The **physics** of binary neutron star mergers

Lecture II

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57th Karpacz Winter School of Theoretical Physics

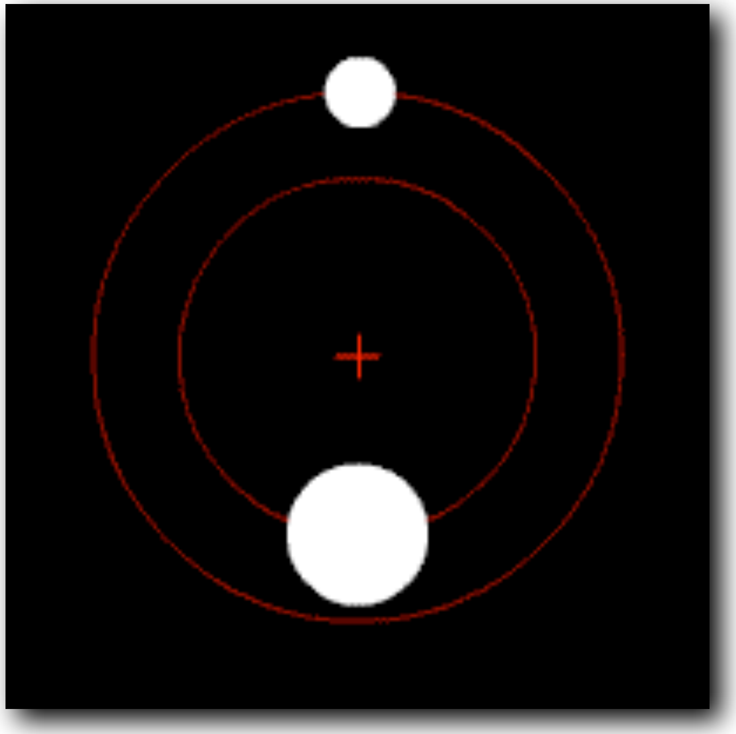
13-19 June 2021, Karpacz

Plan of the lectures

- ✴Lecture I: the **math** of neutron-star mergers
- ✴Lecture II: the **physics** of neutron-star mergers
- ✴Lecture III: the **astrophysics** of neutron-star mergers

- ✴**L. Baiotti and L. Rezzolla, Rep. Prog. Phys. 80, 096901, 2017**
- ✴V. Paschalidis, Classical Quantum Gravity 34, 084002 2017
- ✴Rezzolla and Zanotti, *"Relativistic Hydrodynamics"*, Oxford University Press, 2013

The two-body problem: Newton vs Einstein



Take two objects of mass m_1 and m_2 interacting only gravitationally

In **Newtonian gravity** solution is analytic: there exist closed orbits (circular/elliptic) with

$$\ddot{\boldsymbol{r}} = -\frac{GM}{d_{12}^3}\boldsymbol{r}$$

where $M \equiv m_1 + m_2 \,, \boldsymbol{r} \equiv \boldsymbol{r}_1 - \boldsymbol{r}_2 \,, d_{12} \equiv |\boldsymbol{r}_1 - \boldsymbol{r}_2| \,.$

In **Einstein's gravity** no analytic solution! No closed orbits: the system loses energy/angular momentum via gravitational waves.

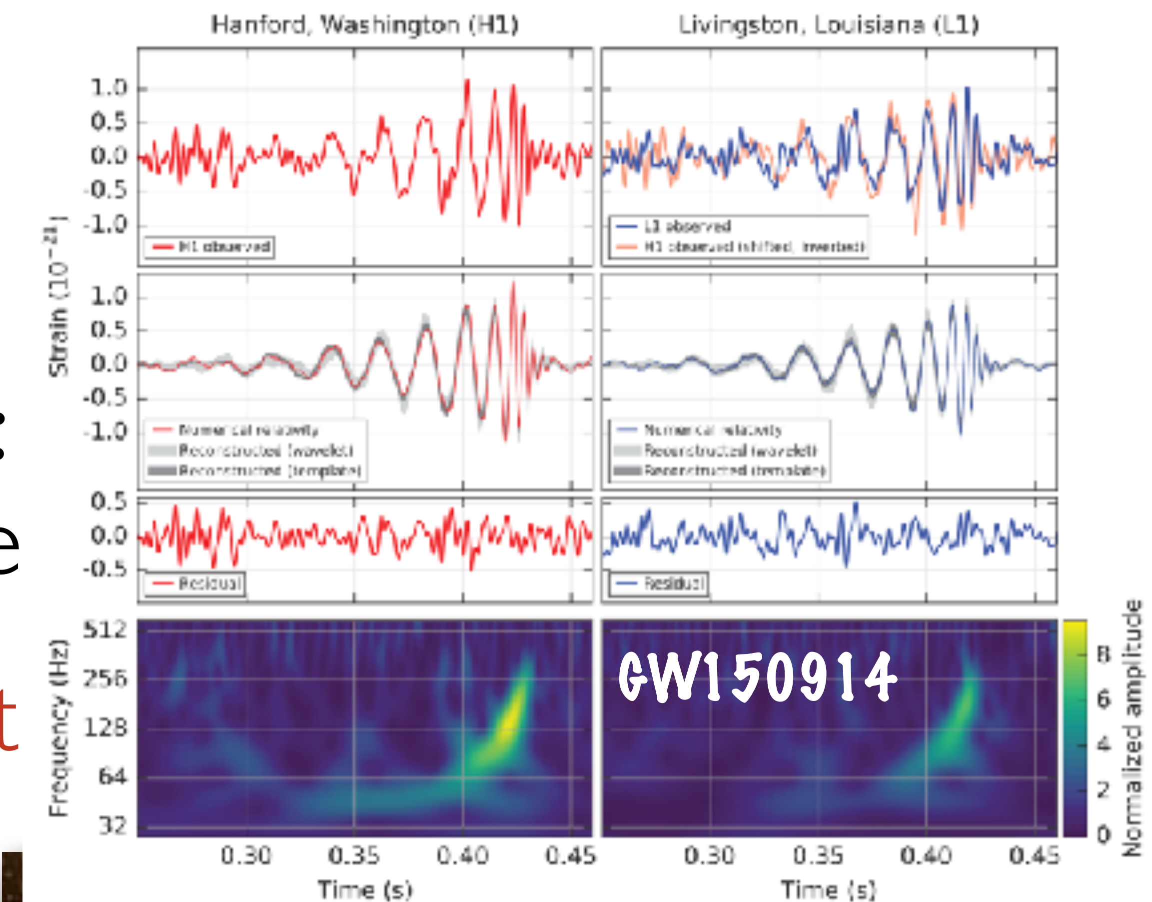
The two-body problem in GR

- For BHs we know what to **expect**:

BH + BH → BH + GWs

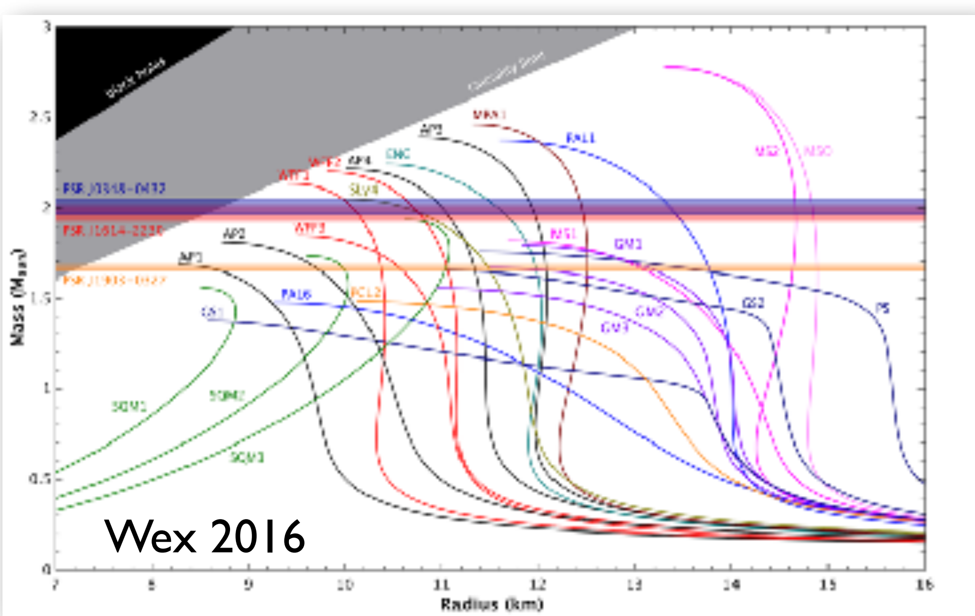
- For NSs the question is more **subtle:** hyper-massive neutron star (HMNS), ie

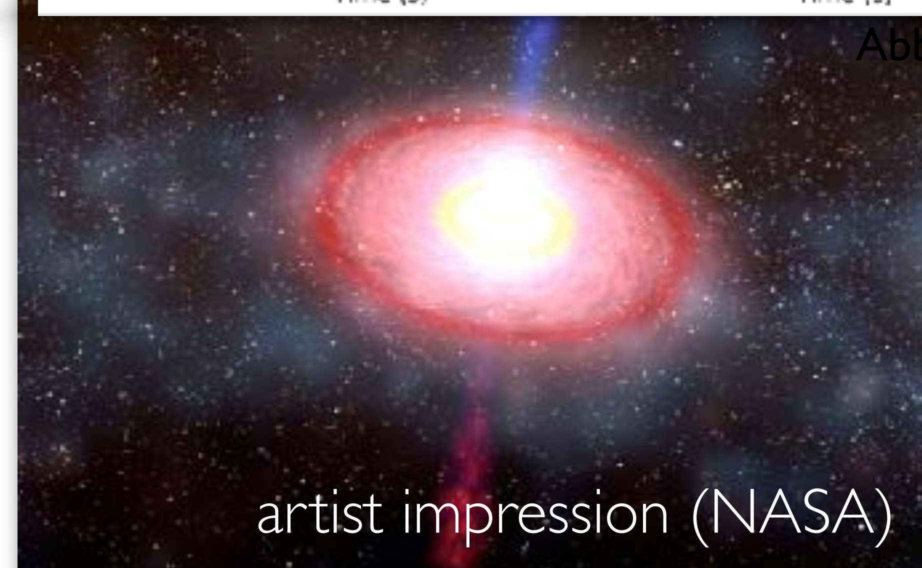
NS + NS → HMNS+**... ?** → BH+t



Abbott+ 2016

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





- **BH+torus** system may tell us on the central engine of **GRBs**

The two-body problem in GR

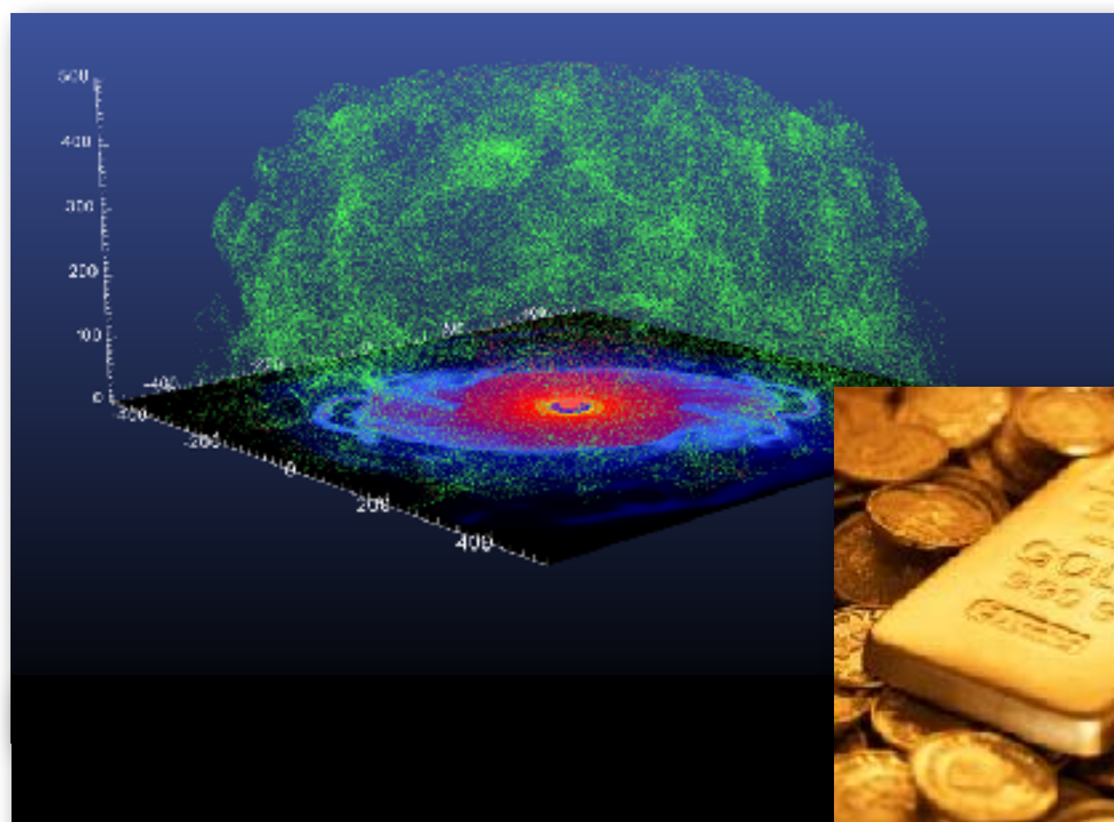
- For BHs we know what to **expect**:

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

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

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

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

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

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

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

In GR these equations do not possess an analytic solution in the regimes we are interested in

Animations: Breu, Radice, LR

merger ⟶ HMNS ⟶ BH + torus

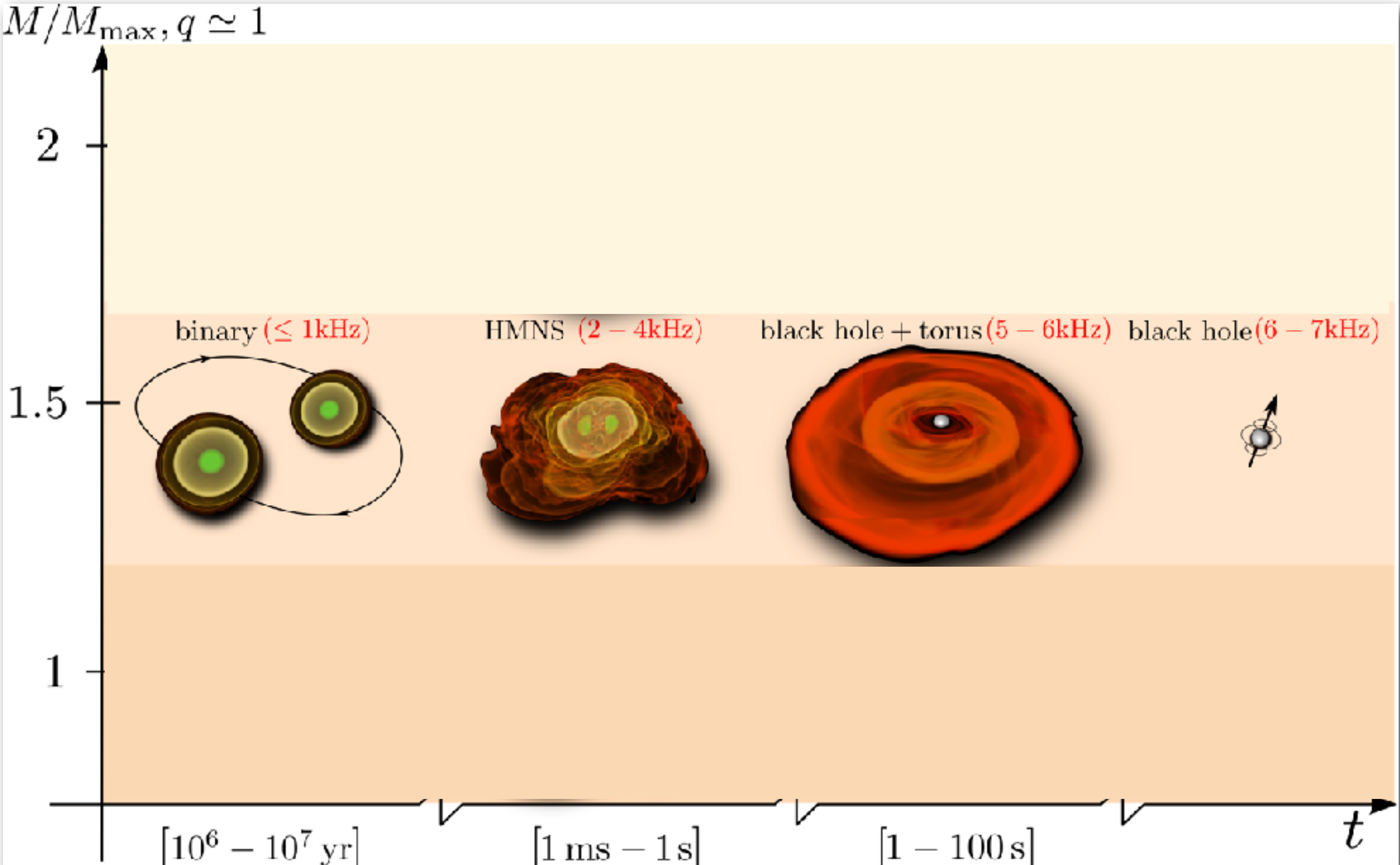
LS220 EOS

merger ⟶ HMNS ⟶ BH + torus

Quantitative differences are produced by:

- **total mass (prompt vs delayed collapse)**

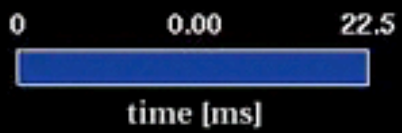
Broadbrush picture



merger ⟶ HMNS ⟶ BH + torus

Quantitative differences are produced by:

- total mass (prompt vs delayed collapse)
- mass asymmetries (HMNS and torus)



Animations: Giacomazzo, Koppitz, LR

Total mass : $3.37\,M_\odot$; mass ratio :0.80;

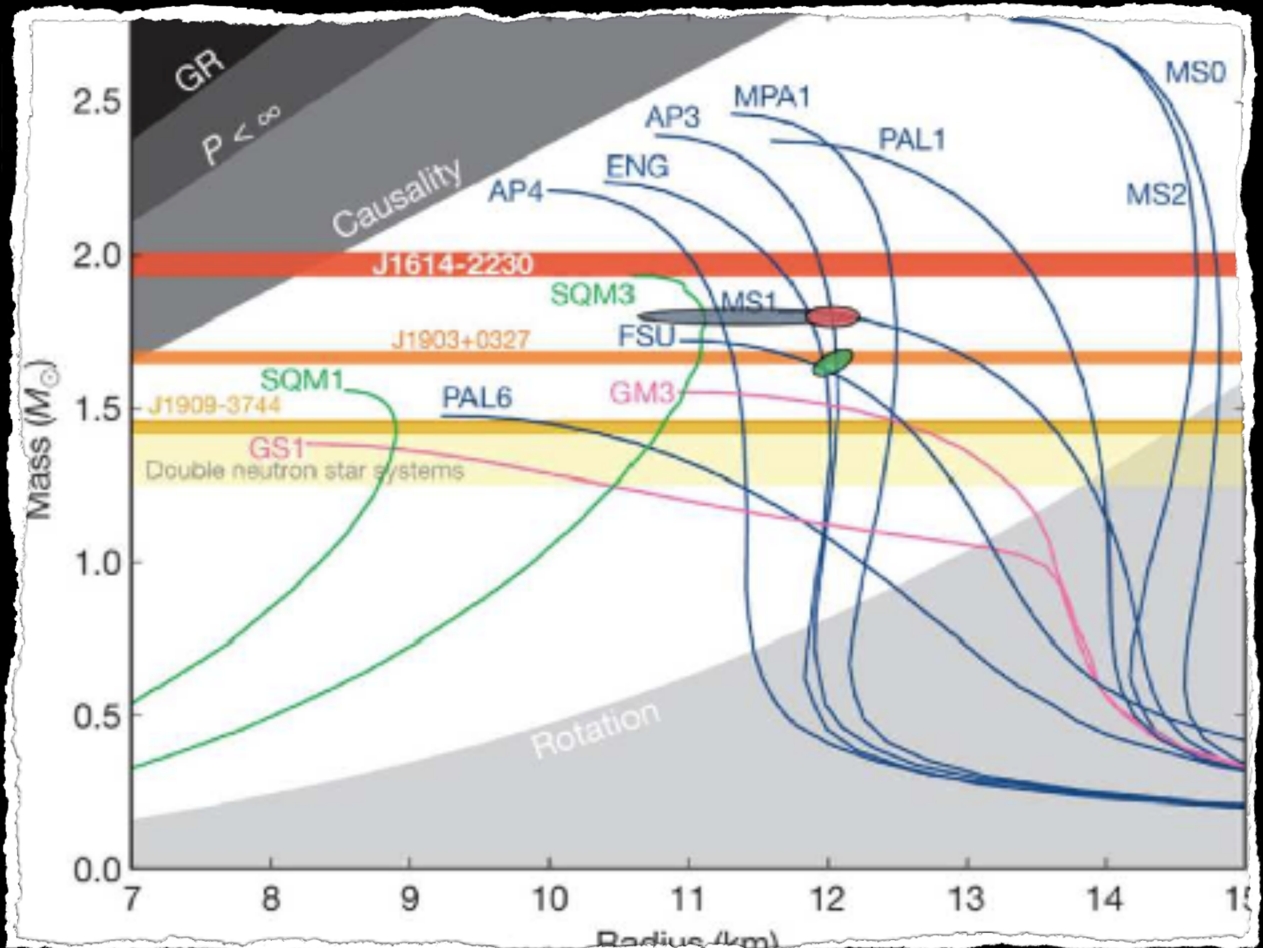
- the torii are generically more massive
- the torii are generically more extended
- the torii tend to stable quasi-Keplerian configurations
- overall unequal-mass systems have all the ingredients needed to create a GRB

merger → HMNS → BH + torus

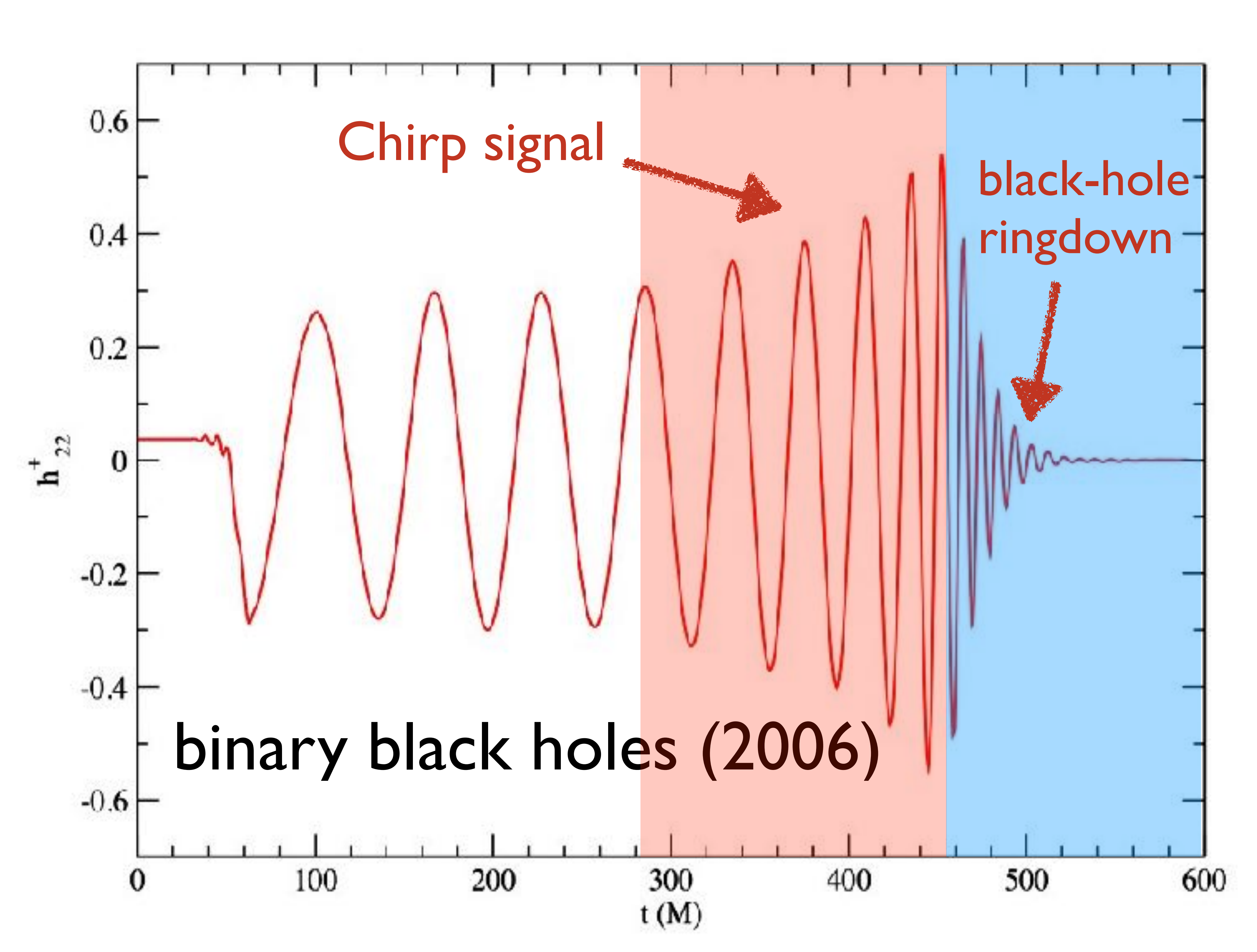
Quantitative differences are produced by:

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

How to constrain the EOS from the GWs



Anatomy of the GW signal



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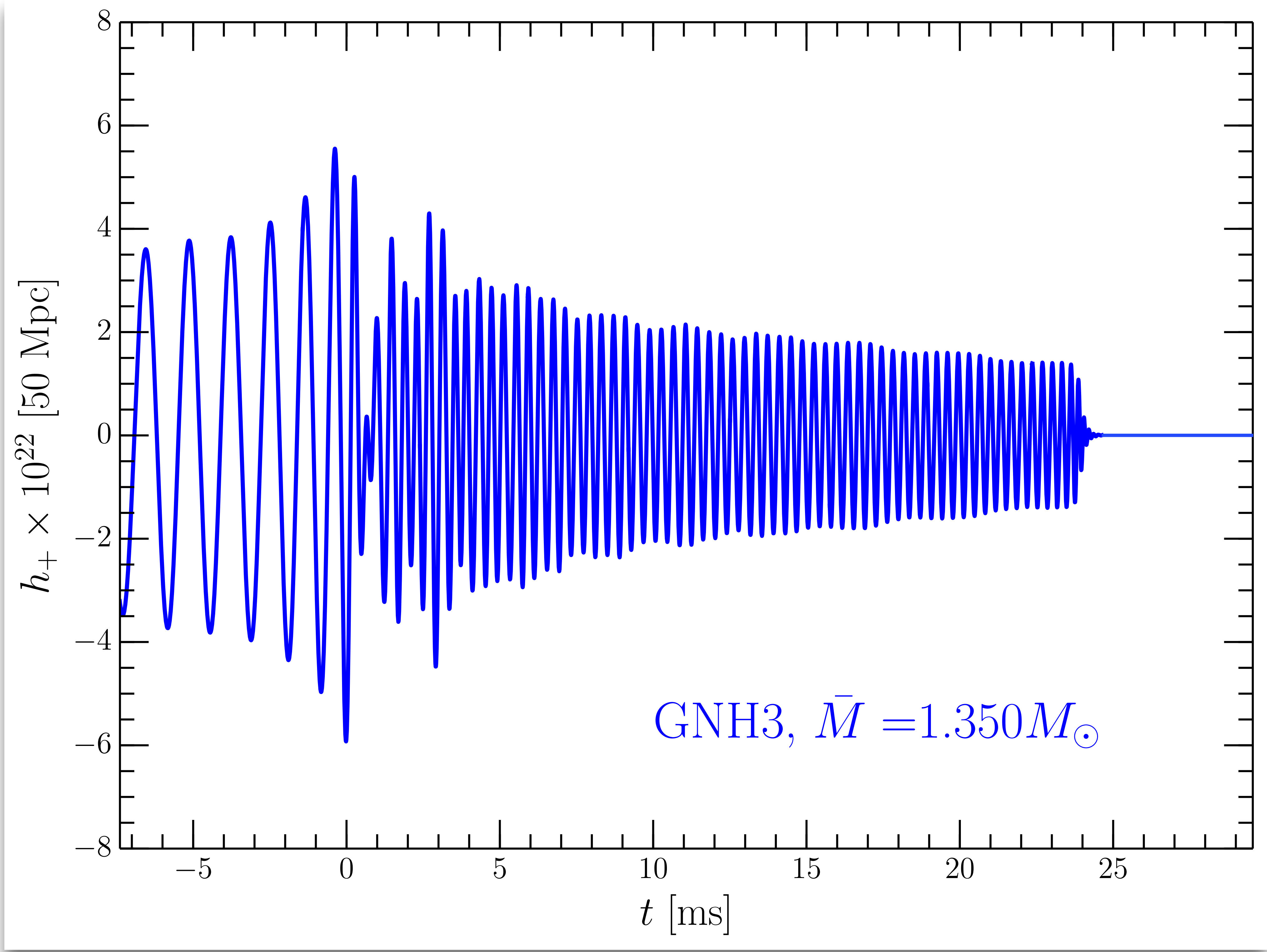

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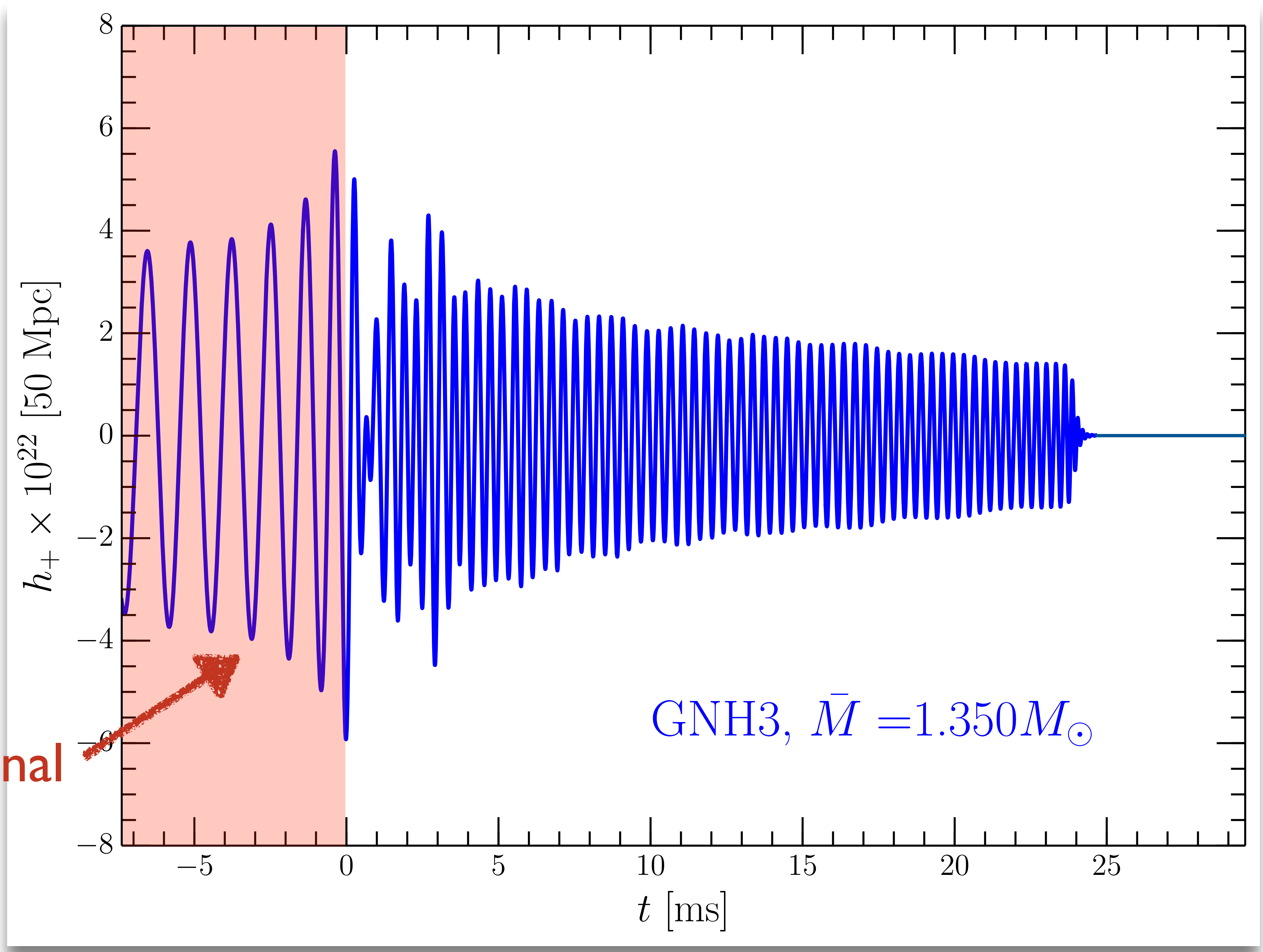
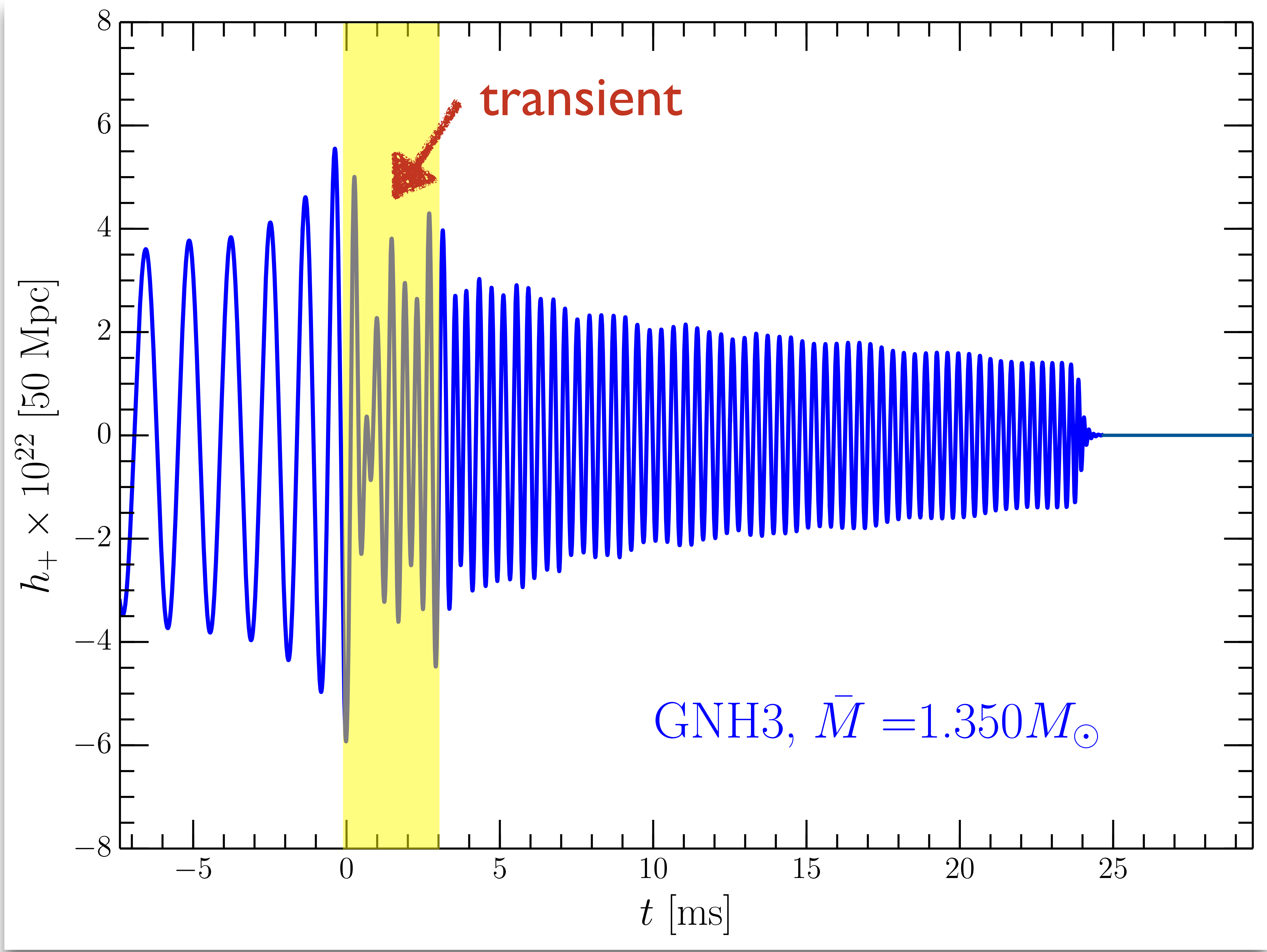


Chirp signal

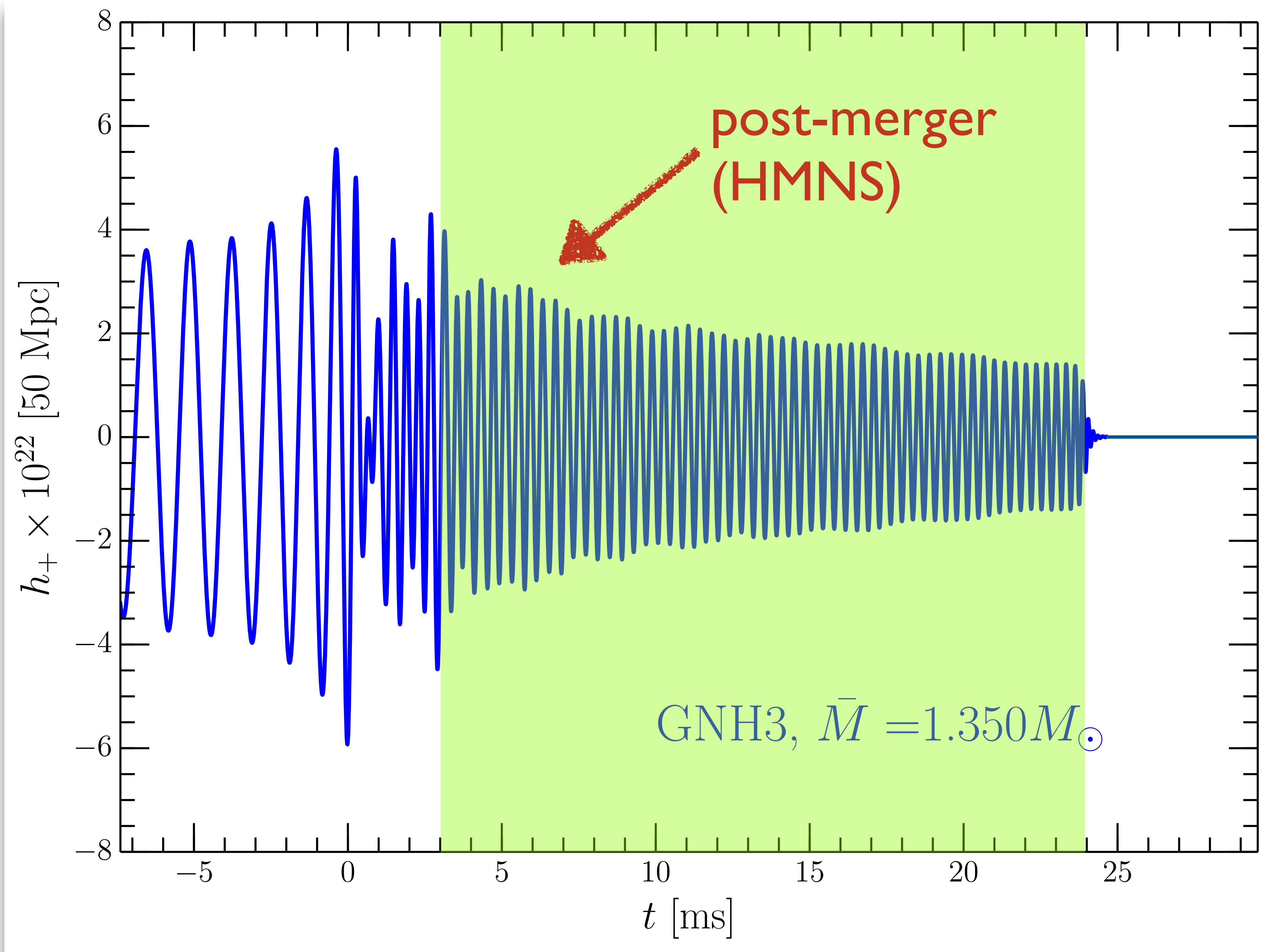
Inspiral: well approximated by PN/EOB; tidal effects important

Anatomy of the GW signal



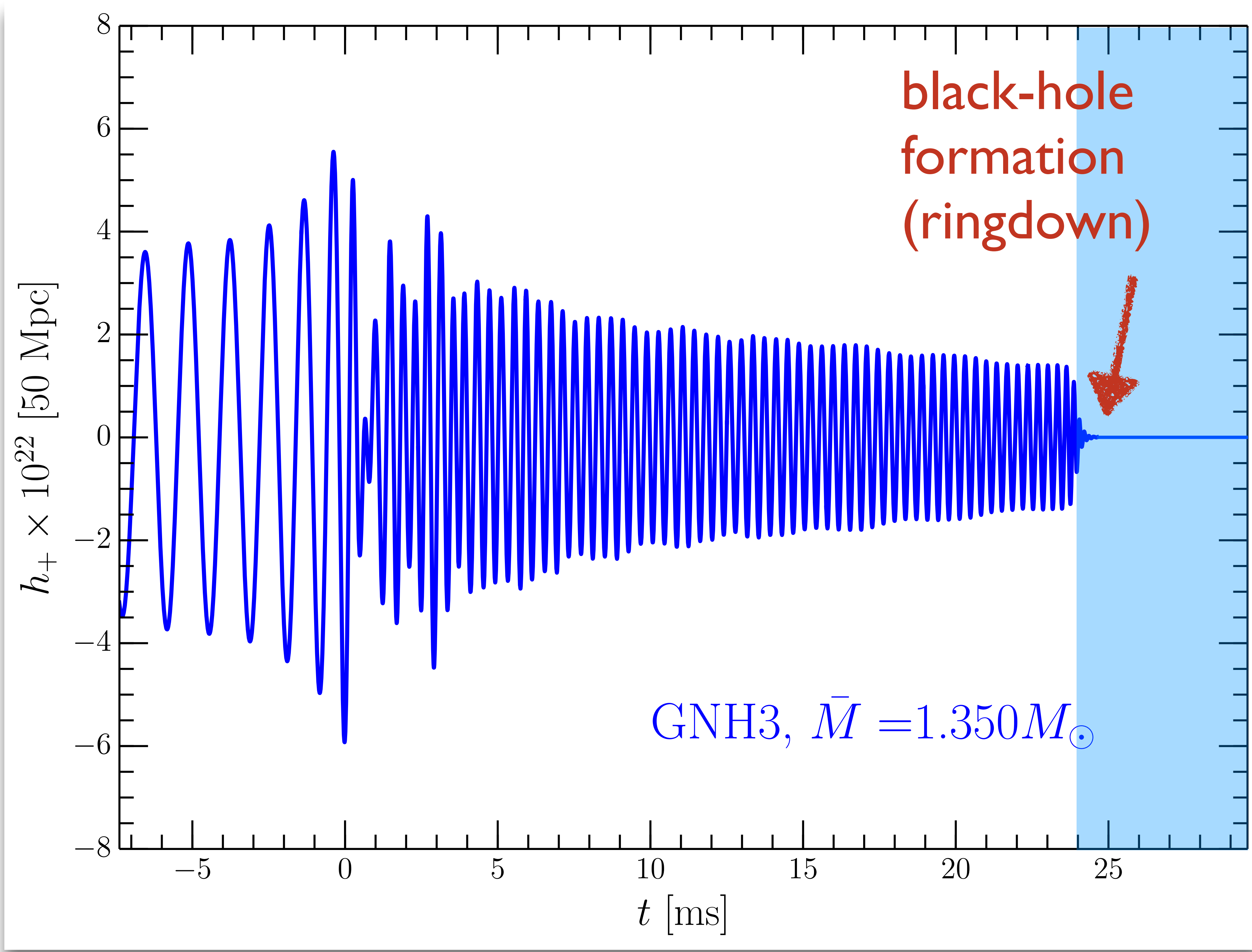
Merger: highly nonlinear but analytic description possible

Anatomy of the GW signal



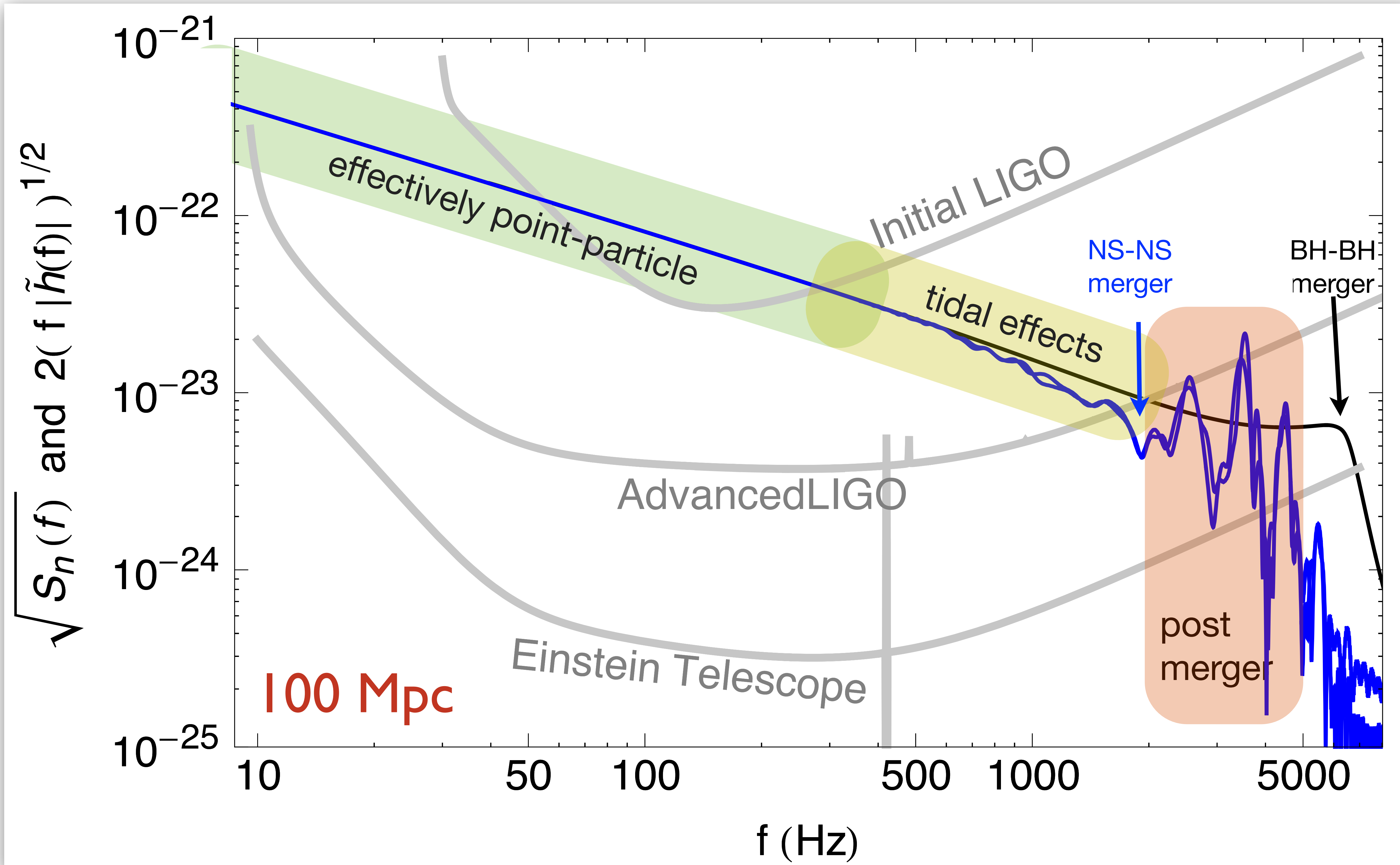
post-merger: quasi-periodic emission of bar-deformed HMNS

Anatomy of the GW signal



Collapse-ringdown: signal essentially shuts off.

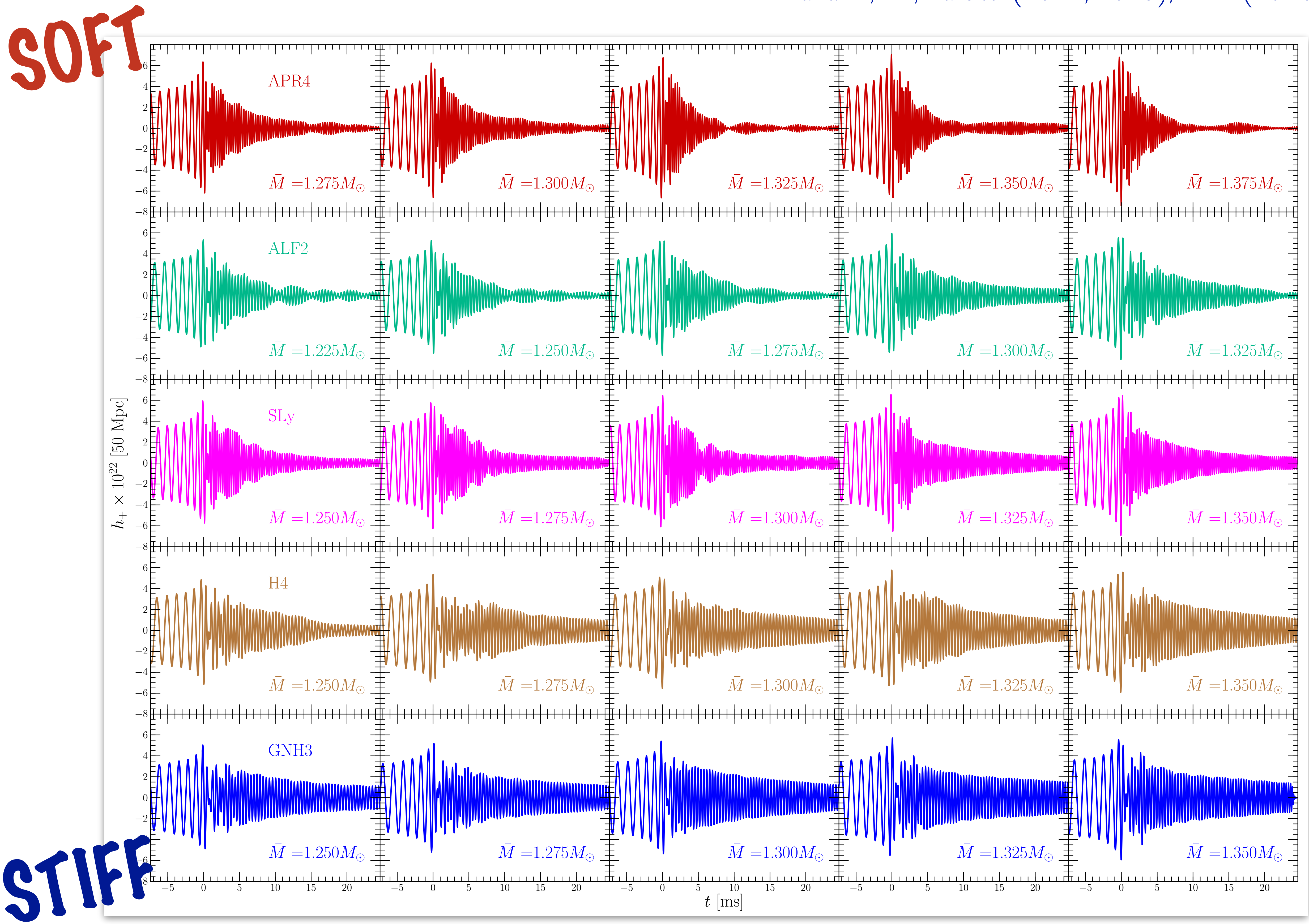
In frequency space



Read et al. (2013)

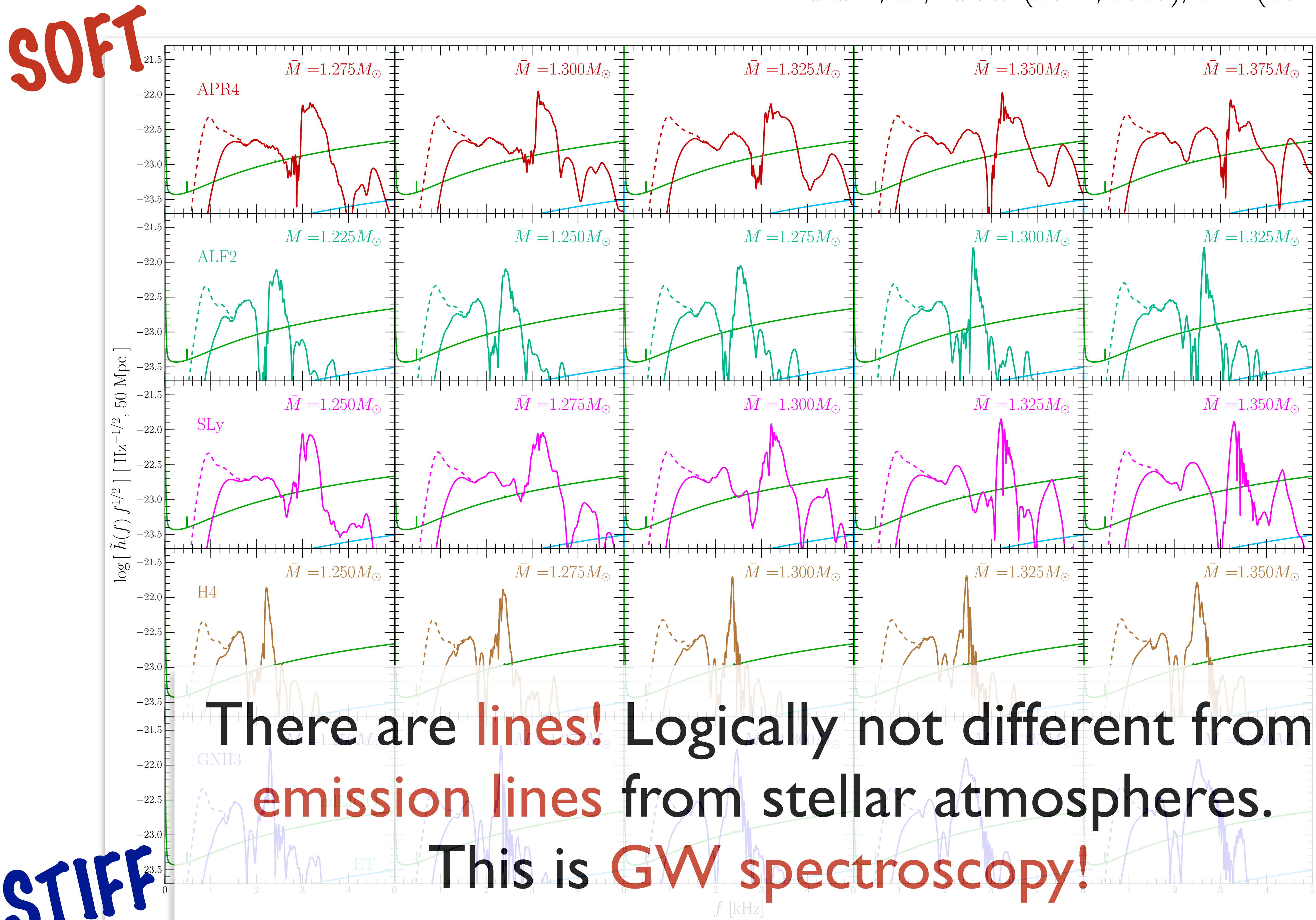
What we can do nowadays

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



Extracting information from the EOS

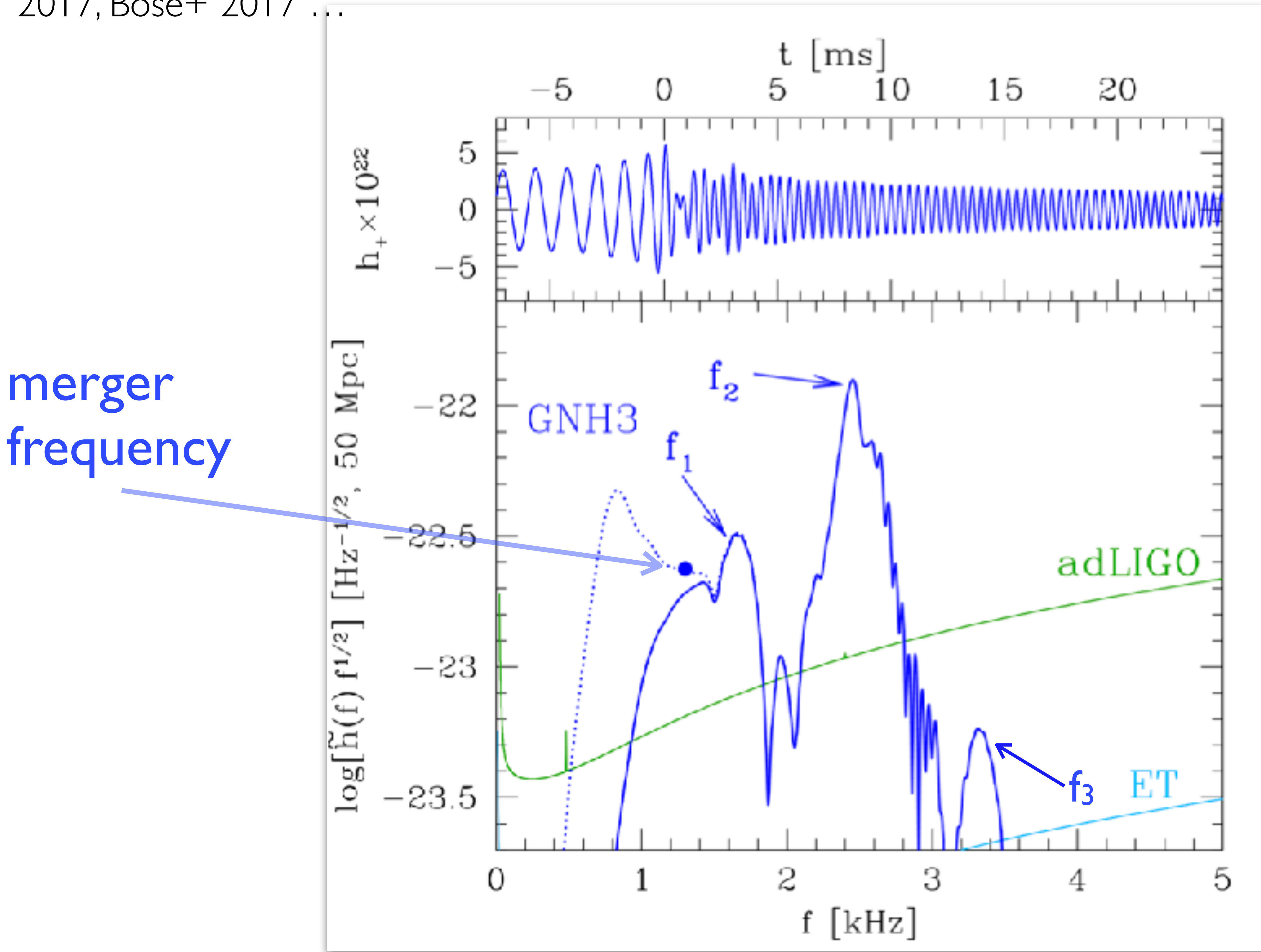
Takami, LR, Baiotti (2014, 2015), LR+ (2016)



There are **lines!** Logically not different from **emission lines** from stellar atmospheres. This is **GW spectroscopy!**

A new approach to constrain the EOS

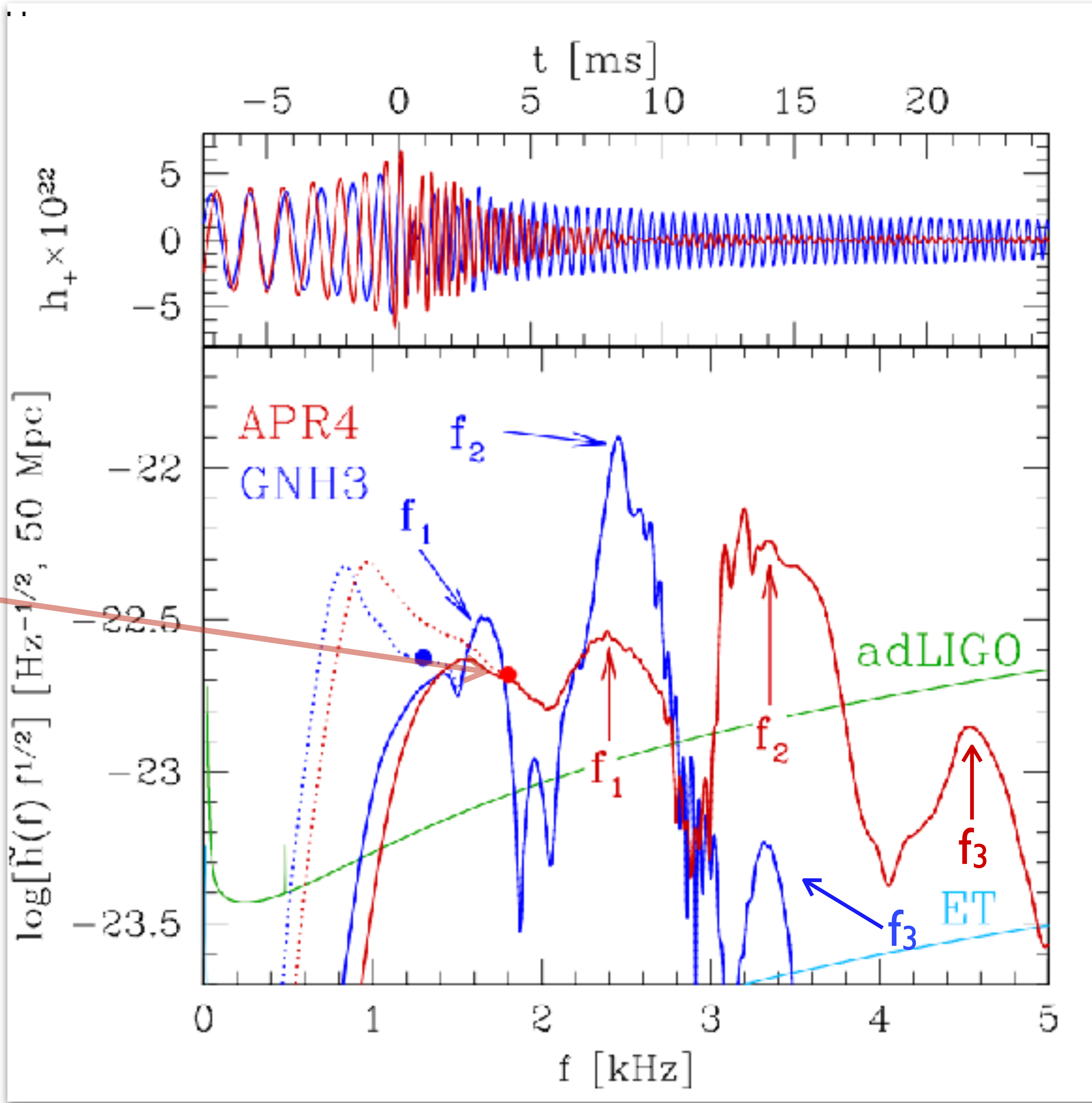
Oechslin+2007, Baiotti+2008, Bauswein+ 2011, 2012, Stergioulas+ 2011, Hotokezaka+ 2013, Takami 2014, 2015, Bernuzzi 2014, 2015, Bauswein+ 2015, Clark+ 2016, LR+2016, de Pietri+ 2016, Feo+ 2017, Bose+ 2017 …



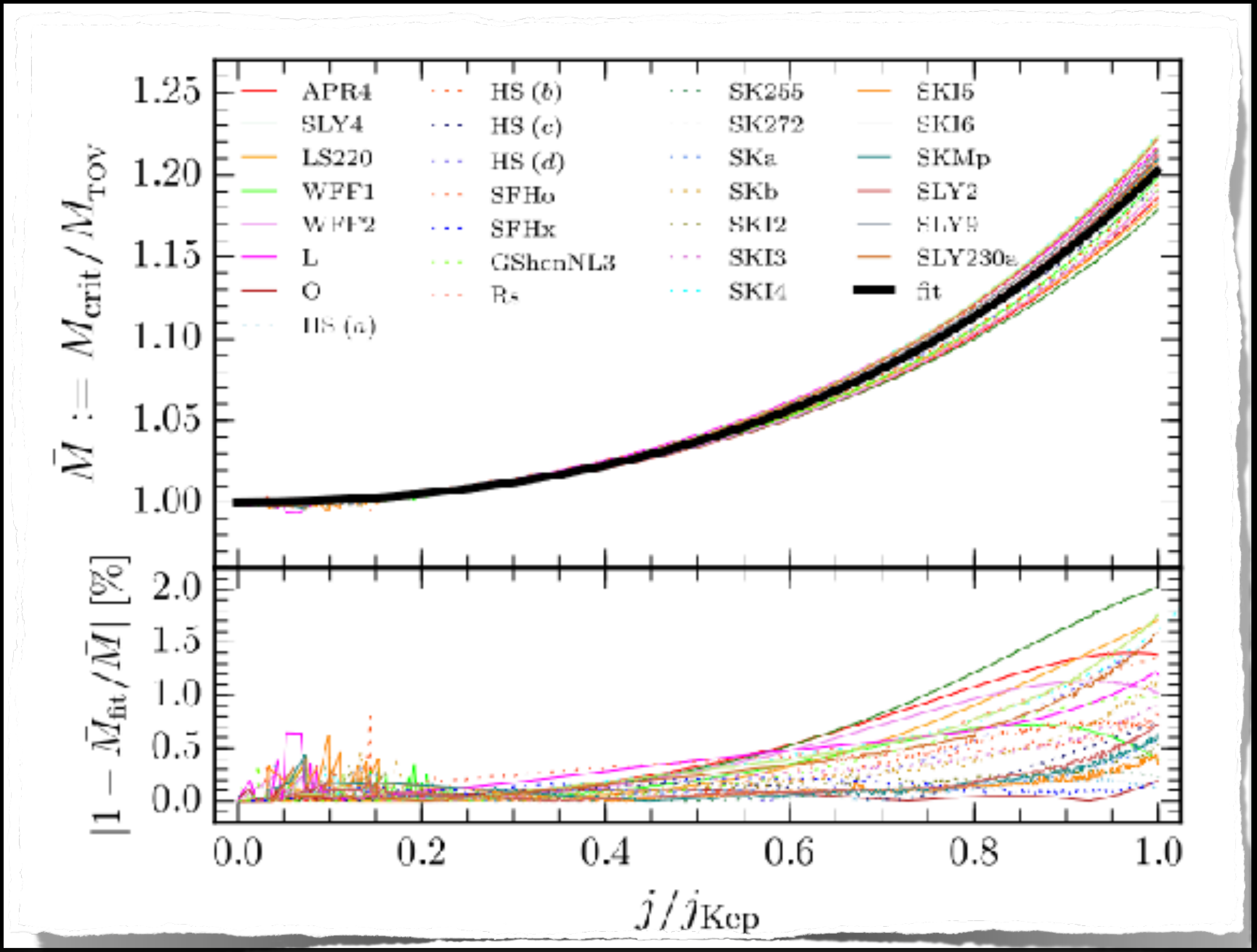
A spectroscopic approach to the EOS

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 …

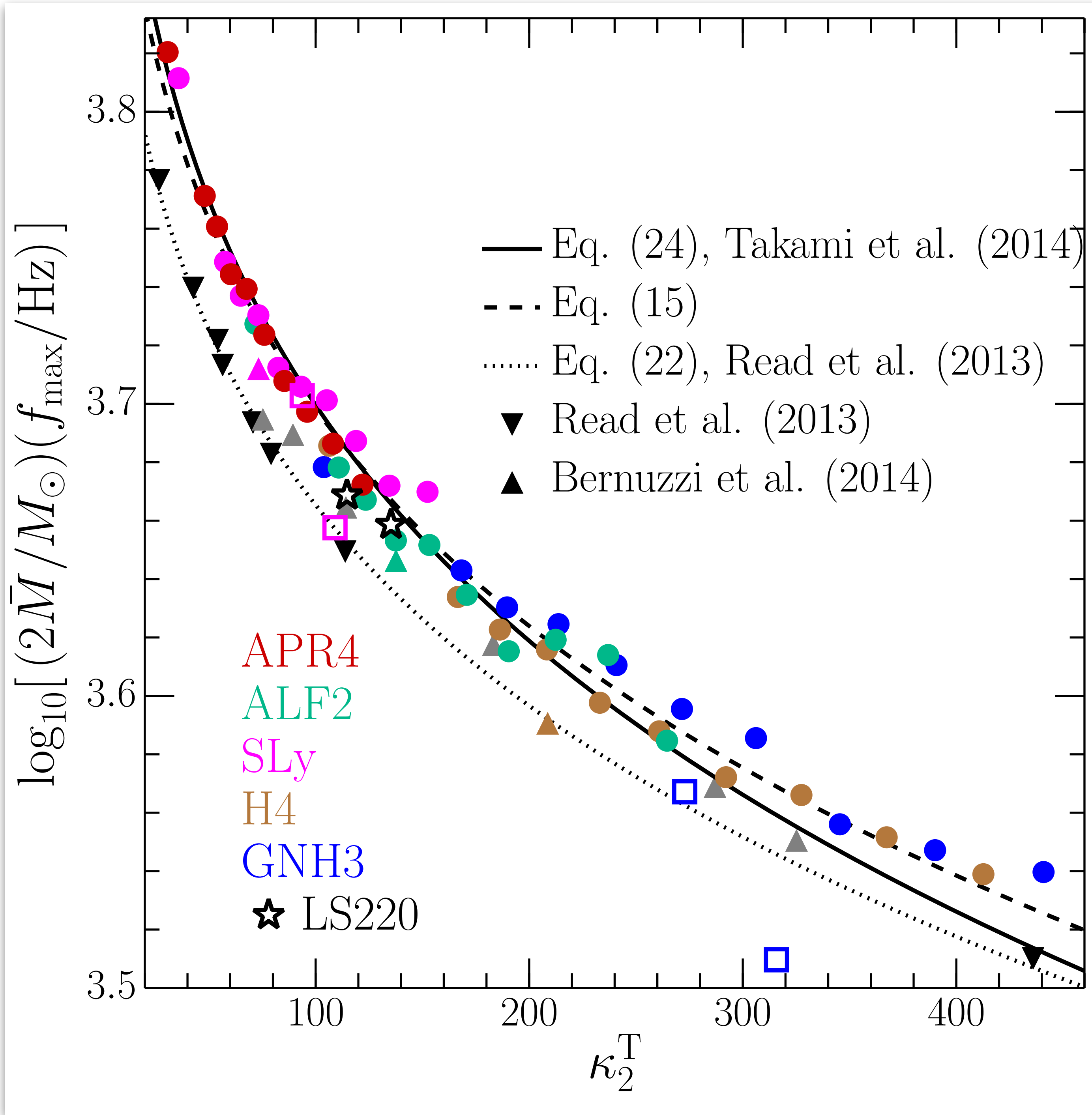
merger frequency



Quasi-universal behaviour



Quasi-universal behaviour: **inspiral**



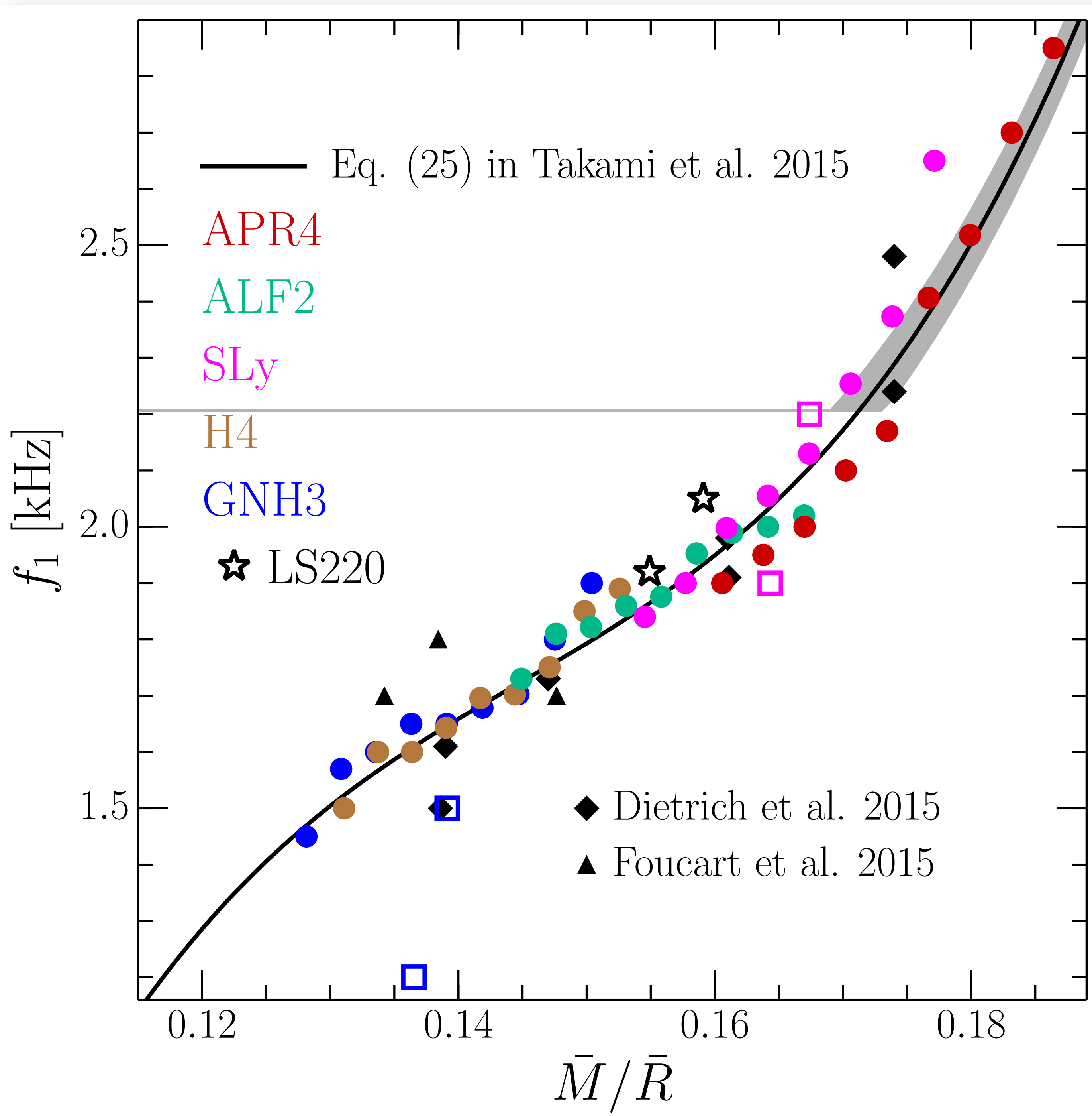
"surprising" result: quasi-universal behaviour of GW frequency at amplitude peak (Read+2013)

Many other simulations have confirmed this (Bernuzzi+ 2014, Takami+ 2015, LR+2016) .

Quasi-universal behaviour in the **inspiral** implies that once f_{max} is measured, so is tidal deformability, hence $I,\ Q,\ M/R$

$$\Lambda = \frac{\lambda}{\bar{M}^5} = \frac{16}{3}\kappa_2^T$$ tidal deformability or Love number

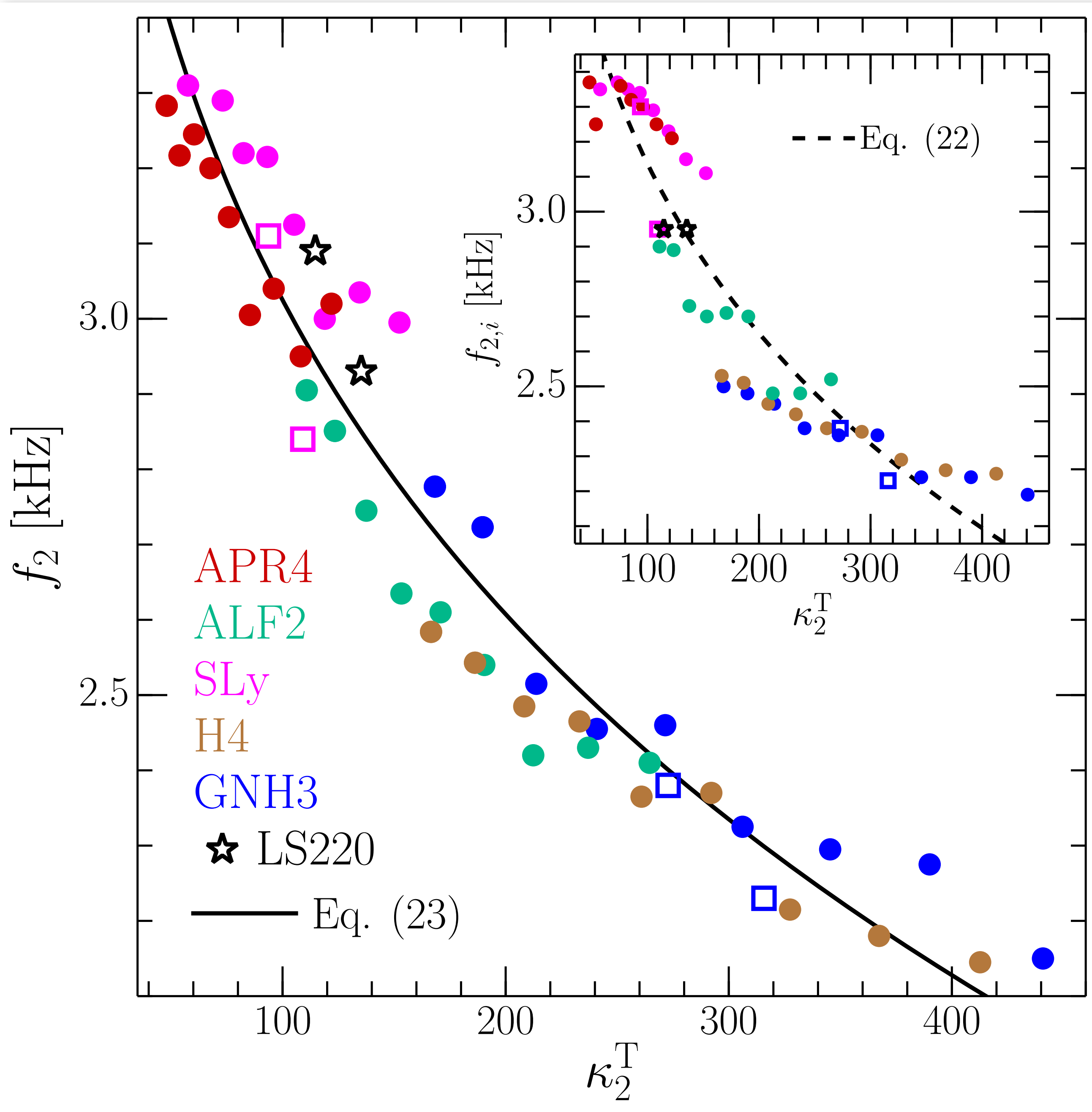
Quasi-universal behaviour: **post-merger**



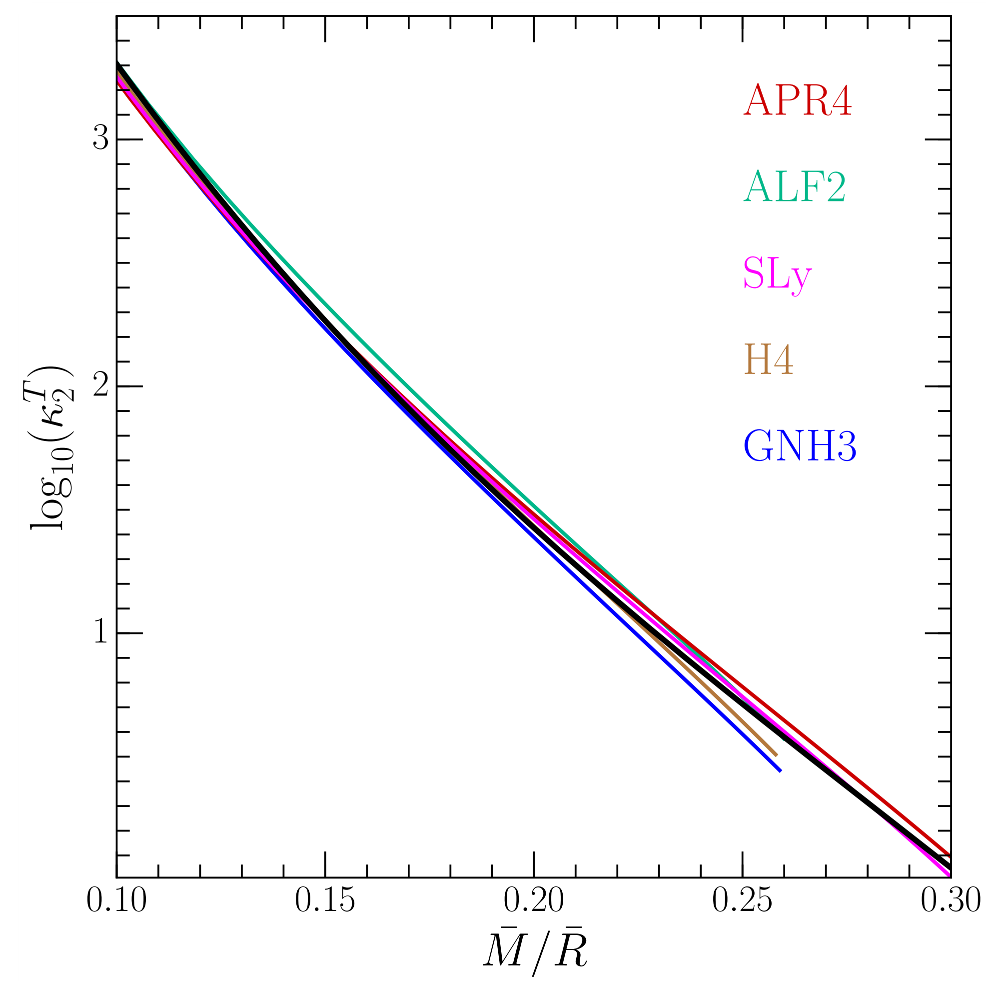
We have found **quasi-universal behaviour:** i.e., the properties of the spectra are only weakly dependent on the EOS.

This has profound implications for the analytical modelling of the GW emission: "what we do for one EOS can be extended to all EOSs."

Quasi-universal behaviour: **post-merger**



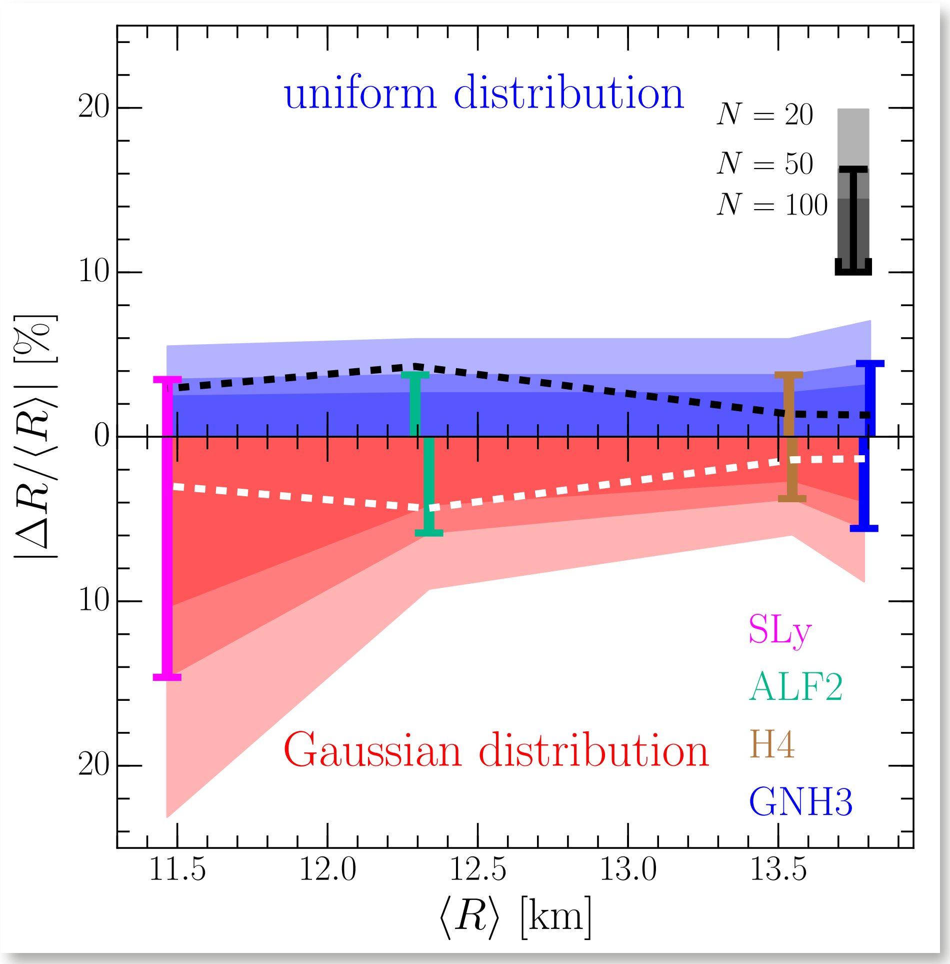
- Correlations with Love number found also for high frequency peak f_2.
- This and other correlations are **weaker** but equally useful.



- Important correlation also between **compactness** and **deformability**

A spectroscopic approach to the EOS

- **Universal behaviour** and analytic modelling of post-merger relates position of these peaks with the EOS.
- Observation of the post-merger signal would constrain significantly the stellar radius; given ***N* detections.**



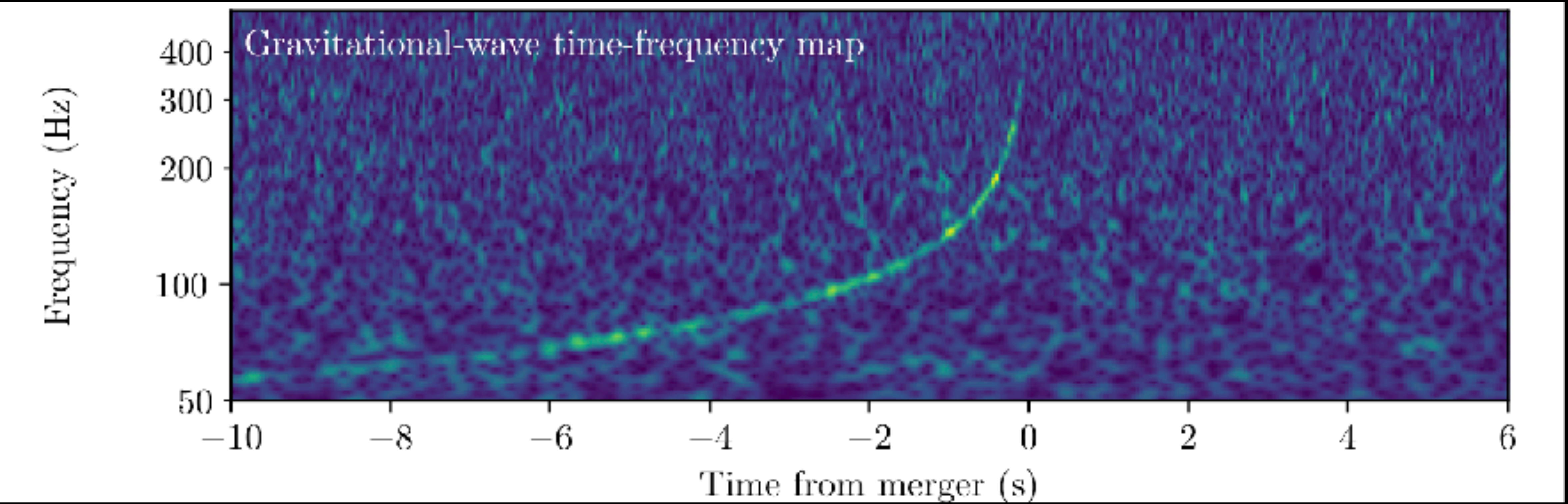
- **stiff EOSs**: $|\Delta R/\langle R\rangle| < 10\%$ ***N~20*** detect.
- **soft EOSs**: $|\Delta R/\langle R\rangle| \sim 10\%$ ***N~50*** detect.
- discriminating stiff/soft EOSs possible even with moderate ***N***
- golden binary: **SNR ~ 6** at **30 Mpc** $|\Delta R/\langle R\rangle| \lesssim 2\%$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

GW170817, maximum mass, radii and tidal deformabilities

LR, Most, Weih, ApJL (2018)

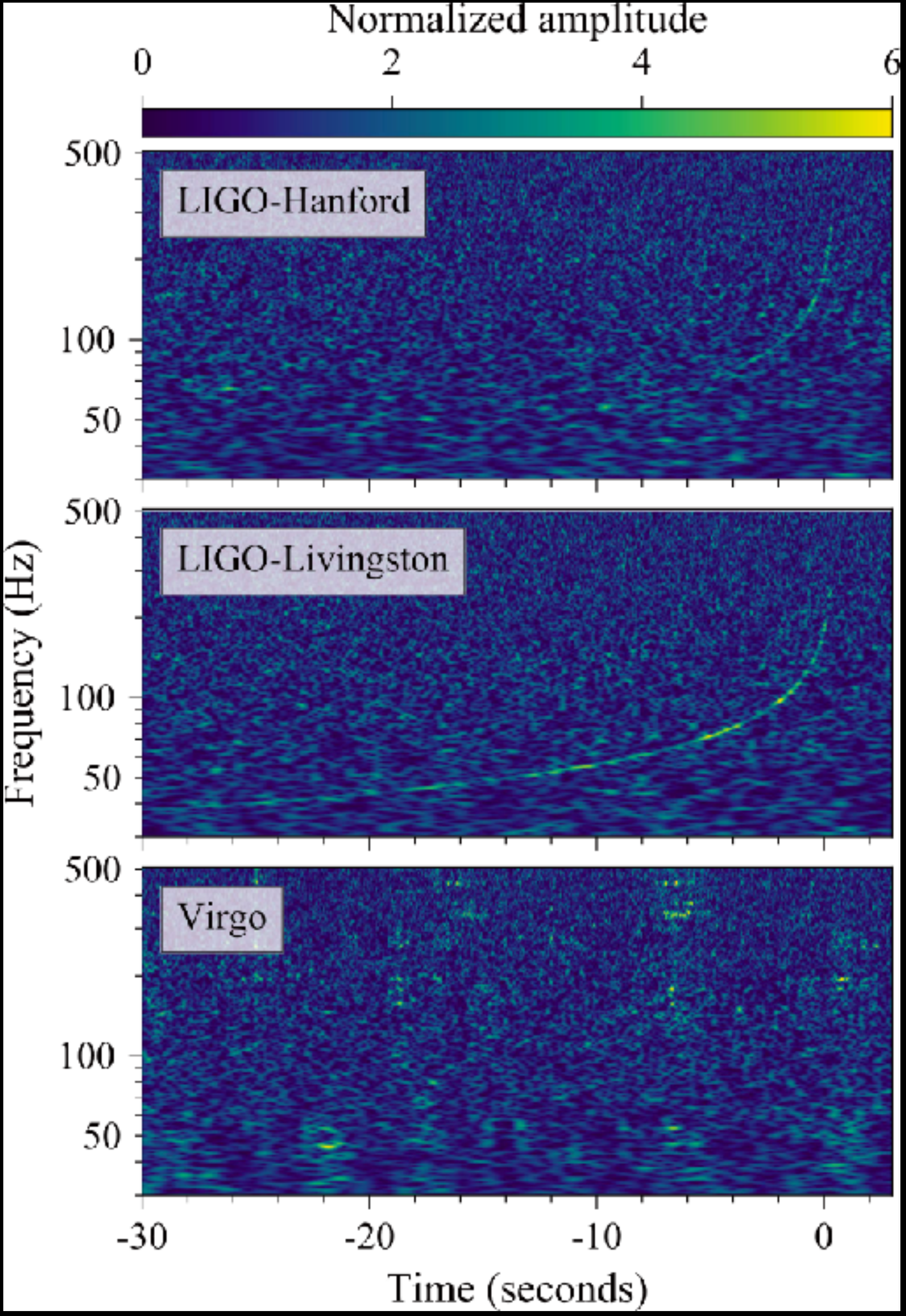
Most, Weih, LR, Schaffner-Bielich, PRL (2018)

Köppel, Bovard, LR, ApJL (2018)



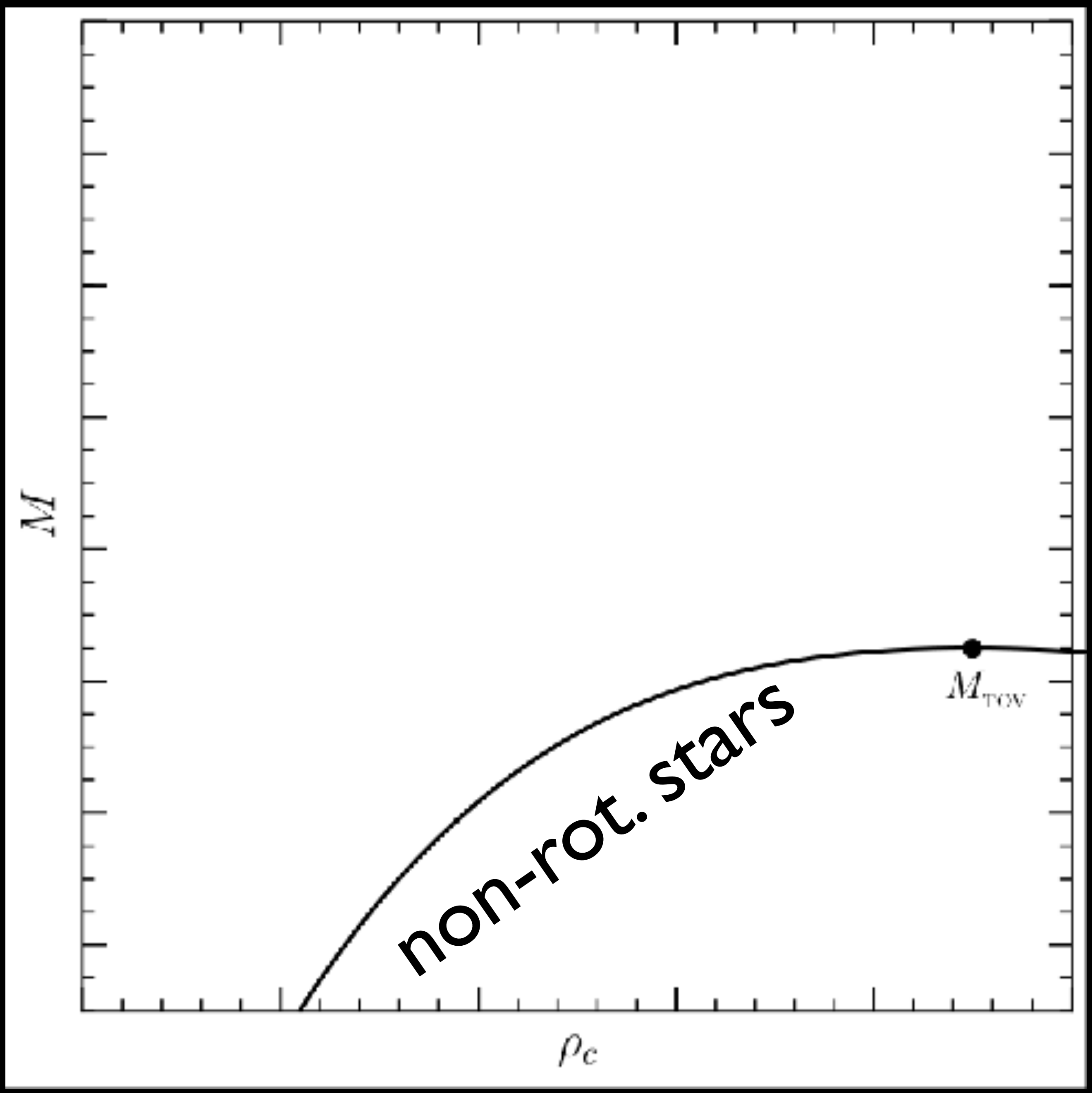
GW170817: the first binary neutron-star system

- ✴ **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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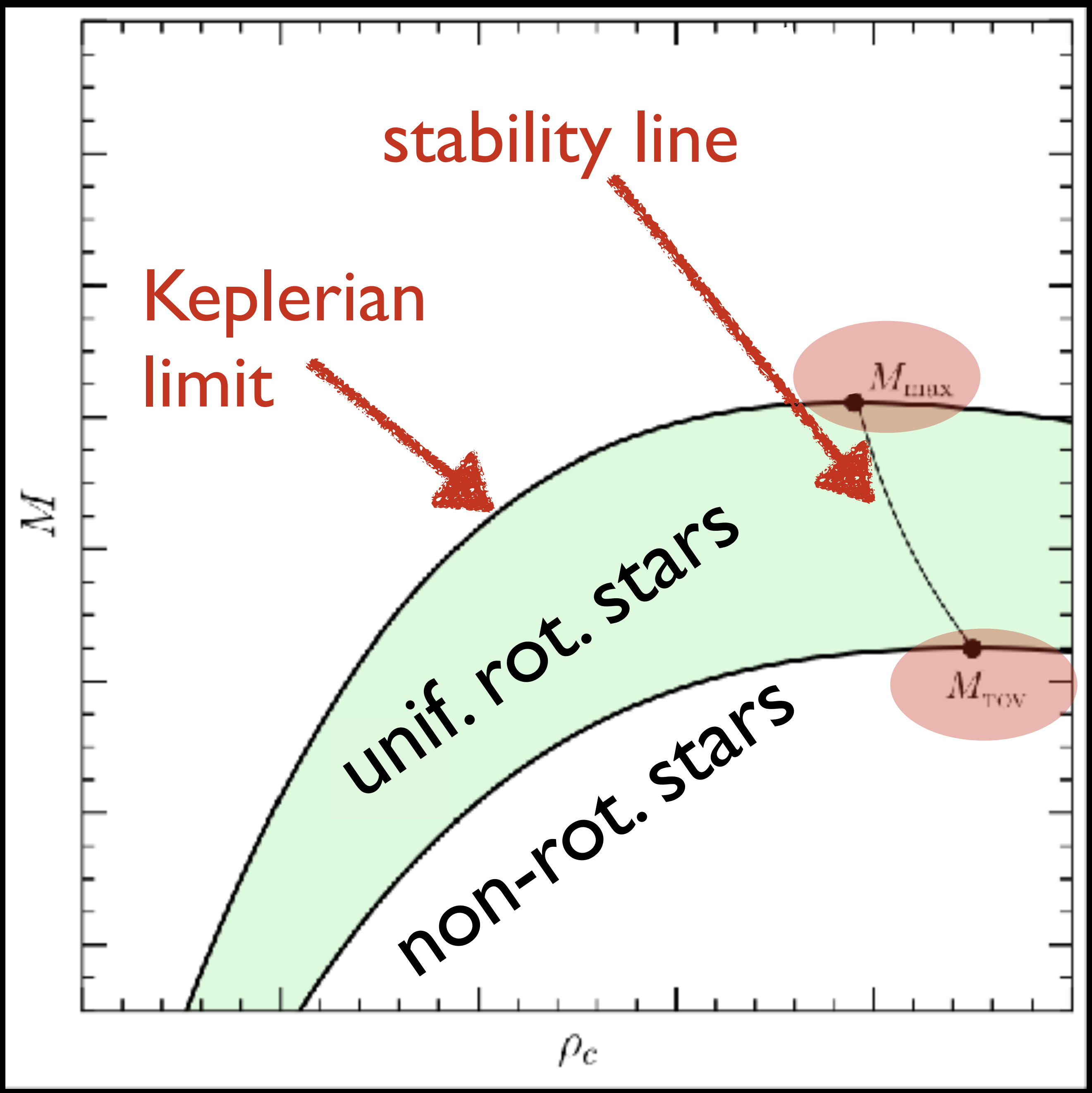

- Sequences of equilibrium models of **nonrotating** stars will have a maximum mass: $M_{\rm TOV}$
- This is true also for **uniformly** rotating stars at mass shedding limit: $M_{\rm max}$
- $M_{\rm max}$ simple and **quasi-universal** function of $M_{\rm TOV}$ (Breu & LR 2016)

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

Limits on the maximum mass

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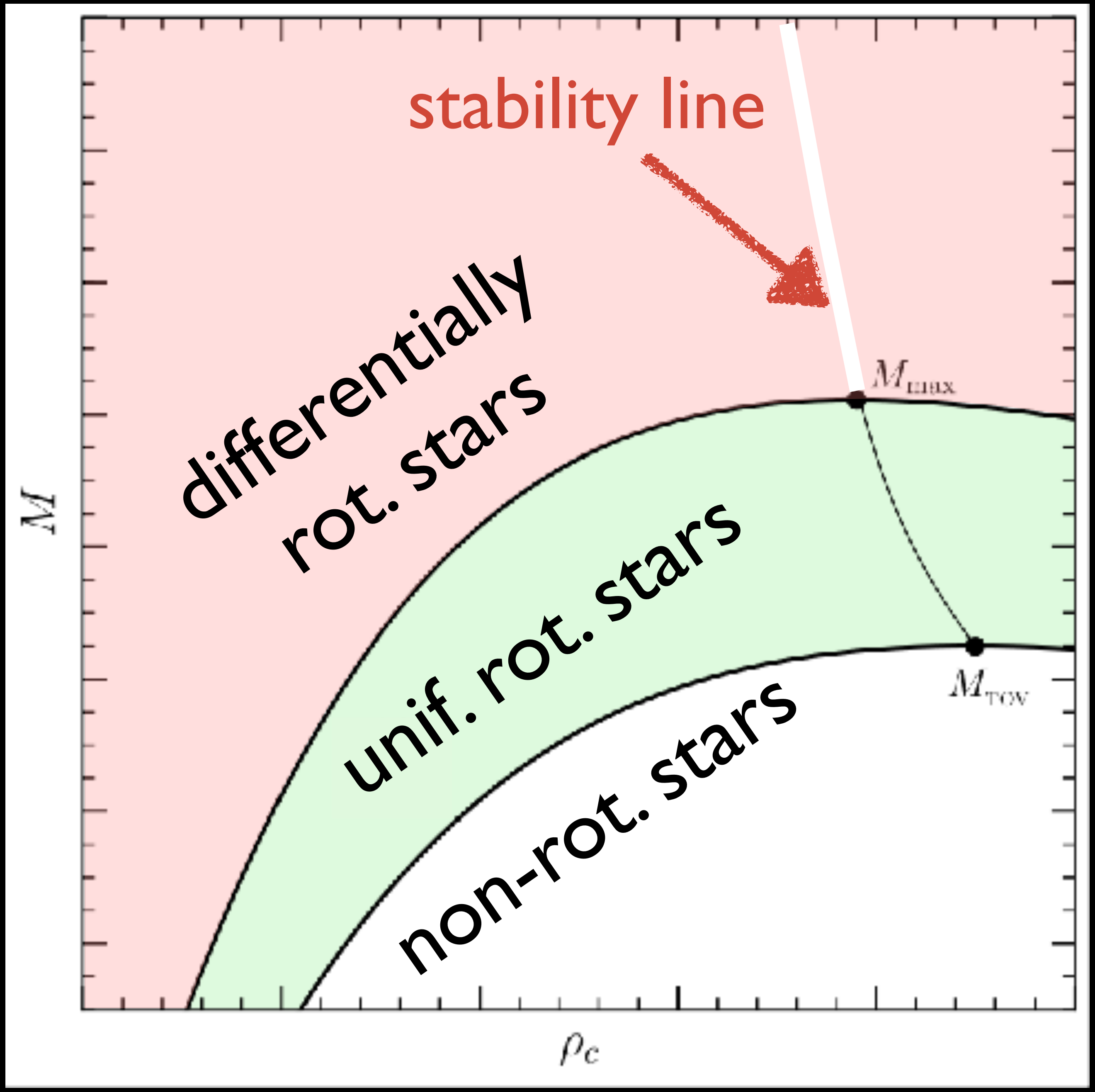
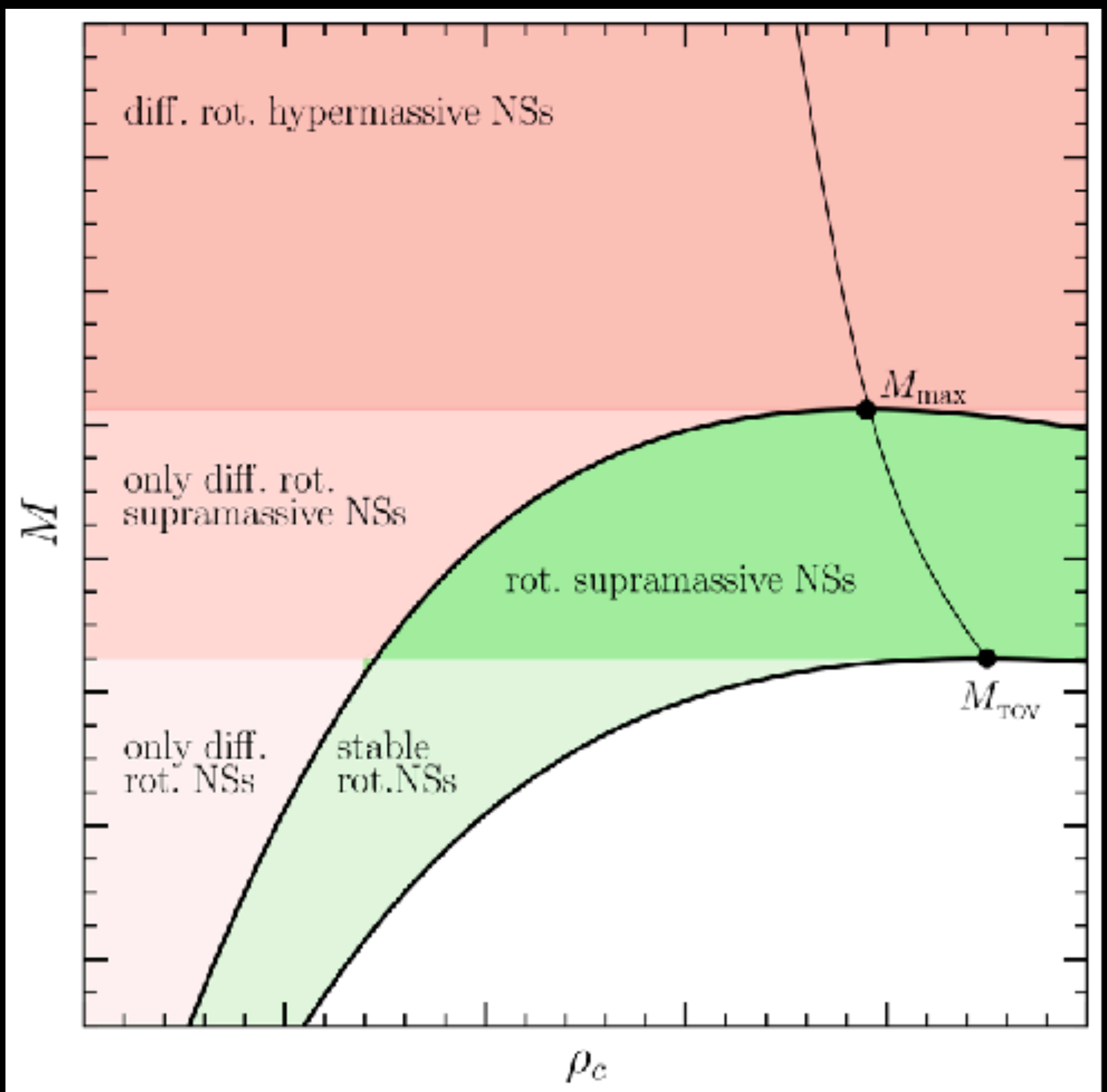


- **Green** region is for **uniformly** rotating equilibrium models.
- **Salmon** region is for **differentially** rotating equilibrium models.
- **Stability line** is simply extended in larger space (Weih+18)

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.
- Supramassive stars have:

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

- Hypermassive stars have:

$$M > M_{\max}$$

Limits on the maximum mass

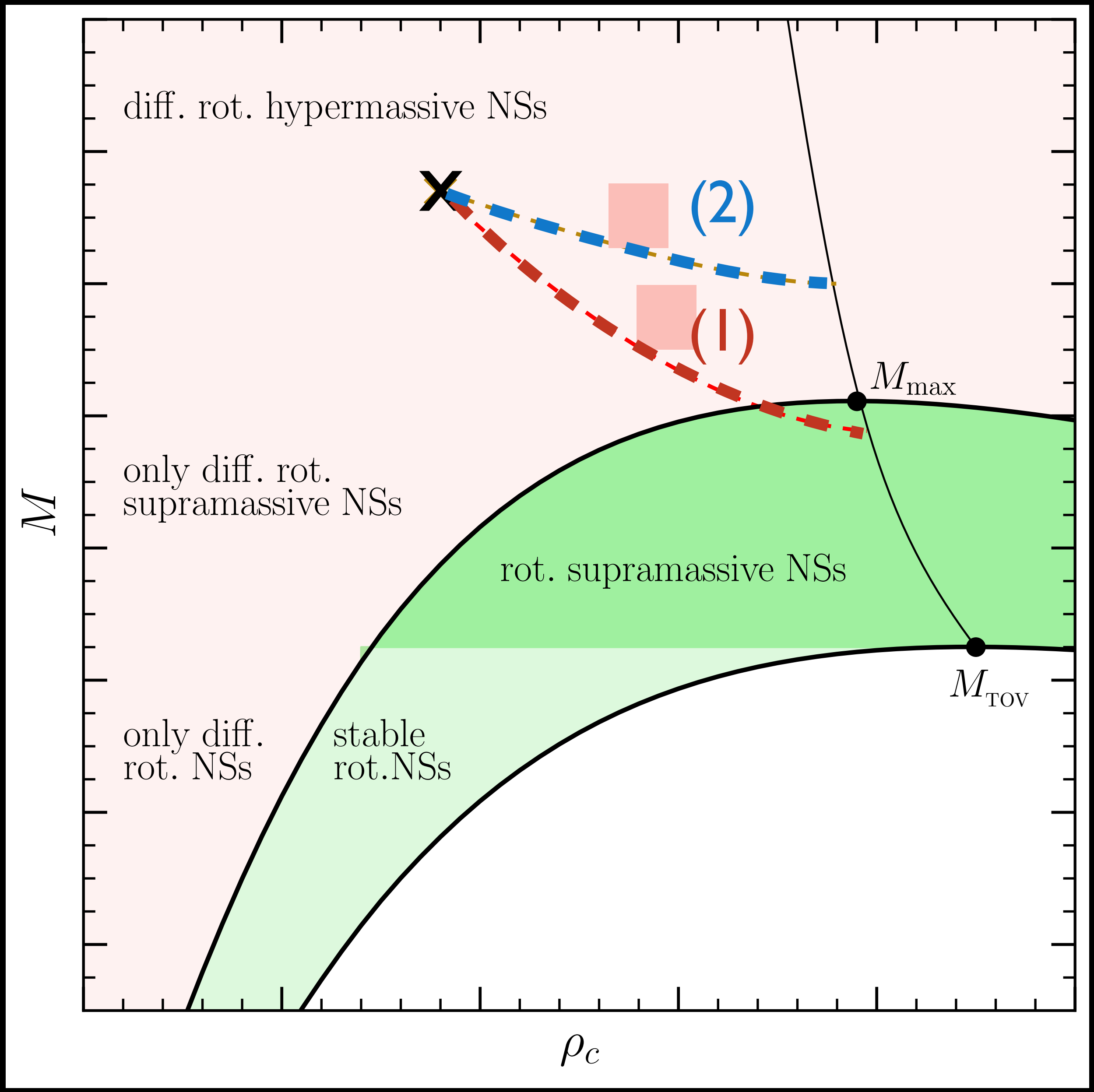
- GW170817 produced object **"X"**; GRB implies a BH has been formed: **"X"** followed two possible tracks: **fast (2)** and **slow (1)**

- 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 (2)**
- Use measured **gravitational mass** of GW170817
- Remove **rest-mass** deduced from kilonova emission (need conversion)
- Use **universal relations** and account for errors to obtain

pulsar timing

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

universal relations and GW170817; similar estimates by other groups

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, ie 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

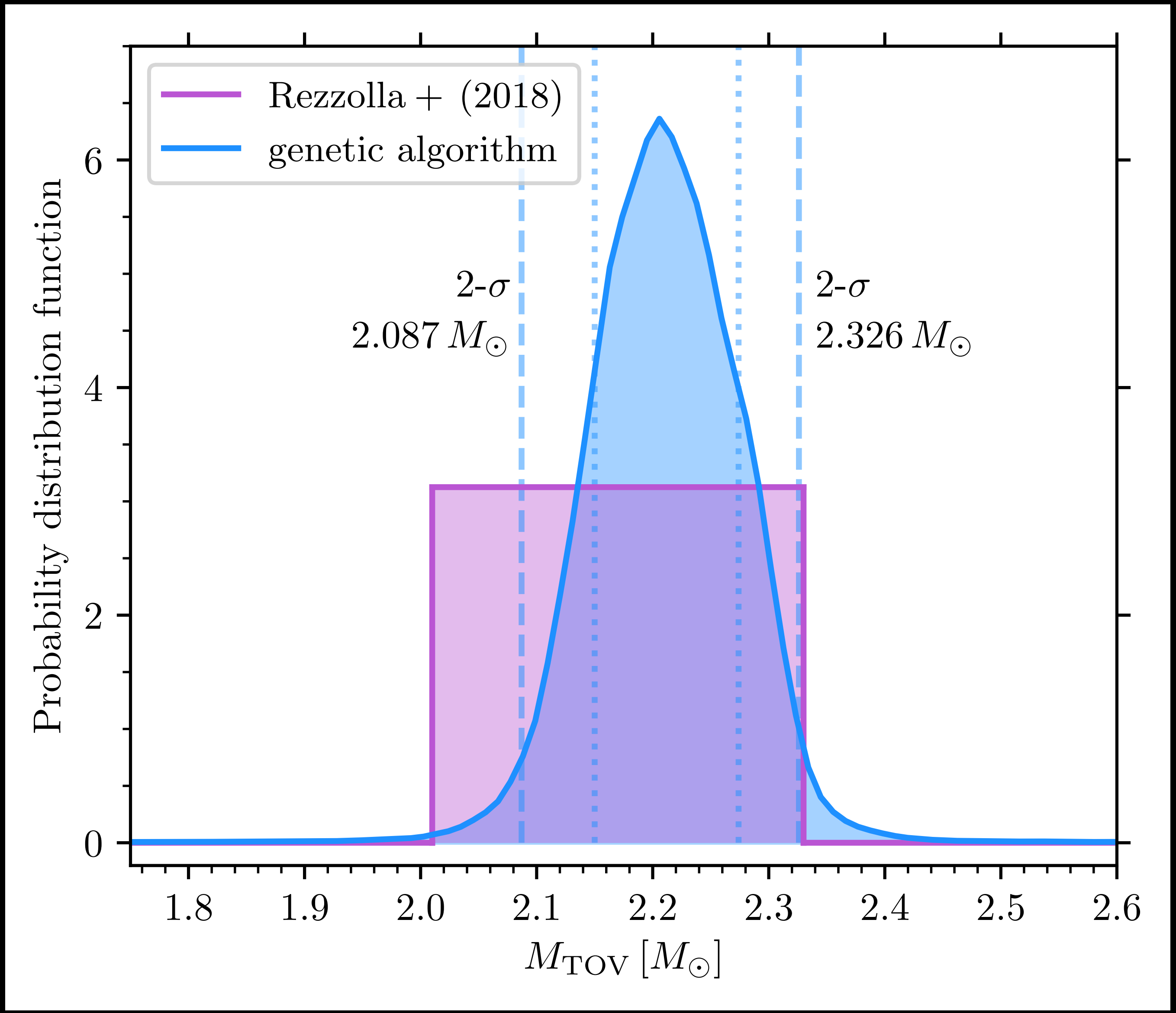
- A **genetic algorithm** is used to sample through the parameter space of the 10 free parameters.

- 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.

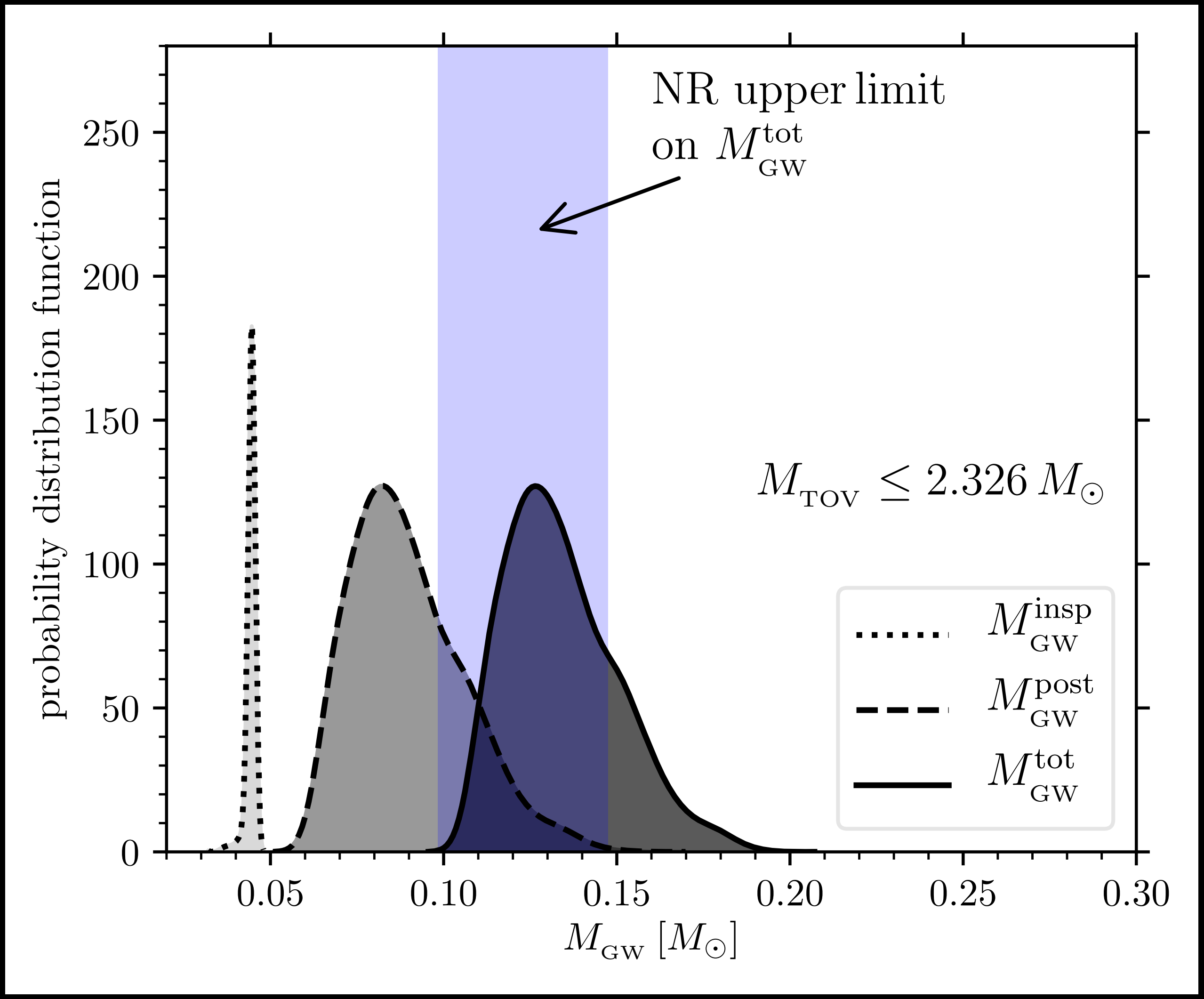
- Consider first previous estimate:

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

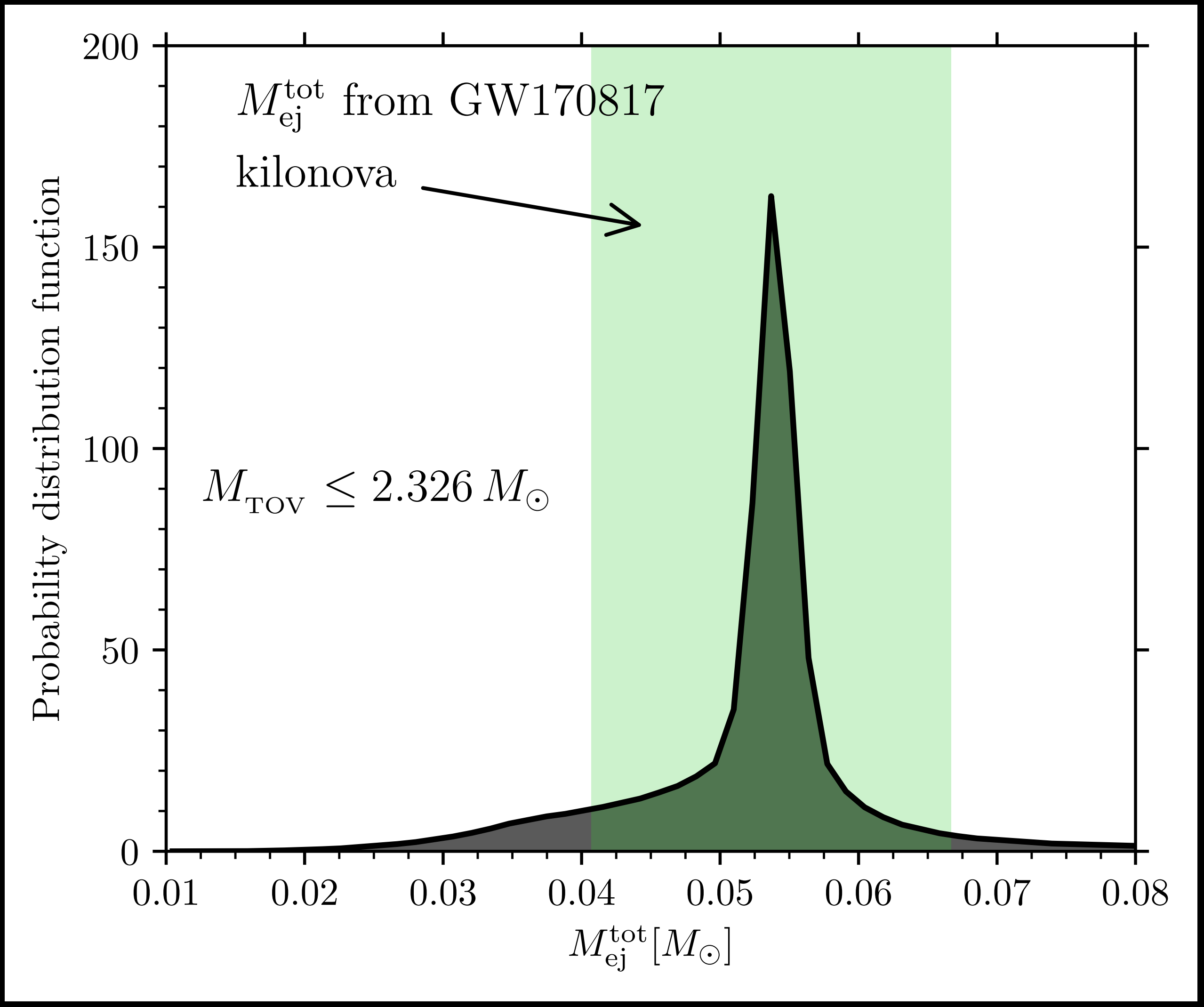
$$M_{\rm TOV}/M_\odot \leq 2.16^{+0.17}_{-0.15}$$



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

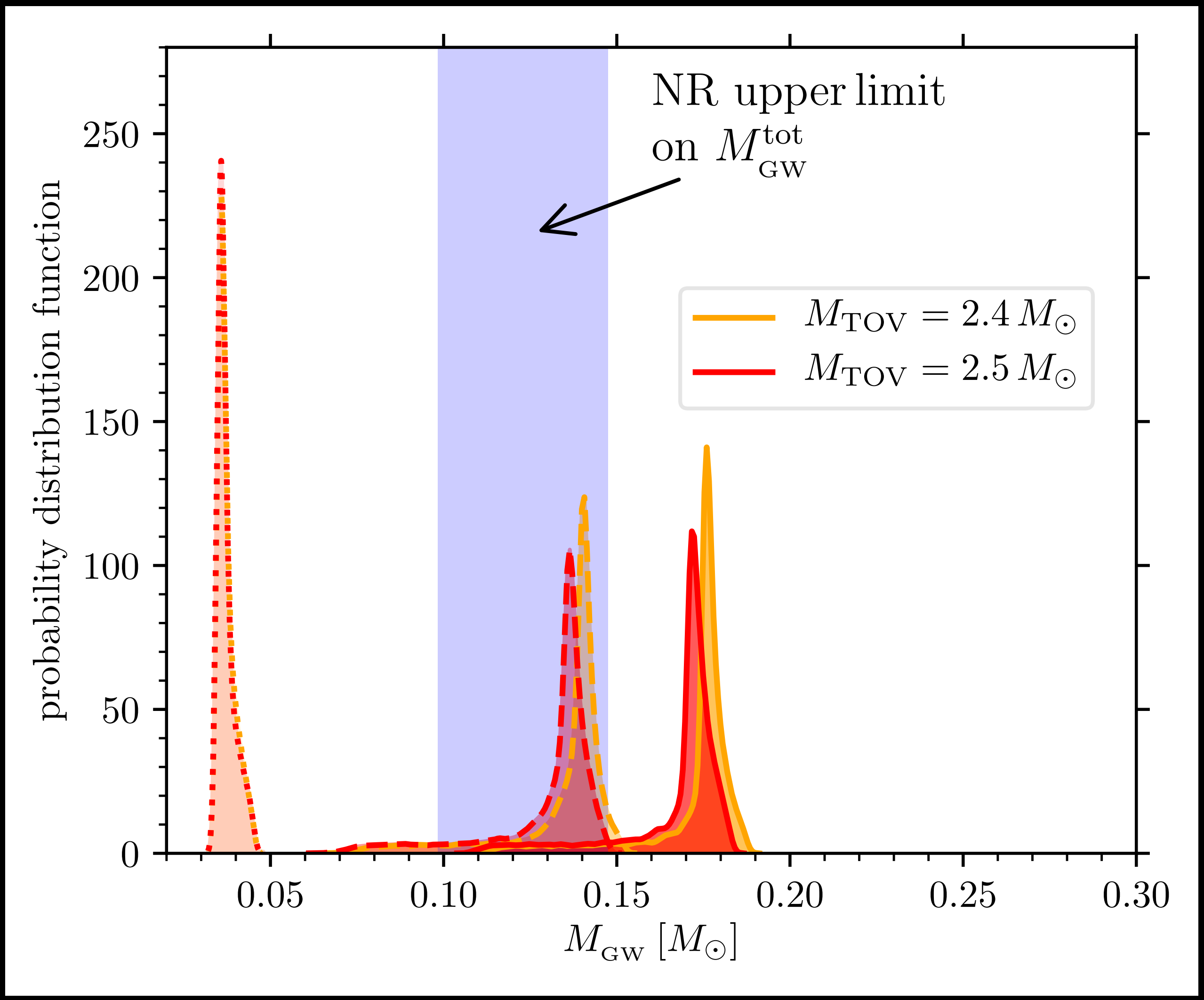


- Total mass emitted in GWs is in perfect **agreement** with predictions from numerical relativity

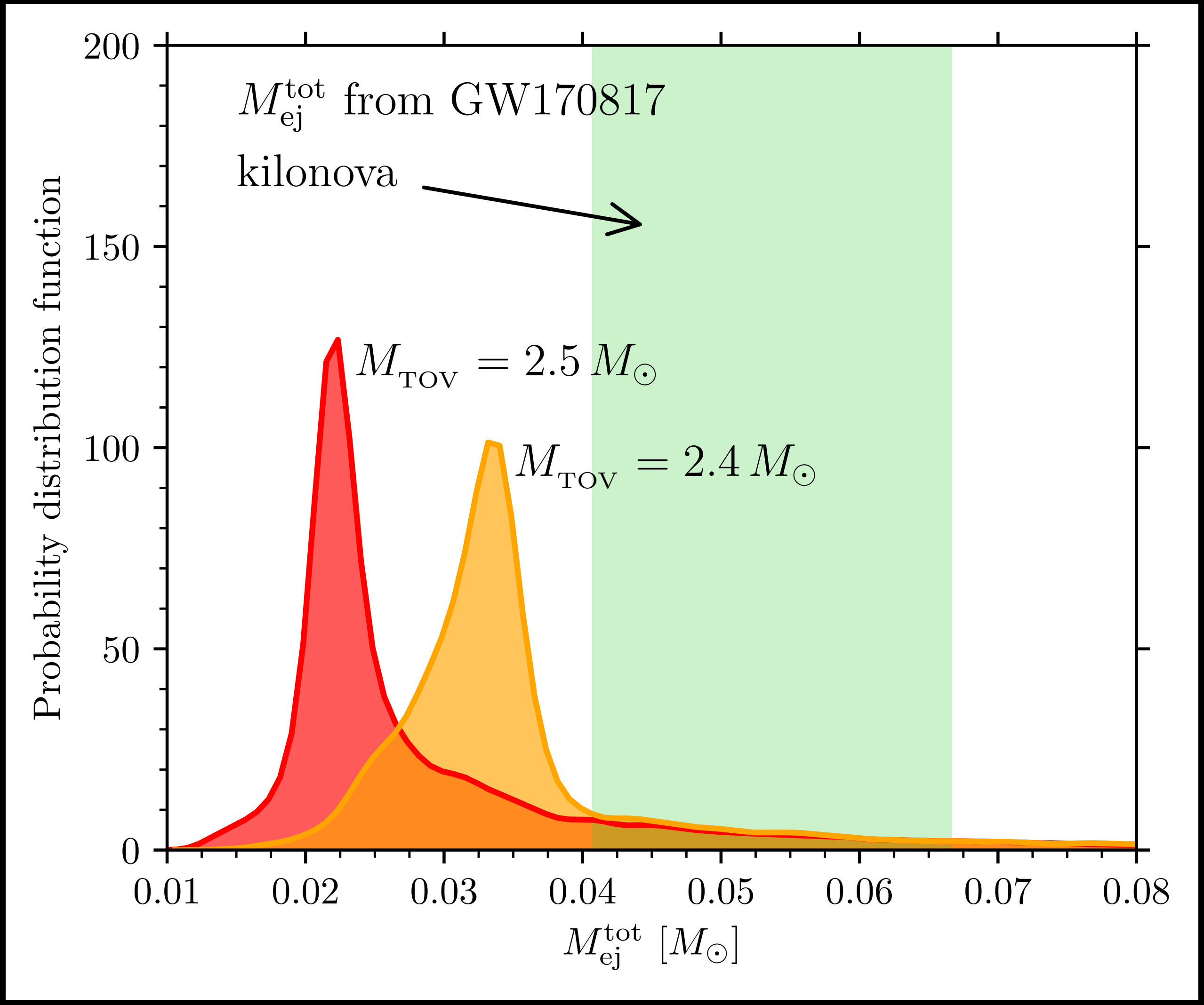


- Total mass ejected is in perfect **agreement** with predictions from kilonova signal

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)

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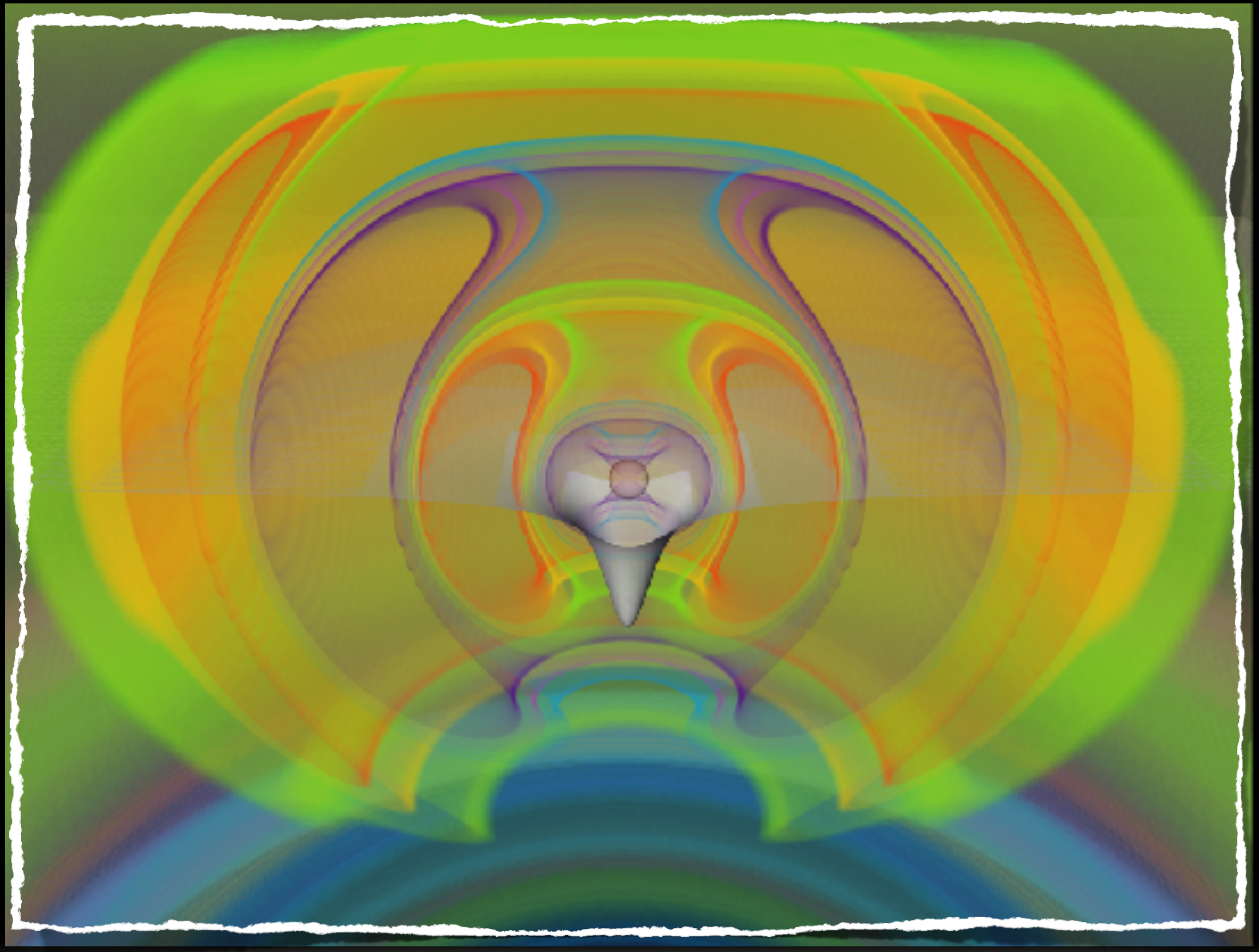
smallest BH or heaviest NS!

- 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

GW170817, maximum mass, radii and tidal deformabilities

LR, Most, Weih (2018)

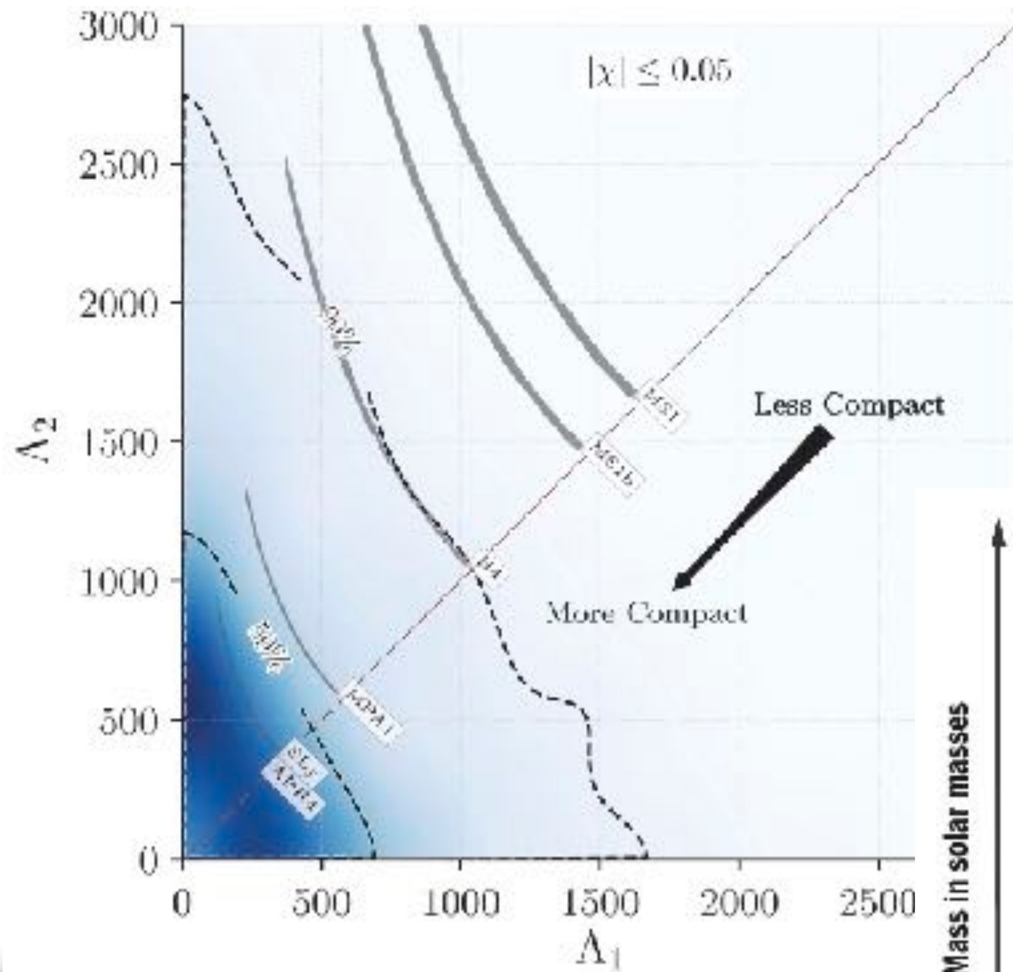
Most, Weih, LR, Schaffner-Bielich (2018)



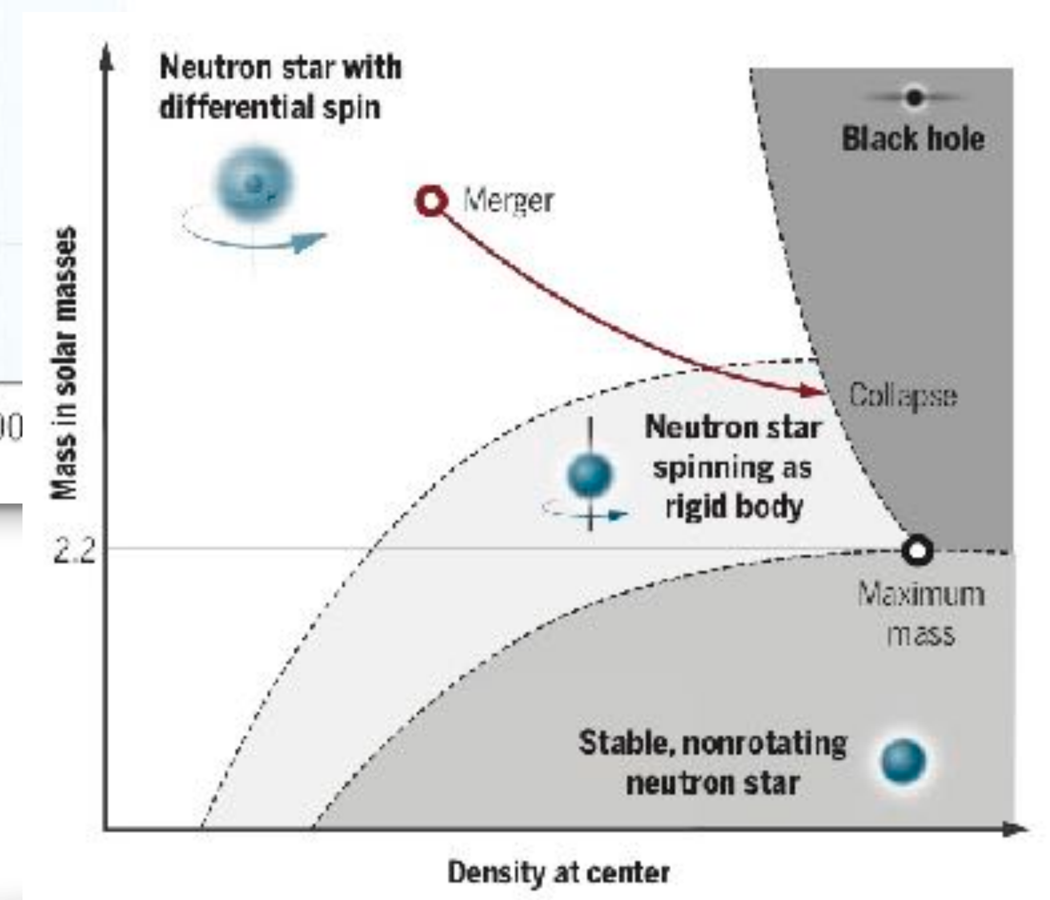
Limits on radii and deformabilities

- We have produced **10^6 EOSs** with about **10^9 stellar models.**

- Can impose differential constraints from the **maximum mass** and from the **tidal deformability** from GW170817?



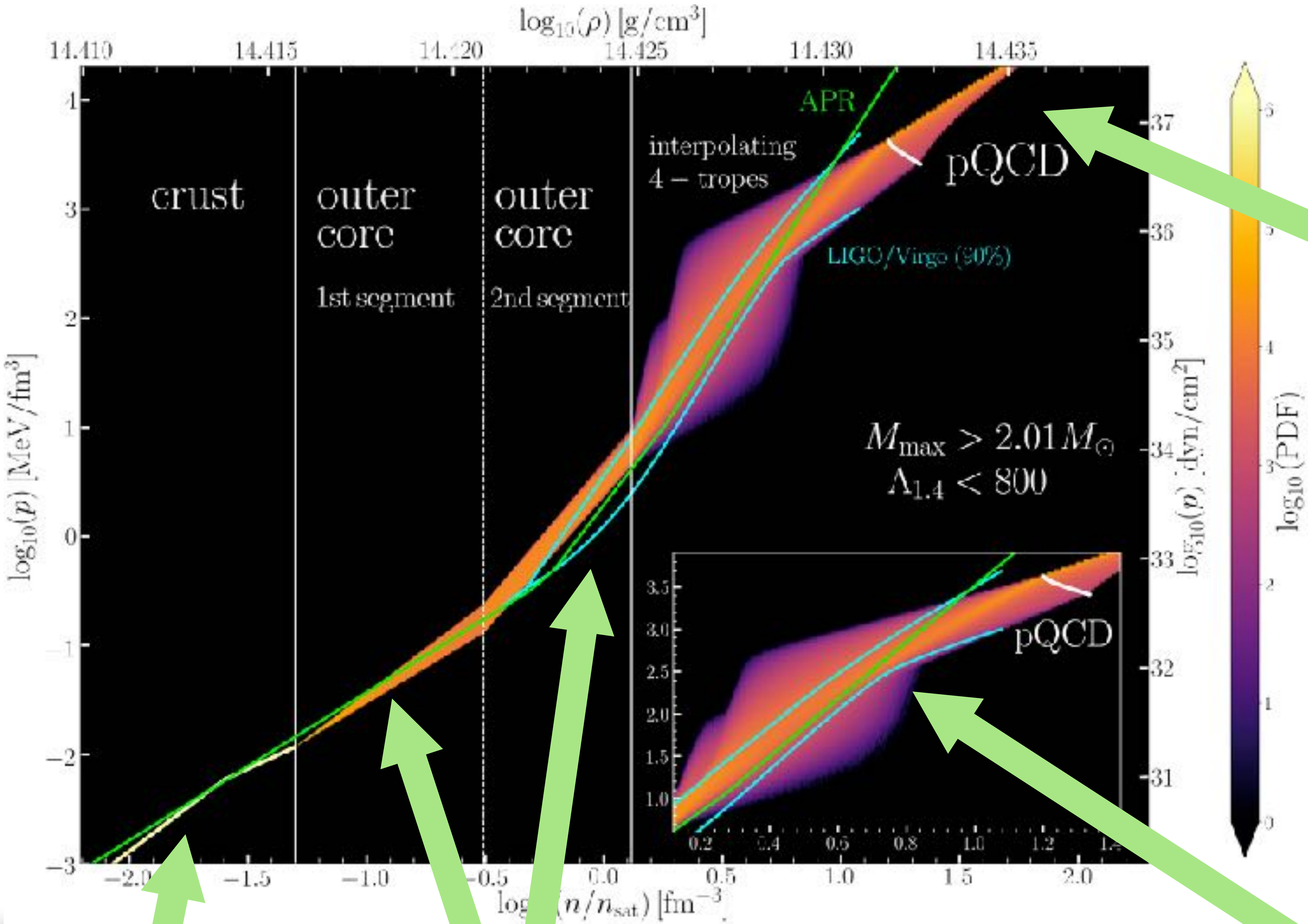
Abbott+ 2017



LR+ 2017

parametrising our ignorance

- Construct most generic family of NS-matter EOSs



from μ_b=2.6GeV NNLO pQCD Kurkela+ (2014) Fraga+ (2014)

interpolation by matching 4 polytropes

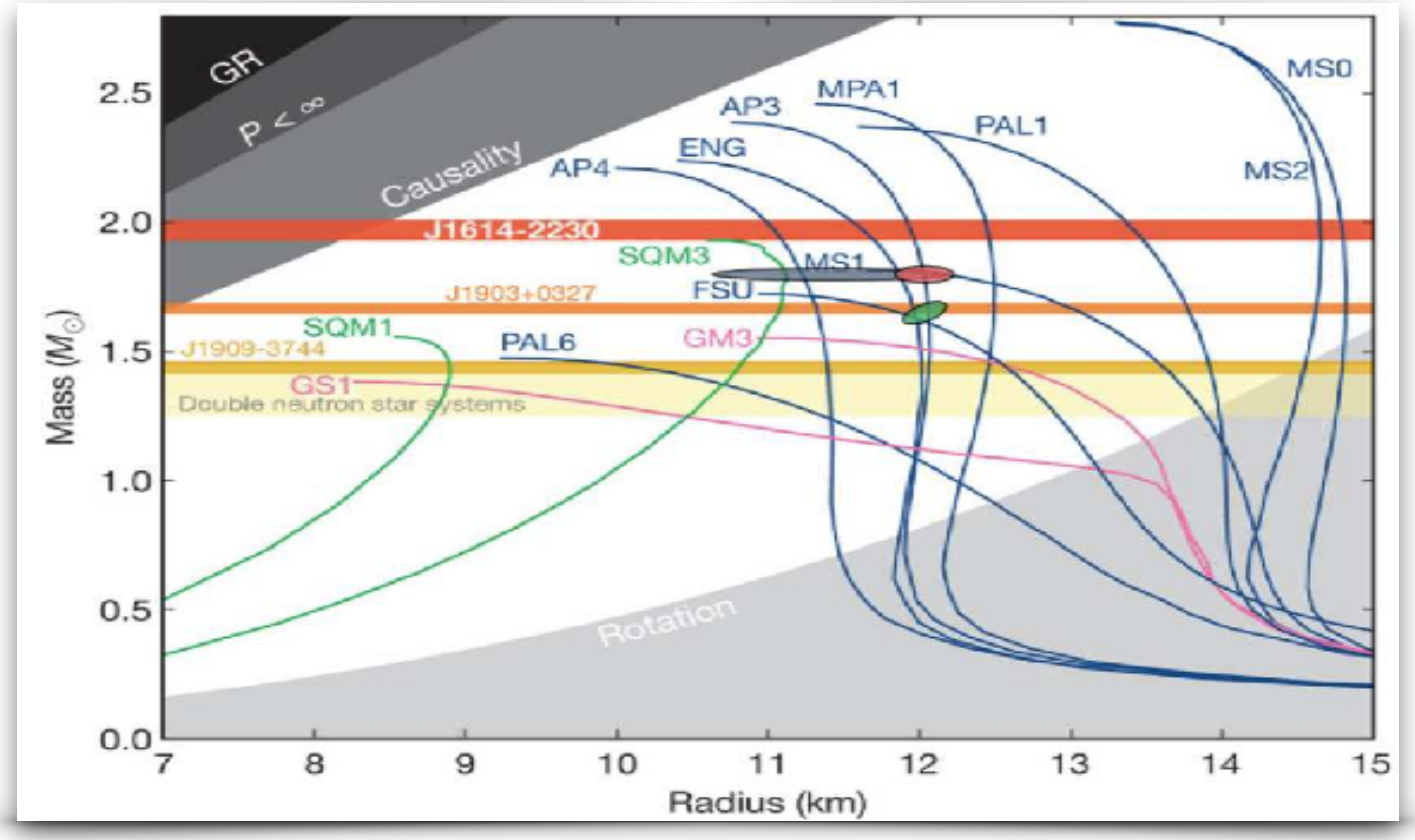
BPS

polytropic fit of Drischler+ (2016) (large impact on results)

Mass-radius relations

- We have produced **10^6 EOSs** with about **10^9 stellar models.**

- Can impose differential constraints from the **maximum mass** and from the **tidal deformability** from **GW170817**

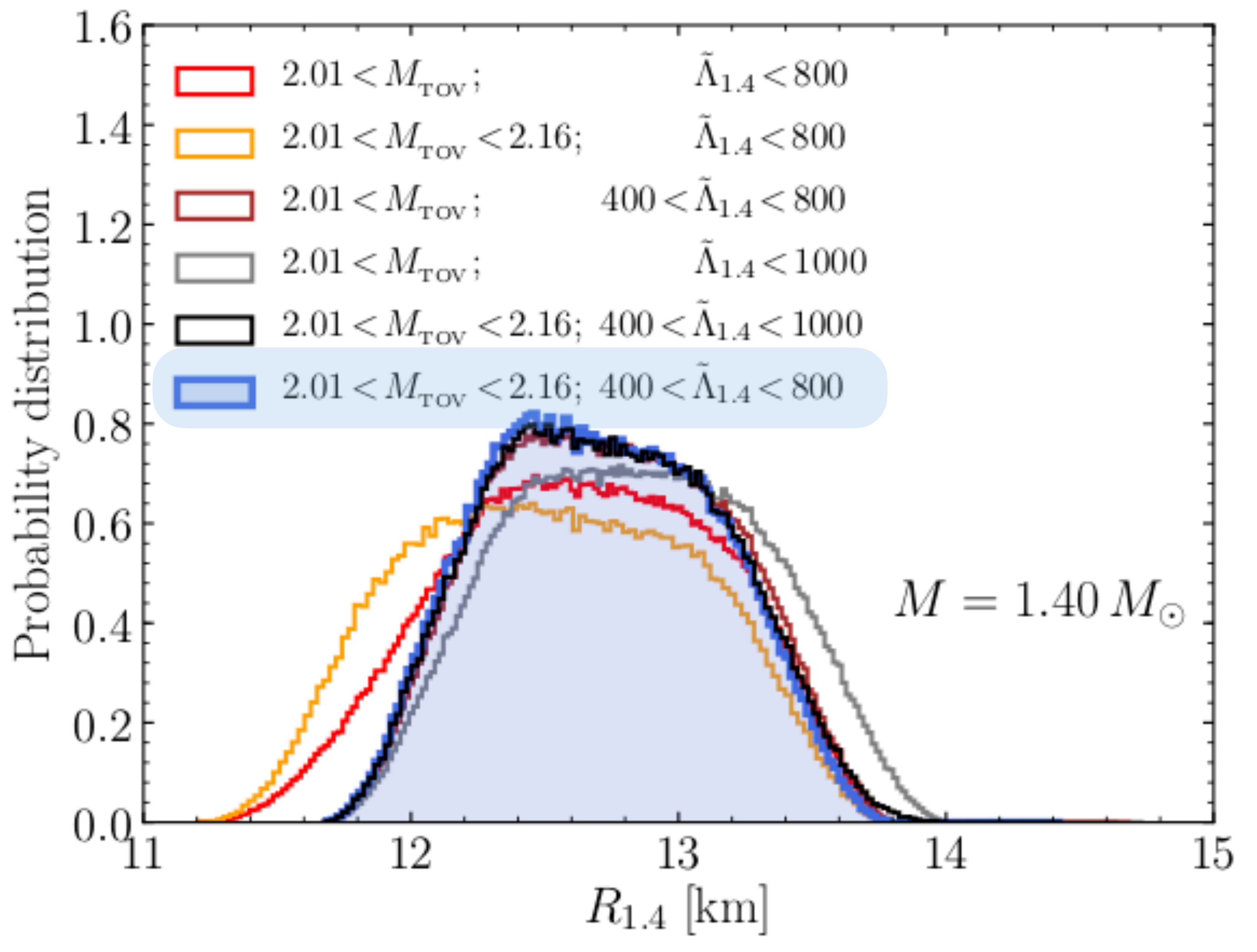


one-dimensional cuts

- Closer look at a mass of $M = 1.40\, M_\odot$
- Can play with different constraints on maximum mass and tidal deformability.
- Overall distribution is very robust

$$12.00 < R_{1.4}/\mathrm{km} < 13.45$$

$$\bar{R}_{1.4} = 12.45\,\mathrm{km}$$



Constraining tidal deformability

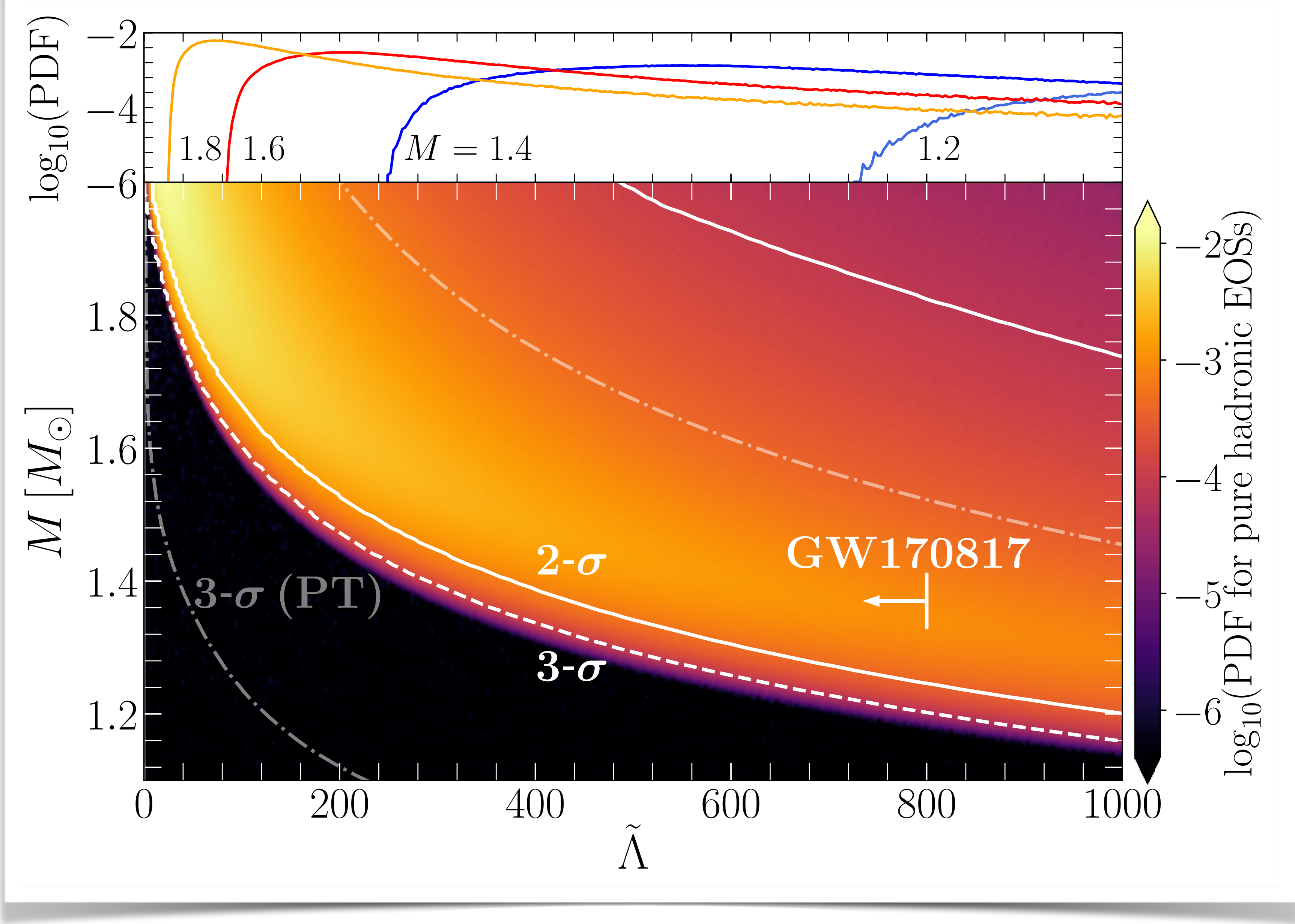
- Can explore statistics of all properties of our 10^9 models.
- In particular can study PDF of tidal deformability: $\tilde{\Lambda}$

- LIGO has already set upper limit:

$$\tilde{\Lambda}_{1.4} \lesssim 800$$

- Our sample naturally sets a lower limit:

$$\tilde{\Lambda}_{1.4} > 375$$



On the importance of a lower limit for $\tilde{\Lambda}$

- Closer look at a mass of $M = 1.40\, M_\odot$
- Can play with different constraints on maximum mass and tidal deformability.
- Overall distribution is very robust

$$12.00 < R_{1.4}/\mathrm{km} < 13.45$$

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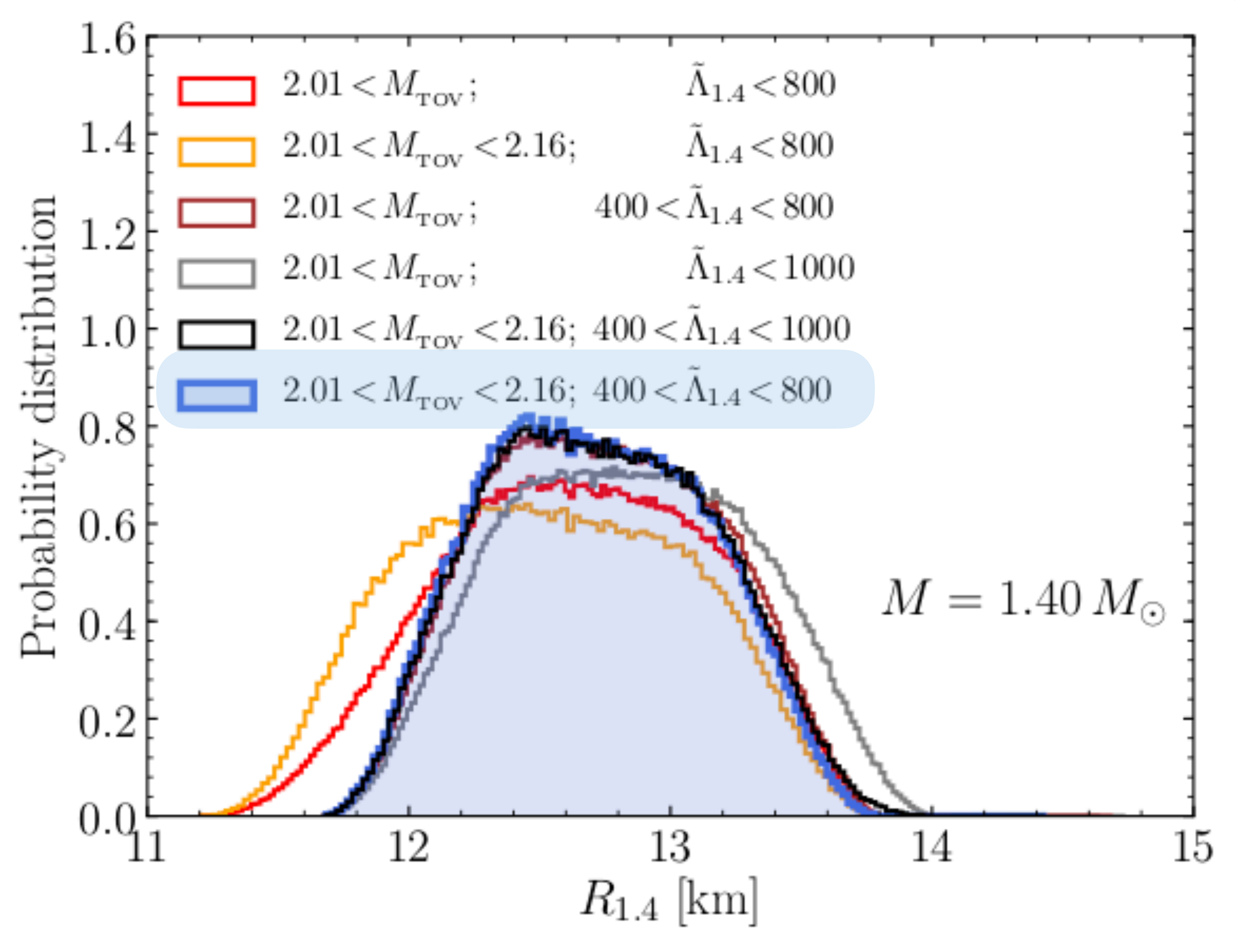
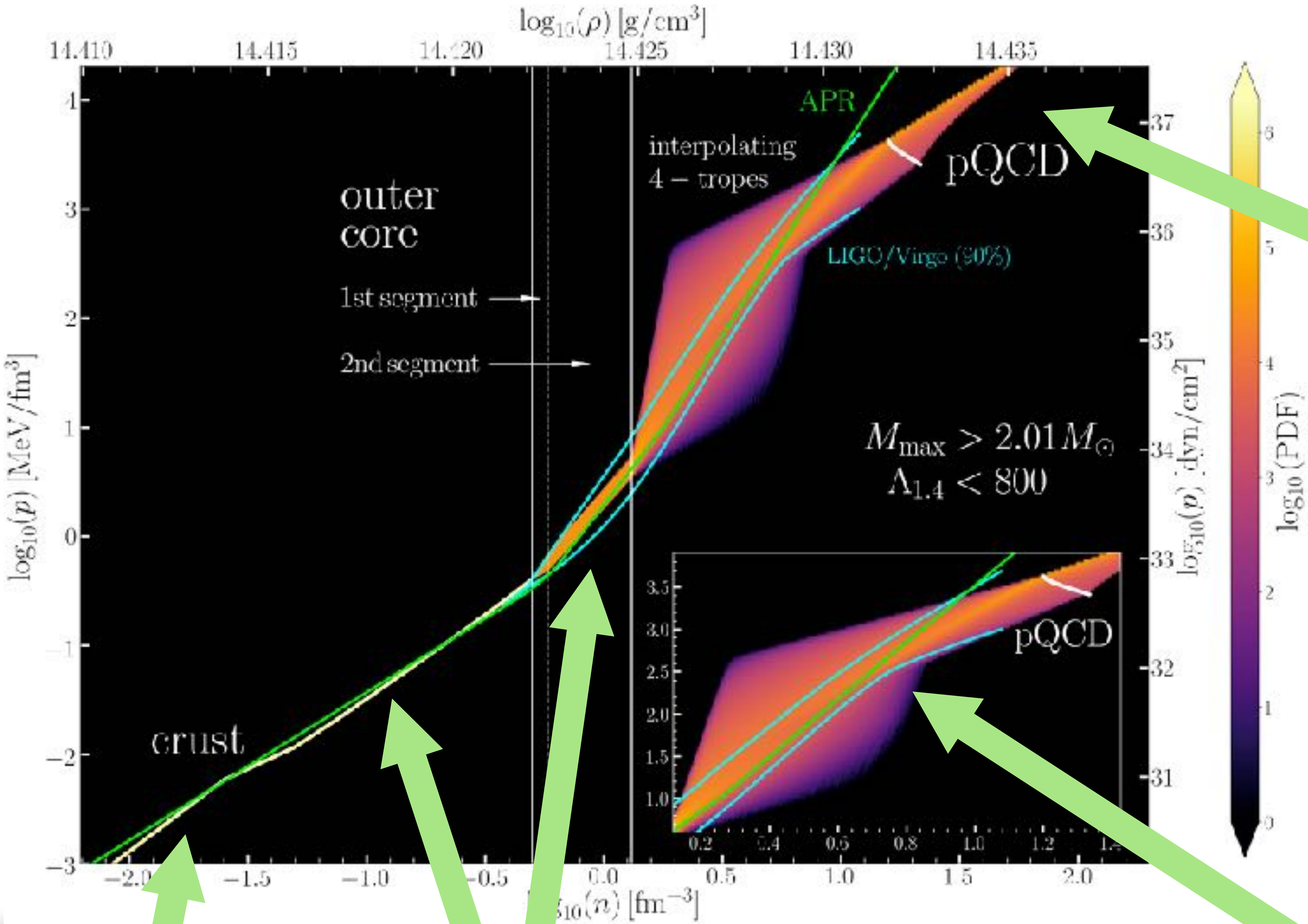


In other words, stringent lower limits on $\tilde{\Lambda}$ have huge impact: exclude softest EOSs

On the importance of the **outer-core**

- Improved prescriptions known for **outer core**, e.g., Drischler+ 2017



from μ_b=2.6GeV
NNLO pQCD
Kurkela+ (2014)
Fraga+ (2014)

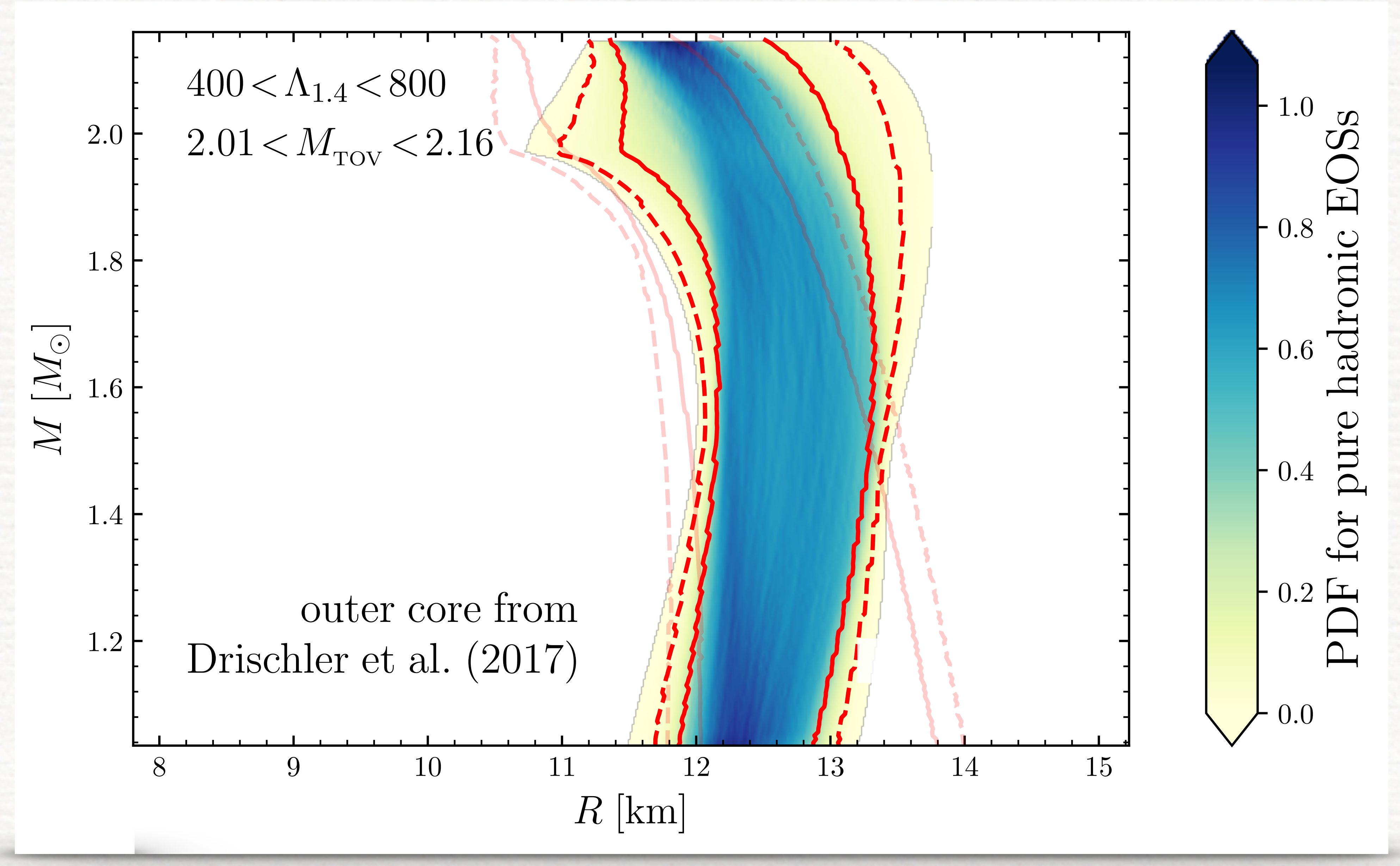
interpolation
by matching 4
polytropes

fit of Drischler+ (2017)

BPS

On the importance of the **outer-core**

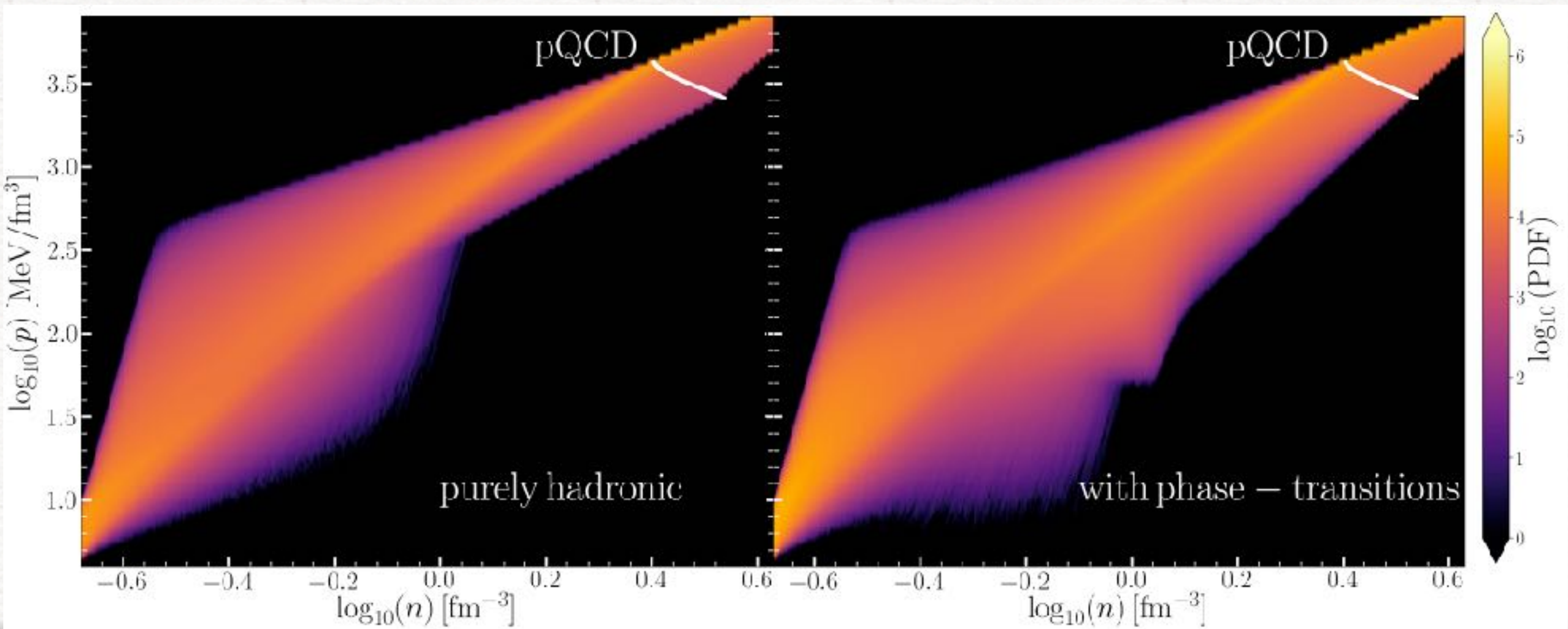
- Improved prescriptions known for **outer core**, e.g., Drischler+ 2017



Lesson: radius constraints depends strongly on stiffness (uncertainty) of EOS for $0.5 \lesssim n/n_s \lesssim 1.3$

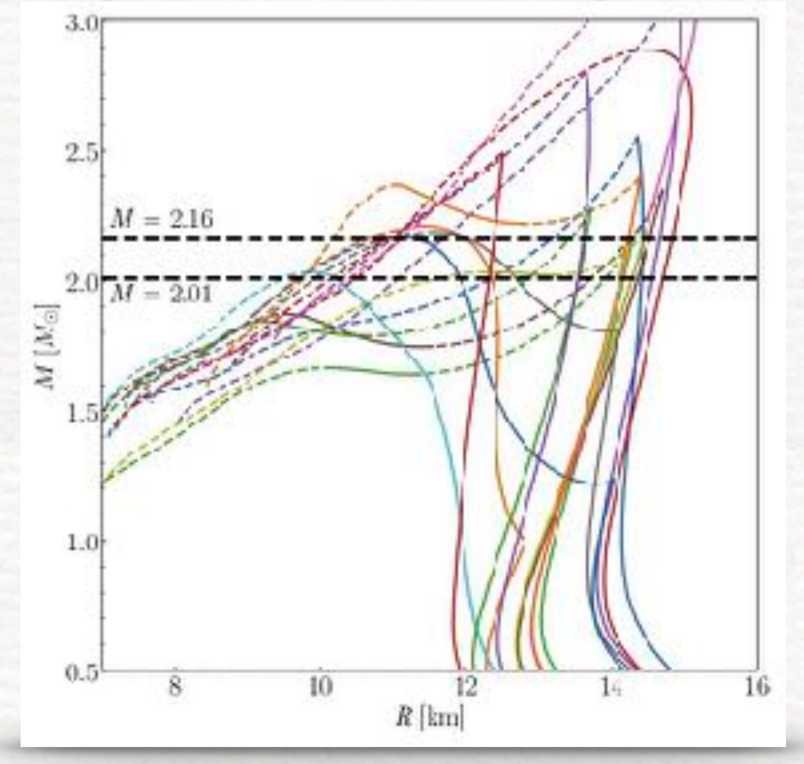
What about **phase transitions**?

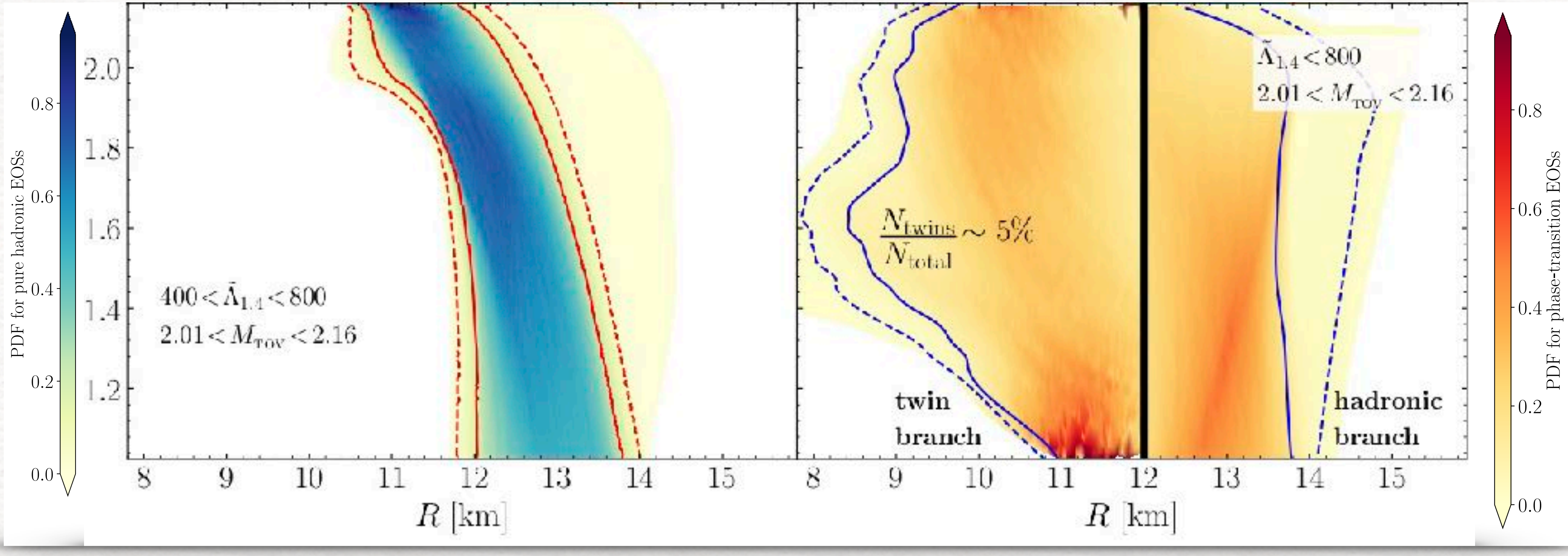
- All EOSs so far are purely hadronic; a conservative but probably **reasonable** assumption.
- What about the possibility of **phase transitions**?
- These are not trivial but not too difficult to model.



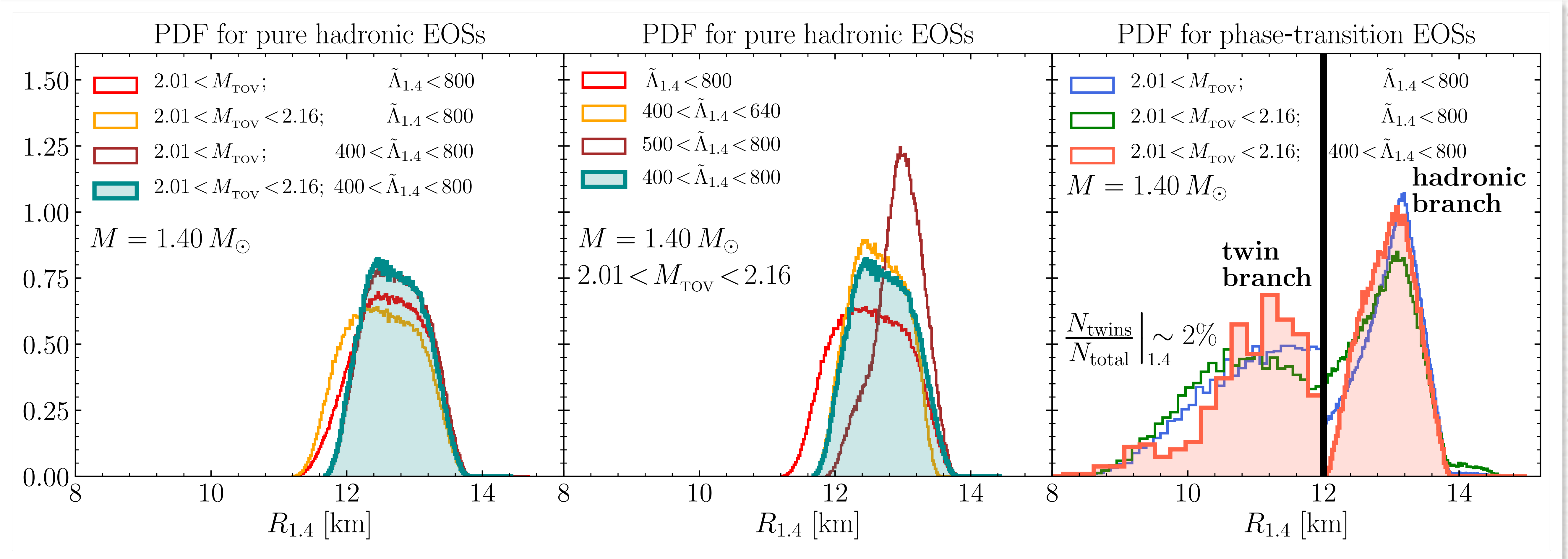
Mass-radius relations

- Presence of a phase transition leads to second stable branch and "**twin-star**" models.





One-dimensional cuts: PTs



Applying all constraints from GW170817:

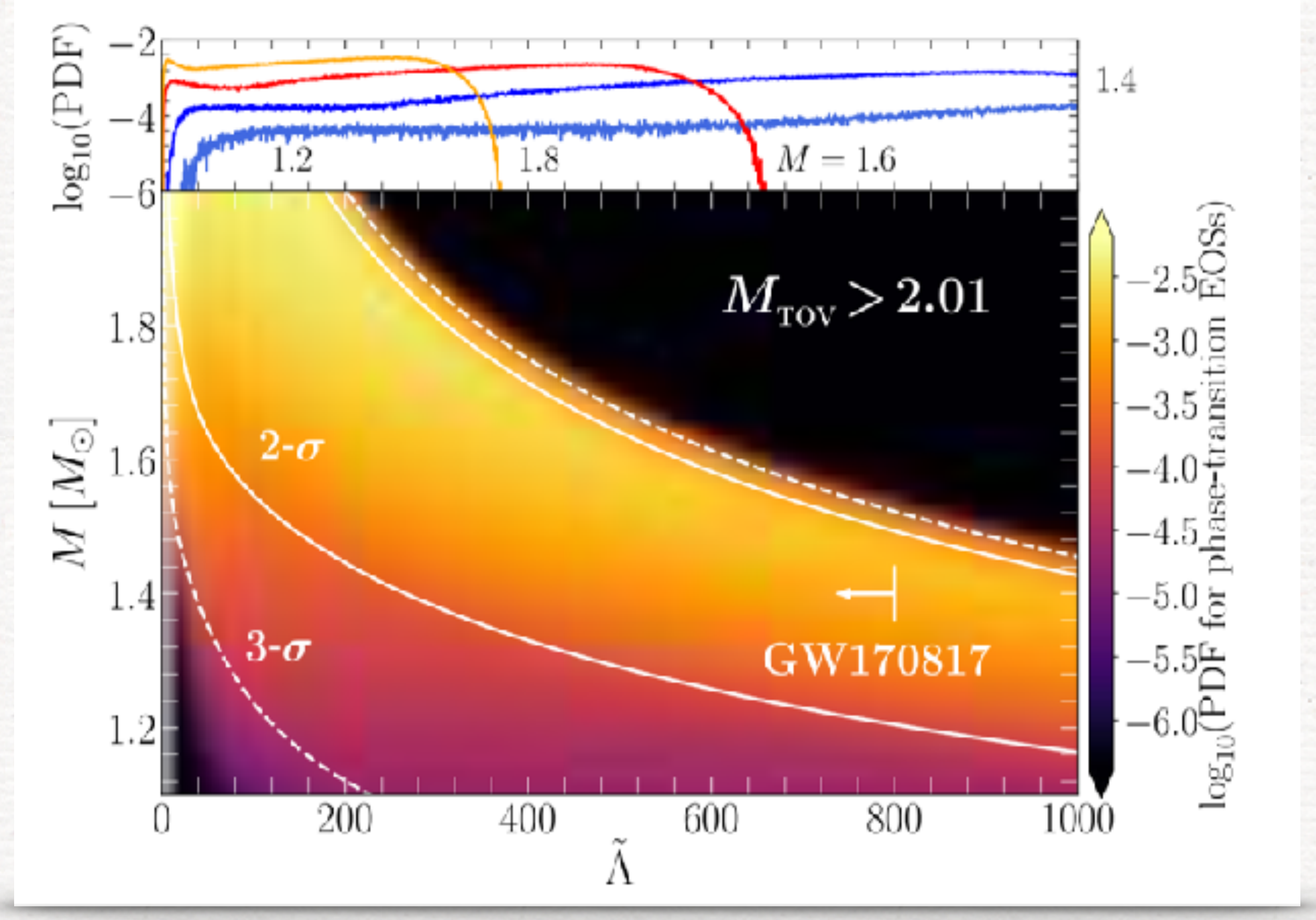
$12.00 < R_{1.4}/\mathrm{km} < 13.45$ $\bar{R}_{1.4} = 12.45\,\mathrm{km}$ hadronic EOS

$8.53 < R_{1.4}/\mathrm{km} < 13.74$ $\bar{R}_{1.4} = 13.06\,\mathrm{km}$ phase transitions

Constraining tidal deformability: **PT**s

- Can repeat considerations with EOSs having PTs
- Lower limit much weaker: $\tilde{\Lambda}_{1.4} \gtrsim 35$
- Large masses have sharp cut-off on upper limit:

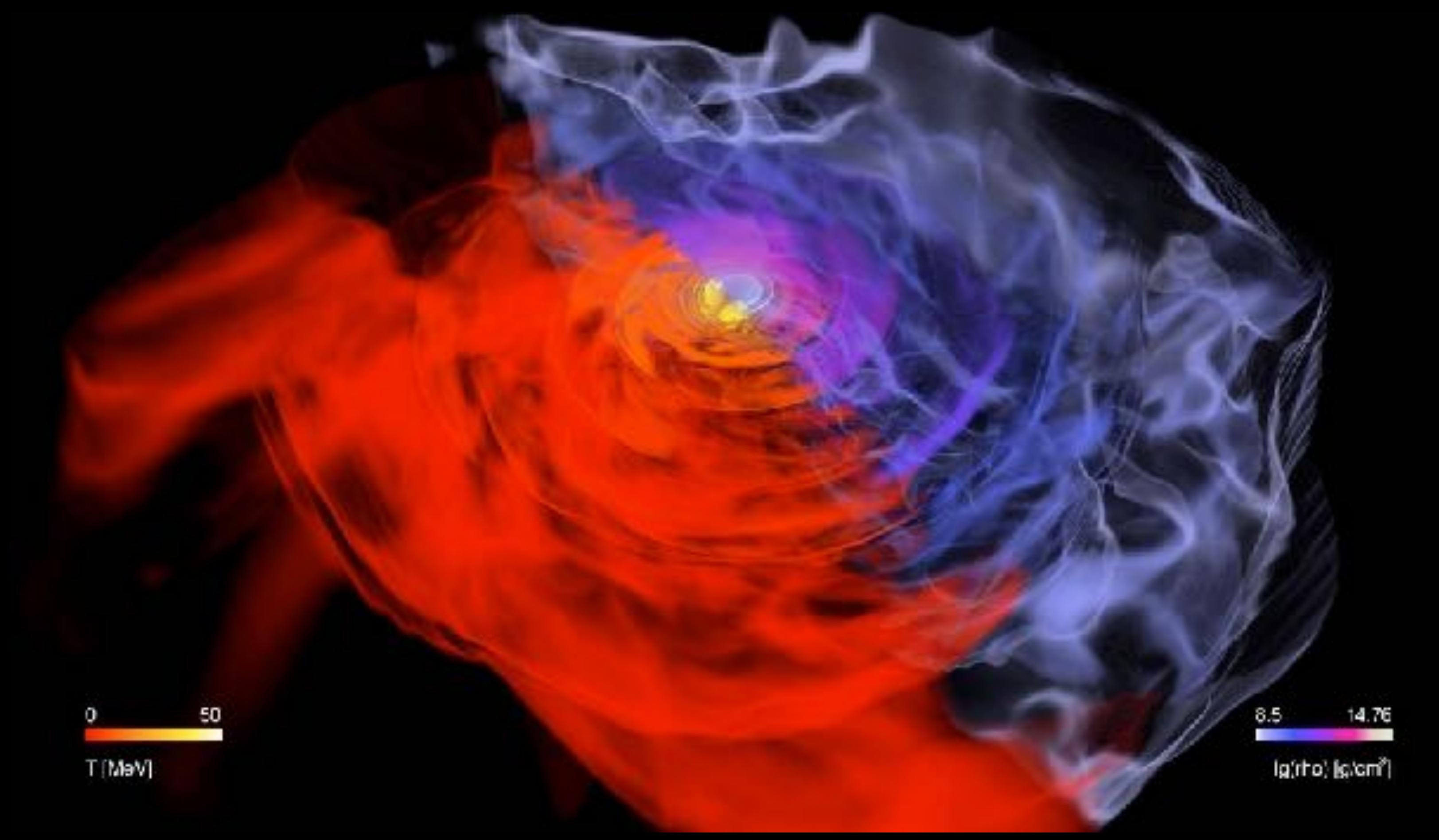
$$\tilde{\Lambda}_{1.7} \lesssim 460$$



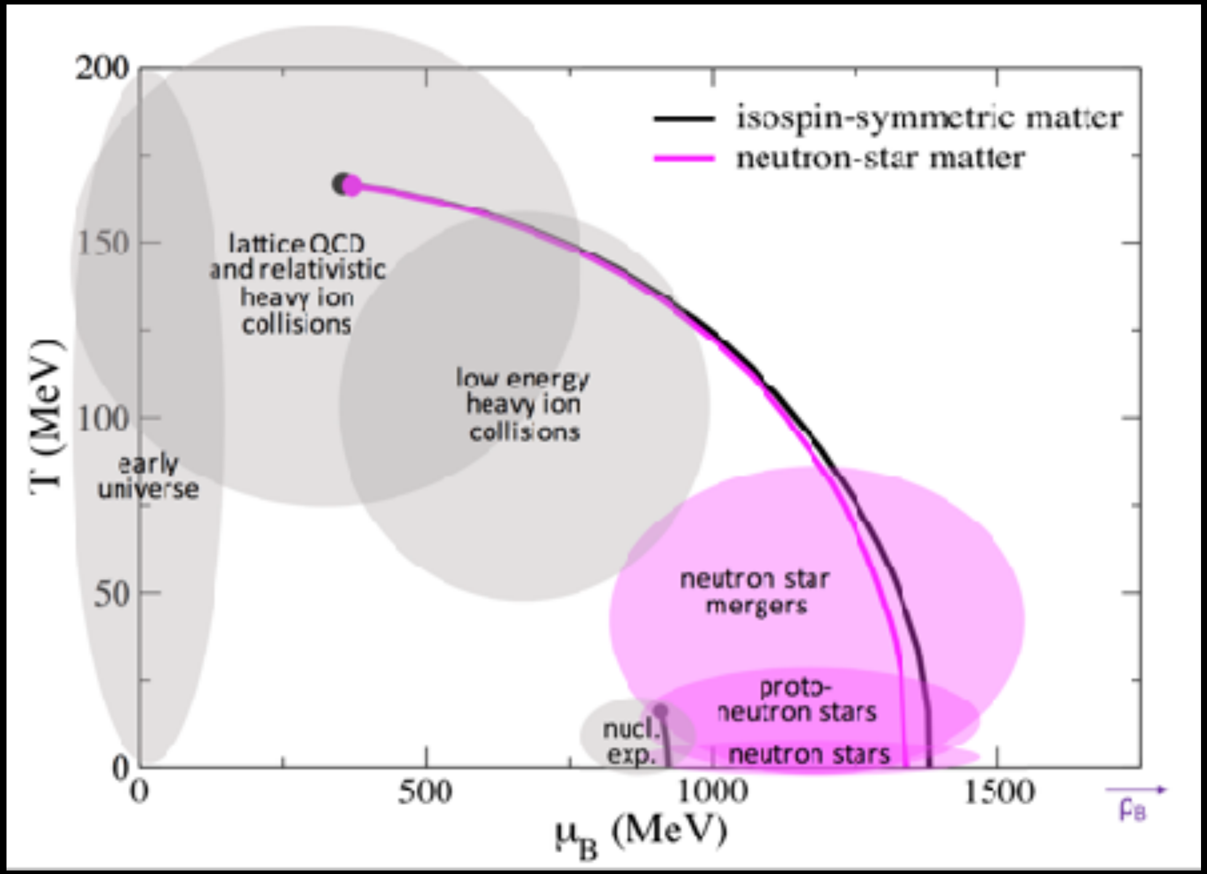
Hence, detection with $\tilde{\Lambda}_{1.7} \sim 600$ would rule out twin stars!

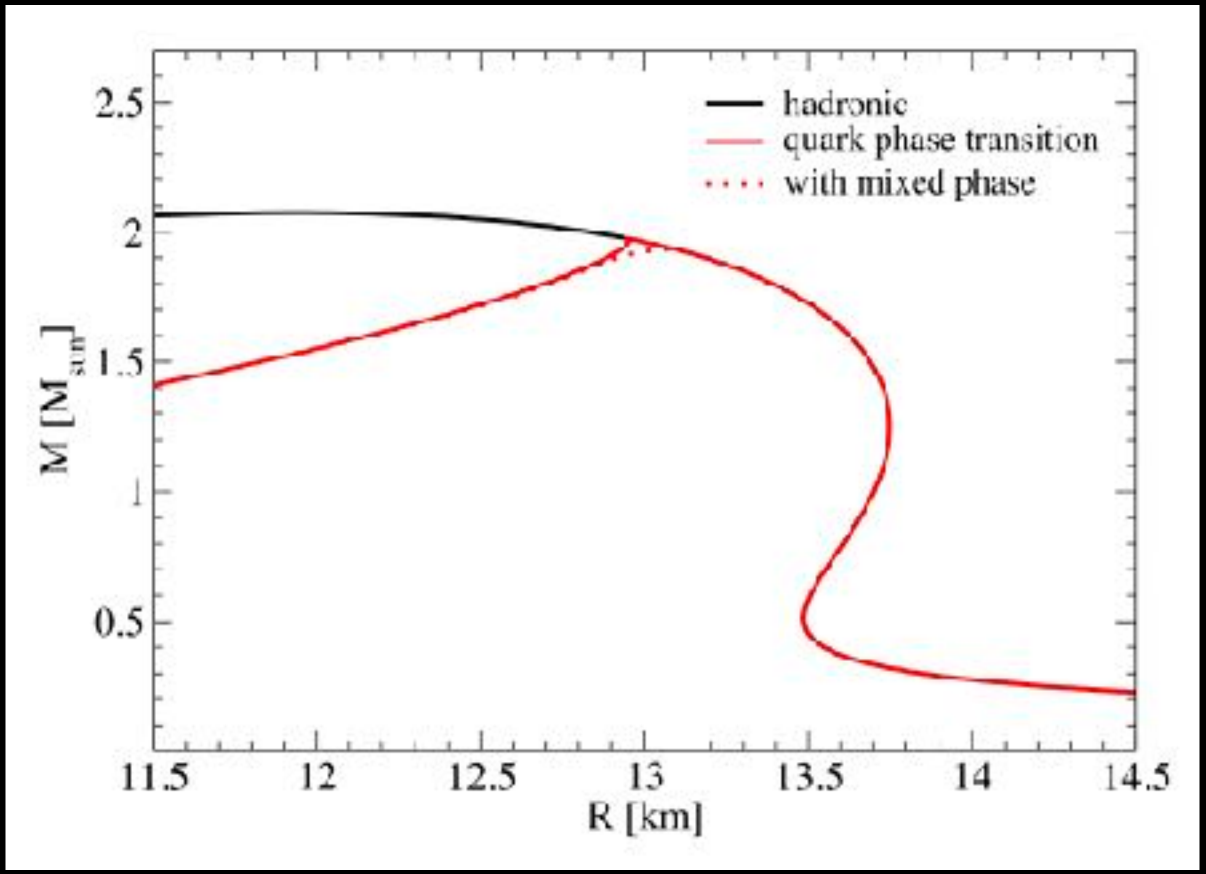
Phase transitions and their signatures

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



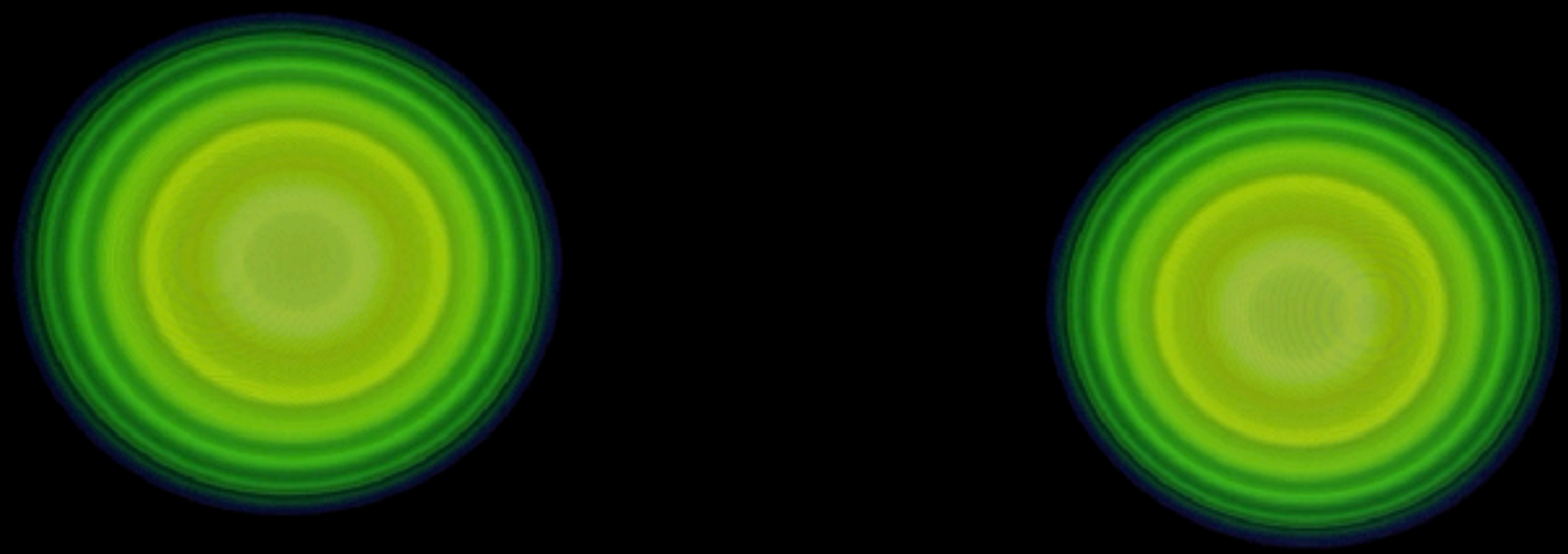
- **Isolated** neutron stars probe a small fraction of phase diagram.
- Neutron-star **binary** mergers reach temperatures up to 80 MeV and probe regions complementary to experiments.

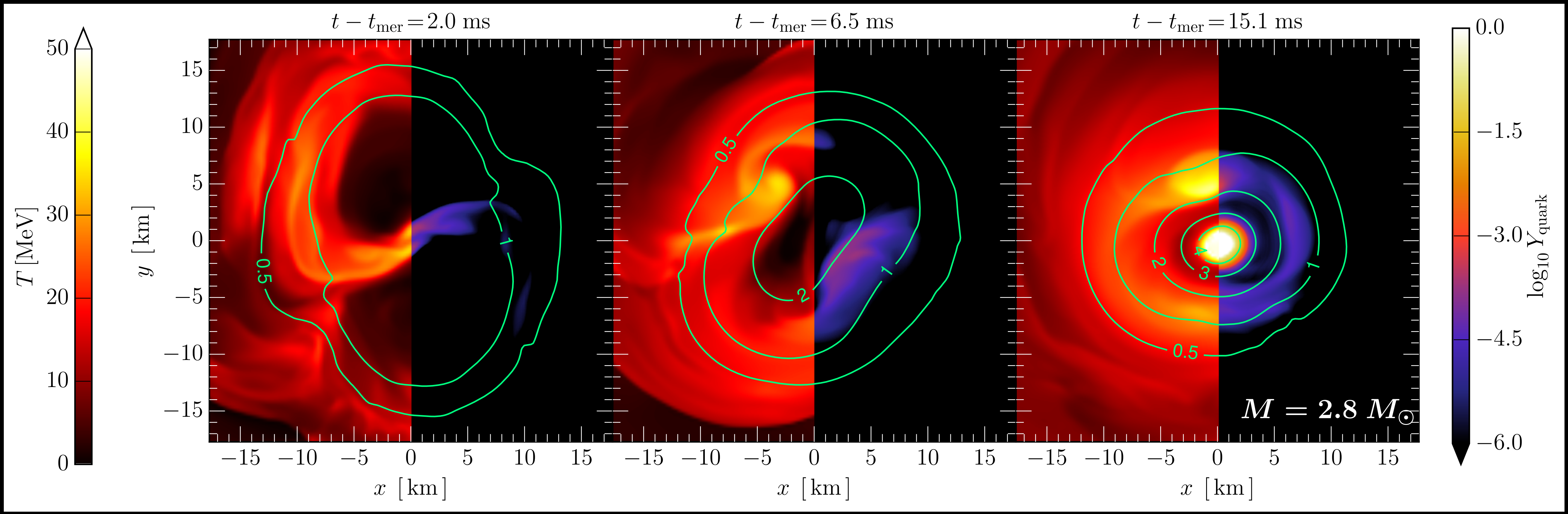




- Considered EOS based on Chiral Mean Field (CMF) model, based on a nonlinear SU(3) sigma model.
- Appearance of quarks can be introduced naturally.

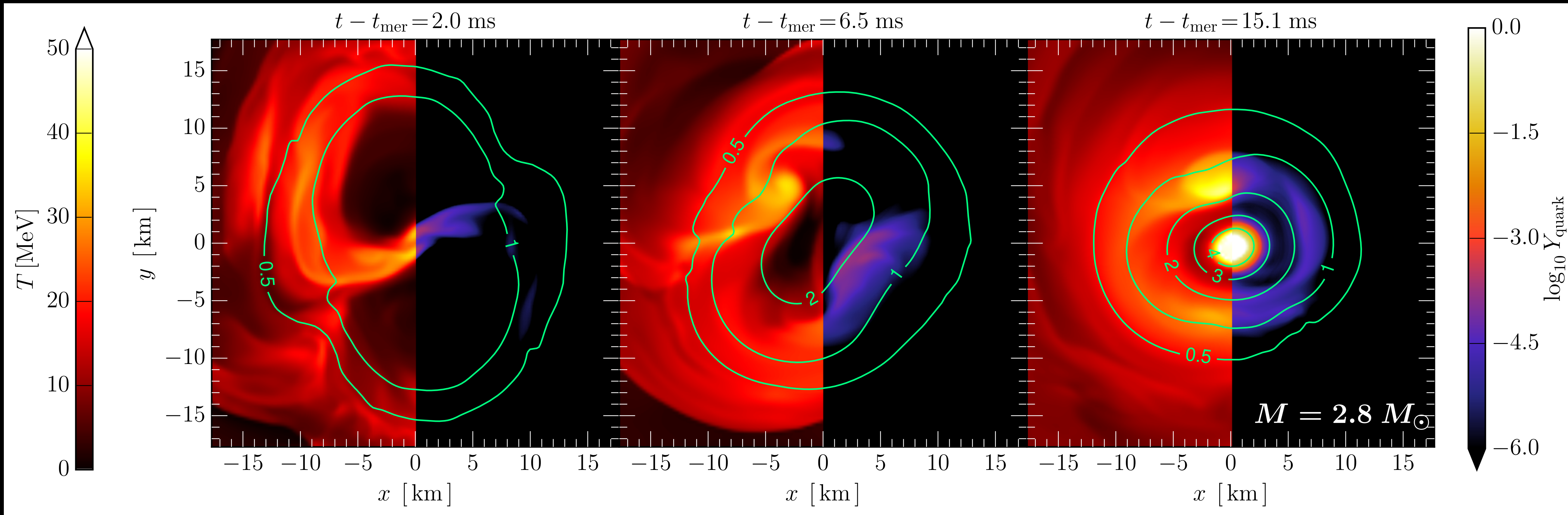
Animations: Weih, Most, LR

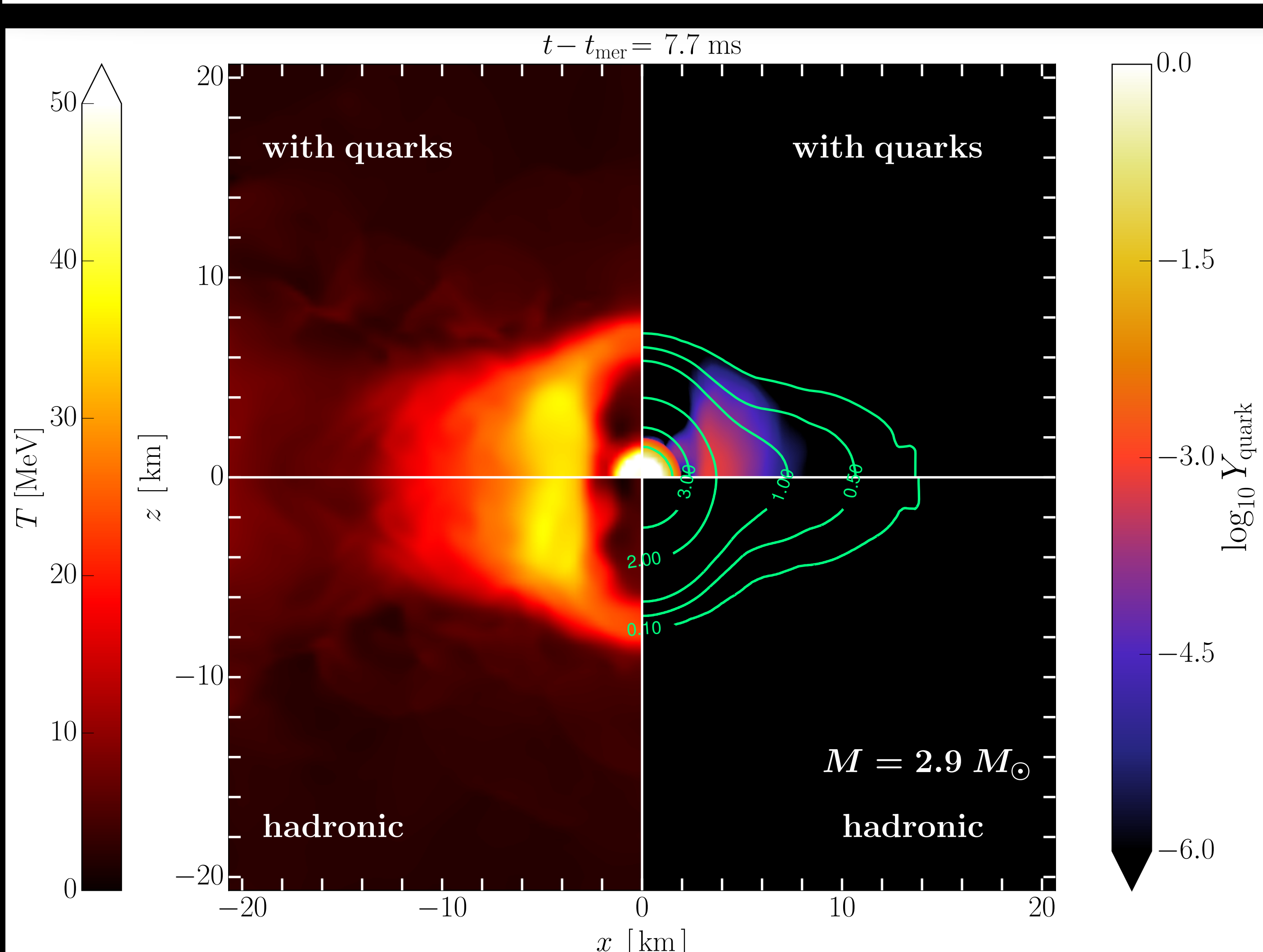




Quarks appear at sufficiently large **temperatures** and **densities.**

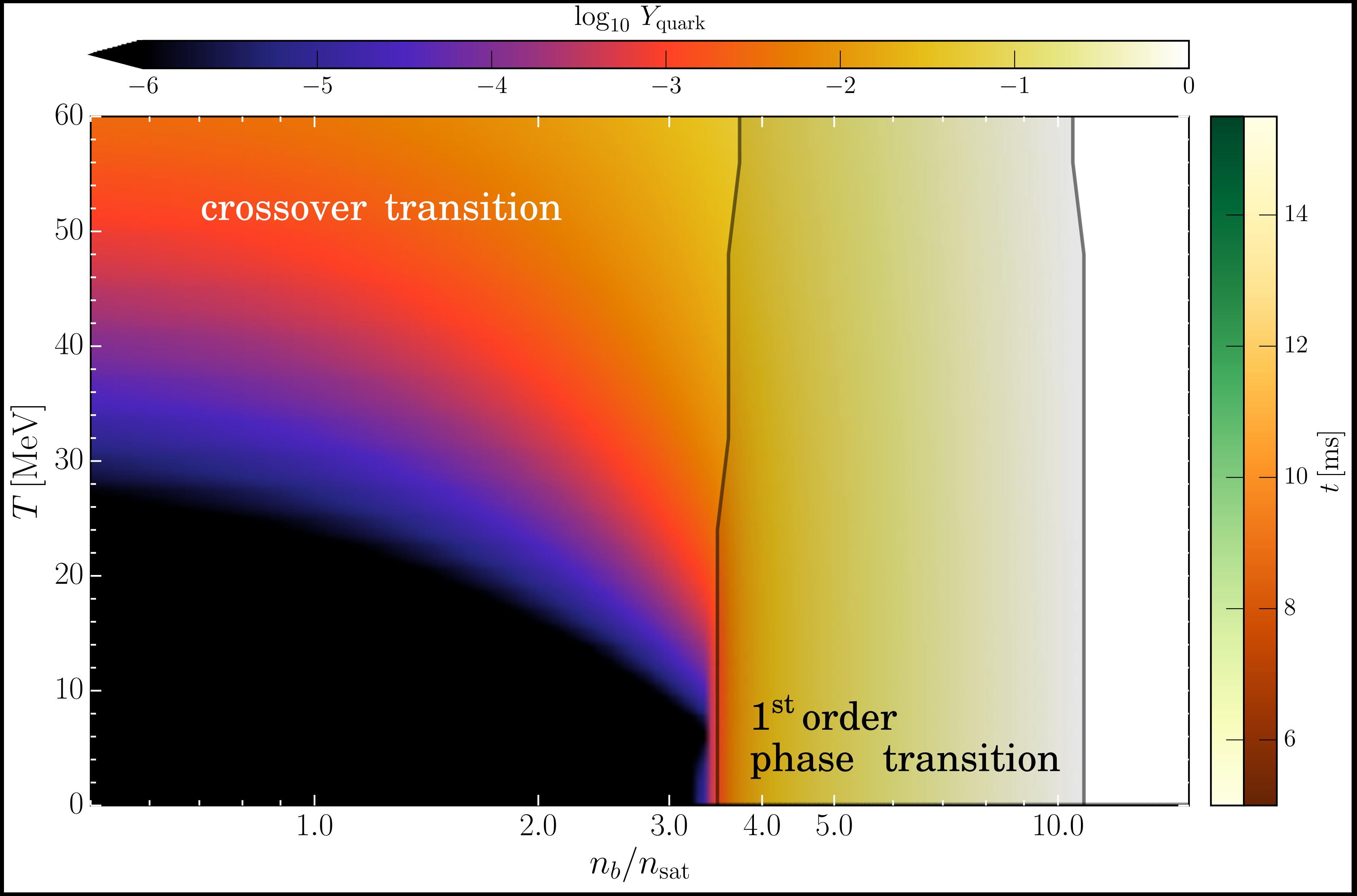
When this happens the **EOS** is considerably **softened.**





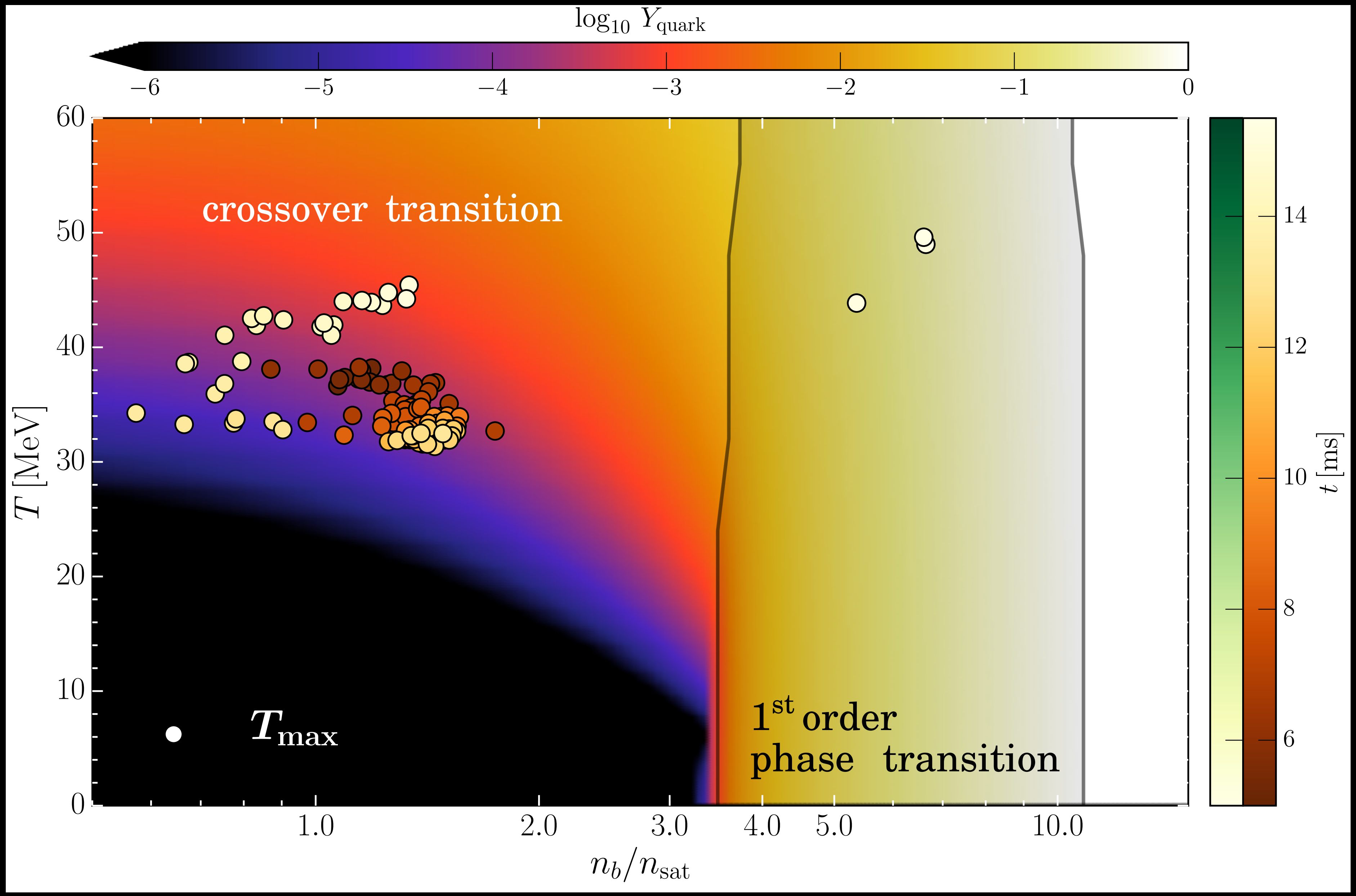
- Quarks appear at sufficiently large temperatures and densities.
- For EOS without quarks, the dynamics (temperature distrib.) is very similar, but no PT.

Comparing with the phase diagram



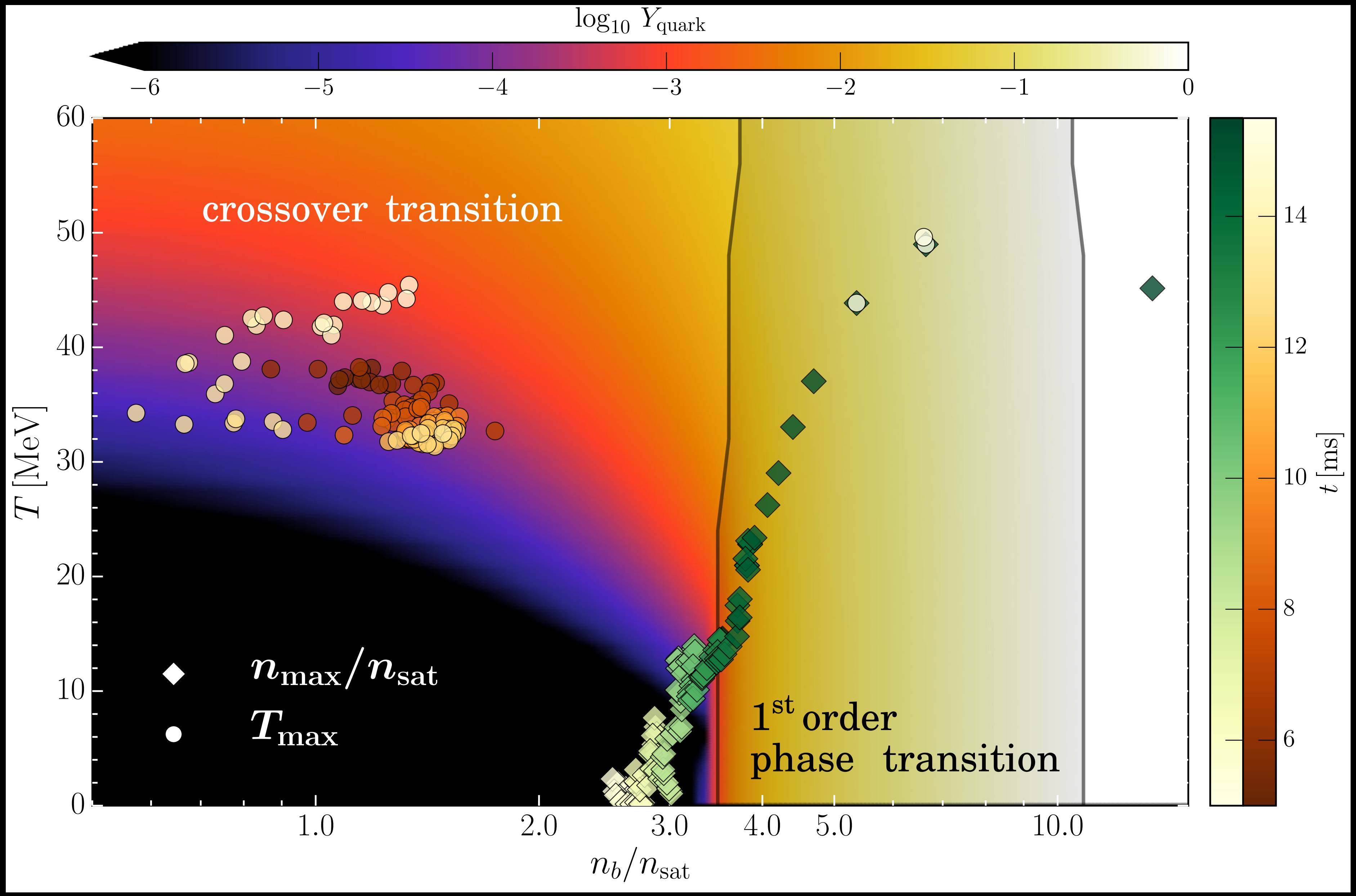
- Phase diagram with quark fraction

Comparing with the phase diagram



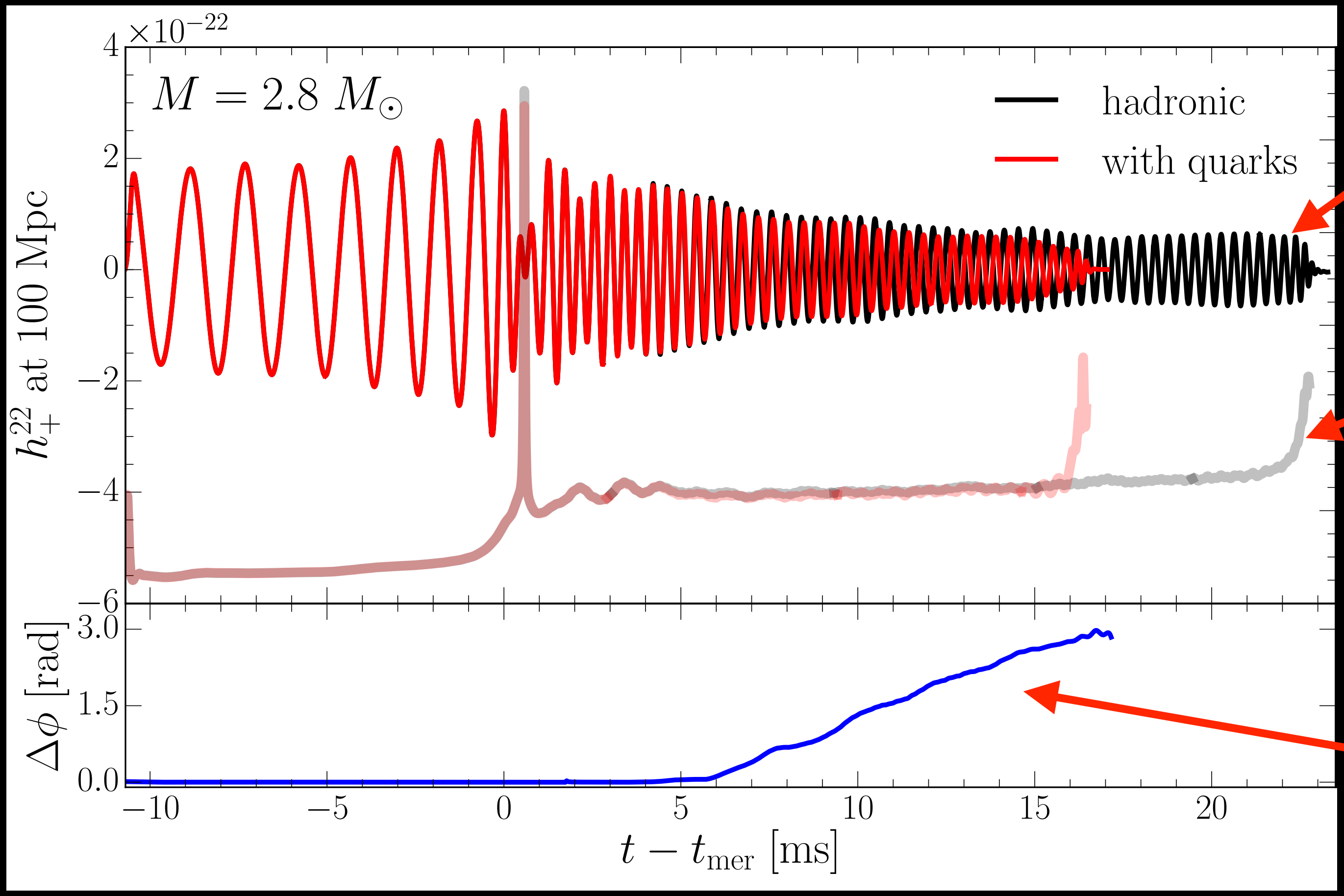
- Phase diagram with quark fraction
- Circles show the position in the diagram of the maximum temperature as a function of time

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

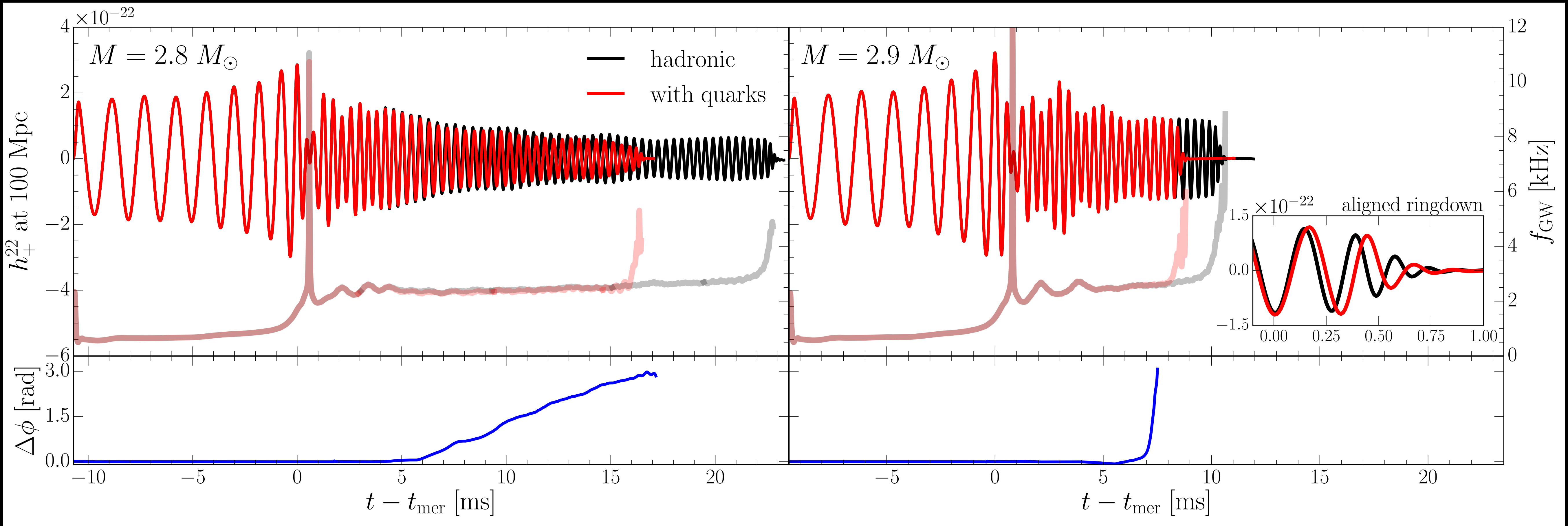


- After ~ 5 ms, quark fraction is large enough to change quadrupole moment and yield differences in the waveforms.
- Sudden softening of the phase transition leads to collapse and **large difference** in phase evolution.

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

Gravitational-wave emission

“low-mass” binary   “high-mass” binary

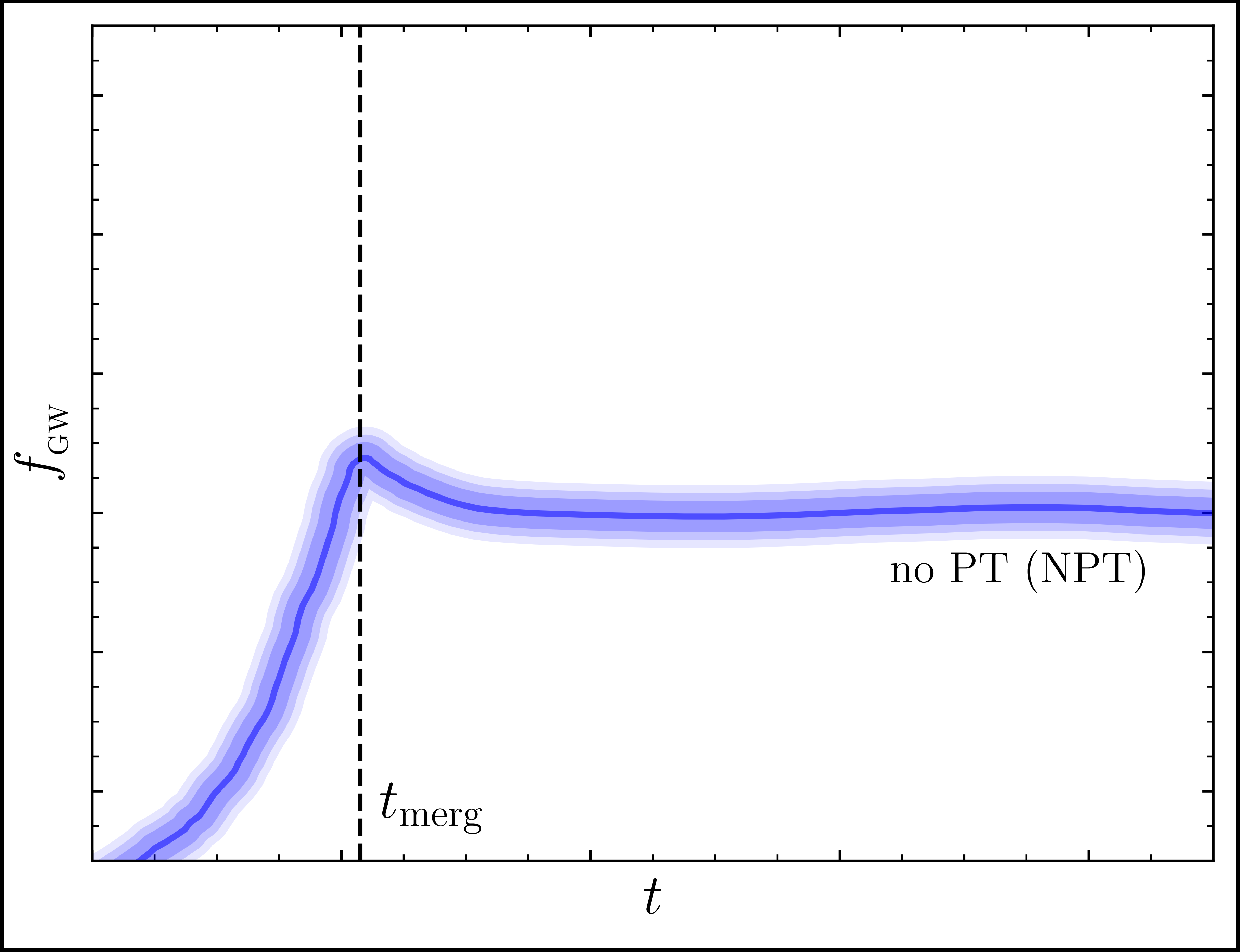


- In **low-mass binary**, after ~ 5 ms, quark fraction is large enough to change quadrupole moment and yield differences in the waveforms.
- In **high-mass binary**, phase transition takes place rapidly after ~ 5 ms. Waveforms are similar but **ringdown** is **different** (free fall for PT).

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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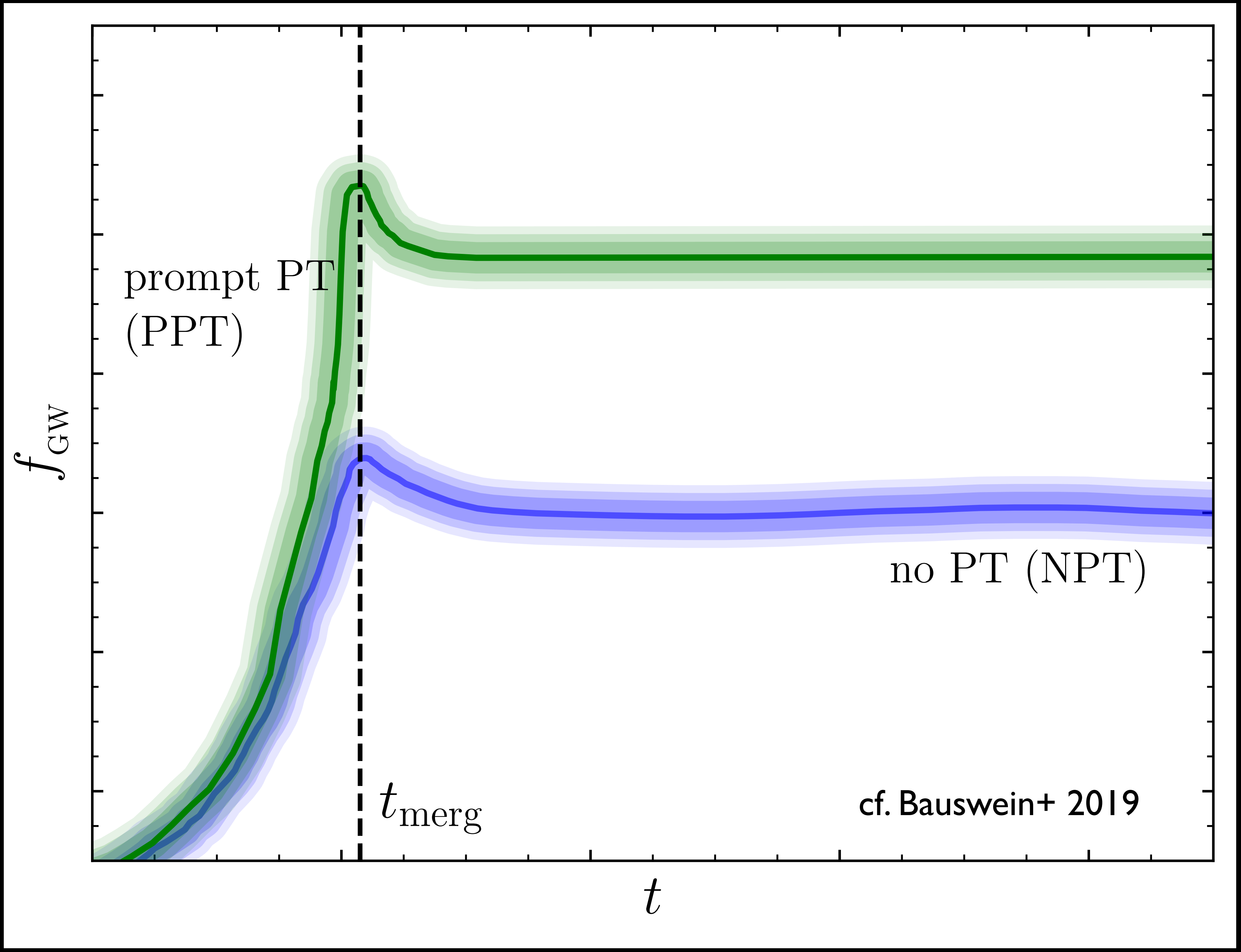

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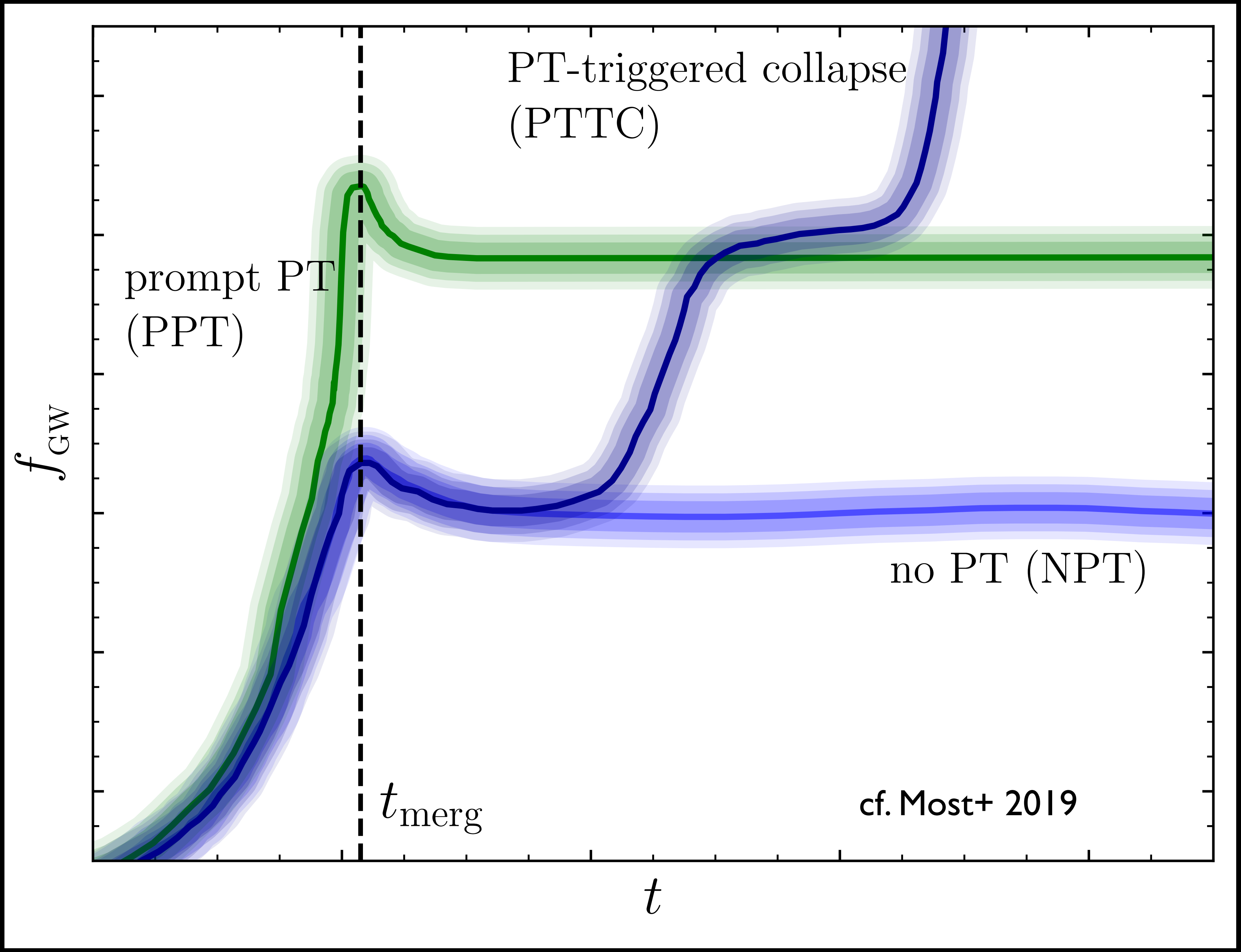

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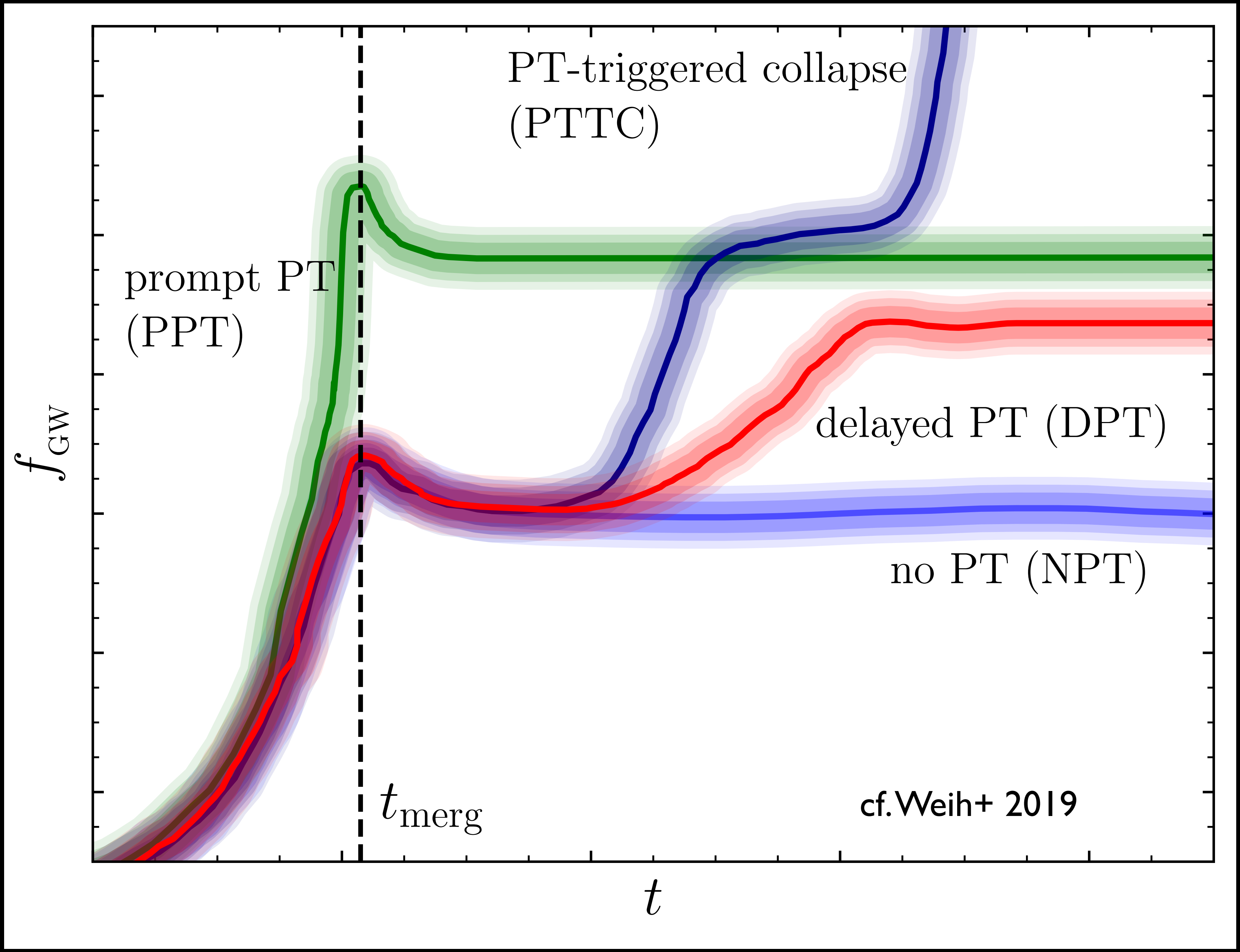
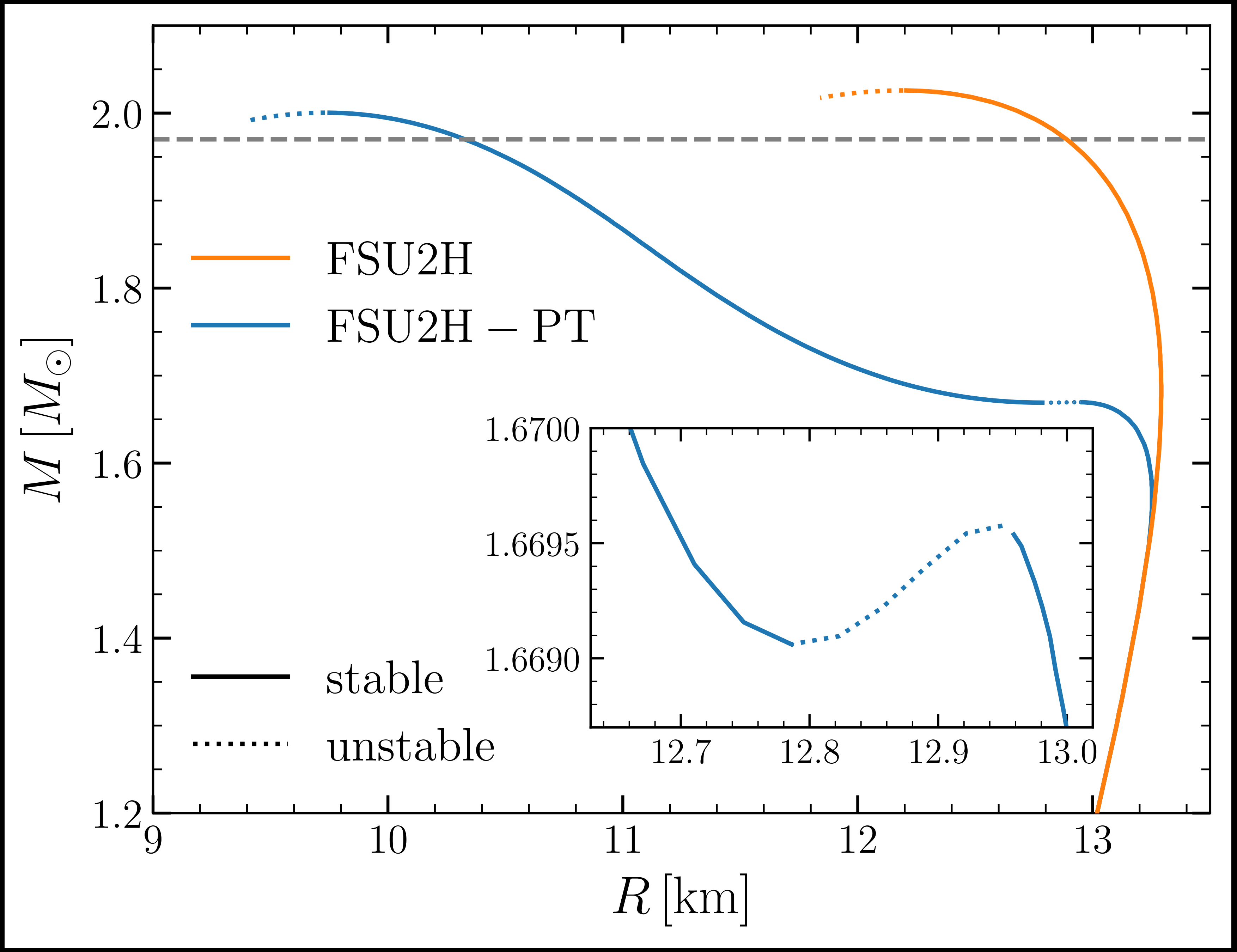


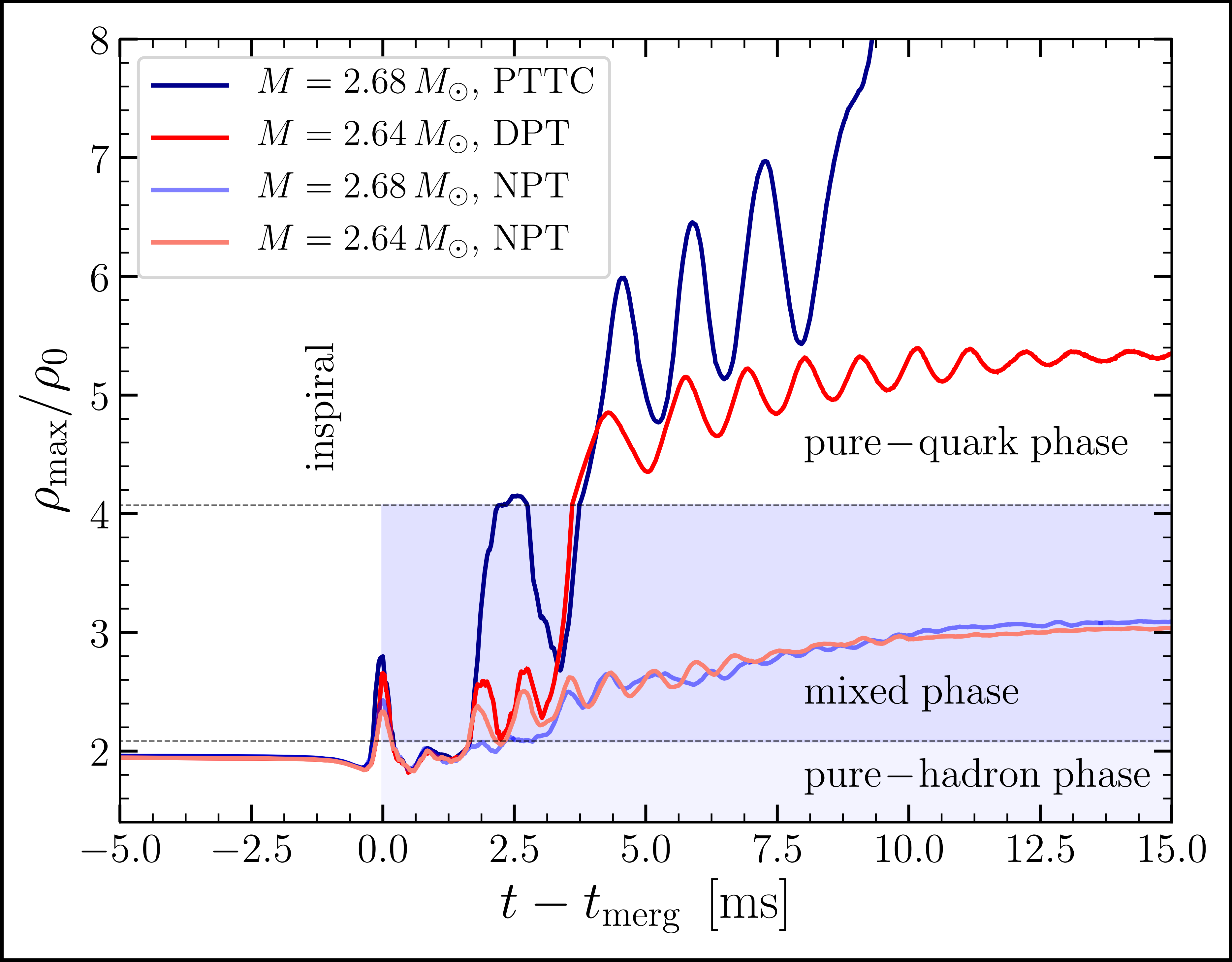
A more comprehensive picture

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



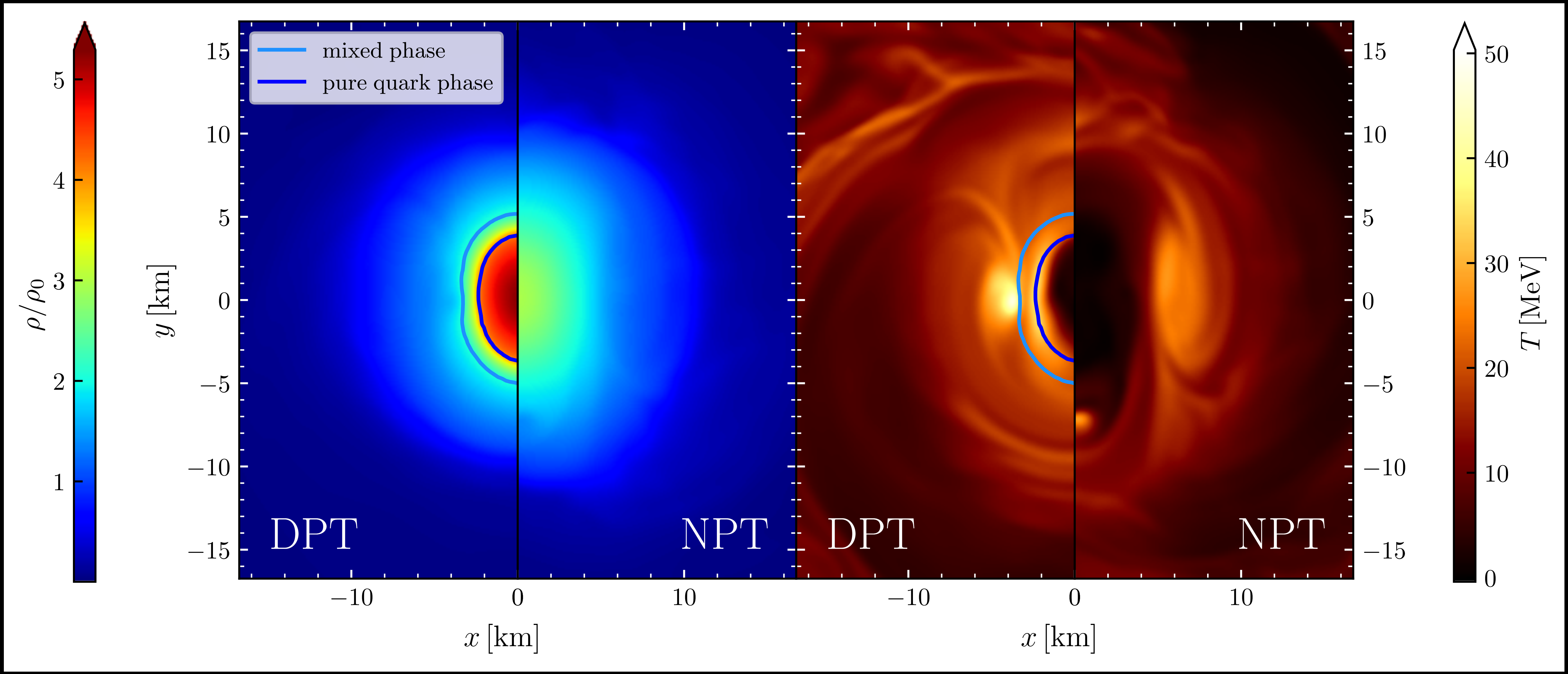
A more comprehensive picture

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



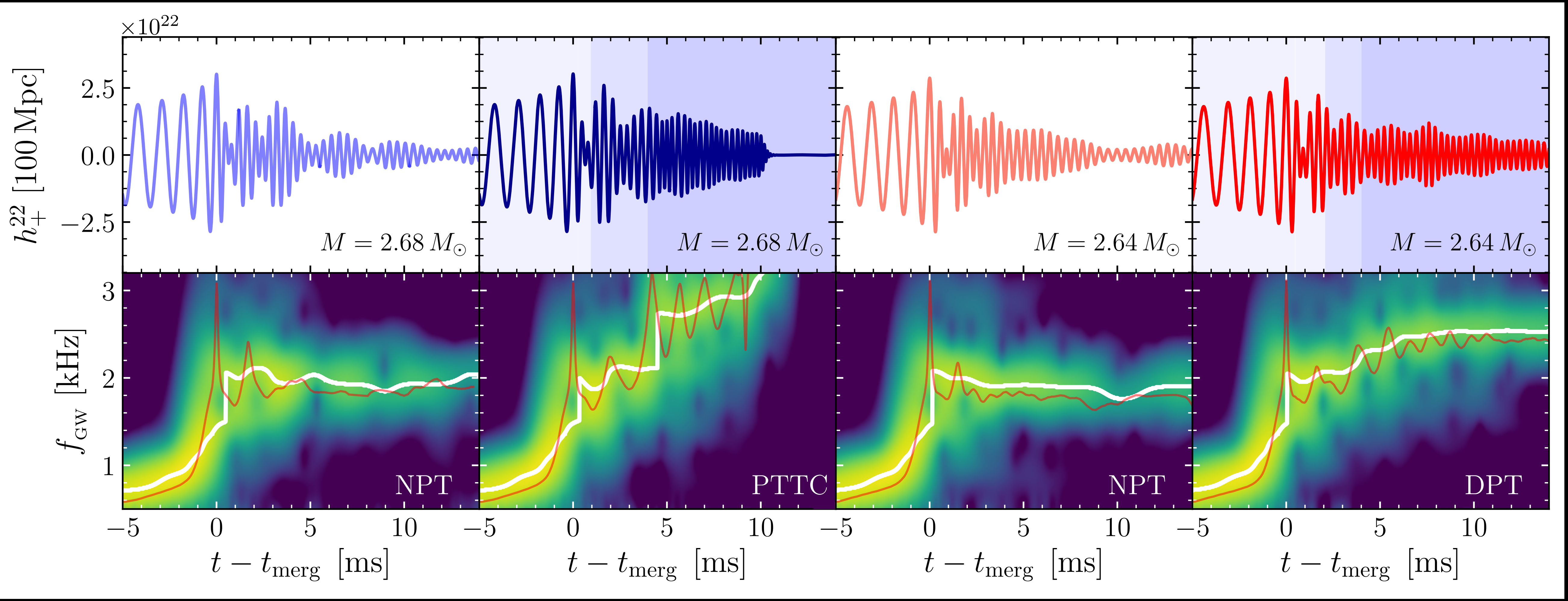
A more comprehensive picture

Comparison of density and temperature distributions on the equatorial plane for binaries with and without a DPT. Note the hot ring in the mixed phase present in the case of DPT



A more comprehensive picture

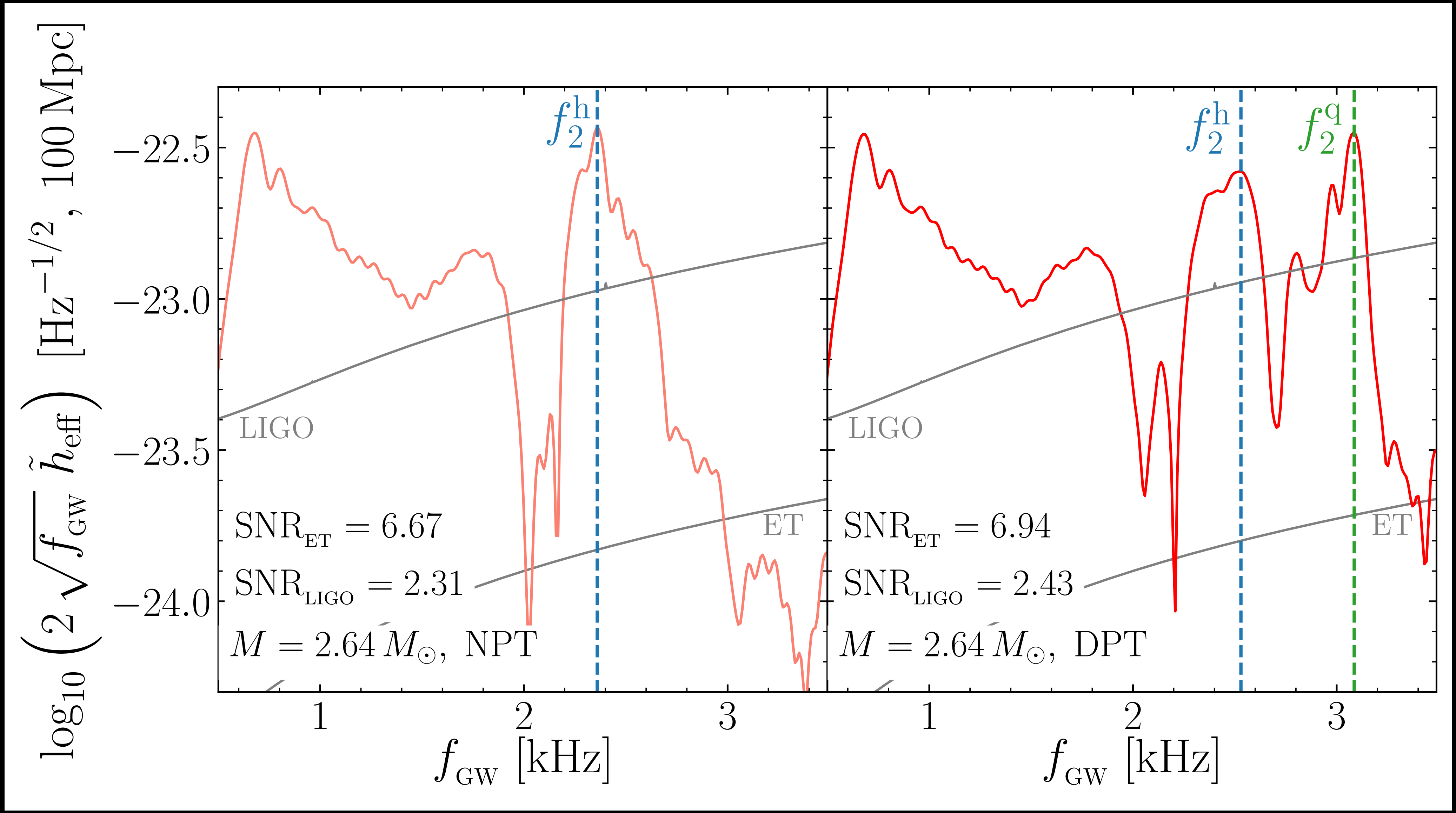
Different signatures are also quite transparent when shown in terms of the gravitational waves and their spectrograms.



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

A more comprehensive picture

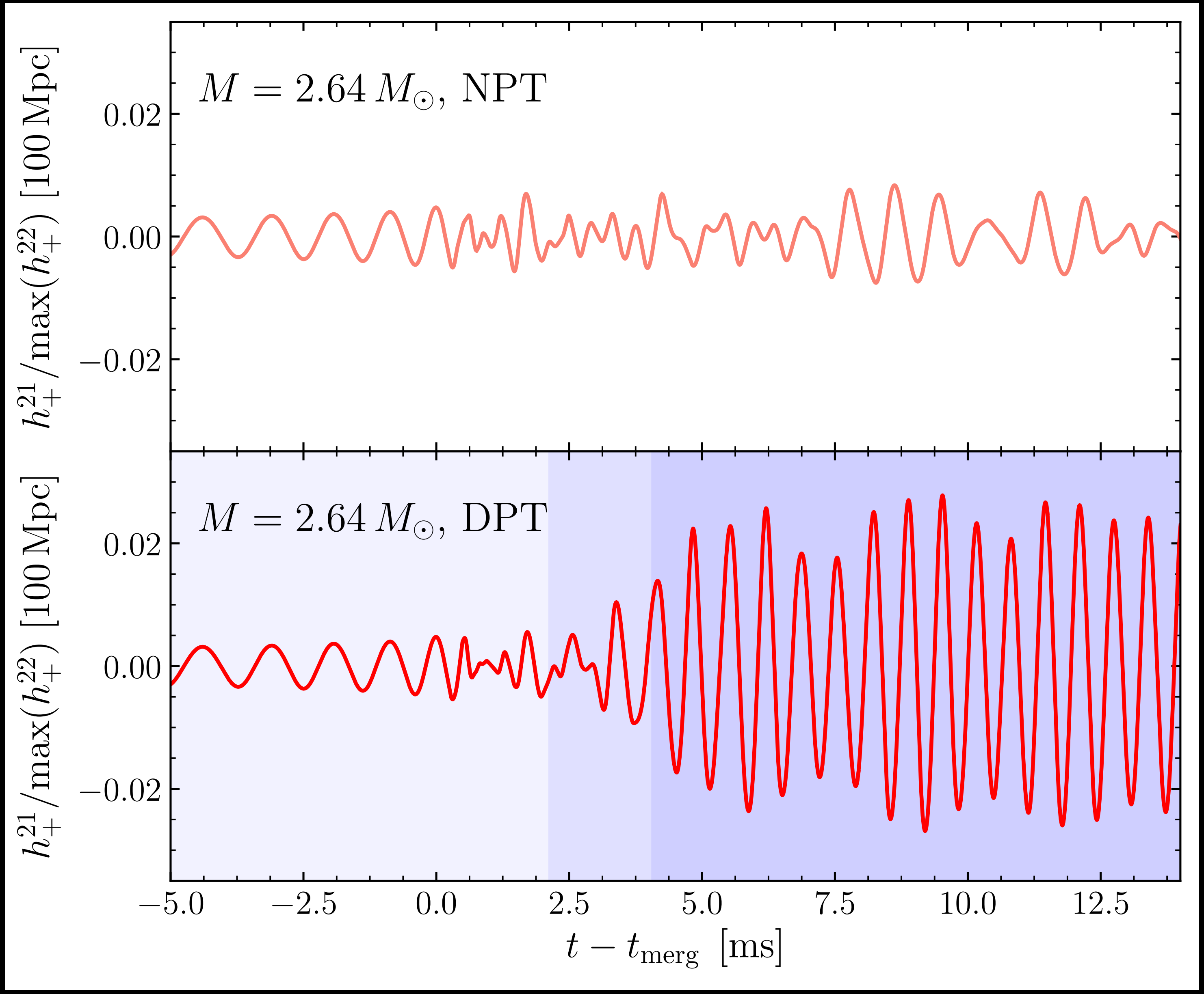
Different signatures are also quite transparent when shown in terms of the gravitational waves and their spectrograms.



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

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.

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.

✳Merging binaries with magnetic fields can lead to the formation of **jet structures** and match phenomenology of SGRBs.

✳**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**

$$M_{\rm th}/M_{\rm TOV} \approx 1.41 \quad R_{\rm TOV} \geq 9.74^{+0.14}_{-0.04}\,{\rm km}$$ **threshold mass**

✳A phase transition after a BNS merger leaves GW **signatures** and opens a gate to access quark matter beyond accelerators

Recap

- ☑ Spectra of post-merger shows clear "**quasi-universal**" peaks
- ☑ GW spectroscopy possible with post-merger signal
- ☑ Unless binary very close, peaks have SNR ~ 1. Multiple signals can be stacked and SNR will increase coherently.
- ☑ Only inspiral detected in GW170817 but new limits set on:

Maximum mass

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

Typical radii and tidal deformabilities

$12.00 < R_{1.4}/{\rm km} < 13.45 \quad \tilde{\Lambda}_{1.4} > 375$ hadronic EOSs

$8.53 < R_{1.4}/{\rm km} < 13.74 \quad \tilde{\Lambda}_{1.4} \gtrsim 35 \;\; \tilde{\Lambda}_{1.7} \lesssim 460$ phase transitions

- ☑ Phase transition can take place after merger leading to clear signatures: mismatch between inspiral and postmerger.