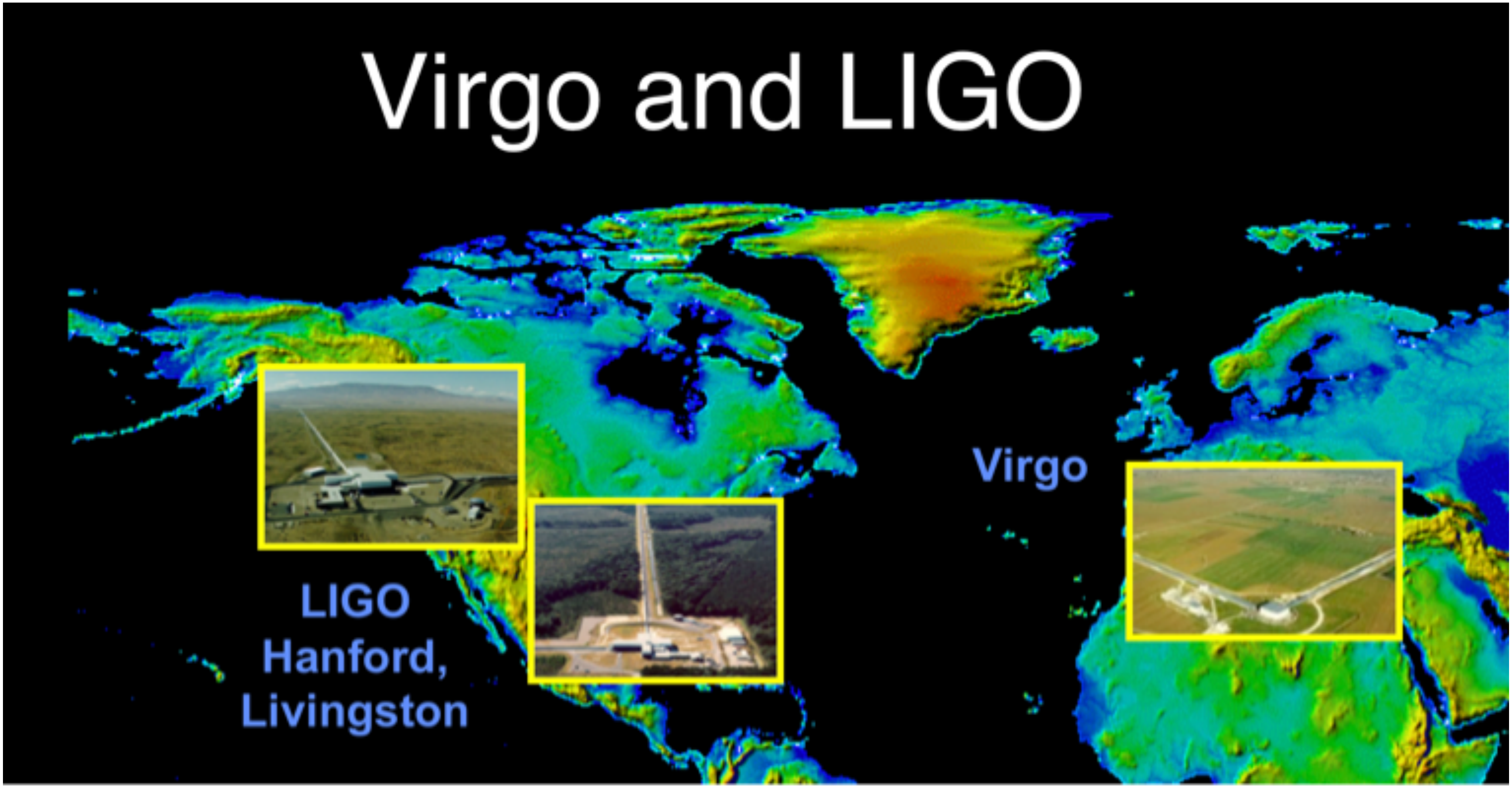
LIGO thanks the NSF for its vision and support!

LIGO's past and future observations of Black Hole and Neutron Star Binaries

Marcel Grossmann, Rome
3 July 2018

David Shoemaker
For the LIGO and Virgo Scientific Collaborations

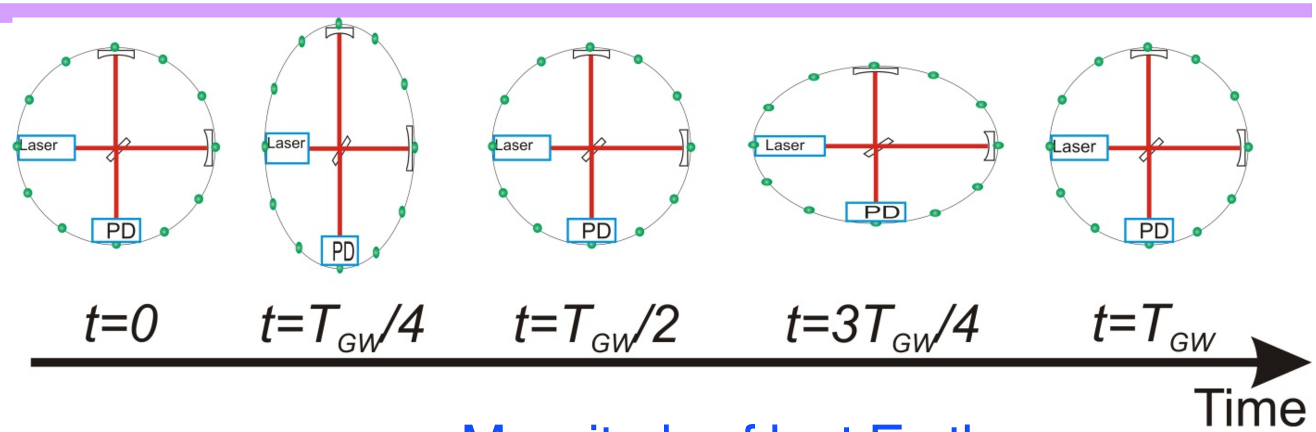
Credits
Measurement results: LIGO/Virgo Collaborations,
PRL 116, 061102 (2016); Phys. Rev. Lett. 119, 161101 (2017);
Phys. Rev. Lett. 119, 141101 (2017); Phys. Rev. Lett. 118, 221101 (2017);
Phys. Rev. Lett. 116, 241103 (2016)
Simulations: SXS Collaboration; LIGO Laboratory
Slides from (among others) L. Nuttall, P. Fritschel, L. Cadonati, P. Shawhan, A. Nitz, L. Singer
Photographs: LIGO Laboratory; MIT; Caltech; Virgo



- Observe together as a Network of GW detectors
- Coordinated talks –
  - Today: Detection and analysis principles (David Shoemaker, LSC)
  - Tomorrow: Physics, Astrophysics, and the Future (Jo van den Brand, Virgo)

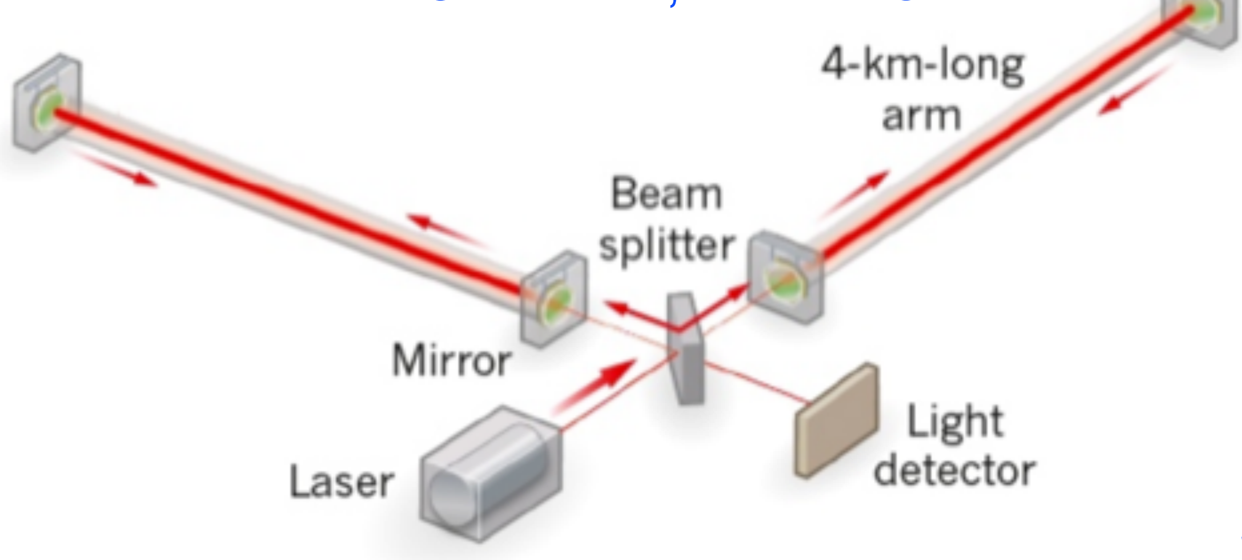
What is our measurement technique?

- Enhanced **Michelson interferometers**
  - » LIGO, Virgo use variations
- GWs modulate the distance between the end test mass and the beam splitter
- The interferometer acts as a transducer, turning GWs into photocurrent proportional to the strain amplitude
- **Arms are short compared to our GW wavelengths, so longer arms make bigger signals**
  → multi-km installations

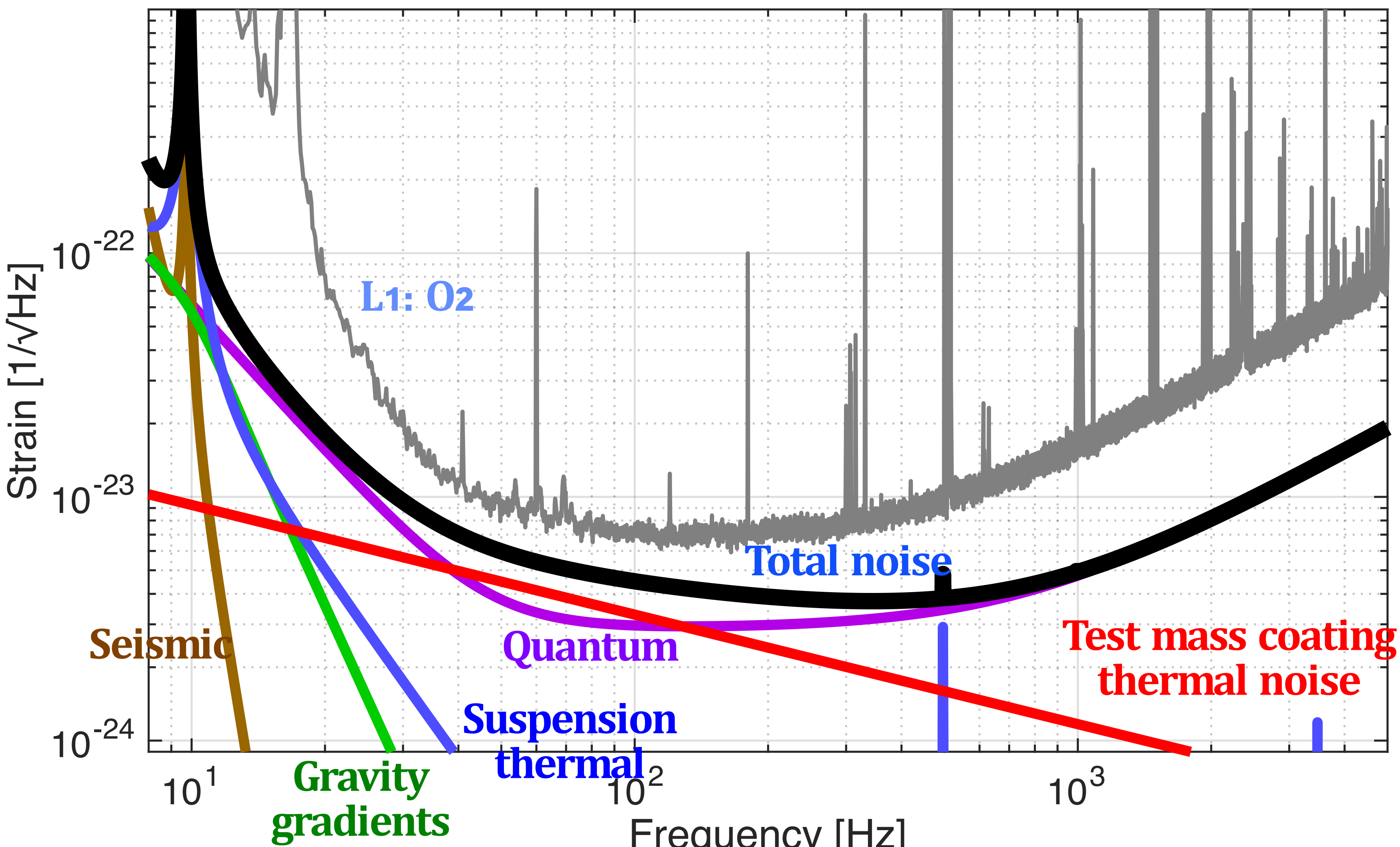


$$\boxed{h \approx \frac{\Delta L}{L}}$$

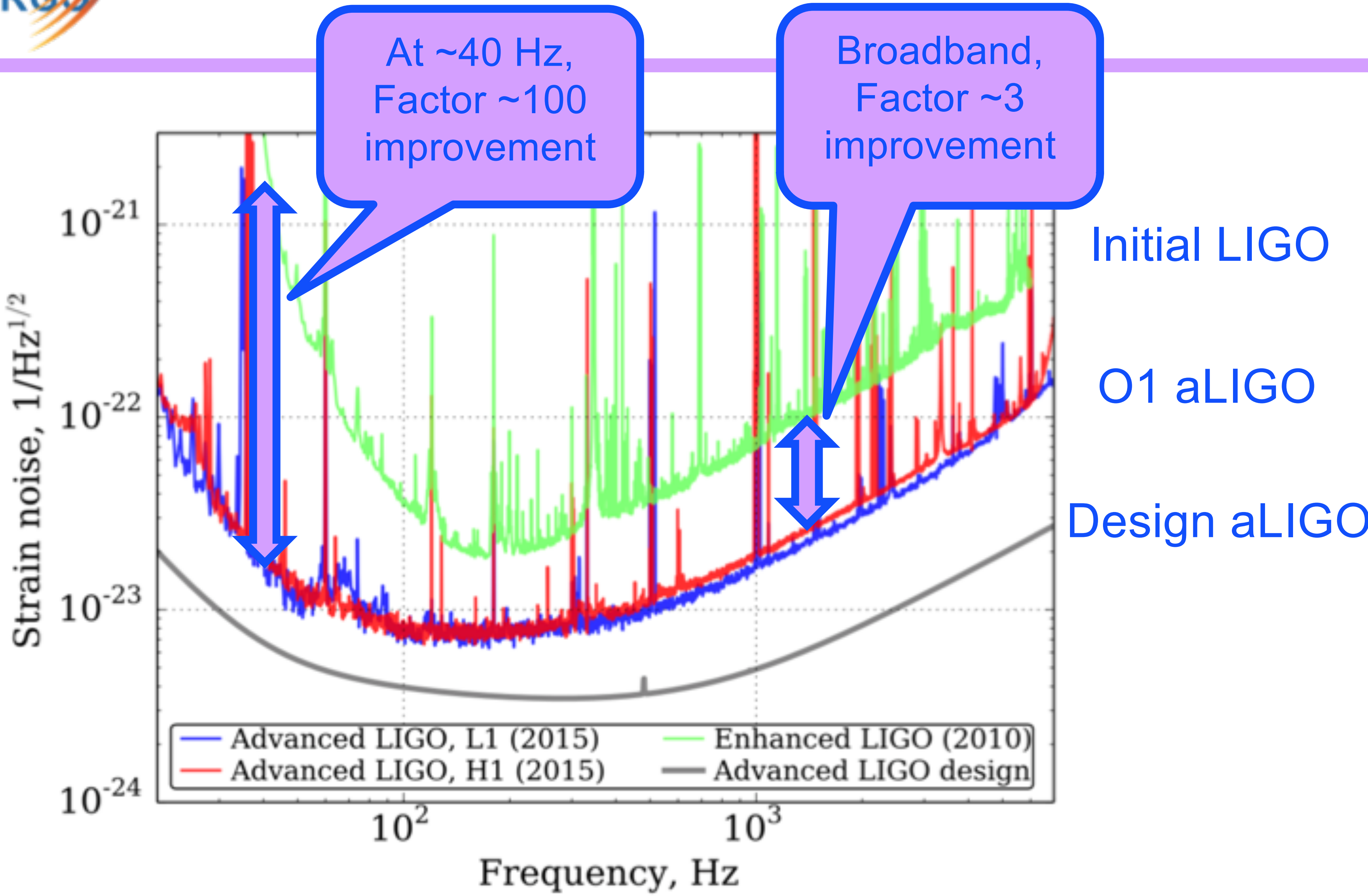
Magnitude of h at Earth:
Detectable signals h ~ 10^{-21}
(1 hair / Alpha Centauri)
For $L = 1$ m, $\Delta L = 10^{-21}$ m
For $L = 4$km, **$\Delta L = 4\text{x}10^{-18}$ m**



Adv LIGO Target Design
Sensitivity, basic noise sources



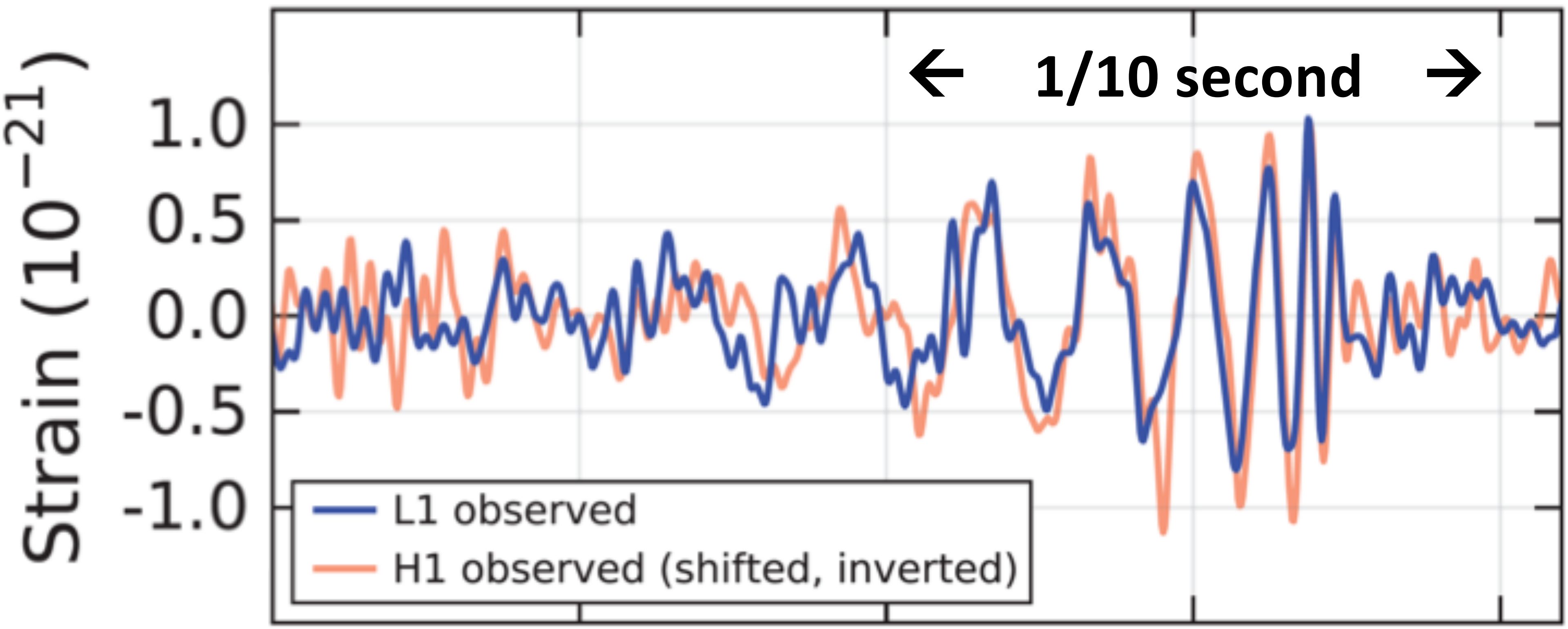
LIGO Sensitivity for first Observing runs



Final Slide from my talk at MG 14 August 2015:

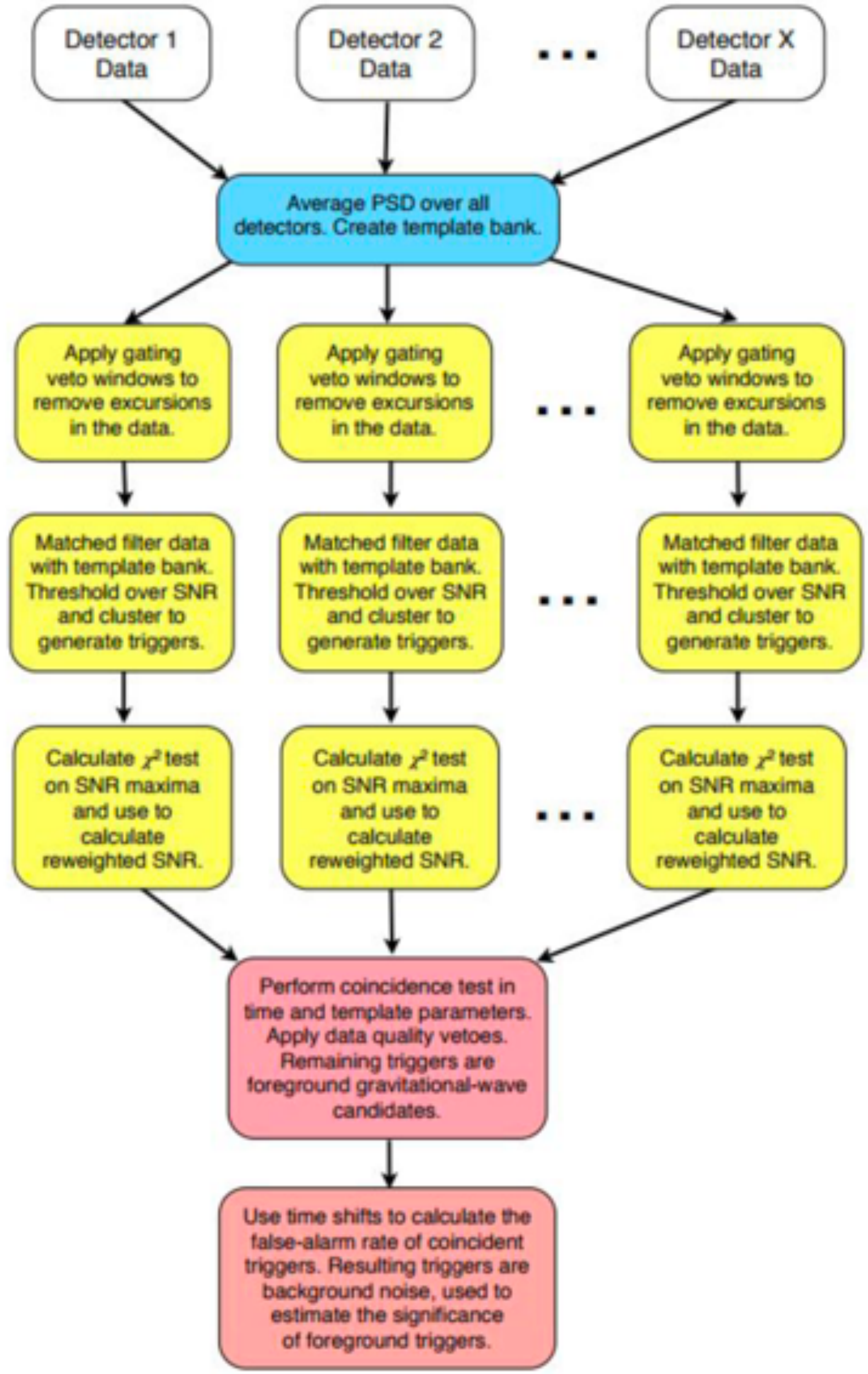
The first signal came *one month* later

- September 14, 2015, seen at the two LIGO observatories
  - » Delay between the two of 6.9 msec removed in plot below
- Binary Black Hole inspiral; assuming GR, best fit 36, 29 $M_\odot$, 410 Mpc

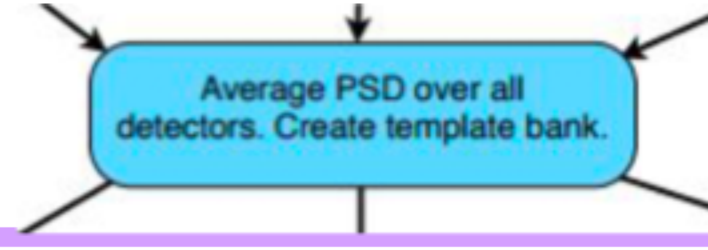


How do we prepare and analyze data?

- Discuss only binary inspirals here
  - Burst, Continuous Wave, and Stochastic have different approaches
- Assume GR is correct for the search
- Ideal detector noise would be stationary, Gaussian, and uncorrelated between the two detectors
- In reality, none of these properties hold exactly for LIGO data; our data analysis searches are crafted to be robust against these characteristics
- More information for those interested in the details can be found in materials for an Open Data Workshop held – https://losc.ligo.org/s/workshop1/course.html



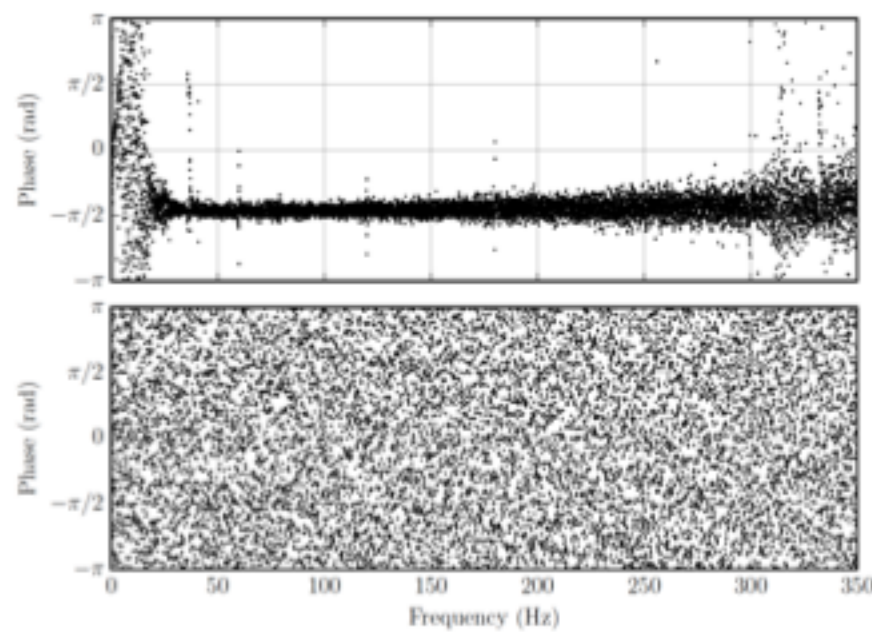
Forming the PSD: Windowing



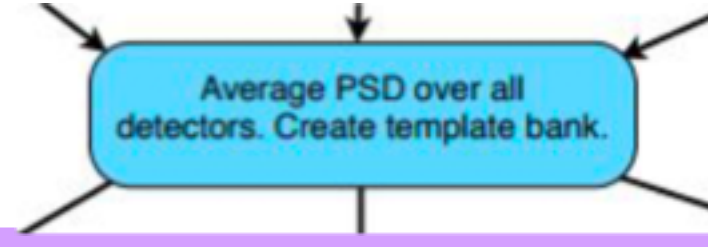
- To create the efficient template bank we need to know the Power Spectral Density (PSD) of the detector noise
- The discrete Fourier transform assumes that data are periodic
- Real detector data are *not* periodic as the last point in one segment of data, s_{N-1} , will be correlated with the 1st point of the next segment of data, s_N , but not the first point of the segment of data
- A standard technique to partially mitigate the artificial imposition of periodicity is to window the data segment

The phases of the discrete Fourier transform of the LIGO noise at Hanford, WA (H1) at the time of GW150914

- The phase spectrum of 32 s of unwindowed data.
- The phase spectrum of the same data after applying a Hann window

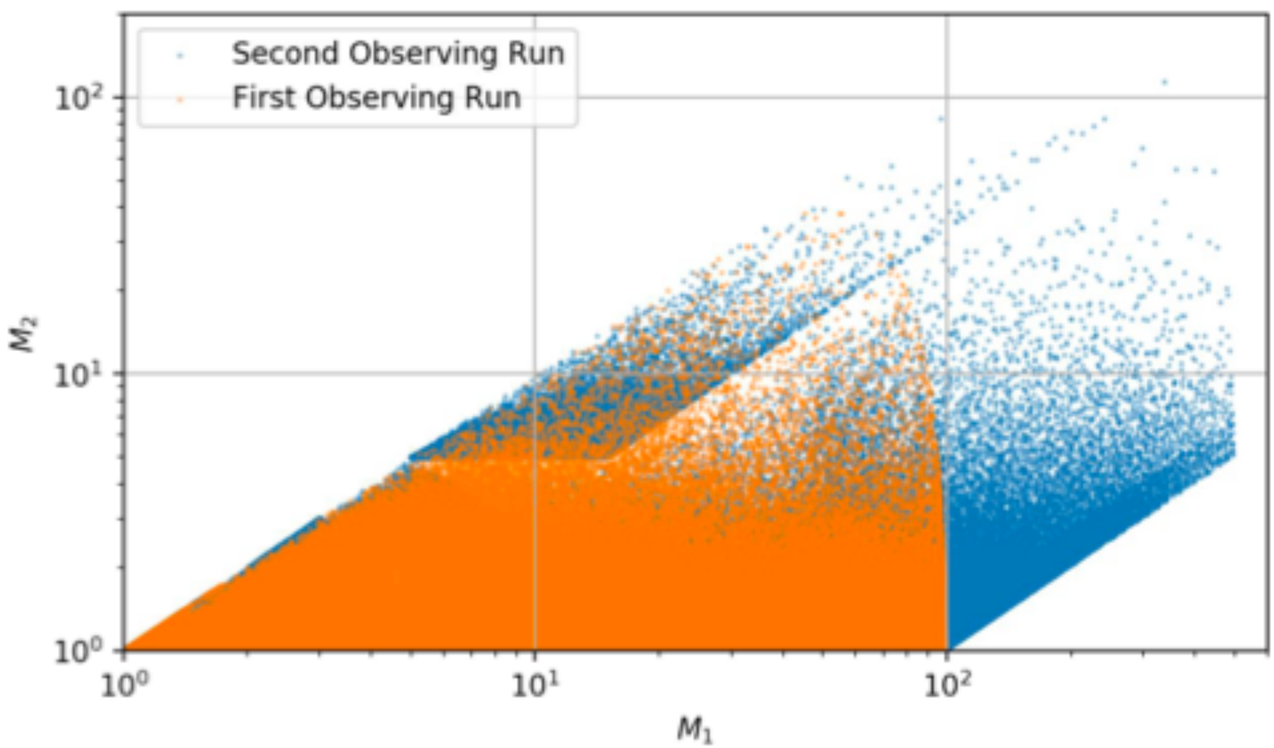


Making a set of search templates

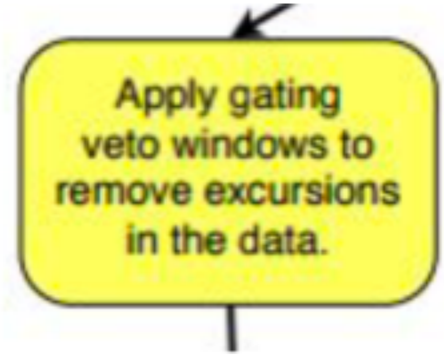


- Construct a stochastically-distributed set of templates based on GR
  - » Component mass of each object in the 'detector frame' (i.e., redshifted)
  - » Spin aligned with the orbital angular momentum
  - » Only the dominant mode (spherical harmonics)
- Require that we would lose no more than 10% of signals anywhere in our parameter space

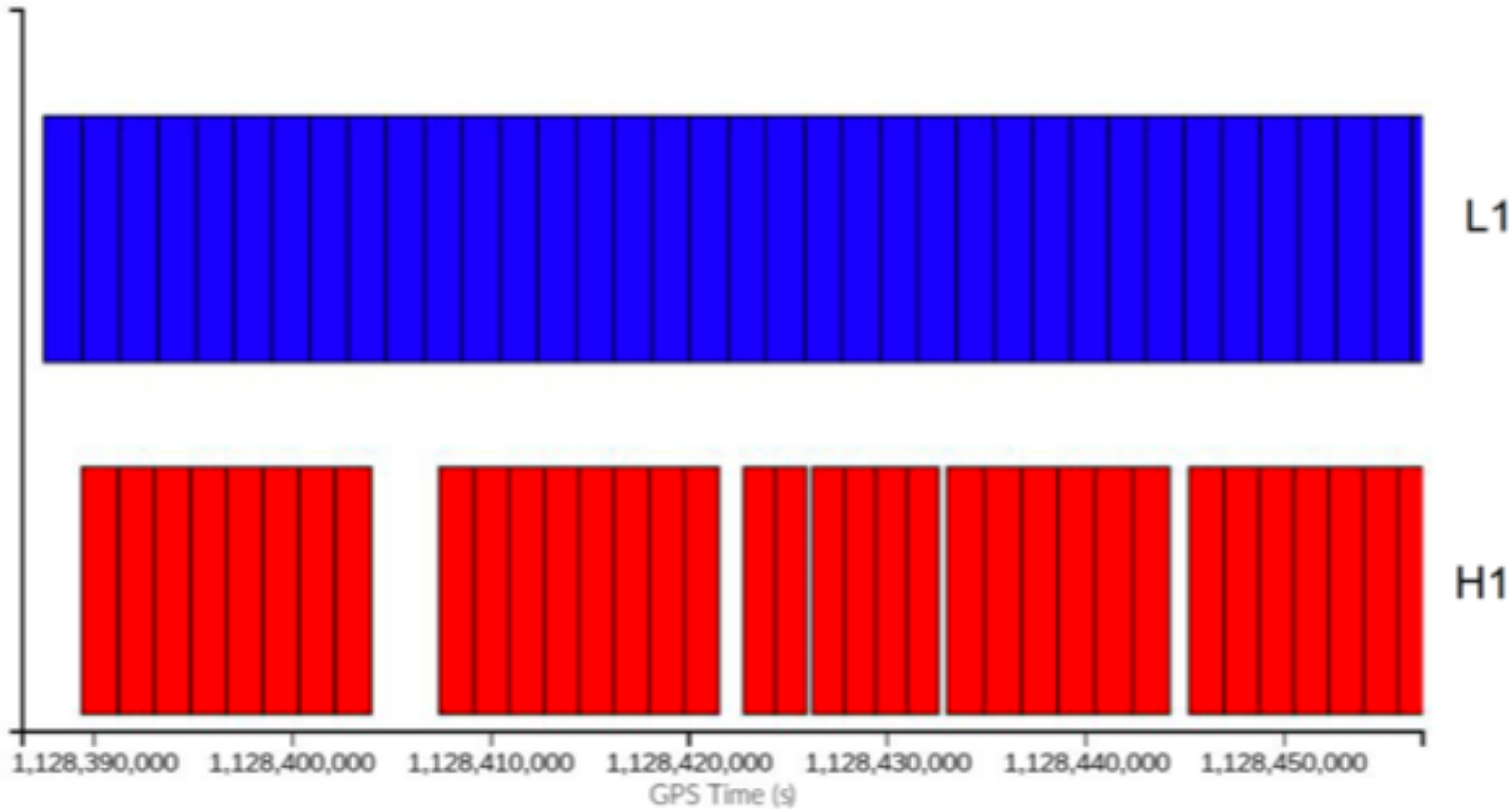
- → ~250,000 templates
- Added more high-mass templates after GW150914!



Remove clearly defective data



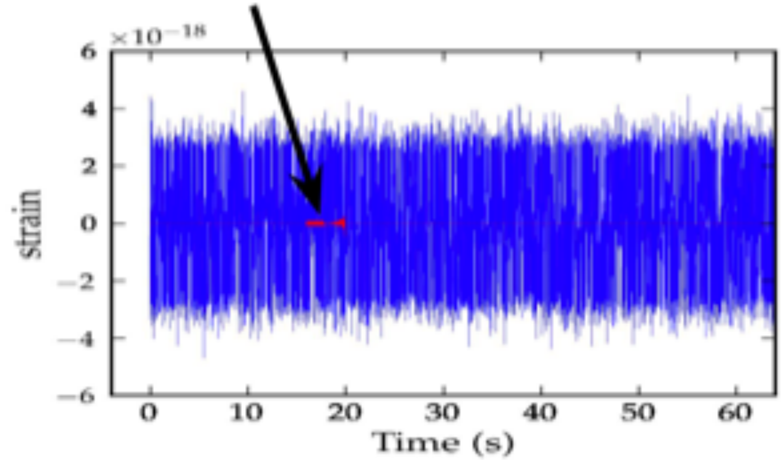
- Many causes and indicators
  - External seismic disturbances
  - Internal mechanical stress release
  - Signals in excess of dynamic range



Matched Filter

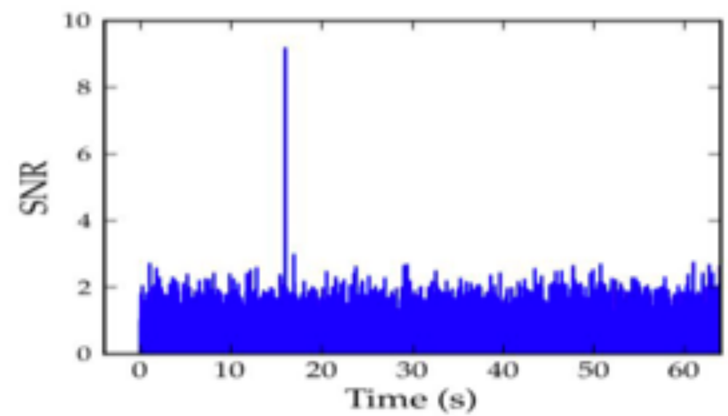
Matched filter data with template bank. Threshold over SNR and cluster to generate triggers.

Signal embedded in strain data **s(t)**



$\otimes$

Model waveform filters: **h(t)**



FFT of data

Template can maybe be generated in frequency domain using stationary phase approximation

$$C(t) = 4 \int_0^{\infty} \frac{\tilde{s}(f)\ \tilde{h}^*(f)}{S_n(f)}\ e^{2\pi i f t}\ df$$

Noise power spectral density

Matched Filter

Matched filter data with template bank. Threshold over SNR and cluster to generate triggers.

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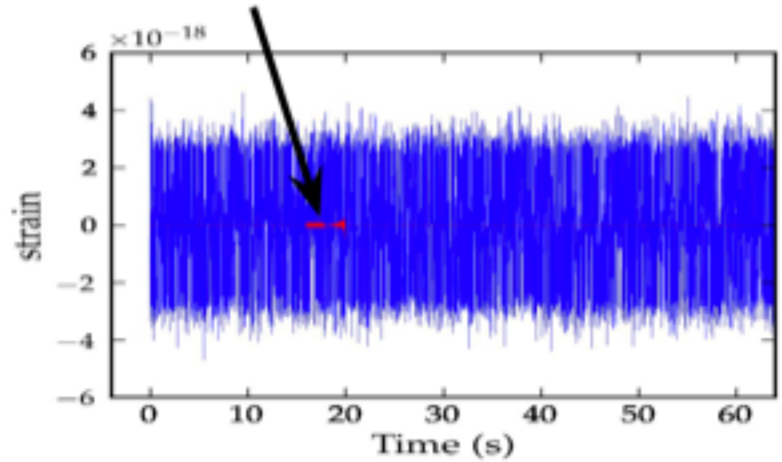

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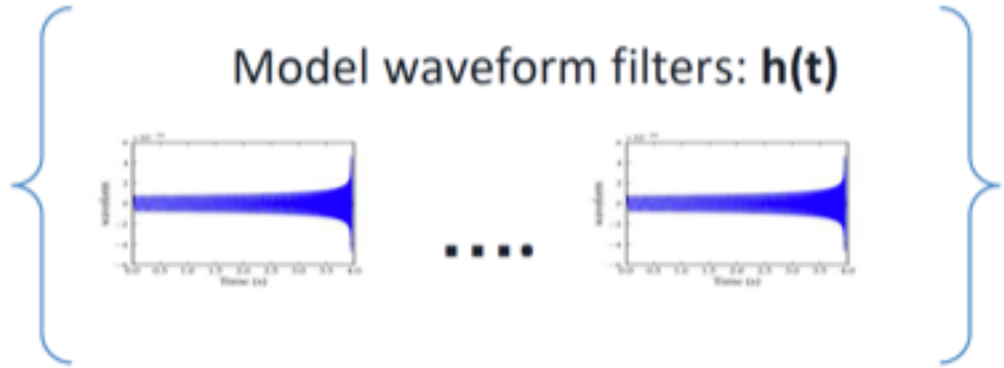

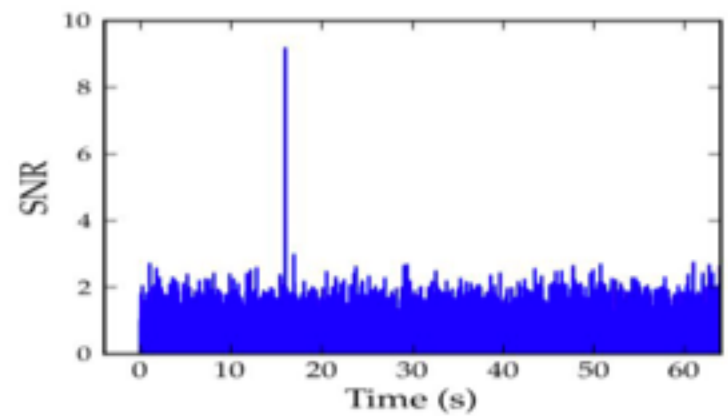

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Noise power spectral density

Quasi-stationary Noise around GW150914

- The noise is colored (Seismic, Thermal, photon shot noise)
- There are carefully-studied narrow line-like features also:
  - Digital acquisition (can be GPS synchronized between detectors)
  - Harmonics of the 60 Hz power lines (again, synch. Possible)
  - Resonant modes of the suspension systems
  - Calibration lines
  - Acoustic pickup
- These are ***suppressed*** by orders of magnitude by the optimal matched filtering process

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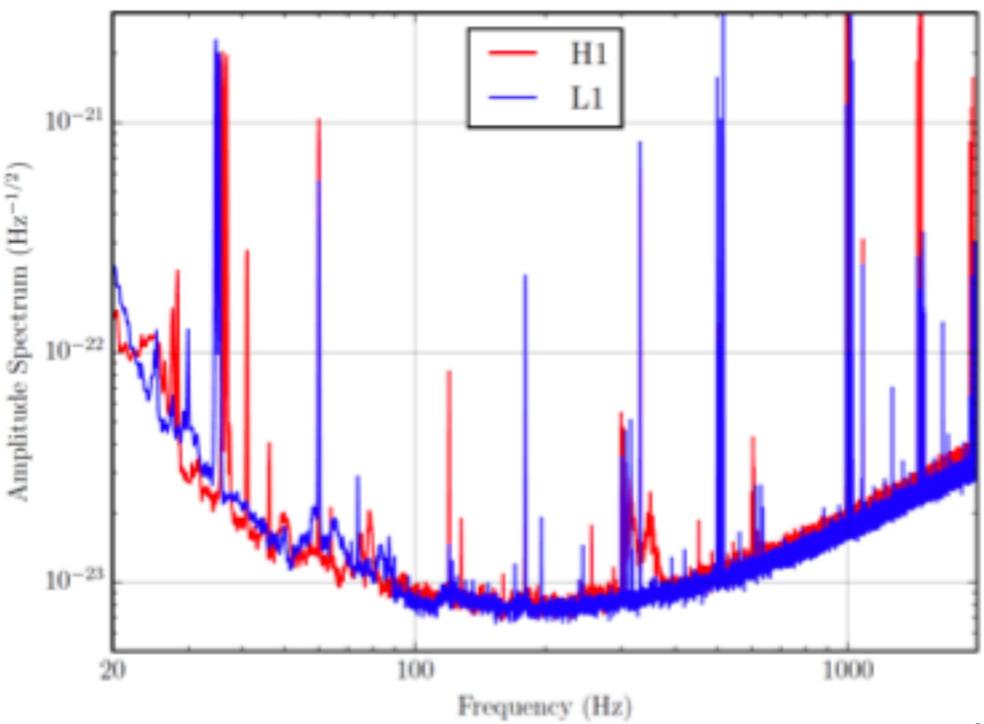

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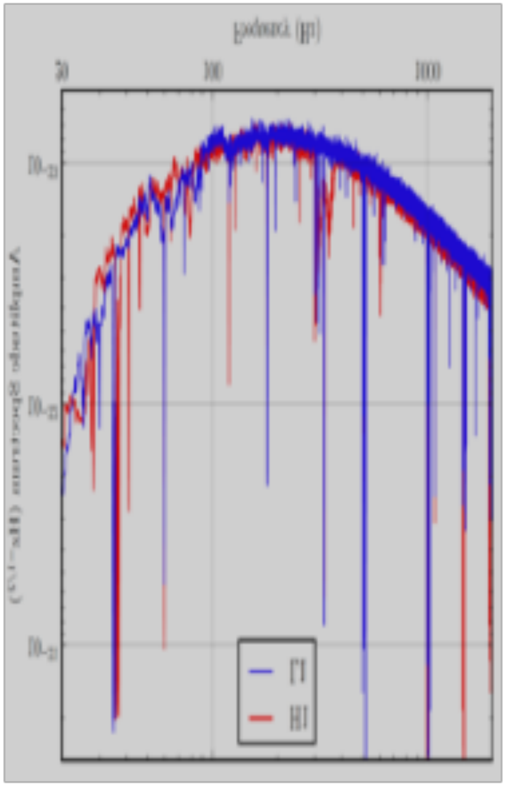
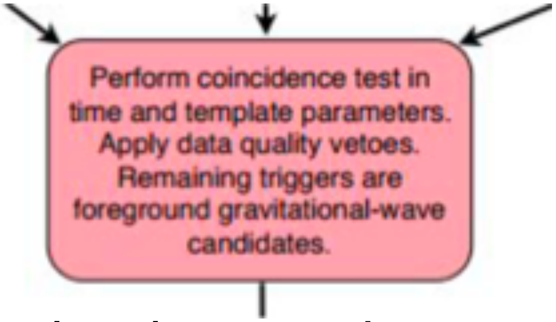
- These are ***suppressed*** by orders of magnitude by the optimal matched filtering process
- The **square** of the inverse of the amplitude spectrum

$$C(t) = 4 \int_0^\infty \frac{\tilde{s}(f)\ \tilde{h}^*(f)}{S_n(f)}\ e^{2\pi i f t}\ df$$

Noise power spectral density

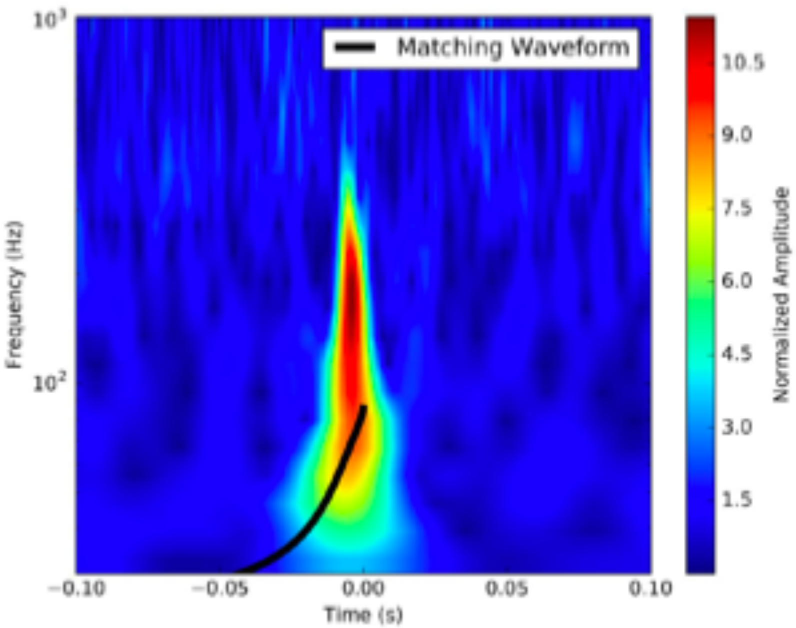


Non-stationary noise



Require that the Signal is…:

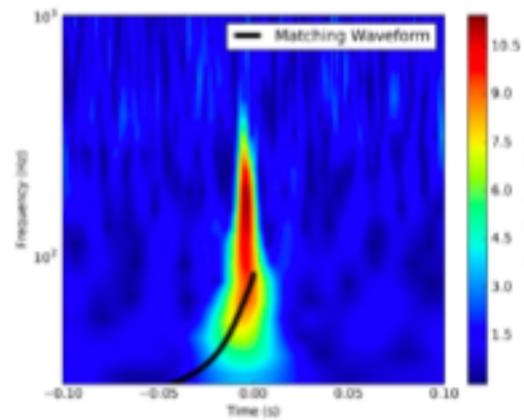
- Seen in multiple detectors within light travel time between the observatories
- Relative amplitude and phase of observed signal consistent with a single astrophysical source
- Signal morphology be consistent between observatories
- Consistency between signal model and observed data
  - » SNR contribution by frequency band
  - » Autocorrelation function
  - » SNR distribution over template bank
- Transient instrumental noise excitations – Glitches – must be excluded
- Check over 200 000 auxiliary channels
  - » motion of the ground or optics tables, magnetic and electric field variations, acoustic disturbances, or cosmic ray showers
  - » Couplings are determined via excitation



Require that the signal is internally consistent

Calculate χ^2 test on SNR maxima and use to calculate reweighted SNR.

- Re-weight the SNR by a time-frequency test of signal consistency
- For each maximum we calculate a chi-squared statistic to test whether the data in several different frequency bands are consistent with the matching template
- This gives a powerful veto of noise pulses which start out looking like an inspiral but deviate shortly thereafter

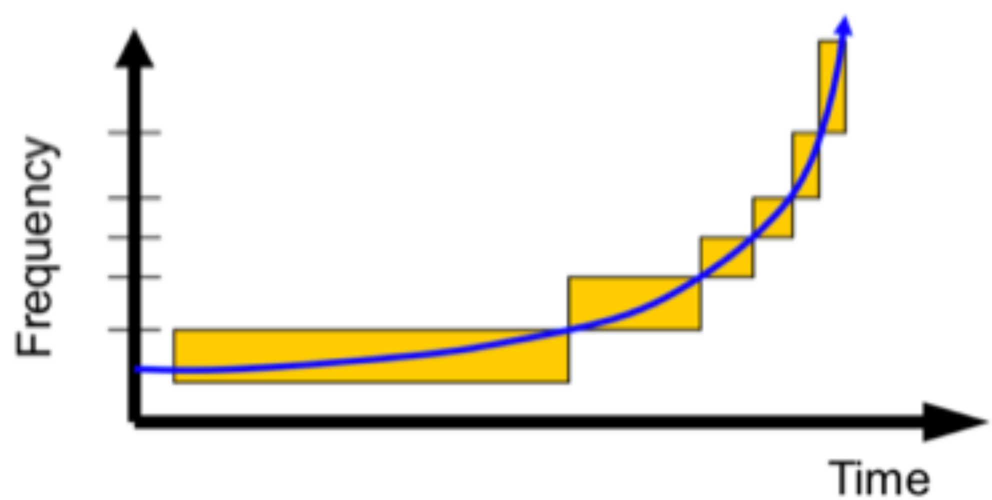


Chi-squared test

Allen, PRD 71, 062001 (2005)

Divide template into p parts, calculate

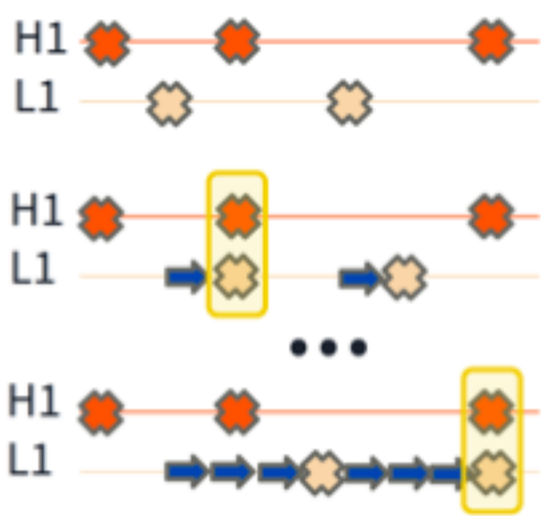
$$\chi^2(t) = p\sum_{l=1}^{p} \| C_l(t) - C(t)/p \|^2$$



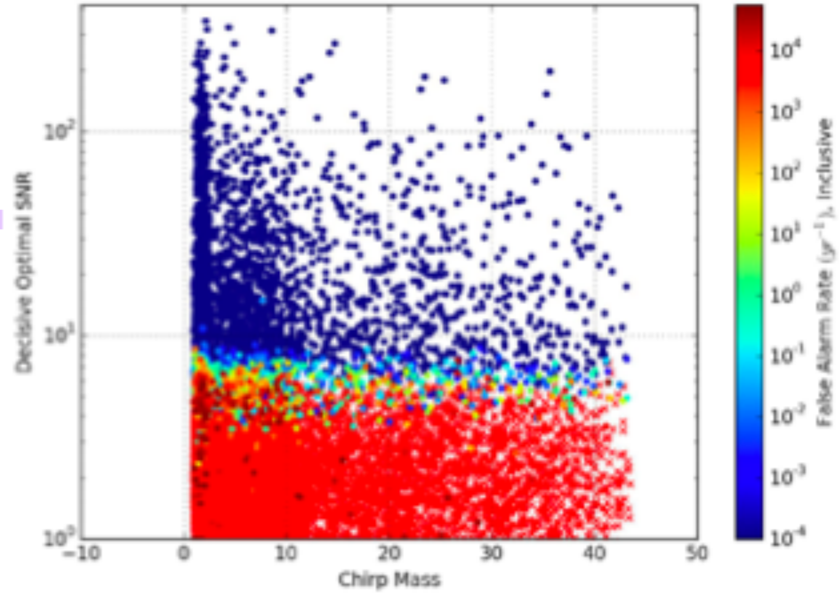
Estimate the Significance

Use time shifts to calculate the false-alarm rate of coincident triggers. Resulting triggers are background noise, used to estimate the significance of foreground triggers.

- We time shift the data of one detector relative to the other
- Coincidences in time slides are background triggers
- Any correlations in the background noise of the two detectors would show up here as peaks in time slides
- **IF the proper windowing, rejection of defective data, and optimal filtering is applied, no anomalous correlations are observed – just random coincidences**
- This process assures that the estimation of significance takes into account our non-Gaussian, non-stationary noise



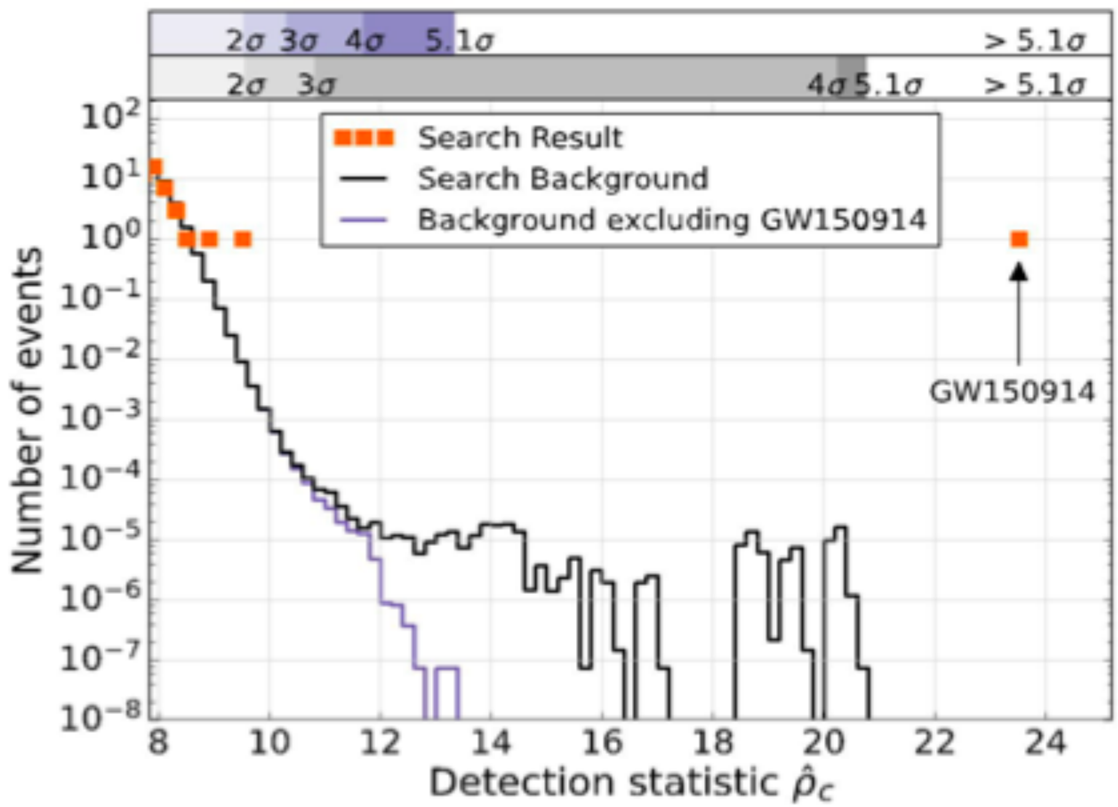
Test the system



- Inject hundreds of thousands of test signals in software
- **See that the multiple, independently-developed pipelines find the signals and characterize them correctly**
  - No accidental software injection could be confused with a real event; a real event shows up in many internal channels
- We do perform some hardware signal injections in an end-to-end test
  - These are not ‘blind’ – they are announced, and the excitation signal is clear in the monitoring channels
  - No accidental (or nefarious) hardware injection could sneak in; the excitation channels are checked as part of the detection process, experimental spaces monitored with video, electronics safety-taped shut
- By the way – our hardware injection actuator does not have enough high-frequency power to hardware-inject a binary neutron star inspiral!

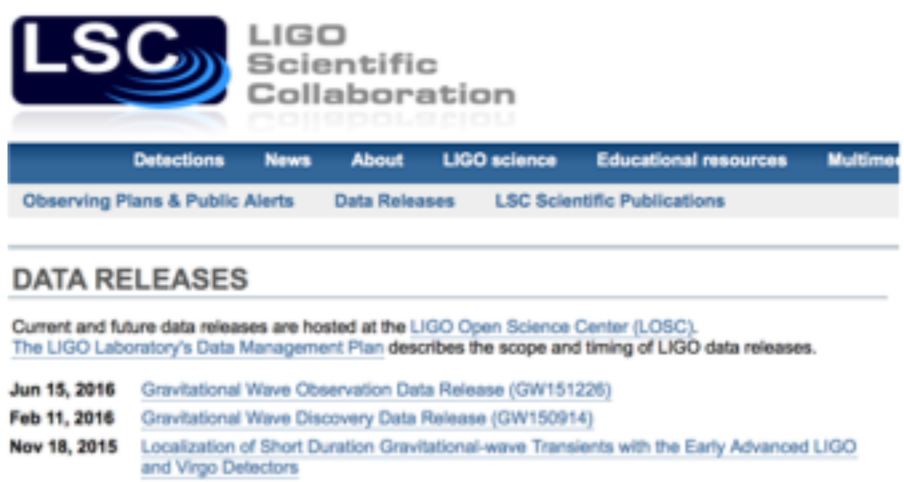
Success!

- A valid signal survives all these processes and tests
- Can proceed with parameter estimation, inferences about physics



O1-O2 Data

- Completing search on the O2 data
- Catalog of all events in preparation
- Other searches (Burst, Continuous Wave, Stochastic) also in process
  - » Continuous Wave searches are particularly compute- and so time-intensive
- Per the Data Management Plan, the strain data from the entire O2 run will be released in February 2019
  - » Look forward to independent analysis and perhaps discoveries



Speaking of analysis of LIGO Data

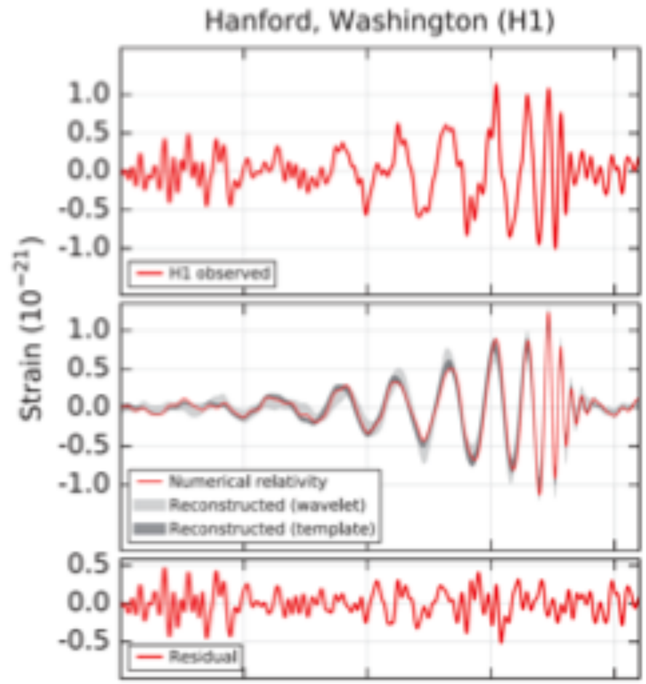
- GWOSC (https://losc.ligo.org/about/) hosts
  - » GW strain data around the time of each reported event
  - » Event localization (SkyMaps)
  - » Full Data sets (all O1 data now there; O2 data in Feb 2019)
  - » Tutorials – please note, these are demonstration analysis programs, not those we use
  - » Software links for much of our production software
    - – 'PyCBC', one of the inspiral analysis pipelines is now well packaged

- Intend for it to grow in detail and scope

Speaking of analysis of LIGO Data

- LSC and Virgo are glad to see analyses of GW data beyond the Collaborations
  - Tests of confidence in results, alternative approaches
  - Searches for events the LVC did not find
  - Searches for hypothesized event types not targeted by LVC
  - Growth in the field
- Papers appearing using data from GWOSC
- Growing list compiled at https://losc.ligo.org/projects/

- Input from community helping us adjust how we provide derived data, providing insights – e.g.:
  - As Creswell et al. found, figure in GW150914 PRL did not have exact residuals
  - Now adding posterior samples from parameter estimation (not in LIGO Data Management Plan)



LIGO Open Science Center

LIGO is operated by California Institute of Technology and Massachusetts Institute of Technology
and supported by the U.S. National Science Foundation.

Projects with LOSC data

Some examples of projects using LIGO data are shown on this page.

Listing a project here does not imply endorsement by LIGO Laboratory or the LIGO Scientific Collaboration.

If you have completed a project with LIGO data, please let us know!

2018

Observational evidence of the central engine to GRB170817A
Maurice H.P.M. van Putten
arXiv:1806.02165

Constraining the nuclear equation of state with GW170817
Soumi De, Daniel Finstad, James M. Lattimer, Duncan A. Brown, Edo Berger, Christopher M. Biwer
arXiv:1804.08583

Measuring the viewing angle of GW170817 with electromagnetic and gravitational waves
Daniel Finstad, Soumi De, Duncan A. Brown, Edo Berger, Christopher M. Biwer
arXiv:1804.04179

GW170817 event rules out general relativity in favor of vector gravity?
Anatoly A. Svidzinsky, Robert C. Hilborn
arXiv:1804.03520

Echoes from the Abyss: A highly spinning black hole remnant for the binary neutron star merger GW170817
Jahed Abedi, Niayesh Afshordi
arXiv:1803.10454

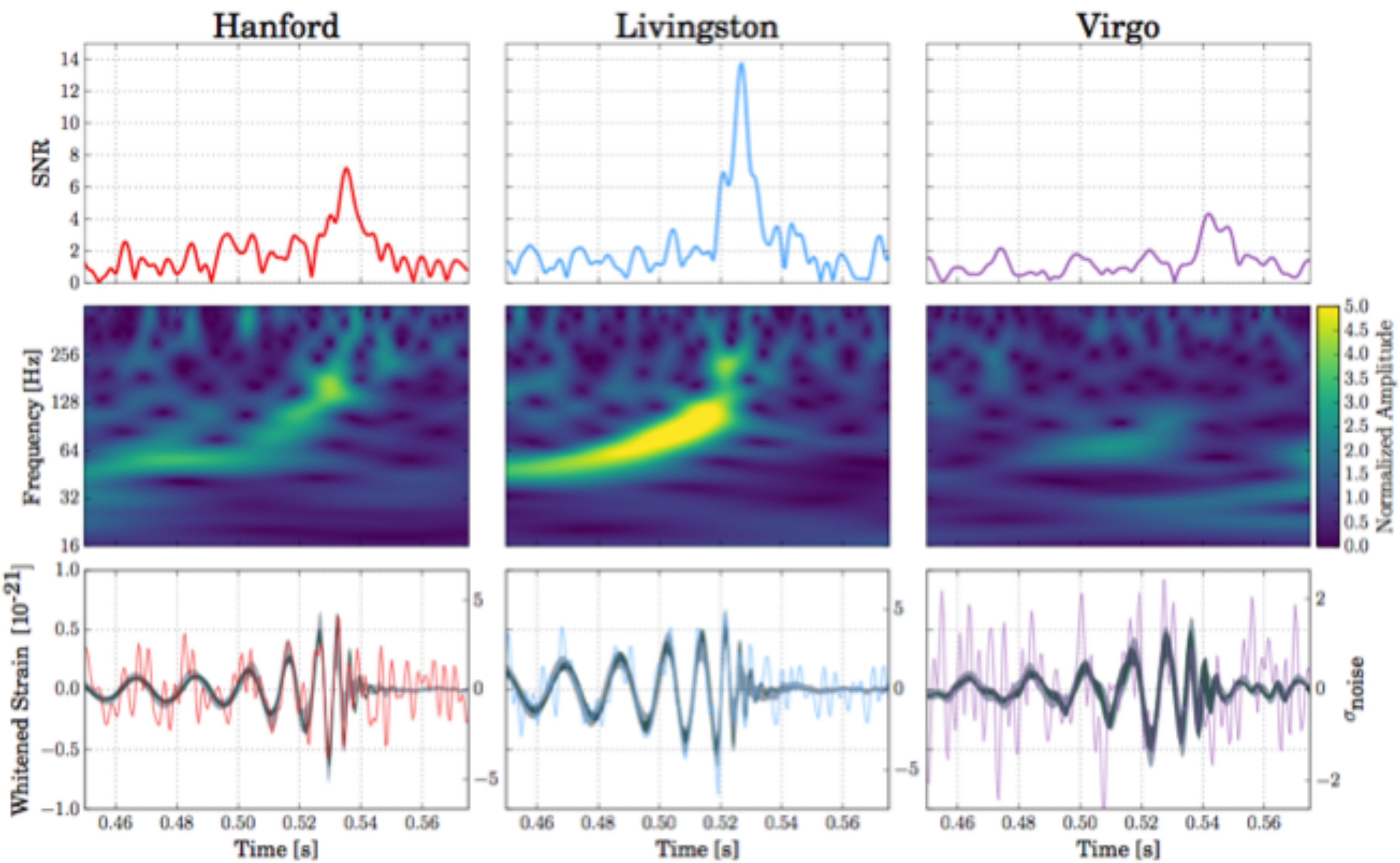
Degeneracy of gravitational waveforms in the context of GW150914
James Creswell, Hao Liu, Andrew D. Jackson, Sebastian von Hausegger, Pavel Naselsky
arXiv:1803.02350

Gravitational Wave Polarization Analysis of GW170814
Robert C. Hilborn
arXiv:1802.01193

What else have we seen?
Focus on two events jointly detected by Virgo and LIGO

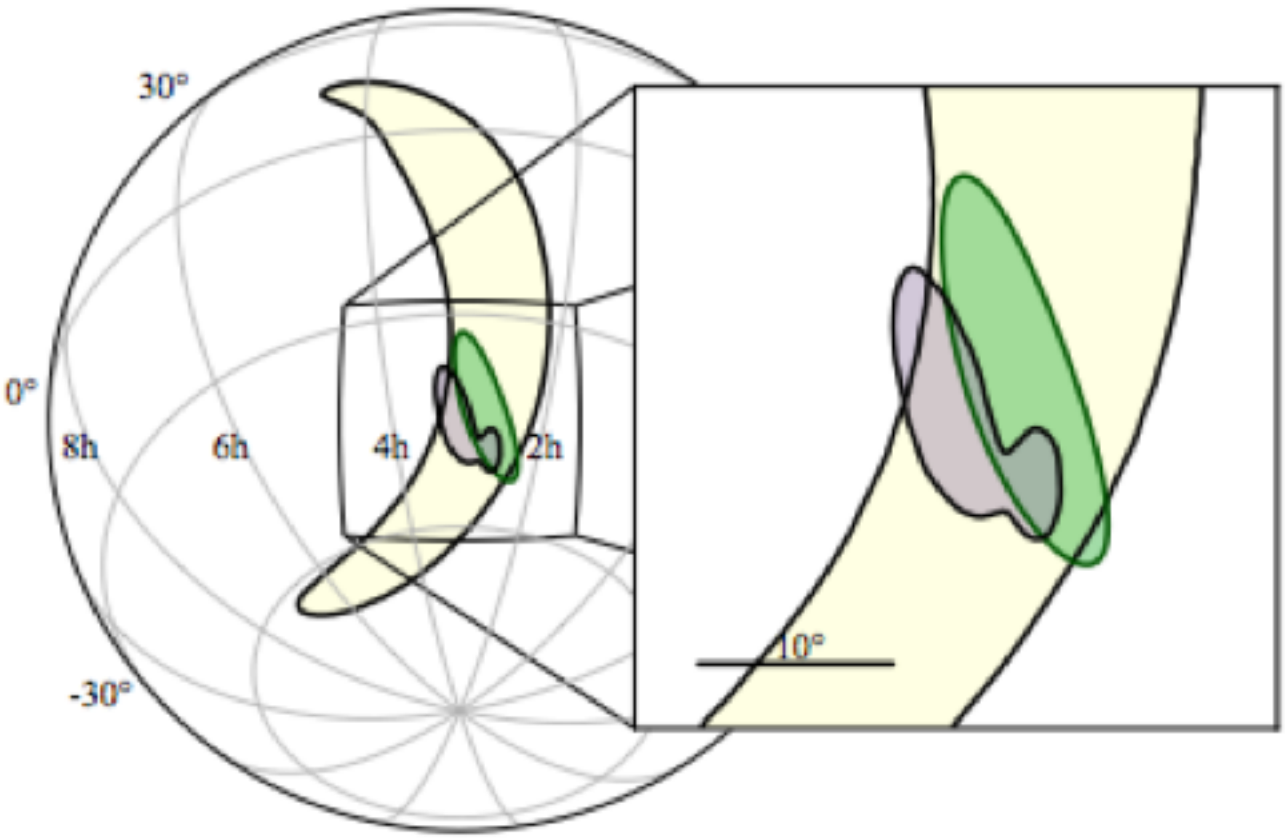
GW170814

The first GW signal observed by LIGO-Hanford, LIGO-Livingston and Virgo

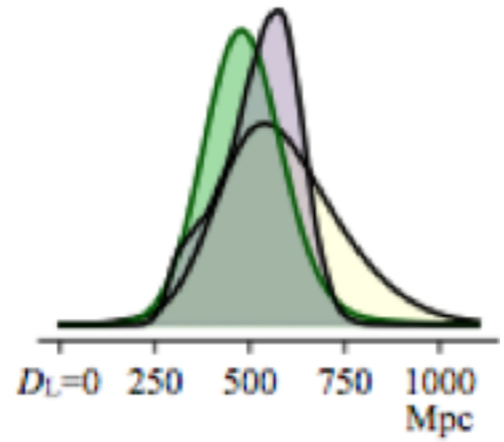


B. P. Abbott et al., *A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence*, 2017, Phys. Rev. Lett., 119, 141101

Skymap enabled with GW170814

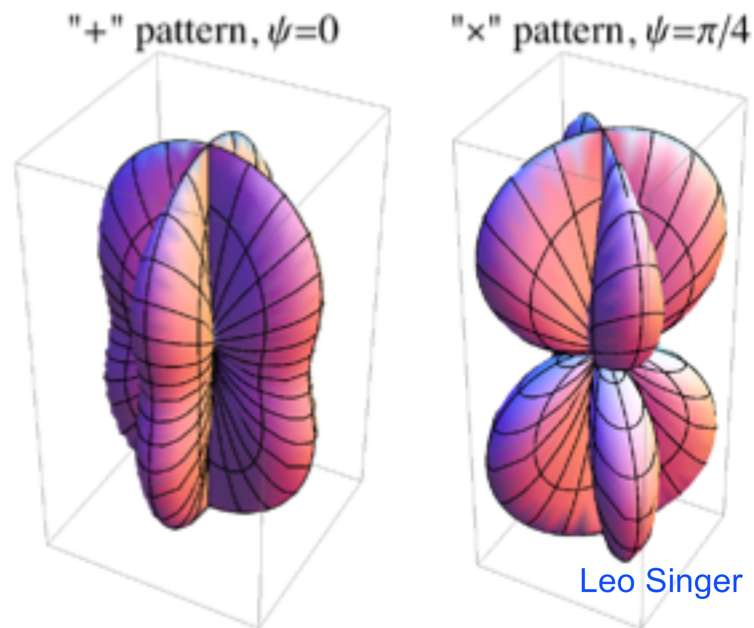


Skymap area reduced
~20x



Volume reduced
~34x

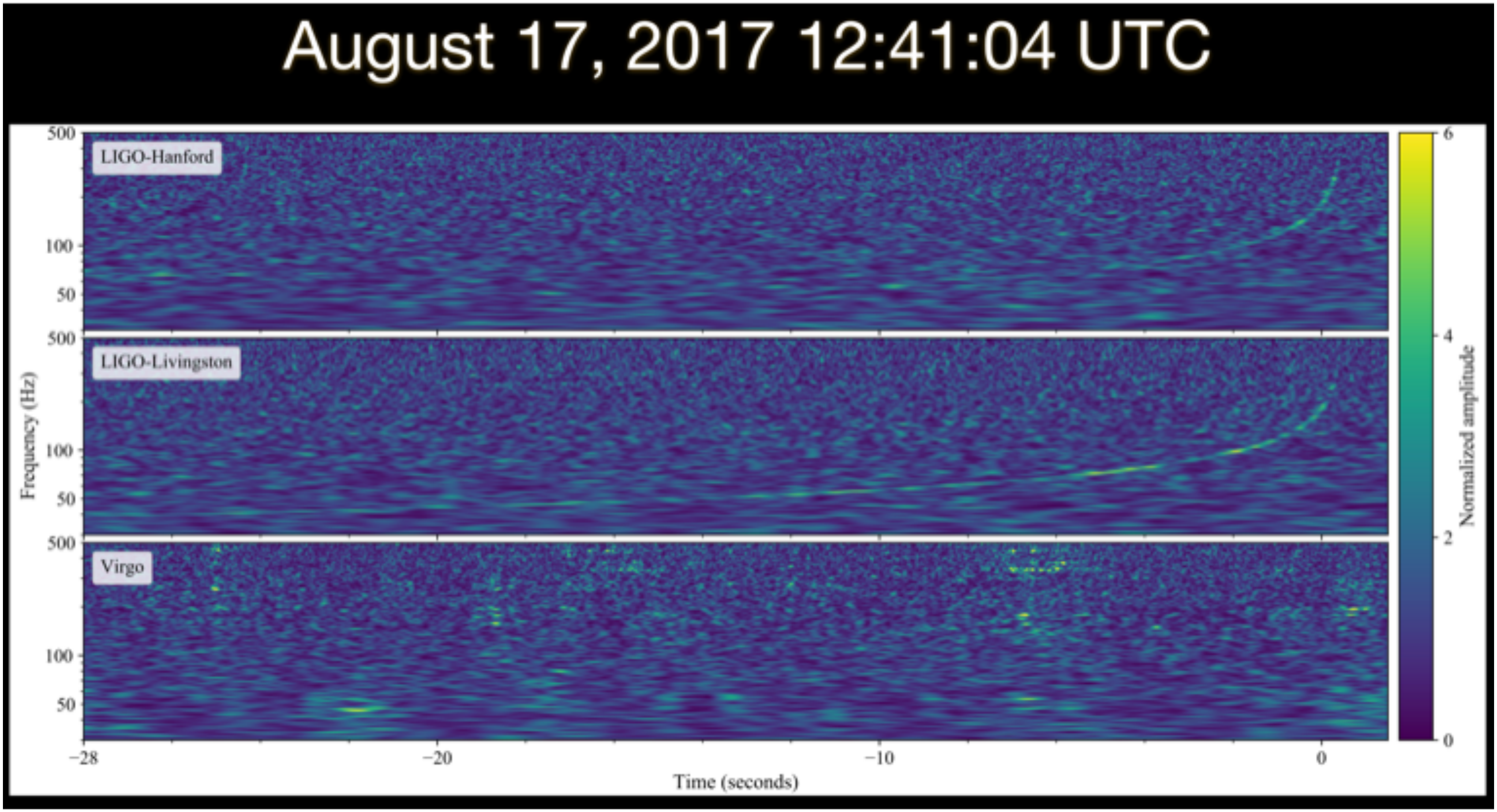
Forming the Sky map



Leo Singer

- Analysis treats the detectors as phased array antenna (aperture synthesis)
- Localization of short-duration GW signals requires coherent consistency among the data recorded by the different detectors
  - » The antennas have known sensitivity patterns for each polarization that are slowly varying functions of direction
  - » The waves come in a linear combination of two polarizations
  - » The relative times, phases, and amplitudes on arrival at all of the antennas depend on the relative positions and orientations of the source and all of the antennas
  - » We determine the location of the source by "phasing up" the antennas for a particular direction and comparing with what was actually received, then repeating for all directions on the sky.

One more detection: GW170817



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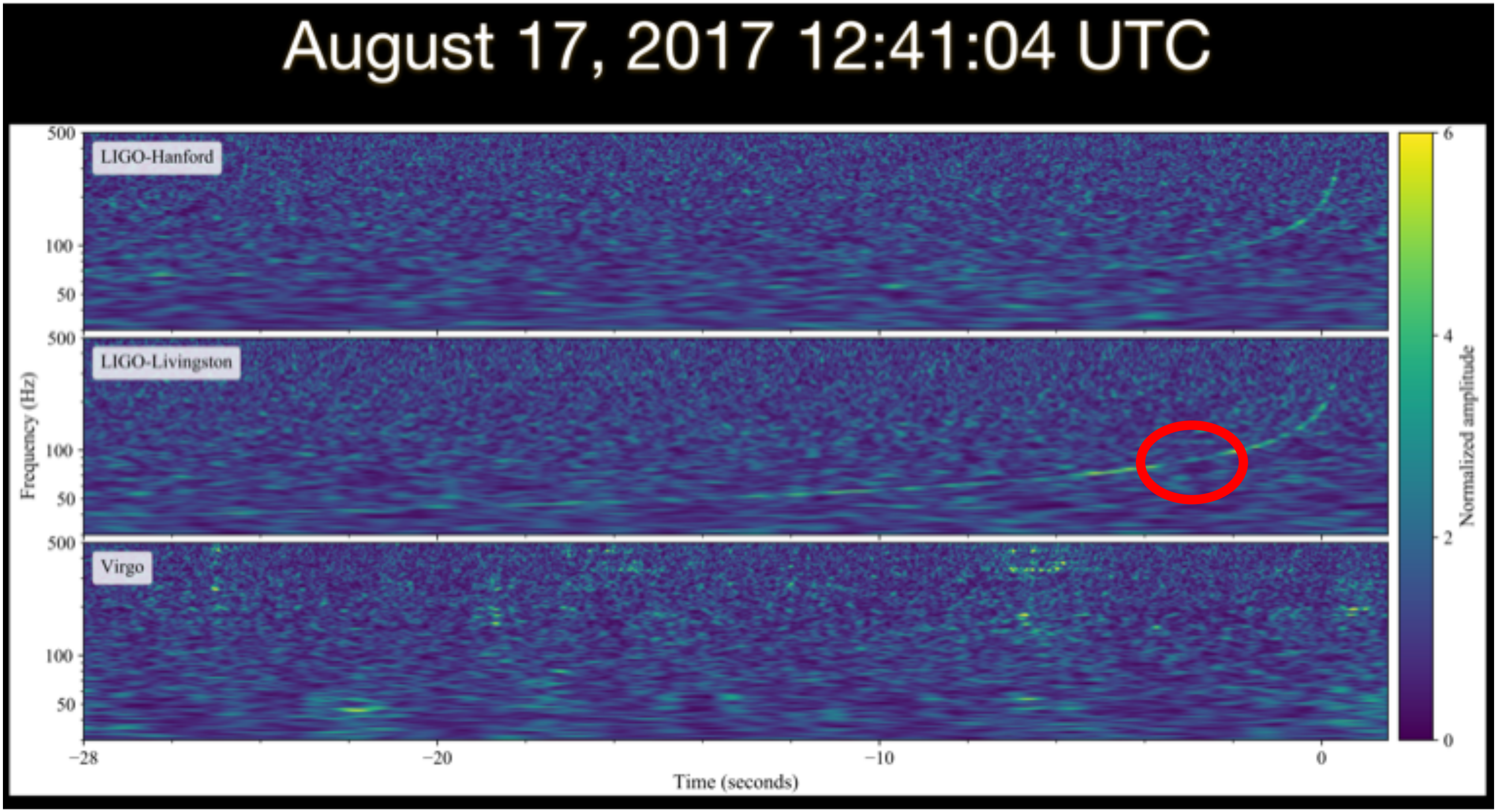
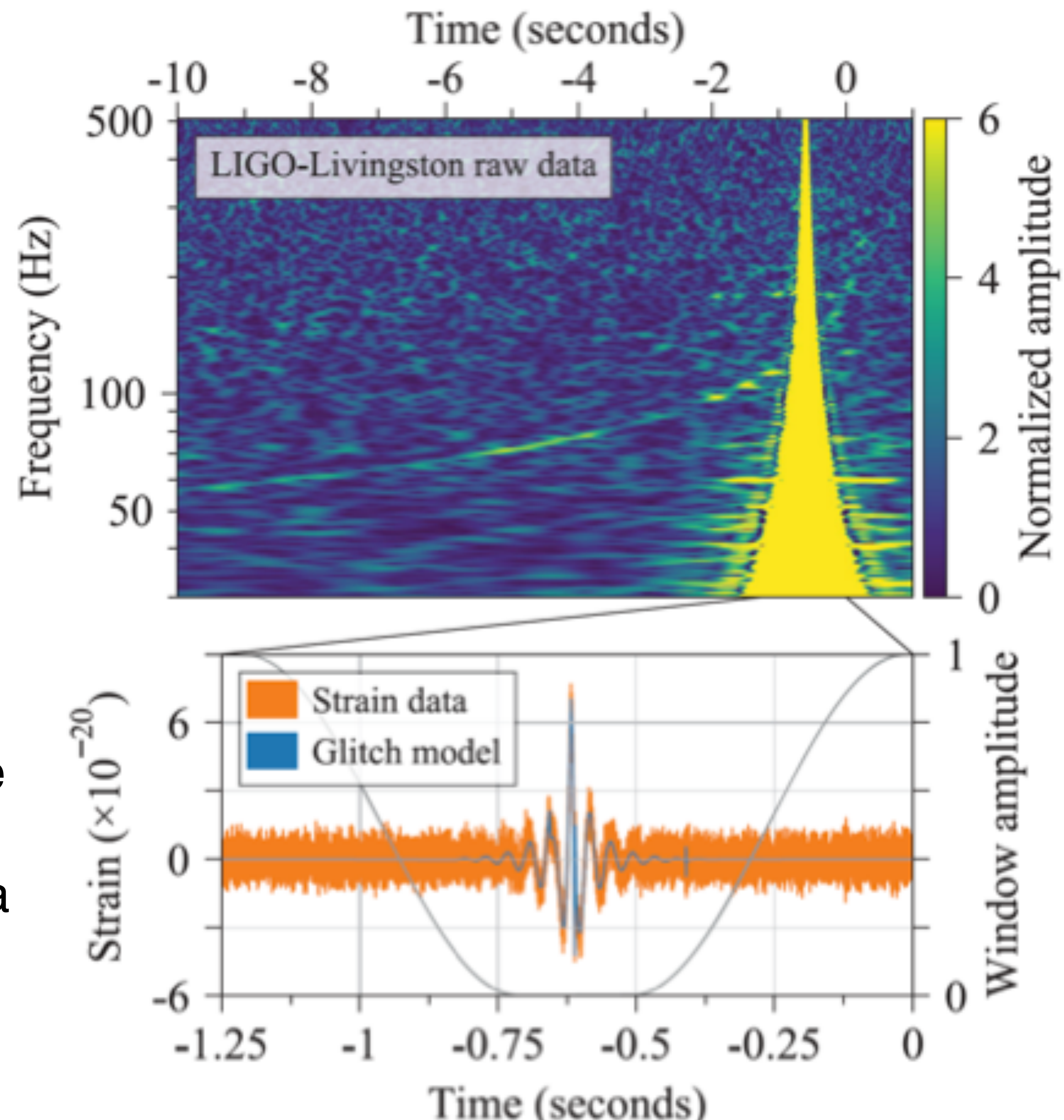


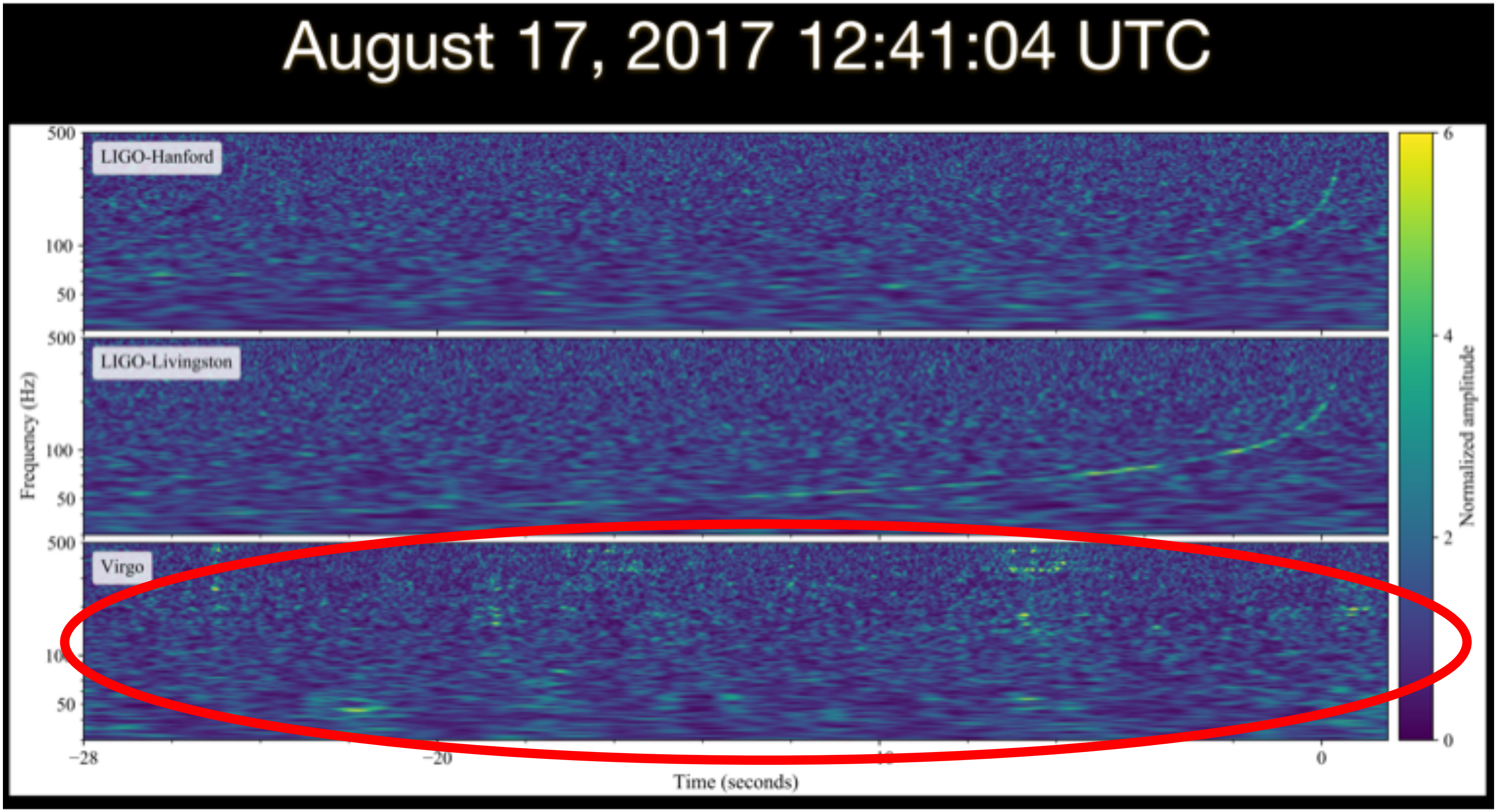
Glitch in Livingston data

- Time-frequency representation of the raw LIGO-Livingston data

- Raw LIGO-Livingston strain data
- Grey: Gating veto window for skymap produced ~4.5h after the event
- Blue: model subtracted from data for parameter estimation later

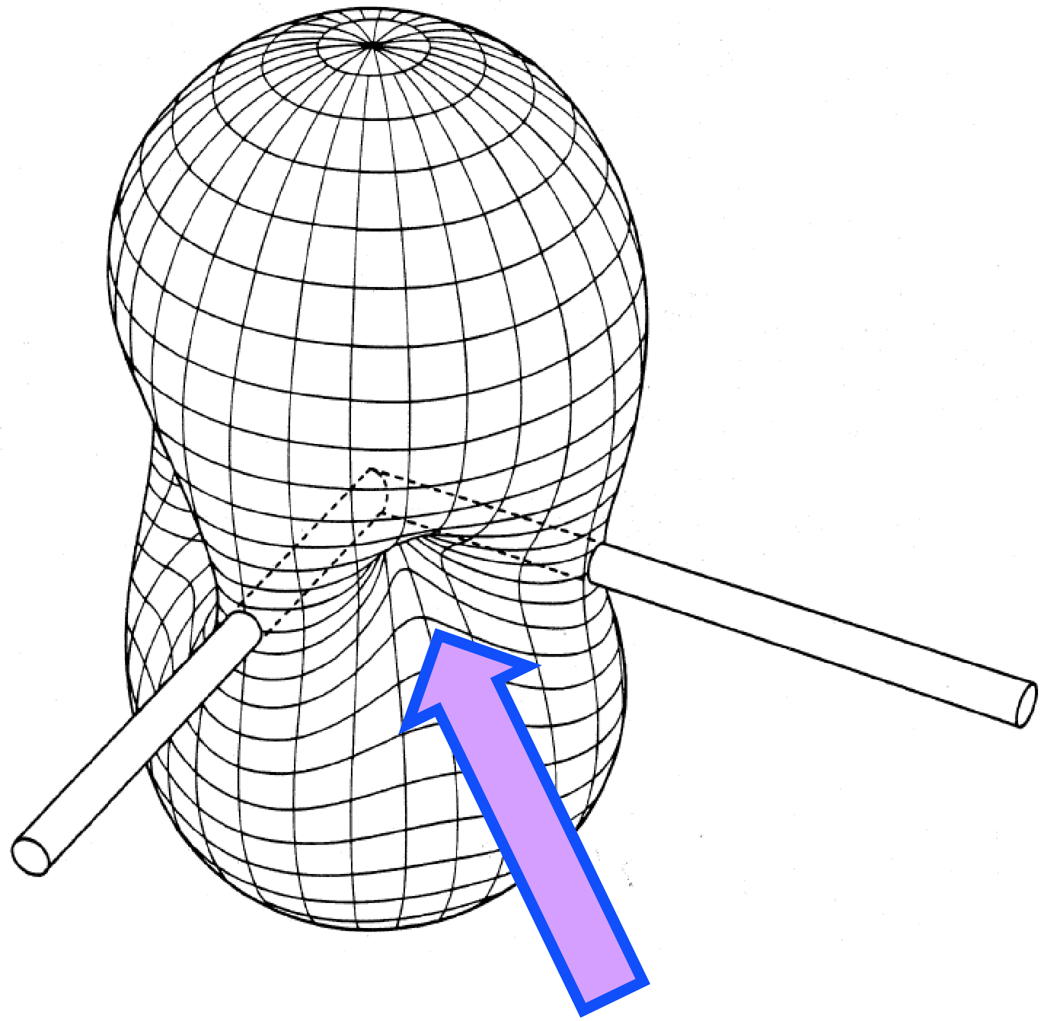


One more detection: GW170817

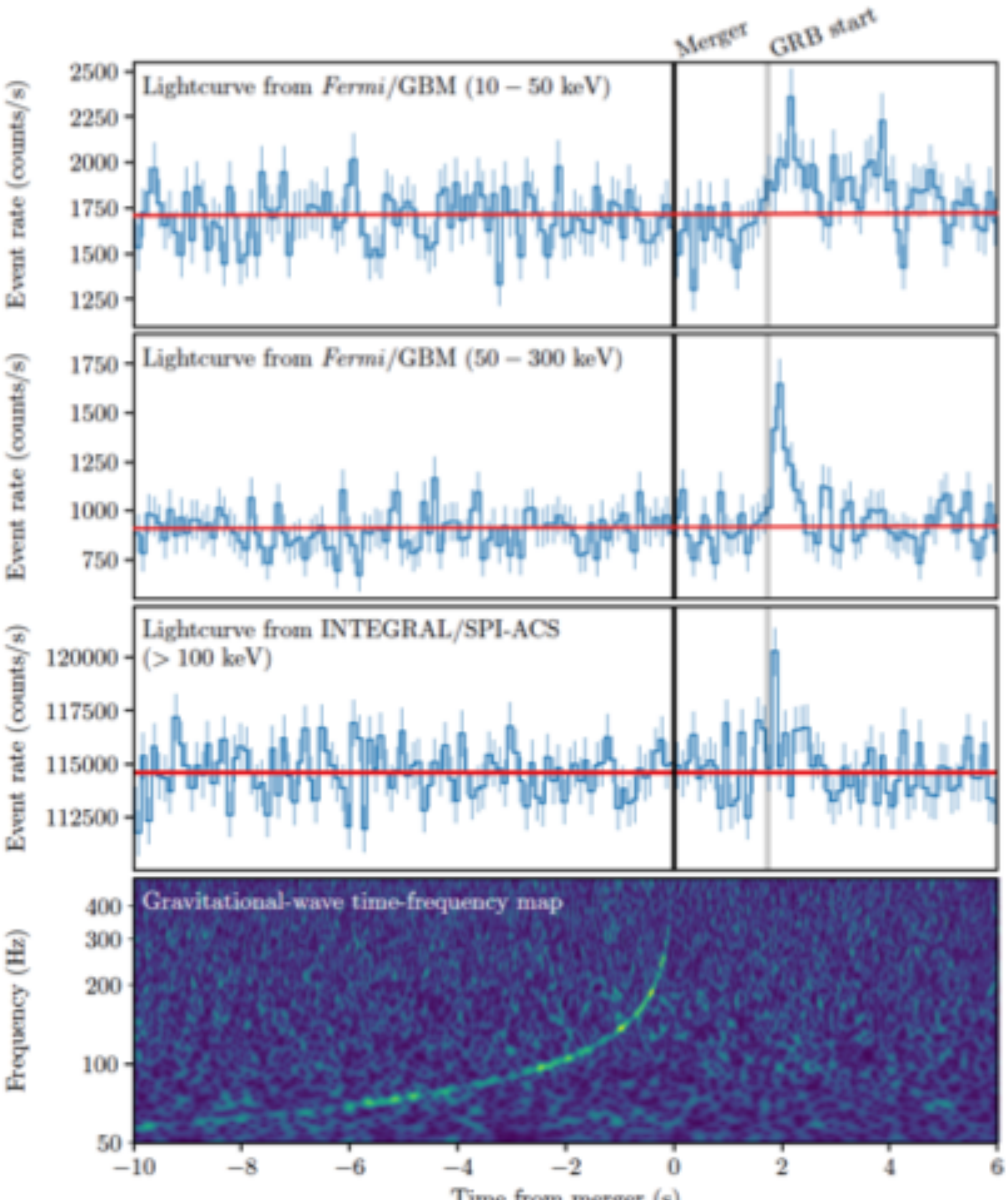


Antenna pattern for a single detector

- Maximal for overhead or underfoot source
- 1/2 for signals along one arm
- …and zero at 45 degrees
- GW170817 fell on Virgo close to 45 degrees
- Did no harm for localization, given our ‘aperture synthesis’ approach. (GW170814 proved the detector was working)



GRB 170817A



GRB 170817A occurs (1.74 ± 0.05) seconds after GW170817

It was autonomously detected in-orbit by Fermi-GBM (GCN was issued 14s after GRB) and in the routine followup search for short transients by INTEGRAL SPI-ACS

Probability that GW170817 and GRB 170817A occurred this close in time and with location agreement by chance is 5.0×10^{-8} (Gaussian equivalent significance of 5.3σ)

BNS mergers are progenitors of (at least some) SGRBs

B. P. Abbott et al., *Gravitational Waves and Gamma Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A,* 2017, ApJL 848, L13

Chronology of GW170817

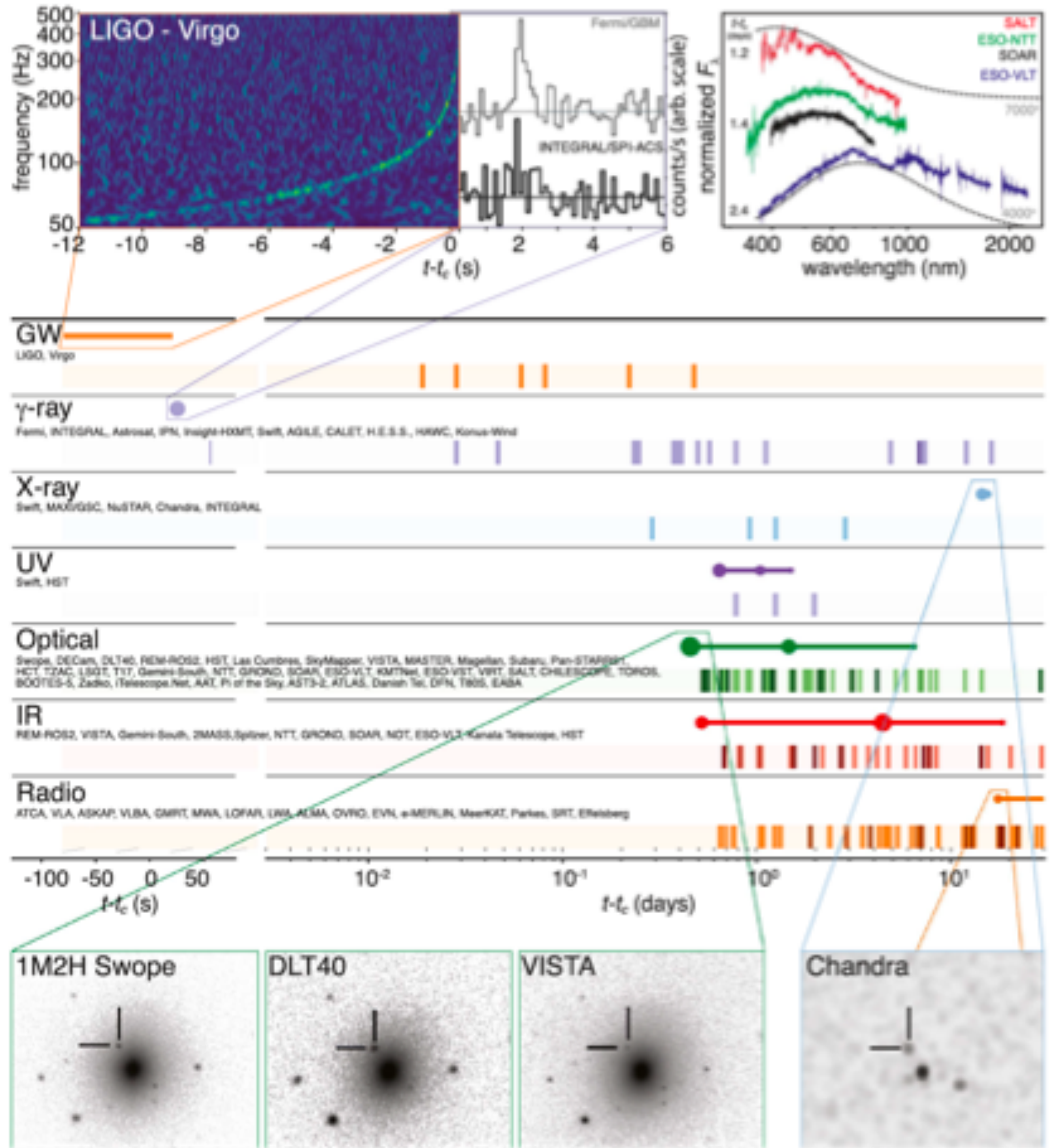
- **12:41:04 - Event time at Earth**
- 12:41:06 - Low significance GRB trigger from Fermi
- 12:47:18 - gstlal uploads an H1-only trigger with a FAR=3.5 x 10^{-12} Hz
- 12:47:22 - RAVEN algorithm initiates coincidence search GW-GRB
- 12:47:31 - RAVEN finds coincidence, improves FAR to 1.95e-16 Hz
- 12:58:25 - Chad Hanna applies the ADVREQ label to the event.
- 12:59:29 - Label H1OPS is applied by Observatory
- 12:59:46 - Label L1OPS is applied by Observatory
- 13:00:07 - Label V1OPS is applied by Observatory
- 13:03:11 - Nicolas Menzione applies the V1OK label
- 13:05:47 - Alan Weinstein applies the ADVOK label
- **13:08:15 - First machine-readable alert sent. T_0 + 27 minutes**
- 13:08:09 - Marc (Doug) Lormand applies the L1OK label
- 13:17:33 - Corey Gray applies the H1OK label
- 13:21:42 - GCN 21505 sent by LIGO and Virgo collaborations
- 13:47:37 - GCN 21506: GBM-LIGO Group reports on the time-coinci GRB
- **17:54:51 - GCN 21513 with the H1,L1,V1 map. T_0 + 5h14m**
- **17/08/18 01:05:23 - Swope GCN 21529 Optical counterpart T_0 + 11 hours**

A handful of very excited GW scientists looking at data

A handful of very excited observers preparing their searches

GW170817 Followup Observations

- No need for me to say anything on this!



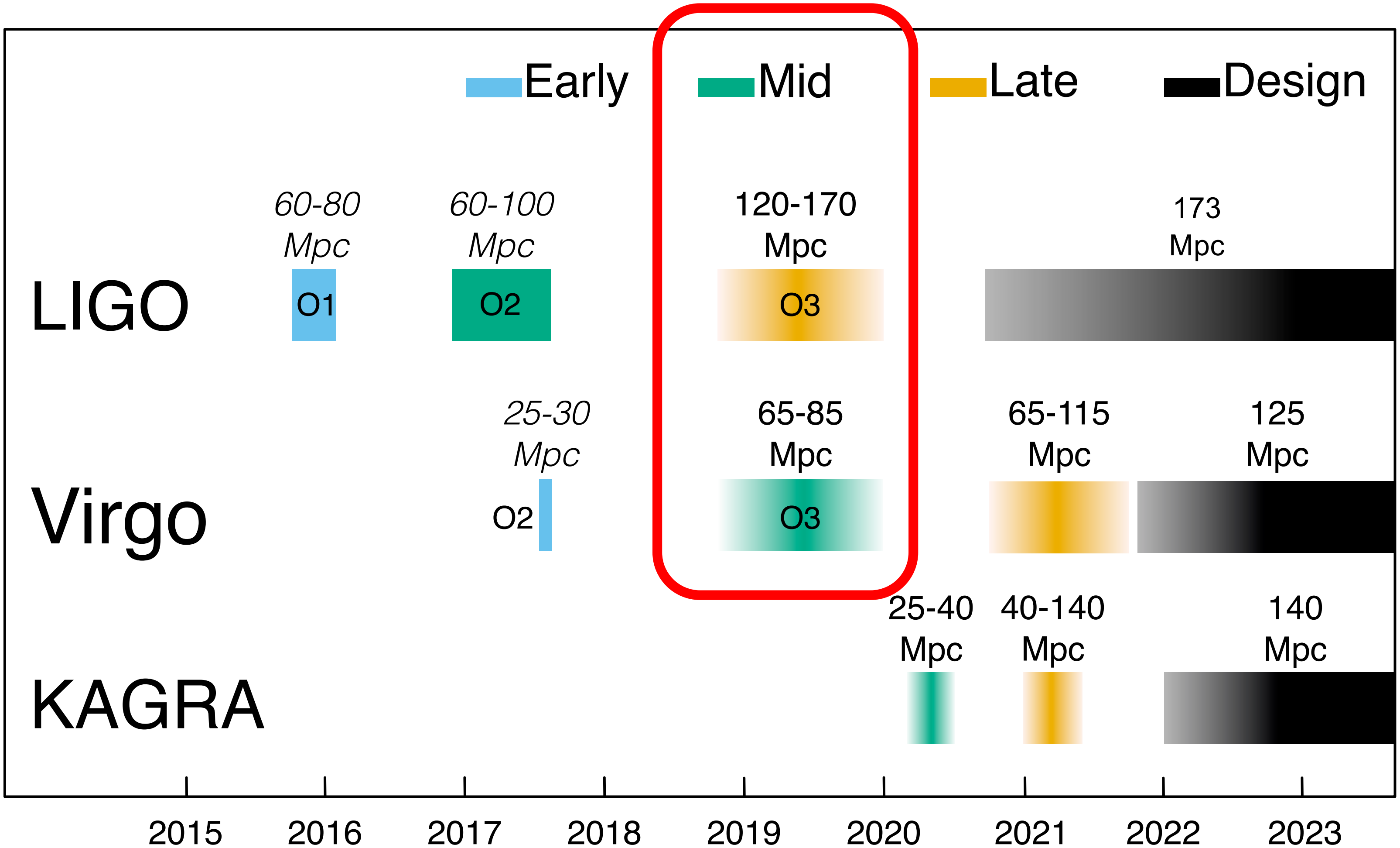
LIGO Scientific Collaboration and Virgo Collaboration

~1500 members, ~120 institutions, 21 countries

What does the future hold?

Plausible Observing Timeline

Binary Neutron Star Range

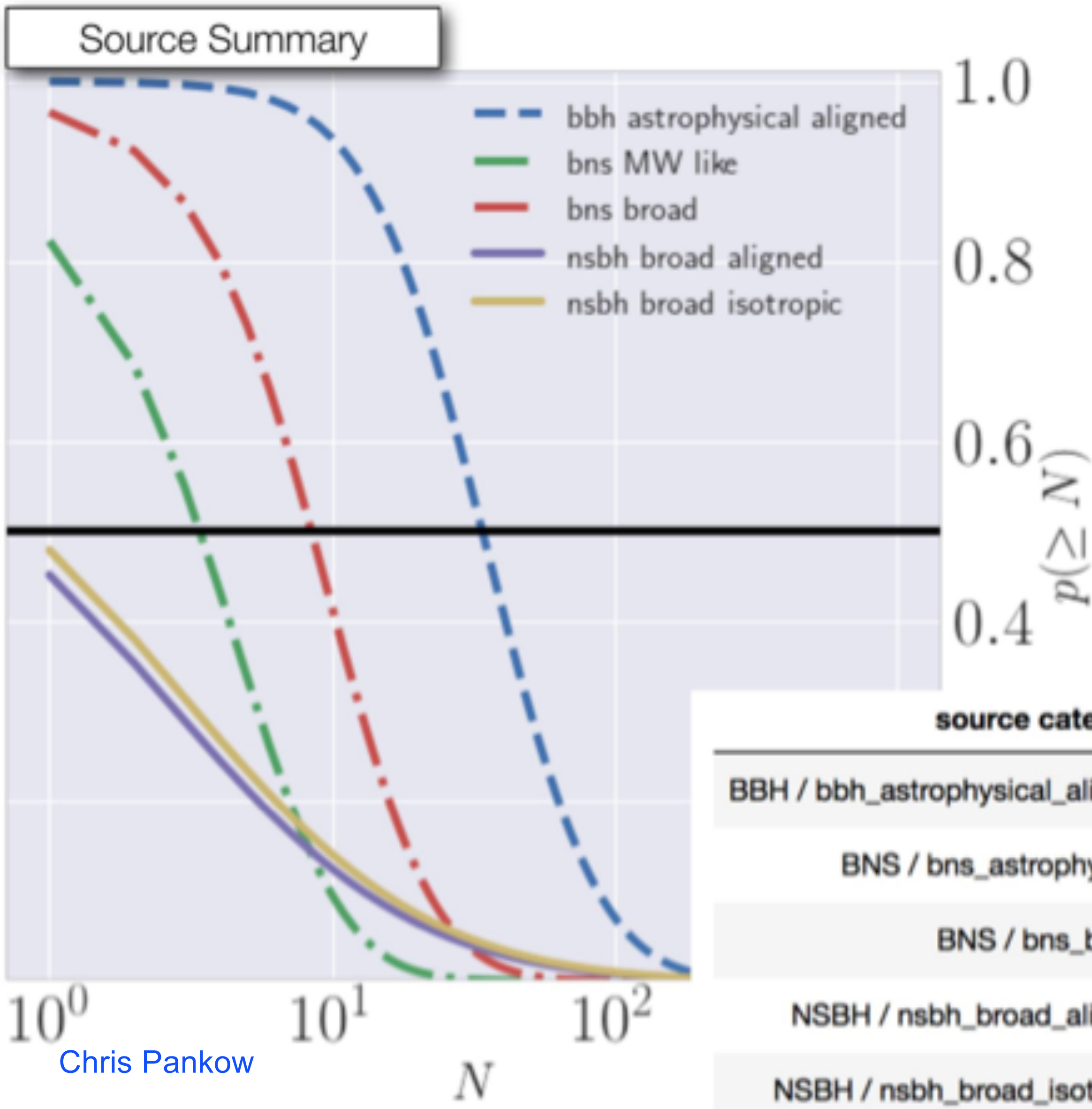


Adapted from B. P. Abbott et al., *Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA*, 2016, Living Rev. Relativity 19

The O3 Observing Run

- Current start date February 2019
- Duration roughly one calendar year
- Engineering runs in ~October and ~January
- LIGO and Virgo synchronized, sharing real-time data
  - » Joint alerts, MoUs, publications
- KAGRA may join toward end of O3
- LIGO instruments 120 Mpc (BNS, SNR 8, averaged)
- Virgo: 20 → 60 Mpc
- **→ Network ~x2 better**
- Better SNR for a given source; more detailed information, less ambiguity
- Greater reach, higher rates

Rates in O3



Chris Pankow

There are caveats, but the general picture is:

BBH: at least a few per month, maybe more

BNS: 1–10, possibly up to ~1 per month

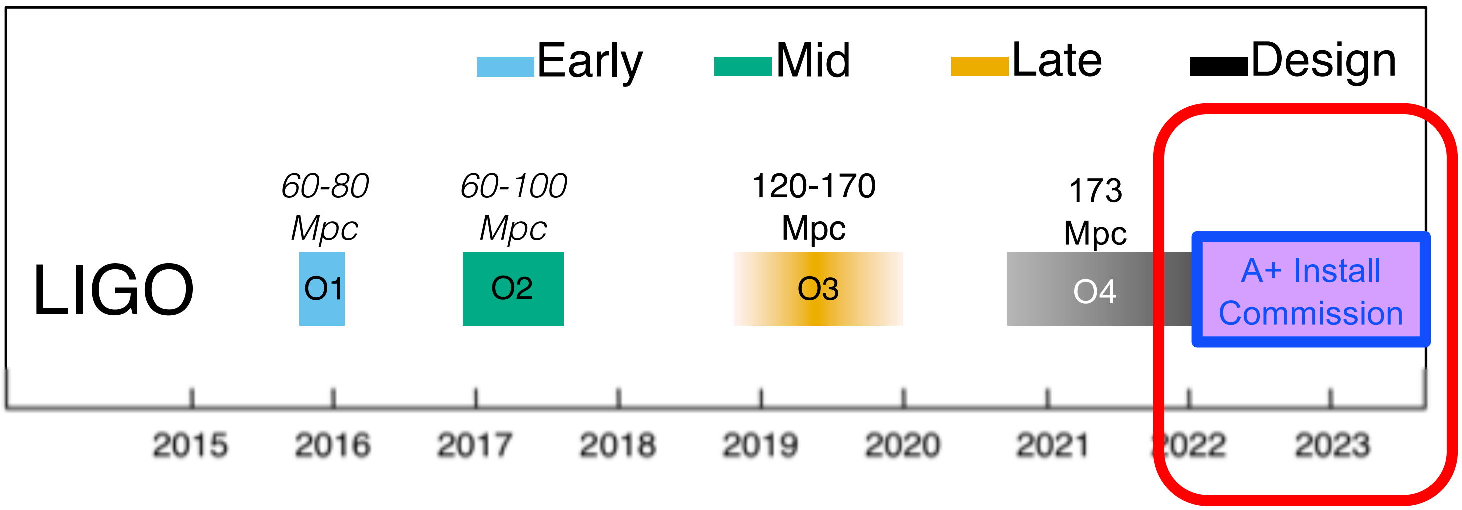
NSBH: Could detect one or more during O3, but uncertain. We'll see!

source category	full year VT	N_d
BBH / bbh_astrophysical_aligned	6.8×10^8 Mpc^3 yr	34^{+79}_{-25}
BNS / bns_astrophysical	3.2×10^6 Mpc^3 yr	4^{+9}_{-4}
BNS / bns_broad	7.3×10^6 Mpc^3 yr	9^{+19}_{-7}
NSBH / nsbh_broad_aligned	5.0×10^7 Mpc^3 yr	1^{+24}_{-1}
NSBH / nsbh_broad_isotropic	5.7×10^7 Mpc^3 yr	1^{+28}_{-1}

Once O3 is running, ~February 2019:

- Fundamental change for O3: Open Public Alerts for Triggers
  - No more standard EM follow-up MOUs or private GCN alerts!
  - LIGO/Virgo to release public alerts for **all event candidates for which we have reasonable confidence**
    - For binary mergers: target 9 out of 10 valid
    - More restrictive threshold for unmodeled GW burst candidates
    - We can "promote" a weaker GW candidate if it is coincident with a GRB, core-collapse supernova, etc.
  - We'll provide basically the **same information as in O2**: significance, time, binary type classification, sky position and distance 3D map
    - Considering adding some more information to aid prioritization
  - We'll provide **automatic *preliminary* alerts** before human vetting – goal is to provid this within minutes
- See https://www.ligo.org/scientists/GWEMalerts.php for more info

LIGO Roadmap: A+



- An incremental upgrade to aLIGO that leverages existing technology and infrastructure, with minimal new investment, and moderate risk
- Target: factor of 1.7 increase in range over aLIGO

  ➔ **About a factor of 4-7 greater CBC event rate**
- Stepping stone to third-generation (3G) detector technology
- Bridge to future 3G GW astrophysics, cosmology, and nuclear physics
- Can be observing within 6 years (mid-2024)
- **– Jo van den Brand will talk about the further future tomorrow.**

A bright future for a new field