Neutron stars: from macroscopic collisions to microphysics

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“RHIC Beam Energy Scan:
Theory and Experiment”

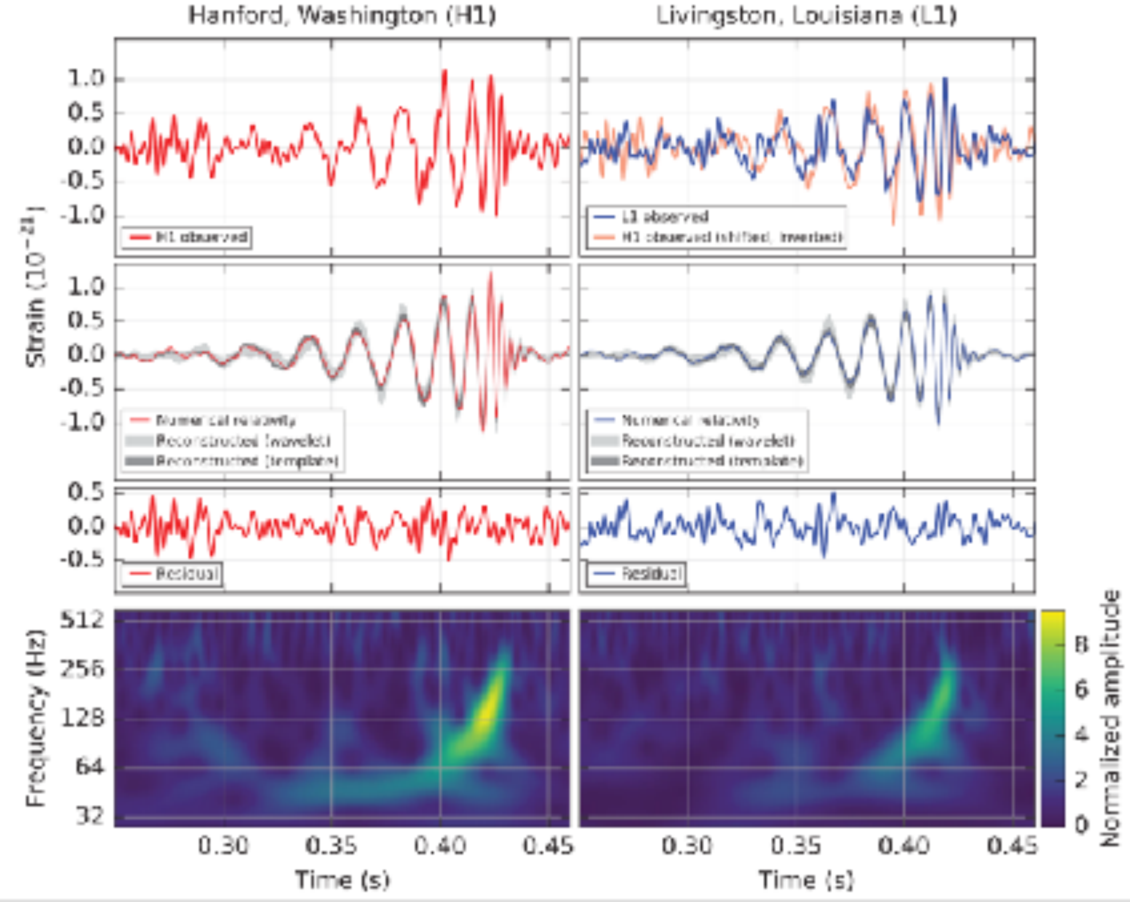
Plan of the talk

- The richness of merging binary neutron stars
- GW spectroscopy: EOS from frequencies
- GW170817: a game changer:
  - ✴ maximum mass
  - ✴ radii and deformabilities
- Signatures of quark-hadron phase transitions

The two-body problem in GR

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

BH + BH → BH + GWs



GW150914

The two-body problem in GR

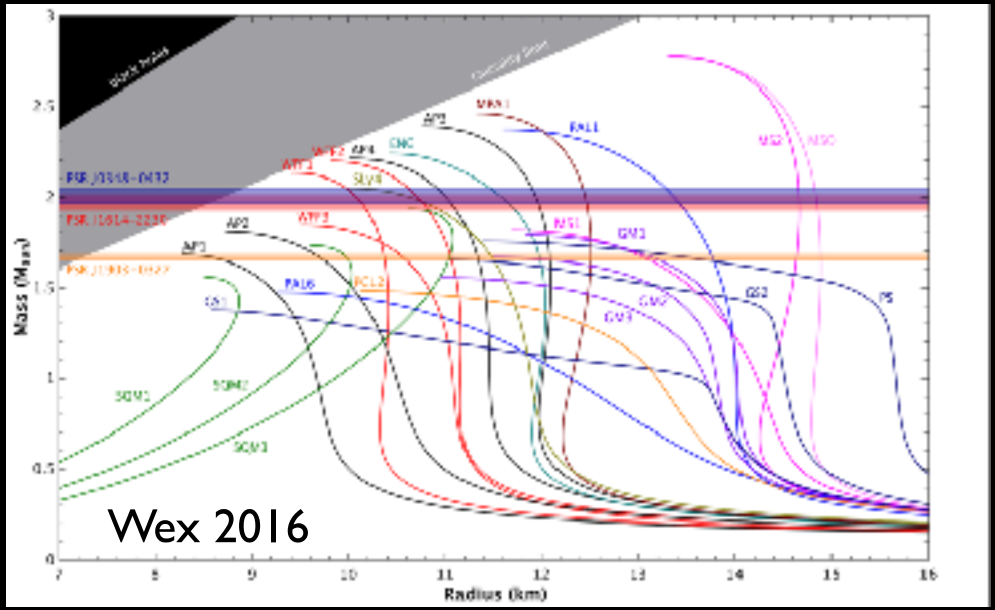
- For black holes the process is very **simple**:

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

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



Wex 2016

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

The two-body problem in GR

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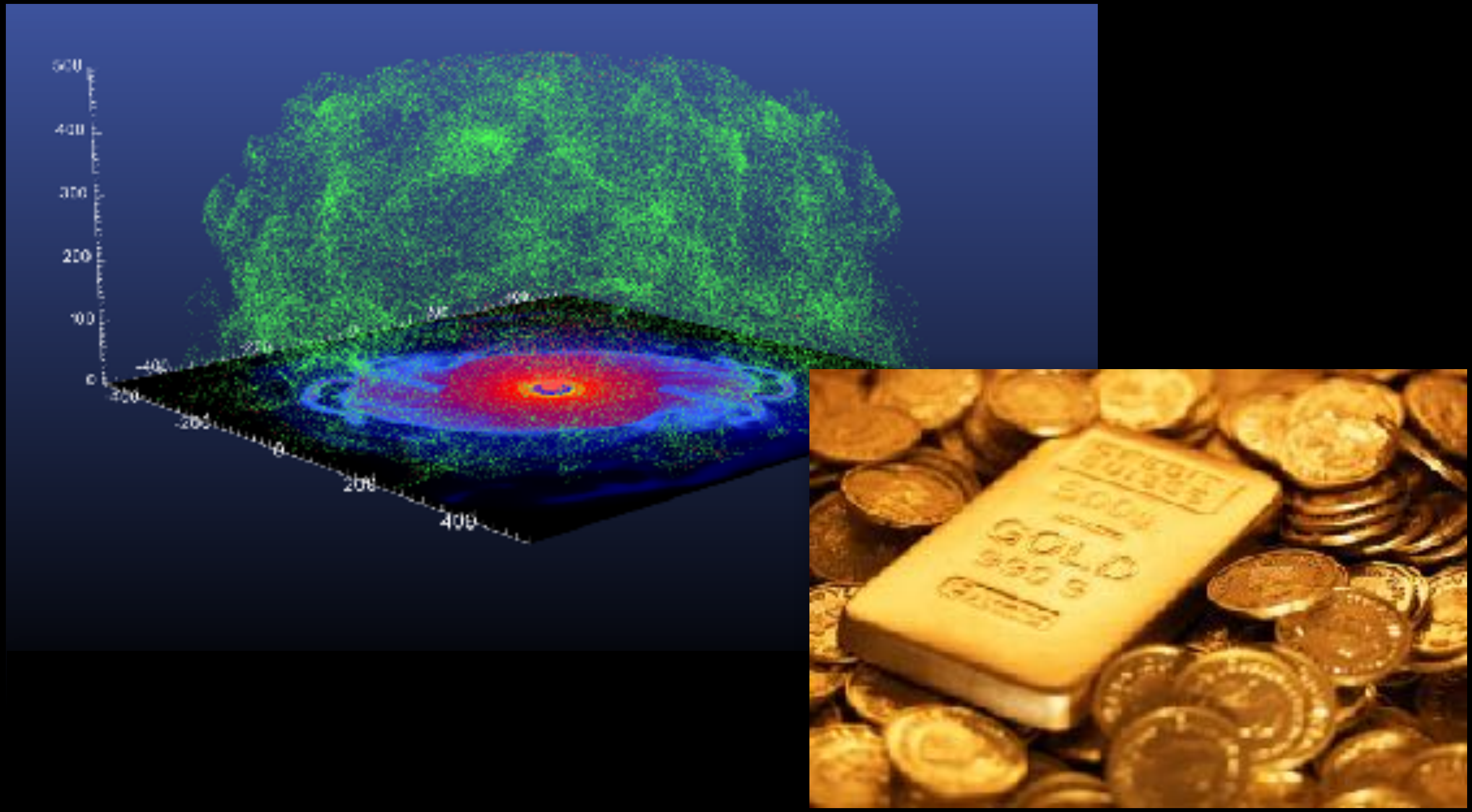
NS + NS → HMNS+... ? → BH+torus+... ? → BH + GWs

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



The equations of numerical relativity

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

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

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

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

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

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

The equations of numerical relativity

All are covariant tensor equations. However: **Einstein equations** involve smooth fields (metric, extrinsic curvature).

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu}\, R = 8\pi T_{\mu\nu}$$

Conservation equations discontinuous fields (shocks).

$$\nabla_\mu T^{\mu\nu} = 0\,, \quad \nabla_\mu (\rho u^\mu) = 0$$

Hence, **numerical methods** are significantly **different.**

Einstein equations: CCZ4 formulation

$$\begin{aligned}
\partial_t\tilde{\gamma}_{ij} &= -2\alpha\tilde{A}_{ij}^{\mathrm{TF}} + 2\tilde{\gamma}_{k(i}\partial_{j)}\,\beta^k - \frac{2}{3}\tilde{\gamma}_{ij}\partial_k\,\beta^k + \beta^k\partial_k\tilde{\gamma}_{ij}\,, \\
\partial_t\tilde{A}_{ij} &= \phi^2\left[-\nabla_i\nabla_j\alpha + \alpha\left(R_{ij} + \nabla_i Z_j + \nabla_j Z_i - 8\pi S_{ij}\right)\right]^{\mathrm{TF}} + \alpha\tilde{A}_{ij}\left(K - 2\Theta\right) \\
&\quad -2\alpha\tilde{A}_{il}\tilde{A}^l_j + 2\tilde{A}_{k(i}\partial_{j)}\,\beta^k - \frac{2}{3}\tilde{A}_{ij}\partial_k\,\beta^k + \beta^k\partial_k\tilde{A}_{ij}\,, \\
\partial_t\phi &= \frac{1}{3}\alpha\phi K - \frac{1}{3}\phi\partial_k\beta^k + \beta^k\partial_k\phi\,, \\
\partial_t K &= -\nabla^i\nabla_i\alpha + \alpha\left(R + 2\nabla_i Z^i + K^2 - 2\Theta K\right) + \beta^j\partial_j K - 3\alpha\kappa_1\left(1 + \kappa_2\right)\Theta + 4\pi\alpha\left(S - 3\tau\right)\,, \\
\partial_t\hat{\Gamma}^i &= 2\alpha\left(\tilde{\Gamma}^i_{jk}\tilde{A}^{jk} - 3\tilde{A}^{ij}\frac{\partial_j\phi}{\phi} - \frac{2}{3}\tilde{\gamma}^{ij}\partial_j K\right) + 2\tilde{\gamma}^{ki}\left(\alpha\partial_k\Theta - \Theta\partial_k\alpha - \frac{2}{3}\alpha K Z_k\right) - 2\tilde{A}^{ij}\partial_j\alpha \\
&\quad +\tilde{\gamma}^{kl}\partial_k\partial_l\beta^i + \frac{1}{3}\tilde{\gamma}^{ik}\partial_k\partial_l\beta^l + \frac{2}{3}\tilde{\Gamma}^i\partial_k\beta^k - \tilde{\Gamma}^k\partial_k\beta^i + 2\kappa_3\left(\frac{2}{3}\tilde{\gamma}^{ij}Z_j\partial_k\beta^k - \tilde{\gamma}^{jk}Z_j\partial_k\beta^i\right) \\
&\quad +\beta^k\partial_k\hat{\Gamma}^i - 2\alpha\kappa_1\tilde{\gamma}^{ij}Z_j - 16\pi\alpha\tilde{\gamma}^{ij}S_j\,, \\
\partial_t\Theta &= \frac{1}{2}\alpha\left(R + 2\nabla_i Z^i - \tilde{A}_{ij}\tilde{A}^{ij} + \frac{2}{3}K^2 - 2\Theta K\right) - Z^i\partial_i\alpha + \beta^k\partial_k\Theta - \alpha\kappa_1\left(2 + \kappa_2\right)\Theta - 8\pi\alpha\,\tau\,, \\
\partial_t\alpha &= -2\alpha\left(K - 2\Theta\right) + \beta^k\partial_k\alpha\,, \\
\partial_t\beta^i &= fB^i + \beta^k\partial_k\beta^i\,, \\
\partial_t B^i &= \partial_t\hat{\Gamma}^i - \beta^k\partial_k\hat{\Gamma}^i + \beta^k\partial_k B^i - \eta B^i\,,
\end{aligned}$$

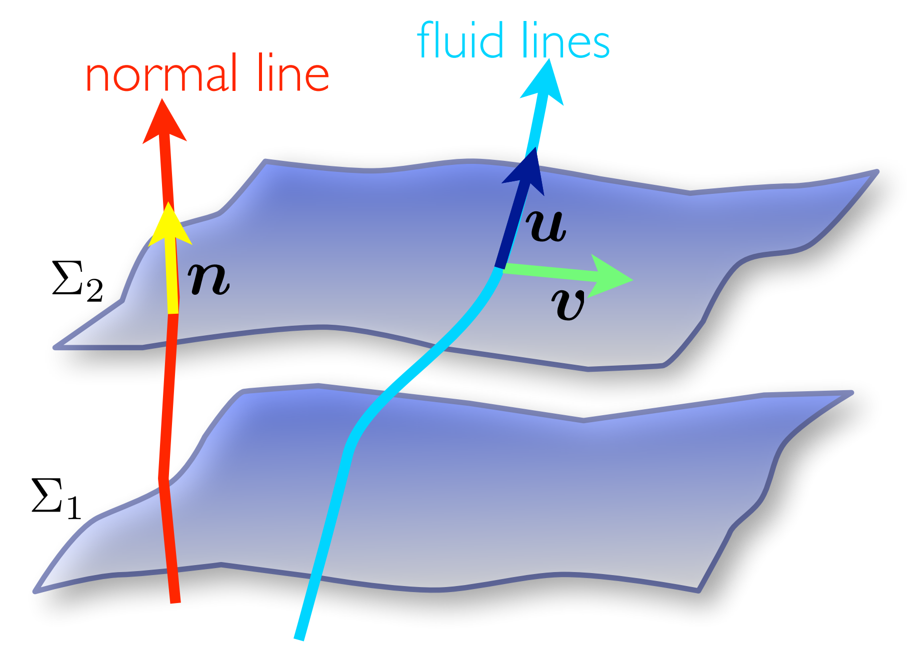
Total system in 1st-order form has 58 variables

GRHD/GRMHD equations: Valencia formulation

- They express conservation laws with discontinuities.
- Casting them in **conservation form** guarantees that:
  - lead to a **well-posed** problem.
  - solution converges to the correct **weak solution** of problem.

$$\partial_t\left(\sqrt{\gamma}\,\boldsymbol{U}\right) + \partial_i\left(\sqrt{\gamma}\,\boldsymbol{F}^i\right) = \boldsymbol{S}$$

$$\boldsymbol{U} := \begin{pmatrix} \rho W \\ \rho h W^2 v_j \\ \rho h W^2 - p \end{pmatrix}, \quad \boldsymbol{F}^i := \begin{pmatrix} \alpha v^i D - \beta^i D \\ \alpha S^i{}_j - \beta^i S_j \\ \alpha S^i - \beta^i E \end{pmatrix}$$



Animations: Breu, Radice, LR

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

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

LS220 EOS

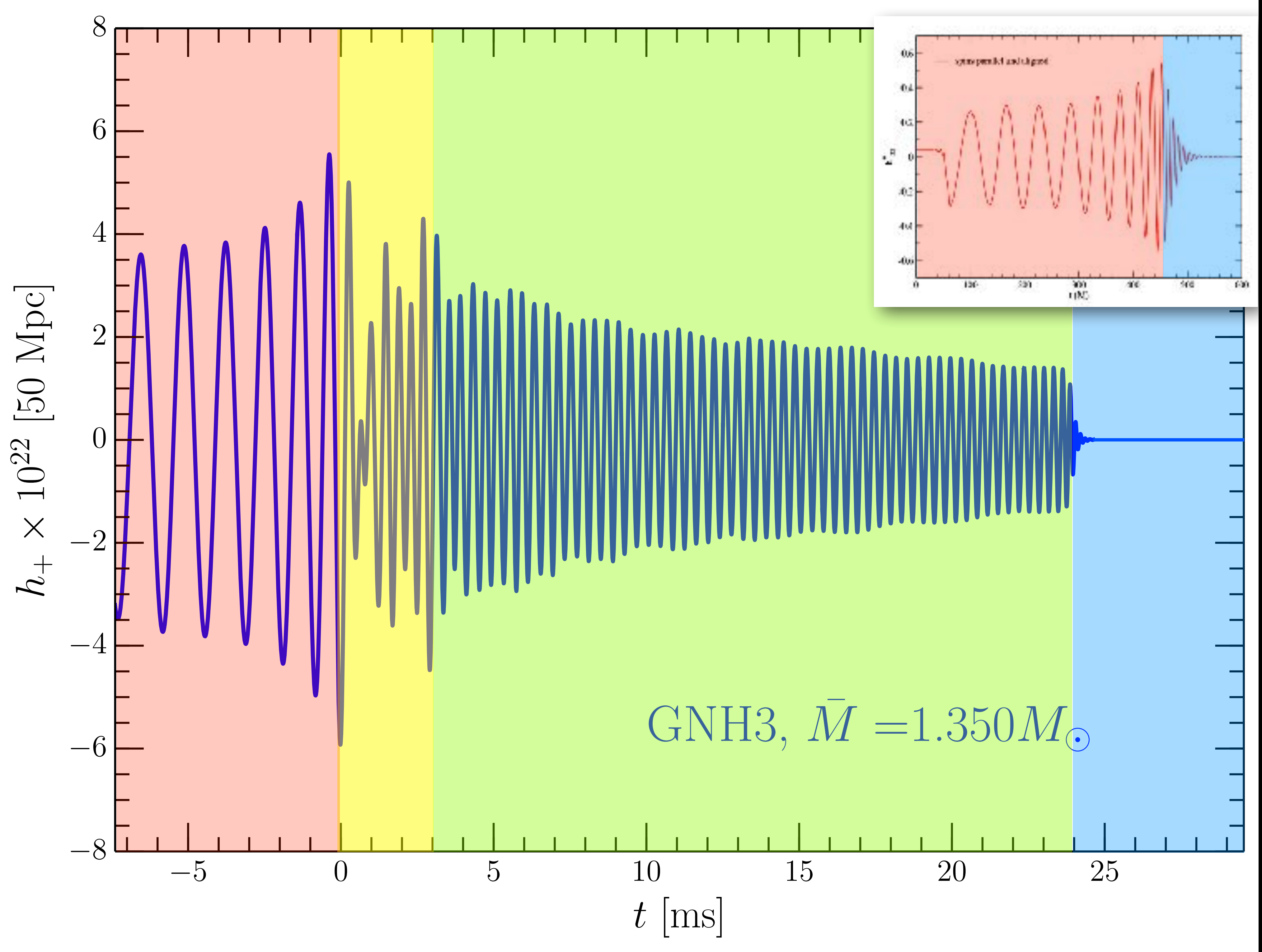
Qualitatively, this is what normally happens:

merger → HMNS → BH + torus

Quantitatively, differences are produced by:

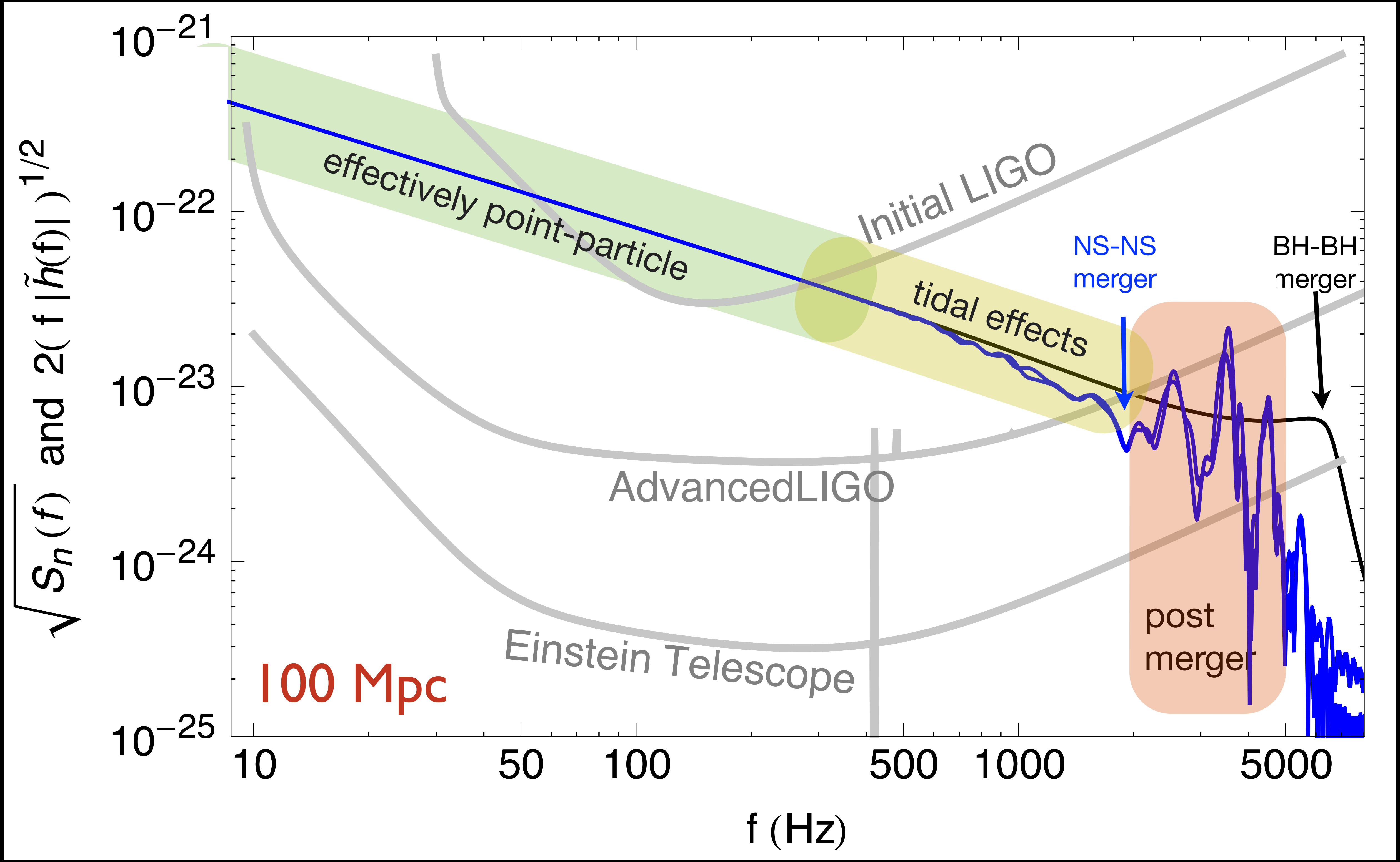
- total mass (prompt vs delayed collapse)
- mass asymmetries (HMNS and torus)
- soft/stiff EOS (inspiral and post-merger, PT)
- magnetic fields (equil. and EM emission)
- radiative losses (equil. and nucleosynthesis)

Anatomy of the GW signal



Postmerger signal: peculiar of binary NSs

In frequency space

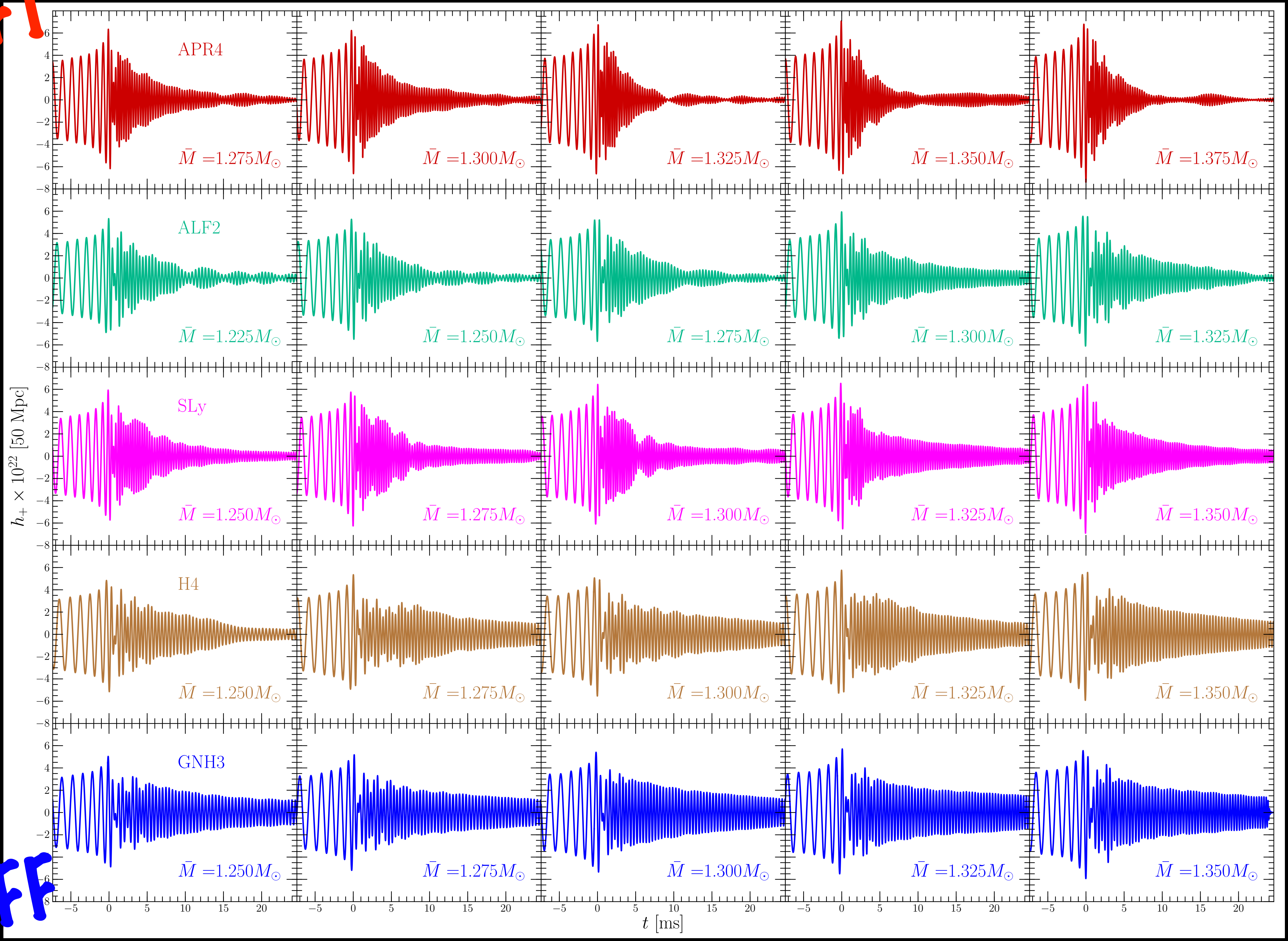


Read et al. (2013)

What we can do nowadays

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

SOFT

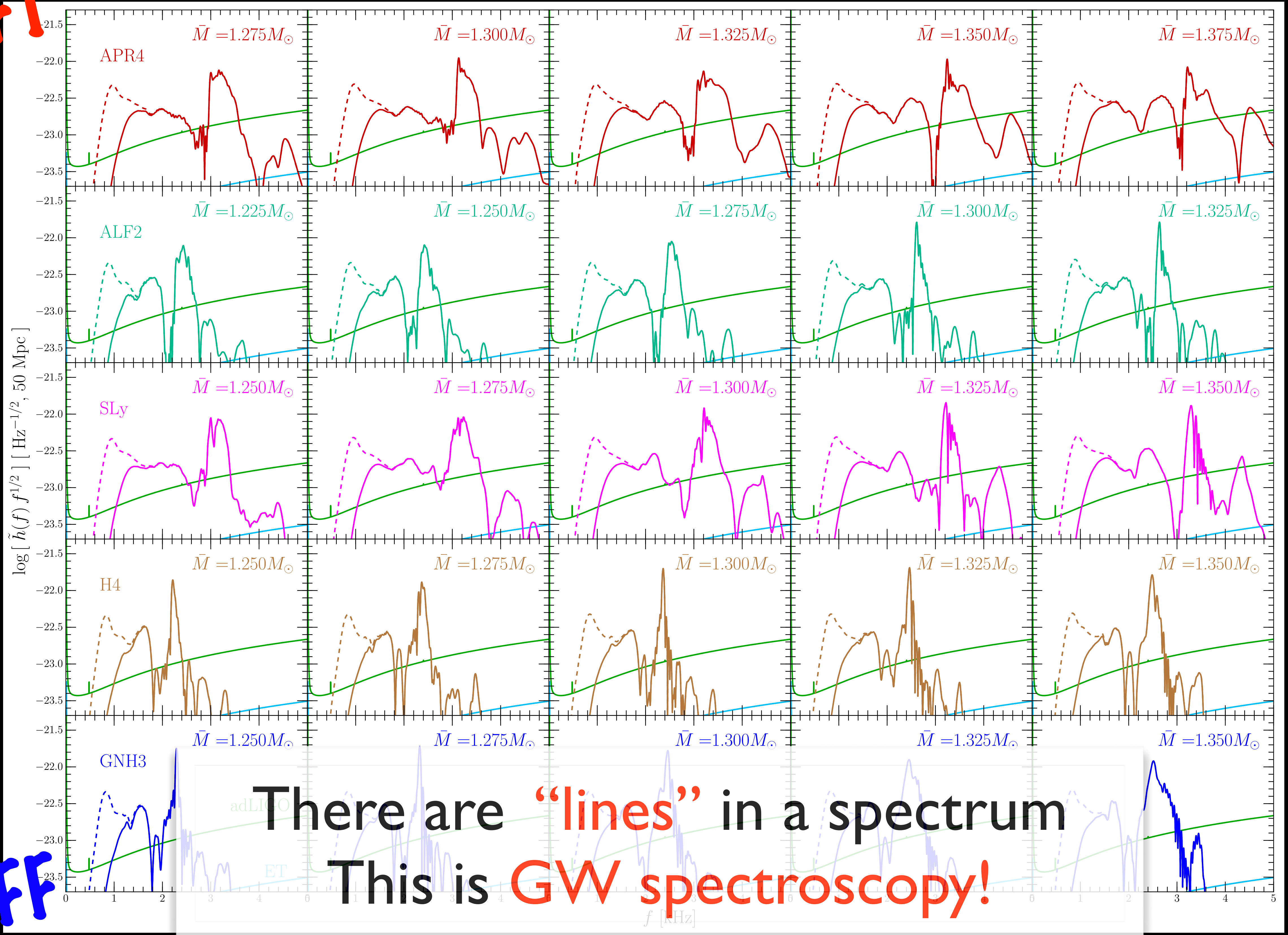


STIFF

Extracting information from the EOS

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

SOFT



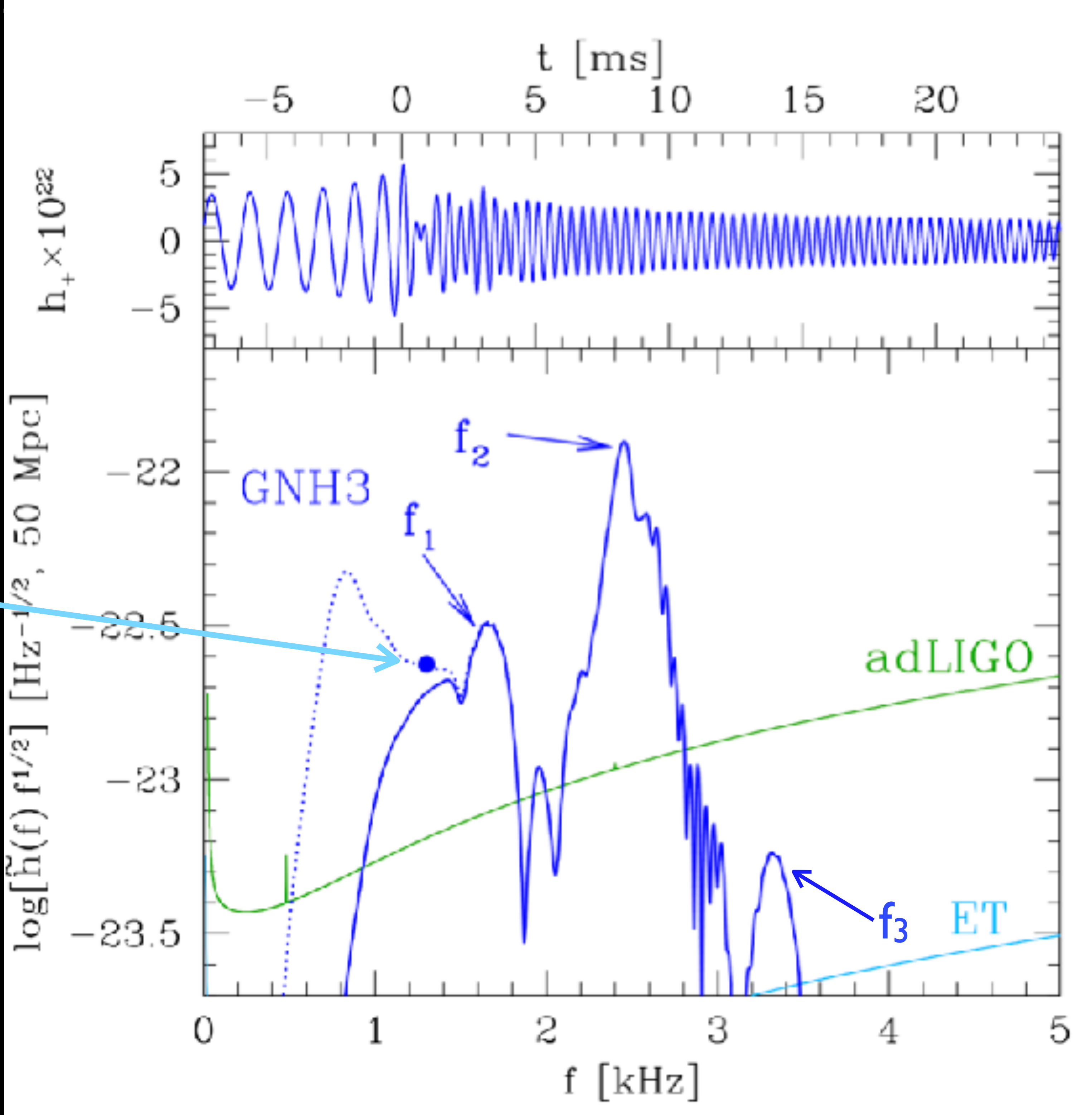
STIFF

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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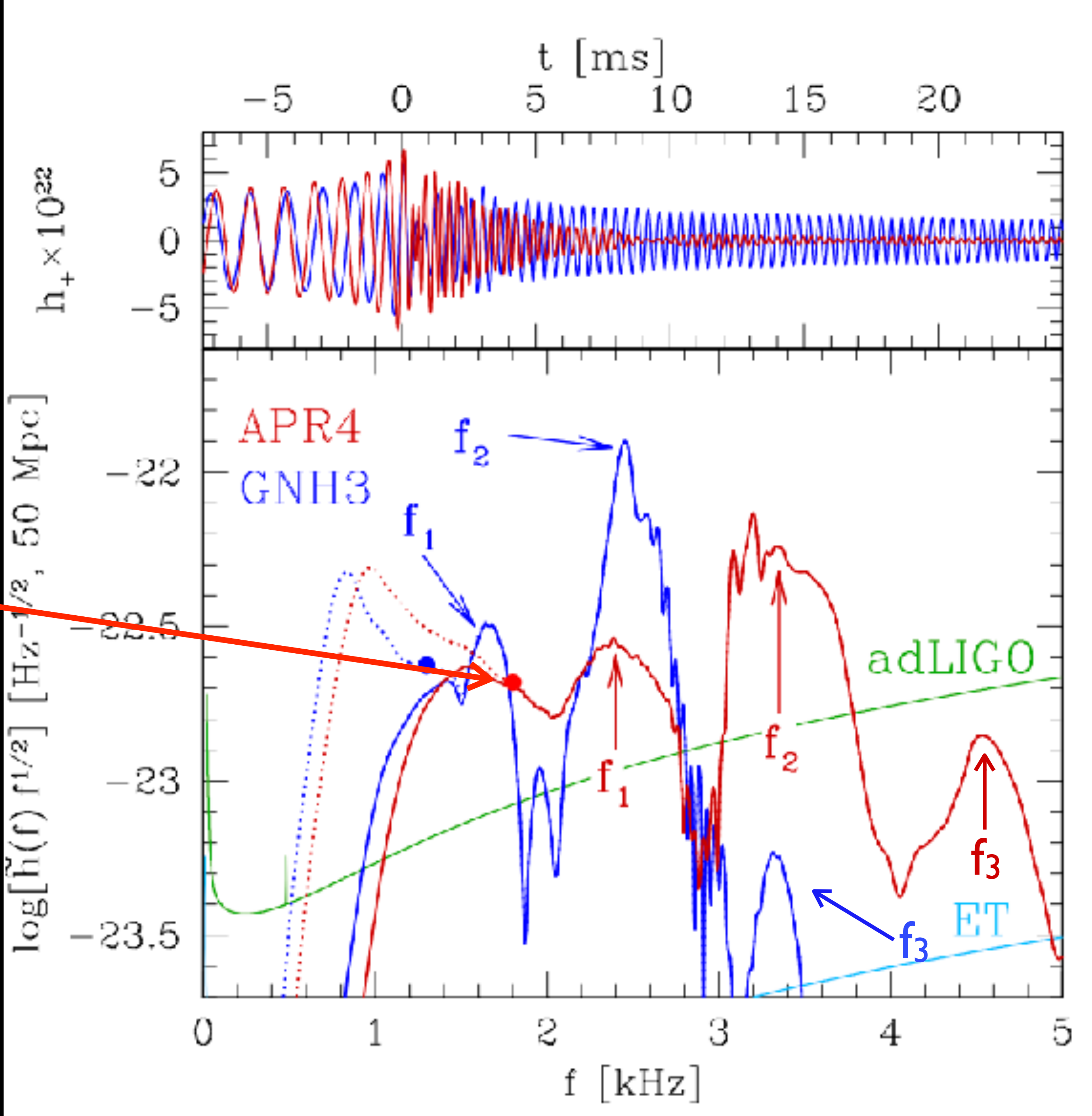
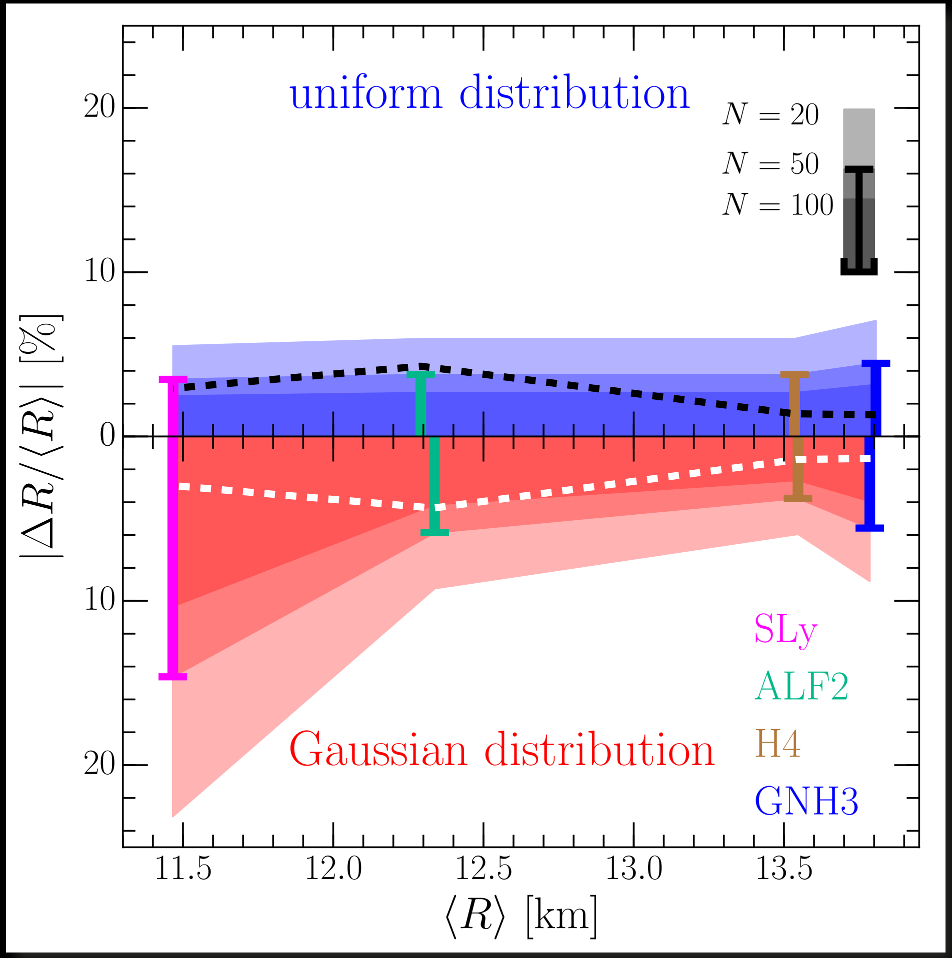
merger frequency



A spectroscopic approach to the EOS

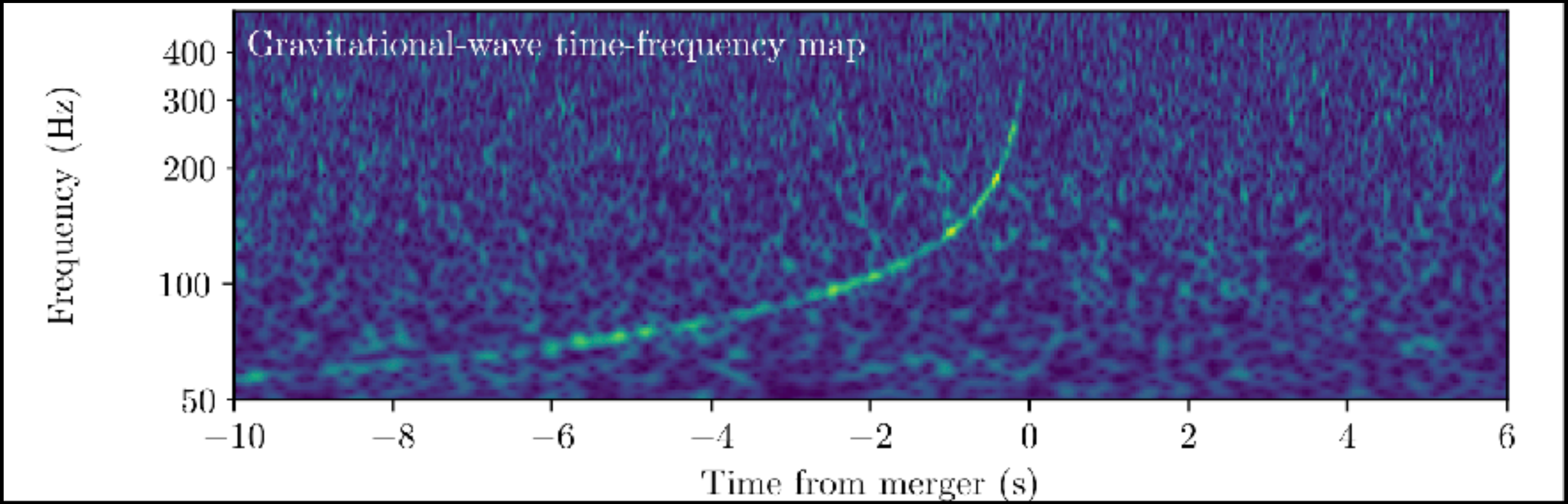
- **Universal behaviour** and **analytic modelling** of post-merger relates position of these peaks with the EOS.
- Question: how well can we constrain the EOS (radius) given ***N* detections?**



- 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)

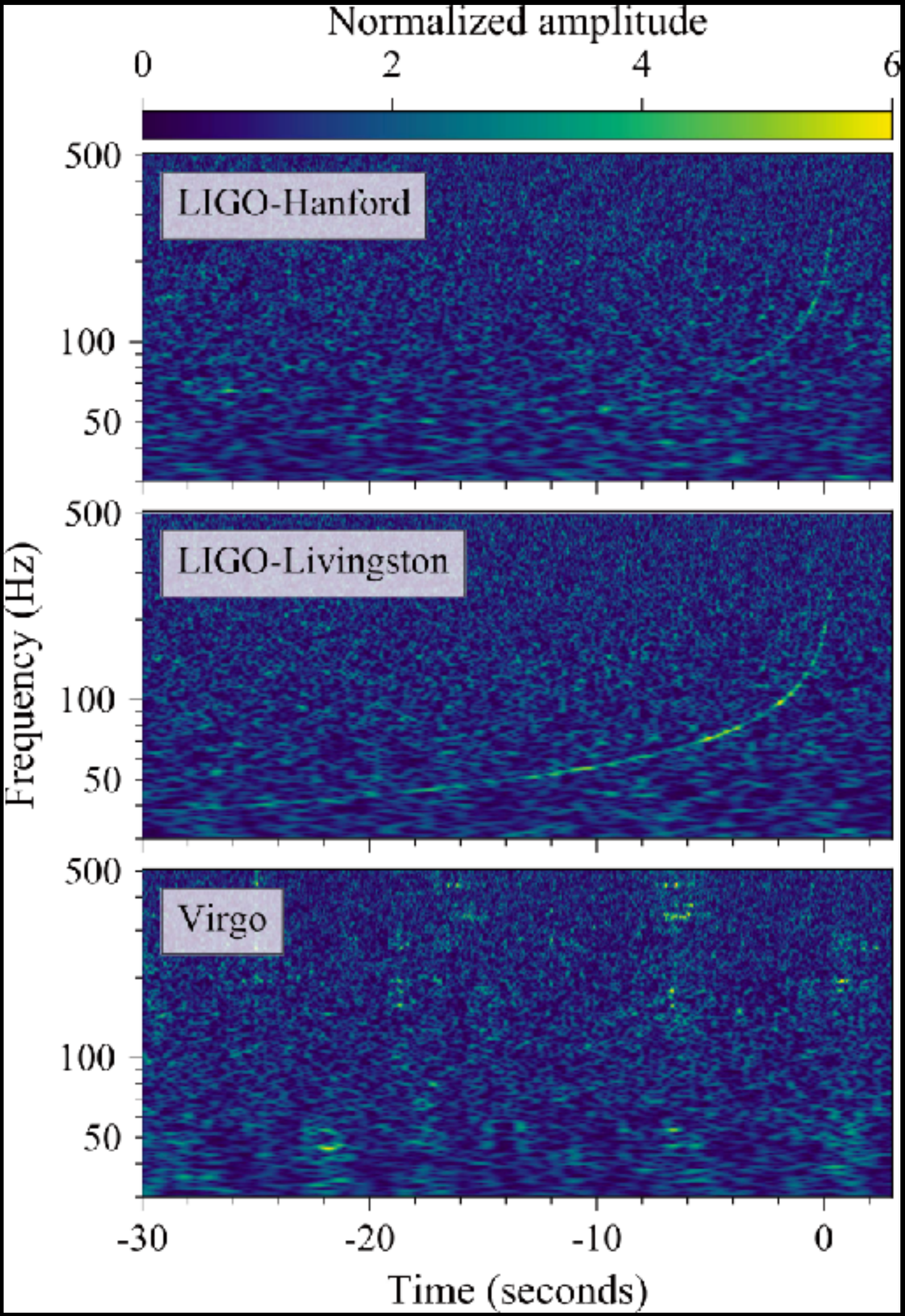
GW170817: a game changer



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

GW170817: the first binary neutron-star system

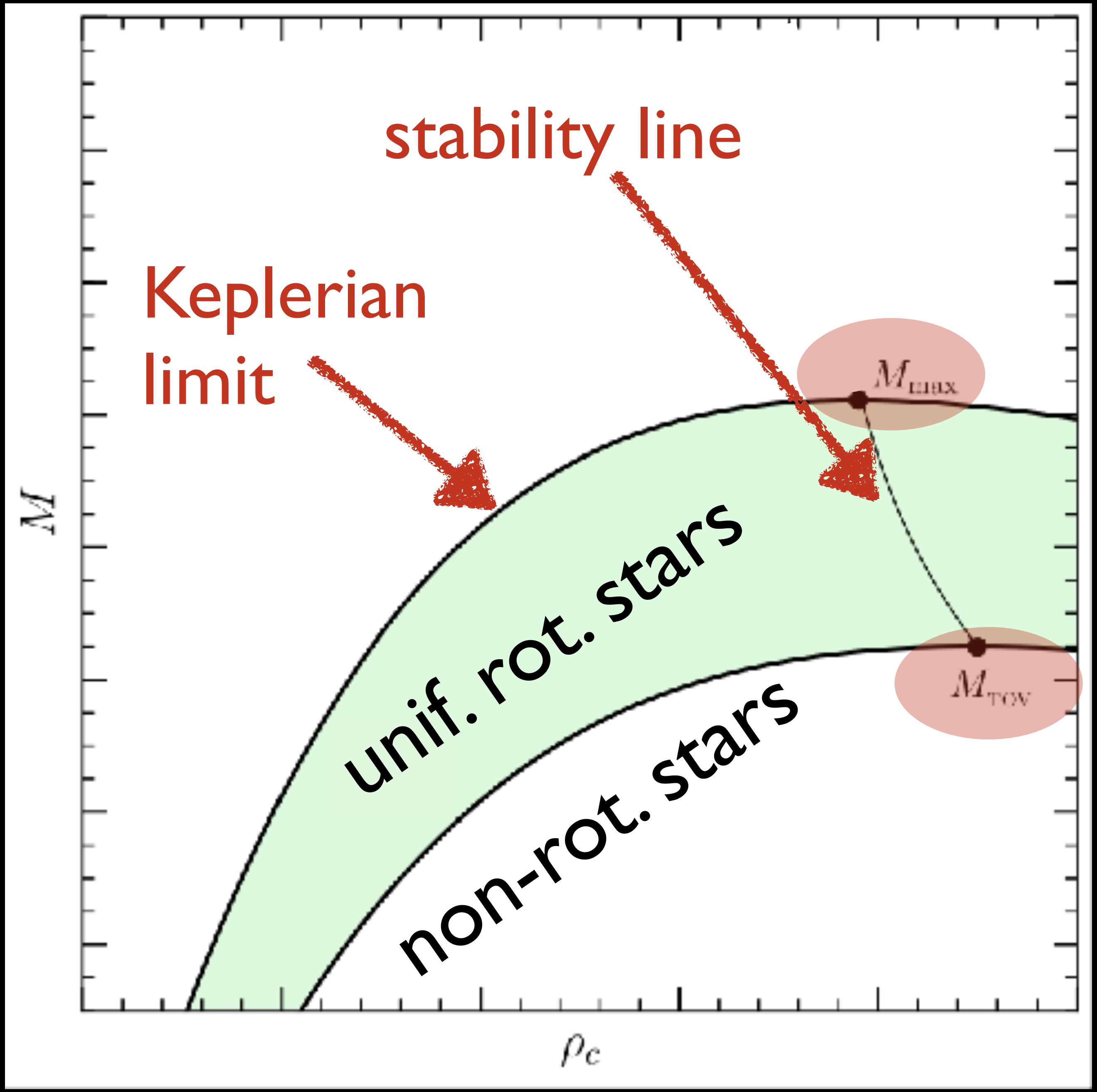
- **Unfortunately** only the **inspiral** signal was detected.
- **Fortunately** this was **sufficient** to set a number of constraints on max. mass, tidal deformability, radii, etc.



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: $M_{\rm TOV}$
- 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)

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

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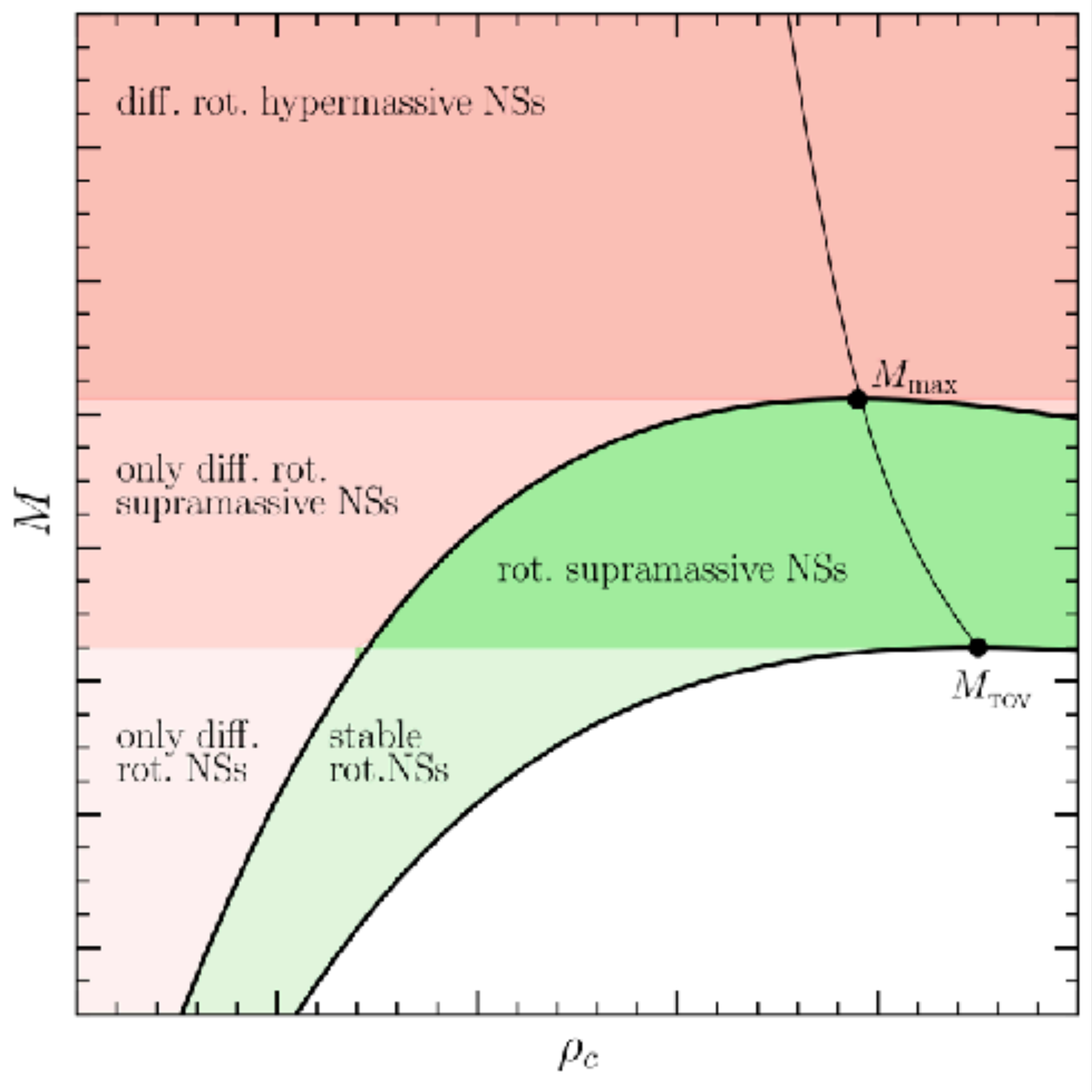


- **Green** region is for **uniformly** rotating equilibrium models.
- **Salmon** region is for **differentially** rotating equilibrium models.
- **Supramassive** stars have:

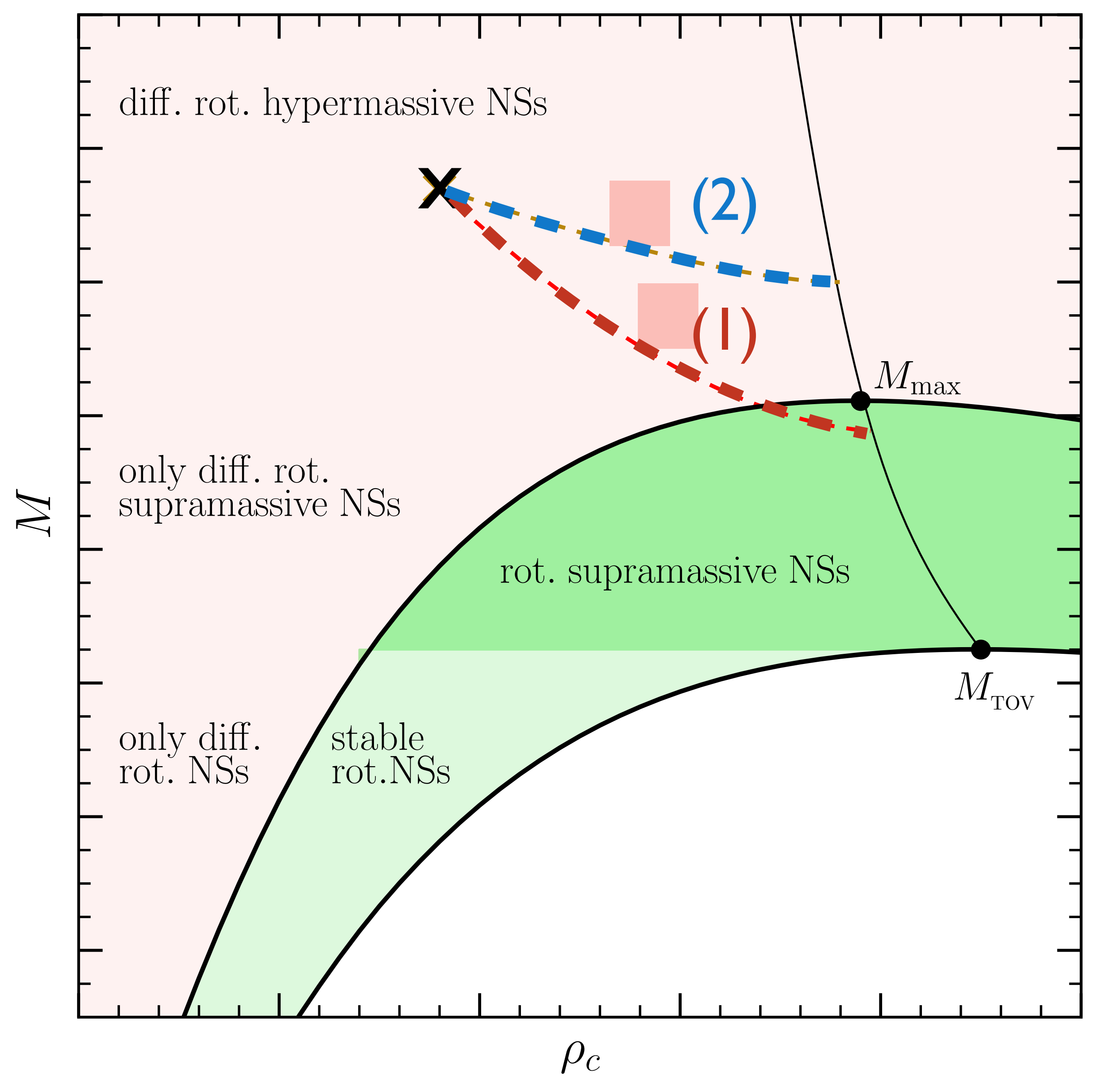
$$M > M_{\rm TOV}$$

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

pulsar timing

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

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

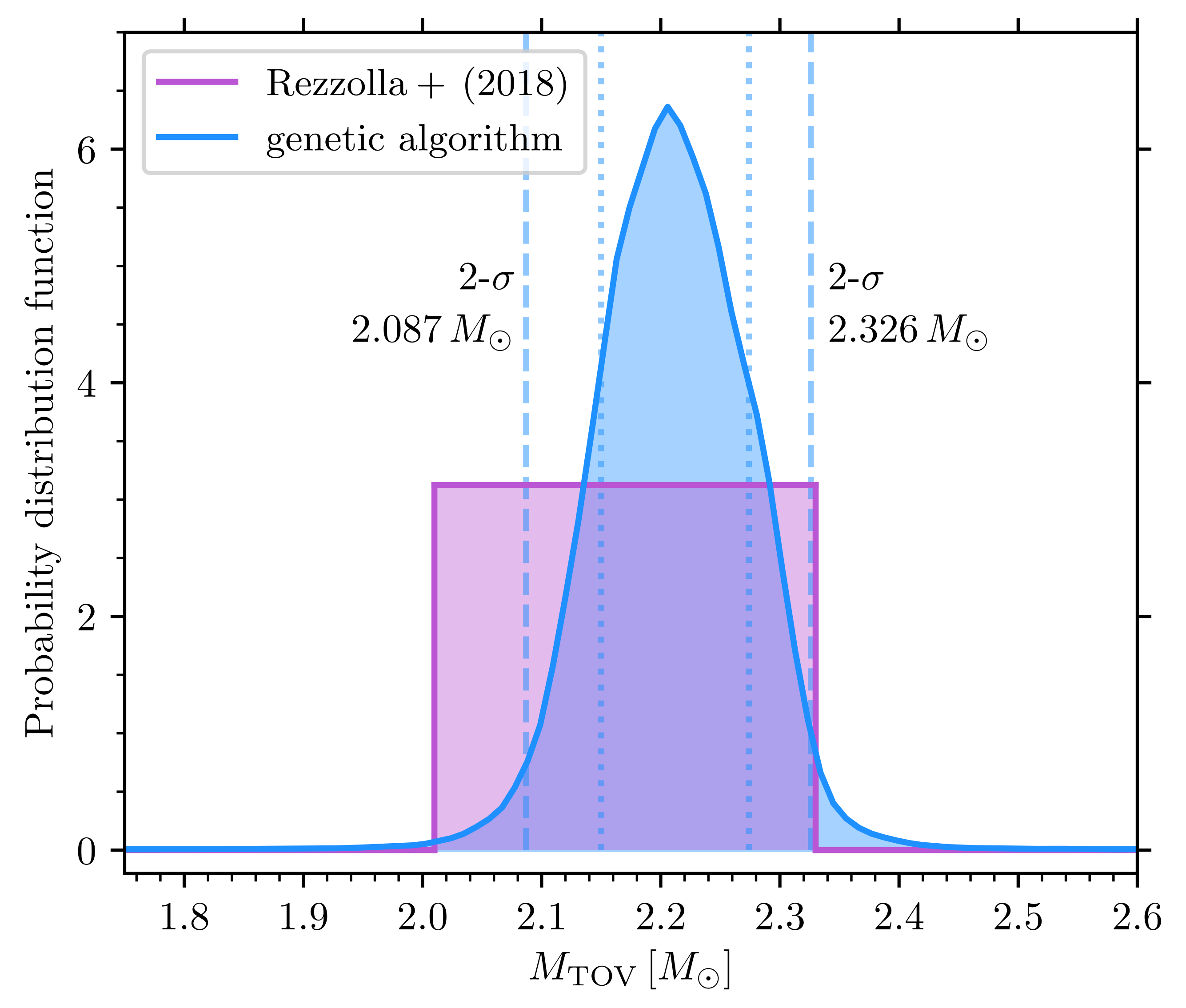
- A **genetic algorithm** is used to sample through the parameter space of the 10 free parameters.

- 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.

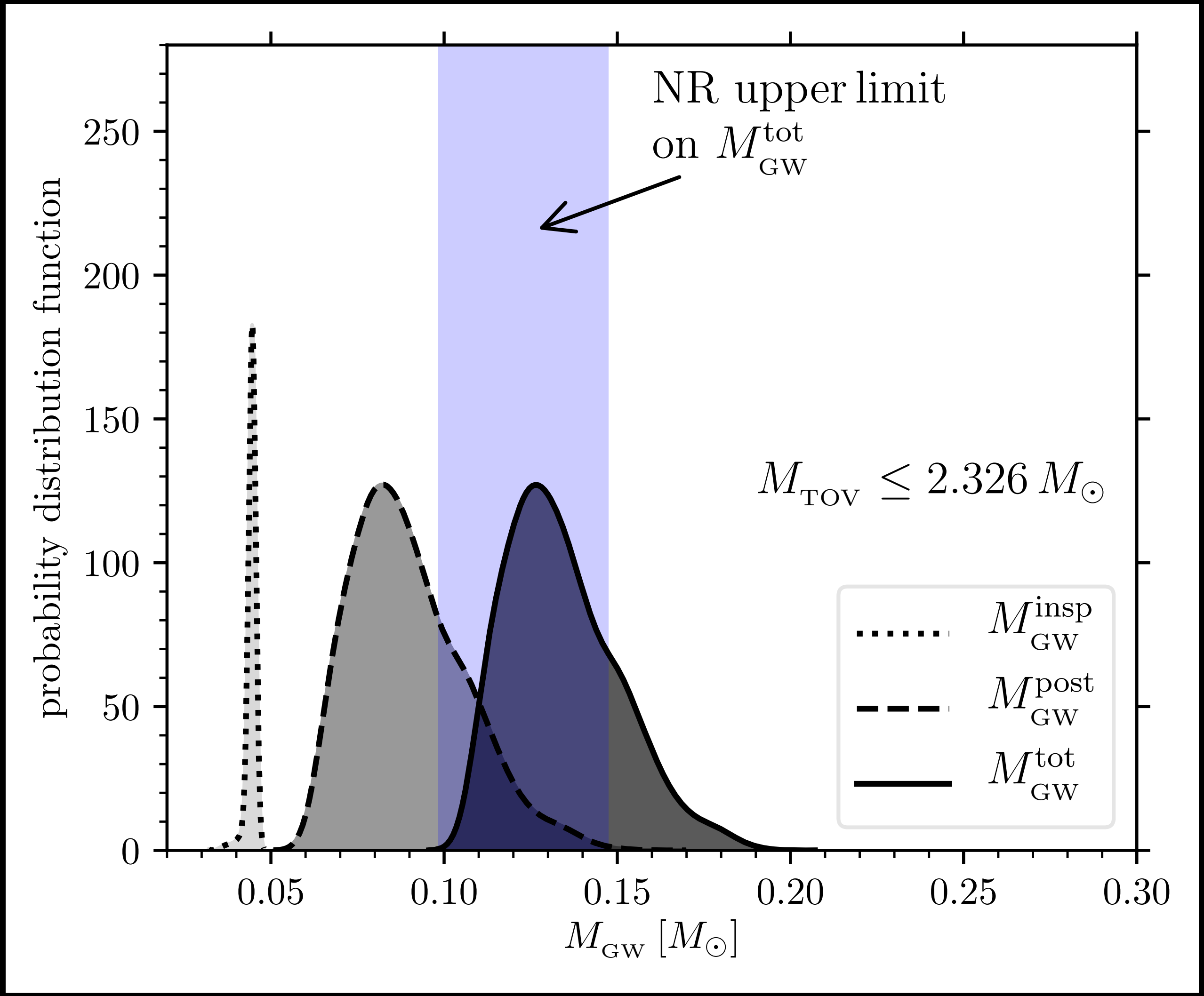
- Consider first previous estimate:

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

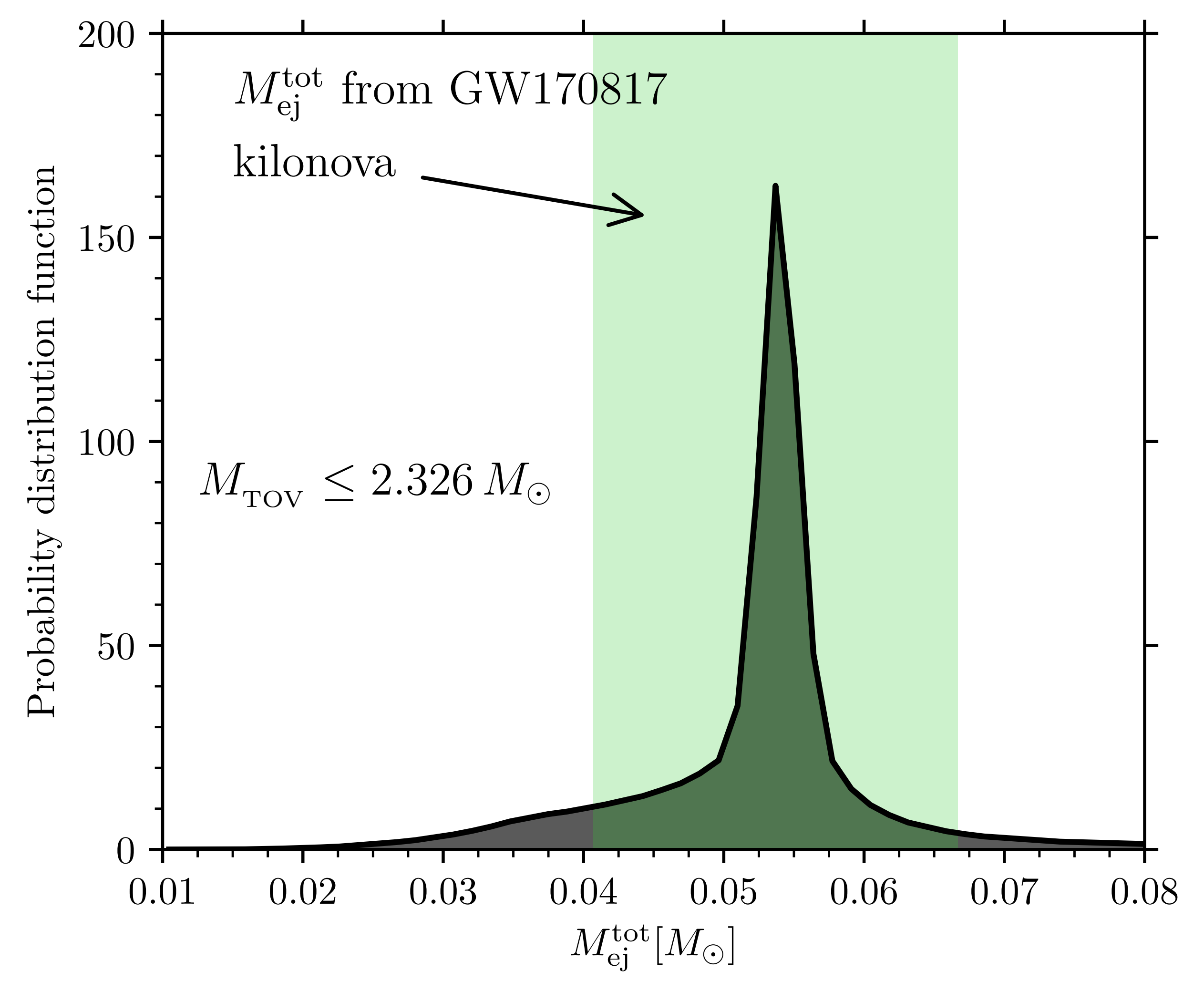
$$M_{\rm TOV}/M_\odot \leq 2.16^{+0.17}_{-0.15}$$



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

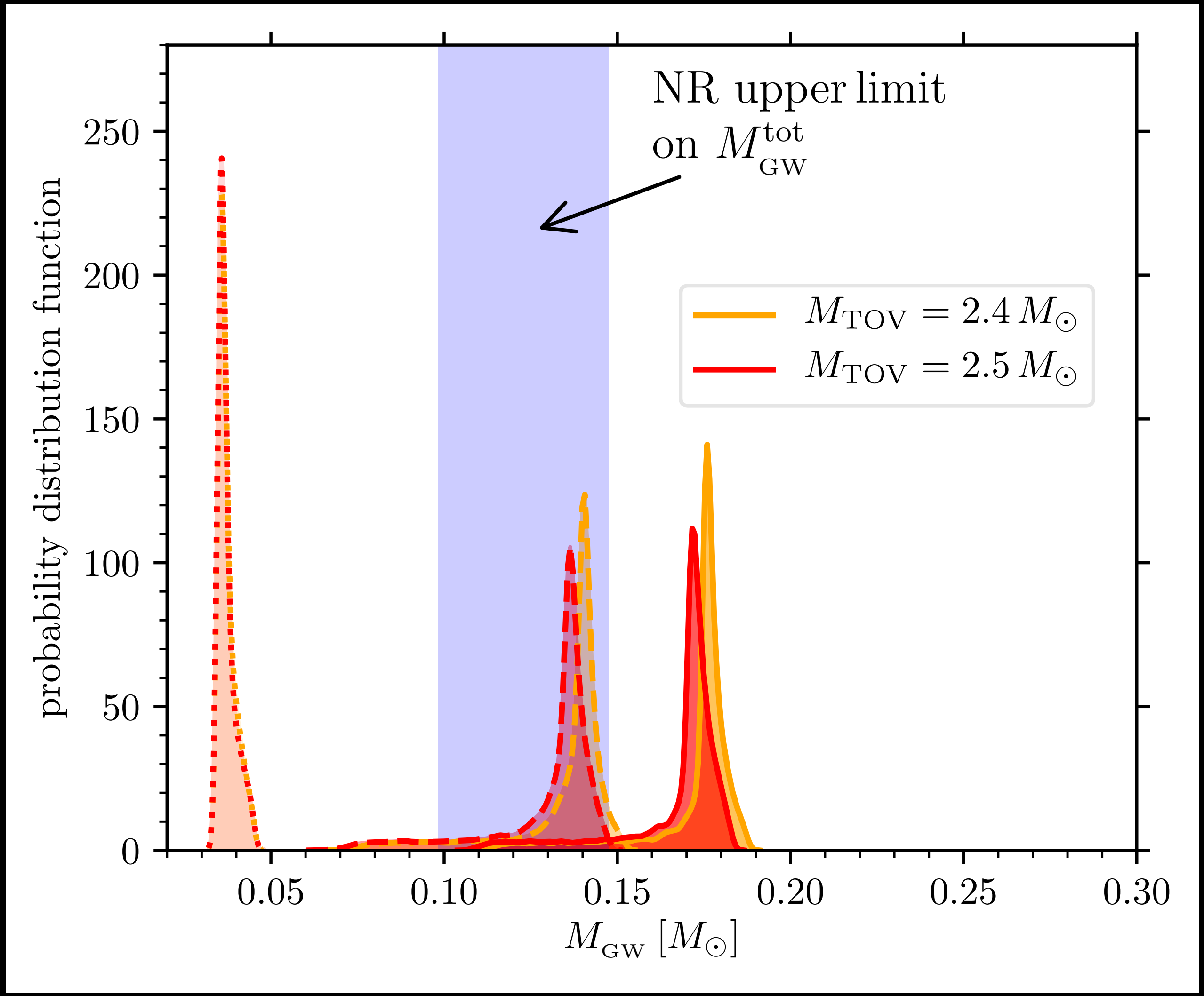


- Total mass emitted in GWs is in perfect **agreement** with predictions from numerical relativity



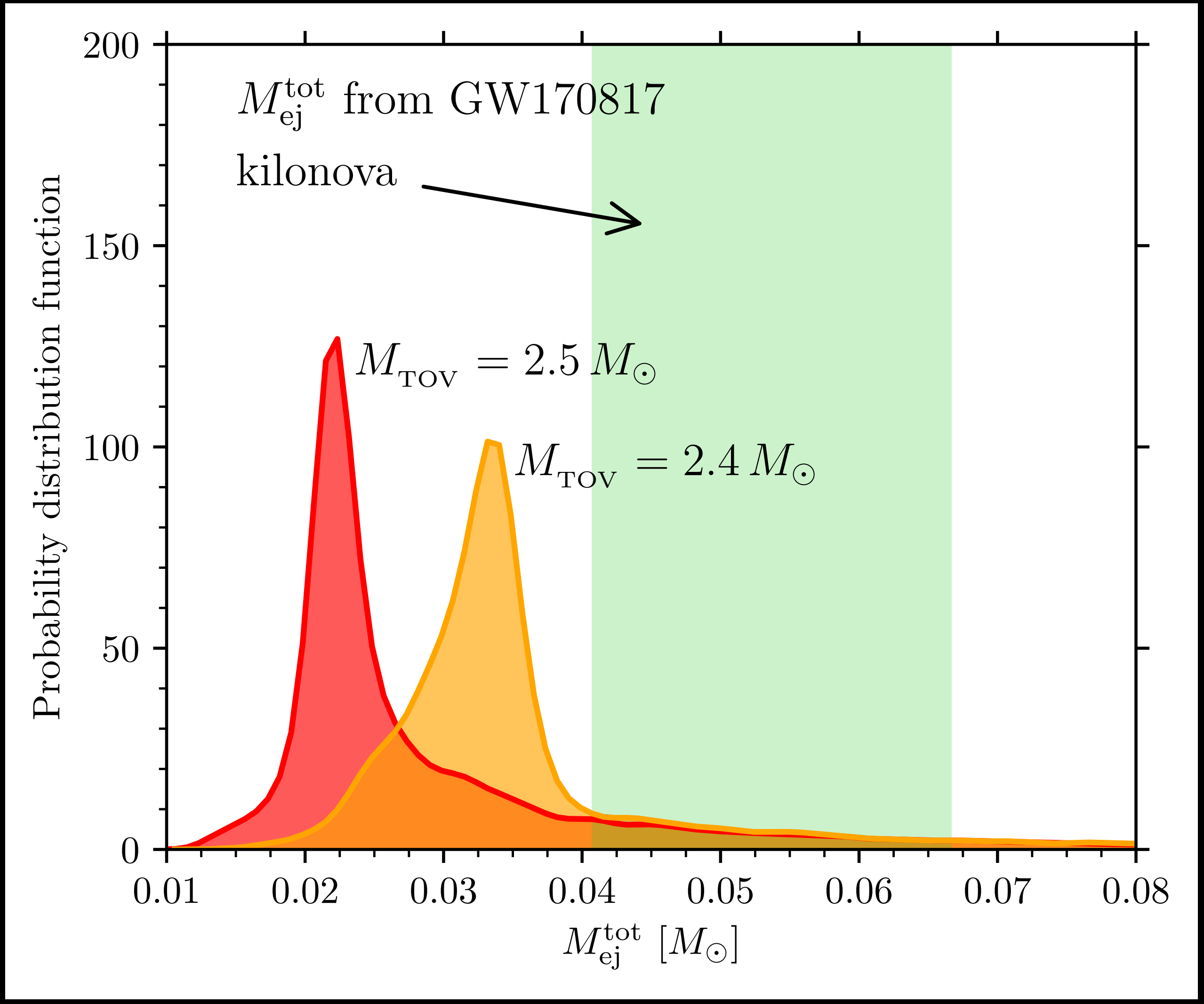
- Total mass ejected is in perfect **agreement** with predictions from kilonova signal

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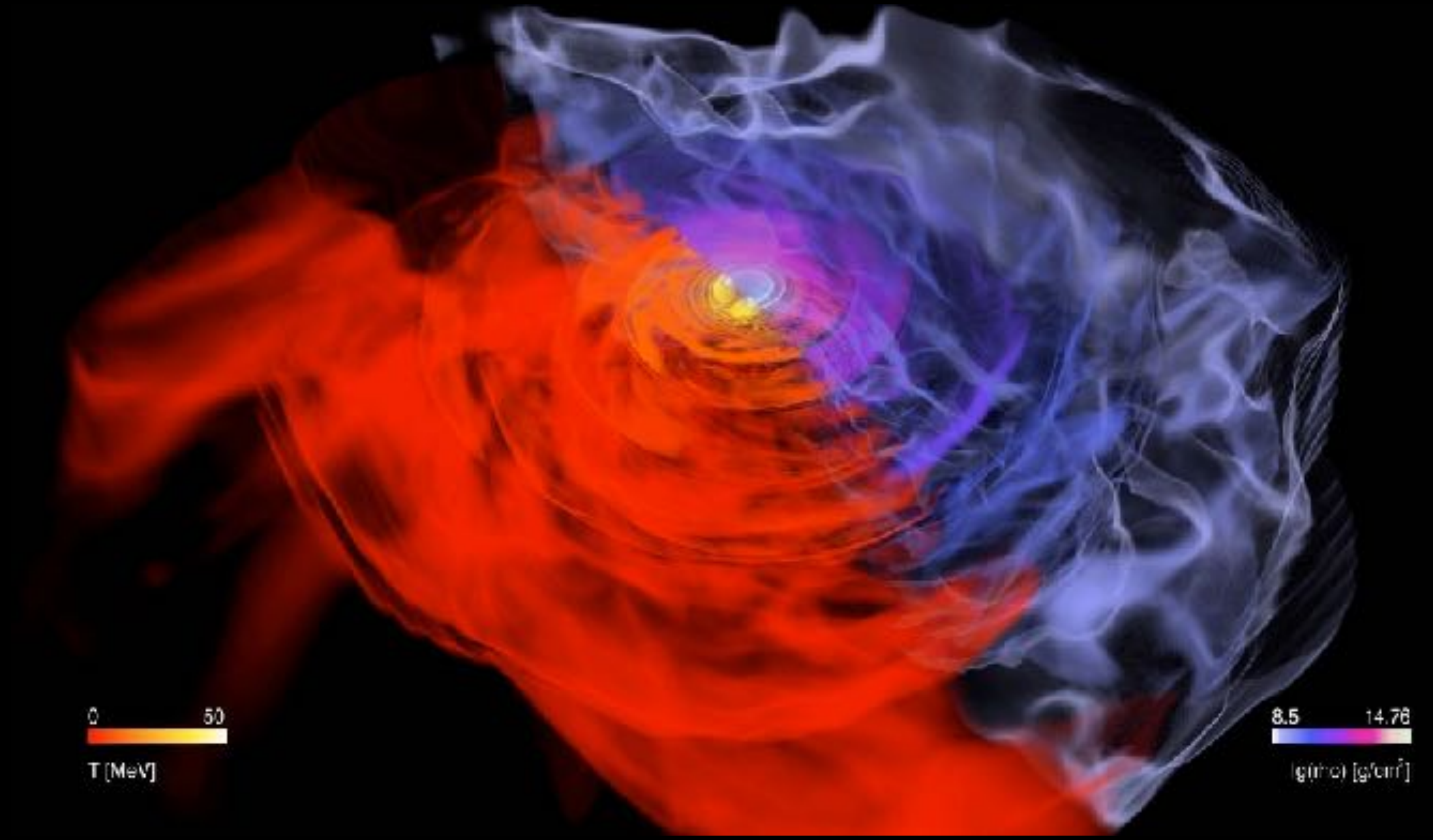
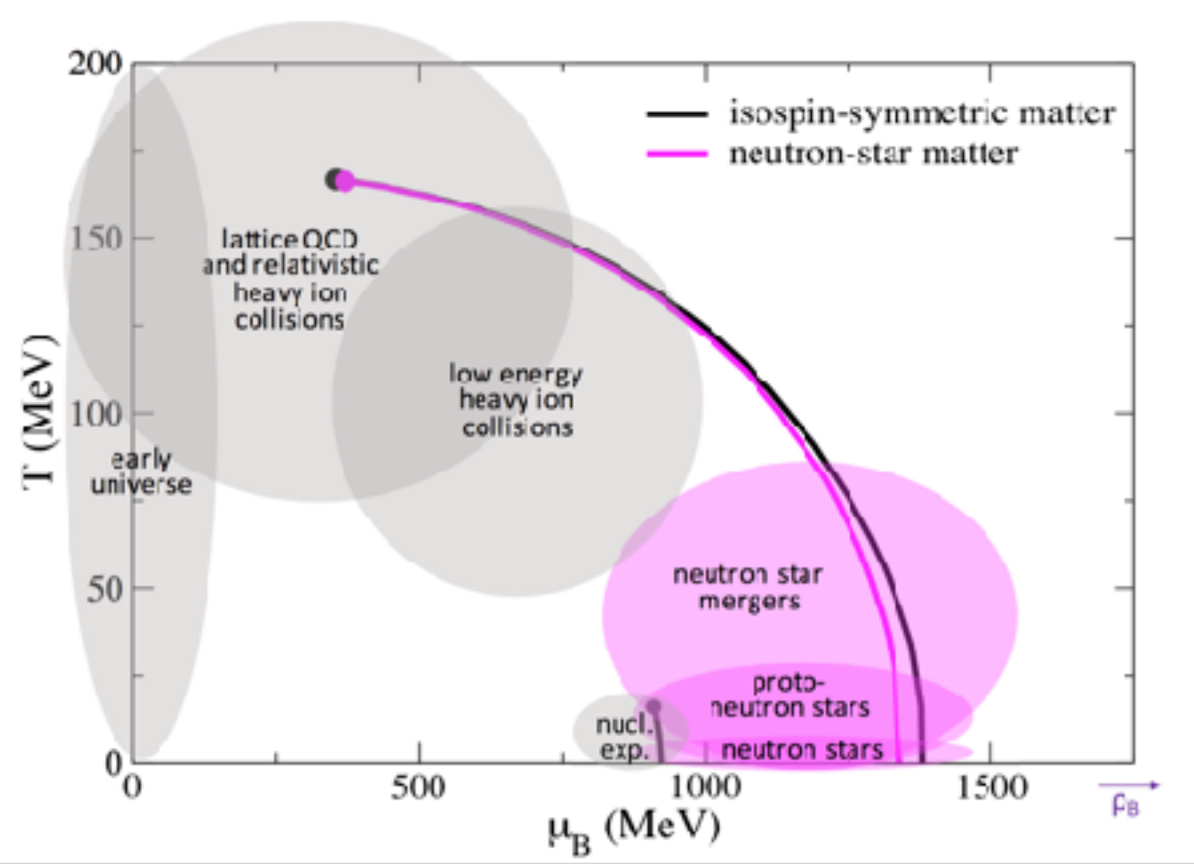
- If secondary in GW190814 was a NS, all previous considerations are incorrect.
- No EM counterpart was observed with GW190814 and no estimates possible on ejected matter or timescale for survival.
- **How do we solve this tension?**
- Solution: secondary in GW190814 **was a BH at merger** but could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

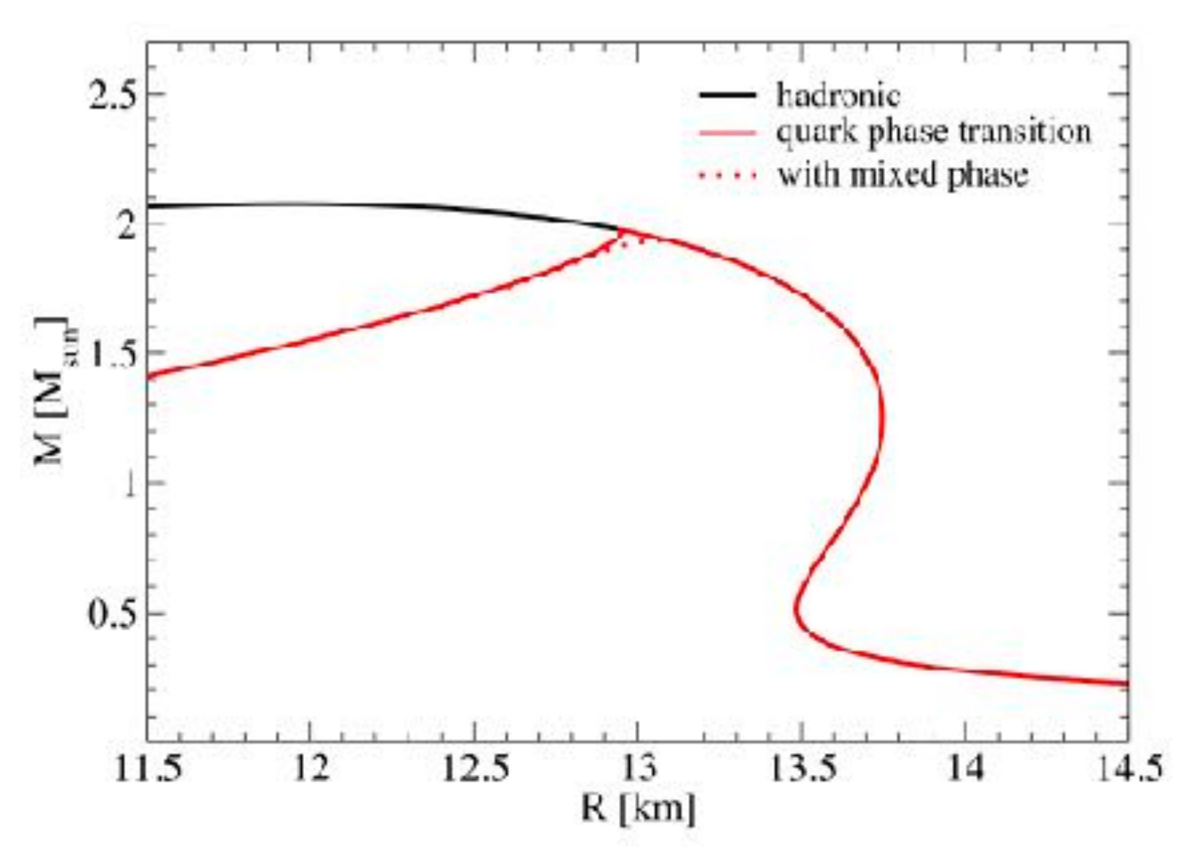
Phase transitions and their signatures



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

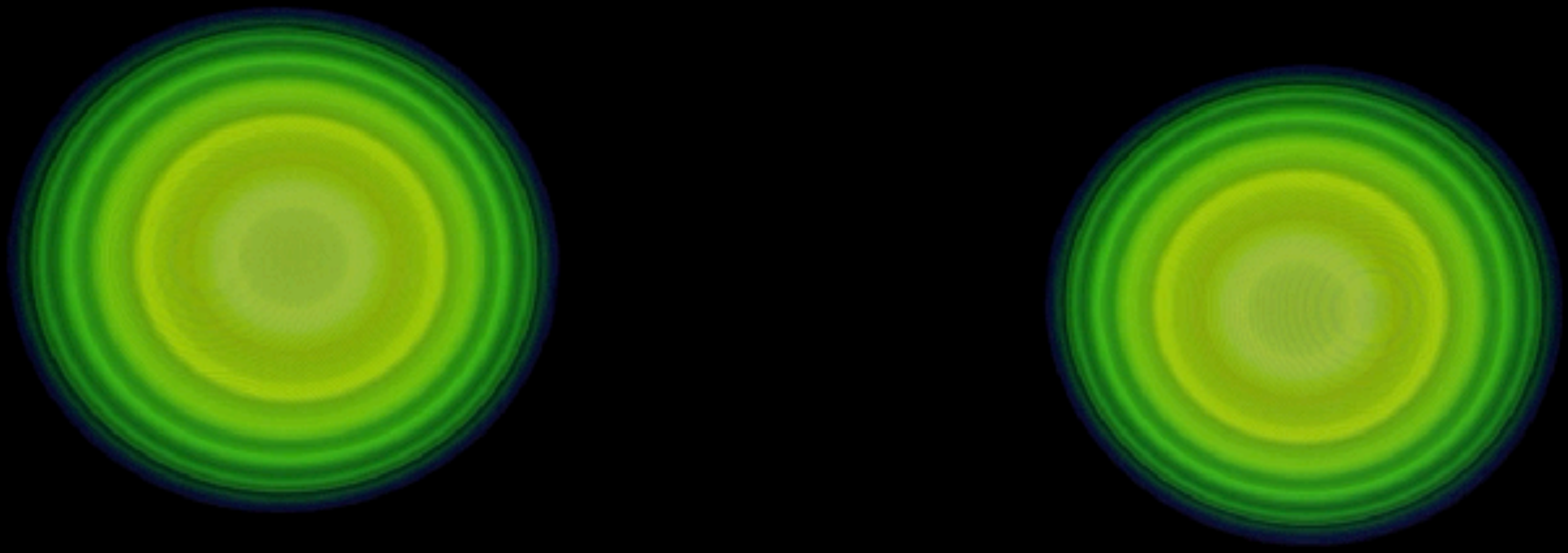
- **Isolated** neutron stars probe a small fraction of phase diagram.
- Neutron-star **binary** mergers reach temperatures up to 80 MeV and probe regions complementary to experiments.

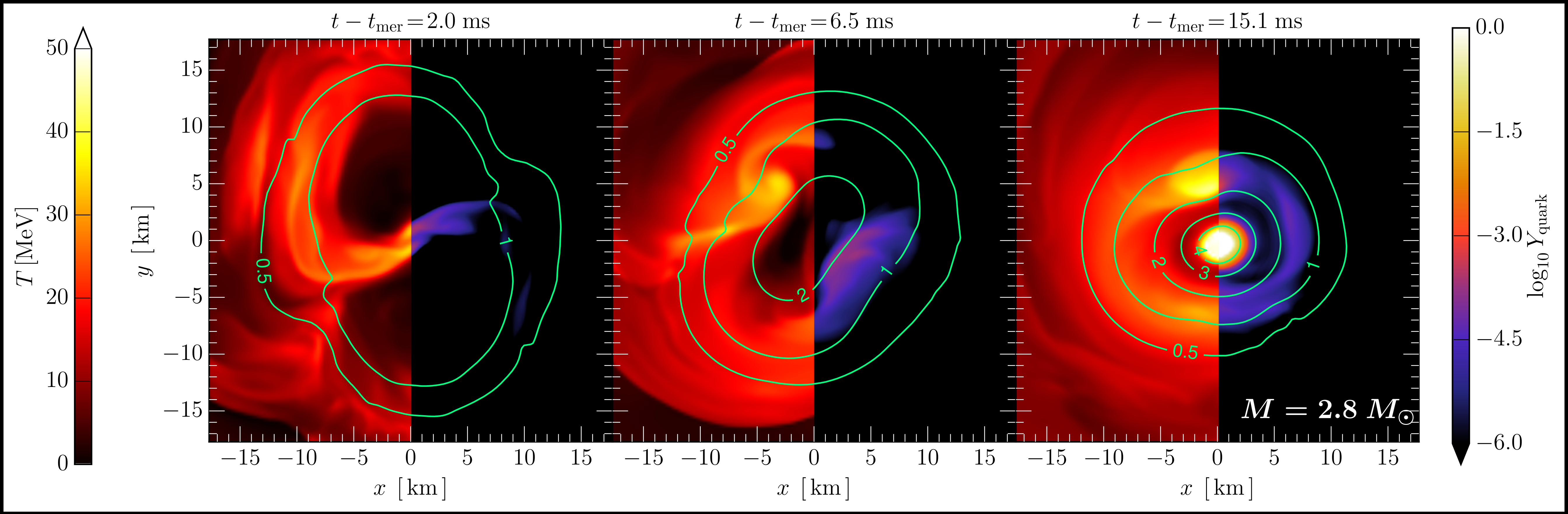




- Considered EOS based on Chiral Mean Field (CMF) model, based on a nonlinear SU(3) sigma model.
- Appearance of quarks can be introduced naturally.

Animations: Weih, Most, LR

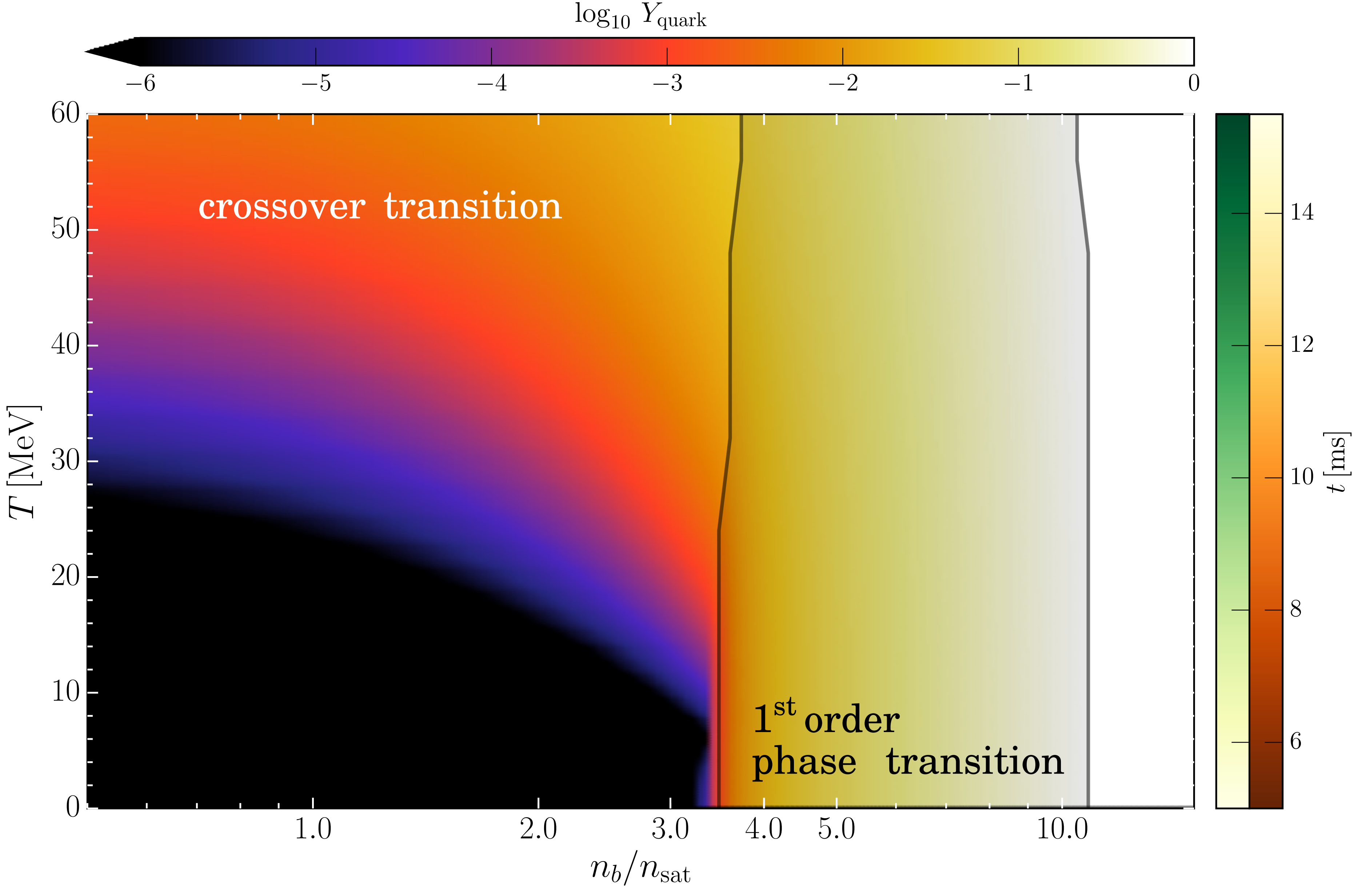




Quarks appear at sufficiently large temperatures and densities.

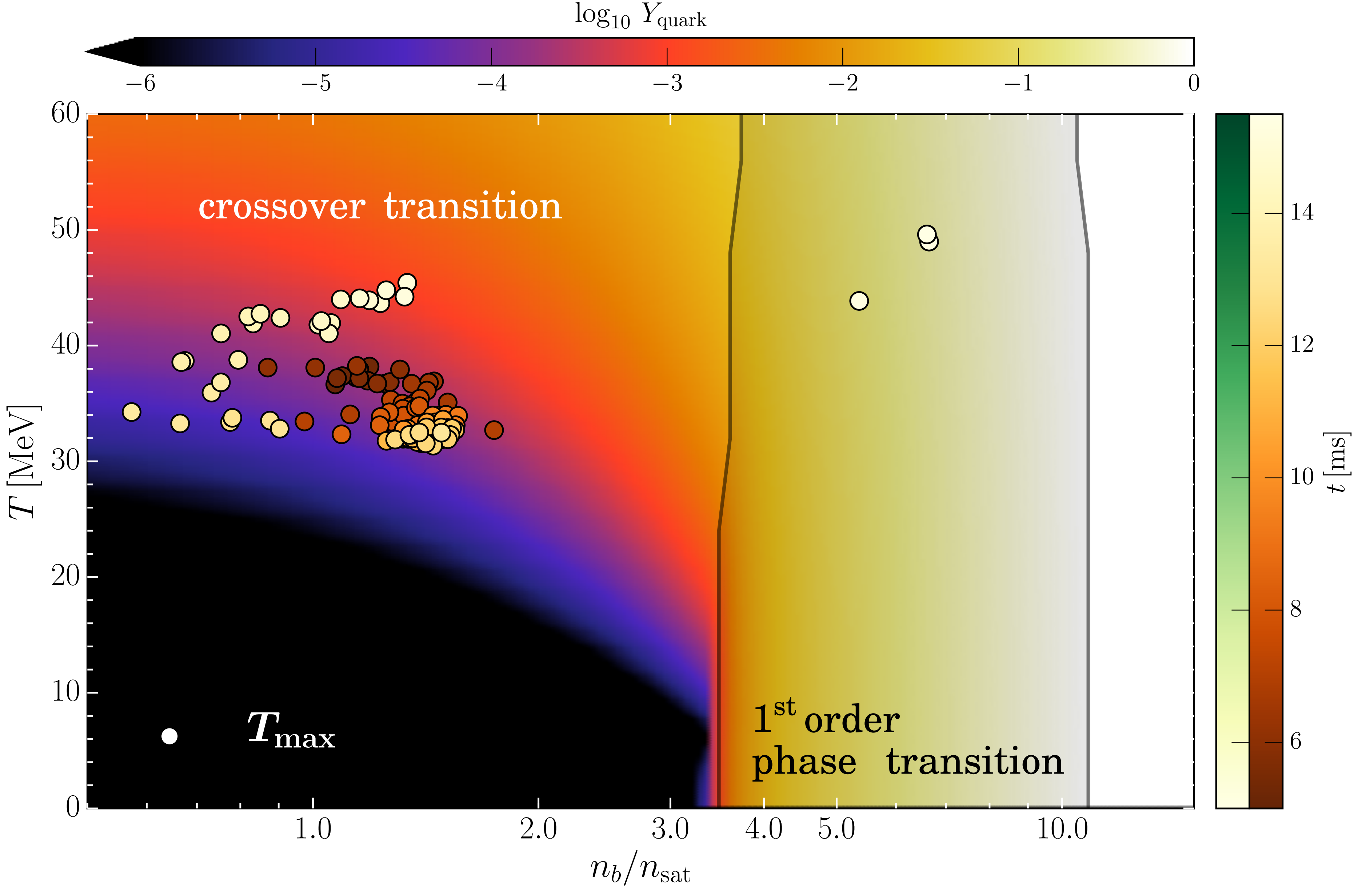
When this happens the EOS is considerably softened and a BH produced.

Comparing with the phase diagram



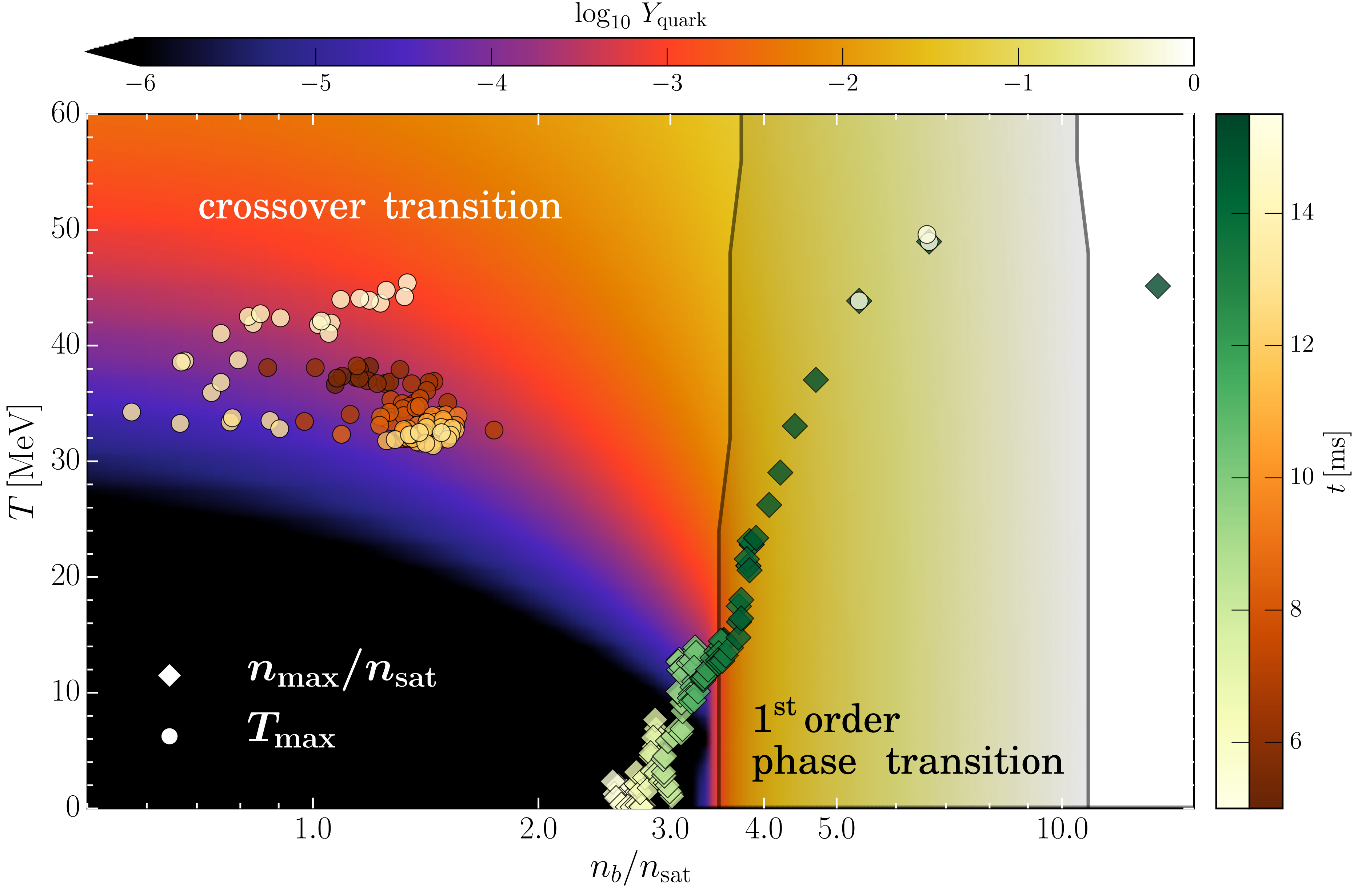
- Phase diagram with quark fraction

Comparing with the phase diagram



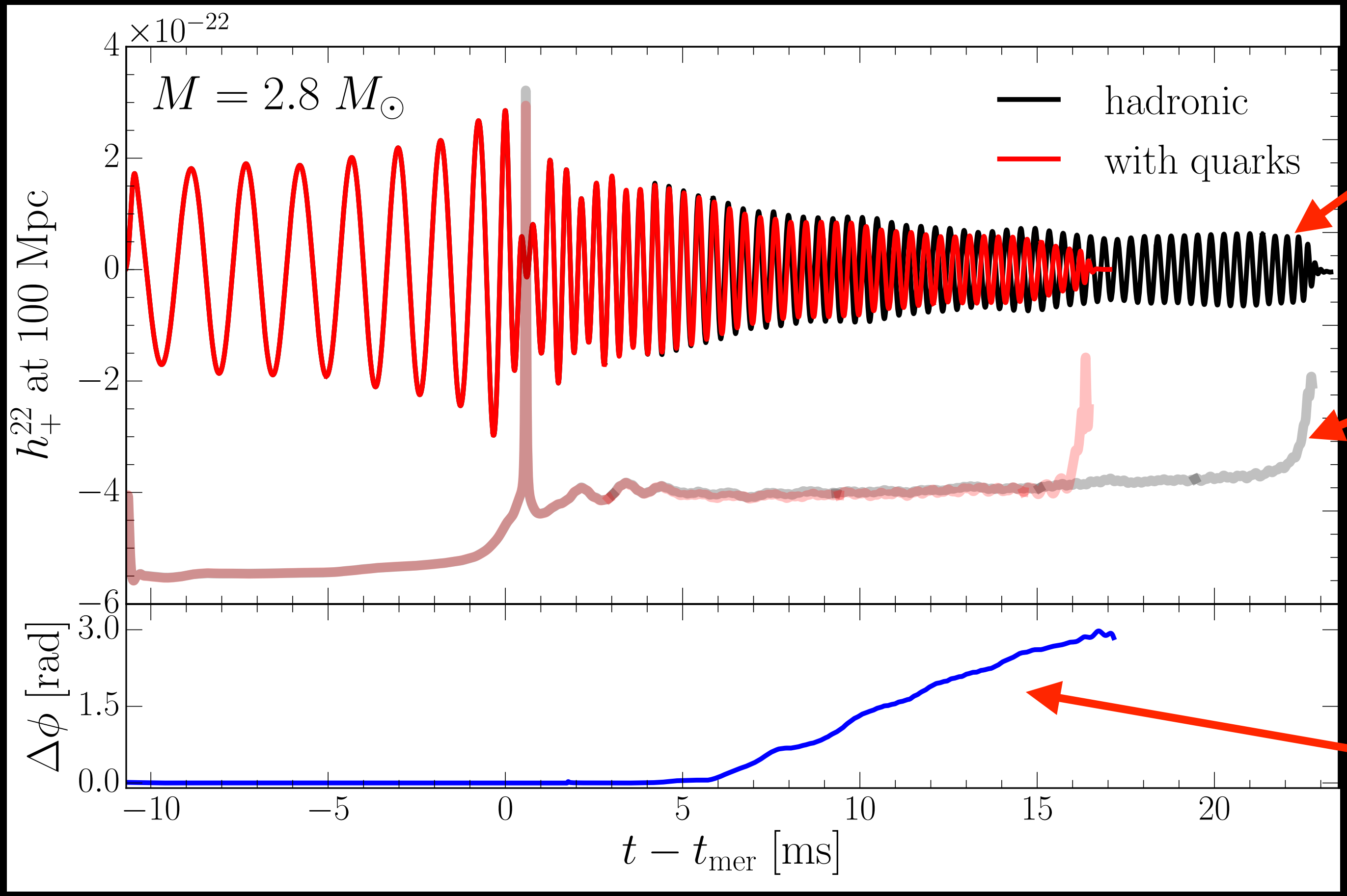
- Phase diagram with quark fraction
- Circles show the position in the diagram of the maximum temperature as a function of time

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



waveforms

GW frequencies

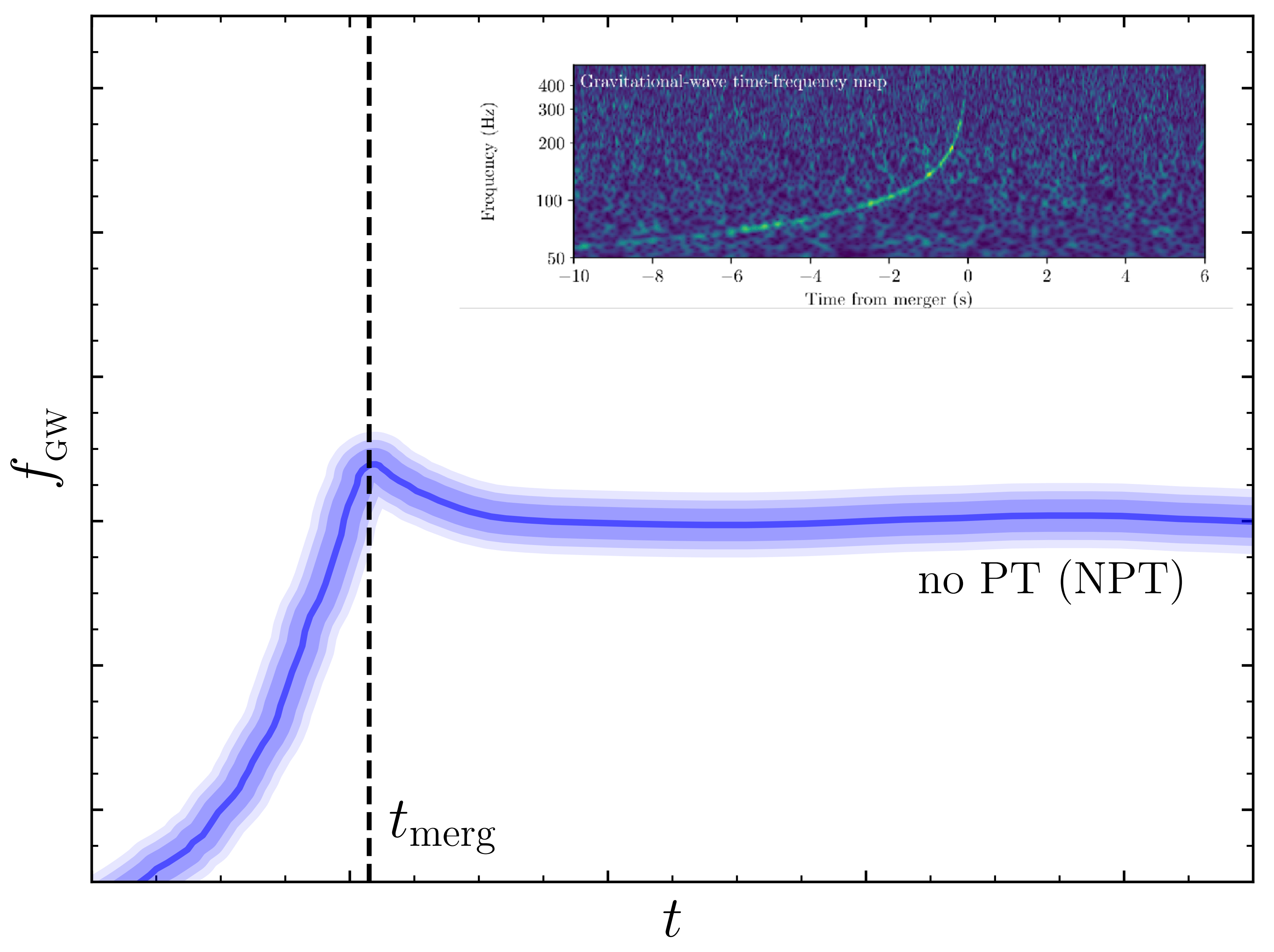
phase difference

- 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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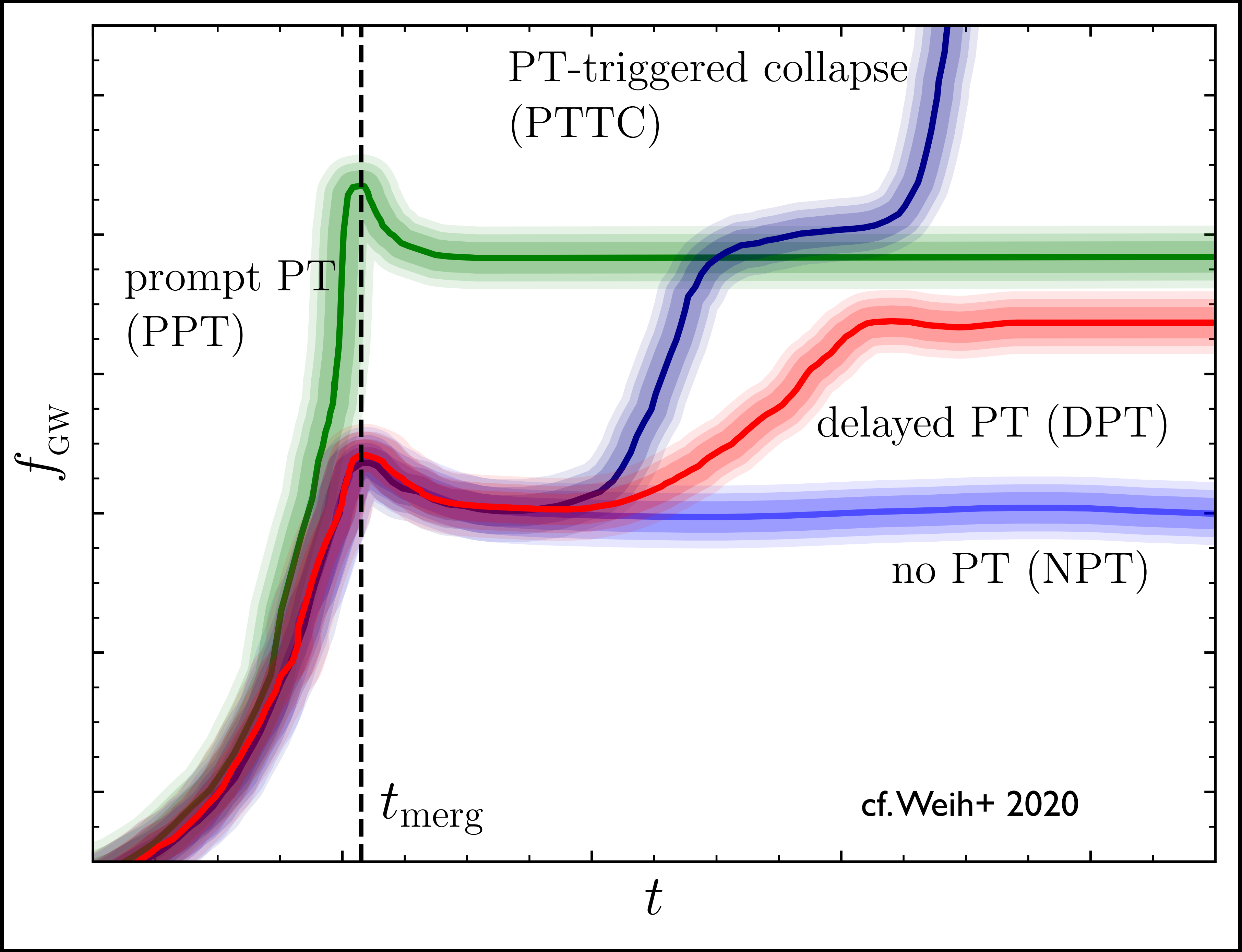
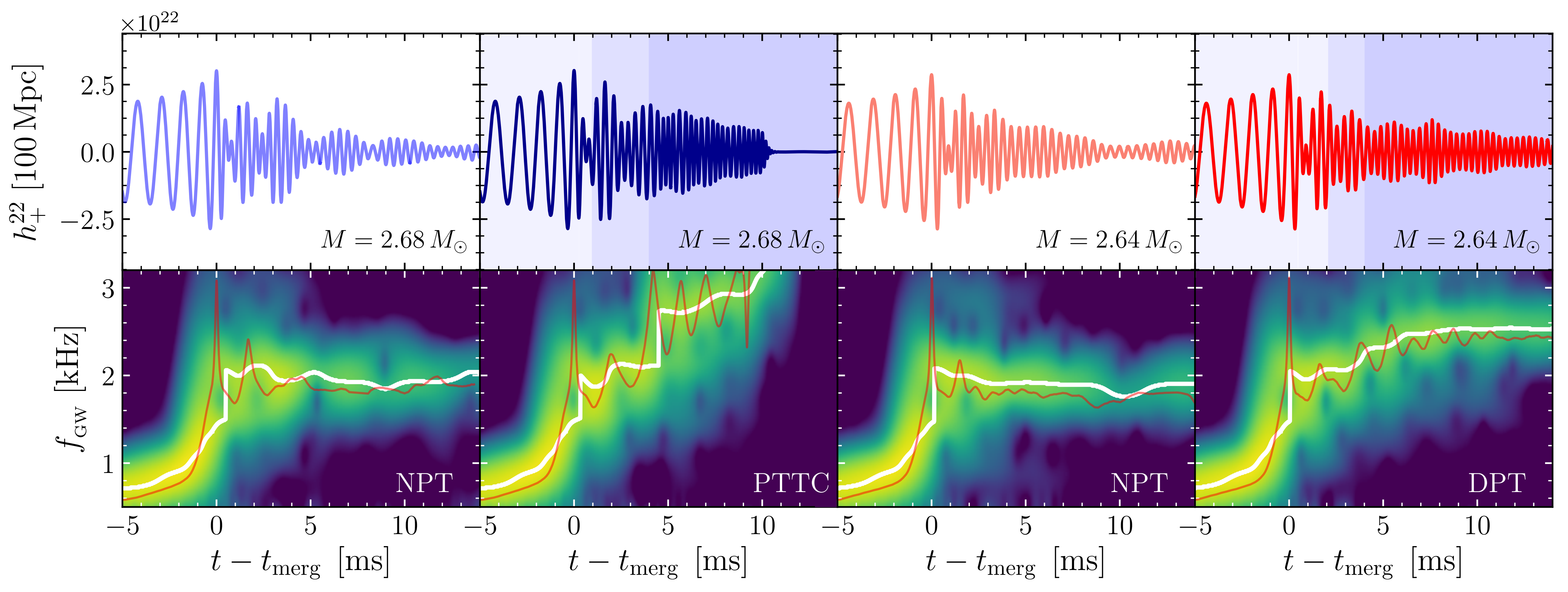


A more comprehensive picture

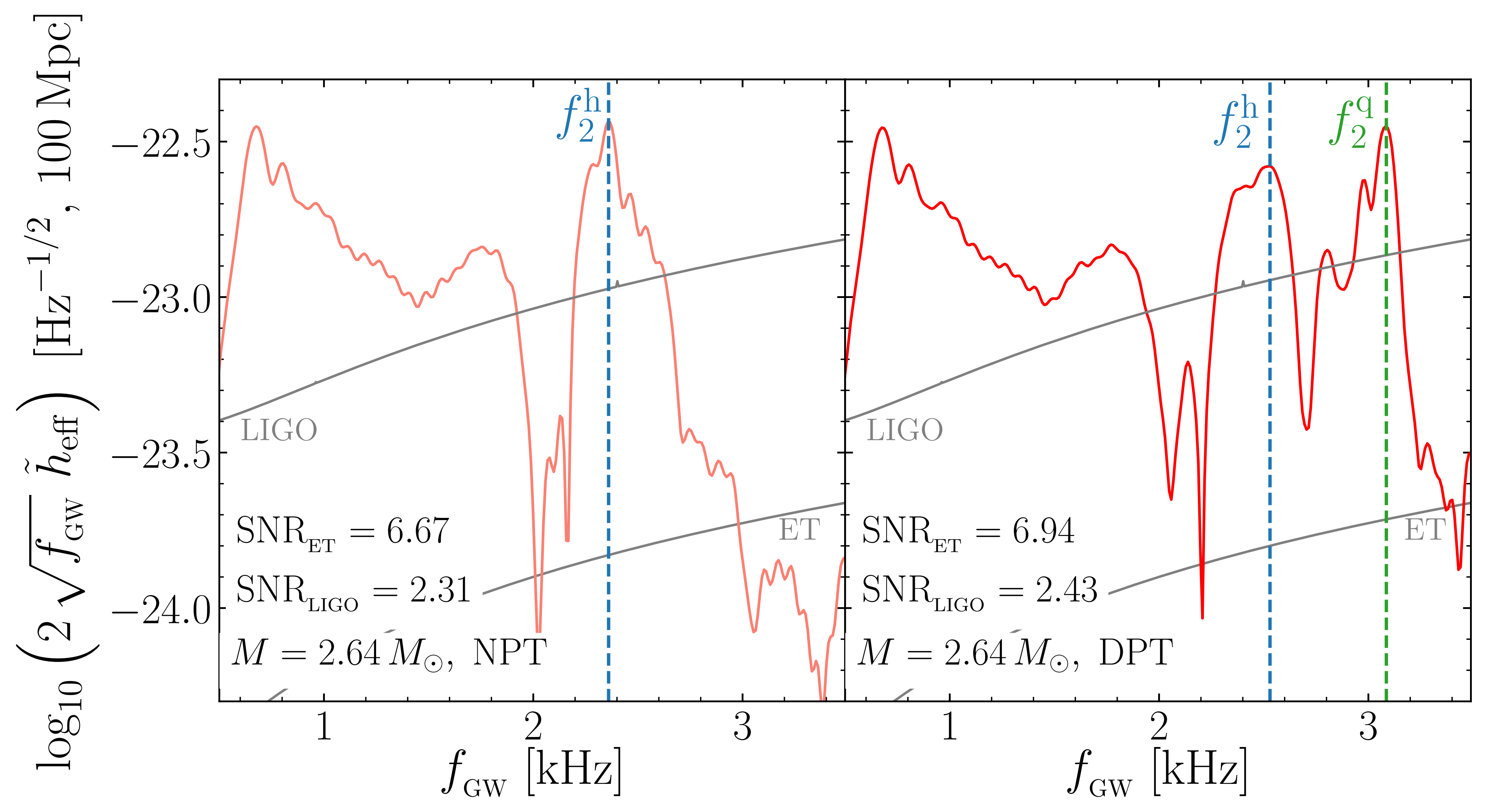
Different signatures are also quite transparent when shown in terms of the gravitational waves and their spectrograms.



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

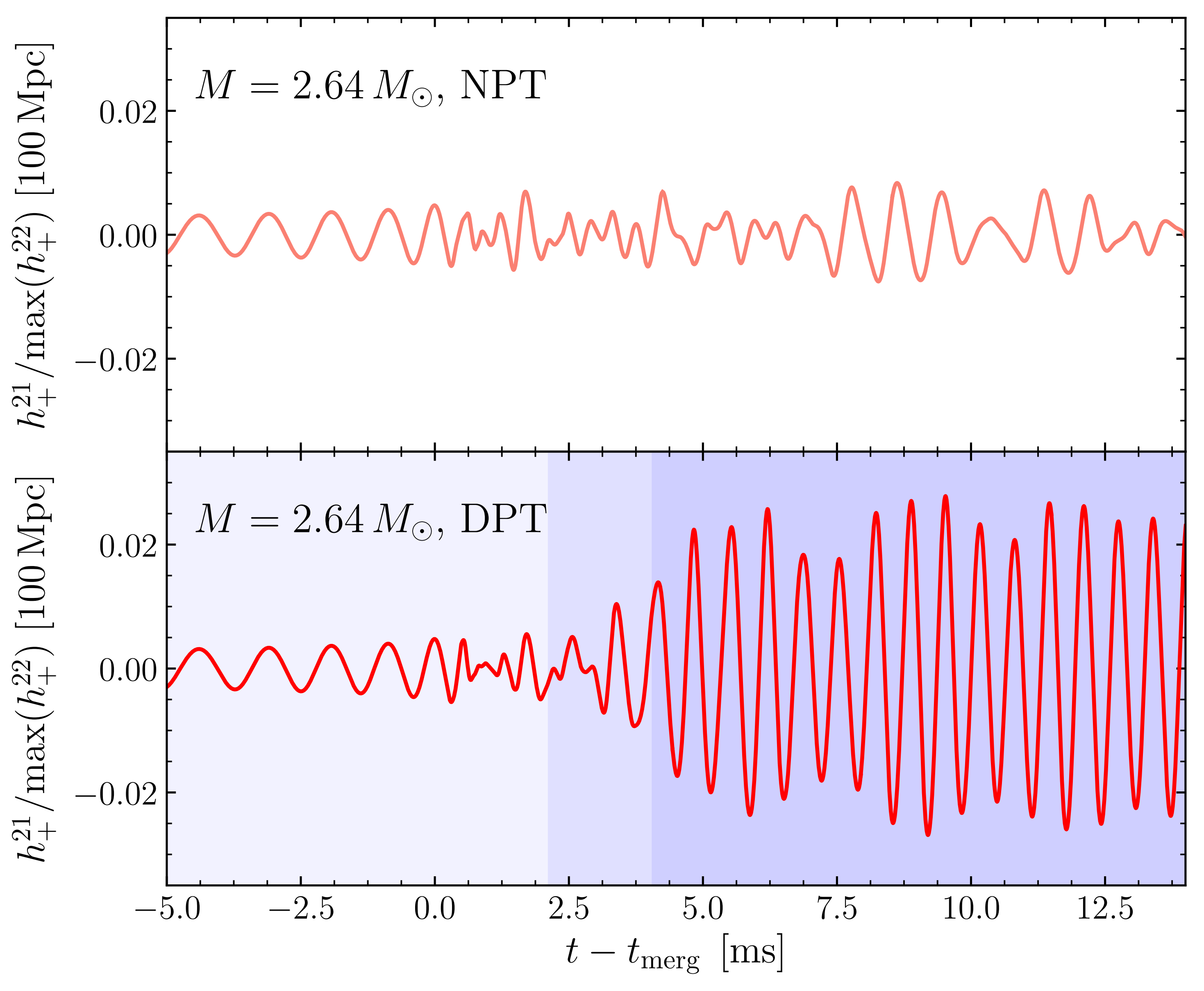
Different signatures are also quite transparent when shown in terms of the gravitational waves and their spectrograms.



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.

✳Threshold mass has universal behaviour with **spin** and **mass ratio**

✳**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

Conclusions

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

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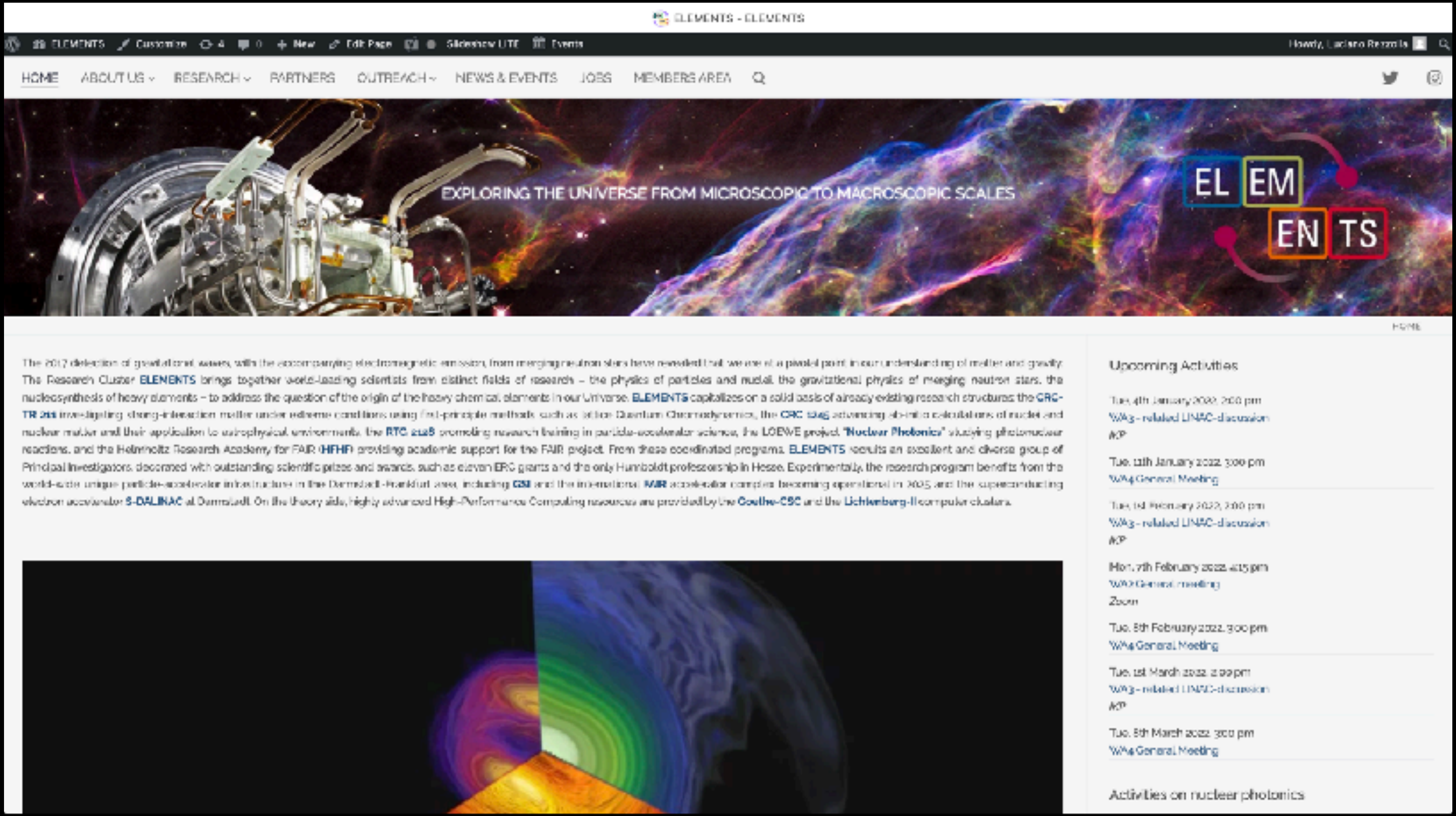

The 2017 detection of gravitational waves, with the accompanying electromagnetic emission, from merging neutron stars have revealed that we are at a pivotal point in our understanding of matter and gravity. The Research Cluster **ELEMENTS** brings together world-leading scientists from distinct fields 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** capitalizes 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 (**HFHF**) 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 world-wide 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.

Upcoming Activities

Tue, 4th January 2022, 2:00 pm
WA3 - related LINAC-discussion
IKP

Tue, 11th January 2022, 3:00 pm
WA4 General Meeting

Tue, 1st February 2022, 2:00 pm
WA3 - related LINAC-discussion
IKP

Mon, 7th February 2022, 4:15 pm
WA2 General meeting
Zoom

Tue, 8th February 2022, 3:00 pm
WA4 General Meeting

Tue, 1st March 2022, 2:00 pm
WA3 - related LINAC-discussion
IKP

Tue, 8th March 2022, 3:00 pm
WA4 General Meeting

Activities on nuclear photonics