Signatures of quark-hadron phase transitions in neutron-star mergers

Luciano Rezzolla

Institute for Theoretical Physics, Frankfurt

V. Dexheimer, M. Hanauske, E. Most, J. Papenfort, S. Schramm, H. Stoecker

June 10th, 2019

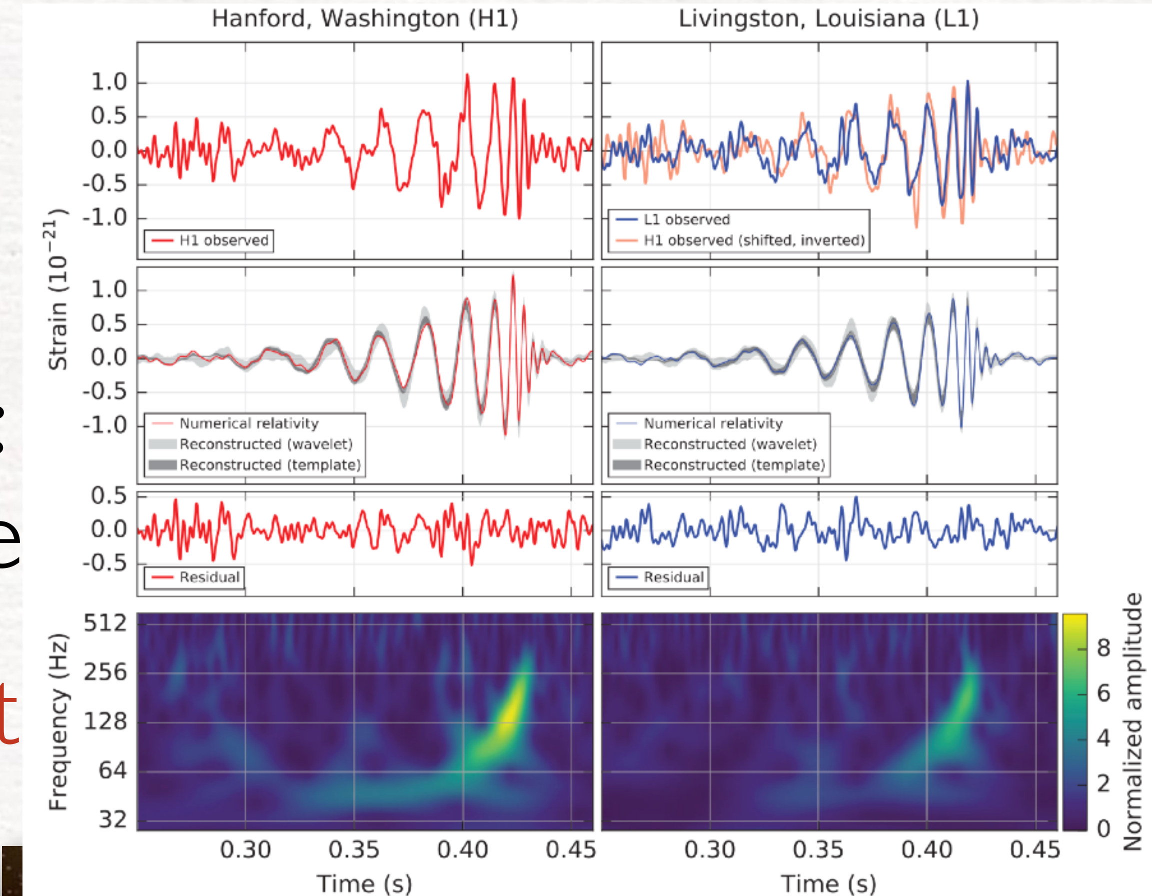
The two-body problem in GR

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

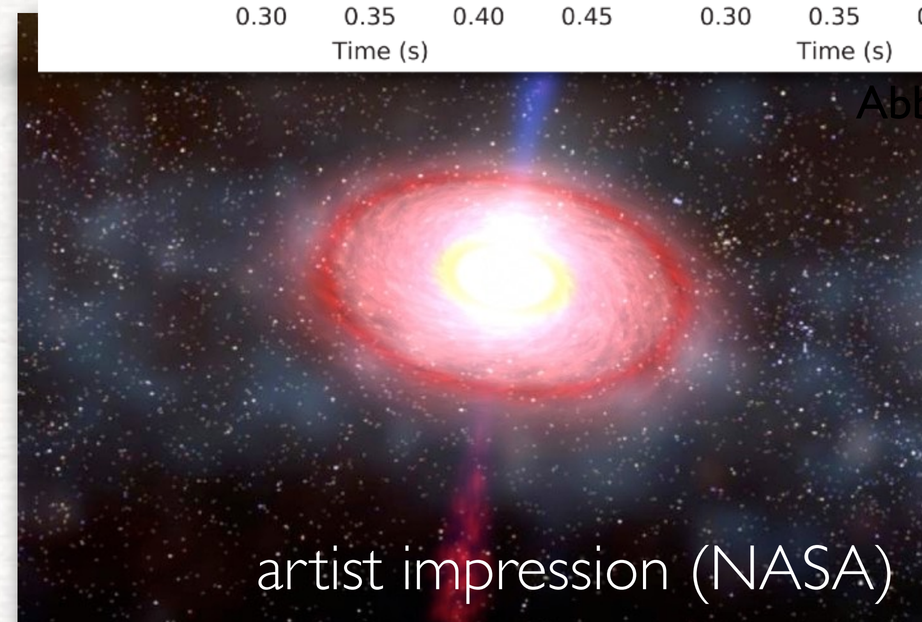
BH + BH ⟶ BH + GWs

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

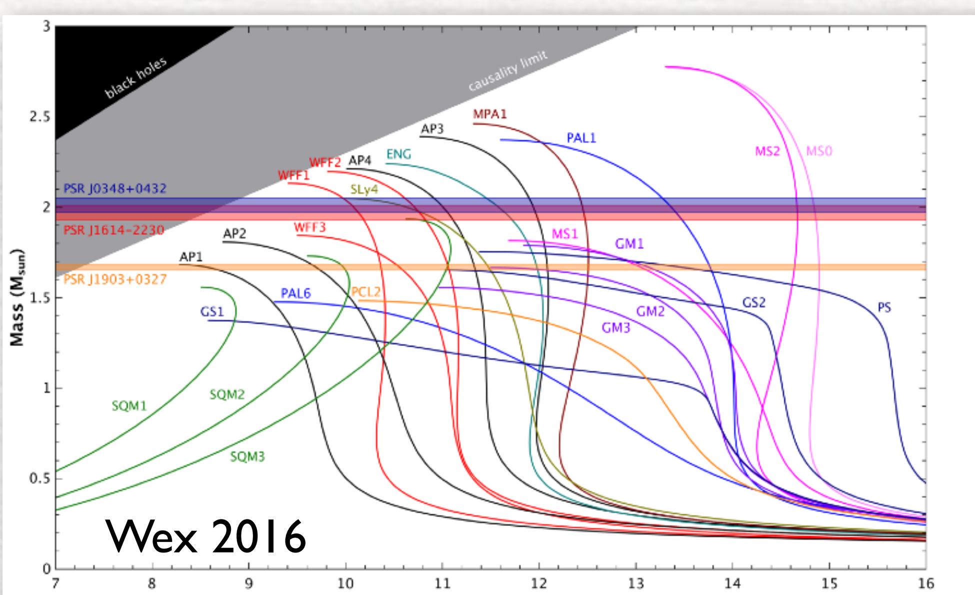
NS + NS ⟶ HMNS+**... ?** ⟶ BH+t



Abbott+ 2016



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



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

The two-body problem in GR

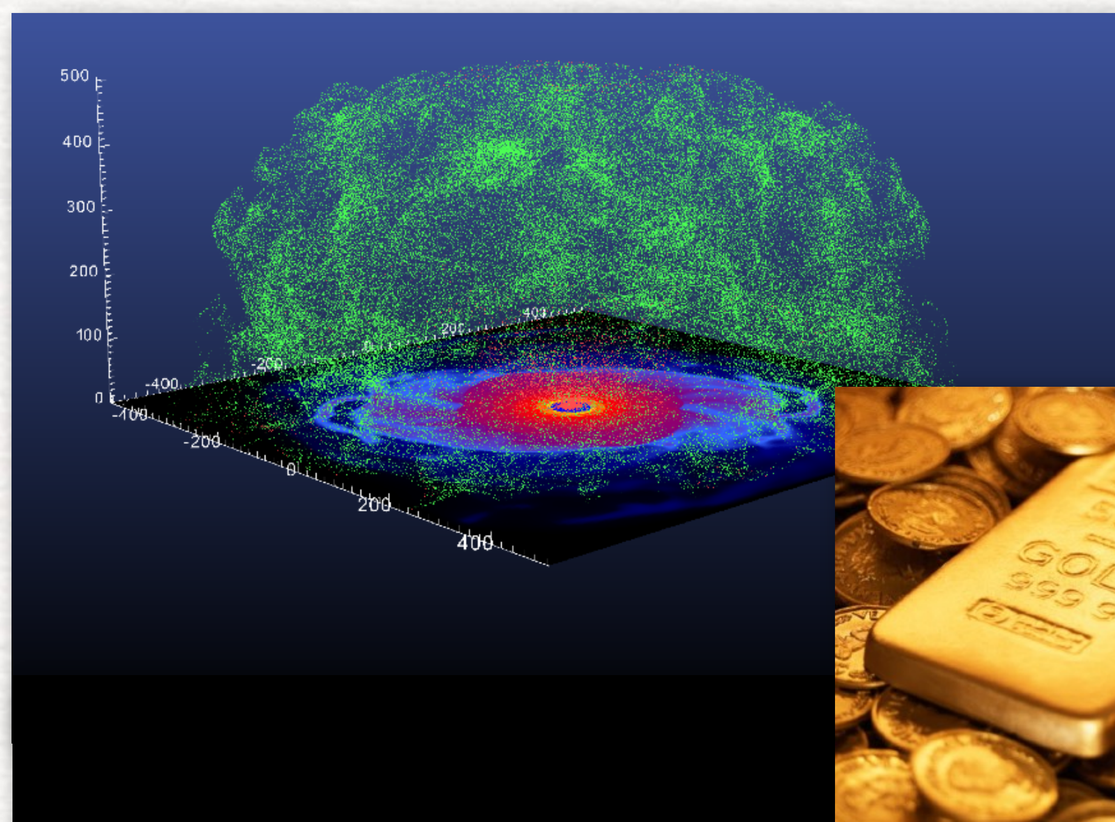
- For BHs we know what to **expect**:

BH + BH → BH + GWs

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

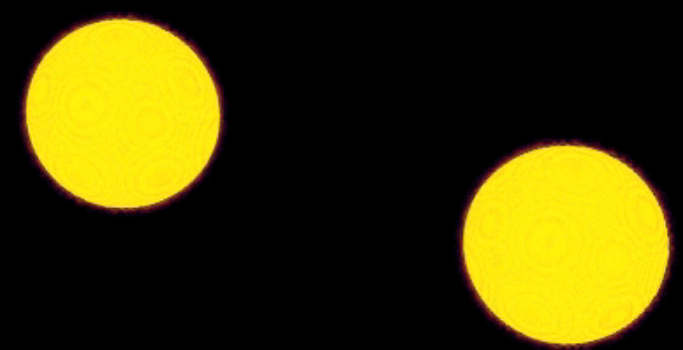
NS + NS → HMNS+**... ?** → BH+torus+**... ?** → BH + GWs

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



Animations: Breu, Radice, LR

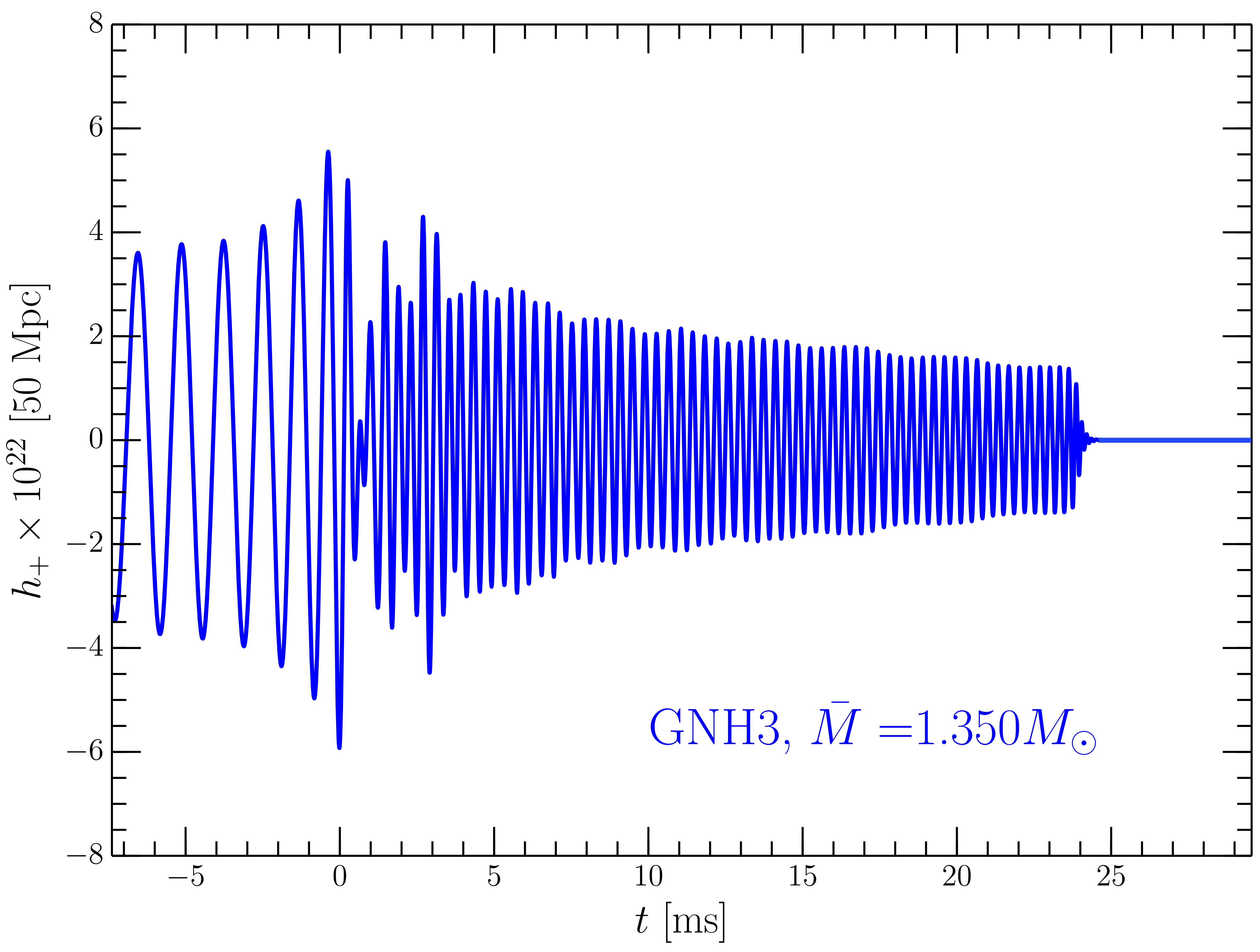
A prototypical simulation with possibly the best code looks like this...



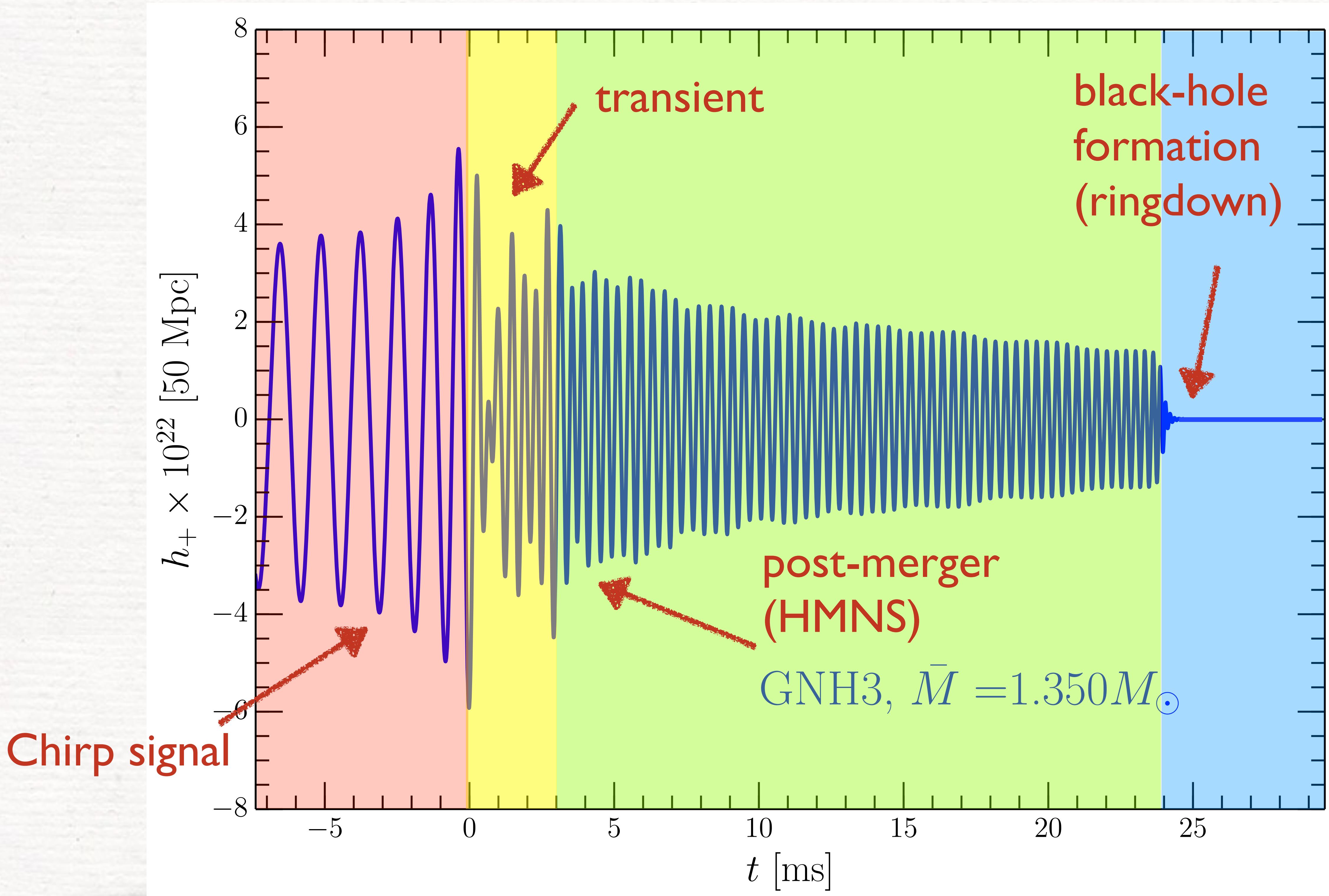
merger ⟶ HMNS ⟶ BH + torus

LS220 EOS

Anatomy of GW signal

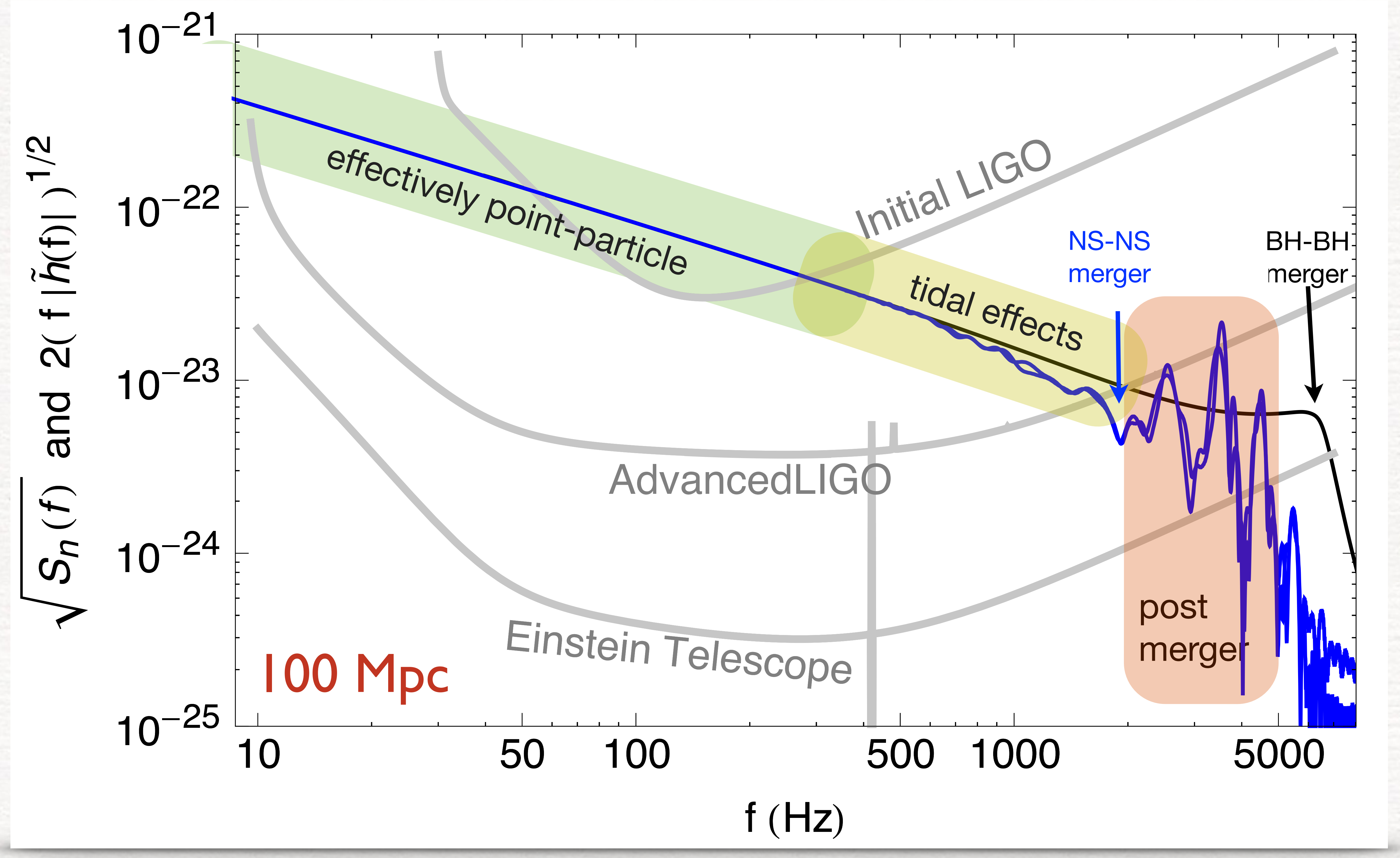


Anatomy of GW signal



Postmerger signal: peculiar of binary NSs

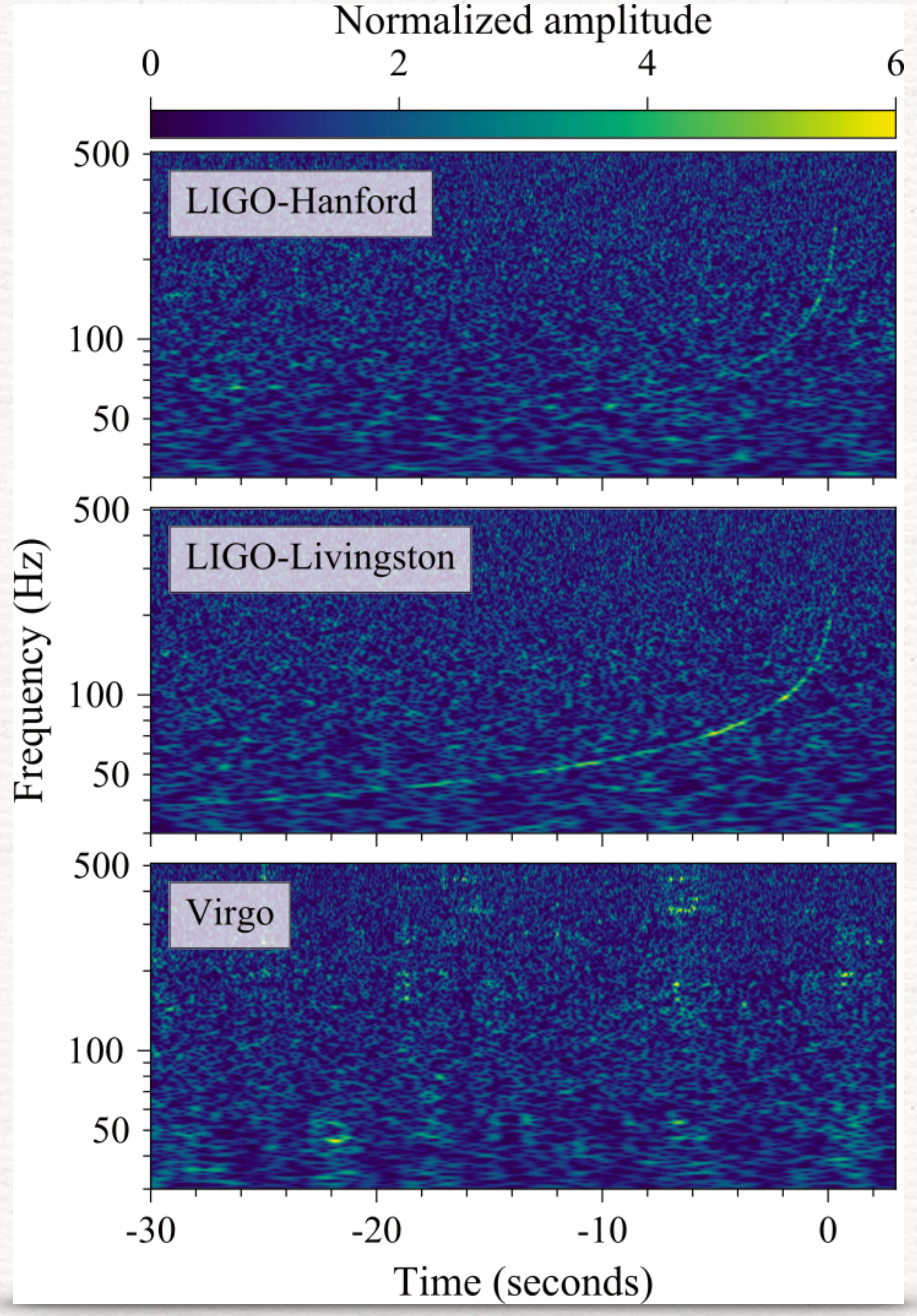
In frequency space



Read et al. (2013)

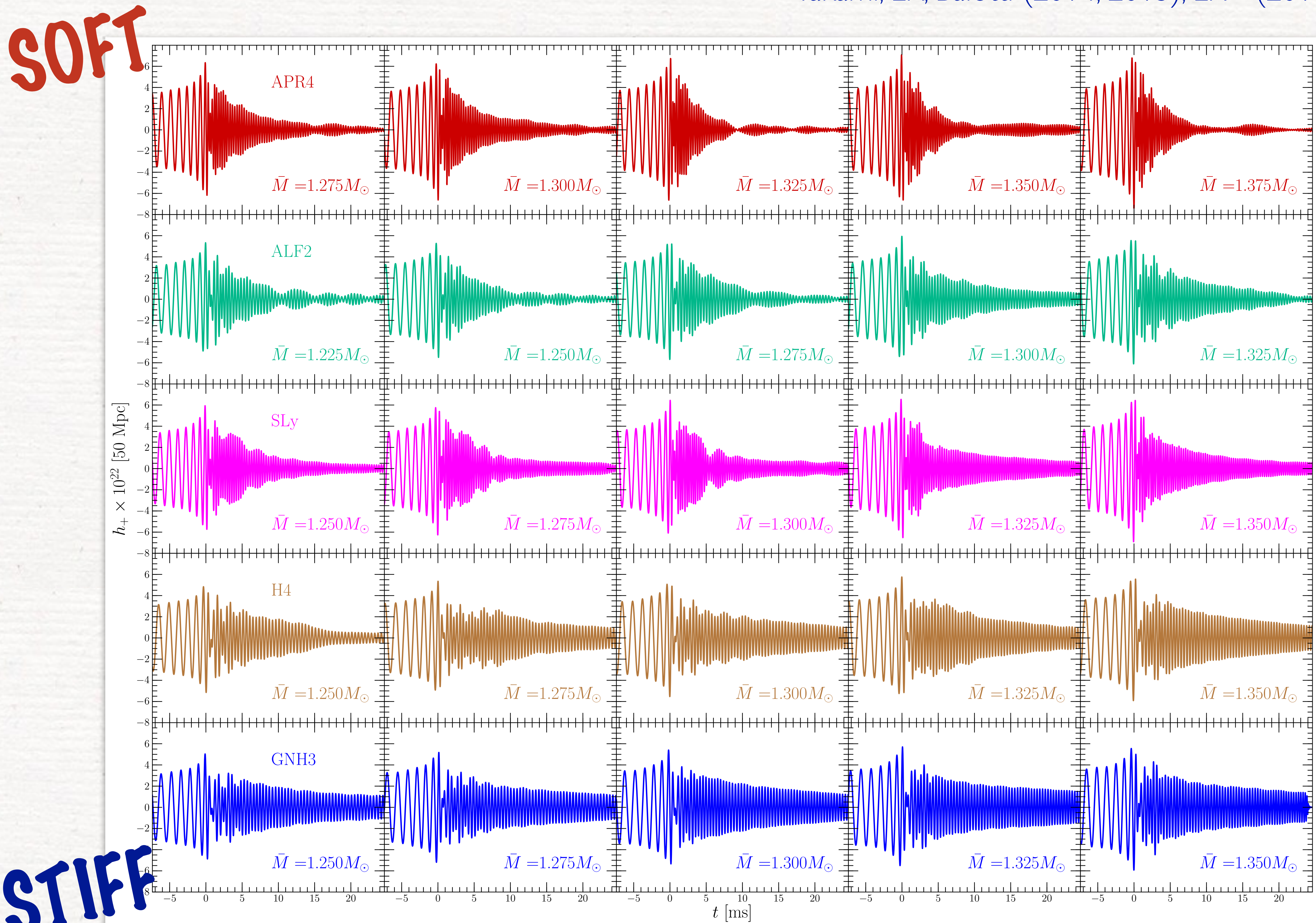
GW170817:
the first binary neutron-star system

- **Unfortunately** only the **inspiral** signal was detected.
- **Fortunately** this was **sufficient** to set a number of constraints on max. mass, tidal deformability, radii, etc.
- **Gold mine** is in the **post-merger** for there is a lot of information there, also about **phase transitions!**



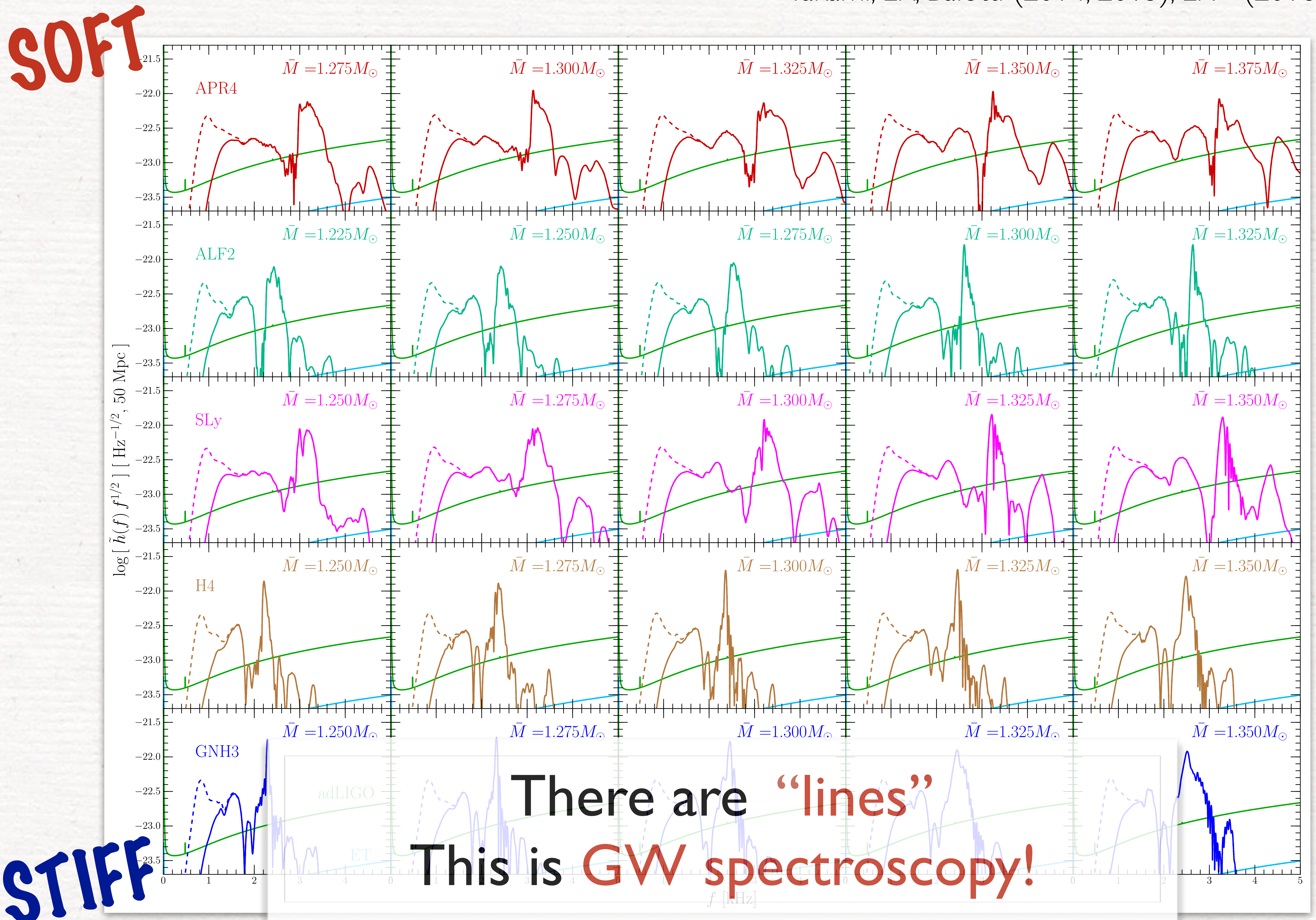
What we can do nowadays

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



Extracting information from the EOS

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



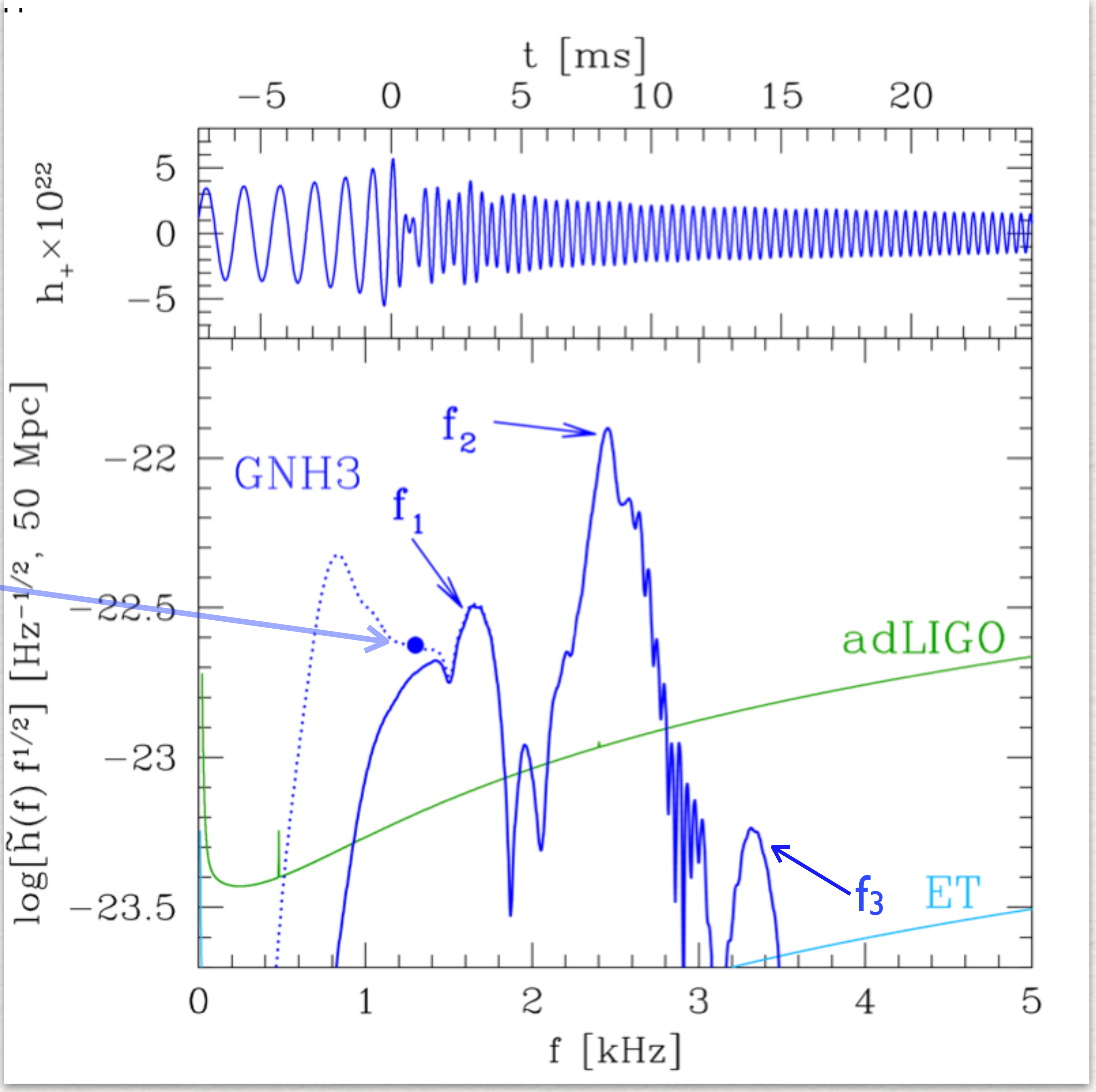
There are "lines"

This is GW spectroscopy!

A spectroscopic approach to 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 …

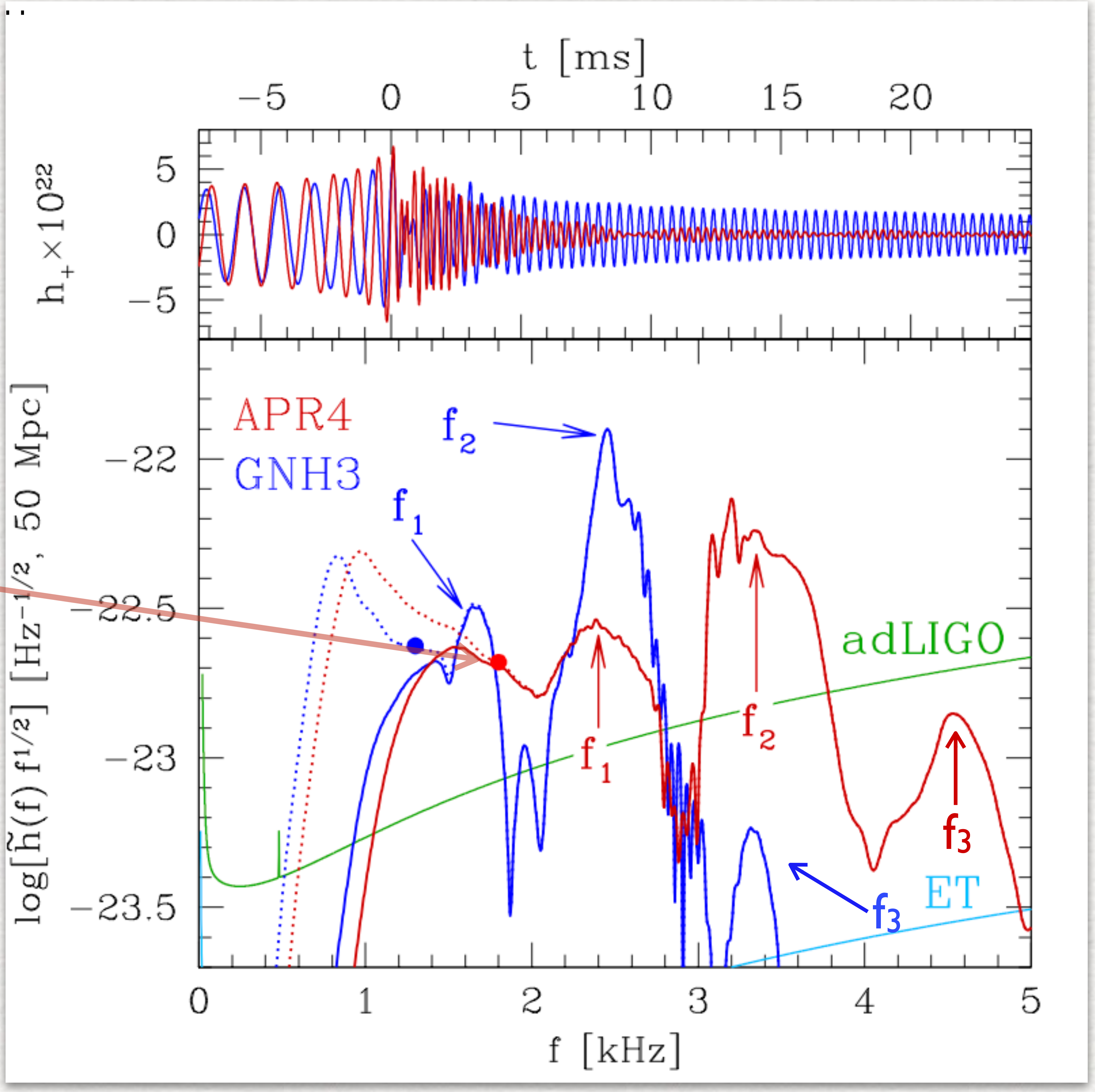
merger frequency



A spectroscopic approach to 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 …

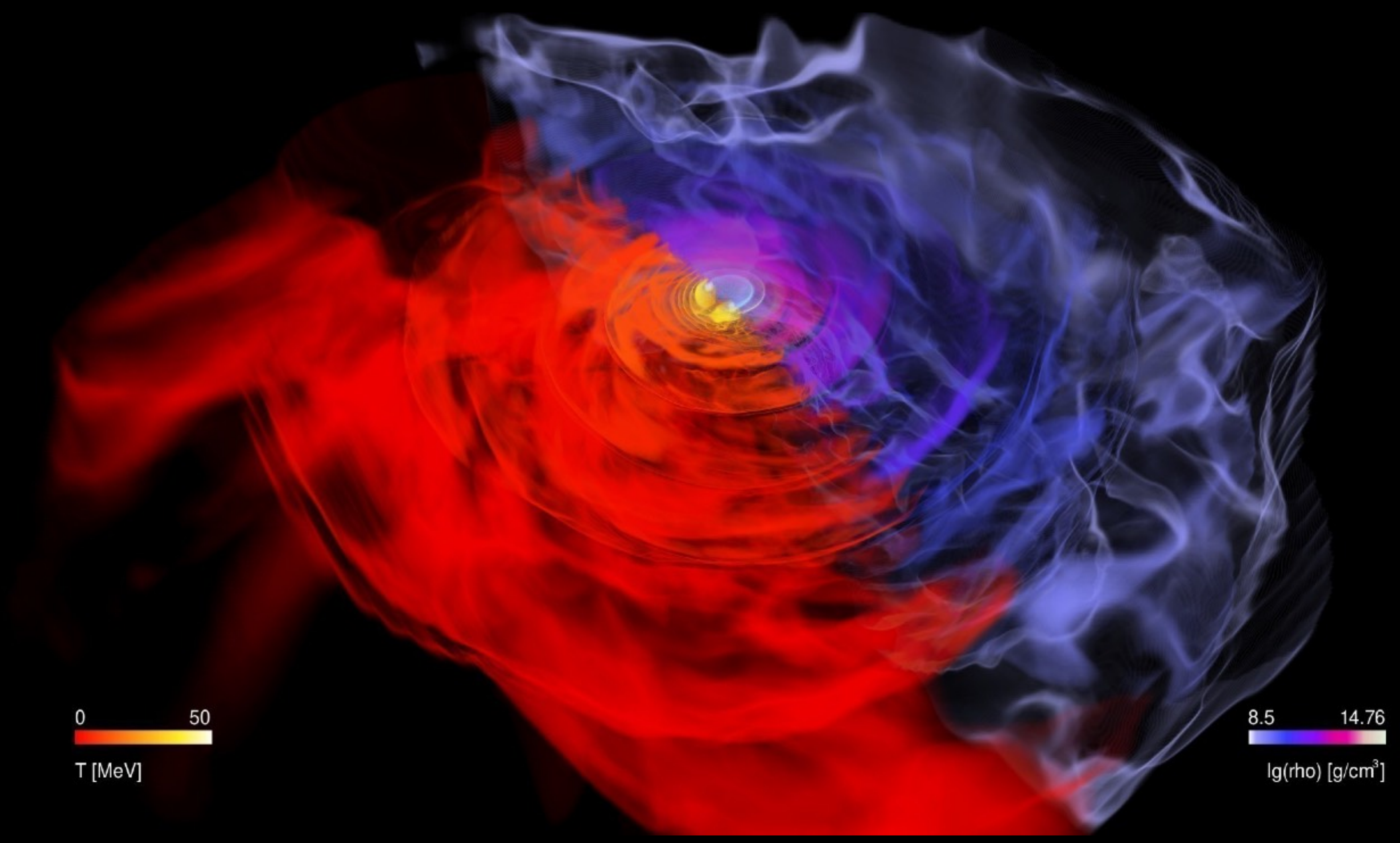
merger frequency



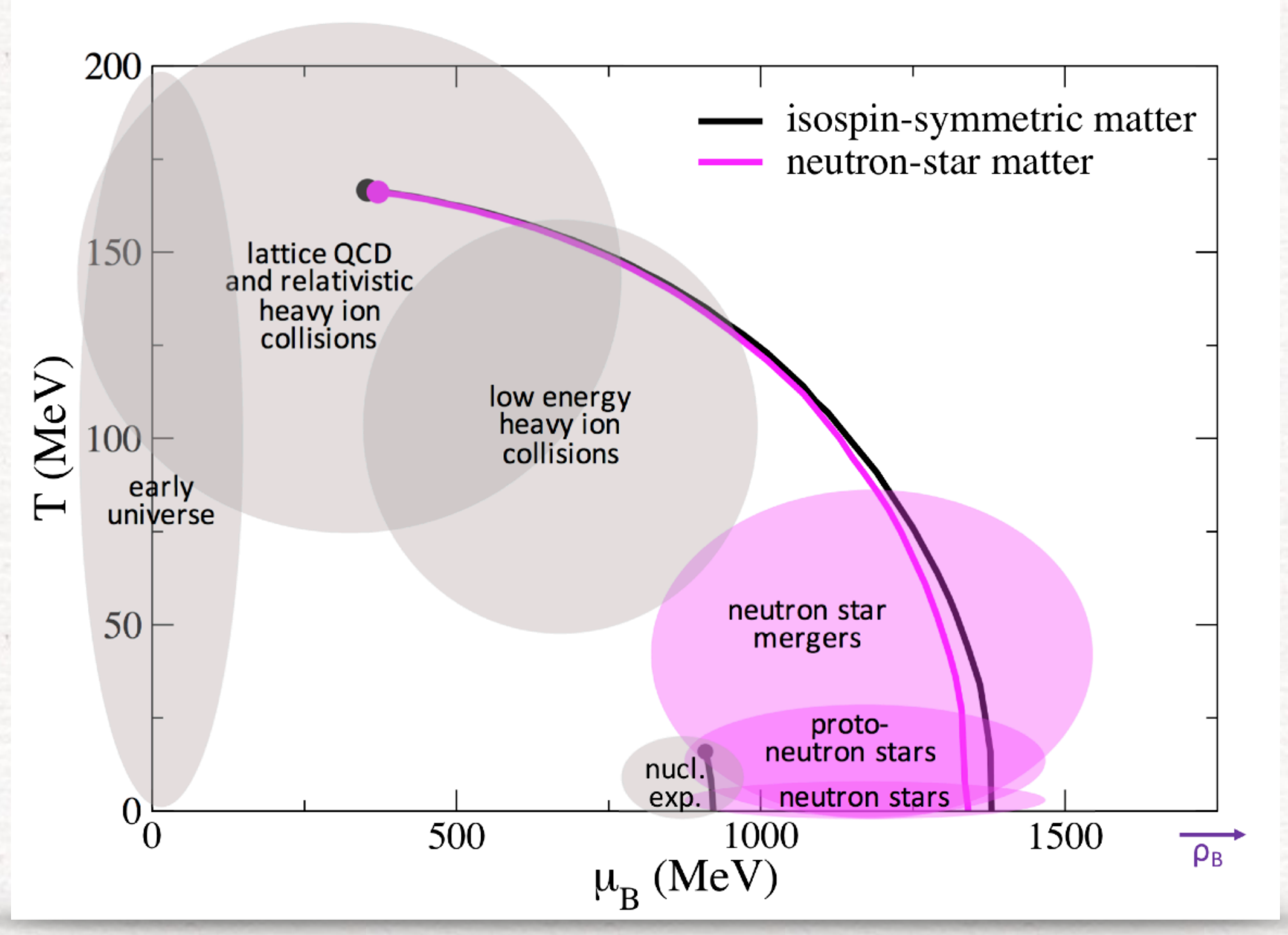
Phase transitions and their signatures

Most, Papenfort, Dexheimer, Hanauske, Schramm, Stoecker, LR (2019)

see also Bauswein, Bastian, Blaschke, Chatziioannou, Clark, Fischer, Oertel (2019)



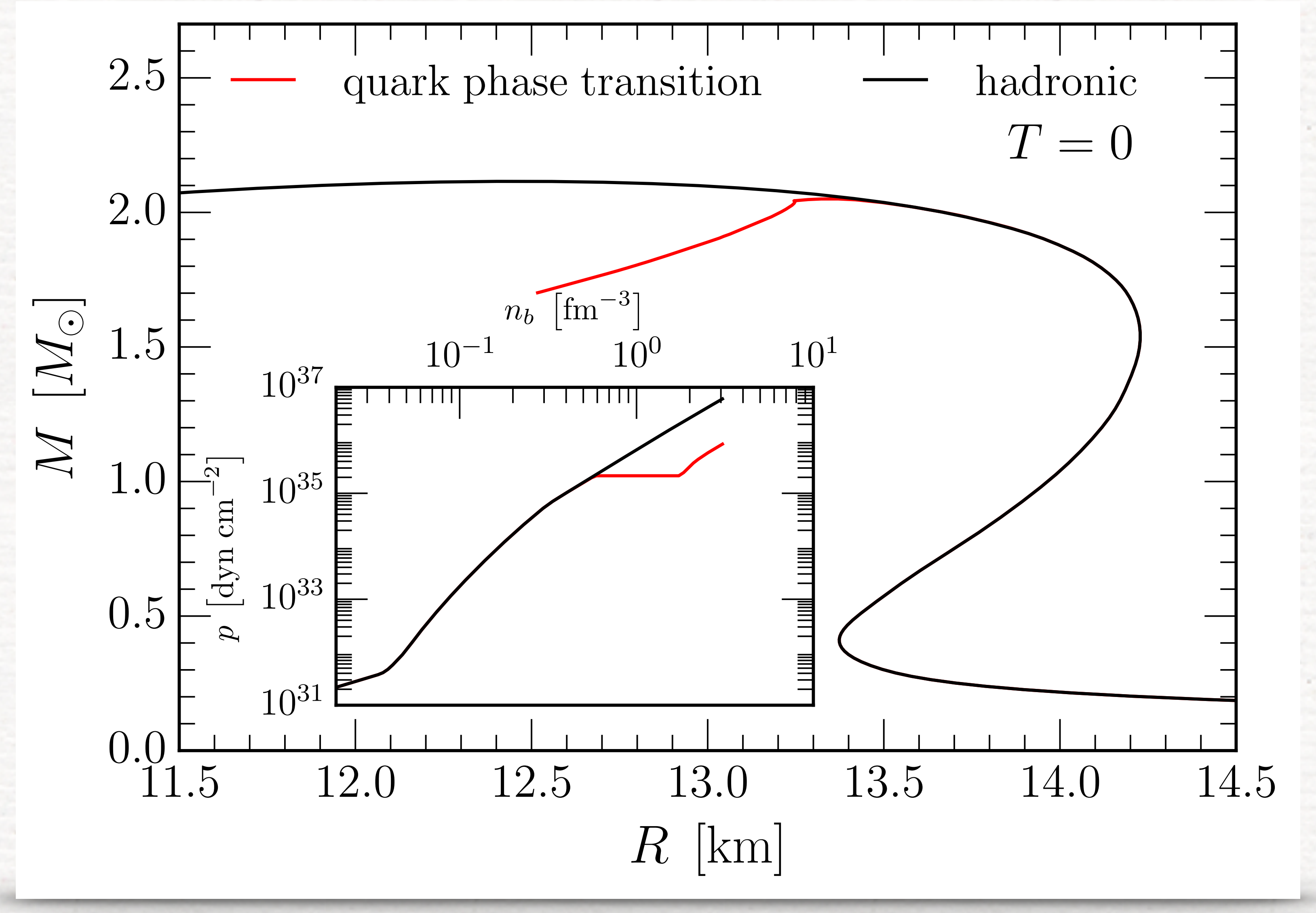
- **Strangeness** is expected in neutron stars both in the inspiral (hyperons) and possibly after merger (strange quarks?)
- **Isolated** neutron stars probe a small fraction of phase diagram

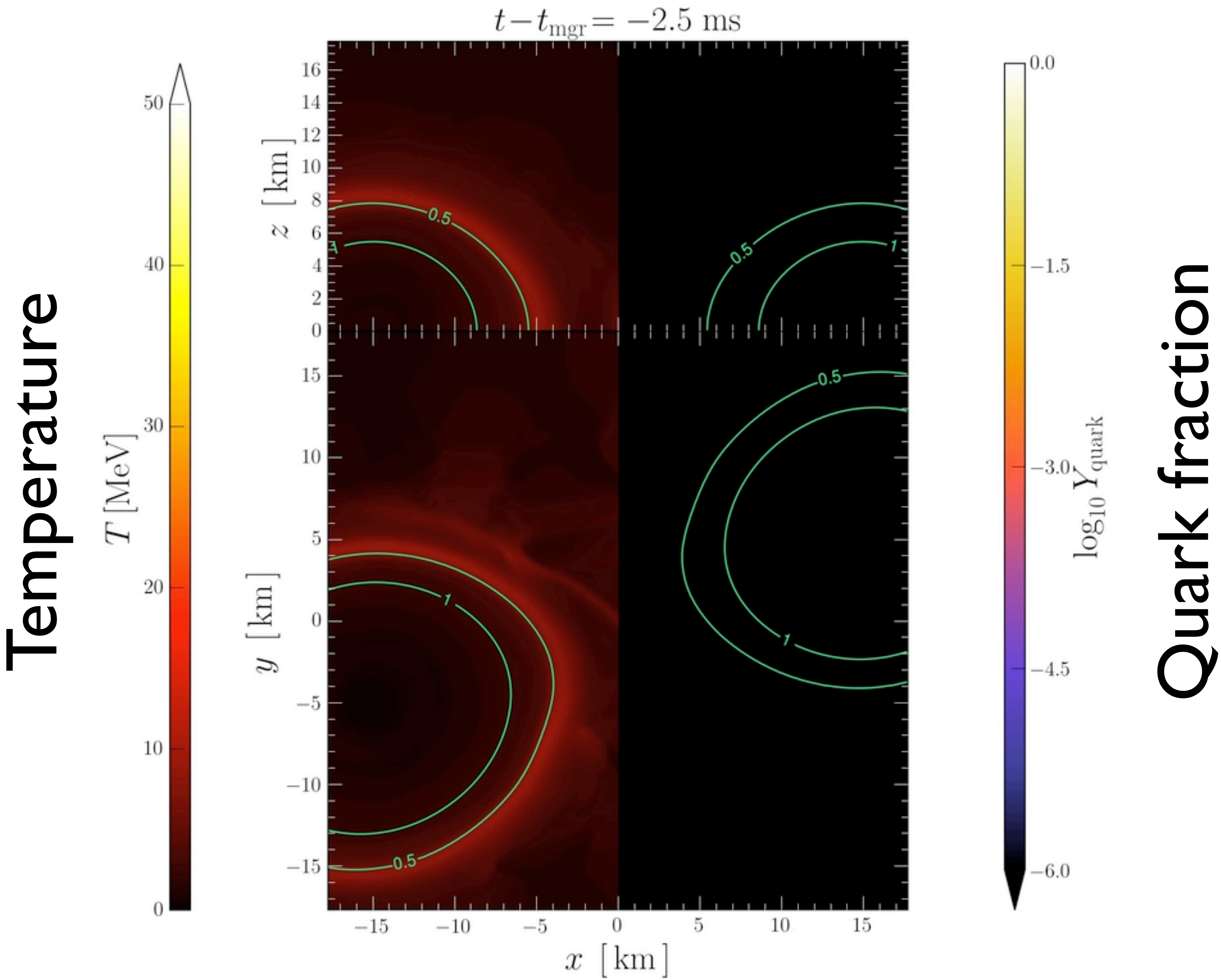


- **Neutron-star binary** mergers reach temperatures up to 80 MeV and probe regions complementary to experiments

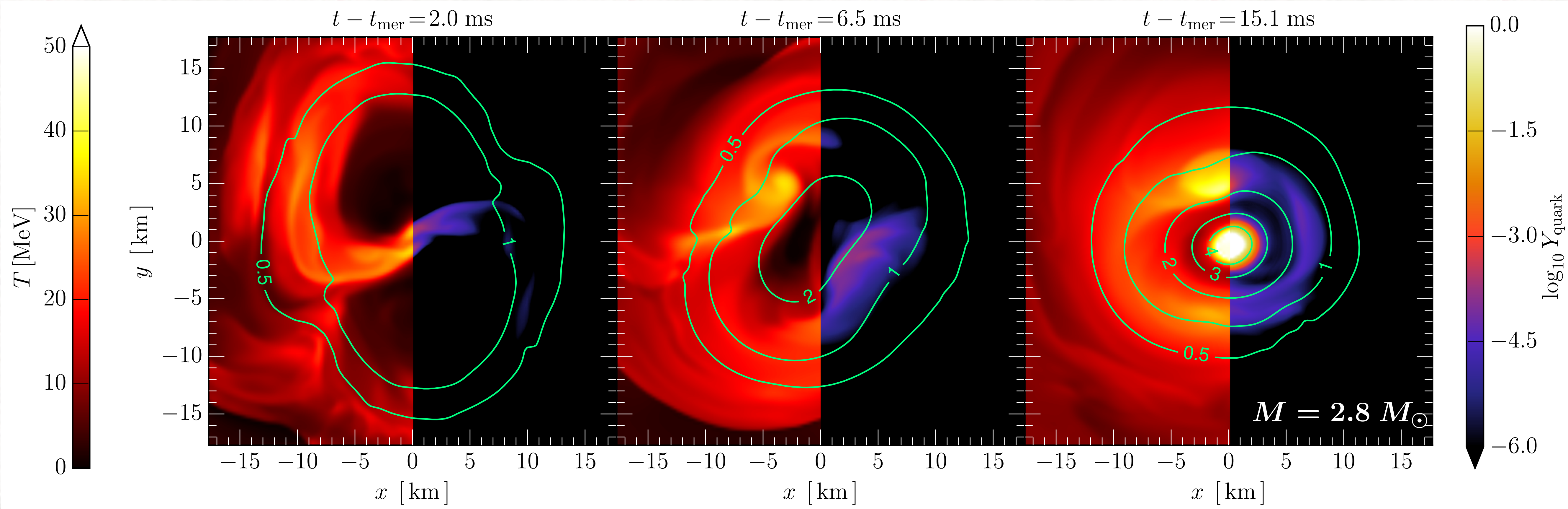
Modelling the EOS

- EOS based on Chiral Mean Field (CMF) and nonlinear SU(3) sigma model
- Includes hyperons and quarks that can be turned on/off
- Uses Polyakov loop to implement a strong first order phase transition
- Includes a cross-over transition at high temperatures

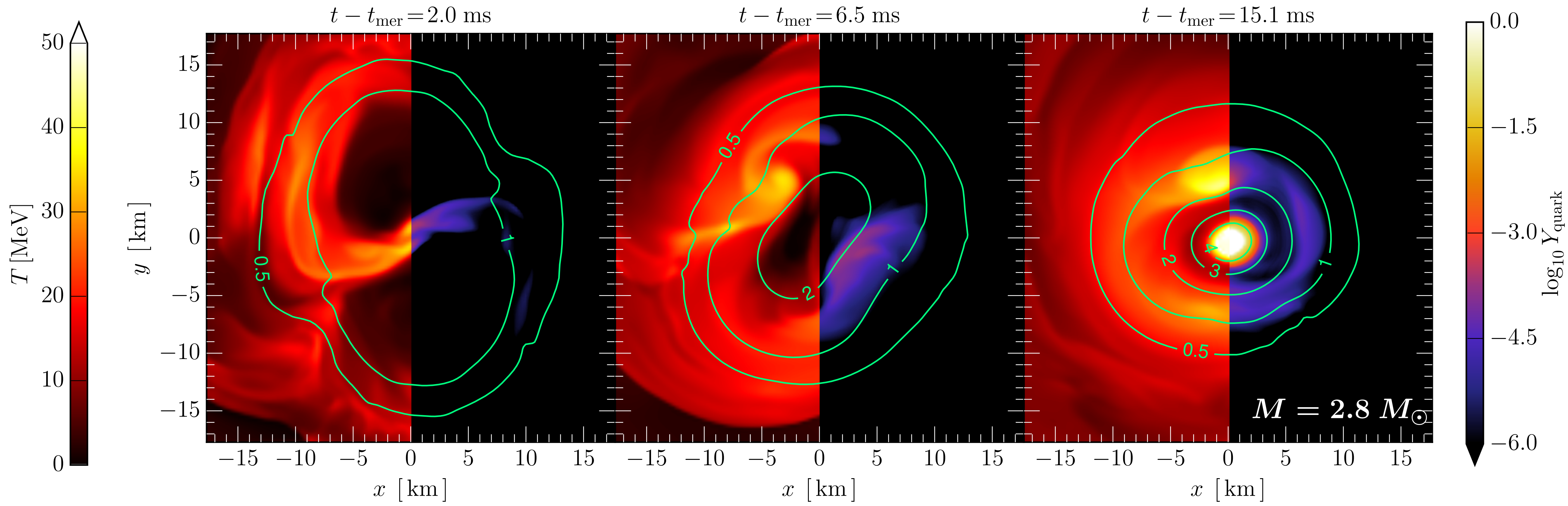


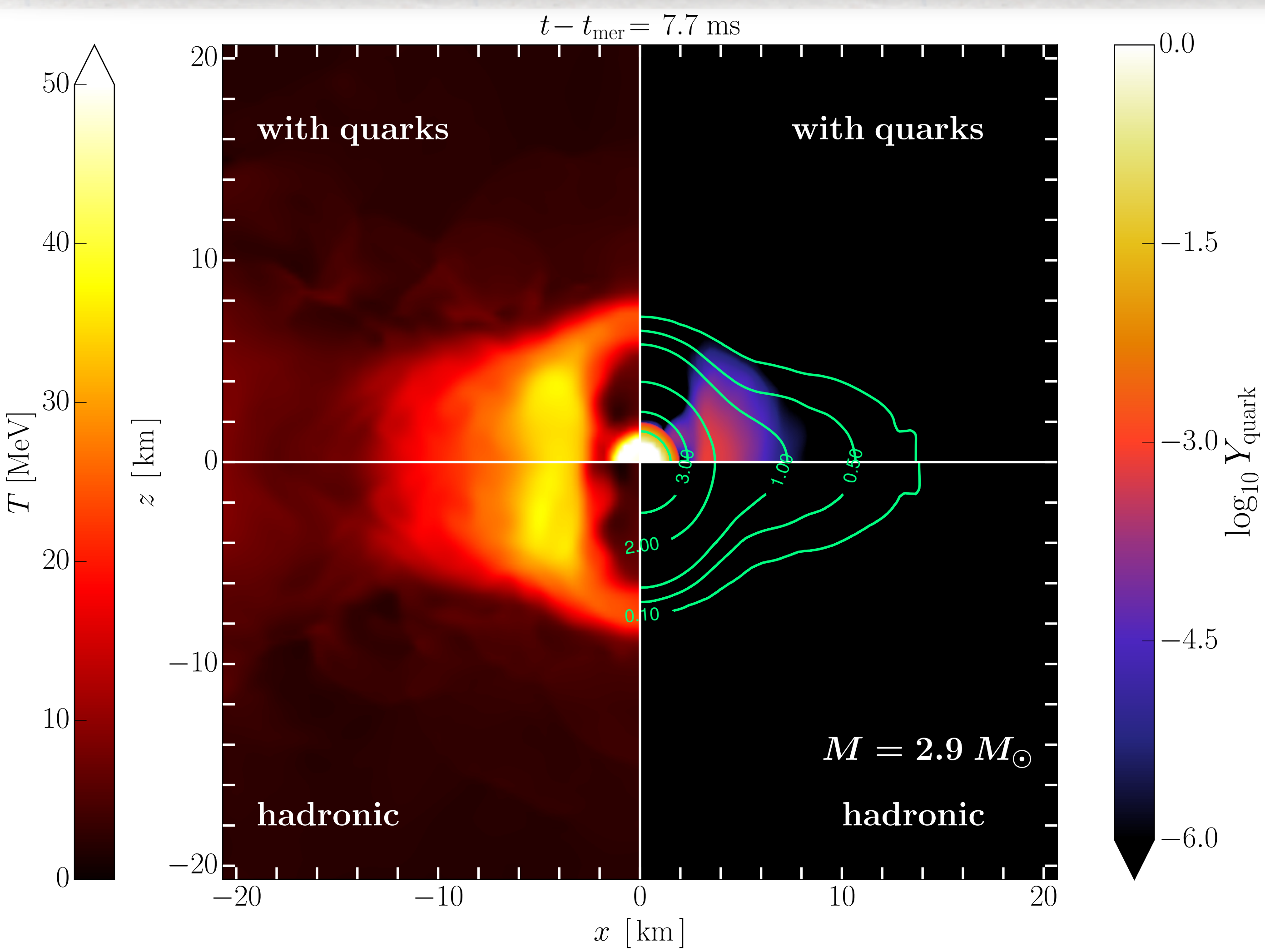


Temperature
$t - t_{\rm mgr} = -2.5$ ms
T [MeV]
z [km]
y [km]
x [km]
$\log_{10} Y_{\rm quark}$
Quark fraction
0.5
1



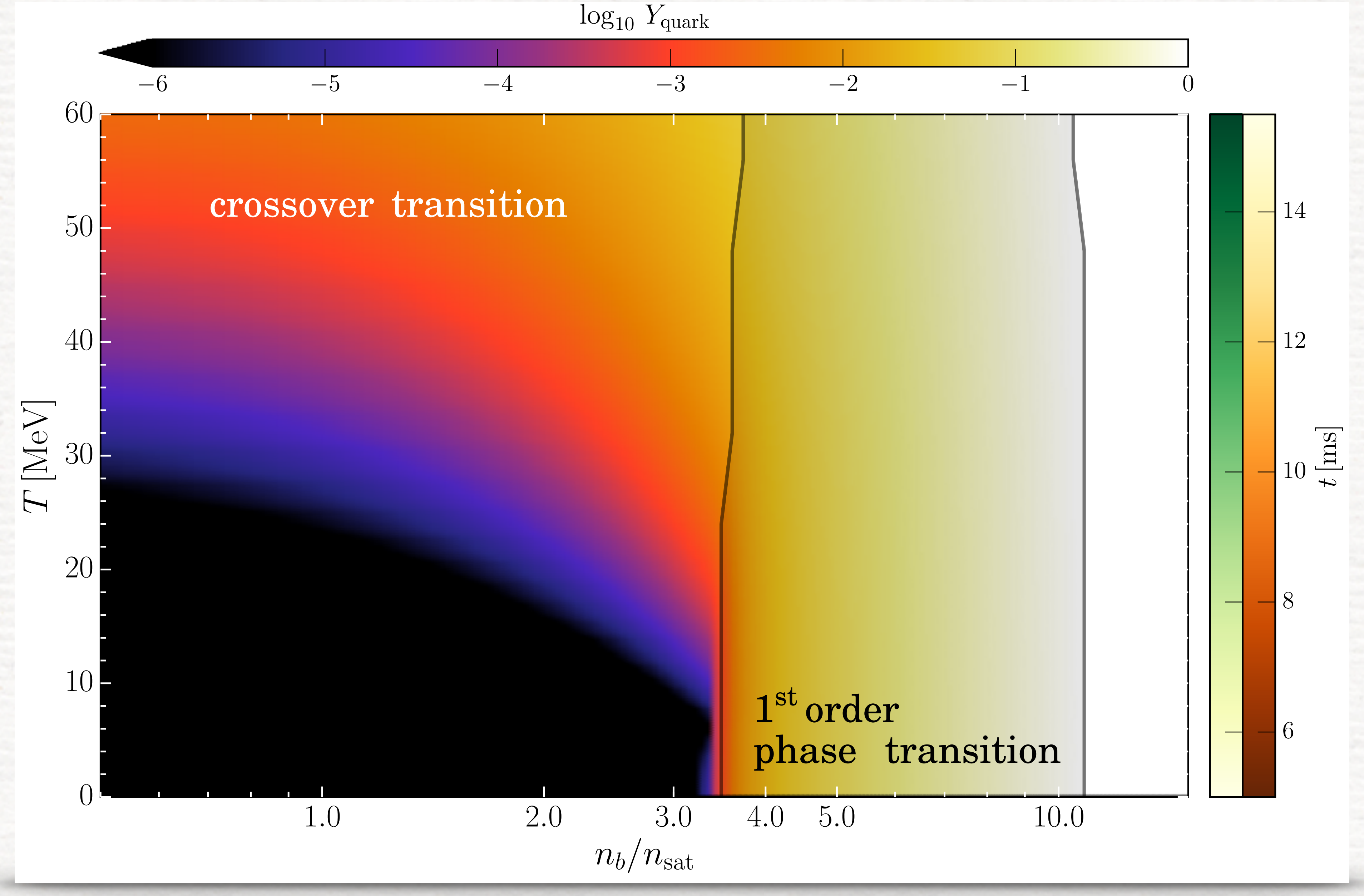
- EOS based on Chiral Mean Field (CMF) model, based on a nonlinear SU(3) sigma model.
- Quarks appear at sufficiently large temperatures and densities.





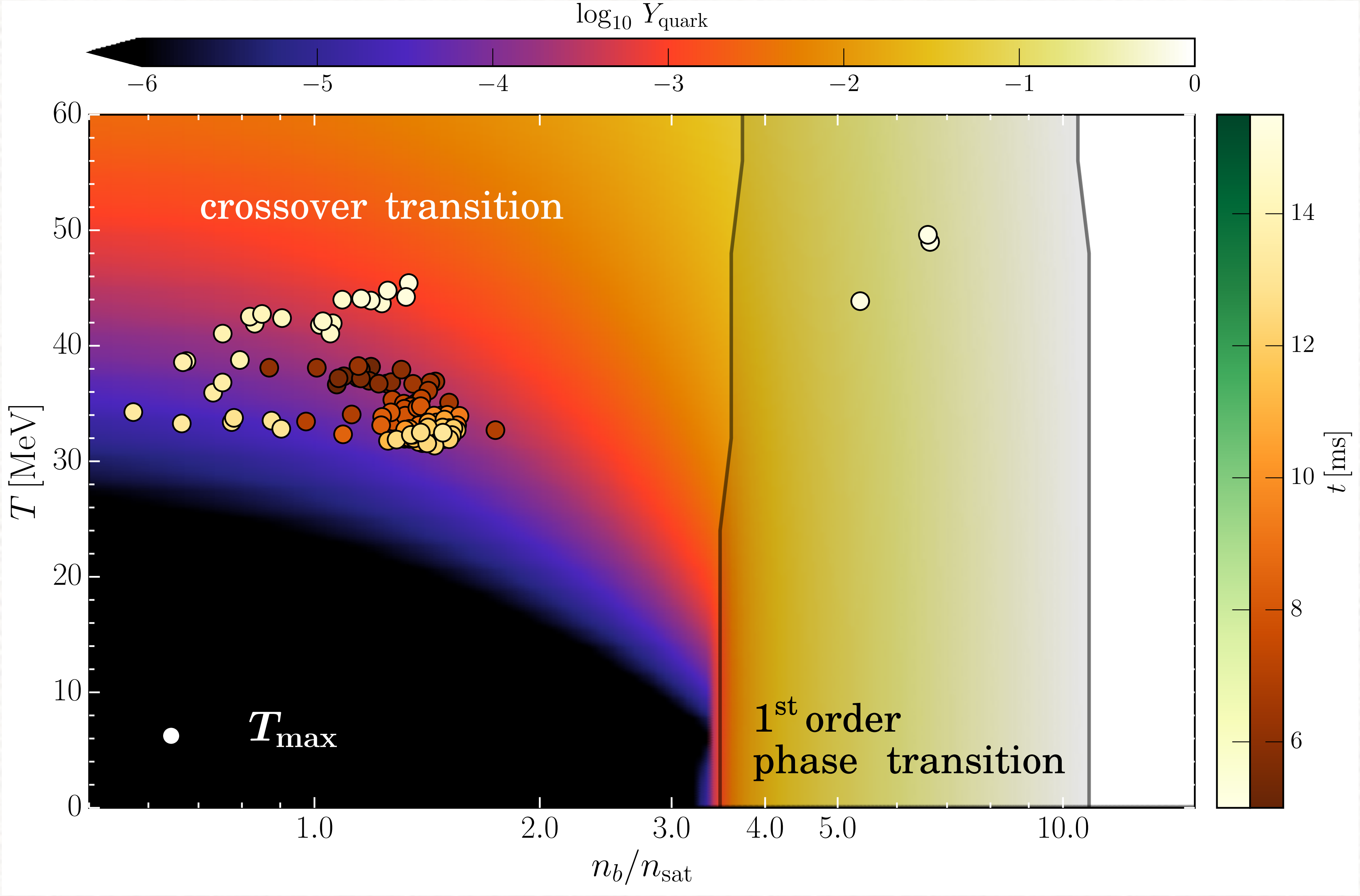
- EOS based on Chiral Mean Field (CMF) model, based on a nonlinear SU(3) sigma model.
- Quarks appear at sufficiently large temperatures and densities.
- For EOS without quarks, the dynamics is very similar, but no PT.

Comparing with the phase diagram



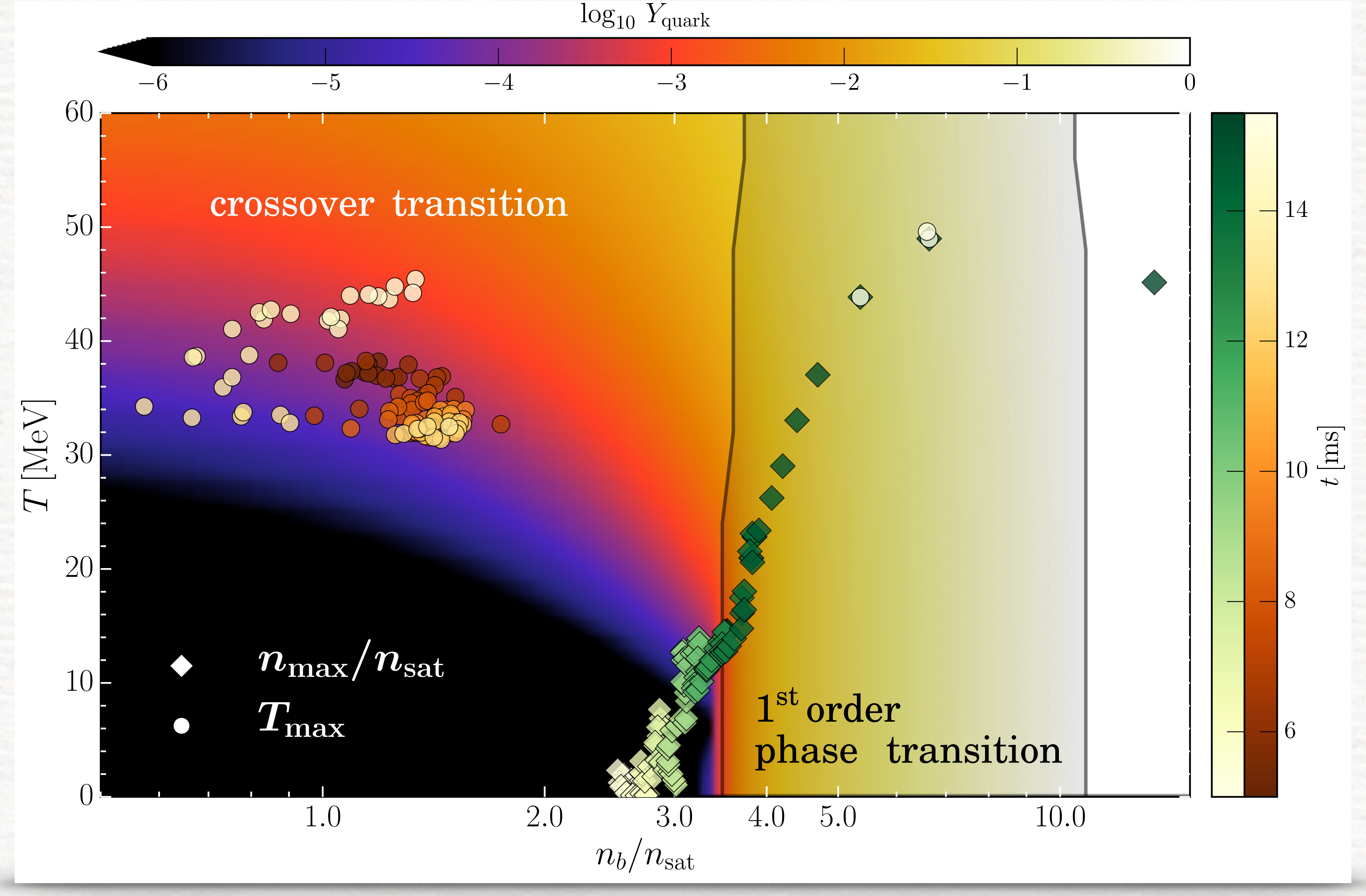
- Phase diagram with quark fraction

Comparing with the phase diagram



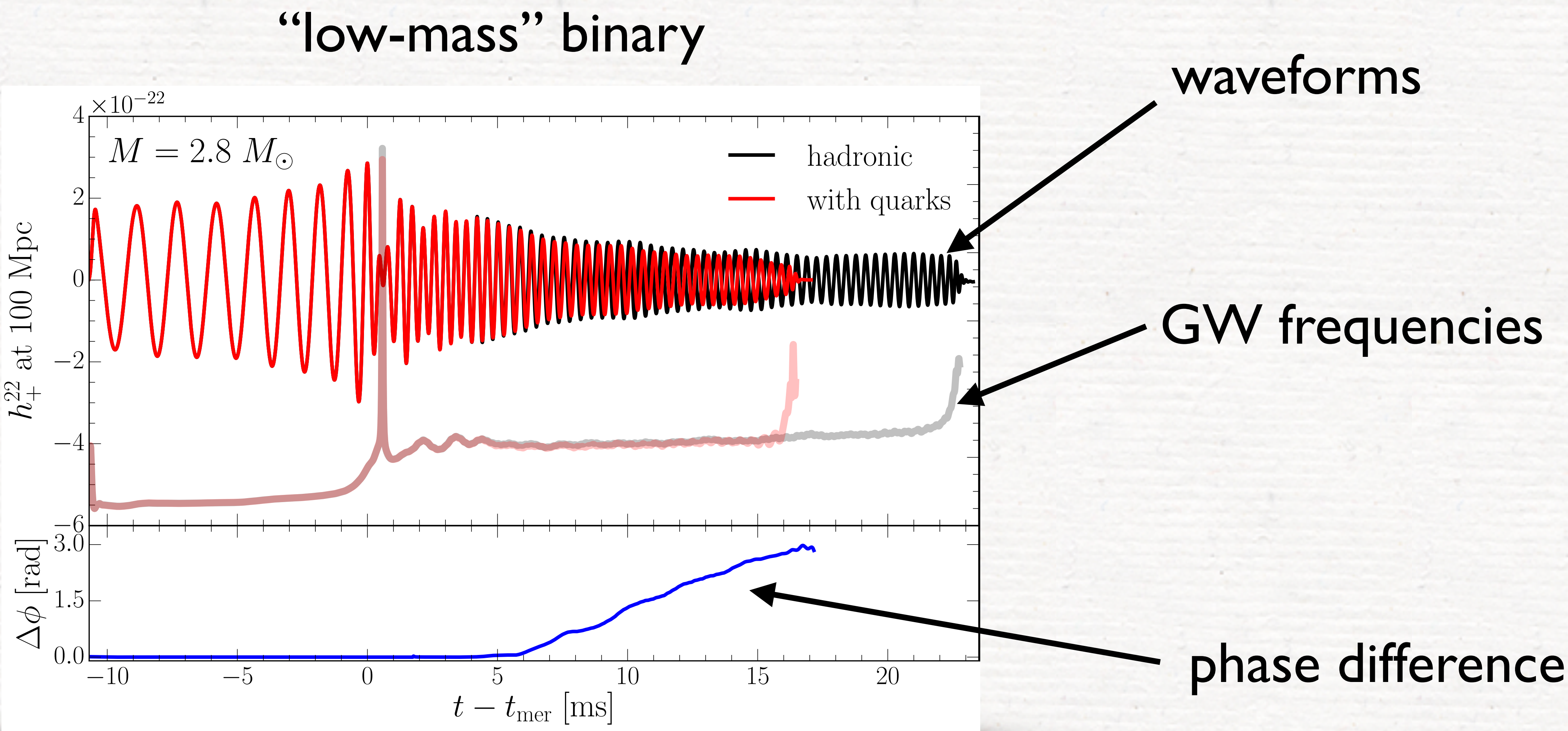
- Phase diagram with quark fraction
- Circles show the position in the diagram of the maximum temperature as a function of time

Comparing with the phase diagram



- Reported are the evolution of the max. temperature and density.
- Quarks appear already early on, but only in small fractions.
- Once sufficient density is reached, a full phase transition takes place.

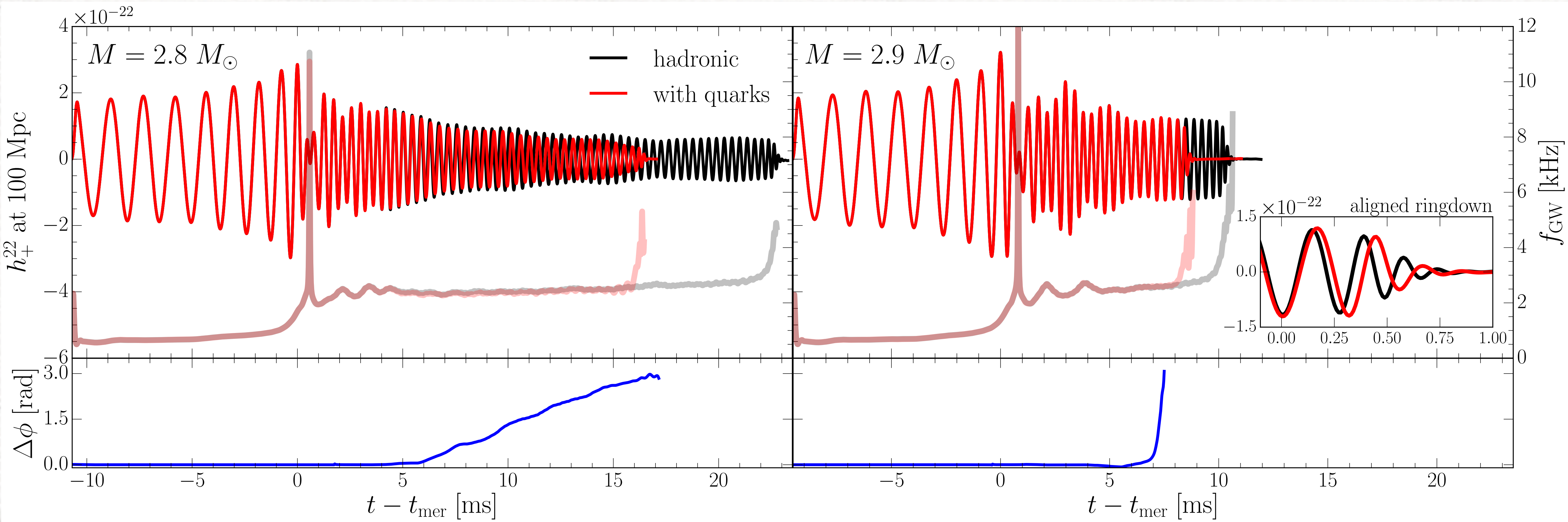
Gravitational-wave emissiom



- In **low-mass binary**, after ~ 5 ms, quark fraction is large enough to change quadrupole moment and yield differences in the waveforms.
- Note the phase difference is **zero** in the inspiral.
- Sudden softening of the phase transition leads to collapse and **large difference** in phase evolution.

Gravitational-wave emissiom

“low-mass” binary “high-mass” binary



- In **low-mass binary**, after ~ 5 ms, quark fraction is large enough to change quadrupole moment and yield differences in the waveforms.
- In **high-mass binary**, phase transition takes place rapidly after ~ 5 ms. Waveforms are similar but **ringdown** is **different** (free fall for PT).

Observing mismatch between **inspiral** (fully hadronic) and **post-merger** (phase transition): clear **signature** of a **PT**.

Conclusions

✴Spectra of post-merger shows peaks, some **"quasi-universal"**.

✴When used together with tens of observations, they will set tight constraints on EOS: radius known with ~1 km precision.

✴**GW170817** has already provided new limits on

$2.01^{+0.04}_{-0.04} \leq M_{\rm TOV}/M_{\odot} \lesssim 2.16^{+0.17}_{-0.15}$ maximum mass

$12.00 < R_{1.4}/{\rm km} < 13.45 \quad \tilde{\Lambda}_{1.4} > 375$ radius, tidal deformability

✴**GWs**: new probe of high-density matter and of **QCD** to be used in conjunction with **laboratory experiments**.

✴A phase transition after a BNS merger leaves a GW signature and opens a gate to access quark matter beyond accelerators