Binary Neutron Stars: from macroscopic collisions to microphysics

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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

The two-body problem in GR

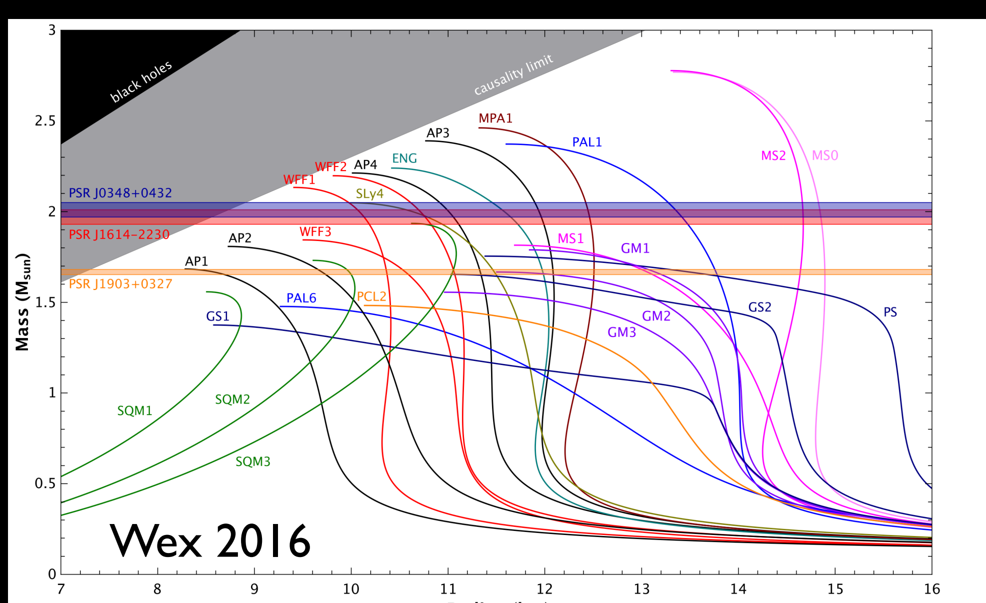
- For black holes the process is very **simple:**

BH + BH → BH + GWs

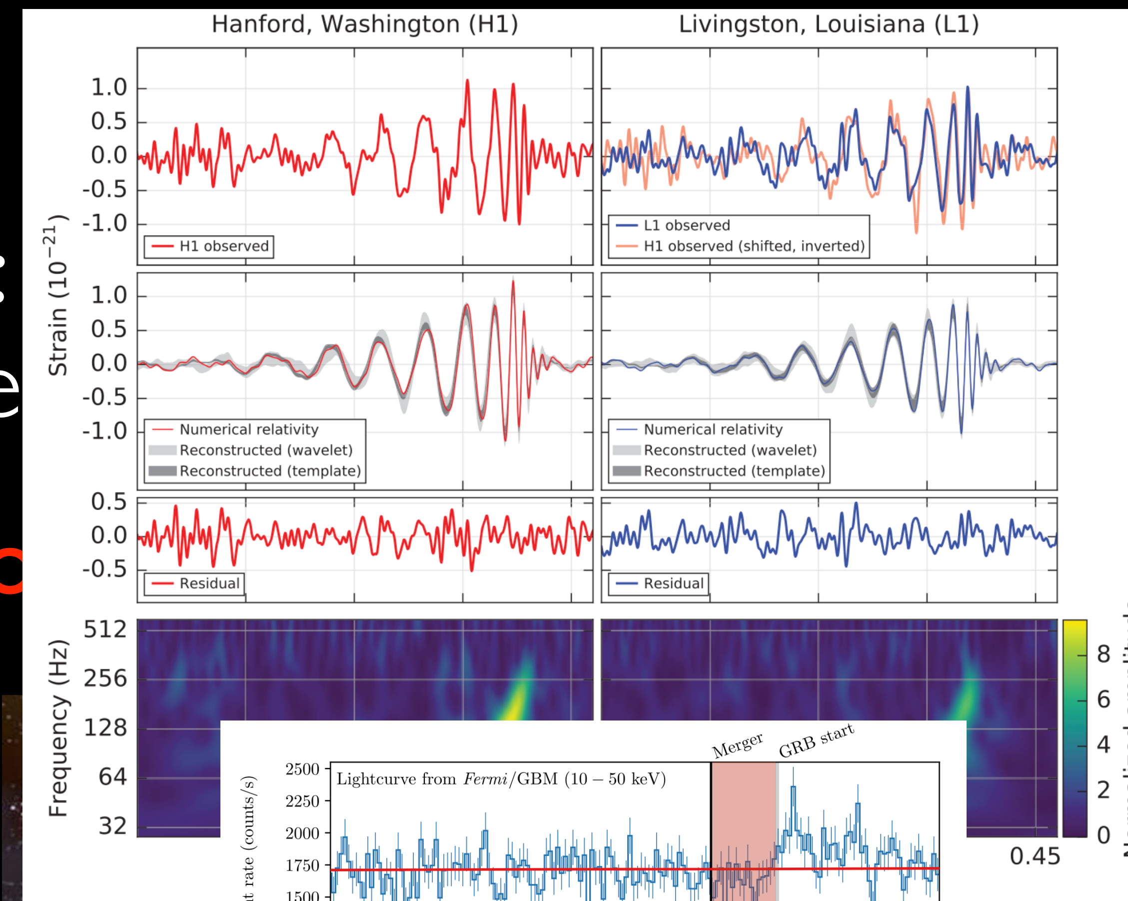
- For NSs the question is more **subtle:**
hyper-massive neutron star (HMNS), ie

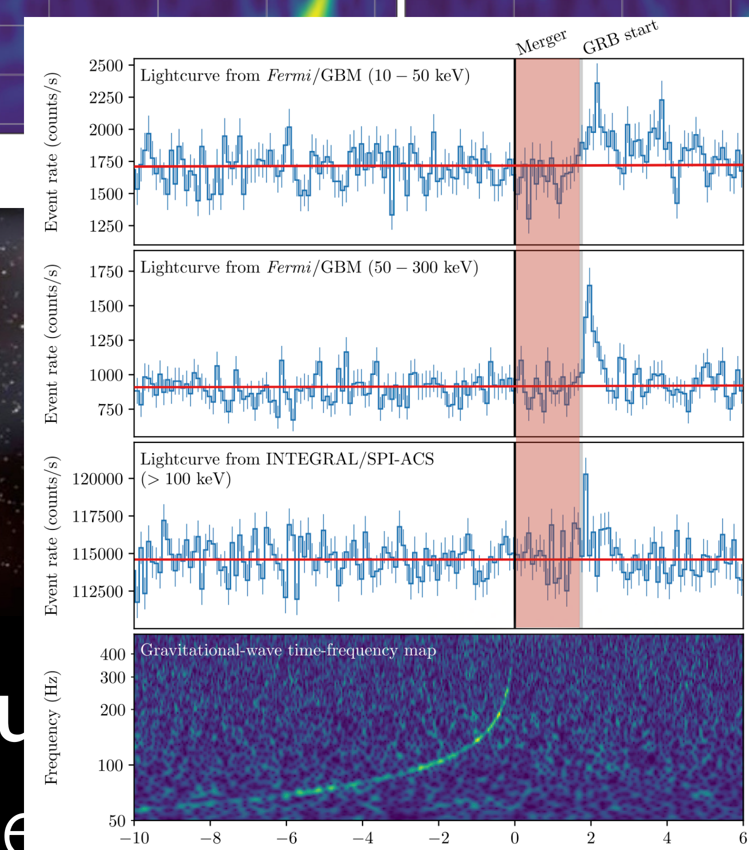
NS + NS → HMNS+... ? → BH+to

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



GW150914





- BH+toru us

on the ce RBs

GW170817

The two-body problem in GR

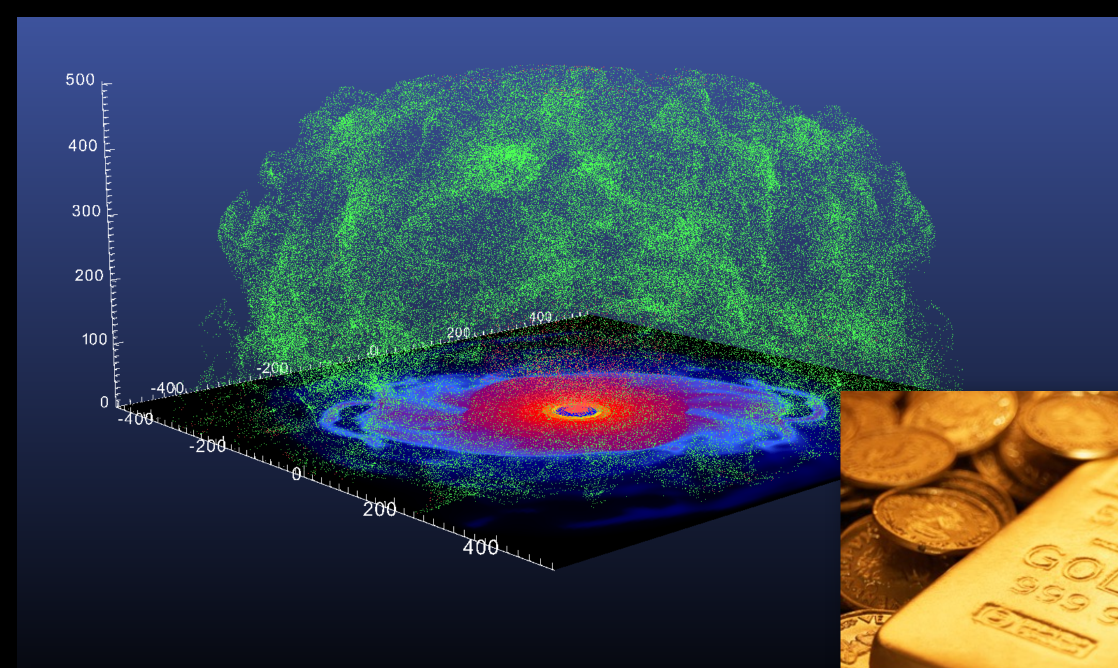
- For black holes the process is very **simple**:

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:

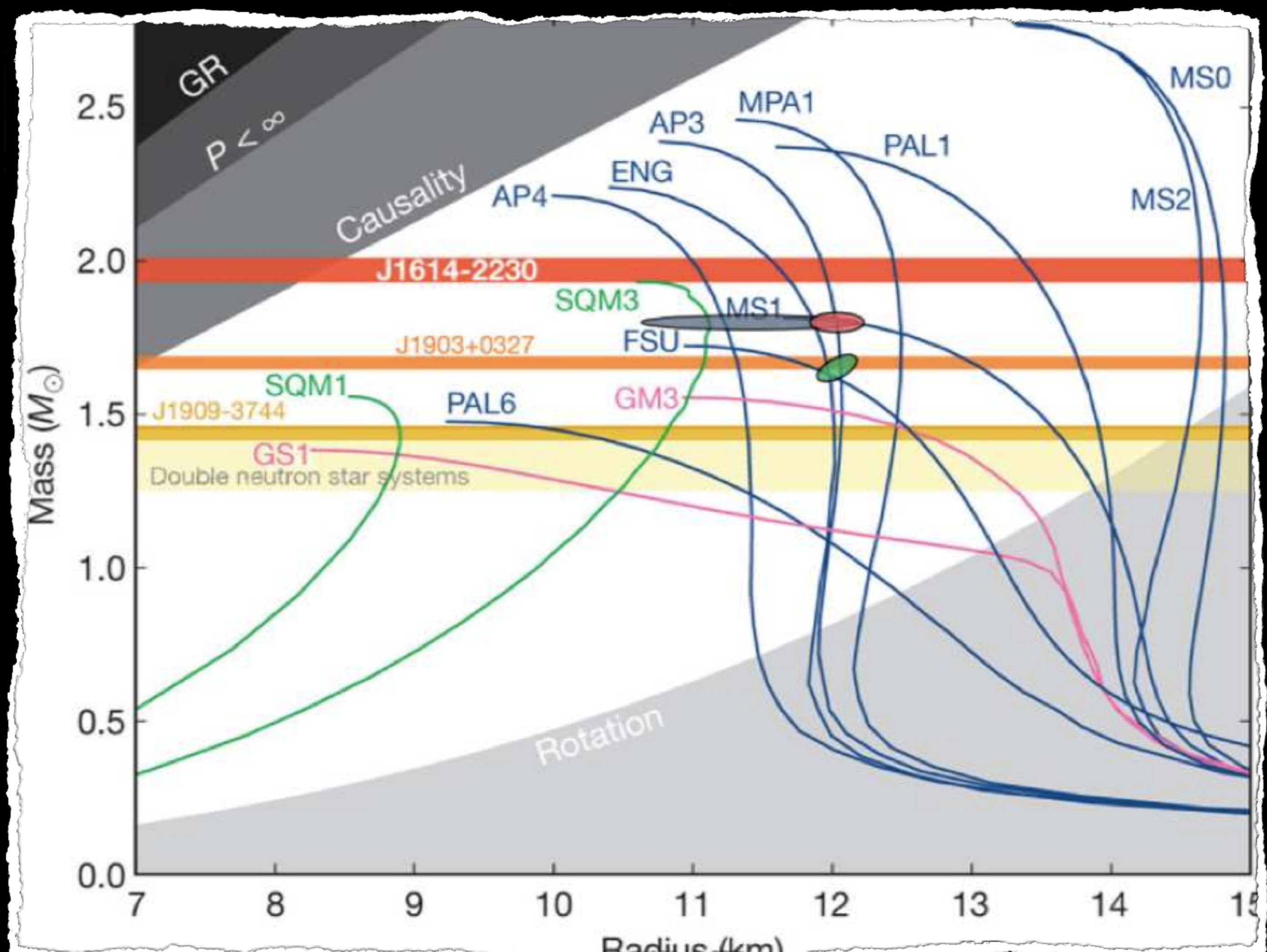
NS + NS ⟶ HMNS+... ? ⟶ BH+torus+... ? ⟶ BH + GWs

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

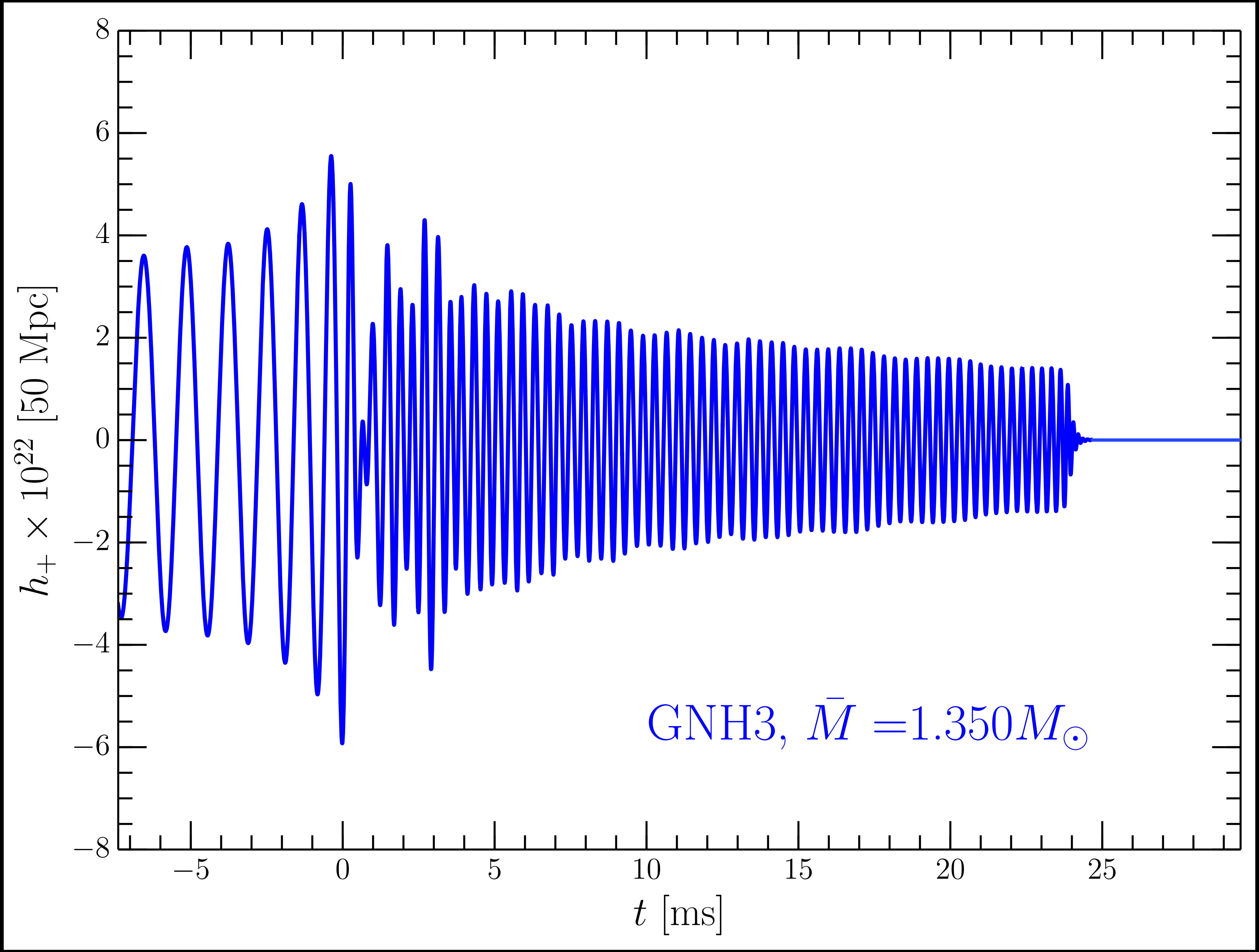


GW spectroscopy: EOS from frequencies

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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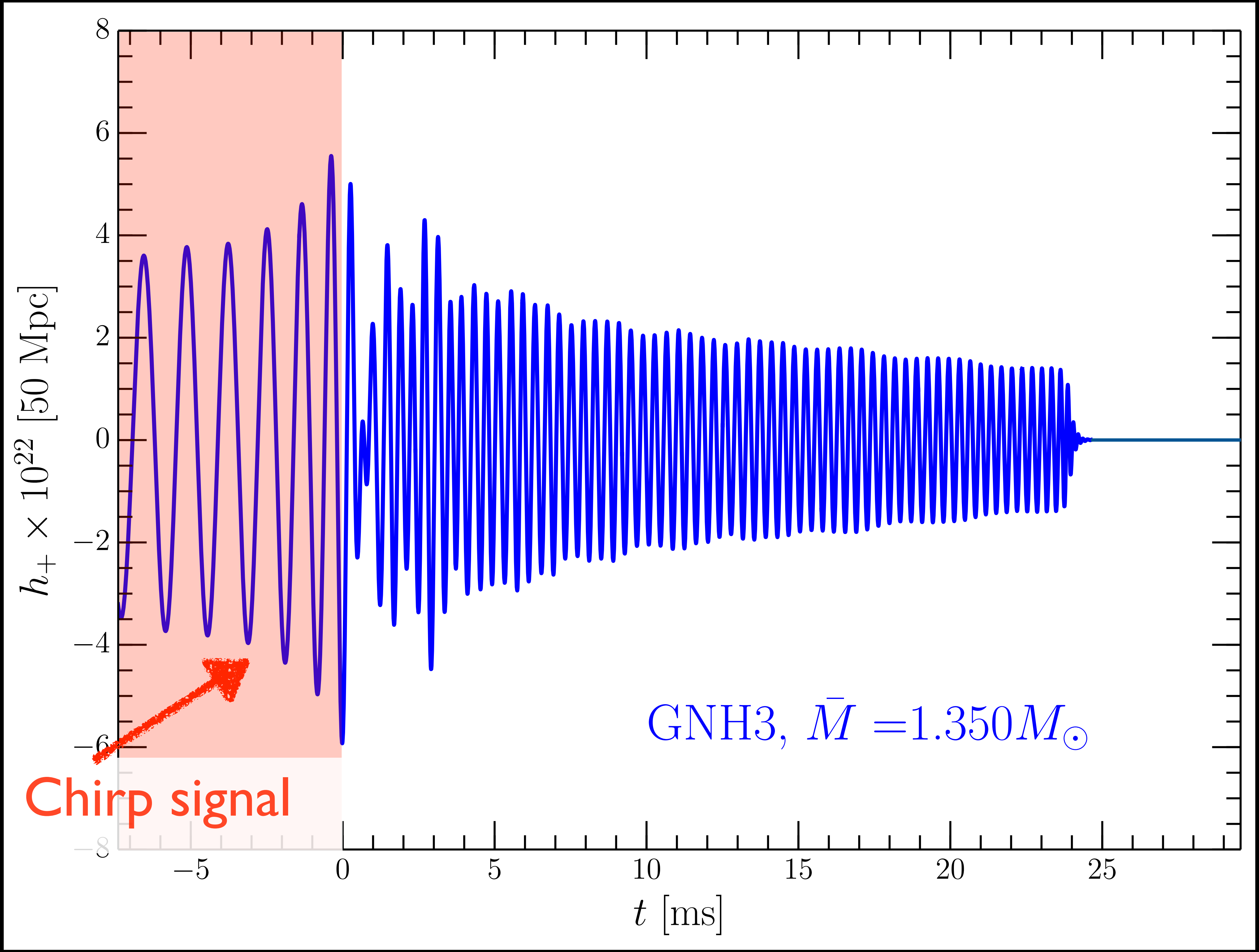
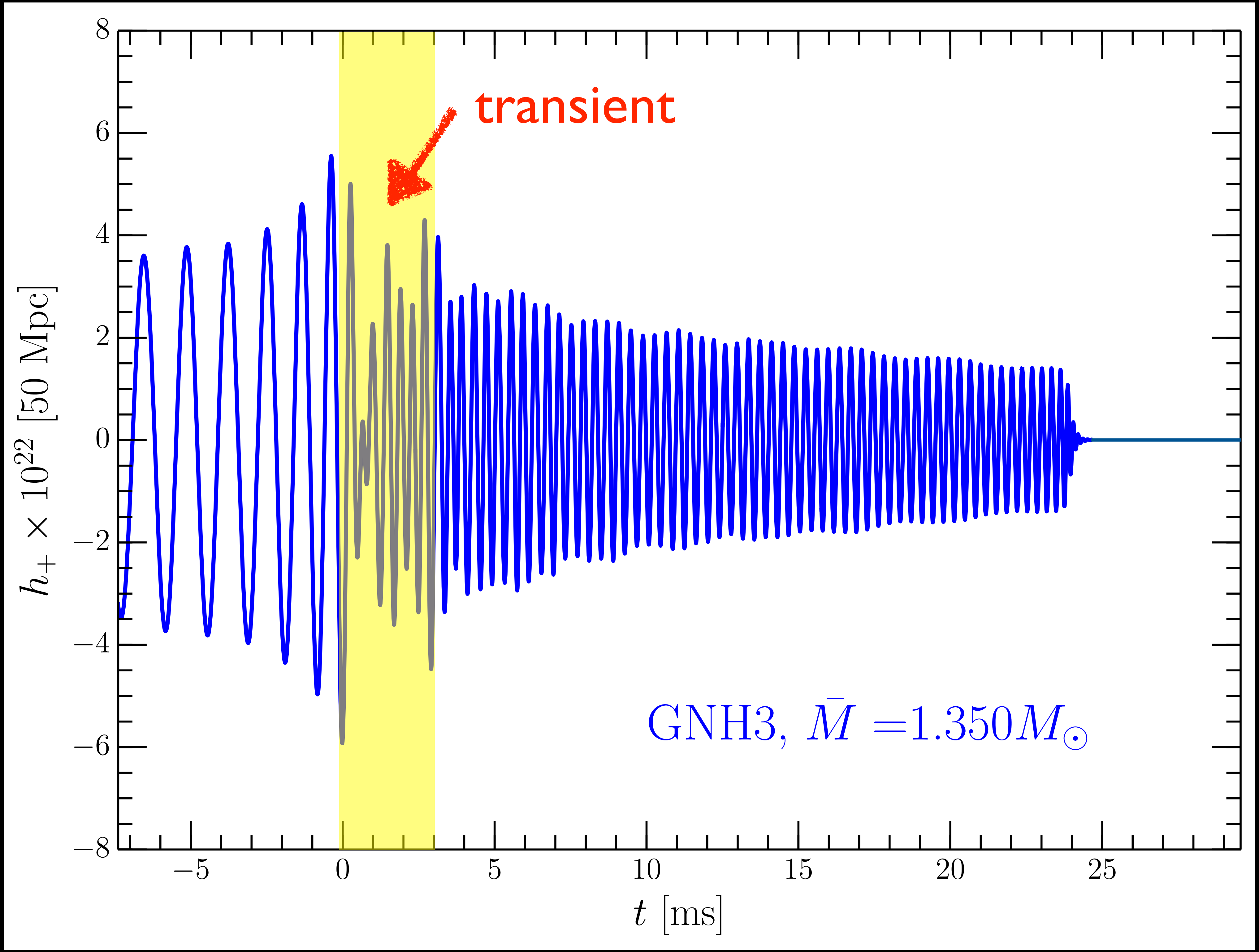


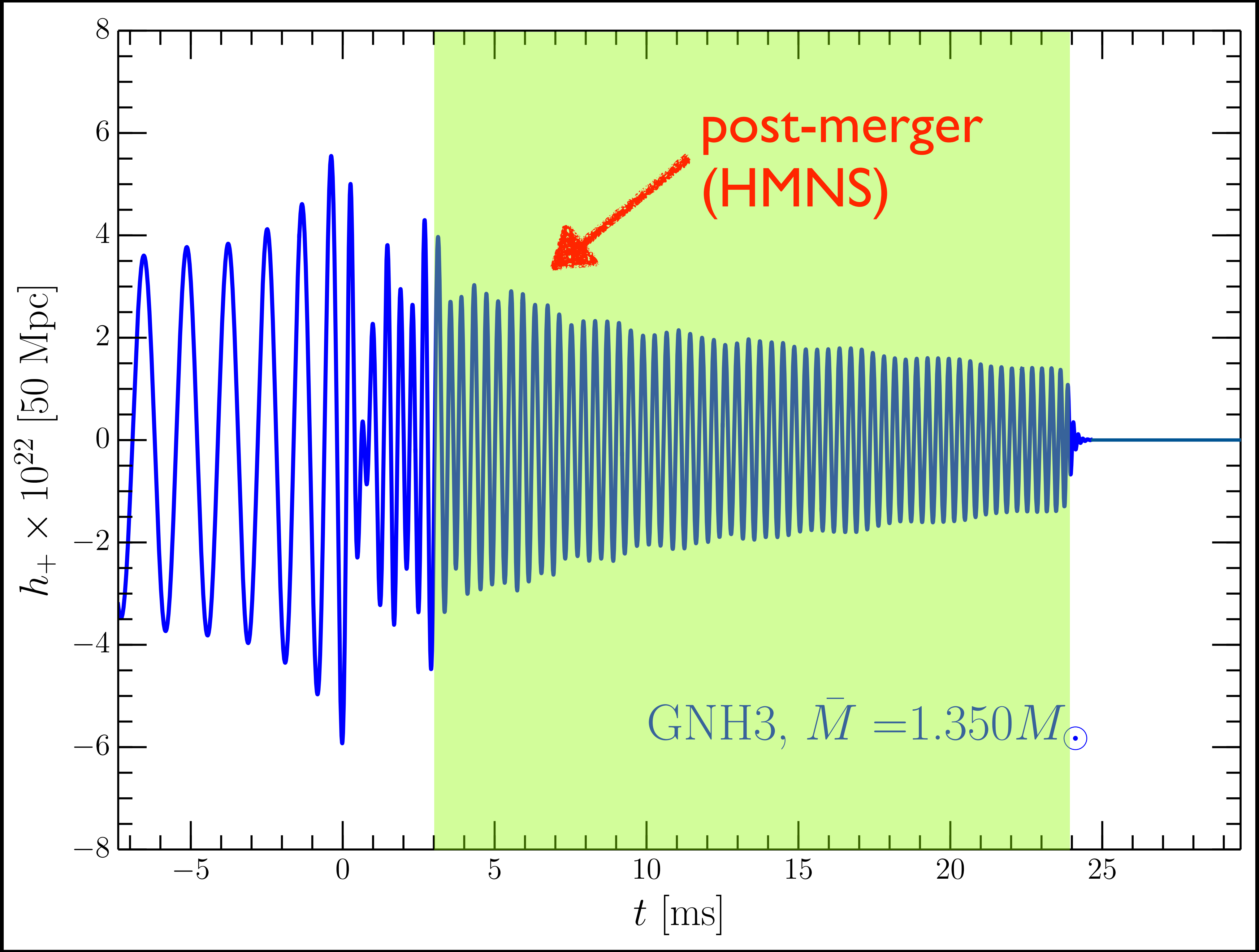
Inspiral: well approximated by PN/EOB; tidal effects important

Anatomy of the GW signal



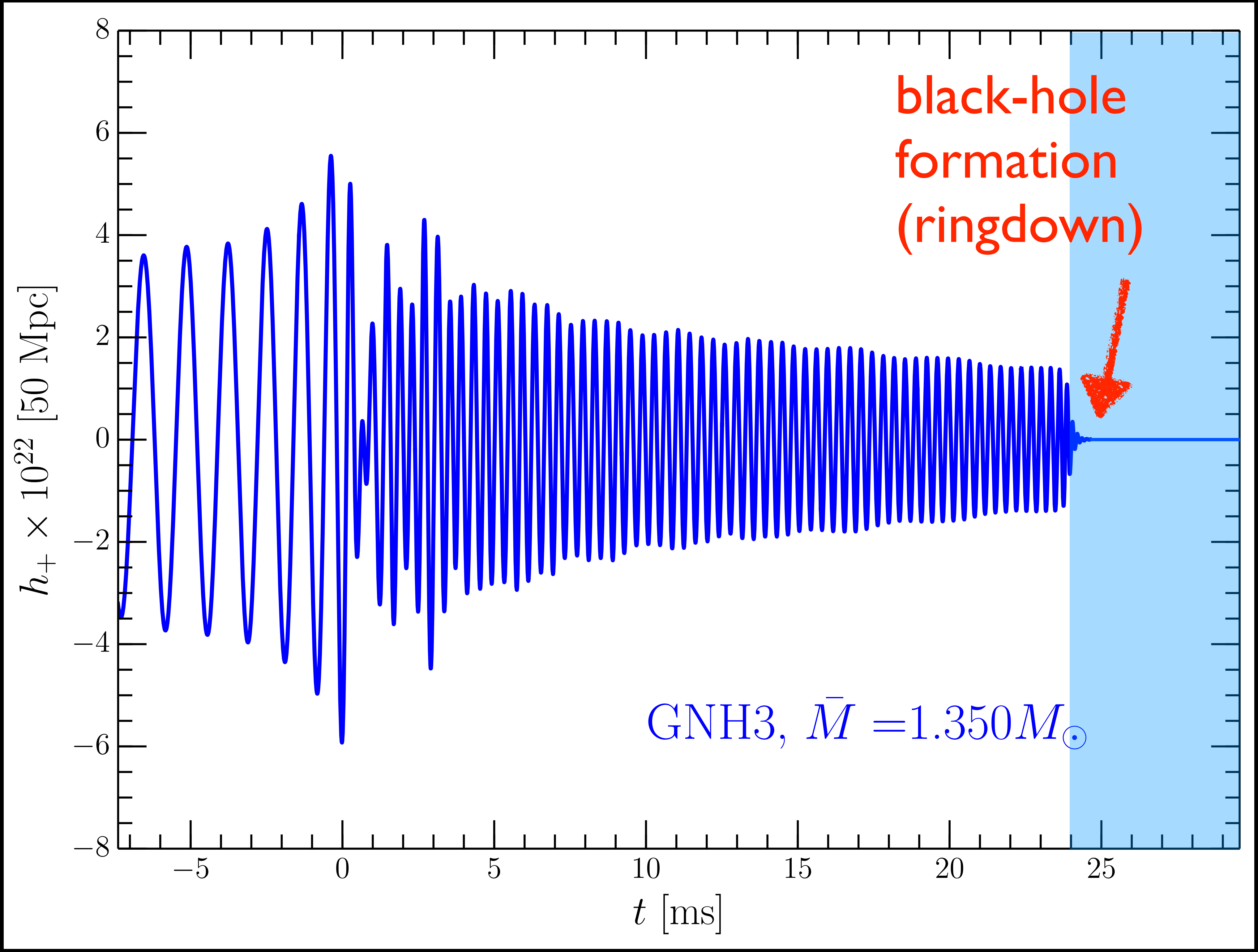
Merger: highly nonlinear but analytic description possible

Anatomy of the GW signal



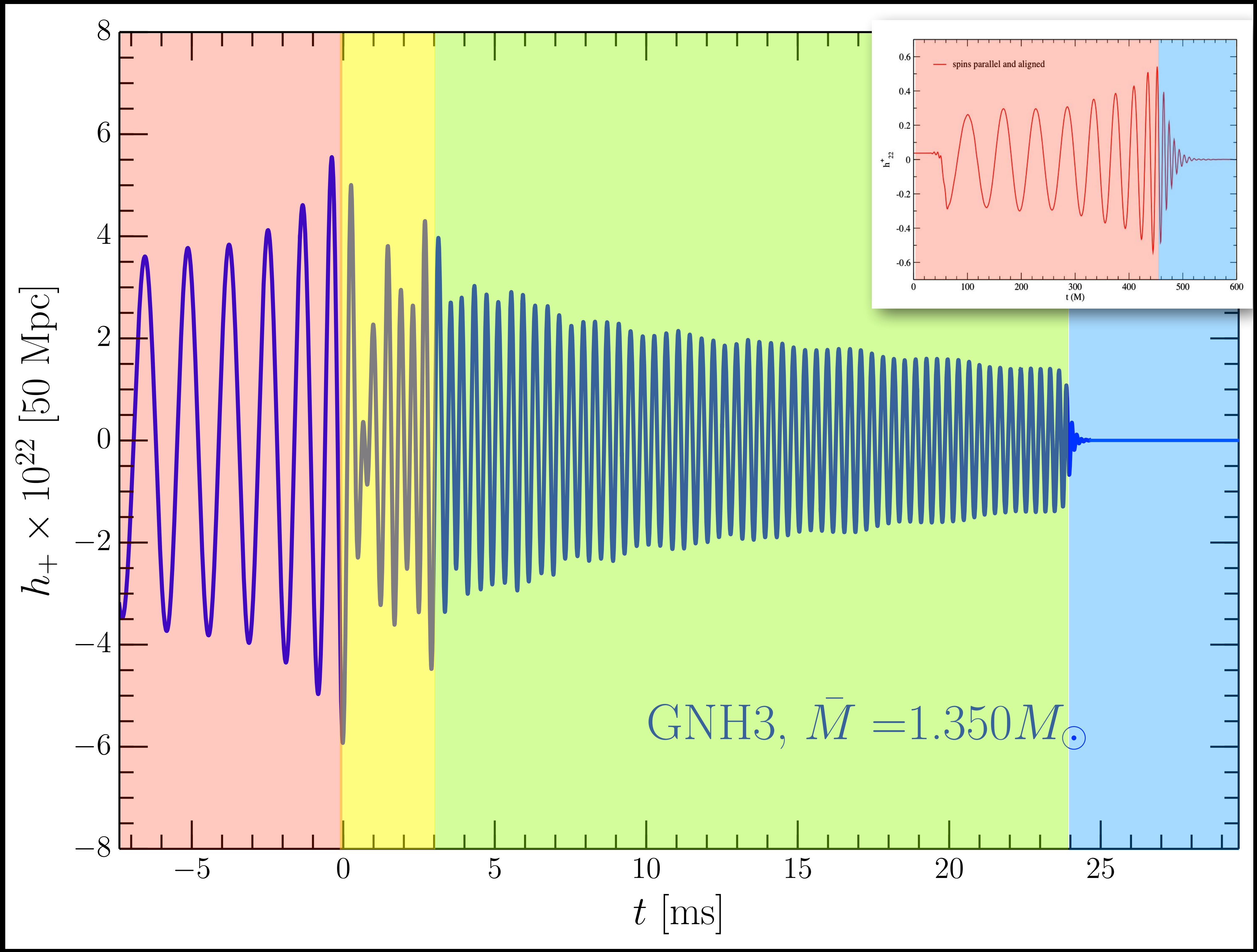
post-merger: quasi-periodic emission of bar-deformed HMNS

Anatomy of the GW signal



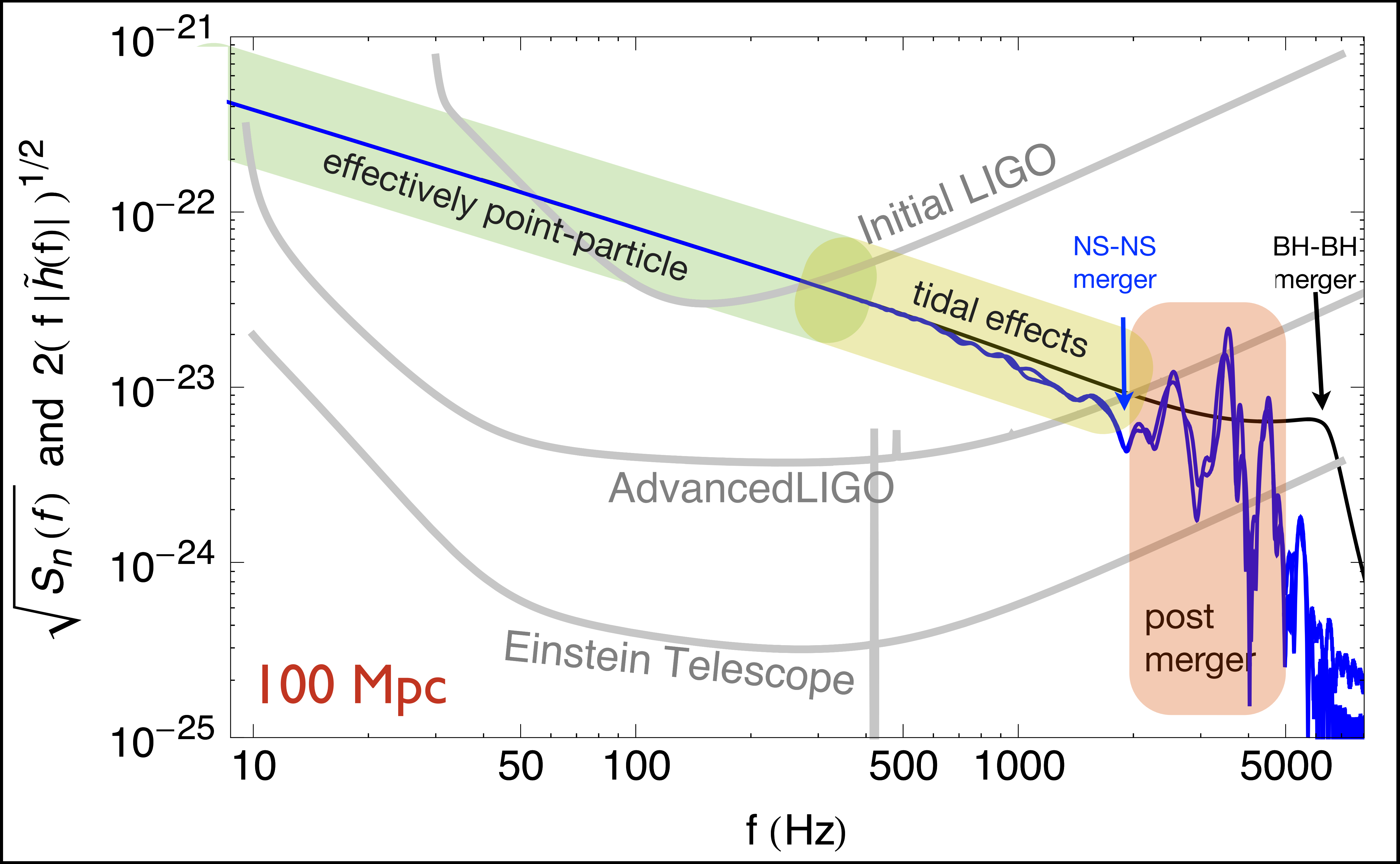
Collapse-ringdown: signal essentially shuts off

Anatomy of the GW signal



Postmerger signal: peculiar of binary NSs

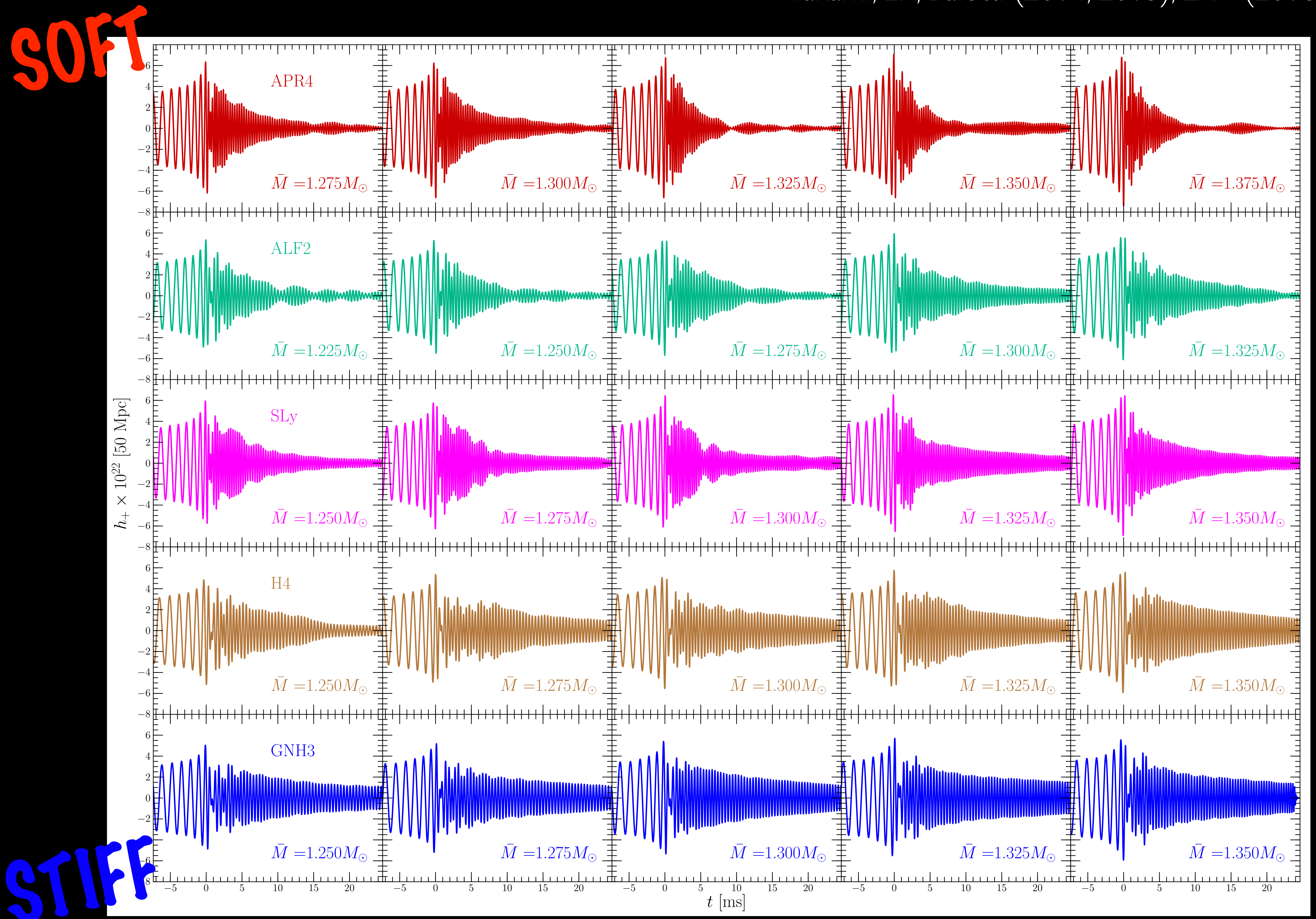
In frequency space



Read et al. (2013)

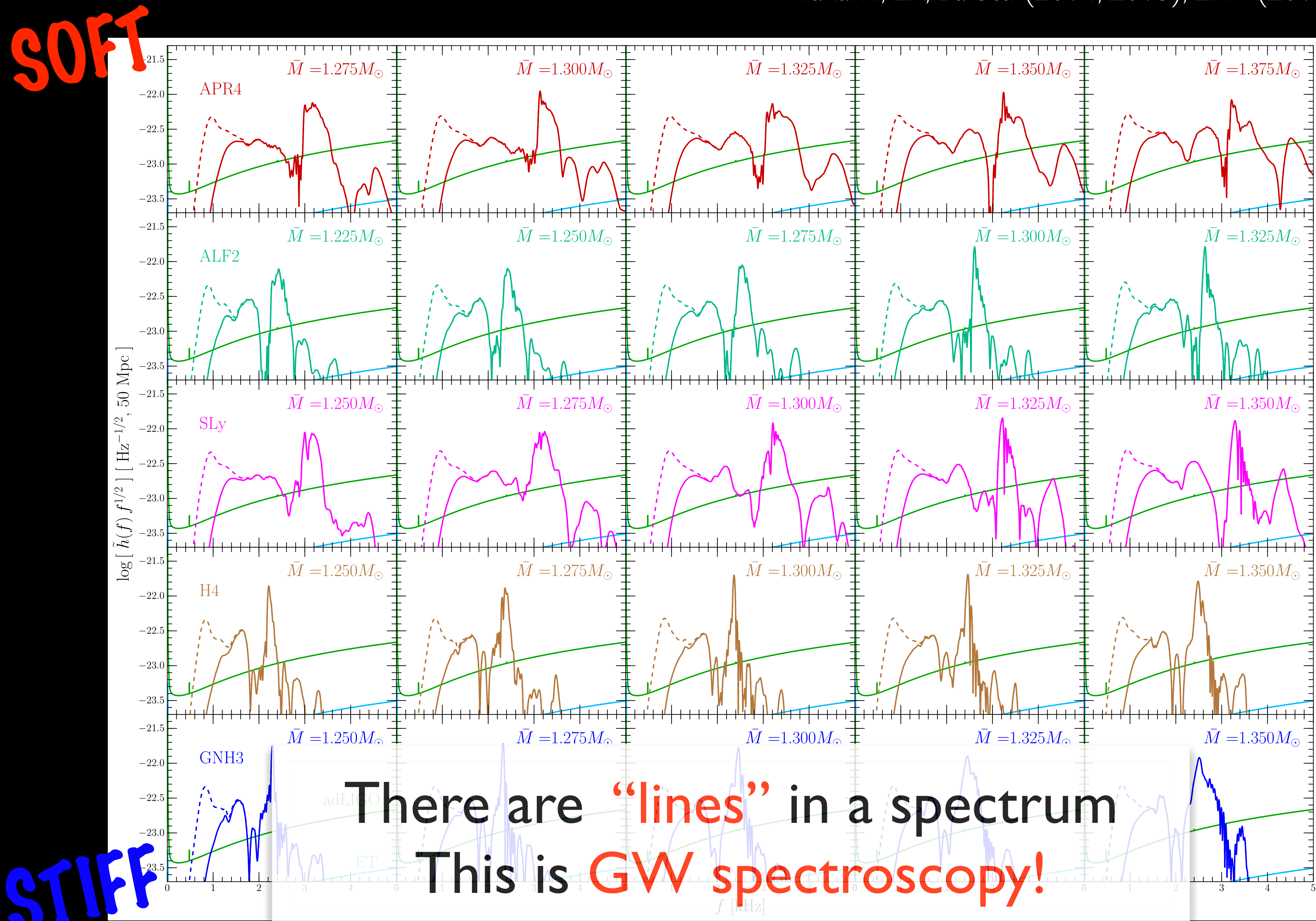
What we can do nowadays

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



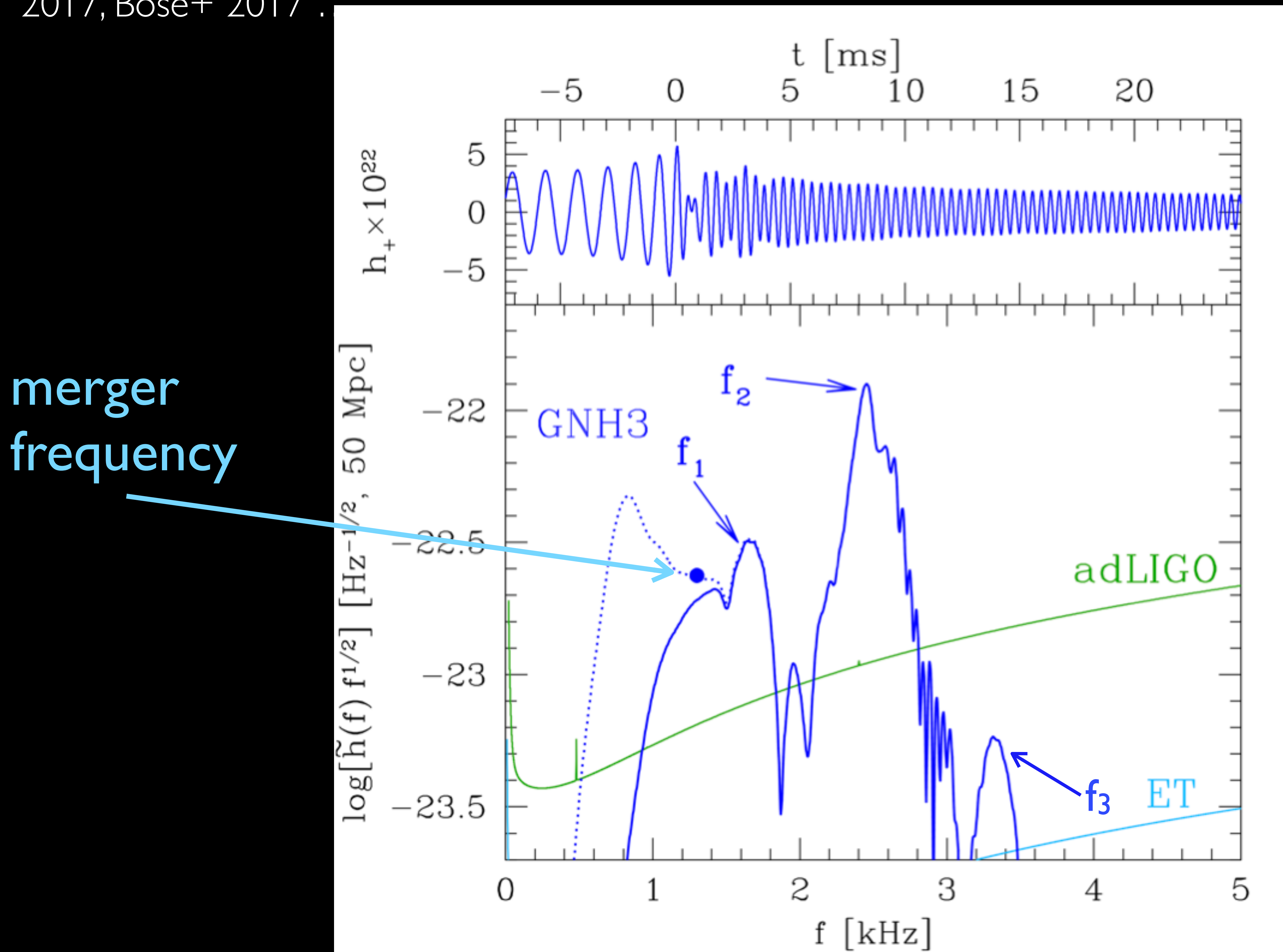
Extracting information from the EOS

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



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 .



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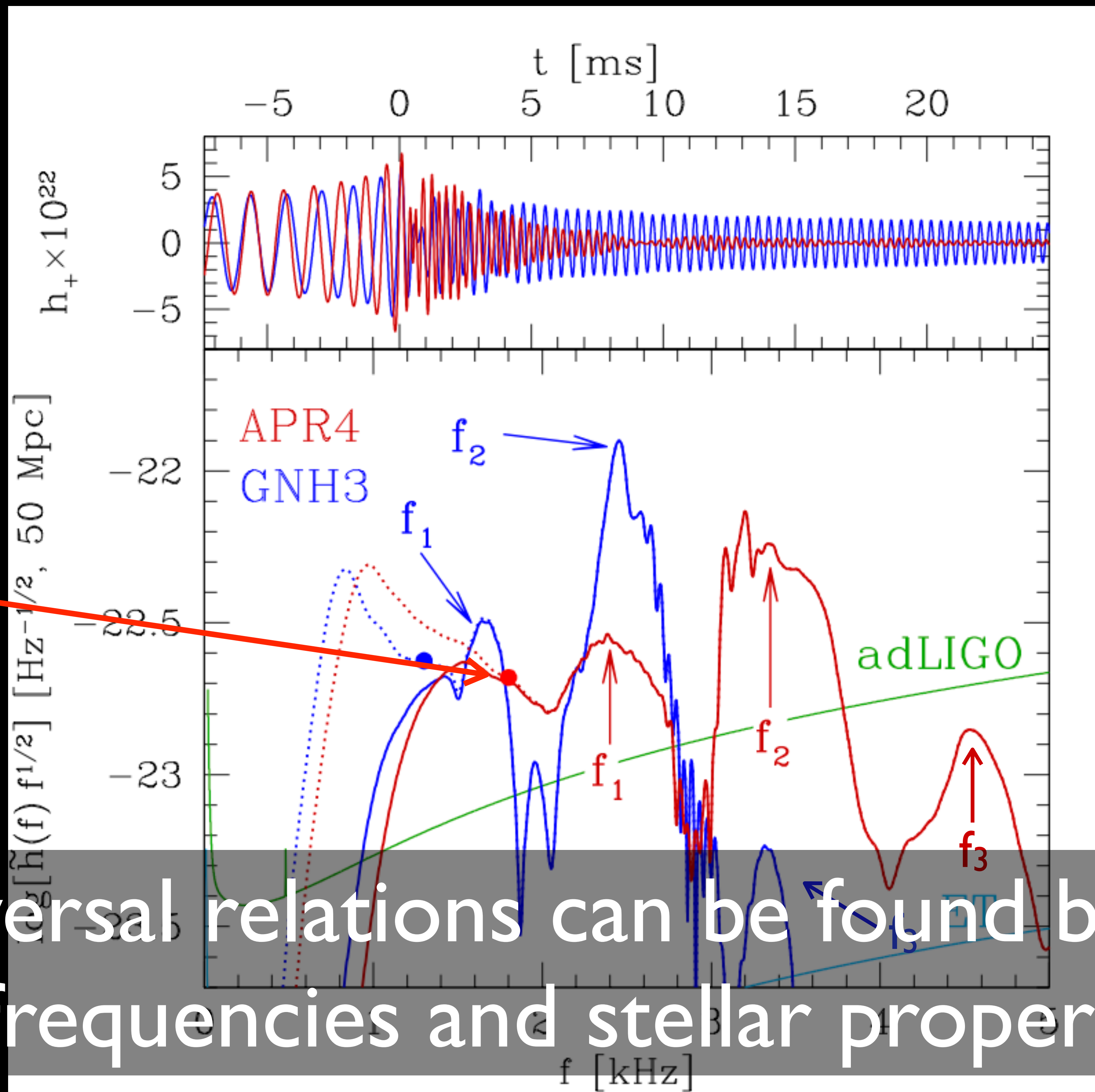
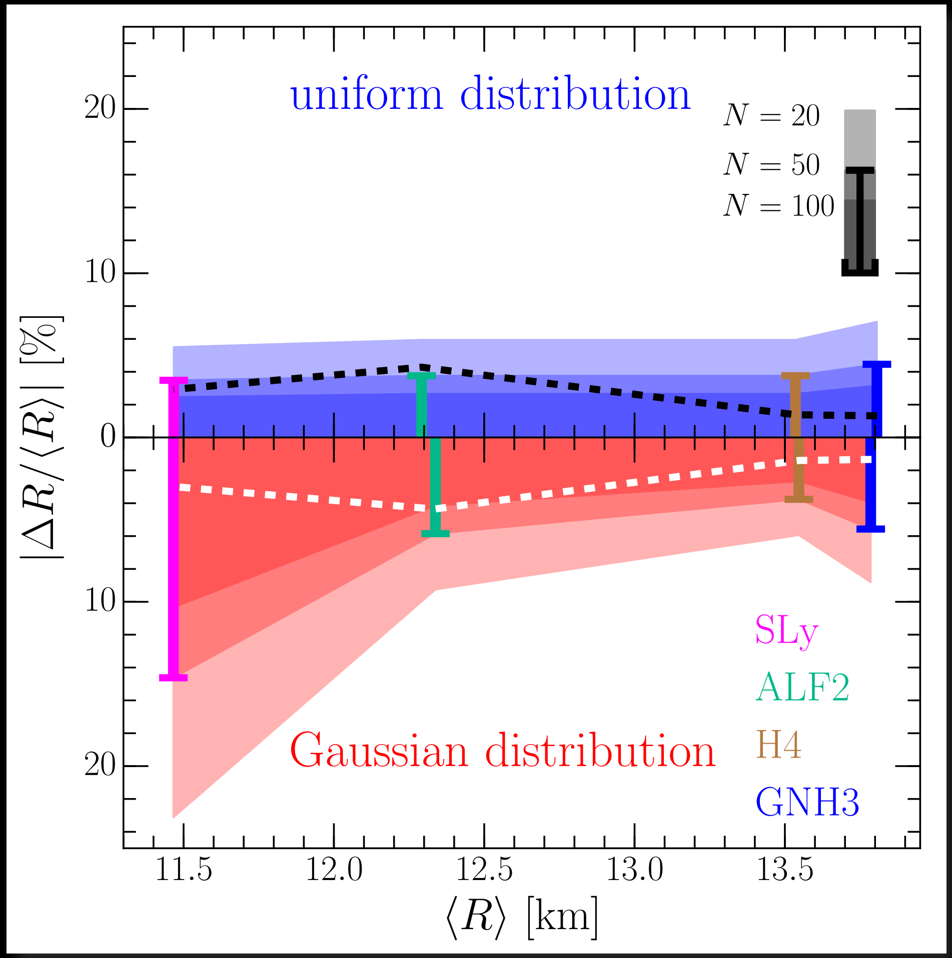
merger frequency



Universal relations can be found between frequencies and stellar properties

A spectroscopic approach to the EOS

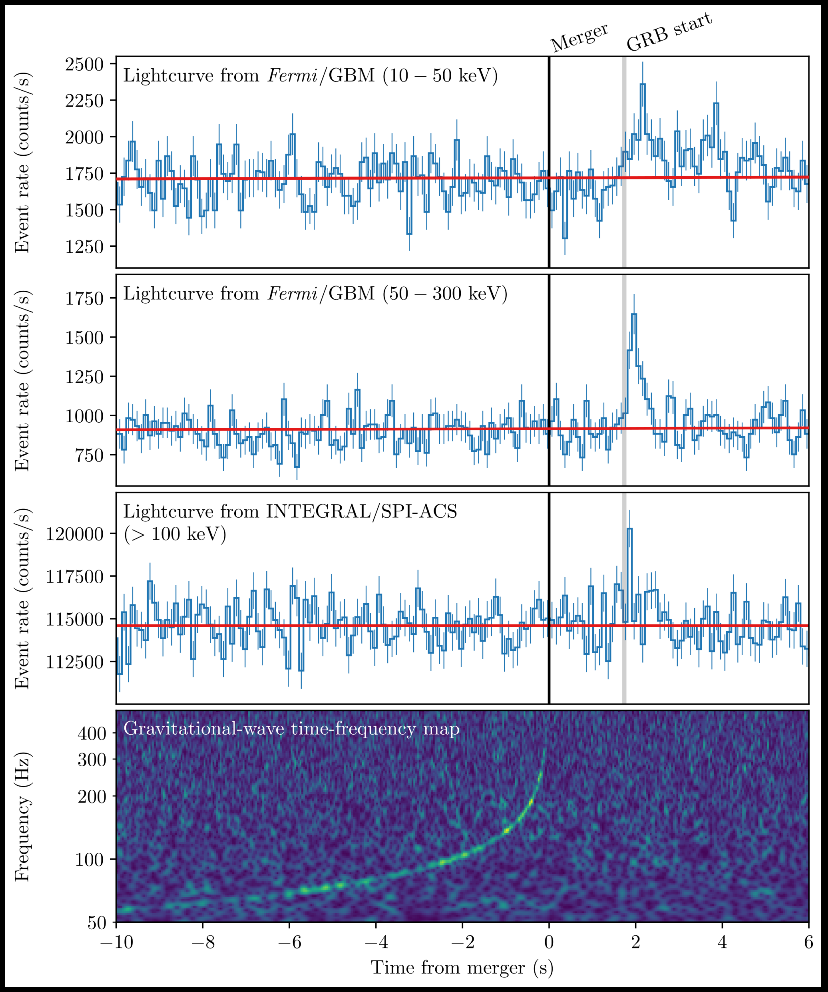
- **Universal behaviour** and **analytic modelling** of post-merger relates position of these peaks with the EOS.
- Question: how well can we constrain the EOS (radius) given ***N* detections?**



- discriminating stiff/soft EOSs possible even with moderate ***N~10***
- stiff EOSs: $|\Delta R/\langle R\rangle| < 10\%$ for ***N~20***
- soft EOSs: $|\Delta R/\langle R\rangle| \sim 10\%$ for ***N~50***
- golden binary: **SNR ~ 6** at **30 Mpc**
  $|\Delta R/\langle R\rangle| \simeq 2\%$ at 90% confidence

Baiotti, Bose, LR, Takami PRL, PRD (2015-2018)

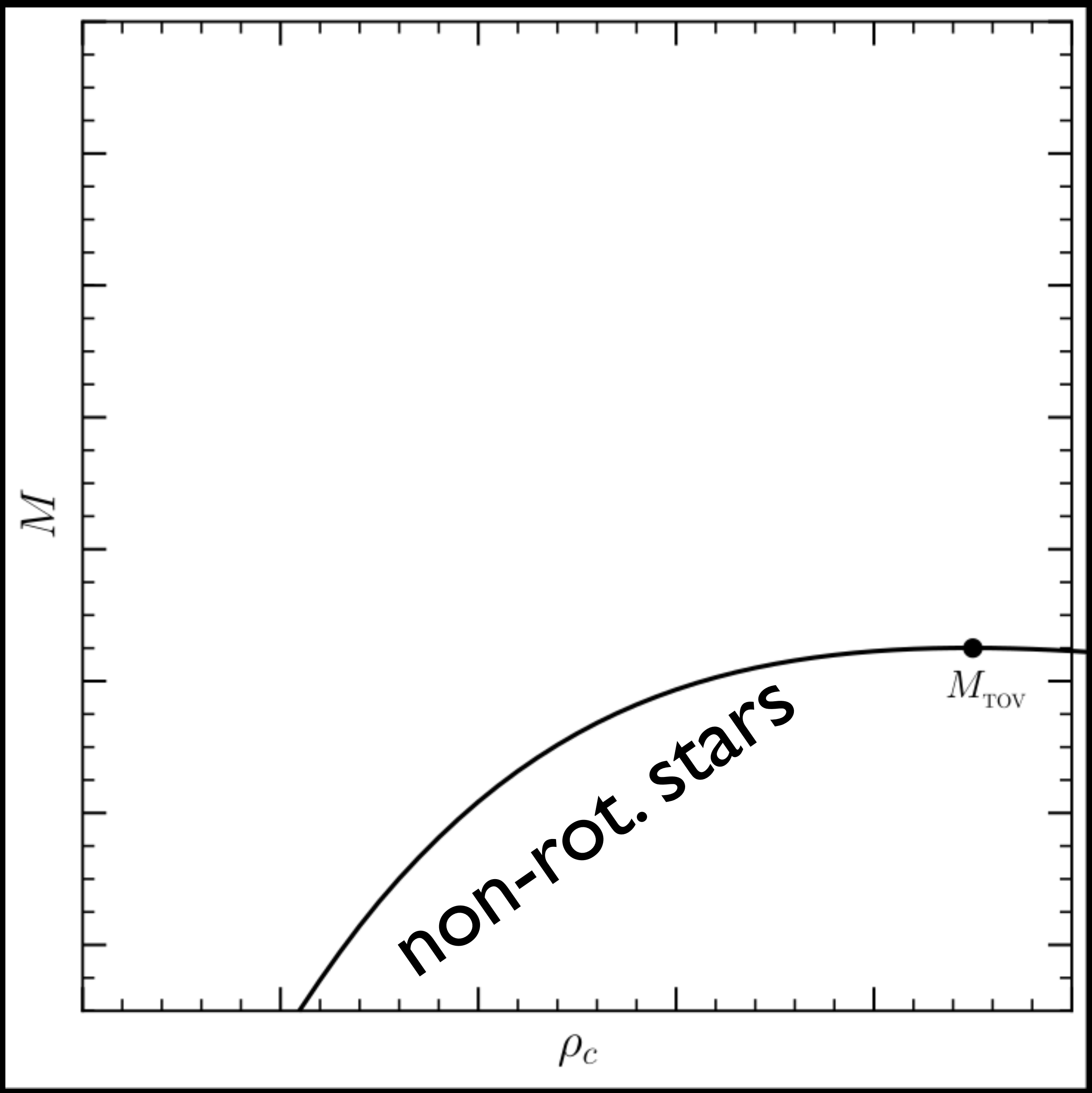
GW170817, GW190814
and maximum mass



LR, Most, Weih, ApJL (2018)
Most, Weih, LR, Schaffner-Bielich, PRL (2018)
Nathanail, Most, LR, ApJL (2021)
Musolino, Ecker, LR, arXiv (2023)

Limits on the maximum mass

- The remnant of GW170817 was a hypermassive star, i.e. a differentially rotating object with initial **gravitational** mass:
$$M_1 + M_2 = 2.74^{+0.04}_{-0.01}\, M_\odot$$



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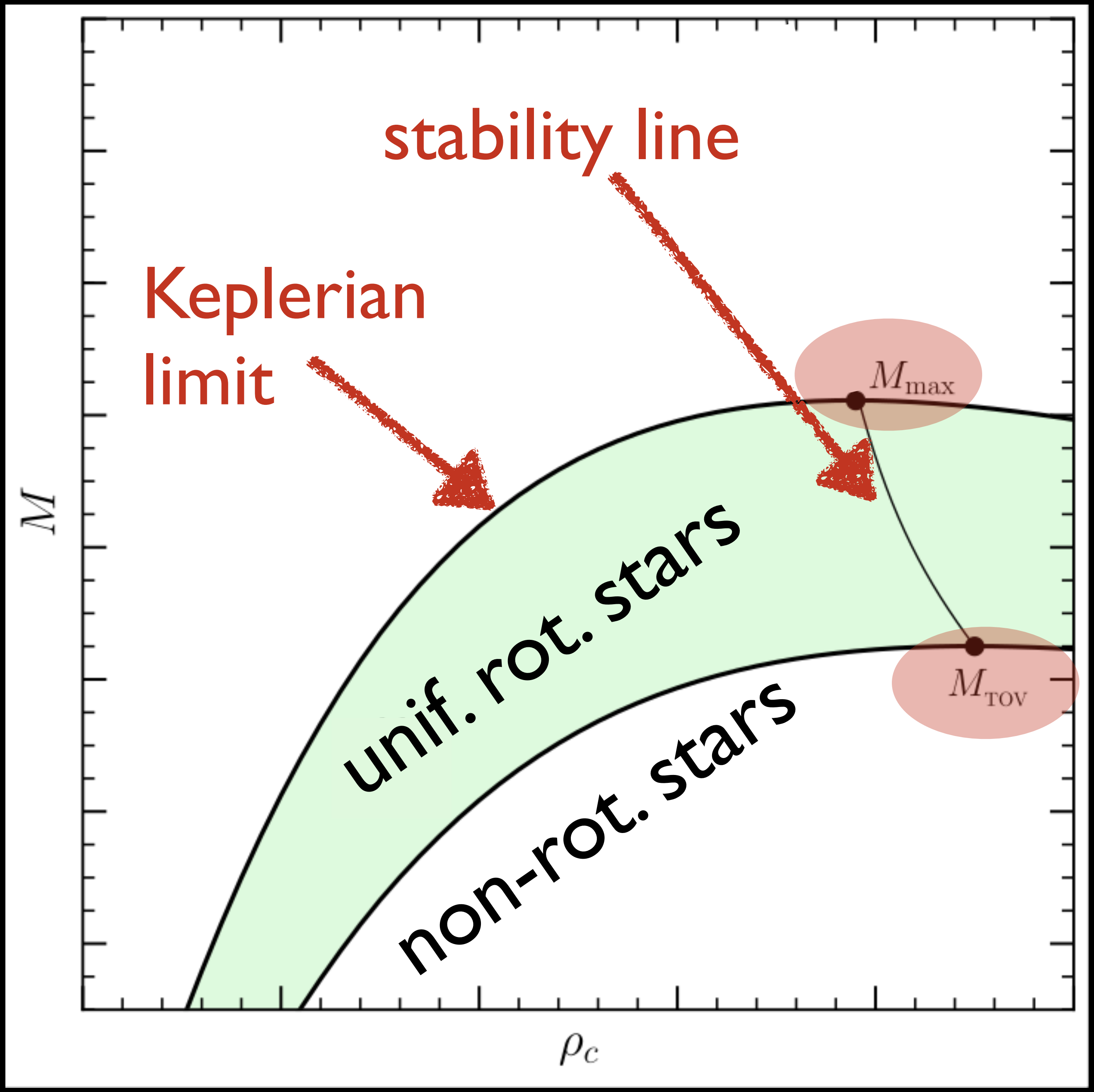

- Sequences of equilibrium models of **nonrotating** stars will have a maximum mass: $M_{\rm TOV}$
- This is true also for **uniformly** rotating stars at mass shedding limit: $M_{\rm max}$
- $M_{\rm max}$ simple and **quasi-universal** function of $M_{\rm TOV}$ (Breu & LR 2016)

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

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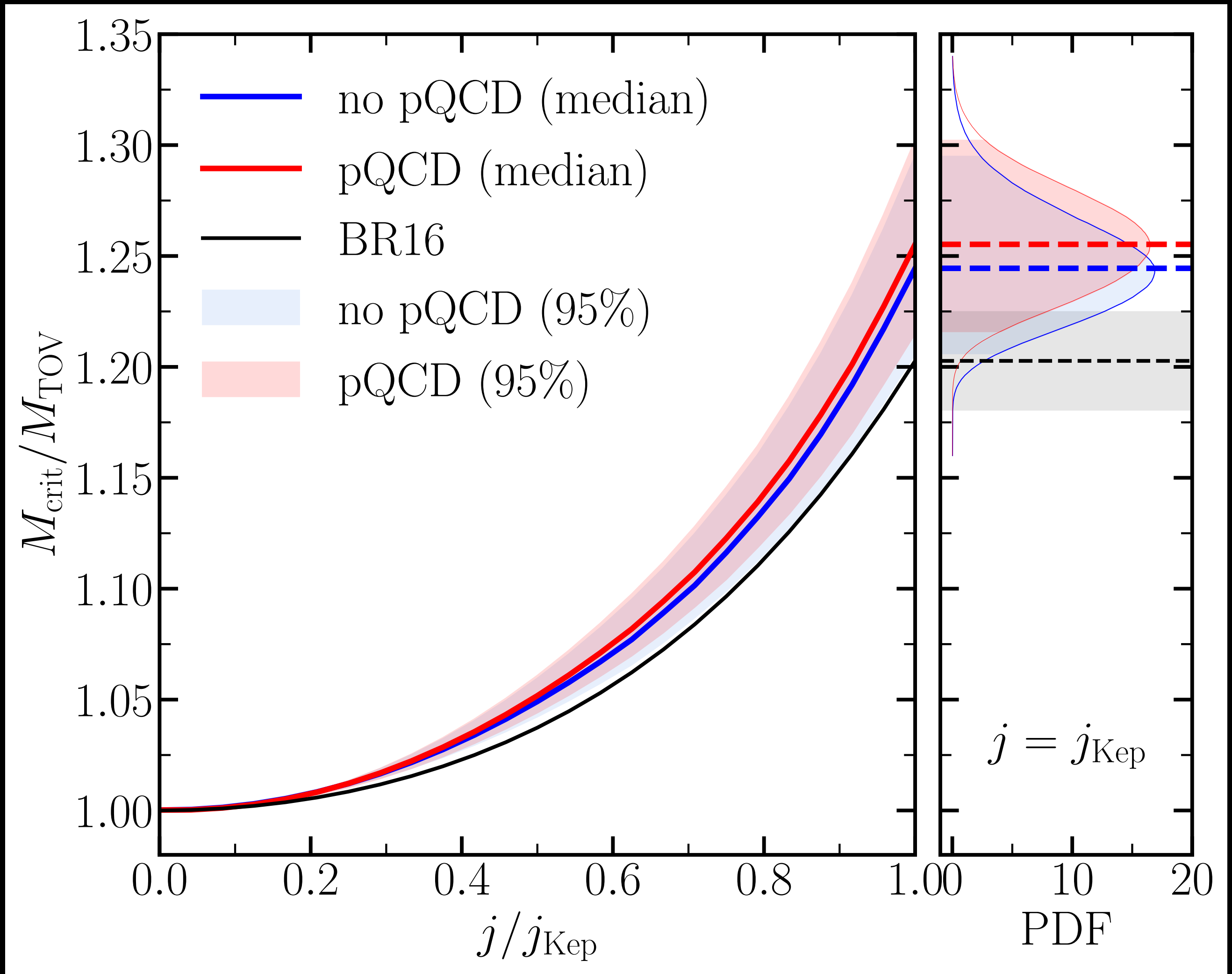

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$$M_{\rm max} = 1.25^{+0.05}_{-0.04}\, M_{\rm TOV}$$

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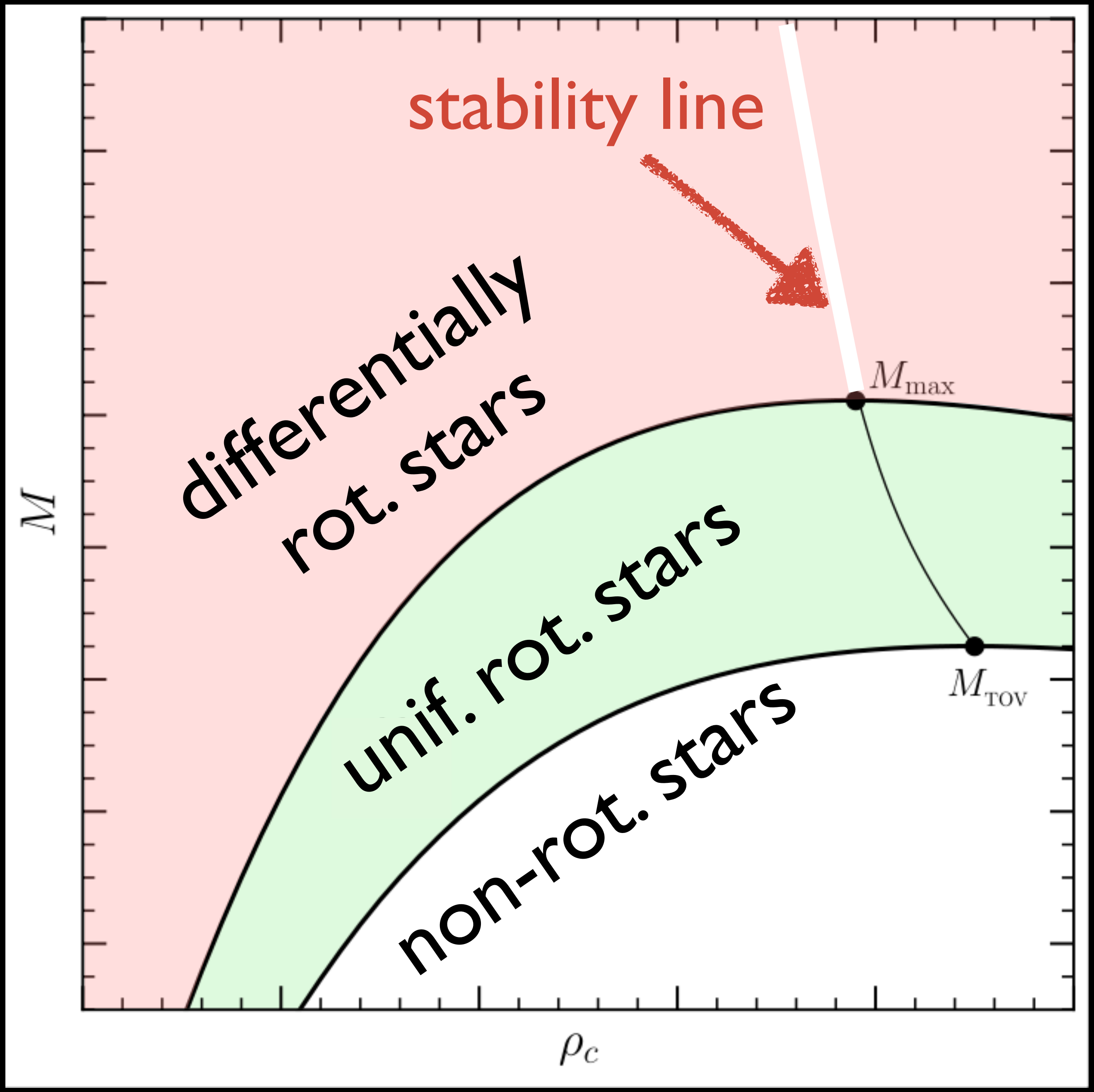


- **Green** region is for **uniformly** rotating equilibrium models.
- **Salmon** region is for **differentially** rotating equilibrium models.
- **Stability line** is simply extended in larger space (Weih+18)

Limits on the maximum mass

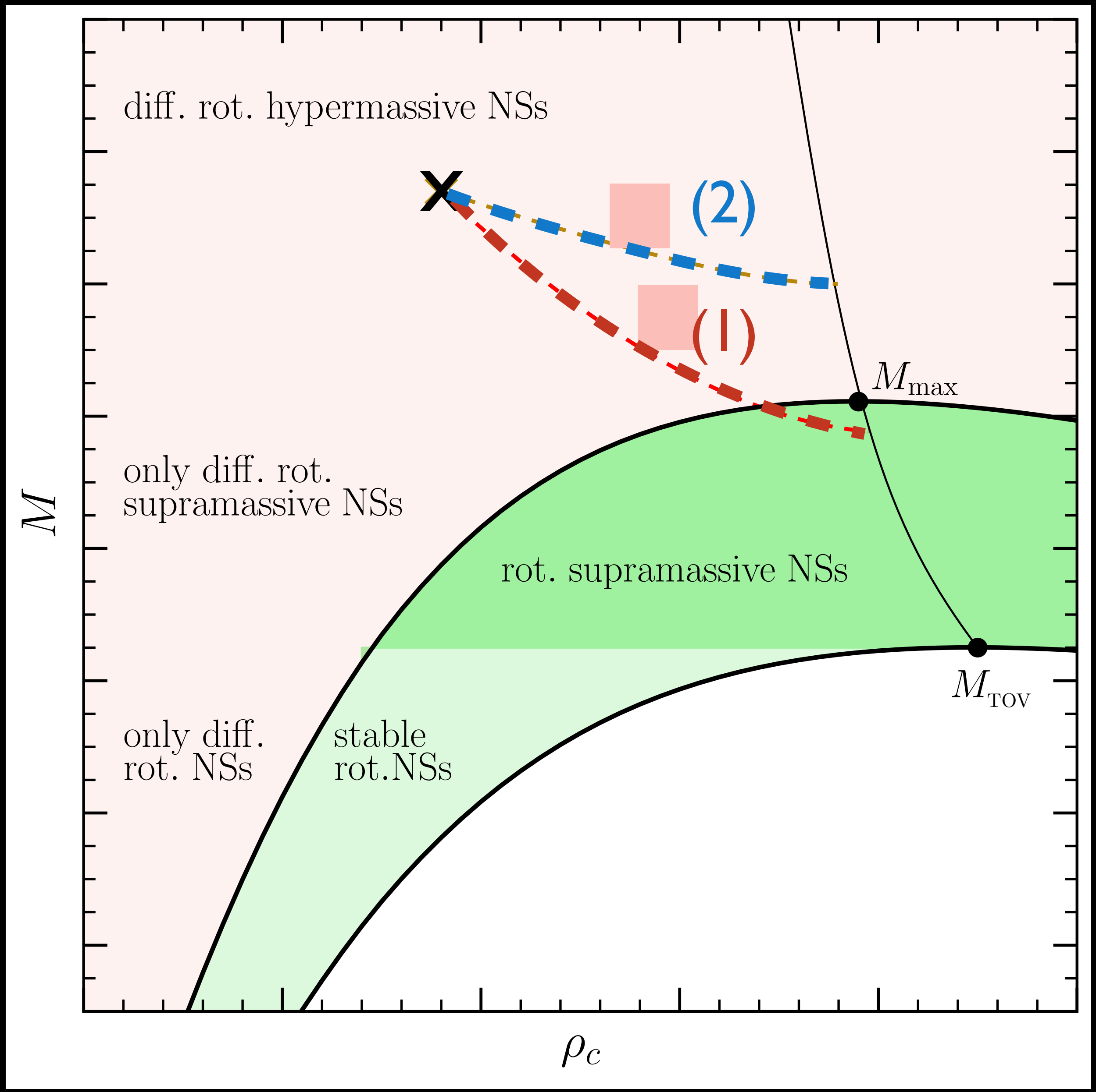
- GW170817 produced object **"X"**; GRB implies a BH has been formed: **"X"** followed two possible tracks: **fast (2)** and **slow (1)**

- 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 (I)**

- Use measured **gravitational mass** of GW170817

- Remove **rest-mass** deduced from kilonova emission (need conversion baryon/gravitational)

- Use **universal relations,** 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 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

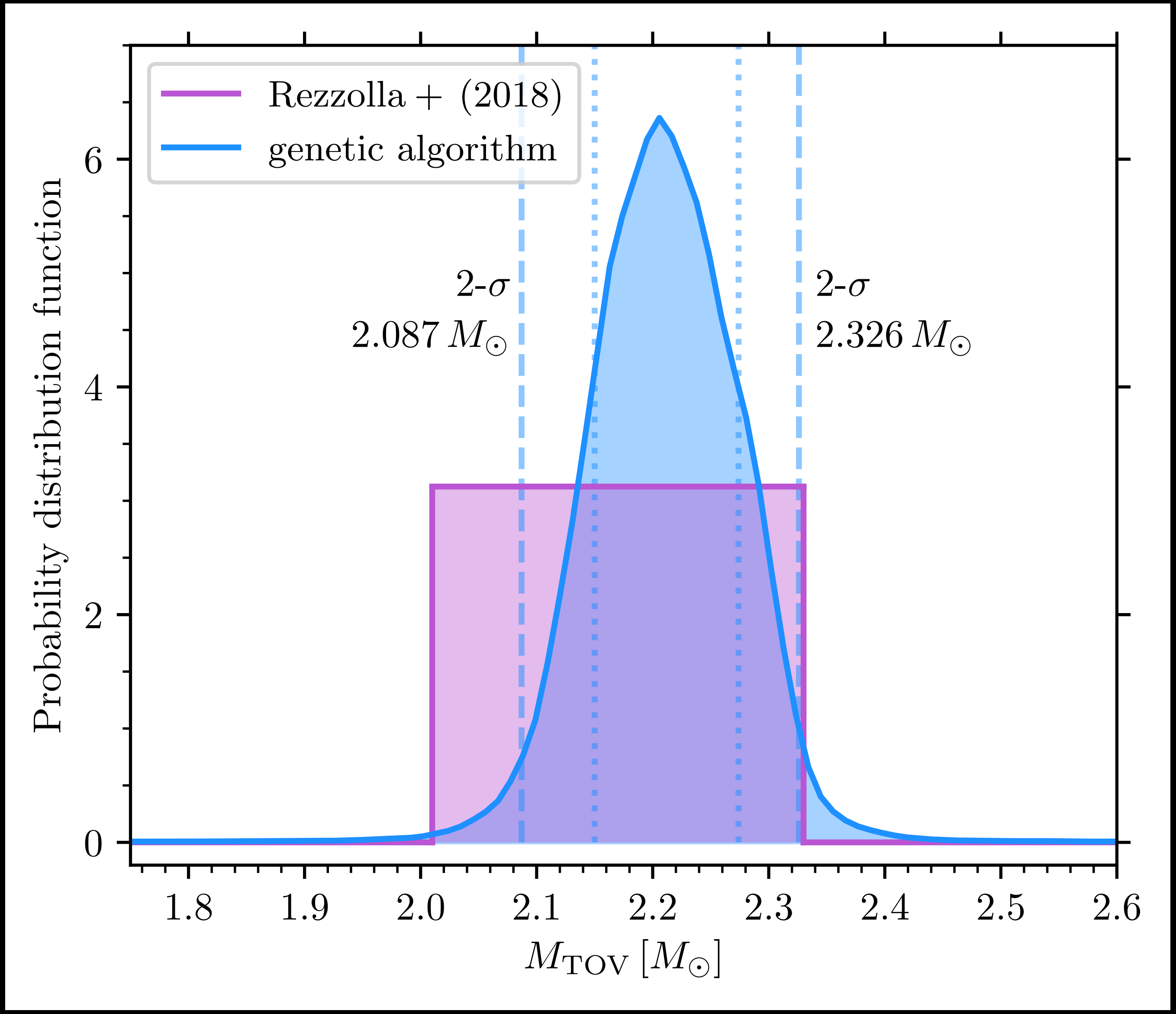
- A **genetic algorithm** is used to sample through the parameter space of the 10 free parameters.

- 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.

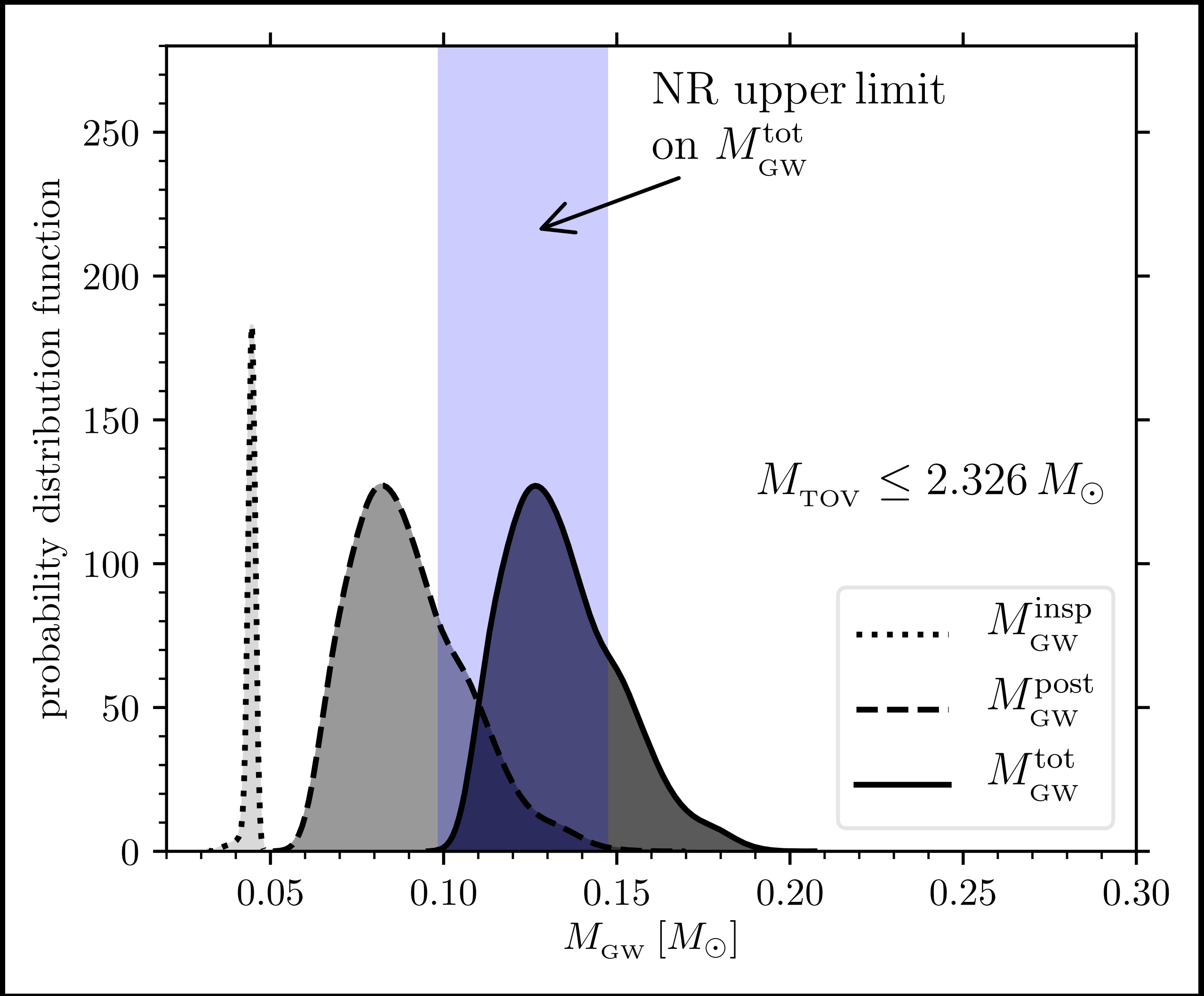
- Consider first previous estimate:

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

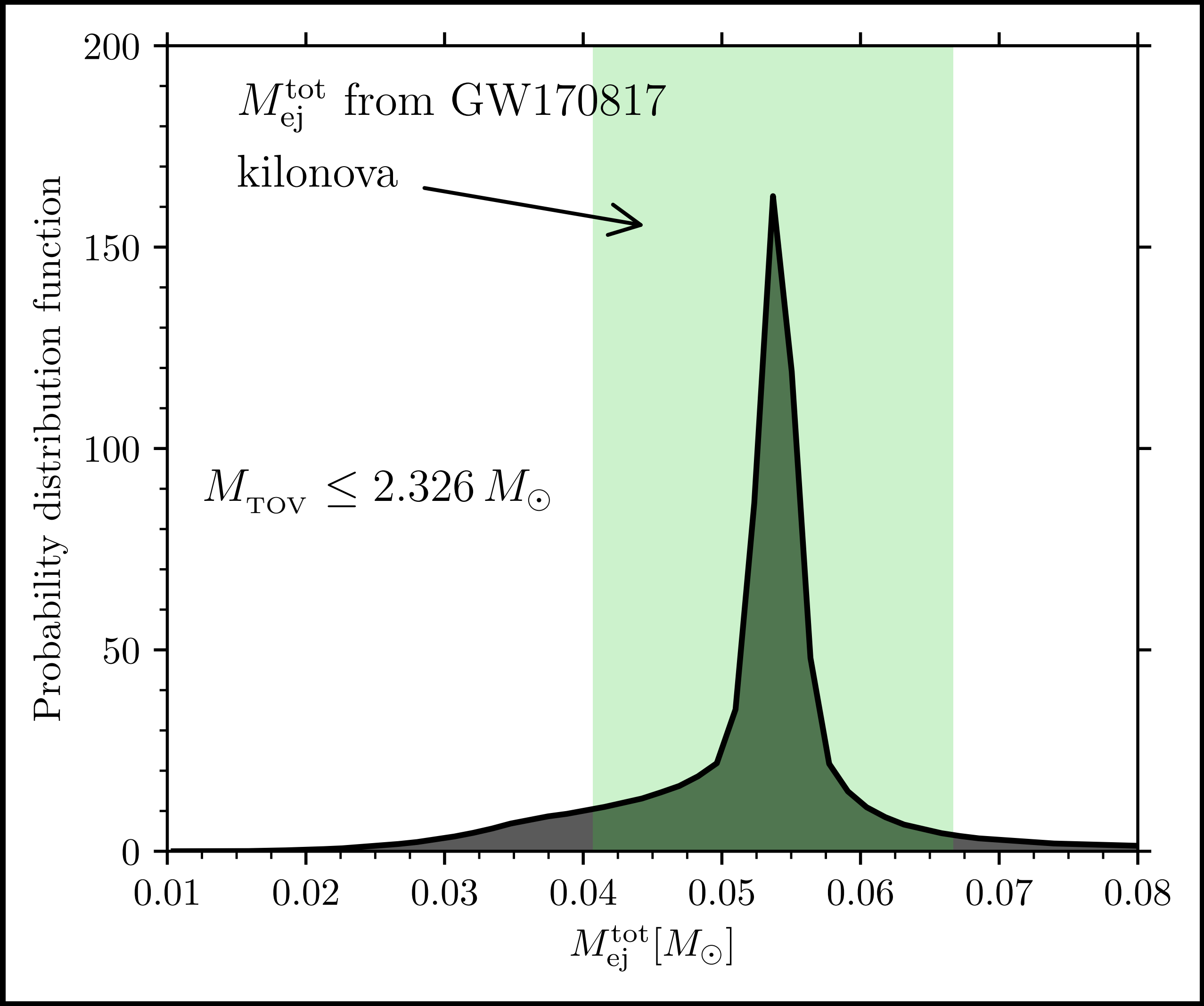
$$M_{\rm TOV}/M_\odot \leq 2.16^{+0.17}_{-0.15}$$



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

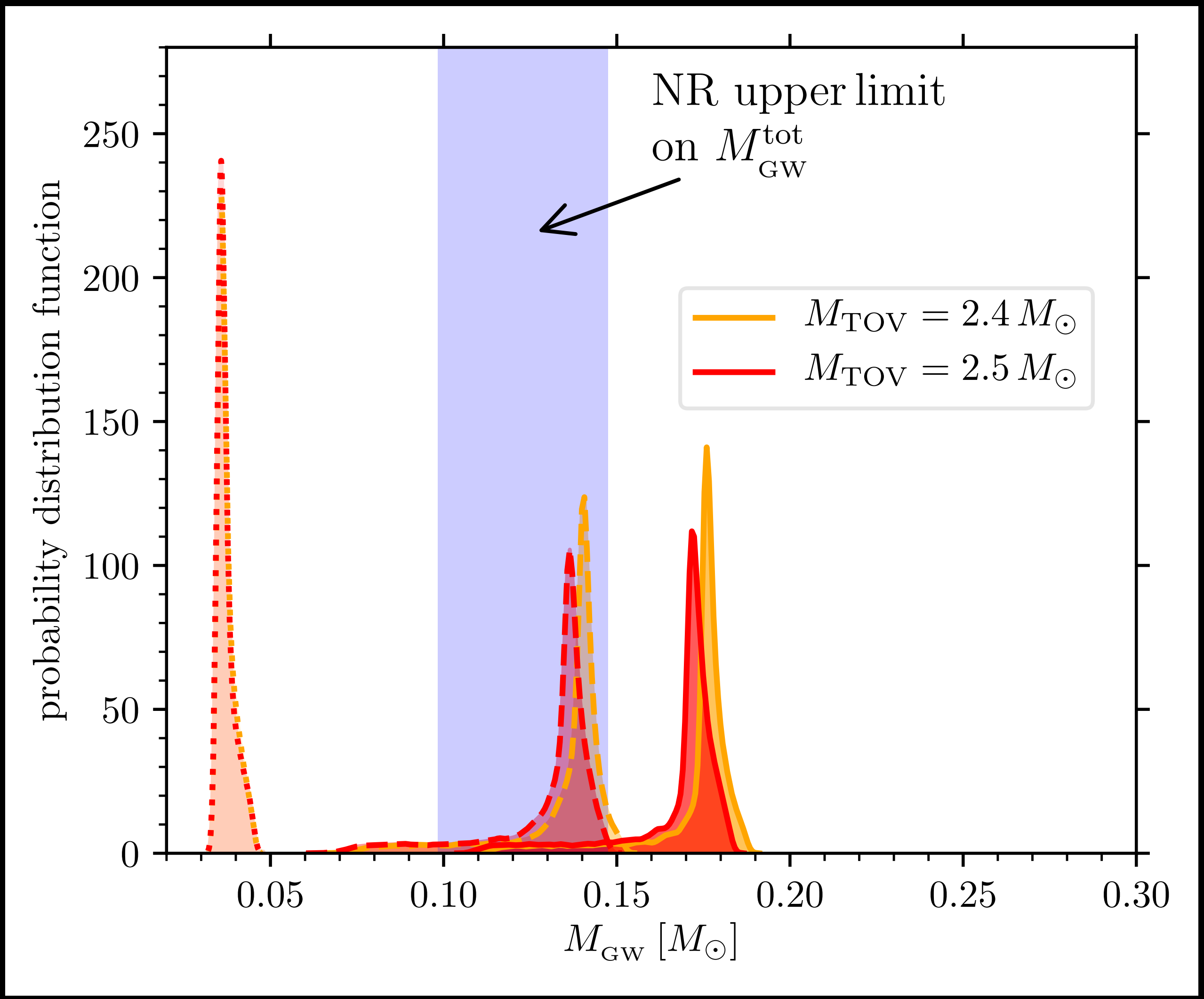


- Total mass emitted in GWs is in perfect **agreement** with predictions from numerical relativity

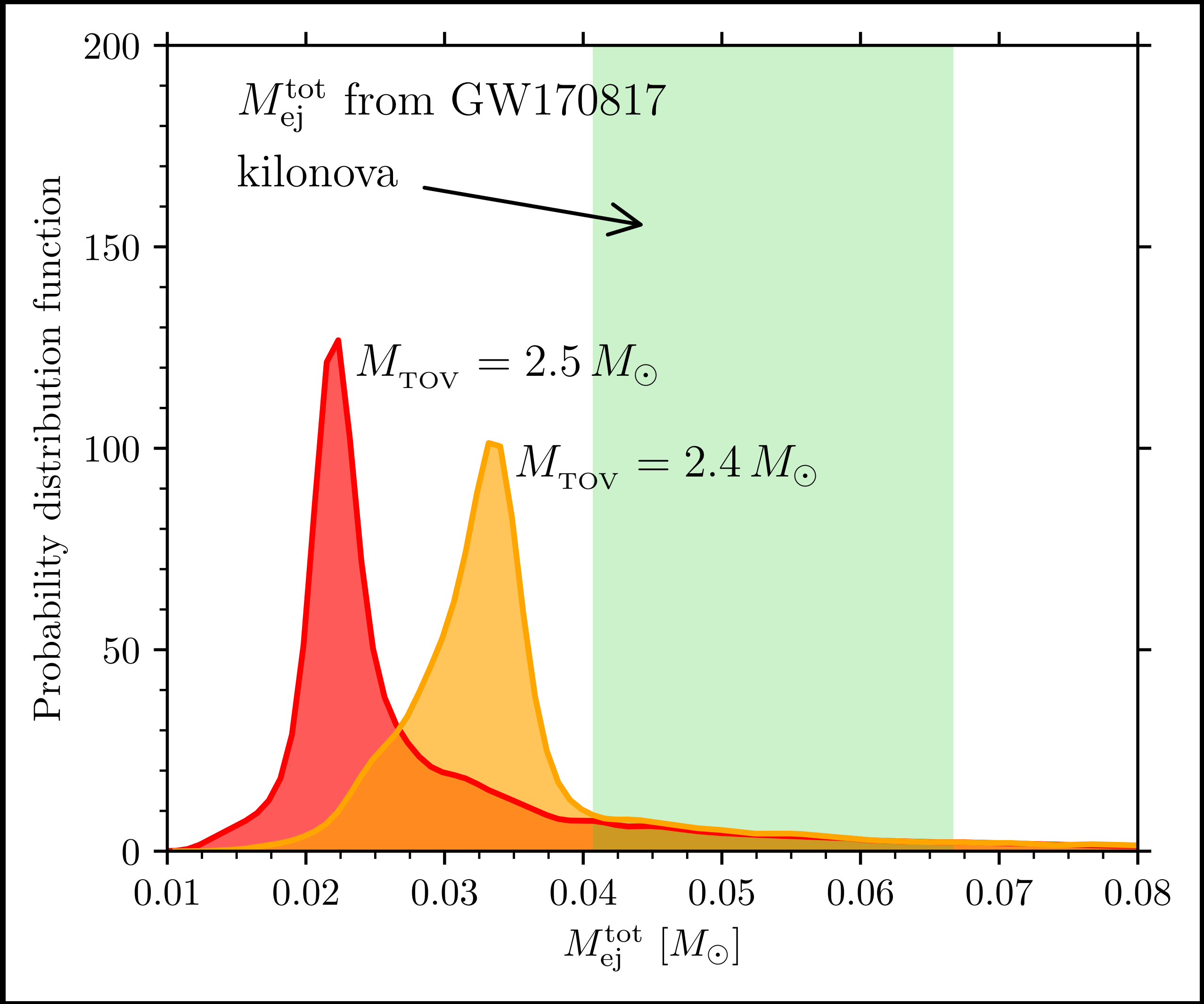


- Total mass ejected is in perfect **agreement** with predictions from kilonova signal

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

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

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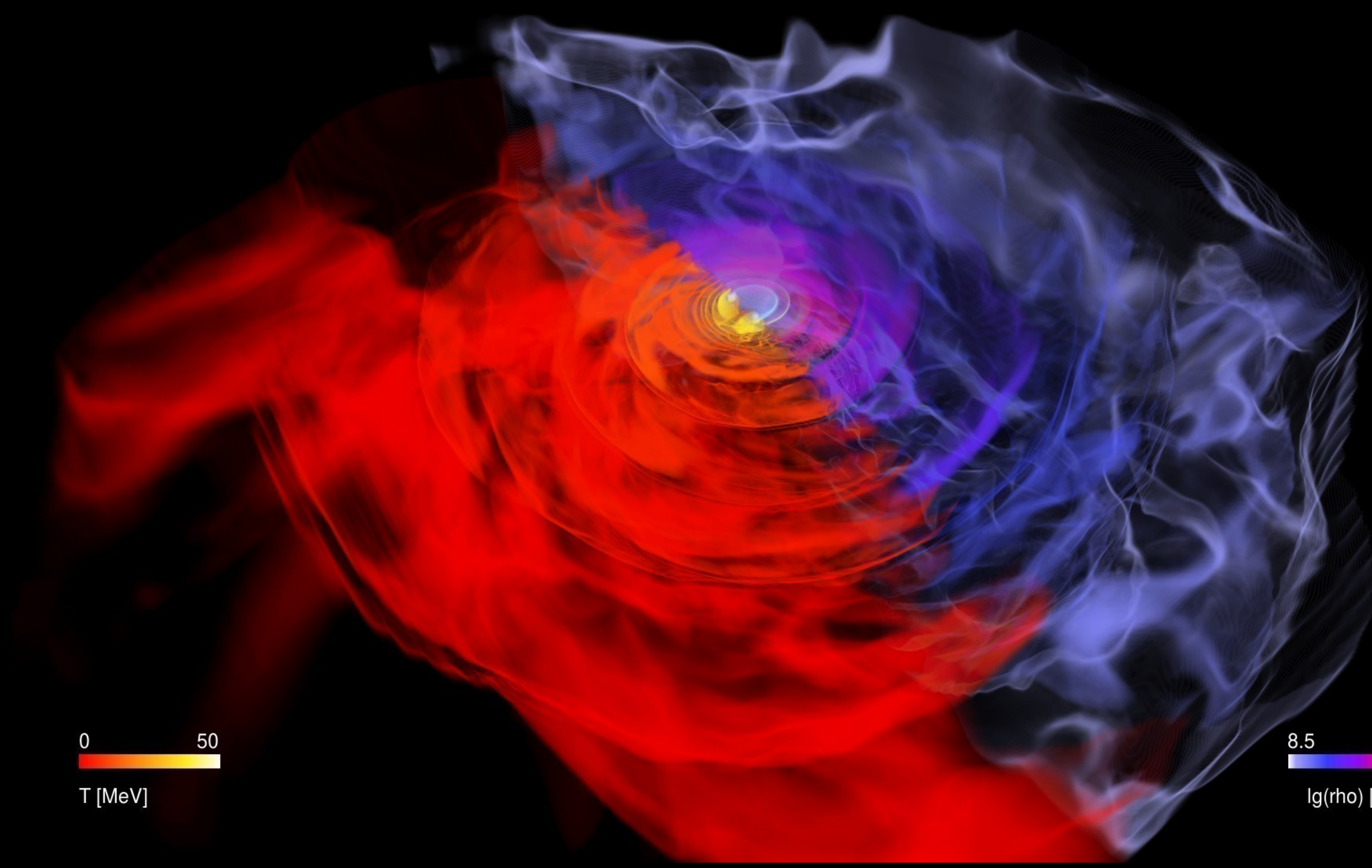
smallest BH or heaviest NS!

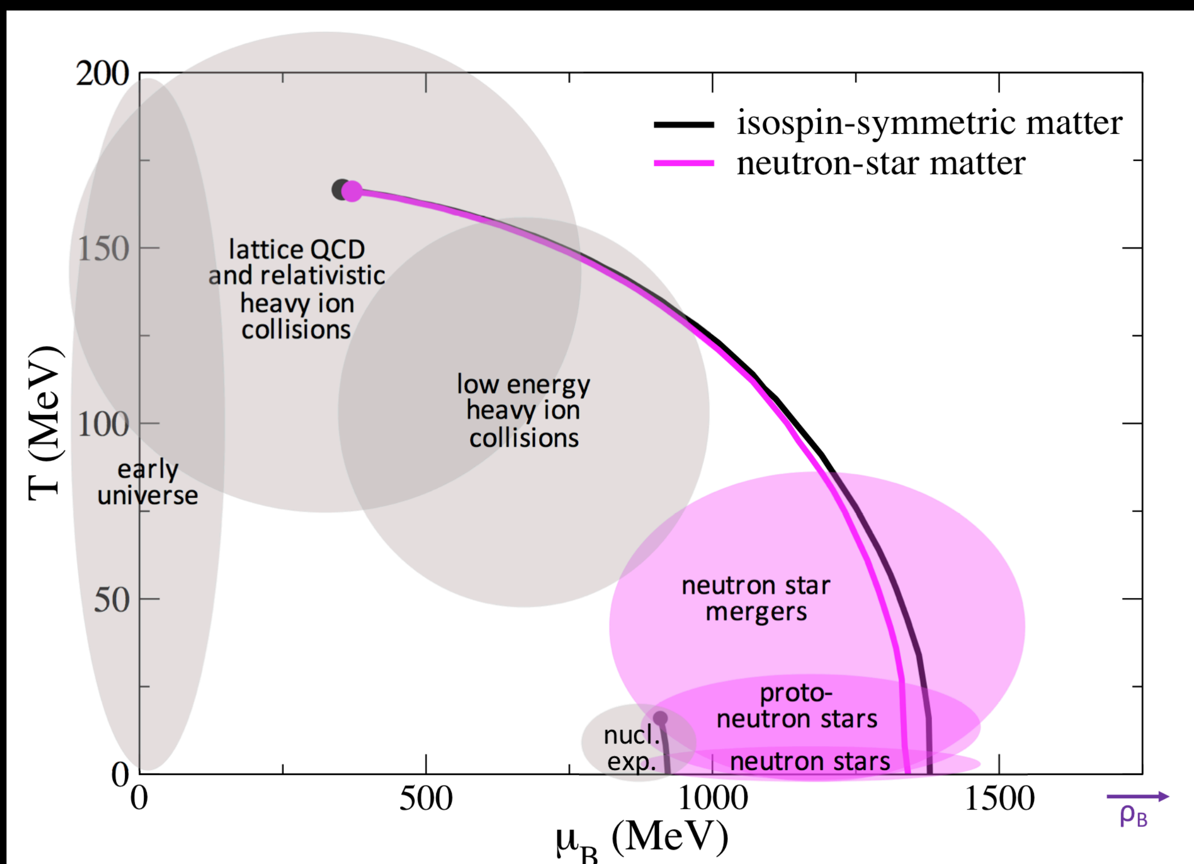
- If secondary in GW190814 was a NS, all previous considerations are incorrect.
- No EM counterpart was observed with GW190814 and no estimates possible on ejected matter or timescale for survival.
- **How do we solve this tension?**
- Solution: secondary in GW190814 **was a BH at merger** but could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

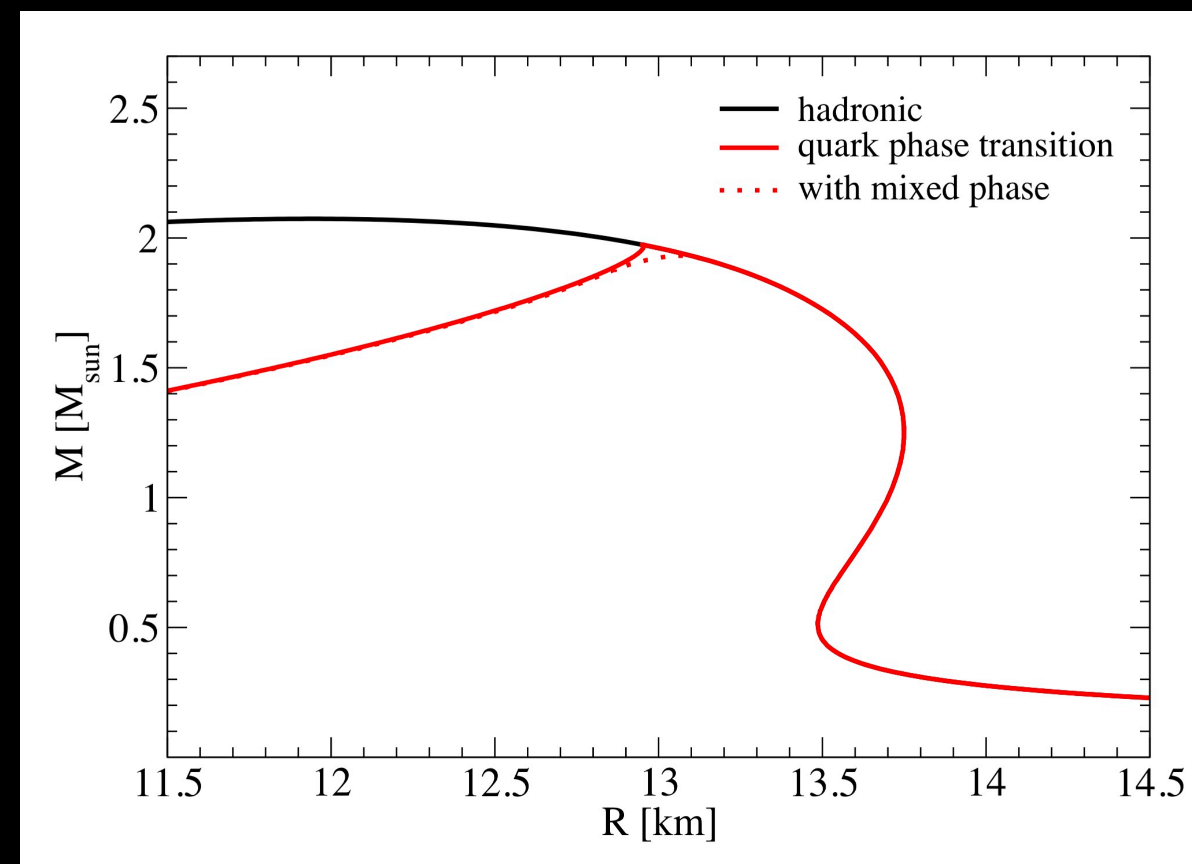
Phase transitions and their signatures



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.

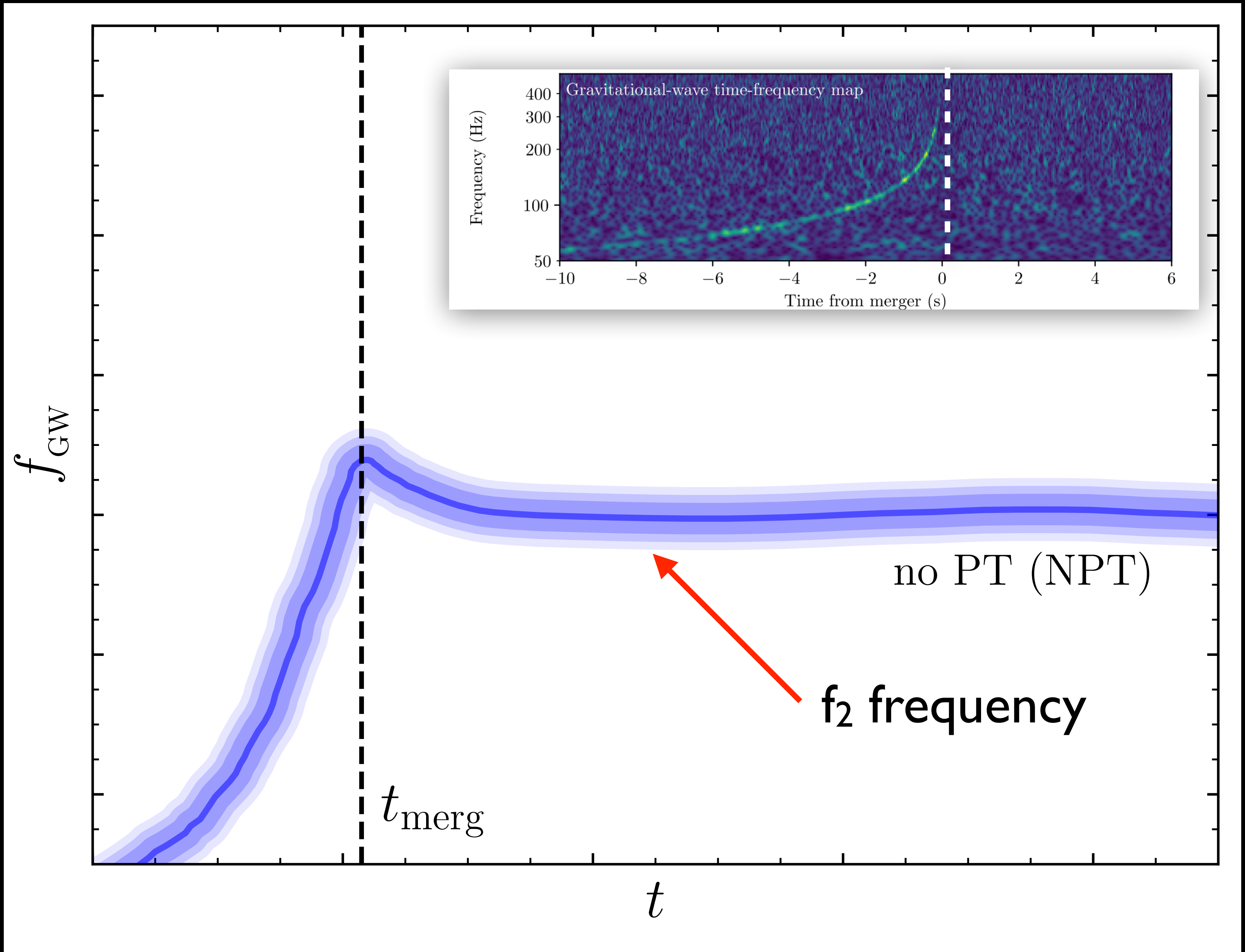




- Considered EOS based on Chiral Mean Field (CMF) model, based on a nonlinear SU(3) sigma model.
- Appearance of quarks can be introduced naturally.

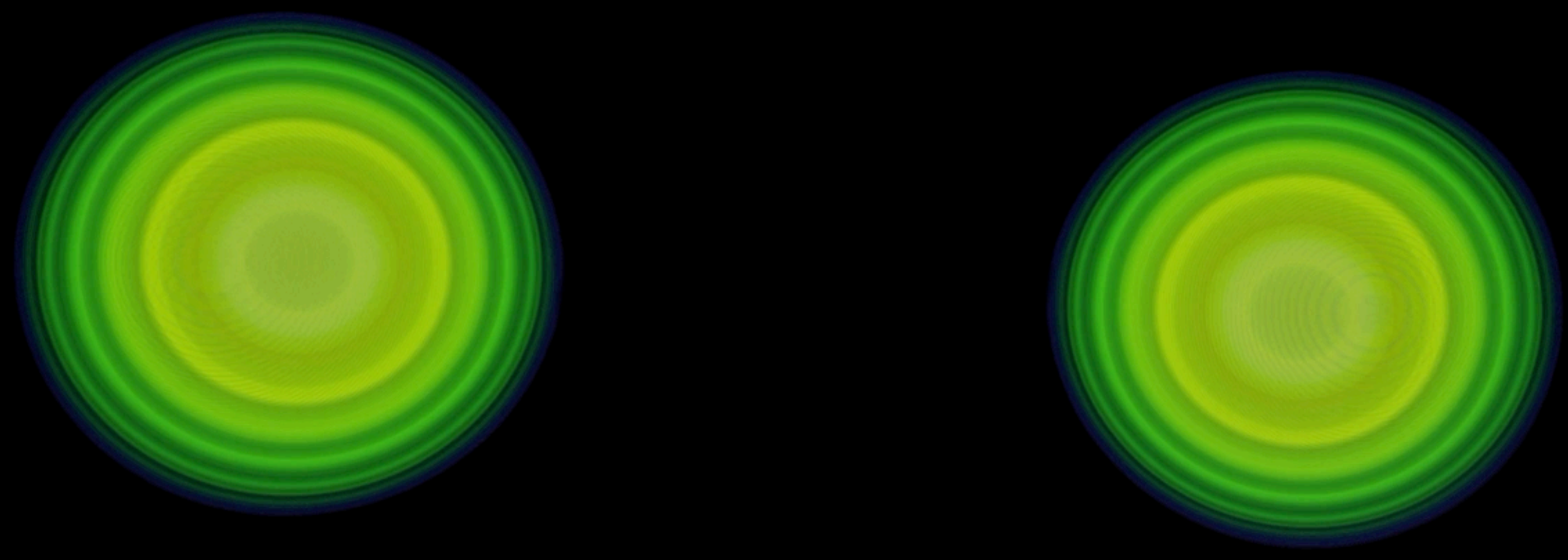
A zoology of behaviours

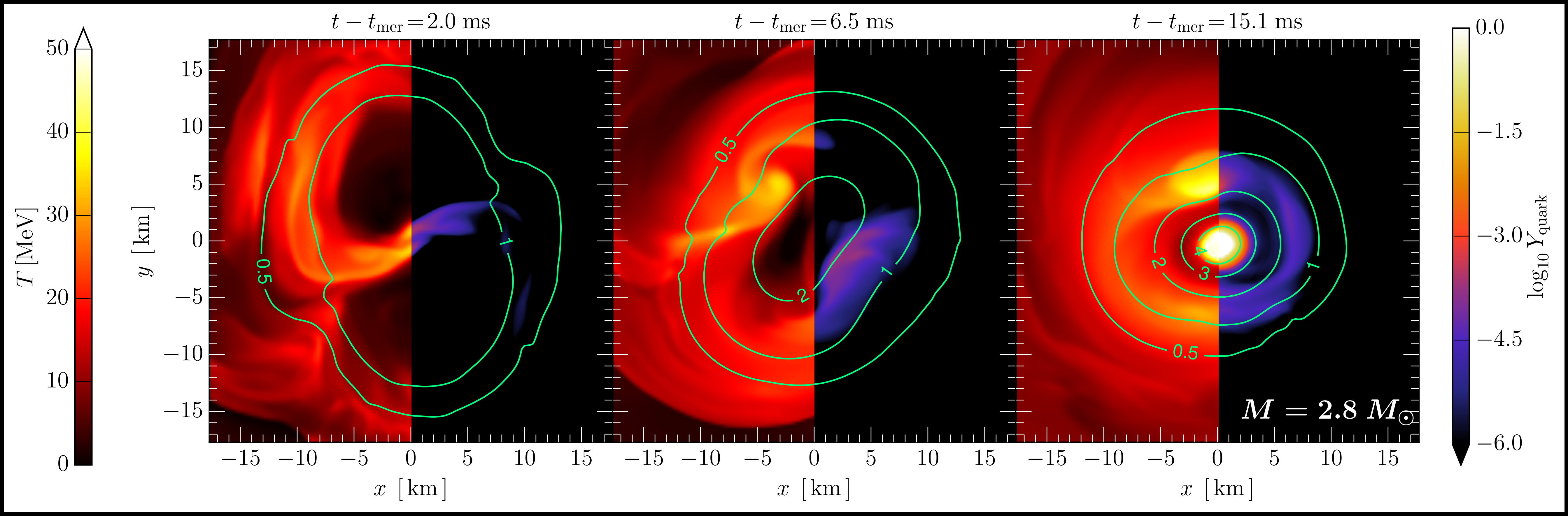
The occurrence of a PT considerably enriches the range of possible scenarios in the GW emission



Animations: Weih, Most, LR

Simulation of a phase-transition triggered collapse (PTTC)

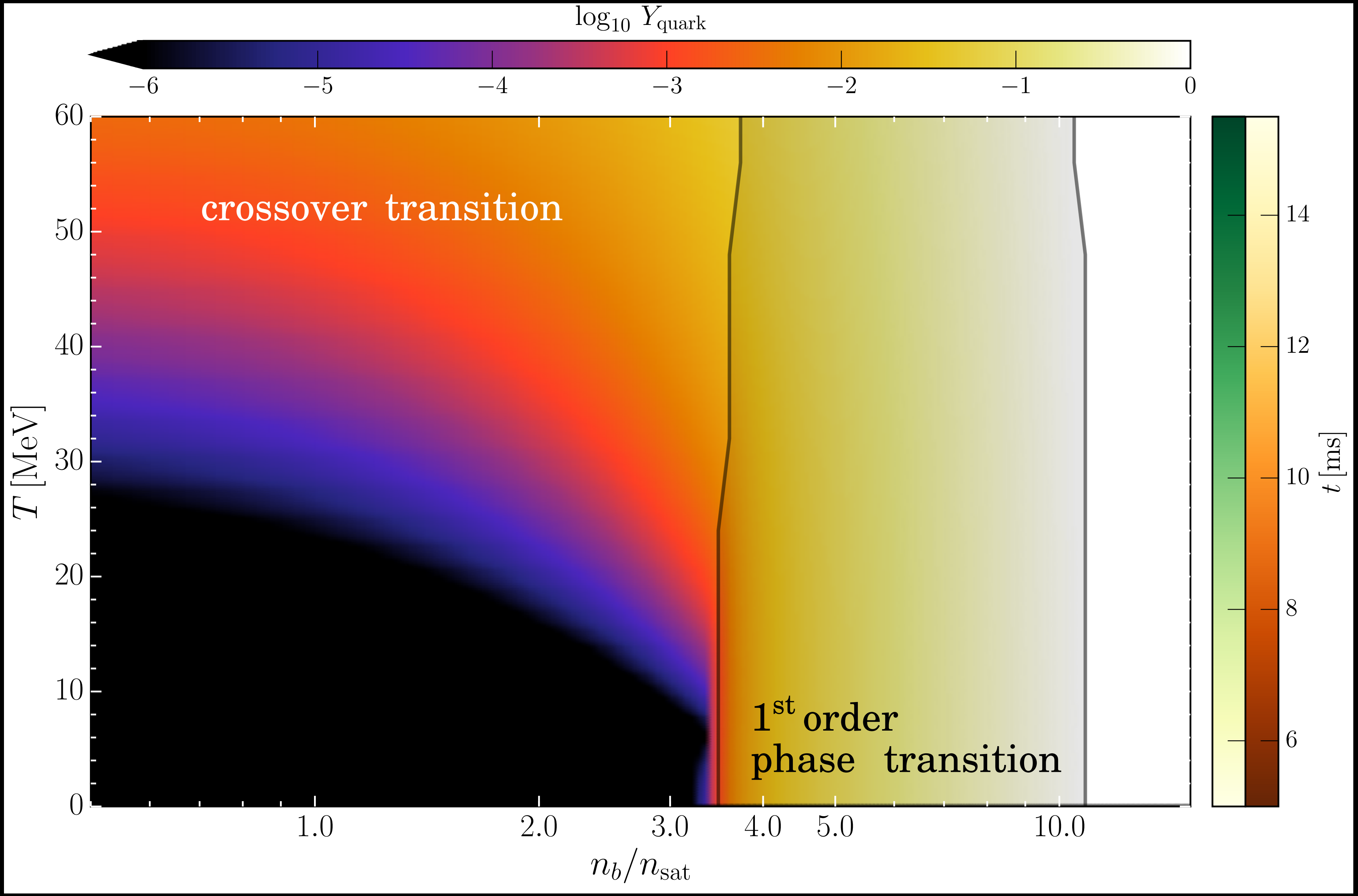




Quarks appear at sufficiently large temperatures and densities.

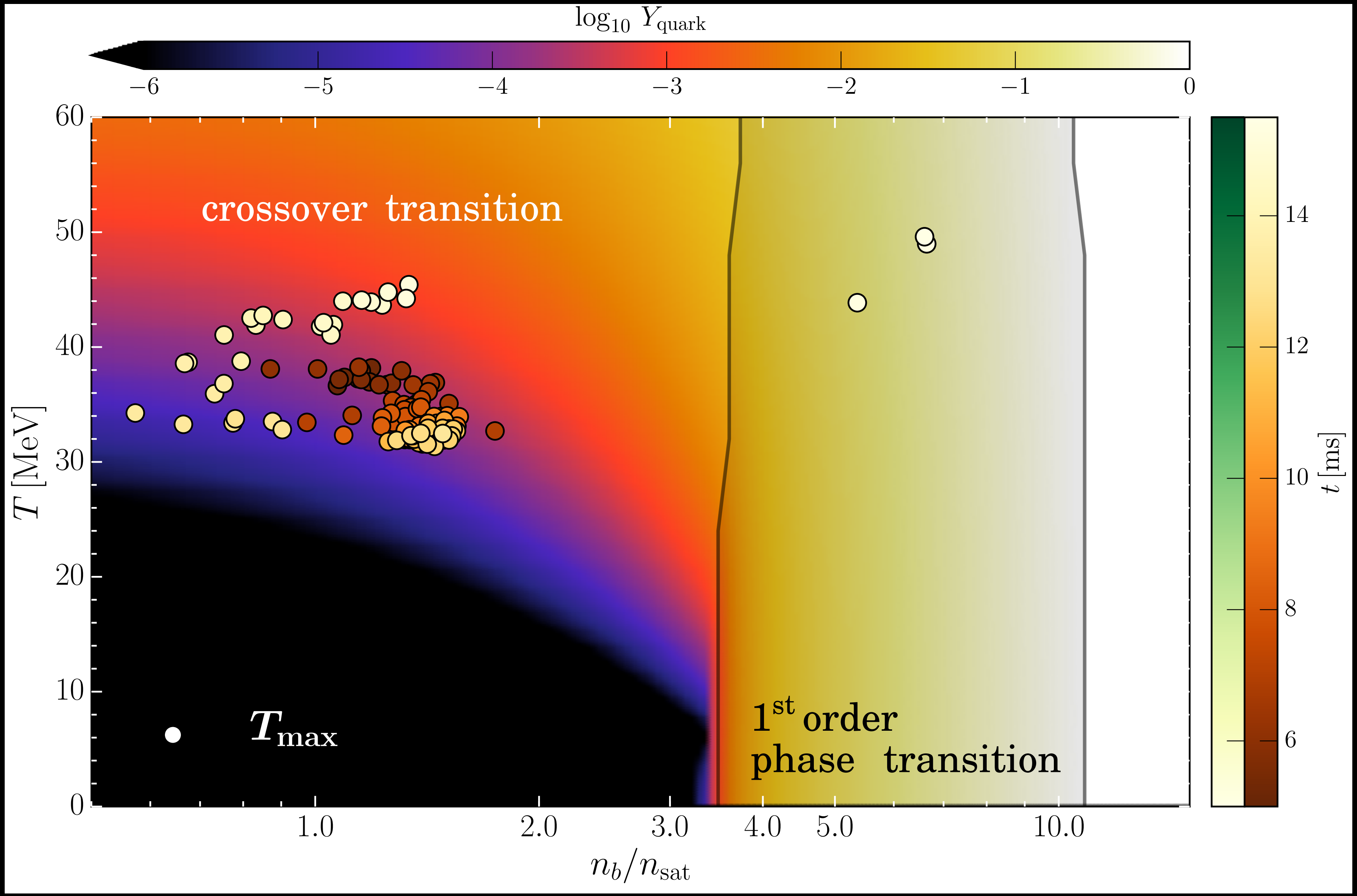
When this happens the EOS is considerably softened and a BH produced.

Comparing with the phase diagram



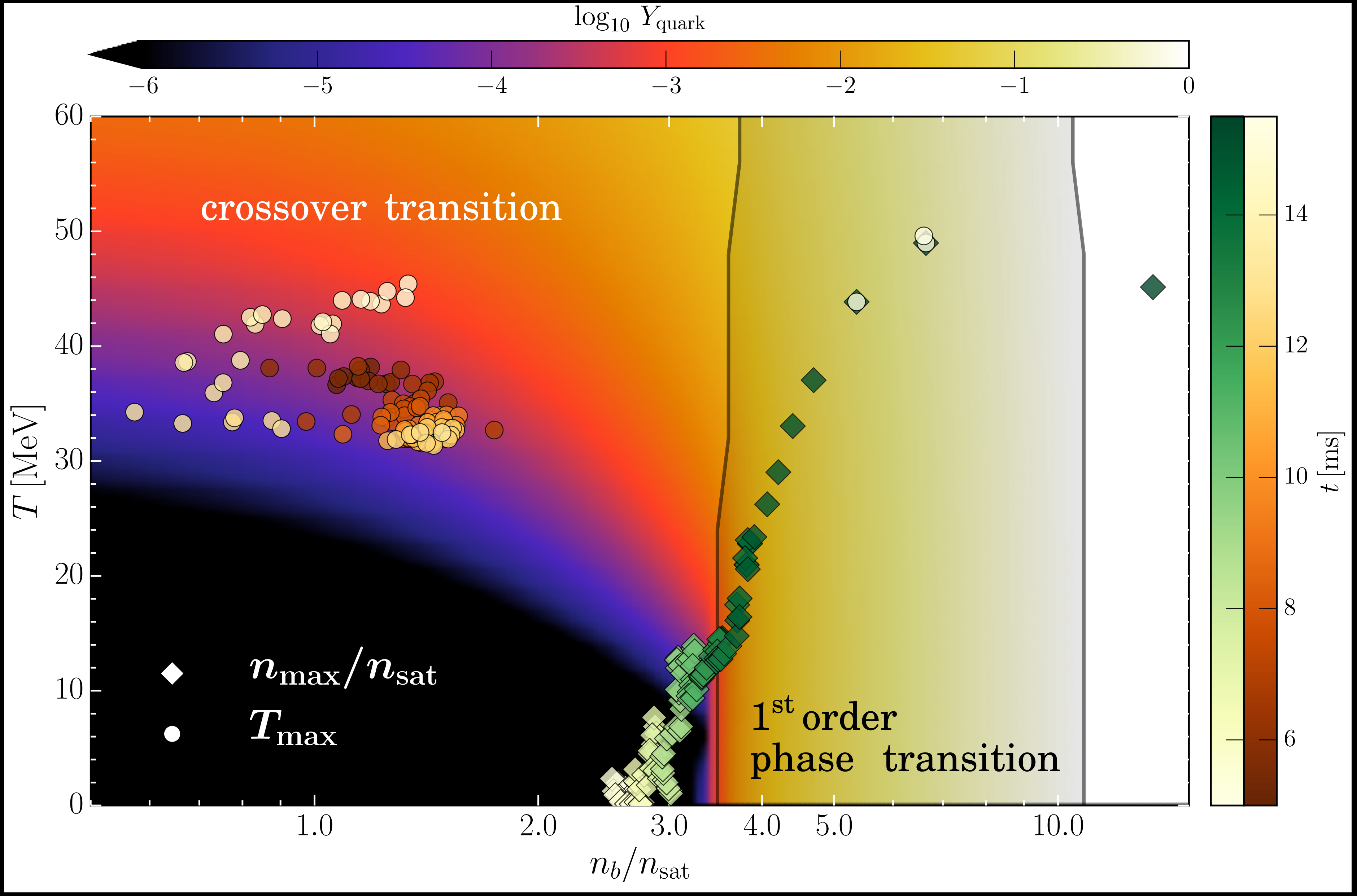
- Phase diagram with quark fraction

Comparing with the phase diagram



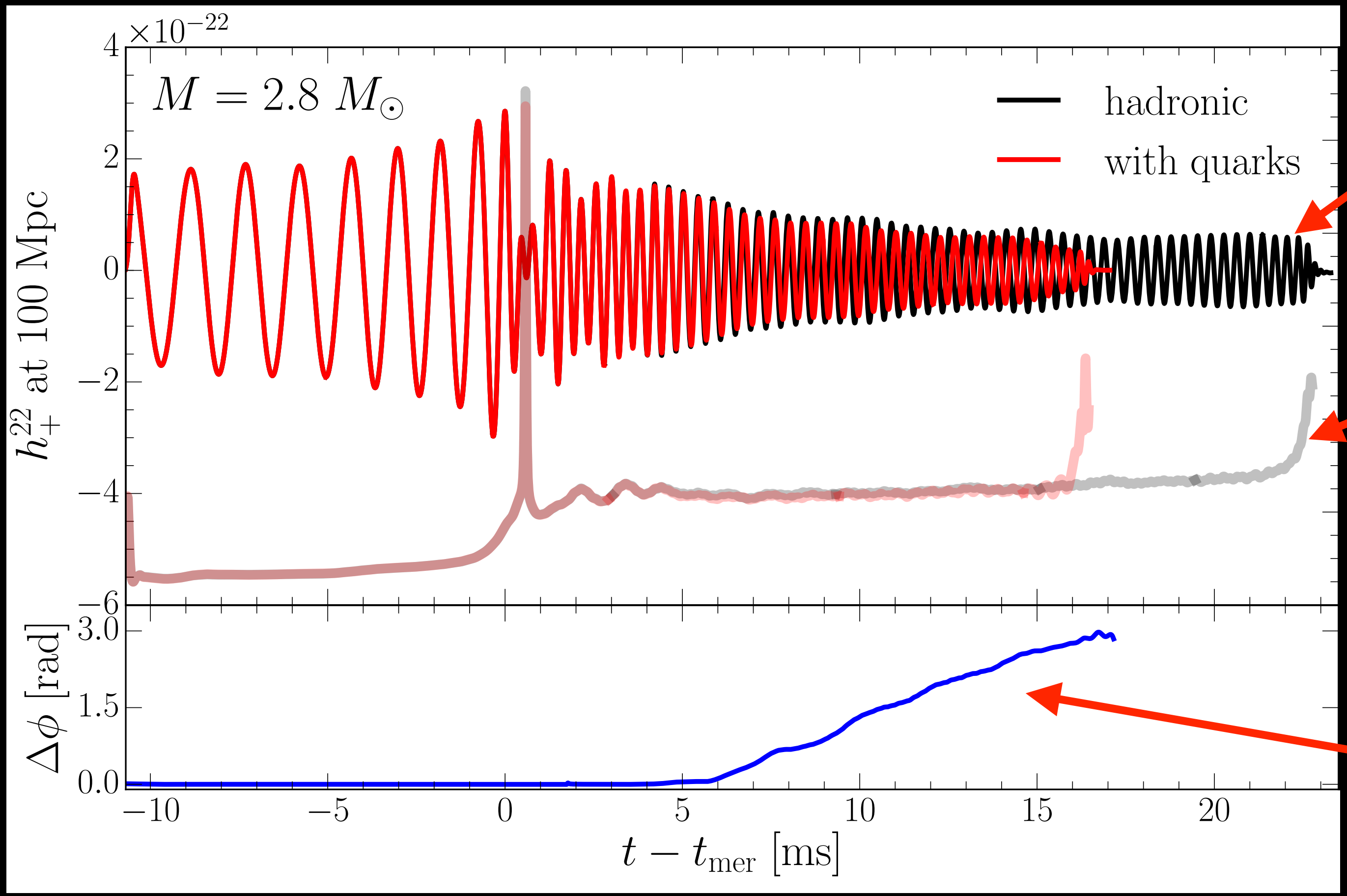
- Phase diagram with quark fraction
- Circles show the position in the diagram of the maximum temperature as a function of time

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 emission



waveforms

GW frequencies

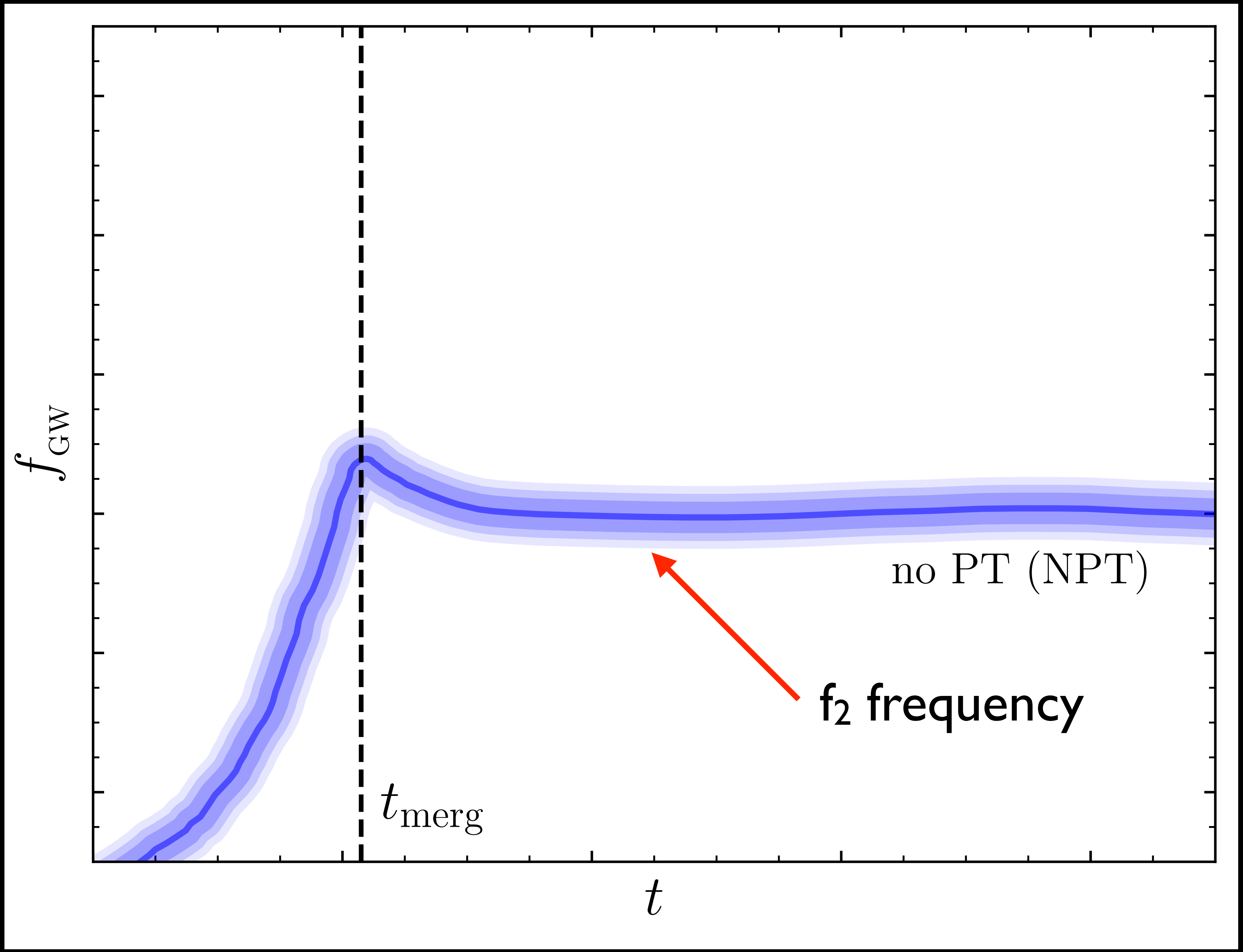
phase difference

- 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 zoology of behaviours

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



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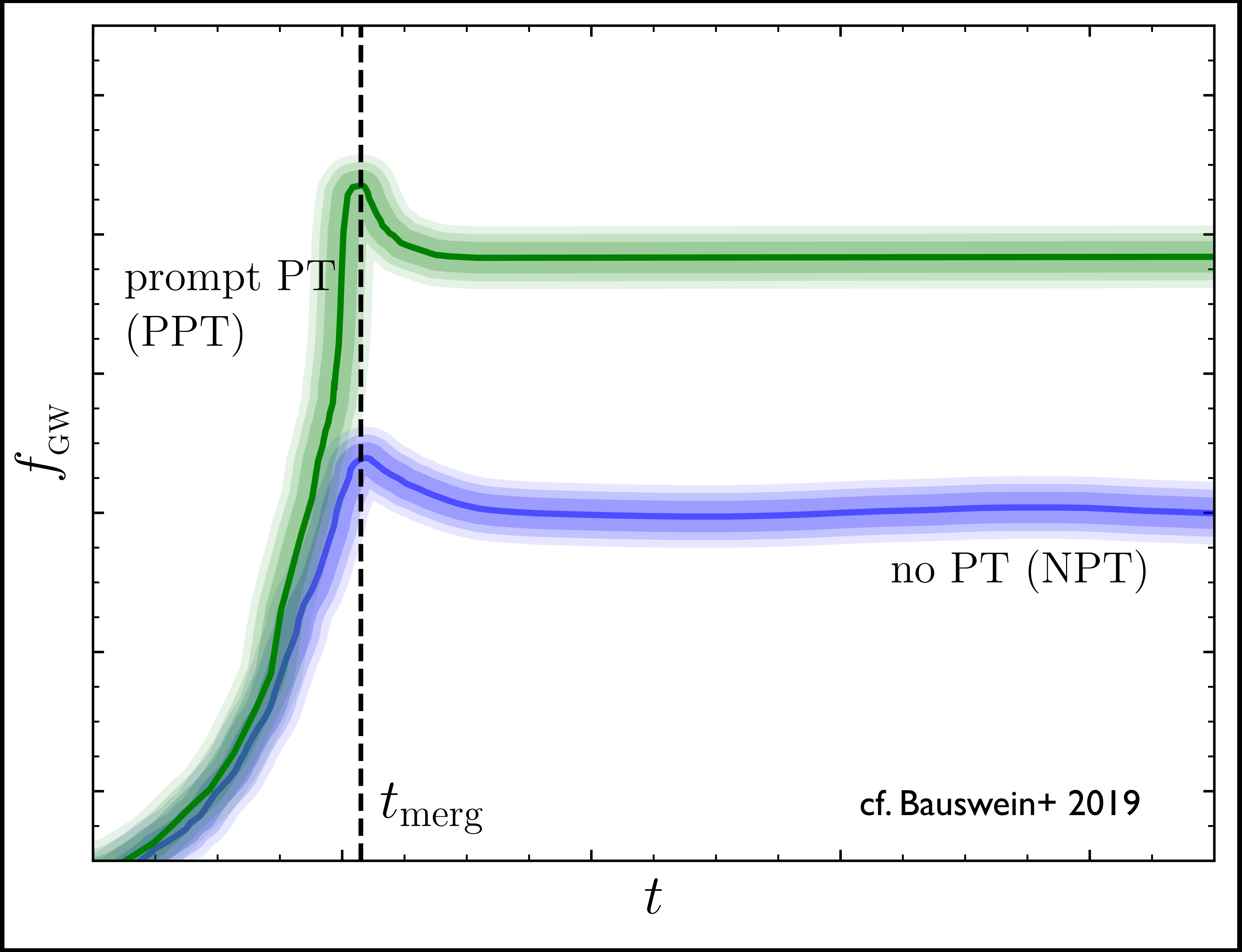

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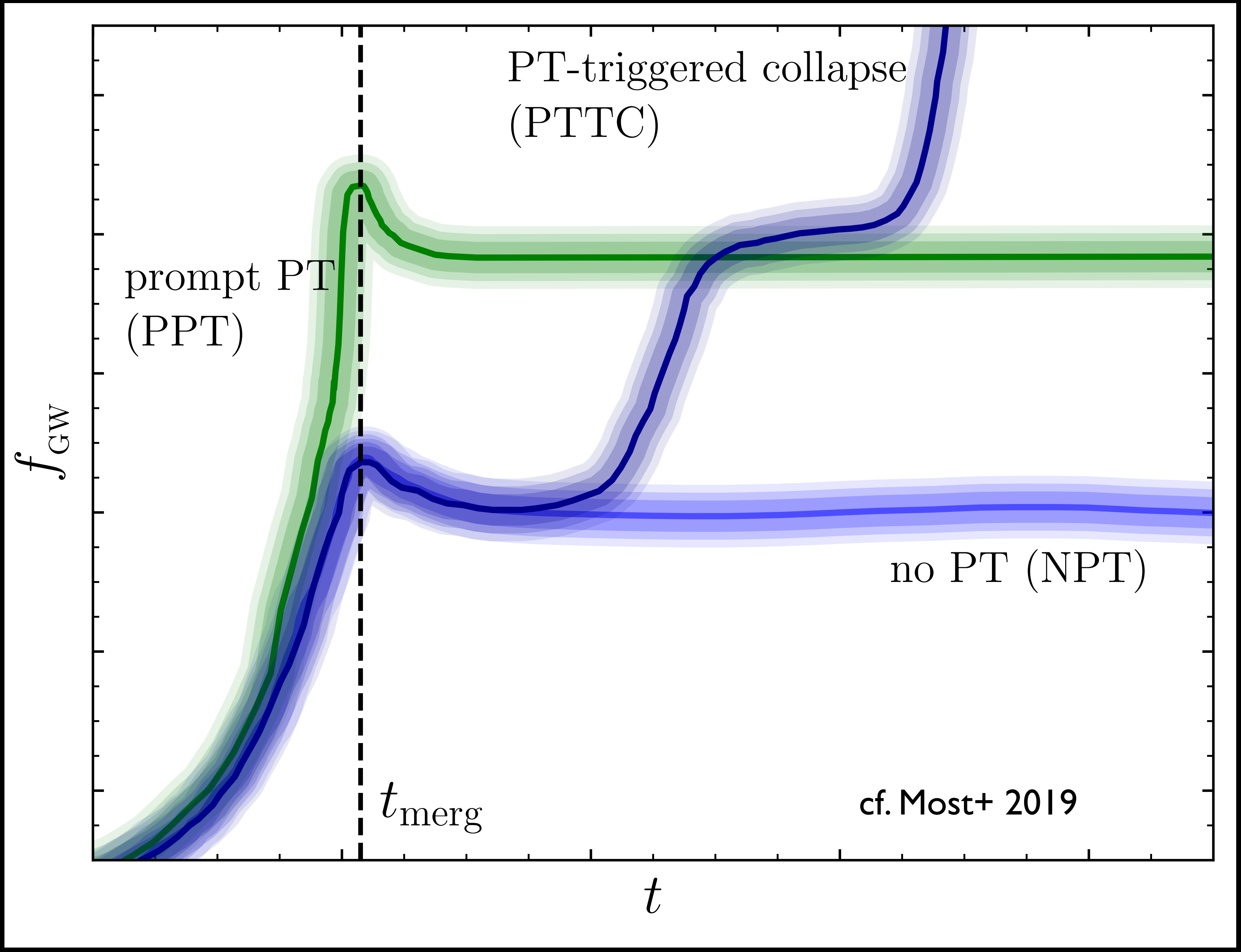

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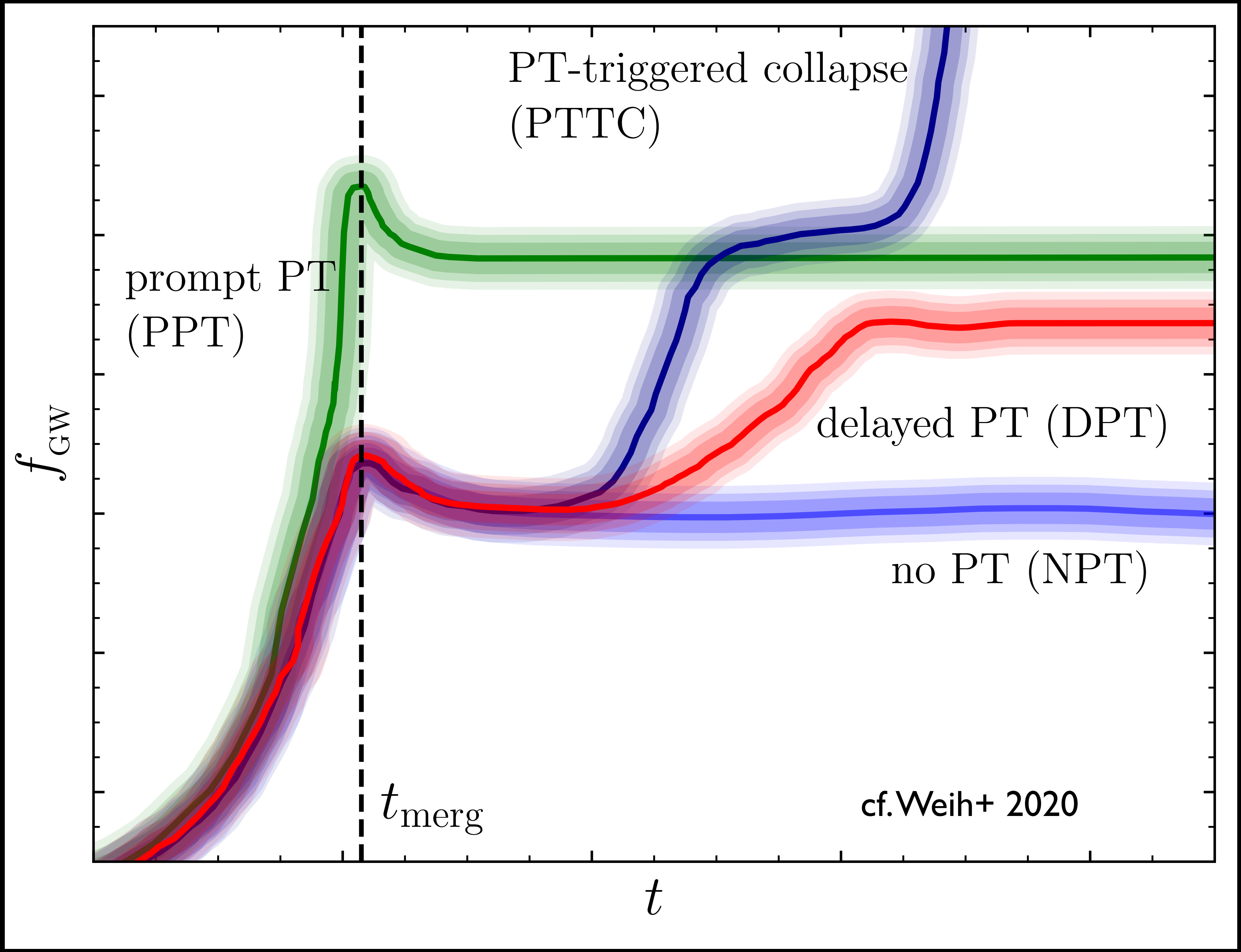
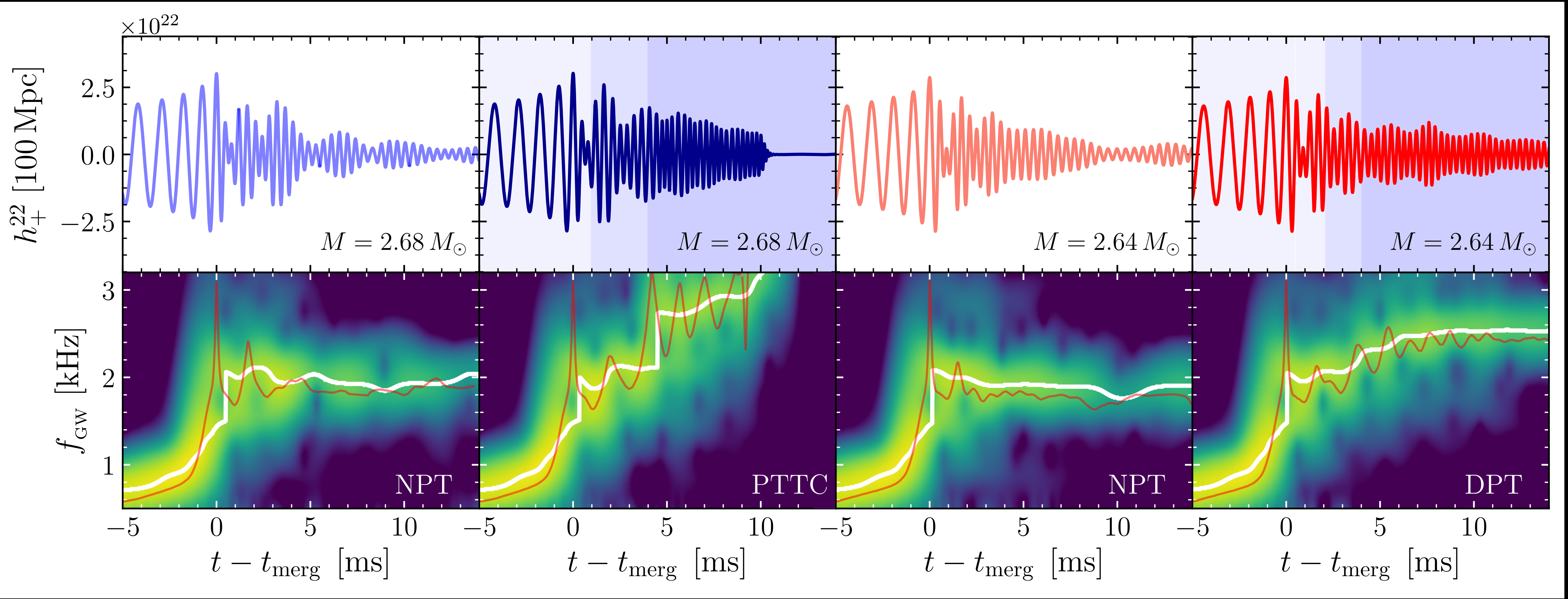


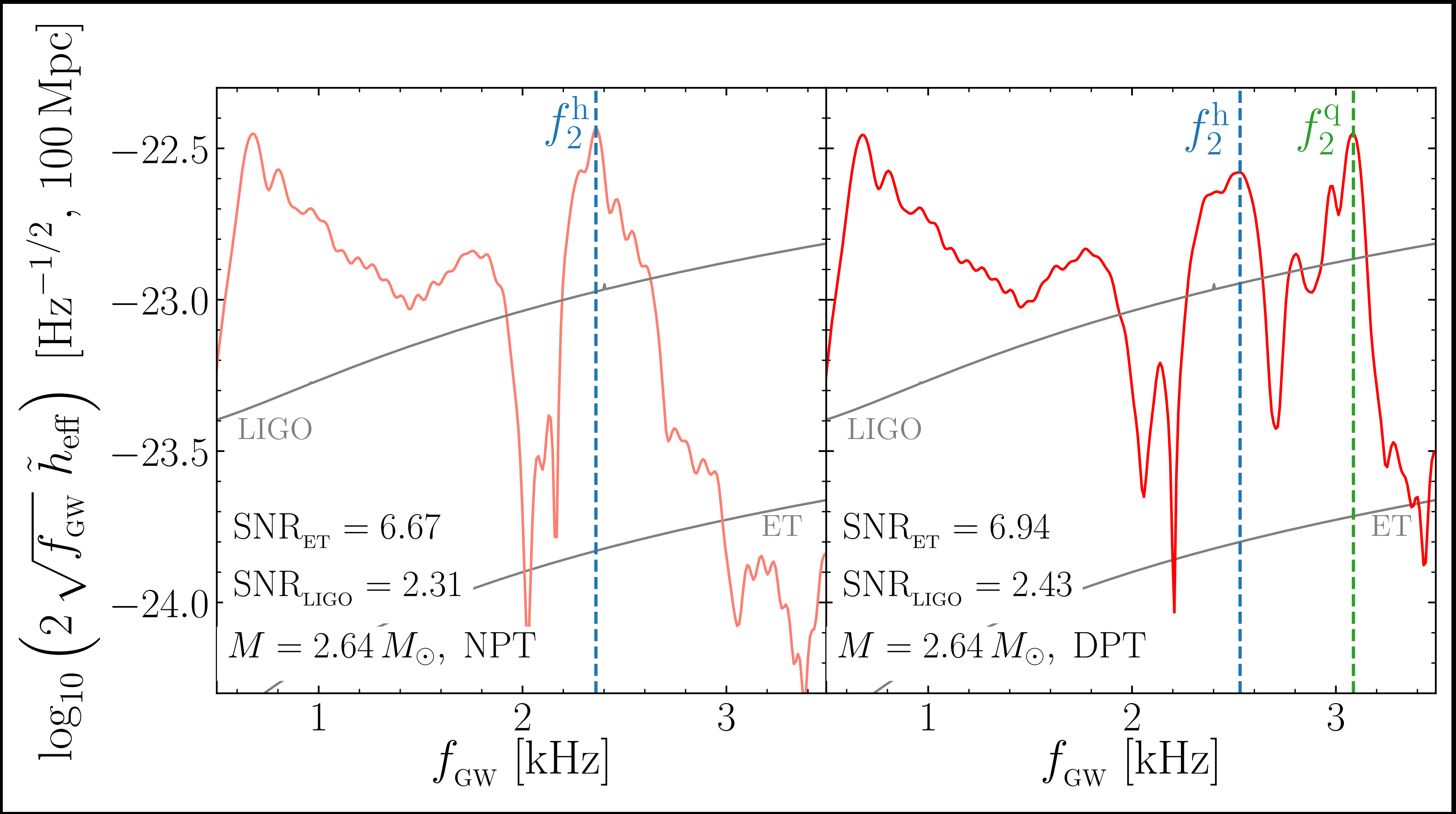
A more comprehensive picture

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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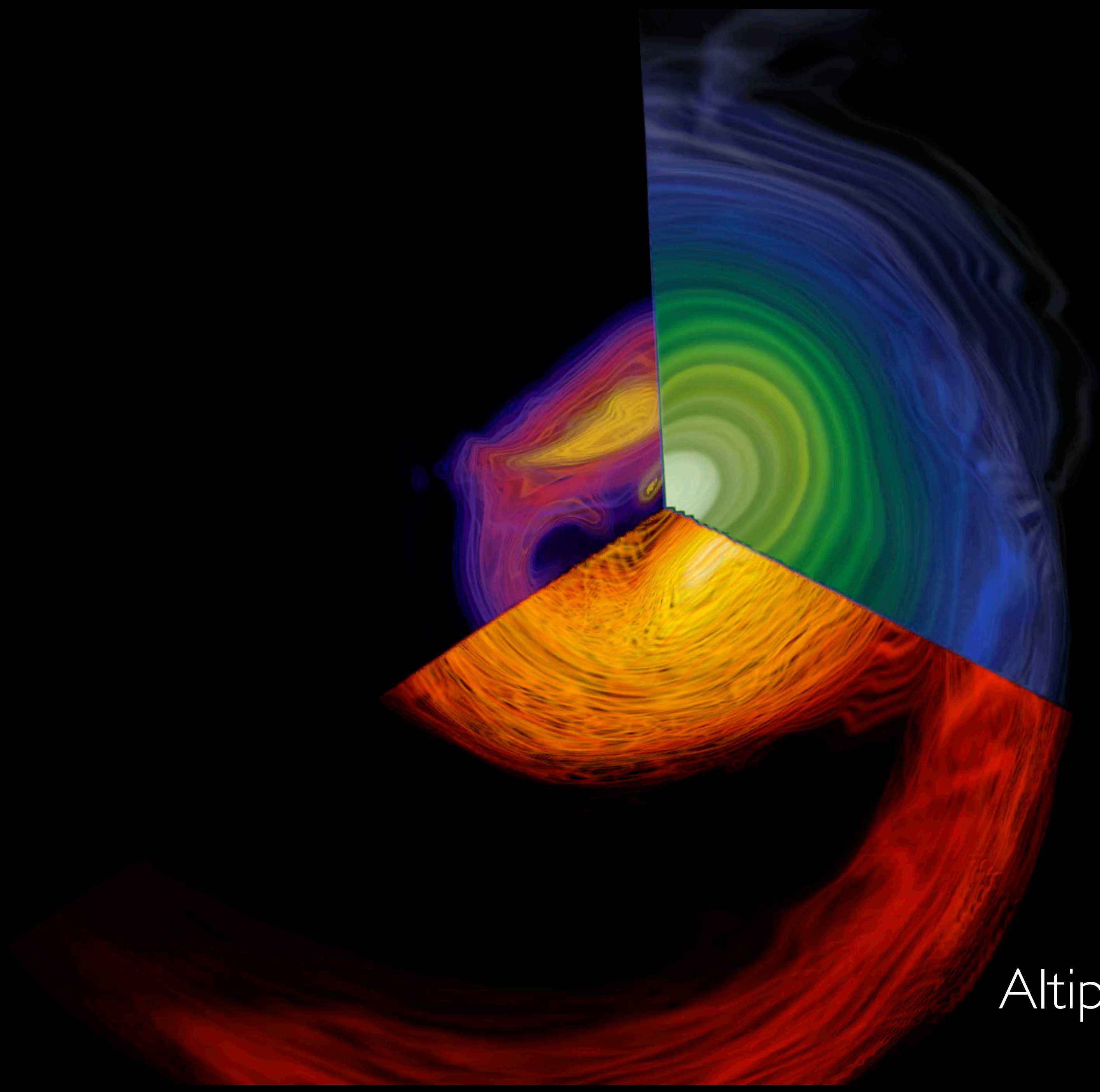
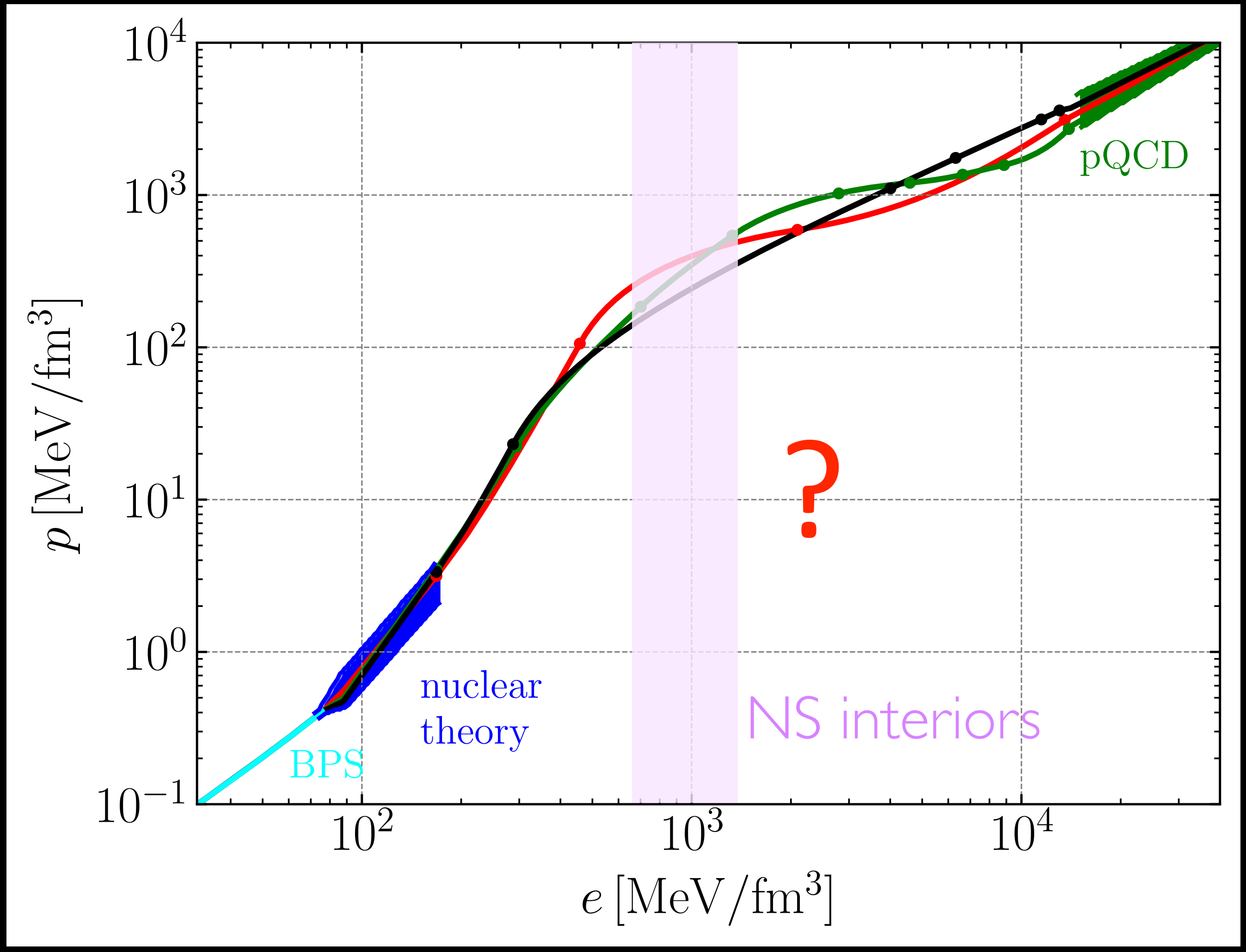
On the sound speed in neutron stars

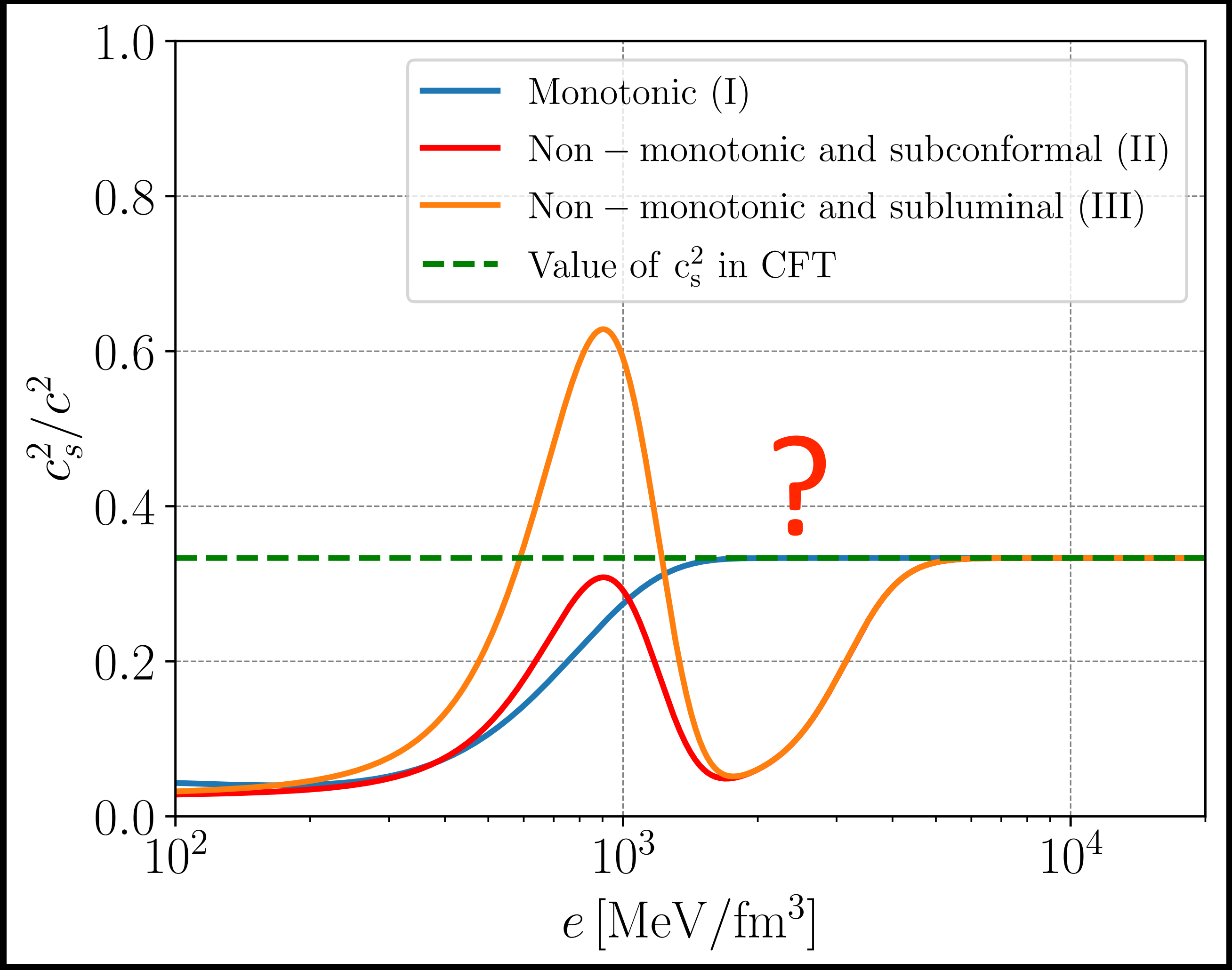


Altiparmak, Ecker, LR (2022a)
Ecker, LR (2022b)
Ecker, LR (2022c)

A very basic question

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





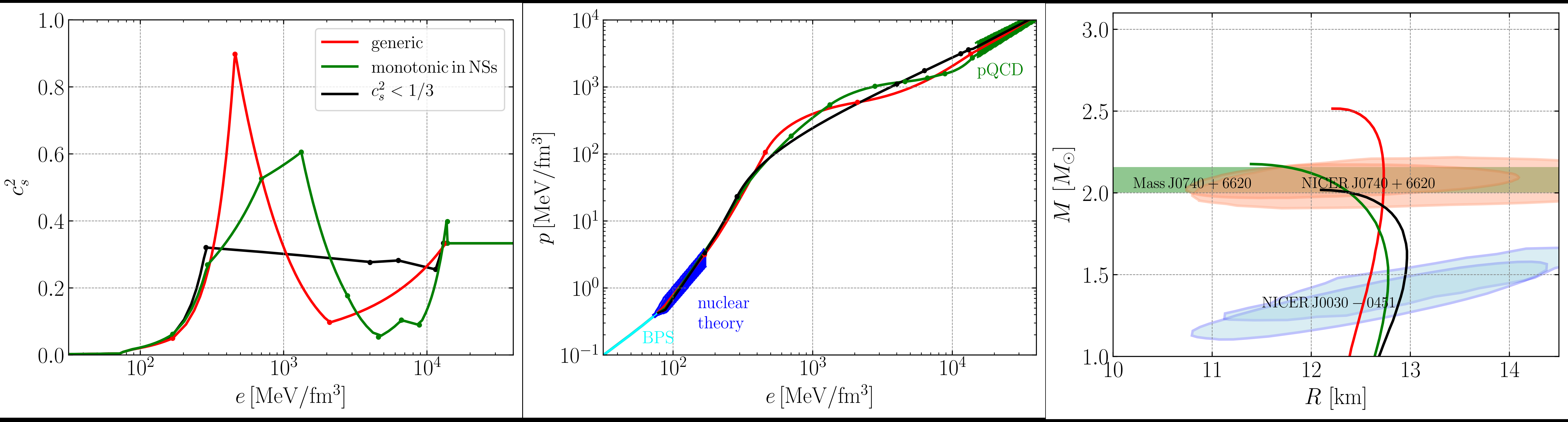
i) monotonic and sub-conformal: $c_s^2 < 1/3$ (blue)

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

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

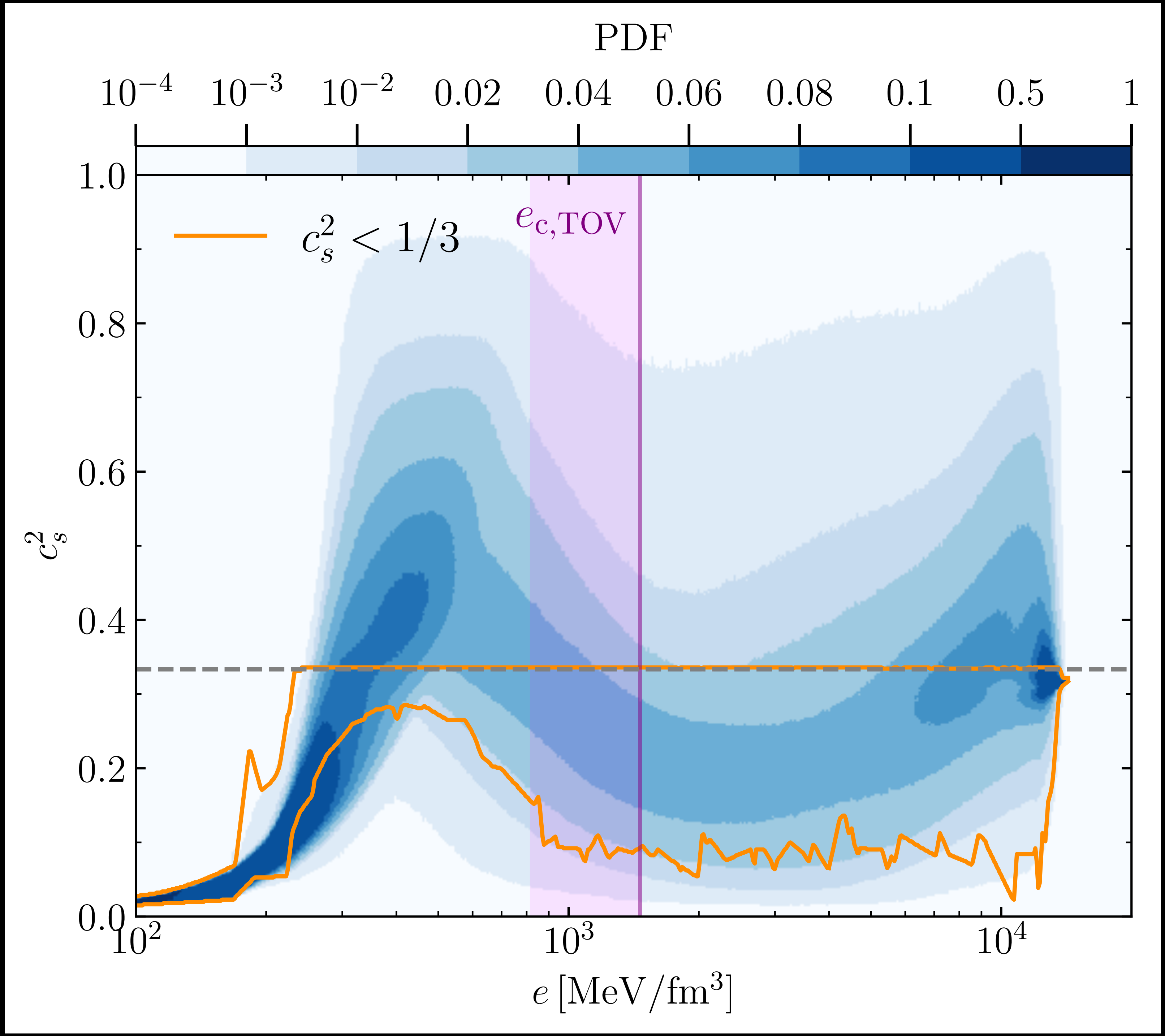
- Lacking stronger constraints, an **agnostic approach** is viable and followed by many (eg piecewise polytropes, Most+ 2018)

- Alternative, we can 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, ~ 10% of our EOSs survives and provides robust statistics from which we compute PDFs.

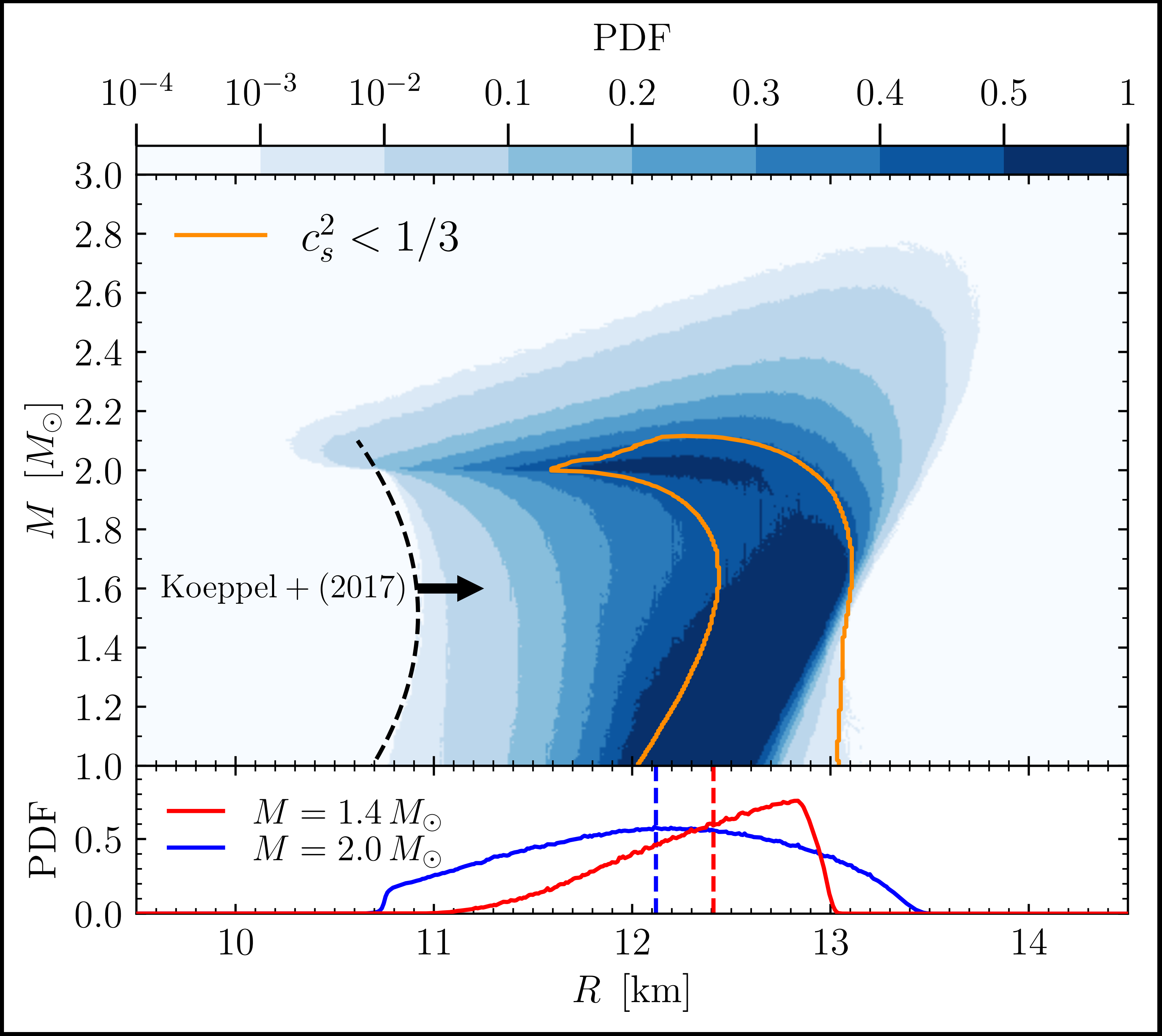
Sound speed PDF



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

No monotonic sub-conformal EOS found.

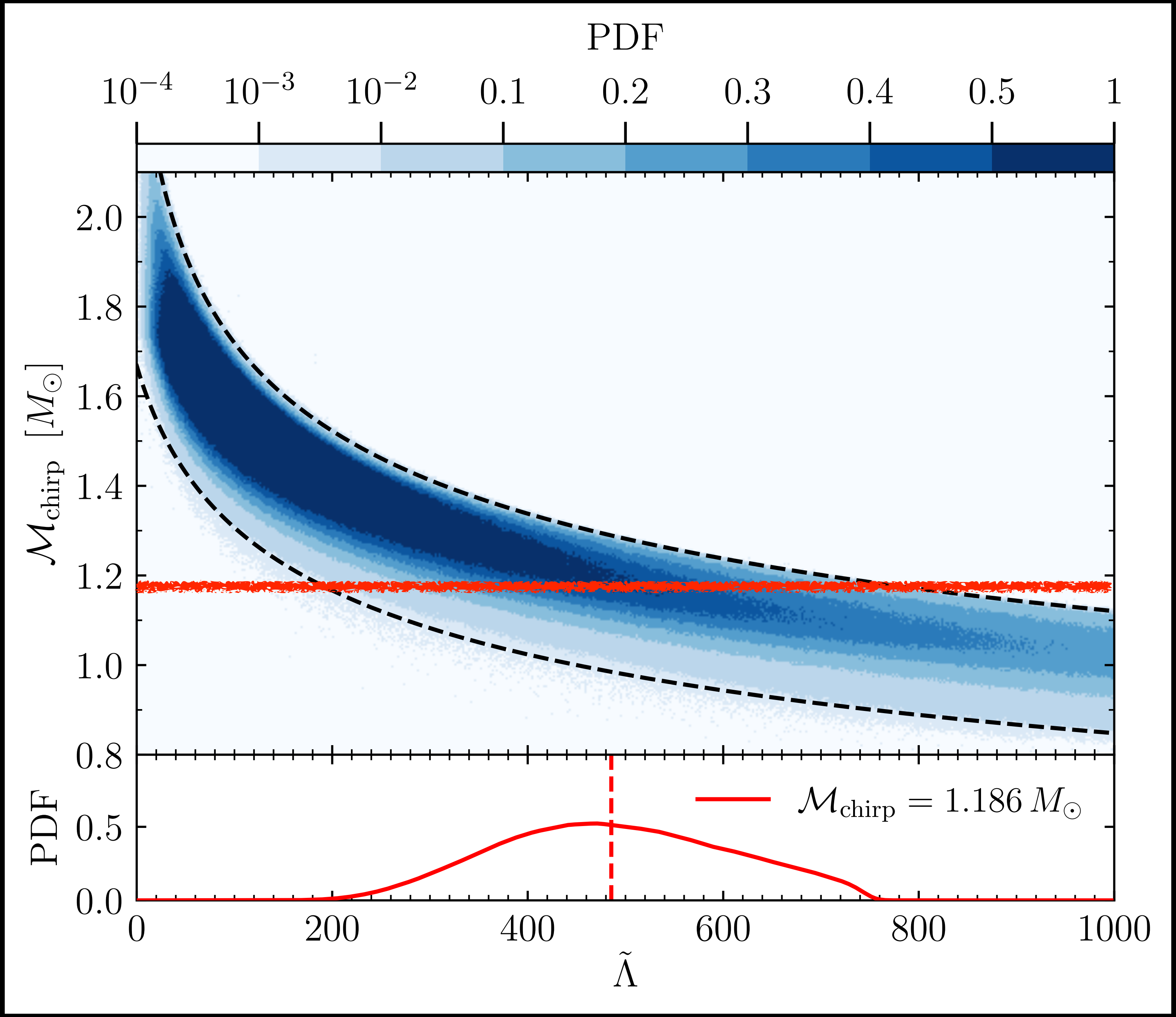
A more comprehensive picture



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

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

A more comprehensive picture



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

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?

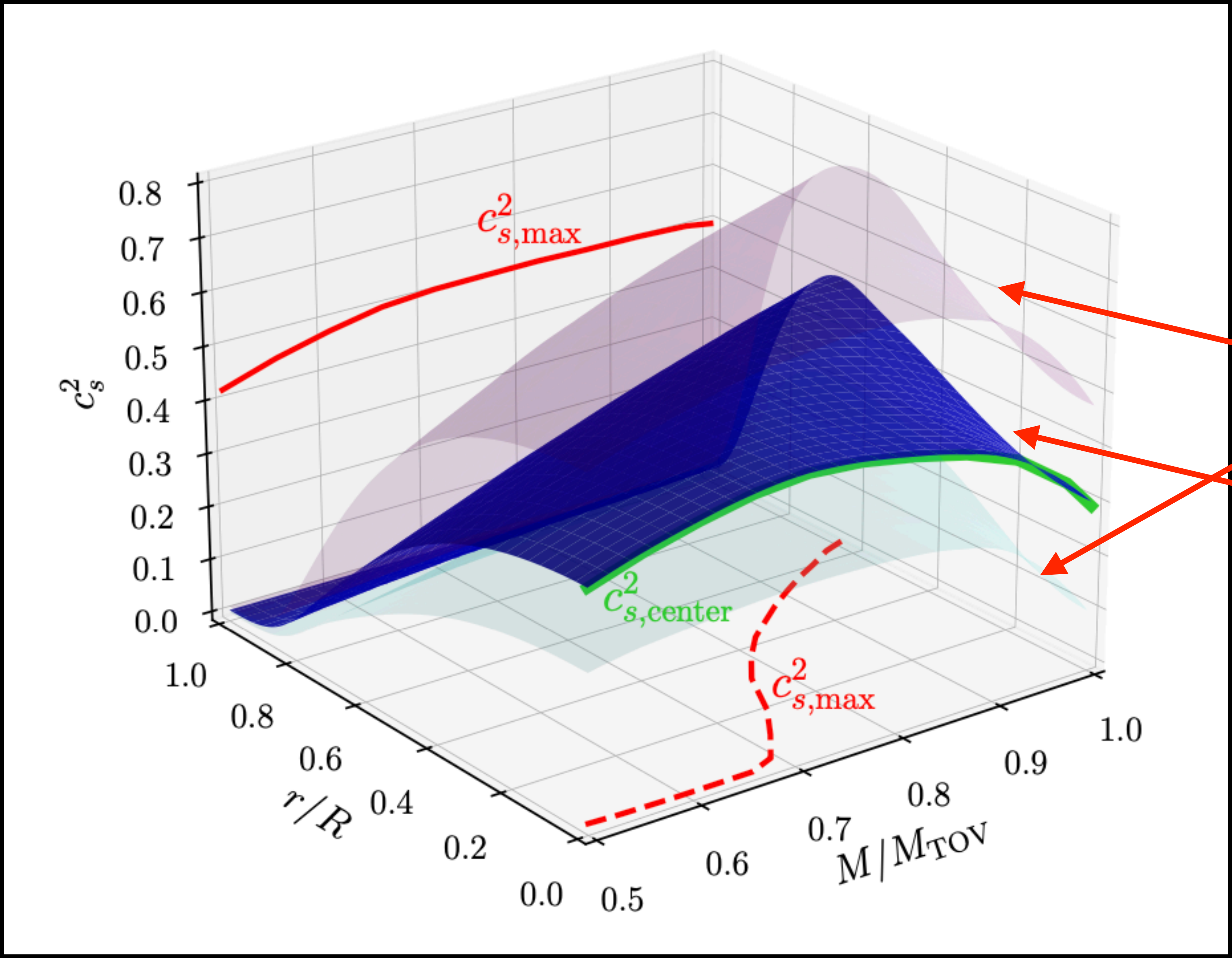
Hard to answer: every EOS will have its own *(M, R)* relation

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

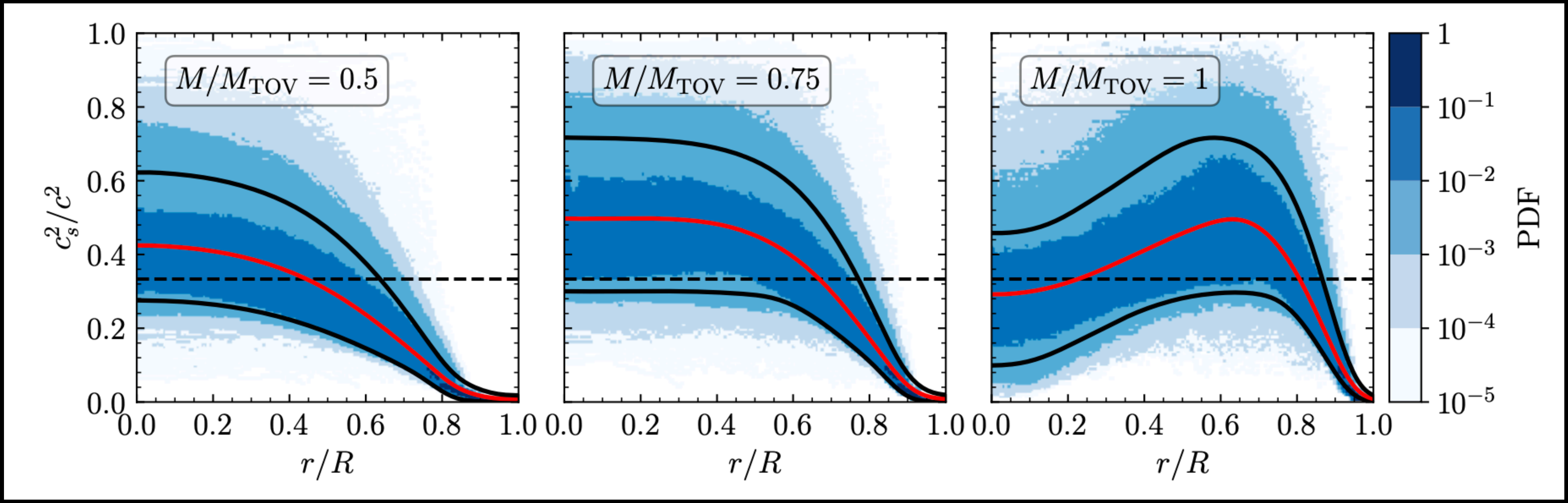
$c_s/c \in [0, 1]$, $r/R \in [0, 1]$, $M/M_{\rm TOV} \in [0, 1]$: EOS independent

A scale-independent representation

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



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)

In other words:

"Light" stars: stiff core, soft mantle

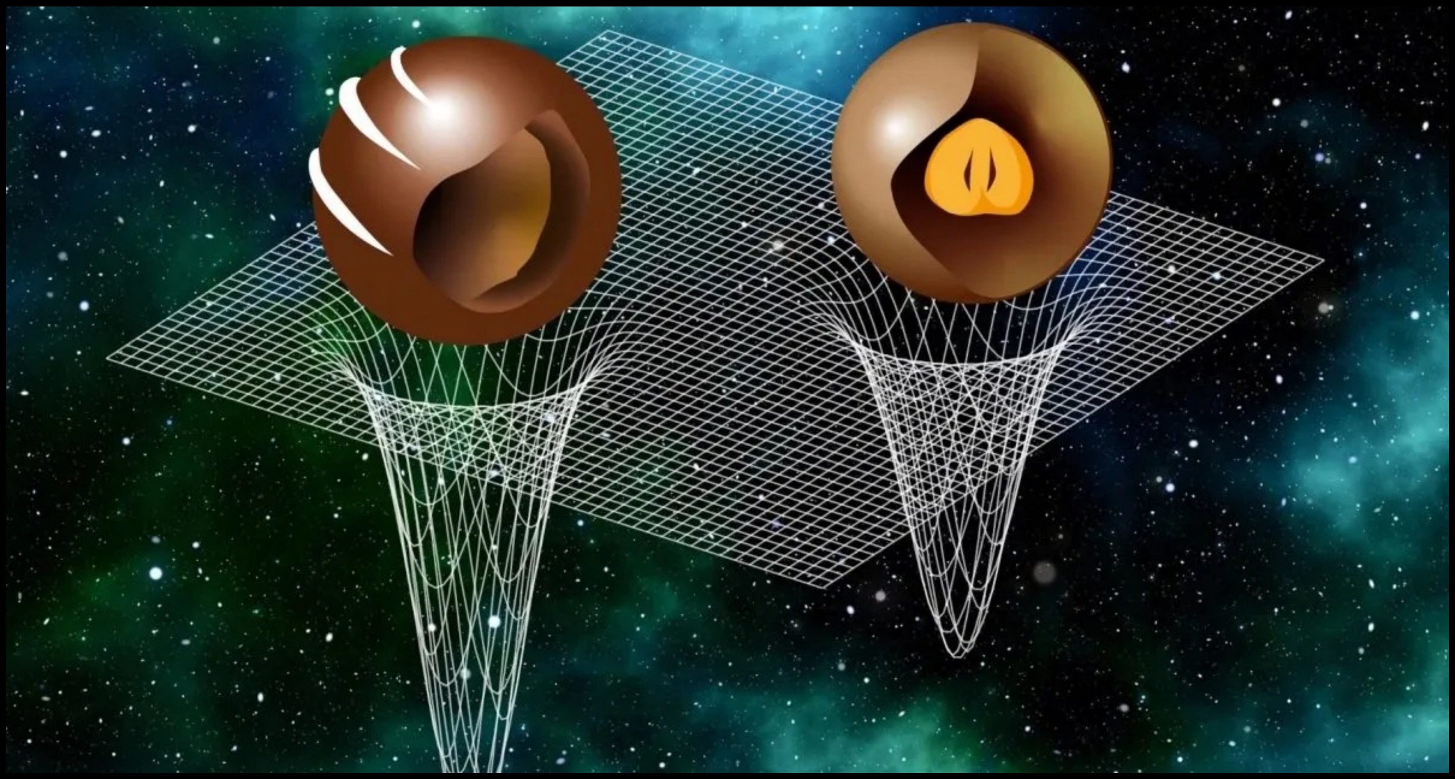
"Heavy" stars: soft core, stiff mantle

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

Frankfurter Allgemeine

ZEITUNG FAZ.NET



Conclusions

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

✳**GW170817, GW190814** 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)