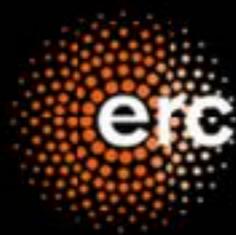


Binary neutron stars: from macroscopic collisions to microphysics

Luciano Rezzolla

Institute for Theoretical Physics, Frankfurt

Seattle (Frankfurt)
21.04.22



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

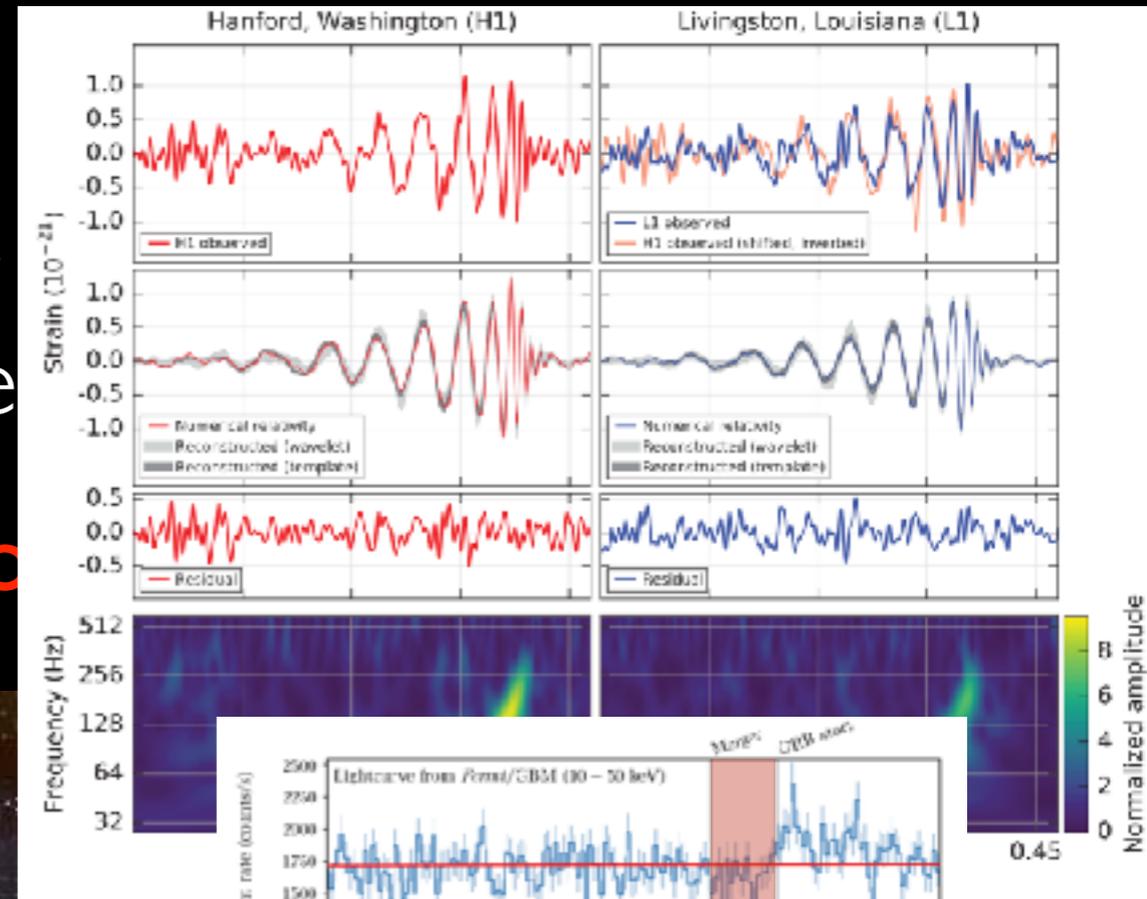
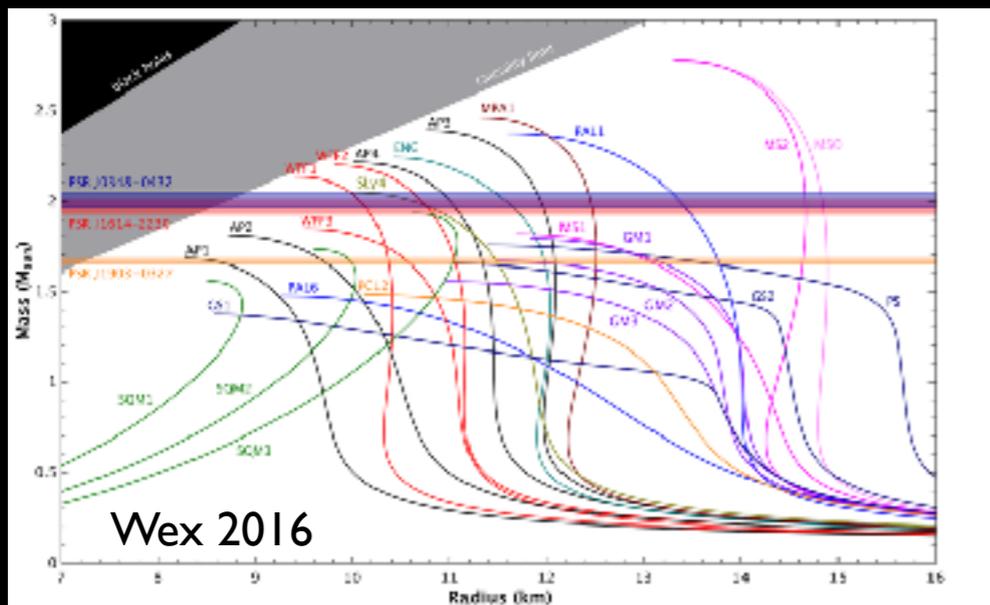
- For black holes the process is very **simple**:

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

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

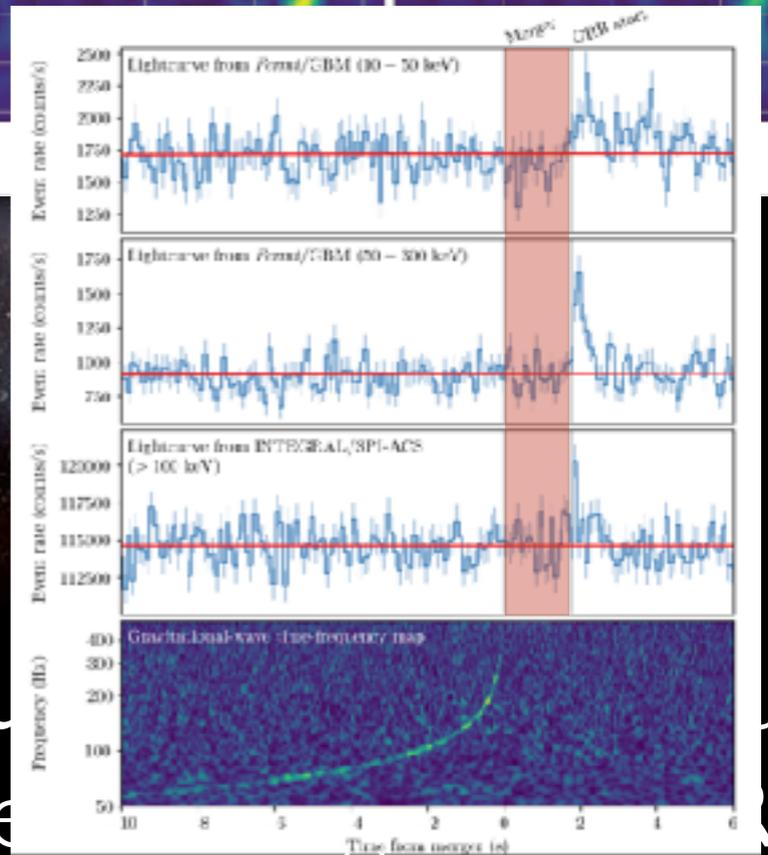
$$\text{NS} + \text{NS} \longrightarrow \text{HMNS} + \dots ? \longrightarrow \text{BH} + \text{torus}$$

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



GW150914

- **BH+torus**
on the ice
GW170817



NS
Bs

The two-body problem in GR

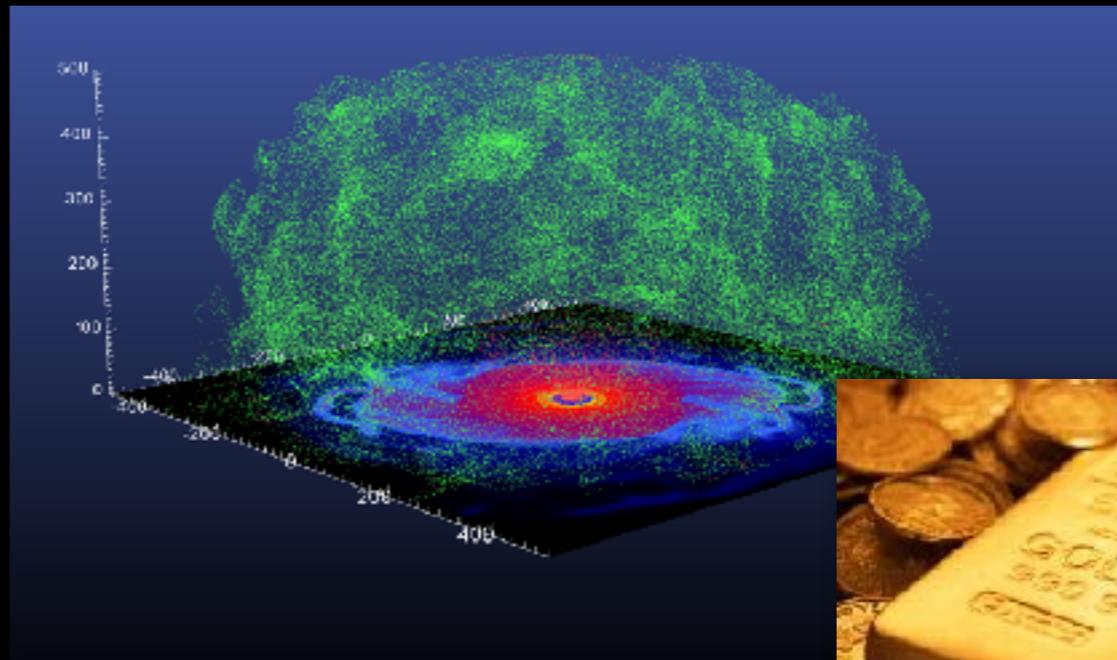
- For black holes the process is very **simple**:



- For NSs the question is more **subtle**: the merger leads to an hyper-massive neutron star (HMNS), ie a metastable equilibrium:



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



The equations of numerical relativity

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

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

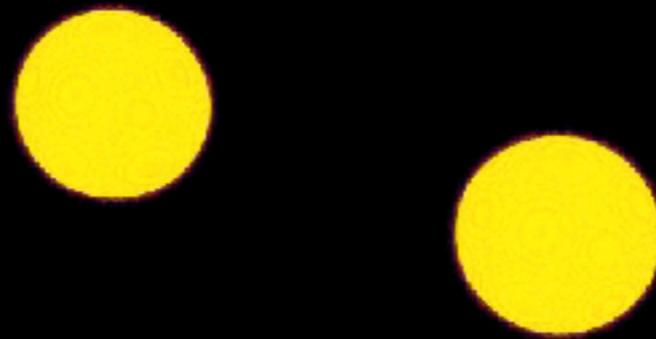
$$\nabla_{\mu}(\rho u^{\mu}) = 0, \text{ (cons. rest mass)}$$

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

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

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

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



merger \longrightarrow HMNS \longrightarrow $M \approx 2 \times 1.35 M_{\odot}$ BH + torus
LS220 EOS

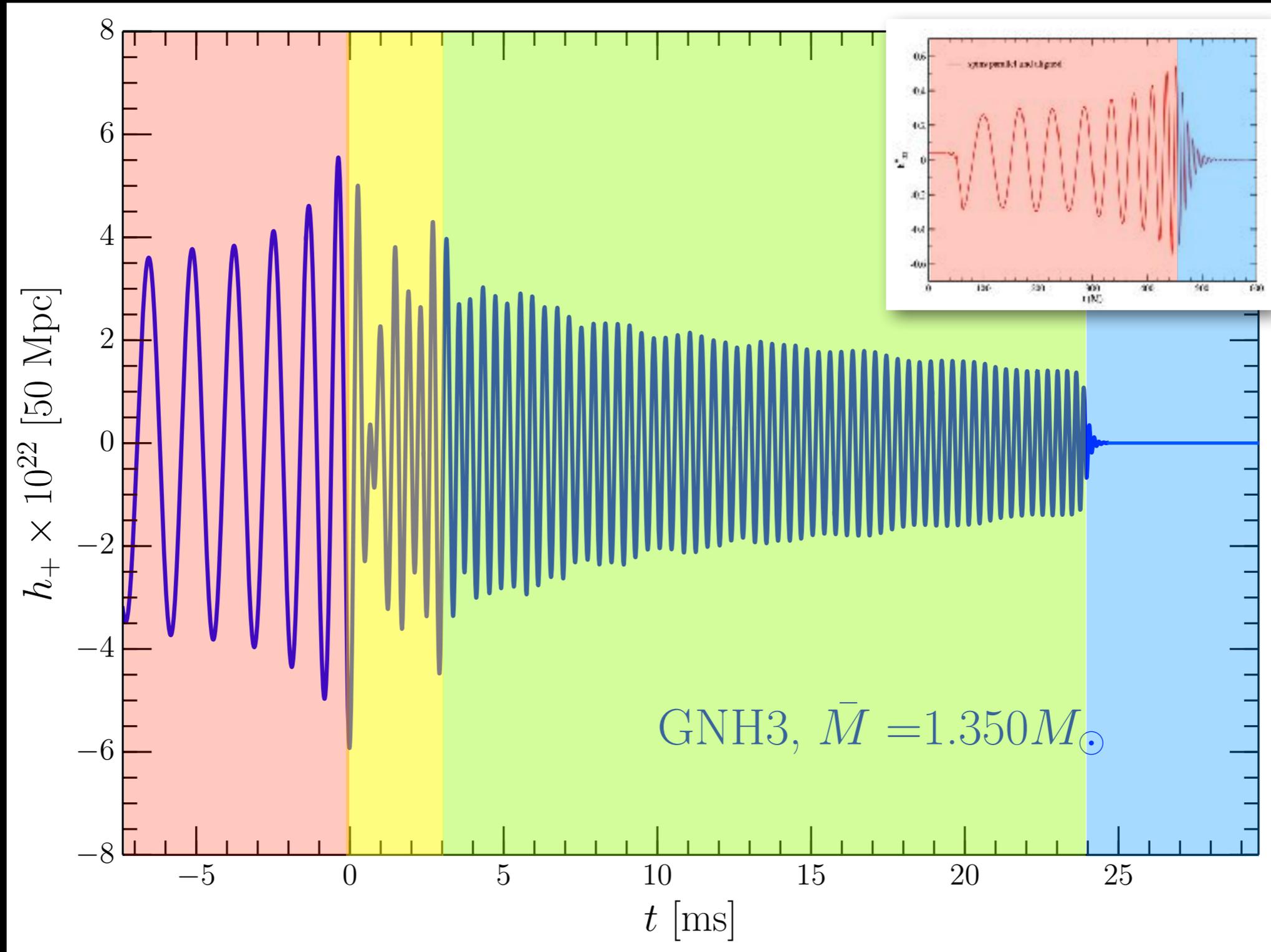
Qualitatively, this is what normally happens:

merger \longrightarrow HMNS \longrightarrow BH + torus

Quantitatively, differences are produced by:

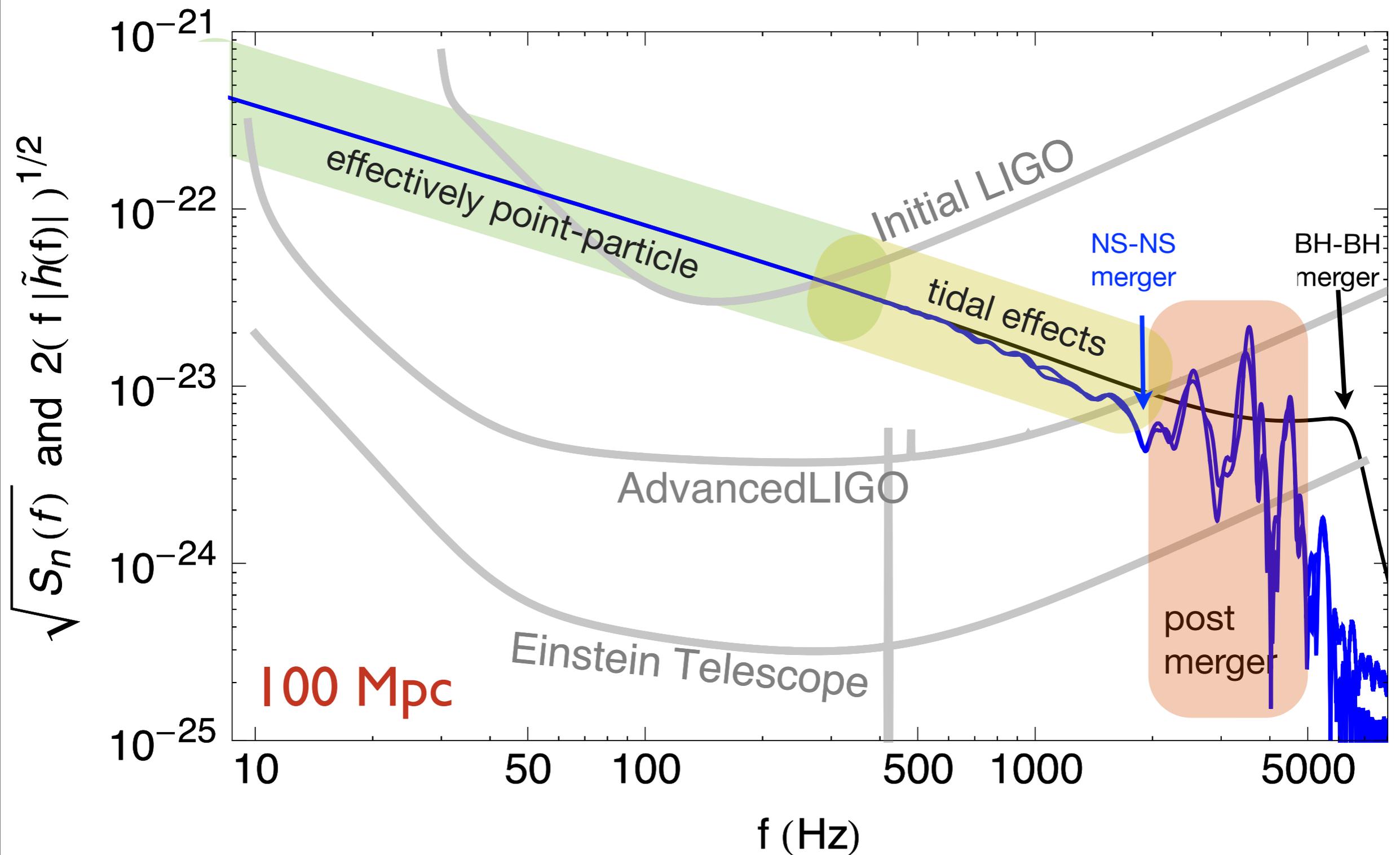
- total **mass** (prompt vs delayed collapse)
- mass **asymmetries** (HMNS and torus)
- soft/stiff **EOS** (inspiral and post-merger, PT)
- **magnetic fields** (equil. and EM emission)
- **radiative** losses (equil. and nucleosynthesis)

Anatomy of the GW signal



Postmerger signal: peculiar of binary NSs

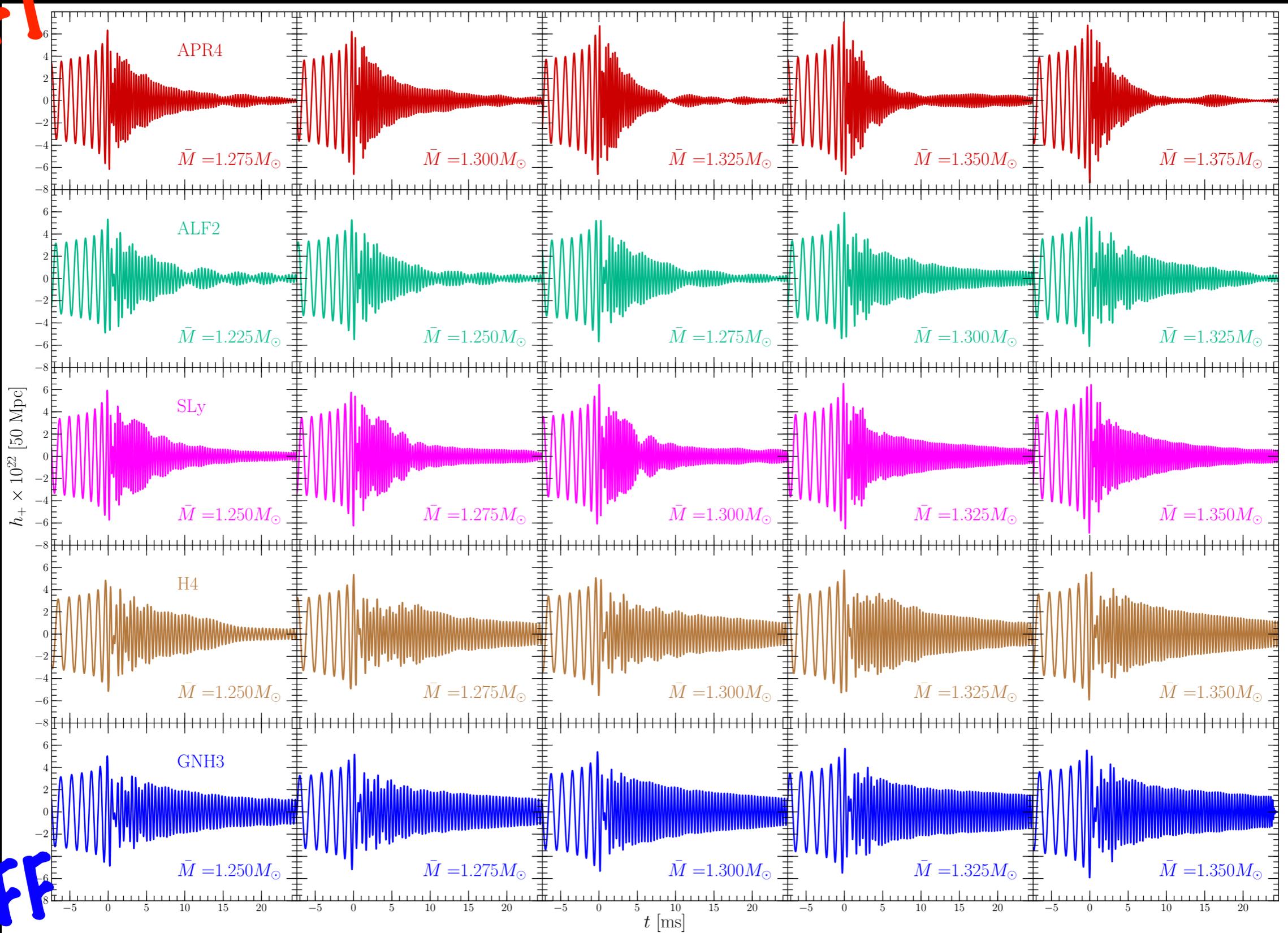
In frequency space



What we can do nowadays

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

SOFT

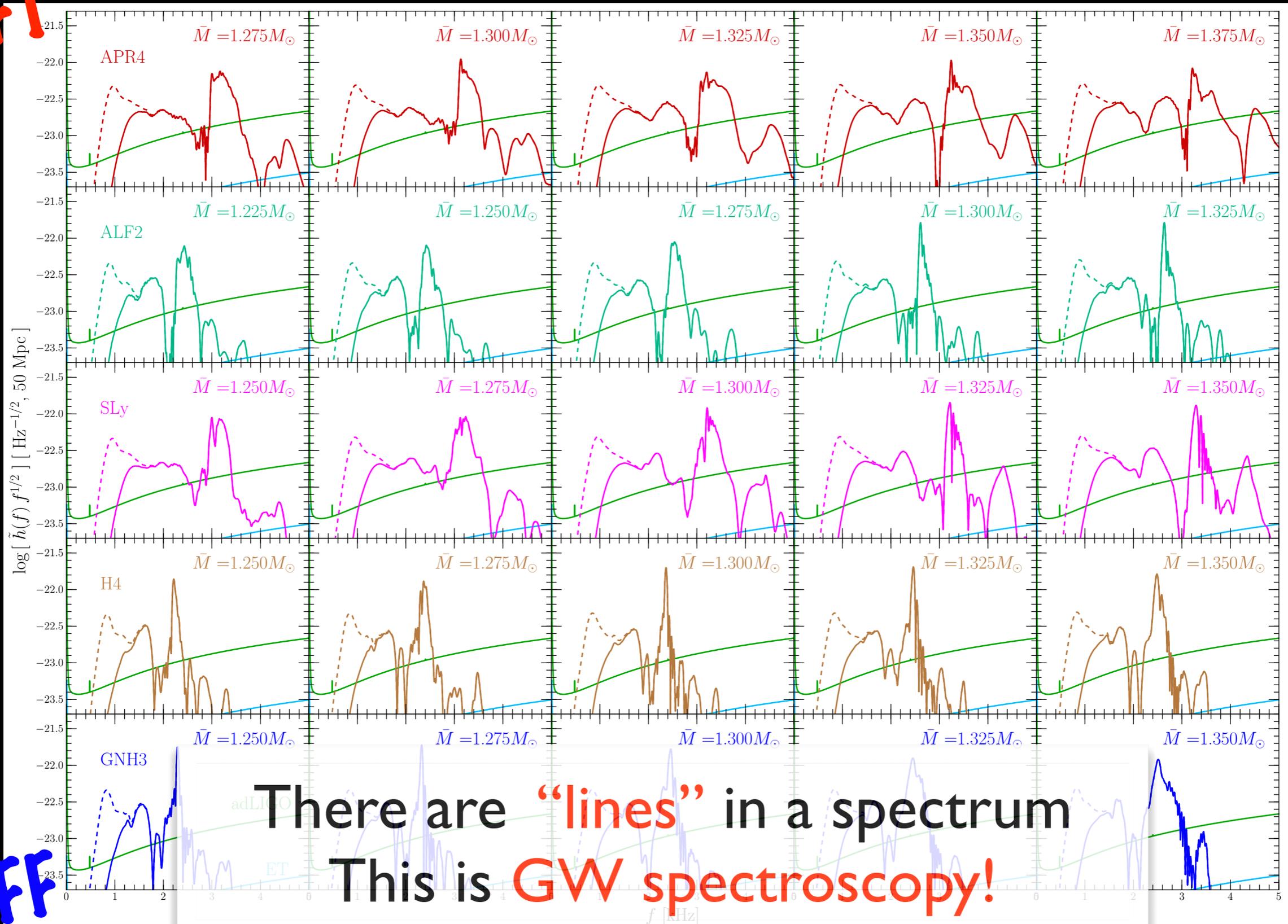


STIFF

Extracting information from the EOS

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

SOFT

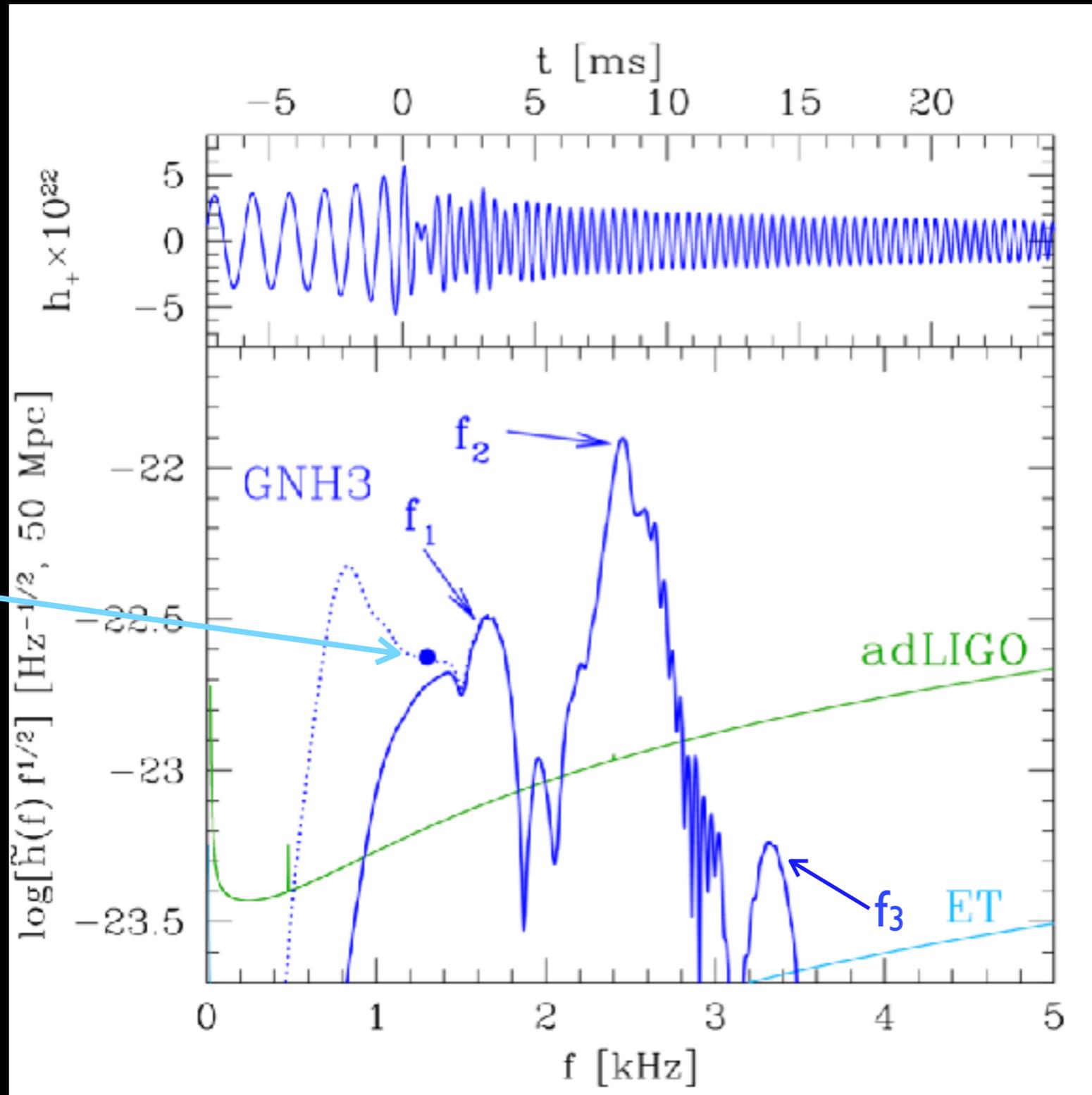


STIFF

A spectroscopic approach to the EOS

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

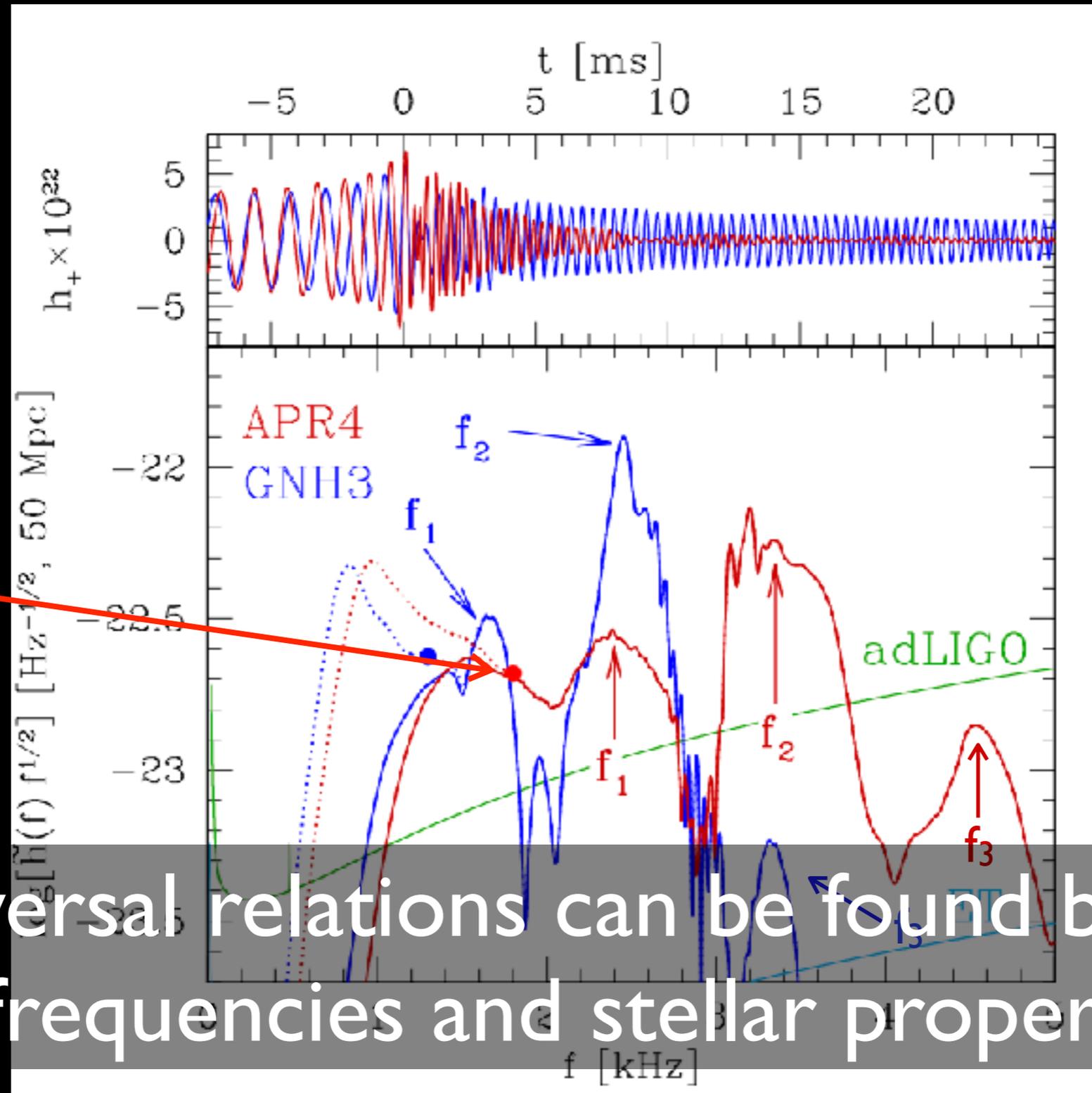
merger
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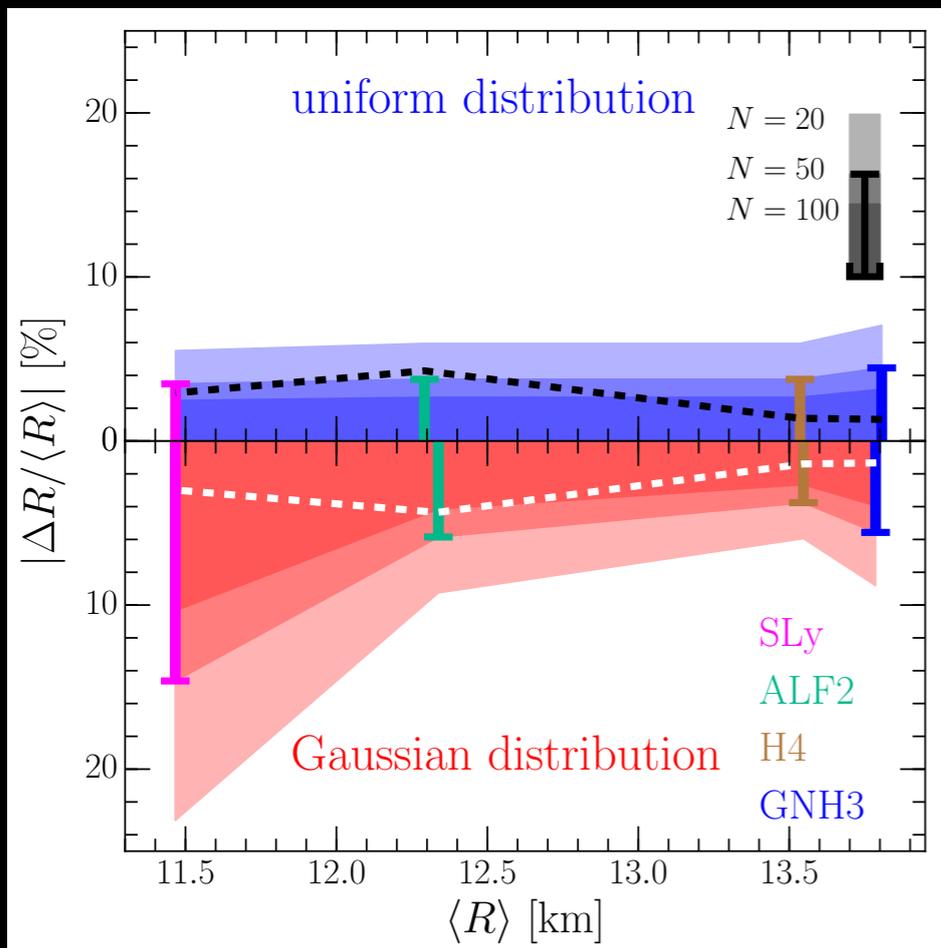
merger
frequency



Universal relations can be found between frequencies and stellar properties

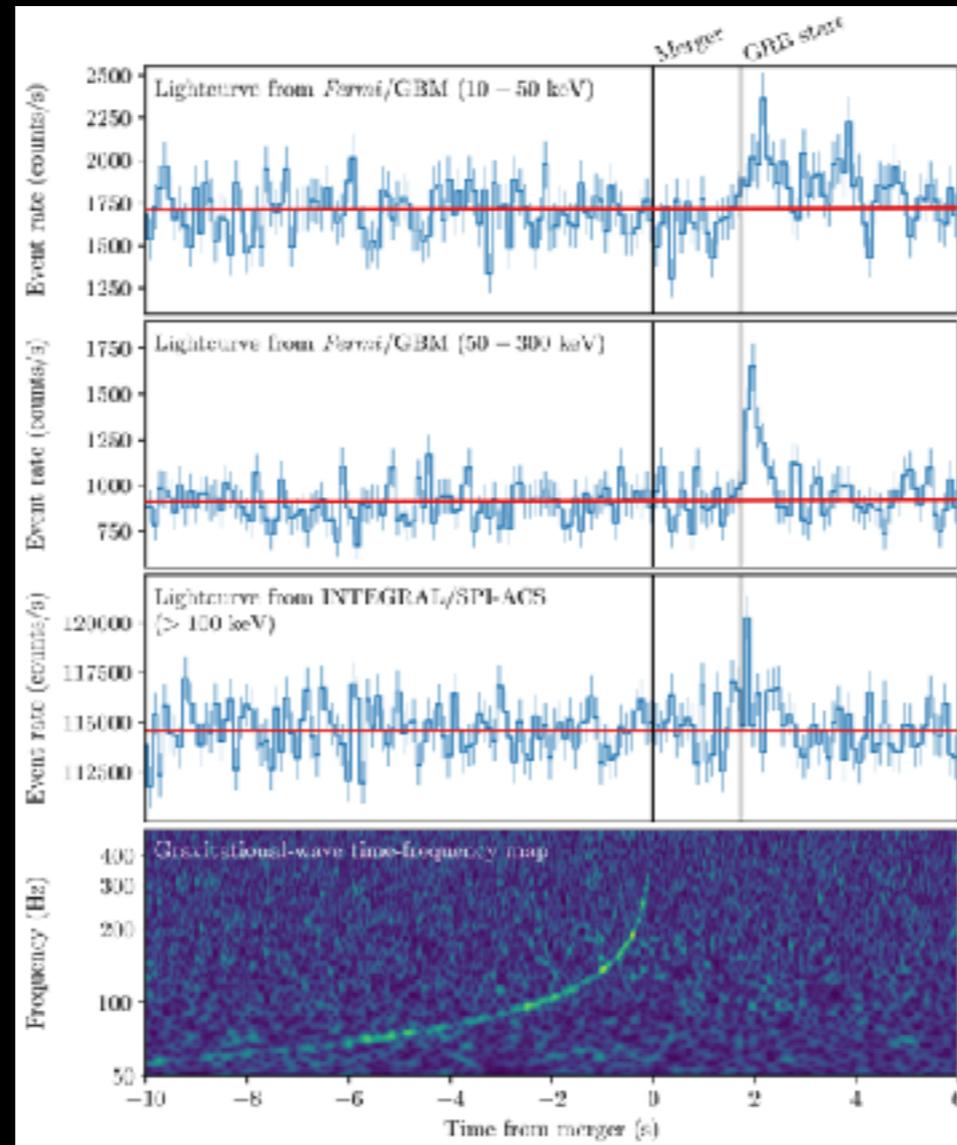
A spectroscopic approach to the EOS

- **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 **$N \sim 10$**
- stiff EOSs: $|\Delta R / \langle R \rangle| < 10\%$ for **$N \sim 20$**
- soft EOSs: $|\Delta R / \langle R \rangle| \sim 10\%$ for **$N \sim 50$**
- golden binary: **$\text{SNR} \sim 6$** at **30 Mpc**
 $|\Delta R / \langle R \rangle| \simeq 2\%$ at 90% confidence

GW170817: a game changer



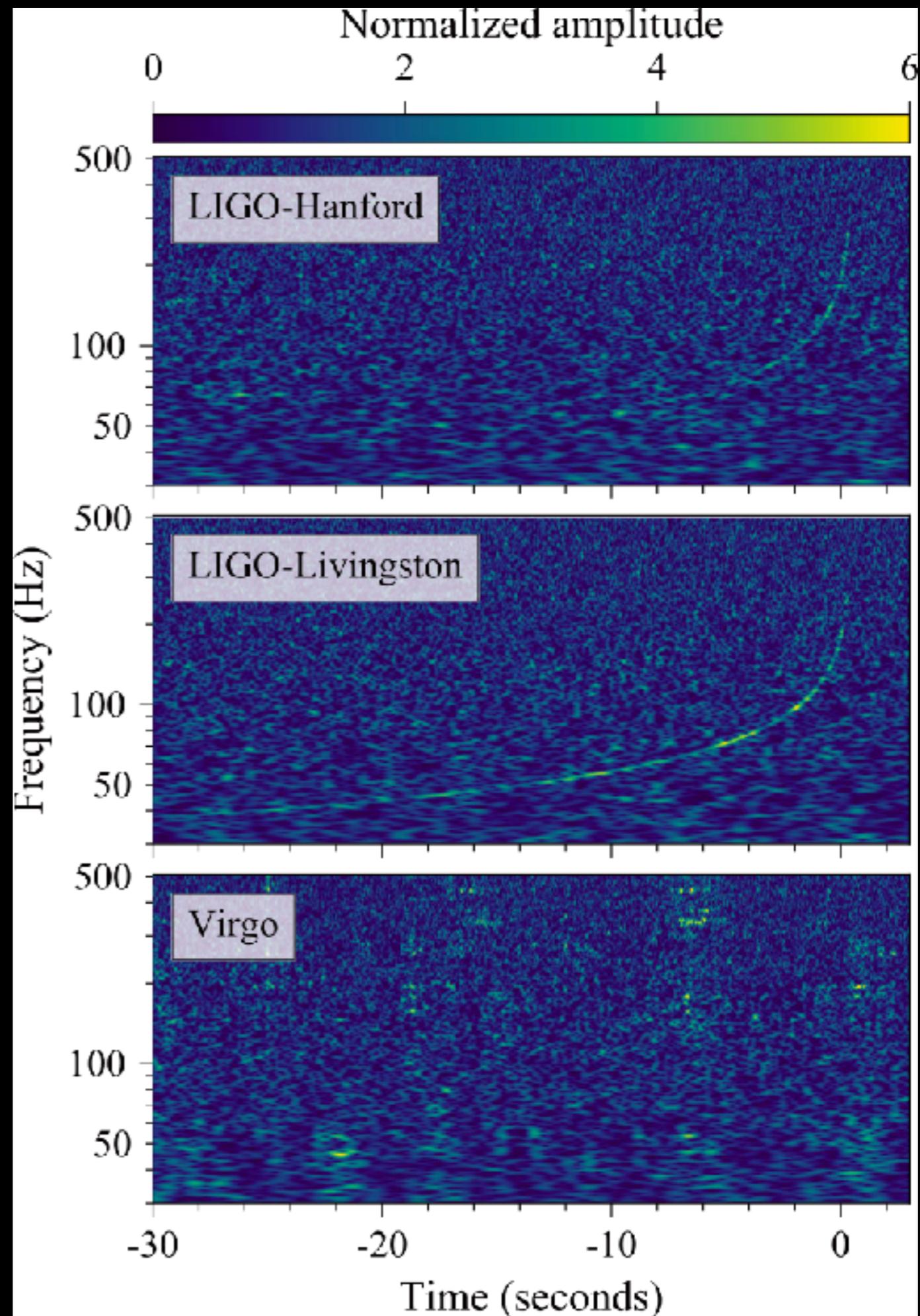
LR, Most, Weih, ApJL (2018)

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.

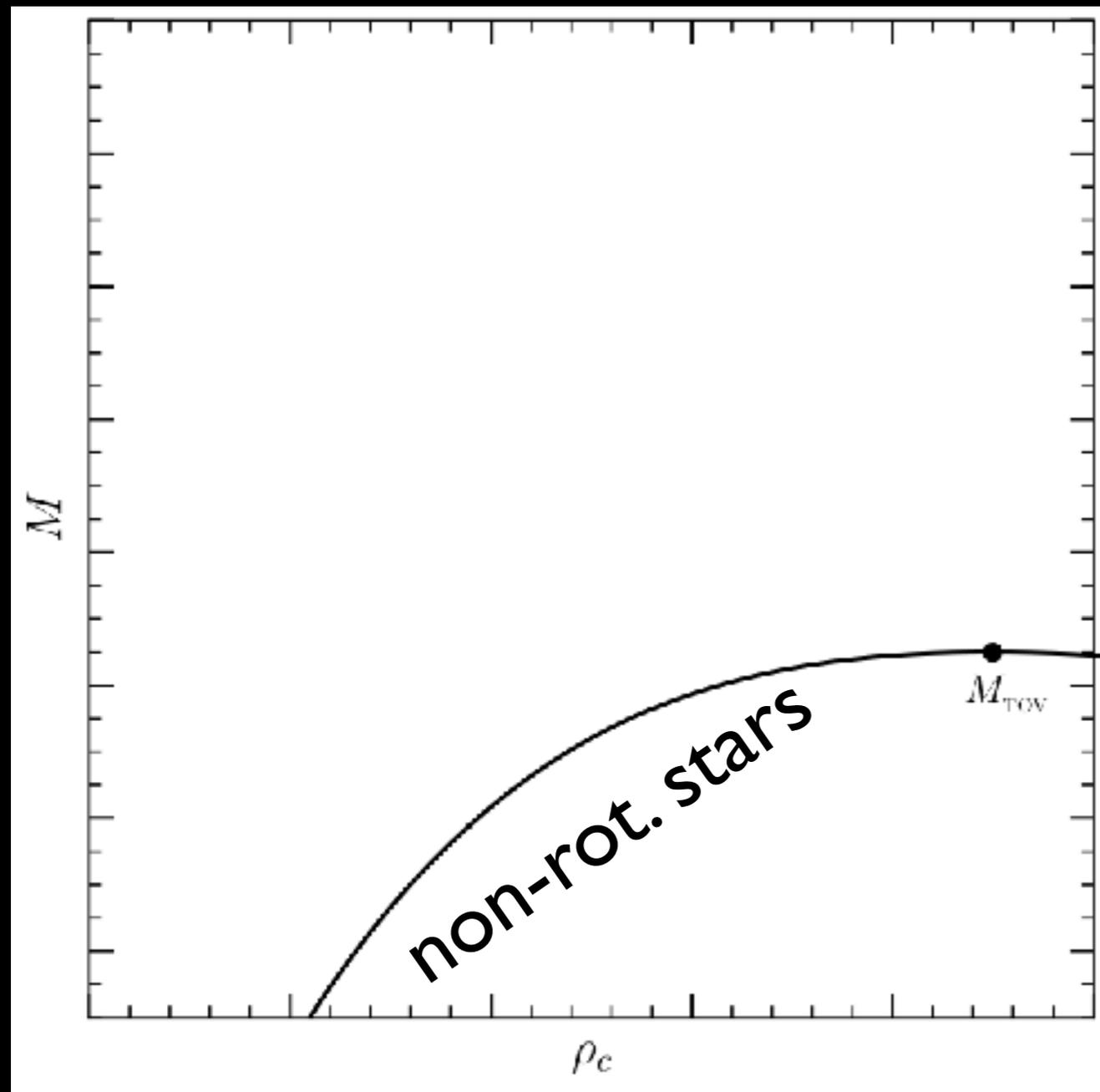


Limits on the maximum mass

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

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

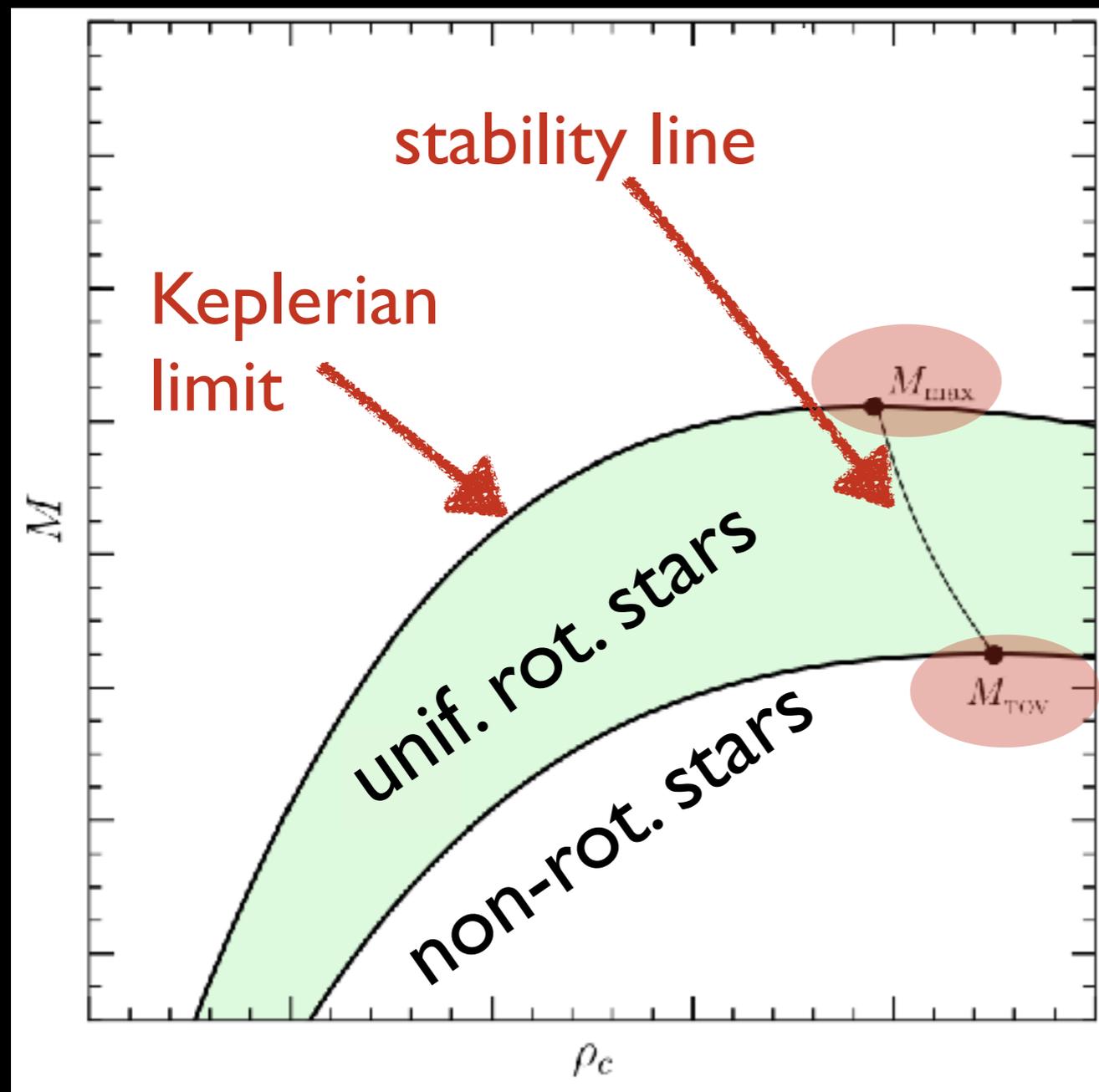
- Sequences of equilibrium models of **nonrotating** stars will have a maximum mass: M_{TOV}



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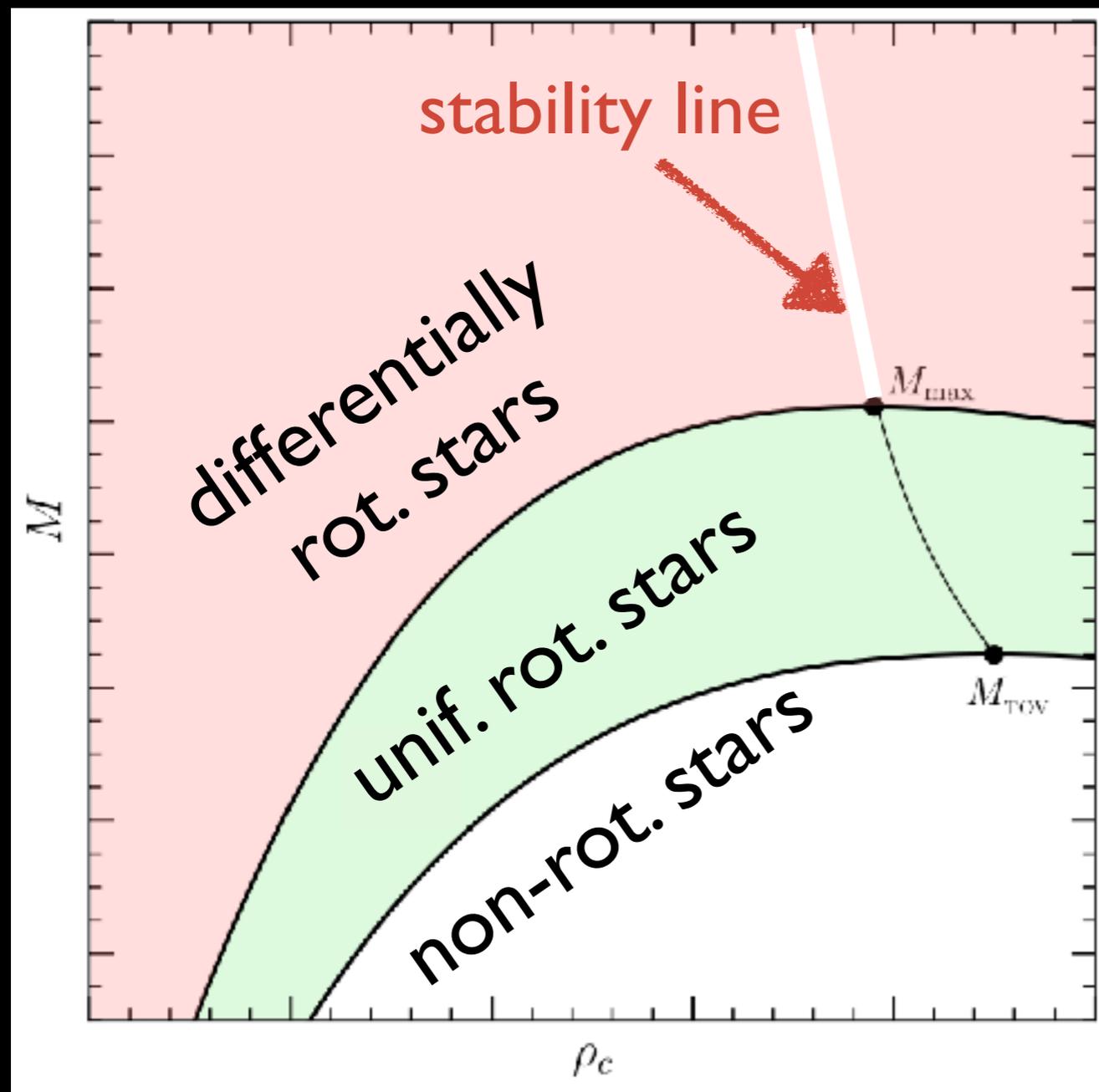
- Sequences of equilibrium models of **nonrotating** stars will have a maximum mass: M_{TOV}
- This is true also for **uniformly** rotating stars at mass shedding limit: M_{max}
- M_{max} simple and **quasi-universal** function of M_{TOV} (Breu & LR 2016)

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

Limits on the maximum mass

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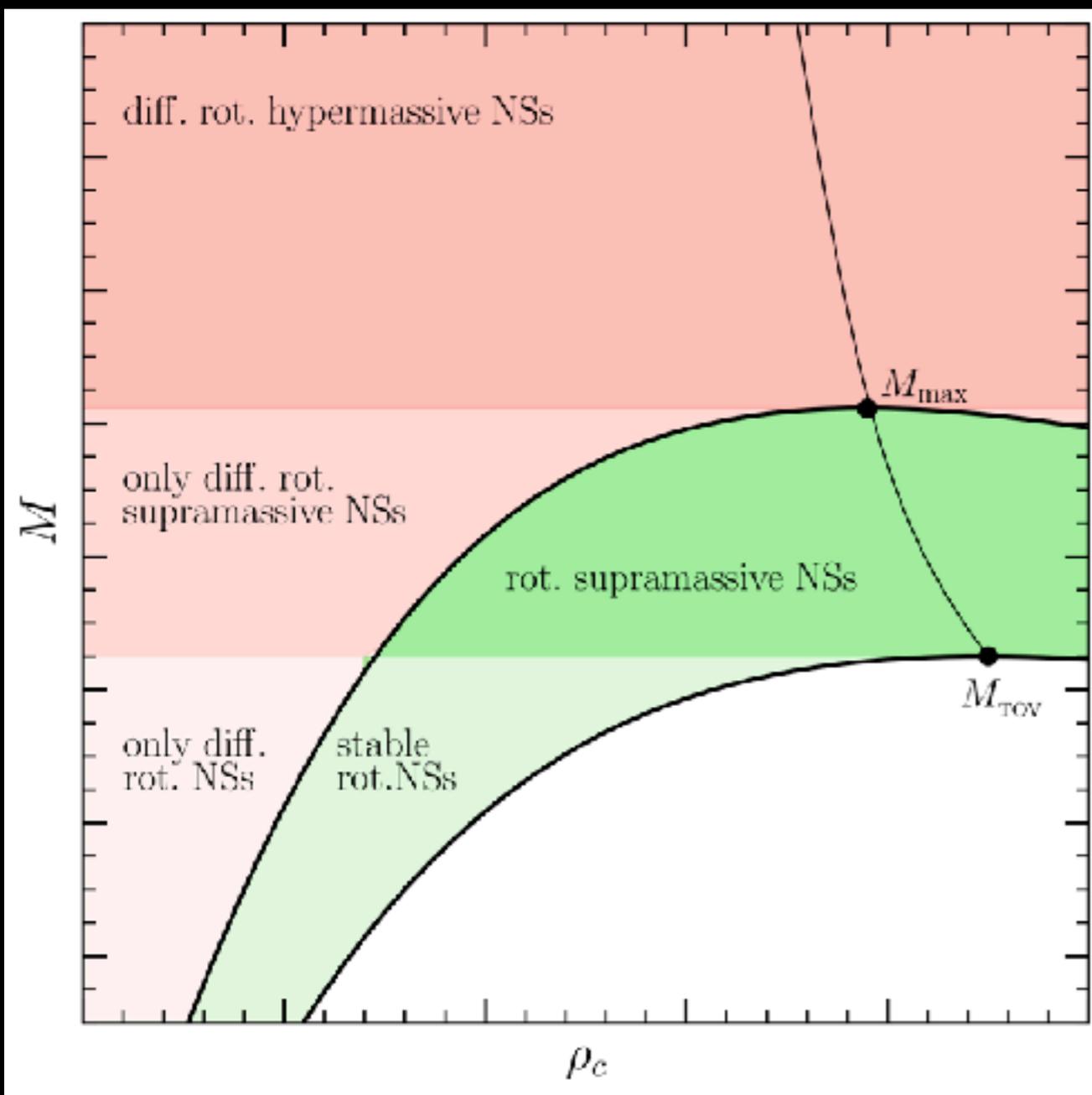


- Green** region is for **uniformly** rotating equilibrium models.
- Salmon** region is for **differentially** rotating equilibrium models.
- Stability line** is simply extended in larger space (Weih+18)

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:

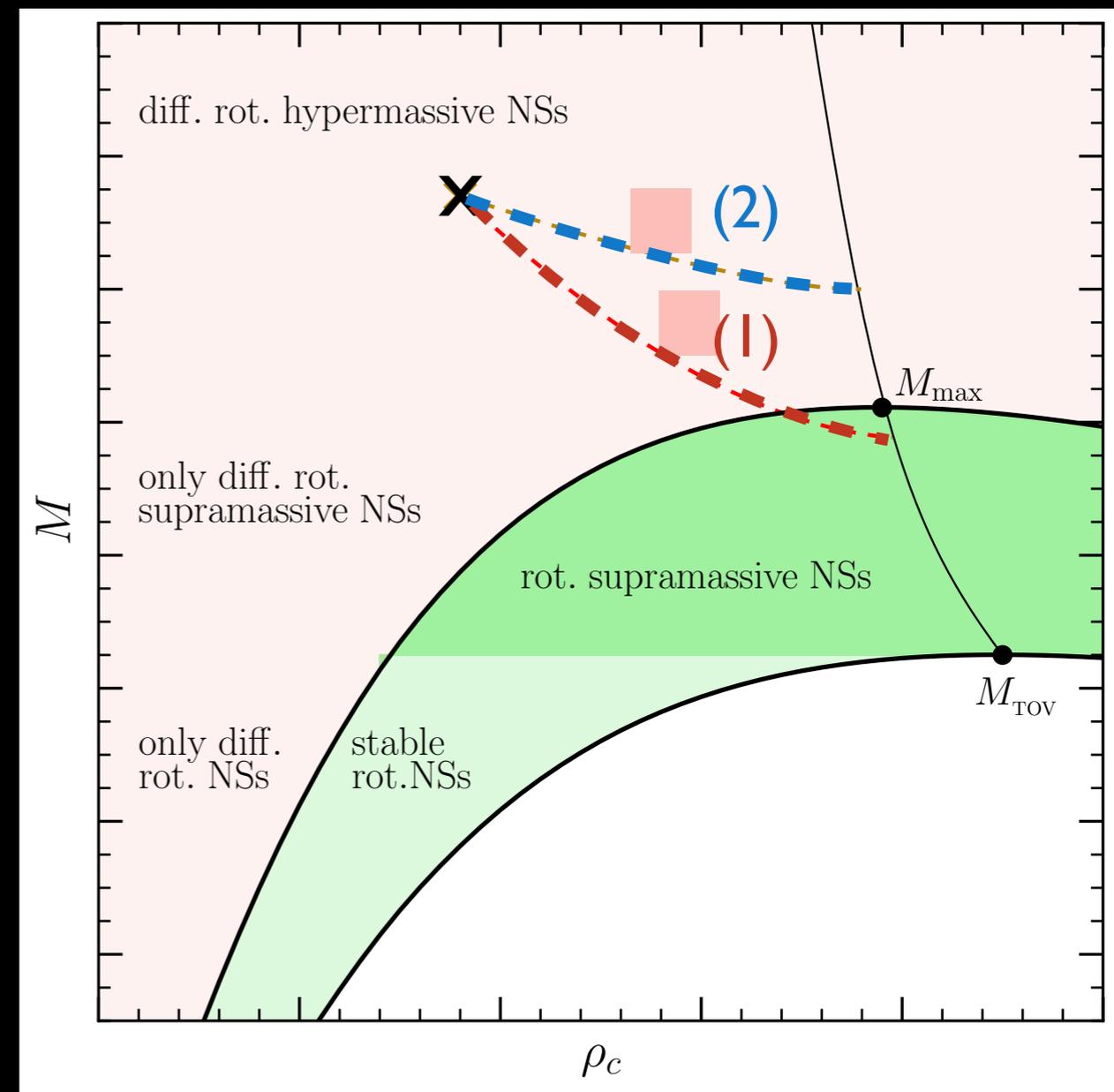
$$M > M_{\text{TOV}}$$

- Hypermassive** stars have:

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

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_{\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

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

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

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

$$M_2 = 2.50 - 2.67 M_{\odot} \quad \text{smallest BH or heaviest NS!}$$

- 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

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

- 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

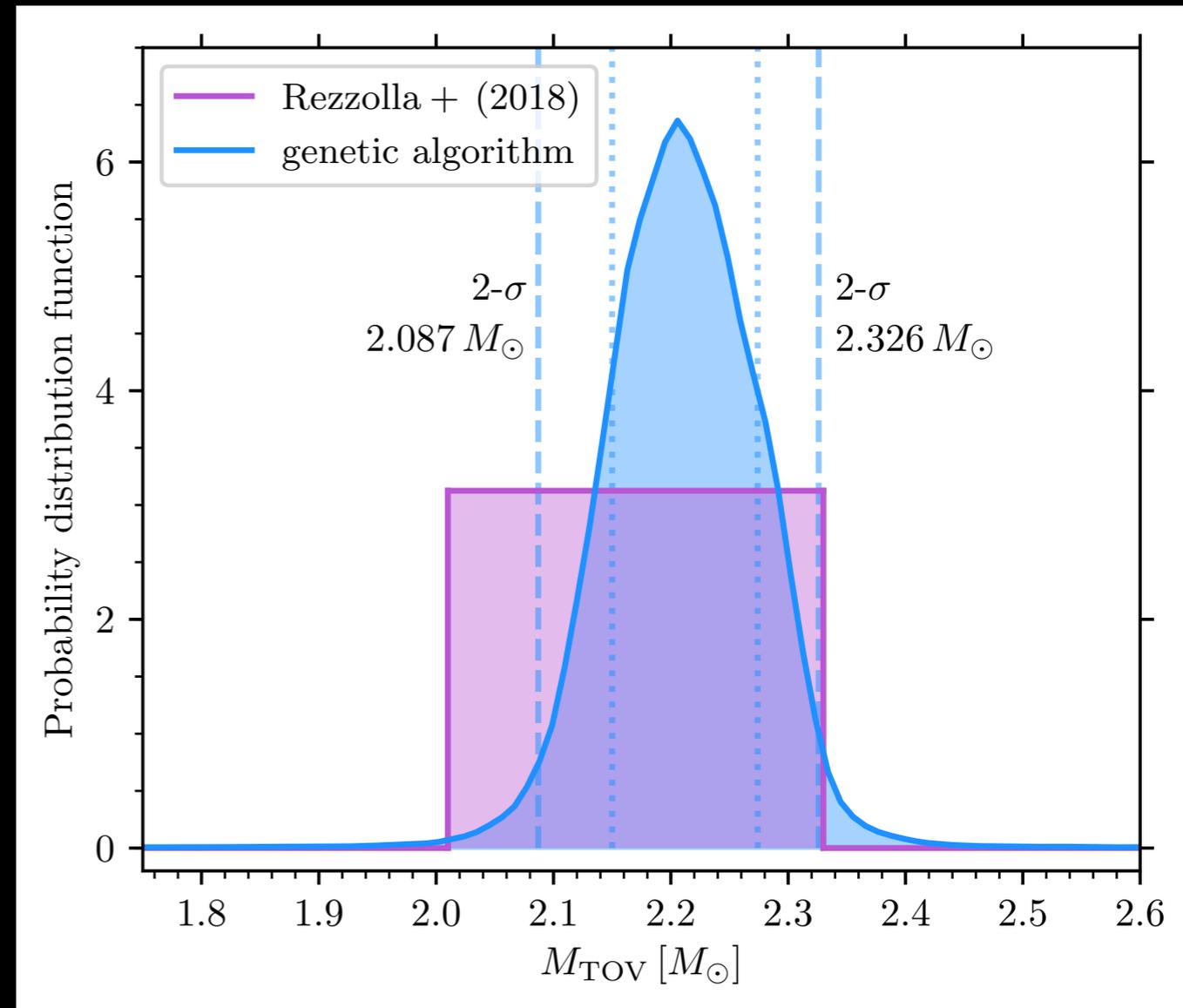
- A **genetic algorithm** is used to sample through the parameter space of the 10 free parameters.

- 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.

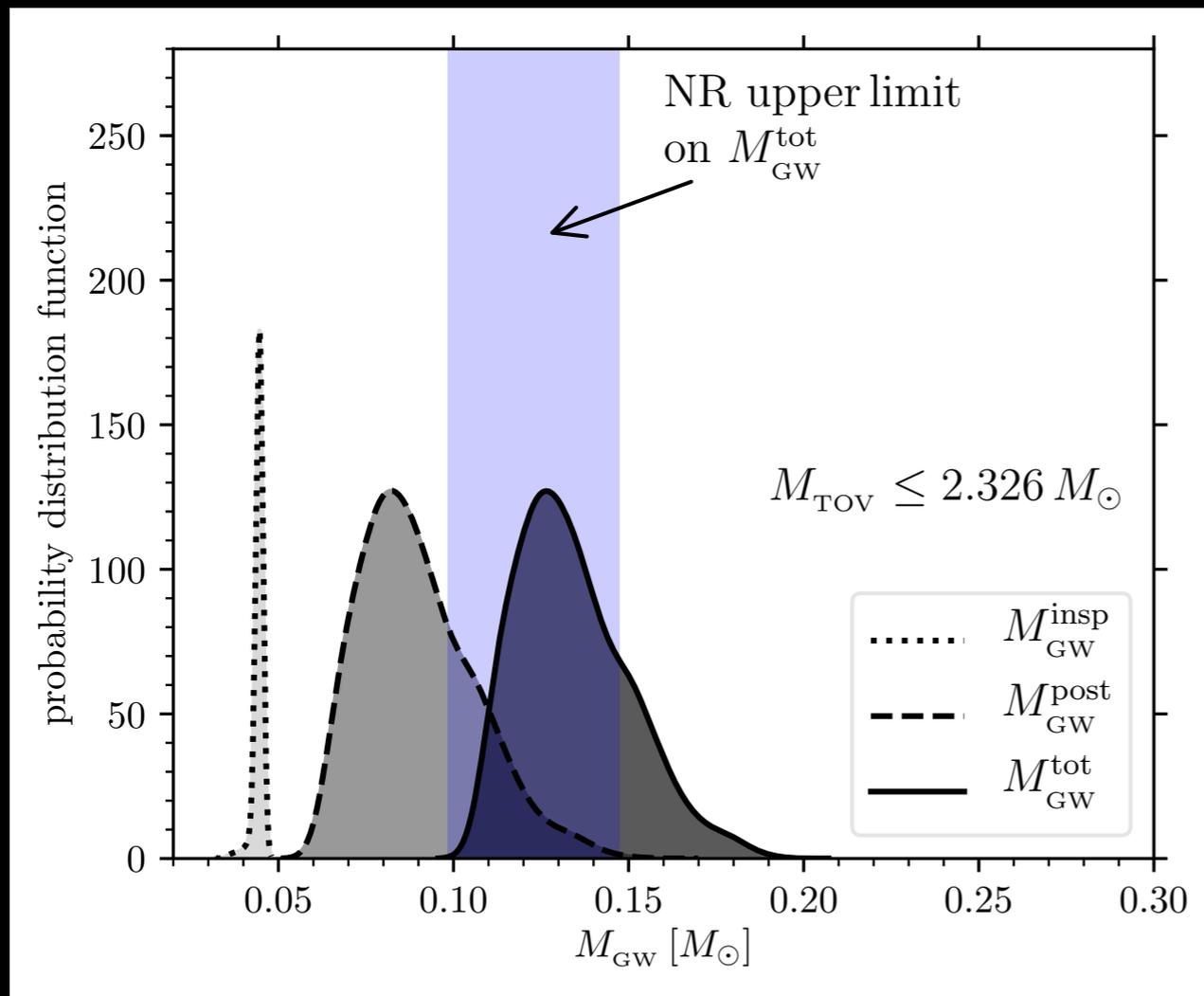
- Consider first previous estimate:

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

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

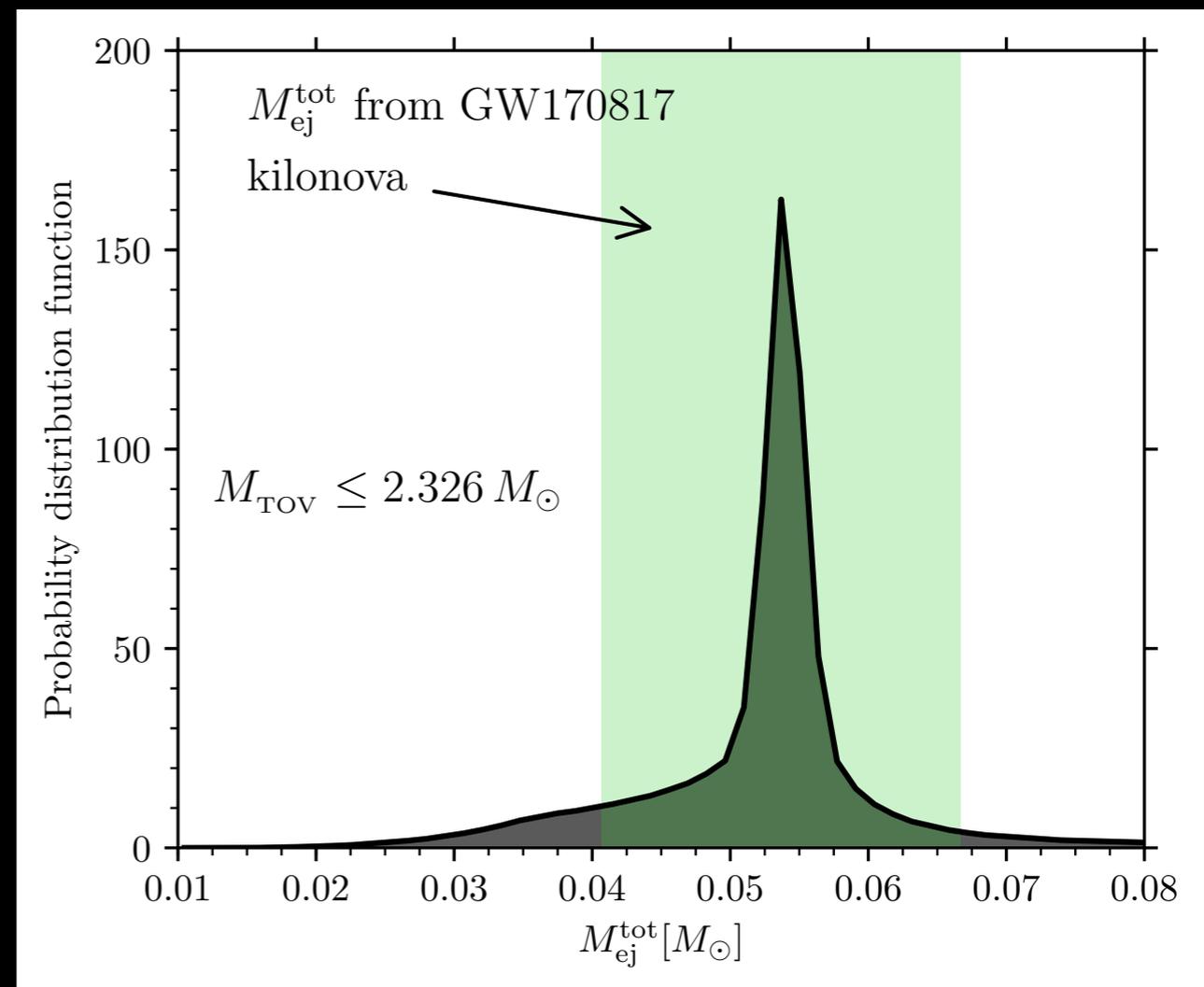


First hypothesis: $M_{\text{TOV}}/M_{\odot} \lesssim 2.3$

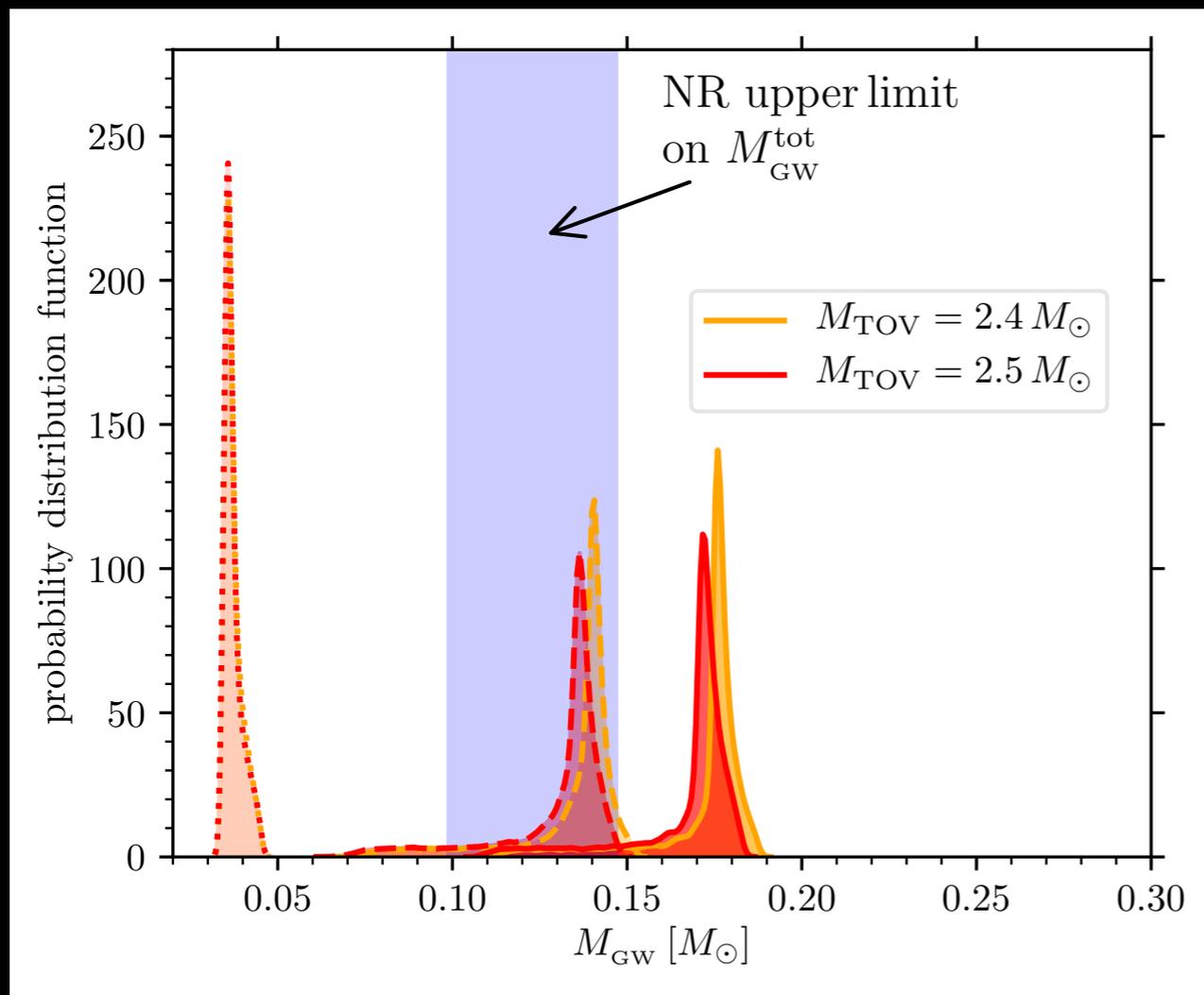


- Total mass ejected is in perfect **agreement** with predictions from kilonova signal

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

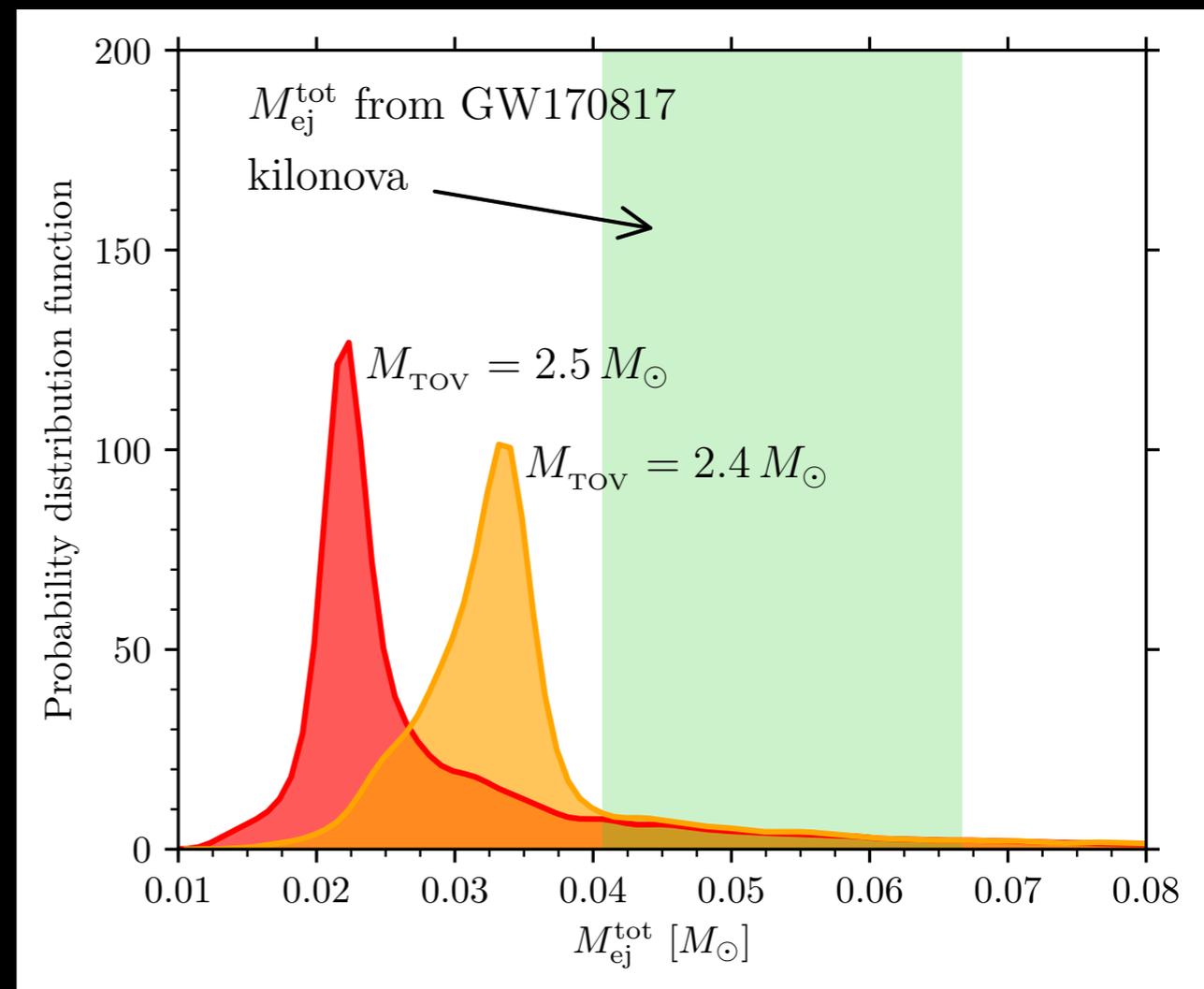


Second hypothesis: $M_{\text{TOV}}/M_{\odot} \gtrsim 2.5$



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

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



Tension on the maximum mass

Nathanail, Most, LR (2020)

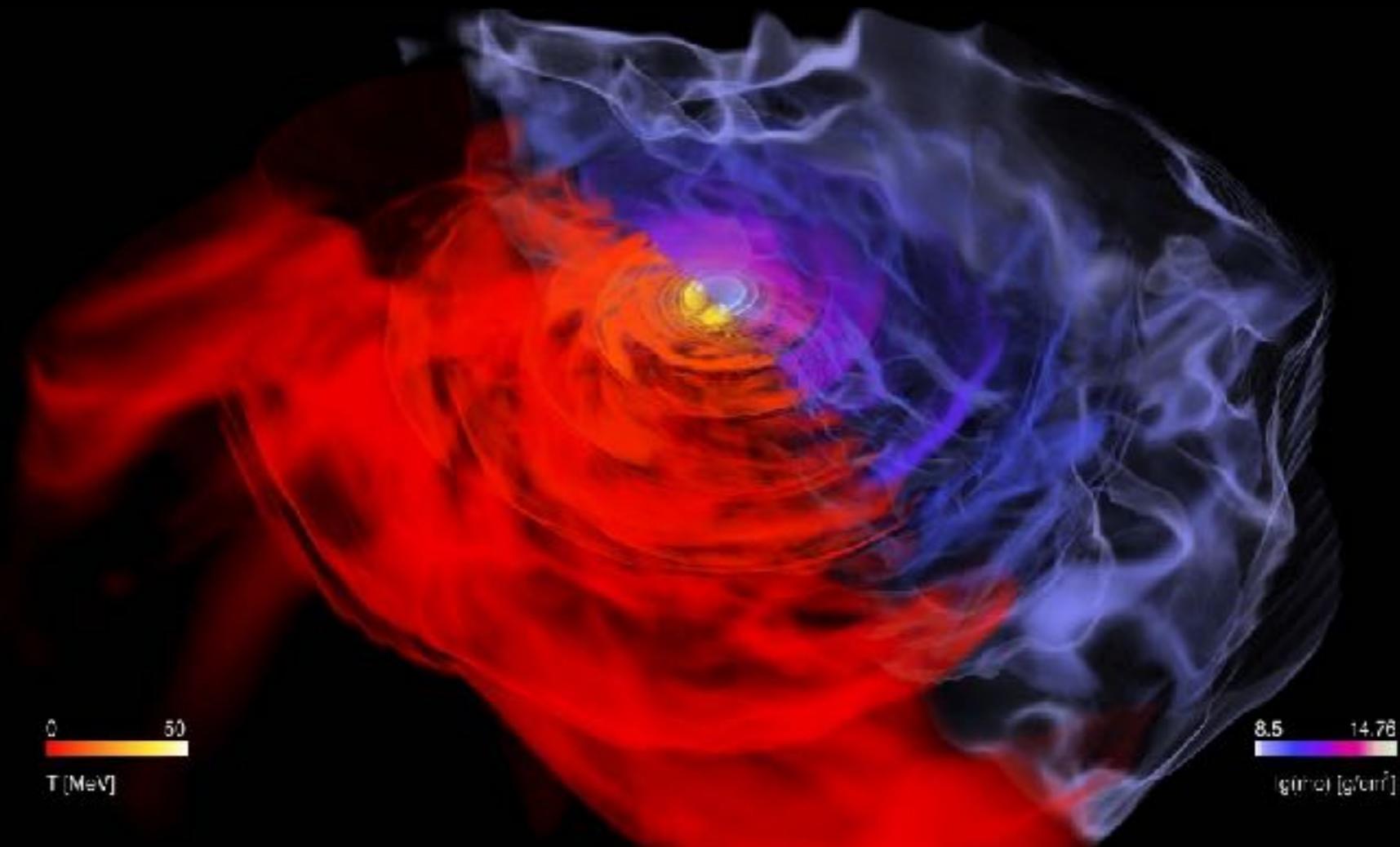
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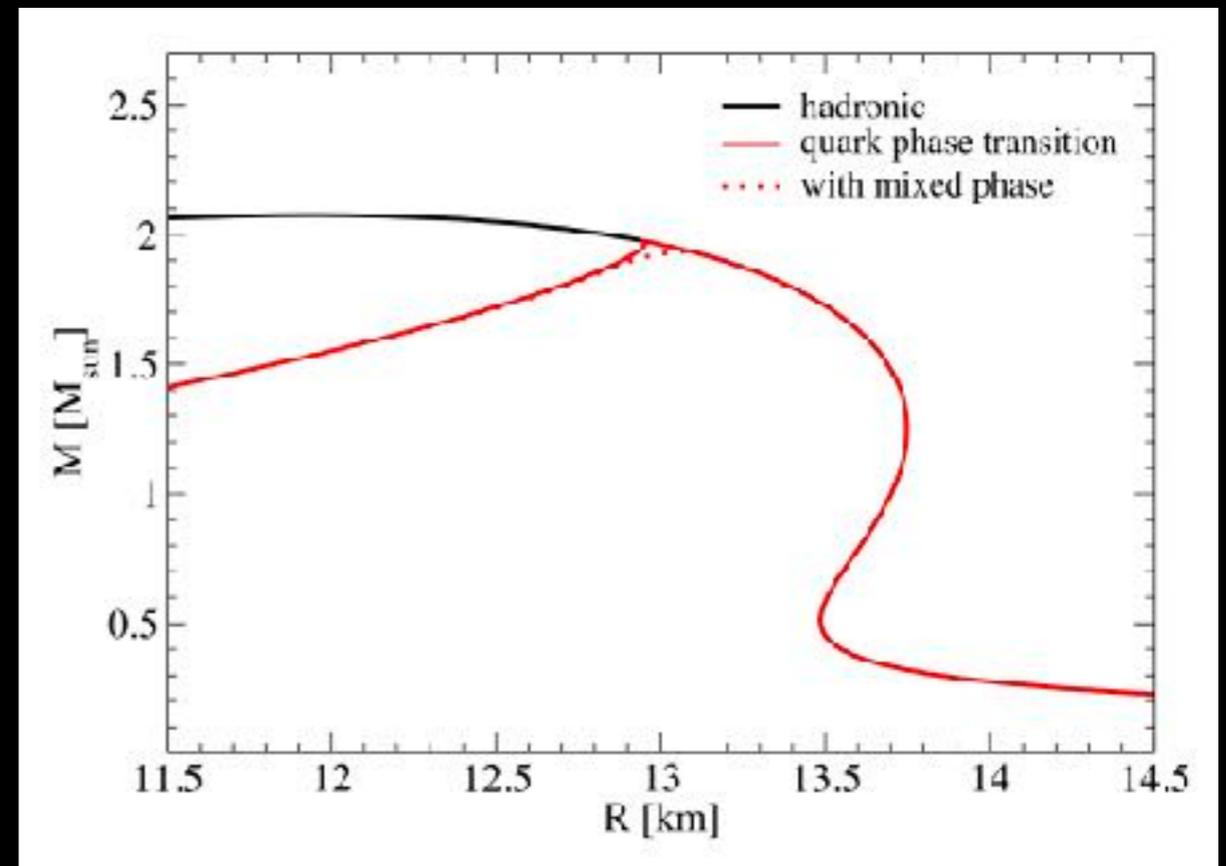
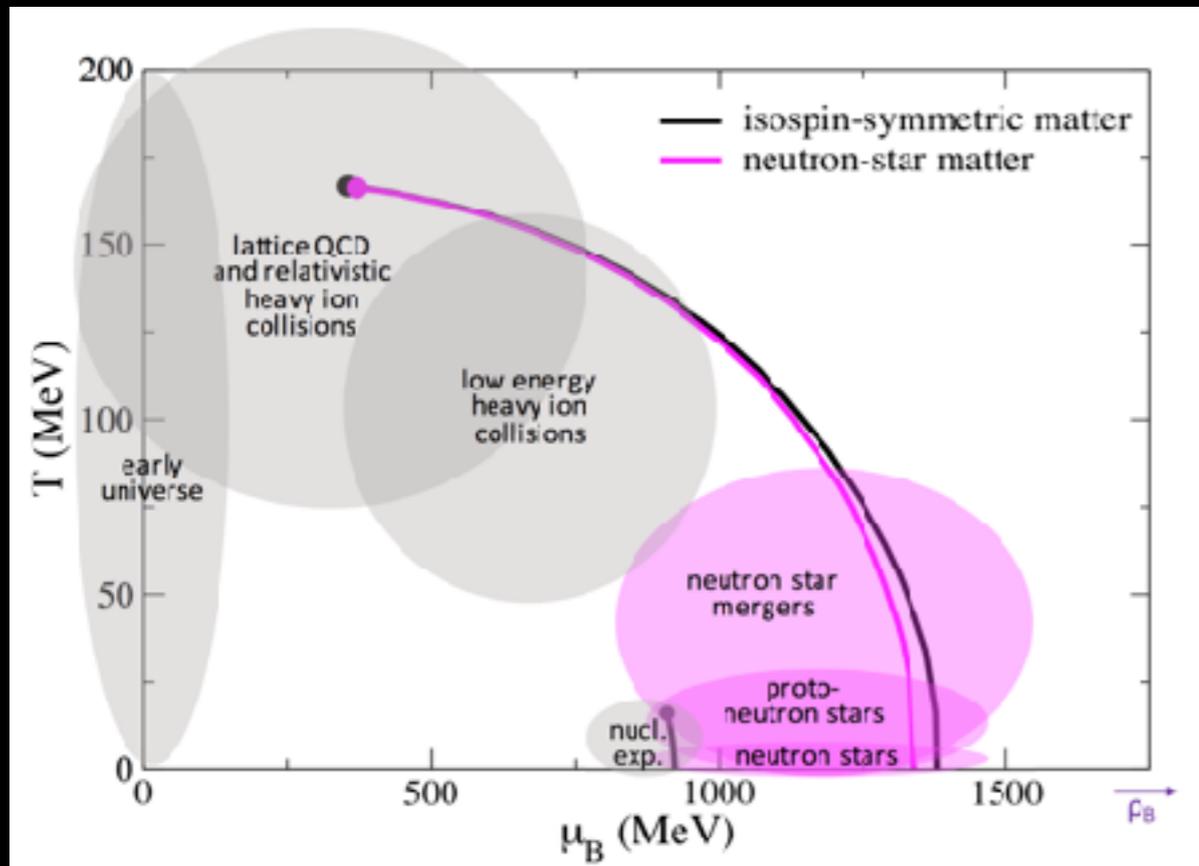
- If secondary in GW190814 was a NS, all previous considerations are incorrect.
- No EM counterpart was observed with GW190814 and no estimates possible on ejected matter or timescale for survival.
- **How do we solve this tension?**
- Solution: secondary in GW190814 was a **BH at merger** but could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

Phase transitions and their signatures



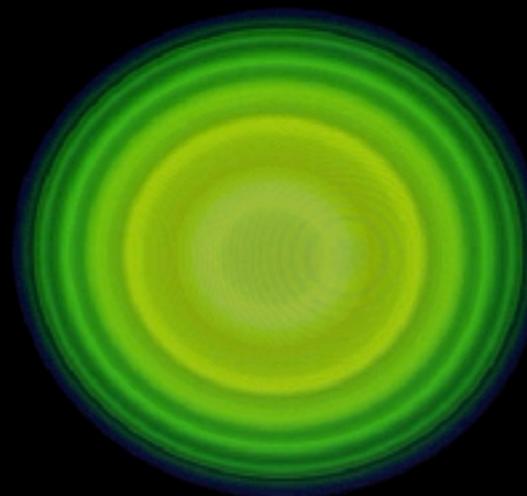
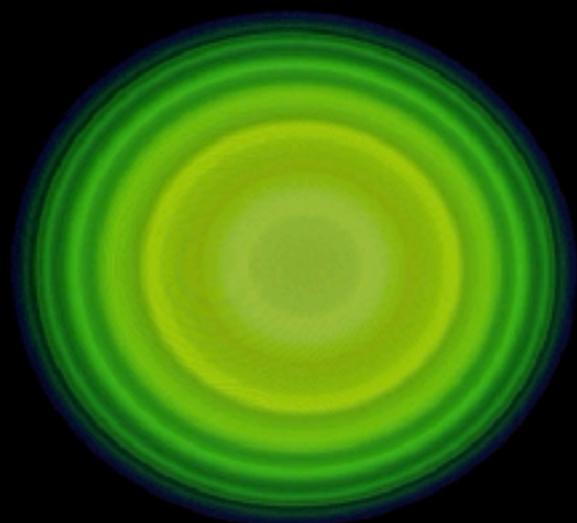
Most, Papenfort, Dexheimer, Hanauske, Schramm, Stoecker, LR (2019)
Weih, Hanauske, LR (2020)

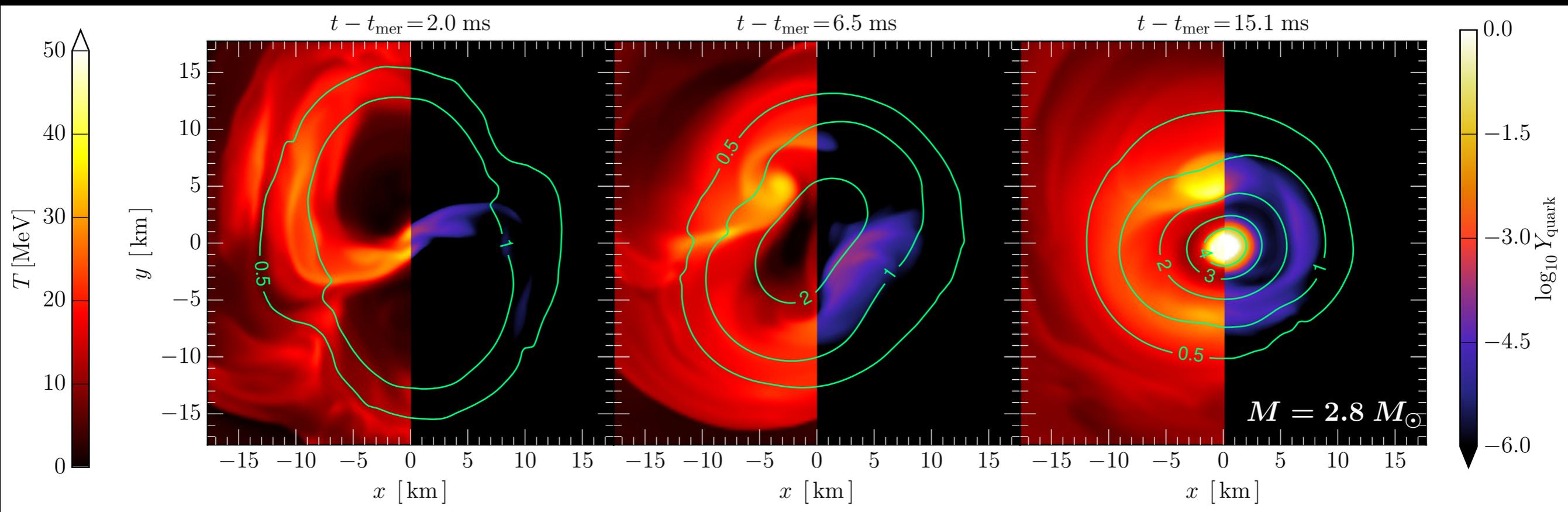
- **Isolated** neutron stars probe a small fraction of phase diagram.
- Neutron-star **binary** mergers reach temperatures up to **80 MeV** and probe regions complementary to experiments.



- 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

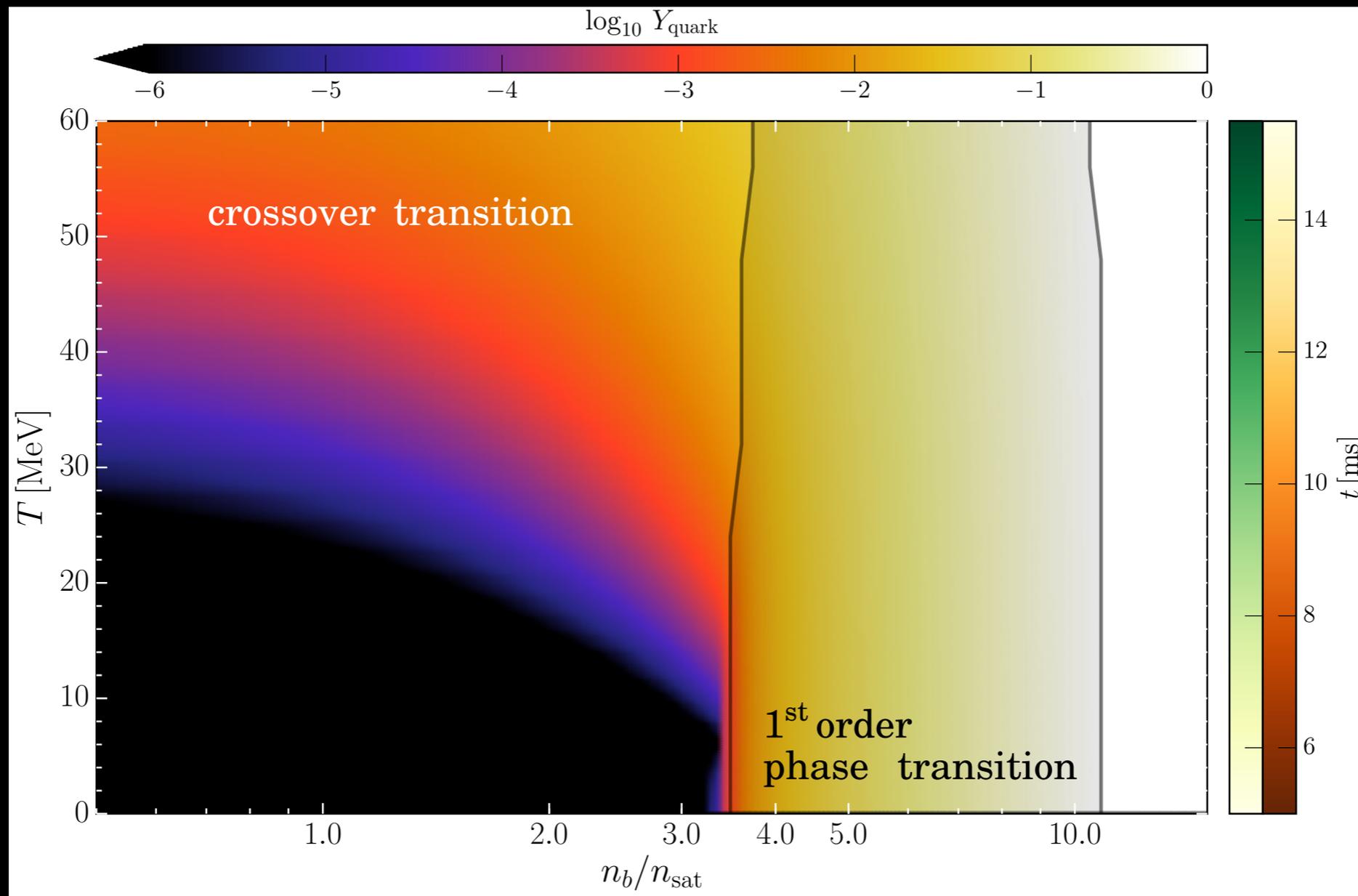




Quarks appear at sufficiently large
temperatures and **densities**.

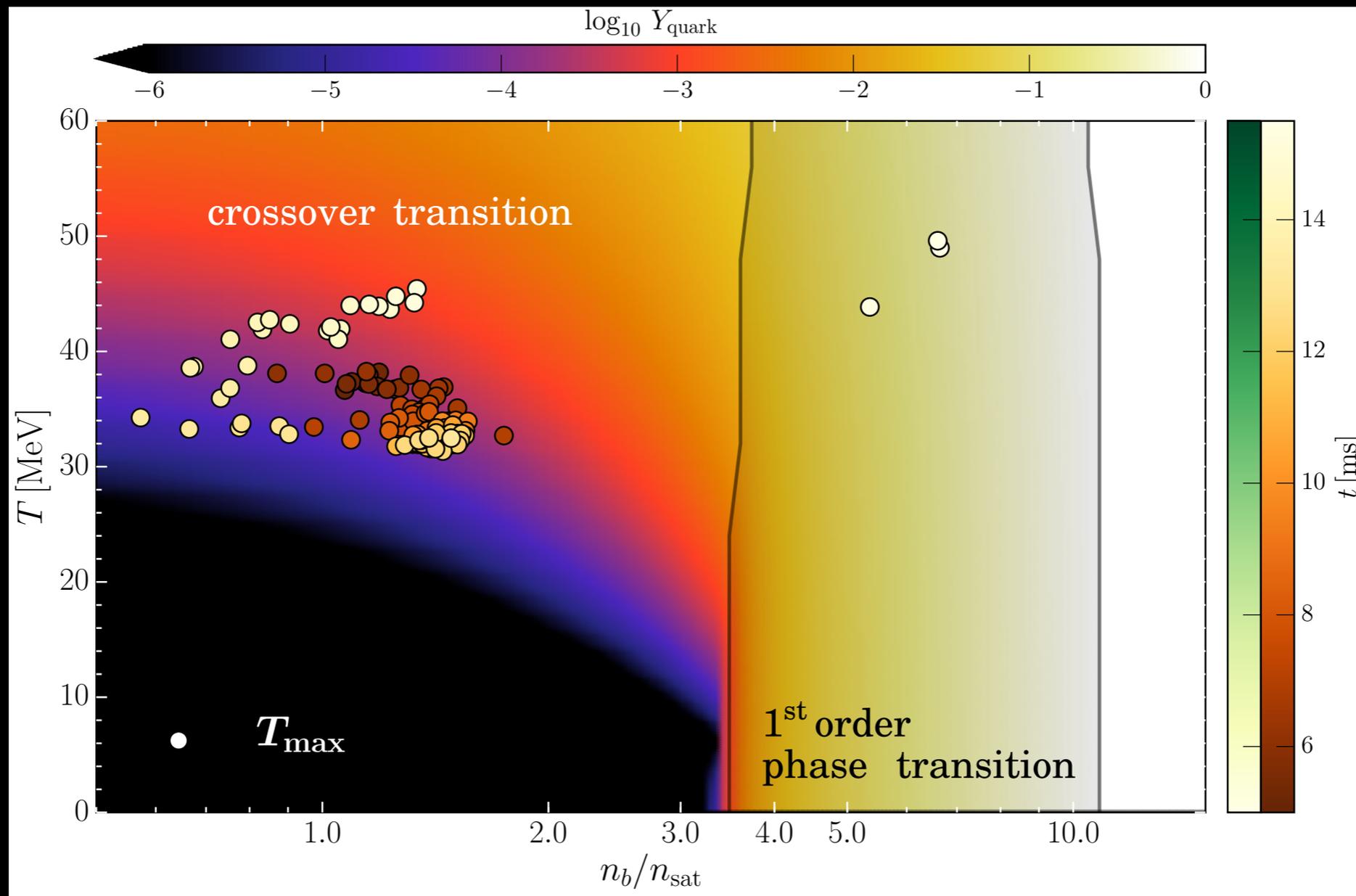
When this happens the **EOS** is
 considerably **softened** and a BH produced.

Comparing with the phase diagram



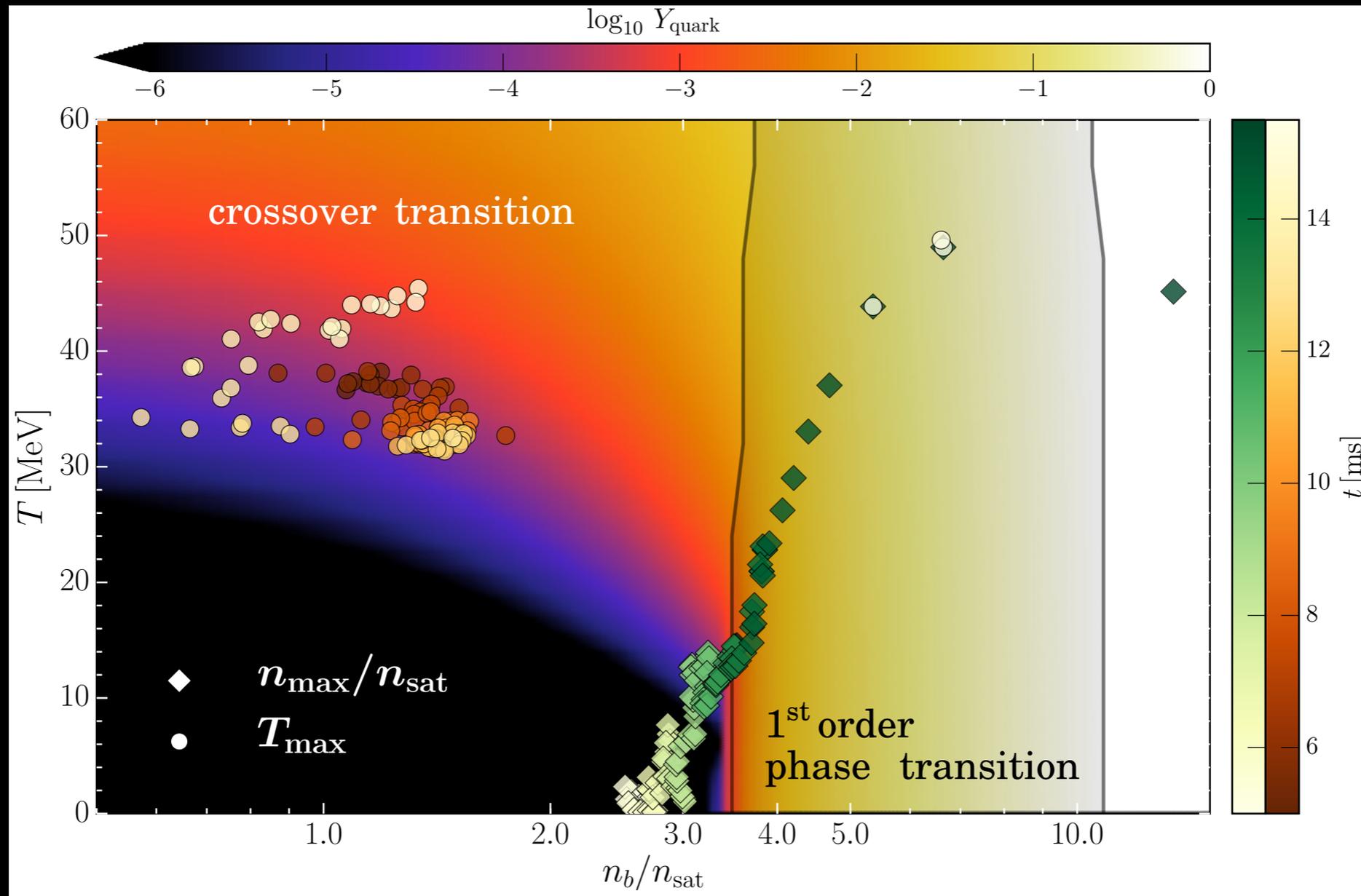
- Phase diagram with quark fraction

Comparing with the phase diagram



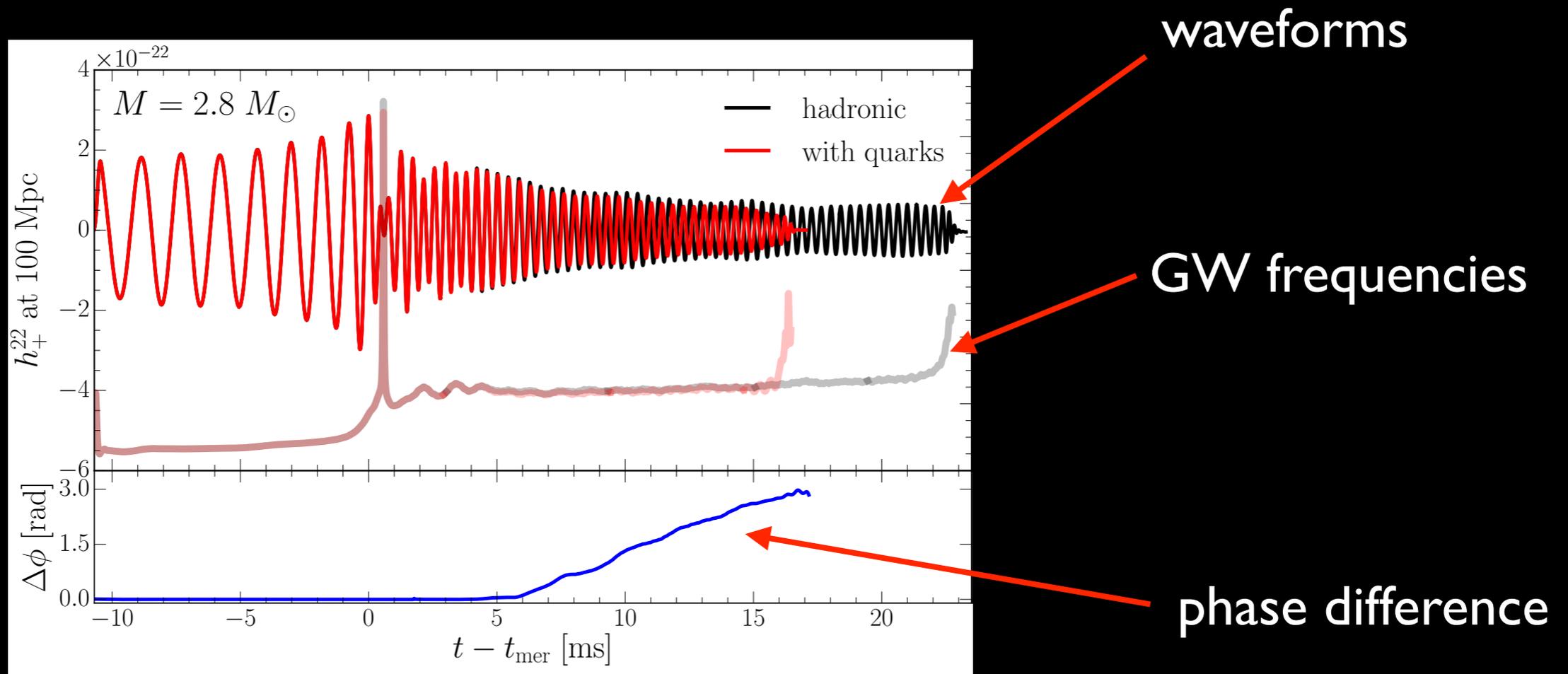
- Phase diagram with quark fraction
- Circles show the position in the diagram of the maximum temperature as a function of time

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

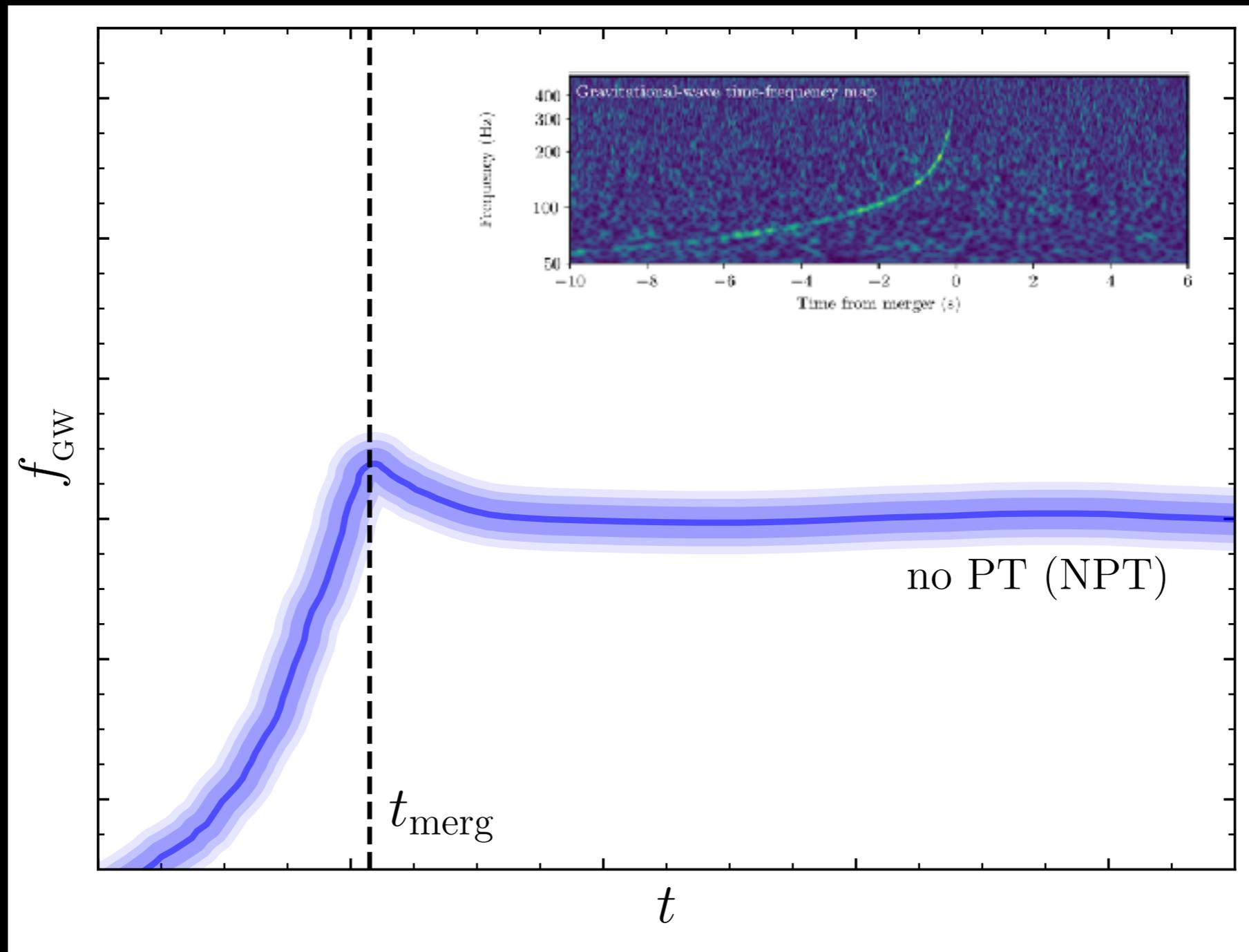


- After ~ 5 ms, quark fraction is large enough to change quadrupole moment and yield differences in the waveforms.
- Sudden softening of the phase transition leads to collapse and **large difference** in phase evolution.

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

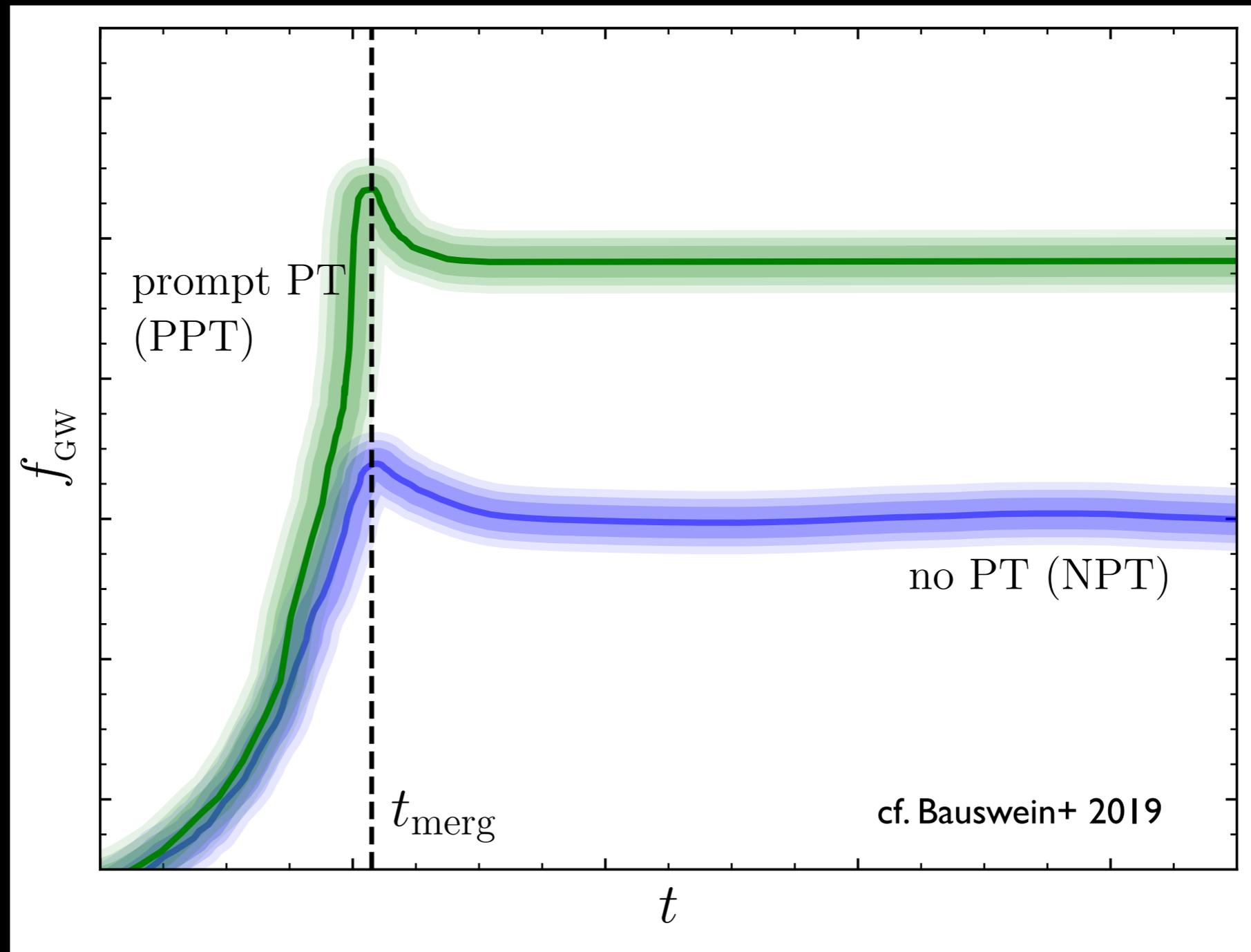
A more comprehensive picture

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



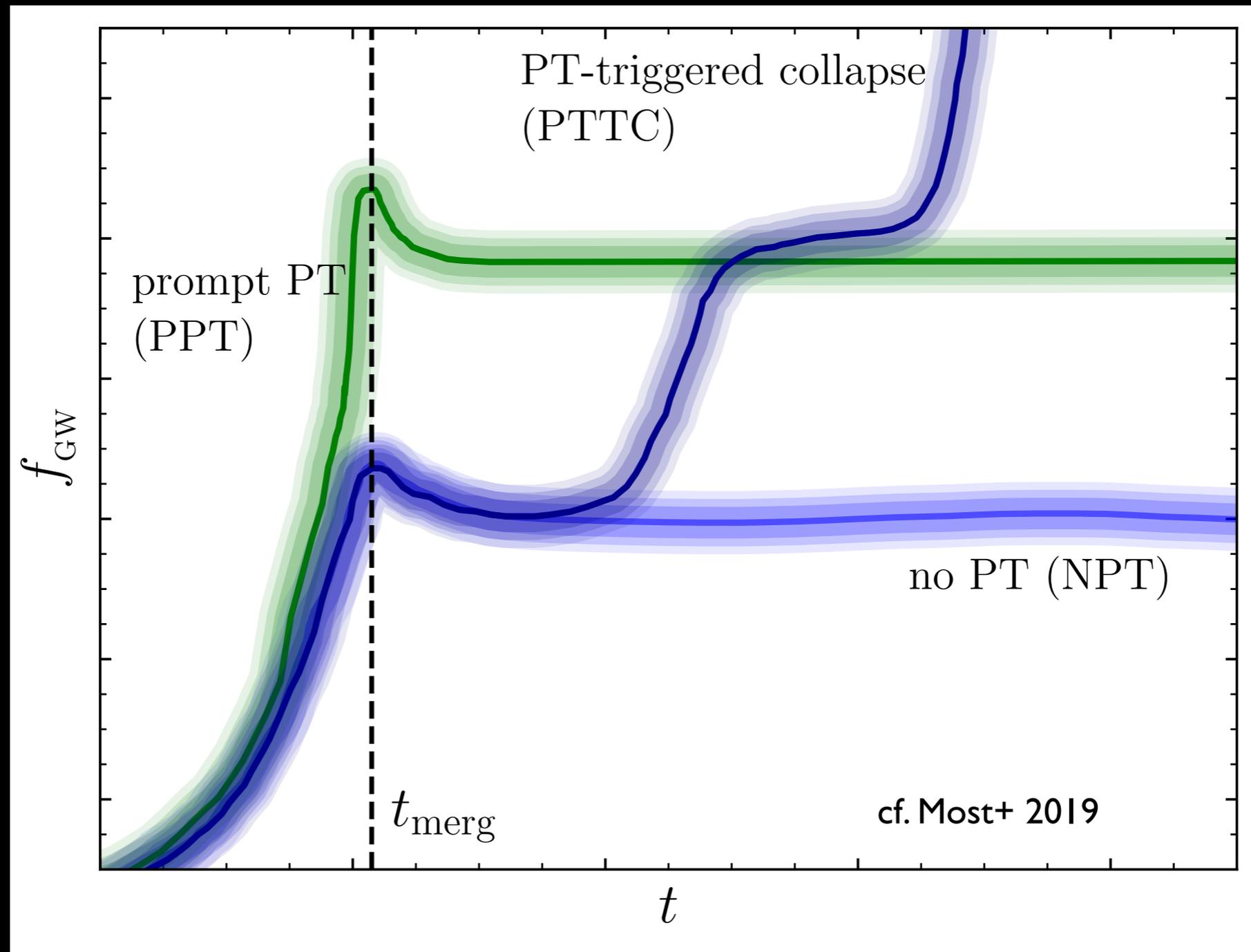
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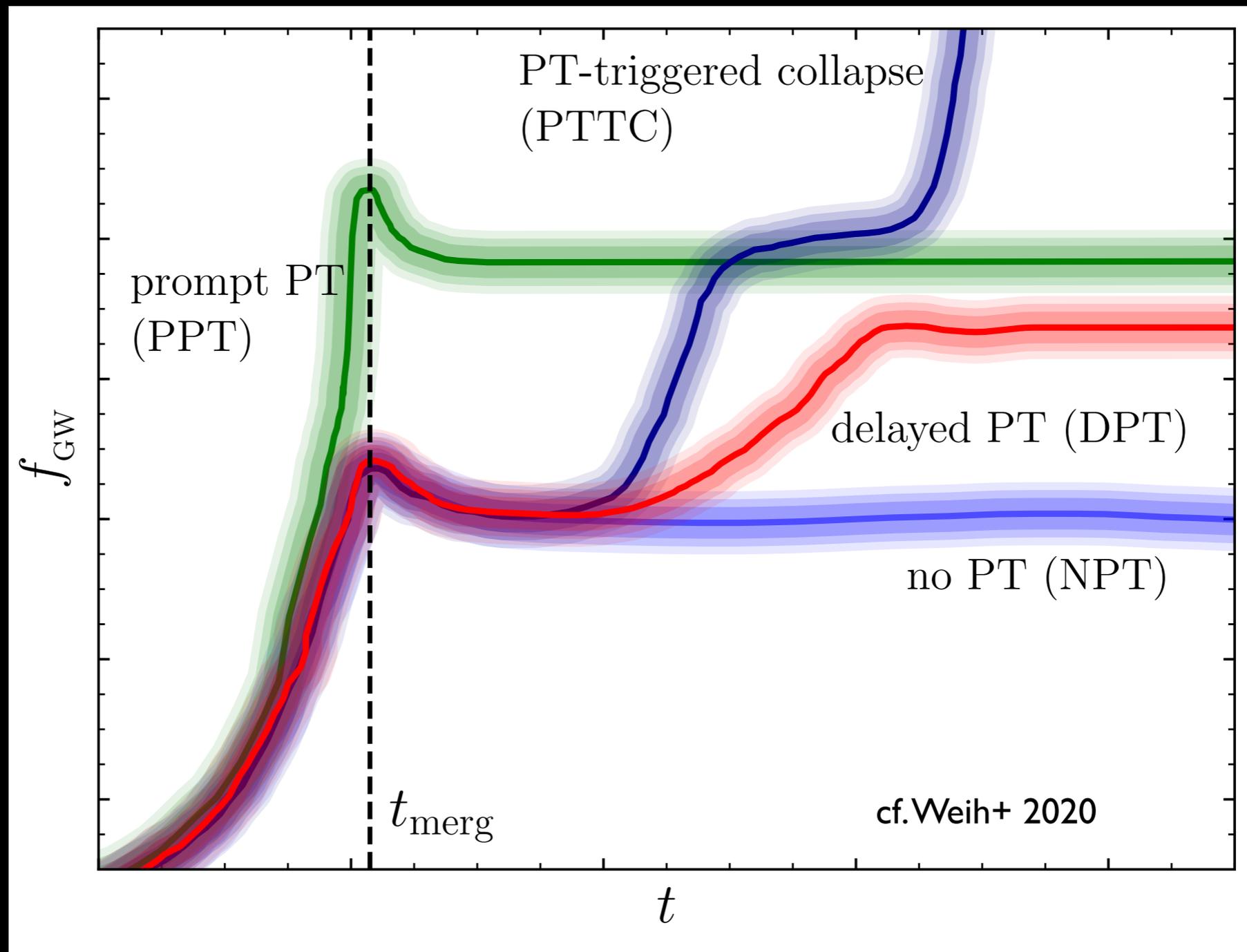
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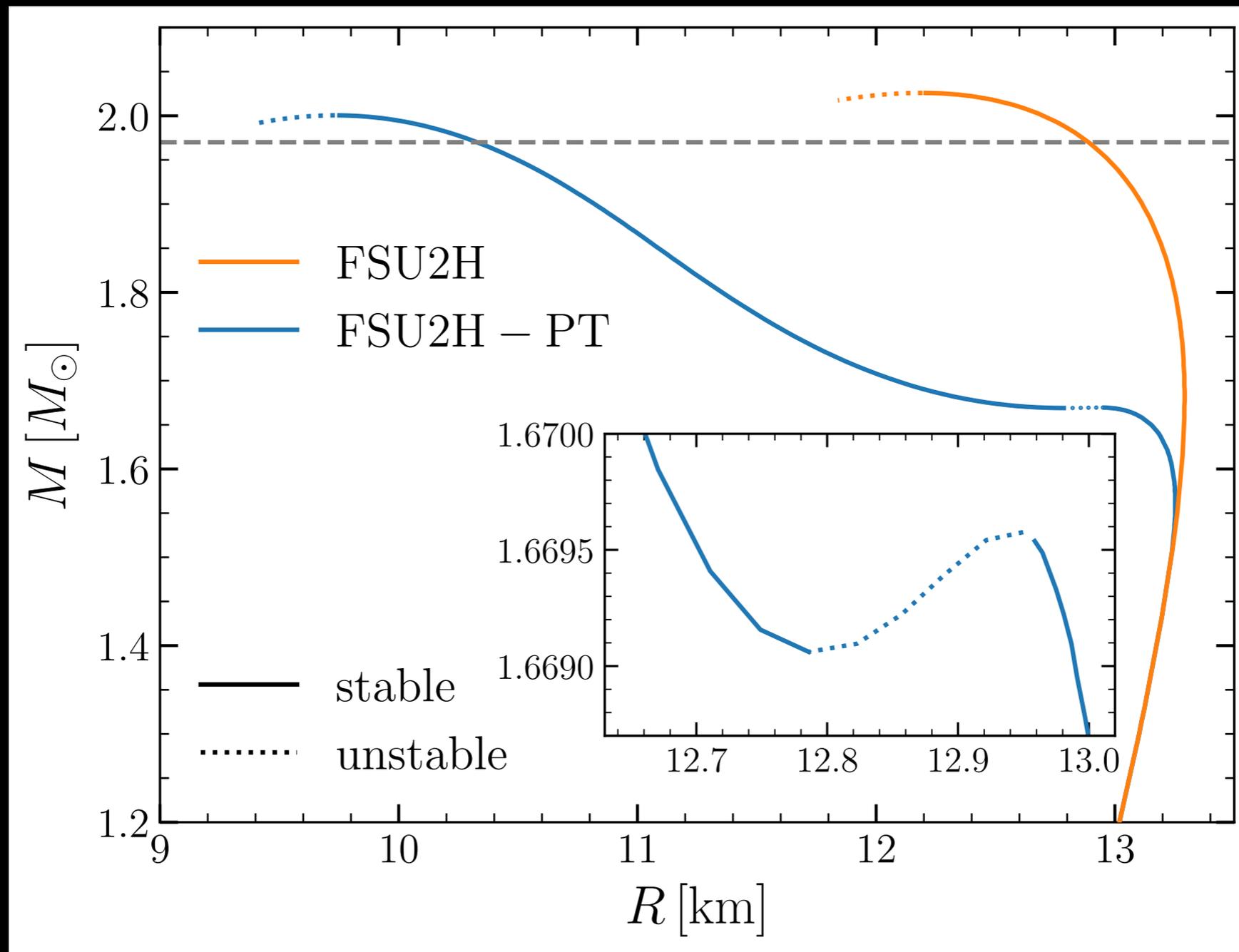
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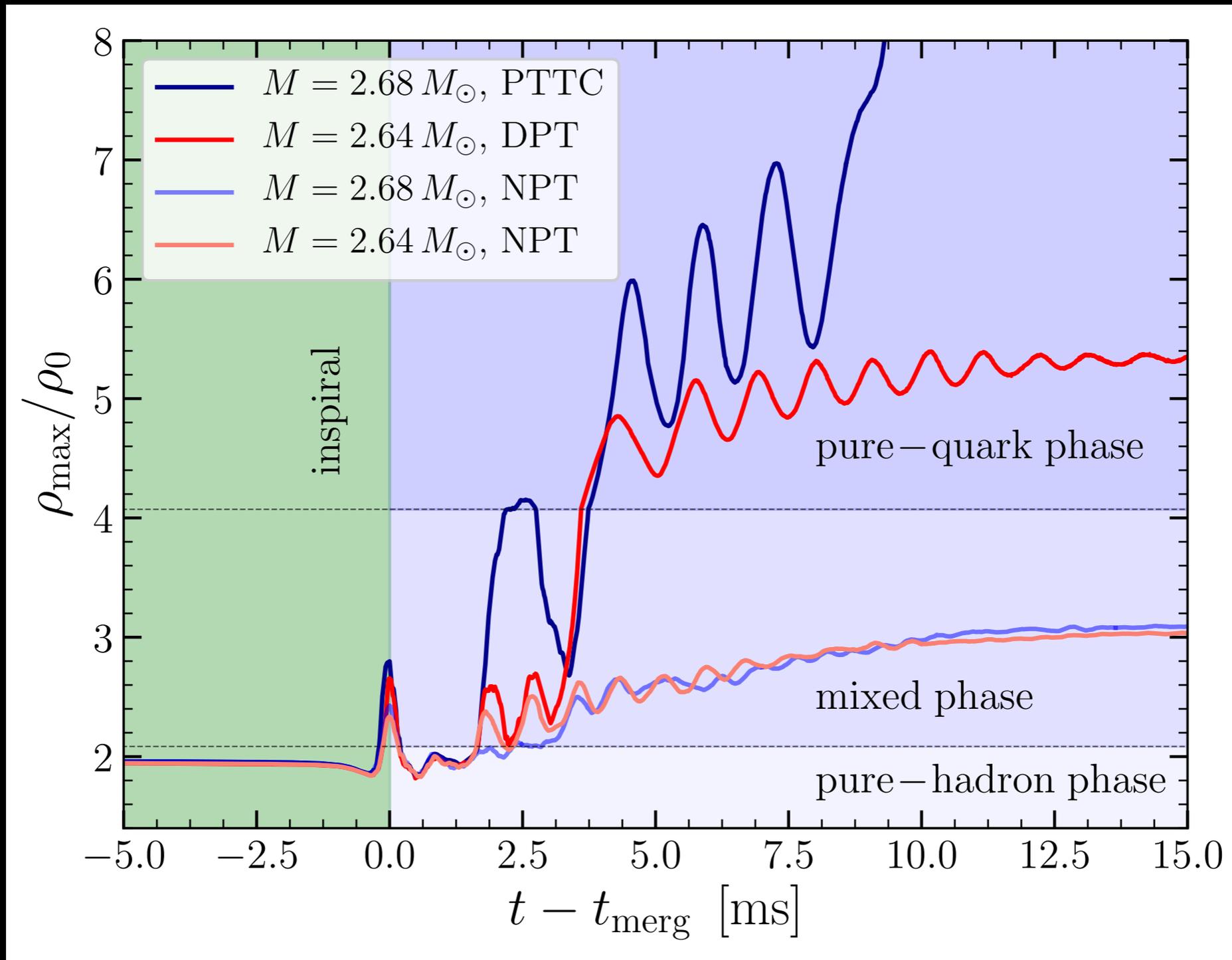
A more comprehensive picture

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



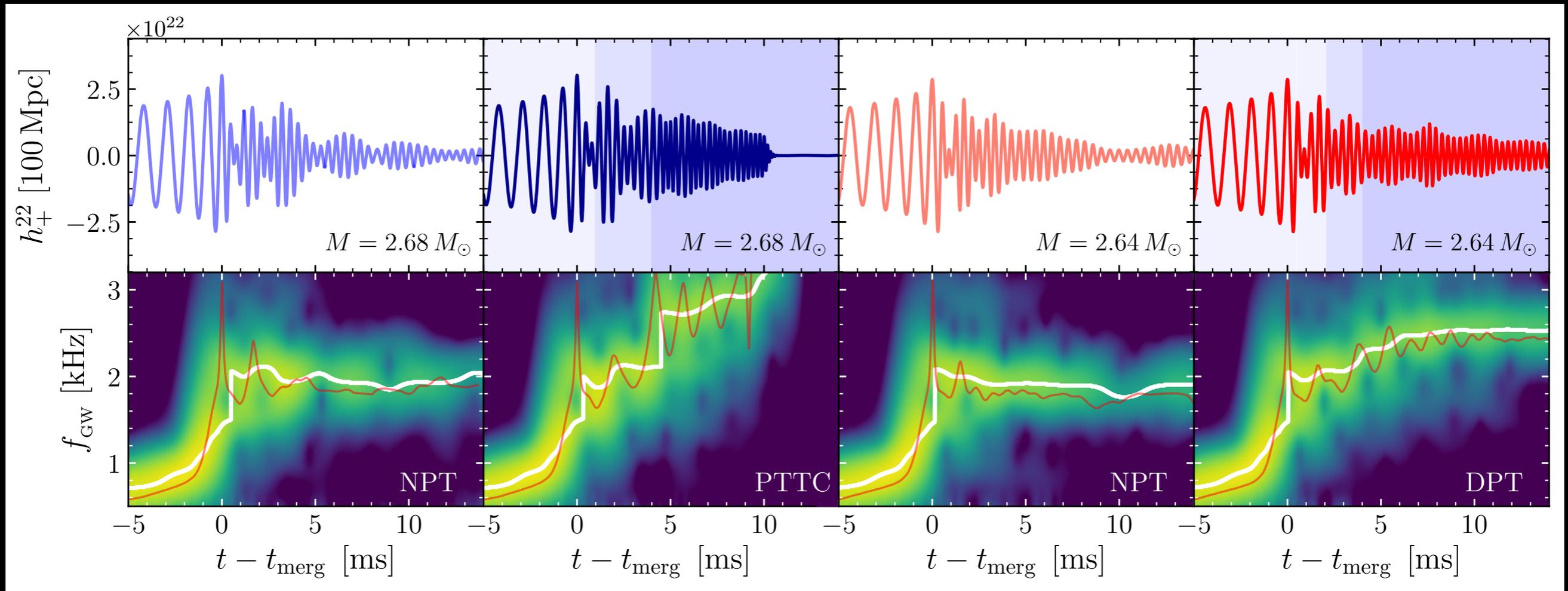
A more comprehensive picture

Best understood in terms of the evolution of the normalise maximum rest-mass density: ρ_{\max}/ρ_0



A more comprehensive picture

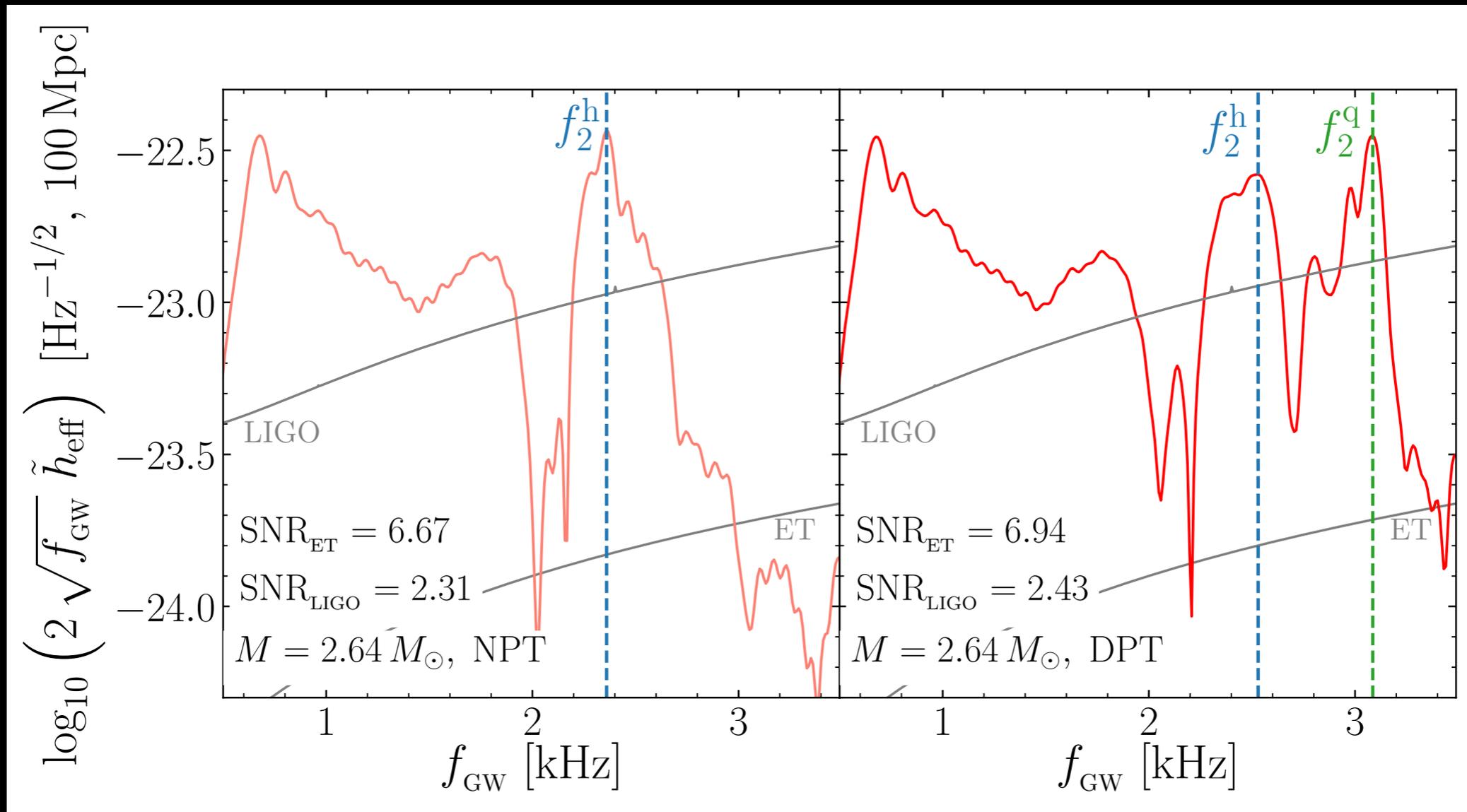
Different signatures are also quite transparent when shown in terms of the gravitational waves and their spectrograms.



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

A more comprehensive picture

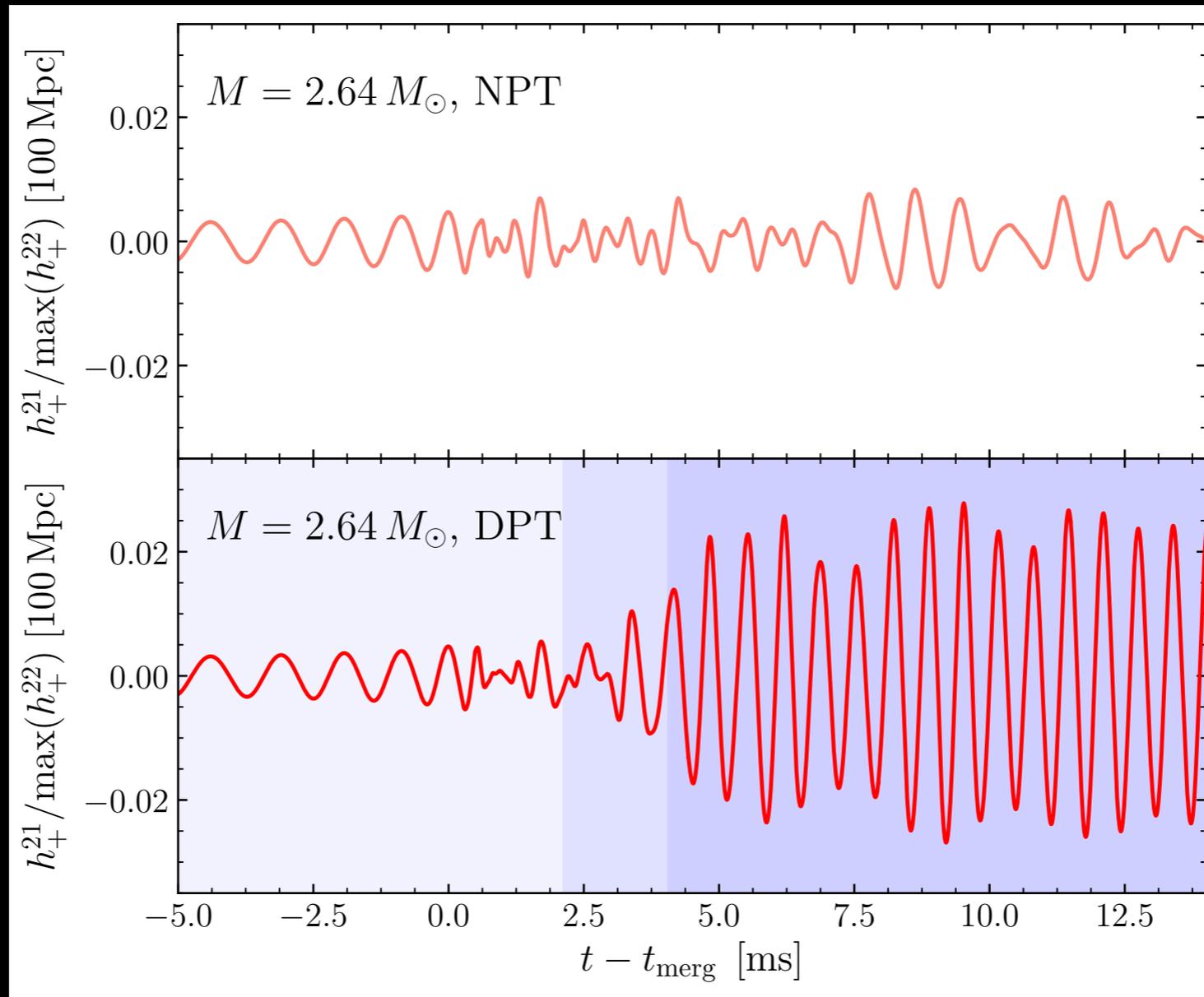
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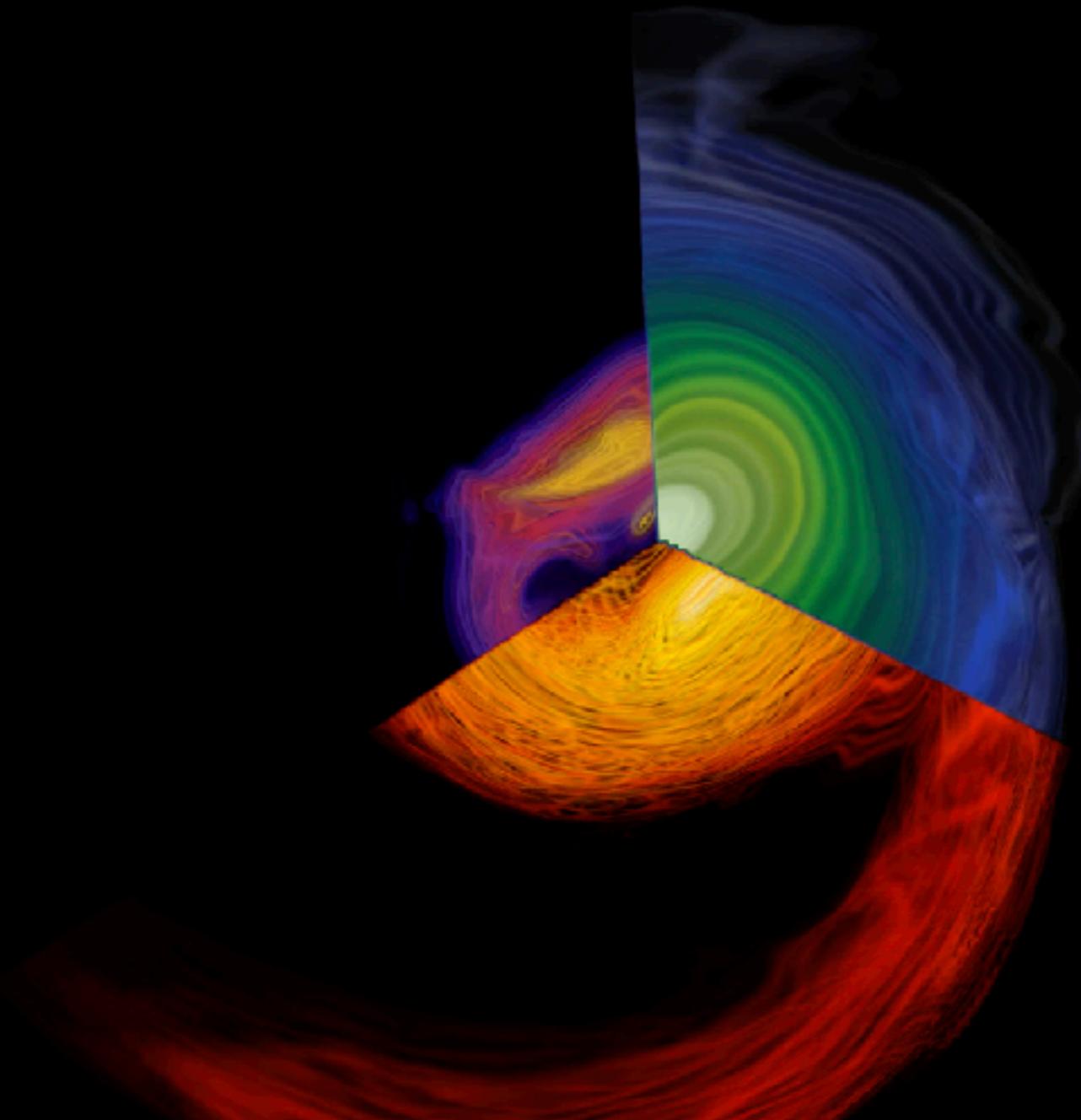
A more comprehensive picture

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



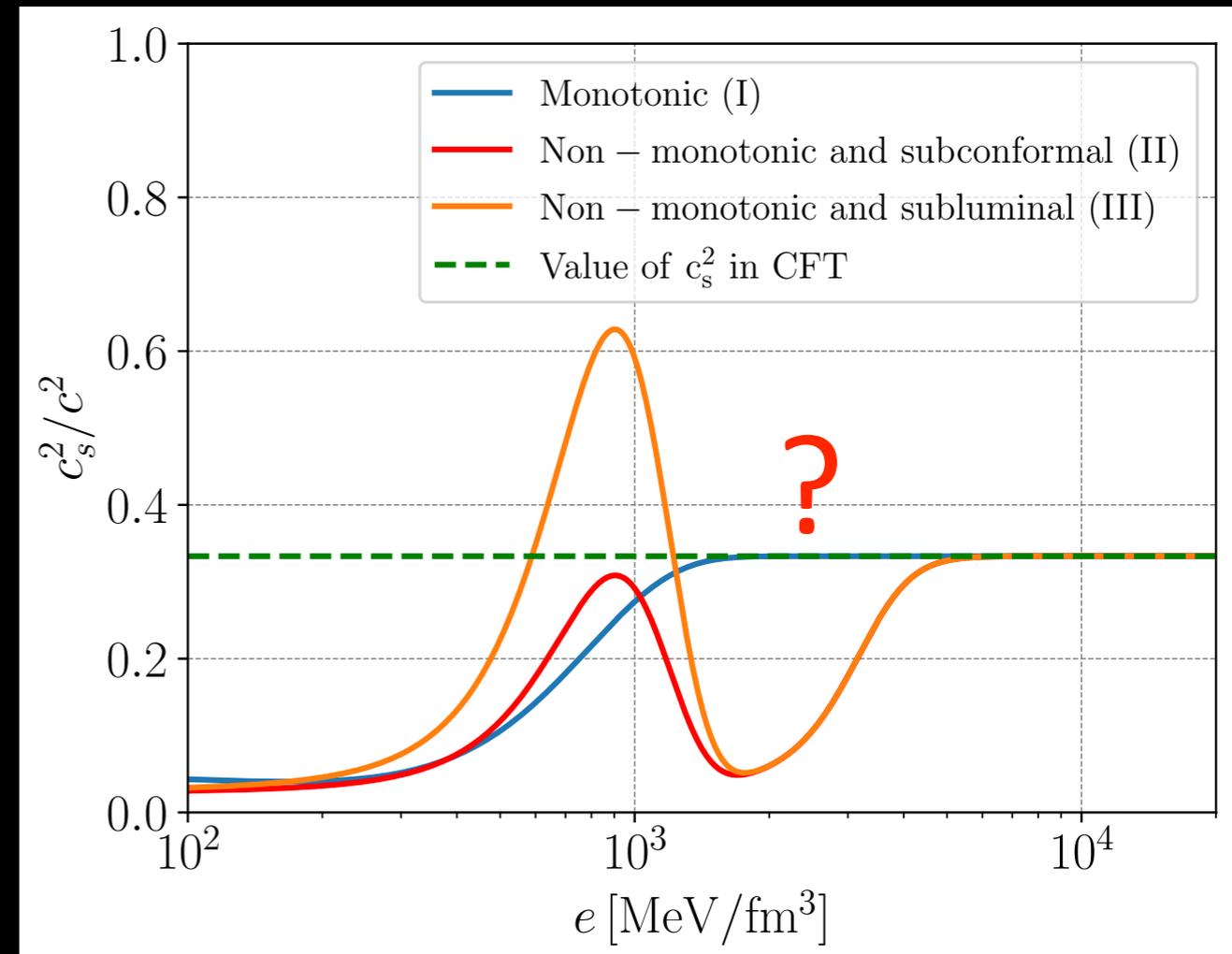
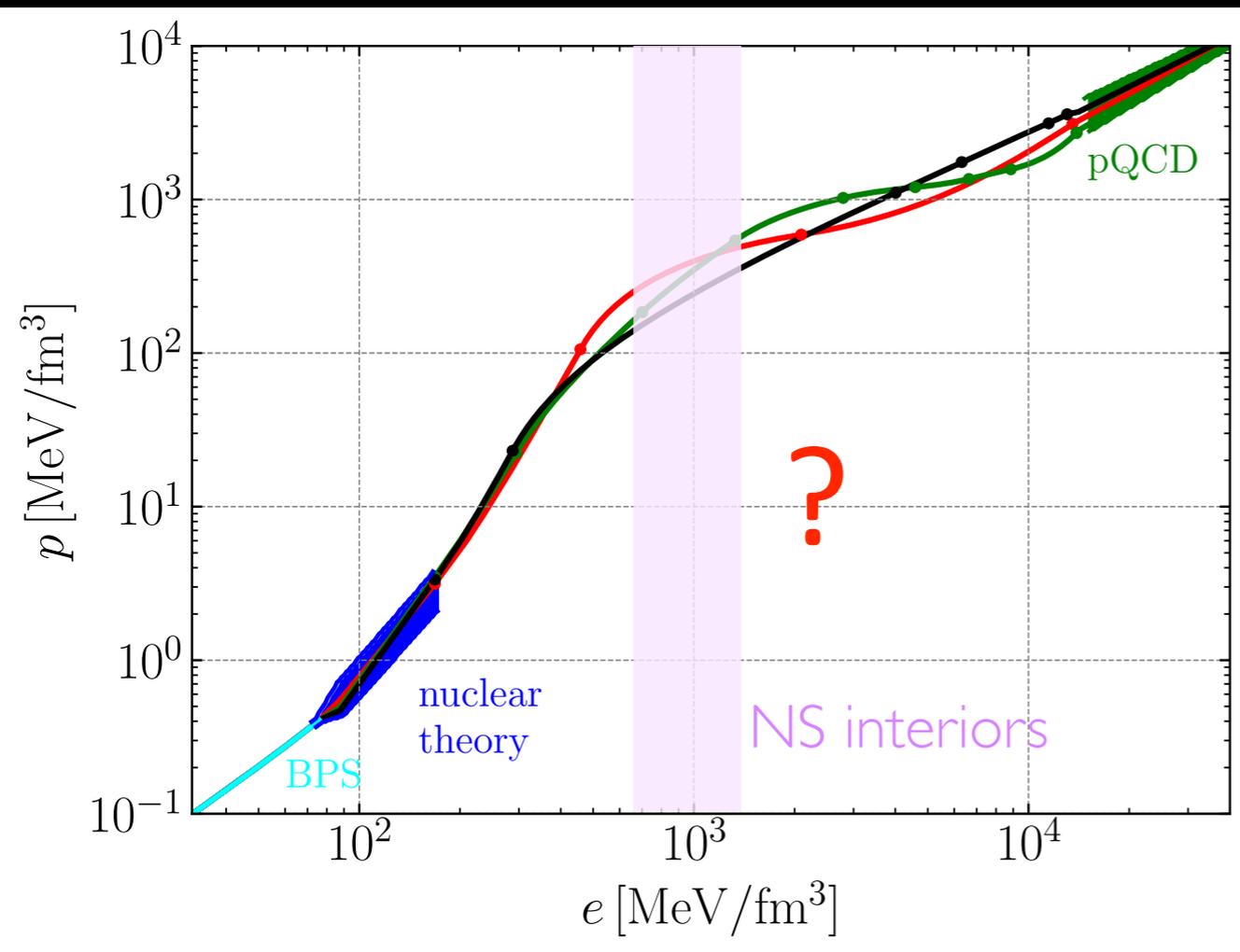
The mode is triggered by the PT and the non-axisymmetric deformations it produces.

On the sound speed in neutron stars



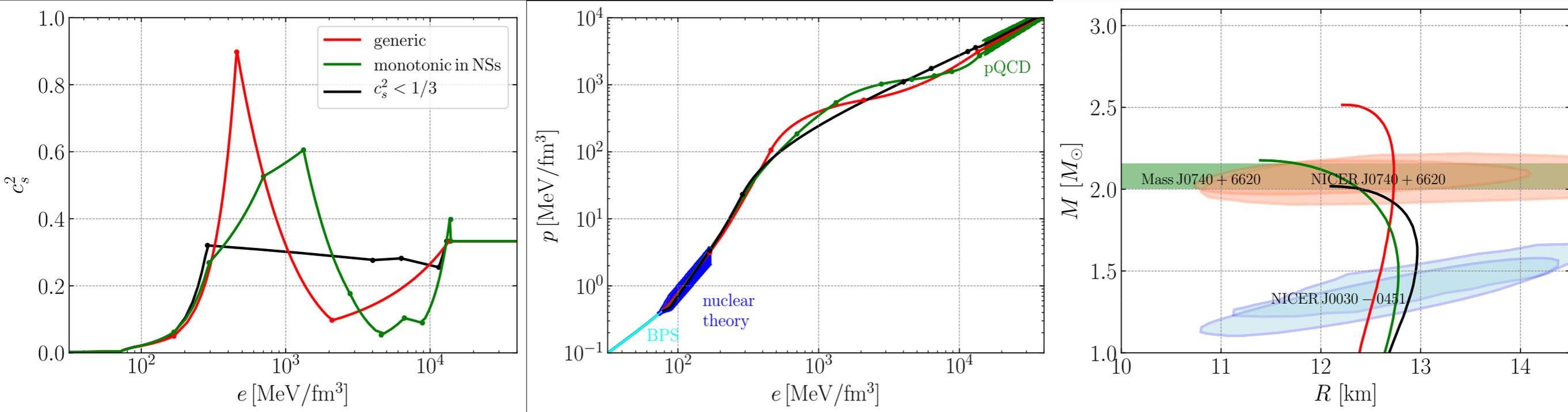
A very basic question

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



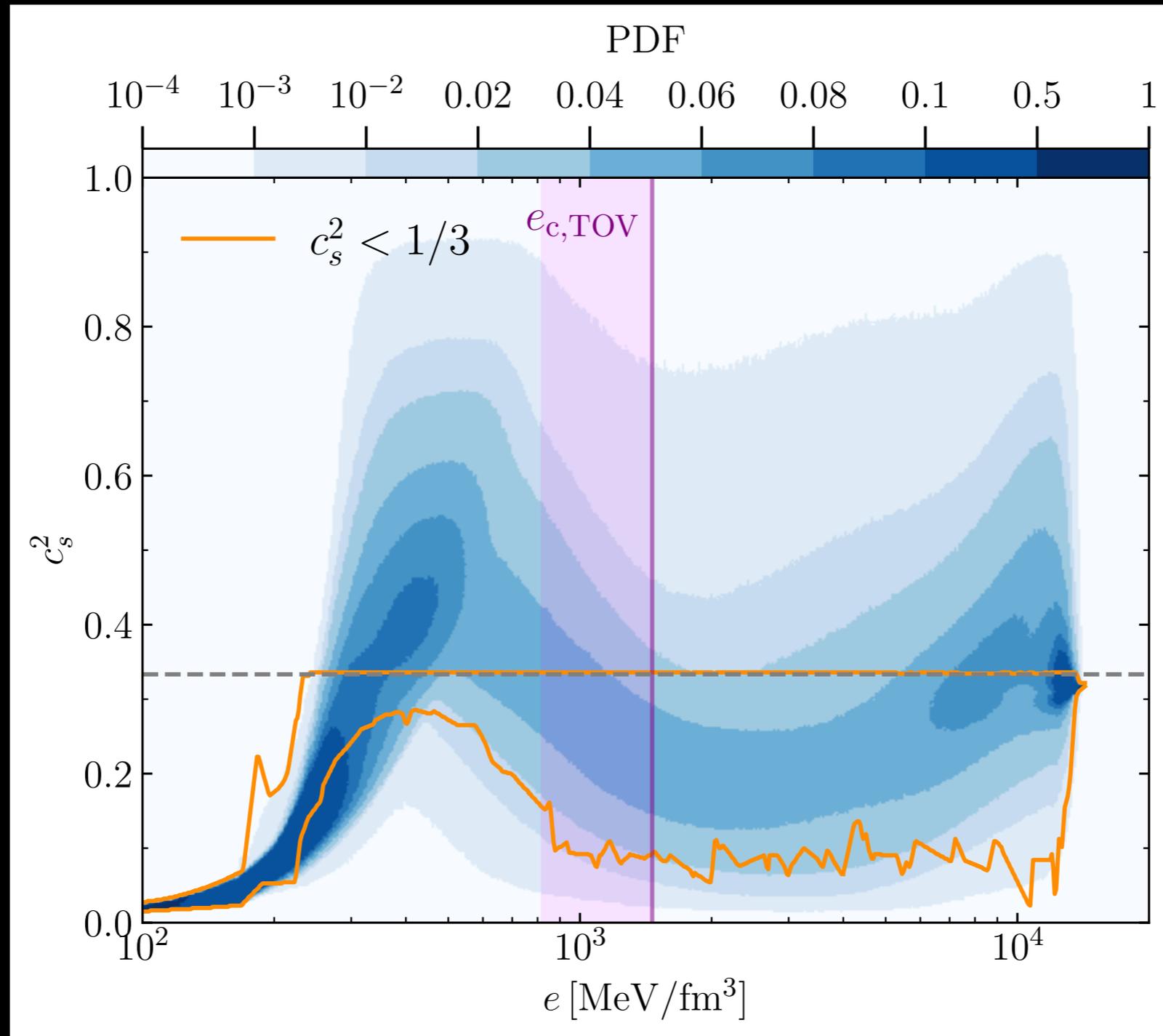
- i) monotonic and sub-conformal: $c_s^2 < 1/3$;
- ii) nonmonotonic and sub-conformal: $c_s^2 < 1/3$;
- iii) nonmonotonic and sub-luminal: $c_s^2 < 1$

- 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)



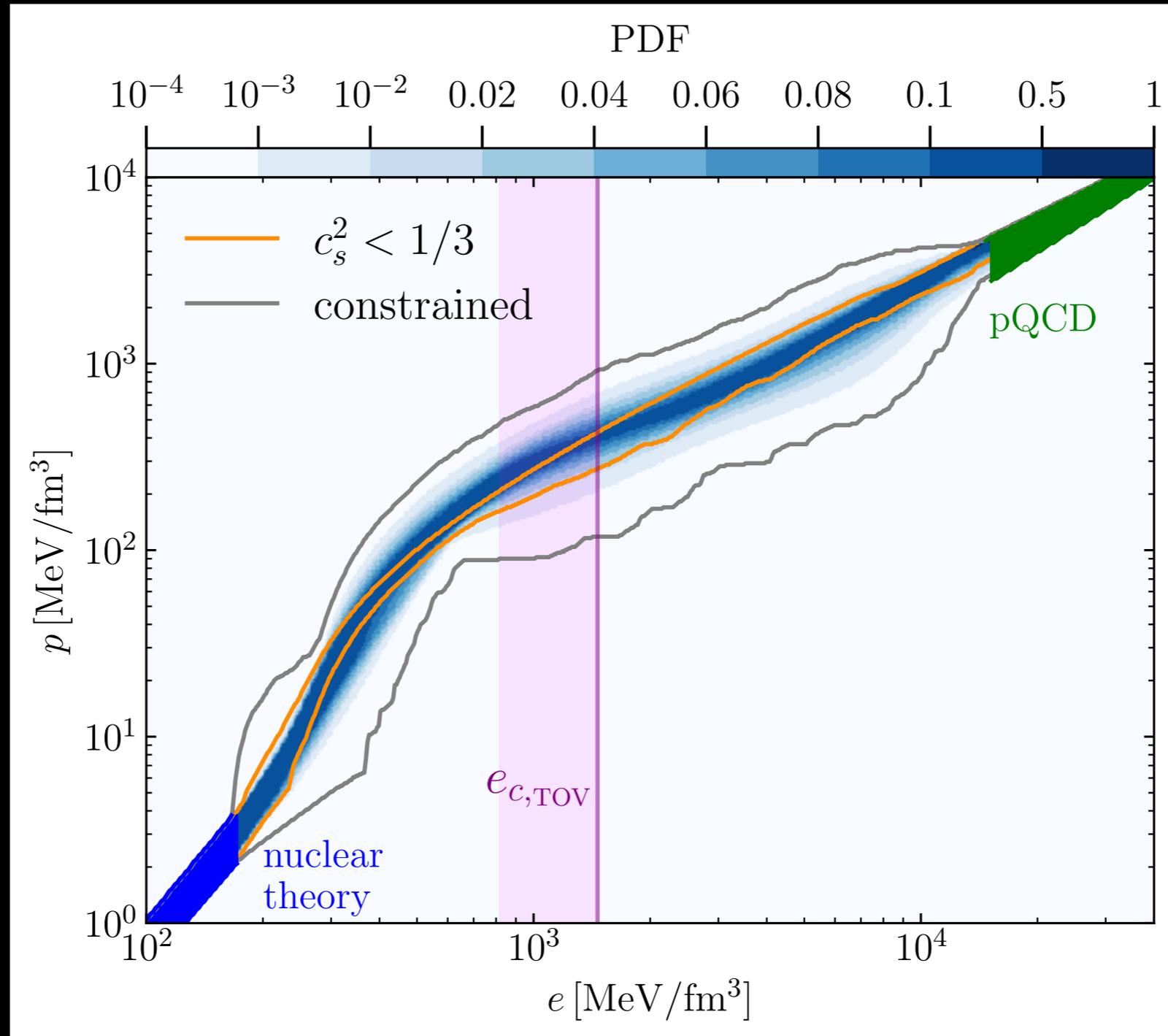
- Once an EOS is produced, we check it satisfies astrophysical constraints (max. mass, NICER limits). Repeat 1.5×10^7 times...
- In this way, $\sim 10\%$ of our EOSs survives and provides robust statistics from which we compute PDFs.

Sound speed PDF



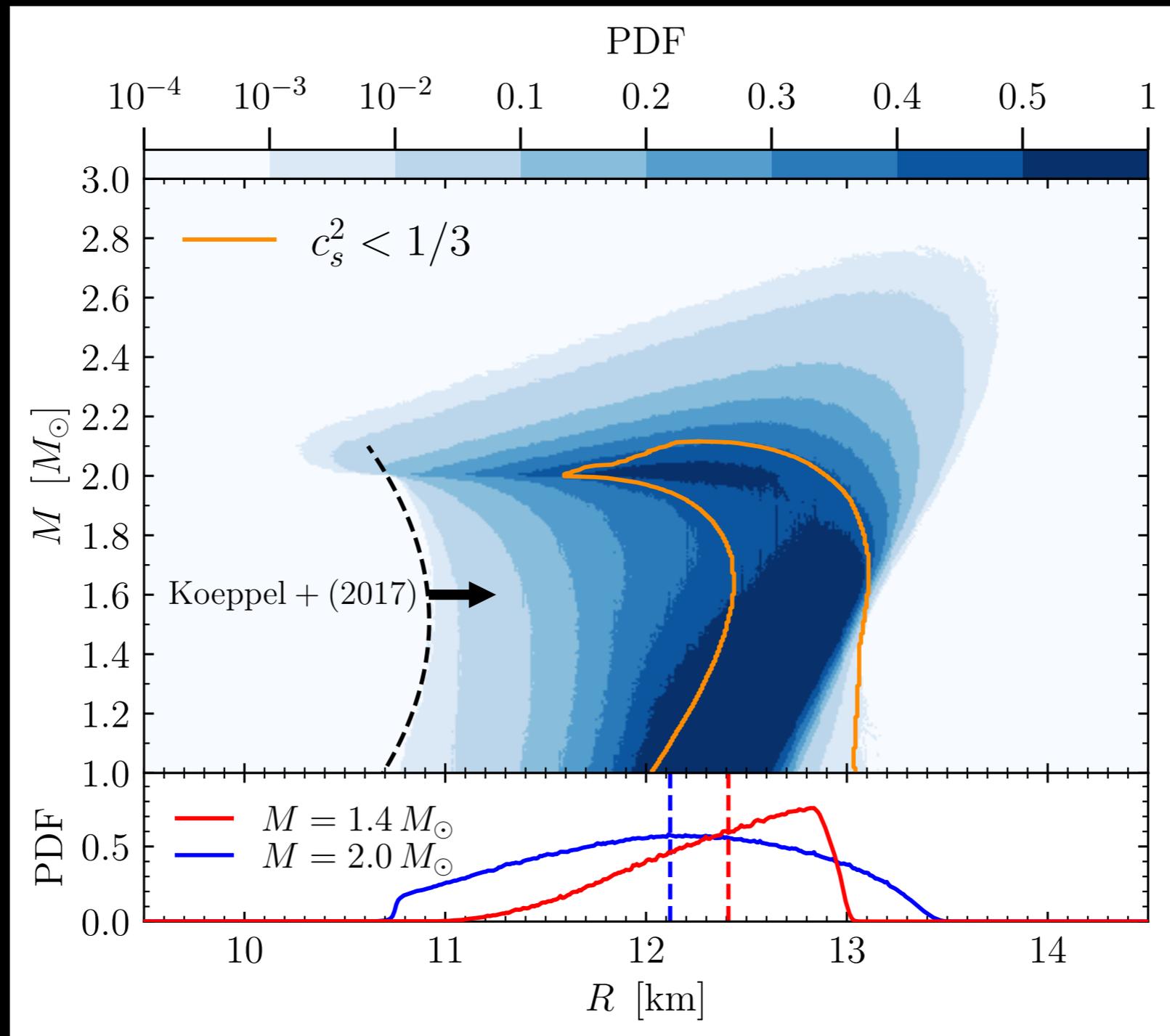
Orange line marks region of sub-conformal EOSs (0.03%).
No monotonic sub-conformal EOS found.

EOS PDF



Orange line marks region of sub-conformal EOSs (0.03%).
Note that 99% confidence region is very thin.

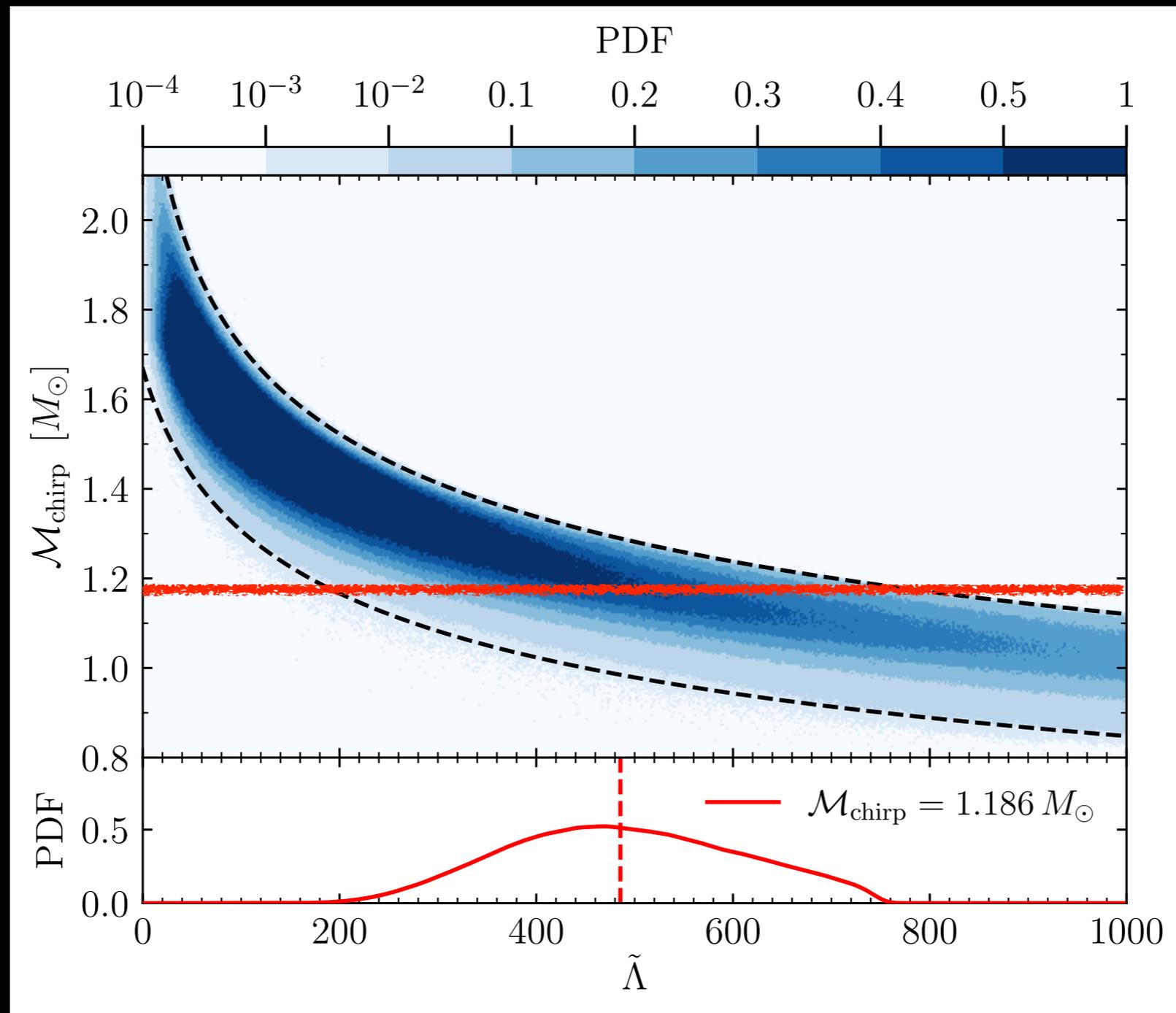
A more comprehensive picture



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

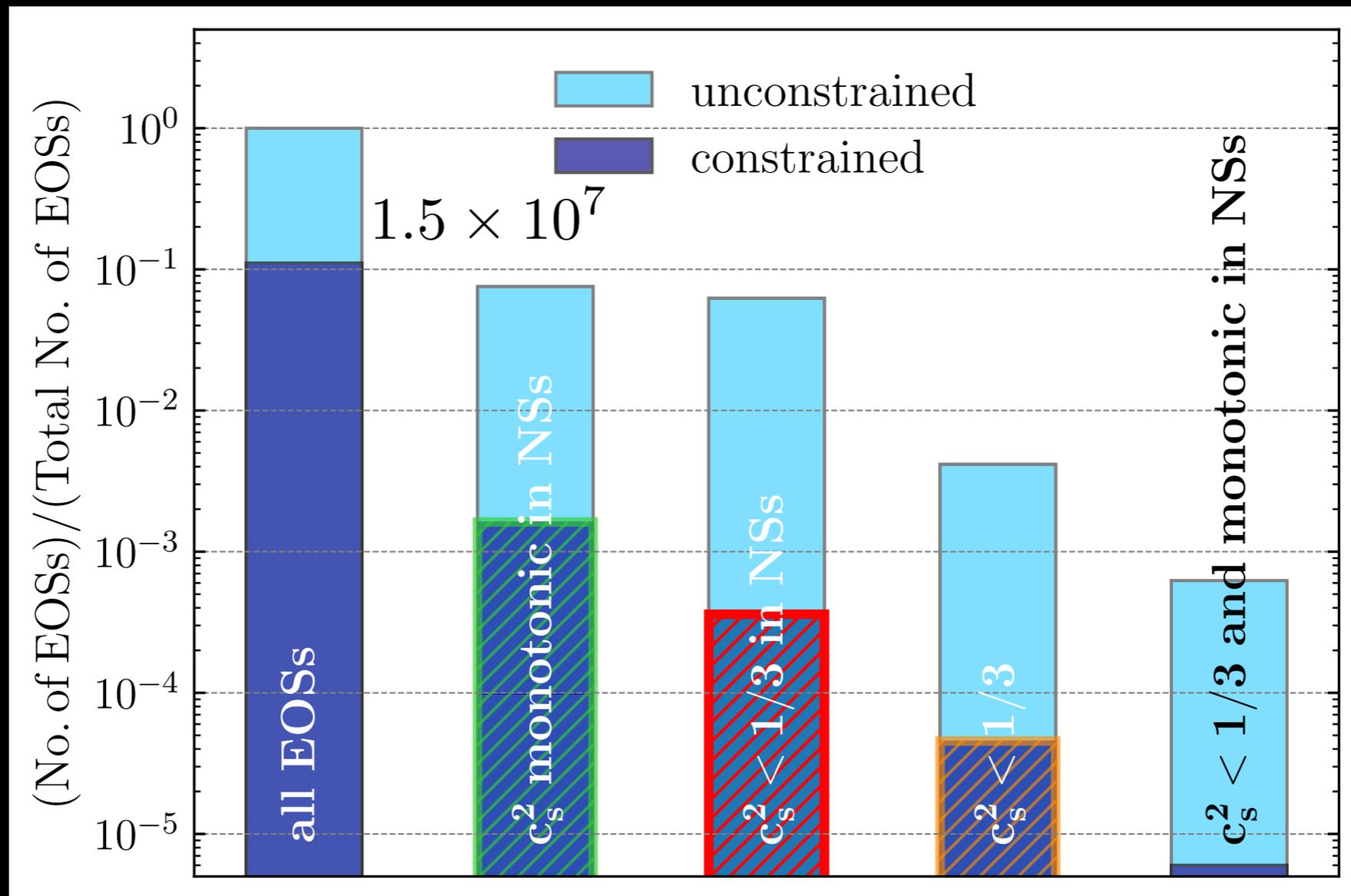
Lower bound on radii matches Köppel+ prediction from threshold mass.

A more comprehensive picture



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

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

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

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

*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 part of **ELEMENTS**, an Hessian Research Cluster with Frankfurt Darmstadt and Giessen

Visit our site at: <https://elements.science>

The screenshot shows the homepage of the ELEMENTS website. At the top, there is a navigation menu with links for HOME, ABOUT US, RESEARCH, PARTNERS, OUTREACH, NEWS & EVENTS, JOBS, and MEMBERS AREA. Below the navigation is a hero banner with a background image of a particle detector and a colorful nebula. The banner text reads "EXPLORING THE UNIVERSE FROM MICROSCOPIC TO MACROSCOPIC SCALES" and features the ELEMENTS logo. Below the banner is a main text block that reads: "The 2017 detection of gravitational waves, with the accompanying electromagnetic emission, from merging neutron stars have revealed that we are at a pivotal point in our understanding of matter and gravity. The Research Cluster ELEMENTS brings together world-leading scientists from distinct fields of research – the physics of particles and nuclei, the gravitational physics of merging neutron stars, the nucleosynthesis of heavy elements – to address the question of the origin of the heavy chemical elements in our Universe. ELEMENTS capitalises on a solid basis of already existing research structures: the CRC-TR 211 investigating strong-interaction matter under extreme conditions using first-principle methods such as lattice Quantum Chromodynamics, the CRC 1245 advancing ab-initio calculations of nuclei and nuclear matter and their application to astrophysical environments, the RTG 2128 promoting research training in particle-accelerator science, the LOEWE project "Nuclear Photonics" studying photonuclear reactions, and the Helmholtz Research Academy for FAIR (HRFA) providing academic support for the FAIR project. From these coordinated programs, ELEMENTS recruits an excellent and diverse group of Principal Investigators, decorated with outstanding scientific prizes and awards, such as eleven ERC grants and the only Humboldt professorship in Hesse. Experimentally, the research program benefits from the worldwide unique particle-accelerator infrastructure in the Darmstadt-Frankfurt area, including GSI and the International FAIR accelerator complex becoming operational in 2025 and the superconducting electron accelerator S-DALINAC at Darmstadt. On the theory side, highly advanced High-Performance Computing resources are provided by the Goethe-CSC and the Lichtenberg-II computer clusters."

Below the main text is a large image showing a colorful, abstract visualization of particle interactions or a simulation. To the right of the main text is a sidebar titled "Upcoming Activities" with a list of events:

- Tue, 4th January 2022, 2:00 pm
WAG - related LINAC-discussion
atP
- Tue, 11th January 2022, 3:00 pm
WAG General Meeting
- Tue, 1st February 2022, 2:00 pm
WAG - related LINAC-discussion
atP
- Mon, 7th February 2022, 2:15 pm
WAG General meeting
Zoom
- Tue, 8th February 2022, 3:00 pm
WAG General Meeting
- Tue, 1st March 2022, 2:00 pm
WAG - related LINAC-discussion
atP
- Tue, 8th March 2022, 3:00 pm
WAG General Meeting

At the bottom of the sidebar, there is a link for "Activities on nuclear photonics".