NEUTRON STAR EQN OF STATE FROM GRAVITATIONAL WAVE OBSERVATIONS

COMPACT STARS IN THE QCD PHASE DIAGRAM VII
JUNE 11-15, ADVANCED SCIENCE RESEARCH CENTER
CUNY, NEW YORK

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on behalf of the LIGO Scientific Collaboration and Virgo Collaboration

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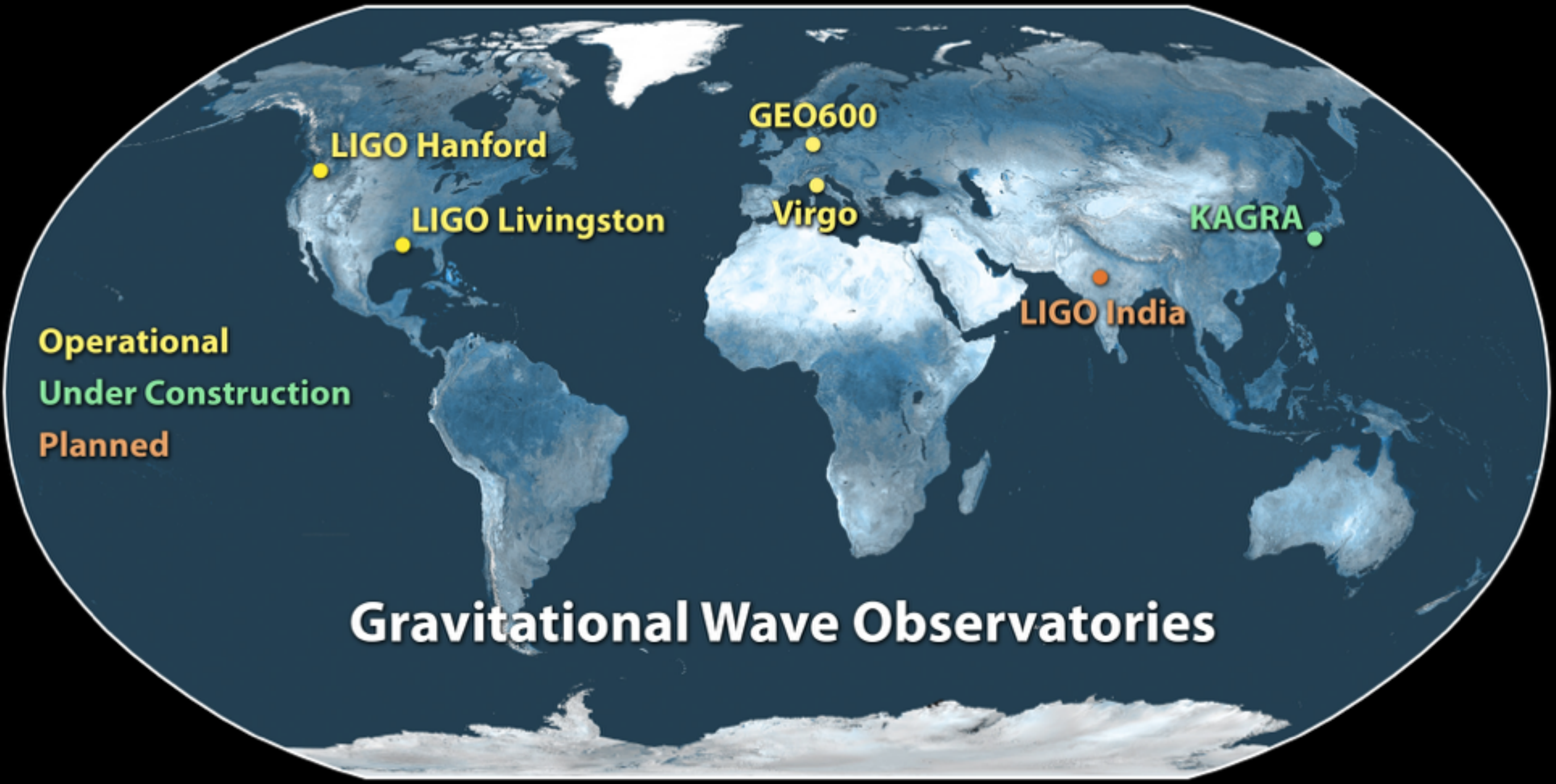
OVERVIEW

- GW170817: first observation of a binary neutron star merger
  - source properties and constraint on tidal deformability
- refined analysis (cleaned data, improved models and analysis)
  - universal relations, parameterized models
- results
  - tidal deformability
  - neutron star radius
  - equation of state

LASER INTERFEROMETER GRAVITATIONAL-WAVE DETECTORS



Credit: LVC/EPO

LIGO-LIVINGSTON OBSERVATORY

Credit: LIGO Livingston

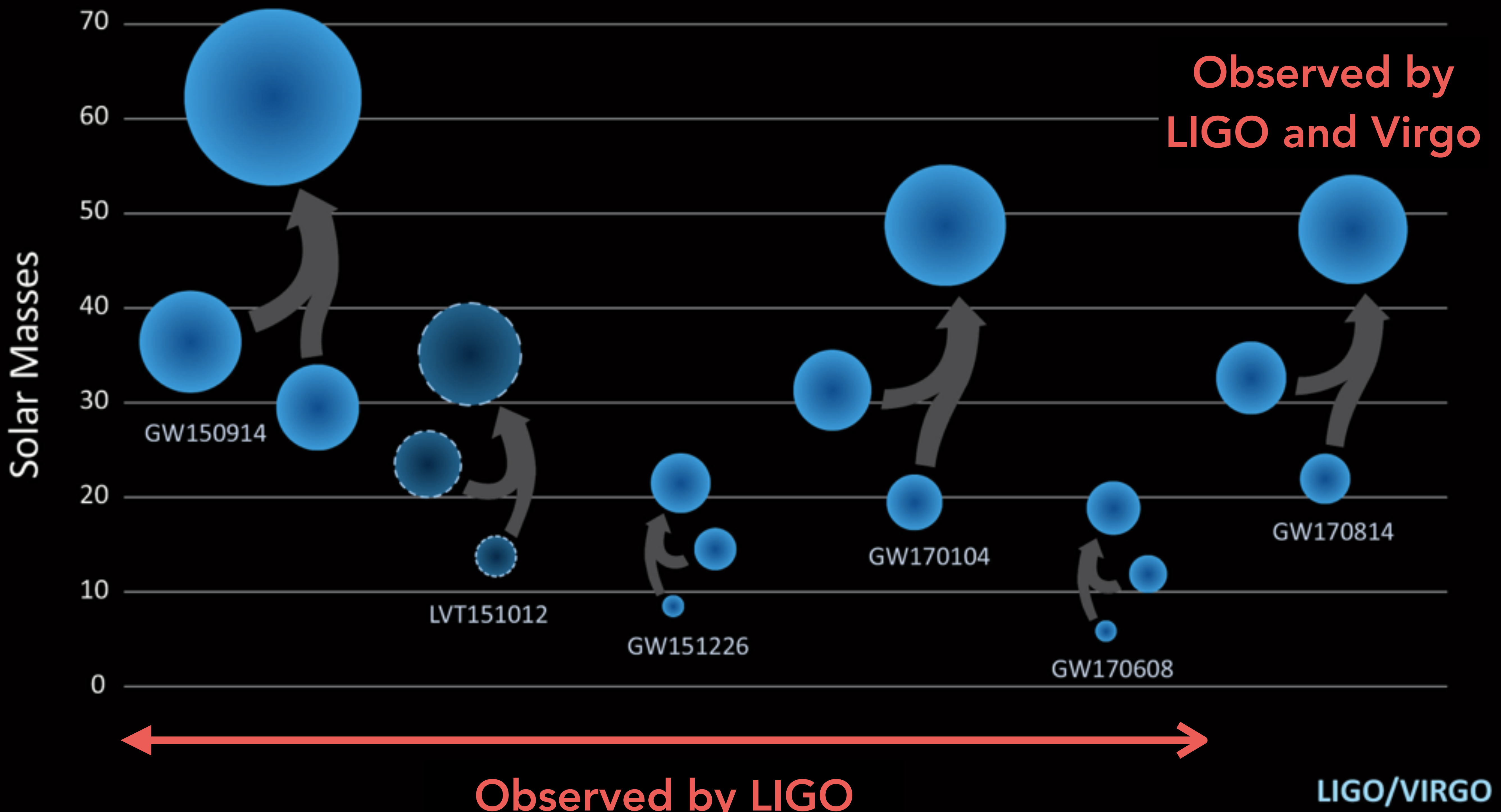
LIGO-HANFORD OBSERVATORY

Credit: LIGO Hanford

VIRGO AT CASCINA, ITALY

Credit: Virgo

BINARY BLACK HOLE MERGERS IN LIGO AND VIRGO



Observed by LIGO and Virgo

Observed by LIGO

GW170817: DISCOVERY OF A MERGING NEUTRON STAR BINARY

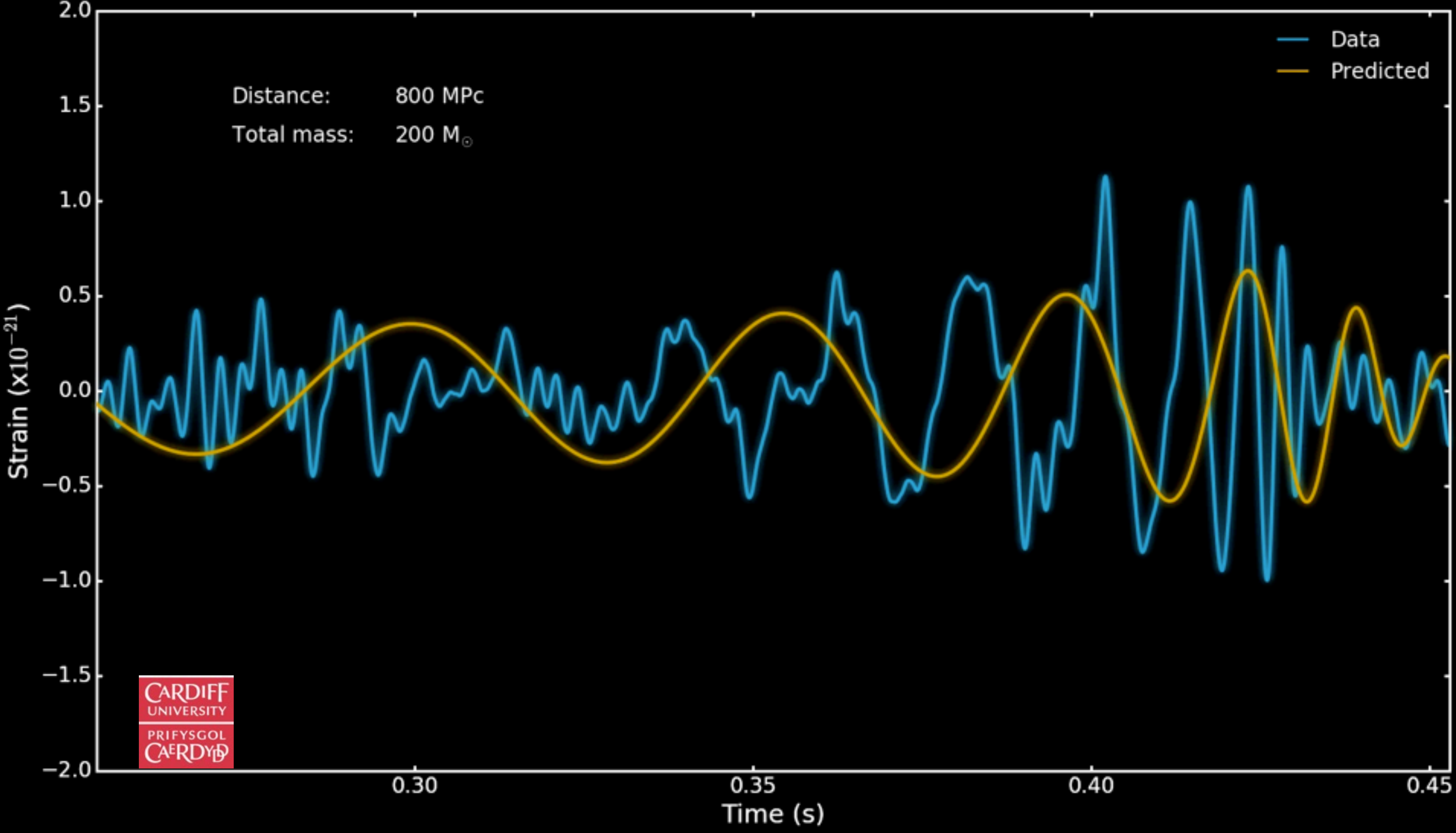
Credit: University of Warwick / Mark Garlick

DETECTION AND MEASUREMENT

- detection and characterization uses matched filtering
  - rapid analysis algorithms that can issue alerts with ~ minute latency
  - working on issuing alerts even before merger
- requires very accurate waveforms
  - >3 decades of effort on analytical and numerical modeling of waveform, and still ongoing
- Bayesian methods for parameter estimation and model inference

$$p(\vec{\vartheta}|d) \propto p(\vec{\vartheta})p(d|\vec{\vartheta})$$

HOW DO WE KNOW WHAT PRODUCED THE SIGNAL?

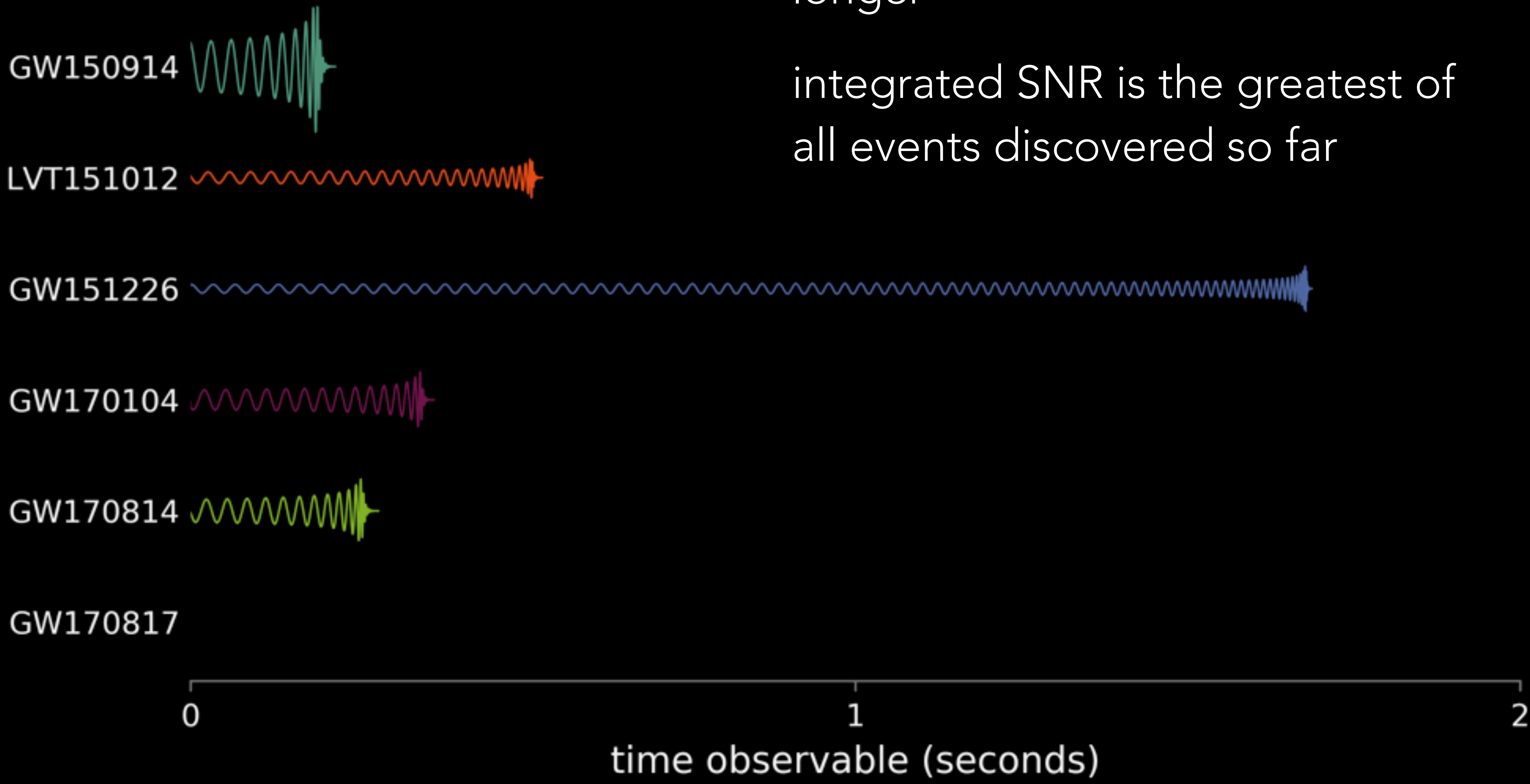


Data & Best-fit Waveform: LIGO Open Science Center (losc.ligo.org); Prediction & Animation: C.North/M.Hannam (Cardiff U

GW170817 LASTED FOR SEVERAL MINUTES IN BAND

smaller amplitude, but lasts a lot longer

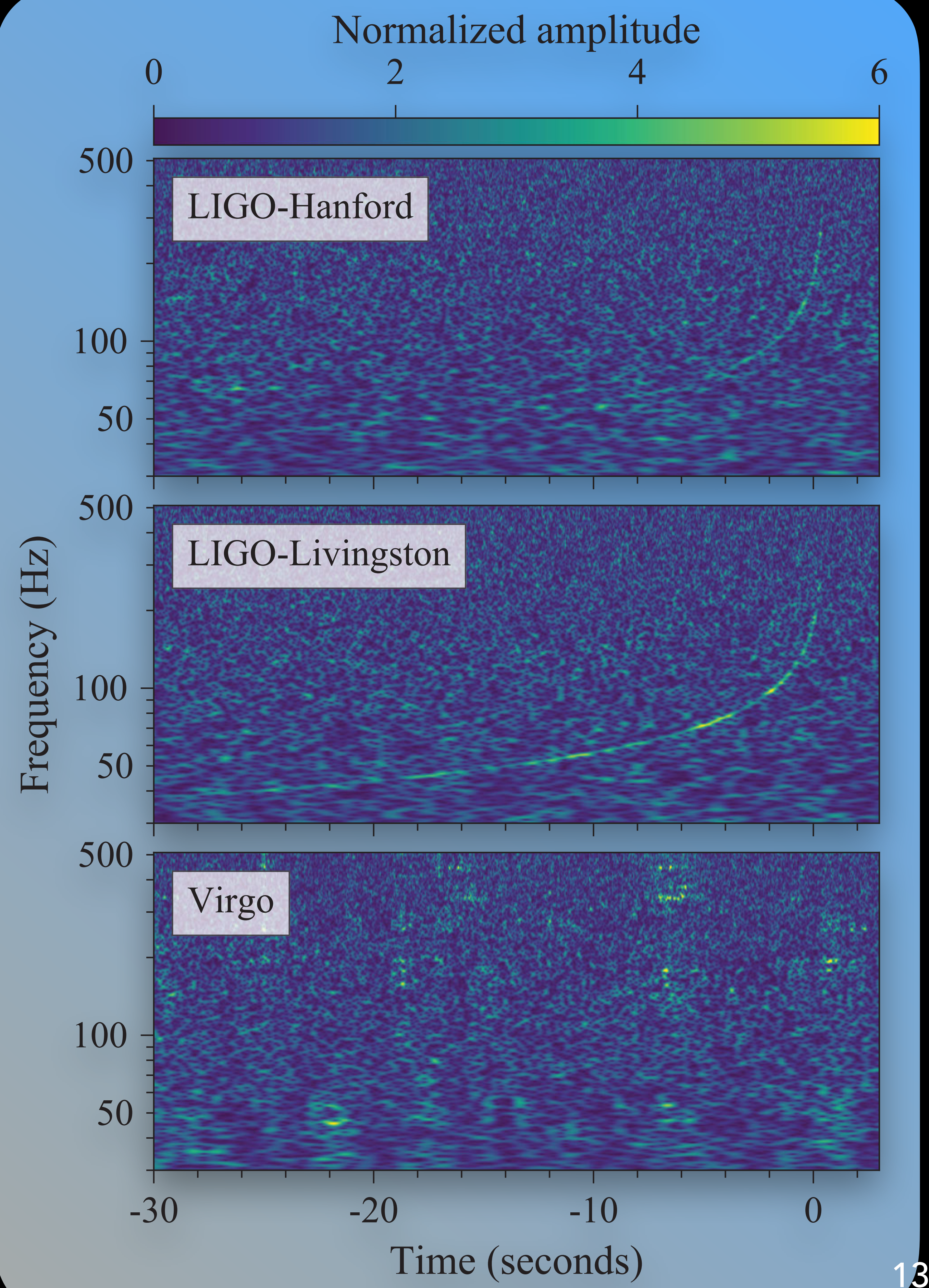
integrated SNR is the greatest of all events discovered so far



LIGO/University of Oregon/Ben Farr

TIME-FREQUENCY MAP OF GW170817

- matched filter SNR=32
  - loudest yet of all
- False alarm rate $10^{-6}\,\mathrm{yr}^{-1}$
  - most significant of all events discovered so far



Abbott+, PRL 119, 161101 (2017)

SPEED OF GRAVITATIONAL WAVES

Fermi

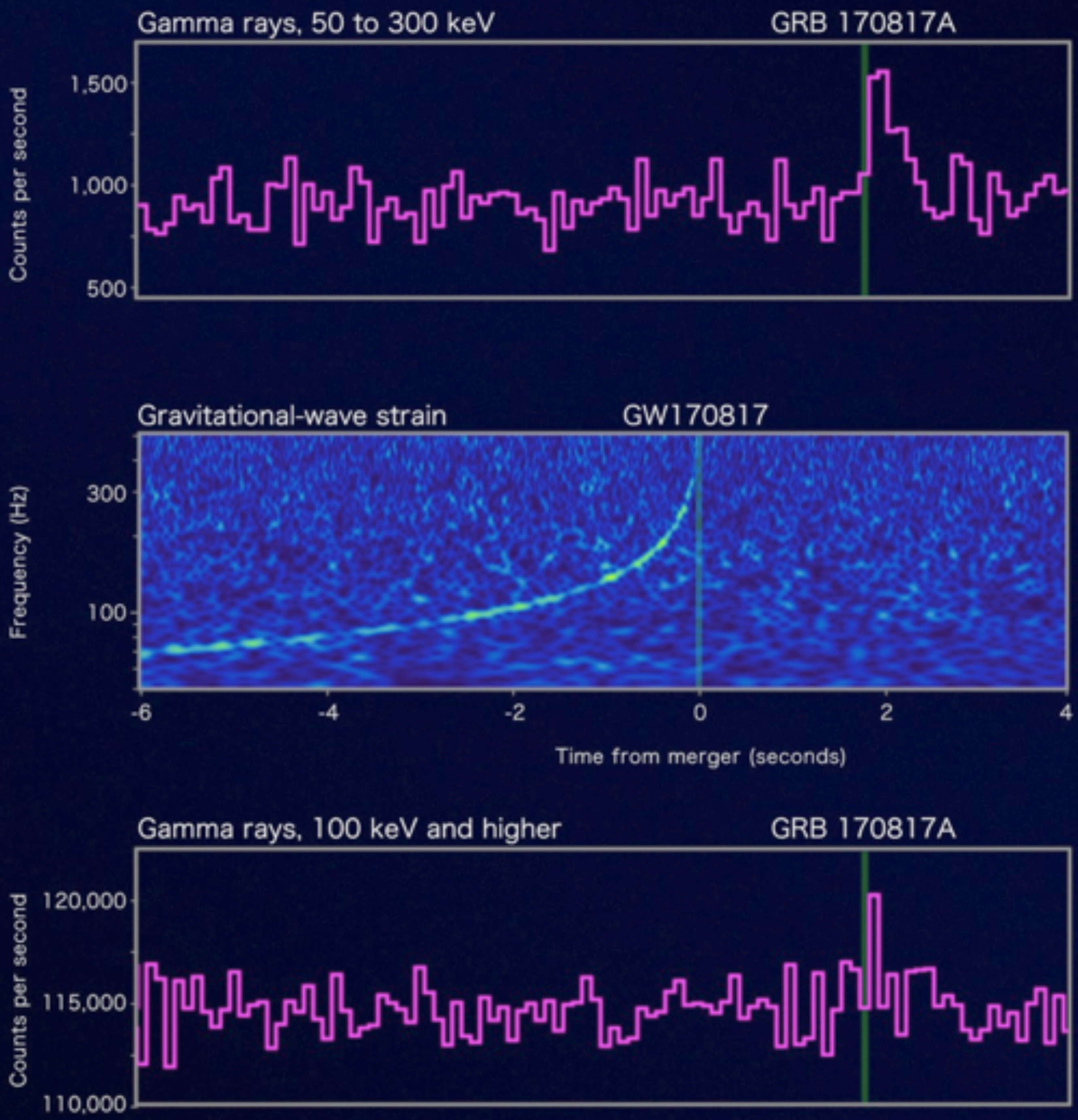
Reported 16 seconds
after detection

LIGO-Virgo

Reported 27 minutes after detection

INTEGRAL

Reported 66 minutes
after detection

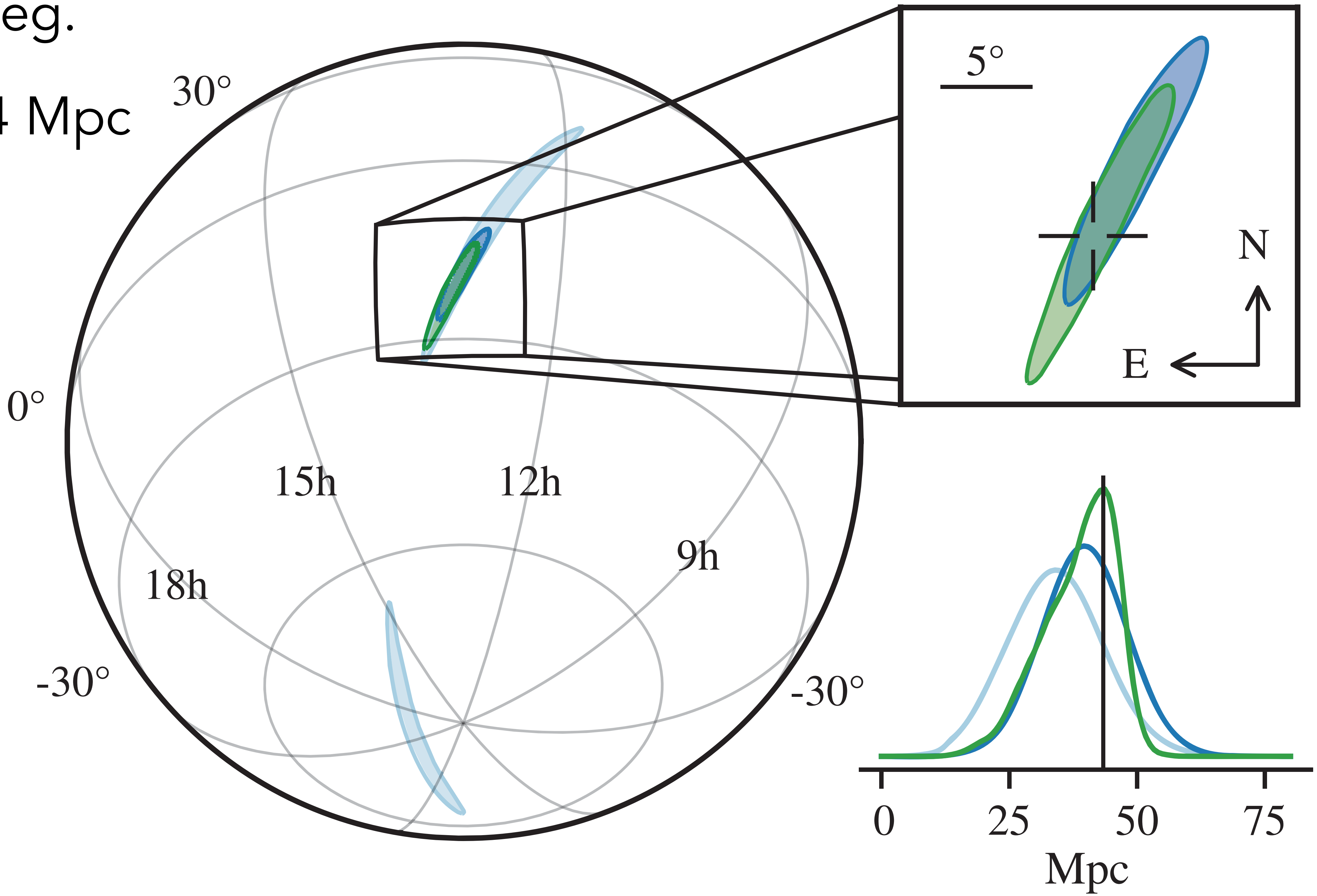


$$\frac{1.7\,\mathrm{s}}{40\,\mathrm{Mpc}/c} \sim 4 \times 10^{-16} \qquad -3 \times 10^{-15} \leq \frac{v_{\mathrm{GW}} - v_{\mathrm{EM}}}{v_{\mathrm{EM}}} \leq 7 \times 10^{-16}$$

The Astrophysical Journal Letters, 848:L13 (27pp), 2017

SKY POSITION AND DISTANCE

- 28 sq. deg.
- 40+8-14 Mpc



- most precisely localized yet

Abbott+, PRL 119, 161101 (2017)

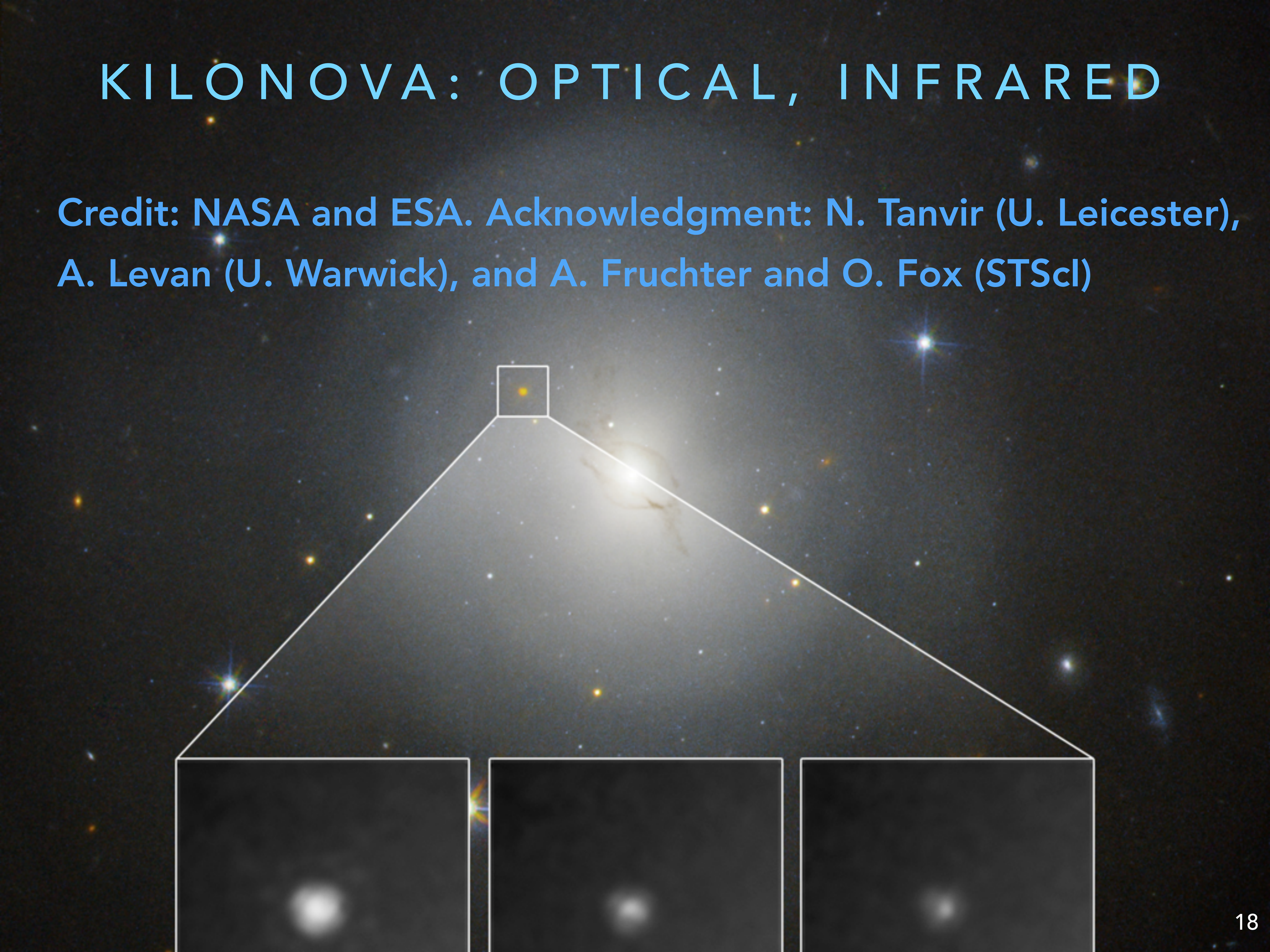
ELECTROMAGNETIC FOLLOW-UP OF GW170817

Credit: Ligo Virgo

HOST LOCATED IN NGC 4993

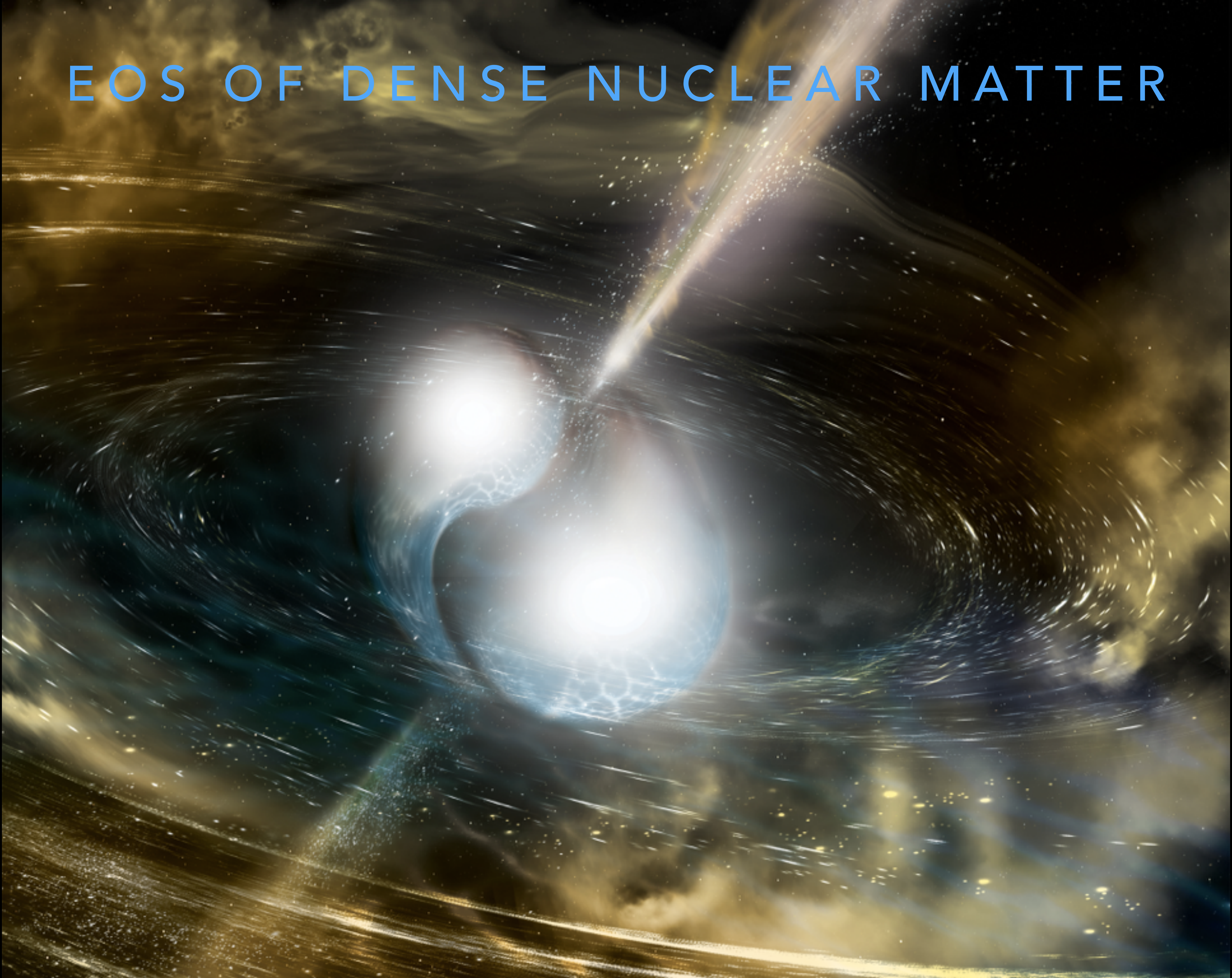
Credit: Hubble Space Telescope, ESA and NASA

KILONOVA: OPTICAL, INFRARED

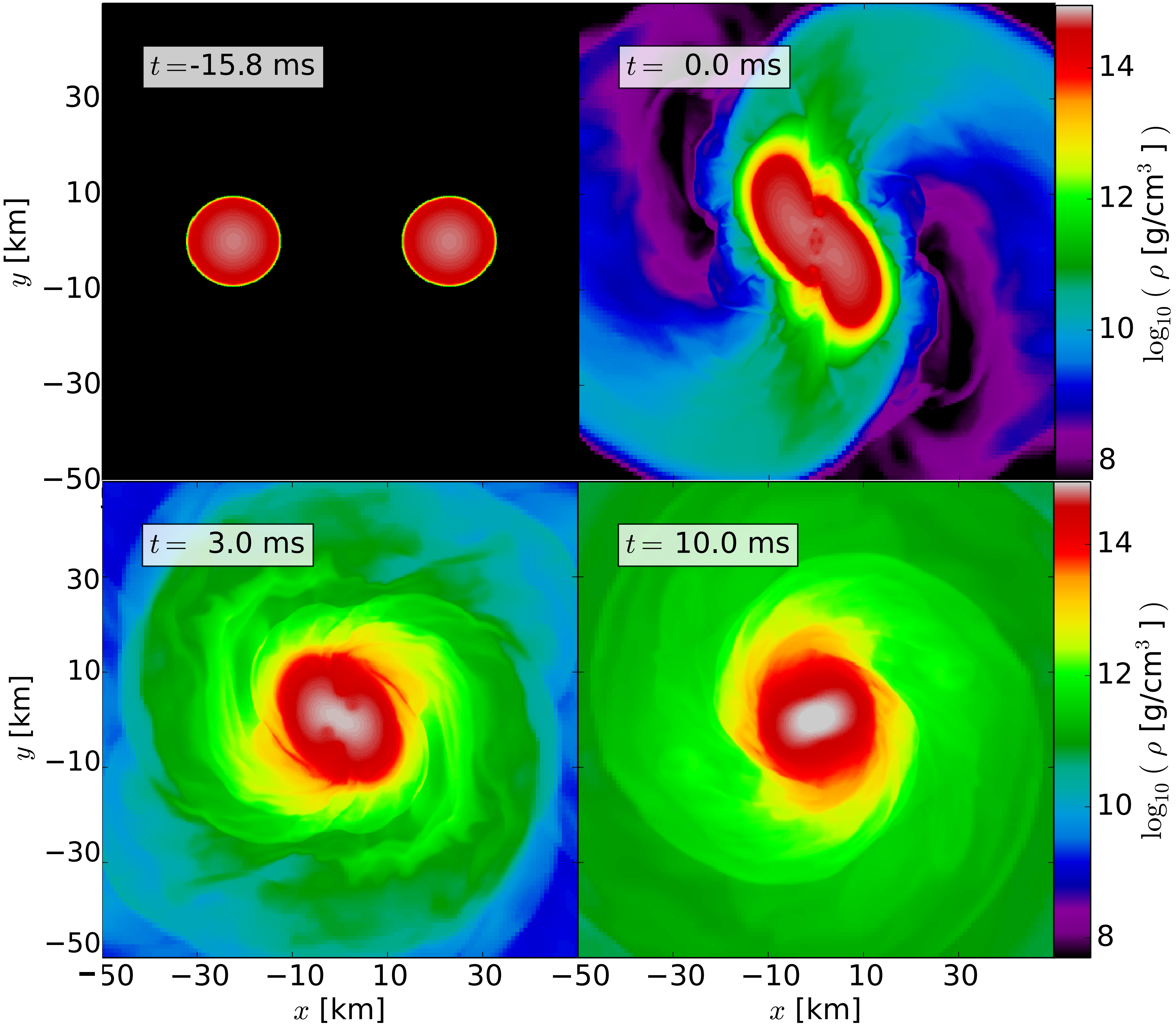


Credit: NASA and ESA. Acknowledgment: N. Tanvir (U. Leicester), A. Levan (U. Warwick), and A. Fruchter and O. Fox (STScI)

EOS OF DENSE NUCLEAR MATTER

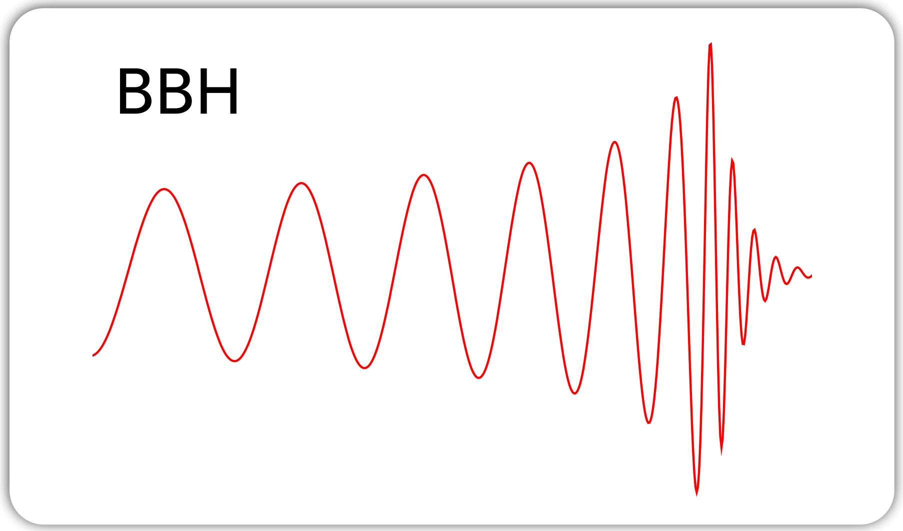


SIMULATION OF A BINARY NEUTRON STAR MERGER

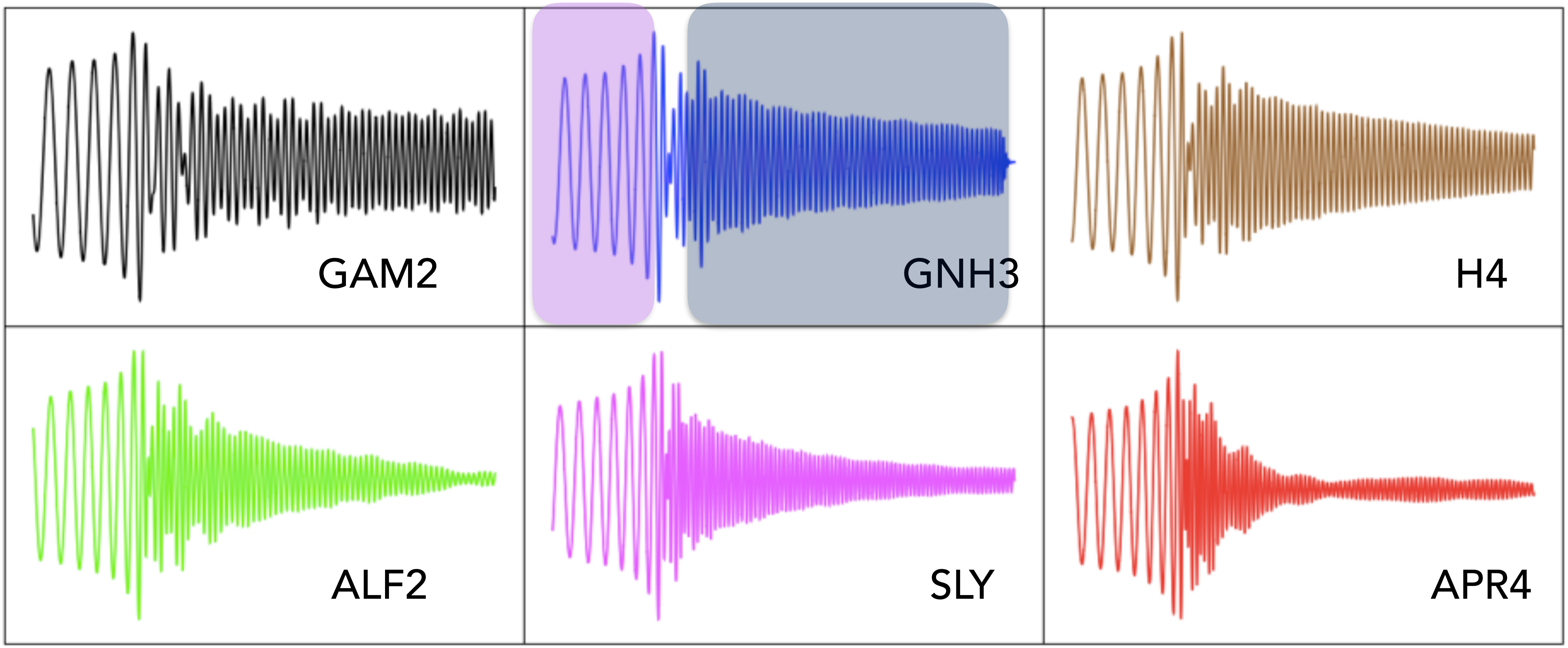


Takami+ 2014

BINARY BLACK HOLE SIGNAL COMPARED TO BINARY NEUTRON STAR SIGNAL



- inspiral phase: well described by post-Newtonian approximation + tides
- post-merger bar-deformed hyper-massive neutron star



TIDAL DEFORMABILITY OF NEUTRON STARS

- tidal field ***ε*** of one of one companion induces a quadrupole moment ***Q*** in the other

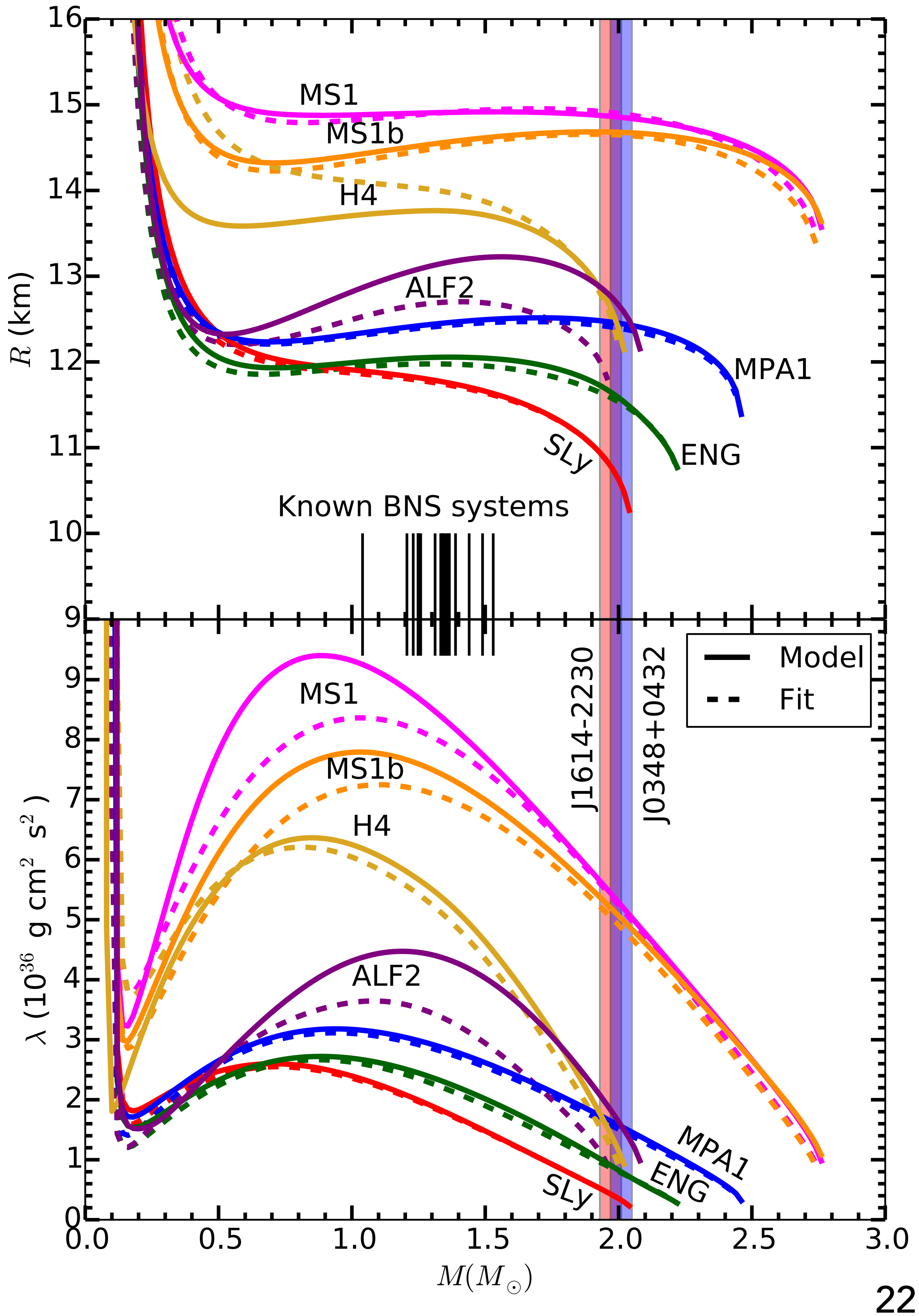
- in the adiabatic approximation

$$Q_{ij} = -\lambda(m)\,\epsilon_{ij}, \quad \lambda(m) = \frac{2}{3G}k_2(m)R^5$$

- ***λ(m)*** is tidal deformability, ***k₂(m)*** is the 2nd second Love number (varies from 0.05-0.15) and ***R*** is the NS radius (8 km-16 km)

- dimensionless tidal deformability

$$\Lambda = G\lambda(Gm/c^2)^{-5}, \quad \Lambda \sim 100\text{–}6000$$



TIDAL EFFECTS DURING INSPIRAL

$$\Psi(v) = \Psi_{\rm PP}(v) + \Psi_{\rm tidal}(v),$$

$$\begin{aligned}
\Psi_{\rm tidal}(v) \;=\; & \frac{3}{128\eta} v^{-5} \sum_{A=1}^{2} \frac{\lambda_A}{M^5 X_A} \Big[-24\,(12 - 11X_A)\, v^{10} \\
& + \frac{5}{28}\left(3179 - 919X_A - 2286X_A^2 + 260X_A^3\right) v^{12} \\
& + 24\pi(12 - 11X_A) v^{13} \\
& - 24\left(\frac{39927845}{508032} - \frac{480043345}{9144576}X_A + \frac{9860575}{127008}X_A^2 \right. \\
& \left. - \frac{421821905}{2286144}X_A^3 + \frac{4359700}{35721}X_A^4 - \frac{10578445}{285768}X_A^5\right) v^{14} \\
& + \frac{\pi}{28}\left(27719 - 22127X_A + 7022X_A^2 - 10232X_A^3\right) v^{15} \Big]
\end{aligned}$$

$$X_A = m_A/M,\; A = 1, 2,\; \text{and}\; \lambda_A = \lambda(m_A)$$

Flanagan, Hinderer 2008; Vines, Flanagan, Hinderer 2014; Damour, Nagar, Villain 2012

SPIN-INDUCED TIDAL DEFORMATION

- Spin-induced deformation leads to quadrupole

$$\Psi_{\rm QM}(v) = -\frac{30}{128\eta}\sigma_{\rm QM} v^{-1},$$

$$\sigma_{\rm QM} = -\frac{5}{2}\sum_{A=1,2} q_A \left(\frac{m_A}{M}\right)^2 \left[3(\hat{\chi}_A\cdot\hat{L})^2 - 1\right]$$

$$\simeq \frac{5}{2}\sum_{A=1,2} a(m_A) \left(\frac{m_A}{M}\right)^2 \left[3(\hat{\chi}_A\cdot\hat{L})^2 - 1\right] \chi_A^2$$

$$q \simeq -a\chi^2,$$

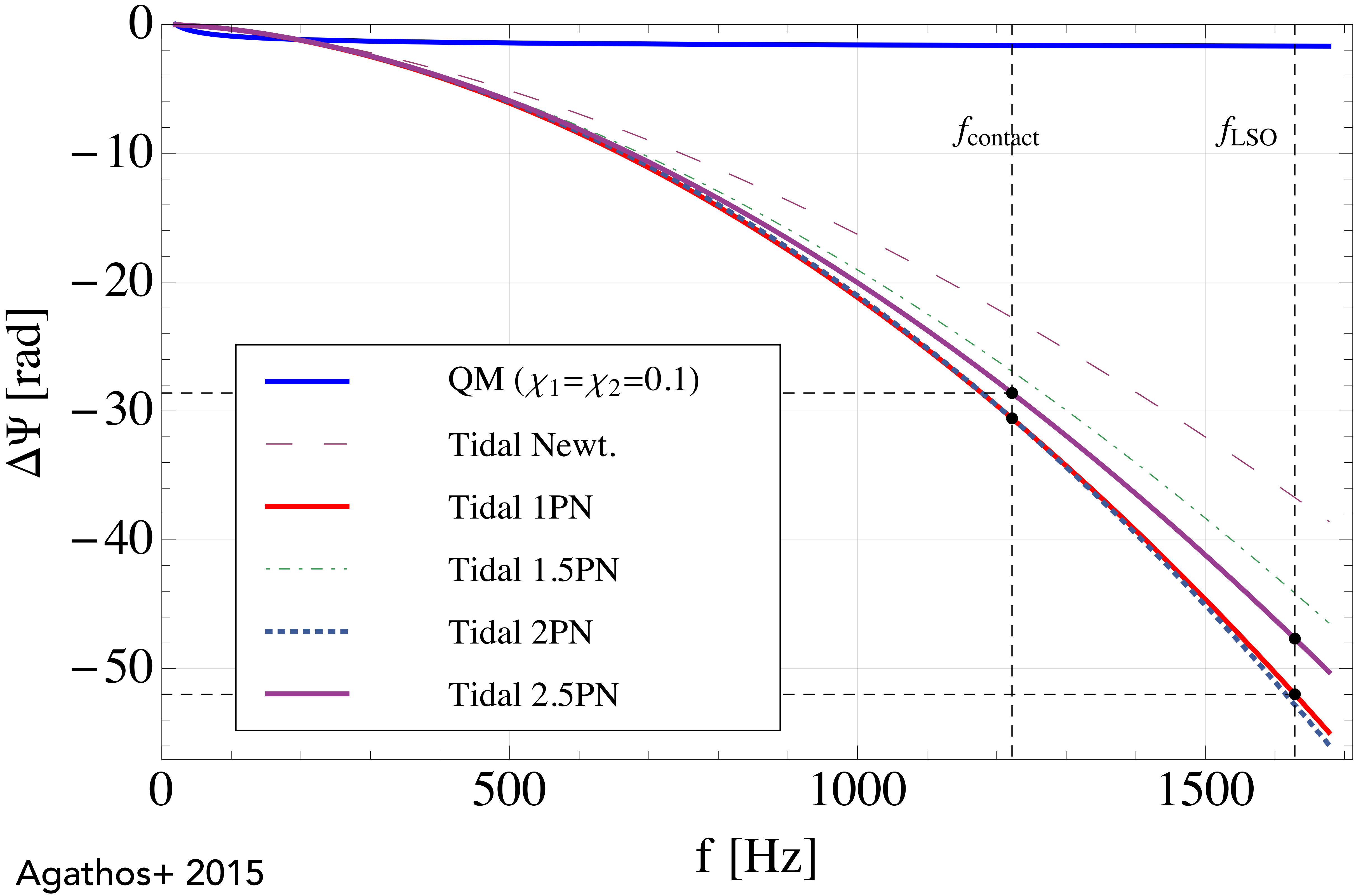
Poisson 1998;
Laarakkers+Poisson 1999

$a(m)$ depends really only on tidal deformability

$$\ln a(m) = 0.194 + 0.0936 \ln\frac{\lambda}{m^5} + 0.0474\left(\ln\frac{\lambda}{m^5}\right)^2 - 4.21\times10^{-3}\left(\ln\frac{\lambda}{m^5}\right)^3 + 1.23\times10^{-4}\left(\ln\frac{\lambda}{m^5}\right)^4$$

Yagi, Yunes 2013a, 2013b

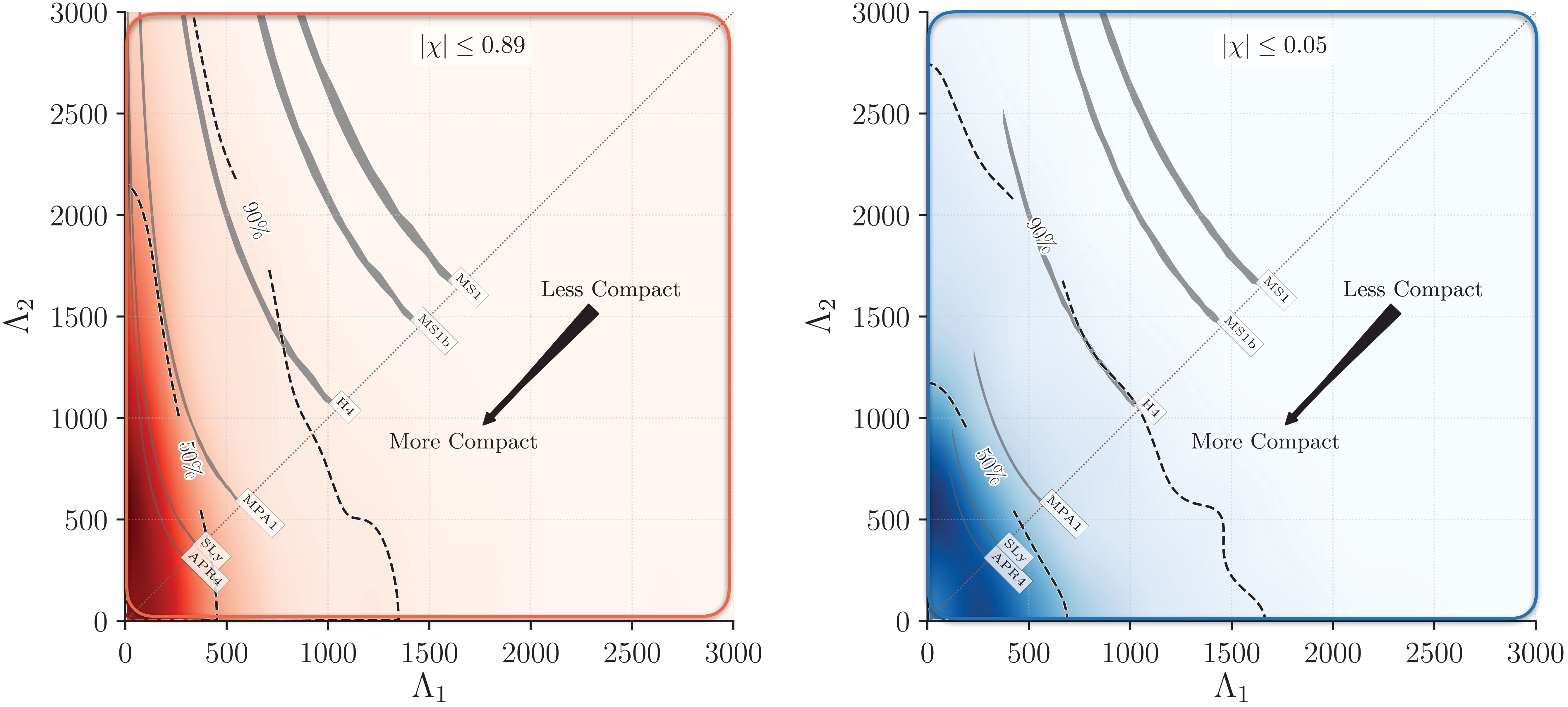
HOW BIG IS THE TIDAL EFFECT?



Agathos+ 2015

FIRST RESULT ON Λ

- TaylorF2 - a PN-based model used, Λ_1 and Λ_2 independent



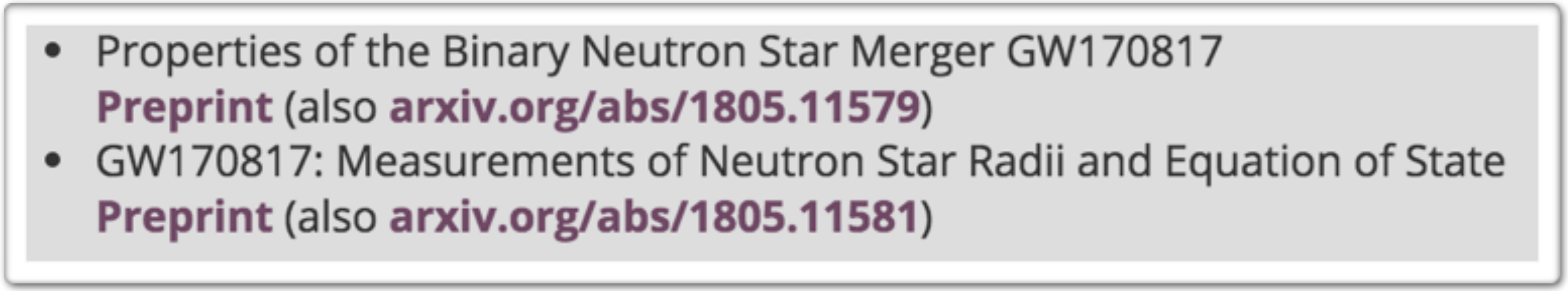
Black hole companion cannot be ruled out

Abbott+, PRL 119, 161101 (2017)

IMPROVEMENTS SINCE 10/2017

- **first step: “minimal assumptions”**
  - re-calibrated Virgo data (reduced calibration uncertainty)
  - known source location: NGC4993
  - **more accurate waveform models**
  - reduced lower frequency cutoff: 23 Hz, down from 30 Hz

- **second step**
  - source contains two neutron stars
  - neutron star spins are low, $\chi < 0.05$
  - both stars are described by the same equation of state
  - max total mass of the neutron star is at least ~ 2 solar mass



- Properties of the Binary Neutron Star Merger GW170817
  Preprint (also **arxiv.org/abs/1805.11579**)
- GW170817: Measurements of Neutron Star Radii and Equation of State
  Preprint (also **arxiv.org/abs/1805.11581**)

WAVEFORM MODELS

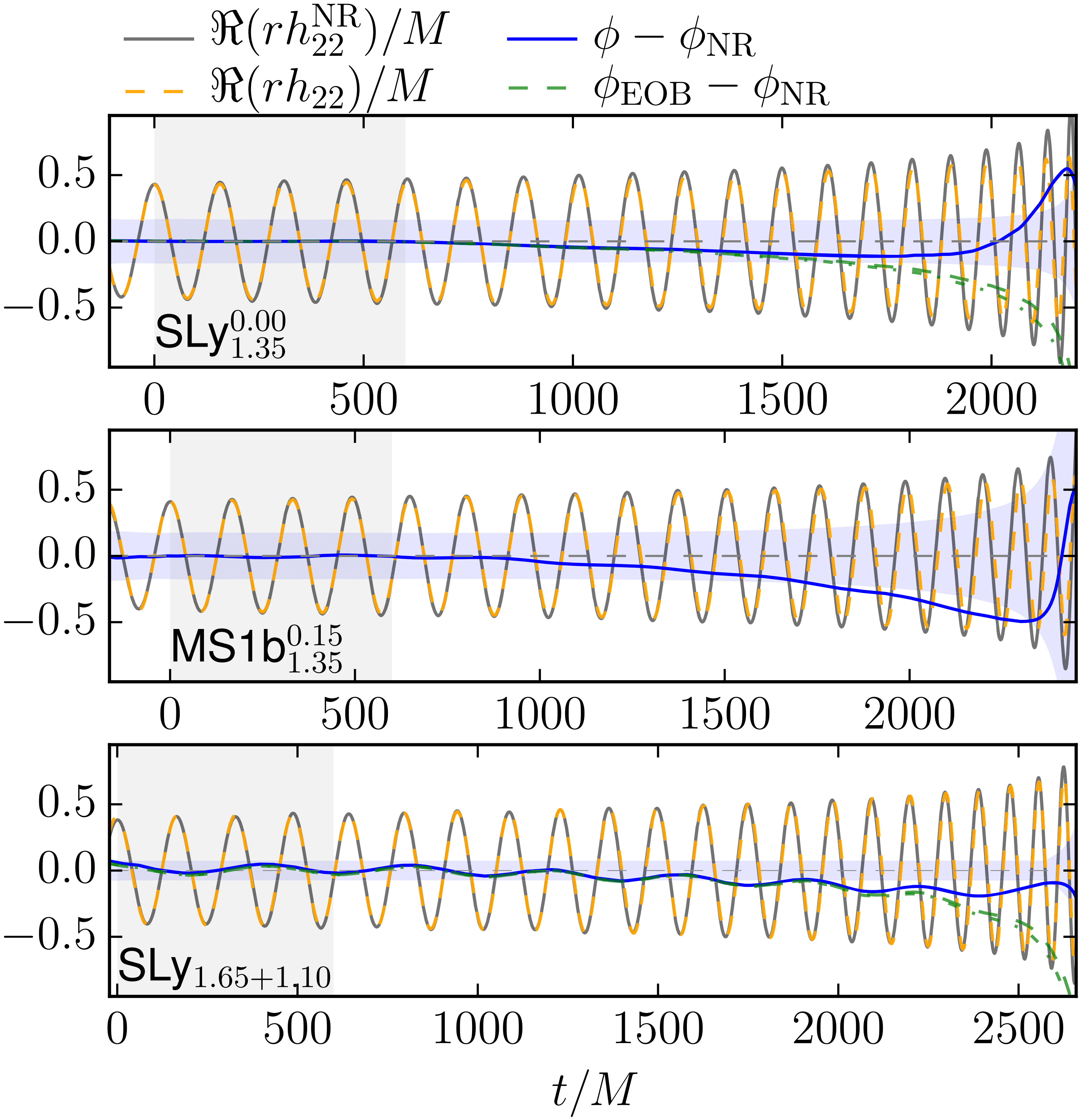
model	tidal effects	spin-induced quadrupole	precession	comment
TaylorF2 (1)	6PN (5)	none	none	basic
SEOBNRT (2)	matched to NR simulations (6)	none	none	relevant physical effects
PhenomDNRT (3)	matched to NR simulations (6)	none	none	relevant physical effects
PhenomPNRT (4)	matched to NR simulations (6)	3PN	yes	many physical effects

(1) BSS+(1991), Bohe+ (2013, 2015), Arun+ (2009), Mikoczi+ (2005), Mishra+ (2016)
(2) Bohe+ (2017), Pürrer (2014),
(3) Husa+ (2016), Khan+ (2016)
(4) Hannam+ (2014)
(5) Vines+ (2017)
(6) Dietrich+ (2016, 2018)

Abbott+, arXiv 1805.11579

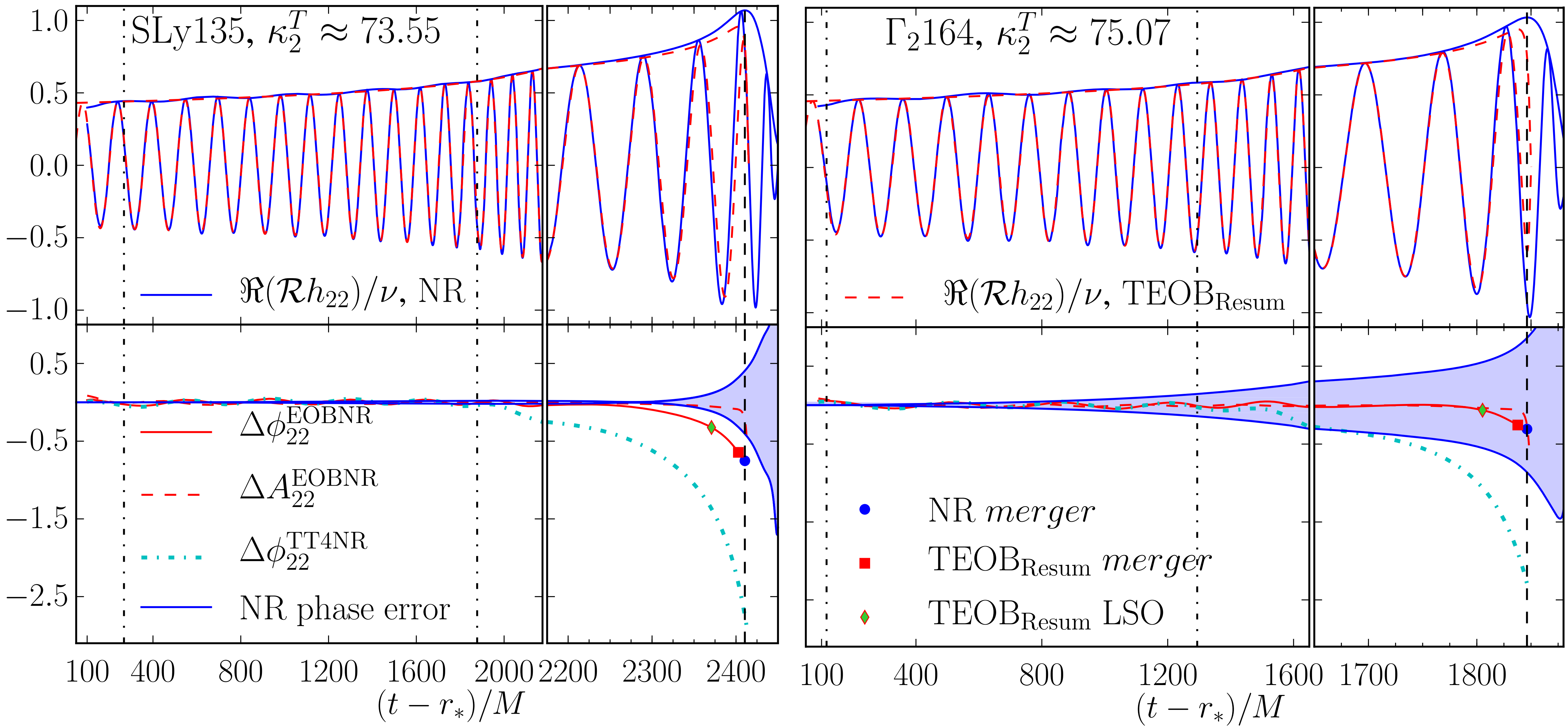
AN EFFECTIVE ONE-BODY MODEL

- approximate analytical description matched to numerical simulations of binary neutron star mergers
- post-Newtonian expressions are resummed to obtain better agreement with simulations



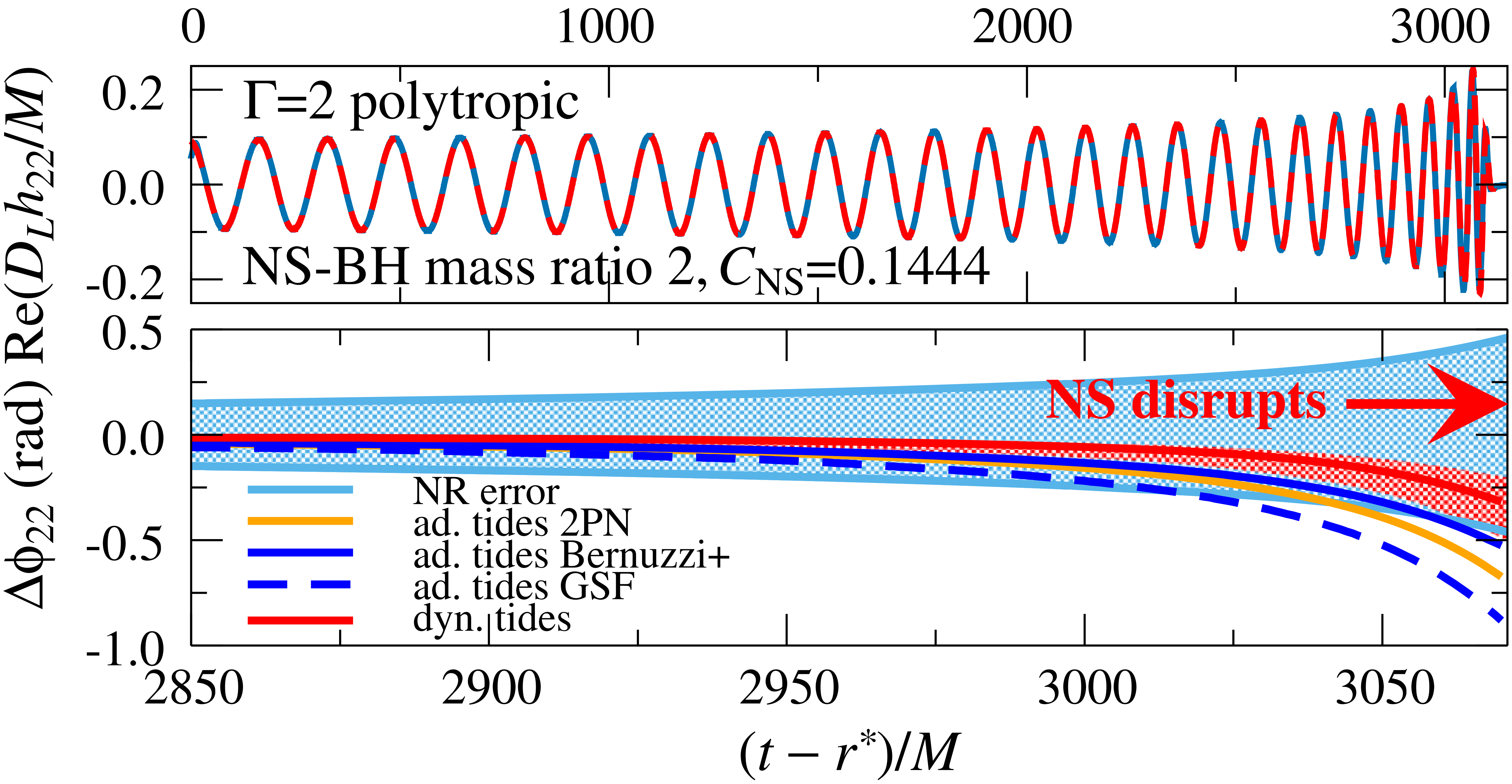
Dietrich, Hinderer Phys. Rev. D 95.124006

ANOTHER EXAMPLE OF A DOUBLE BINARY NEUTRON STAR SYSTEM



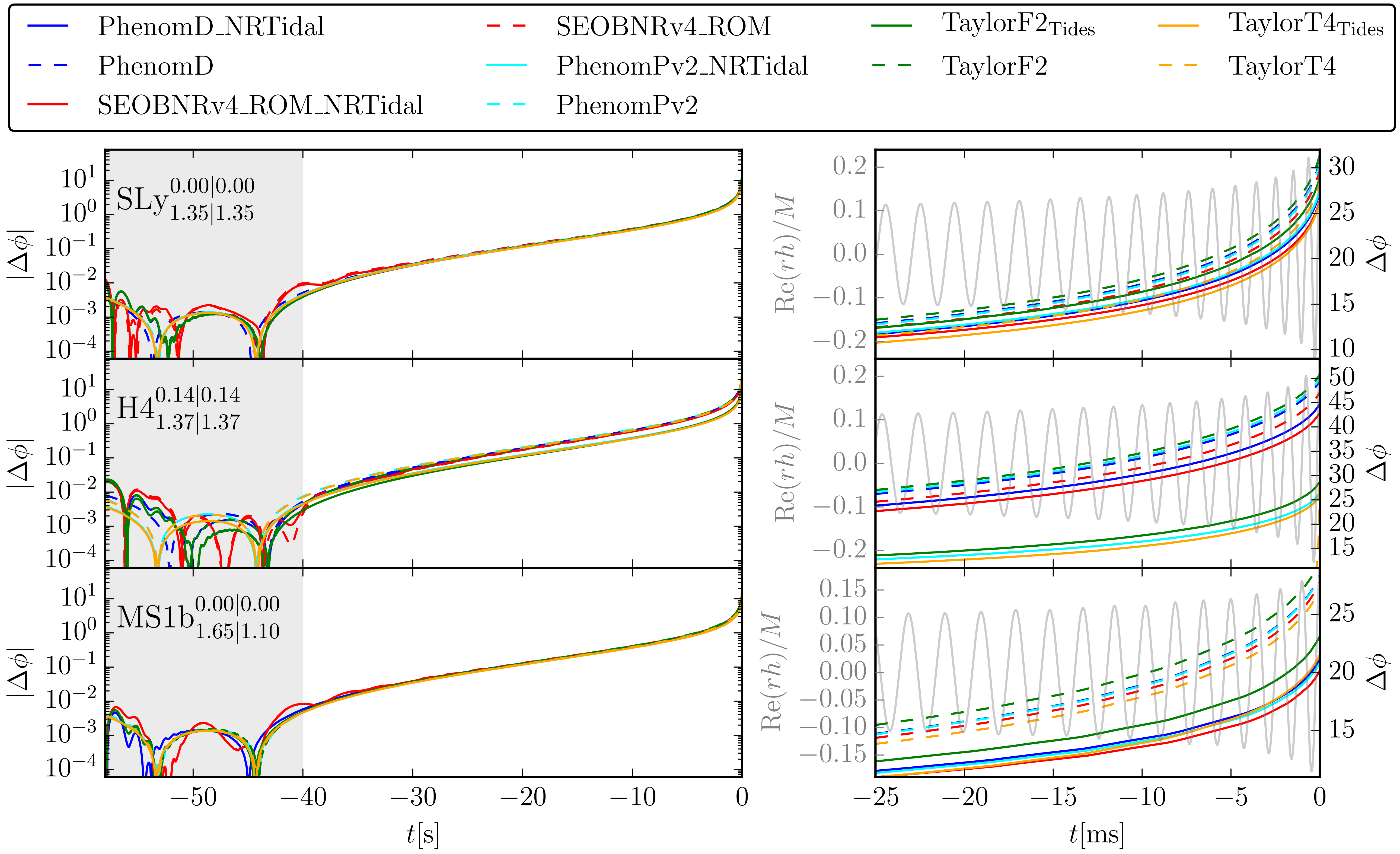
Bernuzzi+ PRL:114.161103, 2015

NS-BH SYSTEM



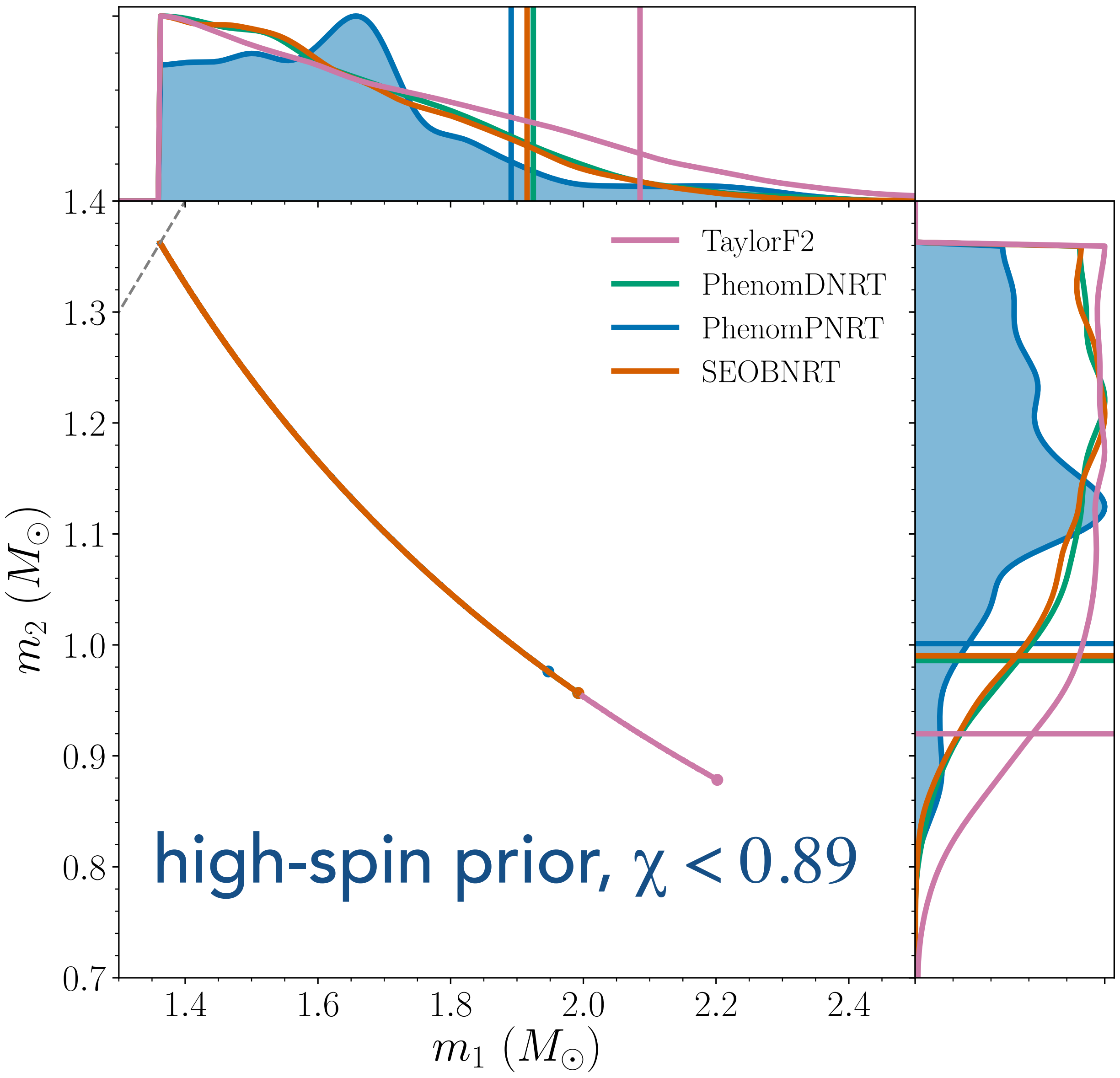
Hinderer+ PRL:116.181101, 2016

COMPARISON OF MODELS

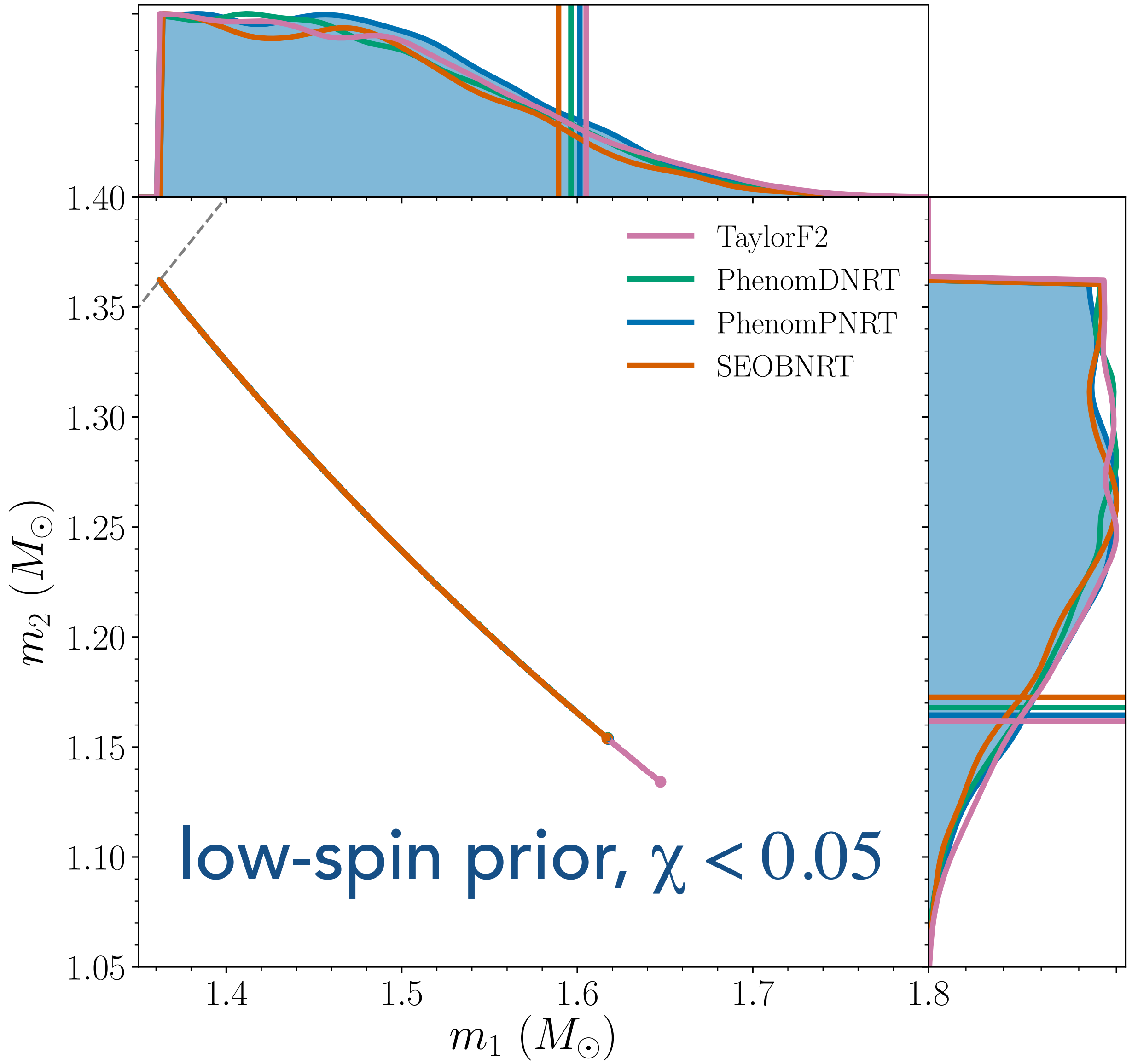


Dietrich+ arXiv:1804.02235

COMPONENT MASSES



high-spin prior, $\chi < 0.89$



low-spin prior, $\chi < 0.05$

$$m_1 \in (1.36,\ 1.89)\ \mathrm{M}_\odot$$

$$m_2 \in (1.00,\ 1.36)\ \mathrm{M}_\odot$$

$$m_1 \in (1.36,\ 1.60)\ \mathrm{M}_\odot$$

$$m_2 \in (1.16,\ 1.36)\ \mathrm{M}_\odot$$

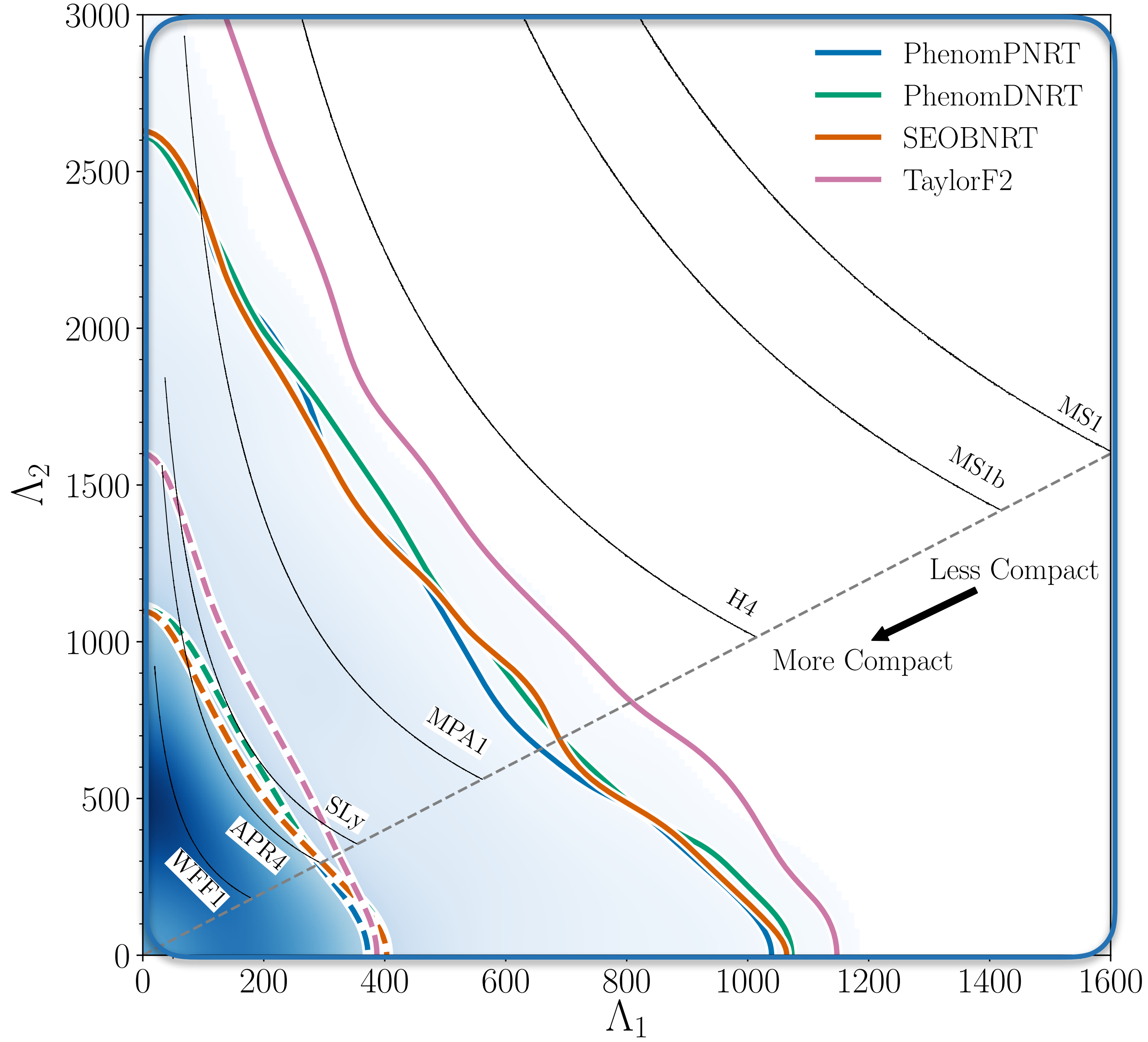
Abbott+, arXiv 1805.11579

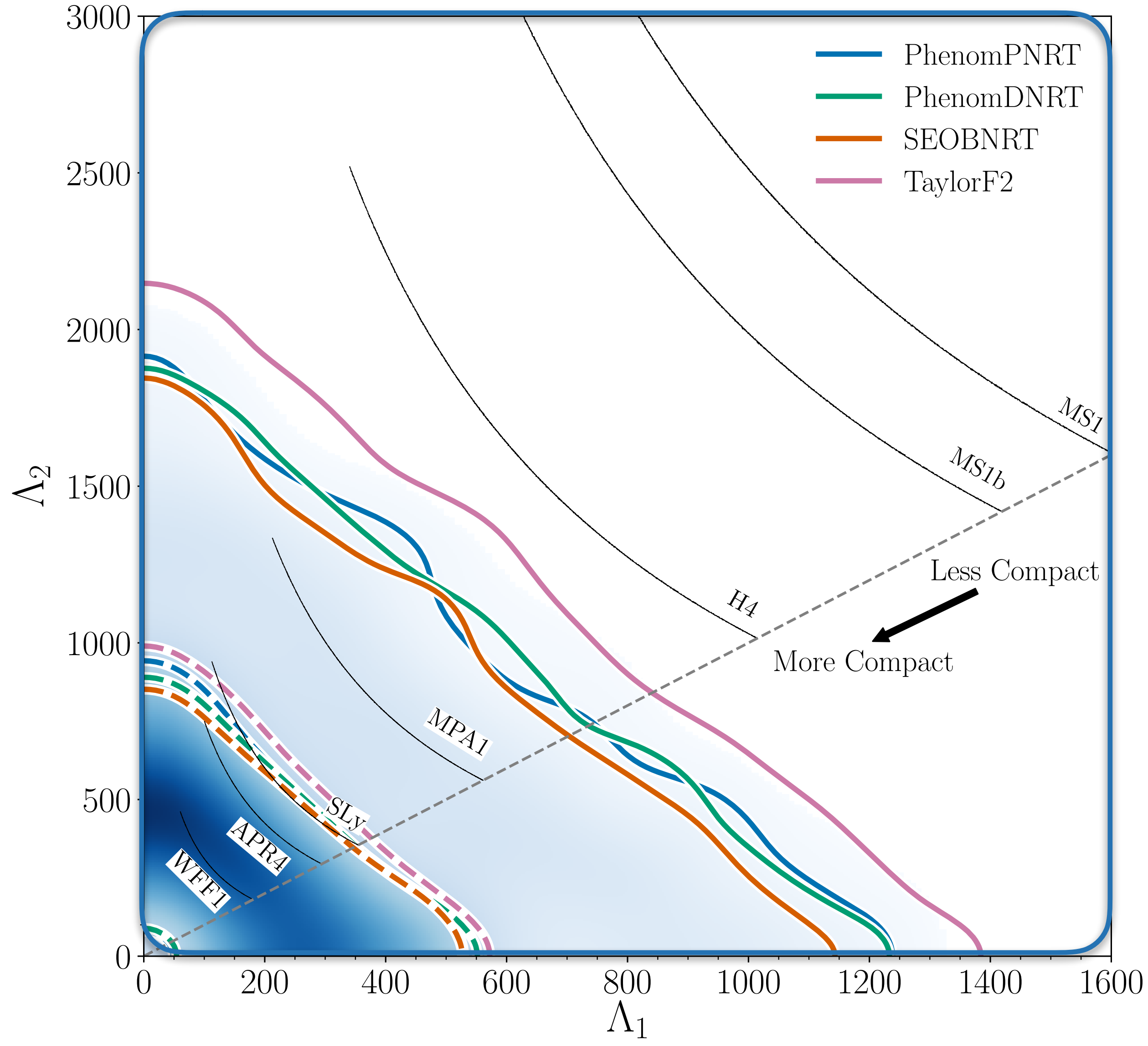
UNIVERSAL RELATIONS AND PARAMETRIZED EOS

- a possible approach (not pursued in the current papers)
  - use model selection to determine which EOS is favored by data
  - this will be time consuming and compute intensive
- use EOS-insensitive, universal relations to measure posterior distribution of tidal deformability
  - infer posterior distribution of radius of each neutron star using universal relations
- directly sample the EOS using parametrized relations
  - similar to the first choice above but far less compute intensive

Universal Relations: Yagi+Yunes 2013, 2015, 2016, 2017; Chatziioannou 2018;
Parameterized Relations: Lindblom 2010, 2018; Lackey+Wade 2015; Carney+ 2018

RESULTS BASED ON MINIMAL ASSUMPTIONS





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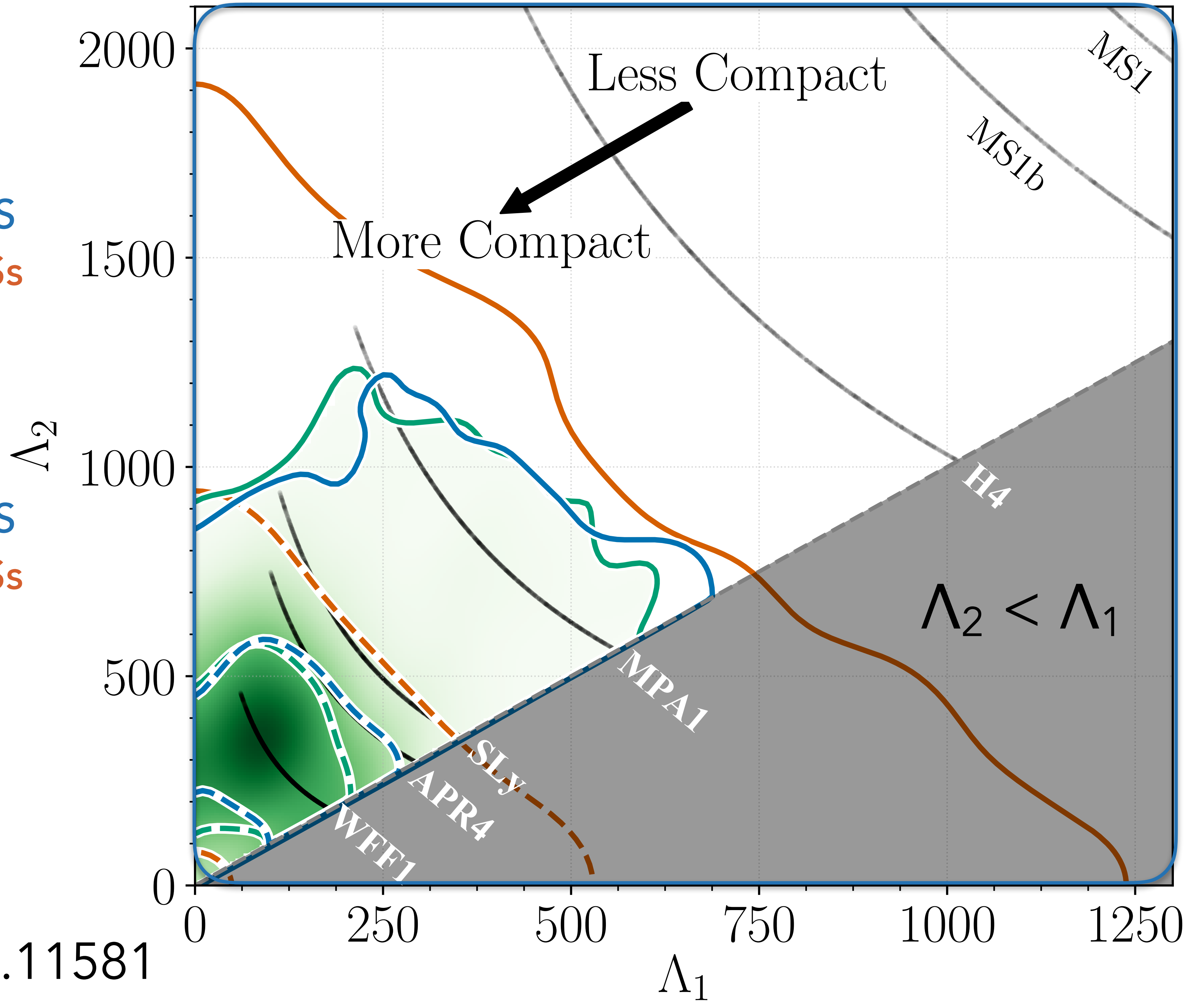
IMPROVED RESULTS ASSUMING BOTH COMPANIONS ARE NEUTRON STARS

90% CI

- EOS insensitive
- parametrized EOS
- independent EOSs

50% CI

- EOS insensitive
- parametrized EOS
- independent EOSs



Abbott+, arXiv 1805.11581

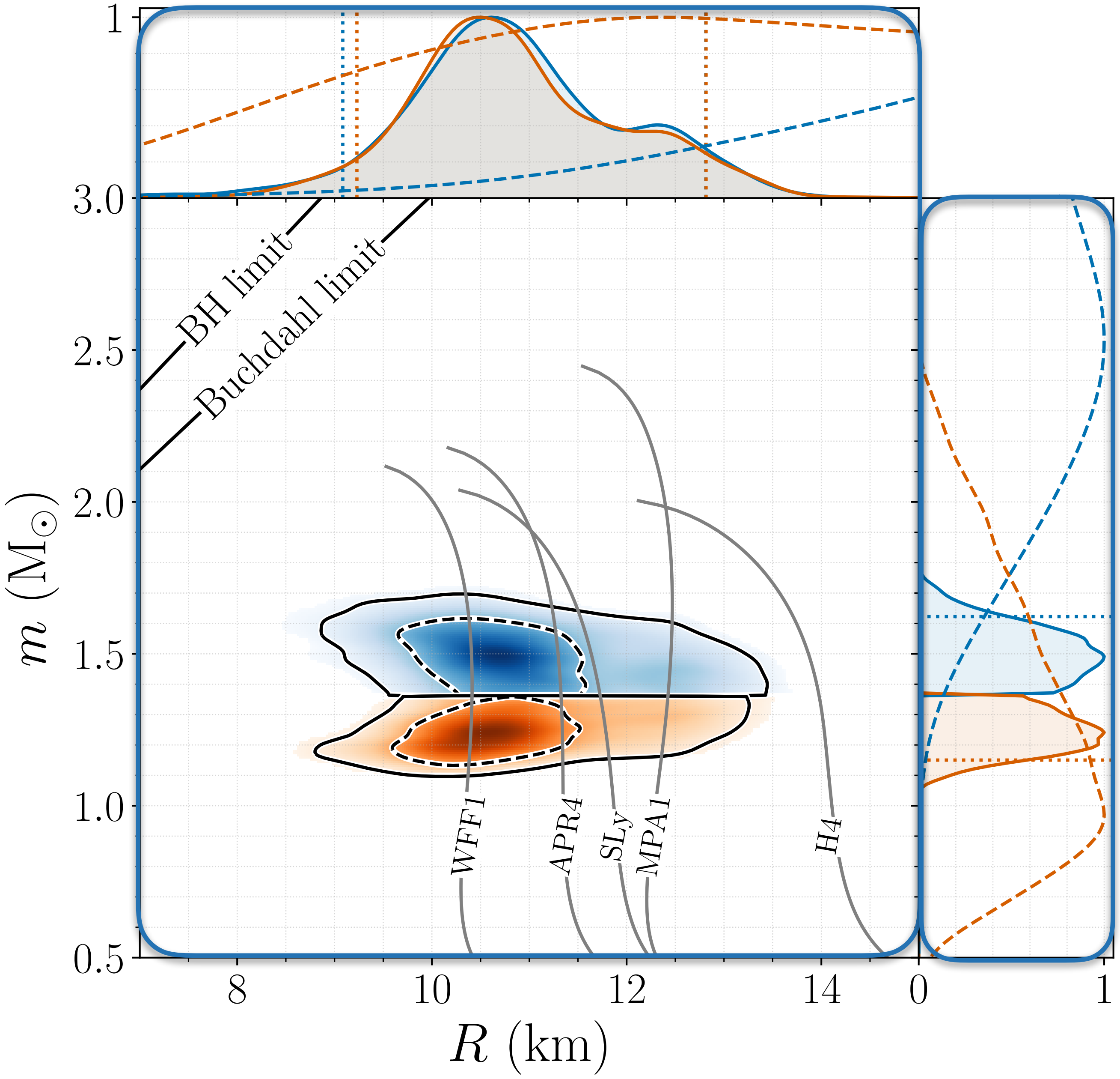
GW170817: TIDAL DEFORMABILITY CONSTRAINTS

- under minimal assumptions about the nature of companions:
    - $0 < \Lambda_{1.4} < 630$ (large spin priors) or $70 < \Lambda_{1.4} < 720$ (low spins)
- assuming that GW170817 contained two neutron stars and have low spins:
    - $70 < \Lambda_{1.4} < 580$

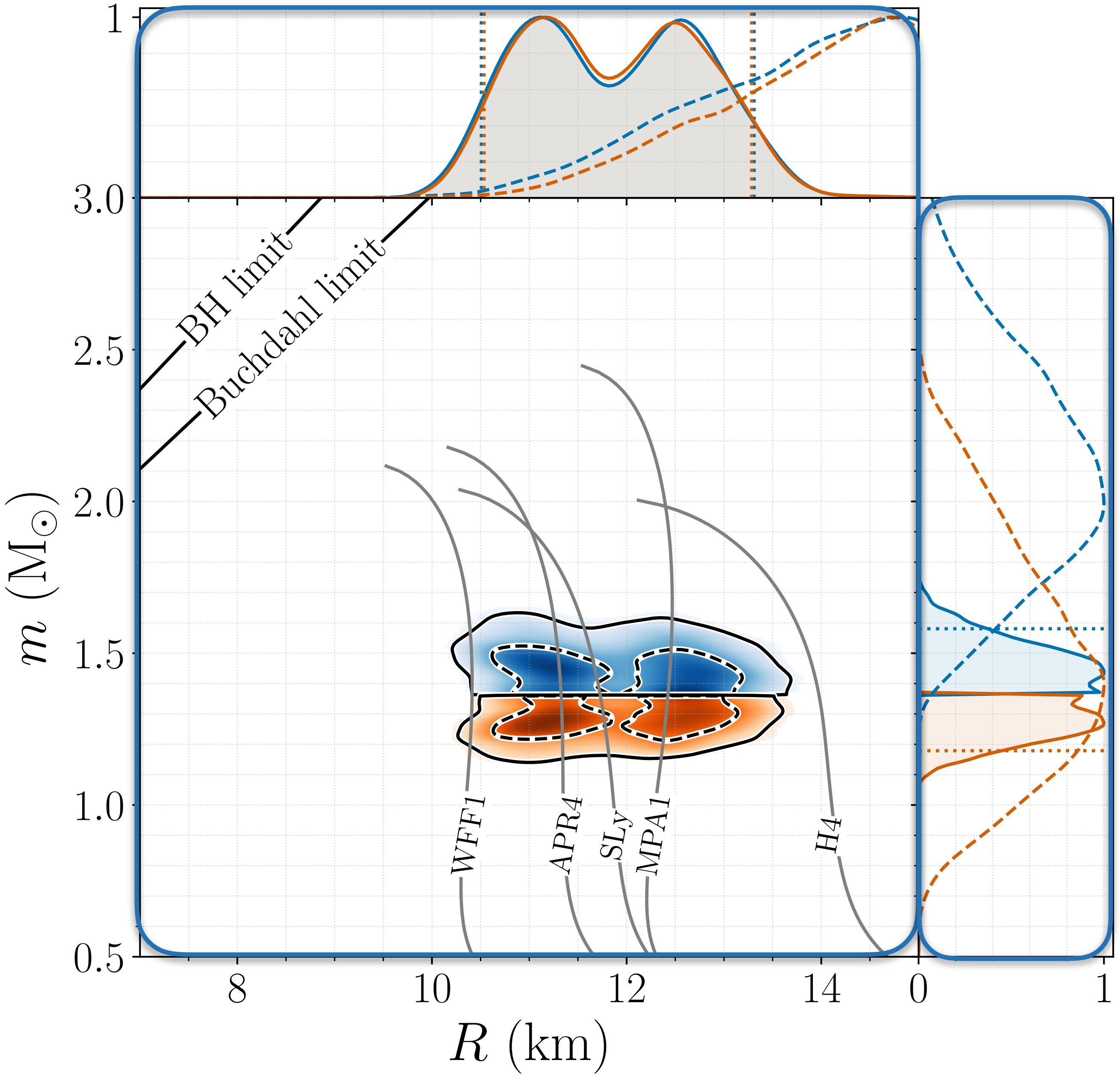
Abbott+, arXiv 1805.11581

NS RADIUS

EOS insensitive



parameterized EOS and assume NS mass of at least ~ 2 solar mass



Abbott+, arXiv 1805.11581

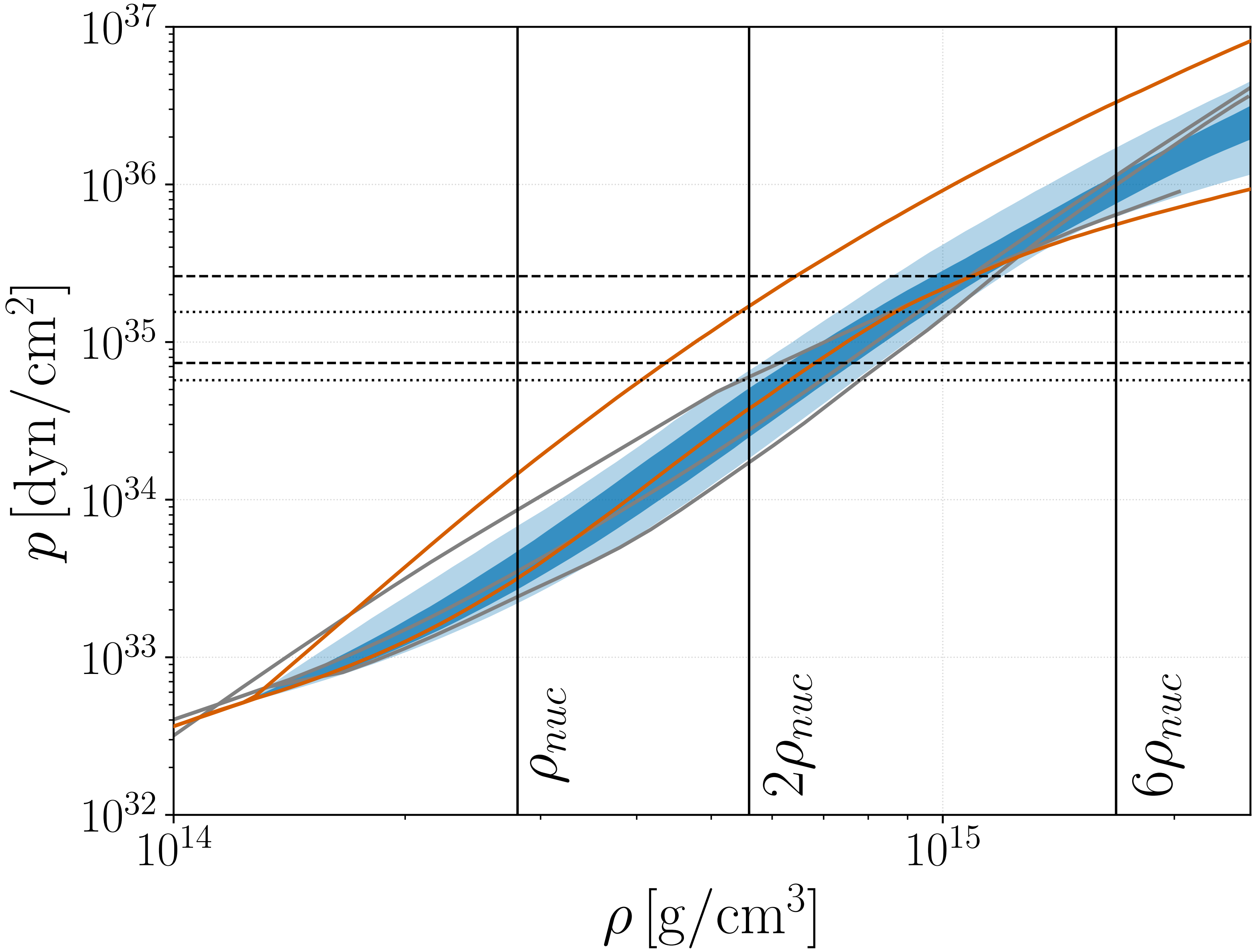
GW170817: RADIUS CONSTRAINTS

- constraints on NS radius based on:
  - EOS insensitive analysis: 9.1 km $< R_1 <$ 12.8 km, 9.2 km $< R_2 <$ 12.8 km
  - Parametrized EOS and EOS consistent with heaviest observed NS: 10.5 km $< R_{1,2} <$ 13.3 km
    - not imposing heaviest NS constraint gives results similar to EOS insensitive analysis
- softer EoS (e.g. APR4) are preferred over stiffer EoS (e.g. MS1 or H4)

Abbott+, arXiv 1805.11581

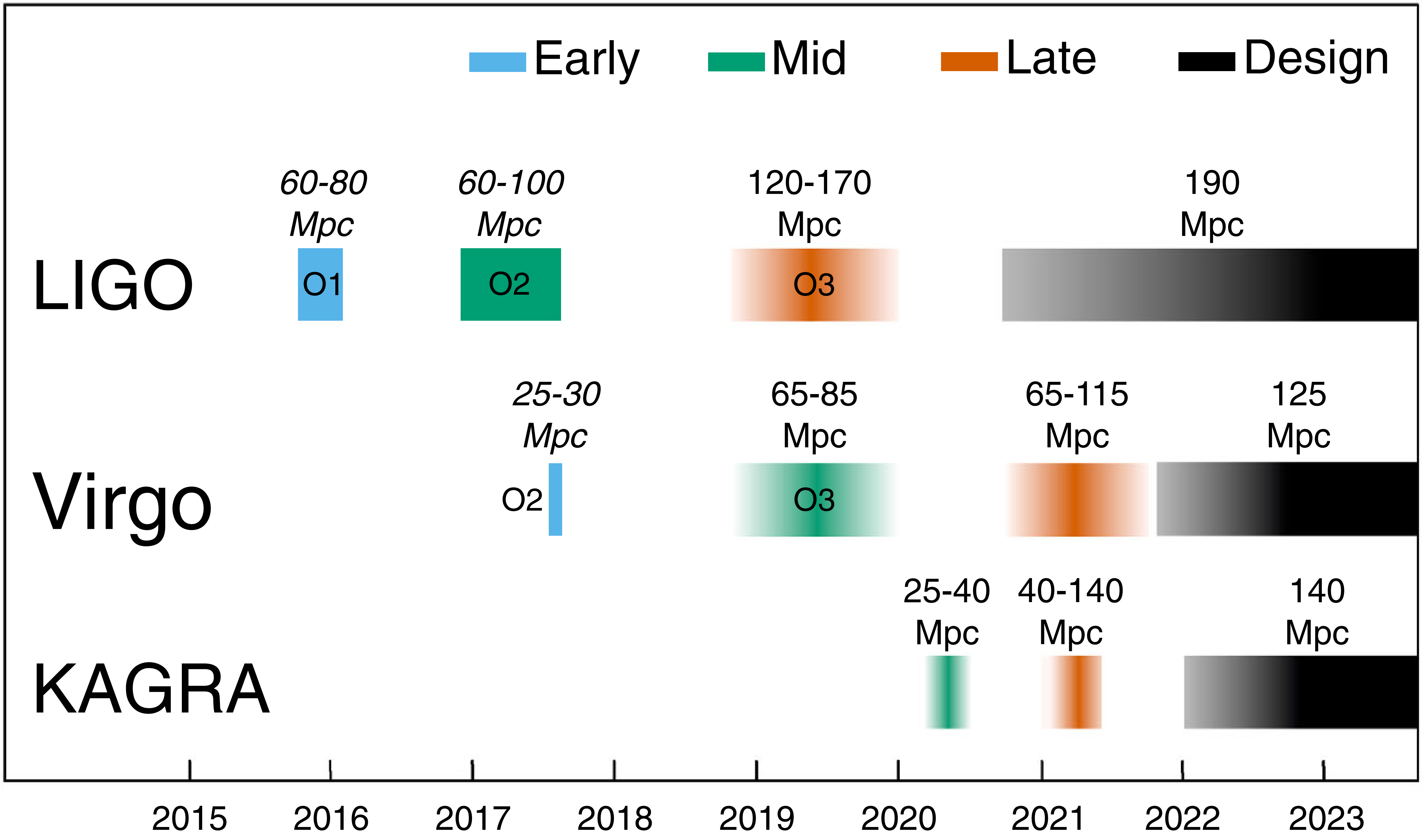
DIRECT CONSTRAINT ON EOS

- EOS should support a NS mass of at least 1.97 solar mass
- orange: 90% prior
- dark (light) blue shaded: 50% (90%) posterior
- grey: H4, APR4, WFF1



Abbott+, arXiv 1805.11581

FUTURE RUN PLANS



Abbott+, Living Rev Relativ (2018) 21:3

PROSPECTS

- third observing run (O3) from early 2019
  - aLIGO range: 120-170 Mpc, Virgo range: 65-85 Mpc
- design sensitivity by 2020+
  - advanced LIGO range: 190 Mpc, Virgo range: 125 Mpc
- binary neutron star rate inferred from GW170817
  - volumetric rage: [300, 5000] mergers yr^{-1} Mpc^{-3}
  - implied detection rate in O3: 1-50 per year and at design:

Abbott+, Living Rev Relativ (2018) 21:3

EXTRA SLIDES AND QUESTIONS

NUMERICAL RELATIVITY SIMULATIONS

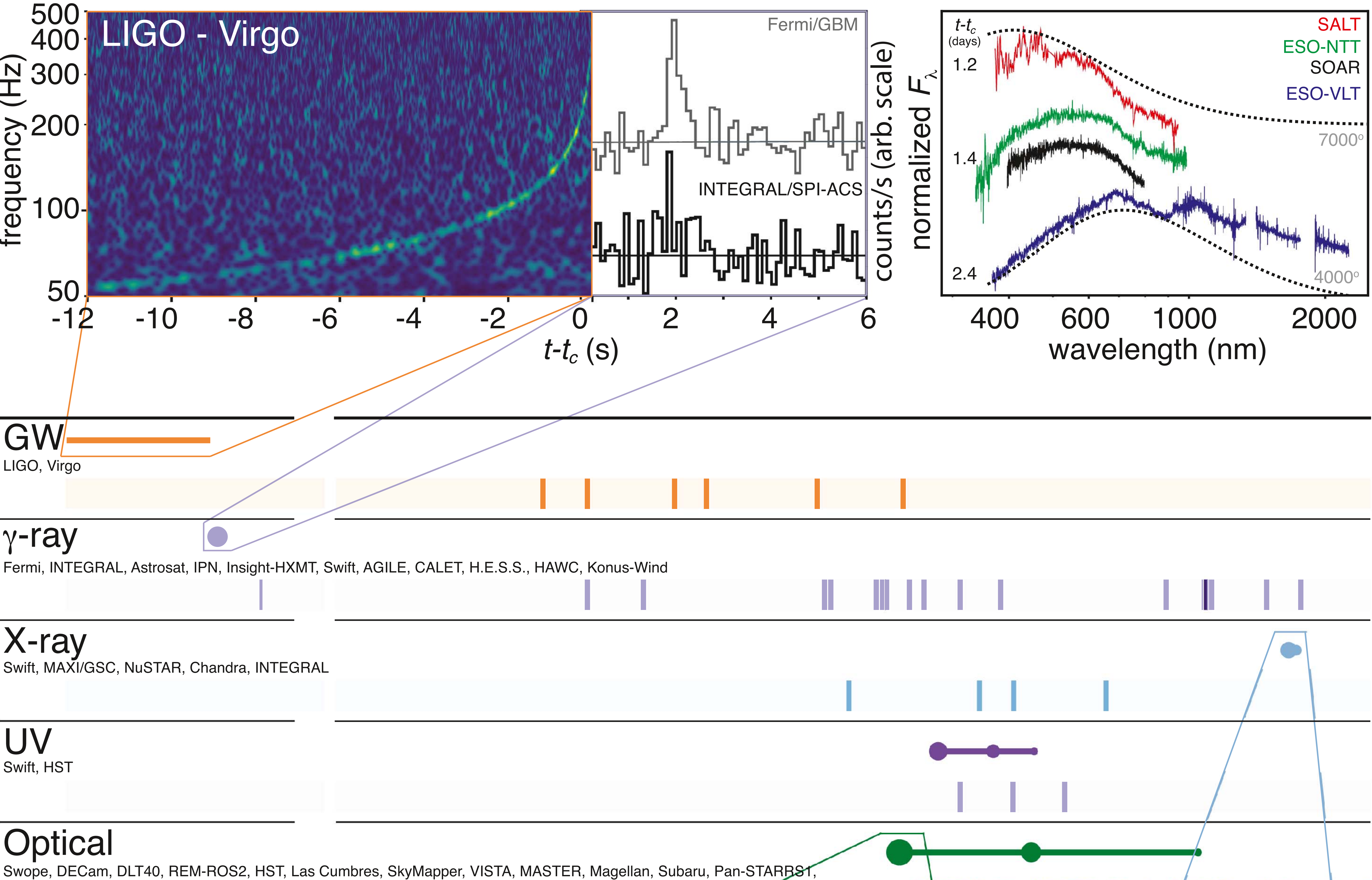
- what physical effects are still lacking?
  - neutrino transport, magnetic fields, hyperons/quark-gluon plasma
- how do simulations from different groups compare?
- how well do simulations cover the parameter space?
  - component masses, mass ratio, spins,
- simulations of neutron star-black hole mergers
  - parameter space coverage (as above)
  - up to what mass ratios are matter effects relevant
    - for GW modeling, for EM observation
  - simulations of ~1:1 neutron star-black hole mergers

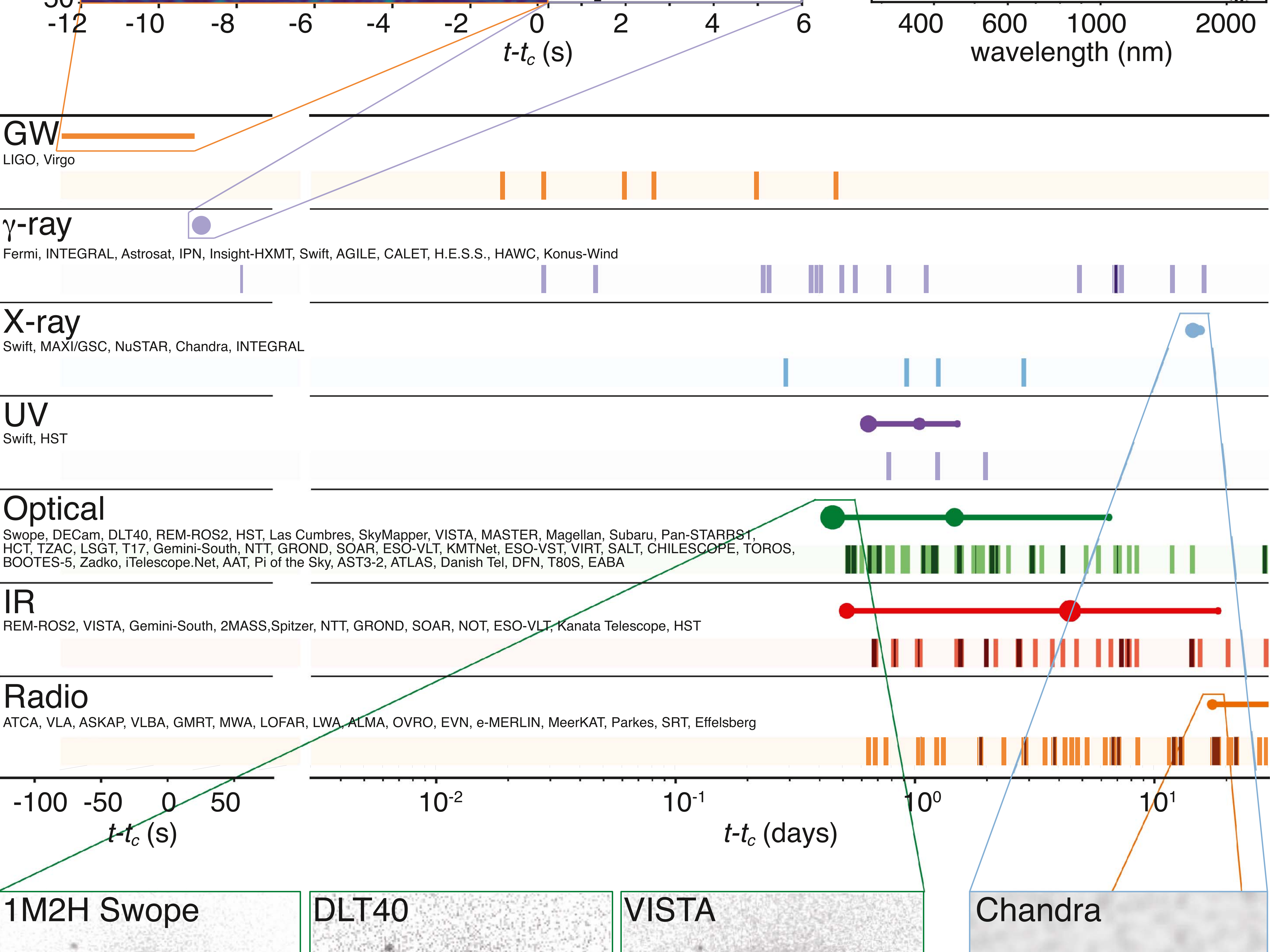
ANALYTICAL MODELING

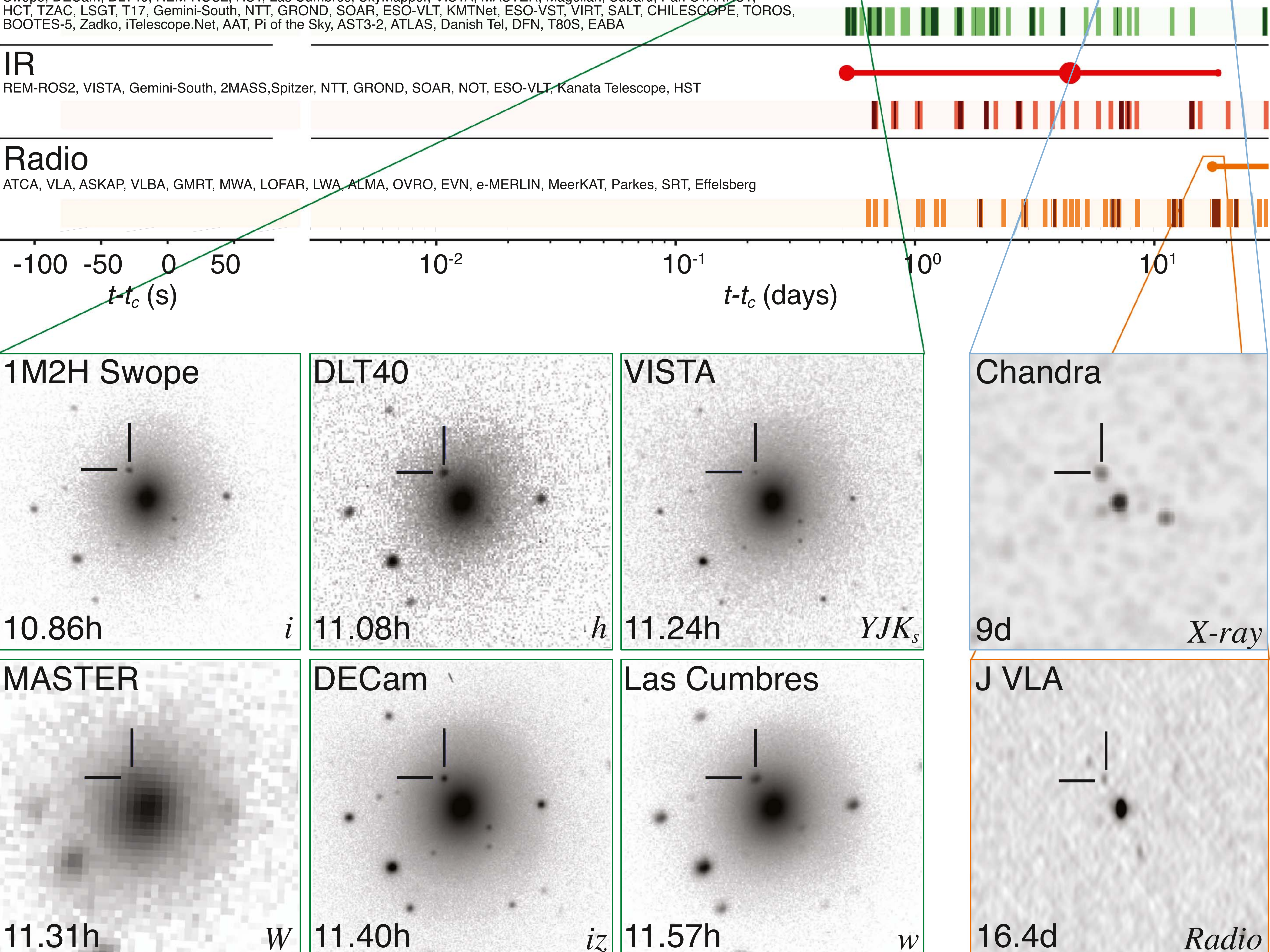
- are waveform models good enough for unbiased estimation of NS EoS?
  - waveform models based on independent NR simulations
  - comparison of analytical models across the parameter space
- physics that is lacking in modeling
  - spins, magnetic fields, equations of state
- post-merger models
  - spectra, time-domain models
- inspiral-post merger unified models
  - what, if anything, do we gain by IPM models?

ANALYSIS METHODS

- are our analysis methods mature?
  - what further improvements are needed in inference techniques?
- prior probability distribution of parameters
  - what priors are appropriate for: masses, spins, and magnetic fields
- can we continue to assume the same EoS for both companions?
  - phase transition, distinguishing NS-BH vs NS-NS
- does EoS parametrization work for all SNRs and for EoS?
  - do we need to work with specific EoS for very loud signals or when combining a large number of events?


LIGO - Virgo
frequency (Hz)
500
400
300
200
100
50
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
-12
-10
-8
-6
-4
-2
0
2
4
6
t-t_c (s)
t-t_c (days)
1.2
1.4
2.4
normalized F_λ
SALT
ESO-NTT
SOAR
ESO-VLT
7000°
4000°
400
600
1000
2000
wavelength (nm)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1,

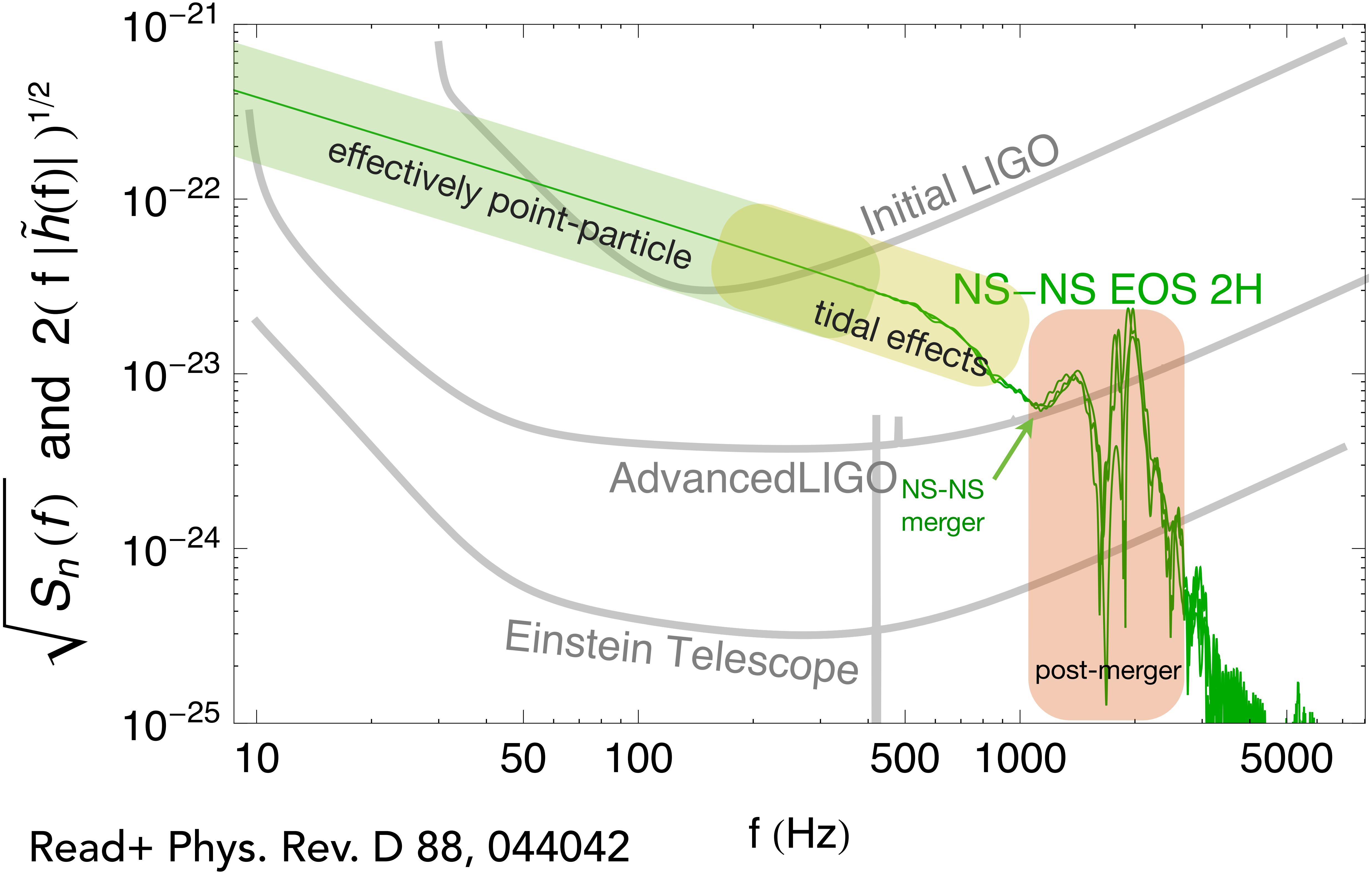

-12
-10
-8
-6
-4
-2
0
2
4
6
t-t_c (s)
400
600
1000
2000
wavelength (nm)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
-100
-50
0
50
t-t_c (s)
10^-2
10^-1
10^0
10^1
t-t_c (days)
1M2H Swope
DLT40
VISTA
Chandra


HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS,
BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
-100
-50
0
50
t-t_c (s)
10^{-2}
10^{-1}
10^0
10^1
t-t_c (days)
1M2H Swope
10.86h
i
DLT40
11.08h
h
VISTA
11.24h
YJK_s
Chandra
9d
X-ray
MASTER
11.31h
W
DECam
11.40h
iz
Las Cumbres
11.57h
w
J VLA
16.4d
Radio

HOW DIFFERENT ARE THE SPECTRA FOR DIFFERENT EOS?

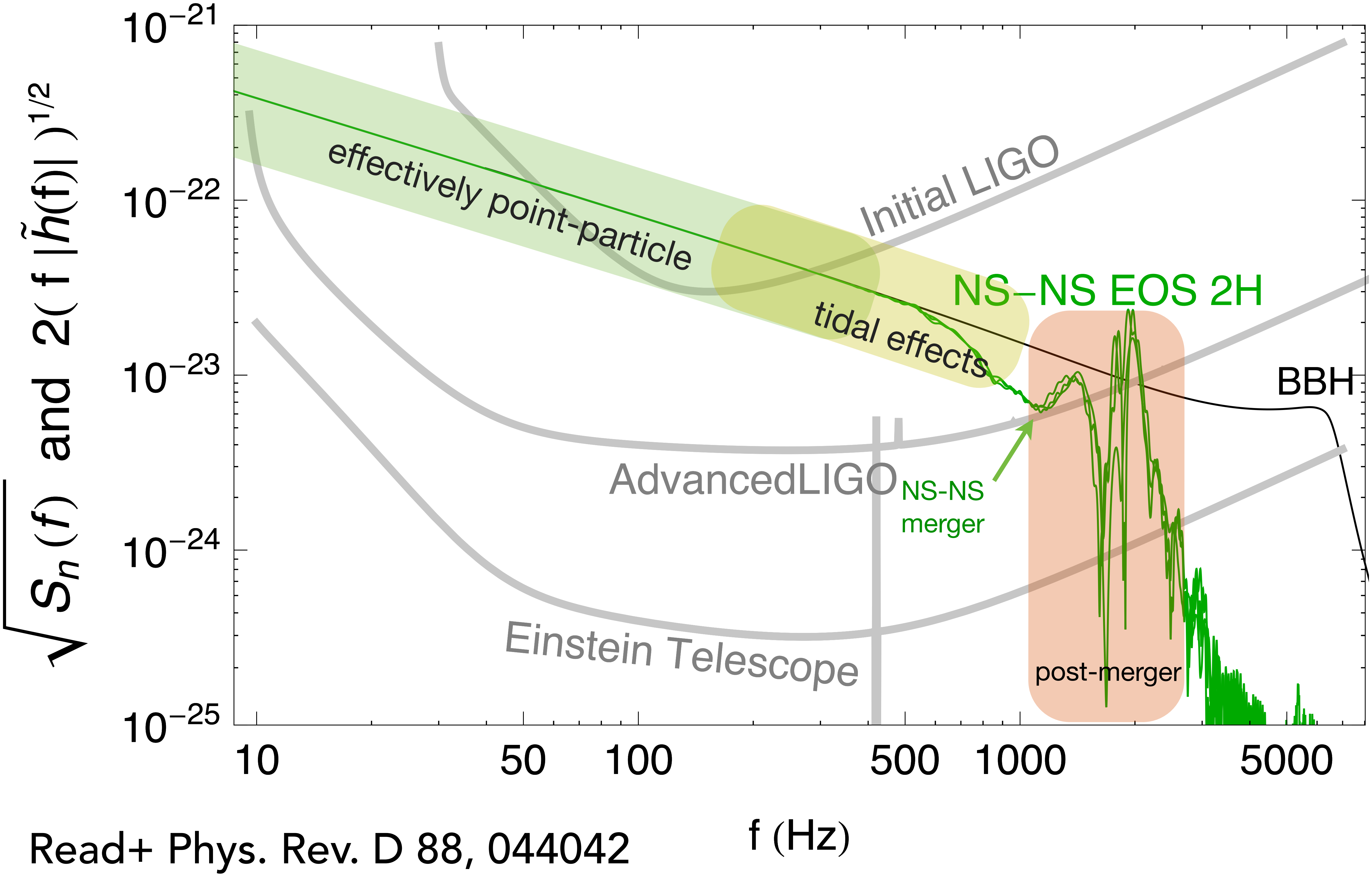
- 1.35 - 1.35 solar mass neutron stars
  - (same mass BBH for comparison)
- Effective distance 100 Mpc: optimally oriented
- EOS 2H: Large-radius stars (>15 km) - hard EOS
- EOS HB: Moderate-radius stars (~11.6km) - soft EOS
- Results based on Read et al Phys. Rev. D 88, 044042 (arXiv:1306.4065)

HARD EQUATION OF STATE



Read+ Phys. Rev. D 88, 044042

HARD EQUATION OF STATE



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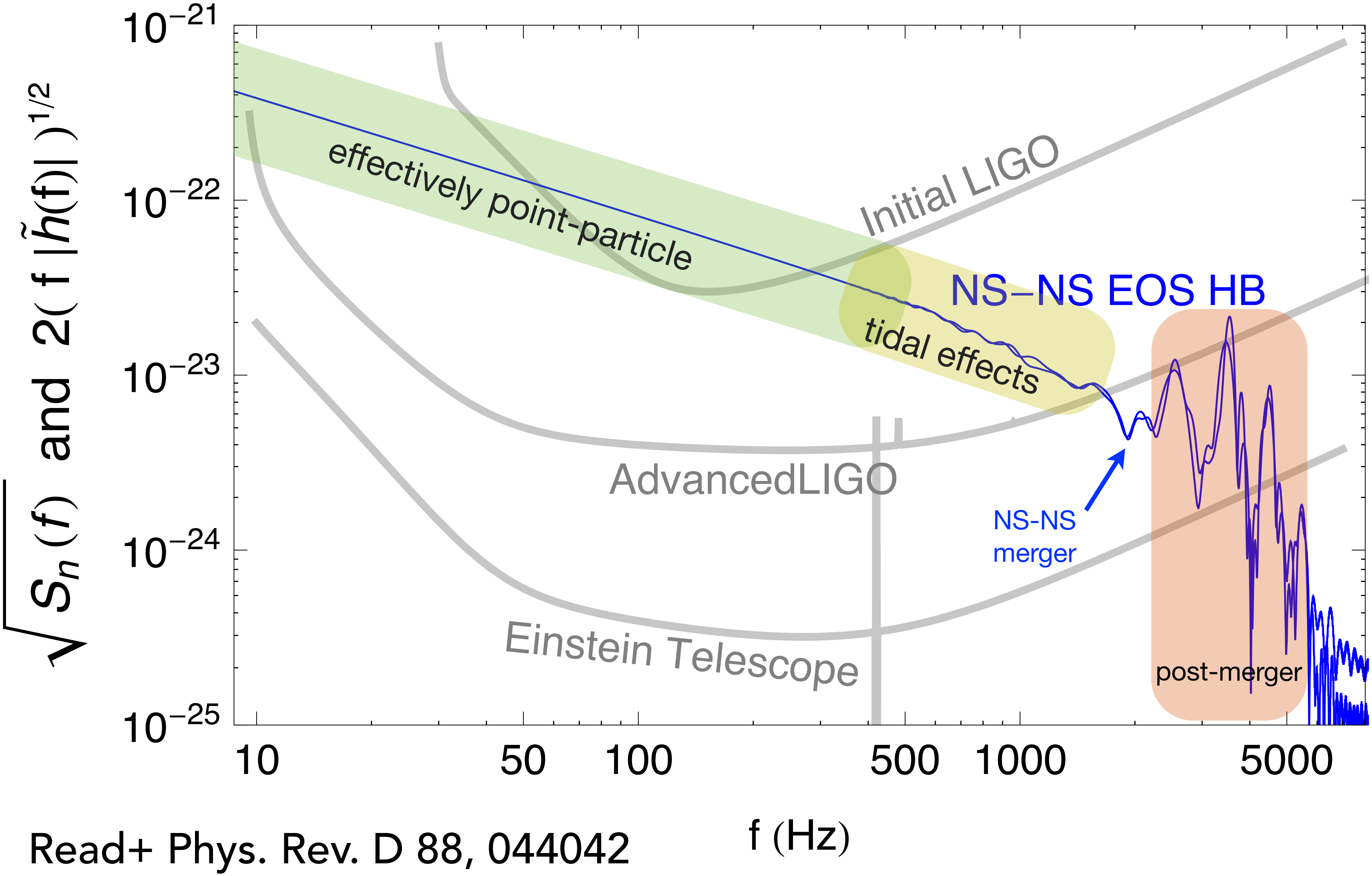
SOFT EQUATION OF STATE



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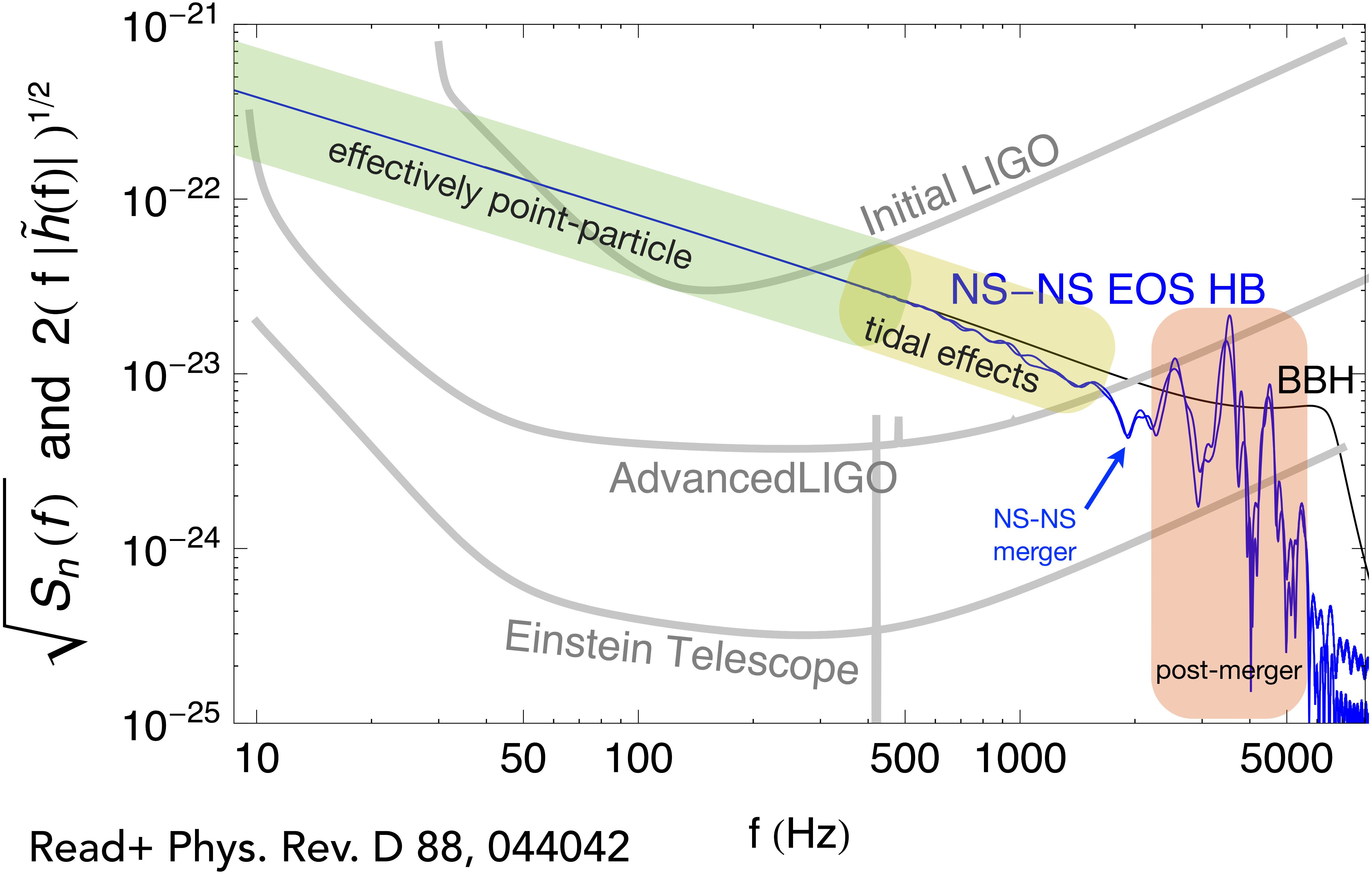
SOFT EQUATION OF STATE



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