

Binary neutron stars: from macroscopic collisions to microphysics

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Plan of the talk

- Modelling neutron-star mergers
- GW spectroscopy: EOS from frequencies
- Signatures of quark-hadron phase transitions
- On the sound speed in neutron stars

The two-body problem in GR

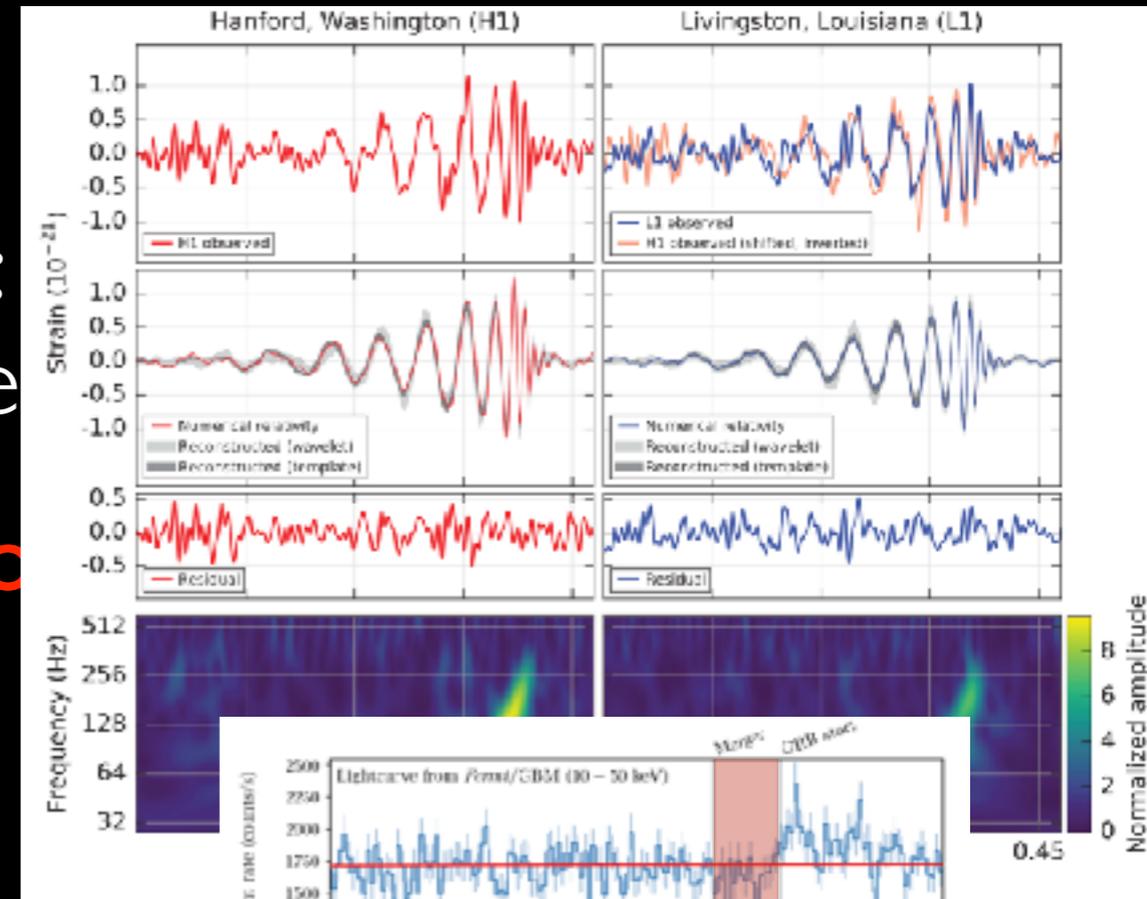
- For black holes the process is very **simple**:

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

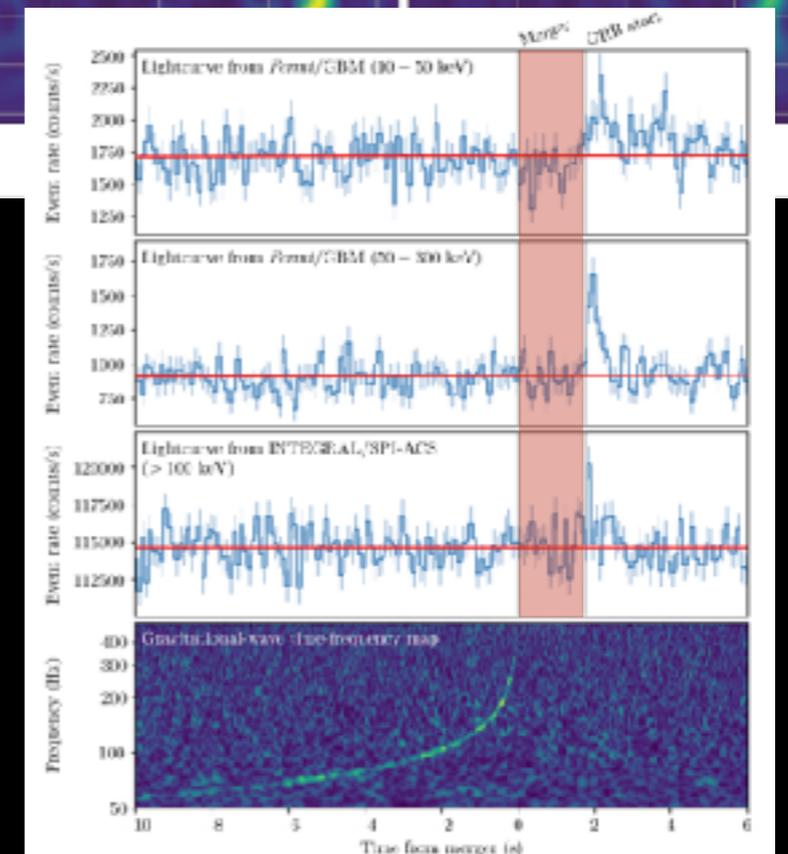
- For NSs the question is more **subtle**:
hyper-massive neutron star (HMNS), i.e.

$$\text{NS} + \text{NS} \longrightarrow \text{HMNS} + \dots ? \longrightarrow \text{BH} + \text{GWs}$$

GW150914



GW170817



The mathematics of the problem

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

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

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

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

$$p = p(\rho, \epsilon, Y_e, \dots), \quad (\text{equation of state})$$

$$T_{\mu\nu} = T_{\mu\nu}^{\text{fluid}} + T_{\mu\nu}^{\text{EM}} + \dots \quad (\text{energy - momentum tensor})$$

fields: finite-difference, pseudo-spectral methods

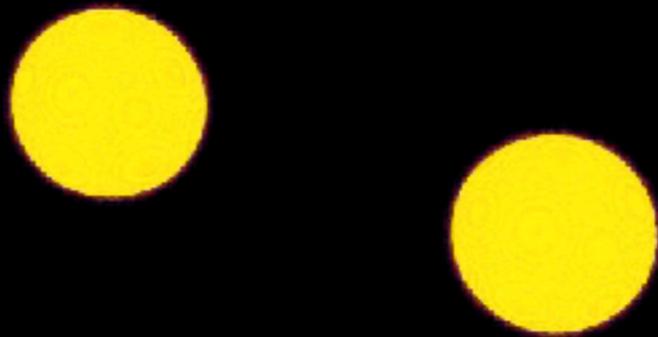
matter: high-resolution-shock-capturing, finite volume, finite differences

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



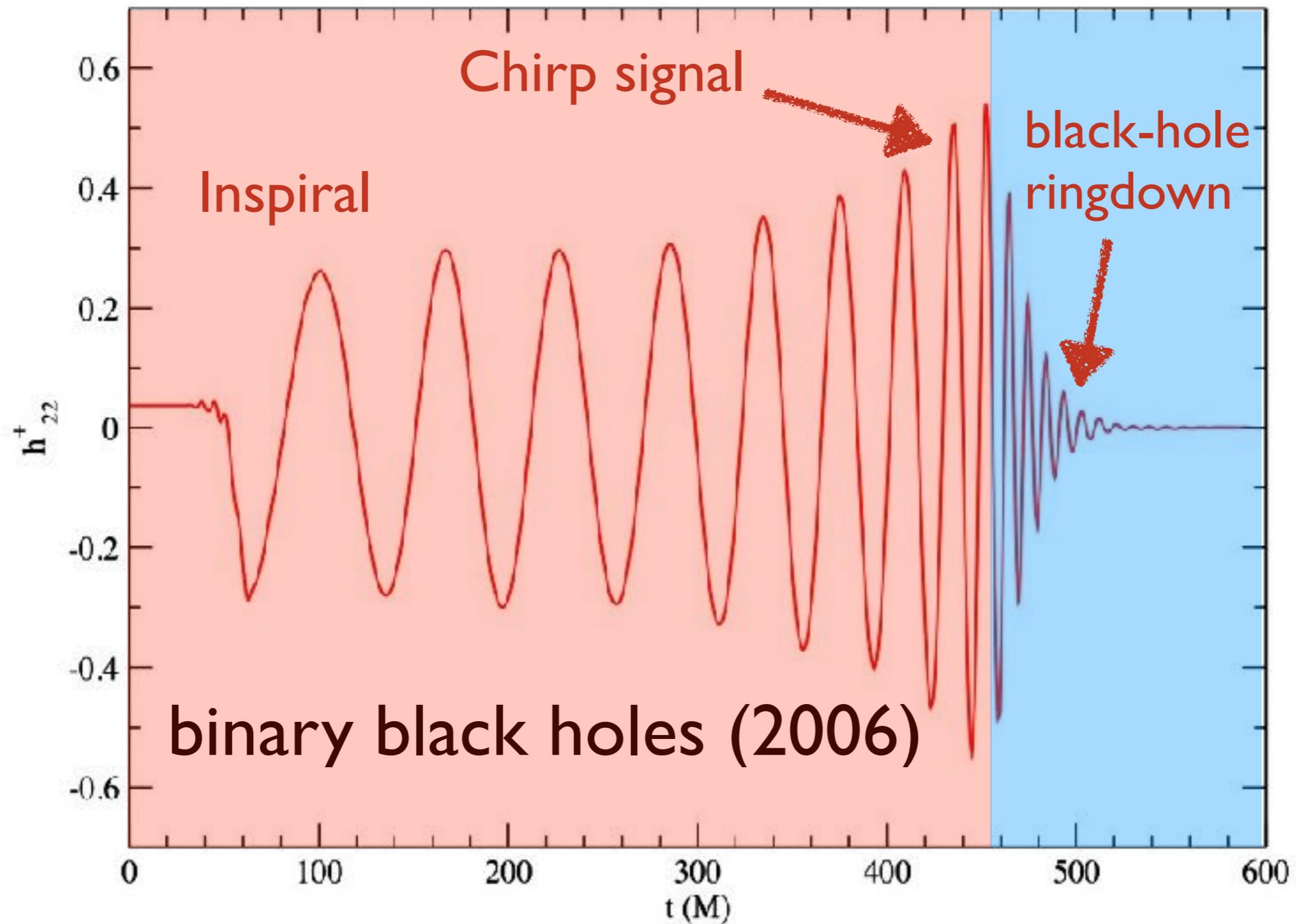
$$M = 2 \times 1.35 M_{\odot}$$

LS220 EOS

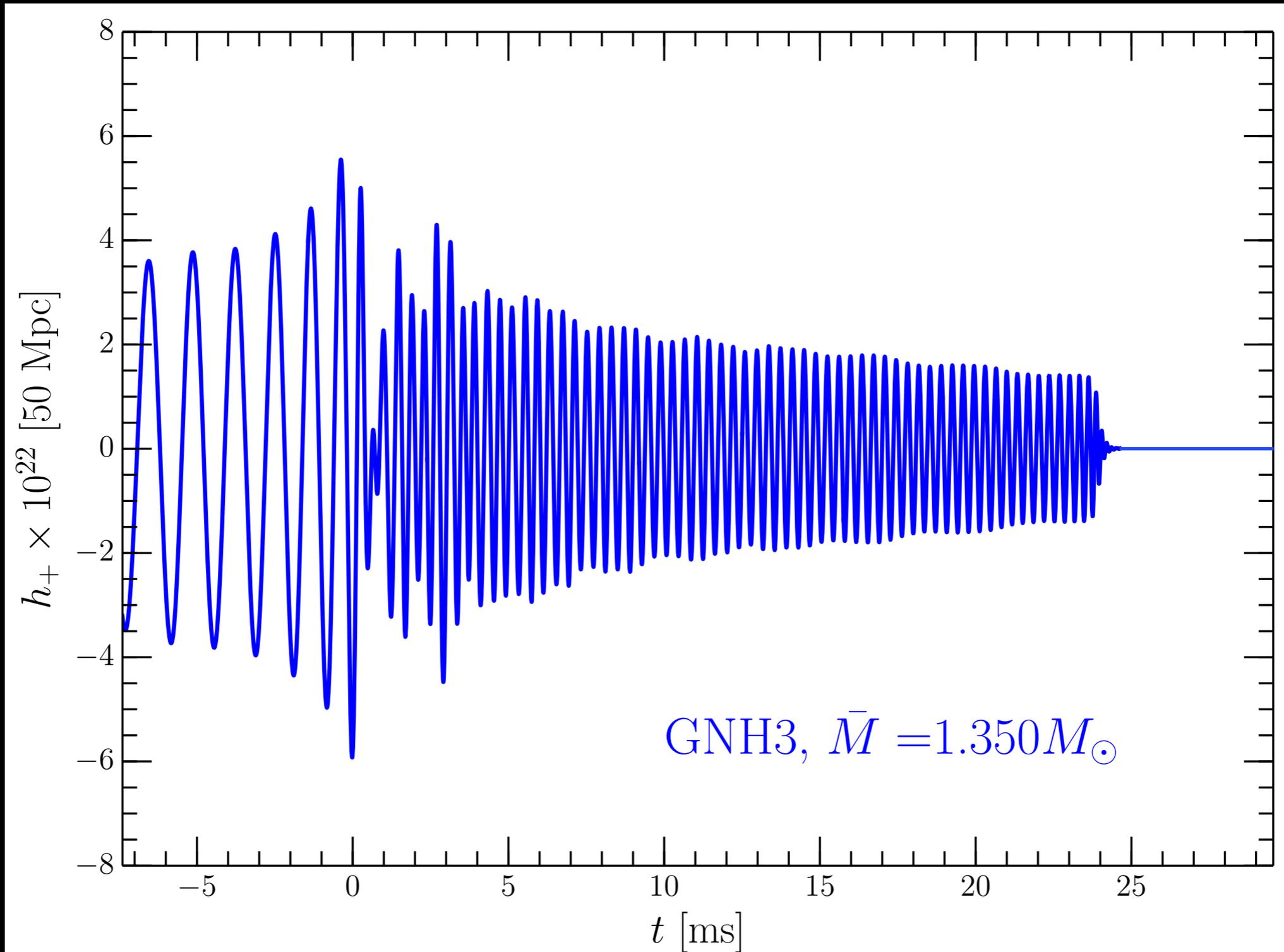


merger → HMNS → BH + torus

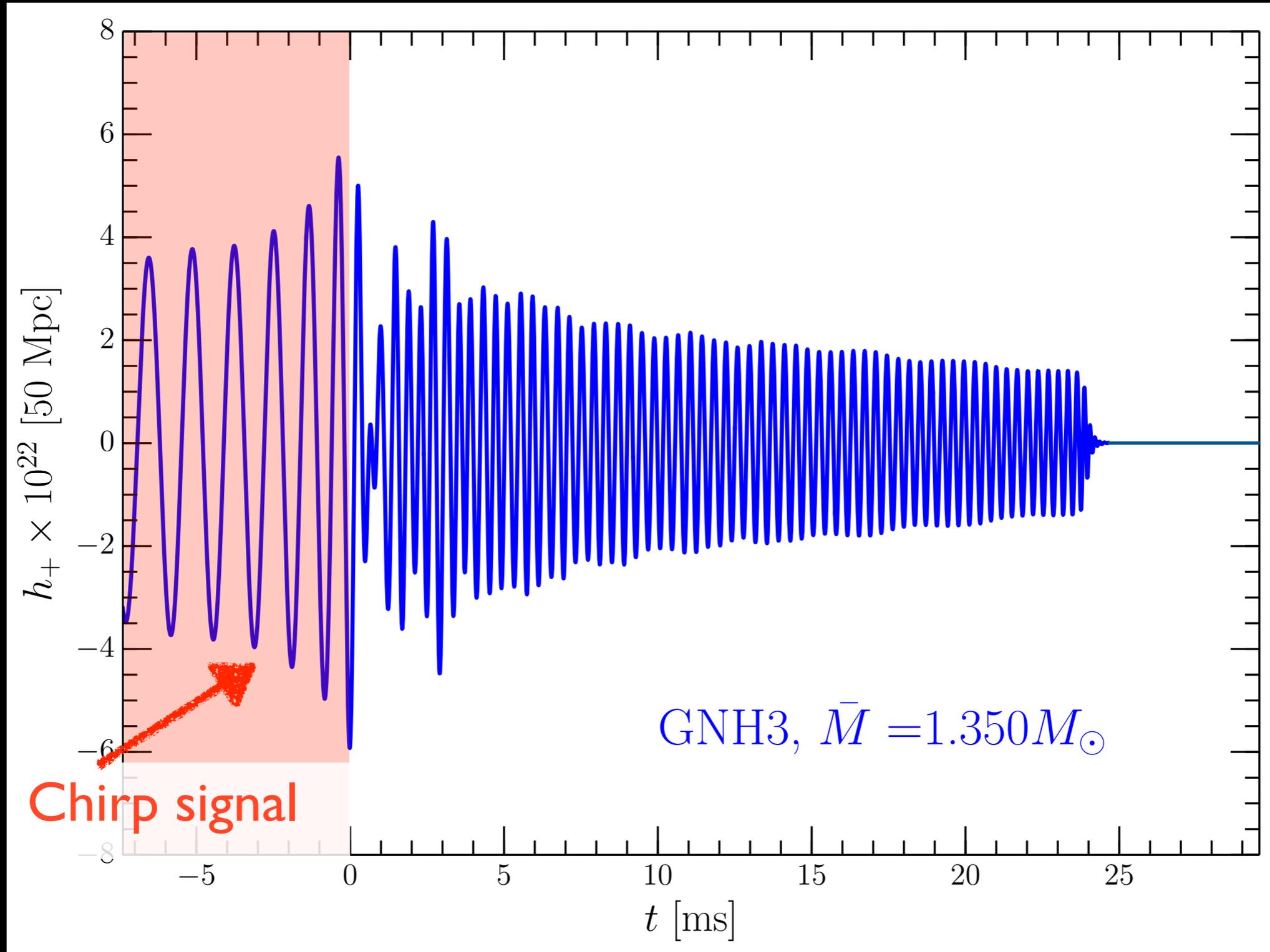
Anatomy of the GW signal



Anatomy of the GW signal

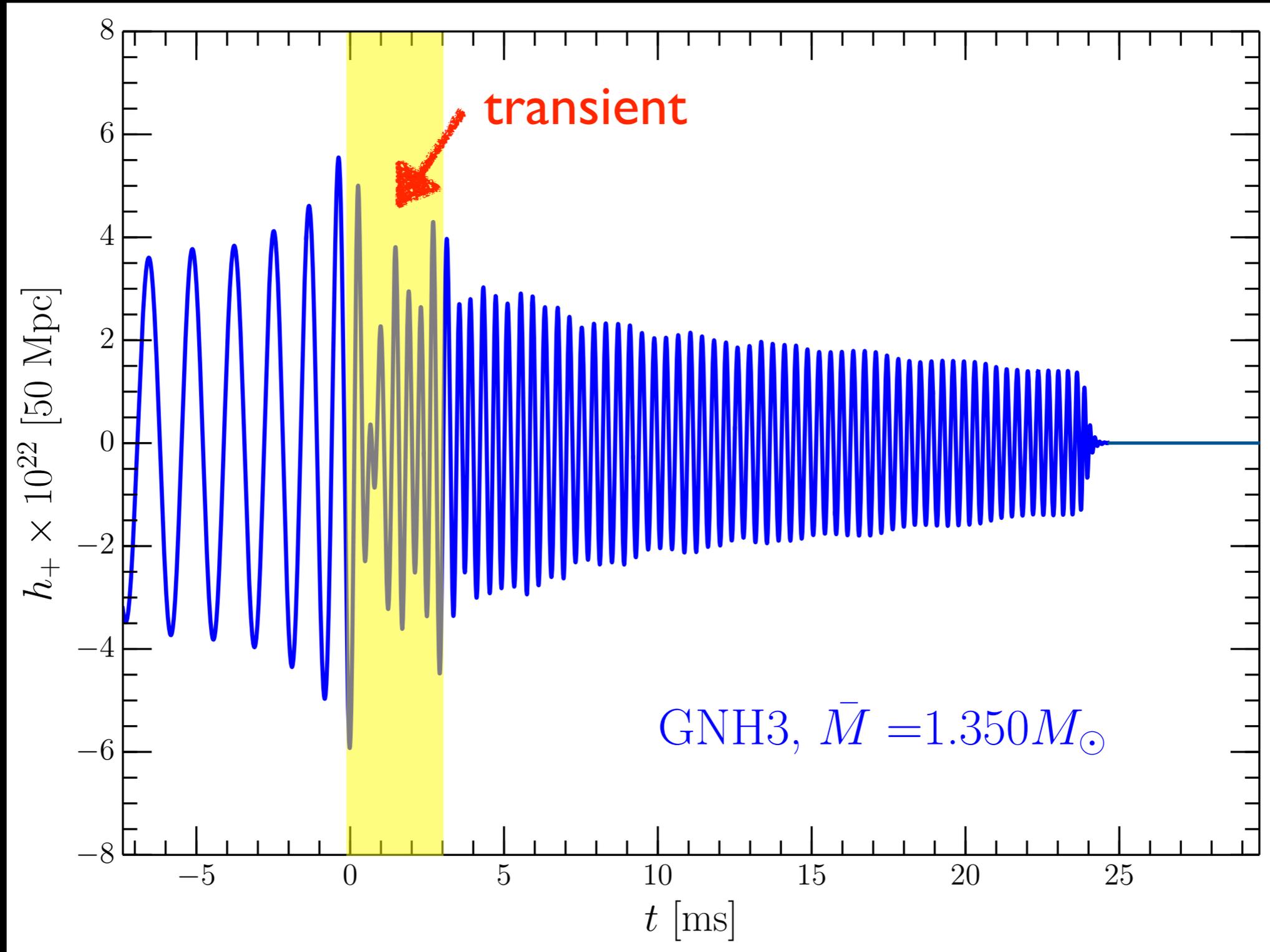


Anatomy of the GW signal



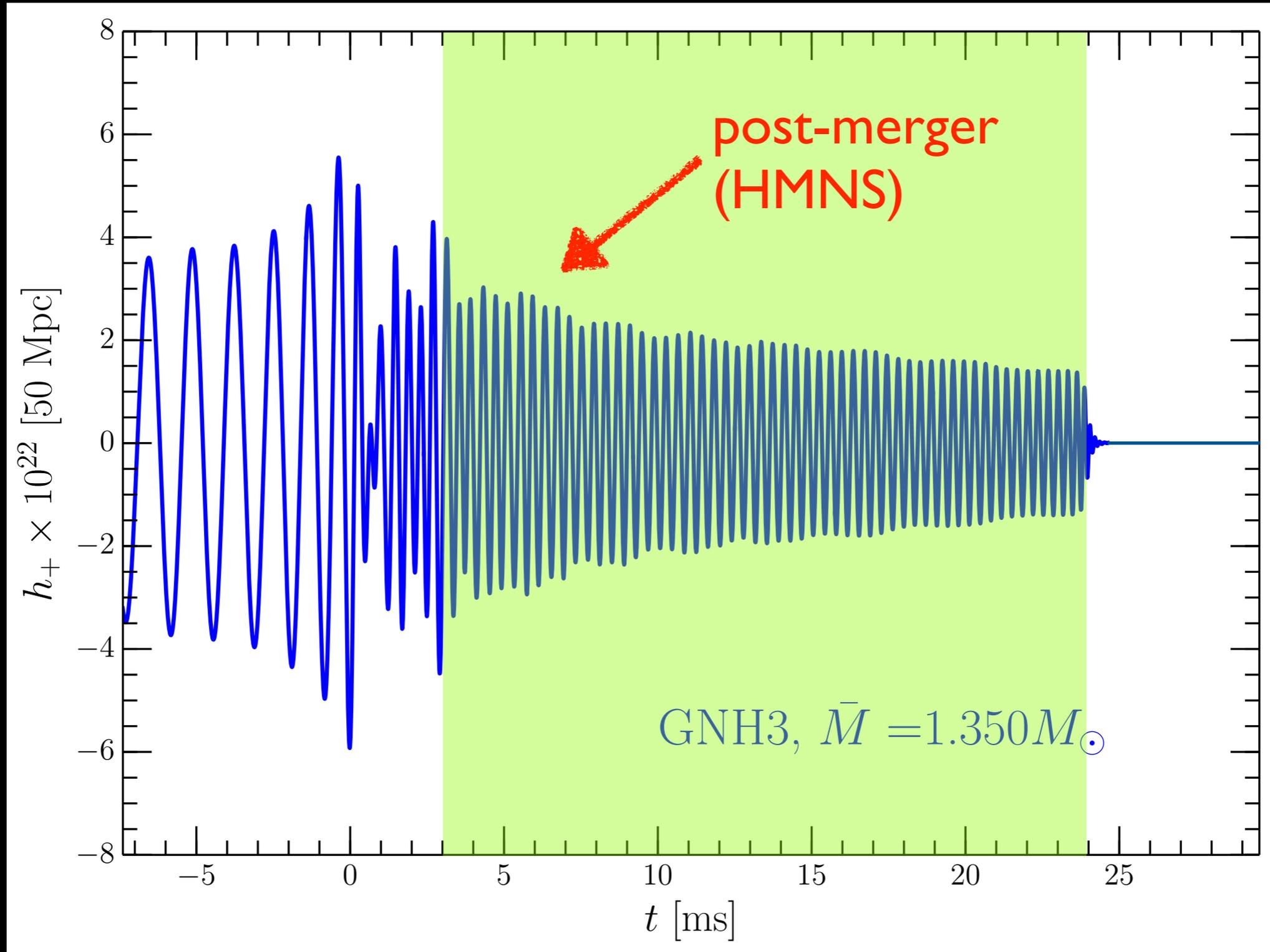
Inspiral: well approximated by PN/EOB; tidal effects important

Anatomy of the GW signal



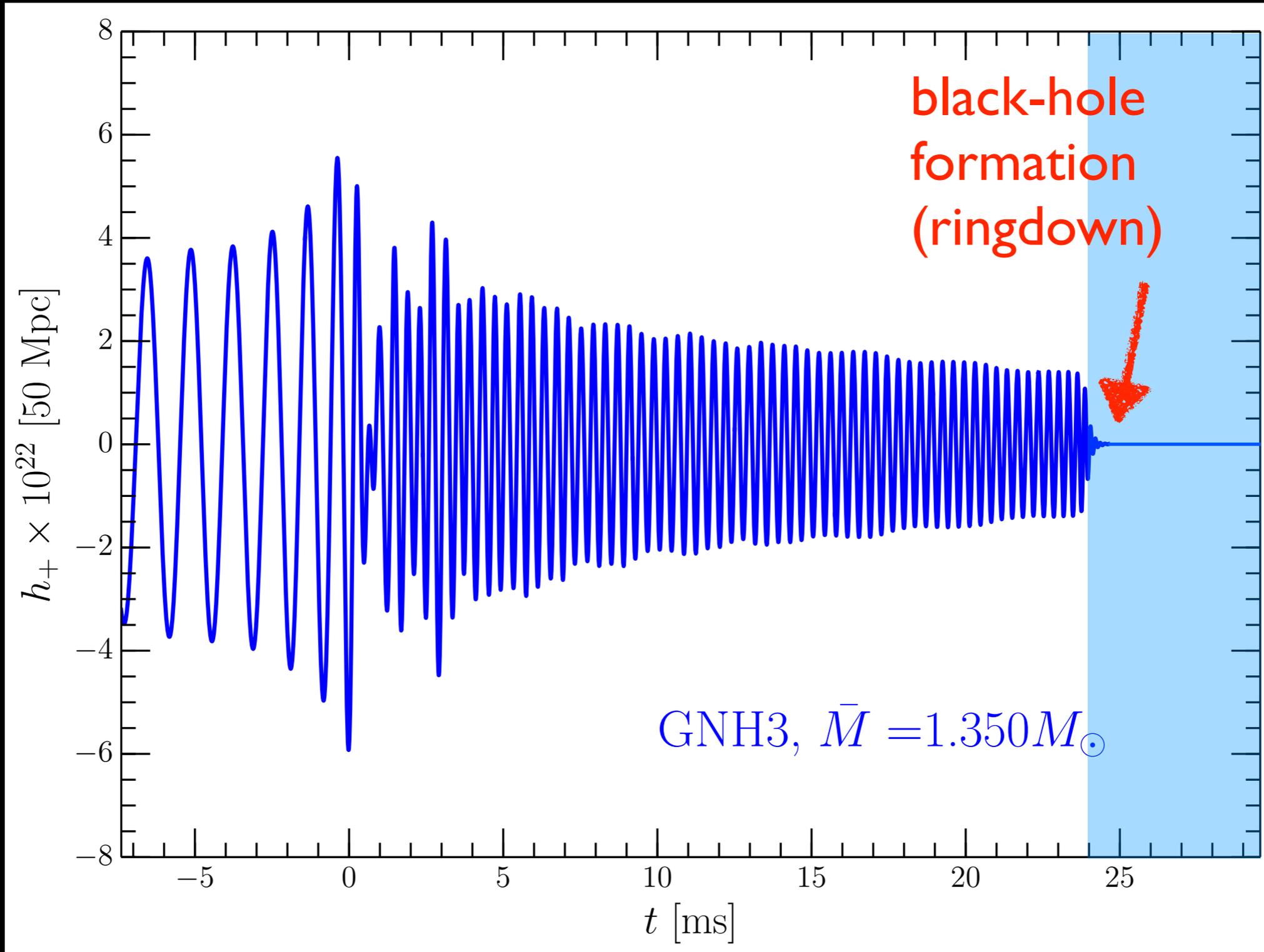
Merger: highly nonlinear but analytic description possible

Anatomy of the GW signal



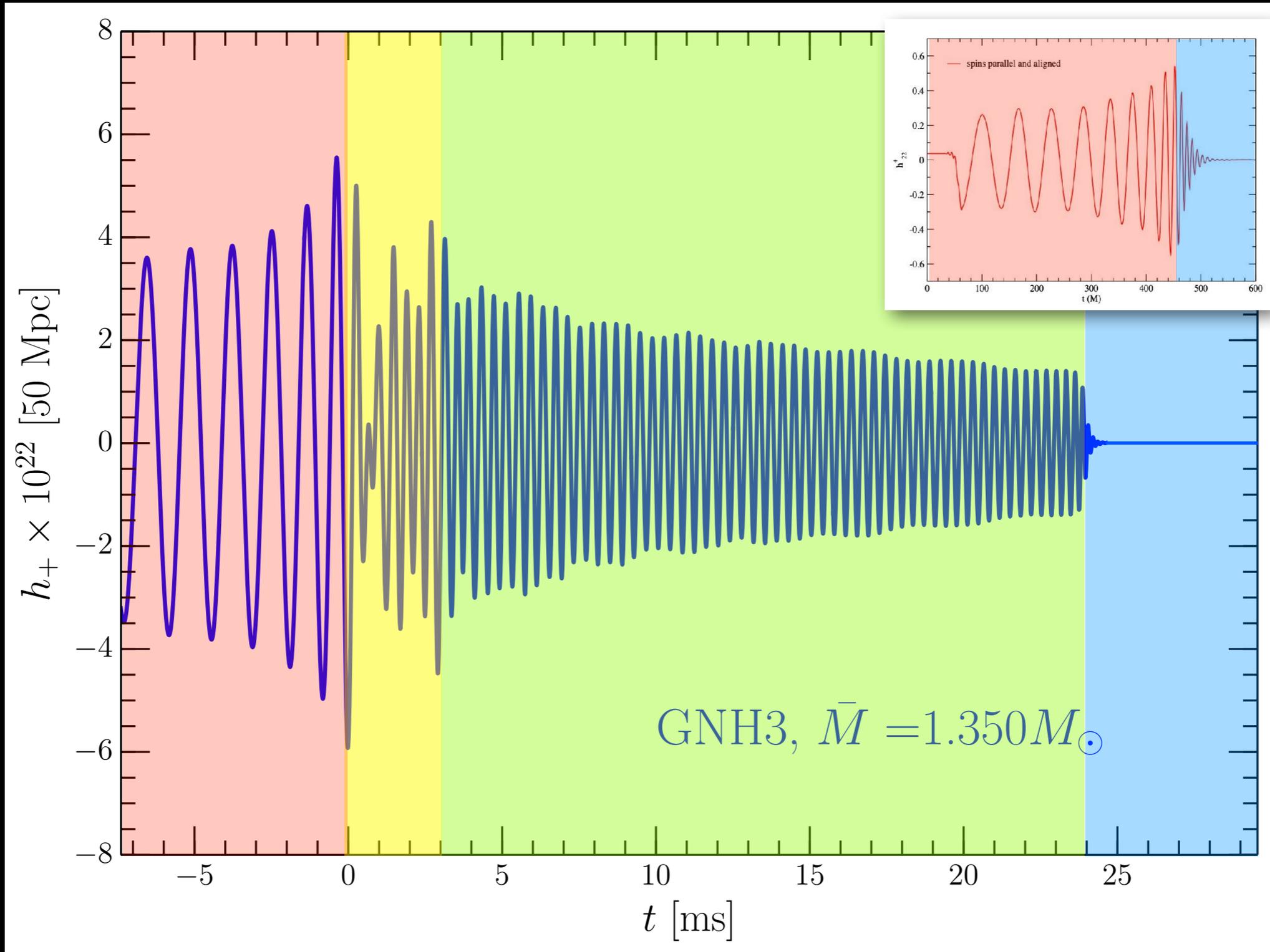
post-merger: quasi-periodic emission of bar-deformed HMNS

Anatomy of the GW signal



Collapse-ringdown: signal essentially shuts off

Anatomy of the GW signal

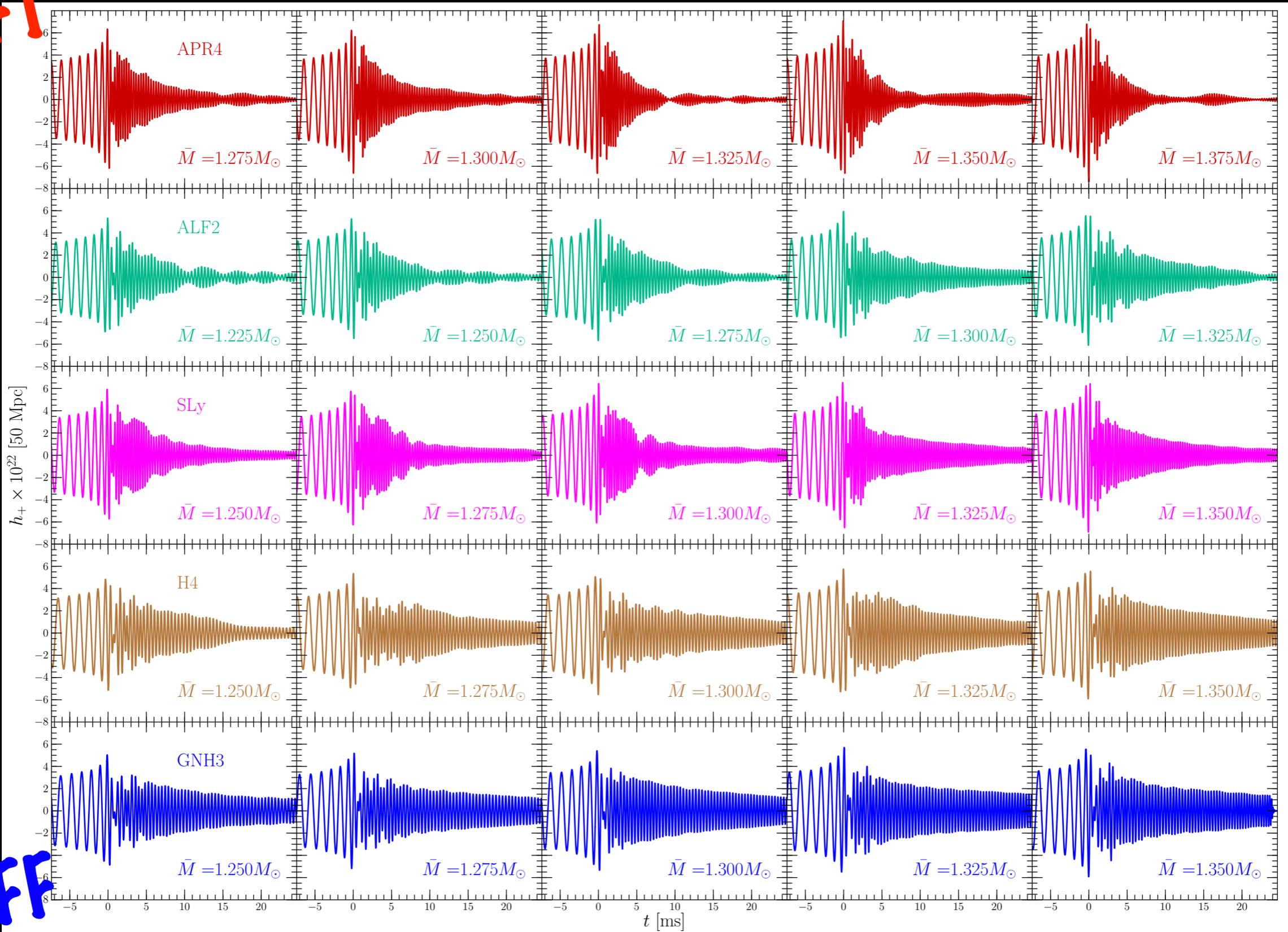


Postmerger signal: peculiar of binary NSs

GW spectroscopy

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

SOFT

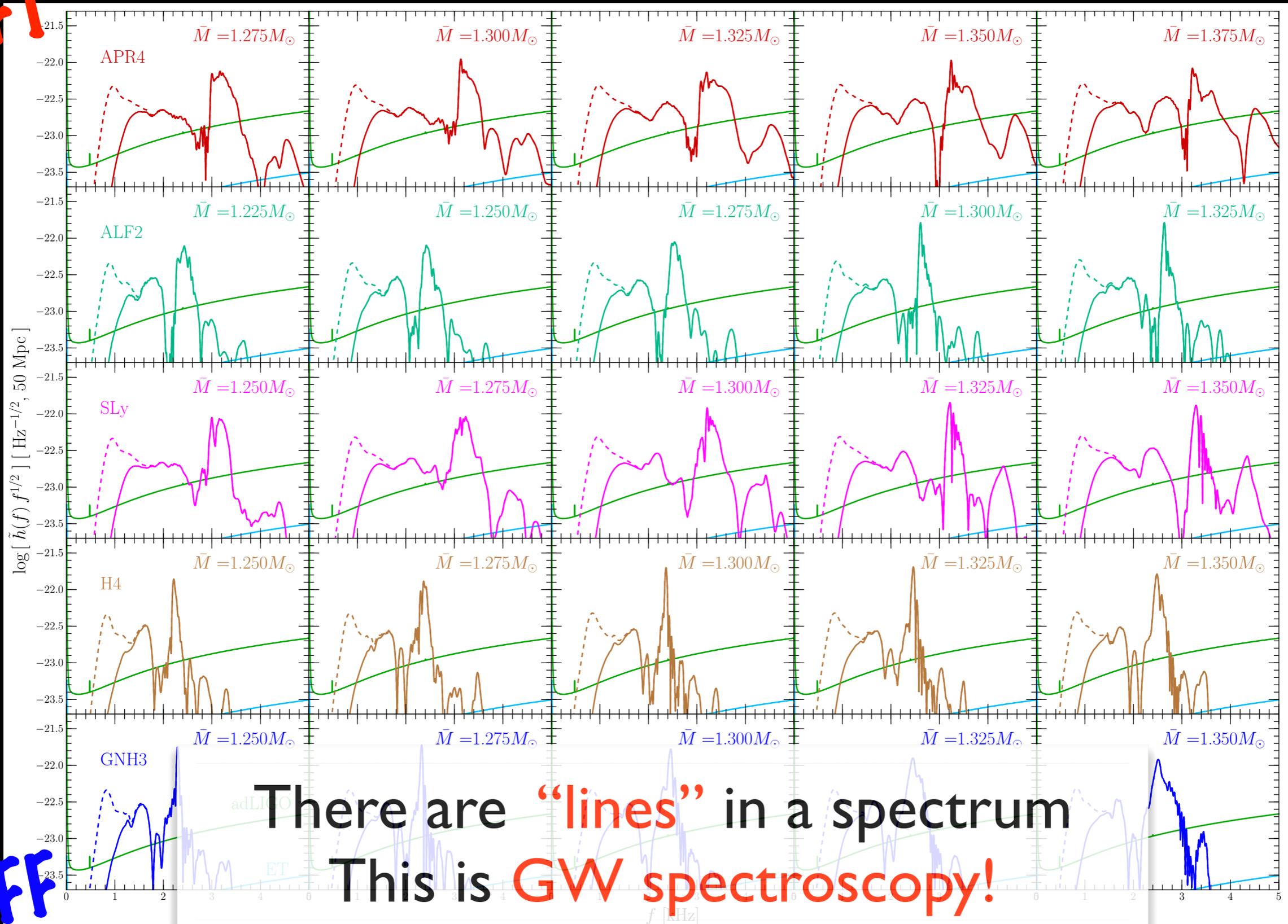


STIFF

Extracting information from the EOS

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

SOFT

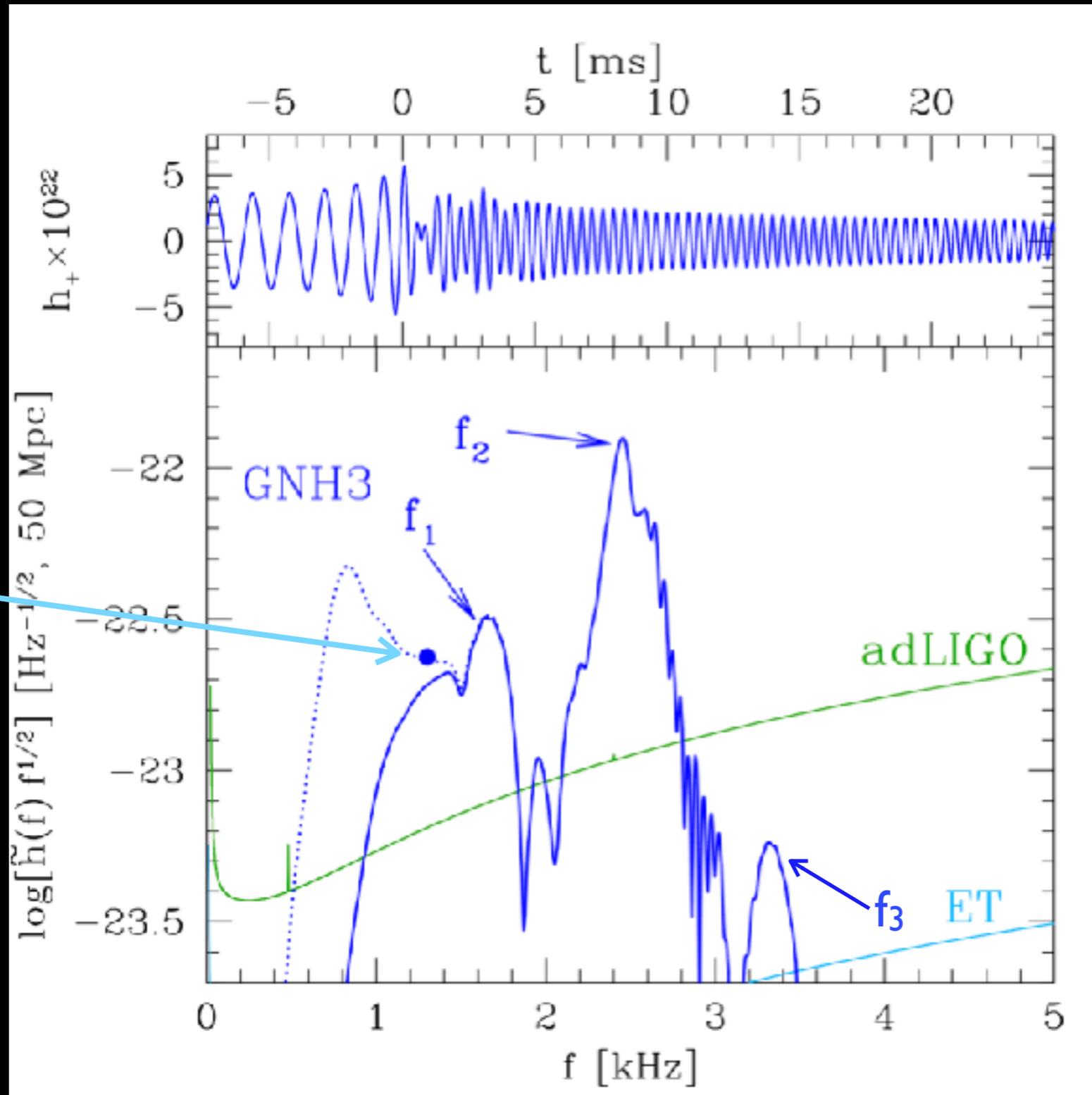


STIFF

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 .

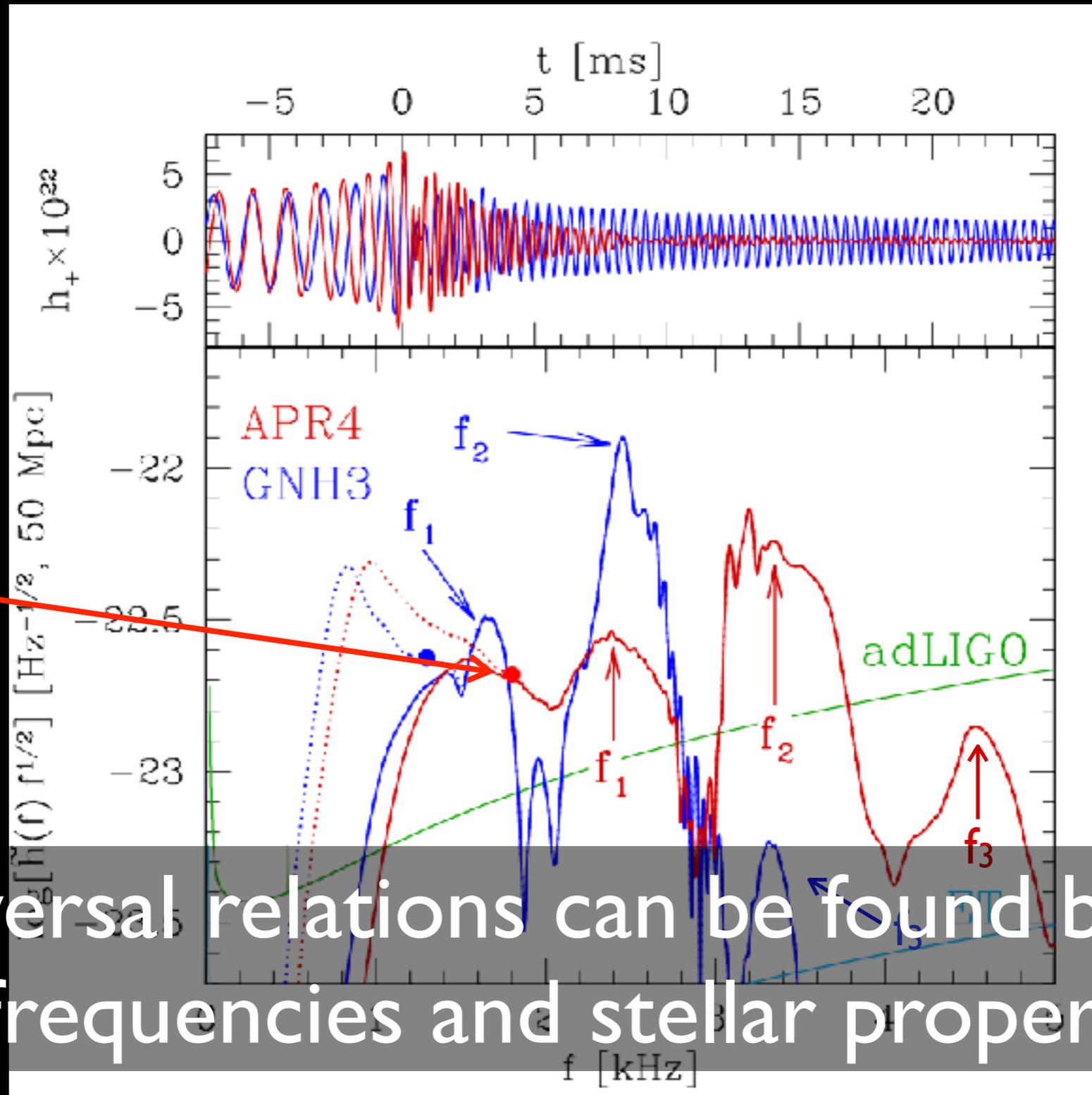
merger
frequency



A spectroscopic approach to the EOS

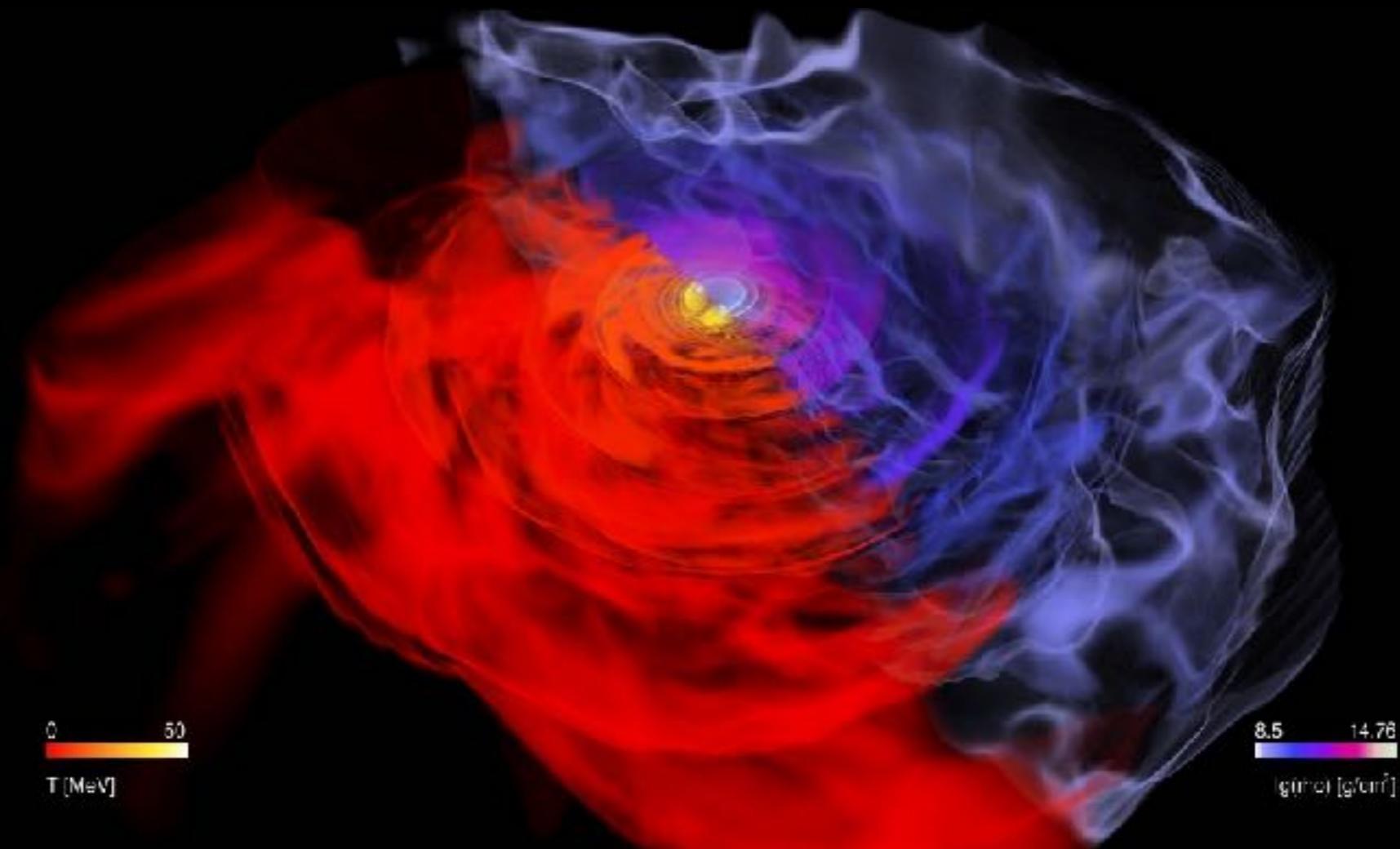
Oechslin+2007, Baiotti+2008, Bauswein+ 2011, 2012, Stergioulas+ 2011, Hotokezaka+ 2013, Takami 2014, 2015, Bernuzzi 2014, 2015, Bauswein+ 2015, Clark+ 2016, LR+2016, de Pietri+ 2016, Feo+ 2017, Bose+ 2017 .

merger
frequency



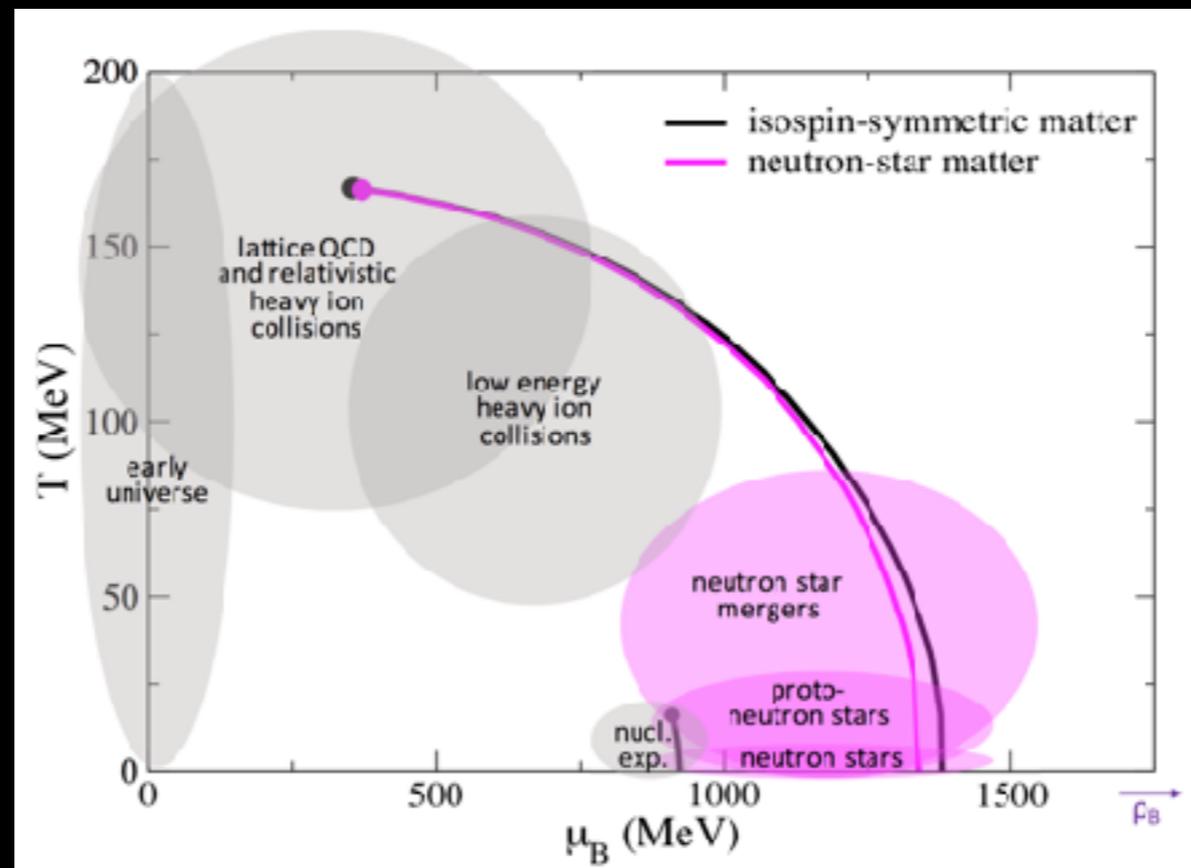
Universal relations can be found between frequencies and stellar properties

Phase transitions and their signatures

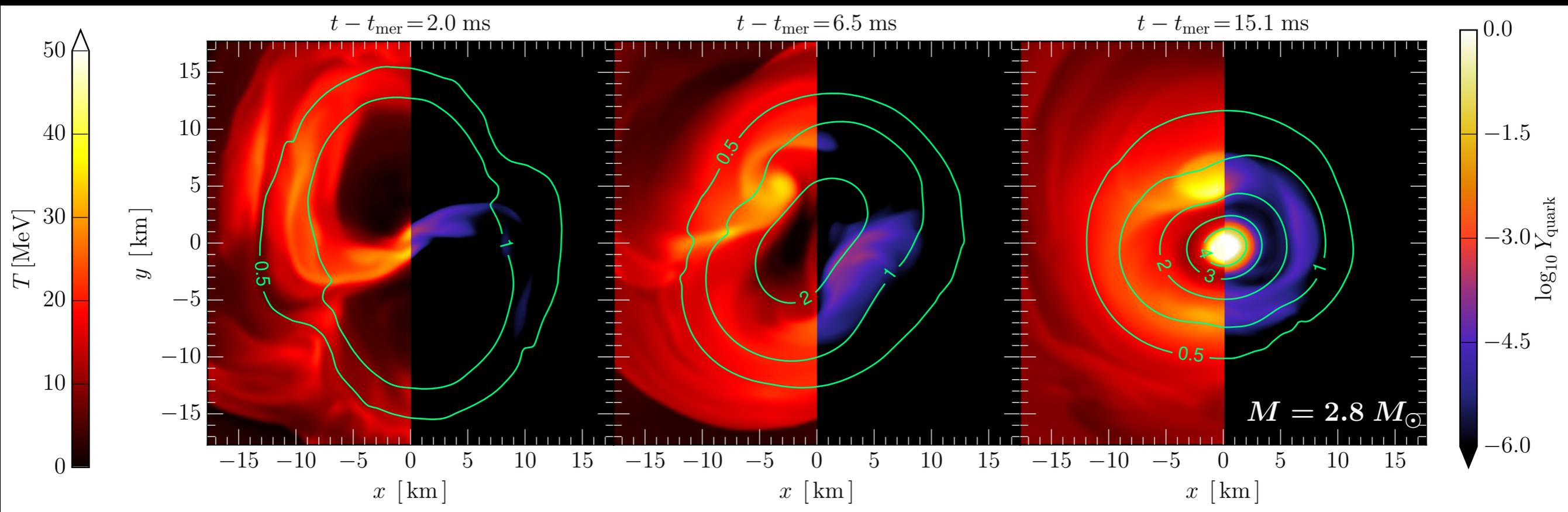


Most, Papenfort, Dexheimer, Hanauske, Schramm, Stoecker, LR (2019)
Weih, Hanauske, LR (2020)
Tootle, Ecker, Topolski, Demircik, Järvinen, LR (2022)

- **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.



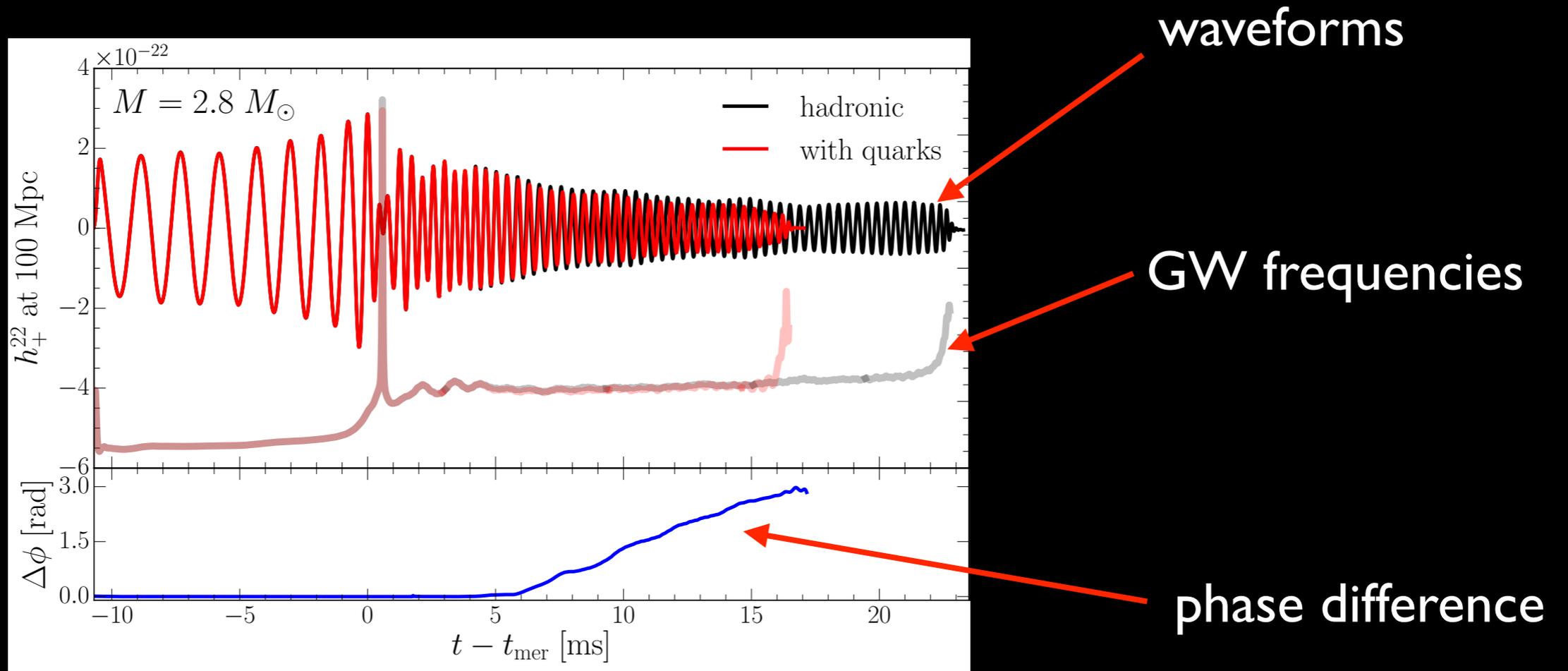
- Considered EOS based on Chiral Mean Field (CMF) model, based on a nonlinear SU(3) sigma model.
- Appearance of quarks can be introduced naturally.



Quarks appear at sufficiently large
temperatures and **densities**.

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

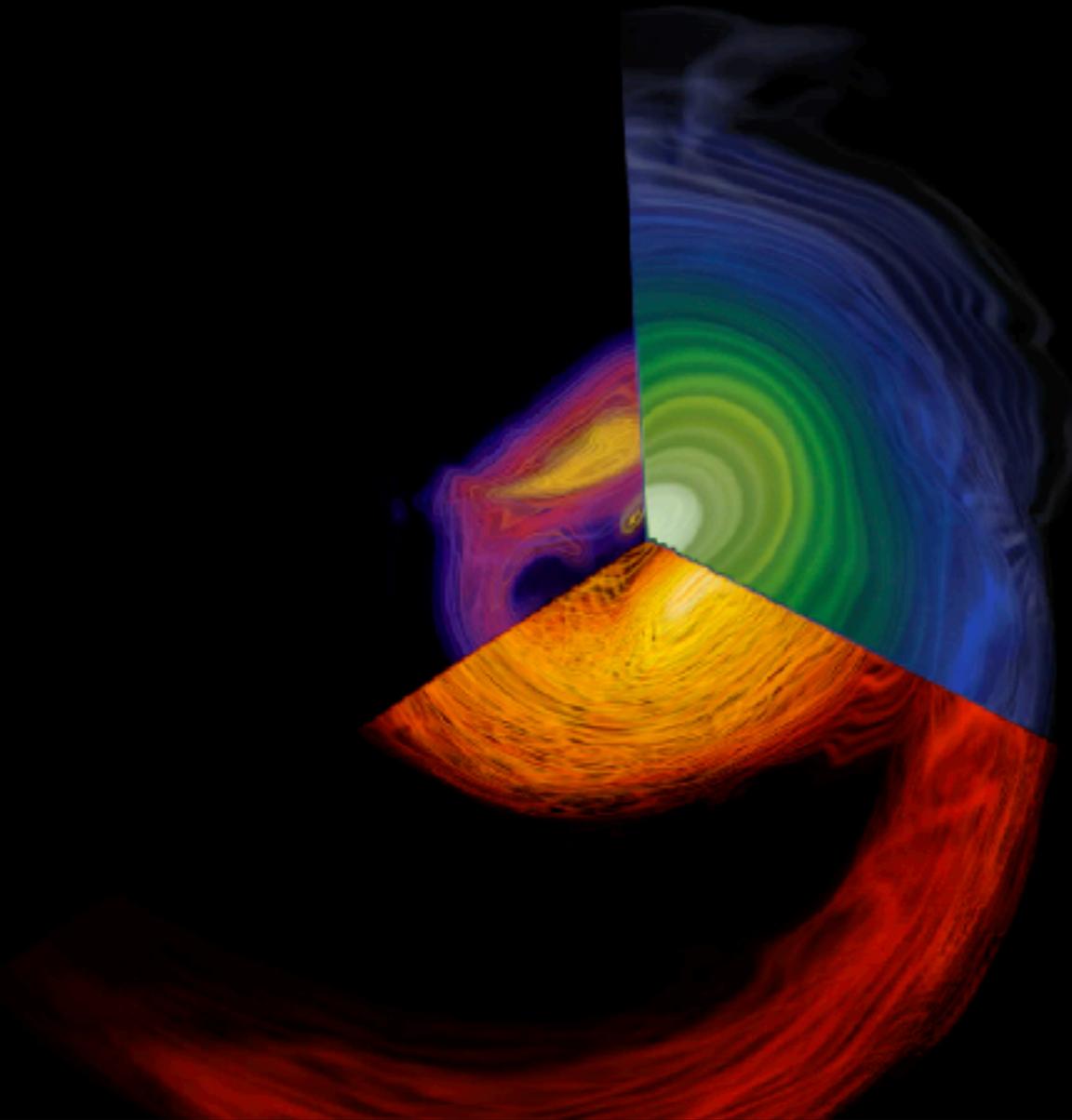
Gravitational-wave emission



- 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**

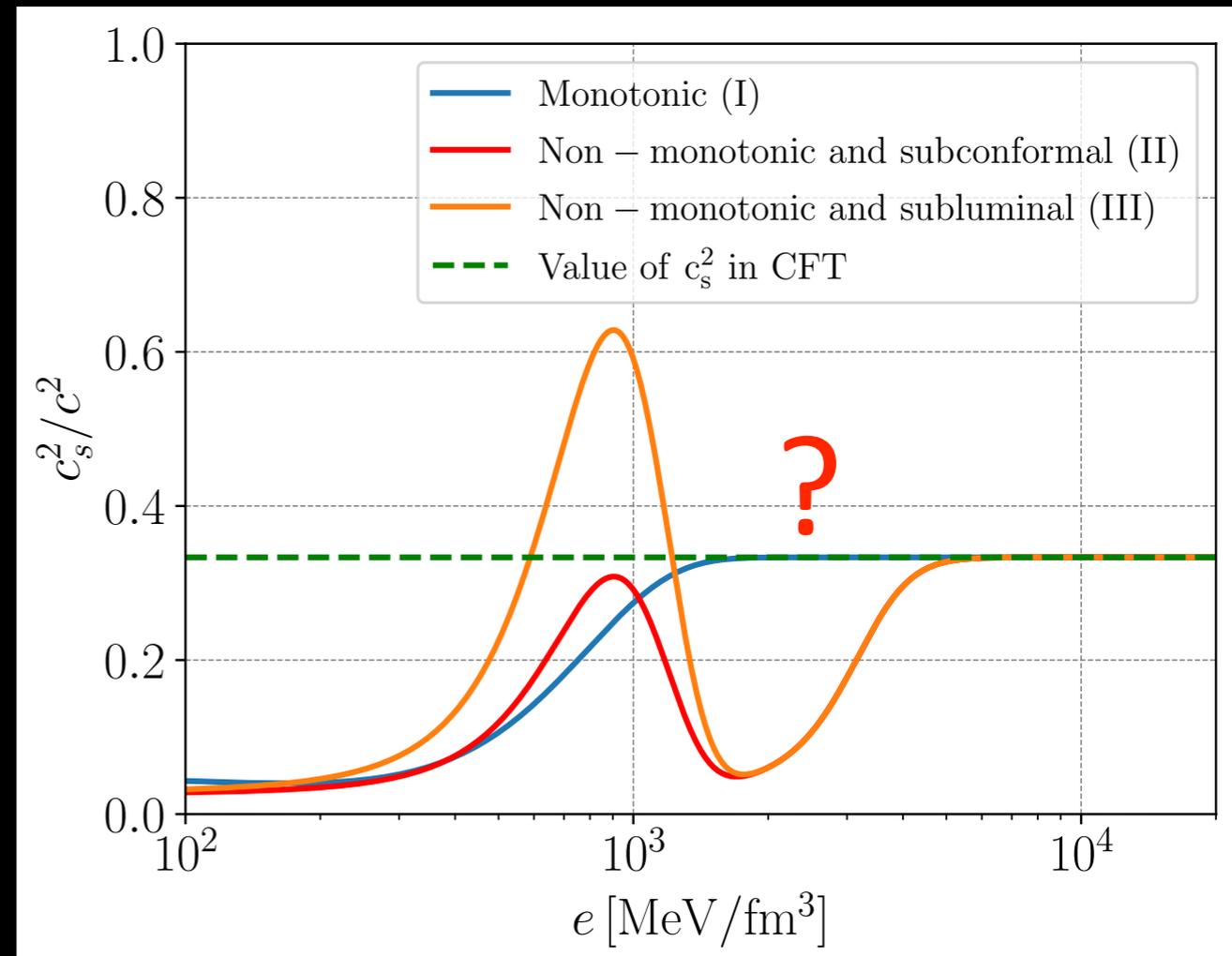
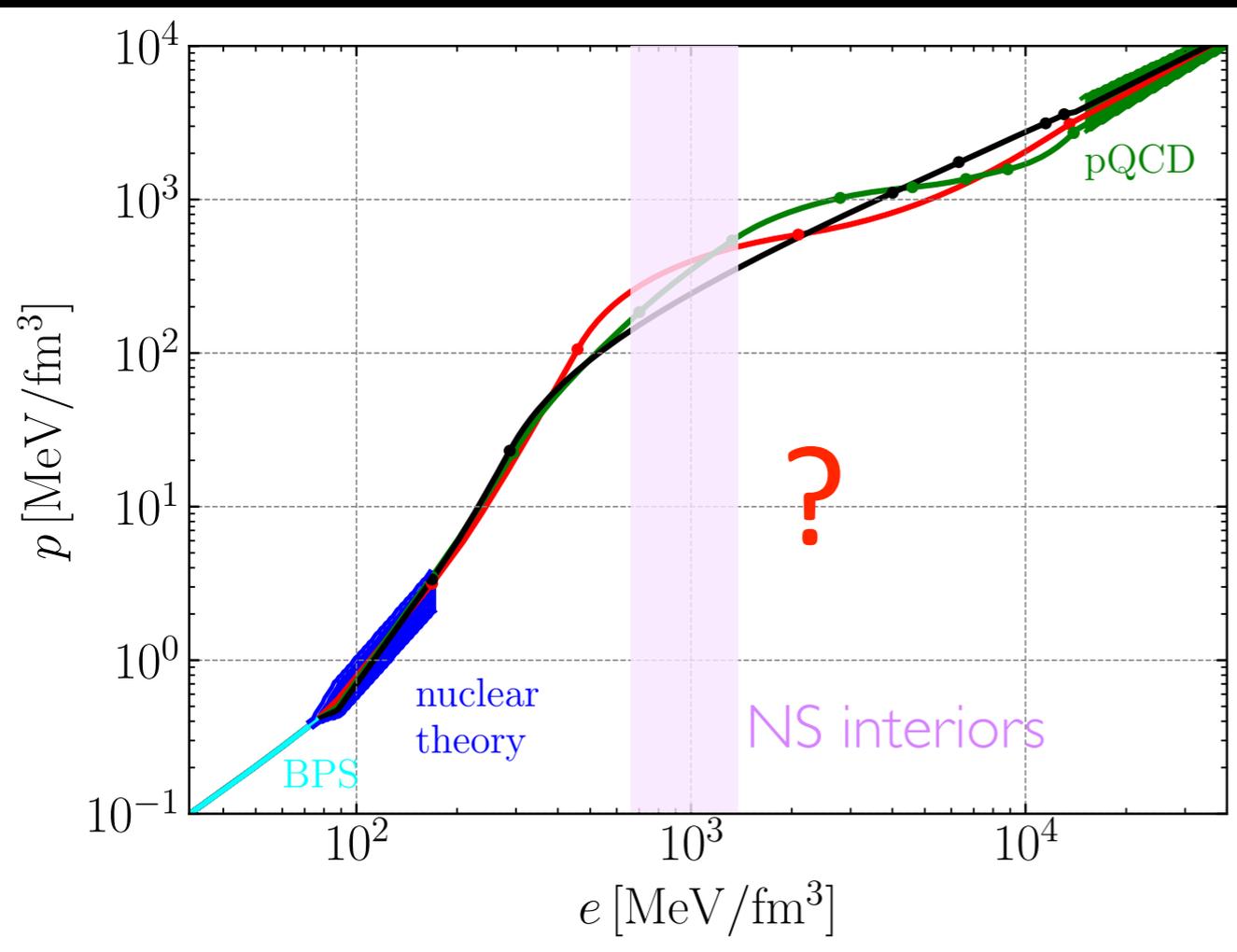
On the sound speed in neutron stars



Altiparmak, Ecker, LR (2022a)
Ecker, LR (2022b)
Ecker, LR (2022c)

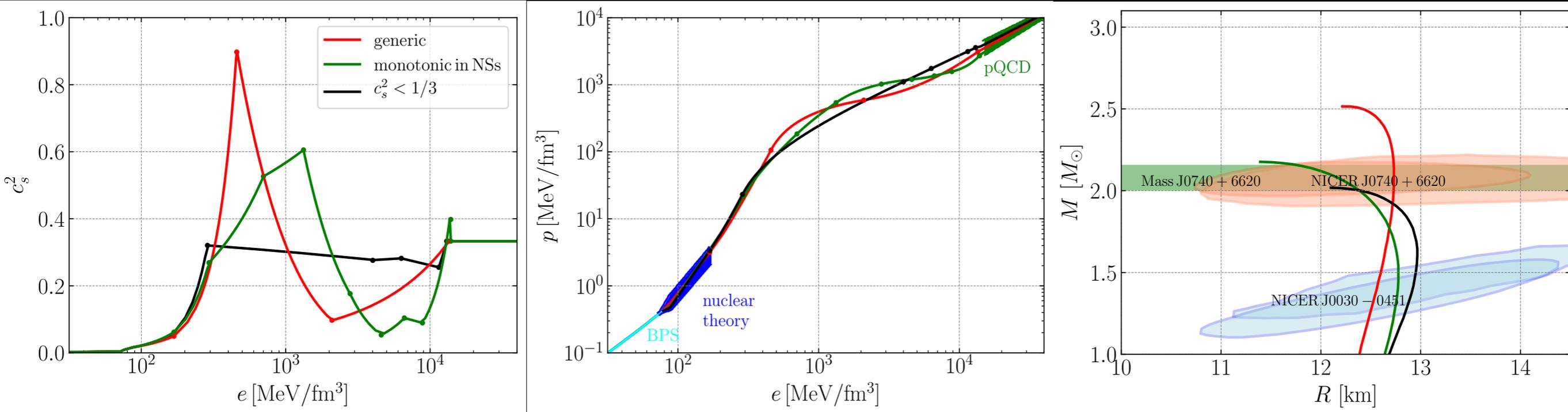
A very basic question

The EOS of nuclear matter still remains an open question. Some information is available but freedom is still large



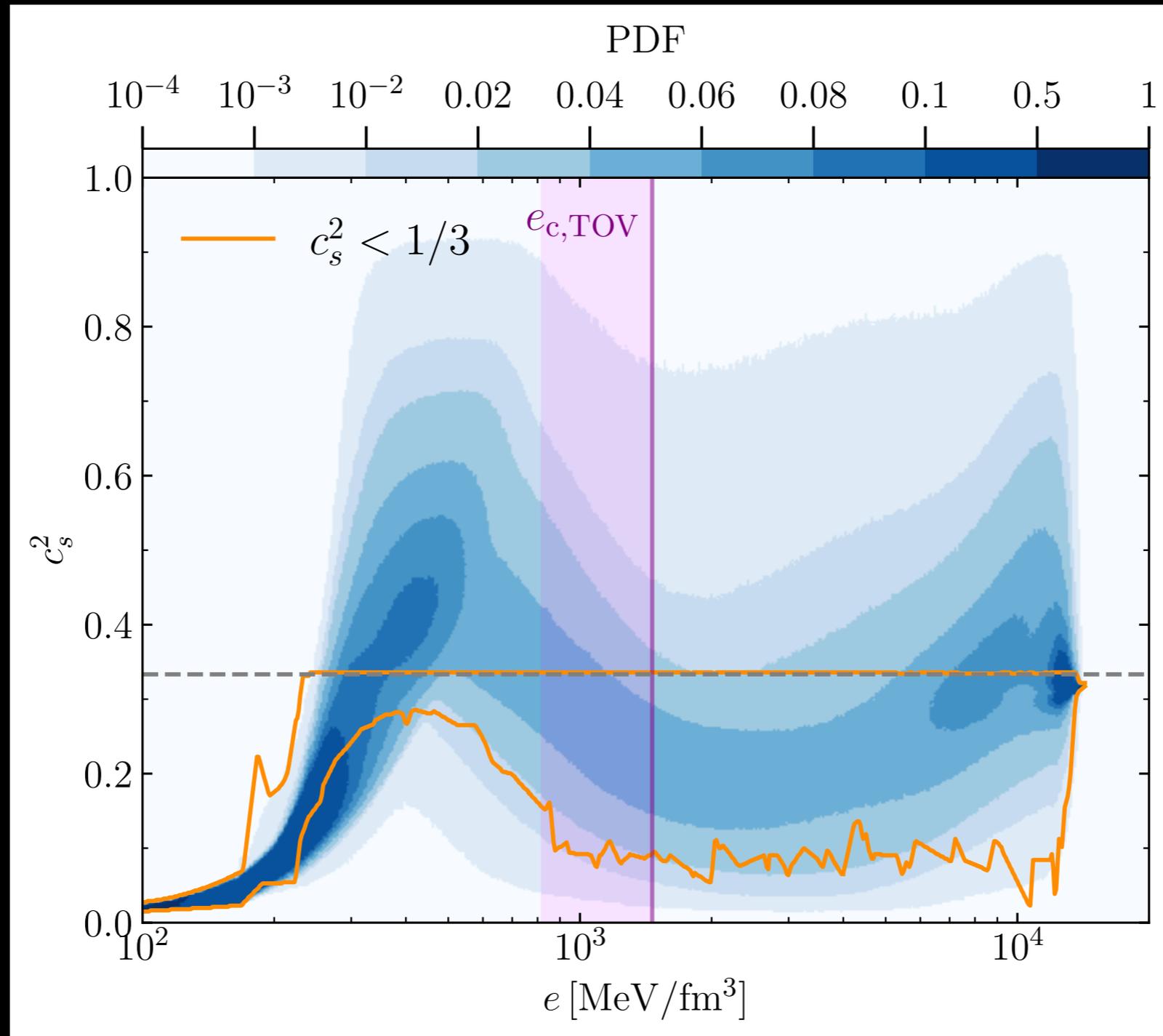
- i) monotonic and sub-conformal: $c_s^2 < 1/3$;
- ii) non-monotonic and sub-conformal: $c_s^2 < 1/3$;
- iii) non-monotonic and sub-luminal: $c_s^2 < 1$

- Lacking stronger constraints, an **agnostic approach** is reasonable and followed by many (eg piecewise polytropes, Most+ 2018)
- Here, instead, we build an EOS starting from a piecewise prescription of the sound speed (7 segments are sufficient)



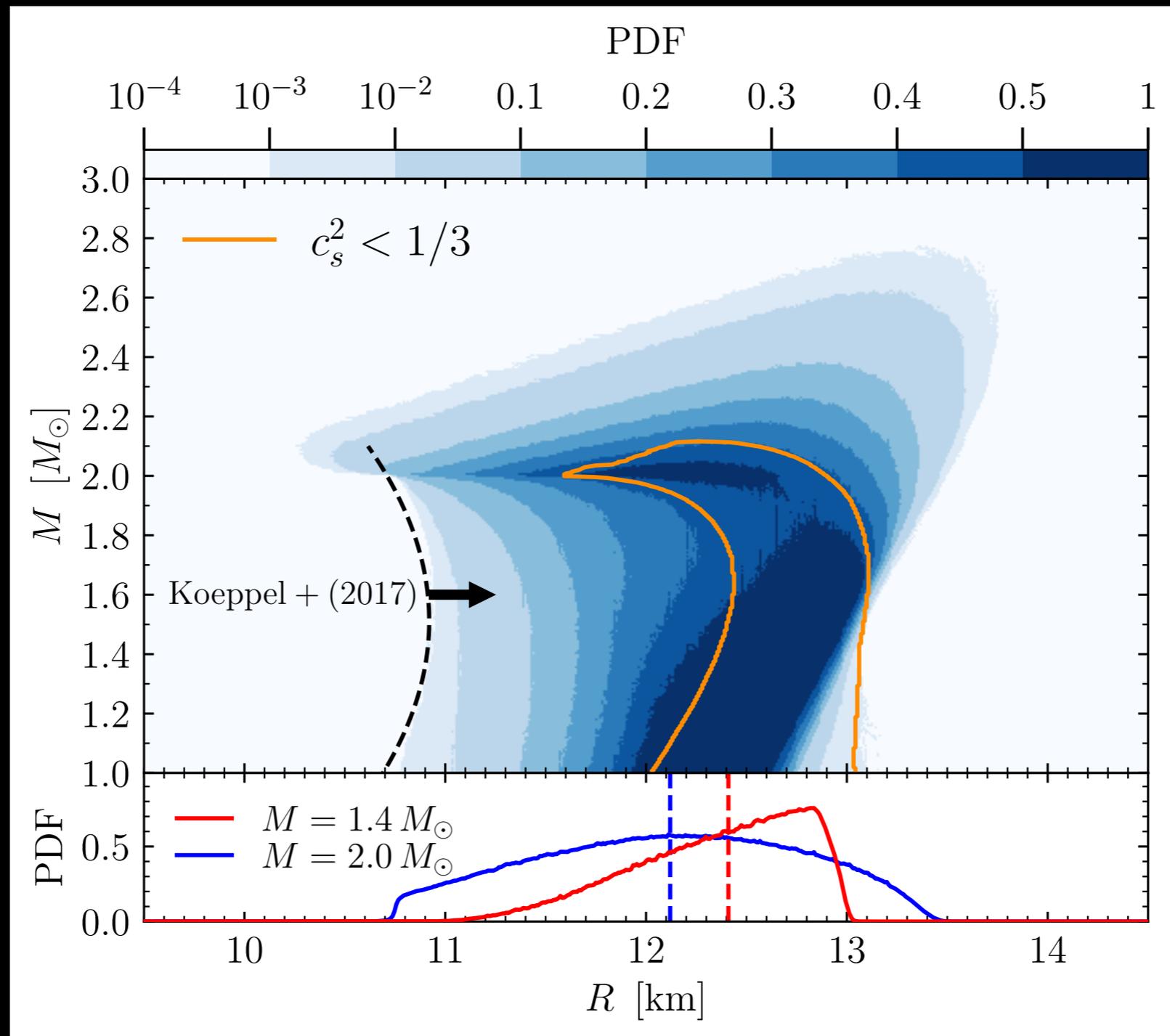
- Once an EOS is produced, we check it satisfies astrophysical constraints (max. mass, NICER limits). We repeat 1.5×10^7 times...
- In this way, $\sim 10\%$ of our EOSs survives and provides robust statistics from which we compute PDFs.

Sound speed PDF



Orange line marks region of sub-conformal EOSs (0.03%).
No monotonic sub-conformal EOS found.

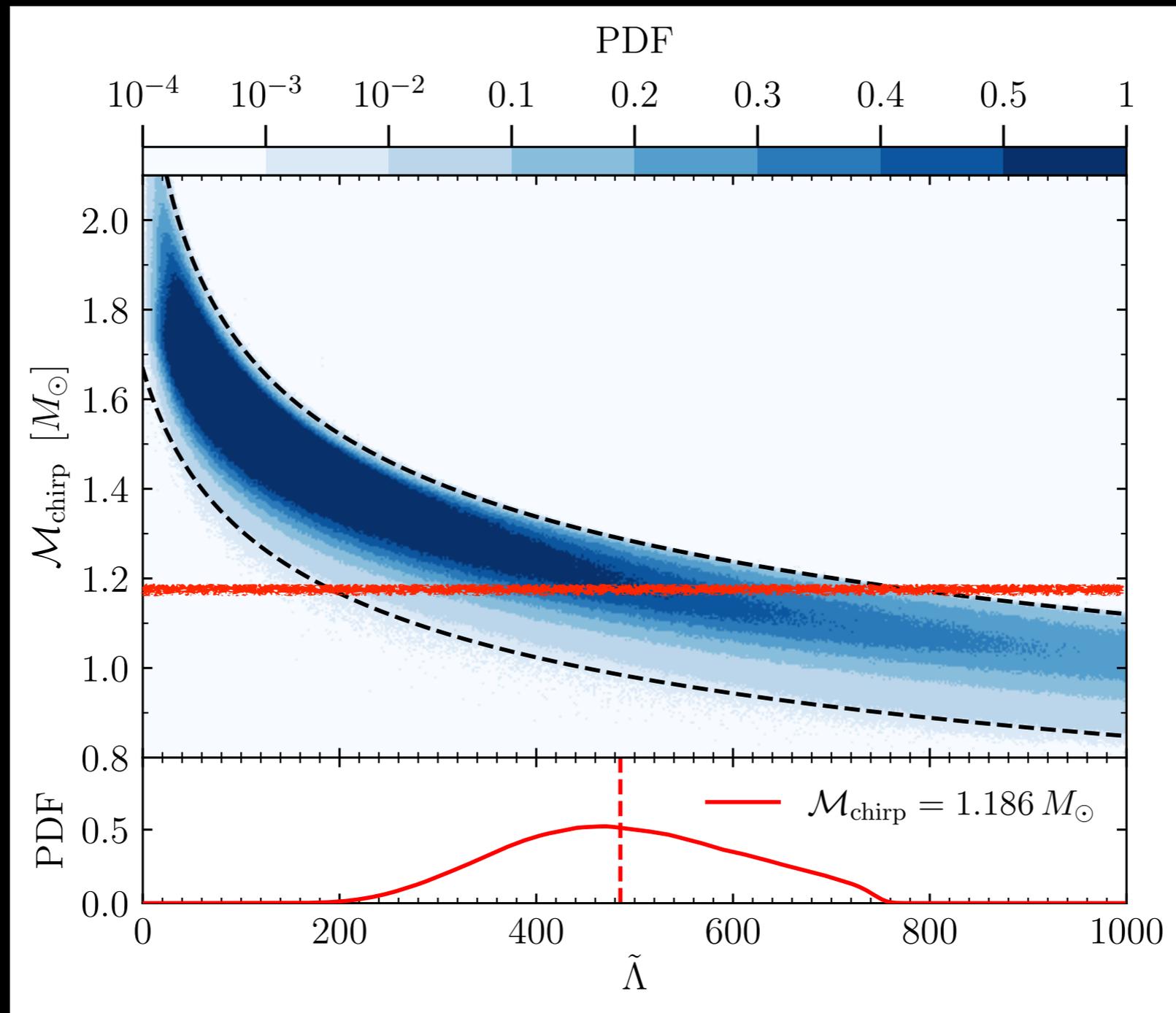
A more comprehensive picture



M -const. sections: $R_{1.4} = 12.42^{+0.52}_{-0.99}$ km; $R_{2.0} = 12.12^{+1.11}_{-1.23}$ km

Lower bound on radii matches Köppel+ prediction from threshold mass.

A more comprehensive picture



Simple behaviour of binary tidal deformability: $\tilde{\Lambda}_{\text{min (max)}} = a + b \mathcal{M}_{\text{chirp}}^c$
Straightforward bounds once a detection is made.

A scale-independent representation

With this large sample one may ask simple but basic questions:

- How does the sound speed vary in a star?
- Is the maximum sound speed at the center of the star?
- Does the maximum value attain a constant value?
- How does all this change with the assumptions made?

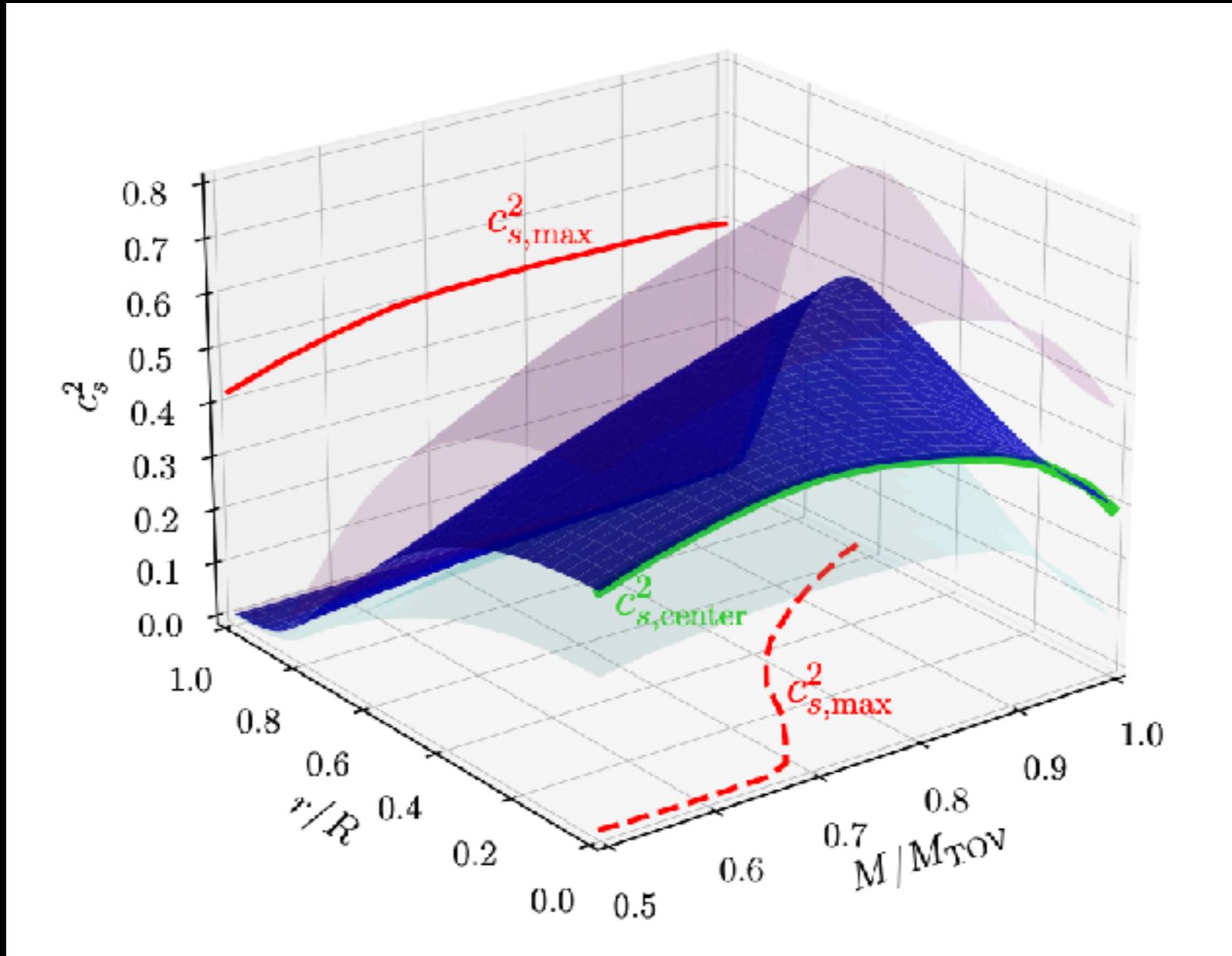
Hard to answer: every EOS will have its own (M, R) relation

$$c_s \in [0, c], \quad r \in [0, R], \quad M \in [0, M_{\text{TOV}}] : \text{EOS dependent}$$

$$c_s/c \in [0, 1], \quad r/R \in [0, 1], \quad M/M_{\text{TOV}} \in [0, 1] : \text{EOS independent}$$

A scale-independent representation

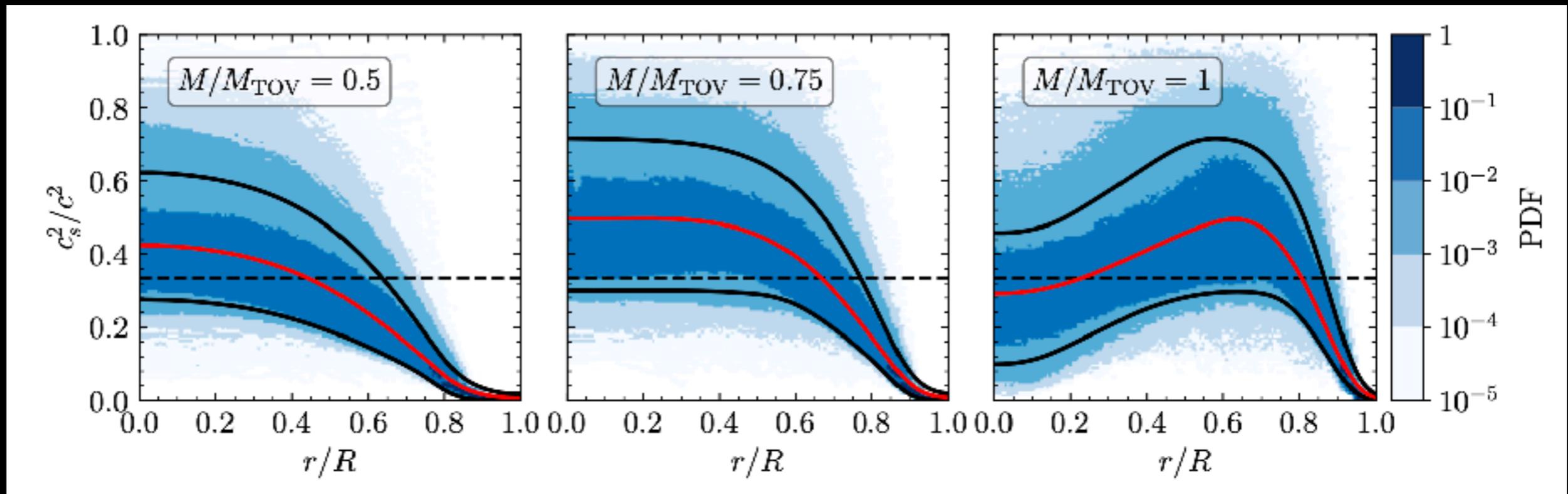
All information contained in a unit cube: $(c_s/c, r/R, M/M_{\text{TOV}})$



A scale-independent representation

“Light” stars: c_s^2 monotonic with maximum at stellar center

“Heavy” stars: c_s^2 non-monotonic with maximum far from center



“Light” stars: stiff core, soft mantle

“Heavy” stars: soft core, stiff mantle

Press release: “...neutron stars behave like chocolate pralines. Light stars have stiff core and soft exterior; heavy stars have soft core and hard exterior.

The “sweetest” discovery of the year



Conclusions

- Spectra of post-merger shows peaks, some **"quasi-universal"**.
- A **phase transition** after a BNS merger leaves GW **signatures** and opens a gate to access quark matter beyond accelerators.
- **Sound speed** in neutron stars cannot be sub-conformal and monotonic; likely to be super-conformal somewhere in the interior.
- **Sound speed** monotonic in light stars (max at centre), non-monotonic in heavy stars (max in mantle).