January 19, 2016

LIGO Hanford and Livingston

O2 — November 30, 2016 to August 25, 2017

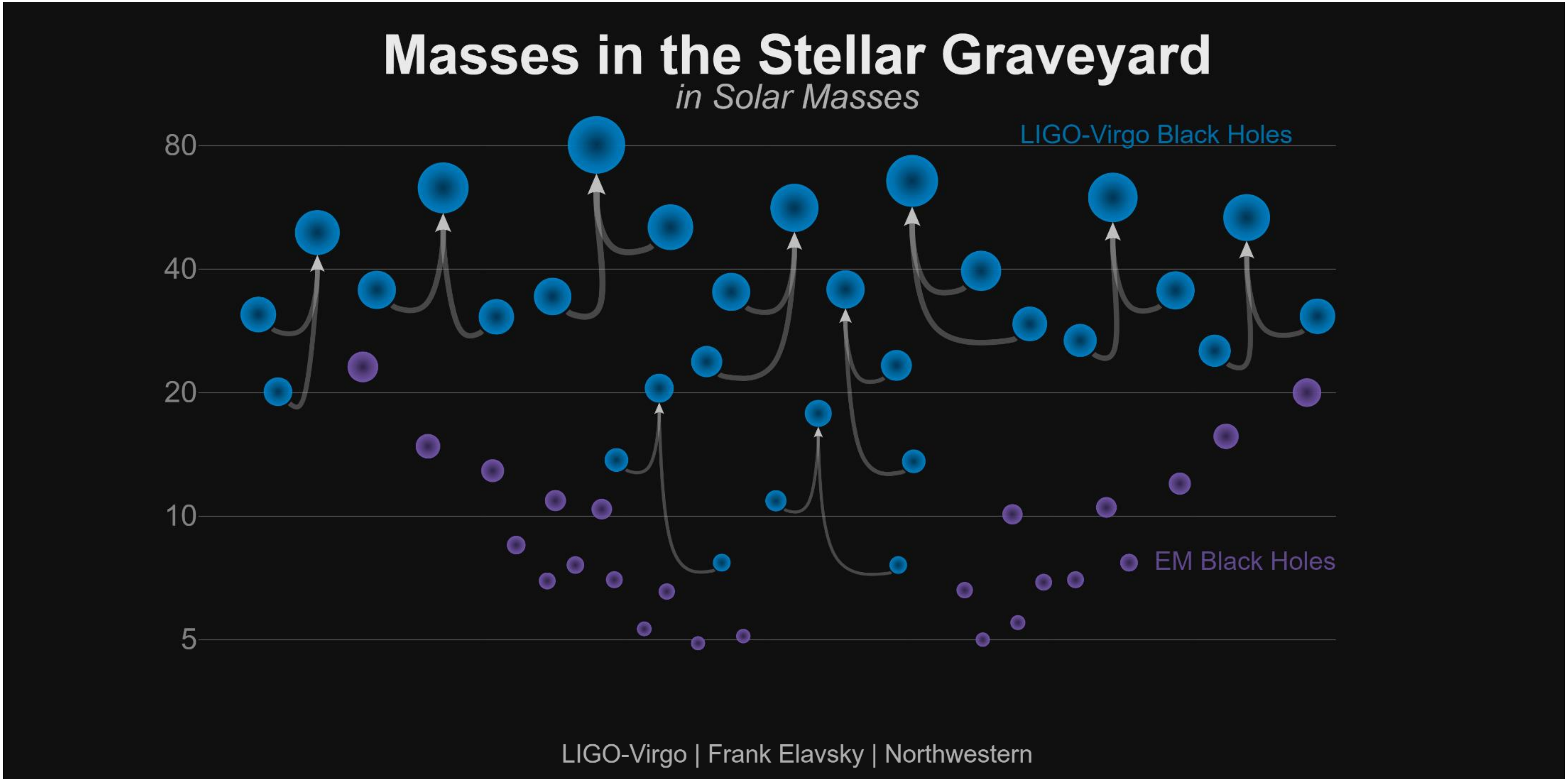
Initially, just the two LIGO observatories

Virgo joined on August 1, 2017

O3 — Began April 1, 2019

Both LIGO observatories plus Virgo

Ten binary black hole mergers detected in O1+O2!



Browse events at https://ligo.northwestern.edu/media/mass-plot/index.html

Highlights: Binary Black Hole Mergers

Exploring the Properties of GW Events

Bayesian parameter estimation: Adjust physical parameters of waveform model to see what fits the data from all detectors well

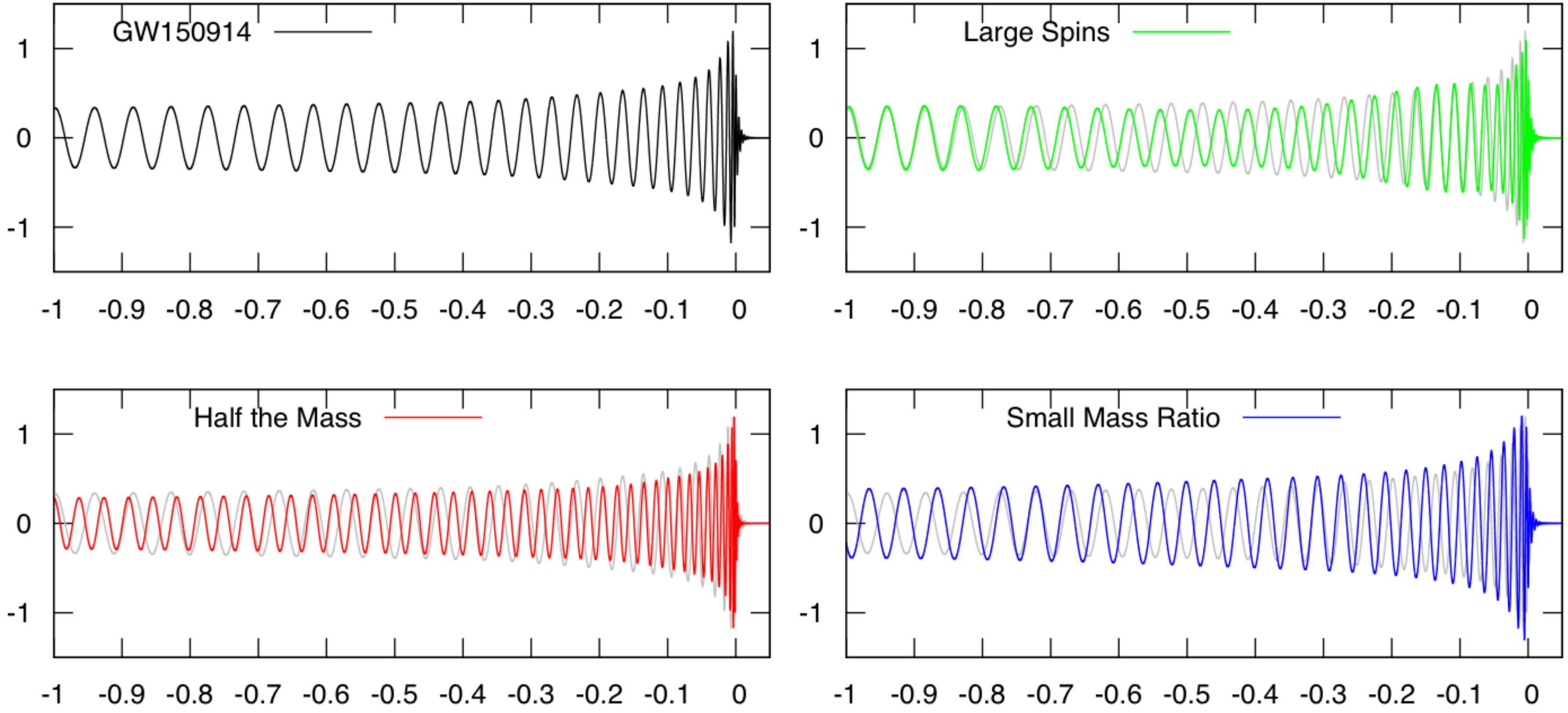


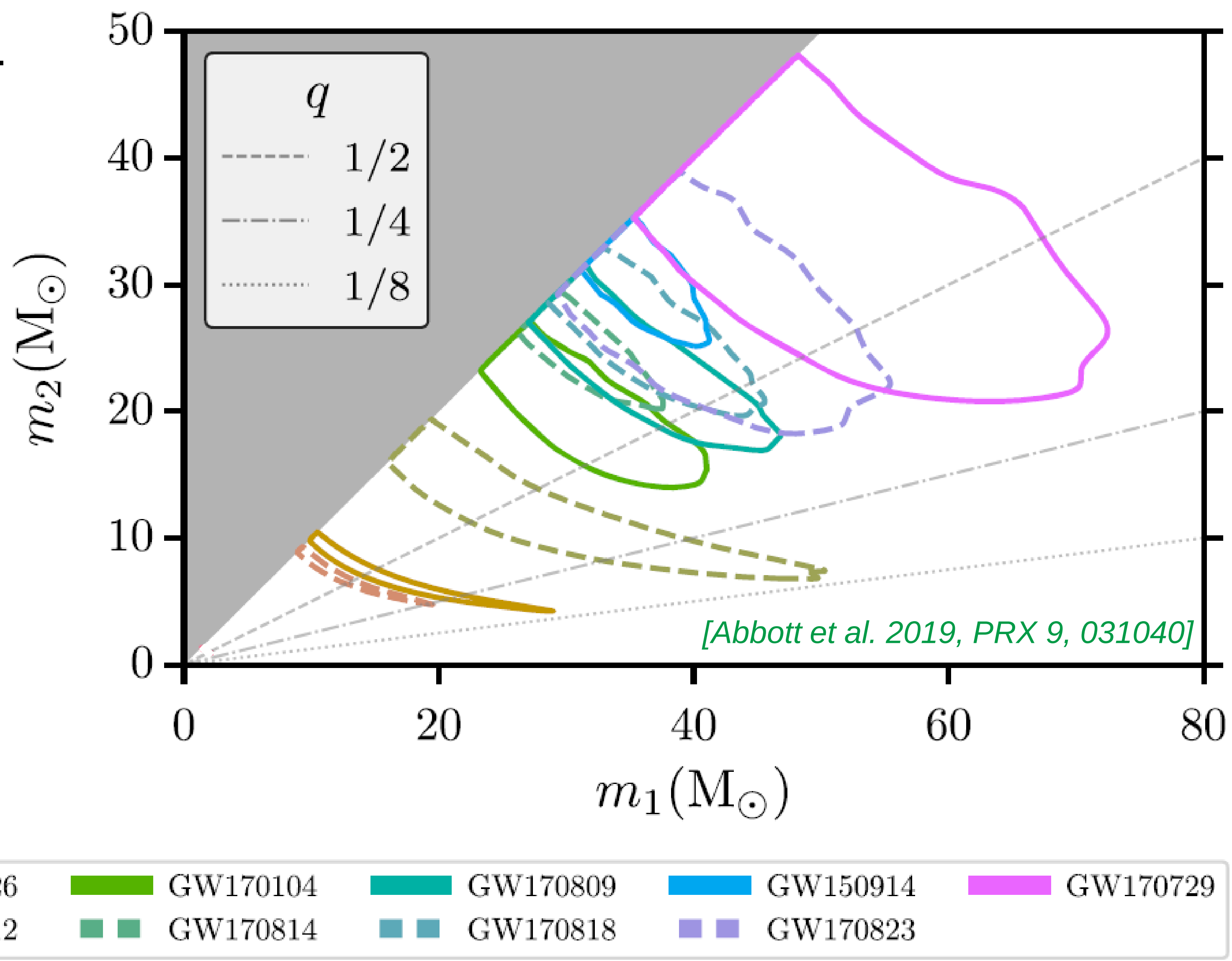
Illustration by N. Cornish and T. Littenberg

➔ **Get ranges of likely ("credible") parameter values**

Population of Merging BBHs: Masses

Mass ratio (*q*) consistent with 1 for all these events, but with significant uncertainty

- The data determines "chirp mass" best for low-mass BBHs, and total mass best for high-mass BBHs

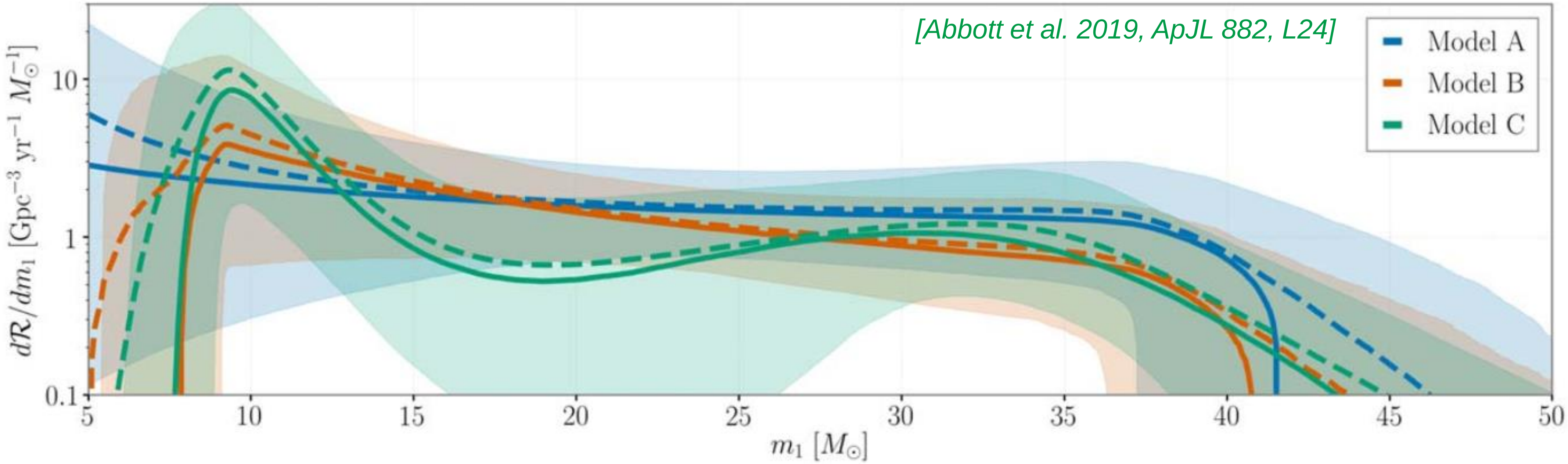


Population of Merging BBHs: Mass Distribution

Want to infer true population of merging BBH systems from observed events

Simulating detectable range, which depends strongly on masses

Different models can fit the data, but they tend to drop off around $45\ M_{\odot}$ for m_1

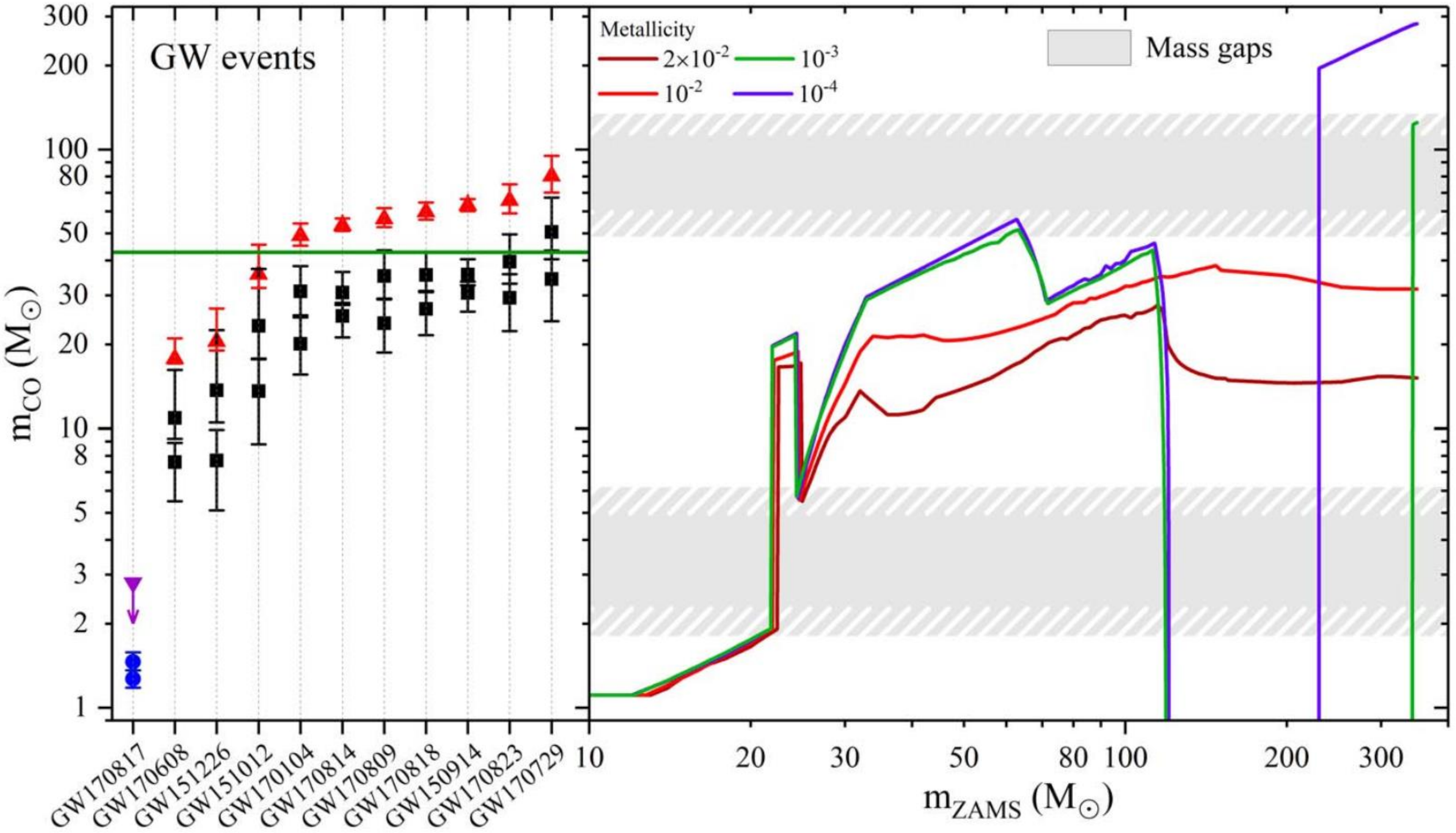


Caution: model-dependent, including assumptions about q and spin distribution (not shown here)

… Seemingly Consistent with "Mass Gaps"

Stellar evolution models suggest that remnant BHs only span a certain mass range

Above ~125 $M_\odot$, stars are disrupted in pair instability or pulsational pair instability supernova



[Abbott et al. 2019, ApJL 882, L24]

Population of Merging BBHs: Spins

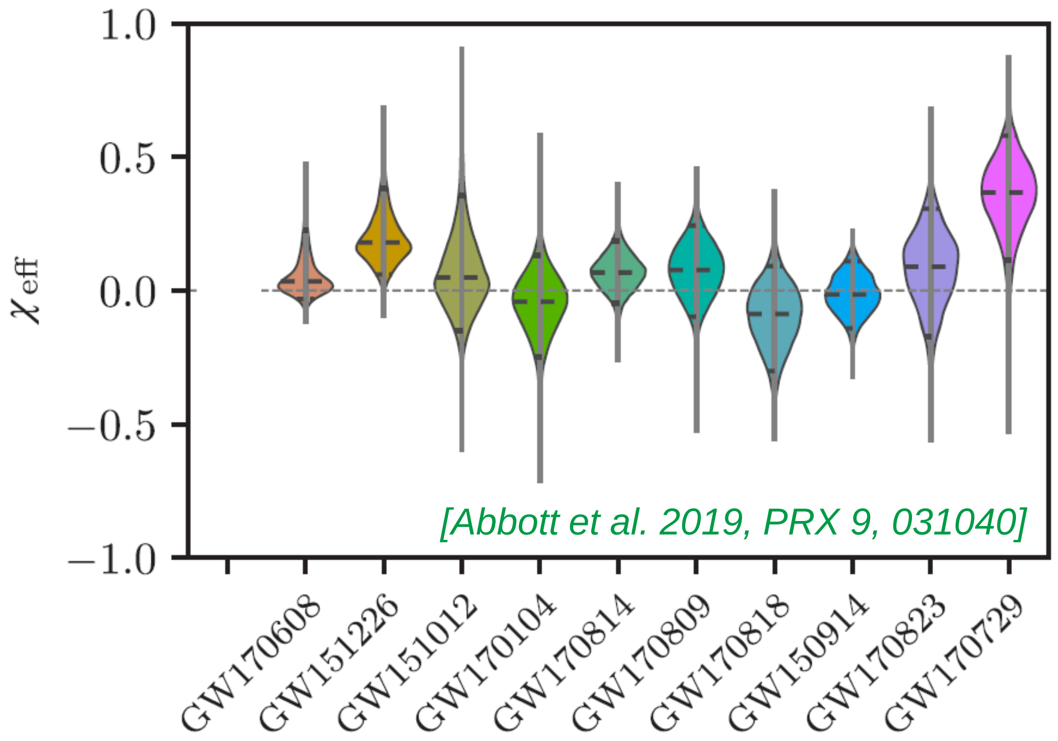
A key parameter that could help distinguish among different formation pathways:

- A massive binary star system with sequential core-collapses
- Chemically homogeneous evolution of a pair of massive stars in close orbit
- Dynamical formation of binary from two BHs in a dense star cluster
- Binaries formed from a population of primordial black holes

The data determines an "effective spin" parameter χ_{eff} the best

$$\chi_{\text{eff}} = \frac{c}{G}\left(\frac{\boldsymbol{S}_1}{m_1} + \frac{\boldsymbol{S}_2}{m_2}\right) \cdot \frac{\hat{\boldsymbol{L}}}{M}$$

Most of our BBH have χ_{eff} consistent with 0, though two (GW151226 and GW170729) evidently have nonzero values



Highlights: Binary Neutron Star Merger

August 17, 2017: a binary neutron star merger!

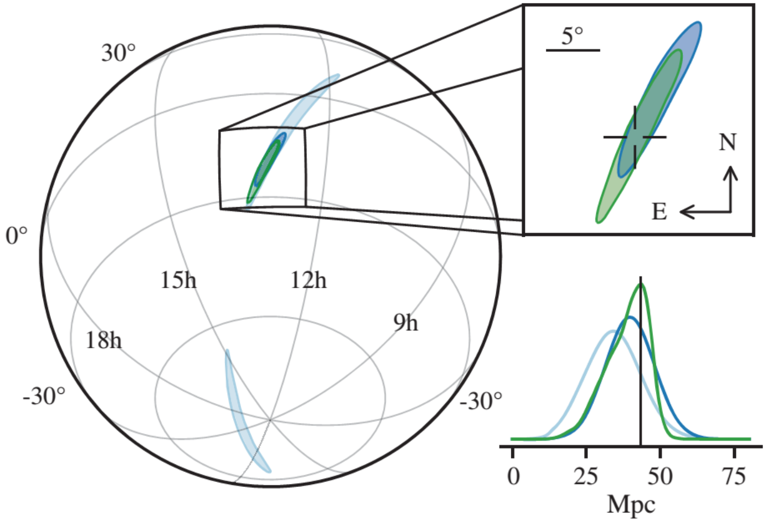
GW170817

Initially found using a template with typical neutron star masses

And coincident (within ~2 sec) with a short gamma-ray burst (GRB) detected by the GBM instrument on the Fermi satellite!

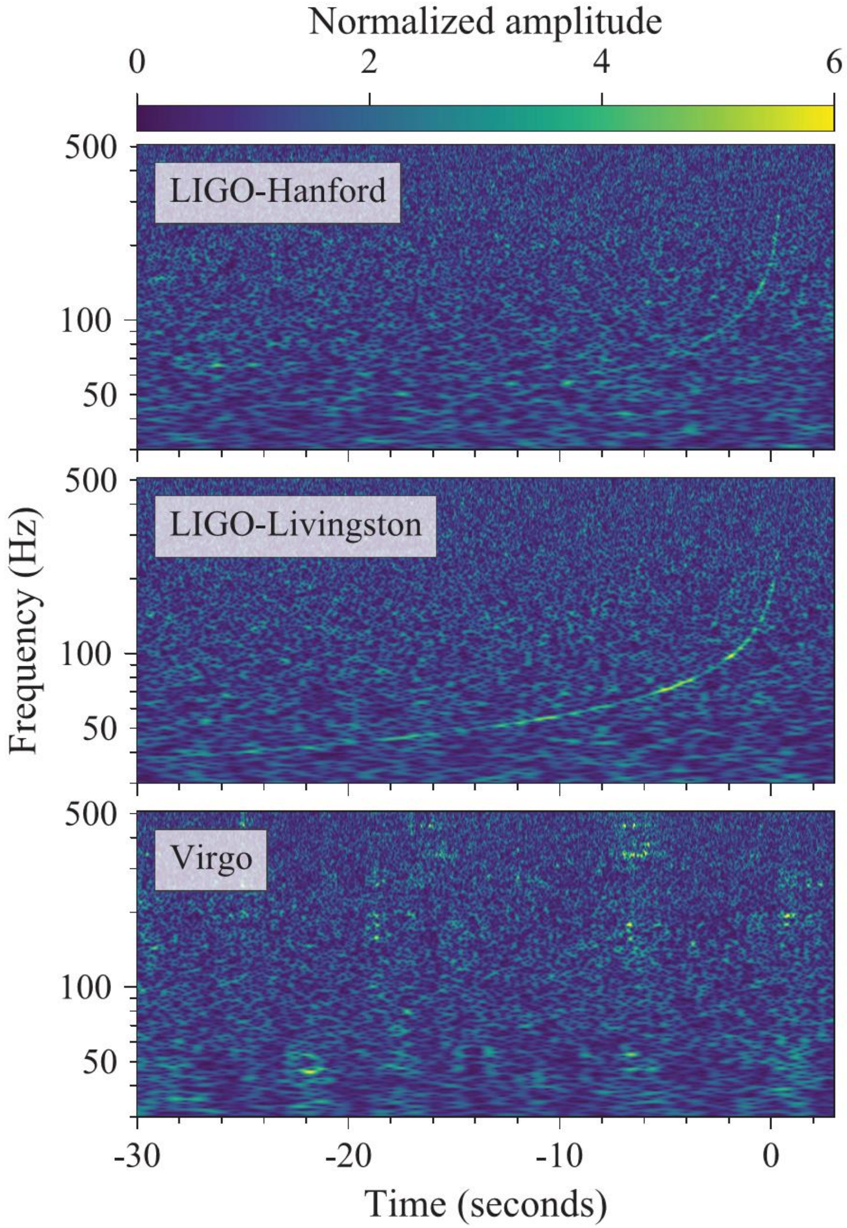
Visible in LIGO spectrograms!

We located it in the sky it pretty well



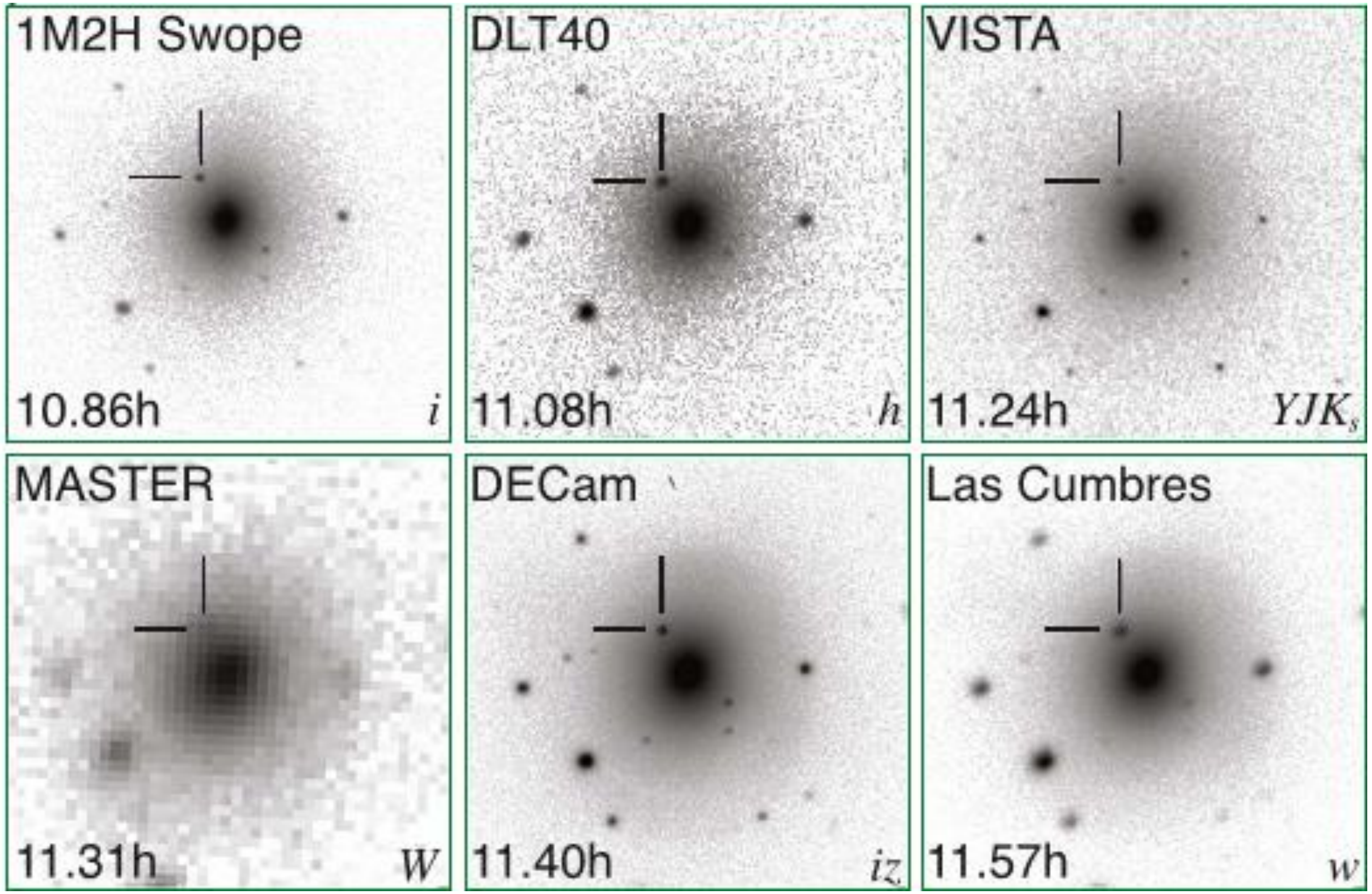
To an area of ~31 deg^2
(after working around a glitch in the LIGO-Livingston data),
ultimately to ~16 deg^2

[Abbott et al. 2017, PRL 119, 161101]



Astronomers found the optical counterpart!

Independently found by 6 teams, within a span of ~45 minutes, in the galaxy NGC 4993



GRB 170817A

GW170817

SSS17a

DLT17ck

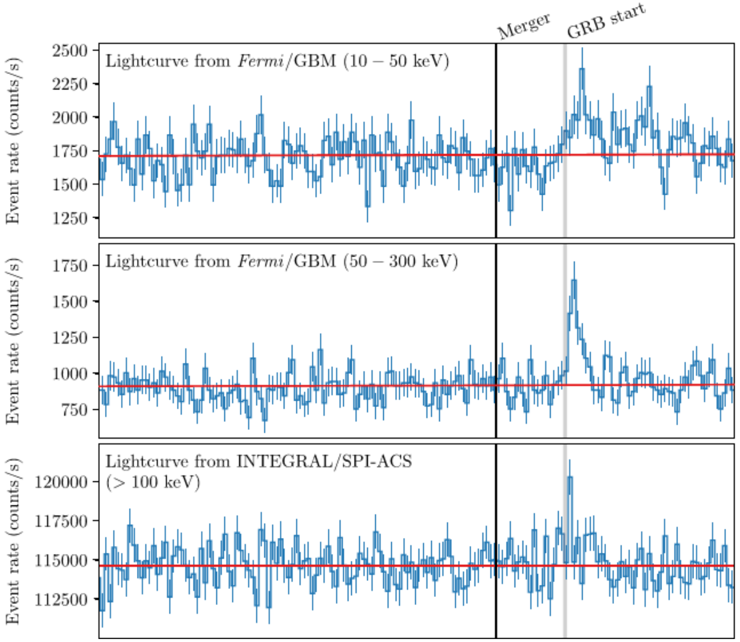
MASTER J130948.10-232253.3

→ AT 2017gfo

[Abbott and many others 2017, ApJL 848, L12]

GRB 170817A / AT2017gfo Electromagnetic Signatures

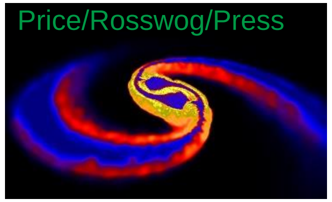
Gamma-Ray Burst



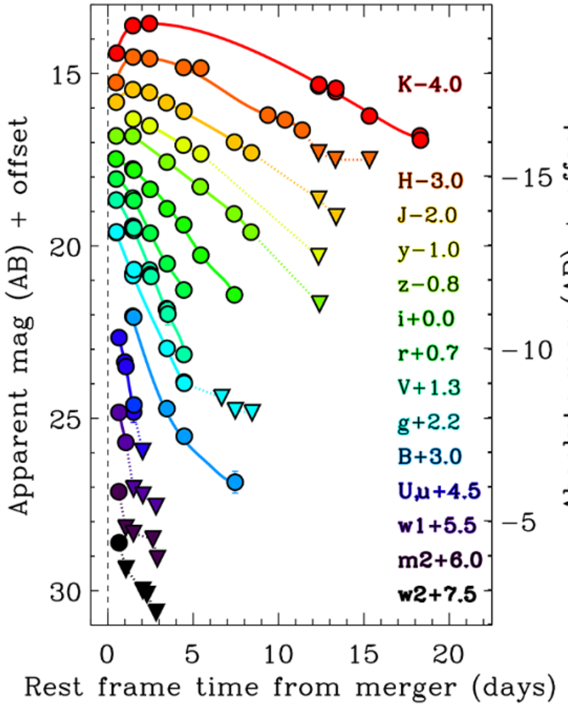
[LSC, Fermi-GBM and INTEGRAL 2017, ApJL 848, L13]

Pretty typical observed properties, but very dim (i.e., low E_{iso}) considering how close it was

Kilonova

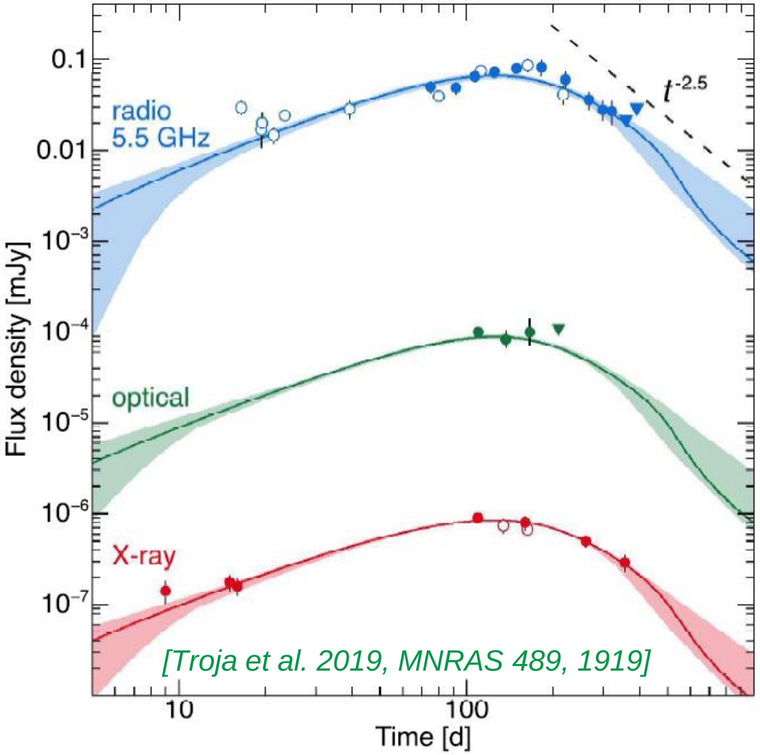


Thermal emission from ejected material, heated by decay of *r*-process elements formed in event



[Drout et al. 2017, Science 10.1126/science.aaq0049]

Afterglow



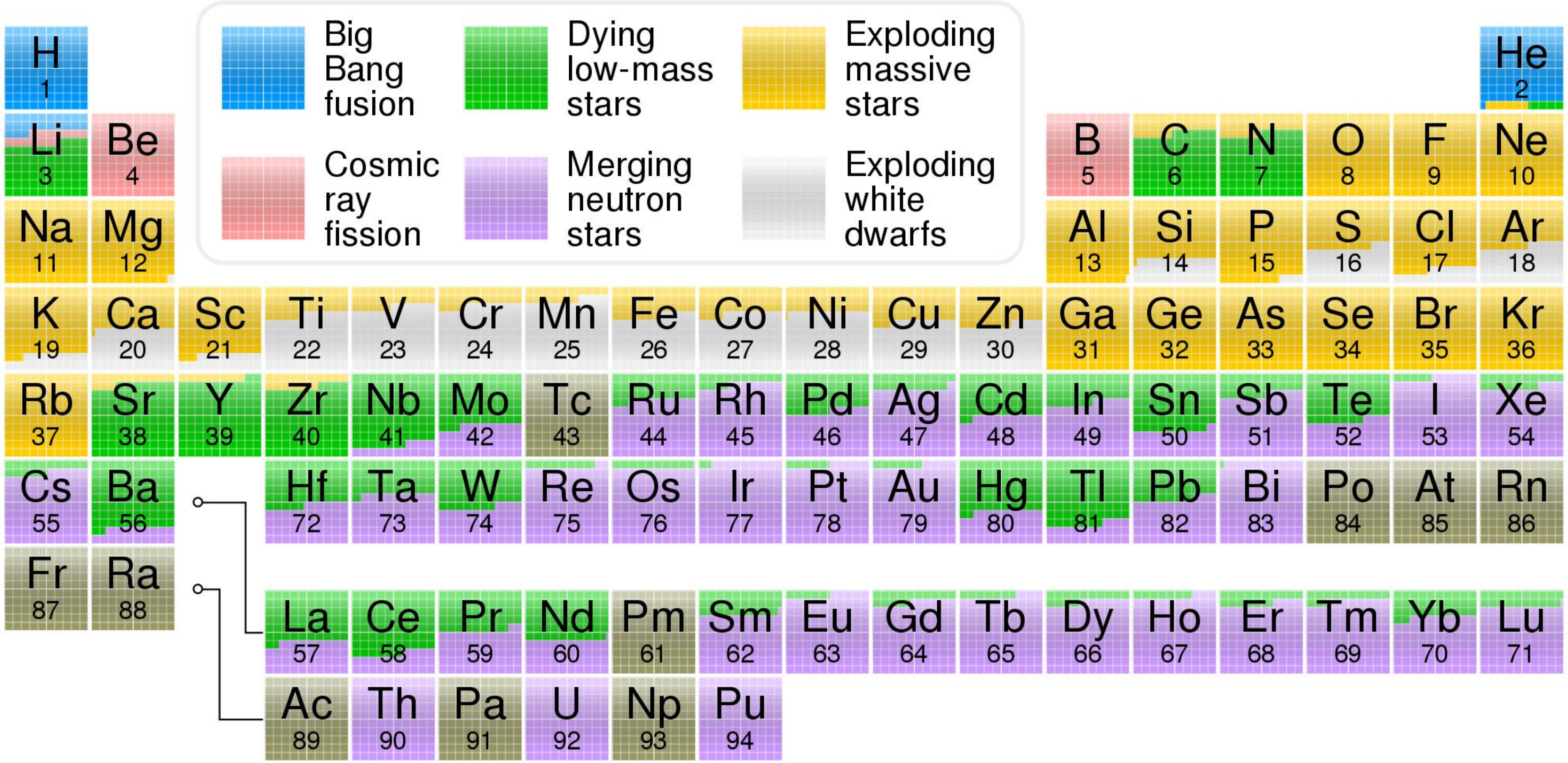
[Troja et al. 2019, MNRAS 489, 1919]

Slow onset and rise, constant spectral index completes picture of a successful off-axis jet

Implication for heavy elements

In the past few years, it has become clear that neutron star mergers—not supernovae—produce most of the very heavy elements

“r-process nucleosynthesis” from rapid neutron capture



[Figure from Wikipedia “r-process” article]

Probing Cosmology

GR relates <u>absolute</u> GW signal amplitude to luminosity distance

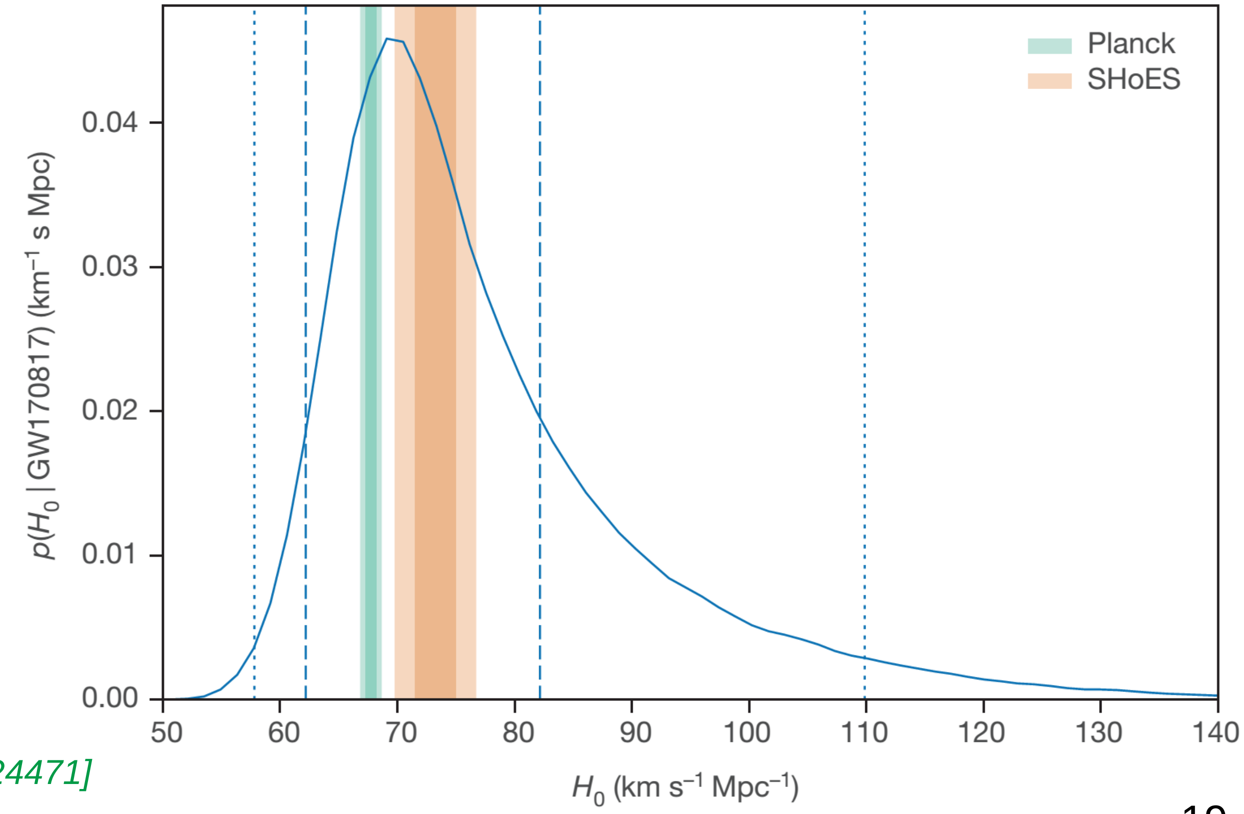
… assuming that other source parameters are known: masses, orbit inclination angle, etc.

➔ A binary merger is a "standard siren", measuring distance
(but with uncertainty if other source parameter aren't known precisely)

Using GW170817, combining the GW distance estimate with measured redshift of its host galaxy NGC 4993, we measured the Hubble constant:

➔ $\boldsymbol{H_0} = \mathbf{70^{+12}_{-8}}$ km/s per megaparsec

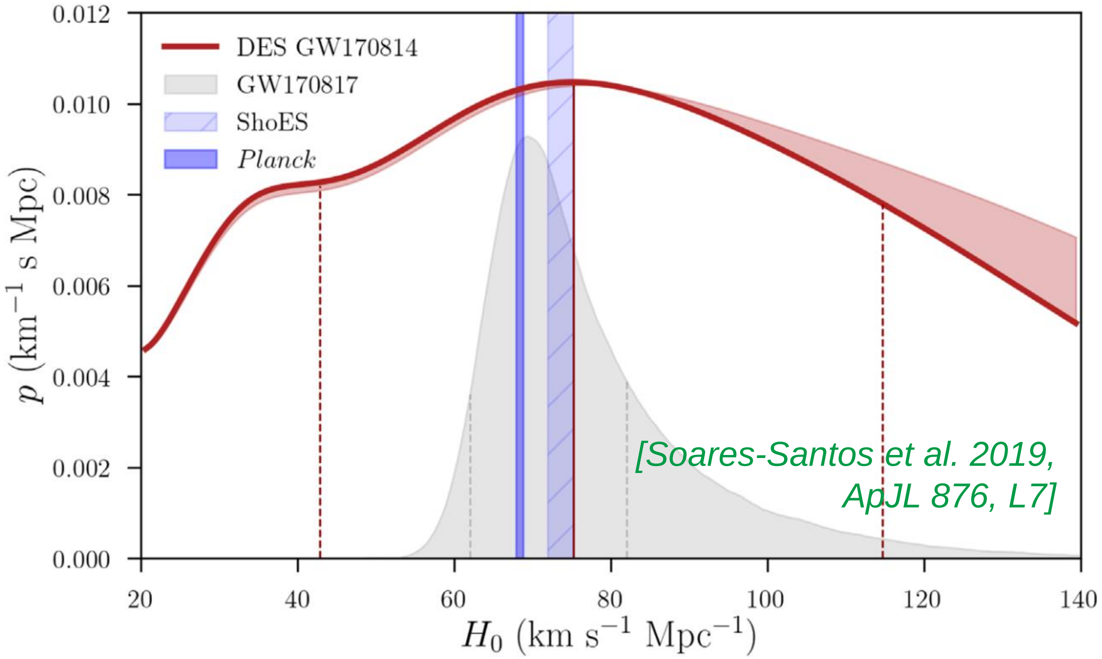
The uncertainty here is dominated by the unknown inclination of the binary orbit; using radio VLBI or kilonova observations allows one to constrain it further



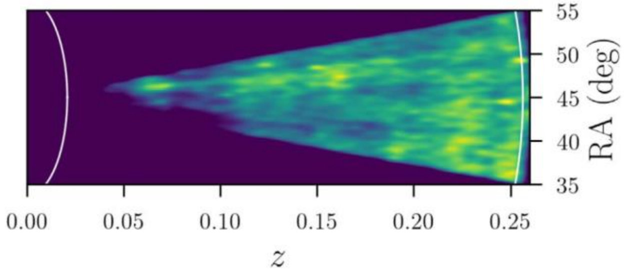
[Abbott et al. 2017, Nature doi:10.1038/nature24471]

Probing Cosmology Using BBH Mergers Too

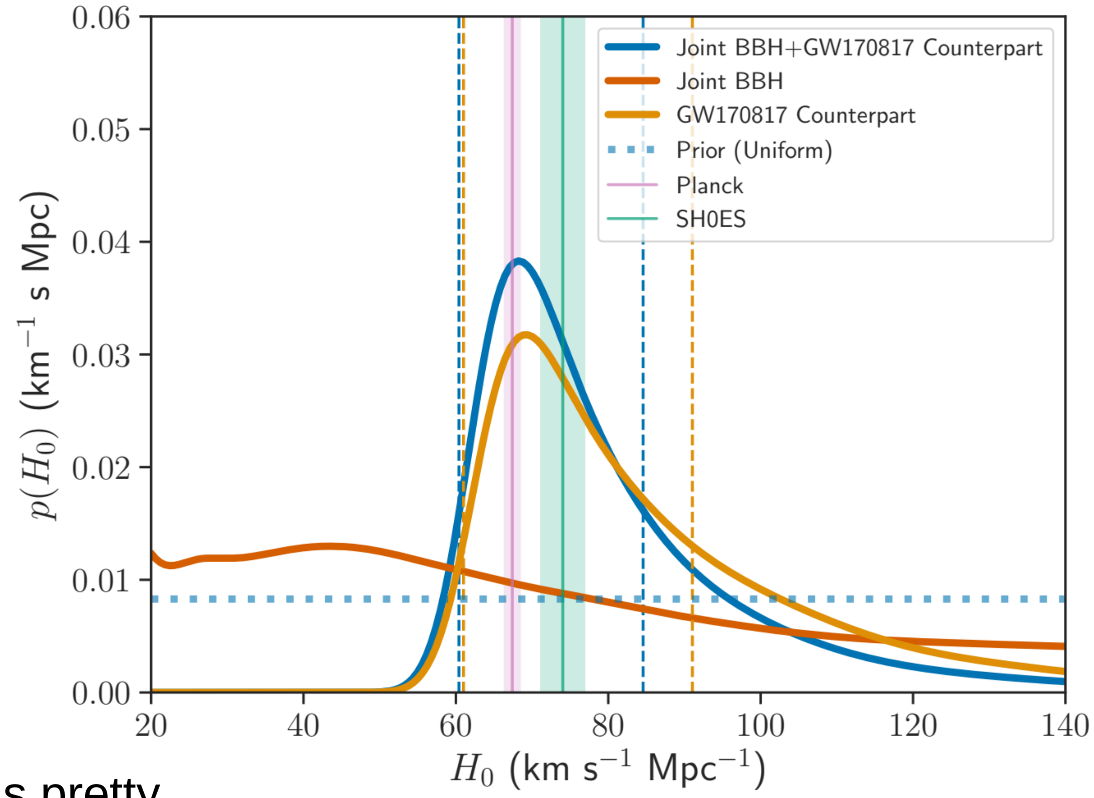
Using statistical association of GW170814 with galaxies cataloged by the Dark Energy Survey



[Soares-Santos et al. 2019, ApJL 876, L7]



Using statistical method with 5 BBH mergers and galaxy catalogs, combined with GW170817



[Abbott et al., arXiv:1908.06060]

The BBH sample is pretty weak at this point…

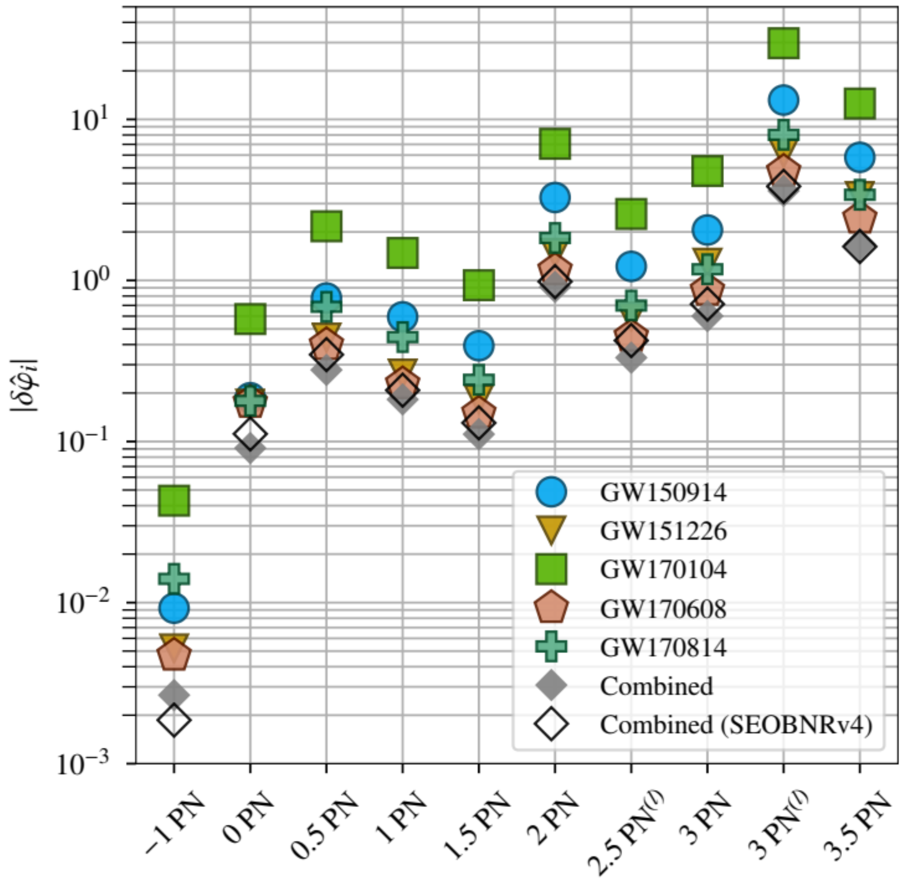
Other Analyses and GW Signal Searches

Tests of GR

Speed of gravitational waves vs. light

Upper limit on the mass of the graviton (if it exists): $4.7 \times 10^{23}\ \mathrm{eV/c^2}$ **(combined analysis)**

Inspiral waveform deviations due to dipole gravitational radiation, or as arbitrary deviations from post-Newtonian expansion coefficients



Limits on alternate polarizations in GW signal

[Abbott et al. 2019, PRL 123, 011102]

[Abbott et al., PRD in press, arXiv:1903.04467]

Searches for Other Transient GW Signals

Multi-messenger searches for GW signals associated with:

GRBs (other than GRB 170817A)

Magnetar flares

Nearby core-collapse supernovae

[Abbott et al. arXiv:1907.01443; ApJ 874, 163; arXiv:1908.03584]

Search for sub-solar-mass binary mergers

Dark matter could be primordial BBH systems?

Searches for more general GW burst signals

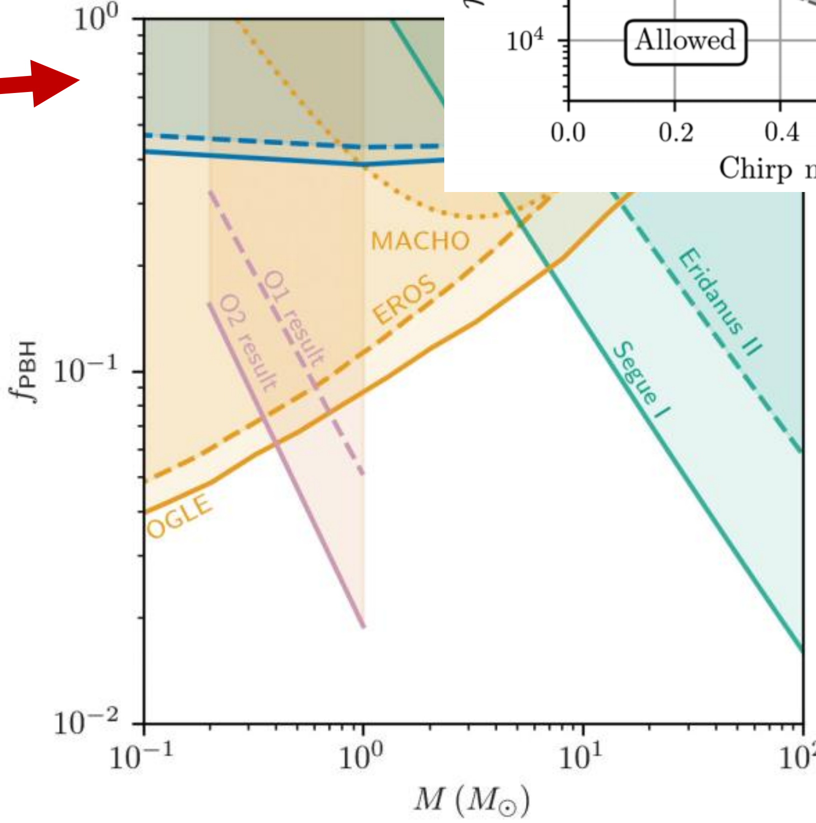
Short-duration (less than a few seconds)

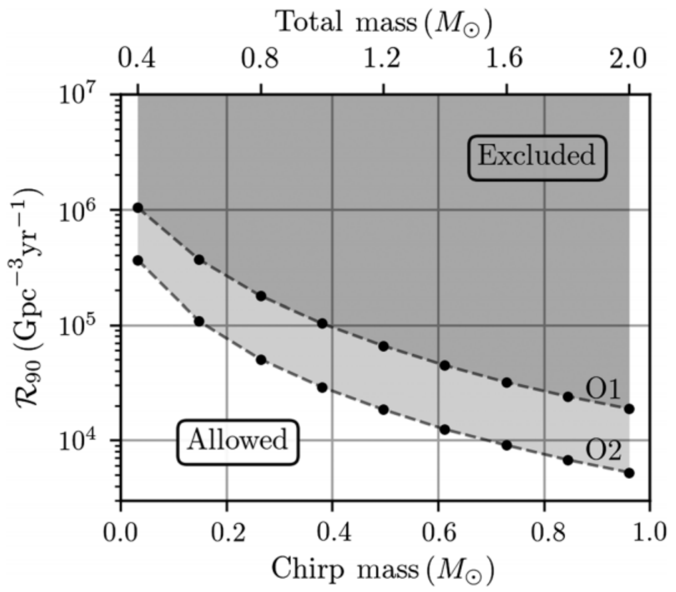
Long-duration

Intermediate-mass binary black holes

Eccentric binary black holes

[Abbott et al. PRD 100, 024017; PRD 99, 104033; PRD 100, 064064; ApJ 883, 149]





[Abbott et al. 2019, PRL 123, 161102]

Searches for Continuous GW Signals

Quasiperiodic GW signals from rotating neutron stars

GW emission requires a small deviation from axisymmetry

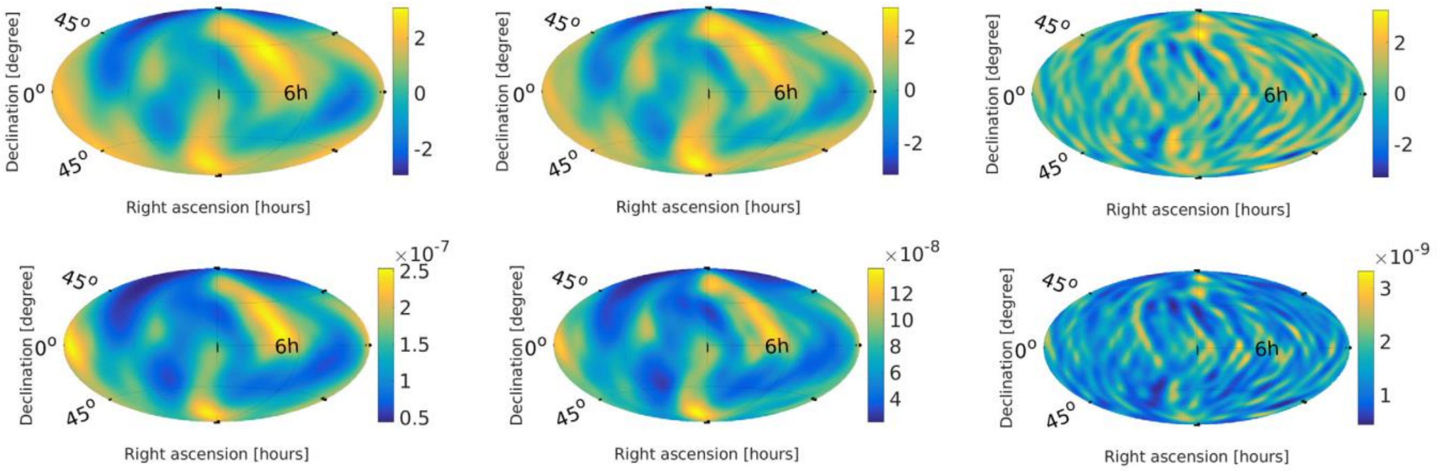
Search for GWs from known radio pulsars at the pulsar's rotation frequency, at twice the rotation frequency, and in a narrow frequency band *[Abbott et al., PRD 100, 024004; PRD 99, 122002]*

Search over a wide parameter space for quasiperiodic GWs coming from Sco X-1, which is the brightest low-mass X-ray binary (LMXB) *[Abbott et al., arXiv:1906.12040]*

All-sky isotropic and directional searches for a stochastic GW background

Constrain energy density of background GWs: $\Omega_{GW} < 6.0 \times 10^{-8}$ (assuming flat in frequency)

Directional: (for different power-law indices)



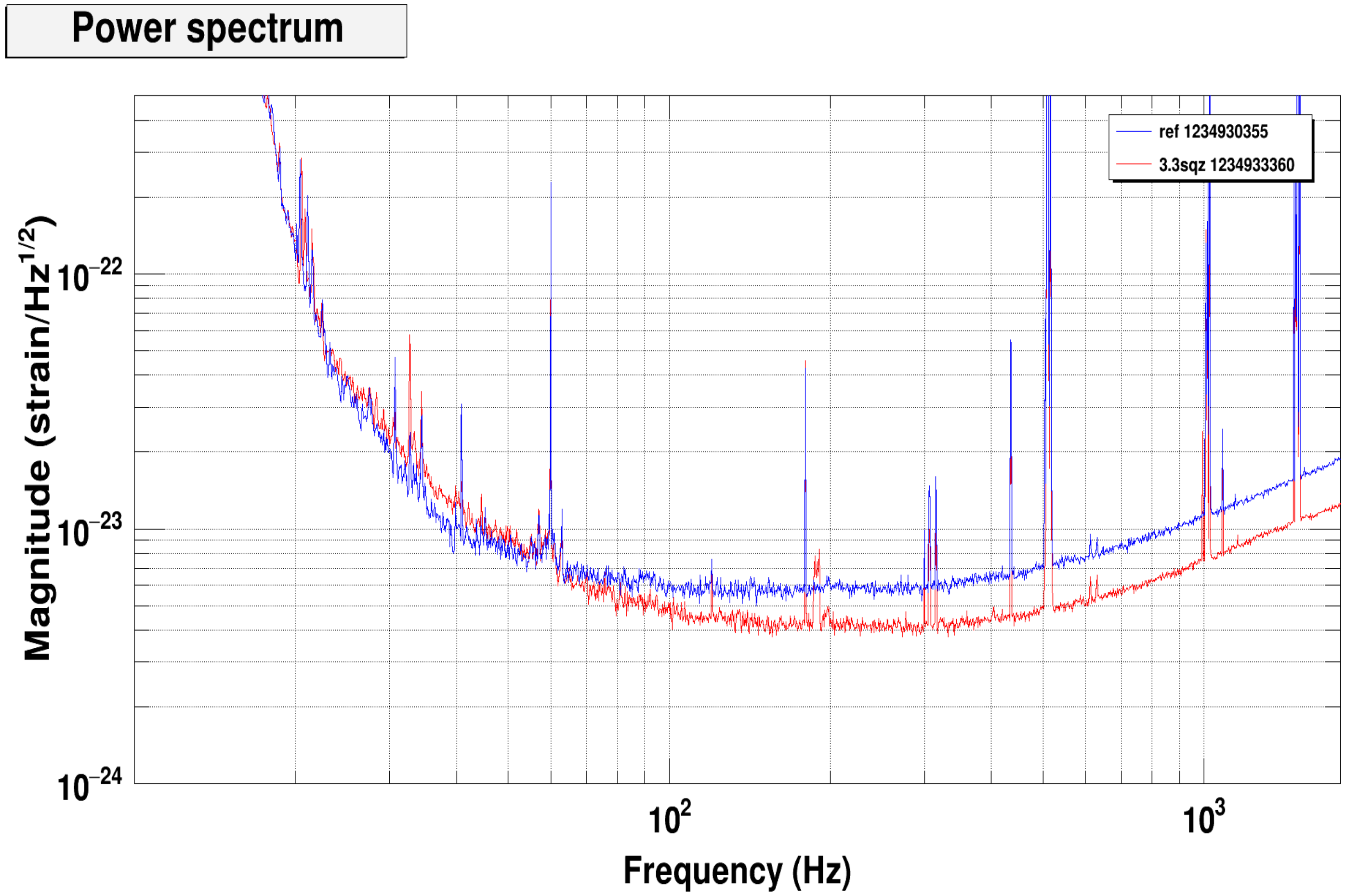
[Abbott et al. 2019, PRD 100, 061101(R); PRD 100, 062001]

Current and Future Observations

Making LIGO and Virgo Better, 2017–19

The detectors were down for ~1.5 years for lots of work:

- Test mass and reaction mass replacements
- Test mass “acoustic mode” dampers
- Better control of scattered light
- Laser upgrade
- **Squeezed light** source installation
- Large gate valve repair
- etc.

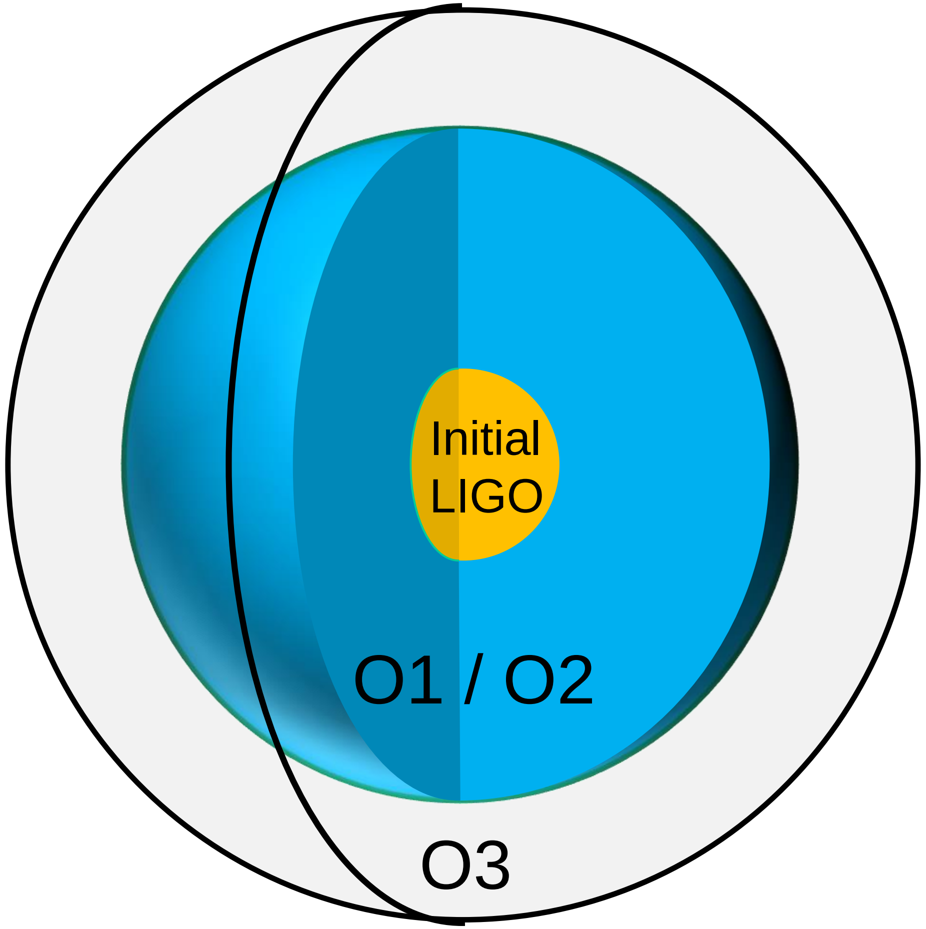


The O3 observing run began on April 1, 2019 and will run through April 30, 2020

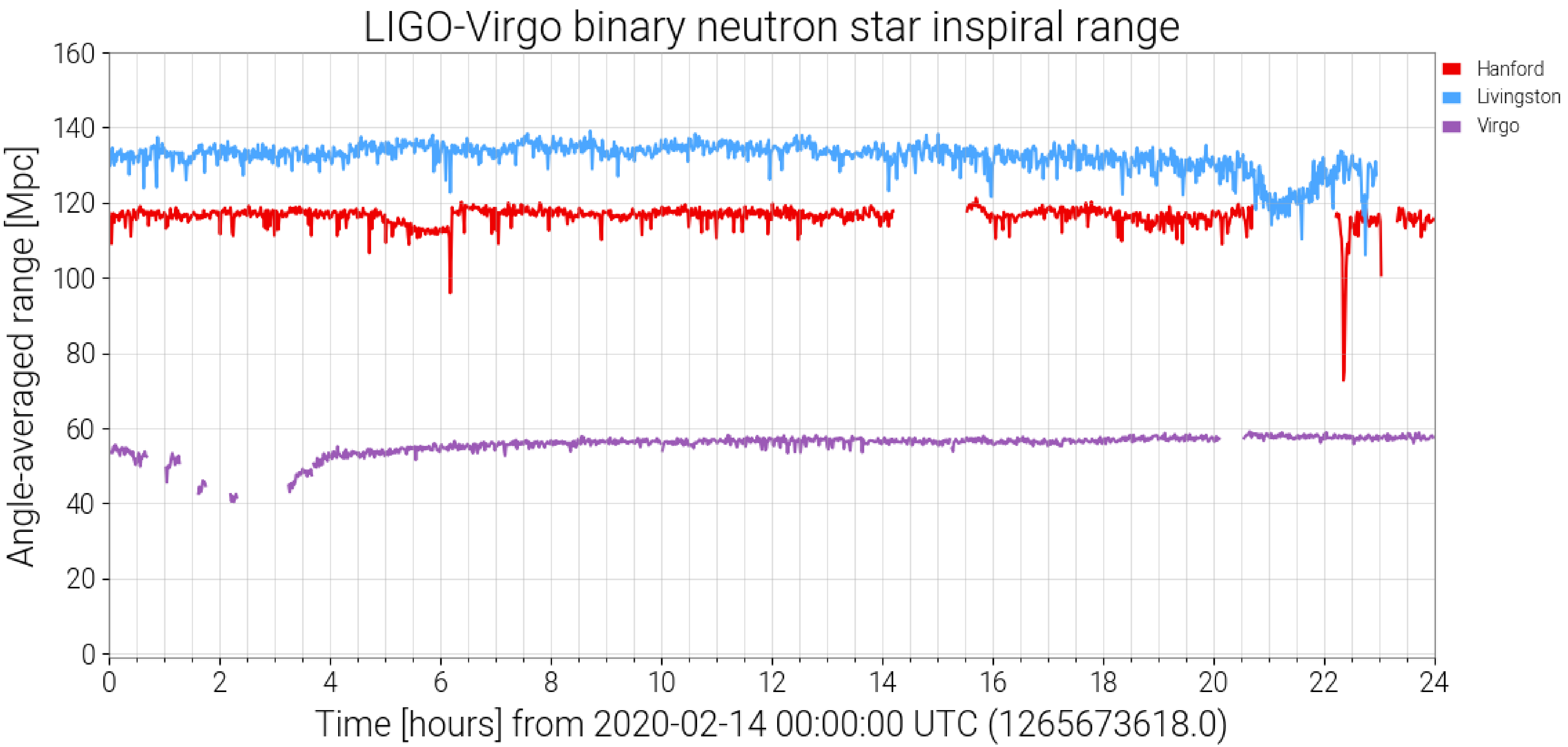
How detection rate scales with range

O3 has ~30% greater range than O1/O2

➔ $(1.3)^3 = 2.2$ **times the volume**



How have we done in O3 so far?



You can find detector status pages, public (O1+O2) data and analysis tutorials at
www.gw-openscience.org

GraceDB — Gravitational-Wave Candidate Event Database

HOME | PUBLIC ALERTS | SEARCH | LATEST | DOCUMENTATION

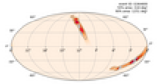
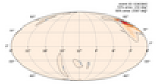
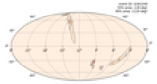
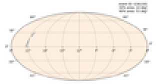
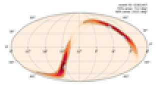
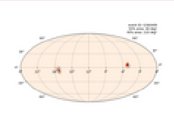
as of today

LIGO/Virgo O3 Public Alerts

Detection candidates: 51

https://gracedb.ligo.org/superevents/public/O3/

SORT: EVENT ID (A-Z)

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
S200219ac	BBH (96%), Terrestrial (4%)	Feb. 19, 2020 09:44:15 UTC	GCN Circulars Notices | VOE		1 per 2.3819 years	
S200213t	BNS (63%), Terrestrial (37%)	Feb. 13, 2020 04:10:40 UTC	GCN Circulars Notices | VOE		1 per 1.7934 years	
S200208q	BBH (99%)	Feb. 8, 2020 13:01:17 UTC	GCN Circulars Notices | VOE		1 per 12.587 years	
S200129m	BBH (>99%)	Jan. 29, 2020 06:54:58 UTC	GCN Circulars Notices | VOE		1 per 4.7313e+23 years	
S200128d	BBH (97%), Terrestrial (3%)	Jan. 28, 2020 02:20:11 UTC	GCN Circulars Notices | VOE		1 per 1.9238 years	
S200116ah	NSBH (>99%)	Jan. 16, 2020 11:56:42 UTC	GCN Circulars Notices | VOE		1 per 15618 years	RETRACTED

Tally of O3 Candidates

Out of the 51 (non-retracted) candidates shared in public alerts so far:

34 BBH candidates (mostly strong detections)

5 BNS candidates

6 NS-BH candidates

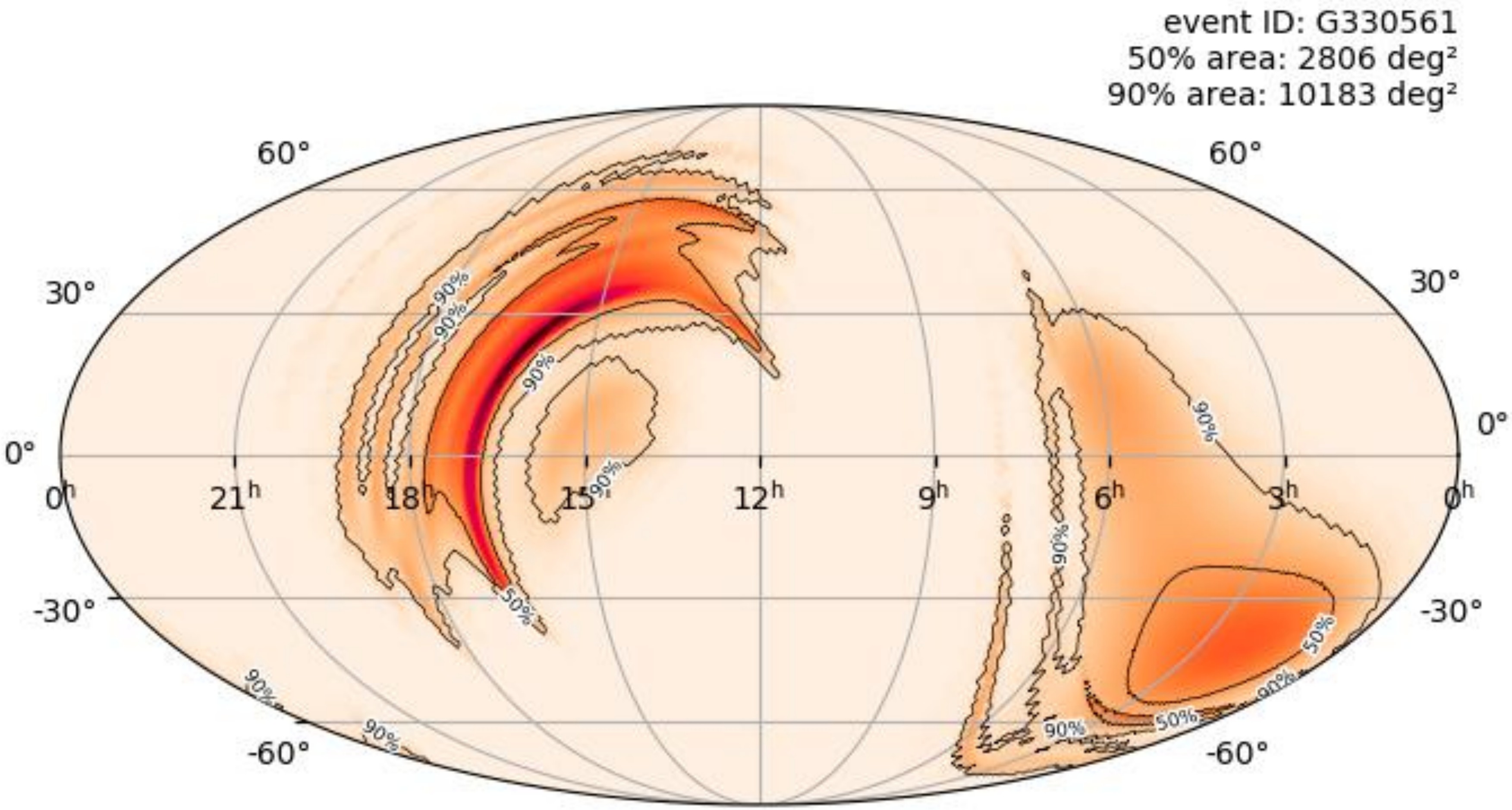
3 “mass gap” candidates

3 most likely terrestrial

But note that the majority of BNS and NS-BH candidates are fairly marginal

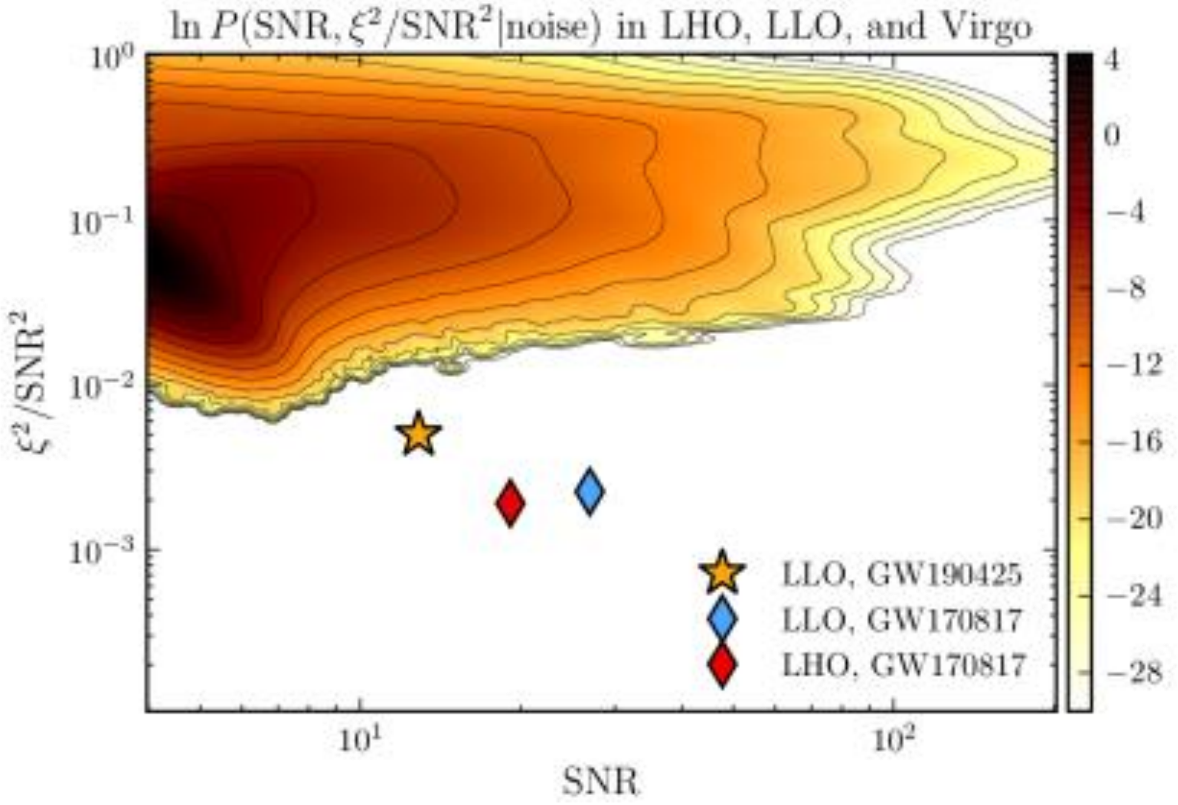
Best O3 binary neutron star candidate so far: S190425z

Binary neutron star merger detected strongly by LIGO Livingston, and weakly (sub-threshold) by Virgo. (LIGO Hanford was off ☹)

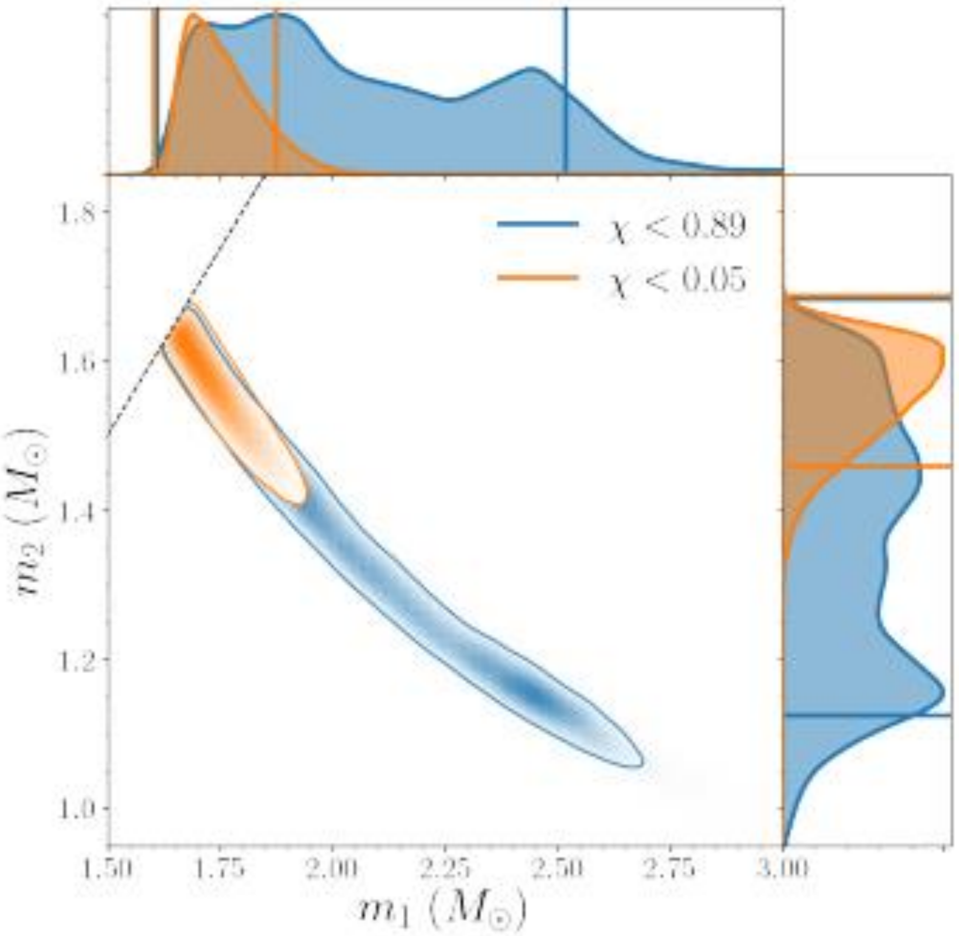


Confirmed! GW190425, our first published detection of O3

Not as strong an event as GW170817, but clearly separated from background (noise)



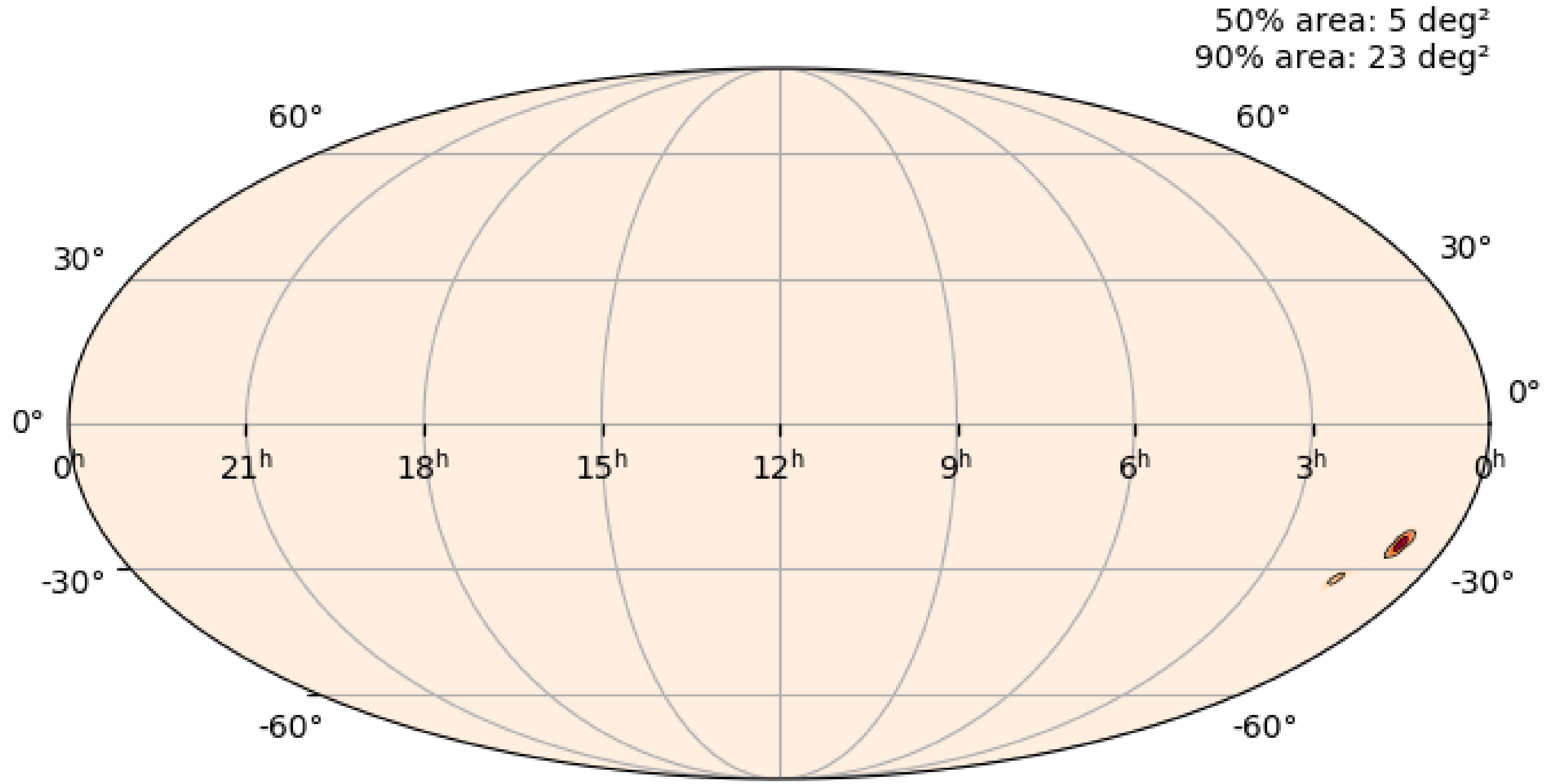
ApJL accepted; preprint at
https://arxiv.org/abs/2001.01761



Total mass ~ $3.4\, M_{\odot}$!
(Larger than any other known BNS system)

S190814bv: Likely neutron star–black hole mixed binary!

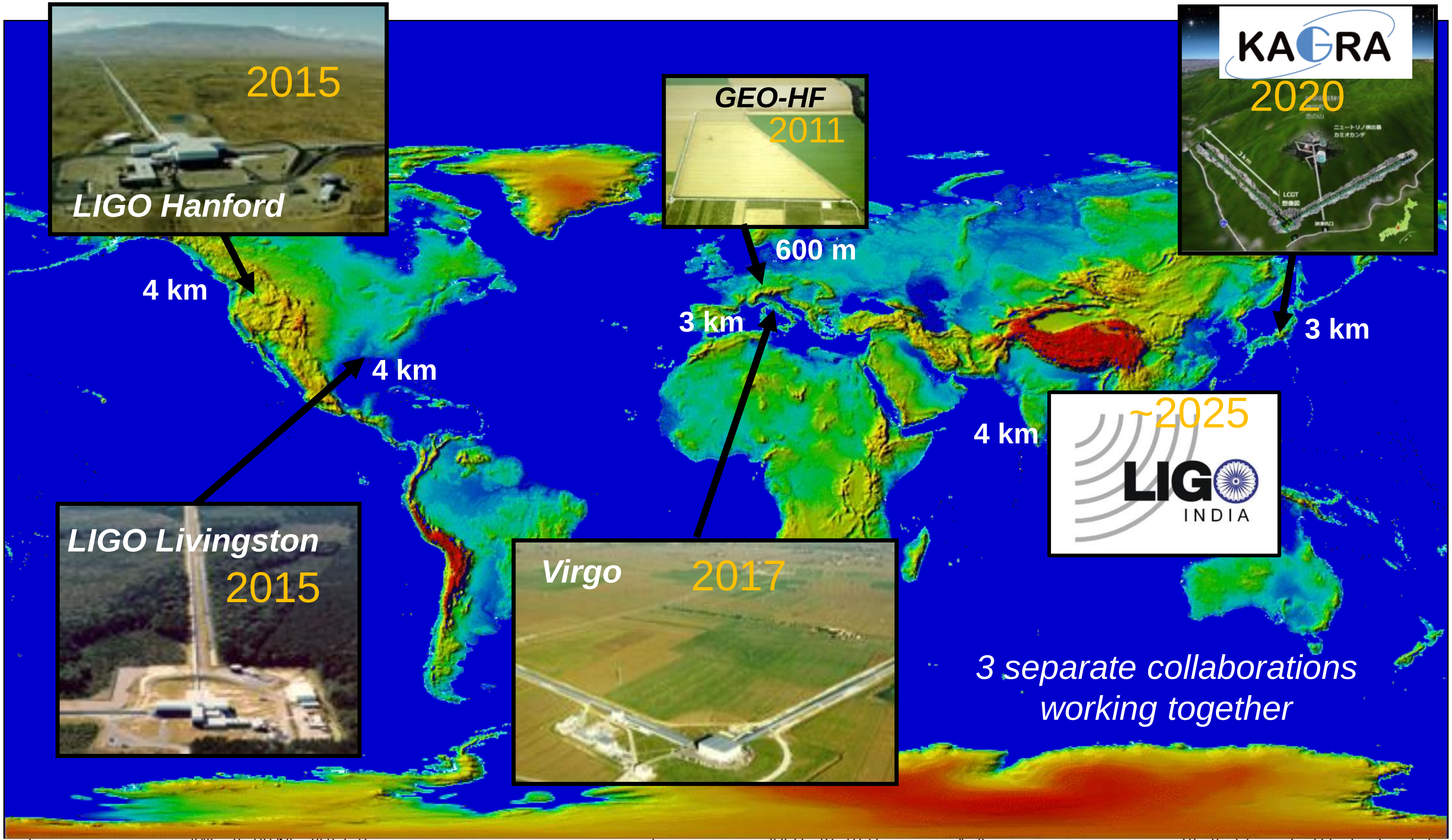
Detected rather confidently by both LIGO detectors *and* Virgo



Astronomers looked for and followed up potential counterparts, but nothing convincing…

Over 100 “circulars” (rapid communications) about this event were issued

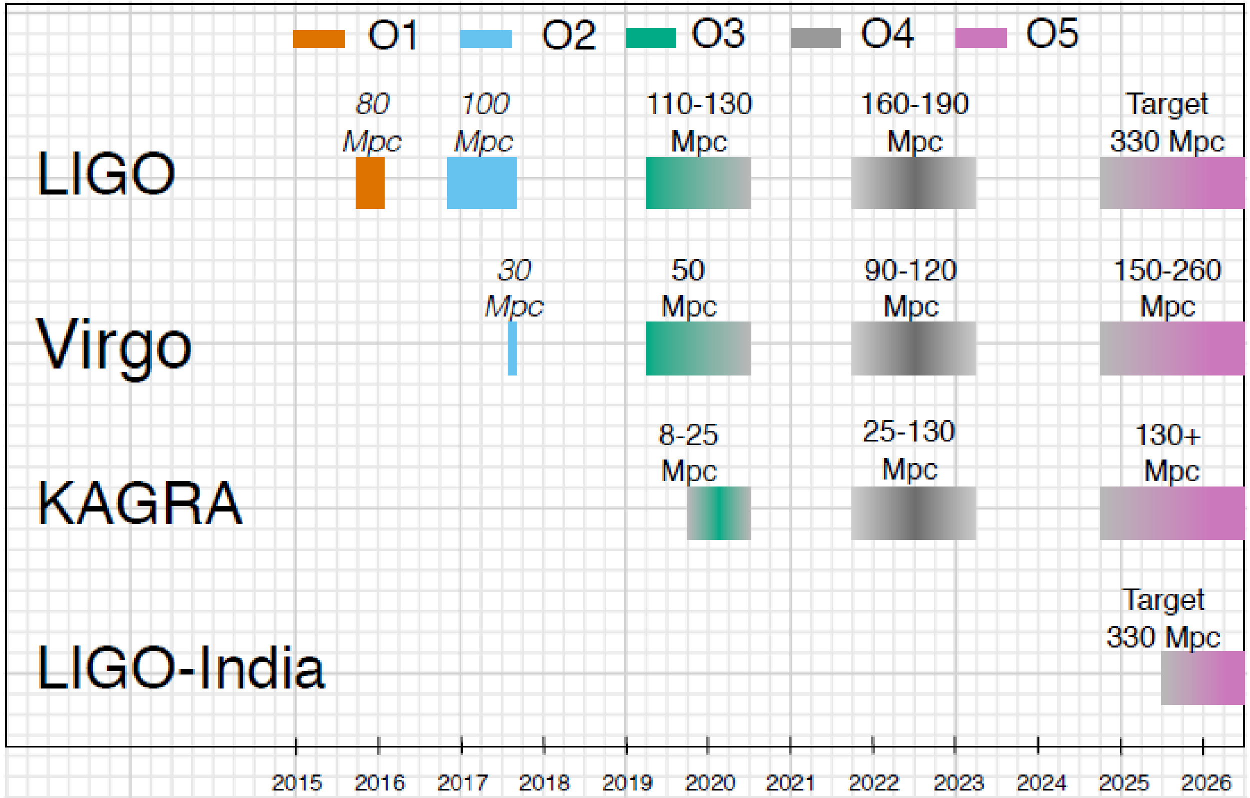
Expanding the network of Advanced GW detectors



Evolution of the GW Detector Network

Further Advanced LIGO / Virgo commissioning and upgrades are in progress

Including the A+ Project and Advanced Virgo Plus



The KAGRA detector in Japan is currently being commissioned

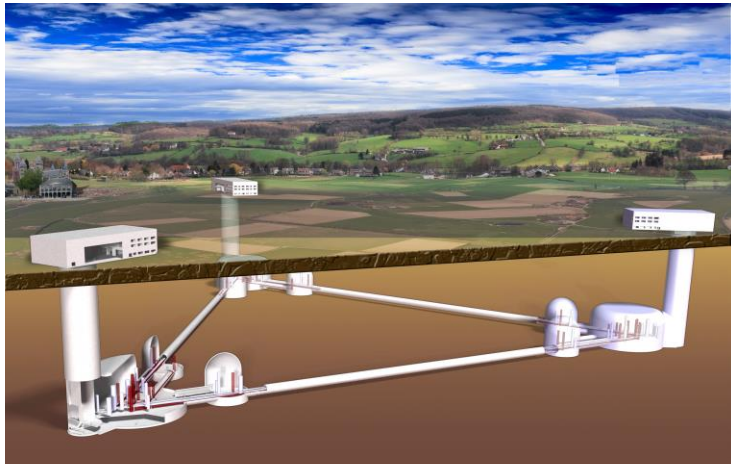
A site has been selected for the LIGO-India observatory, and ground will be broken soon

➔ By the mid-2020s, will have five highly sensitive detectors distributed around the Earth

Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA, arXiv:1304.0670 (new version as of September 2019)

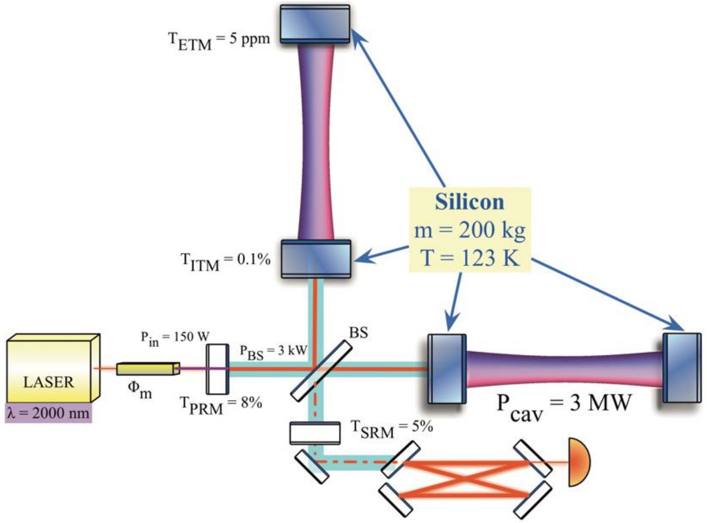
Third-Generation GW Detectors

Being pursued as a globally coordinated effort under the auspices of a subcommittee of the Gravitational Wave International Committee, GWIC 3G



Einstein Telescope (European project)

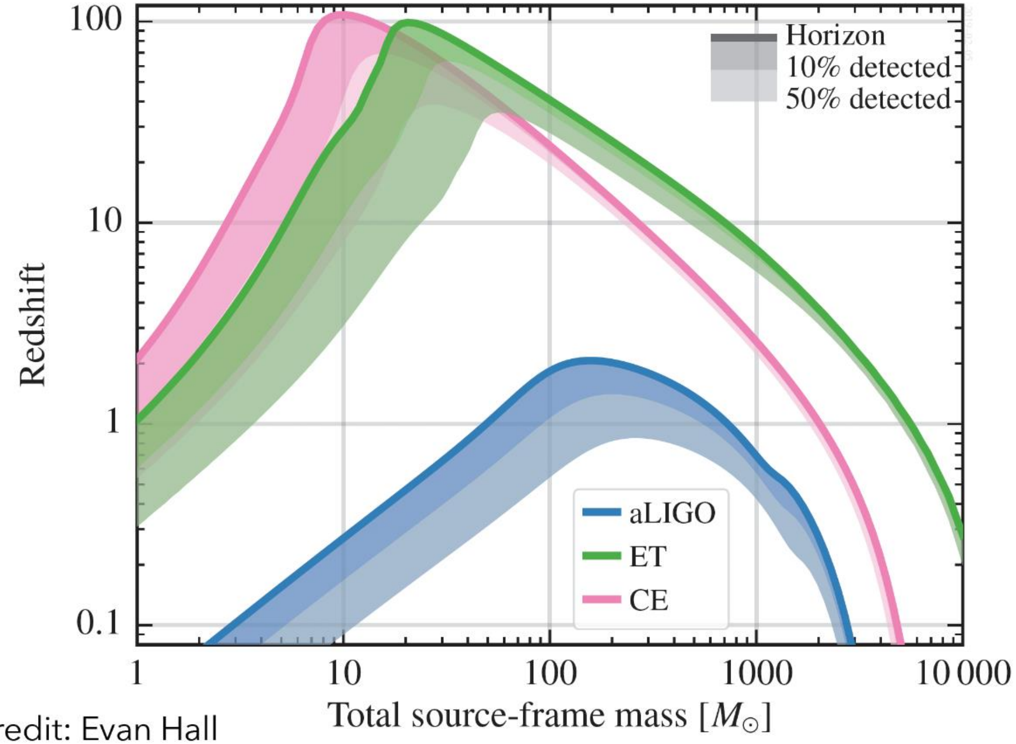
Underground triangular array of detectors



Cosmic Explorer (U.S. project)

Surface detector with arms up to 40 km long

3G NETWORK SENSITIVITY



Credit: Evan Hall

Could begin operating around 2030

Summary and Outlook

After decades of patient work, we've confirmed another major prediction of GR and launched a new kind of astronomy!

So far, we have detected a few dozen binary black hole mergers, at least two binary neutron stars, and at least one likely BH-NS

- We have tested detailed predictions from General Relativity
- We're getting a picture of the population of merging black holes
- Our very first binary neutron star merger was accompanied by a spectacular counterpart observed at all electromagnetic wavelengths

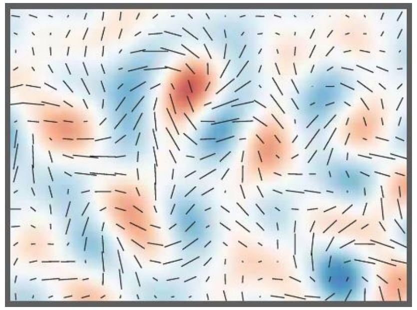
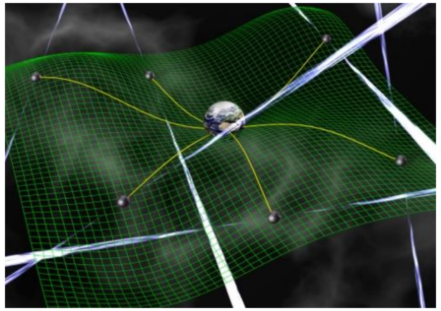
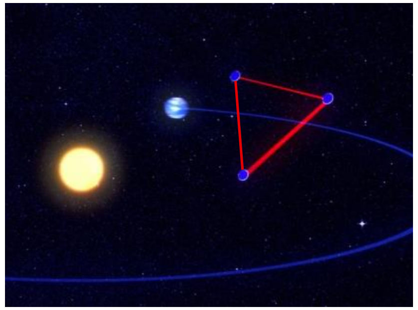
The O3 run continues to give us about one event per week

… and the international GW detector network is on track to grow

Learn more at www.ligo.org

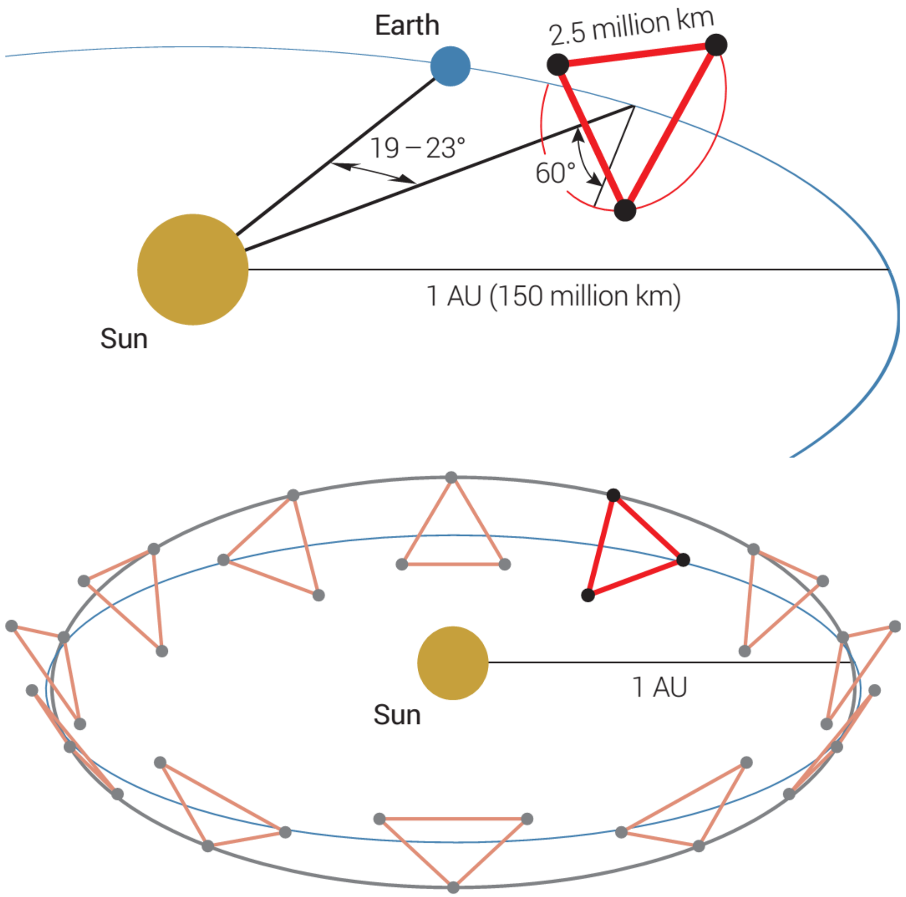
Extra slides

The Wide Spectrum of Gravitational Waves

	$\sim 10^{-17}$ Hz	$\sim 10^{-8}$ Hz	$\sim 10^{-2}$ Hz	~ 100 Hz
Likely sources	**Primordial GWs from inflation era**	***Gravitational radiation driven Binary Inspiral + Merger***		
		Supermassive BHs	Massive BHs, extreme mass ratios	Neutron stars, stellar-mass BHs
		Cosmic strings?	**Ultra-compact Galactic binaries**	**Spinning NSs** **Stellar core collapse** Cosmic strings?
Detection method	B-mode polarization patterns in cosmic microwave background	Pulsar Timing Array (PTA) campaigns	Interferometry between spacecraft	Ground-based interferometry
	 BICEP2	 David Champion	 AEI/MM/exozet	 LIGO Laboratory
Projects	BICEP2/Keck, ACT, EBEX, POLARBEAR, SPTpol, SPIDER, …	NANOGrav, European PTA, Parkes PTA	LISA, DECIGO	LIGO, GEO 600, Virgo, KAGRA

Gravitational wave detection with spacecraft: LISA

Use laser interferometry to measure changes in the distances among a trio of spacecraft in orbit around the Sun



Forms two independent Michelson interferometers plus a Sagnac null channel

~milliHertz sources:

Supermassive black hole binaries

Intermediate mass BH binaries

Extreme mass ratio inspirals (maps spacetime near BH)

Galactic compact binaries

Stochastic GW background?

[Danzmann et al. 2017, LISA Proposal to ESA]