Gravitational wave observations of compact binary coalescences

Credit: LSC/Sonoma State University/Aurore Simonnet

Katerina Chatziioannou

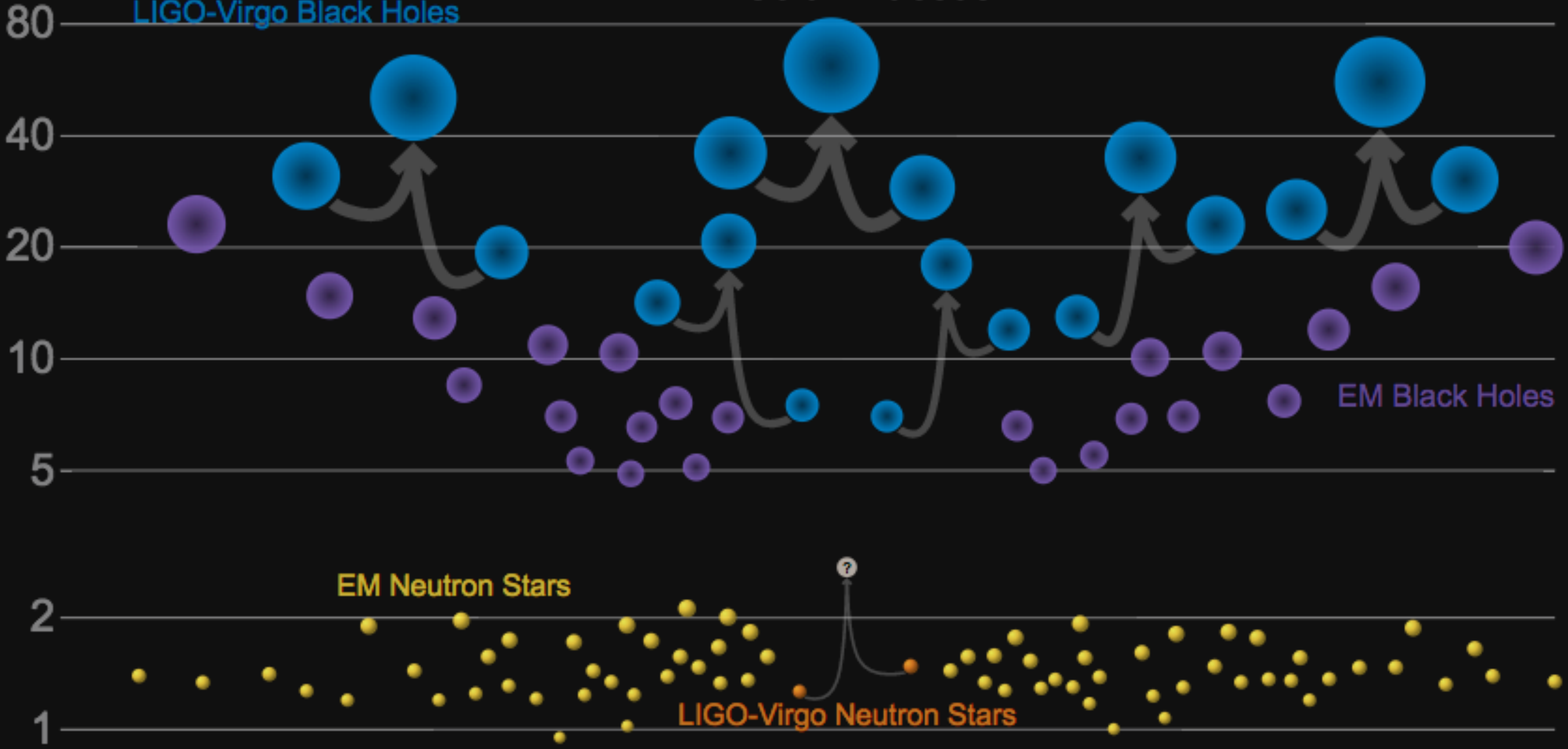
Canadian Institute for Theoretical Astrophysics

For the LIGO Scientific and VIRGO Collaborations

Lake Louise Winter Institute 2018

Masses in the Stellar Graveyard

in Solar Masses



LIGO-Virgo | Frank Elavsky | Northwestern

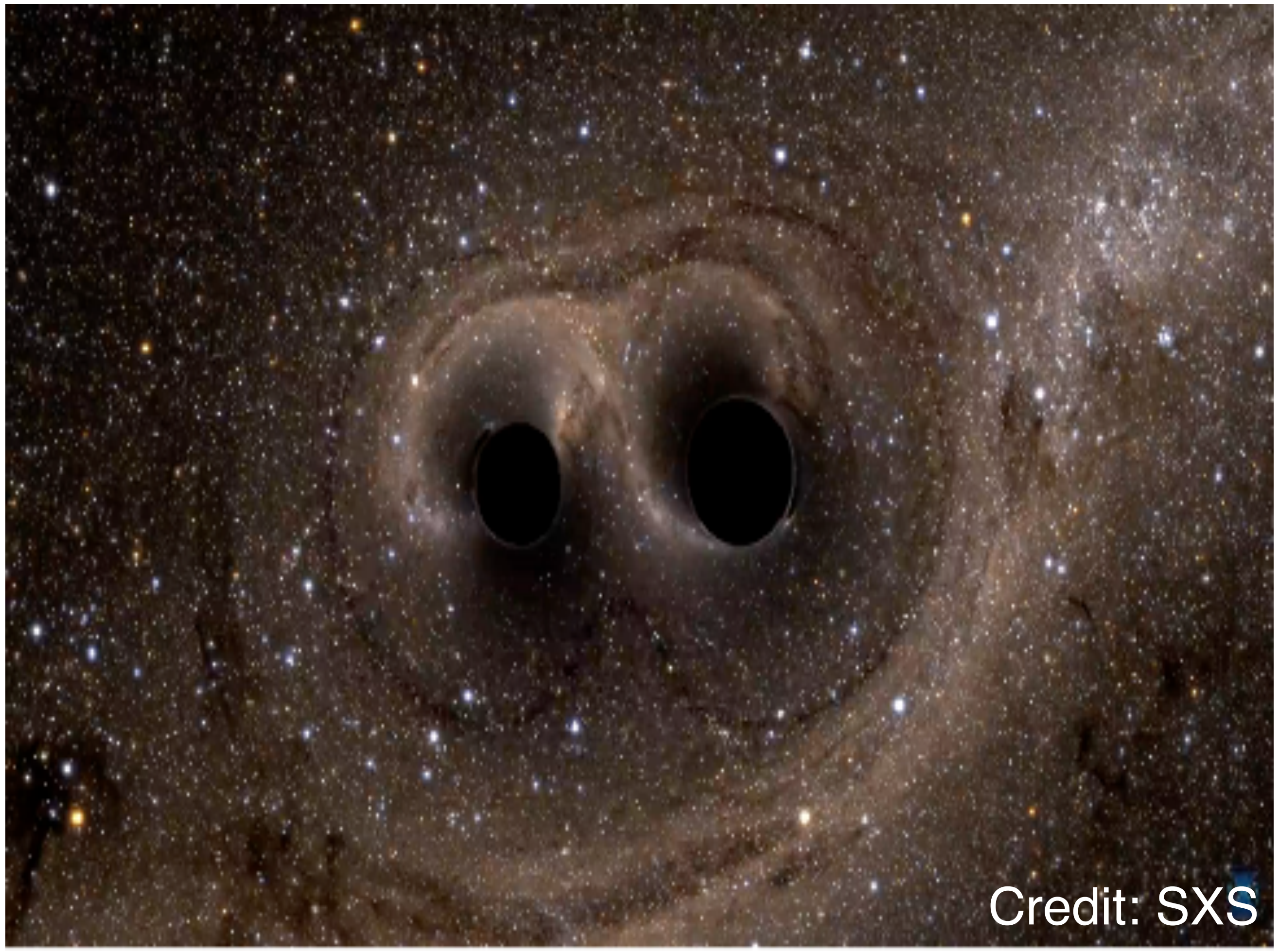
Gravitational waves

Definition: Wave-like perturbation of the gravitational field

$$\Box h_{\mu\nu} = T_{\mu\nu}$$

Generation: Accelerating masses (changing quadrupole and higher multipole moments)

$$h_{ij} \sim \frac{1}{R}\frac{d^2 Q_{ij}}{dt^2}$$


Credit: SXS

Amplitude: Small

$$h \sim \frac{G}{c^4}\frac{mu^2}{R} \sim 10^{-22}$$

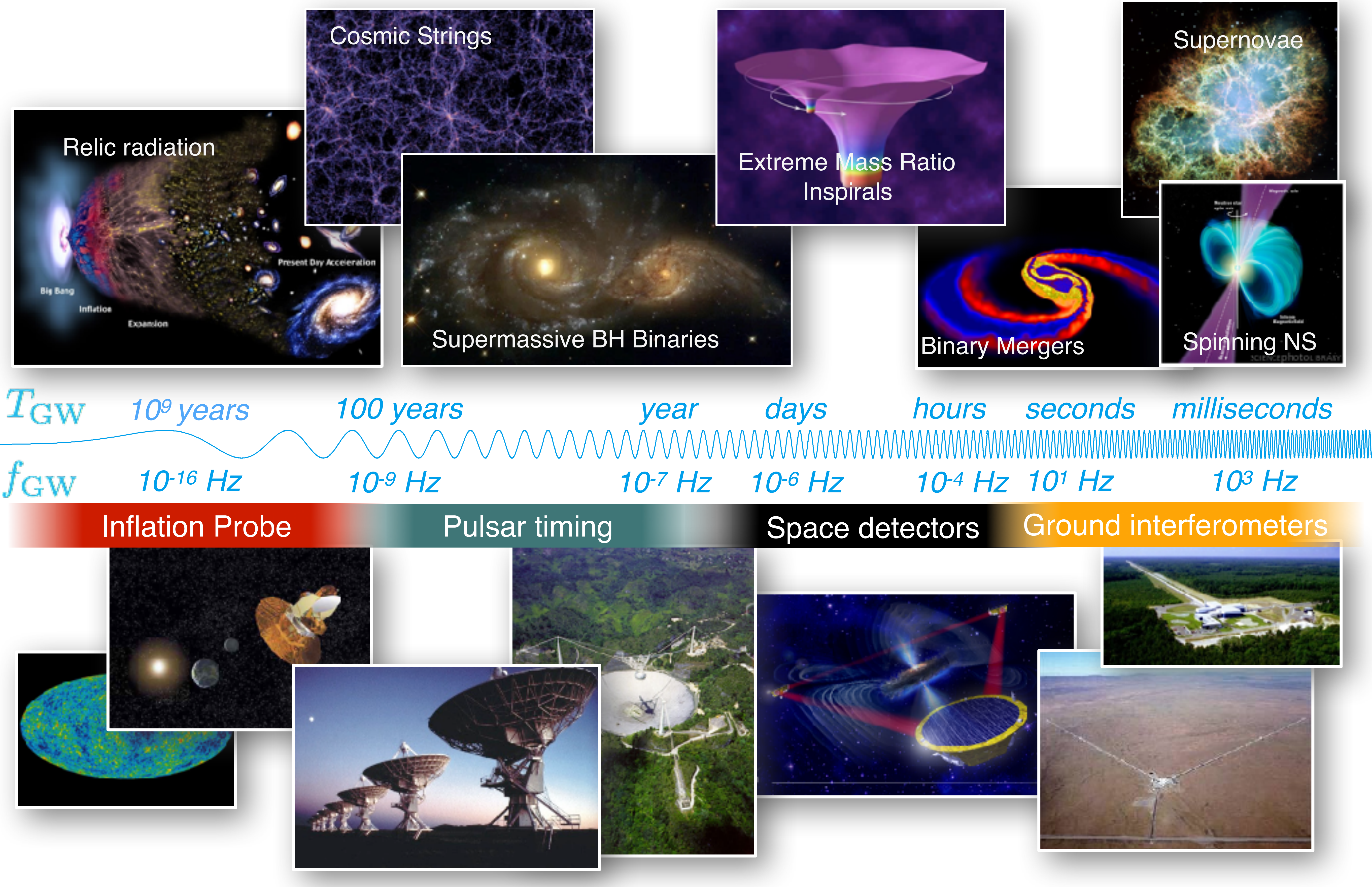
Propagation: Light speed, weakly interacting

Spectrum: Kepler 3rd Law: $f \sim \sqrt{\frac{m}{r_{12}^3}} \sim \frac{1}{m}$, $E_{rad} \sim \% m$

Example: for GW150914, $E_{\rm GW} \sim 3 M_\odot$

More luminous than the entire EM universe

The Gravitational Wave Spectrum



Relic radiation

Cosmic Strings

Supermassive BH Binaries

Extreme Mass Ratio Inspirals

Binary Mergers

Supernovae

Spinning NS

T_{GW} — 10^9 years — 100 years — year — days — hours — seconds — milliseconds

f_{GW} — 10^{-16} Hz — 10^{-9} Hz — 10^{-7} Hz — 10^{-6} Hz — 10^{-4} Hz — 10^1 Hz — 10^3 Hz

Inflation Probe — Pulsar timing — Space detectors — Ground interferometers

LIGO

LIGO Scientific Collaboration

LSC

Caltech
American University
Andrews University
Washington State University
California State University Fullerton
PennState
Southern University and Agricultural & Mechanical College
Massachusetts Institute of Technology
Leland Stanford Junior University
The University Of Sheffield.
University of Maryland
indigo
Texas Tech University
Hillsdale College
Montclair State University
清華大學 Tsinghua University
Université de Montréal
Monash University
Universitat de les Illes Balears
International Institute of Physics
Cal State LA
Bellevue College
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The University of Adelaide Australia
NCSA
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Columbia University in the City of New York
OzGrav
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The University of Western Australia
R·I·T
Sonoma State University
University of Minnesota
RRCAT
Cornell University
The University of Chicago
आई आई टी हैदराबाद IIT Hyderabad
University of Washington
NASA
LSU Louisiana State University
Colorado State University
Charles Sturt University
Marshall Space Flight Center
Chennai Mathematical Institute
東京大学 The University of Tokyo
Università degli Studi del Sannio
ACIGA
ICTS International Centre for Theoretical Sciences Tata Institute of Fundamental Research
University of Birmingham
Georgia Institute of Technology
Korean Gravitational-Wave Group
Universität Hamburg Der Forschung | Der Lehre | Der Bildung
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Embry-Riddle Aeronautical University
Villanova University
Whitman College
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Swinburne University of Technology
The University of Mississippi
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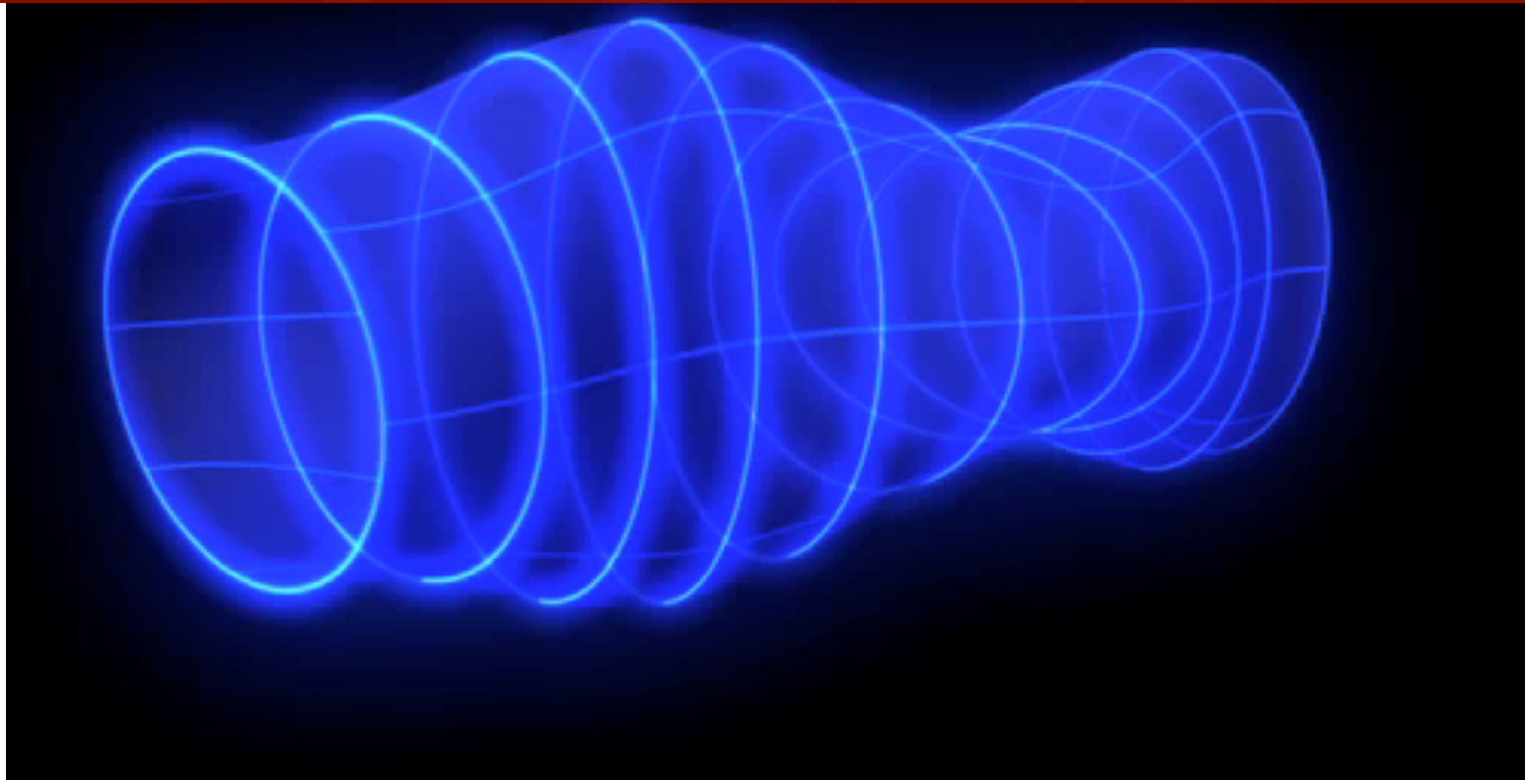
CITA ICAT
King's College London
IISER Kolkata
NASA Goddard Space Flight Center
GEO 600
Max Planck Institute for Gravitational Physics Albert Einstein Institute
Leibniz Universität Hannover
University of Zurich

Three detectors (for now)

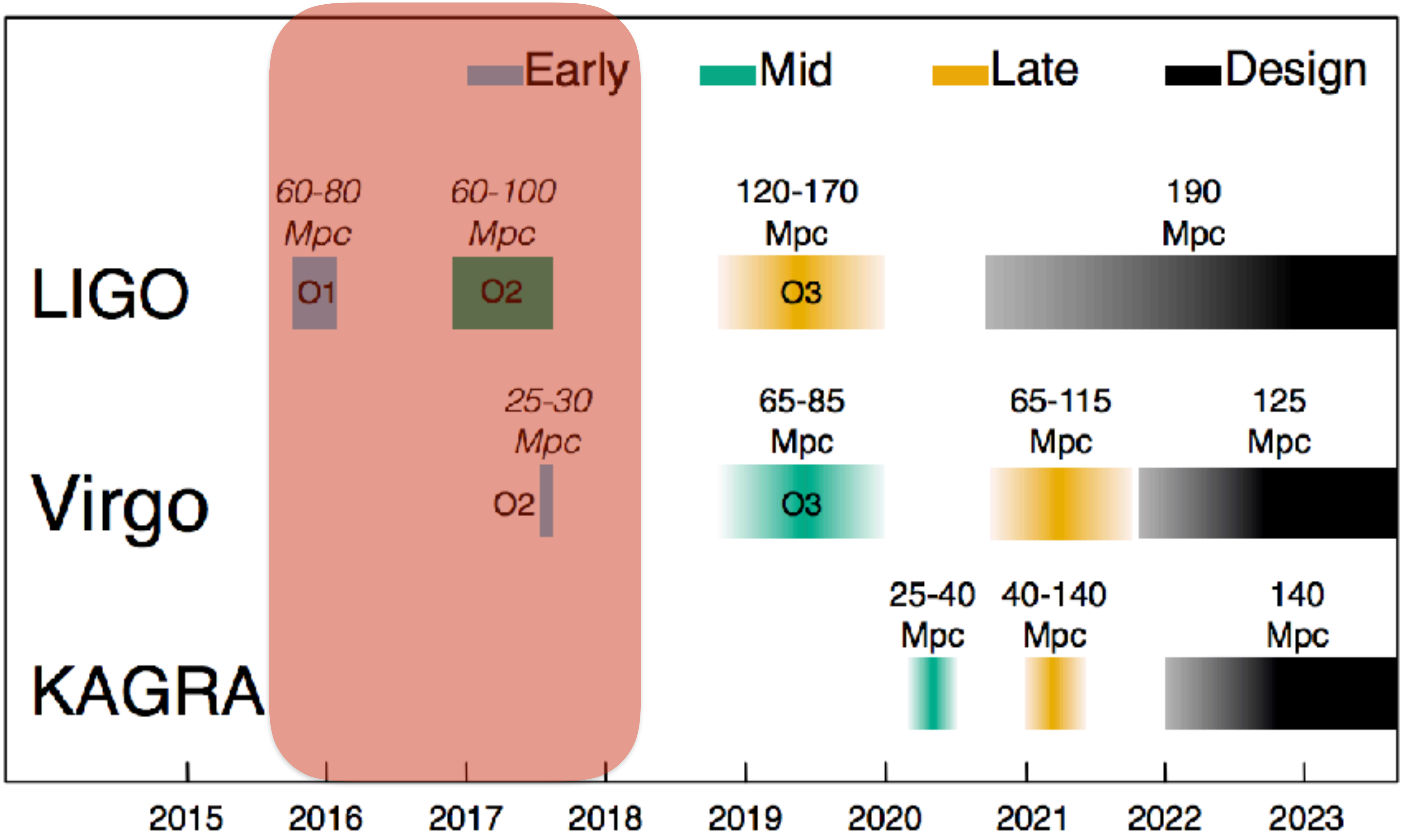


LIGO Hanford

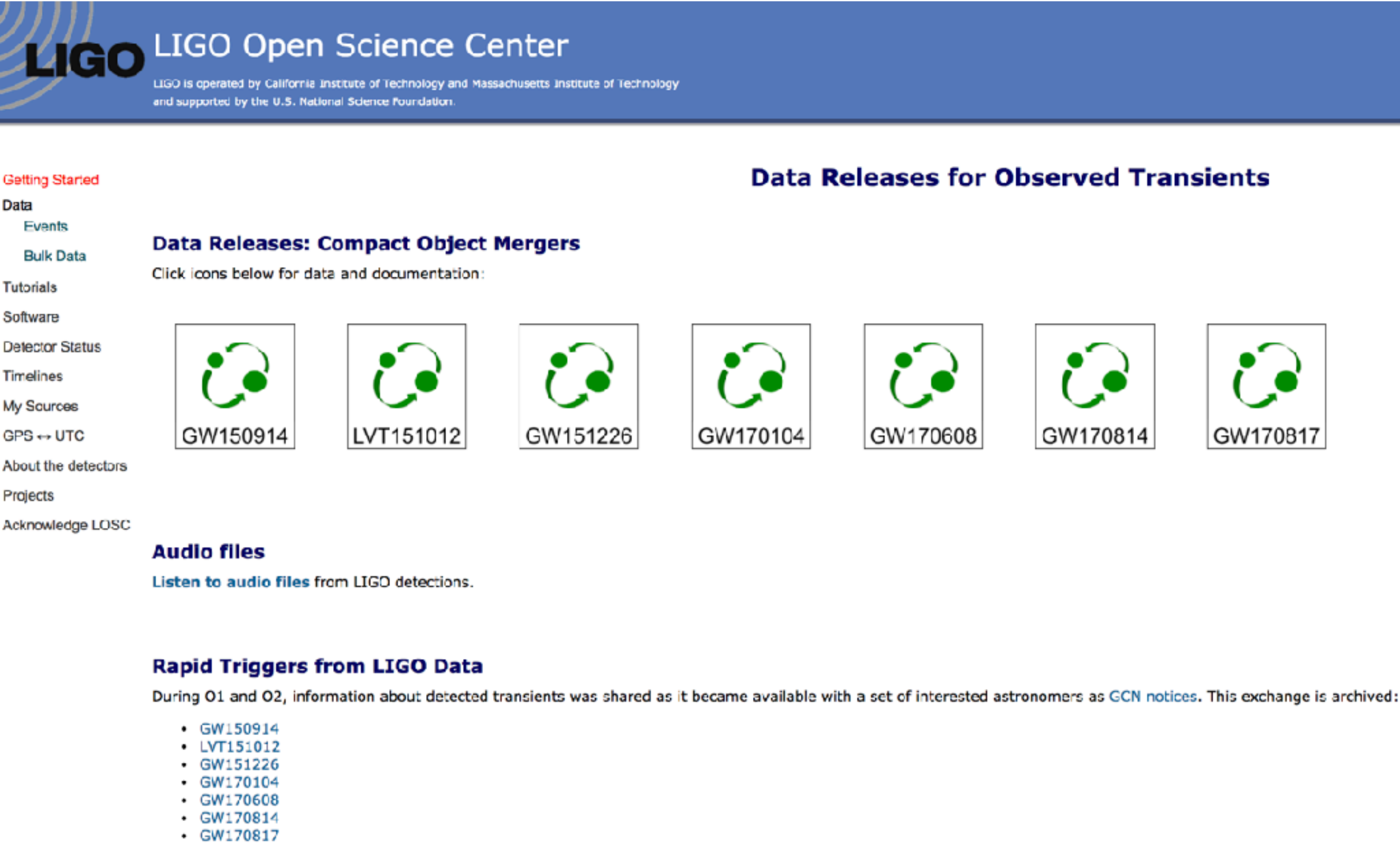
Virgo

LIGO Livingston

Observing schedule



LVC LRR 19 (2016) 1



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.

Data Releases for Observed Transients

Data Releases: Compact Object Mergers

Click icons below for data and documentation:

Audio files

Listen to audio files from LIGO detections.

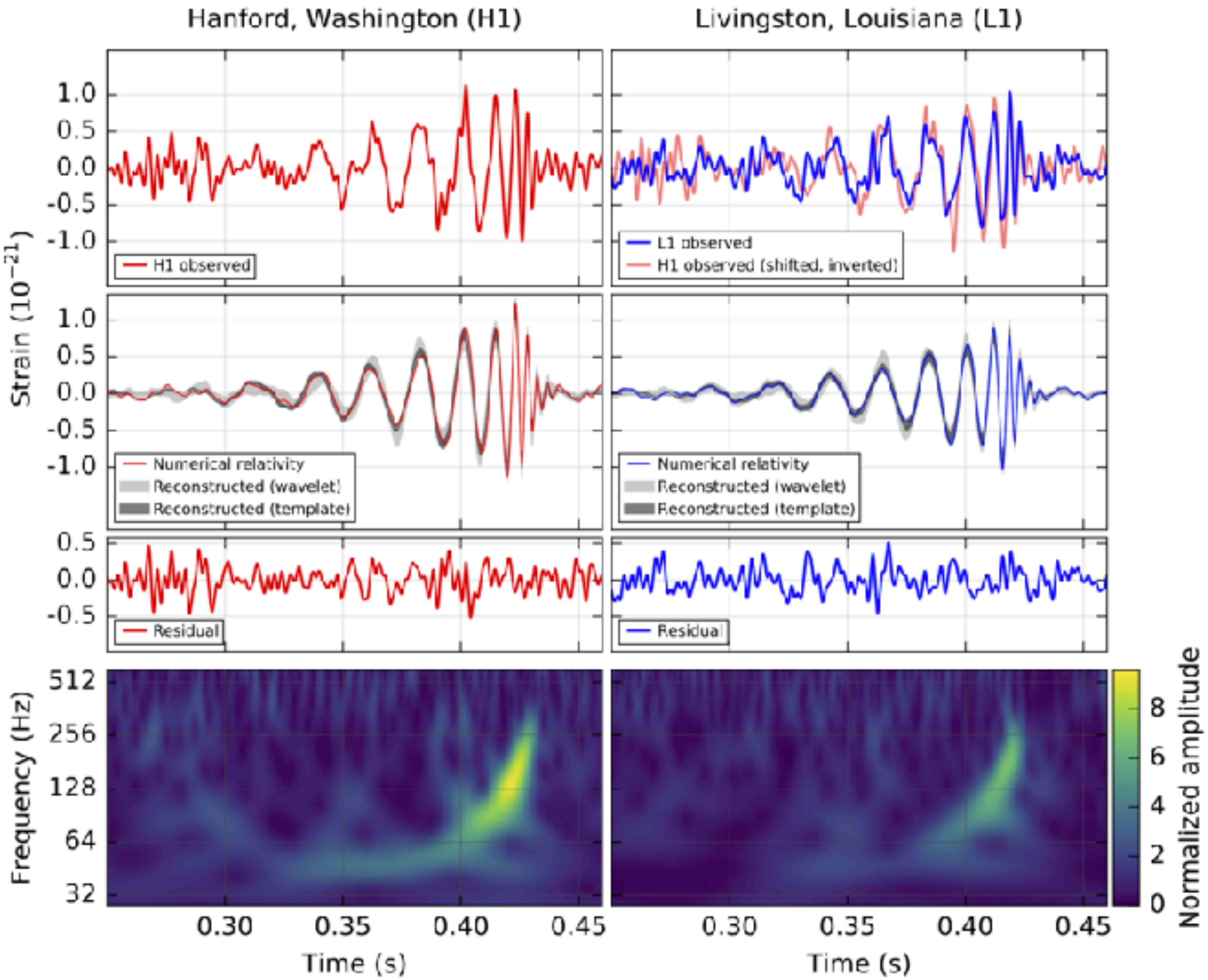
Rapid Triggers from LIGO Data

During O1 and O2, information about detected transients was shared as it became available with a set of interested astronomers as GCN notices. This exchange is archived:

- GW150914
- LVT151012
- GW151226
- GW170104
- GW170608
- GW170814
- GW170817

https://losc.ligo.org/events/

September 14, 2015



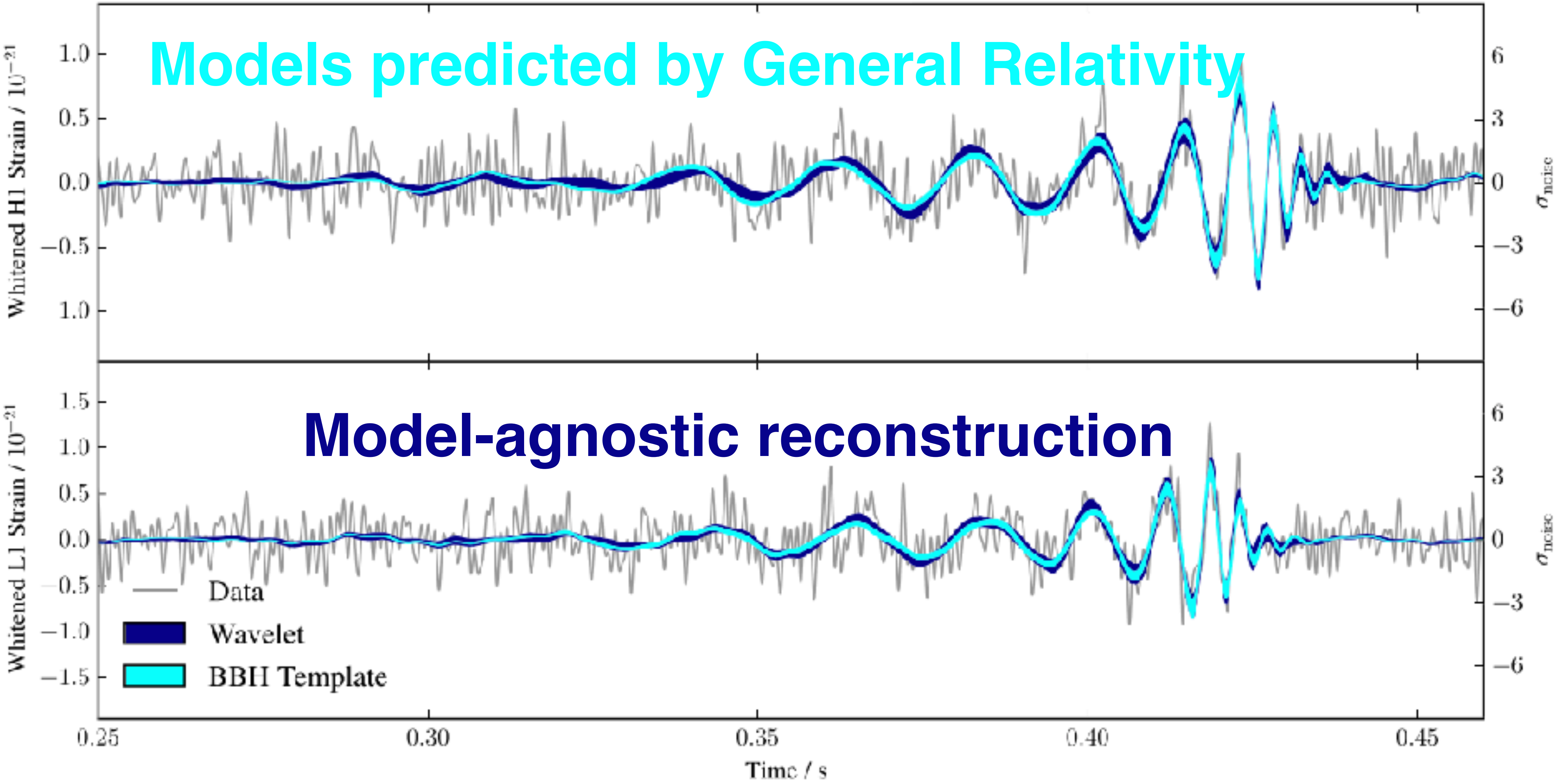
First gravitational wave detection

First black hole binary detection

Heaviest black hole

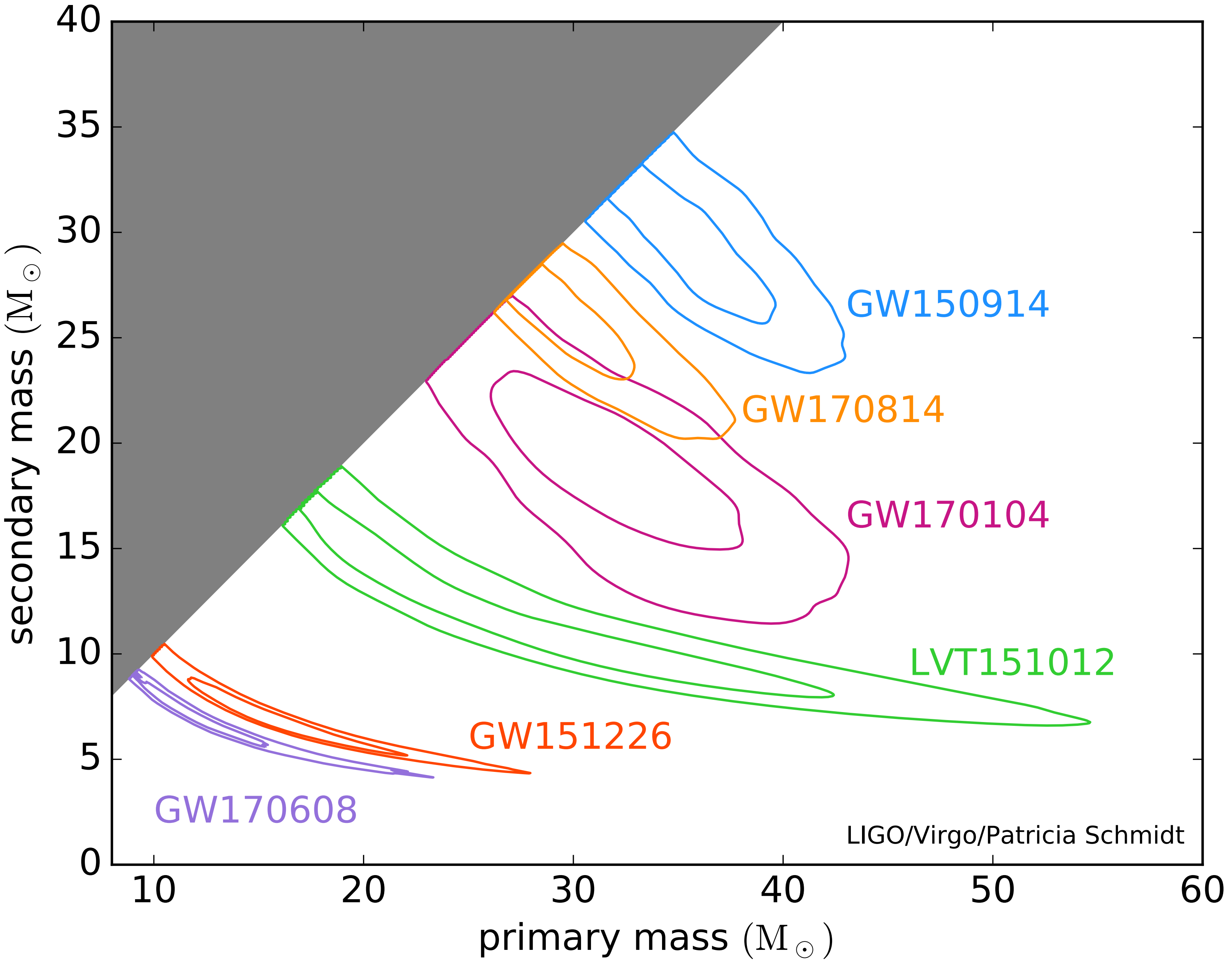
LVC PRL 116, 061102 (2016)

GW150914



LVC PRL 116, 241102 (2016)

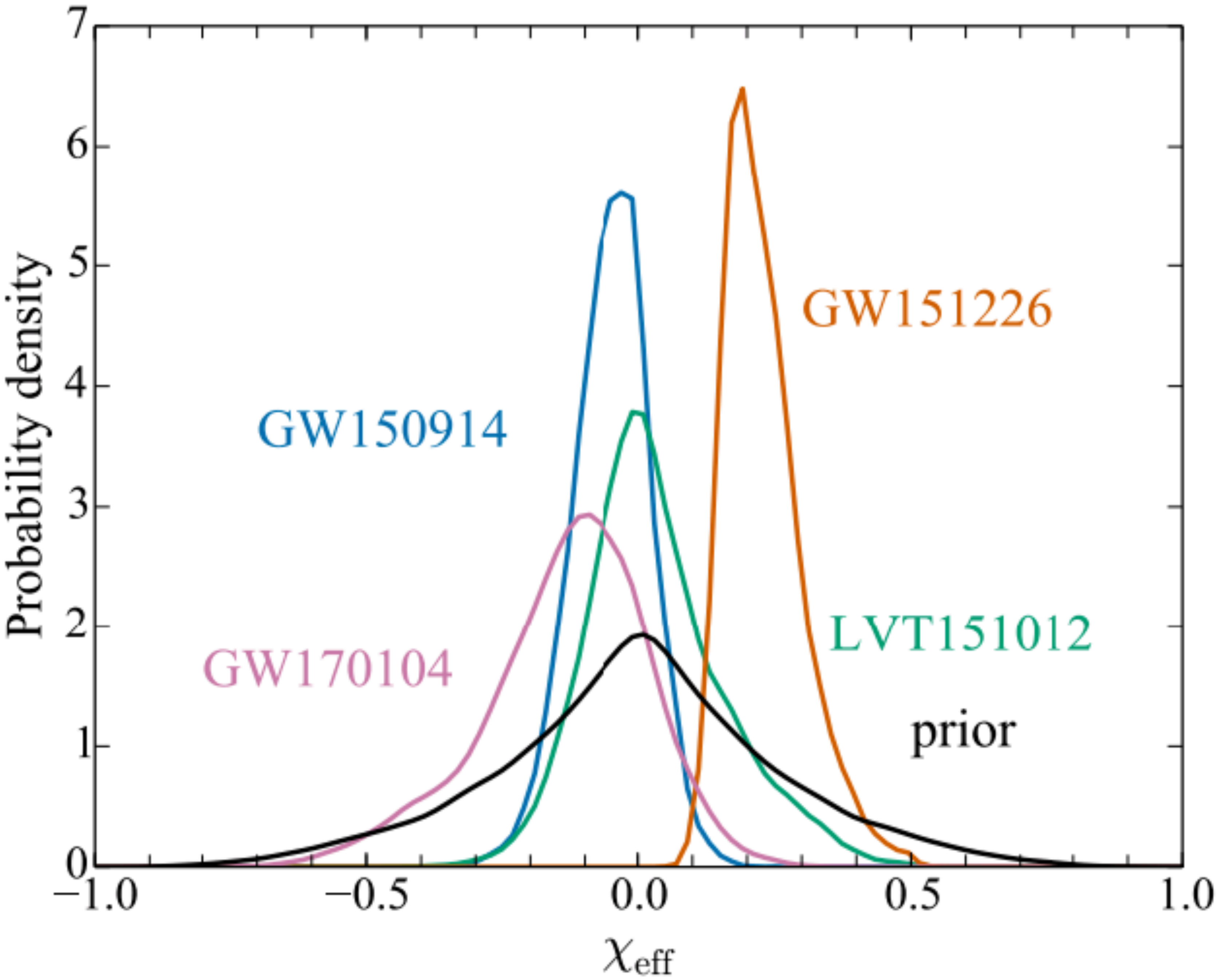
And before you know it…



6 black hole binaries of varying masses

Credit: ButterlyLove1/Christopher Berry

Spinning black holes

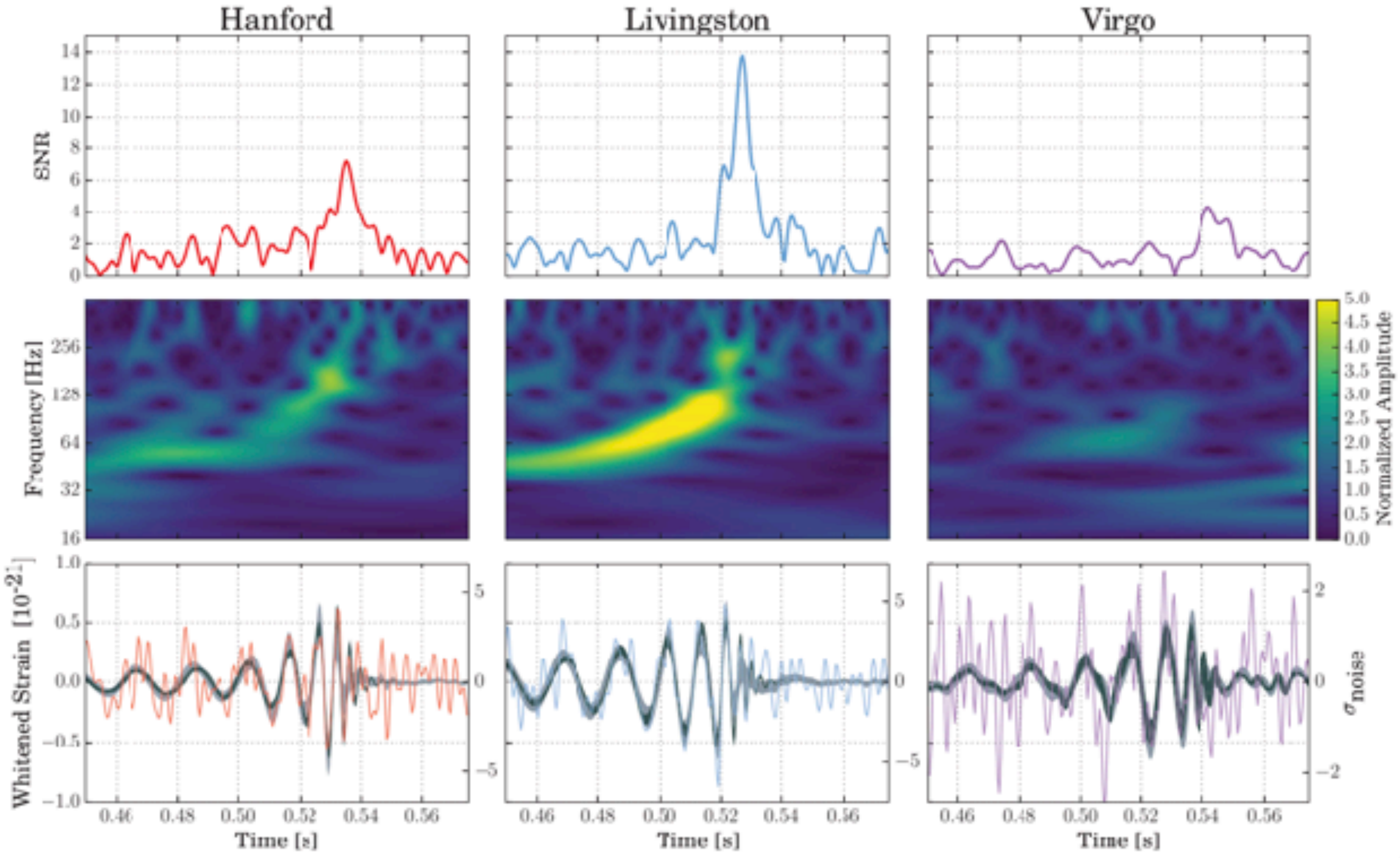


$$\chi_{\rm eff} = \frac{m_1\chi_{1,z} + m_2\chi_{2,z}}{m_1 + m_2}$$

Spin measurements have important consequences for astrophysical formation channels

LVC PRL 118, 221101 (2017)

August 14, 2017



LVC PRL 119, 141101 (2017)

First event seen by 3 detectors

An order of magnitude improvement in sky localization

$$1160\text{deg}^2 \rightarrow 60\text{deg}^2$$

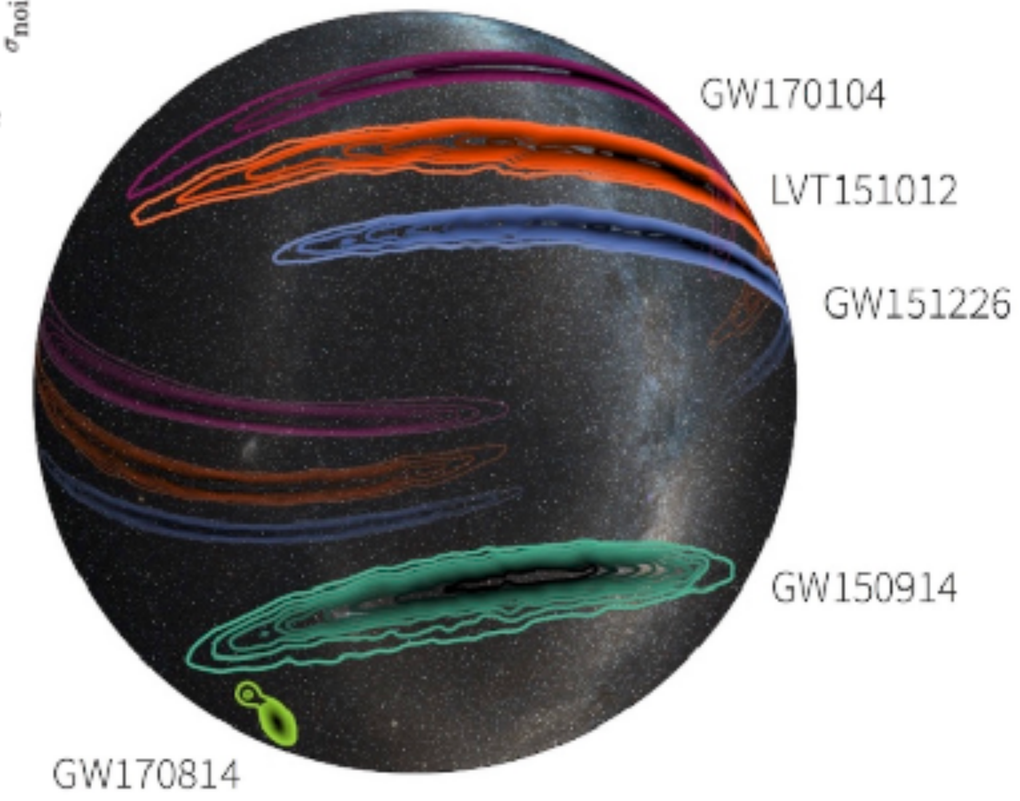
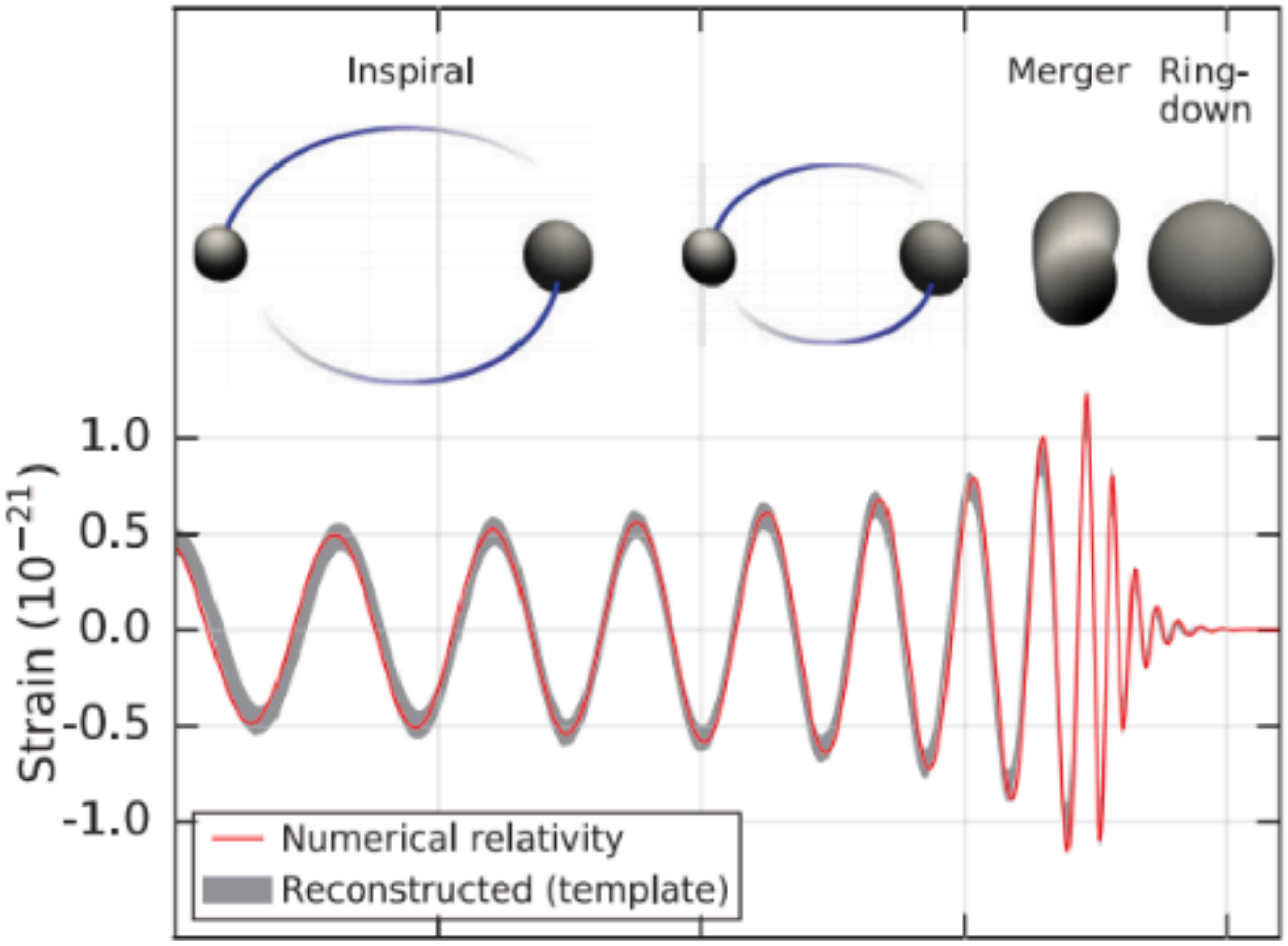


Image credit: LIGO/Virgo/Caltech/MIT/Leo Singer (Milky Way image: Axel Mellinger)

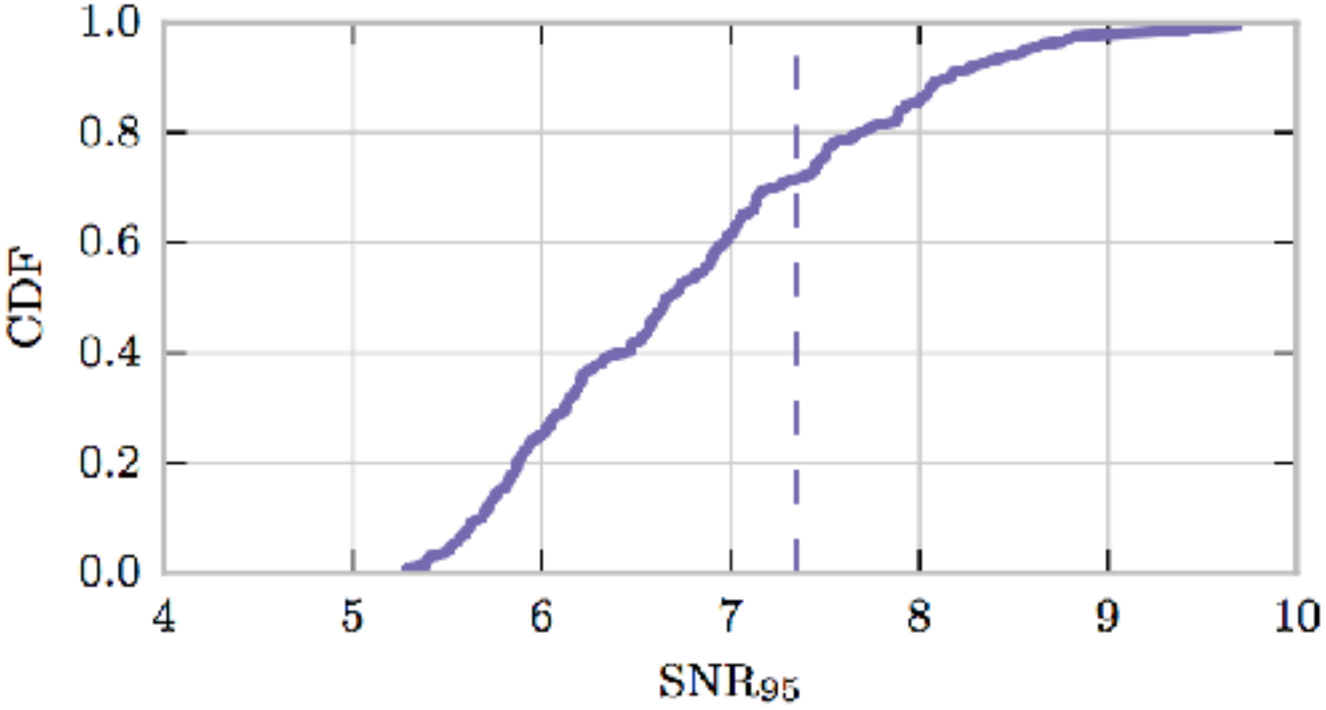
Do the signals agree with General Relativity?

Yes, as far as we can tell



LVC PRL 116, 061102 (2016)

SNR~7, no statistically significant residual power



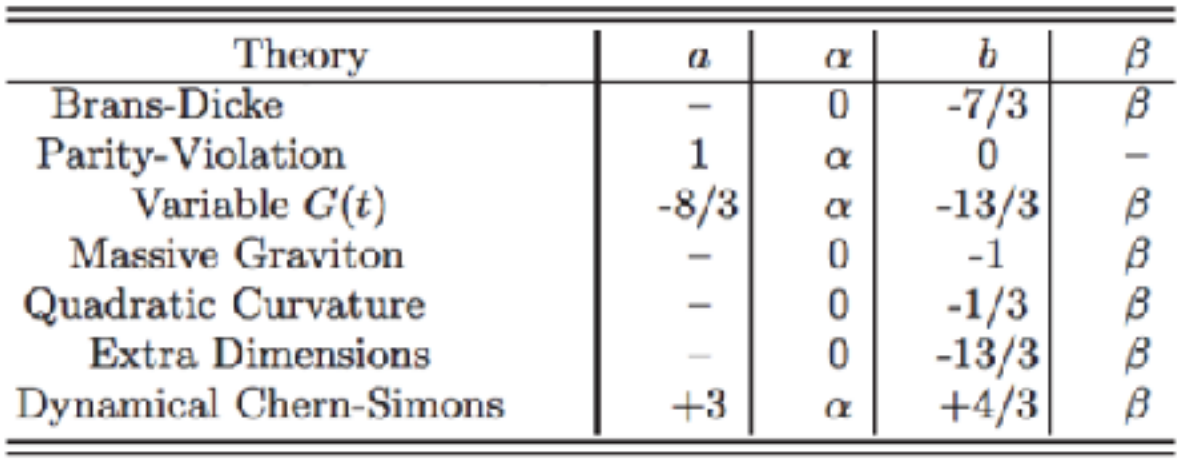
LVC PRL 116, 221101 (2016)

Parametric deviations

$$\tilde{h} \sim \tilde{A}(f;\vec{\theta}_{GR})e^{i\sum_i p_i(\vec{\theta}_{GR})f^i}$$

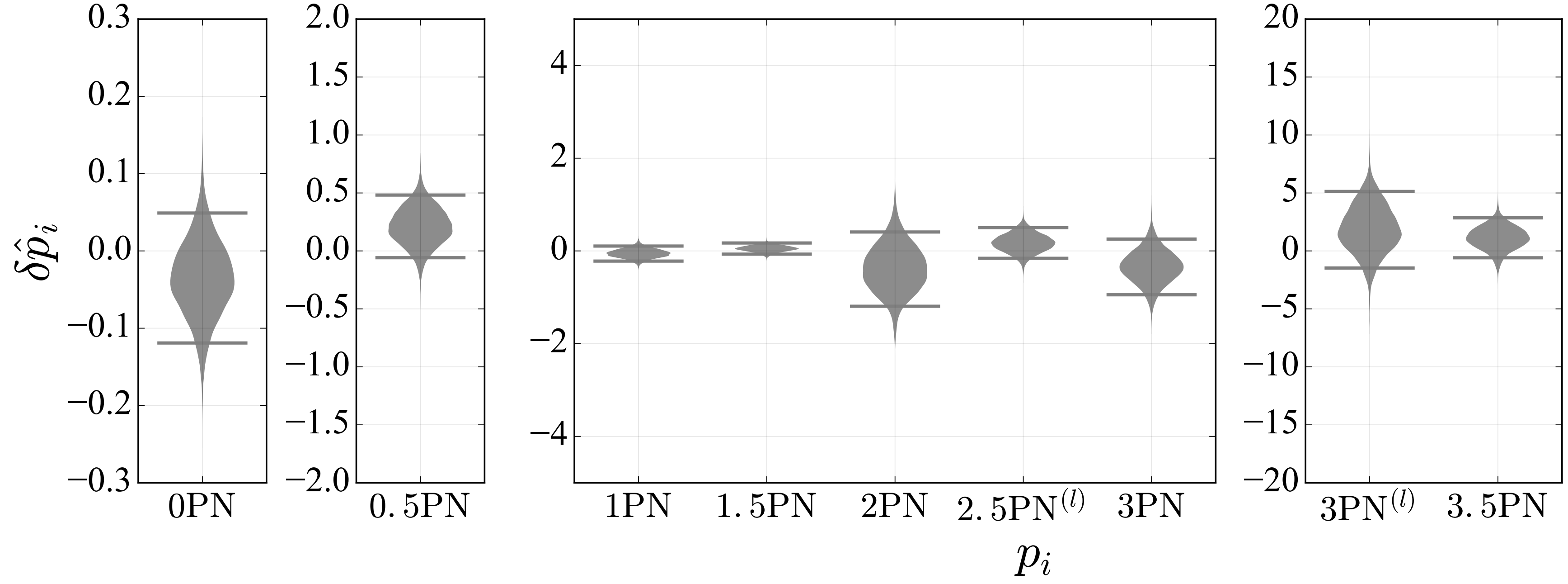
$$p_i \rightarrow p_i(1+\delta p_i)$$

Yunes and Pretorius PRD 80, 122003 (2009)



Theory	a	α	b	β
Brans-Dicke	–	0	-7/3	β
Parity-Violation	1	α	0	–
Variable $G(t)$	-8/3	α	-13/3	β
Massive Graviton	–	0	-1	β
Quadratic Curvature	–	0	-1/3	β
Extra Dimensions	–	0	-13/3	β
Dynamical Chern-Simons	+3	α	+4/3	β

Cornish+ PRD 84, 062003 (2010)

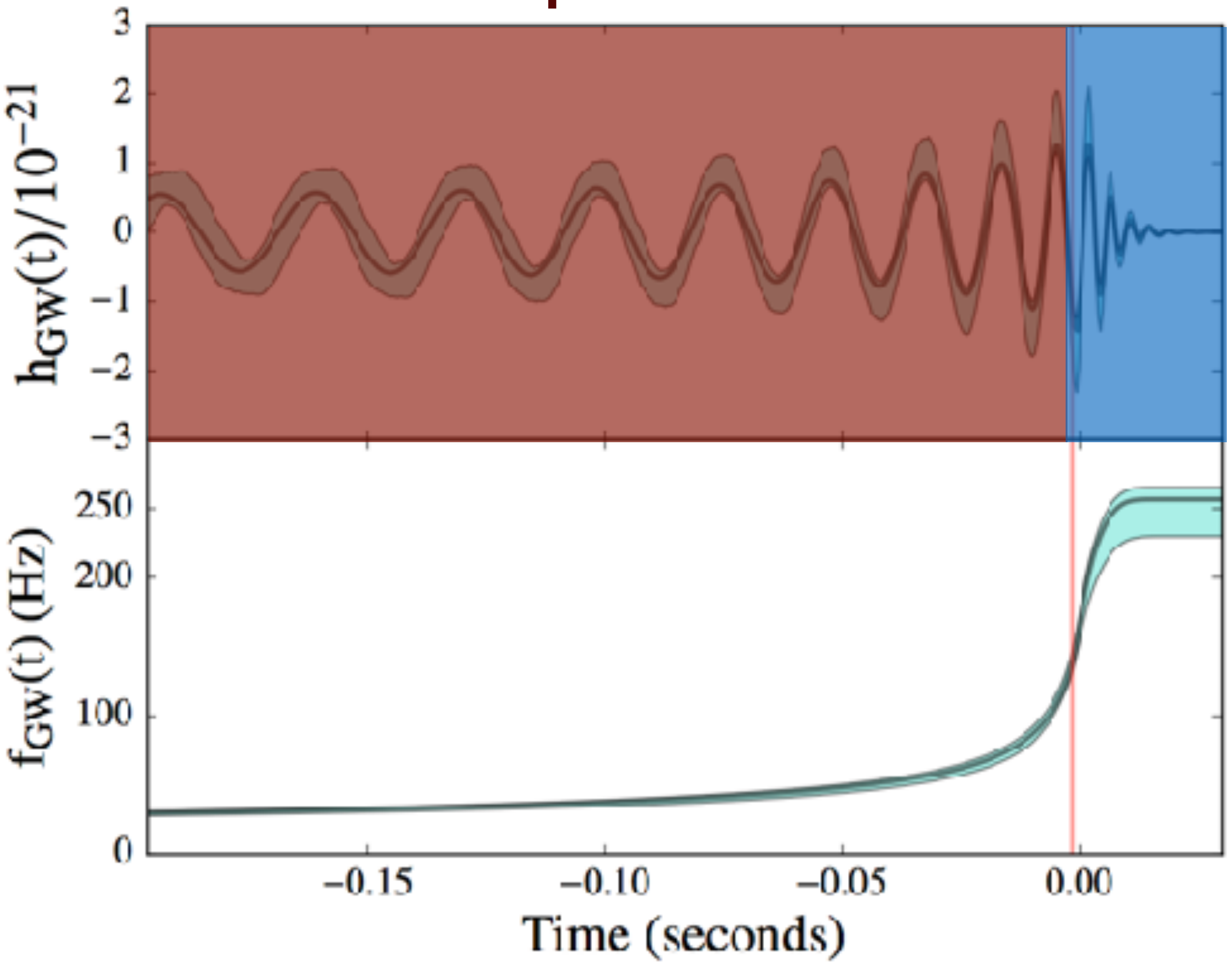


LVC PRL 118, 221101 (2017)

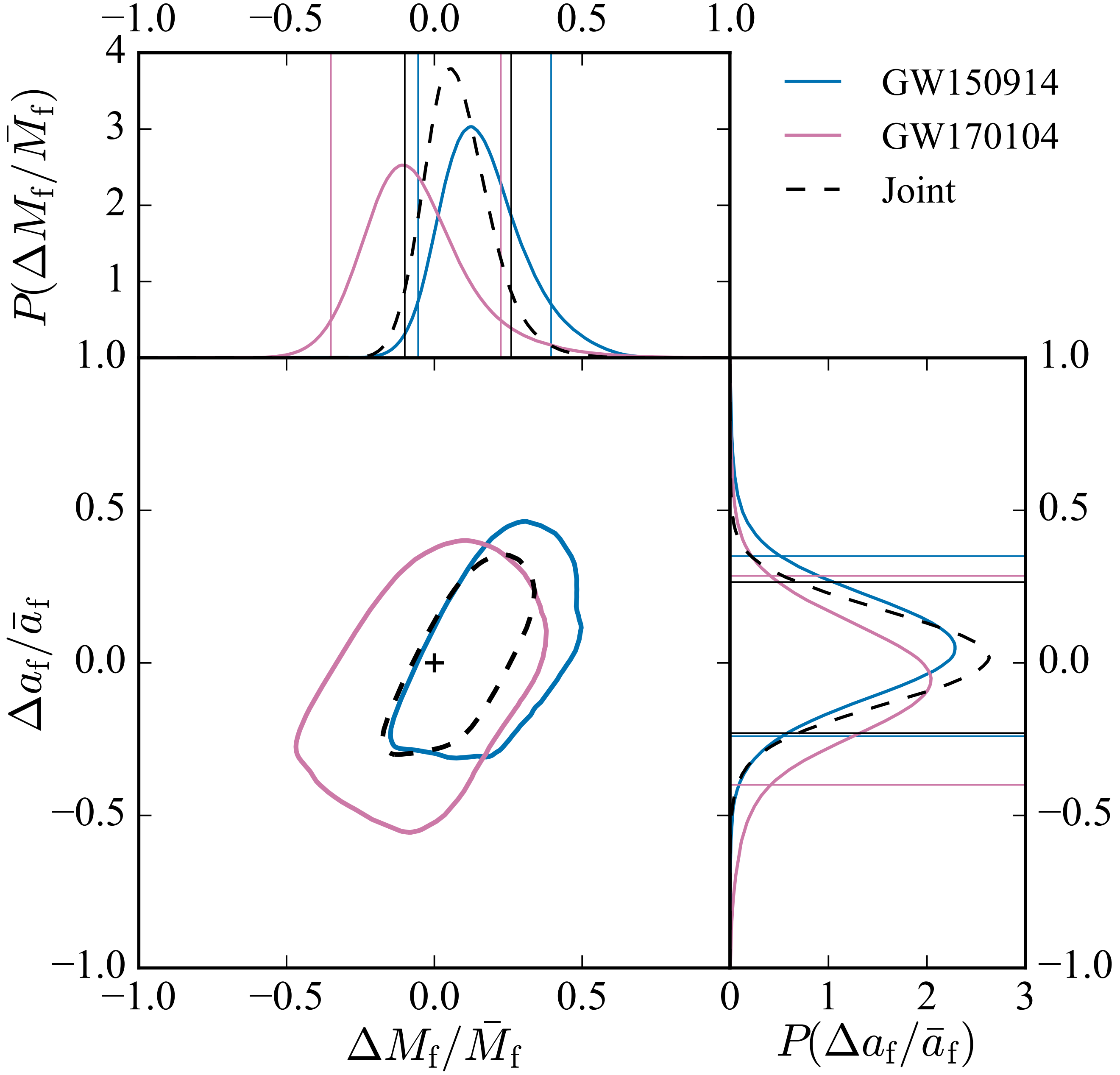
Final object consistency

Initial masses and spins

Final mass and spin



LVC PRL 116, 221101 (2016)



LVC PRL 118, 221101 (2017)

Propagation effects

Modified dispersion arises when Lorentz invariance is violated

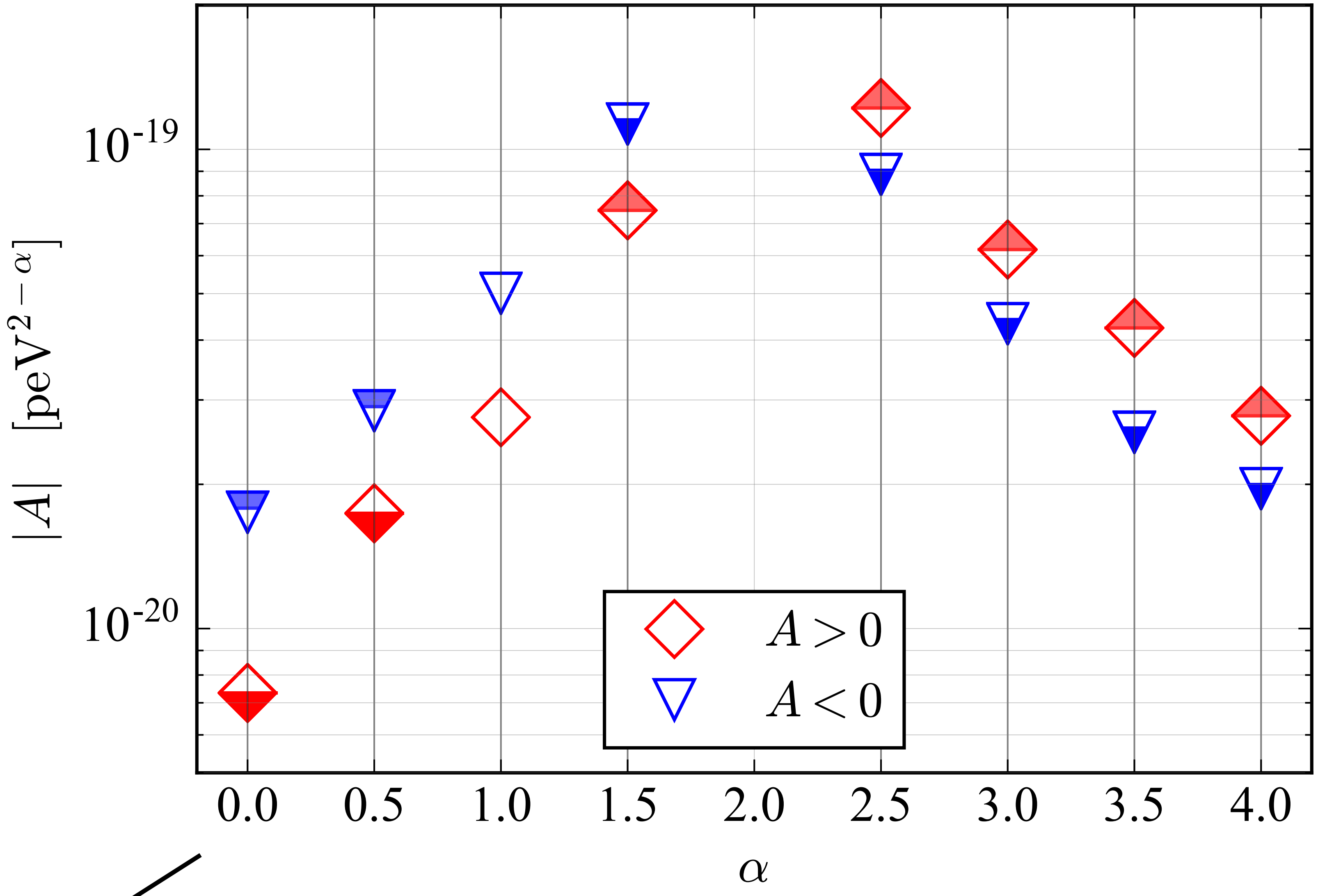
$$E^2 = p^2 c^2 + A p^\alpha c^\alpha$$

$$\delta v_g \sim \frac{\text{GW period}}{\text{travel time}} \sim \frac{\text{GW wavelength}}{\text{distance}}$$

$$\text{For 800Mpc and 250Hz, } \delta v_g \sim 5 \times 10^{-20}$$

Modified dispersion

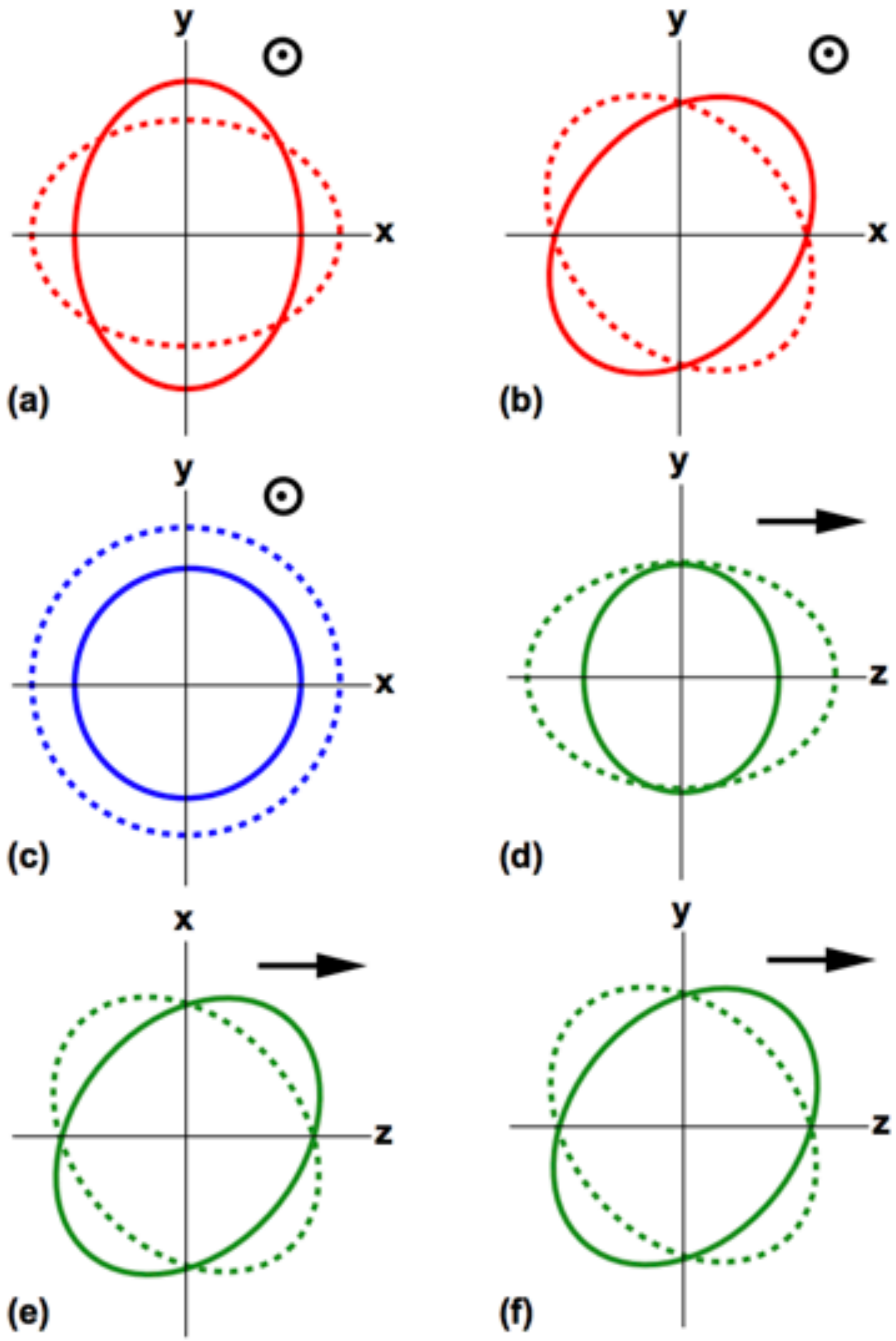
$$\delta v_g \sim A E^{\alpha-2} \Rightarrow A \sim \delta v_g E^{2-\alpha} \sim \delta v_g (h_{\rm Pl} f)^{2-\alpha} \sim 10^{-20} {\rm peV}^{2-\alpha}$$



$$m_g \leq 7.7 \times 10^{-23} {\rm eV/c}^2$$

LVC PRL 118, 221101 (2017)

Gravitational wave polarization

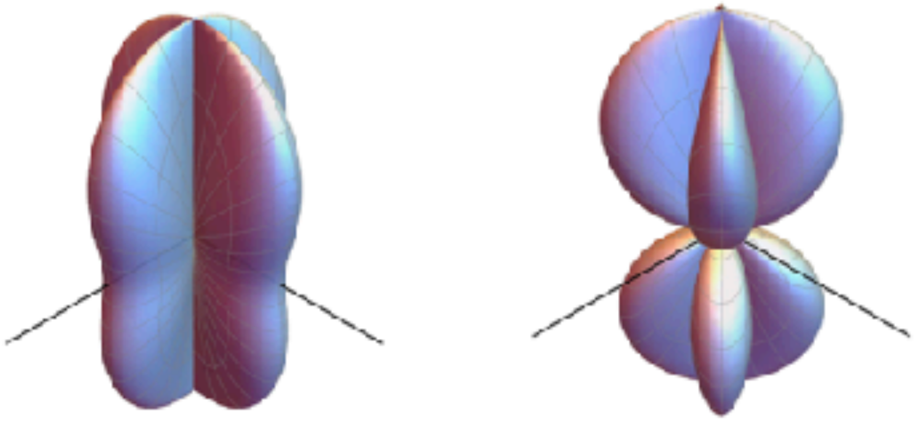


General Relativity possesses only two tensor degrees of freedom

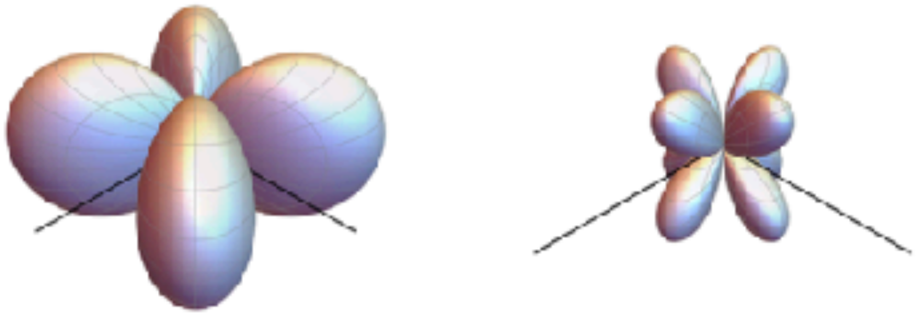
$$[h_{ij}] = \begin{pmatrix} h_{\mathrm{b}} + h_{+} & h_{\times} & h_{\mathrm{x}} \\ h_{\times} & h_{\mathrm{b}} - h_{+} & h_{\mathrm{y}} \\ h_{\mathrm{x}} & h_{\mathrm{y}} & h_{\mathrm{l}} \end{pmatrix}$$

Will LRR 17 (2014), 4

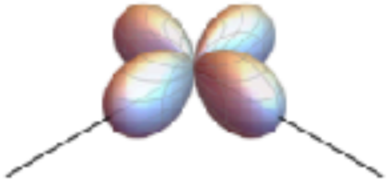
Detector response



(a) Plus (+) (b) Cross (×)



(c) Vector-x (x) (d) Vector-y (y)



(e) Scalar (s)

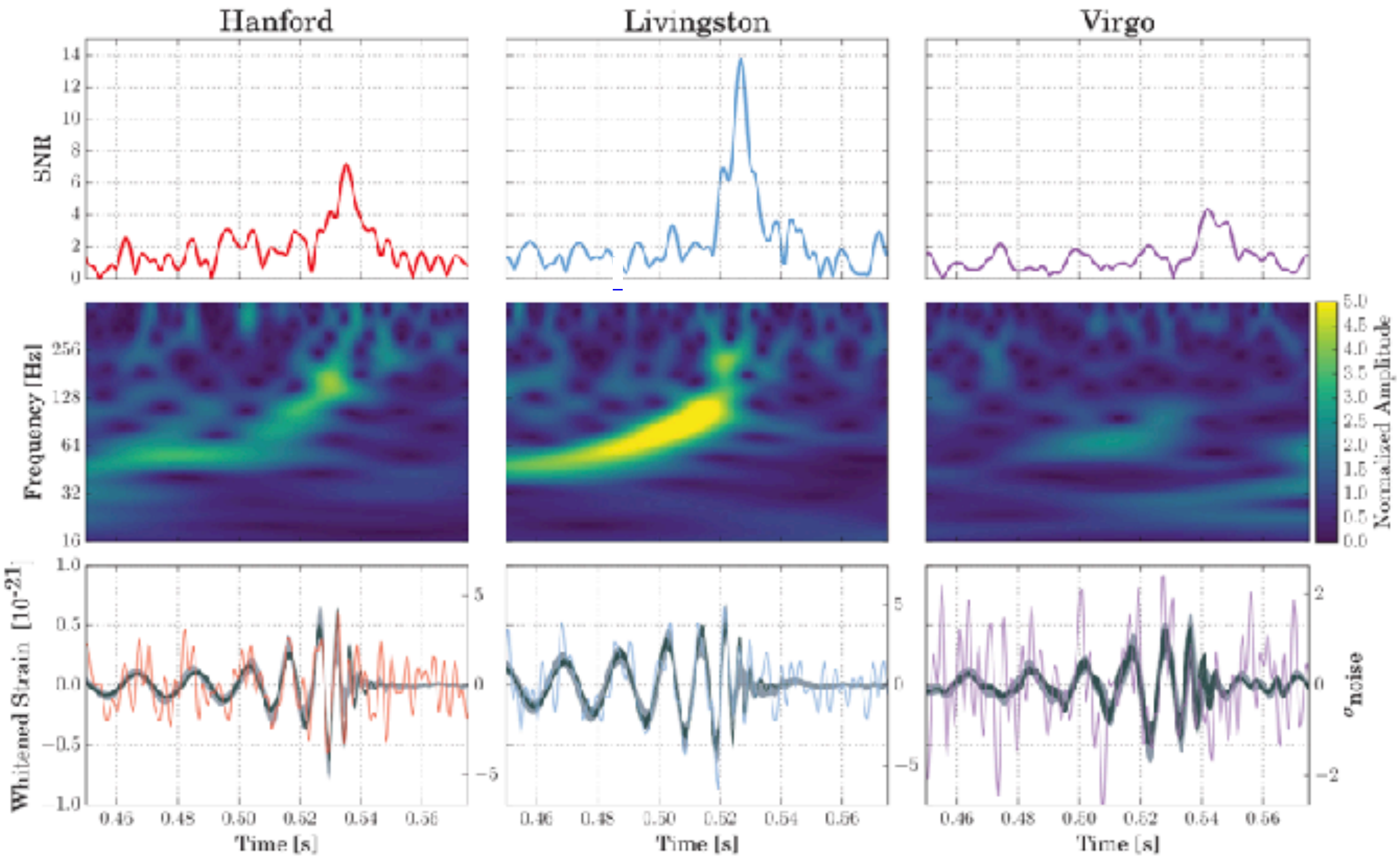
Affects the inferred sky location

Inconclusive when we only have 2 detectors

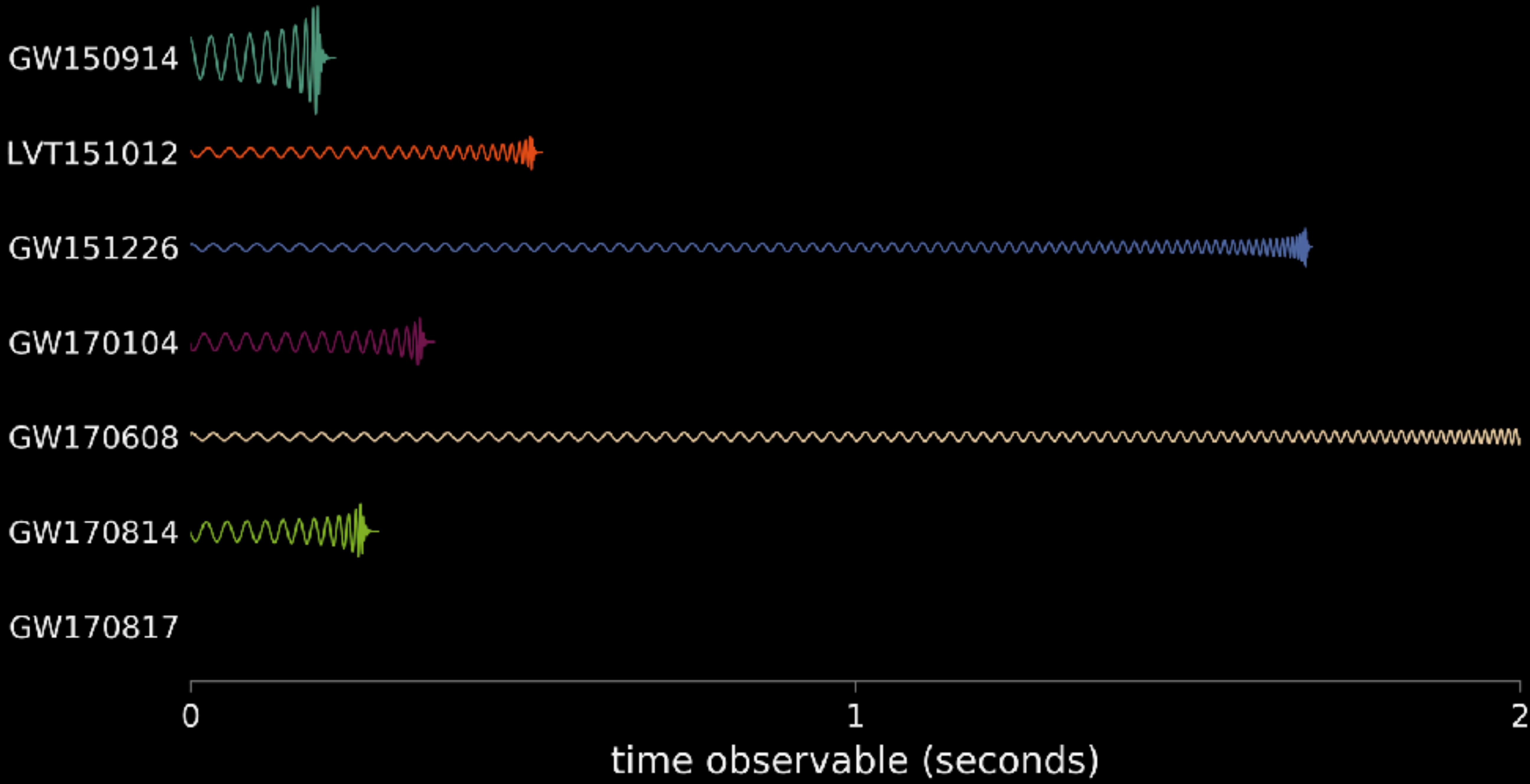
Isi+ PRD 96, 042001 (2017)

Three detectors: GW170814

Tensor modes preferred by more than 1000:1 (scalar) and 200:1 (tensor)

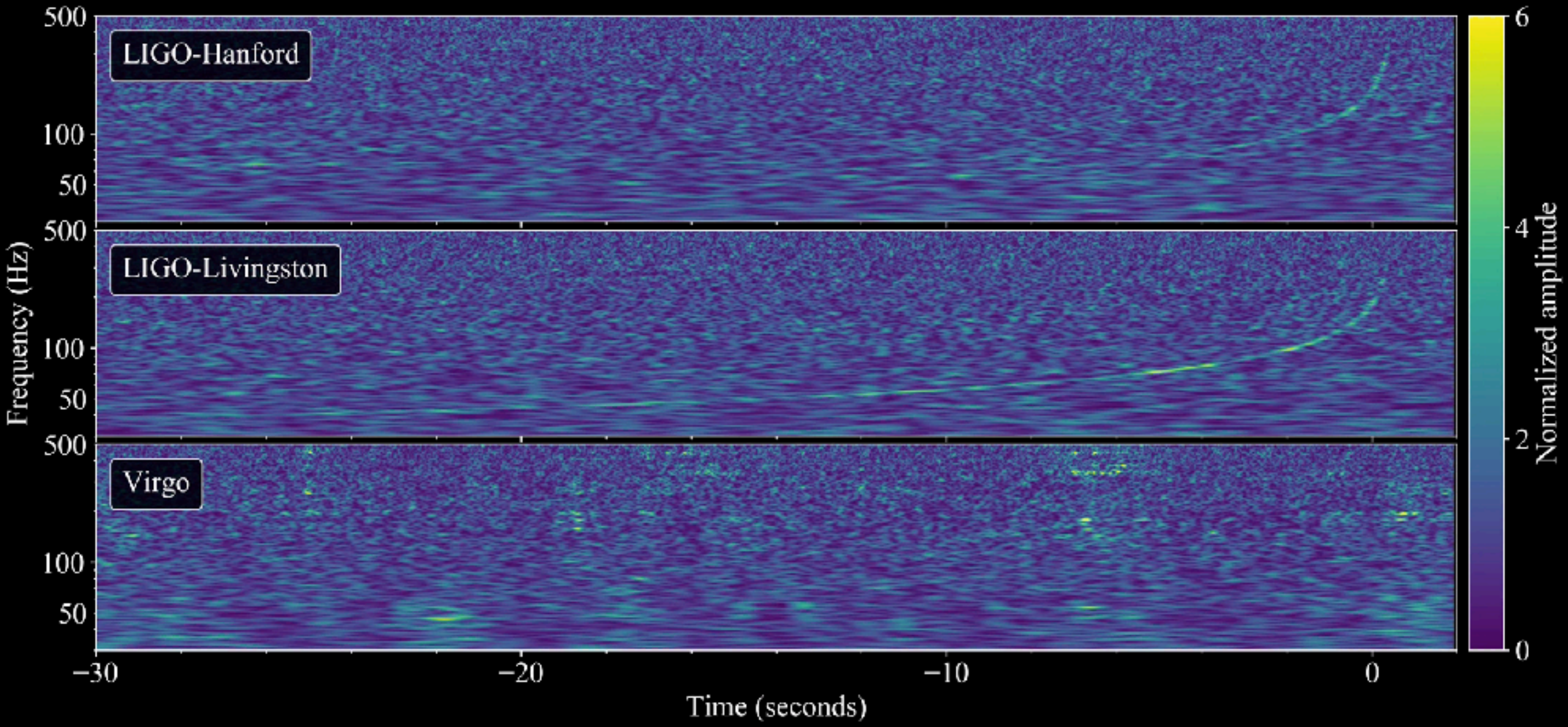


LVC PRL 119, 141101 (2017)
Isi and Weistein (arxiv:1710.03794)



LIGO/University of Oregon/Ben Farr

August 17, 2017

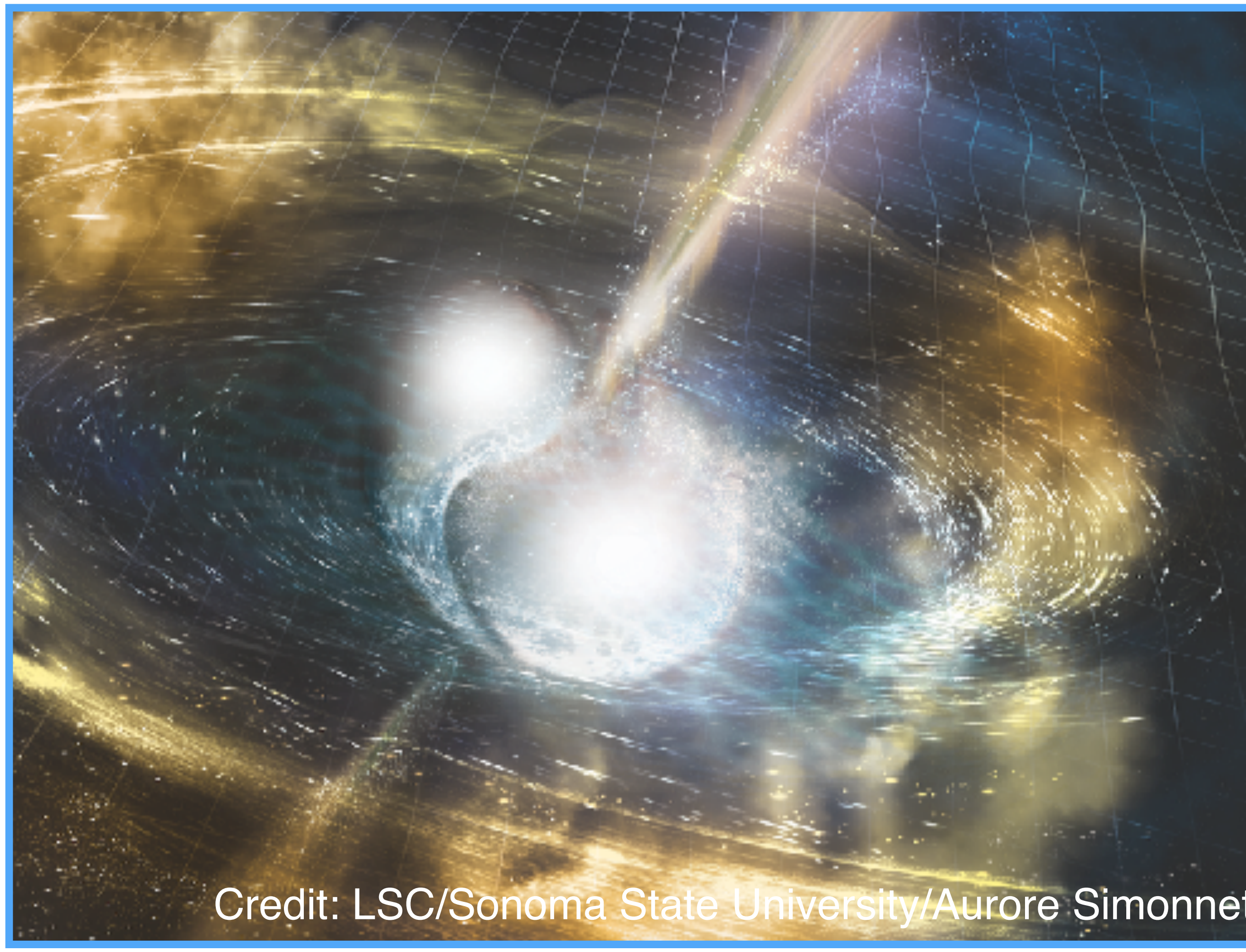


Credit: LIGO/Virgo/Lovelace, Brown, Macleod, McIver, Nitz

GW170817

First detection of a binary neutron star coalescence

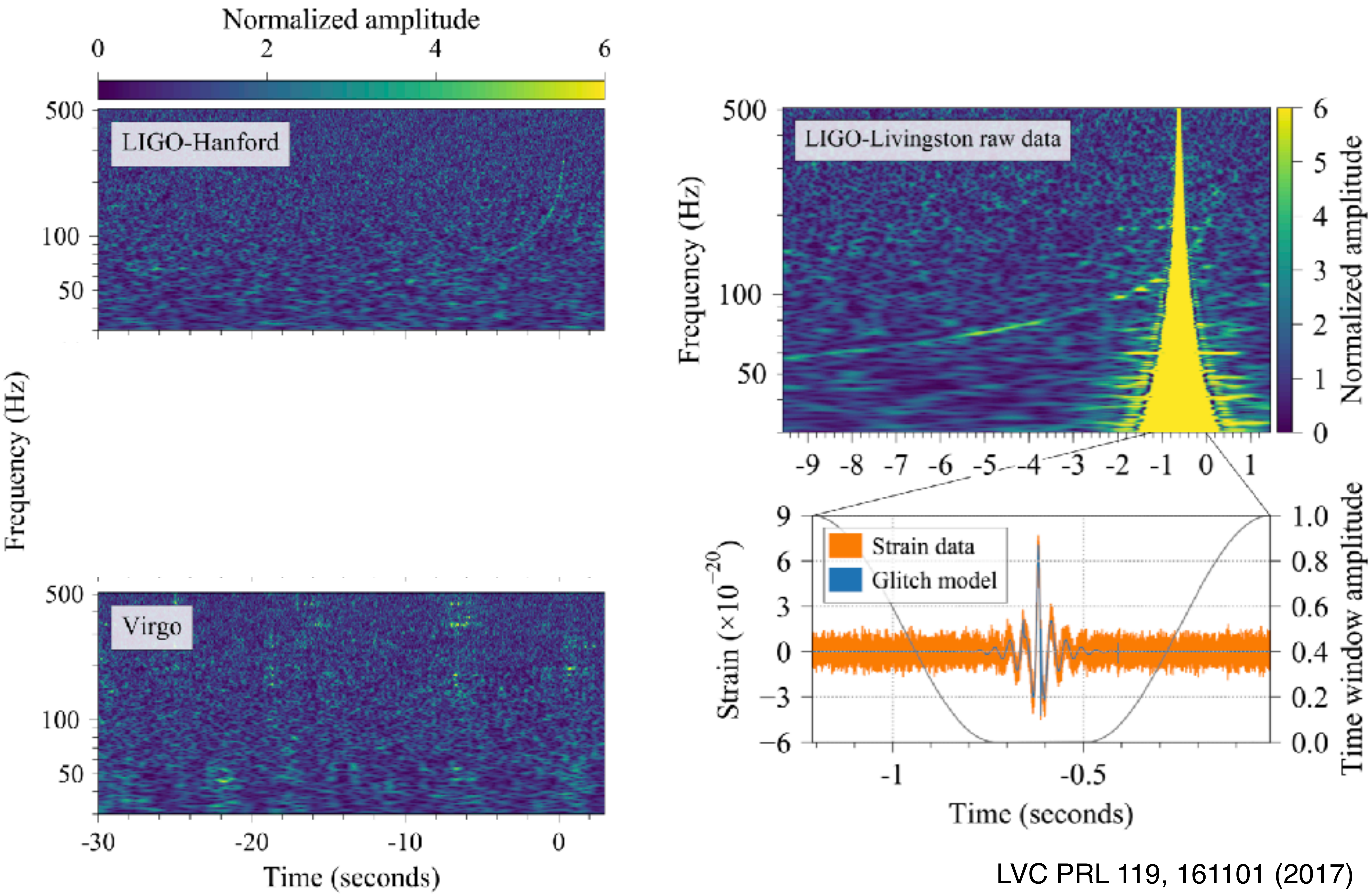
✓Gravitational wave
✓Short gamma ray burst
✓Optical/UV emission
✓X-ray (ongoing)
✓Radio (ongoing)



Credit: LSC/Sonoma State University/Aurore Simonnet

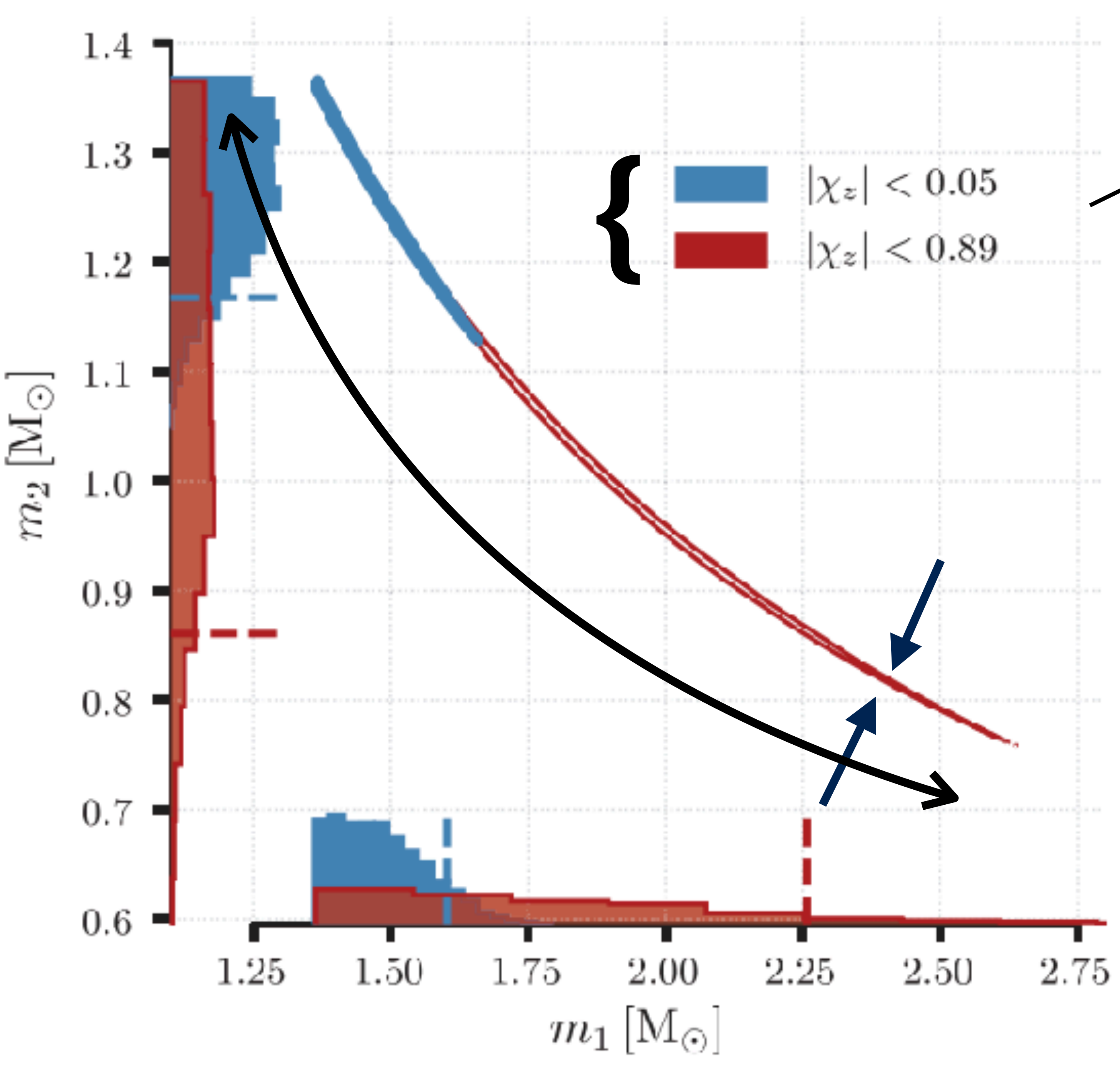
- Properties of supranuclear matter
- Astrophysical origin on sGRBs
- Origin of heavy elements
- Measurement of the Hubble constant
- Constraints on the speed of gravity

Binary neutron star



LVC PRL 119, 161101 (2017)

Masses



$$\chi \sim 0.4 \frac{1\mathrm{ms}}{T}$$

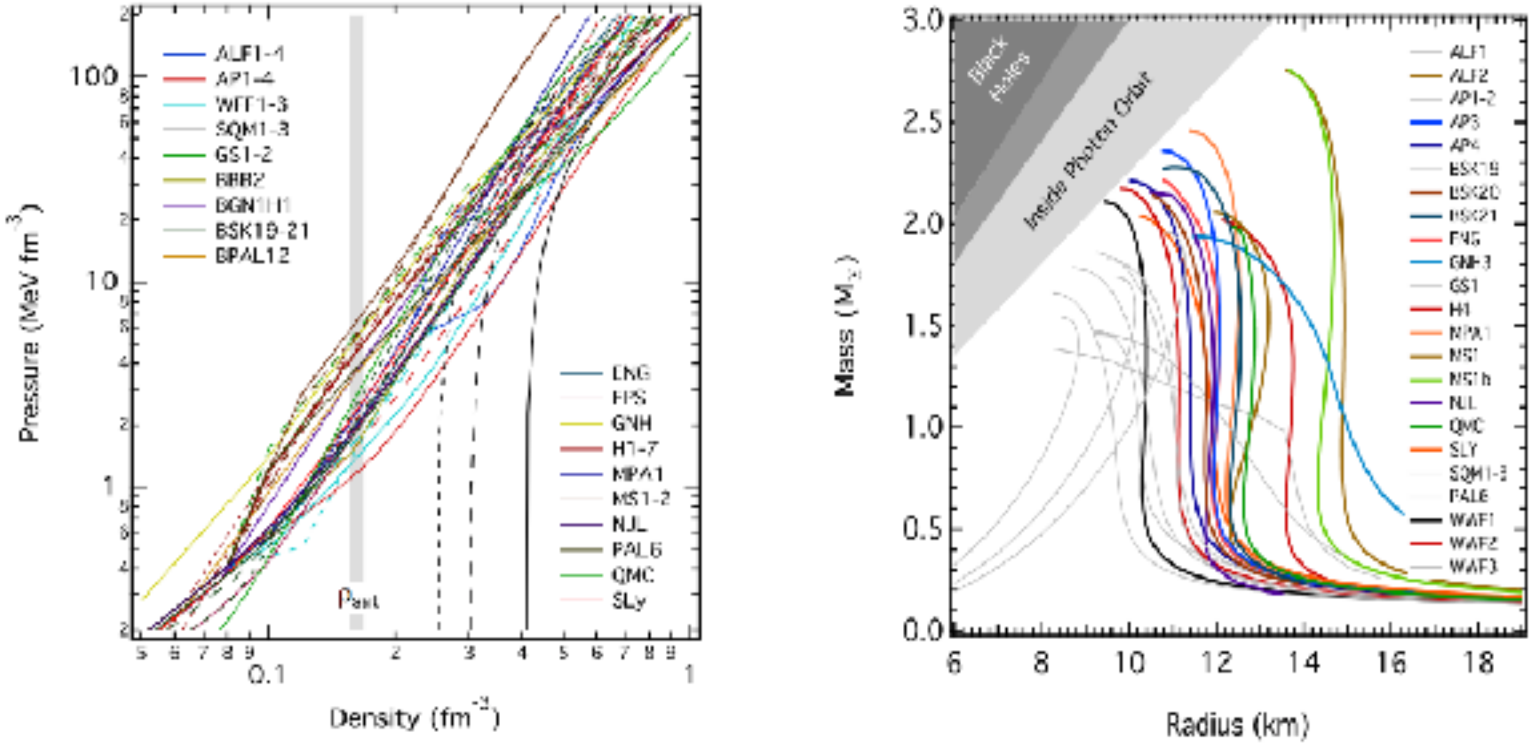
The chirp mass is measured very well

The mass ratio is measured less well

The mass ratio is correlated with the spin

LVC PRL 119, 161101 (2017)

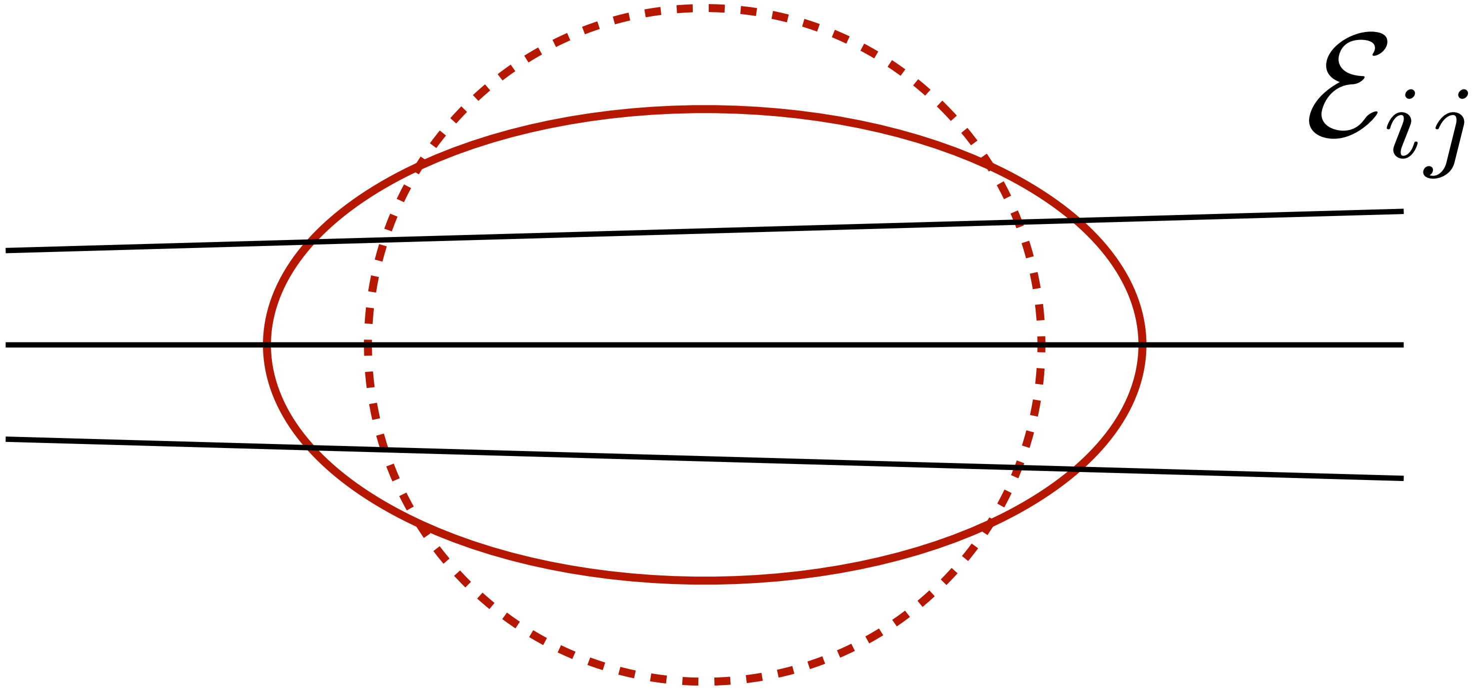
Extreme matter



Neutron stars are extended bodies with structure

Ozel, Freire (AnnuRev. of Astronomy and Astrophysics 54,401-440)

$$Q_{ij} = -\Lambda \mathcal{E}_{ij}$$

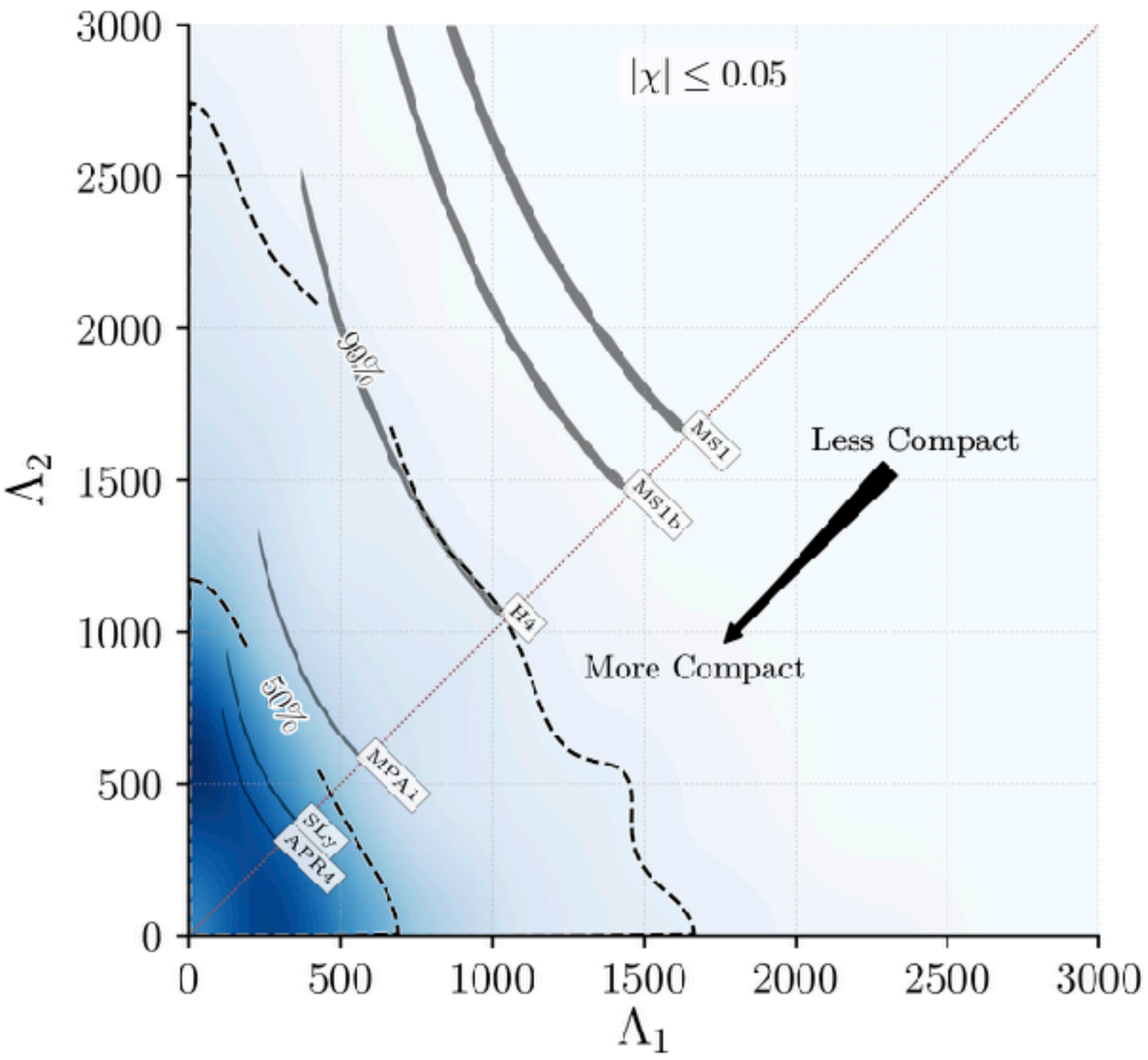


Credit: Aaron Zimmerman

Deformability

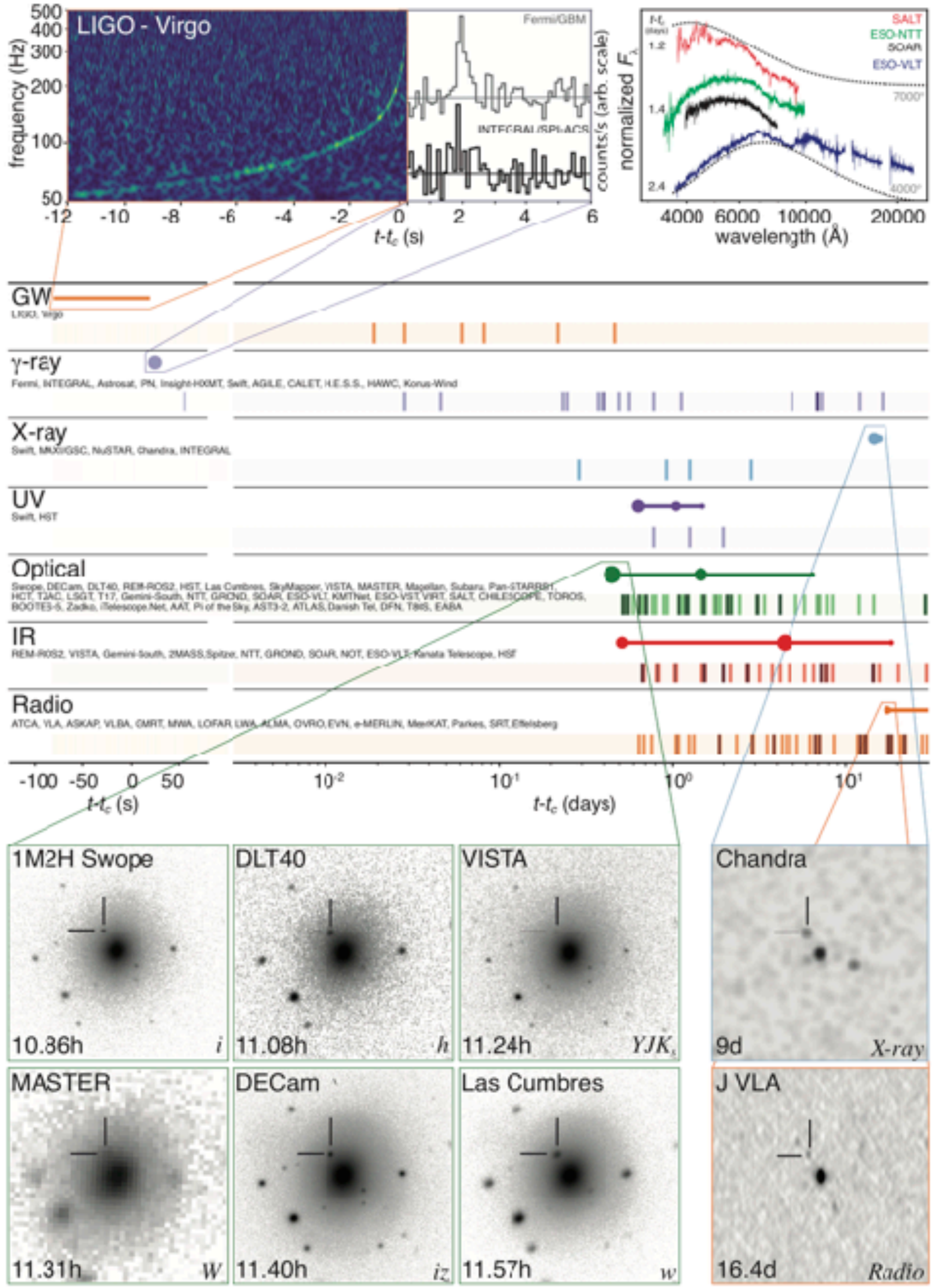
The tidal deformation accelerates the inspiral (additional energy sinks)

Radius upper limit
R<14km



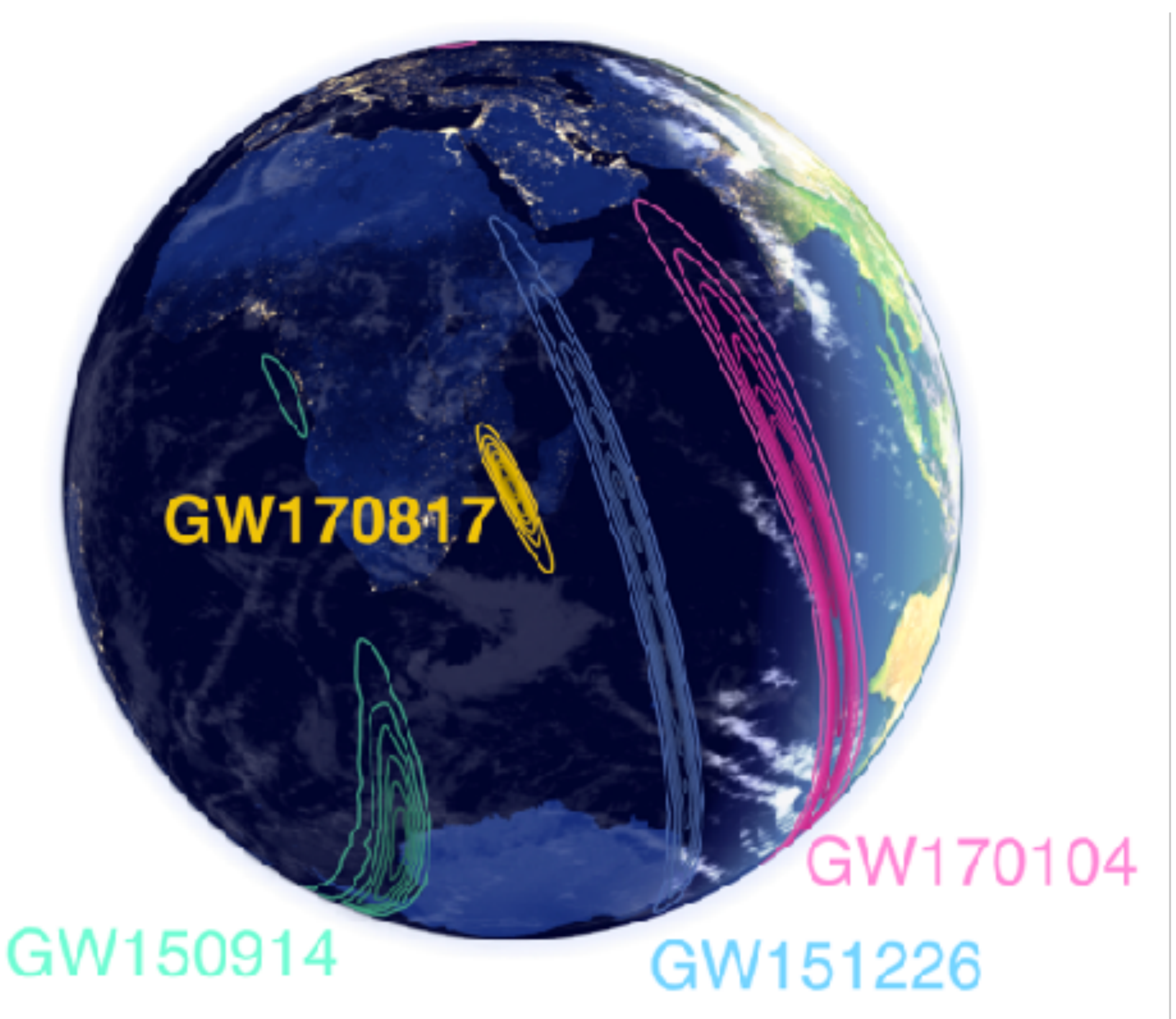
LVC PRL 119, 161101 (2017)

Extensive followup



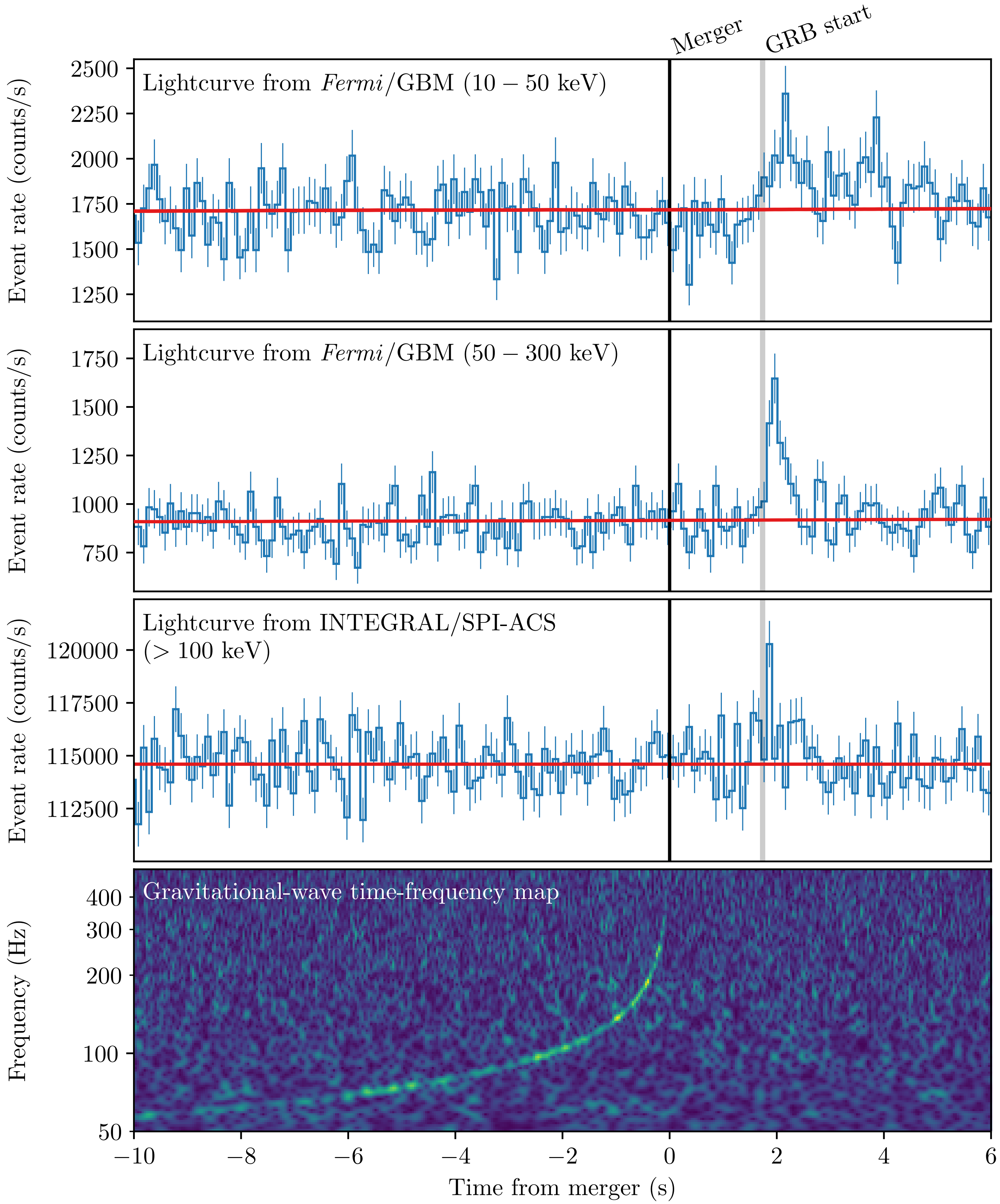
LVC & EM partners, ApJL 848, 12 (2017)

GW localization enabled EM followup



Credit: LIGO/VIRGO/NASA/Leo Singer

Short gamma ray burst



LVC & Fermi GBM & INTEGRAL, ApJL 848, 13 (2017)

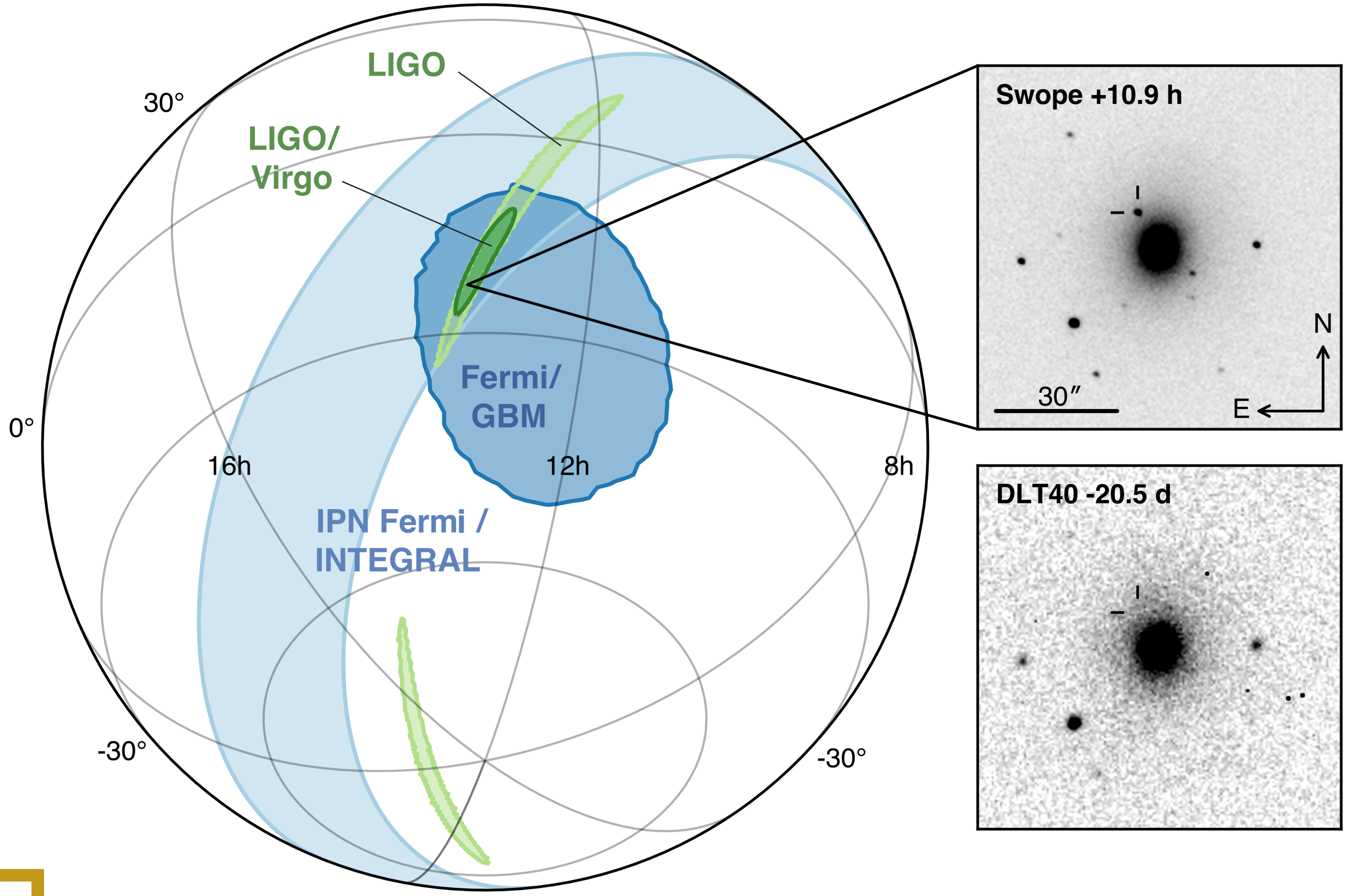
BNS coalescences are the progenitors of sGRBs

Bound on the speed of gravity

$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\mathrm{EM}}} \leqslant +7 \times 10^{-16}$$

Optical emission

kilonova: radioactive decay of r-process elements

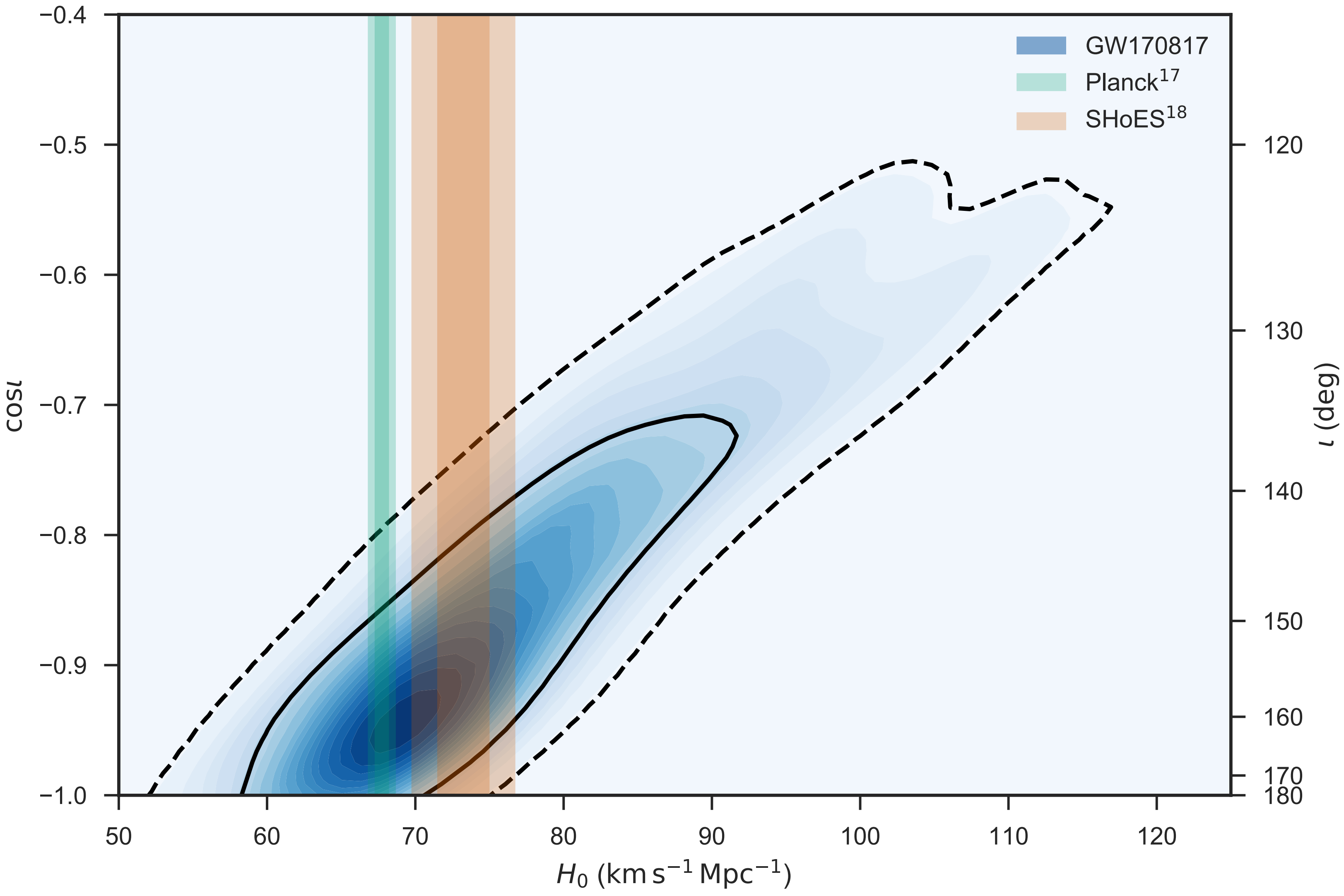


BNS coalescences are a heavy-element production site

LVC & EM partners, ApJL 848, 12 (2017)

Cosmology

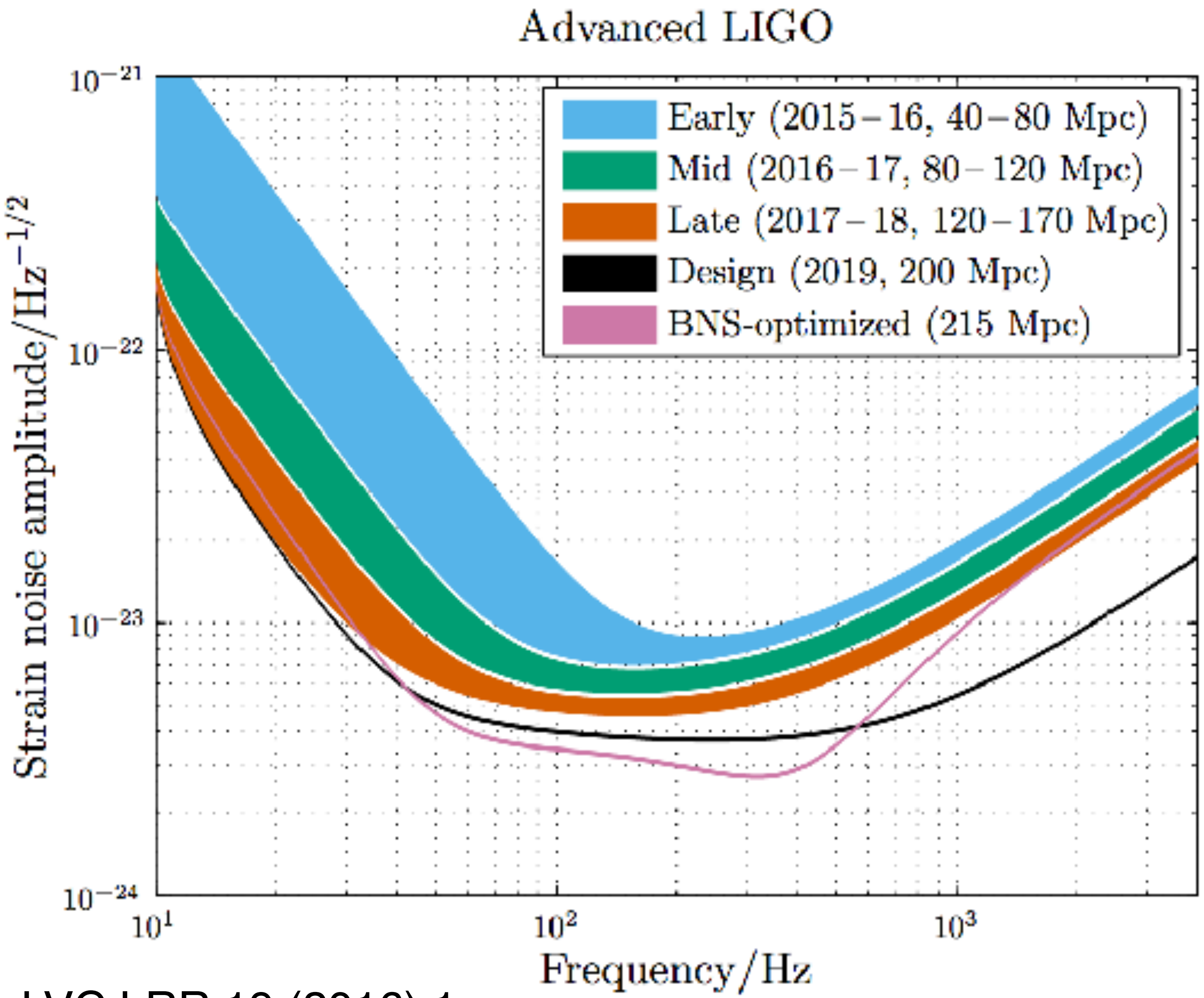
Combining information from GW and EM



Consistent with existing measurements

LVC & EM partners, Nature (2017)

Looking ahead

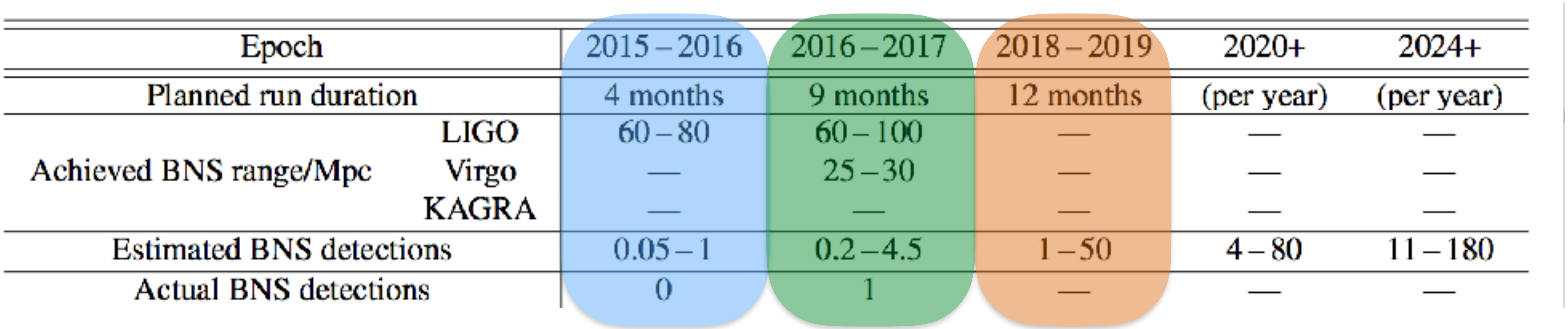


LVC LRR 19 (2016) 1

At design sensitivity

BNS: 0.4-400/year
NSBH: 0.2-300/year
BBH: 0.4-1000/year

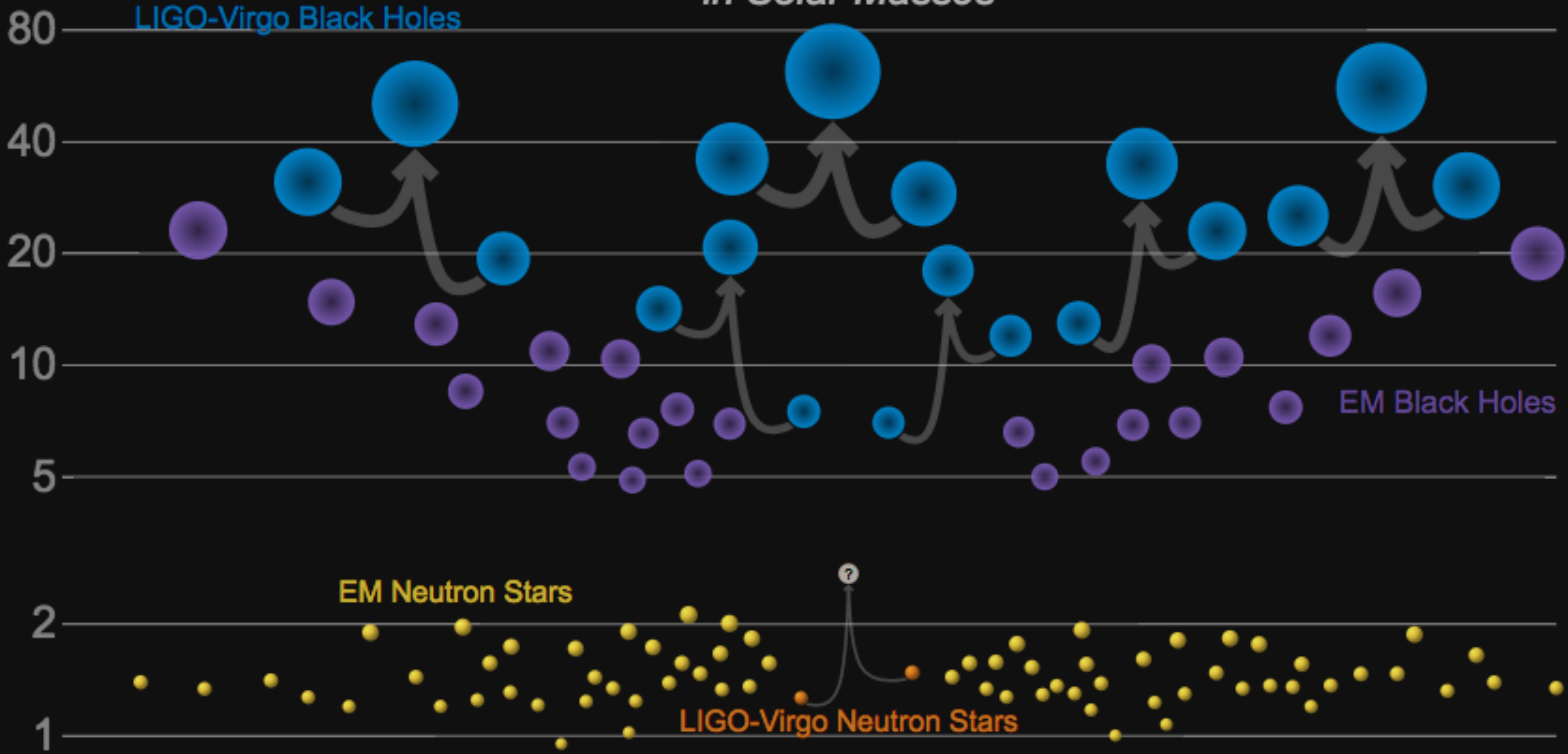
LVC ApJL 832, 2 (2016)
LVC CQG 27, 173001 (2010)



Epoch		2015 – 2016	2016 – 2017	2018 – 2019	2020+	2024+
Planned run duration		4 months	9 months	12 months	(per year)	(per year)
Achieved BNS range/Mpc	LIGO	60 – 80	60 – 100	—	—	—
	Virgo	—	25 – 30	—	—	—
	KAGRA	—	—	—	—	—
Estimated BNS detections		0.05 – 1	0.2 – 4.5	1 – 50	4 – 80	11 – 180
Actual BNS detections		0	1	—	—	—

Masses in the Stellar Graveyard

in Solar Masses



LIGO-Virgo | Frank Elavsky | Northwestern