What have we learned from GW170817?

Tomek Bulik

Astronomical Observatory, University of Warsaw
and
Astrocent, Nicolaus Copernicus Astronomical Center, Warsaw

Based on LIGO and VIRGO results.

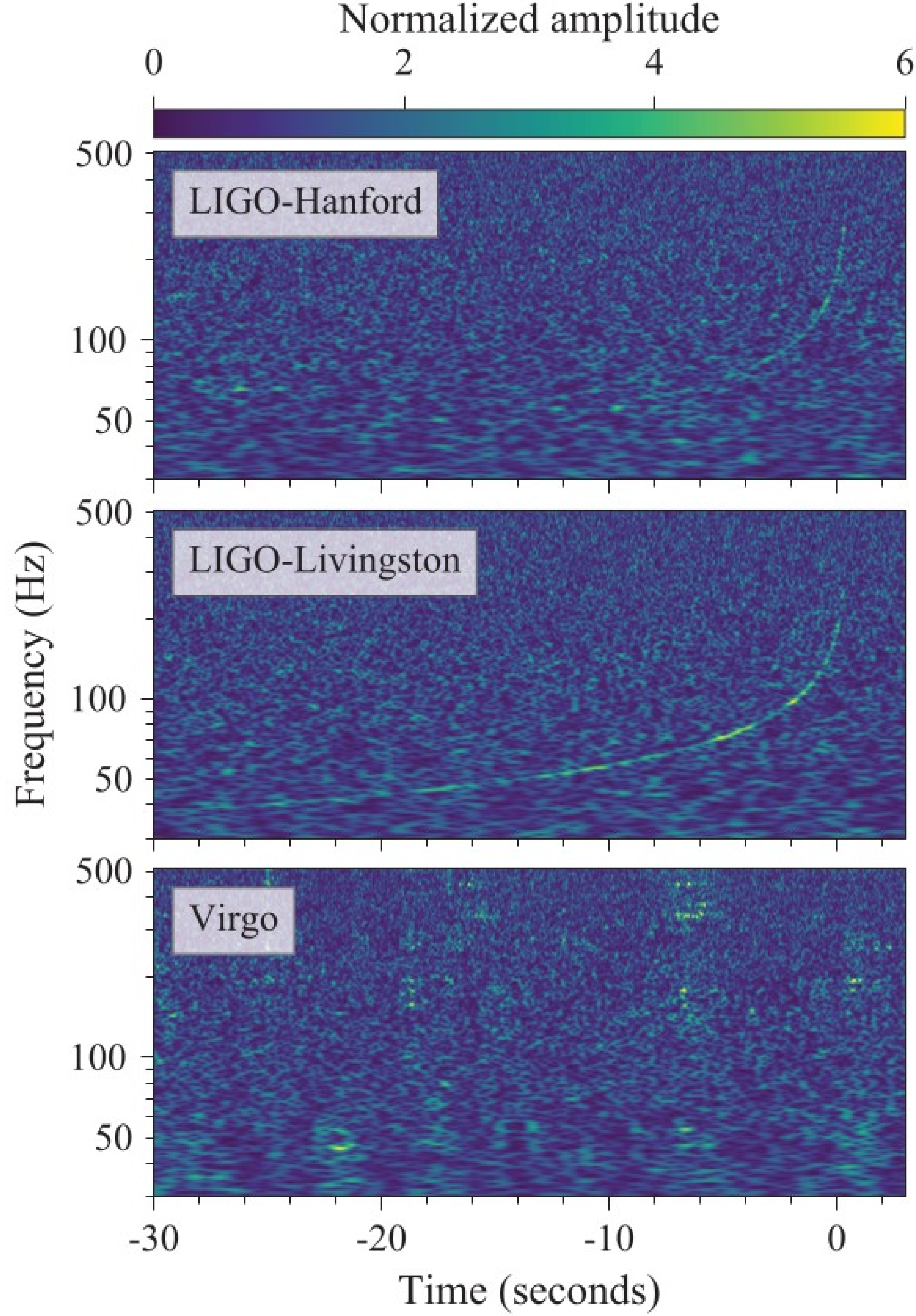
Outline

- Observations
- NS star properties
- Fundamental physics
- Astrophysics

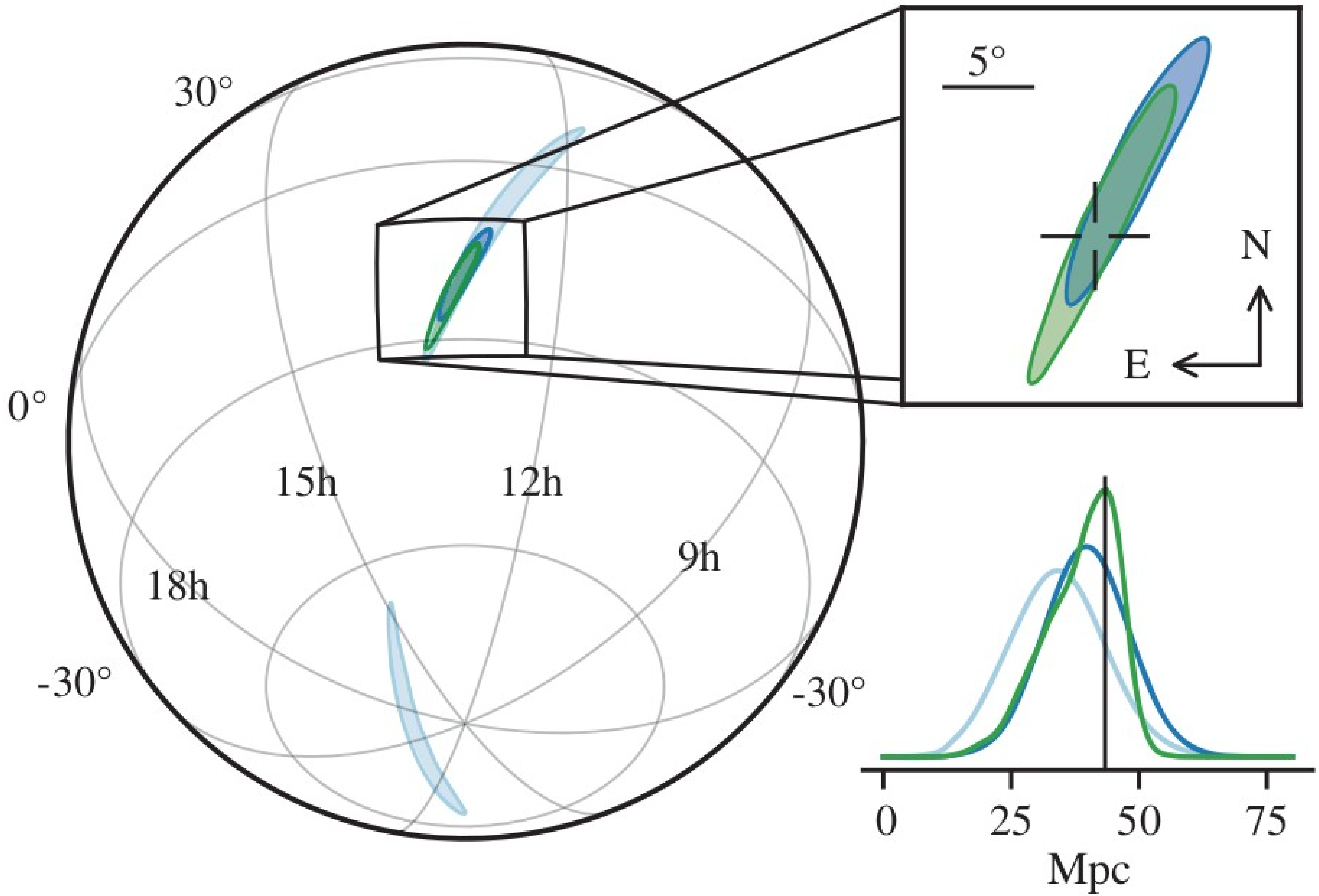
Observations

Compbined SNR = 32.6

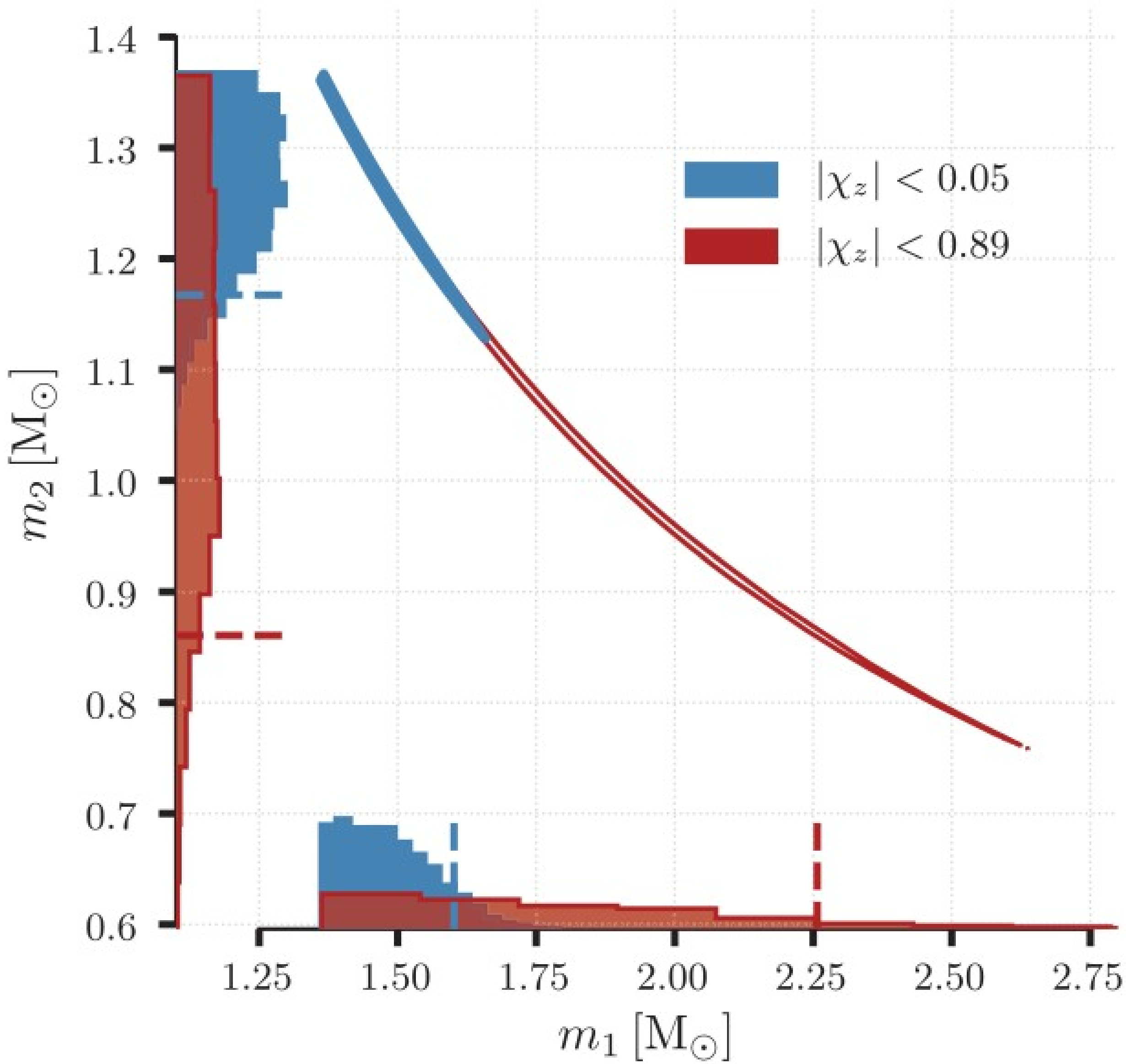
FAR < 1 in 80000 years



Sky position and distance

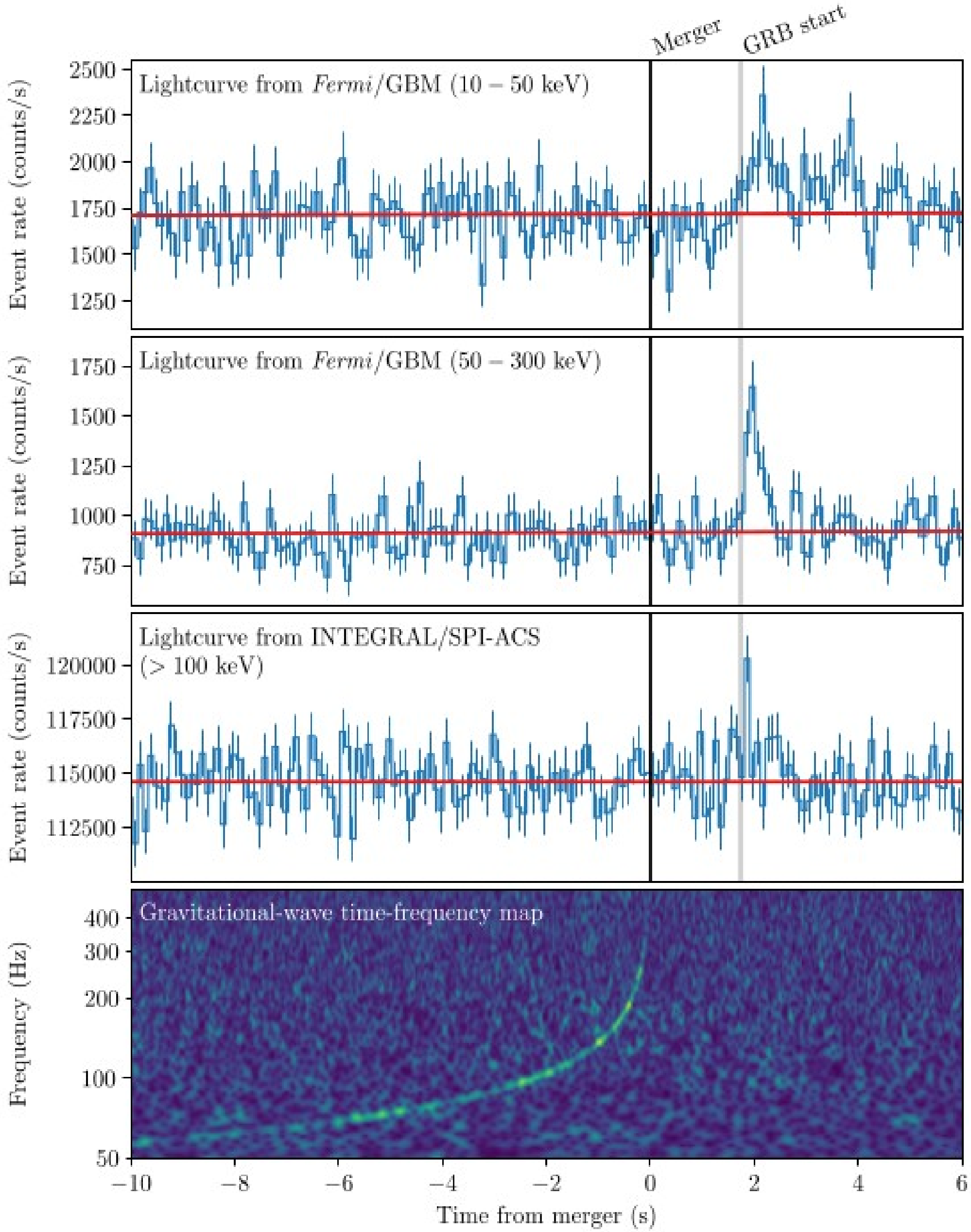


Masses

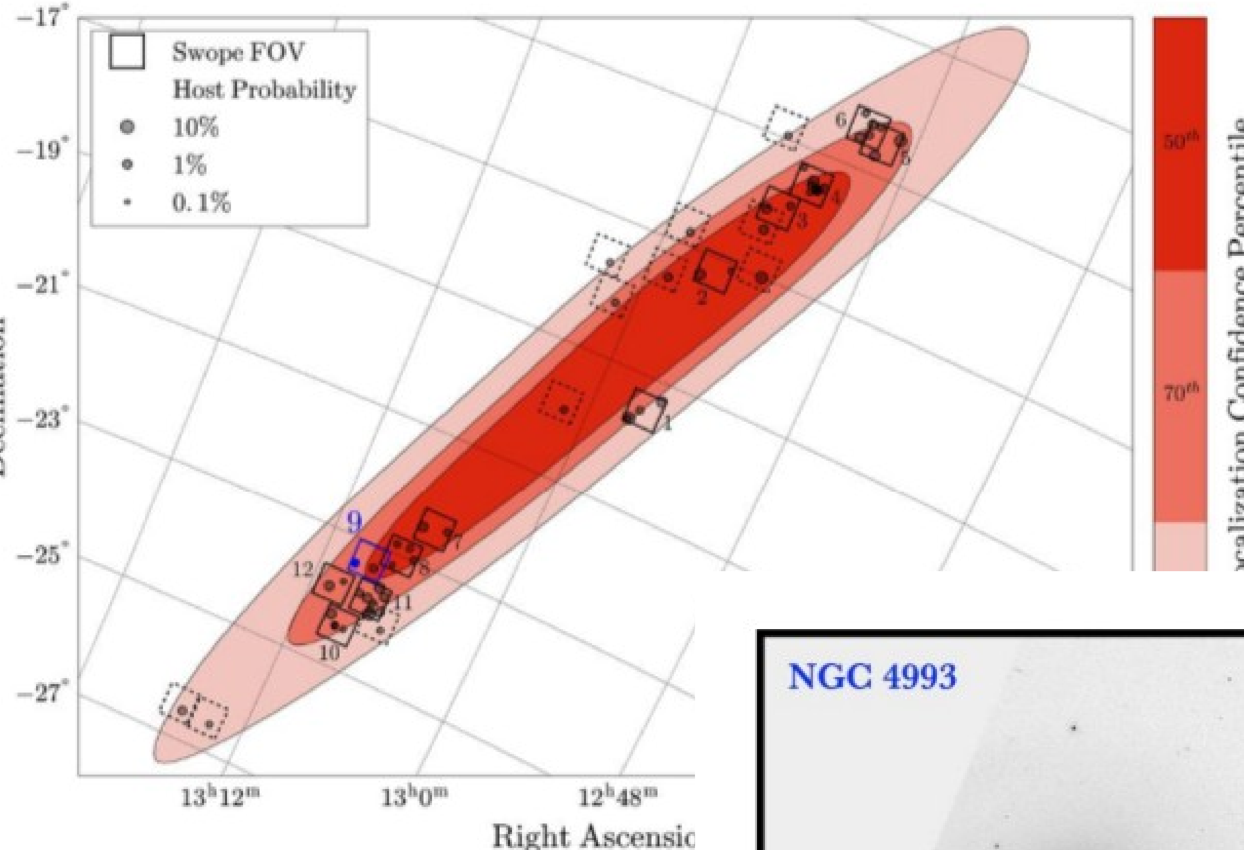


1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
$m_2\,[\mathrm{M}_\odot]$
1.25
1.50
1.75
2.00
2.25
2.50
2.75
$m_1\,[\mathrm{M}_\odot]$
$|\chi_z| < 0.05$
$|\chi_z| < 0.89$

GRB at the same time



Optical counterpart



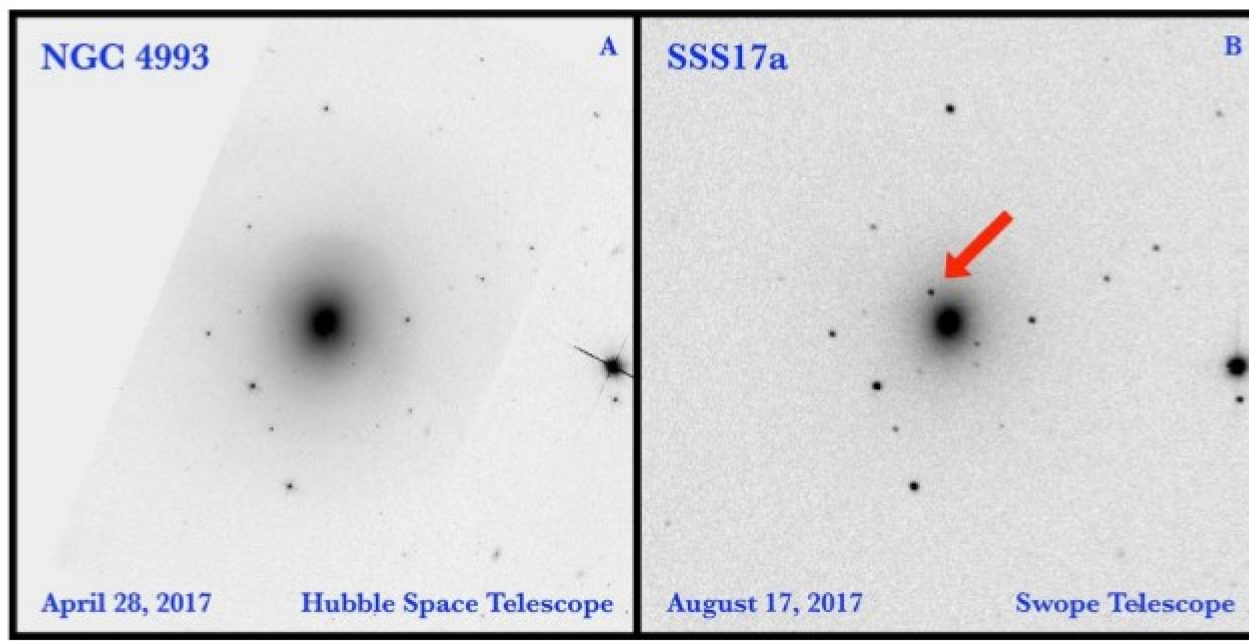


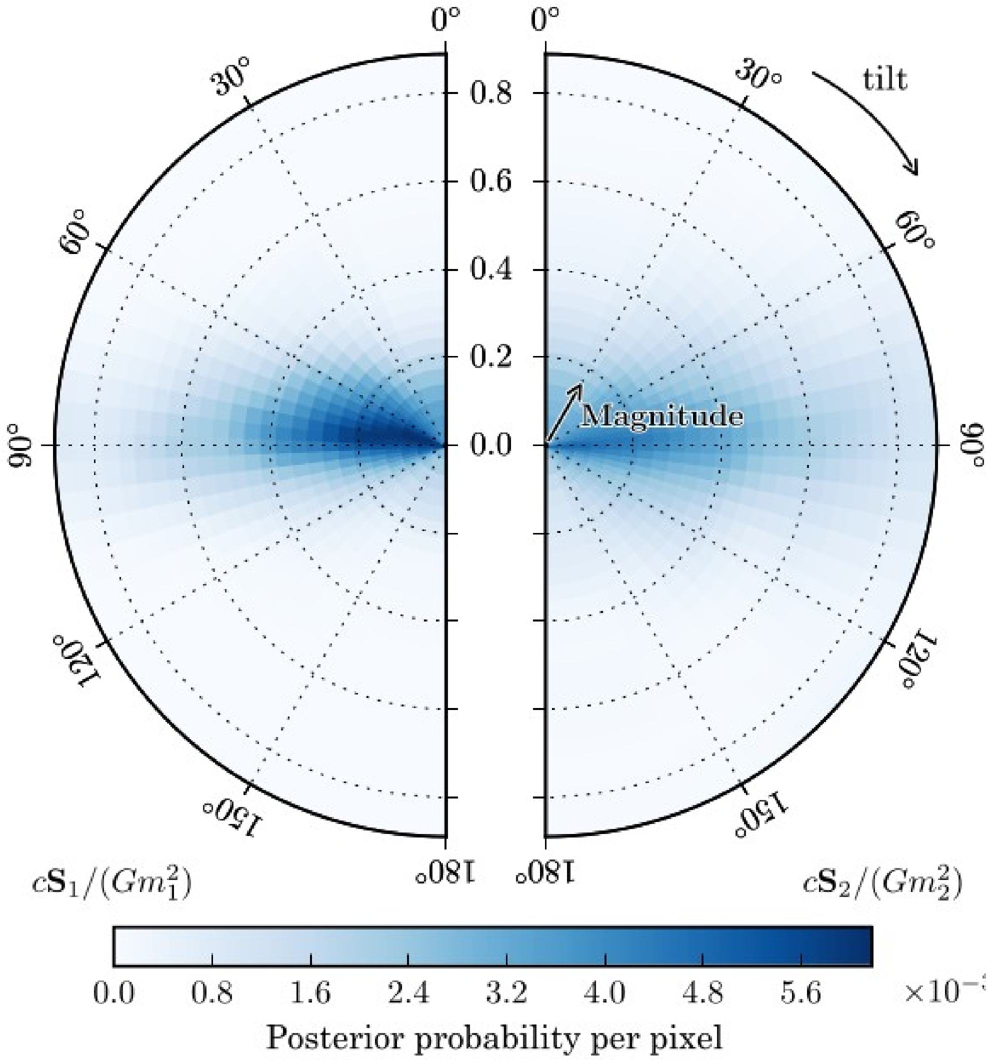
Fig. 4. 3×3 arcminute images centered on NGC 4993 with North up
and East left. (A) *Hubble Space Telescope* F606W-band (broad V)

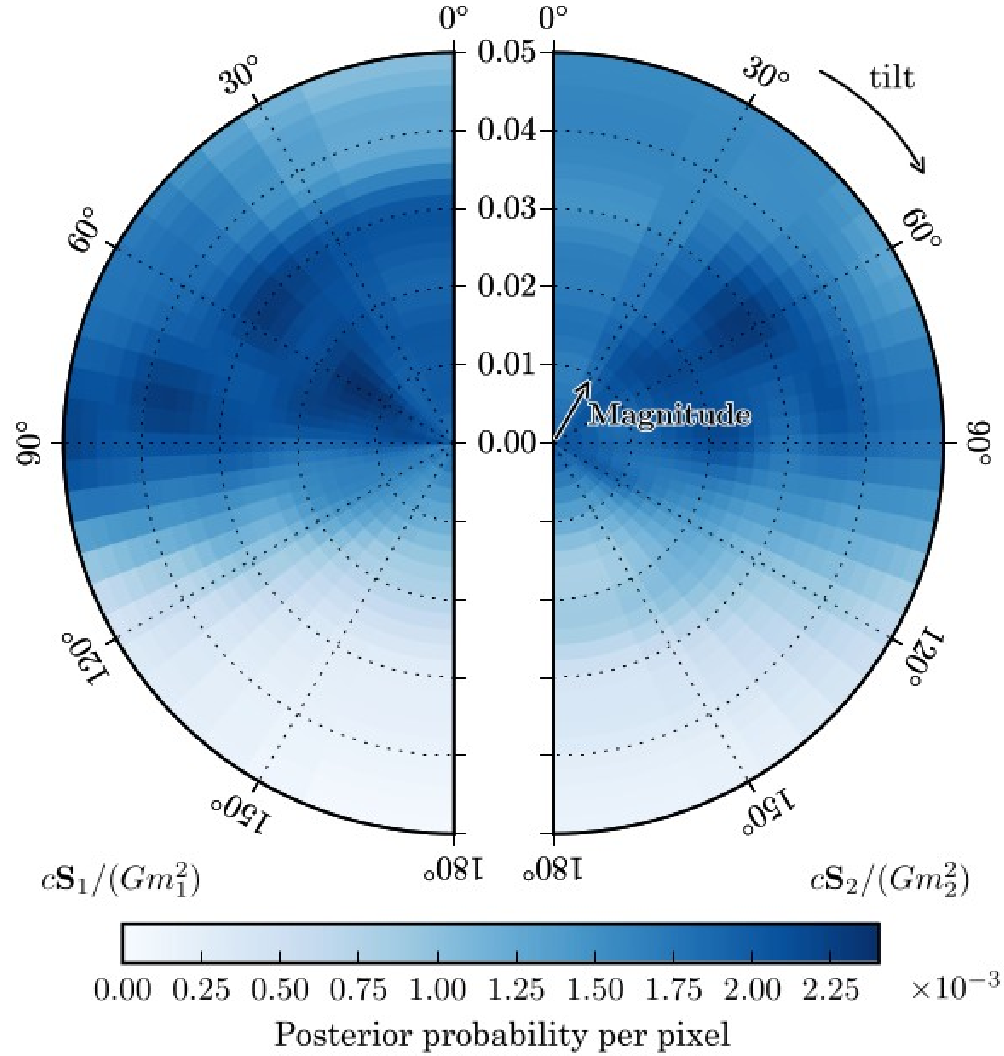
Parameters

TABLE I. Source properties for GW170817: we give ranges encompassing the 90% credible intervals for different assumptions of the waveform model to bound systematic uncertainty. The mass values are quoted in the frame of the source, accounting for uncertainty in the source redshift.

	Low-spin priors ($\lvert\chi\rvert \leq 0.05$)	High-spin priors ($\lvert\chi\rvert \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

Spins – two cases



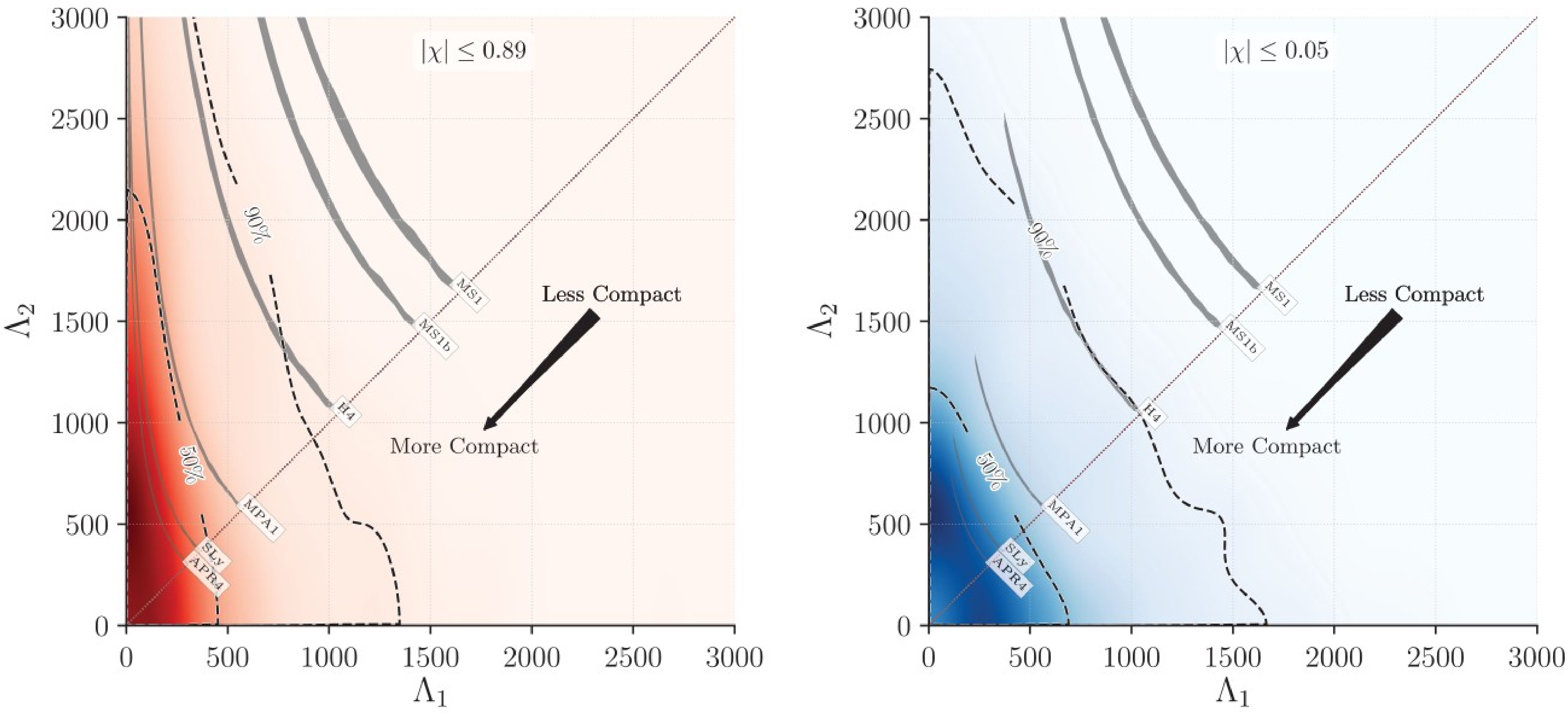


Observations summary

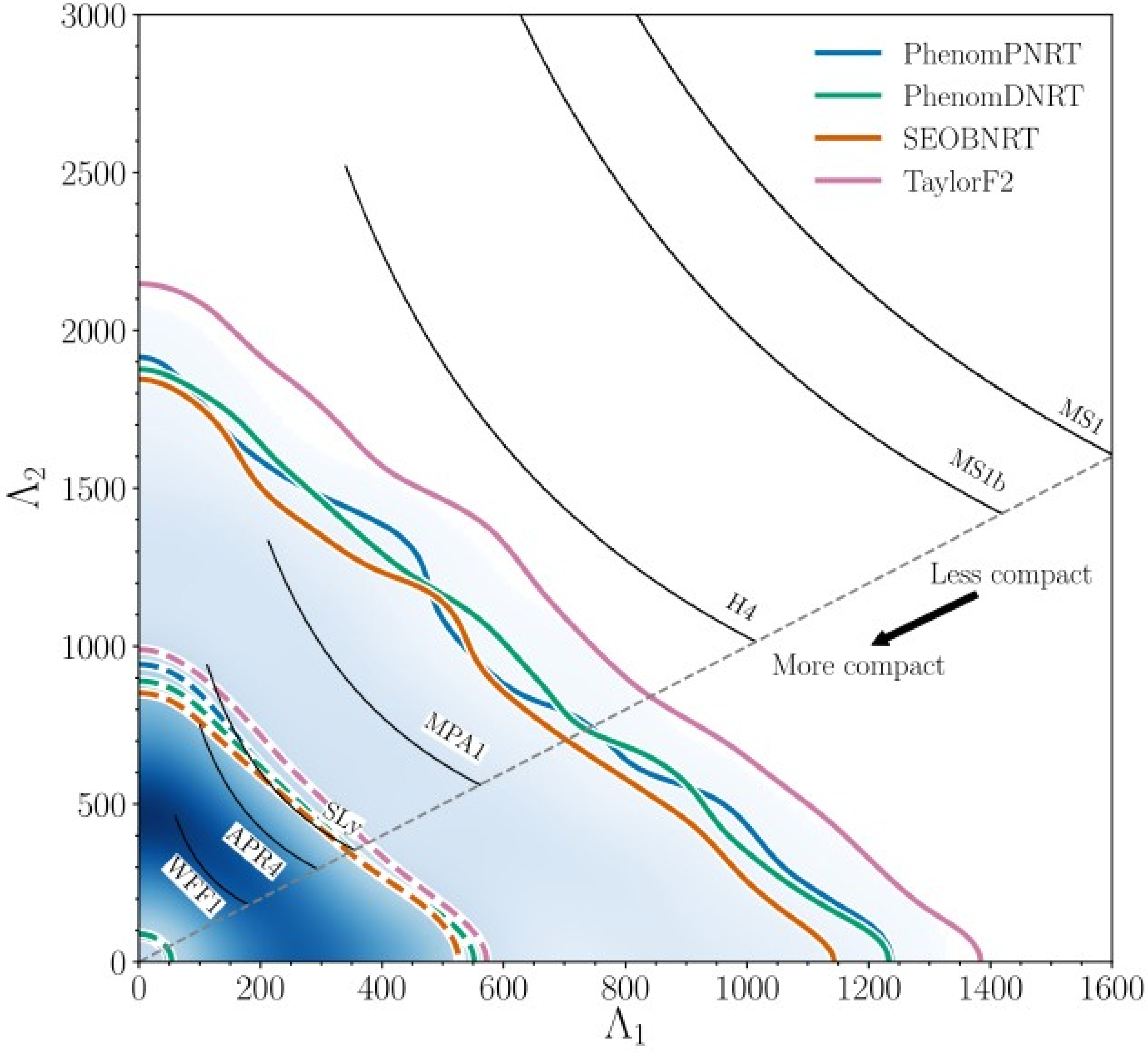
- GW observations for 30sec
- GRB at the same time
- Multiwavelength afterglow
- No VHE photons detected
- No neutrinos detected
- Masses in the NS range
- Low spins likely

Neutron star physics

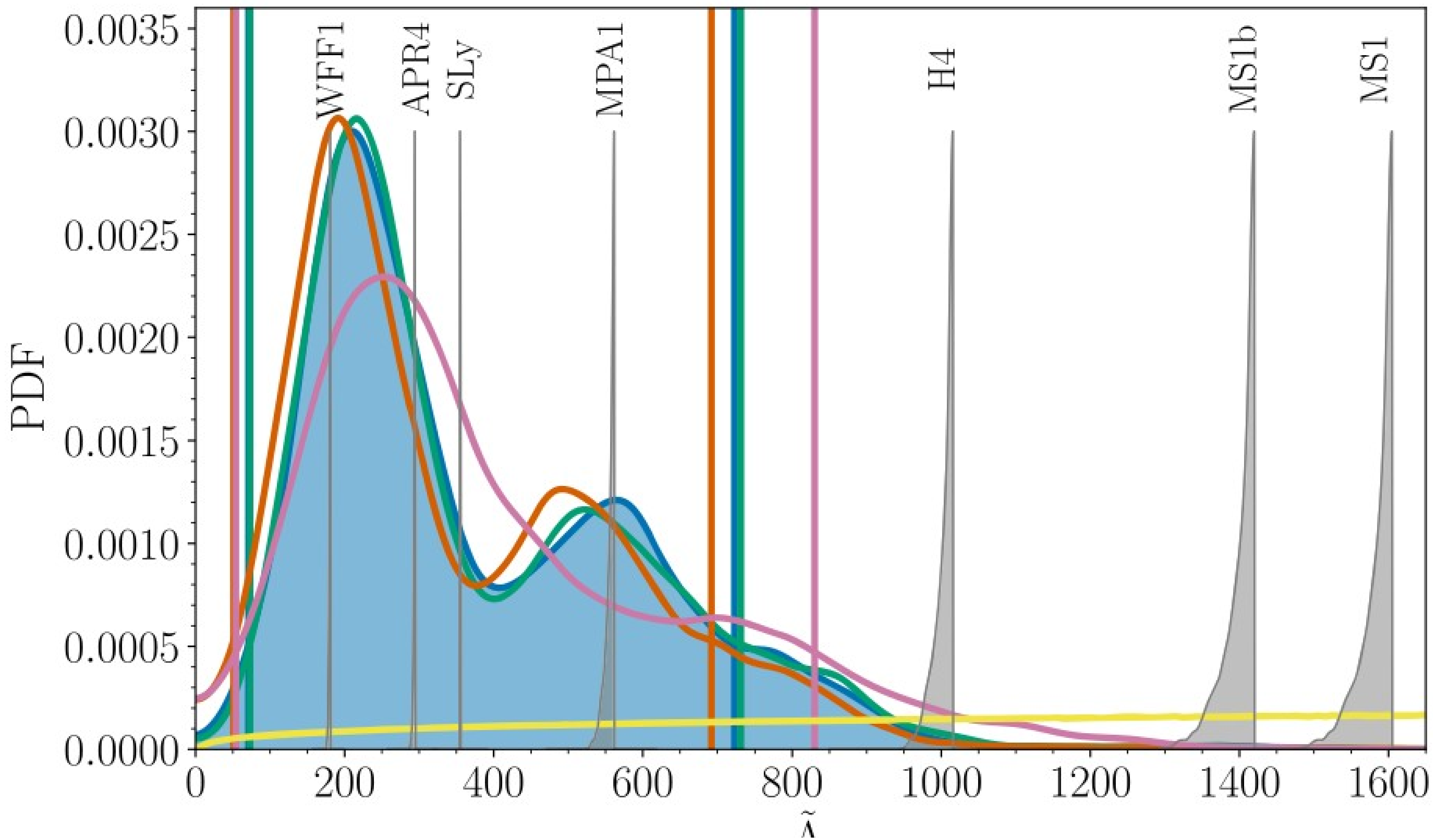
Tidal deformability - first look upper limits



Tidal deformability - detailed analysis



Tidal deformability



$$\tilde{\Lambda} = \frac{16}{13} \frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}.$$

Tidal deformability summary

- Hi spin case – upper limits
- Lo spin case – constraints

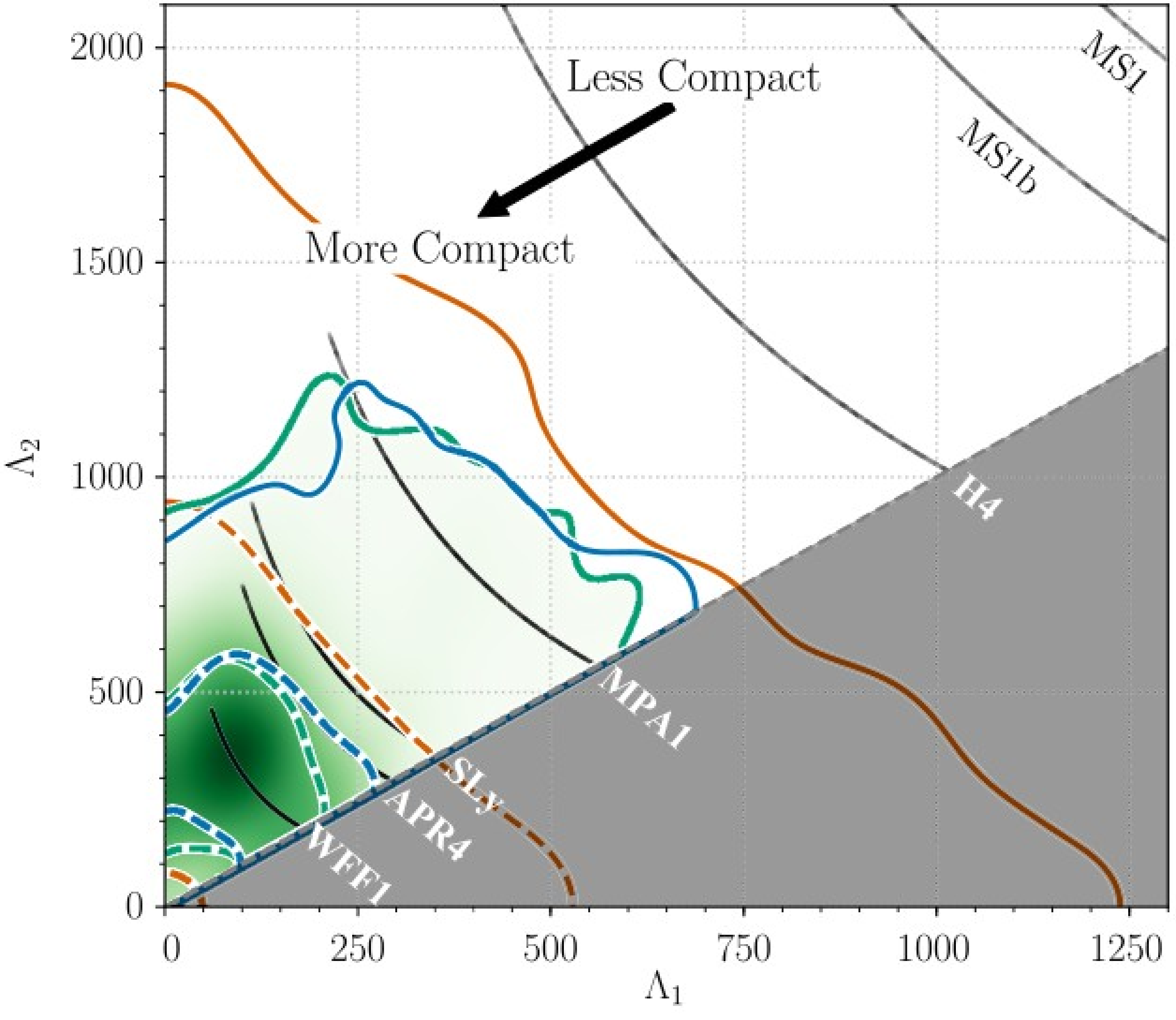
$$\Lambda = \begin{array}{ccc} 340^{+580}_{-240}/340^{+490}_{-290} & 280^{+490}_{-190}/280^{+410}_{-230} & 300^{+520}_{-190}/300^{+430}_{-230} \\ 280^{+430}_{-220}/280^{+280}_{-280} & 340^{+520}_{-260}/340^{+350}_{-330} & 310^{+510}_{-240}/310^{+380}_{-290} \end{array}$$

- Favors low values – compact NS

NS radii and EOS

- Assume common EOS for two NS
- Parametrize EOS as polynomial
- Stitch to Sly Eos for low densities
- Impose causality
- Must support 1.97Msun NS, or the highest mass in fit

Constrain tidal defomability again

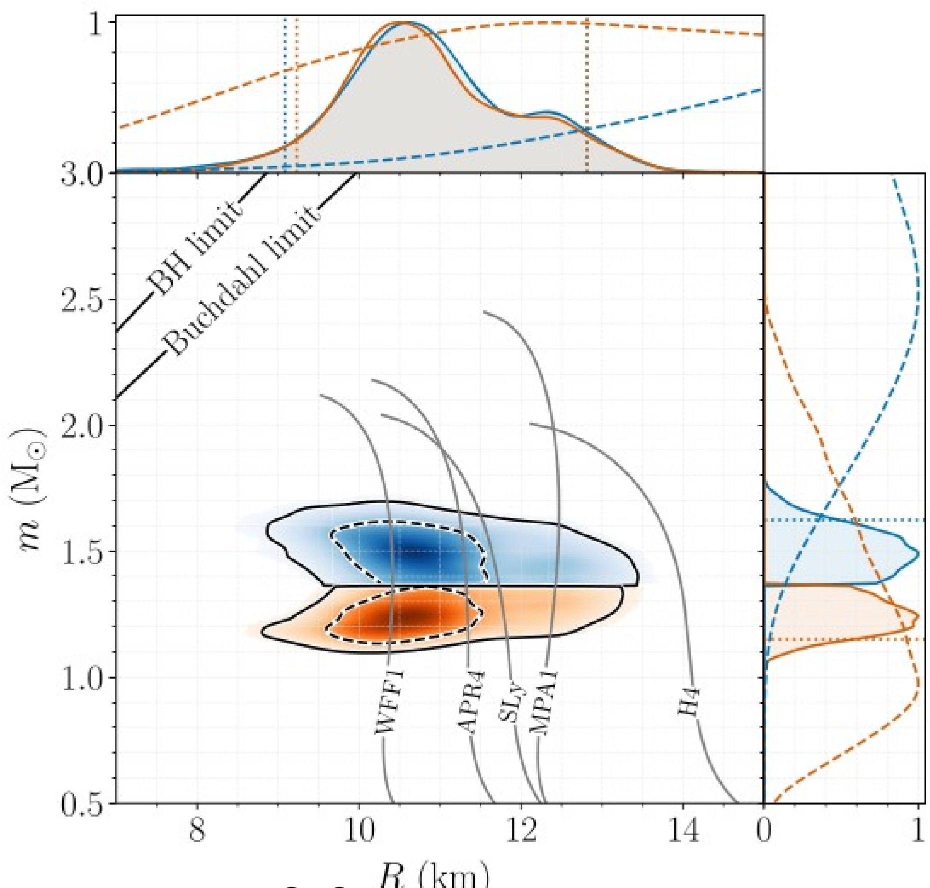


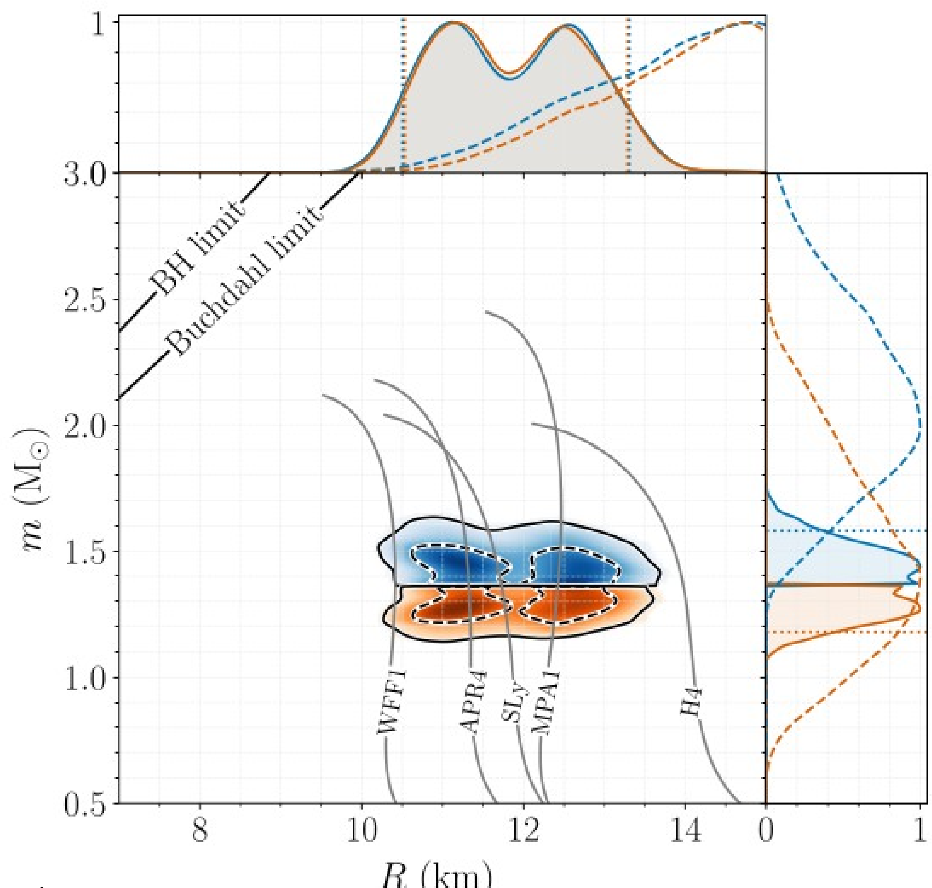
Then use the Lambda-Compactness relation to constrain the radii.

Mass radius plot

EOS insensitive

Parameterized EOS

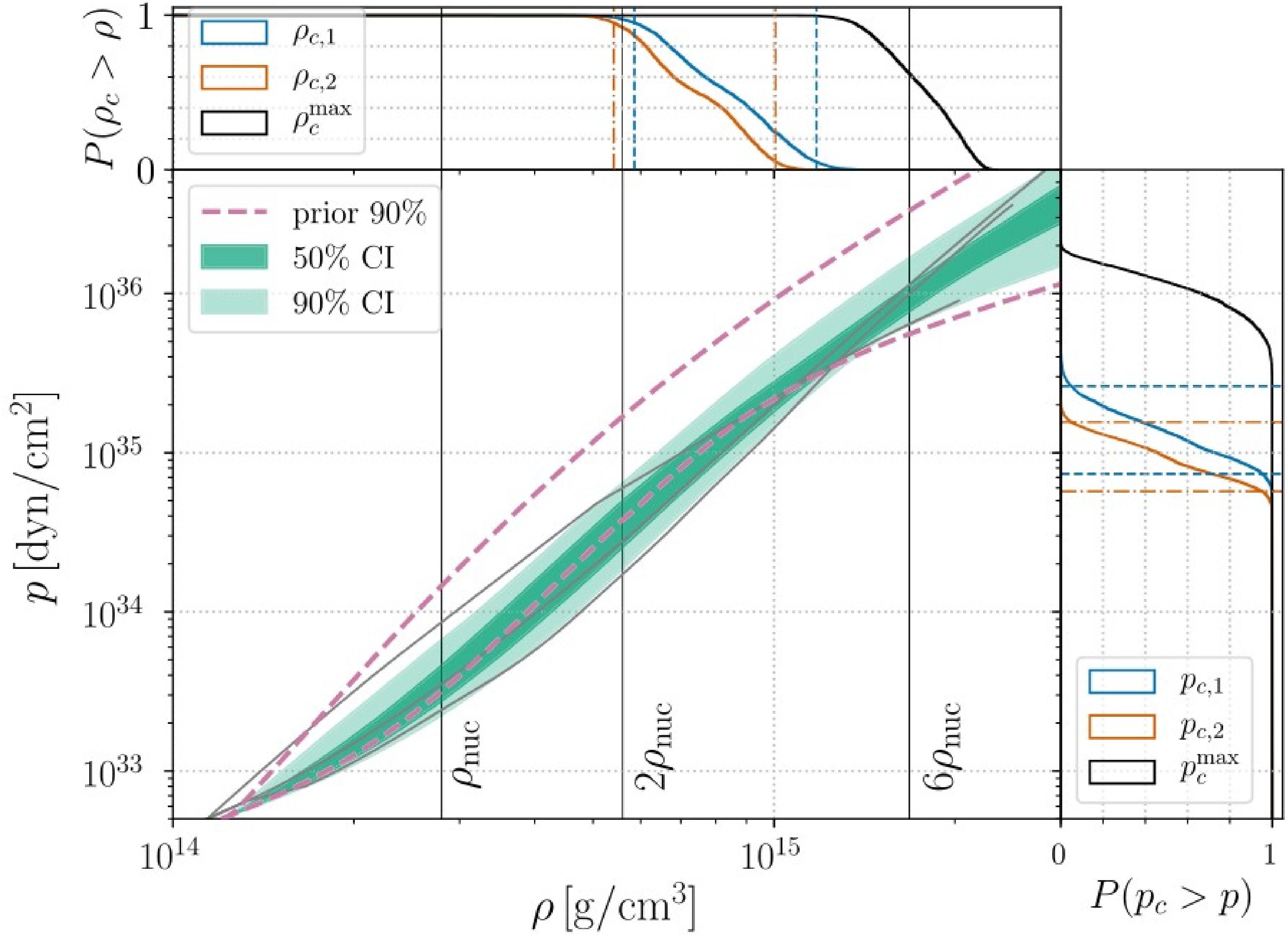




$$R_1 = 10.8^{+2.0}_{-1.7}\text{km}, \quad R_2 = 10.7^{+2.1}_{-1.5}\text{km}$$

$$R_1 = 11.9^{+1.4}_{-1.4}\text{km}, \quad R_2 = 11.9^{+1.4}_{-1.4}\text{km}$$

Constraints on EOS

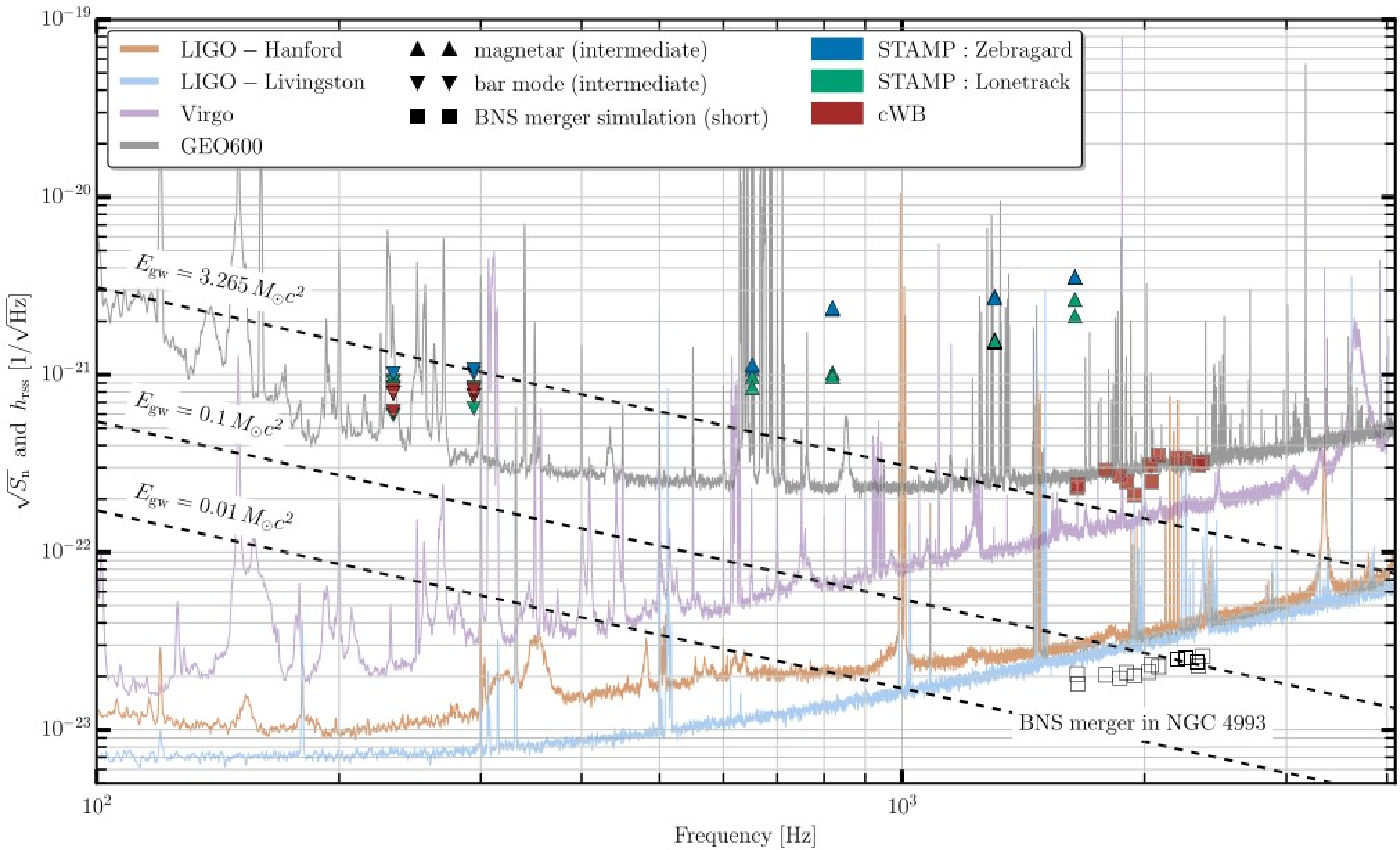


Summary of NS -EOS properties

- NS are rather small at 1.3-1.5 Msun
- Tidal defomability is on the lower end of scale
- Yet must sustain maximal mass up to 2.14 Msun
- One can start measuring the EOS!

Post-merger and remnant search

Short duration search



Short duration search

Table 1
Sensitivity of the cWB Pipeline to Waveforms Generated by Binary NS Simulations

Equation of State	m_1 ($M_\odot$)	m_2 ($M_\odot$)	$\bar{f}$ (Hz)	Simulation	$h_{\rm rss}$ (expected) ($10^{-22}/\sqrt{\rm Hz}$)	$h_{\rm rss}^{50\%}$ ($10^{-22}/\sqrt{\rm Hz}$)
H4 (Glendenning & Moszkowski 1991)	1.25	1.25	1946	Takami et al. (2015)	0.21	2.1
H4 (Glendenning & Moszkowski 1991)	1.3	1.3	2083	Takami et al. (2015)	0.23	3.5
H4 (Glendenning & Moszkowski 1991)	1.35	1.35	2247	Ciolfi et al. (2017)	0.26	3.4
H4 (Glendenning & Moszkowski 1991)	1.42	1.29	2192	Ciolfi et al. (2017)	0.26	3.4
H4 (Glendenning & Moszkowski 1991)	1.54	1.26	2030	Kawamura et al. (2016)	0.22	3.1
LS220 (Lattimer & Swesty 1991)	1.20	1.50	1900	Bauswein et al. (2013a)	0.22	2.5
SHT (Shen et al. 2010)	1.40	1.40	1788	Kastaun et al. (2017)	0.21	2.9
SFHx (Steiner et al. 2013)	1.2	1.5	1650	Bauswein et al. (2013a)	0.21	2.3
SFHx (Steiner et al. 2013)	1.35	1.35	2040	Bauswein et al. (2013a)	0.24	2.5
SLy (Douchin & Haensel 2001)	1.25	1.25	2333	Takami et al. (2015)	0.23	3.2
SLy (Douchin & Haensel 2001)	1.3	1.3	2325	Takami et al. (2015)	0.25	3.1
SLy (Douchin & Haensel 2001)	1.35	1.25	2363	Takami et al. (2015)	0.27	3.2
TMA (Toki et al. 1995)	1.20	1.50	1864	Bauswein et al. (2013a)	0.19	3.2
TMA (Toki et al. 1995)	1.35	1.35	1653	Bauswein et al. (2013a)	0.20	2.4

Note. Waveforms were selected to represent a variety of equations of state (first column) and progenitor mass configurations (second and third columns). The fourth column is the mean frequency for each waveform $\bar{f}$, and the fifth column is the reference for the BNS simulation. The sixth column is the root-sum-squared strain $h_{\rm rss}$ predicted by that simulation for a post-merger signal from a BNS with a distance and inclination consistent with estimates from the inspiral analysis (Abbott et al. 2017a). The seventh column shows the $h_{\rm rss}$ required for 50% detection efficiency with a false-alarm probability of 10^{-4}, $h_{\rm rss}^{50\%}$.

Long duration search

Table 5
FreqHough Search Sensitivities Estimated from Simulated Signals (Injections) Following the Power-law Spin-down Model with Braking Index $n = 5$

T_{SFT} (s)	f_{start} (Hz)	τ (s)	ϵ	$d^{90\%}$ (Mpc)	$E_{gw}^{90\%}$ ($M_{\odot}c^2$)
2	390	4.15×10^2	5.91×10^{-2}	$0.78^{+0.05}_{-0.04}$	$4.76^{+0.59}_{-0.50} \times 10^0$
2	440	4.65×10^2	4.39×10^{-2}	$0.83^{+0.06}_{-0.05}$	$5.42^{+0.75}_{-0.62} \times 10^0$
2	490	5.15×10^2	3.36×10^{-2}	$0.79^{+0.06}_{-0.05}$	$7.39^{+1.08}_{-0.89} \times 10^0$
2	540	5.65×10^2	2.64×10^{-2}	$0.72^{+0.05}_{-0.04}$	$1.06^{+0.15}_{-0.12} \times 10^1$
2	590	6.15×10^2	2.12×10^{-2}	$0.75^{+0.06}_{-0.05}$	$1.19^{+0.20}_{-0.16} \times 10^1$
…	…	…	…	…	…

Note. Each row corresponds to injections marginalized over a 50 Hz band in f_{start} (where $f_{start} = f_{gw}(t_{start} = t_c + \Delta t)$) and random $\cos \iota$; sensitivities are at 90% confidence.

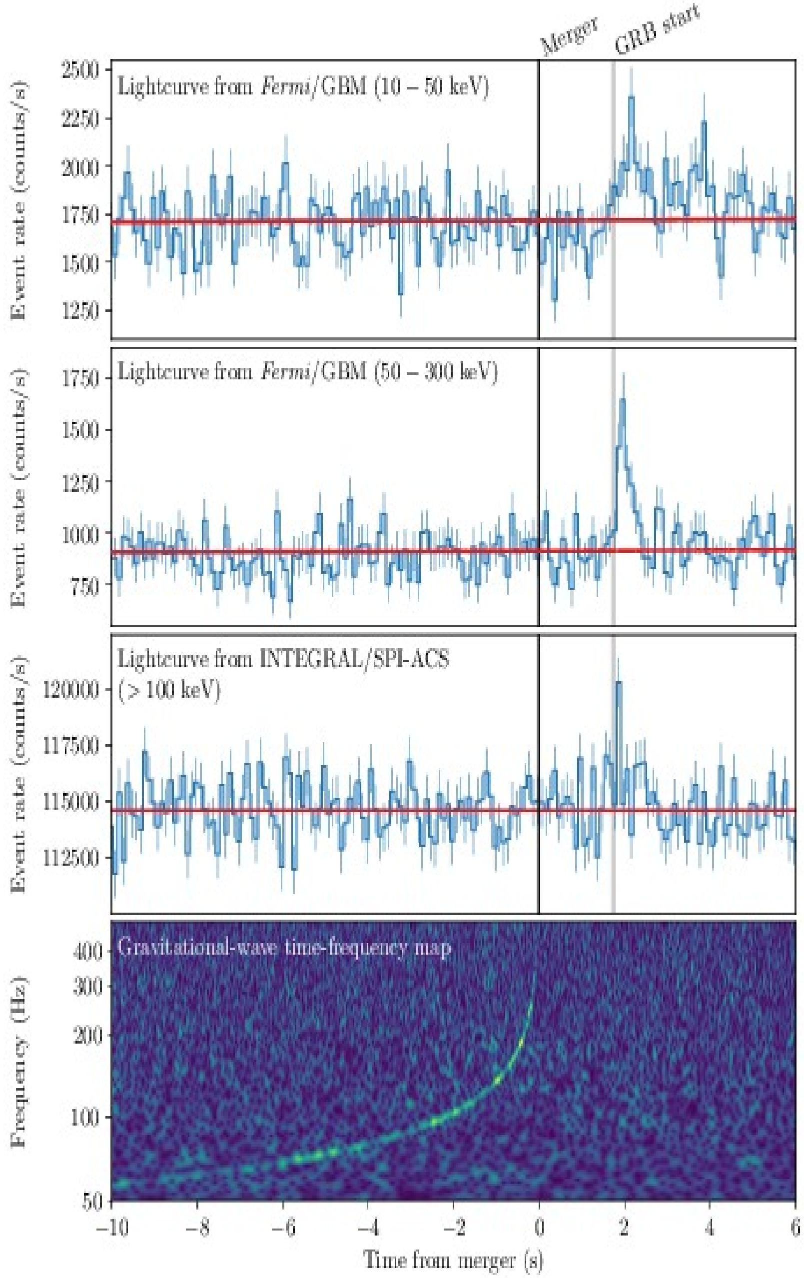
Post merger summary

- Search for short duration -yields no results
- Sensitivity – 10 times too low
- ET, Cosmic Explorer will be sesitive enough

Fundamental physics

- Speed of gravity
- Dispersion relation
- Dimension of space
- GR validity
  - Motion of two bodies, PN corrections
  - GW polarizations

Speed of gravity



Time delay - 1.7 s, let us assume it is less than 10s

Distance 40 Mpc = 4.10 x 10^{15} light s, let us assume a lower limit of 26Mpc

Relative difference of speed

$$-3 \times 10^{-15} < \frac{\delta c_g}{c} < 7 \times 10^{-15}$$

Dispersion relation

- Does speed of GW depend on frequency?

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

$$m_g < 9.51 \times 10^{-22}\mathrm{eV}$$

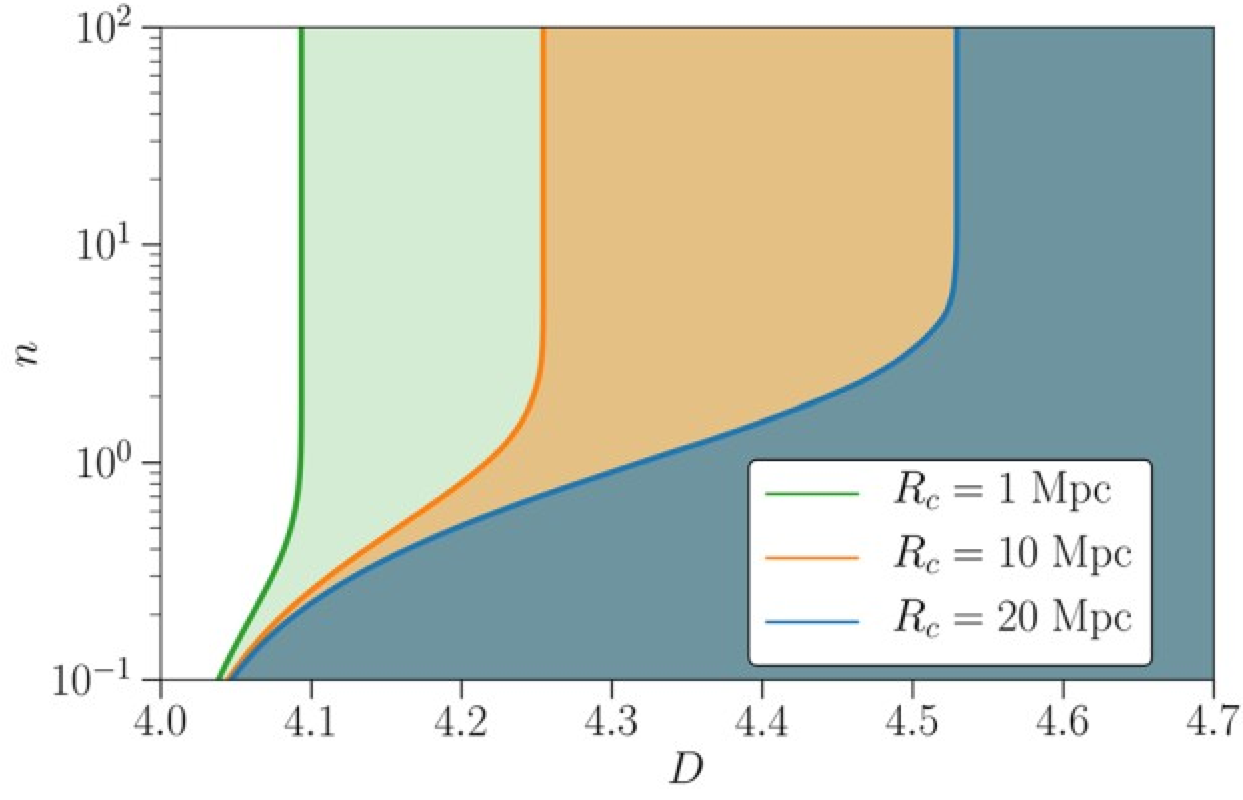
- Limits less stringent than for BBH sources.

Space dimensions

- Leakage of GW energy to other dimesions

$$h \propto \frac{1}{d_L^{GW}} = \frac{1}{d_L^{GW}} \left[1 + \left(\frac{d_L^{EM}}{R_c} \right)^n \right]^{-(D-4)/2n}$$

- Difference in estimate of the luminosity distance



GR validity

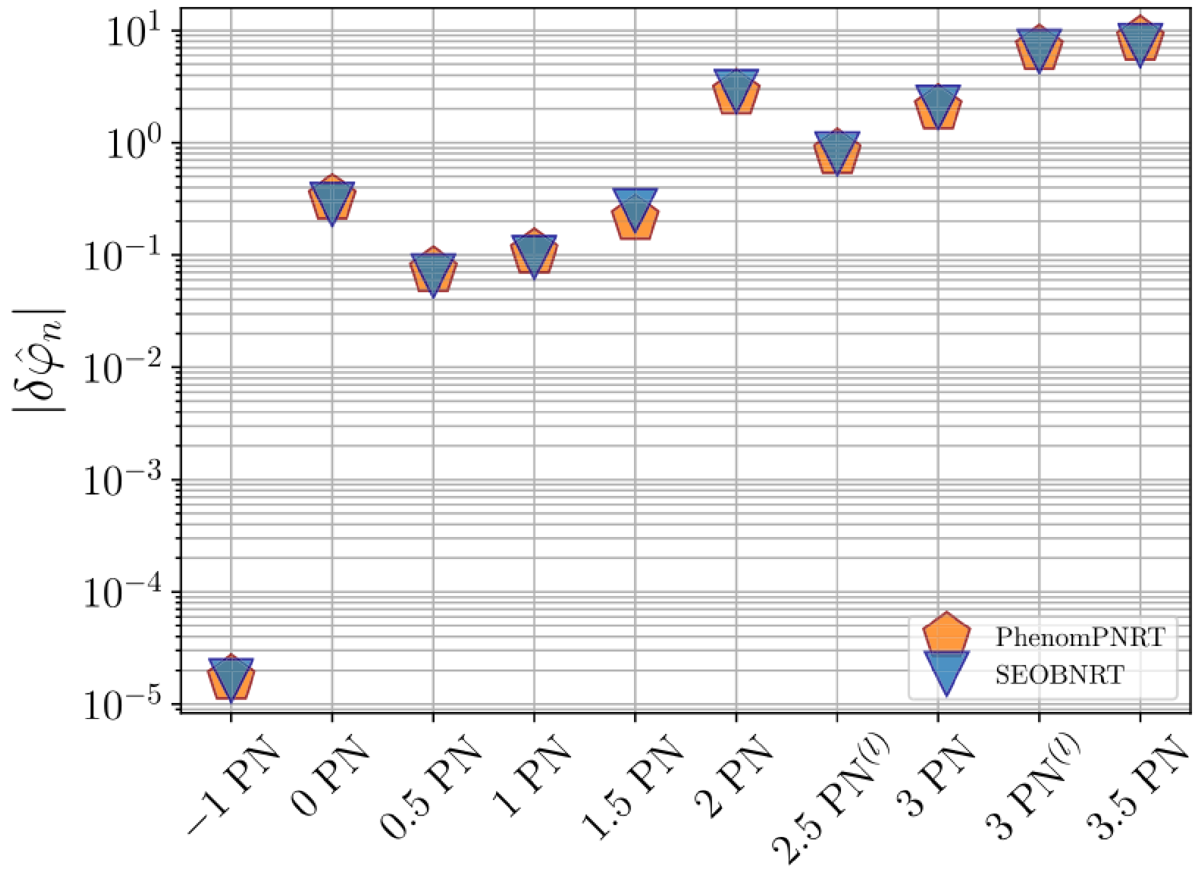


FIG. 2. 90% upper bounds on deviations $|\delta\hat{\varphi}_n|$ in the PN coefficients following from the posterior density functions shown in Fig. 1.

GW polarizations

- GR predicts only two polarizations
- Search for other modes
- Very strong Bayesian preference for tensor modes → GR is valid.

Summary of fundamental physics

- GR works
- Very stringent constraints on deviations from GR
- Future observations may improve these by a factor of ten

Astrophysics

- Rates
- Progenitors
- GRB science
- Heavy elements production
- Cosmology

The merger rate densities

- BBH estimate $R = 9.7 - 101\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- BNS estimate $R = 110 - 3840\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- The local supernova rate ~ $10^5\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- The BH formation rate is ~ $10^4\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- About 1 black hole in a 100-1000 ends up in a merging binary
- Similarily NS: 1 in 100-1000 is in a merging binary!

The rate implications

- Total GW luminosity density in the sky from NSNS mergers

$$\mathcal{L}_{GW} = 1500 \frac{0.025 M_\odot c^2}{3.1 \times 10^7 \mathrm{s}} \approx 2.5 \times 10^{48} \mathrm{erg s^{-1} Gpc^{-3}}$$

- The luminosity density of BHBH mergers is about 10 times larger

$$\mathcal{L}_{GW} = 50 \frac{2.0 M_\odot c^2}{3.1 \times 10^7 \mathrm{s}} \approx 10^{49} \mathrm{erg s^{-1} Gpc^{-3}}$$

- EM luminosity density of all galaxies:

$$\mathcal{L}_{EM} \approx 10^{50} \mathrm{erg\, s^{-1} Gpc^{-3}}$$

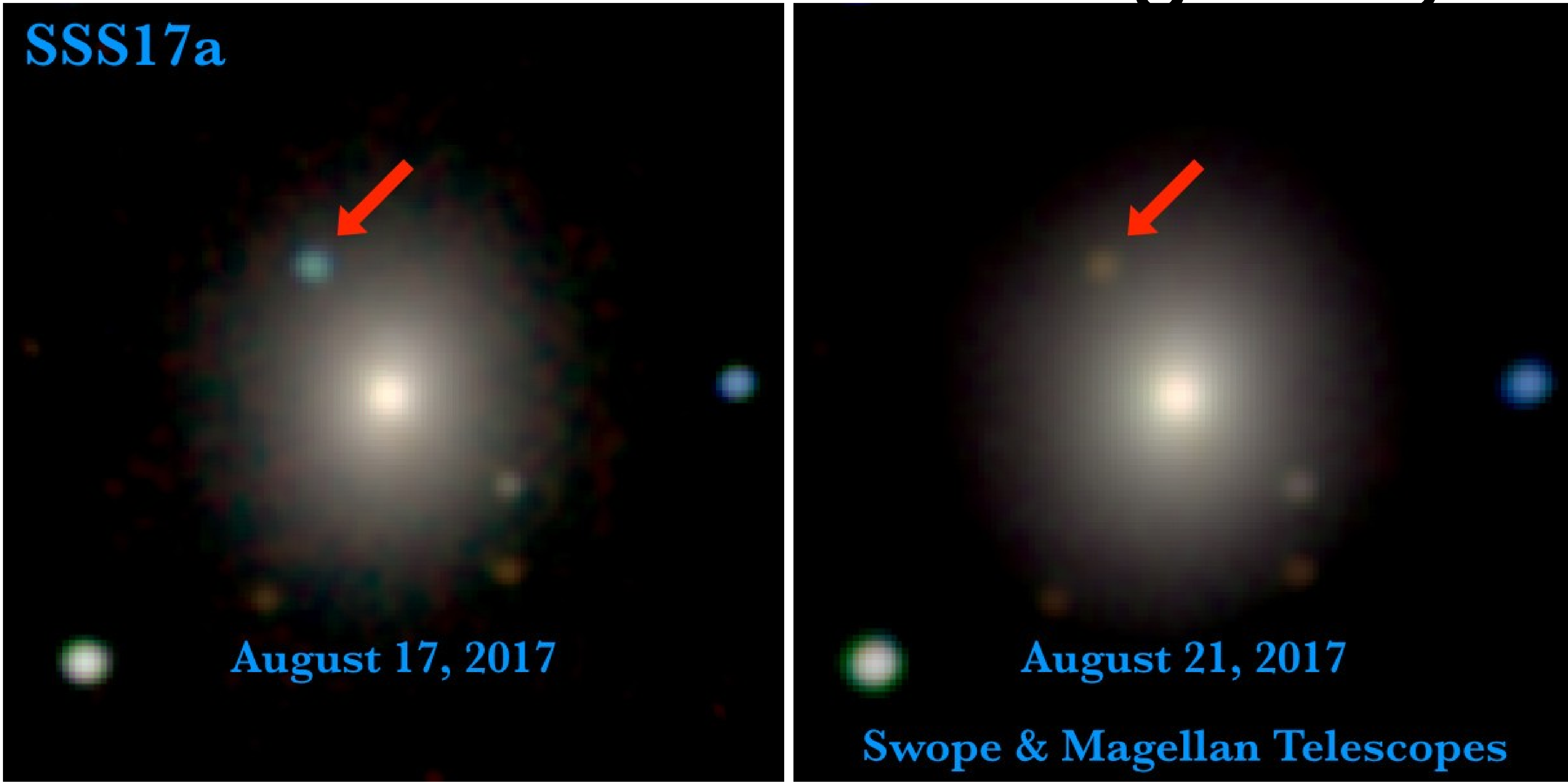
Basic rate arguments

- Formation scenario must be generic
- Exceptional environments must produce BBH and BNS with extremly high efficiency
- Globular clusters are not favoured, but can contribute
- I am sceptical about exotic models

What options do we have?

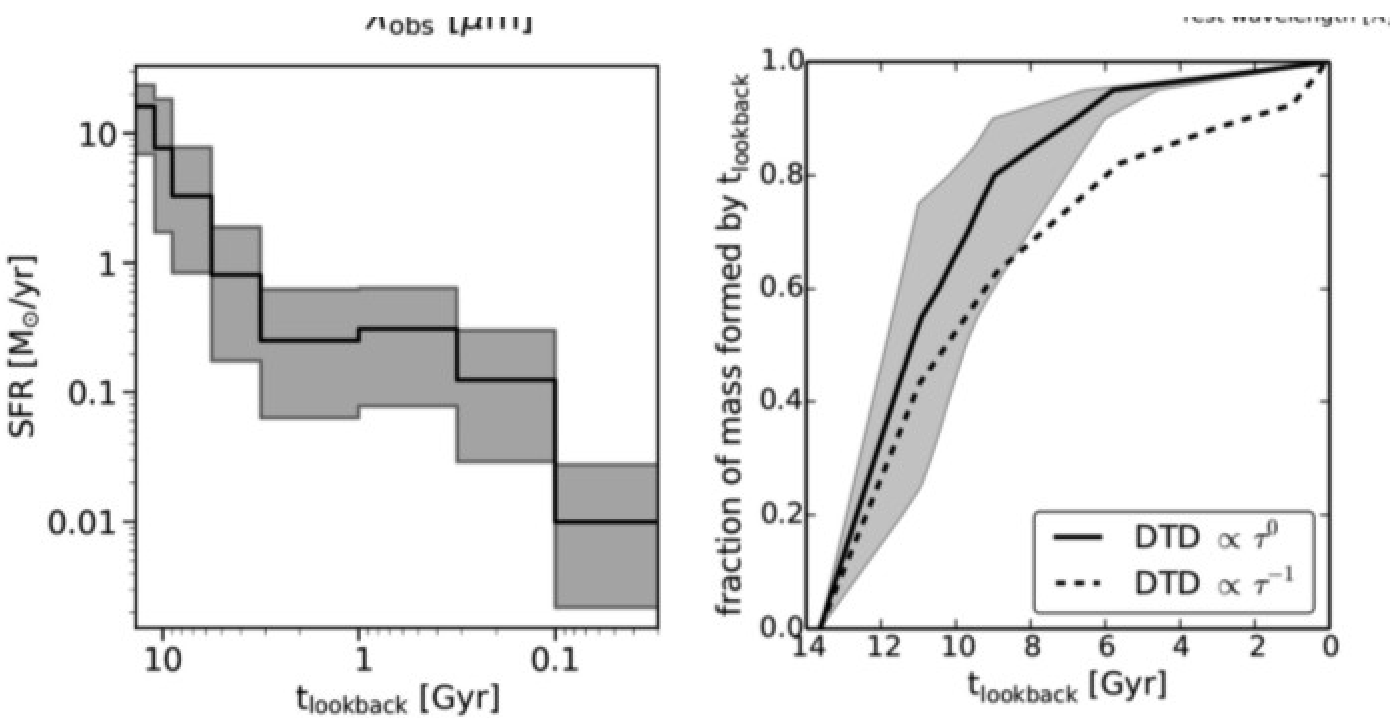
- Binary evolution
  - Standard
  - Chemically homogenous case
- Evolution in the clusters
- Exotica
  - Pop III stars
  - Exceptional environments.

BNS: all that + host galaxy



NGC 4993 – old elliptical with no traces of str formation for th last 1-2Gyrs,
merger on the ourskirts of the galaxy.

Star formation history estimate



Is there something missing about formation of such systems?

Blanchard 2017

GRB science

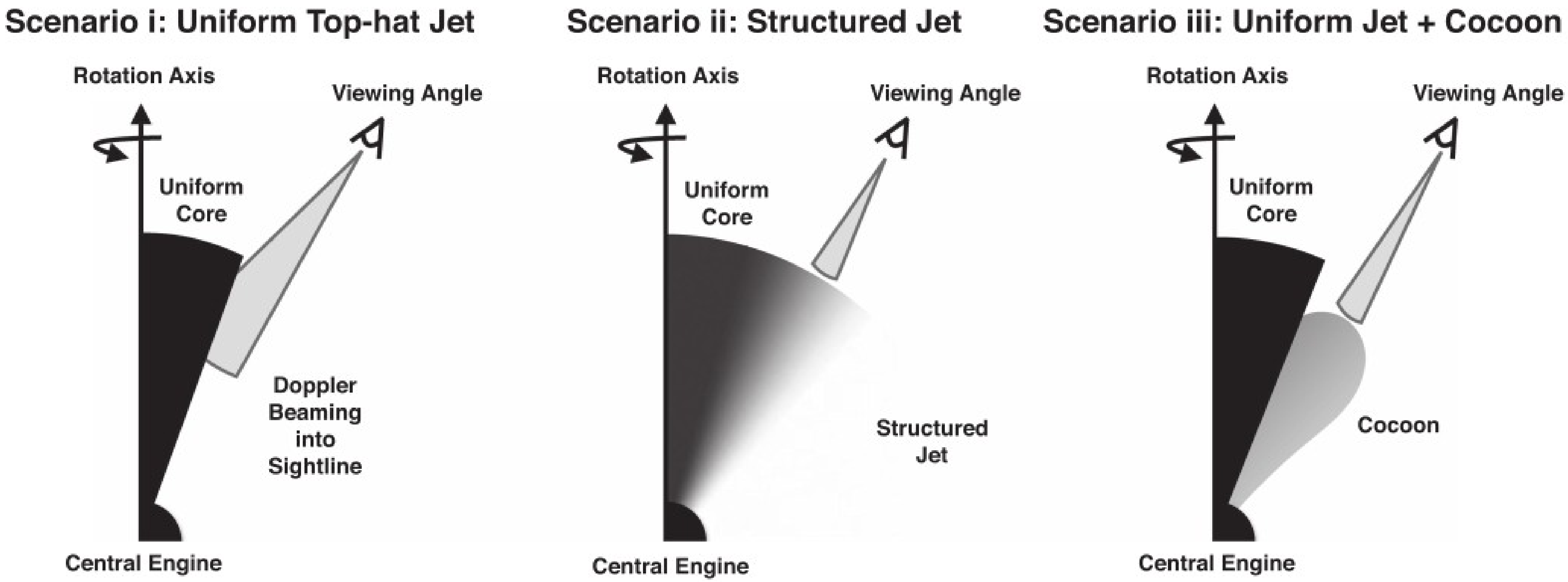
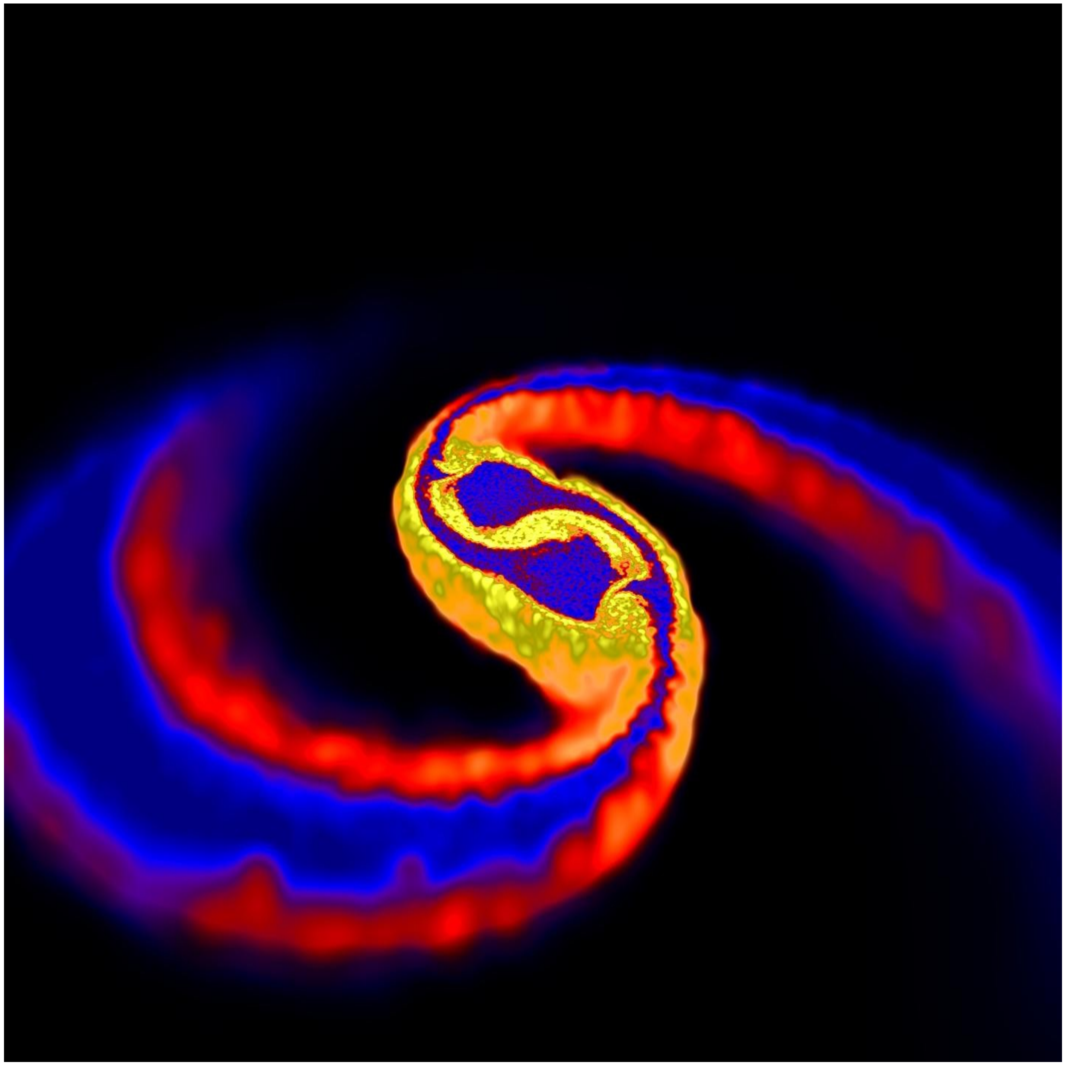


Figure 5. Three potential jet viewing geometries and jet profiles that could explain the observed properties of GRB 170817A, as described by scenarios (i)–(iii) in Section 6.2.

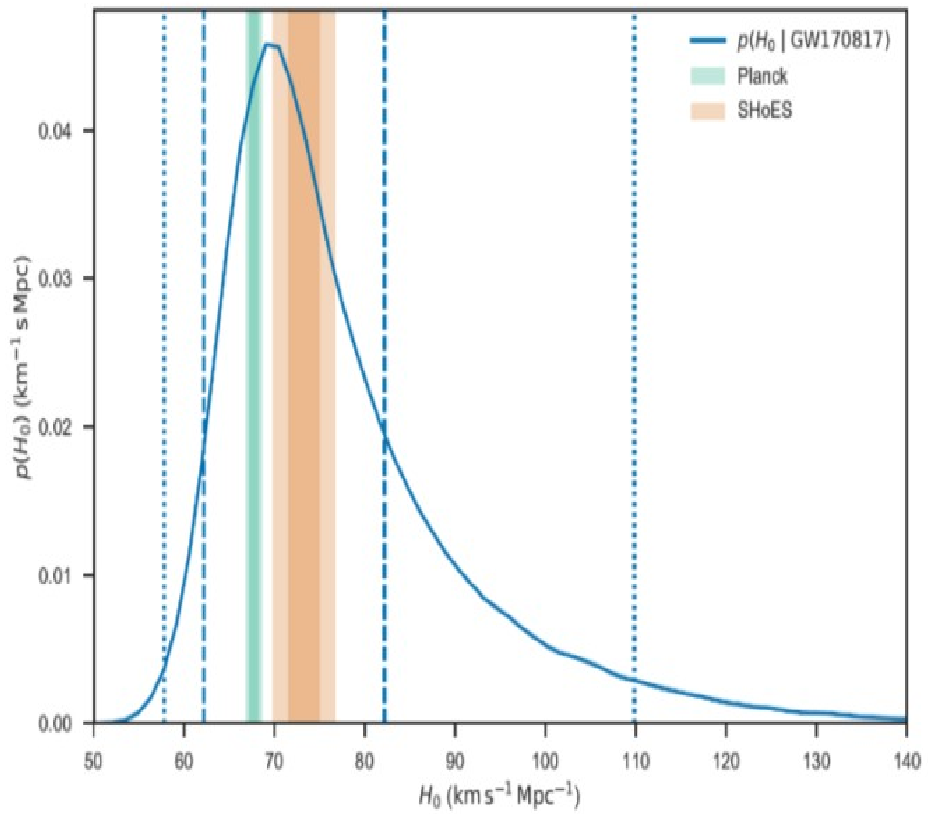
Heavy element production



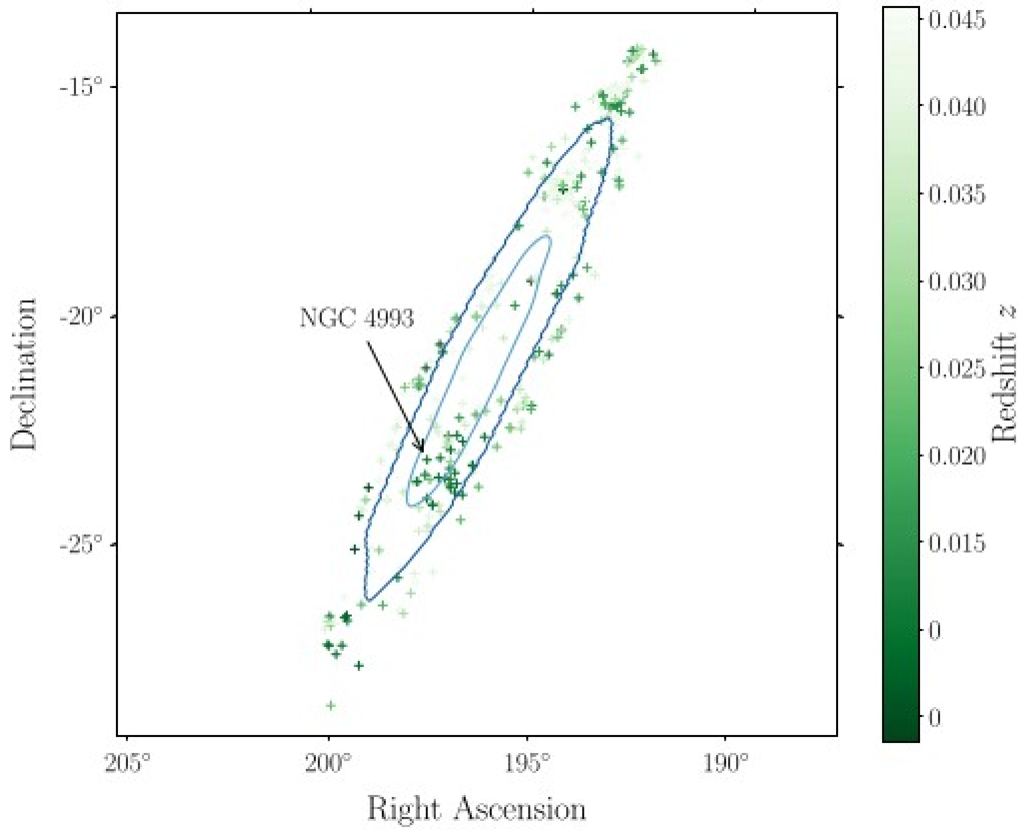
Cosmology

Binary as a standard siren:
Location and orientation needed
LHV: detection, location
From GW: distance
Optical detection: redshift
Together – Hubble constant !!!

$$H_0 = 70^{+12}_{-8} \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

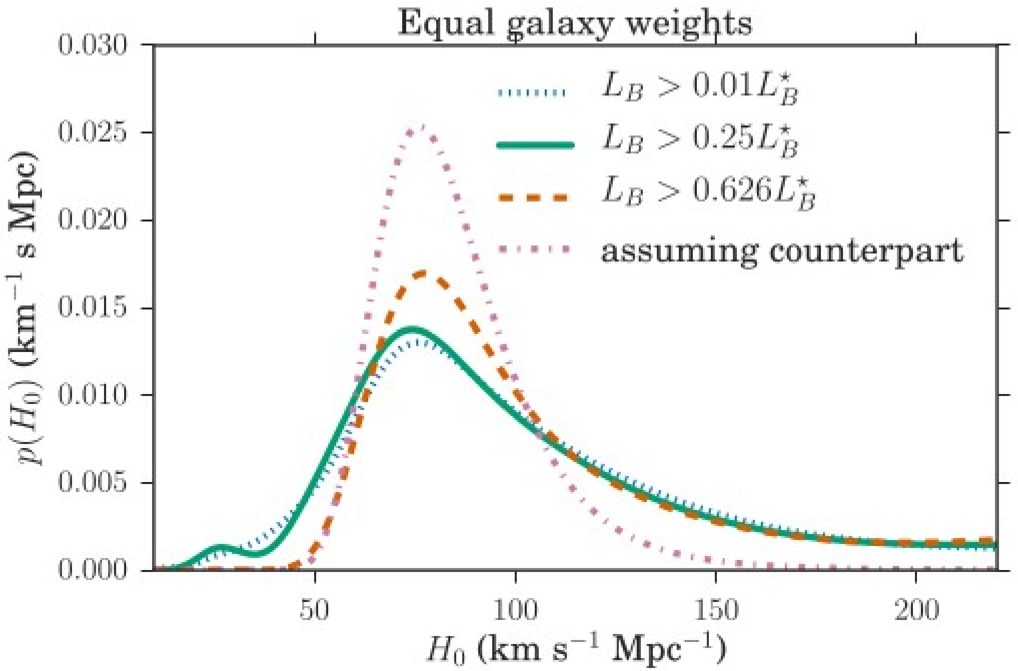


Hubble without EM

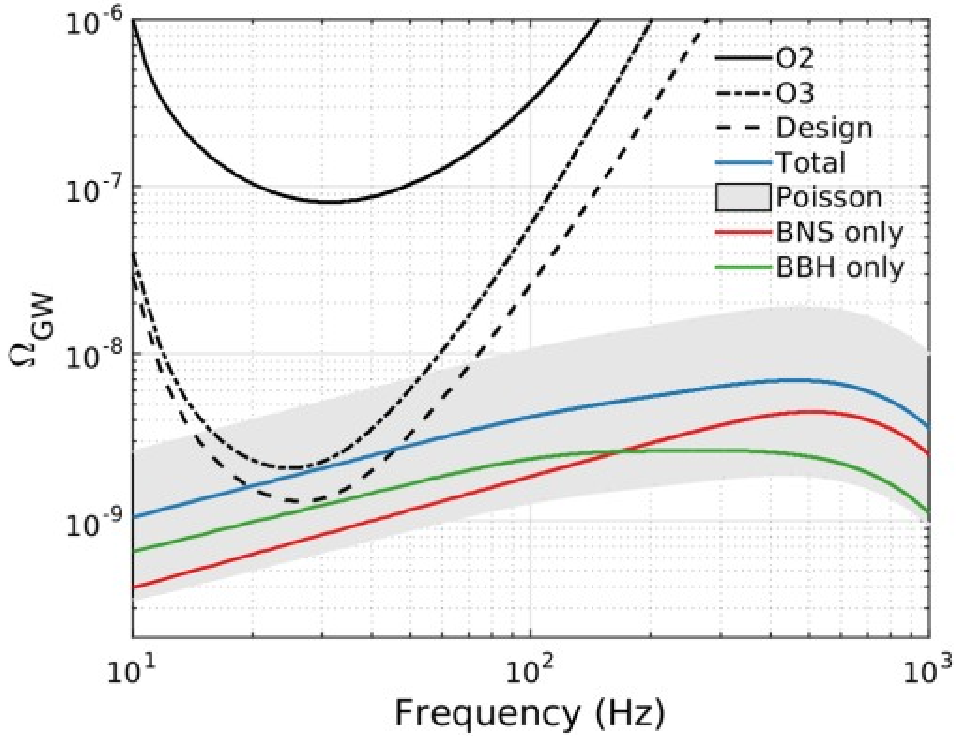


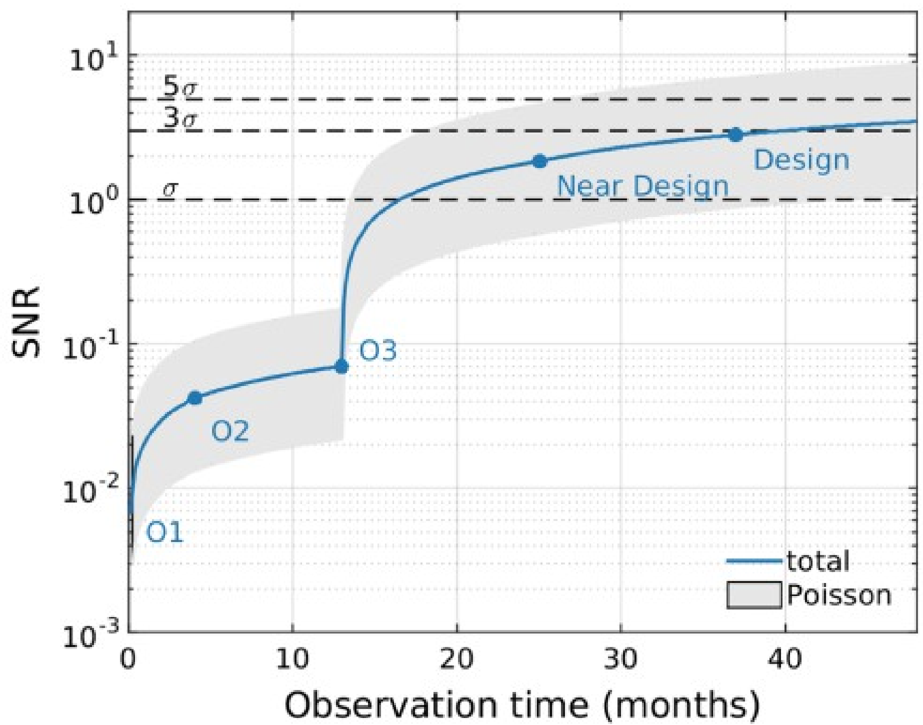
Great potential for future observations.

May solve the Hubble constant proble,



GW background





Astrophysics summary

- A number of astrophysical uses
- Origin – binary evolution but other options may work too
- Cosmology – need hudreds of sources
- High redshift mergers – through GW background
- Chemical evolution
- Connection with GRBs finally settled for good

When can we expect a next GW10817 event?

Assuming the rate is 500 Gpc^-1 yr^-1

We get one event per 4 years within 50 Mpc

And 2 events per year within 100 Mpc

Detectability depends on uptime. Assuming 3 detector time of 50% for O4 (two years) , we should see 2 events within 100Mpc, and ¼ of event within 50Mpc.

GW170817 was very unique!

Summary

- Neutron stars are small
- EOS is …..
- GW works
- GW binaries are great tools for astrophysics