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: a game changer
- 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

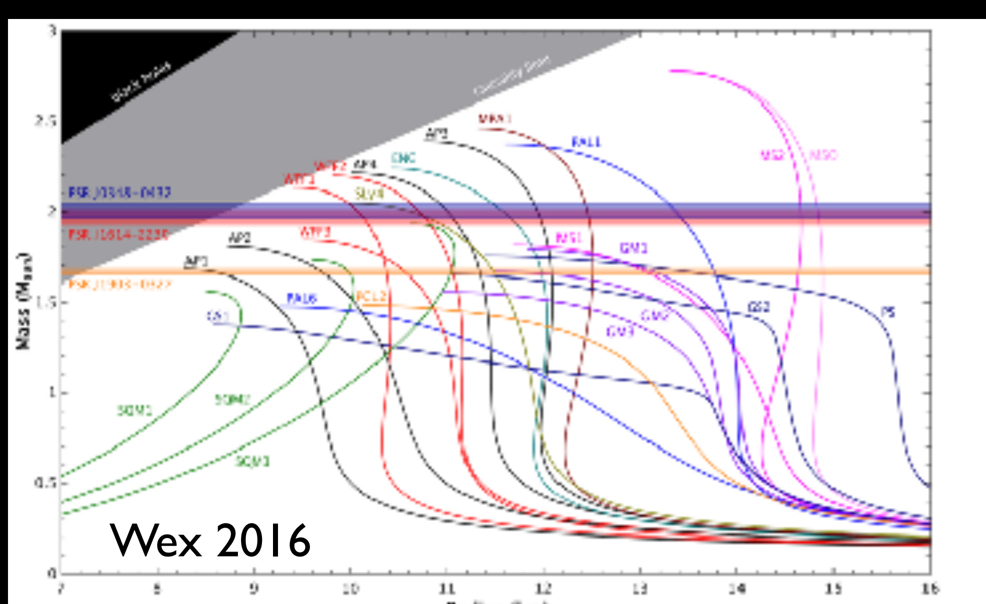
- For black holes the process is very **simple:**

BH + BH ⟶ BH + GWs

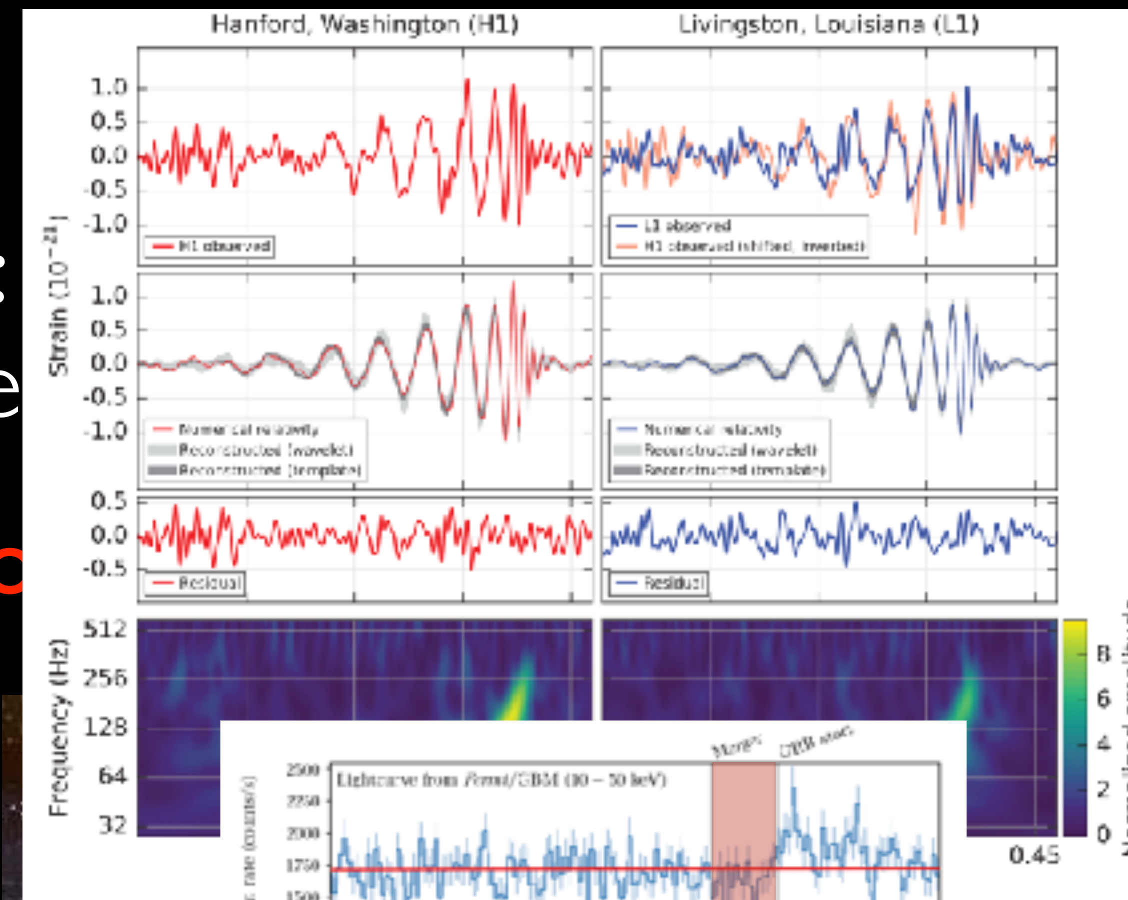
- For NSs the question is more **subtle:**
hyper-massive neutron star (HMNS), ie

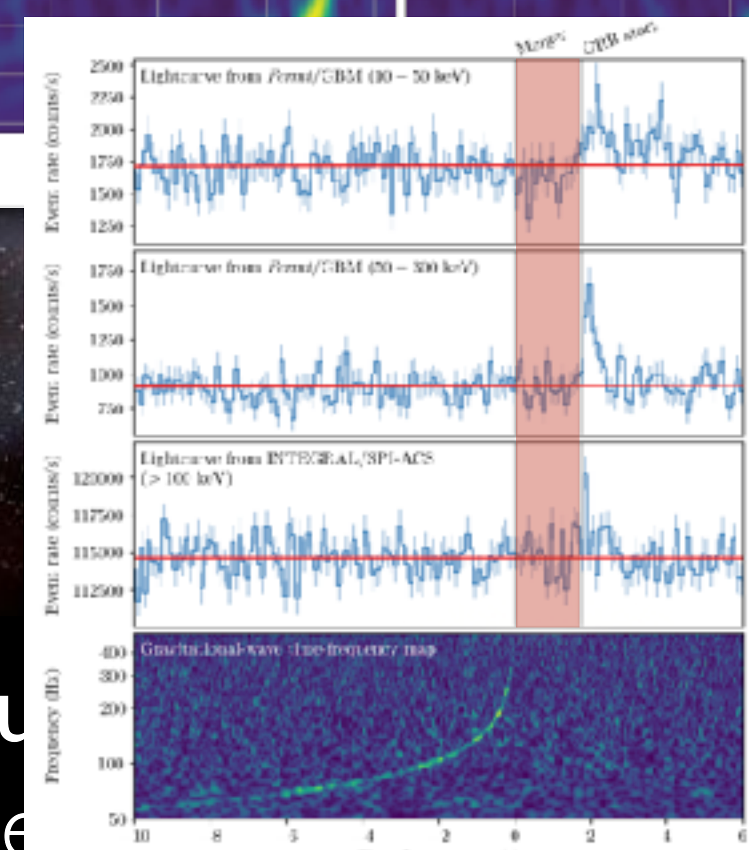
NS + NS ⟶ HMNS+... ? ⟶ BH+to

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



GW150914





- BH+toru ... us
on the ce ... RBs

GW170817

The two-body problem in GR

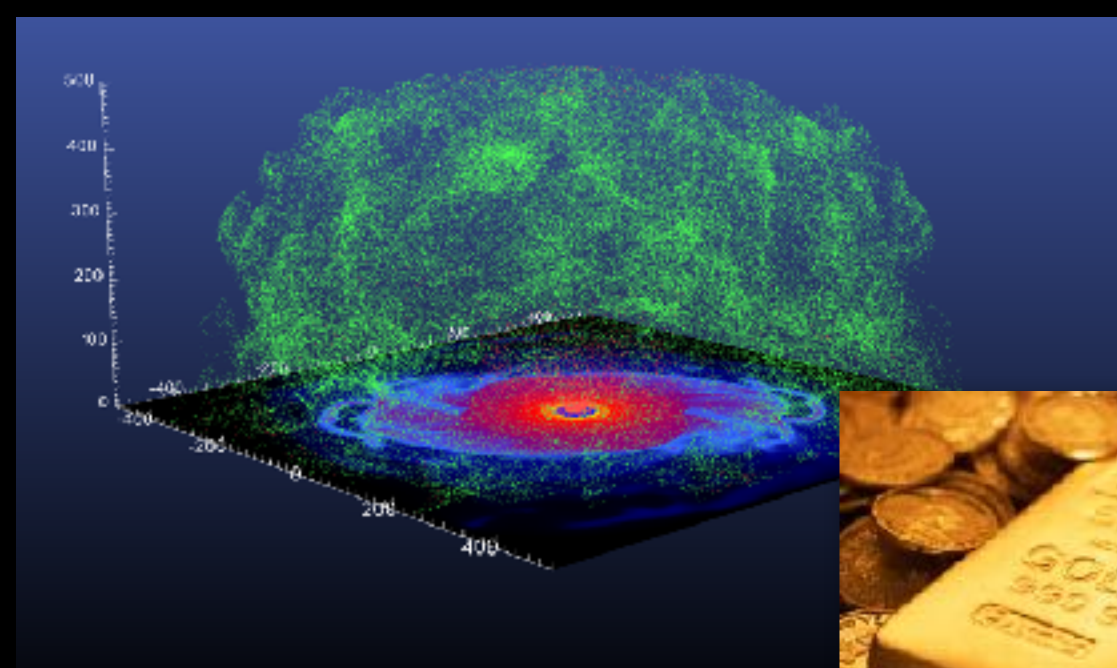
- For black holes the process is very **simple**:

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



The equations of numerical relativity

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

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

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

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

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

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

Animations: Breu, Radice, LR

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

merger → HMNS → BH + torus

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

LS220 EOS

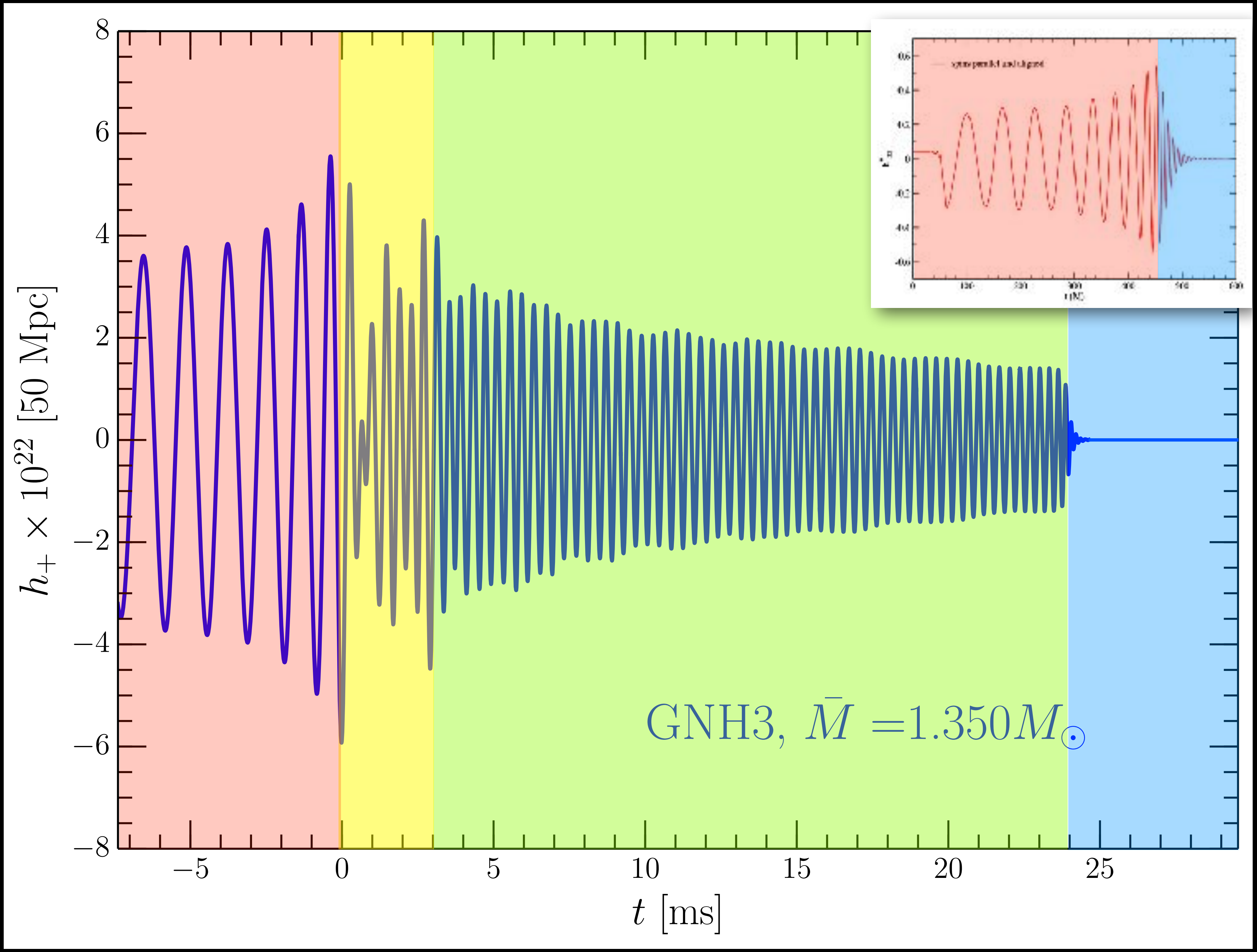
Qualitatively, this is what normally happens:

merger $\longrightarrow$ HMNS $\longrightarrow$ BH + torus

Quantitatively, differences are produced by:

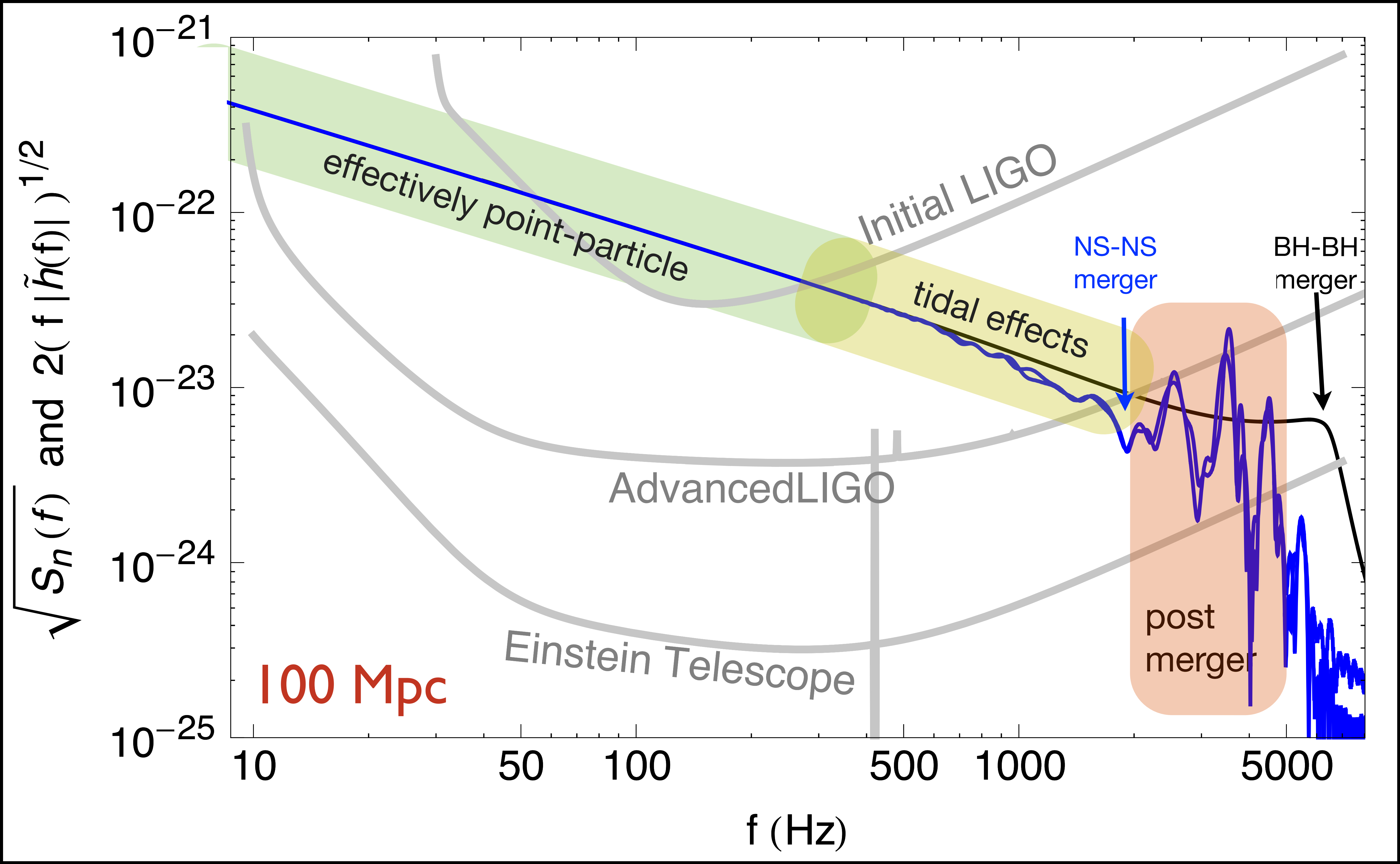
- total mass (prompt vs delayed collapse)
- mass asymmetries (HMNS and torus)
- soft/stiff EOS (inspiral and post-merger, PT)
- magnetic fields (equil. and EM emission)
- radiative losses (equil. and nucleosynthesis)

Anatomy of the GW signal



Postmerger signal: peculiar of binary NSs

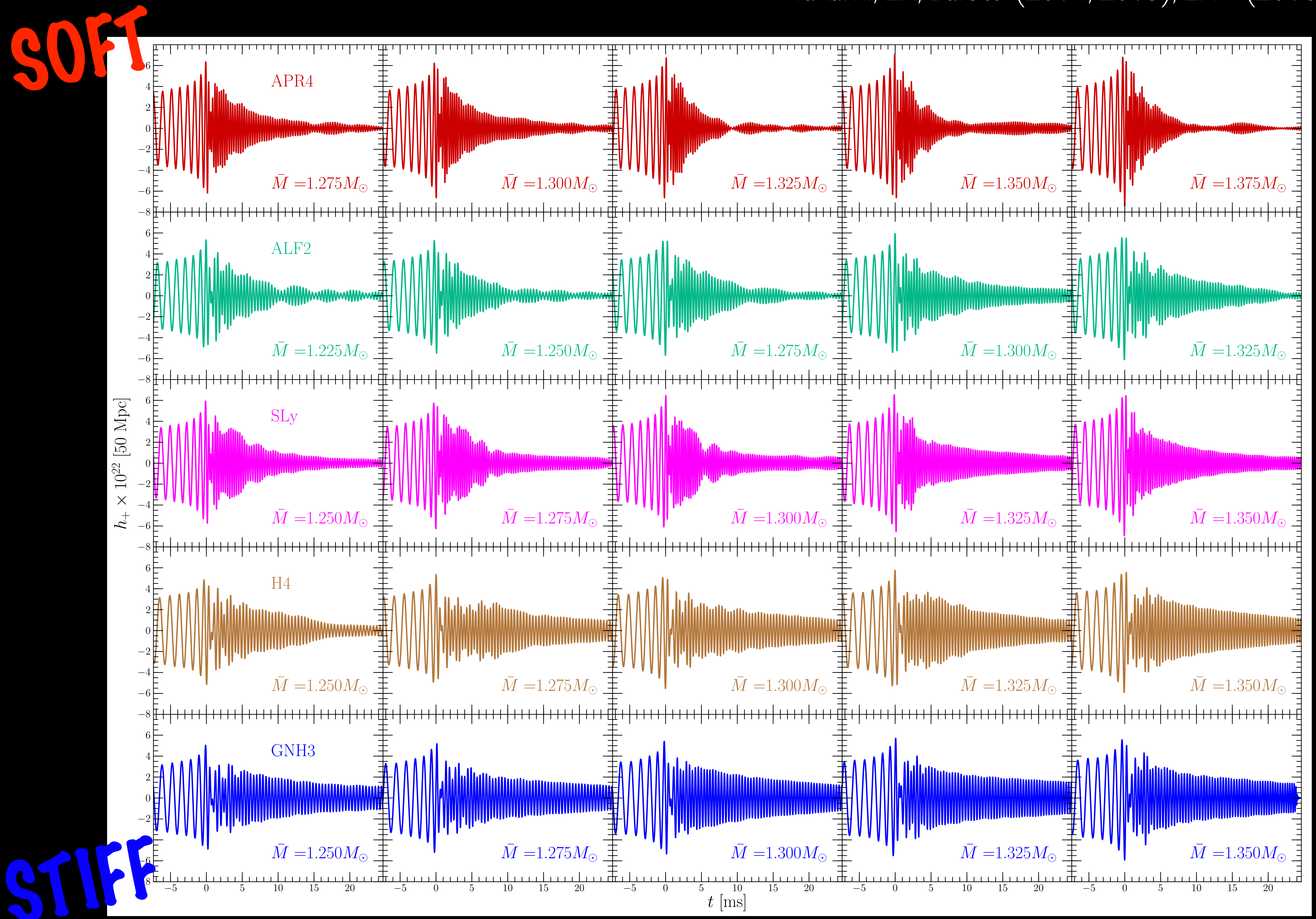
In frequency space



Read et al. (2013)

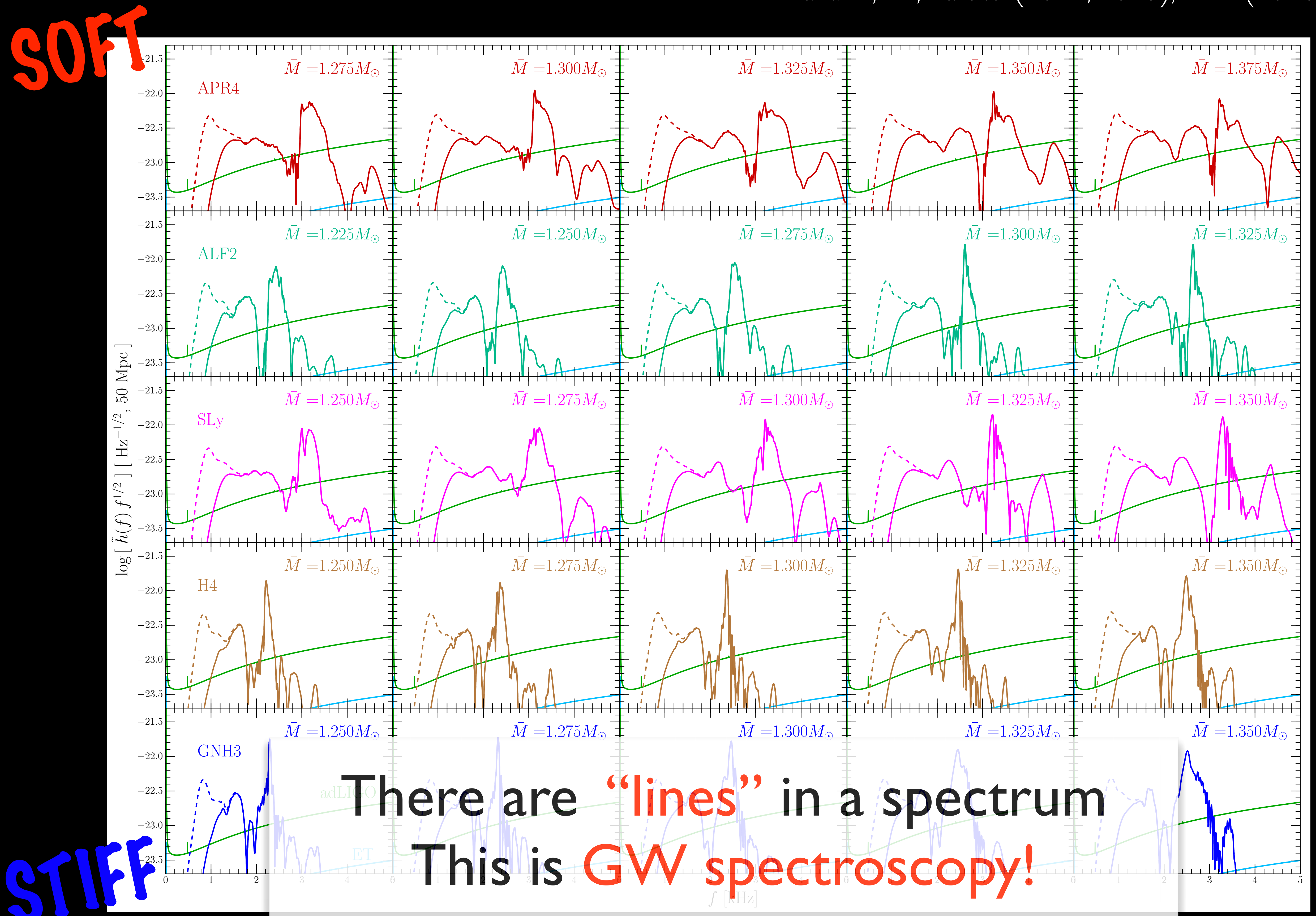
What we can do nowadays

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



Extracting information from the EOS

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



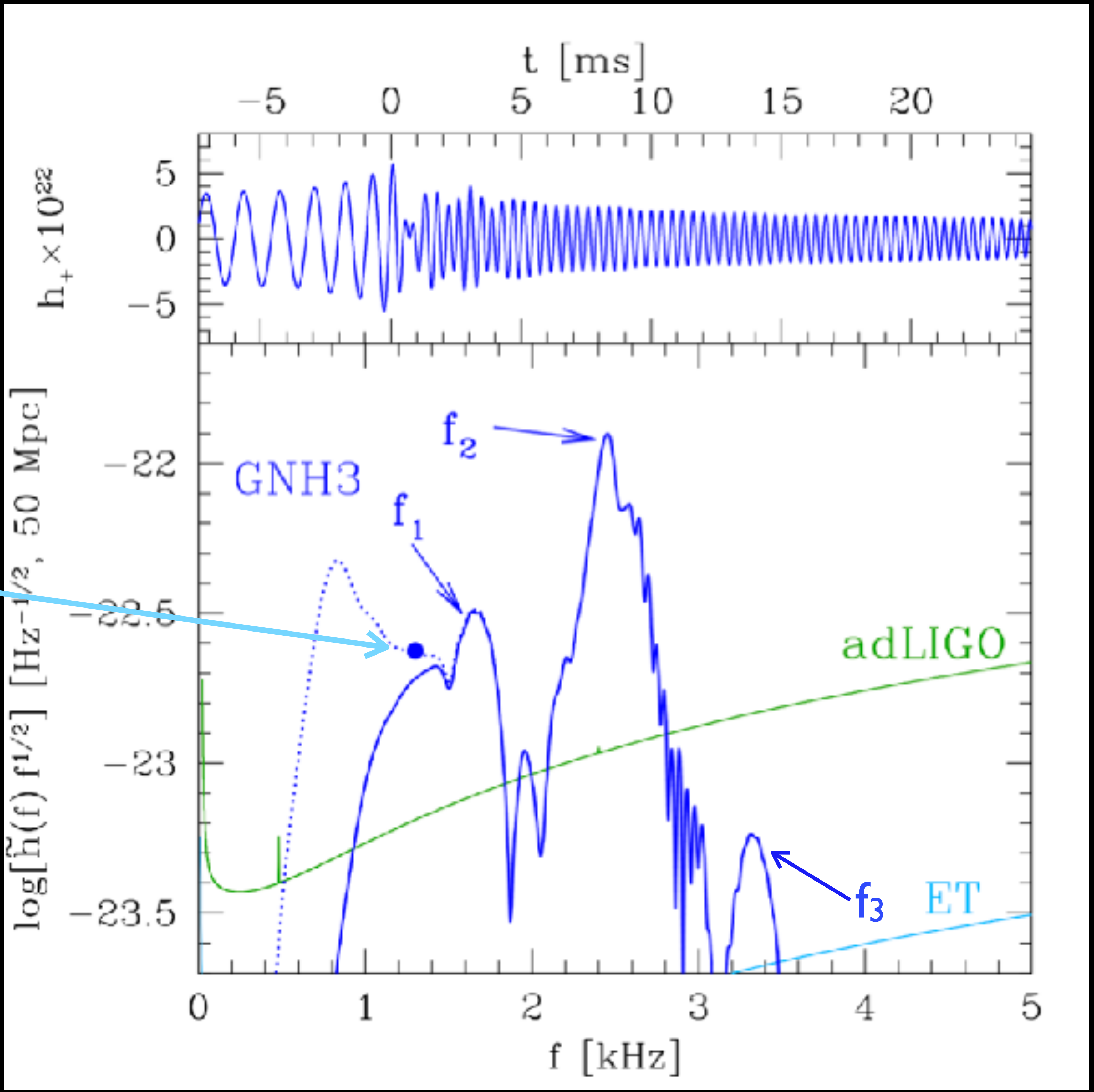
There are "lines" in a spectrum

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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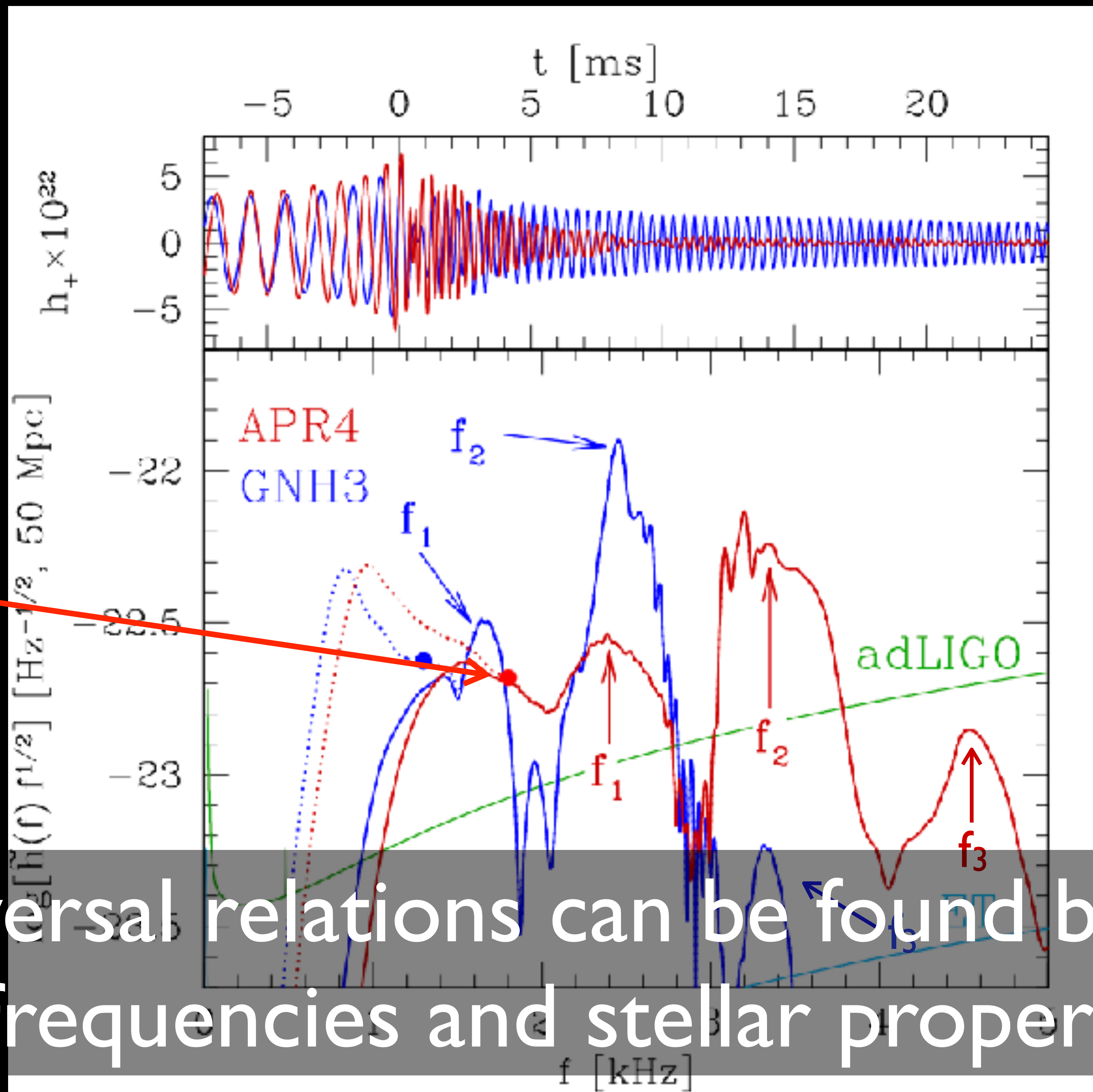
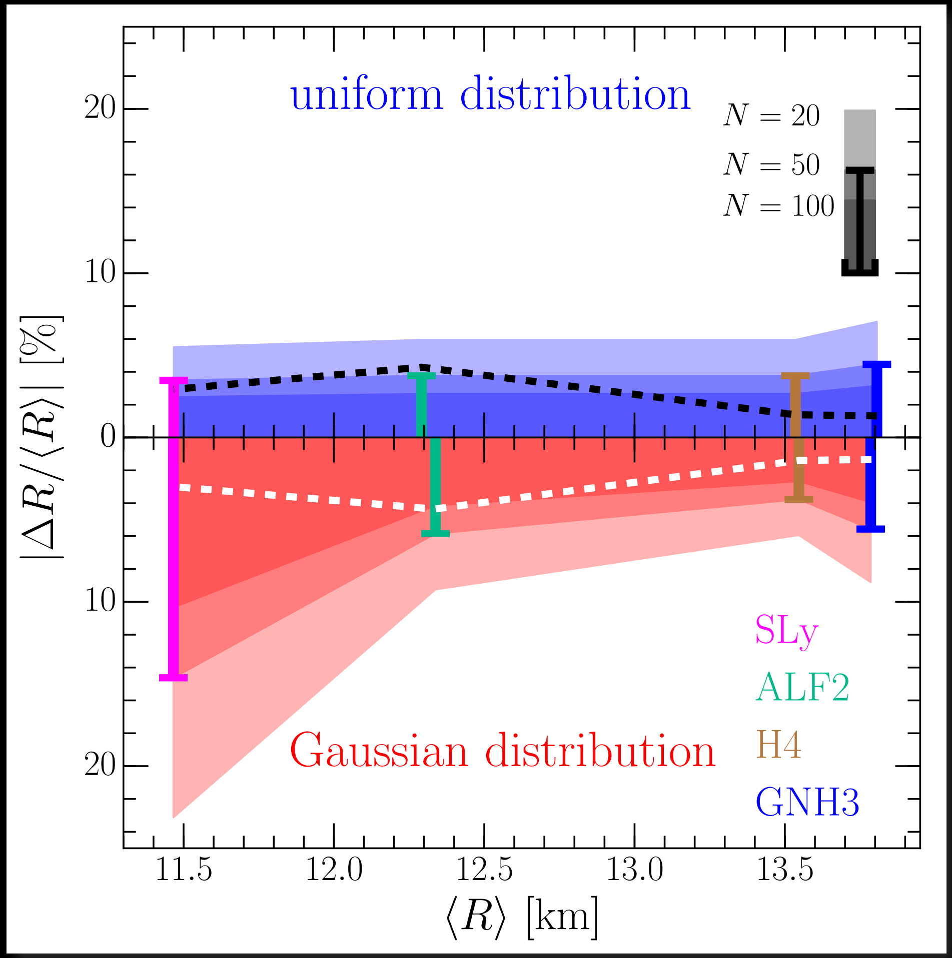
merger frequency



Universal relations can be found between frequencies and stellar properties

A spectroscopic approach to the EOS

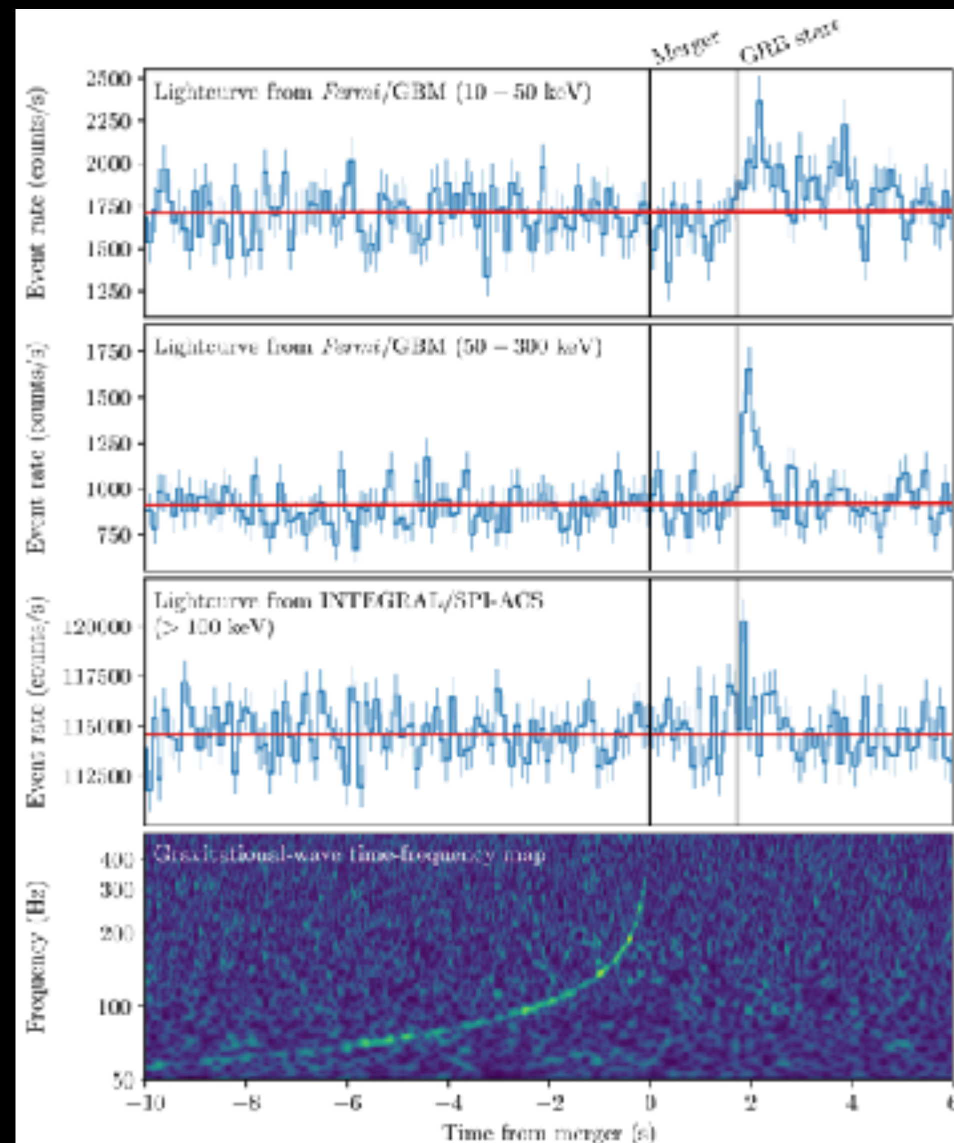
- **Universal behaviour** and **analytic modelling** of post-merger relates position of these peaks with the EOS.
- Question: how well can we constrain the EOS (radius) given ***N* detections?**



- 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)

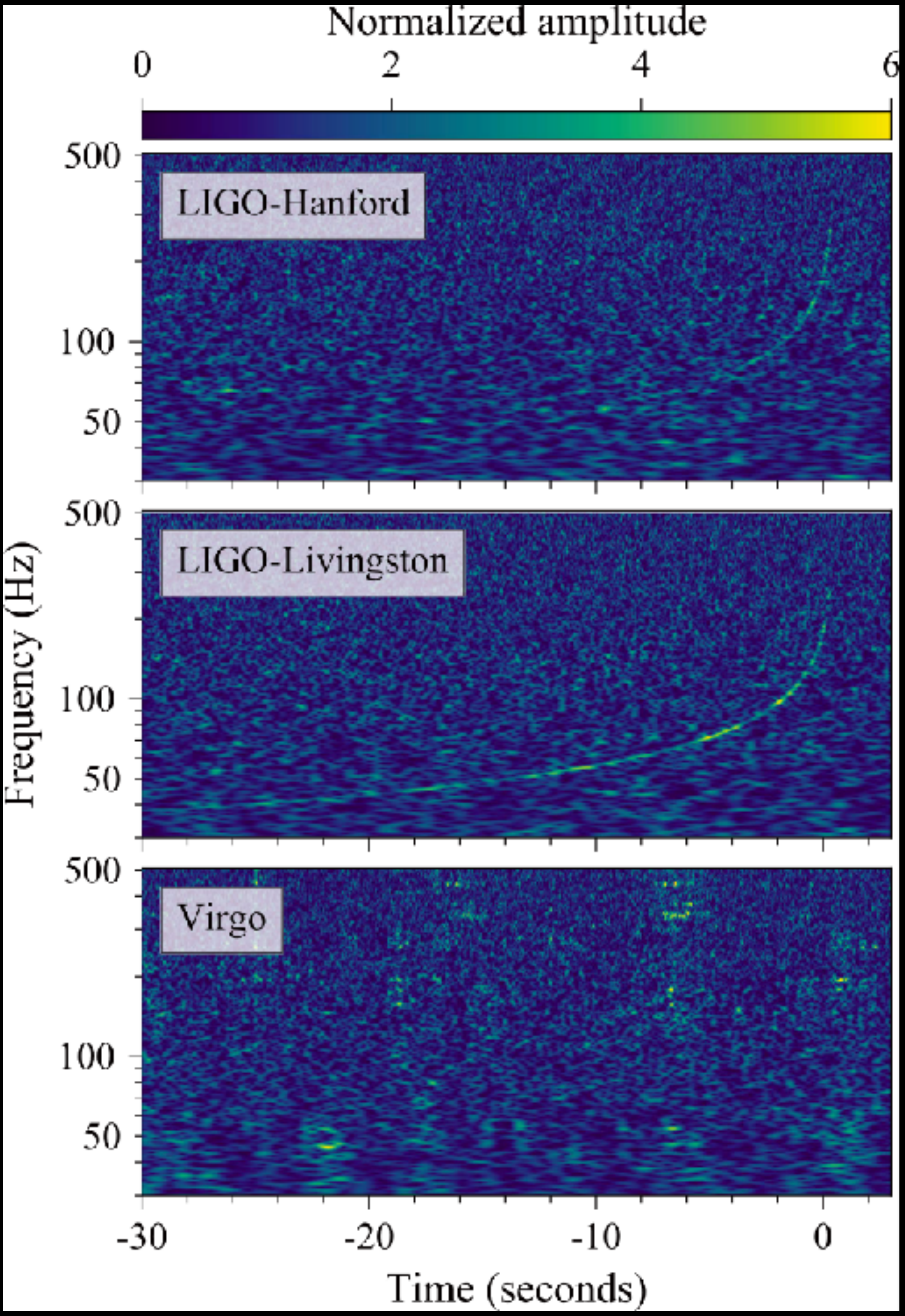
GW170817: a game changer



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

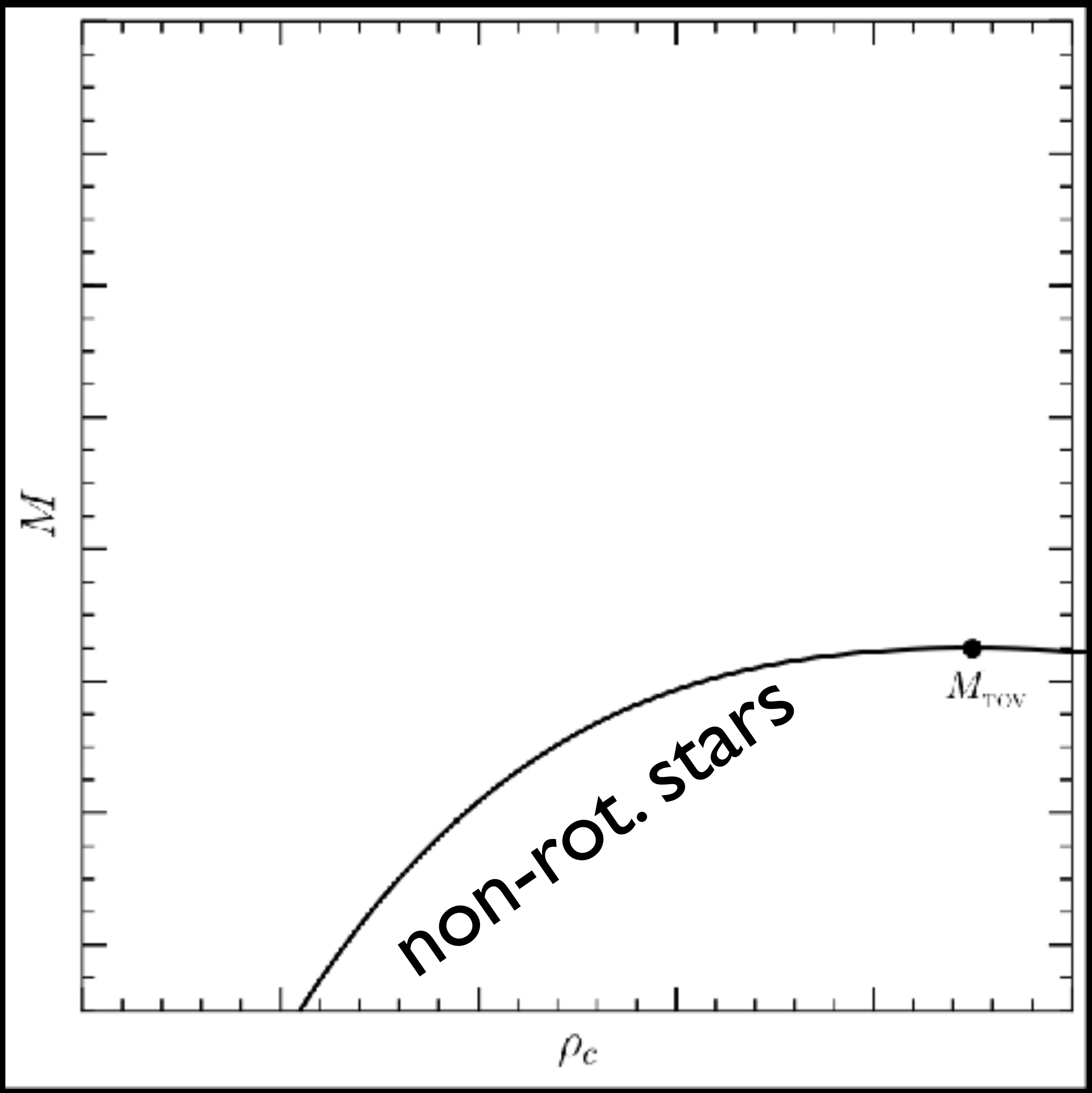
GW170817: the first binary neutron-star system

- ✴ **Unfortunately** only the **inspiral** signal was detected.
- ✴ **Fortunately** this was **sufficient** to set a number of constraints on max. mass, tidal deformability, radii, etc.



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: $M_{\rm TOV}$

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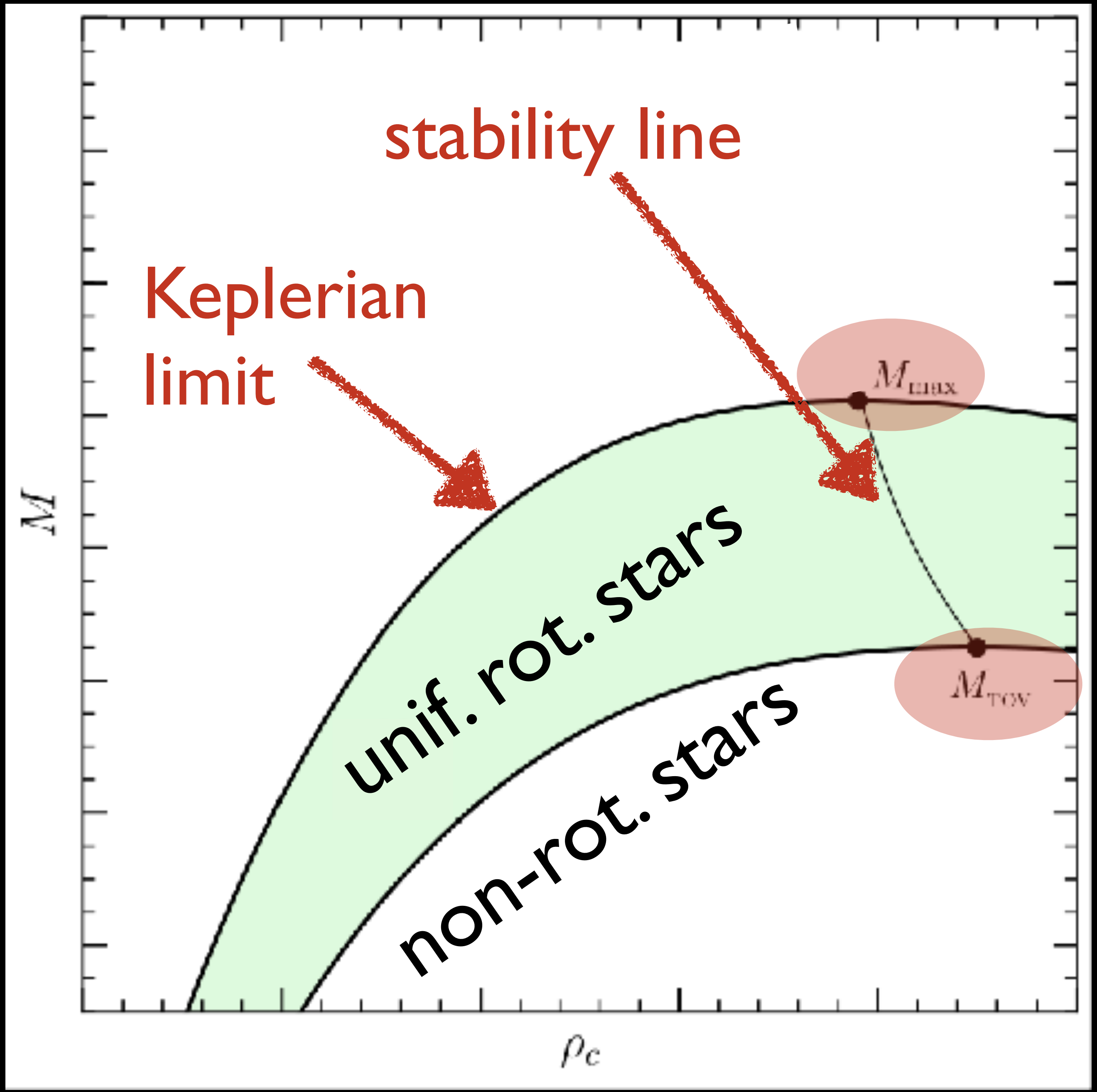

- Sequences of equilibrium models of **nonrotating** stars will have a maximum mass: $M_{\rm TOV}$
- This is true also for **uniformly** rotating stars at mass shedding limit: $M_{\rm max}$
- $M_{\rm max}$ simple and **quasi-universal** function of $M_{\rm TOV}$ (Breu & LR 2016)

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

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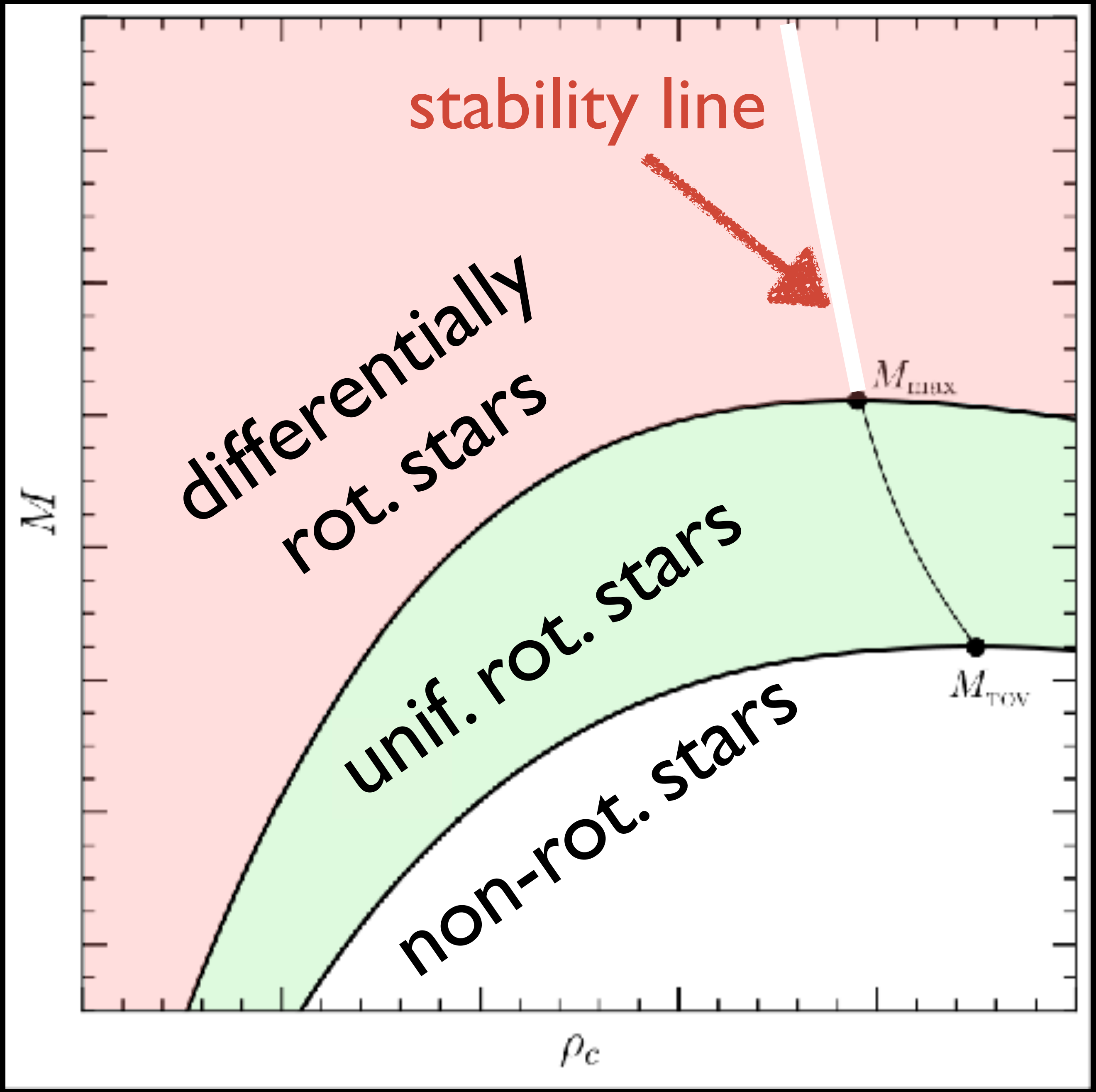

- Green region is for **uniformly** rotating equilibrium models.
- Salmon region is for **differentially** rotating equilibrium models.
- Stability line is simply extended in larger space (Weih+18)

Limits on the maximum mass

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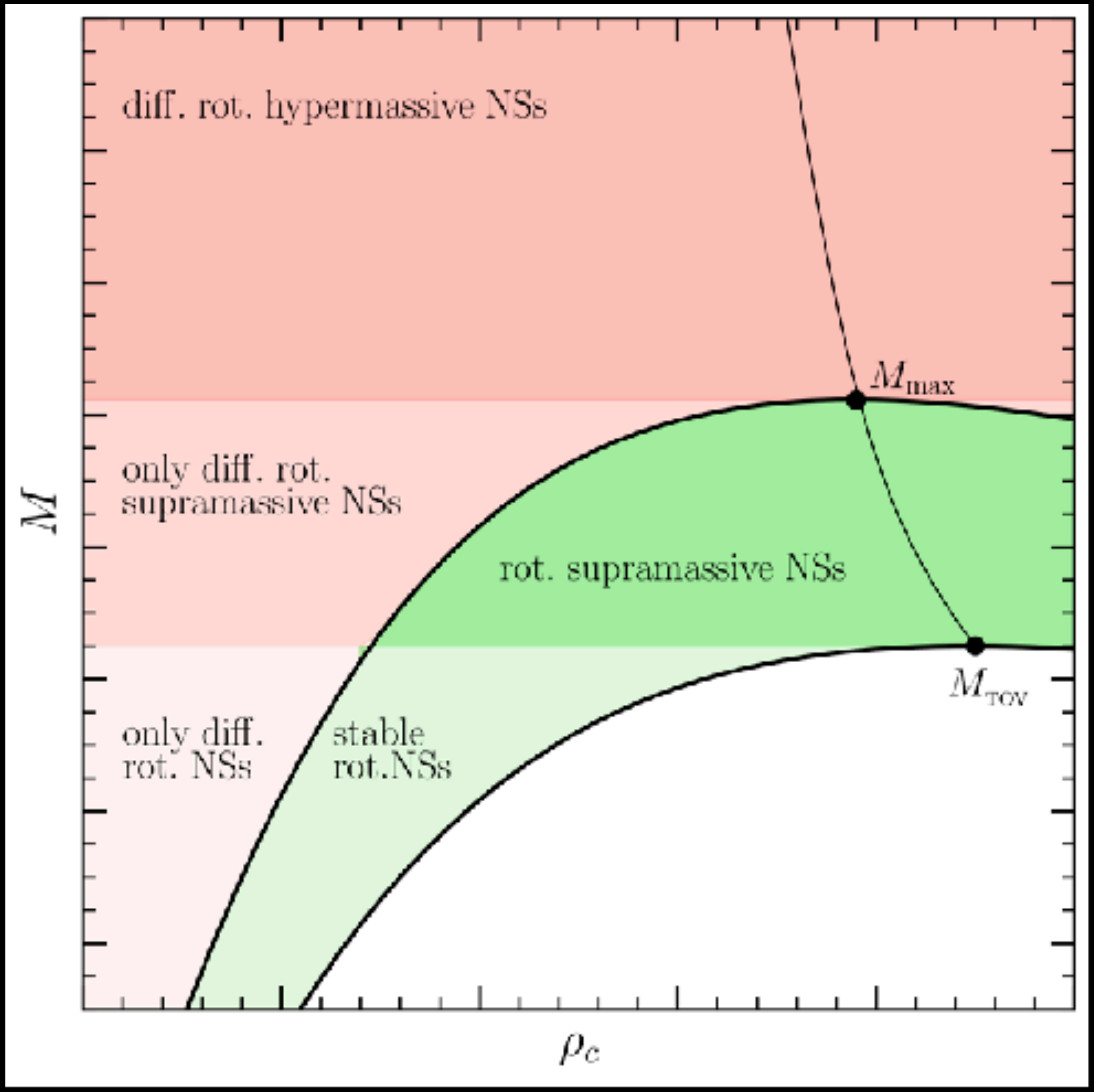


- Green region is for **uniformly** rotating equilibrium models.
- Salmon region is for **differentially** rotating equilibrium models.
- Supramassive stars have:

$$M > M_{\rm TOV}$$

- Hypermassive stars have:

$$M > M_{\rm max}$$

Limits on the maximum mass

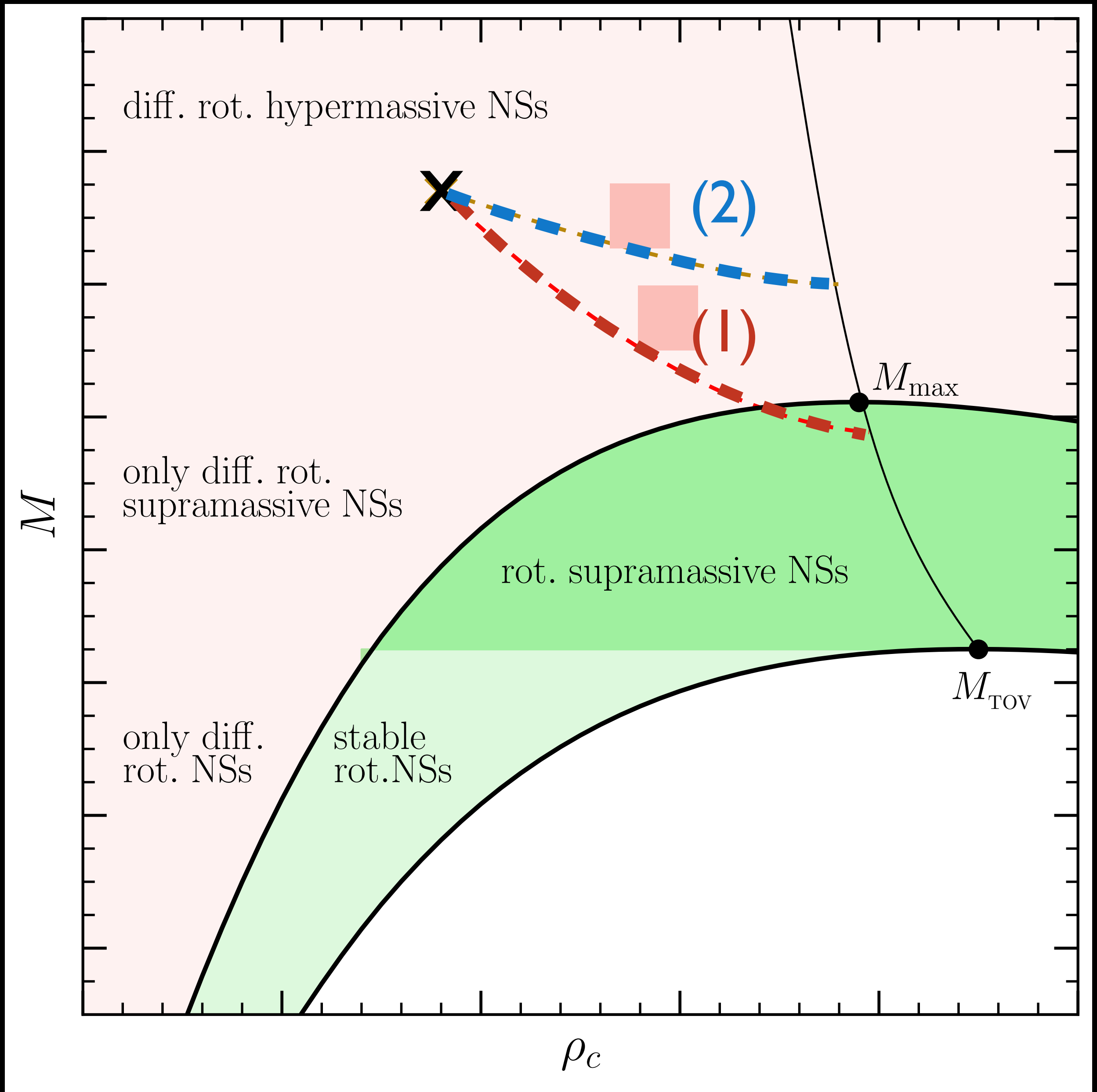
- GW170817 produced object **"X"**; GRB implies a BH has been formed: **"X"** followed two possible tracks: **fast (2)** and **slow (1)**

- 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,** 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

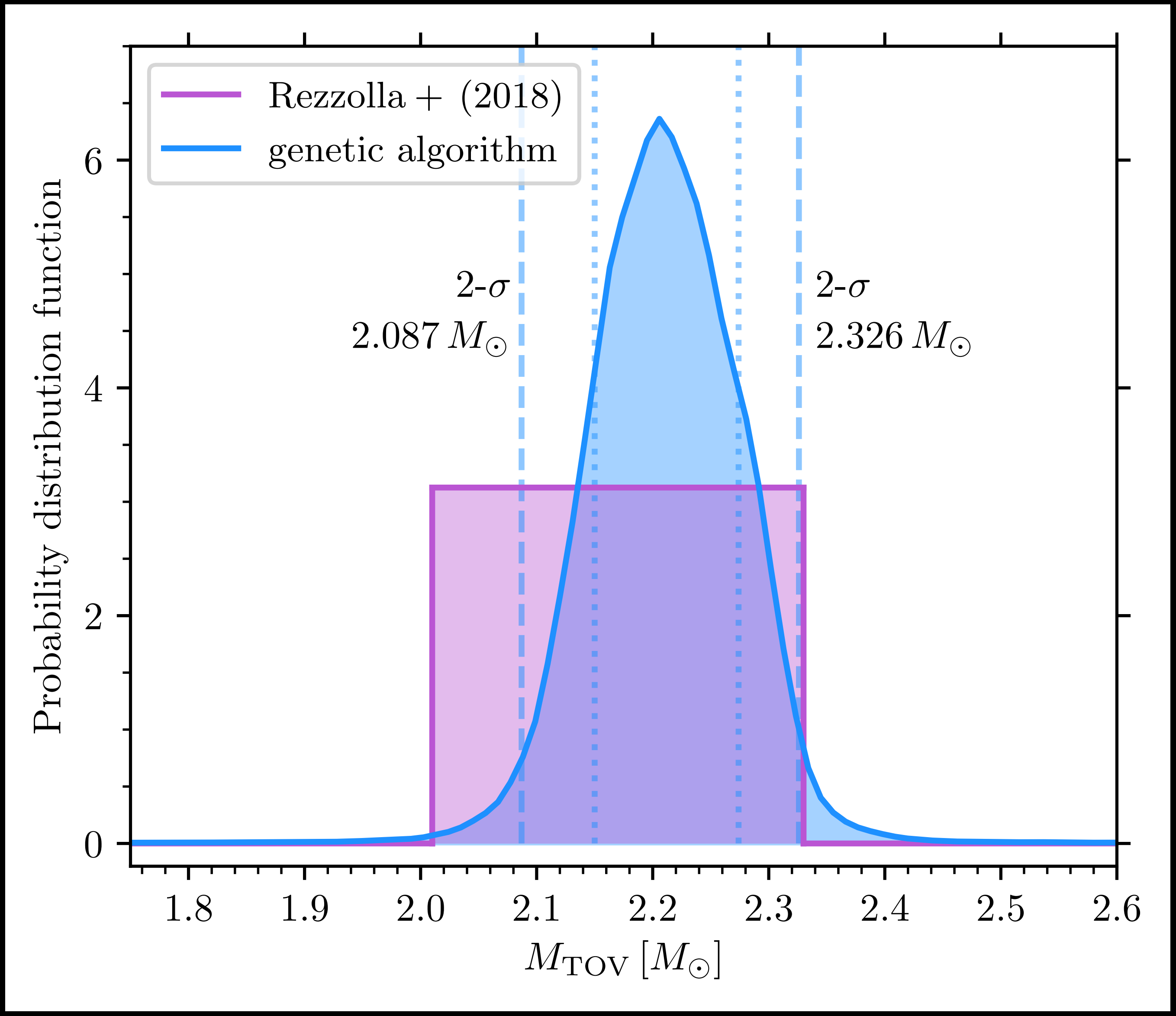
- A **genetic algorithm** is used to sample through the parameter space of the 10 free parameters.

- 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.

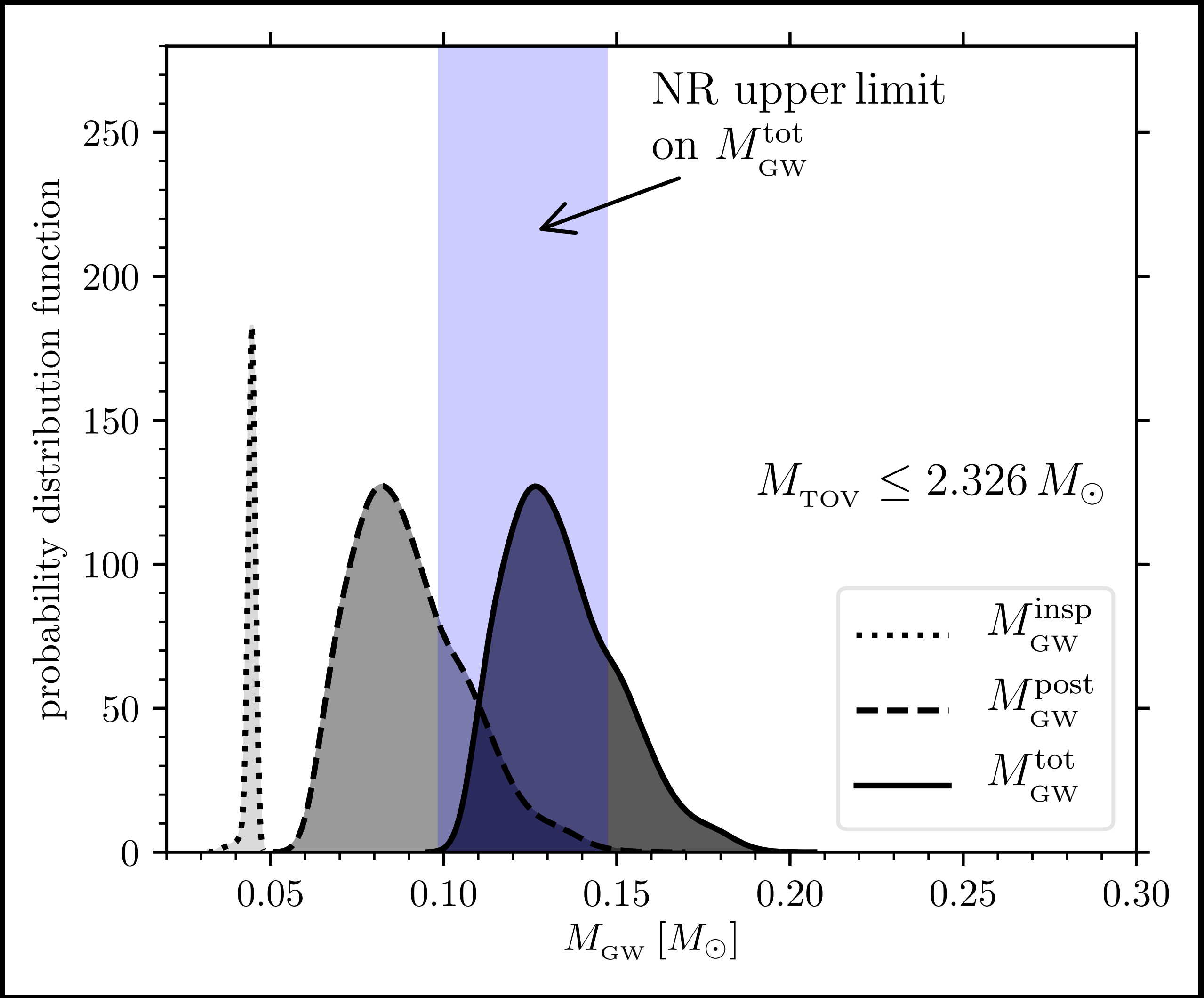
- Consider first previous estimate:

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

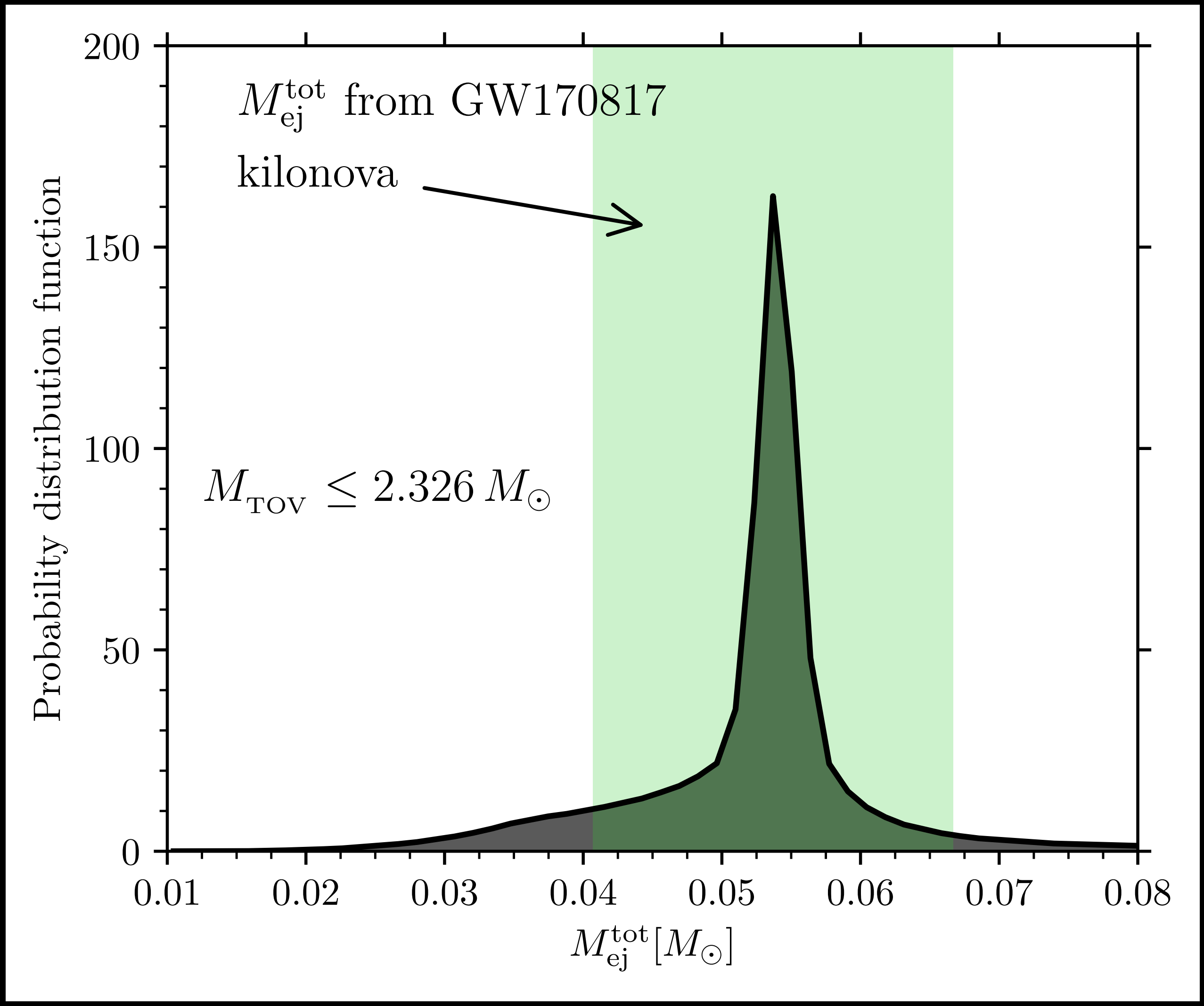
$$M_{\rm TOV}/M_{\odot} \leq 2.16^{+0.17}_{-0.15}$$



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

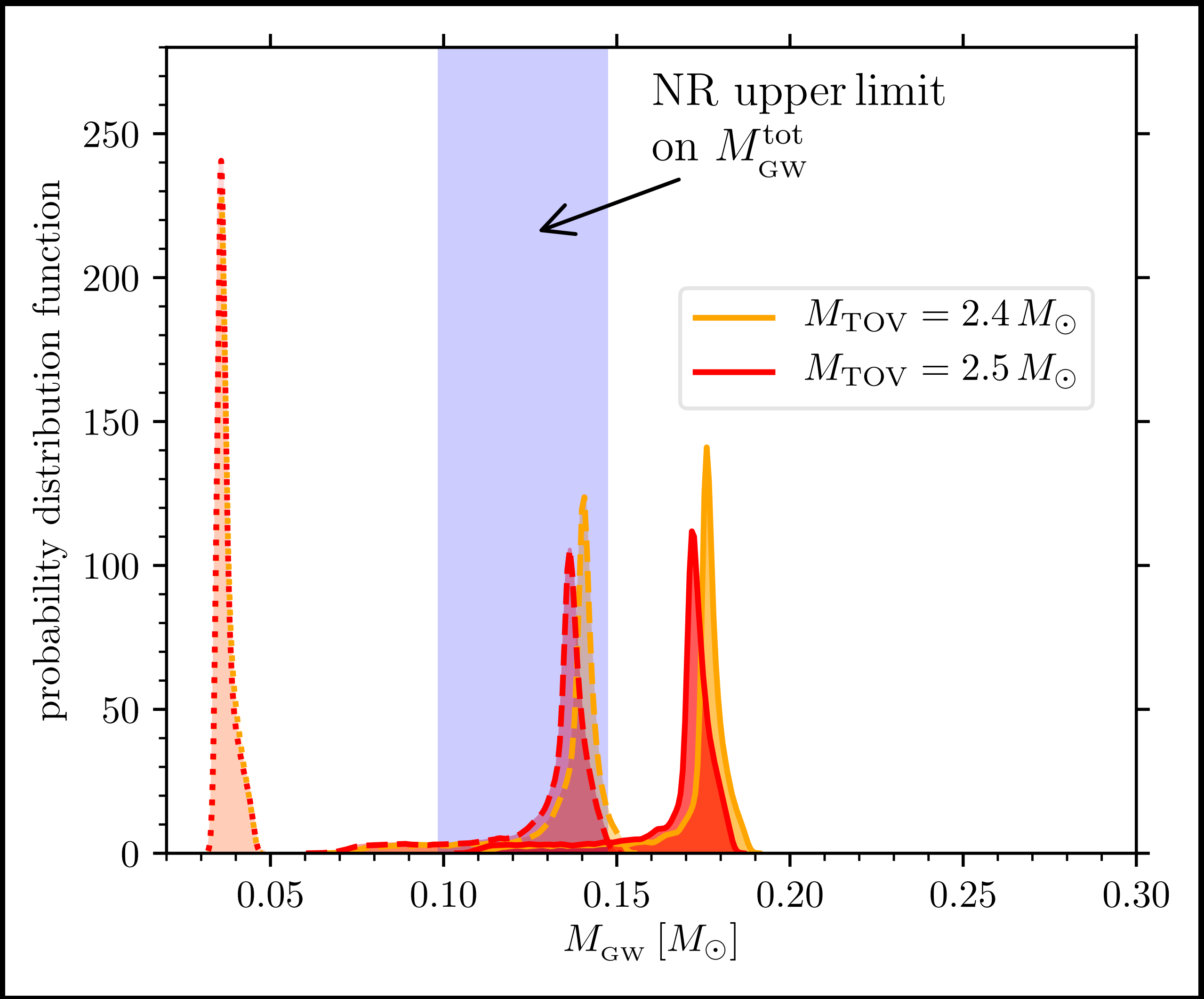


- Total mass emitted in GWs is in perfect **agreement** with predictions from numerical relativity



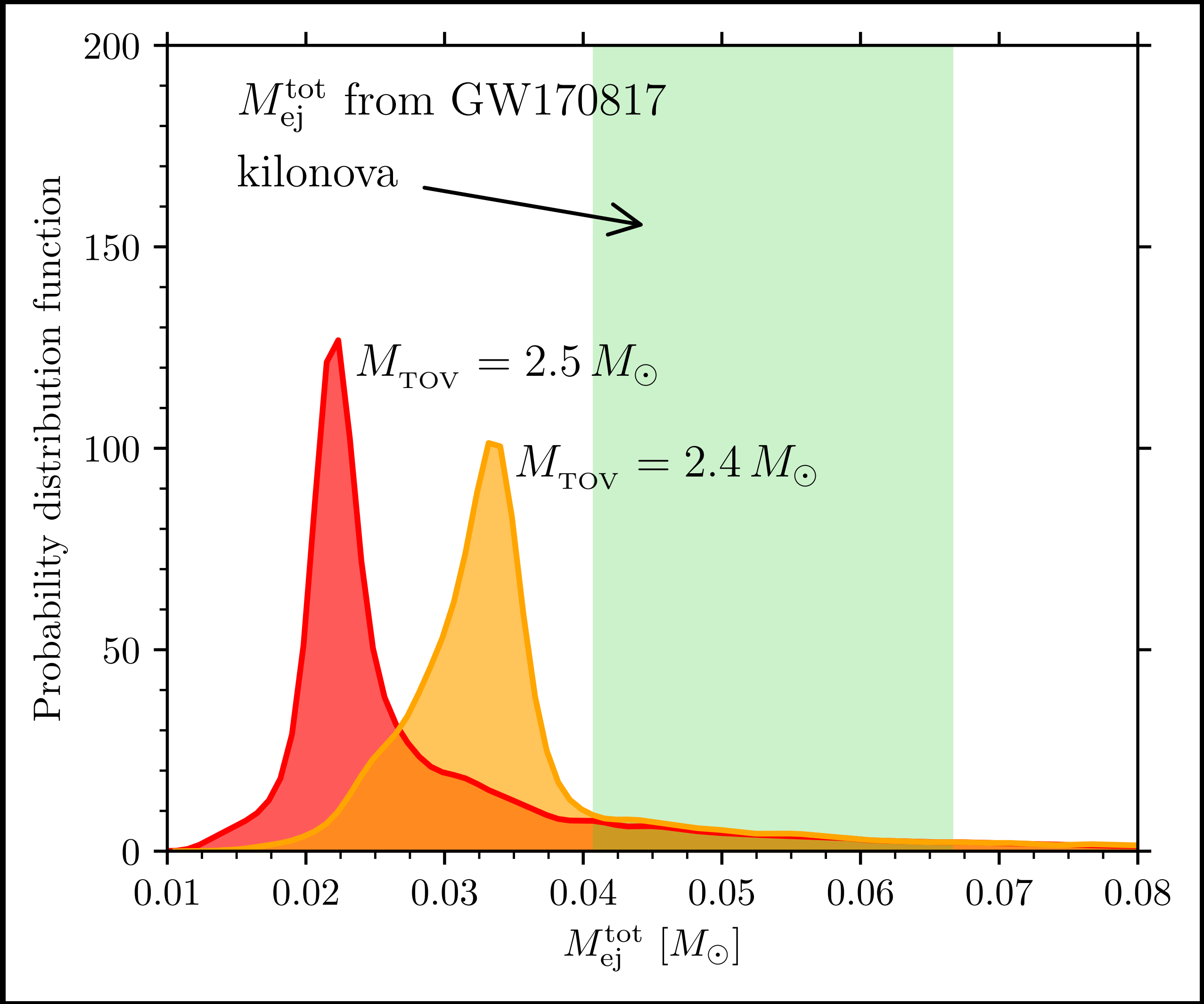
- Total mass ejected is in perfect **agreement** with predictions from kilonova signal

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.



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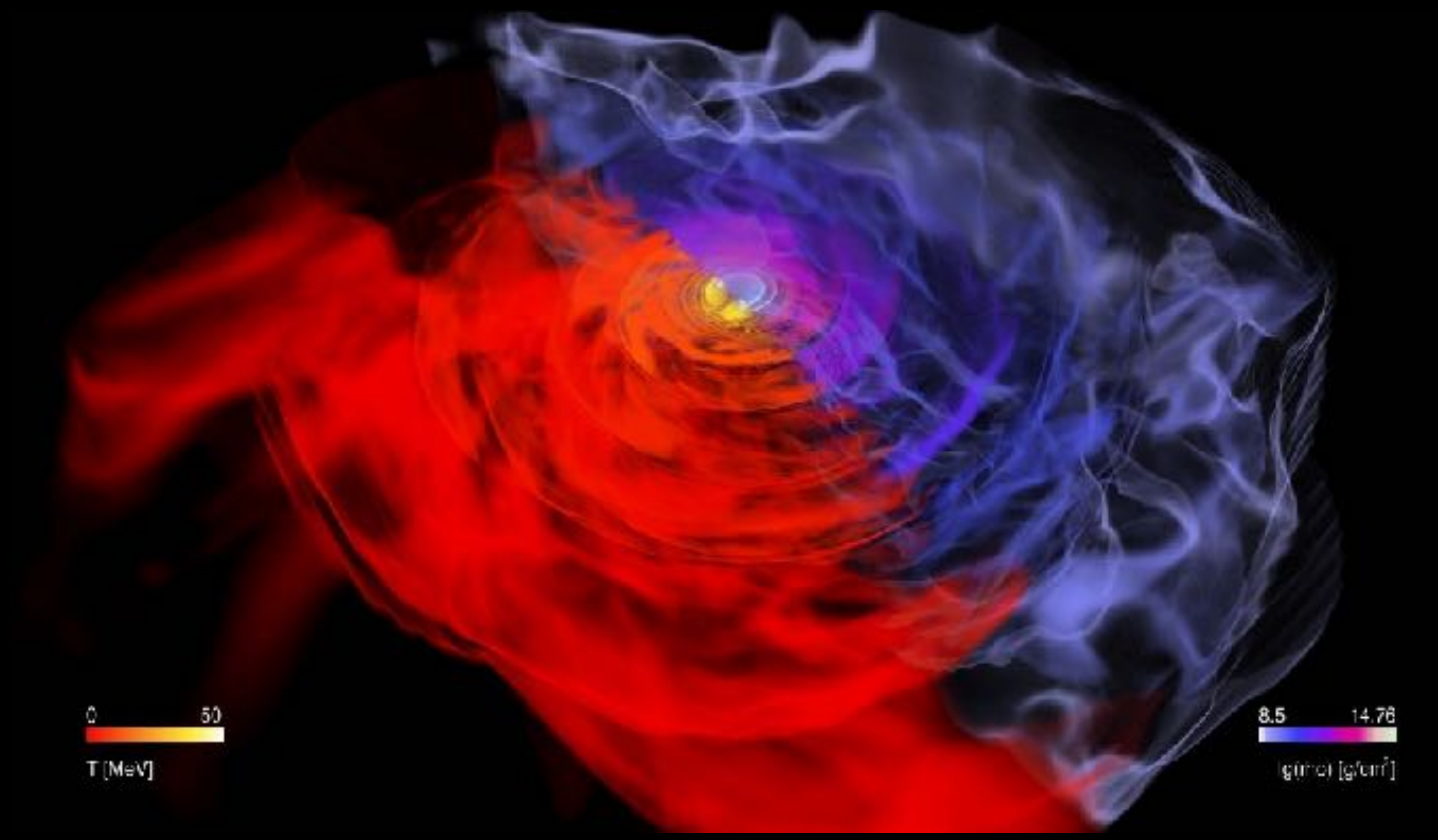
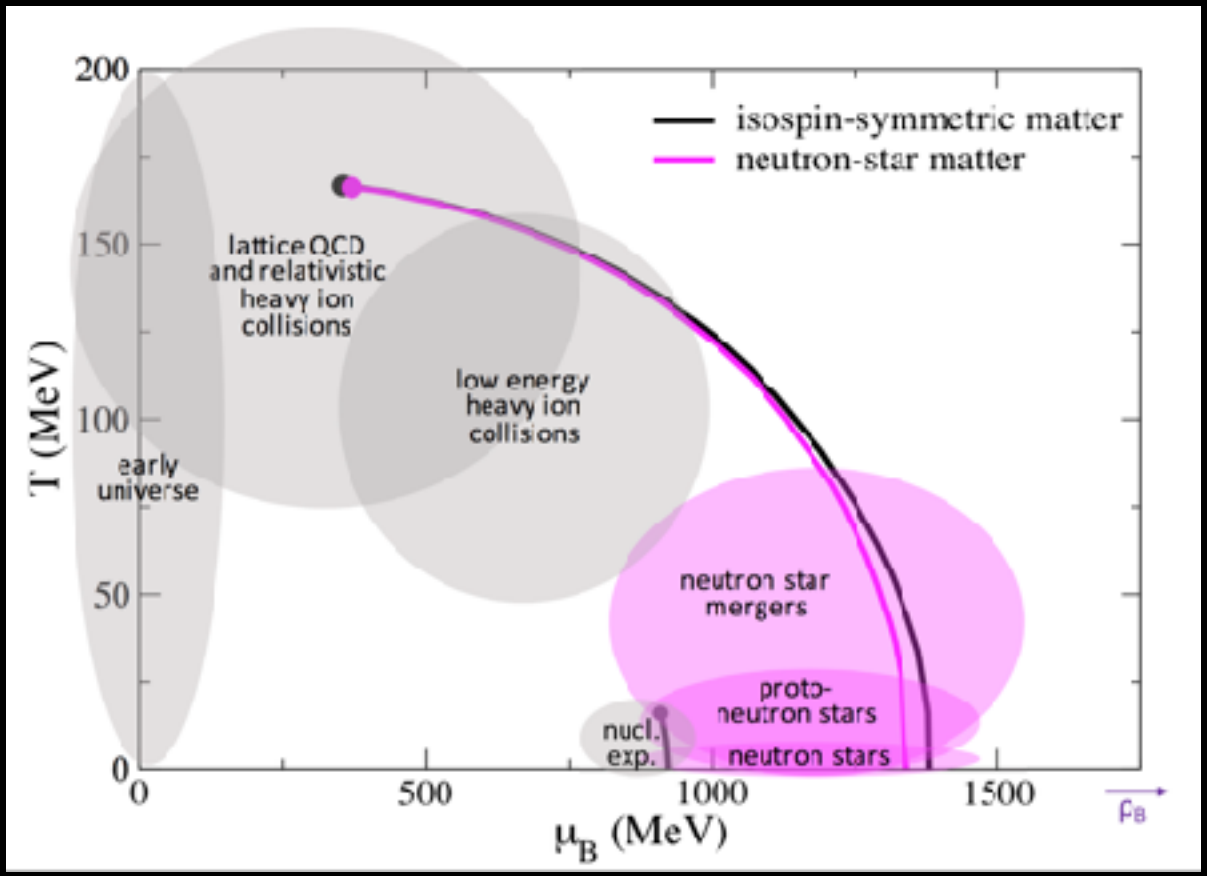
- If secondary in GW190814 was a NS, all previous considerations are incorrect.
- No EM counterpart was observed with GW190814 and no estimates possible on ejected matter or timescale for survival.
- **How do we solve this tension?**
- Solution: secondary in GW190814 **was a BH at merger** but could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

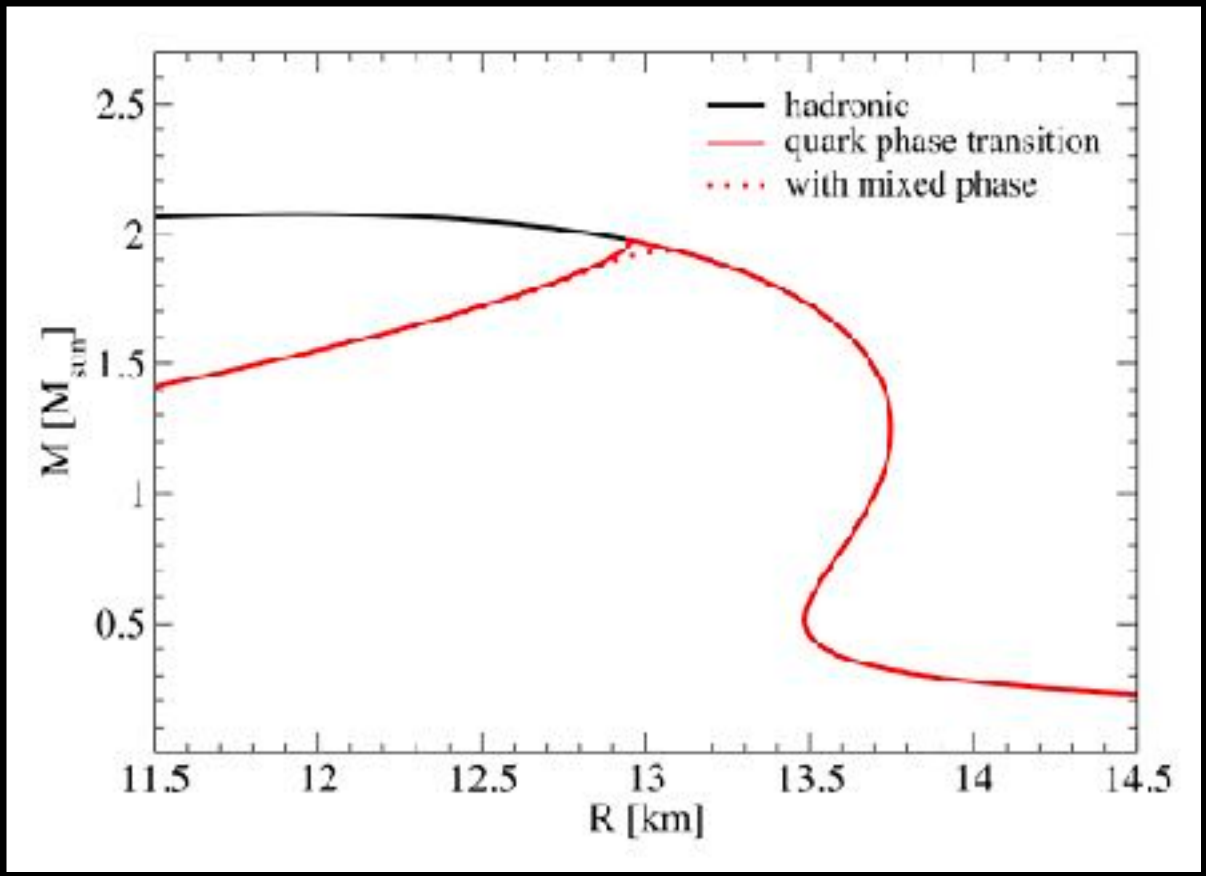
Phase transitions and their signatures



Most, Papenfort, Dexheimer, Hanauske, Schramm, Stoecker, LR (2019)
Weih, Hanauske, LR (2020)

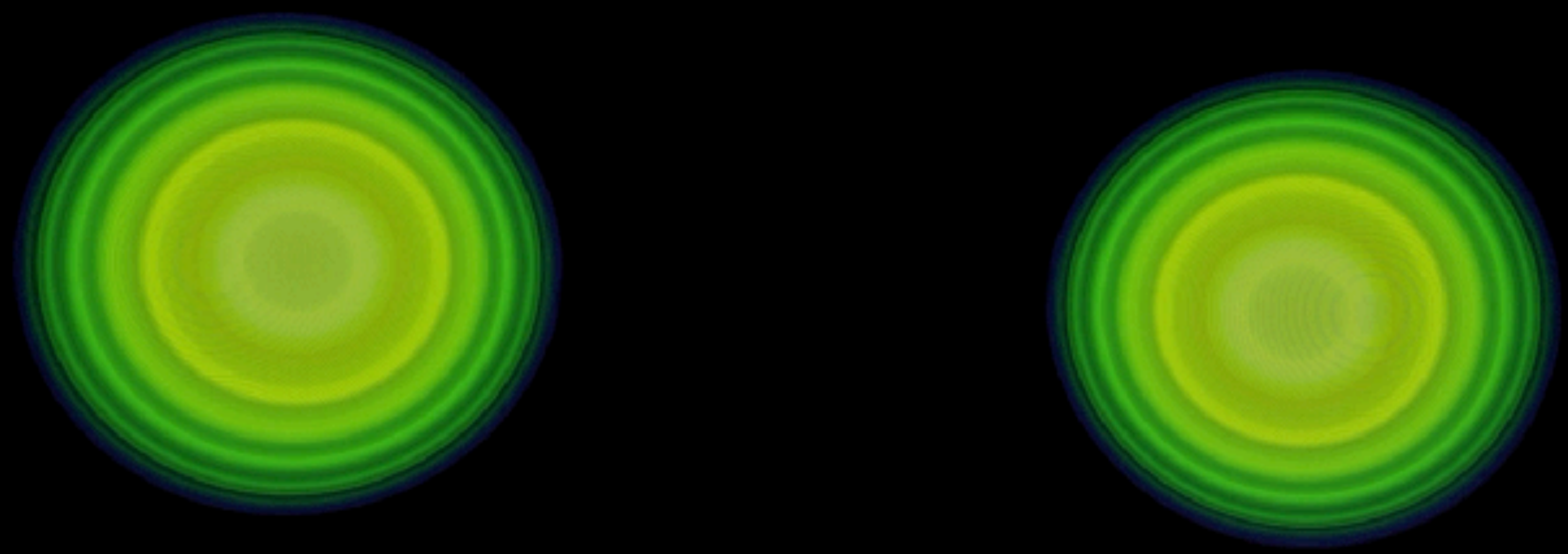
- **Isolated** neutron stars probe a small fraction of phase diagram.
- Neutron-star **binary** mergers reach temperatures up to 80 MeV and probe regions complementary to experiments.

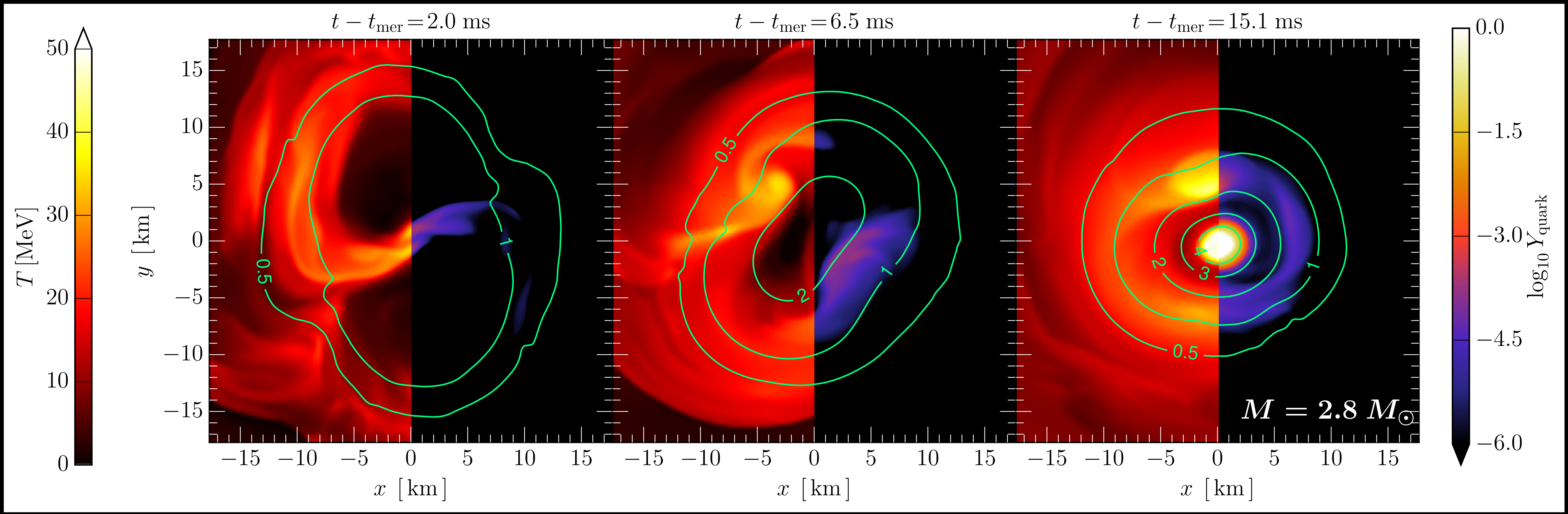




- Considered EOS based on Chiral Mean Field (CMF) model, based on a nonlinear SU(3) sigma model.
- Appearance of quarks can be introduced naturally.

Animations: Weih, Most, LR

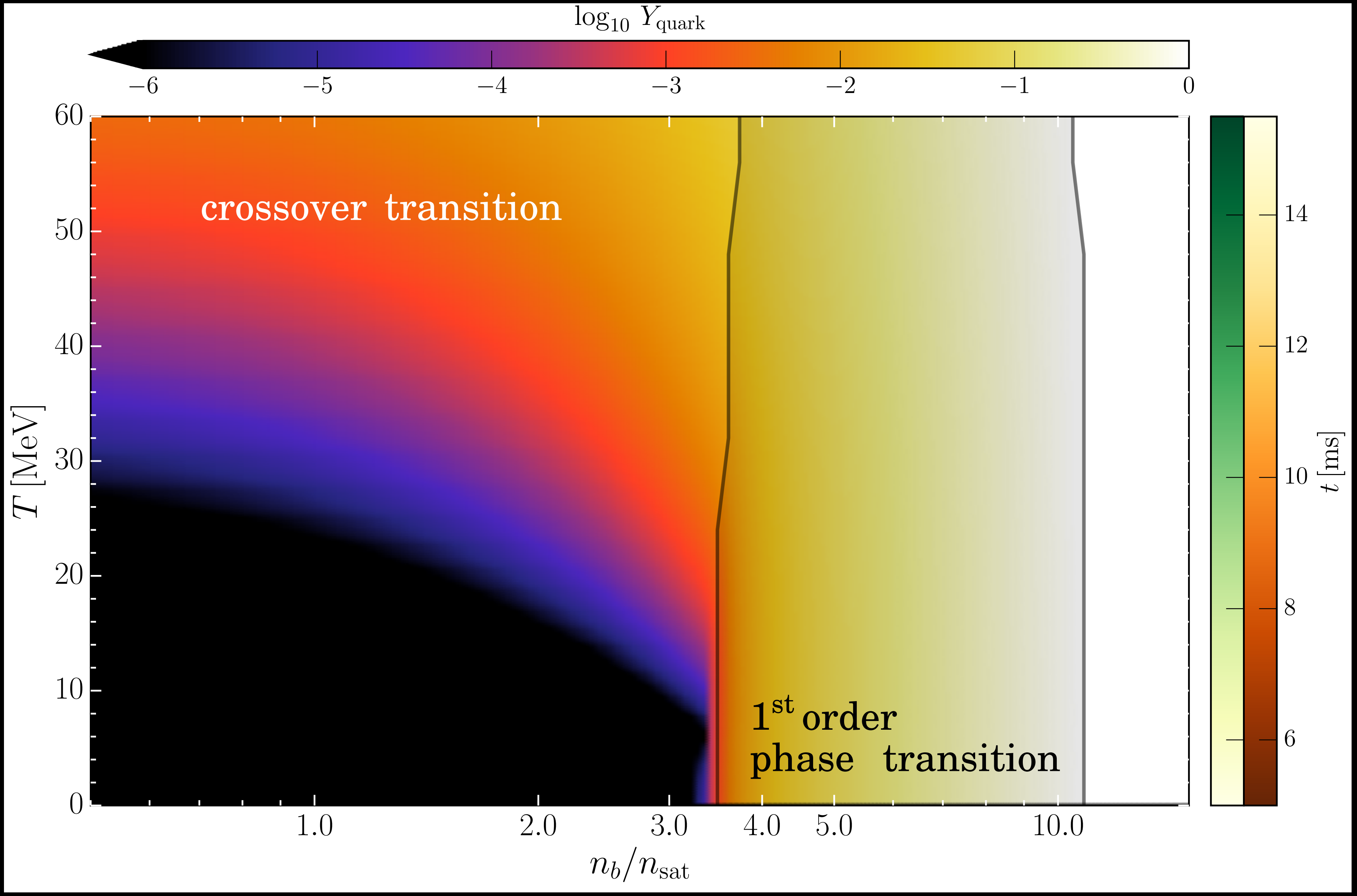




Quarks appear at sufficiently large temperatures and densities.

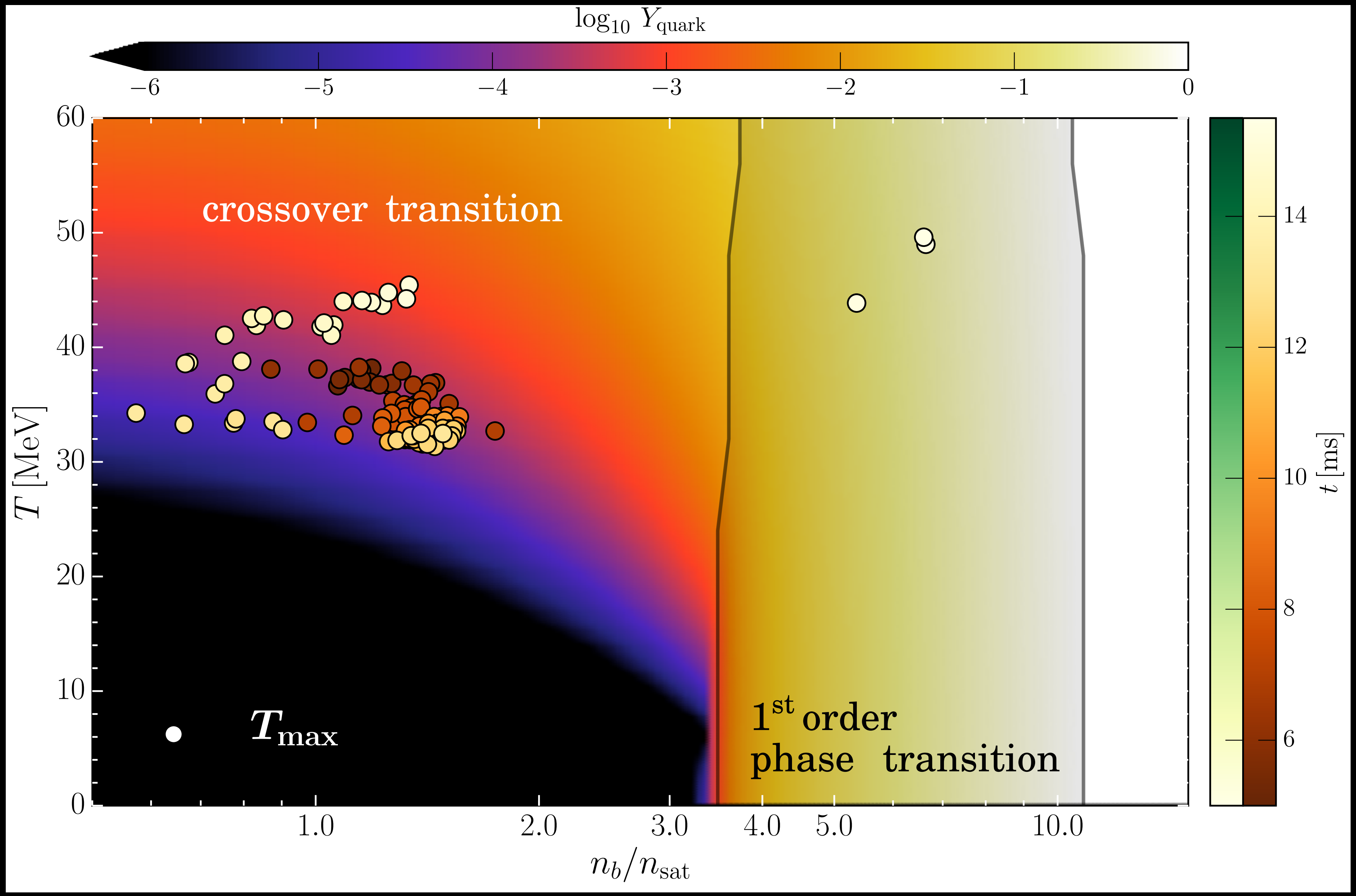
When this happens the EOS is considerably softened and a BH produced.

Comparing with the phase diagram



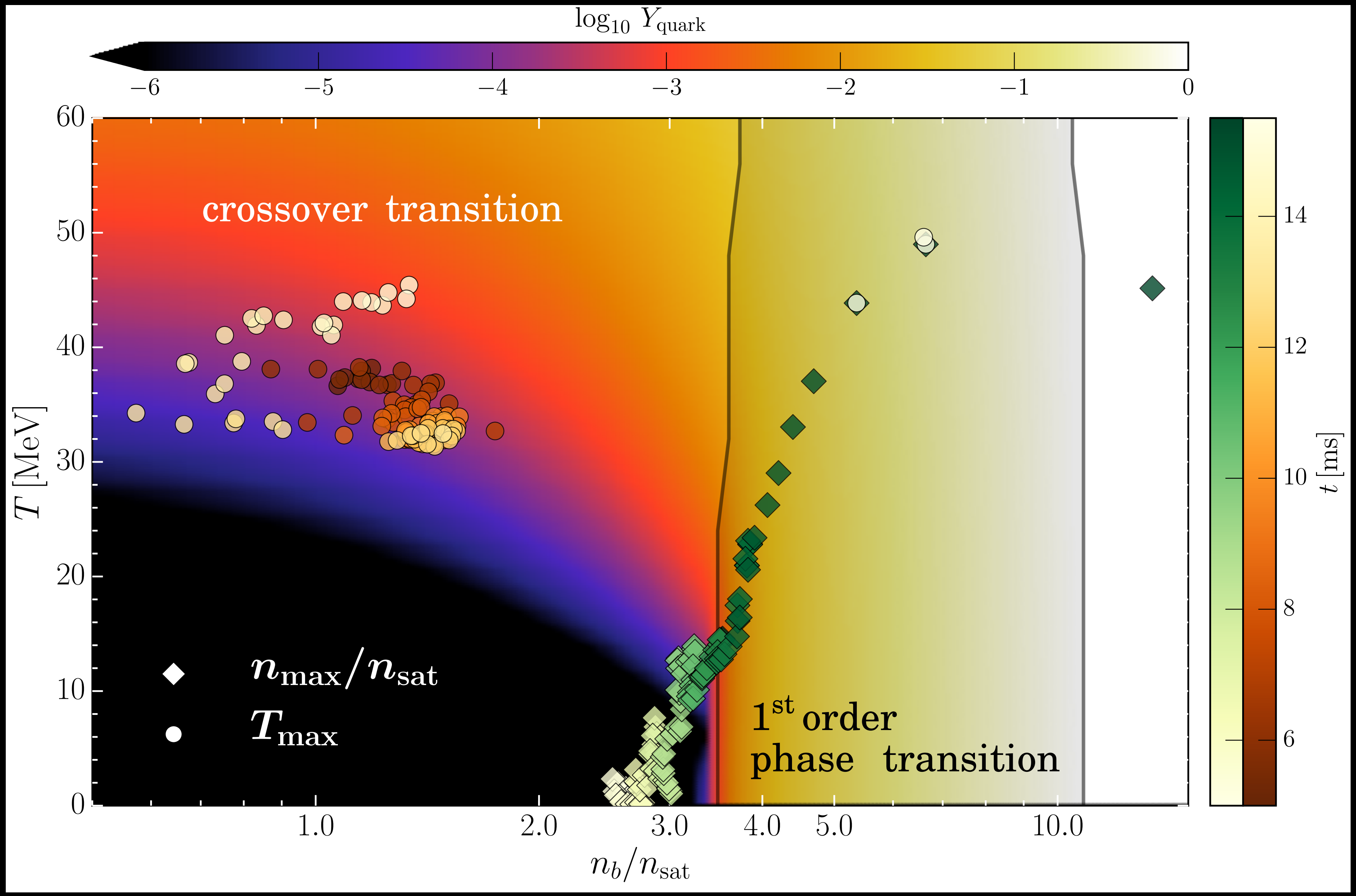
- Phase diagram with quark fraction

Comparing with the phase diagram



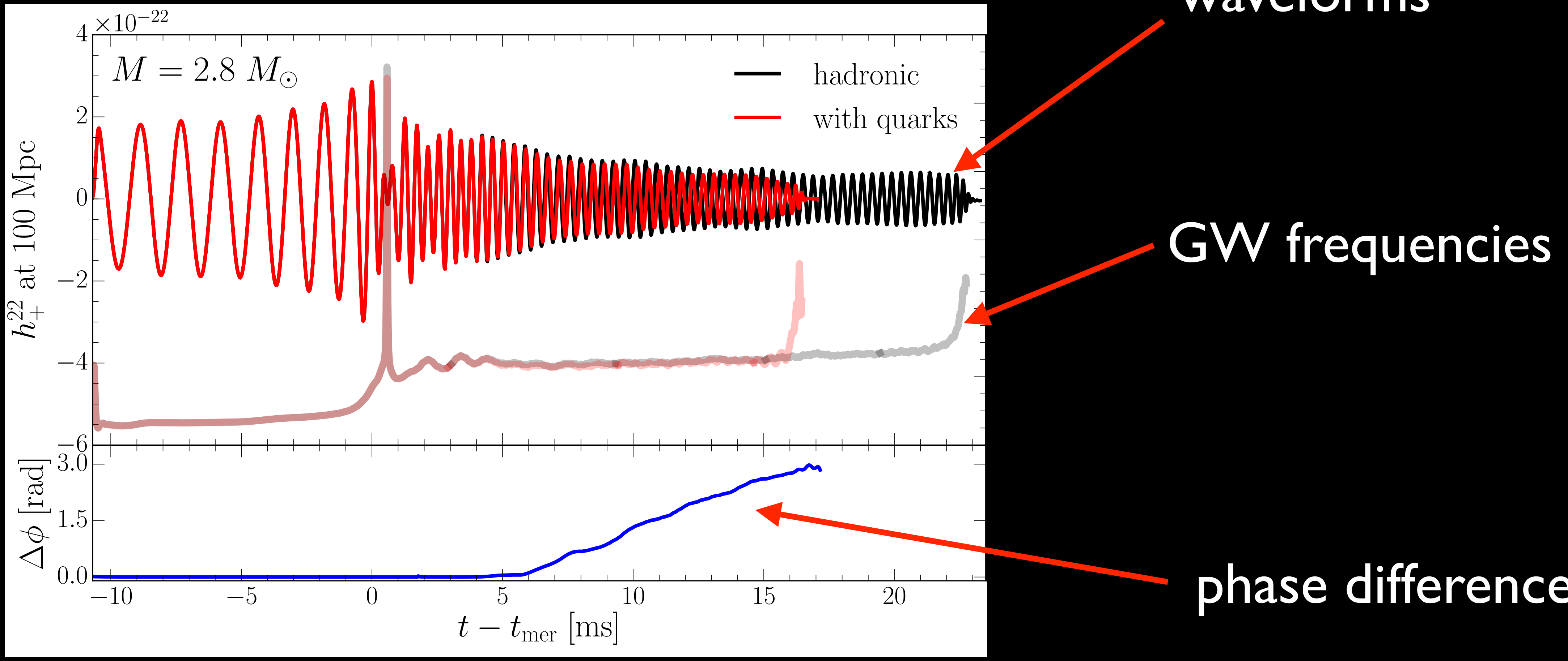
- Phase diagram with quark fraction
- Circles show the position in the diagram of the maximum temperature as a function of time

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

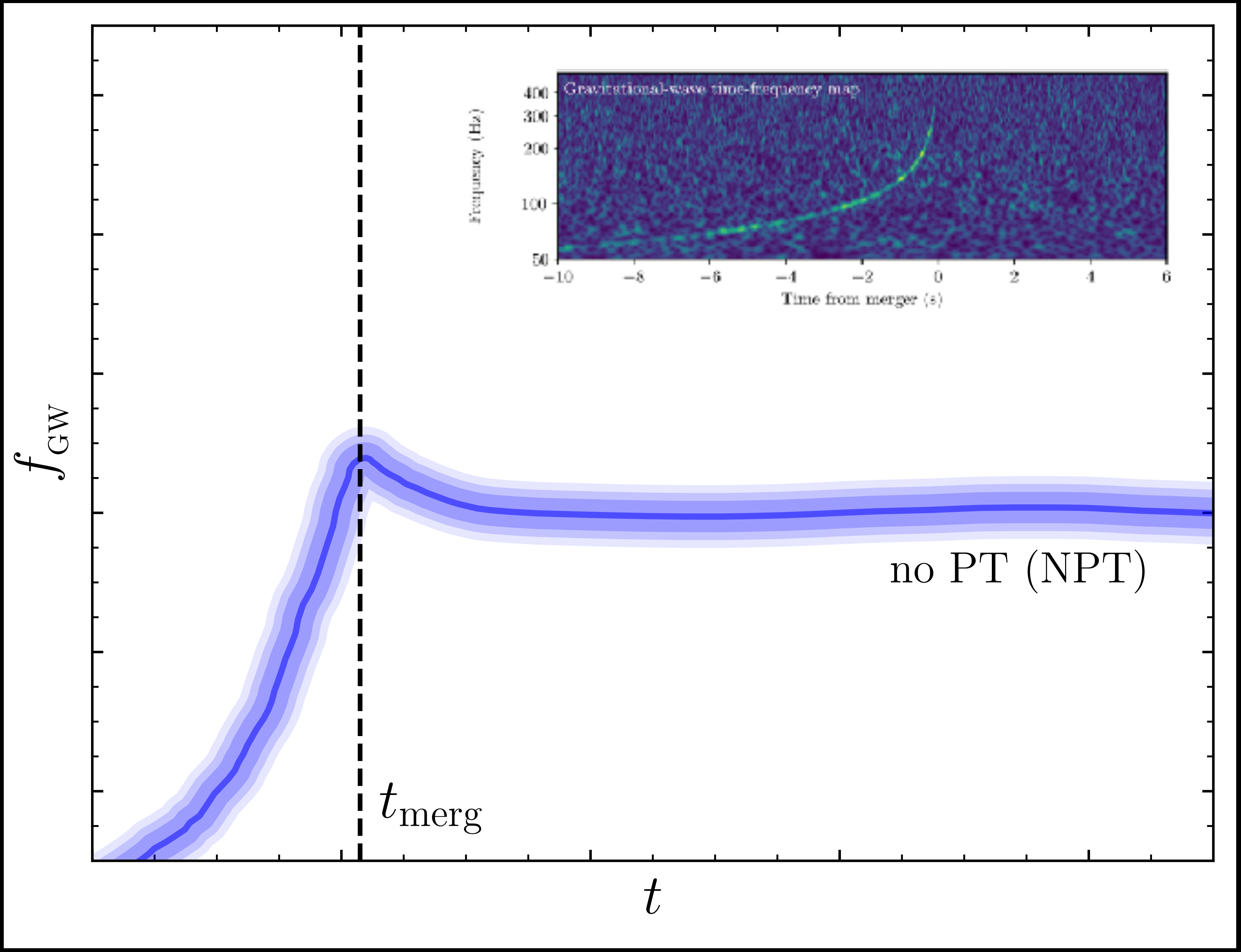


- After ~ 5 ms, quark fraction is large enough to change quadrupole moment and yield differences in the waveforms.
- Sudden softening of the phase transition leads to collapse and **large difference** in phase evolution.

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

A more comprehensive picture

We have recently added another possible scenario for a post-merger **PT,** which completes the picture of possible scenarios (Weih, Hanauske, LR 2020).



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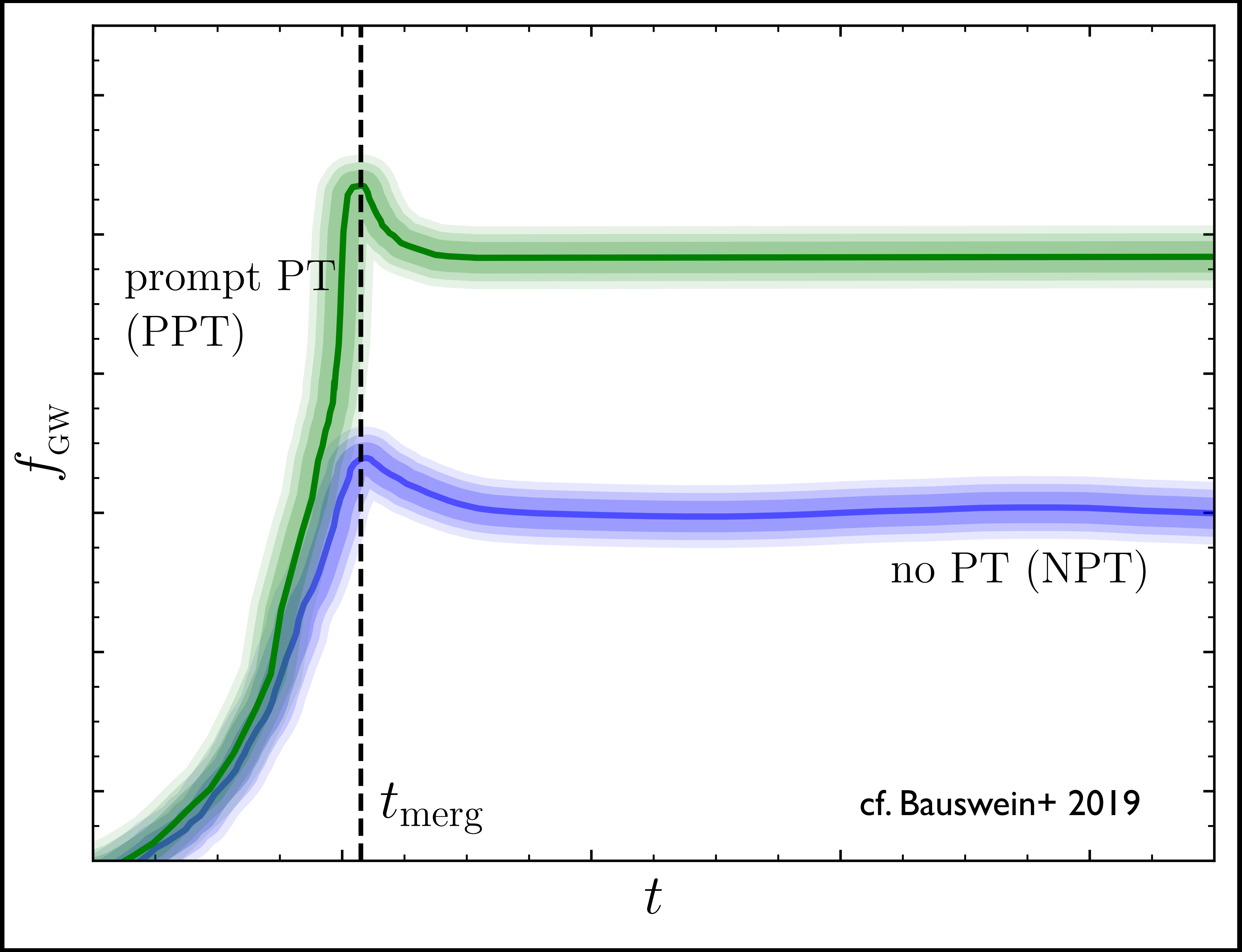

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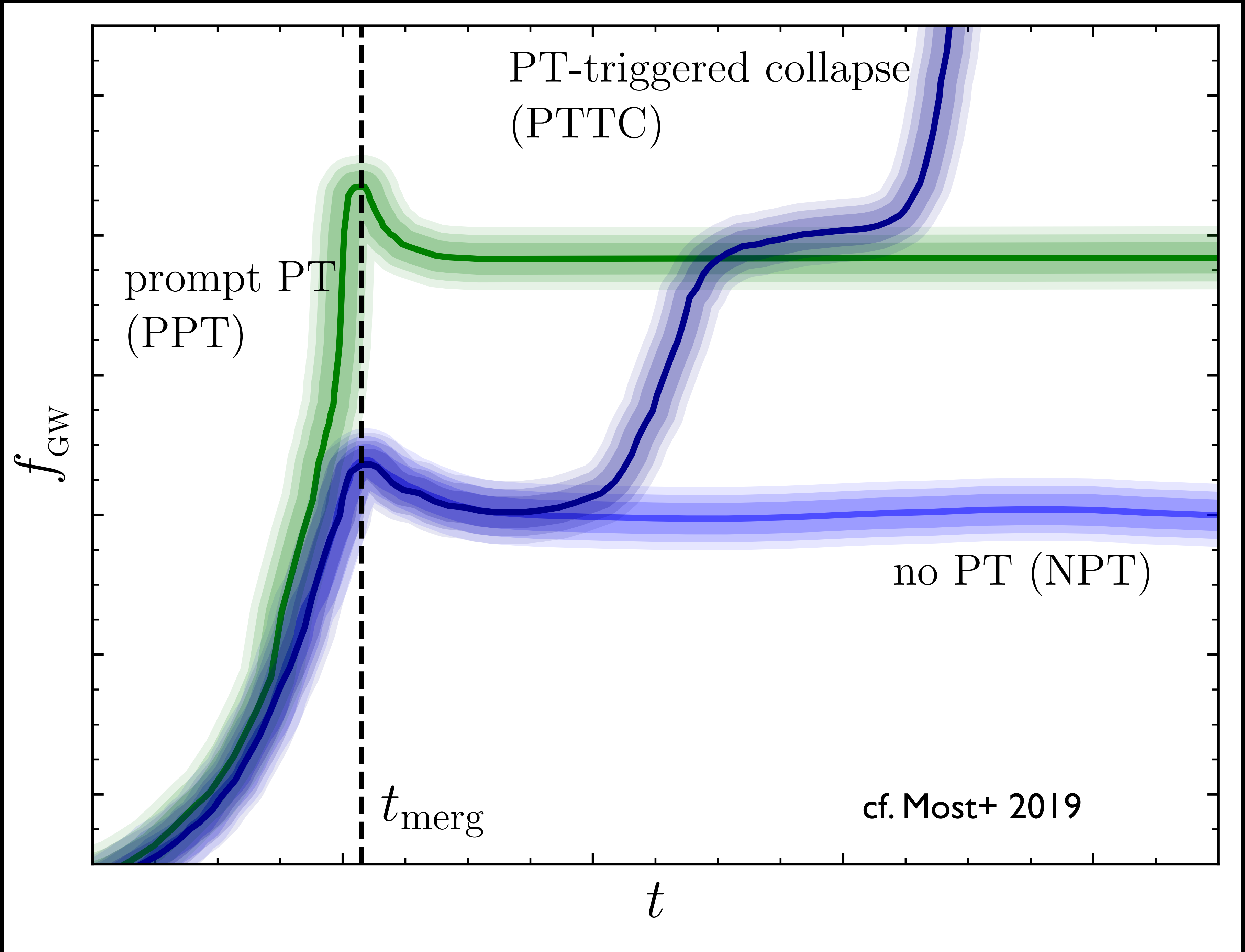

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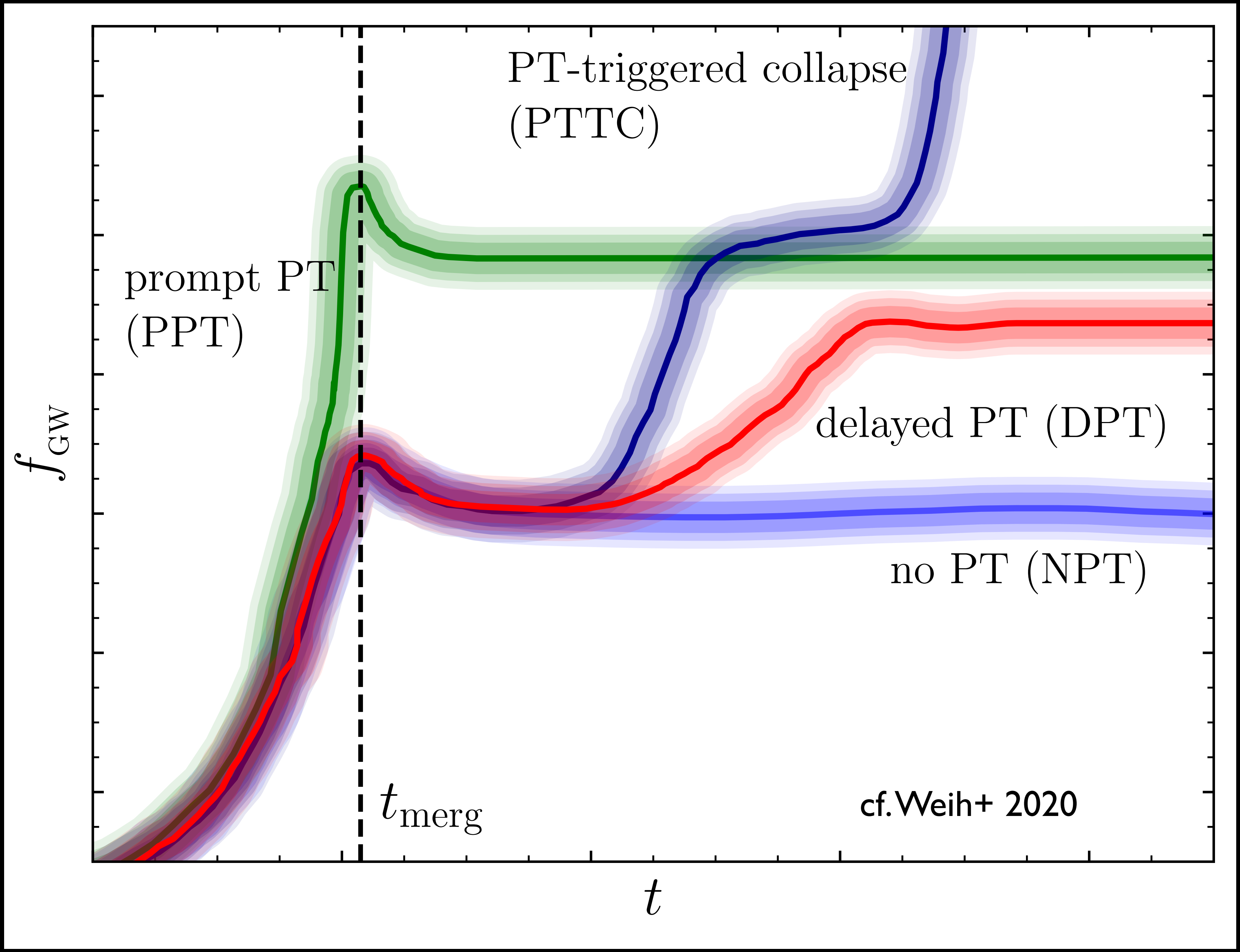
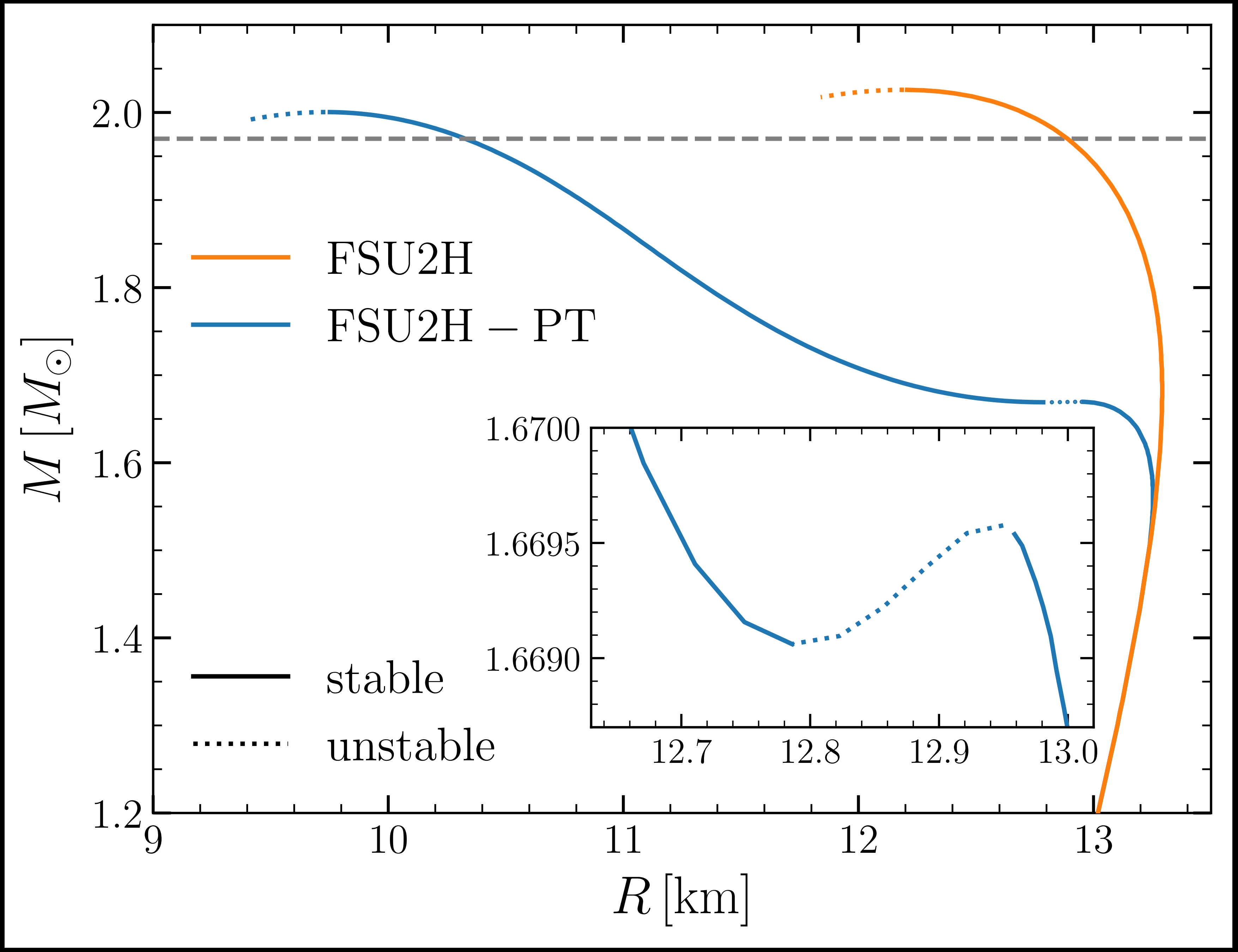


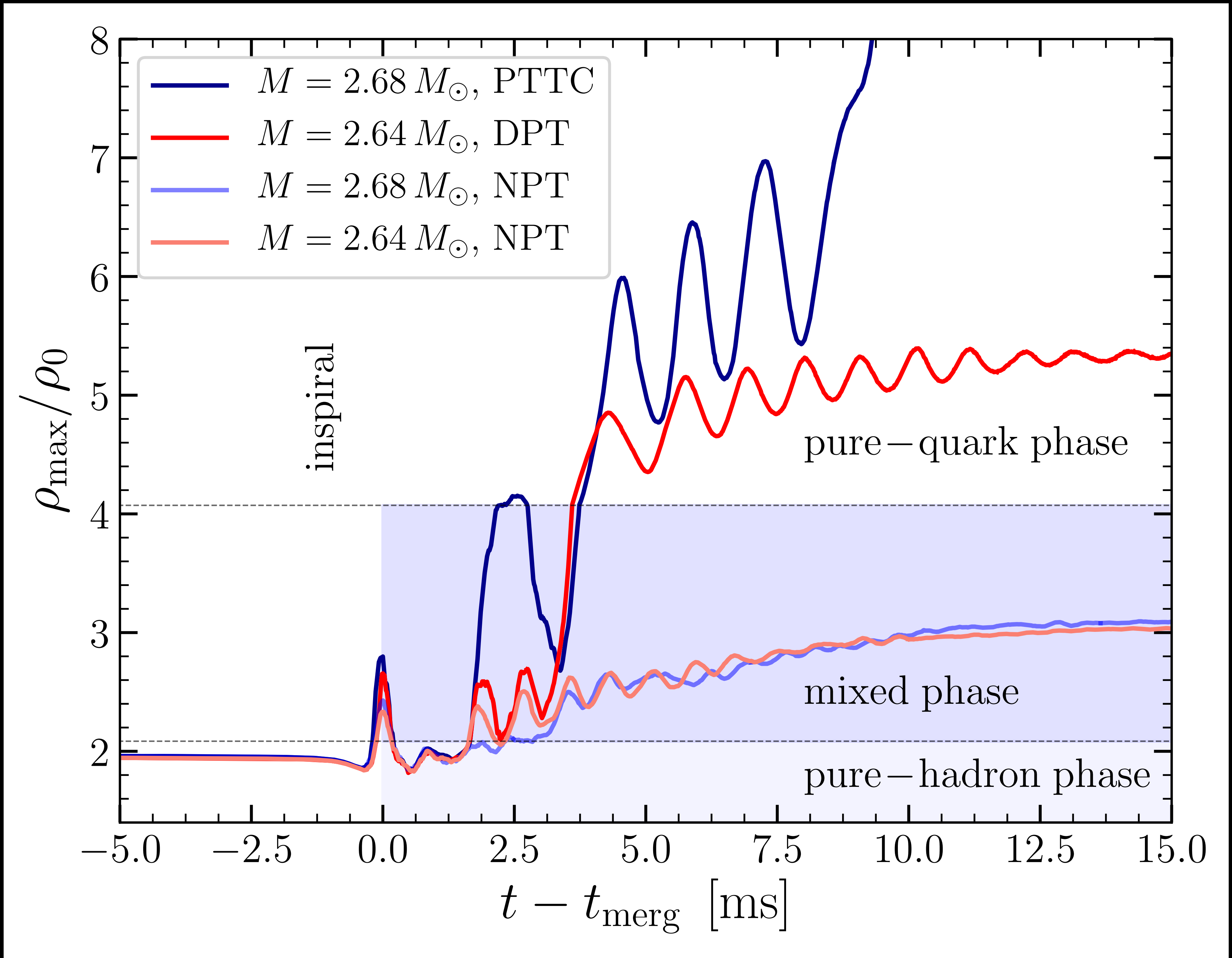
A more comprehensive picture

Characteristic properties of twin-stars: note the presence of a second stable branch of equilibrium configurations



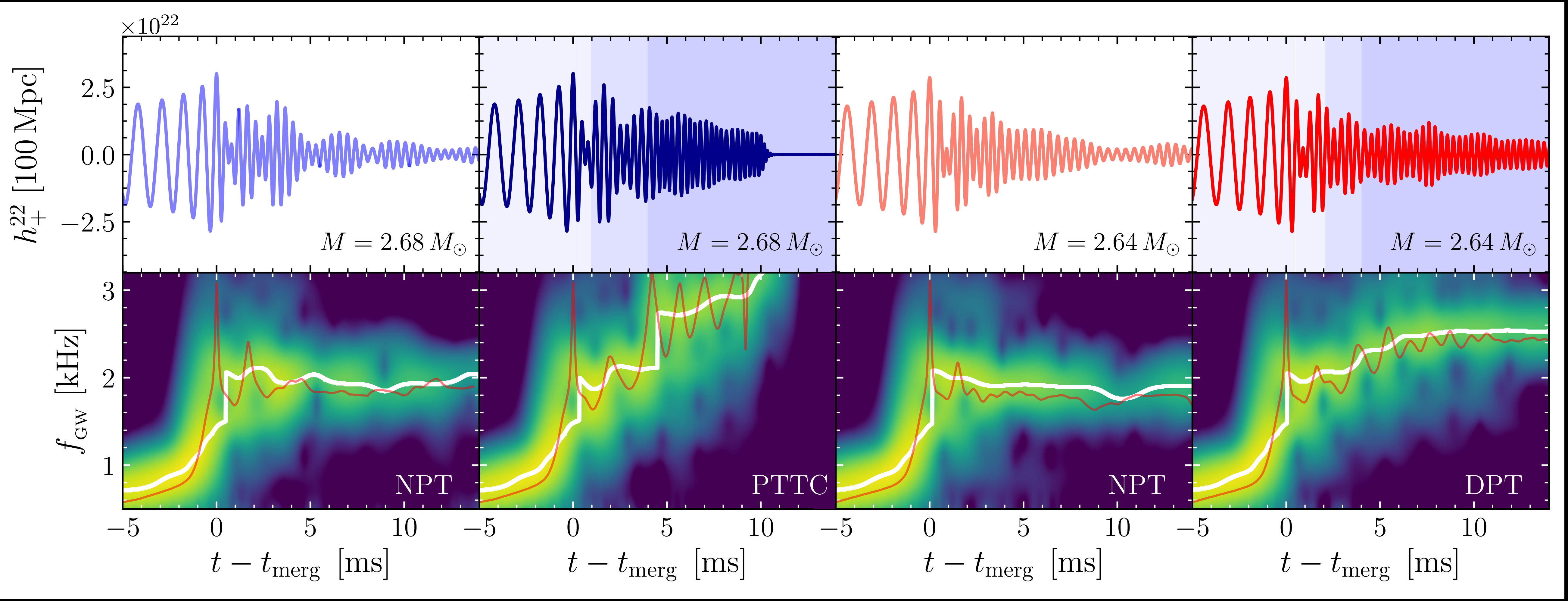
A more comprehensive picture

Best understood in terms of the evolution of the normalise maximum rest-mass density: $\rho_{\max}/\rho_0$



A more comprehensive picture

Different signatures are also quite transparent 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

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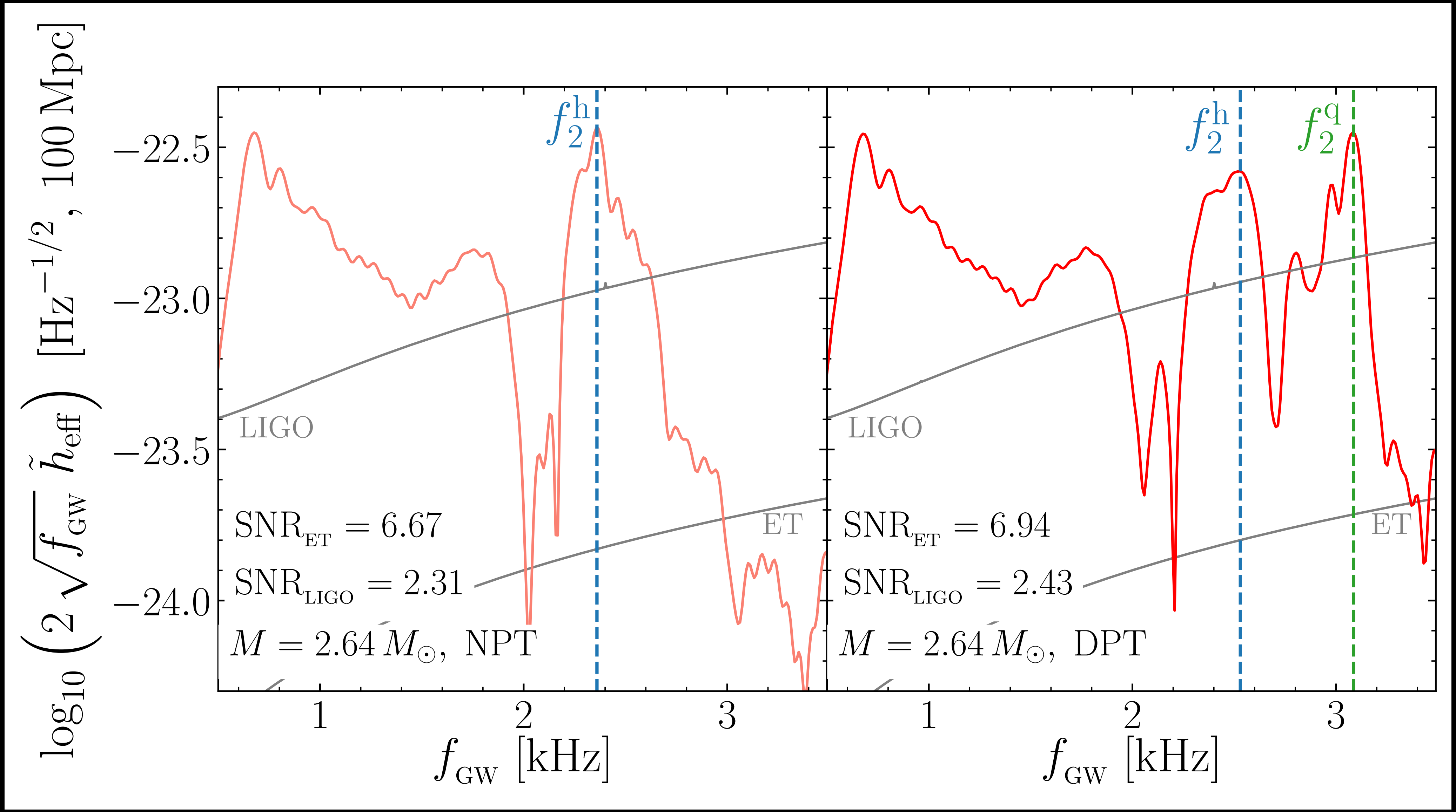
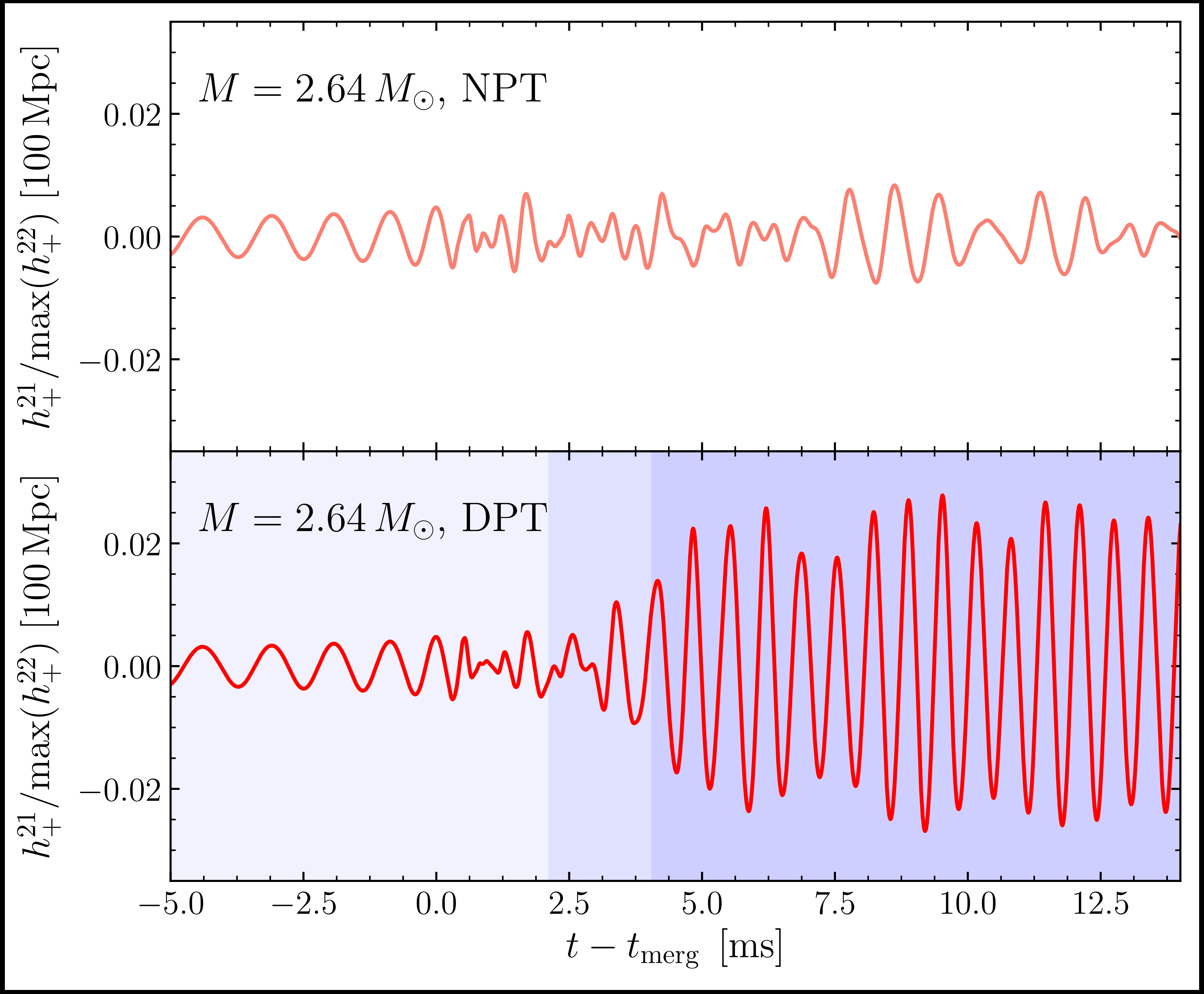


Importance of **DPT** is that it leads to **two** different "stable" f_2 **frequencies** that are easily distinguishable in the PSD

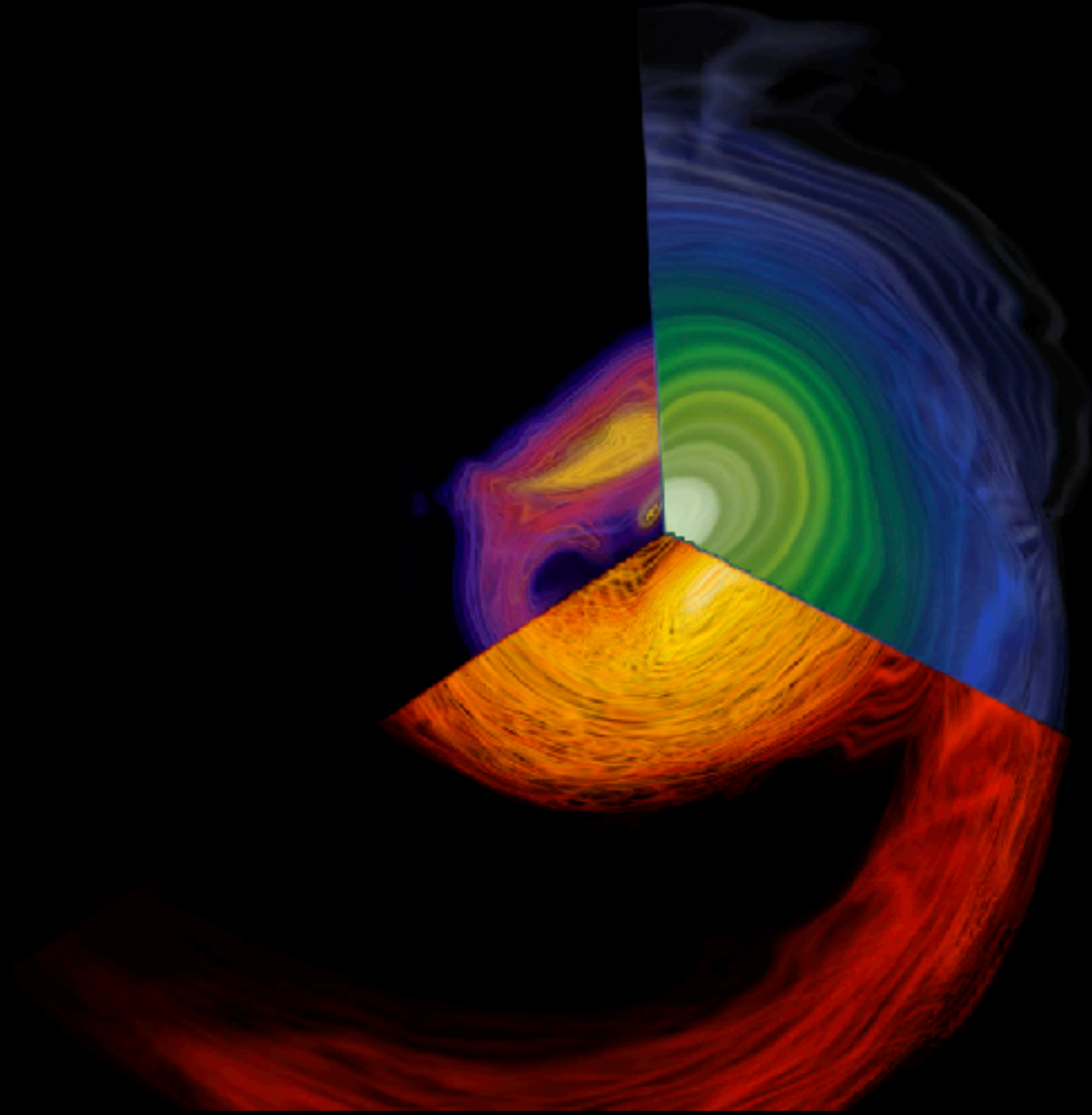
A more comprehensive picture

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.

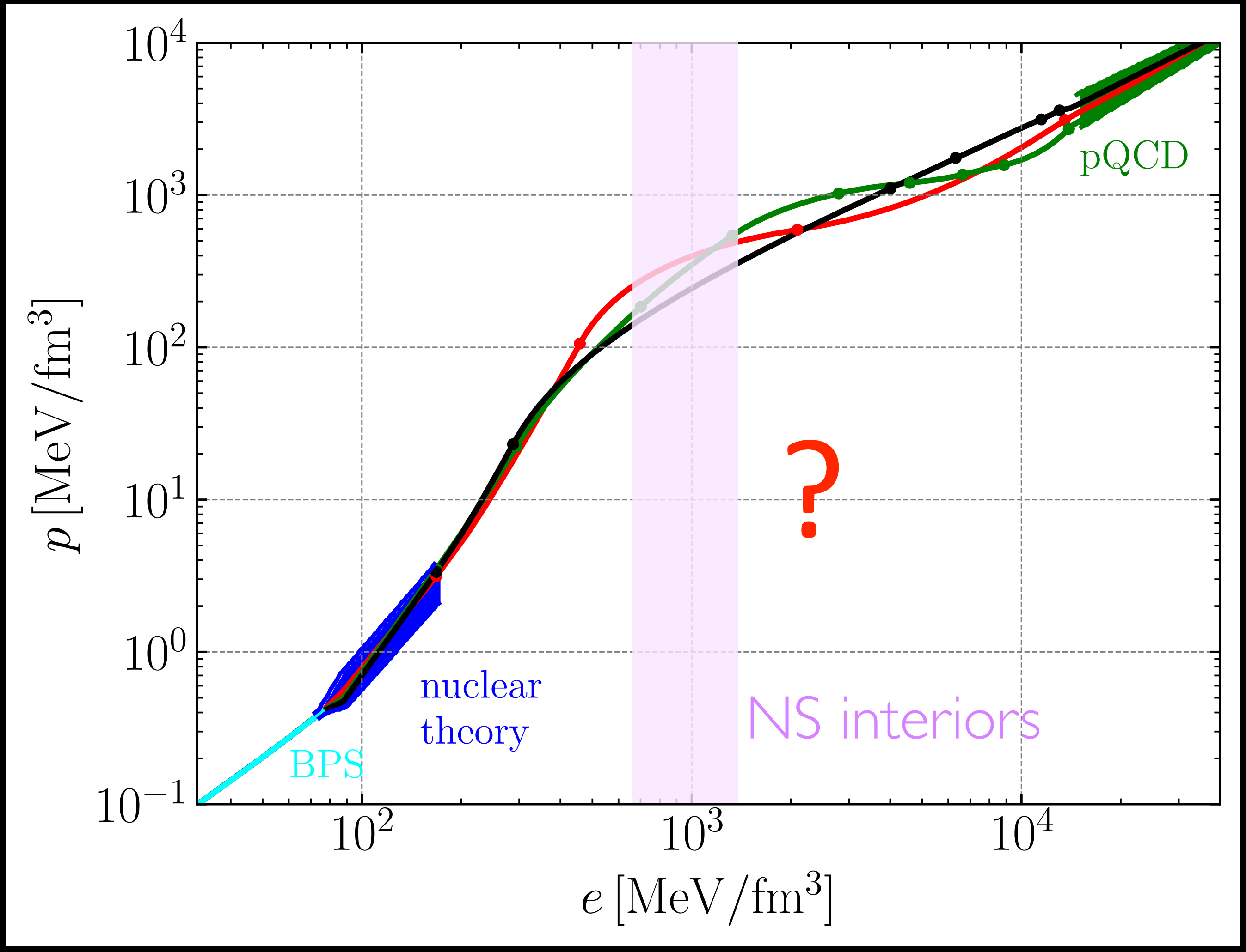
On the sound speed in neutron stars

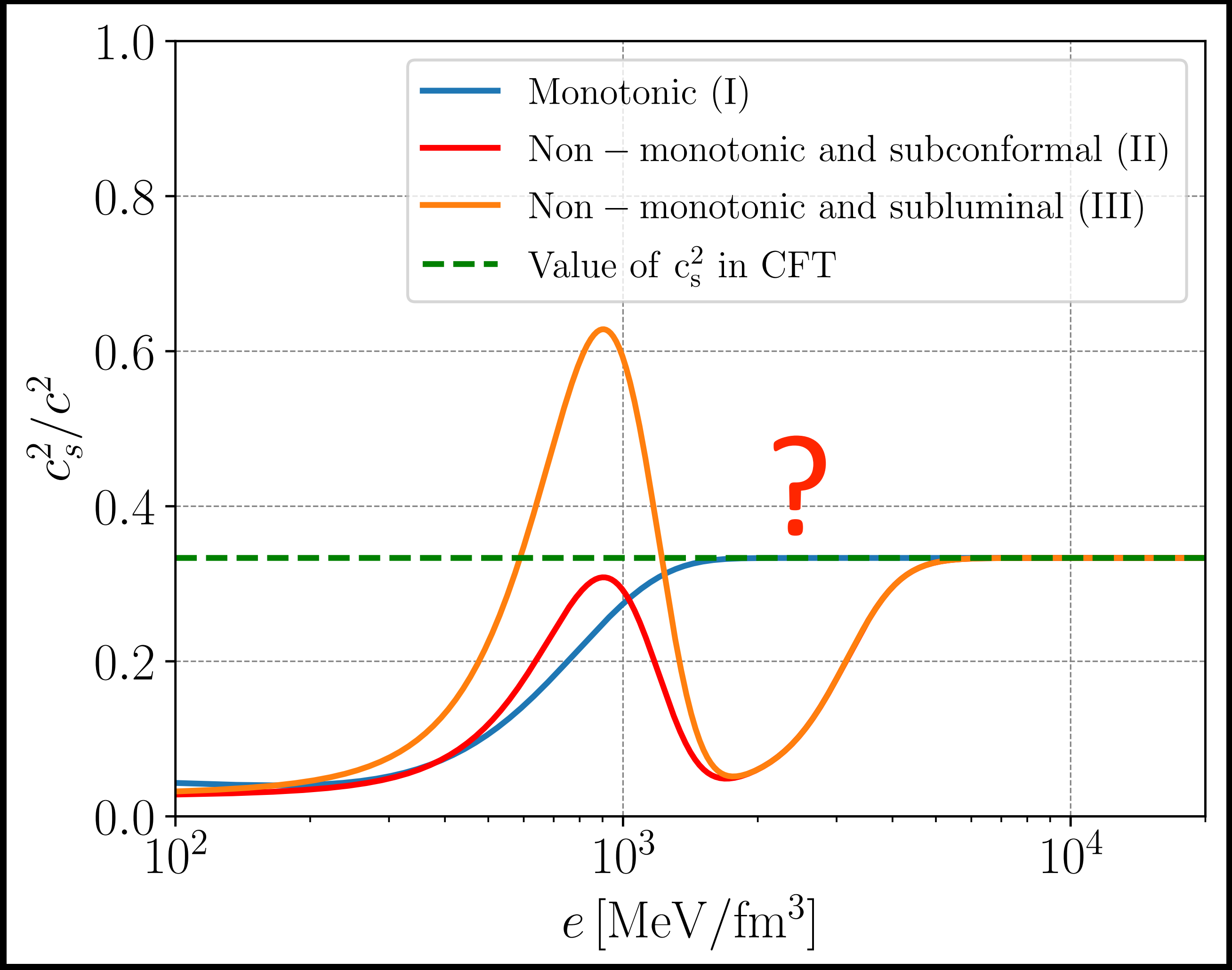


Altiparmak, Ecker, LR (2022)

A very basic question

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



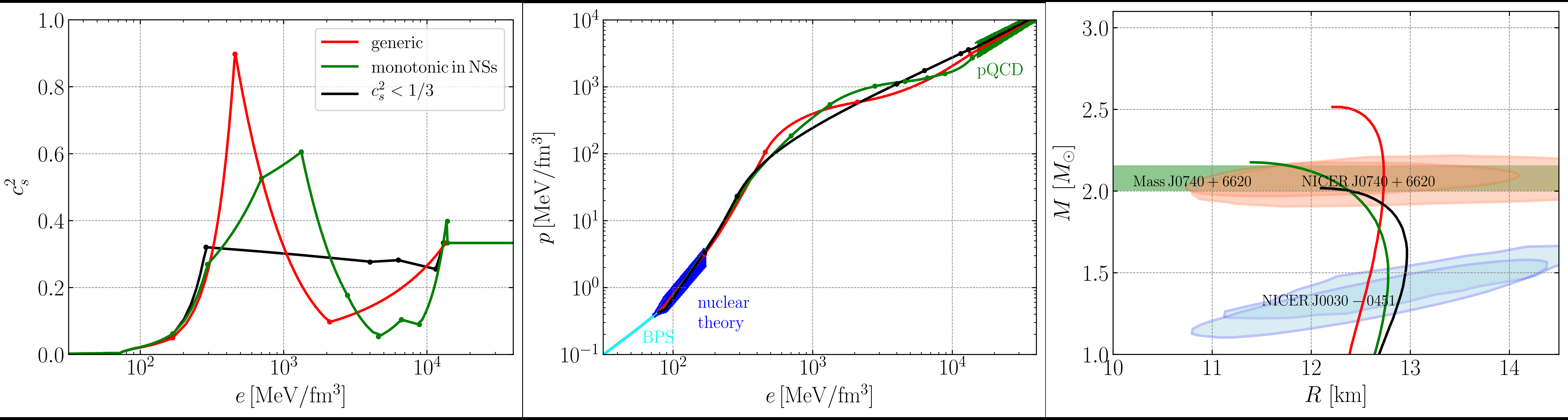


i) monotonic and sub-conformal: $c_s^2 < 1/3\,;$

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

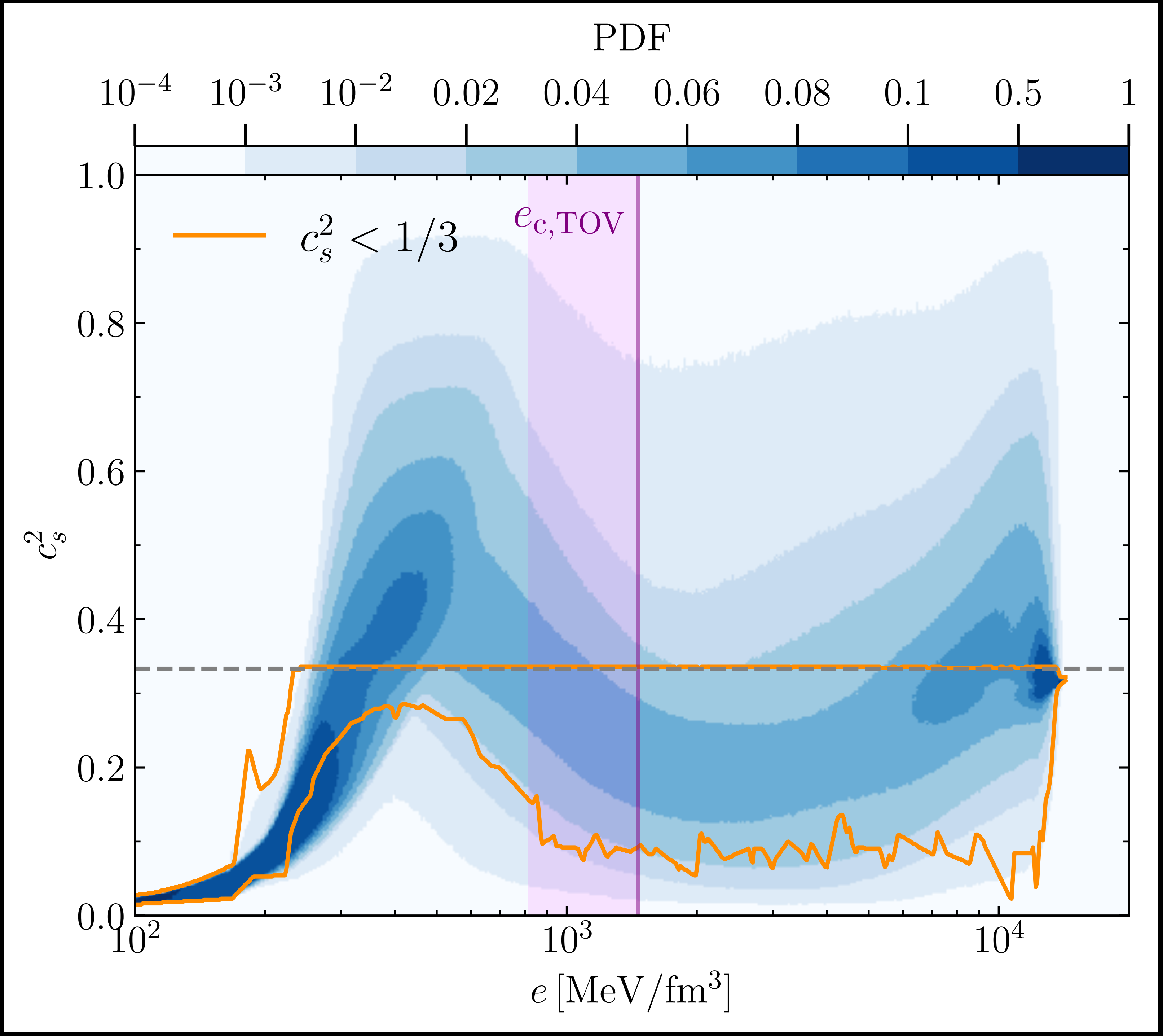
iii) nonmonotonic and sub-luminal: $c_s^2 < 1$

- Lacking stronger constraints, an agnostic approach is viable and followed by many (mostly piecewise polytropes)
- 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). Repeat 1.5×10^7 times…
- In this way, ~ 10% of our EOSs survives and provides robust statistics from which we compute PDFs.

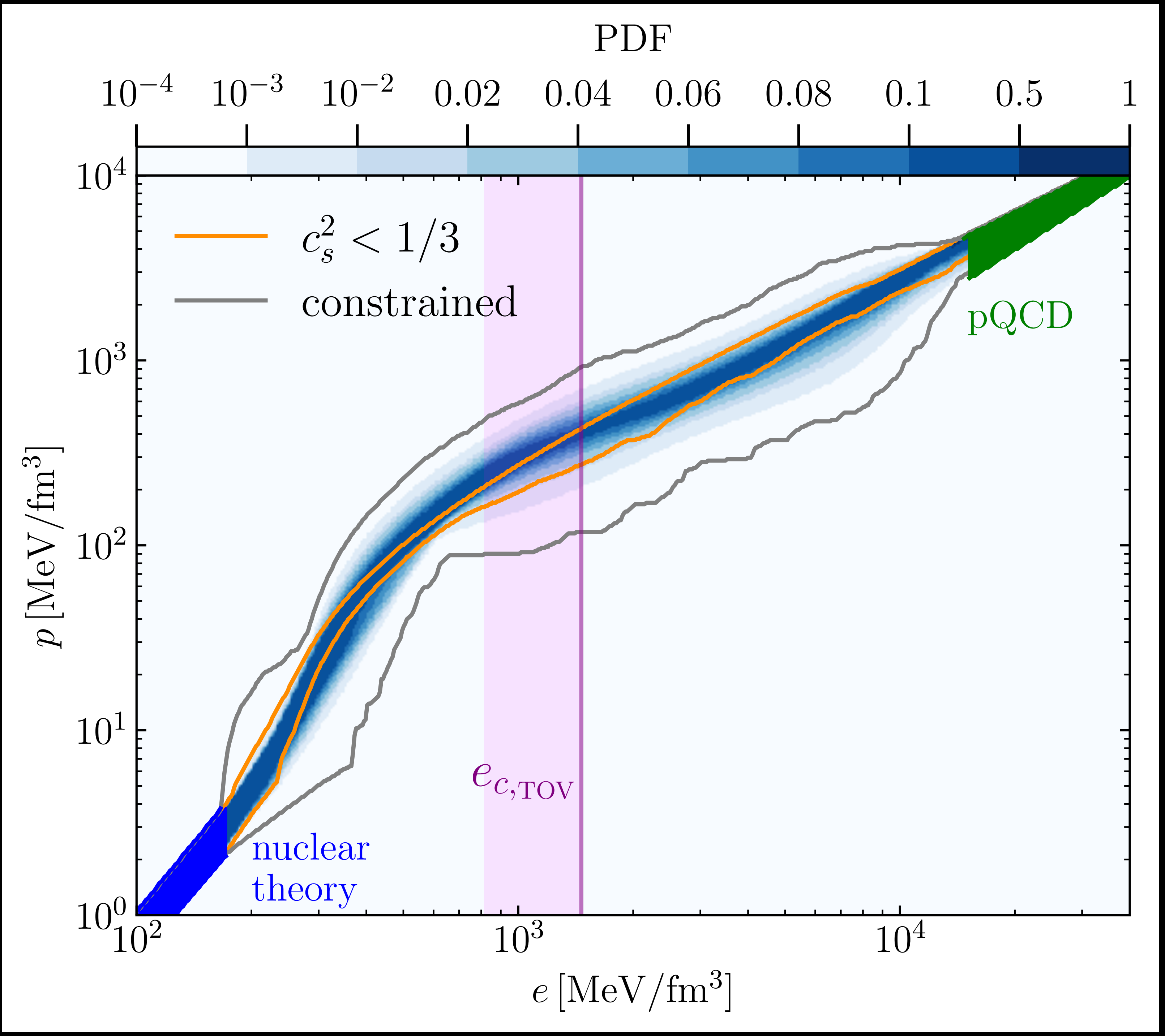
Sound speed PDF



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

No monotonic sub-conformal EOS found.

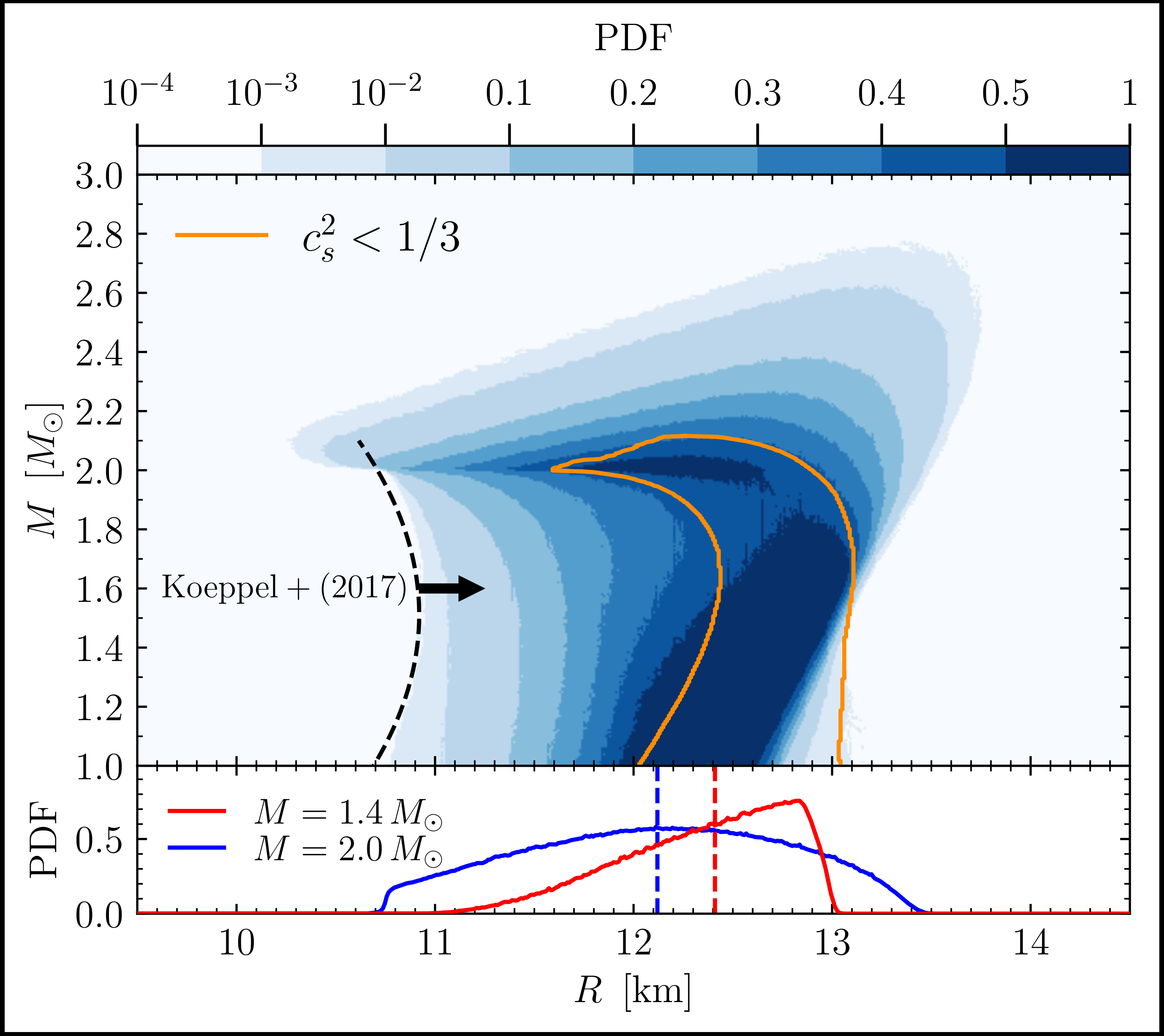
EOS PDF



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

Note that 99% confidence region is very thin.

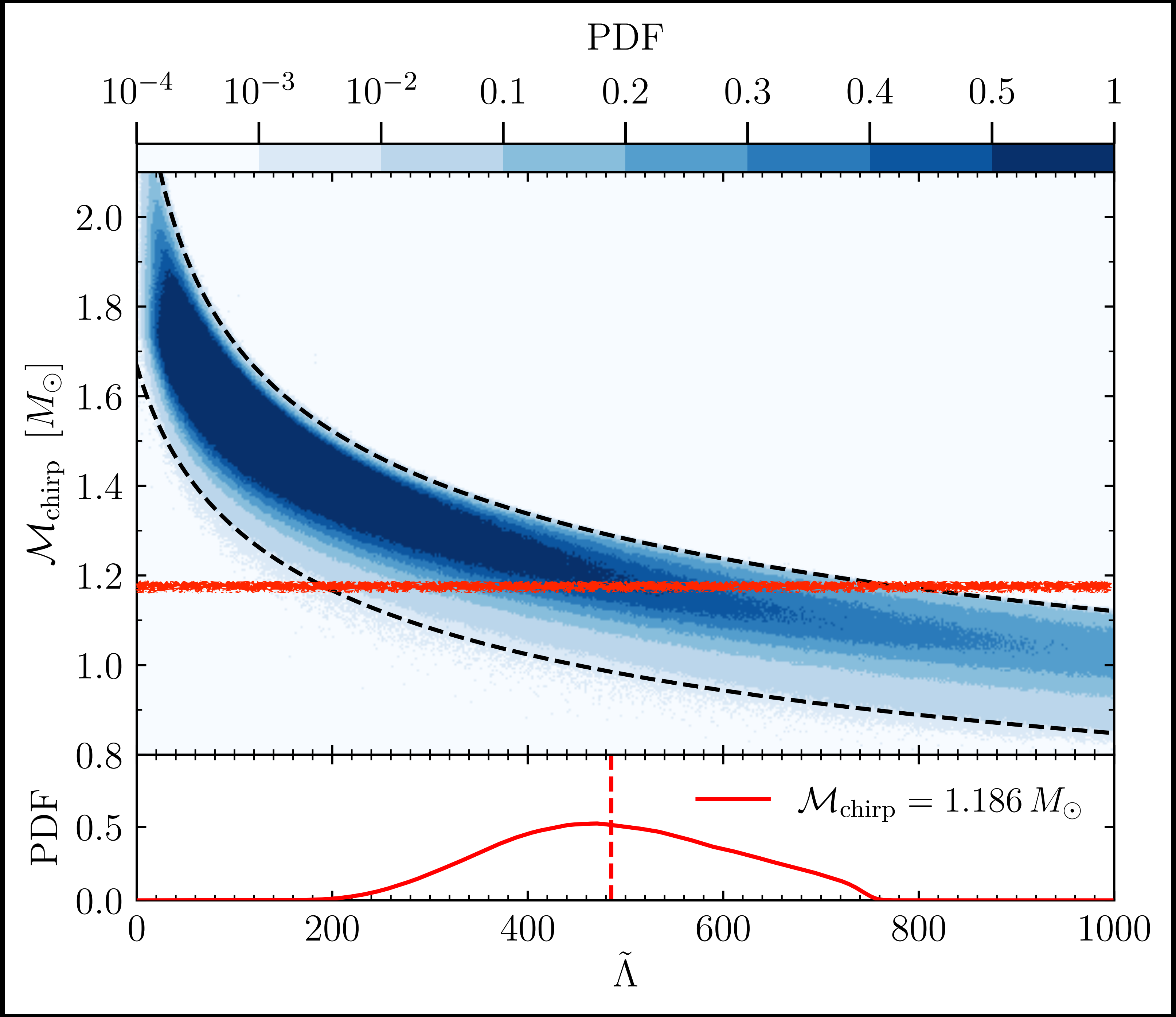
A more comprehensive picture



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.

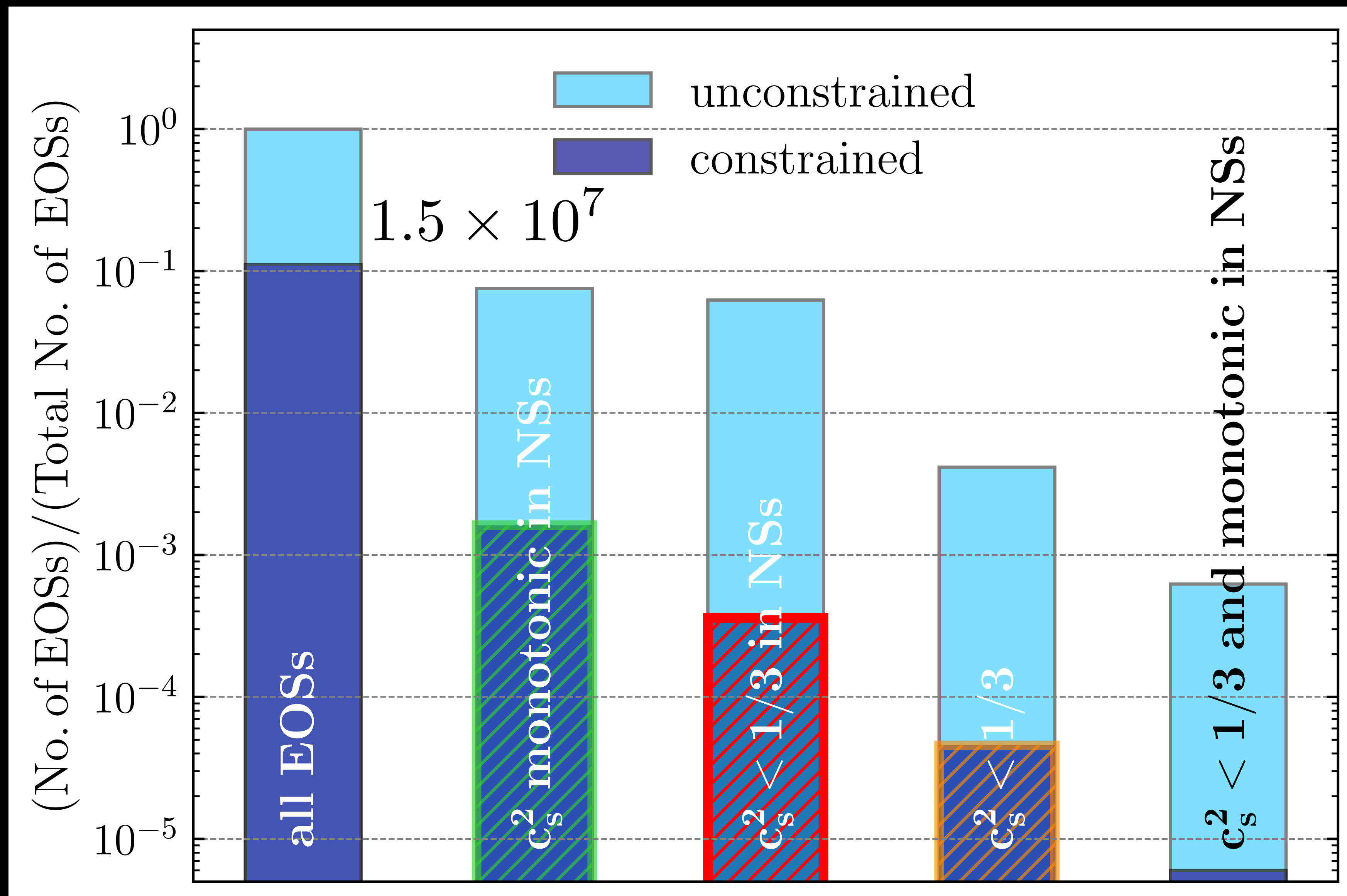
A more comprehensive picture



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: $c_s^2 < 1/3$;

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

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

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

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

Conclusions

Much of the research presented is is part of **ELEMENTS**, an Hessian Research Cluster with Frankfurt Darmstadt and Giessen

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