Gravitational Wave Transient Sources
What we learn from them

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For the LIGO Scientific Collaboration
and the Virgo Collaboration

CRIS 2018 – June 20, 2018

Ground-based GW detectors

- 1st generation interferometric detectors
  - Initial LIGO, Virgo, GEO600

Unlikely detection

Science data taking
First rate upper limits
Set up network observation

- Enhanced LIGO, Virgo+

Improved sensitivity

Laid ground for multi-messenger astronomy

- 2nd generation detectors
  - Advanced LIGO, Advanced Virgo, GEO-HF, KAGRA

VOUS ÊTES ICI

First detections

Toward routine GW observation
Multi-messenger astronomy

2.5 G

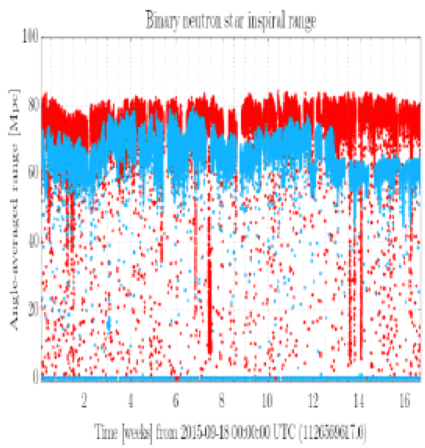
A+
AdV+
Voyager

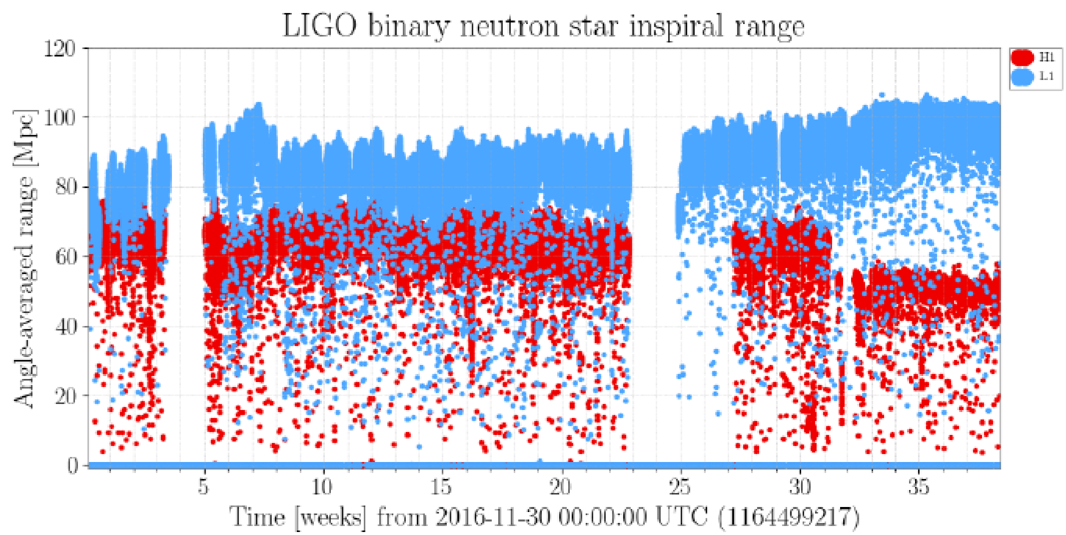
- 3rd generation detectors
  - Einstein Telescope, Cosmic Explorer

Thorough observation of Universe with GW

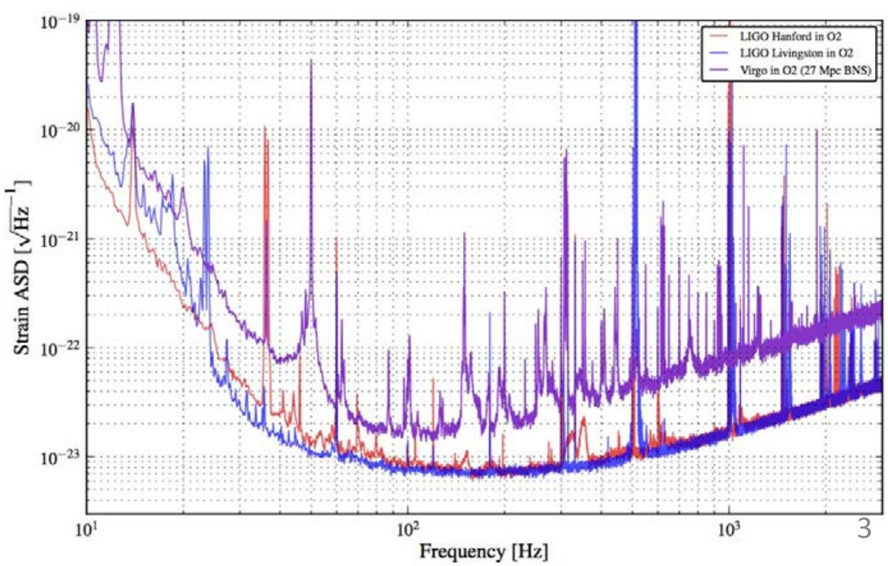
O1 & O2 Observing Runs

LIGO 2010 ★



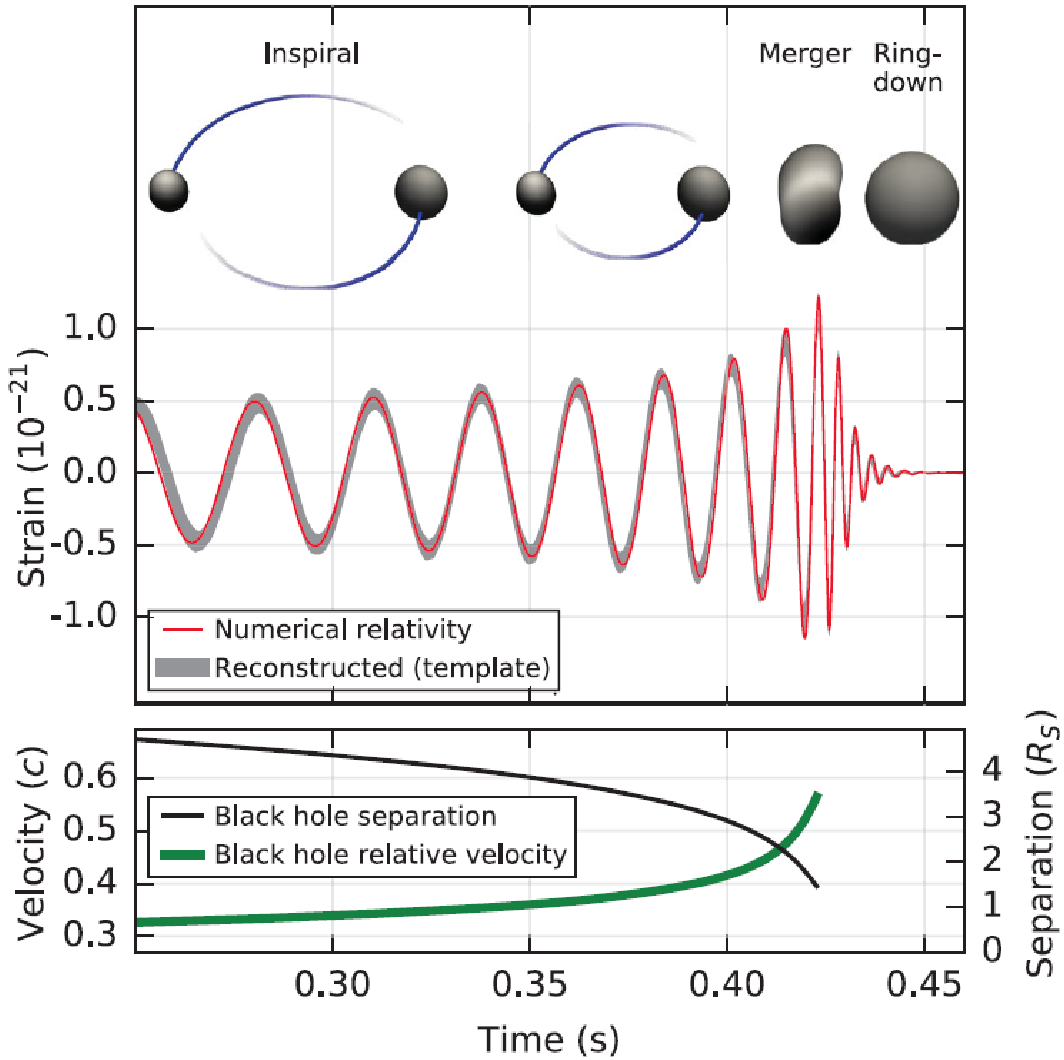


- Binary neutron star range
  - Average horizon distance
  - Horizon ~ 2.26 x range
- O1: 16 weeks
- O2: 37 weeks
- Virgo joined for last month of O2

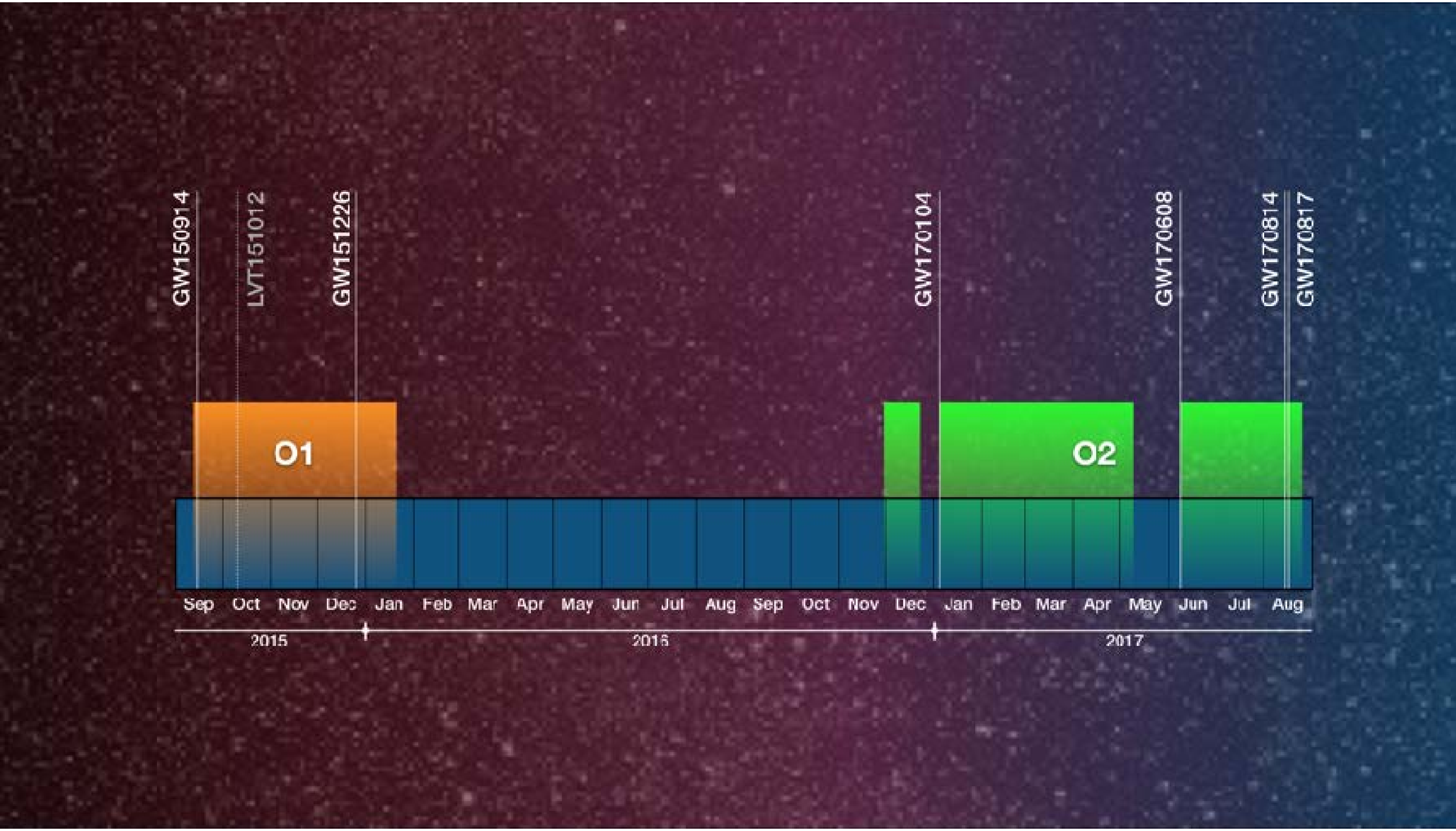


Compact Binary Coalescences

- BH + BH, NS + NS, NS + BH systems
- Waveform models from analytical and numerical relativity
- Event dynamics probes strong field gravity
- Standard candles
- Rare events
  - Rates now measured
  - R_{BBH} = 12 - 213 Gpc^{-3} yr^{-1}
  - R_{BNS} = 320 - 4740 Gpc^{-3} yr^{-1}



Detections in O1 & O2 runs so far



O2 BBH so far

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

THE ASTROPHYSICAL JOURNAL LETTERS, 851:L35 (11pp), 2017 December 20 https://doi.org/10.3847/2041-8213/aa9f0c

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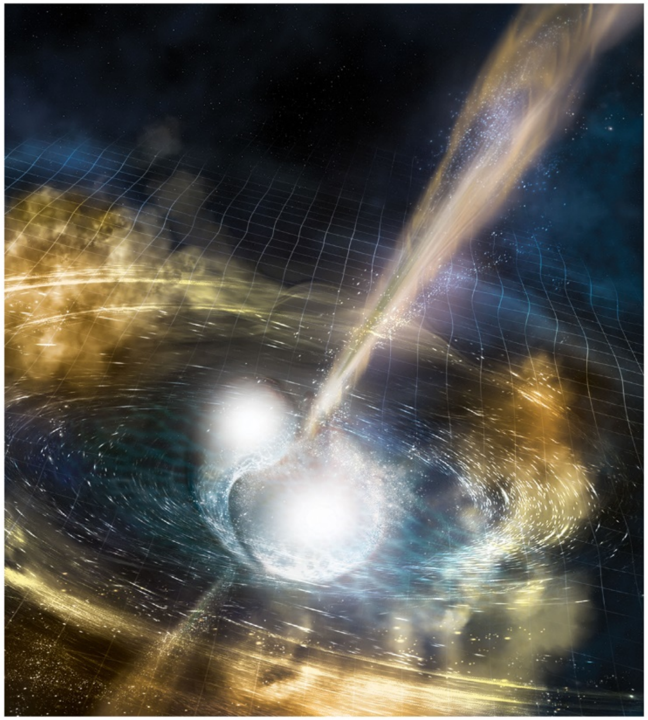
GW170608: Observation of a 19 Solar-mass Binary Black Hole Coalescence

PRL 119, 141101 (2017) PHYSICAL REVIEW LETTERS week ending 6 OCTOBER 2017

GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence

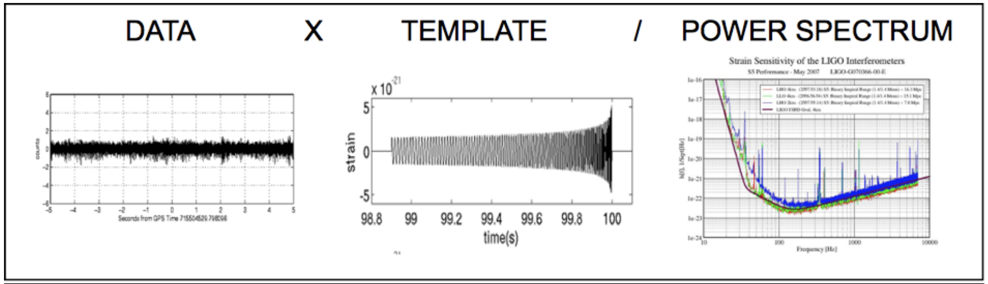
GW170817

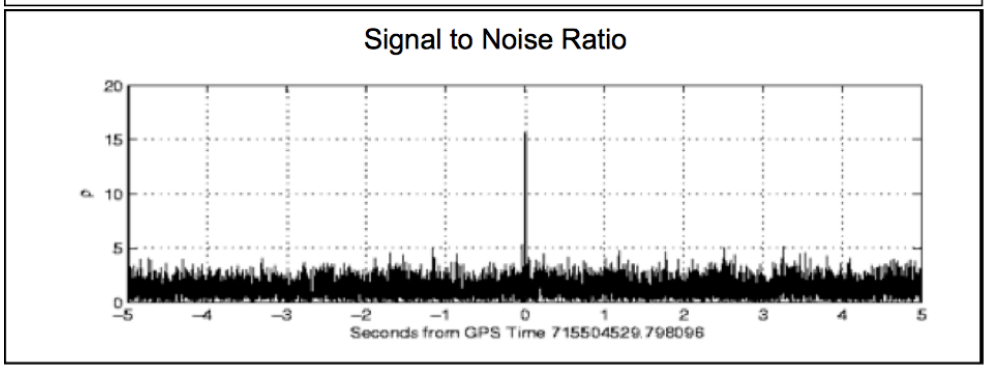
- Brightest GW signal so far
  - SNR = 32
- Closest source so far
  - Luminosity distance 40^{+8}_{-14} Mpc
- Measured masses consistent with known neutron star masses
- Localized (low latency) within 31 deg^2
- Multiple EM counterparts
  - Gamma, X-ray, optical, radio
- Confirmation of the link between BNS mergers and short GRBs
- Event associated with galaxy NGC 4993 and kilonova AT2017gfo



PRL 119, 161101 (2017)

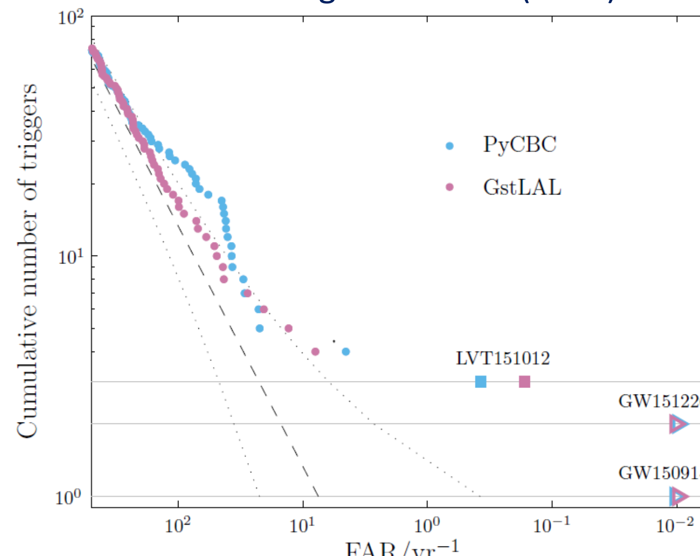
Detecting CBC signals





- ❑ Rely on accurate waveform model to perform matched filtering
- ❑ Scan space of intrinsic parameters driving system dynamics – masses, spins

Living Rev Relativ (2018) 21:3

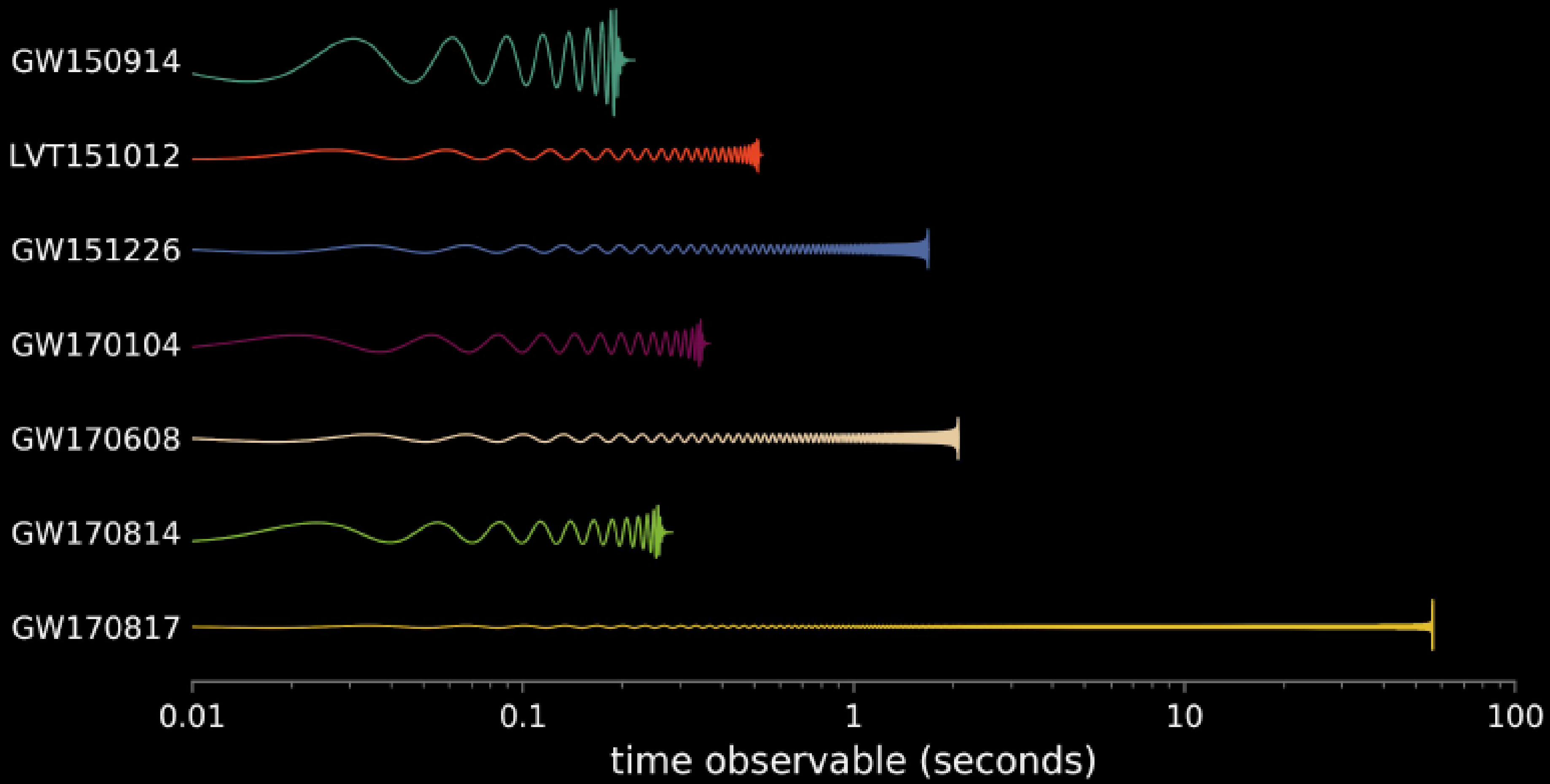


- ❑ Get background under control
  - ➢ Detector noise not Gaussian/stationary
  - ➢ Measure background from data
  - ➢ Require multi-detector coincidence
  - ➢ Monitor detector behavior/environment and veto transient disturbances
  - ➢ Check consistency with signal
- ❑ Estimate significance from false alarm rate

Characterizing CBC sources

- Intrinsic parameters (8 – 10)
  - Masses (2) + Spins (6) $\pm$ Tidal deformability (2)
- Extrinsic parameters (9)
  - Location : luminosity distance, right ascension, declination (3)
  - Orientation: inclination, polarization (2)
  - Time and phase of coalescence (2)
  - Eccentricity (2)
- Parameter estimation based on coherent analysis across detector network
  - Bayesian framework: Computes likelihood of data given parameters, based on match between data and predicted waveform
  - Explores full multidimensional parameter space with fine stochastic sampling
- Infrastructure also allows to do model selection
  - Constrain possible deviations from General Relativity in signal

Signal Diversity



LIGO/University of Oregon/Ben Farr

Do we understand the progenitors?

Source population

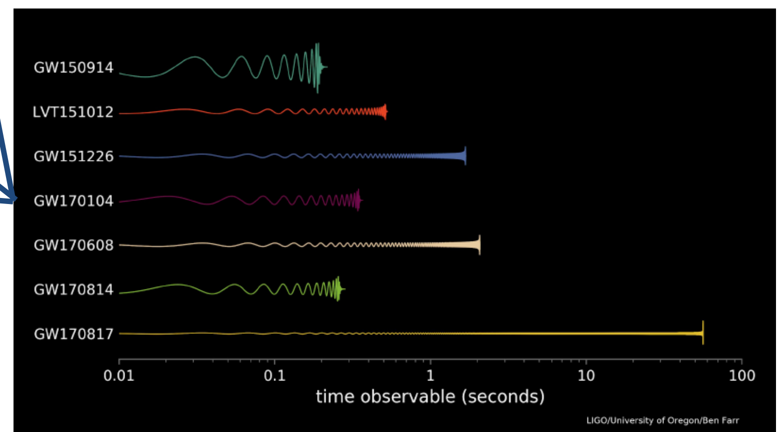
Binary formation and evolution

Masses

Spins

Merger rates

Tidal deformability



Neutron stars
What is their structure?

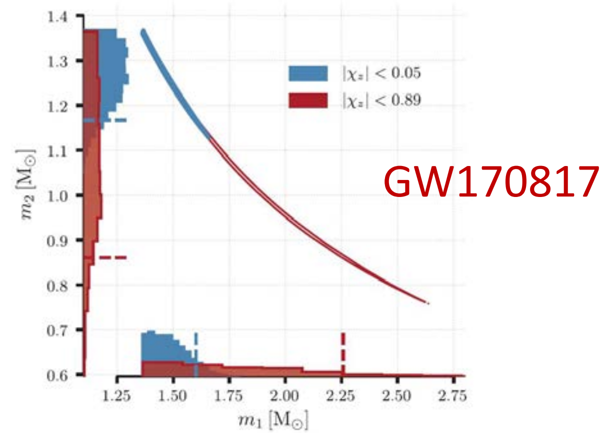
Black holes
Are they the BH of GR?

Masses and Spins

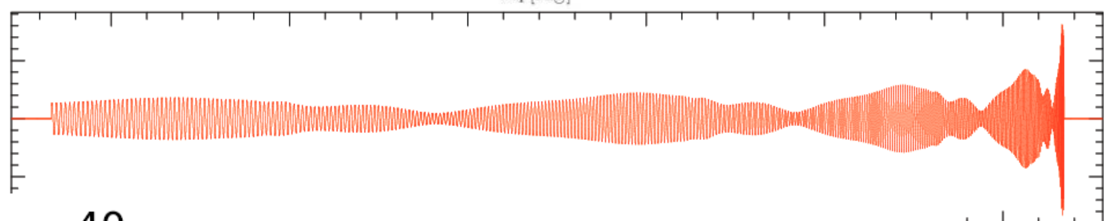
- Inspiral
  - Leading order: driven by chirp mass
  - Next to leading order: mass ratio, spin components // orbital angular momentum
  - Higher orders: full spin DOF

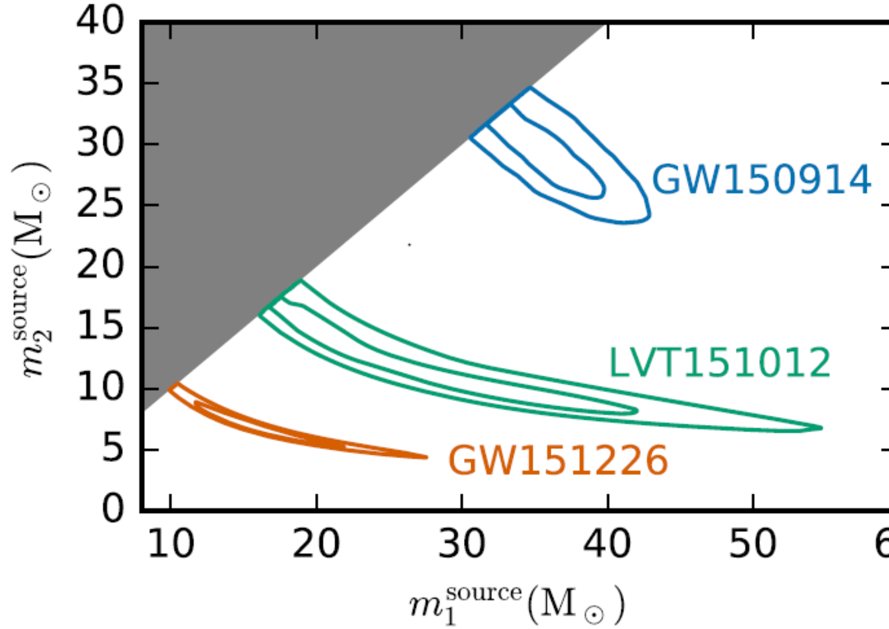
- Additional spin effect
  - If not // orbital angular momentum: orbital plane precession
  - ➔ Amplitude and phase modulation

- Merger and ringdown
  - Primarily governed by final black hole mass and spin



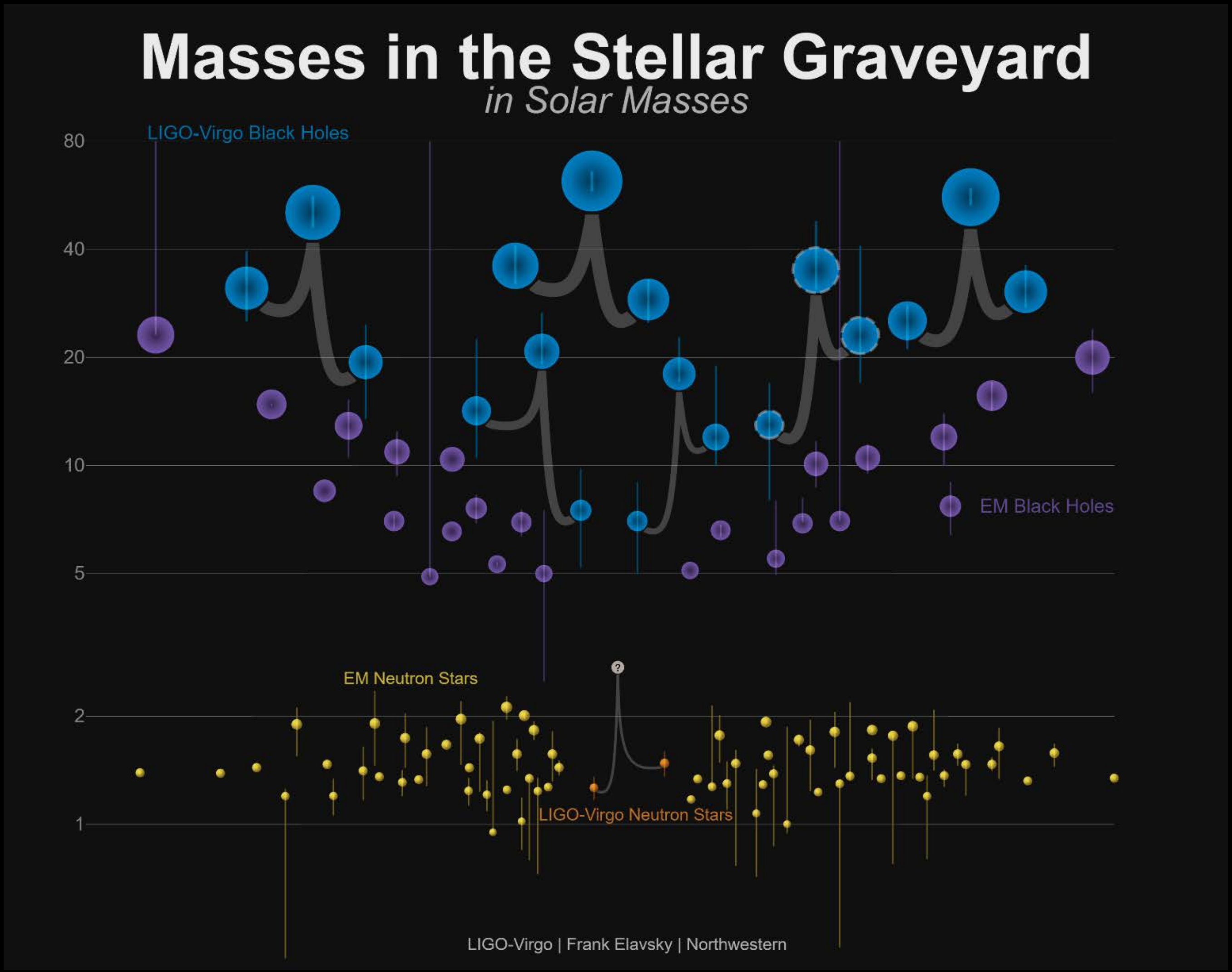
PRL 119, 161101 (2017)





arXiv:1606.04856

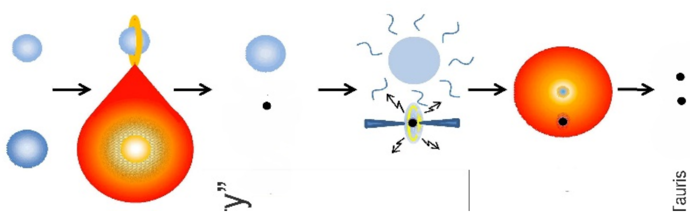
Masses

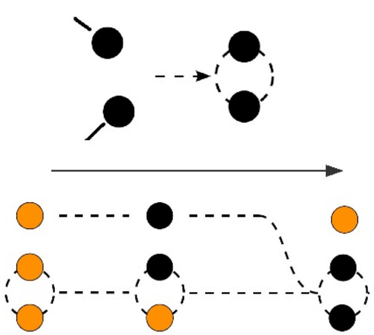


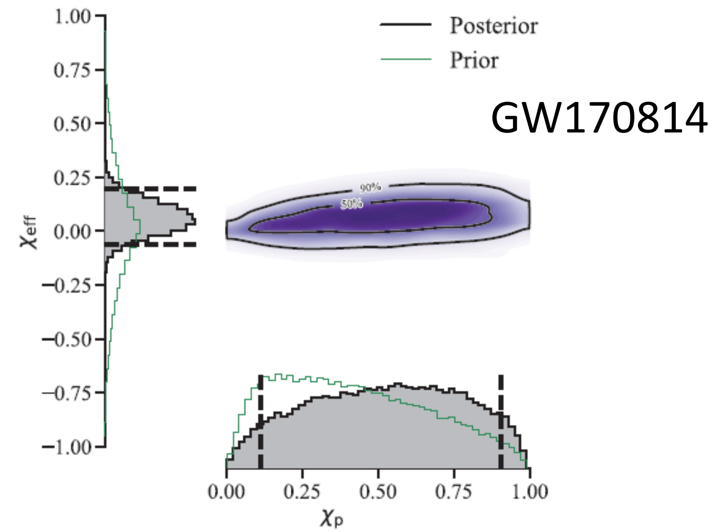
- Heavy stellar mass BHs ($> 25\ M_{\odot}$)
  - Weak massive-star winds
  - Formation in environment with low metallicity
- GW170817 remnant
  - Lightest BH or heaviest NS known

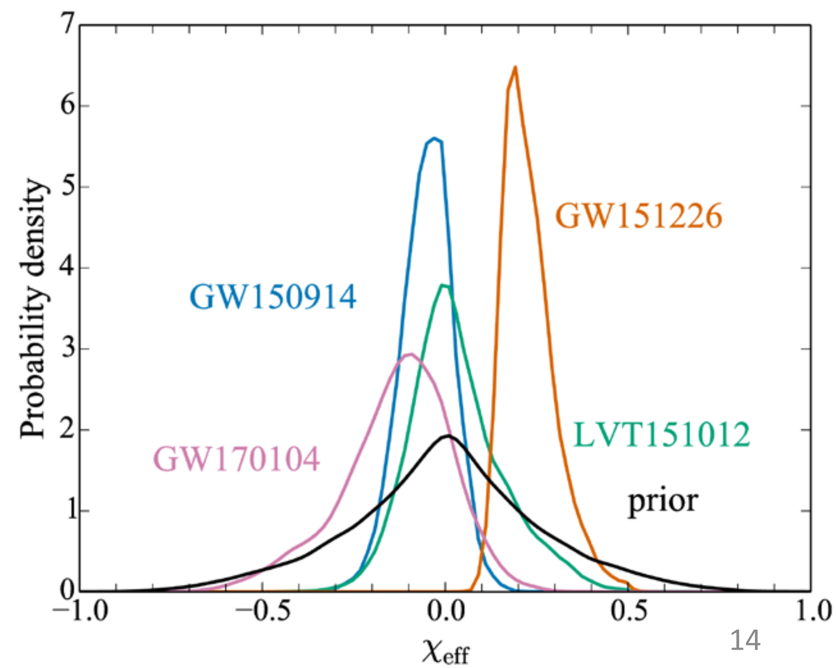
Spins

- Spins difficult to measure – sub-dominant effect on waveforms
- Spins possible discriminator for BBH formation history
  - BHs in dynamically formed binaries in dense stellar environments expected to have spins distributed isotropically
  - For field populations, stellar evolution expected to induce BH spins preferentially aligned with the orbital angular momentum





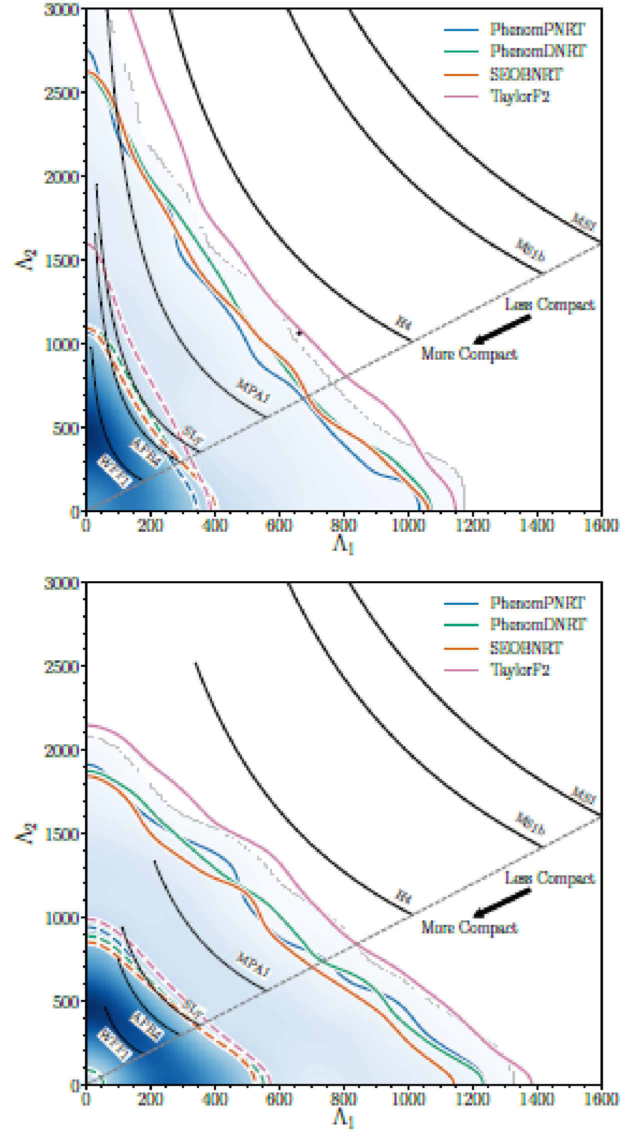




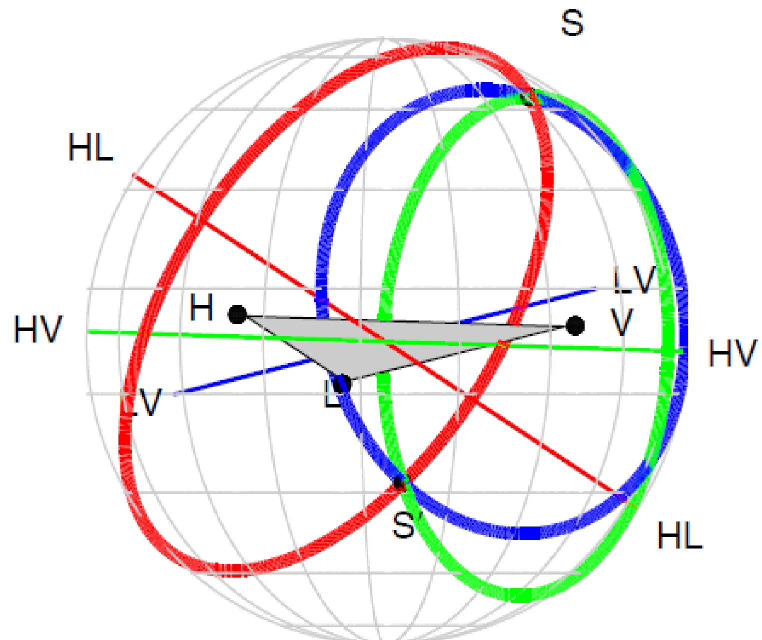
Neutron Star Tidal Deformability

- Tidal effects in BNS signal
  - Point particle approximation breaks down before end of inspiral
  - Companion tidal field induces mass-quadrupole moment and accelerates coalescence
  - Ratio of induced quadrupole moment to tidal field $\propto$ tidal deformability Λ
  - Subdominant effect – like spins, mass ratio – potentially observable above 600 Hz
  - Allows to constrain NS equation of state and radius
  - From GW
    - NS EoS predicting less compact stars disfavored
    - NS radius ~12 km   arXiv:1805.11581
  - Electromagnetic observations provide additional constraints

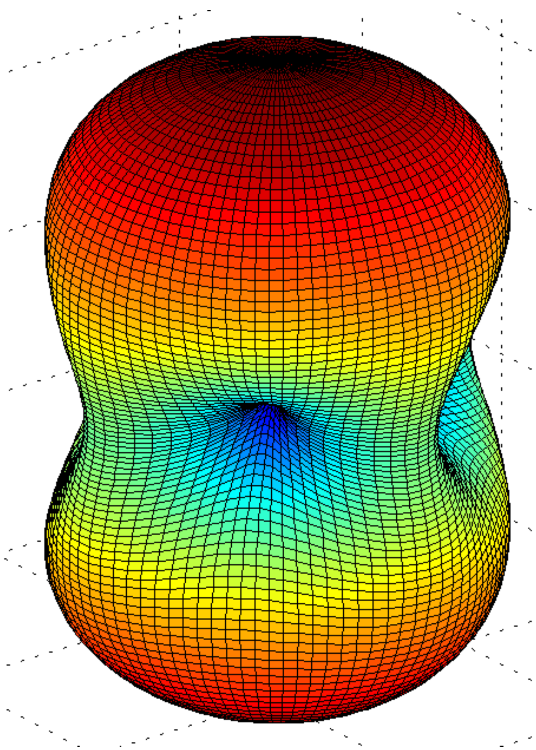
arXiv:1805.11579



Localization

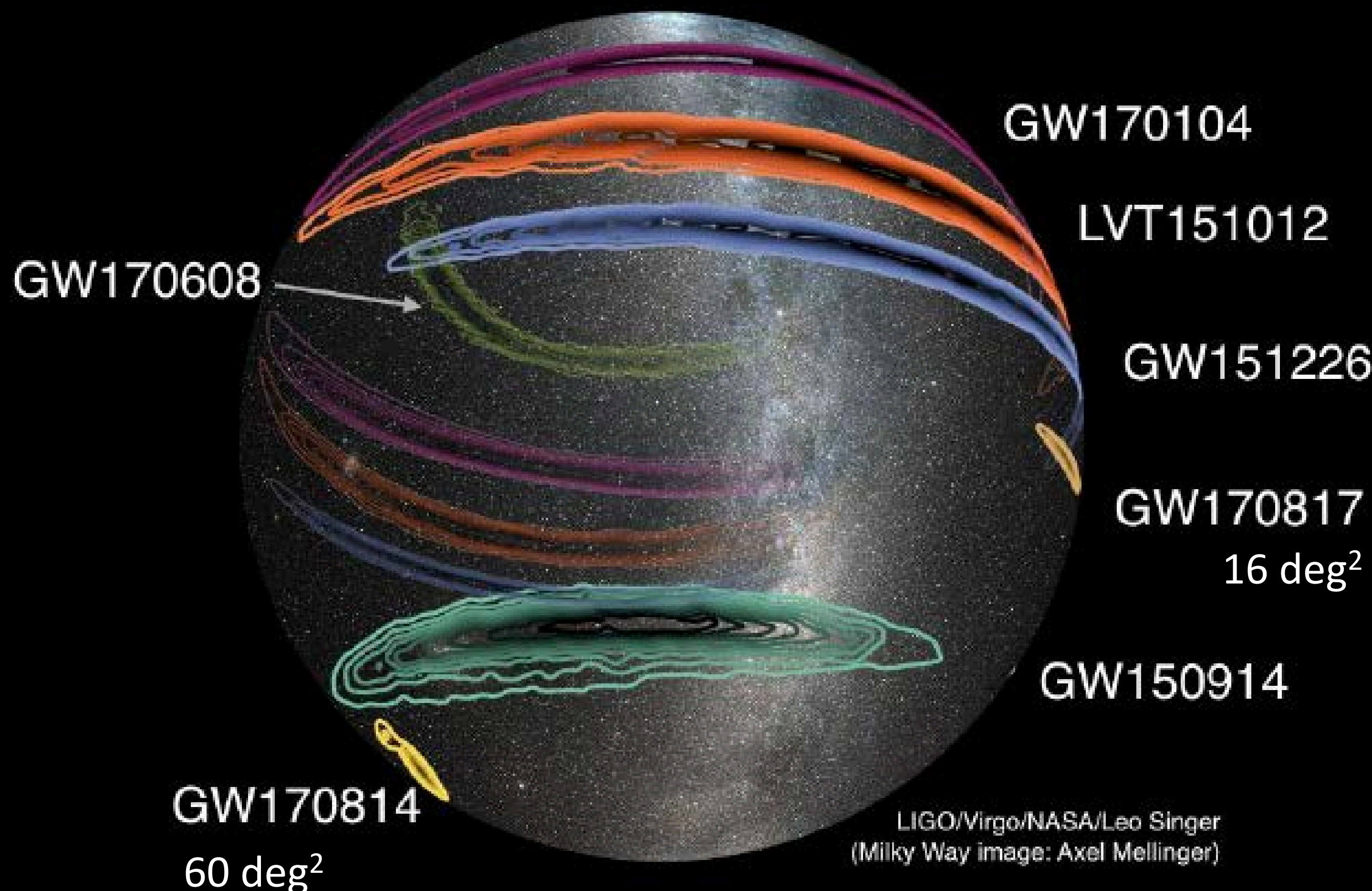


- Primarily from time delay between detectors
- Amplitude and phase information help



- Key input for EM follow-up and counterpart search
- Ultimate localization from Bayesian inference – multi-detector, coherent model – on data with final calibration

Localization of Sources so far

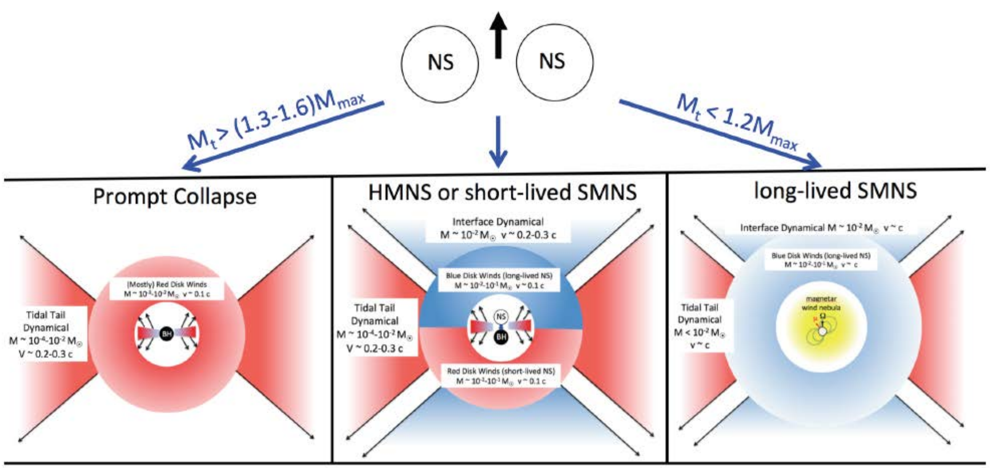


Do we understand the remnants?

- Not very well – yet – for lack of sensitivity at high frequency

- Kerr nature of CBC remnant can be shown by observing multiple quasinormal modes in post-merger signal
  - Well modelled but low SNR

- Fate of BNS remnant should leave prints in both GW and EM signals
  - But difficult to observe and read the prints

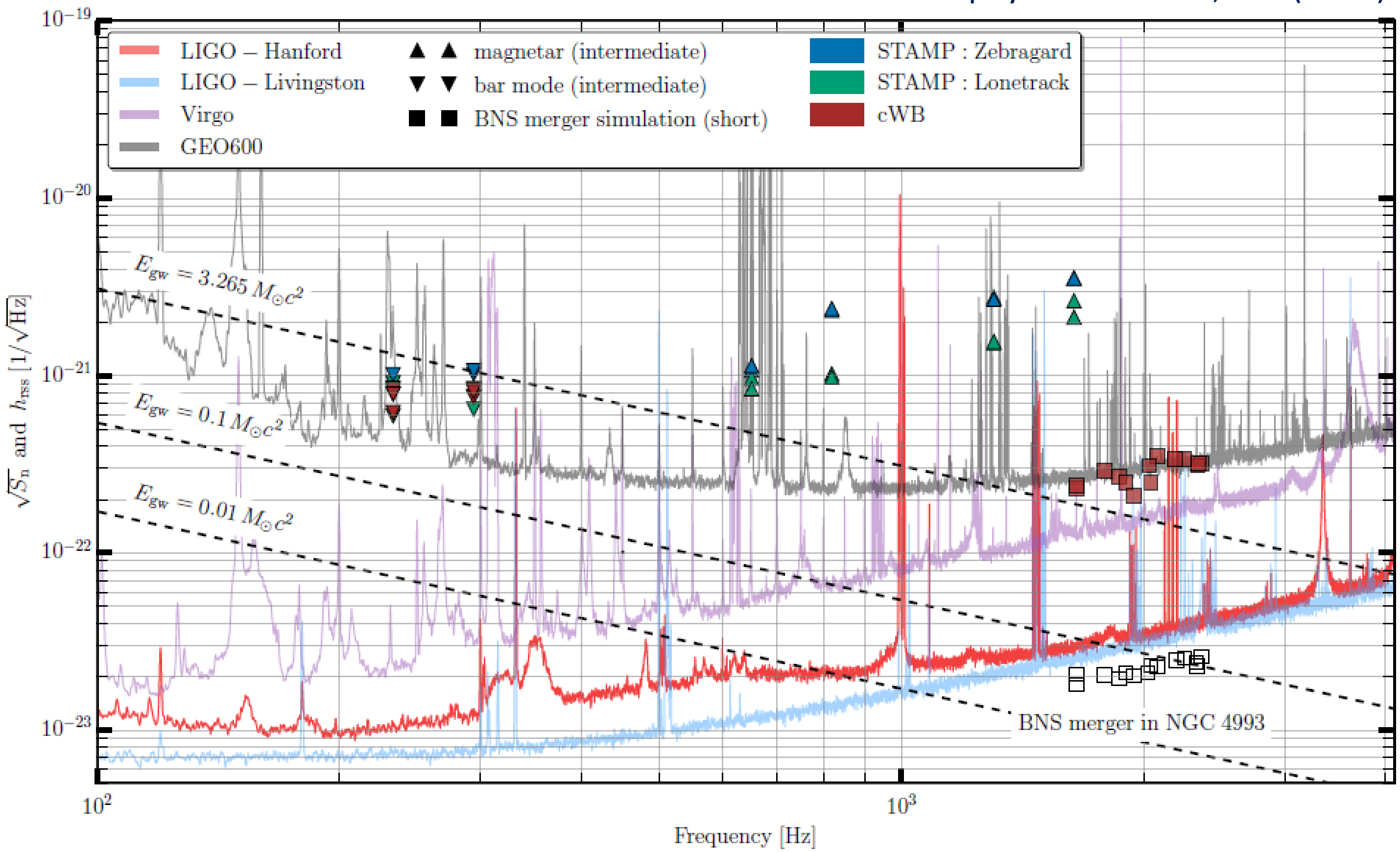


Margalit & Metzger

Search for post-merger GW signal from GW170817 remnant

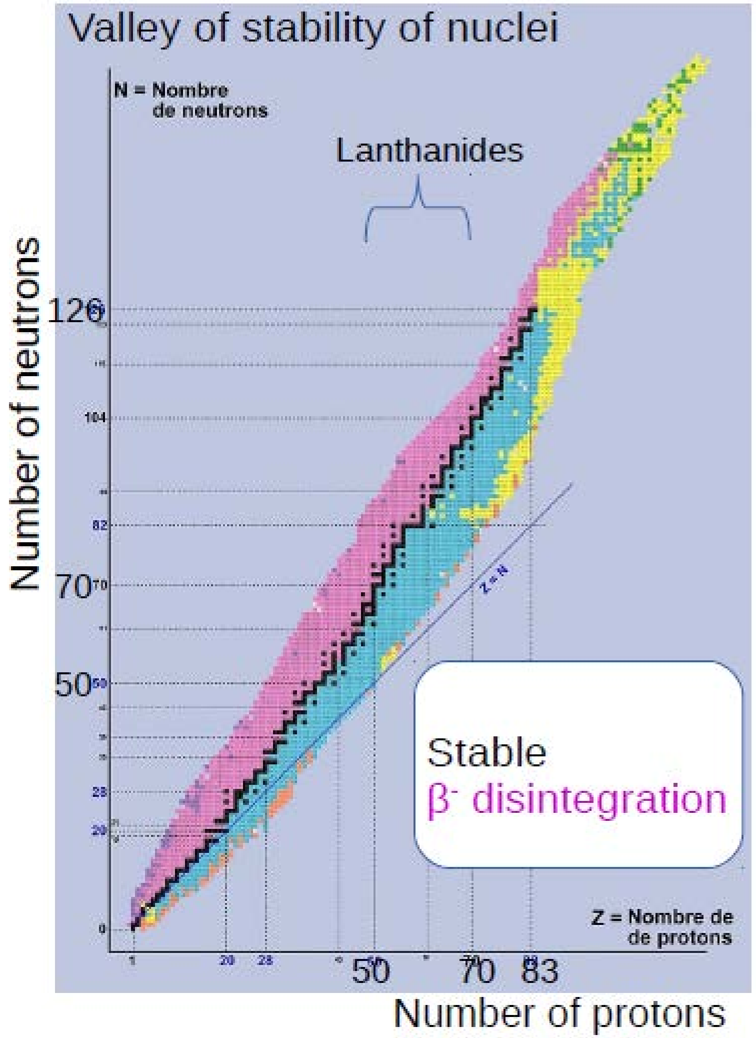
Astrophys. J. Lett. 851, L16 (2017)

- < ~ 1s signal from hypermassive NS
- < ~ 500s signal from supramassive NS
- Upper limits still an order of magnitude larger than most models



Kilonova & Nucleosynthesis

- Rapid neutron capture nucleosynthesis in merger ejecta
  - Need very neutron-rich matter to forge heaviest r-process elements $58 \leq Z \leq 90$
  - AT2017gfo IR lightcurve and spectra indicate heavy r-process elements
- Accumulated nucleosynthesis could account for all heavy elements in Galaxy
  - Depends on ejecta mass and composition, and on merger rate

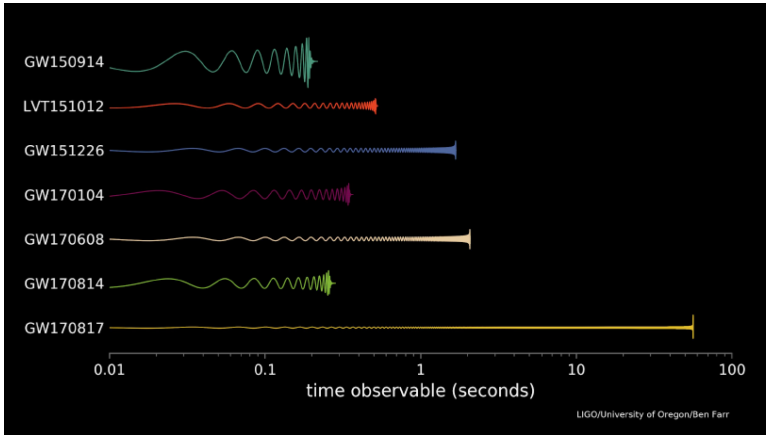


Are GWs as predicted by GR ?

Polarization modes

Propagation speed

Binary dynamics



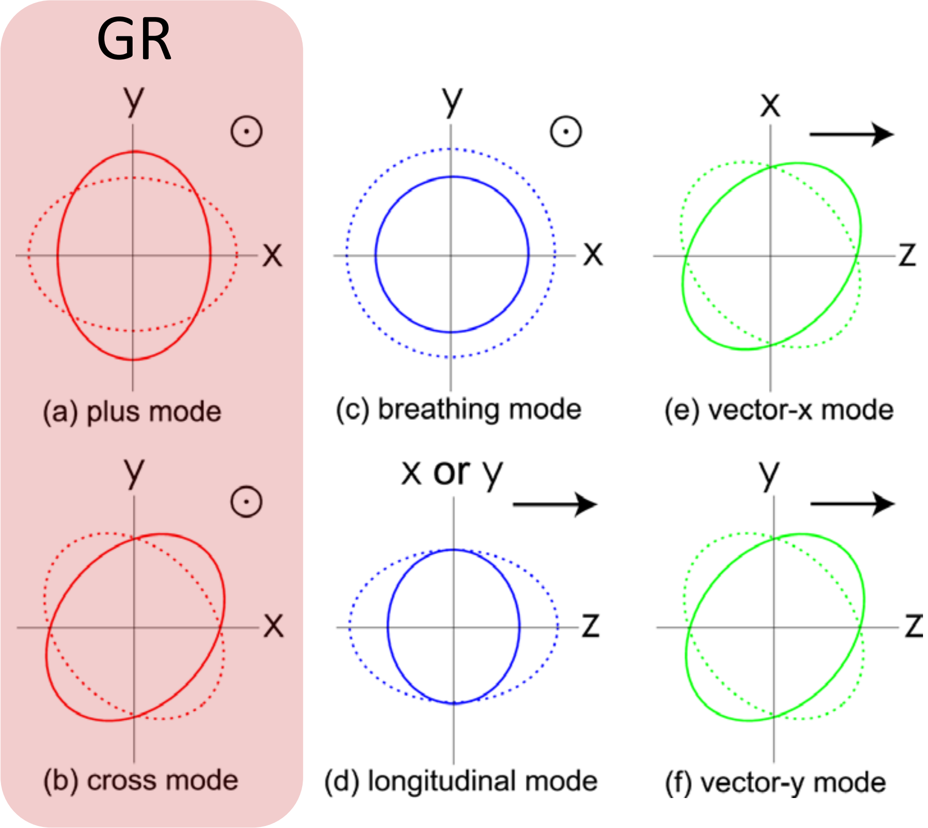
Graviton mass

Lorentz invariance

Equivalence principle

GW Polarizations

- Generic metric theories of gravity allow up to six polarizations
- GR allows two tensor polarizations, + and x
- LIGO instruments have similar orientation ➔ record same combination of polarizations
- Virgo has different orientation ➔ breaks degeneracy

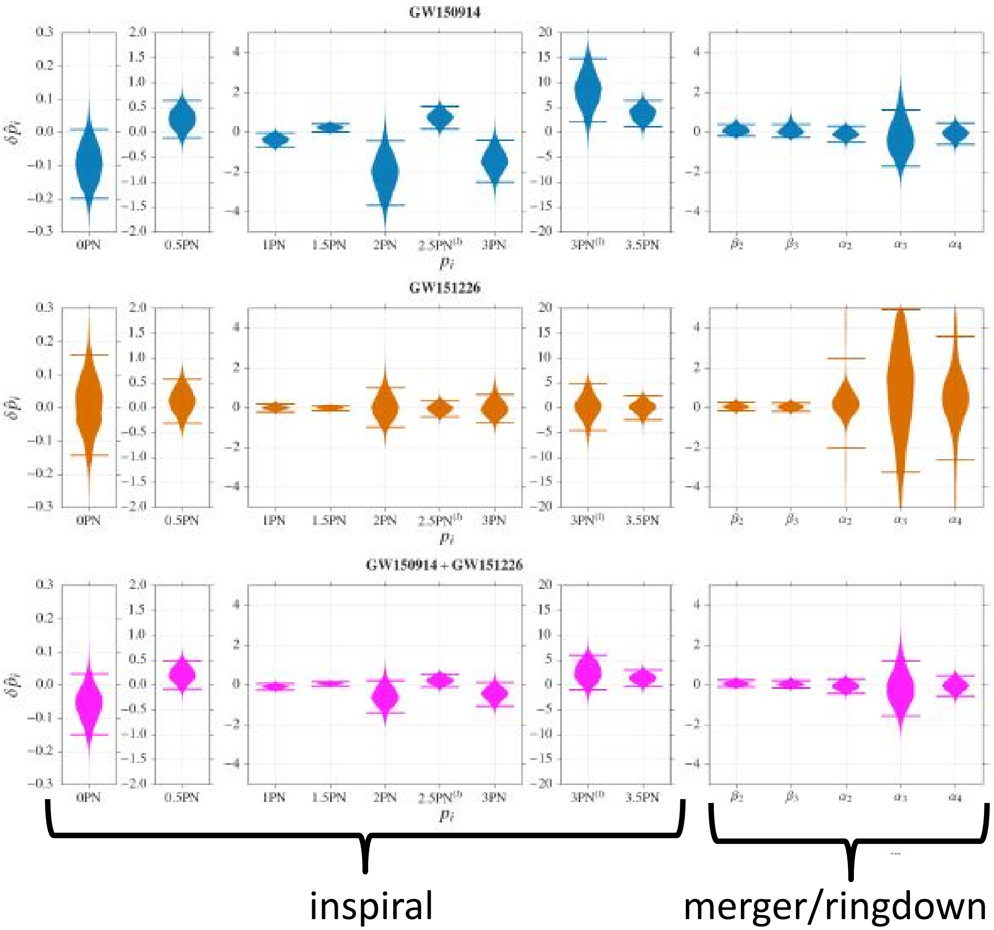


- GW geometry probed directly through projection of metric perturbation onto detector network
- GW170814: pure tensor polarization strongly favored over pure scalar or vector polarizations

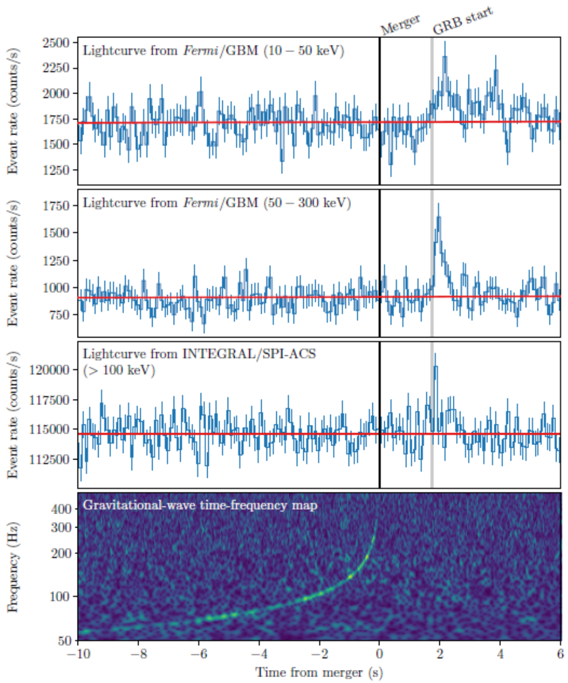
Testing GR with BBH mergers

- Most relativistic binary pulsar known today
  - J0737-3039, orbital velocity
    $$v/c \sim 2 \times 10^{-3}$$
- BBH mergers
  - Strong field, non linear, high velocity regime
    $$v/c \sim 0.5$$
- No evidence for deviation from GR in waveform, place empirical bounds on high order post-Newtonian coefficients

PHYSICAL REVIEW X 6, 041015 (2016)



Testing some GR cornerstones (I)



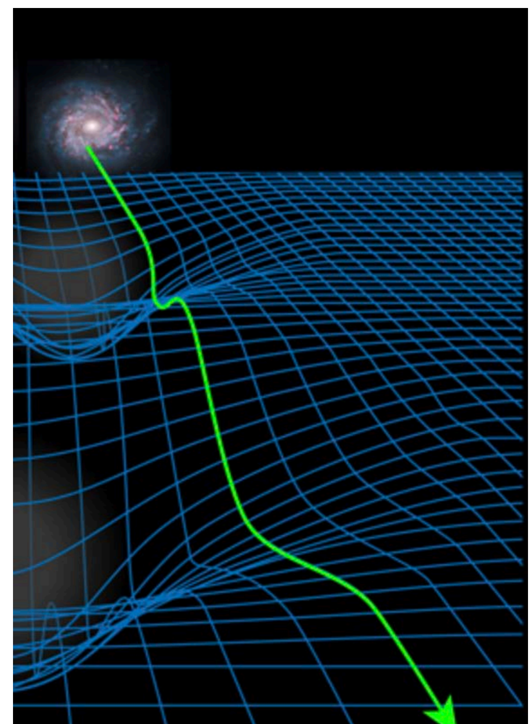
- GW propagation speed
  - GW170817 – GRB 170817A: delay of 1.74 ± 0.05 s over > 85 million years propagation
  - Assume Gamma emission delayed by [0,10]s

$$-3 \times 10^{-15} \leq \frac{v_{GW} - v_{EM}}{v_{EM}} \leq 7 \times 10^{-16}$$

- Equivalence principle
  - EM radiation and GWs affected by background gravitational potentials in the same way ?
  - Shapiro delay $\delta t_S = -\frac{1+\gamma}{c^3} \int_{\mathbf{r}_e}^{\mathbf{r}_o} U(\mathbf{r}(l))dl$

$$-2.6 \times 10^{-7} \leq \gamma_{GW} - \gamma_{EM} \leq 1.2 \times 10^{-6}$$

- Many alternative theories of gravity ruled out



APS/Alan Stonebraker

Testing some GR cornerstones (II)

- Lorentz invariance: Look for possible dispersion in signal propagation

$$\left(\frac{v}{c}\right)^2 = 1 - \left(\frac{hc}{\lambda_g E}\right)^2$$

- GW150914 + GW151226 + GW170104

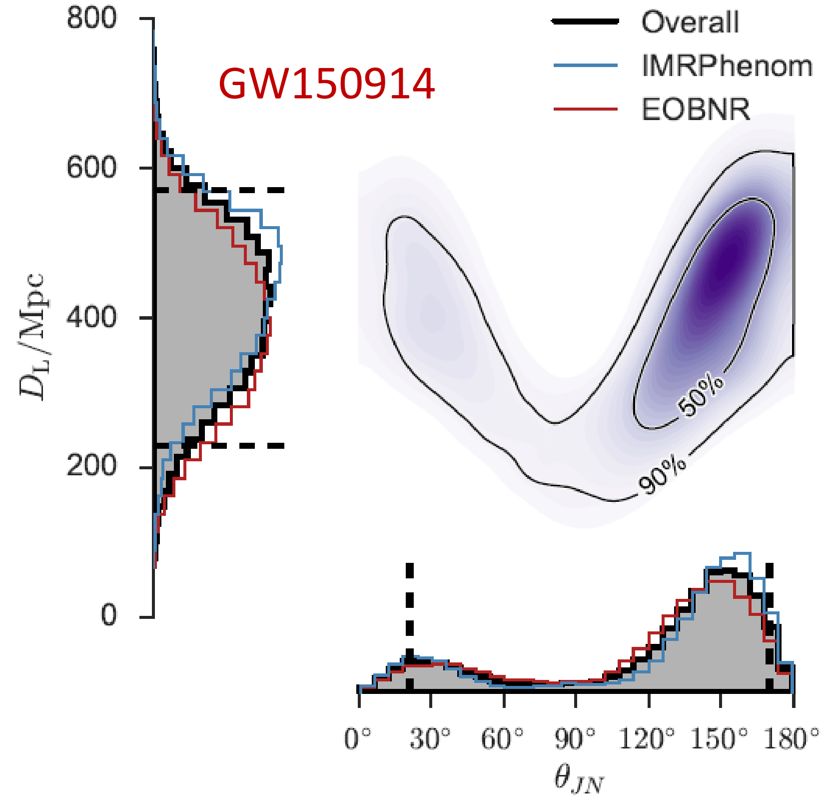
PRL 118, 221101 (2017)

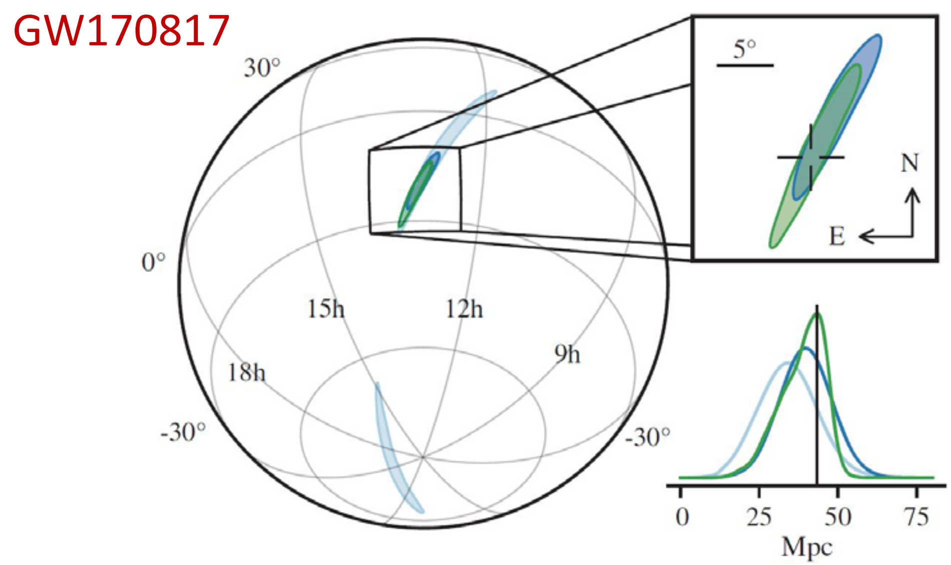
$$\lambda_g > 1.6 \times 10^{13}\, km$$

  - Bound graviton mass $m_g \leq 7.7 \times 10^{-23}\, eV/c^2$
  - More constraining than bounds from Solar System and binary pulsar observations
  - Less constraining than model dependent bounds from large scale dynamics of galactic clusters and weak gravitational lensing observations

Source Distance

- CBC sources are standard sirens
  - Masses encoded in waveform
  - Once masses are known, amplitude gives distance
  - But some degeneracy with binary inclination and source location





Measuring the Hubble Constant

- GW17081 – AT2017gfo
  - GW only
    - Luminosity distance = 40^{+8}_{-14} Mpc at 90% CL
  - Assuming sky position of AT2017gfo
    - $d = 43.8^{+2.9}_{-6.9}$ Mpc at 68% CL
  - H_0 uncertainty from statistics, geometrical degeneracy with system inclination, and galaxy peculiar velocity

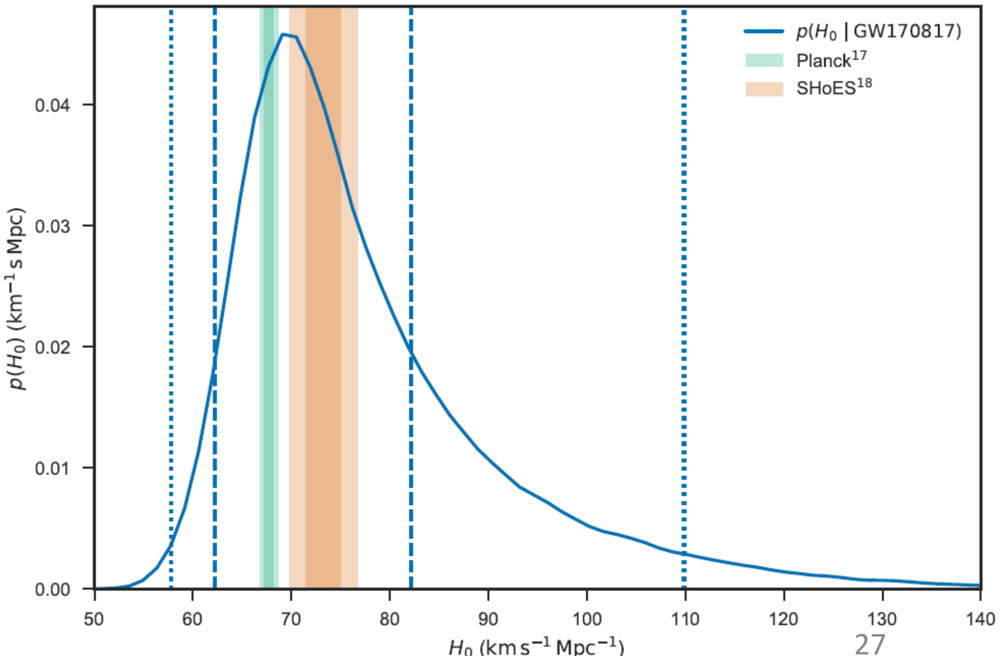
$$v_H = H_0 d$$

Hubble flow velocity from host galaxy NGC4993

Distance from GW

$$H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Independent of any cosmic distance ladder



Nature 551, 85 (2017)

Prospects for Near Future

- O2: 1/2 – 1/4 of the design sensitivity of Advanced LIGO and Advanced Virgo
- Currently both LIGO and Virgo improving sensitivity of instruments
- Next: ~1 year long O3 run
  - Start early 2019
  - LIGO BNS range ~ 120 Mpc, Virgo ~ 65 Mpc
- Best guesses for O3
  - BBH: Several per month to several per week
  - BNS: 1 to 10 in the year-long run
  - NSBH: N=0 not ruled out in any scenario, most give ~50% N>0
- More events, more physics… more breakthroughs?
  - Eagerly waiting for next galactic supernova

Conclusion

- A growing family of GW transient sources
  - 6 BBH mergers, including first triple detection with Advanced Virgo
  - 1 BNS merger, with multi-wavelength follow-up
- Multi-messenger GW astronomy now a reality
- GW observations are delivering the expected returns for fundamental physics, astrophysics, cosmology
- Full O2 analyses on-going
- More to come in O3…