The physics and astrophysics of merging neutron-star binaries

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Plan of the talk

- ✶The benefits of studying merging binary NSs
- ✶Anatomy of GW signal: frequencies and EOS
- ✶GW170817 and radius measurements
- ✶Dissipative effects: are they important?
- ✶Ejected mass and nucleosynthesis

The two-body problem in GR

- For BHs we know what to **expect**:

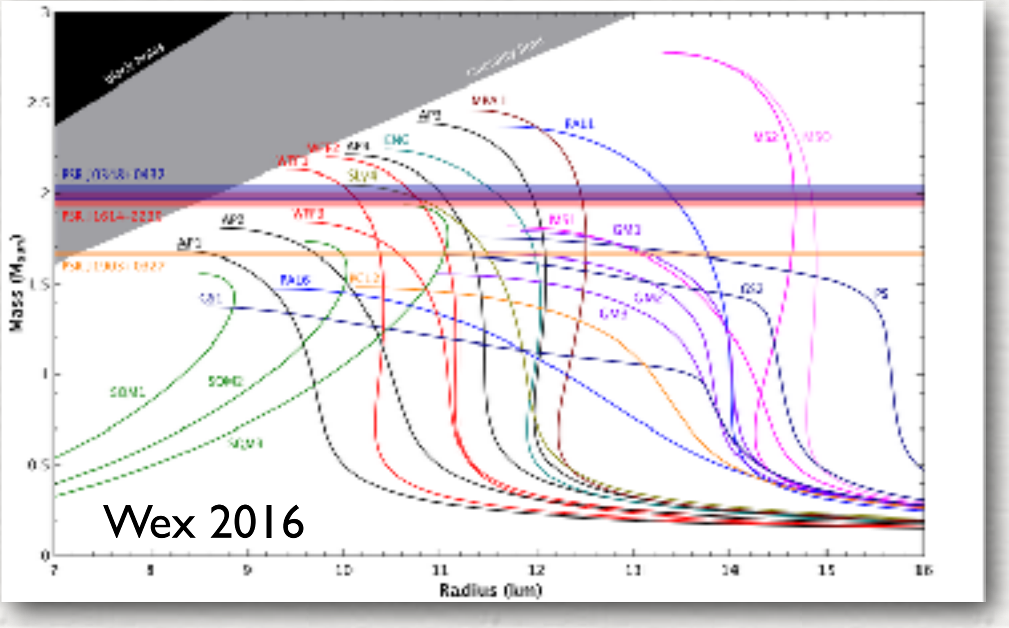
BH + BH ⟶ BH + GWs

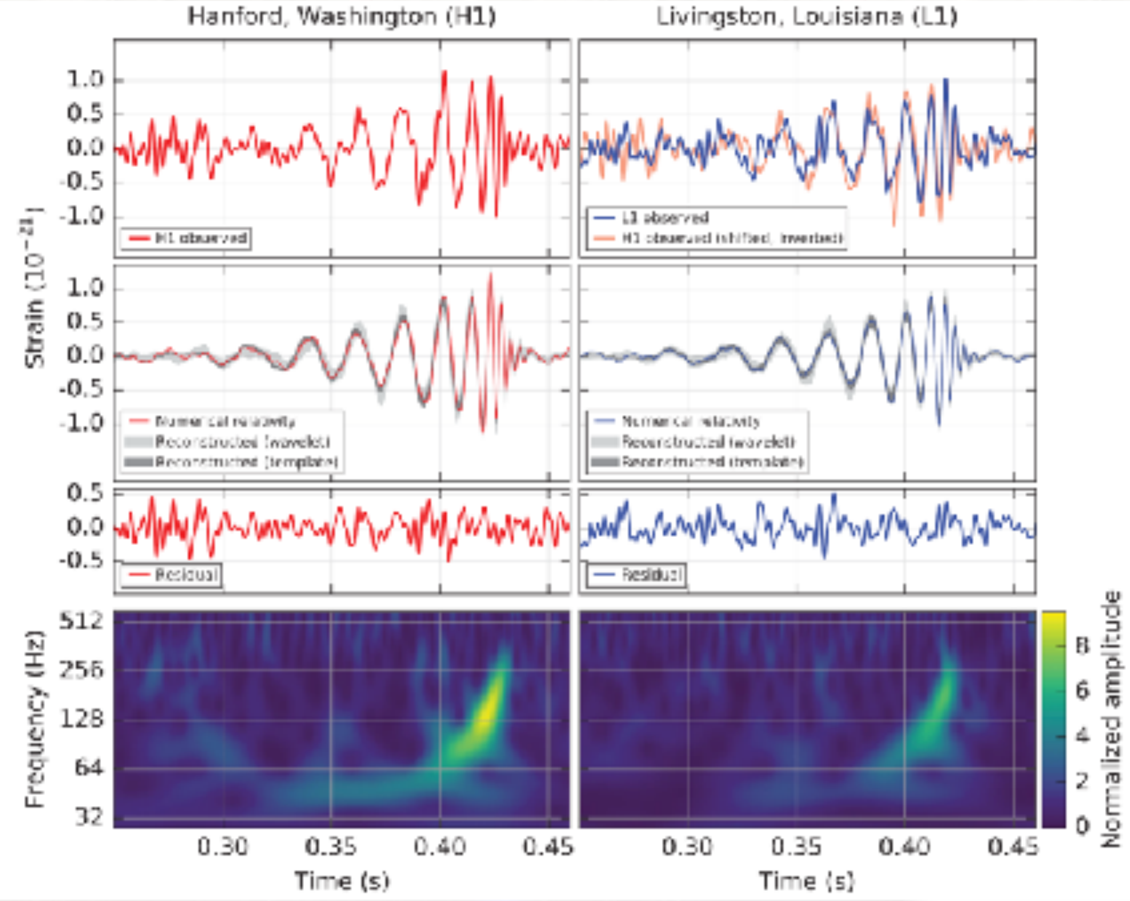
- For NSs the question is more **subtle**:

hyper-massive neutron star (HMNS), ie

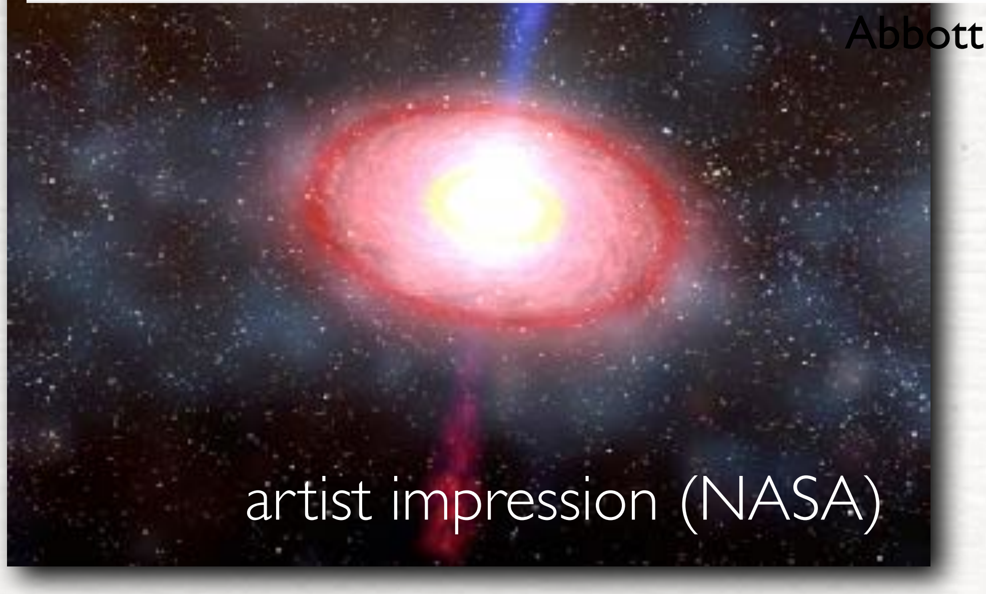
NS + NS ⟶ HMNS + **... ?** ⟶ B

- **HMNS** phase can provide clear information on **EOS**





Abbott+ 2016



- **BH+torus** system may tell us on the central engine of **GRBs**

The two-body problem in GR

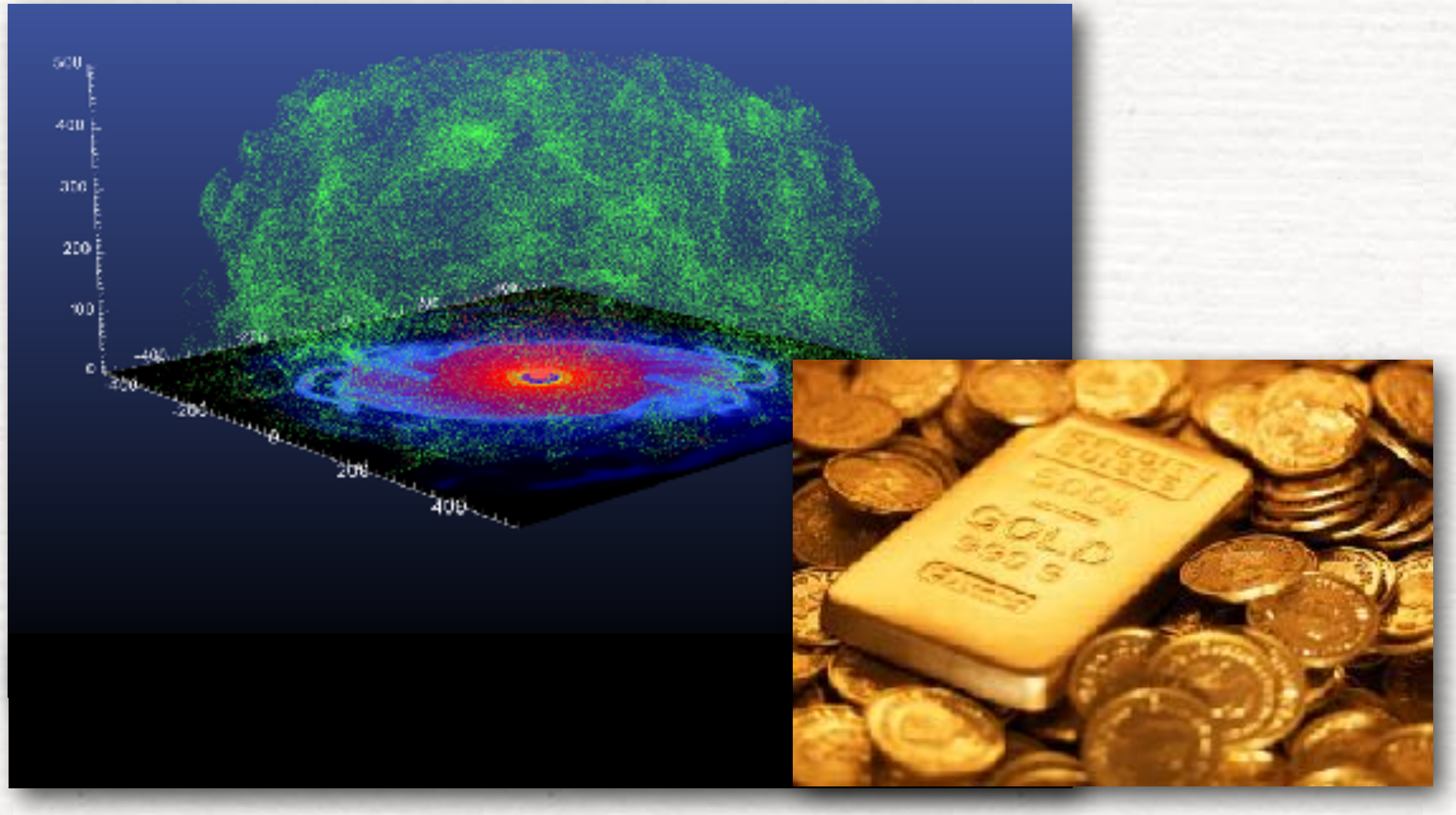
- For BHs we know what to **expect**:

$$\text{BH} + \text{BH} \longrightarrow \text{BH} + \text{GWs}$$

- For NSs the question is more **subtle:** the merger leads to an hyper-massive neutron star (HMNS), ie a metastable equilibrium:

$$\text{NS} + \text{NS} \longrightarrow \text{HMNS} + \textbf{... ?} \longrightarrow \text{BH} + \text{torus} + \textbf{... ?} \longrightarrow \text{BH}$$

- **ejected matter** undergoes nucleosynthesis of heavy elements



Animations: Breu, Radice, LR

merger $\longrightarrow$ HMNS $\longrightarrow$ BH + torus

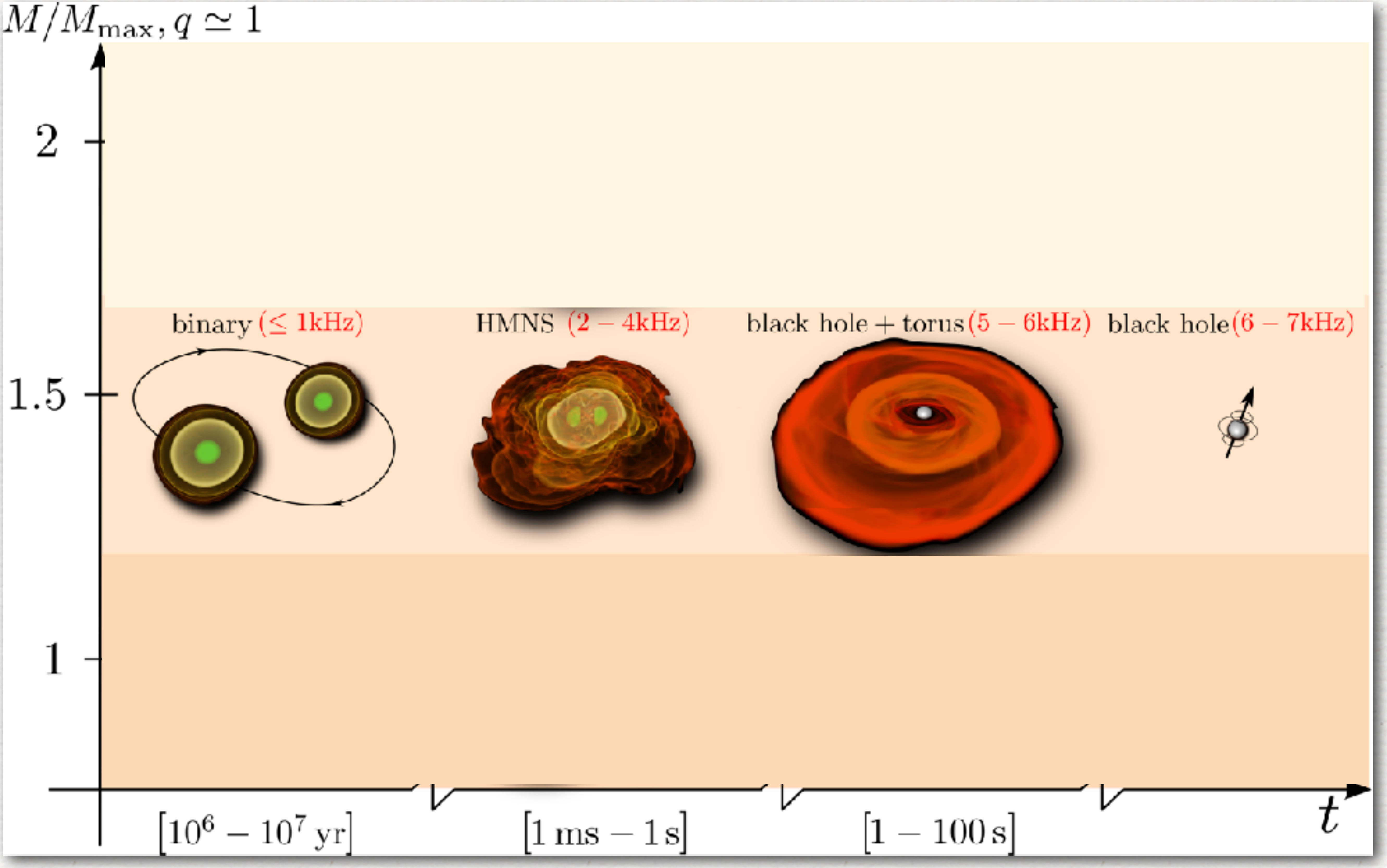
LS220 EOS

merger → HMNS → BH + torus

Quantitative differences are produced by:

- **total mass (prompt vs delayed collapse)**

Broadbrush picture



merger → HMNS → BH + torus

Quantitative differences are produced by:

- total mass (prompt vs delayed collapse)
- mass asymmetries (HMNS and torus)

Animations: Giacomazzo, Koppitz, LR

$$\text{Total mass : } 3.37\, M_{\odot}; \quad \text{mass ratio :}0.80;$$

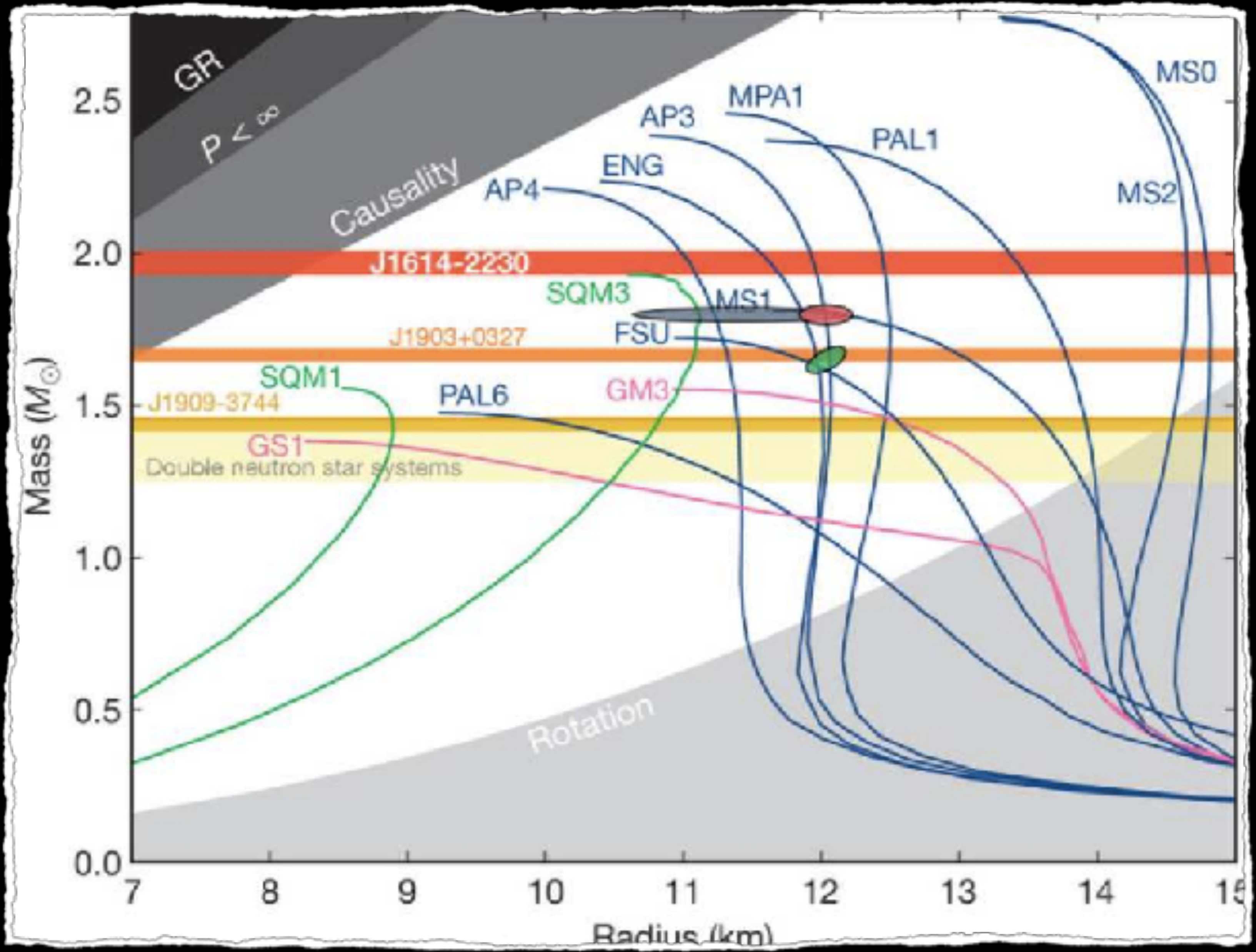
- the torii are generically more massive
- the torii are generically more extended
- the torii tend to stable quasi-Keplerian configurations
- overall unequal-mass systems have all the ingredients needed to create a GRB

merger → HMNS → BH + torus

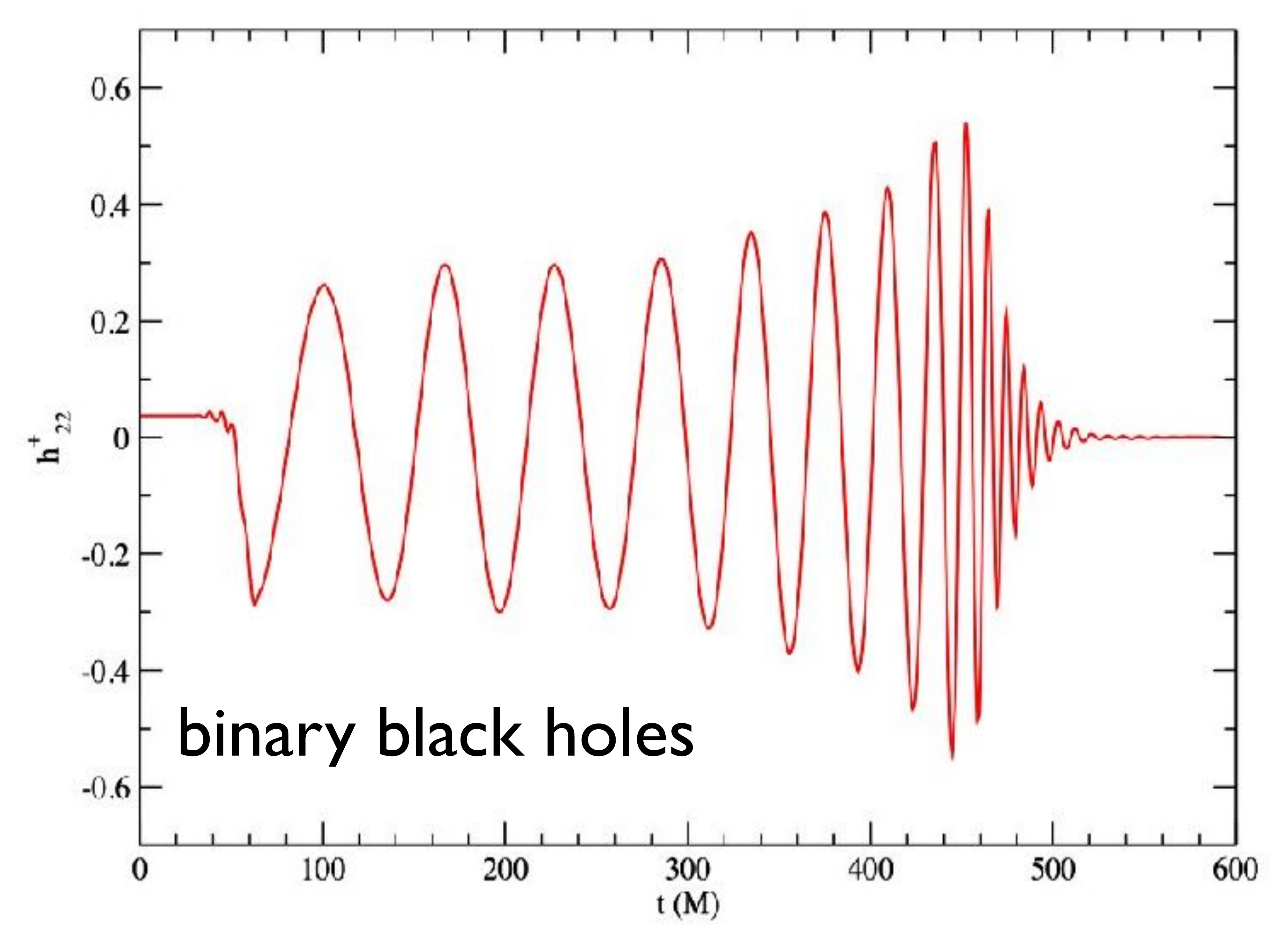
Quantitative differences are produced by:

- total mass (prompt vs delayed collapse)
- mass asymmetries (HMNS and torus)
- soft/stiff EOS (inspiral and post-merger)
- magnetic fields (equil. and EM emission)
- radiative losses (equil. and nucleosynthesis)

How to constrain the EOS

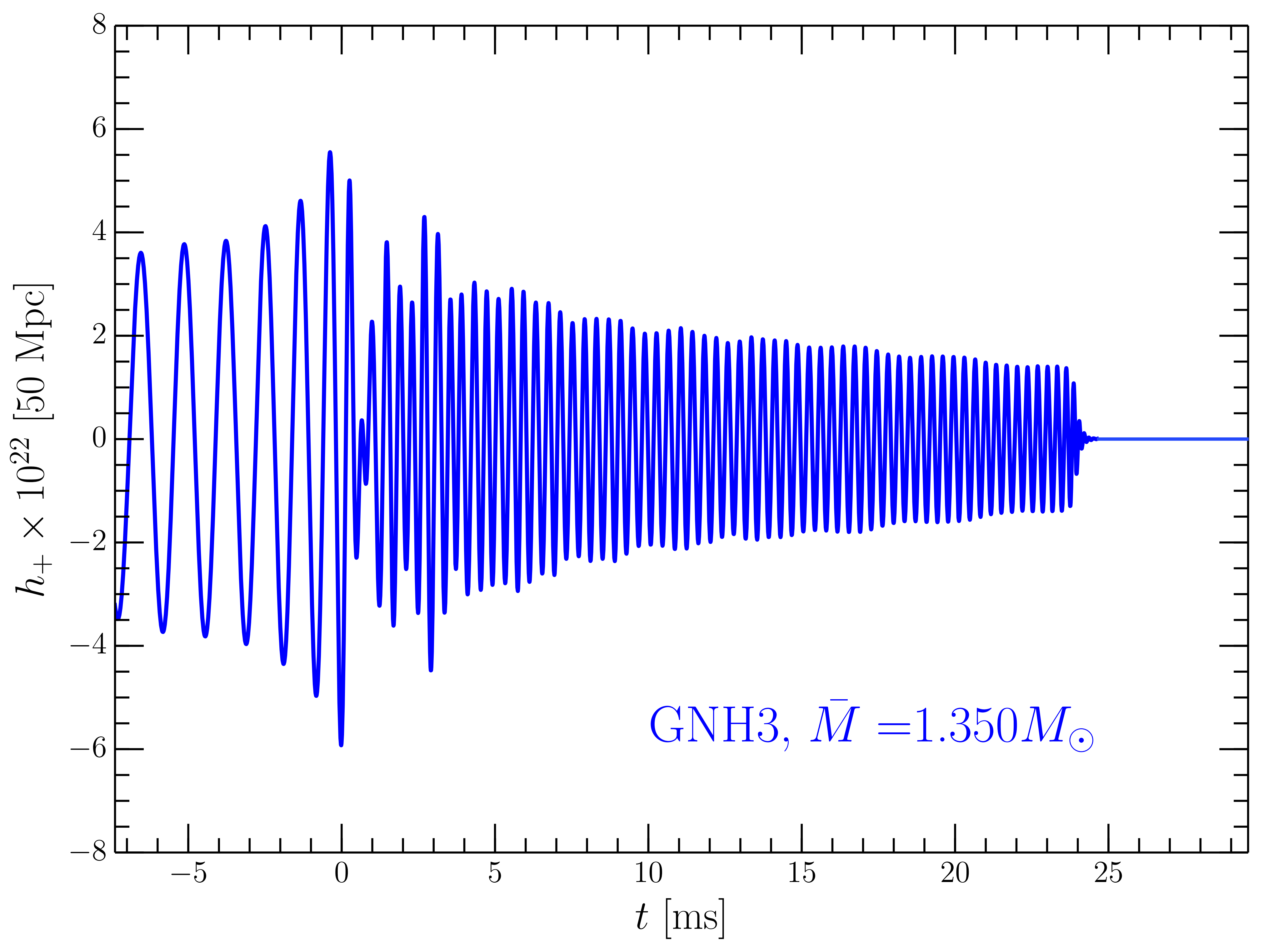


Anatomy of the GW signal

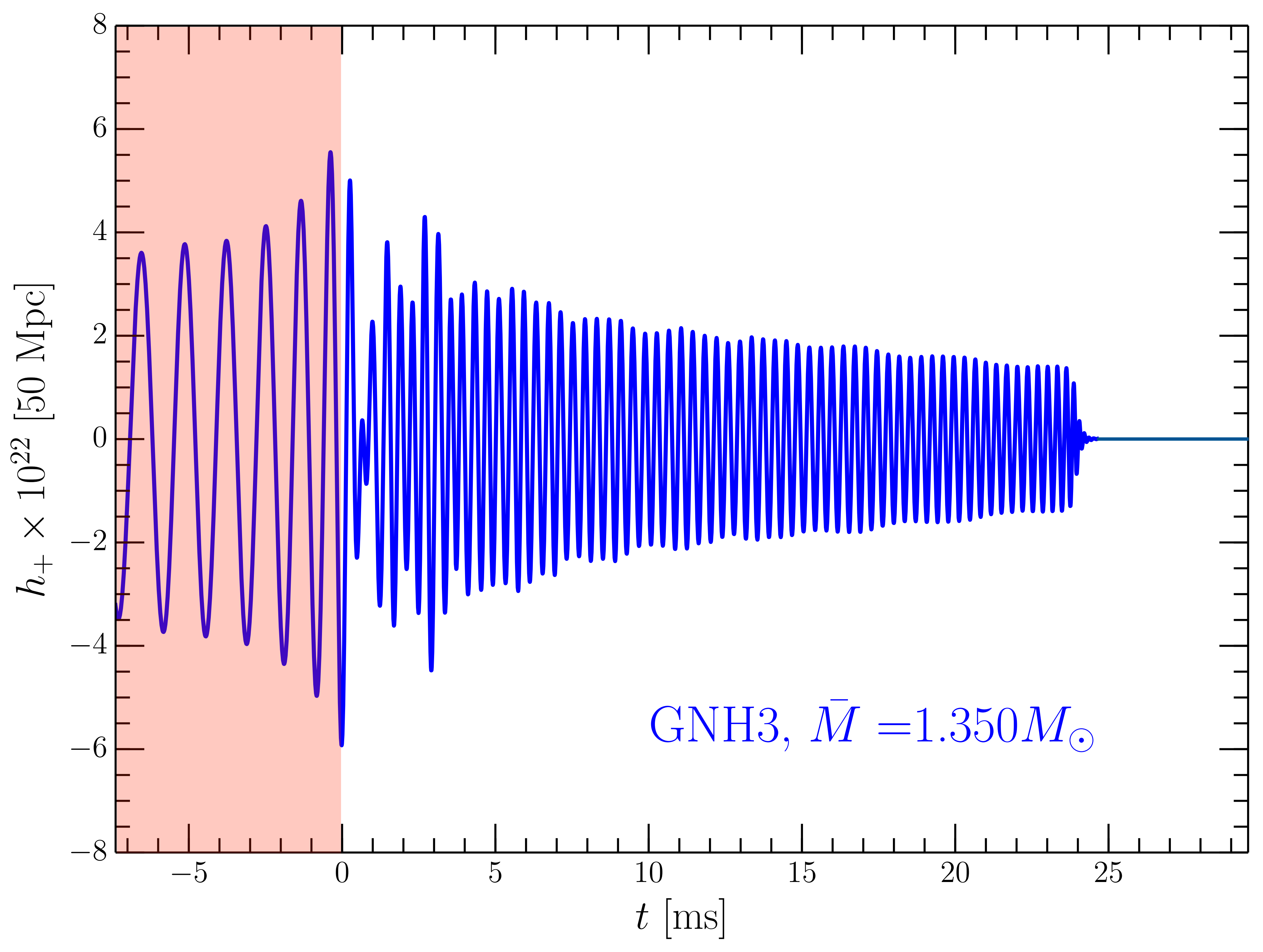


binary black holes

Anatomy of the GW signal

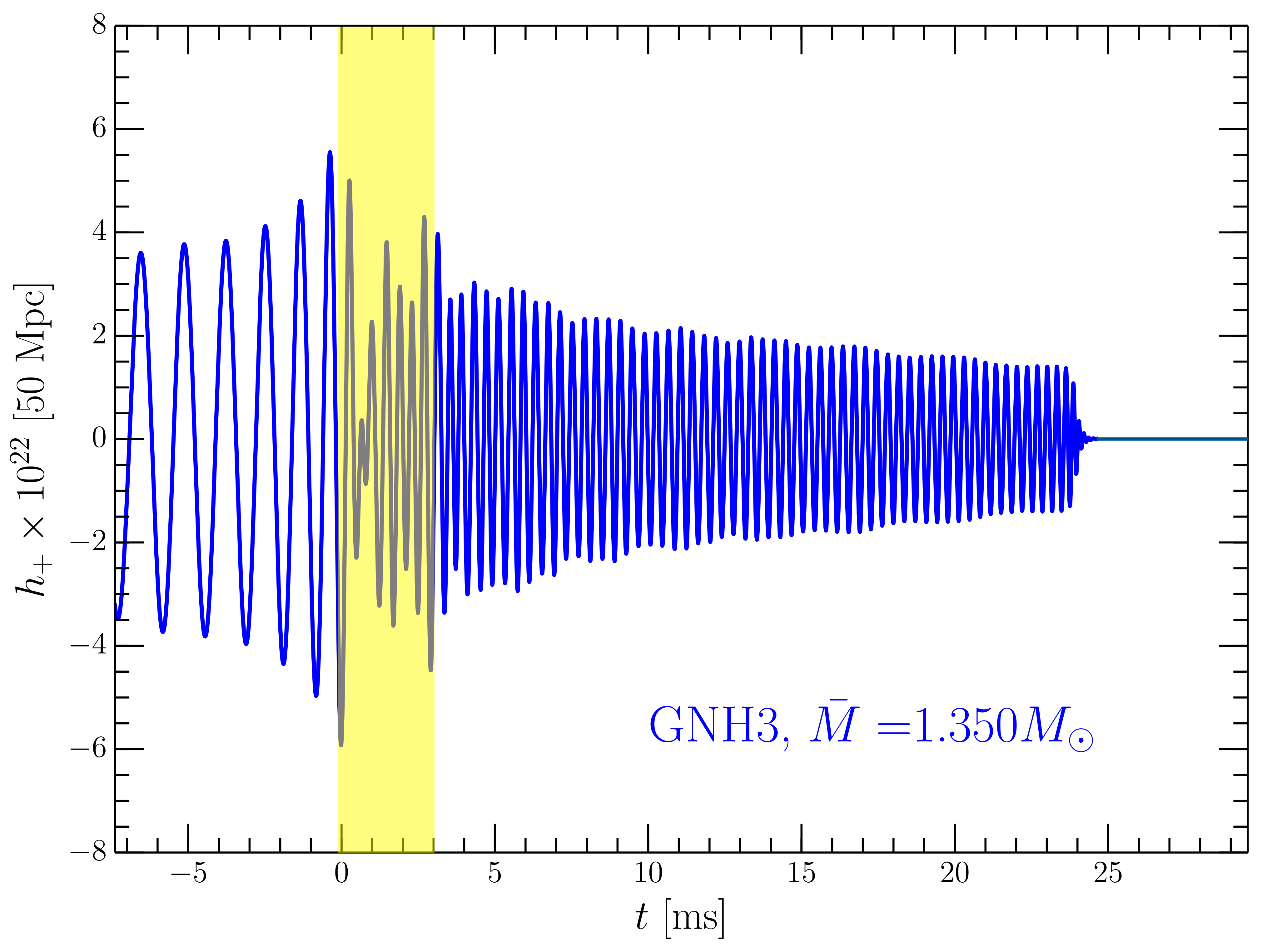


Anatomy of the GW signal



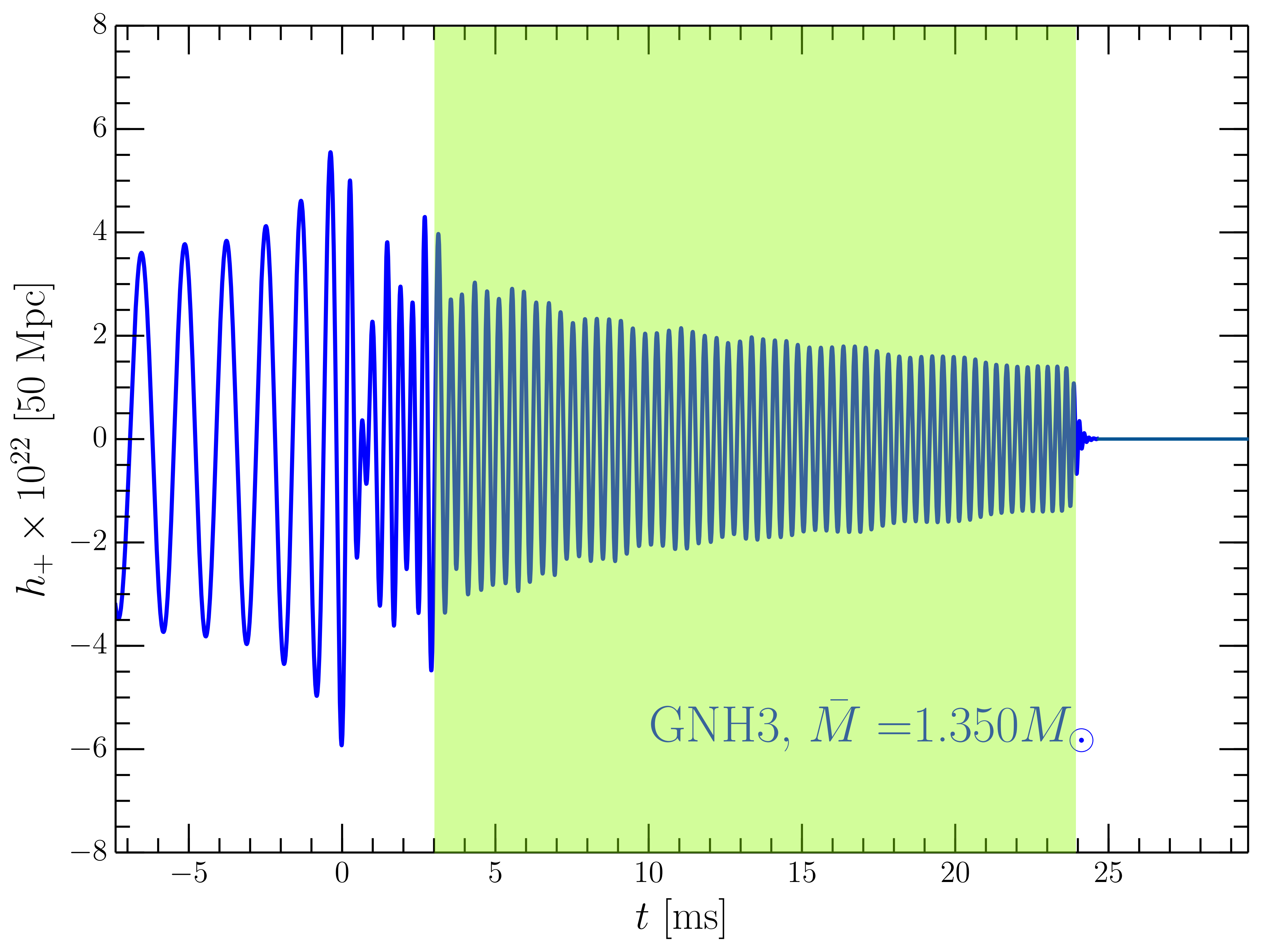
Inspiral: well approximated by PN/EOB; tidal effects important

Anatomy of the GW signal



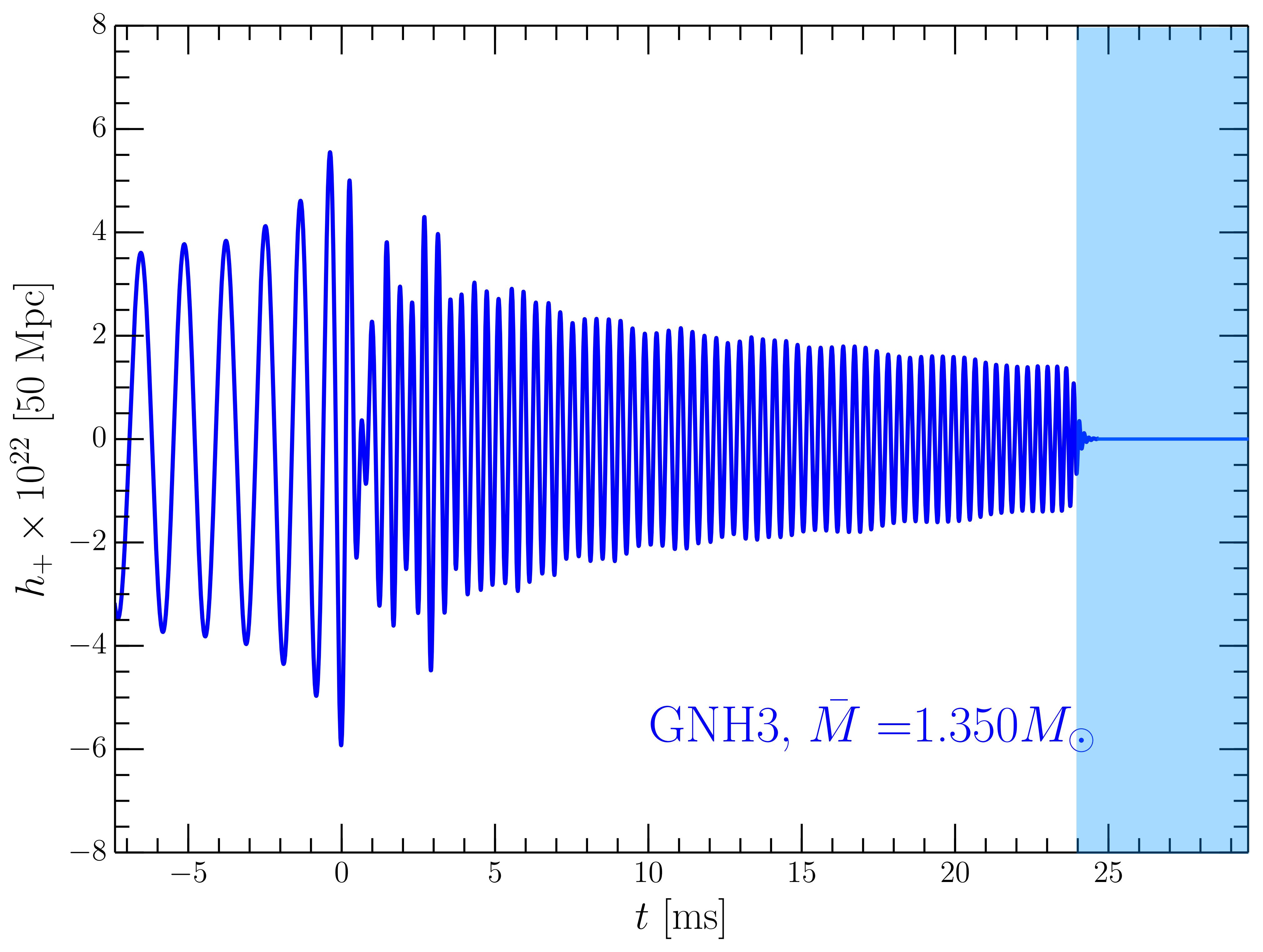
Merger: highly nonlinear but analytic description possible

Anatomy of the GW signal



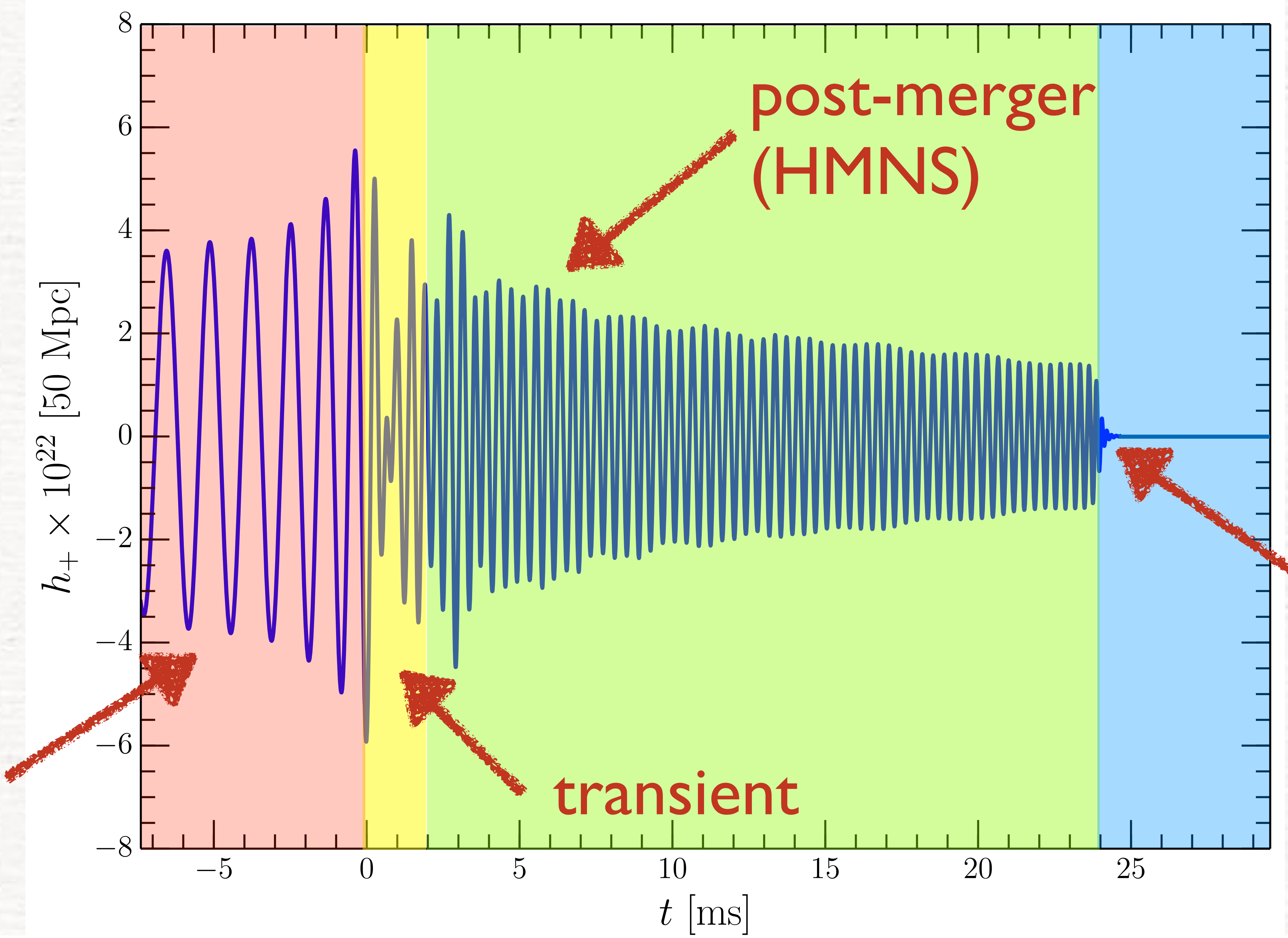
post-merger: quasi-periodic emission of bar-deformed HMNS

Anatomy of the GW signal



Collapse-ringdown: signal essentially shuts off.

Anatomy of the GW signal

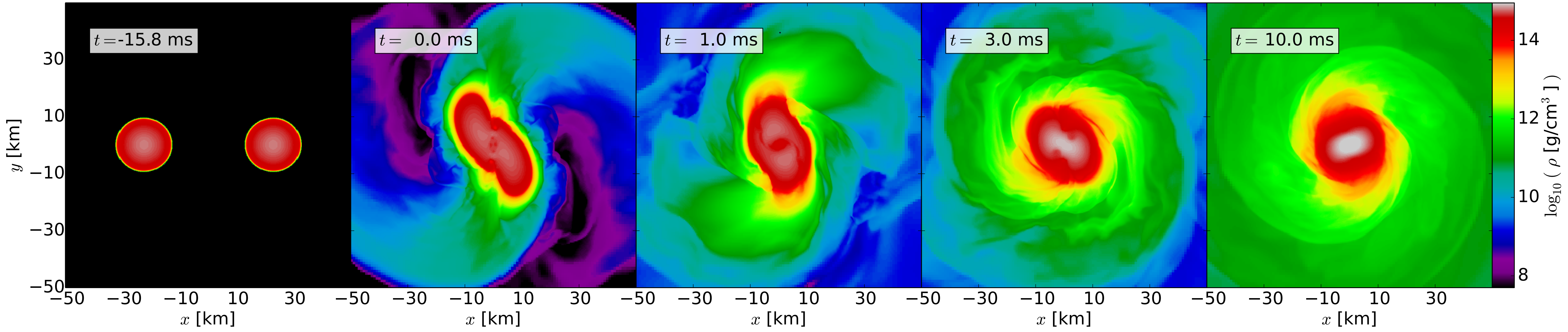


post-merger
(HMNS)

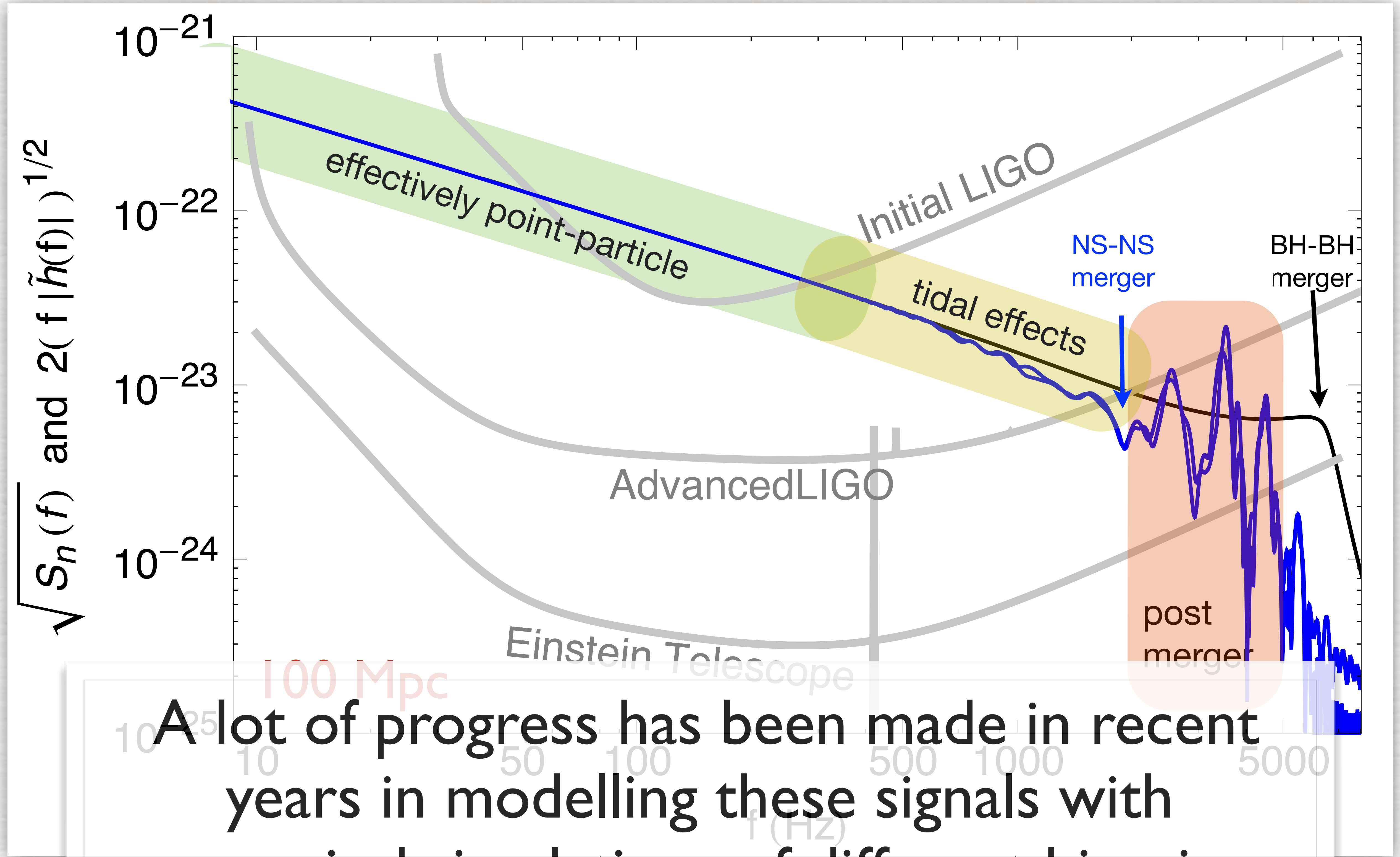
Chirp signal

transient

black-hole
formation
(ringdown)



In frequency space

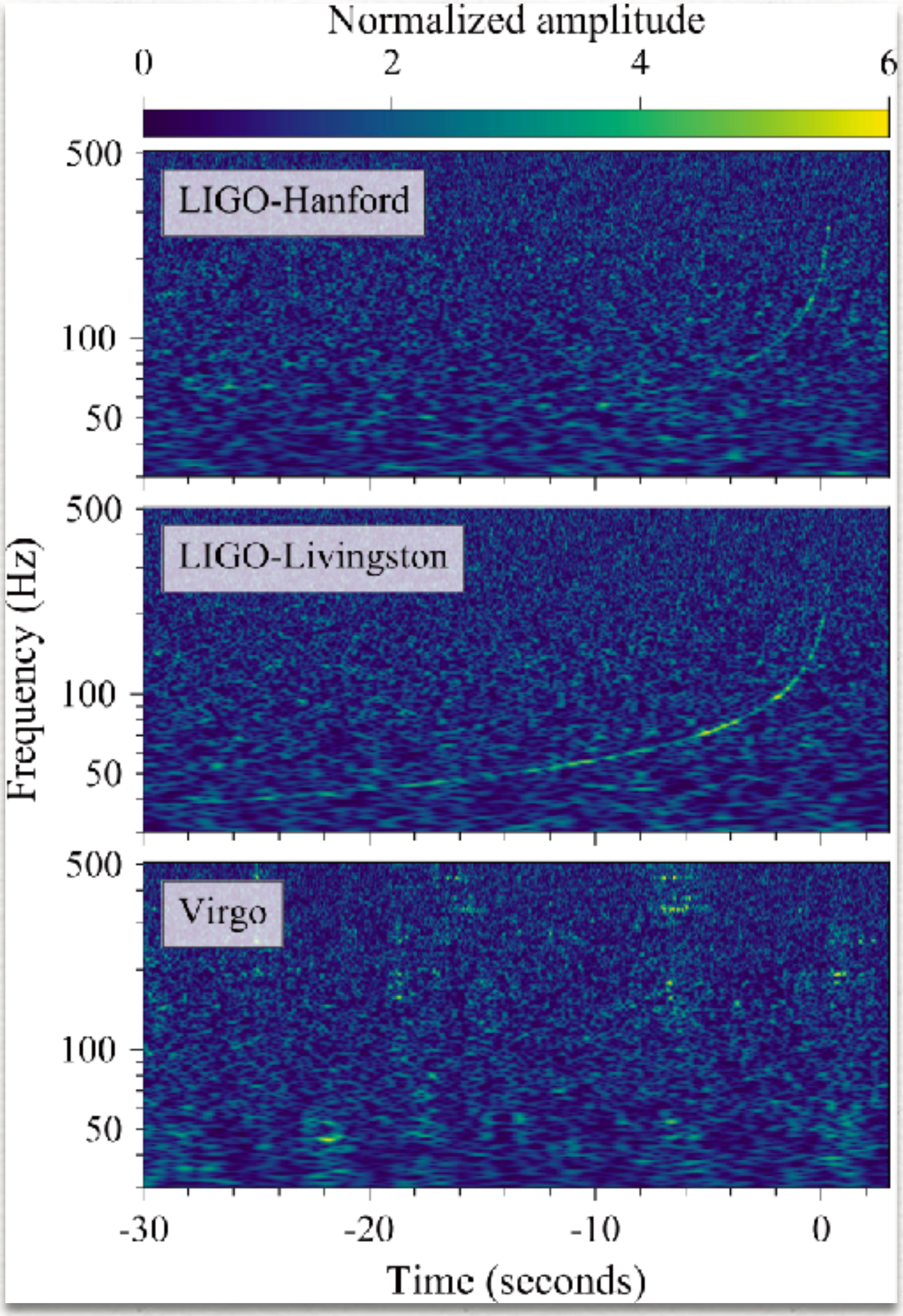


A lot of progress has been made in recent years in modelling these signals with numerical simulations of different binaries

Read et al. (2013)

GW170817

- On 16 October 2017 the LSC/Virgo collaboration announced detection of the gravitational signal from merging binary neutron-star system.



GW170817

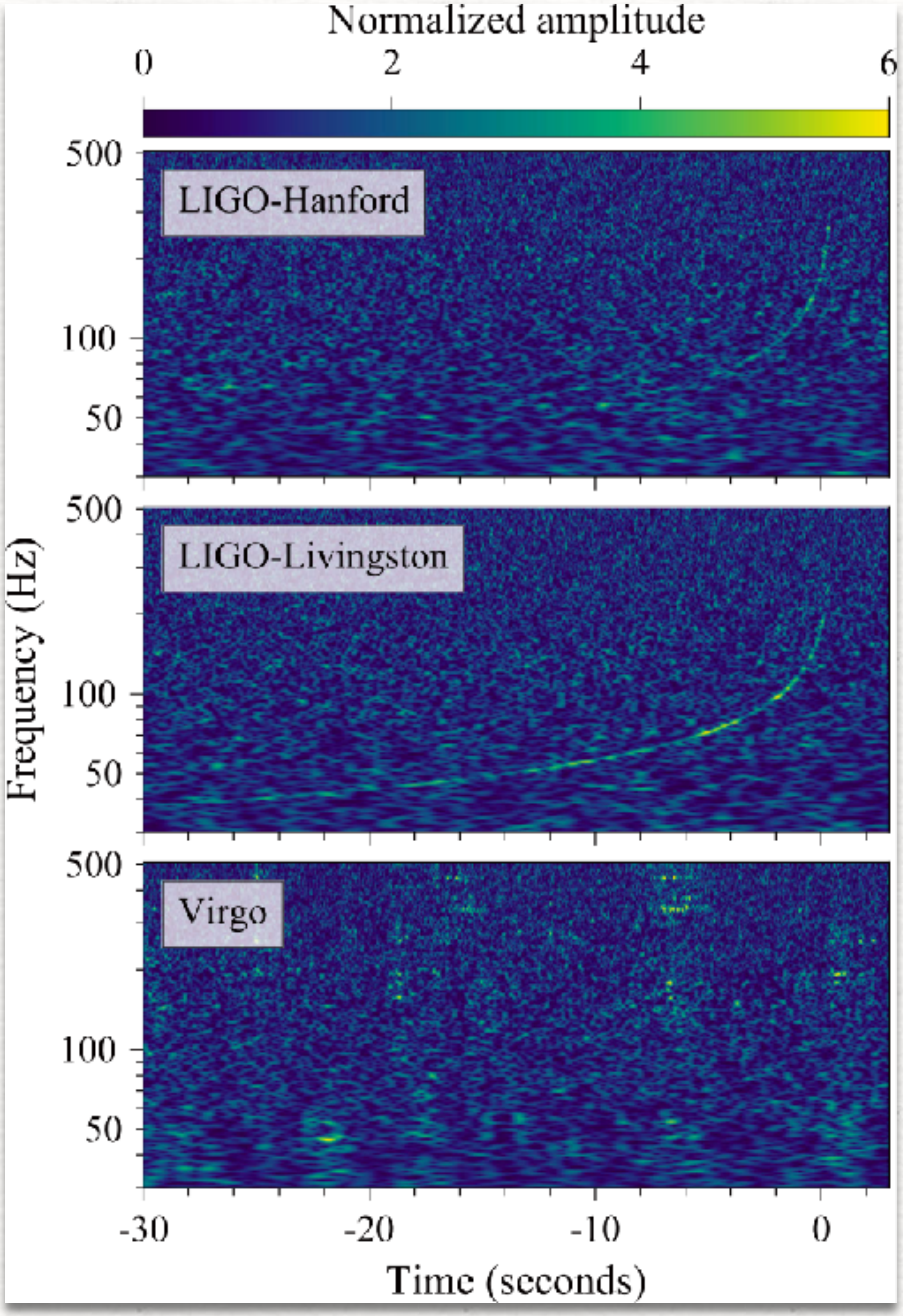
- On 16 October 2017 the LSC/Virgo collaboration announced detection of the gravitational signal from merging binary neutron-star system.
- Total mass:

$$M_1 + M_2 = 2.74^{+0.04}_{-0.01} M_\odot$$

- Individual masses:

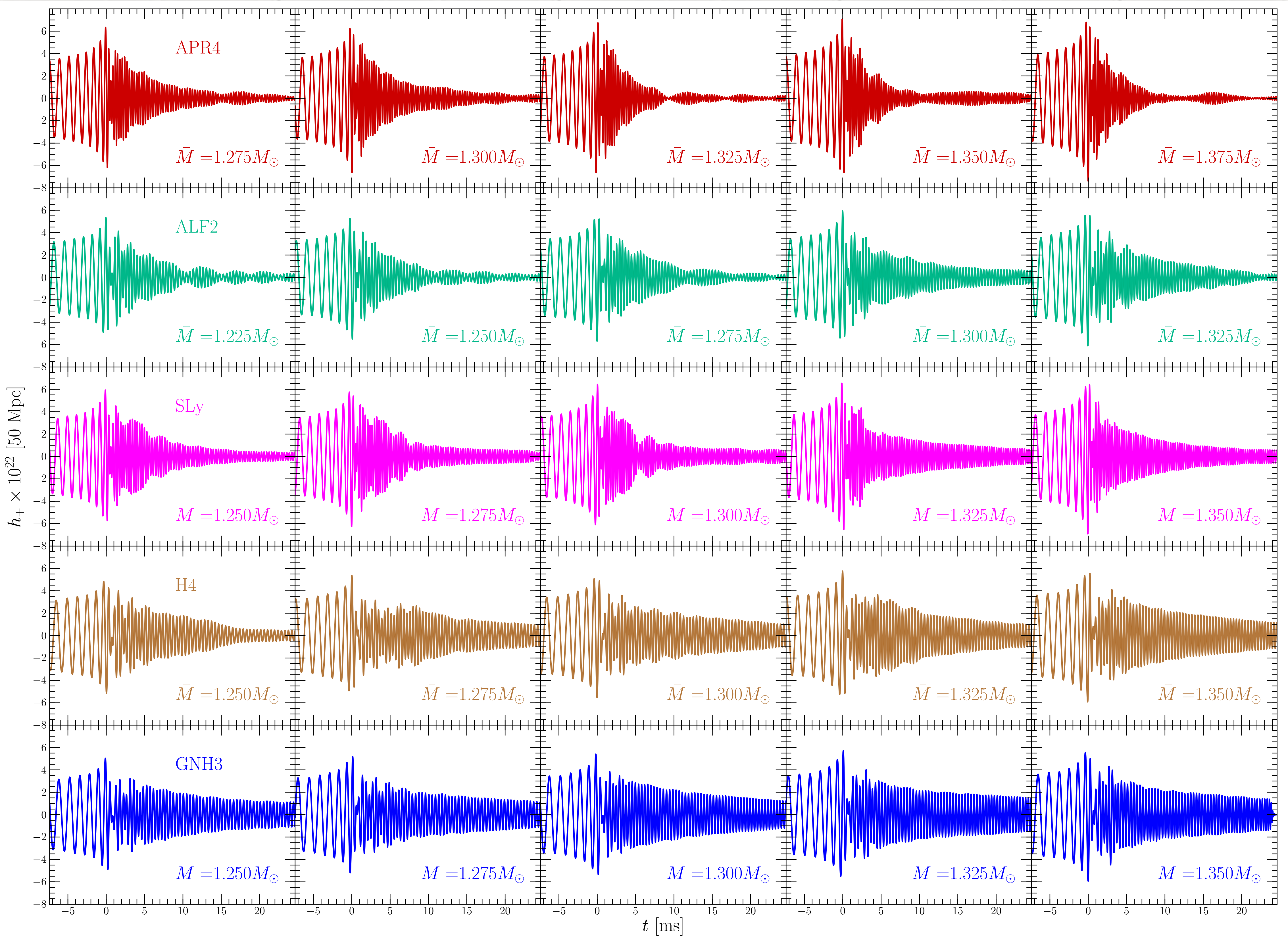
$$M_1 = 1.36 - 1.60 M_\odot$$

$$M_2 = 1.17 - 1.36 M_\odot$$



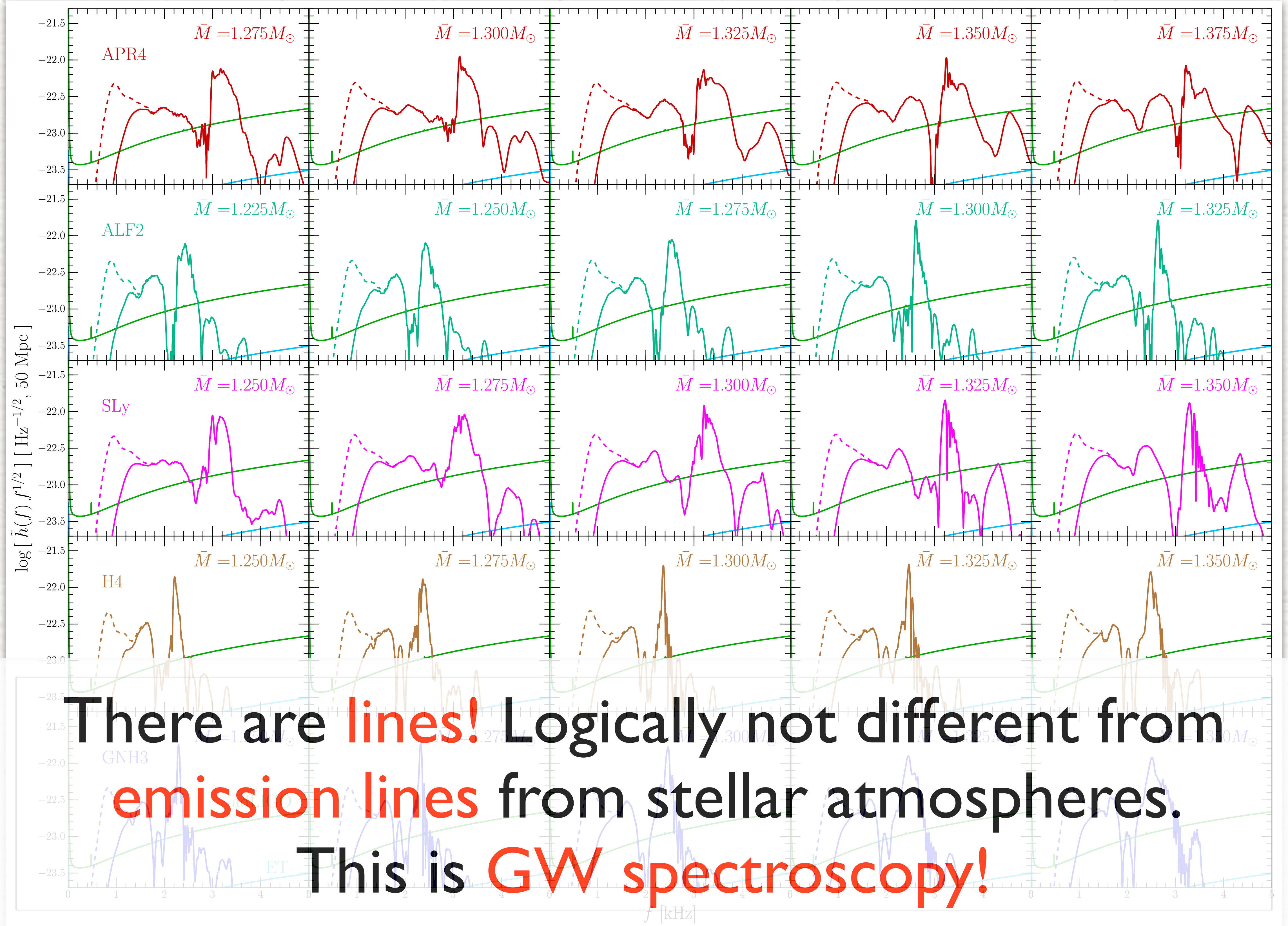
What we can do nowadays

Takami, LR, Baiotti (2014, 2015), LR+ (2016)



Extracting information from the EOS

Takami, LR, Baiotti (2014, 2015), LR+ (2016)



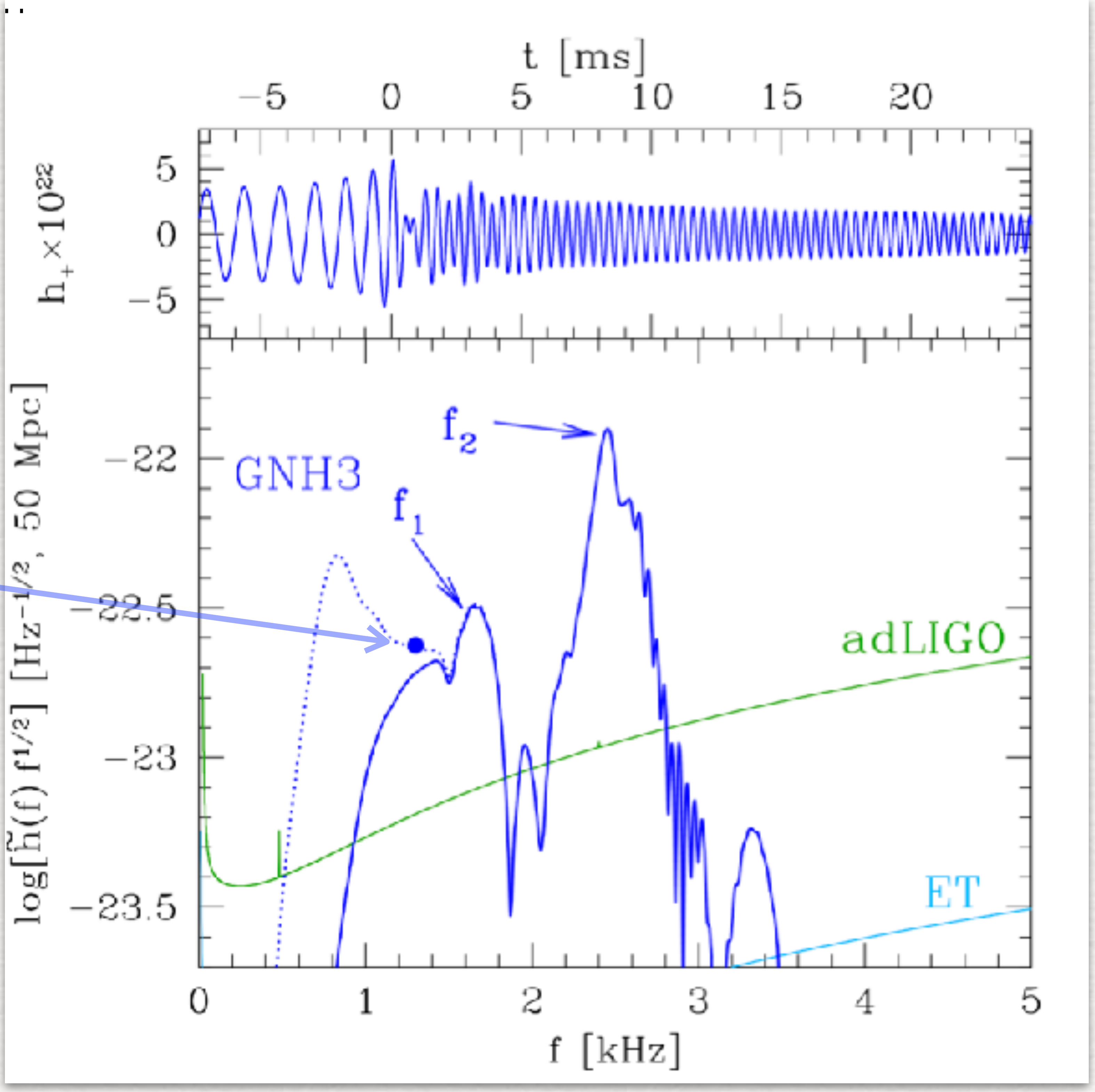
There are **lines!** Logically not different from **emission lines** from stellar atmospheres.

This is **GW spectroscopy!**

A new approach to constrain the EOS

Oechslin+2007, Baiotti+2008, Bauswein+ 2011, 2012, Stergioulas+ 2011, Hotokezaka+ 2013, Takami 2014, 2015, Bernuzzi 2014, 2015, Bauswein+ 2015, Clark+ 2016, LR+2016, de Pietri+ 2016, Feo+ 2017, Bose+ 2017 …

merger frequency



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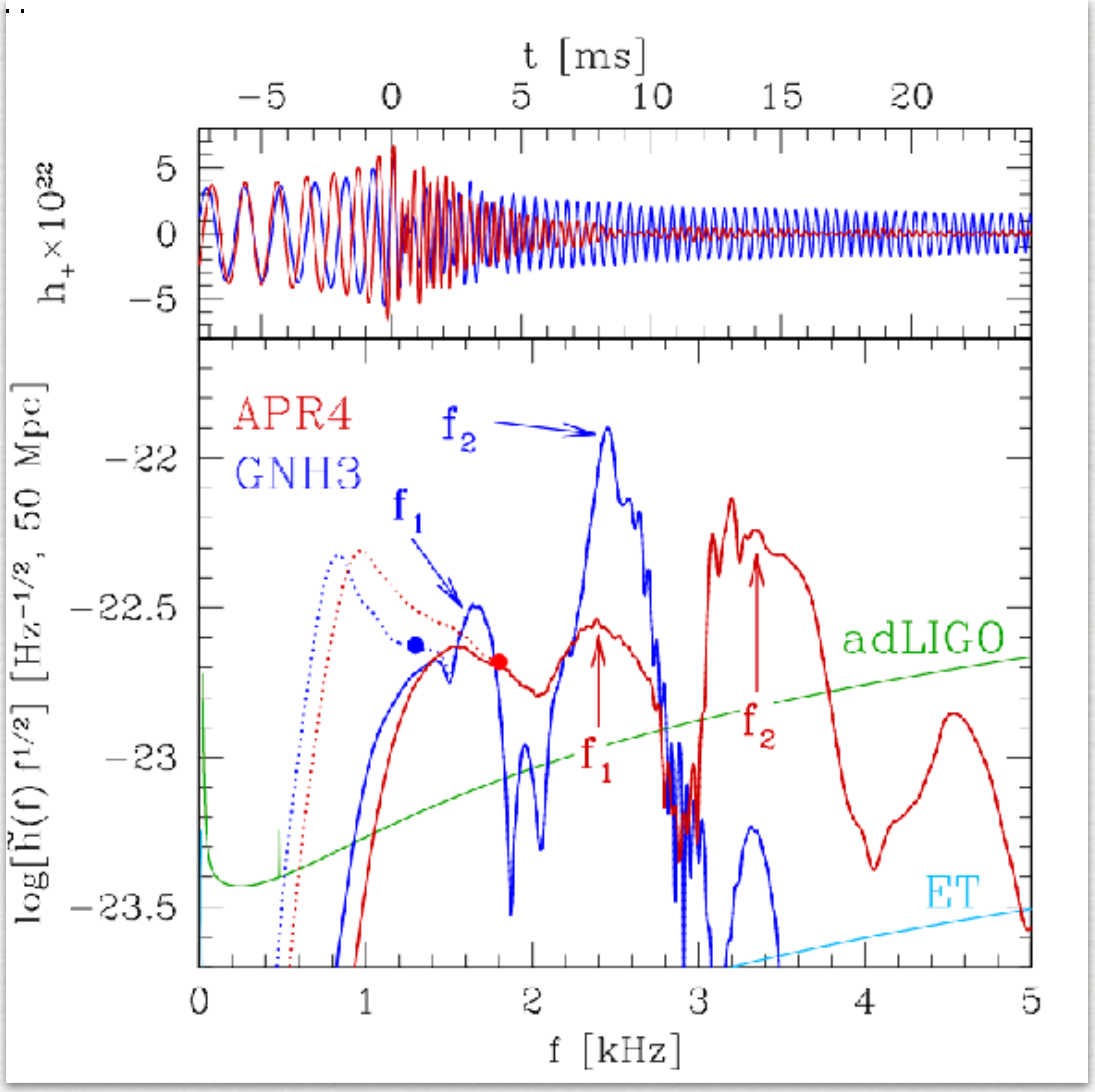
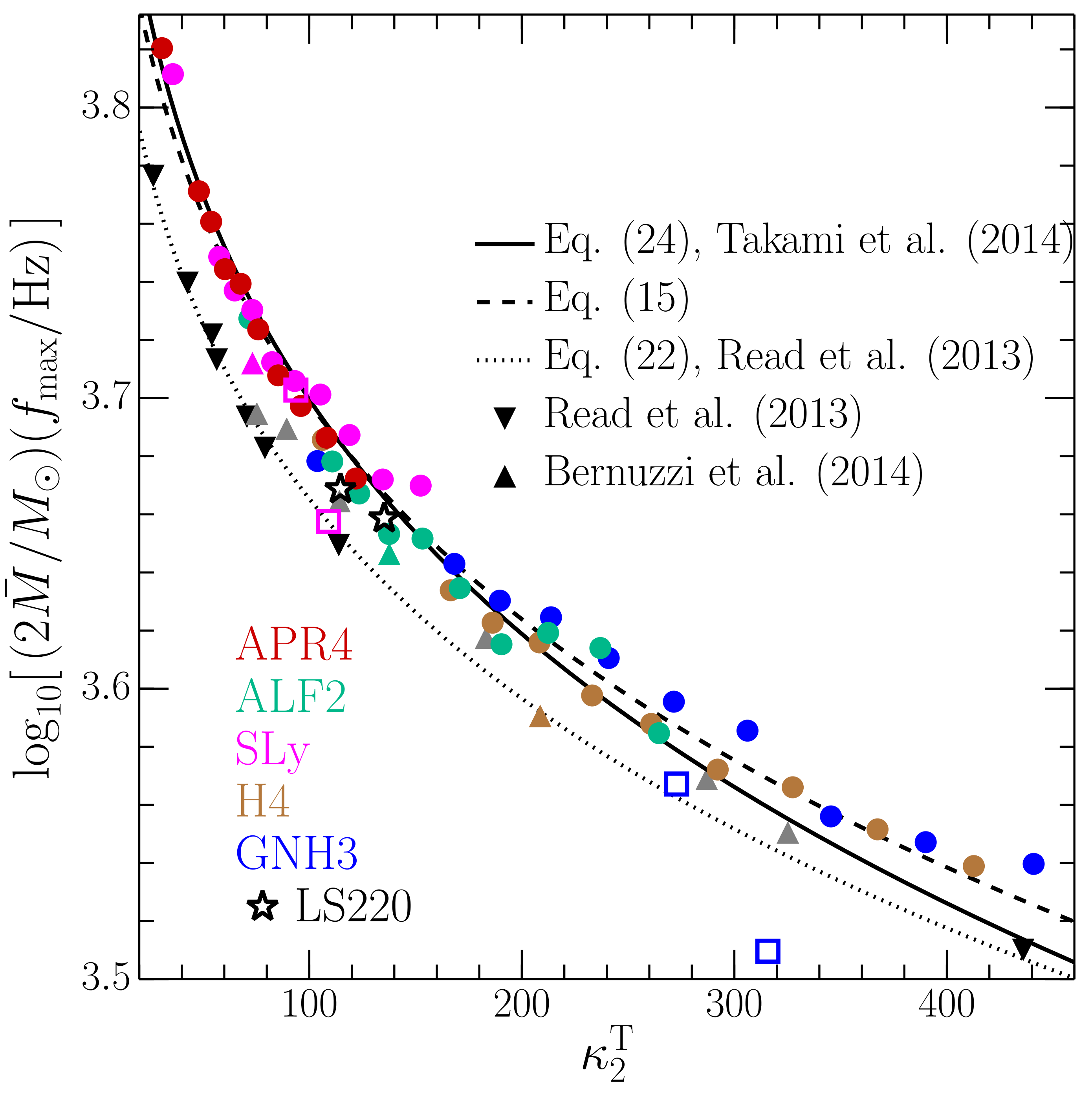


Quasi-universal behaviour

Quasi-universal behaviour: **inspiral**



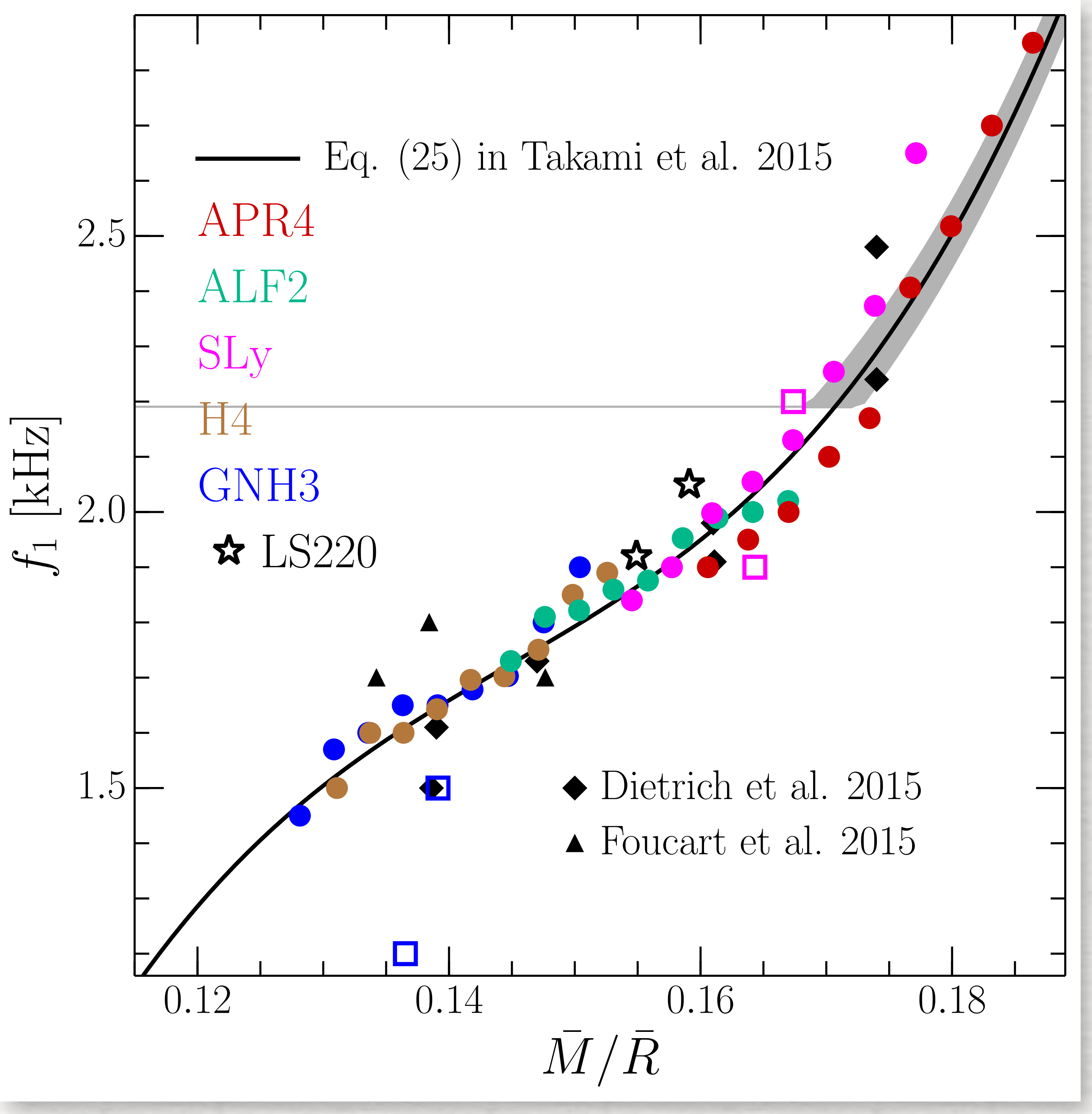
"surprising" result: quasi-universal behaviour of GW frequency at amplitude peak (Read+2013)

Many other simulations have confirmed this (Bernuzzi+ 2014, Takami+ 2015, LR+2016) .

Quasi-universal behaviour in the **inspiral** implies that once **f_{max}** is measured, so is tidal deformability, hence $I, \ Q, \ M/R$

$$\Lambda = \frac{\lambda}{\bar{M}^5} = \frac{16}{3}\kappa_2^T$$ tidal deformability or Love number

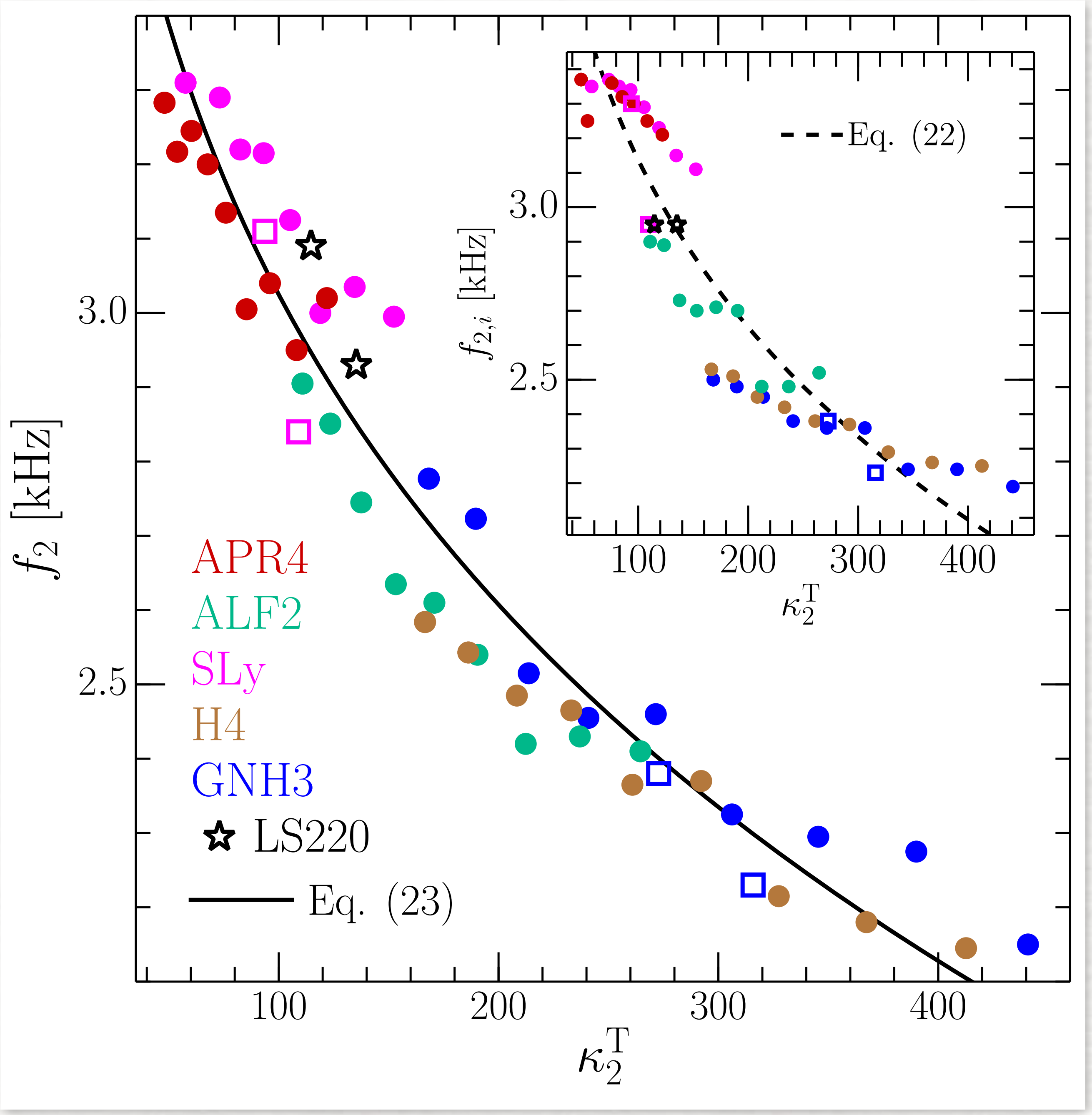
Quasi-universal behaviour: **post-merger**



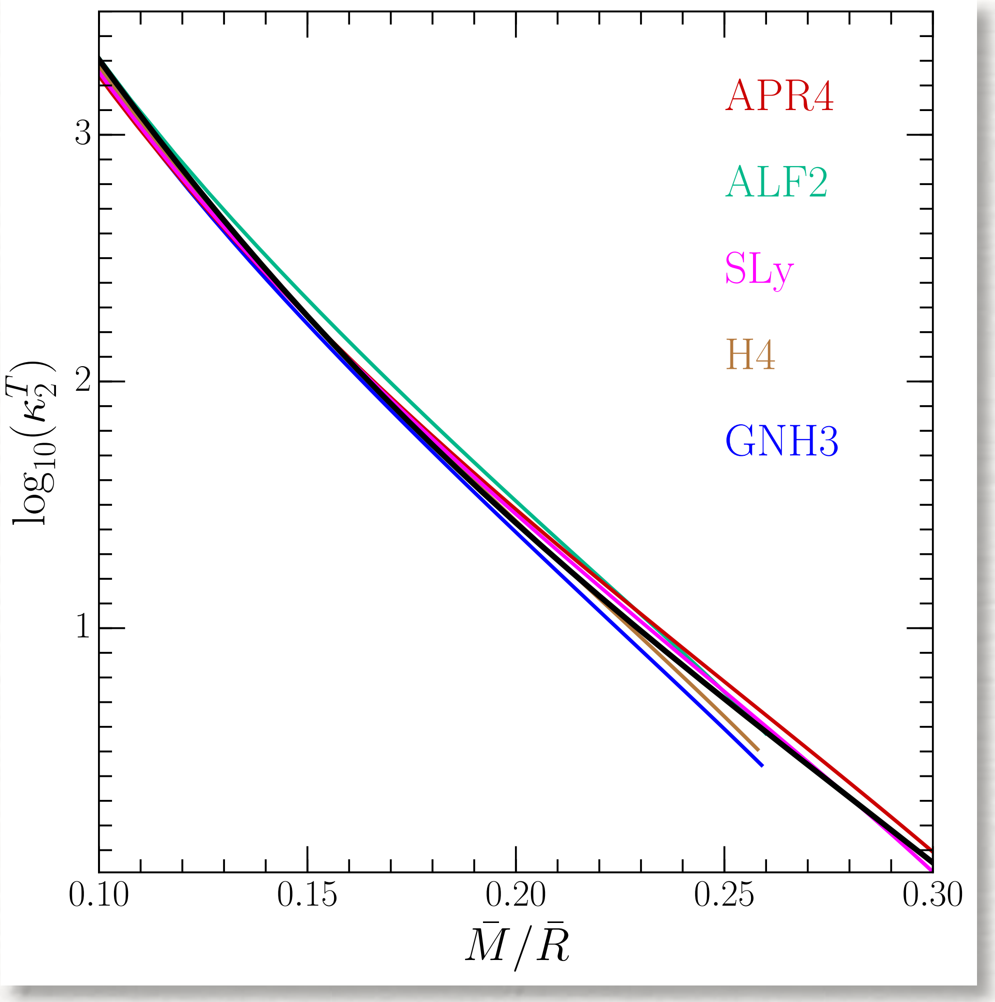
We have found **quasi-universal behaviour:** i.e., the properties of the spectra are only weakly dependent on the EOS.

This has profound implications for the analytical modelling of the GW emission: "what we do for one EOS can be extended to all EOSs."

Quasi-universal behaviour: **post-merger**



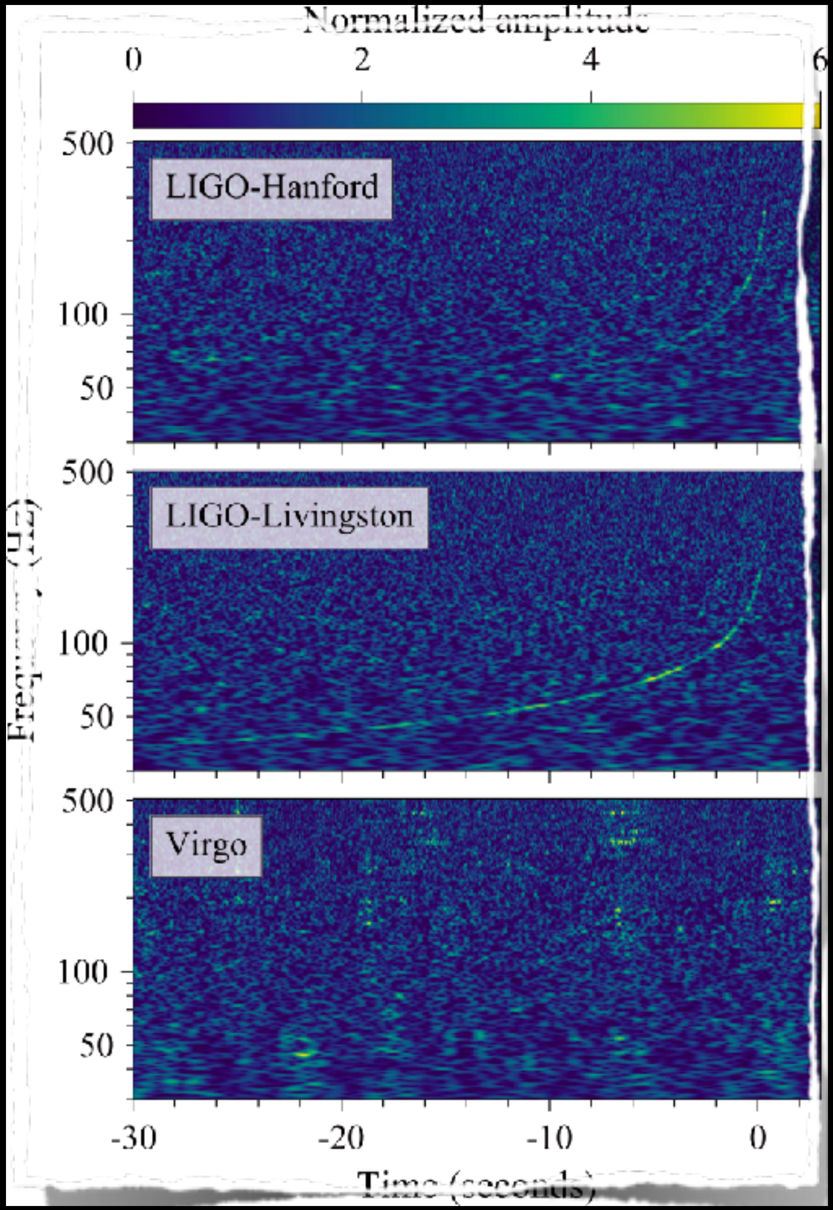
- Correlations with Love number found also for high frequency peak f_2.
- This and other correlations are **weaker** but equally useful.



- Important correlation also between **compactness** and **deformability**

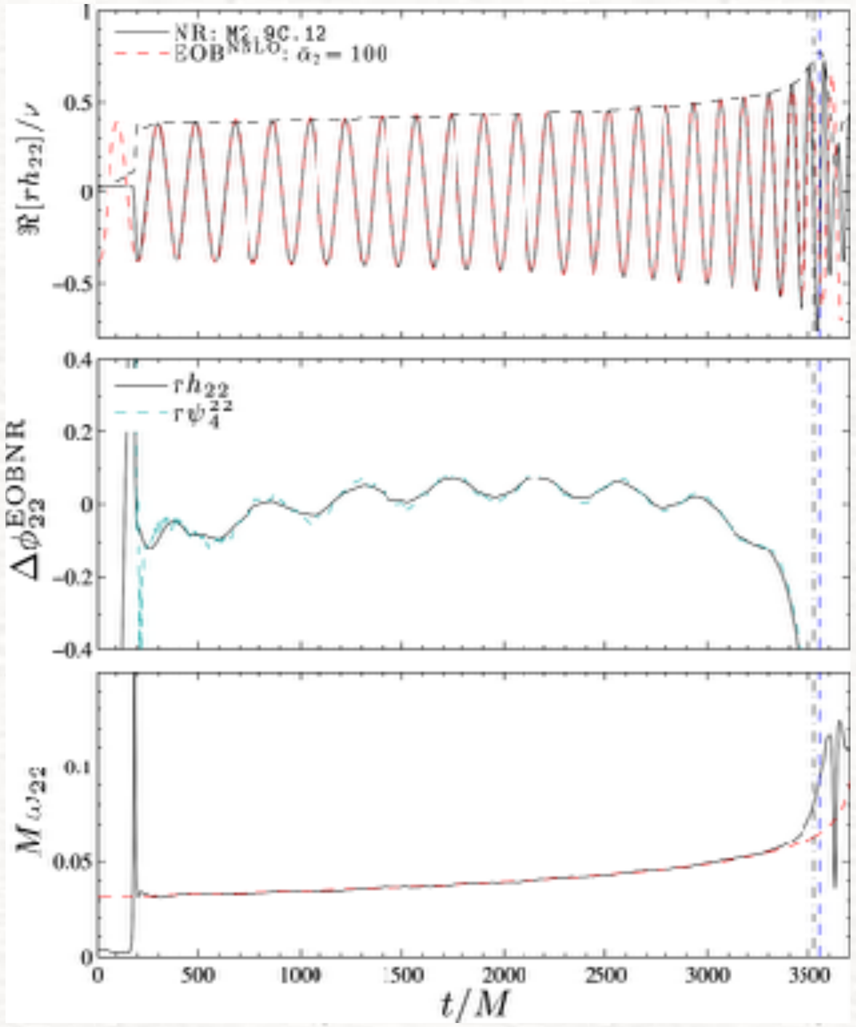
Radius estimate from binary population

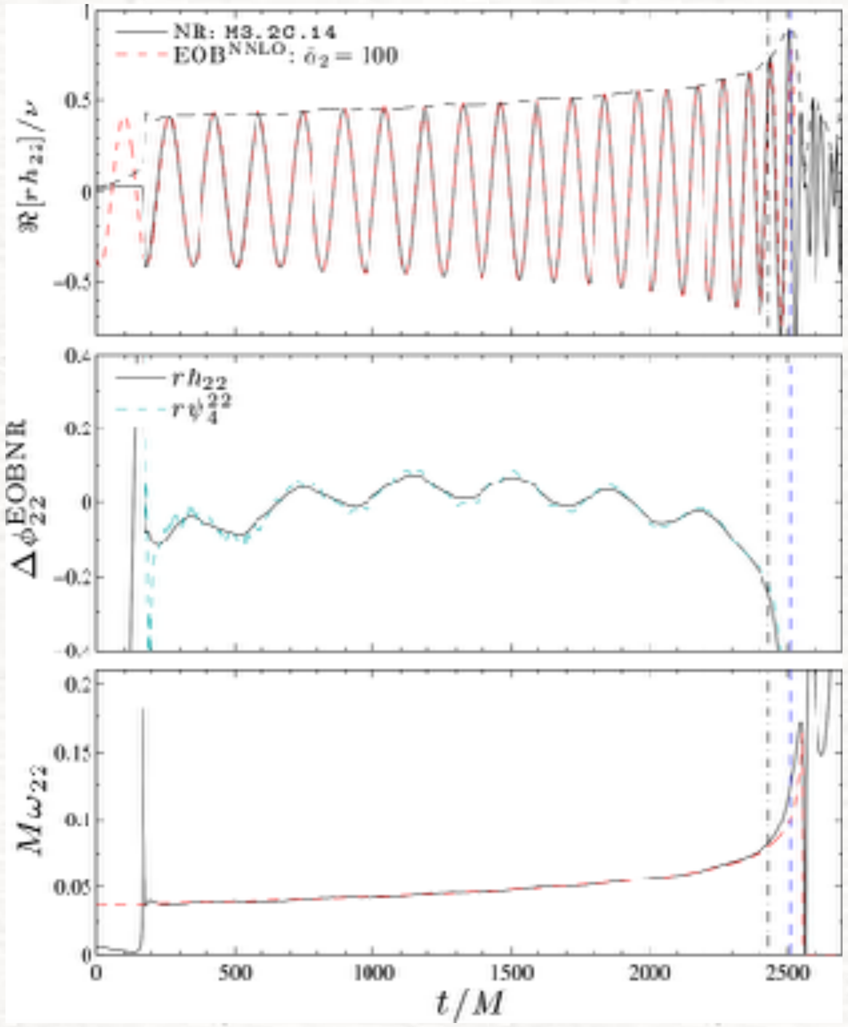
Bose, Chakravarti, LR, Sathyaprakash, Takami (2018)



Analytical modelling of waveform

- **Analytical** modelling of signal is essential for statistical analysis
- **Inspiral** well reproduced with PN or EOB (Baiotti+11, Bernuzzi+15a, 15b, Lackey+ 16, Hotokezaka+15, Hinderer+ 16)





- **Inspiral** also benefits from very accurate codes, **WhiskyTHC**: highest demonstrated convergence order (Radice+13, 13b)

Spectroscopy is useful but hard

- Measuring post-merger not easy: H4, $M = 2 \times 1.35\, M_\odot$

$$|2\tilde{h}(f)\, f^{1/2}| \simeq 10^{-22}/\sqrt{\mathrm{Hz\ at}}\ f = f_2 \simeq 2470\,\mathrm{Hz}$$

$$\mathrm{SNR} \simeq |2\tilde{h}(f) f^{1/2}| [\delta f/(f\, S_h(f))]^{1/2} \simeq 1.8$$

- However, multiple detections will provide excess power and SNRs can add up statistically providing information.
- Idea not new and implemented in the past (Del Pozzo+ 2013, Agathos+ 2015, Clark+ 2015, 2016); there's a new twist here.

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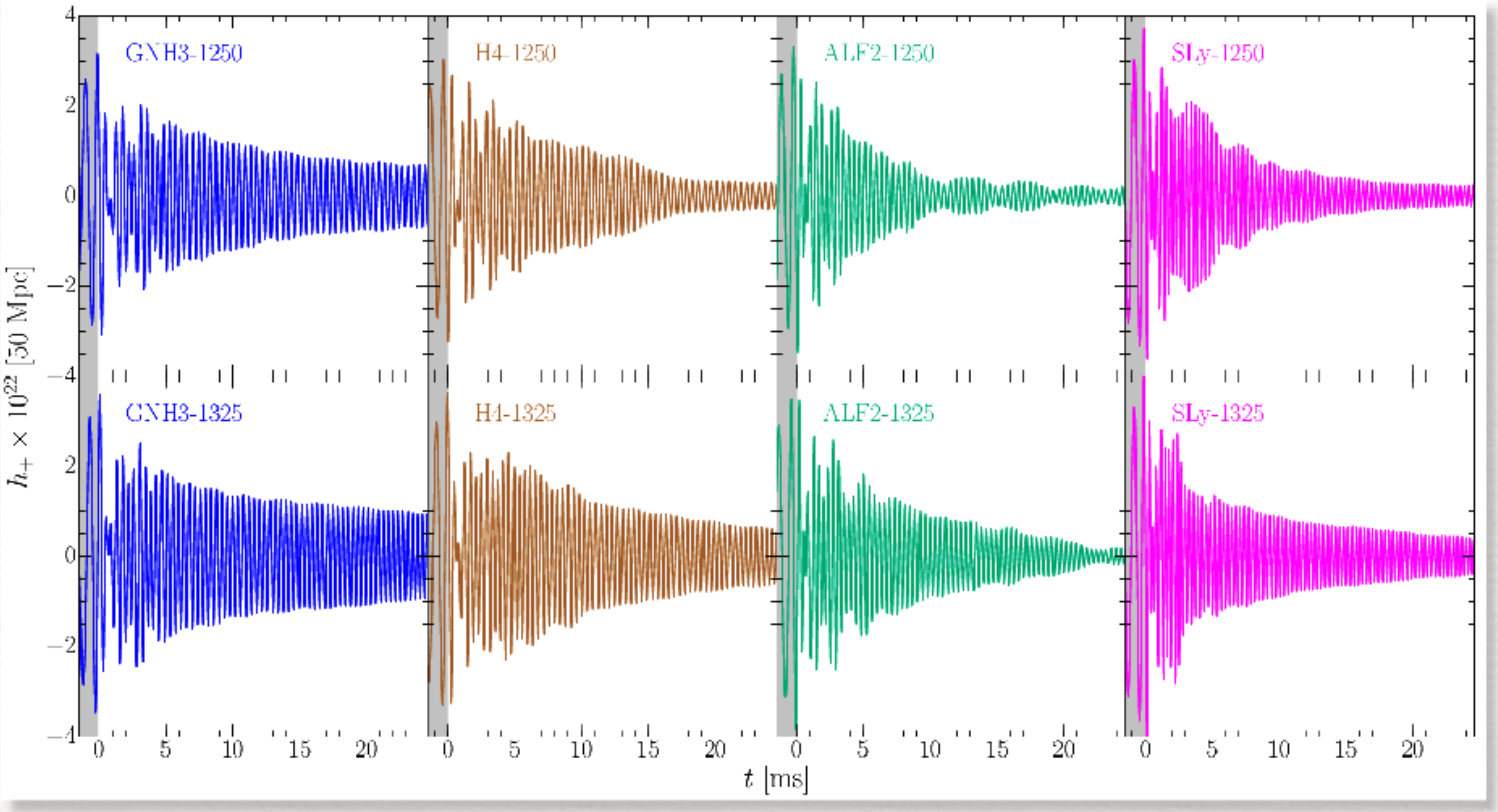
- However, multiple detections will provide excess power and SNRs can add up statistically providing information.
- Idea not new and implemented in the past (Del Pozzo+ 2013, Agathos+ 2015, Clark+ 2015, 2016); there's a new twist here.
- **Analytical modelling** of post-merger GW via main frequencies ($f_{\mathrm{max}}, f_1, f_2$) and **universal relations** allow us to relate **inspiral** and **postmerger** to progenitor stars.

Analytical modelling of postmerger waveform

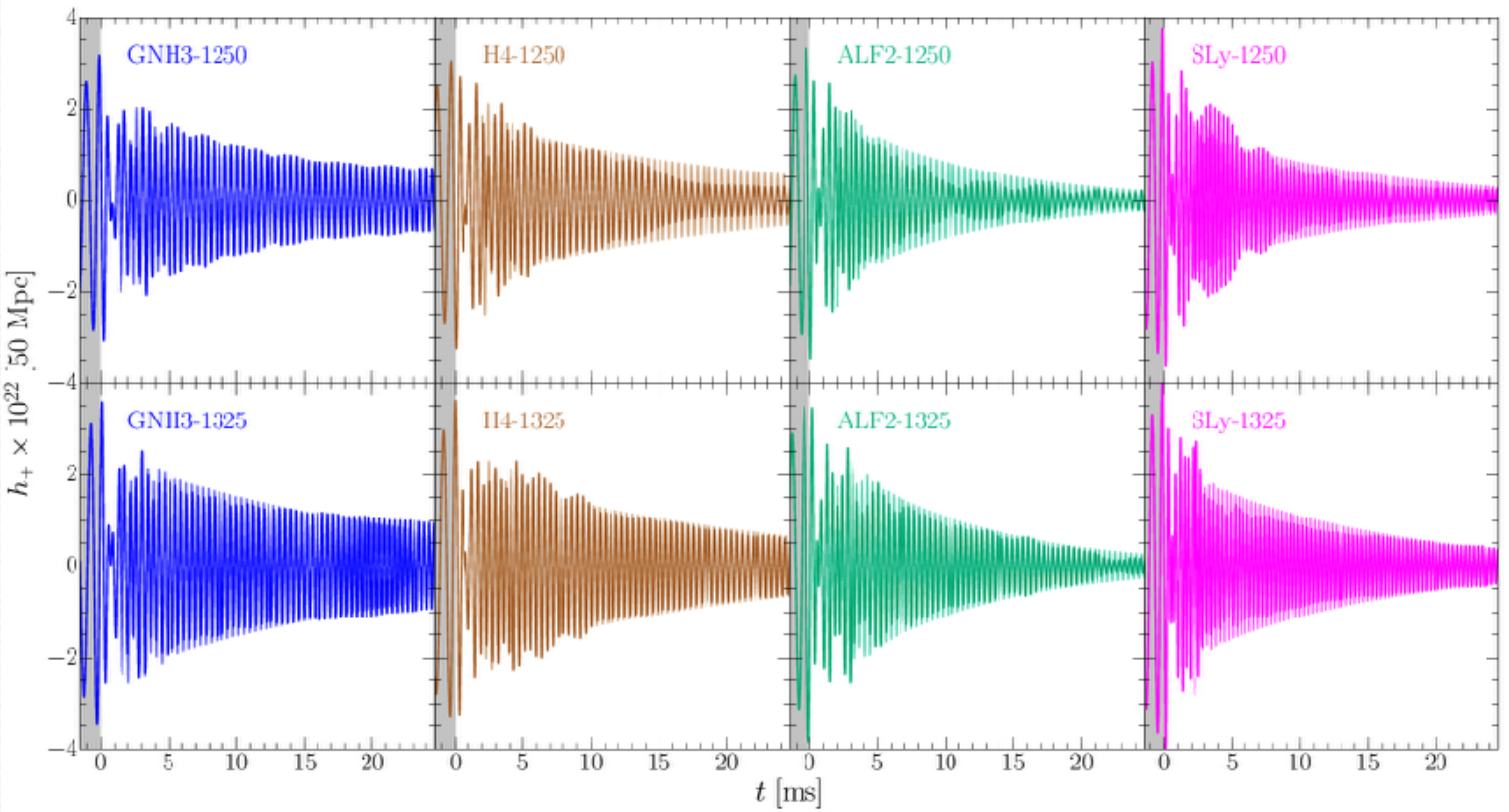
- **Postmerger** appears hopeless but isn't (Clark+14, 16; Bose+17)



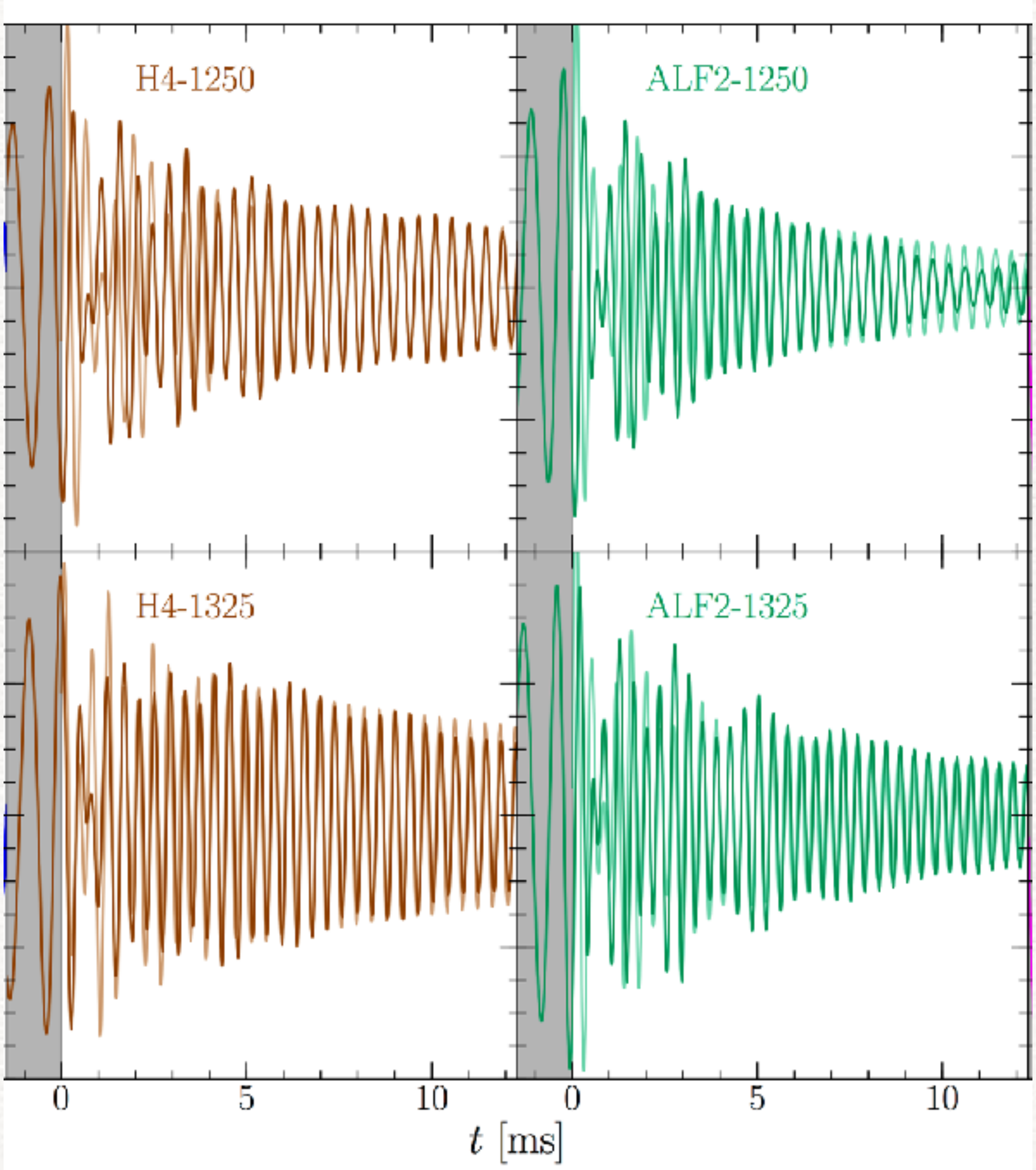
Analytical modelling of postmerger waveform

- Knowledge of spectral properties provides **analytic ansatz**

$$\begin{aligned} h(t) = \alpha \exp(-t/\tau_1)\big[&\sin(2\pi f_1 t) + \sin(2\pi(f_1 - f_{1\epsilon})t) + \\ &\sin(2\pi(f_1 + f_{1\epsilon})t)\big] + \\ &\exp(-t/\tau_2)\sin(2\pi f_2 t + 2\pi\gamma_2 t^2 + \pi\beta_2)\,. \end{aligned}$$

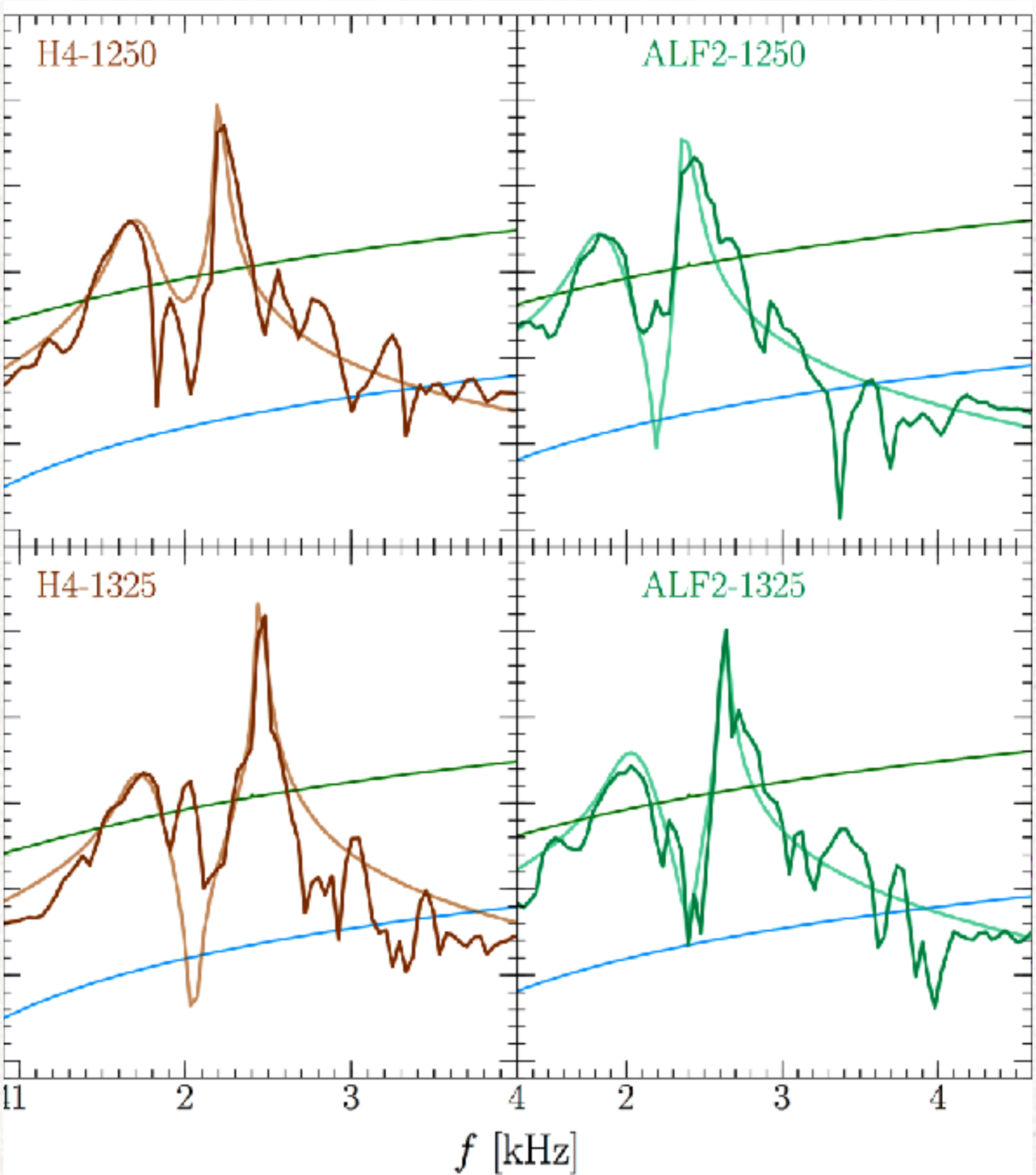


Analytical modelling of postmerger waveform



- Overall pretty decent fit in **phase**
- Fit in **amplitude** is less good but also less important

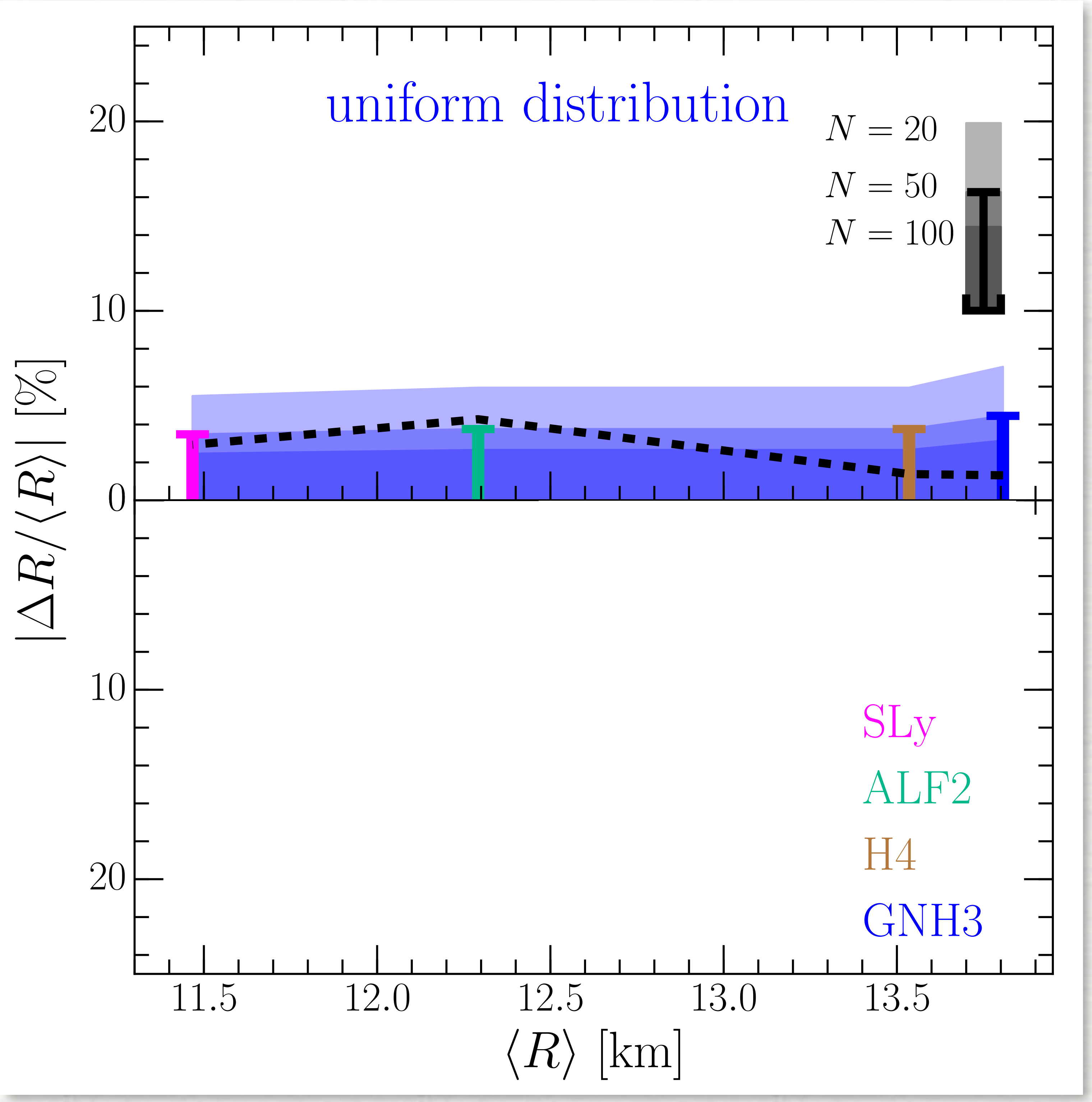
Analytical modelling of postmerger waveform



- Good match is clear also in **frequency space**

In summary: despite the complex signal, an **analytic** description of the **full GW signal** is now possible.

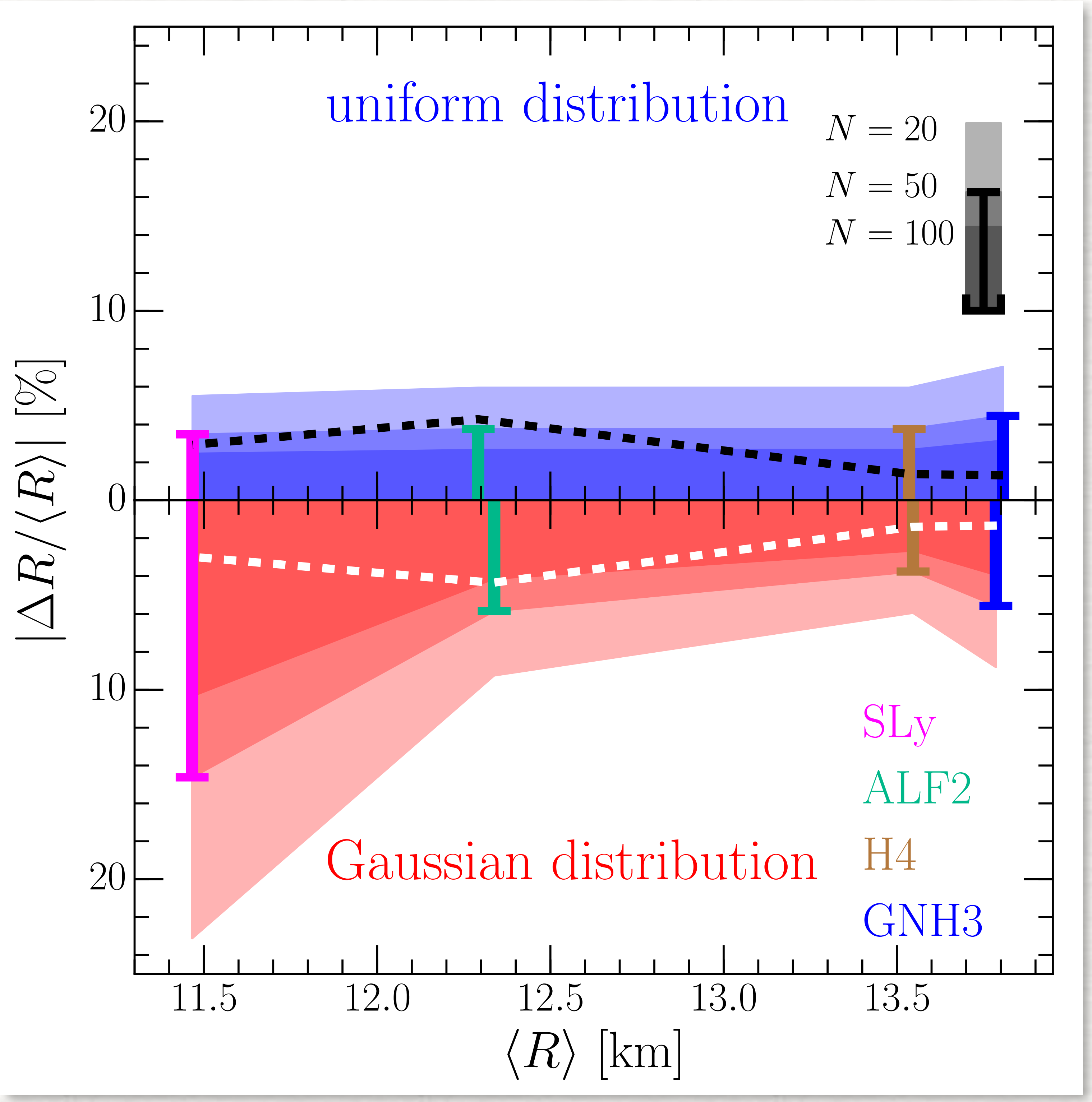
Constraining the radius: MonteCarlo vs Fisher



- **uniform** distribution in mass [1.21, 1.38] M⊙

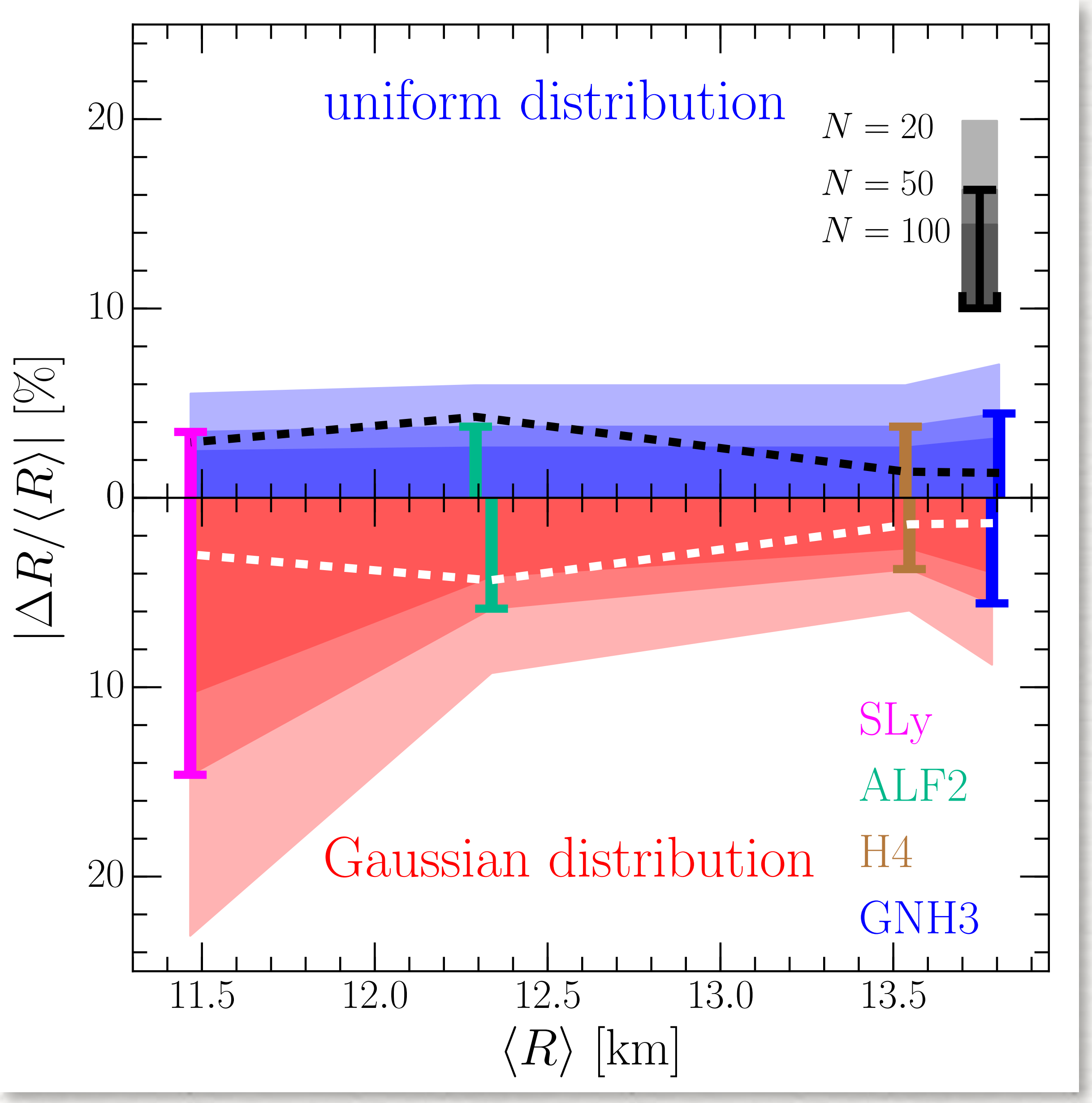
  between 100 and 300 Mpc; isotropic distribution in space.
- dashed lines for results of Fisher-matrix analysis with N=50
- errors scale like $\sqrt{N}$

Constraining the radius: MonteCarlo vs Fisher



- **Gaussian** distribution in mass [1.21, 1.38] M☉ centred at 1.35 M☉ with variance 0.05 Binaries are between 100 and 300 Mpc; isotropic distribution in space.
- dashed lines for results of Fisher-matrix analysis with N=50
- errors scale like $\sqrt{N}$

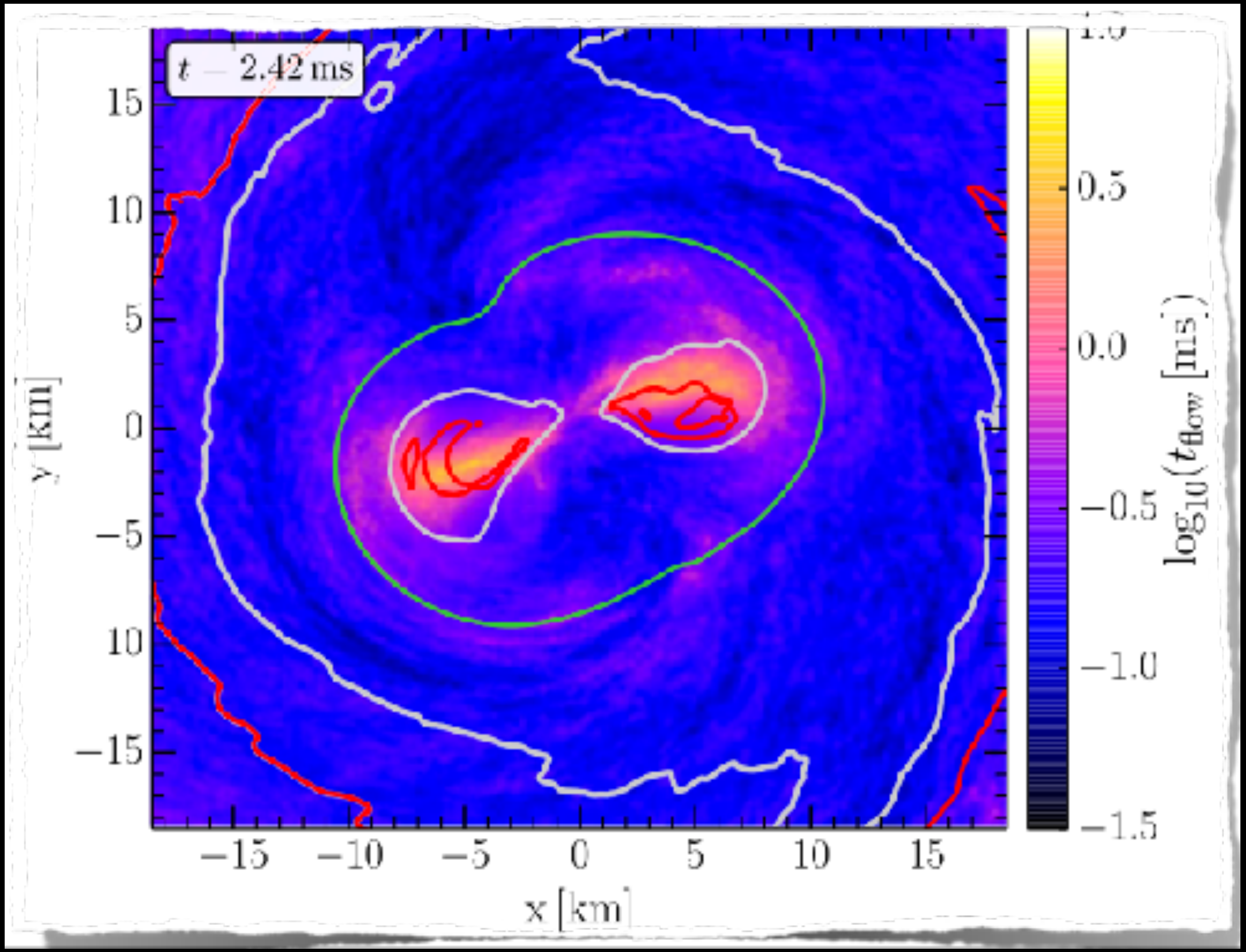
All in all



- stiff EOSs: $|\Delta R/\langle R\rangle| < 10\%$ for ***N~20***
- soft EOSs: $|\Delta R/\langle R\rangle| \sim 10\%$ for ***N~50***
- discriminating stiff/soft EOSs will possible even with moderate ***N***
- discriminating two-stiff /two-soft EOSs will be harder
- very soft EOSs remain a challenge
- golden binary: **SNR ~ 6** at **30 Mpc** $|\Delta R/\langle R\rangle| \lesssim 2\%$ at 90% confidence

Viscous dissipation in the post-merger

Alford, Bovard, Hanauske, LR, Schwenzer (2018)



Viscous contributions

- Viscous dissipation is normally neglected in numerical modelling on assumption microscopic viscosity too small.
- Possible channels are:
  1. nuclear-matter **shear** viscosity
  2. nuclear-matter **bulk** viscosity
  3. neutrino **shear** viscosity (Guilet+ 2016)
  4. "**MRI**-induced" **viscosity** (Radice2017, Shibata+2017a, b)
- Channels 3. and 4. act on timescales typical of MRI, which depends on B-field and very **uncertain** still.
- Impact on GWs depends on value for viscous angular momentum transport; everyone's bet?… $\tau \gtrsim 10-100\,\mathrm{ms}$

Viscous contributions: 1. **shear viscosity**

- Low-temperature, **electron-dominated** regime, i.e.

$T \lesssim 10\,\mathrm{MeV}$

$$\tau_\eta^{(e)} \approx 1.6\times10^8\,\mathrm{s}\left(\frac{z_\mathrm{typ}}{1\,\mathrm{km}}\right)^2\left(\frac{T}{1\,\mathrm{MeV}}\right)^{\frac{5}{3}}\left(\frac{n_0}{n_B}\right)^{\frac{5}{9}}\left(\frac{0.1}{x_p}\right)^{\frac{14}{9}},$$

- High-temperature, **neutrino-dominated** regime, i.e.

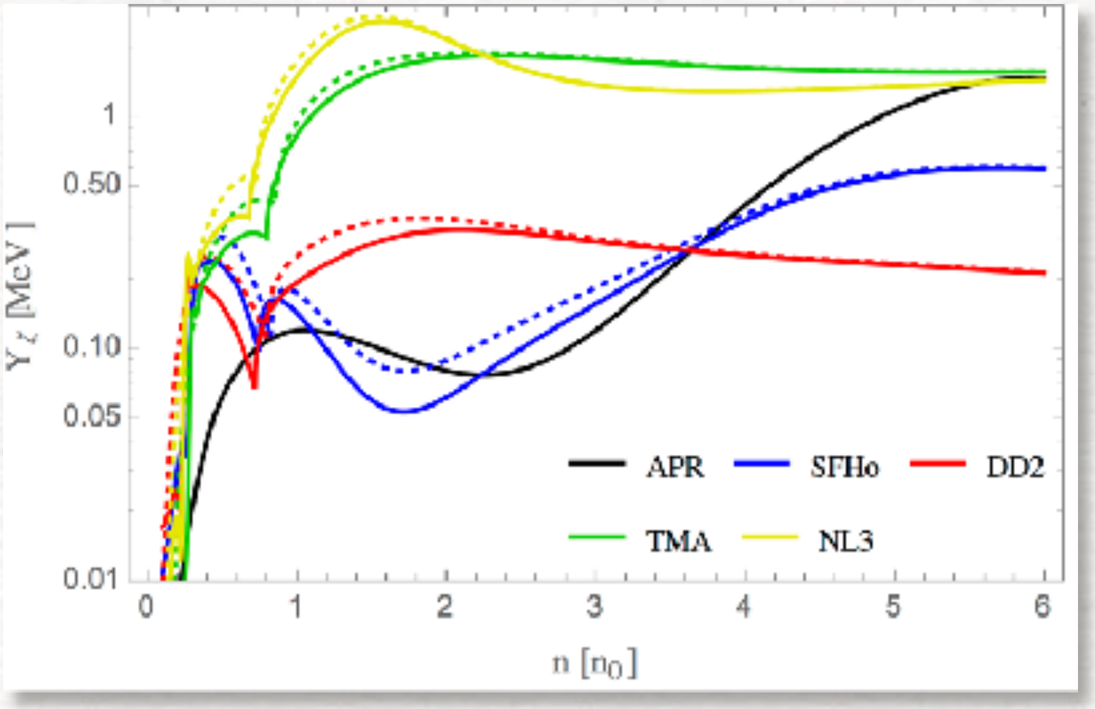
$T \gtrsim 10\,\mathrm{MeV}$

$$\tau_\eta^{(\nu)} \approx 54\,\mathrm{s}\left(\frac{0.1}{x_p}\right)\left(\frac{m_n^*}{0.8\,m_n}\right)^2\left(\frac{\mu_e}{2\,\mu_\nu}\right)^4\left(\frac{z_\mathrm{typ}}{1\,\mathrm{km}}\right)^2\left(\frac{T}{10\,\mathrm{MeV}}\right)^2,$$

Hence, shear viscosity not relevant unless neutrinos dominate and flow is turbulent with $z_\mathrm{typ} \sim 10 - 100\,\mathrm{m}$; not likely

Viscous contributions: 1. **shear viscosity**

- Impact of bulk viscosity depends sensitively on process responsible for flavor re-equilibration.
- If **direct-Urca** dominates, bulk viscosity will be very **small**: never possible for softer EOSs, hard for stiff EOS at small T.
- If **modified-Urca** dominates, then bulk viscosity



$$\mathcal{E}_{\rm comp} \approx K\bar{n}(\Delta n/\bar{n})^2/18$$

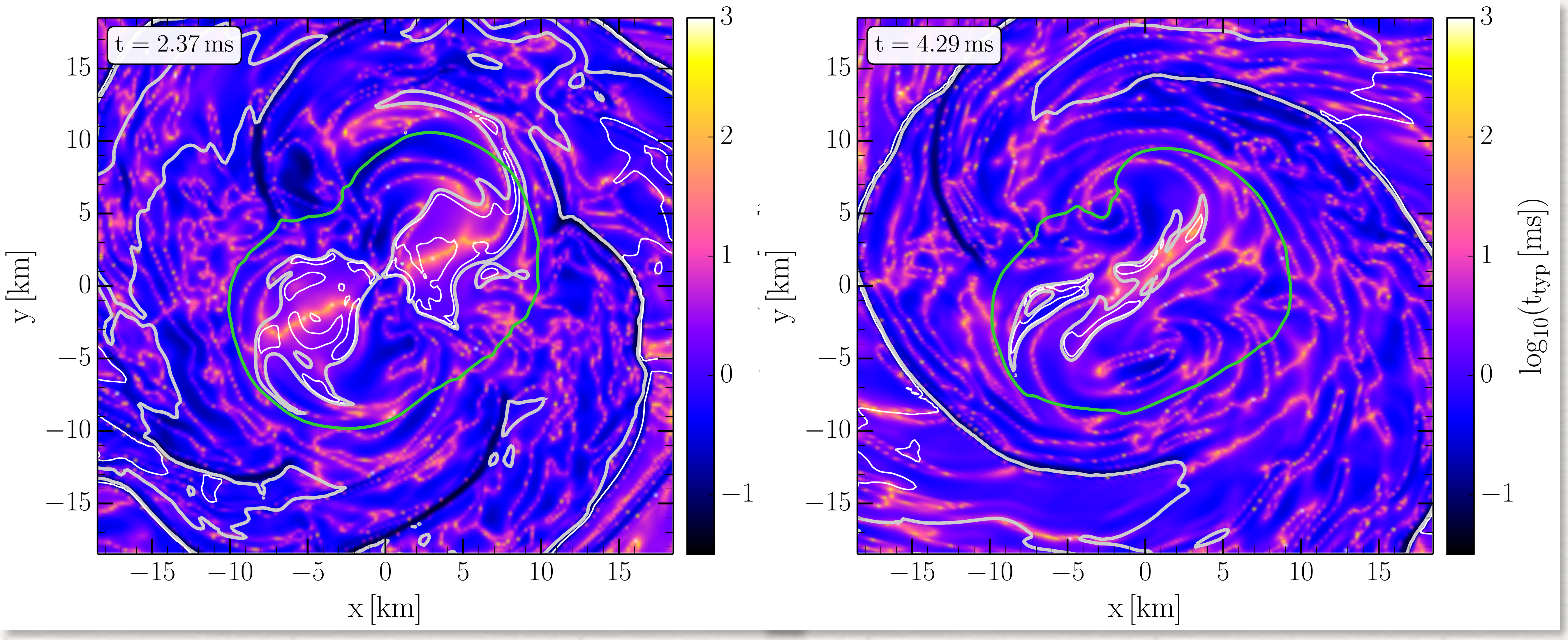
$$\tau_\zeta \equiv \mathcal{E}_{\rm comp}/\left(d\mathcal{E}/dt\right)_{\rm bulk} \approx K\bar{n}\, t^2_{\rm exp}/(36\pi^2\,\bar{\zeta})$$

$$\approx 7\,{\rm ms}\left(\frac{t_{\rm exp}}{1\,{\rm ms}}\right)\left(\frac{K}{250\,{\rm MeV}}\right)\left(\frac{0.1\,{\rm MeV}}{Y_\zeta}\right)$$

$t_{\rm exp} \sim$ bulk-dissipation timescale of internal energy

K: nuclear compressibility at n_0

Viscous contributions



$$t^{\rm inst}_{\rm exp} \sim \frac{\rho}{D_t\rho} = \frac{1}{\nabla\cdot\vec{v}}$$

instantaneous bulk-dissipation timescale can be measured in simulations.

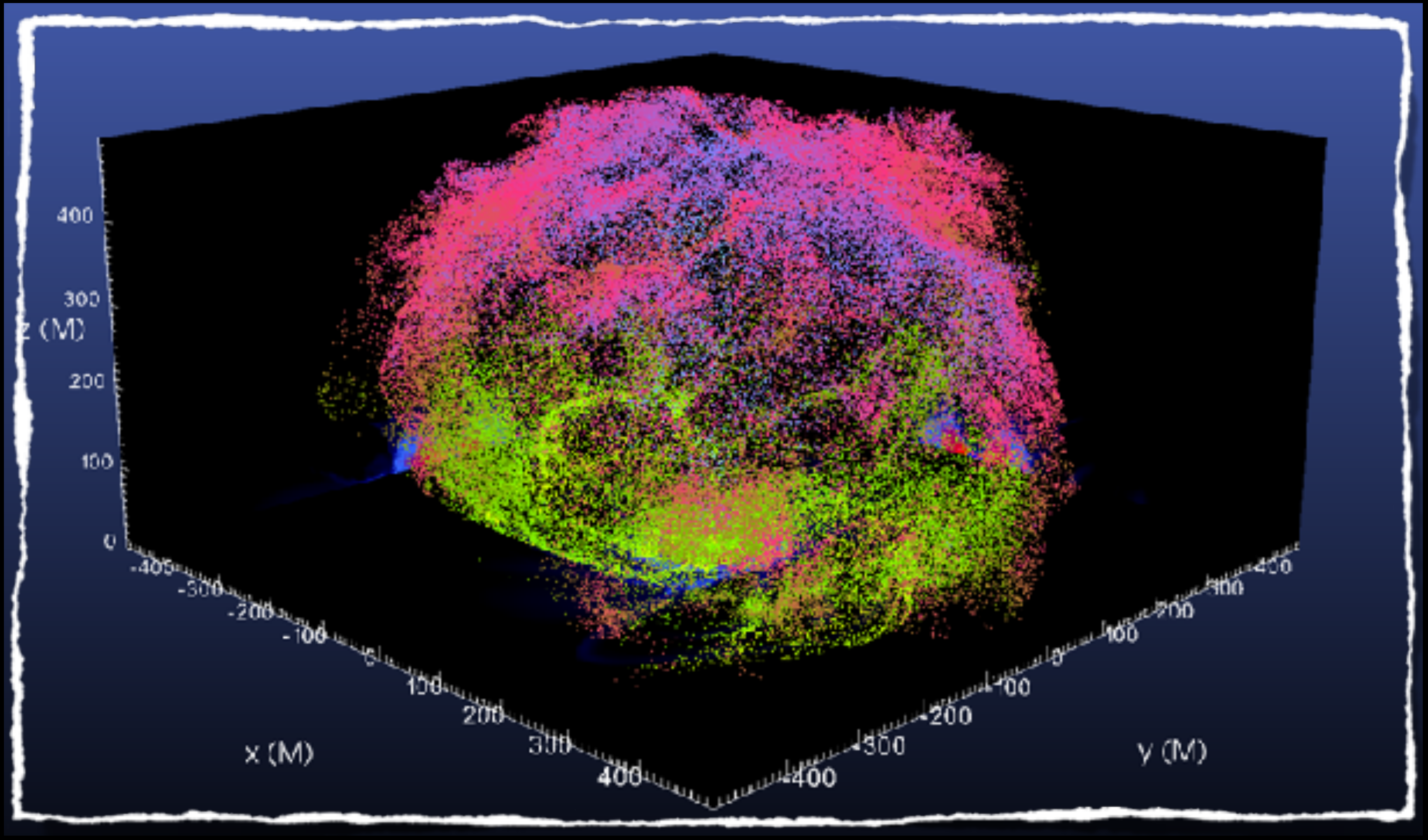
right after merger

$$t_{\rm exp} \lesssim \tau_{\rm dyn} = \frac{R}{c_s}$$

bulk-dissipation timescale comparable with dynamical timescale in large portions of the object: cannot be ignored

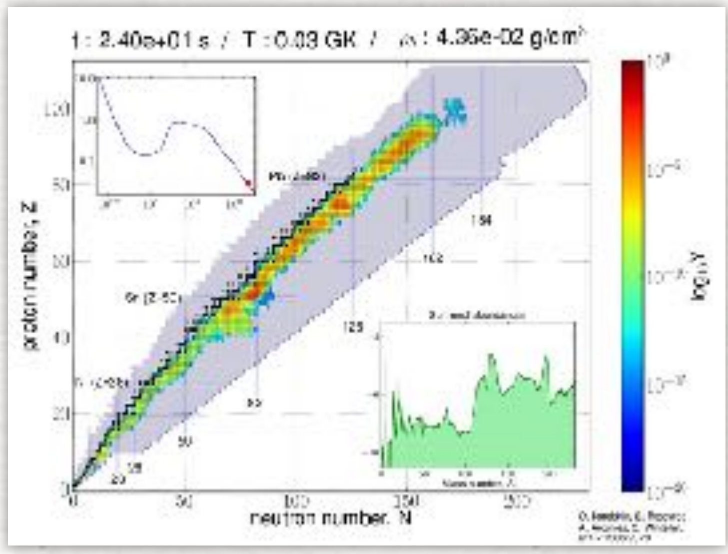
Ejected matter and nucleosynthesis

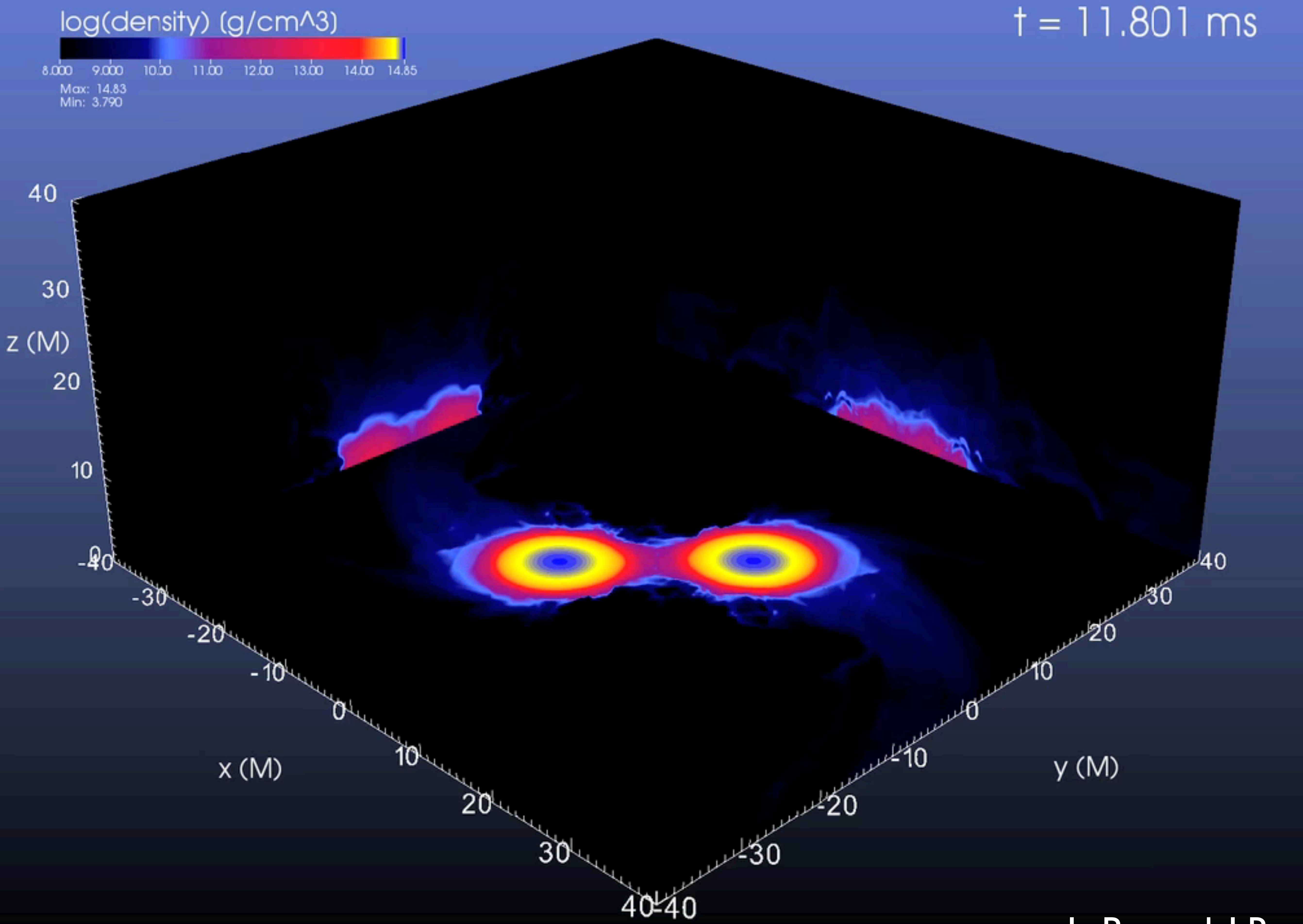
LR, Most, Weih (2018)



Nucleosynthesis

- Already in the 50's, nuclear physicists had tracked the production of elements in stars via nuclear fusion.
- **Heavy elements** $(A \gtrsim 56\,)$ cannot be produced in stellar interiors but can be synthesised during a **supernova**.
- Modern numerical simulations of supernovae have shown that the temperature and energies are not large enough to produce the "**very heavy**" **elements** $(A \gtrsim 120)$.
- To produce such elements one needs very high temperatures and "**neutron-rich**" material.
- **Neutron-star mergers** seem perfect candidates for this process!



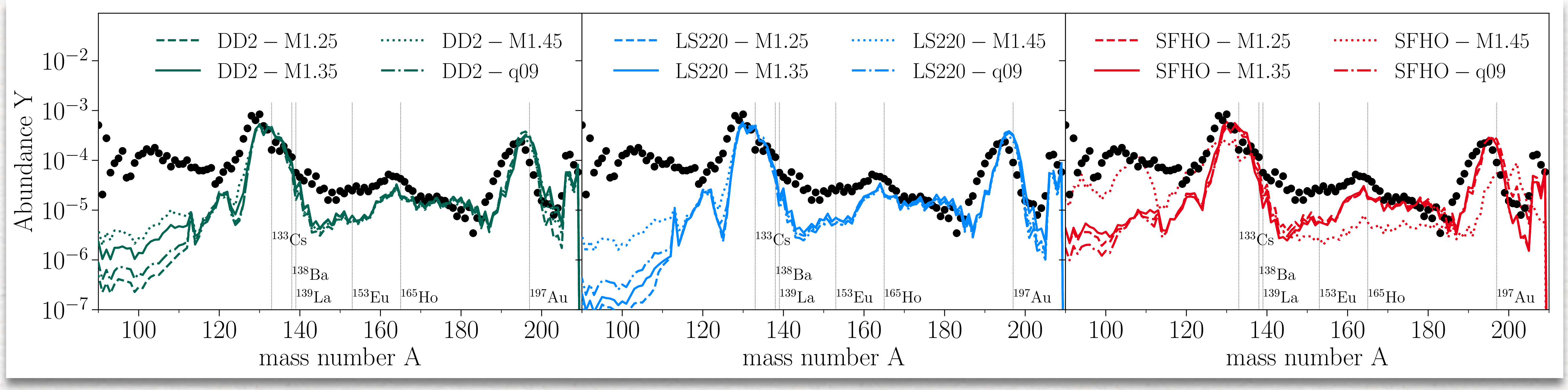

log(density) (g/cm^3)
8.000
9.000
10.00
11.00
12.00
13.00
14.00
14.85
Max: 14.83
Min: 3.790
t = 11.801 ms
z (M)
40
30
20
10
0
x (M)
-40
-30
-20
-10
0
10
20
30
40
y (M)
40
30
20
10
0
-10
-20
-30
-40

L. Bovard, LR

Relative abundances

Bovard+ 17

- Abundance pattern for ***A>120*** in good agreement with solar.
- Even **tiny amounts** of ejected matter $(0.01M_\odot)$ sufficient to explain observed abundances.
- Extremely **robust** behaviour across different **EOSs, masses, nuclear reactions and merger type**



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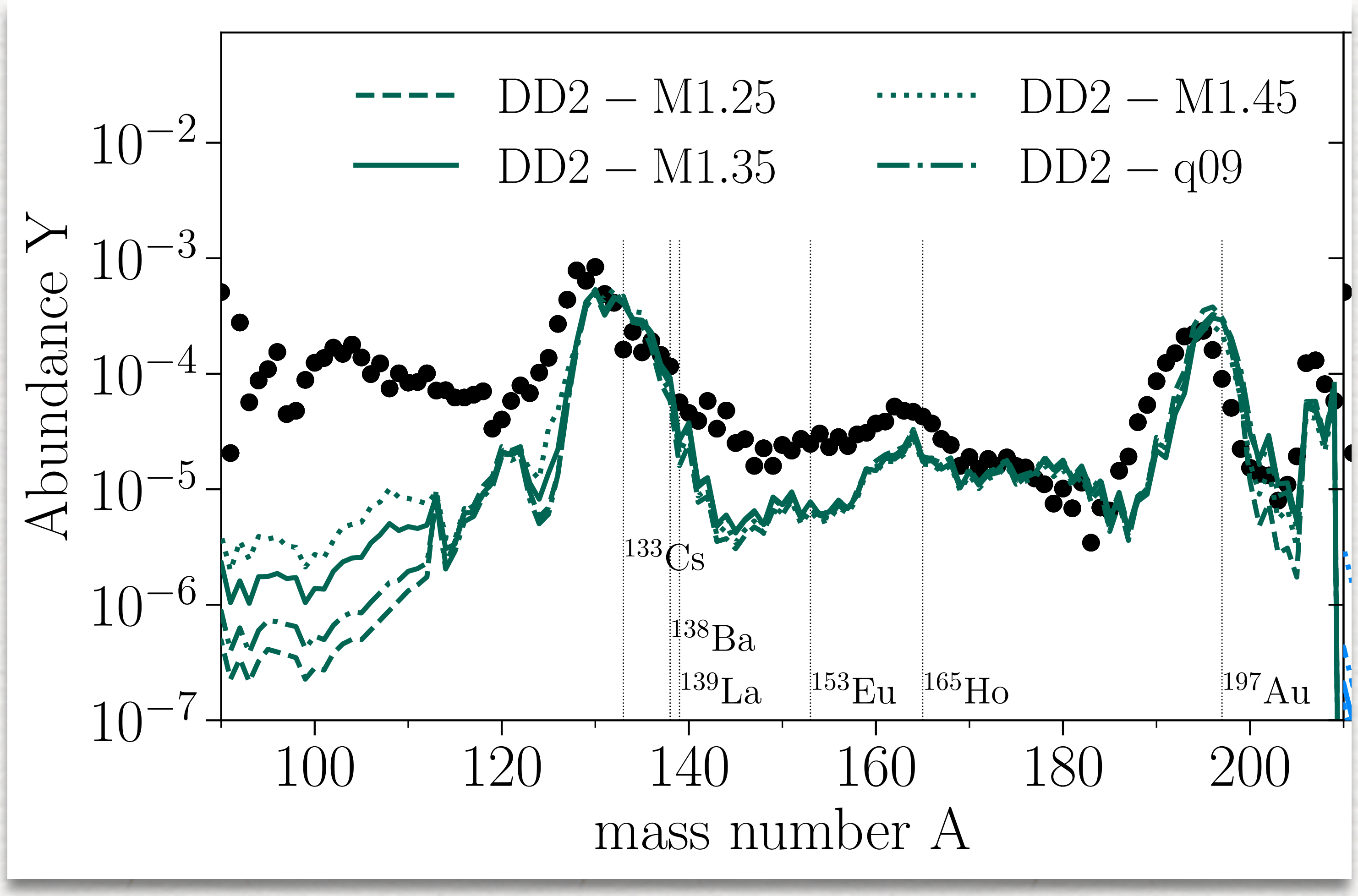
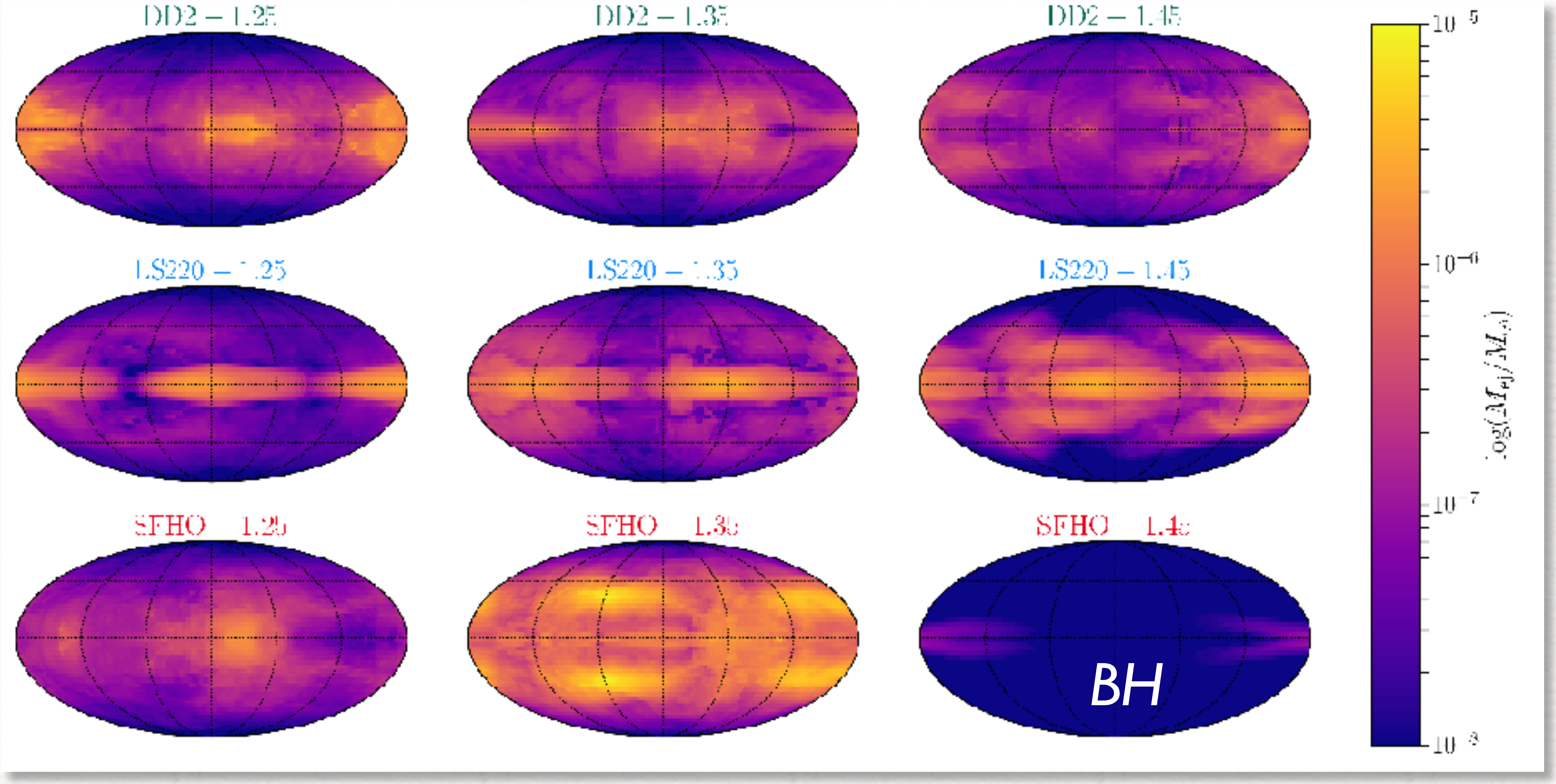


- GW170817 produced total of **16,000** times the mass of the Earth in heavy elements (**10** Earth masses in **gold/platinum**)
- We are not only **stellar dust** but also **neutron-star dust!**

Spatial distributions: M_{ej}

Bovard+ 17

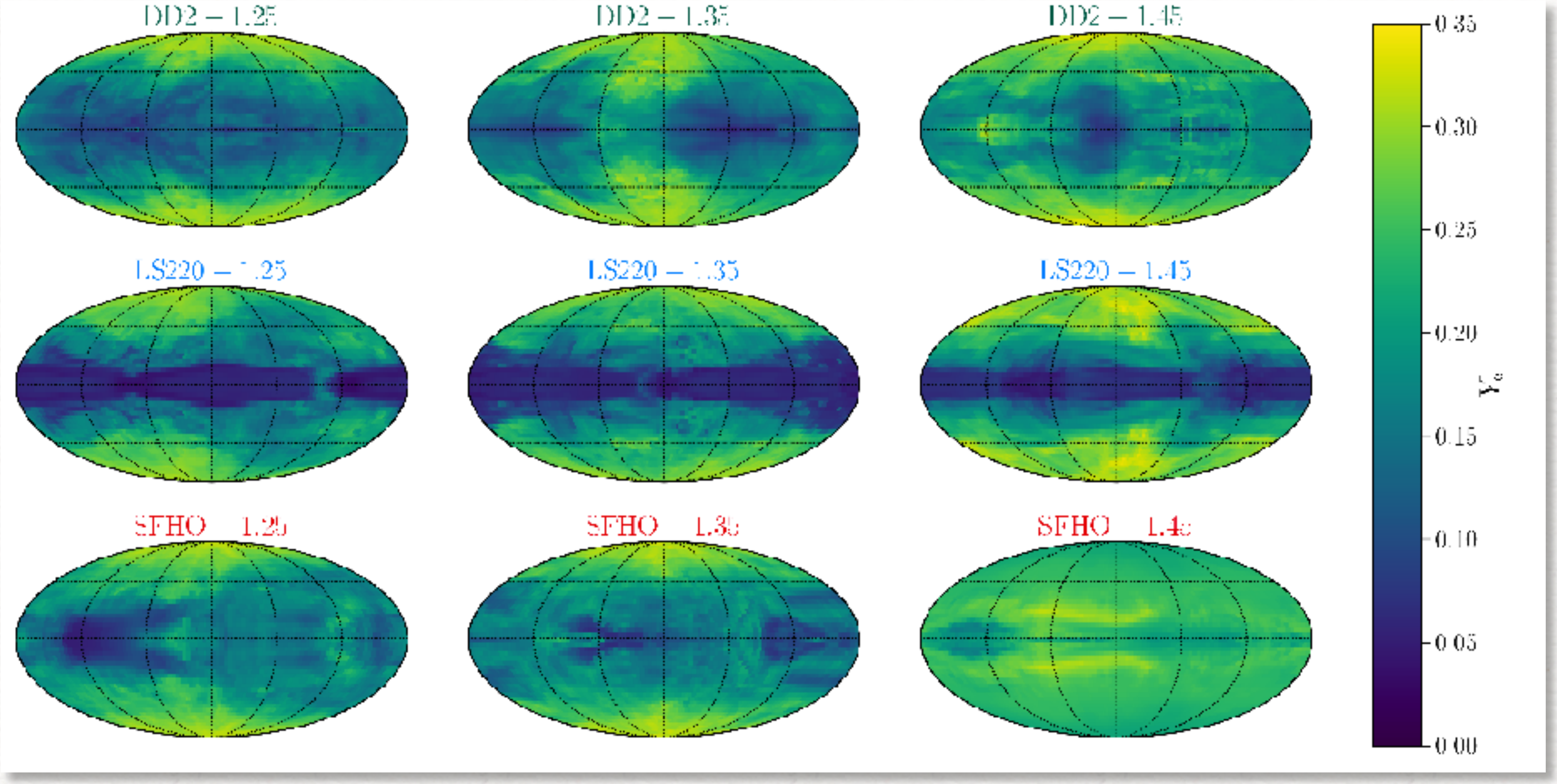


Spatial distribution of M_{ej} impacts detectability of EM counterpart:

- ★ most of M_{ej} lost at low latitudes;
- ★ depending on EOS/mass, contamination also in polar regions

Spatial distributions: Y_e

Bovard+ 17

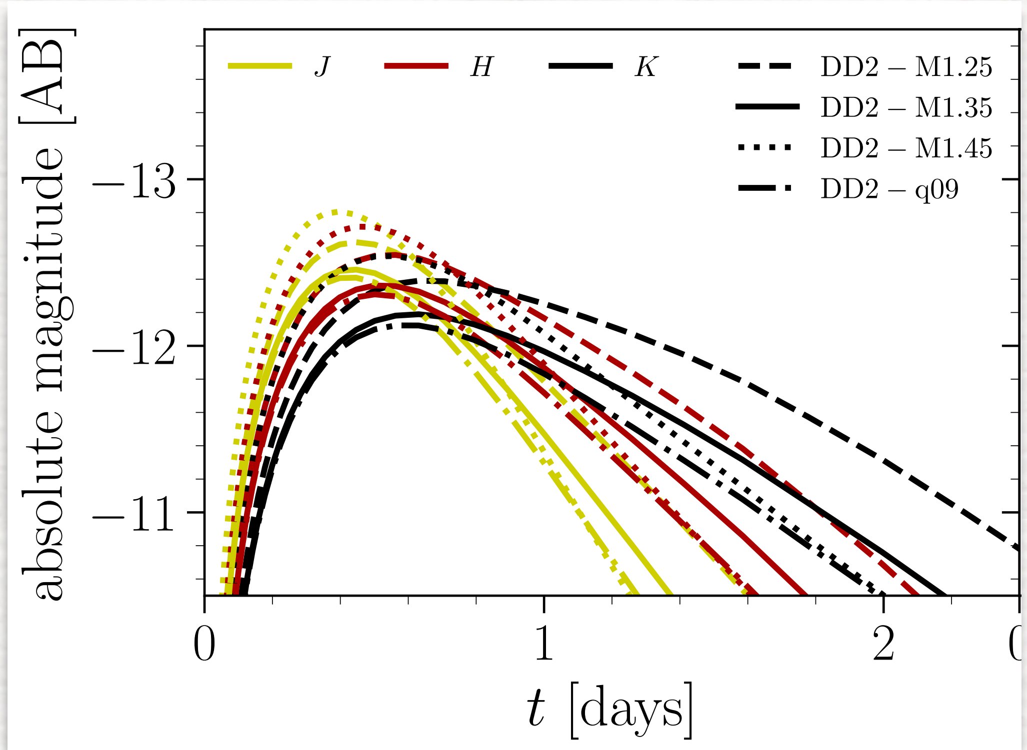


Spatial distribution of Y_e impacts detectability of EM counterpart:

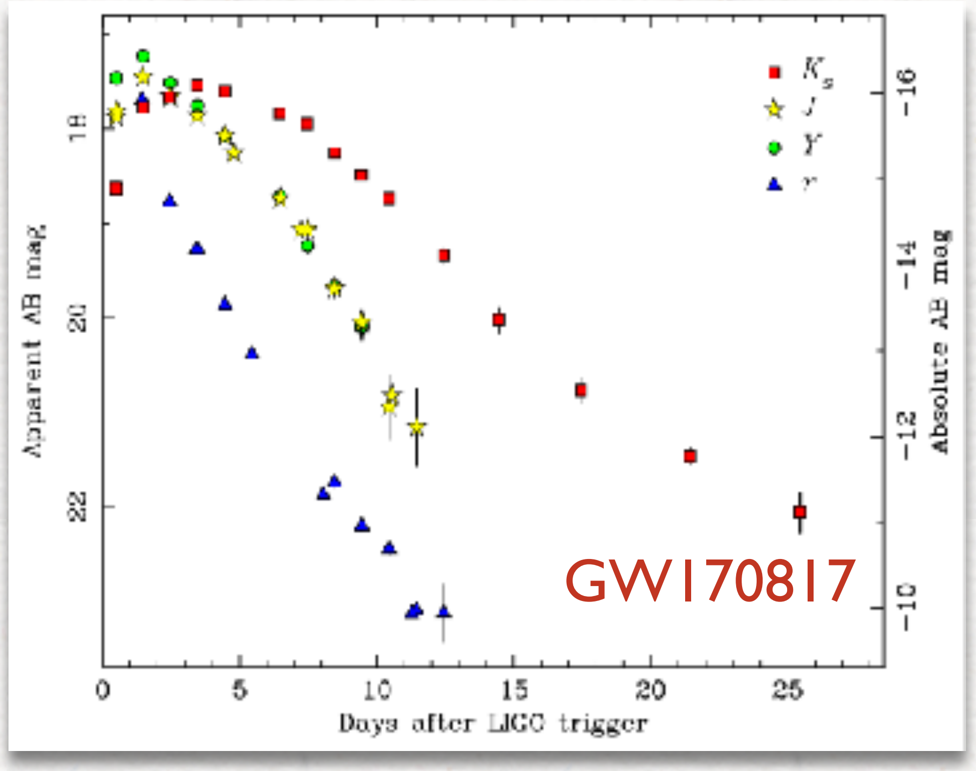
- **high** Y_e in **polar** regions: **blue** (optical) macronova
- **low** Y_e in **equatorial** regions: **red** (FIR) macronova

Kilonova emission

- Ejected matter undergoes **nucleosynthesis** as expands and cools.
- When critical densities and temperatures are reached, matter undergoes radioactive decay emitting light (optical/infrared): kilonova/macronova (Li & Paczynski '98).



simulations



observations

- Astronomical observations of GW170817 show **kilonova emission**: evidence connection GRBs and binary neutron stars!

Conclusions

- ✶Spectra of post-merger shows clear peaks, some of which are **”quasi-universal”**. that is, independent of the EOS
- ✶Used together with tens of observations and analytic modelling of post-merger, universal relations set tight constraints on EOS.
- ✶Magnetic fields unlikely to be detected during the inspiral but **important** after the merger: instabilities and EM counterparts.
- ✶**Mergers** lead to tiny but important ejected matter and macronova emission. “high-*A*” nucleosynthesis very robust.
- ✶ A single event **GW170817** has provided wealth of information and new limits on the **maximum mass**

Merging binaries of NSs are Einstein’s richest laboratory:
GWs, nuclear physics, astrophysics.
Much more in coming years!…