What can we learn from GWs on the EOS of nuclear matter?

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Present and future perspectives in Hadron Physics
Frascati, 17-19.06.2024

Plan of the talk

GWs from BNSs represent a **new tool** to explore **nuclear physics** and the **QCD phase diagram**

(see also Fischer for CCSNe)

- GW spectroscopy: EOS from frequencies
- Signatures of quark-hadron phase transitions

The two-body problem in GR

- For black holes the process is very **simple**:

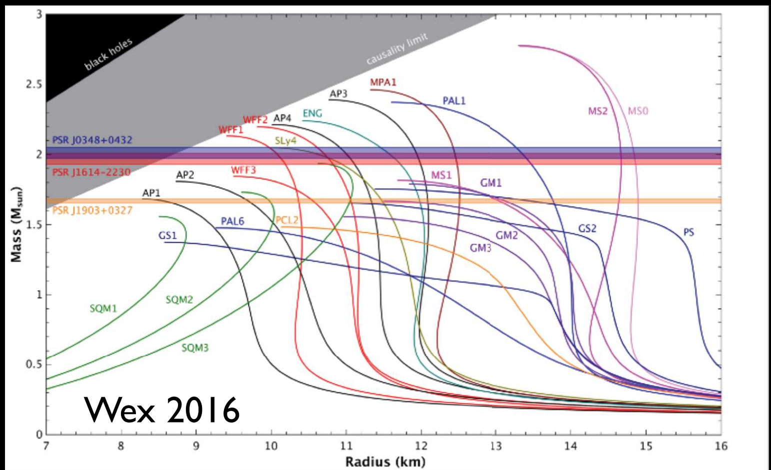
BH + BH ⟶ BH + GWs

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

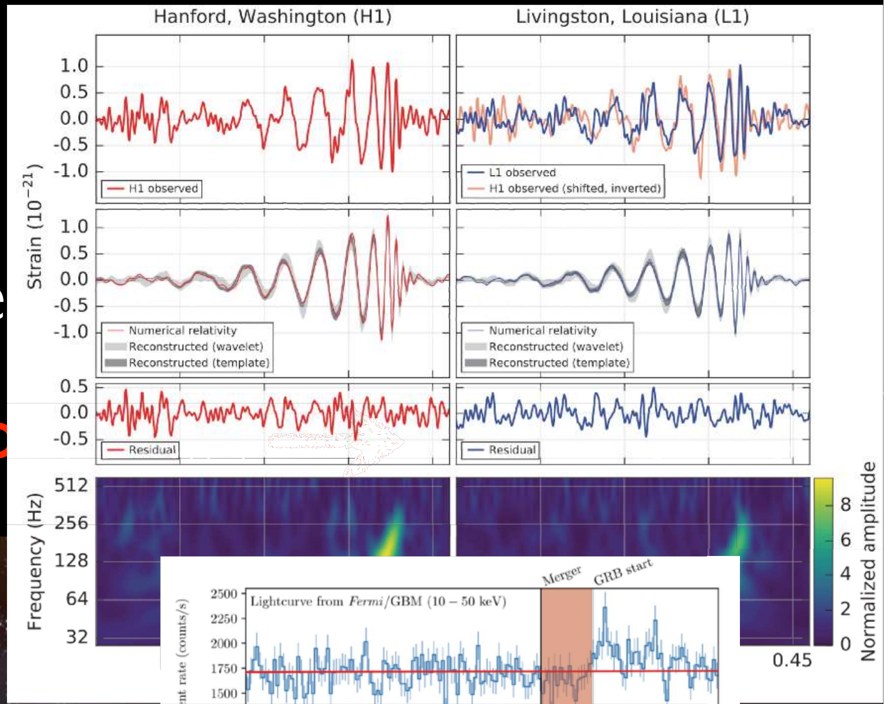
hyper-massive neutron star (HMNS), ie

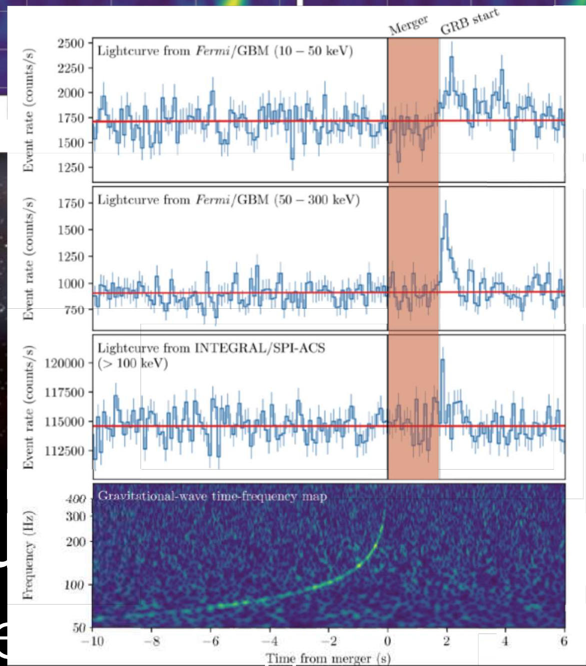
NS + NS ⟶ HMNS+... ? ⟶ BH+to

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



GW150914





- BH+toru ... us

on the ce ... BHs

GW170817

The two-body problem in GR

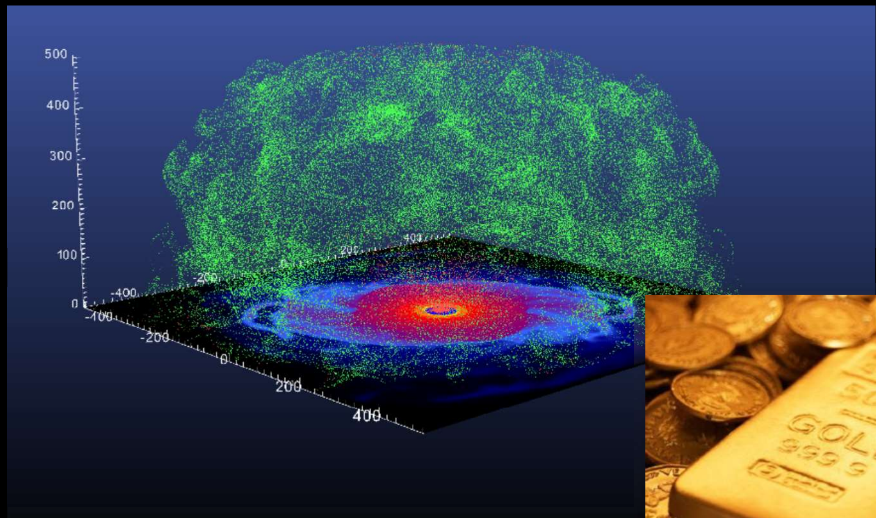
- For black holes the process is very **simple**:

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



$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu} \,,$$ (Einstein equations)

$$\nabla_\mu T^{\mu\nu} = 0 \,,$$ (cons. energy/momentum)

$$\nabla_\mu (\rho u^\mu) = 0 \,,$$ (cons. rest mass)

$$\nabla_\nu F^{\mu\nu} = I^\mu \,, \qquad \nabla_\nu^* F^{\mu\nu} = 0 \,,$$ (Maxwell equations)

$$T_{\mu\nu} = T_{\mu\nu}^{\text{fluid}} + T_{\mu\nu}^{\text{EM}} + T_{\mu\nu}^{\text{rad}} + \ldots$$ (energy − momentum tensor)

Animations: Breu, Radice, LR

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

merger → HMNS → BH + torus

$M = 2 \times 1.35\, M_\odot$

timescale for all this is 0.01-1 sec

LS220 EOS

Qualitatively, this is what normally happens:

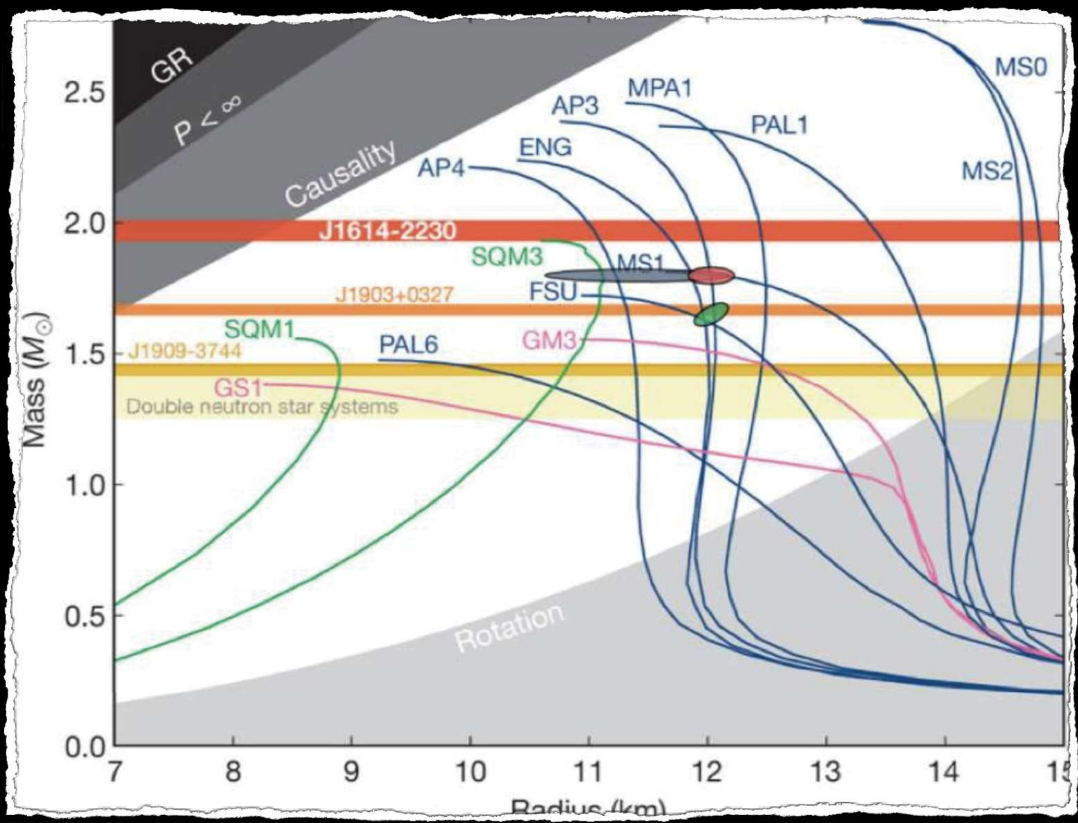
merger → HMNS → BH + torus

Quantitatively, differences are produced by:

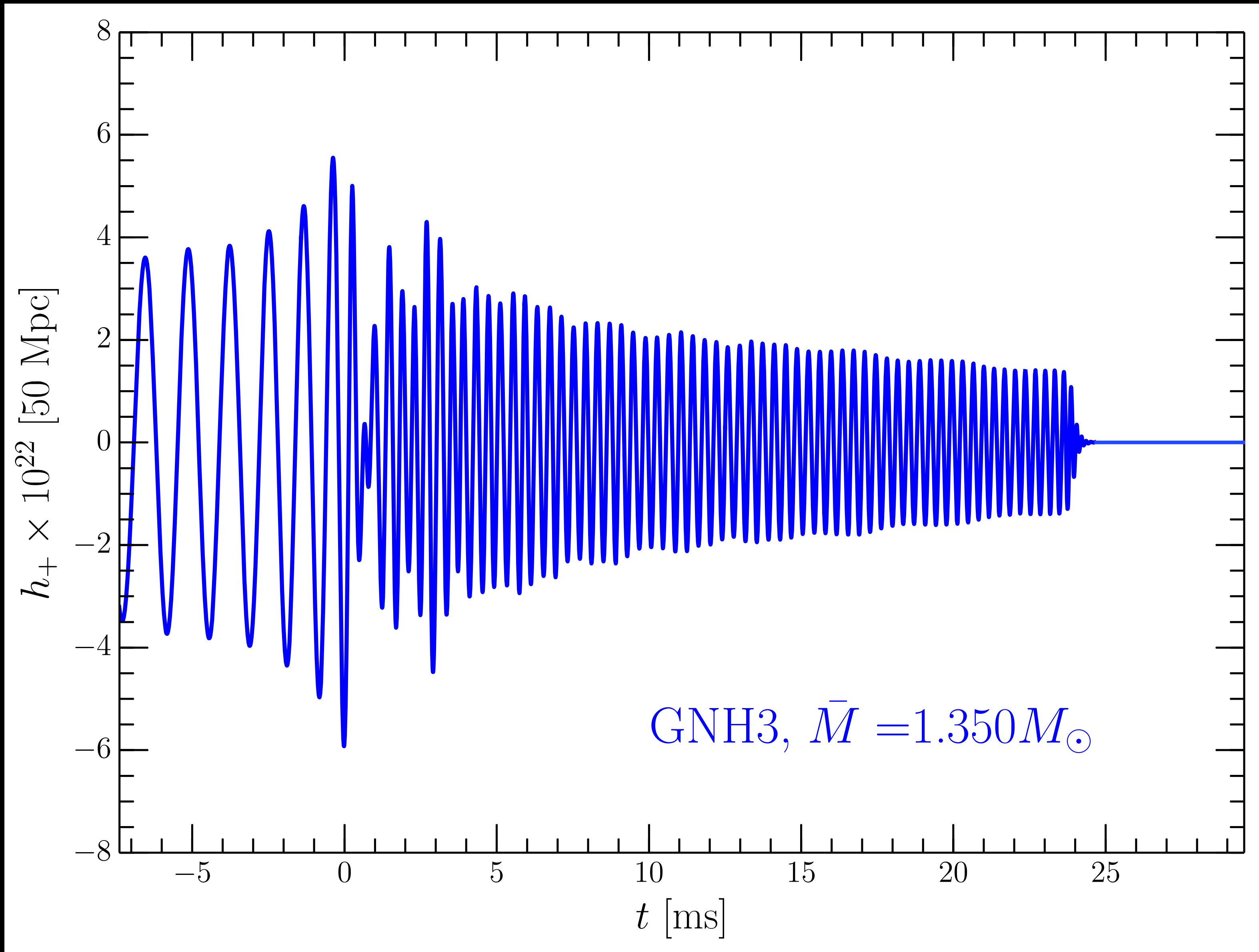
- total mass (prompt vs delayed collapse)
- mass asymmetries (HMNS and torus)
- soft/stiff EOS (inspiral and post-merger, PT)
- magnetic fields (equil. and EM emission)
- radiative losses (equil. and nucleosynthesis)

GW spectroscopy: EOS from frequencies

Takami, LR, Baiotti 2014; Takami, LR, Baiotti 2015; LR, Takami 2016; Bose, LR, + 2017; Zhu, LR 2020,+…



Anatomy of the GW signal



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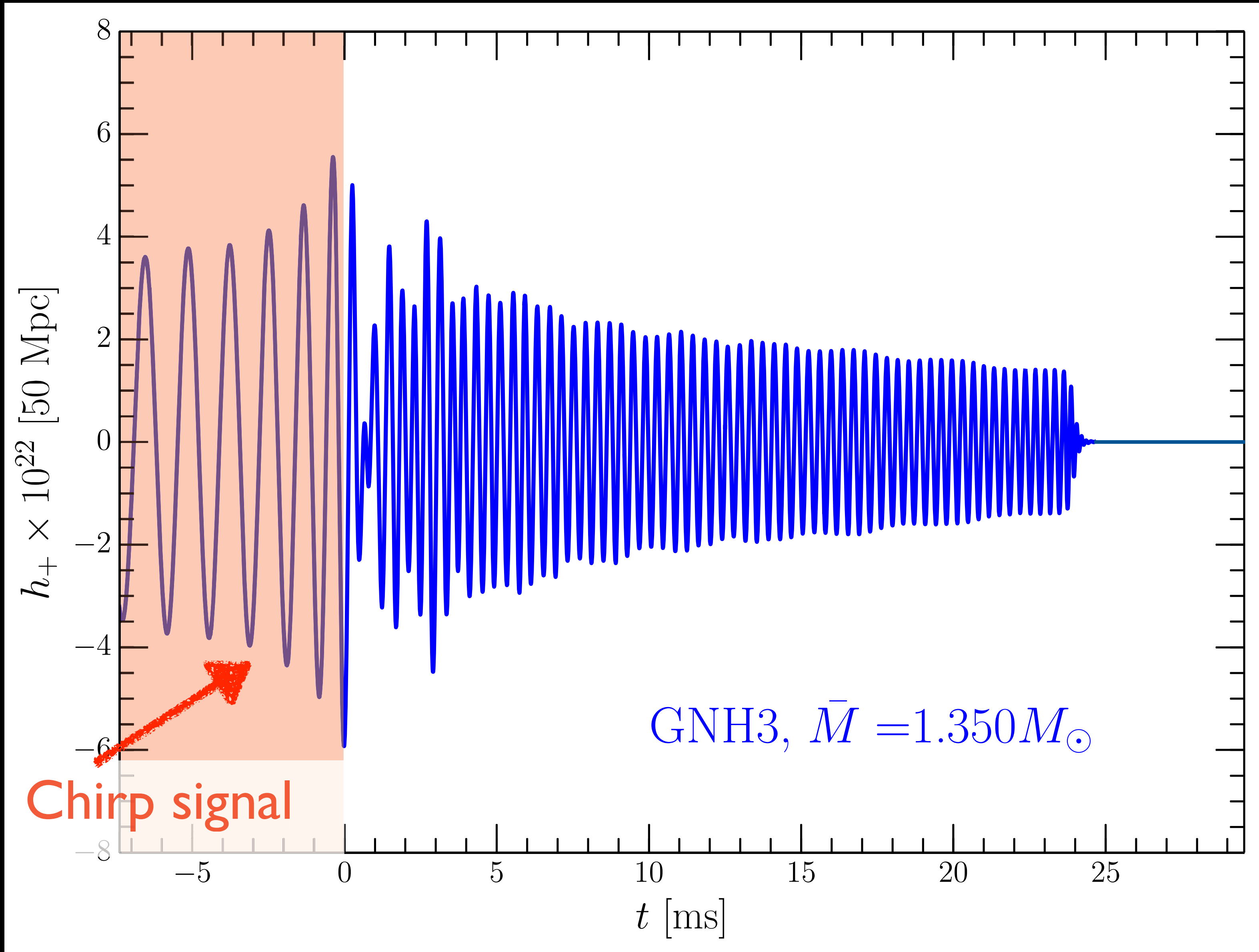
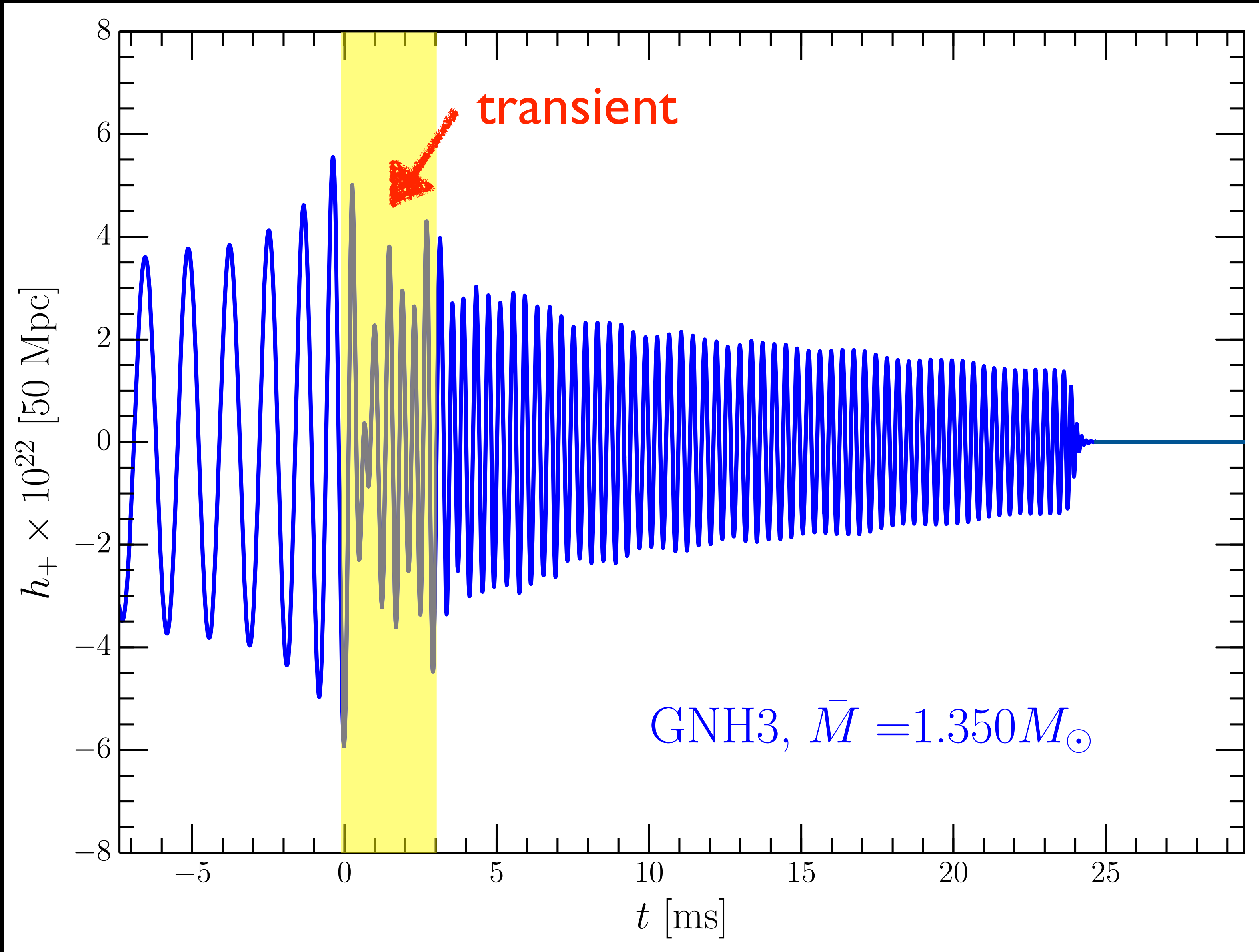


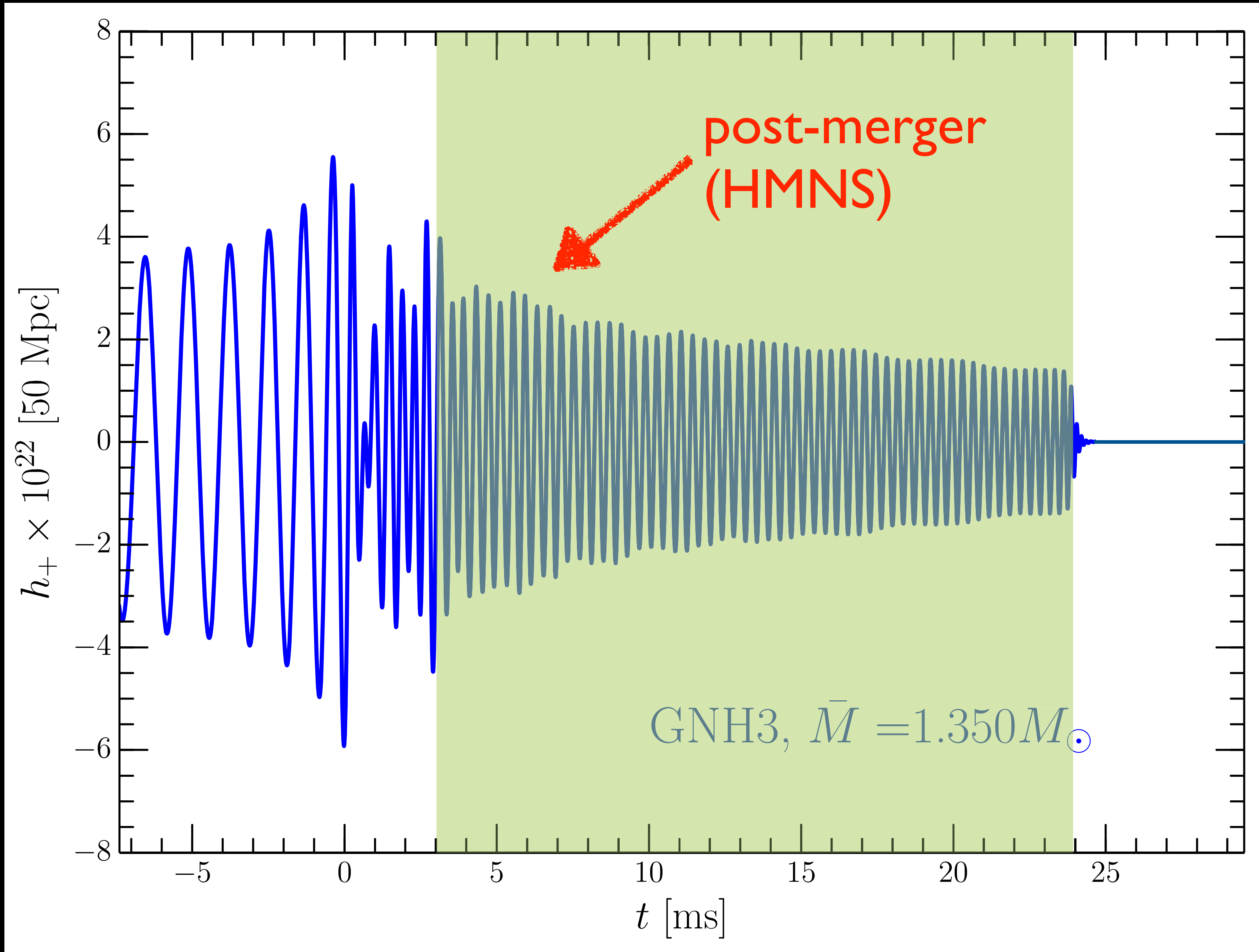
Inspiral: well approximated by PN/EOB; tidal effects important

Anatomy of the GW signal



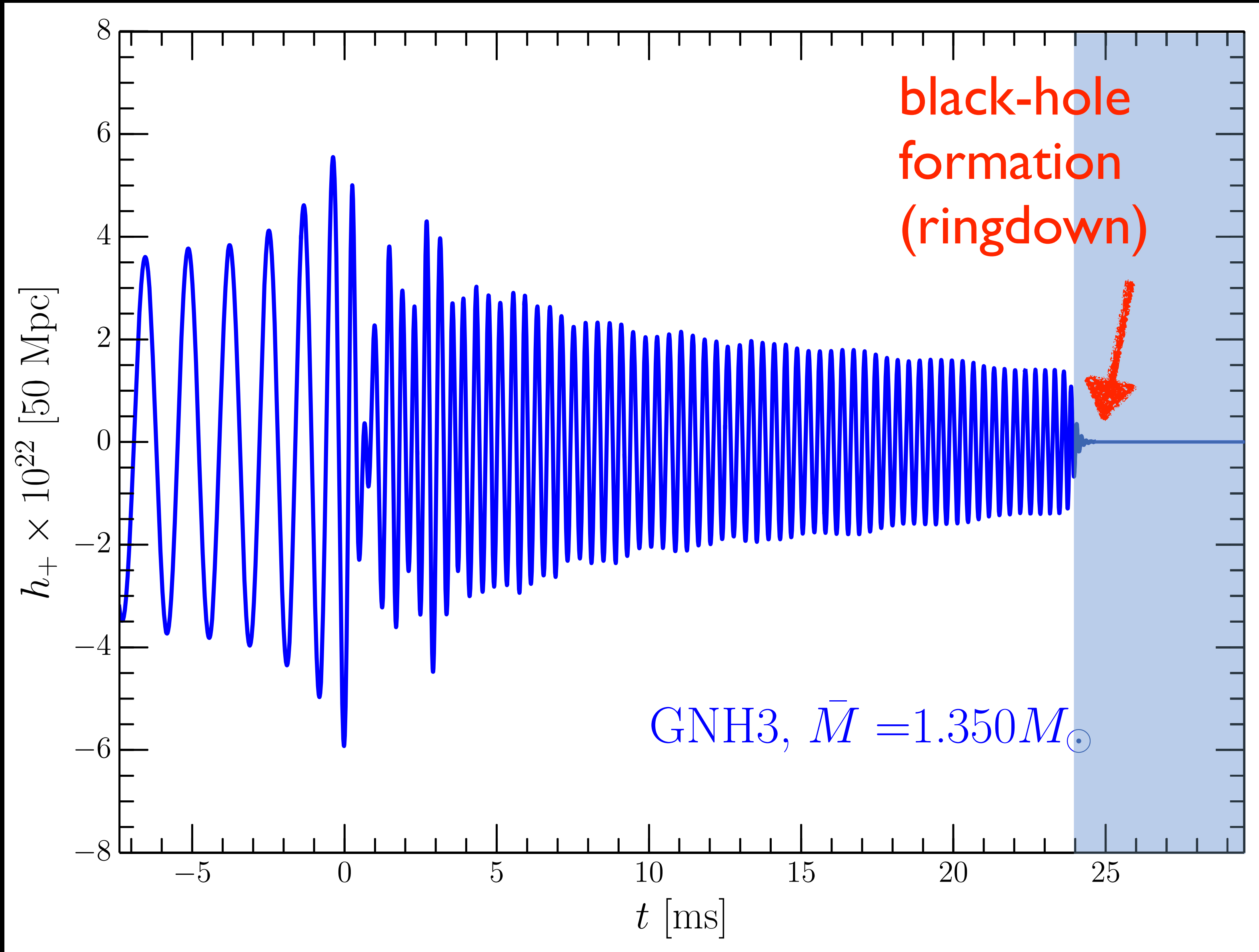
Merger: highly nonlinear but analytic description possible

Anatomy of the GW signal



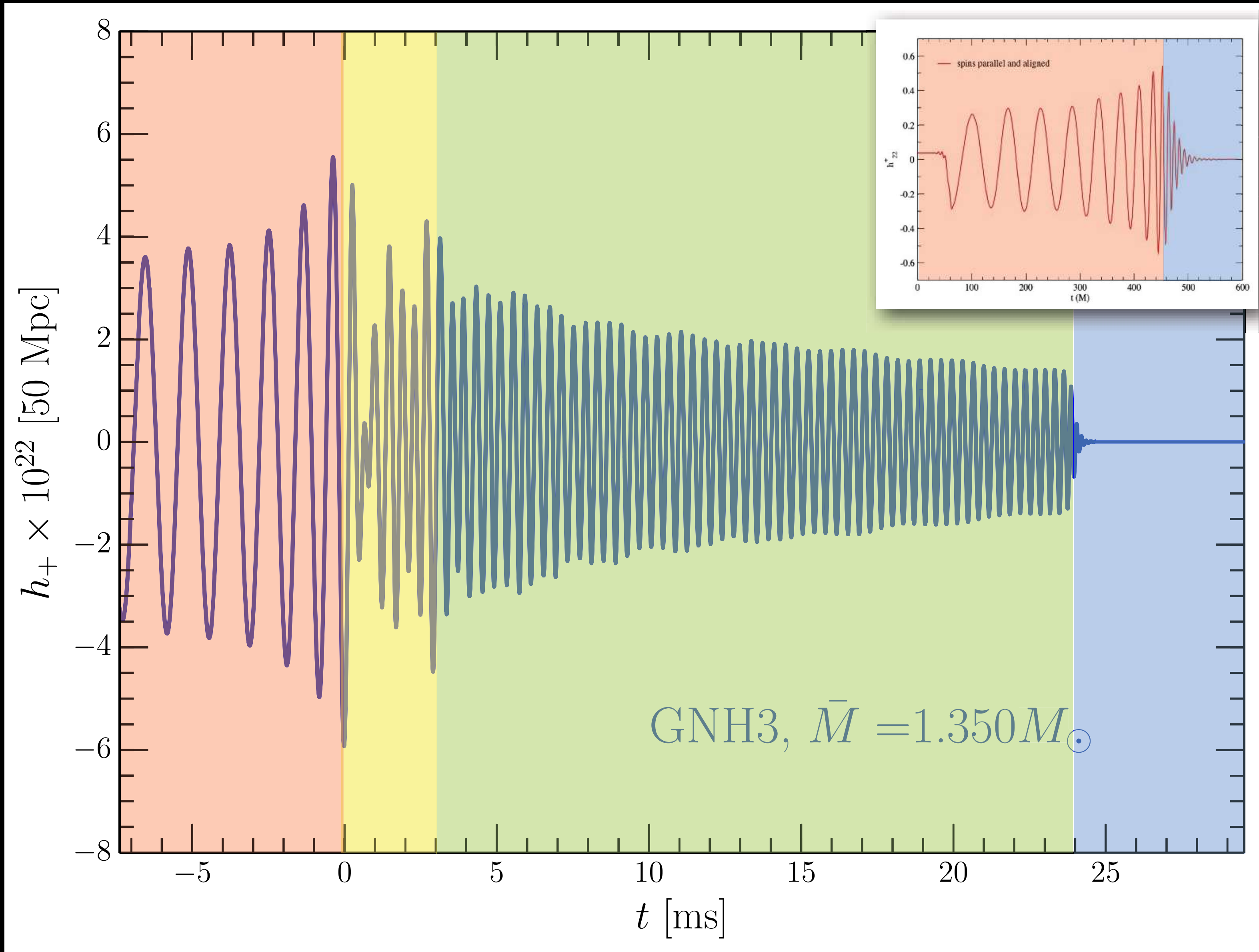
post-merger: quasi-periodic emission of bar-deformed HMNS

Anatomy of the GW signal



Collapse-ringdown: signal essentially shuts off

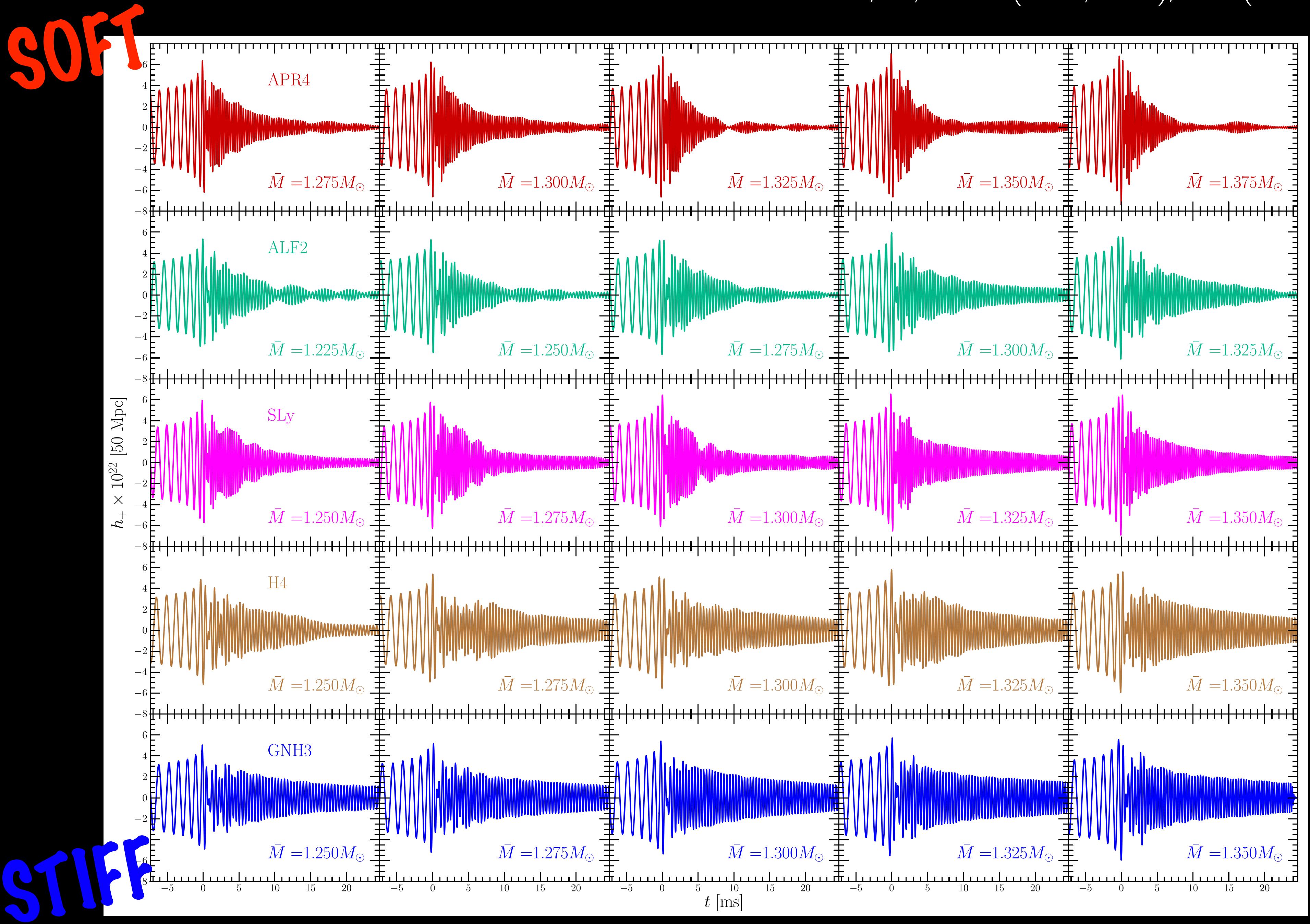
Anatomy of the GW signal



Postmerger signal: peculiar of binary NSs

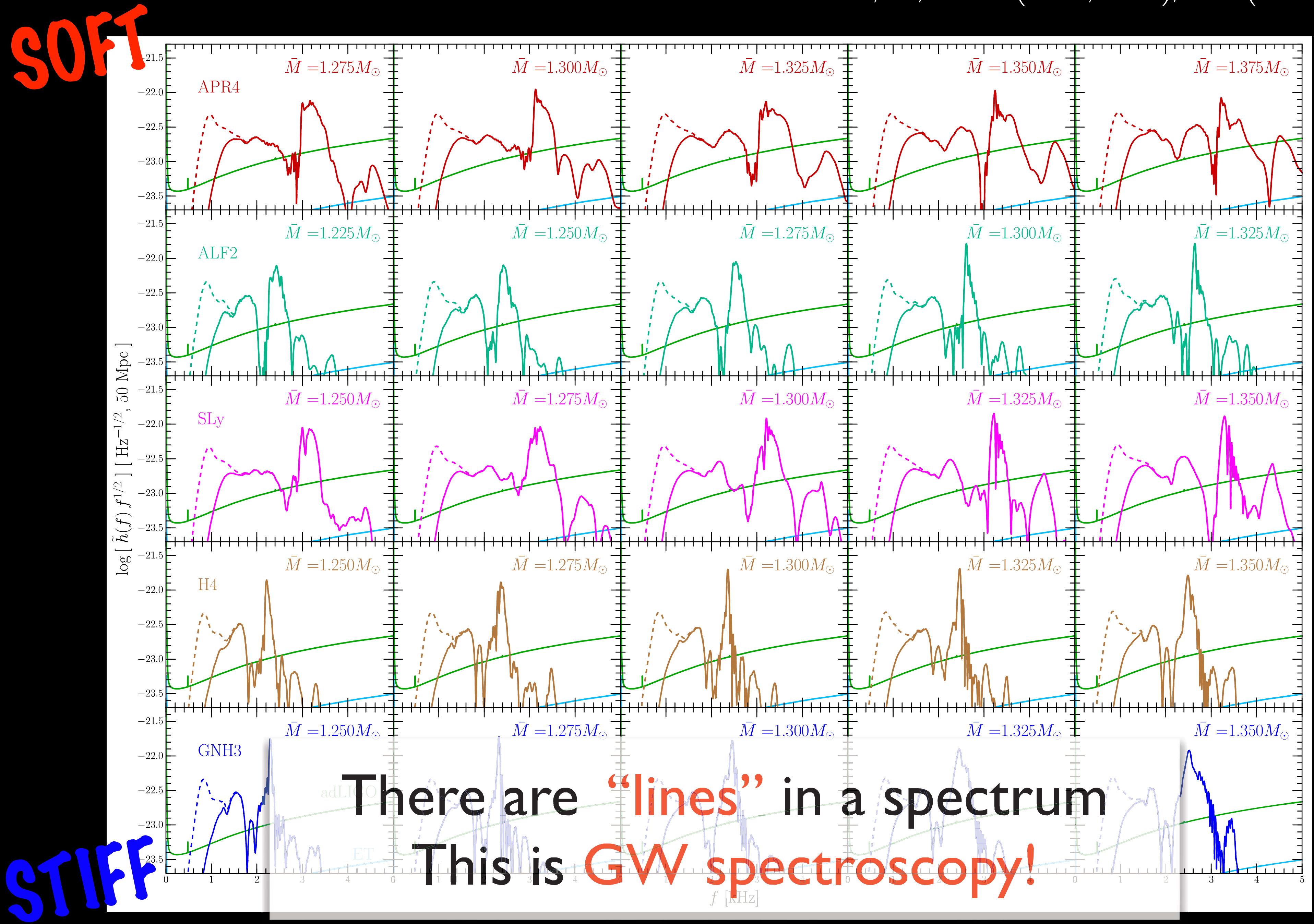
What we can do nowadays

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



Extracting information from the EOS

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

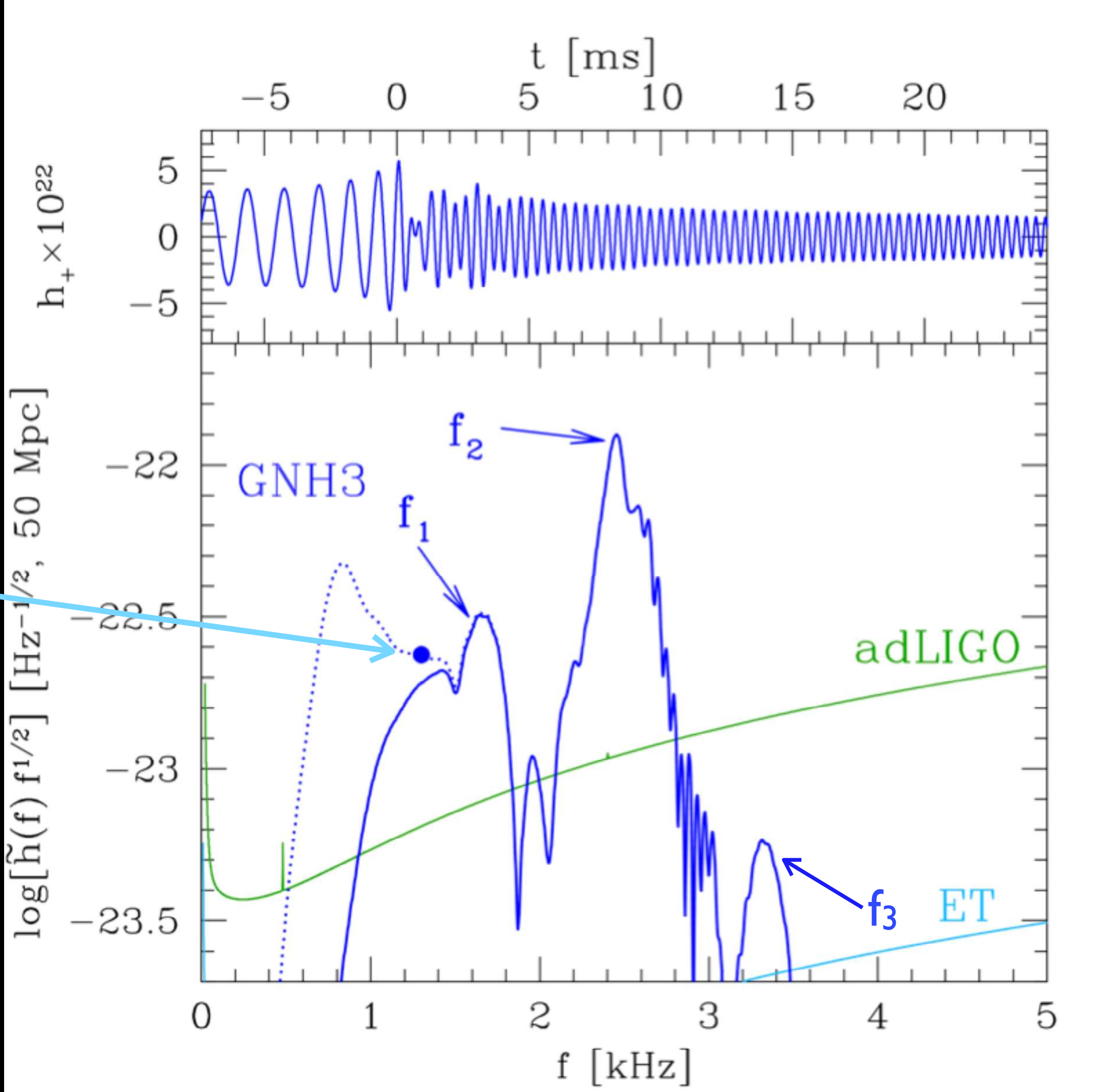


There are "lines" in a spectrum
This is GW spectroscopy!

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



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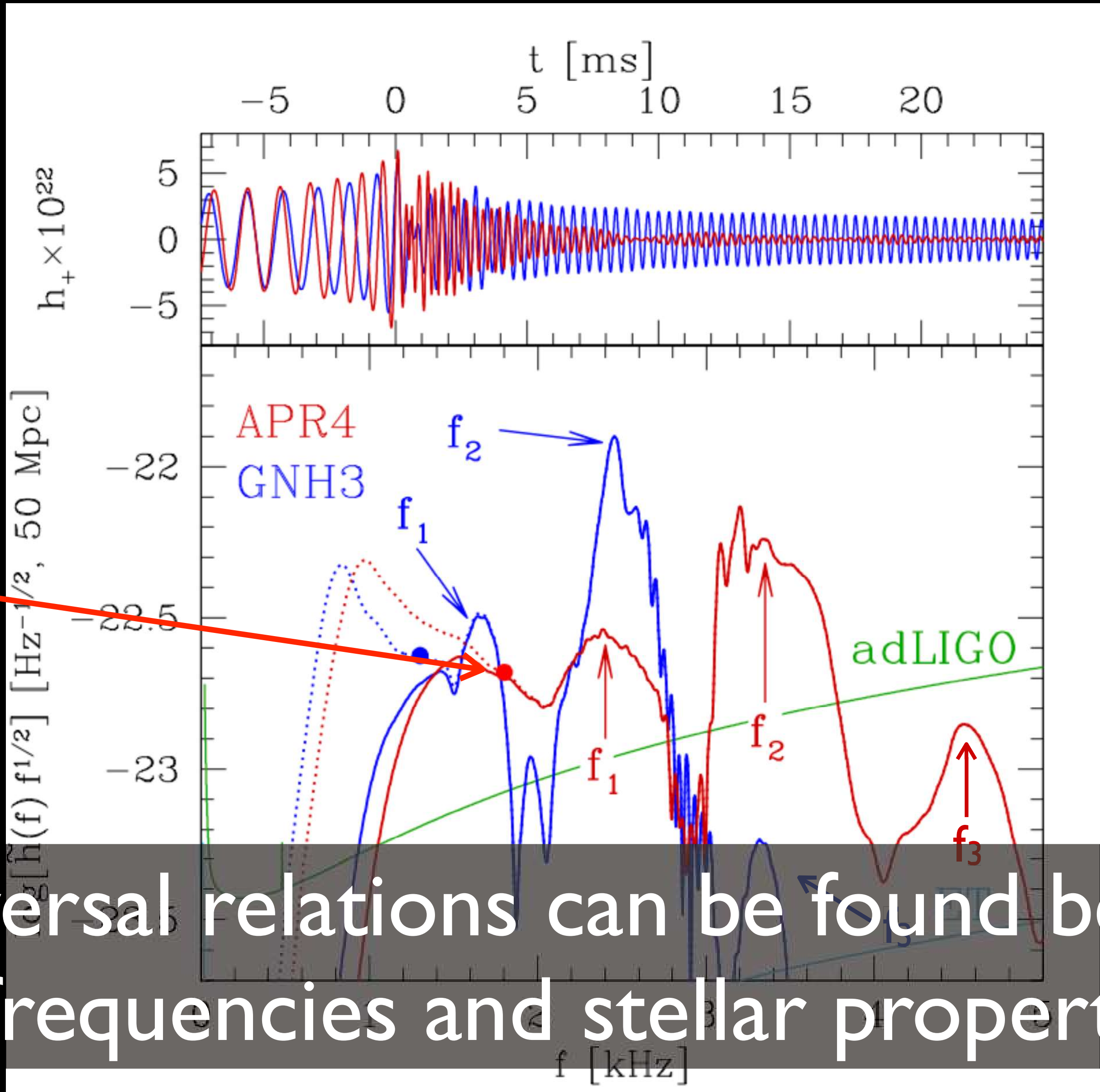
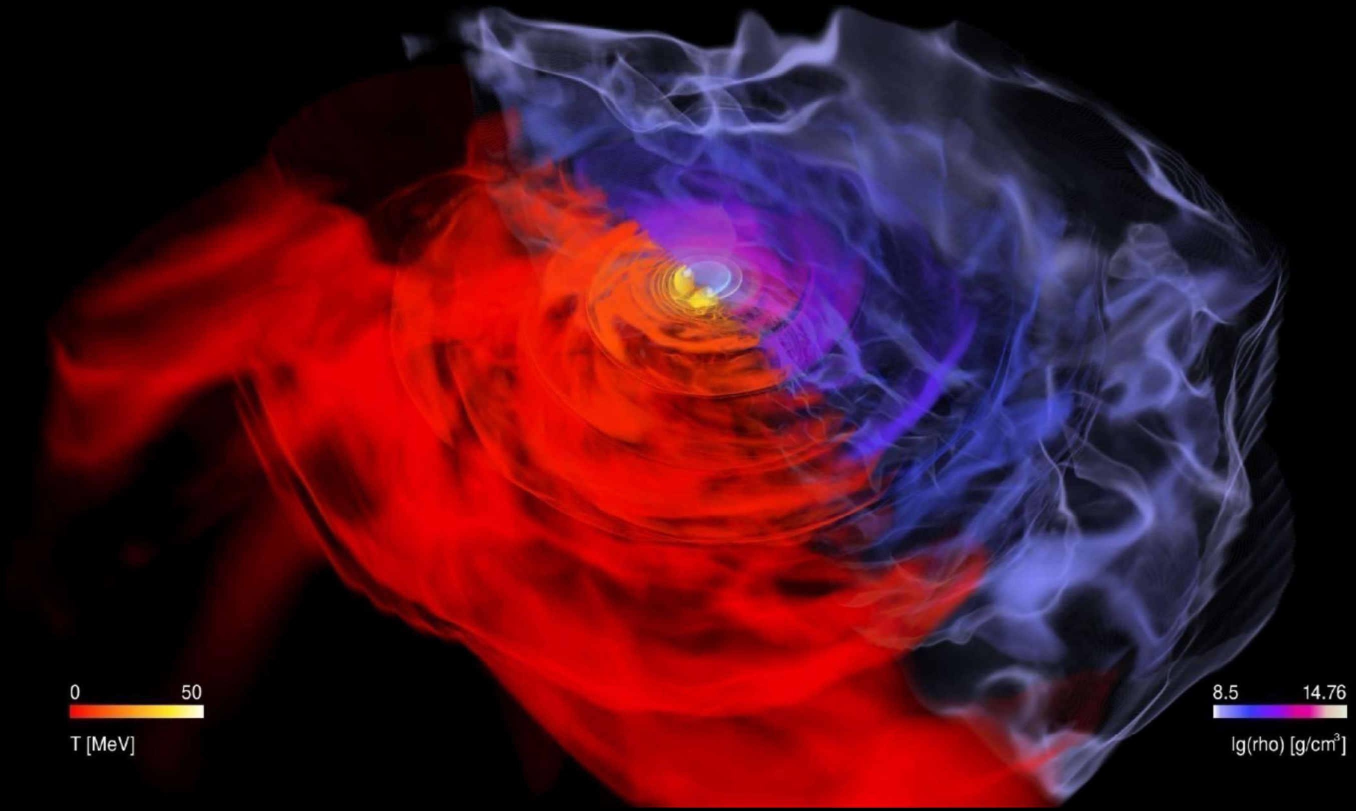
merger frequency



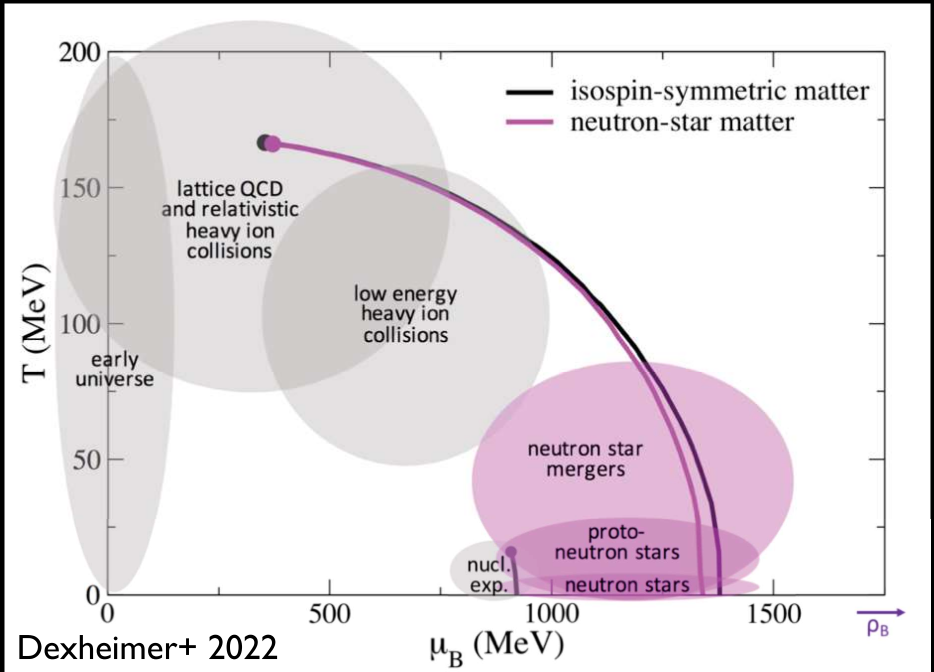
Universal relations can be found between frequencies and stellar properties

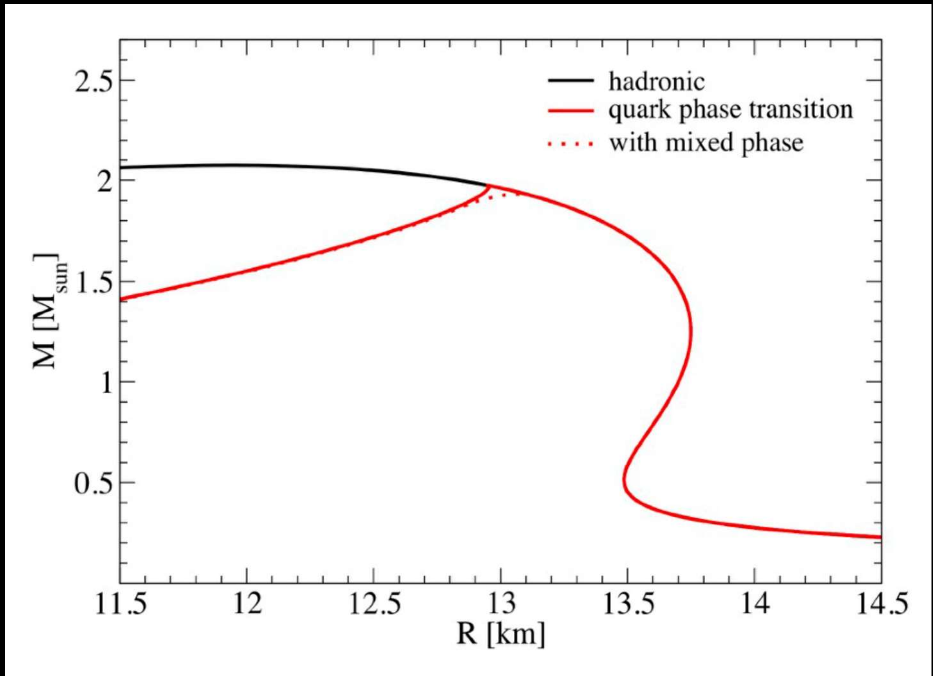
Phase transitions and their signatures



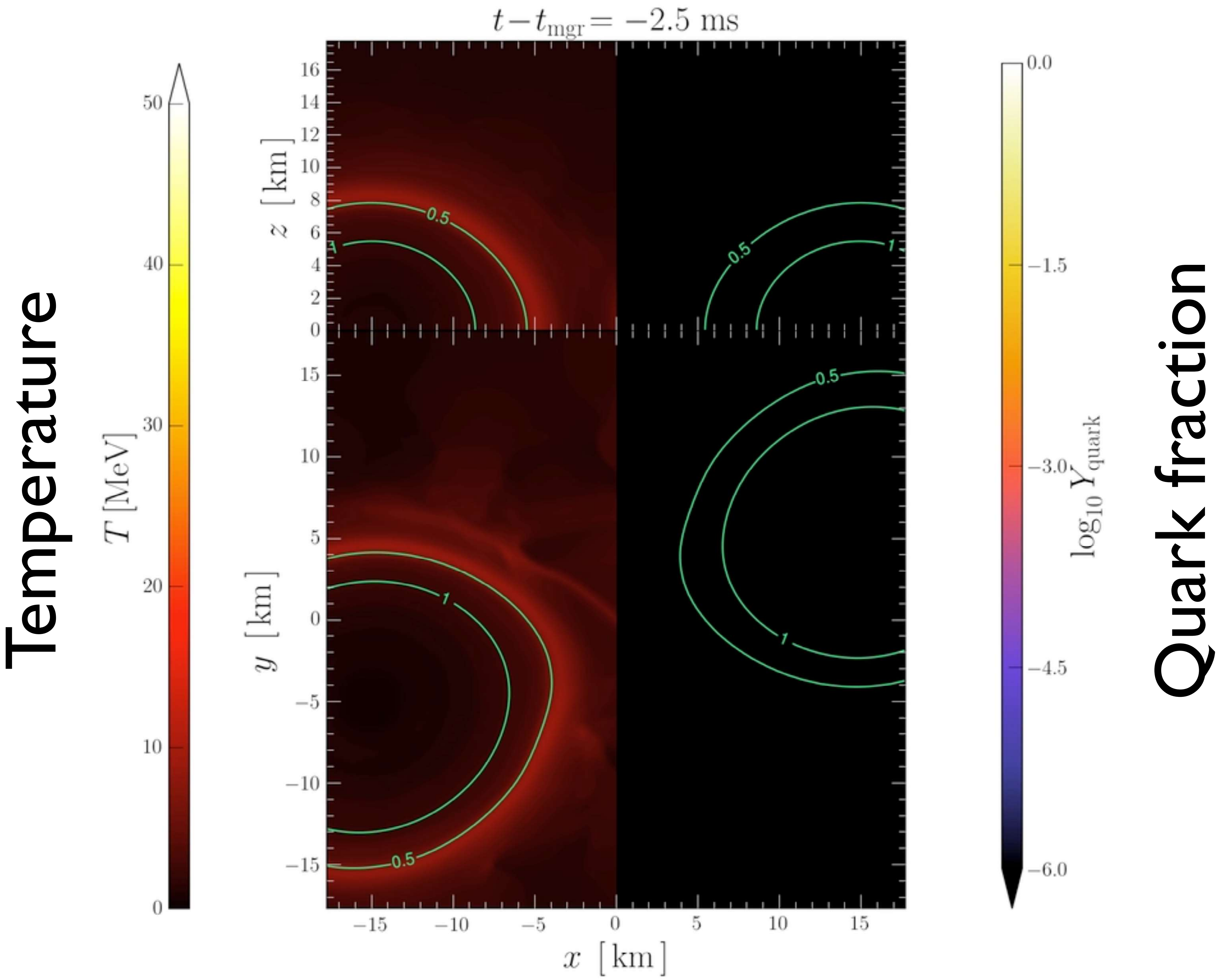
Most, Papenfort, Dexheimer, Hanauske, Schramm, Stoecker, LR (2019)
Weih, Hanauske, LR (2020)
Tootle, Ecker, Topolski, Demircik, Järvinen, LR (2022)

- **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.

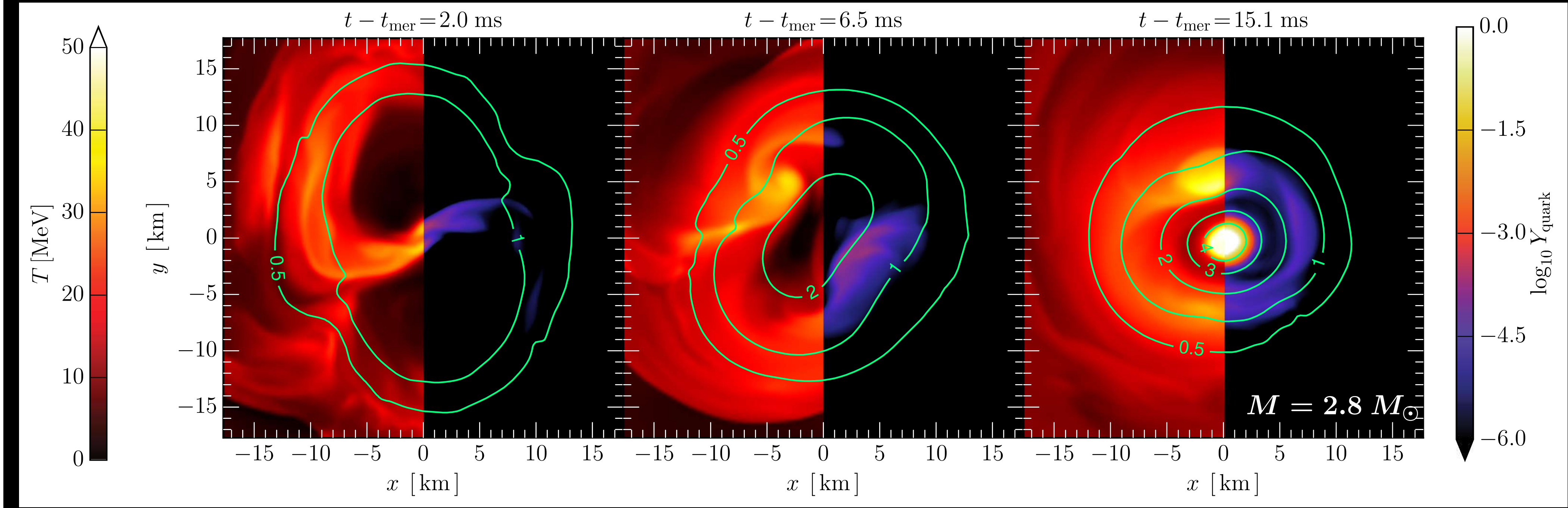




- Considered EOS based on Chiral Mean Field (CMF) model, based on a nonlinear SU(3) sigma model.
- Appearance of quarks can be introduced naturally.



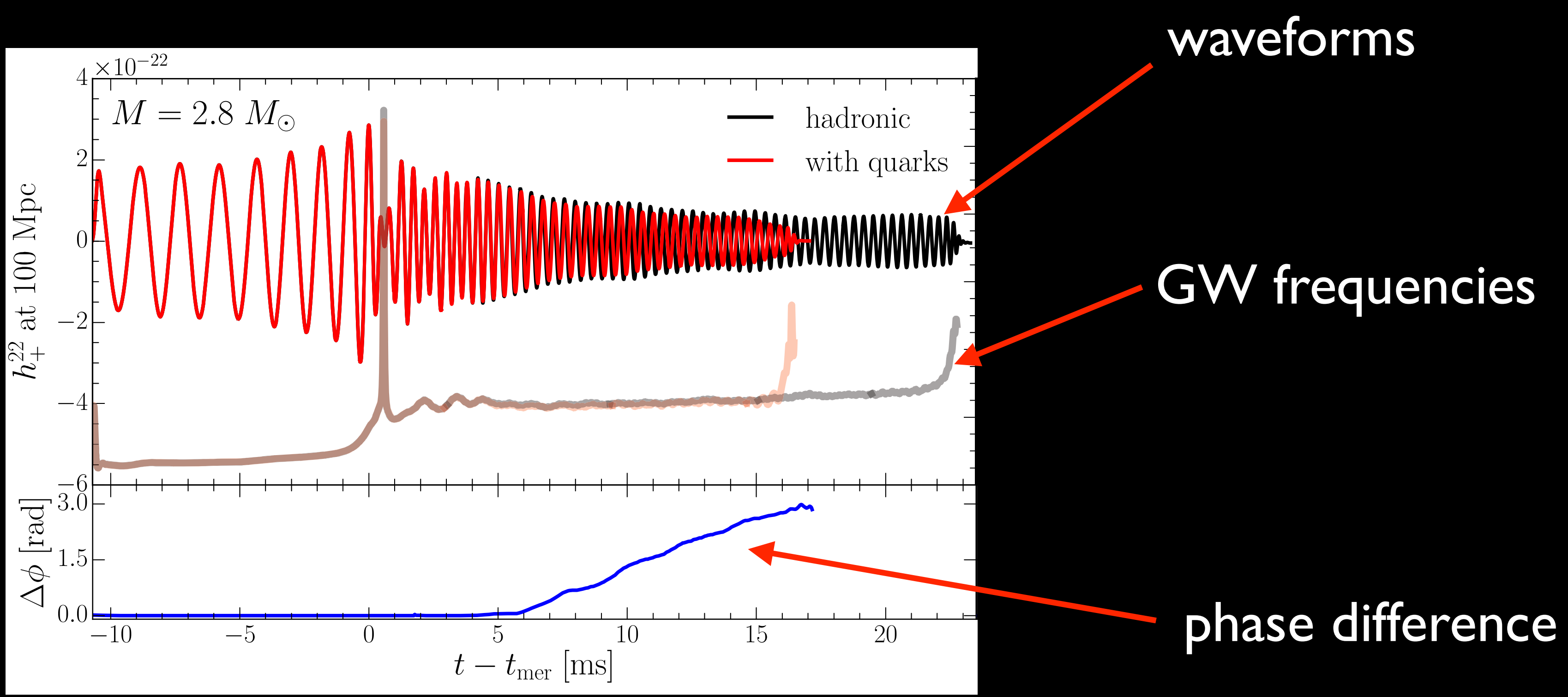
$t - t_{\rm mgr} = -2.5$ ms
Temperature
T [MeV]
Quark fraction
$\log_{10} Y_{\rm quark}$
z [km]
y [km]
x [km]
0.5
1



Quarks appear at sufficiently large temperatures and densities.

When this happens the EOS is considerably softened and a BH produced.

Gravitational-wave emission



- After~5 ms, quark fraction large enough to yield differences in GWs
- Sudden softening of the phase transition leads to collapse and **large difference** in phase evolution.

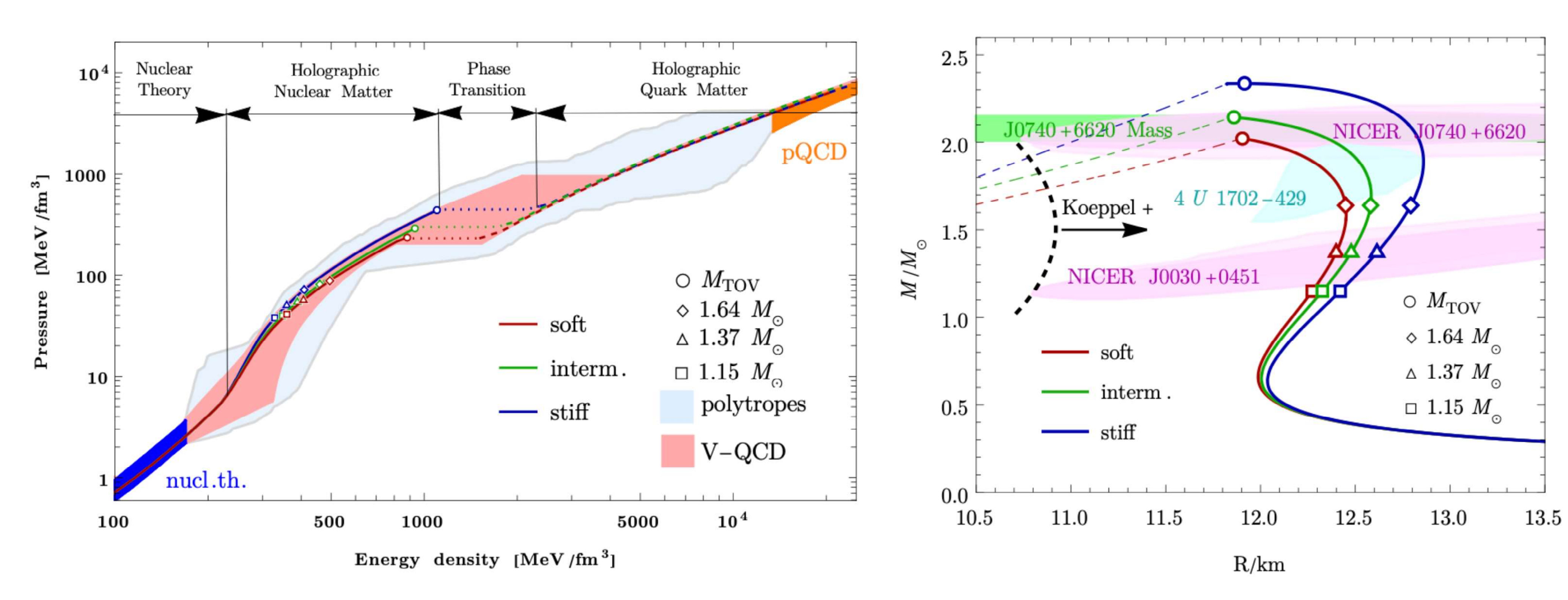
Observing mismatch between **inspiral** (fully hadronic) and **post-merger** (phase transition): clear **signature** of a **PT**

Using a more consistent EOS: V-QCD

Tootle, Ecker, Topolski, Demircik, Järvinen, LR (2022)

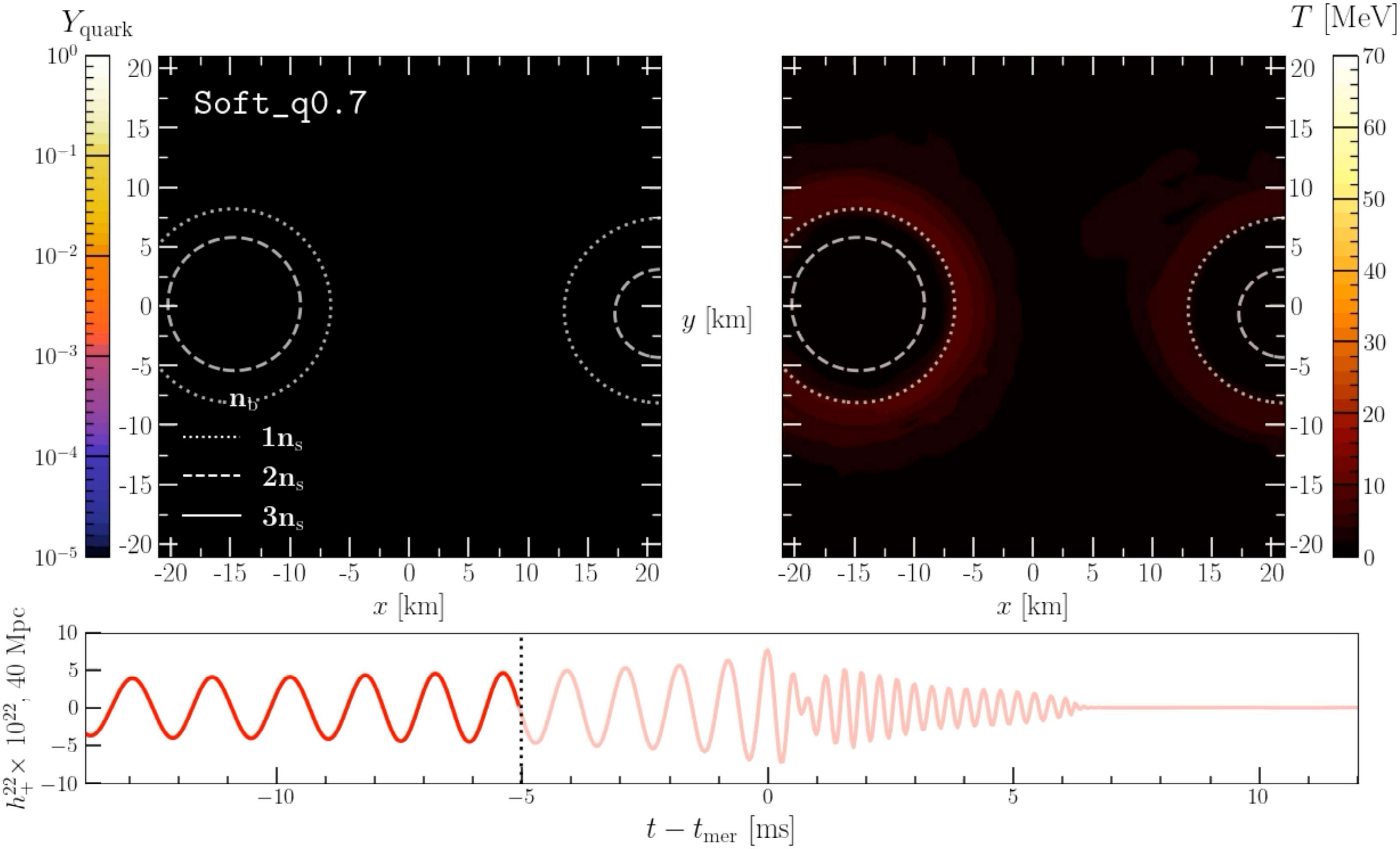
Thermal effects need consistent treatment. Used V-QCD model (Demircik+ 2021) and three variants in terms of stiffness.

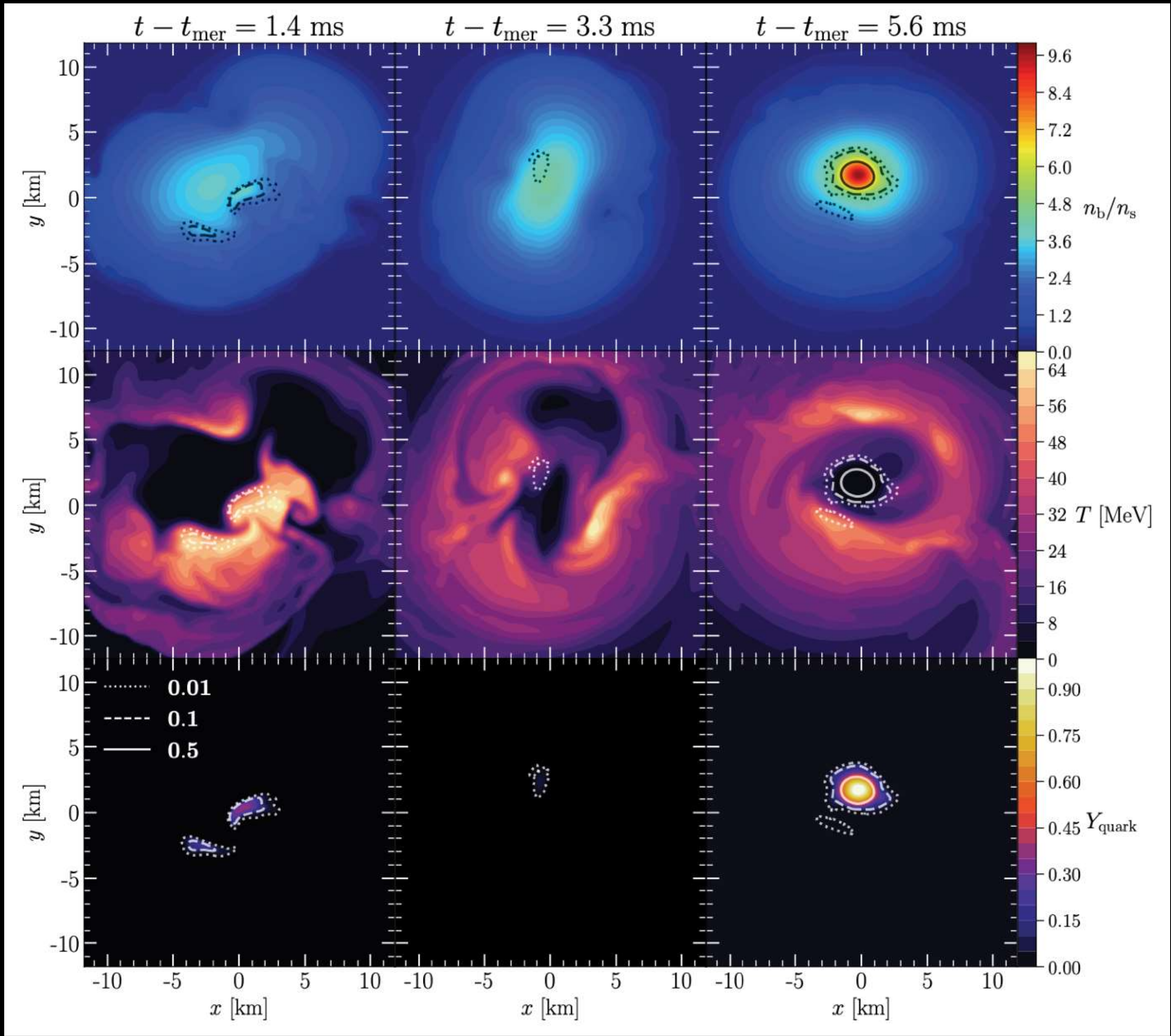
Q: **could GW170817 have collapsed as a result of PT?**



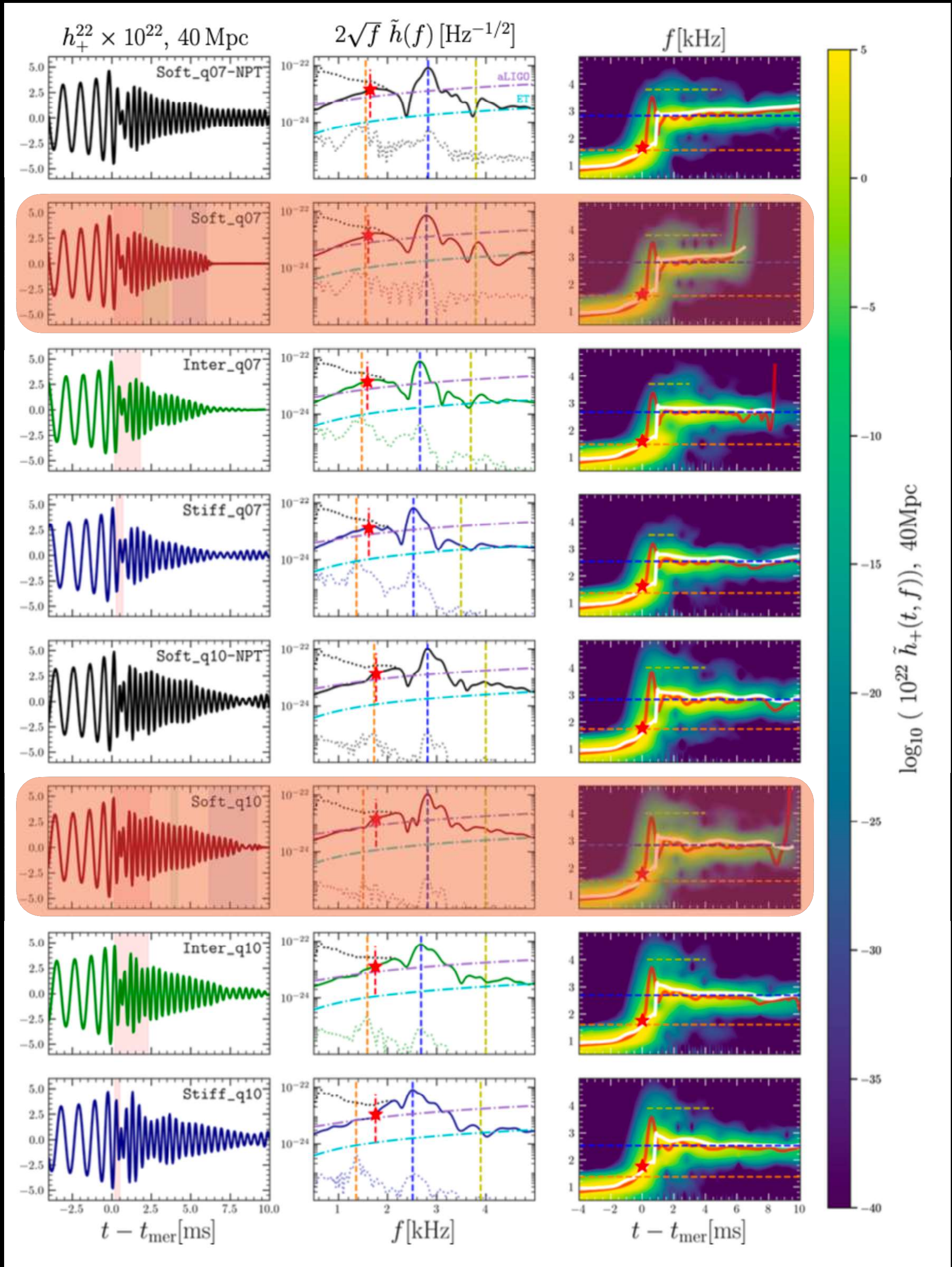
More recently we have explored V-QCD

Tootle, Ecker, Topolski, Demircik, Järvinen, LR (2022)





The dynamics is very similar to previous simplified thermal treatment: as soon as the PT takes place, softening induces a rapid collapse.



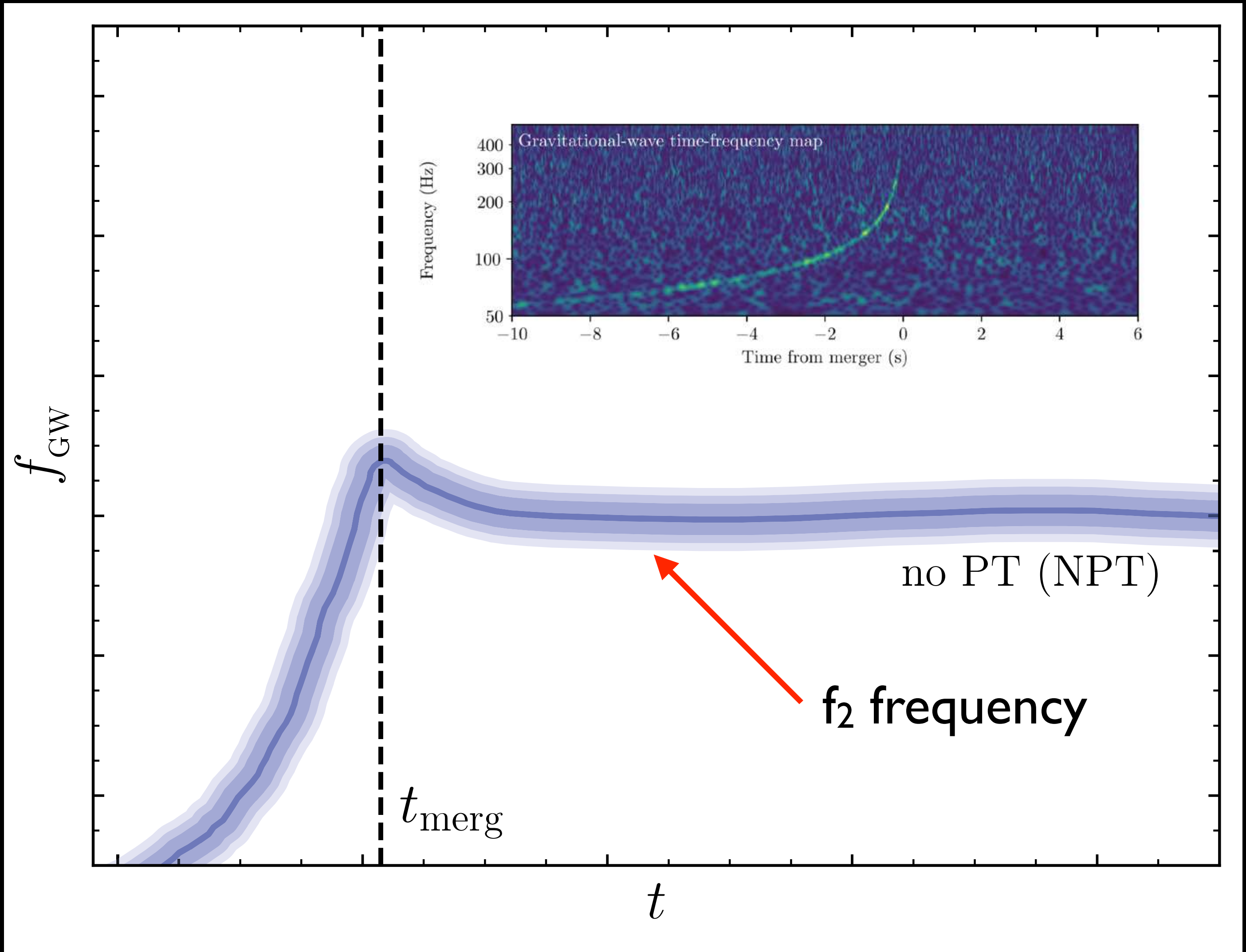
Soft version of V-QCD incompatible with **GW170817:** the collapse takes place after a few ms.

Expectation is the collapse has been after 0.9 s.

Interesting example where **GWs** can **constrain QCD phase diagram.**

A zoology of possible behaviours

The occurrence of a PT considerably enriches the range of possible scenarios in the GW emission



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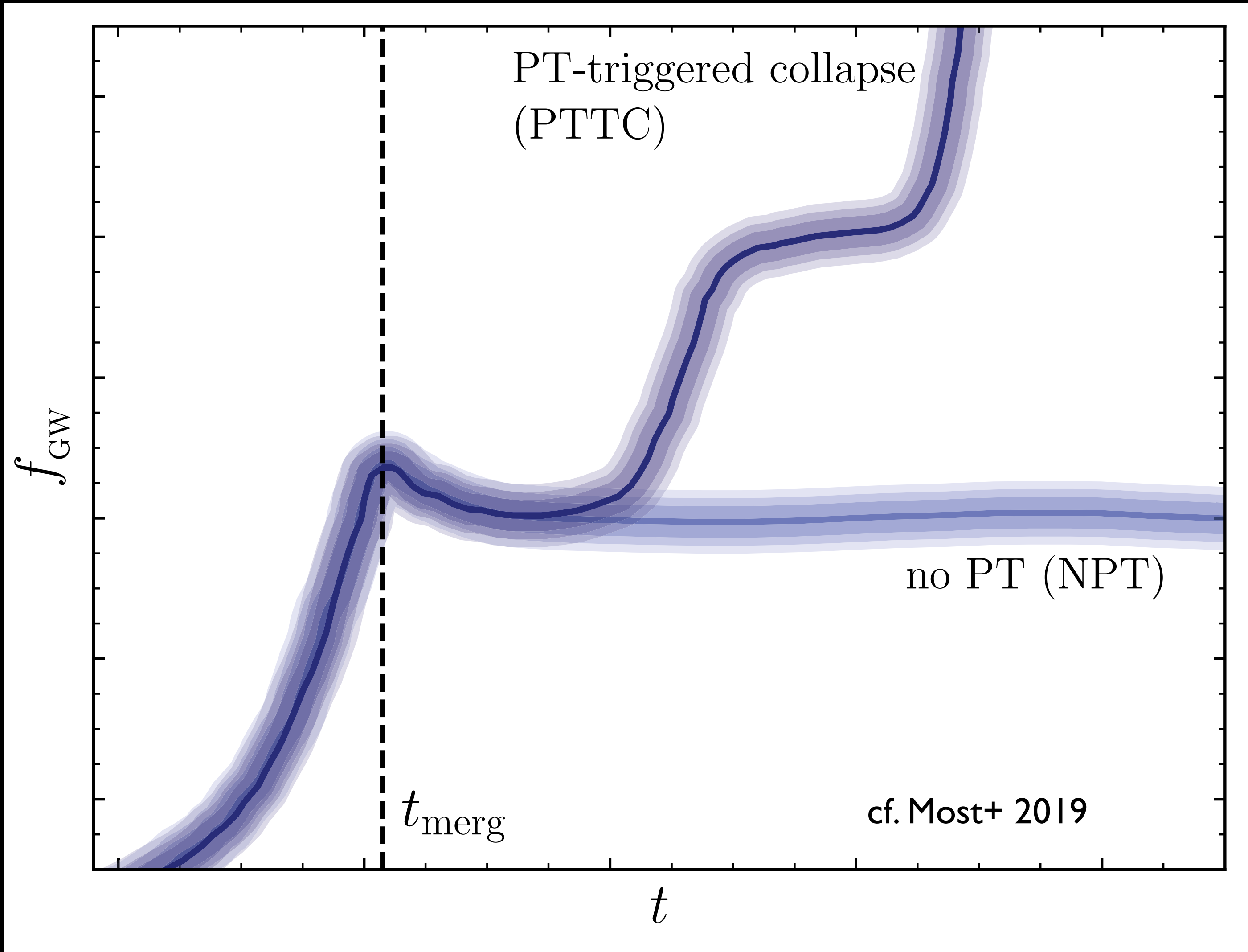

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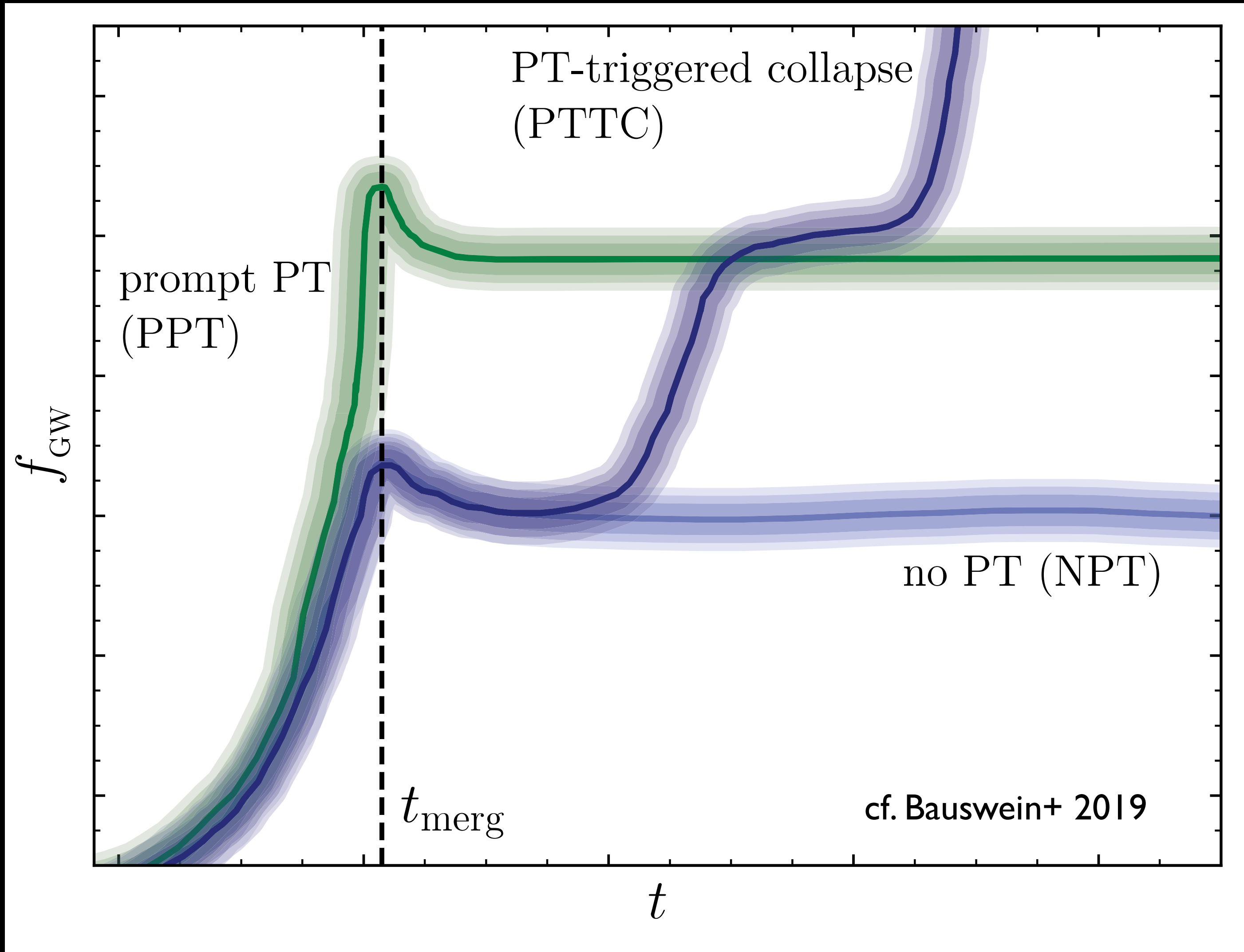

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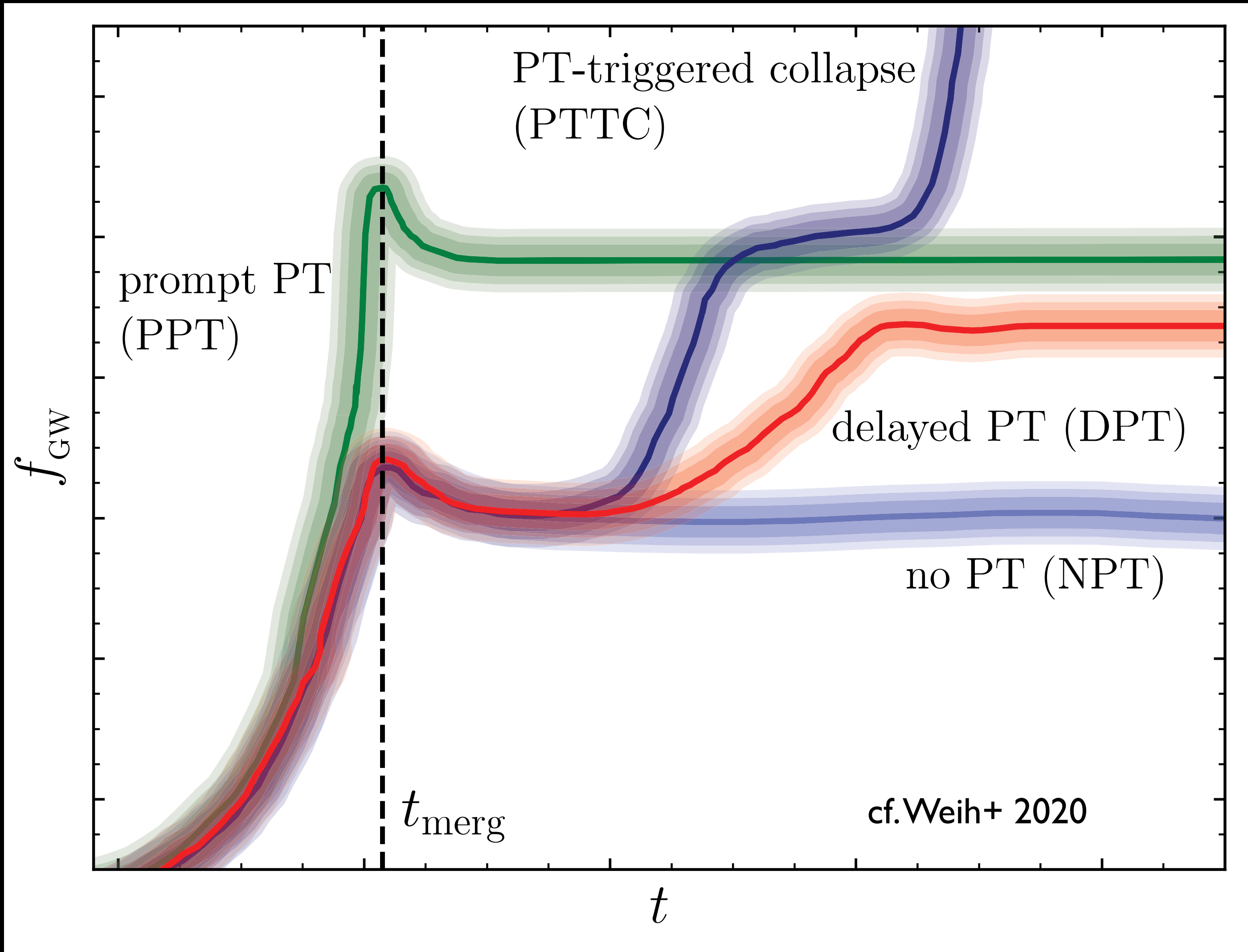
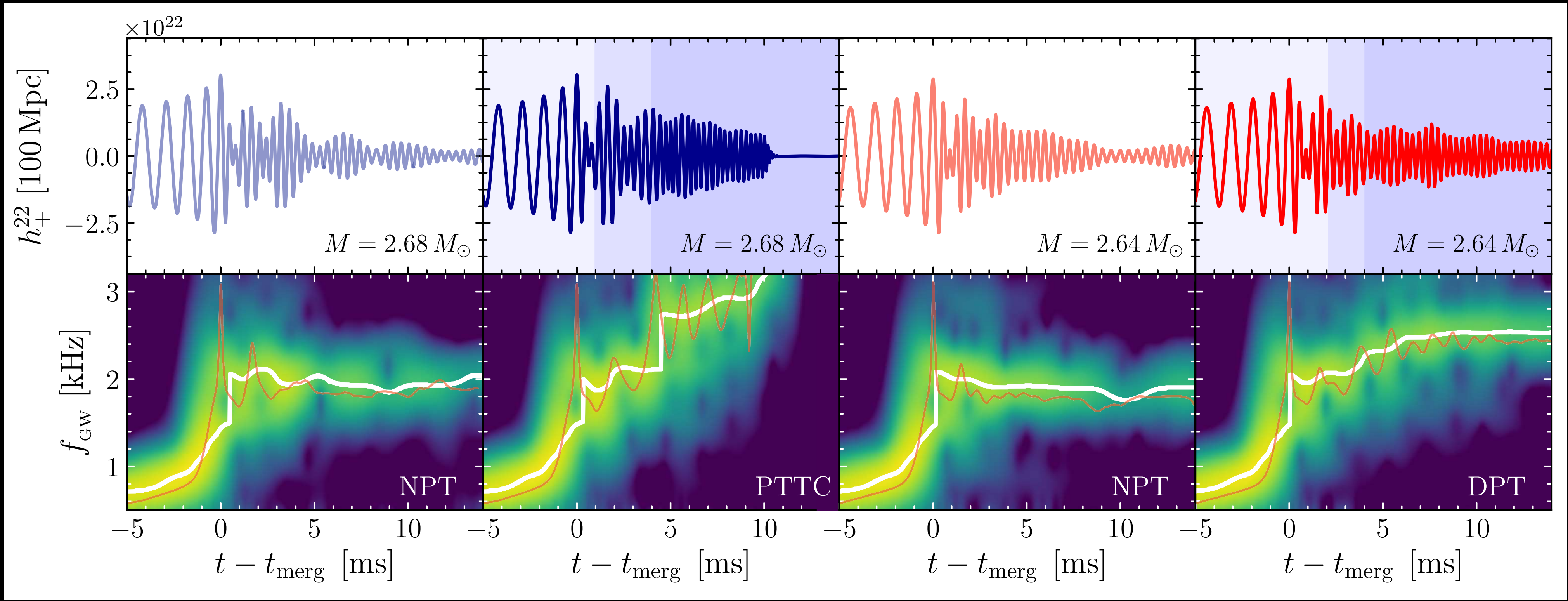


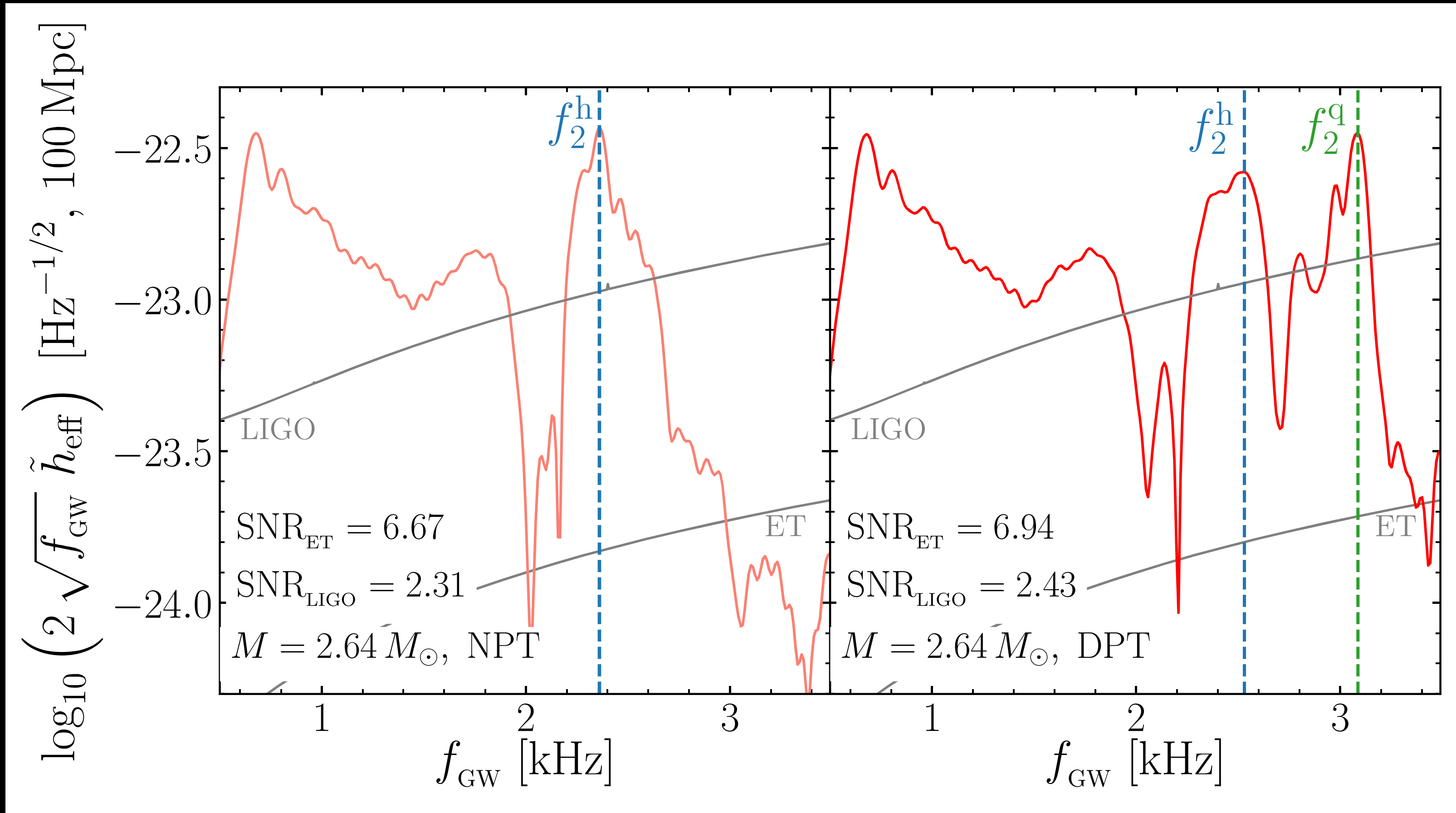
A more comprehensive picture

Zoology discussed above can be recognised when shown in terms of the gravitational waves and their spectrograms.



Importance of **DPT** is that it leads to **two** different "stable" f_2 **frequencies** that are easily distinguishable in the PSD

Why DPT is the most interesting case



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Conclusions

✳Spectra of post-merger shows peaks, some **”quasi-universal”**.

✳Using the post-merger spectra and the high-frequency peaks it is possible to set tight constraints on the **EOS**.

✳A **phase transition** (PT) after a BNS merger leaves **signatures** on the GW signal that can be realistically measured.

✳Depending on the details of the **PT** different **signatures** are possible. Best candidate is a stable **hybrid remnant**.

GWs from BNSs represent a **new tool** to explore **nuclear physics** and the **QCD phase diagram**