Multi-messenger Astrophysics:
The New Era of Gravitational Waves

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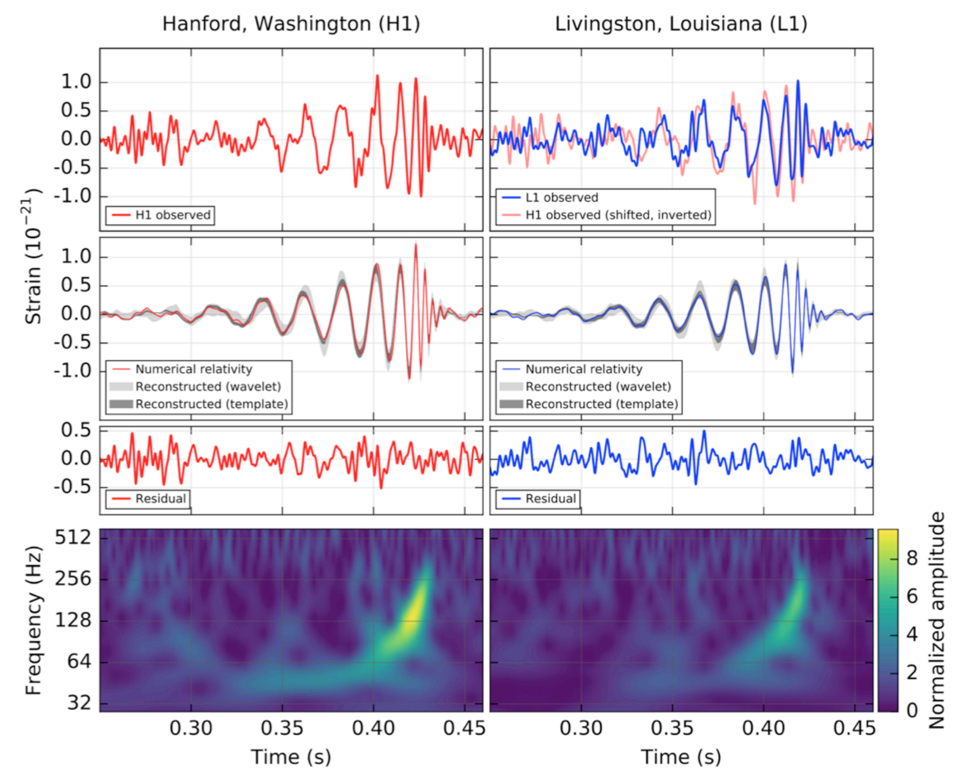
For the LIGO Scientific Collaboration and the Virgo Collaboration

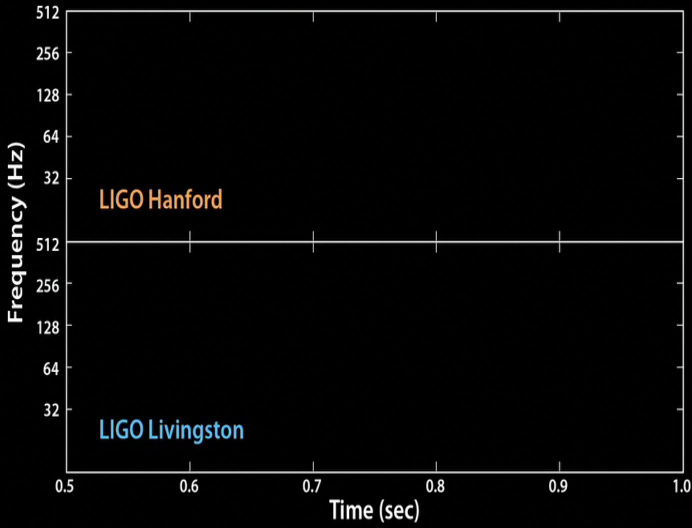
LIGO-G1701857

Image Credit: Aurore Simmonet/SSU

GW150914: The First Binary Black Hole Merger




Andy Bohn, François Hébert, and William Throwe, SXS Collaboration



Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, "Observation of Gravitational Waves from a Binary Black Hole Merger" Phys. Rev. Lett. 116, 061102 (2016)

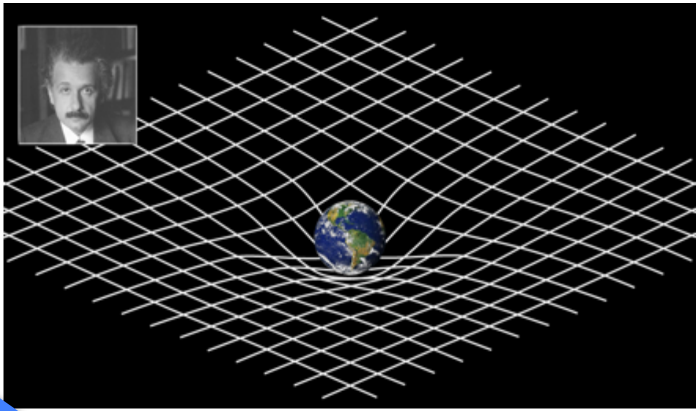
Outline

- *Gravitational Waves and GW Astrophysics*
- *LIGO/Virgo Detectors*
- *Gravitational Waves from Binary Black Hole Mergers*
  - *Detection Confidence*
  - *Astrophysics*
- *Multi-messenger Astronomy with Gravitational Waves*

General Relativity and Gravitational Waves

General Relativity: Einstein Field Equations

$$\boxed{G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}}$$



~ 10^{-43}

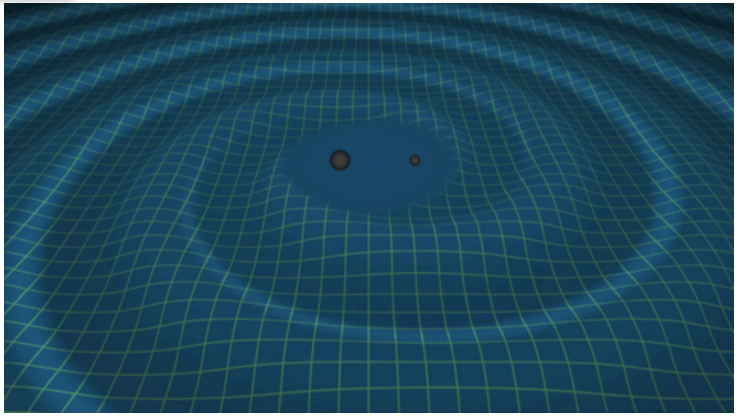
Weak field approximation -- space-time is slightly perturbed from flat space-time:

$$g_{\mu\nu} \approx \eta_{\mu\nu} + h_{\mu\nu}$$

Free Space: $T_{\mu\nu} = 0$

Wave equation for $h_{\mu\nu}$!

$$\boxed{\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right) h_{\mu\nu} = 0}$$



A. Einstein, *Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften* (Berlin,1916), 688696; *Sitzungsberichte der Kniglich Preussischen Akademie der Wissenschaften* (Berlin, 1918), 154167.

"Matter tells space-time how to curve. Space-time tells matter how to move."

John Archibald Wheeler

Gravitational Waves

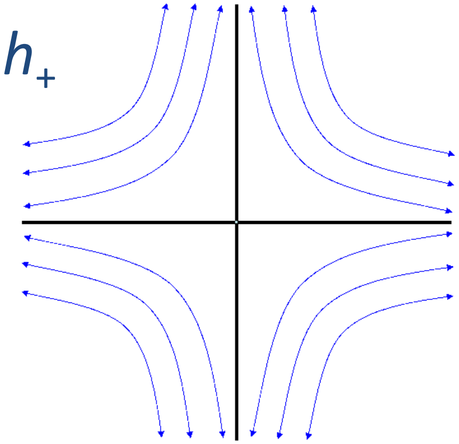
Solution for an outward propagating wave in z-direction:

$$\boxed{h(t,z) = h_{\mu\nu} e^{i(\omega t - kz)} = h_+(t - z/c) + h_\times(t - z/c)}$$

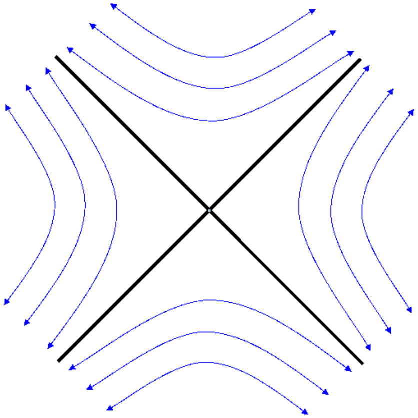
$$h_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

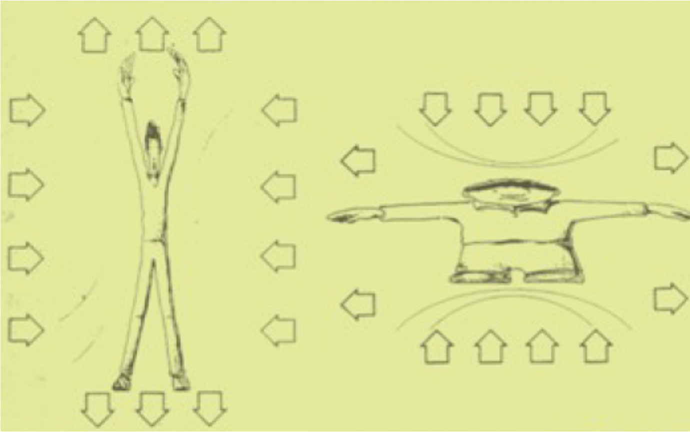
Physically, *h* is a *strain*: ΔL/L

h_+



h_x



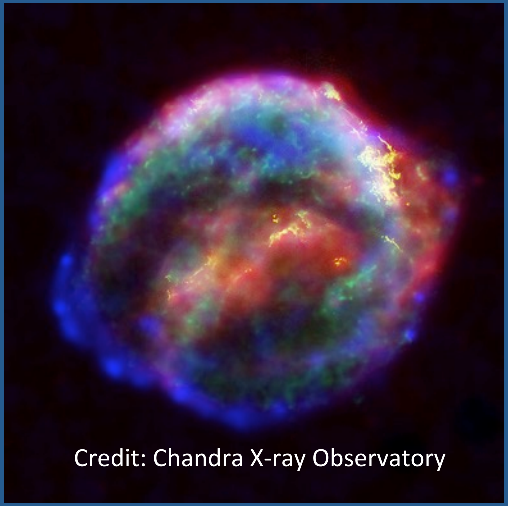


The Astrophysical Gravitational-Wave Source Catalog

Credit: Bohn, Hébert, Throwe, SXS

Coalescing Binary Systems

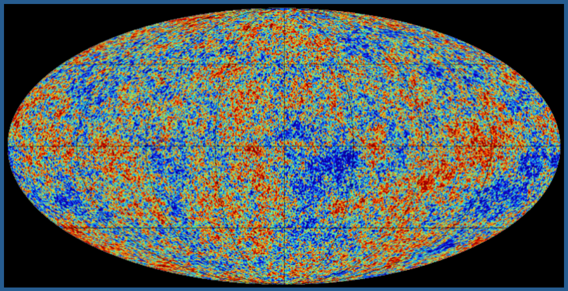
- Black hole – black hole
- Black hole – neutron star
- Neutron star – neutron star
- modeled waveform



Credit: Chandra X-ray Observatory

Transient 'Burst' Sources

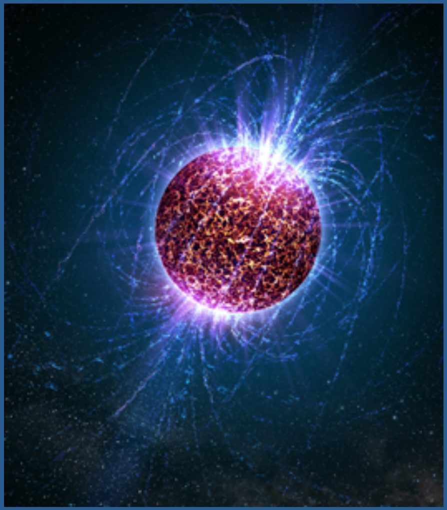
- asymmetric core collapse supernovae
- cosmic strings
- ???
- Unmodeled waveform



Credit: Planck Collaboration

Cosmic GW Background

- residue of the Big Bang
- probes back to < 10^{-15} s
- stochastic, incoherent background
- Difficult (impossible?) for LIGO-Virgo to detect



Credit: Casey Reed, Penn State

Continuous Sources

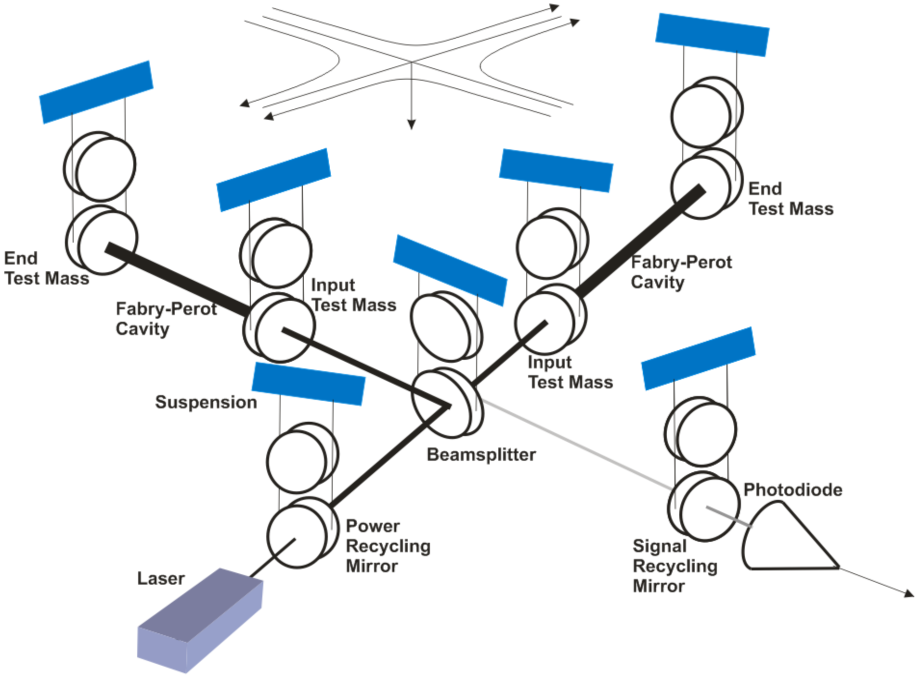
- Spinning neutron stars
- monotone waveform

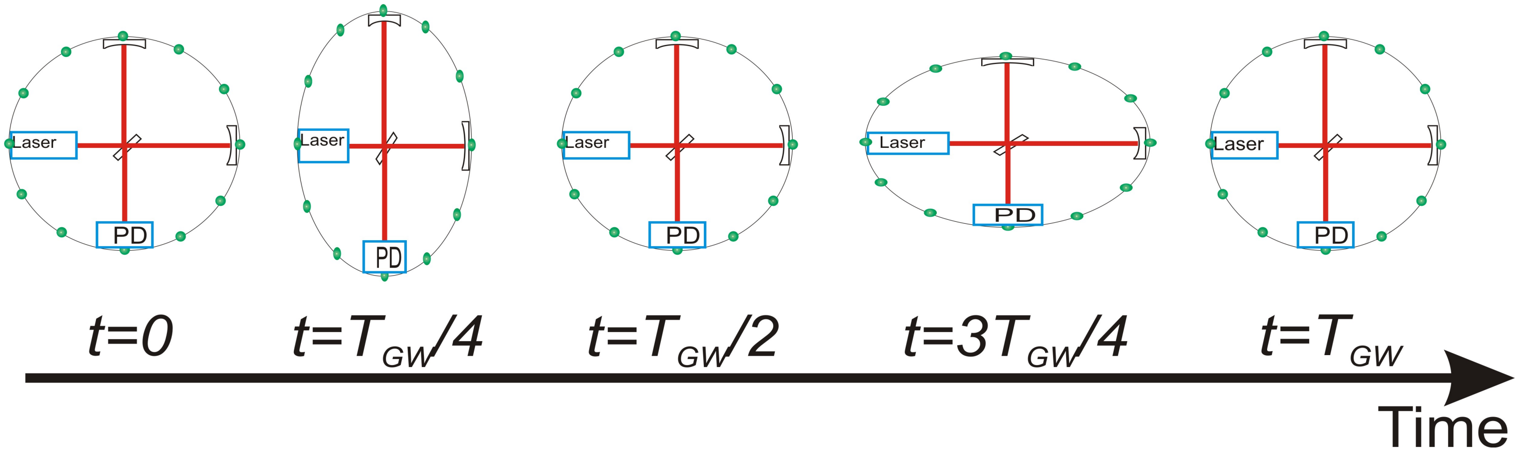
Gravitational Wave Detectors: LIGO and Virgo

Precision Gravitational-wave Interferometry

- LIGO uses enhanced Michelson interferometry
  - With suspended (‘freely falling’) mirrors
- Passing GWs stretch and compress the distance between the end test mass and the beam splitter
- The interferometer acts as a transducer, turning GWs into photocurrent
  - A coherent detector!

Advanced LIGO

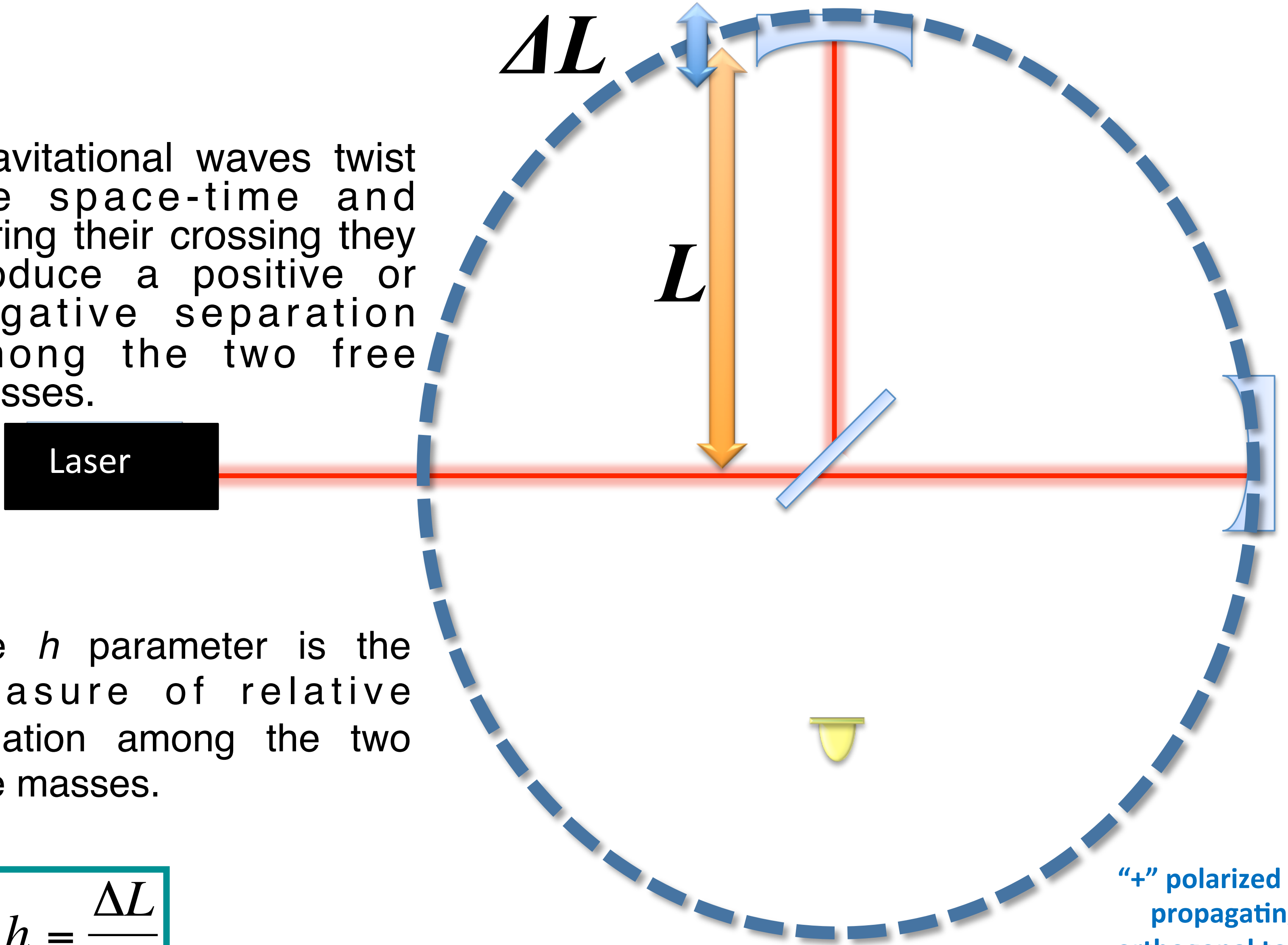




How does an interferometer work?

- Gravitational waves twist the space-time and during their crossing they produce a positive or negative separation among the two free masses.

- The *h* parameter is the measure of relative variation among the two free masses.



"+" polarized GW propagating orthogonal to the screen

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

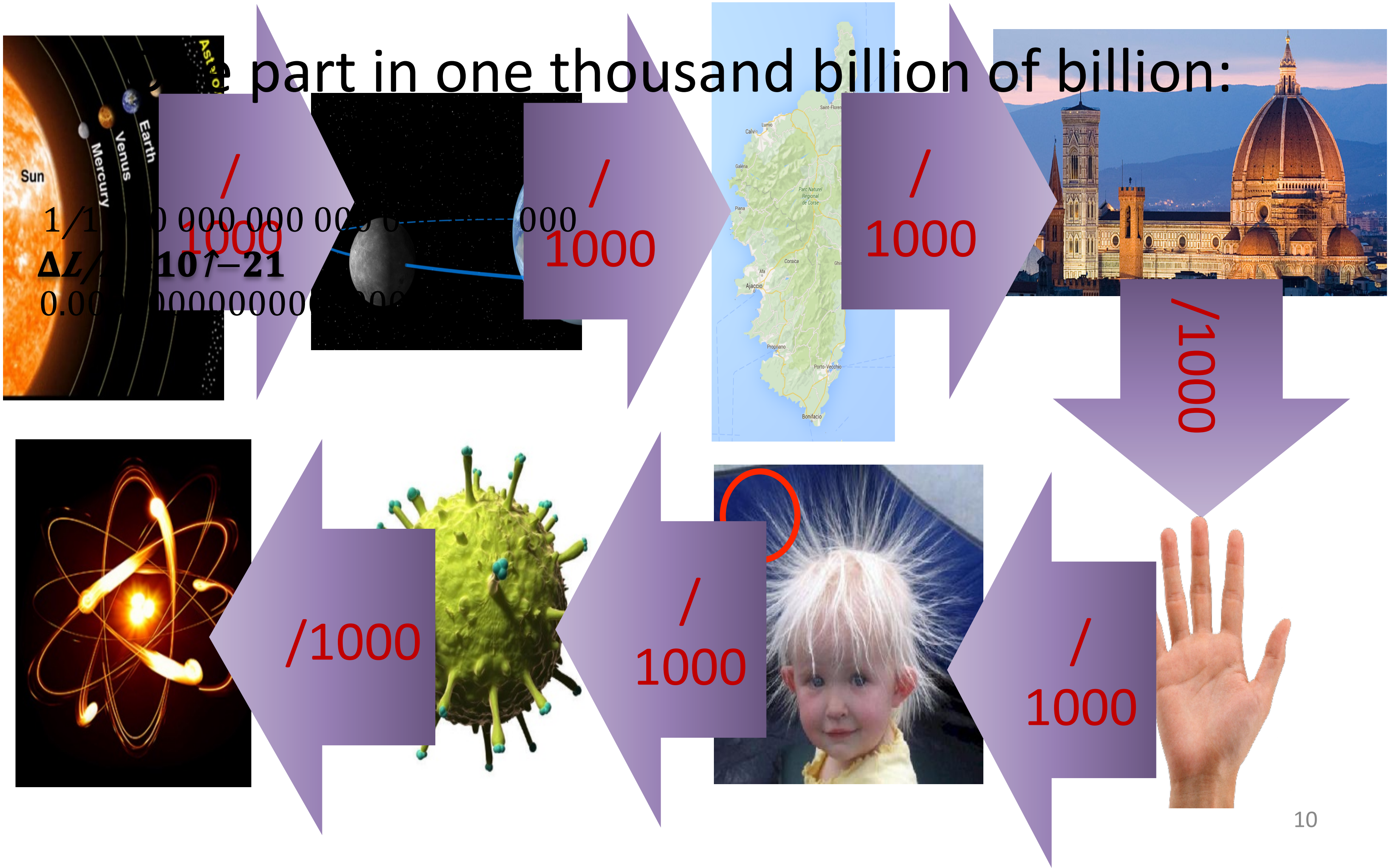
Tiny ripples:

One part in one thousand billion of billion:

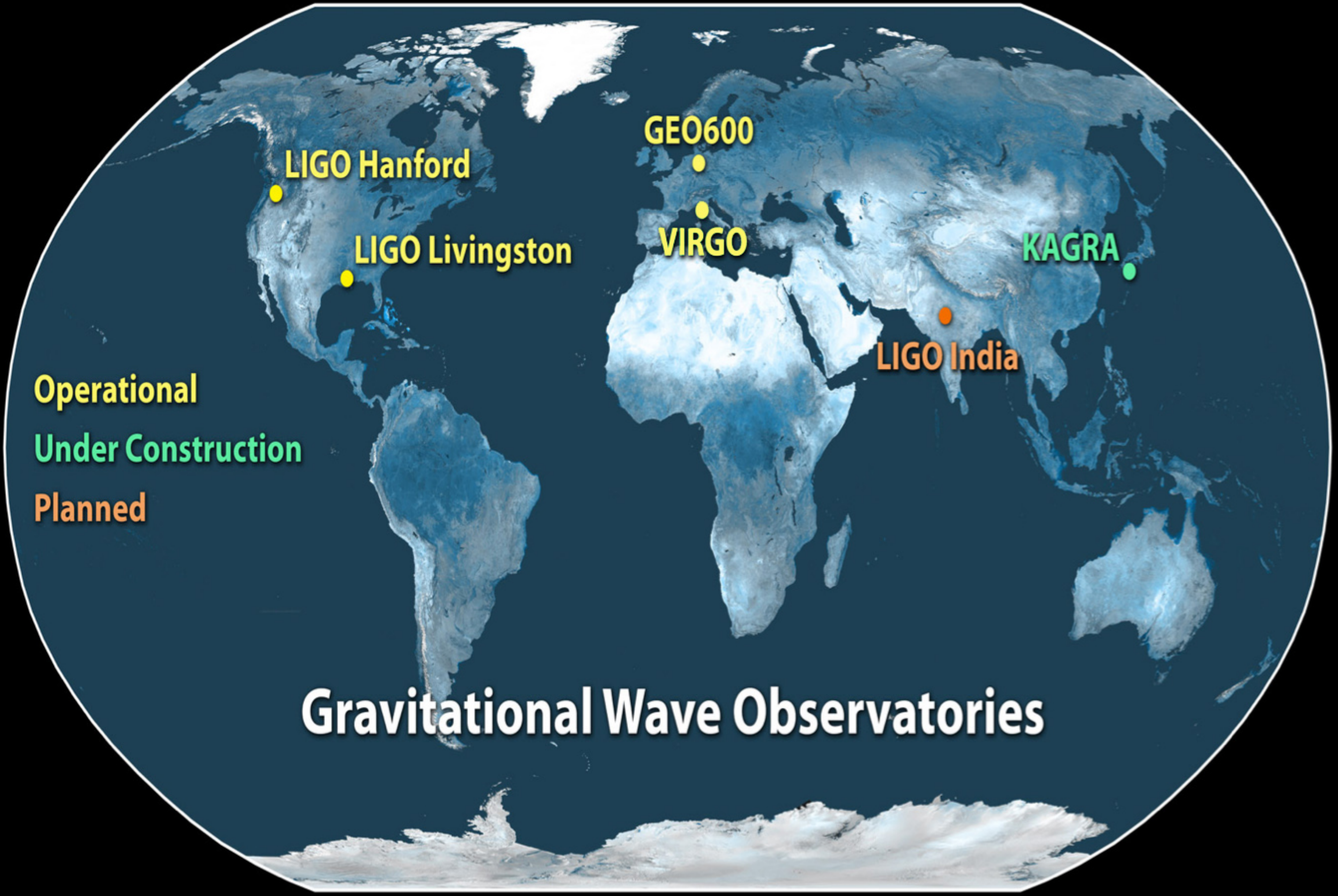
1/1 000 000 000 000 000 000 000

$\Delta L/L = 10^{-21}$

0.000000000000000000001



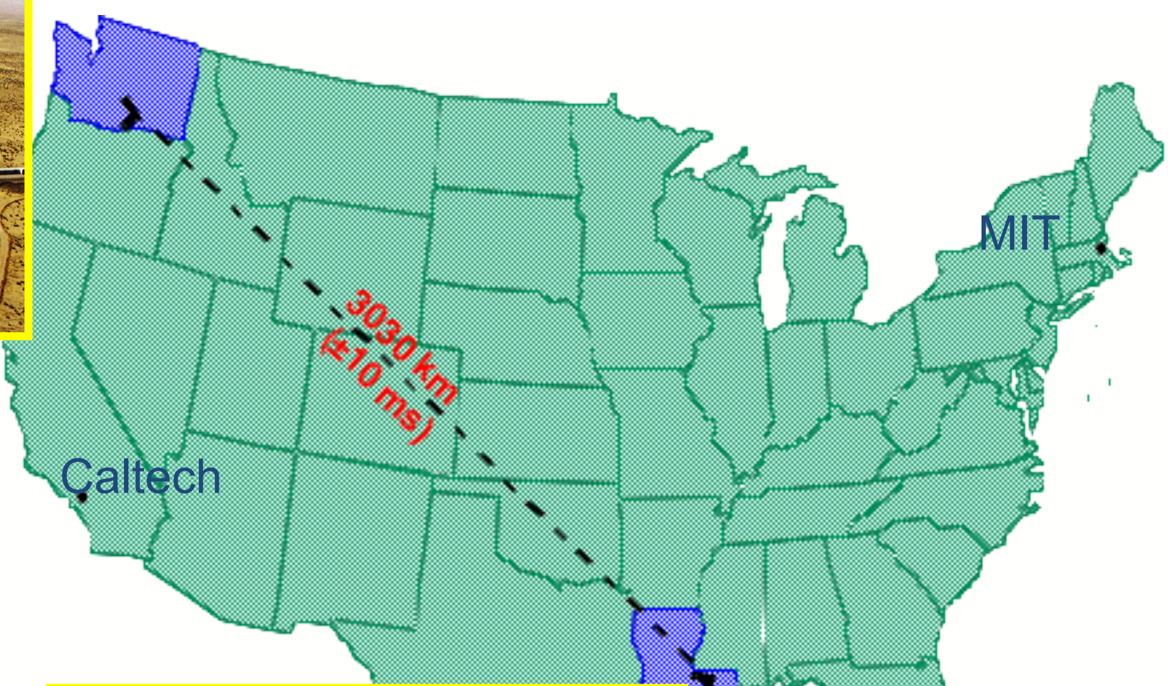
Gravitational Wave Observatories

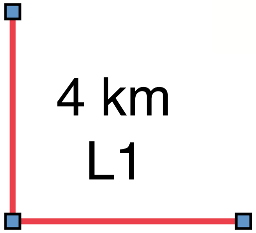


LIGO: Laser Interferometer Gravitational-wave Observatory

Hanford, WA

4 km (H1)

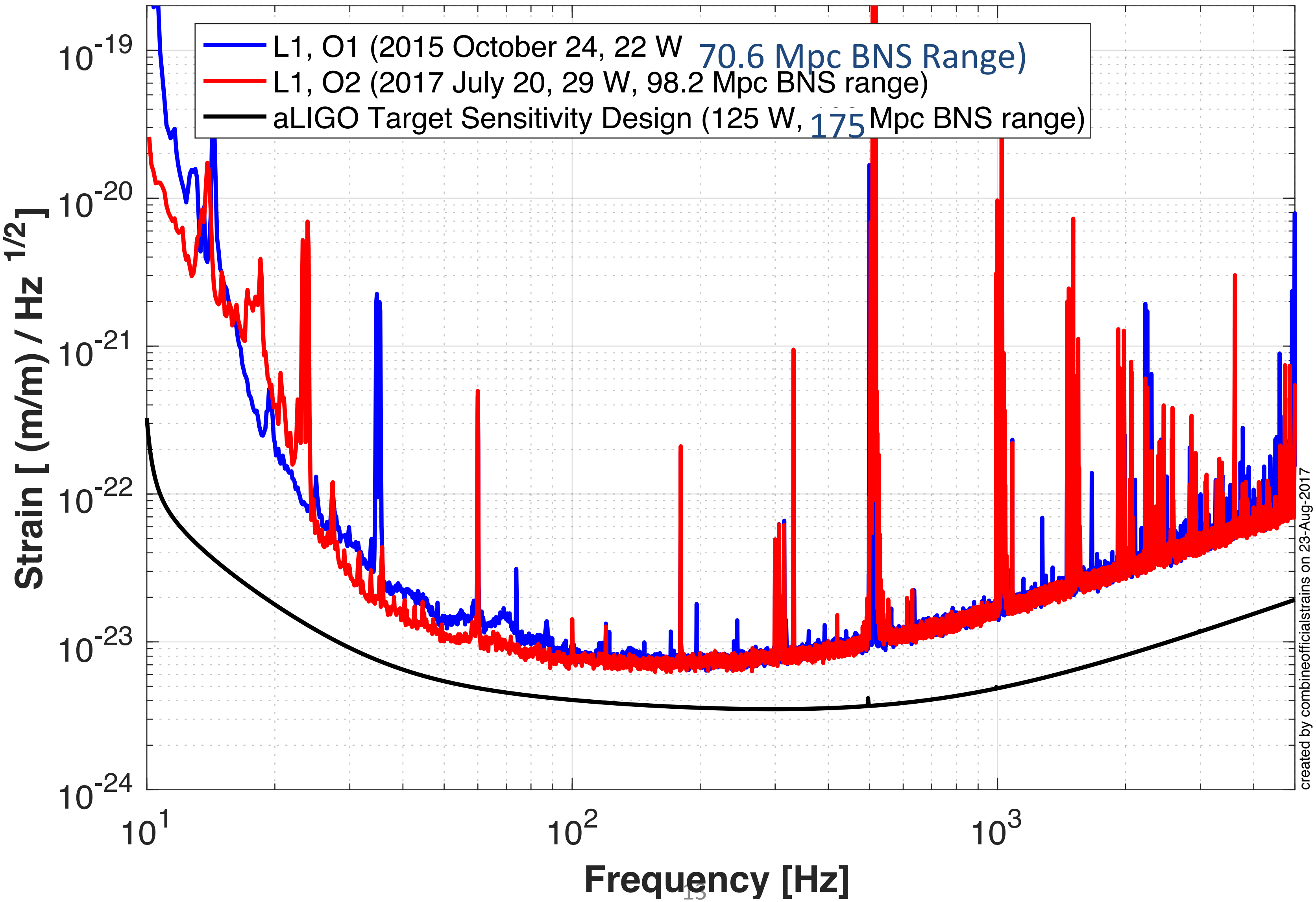




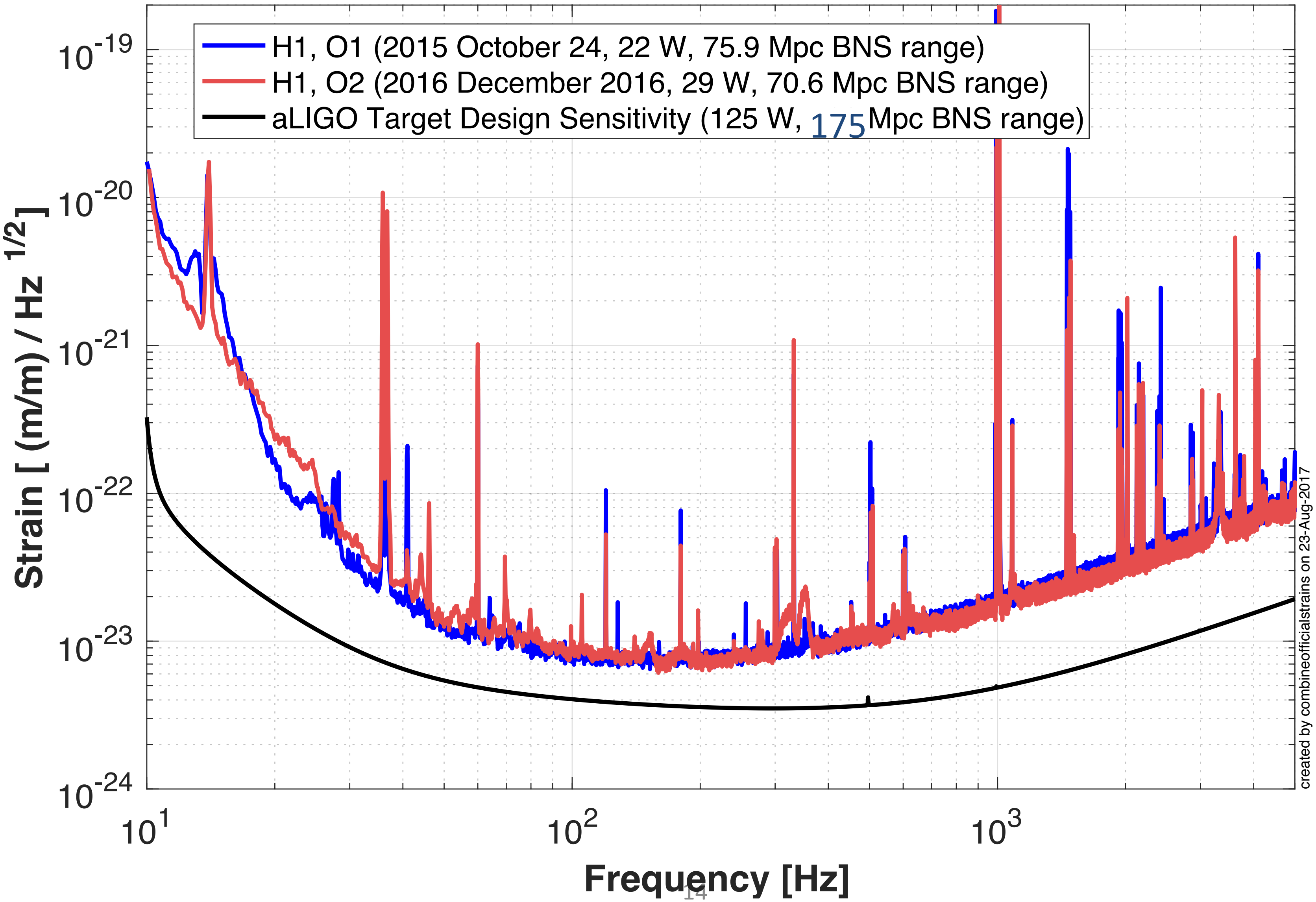
4 km
L1

Livingston, LA

LIGO Livingston Performance



LIGO Hanford Performance



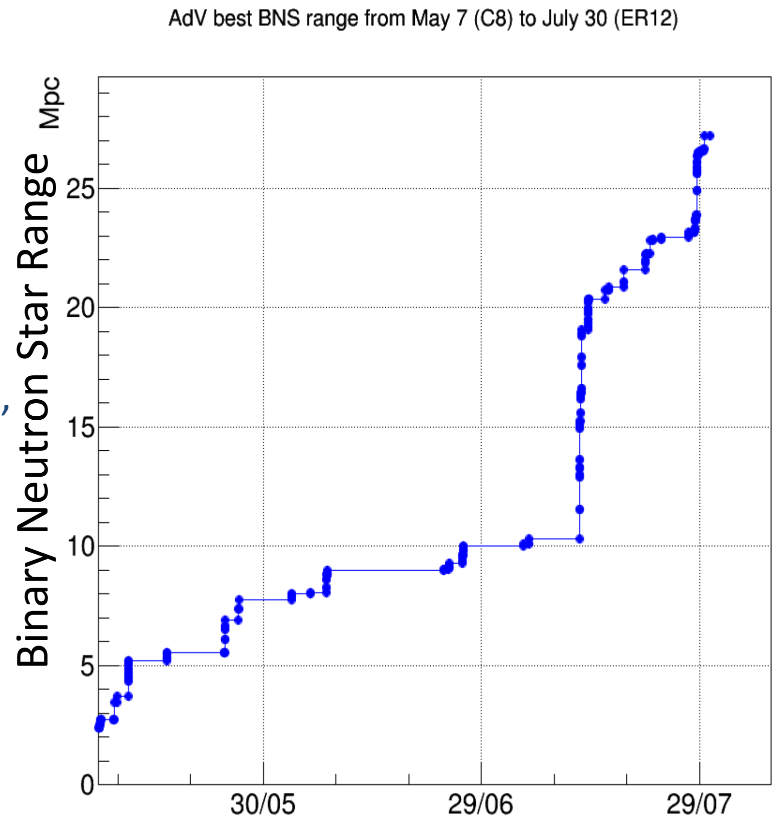
ADVANCED VIRGO

6 EU countries: France, Hungary, Italy, Poland, Spain, and The Netherlands
20 labs, ~280 authors

- APC Paris
- ARTEMIS Nice
- EGO Cascina
- INFN Firenze-Urbino
- INFN Genova
- INFN Napoli
- INFN Perugia
- INFN Pisa
- INFN Roma La Sapienza
- INFN Roma Tor Vergata
- INFN Trento-Padova
- LAL Orsay – ESPCI Paris
- LAPP Annecy
- LKB Paris
- LMA Lyon
- NIKHEF Amsterdam
- POLGRAW(Poland)
- RADBOUD Uni. Nijmegen
- RMKI Budapest
- University of Valencia

Advanced Virgo Progress

- Advanced Virgo integration completed in late 2016, followed by commissioning period
- First project milestone (1h stable lock) reached in March 2017
- First commissioning run (C8) in May 2017
- Sensitivity exceed that of Virgo+ in July, 2017
- Weekend run on May 27 to 29 to test long-term stability, and effectiveness of automation.
- ***Longest stable lock stretch was 69 hours***
- ***Binary neutron star range up to 28 Mpc***
- ***<u>Joined O2 on August 1, 2017</u>***
- Virgo science duty cycle was more than 80% (over last four weeks of O2)



Jul. 19: VSC decides

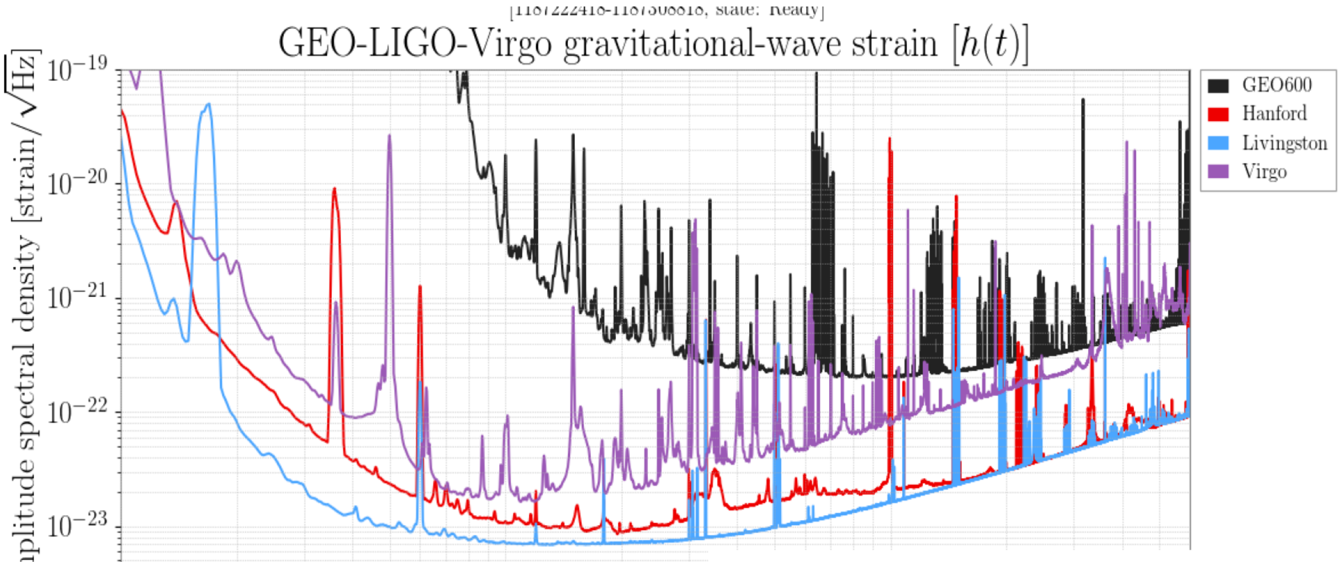
Jul. 25: ER start

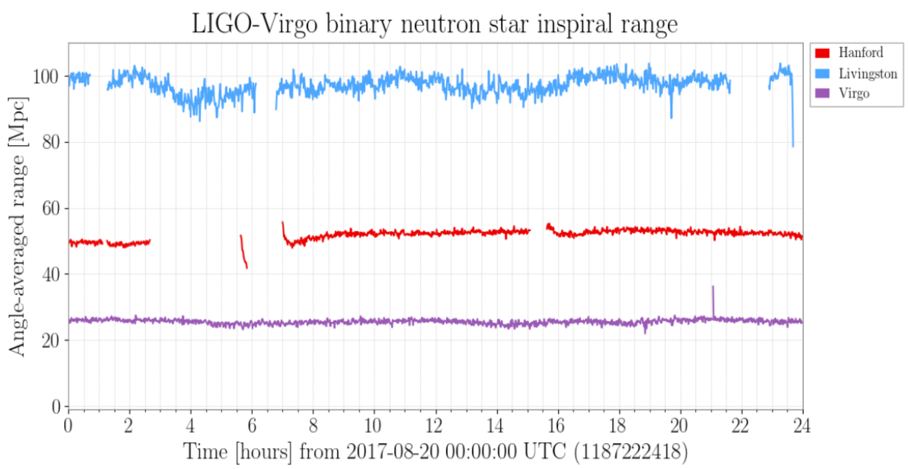
Aug. 1: Virgo joins

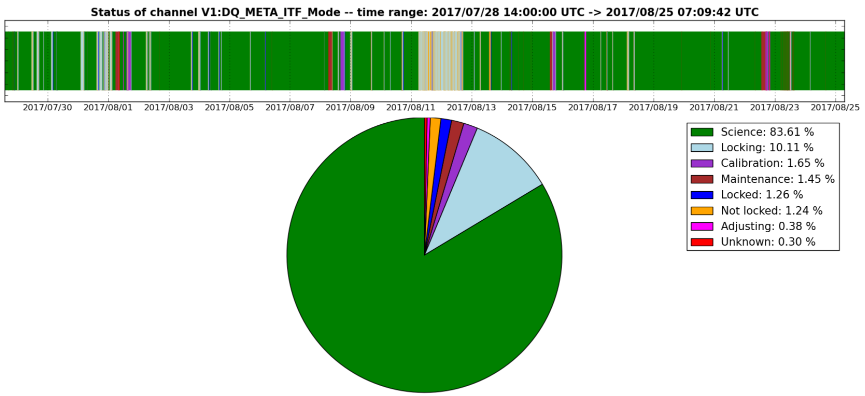
Aug. 25: End of O2

>Aug. 25: Post O2

Advanced Virgo Performance

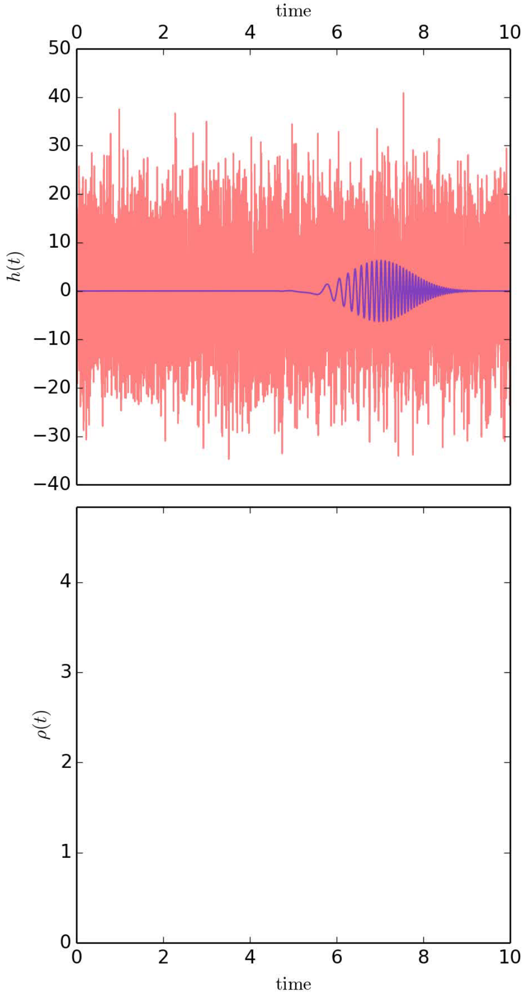






The First Gravitational Wave Detections: Binary Black Holes

Assessing Statistical Significance: Modeled Search

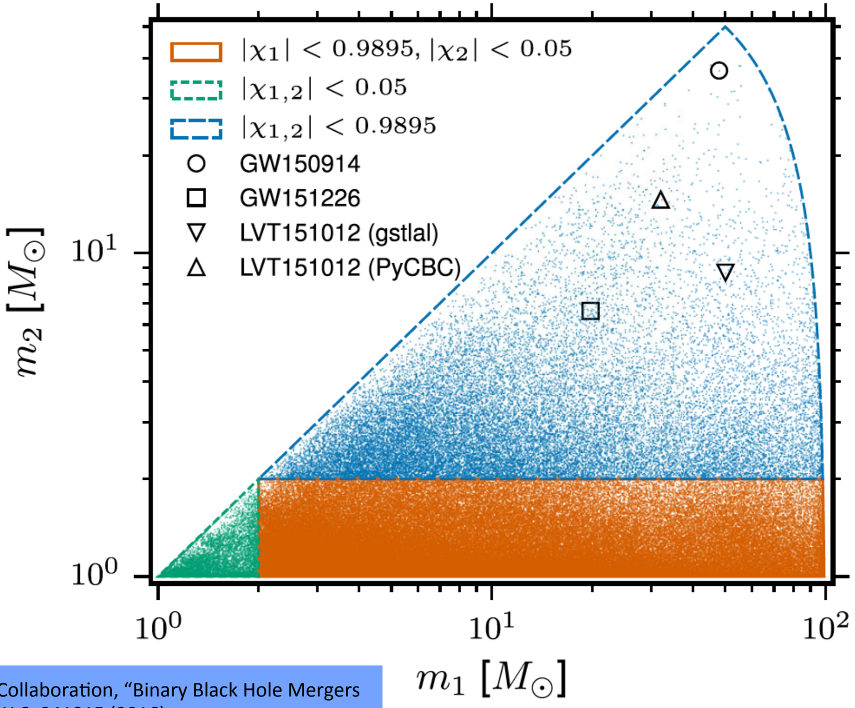


Simulation: Reed Essick, LIGO MIT

- Matched filter search: X-correlation of L1, H1 data streams

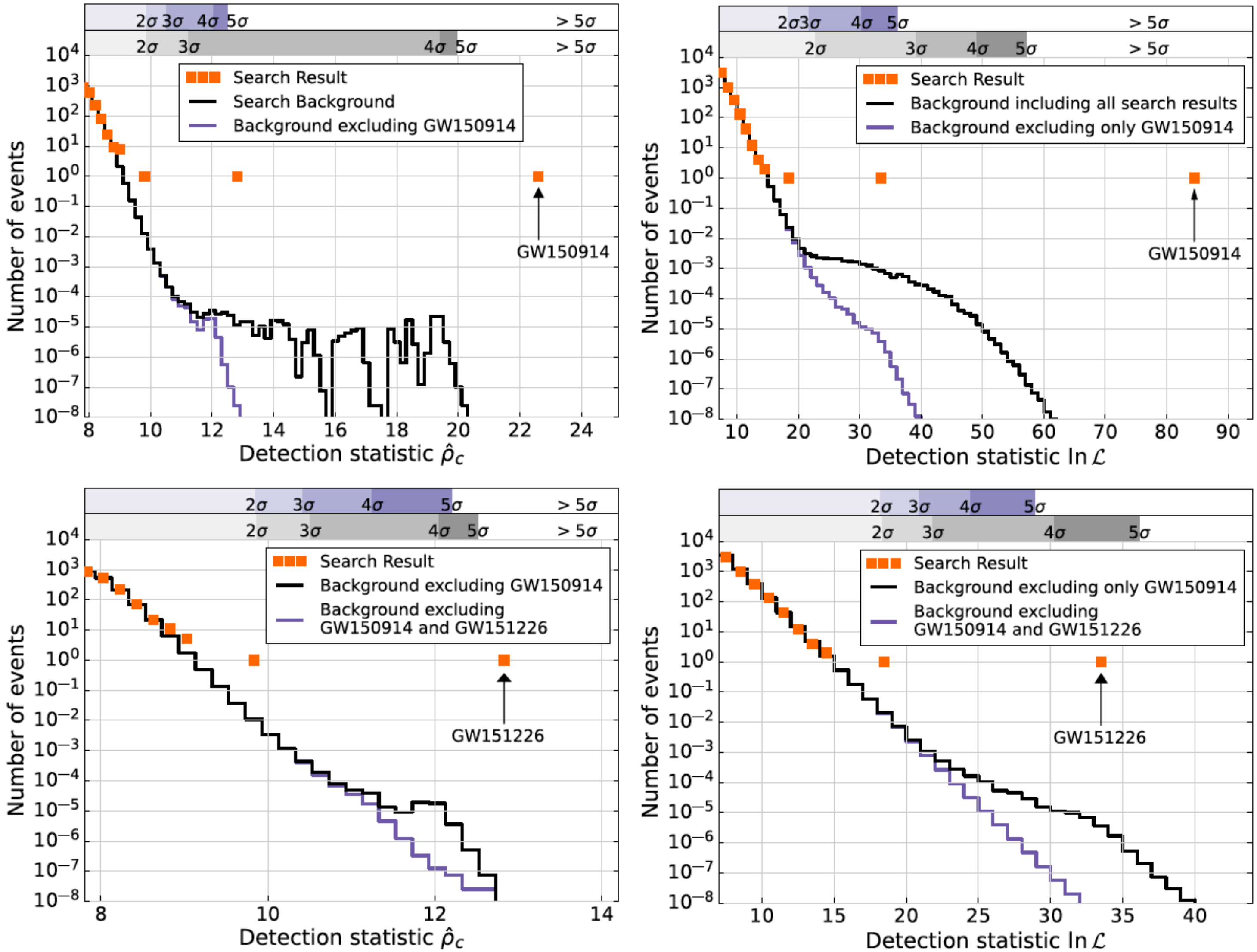
$$\boxed{\rho = \frac{\langle s|h\rangle}{\sqrt{\langle h|h\rangle}}} \qquad \langle a|b\rangle = 4\mathrm{Re}\int_{f_{\mathrm{low}}}^{f_{\mathrm{high}}} \frac{\tilde{a}(f)\tilde{b}^{*}(f)}{S_n(f)}\,df$$

- Background computed from time-shifting coincident data in 100 ms steps
  - For GW150914, 51.5 days → 5x10^6 years



Abbott, et al., LIGO Scientific Collaboration and Virgo Collaboration, "Binary Black Hole Mergers in the first Advanced LIGO Observing Run", Phys. Rev. X 6, 041015 (2016).

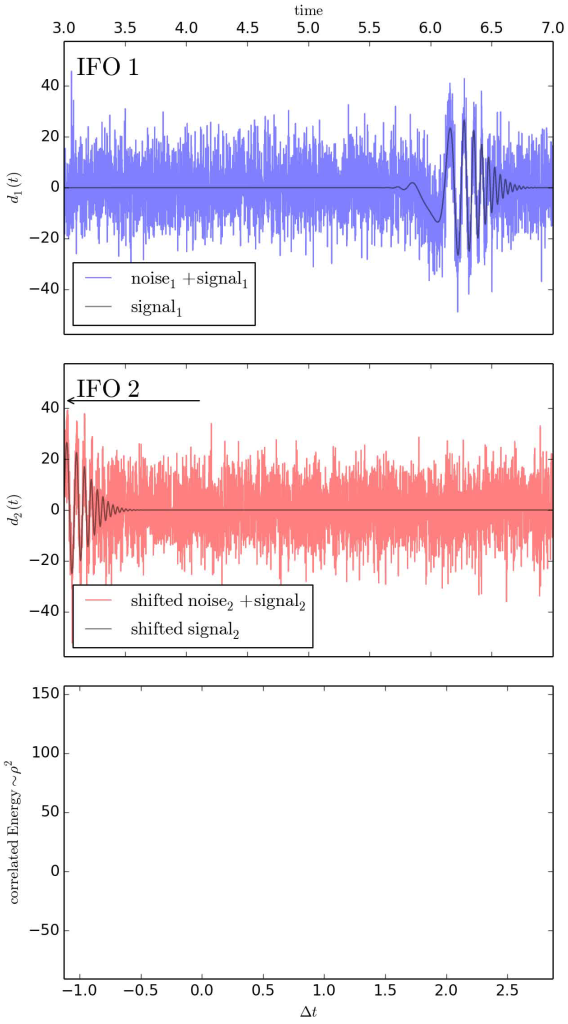
Assessing Statistical Significance: Modeled Search



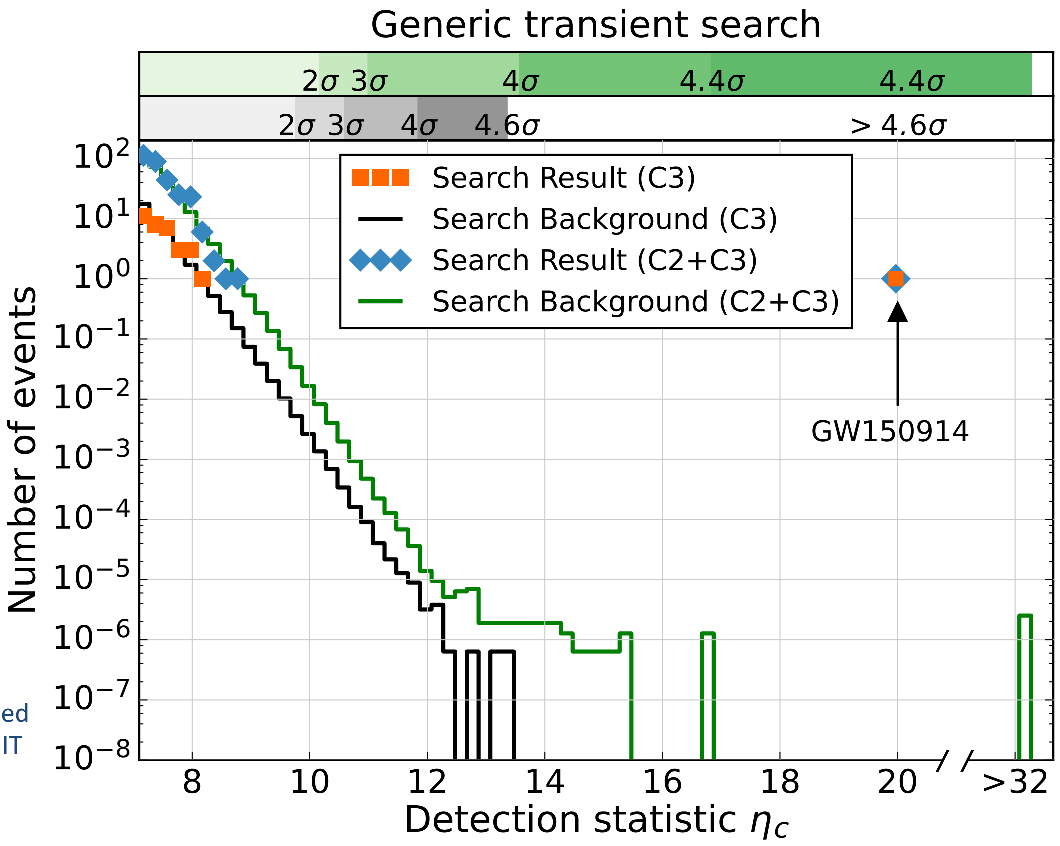
Abbott, et al., LIGO Scientific Collaboration and Virgo Collaboration, "Binary Black Hole Mergers in the first Advanced LIGO Observing Run", Phys. Rev. X 6, 041015 (2016).

Assessing Statistical Significance: Unmodeled Search

- Pipelines look for excess power in time-frequency domain
  - e.g. wavelet basis
  - More sensitive to generic sources, but also to noise transients in the interferometers

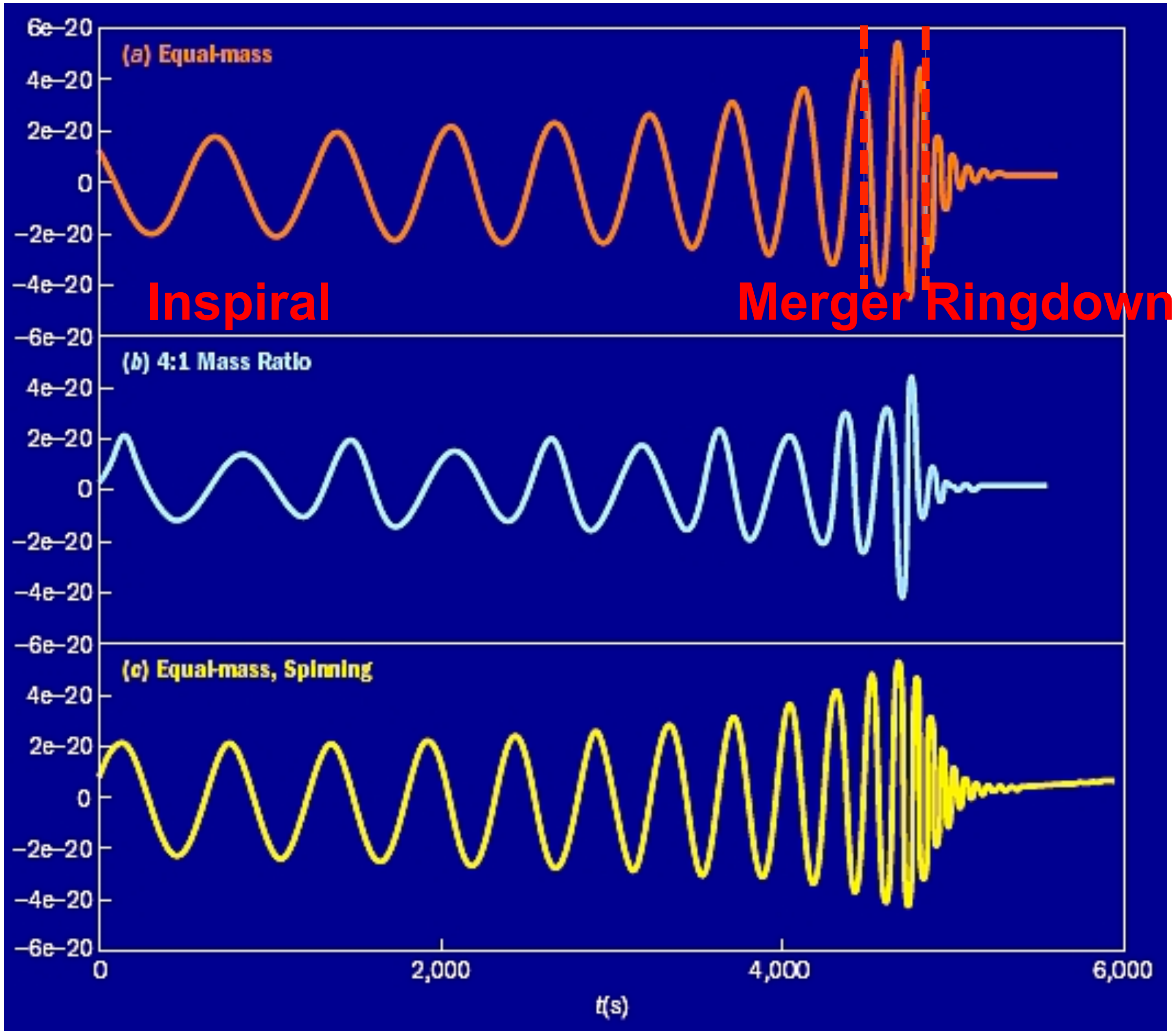


Simulation: Reed Essick, LIGO MIT



Extracting Astrophysical Parameters from GW Waveforms

- Compact object parameters encoded in the waveforms:
  - Constituent masses, constituent spins, sky location, luminosity distance, orbital inclination, time of arrival
- Intrinsic degeneracies make parameter estimation difficult!
  - E.g., luminosity distance vs. inclination angle
- The SNR of the waveform matters
  - often buried in detector noise; lower SNR obscures parameter estimation



LIGO Scientific Collaboration and Virgo Collaboration, "Parameter estimation for compact binary coalescence signals with the first generation gravitational wave detector network" Phys. Rev. D 88(2013) 062001

Extracting Astrophysical Parameters from Waveforms

- **Total Mass:** $M = m_1 + m_2$
- **Mass ratio:** $q = \frac{m_2}{m_1} \leq 1$
- **Chirp Mass:** $\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{M^{1/5}}$

$$\mathcal{M} = \frac{c^3}{G}\left(\frac{5}{96}\pi^{-8/3} f^{-11/3}\dot{f}\right)^{3/5}$$

- **Black Hole Spins:**

$$a_{1,2} = \frac{c}{G m_{1,2}^2}|S_{1,2}|$$

- **Spin component aligned with orbital angular momentum:**

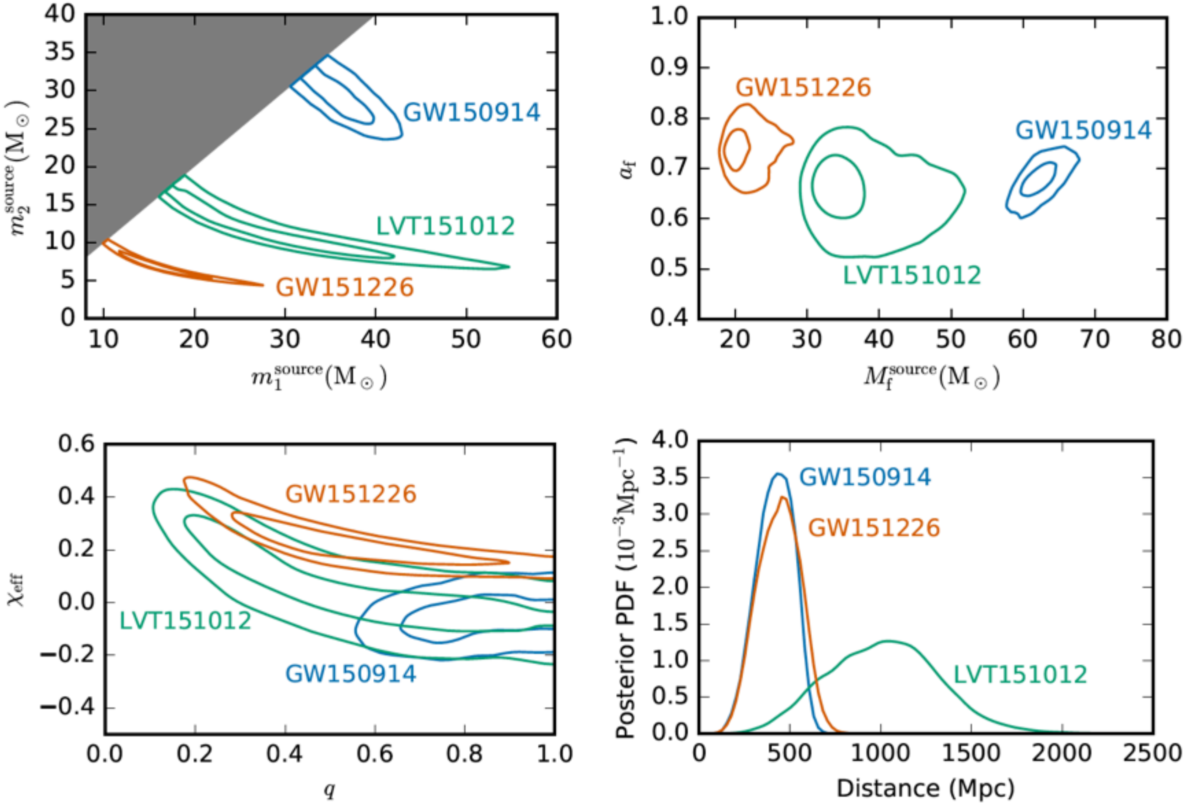
$$\chi_{1,2} = \frac{c}{G m_{1,2}^2} S_{1,2} \cdot \hat{L}$$

- **Effective spin parameter:**

$$\chi_{\rm eff} = \frac{m_1 \chi_1 + m_2 \chi_2}{M}$$

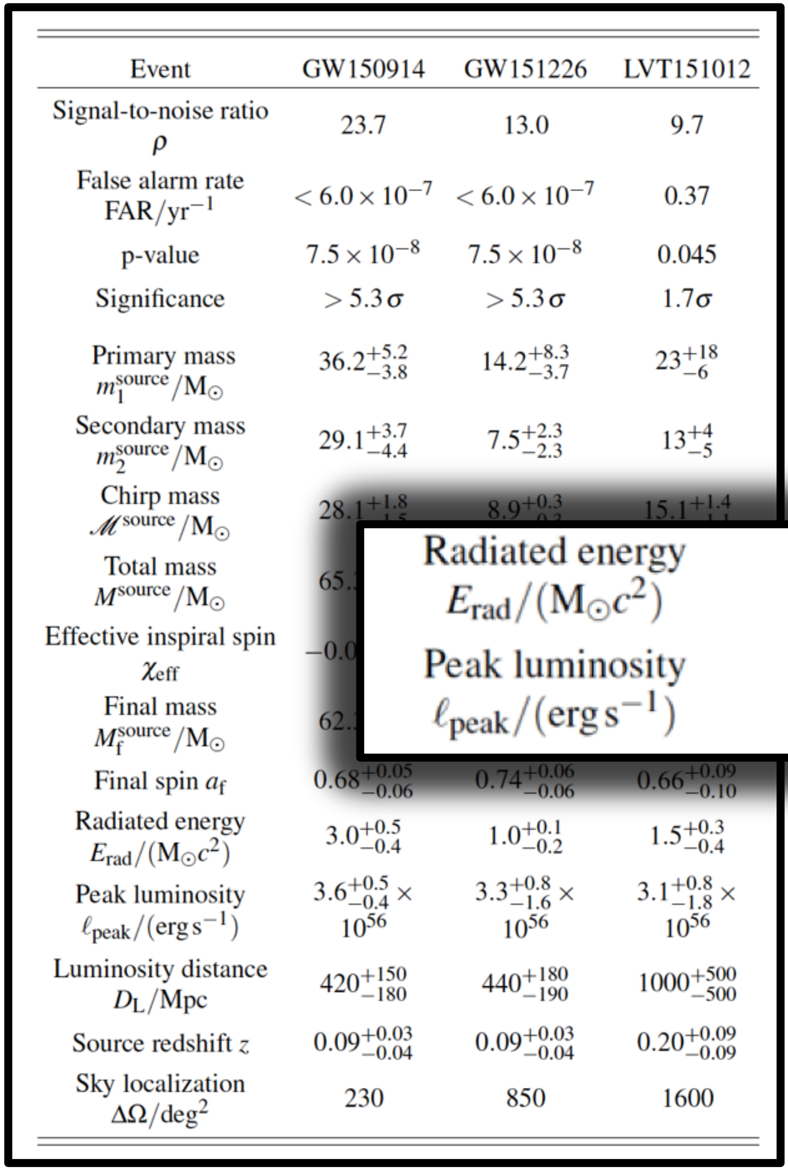
- **Luminosity Distance D_L**

- Bayesian computation of posterior PDFs
  - Markov chain Monte Carlo
  - Nested Sampling



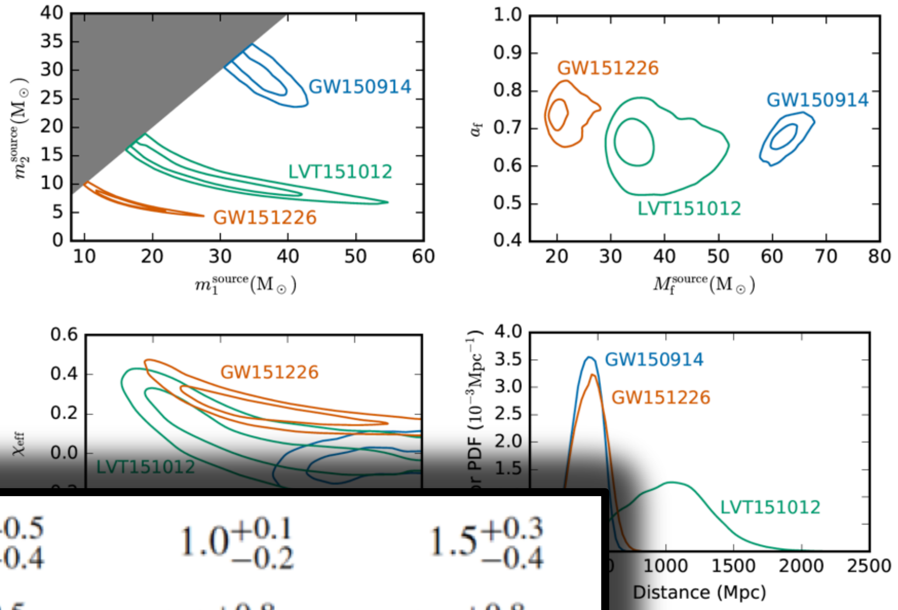
Abbott, et al., LIGO Scientific Collaboration and Virgo Collaboration, “Binary Black Hole Mergers in the first Advanced LIGO Observing Run”, Phys. Rev. X 6, 041015 (2016).

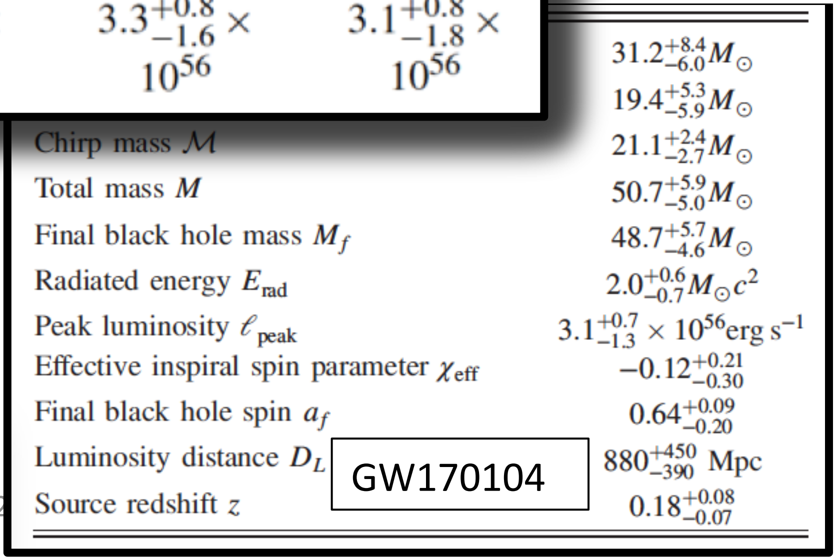
Astrophysical Parameters of the Detected BBH Mergers



Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate $\mathrm{FAR}/\mathrm{yr}^{-1}$	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\sigma$	$> 5.3\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathscr{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	65.		
Effective inspiral spin χ_{eff}	−0.0		
Final mass $M_{\mathrm{f}}^{\mathrm{source}}/\mathrm{M}_\odot$	62.		
Final spin a_{f}	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s}^{-1})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600

Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s}^{-1})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$



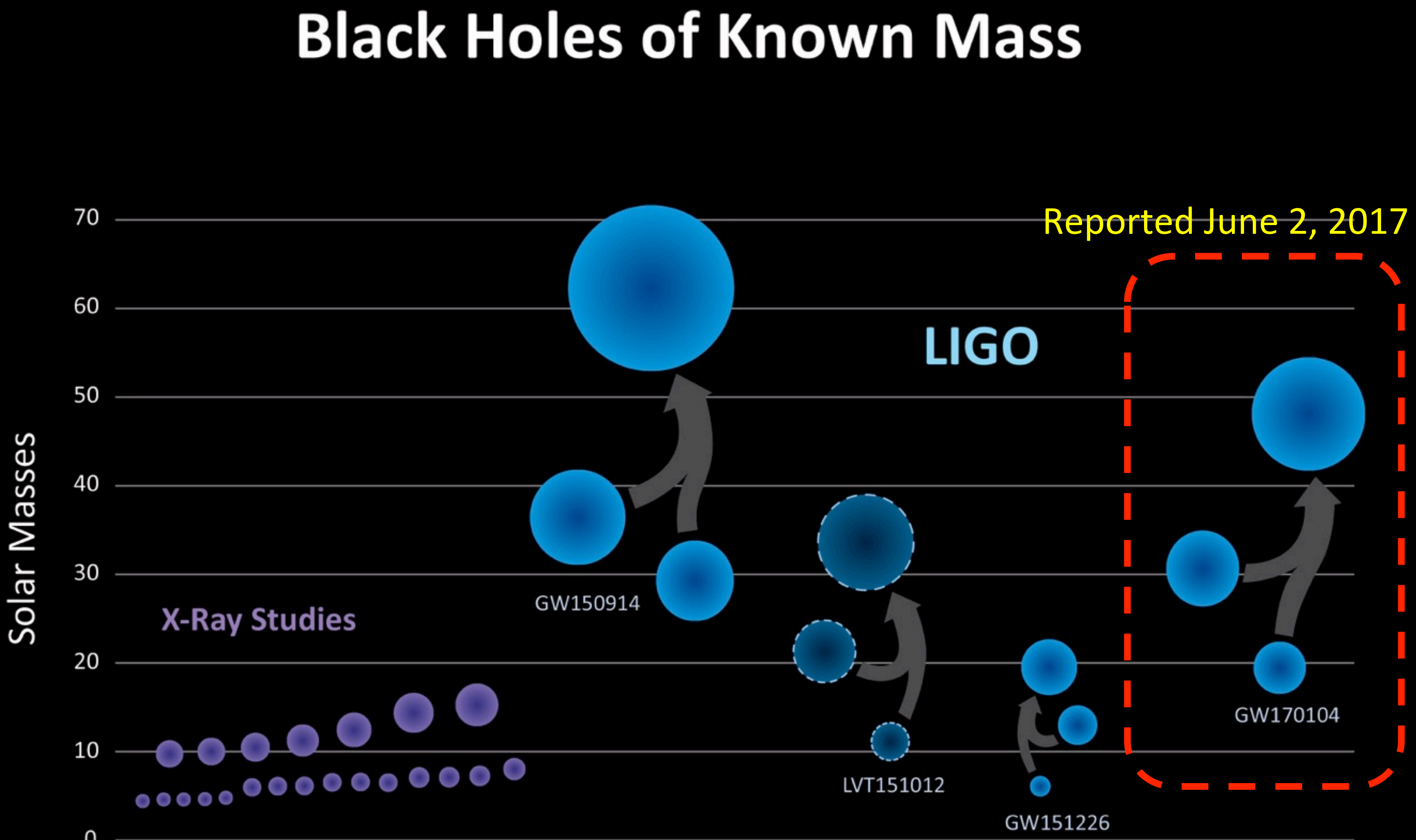


	$31.2^{+8.4}_{-6.0} M_\odot$
	$19.4^{+5.3}_{-5.9} M_\odot$
Chirp mass $\mathcal{M}$	$21.1^{+2.4}_{-2.7} M_\odot$
Total mass M	$50.7^{+5.9}_{-5.0} M_\odot$
Final black hole mass M_f	$48.7^{+5.7}_{-4.6} M_\odot$
Radiated energy E_{rad}	$2.0^{+0.6}_{-0.7} M_\odot c^2$
Peak luminosity ℓ_{peak}	$3.1^{+0.7}_{-1.3} \times 10^{56} \mathrm{erg\ s}^{-1}$
Effective inspiral spin parameter χ_{eff}	$-0.12^{+0.21}_{-0.30}$
Final black hole spin a_f	$0.64^{+0.09}_{-0.20}$
Luminosity distance D_L	880^{+450}_{-390} Mpc
Source redshift z	$0.18^{+0.08}_{-0.07}$

GW170104

What These GW Detections Tell Us About Black Holes

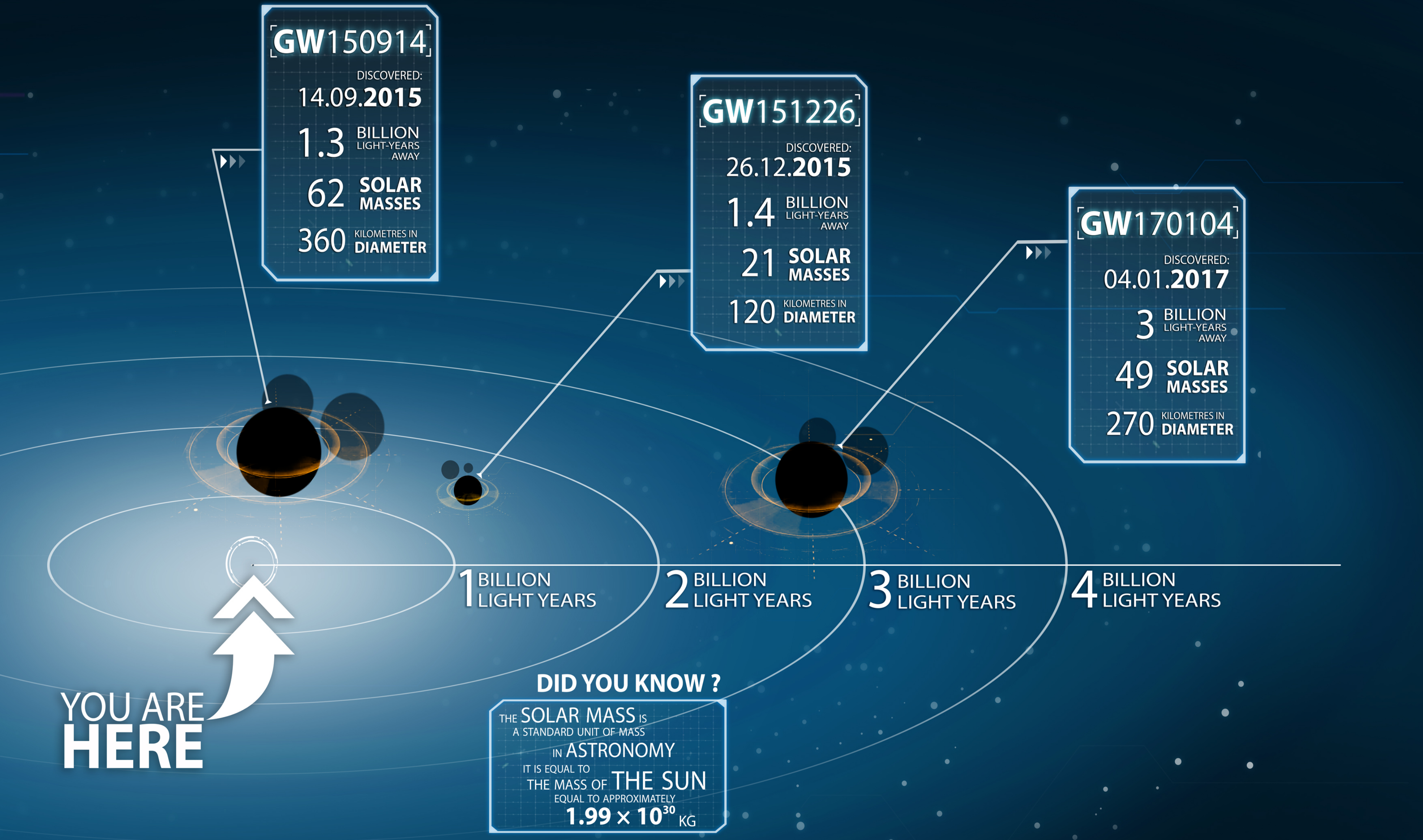
The Newest Black Hole Merger



Reported June 2, 2017

Credit: Robert Hurt/Caltech, Aurore Simmonet, SSU

LIGO'S **GRAVITATIONAL-WAVE** DETECTIONS



GW150914
DISCOVERED:
14.09.**2015**
1.3 BILLION LIGHT-YEARS AWAY
62 **SOLAR MASSES**
360 KILOMETRES IN **DIAMETER**

GW151226
DISCOVERED:
26.12.**2015**
1.4 BILLION LIGHT-YEARS AWAY
21 **SOLAR MASSES**
120 KILOMETRES IN **DIAMETER**

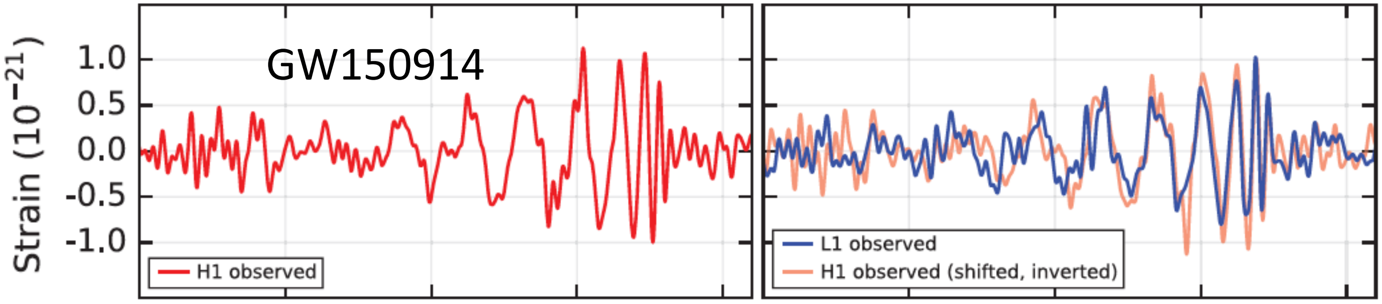
GW170104
DISCOVERED:
04.01.**2017**
3 BILLION LIGHT-YEARS AWAY
49 **SOLAR MASSES**
270 KILOMETRES IN **DIAMETER**

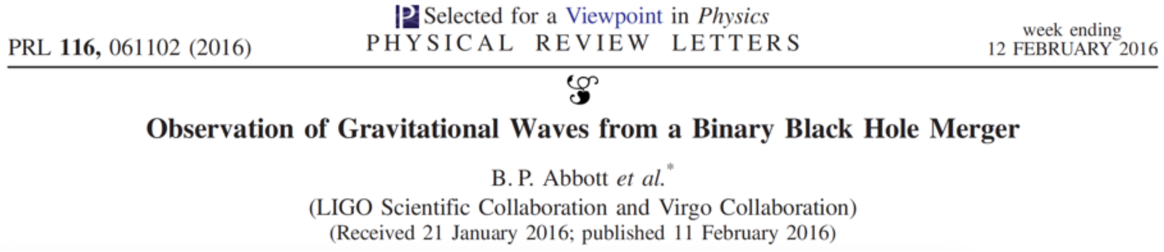
DID YOU KNOW ?

THE SOLAR MASS IS
A STANDARD UNIT OF MASS
IN ASTRONOMY
IT IS EQUAL TO
THE MASS OF THE SUN
EQUAL TO APPROXIMATELY
1.99×10^{30} KG

Data credit: LIGO Scientific Collaboration/OzGrav ARC Centre of Excellence

Black Holes Detected By LIGO

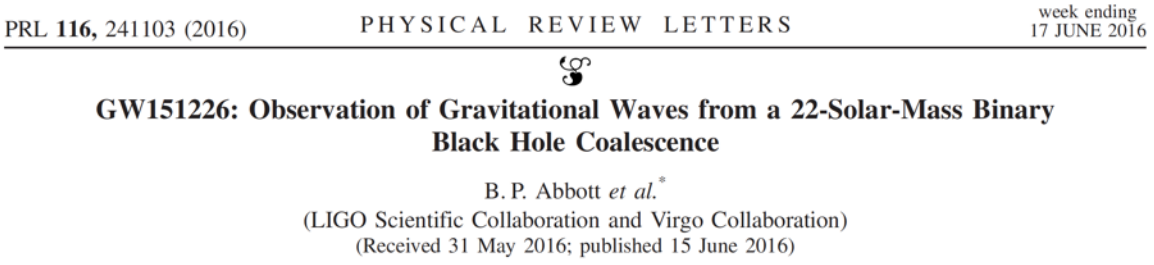



Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

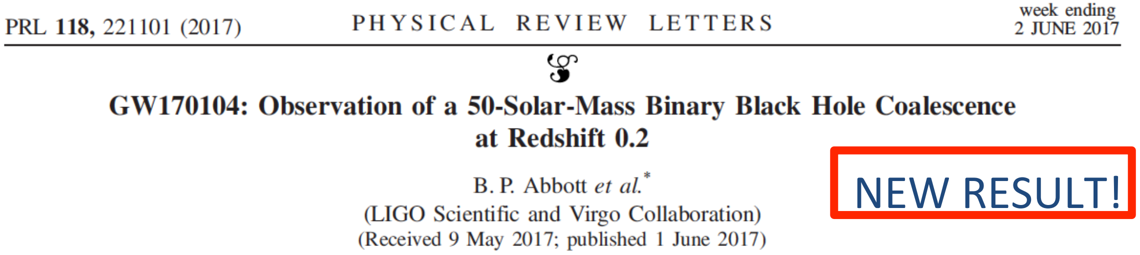
Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)


PRL **116,** 241103 (2016) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2016

GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 31 May 2016; published 15 June 2016)


PRL **118,** 221101 (2017) PHYSICAL REVIEW LETTERS week ending 2 JUNE 2017

GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2

B. P. Abbott *et al.**
(LIGO Scientific and Virgo Collaboration)
(Received 9 May 2017; published 1 June 2017)

NEW RESULT!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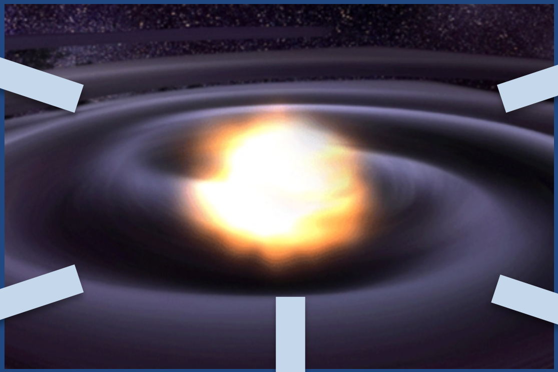
The Future:

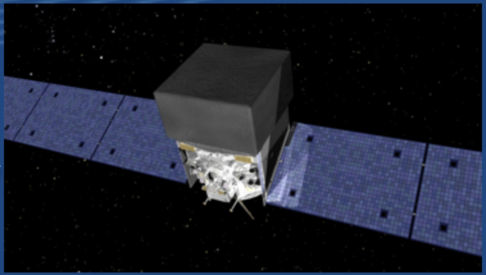
Multi-messenger Astronomy With Gravitational Waves

Multi-messenger Astronomy with Gravitational Waves

Gravitational Waves

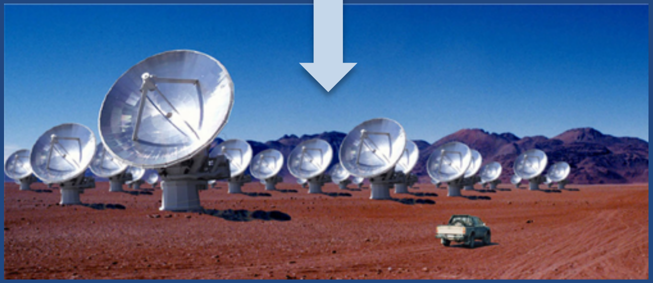
Binary Neutron Star Merger



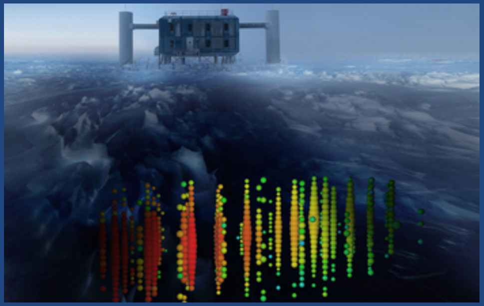


X-rays/Gamma-rays

Visible/Infrared Light



Radio Waves

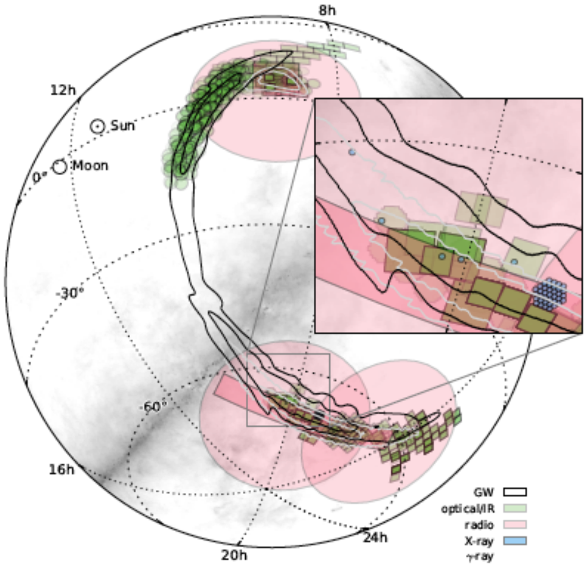


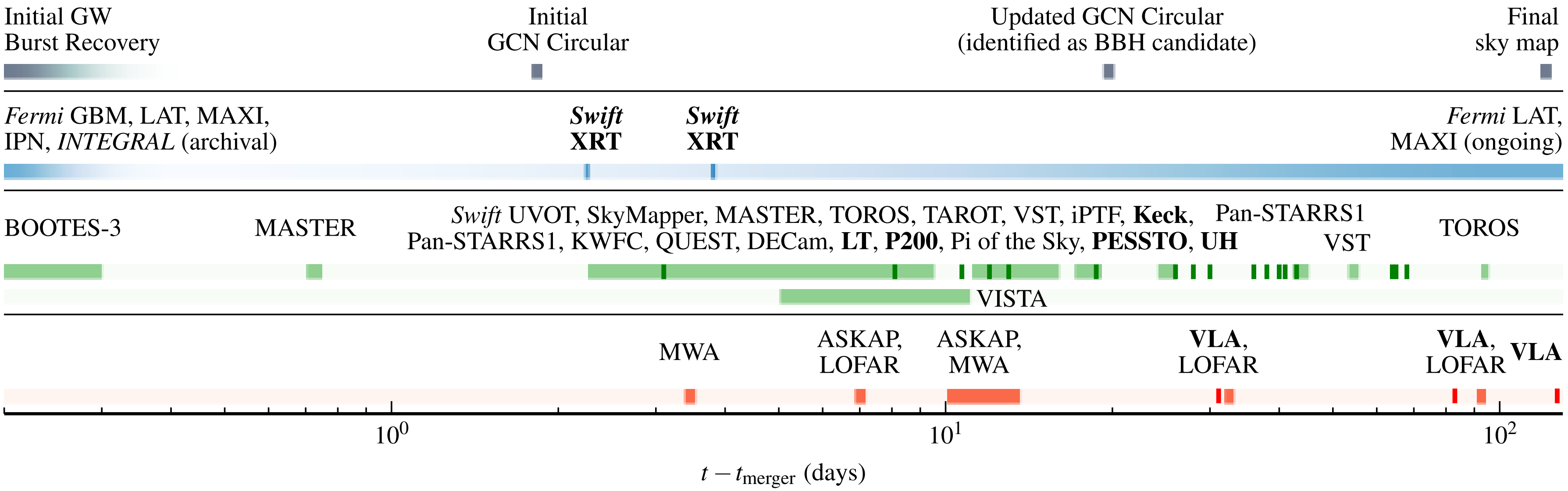
Neutrinos

GW150914 EM Follow Up

- Follow-up observations reported by 25 teams via private Gamma-ray Coordinates Network (GCN) Circulars

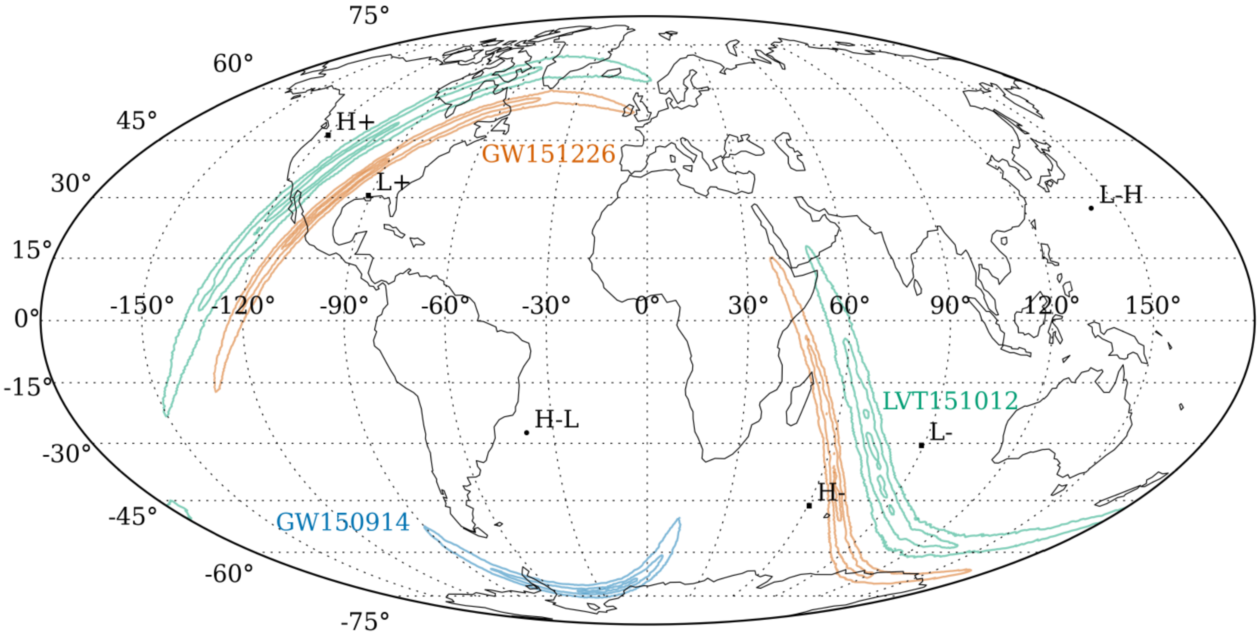
Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, “Localization and Broadband Follow-Up of the Gravitational-Wave Transient GW150914”, Ap. J. Lett, 826:L13, 2016.





Event Sky Location

- With 2 detectors can only limit location to annulus on the sky
  - Preferential angles from interferometer antenna patterns



- 90% credible regions:
  - GW150914: 230 deg^2
  - GW151226: 850 deg^2
  - LVT151012: 1600 deg^2
  - (GW170104: 1200 deg^2)

Event Sky Location

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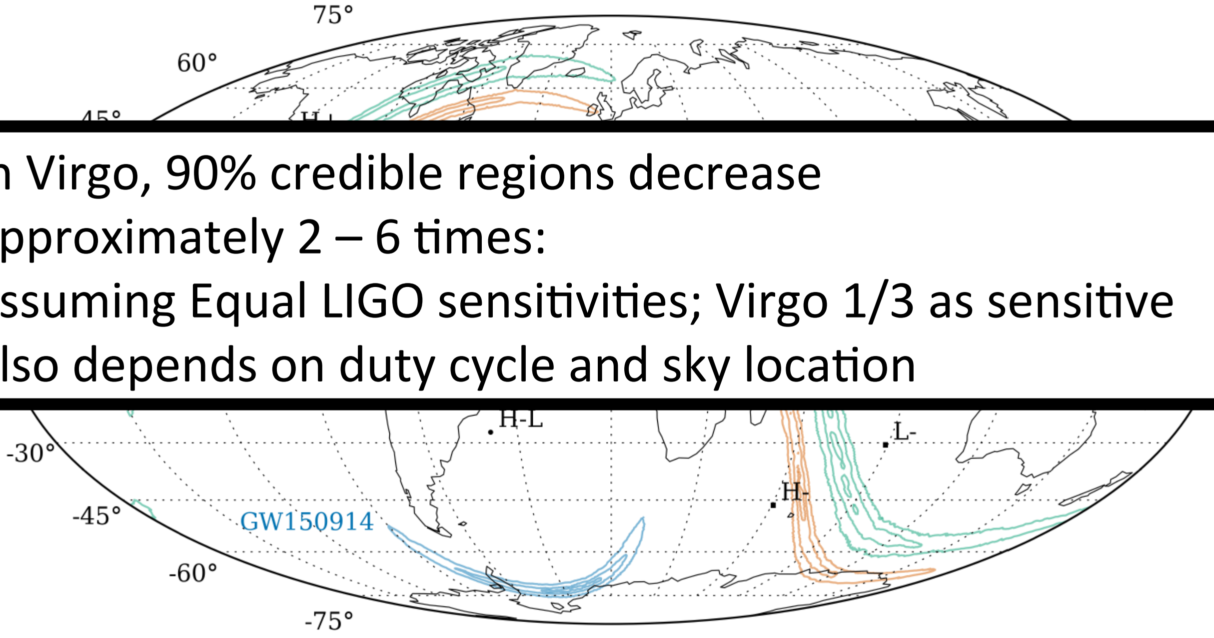
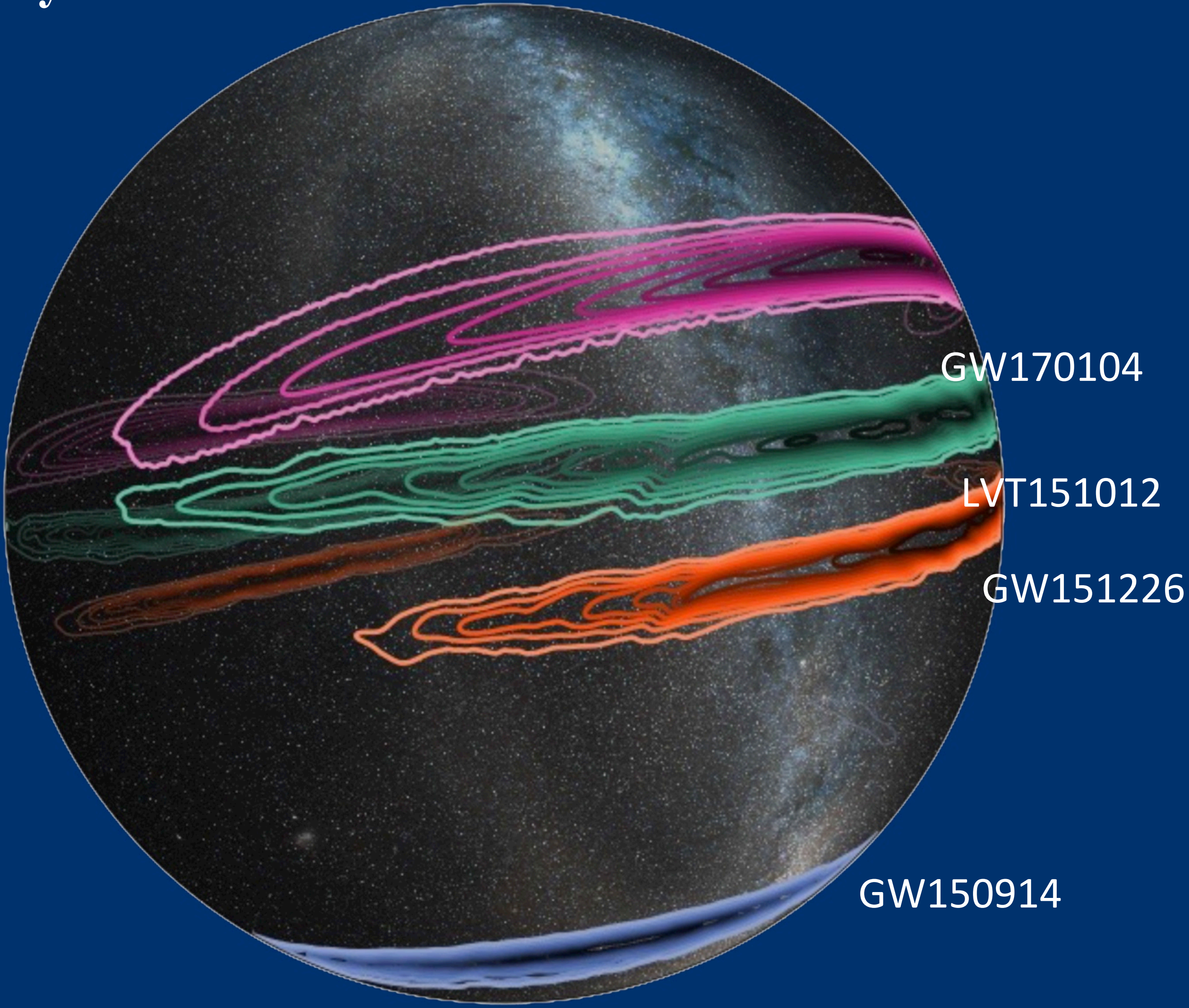


With Virgo, 90% credible regions decrease by approximately 2 – 6 times:

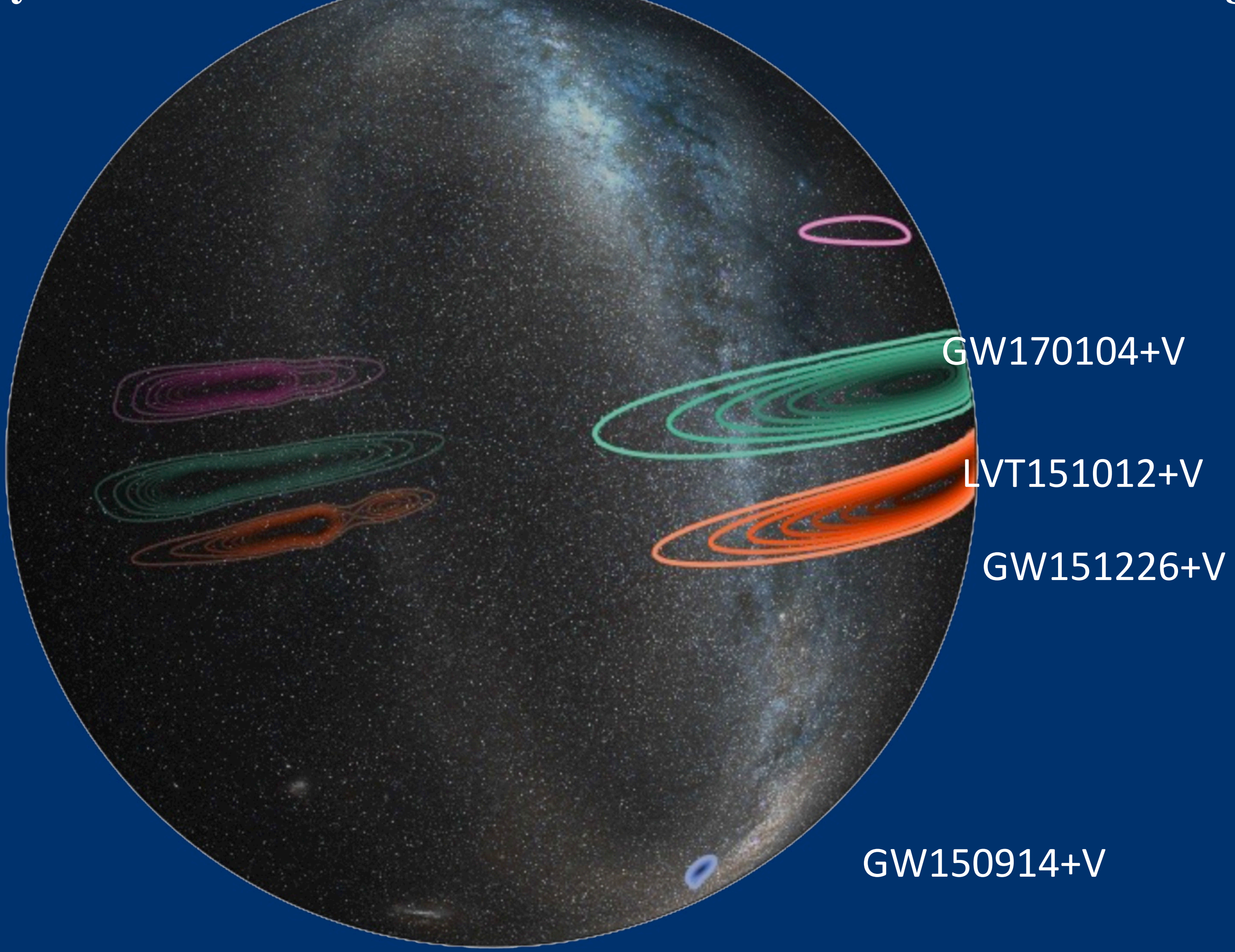
- Assuming Equal LIGO sensitivities; Virgo 1/3 as sensitive
- Also depends on duty cycle and sky location

- 90% credible regions:
  - GW150914: 230 deg^2
  - GW151226: 850 deg^2
  - LVT151012: 1600 deg^2
  - (GW170104: 1200 deg^2)

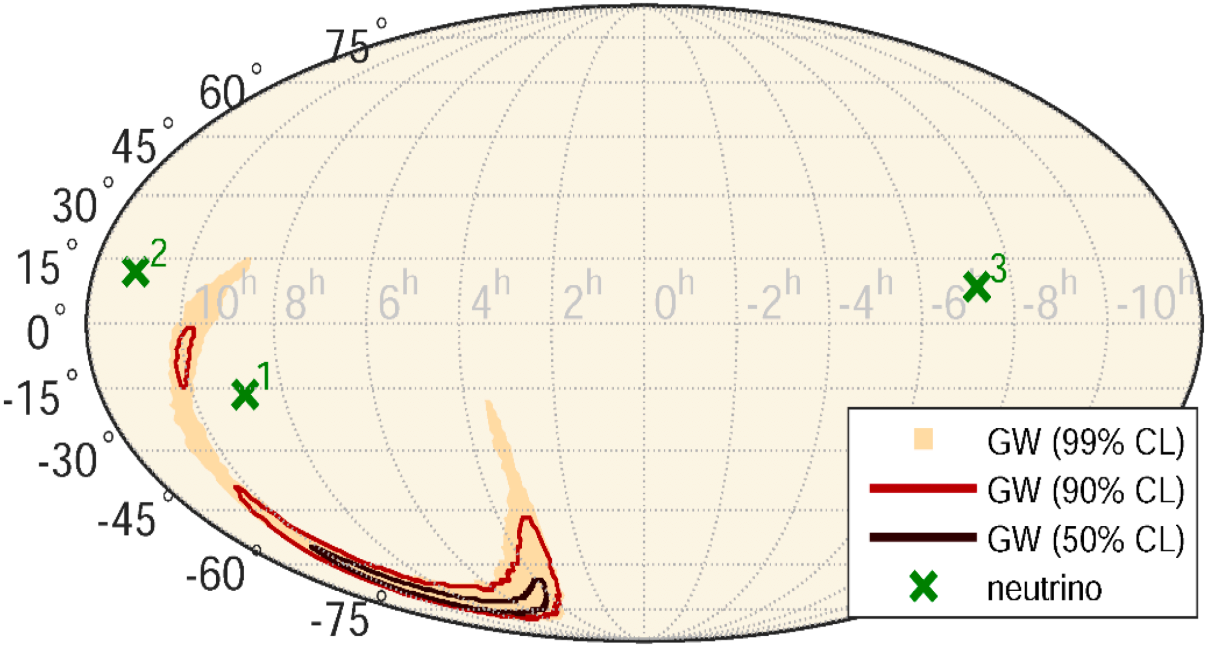
Sky Locations of Gravitational-wave Events: LIGO Only



Sky Locations of Gravitational-wave Events: LIGO + Virgo

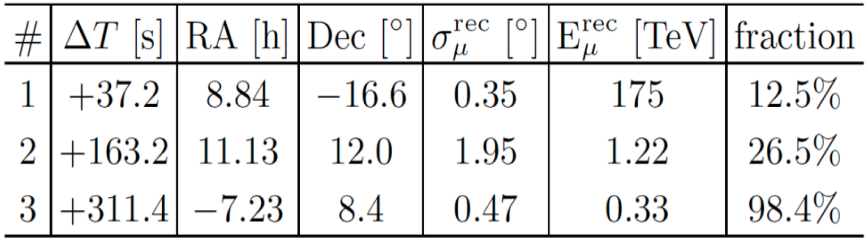


Previous search: GW150914



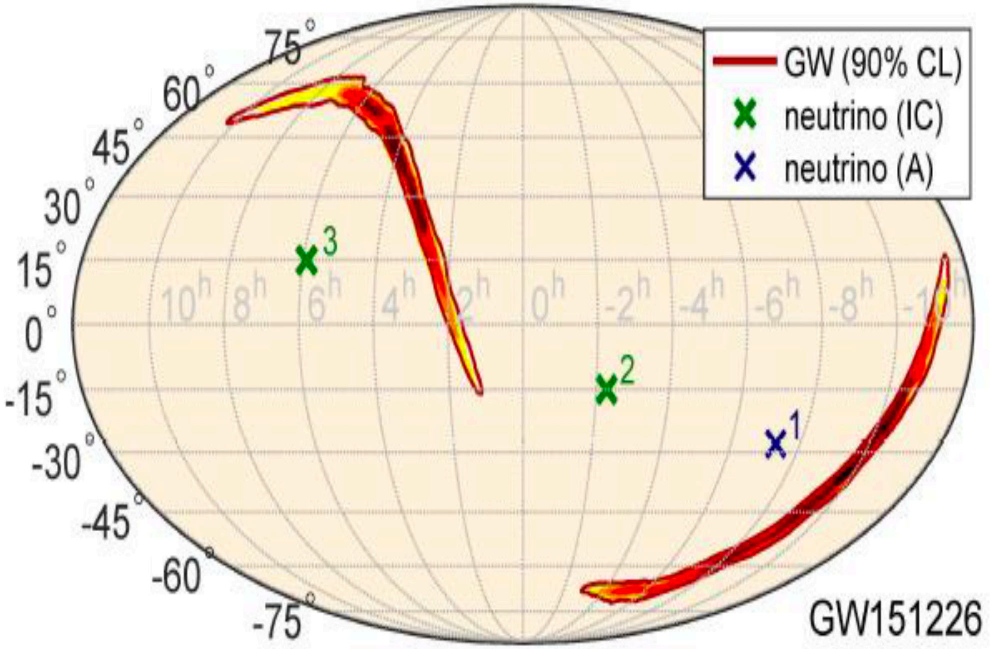
- ANTARES —— FAR ~ 1.2/day
- IceCube —— FAR ~ 2.2+2.2 / 1000s

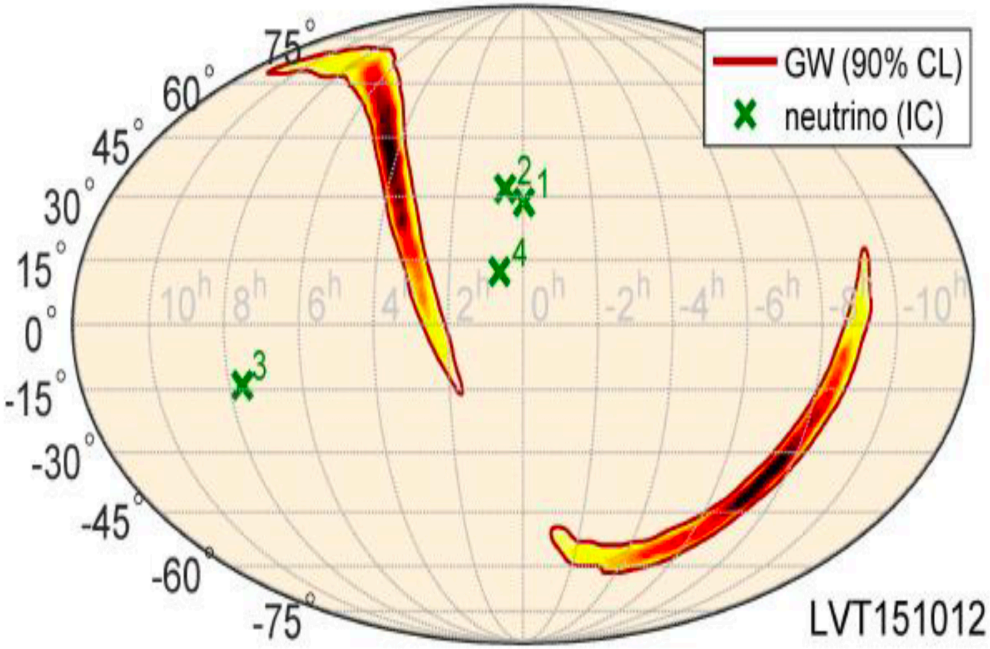
- ~TeV search (standard)
- ~10-100 GeV (DeepCore)
- ultra high energy (PeV)

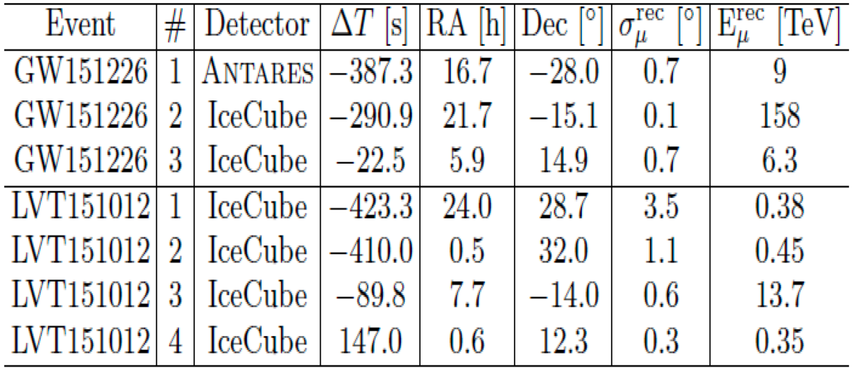


#	ΔT [s]	RA [h]	Dec [°]	$\sigma_\mu^{\mathrm{rec}}$ [°]	E_μ^{rec} [TeV]	fraction
1	+37.2	8.84	−16.6	0.35	175	12.5%
2	+163.2	11.13	12.0	1.95	1.22	26.5%
3	+311.4	−7.23	8.4	0.47	0.33	98.4%

GW151226
&
LVT151012

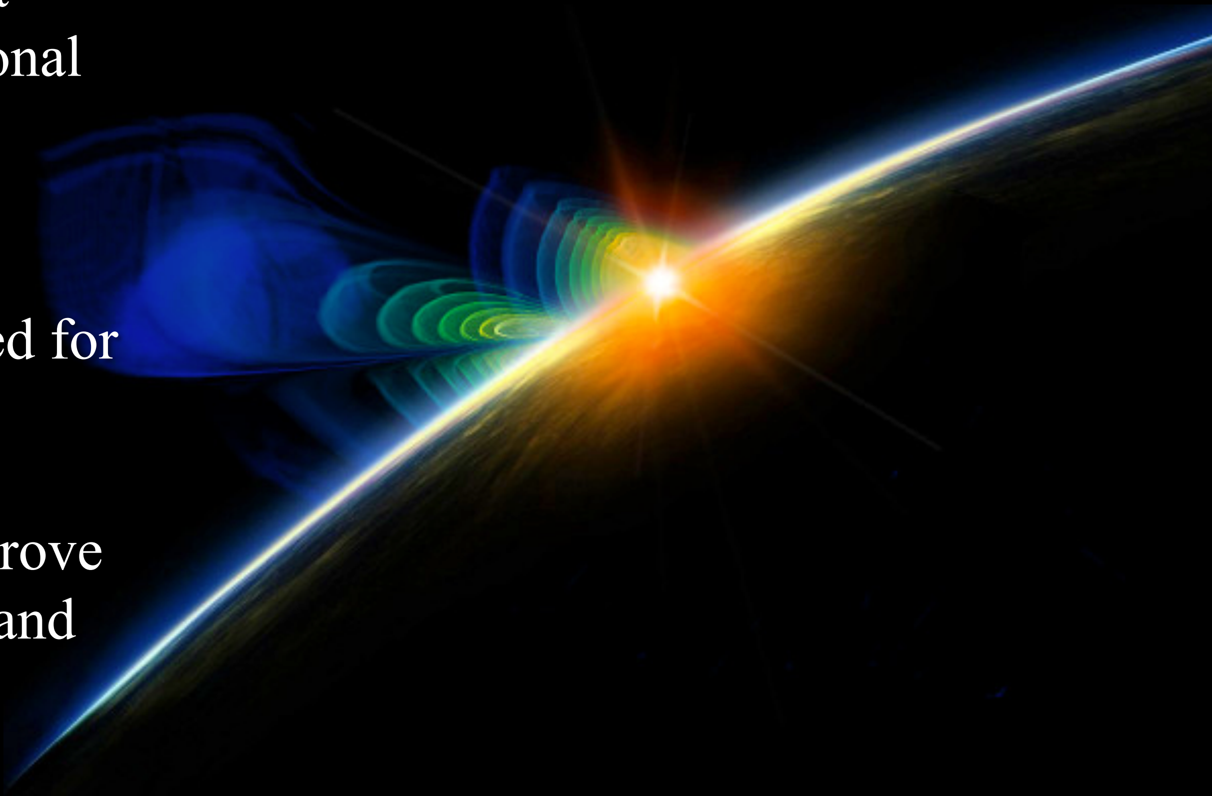






Event	#	Detector	ΔT [s]	RA [h]	Dec [°]	$\sigma_\mu^{\mathrm{rec}}$ [°]	E_μ^{rec} [TeV]
GW151226	1	ANTARES	−387.3	16.7	−28.0	0.7	9
GW151226	2	IceCube	−290.9	21.7	−15.1	0.1	158
GW151226	3	IceCube	−22.5	5.9	14.9	0.7	6.3
LVT151012	1	IceCube	−423.3	24.0	28.7	3.5	0.38
LVT151012	2	IceCube	−410.0	0.5	32.0	1.1	0.45
LVT151012	3	IceCube	−89.8	7.7	−14.0	0.6	13.7
LVT151012	4	IceCube	147.0	0.6	12.3	0.3	0.35

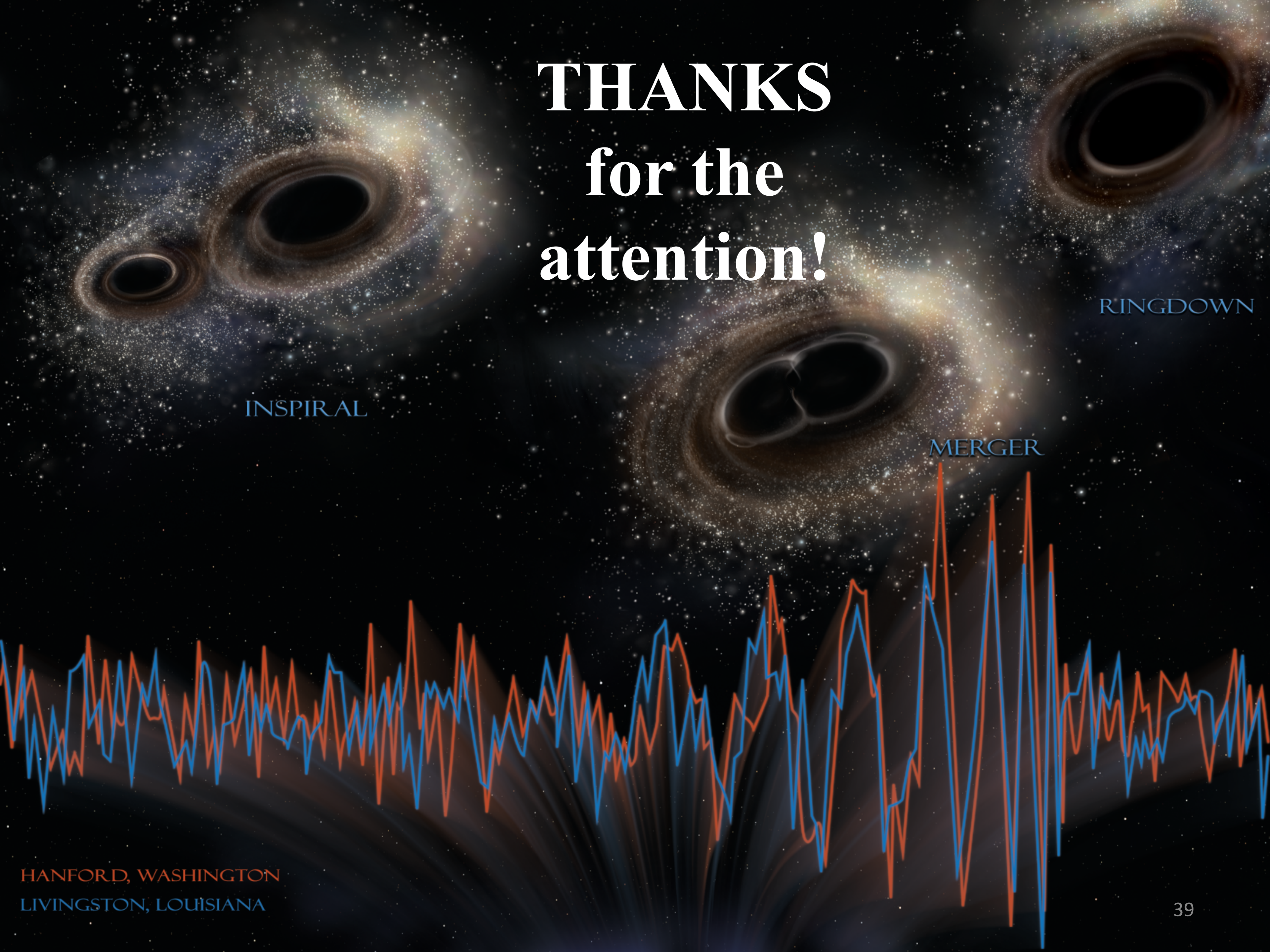
Conclusions



- LIGO-Virgo has made first measurements of gravitational wave amplitude and phase
- Merging binary black hole systems have been observed for the first time!
- Plans are underway to improve LIGO's sensitivity for O3 and beyond
- LIGO-Virgo O2 run completed on August 25

Stay Tuned…

THANKS for the attention!



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BOINC Information

User: Oliver

Team: Albert-Einstein-Institut Hannover (AE

Project Credit: 330046.76

Project RAC: 1266.22

WU Completed: 15.80 %

WU CPU Time: 00:20:45

Search Information

Ascension: 300.40 deg

Declination: 25.10 deg

DM: 498.40 pc/cm3

Orb. Radius: 0.183 ls

Orb. Period: 1003 s

Orb. Phase: 3.85 rad