Nuclear astrophysics with binary neutron stars

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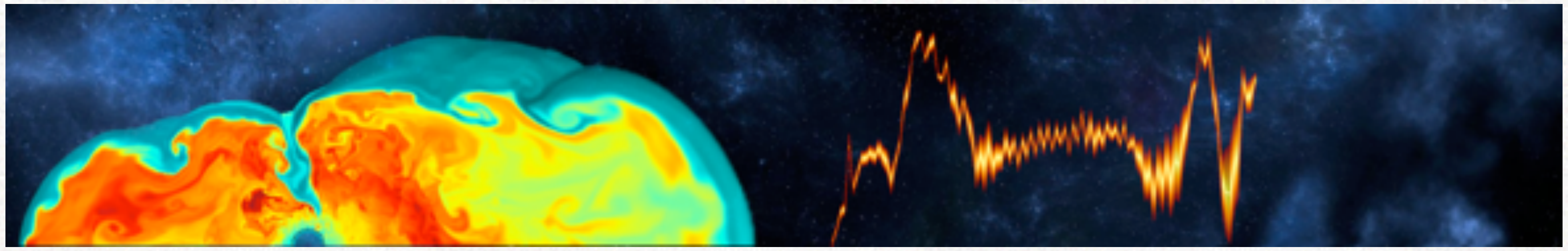


Plan of the talk

- ✴EOS information from GW signal
- ✴Nucleosynthesis: quasi-circular and eccentric binaries
- ✴Electromagnetic counterparts

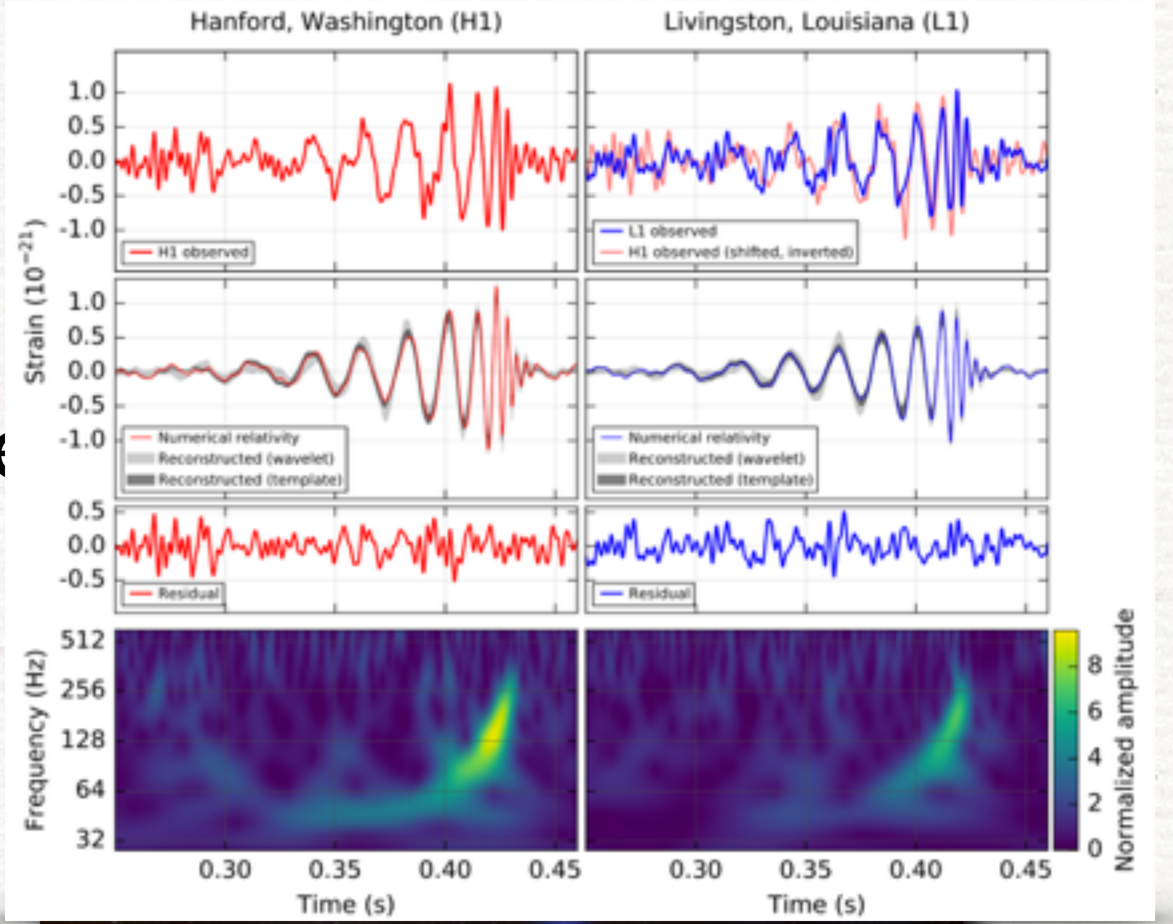
The two-body problem in GR

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

BH + BH → BH + GWs

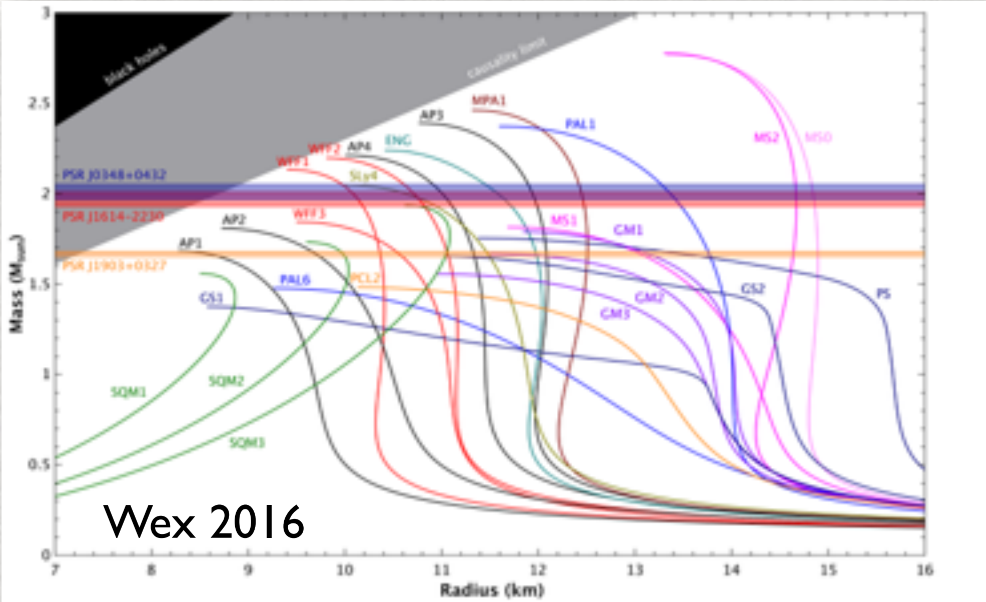
- For NSs the question is more **subtl** hyper-massive neutron star (HMNS),

NS + NS → HMNS + **... ?** →

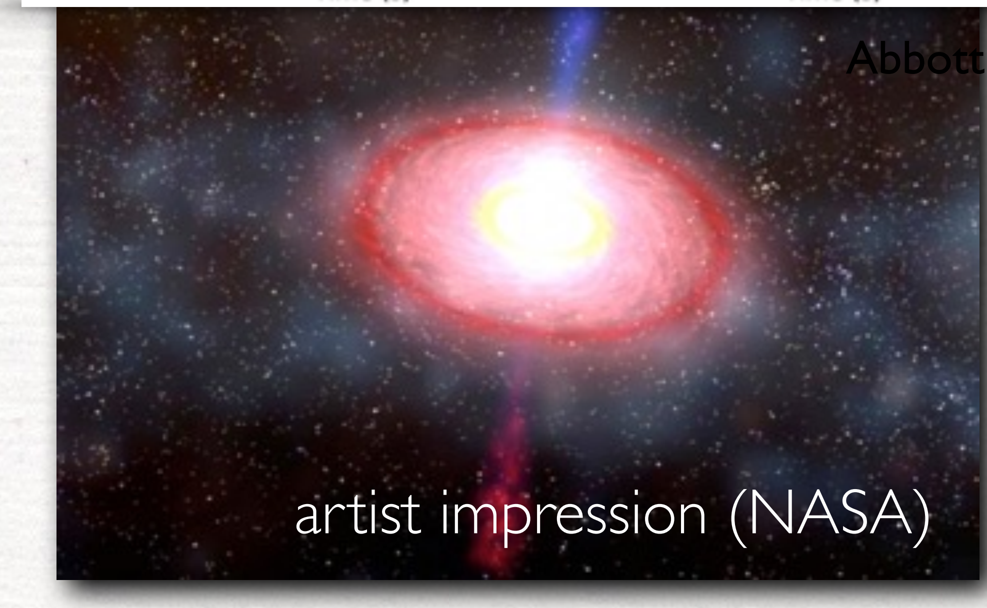


Abbott+ 2016

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



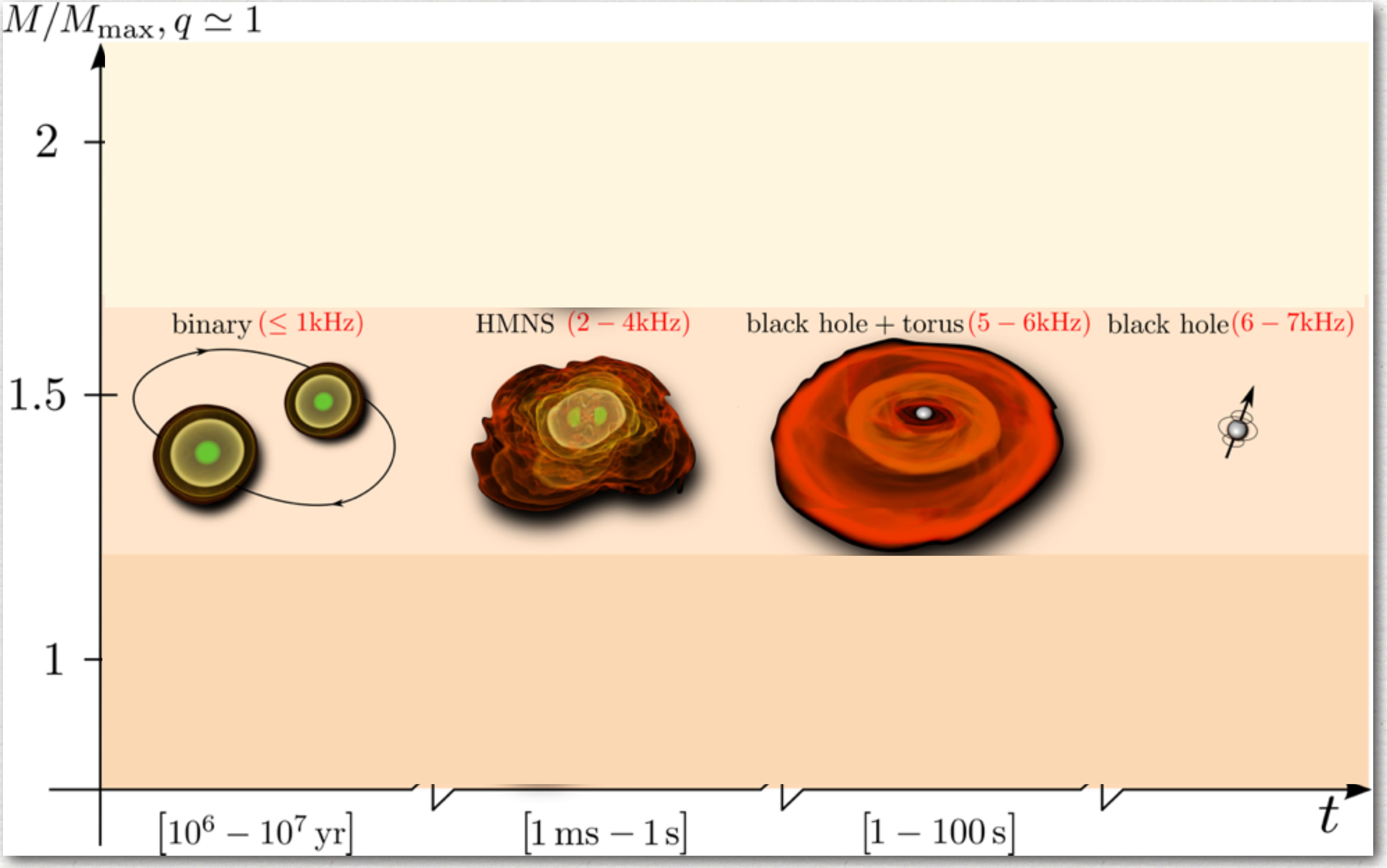
Wex 2016



artist impression (NASA)

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

Broadbrush picture

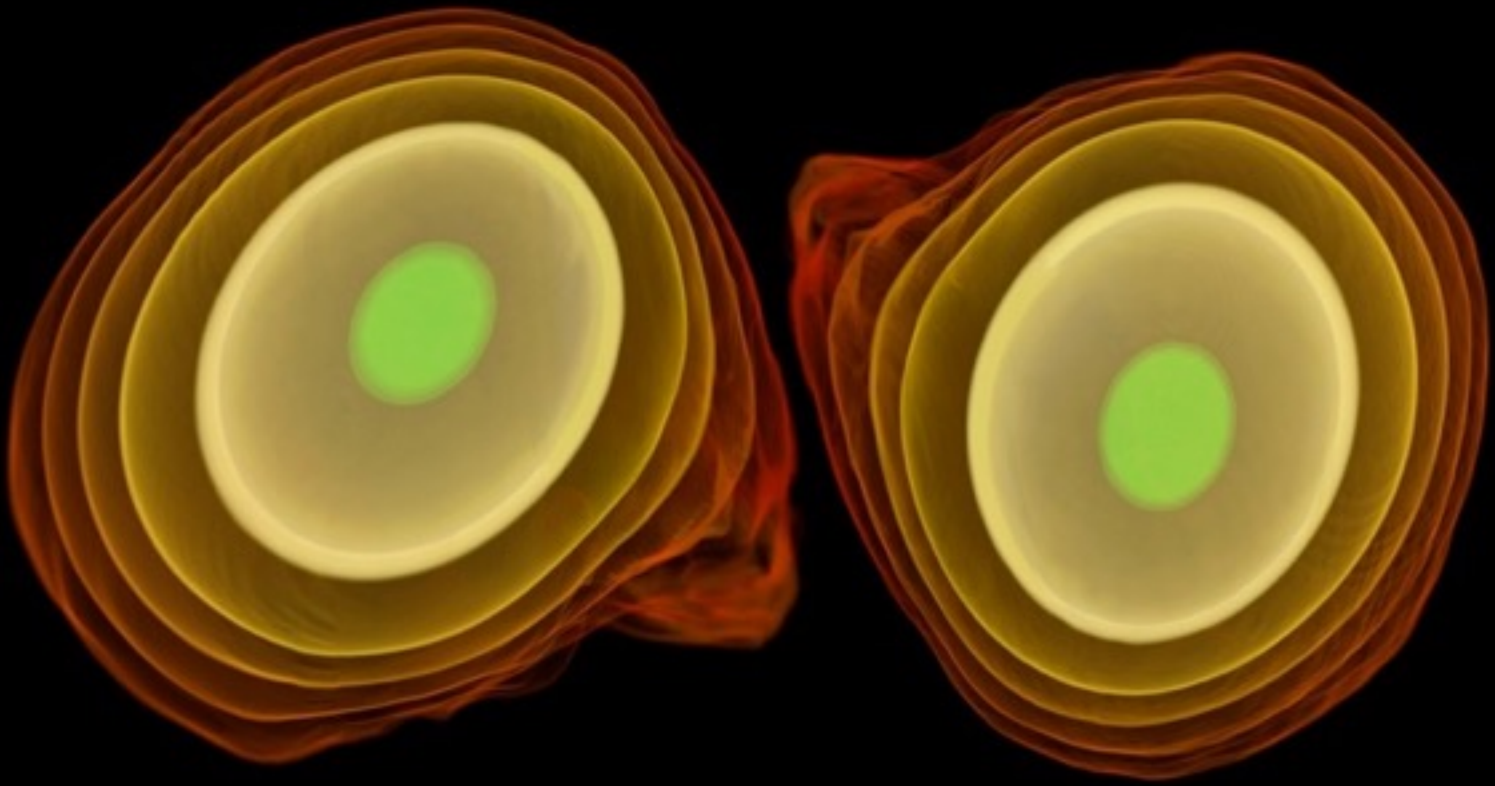


merger → HMNS → BH + torus

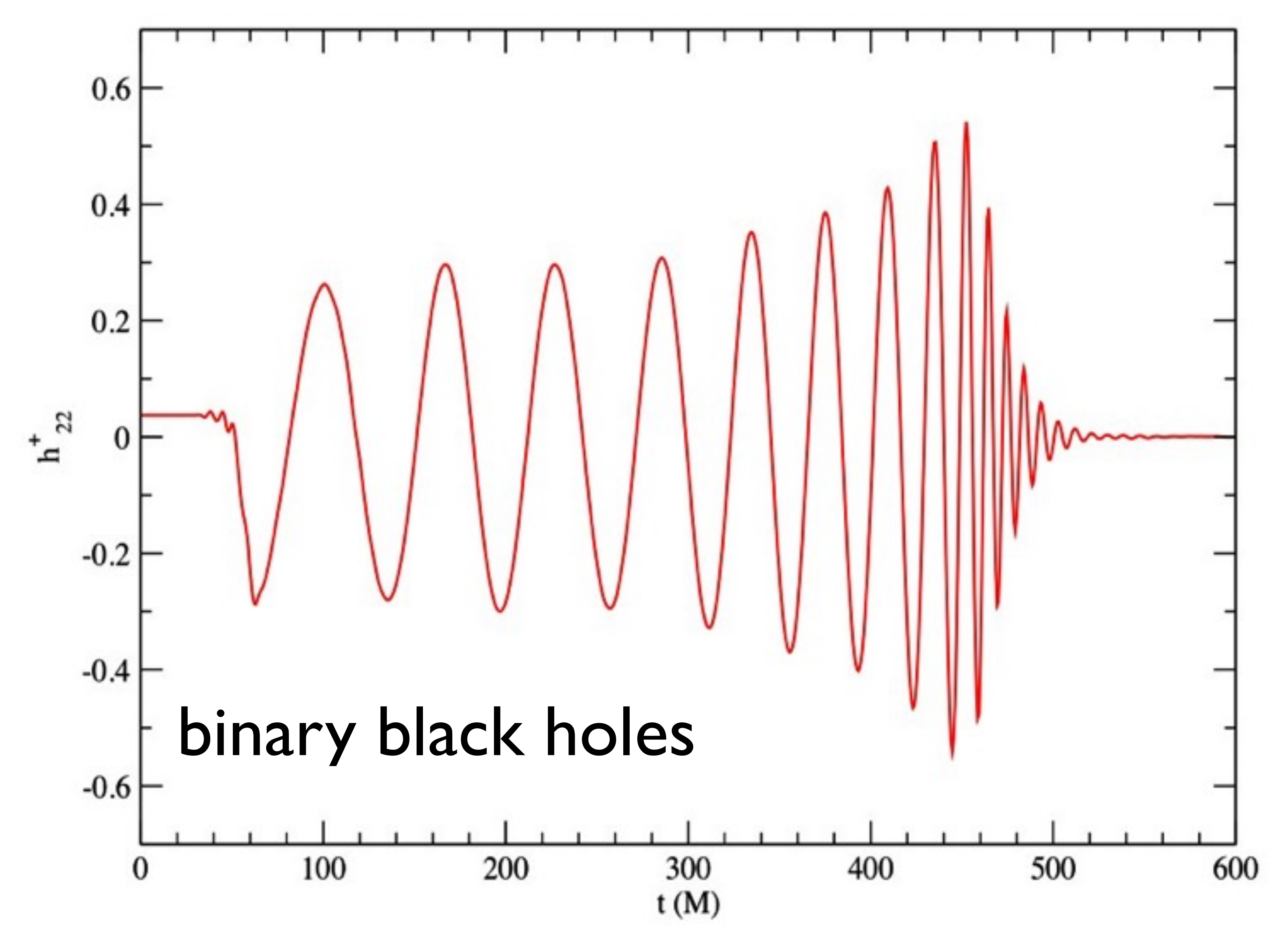
Quantitative differences are produced by:

- 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



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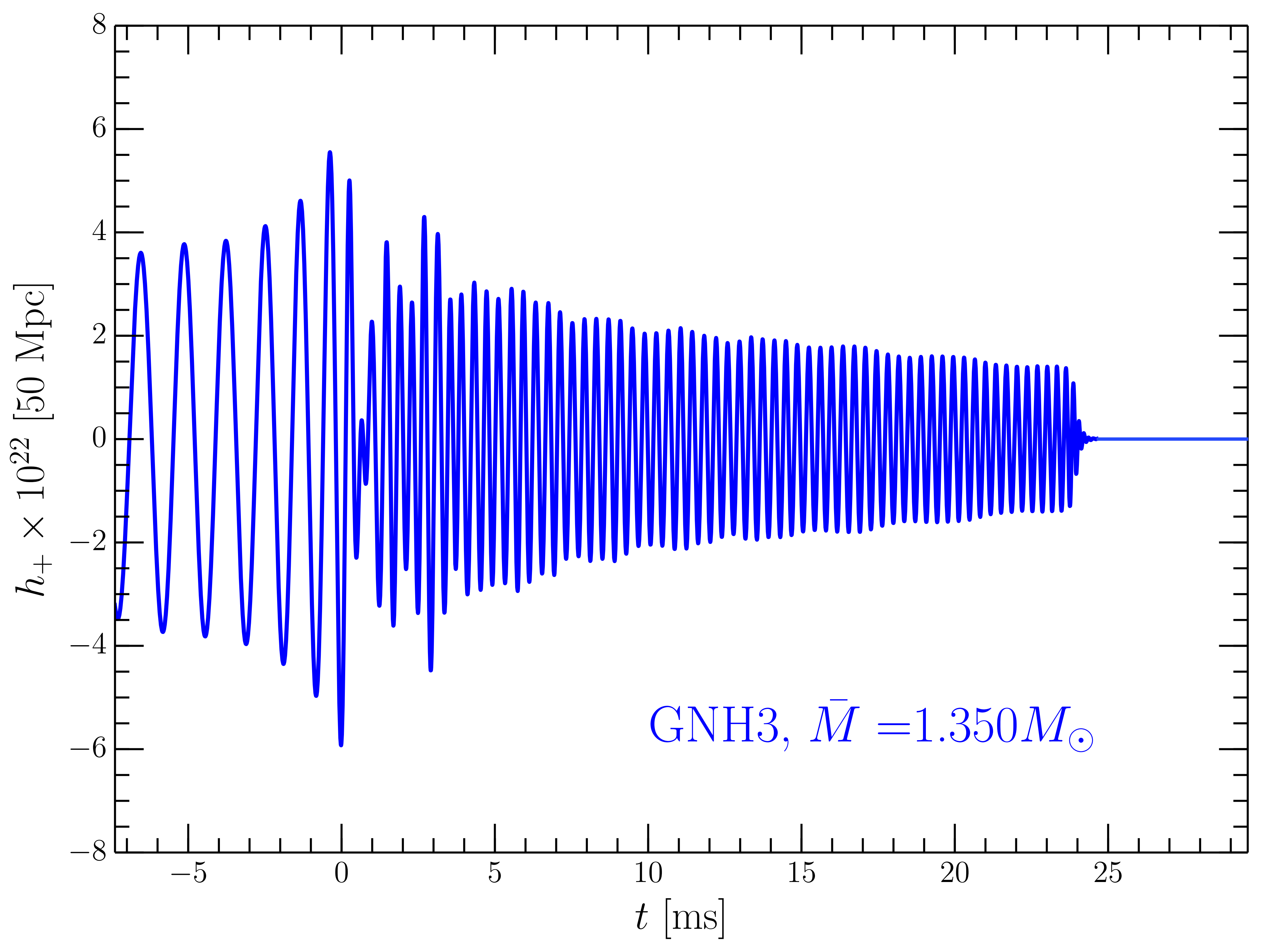

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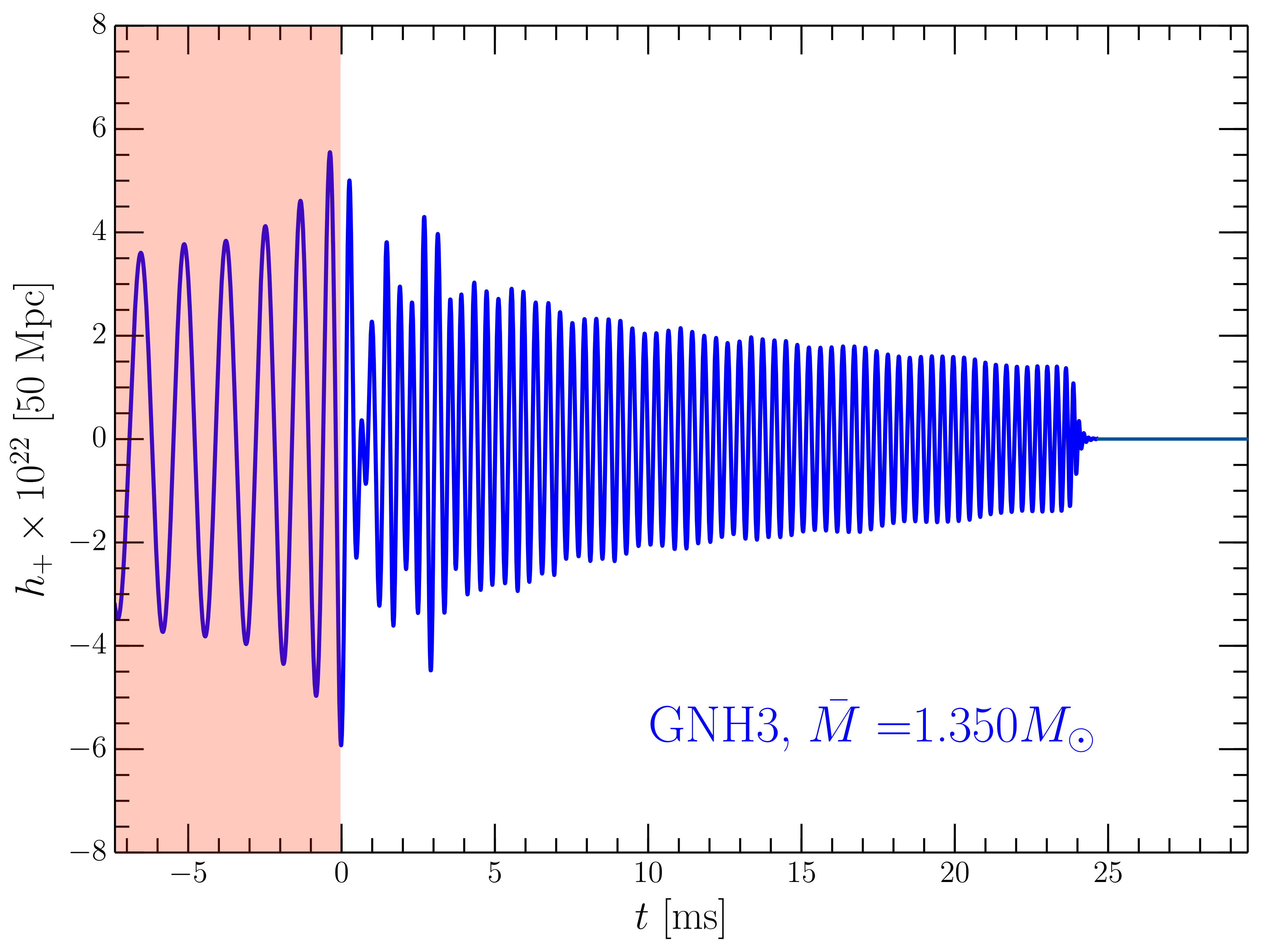
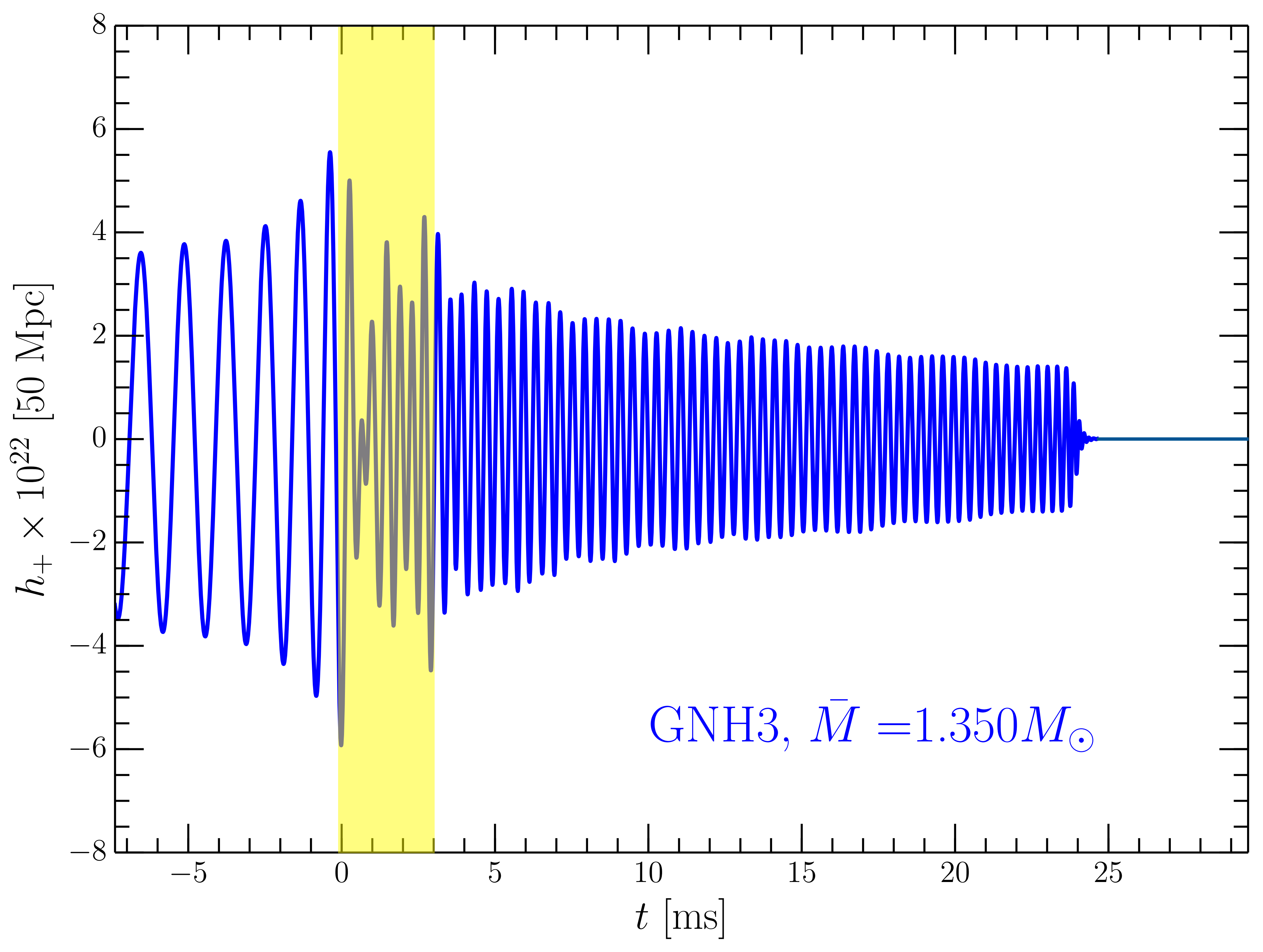


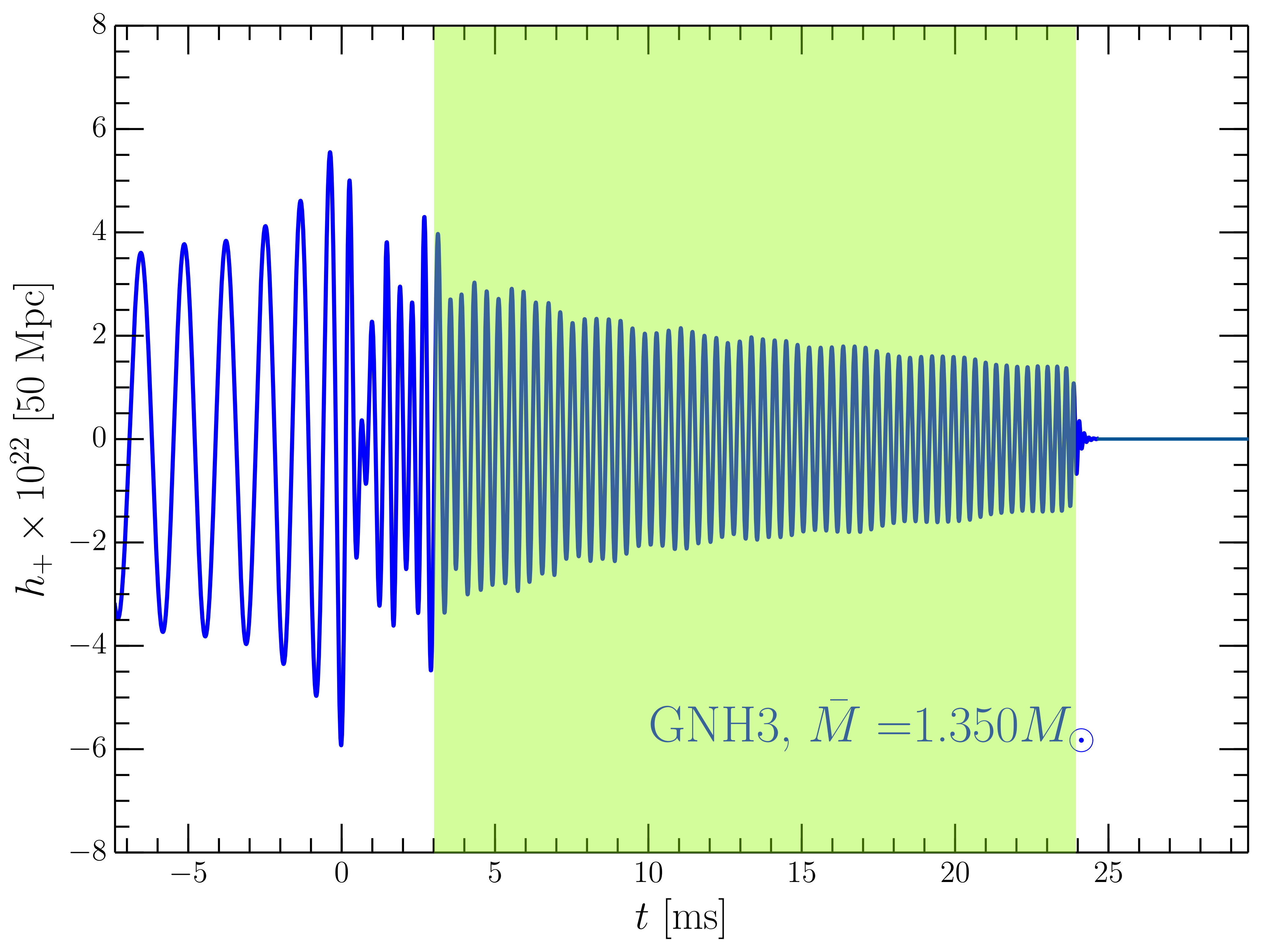
Inspiral: well approximated by PN/EOB; tidal effects important

Anatomy of the GW signal



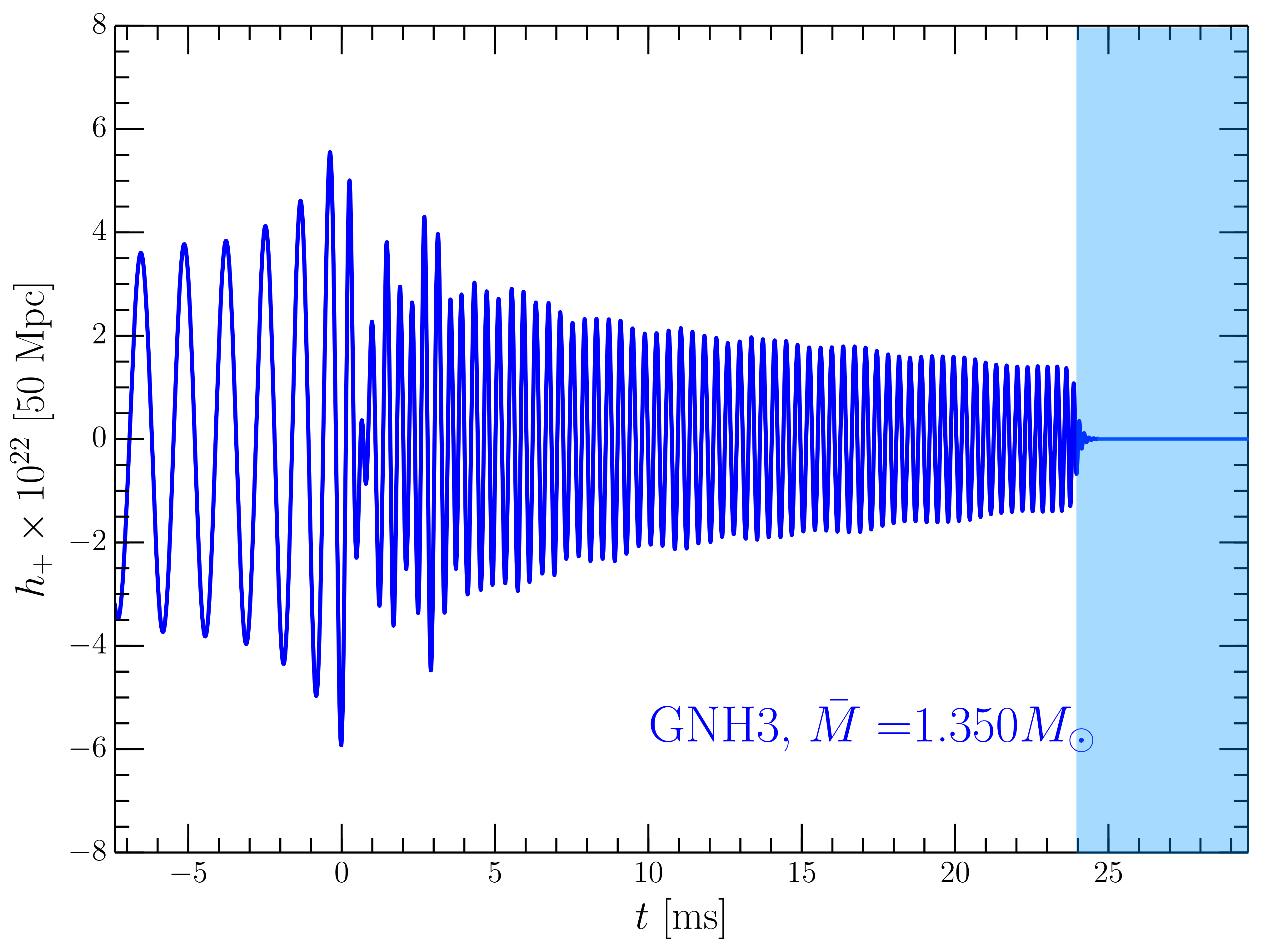
Merger: highly nonlinear but analytic description possible

Anatomy of the GW signal



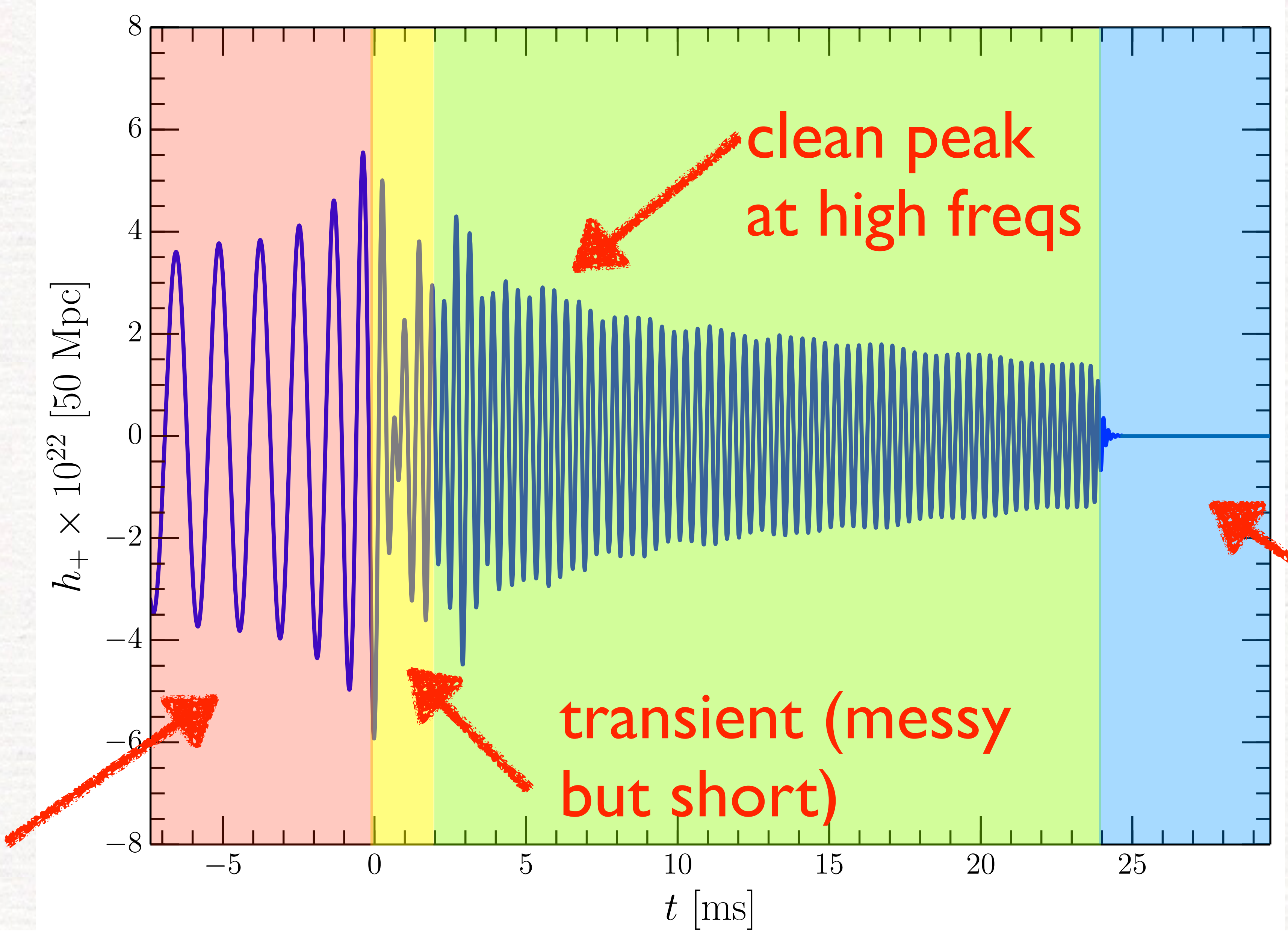
post-merger: quasi-periodic emission of bar-deformed HMNS

Anatomy of the GW signal



Collapse-ringdown: signal essentially shuts off.

Anatomy of the GW signal

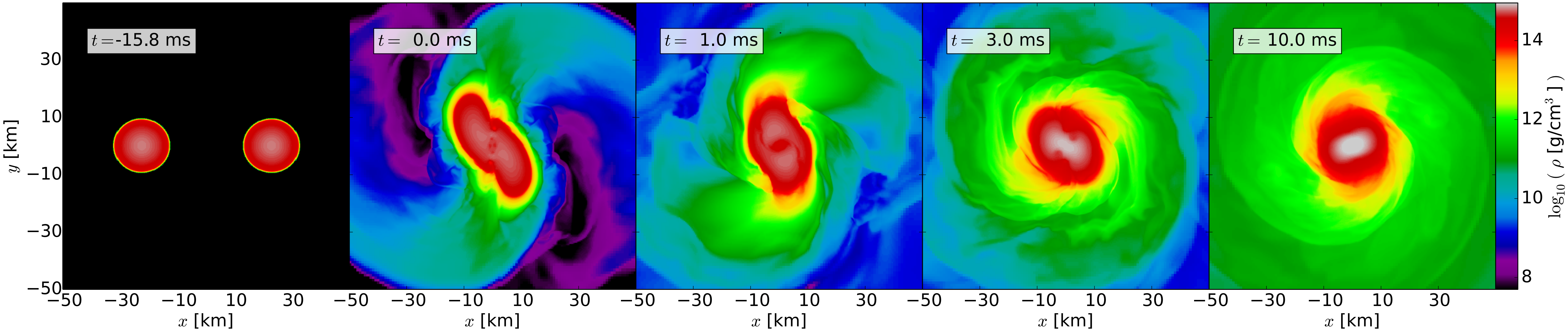


Chirp signal (track from low to high frequencies)

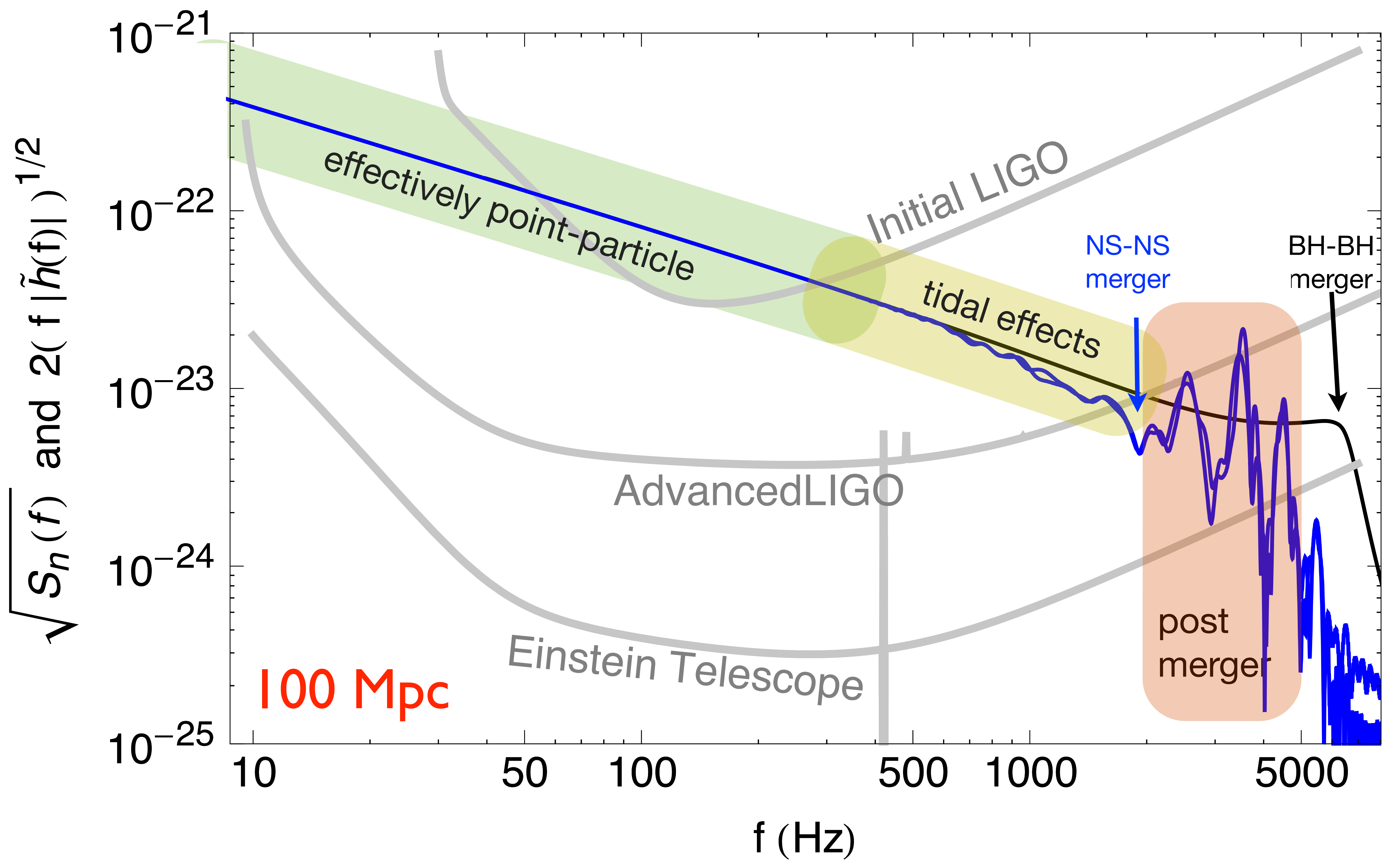
transient (messy but short)

clean peak at high freqs

Cut off (very high freqs)



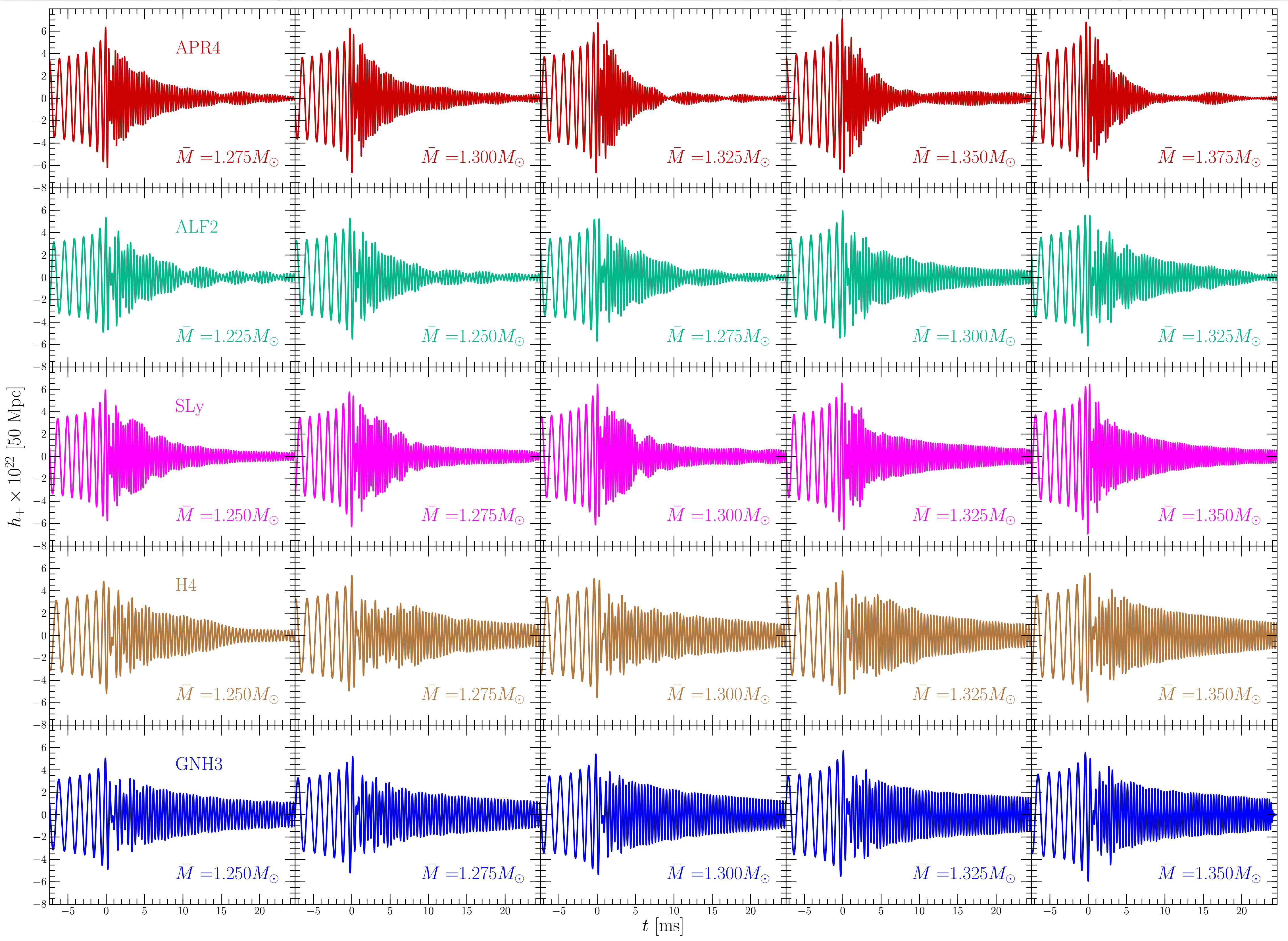
In frequency space



courtesy of Jocelyn Read

Extracting information from EOS

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



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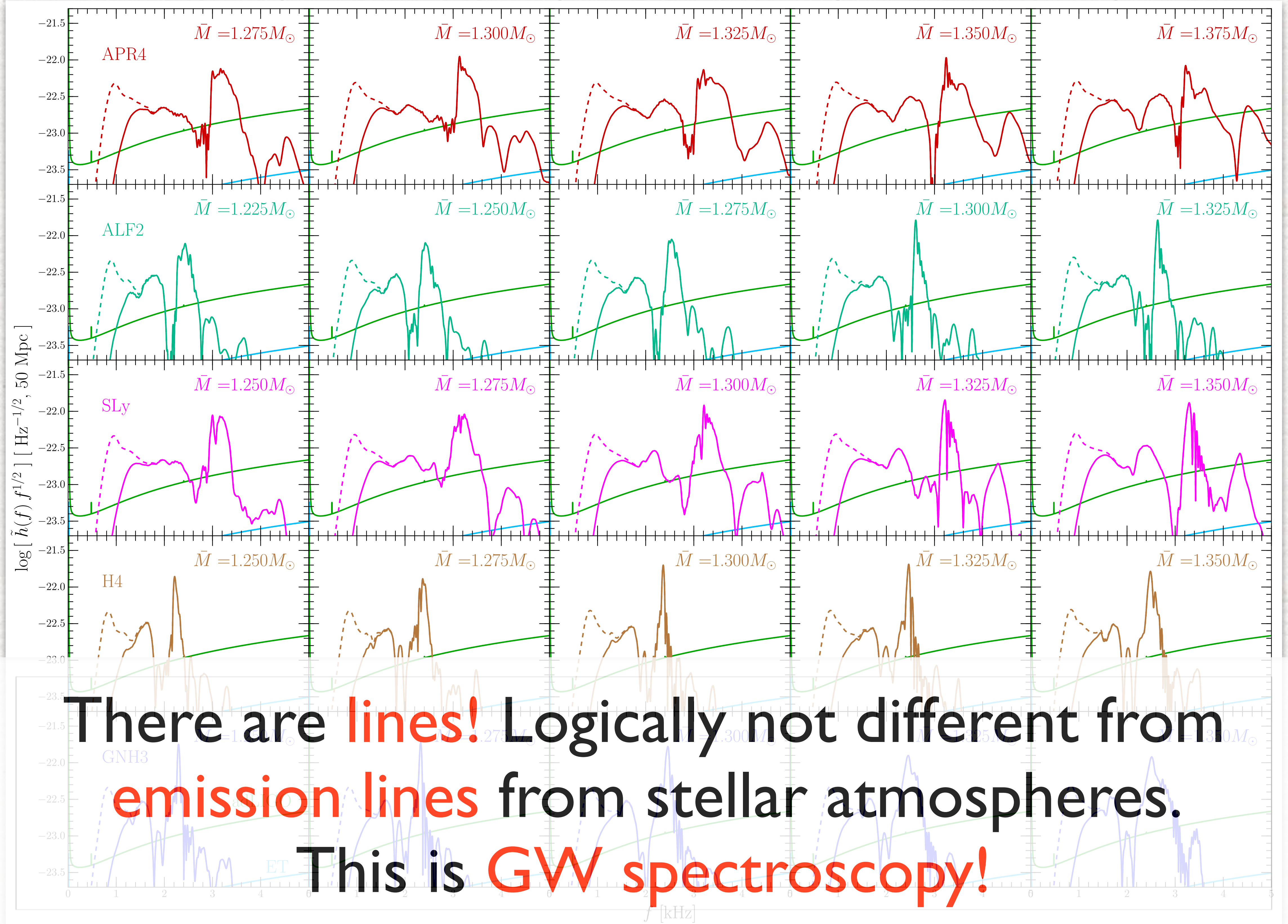
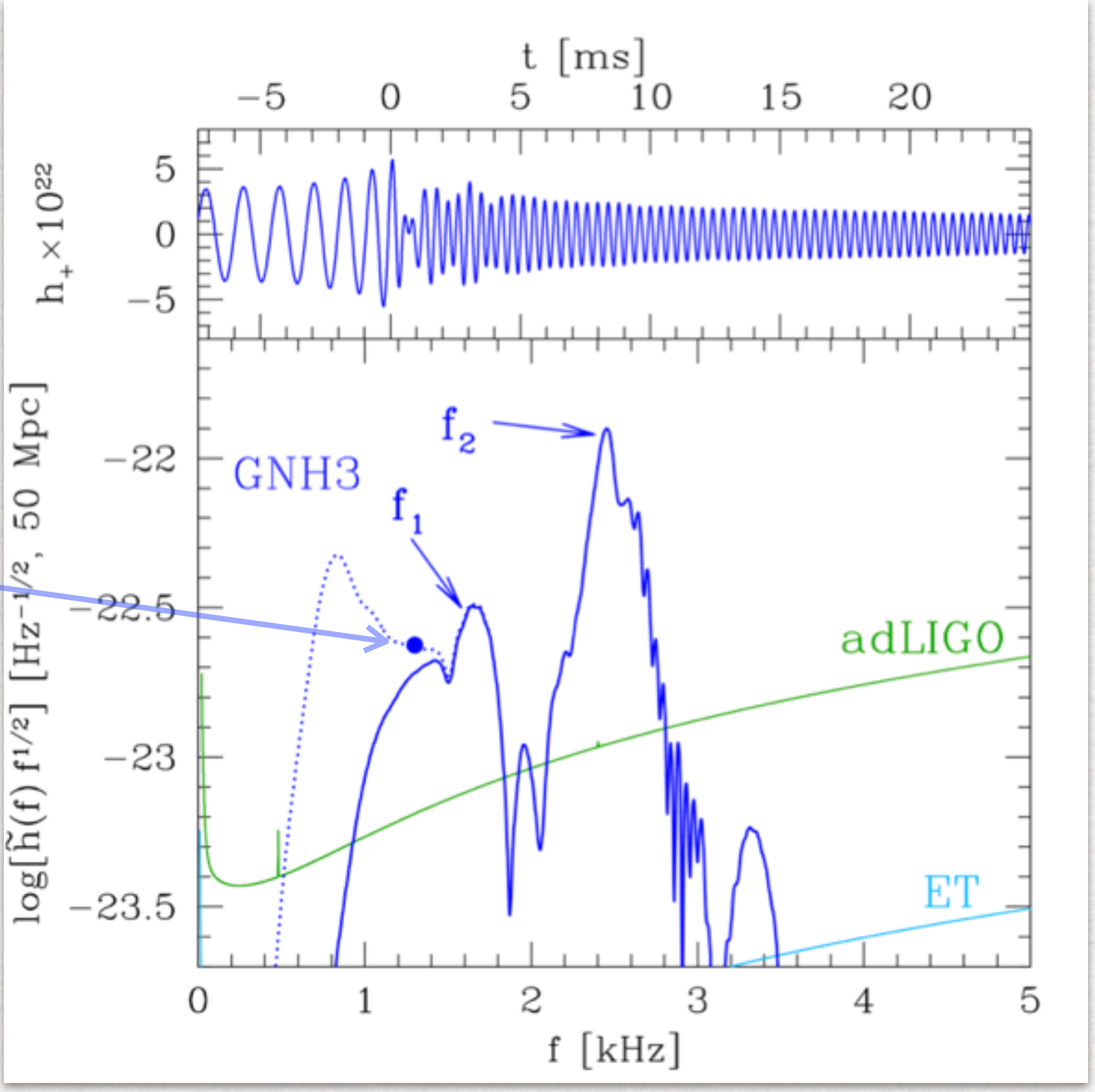


There are lines! Logically not different from emission lines from stellar atmospheres.

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, LR+2016…



merger frequency

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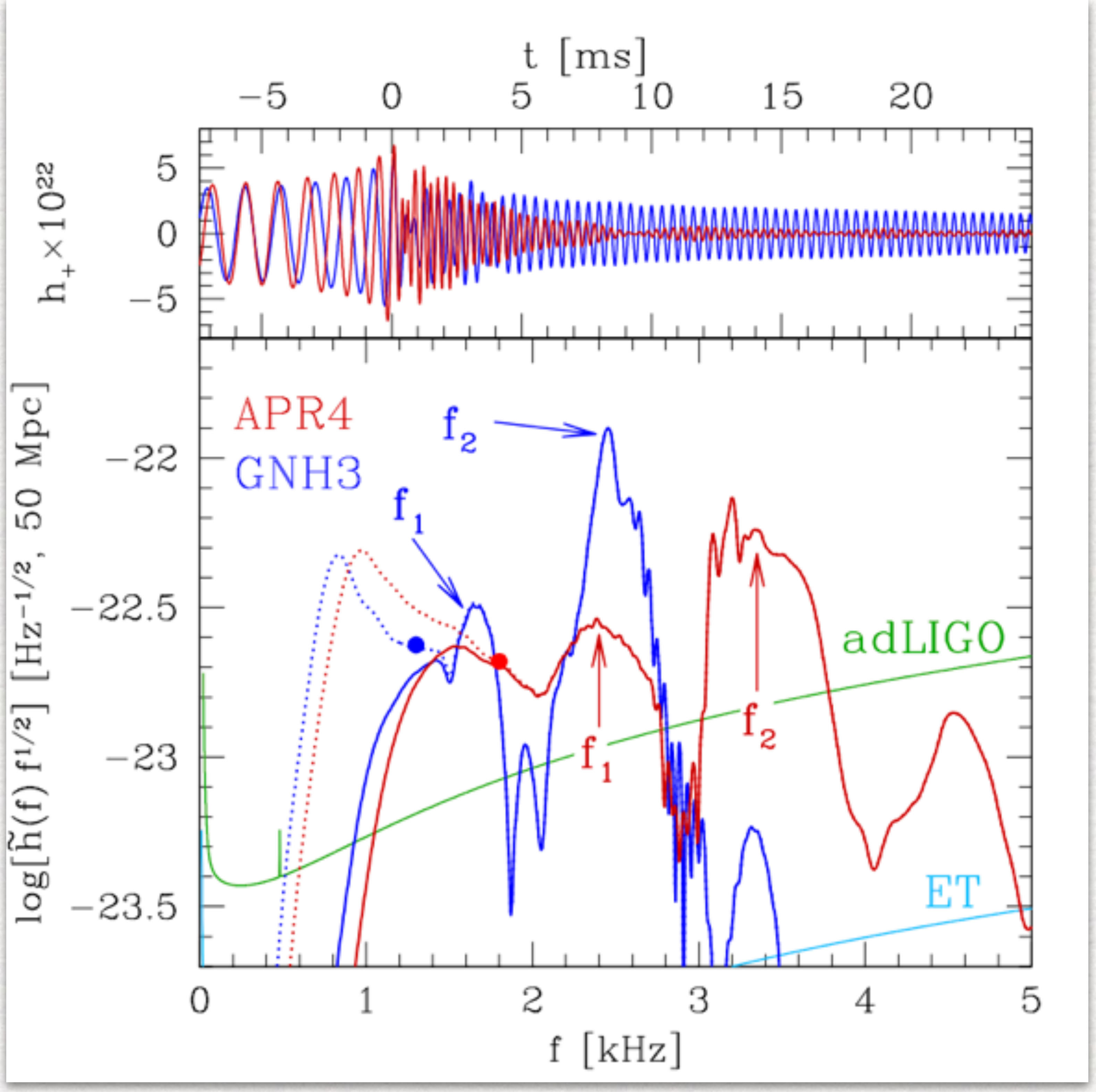
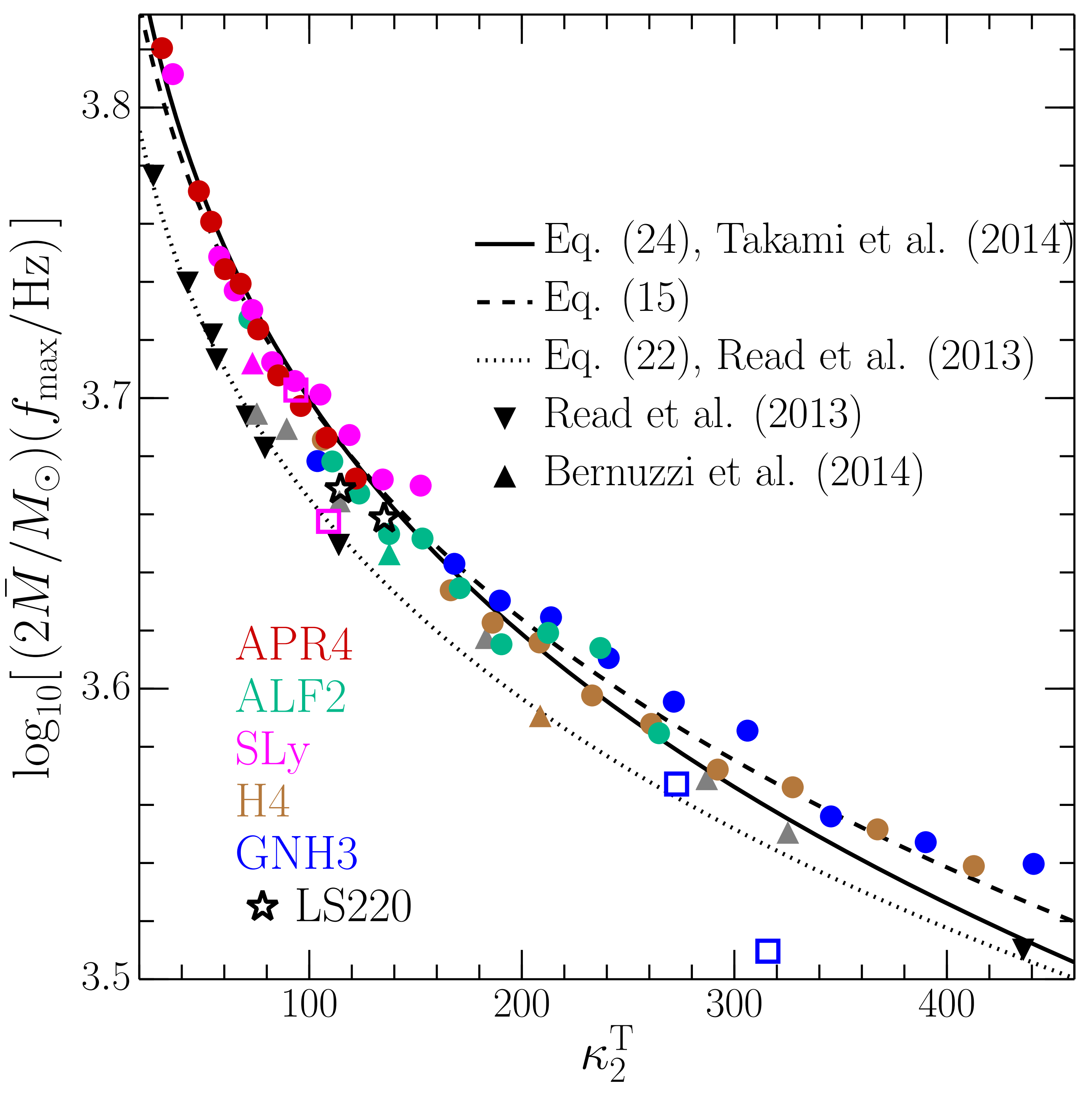


Quasi-universal behaviour: inspiral



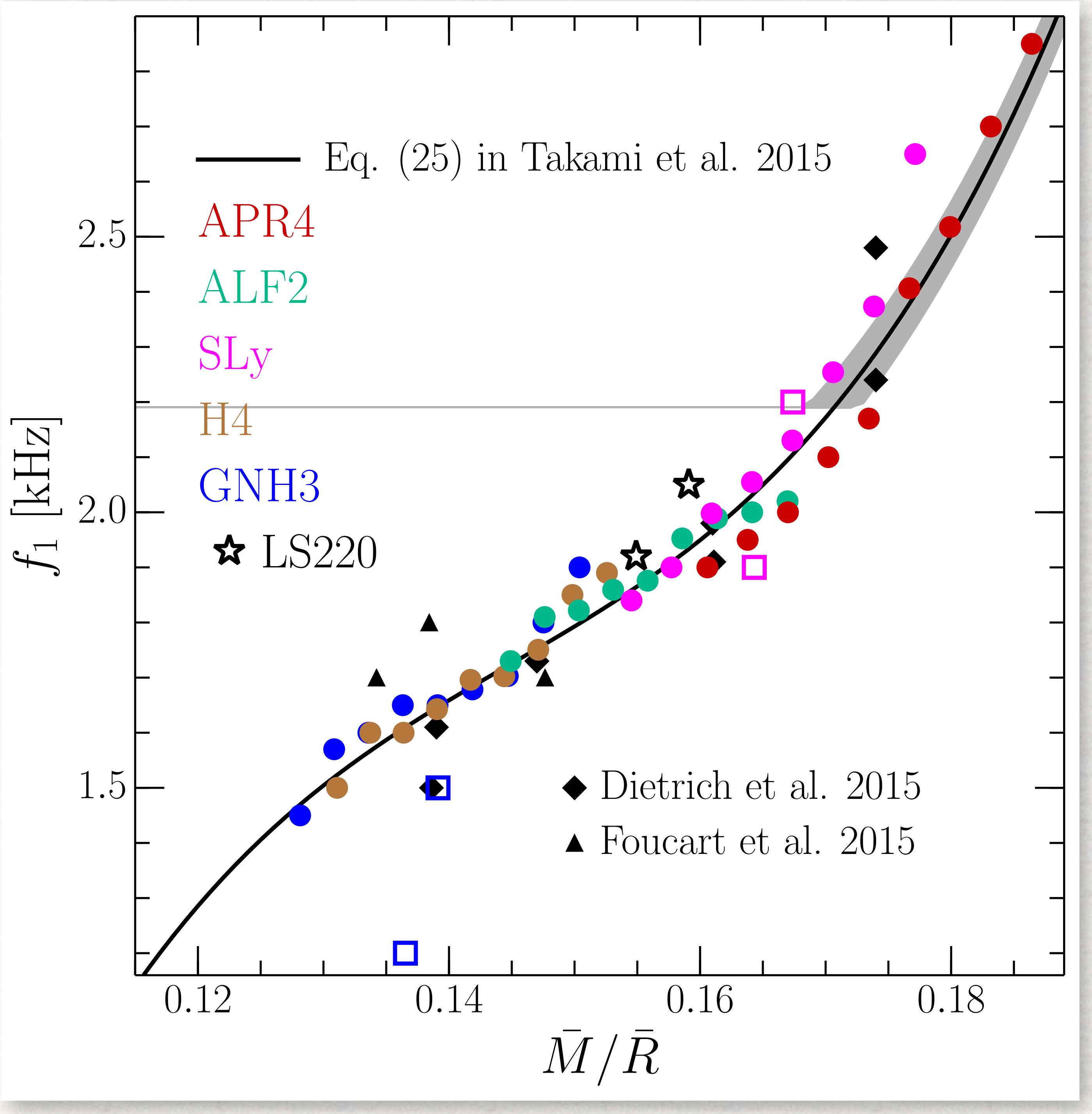
"surprising" result: quasi-universal behaviour of GW frequency at amplitude peak (Read+2013)

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

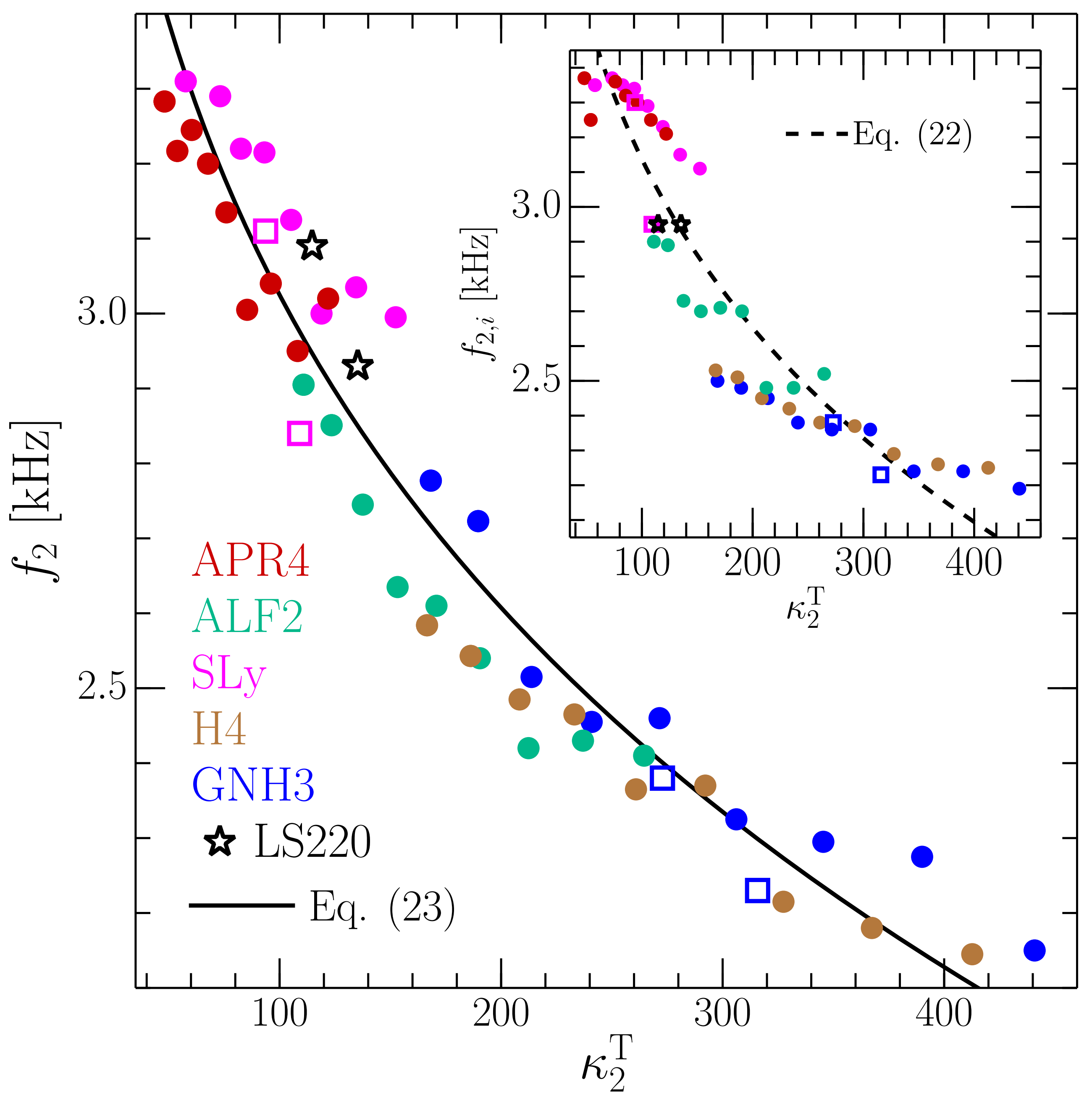


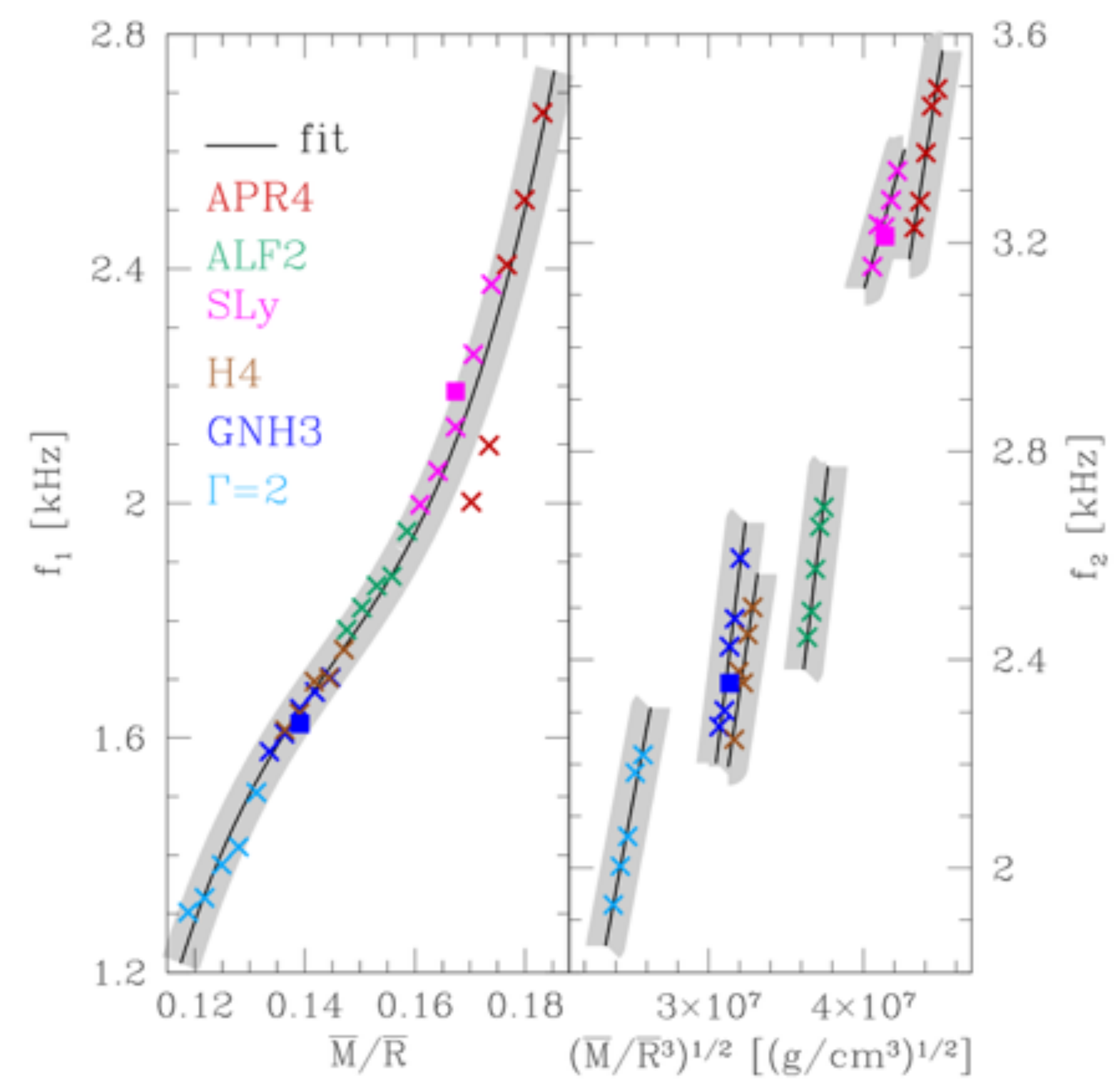
We have found **quasi-universal behaviour:** i.e., the properties of the spectra are only weakly dependent on the EOS.

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**





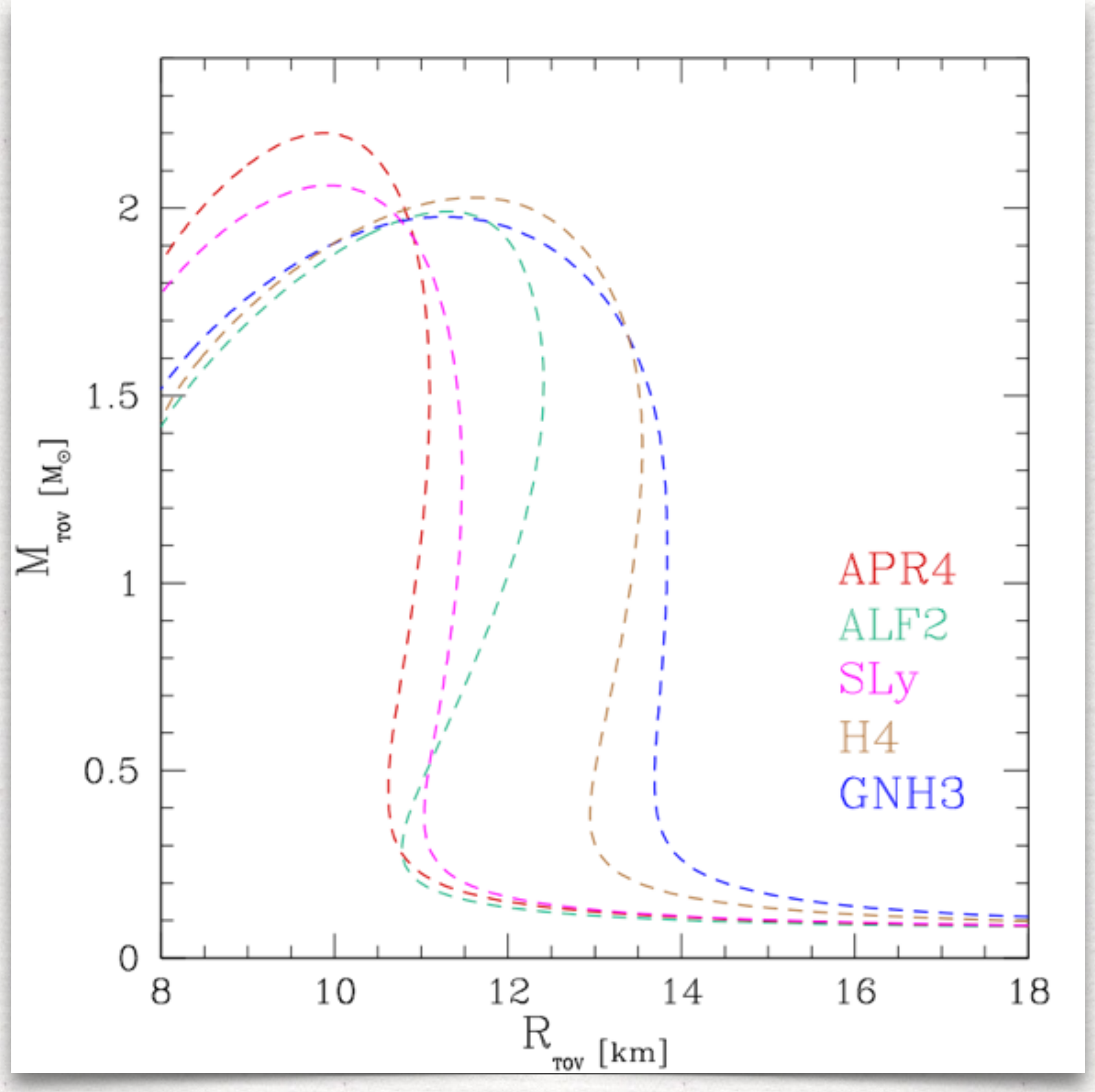
Correlations also with compactness

These other correlations are **weaker** but equally useful.

An example: start from equilibria

Assume that the GW signal from a binary NS is detected and with a SNR high enough that the two peaks are clearly measurable.

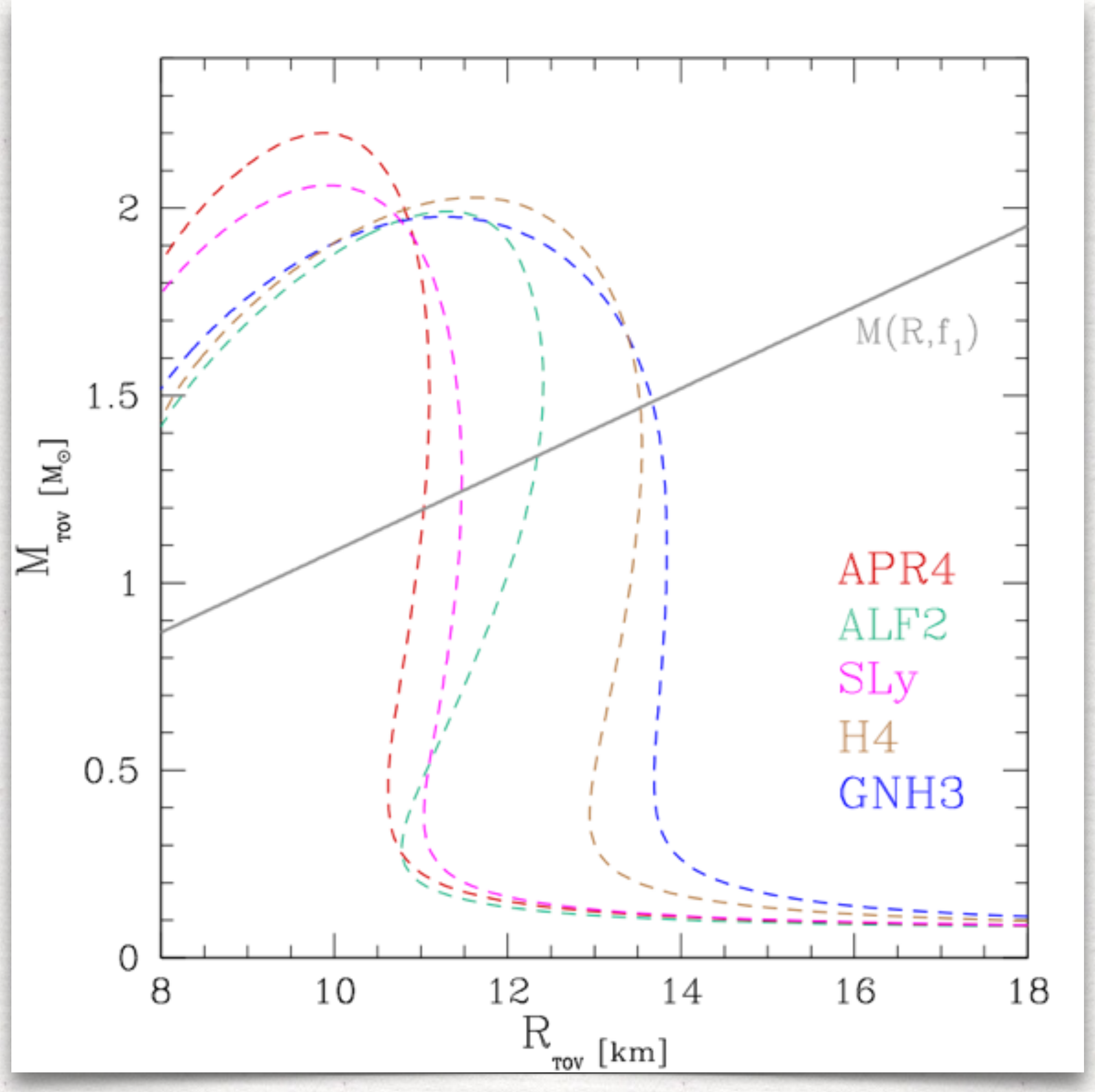
Consider your best choices as candidate EOSs



An example: use the *$M(R,f_I)$* relation

The measure of the **f_I** peak will fix a *$M(R,f_I)$* relation and hence a **single** line in the *(M, R)* plane.

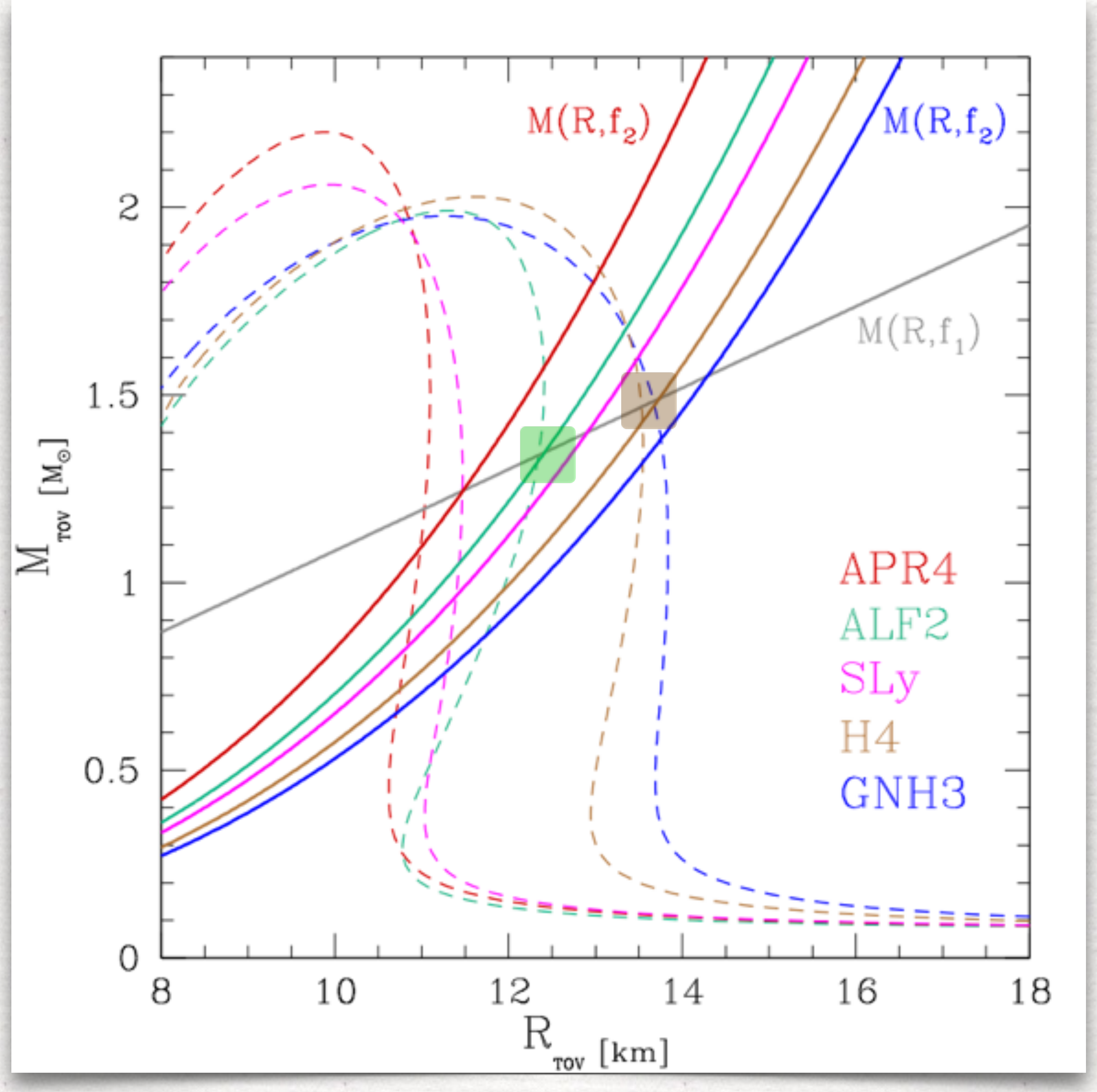
All EOSs will have **one** constraint (crossing).



An example: use the *M(R,f₂)* relations

The measure of the **f₂** peak will fix a relation *M(R,f₂,EOS)* for each EOS and hence a **number** of lines in the *(M, R)* plane.

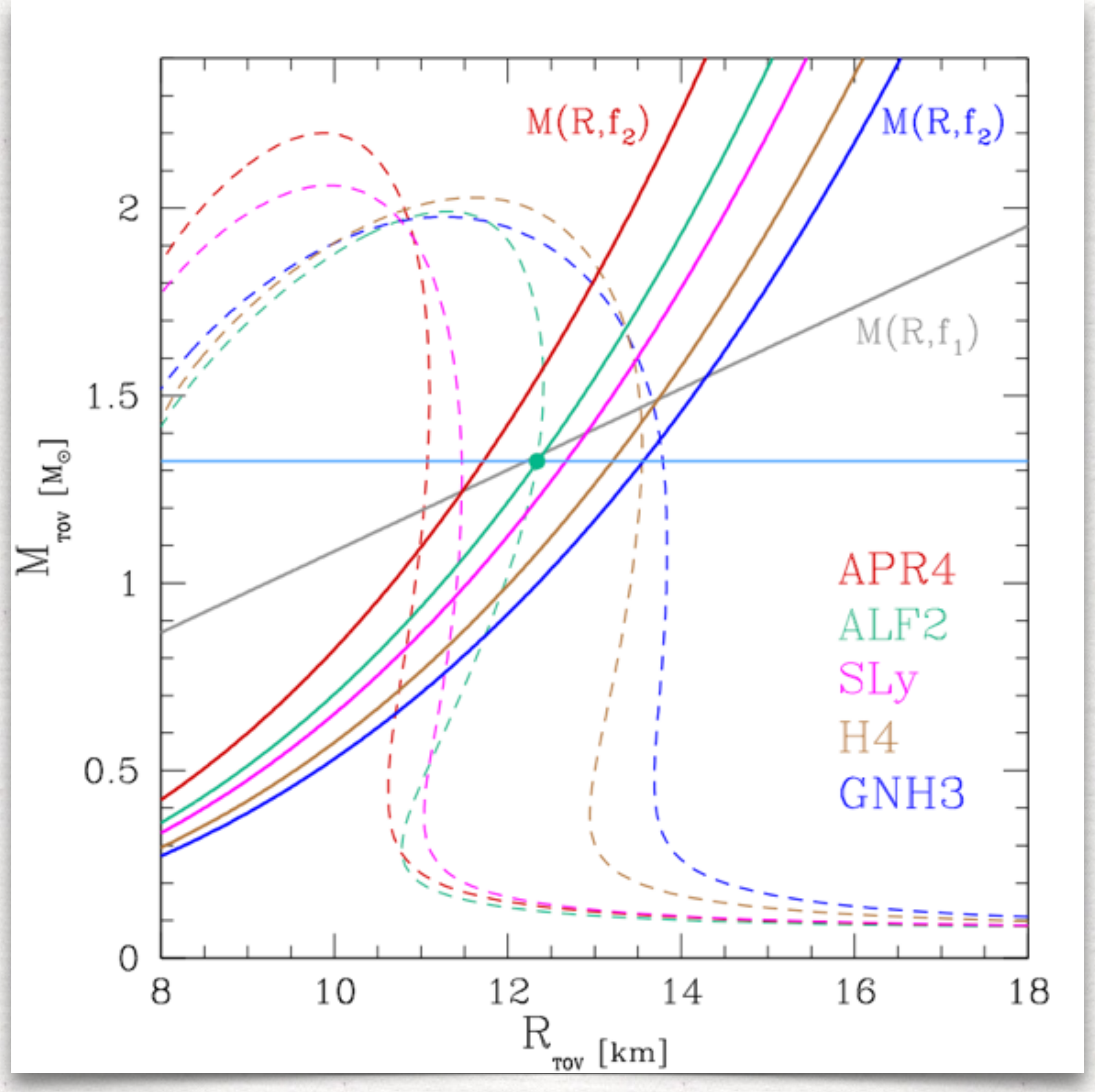
The right EOS will have **three** different constraints (APR, GNH3, SLy excluded)



An example: use measure of the mass

If the mass of the binary is measured from the inspiral, an additional constraint can be imposed.

The right EOS will have **four** different constraints. Ideally, a single detection would be sufficient.

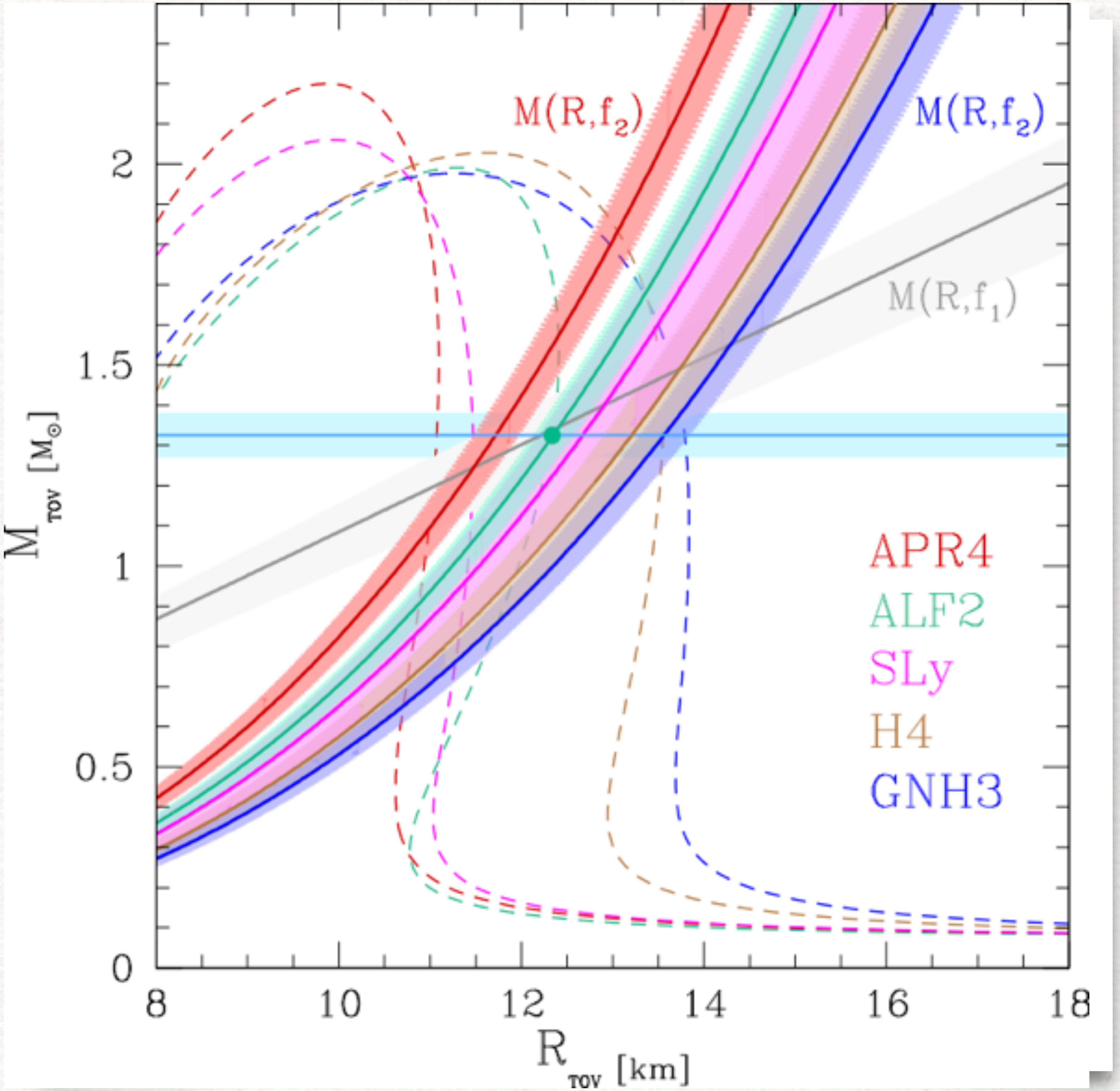


This works for all EOSs considered

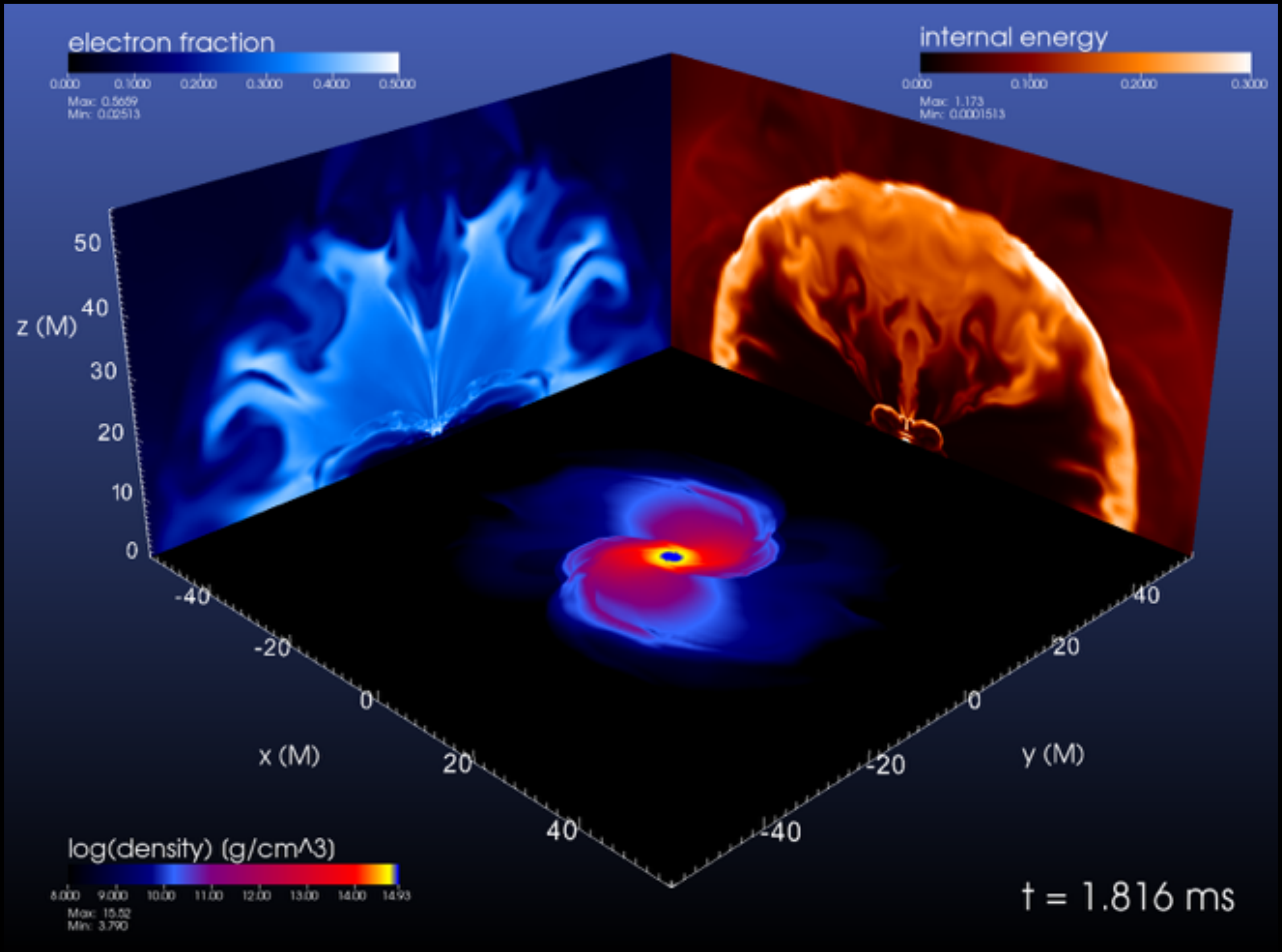
In reality things will be more complicated. The **lines** will be **stripes;** Bayesian probability to get precision on *M*, *R*.

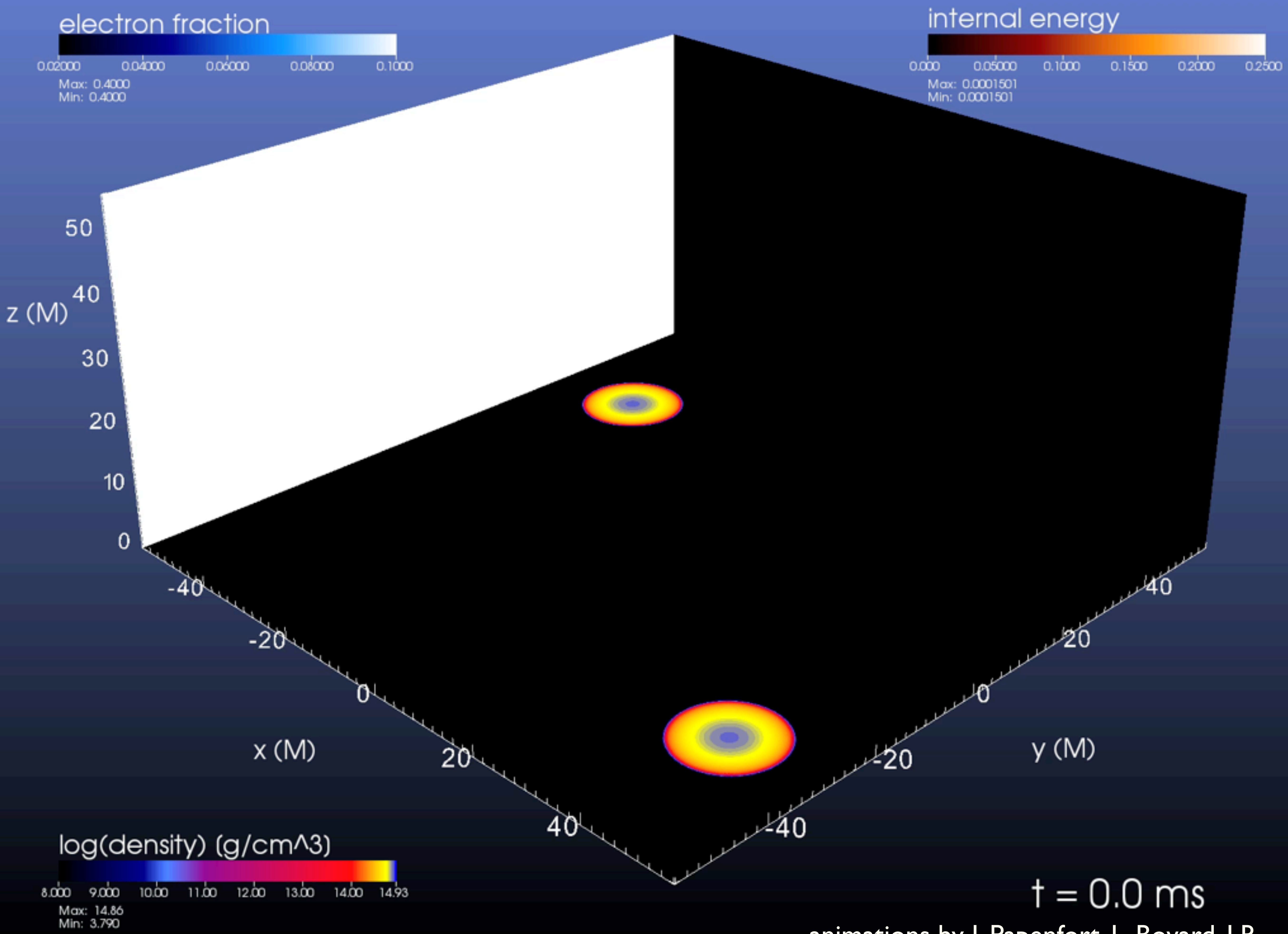
Some numbers:

- at 50 Mpc, freq. uncertainty from Fisher matrix is 100 Hz
- at SNR=2, the event rate is 0.2-2 yr^{-1} for different EOSs.



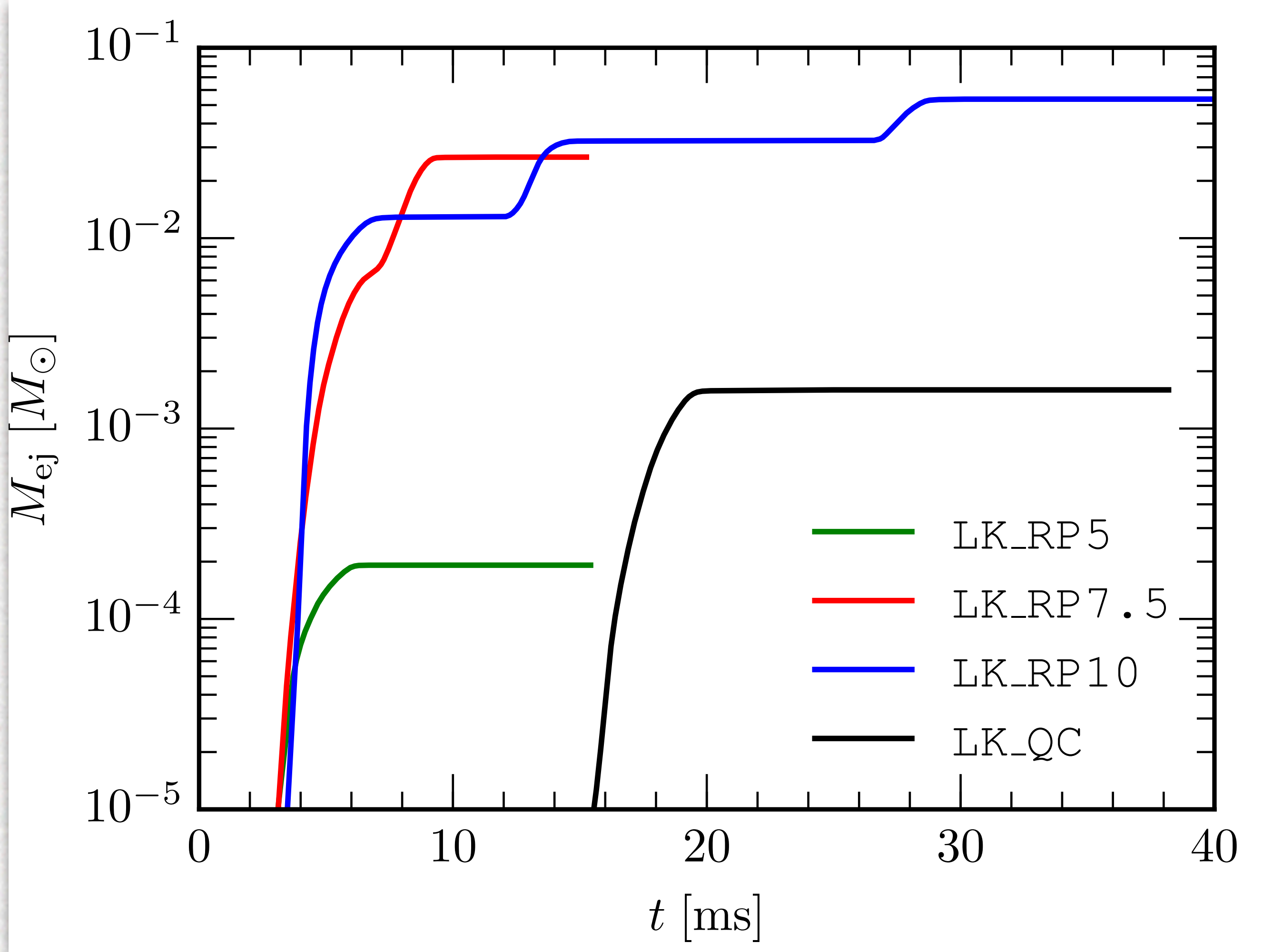
Dynamically captured binaries and nucleosynthesis



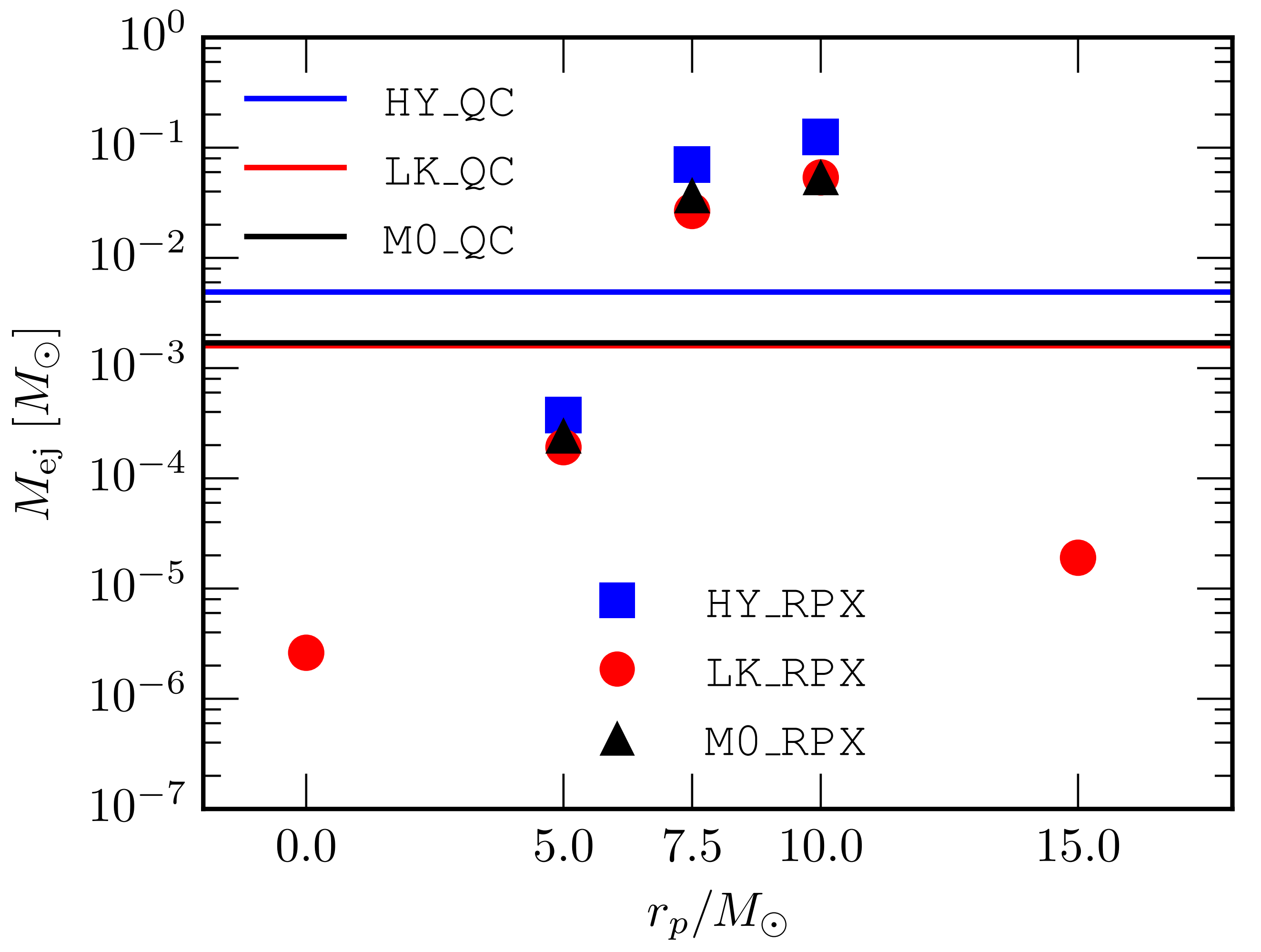


animations by J. Papenfort, L. Bovard, LR

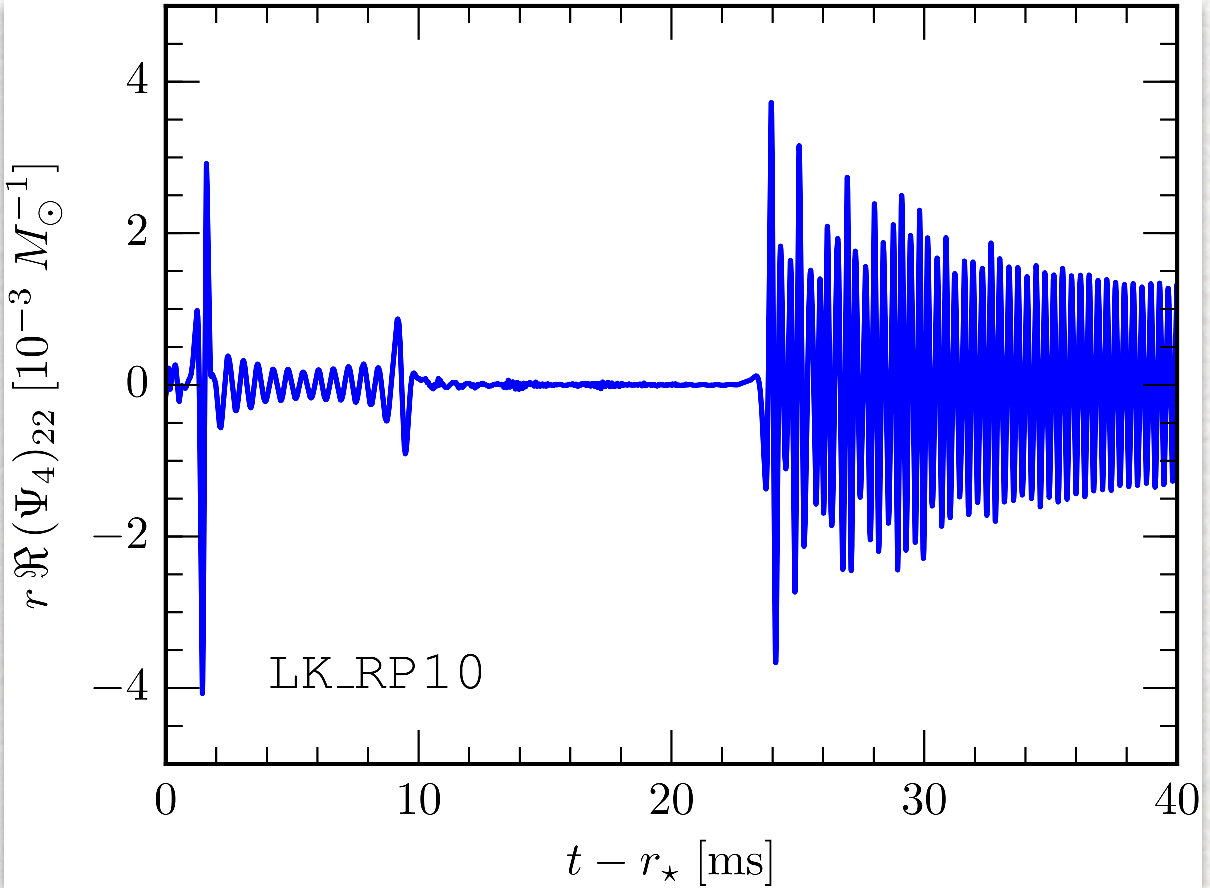
Mass ejection



- Mass ejected depends on impact parameter and takes place at each encounter.
- Quasi-circular binaries have smaller ejected masses (1-2 orders of magnitude)

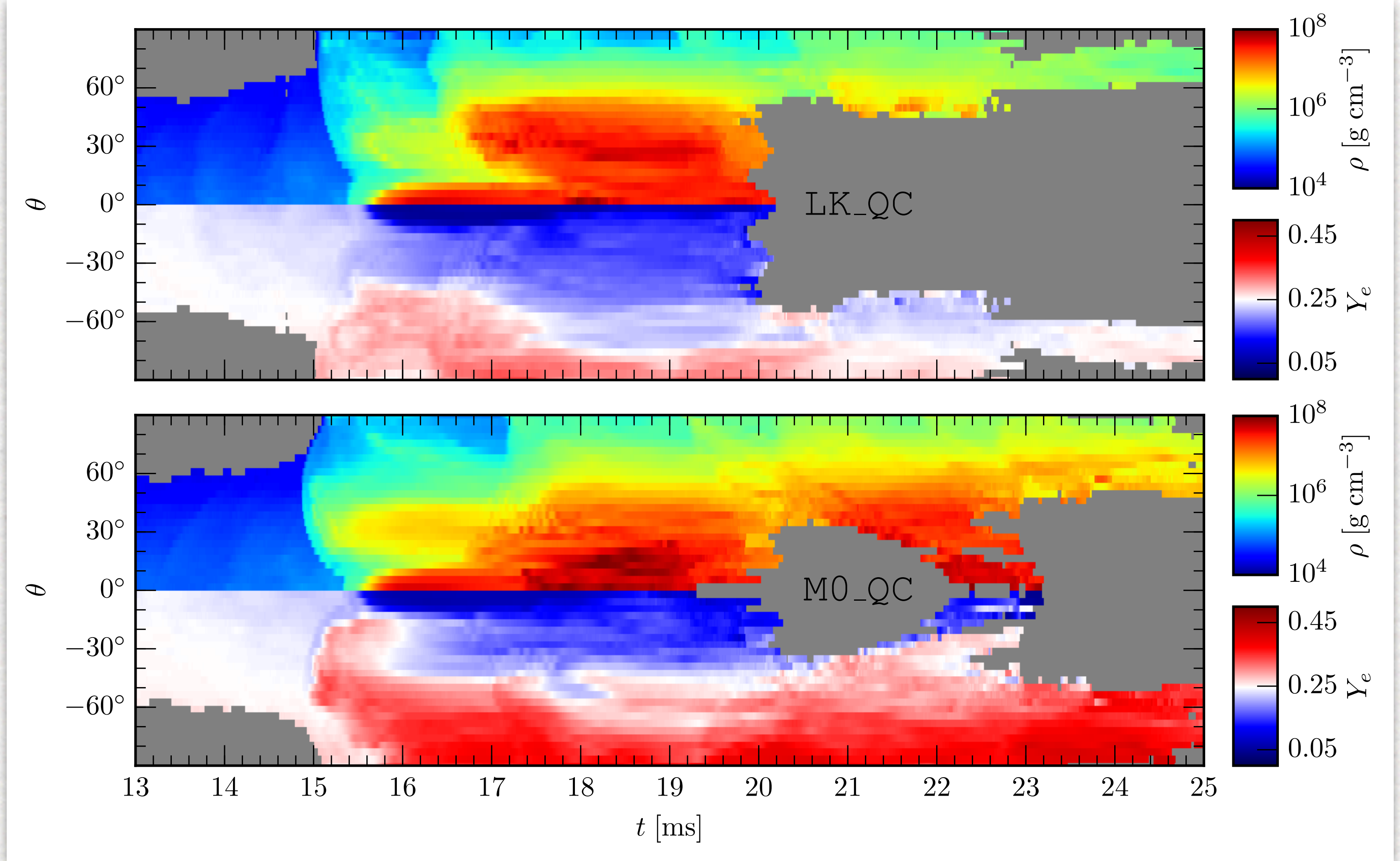


- Mass ejected depends on whether neutrino losses are taken into account (less ejected mass if neutrinos are taken into account)

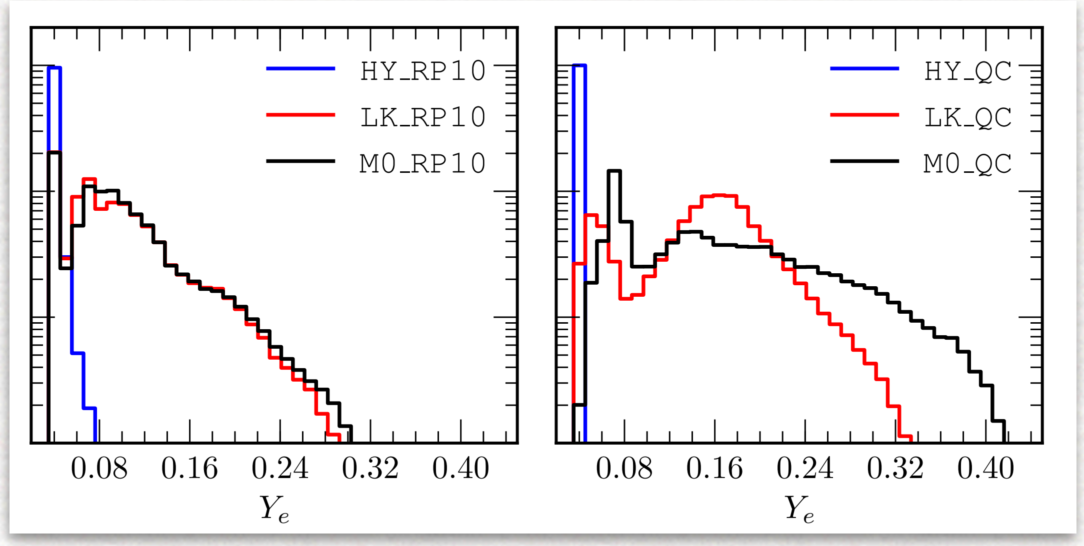


Waveforms have complex morphology: oscillations triggered after first encounter and typical HMNS signal after merger

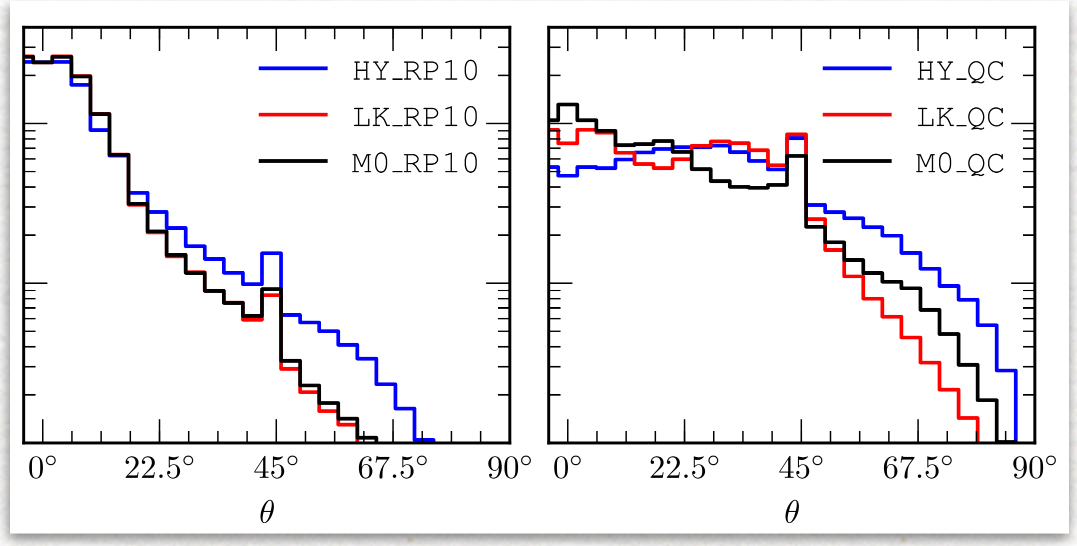
Improved neutrino treatment (M0) leads to larger values of Y_e at high latitudes



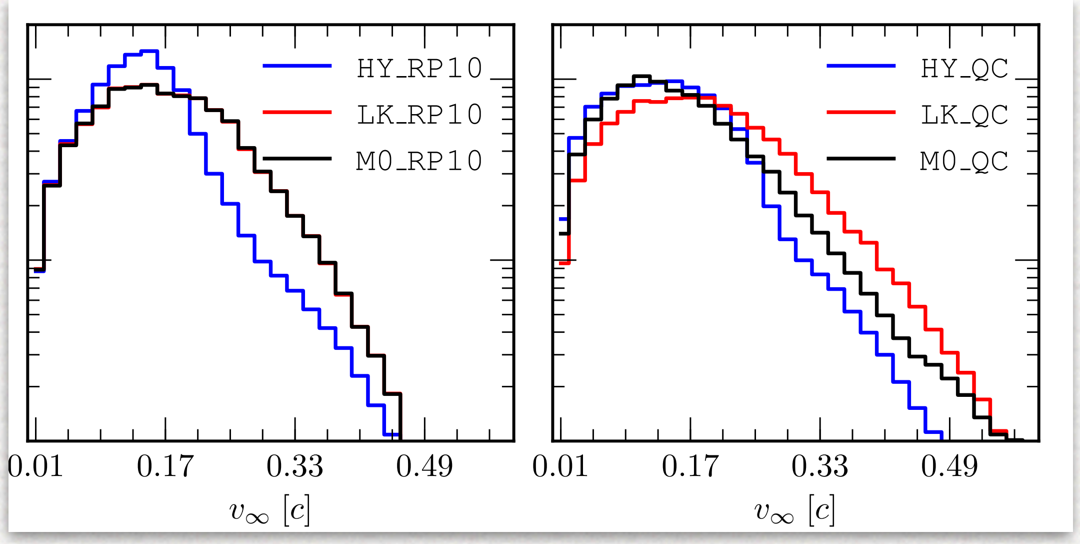
Distributions in electron fraction, entropy, velocity



- **Broad** distribution in *Ye* when neutrino losses are taken into account

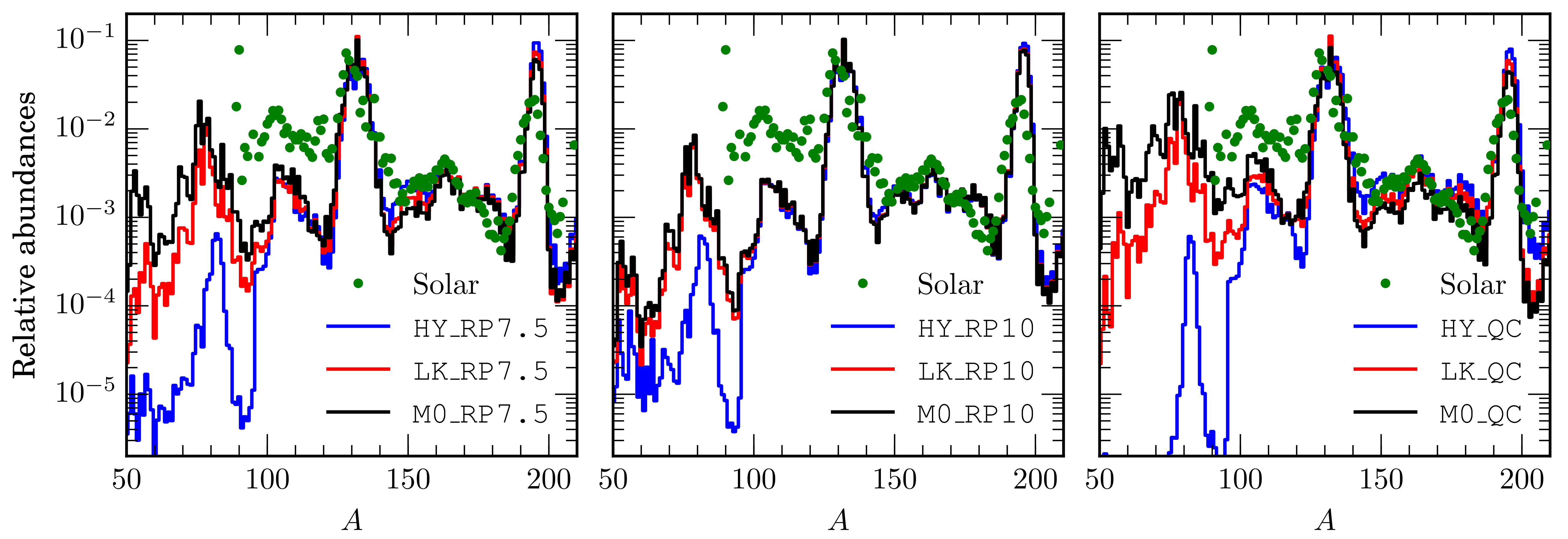


- Mass ejected at all latitudes but predominantly at **low elevations**



- Broad distribution in *asymptotic* velocities **independent** of initial conditions

Nucleosynthesis



- Ejected matter undergoes **nucleosynthesis** as expands and cools.
- Abundance pattern for ***A>120*** is robust and good agreement with solar (2nd and 3rd peak well reproduced)
- Abundances very **robust**: essentially the same for eccentric or quasi-circular binaries

Macronova emission

Energy via radioactive decay of r-process nuclei powers transients in optical/near-infrared with **peak emission** after (Grossman+ 14)

$$t_{\rm peak} = 4.9 \left(\frac{M_{\rm ej}}{10^{-2}\ M_\odot}\right)^{1/2} \times \left(\frac{\kappa}{10\ {\rm cm}^2\ {\rm g}^{-1}}\right)^{1/2} \left(\frac{\langle v_\infty \rangle}{0.1\ c}\right)^{-1/2} {\rm days}\,,$$

The **peak bolometric luminosity** is estimated to be (“ectonova”)

$$L = 2.5 \times 10^{40} \left(\frac{M_{\rm ej}}{10^{-2}\ M_\odot}\right)^{1-\alpha/2} \times \left(\frac{\kappa}{10\ {\rm cm}^2\ {\rm g}^{-1}}\right)^{-\alpha/2} \left(\frac{\langle v_\infty \rangle}{0.1\ c}\right)^{\alpha/2} {\rm erg\ s}^{-1}\,.$$

with radioactive energy release a power law $\dot\epsilon = \dot\epsilon_0 (t/t_0)^{-\alpha},\ \alpha \simeq 1.3$

Eccentric binaries: ~ **4 times more luminous** than quasi-circular; **delayed peak emission:** ~ 8 days (cf. 1.5 days)

Conclusions

✳Modelling of binary NSs in full GR is **mature**: GWs from the inspiral can be computed with precision of binary BHs

✳Spectra of post-merger shows clear peaks, some of which are **”quasi-universal”**. If observed, will set tight constraints on EOS

✳ **Eccentric** binaries are rare but with larger ejected matter and macronova emission.“high-*A*” nucleosynthesis very robust