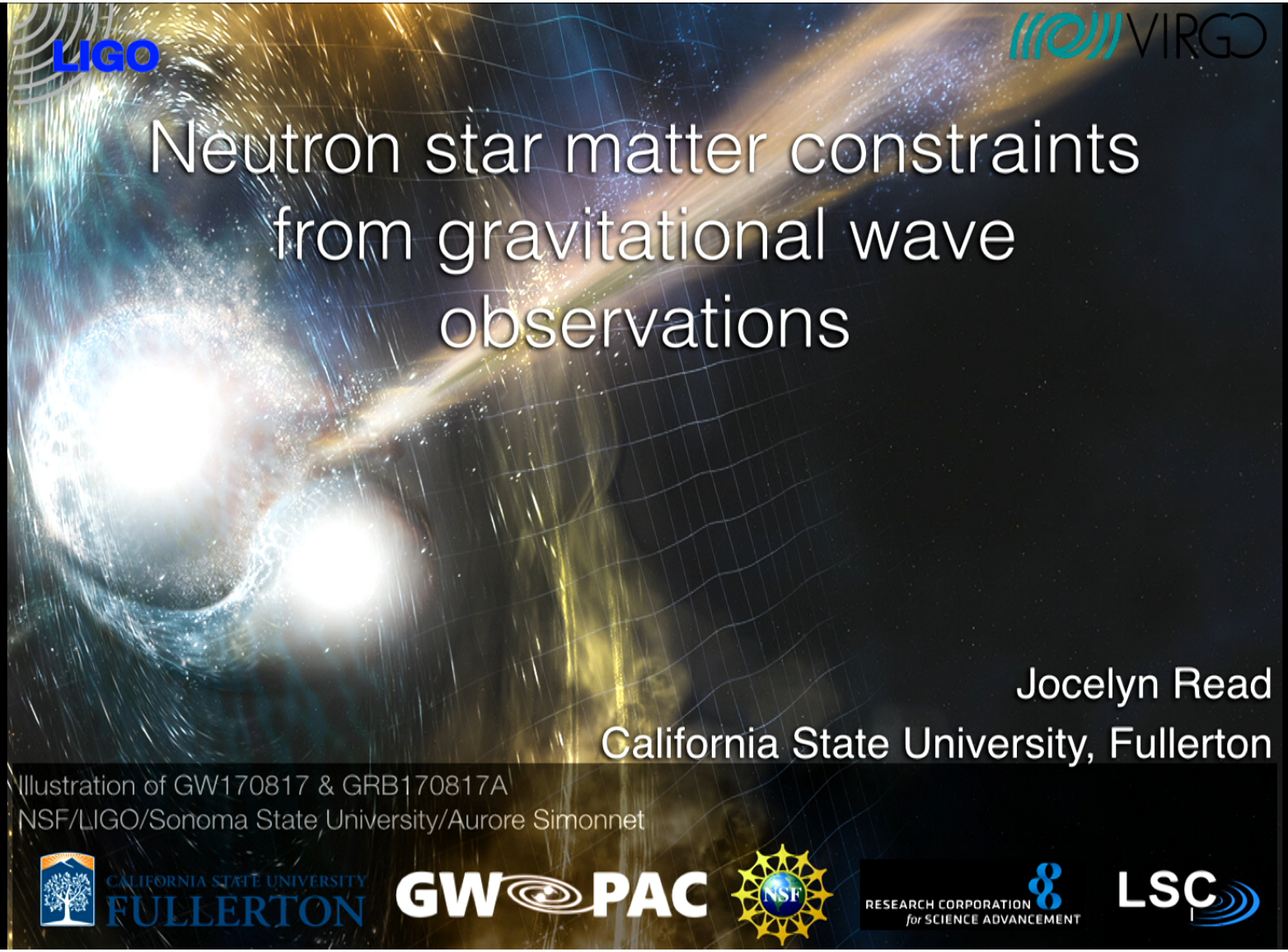
Title: Gravitational-wave observations and neutron star matter

Date: Nov 29, 2018 01:00 PM

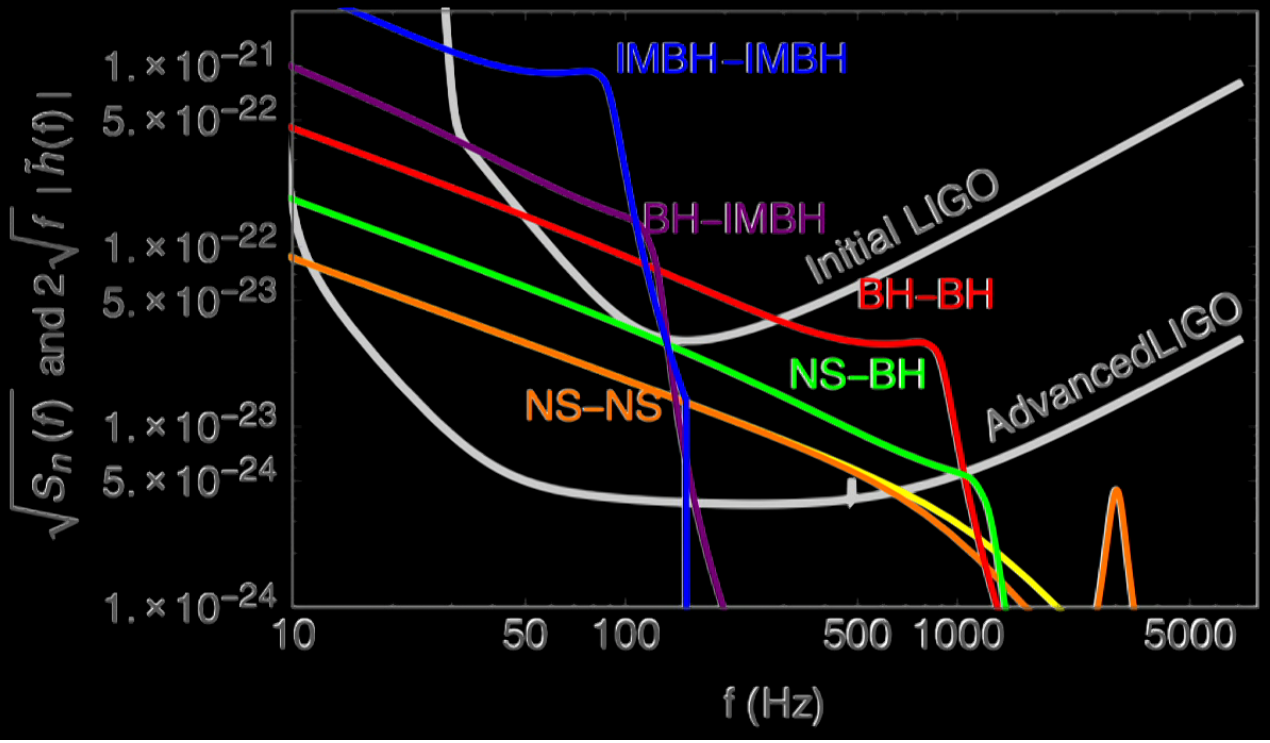
URL: http://pirsa.org/18110036

Abstract: Neutron stars host the densest stable matter in the universe. Accurately modeling their multi-messenger astrophysics relies on a detailed description of the equation of state above nuclear density, and astronomical observations of neutron stars can in turn be used to constrain the properties of such dense matter. On August 17, 2017 the Advanced LIGO and Advanced Virgo detectors discovered the first gravitational-wave signal consistent with a binary neutron star inspiral. The three-dimensional localization of GW170817â€™s source using LIGO and Virgo data enabled a successful electromagnetic follow-up campaign. We are also able to constrain the equation of state of dense matter in neutron stars using the signature of tidal interaction in the gravitational-wave signal. I will outline these constraints, the methods by which they are made, how the gravitational-wave information connects with other observations of neutron stars, and outline future prospects for gravitational-wave astronomy with neutron stars.


LIGO
VIRGO
Neutron star matter constraints from gravitational wave observations
Jocelyn Read
California State University, Fullerton
Illustration of GW170817 & GRB170817A
NSF/LIGO/Sonoma State University/Aurore Simonnet
CALIFORNIA STATE UNIVERSITY FULLERTON
GW PAC
NSF
RESEARCH CORPORATION for SCIENCE ADVANCEMENT
LSC

Binary mergers in LIGO

Sky-averaged GW amplitude for systems at 200 Mpc
(~sky-averaged NS-NS Horizon in A-LIGO design)

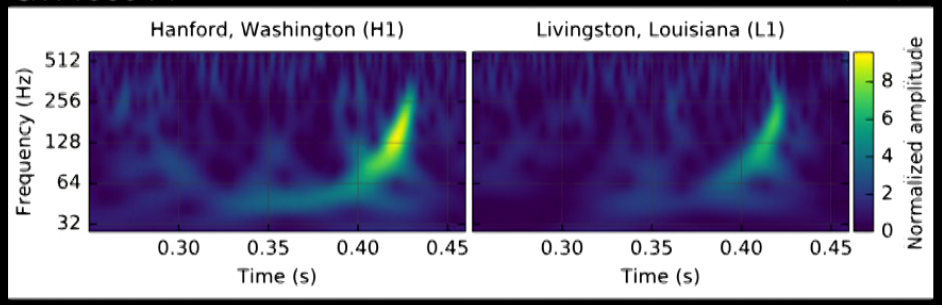


NS
of 1.35 $M_\odot$
BH
of 10 $M_\odot$
IMBH
of 100 $M_\odot$

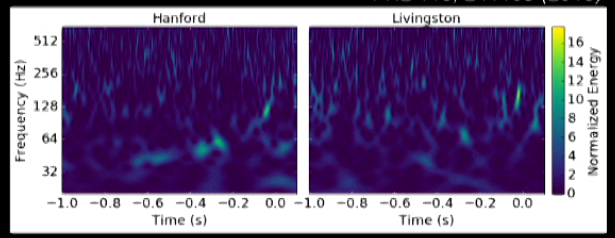
Masses in
detector
frame

BBH detections

GW150914 *PRL 116, 061102 (2016)*

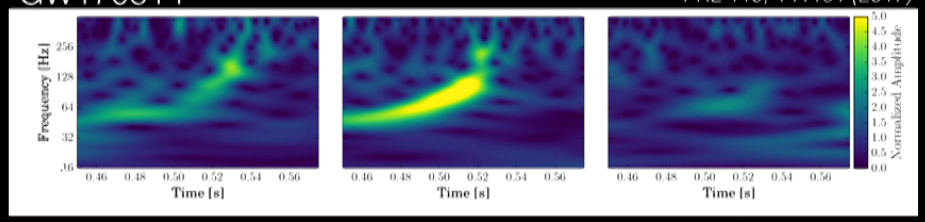


GW151226 *PRL 116, 241103 (2016)*

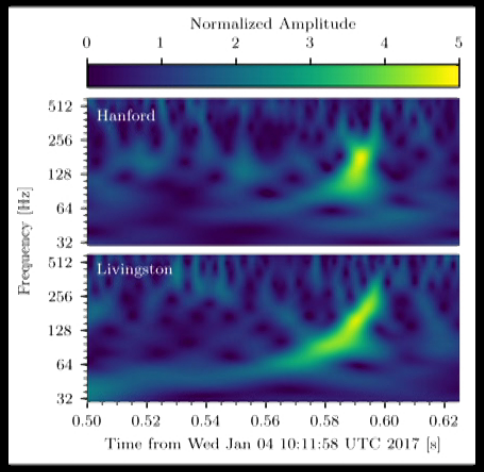


< 2 s of data shown for each

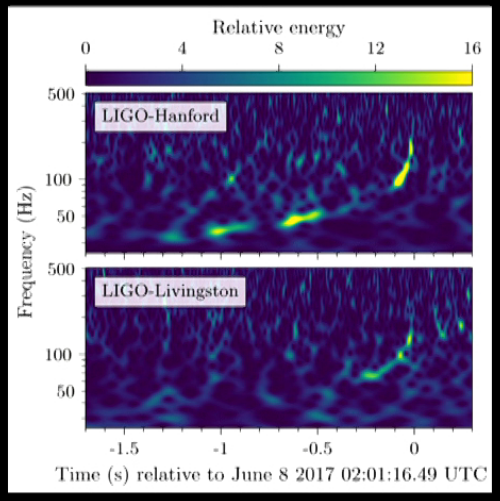
GW170814 *PRL 119, 141101 (2017)*



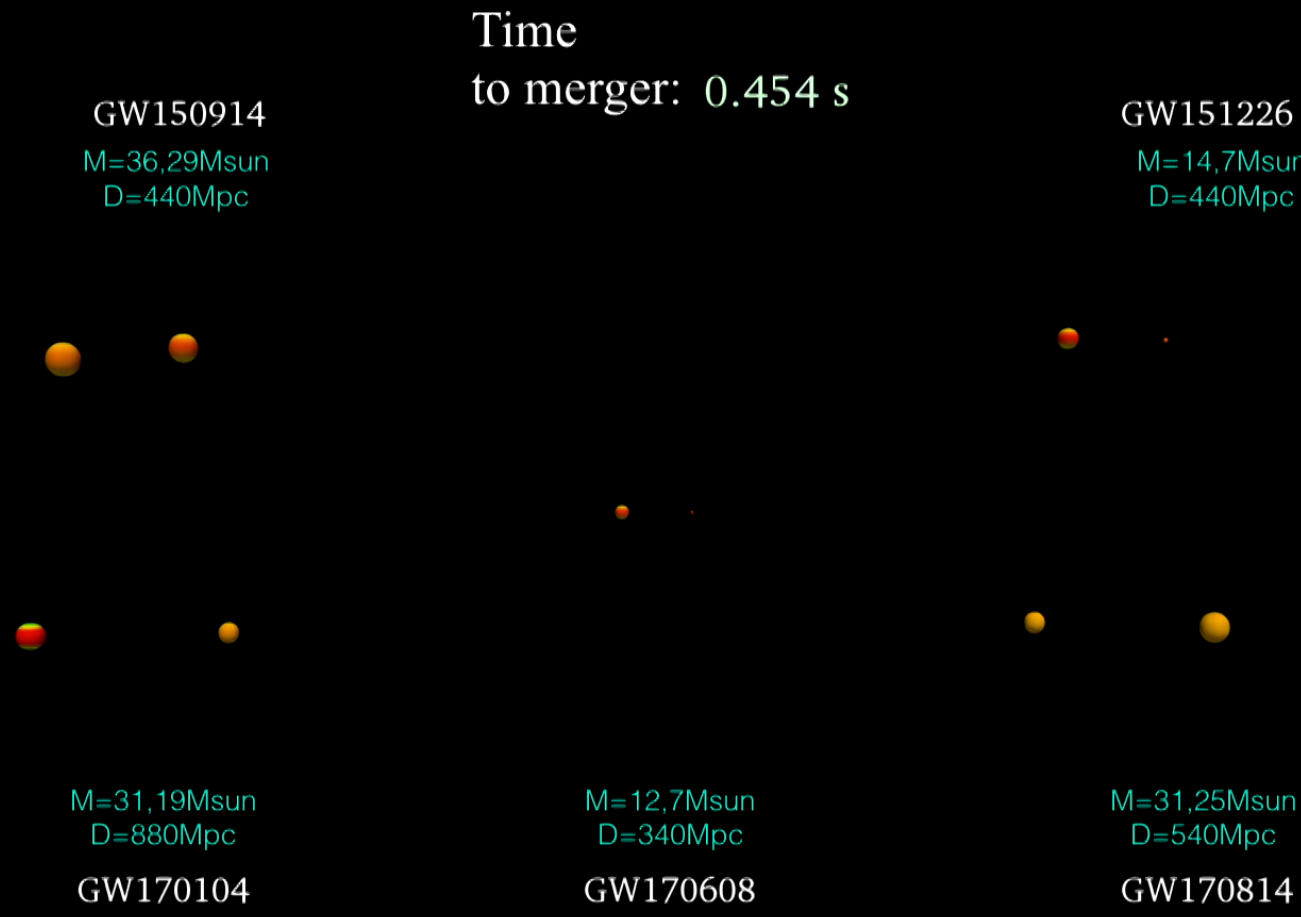
PRL 118, 221101 (2017) GW170104



GW170608

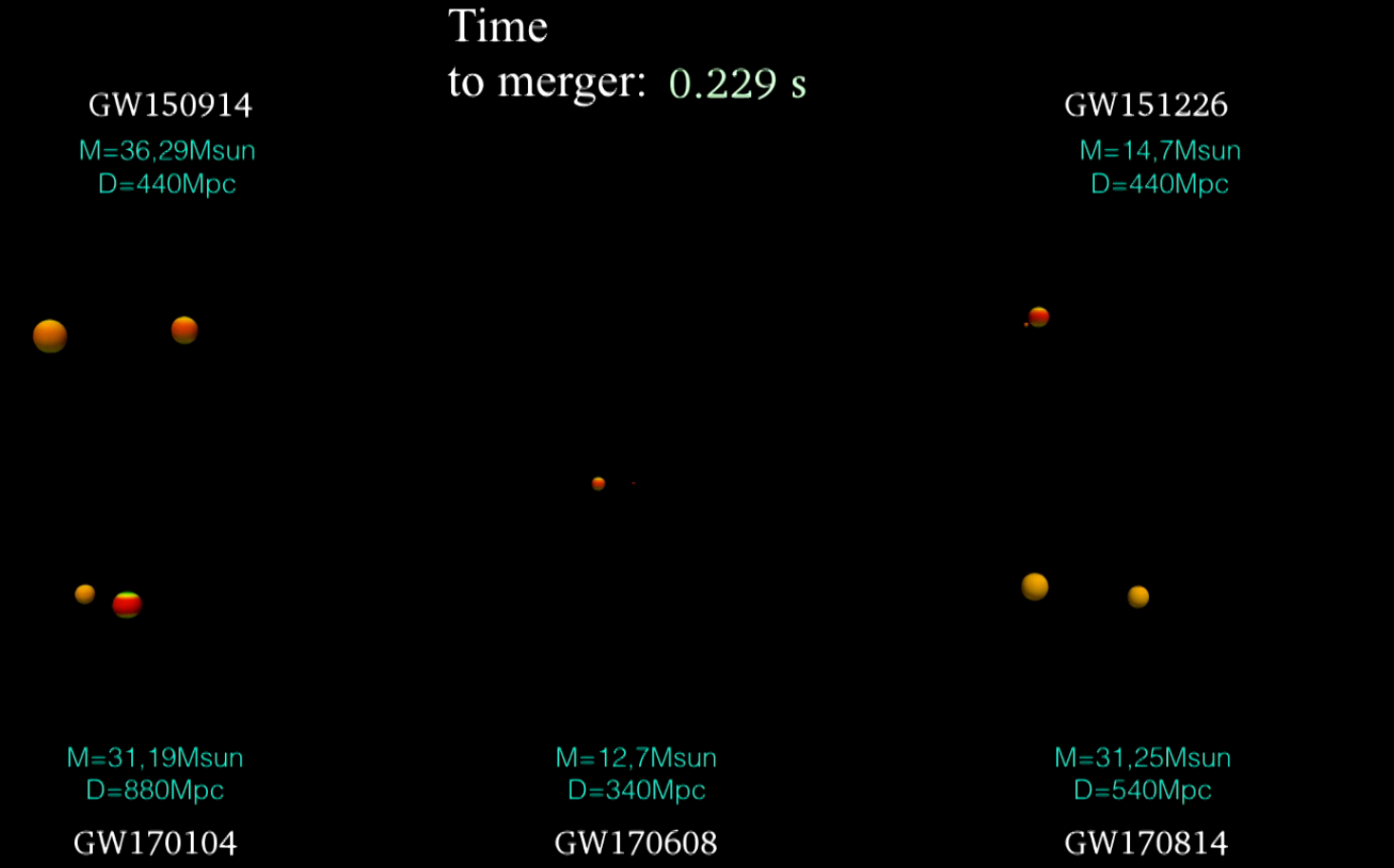


Simulations of BBH sources



Teresa Ramirez/CSUF/SXS

Simulations of BBH sources



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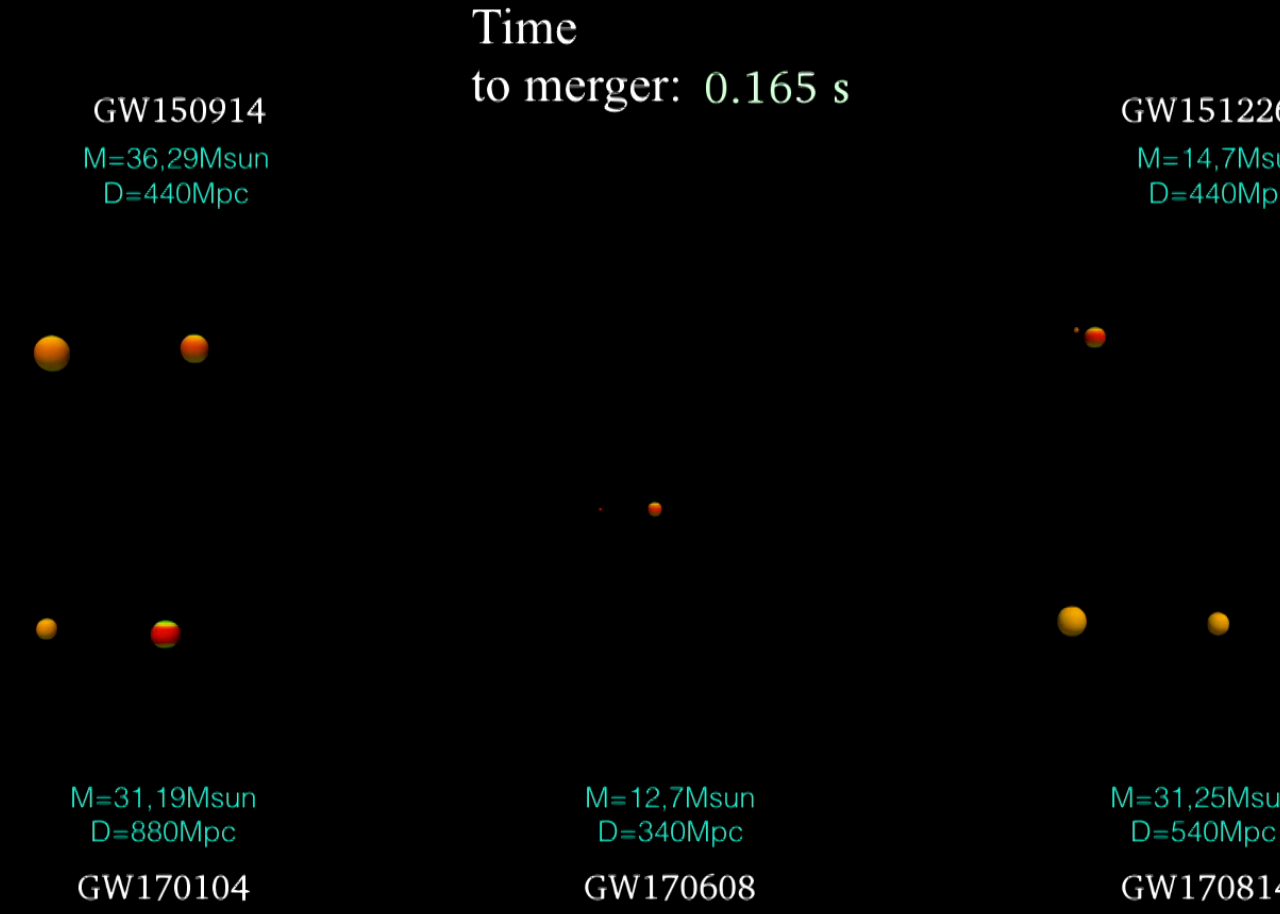
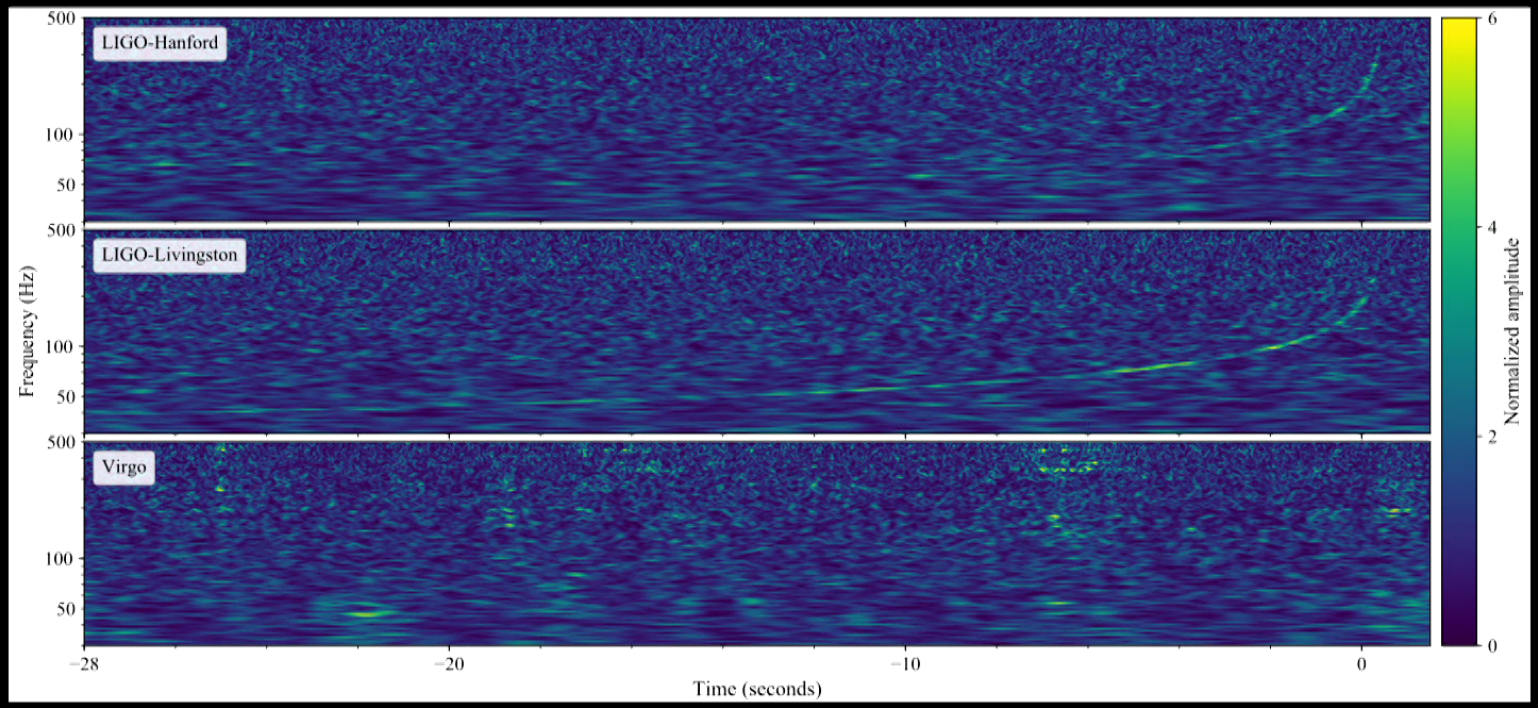
Simulations of BBH sources



Teresa Ramirez/CSUF/SXS

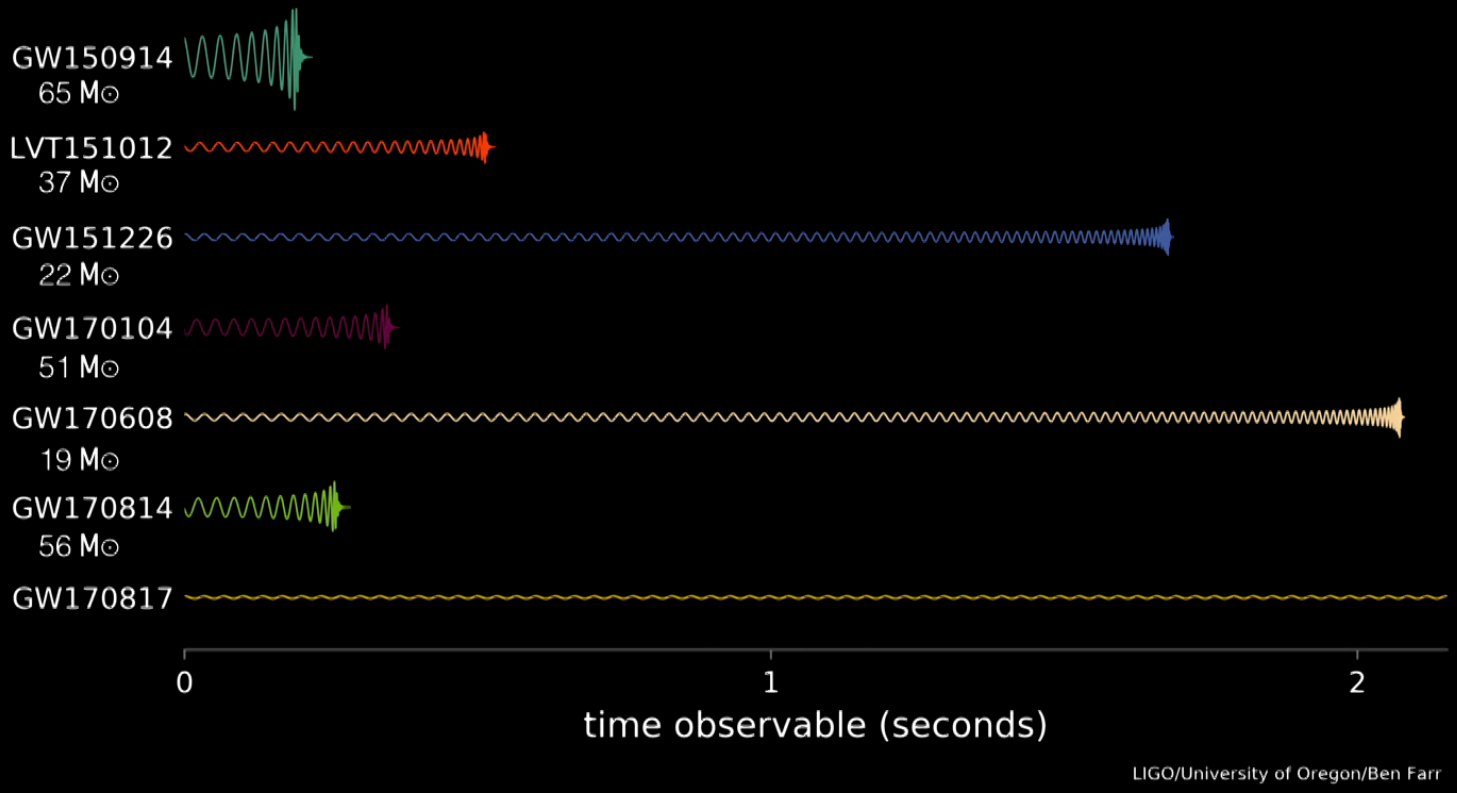
August 17, 2017 12:41:04 UTC



GW170817

LSC/Virgo PRL 119, 161101 (2017)

Recovered Waveforms



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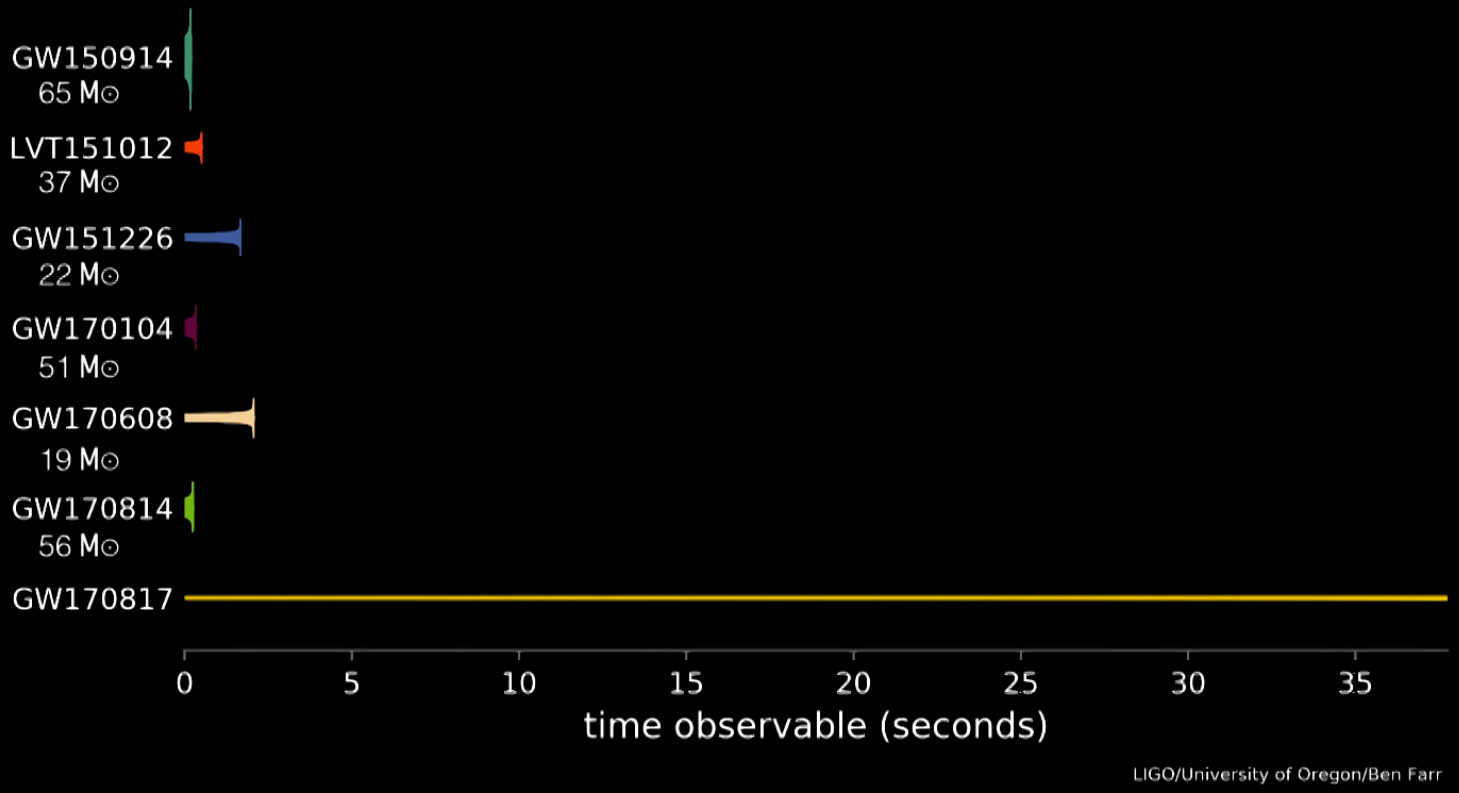
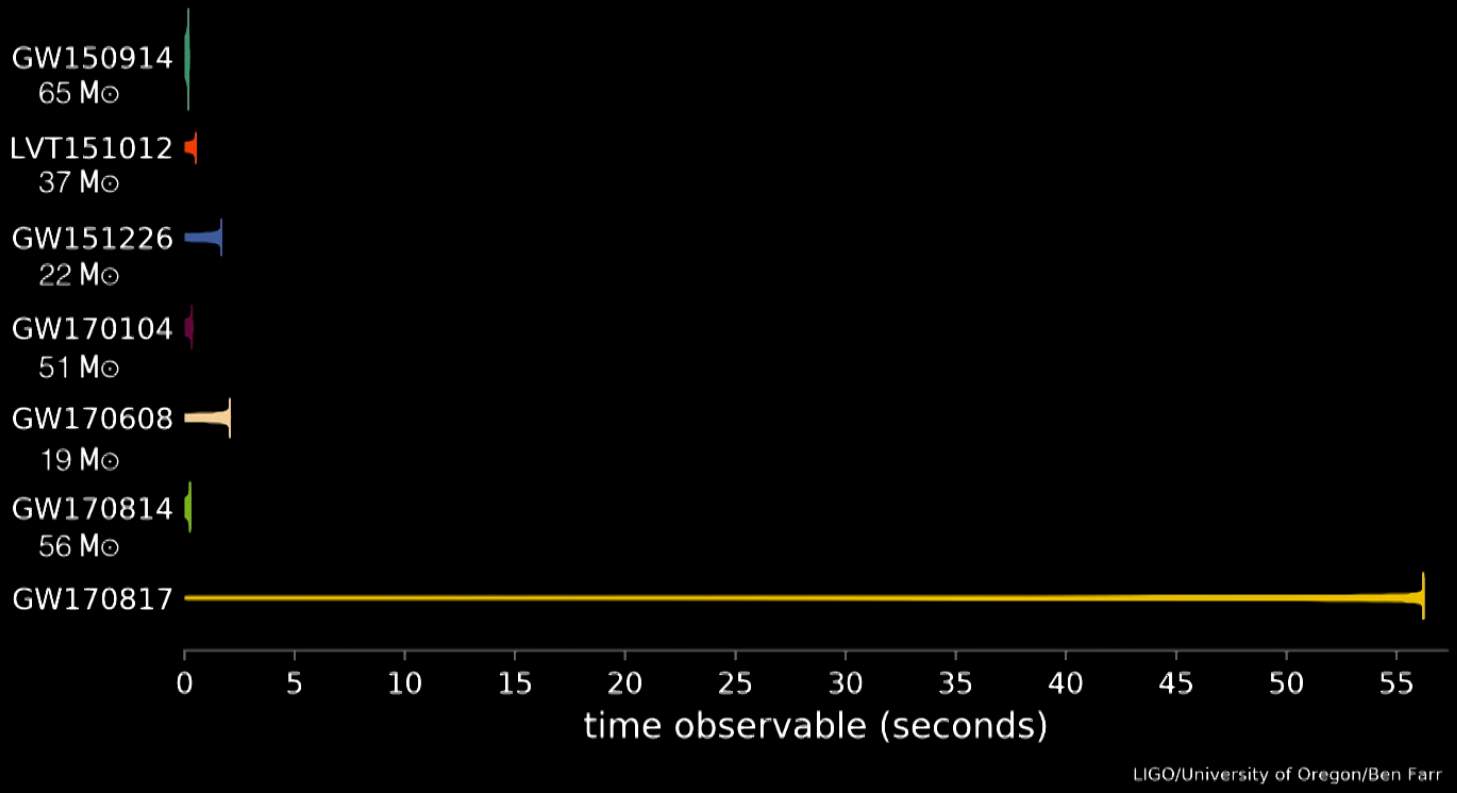
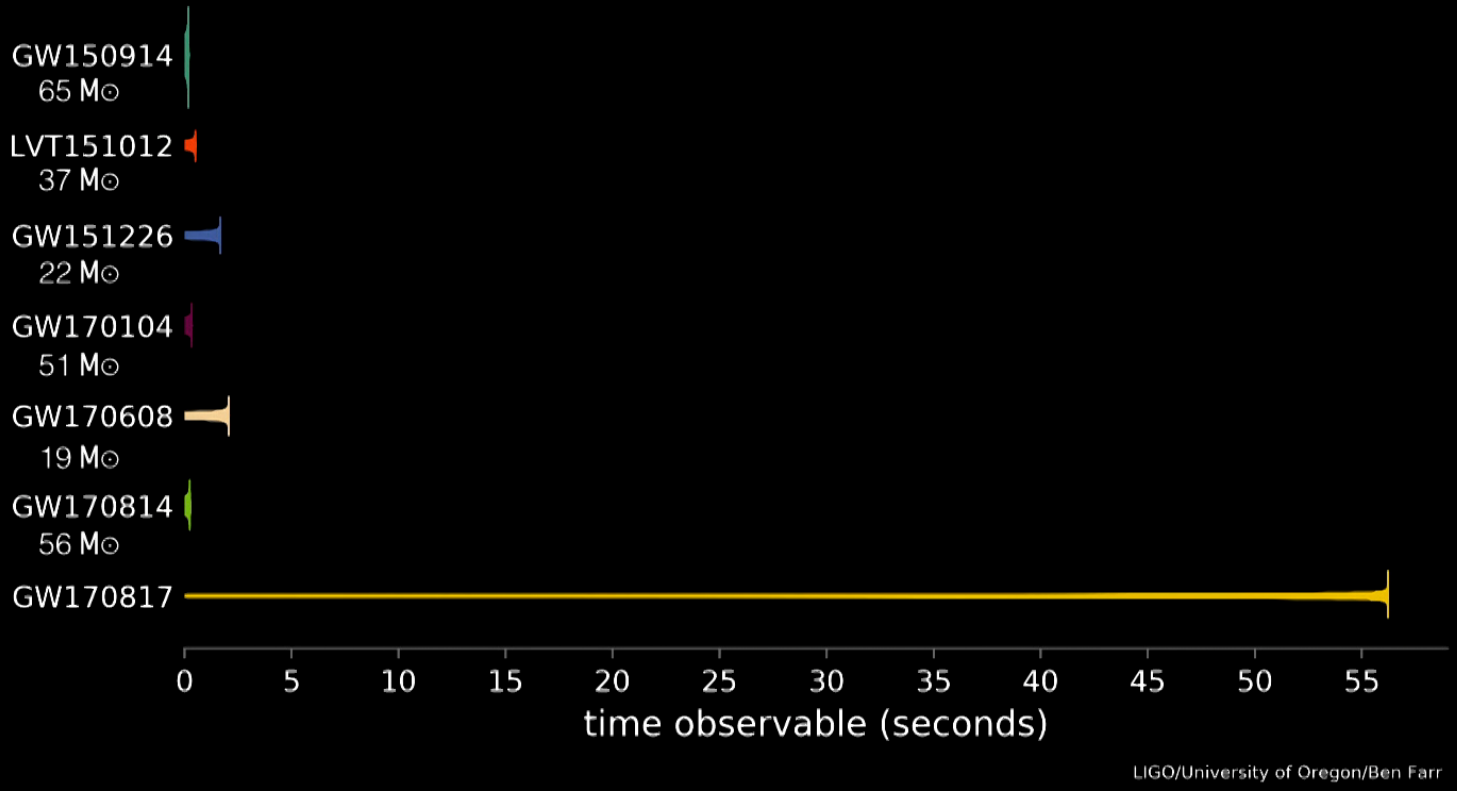
Recovered Waveforms



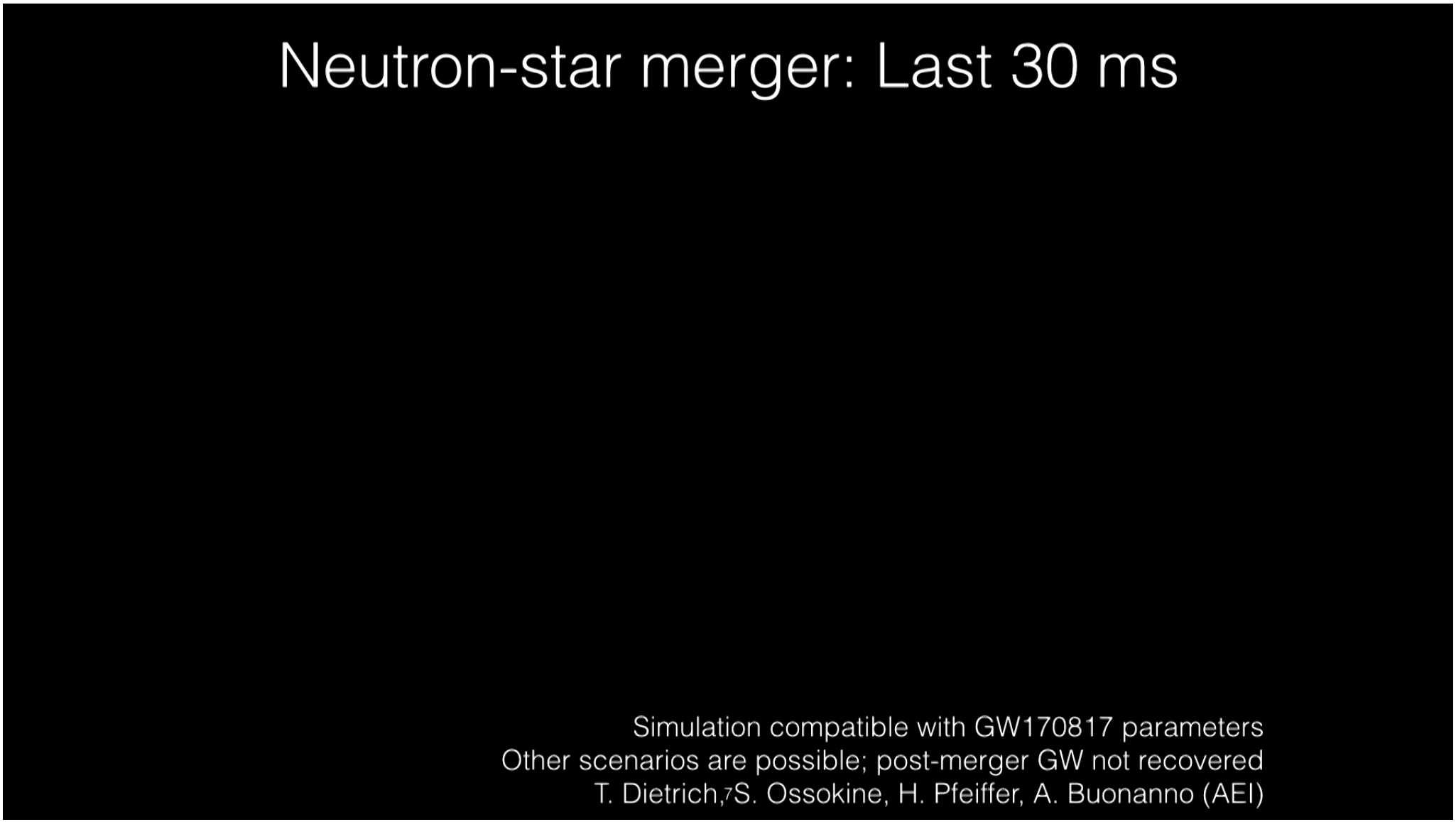
Recovered Waveforms



Recovered Waveforms



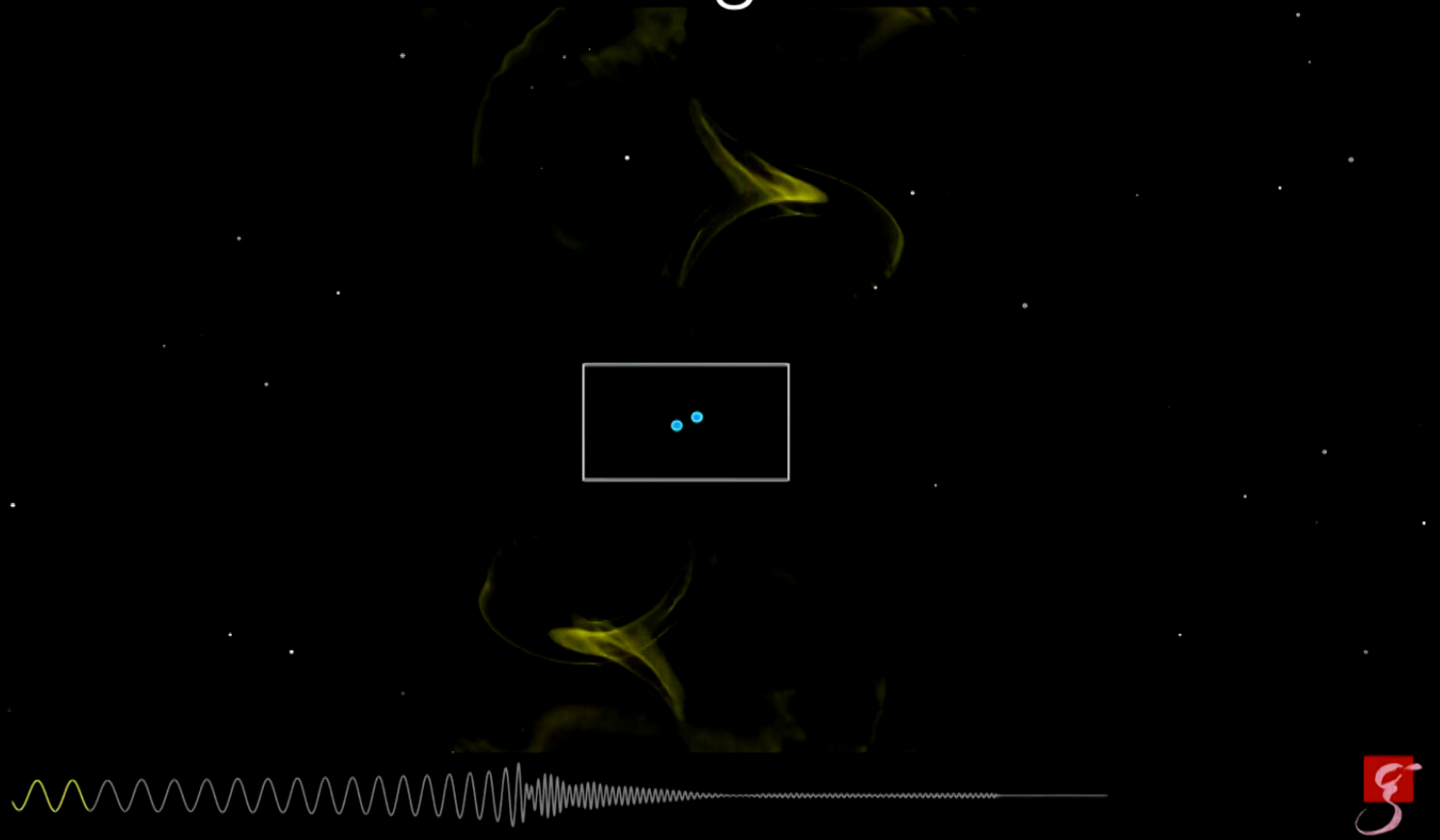
Neutron-star merger: Last 30 ms



Neutron-star merger: Last 30 ms

Simulation compatible with GW170817 parameters
Other scenarios are possible; post-merger GW not recovered
T. Dietrich,[7] S. Ossokine, H. Pfeiffer, A. Buonanno (AEI)

Neutron-star merger: Last 30 ms



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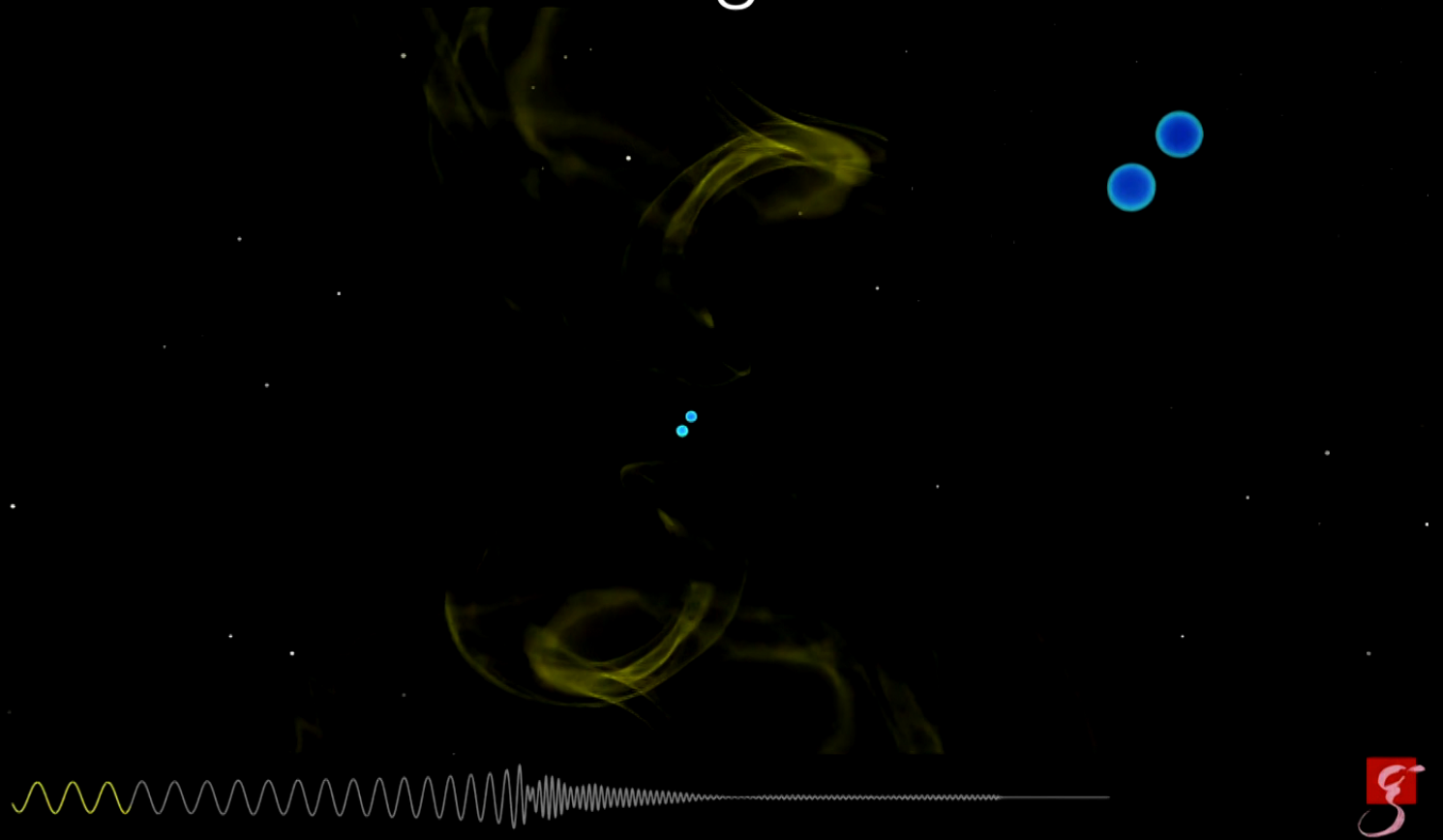

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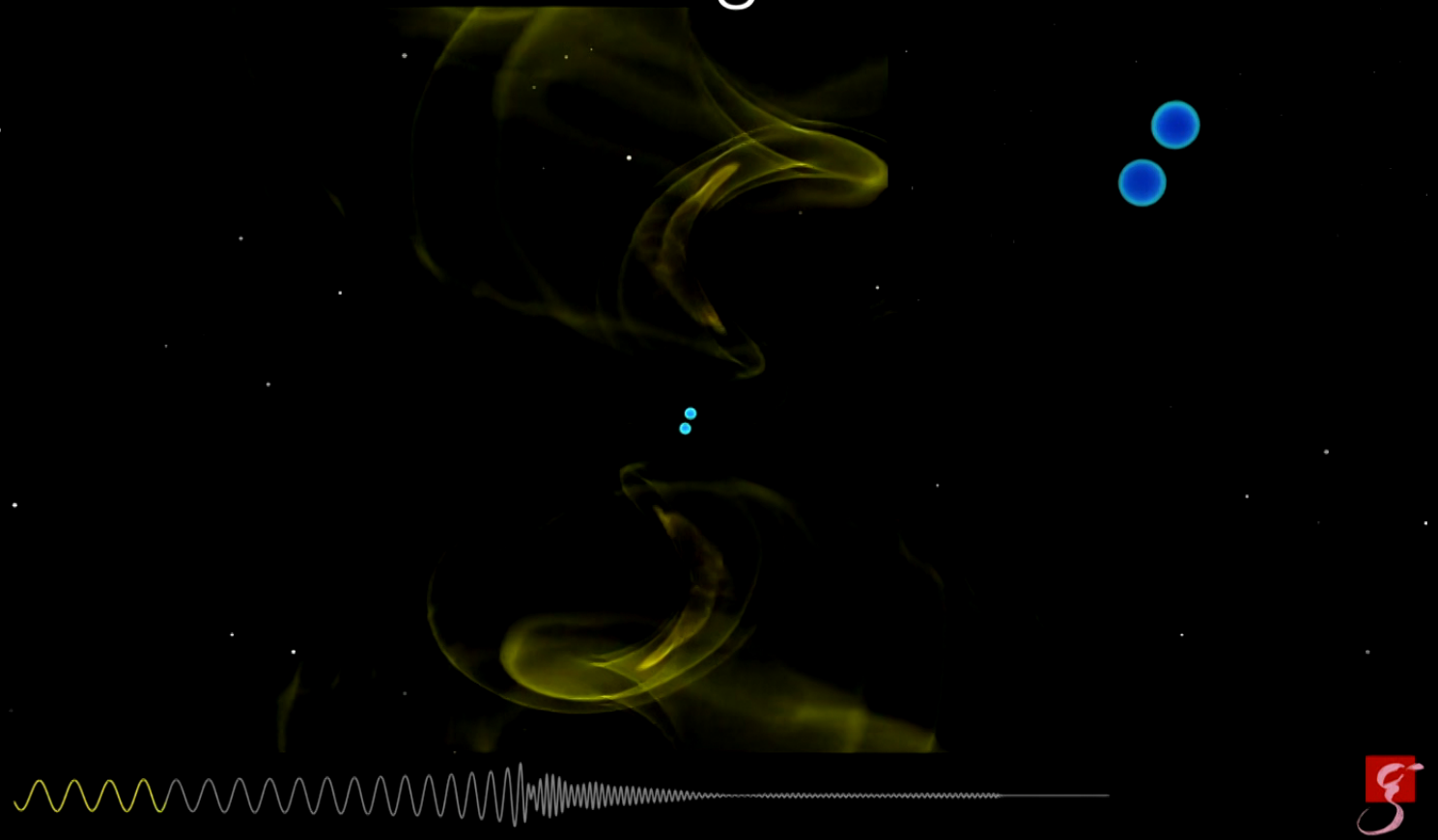

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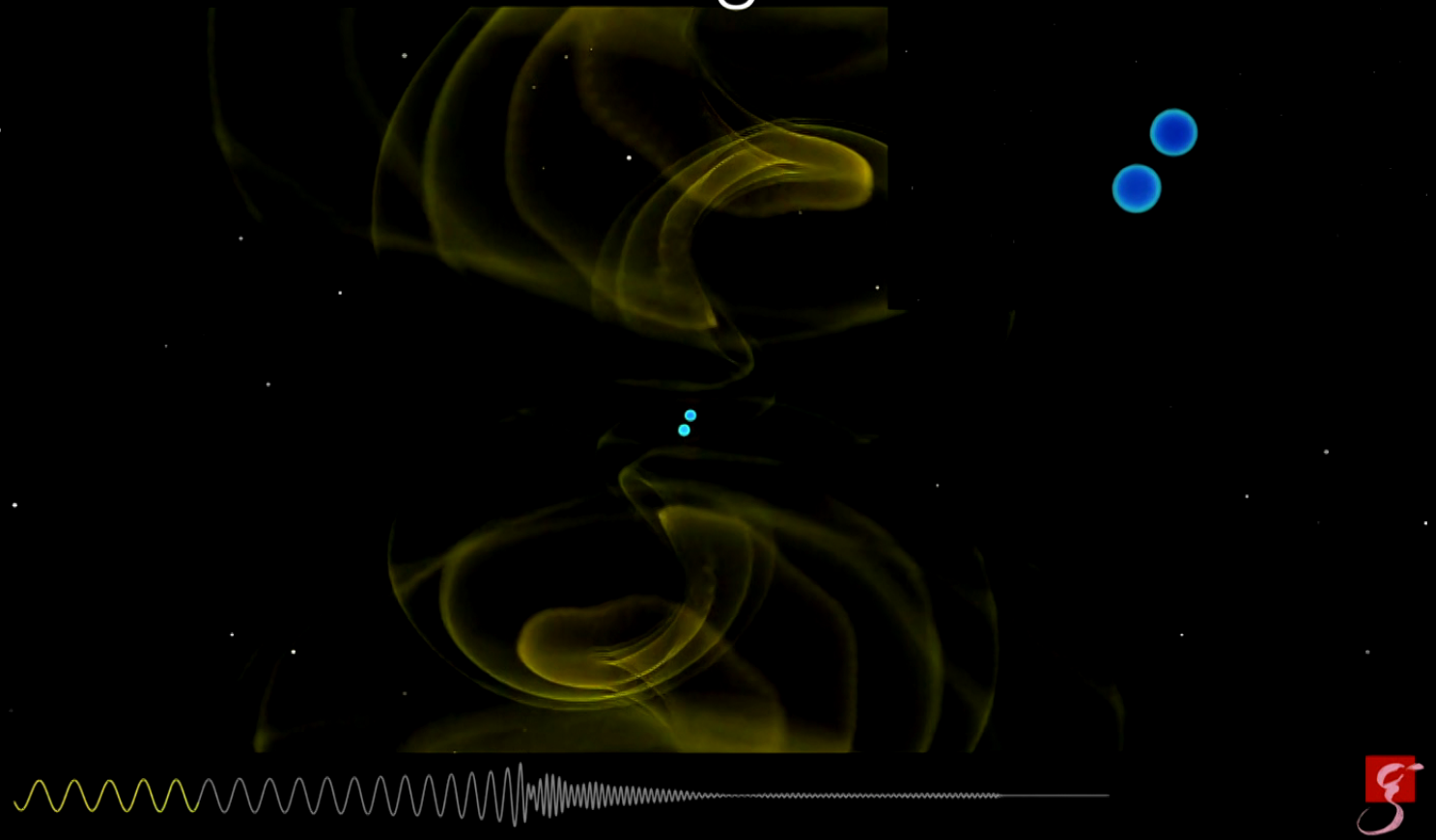

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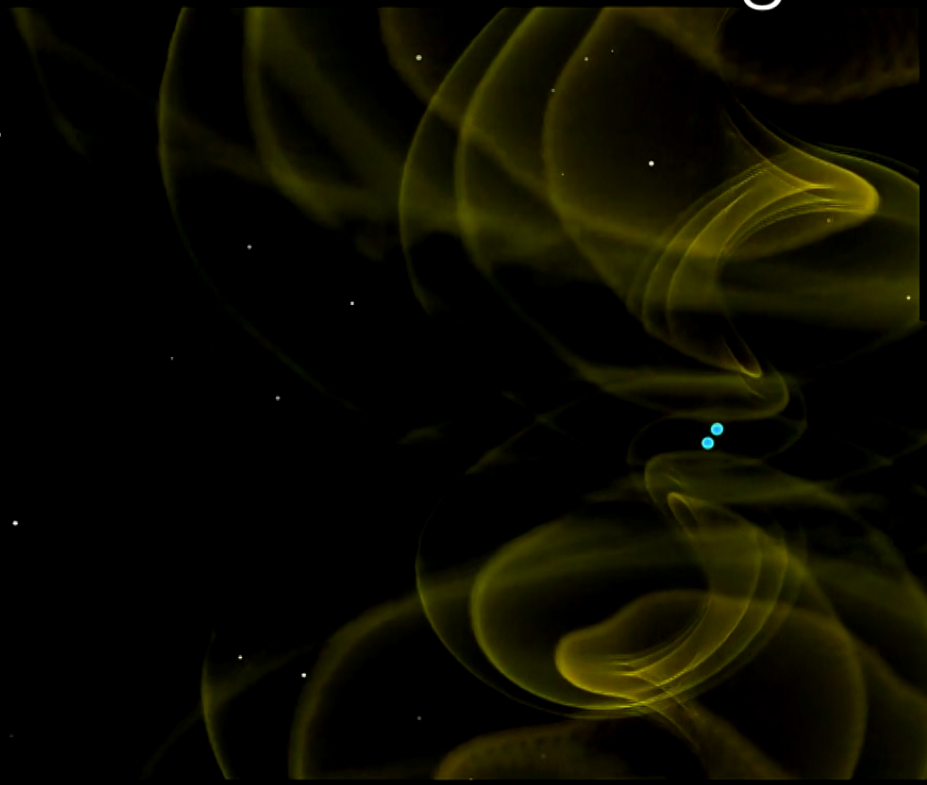

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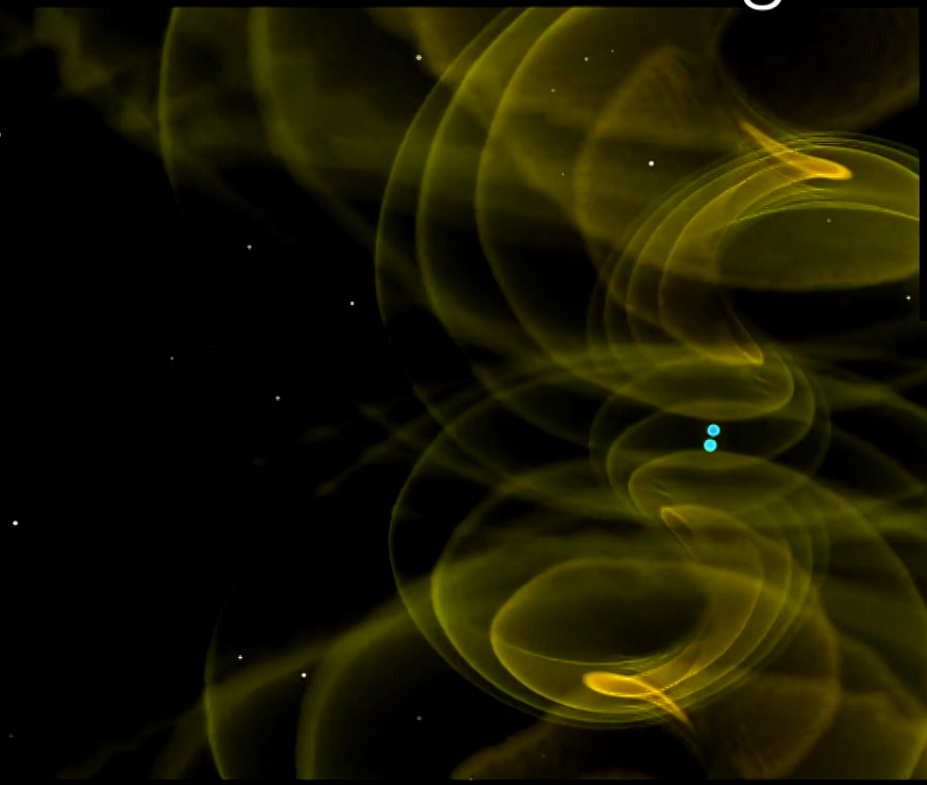

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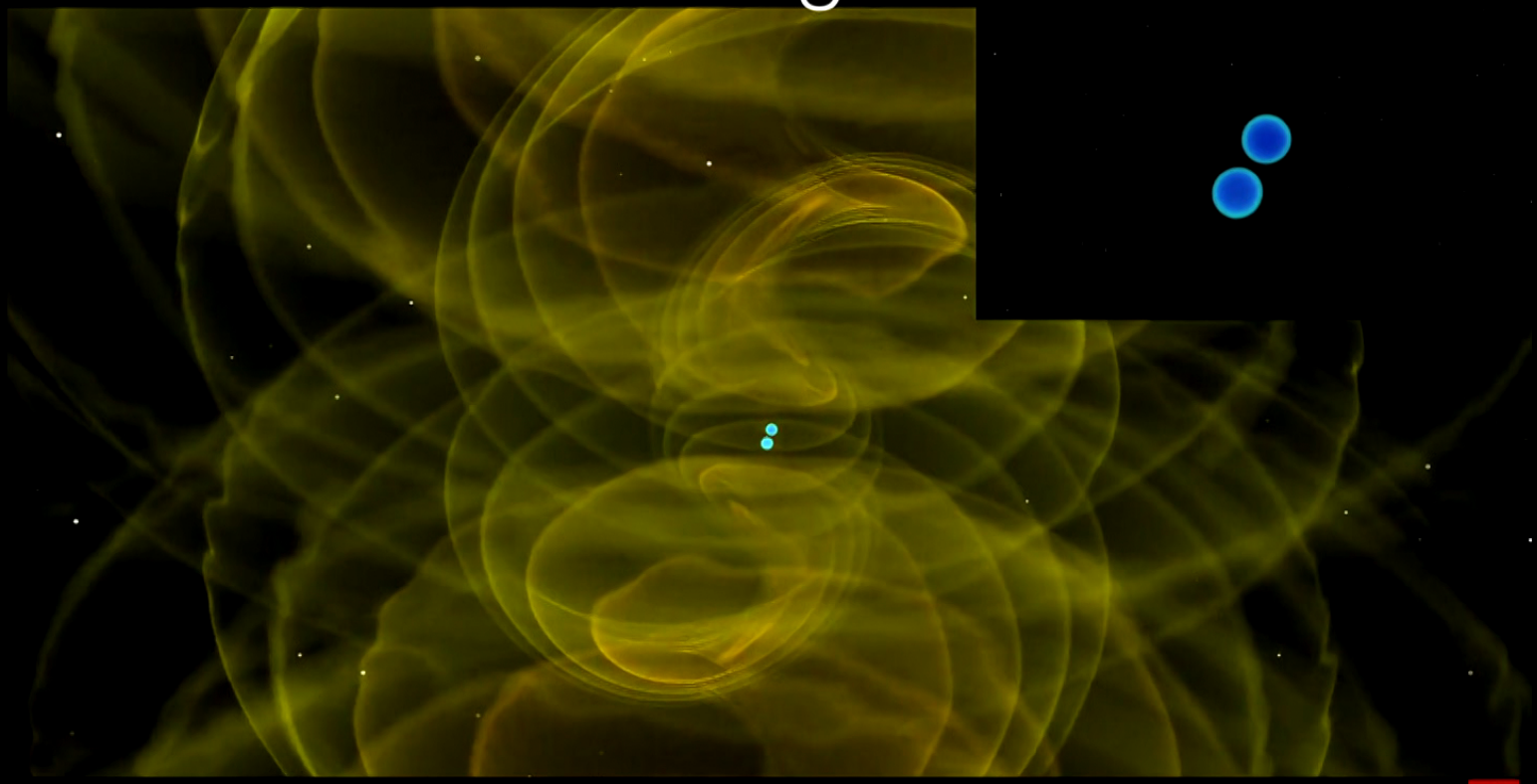

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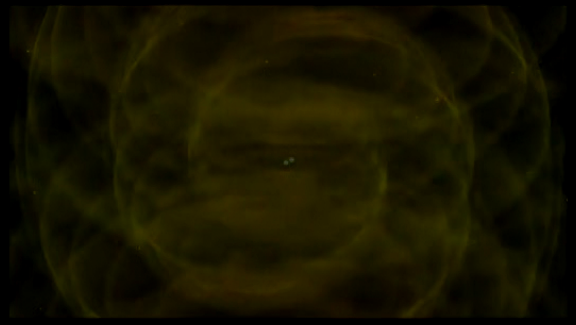

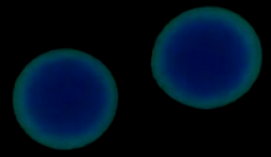

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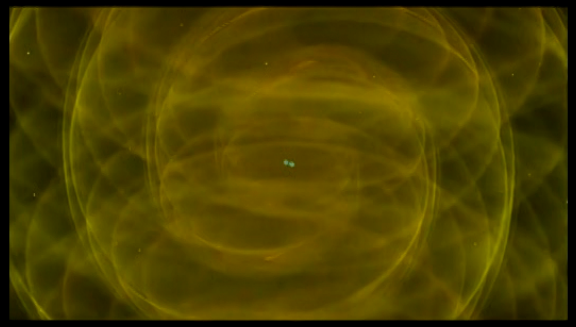

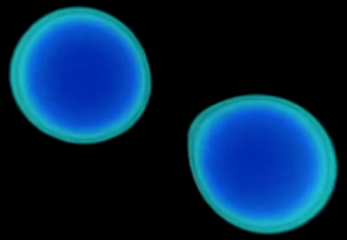

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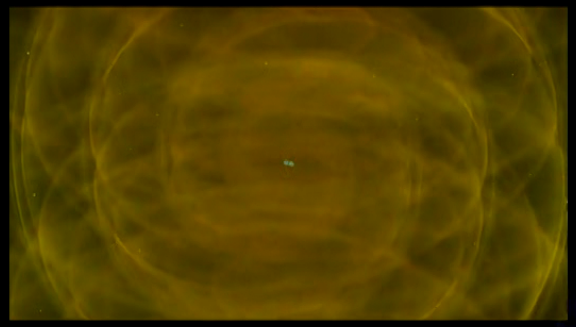

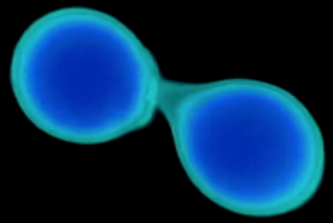

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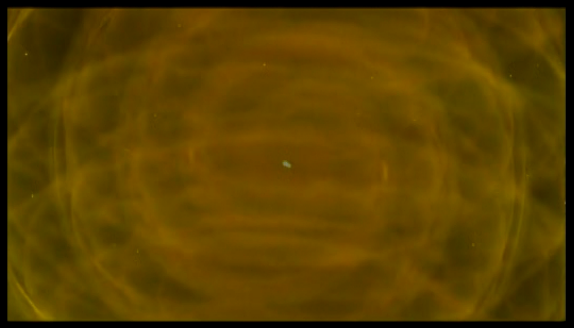

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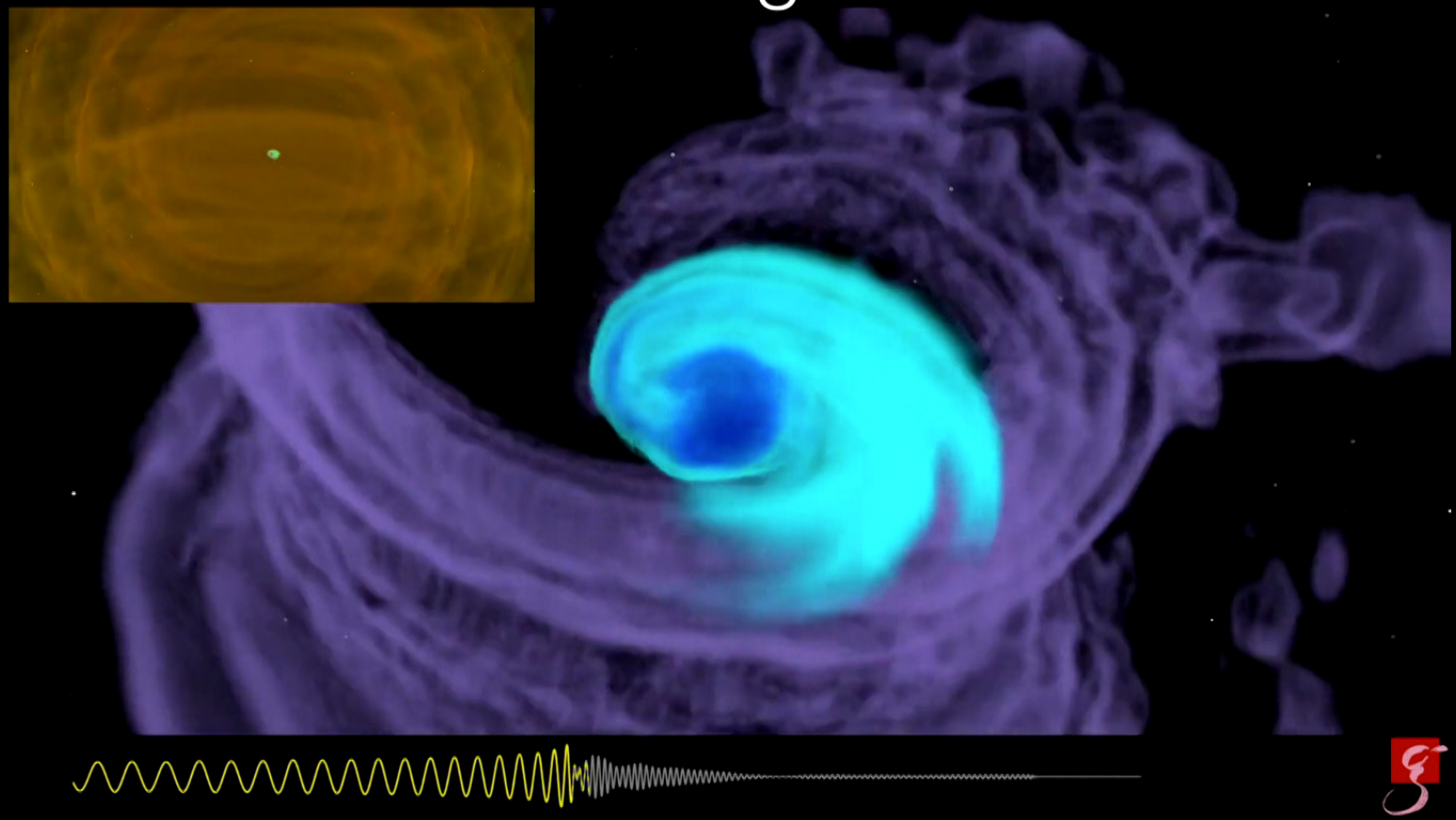

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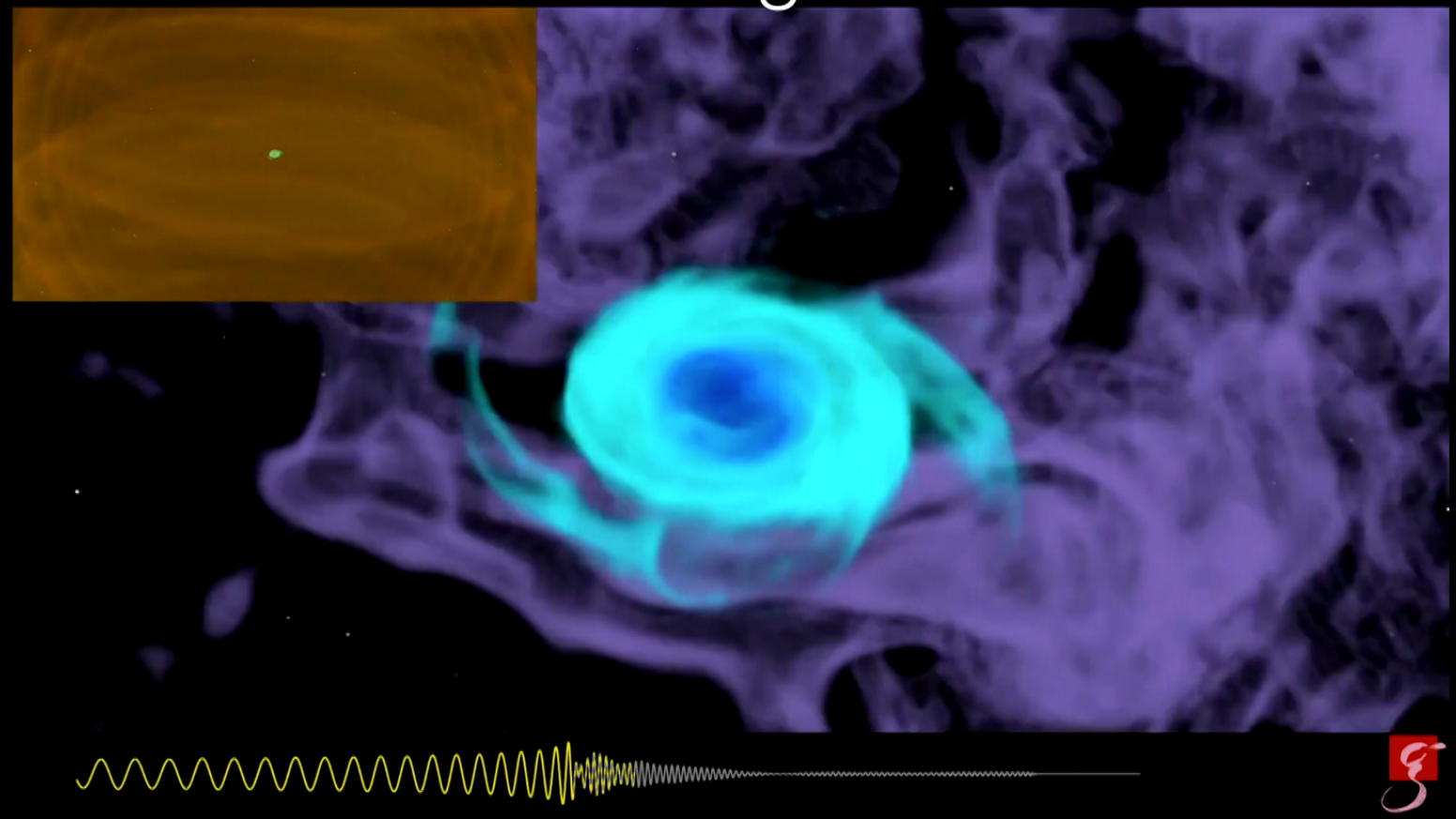

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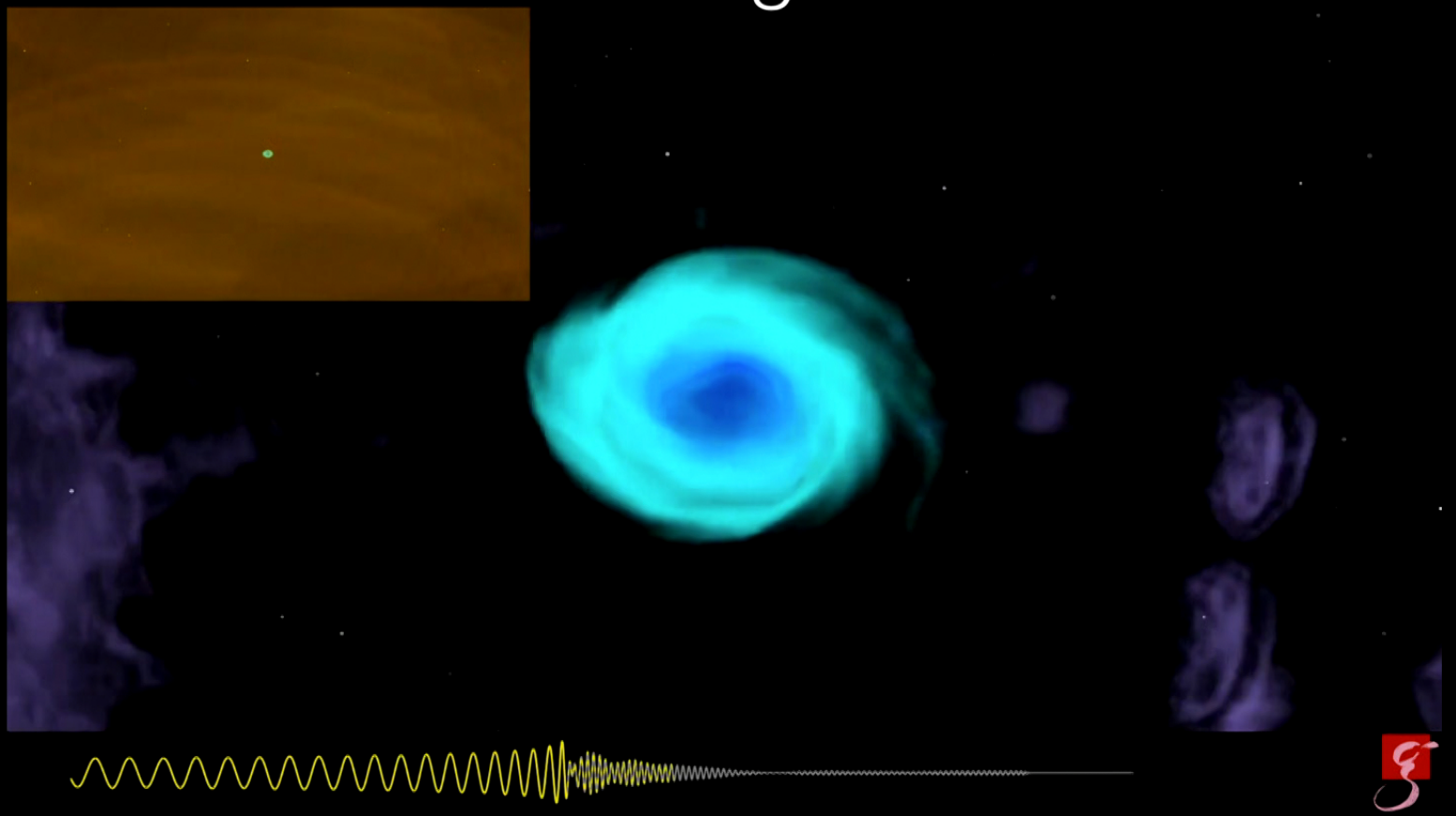

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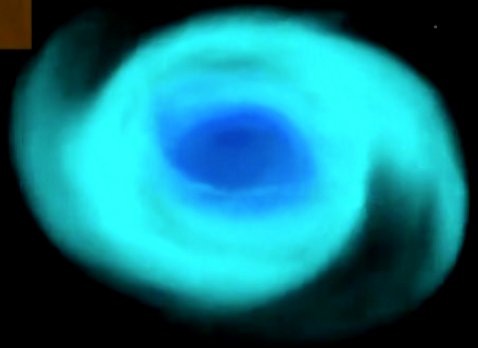

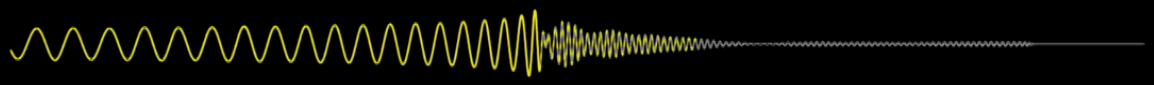

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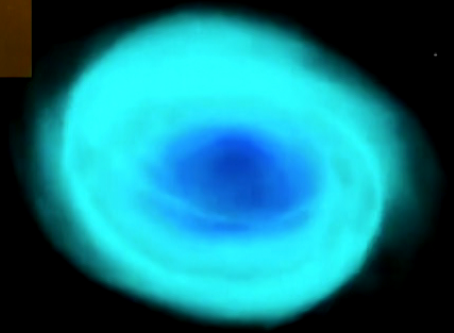

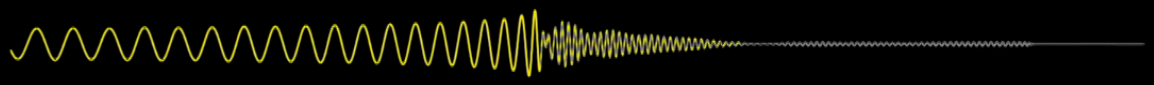

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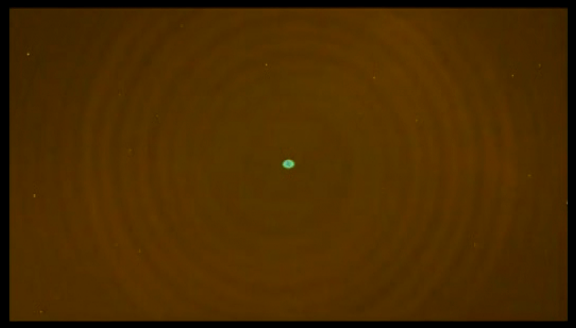

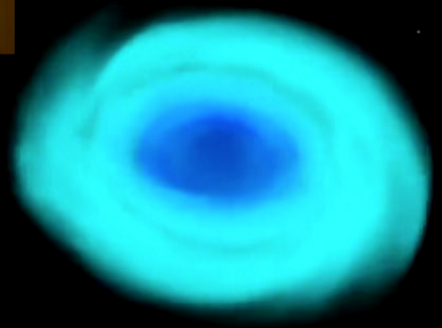

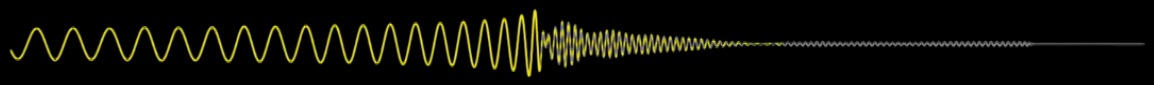

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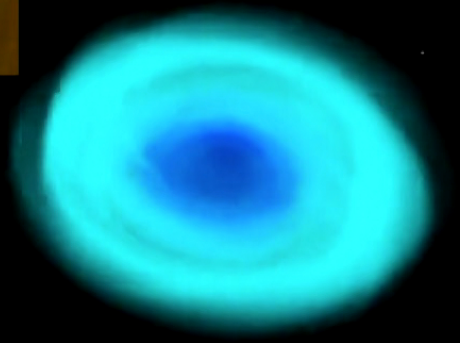

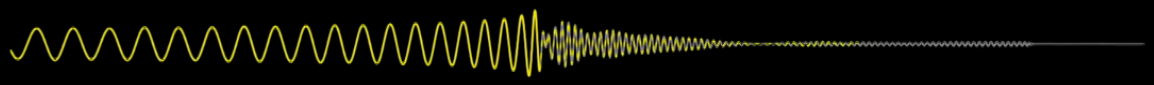

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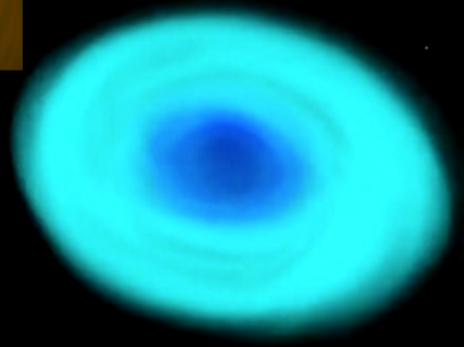

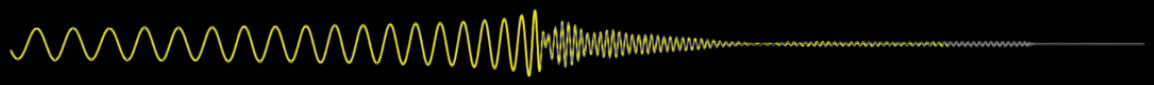

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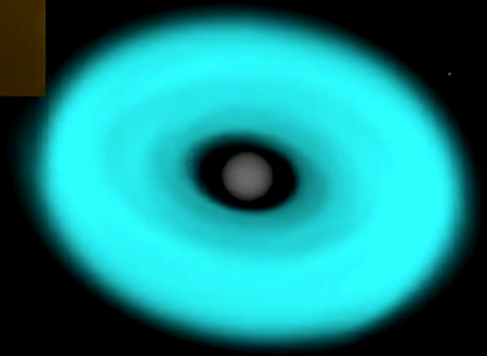

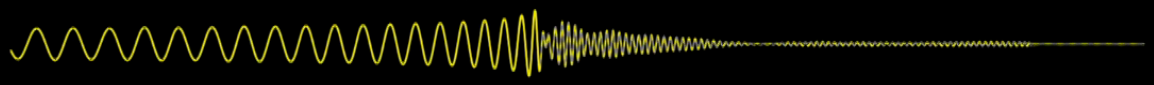

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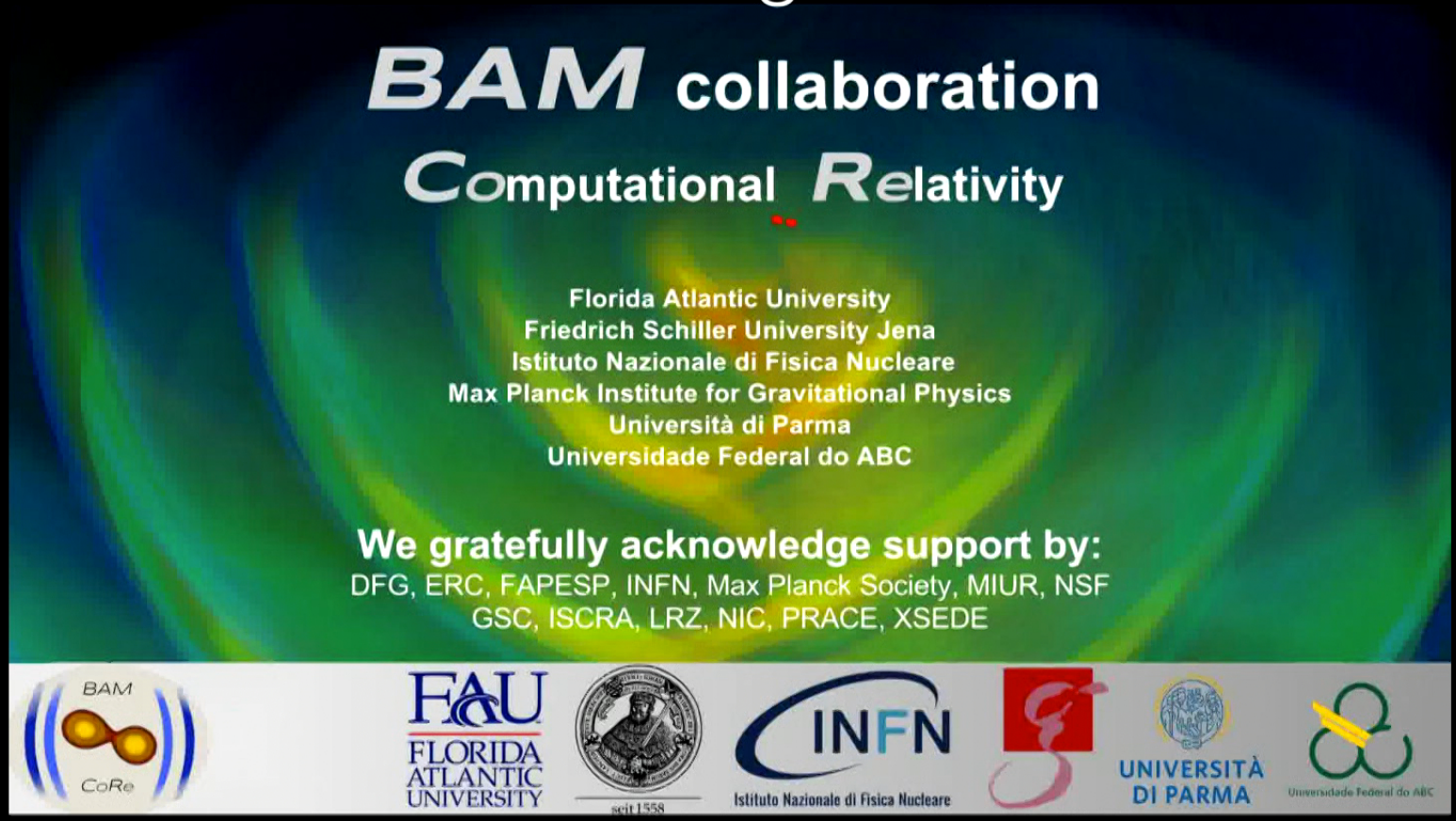

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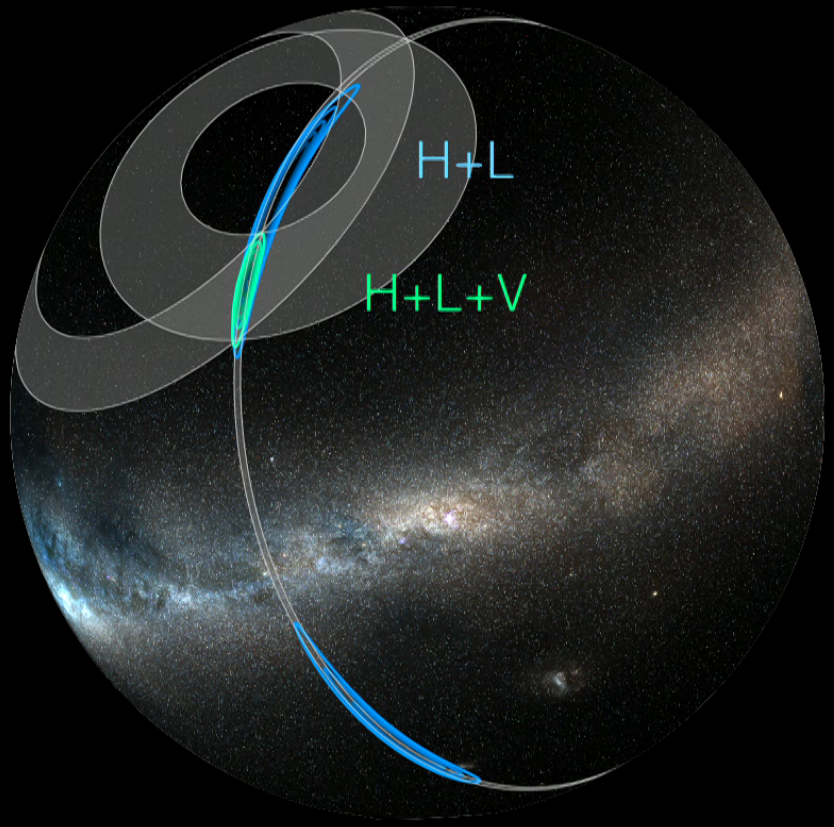
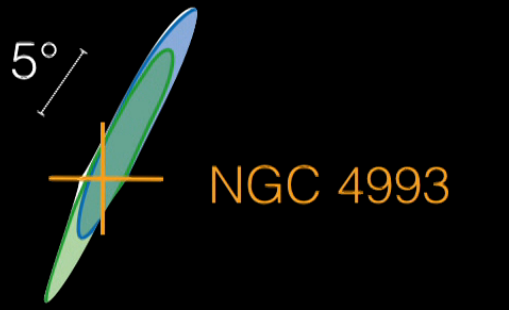
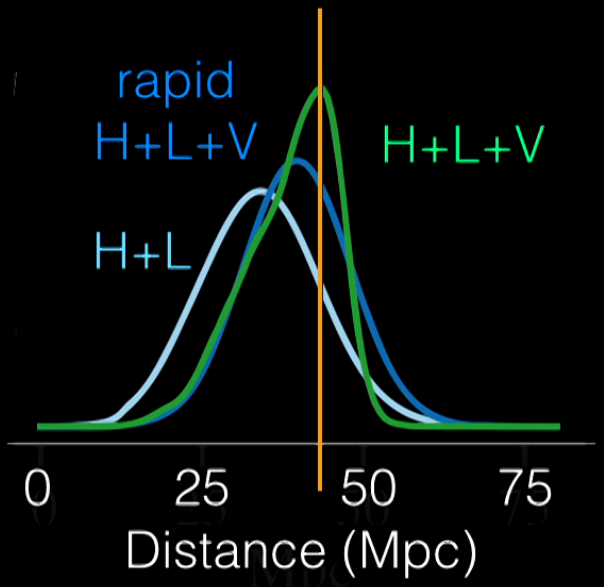
Distance and sky location







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

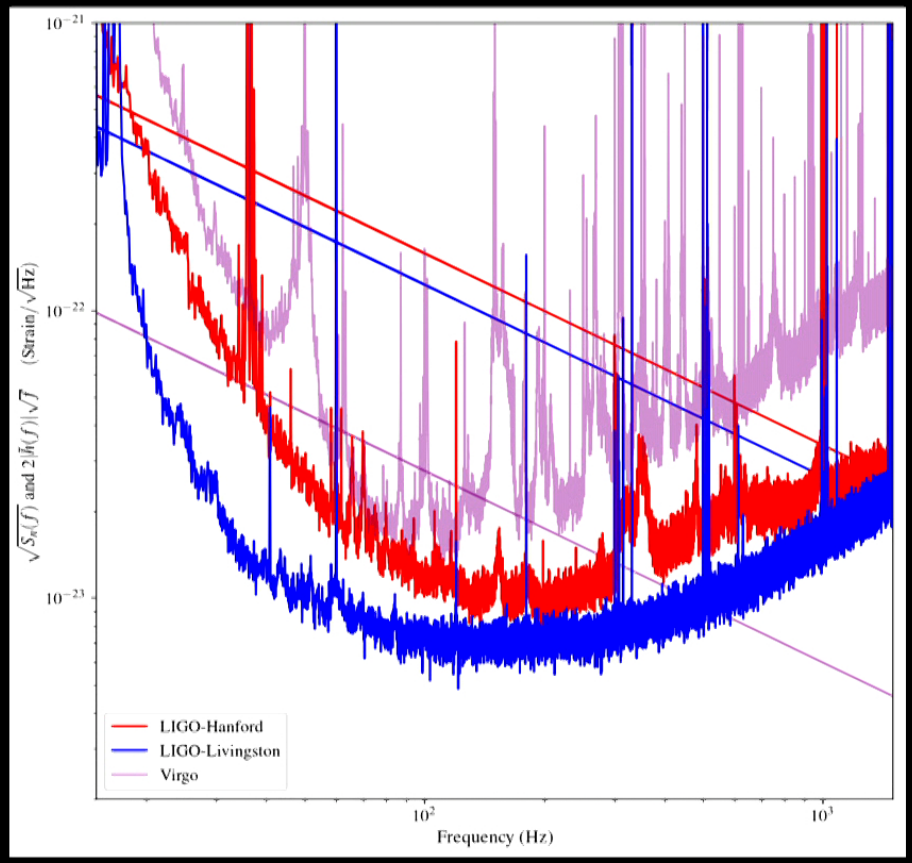
Sky location: Detector dependent strain

Hanford
SNR ~16

Livingston
SNR ~25

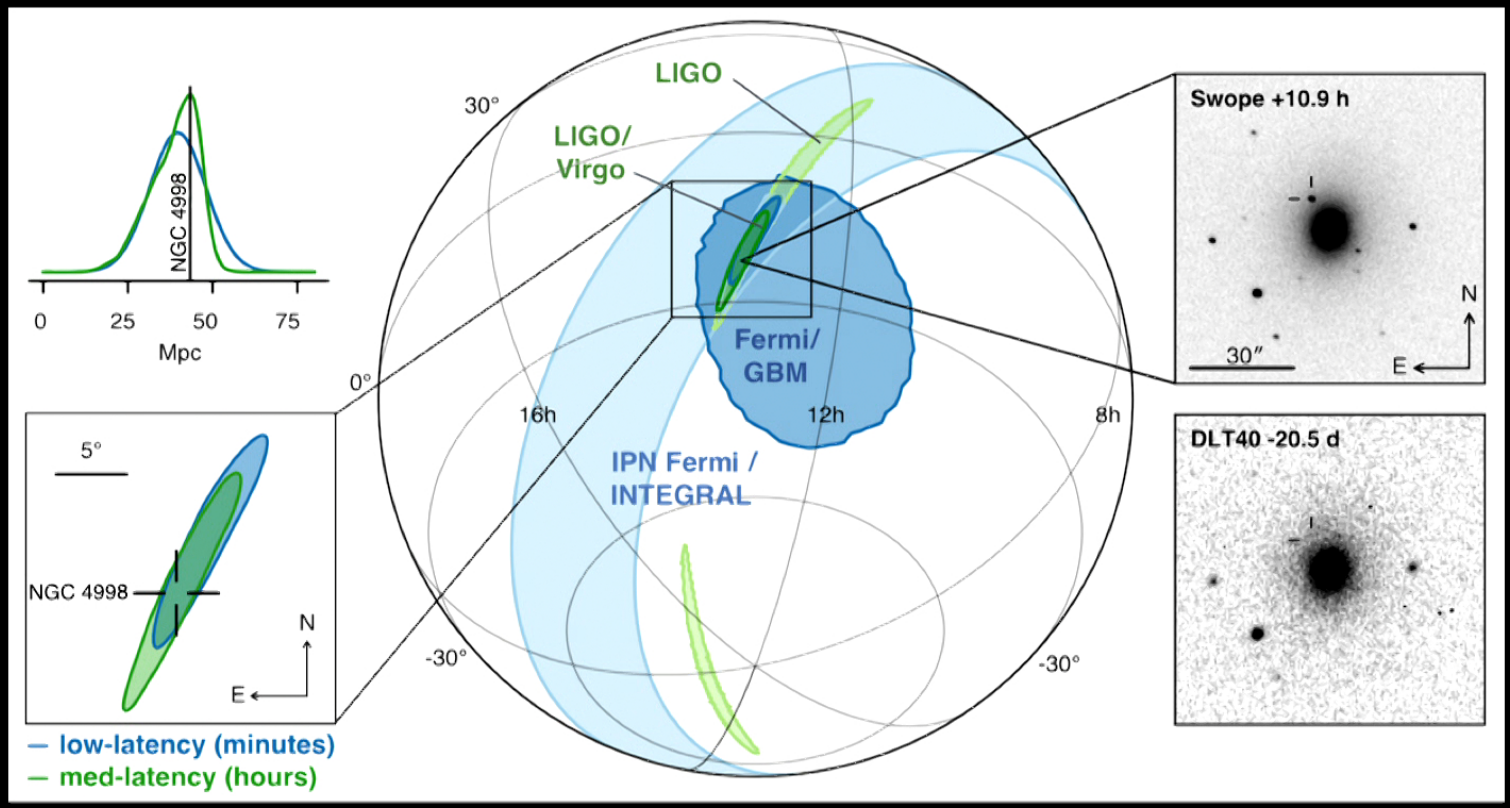
Virgo
SNR ~2

H&L amplitudes recovered by matched-filter search,Virgo reconstruction

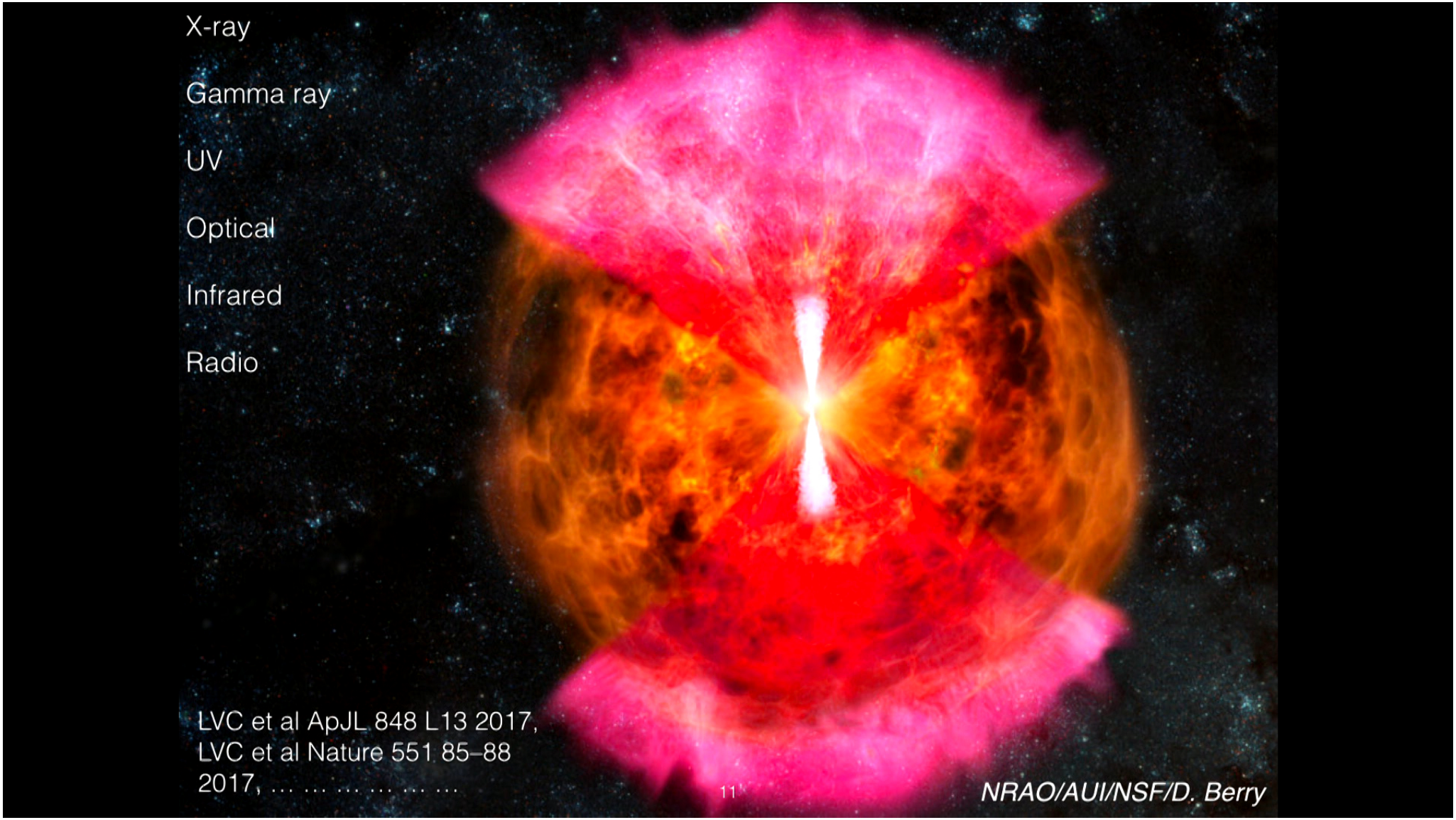


LIGO/Virgo/ Brown, Lovelace, Nitz, Read

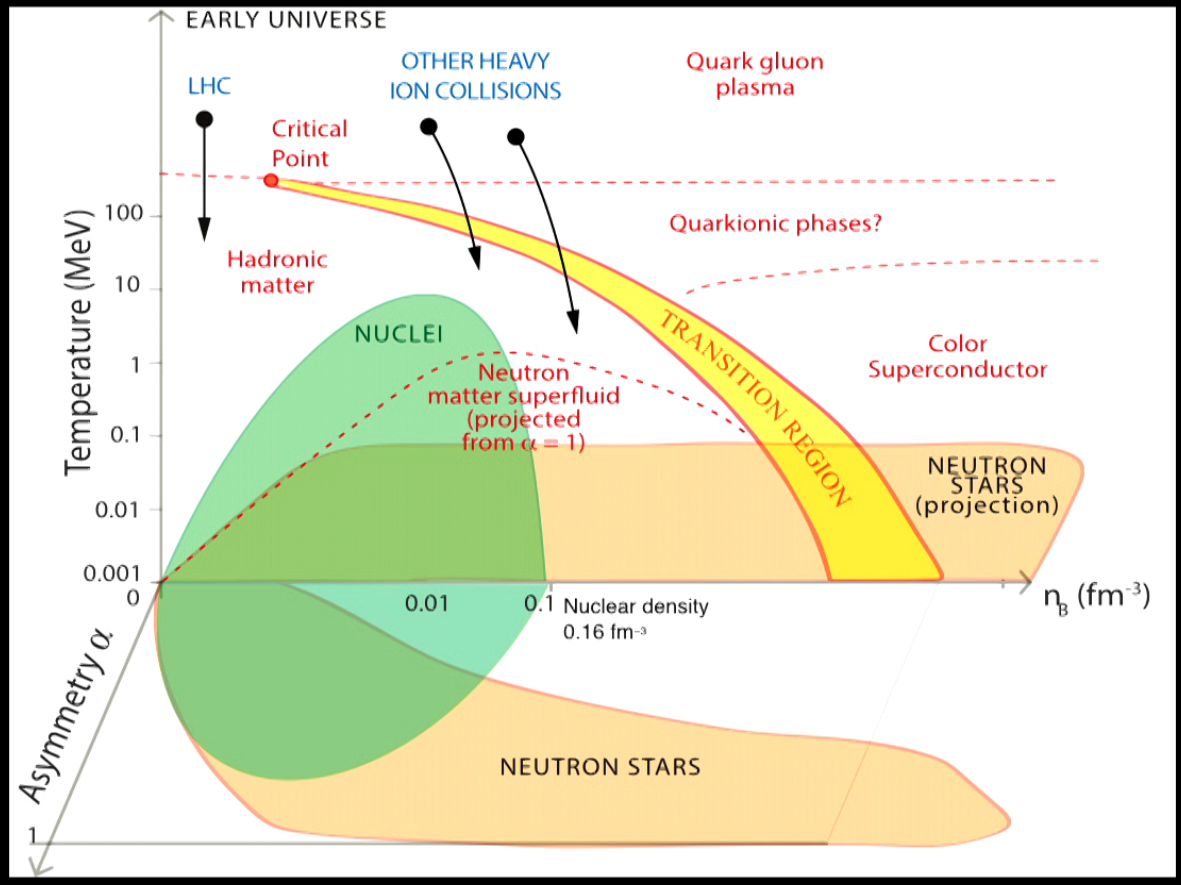
EM counterpart



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


X-ray
Gamma ray
UV
Optical
Infrared
Radio
LVC et al ApJL 848 L13 2017,
LVC et al Nature 551 85–88
2017, … … … … … …
11
NRAO/AUI/NSF/D. Berry

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

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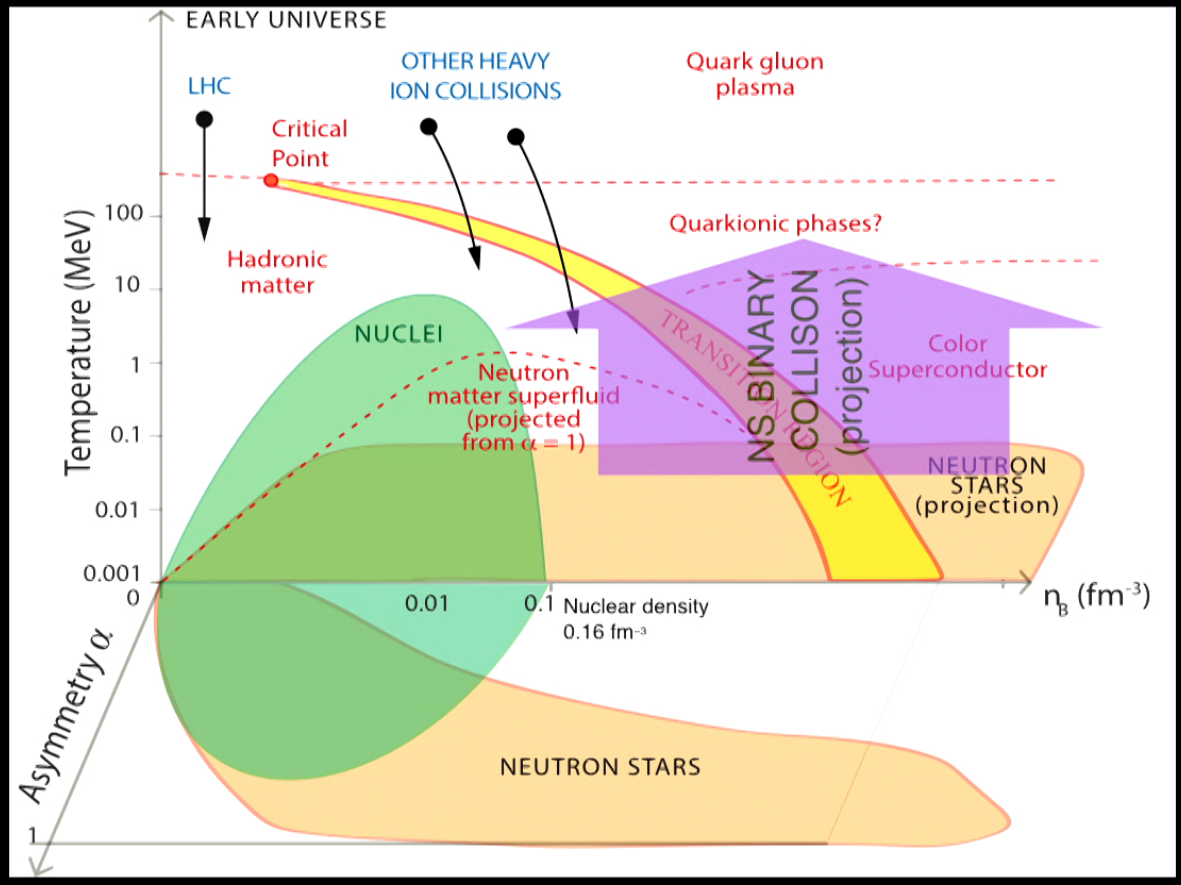

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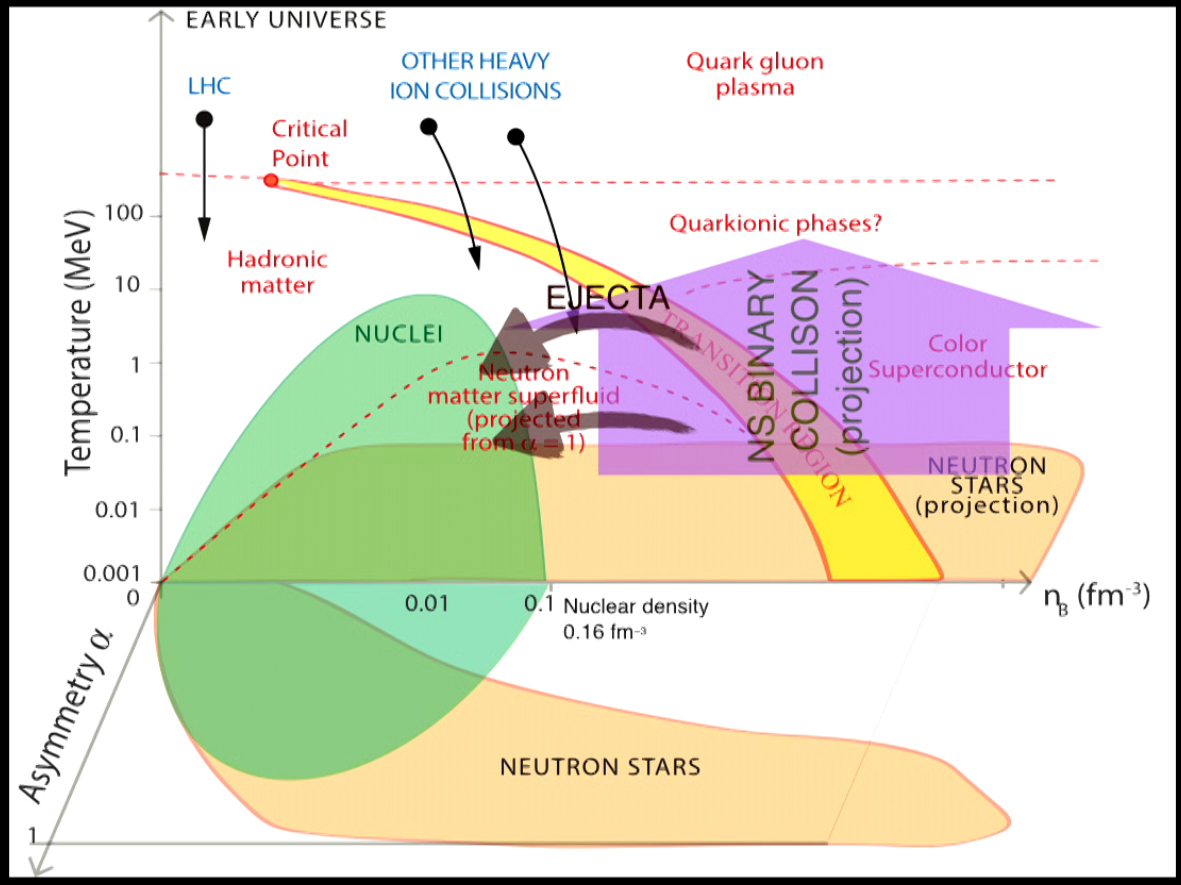

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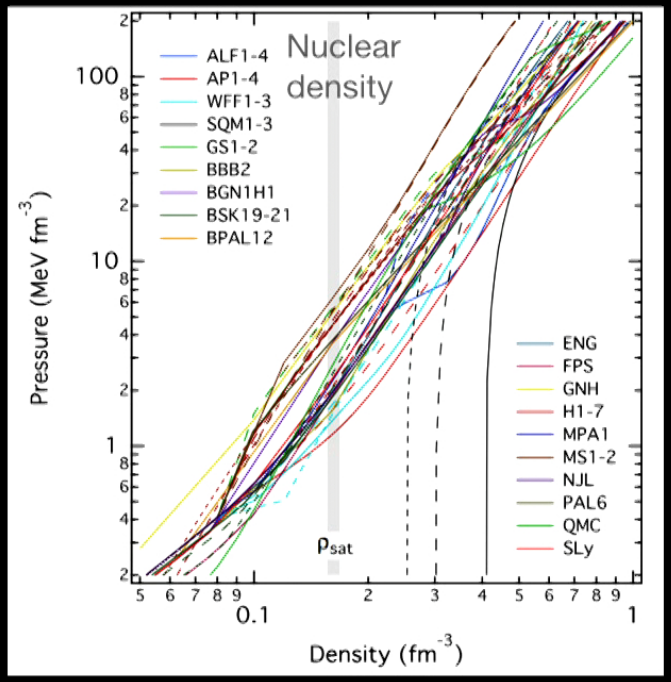
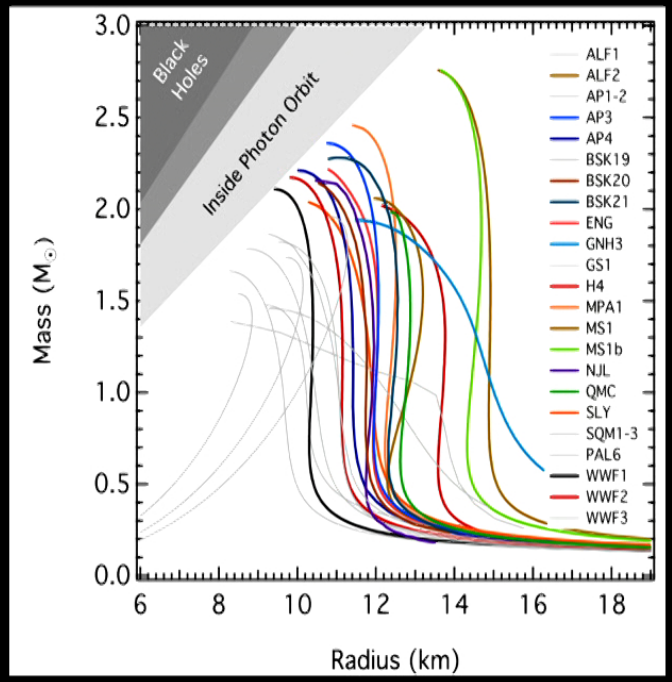
Properties of dense matter

Neutron star properties

Equation of state in cold beta equilibrium

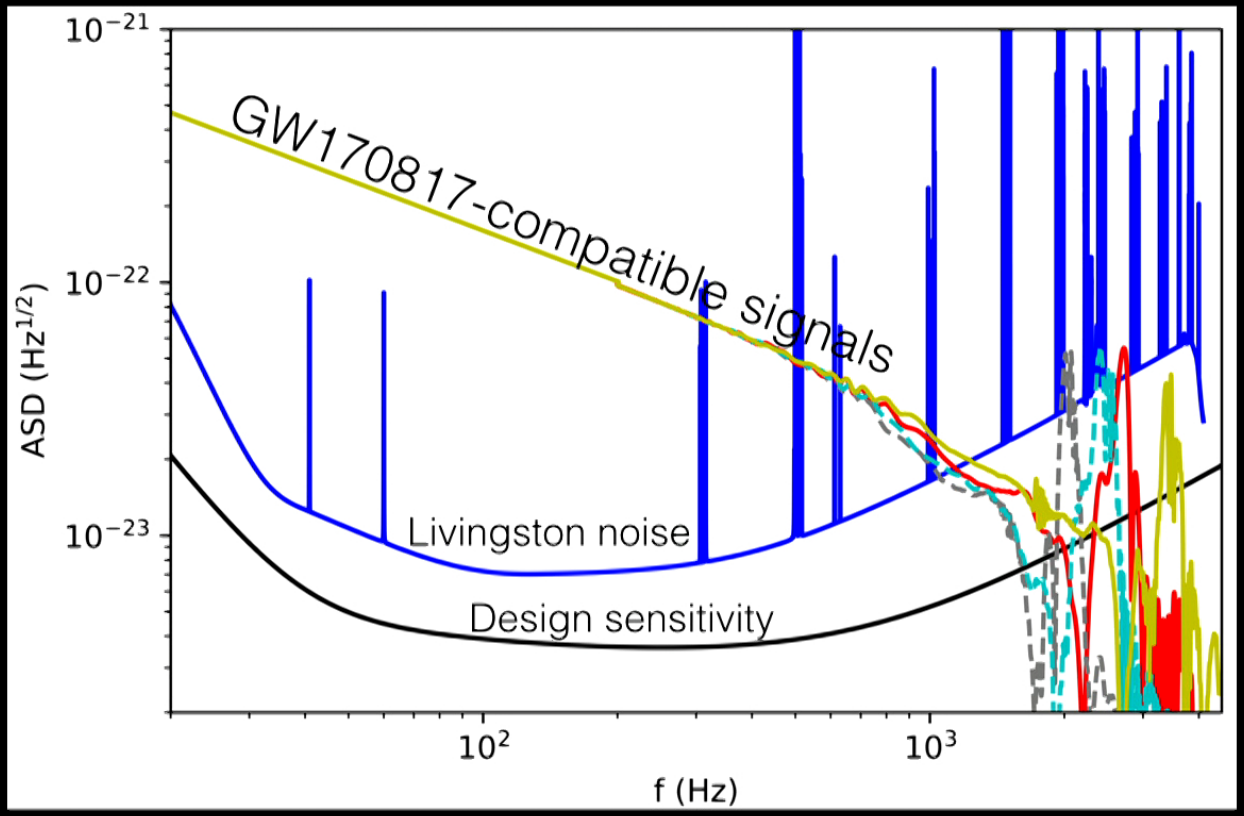
Mass-radius relation, max mass, deformability

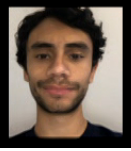




Ozel and Friere 2016

Matter Impact on GW170817





E. Leon/LIGO/Virgo. 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

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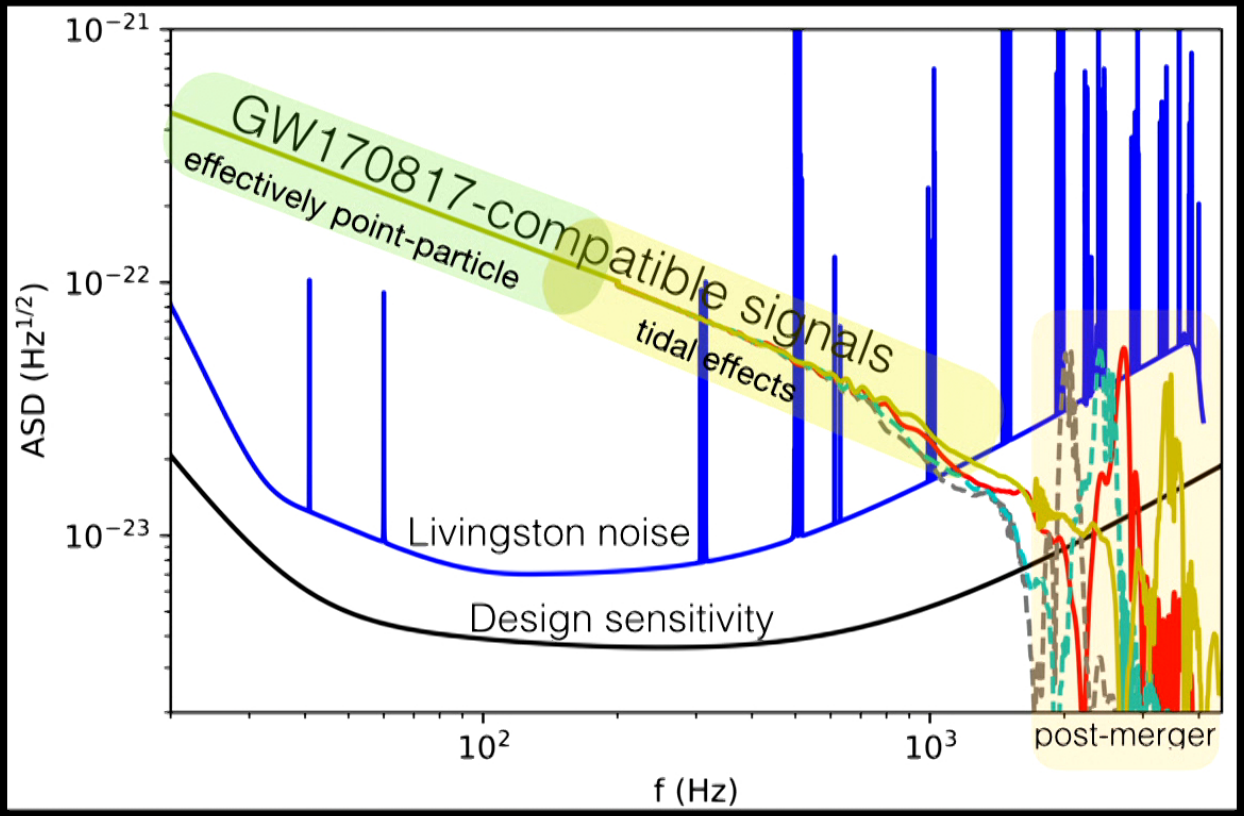

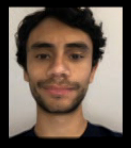

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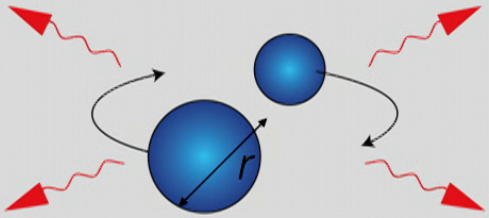
Inspiral and chirp



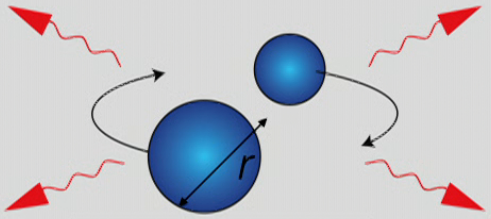
$$m = m_1 + m_2$$
$$\mu = m_1 m_2 / m$$

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

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

- Energy loss -> decreasing radius -> increasing freq

Inspiral and chirp



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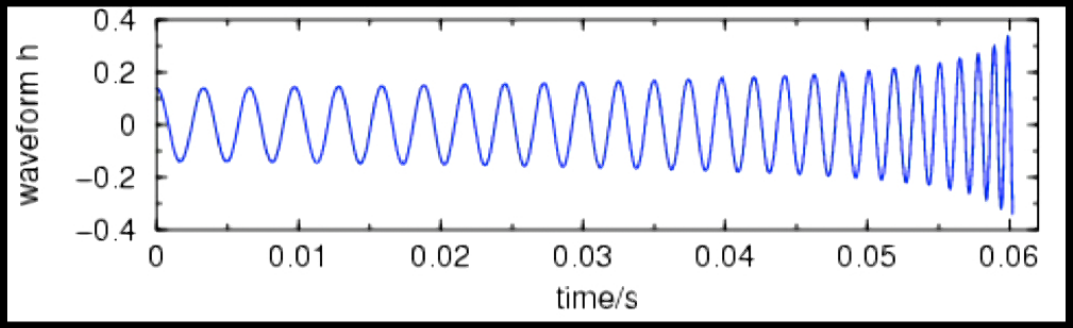
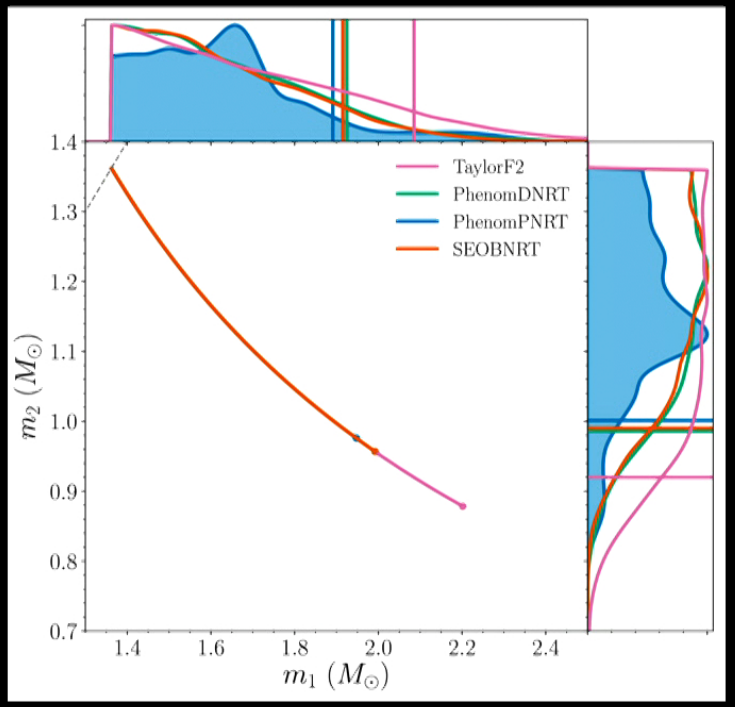
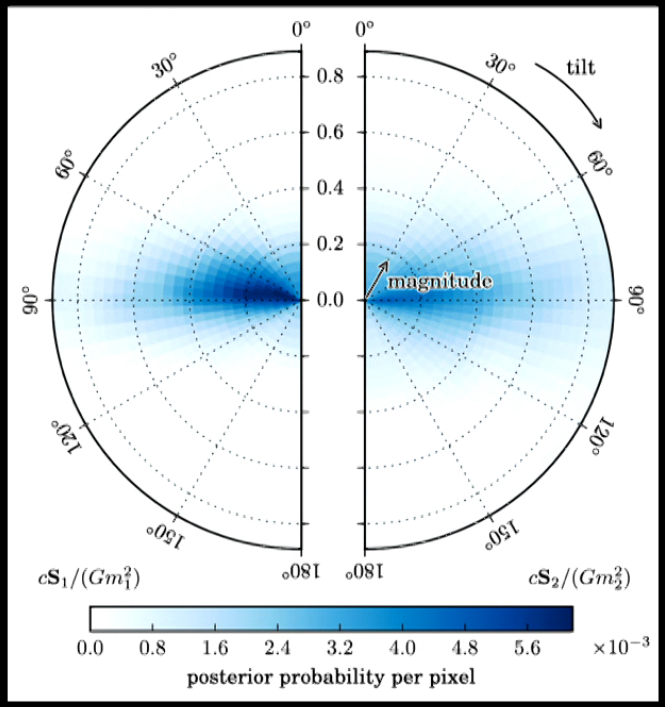
δL/L



GW170817 Masses and Spin

Gravitational-wave strain data
Minimal assumptions about source properties





Update to initial results, LVC Source Properties 1805.11579

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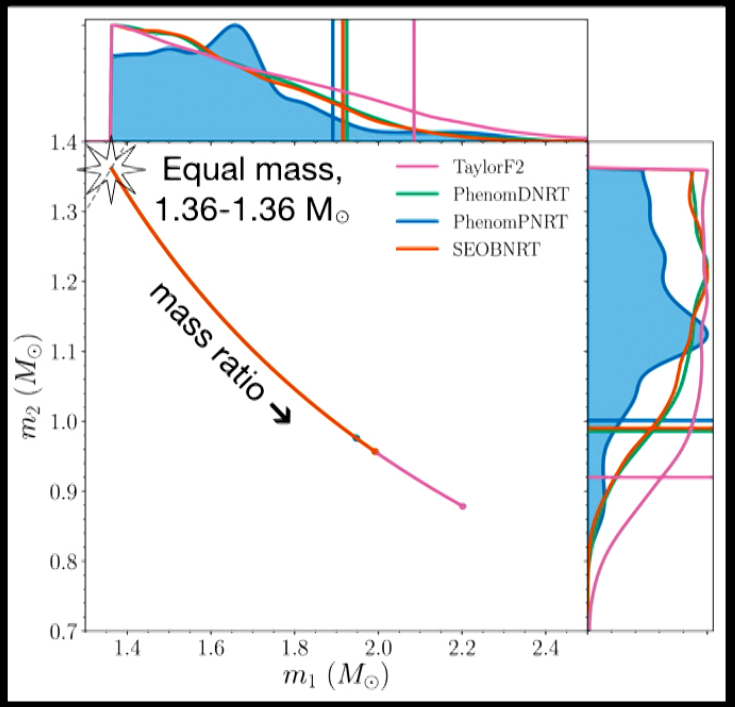

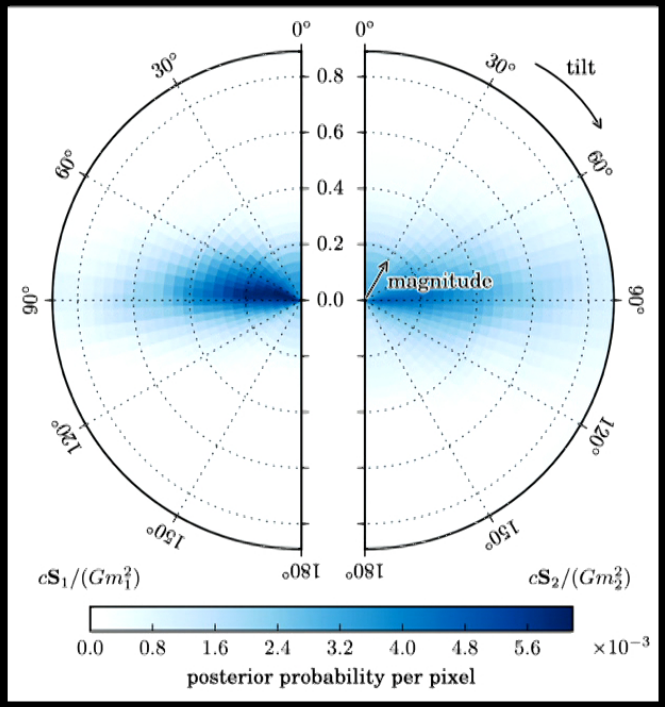

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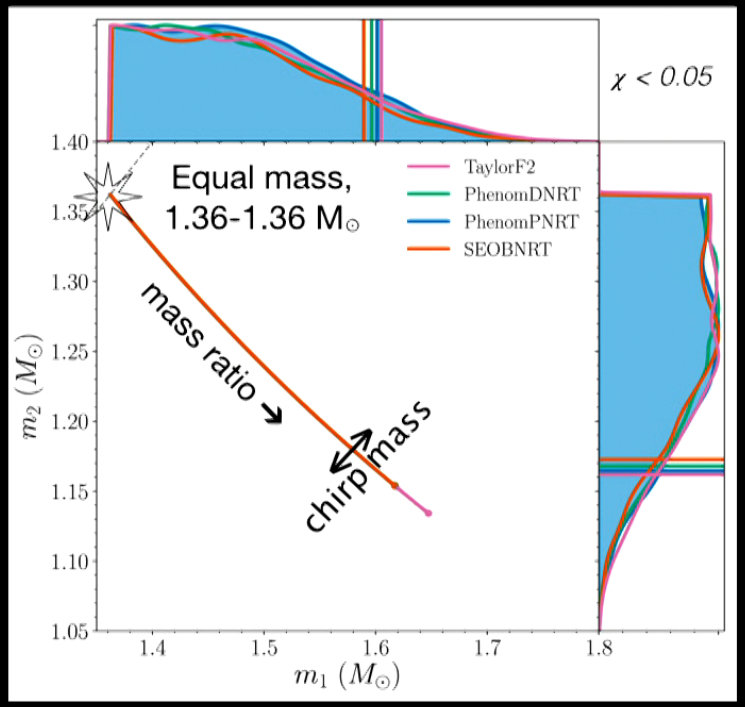
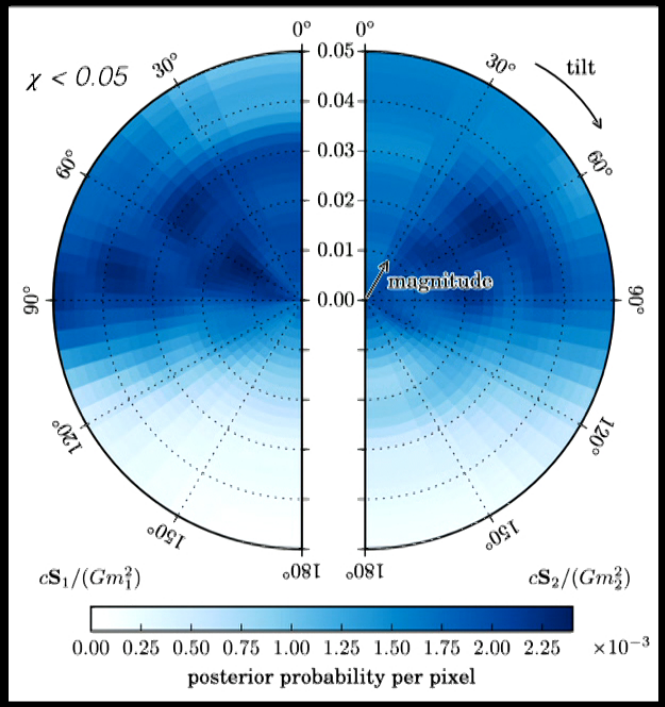
GW170817 Masses and Spin

Assume low spins, motivated by galactic DNS
Limits mass/spin degeneracy, shift toward equal mass





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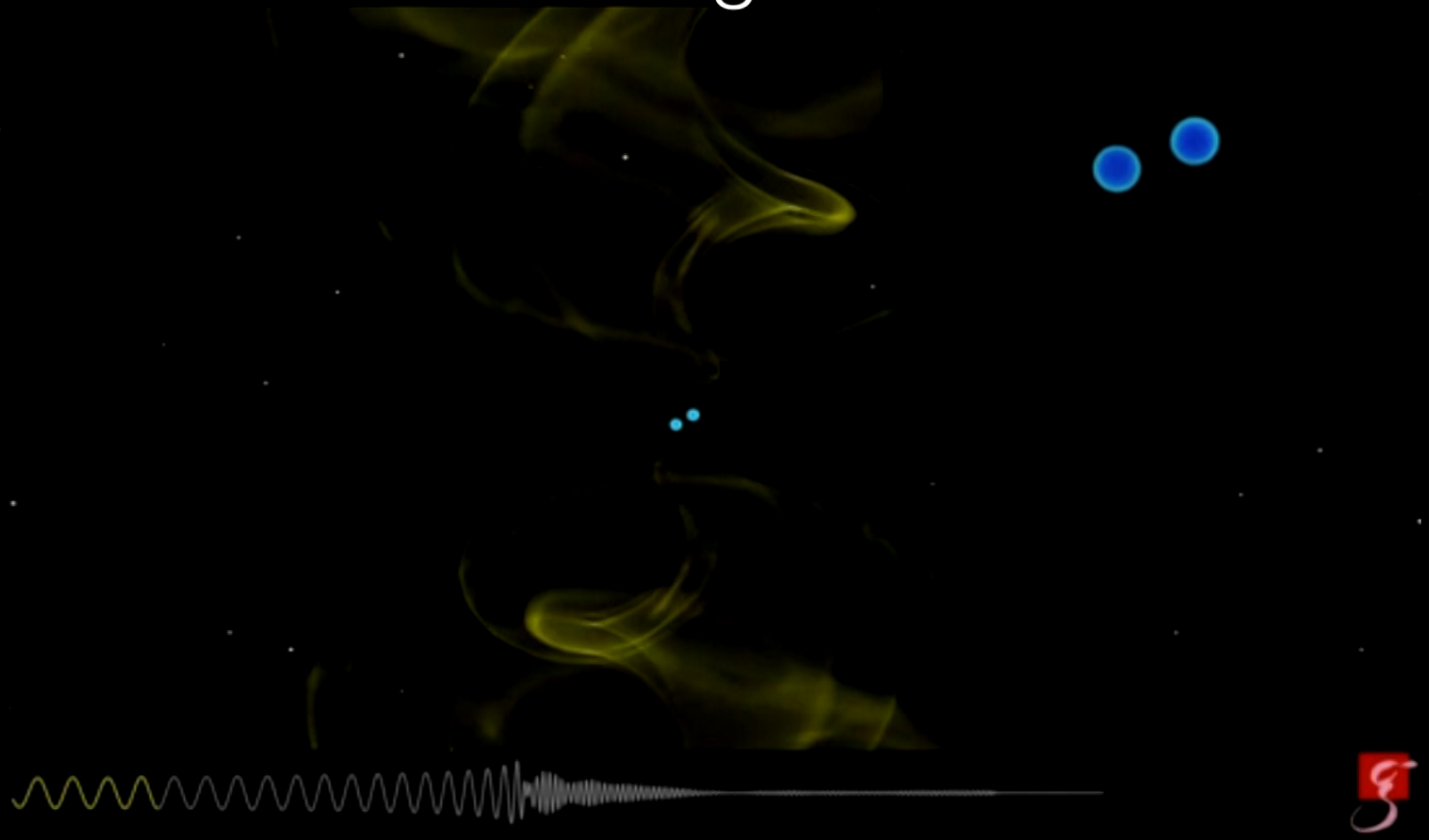
Neutron-star merger: Last 30 ms



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

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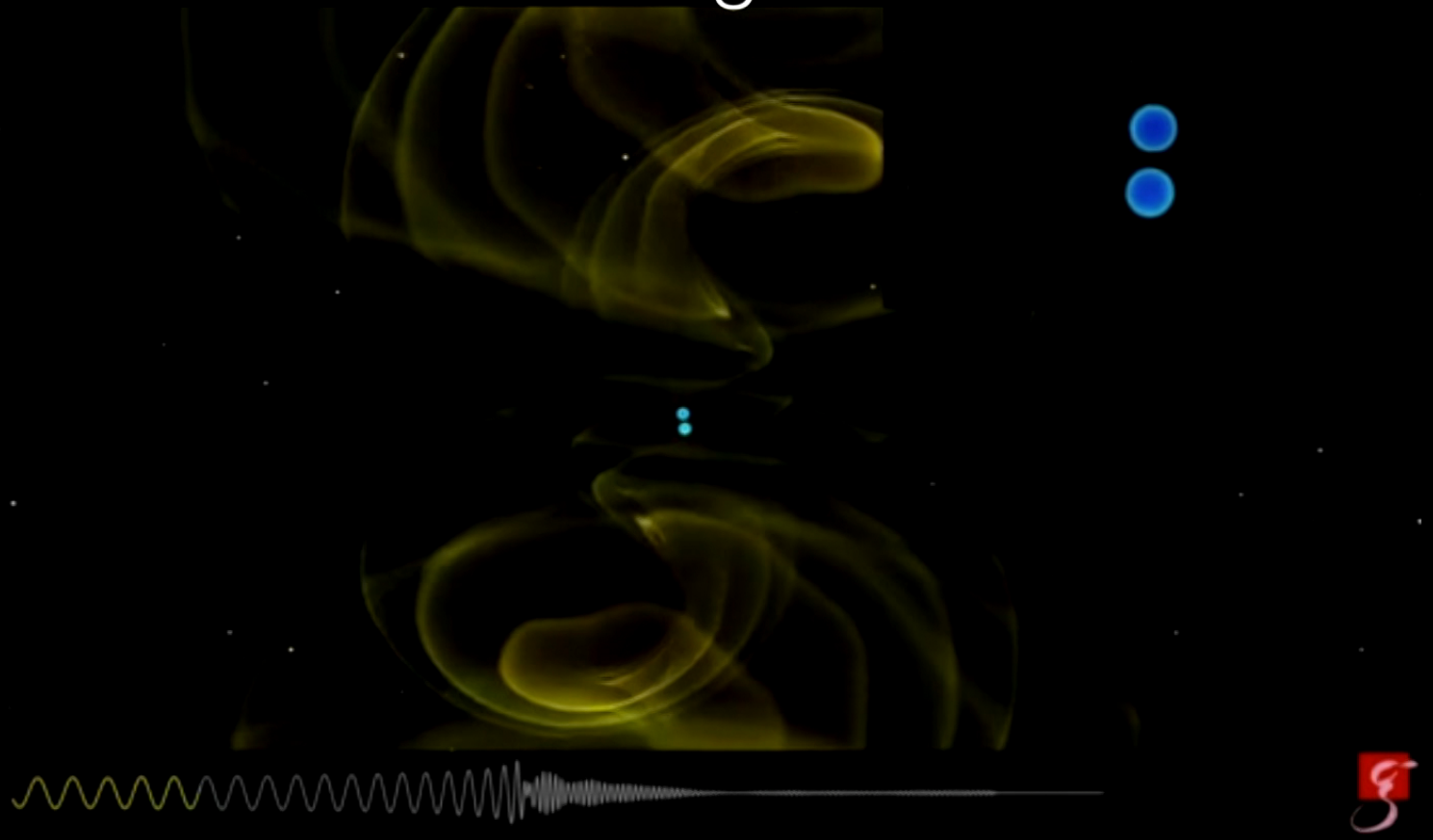

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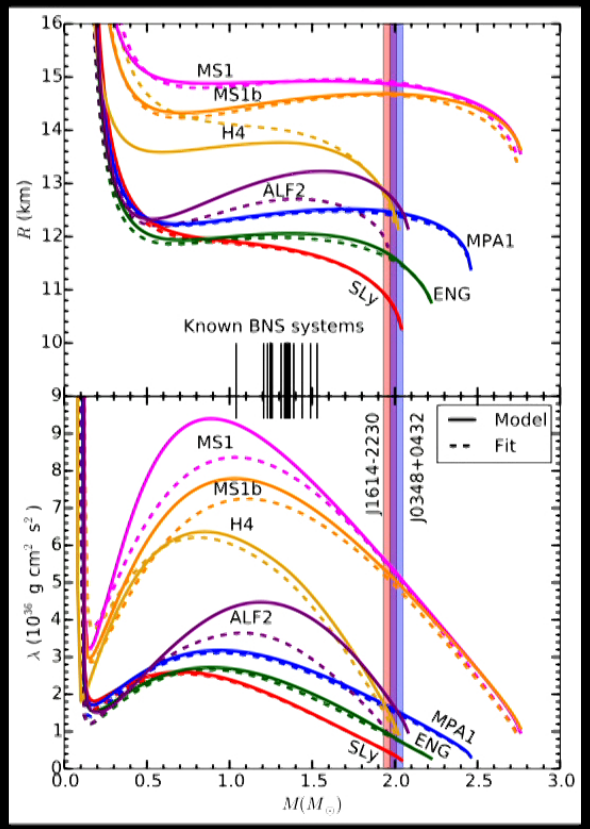
Tidally deformed stars



M/R/Λ Figure from Lackey and Wade 2014

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

$$\lambda = \frac{Q}{\mathcal{E}} = \frac{\text{size of quadrupole deformation}}{\text{strength of external tidal field}}$$

$$\lambda = \frac{2}{3} k_2 R^5$$

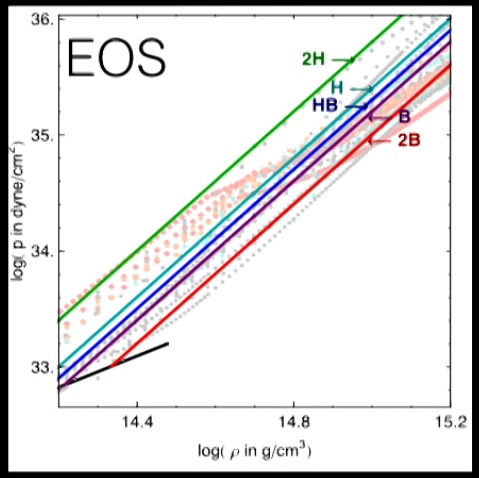
- R radius of star
- k_2 *Relativistic* love numbers (Damour 1983)
  - Mass distribution inside the star, not surface deformation

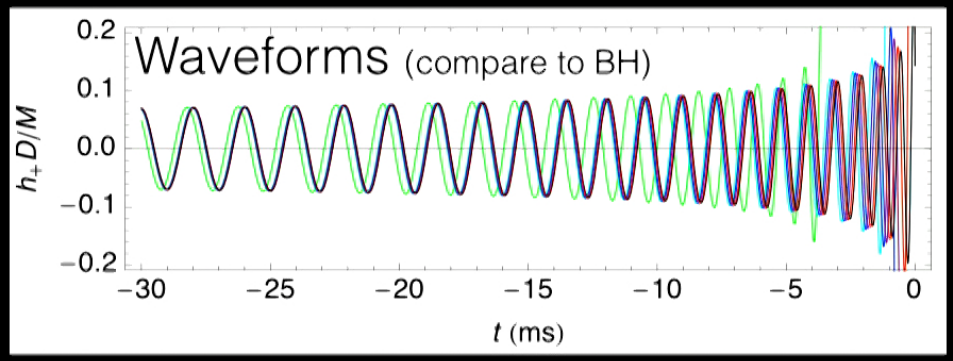
Inspiral matter dependence

- Deformation accelerates inspiral - extra energy into deforming stars, extra quadrupole moment. Modifies waveform proportional to:

$$\Lambda = \frac{2}{3} k_2 \left(\frac{R}{M}\right)^5$$

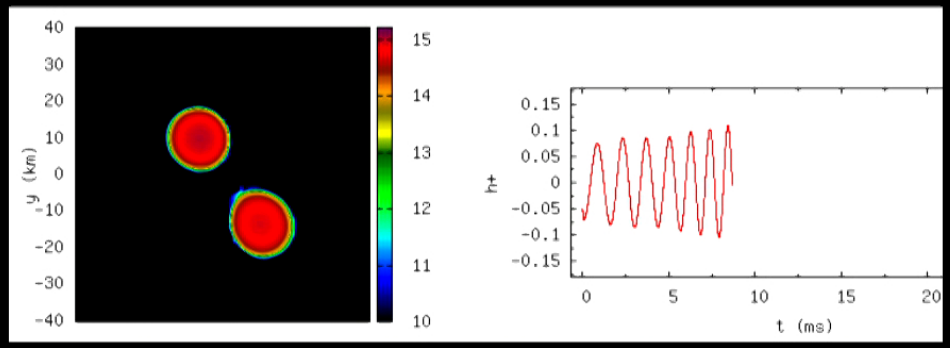
Flanagan & Hinderer 2008





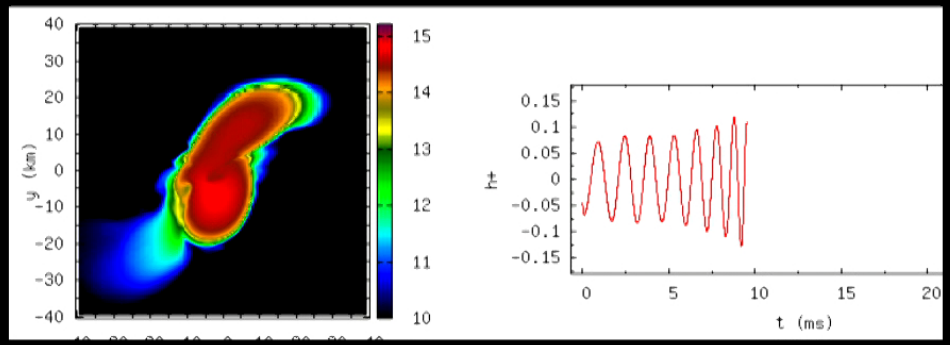
Higher EOS pressures → larger radii → more deformation

Merger matter dependence



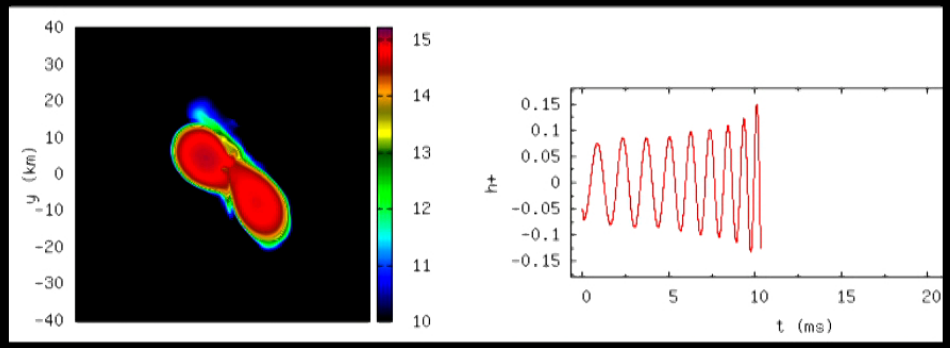
Compact stars: merge at higher frequency, more similar to BBH

Numerical simulations: K. Hotokezaka, YITP



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

Merger matter dependence



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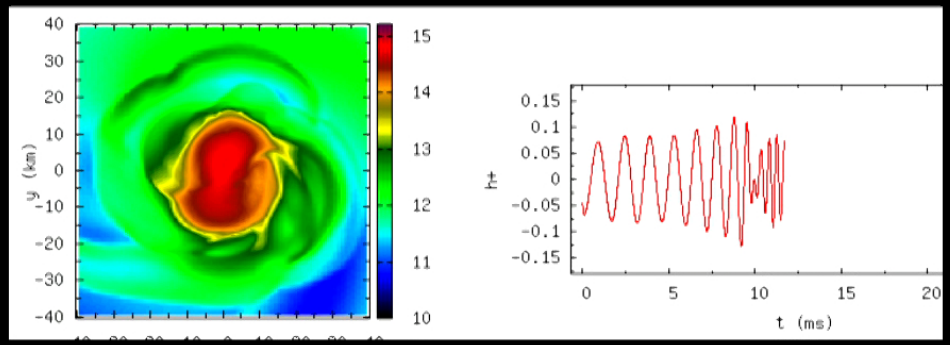

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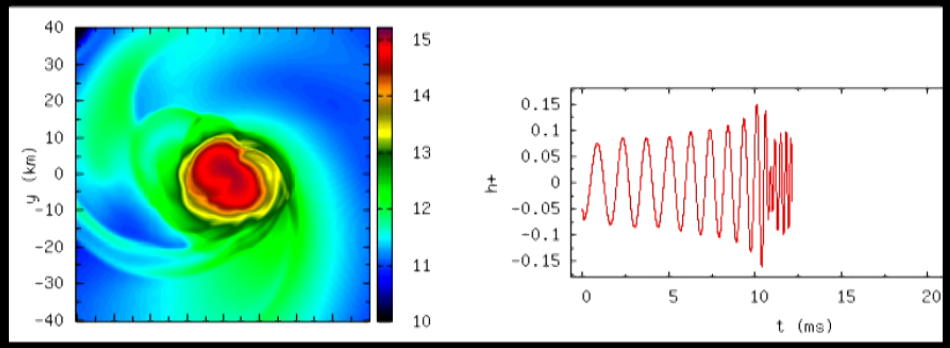

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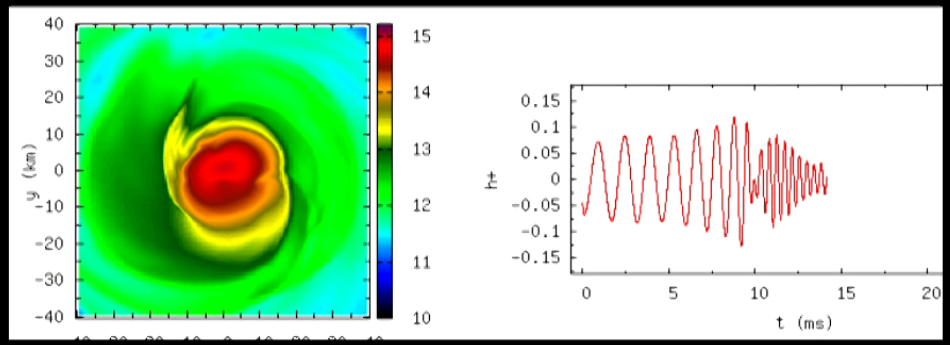

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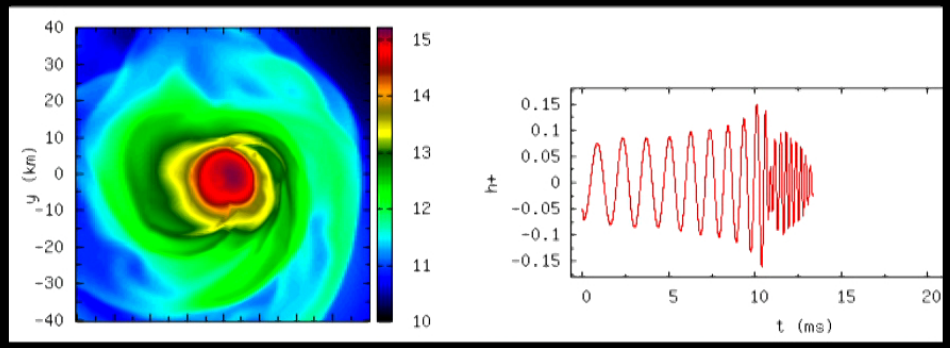

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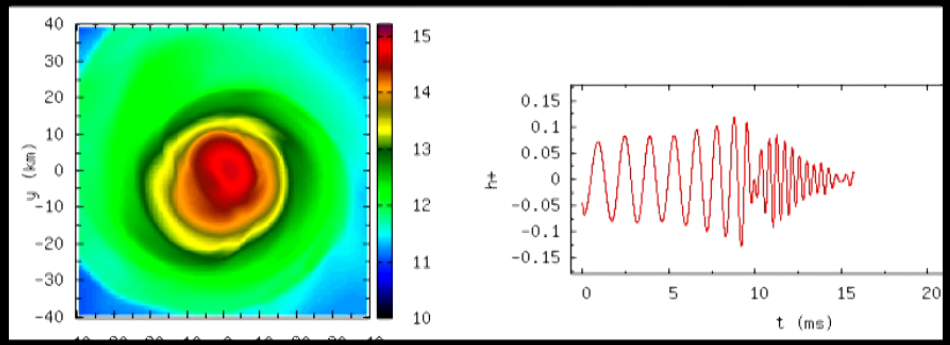

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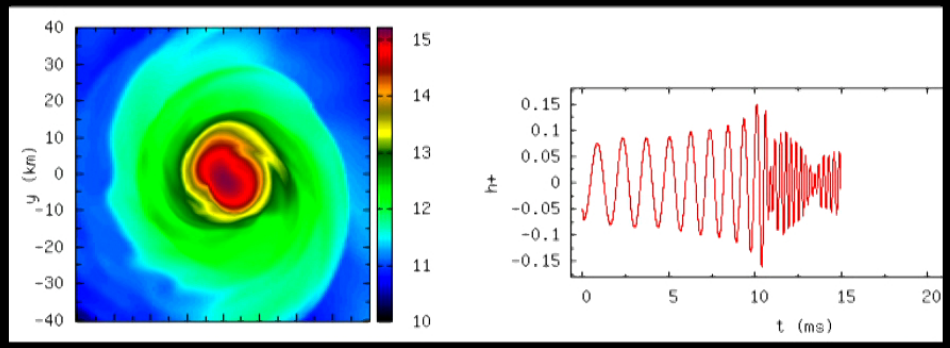

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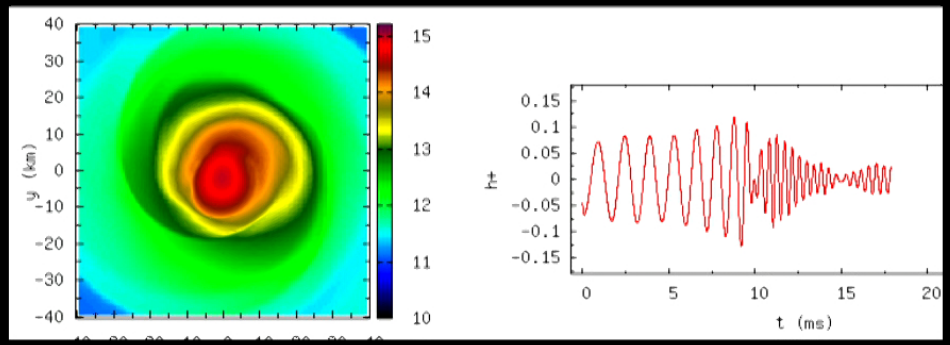

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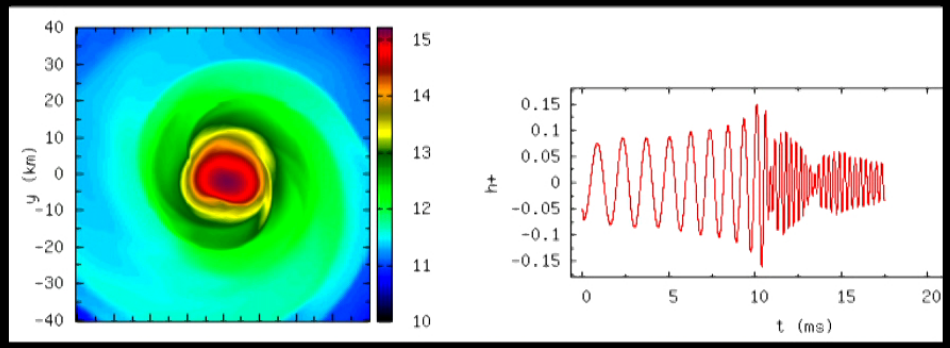

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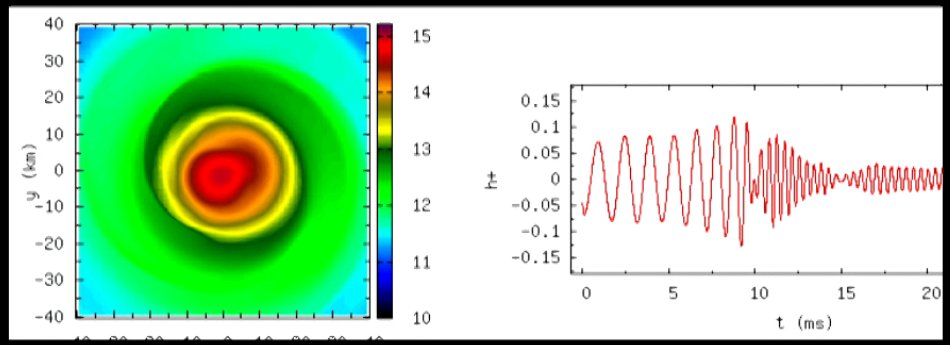

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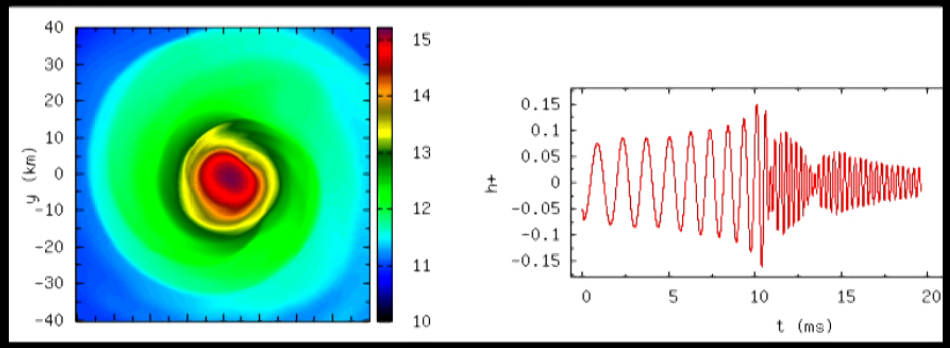

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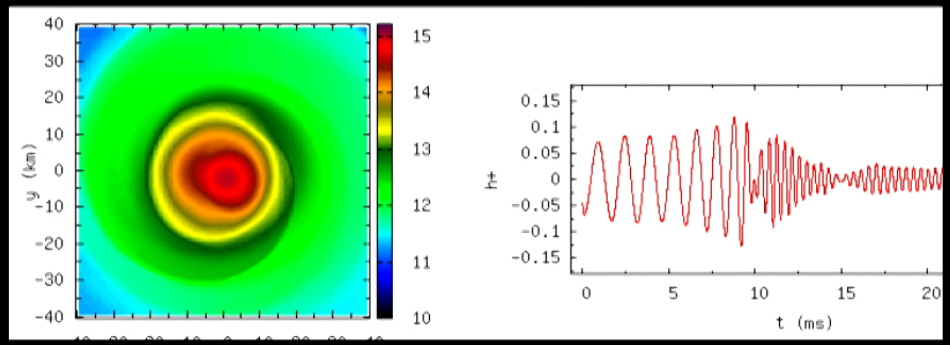

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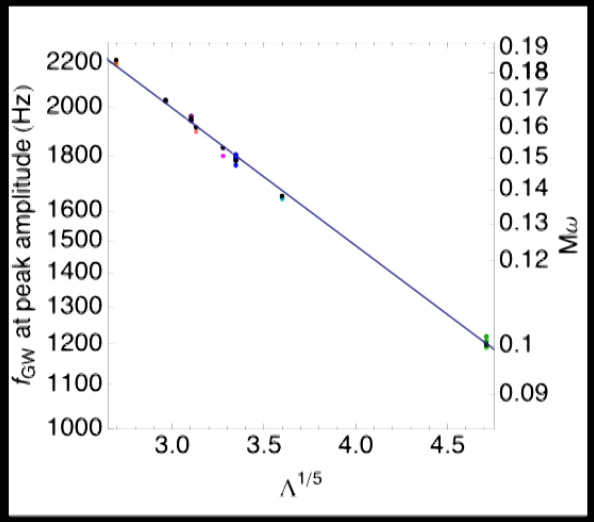
Perturbative tidal deformability characterizes merger

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



- Read et al 1306.4065 Bernuzzi et al 1402.6244

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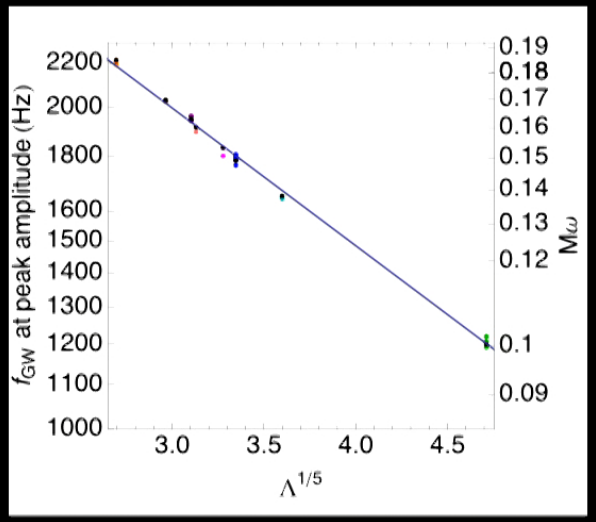

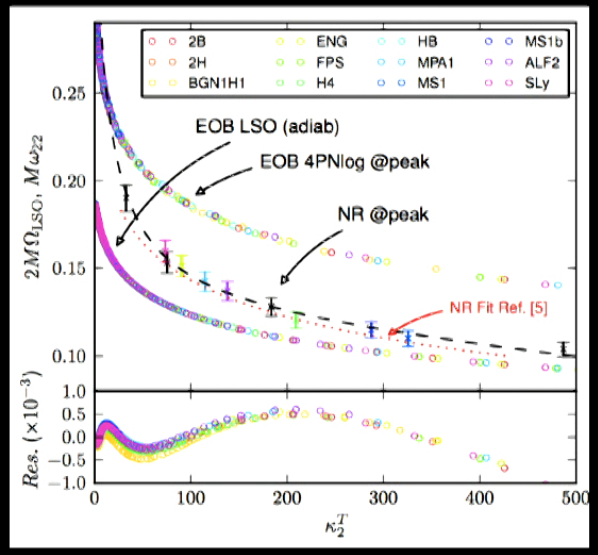

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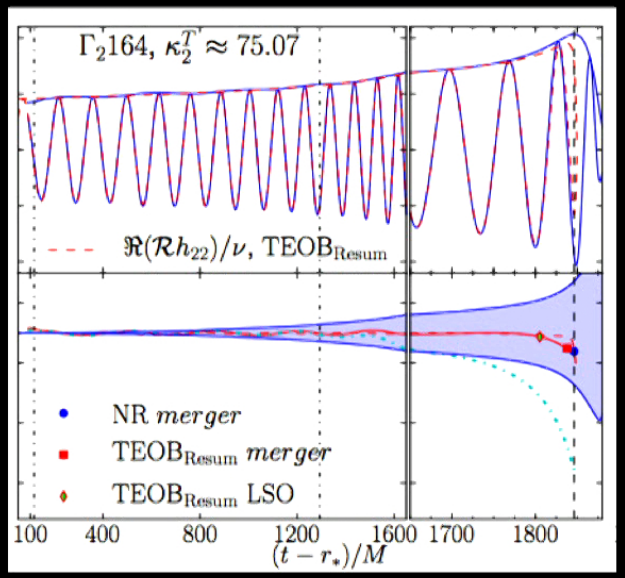
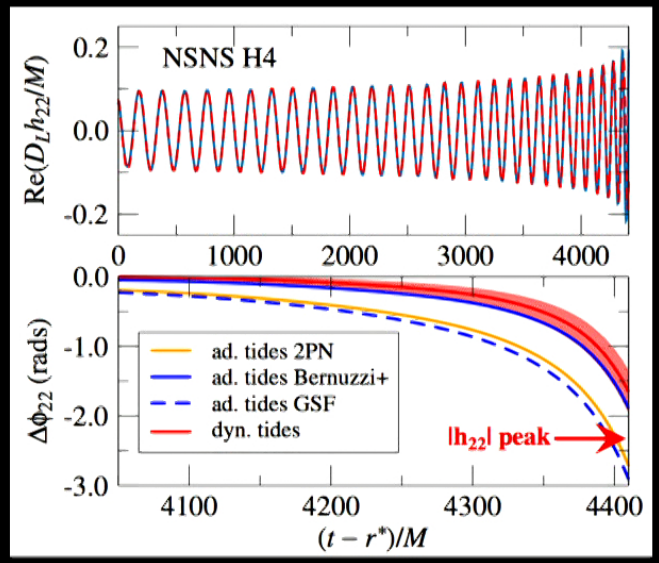
Today's waveform models

- Phenomenological extensions to improve agreement with NR (Bernuzzi, Dietrich, & Tichy 2017 NRTides + SEOB used for GW170817 systematics in LSC/Virgo PRL 119, 161101 (2017))

- EOB plus tidal corrections plus higher-order effects: semi-analytic models capture inspiral-to-merger phase

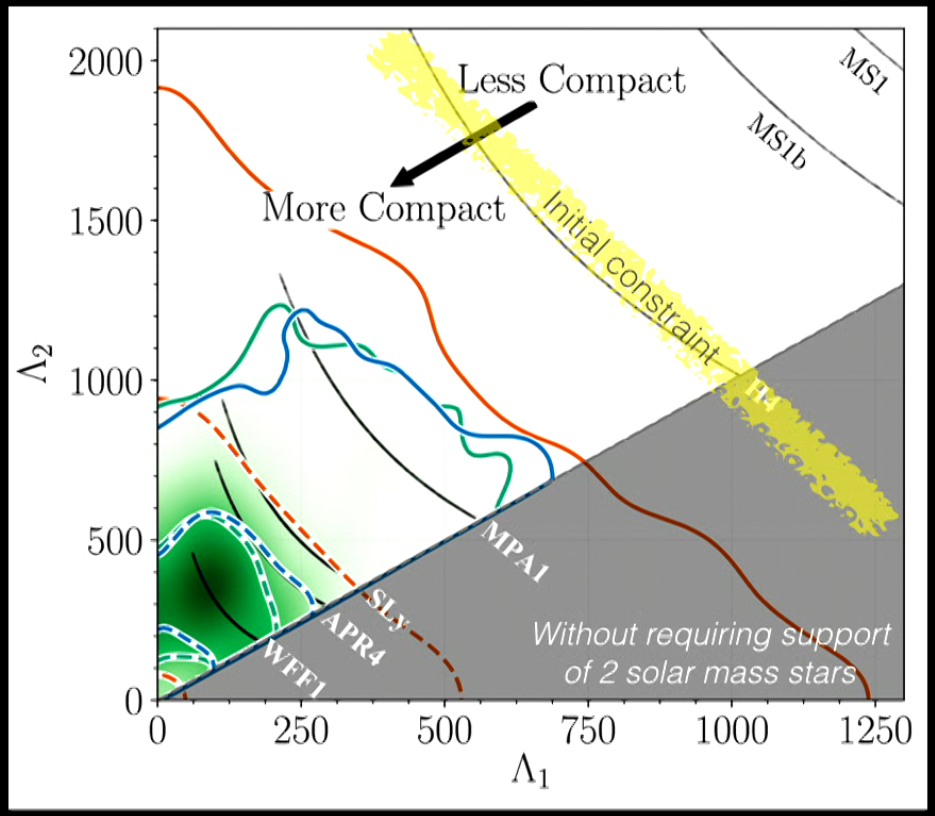




- Bernuzzi et al 1412.4553
- Hinderer et al 1602.00599

Tidal measurements from GW170817

$\chi < 0.05$ $\Lambda_{1.4} < 800$ $\Lambda_{1.4} = 190^{+390}_{-120}$



24

Discovery

LVC PRL 119, 161101 (2017),

Restricted frequencies, simplified waveform model, independent Λ

Updated properties

LVC 1805.11579

Independent Λ

Common EOS

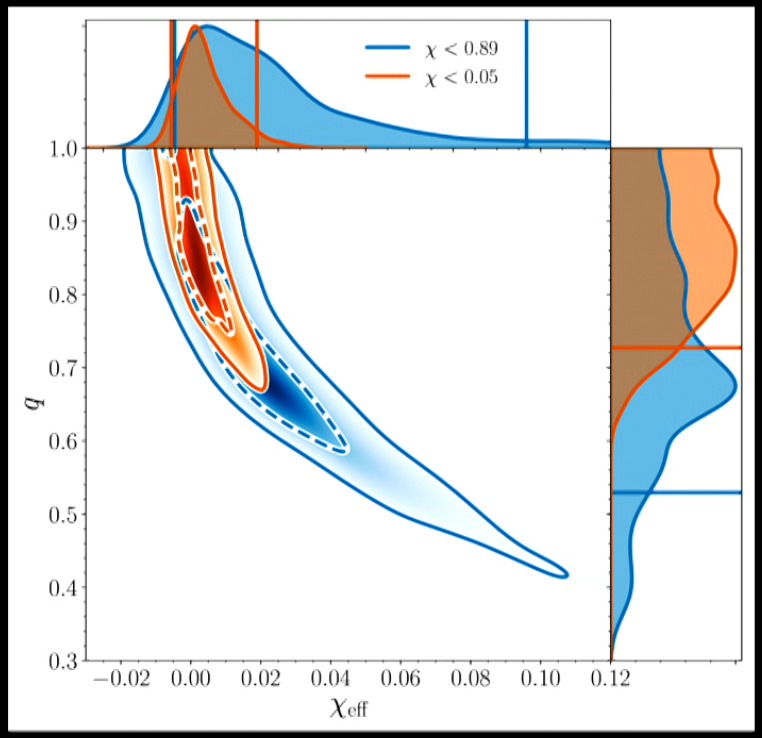
LVC 1805.11581

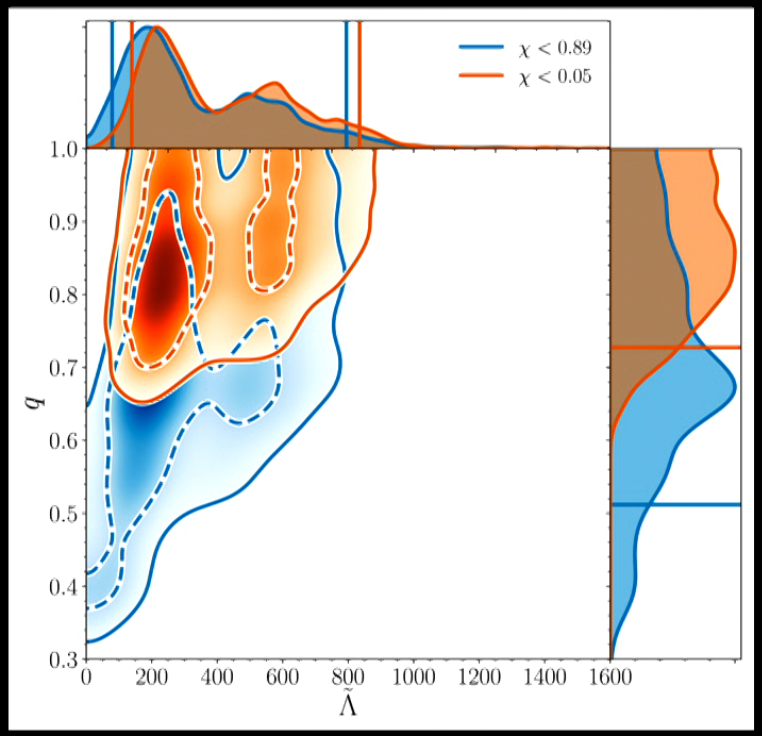
Quasi-universal relations between components

Common spectral-parameterized eos

Correlations with mass and spin

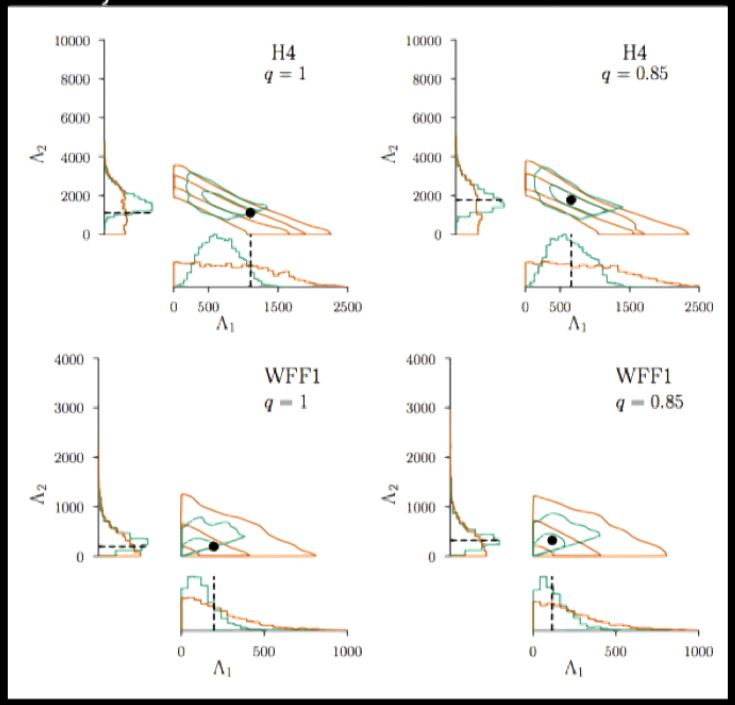
LVC Source Properties *1805.11579*





Common-EOS analysis:
Quasi-universal relations

Injected waveform tests



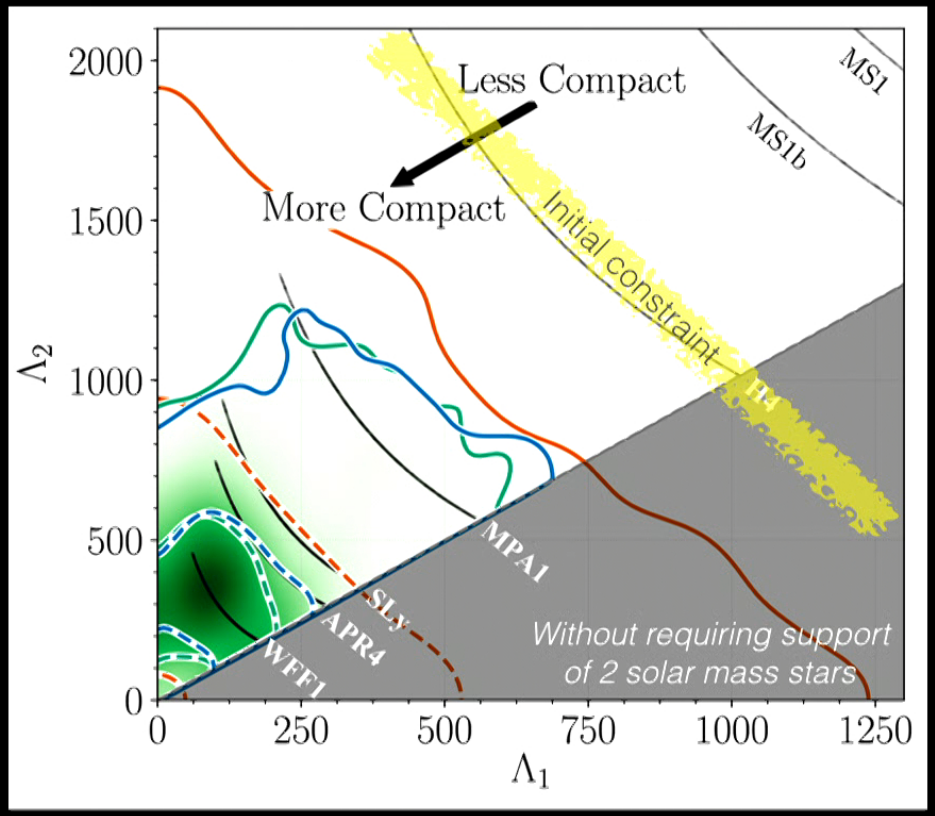
Independent Λ quasi-universal

Chatziioannou et al
1804.03221

- Apply quasi-universal relations determined from candidate EOS
  - Yagi and Yunes, Class. Quant. Grav. 33, 13LT01 (2016)
- Link Λ_1 and Λ_2 in sampling, depending on mass ratio
- Marginalize over relation error; tighter constraints for compact NS injections

Tidal measurements from GW170817

$\chi < 0.05$ $\Lambda_{1.4} < 800$ $\Lambda_{1.4} = 190^{+390}_{-120}$



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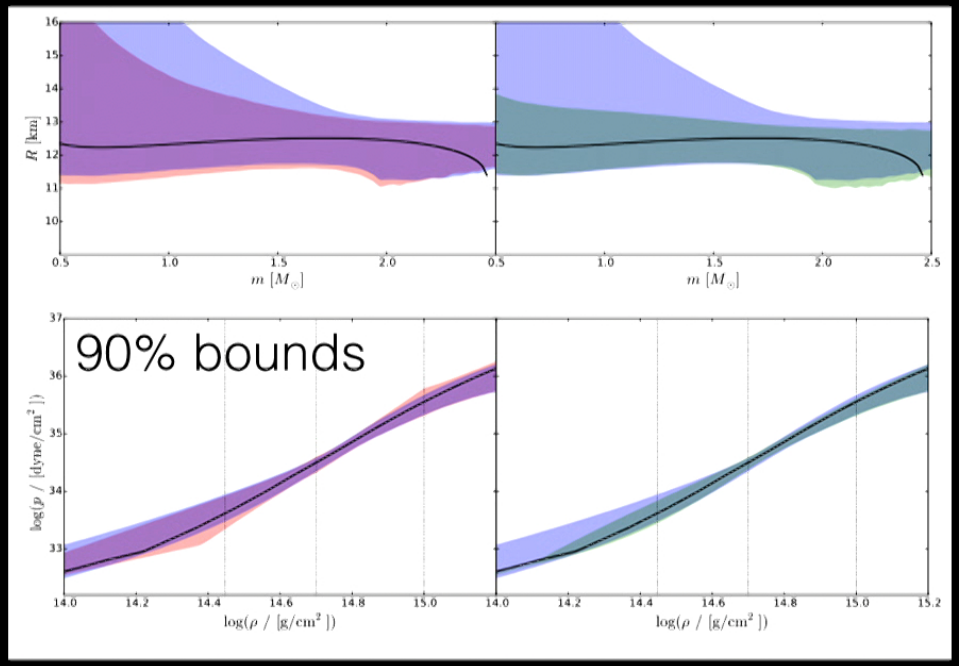
Common-EOS analysis:
Parameterized EOS

Injected waveform tests



Piecewise Polytropes

Spectral Decomposition

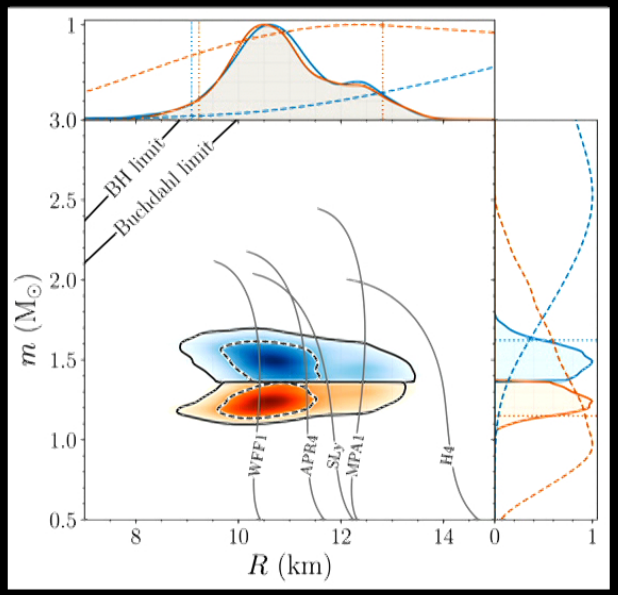
Carney et al 1805.11217

- Parameterize underlying EOS
- Sample in EOS parameters, derive $\Lambda(m_1)$ and $\Lambda(m_2)$ for samples, waveforms
- Enforce causality and support of maximum observed mass
- Direct implications for p(ρ), R(M)

Common-EOS Radius constraints

GW data

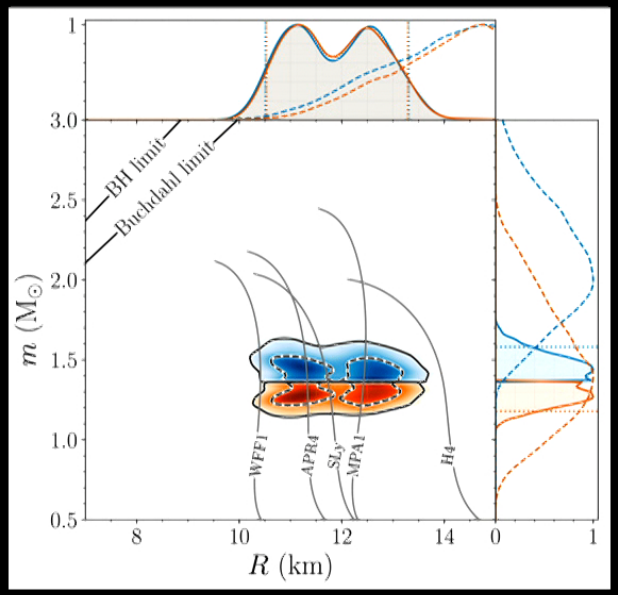
$R_1 = 10.8^{+2.0}_{-1.7}$, $R_2 = 10.7^{+2.1}_{-1.5}$



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

GW data + 1.97 M_{sun} star

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

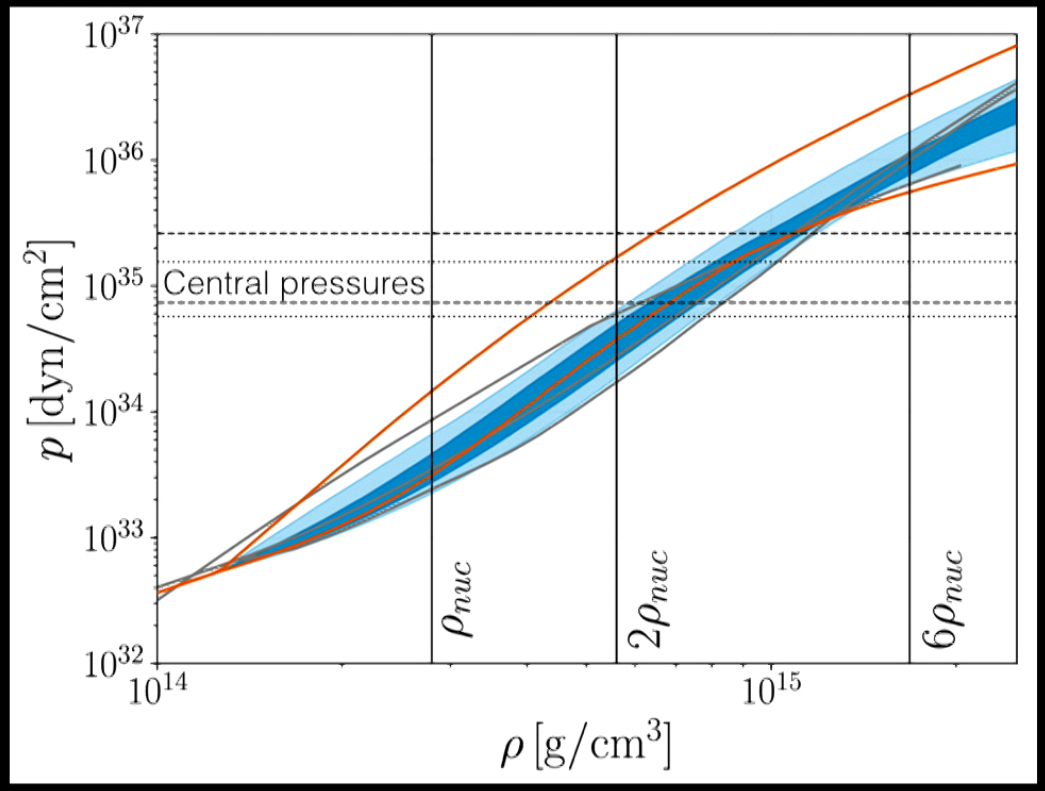


Spectral parameterized EOS

LSC-Virgo EOS 1805.11581

GW170817 + $M_{max} > 1.97\ M_\odot$

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)

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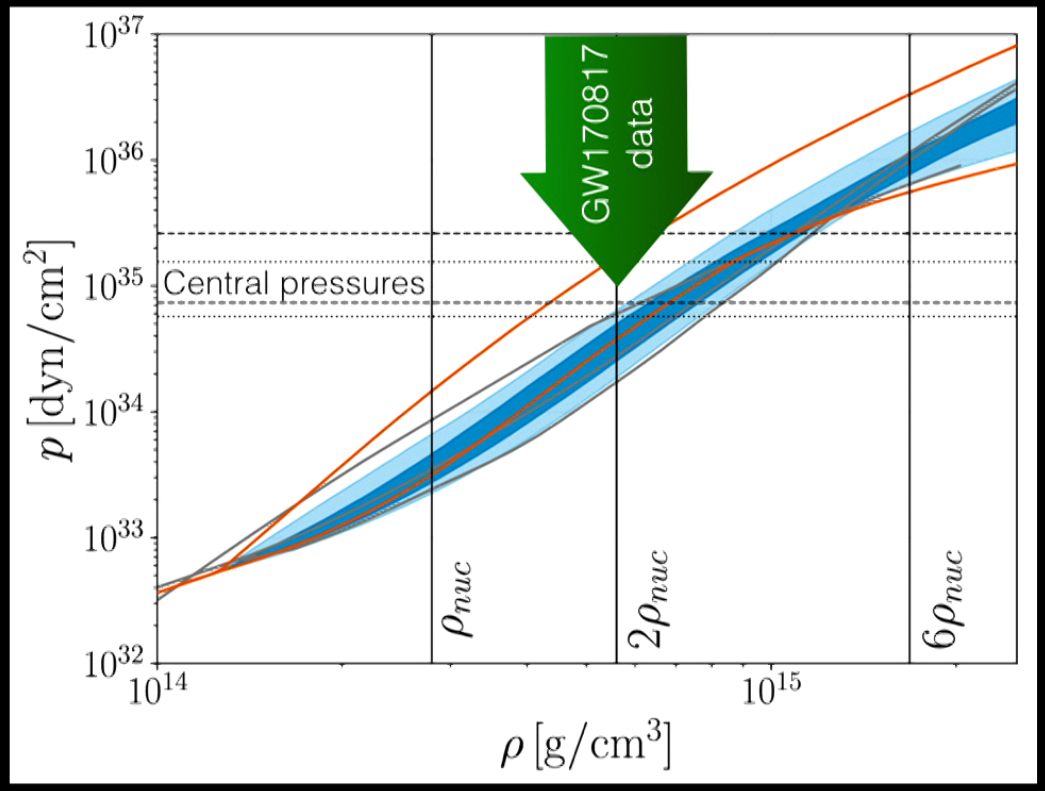

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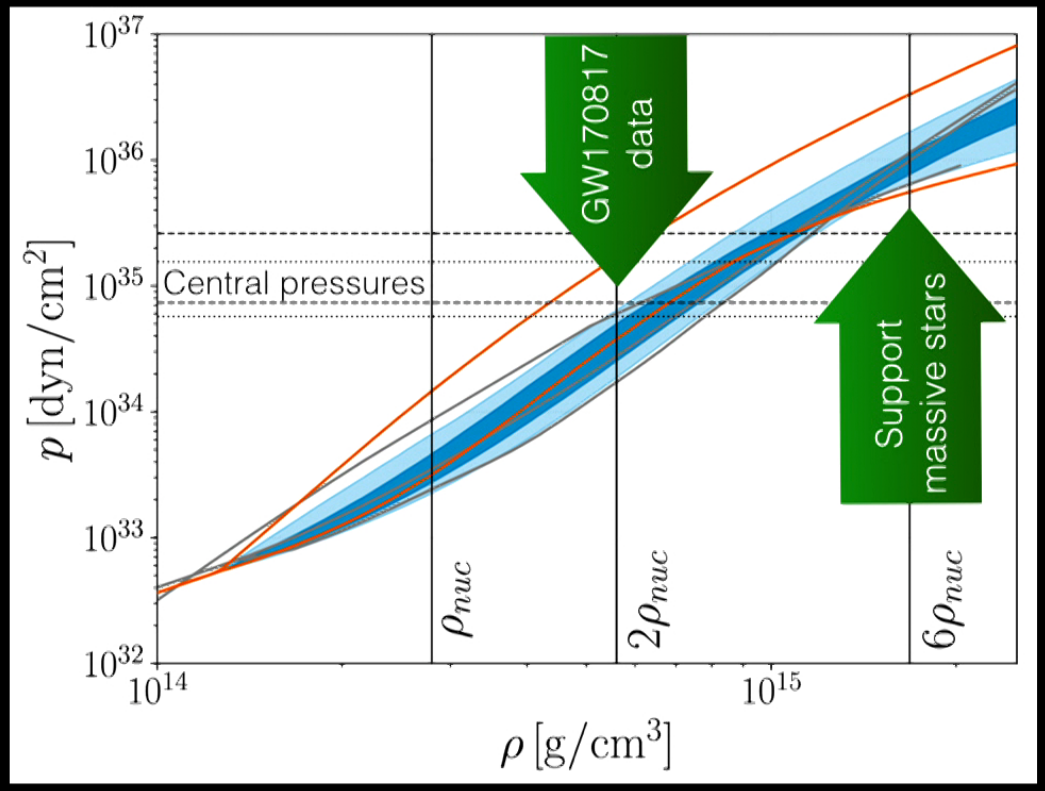

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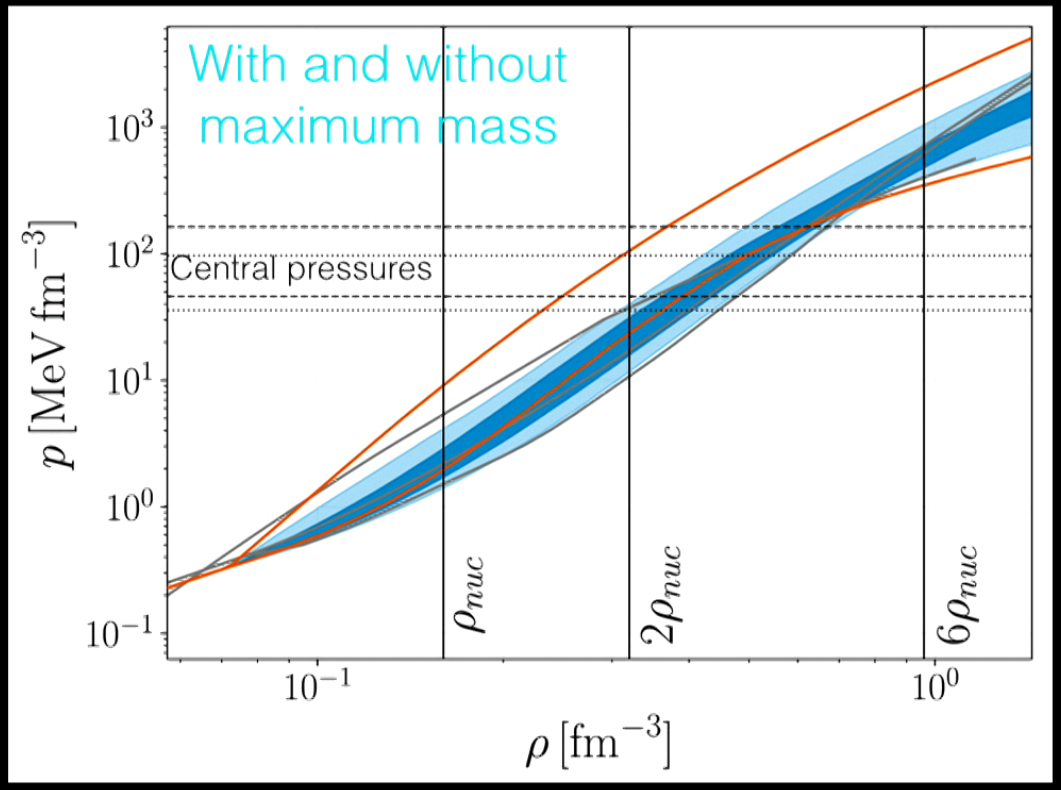

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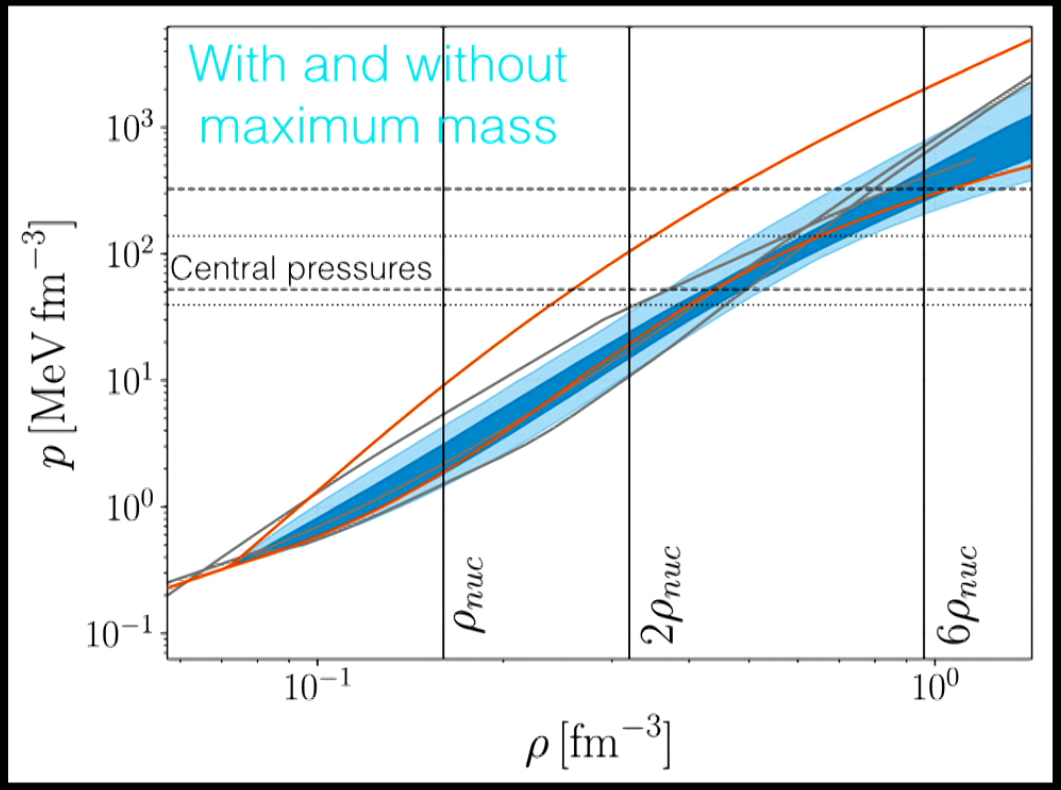

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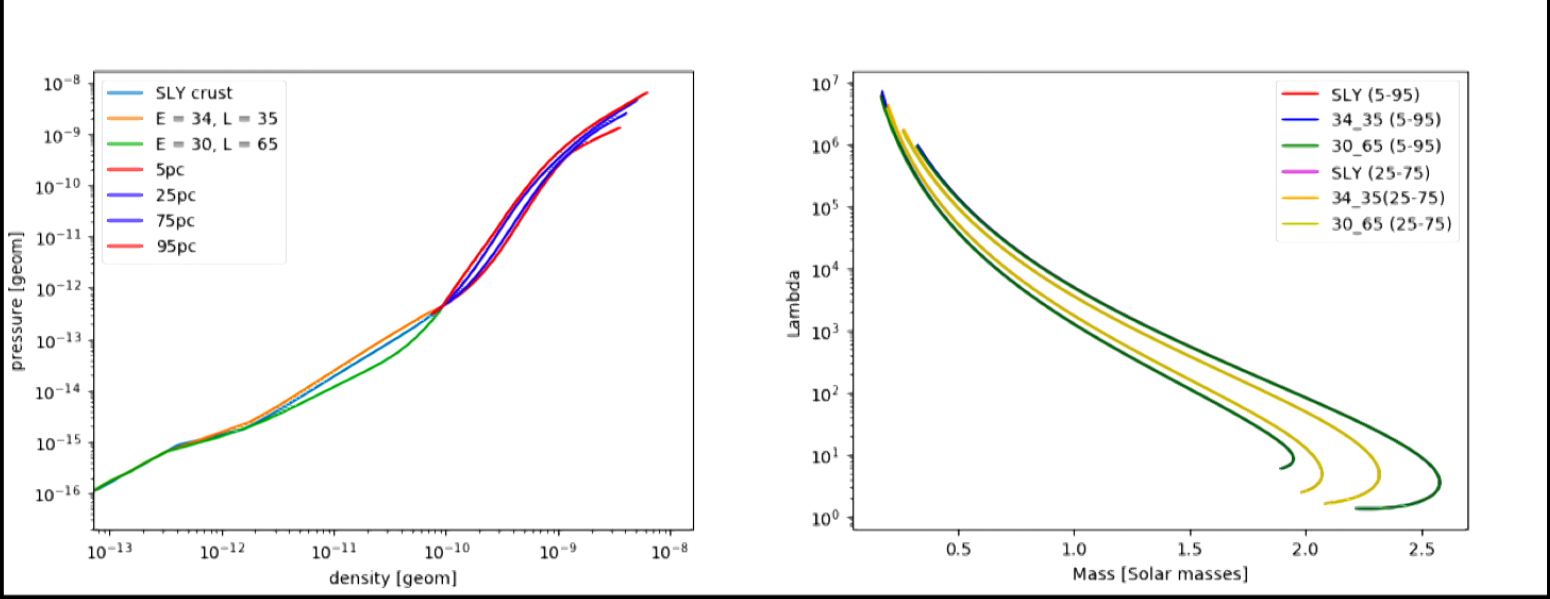
Impact of crust variation

Rossella Gamba, Les Wade, Jocelyn Read, in prep.

Gravitational-waves depend only on above-nuclear density



Systematic uncertainty on radius implications ~0.3km

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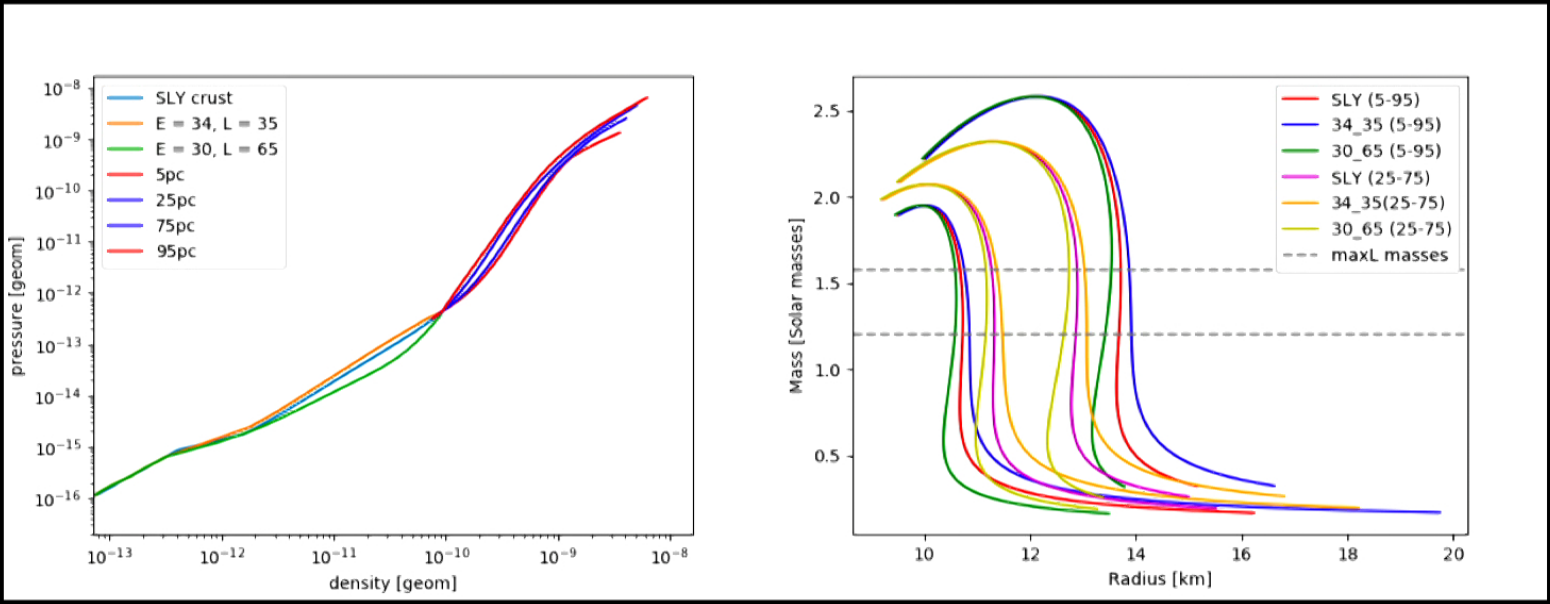
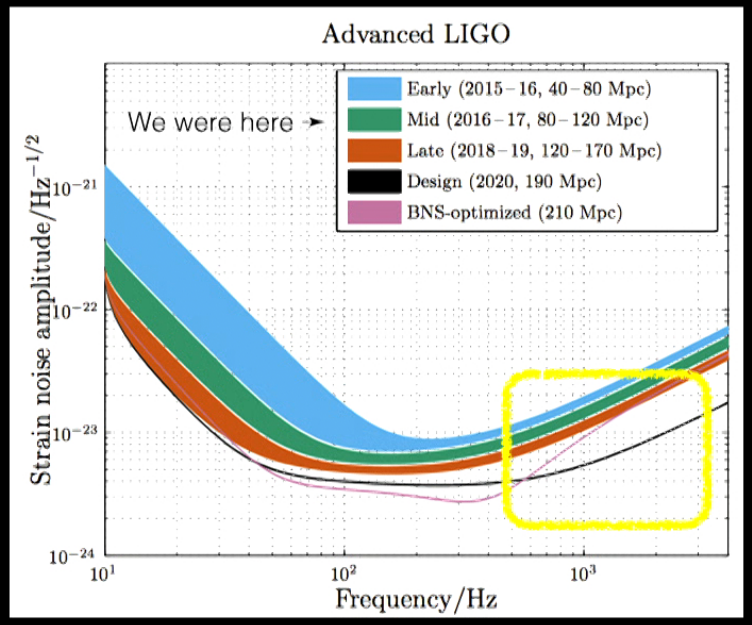


Systematic uncertainty on radius implications ~0.3km

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

Observing Plan (under development)

GW170817-based rate 320–4740 $Gpc^{-3}\ yr^{-1}$ LSC/Virgo PRL 119, 161101 (2017)

BNS VT of O1 ~ $5 \times 10^{-6}\ Gpc^{3}\ yr$ O1 limits on BNS mergers LSC/Virgo 1607.07456

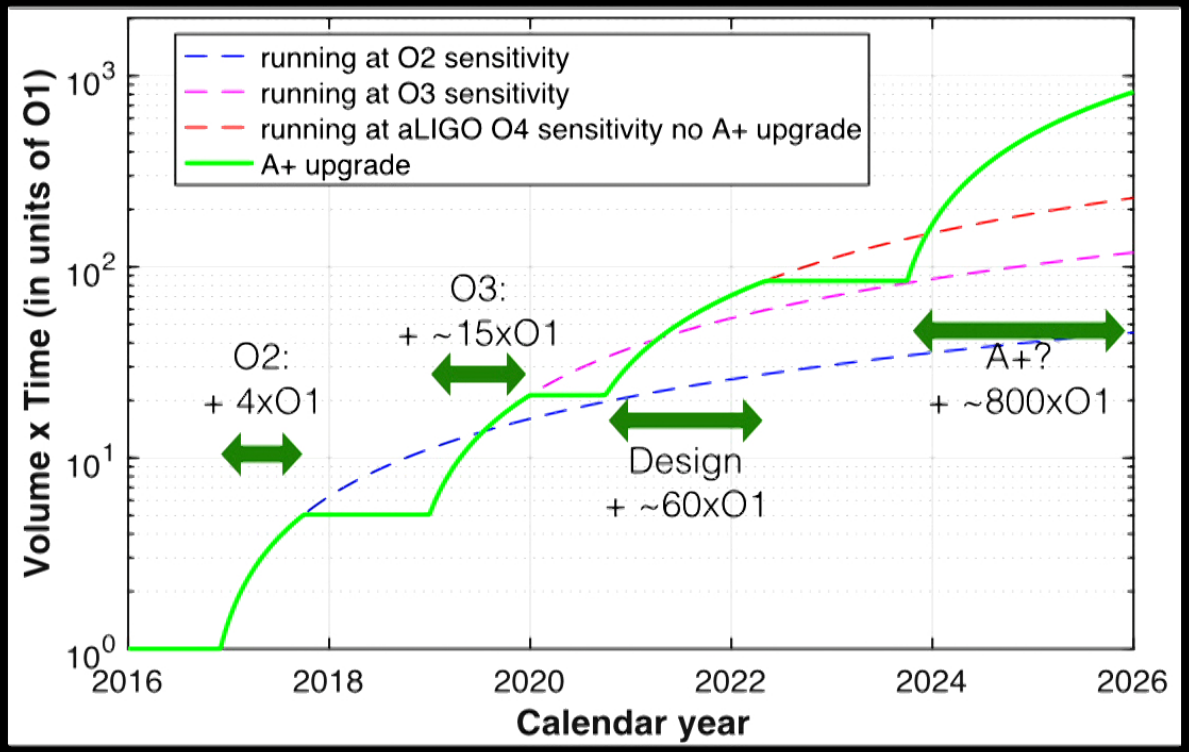
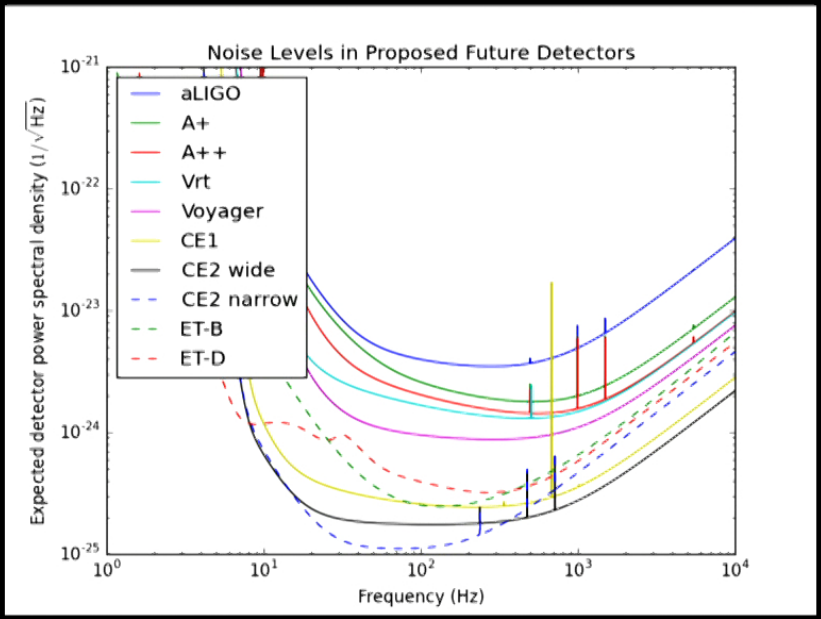


figure: LIGO Lab

Future generations of gravitational-wave observation

Isabella Molina et al, CSUF, in preparation



SLY Postmerger SNR values, GW170817-distance				
aLIGO	A+	A++	CE1	CE2 N
0.338	0.998	1.305	4.702	2.966
CE2W	ET-B	ET-D	Voyager	Vrt
6.038	2.199	2.448	1.721	1.334

Measurement error of NS matter in inspiral scales roughly inversely as sensitivity between 500-1000 Hz

Thank you!