Binary neutron stars: from macroscopic collisions to microphysics

Luciano Rezzolla

Institute for Theoretical Physics, Frankfurt

Opava, 10-14 October 2022

RAGTIME

24th Relativistic Astrophysics Group Meeting

Plan of the talk

- The richness of merging binary neutron stars
- GW spectroscopy: EOS from frequencies
- GW170817, GW190814 and maximum mass
- Signatures of quark-hadron phase transitions
- On the sound speed in neutron stars
- Threshold mass to prompt collapse
- EM counterparts, ejecta, and jets

The two-body problem in GR

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

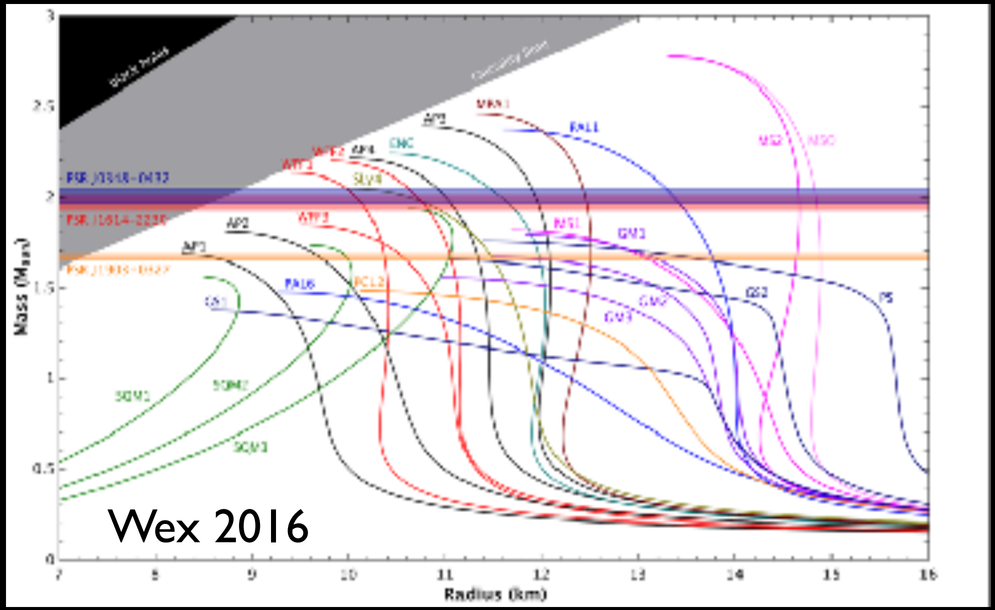
BH + BH ⟶ BH + GWs

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

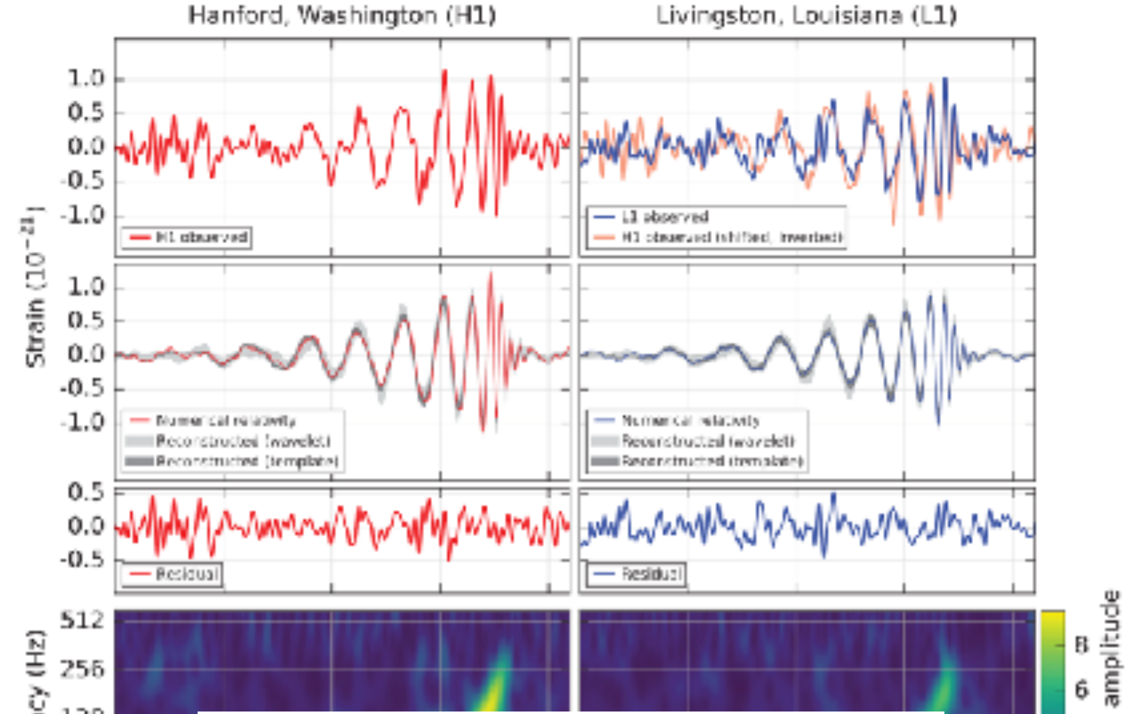
hyper-massive neutron star (HMNS), ie

NS + NS ⟶ HMNS+... ? ⟶ BH+to

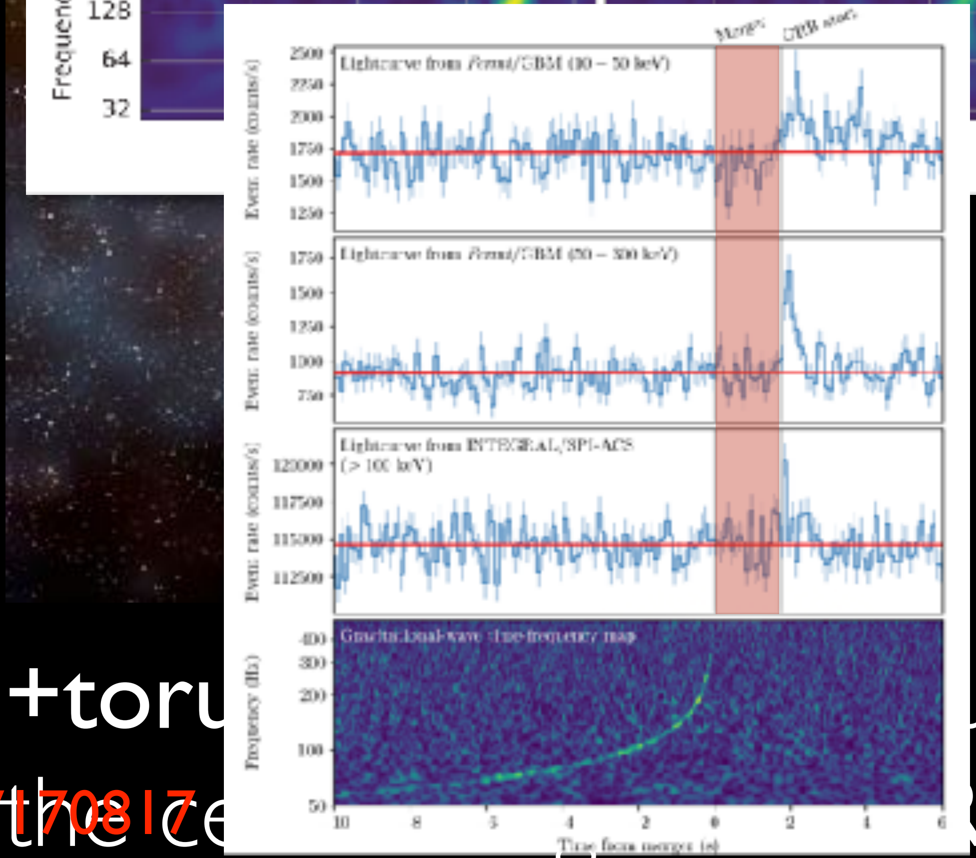
- **HMNS** phase can provide clear information on **EOS**



Wex 2016



GW150914



GW170817

- BH+toru us

on the ce RBs

The two-body problem in GR

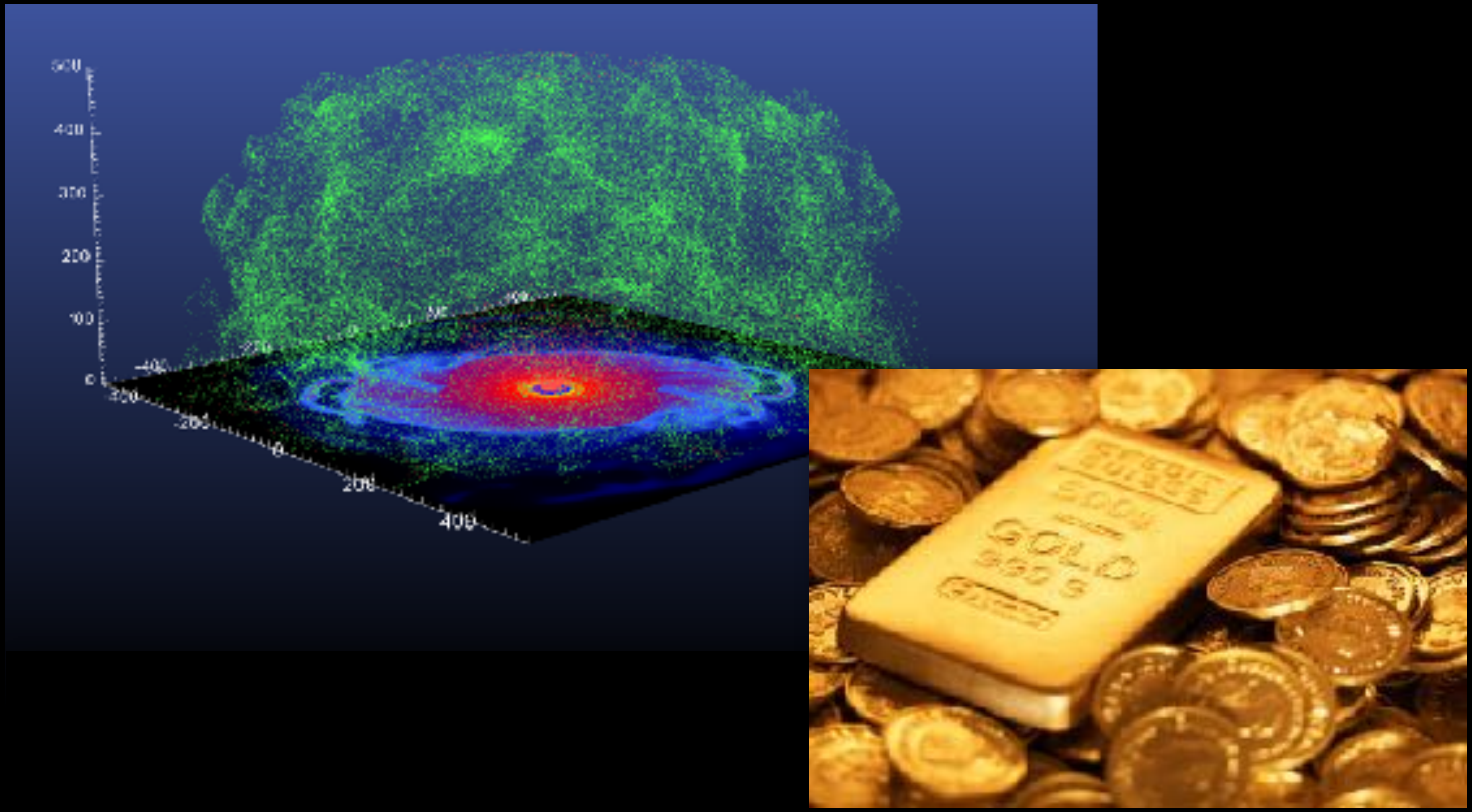
- For black holes the process is very **simple**:

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



The equations of numerical relativity

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

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

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

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

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

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

Animations: Breu, Radice, LR

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

merger → HMNS → BH + torus

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

$\mathrm{LS220\ EOS}$

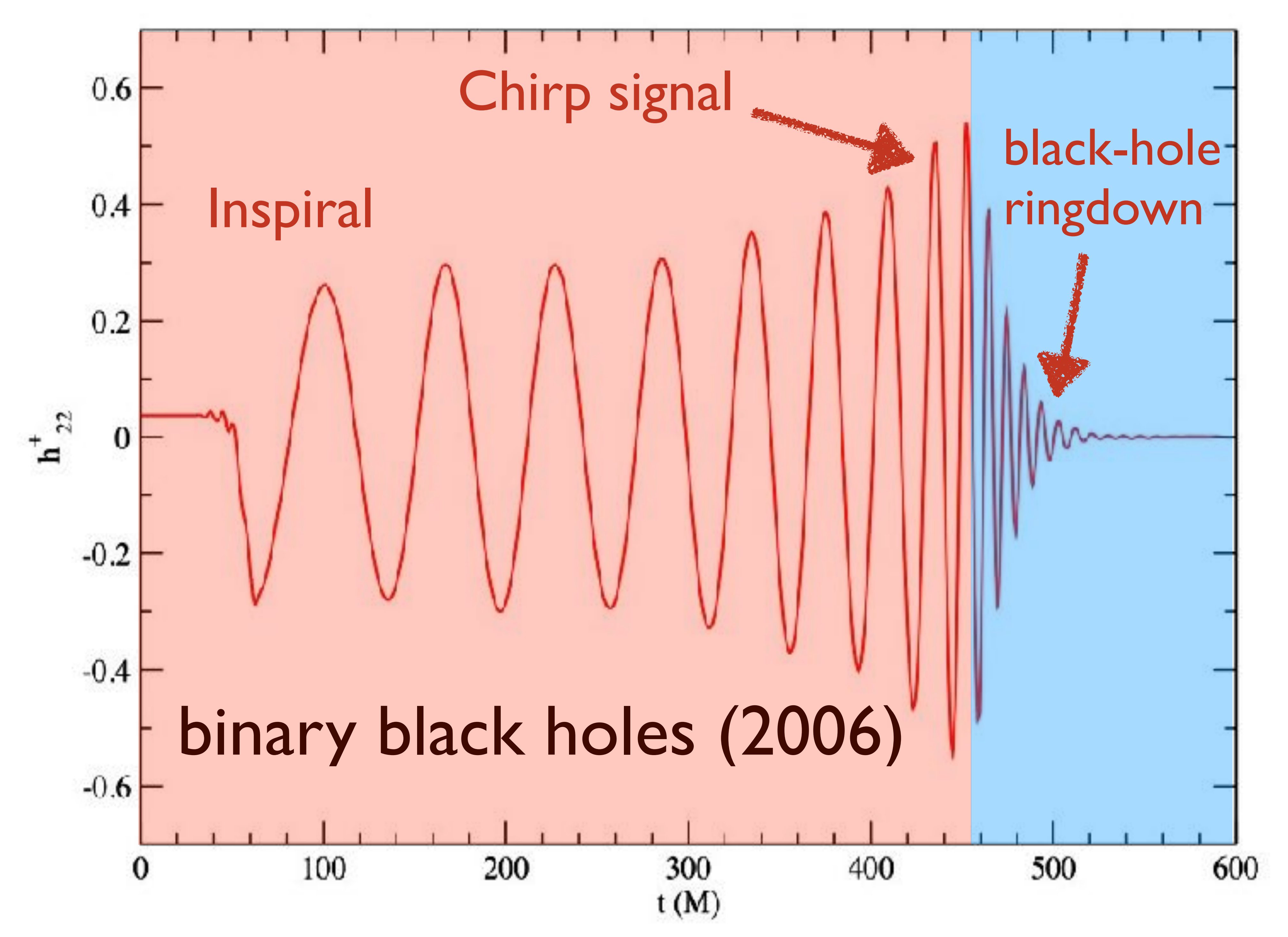
Qualitatively, this is what normally happens:

merger → HMNS → BH + torus

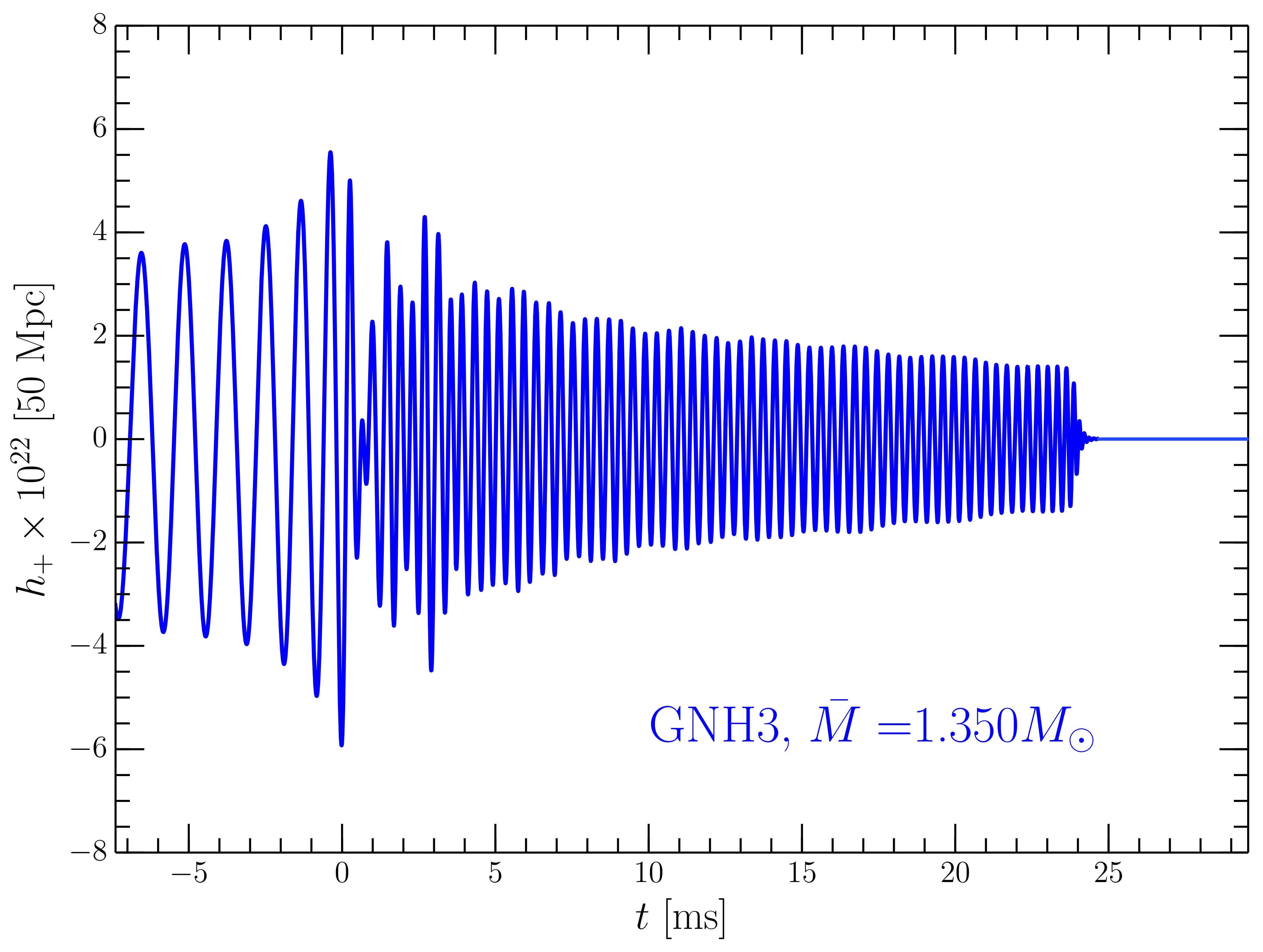
Quantitatively, differences are produced by:

- 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)

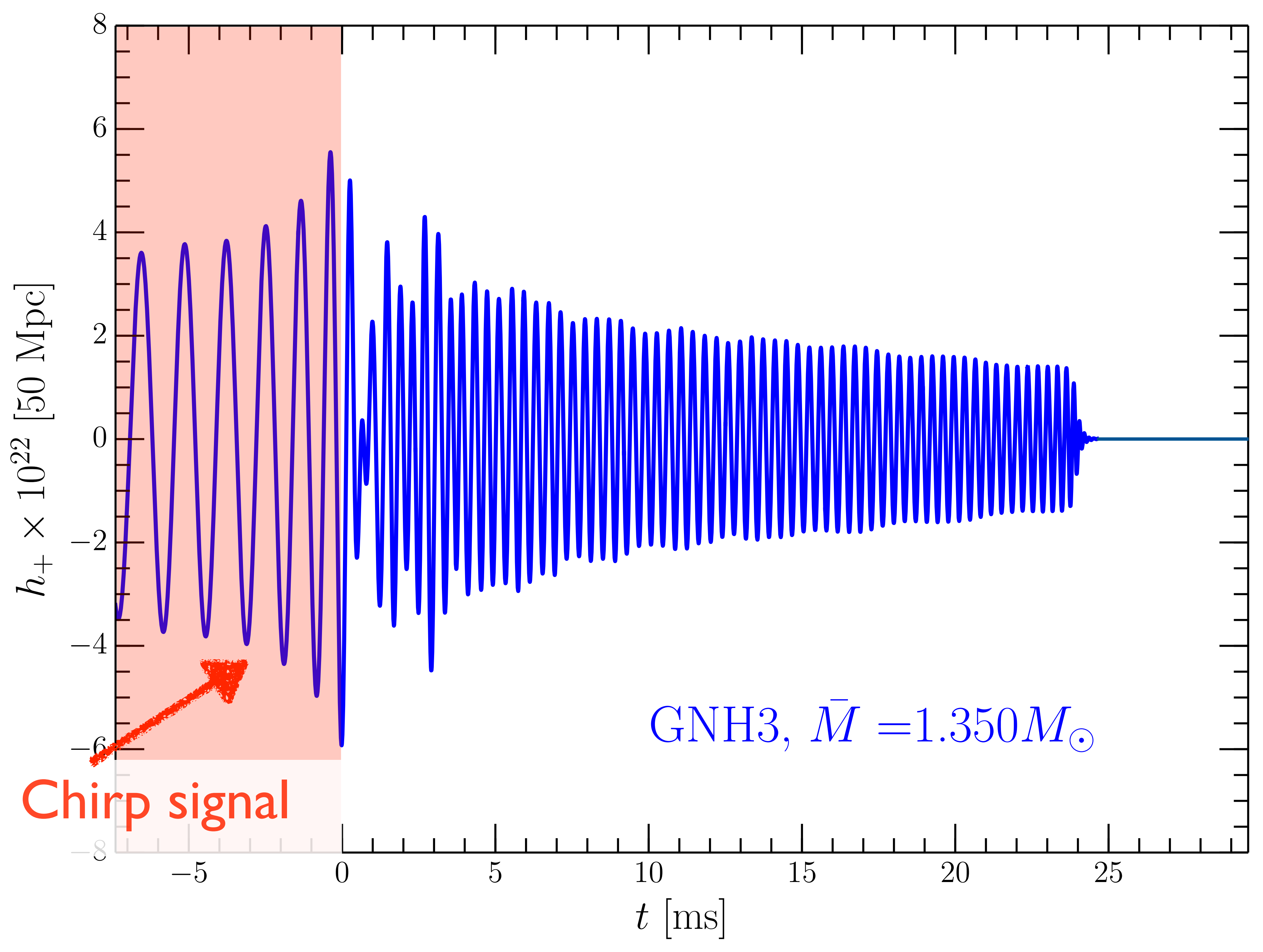
Anatomy of the GW signal



Anatomy of the GW signal

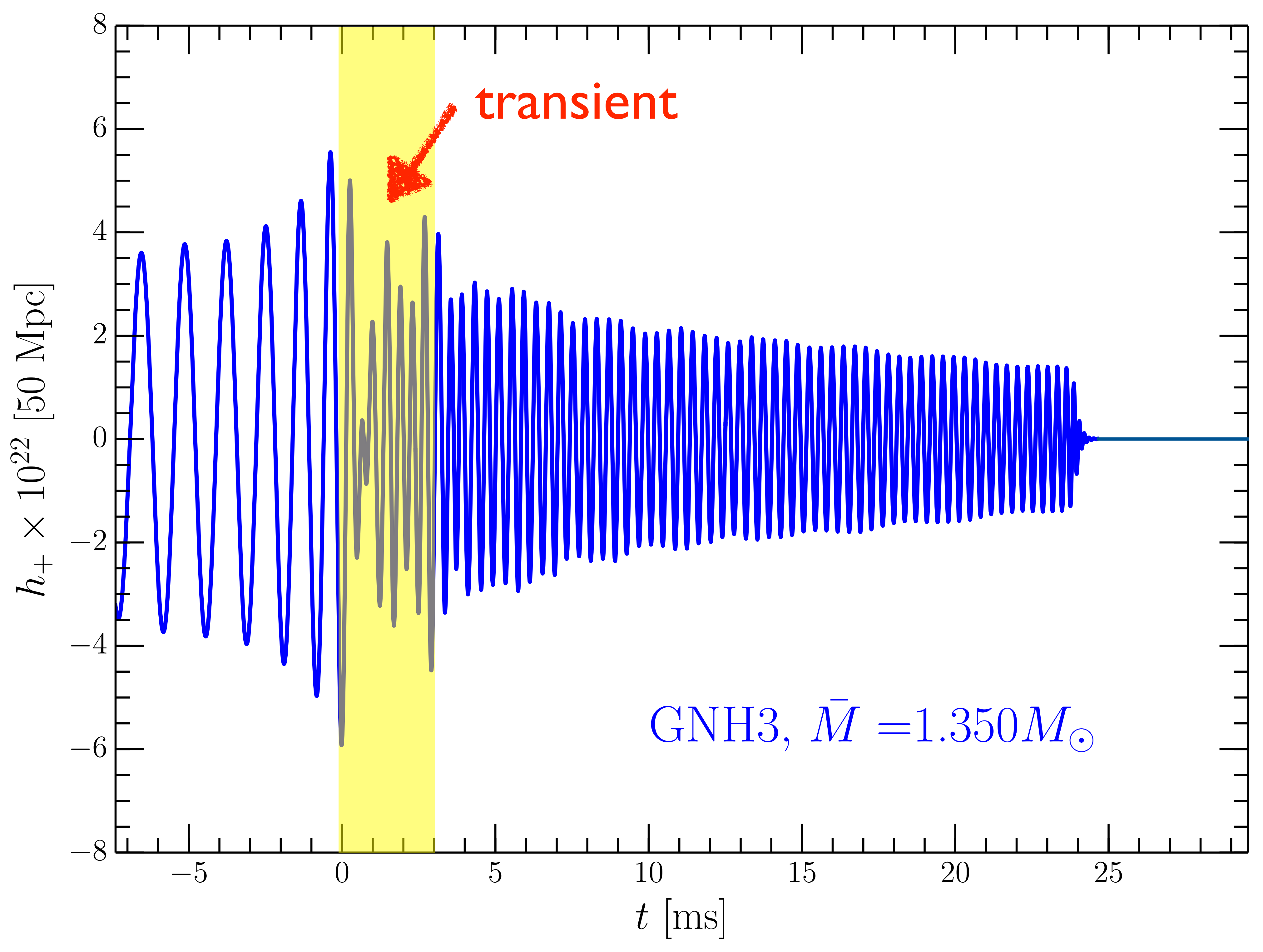


Anatomy of the GW signal



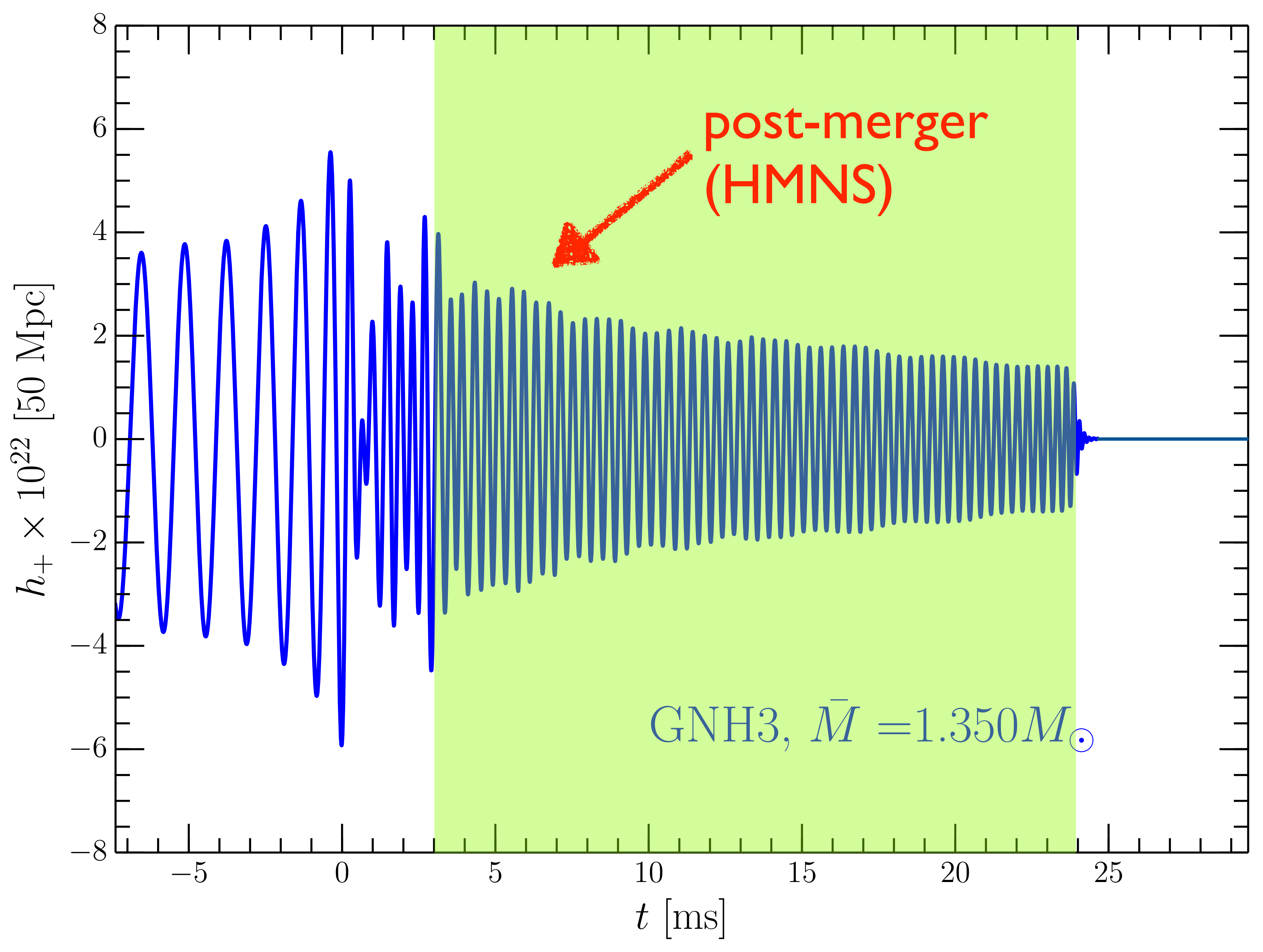
Inspiral: well approximated by PN/EOB; tidal effects important

Anatomy of the GW signal



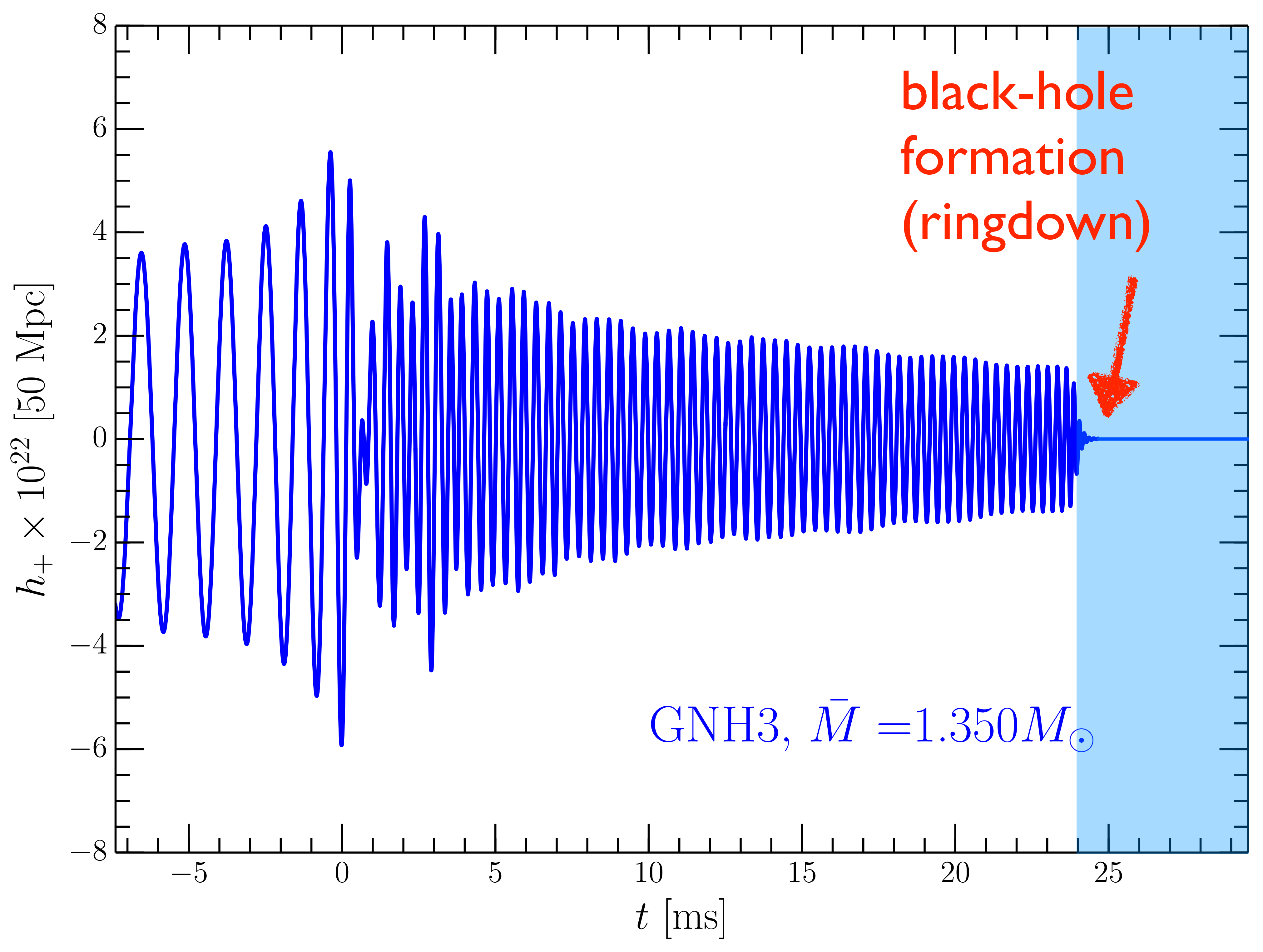
Merger: highly nonlinear but analytic description possible

Anatomy of the GW signal



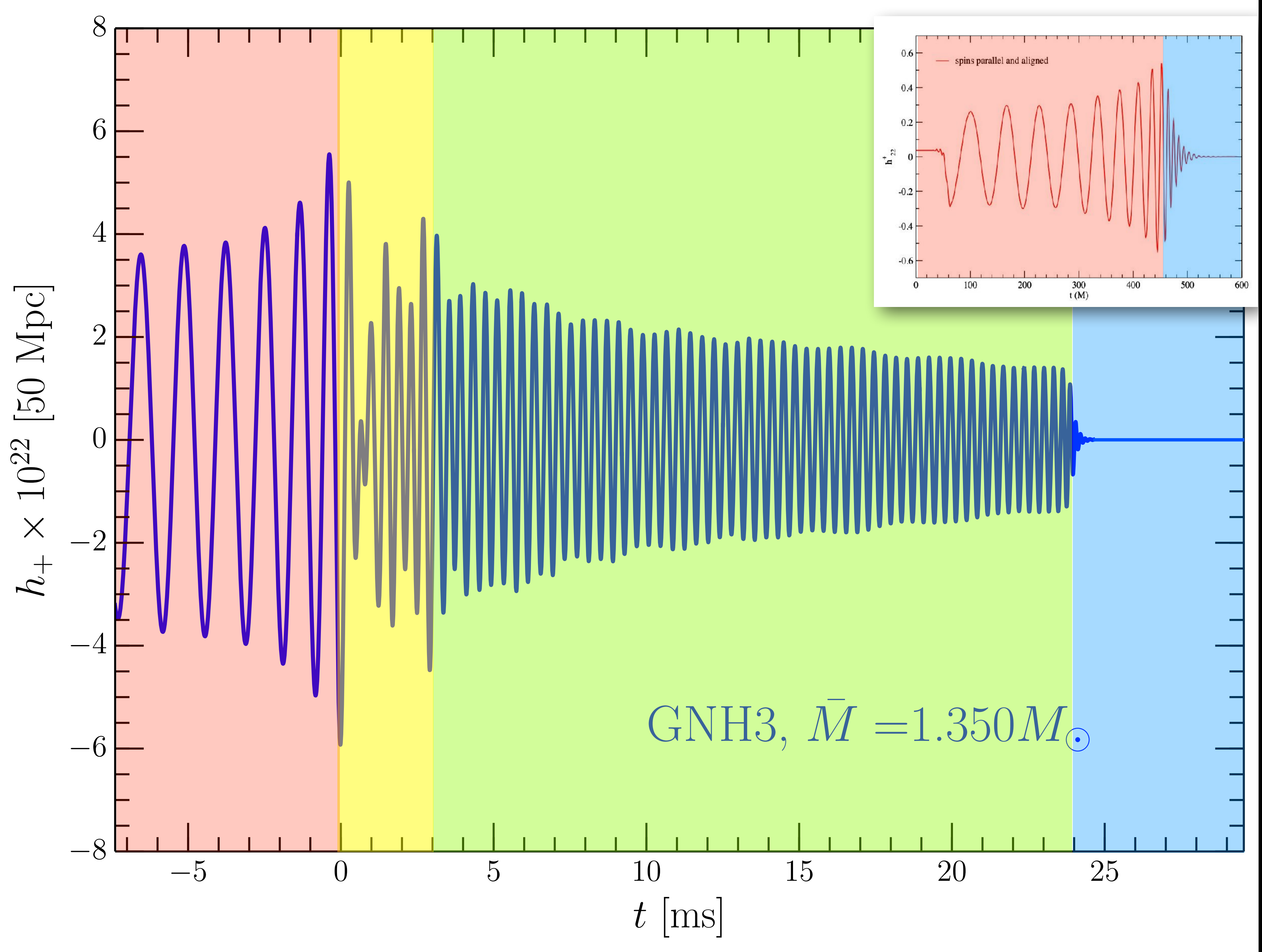
post-merger: quasi-periodic emission of bar-deformed HMNS

Anatomy of the GW signal



Collapse-ringdown: signal essentially shuts off

Anatomy of the GW signal

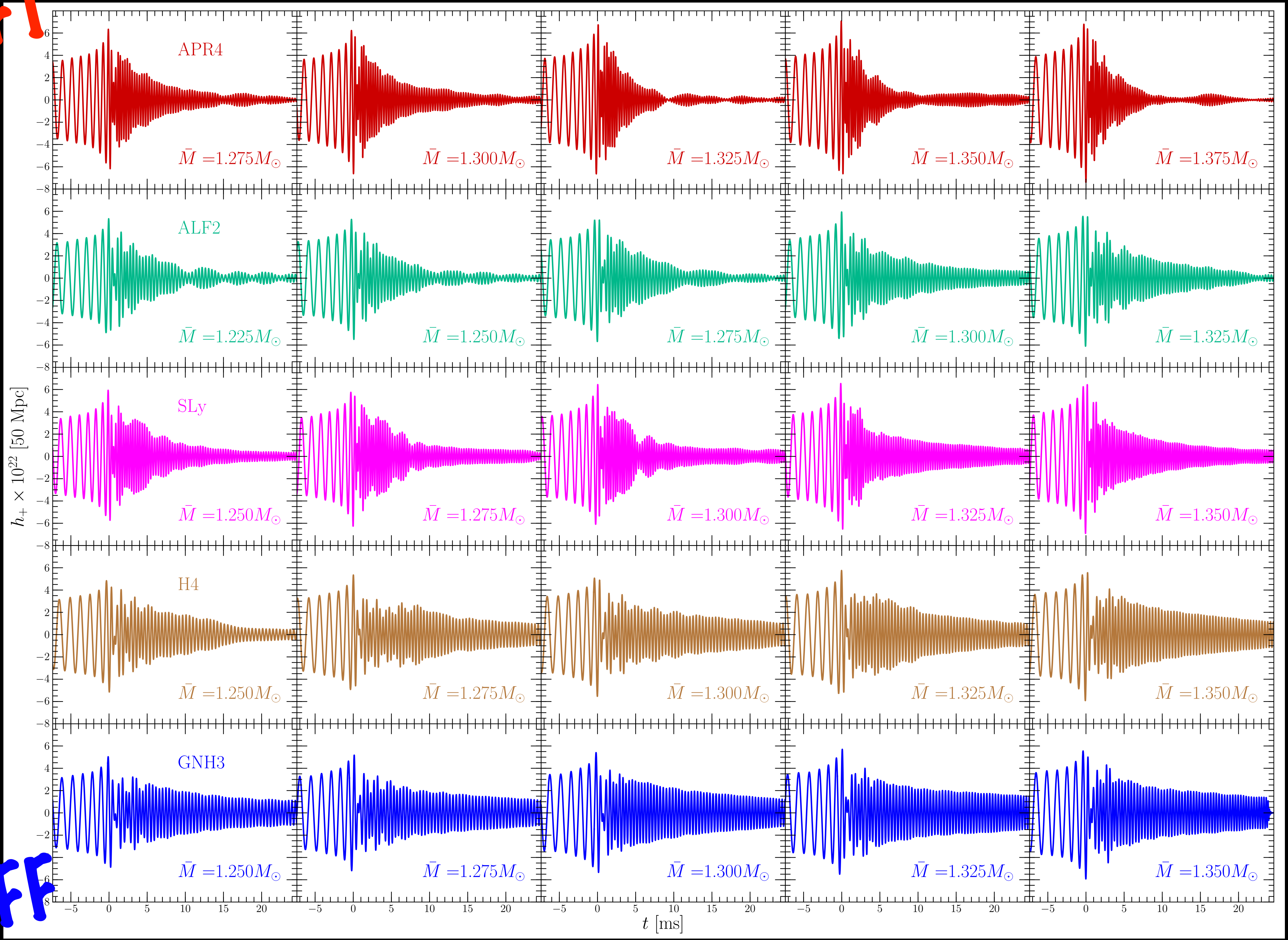


Postmerger signal: peculiar of binary NSs

What we can do nowadays

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

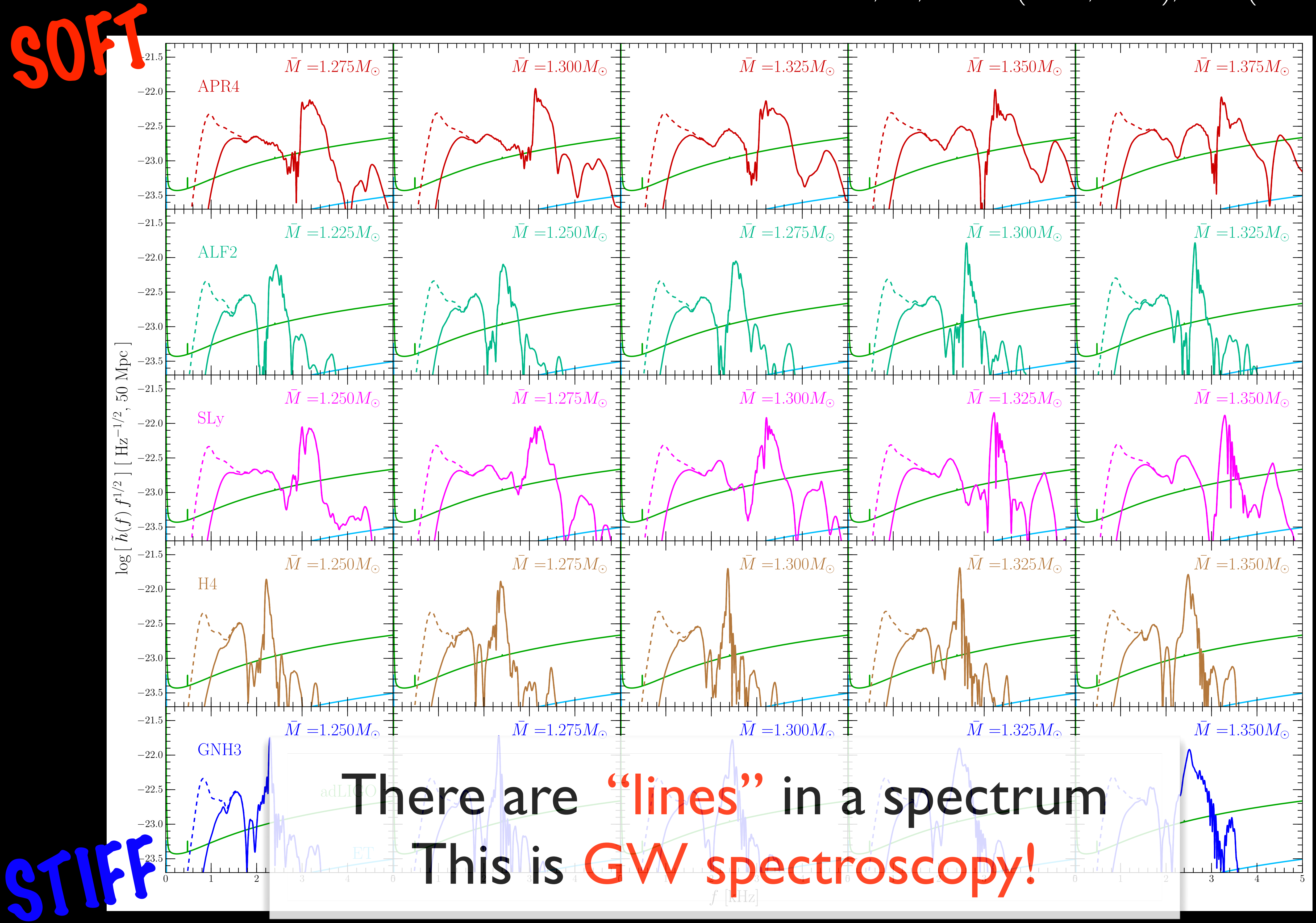
SOFT



STIFF

Extracting information from the EOS

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



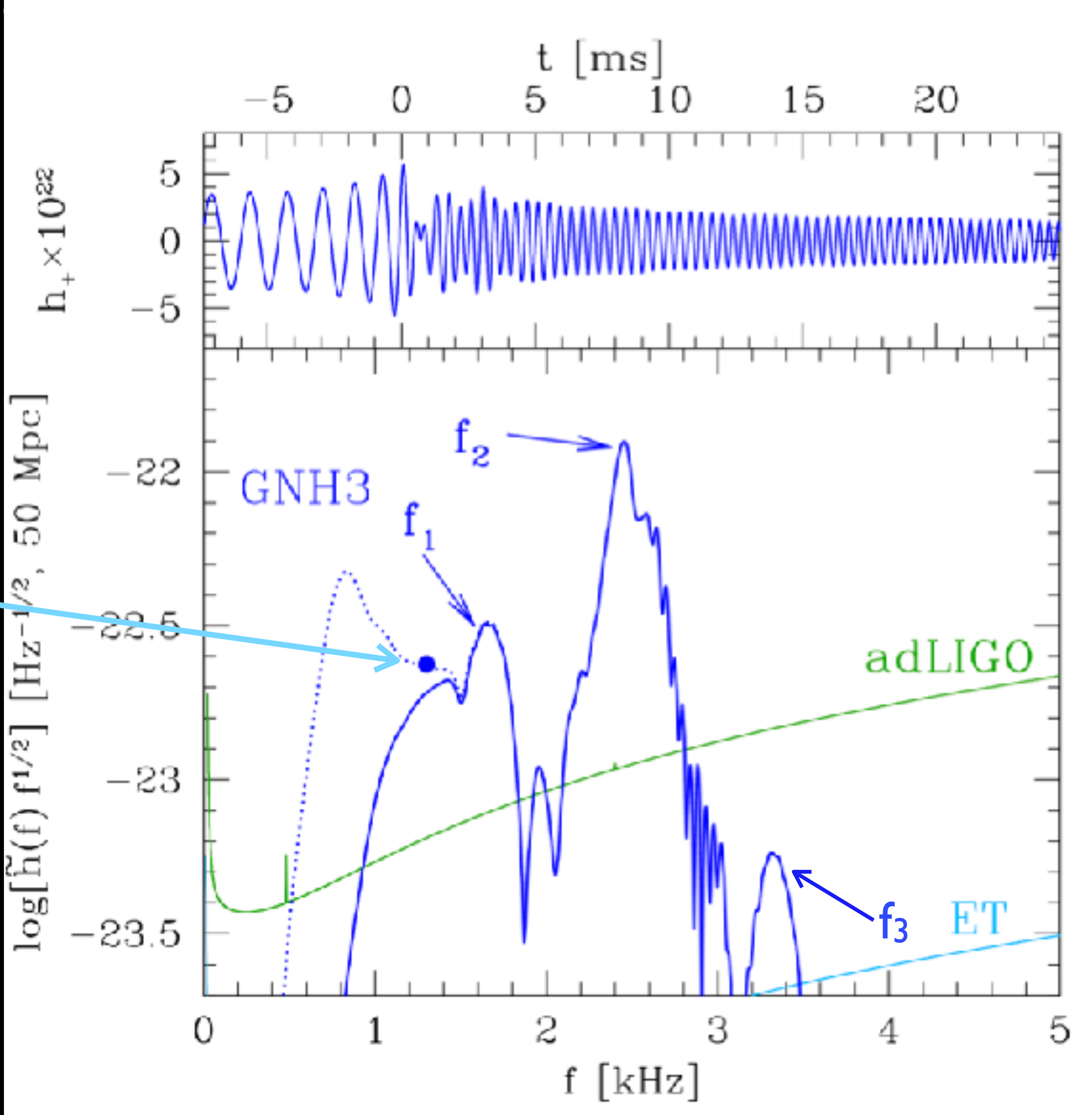
There are "lines" in a spectrum

This is GW spectroscopy!

A spectroscopic approach to the EOS

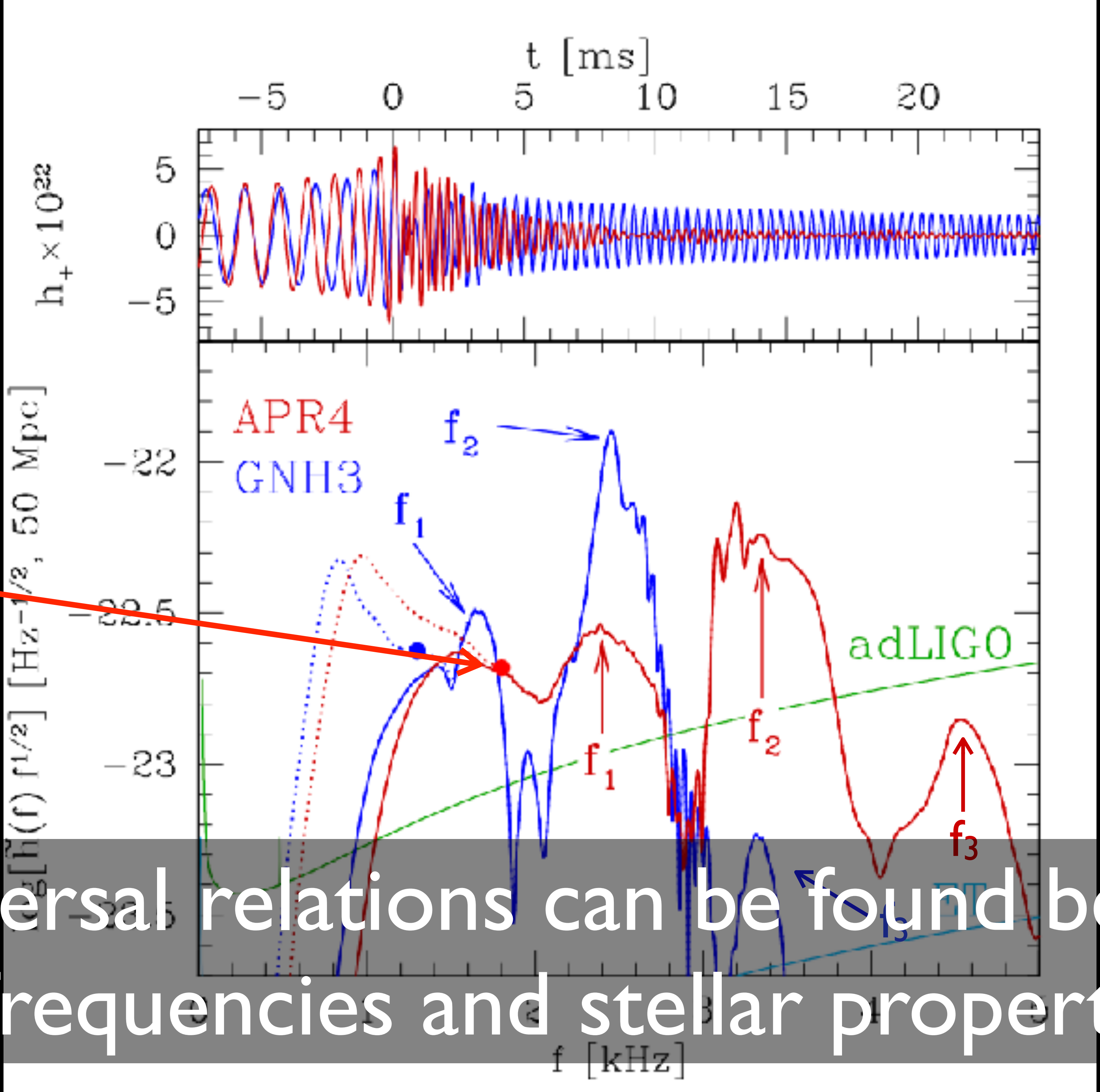
Oechslin+2007, Baiotti+2008, Bauswein+ 2011, 2012, Stergioulas+ 2011, Hotokezaka+ 2013, Takami 2014, 2015, Bernuzzi 2014, 2015, Bauswein+ 2015, Clark+ 2016, LR+2016, de Pietri+ 2016, Feo+ 2017, Bose+ 2017 .

merger frequency



A spectroscopic approach to the EOS

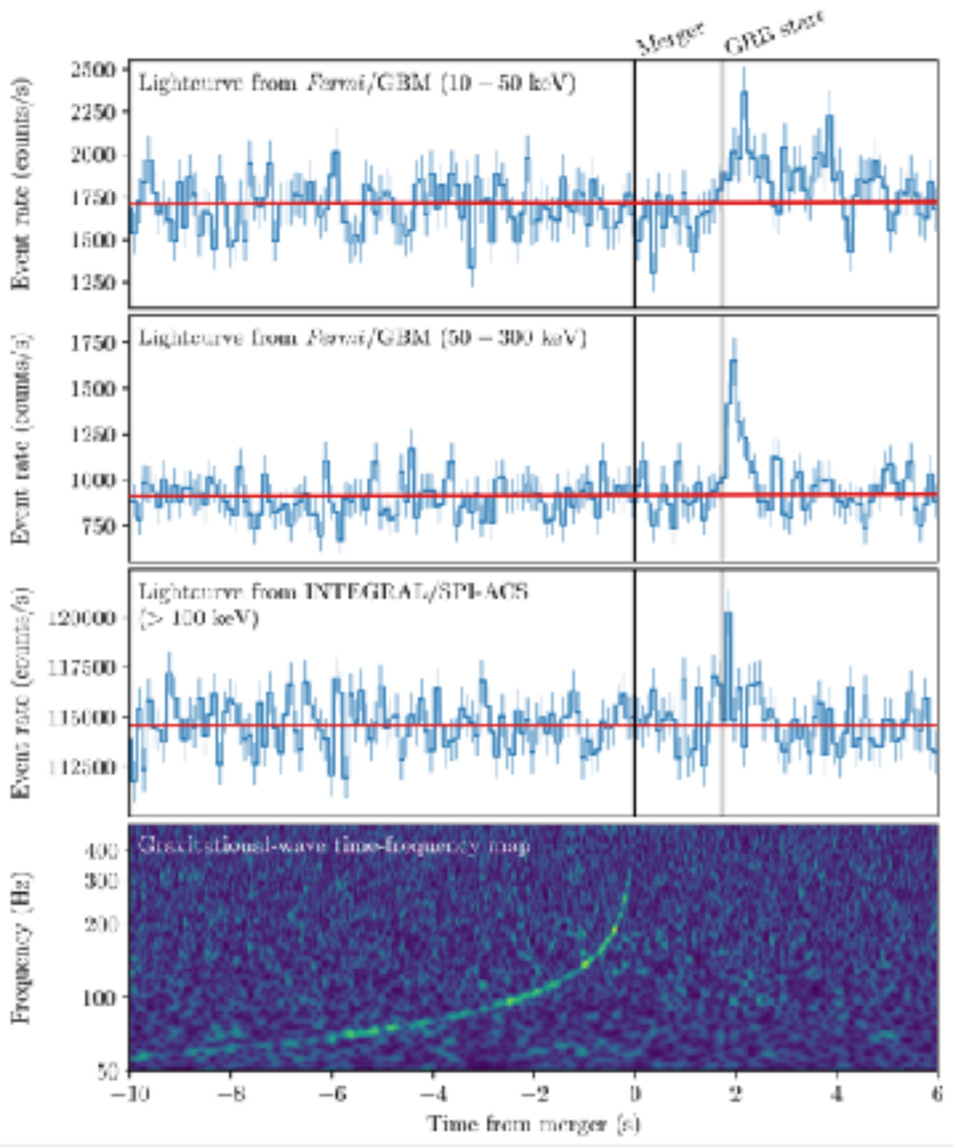
Oechslin+2007, Baiotti+2008, Bauswein+ 2011, 2012, Stergioulas+ 2011, Hotokezaka+ 2013, Takami 2014, 2015, Bernuzzi 2014, 2015, Bauswein+ 2015, Clark+ 2016, LR+2016, de Pietri+ 2016, Feo+ 2017, Bose+ 2017 .



merger frequency

Universal relations can be found between frequencies and stellar properties

GW170817: a game changer

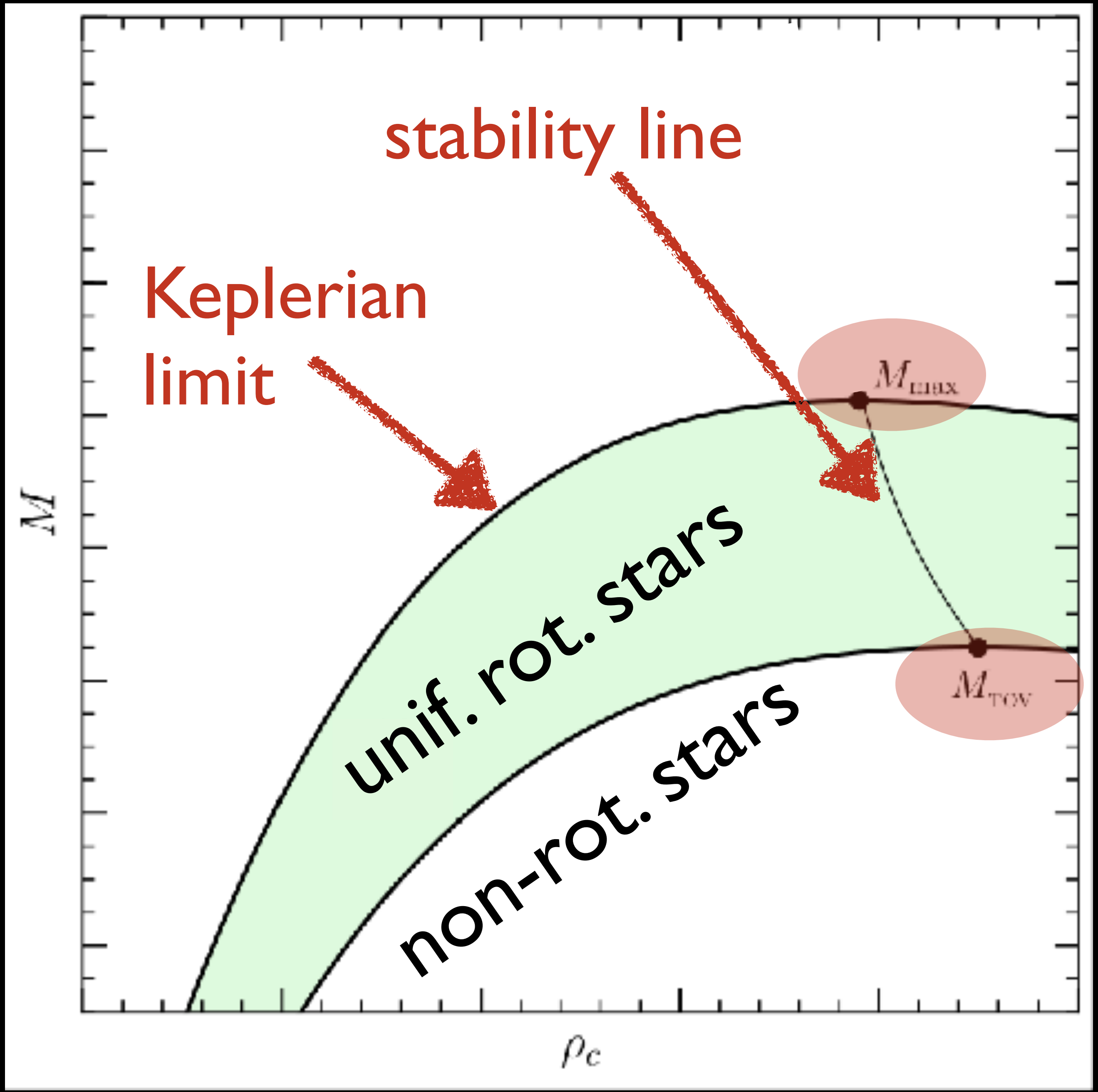


LR, Most, Weih, ApJL (2018)
Most, Weih, LR, Schaffner-Bielich, PRL (2018)
Nathanail, Most, LR, ApJL (2021)

Limits on the maximum mass

- The remnant of GW170817 was a hypermassive star, i.e. a differentially rotating object with initial **gravitational** mass:

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



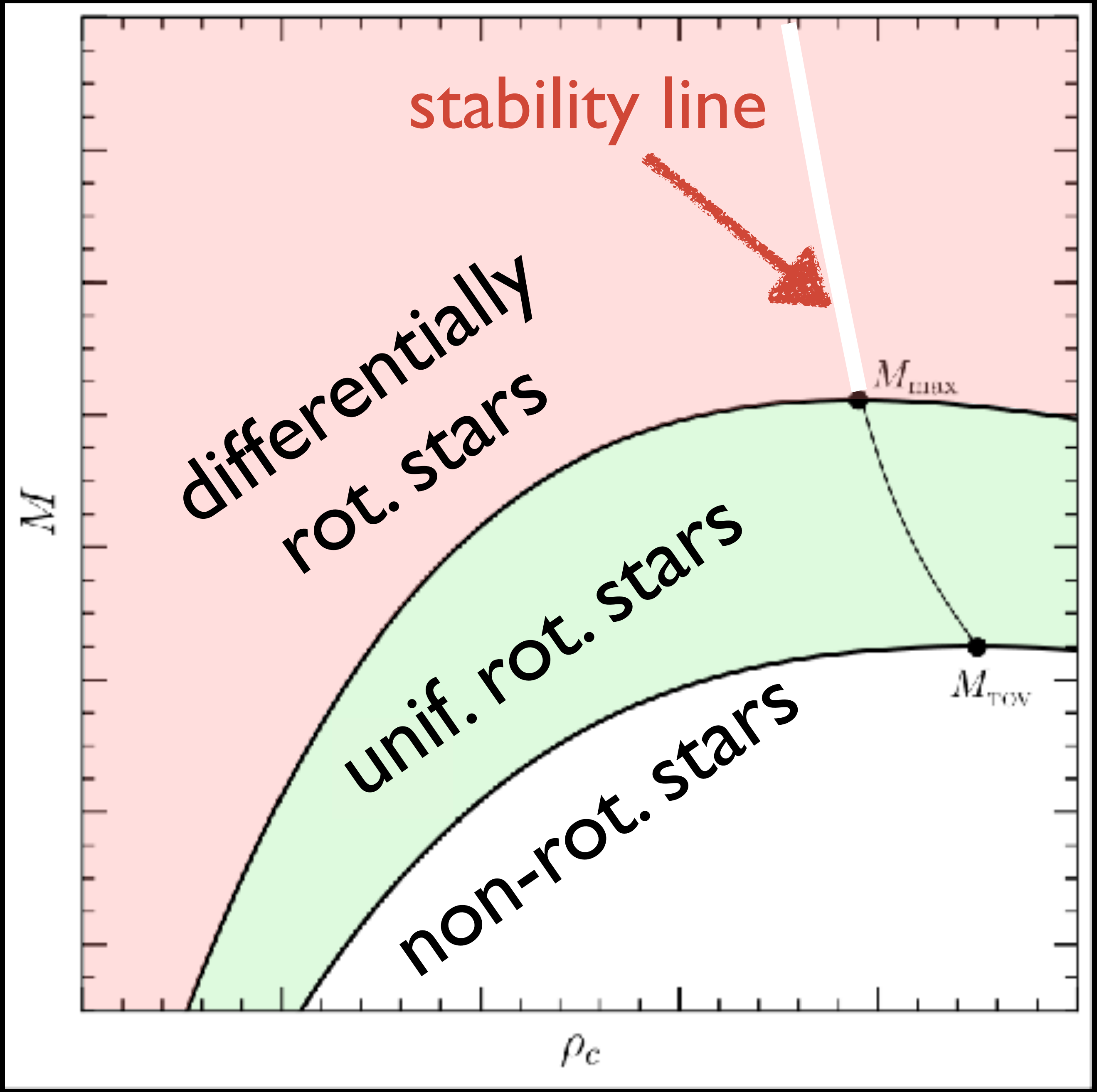
- Sequences of equilibrium models of **nonrotating** stars will have a maximum mass: $M_{\rm TOV}$
- This is true also for **uniformly** rotating stars at mass shedding limit: $M_{\max}$
- $M_{\max}$ simple and **quasi-universal** function of $M_{\rm TOV}$ (Breu & LR 2016)

$$\boxed{M_{\max} = 1.20^{+0.02}_{-0.05}\, M_{\rm TOV}}$$

Limits on the maximum mass

- The remnant of GW170817 was a hypermassive star, i.e. a differentially rotating object with initial **gravitational** mass:

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



- **Green** region is for **uniformly** rotating equilibrium models.
- **Salmon** region is for **differentially** rotating equilibrium models.
- **Stability line** is simply extended in larger space (Weih+18)

Limits on the maximum mass

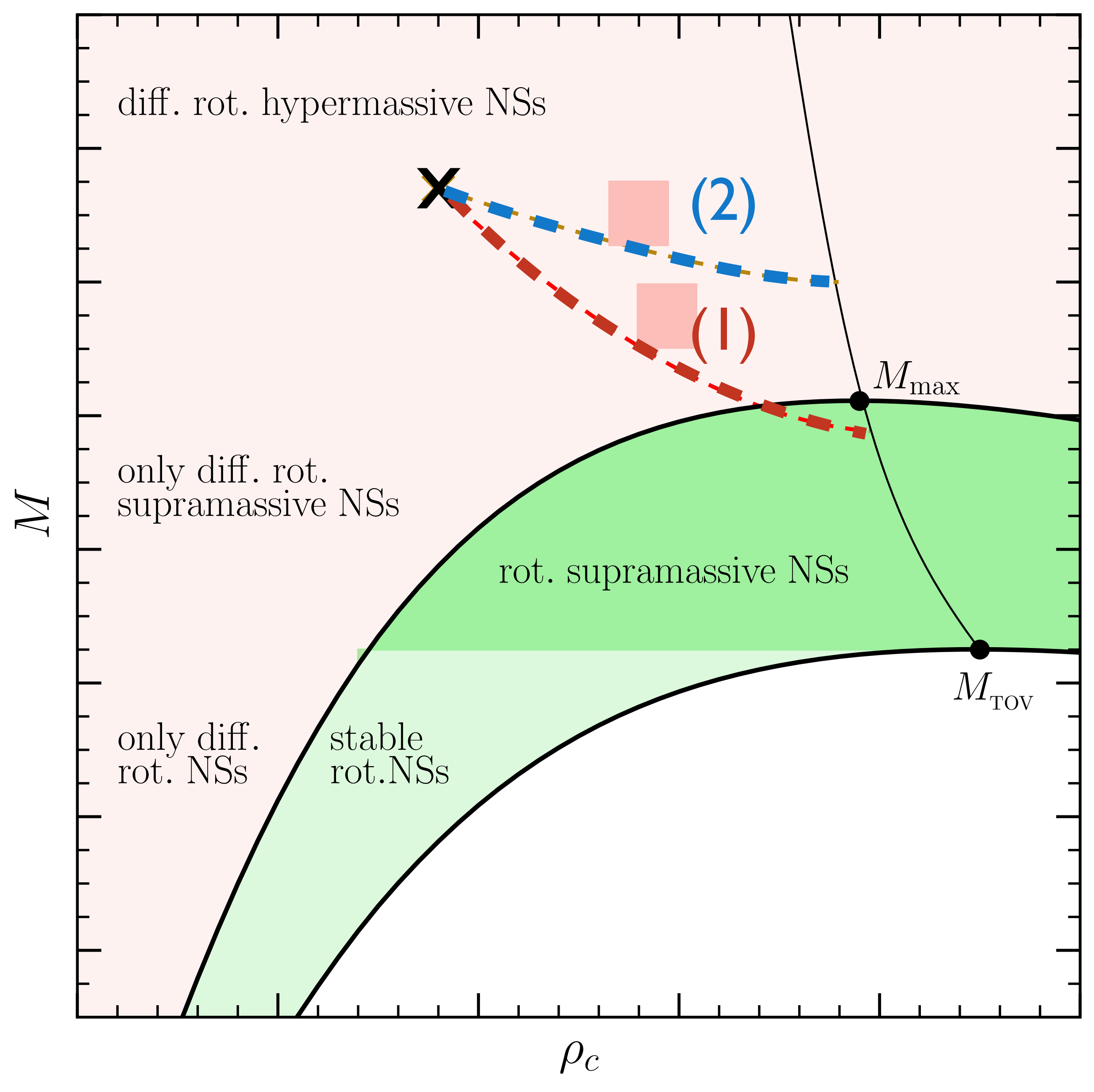
- GW170817 produced object **"X"**; GRB implies a BH has been formed: **"X"** followed two possible tracks: **fast (2)** and **slow (1)**

- It rapidly produced a BH when still **differentially** rotating (2)

- It lost differential rotation leading to a **uniformly** rotating core (1).

- (1) is much more likely because of large ejected mass (long lived).

- Final mass is near $M_{\rm max}$ and we know this is universal!



let’s recap…

- Consider **evolution track (1)**
- Use measured **gravitational mass** of GW170817
- Remove **rest-mass** deduced from kilonova emission (need conversion baryon/gravitational)
- Use **universal relations,** account for errors to obtain

pulsar timing

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

GW170817; similar estimates by other groups (Margalit+ 2018, Shibata+ 2018, Ruiz+ 2018)

Tension on the maximum mass

Nathanail, Most, LR (2021)

- The recent detection of GW190814 has created a significant tension on the maximum mass

$$M_1 = 22.2 - 24.3\, M_\odot$$

$$M_2 = 2.50 - 2.67\, M_\odot$$

smallest BH or heaviest NS!

- If secondary in GW190814 was a NS, all previous results on the maximum mass are incorrect.
- No EM counterpart was observed with GW190814 and no estimates possible for ejected matter or timescale for survival.
- **How do we solve this tension?**

Tension on the maximum mass

- We can nevertheless explore impact of larger maximum mass, i.e., what changes in the previous picture if

$$M_{\rm TOV}/M_{\odot} \gtrsim 2.5 \ ?$$

- In essence, this is a multi-dimensional parametric problem satisfying **conservation** of **rest-mass** and **gravitational mass.**
- Observations provide limits on **gravitational** and **ejected mass.**
- Numerical relativity simulations provide limits on **emitted GWs**
- All the rest is contained in **10 parameters** that need to be varied within suitable ranges.

Genetic algorithm

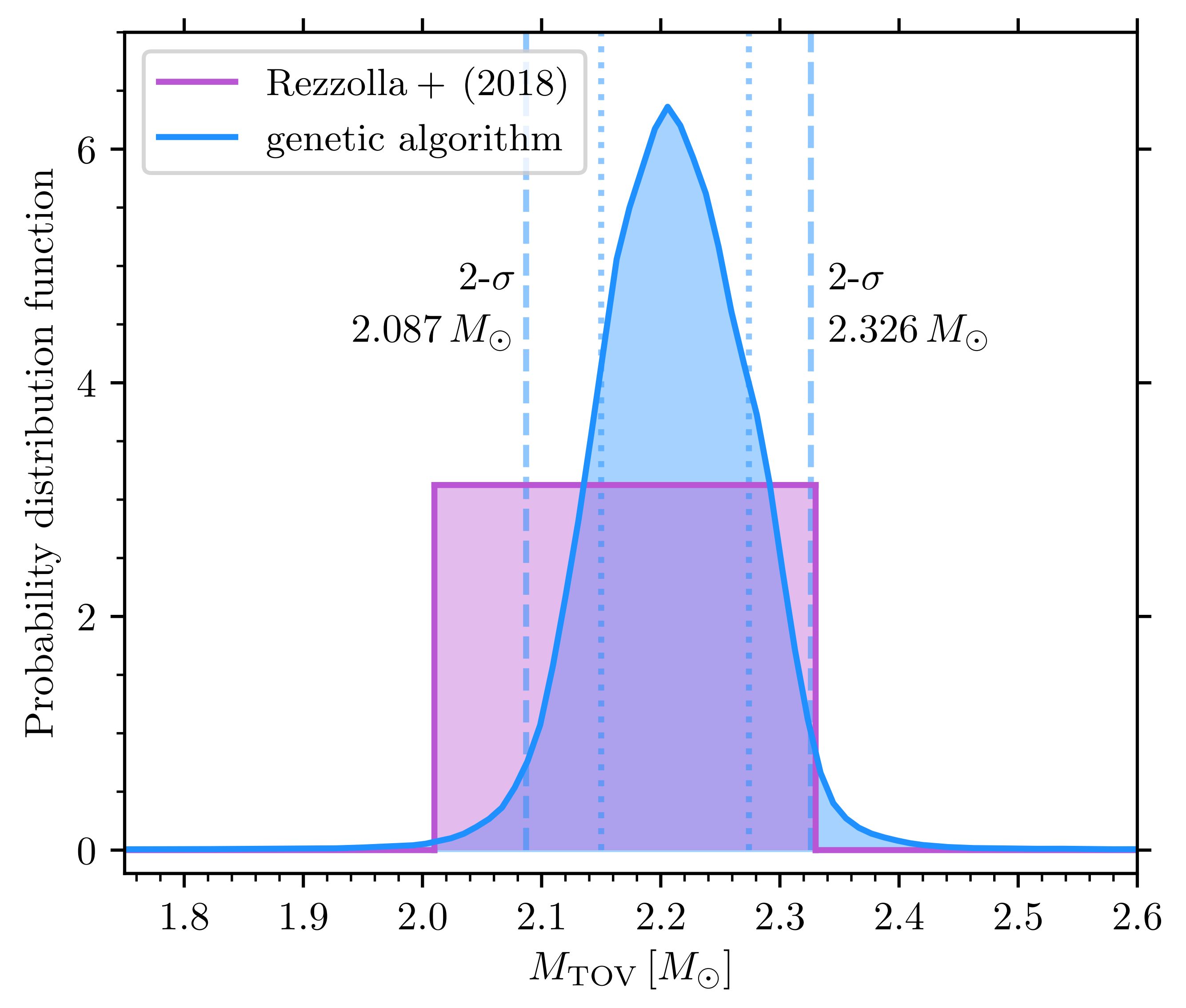
- A **genetic algorithm** is used to sample through the parameter space of the 10 free parameters.

- The algorithm reflects genetic adaptation: given a mutation (i.e. change of parameters) it will be adopted if it provides a better fit to data.

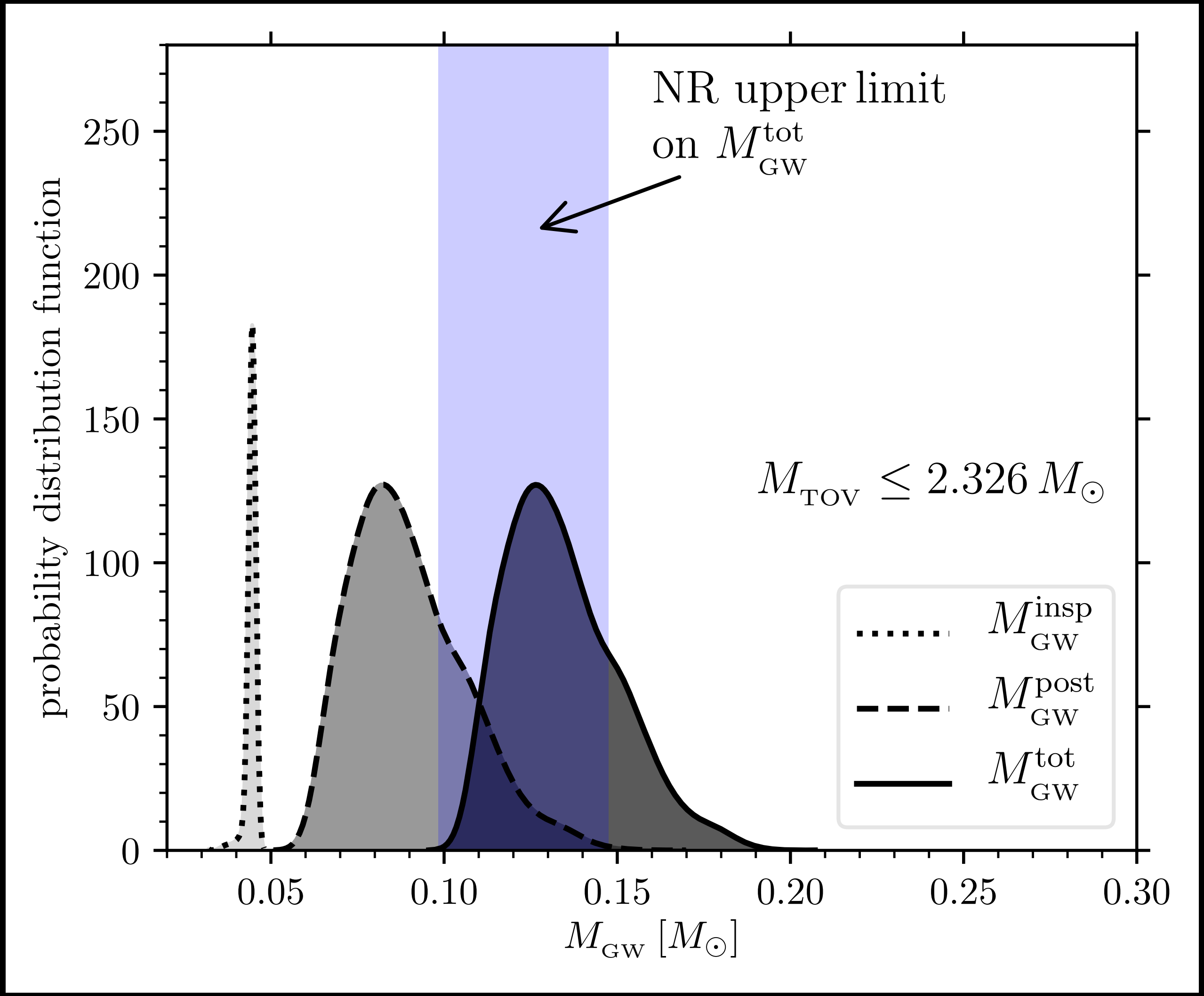
- Consider first previous estimate:

$$M_{\rm TOV}/M_\odot \lesssim 2.3$$

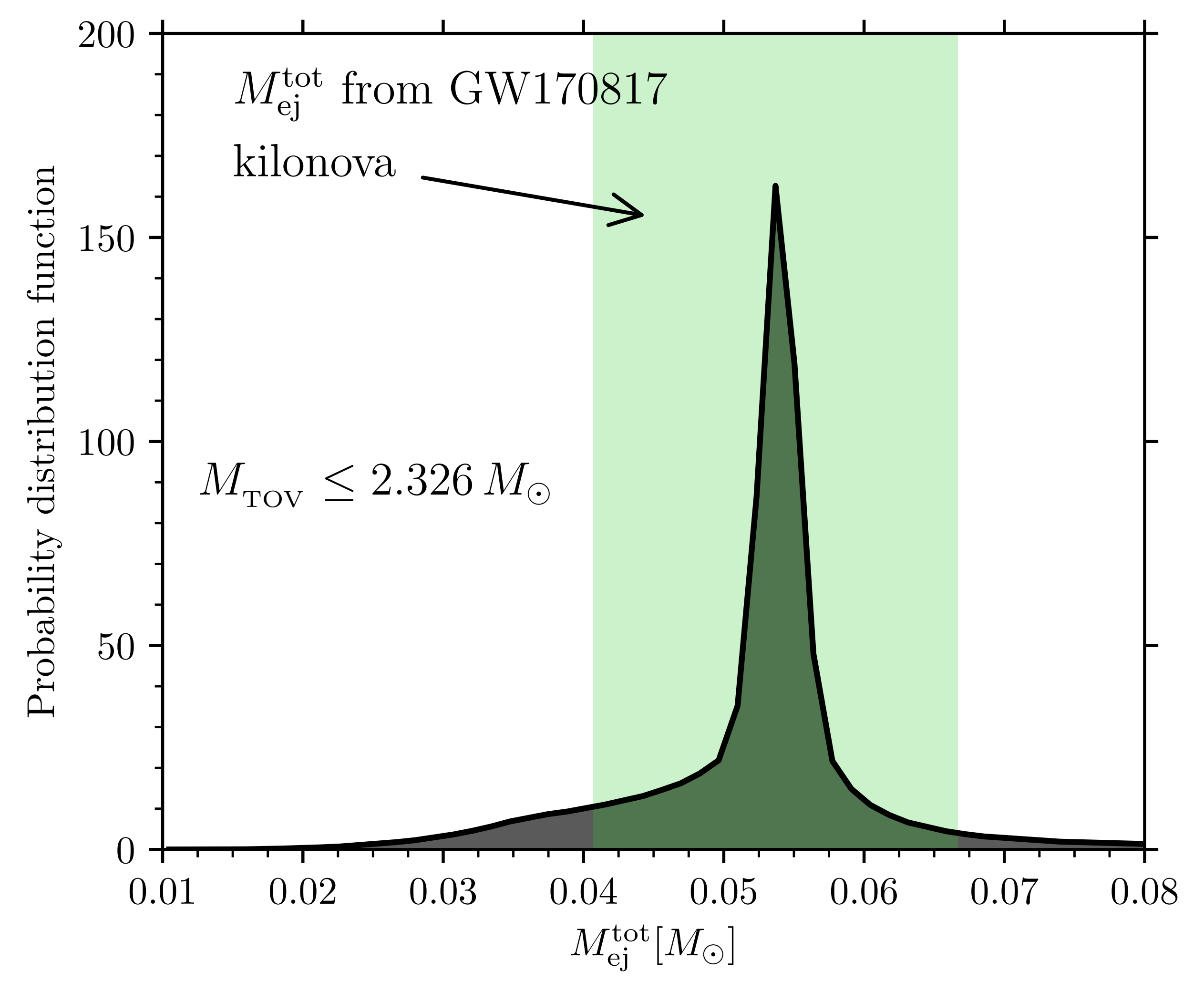
$$M_{\rm TOV}/M_\odot \leq 2.16^{+0.17}_{-0.15}$$



First hypothesis: $M_{\rm TOV}/M_\odot \lesssim 2.3$

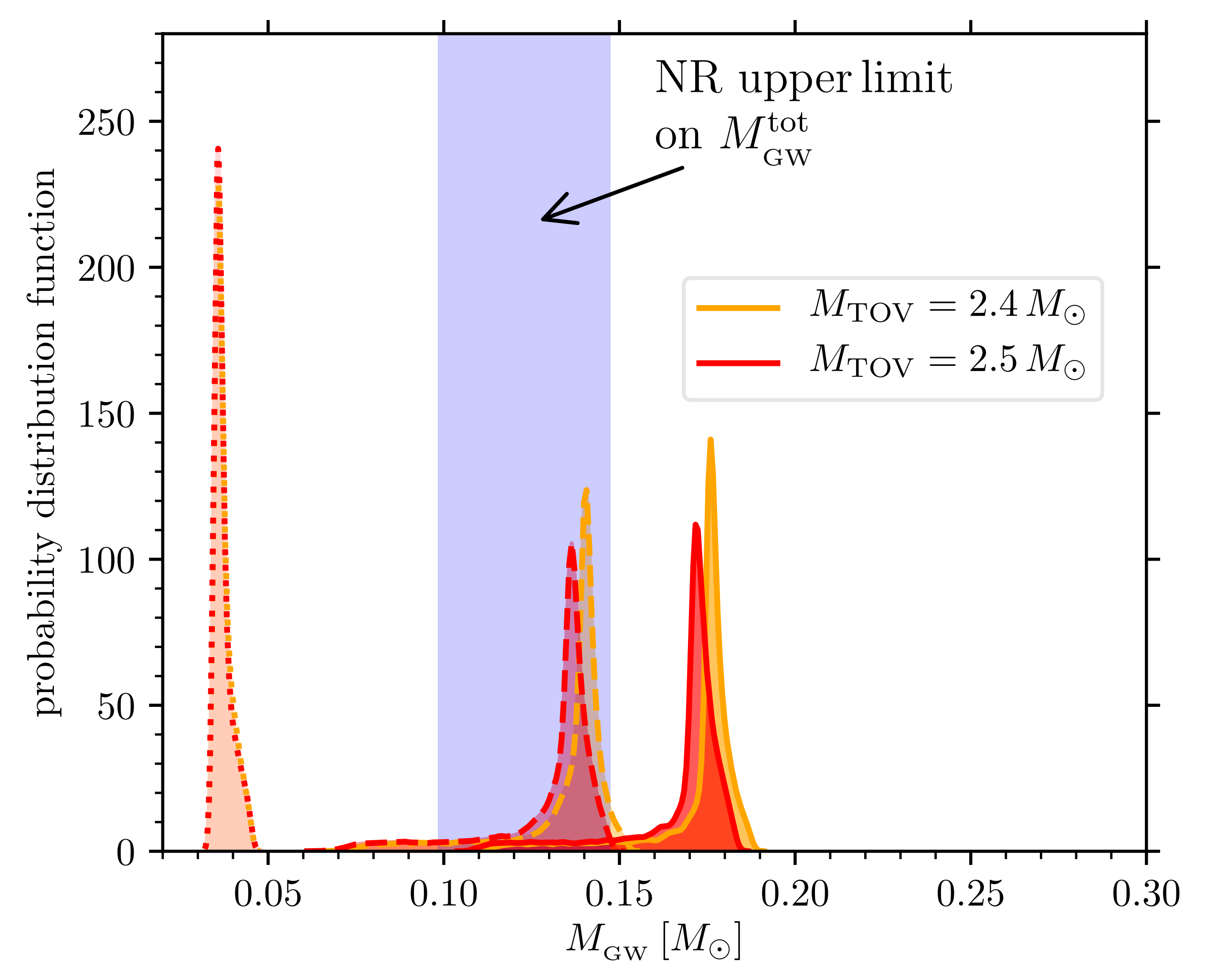


- Total mass emitted in GWs is in perfect **agreement** with predictions from numerical relativity

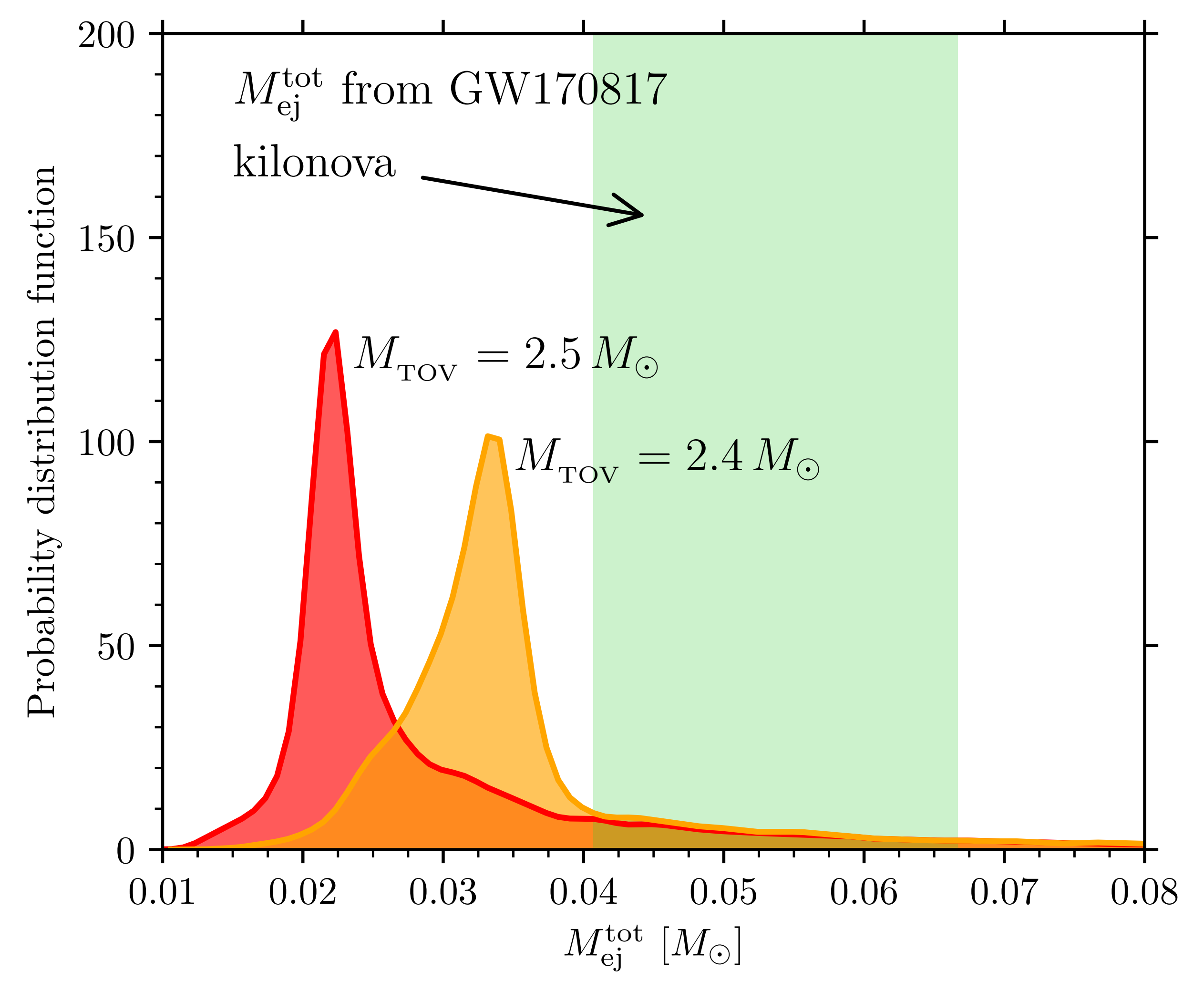


- Total mass ejected is in perfect **agreement** with predictions from kilonova signal

Second hypothesis: $M_{\rm TOV}/M_\odot \gtrsim 2.5$



- Total mass emitted in GWs is **much larger** than predicted from simulations;
- Mismatch becomes worse with larger masses



- Total mass ejected is in perfect **much smaller** than observed from kilonova signal.

Tension on the maximum mass

Nathanail, Most, LR (2020)

- The recent detection of GW190814 has created a significant tension on the maximum mass

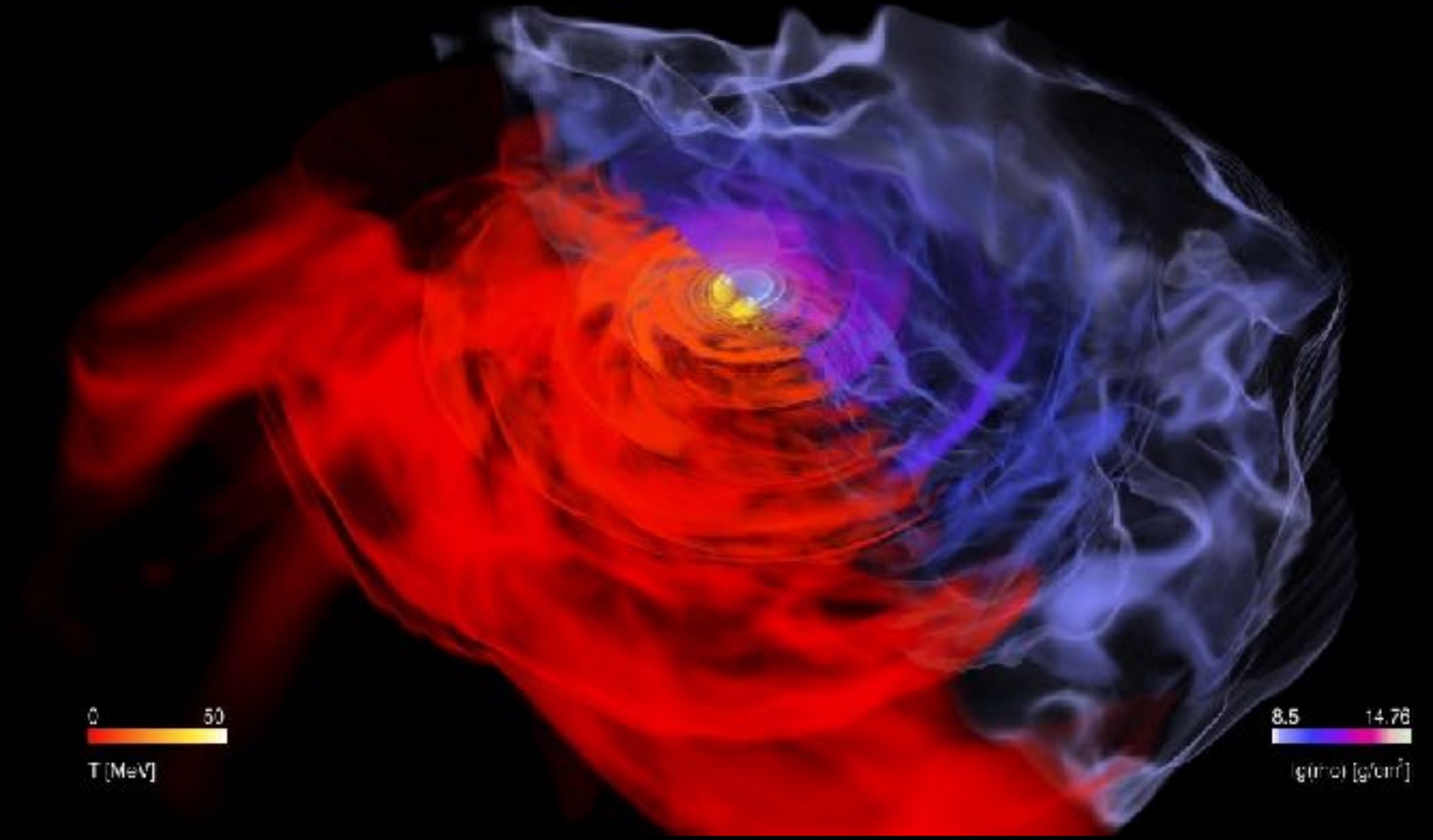
$$M_1 = 22.2 - 24.3\,M_\odot$$

$$M_2 = 2.50 - 2.67\,M_\odot$$

smallest BH or heaviest NS!

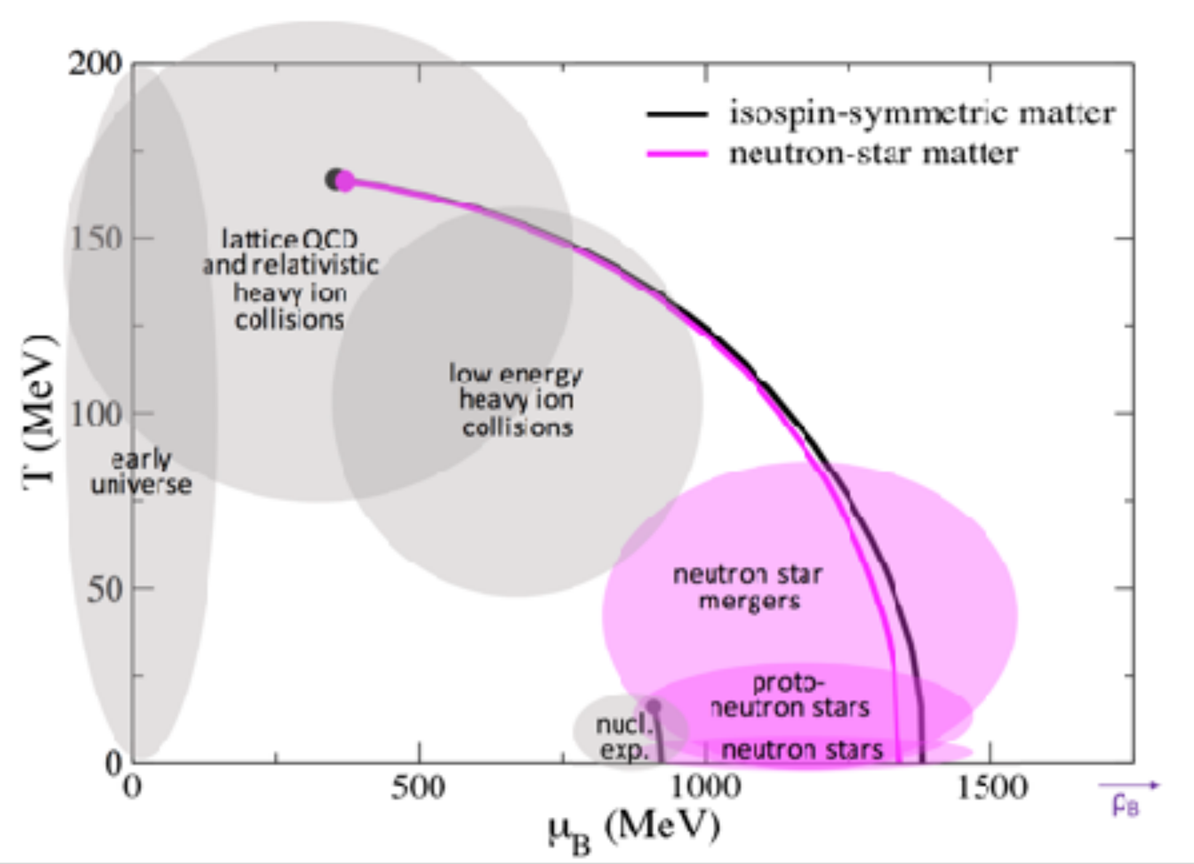
- If secondary in GW190814 was a NS, all previous considerations are incorrect.
- No EM counterpart was observed with GW190814 and no estimates possible on ejected matter or timescale for survival.
- **How do we solve this tension?**
- Solution: secondary in GW190814 **was a BH at merger** but could have been a NS before

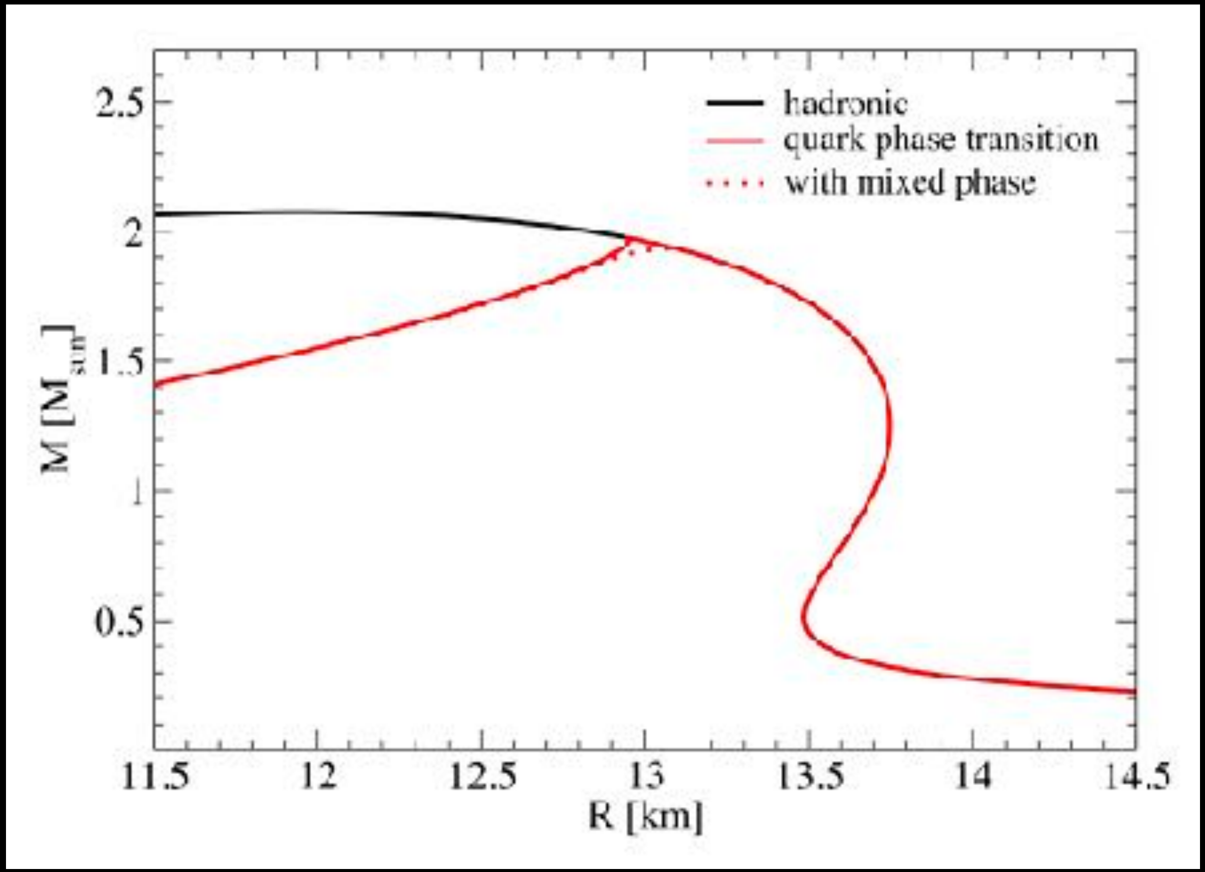
Phase transitions and their signatures



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.

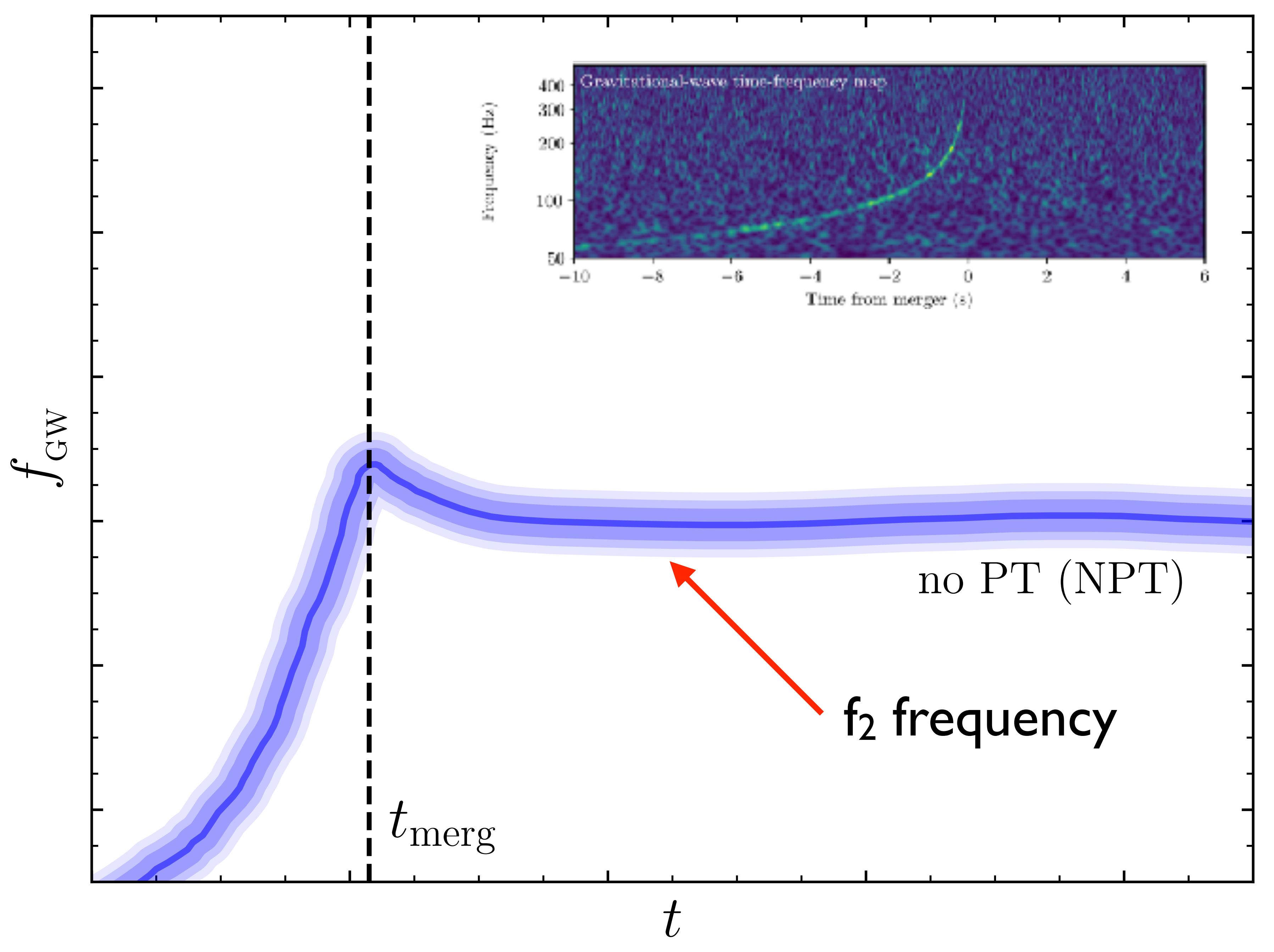




- Considered EOS based on Chiral Mean Field (CMF) model, based on a nonlinear SU(3) sigma model.
- Appearance of quarks can be introduced naturally.

A zoology of behaviours

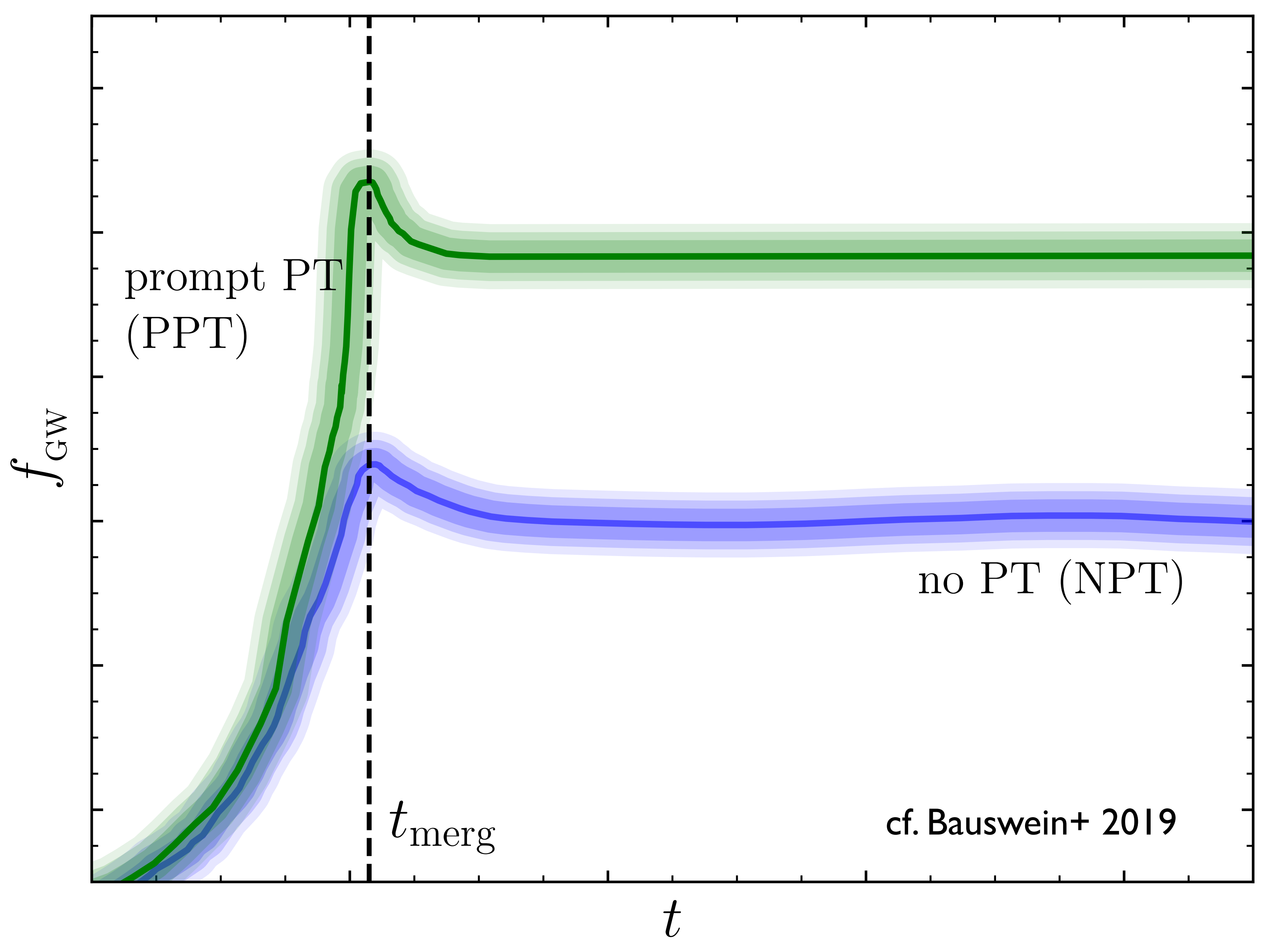
The occurrence of a PT considerably enriches the range of possible scenarios in the GW emission



f_2 frequency

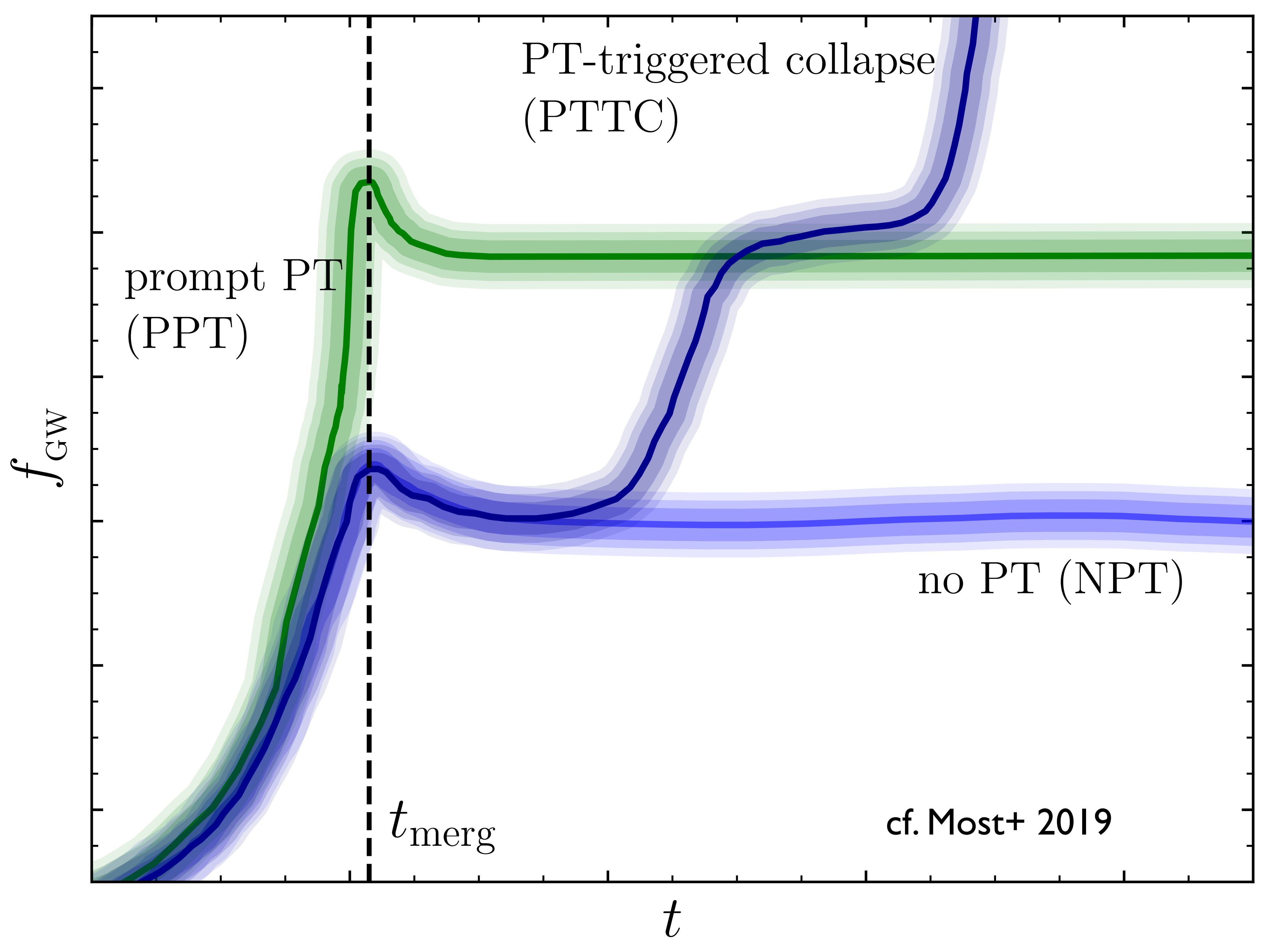
A zoology of behaviours

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



A zoology of behaviours

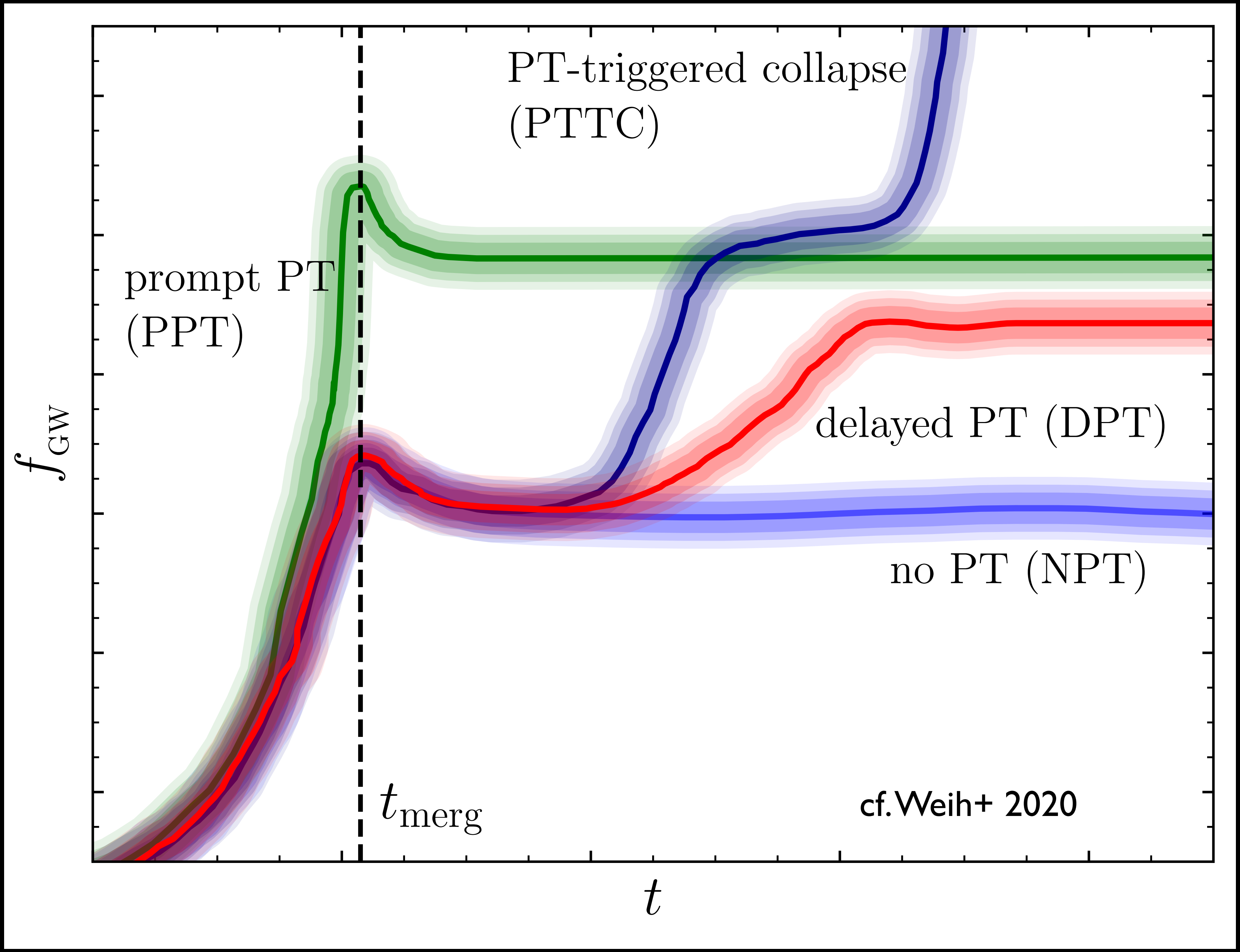
The occurrence of a PT considerably enriches the range of possible scenarios in the GW emission



cf. Most+ 2019

A zoology of behaviours

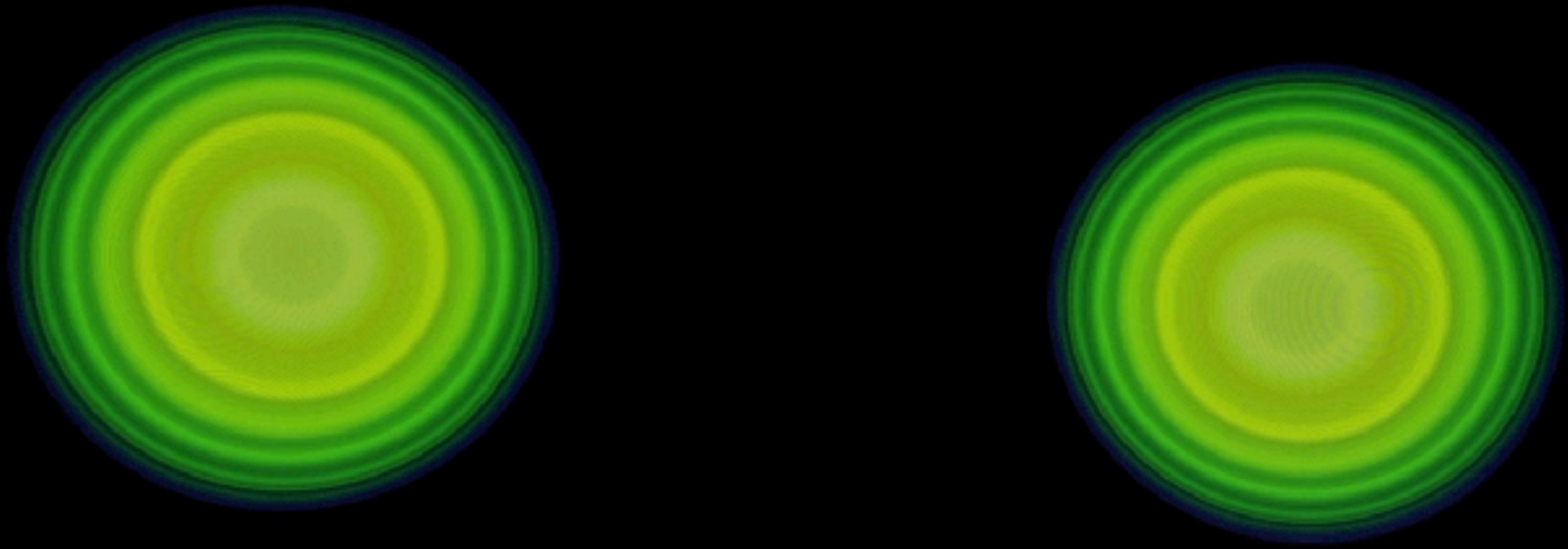
The occurrence of a PT considerably enriches the range of possible scenarios in the GW emission

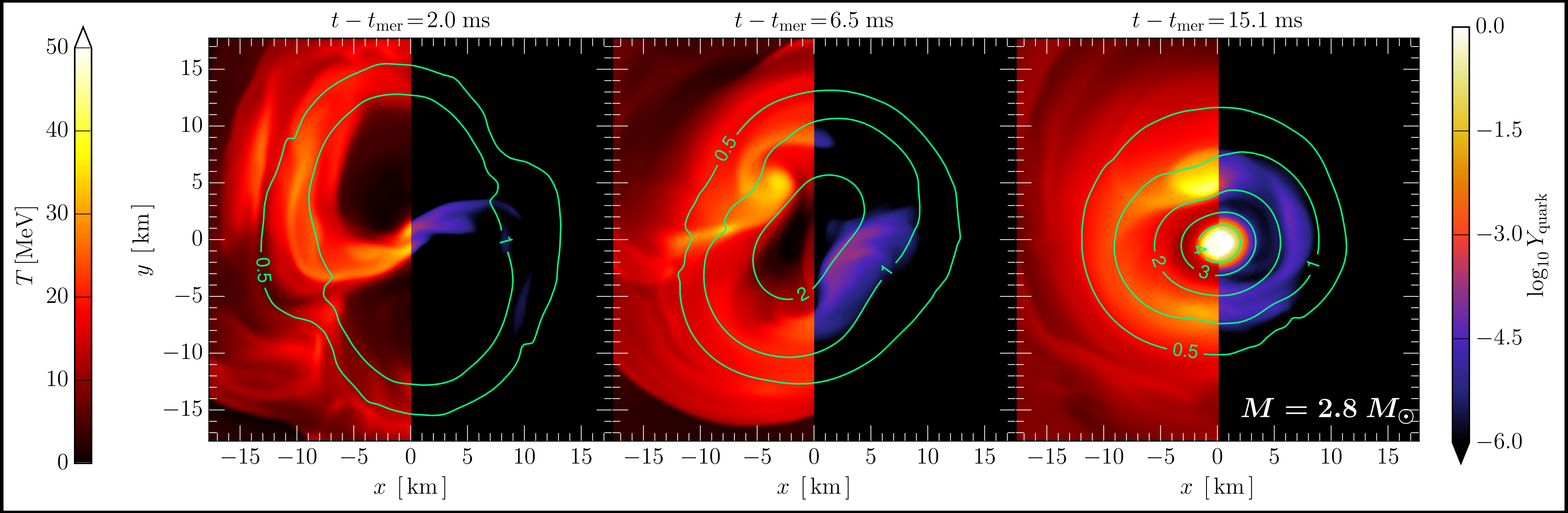


cf. Weih+ 2020

Animations: Weih, Most, LR

Simulation of a phase-transition triggered collapse (PTTC)

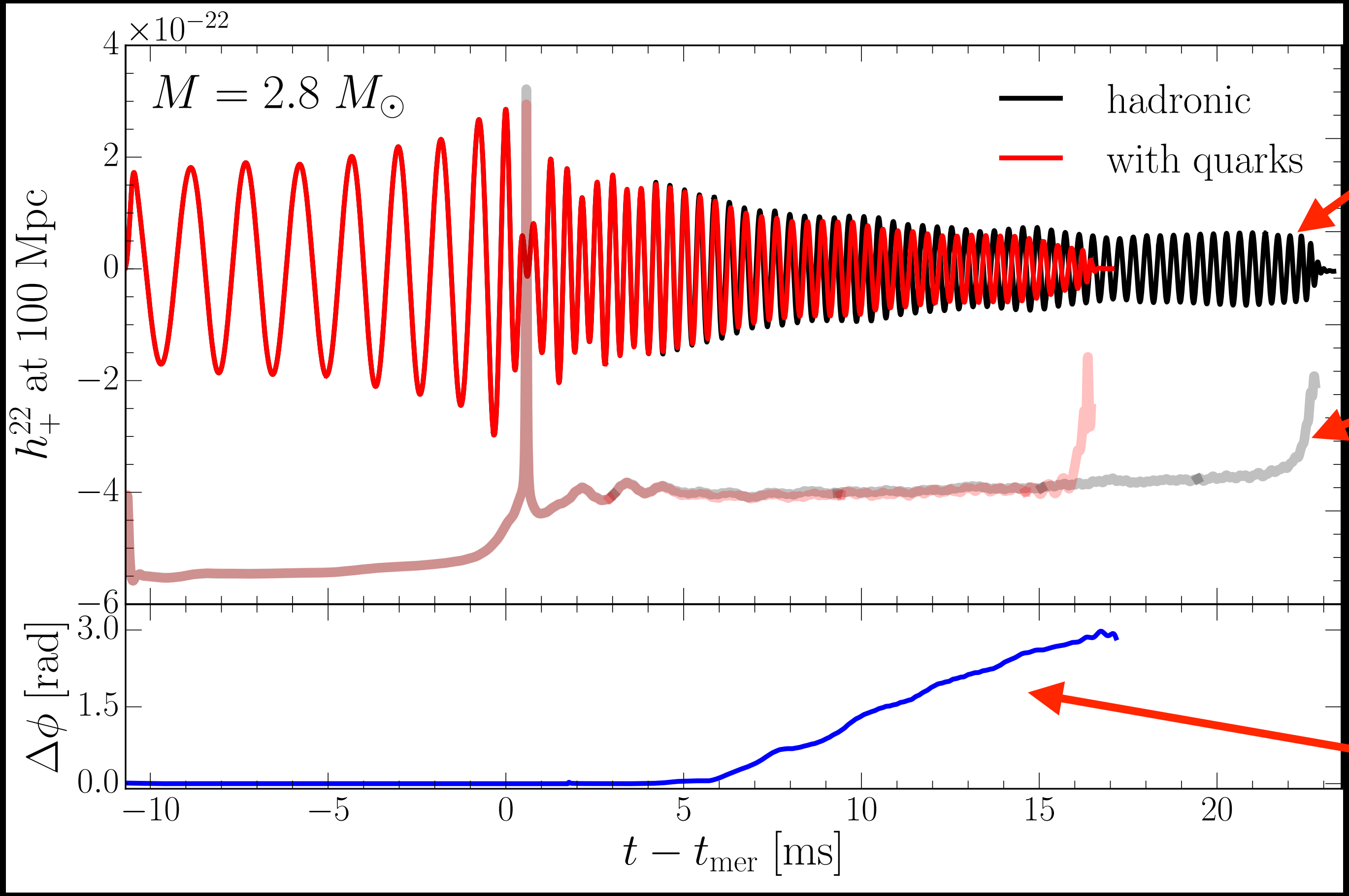




Quarks appear at sufficiently large temperatures and densities.

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

Gravitational-wave emission



waveforms

GW frequencies

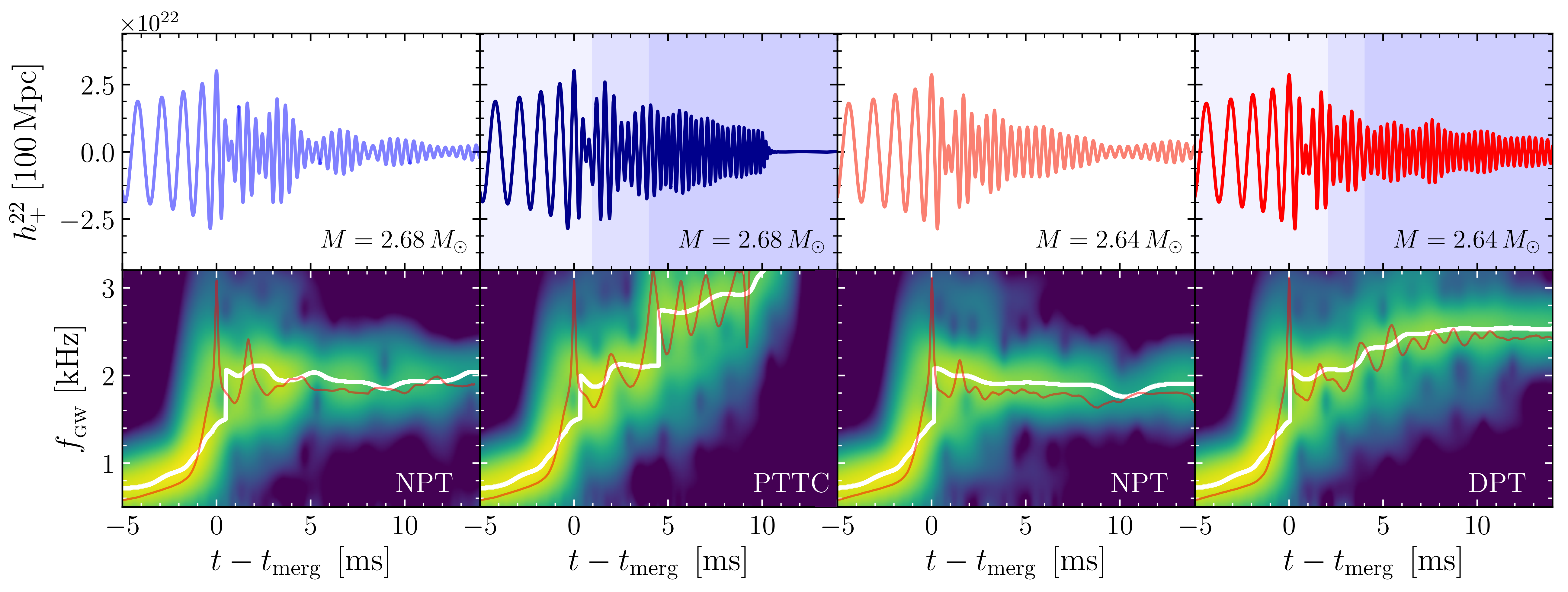
phase difference

- 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**

A more comprehensive picture

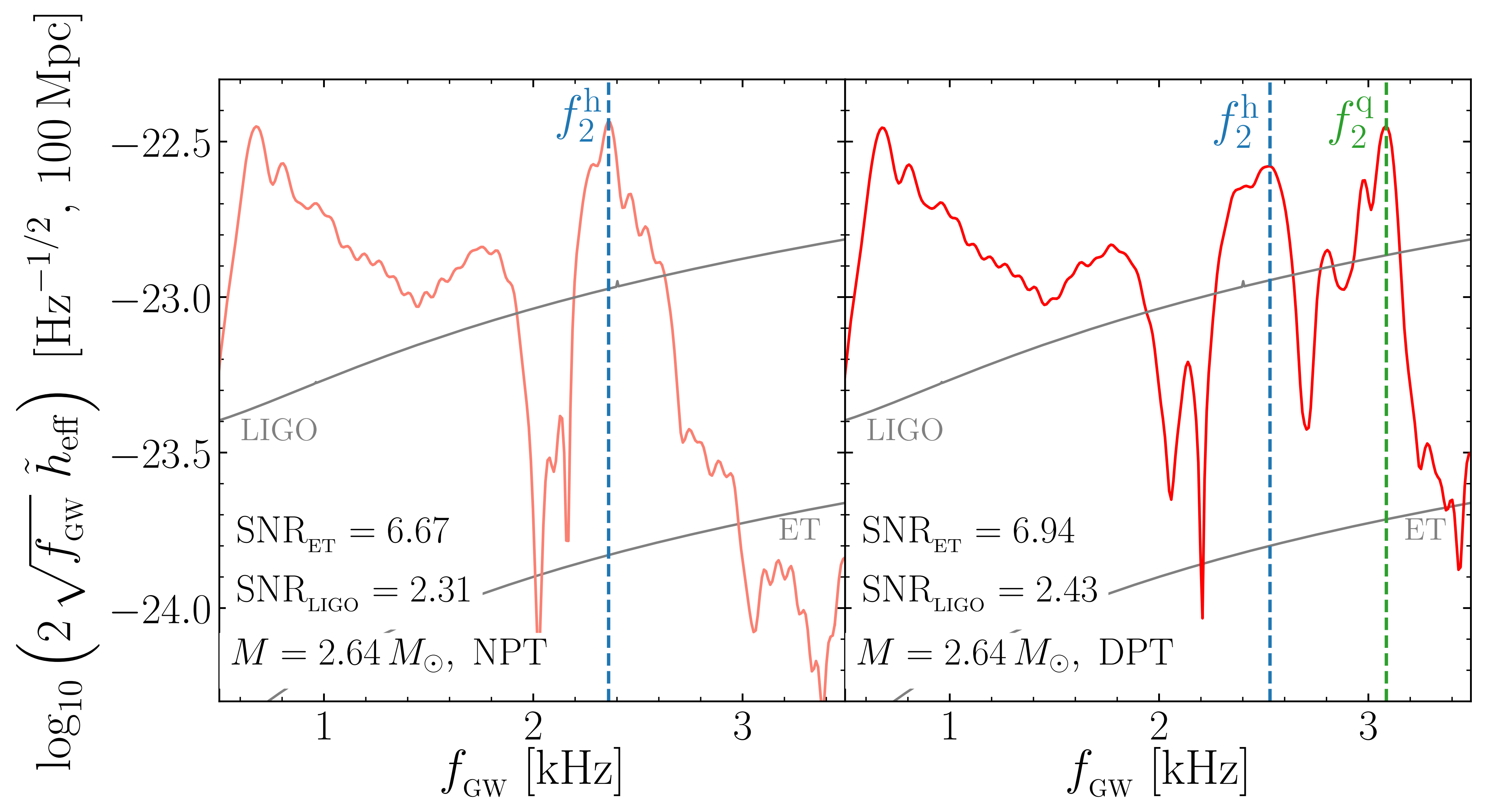
Zoology discussed above can be recognised when shown in terms of the gravitational waves and their spectrograms.



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

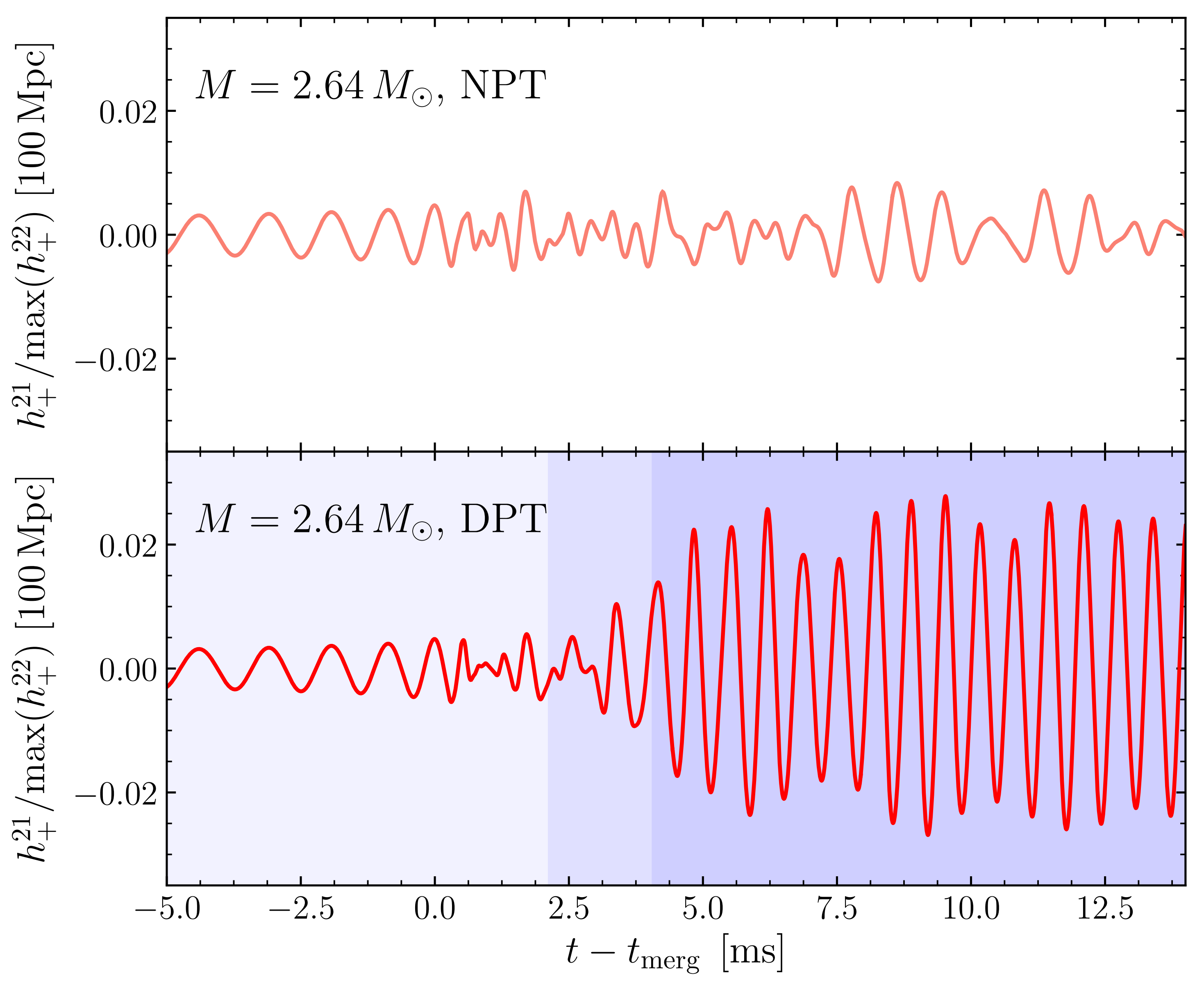
Why DPT is the most interesting case

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



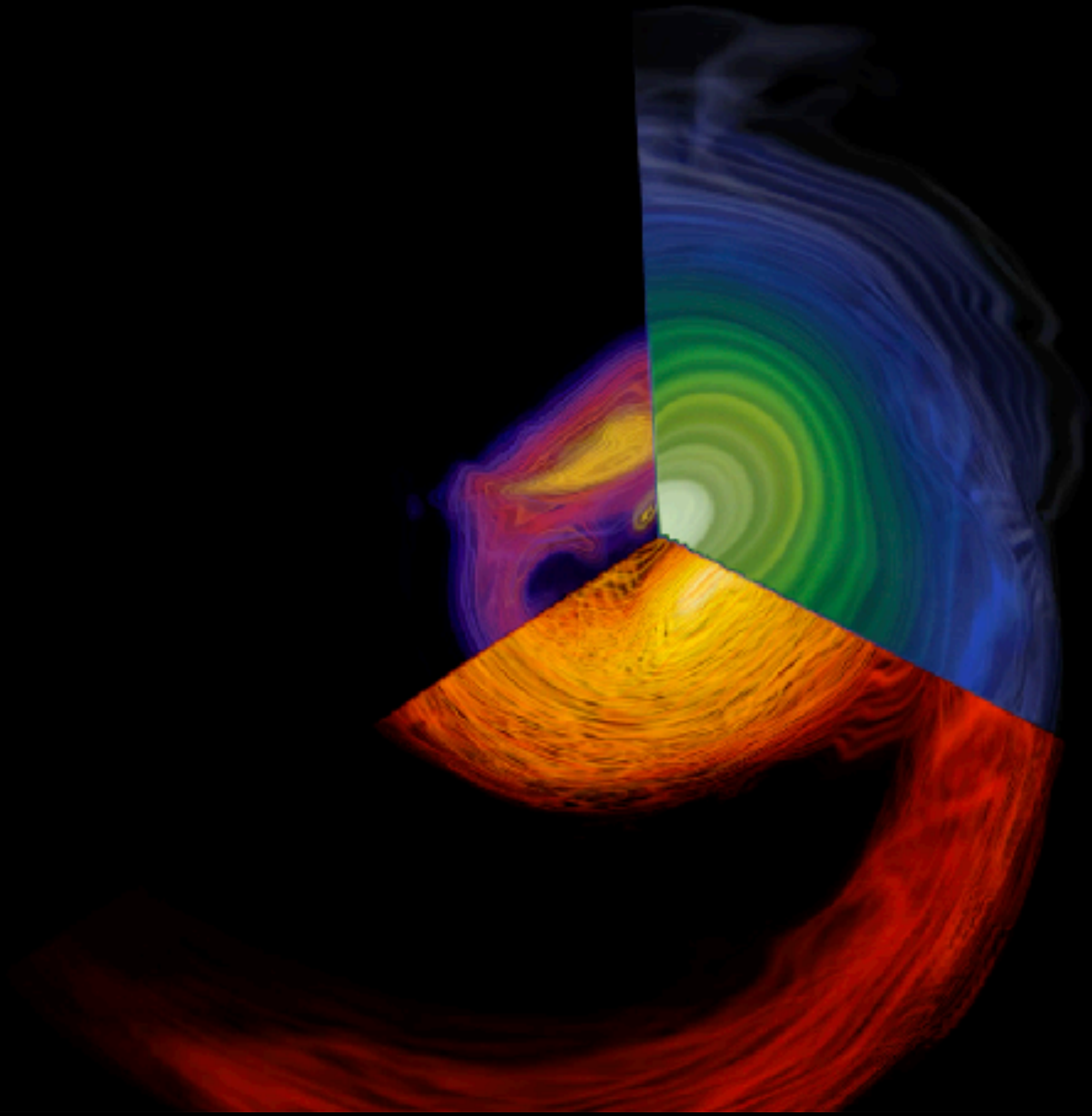
Why DPT is the most interesting case

Another signatures is appearance of an $\ell = 2, m = 1$ mode



The mode is triggered by the PT and the non-axisymmetric deformations it produces.

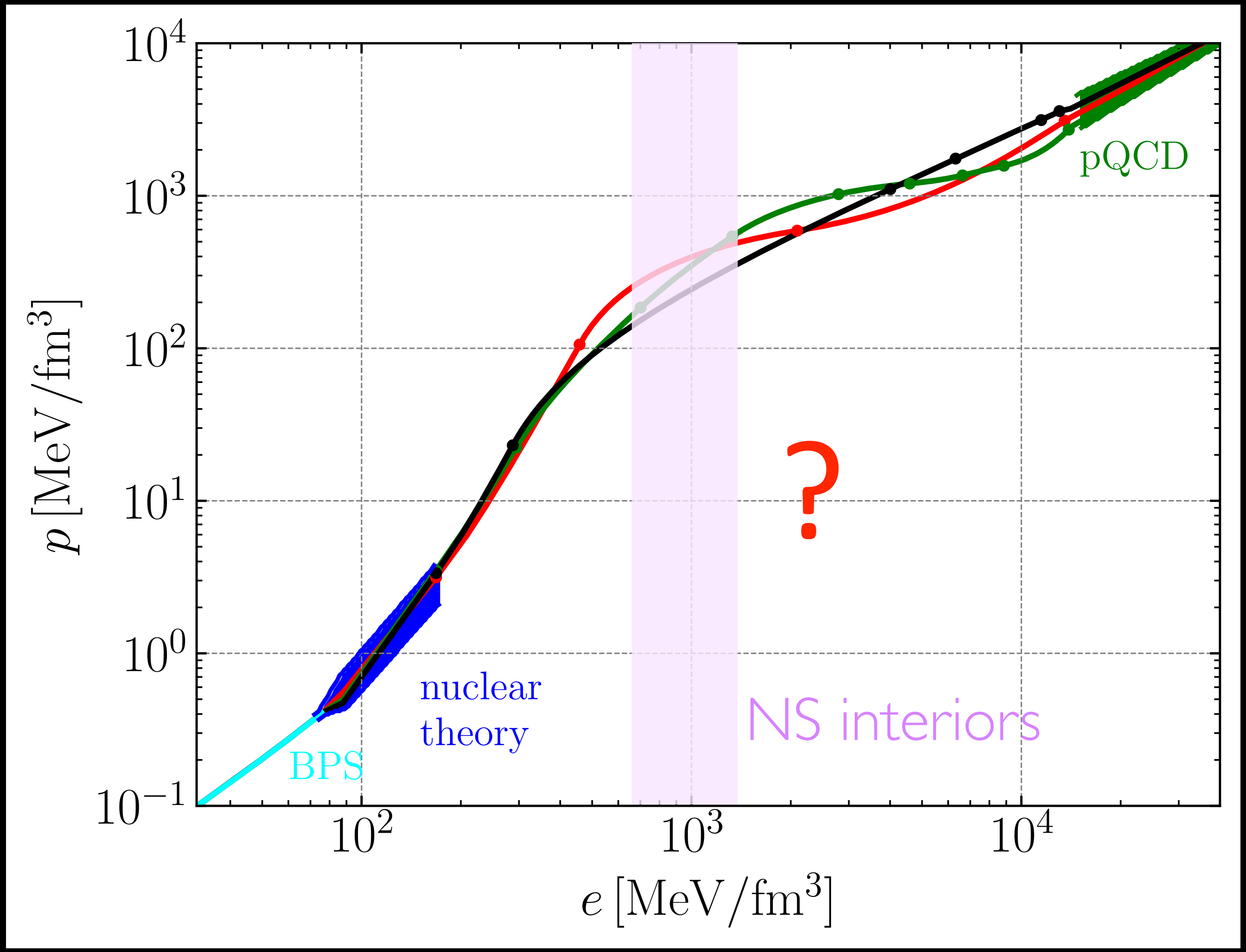
On the sound speed in neutron stars

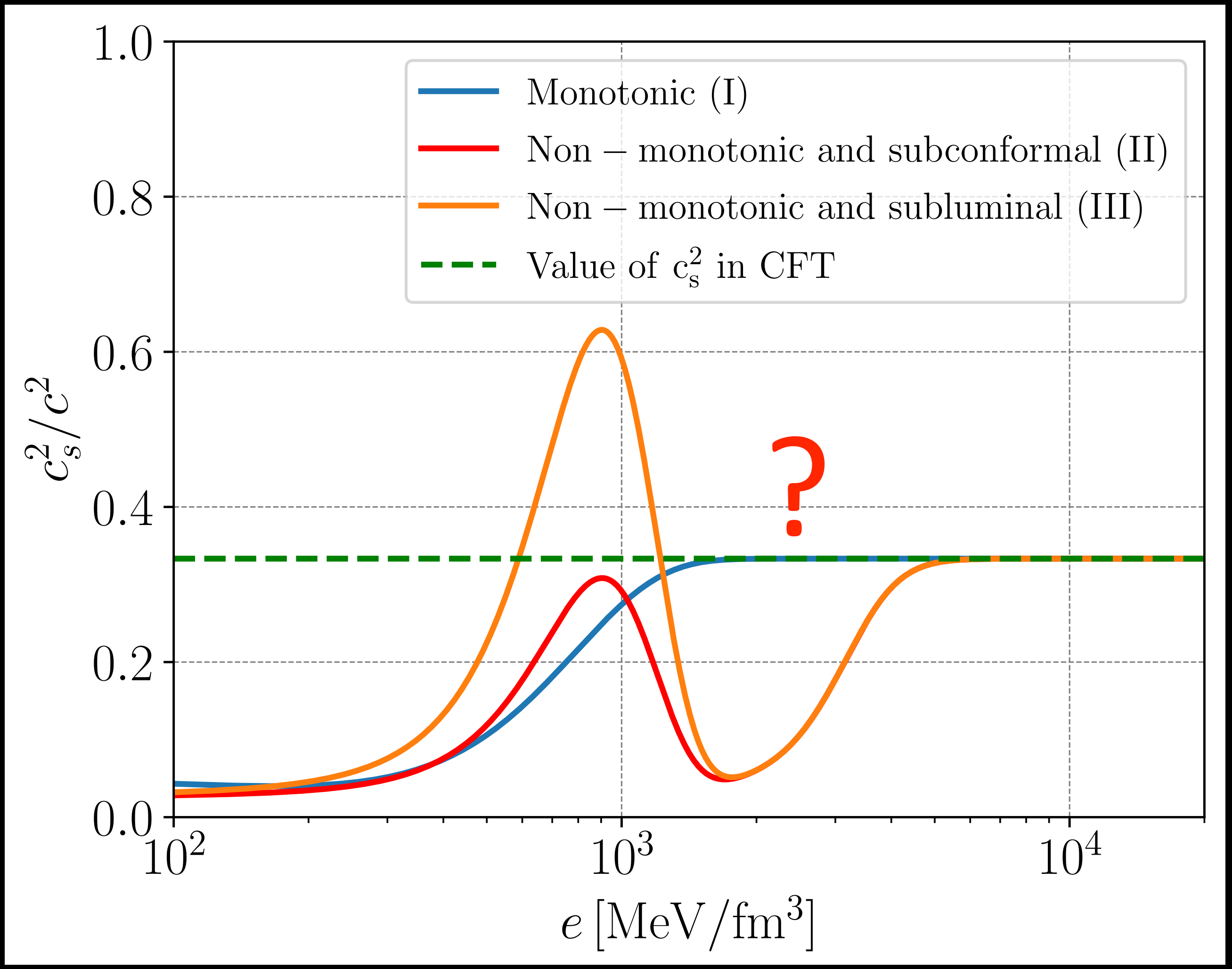


Altiparmak, Ecker, LR (2022a)
Ecker, LR (2022b)
Ecker, LR (2022c)

A very basic question

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





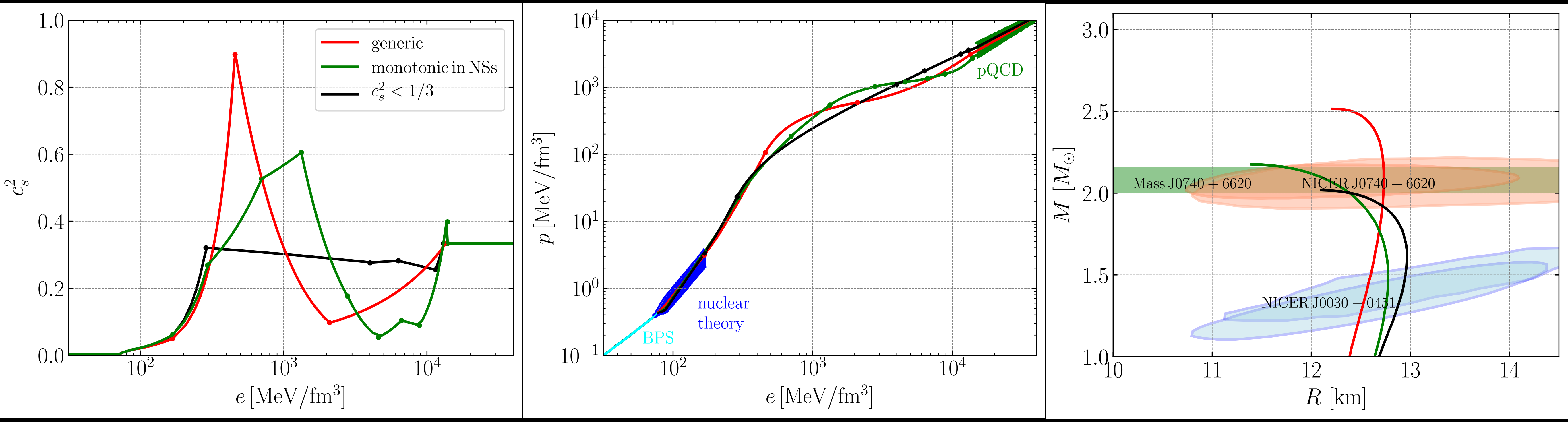
i) monotonic and sub-conformal: $c_s^2 < 1/3$;

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

iii) non-monotonic and sub-luminal: $c_s^2 < 1$

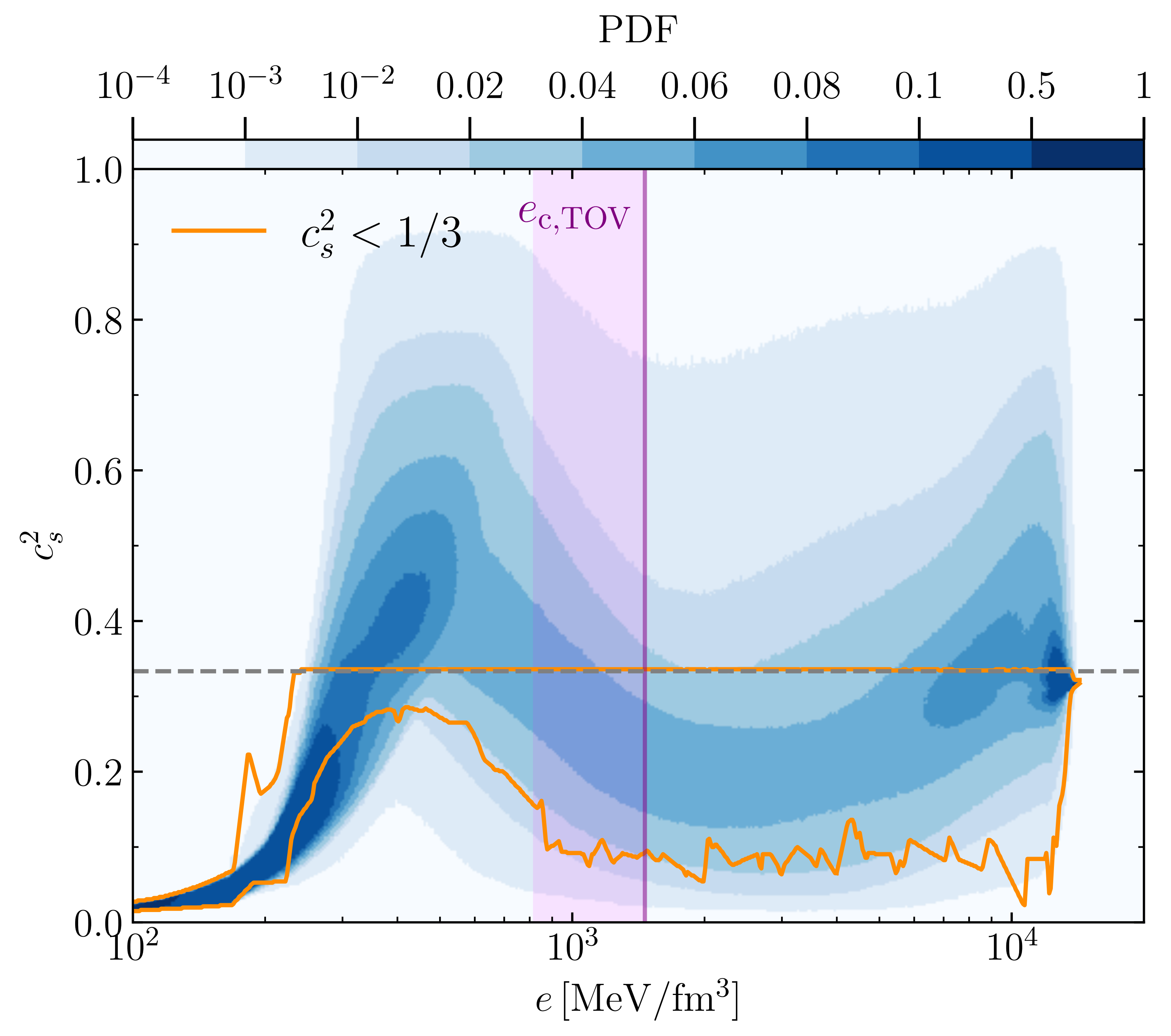
- Lacking stronger constraints, an **agnostic approach** is viable and followed by many (eg piecewise polytropes, Most+ 2018)

- 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 1.5x10^7 times…
- In this way, ~ 10% of our EOSs survives and provides robust statistics from which we compute PDFs.

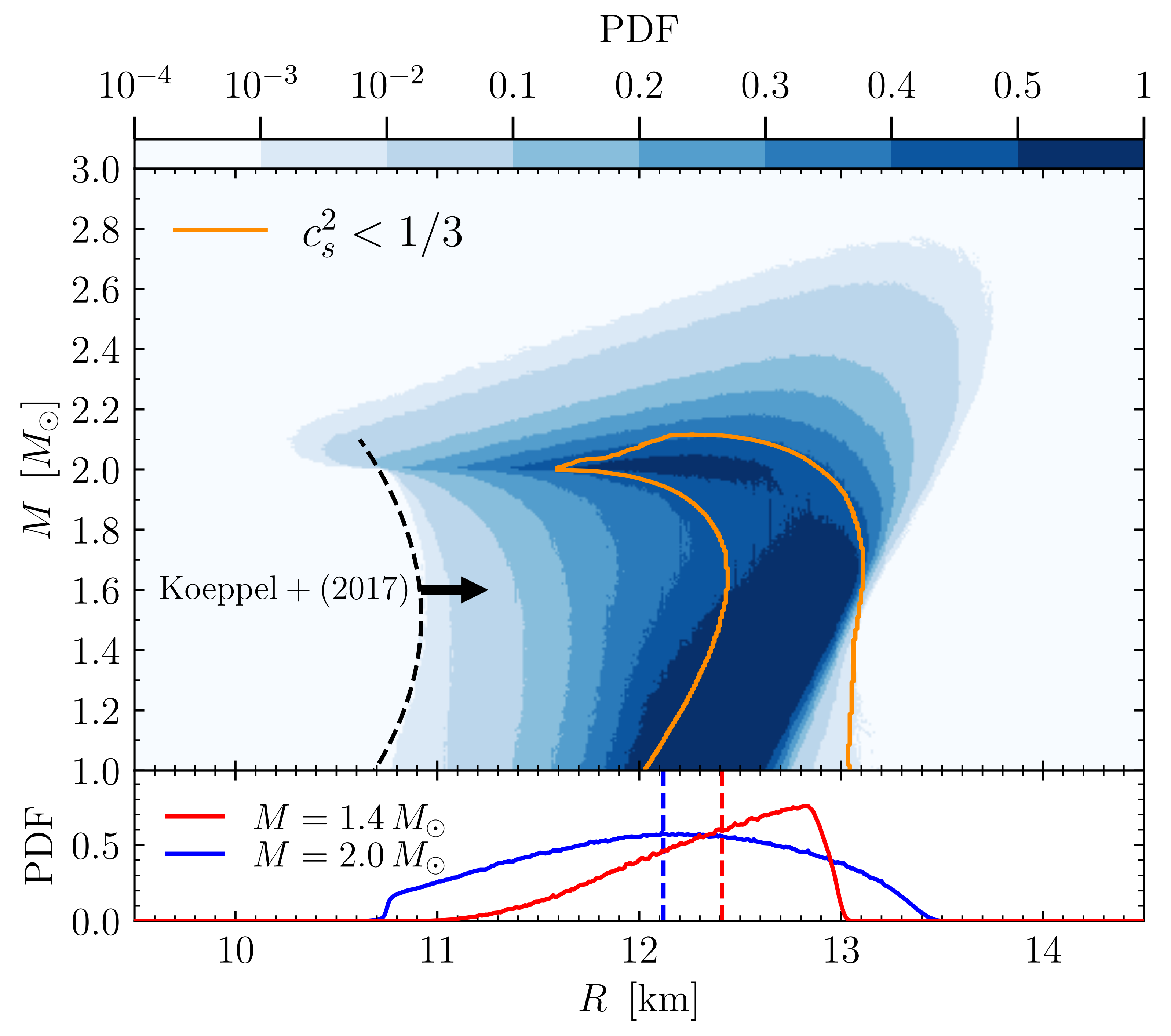
Sound speed PDF



Orange line marks region of sub-conformal EOSs (0.03%).

No monotonic sub-conformal EOS found.

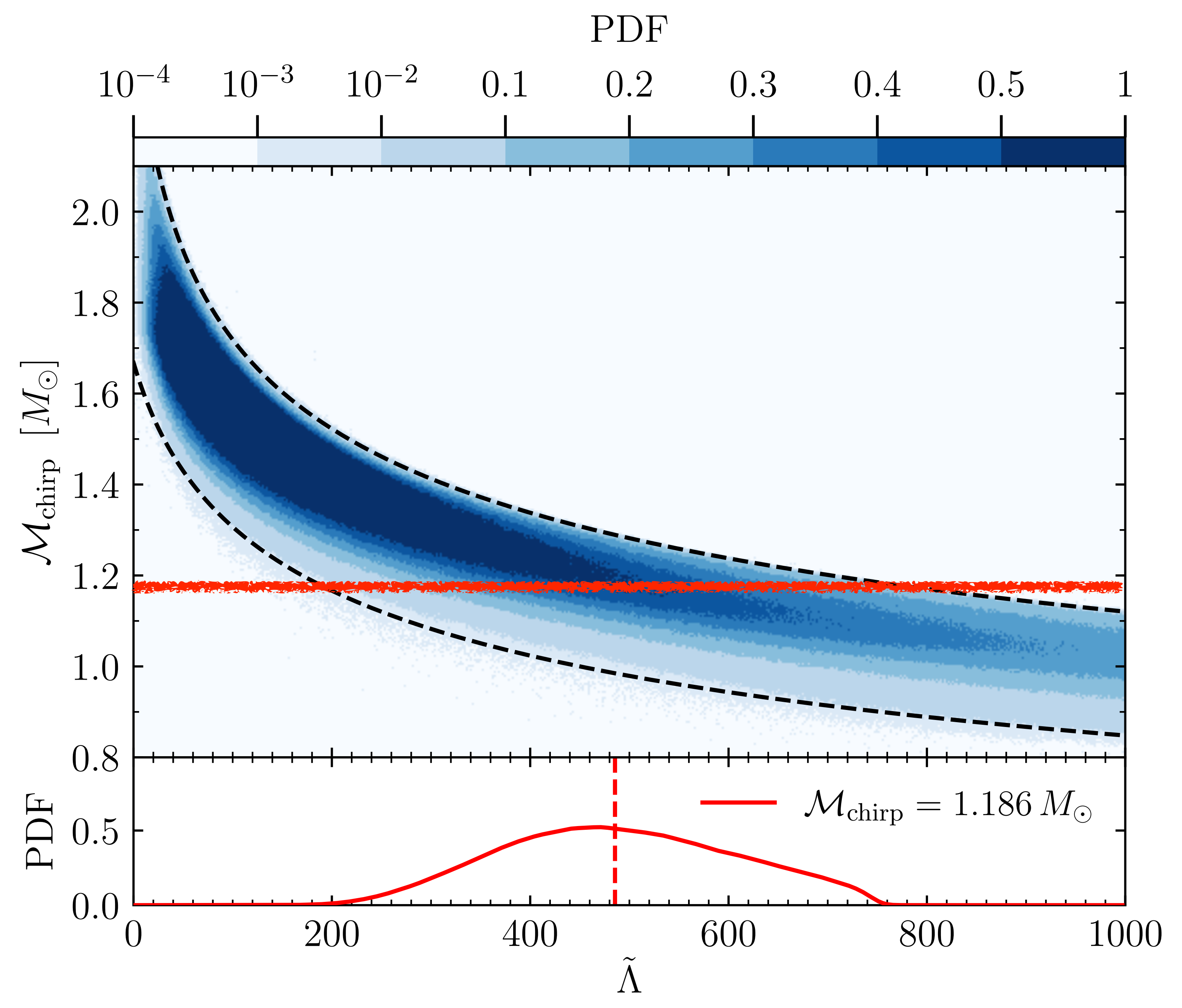
A more comprehensive picture



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

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

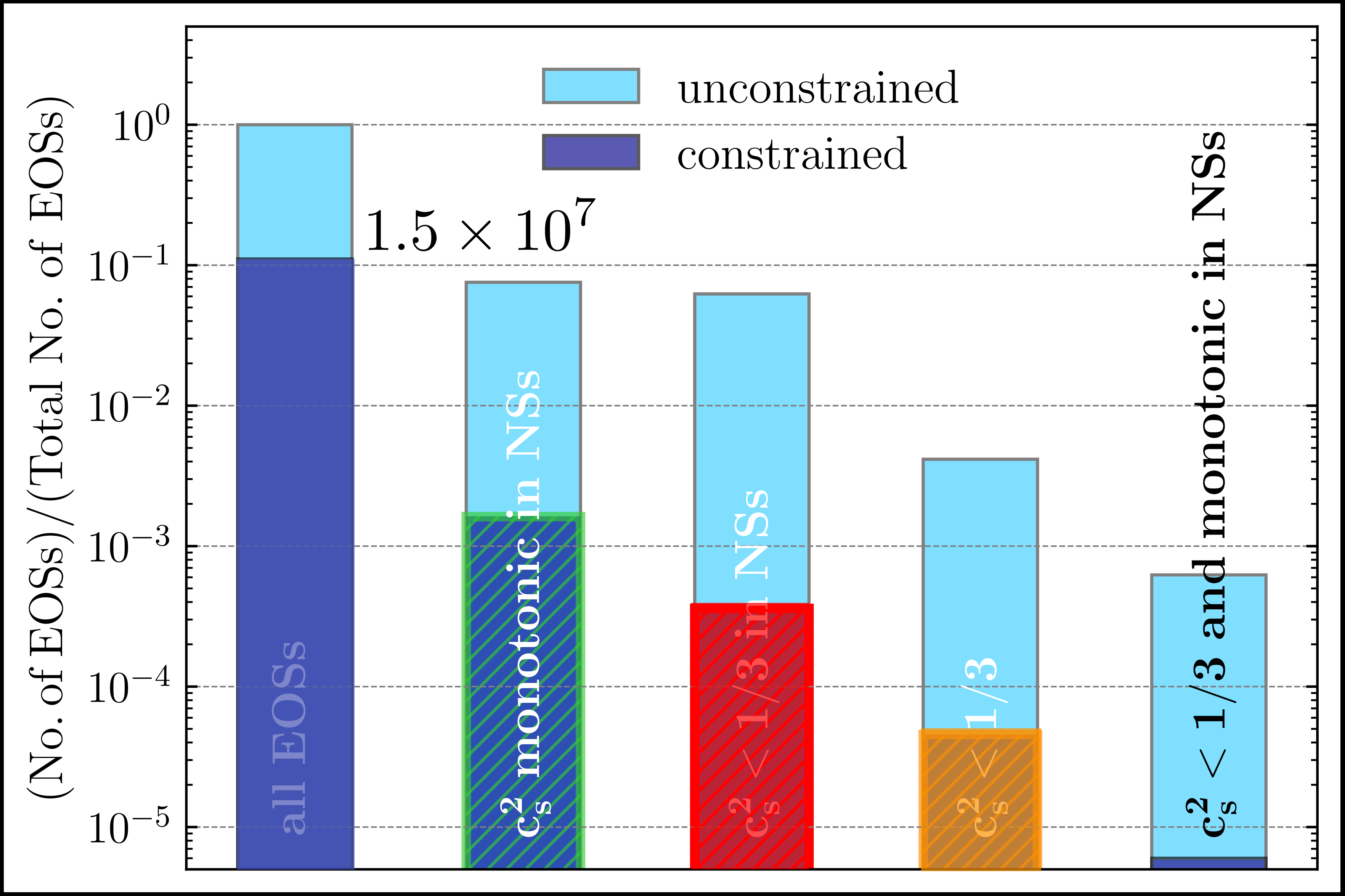
A more comprehensive picture



Simple behaviour of binary tidal deformability: $\tilde{\Lambda}_{\rm min\,(max)} = a + b\,\mathcal{M}^c_{\rm chirp}$

Straightforward bounds once a detection is made.

In summary…



i) monotonic and sub-conformal: $c_s^2 < 1/3$; [0.004%]

ii) non-monotonic and sub-conformal in NSs: $c_s^2 < 1/3$; [0.03%]

iii) nonmonotonic and sub-luminal: $c_s^2 < 1$; [10%]

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?

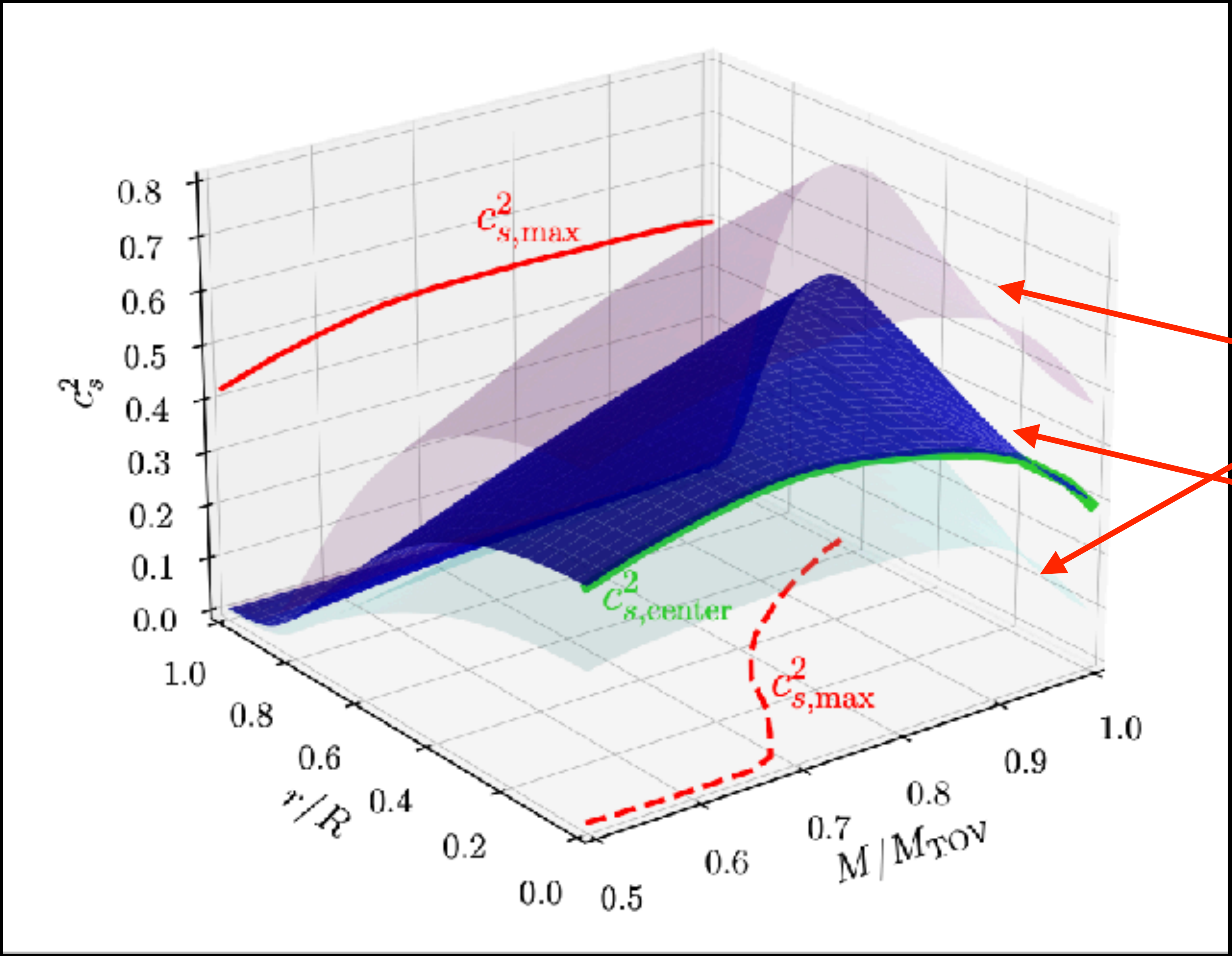
Hard to answer: every EOS will have its own *(M, R)* relation

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

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

A scale-independent representation

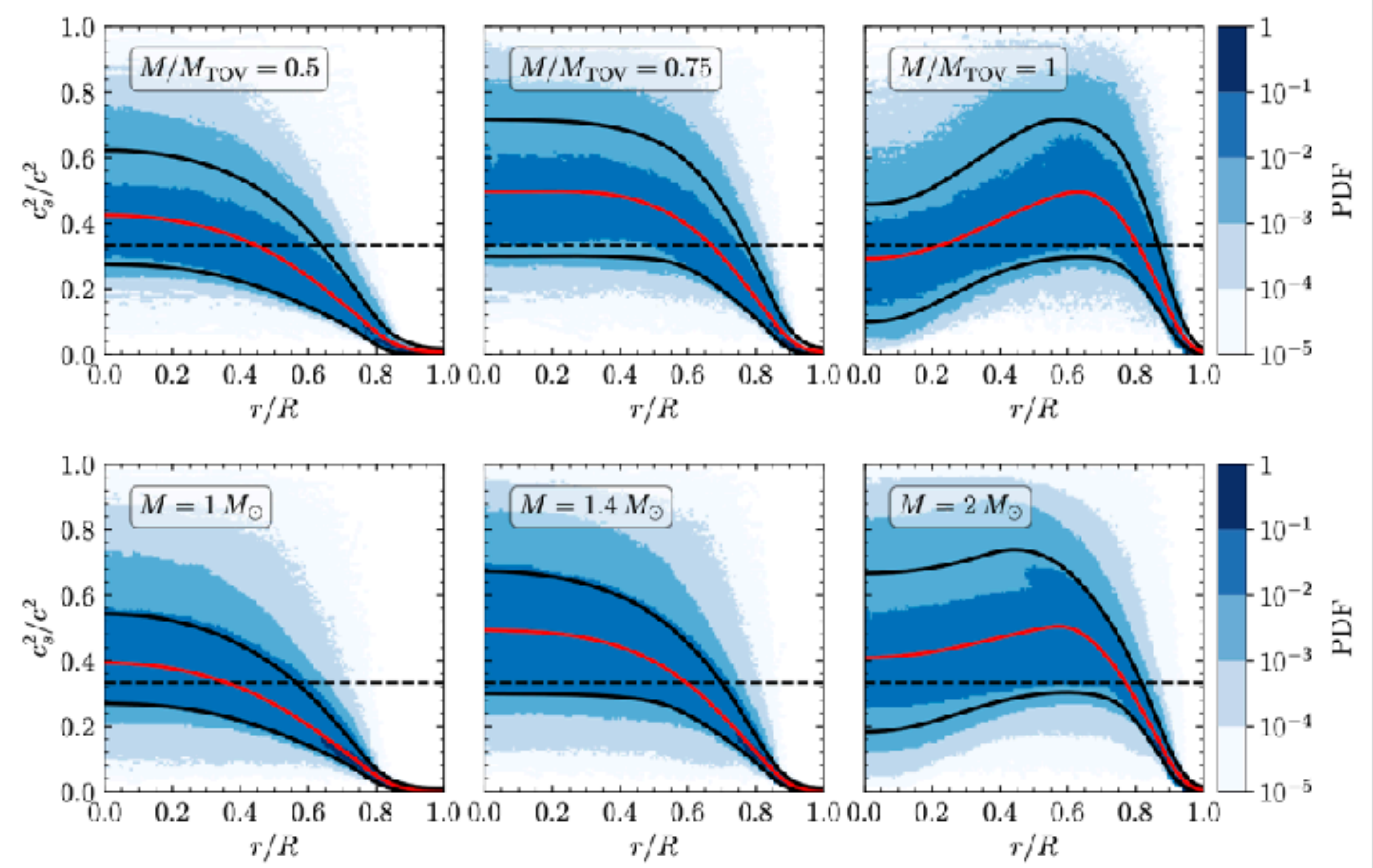
All information contained in a unit cube: $(c_s/c,\ r/R,\ M/M_{\mathrm{TOV}})$



95% confidence

median

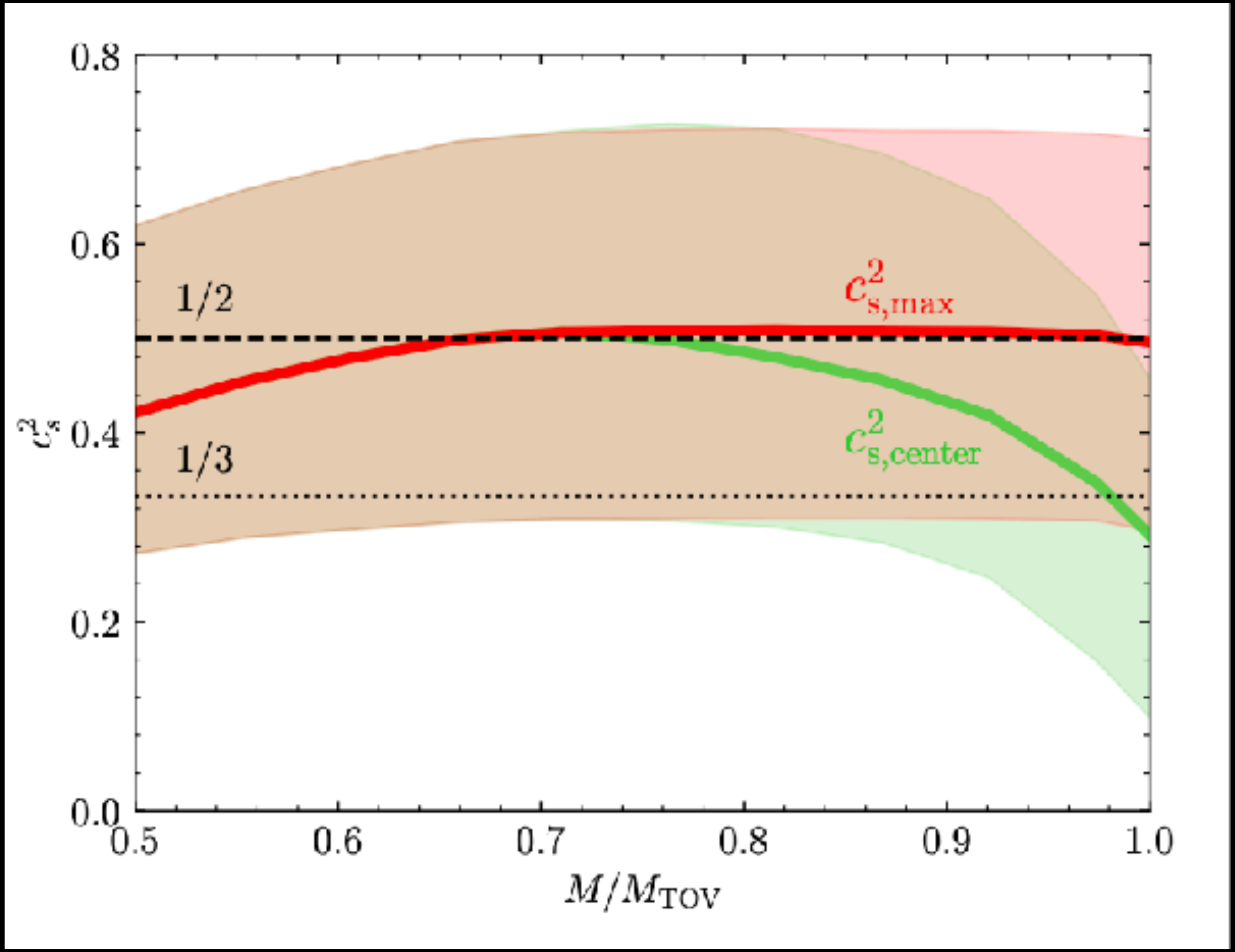
A scale-independent representation



"Light" stars: sound speed monotonic with maximum at stellar center

"Heavy" stars: sound speed non-monotonic with maximum far from stellar center (r/R~0.7)

A scale-independent representation



- Sound speed at center ($c^2_{s,\mathrm{center}}$) decreases as masses increase
- Maximum sound speed ($c^2_{s,\mathrm{max}}$) reaches a constant value; very robust behaviour (the constant varies not behaviour); origin not totally clear.

Conclusions

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

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

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

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

✳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)