GW170817
LIGO/VIRGO Observations of a Neutron Star Merger

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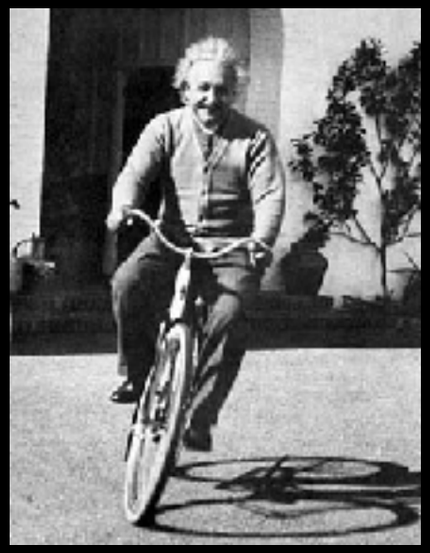
LIGO Document G1800814

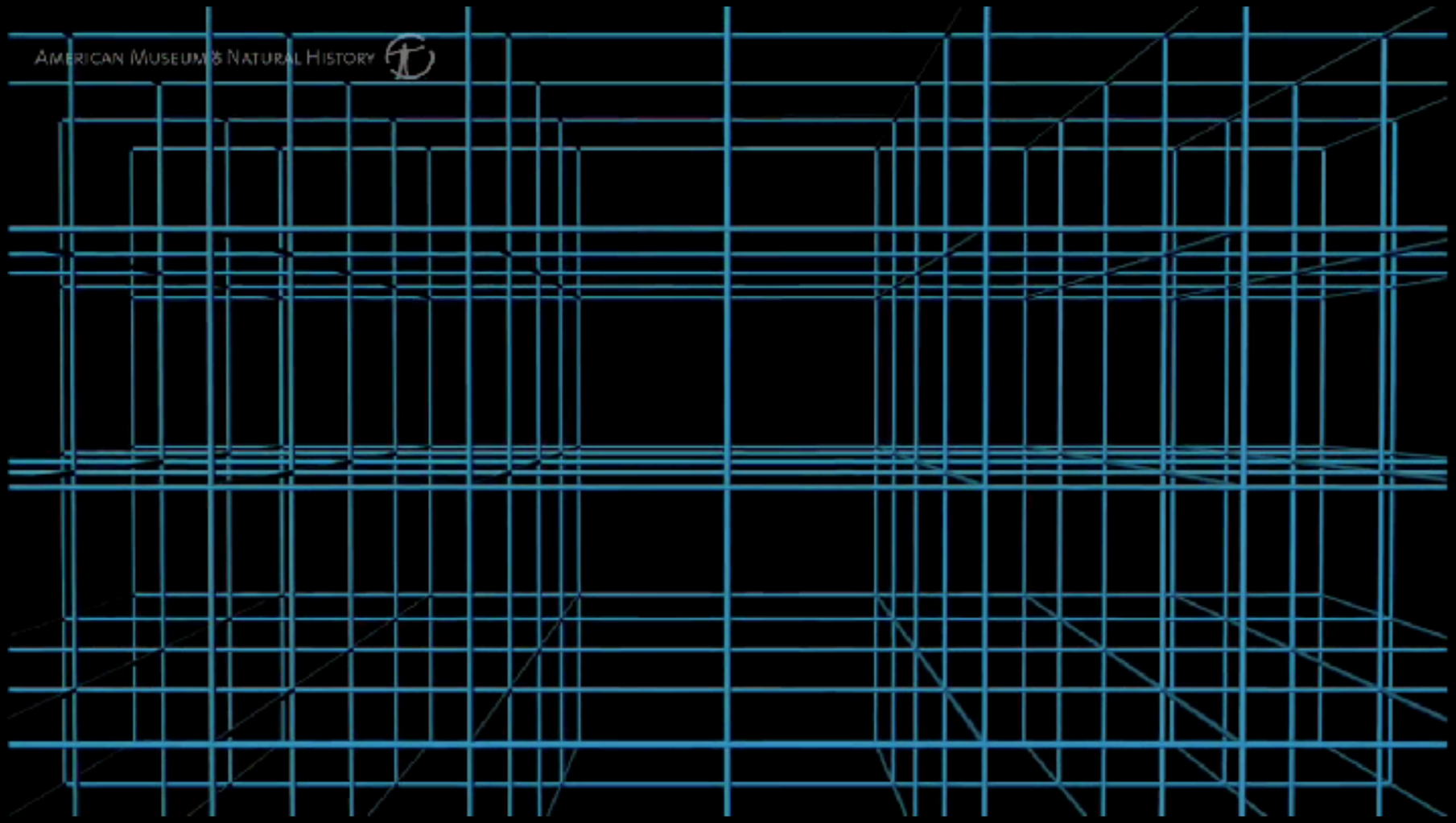
Illustration of GW170817 & GRB170817A
NSF/LIGO/Sonoma State University/Aurore Simonnet

- Intro to gravitational-wave astronomy
- Observation of neutron-star merger GW170817
  - Focus on "*offline*" gravitational-wave analysis (days-months after initial analysis & alerts)
  - Implications for neutron-star matter
- Future GW prospects



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

- John A. Wheeler



American Museum of Natural History
"Gravity: Making Waves"

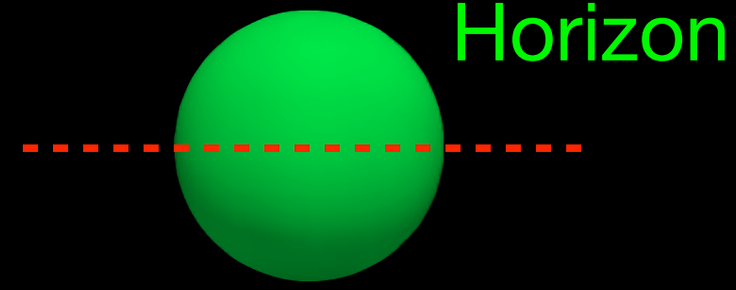
Strong curvature

Palm Springs

Neutron star

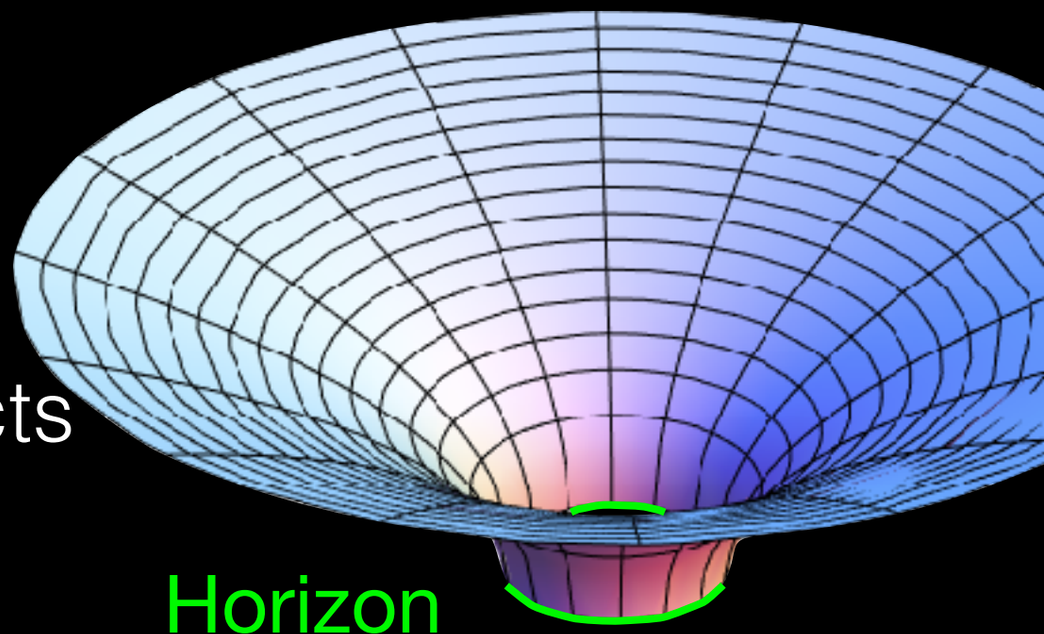
Mass = 1.5 ☀

(small)
Black hole



Mass = 1.5 ☀

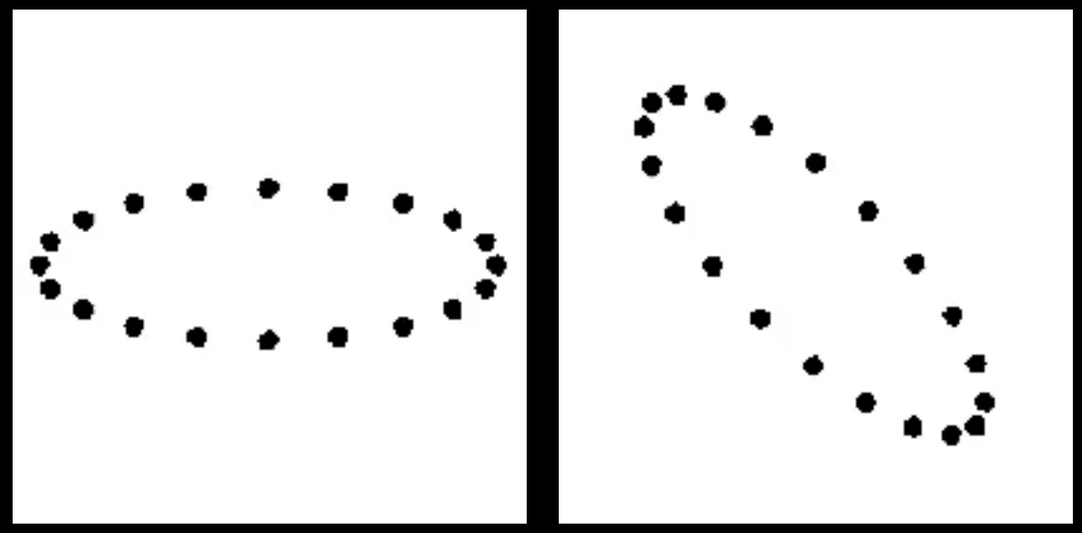
Compact objects



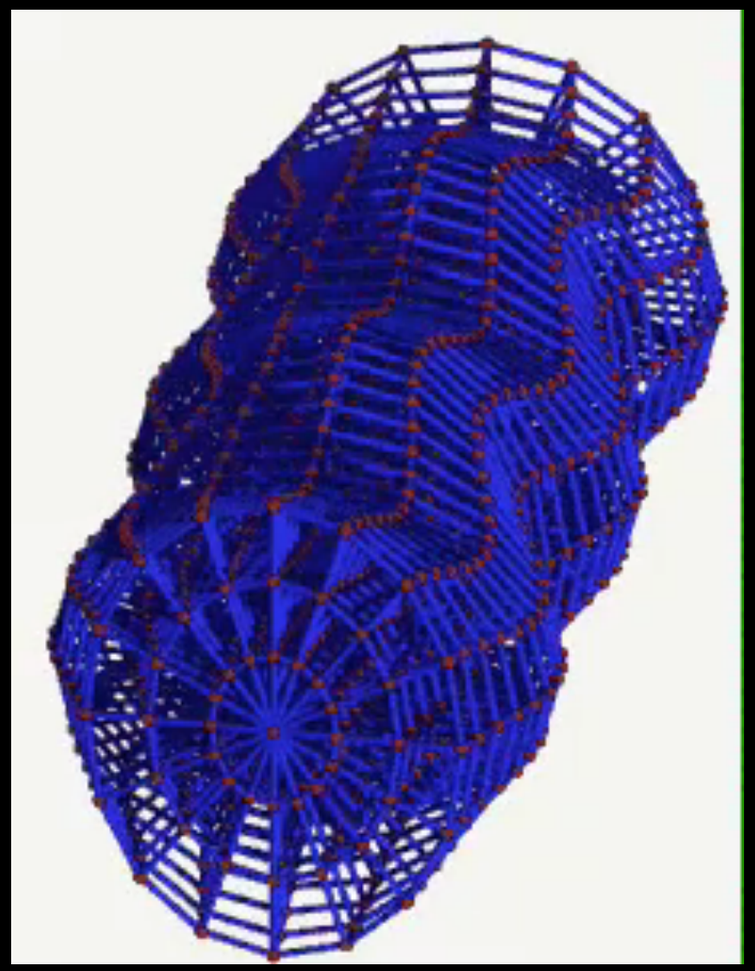
Gravitational waves

- Curvature of spacetime changes around moving objects
- Information propagates away from system at speed of light
- Linearized General Relativity → wave equation
- Waves stretch and squeeze the distance between freely-falling objects (Pirani 1957)

Two polarizations: + and x



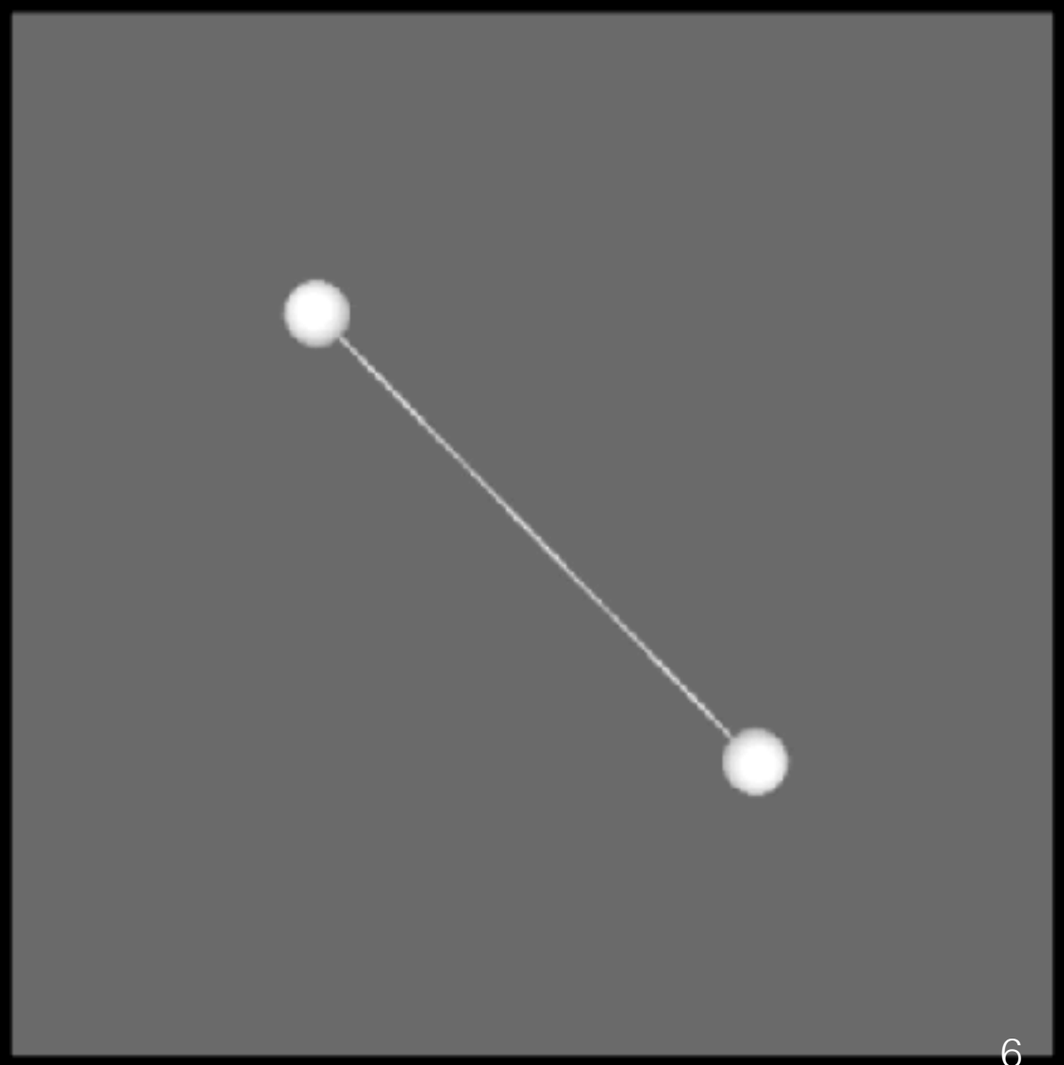
Propagation



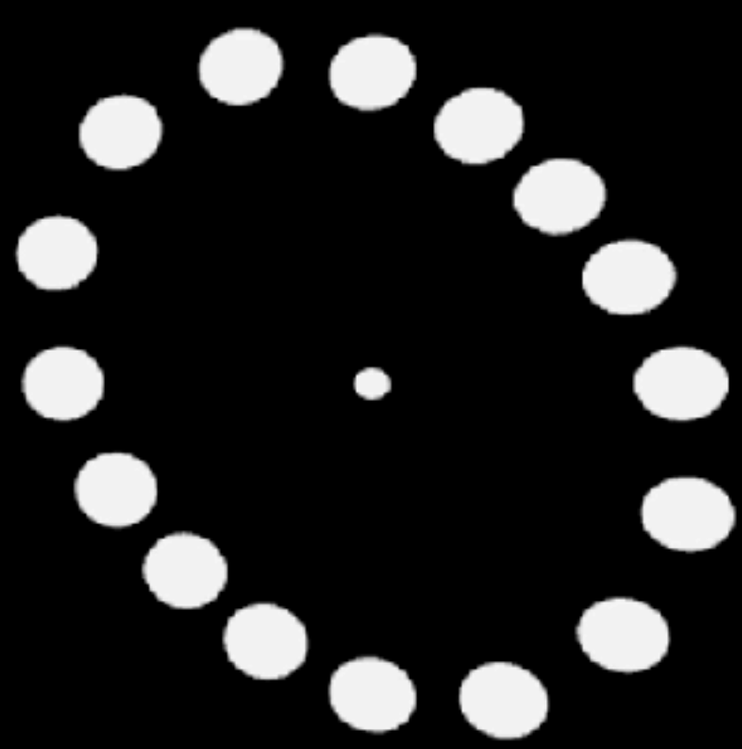
www.einstein-online.info/spotlights/gravWav

Strong gravitational-wave source: compact binaries

Compact objects orbit



Wave effects from above plane of screen



LIGO Hanford, Washington

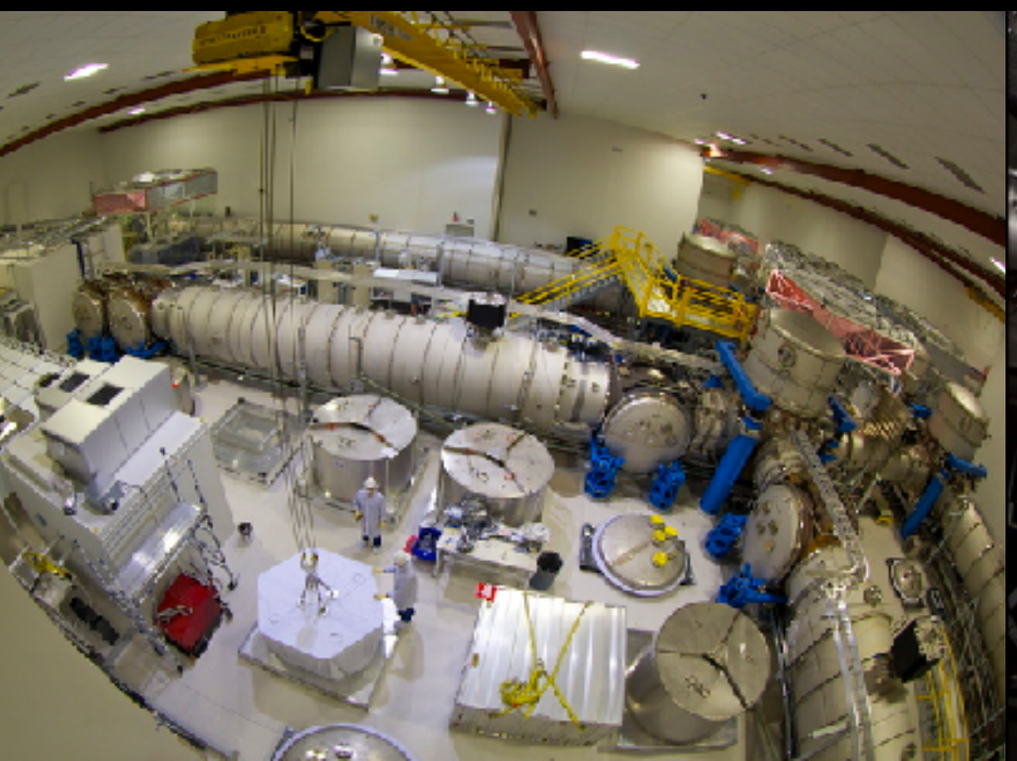
2015+

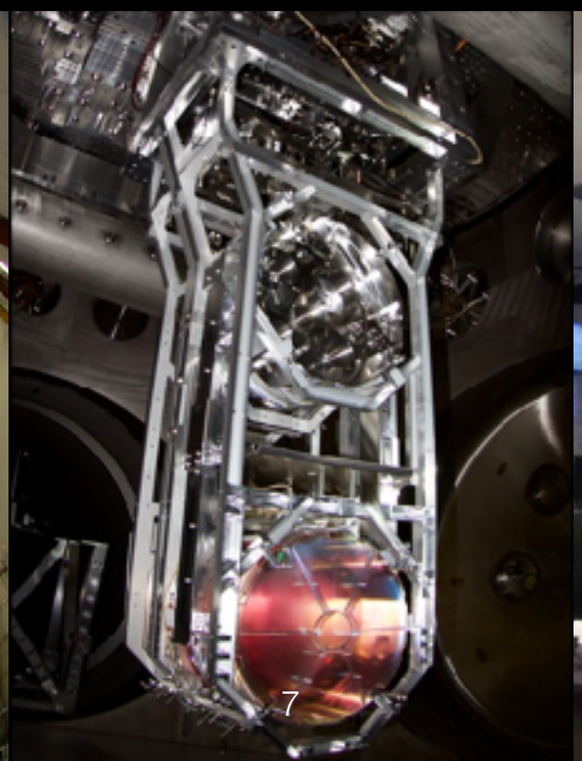
LIGO Livingston, Louisiana

2015+

Virgo, Italy

2017+



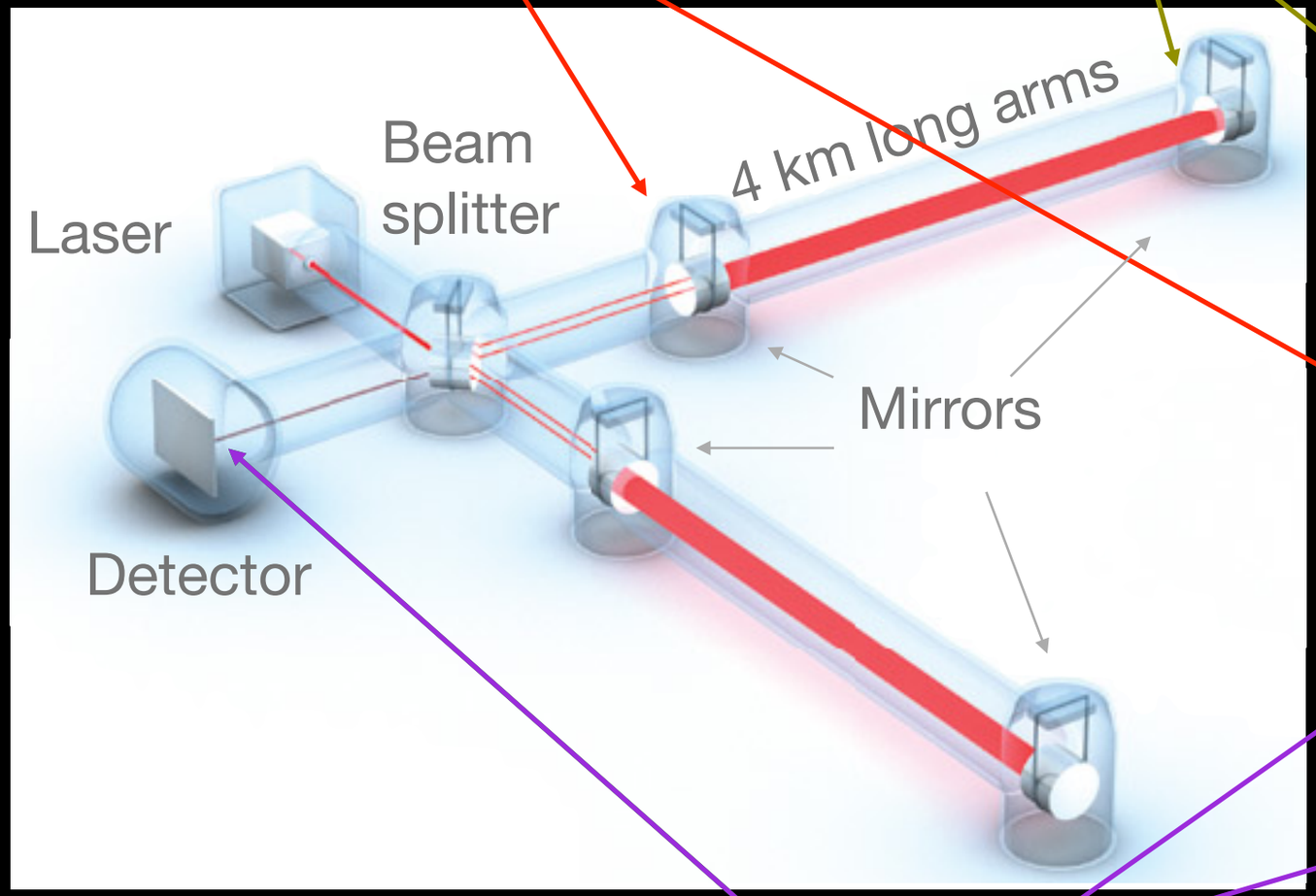


Precision measurement

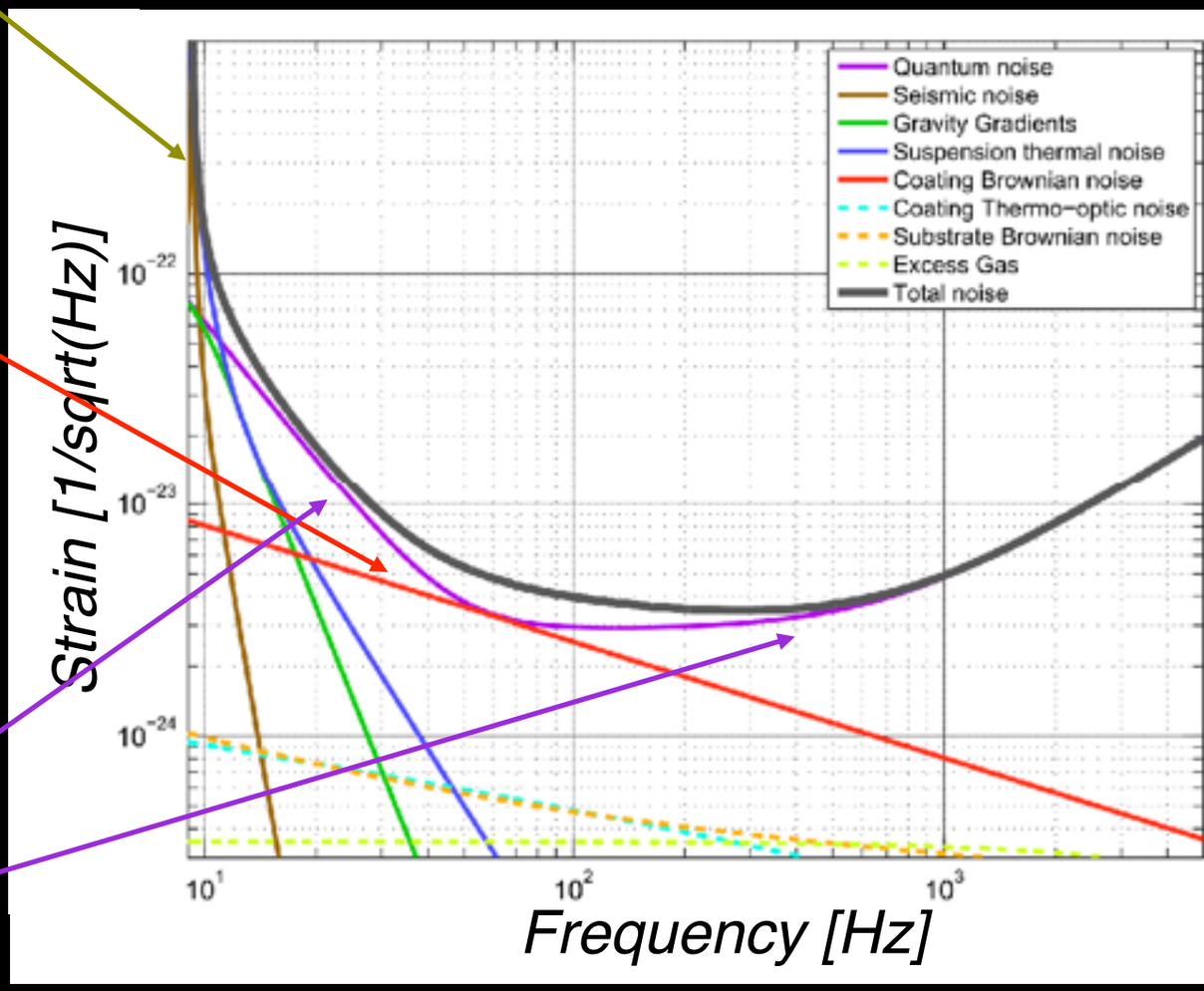
Fractional change from astronomical waves at Earth is $\delta L/L \sim 10^{-21}$

Thermal motion of mirror coatings

Seismic motion of ground shakes mirrors



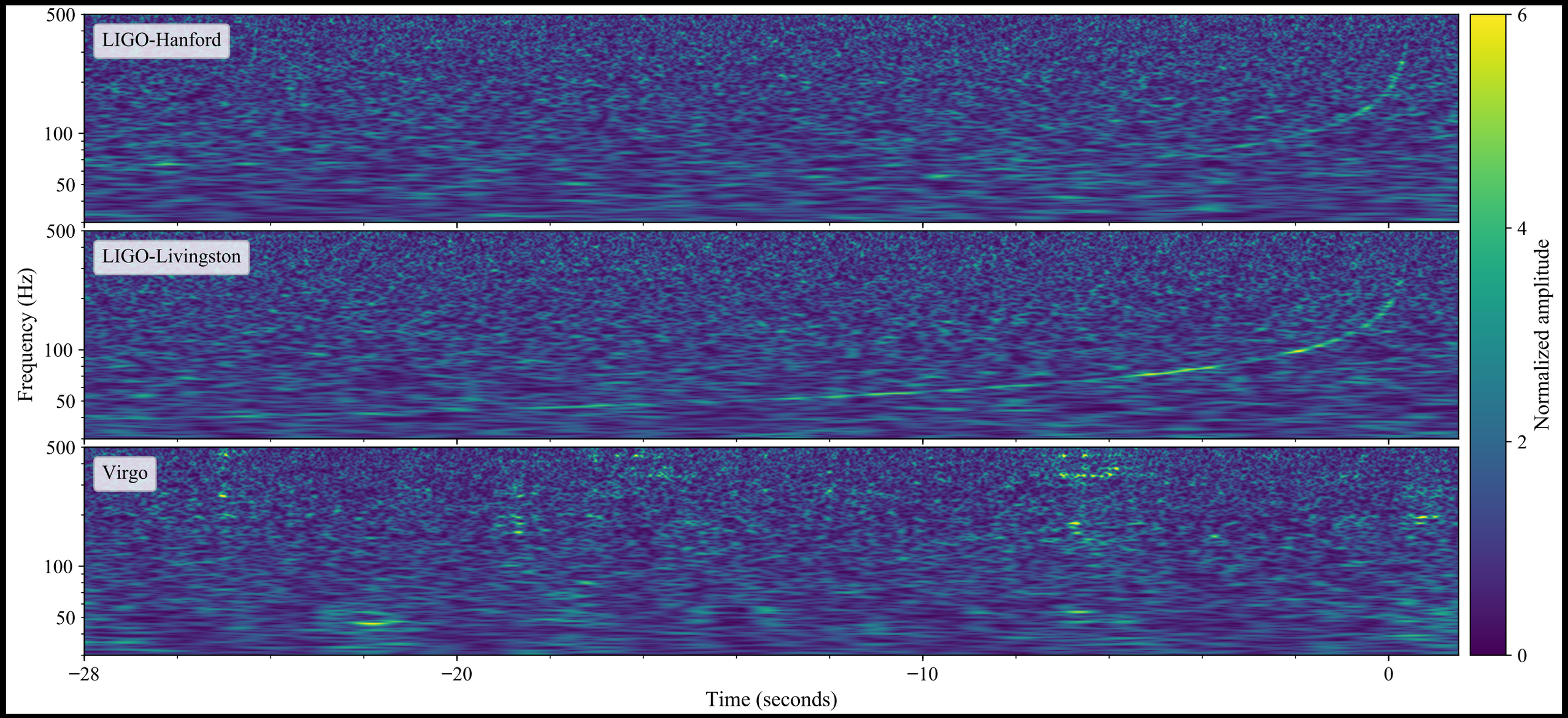
Class. Quantum Grav. 32 (2015) 074001



Quantum noise: radiation pressure and photon shot noise

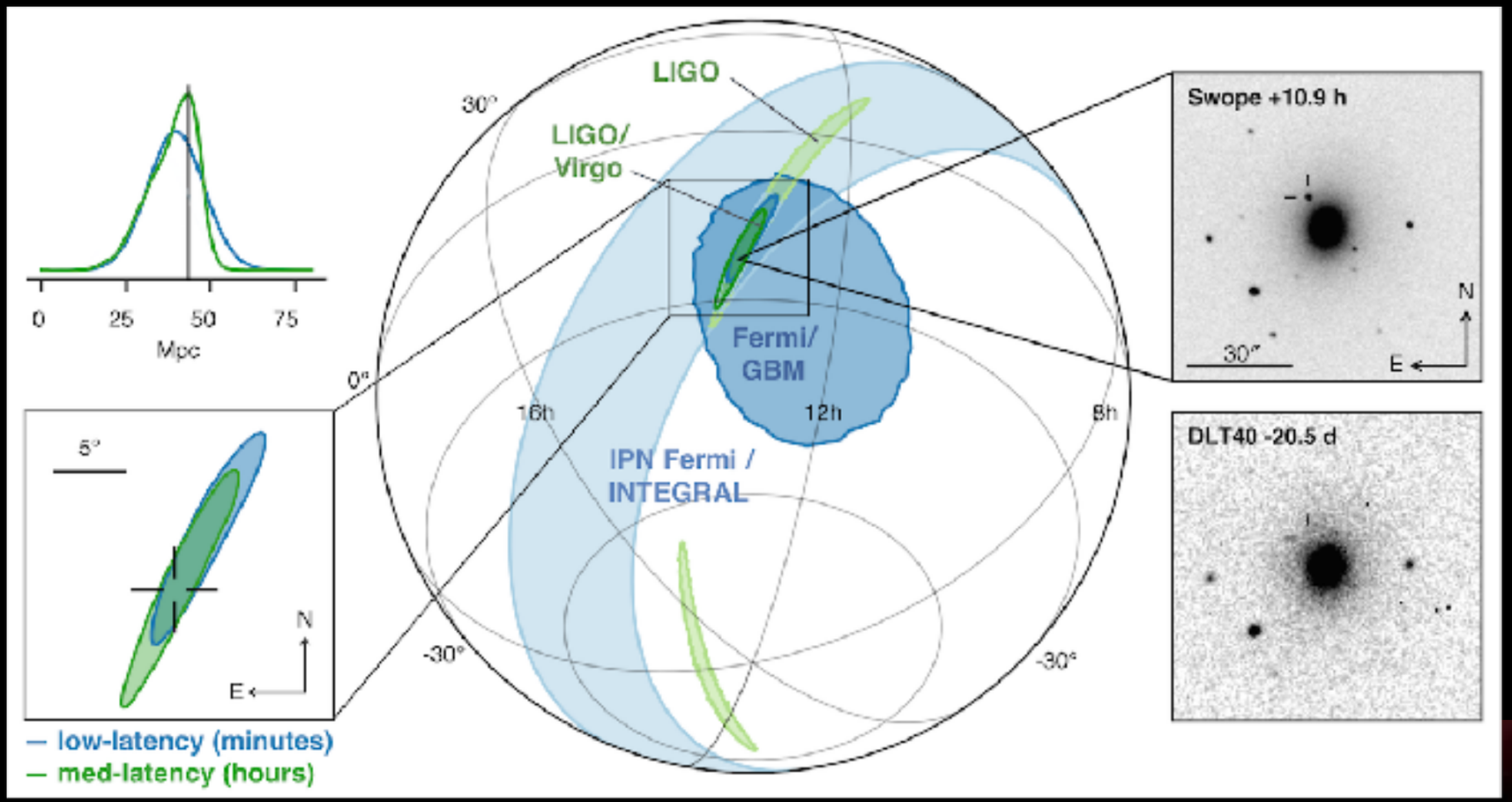
Slide from Josh Smith

August 17, 2017 12:41:04 UTC

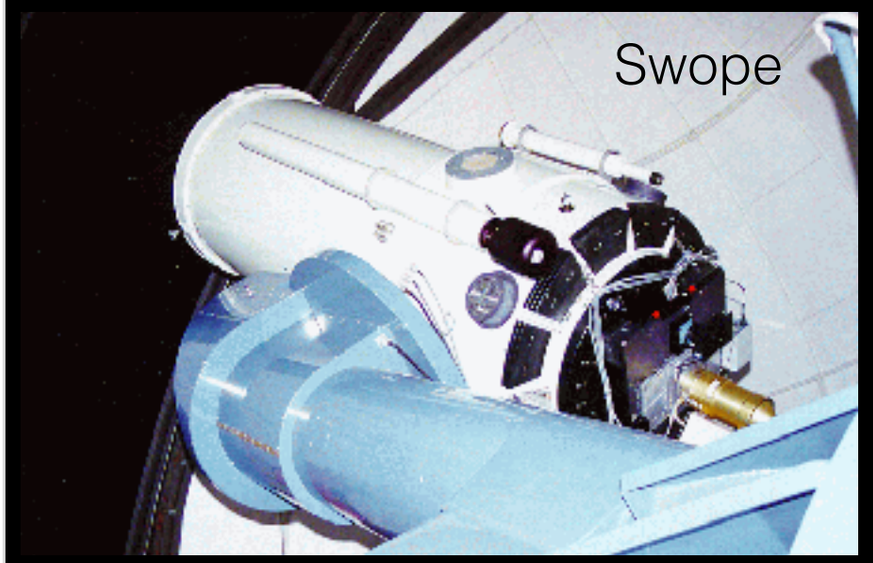


GW170817

LSC/Virgo PRL 119, 161101 (2017)



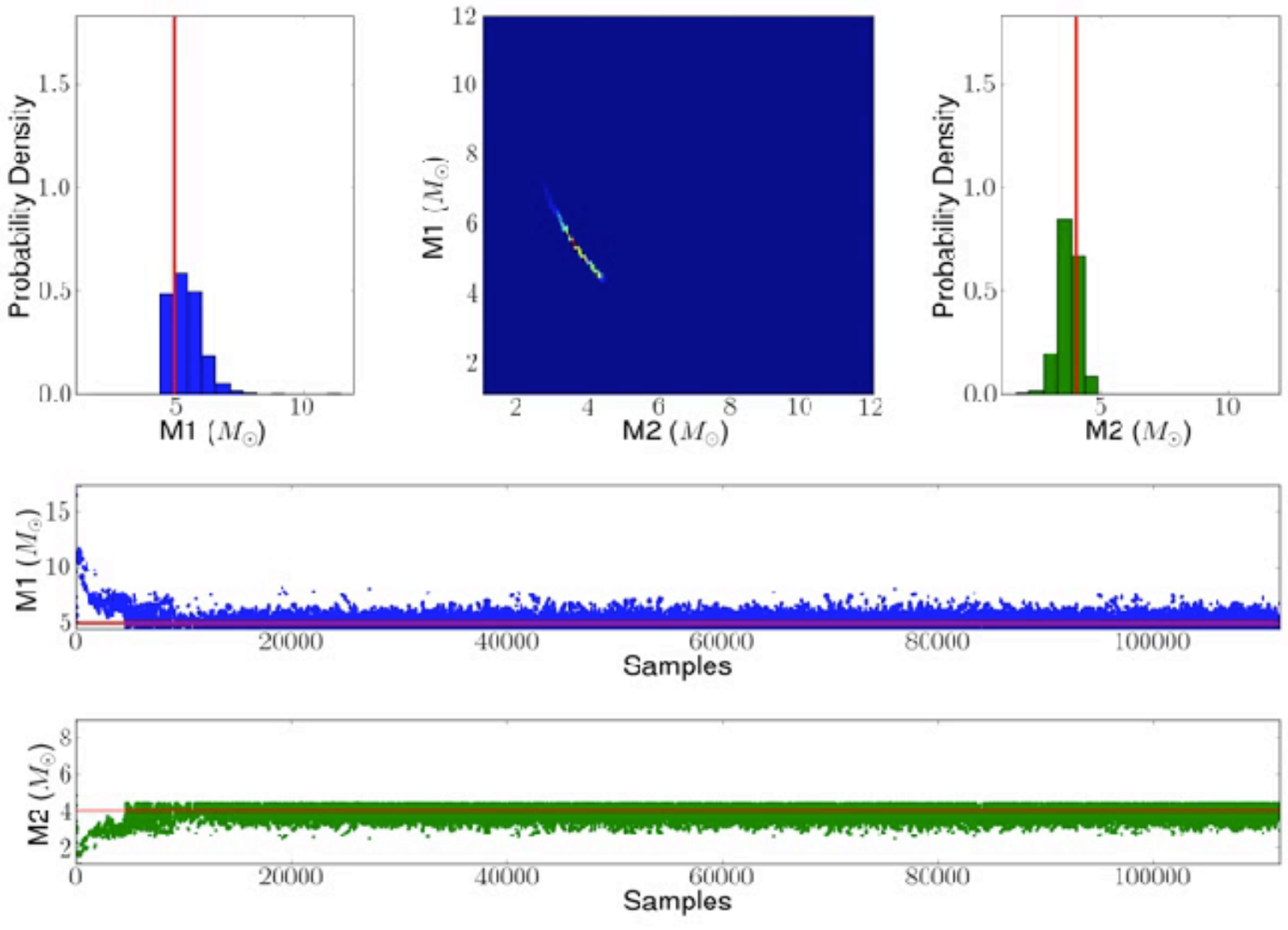
LSC/Virgo et al ApJL, 848:L12, 2017, adapted by V Raymond



LIGO/Virgo

Source properties after detection

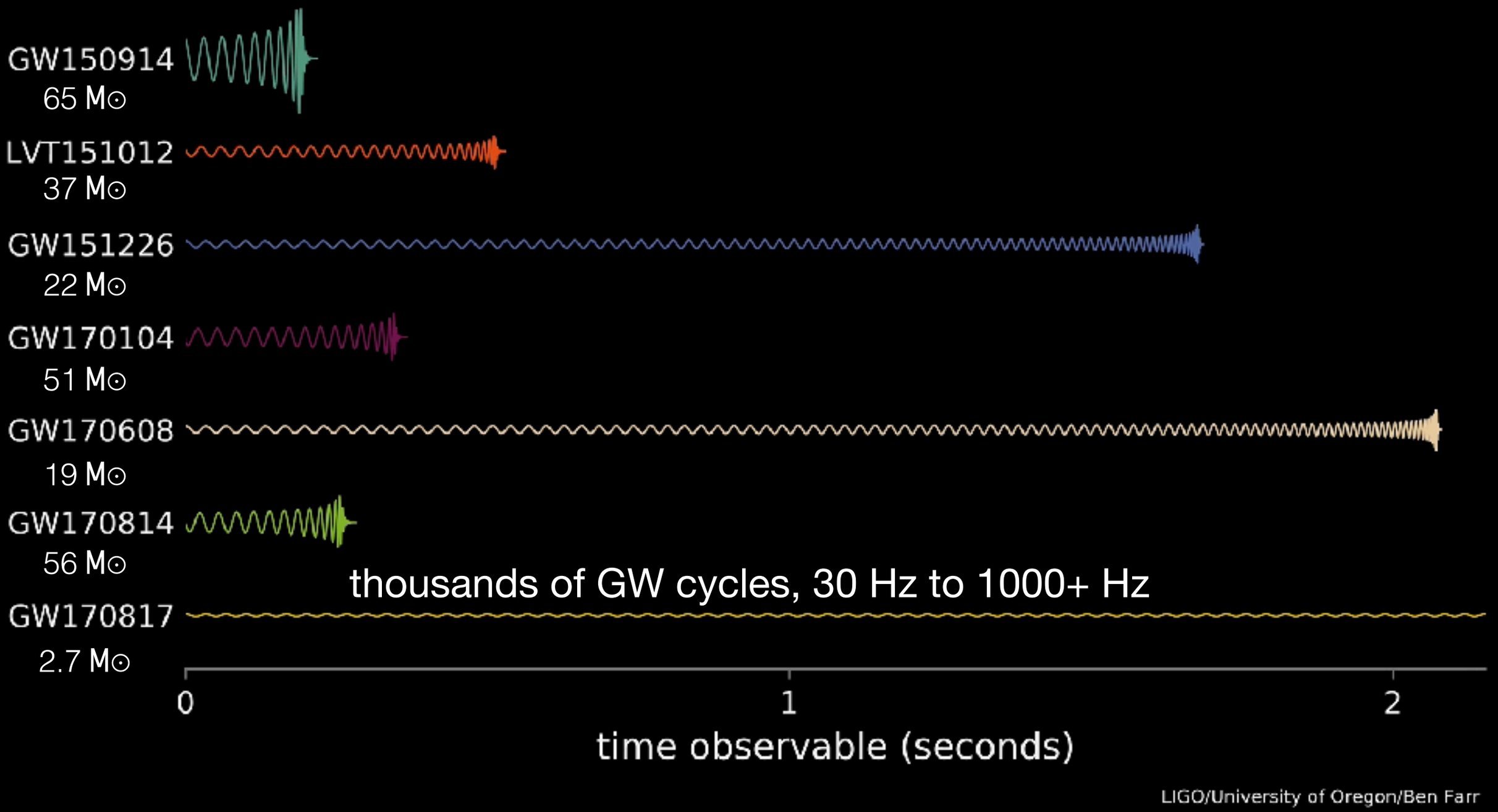
Generating millions of waveform models to compare with data.



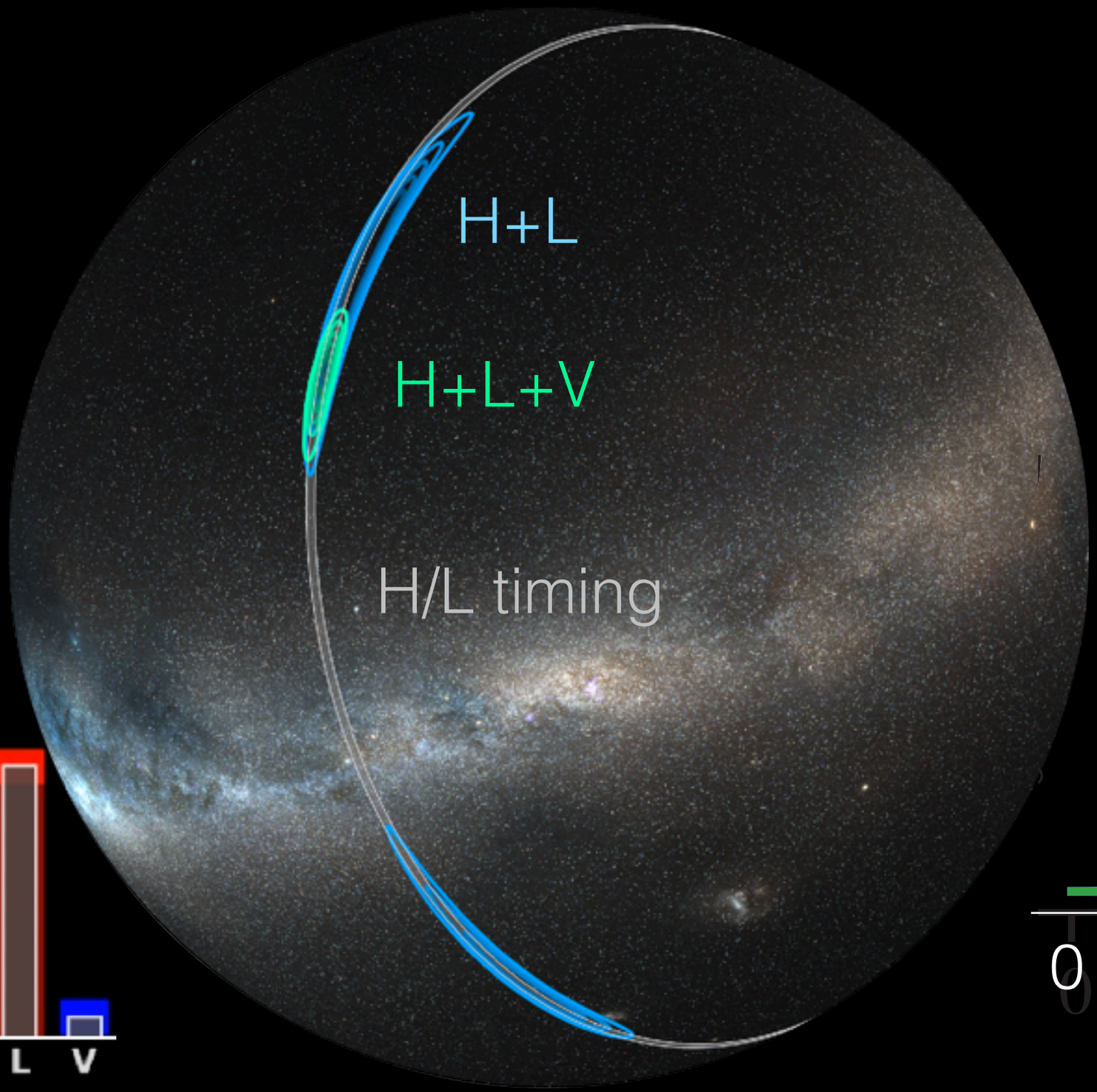
- LEFT: example estimate of masses in BBH system
- LSC/VSC http://arxiv.org/abs/1304.1775, Veitch *et al* https://arxiv.org/abs/1409.7215

UNIVERSITY OF BIRMINGHAM

Recovered Waveforms



Gravitational-wave localization



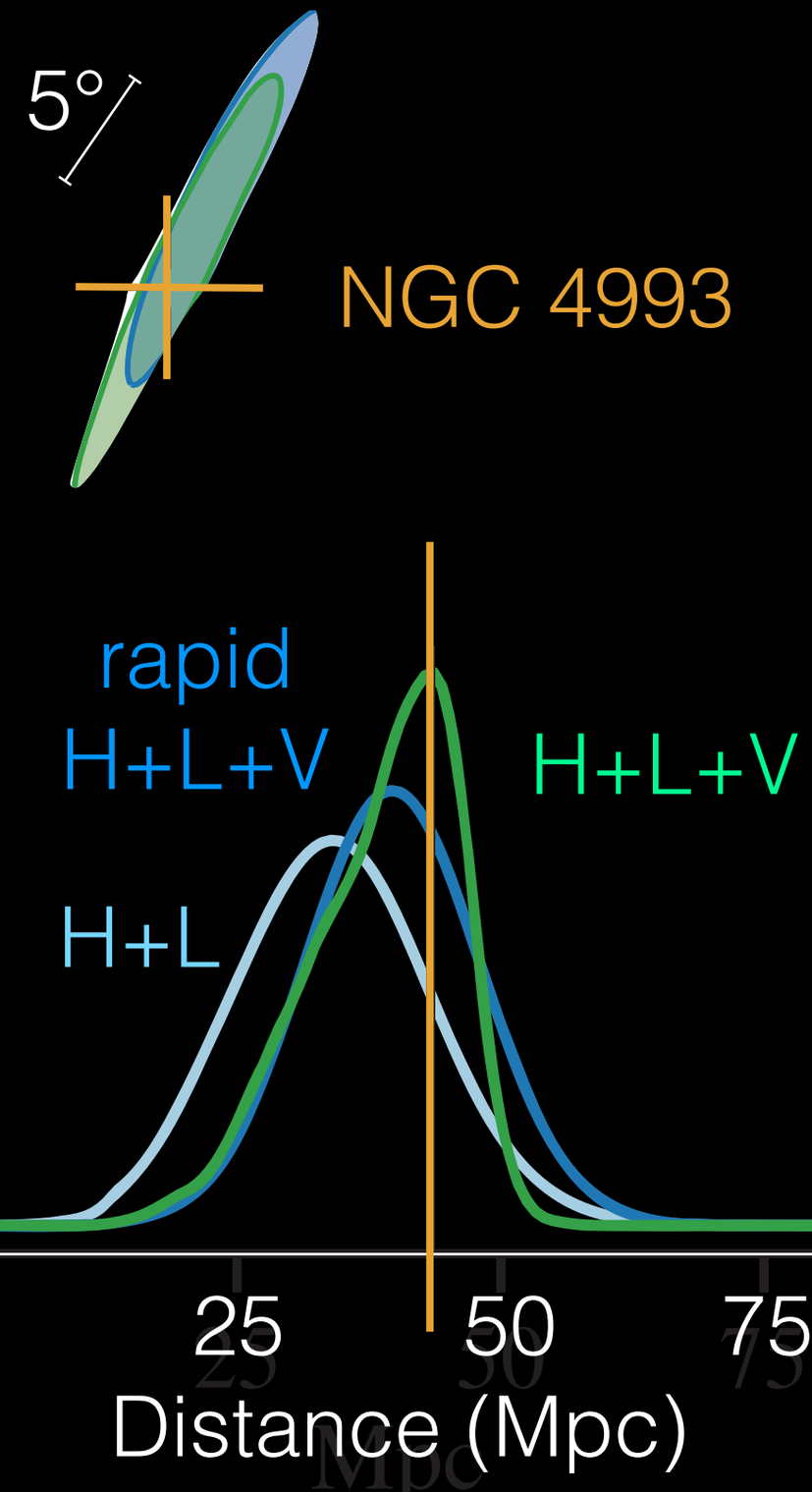
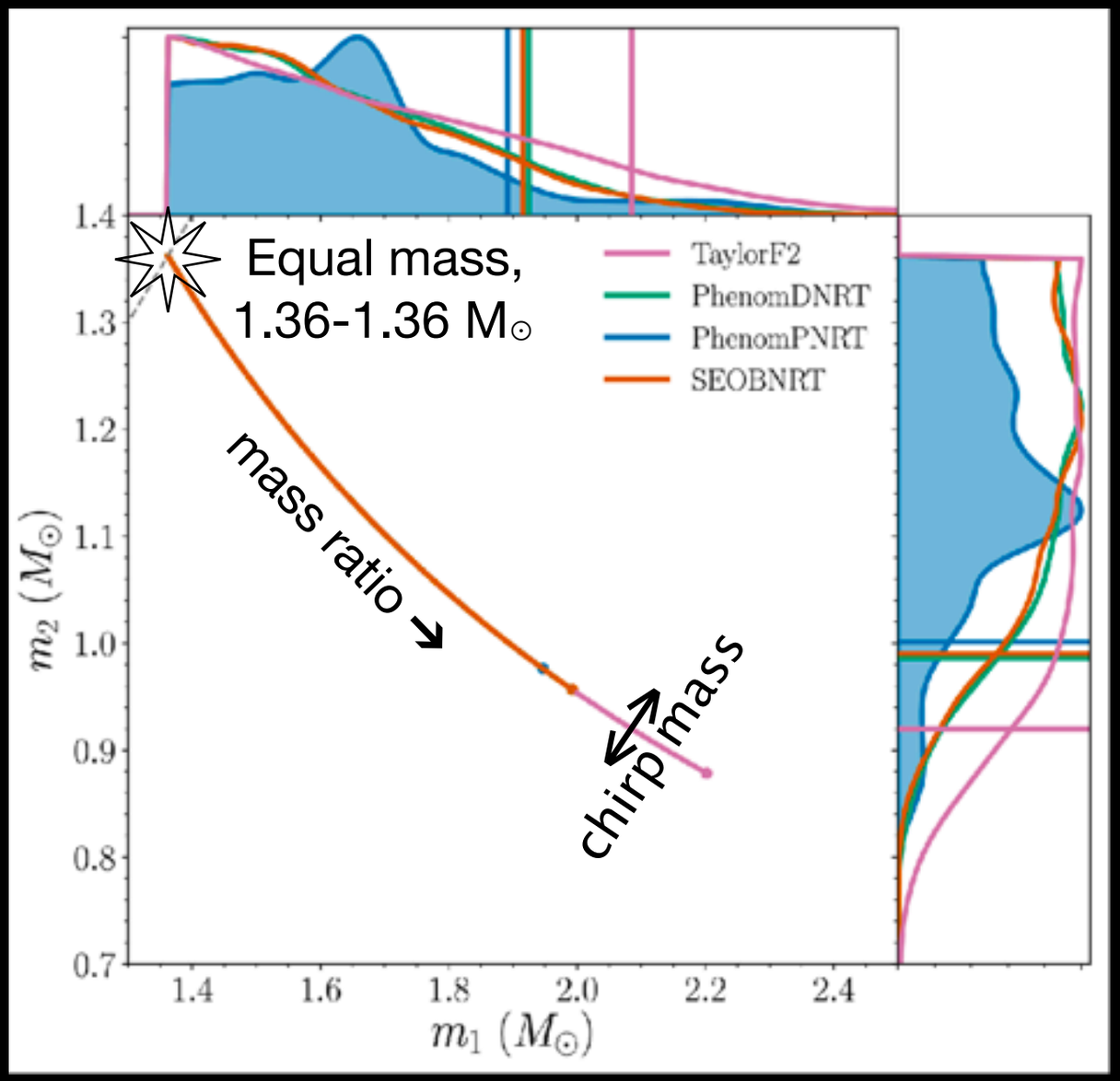


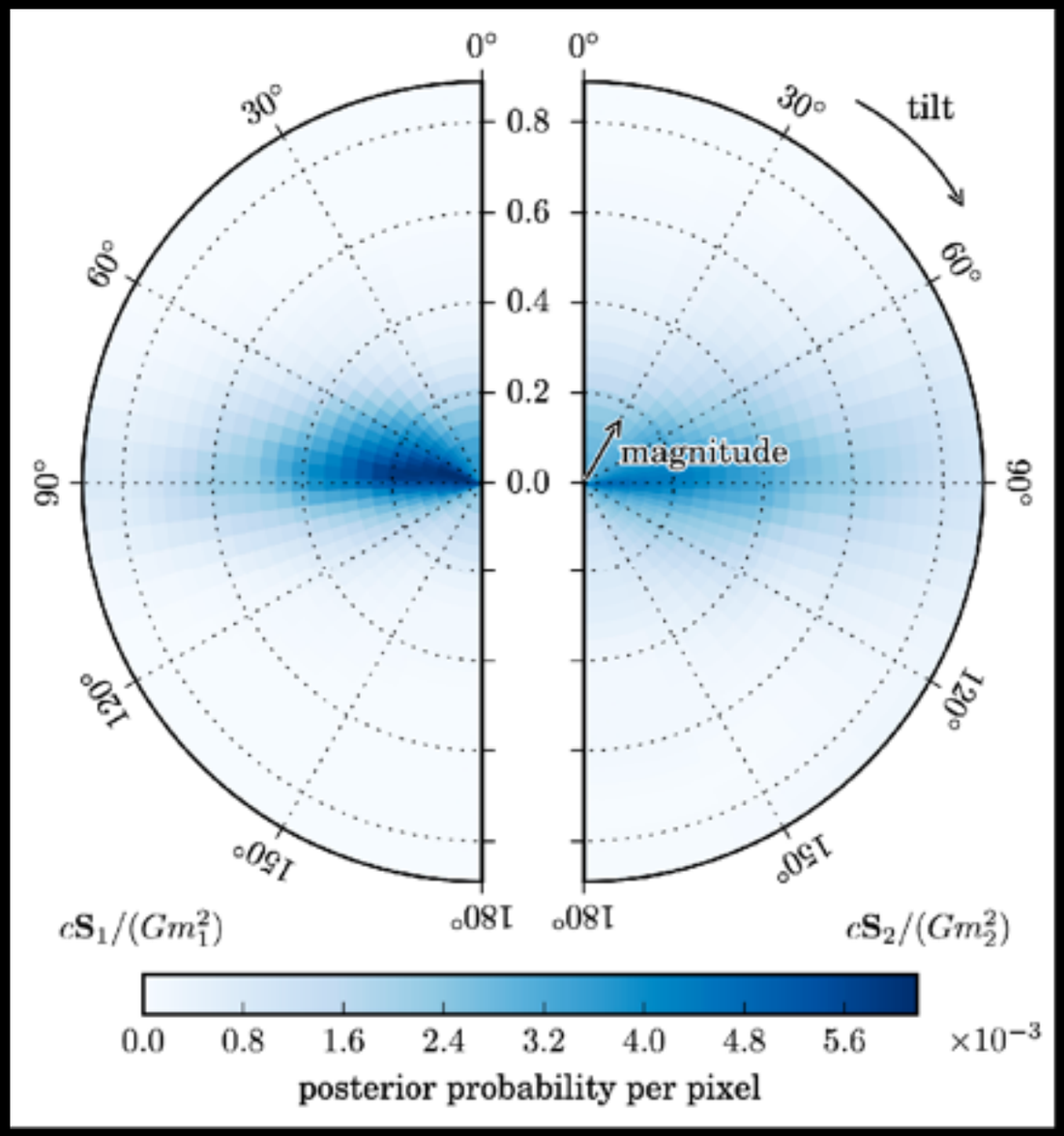
Image LIGO/Virgo/Leo Singer
(Milky Way image: Axel Mellinger)

LVC PRL 119, 161101 (2017)

GW170817 Masses and Spin

Minimal assumptions about source properties
(Talk Friday by Ben Lackey)

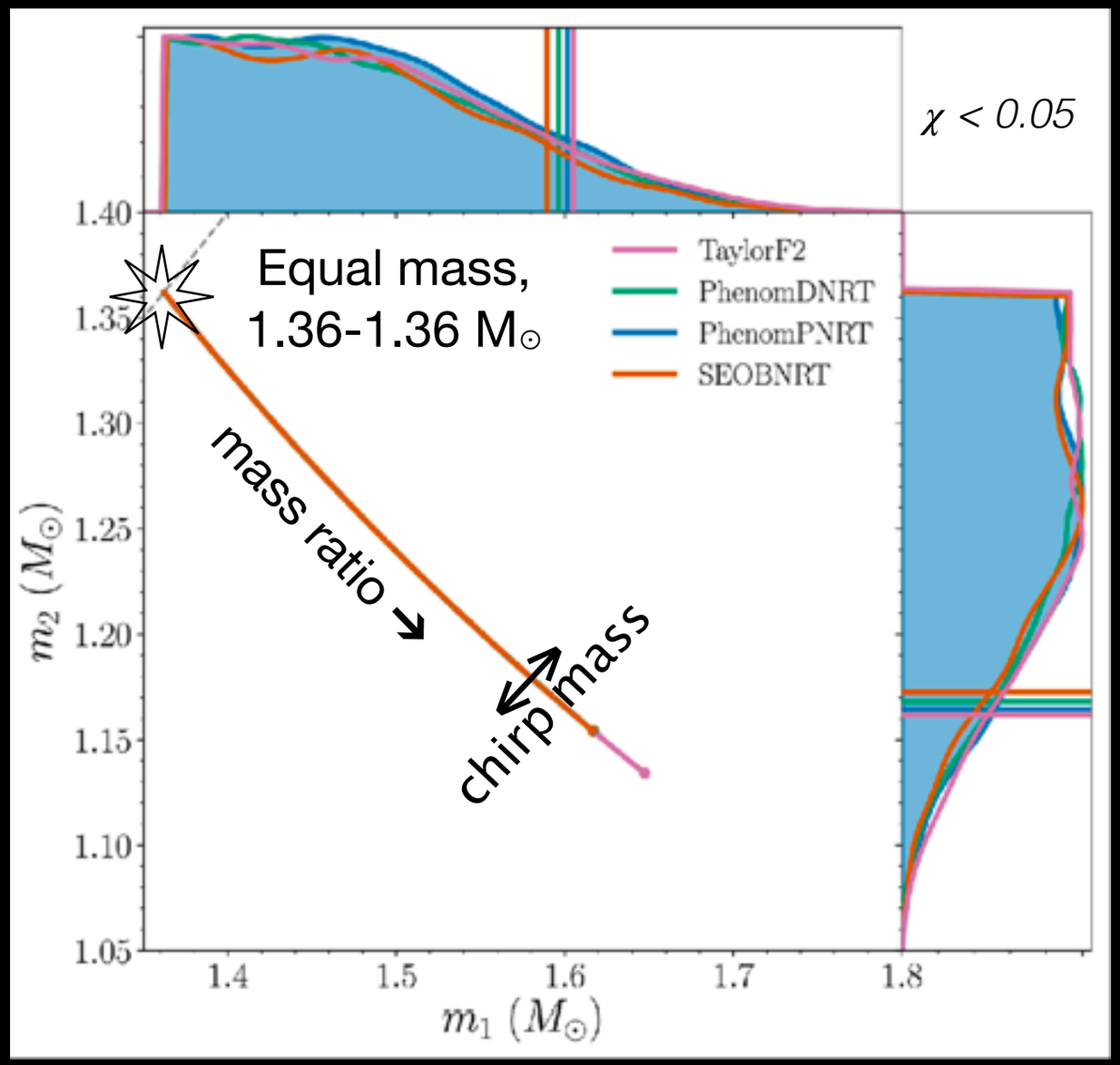


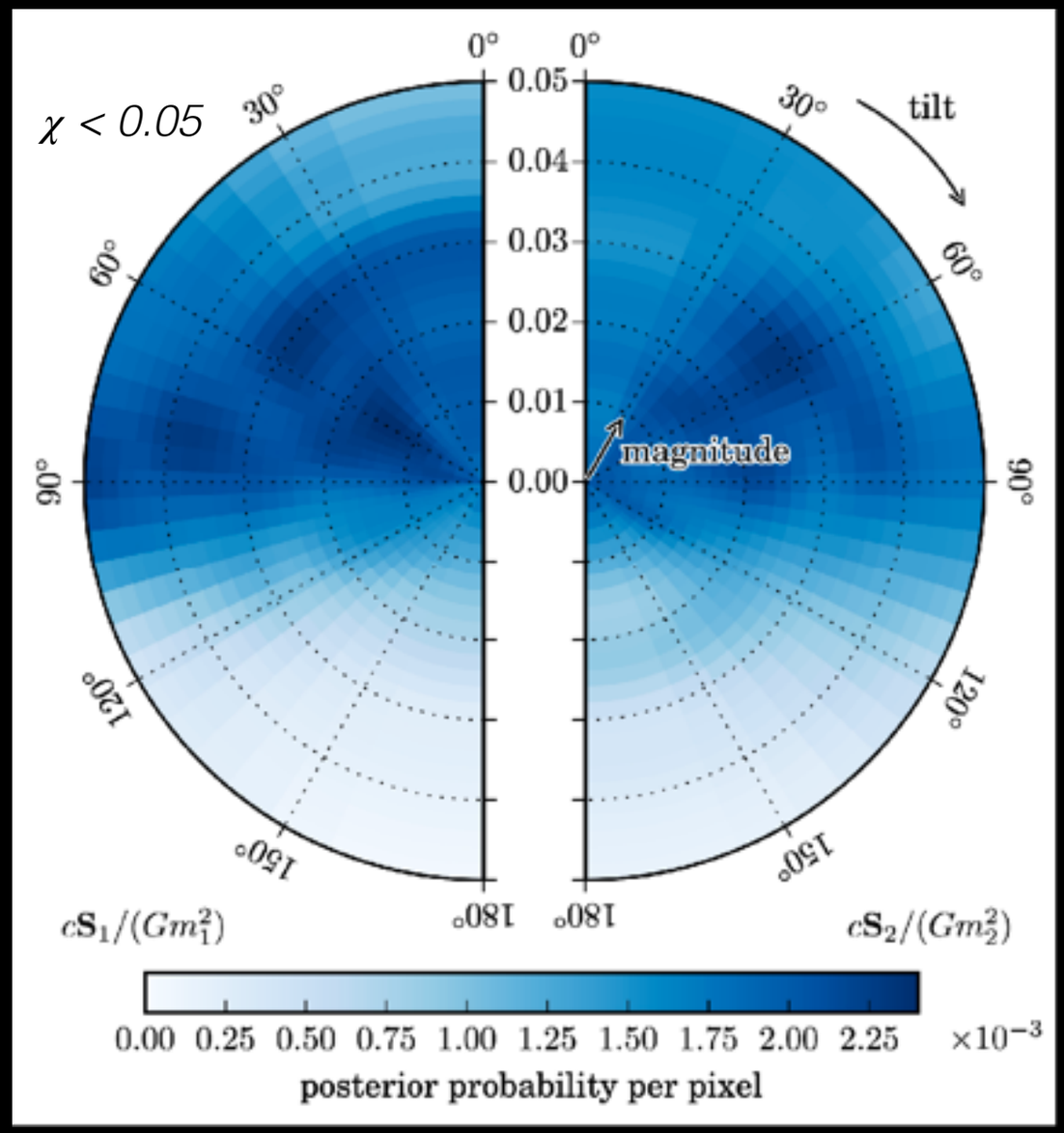


Update to initial results, LVC Source Properties 1805.11579

GW170817 Masses and Spin

Assume low spins, as seen in galactic systems.
Reduced mass/spin degeneracy, shift toward equal mass.



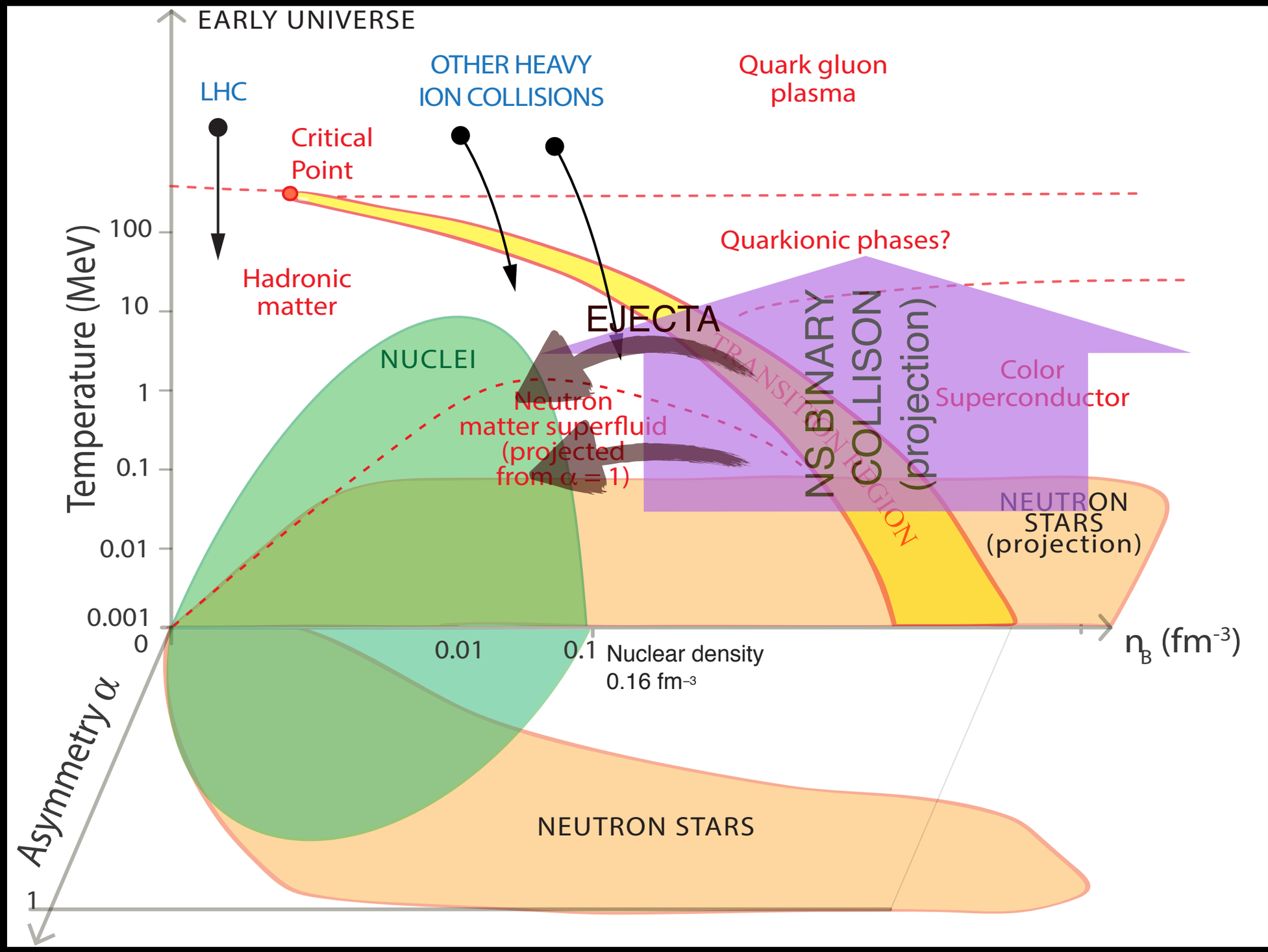


Update to initial results, LVC Source Properties 1805.11579

Neutron-star merger: Last 30 ms

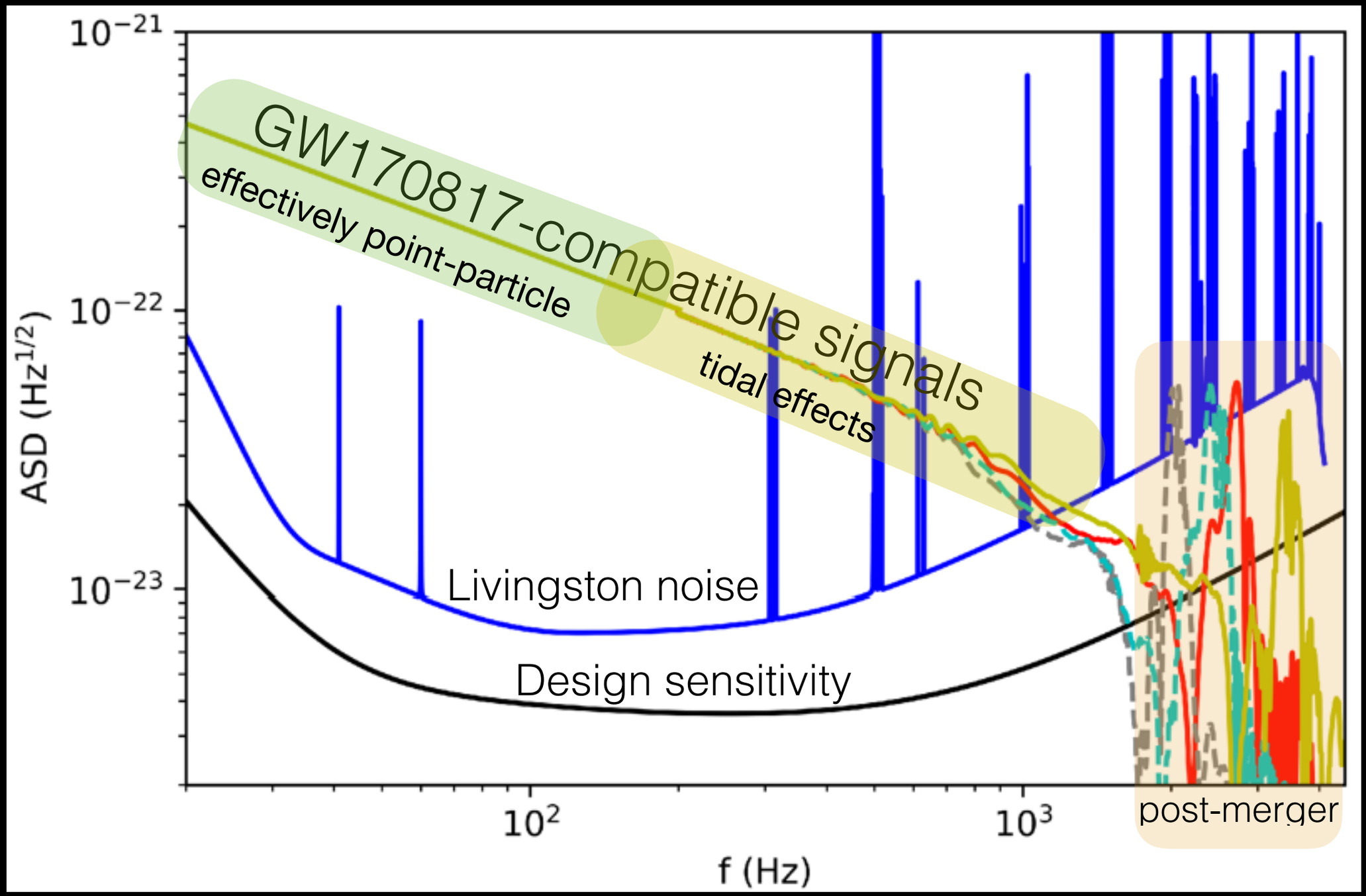
Simulation compatible with GW170817 parameters
Other scenarios are possible; post-merger GW not recovered
T. Dietrich, S. Ossokine, H. Pfeiffer, A. Buonanno (AEI)

Matter in GW170817: An astrophysical collider



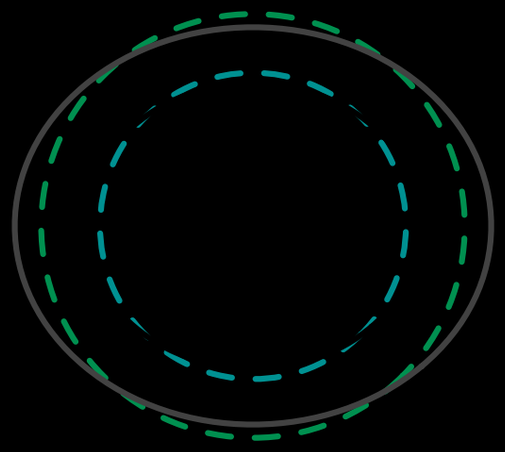
Base figure from Watts et. al. "Probing the neutron star interior and the Equation of State of cold dense matter with the SKA" arxiv:1501.00042

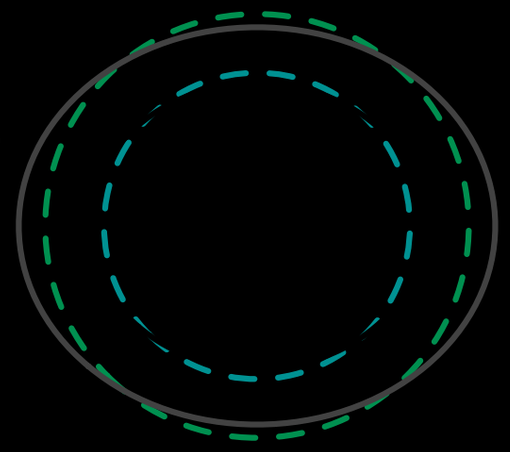
Matter Impact on GW170817



LSC/Virgo/E.Leon. Noise curves from LSC/Virgo SOURCE PROPERTIES, LIGO-T0900288-v3
Numerical simulation data (above ~500 Hz) courtesy Tim Dietrich (AEI/FSU/BAM Collaboration)
Simulations published in Phys. Rev. D95(12):124006 and Phys. Rev. D95(2):024029

Tidally deformed stars





- Response of a given neutron star characterized by its **tidal deformability** or **polarizability:**

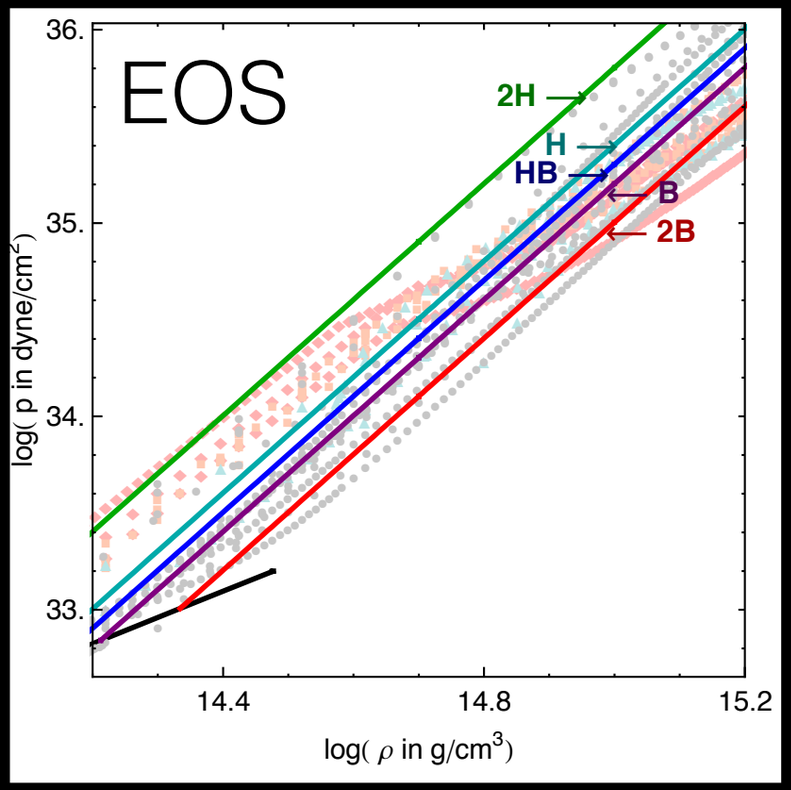
$$\lambda = \frac{Q}{\mathcal{E}} = \frac{\text{size of quadrupole deformation}}{\text{strength of external tidal field}} = \frac{2}{3} k_2 R^5$$

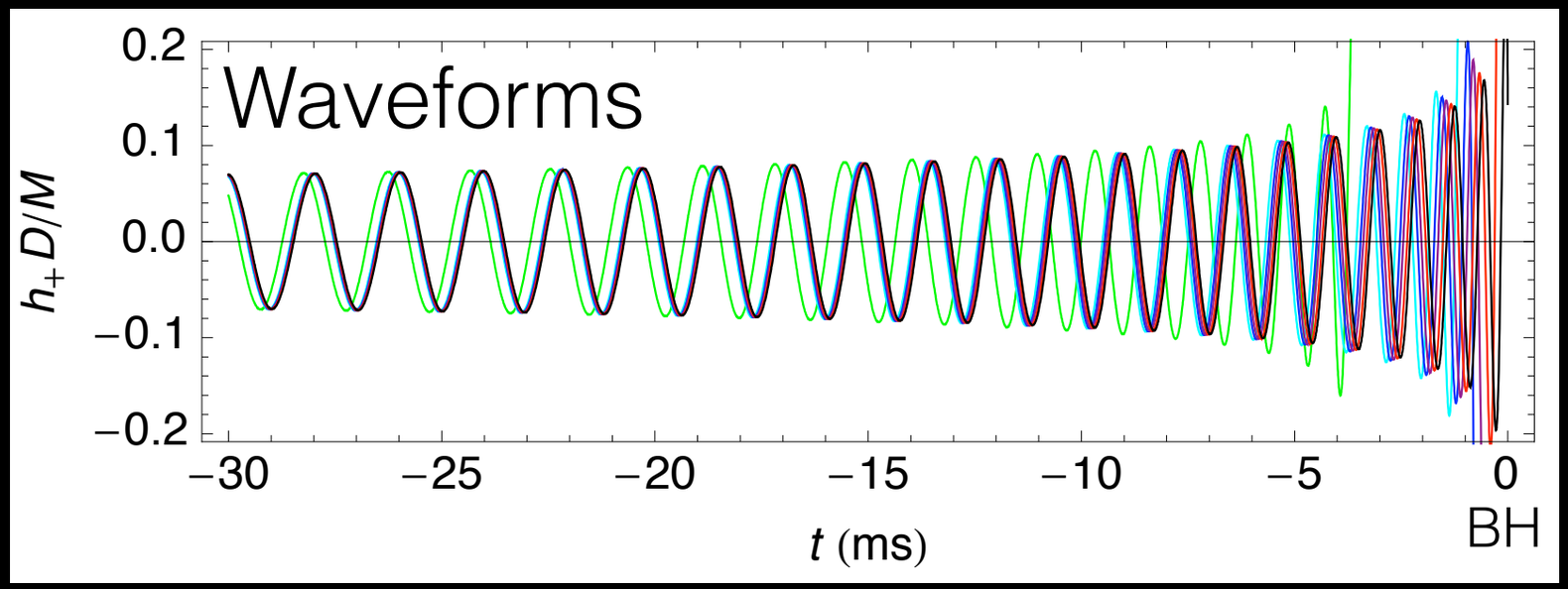
- R radius of star
- k_2 *Relativistic* love numbers (Damour 1983)
  - Mass distribution inside the star

Inspiral matter dependence

- Tides accelerate inspiral - extra energy into deforming stars, extra quadrupole moment.

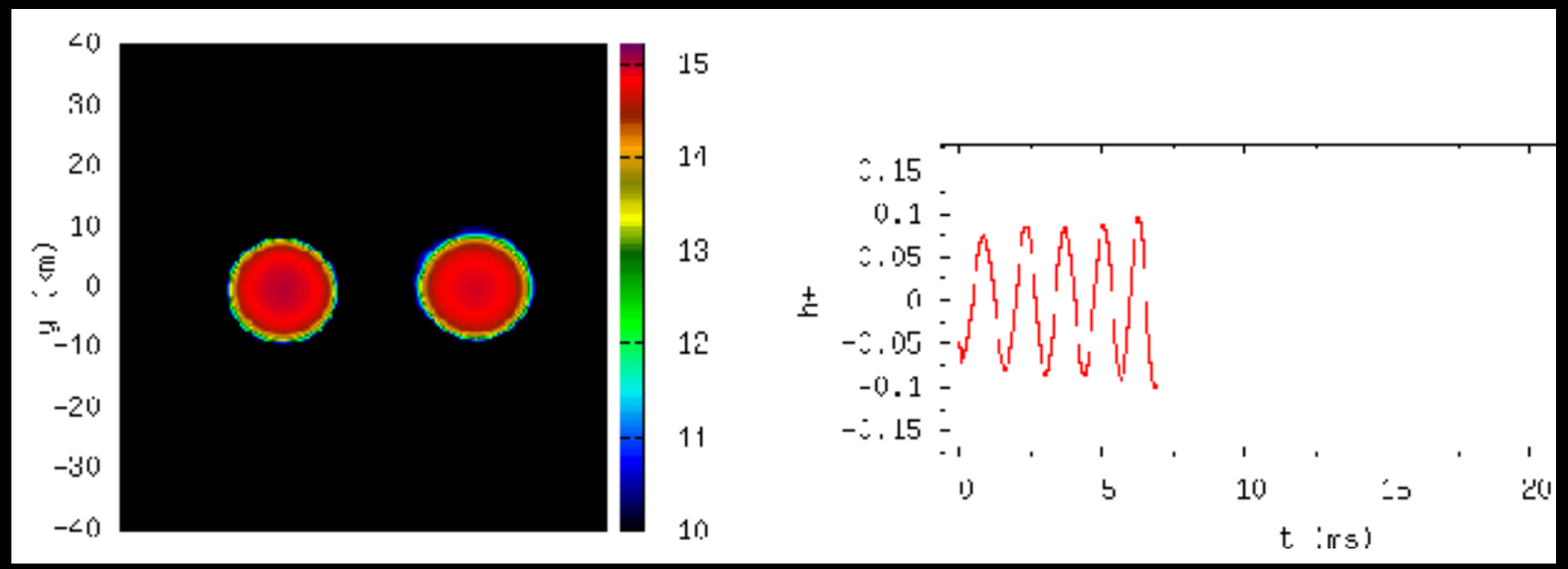
Flanagan & Hinderer 2008





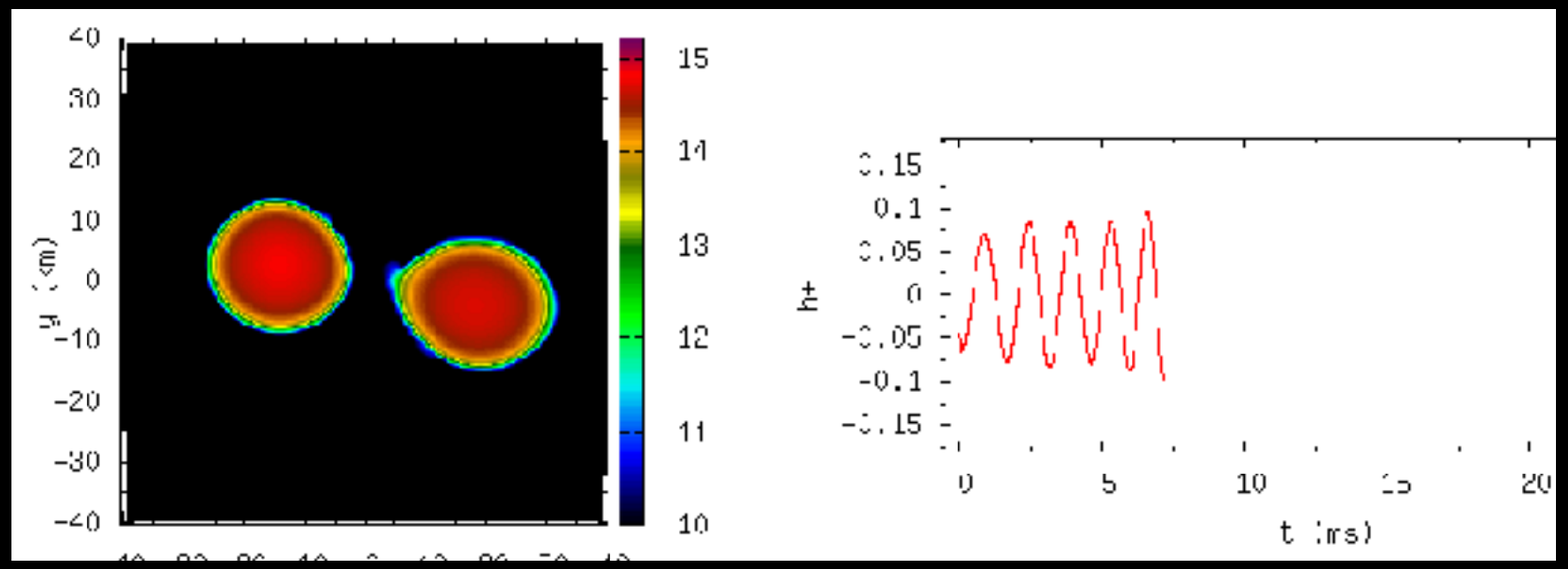
Higher EOS pressures → larger radii → more deformation

Merger matter dependence



Compact stars: merge at higher frequency, more similar to BBH

Numerical simulations: K. Hotokezaka, YITP



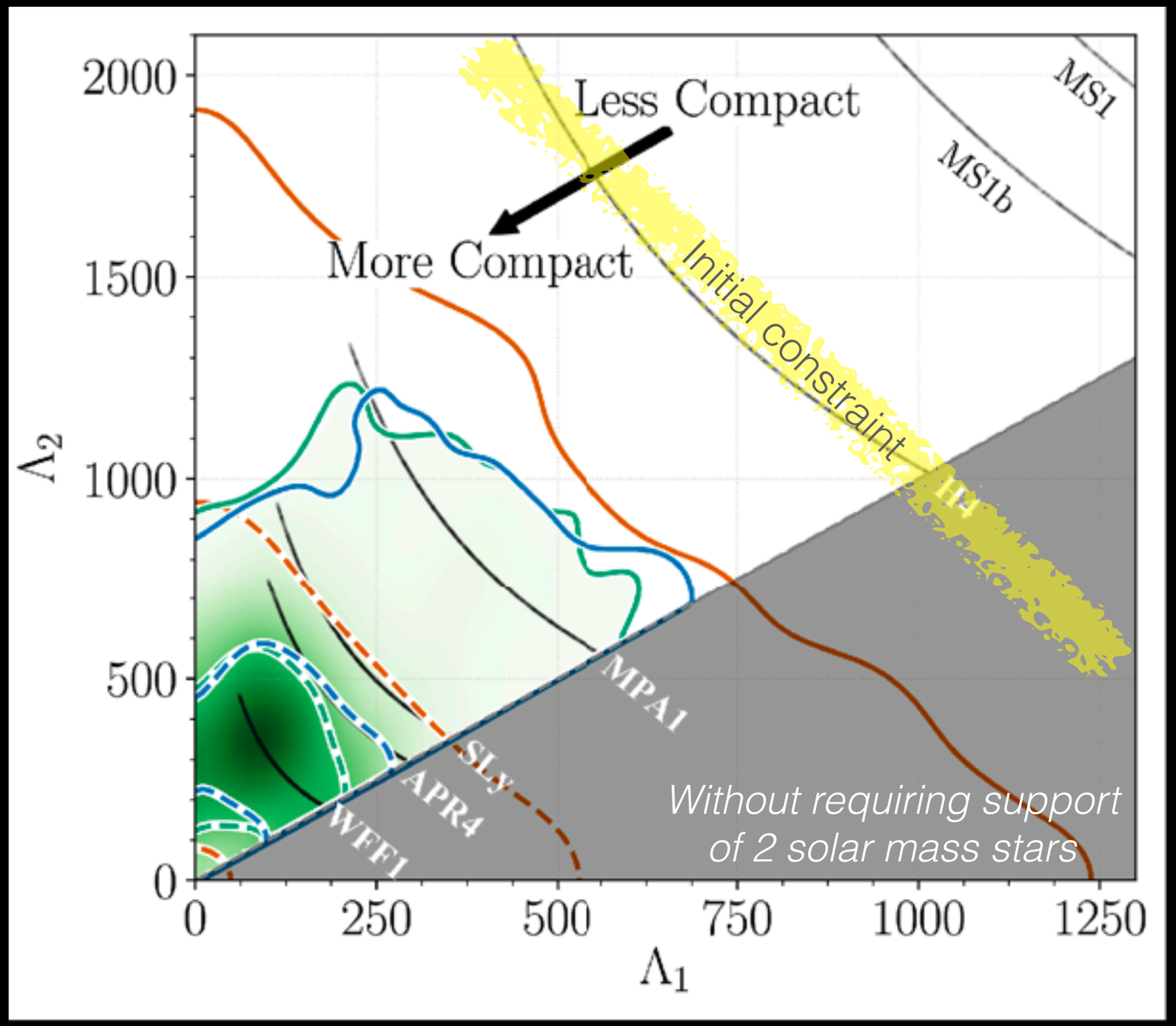
Large-radius stars: collide earlier, merge at lower frequency

Simulations verify/calibrate waveform models for LSC/VSC analyses; functions of star Λs (Bernuzzi, Dietrich, & Tichy 1706.02969)

Tidal measurements from GW170817

$\Lambda_{1.4} = 190^{+390}_{-120}$

$\Lambda_{1.4} < 800$



Discovery

Restricted frequencies, simplified waveform model, independent Λ

Updated properties

Independent Λ

Any spin $\tilde{\Lambda} \leqq 630$,

Low spin $\tilde{\Lambda} = 300^{+420}_{-230}$

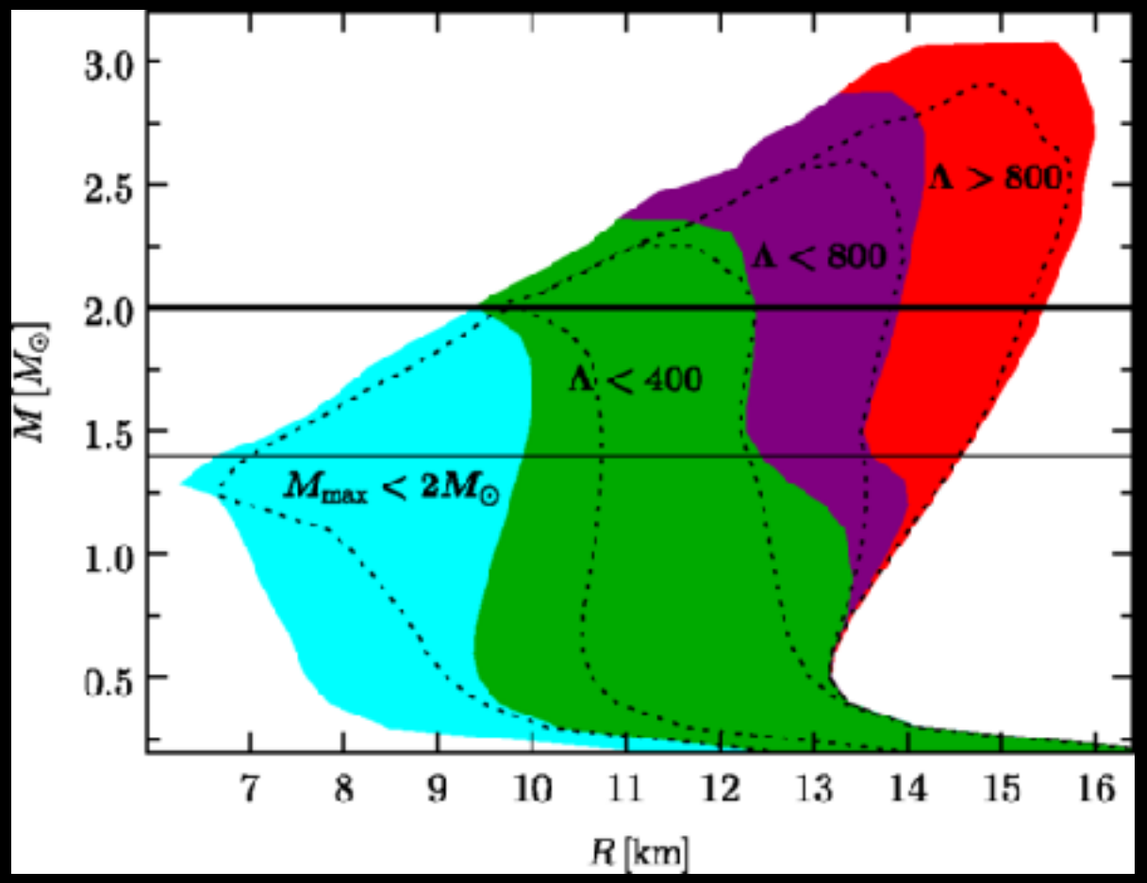
EOS

Quasi-universal relation between components

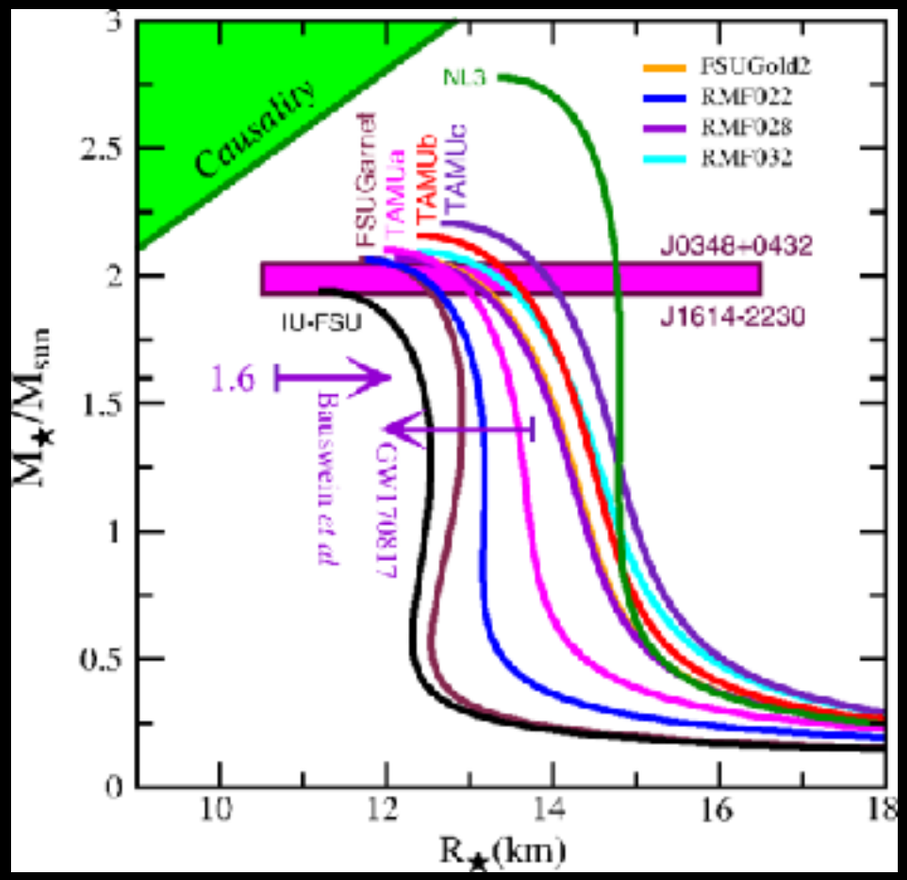
Common spectral-parameterized eos

LSC-Virgo EOS 1805.11581 Source Properties 1805.11579

Implications of first limit: $\Lambda_{1.4} \leqq 800$



Annala et al
Phys. Rev. Lett. 120, 172703
9.9 km < $R_{1.4}$ <13.6 km

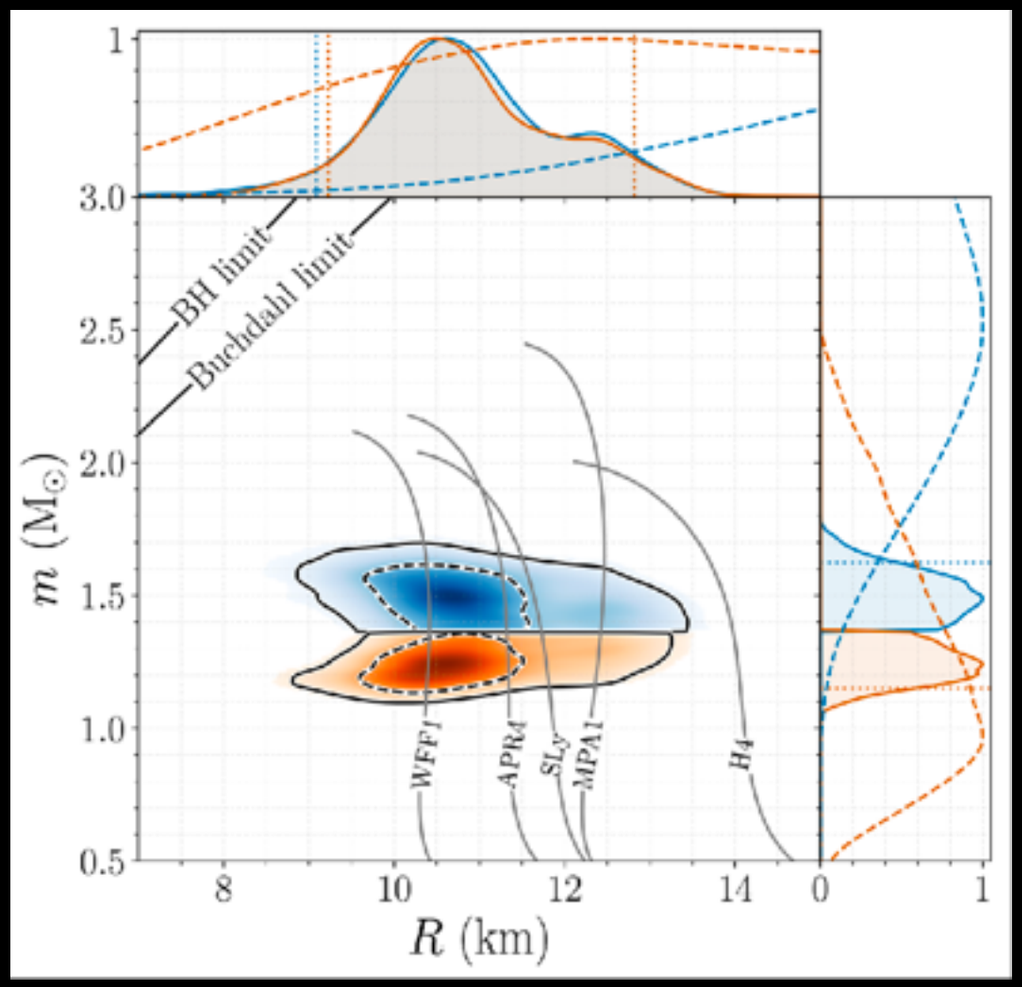


Fattoyev et al
Phys. Rev. Lett. 120, 172702
$R_{1.4}$ < 13.76 km

- See also: Nandi and Char ($R_{1.4} \leq$ 13.2–13.5 km), Raithel et al (R < 13 km), Most et al (12.00 km < $R_{1.4}$ <13.45 km) , Tews et al ($R_{1.4}$ <13.6 km) …
- Independent common-radius result of De et al (8.7 km < R <14.1 km)

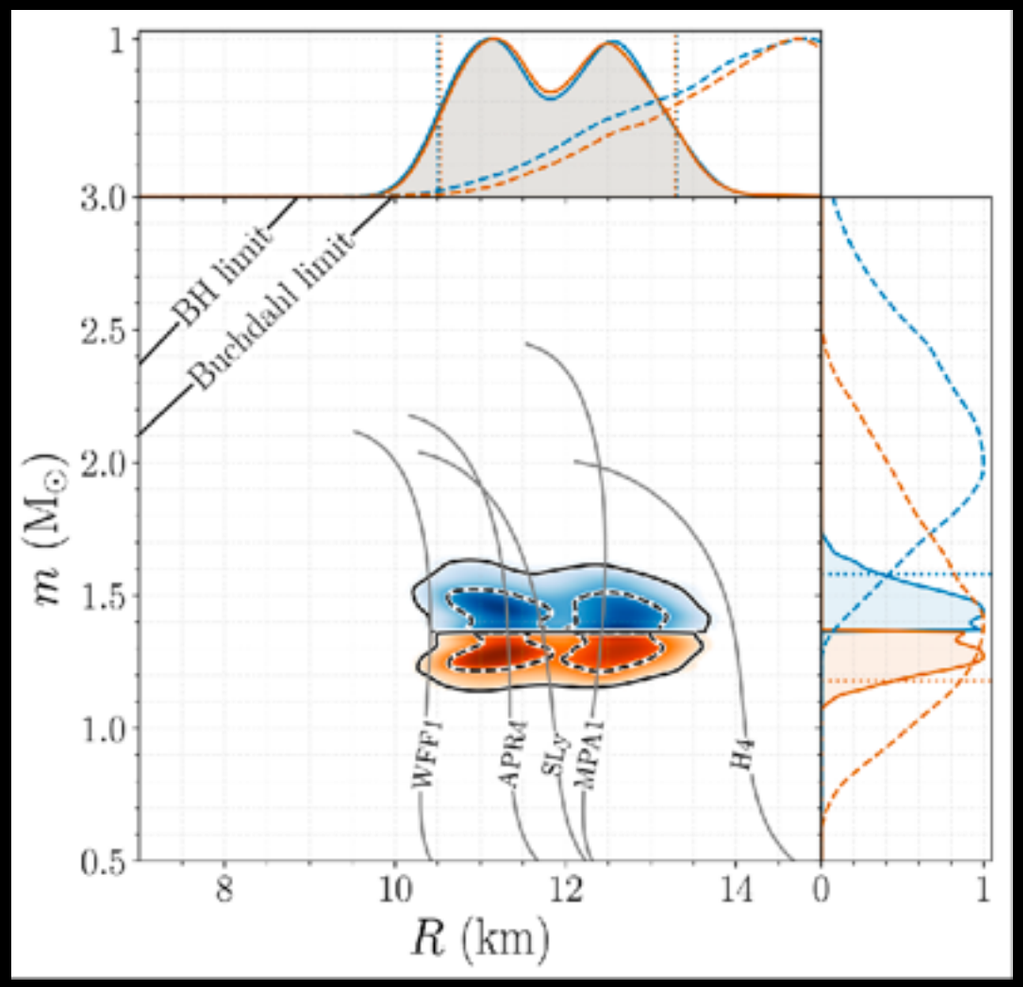
New Common-EOS Radius constraints

$R_1=10.8^{+2.0}_{-1.7}$, $R_2=10.7^{+2.1}_{-1.5}$



Quasi-universal Λ_1-Λ_2 & Λ-R
(similar w/ spectral eos)

$R_1=11.9^{+1.4}_{-1.4}$, $R_2=11.9^{+1.4}_{-1.4}$

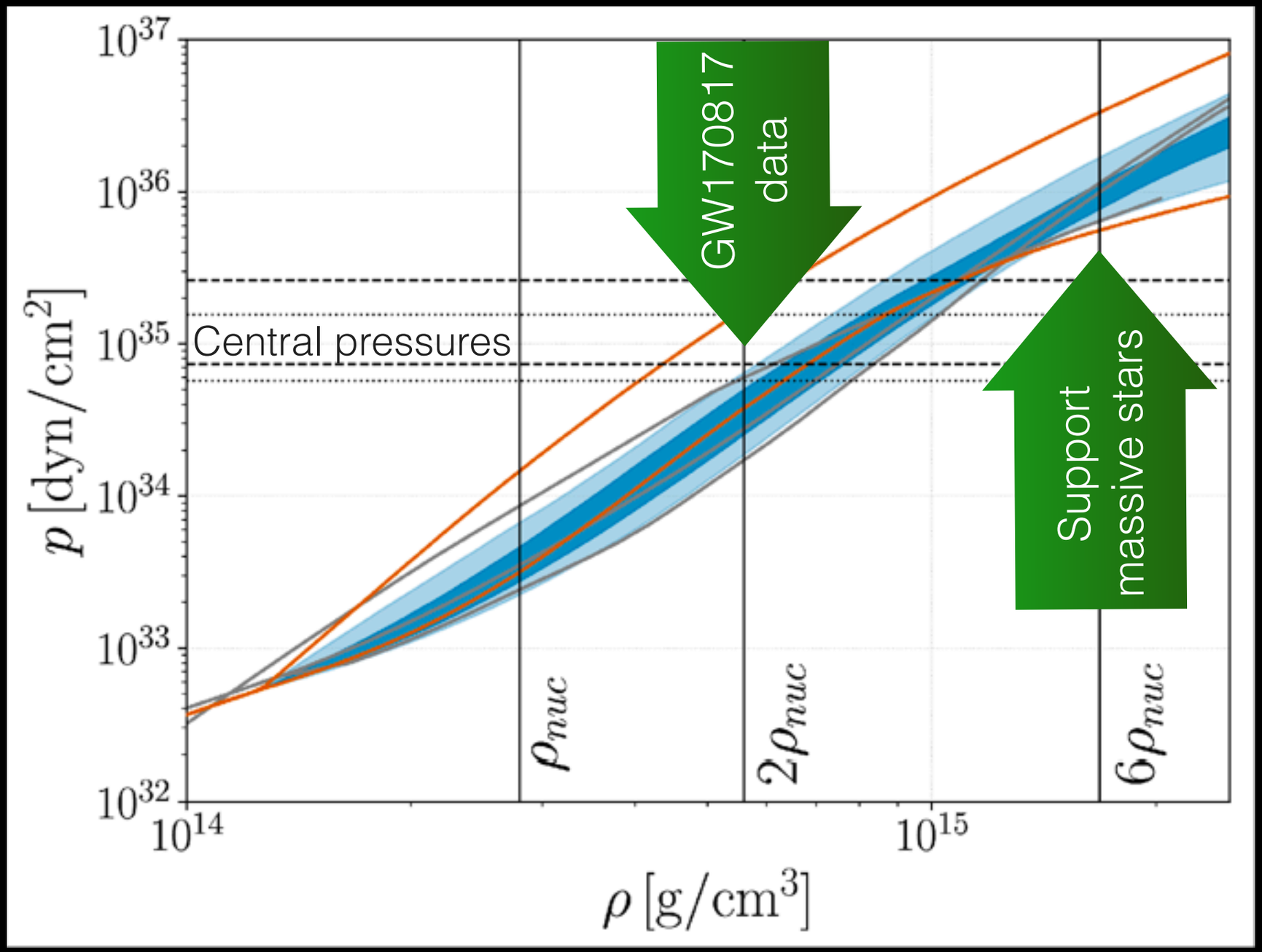


Spectral parameterized eos,
AND support of 1.97 M_{sun} star

LSC-Virgo EOS 1805.11581

GW170817 + M_{max} >1.97 M⊙

Twice saturation: 22^{+11}_{-17} MeV fm^{-3} (GW only: 18^{+7}_{-15} MeV fm^{-3})



Prior
90% range

Posterior
90% (50%) range

For comparison:
H4 (top)
APR4
WFF1 (bottom)

Overlap x-ray constraints (e.g. Steiner, Lattimer, Brown 2010)

LSC-Virgo EOS 1805.11581

And there was light!

X-ray

Gamma ray

UV

Optical

Infrared

Radio

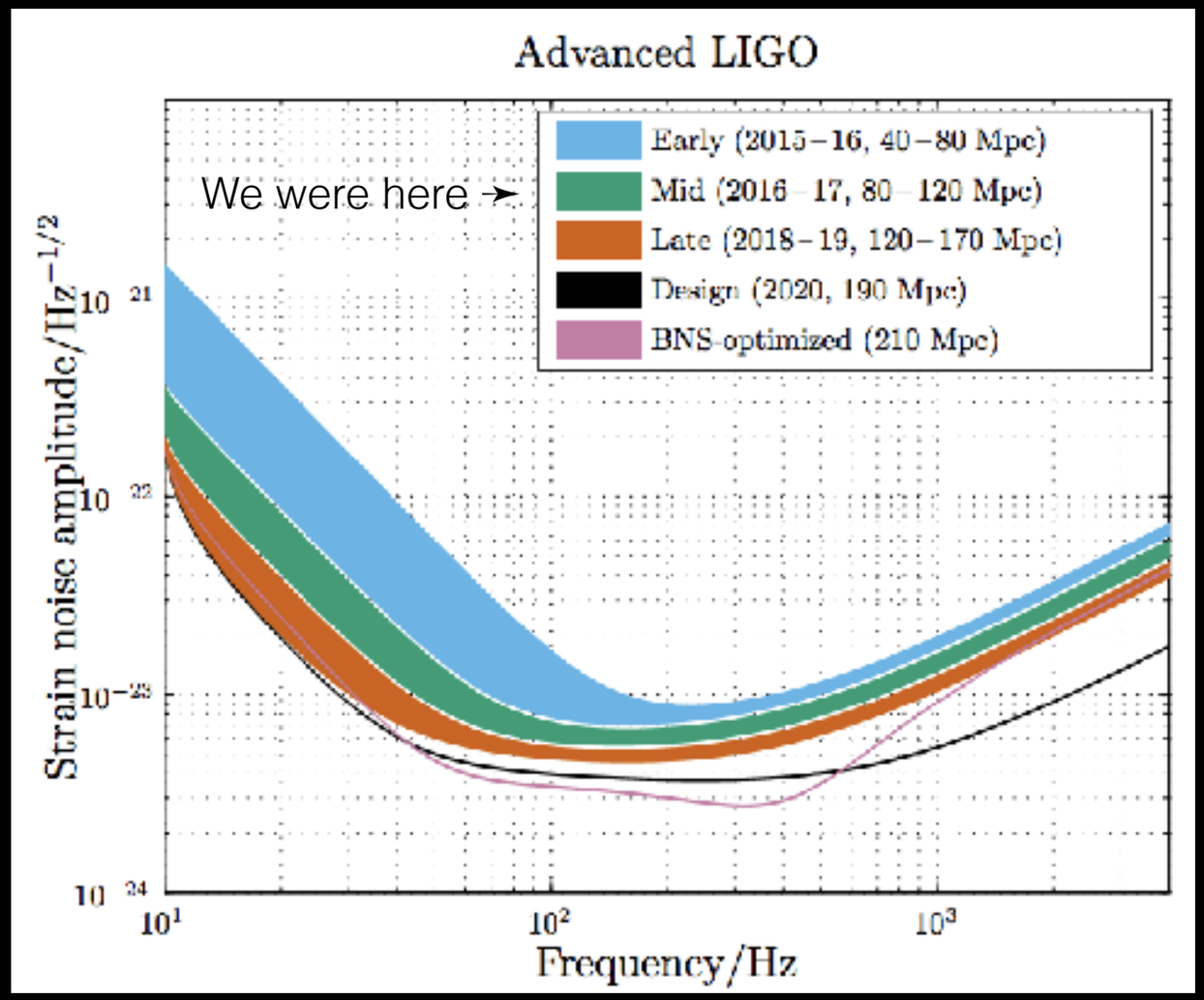
Upcoming talks: additional implications for dense matter

LVC et al ApJL 848 L13 2017, LVC et al Nature 551 85–88 2017, … … … … … … …

NRAO/AUI/NSF/D. Berry

Observing Plan (under development)

- Goal for next few years: improve BNS range by factor ~2, high-frequency sensitivity by factor ~5
- Combine information from multiple detections?



GW170817-based rate

320–4740 Gpc^{-3} yr^{-1}

LSC/Virgo PRL 119, 161101 (2017)

1000 Gpc^{-3} yr^{-1}

⬇

~40 yr^{-1} detected w/ Advanced LIGO Design

LSC/Virgo Class.Quant.Grav.27:173001 (2010)

KAGRA/LIGO/Virgo Observing scenarios, Living Reviews in Relativity; 21:3; 2018

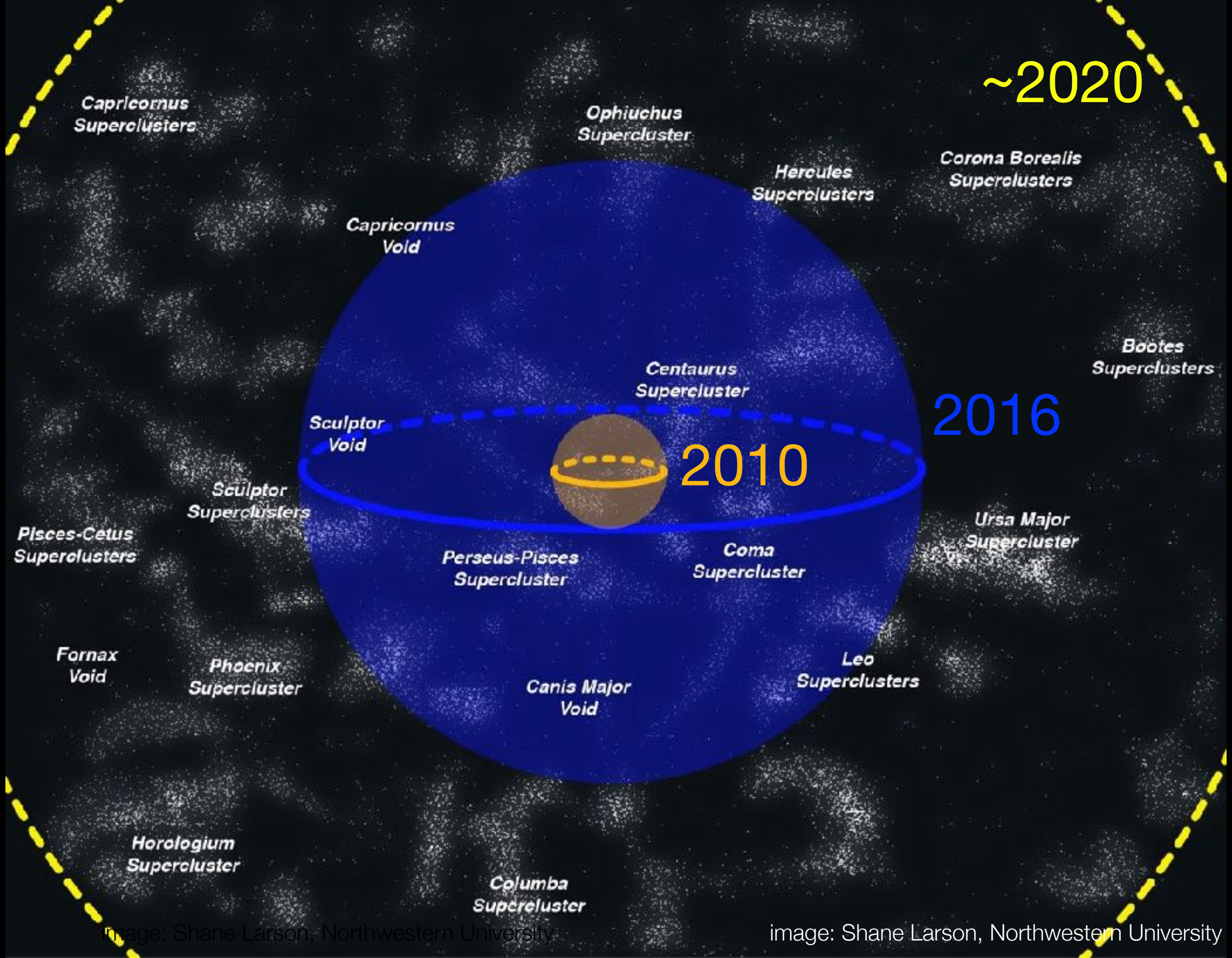
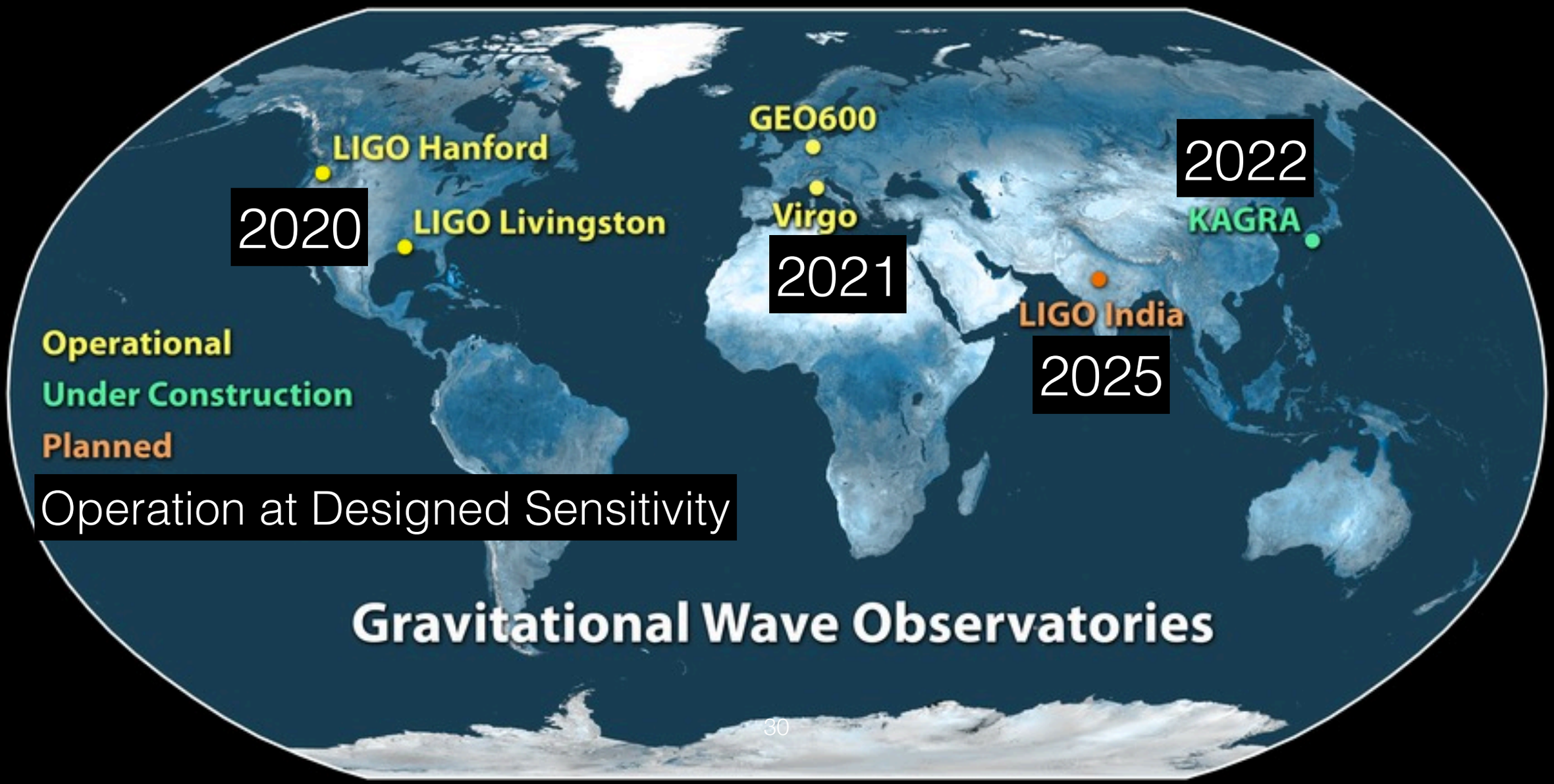


image: Shane Larson, Northwestern University

image: Shane Larson, Northwestern University

Thank you!

International network of gravitational-wave observatories



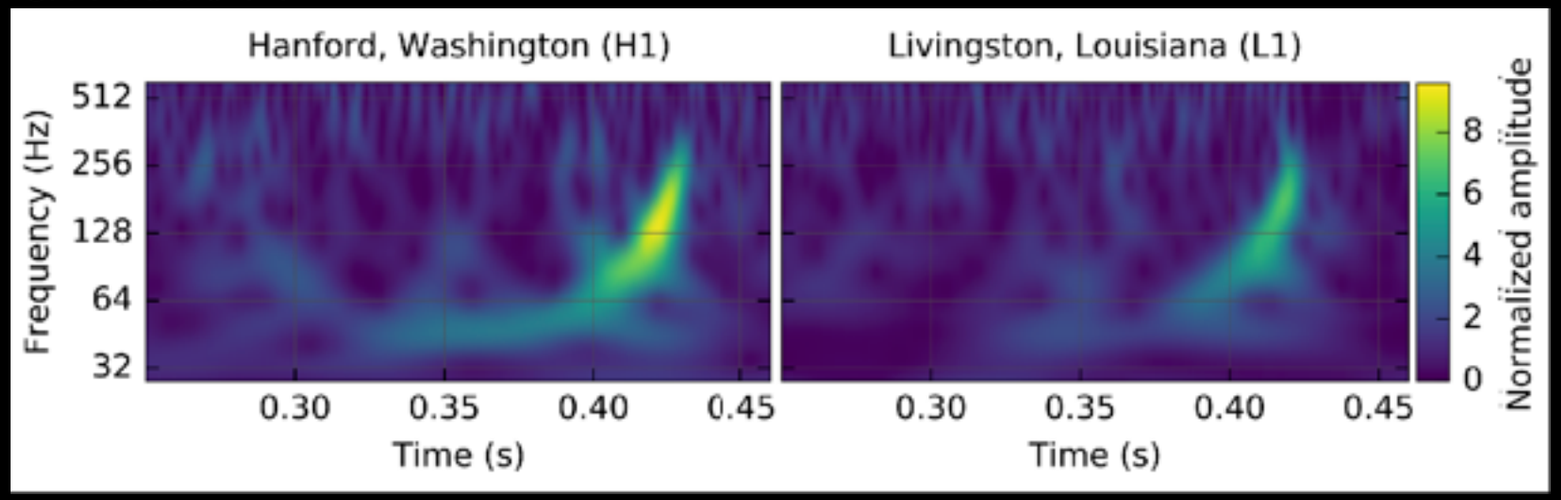
Inspired by TJ Massinger

LIGO / Caltech

BBH detections

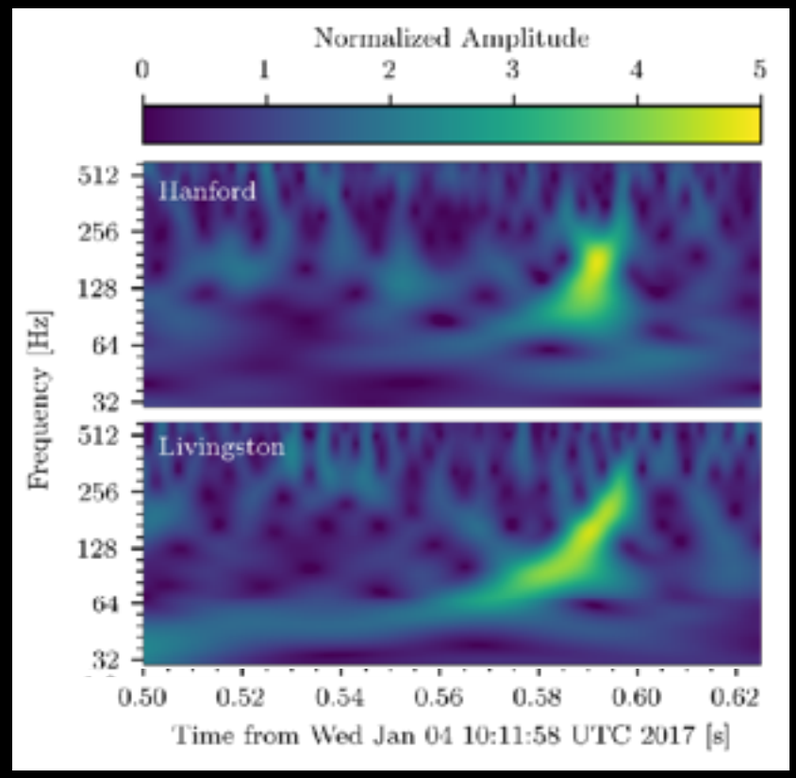
GW150914

PRL 116, 061102 (2016)



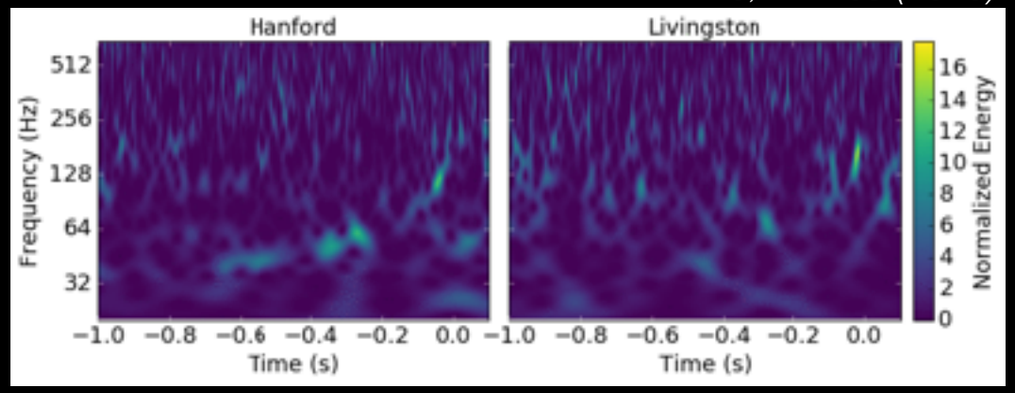
PRL 118, 221101 (2017)

GW170104



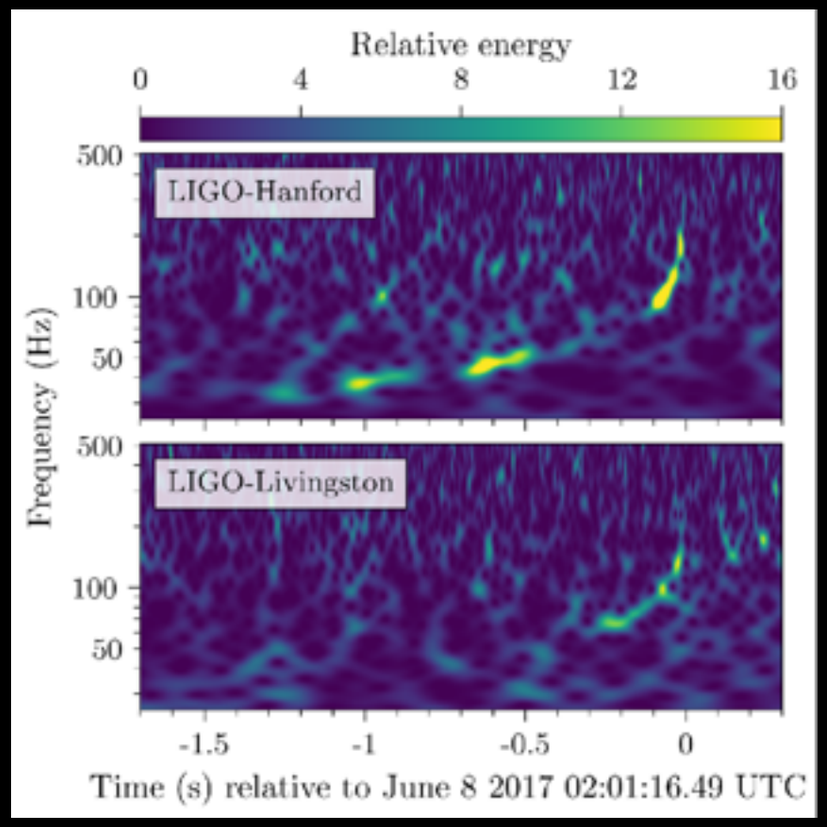
GW151226

PRL 116, 241103 (2016)



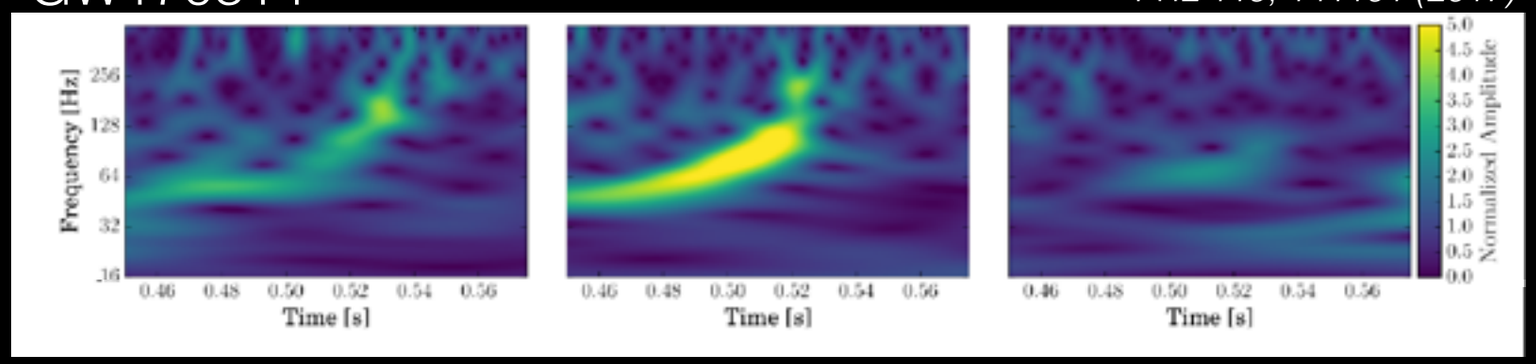
< 2 s of data shown for each

GW170608



GW170814

PRL 119, 141101 (2017)



Simulations of BBH sources

Time
to merger: 0.454 s

GW150914

M=36,29Msun
D=440Mpc

GW151226

M=14,7Msun
D=440Mpc

M=31,19Msun
D=880Mpc

GW170104

M=12,7Msun
D=340Mpc

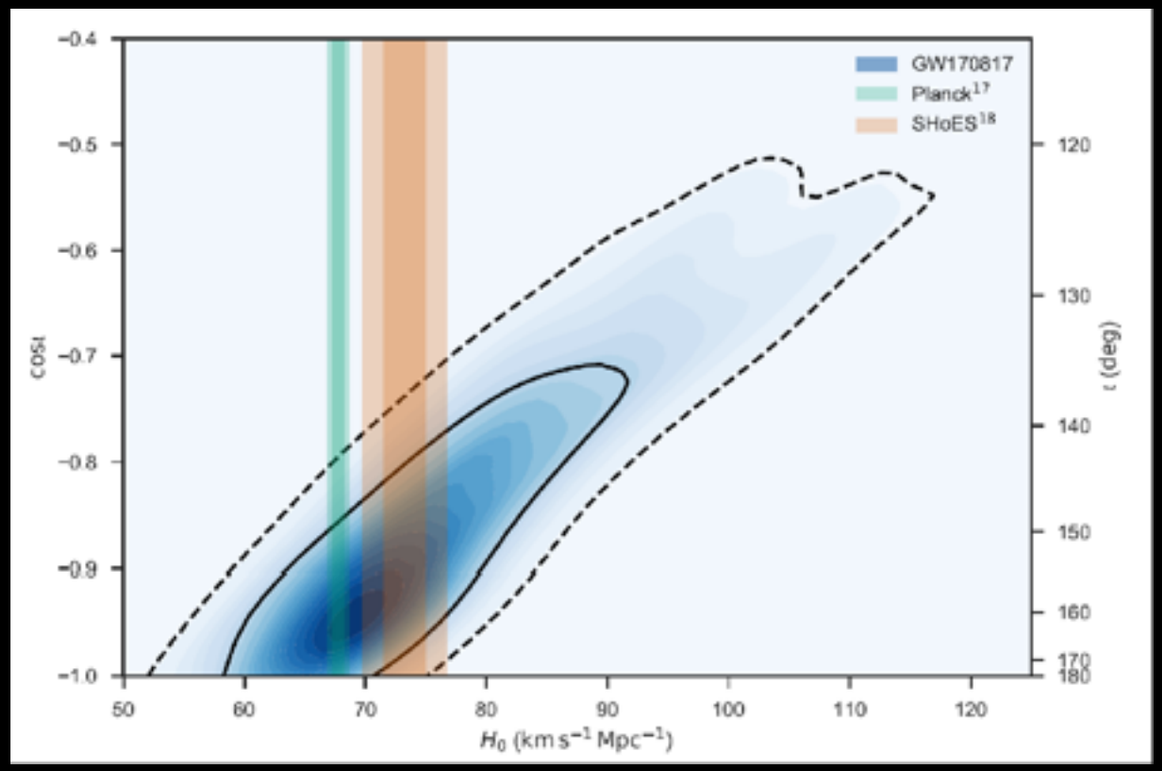
GW170608

M=31,25Msun
D=540Mpc

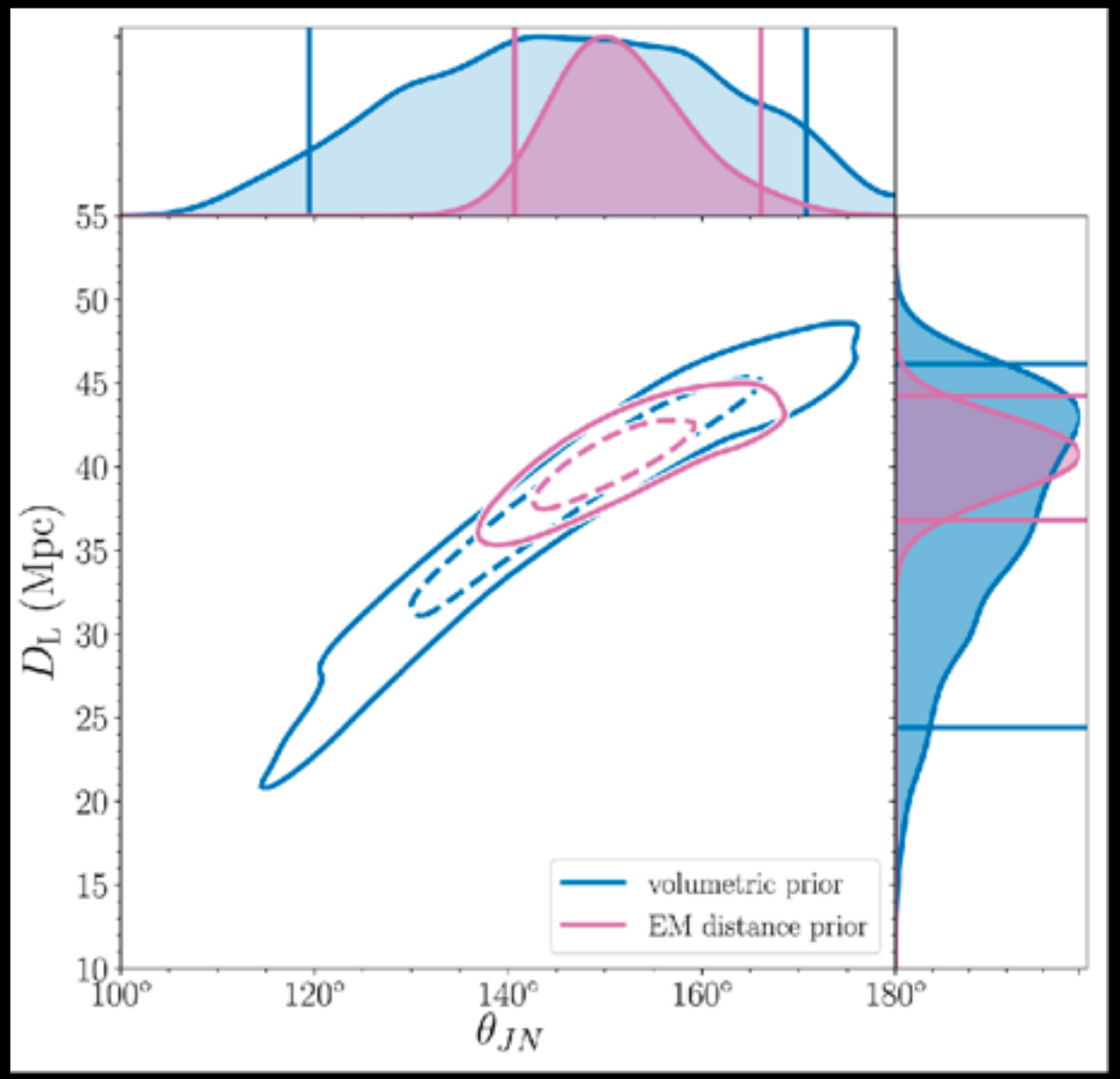
GW170814

Known host galaxy

- Hubble constant / inclination angle constraint
  LVC et al Nature 551 85–88 2017



LVC Source Properties 1805.11579



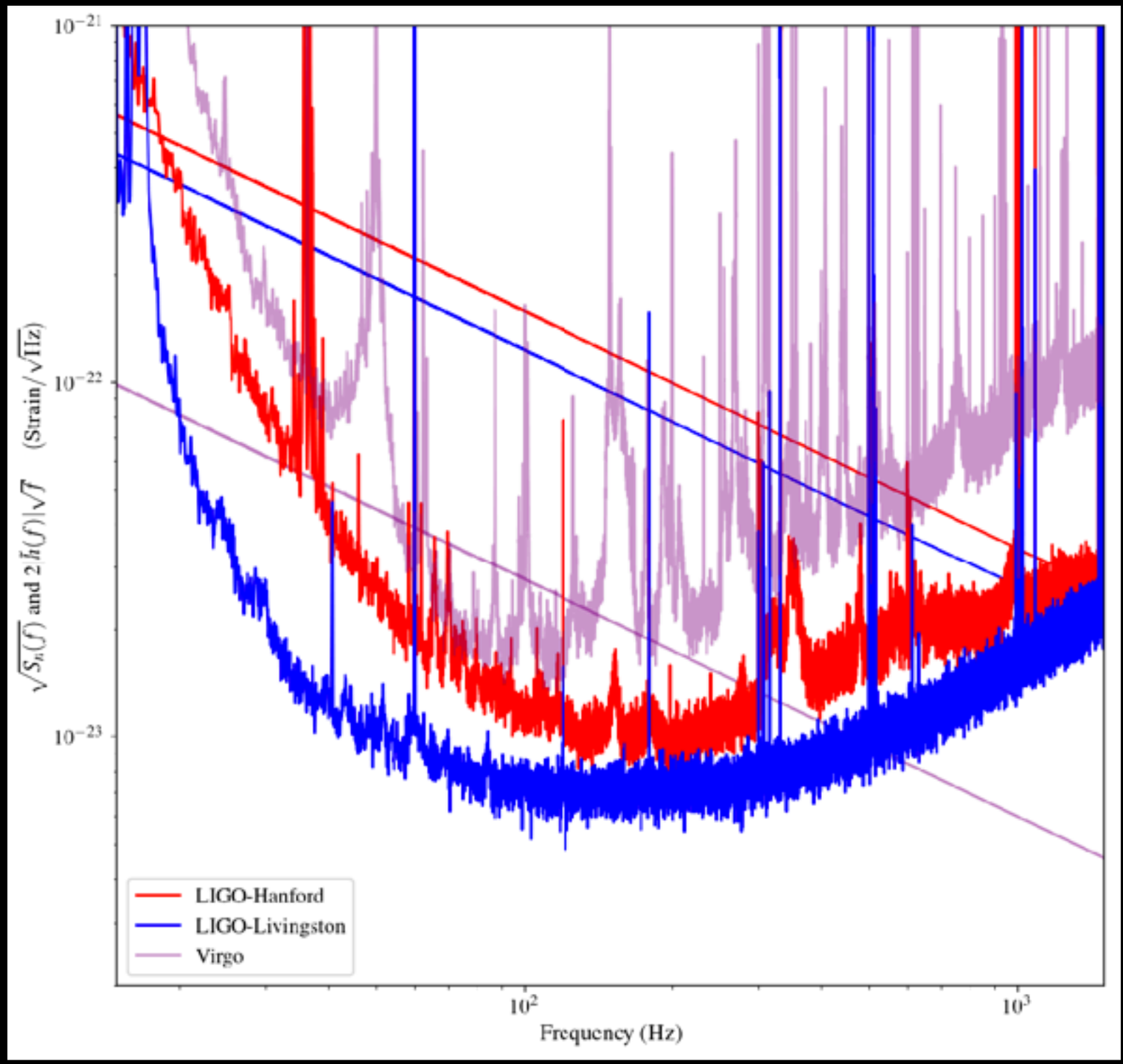
Sky location: Detector dependent strain

Hanford
SNR ~16

Livingston
SNR ~25

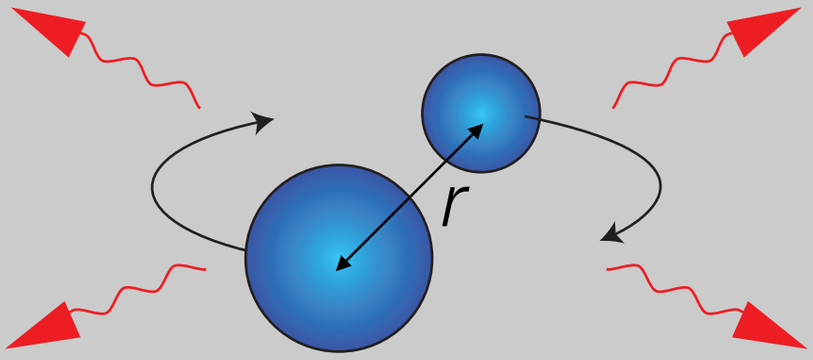
Virgo
SNR ~2

HL amplitudes recovered by matched-filter GW search, Virgo reconstruction



LIGO/Virgo/ Brown, Lovelace, Nitz, and Read

Inspiral and chirp



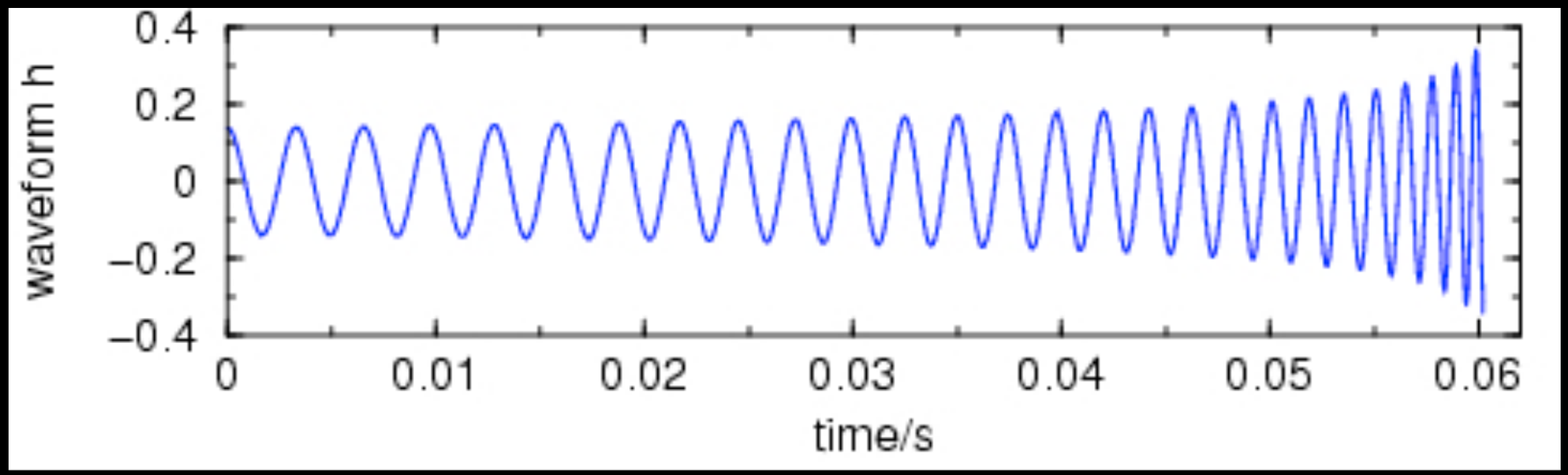
$$m = m_1 + m_2$$
$$\mu = m_1 m_2 / m$$

$$E = -\frac{1}{2}\left(\frac{Gm\mu}{r}\right)(1 + [\mathrm{PN}])$$

$$\dot{E}_{GW} = -\frac{32}{5}\frac{c^5}{G}\left(\frac{\mu}{m}\right)^2\left(\frac{Gm}{c^2 r}\right)^5(1 + [\mathrm{PN}])$$

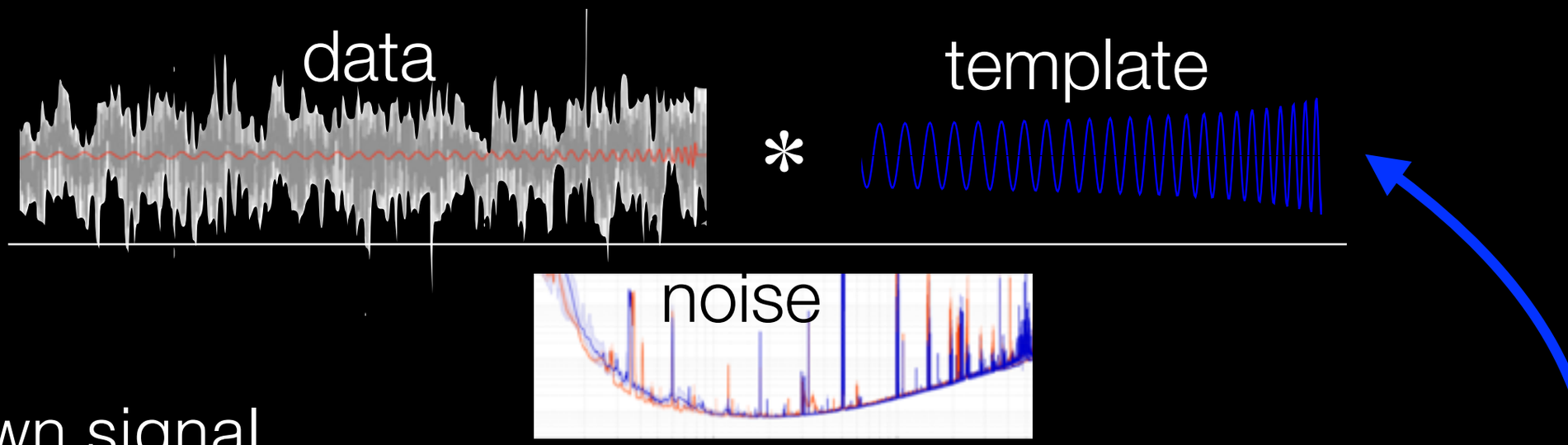
- Energy loss -> decreasing radius -> increasing freq.

δL/L

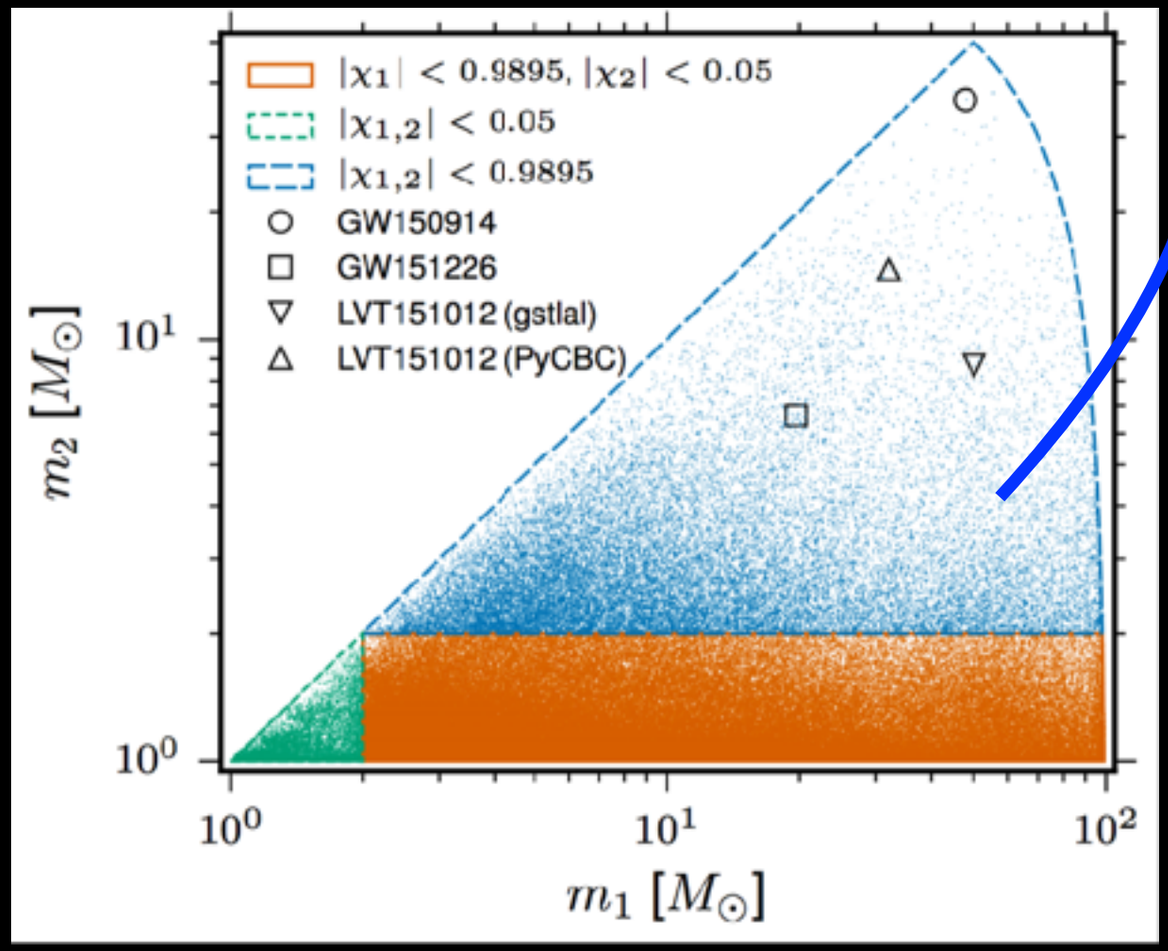


Matched-filter search for compact binary mergers

SNR = data * template / noise



- Integrate known signal predictions against data over many cycles, for coincident time and parameters
  - χ^2-weighted SNR, time slide background estimate
  - Relative likelihood of noise model and signal, single detector background estimate



"Binary Black Hole Mergers in the first Advanced LIGO Observing Run" https://arxiv.org/abs/1606.04856

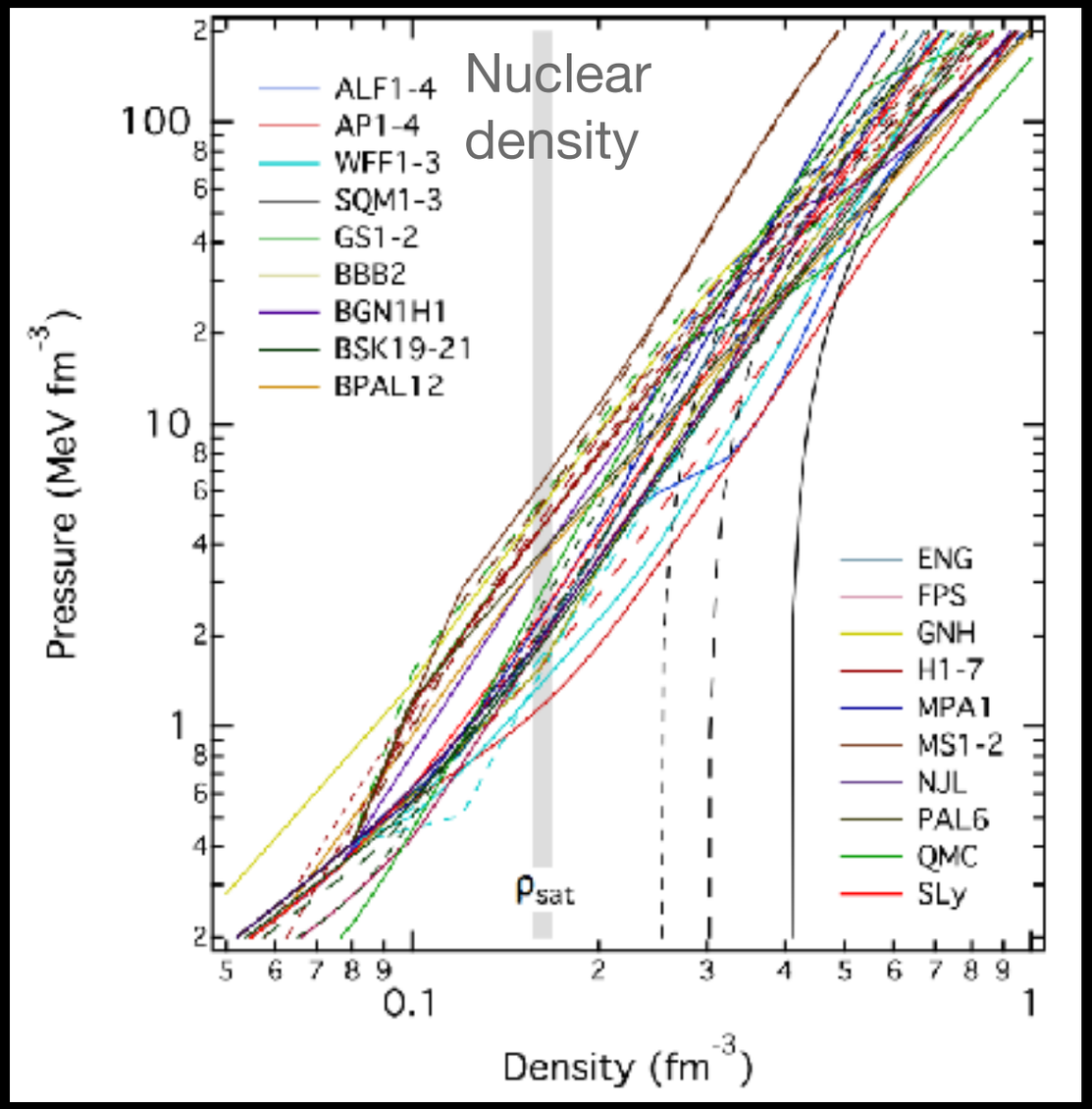
Properties of dense matter

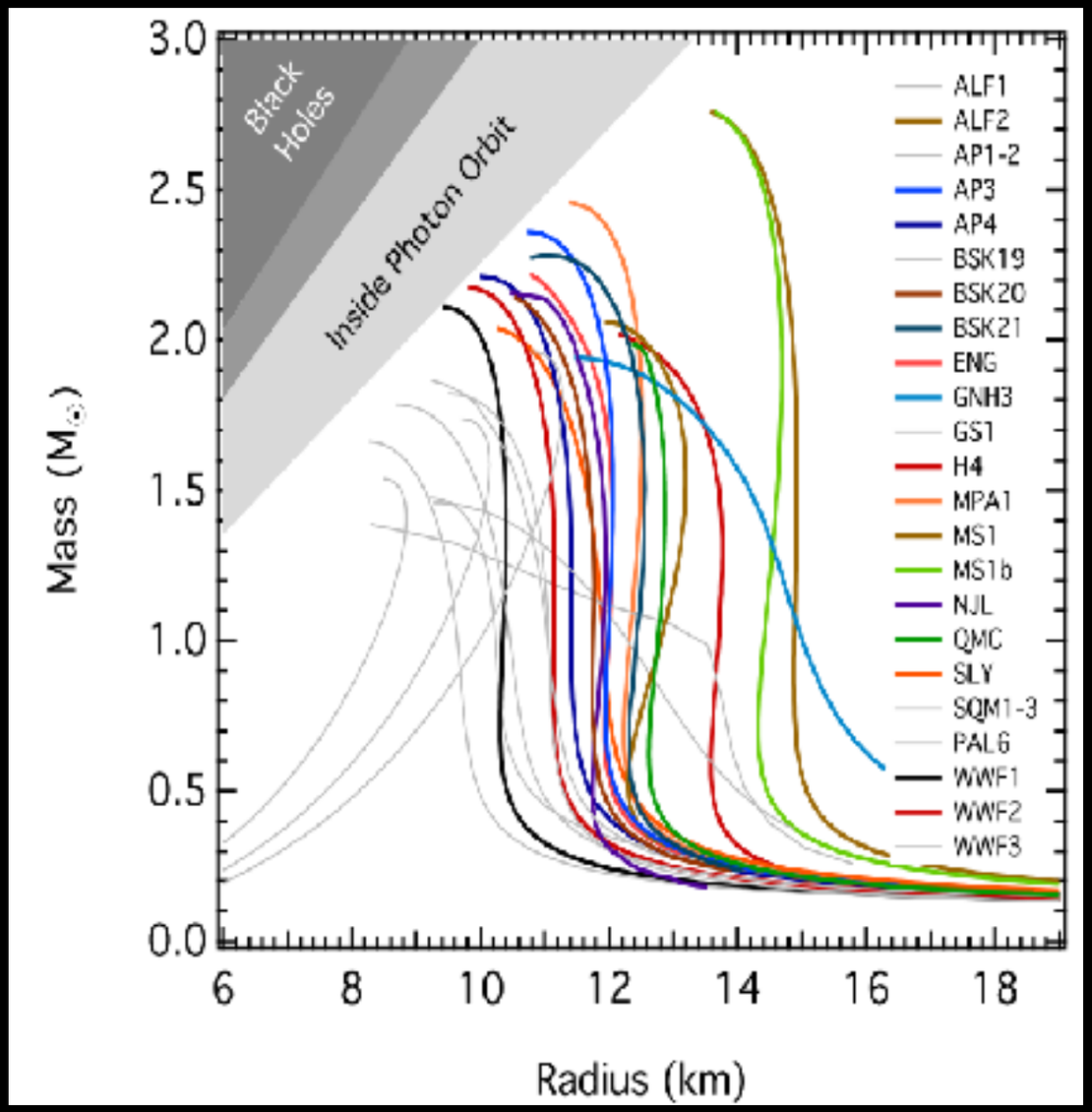
↔

Neutron star properties

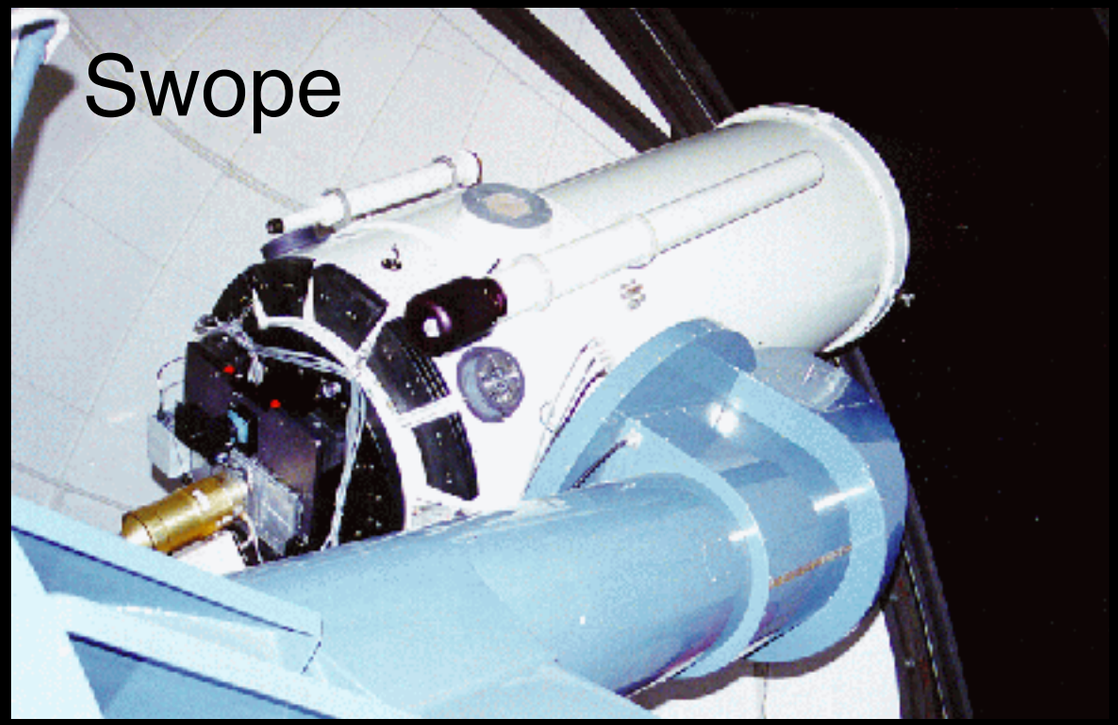
Equation of state in beta equilibrium

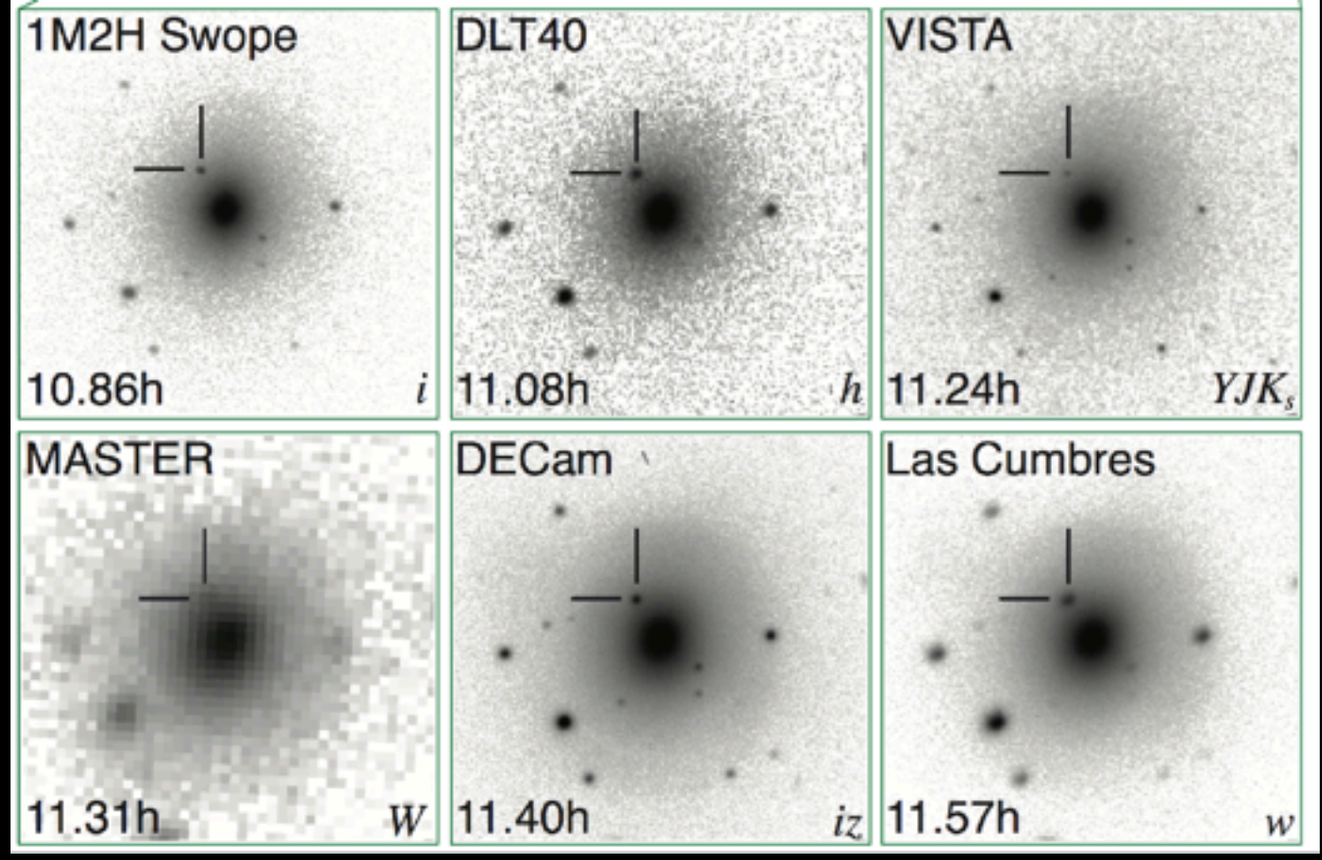
Mass-radius relation, max mass, deformability

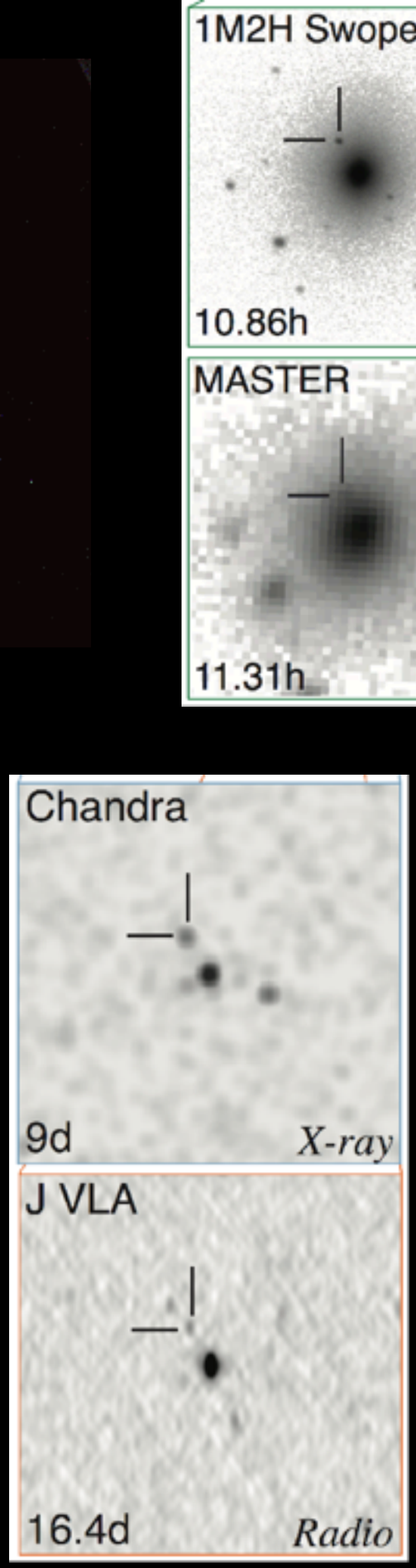




Ozel and Friere 2016







Counterpart identified!

Host galaxy NGC 4993, only 40 Mpc away

Abbott et al ApJL 848 2 (2017)