The physics of binary neutron star mergers

Lecture II

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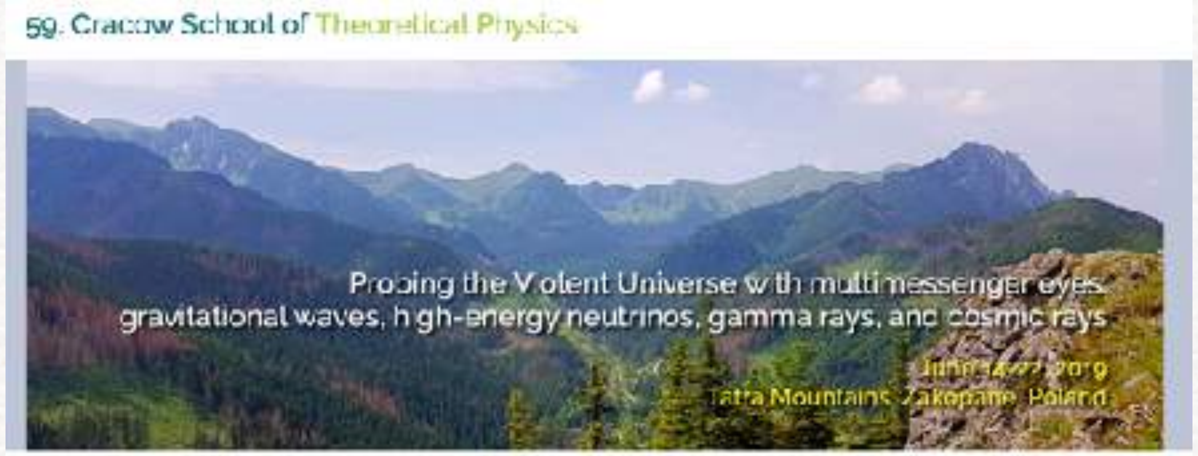
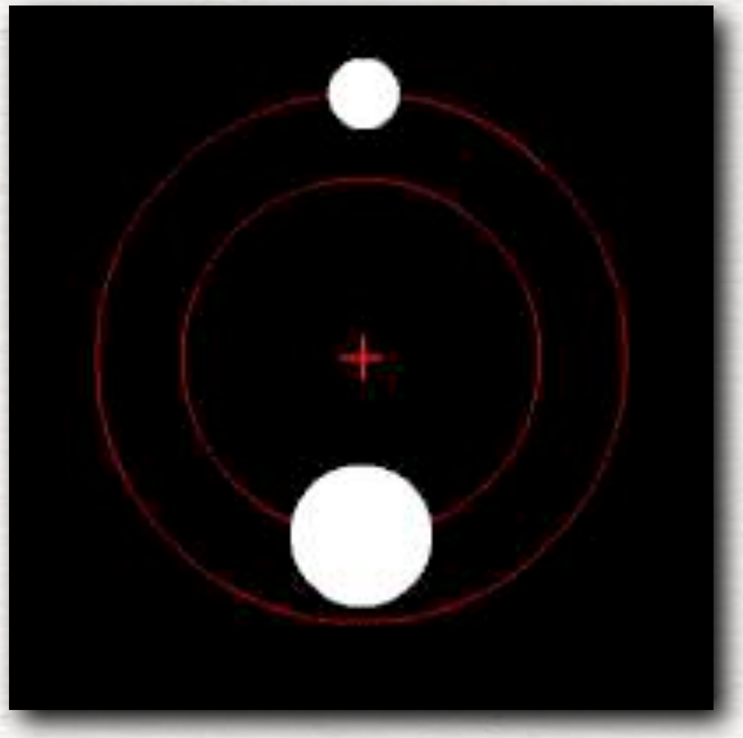


Plan of the lectures

- ✶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

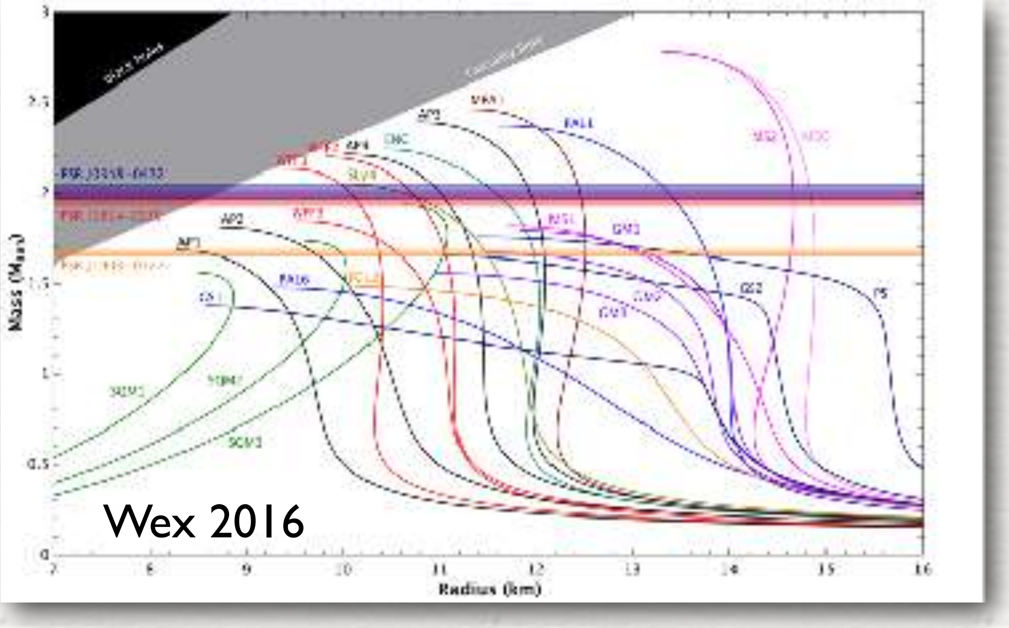
- For BHs we know what to **expect**:

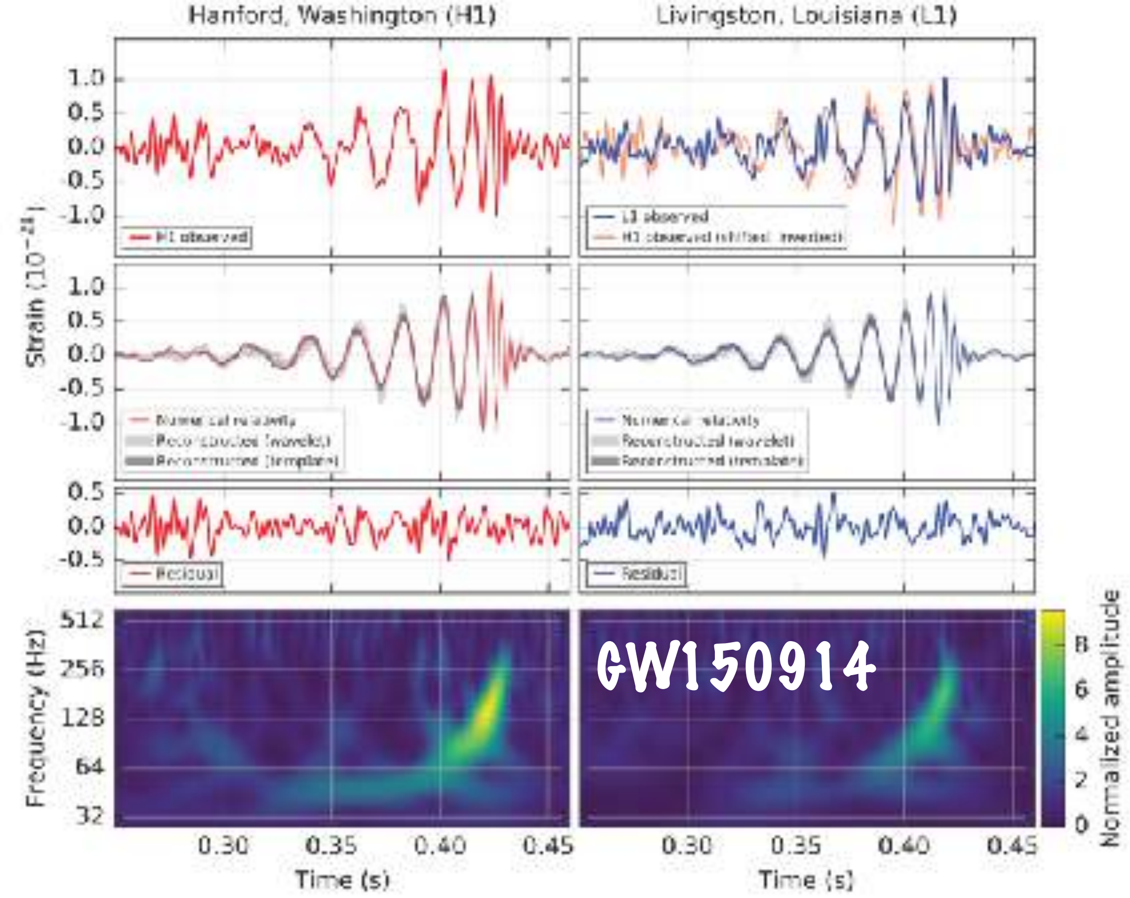
BH + BH → BH + GWs

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

NS + NS → HMNS+**... ?** → BH+t

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





Abbott+ 2016

artist impression (NASA)

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

The two-body problem in GR

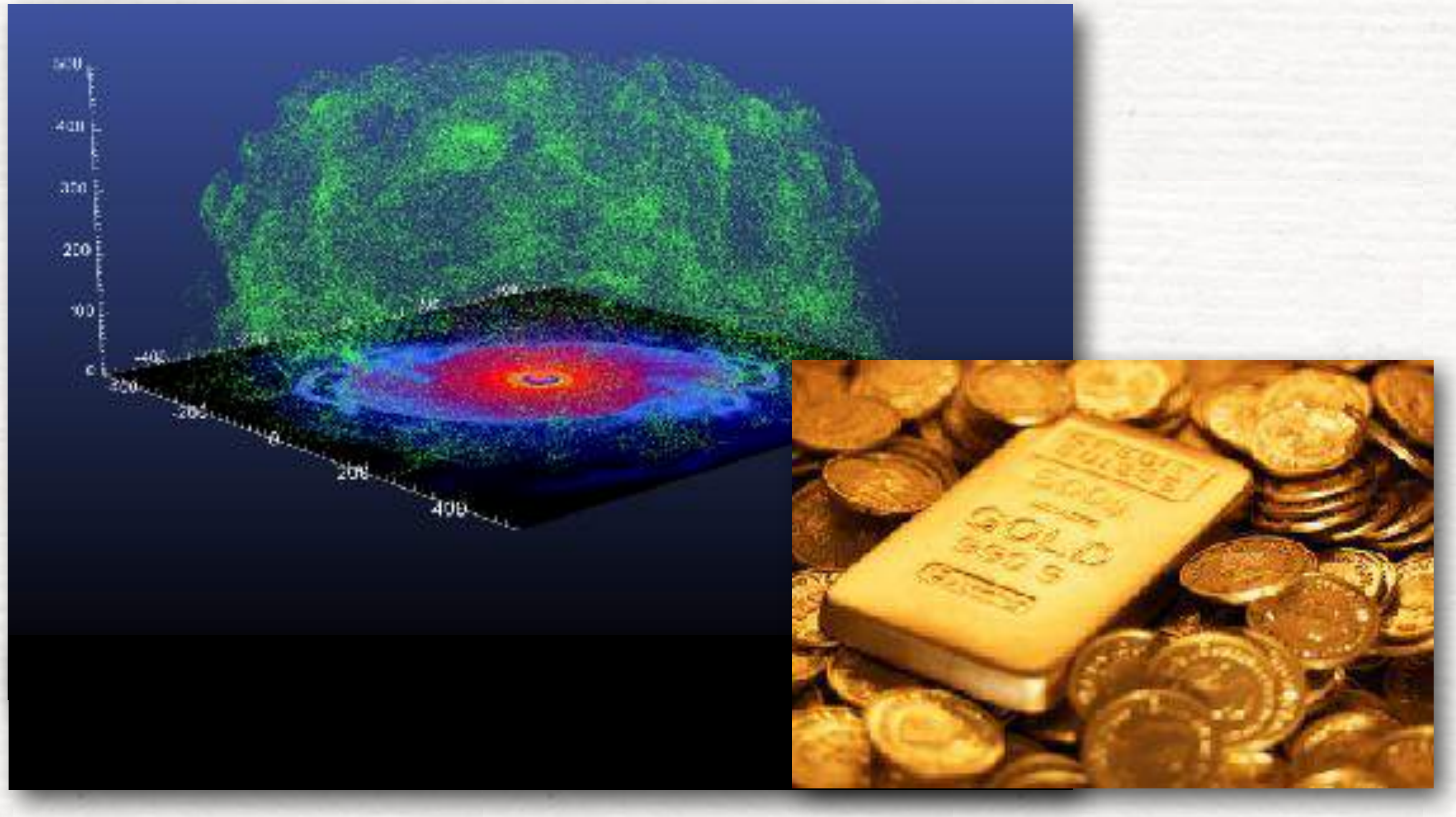
- For BHs we know what to **expect**:

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

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

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

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

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

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

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

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

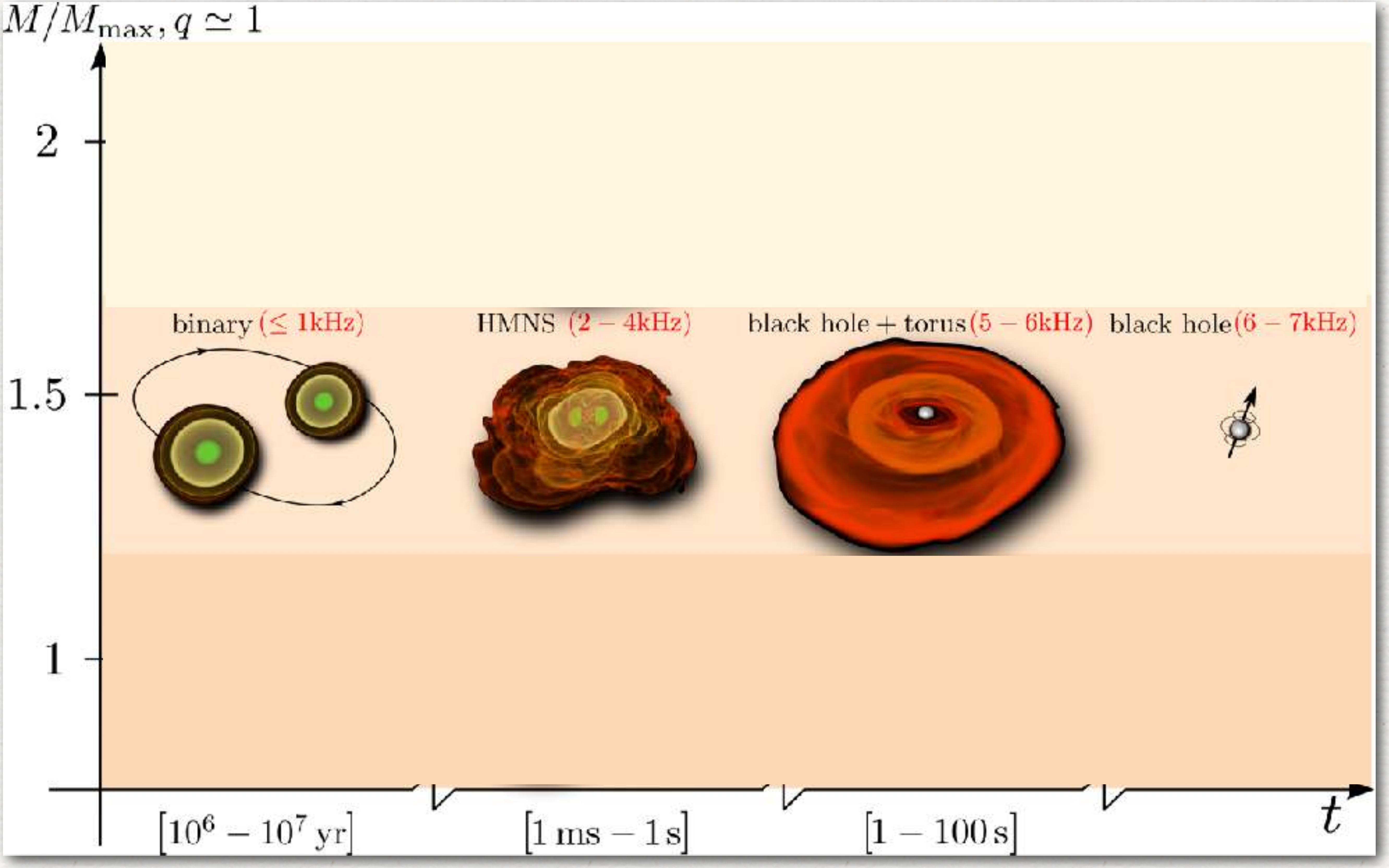
LS220 EOS

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;

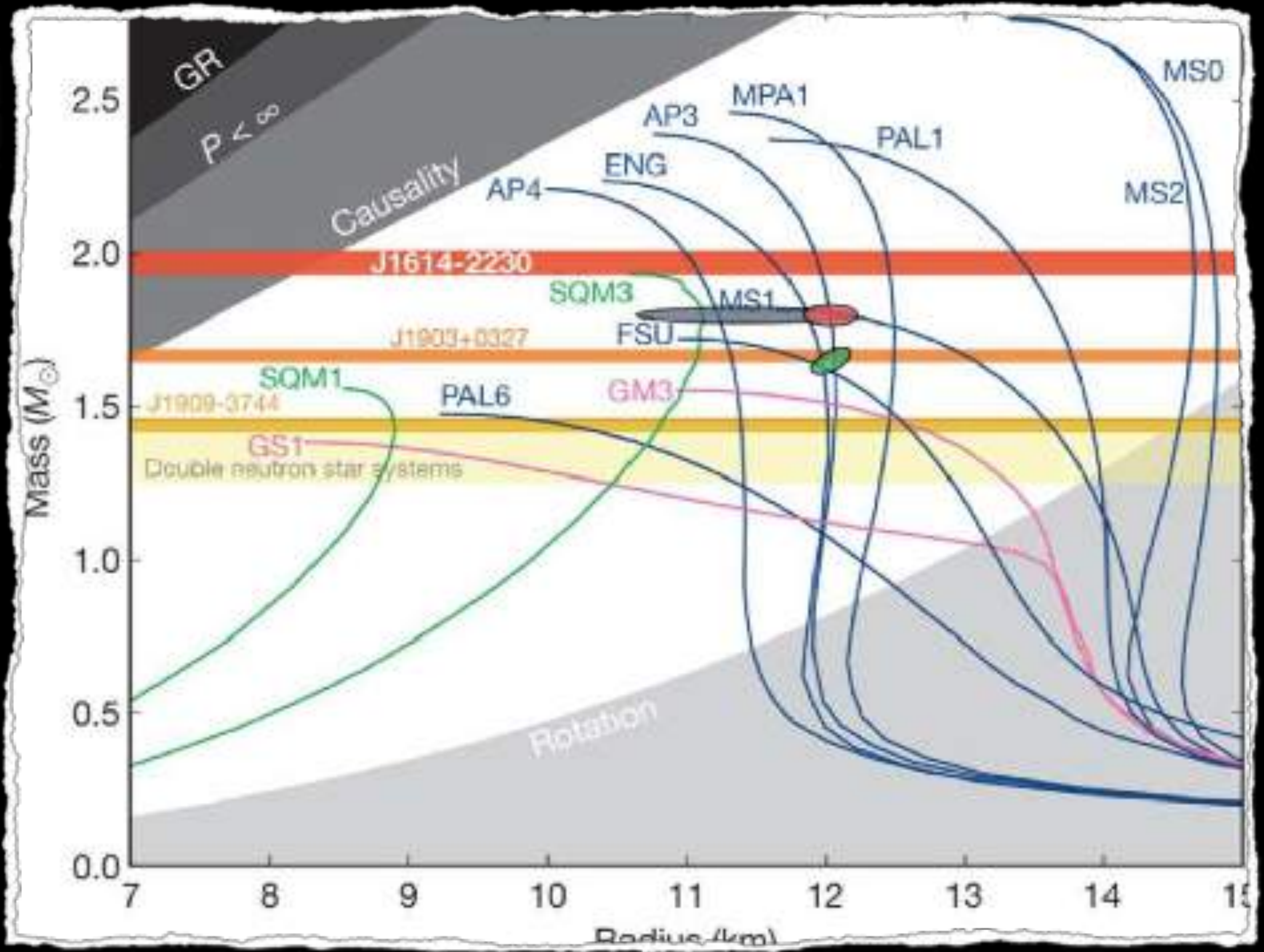
- the torii are generically more massive
- the torii are generically more extended
- the torii tend to stable quasi-Keplerian configurations
- overall unequal-mass systems have all the ingredients needed to create a GRB

merger → HMNS → BH + torus

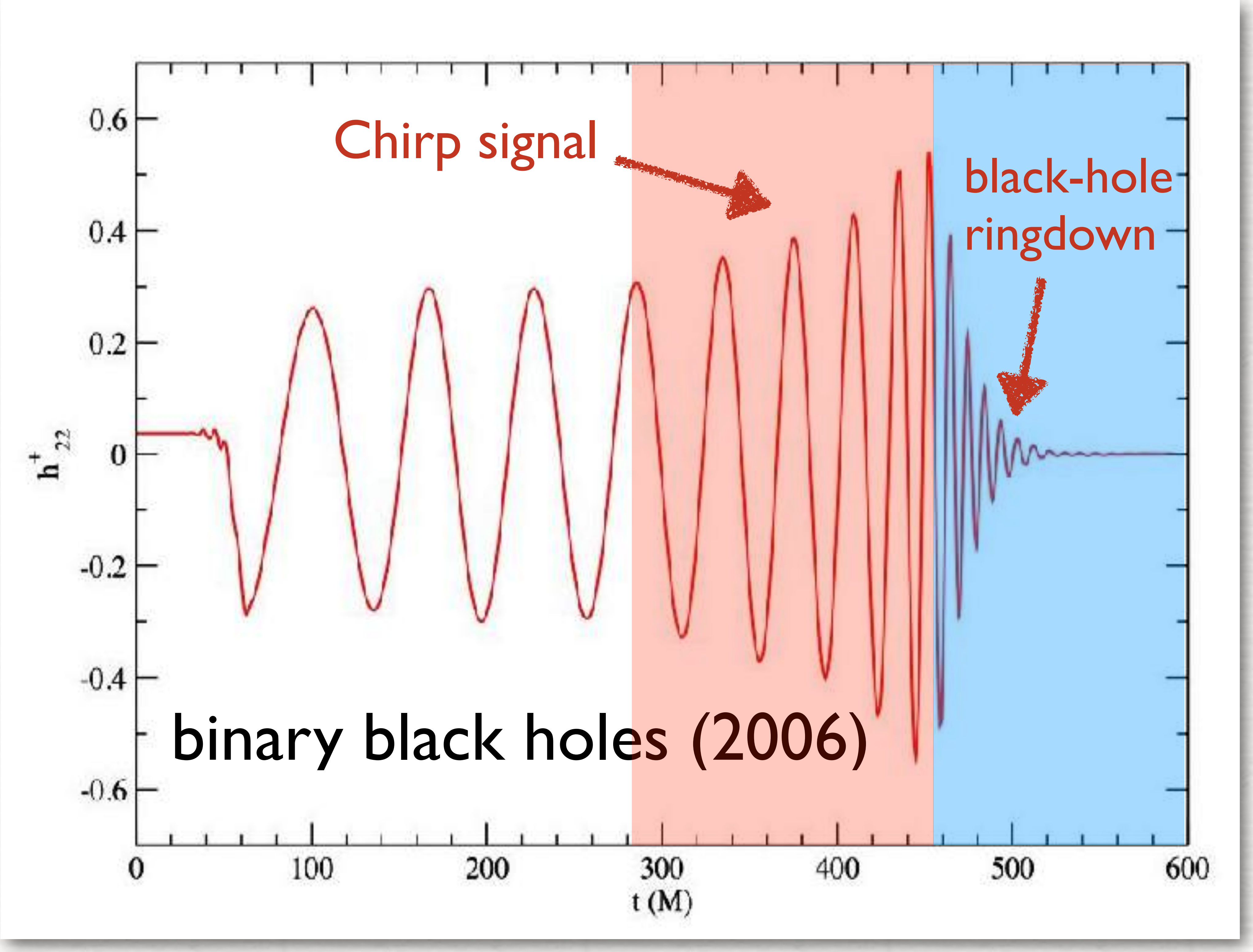
Quantitative differences are produced by:

- 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)

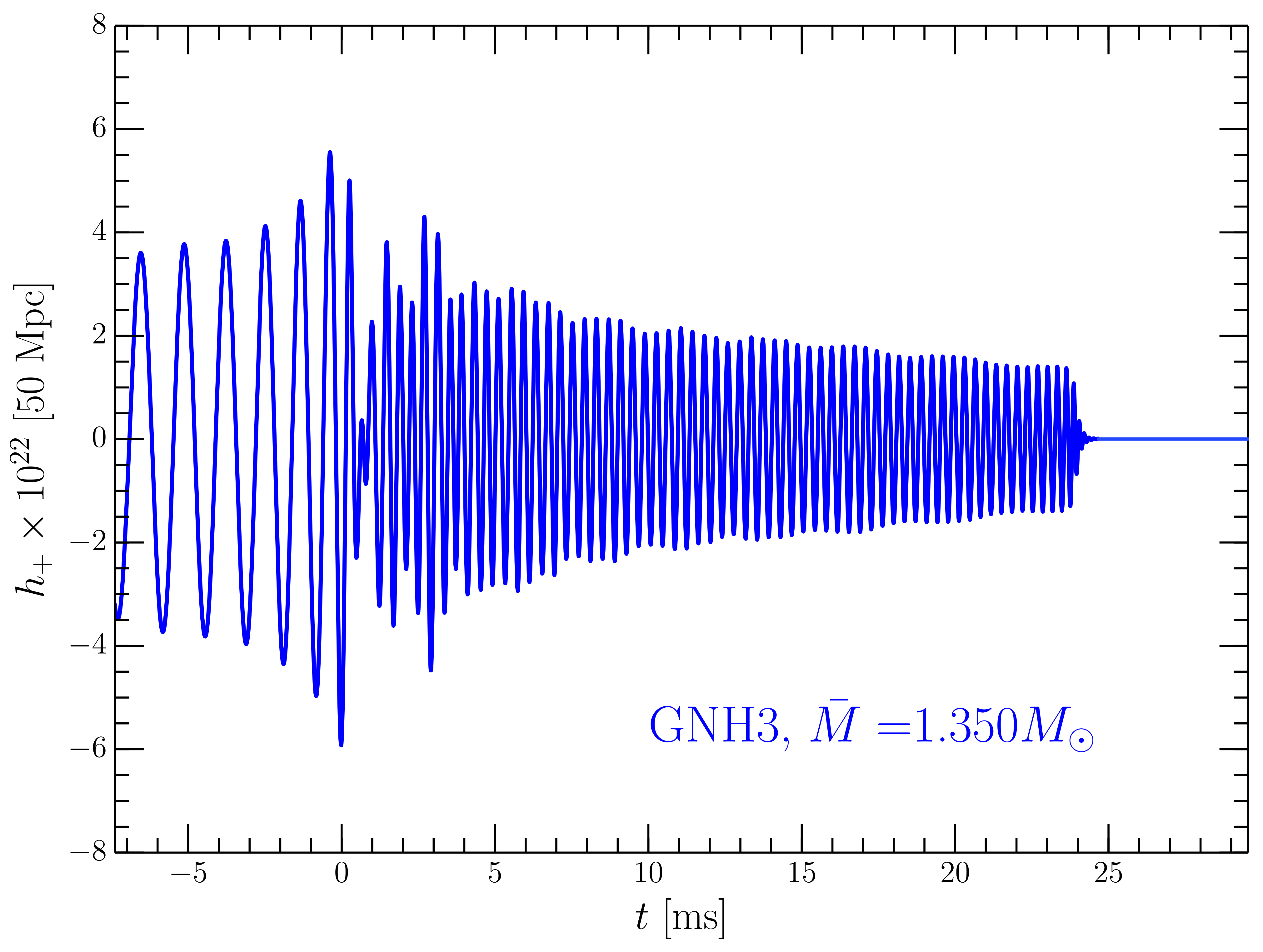
How to constrain the EOS from the GWs



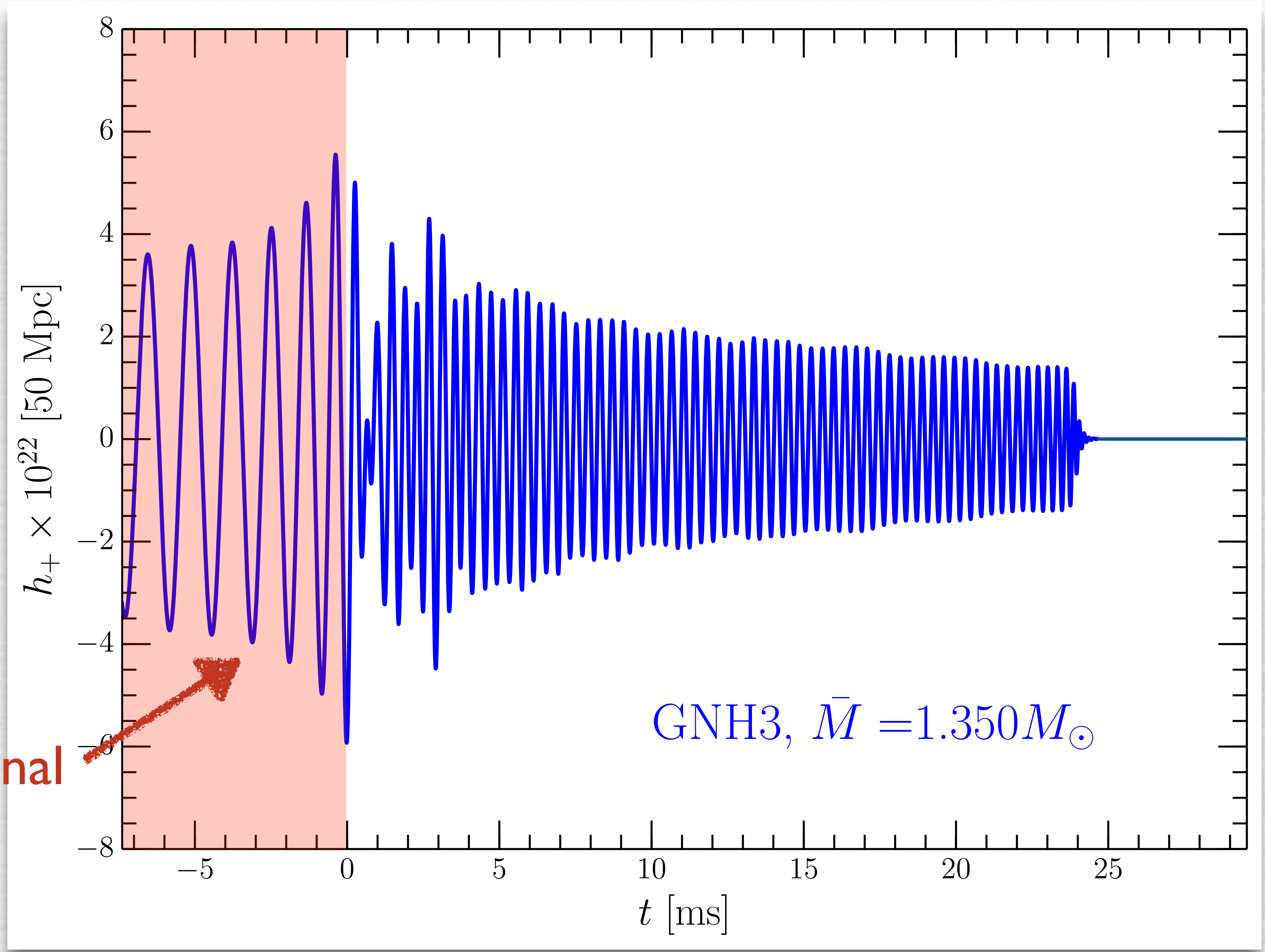
Anatomy of the GW signal



Anatomy of the GW signal



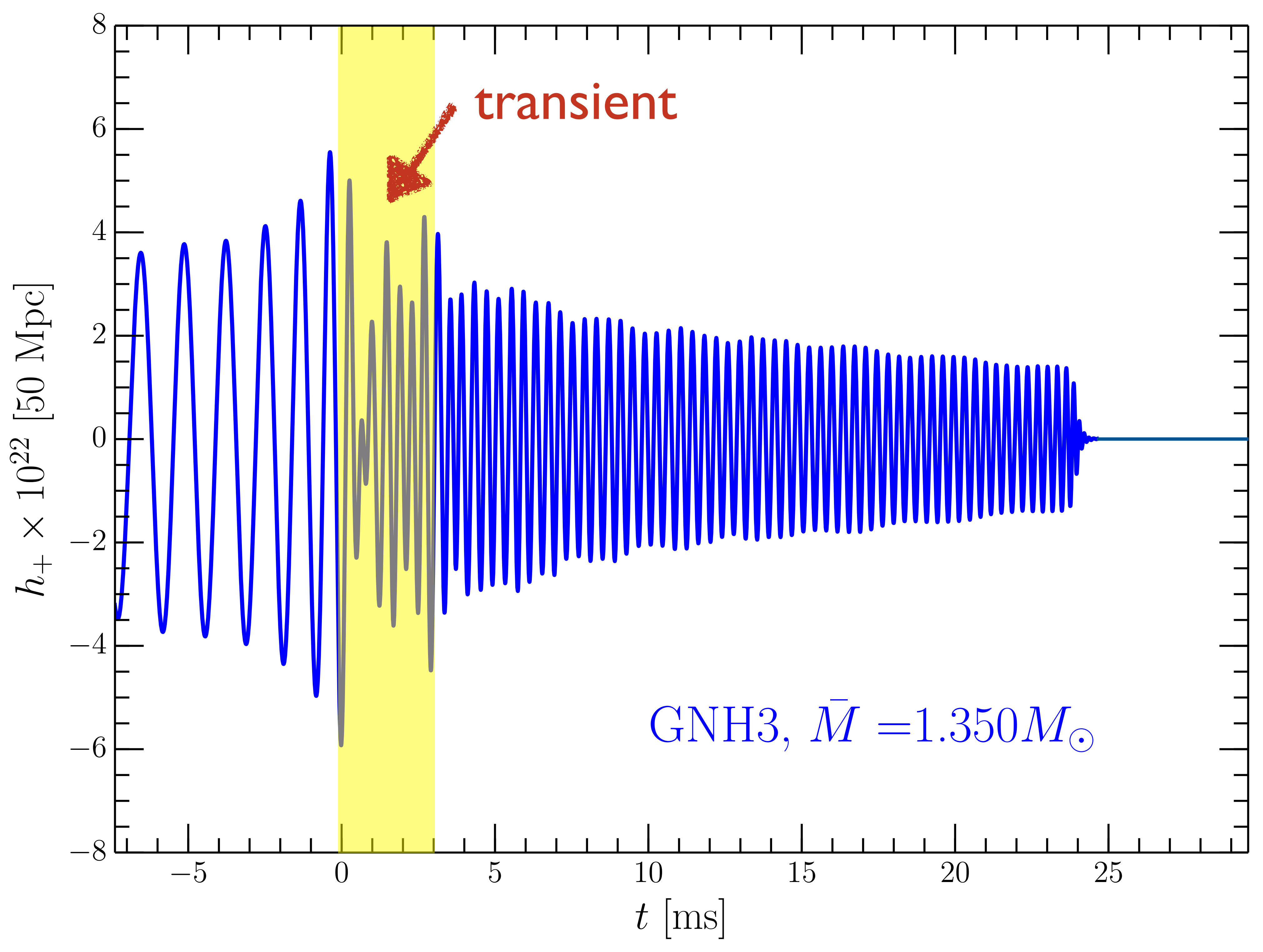
Anatomy of the GW signal



Chirp signal

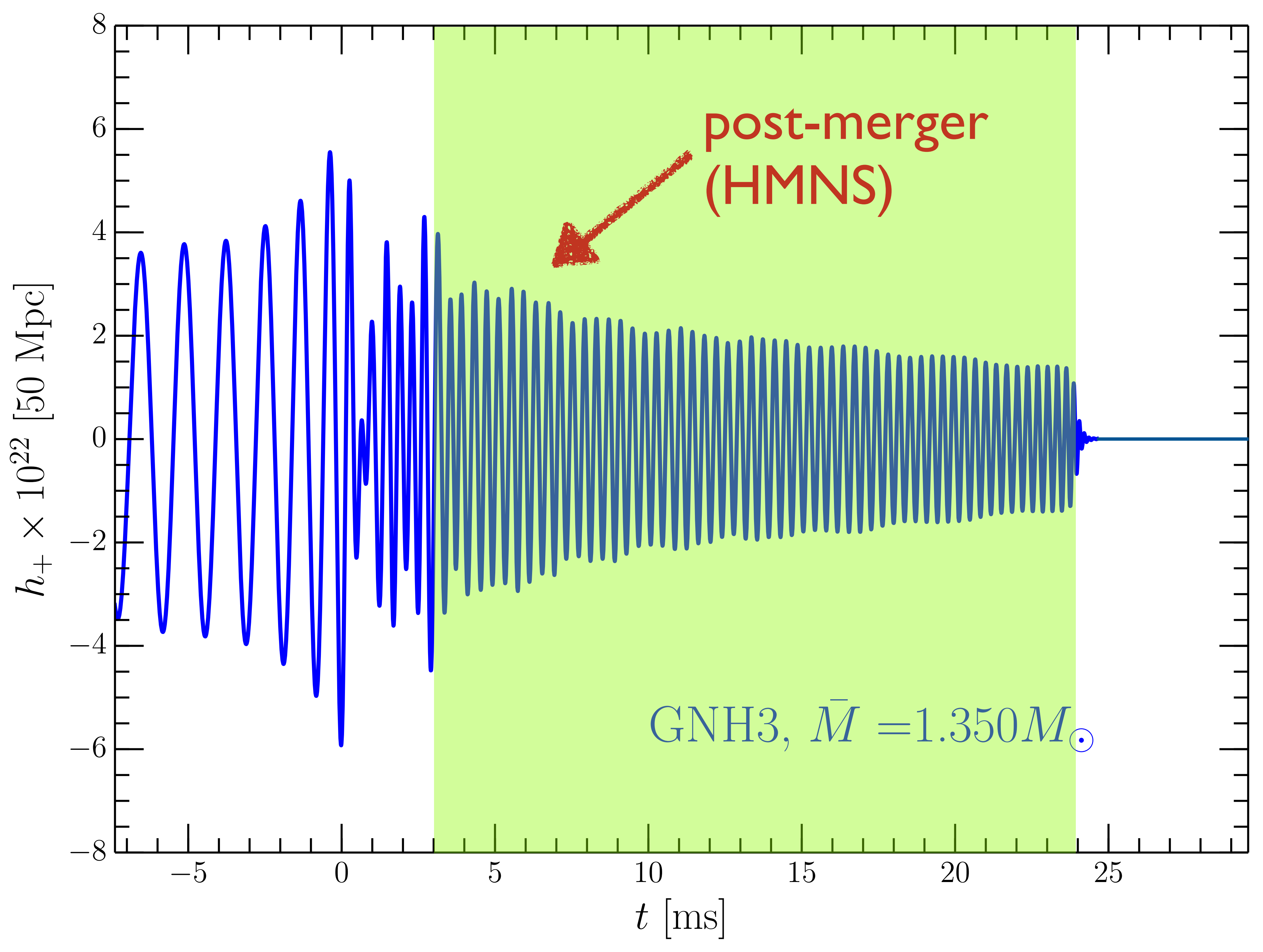
Inspiral: well approximated by PN/EOB; tidal effects important

Anatomy of the GW signal



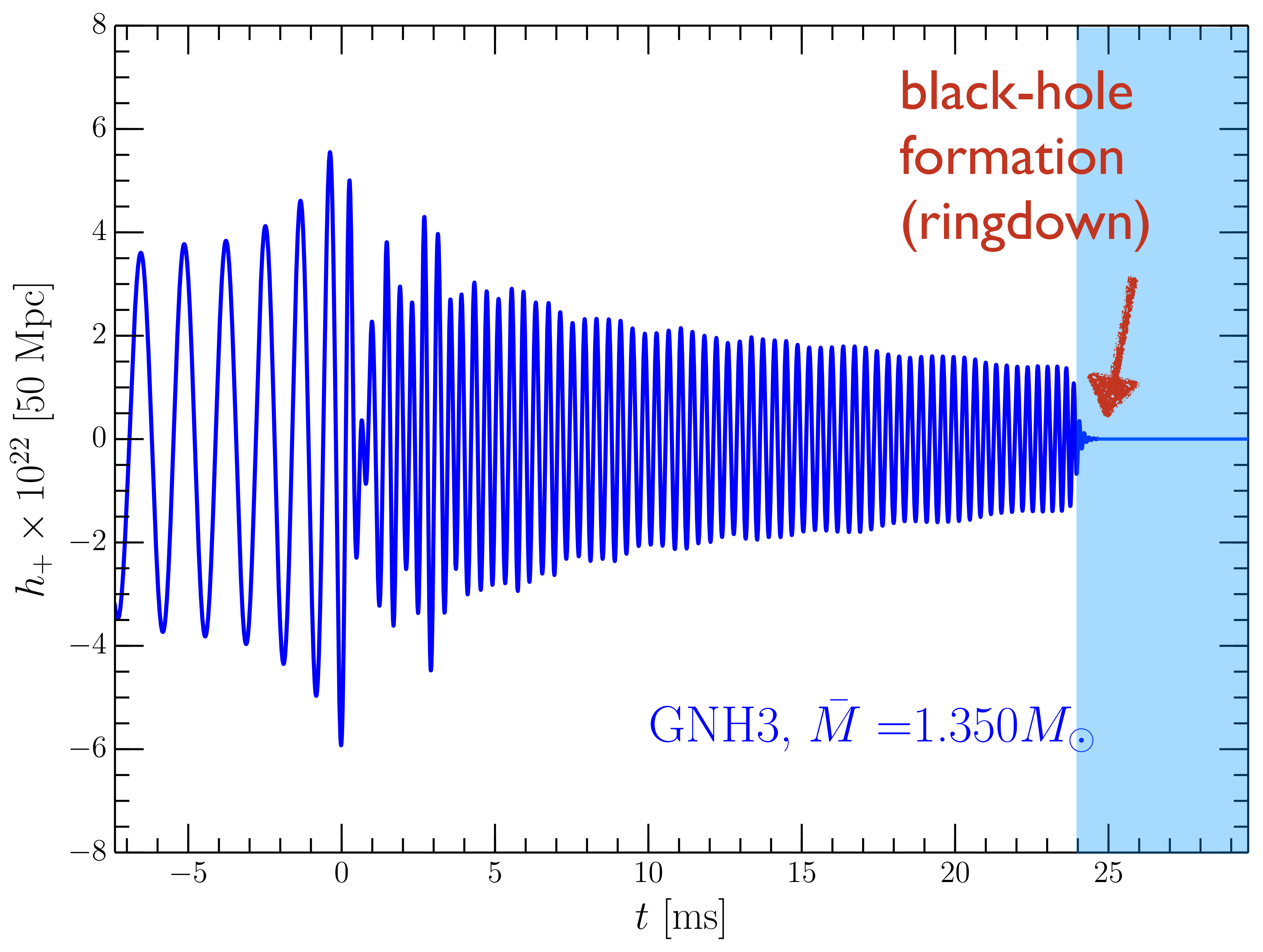
Merger: highly nonlinear but analytic description possible

Anatomy of the GW signal



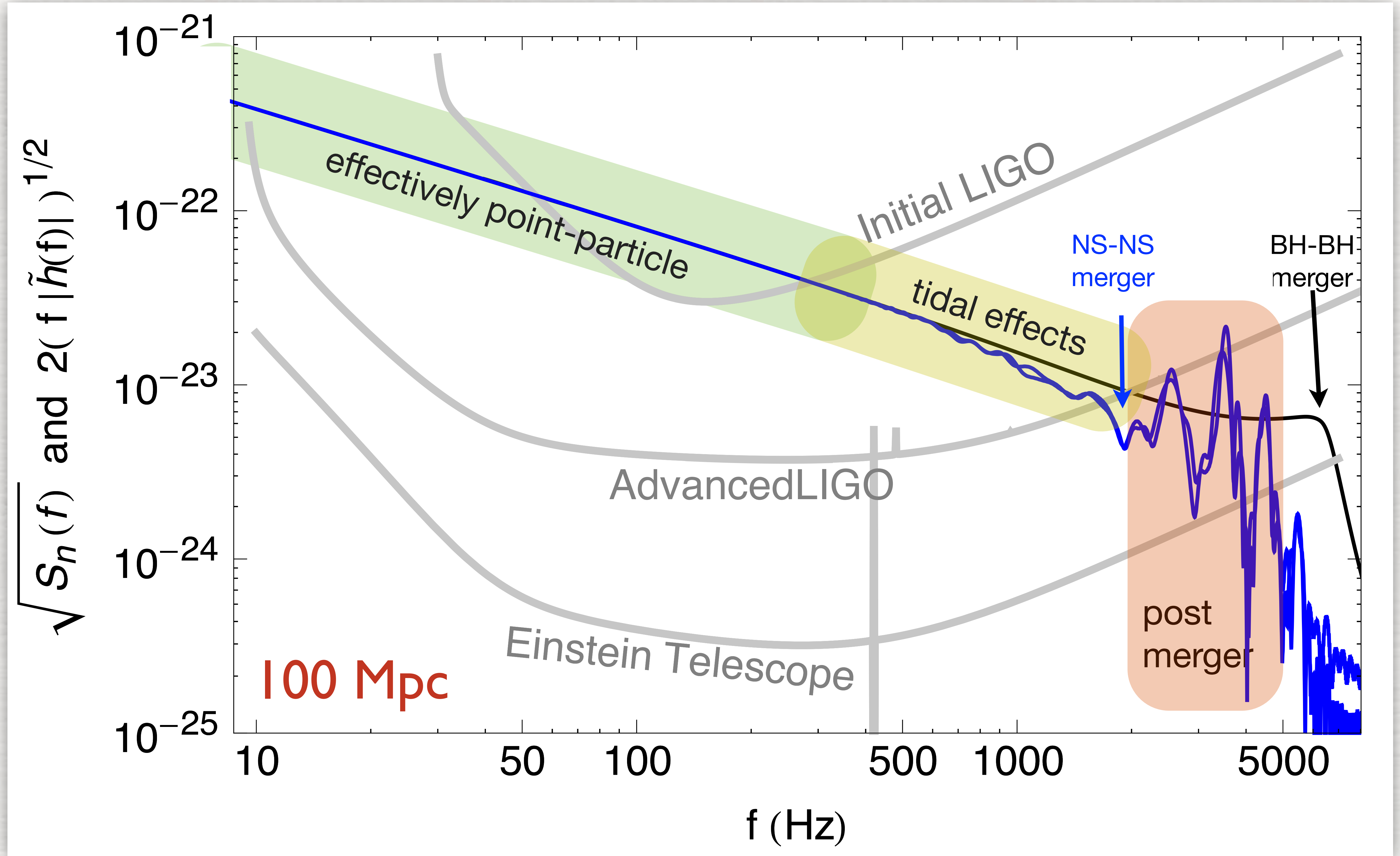
post-merger: quasi-periodic emission of bar-deformed HMNS

Anatomy of the GW signal



Collapse-ringdown: signal essentially shuts off.

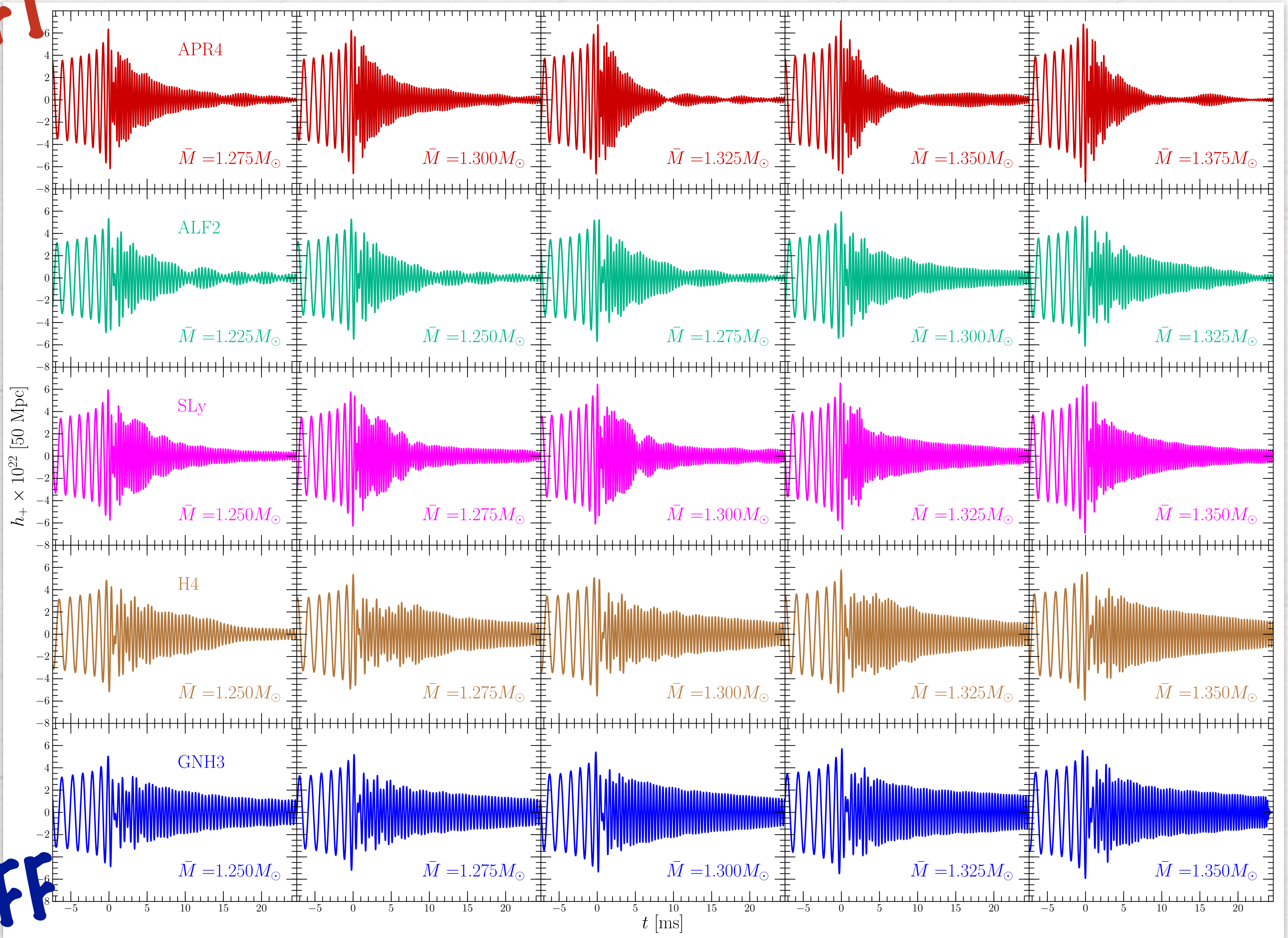
In frequency space



Read et al. (2013)

What we can do nowadays

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

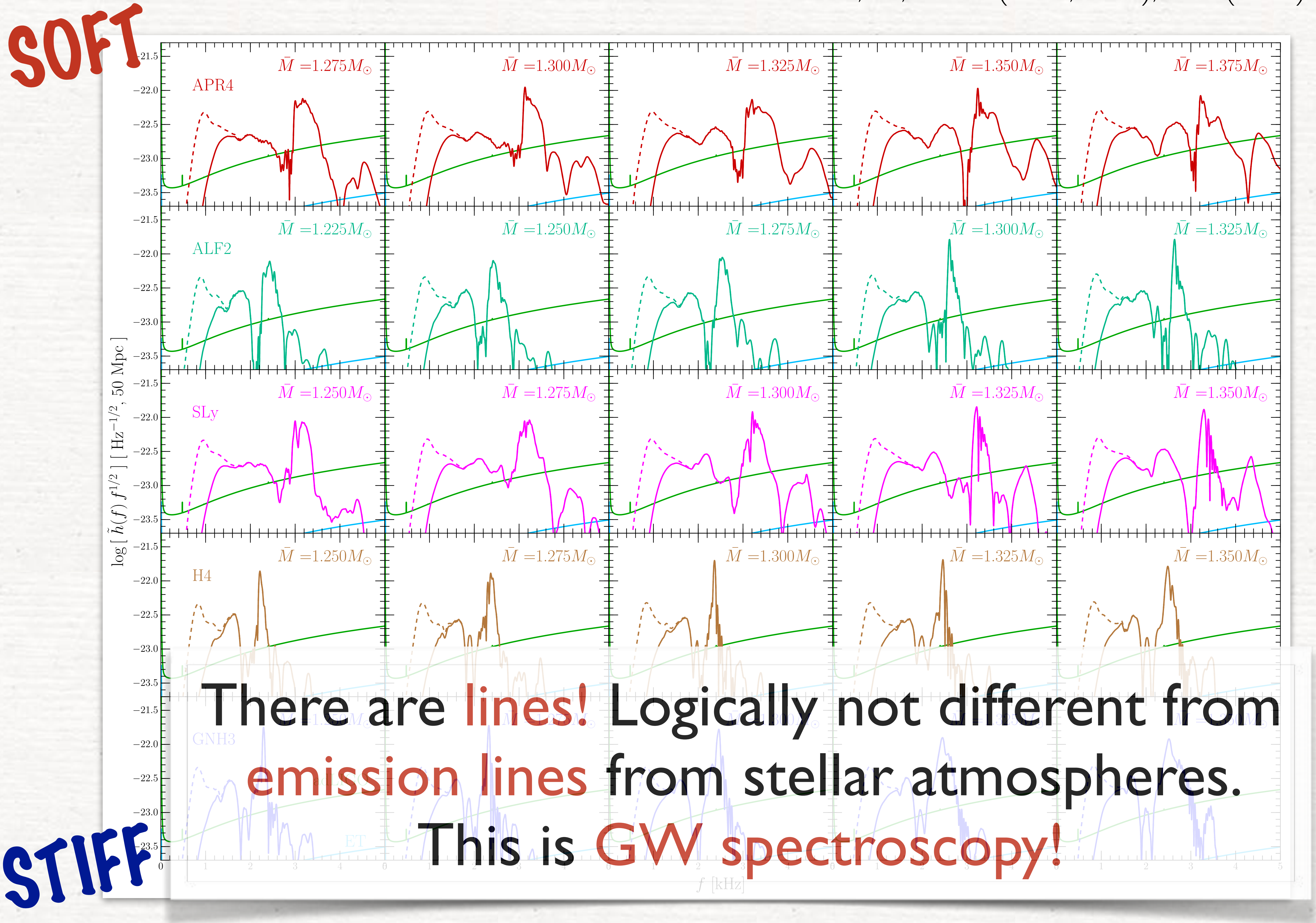


SOFT

STIFF

Extracting information from the EOS

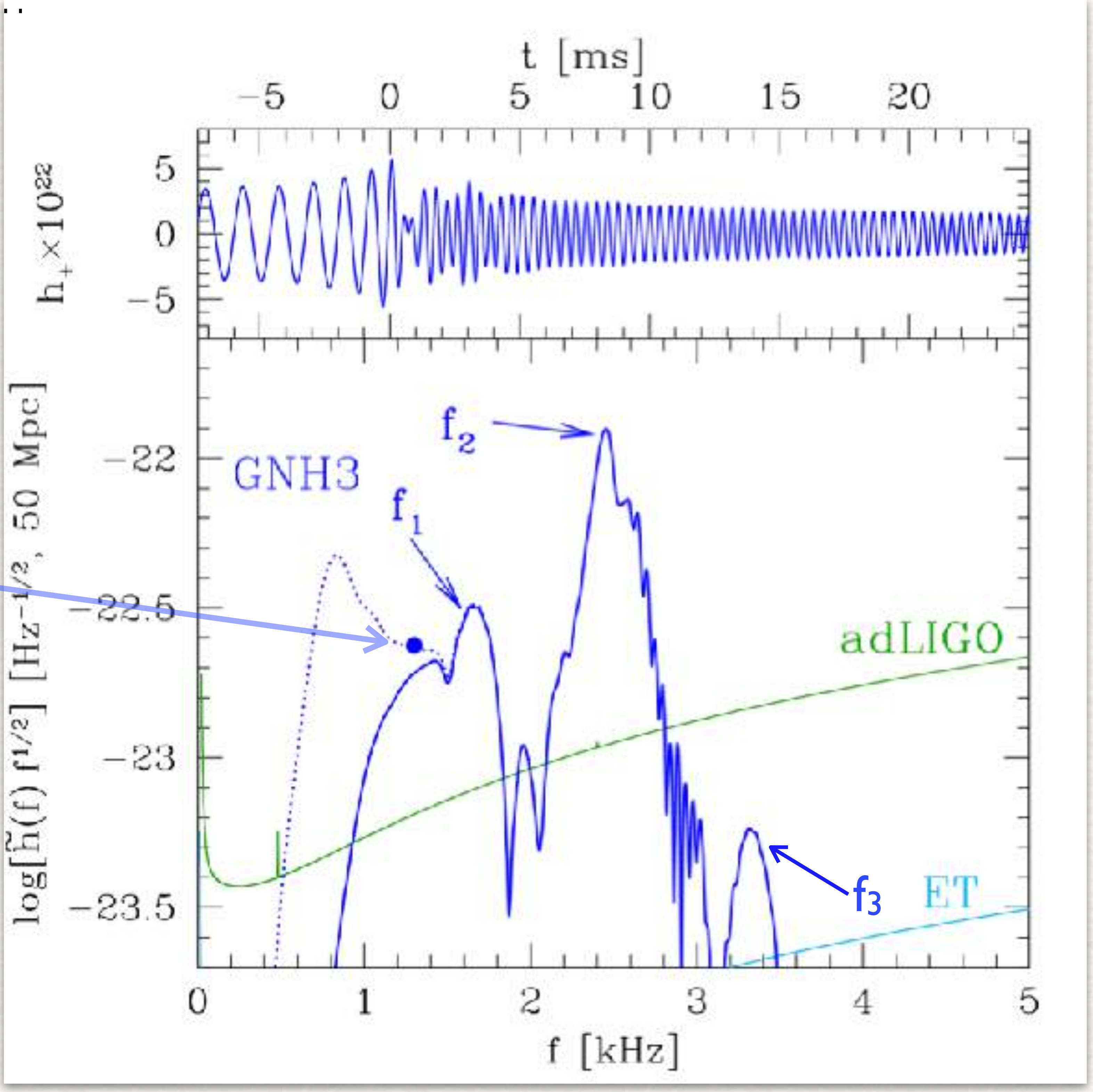
Takami, LR, Baiotti (2014, 2015), LR+ (2016)



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 …

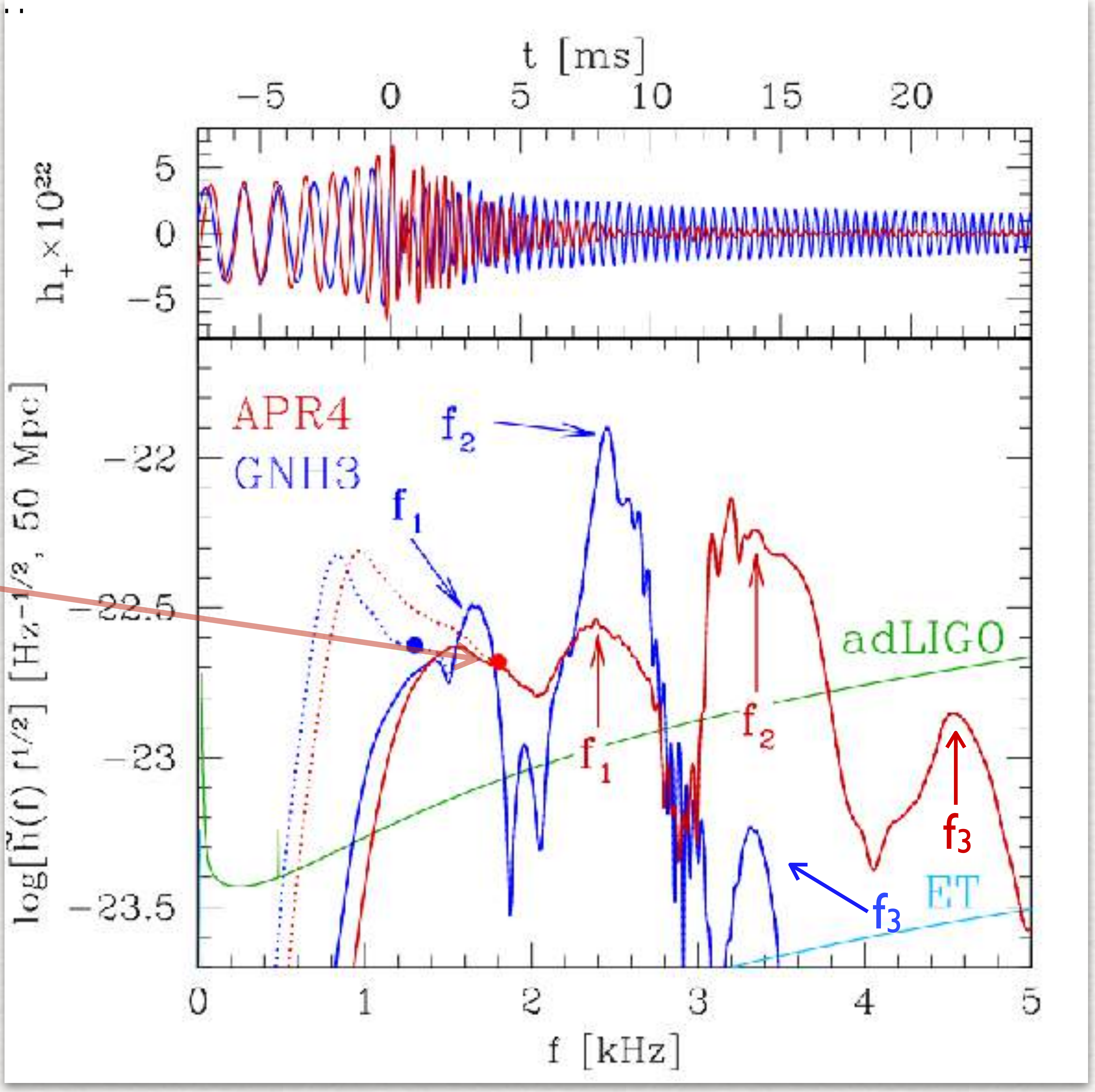


merger frequency

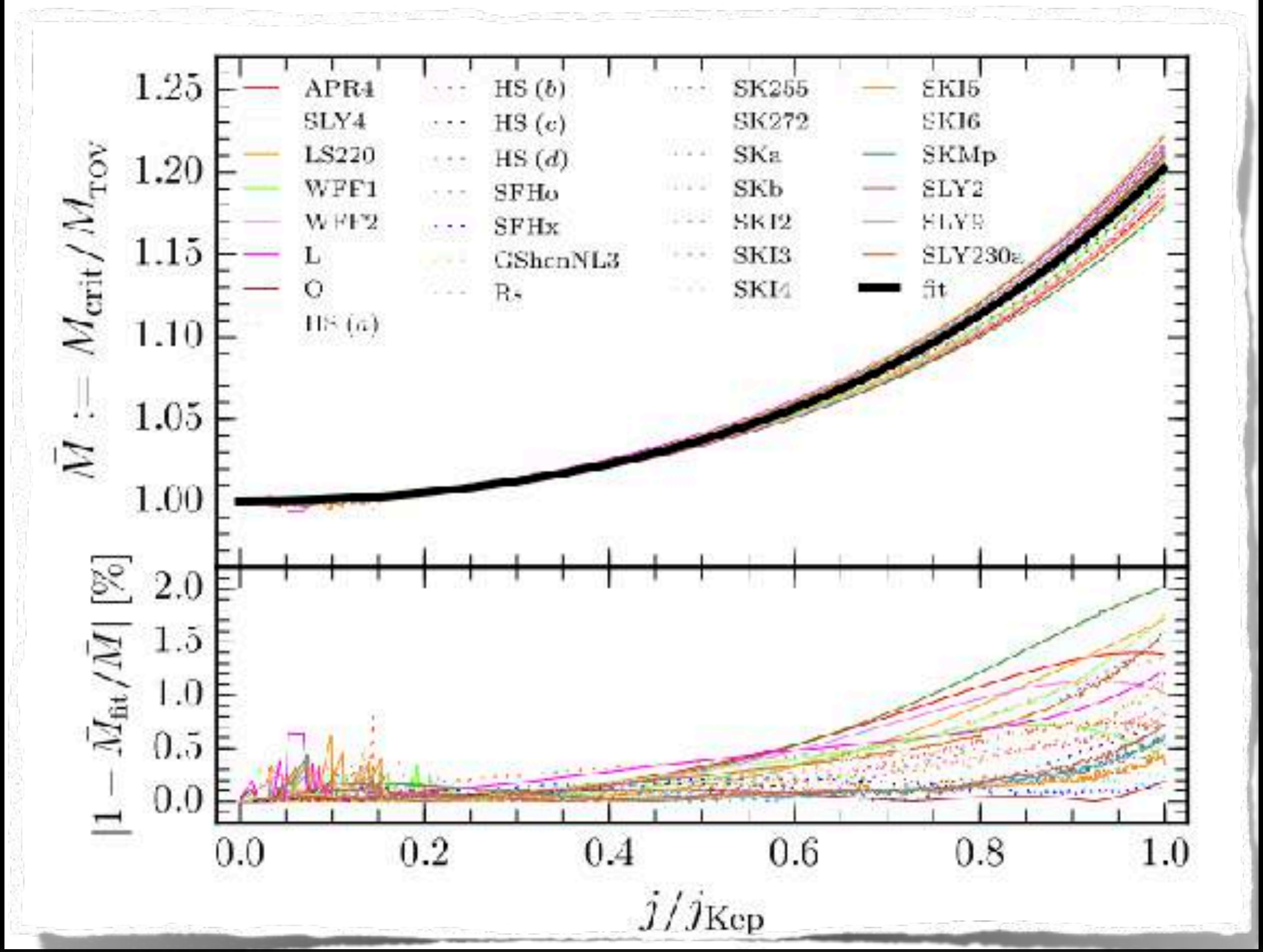
A spectroscopic approach to the EOS

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 …

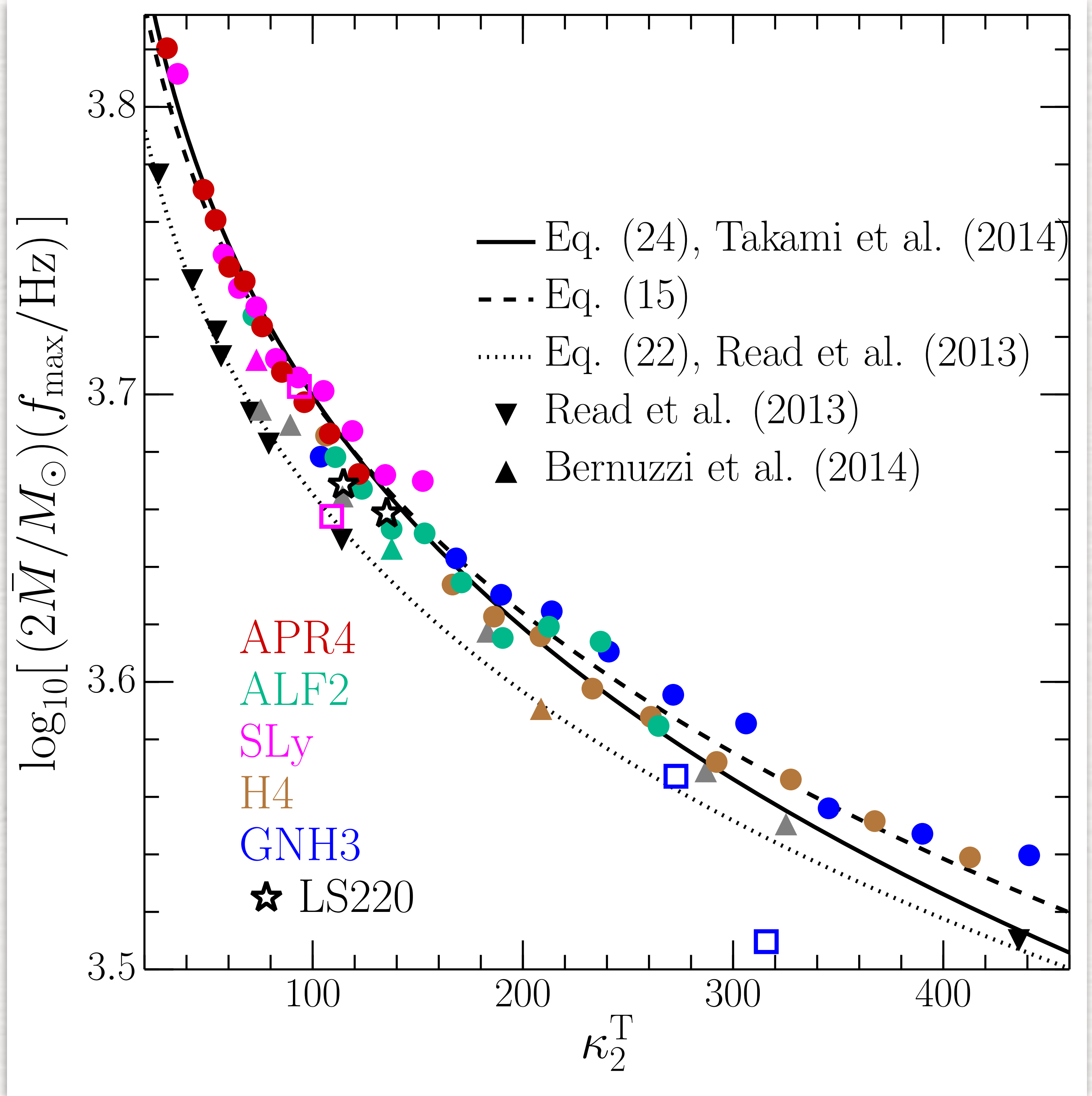
merger frequency



Quasi-universal behaviour



Quasi-universal behaviour: **inspiral**



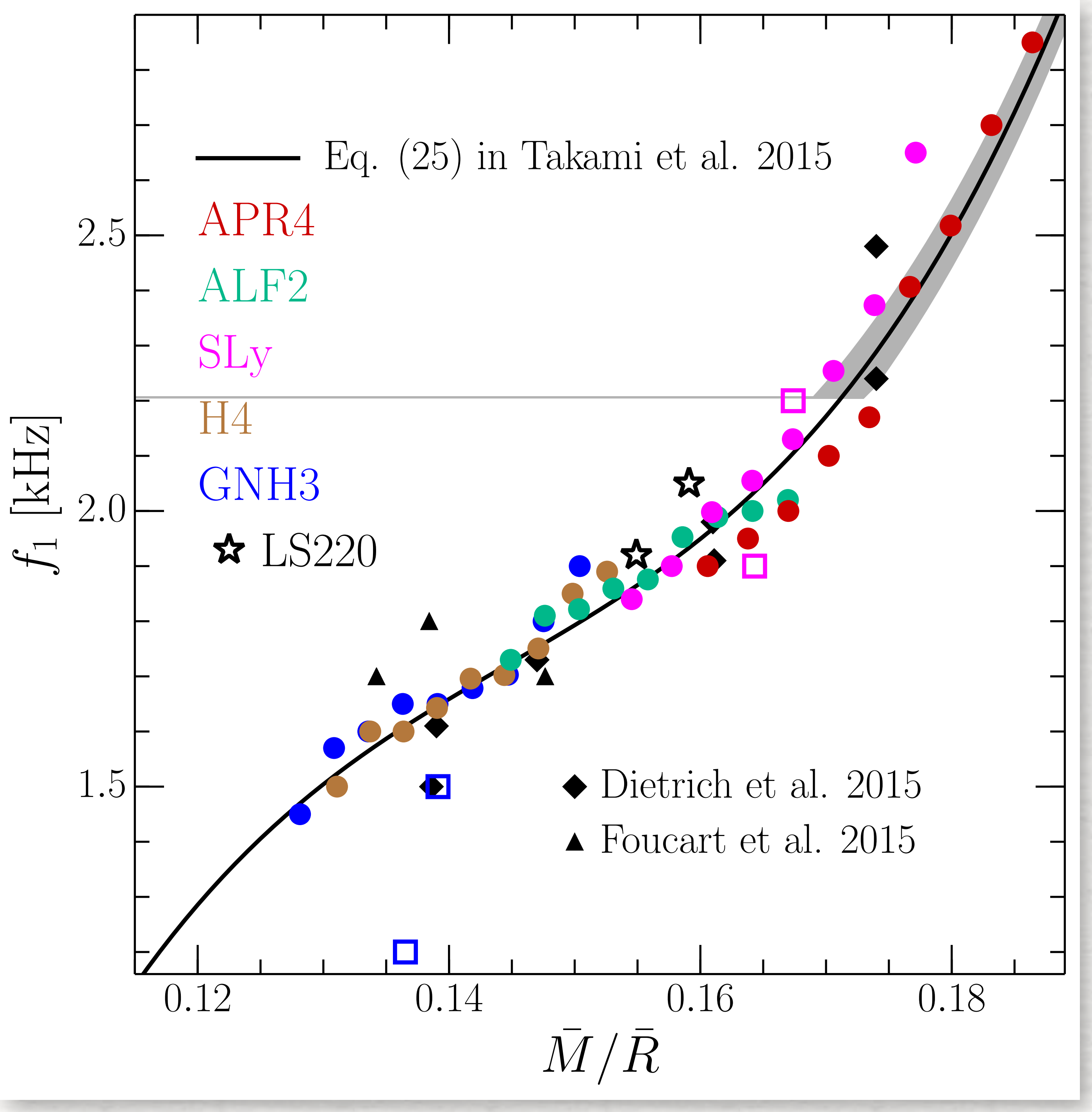
"surprising" result: quasi-universal behaviour of GW frequency at amplitude peak (Read+2013)

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

Quasi-universal behaviour in the **inspiral** implies that once **$f_{\rm max}$** 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

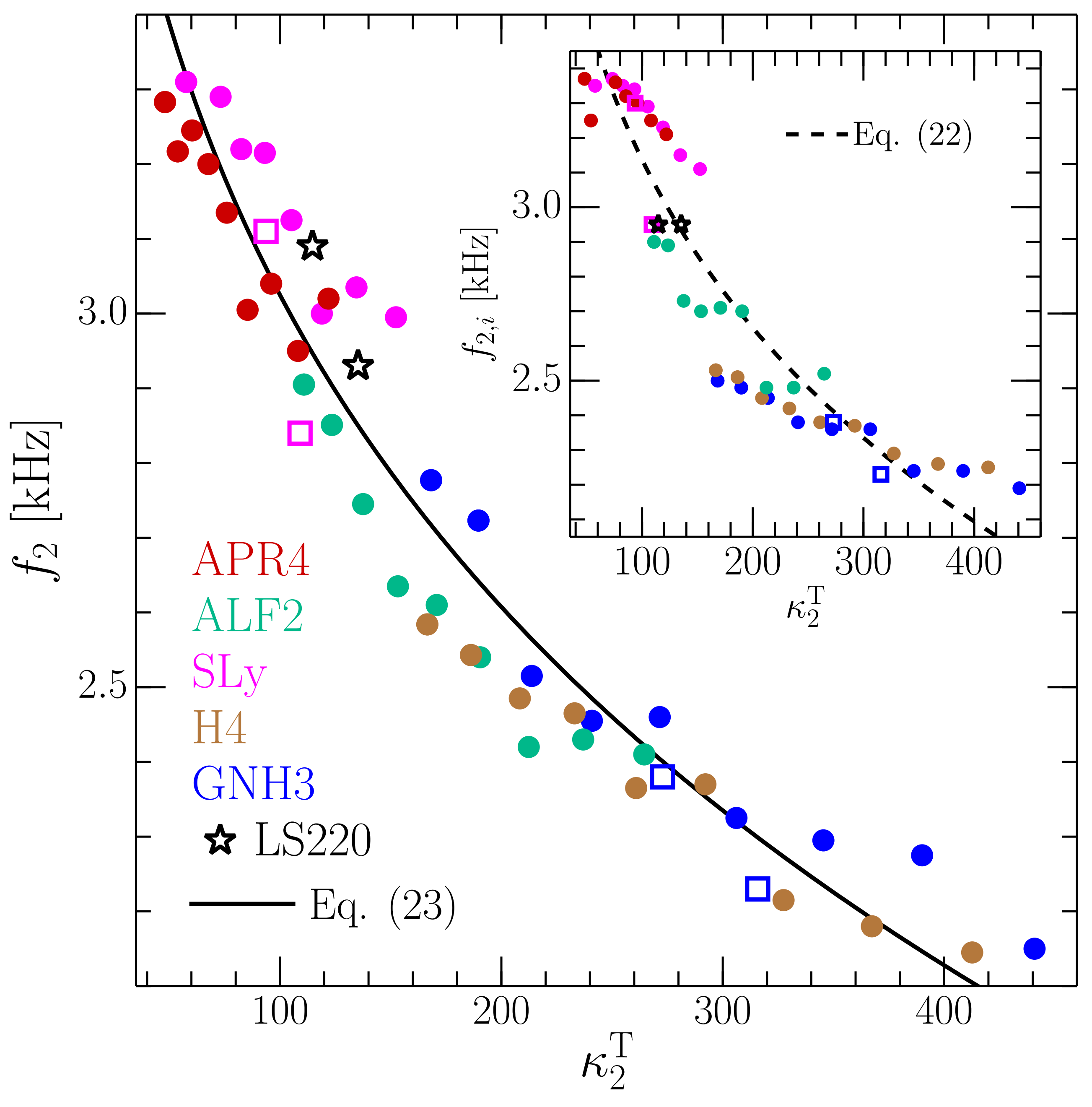
Quasi-universal behaviour: **post-merger**



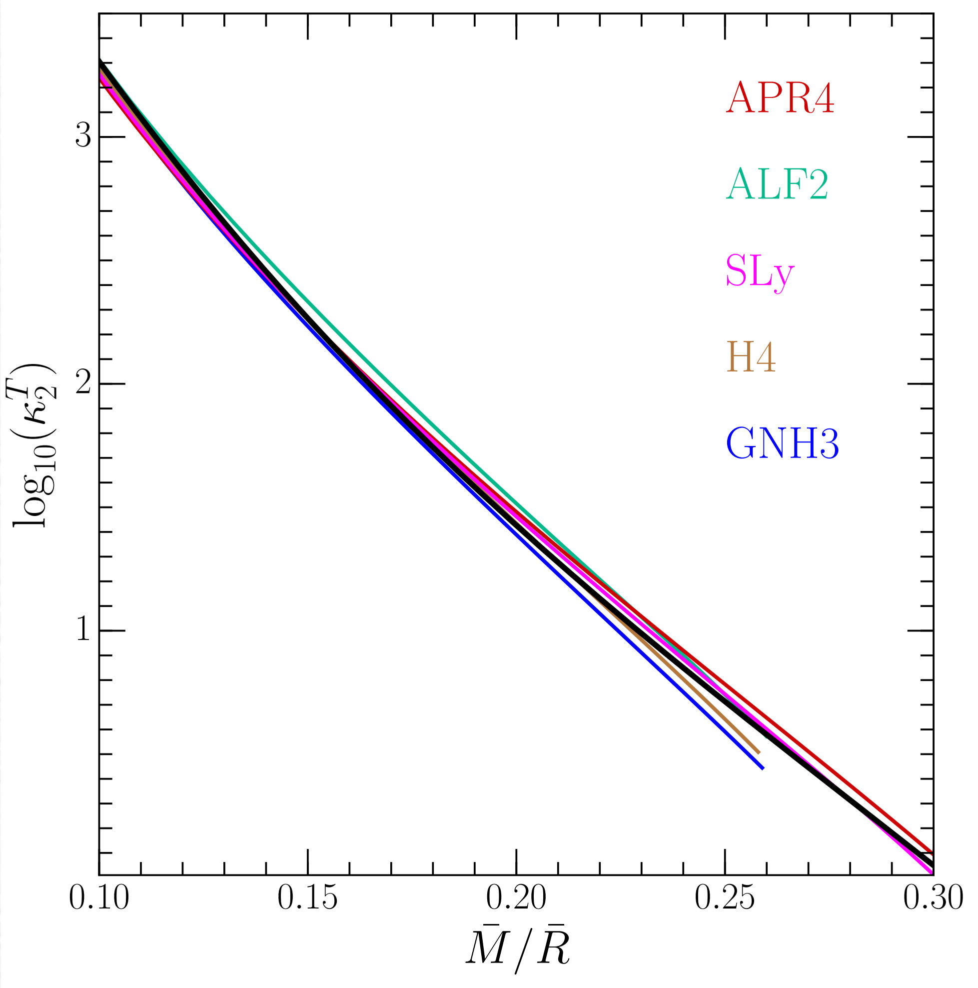
We have found **quasi-universal behaviour:** i.e., the properties of the spectra are only weakly dependent on the EOS.

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.

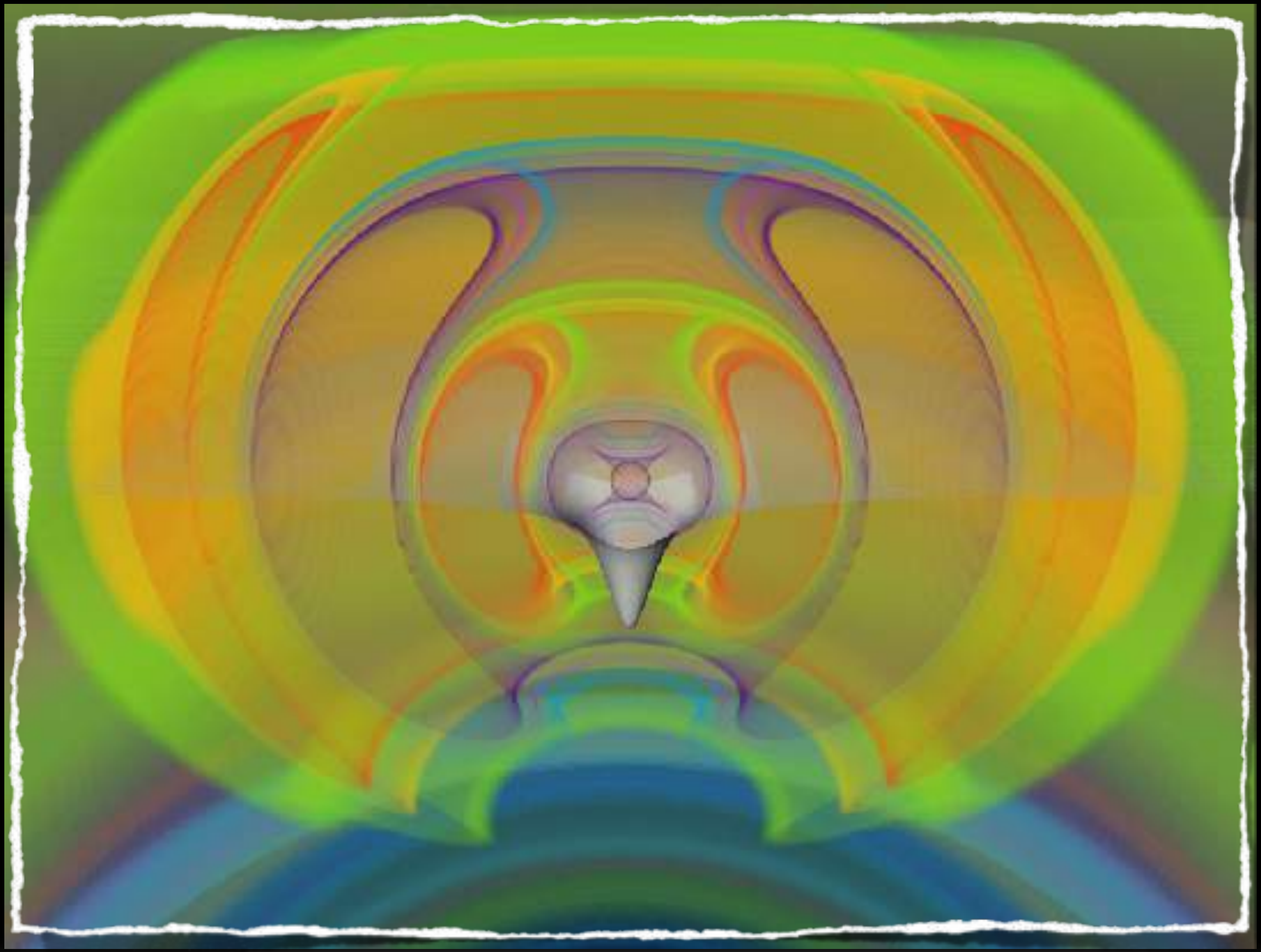


- Important correlation also between **compactness** and **deformability**

GW170817, maximum mass, radii and tidal deformabilities

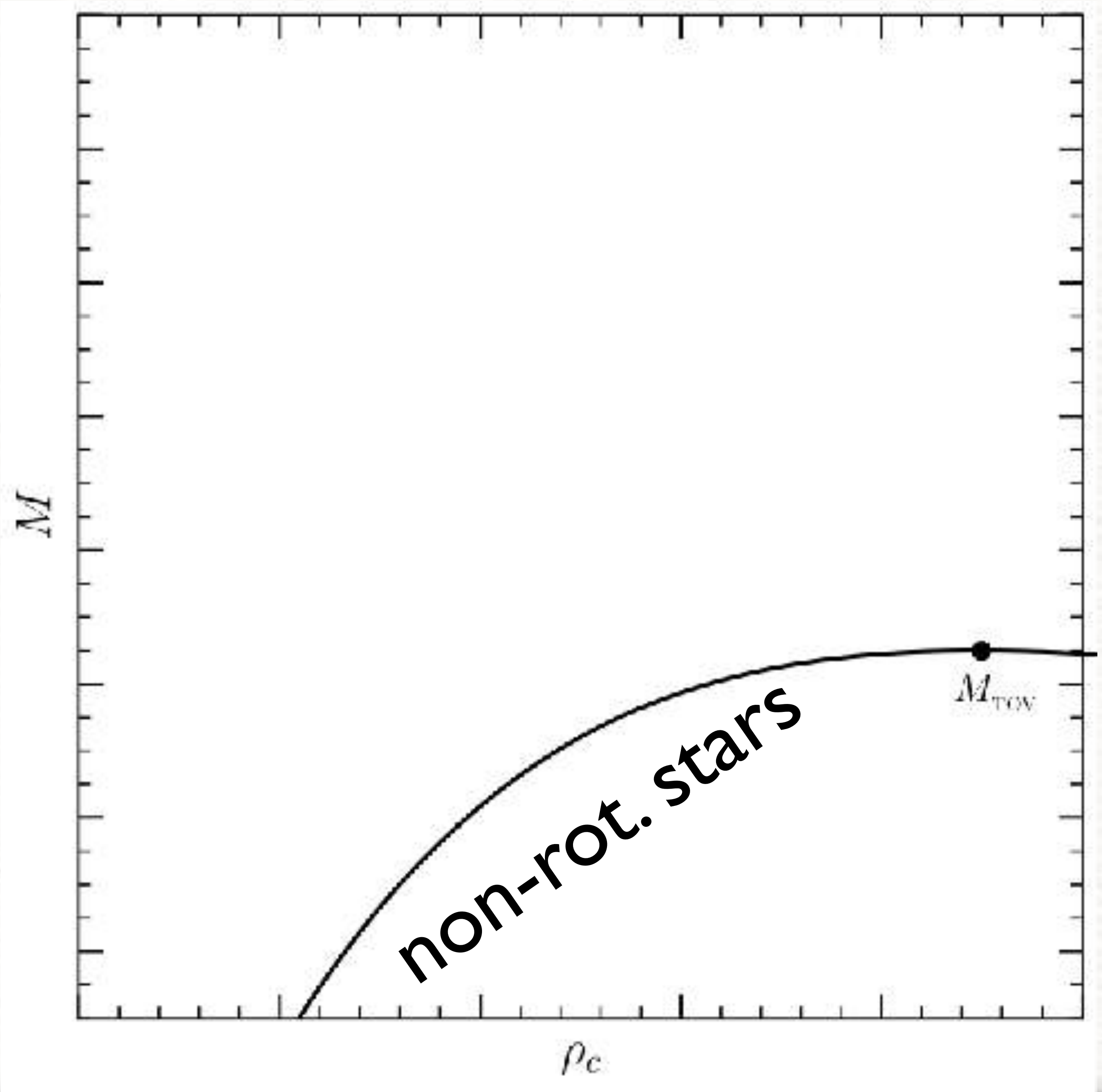
LR, Most, Weih (2018)

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



The outcome of GW170817

- 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: $M_{\rm TOV}$

The outcome of GW170817

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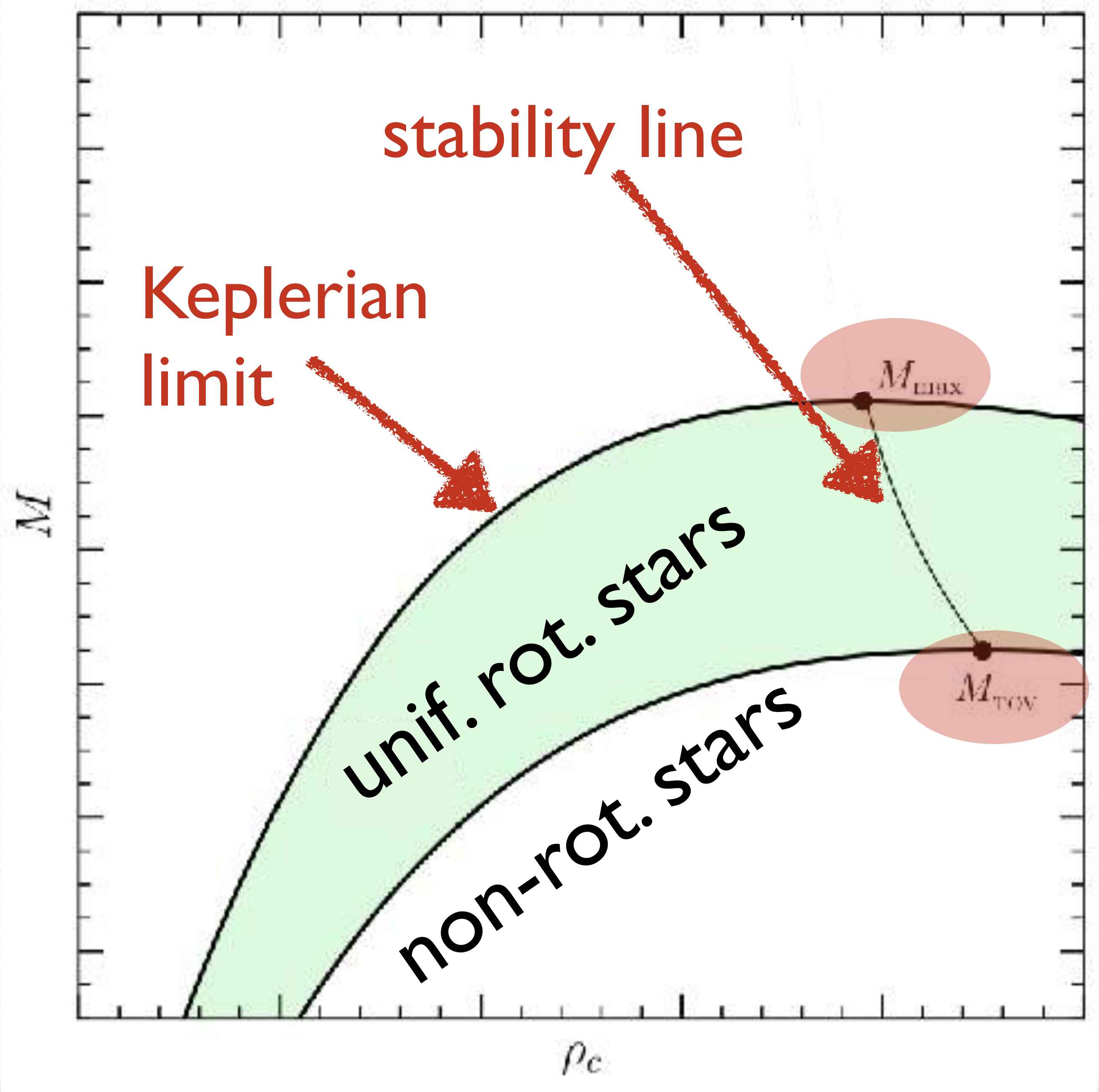

- Sequences of equilibrium models of **nonrotating** stars will have a maximum mass: $M_{\rm TOV}$
- This is true also for **uniformly** rotating stars at mass shedding limit: $M_{\rm max}$
- $M_{\rm max}$ simple and **quasi-universal** function of $M_{\rm TOV}$ (Breu & LR 2016)

$$M_{\rm max} = \left(1.20^{+0.02}_{-0.05}\right) M_{\rm TOV}$$

The outcome of GW170817

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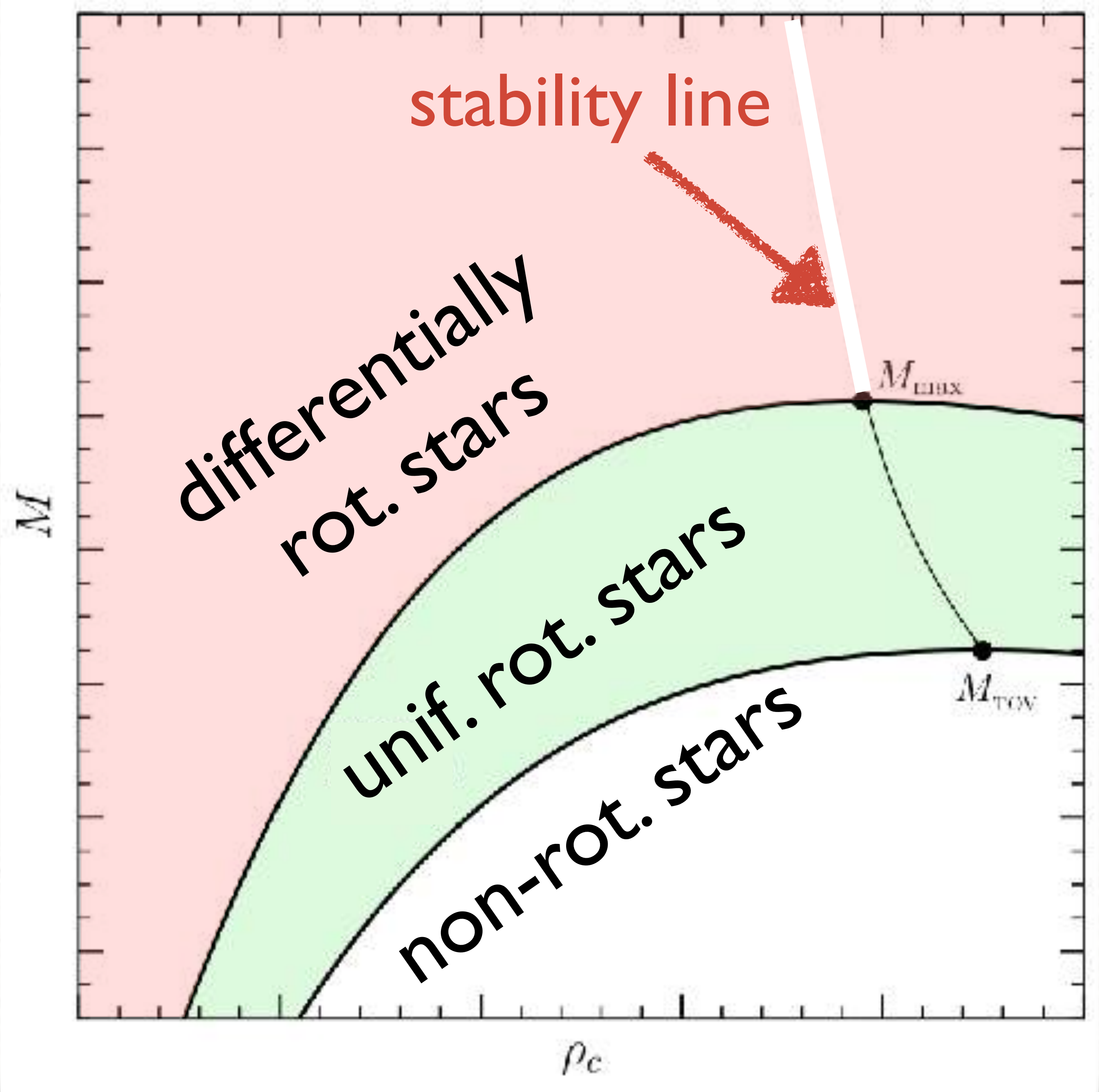
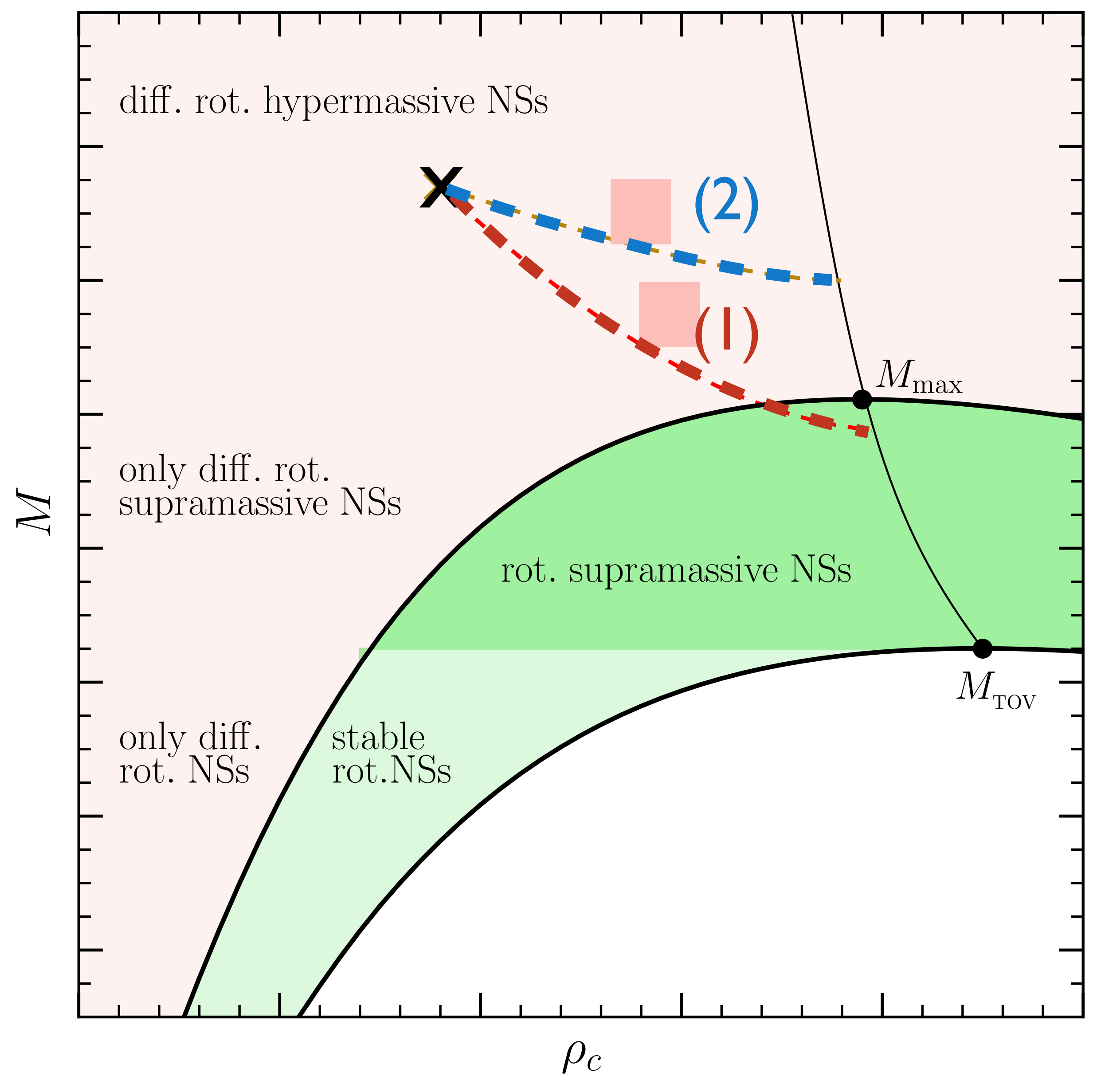


- **Green** region is for **uniformly** rotating equilibrium models.
- **Salmon** region is for **differentially** rotating equilibrium models.
- Stability line is simply extended (Weih+18)

The outcome of GW170817

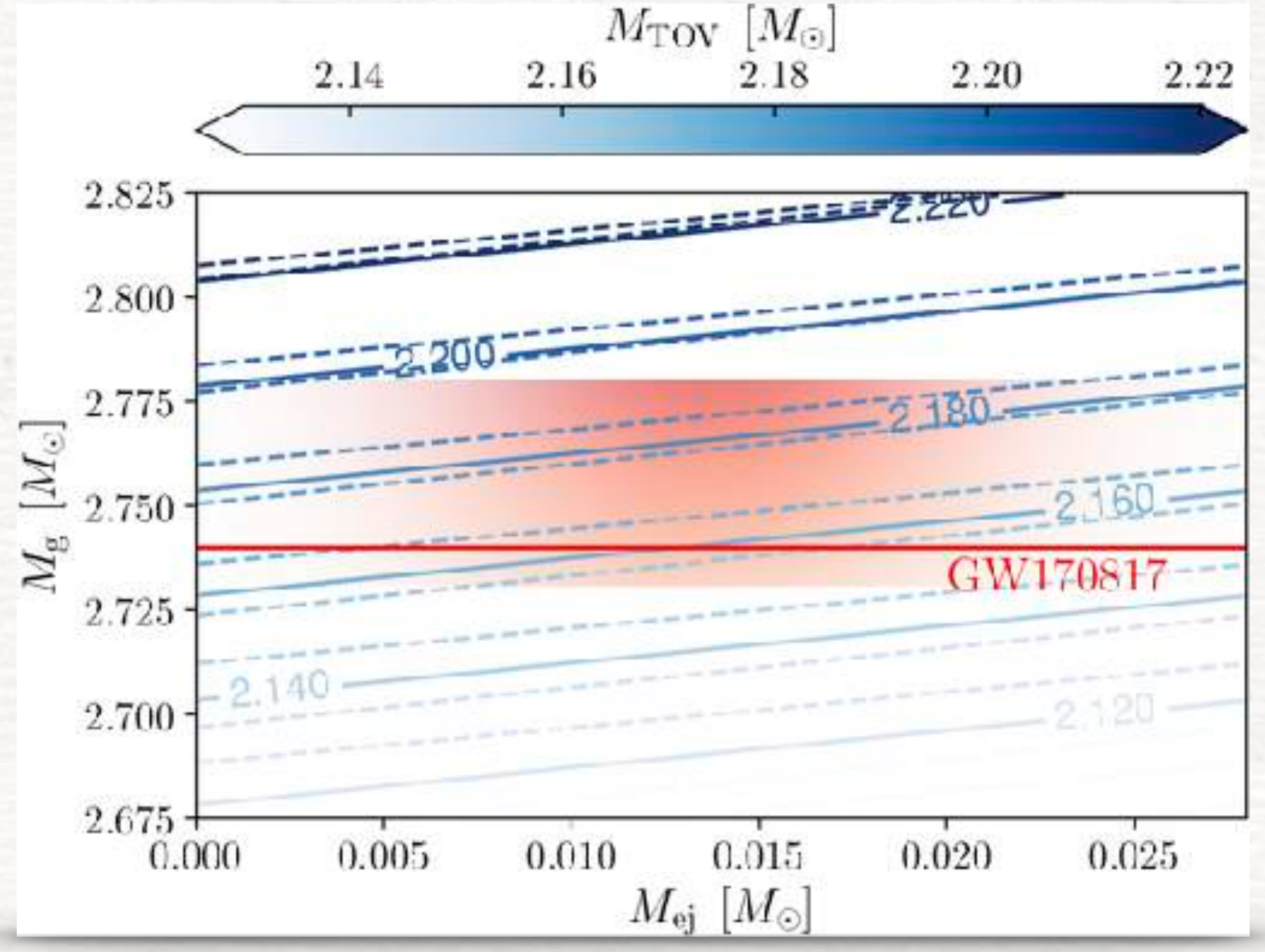
- GW170817 produced object as **"x"**; GRB implies a BH has been formed: **"x"** followed two possible tracks: **fast (2)** and **slow (1)**

- 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…

- The merger product of GW170817 was initially **differentially** rotating but collapsed as **uniformly** rotating object.



- Use measured **gravitational** mass of GW170817

- Remove **rest mass** deduced from kilonova emission

- Use **universal relations** and account errors to obtain

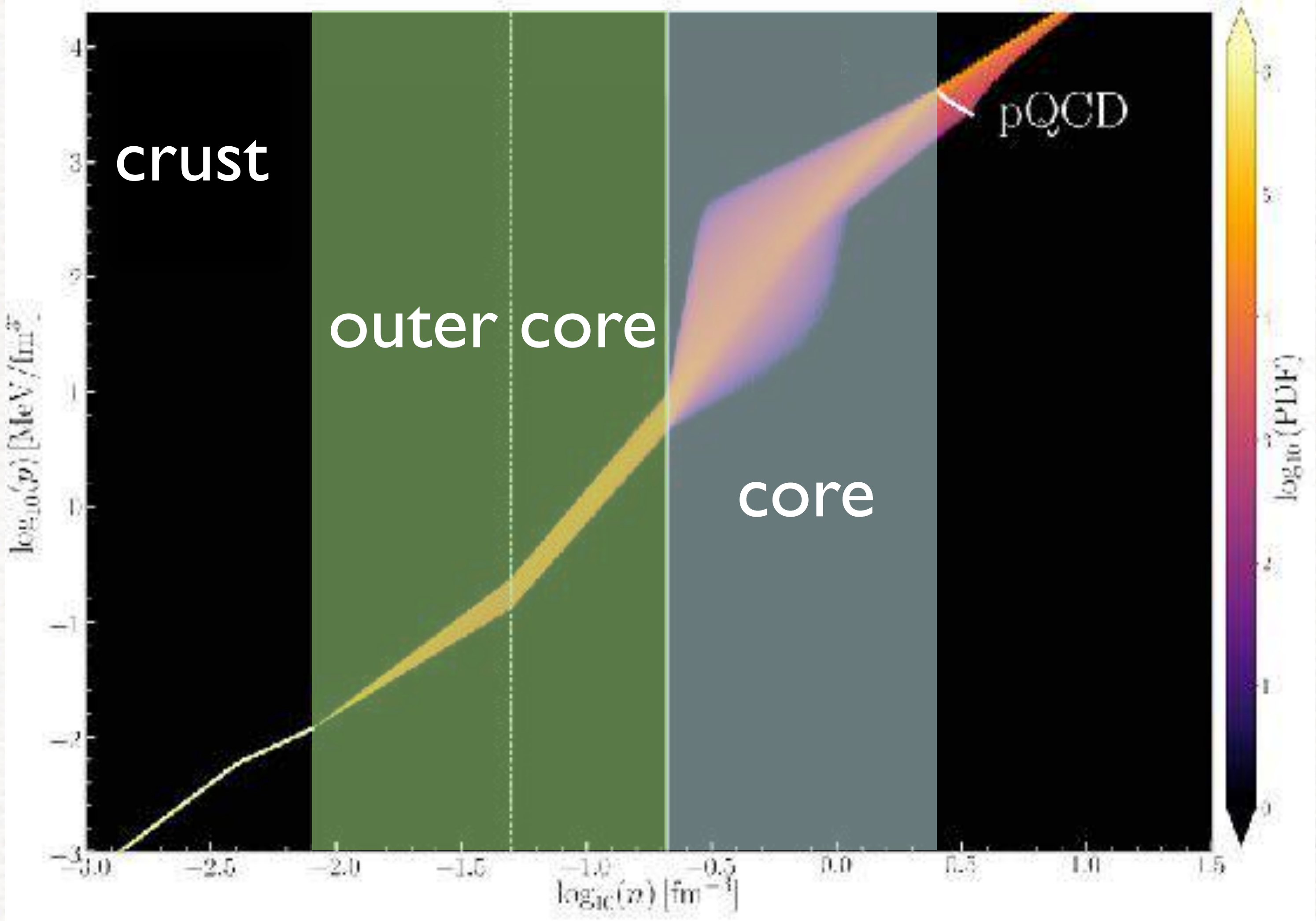
pulsar timing

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

universal relations and GW170817; similar estimates by other groups

Limits on radii and deformabilities

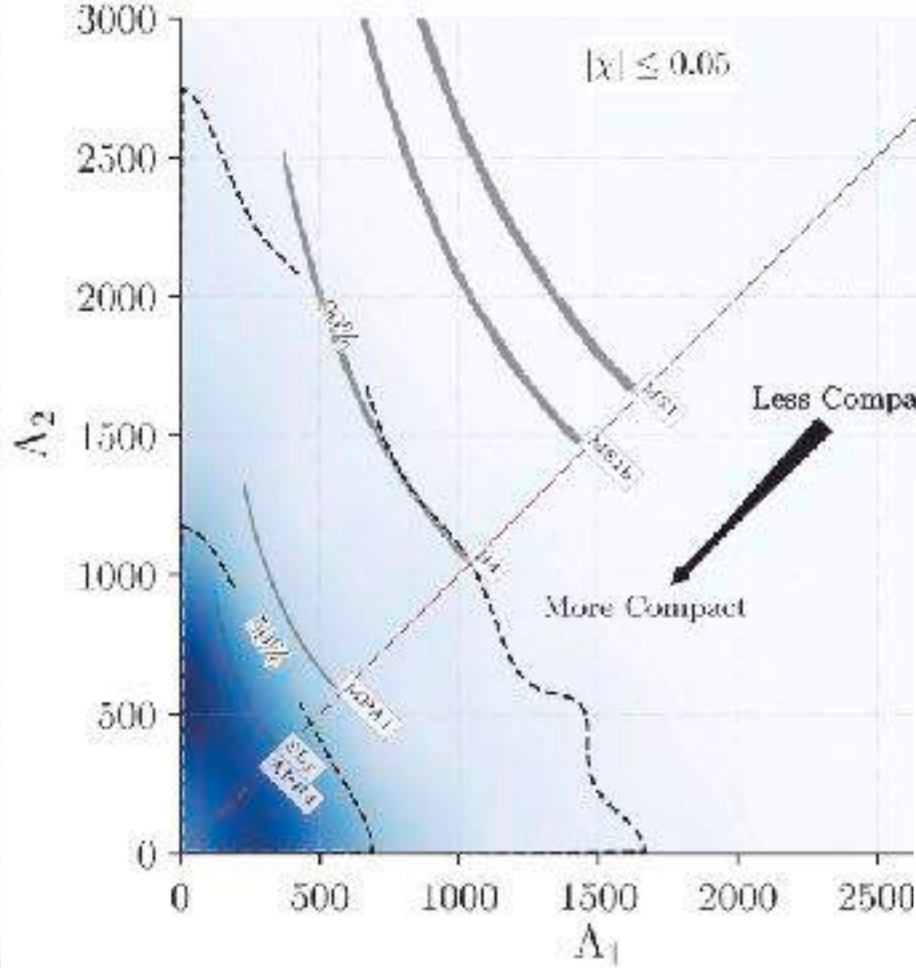
- Constraining NS radii of neutron stars is an effort with thousands of papers published over the last 40 years.
- Question is deeply related with EOS of nuclear matter.
- Can new constraints be set by GW170817?
- Ignorance can be parameterised and EOSs can be built arbitrarily as long as they satisfy specific **constraints** on **low** and **high** densities.



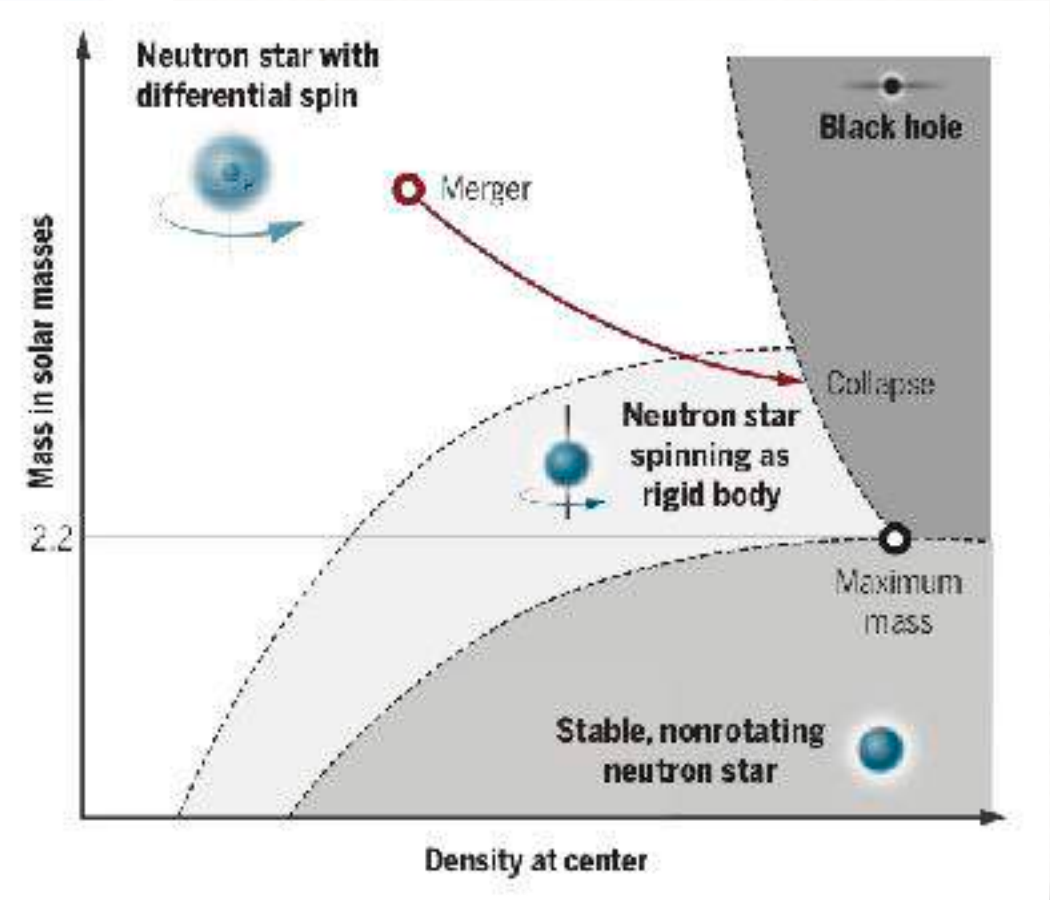
Limits on radii and deformabilities

- 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?



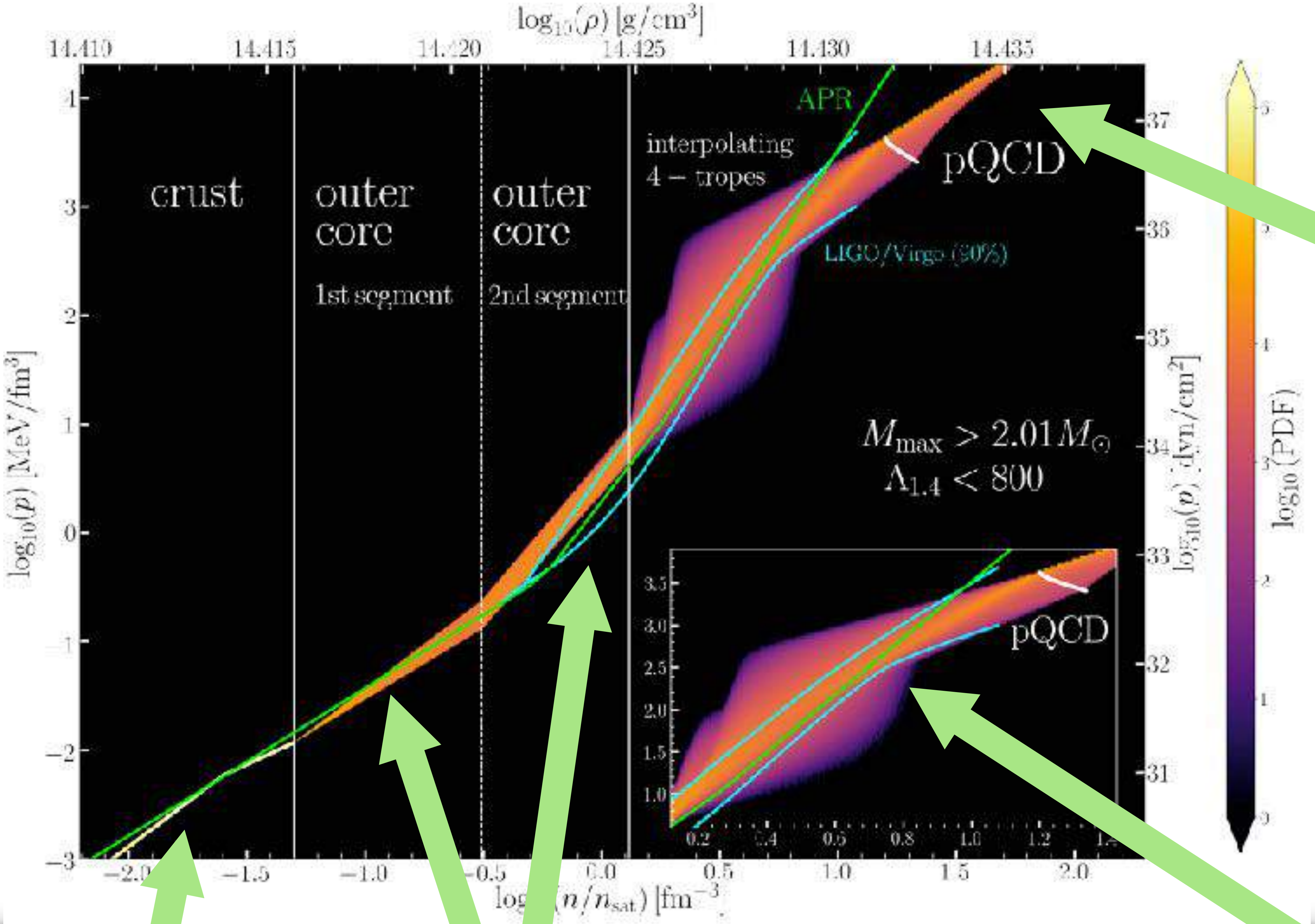
Abbott+ 2017



LR+ 2017

parametrising our ignorance

- Construct most generic family of NS-matter EOSs



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

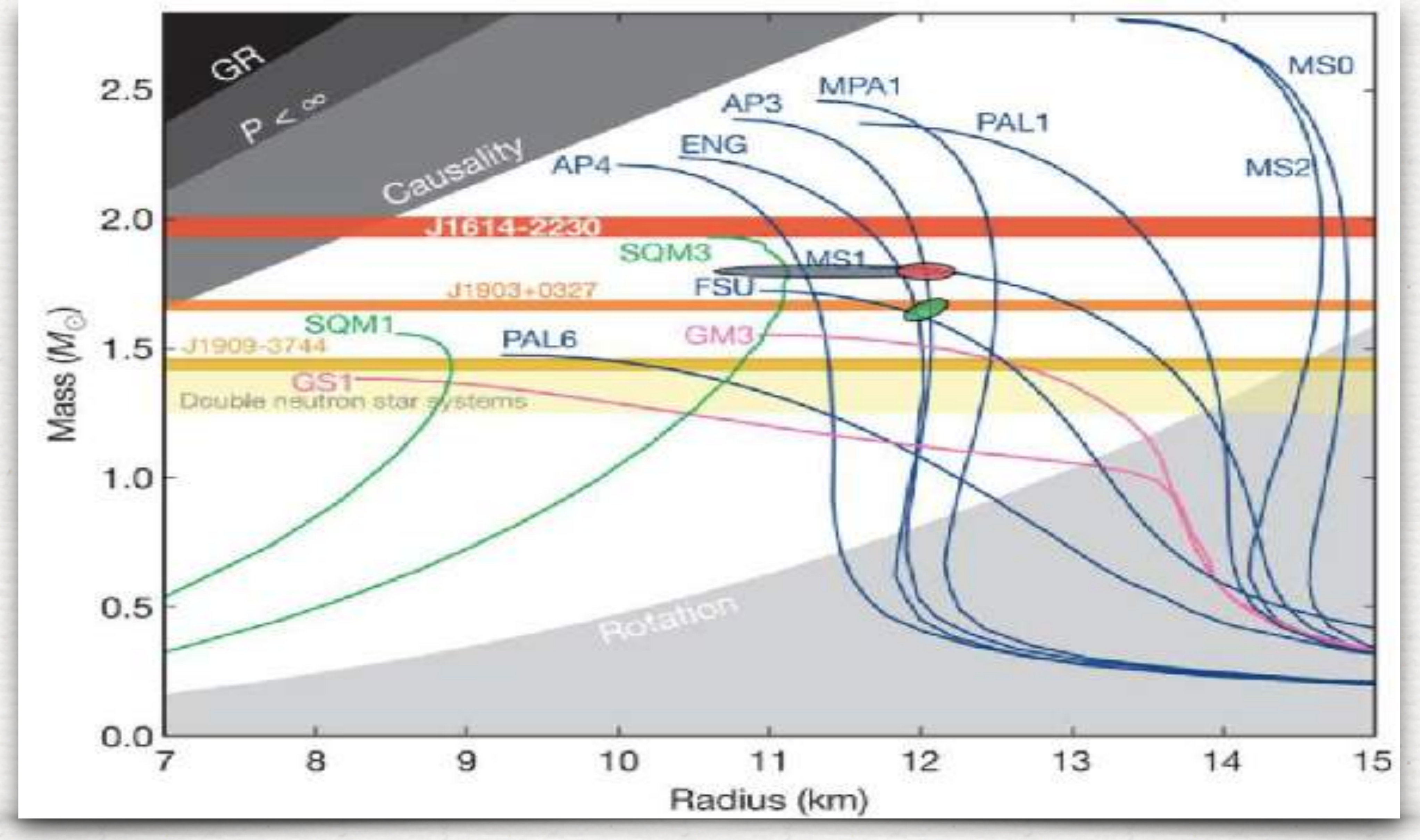
interpolation
by matching 4
polytropes

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

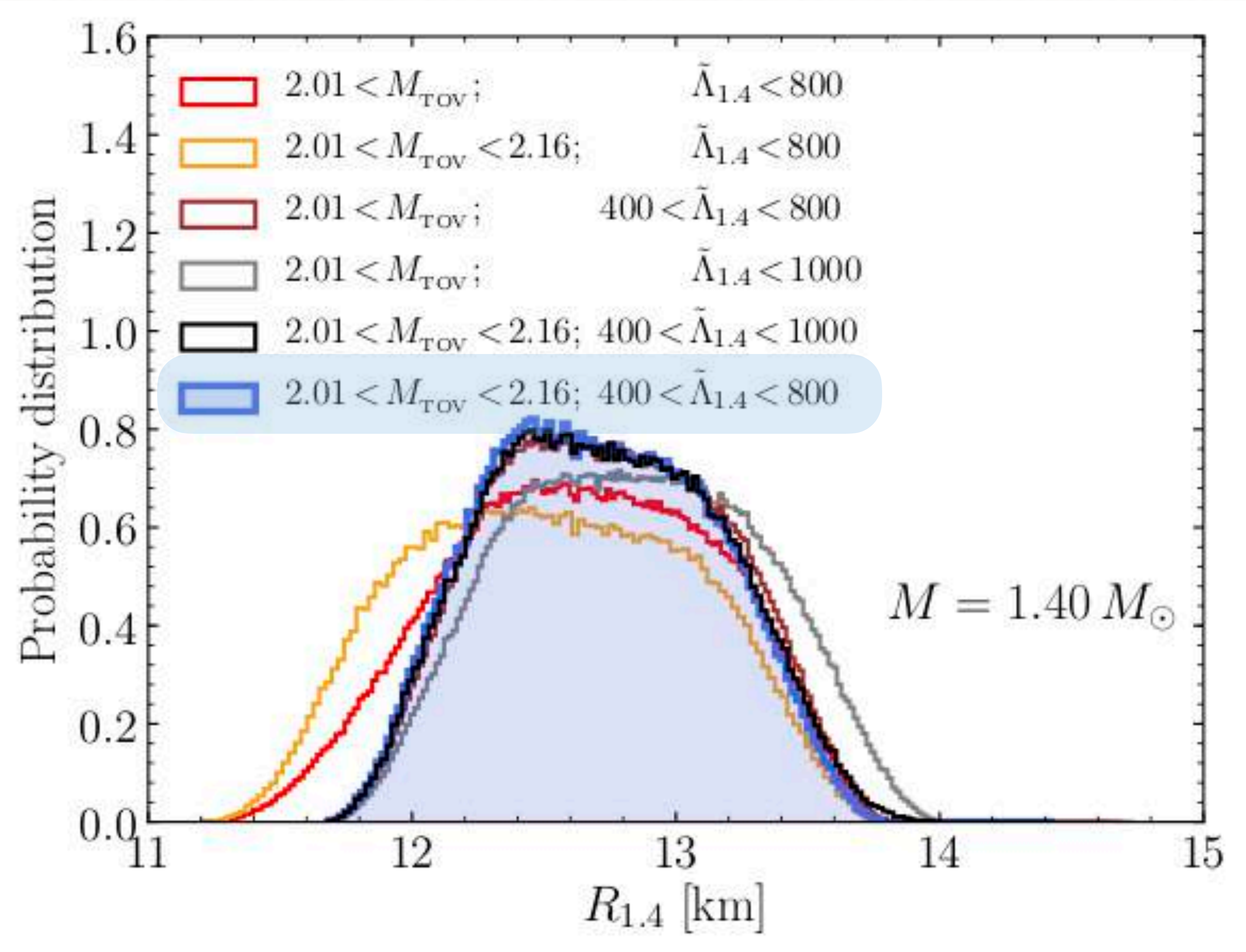


one-dimensional cuts

- 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

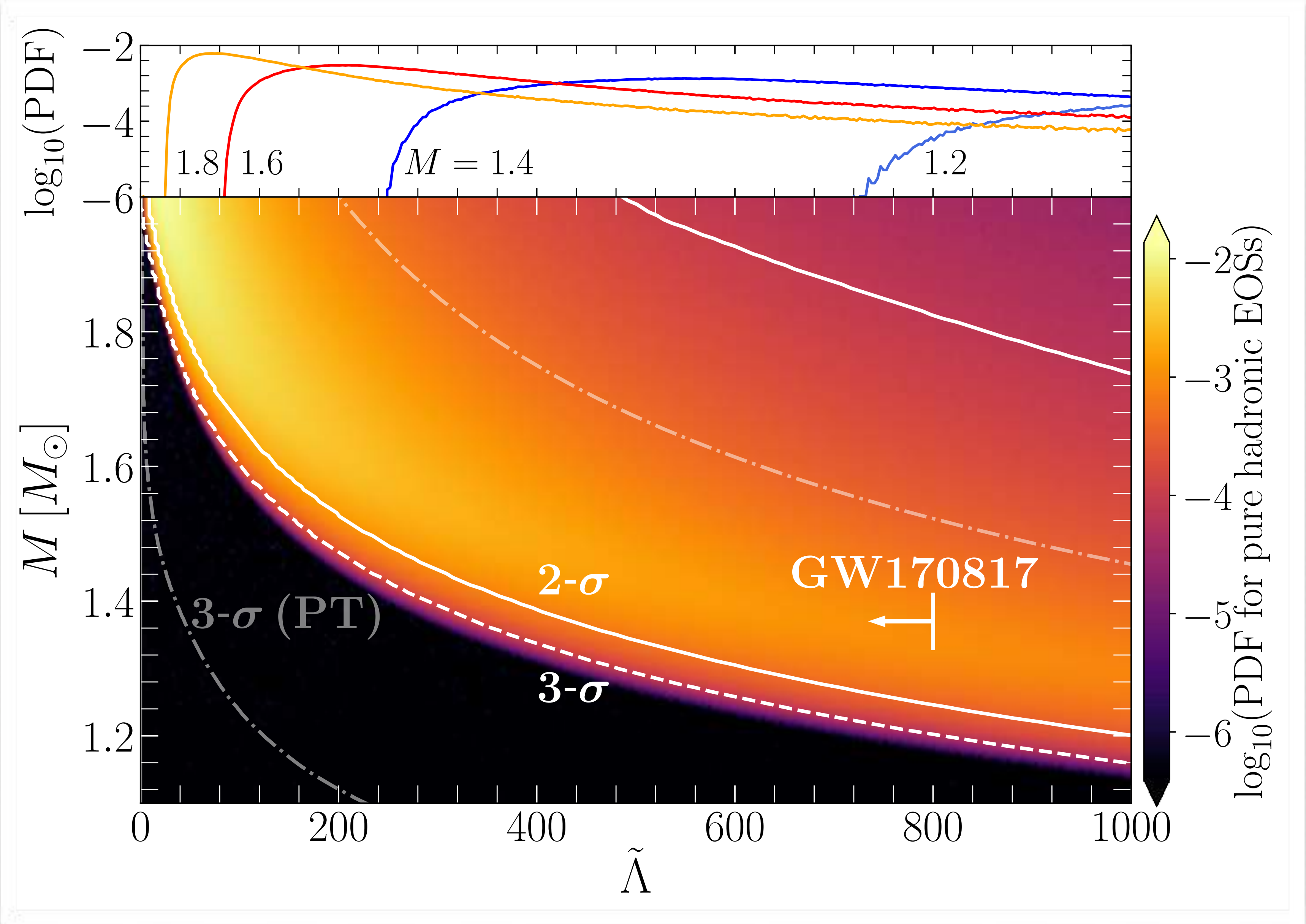
- Can explore statistics of all properties of our 10^9 models.
- In particular can study PDF of tidal deformability: $\tilde{\Lambda}$

- LIGO has already set upper limit:

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

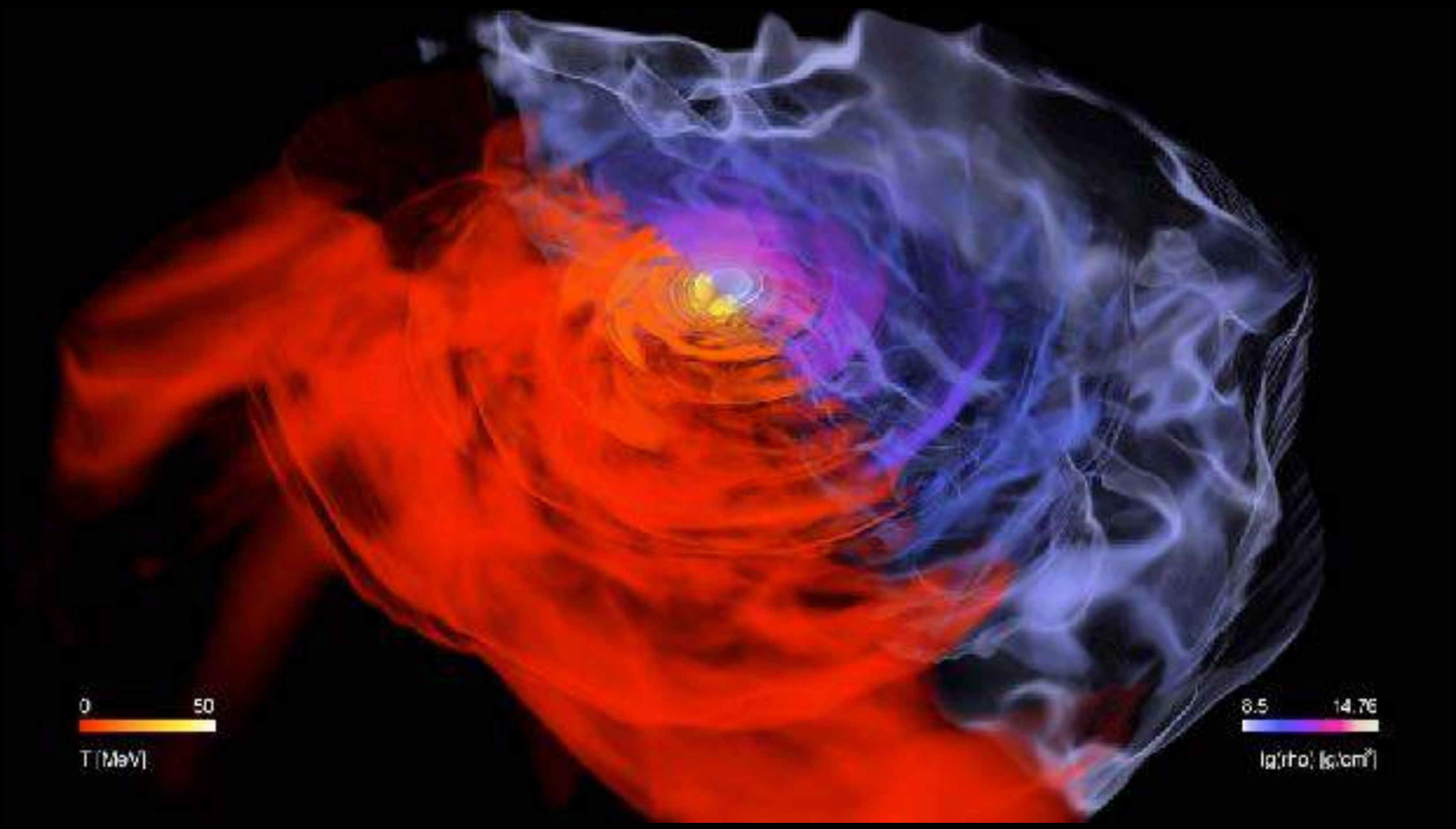
- Our sample naturally sets a lower limit:

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

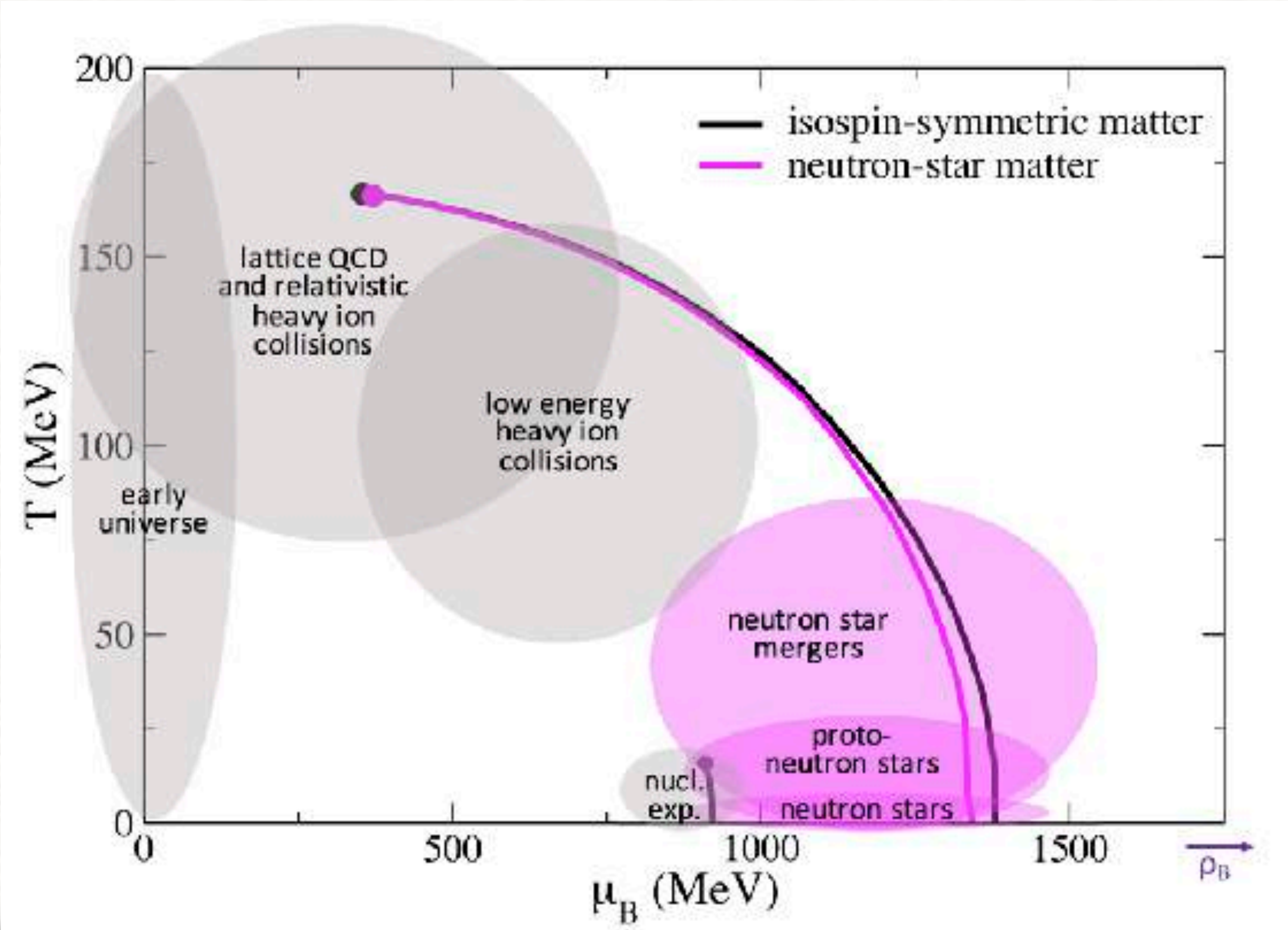


Phase transitions and their signatures

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



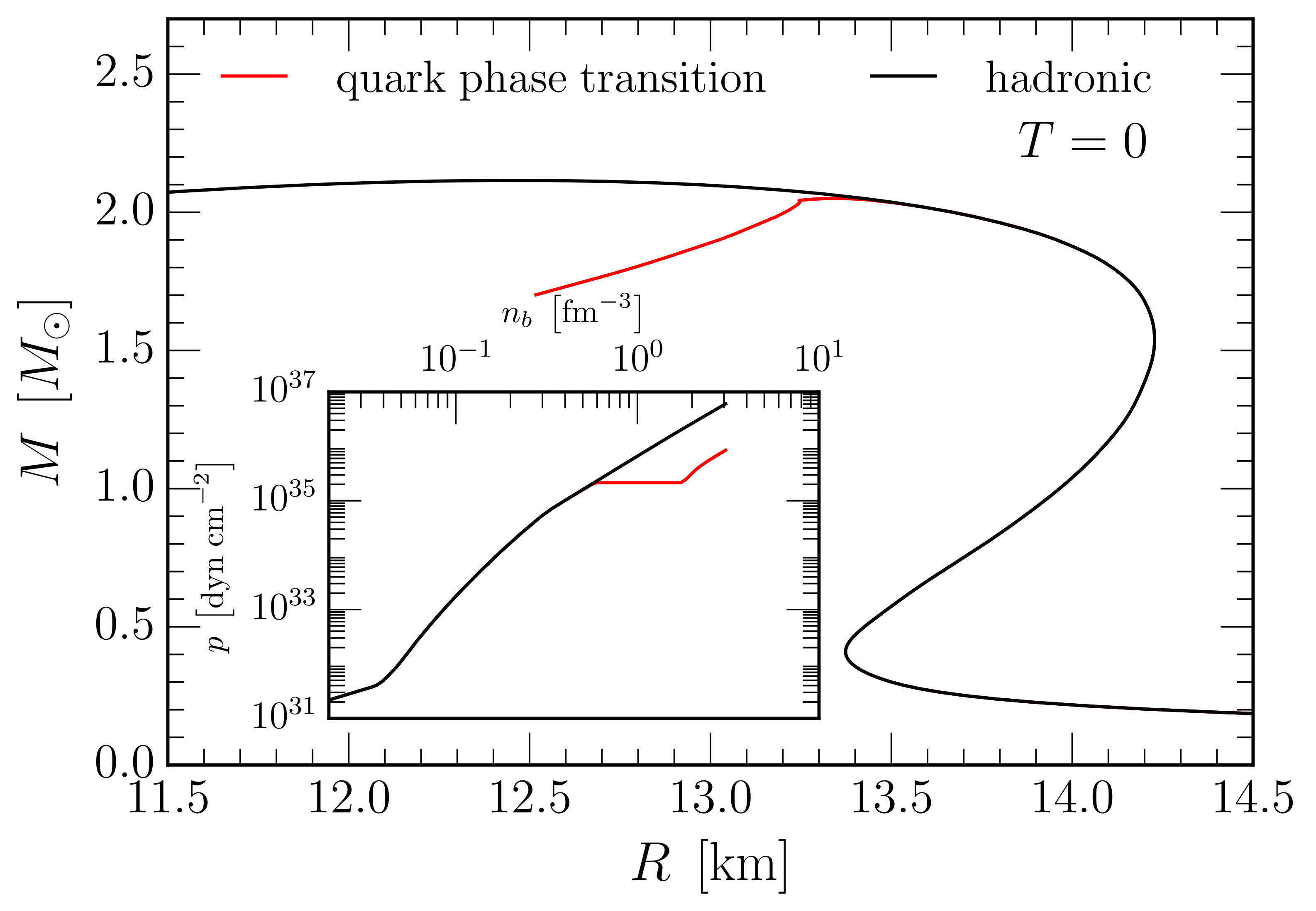
- **Strangeness** is expected in neutron stars both in the inspiral (hyperons) and possibly after merger (strange quarks?)
- **Isolated** neutron stars probe a small fraction of phase diagram



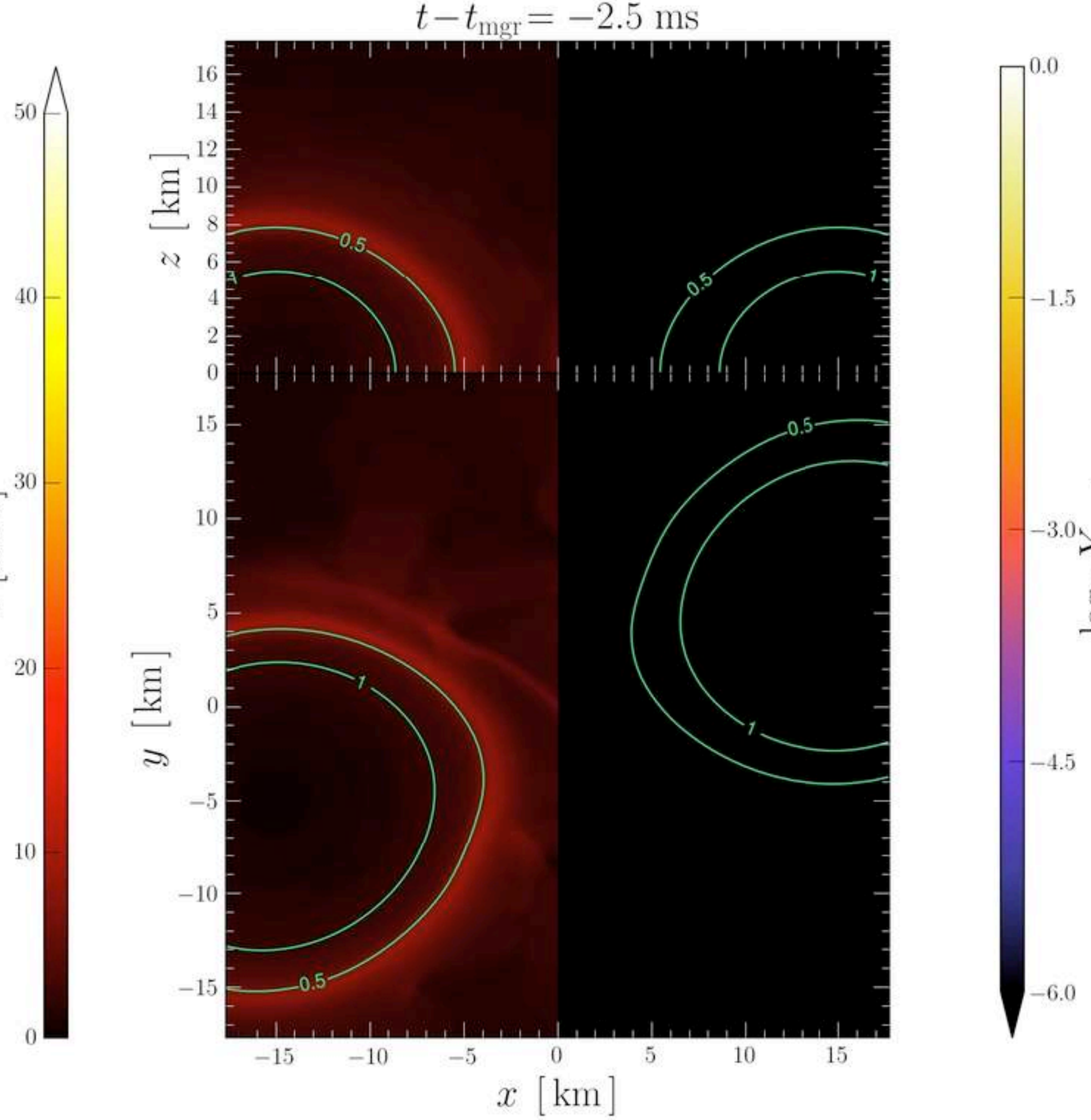
- Neutron-star **binary** mergers reach temperatures up to **80 MeV** and probe regions complementary to experiments

Modelling the EOS

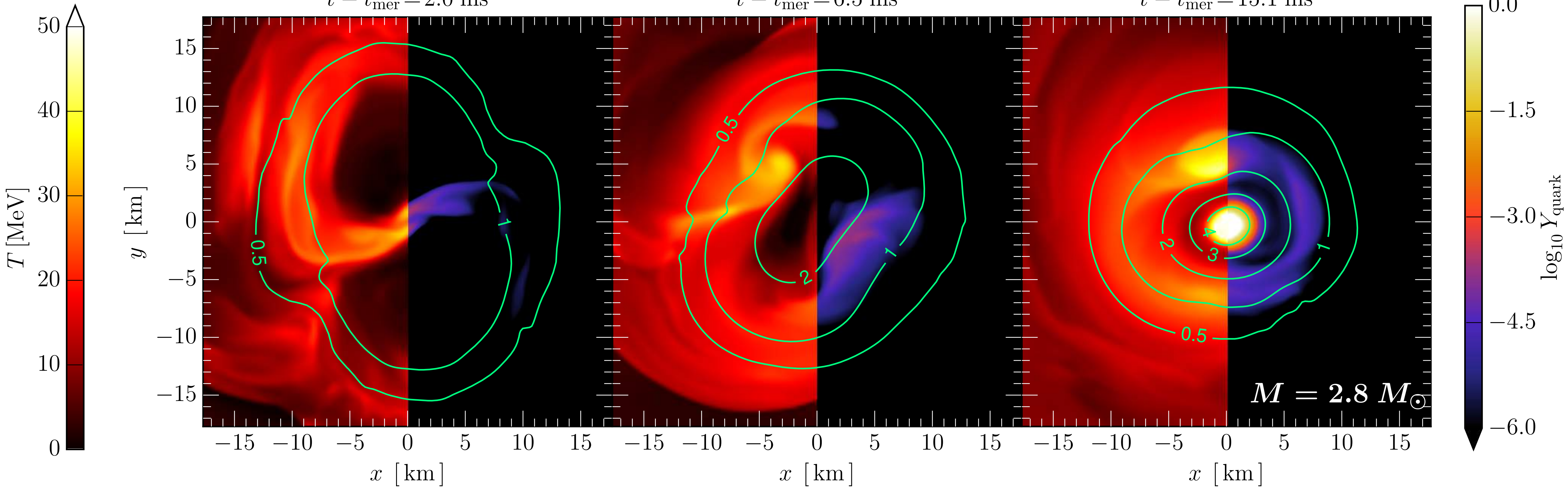
- EOS based on Chiral Mean Field (CMF) and nonlinear SU(3) sigma model
- Includes hyperons and quarks that can be turned on/off
- Uses Polyakov loop to implement a strong first order phase transition
- Includes a cross-over transition at high temperatures



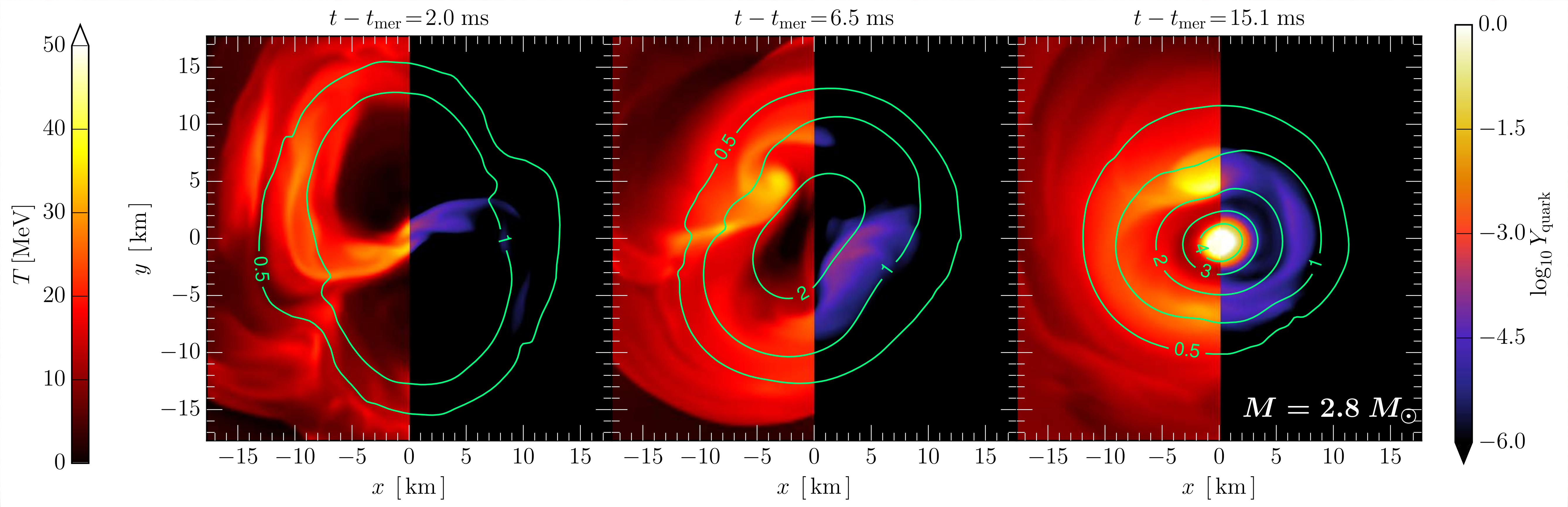
Temperature

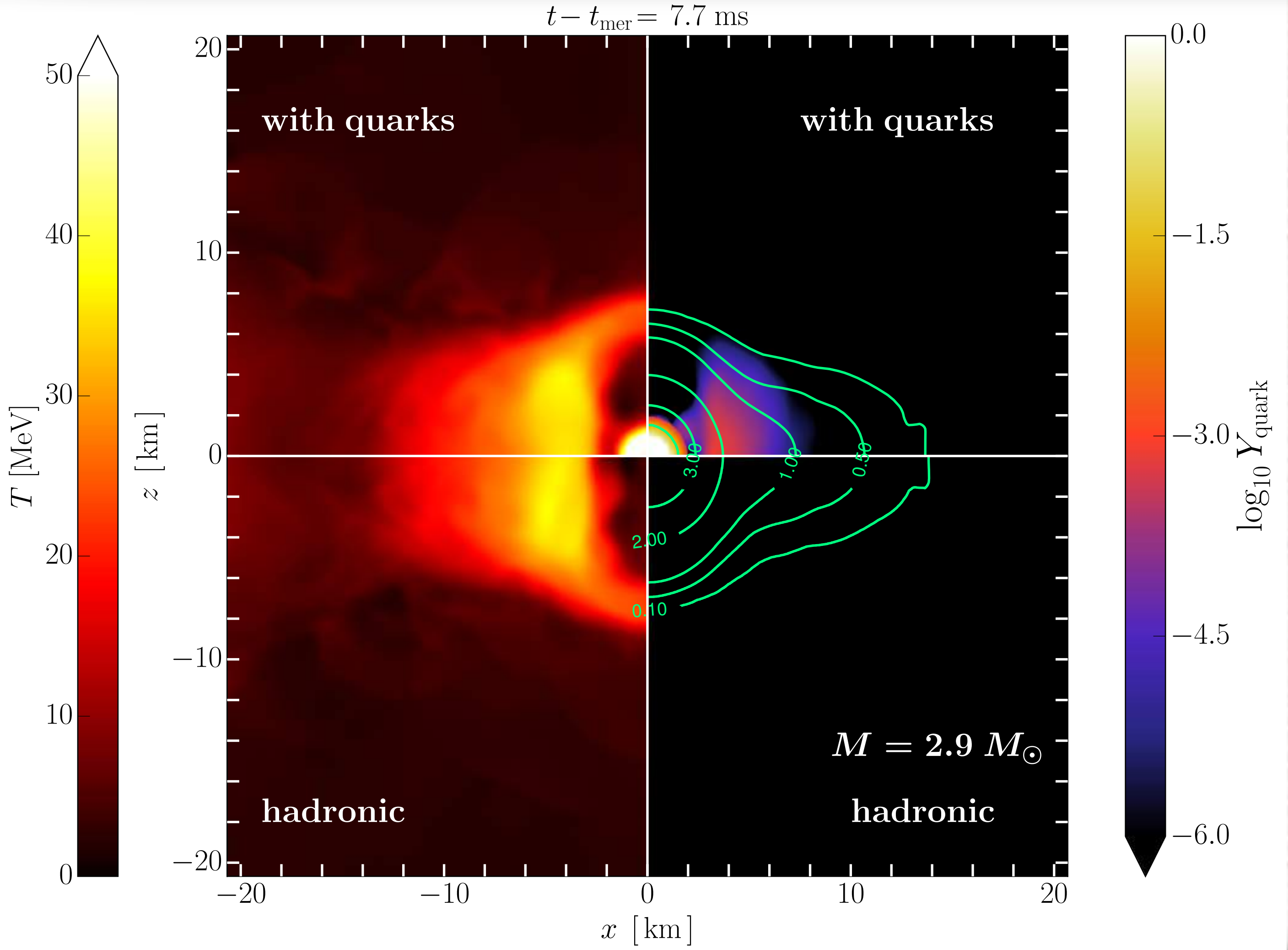


Quark fraction



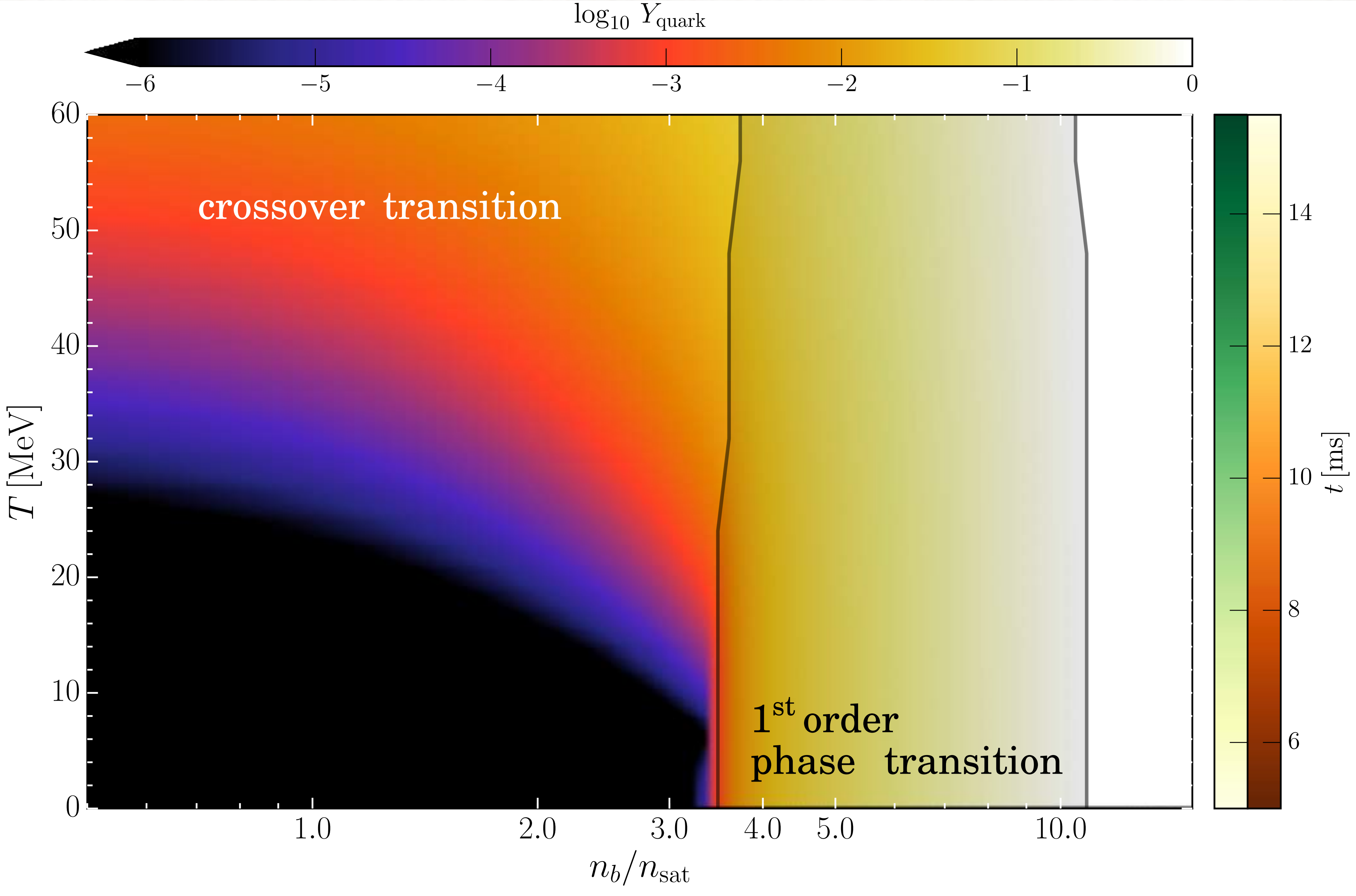
- EOS based on Chiral Mean Field (CMF) model, based on a nonlinear SU(3) sigma model.
- Quarks appear at sufficiently large temperatures and densities.





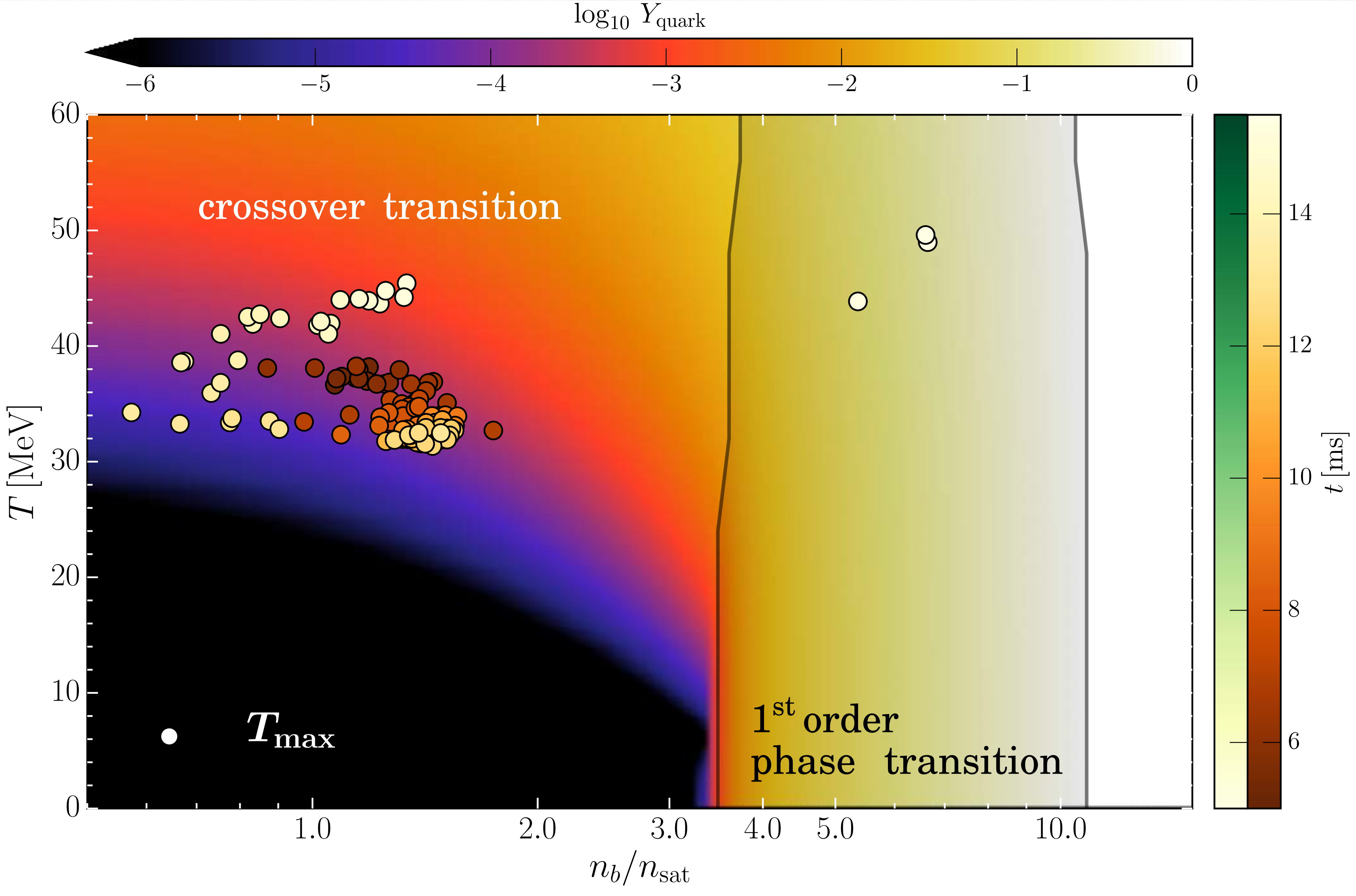
- EOS based on Chiral Mean Field (CMF) model, based on a nonlinear SU(3) sigma model.
- Quarks appear at sufficiently large temperatures and densities.
- For EOS without quarks, the dynamics is very similar, but no PT.

Comparing with the phase diagram



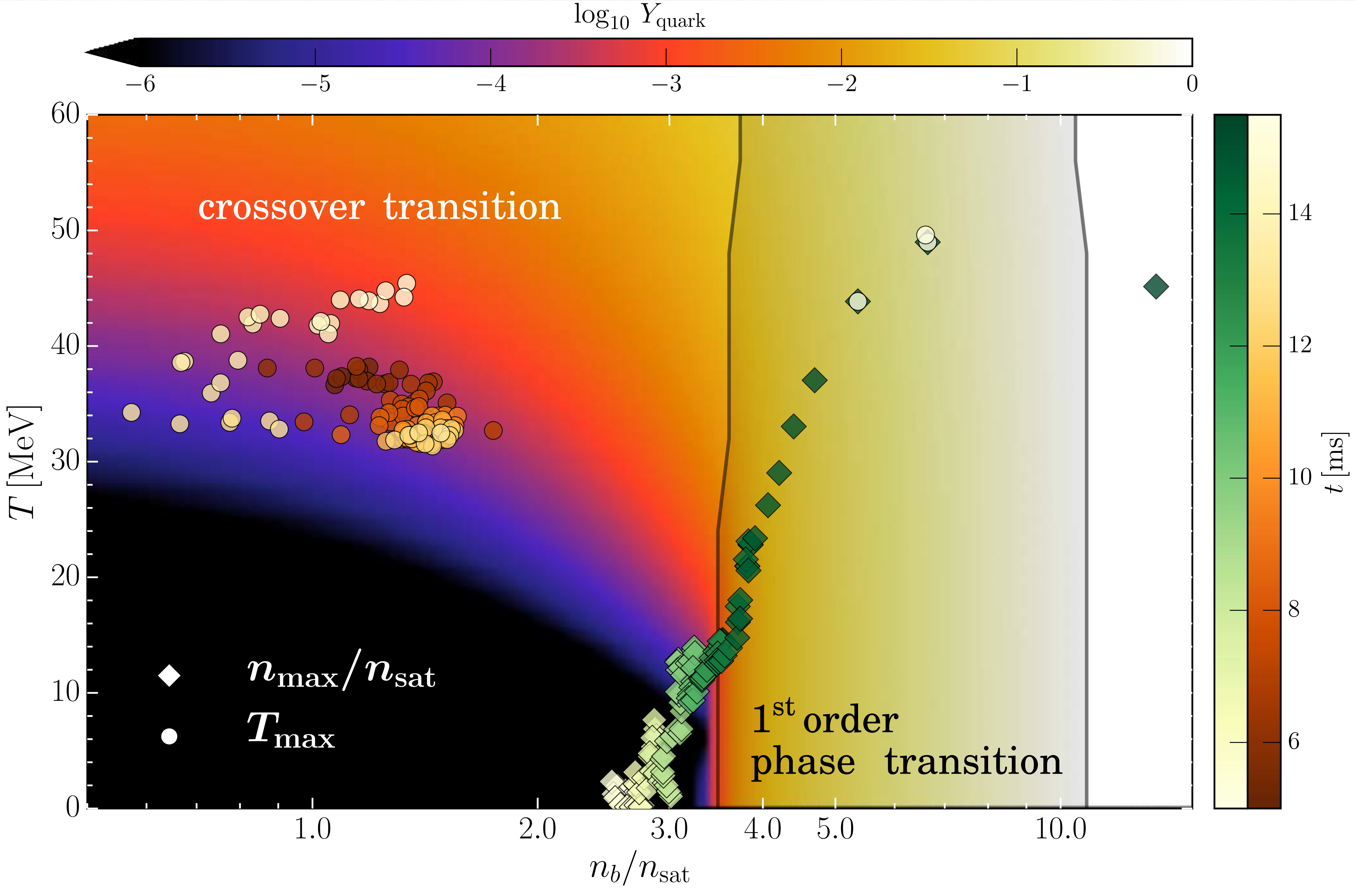
- Phase diagram with quark fraction

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

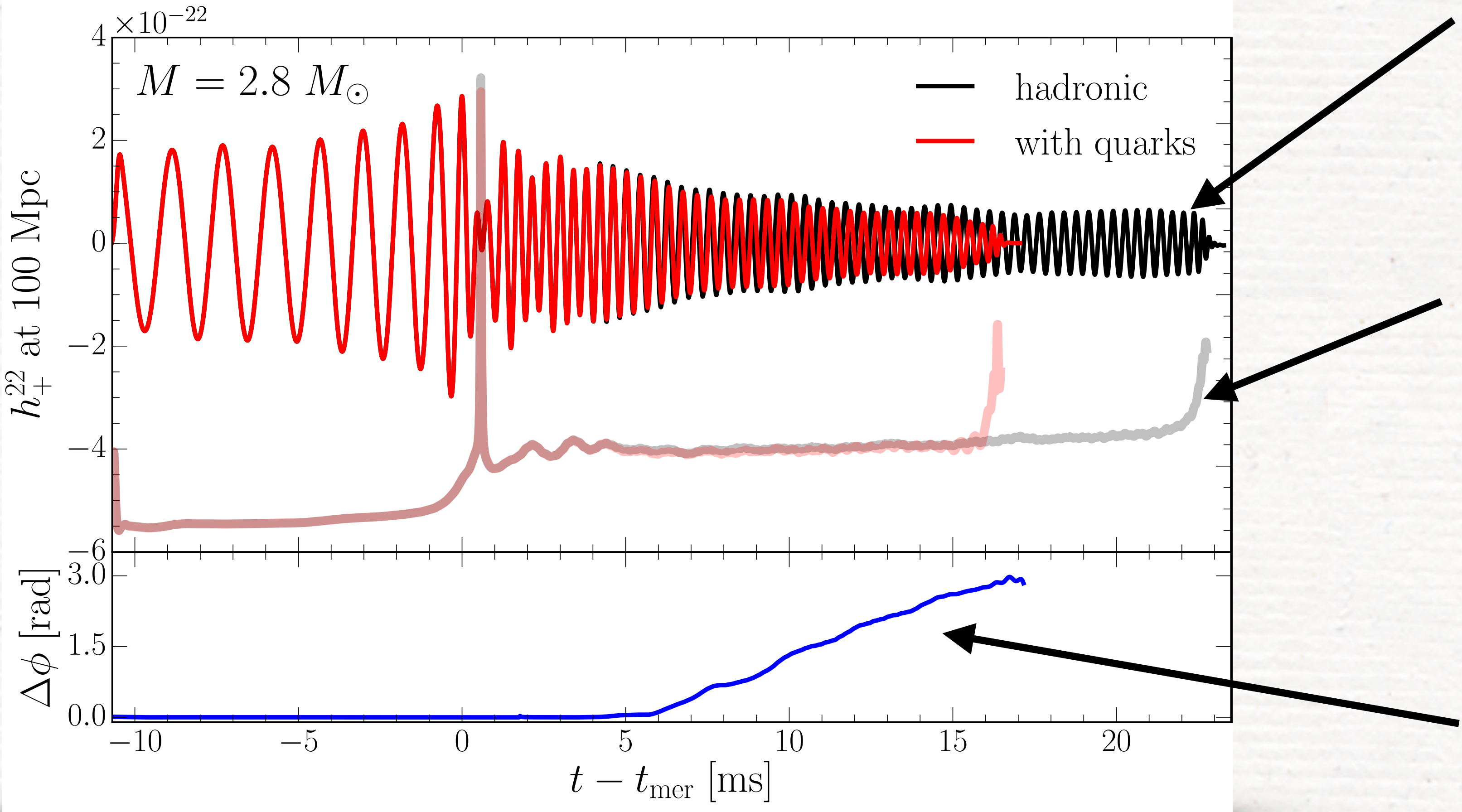
Comparing with the phase diagram



- 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 emissiom

“low-mass” binary



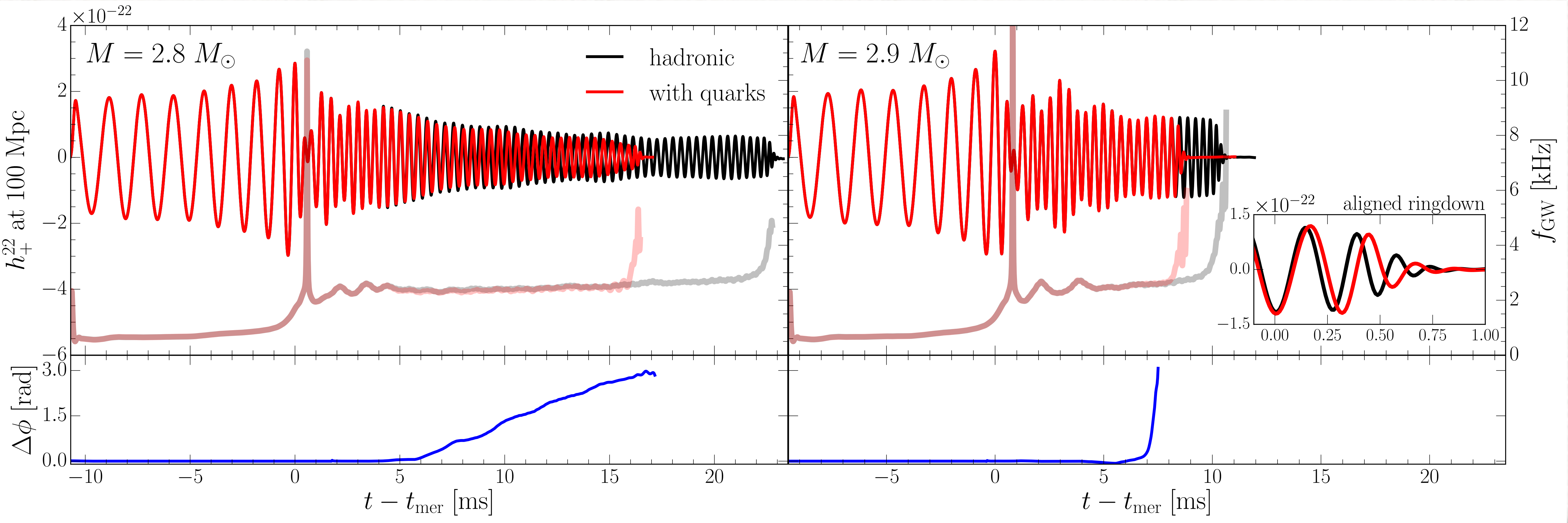
waveforms

GW frequencies

phase difference

- In **low-mass binary**, after ~ 5 ms, quark fraction is large enough to change quadrupole moment and yield differences in the waveforms.
- Note the phase difference is **zero** in the inspiral.
- Sudden softening of the phase transition leads to collapse and **large difference** in phase evolution.

Gravitational-wave emissiom



- 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**.

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.