Inferring the Nature of Postmerger Remnant in GW170817

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Outline

- Binary Neutron Stars Merger
- Postmerger Signals
- Searches of Postmerger
- How to Infer Prompt Collapse
- Conclusions

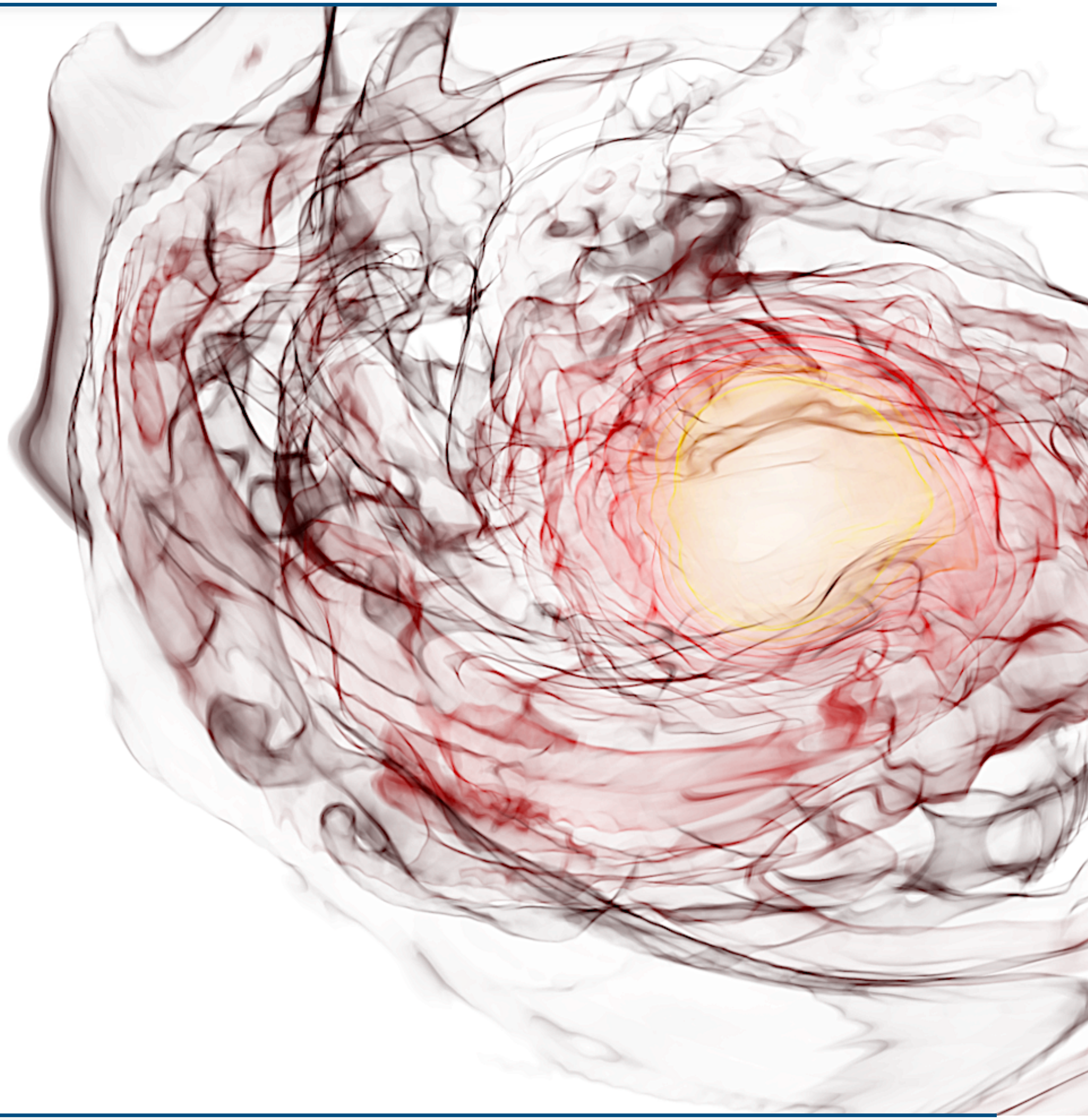
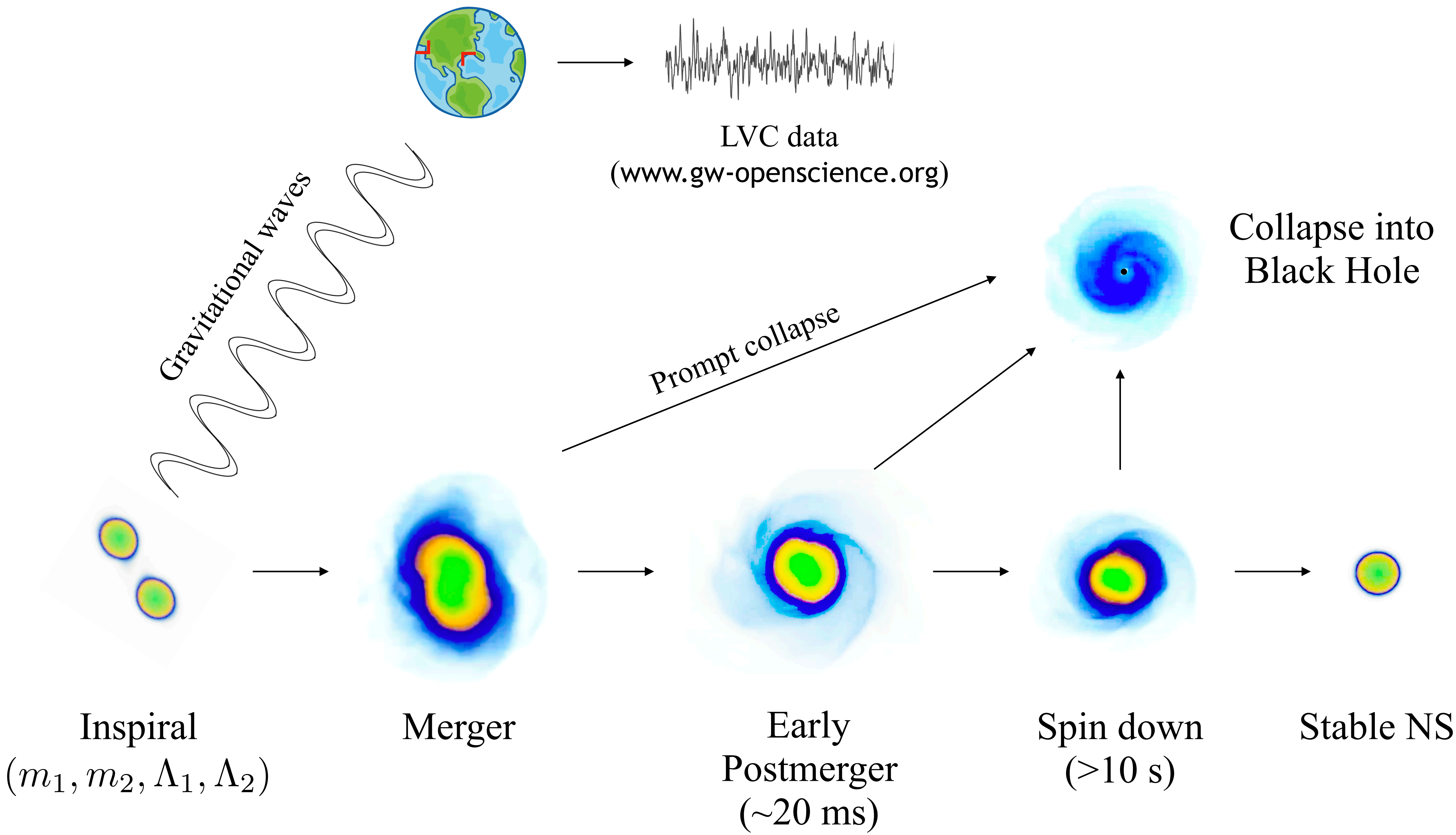


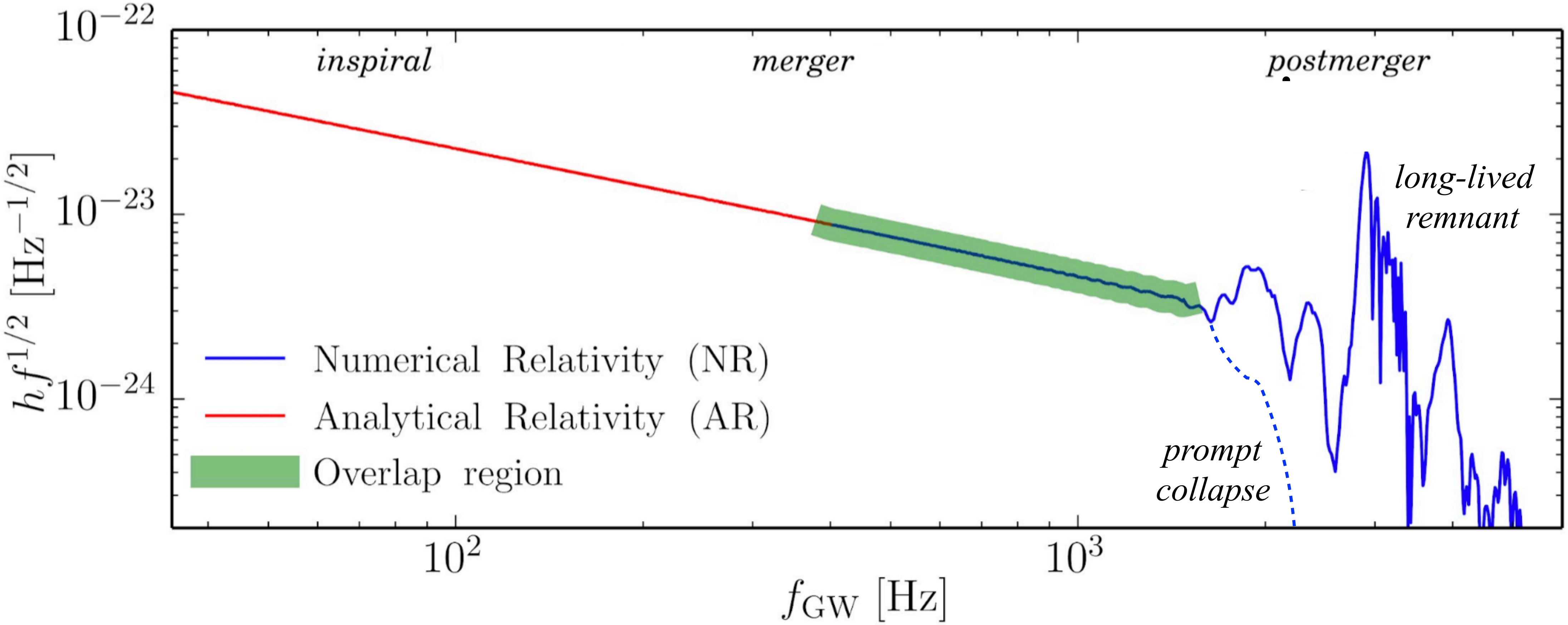
Image retrieved from www.computational-relativity.org

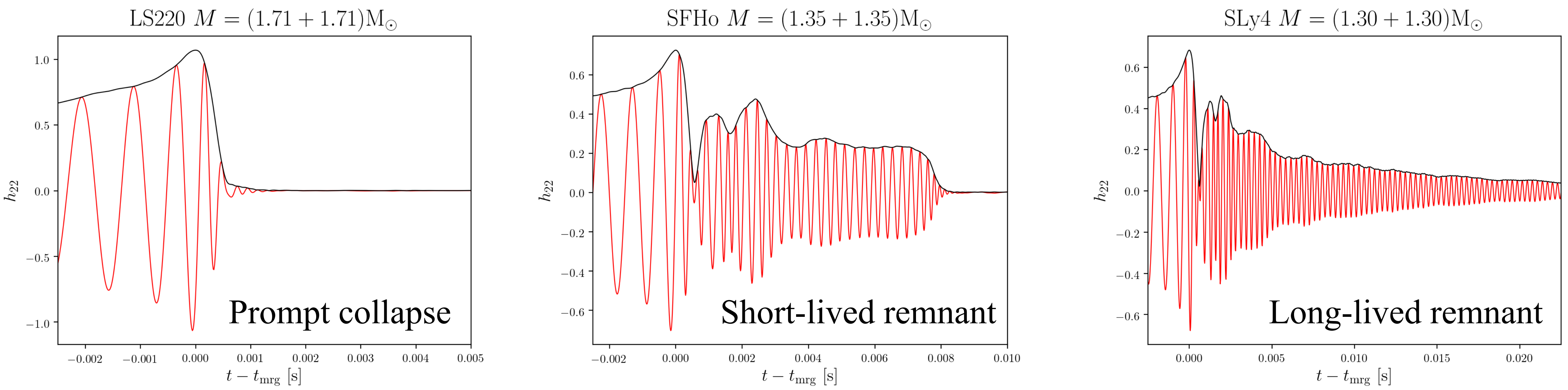
BNS Mergers



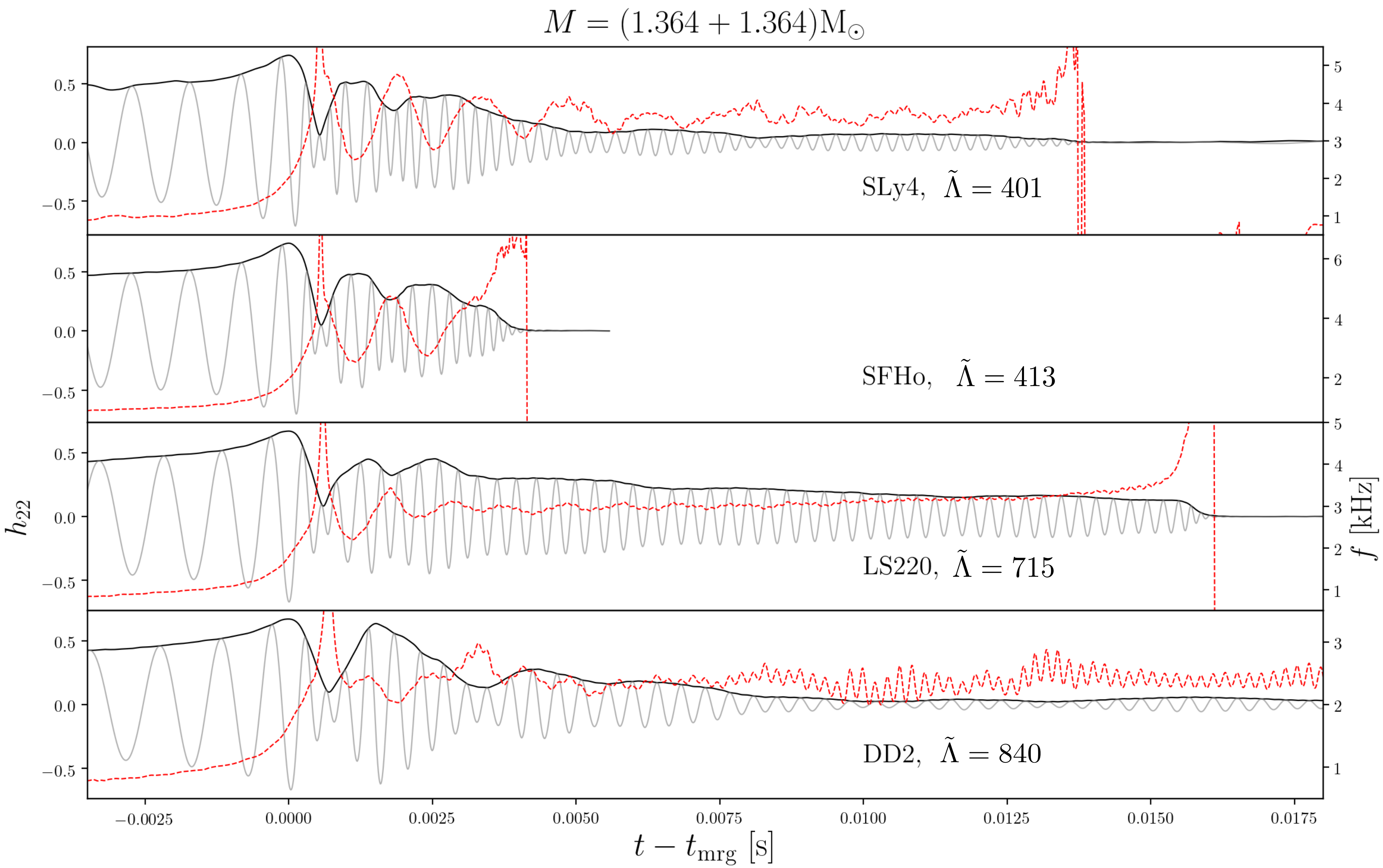
LVC data
(www.gw-openscience.org)
Gravitational waves
Prompt collapse
Collapse into
Black Hole
Inspiral
$(m_1, m_2, \Lambda_1, \Lambda_2)$
Merger
Early
Postmerger
(~20 ms)
Spin down
(>10 s)
Stable NS

BNS Spectrum





Postmerger Properties



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

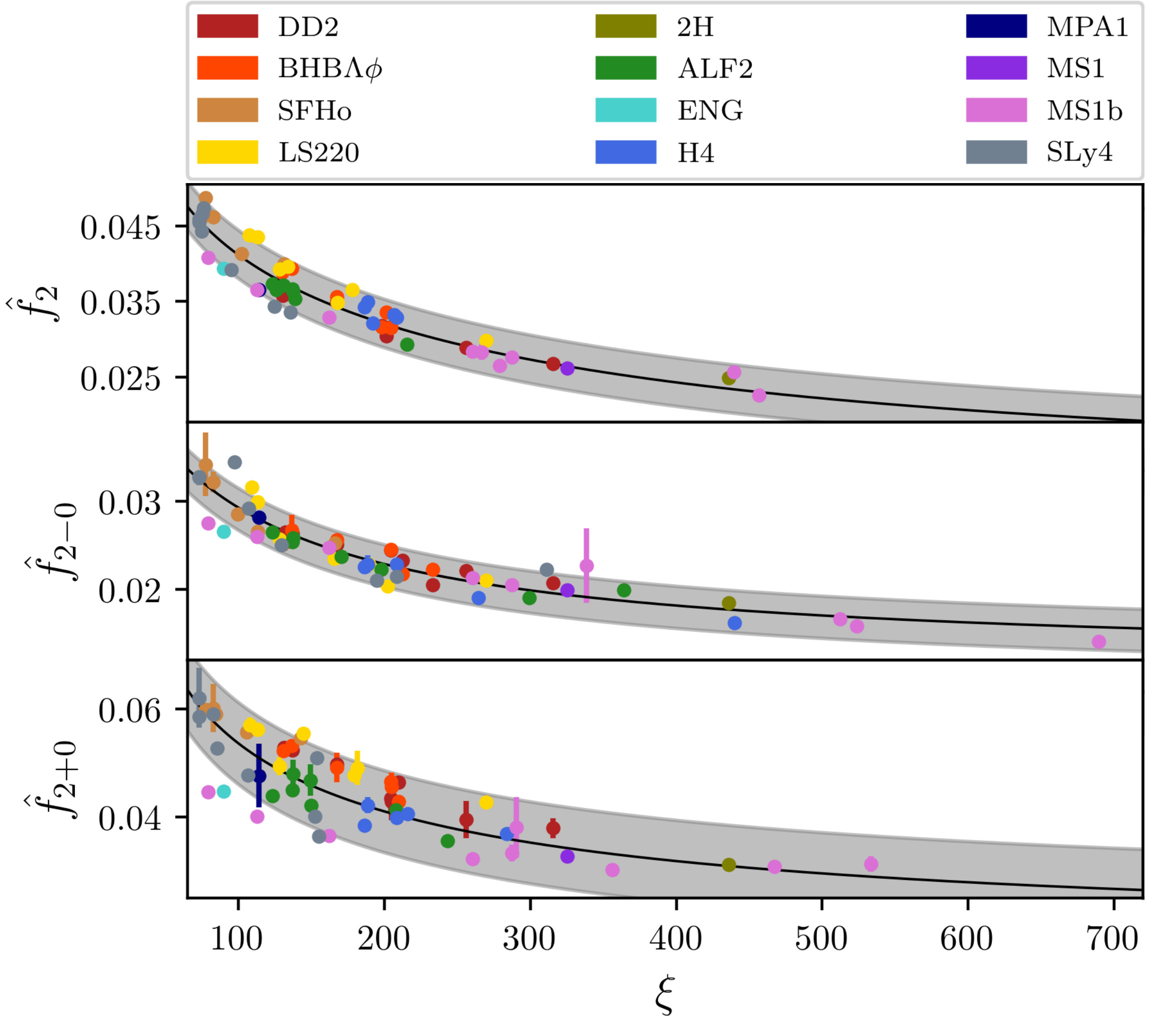
[2] S. Bernuzzi *et al.*, Phys. Rev. D94 (2016)

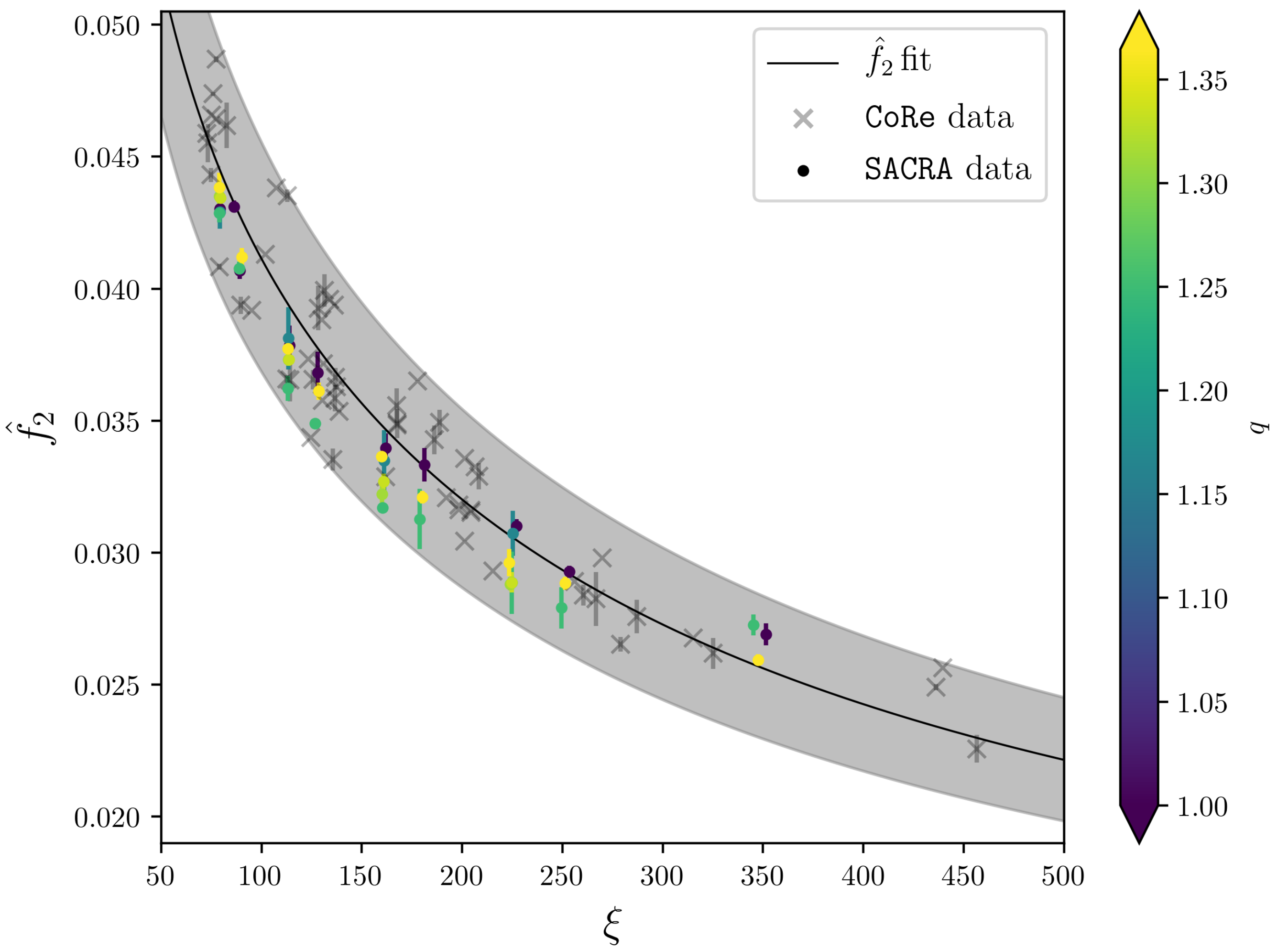
[3] F. Zappa *et al.*, Phys. Rev. Lett. 120 (2018)

Quasi-Universal Relations

- NR fits [4,5] are computed involving 172 simulations from `CoRe` database and 12 different EOS

$$\kappa_2^{\mathrm{T}} = \frac{3}{2}\left[\Lambda_1\left(\frac{m_1}{M}\right)^4\frac{m_2}{M} + (1 \leftrightarrow 2)\right], \qquad \nu = \frac{m_1 m_2}{M^2}, \qquad \xi = \kappa_2^{\mathrm{T}} + c\,(1-4\nu)$$





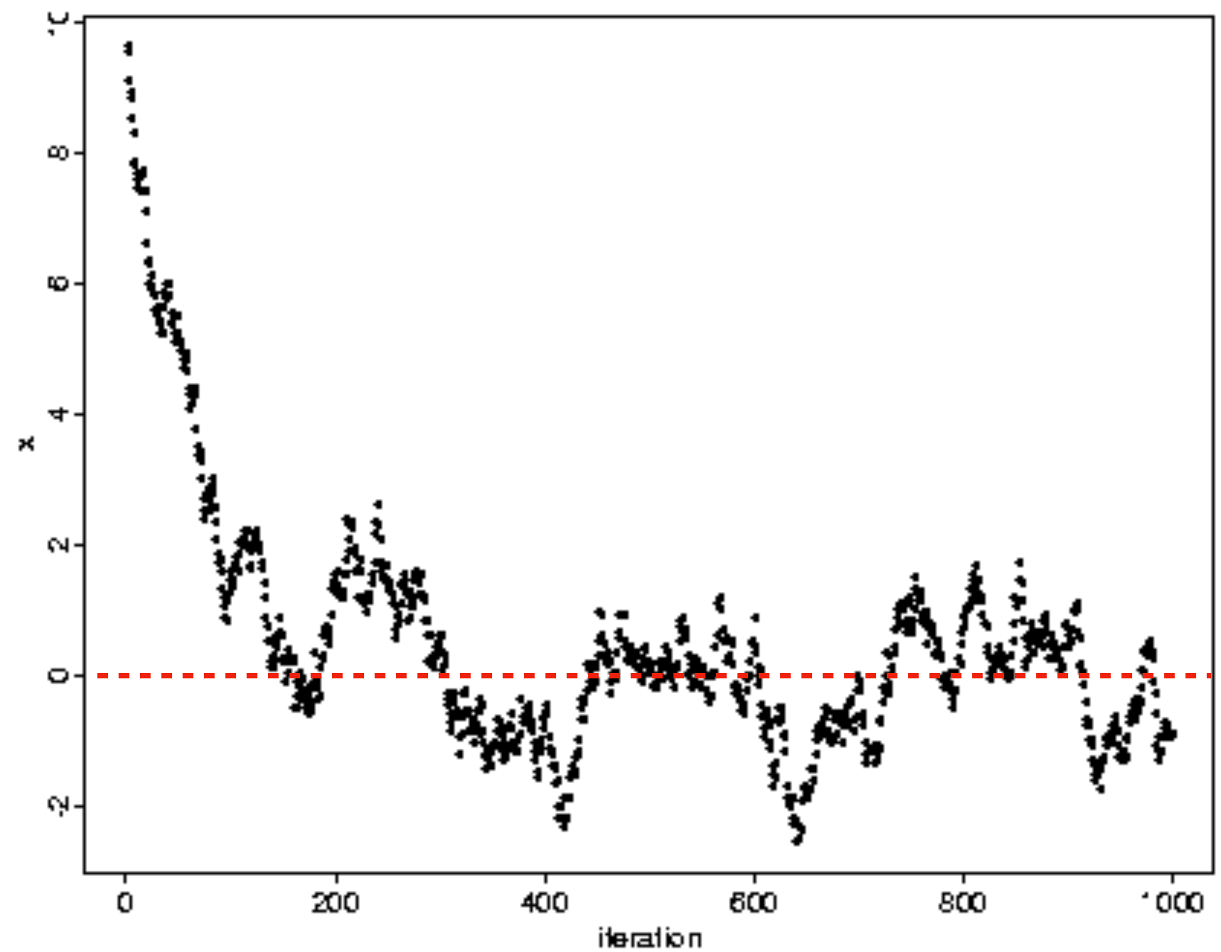
[4] S. Bernuzzi *et al.*, Phys. Rev. Lett. 115 (2015)
[5] M. Breschi *et al.*, arXiv:1908.11418 (2019)

Generally, inference is performed in the frequency domain using MCMC and/or nested sampling

- The algorithm explores the parameters space looking for the maximum likely region

$$\log \mathcal{L} \propto -\frac{1}{2}(s-h|s-h) \qquad (a|b) = 4\Re \int \frac{\tilde{a}^*(f)\,\tilde{b}(f)}{S_n(f)}\,\mathrm{d}f$$

- $s(t) \Rightarrow$ Observed strain(s)
- $h(t, \boldsymbol{\theta}) \Rightarrow$ GW model
- $S_n(f) \Rightarrow$ Sensitivity curve(s)



Other useful quantities:

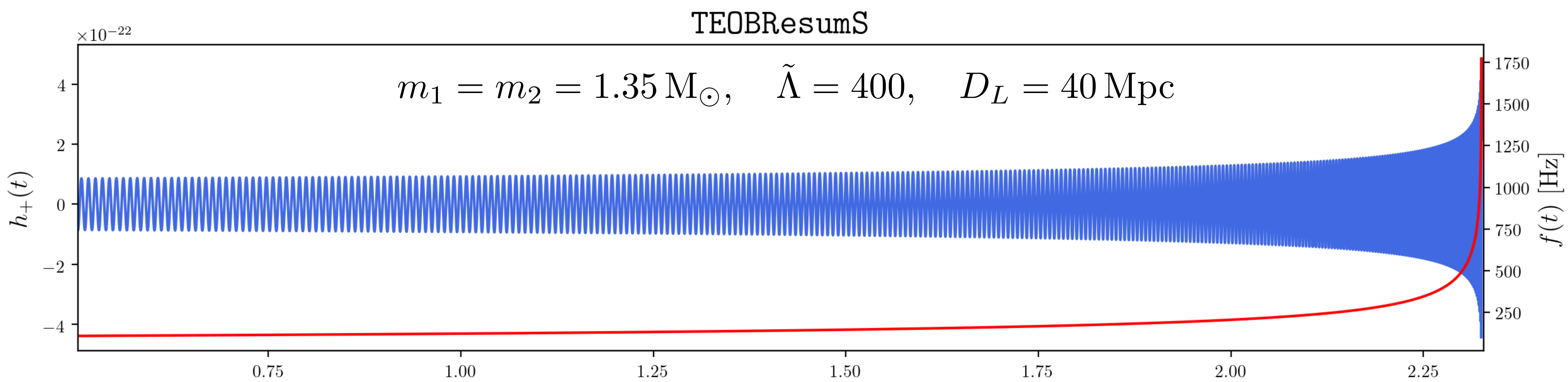
- $\mathrm{SNR} = \sqrt{(h|h)}$
- $\bar{F} = 1 - \max_{t_0,\phi_0} \frac{(h_1|h_2)}{\sqrt{(h_1|h_1)(h_2|h_2)}}$

GW Templates

For GW170817, we use Bayesian inference methods that rely on template GW waveforms

- Effective-One-Body (EOB) approach: `TEOBResumS` [6]
  - Post-adiabatic evolution
  - GE and GM contributions
  - Tidal deformation effects
  - Spin-orbit and self-spin contributions
  - Higher-order modes up to $\ell = 8$

Reliable and fast models are needed in order to conduct accurate estimations



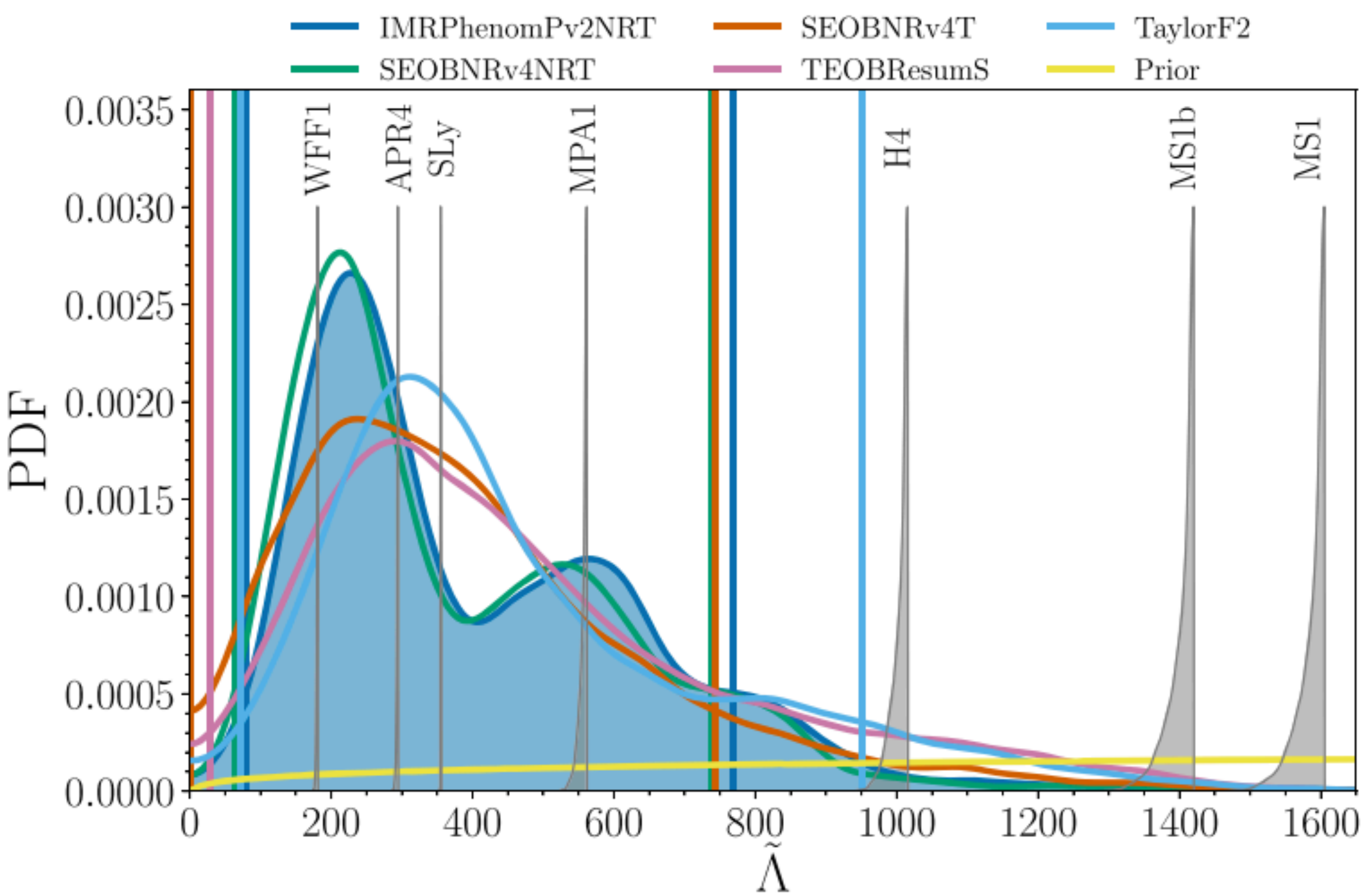
[6] A. Nagar *et al.*, Phys. Rev. D98 (2018)

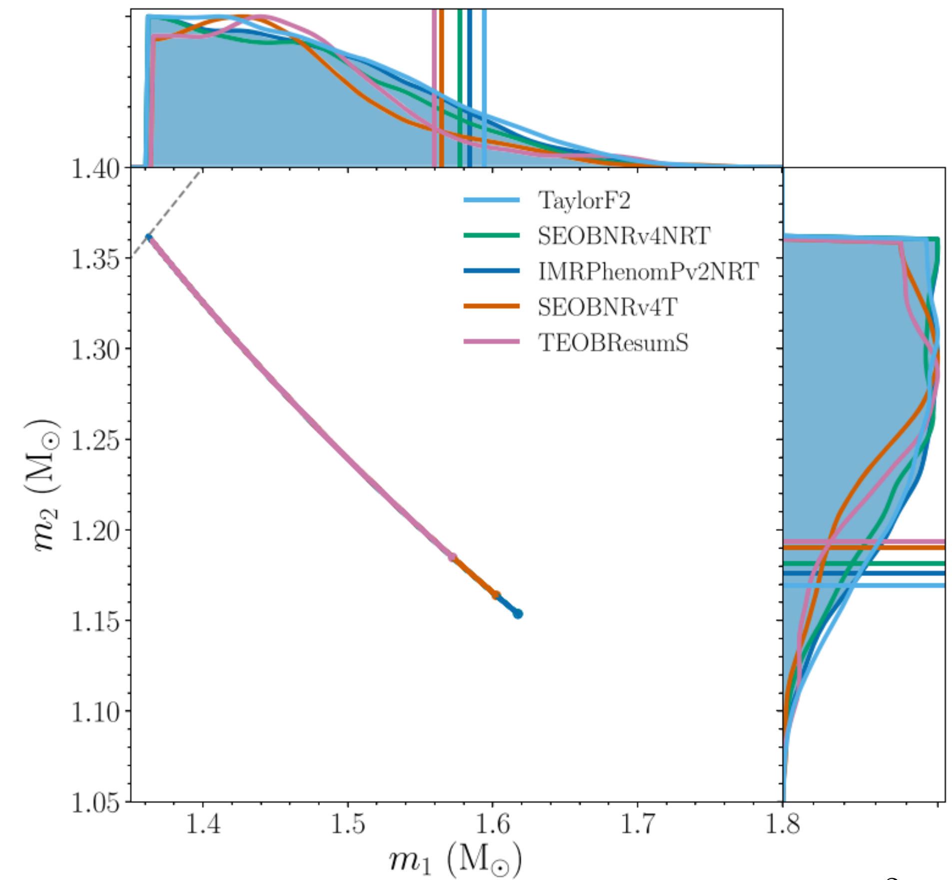
Measurement of GW170817 Inspiral

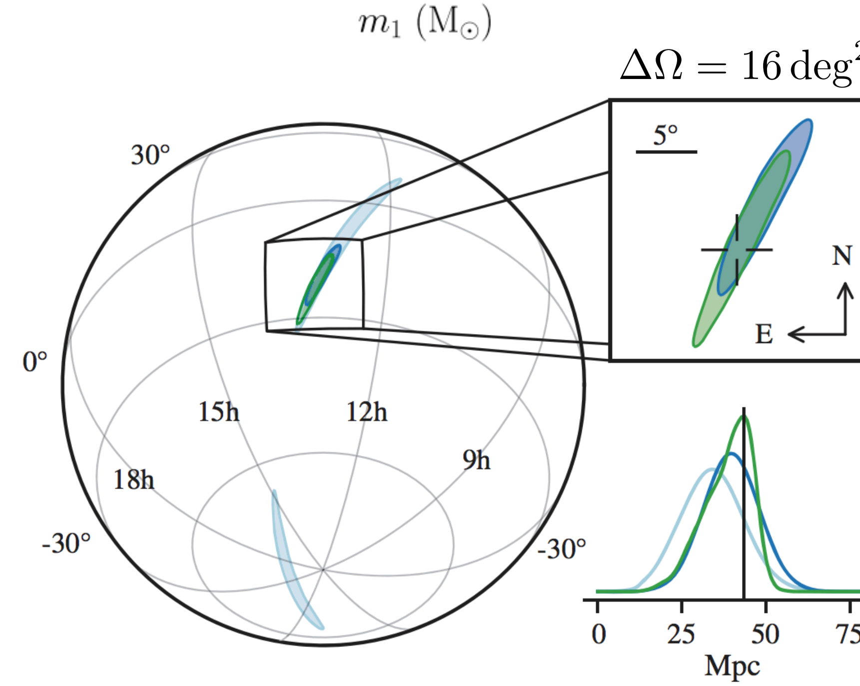
$$\mathcal{M} = 1.186^{+0.001}_{-0.001}\,\mathrm{M}_\odot \qquad \chi_{\mathrm{eff}} = 0.00^{+0.02}_{-0.01}$$

$$m_1 = 1.46^{+0.12}_{-0.10}\,\mathrm{M}_\odot \qquad E_{\mathrm{rad}} \geq 0.04\,\mathrm{M}_\odot c^2$$

$$m_2 = 1.27^{+0.09}_{-0.09}\,\mathrm{M}_\odot \qquad D_L = 40^{+10}_{-10}\,\mathrm{Mpc}$$



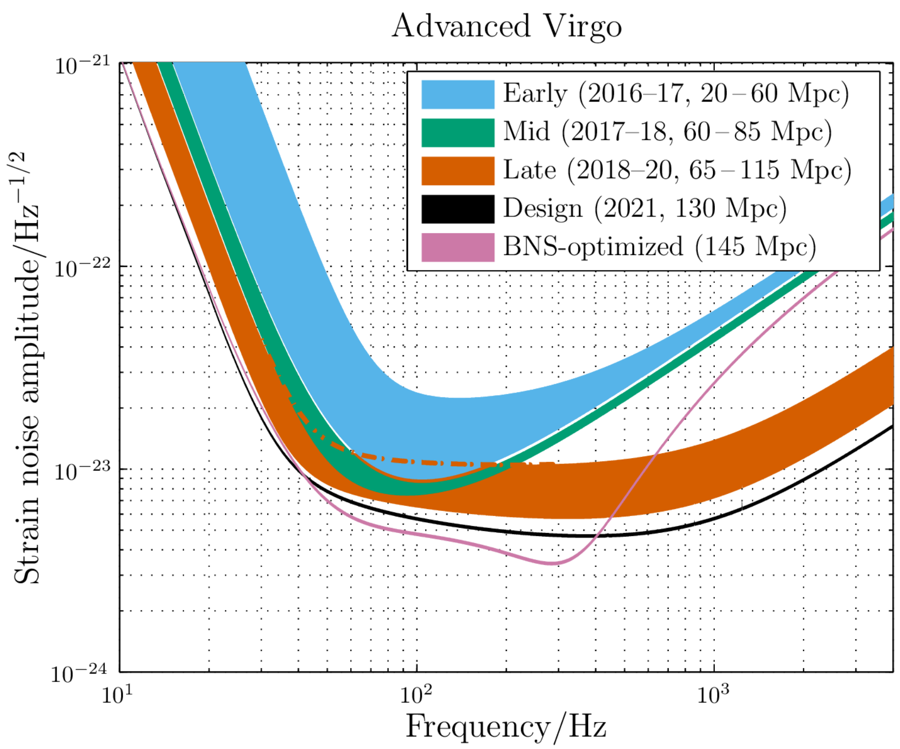




[7] LVC, Phys. Rev. X 9 (2019)

Direct Searches of Postmerger

How can we detect a postmerger signal ?

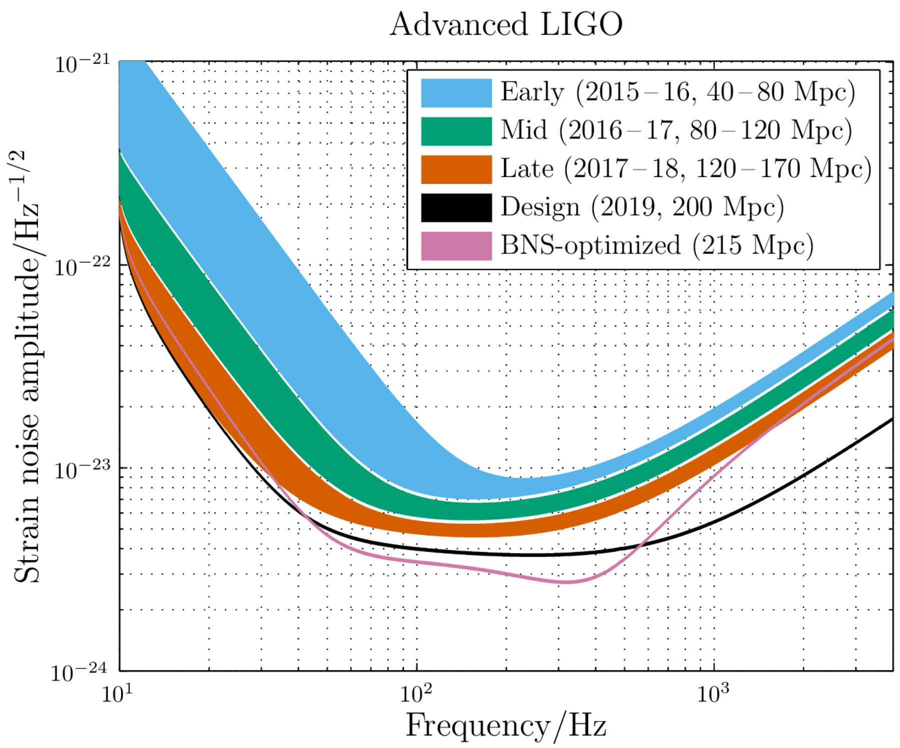


Issues:

- Low sensitivity of the instruments above 1kHz [8]
- Lack of exact reliable model
  - Undefined EOS

Bayesian inference:

- Morphology-independent approach
- Template-based method



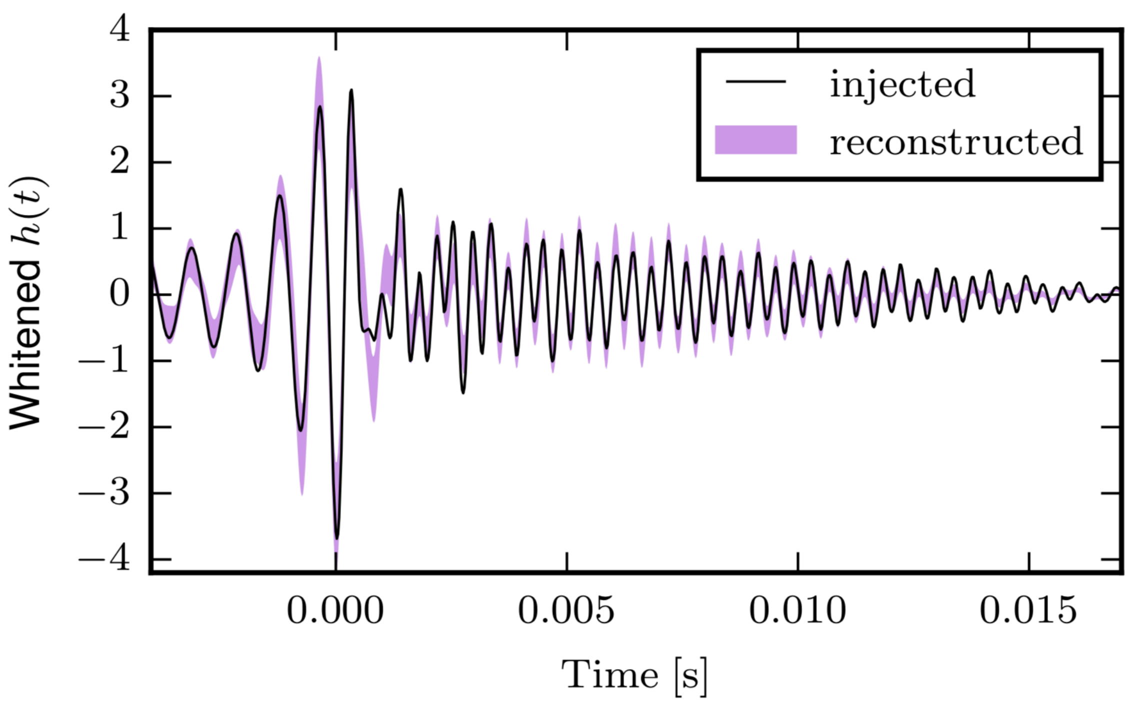
[8] LVC, Living Reviews in Relativity 19, 1 (2016)

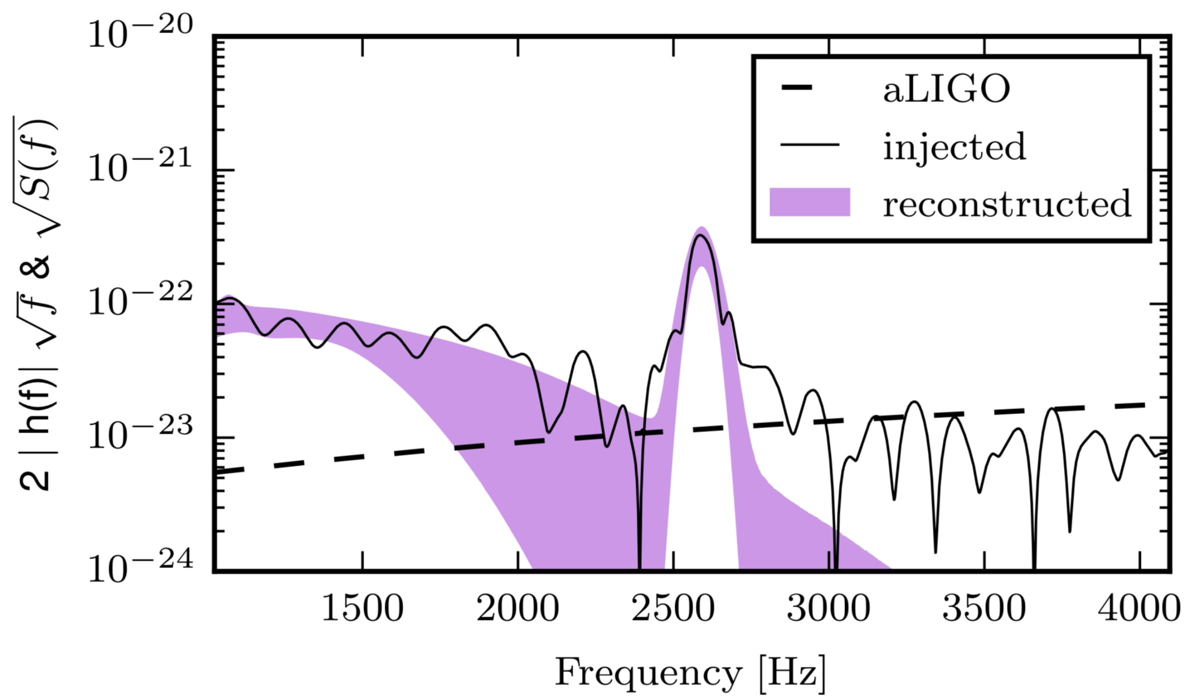
Morphology-Independent Searches: `BayesWave`

`BayesWave` [9] is a Bayesian framework that used wavelets to reconstruct the spectrum of the signal

- Injection studies had shown that the pipeline can detect postmerger signals with SNR~5 [10]

- Application to GW170817 does not show evidence of postmerger signal in the data [11]



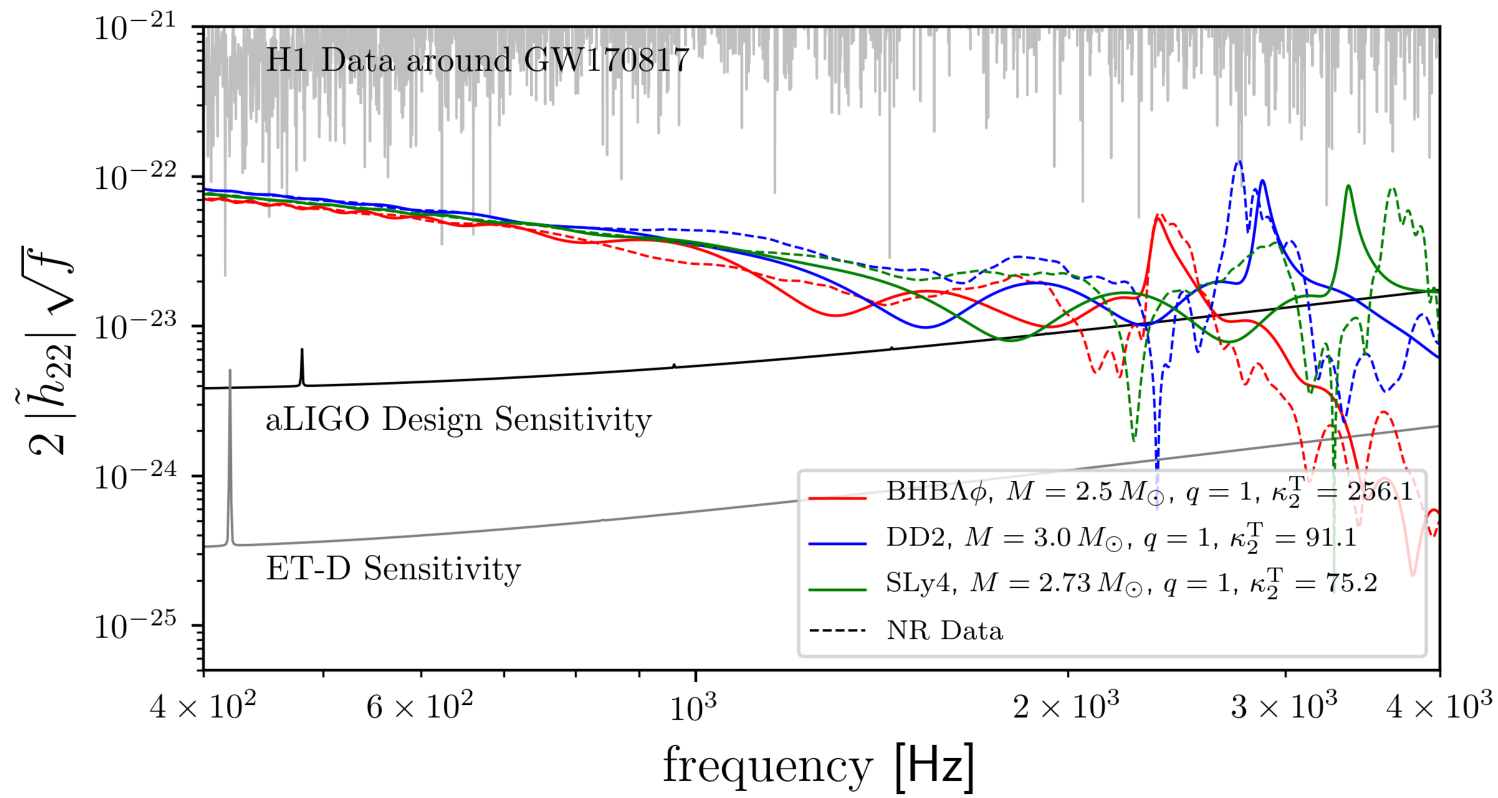


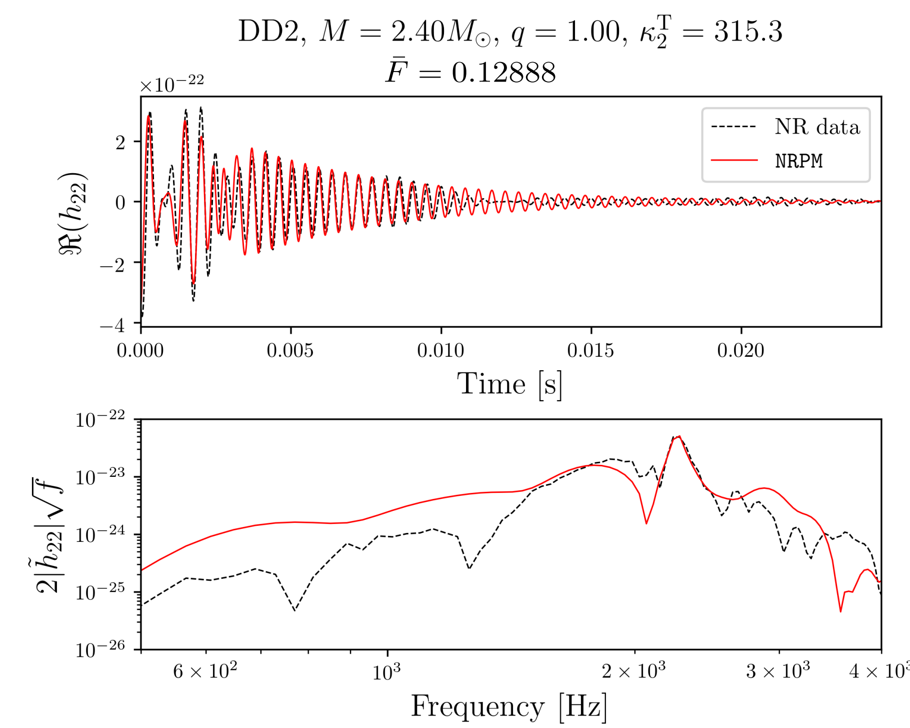
[9] N. J. Cornish *et al.*, C.Q.G. 32 (2015)
[10] K. Chatziioannou *et al.*, Phys. Rev. D 96 (2017)
[11] LVC, ApJL, 851:L16 (2017)

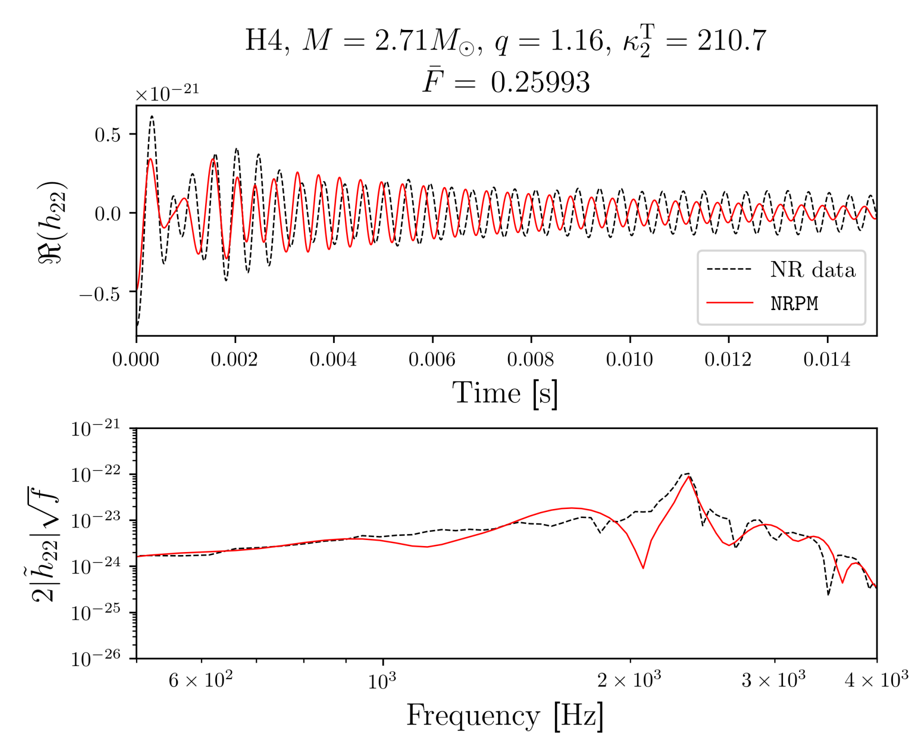
NRPM

NR-informed time-domain waveform for non-spinning BNS remnants [12]

- Constructed with three characteristic frequencies
- Designed to complete EOB model in kHz regime (`TEOBResumS_NRPM`)





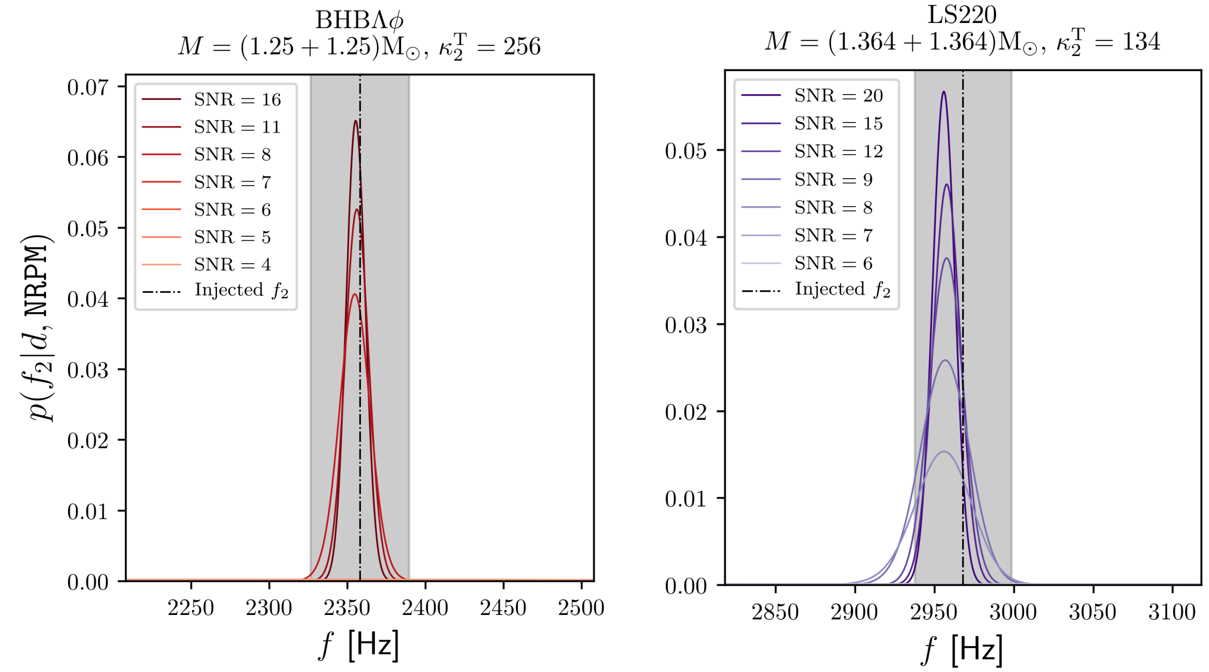


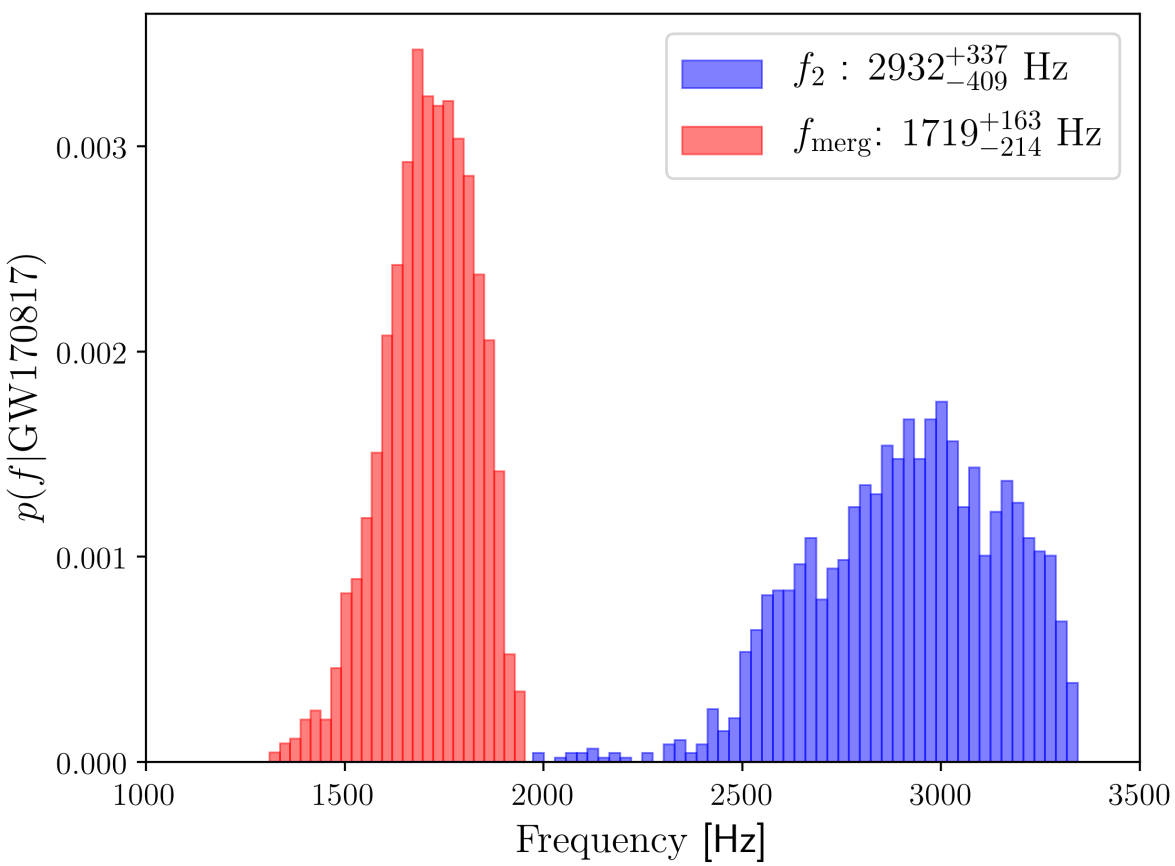
[12] M. Breschi *et al.*, arXiv:1908.11418 (2019)

Template-based Analysis with NRPM

- Injection studies show that NRPM detects postmerger signal with SNR~8

- Application to GW170817 does not show evidence of signal in the data





If GW170817 produced a postmerger signal:

- The SNR is expected to be lower than 1

- Frequency peak should be located at ~3kHz

- With 3G detectors, it is expected SNR~10 for GW170817-like events

[12] M. Breschi *et al.*, arXiv:1908.11418 (2019)

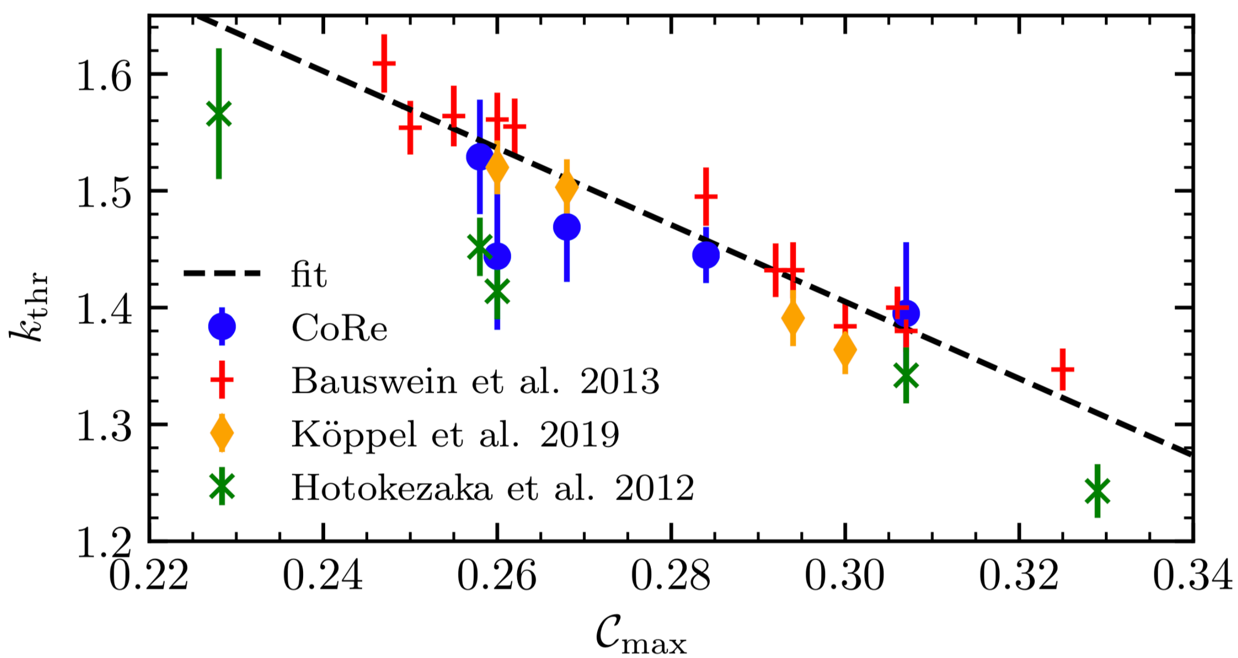
How can we infer the outcome ?

Combining the information from the inspiral and our knowledge coming from NR simulations, it is possible to perform Bayesian inference to infer the outcome of the merger [13]

- Threshold mass method [14]:

$$M_{\rm thr} = k_{\rm thr}\, M_{\rm max}^{\rm TOV}$$

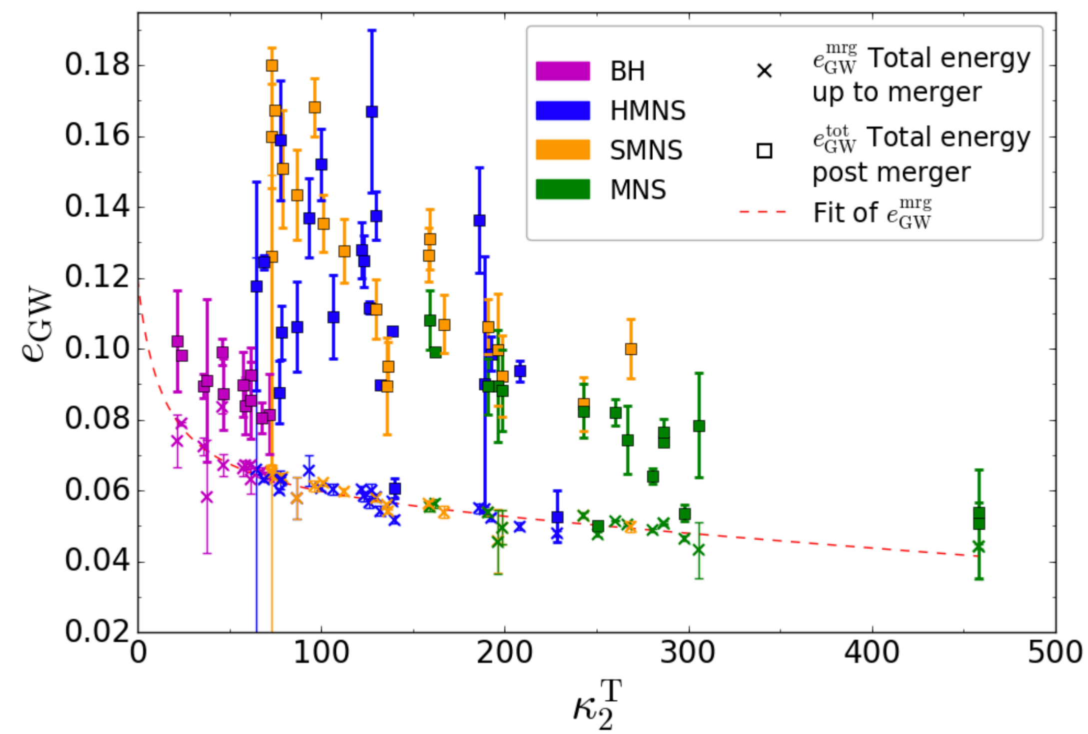
where $k_{\rm thr}$ is estimated using fits of NR simulations as function of the maximum compactness supported by the EOS



- Tidal parameter method [15]:

NR simulations shows that prompt collapse occurs for low values of the tidal parameter,

$$\tilde{\Lambda} < \tilde{\Lambda}_{\rm thr} = 362 \pm 24$$



[13] M. Agathos *et al.*, arXiv:1908.05442 (2019)
[14] K. Hotokezaka *et al.*, Phys.Rev.D (2011)
[15] F. Zappa *et al.*, Phys.Rev.Lett. (2018)

Application to GW170817

Threshold mass method :

We perform a parametrized-EOS sampling, in order to be able to compute the threshold mass. Then,

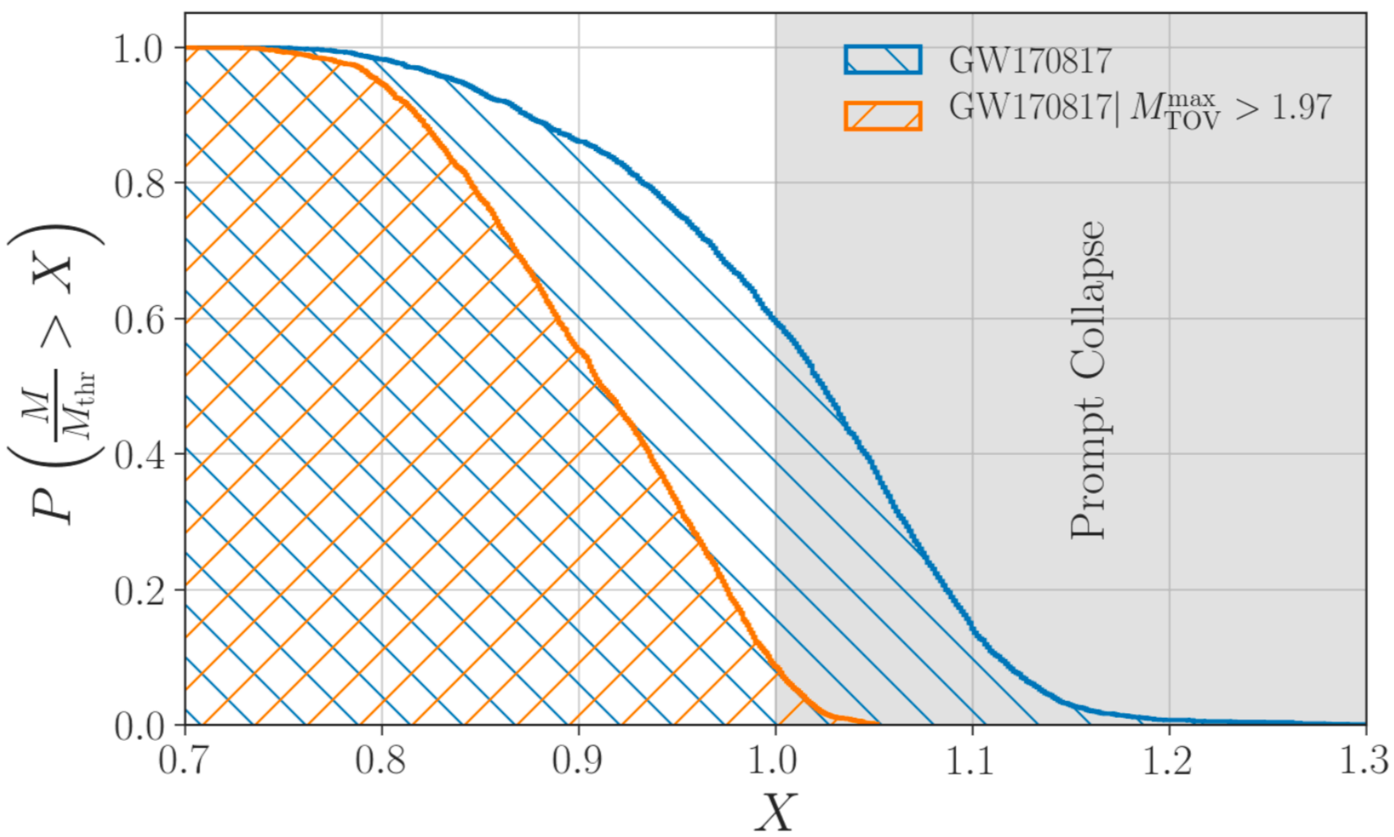
$$P_{\rm PC} = P(M > M_{\rm thr}|d)$$

- Without $M_{\rm max}^{\rm TOV}$-constraint:

$$P_{\rm PC} \approx 0.59$$

- With $M_{\rm max}^{\rm TOV}$-constraint:

$$P_{\rm PC} \approx 0.09$$



$\Longrightarrow$ The max-mass constraint removes part of the EOS parameters space that is too soft to support 1.97 $M_\odot$

[13] M. Agathos *et al.*, arXiv:1908.05442 (2019)

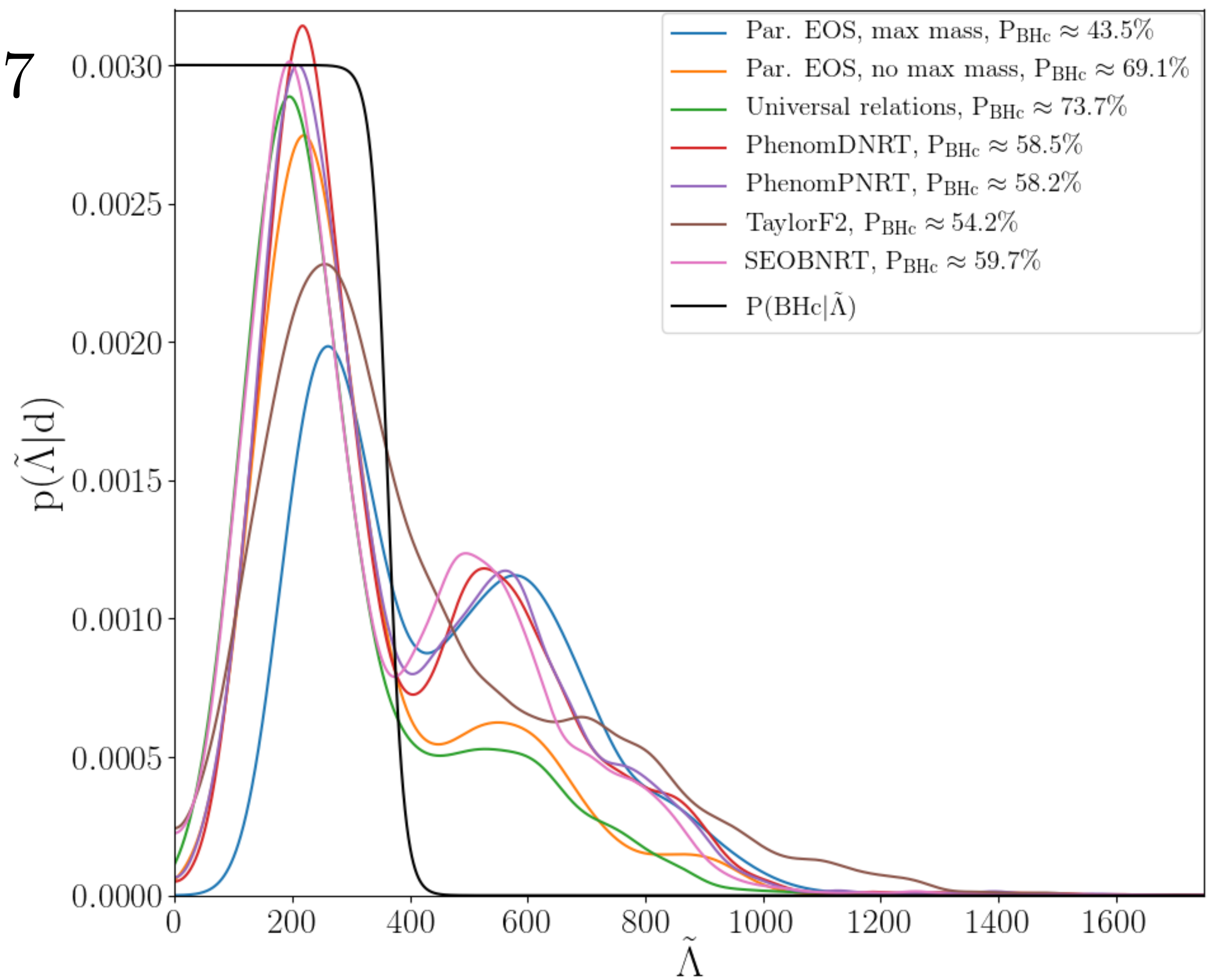
Tidal parameter method :

Now we are interested in the posterior distribution of the tidal parameter

$$P(\mathrm{PC}|\tilde{\Lambda}) = \frac{1}{1 + e^{\frac{\tilde{\Lambda} - \tilde{\Lambda}_0}{\beta}}} \qquad \begin{cases} \tilde{\Lambda}_0 = 362 \\ \beta = 13.7 \end{cases}$$

$$P_{\mathrm{PC}} = \int P(\mathrm{PC}|\tilde{\Lambda})\, P(\tilde{\Lambda}|d)\, \mathrm{d}\tilde{\Lambda}$$

$$\Rightarrow \qquad P_{\mathrm{PC}} \in [0.43, 0.74]$$

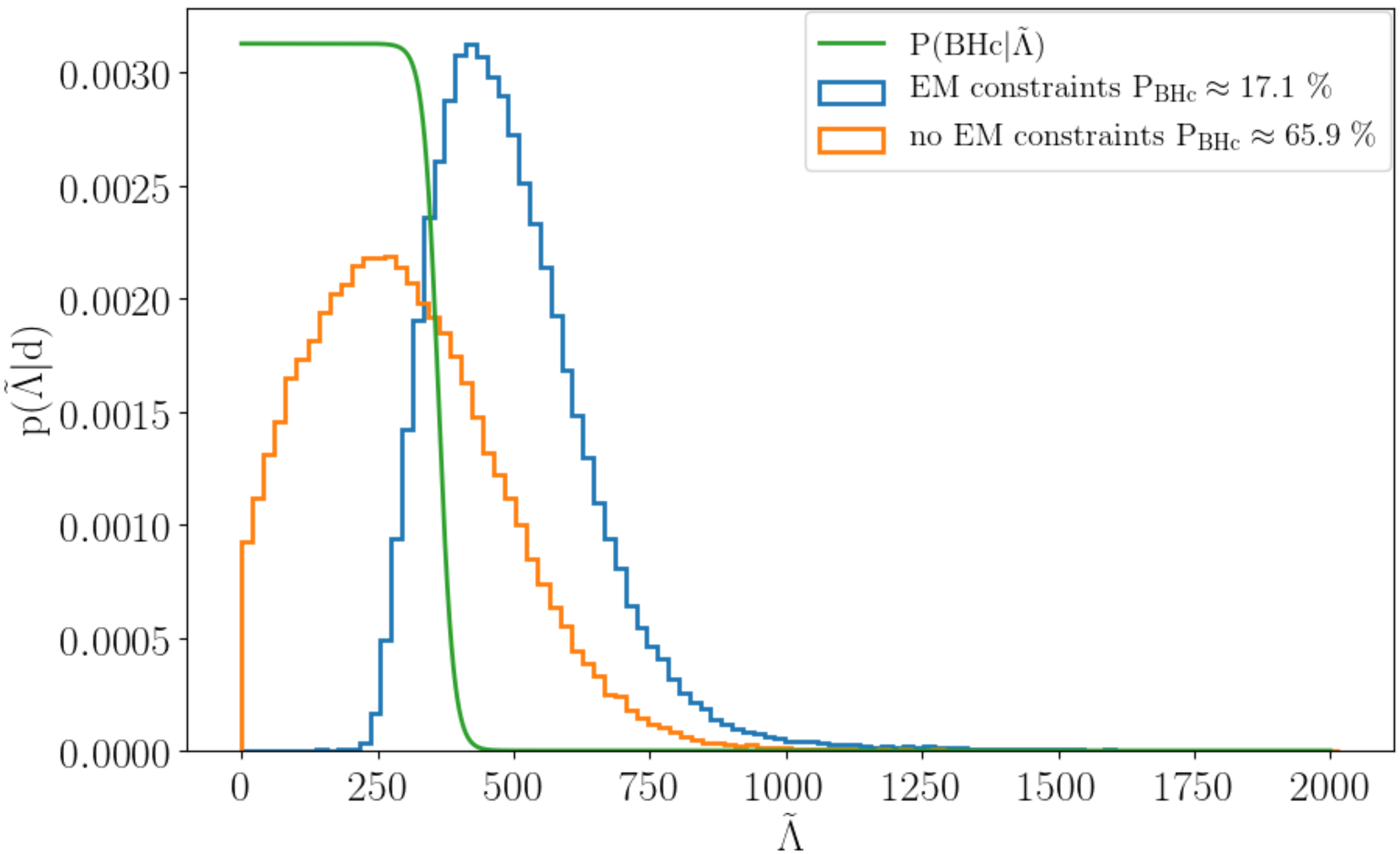


[13] M. Agathos *et al.*, arXiv:1908.05442 (2019)

EM Information

- If we include the information from the EM counterpart [16], the $\tilde{\Lambda}$- method strongly disfavor the prompt collapse

- This behavior is also confirmed by NR simulations (see also Vsevolod Nedora's talk on Wednesday)



[16] D. Radice *et al.*, ApJ 869:130 (2018)

Outlook

- Direct searches do not reveal any postmerger signal in GW170817 data
  - Even if a signal is present in the data, the SNR is too low
- Inference of prompt collapse using inspiral measurement leads to unclear results
  - Recovered parameters lie on the threshold value for both methods
  - Including the information from the EM counterpart, prompt collapse is strongly disfavored

Thank you!