Physik-Combo 2021

Constraints on the nuclear equation of state from binary neutron star mergers

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In collaboration with
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VIRGO

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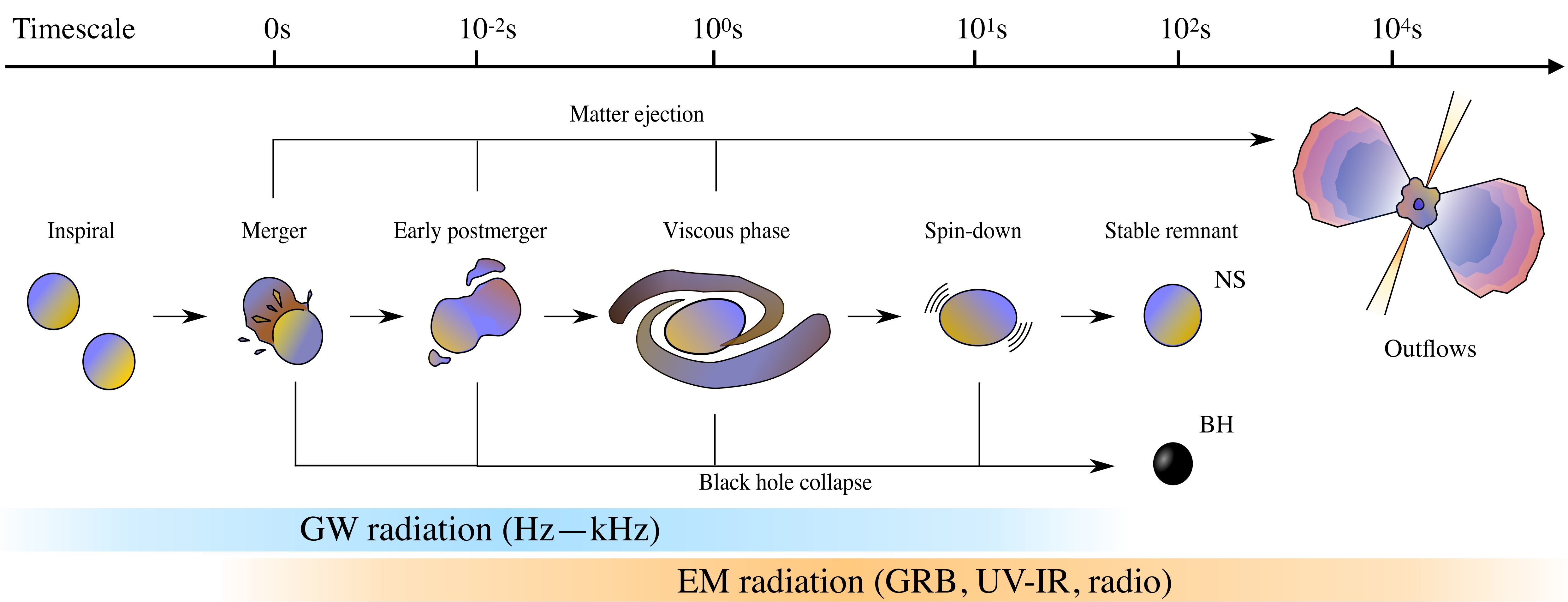
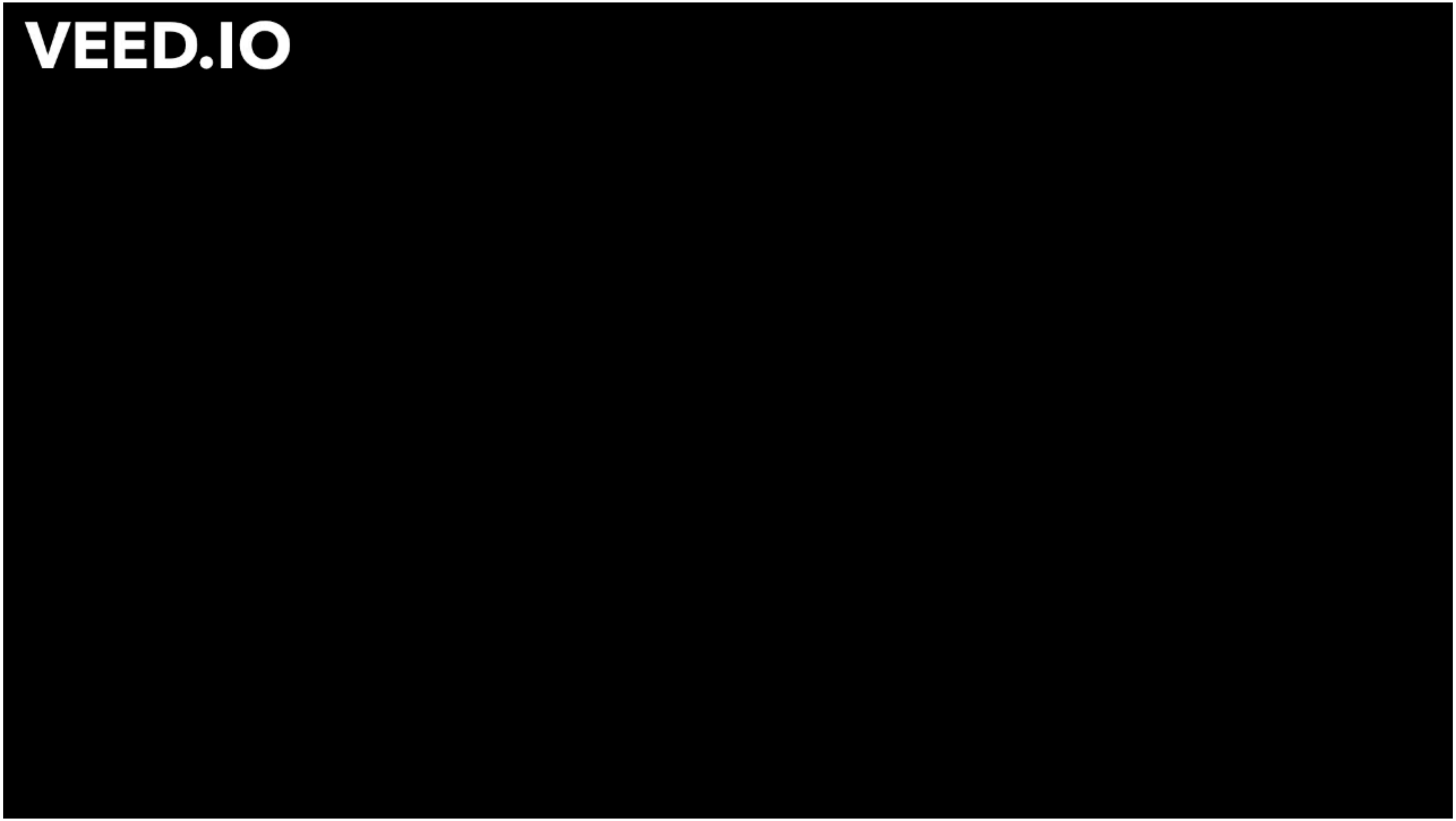
Binary neutron star mergers



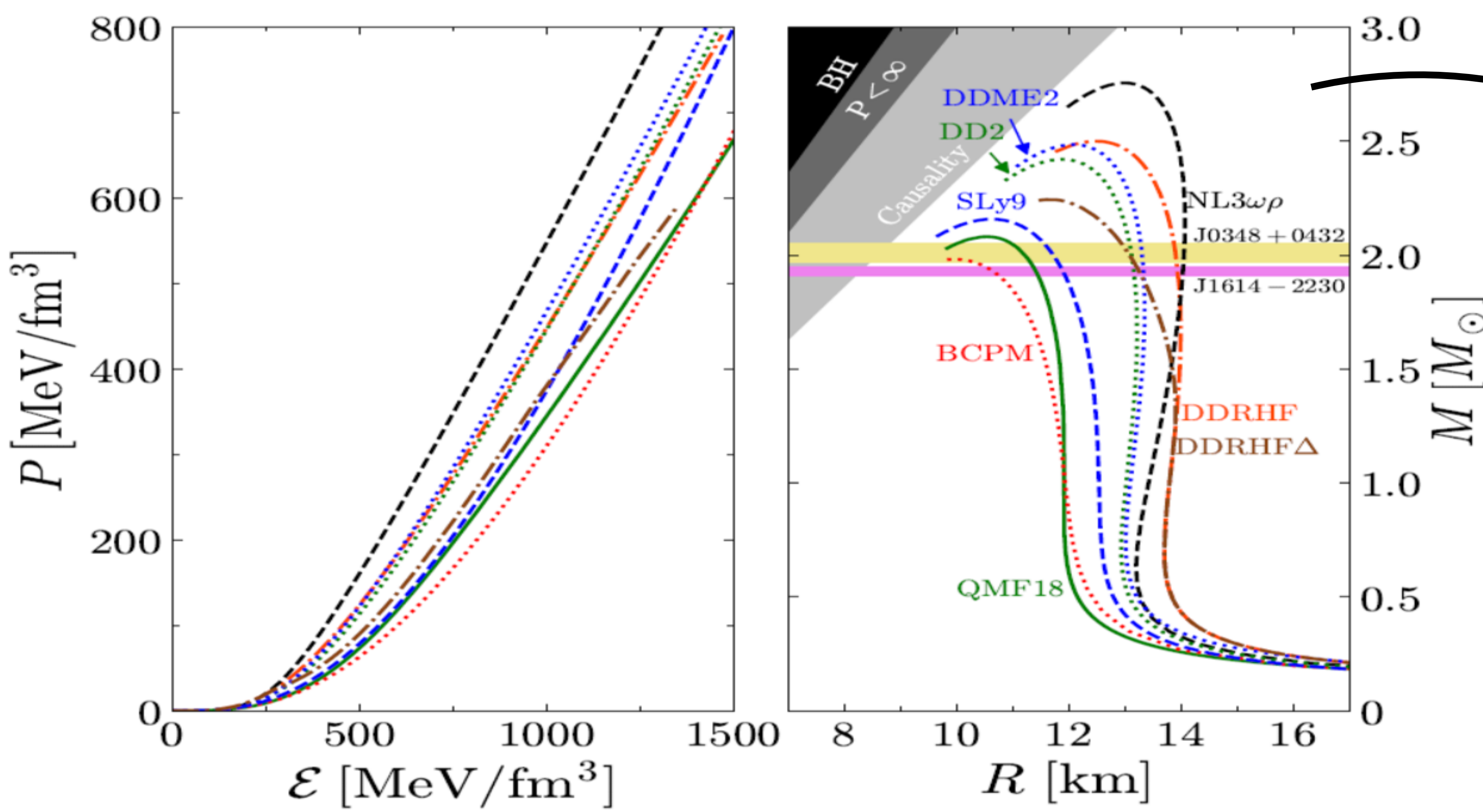
- Single event that requires a **multi-disciplinary description**
- Different messengers carry **complementary information**

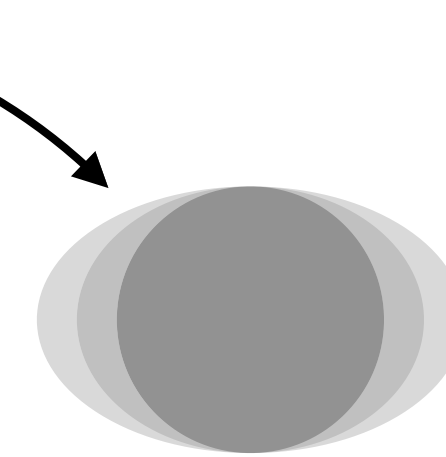
Numerical relativity



- Nuclear interactions between NS components determine the properties of matter, encoded in the **equation of state** (EOS)

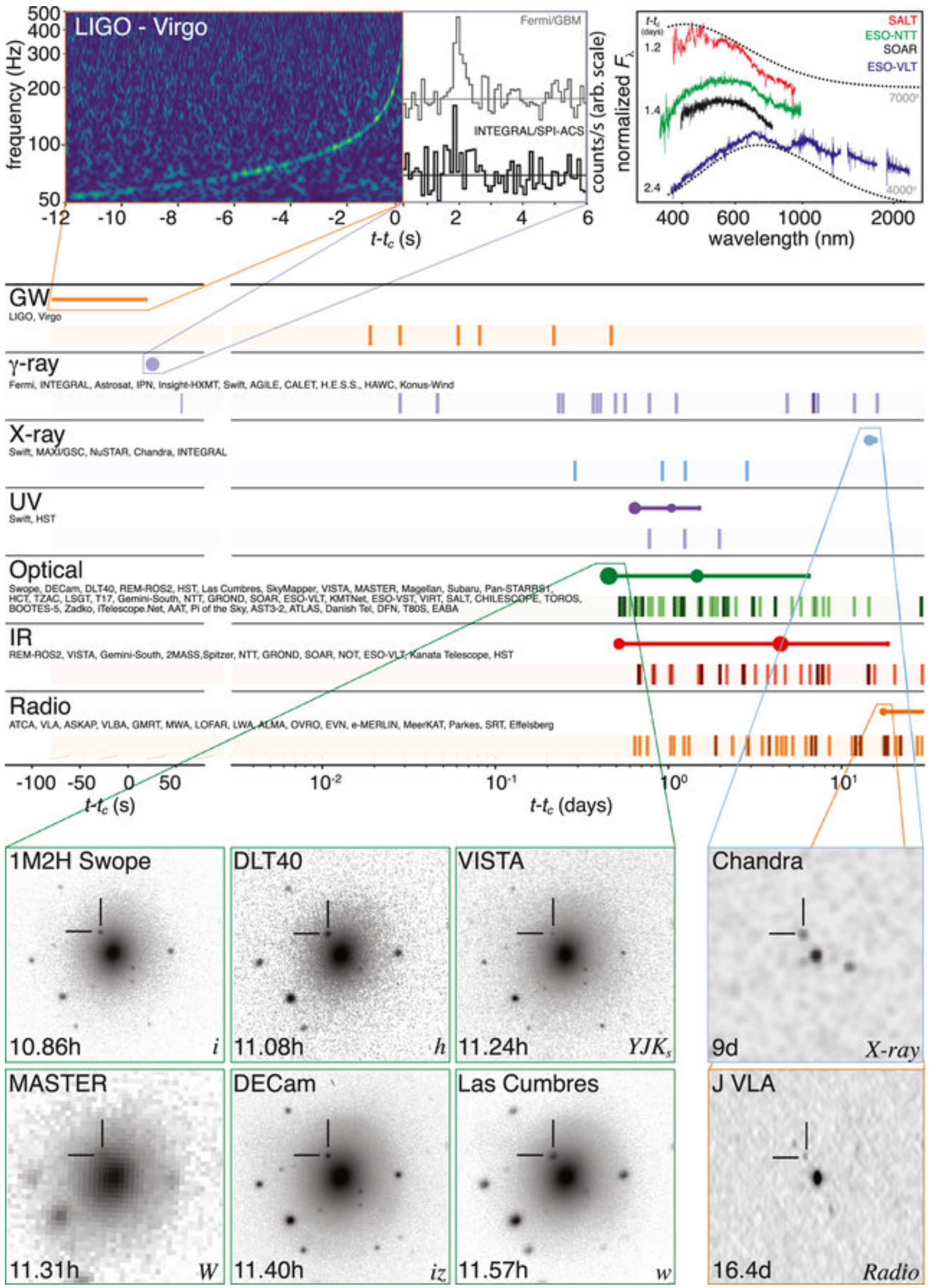
- Observable transients carry information about the matter properties that are direct signatures of the nuclear forces inside the NS





Tidal Deformability
($\tilde{\Lambda}$)

Observations



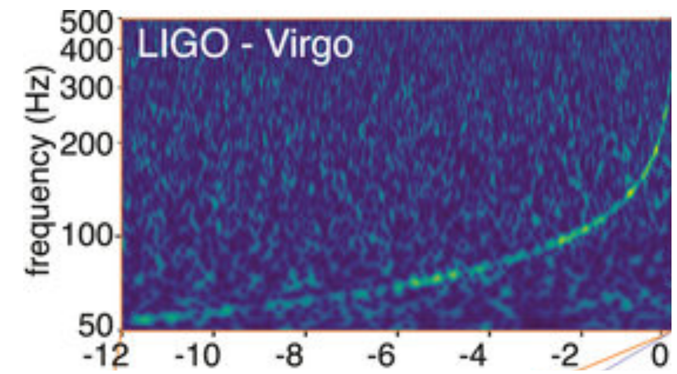
- LIGO-Virgo interferometers detected a GW trigger corresponding to an **inspiralling BNS** [1]
- Fermi and INTEGRAL detected a **GRB** coming from a coincident sky region
- Optical and radio observatories identified an **EM counterpart** in a nearby galaxy, NGC 4993

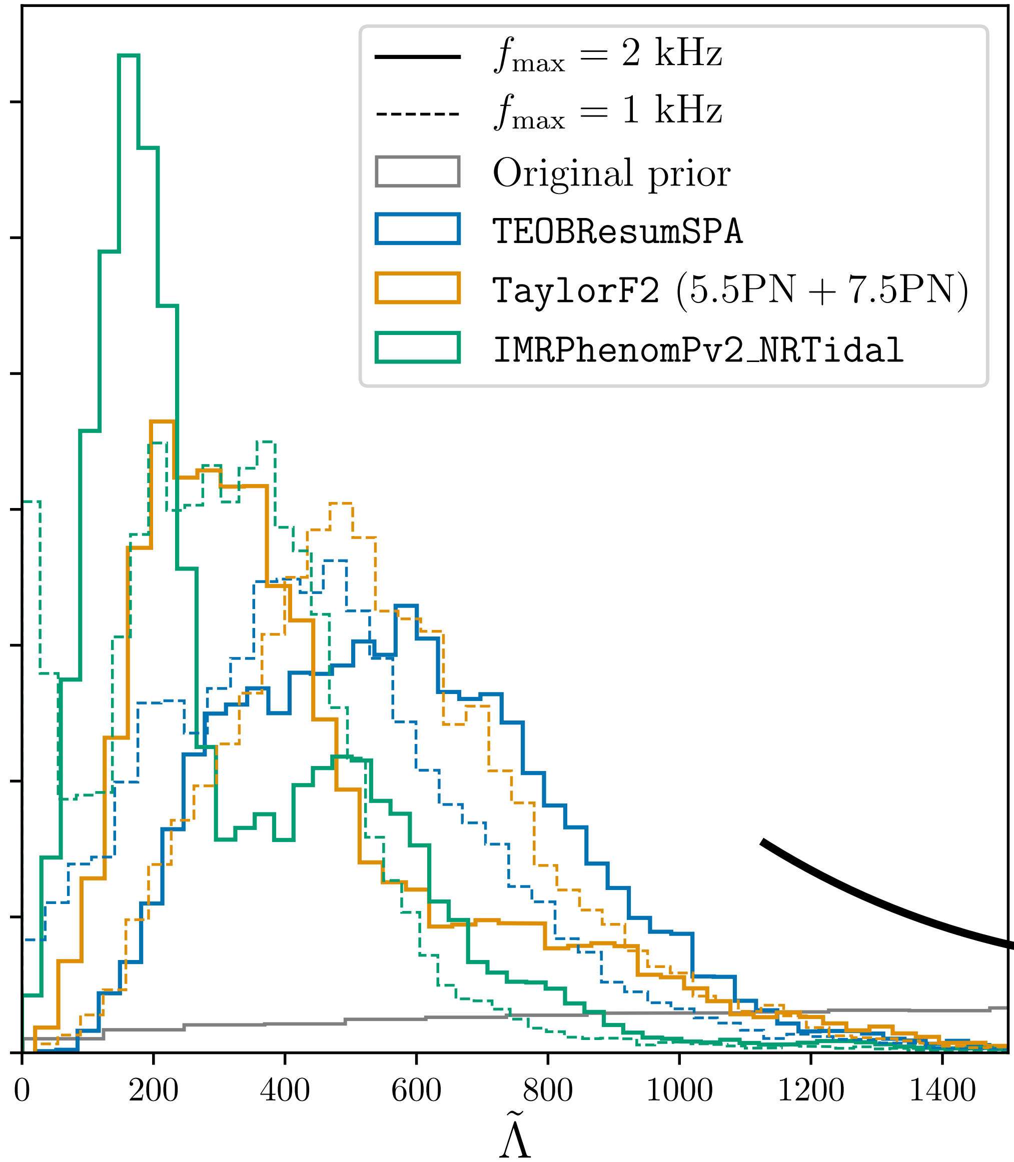
Multimessenger astronomy with compact binary mergers

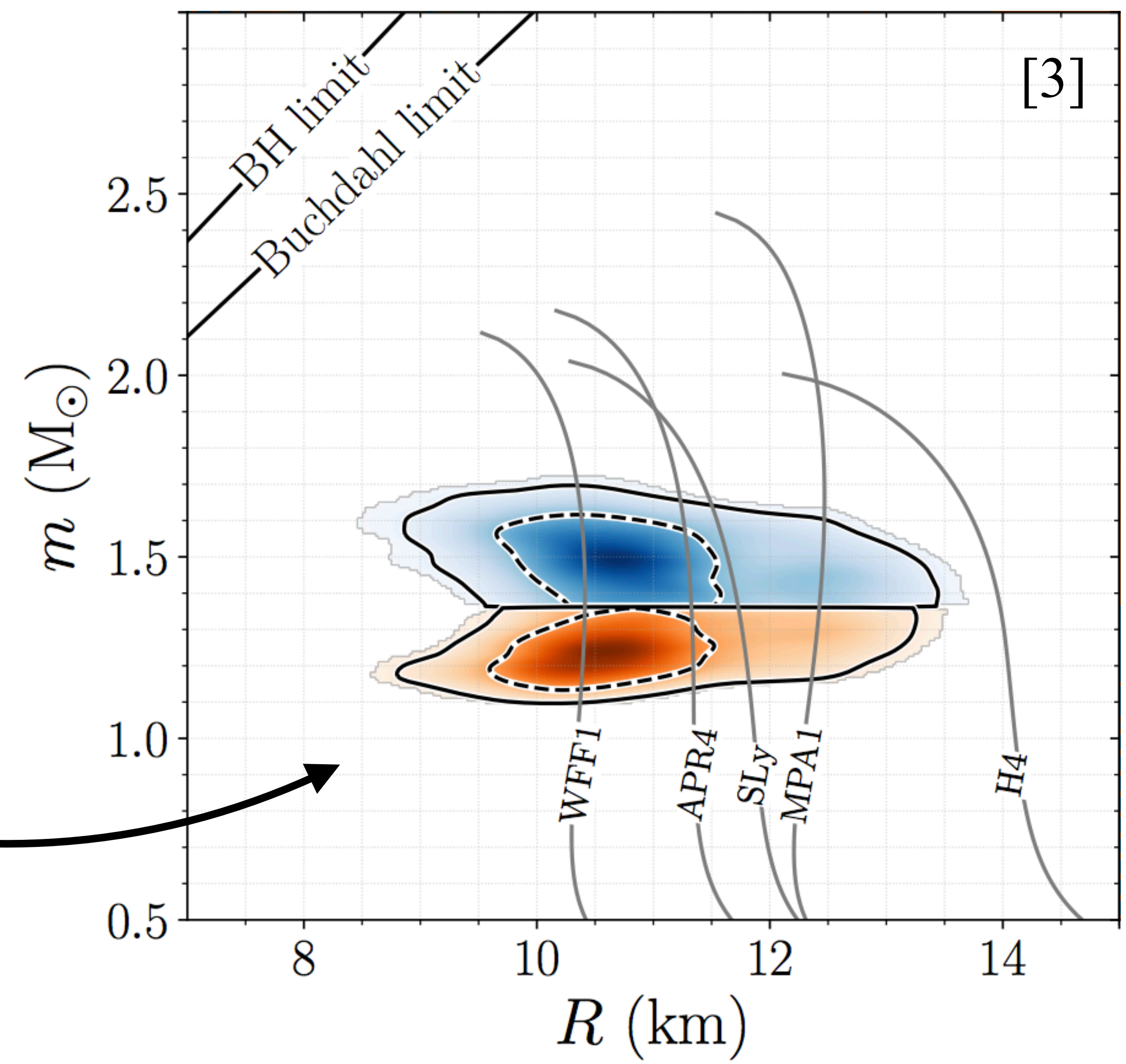
[1] LVC *et al.*, 10.3847/2041-8213/aa91c9 (2017)

GW170817

- We analyze **GW170817** with different template models
- Tidal inference is strongly informed by **high-frequency contribution** [2]



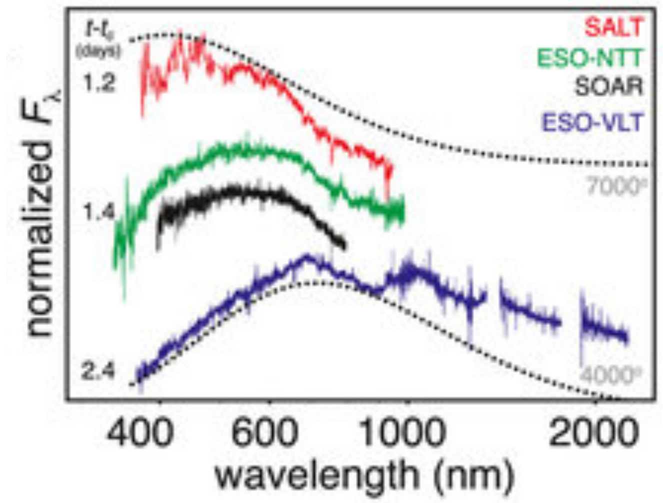




[2] R. Gamba *et al.*, 10.1103/PhysRevD.103.124015 (2020)
[3] LVC, 10.1103/PhysRevLett.121.161101 (2018)

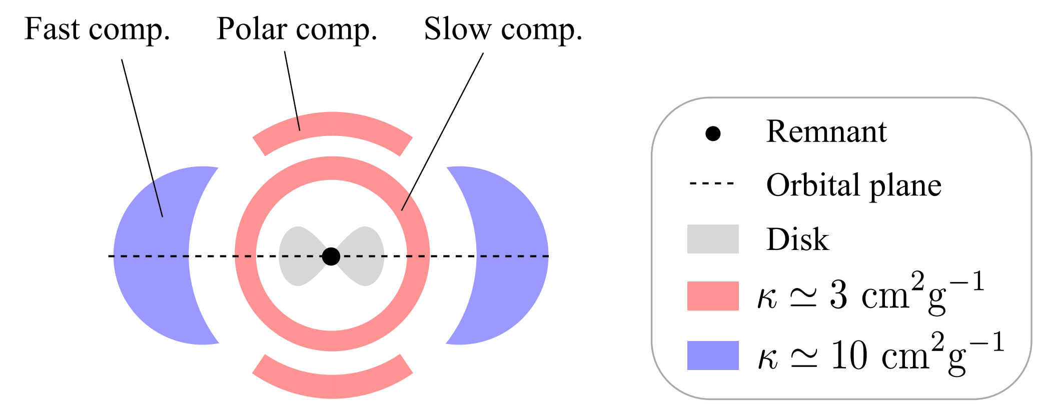
AT2017gfo

- KNe are quasi-thermal emission driven by ***r*-process nucleosynthesis** in a neutron-rich environment

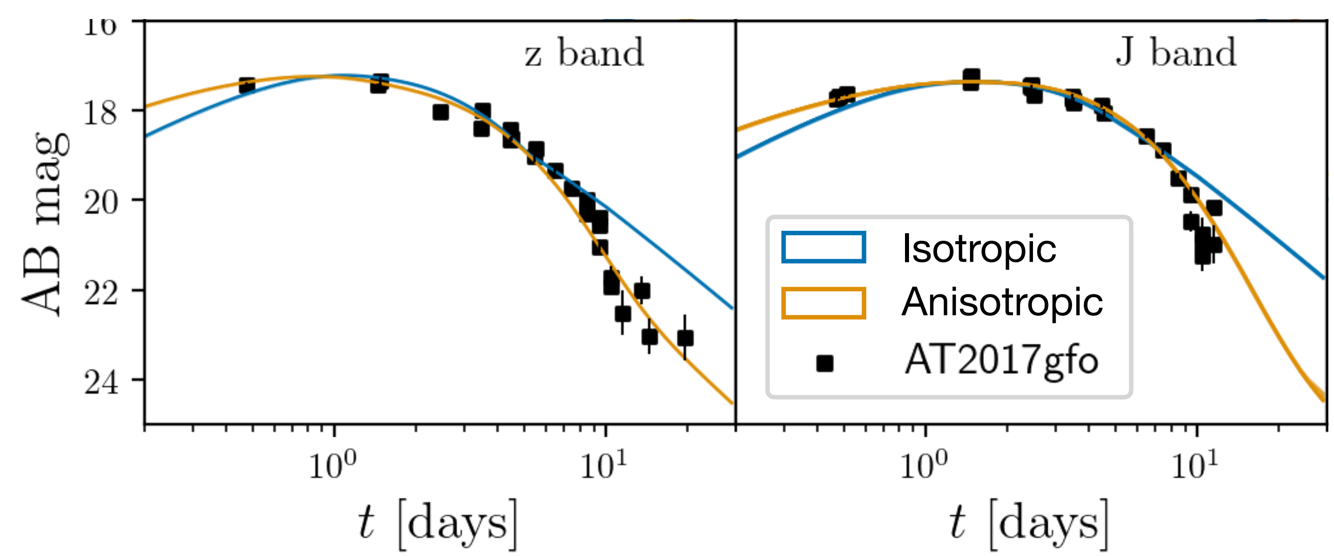


- The luminosity peak moved from the **UV band** to the **IR band** after ~5 day [4]

- We perform kN model selection observing that **multi-component anisotropic ejecta** are favored [5]
  - Fast equatorial component (*blue*)
  - Polar wind due to matter reprocessed by *weak interactions*
  - Slow component (*red*)



- Anisotropic models improve the **late-time characterization**

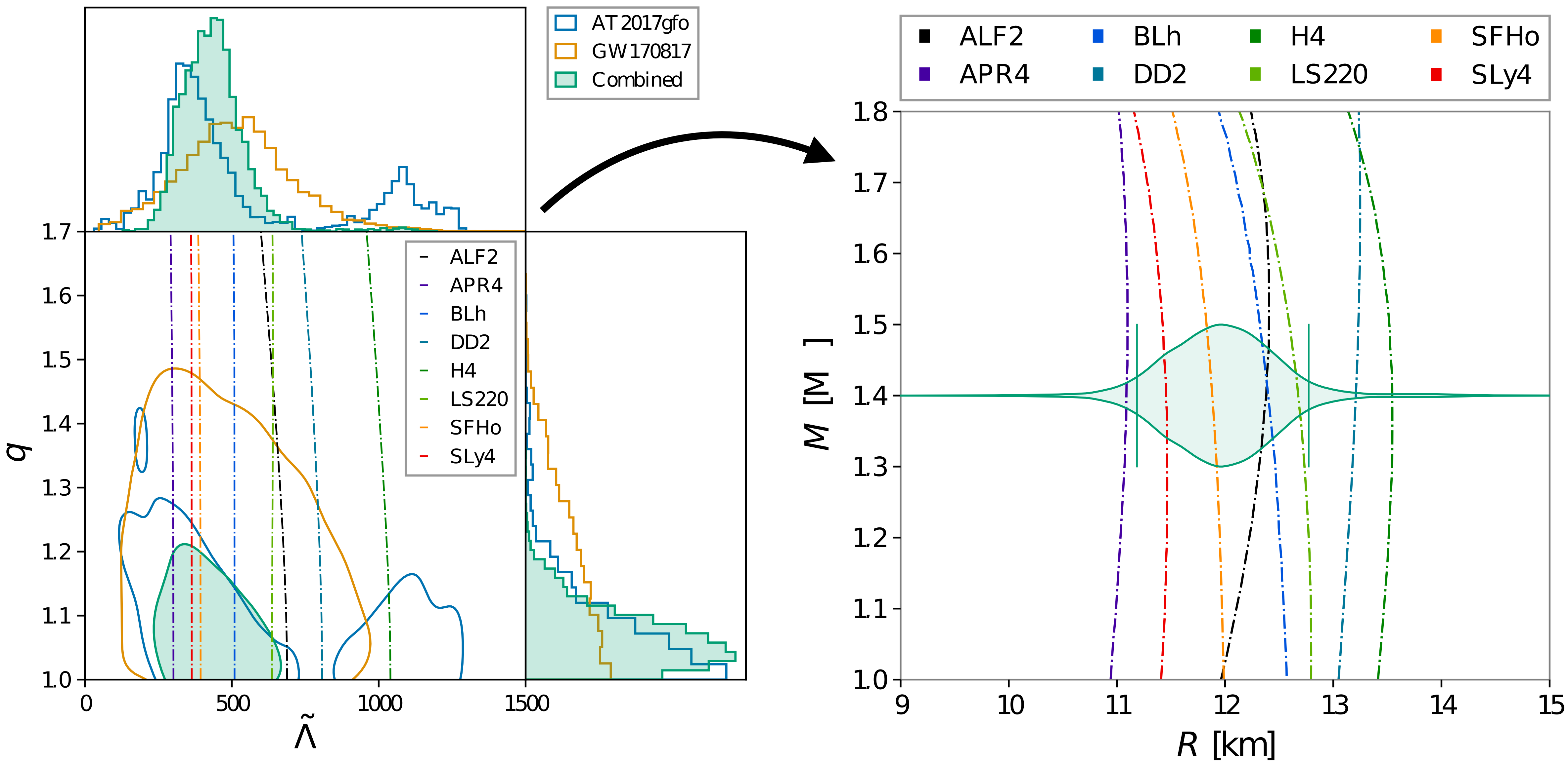


[4] V.A. Villar et al., 10.3847/2041-8213/aa9c84 (2017)
[5] M. Breschi et al., 10.1093/mnras/stab1287 (2021)

EOS inference

- Using **NR-calibrated formulae** ($\mathcal{M} = 1.188\ \mathrm{M}_\odot$) [6], we can map the ejecta properties into the binary parameters,

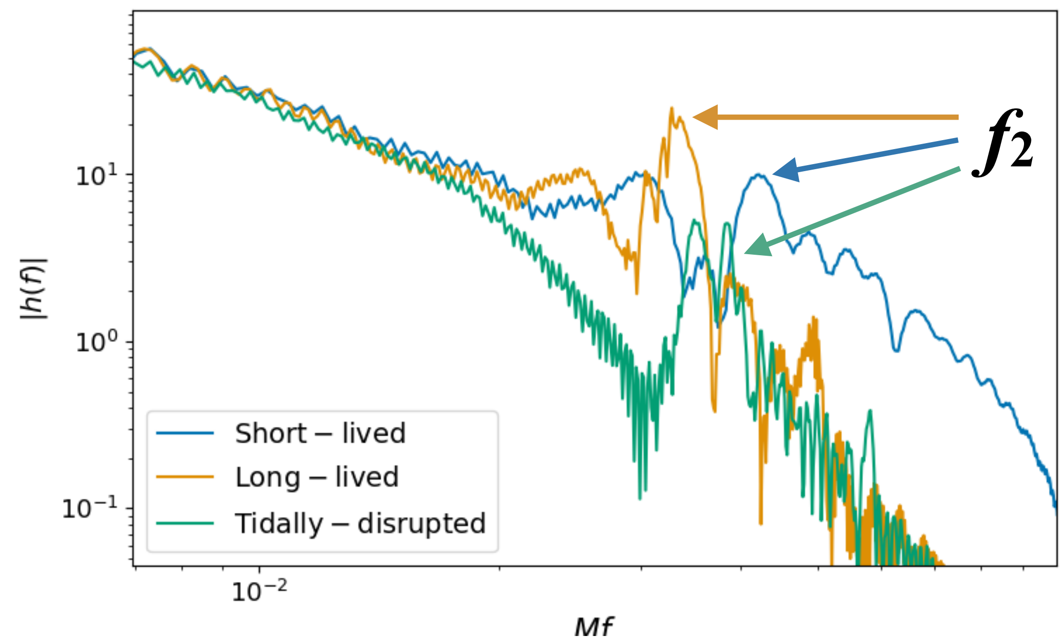
$$\text{kN observation} \xrightarrow{\text{PE}} p(m_{\text{ej}}, v|\boldsymbol{d}_{\text{kn}}) \xrightarrow{\text{NR}} p(q, \tilde{\Lambda}|\boldsymbol{d}_{\text{kn}})$$

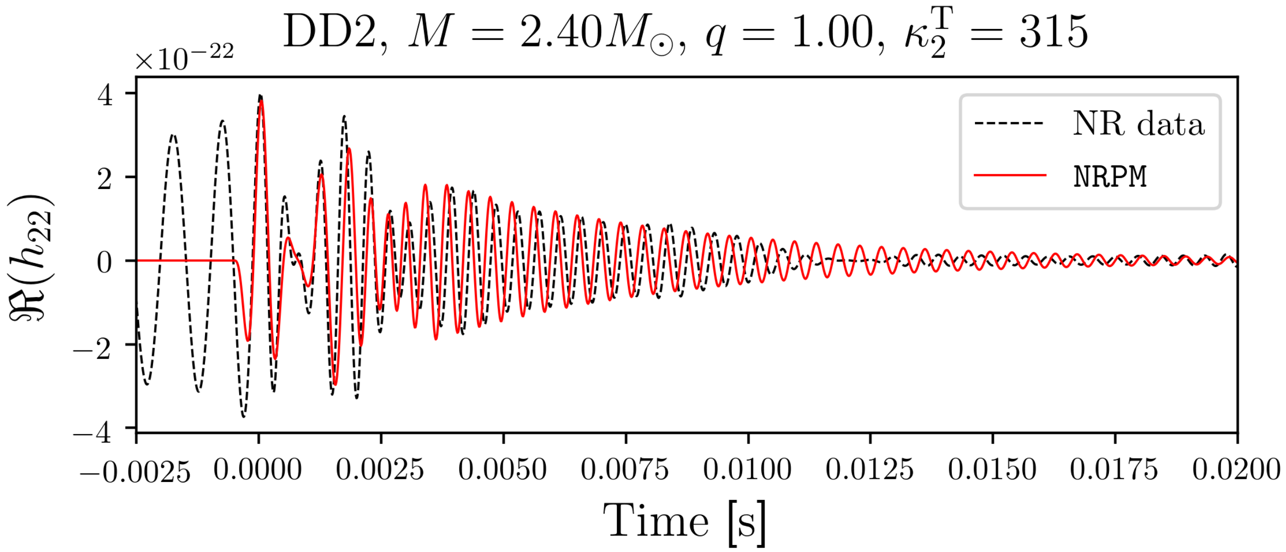


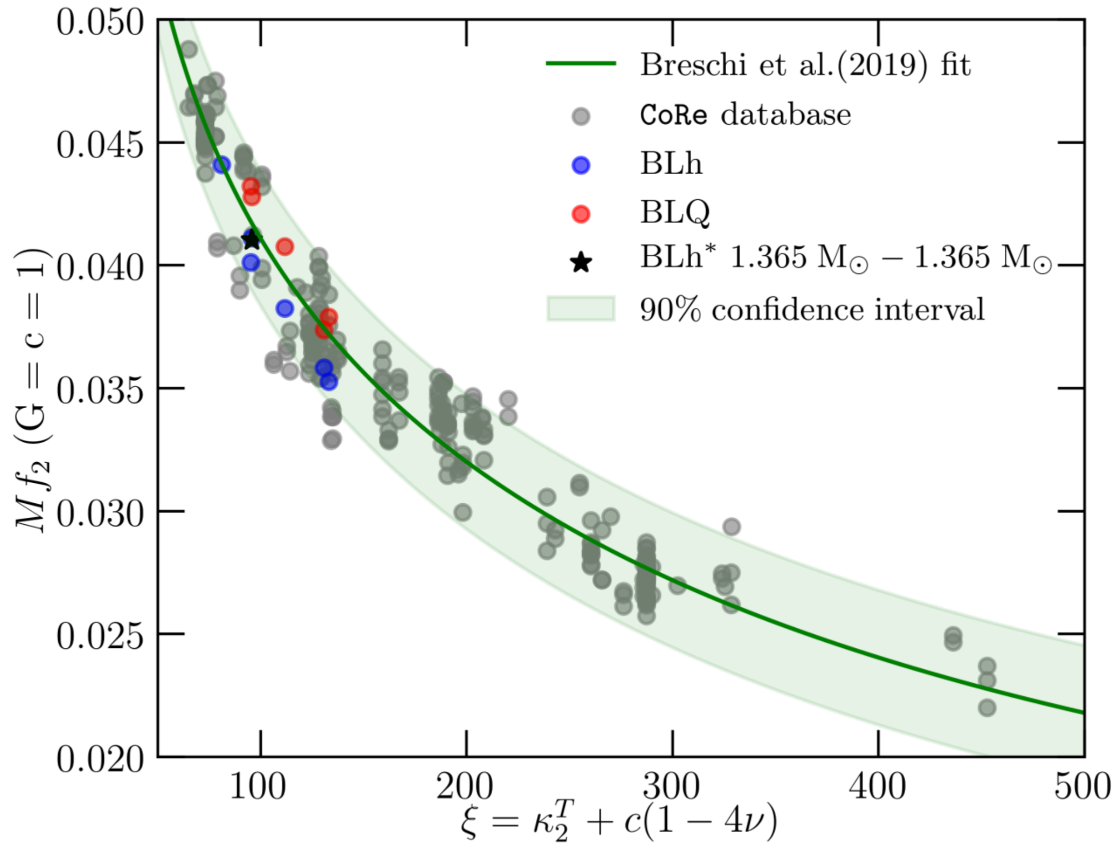
[6] V. Nedora *et al.*, arXiv:2011.11110 (2020)

GW Postmerger

- Not yet observed with current detectors but accessible with NR simulations
- Frequency spectrum characterized by a **dominant frequency peak** f_2 [7.8]
- Phenomenological NR-informed model in the time-domain **NRPM**





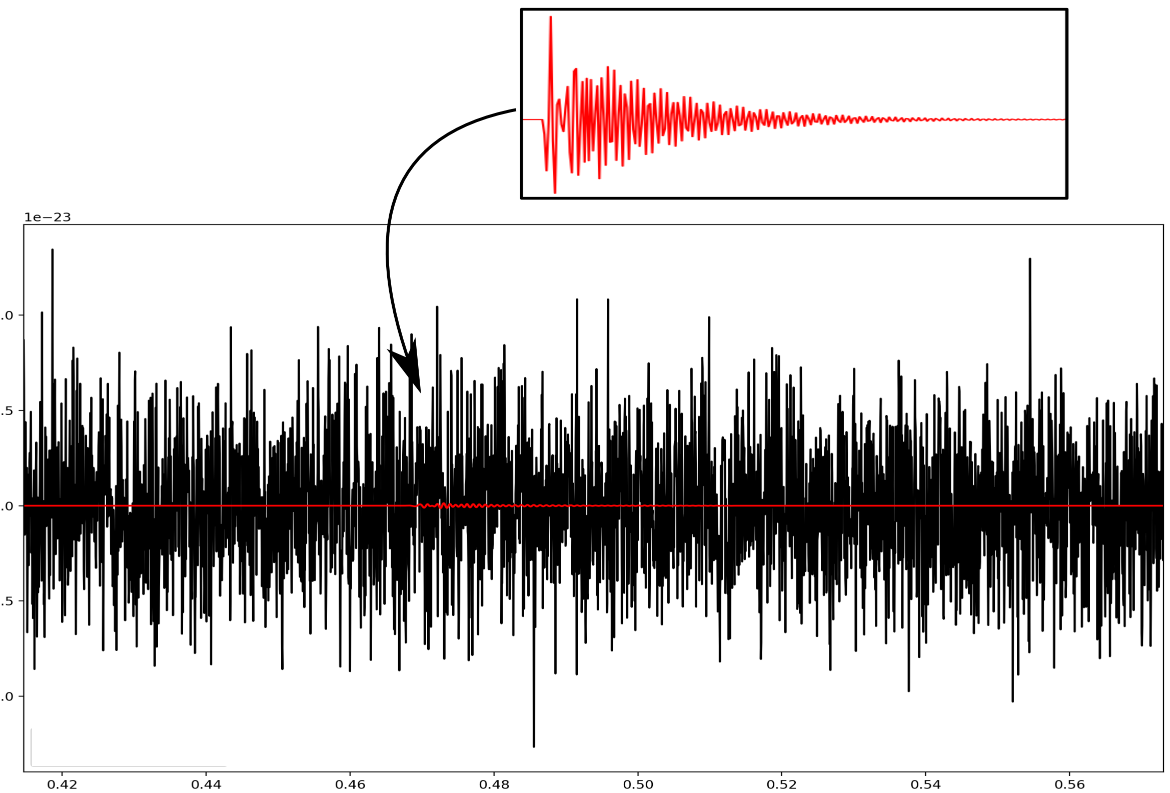


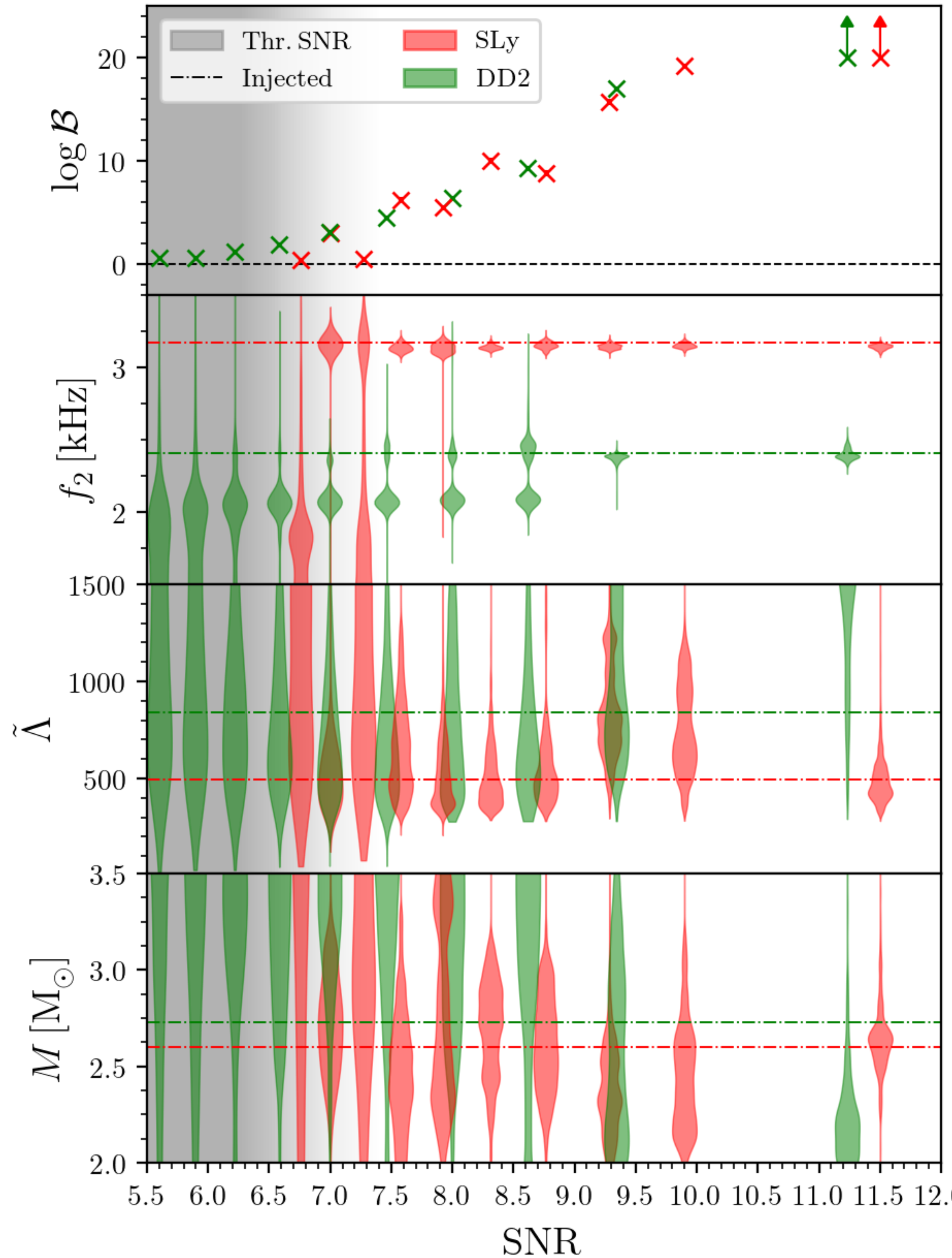
[7] M. Breschi *et al.*, 10.1103/PhysRevD.100.104029 (2019)
[8] A. Prakash *et al.*, arXiv:2106.07885 [astro-ph.HE] (2021)

Next-generation detections

- Injection study with **next-generation detector** (Einstein Telescope) with design sensitivities [9]

    - PM BNS signals are confidently detected for sources located at **~150 Mpc** (SNR 7)

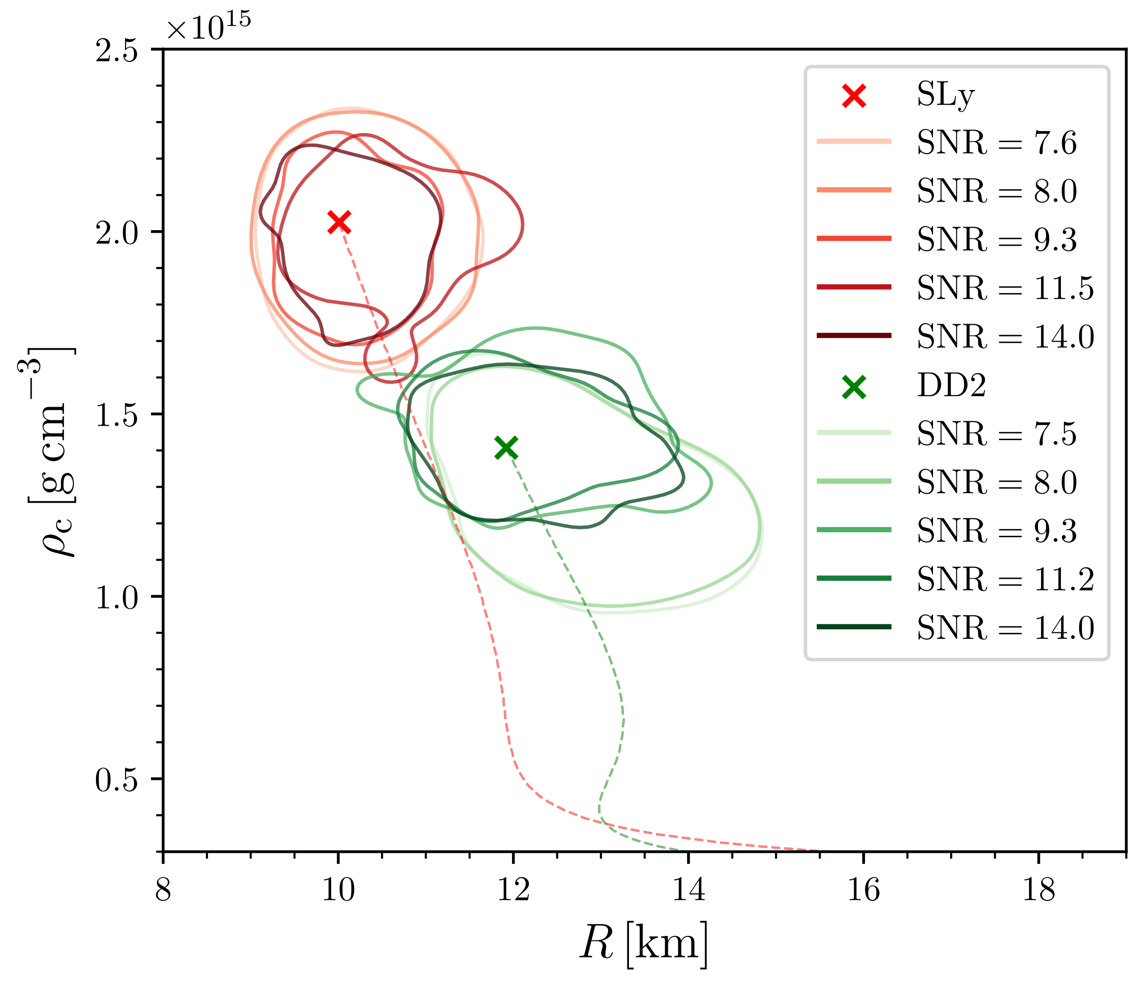


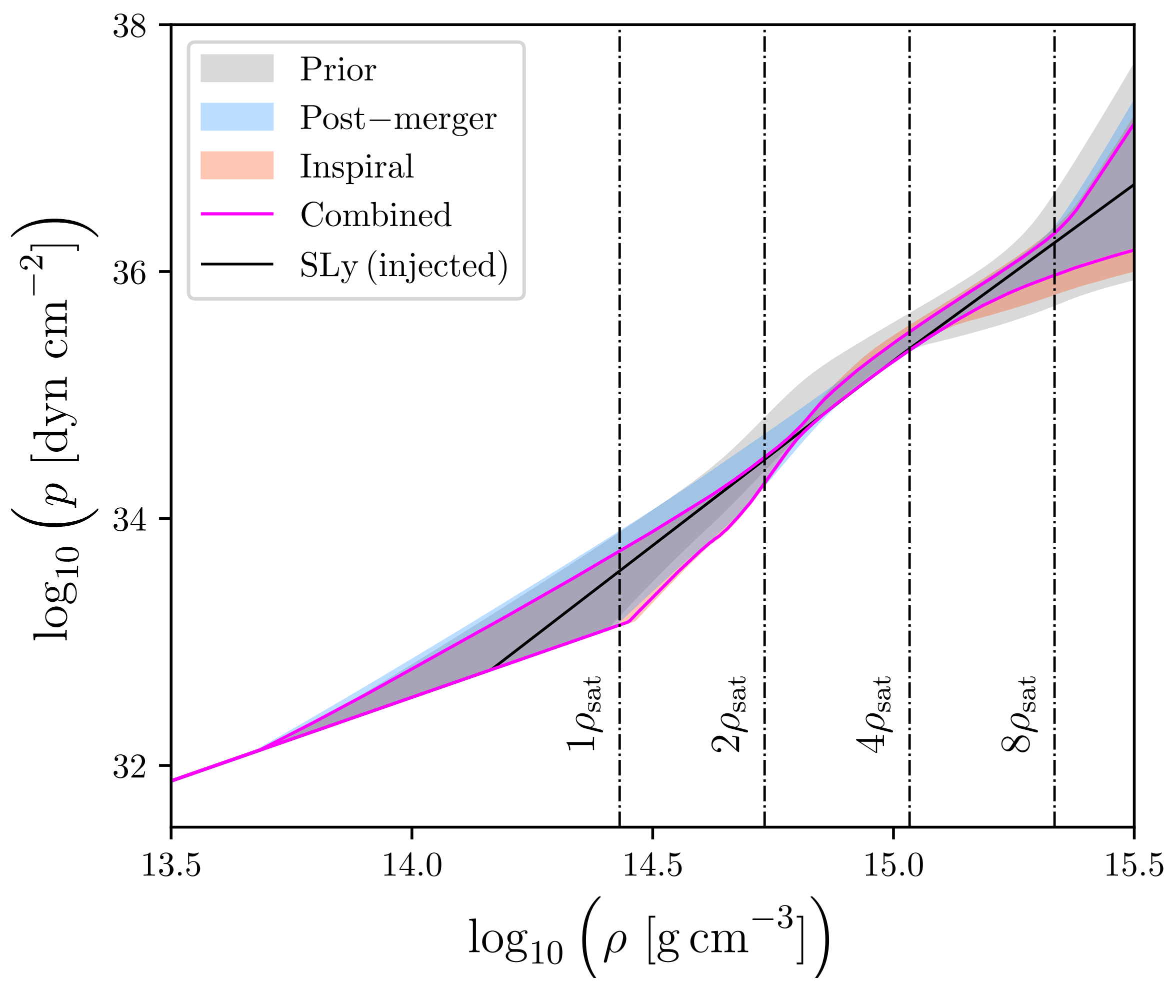


[9] M. Breschi *et al.*, 10.1103/PhysRevD.104.042001 (2021)

High-density constraints

- PM data provide **high-density constraints**, employing inspiral information[10]
- **Full-spectrum BNS** observation is expected to reduce of ~60% the current uncertainties on the nuclear EOS
- EOS inference allows us to estimate the **maximum NS mass** with an accuracy > 10%





[10] M. Breschi *et al.*, (*in preparation*) (2021)

Outlook

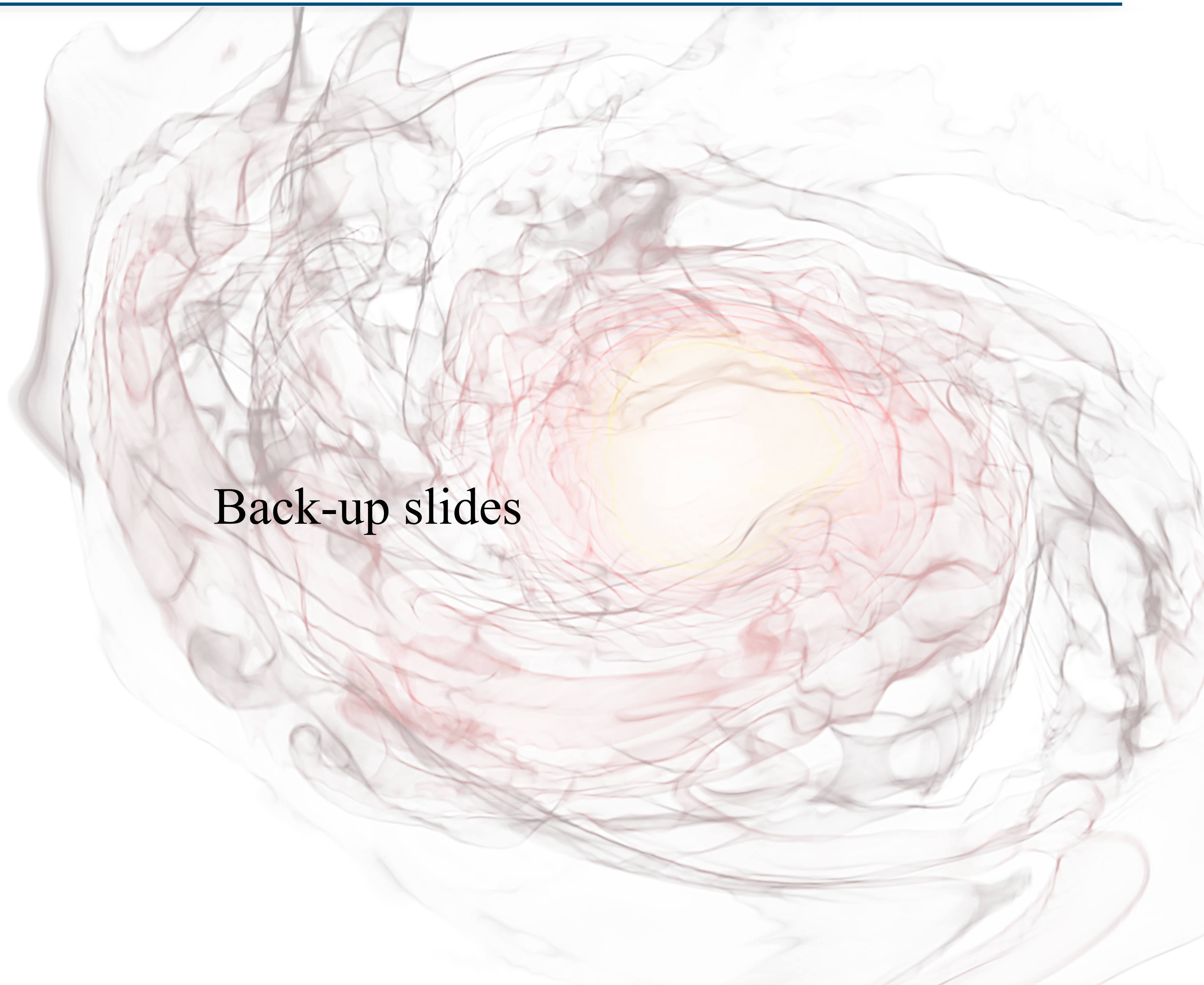
- Current data gives informative results constraining $\boldsymbol{R}_{1.4\mathrm{M}_\odot}$ to 12.2 ± 0.5 km (1σ level)

- **NR-informed formulae** allow us to combine GW+KN inferences

- Next-generation PM data will provide information on the **high-density EOS properties**

- Resources are available on the web
  - **`bajes`** pipeline, `https://github.com/matteobreschi/bajes`
  - **`CoRe`** database, `http://www.computational-relativity.org`

Thanks!



Back-up slides

Bayesian model

- Starting from the **Bayes' theorem**

$$p(\boldsymbol{\theta}|\boldsymbol{d}) = \frac{p(\boldsymbol{d}|\boldsymbol{\theta})\, p(\boldsymbol{\theta})}{p(\boldsymbol{d})}$$

Likelihood function

Prior distribution

Evidence

Posterior distribution

- **GW likelihood** taken as Gaussian in the Fourier domain

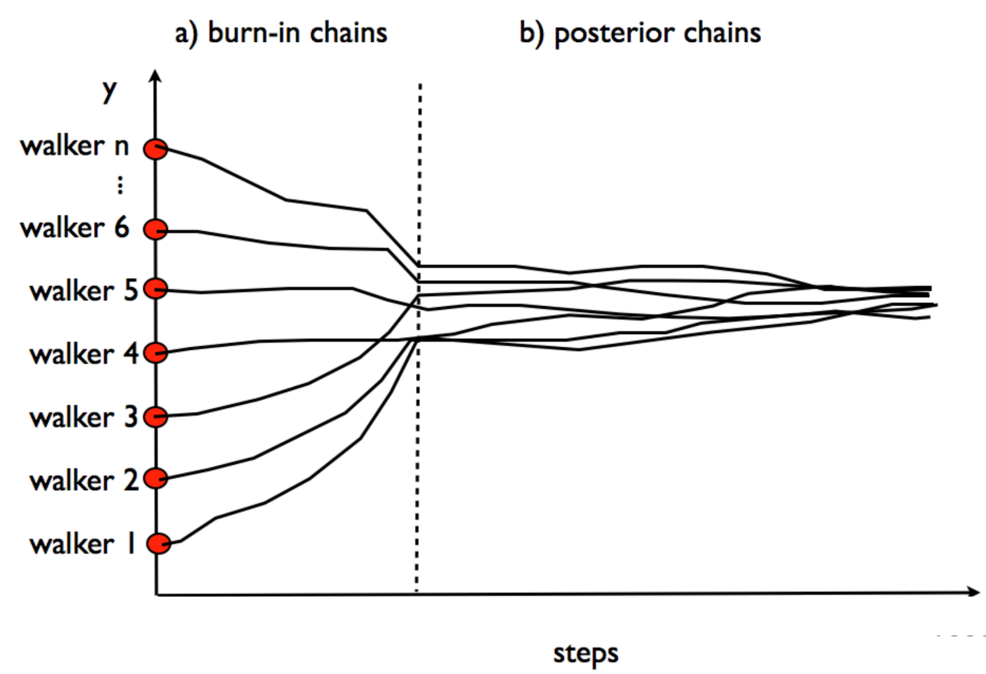
$$\log p(\boldsymbol{d}|\boldsymbol{\theta}) \propto -\frac{1}{2} \int \frac{|\tilde{d}(f) - \tilde{h}(f;\boldsymbol{\theta})|^2}{S_n(f)}\, \mathrm{d}f$$

- **kN likelihood** taken as Gaussian in the bolometric magnitudes

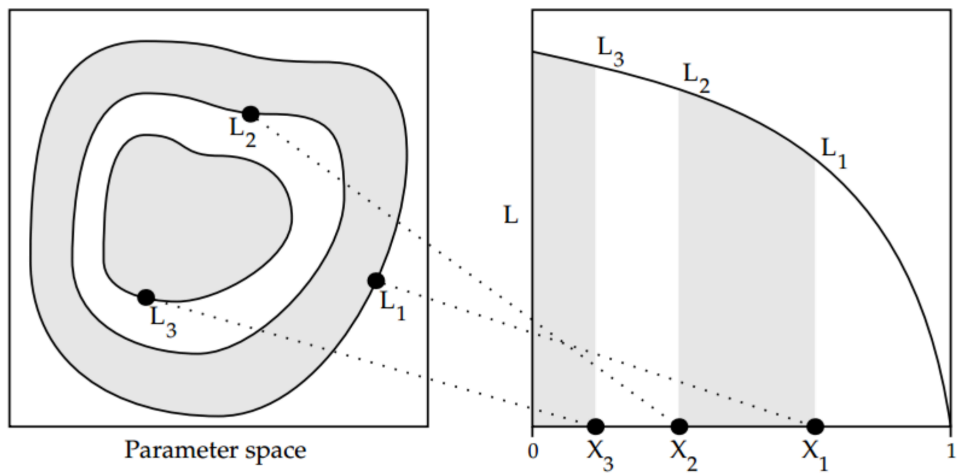
$$\log p(\boldsymbol{d}|\boldsymbol{\theta}) \propto -\frac{1}{2} \sum_b \int \frac{\left[d_b(t) - \ell_b(t;\boldsymbol{\theta})\right]^2}{\sigma_b^2(t)}\, \mathrm{d}t$$

Sampling

- In a realistic scenario, the likelihood is non-trivial
  - Statistical computational methods improve the exploration of the **parameter space**



- **Markov-chain Monte Carlo**
  - Computational thermalization process
  - Reproduce the targeted probability

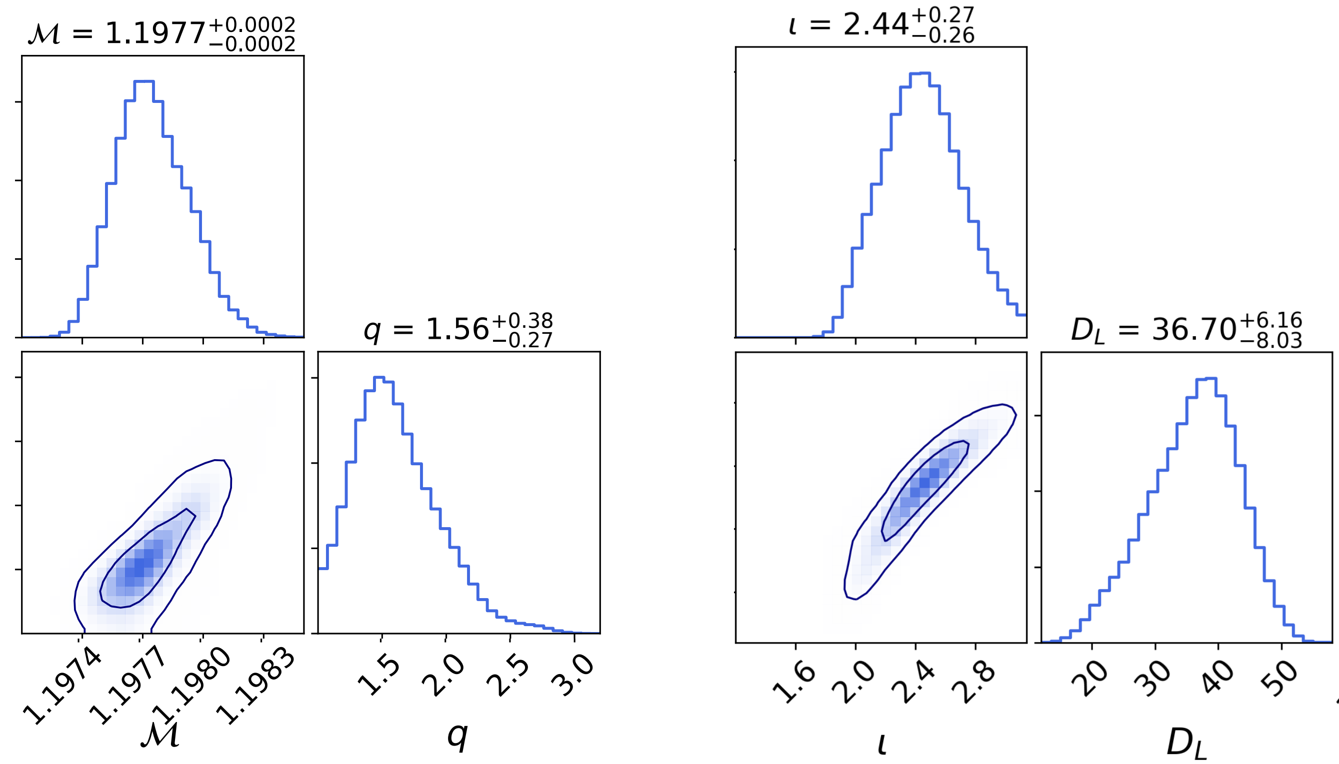


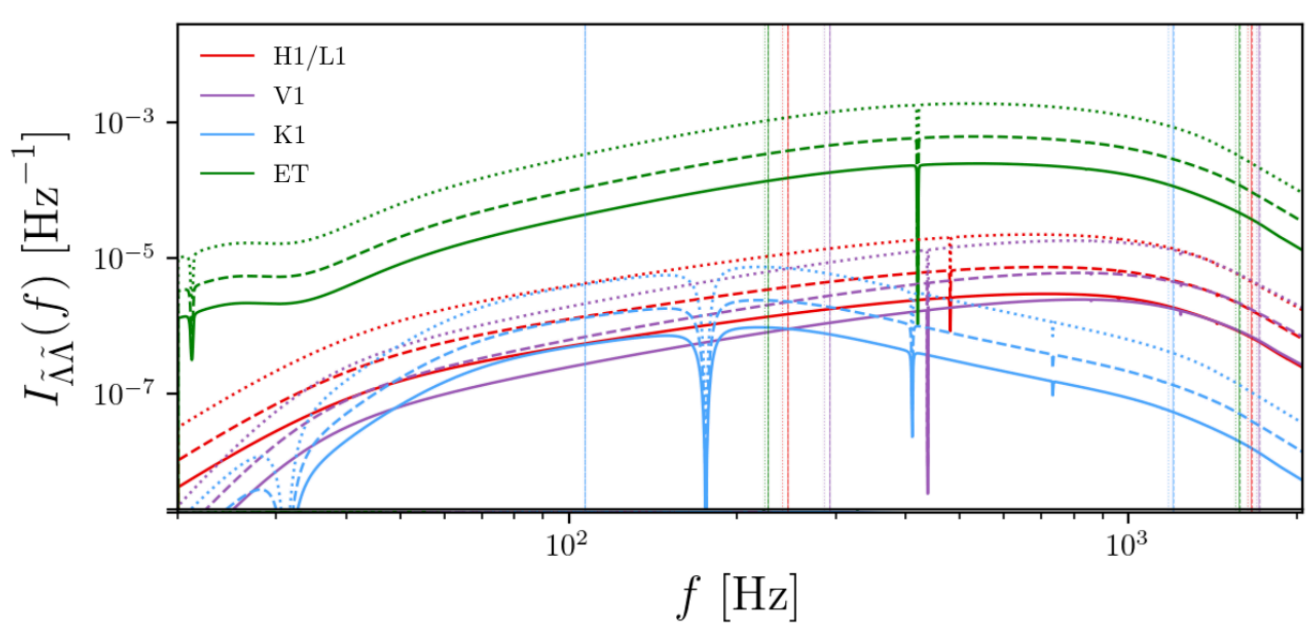
- **Nested sampling** [*]
  - Reconstruct isoprobability contours
  - Bayesian technique for model selection

[*] J. Skilling, doi:10.1214/06-BA127 (2006)

About GW170817

- Chirp mass constrained around around 1.188 M☉
- Mild spin contributions
- Source located at ~40 Mpc
- Discrepancies in tidal parameter with different approximants
- Tidal parameter is informed at high-frequency regimes

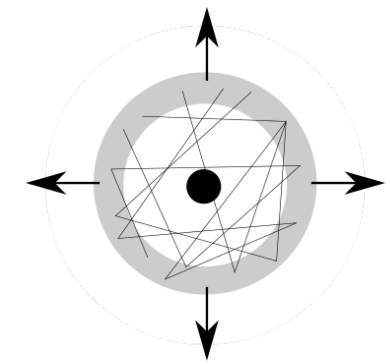




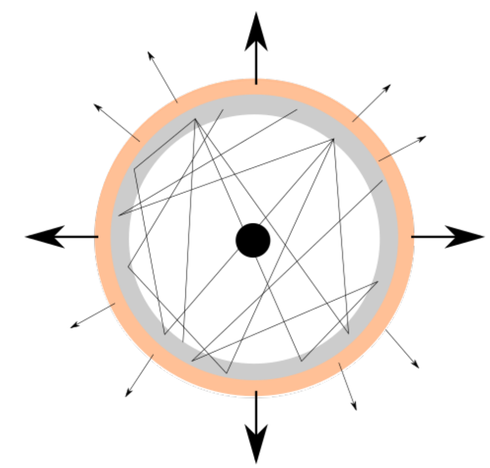
kN lightcurve

- For a fixed profile, a single ejecta shell is characterized by three parameters: **mass**, **velocity** and **gray opacity**

$$\boldsymbol{\theta}_{\rm ej} = \{m, v, \kappa\} \times N_{\rm components}$$



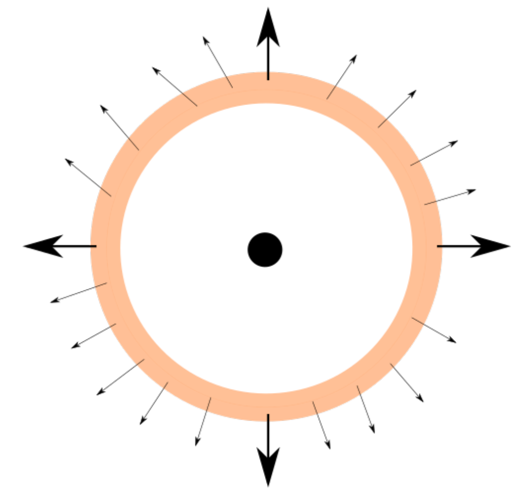
- The **photosphere radius** $R_{\rm ph}$ and the **effective temperature** $T_{\rm eff}$ are estimated for every shell



- Then, the **bolometric flux** is computed as

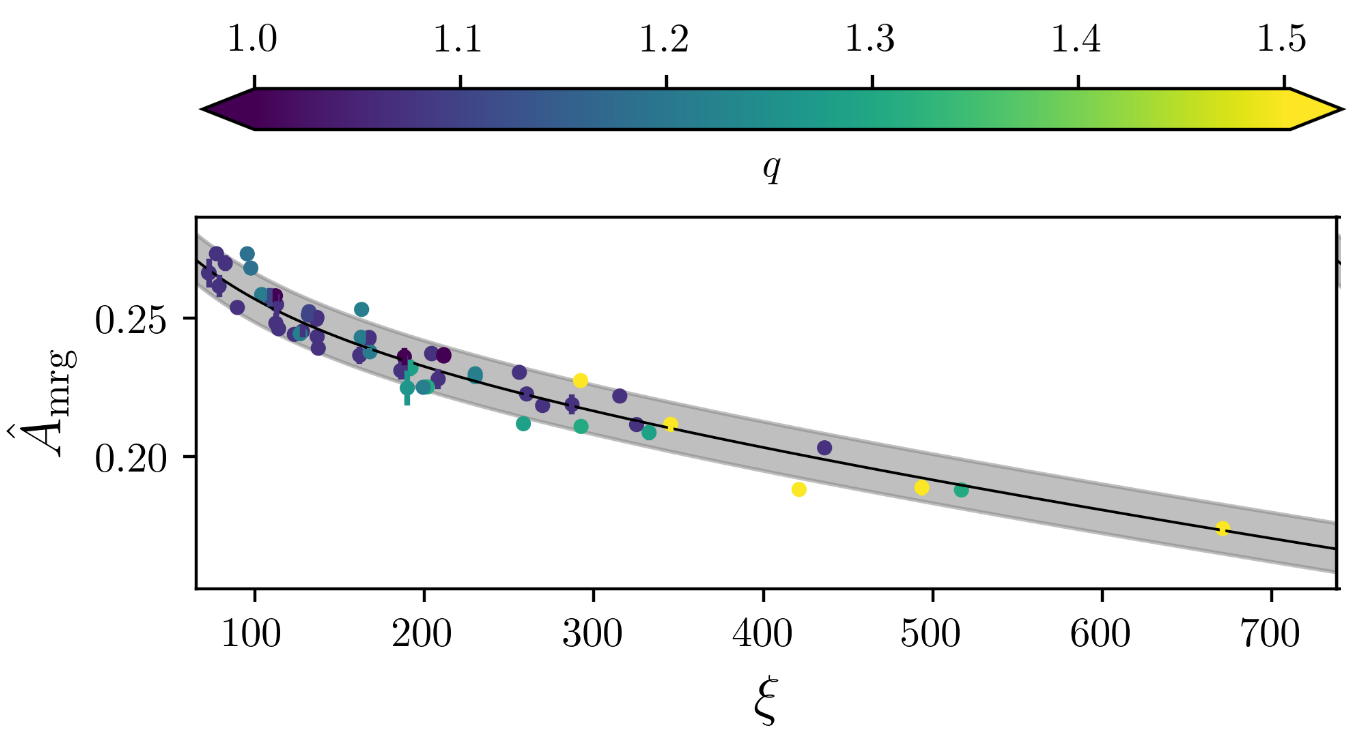
$$F_\nu(\mathbf{n}, t) = \int_{\mathbf{n}_\Omega \cdot \mathbf{n} > 0} \left(\frac{R_{\rm ph}(\Omega, t)}{D_L} \right)^2 B_\nu(T_{\rm eff}(\Omega, t))\ \mathbf{n} \cdot {\rm d}\boldsymbol{\Omega}$$

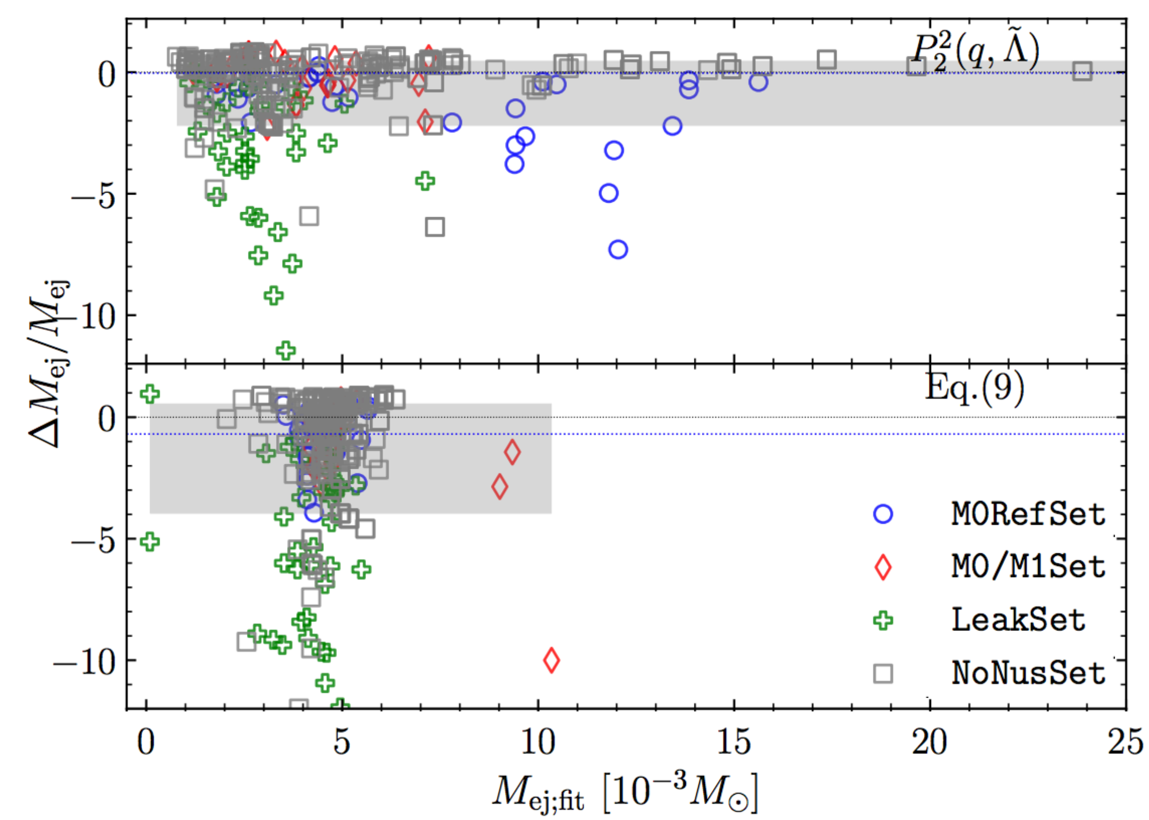
- Finally, the contributions of each shell are gathered together in order to compute the total magnitudes for each photometric band



NR information

- Numerical relativity (NR) information allows observable quantities to be mapped into progenitor parameters through calibrated formulae
  - **Ejecta**: dynamical masses, velocities, opacities and disk masses [*]
  - **Postmerger**: characteristic frequencies, amplitudes and times [#]
  - **Accuracy of the fits** is intrinsically related with NR errors

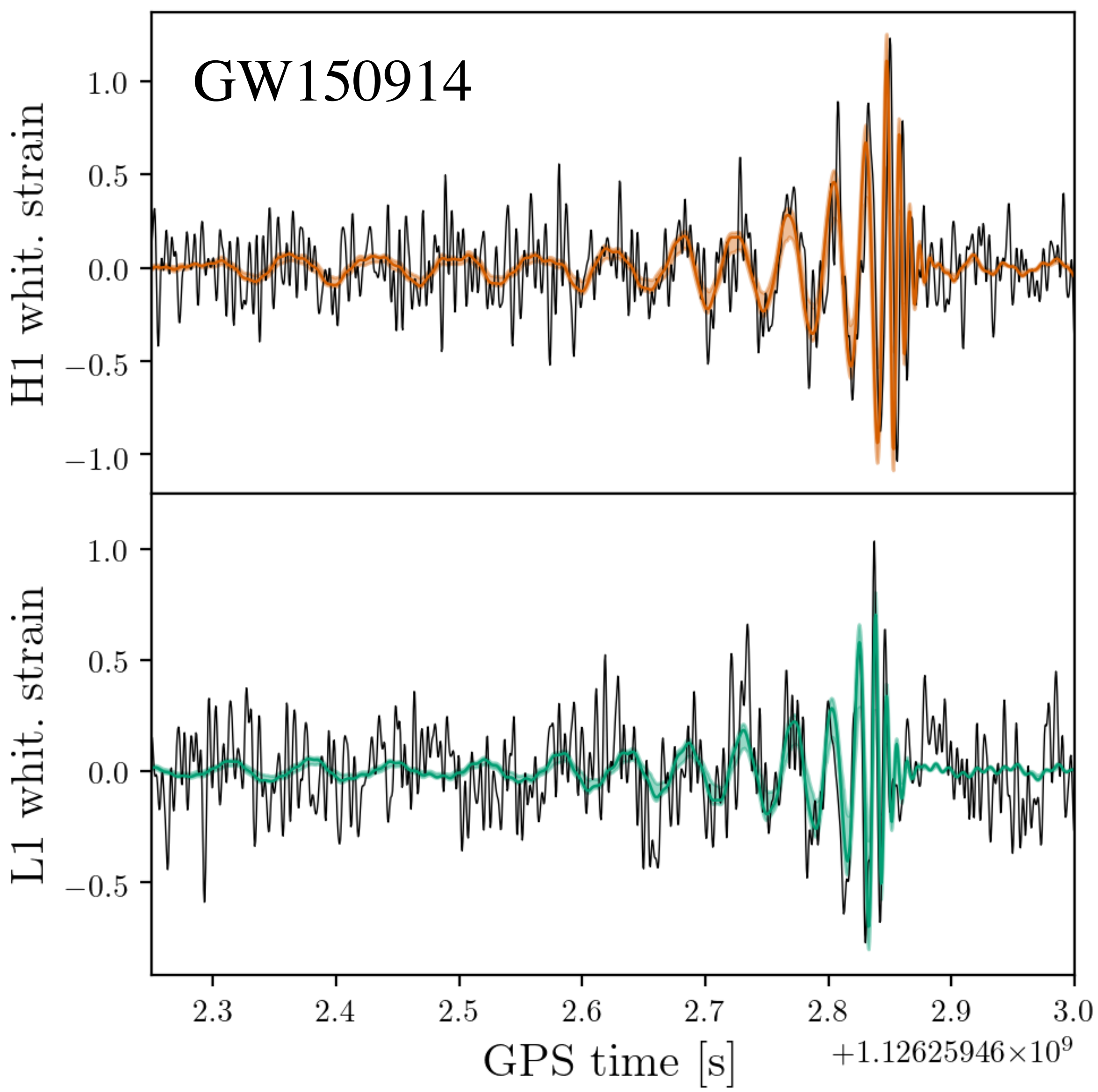


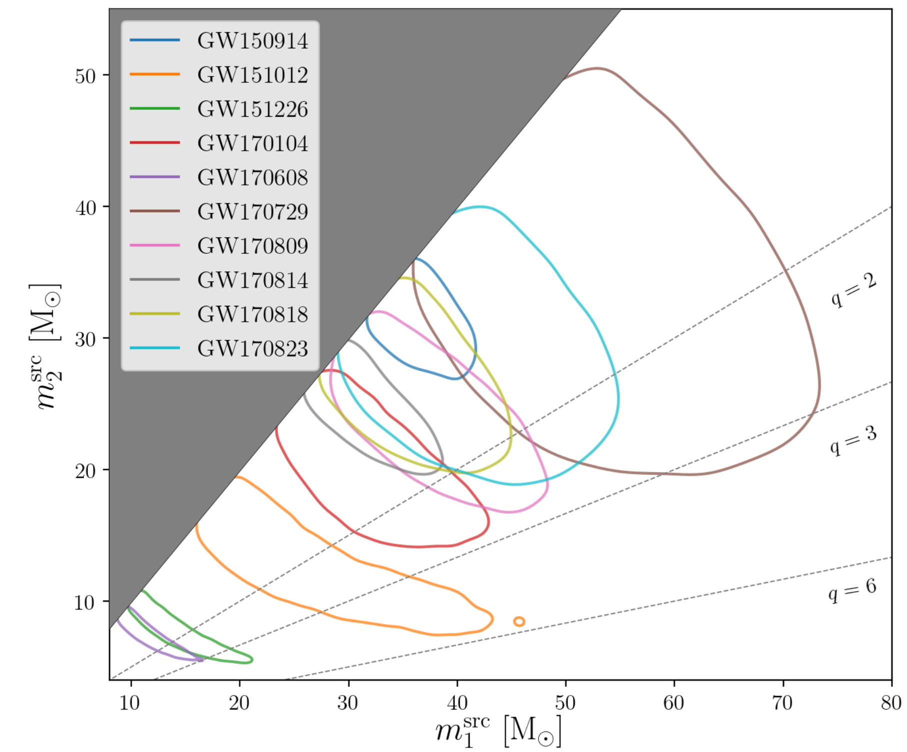


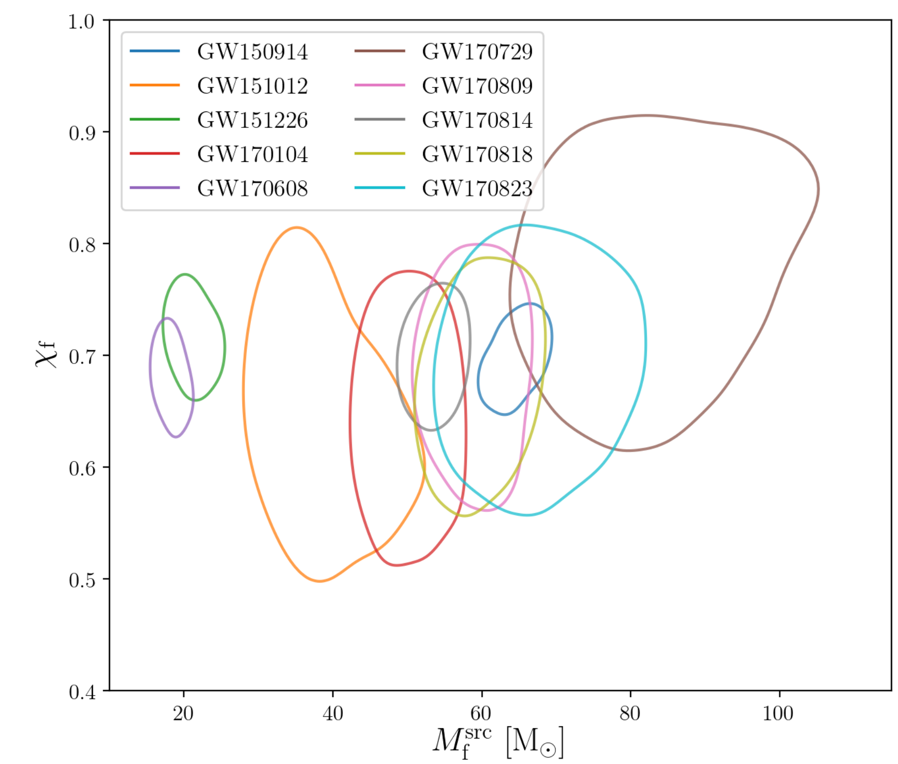
[*] V. Nedora *et al.*, arXiv:2011.11110 (2020)
[#] M. Breschi *et al.*, 10.1103/PhysRevD.100.104029 (2019)

GWTC-1

- We re-analyze the BBH mergers presented in GWTC-1 [*] using the effective-one-body model `TEOBResumS` [#]







[*] LVC, 10.1103/PhysRevX.9.031040 (2019)
[#] A. Nagar *et al.*, 10.1103/PhysRevD.98.104052 (2018)