Binary neutron stars: Einstein's richest laboratory

Luciano Rezzolla

Institute for Theoretical Physics, Frankfurt

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Max-Planck-Institut für Kernphysik

Particle & Astroparticle Physics

Plan of the talk

- The richness of merging binary neutron stars
- GW spectroscopy: EOS from frequencies
- Magnetic fields and EM counterparts
- Ejected mass and nucleosynthesis
- GW170817: a game changer
- Signatures of quark-hadron phase transitions

The two-body problem in GR

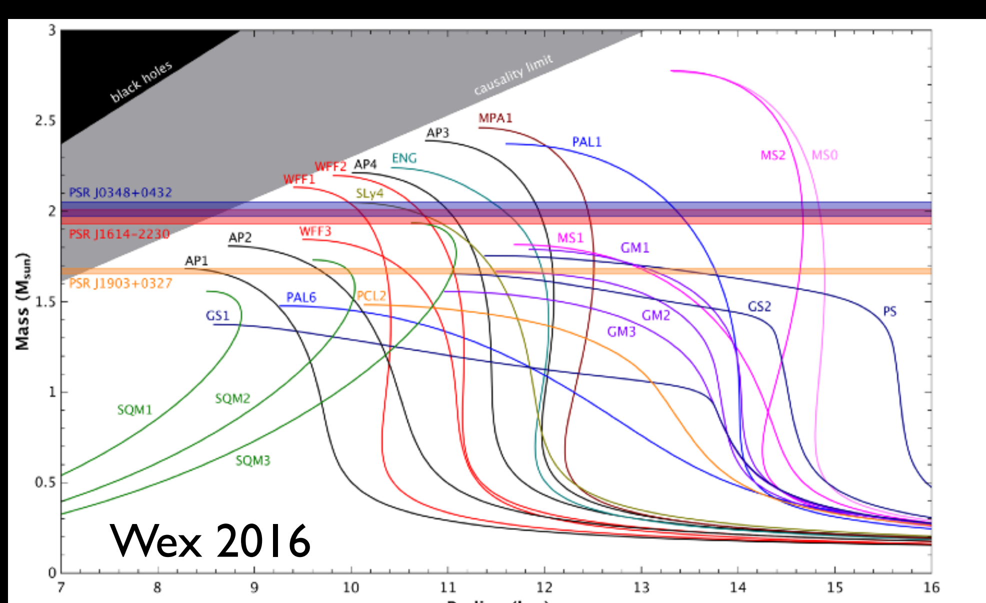
- For black holes the process is very **simple:**

BH + BH → BH + GWs

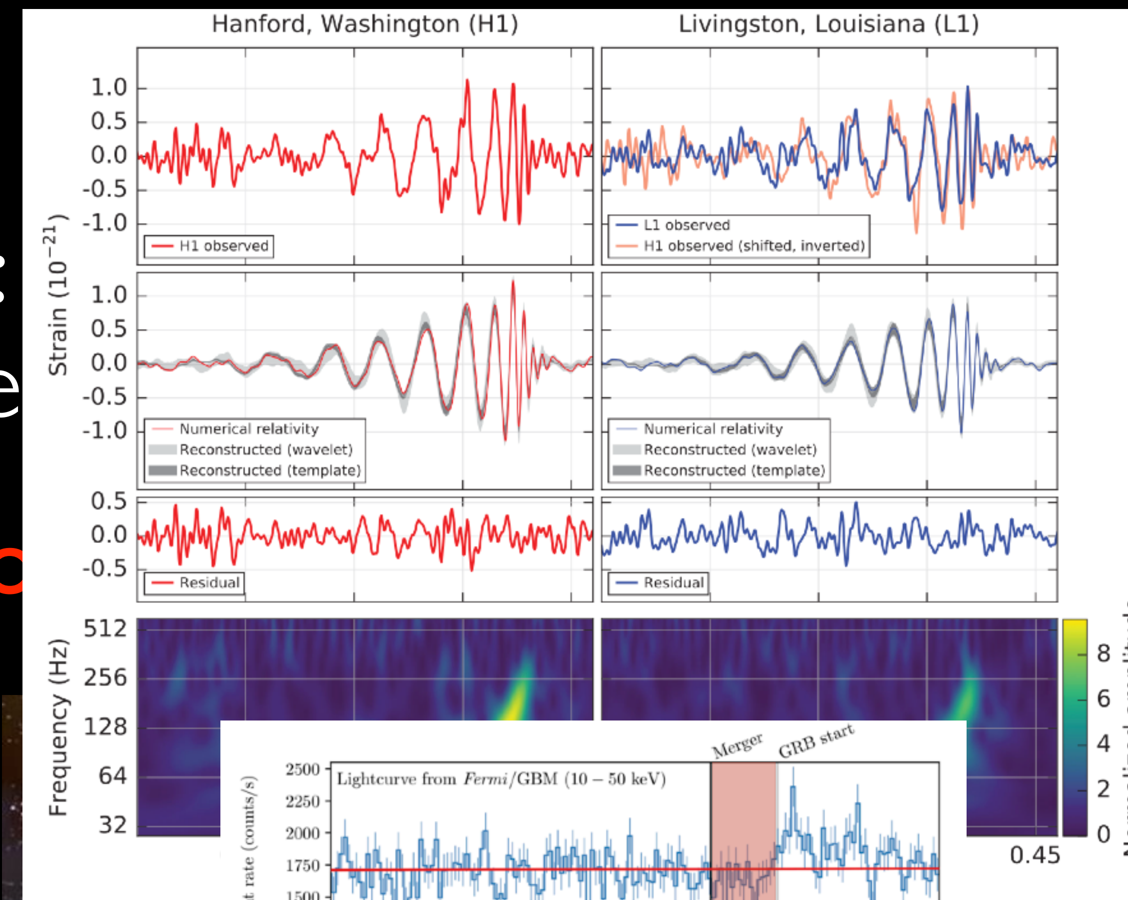
- For NSs the question is more **subtle:**
hyper-massive neutron star (HMNS), ie

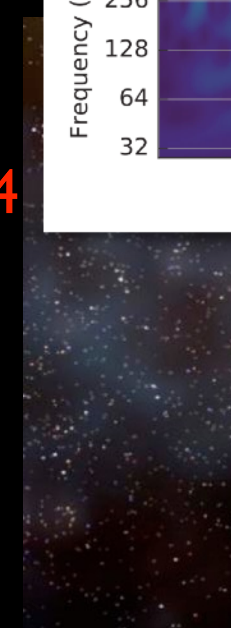
NS + NS → HMNS+... ? → BH+to

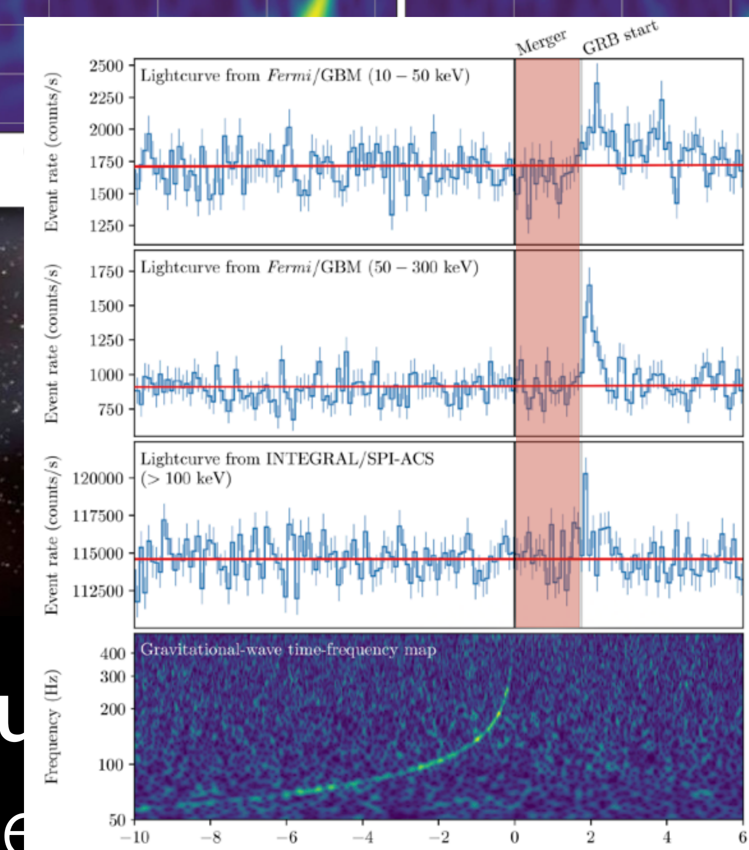
- **HMNS** phase can provide clear information on **EOS**



GW150914







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

GW170817

The two-body problem in GR

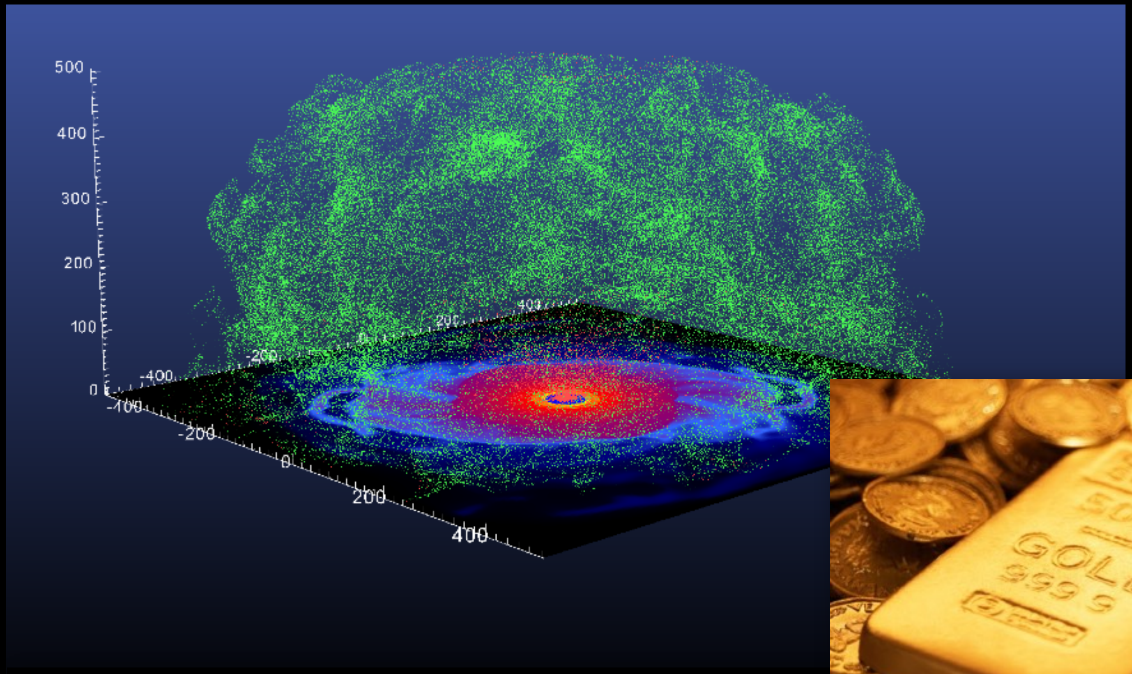
- For black holes the process is very **simple**:

BH + BH ⟶ BH + GWs

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

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

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



The equations of numerical relativity

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

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

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

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

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

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

The "beauty" disappears quickly when implementing them in numerical codes…

$$
\begin{aligned}
\partial_t \tilde{\gamma}_{ij} &= -2\alpha \tilde{A}^{\rm TF}_{ij} + 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]^{\rm 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 &= f B^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

Animations: Breu, Radice, LR

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

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

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

LS220 EOS

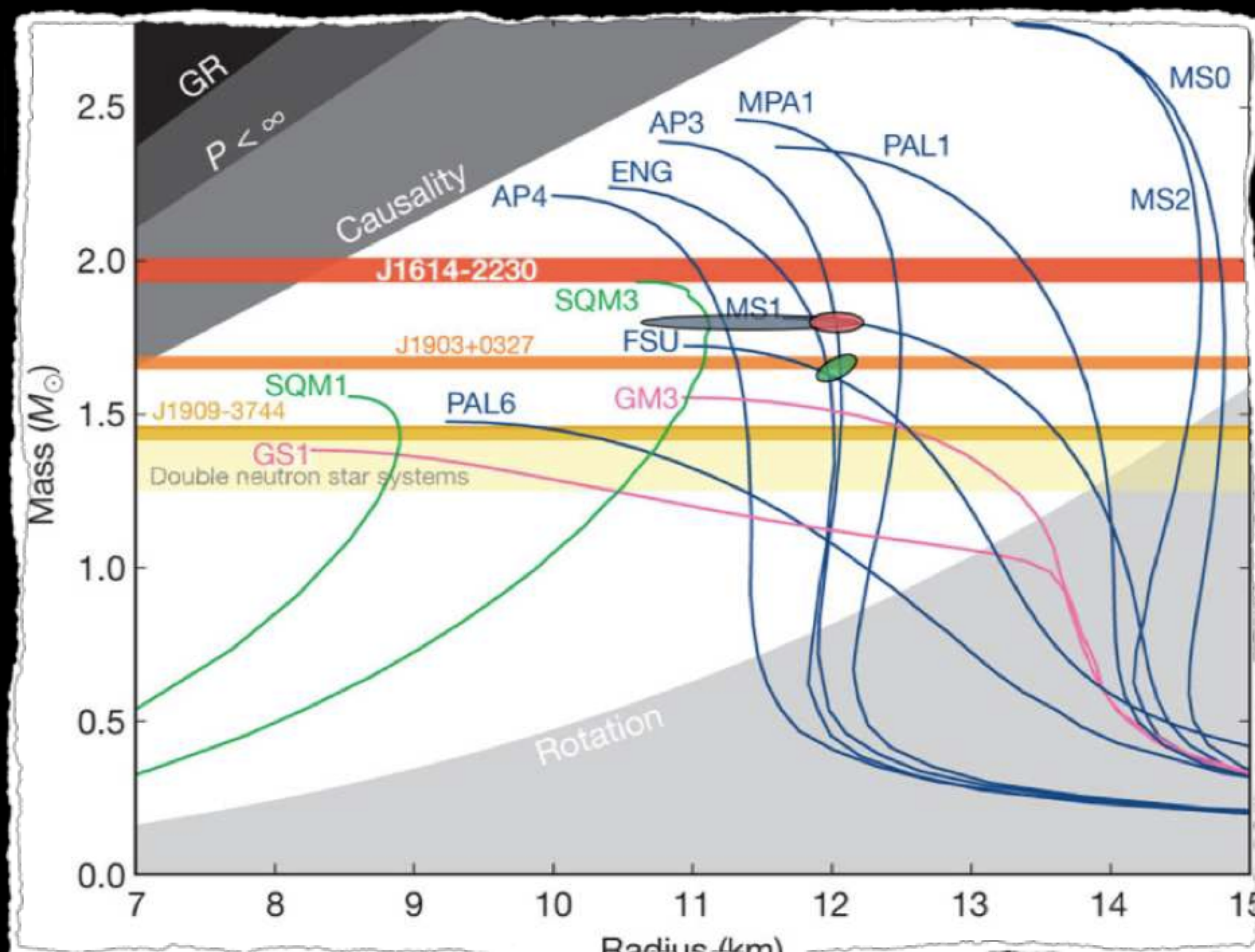
merger → HMNS → BH + torus

Quantitative differences are produced by:

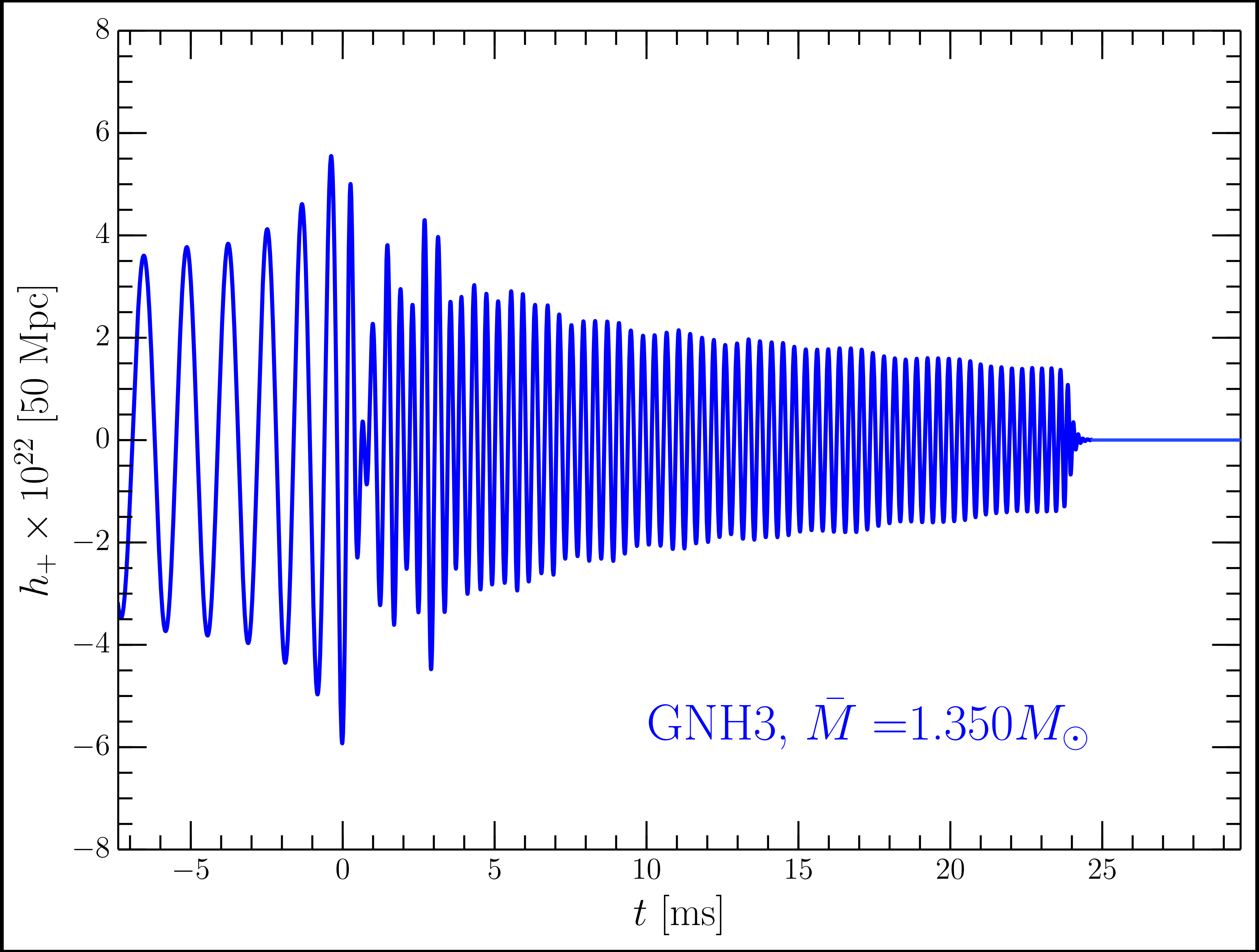
- total mass (prompt vs delayed collapse)
- mass asymmetries (HMNS and torus)
- soft/stiff EOS (inspiral and post-merger)
- magnetic fields (equil. and EM emission)
- radiative losses (equil. and nucleosynthesis)

GW spectroscopy and how to constrain the EOS

Baiotti, Bose, LR, Takami PRL, PRD (2015-2018)



Anatomy of the GW signal



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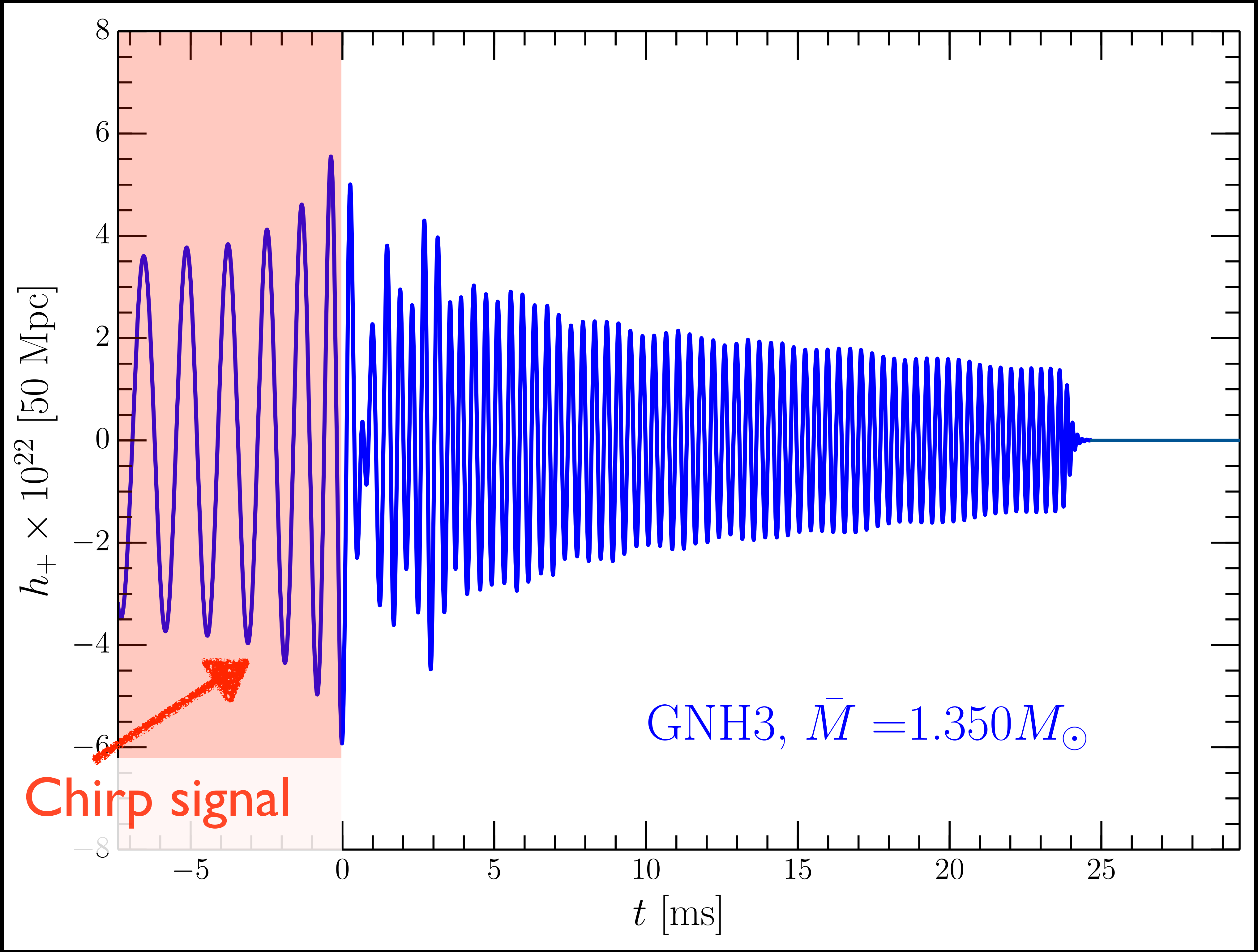
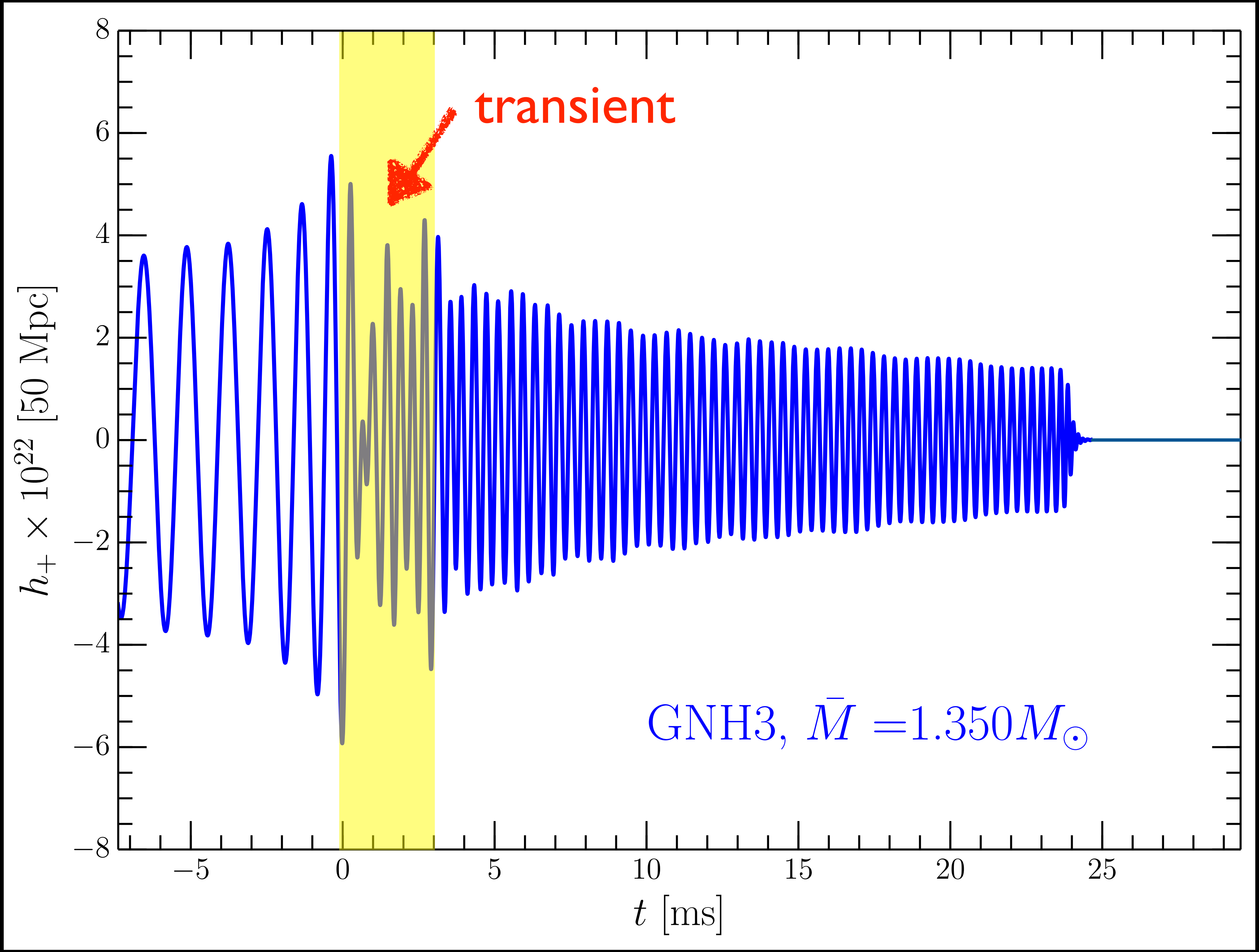


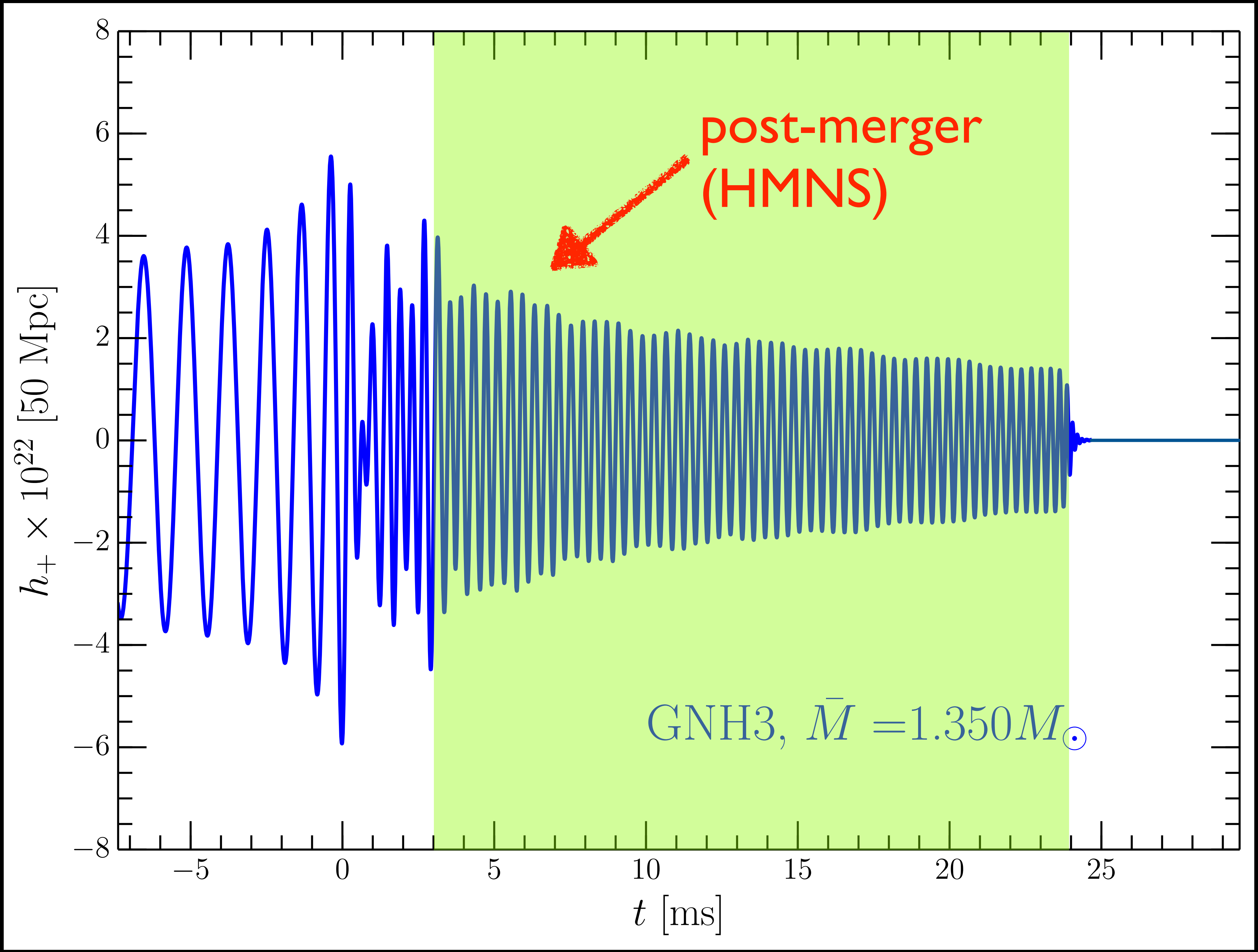
Inspiral: well approximated by PN/EOB; tidal effects important

Anatomy of the GW signal



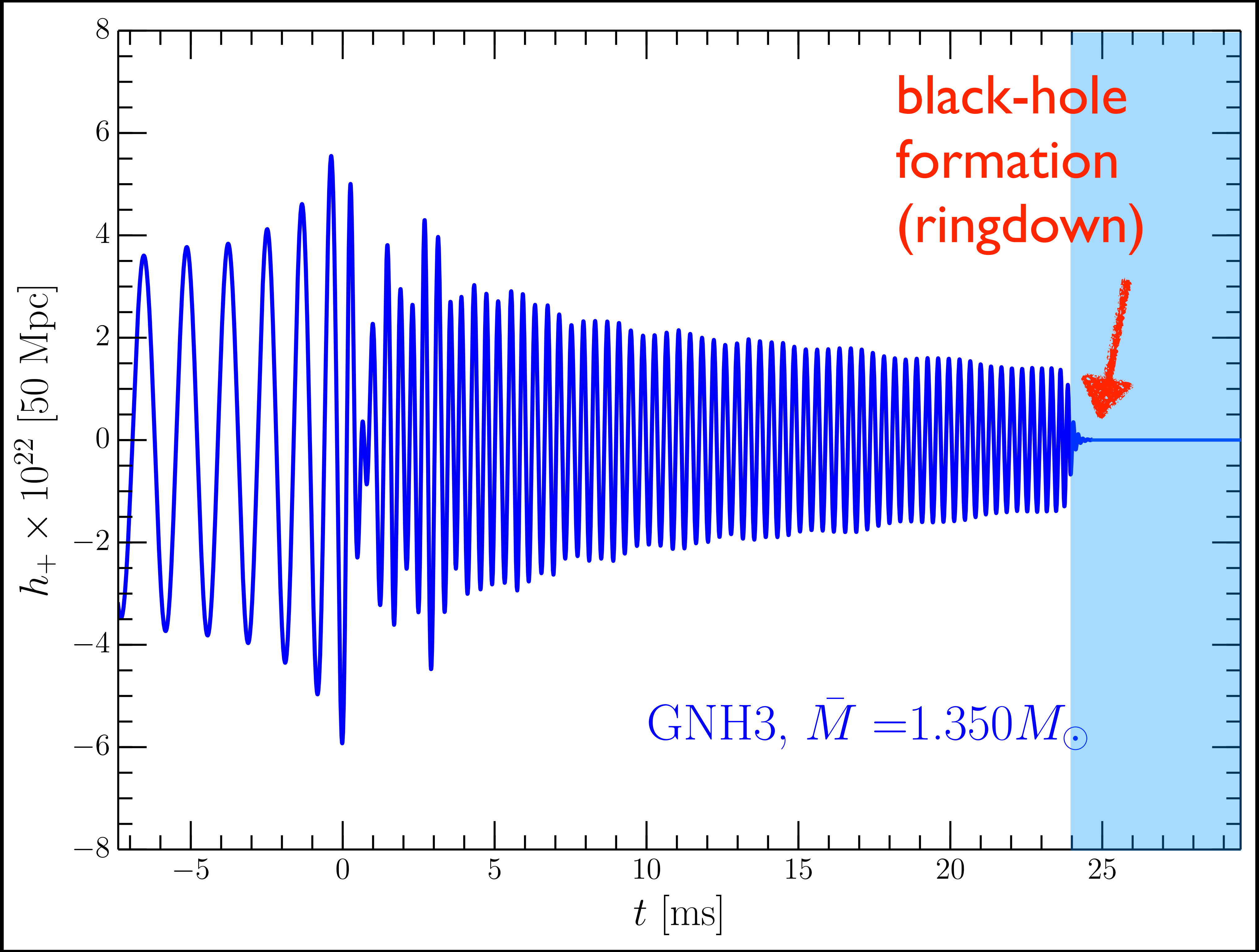
Merger: highly nonlinear but analytic description possible

Anatomy of the GW signal



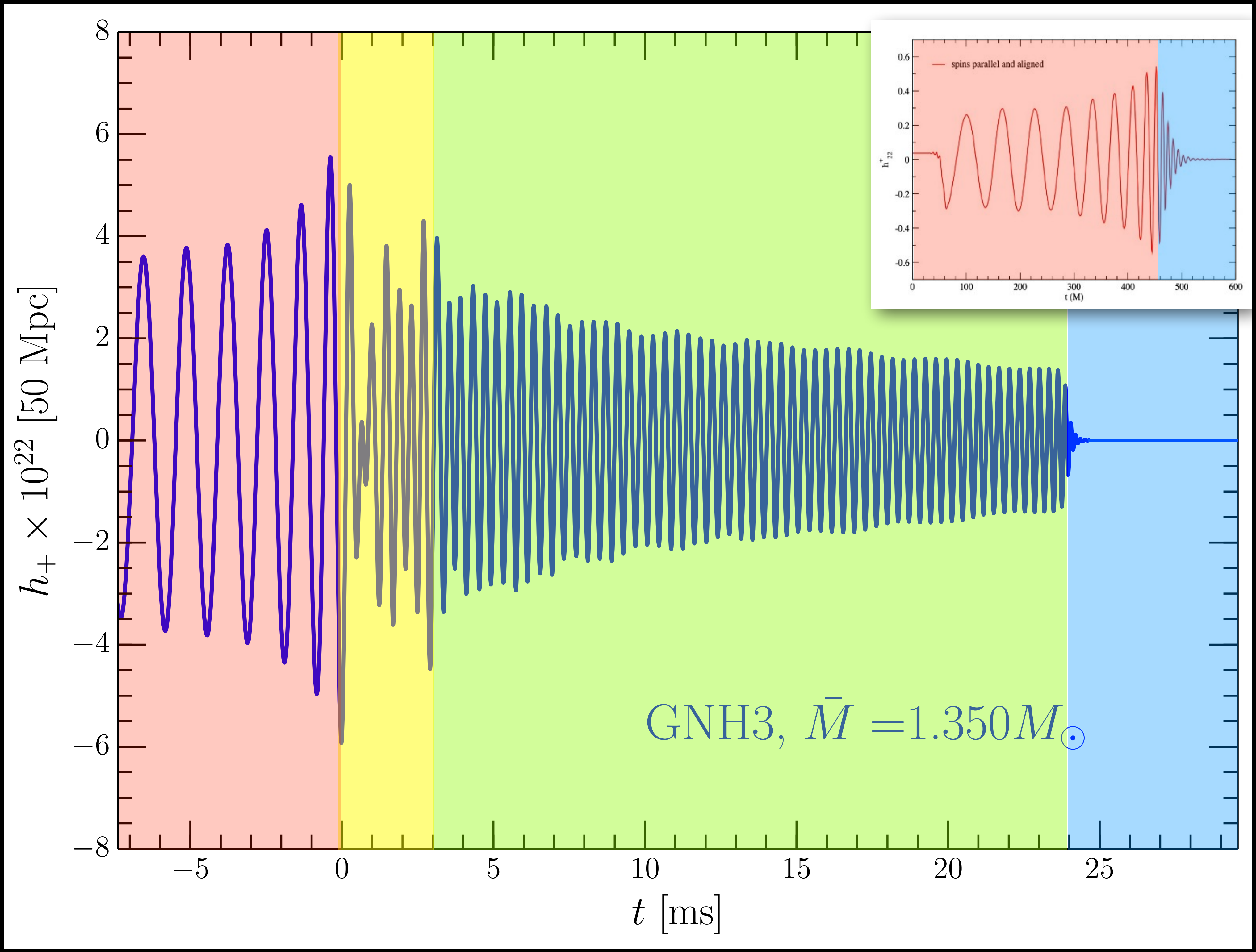
post-merger: quasi-periodic emission of bar-deformed HMNS

Anatomy of the GW signal



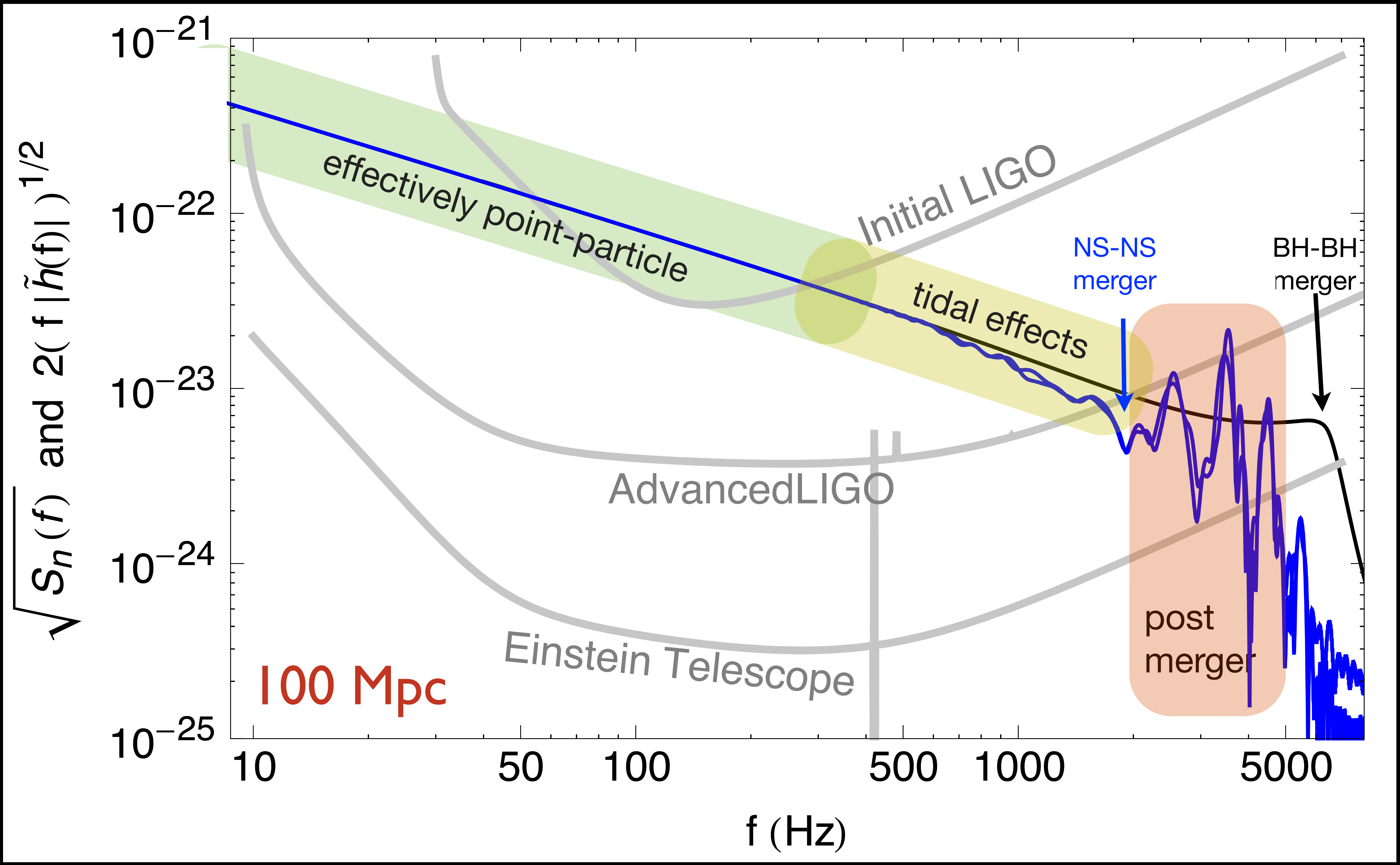
Collapse-ringdown: signal essentially shuts off

Anatomy of the GW signal



Postmerger signal: peculiar of binary NSs

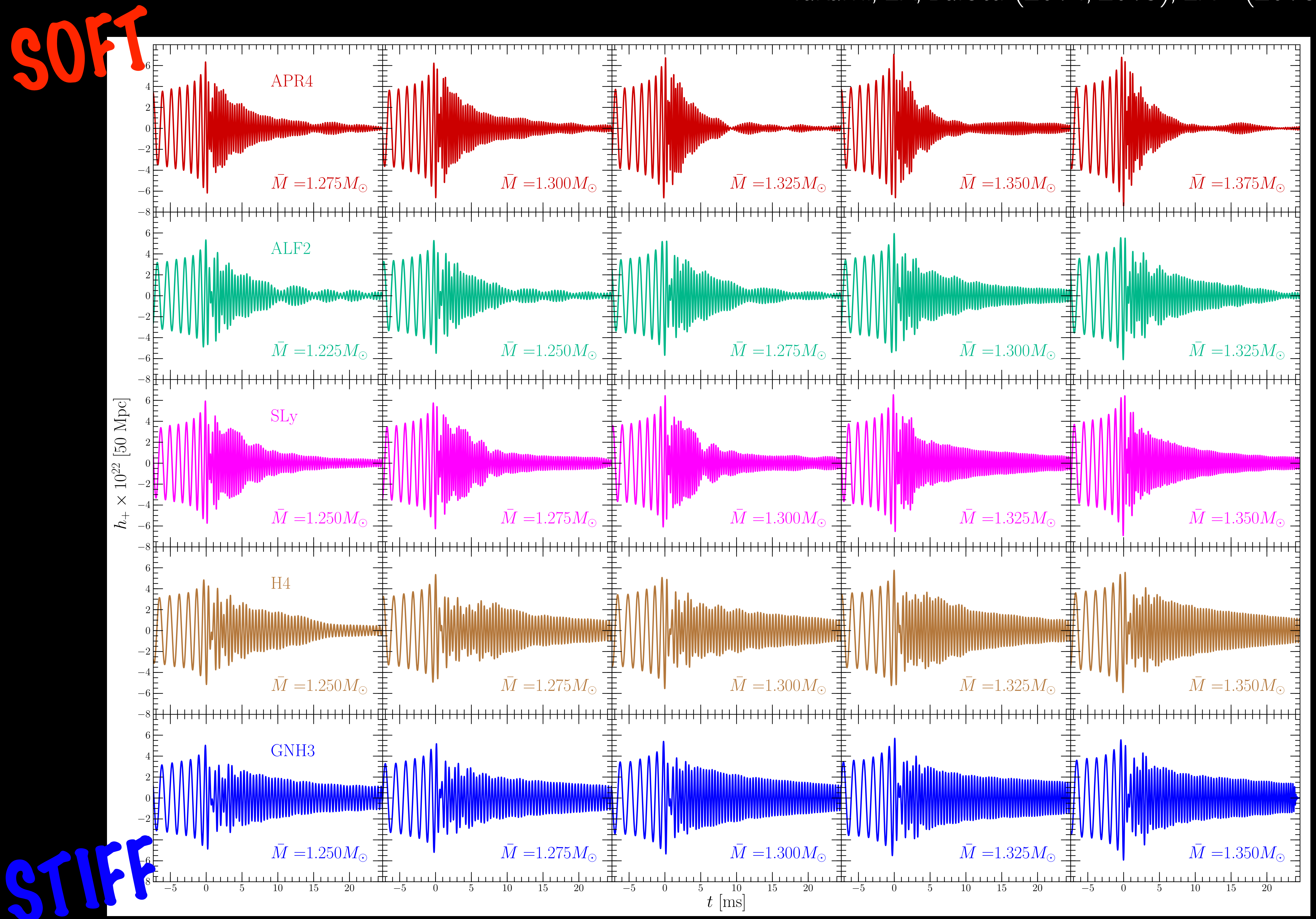
In frequency space



Read et al. (2013)

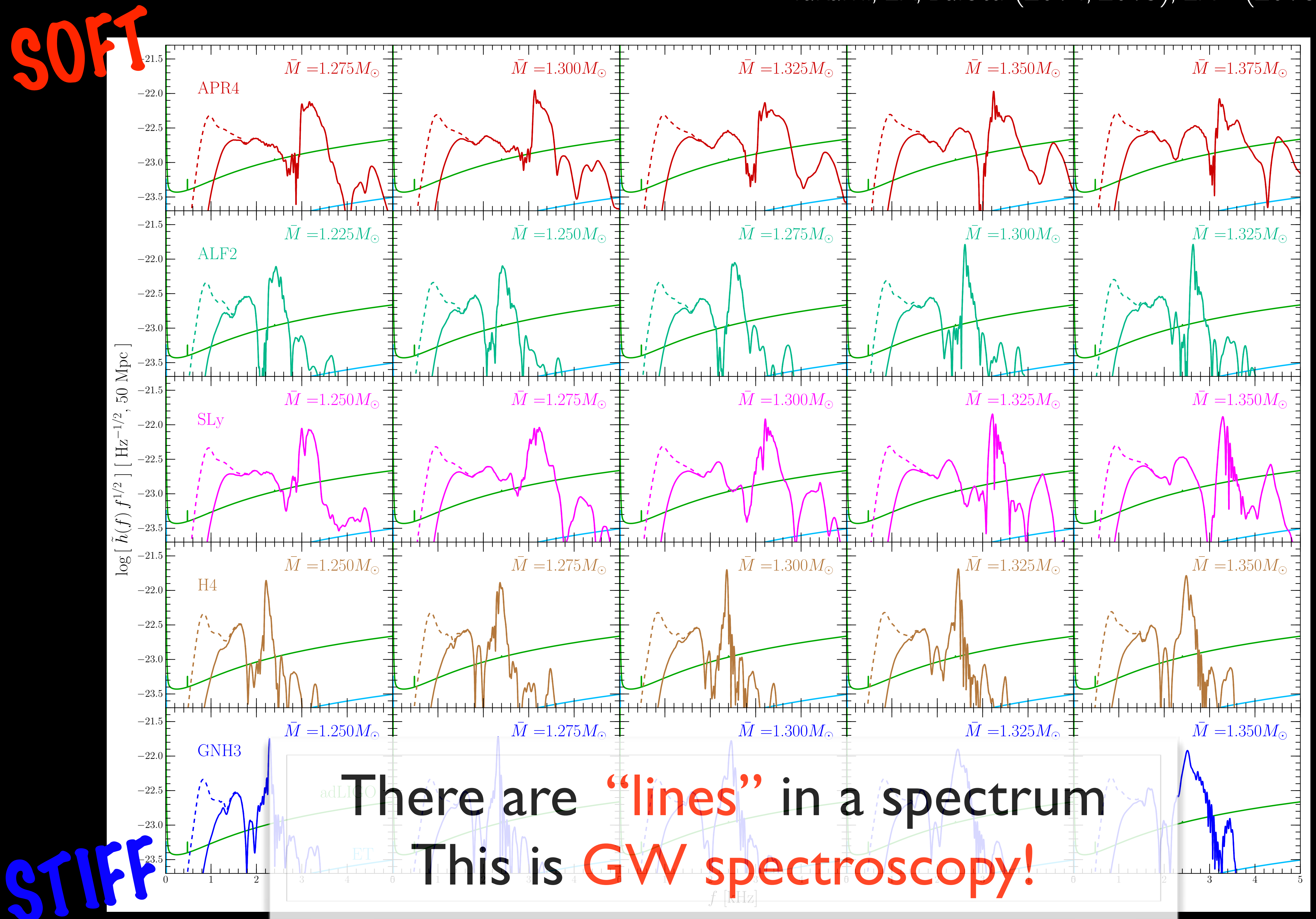
What we can do nowadays

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



Extracting information from the EOS

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

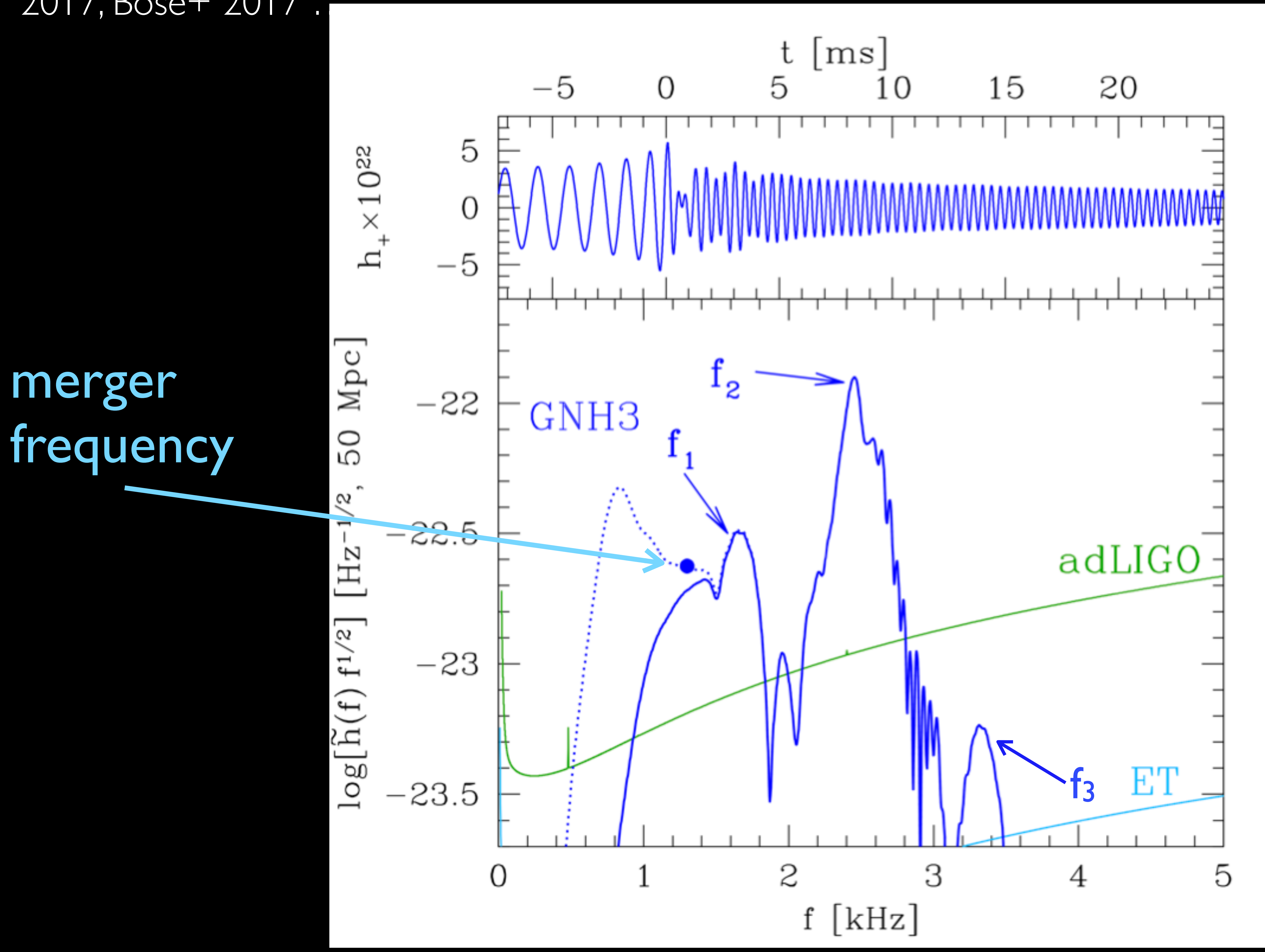


There are "lines" in a spectrum

This is GW spectroscopy!

A spectroscopic approach to the EOS

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



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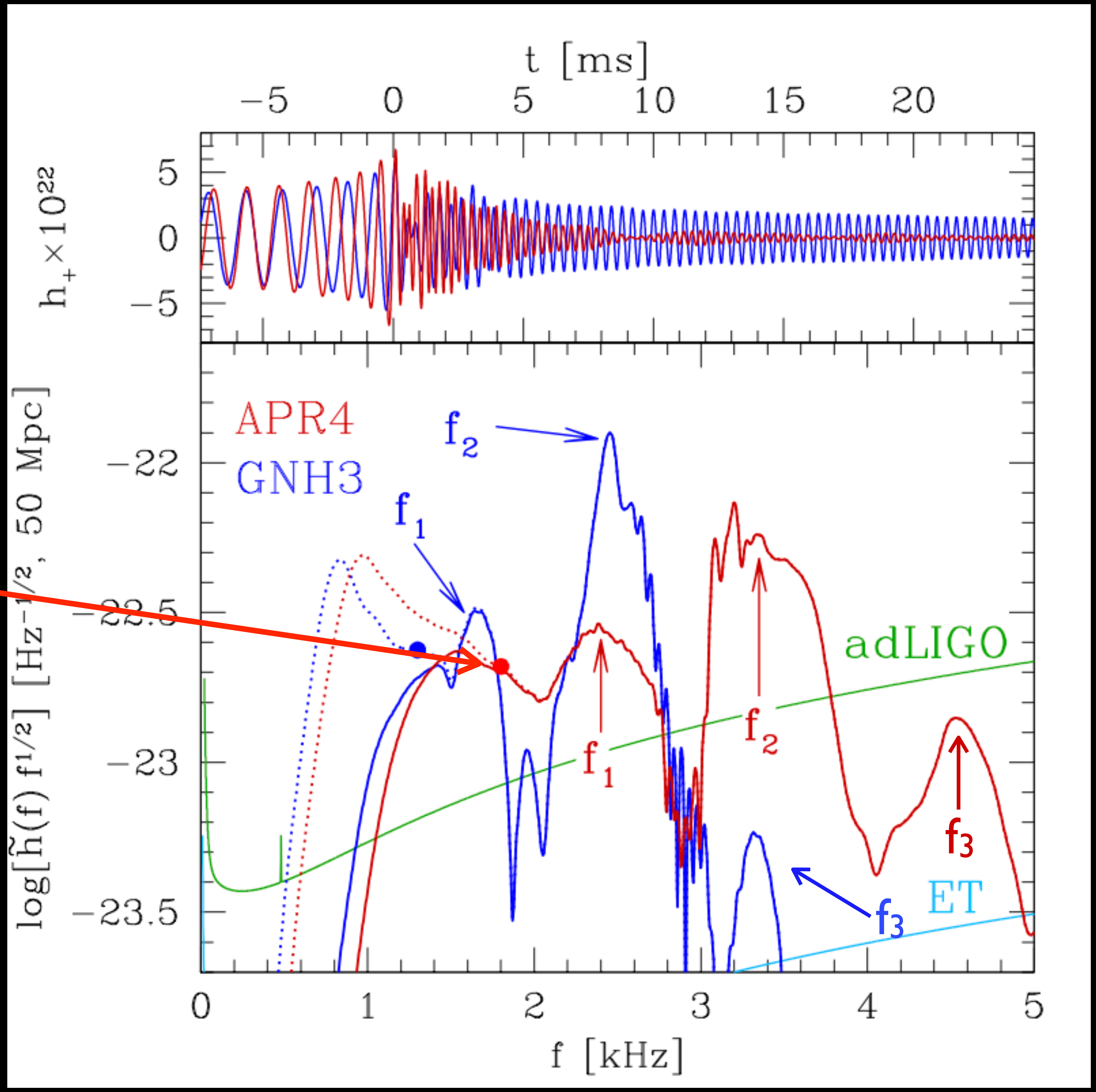
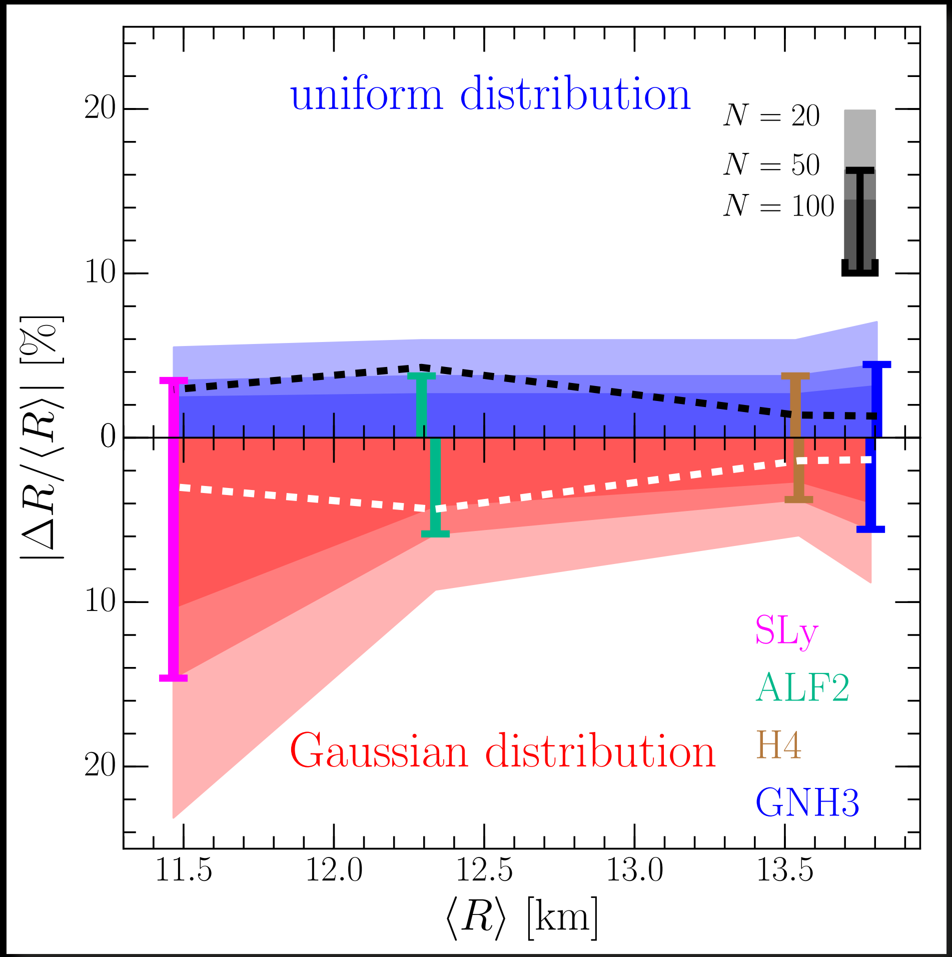
merger frequency



A spectroscopic approach to the EOS

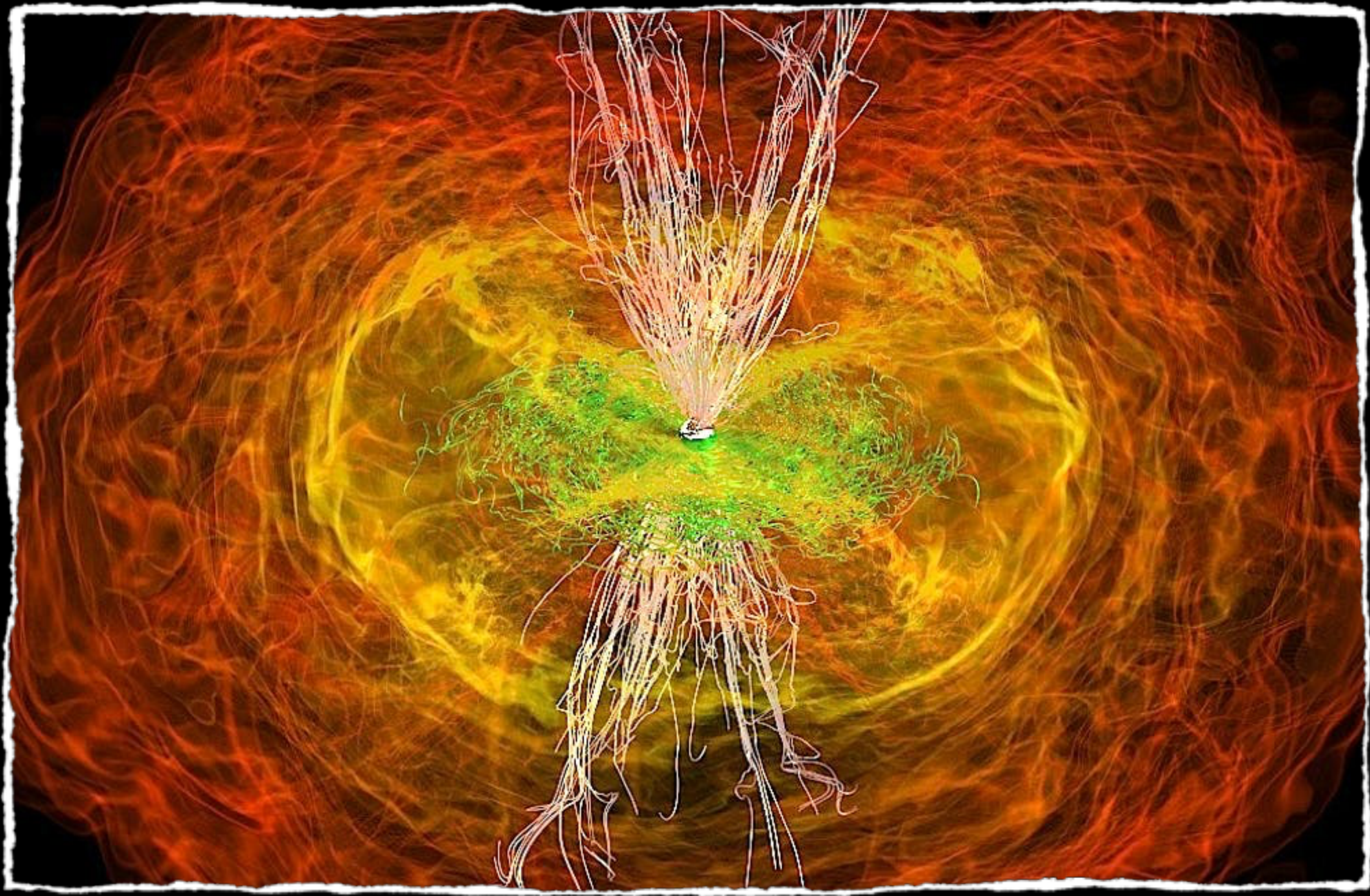
- **Universal behaviour** and analytic modelling of post-merger relates position of these peaks with the EOS.
- Observation of the post-merger signal would constrain significantly the stellar radius; given ***N* detections.**



- 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

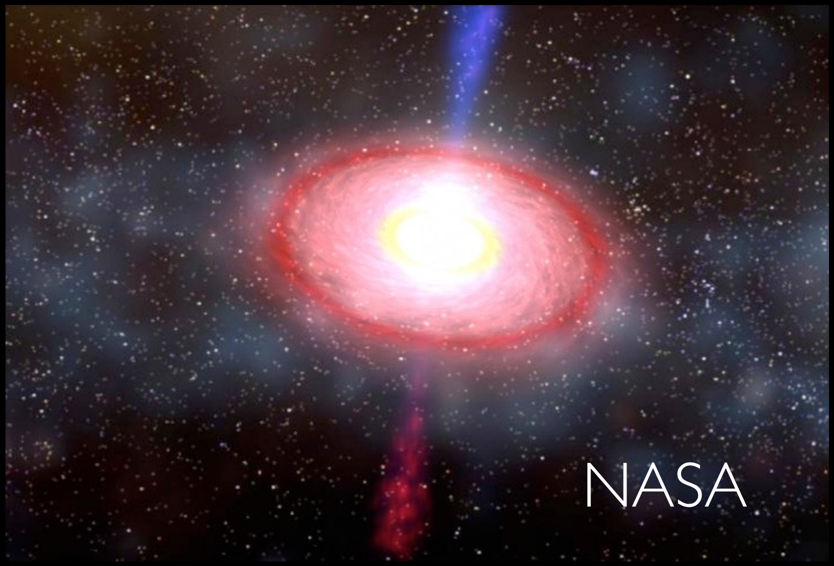
Baiotti, Bose, LR, Takami PRL, PRD (2015-2018)

Electromagnetic counterparts



Electromagnetic counterparts

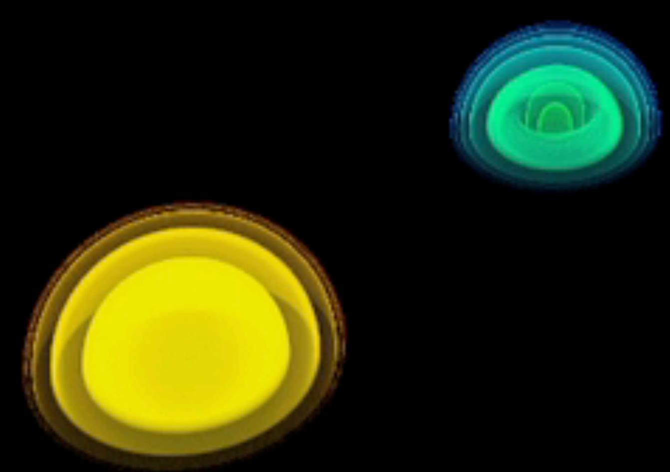
- Since 70's we have observed flashes of gamma rays with enormous energies 10^{50-53} erg: **gamma-ray bursts**.
- There are two families of bursts: "**long**" and "**short**".
- The first ones last **tens** or more of **seconds** and could to be due to the collapse of very massive stars.
- The second ones last **less** than a **second**.
- Merging neutron stars most reasonable explanation but how do you produce a **jet**?



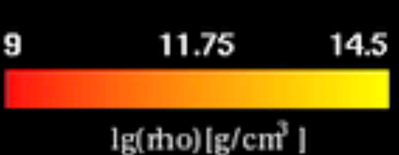
Presence of a jet immediately implies presence of large-scale magnetic fields

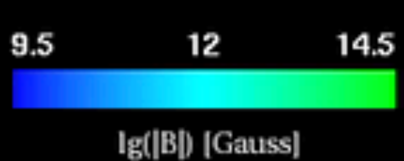
What happens when magnetised stars collide?

Need to solve equations of magnetohydrodynamics in addition to the Einstein equations



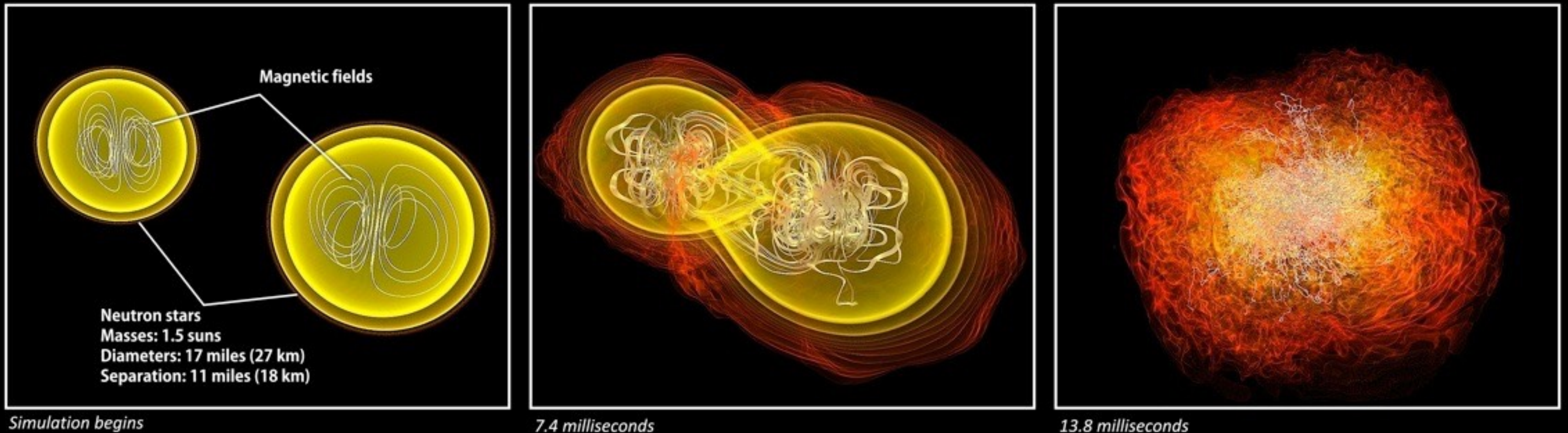
$$M = 1.5\, M_{\odot}, B_0 = 10^{12}\,\mathrm{G}$$



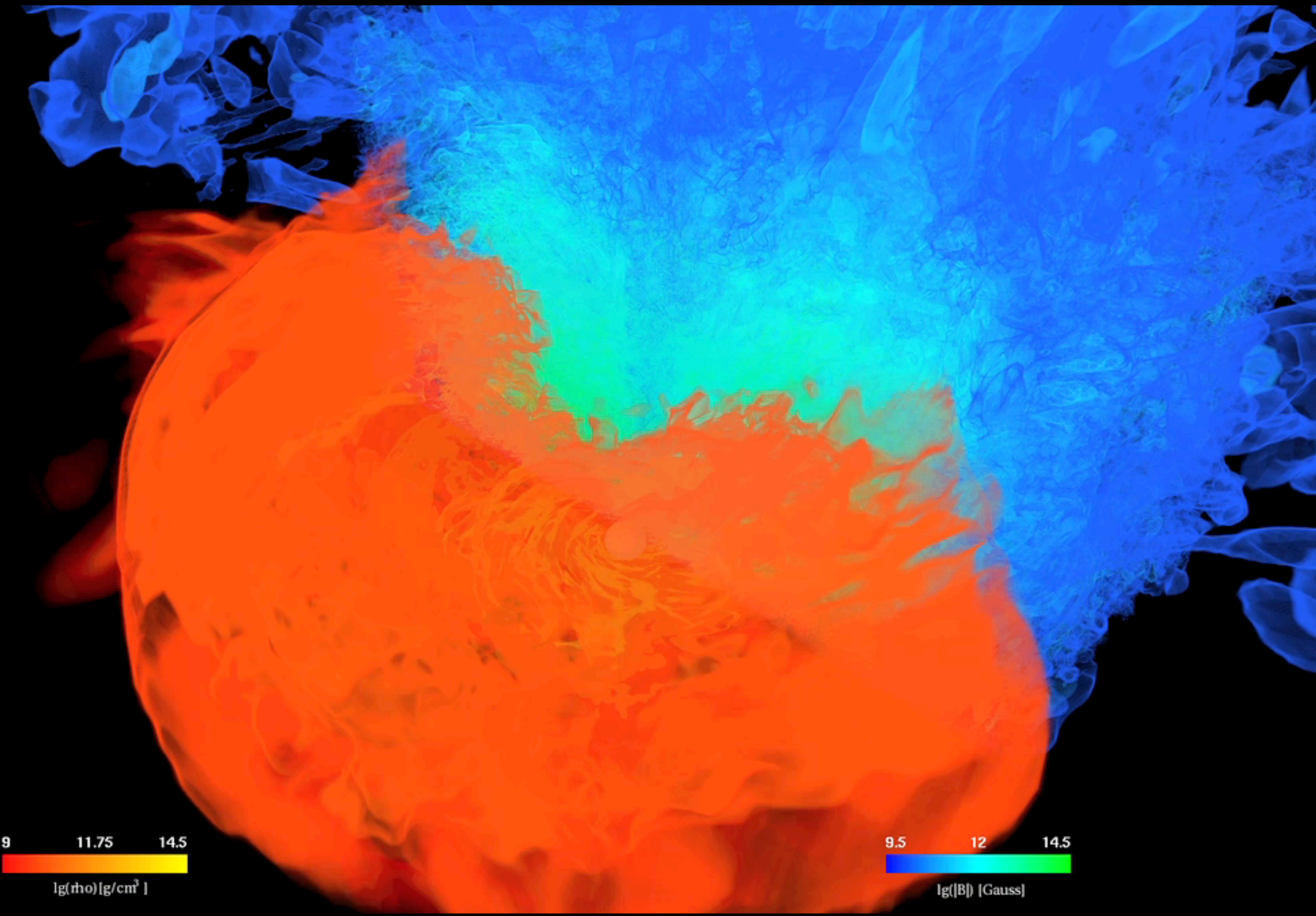


Animations:, LR, Koppitz

What happens when magnetised stars collide?

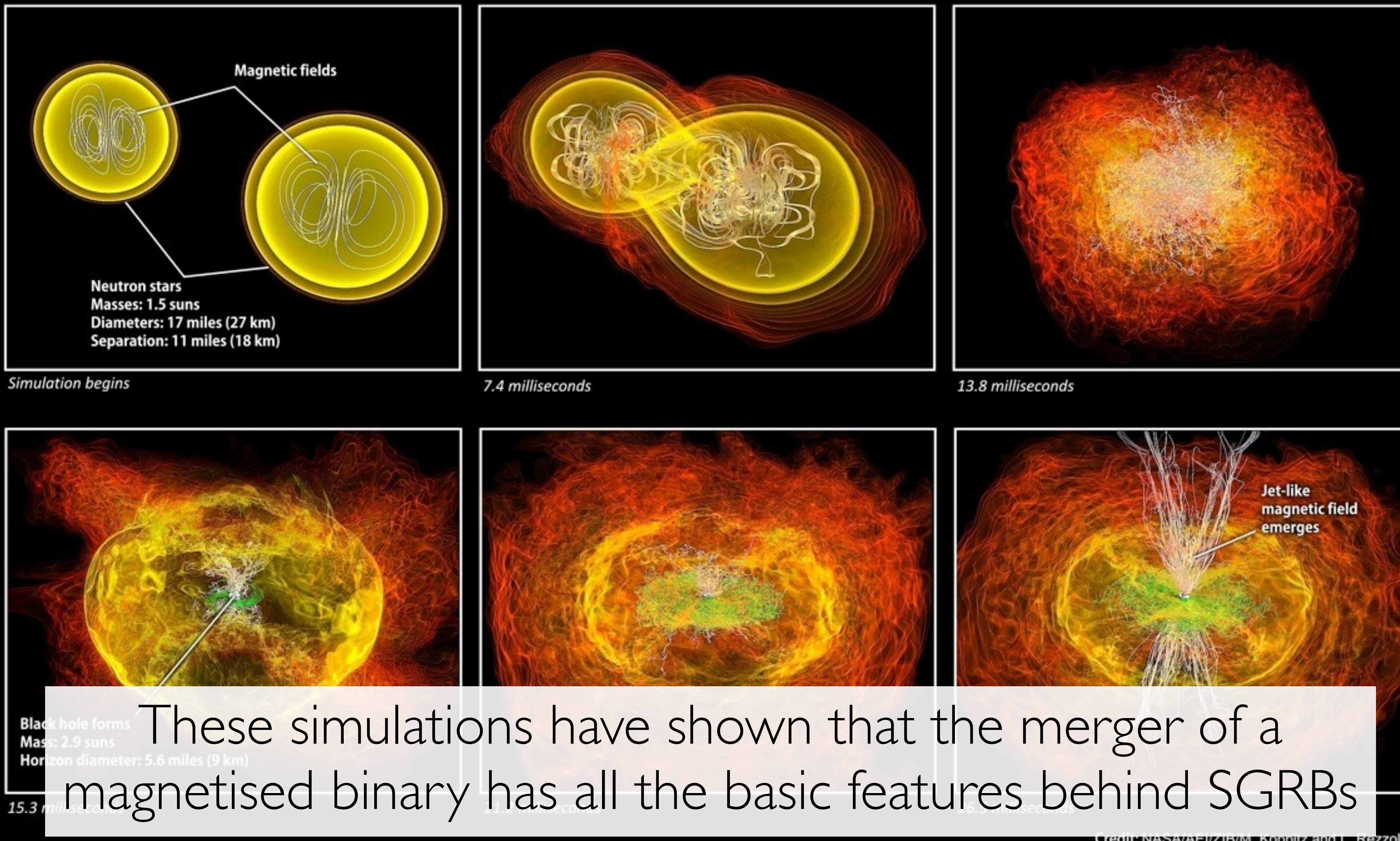


Magnetic fields in the HMNS have complex topology: dipolar fields are destroyed.



9
11.75
14.5
lg(rho) [g/cm3]
9.5
12
14.5
lg(|B|) [Gauss]

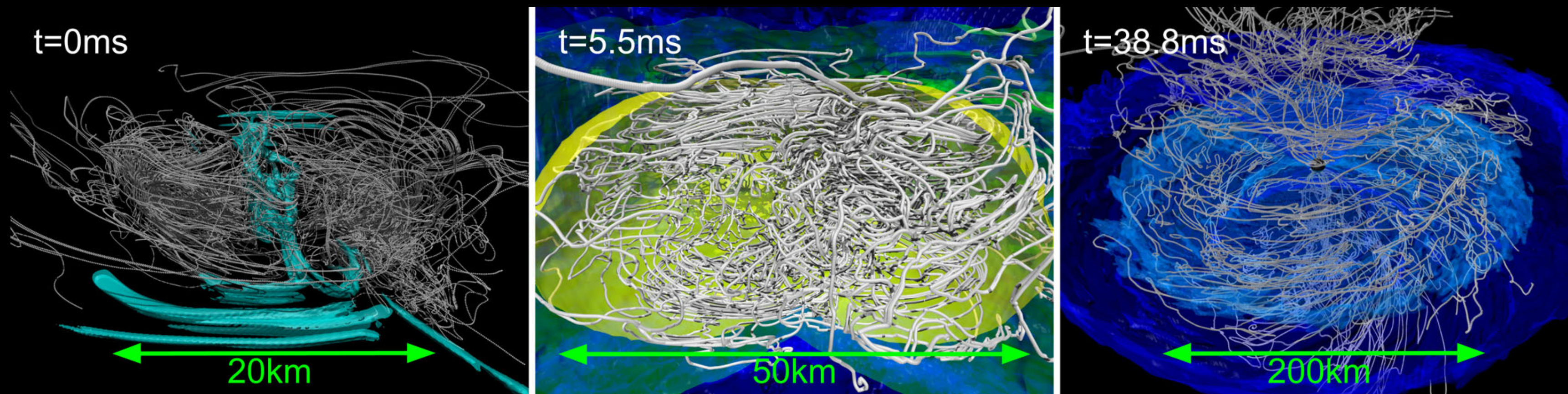
LR+ 2011



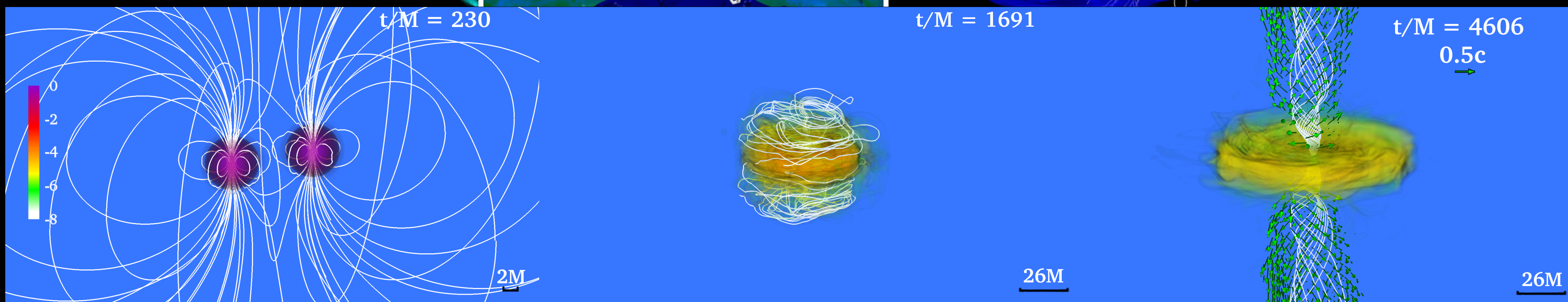
These simulations have shown that the merger of a magnetised binary has all the basic features behind SGRBs

$J/M^2 = 0.83$ $\quad$ $\mathrm{M_{tor}} = 0.063 M_\odot$ $\quad$ $\mathrm{t_{accr}} \simeq M_{\mathrm{tor}}/\dot{M} \simeq 0.3\ \mathrm{s}$

With due differences, other groups confirm this picture



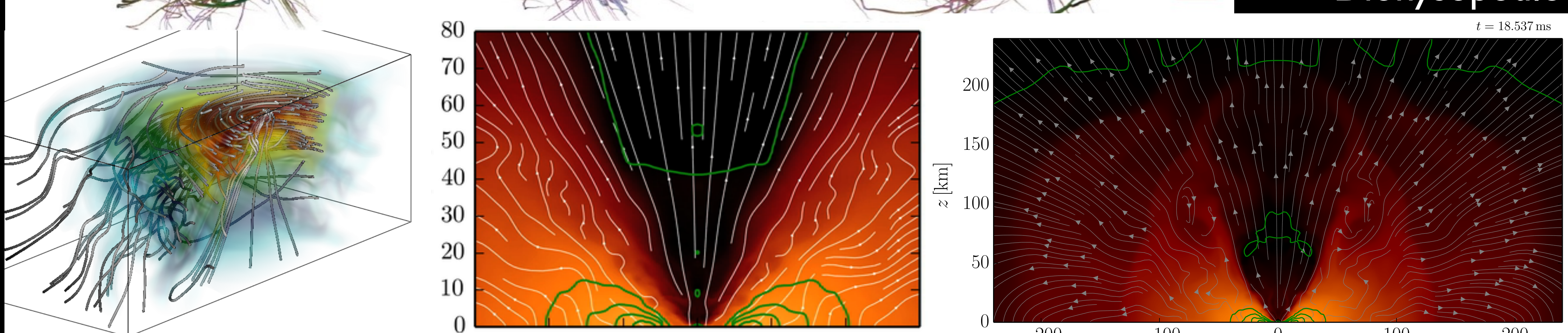
Kiuchi+ 2014



Ruiz+ 2016

Kawamura+2016

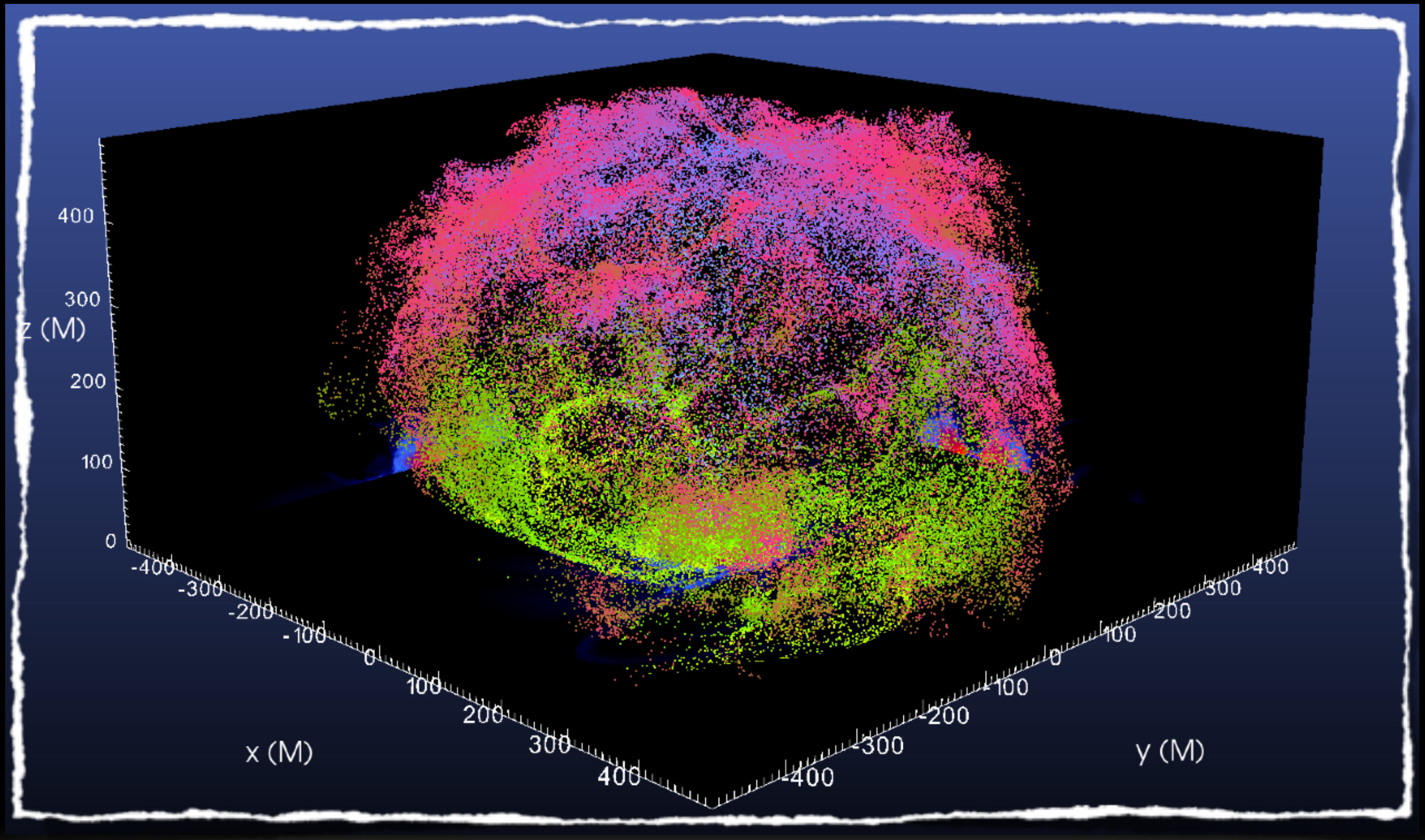
Dionysopoulou+ 2015



RMHD

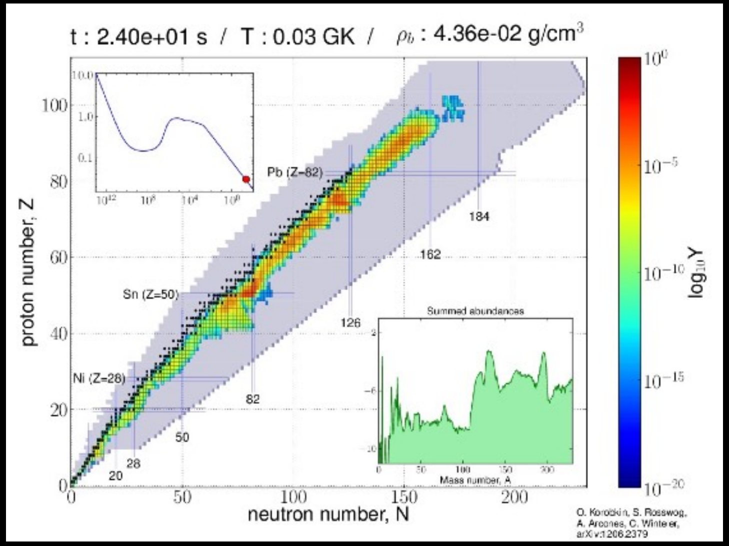
Ejected matter and nucleosynthesis

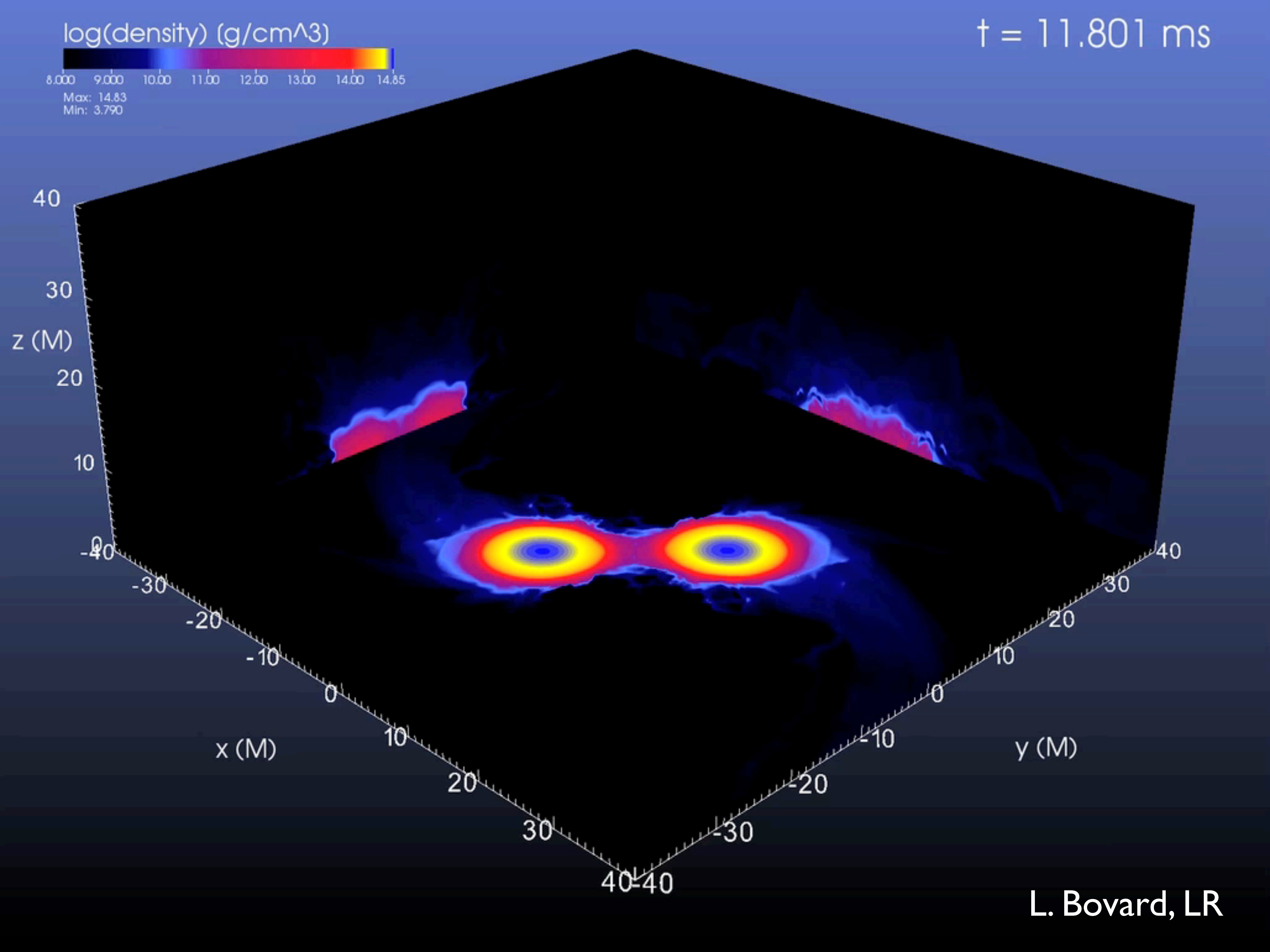
Bovard+ (2017)



Nucleosynthesis

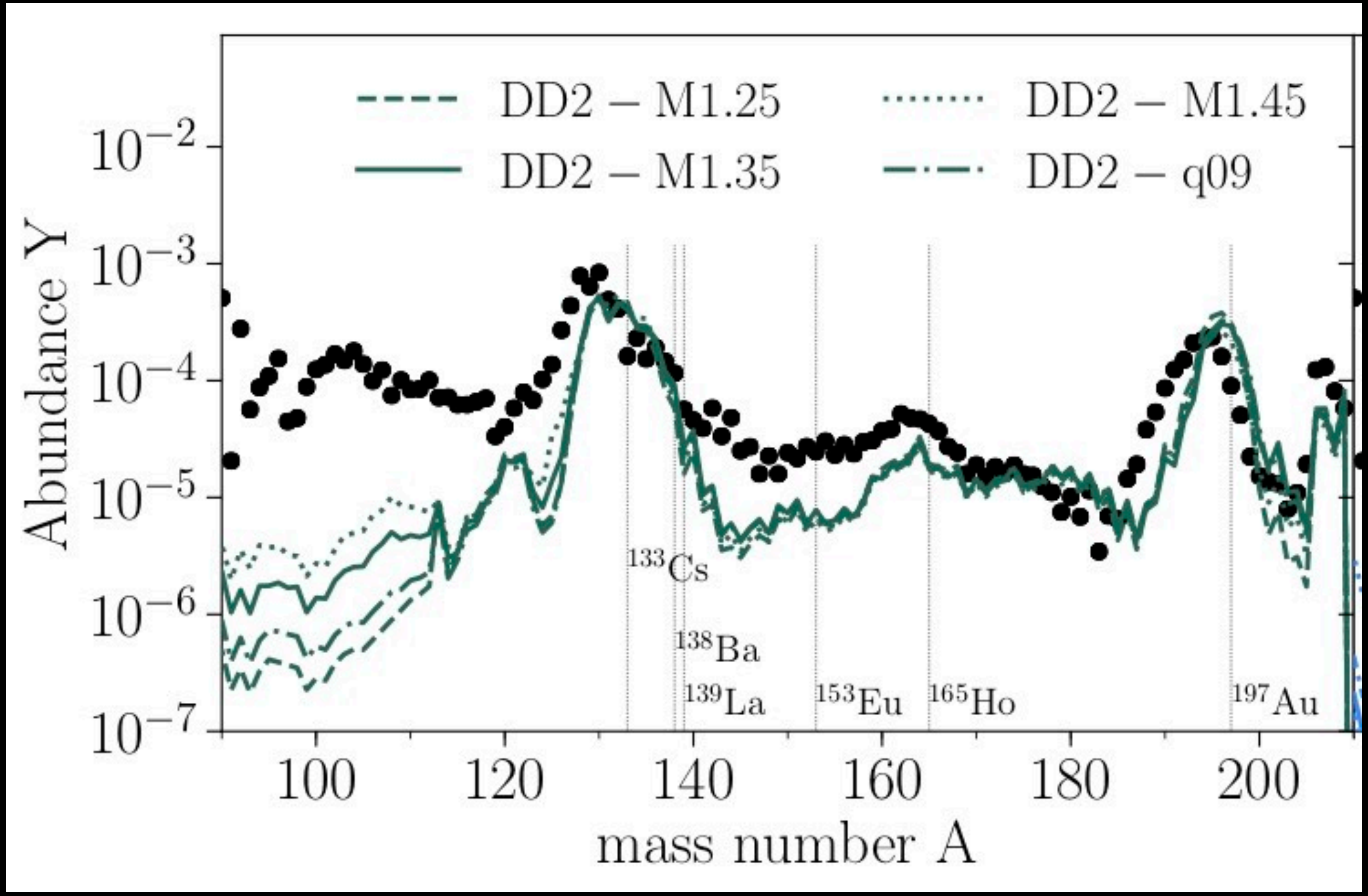
- Already in the 50's, nuclear physicists had tracked the production of elements in stars via nuclear fusion.
- **Heavy elements** ($A>56$) cannot be produced in stellar interiors but can be synthesised during a **supernova.**
- SN simulations have shown that temperatures/energies not enough to produce **"very heavy" elements** ($A>120$).
- To produce such elements very high temperatures and **"neutron-rich"** material is needed.
- **Neutron-star mergers** seem perfect candidates for this process!




log(density) (g/cm^3)
8.000 9.000 10.00 11.00 12.00 13.00 14.00 14.85
Max: 14.83
Min: 3.790
t = 11.801 ms
z (M)
x (M)
y (M)
L. Bovard, LR

Relative abundances

- Mass ejection can either be **dynamical** (shocks; 100 ms) or **secular** (magnetic or neutrino-driven winds; 1-10 s).
- Even **tiny amounts** of ejected matter (*0.01 $M_\odot$*) sufficient to explain observed abundances.
- Abundances for ***A>120*** good agreement with solar. **robust** for different **EOSs, masses, nuclear reactions and merger type**



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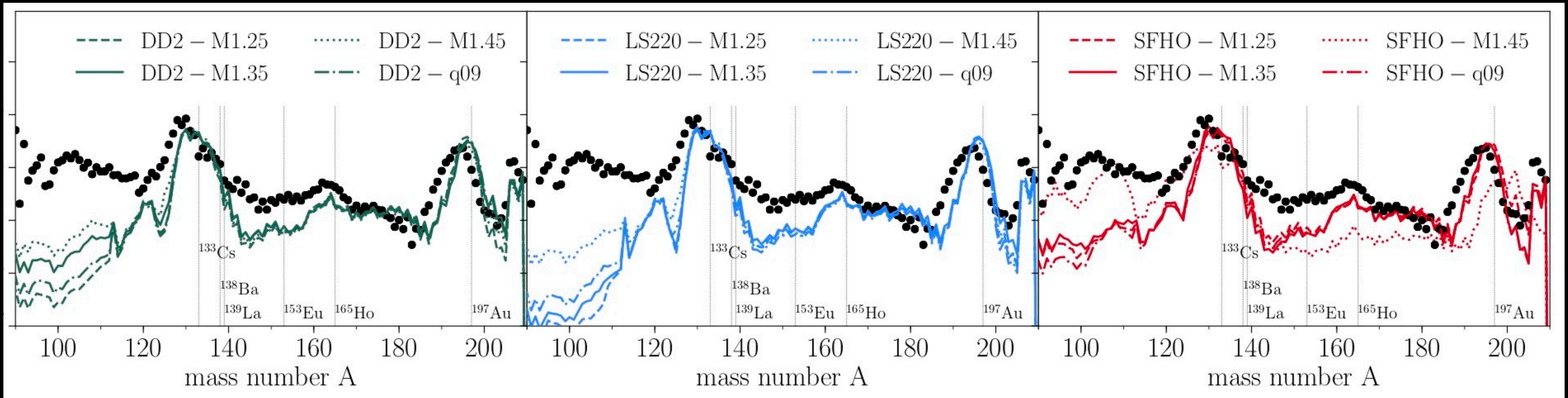

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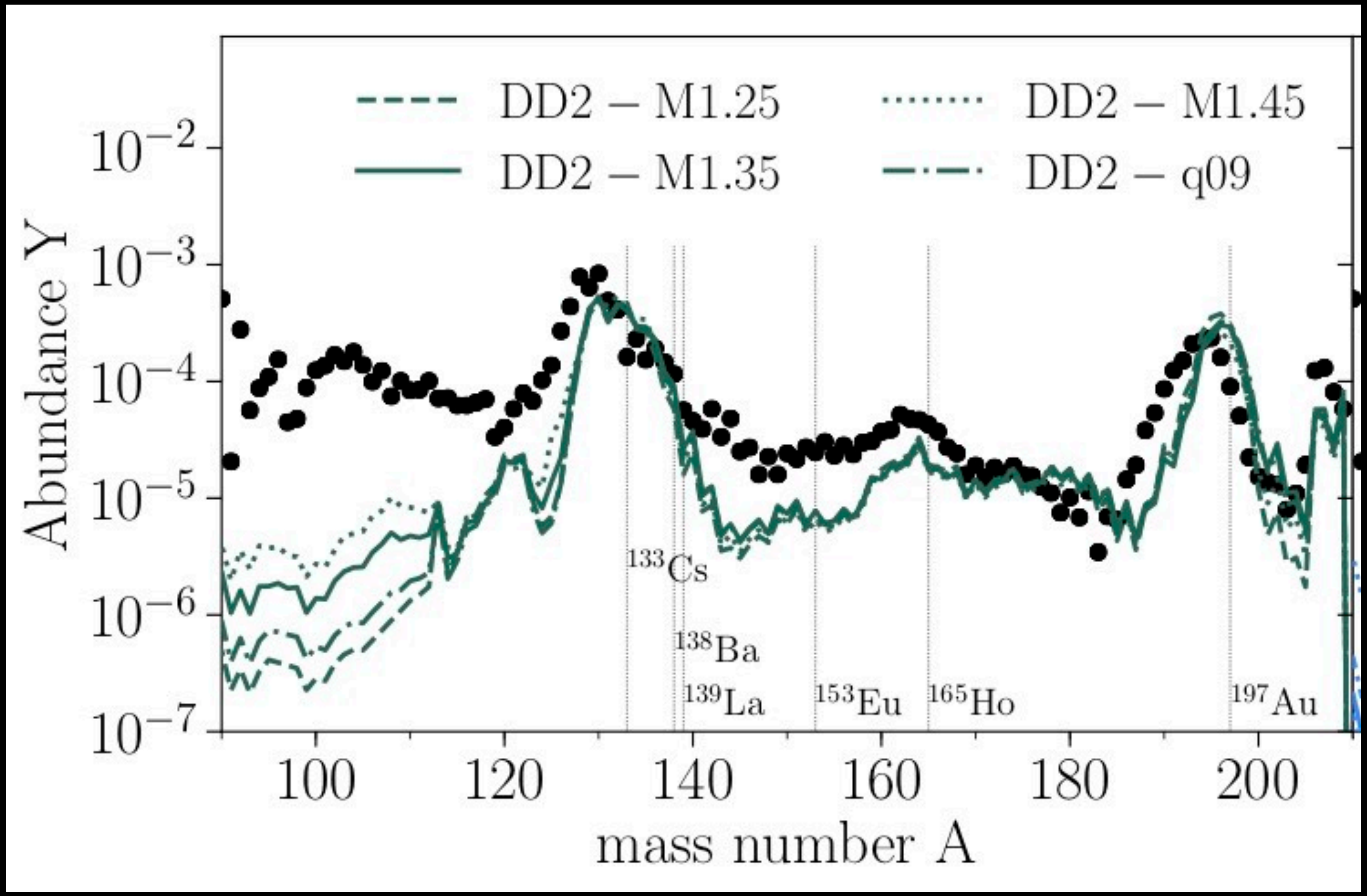


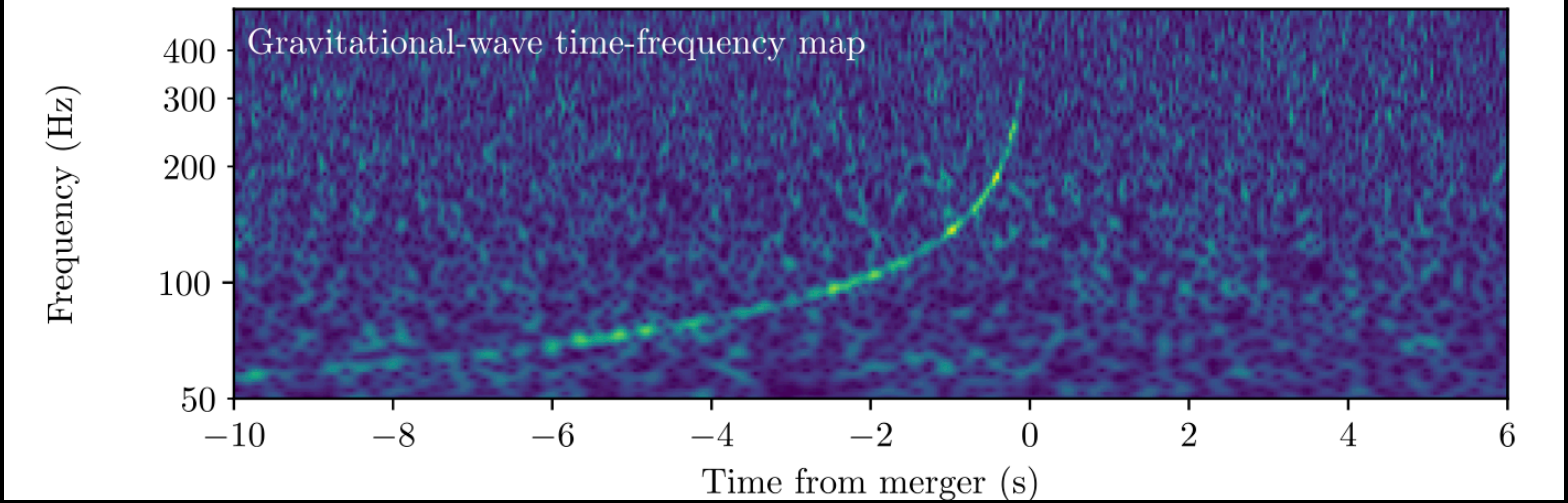
- GW170817 produced total of **16,000** times the mass of the Earth in heavy elements (**10** Earth masses in **gold/platinum**)
- We are not only **stellar dust** but also **neutron-star dust!**

GW170817, maximum mass, radii and tidal deformabilities

LR, Most, Weih, ApJL (2018)

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

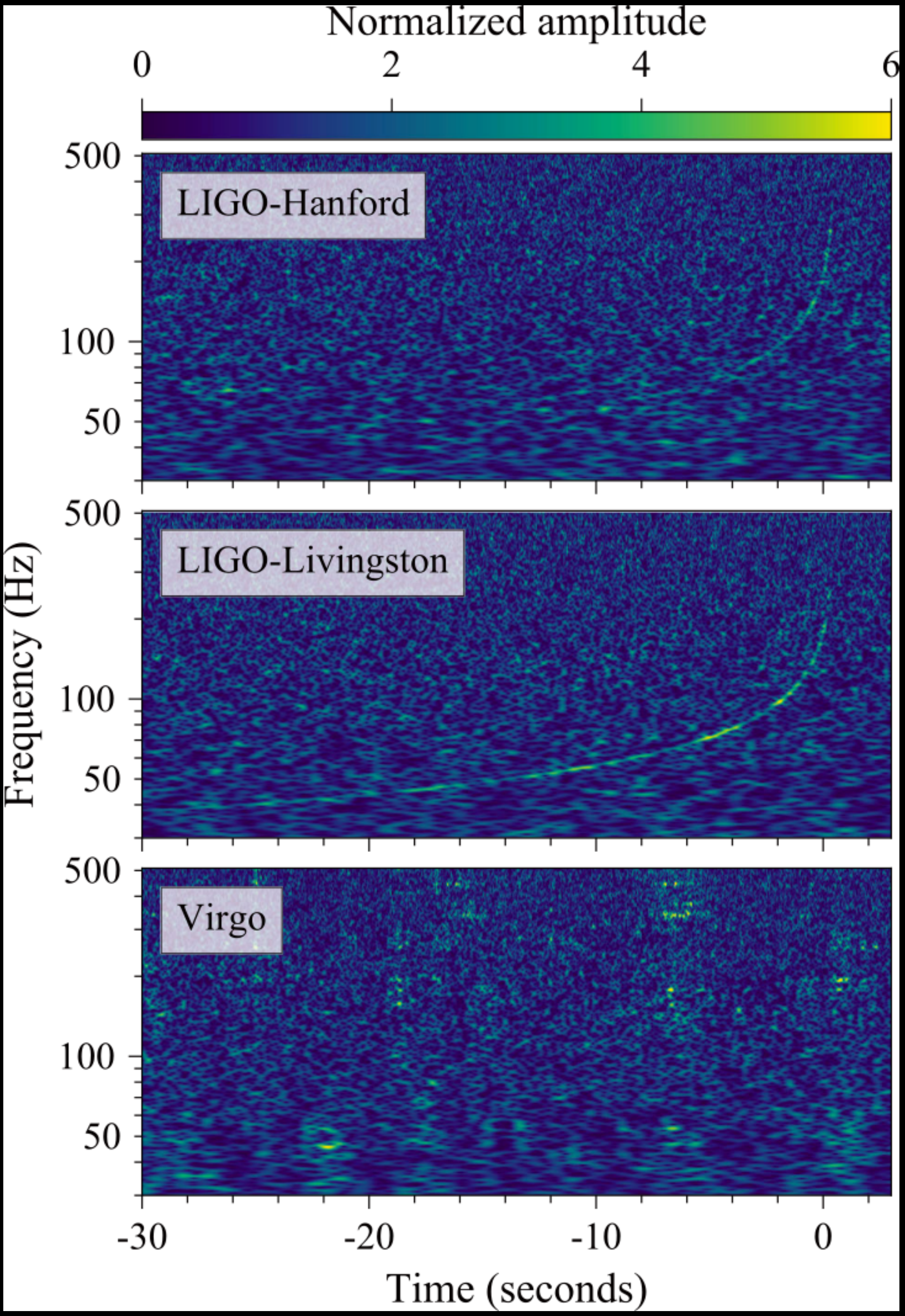
Köppel, Bovard, LR, ApJL (2018)



GW170817: the first binary neutron-star system

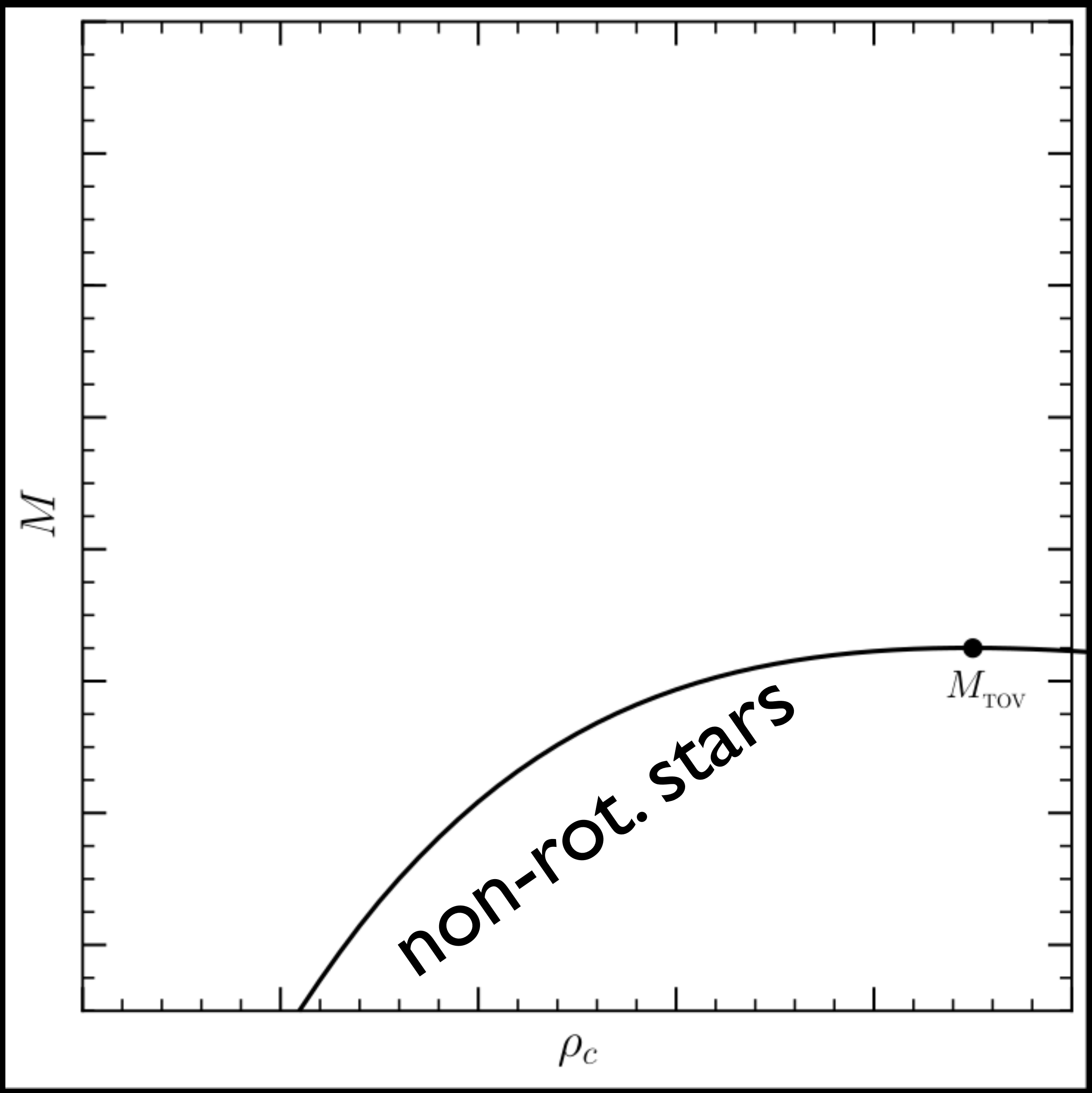
- **Unfortunately** only the **inspiral** signal was detected.

- **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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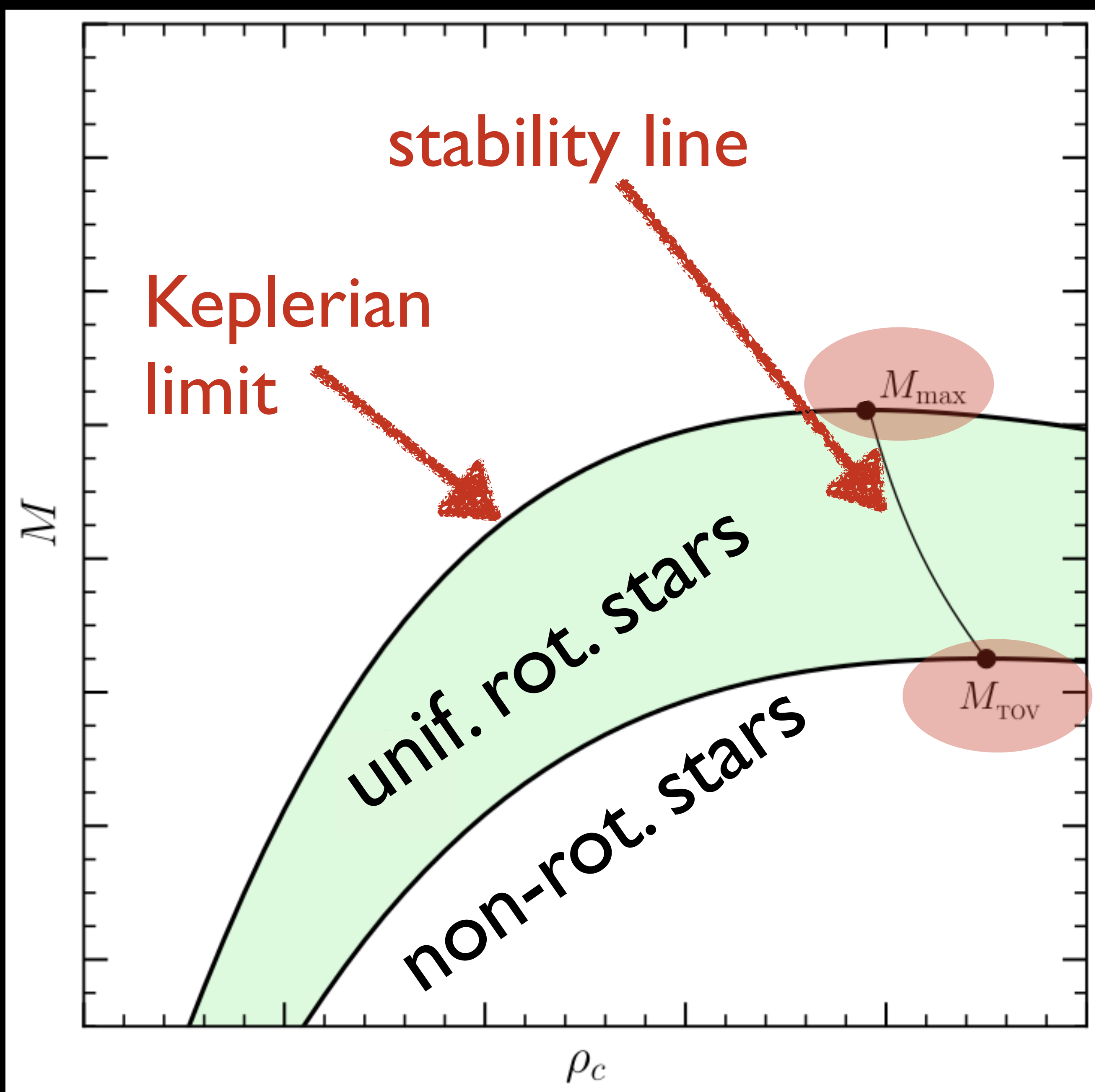

- Sequences of equilibrium models of **nonrotating** stars will have a maximum mass: $M_{\rm TOV}$
- This is true also for **uniformly** rotating stars at mass shedding limit: $M_{\rm max}$
- $M_{\rm max}$ simple and **quasi-universal** function of $M_{\rm TOV}$ (Breu & LR 2016)

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

Limits on the maximum mass

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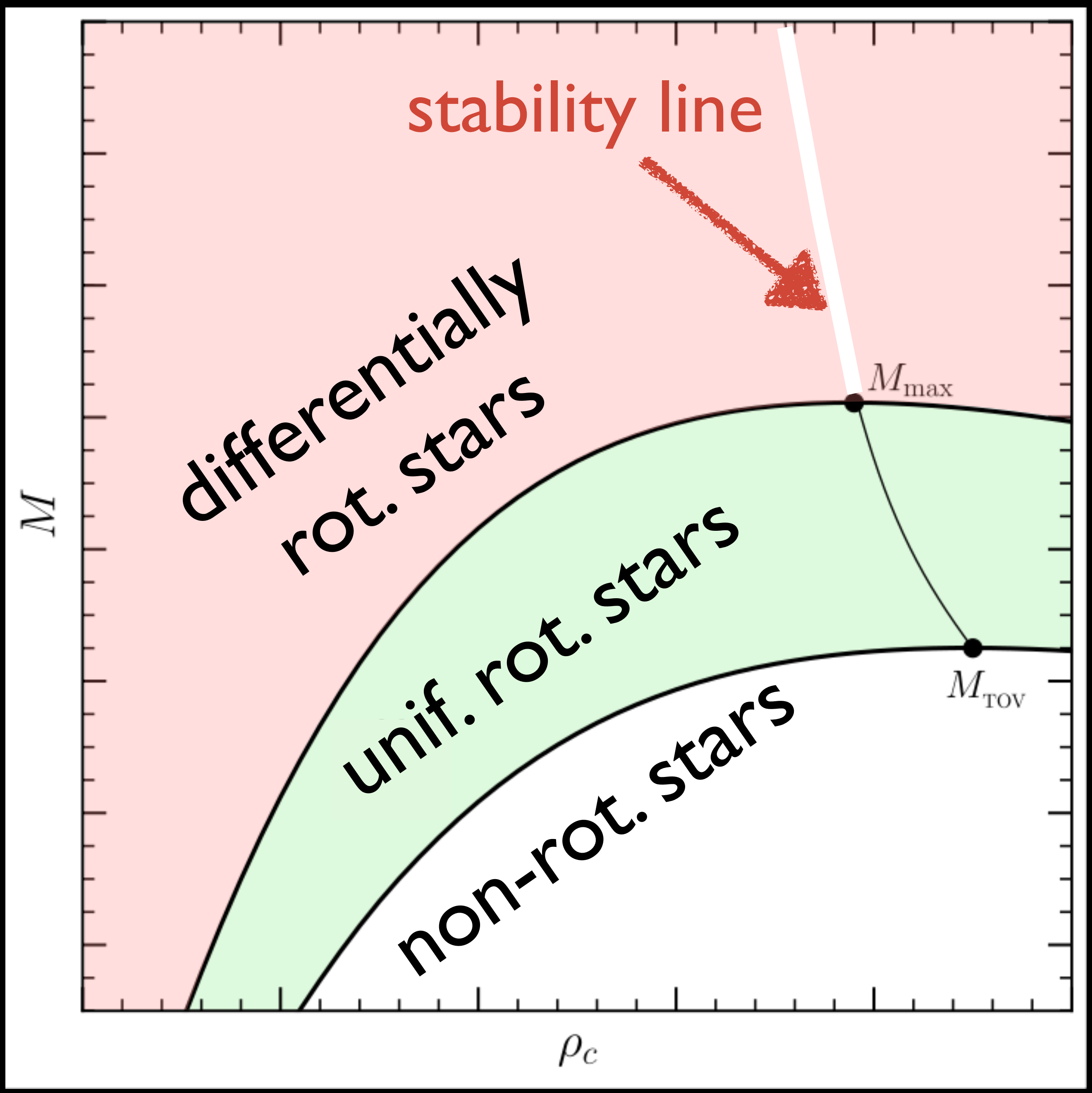
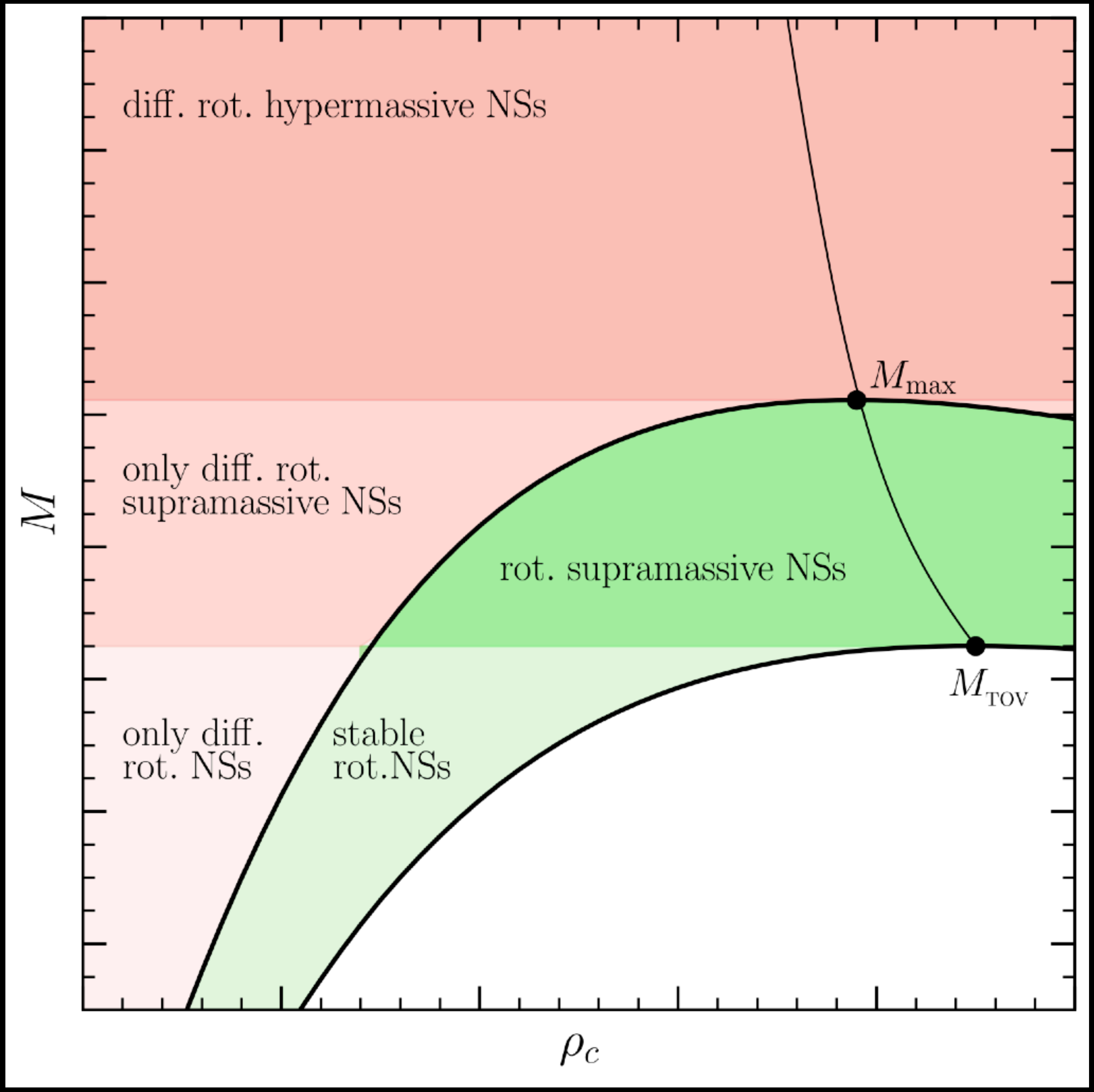


- **Green** region is for **uniformly** rotating equilibrium models.
- **Salmon** region is for **differentially** rotating equilibrium models.
- **Stability line** is simply extended in larger space (Weih+18)

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:

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

Limits on the maximum mass

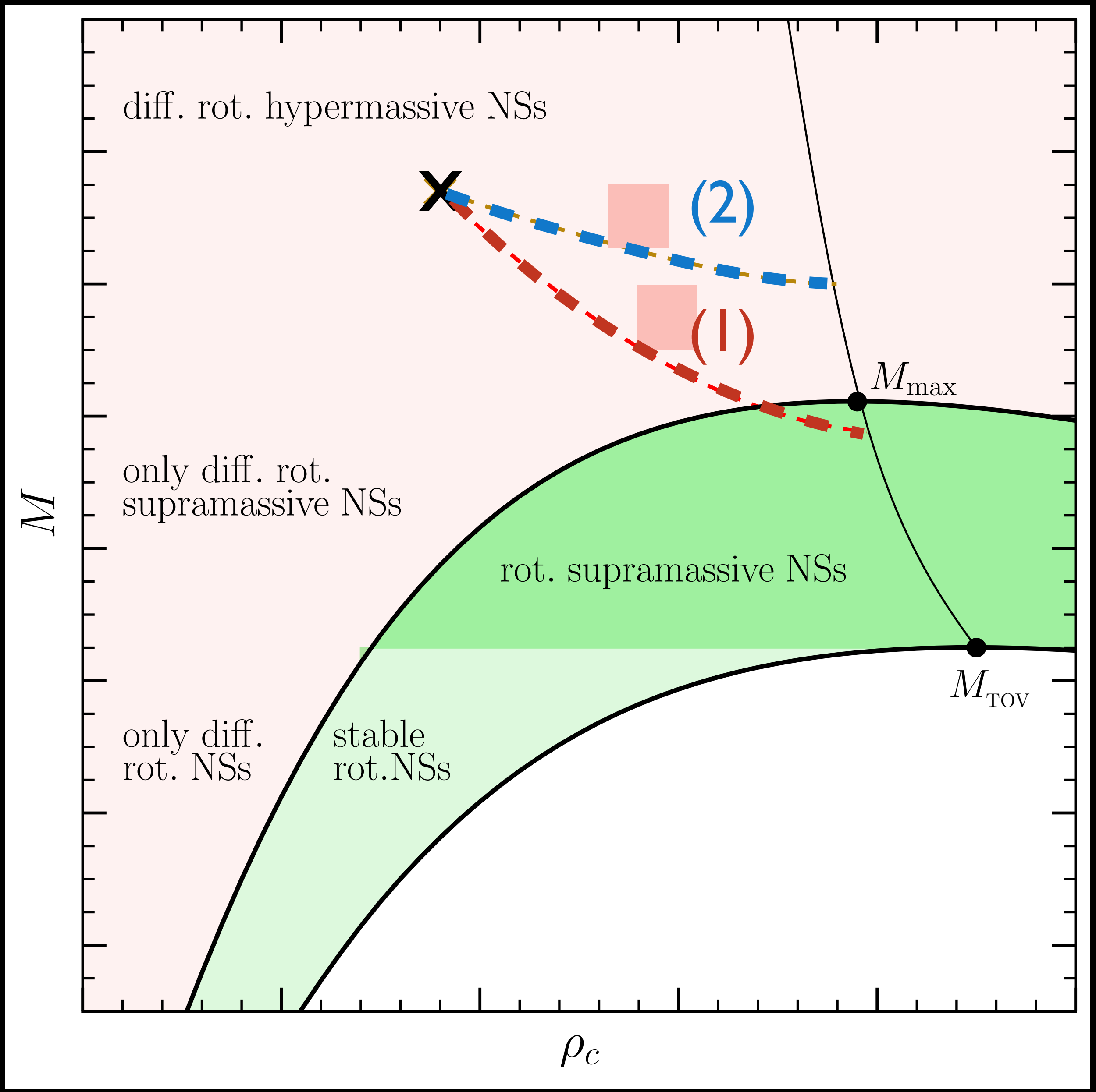
- GW170817 produced object **"X"**; GRB implies a BH has been formed: **"X"** followed two possible tracks: **fast (2)** and **slow (1)**

- 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!



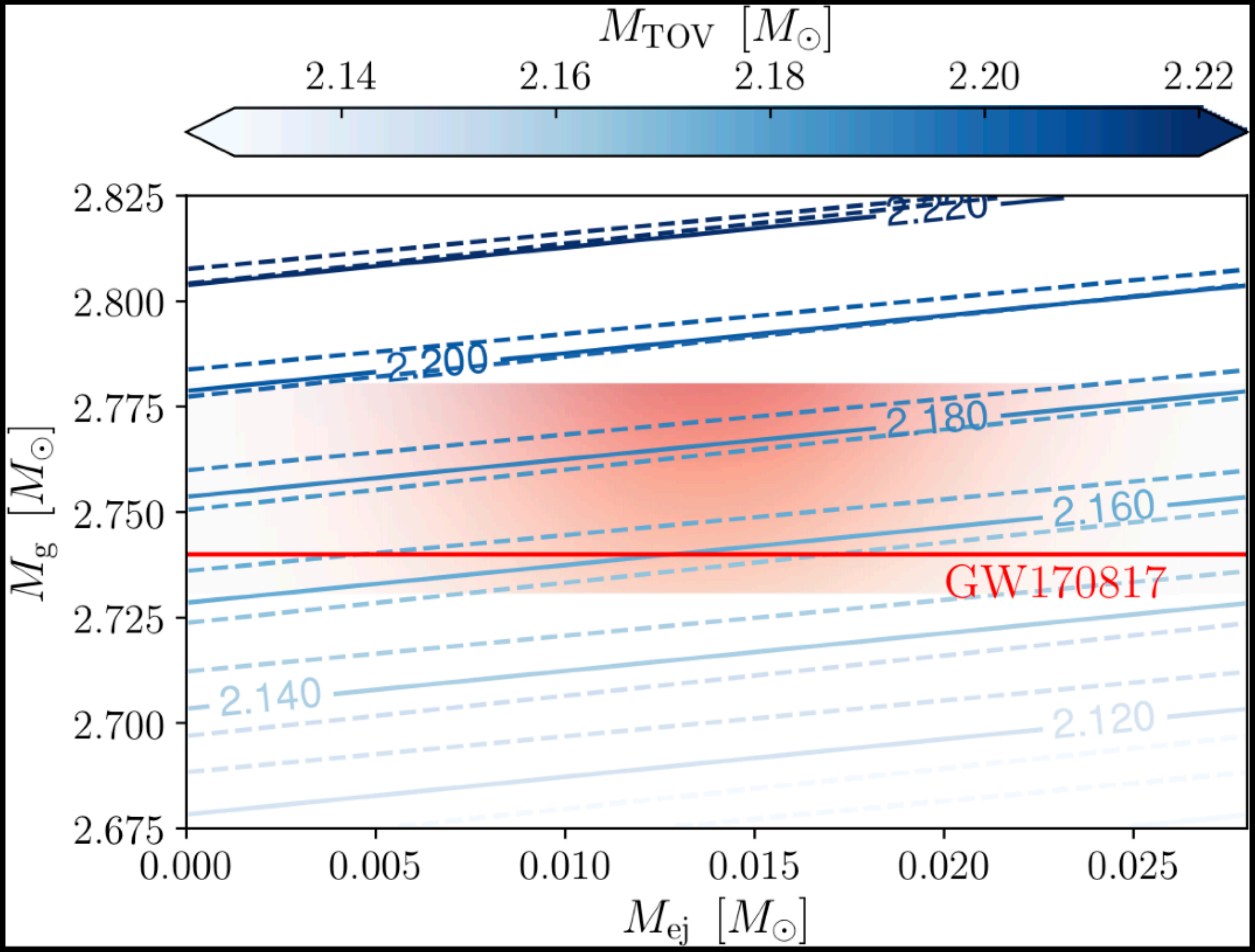
let's recap…

- 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 for errors to obtain



pulsar timing

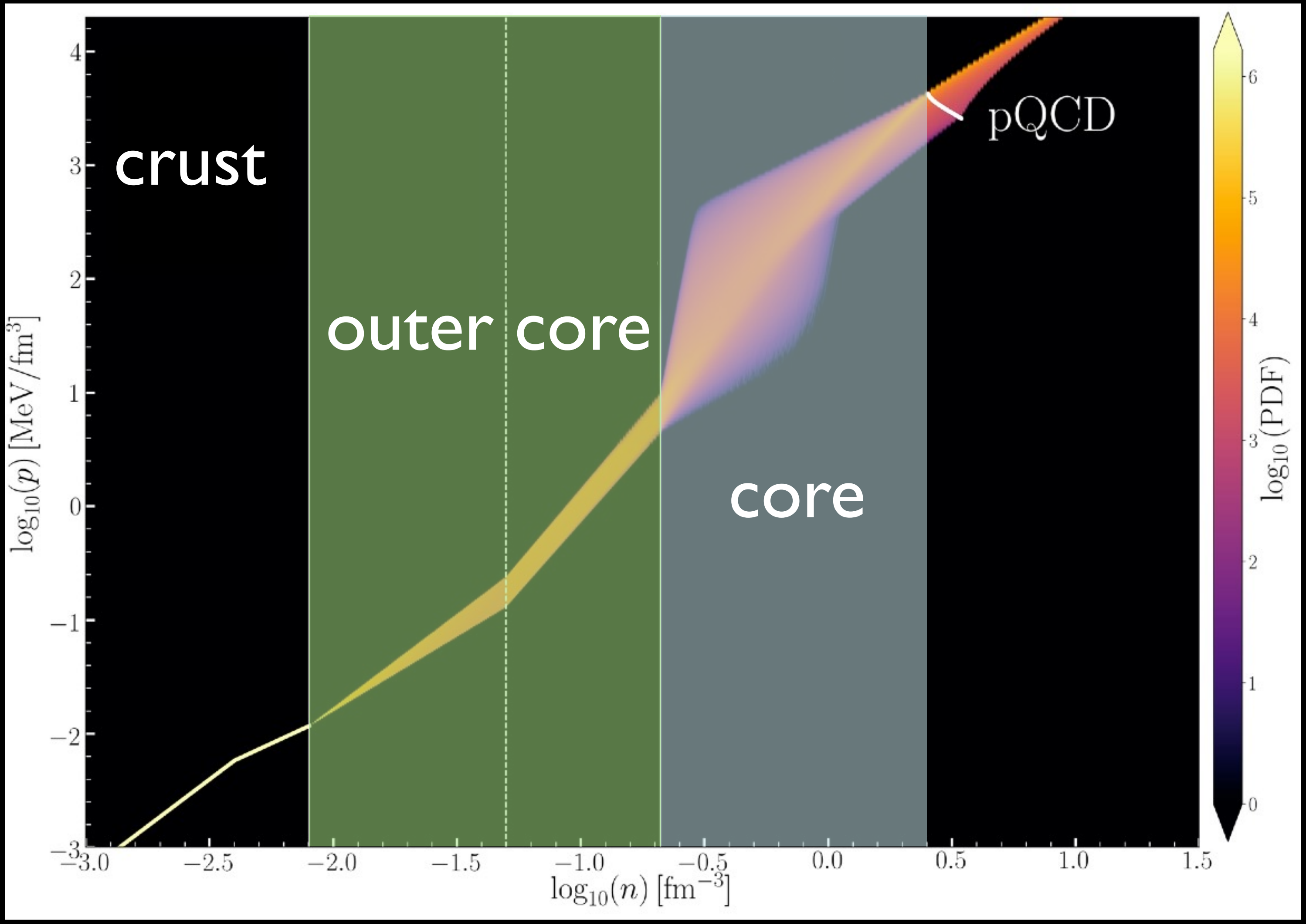
$$2.01^{+0.04}_{-0.04} \leq M_{\rm TOV}/M_\odot \leq 2.16^{+0.17}_{-0.15}$$

universal relations and GW170817; similar estimates by other groups

Limits on radii and deformabilities

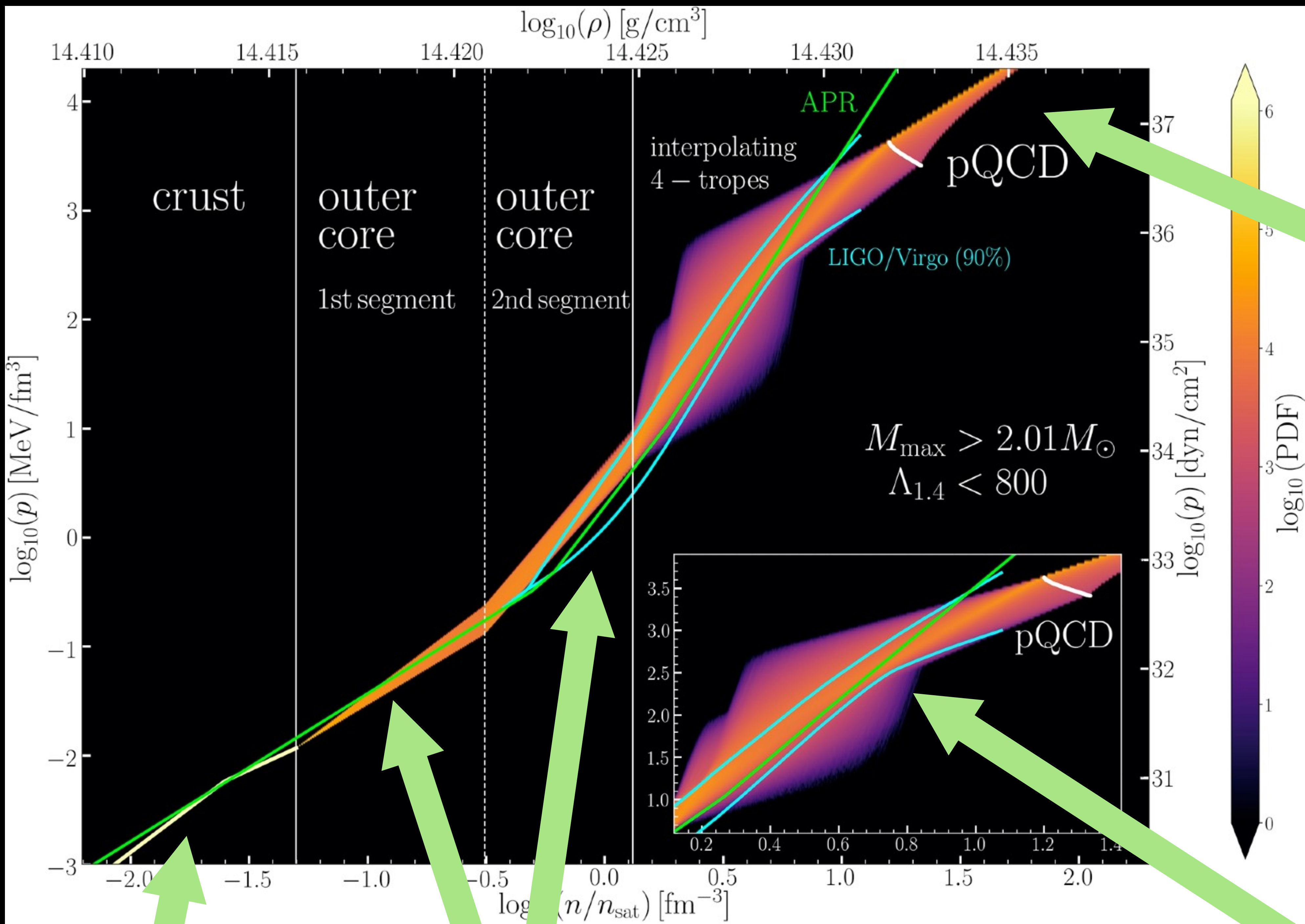
- Can new constraints be set on typical radius and tidal deformability by using GW170817?

- **Ignorance** can be parameterised and EOSs can be built arbitrarily as long as they satisfy specific **constraints** on **low** and **high** densities.



parametrising our ignorance

- Construct most generic family of NS-matter EOSs



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

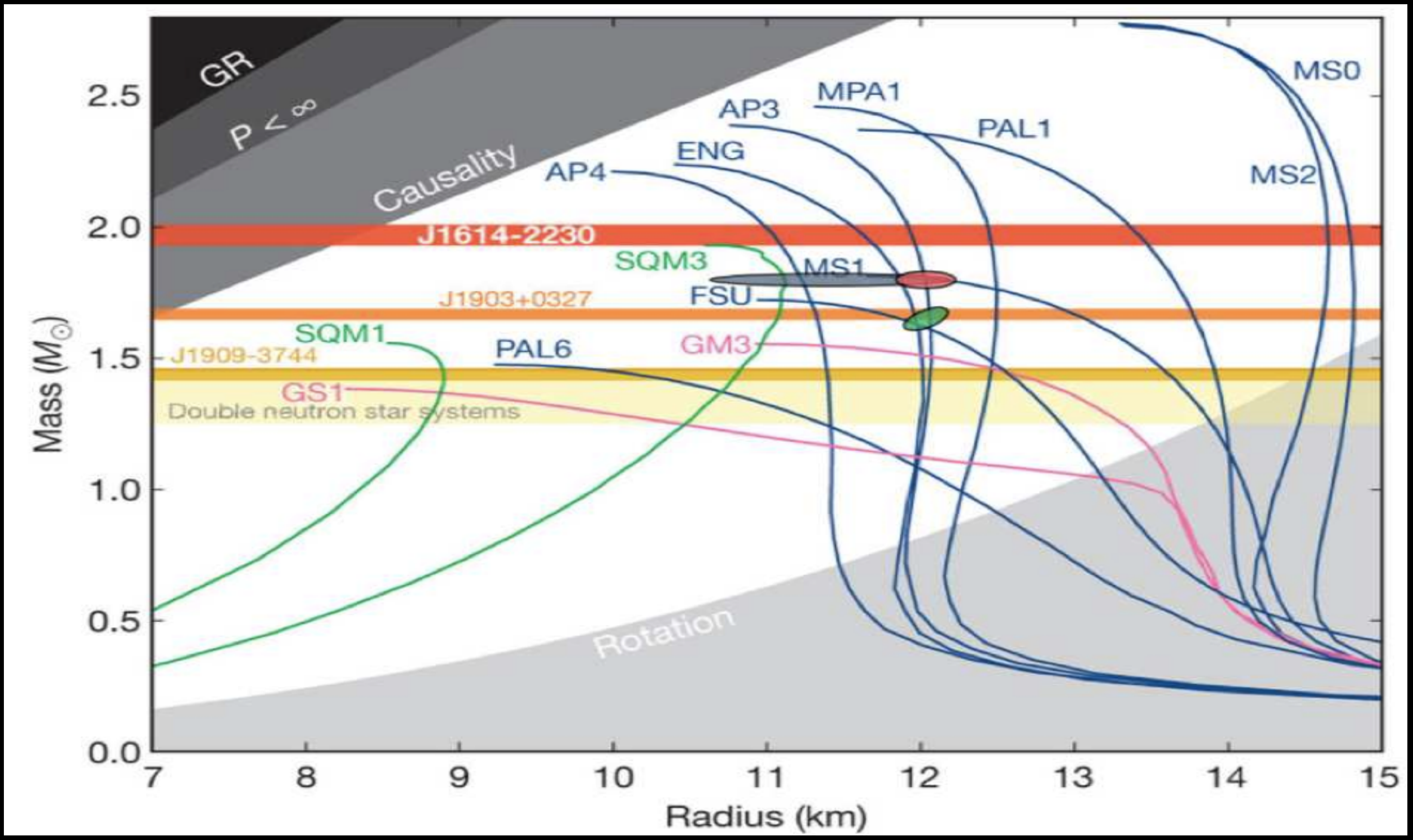
interpolation
by matching 4
polytropes

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



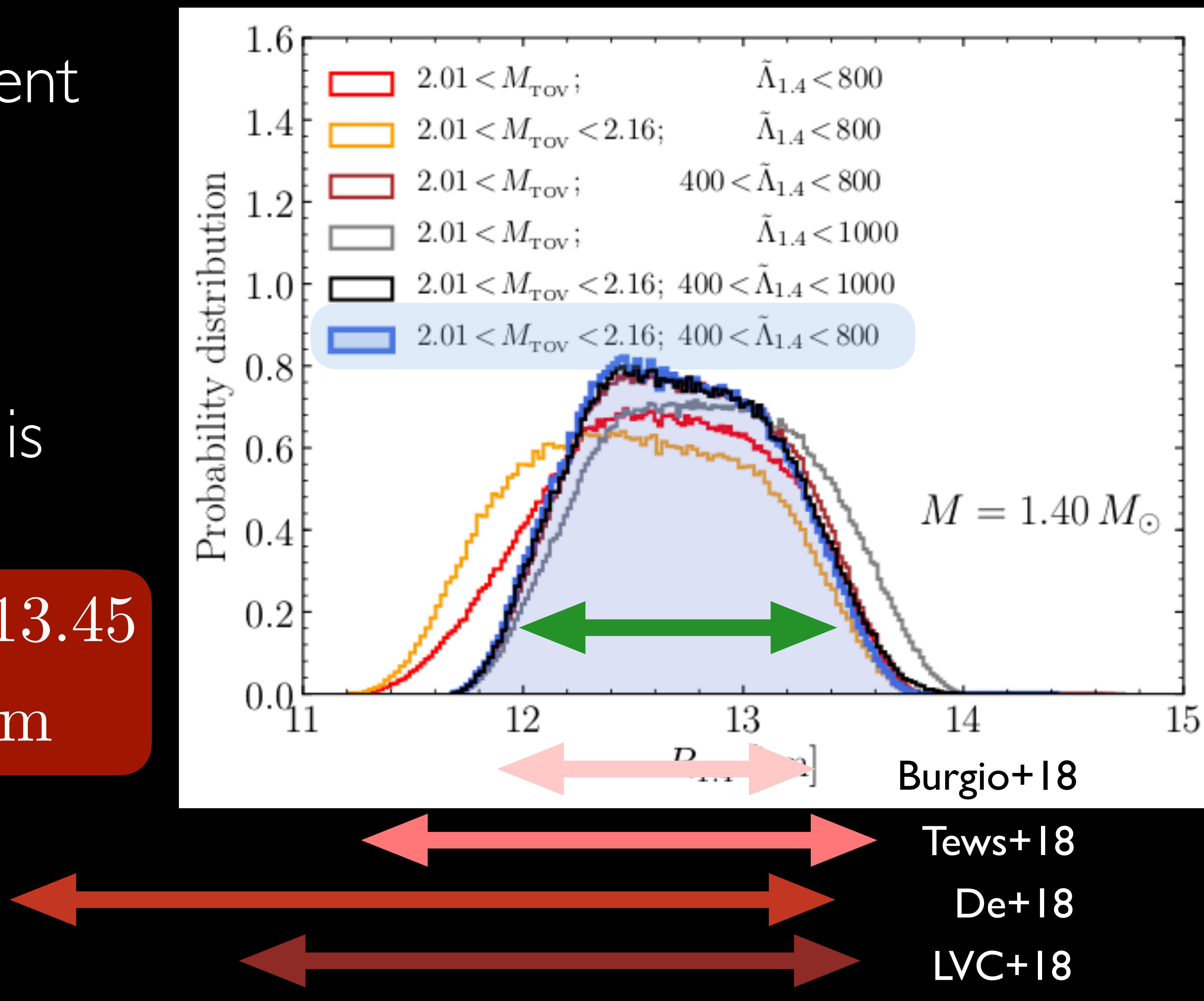
one-dimensional cuts

- Closer look at a mass of $M = 1.40\,M_\odot$

- Can play with different constraints on maximum mass and tidal deformability.

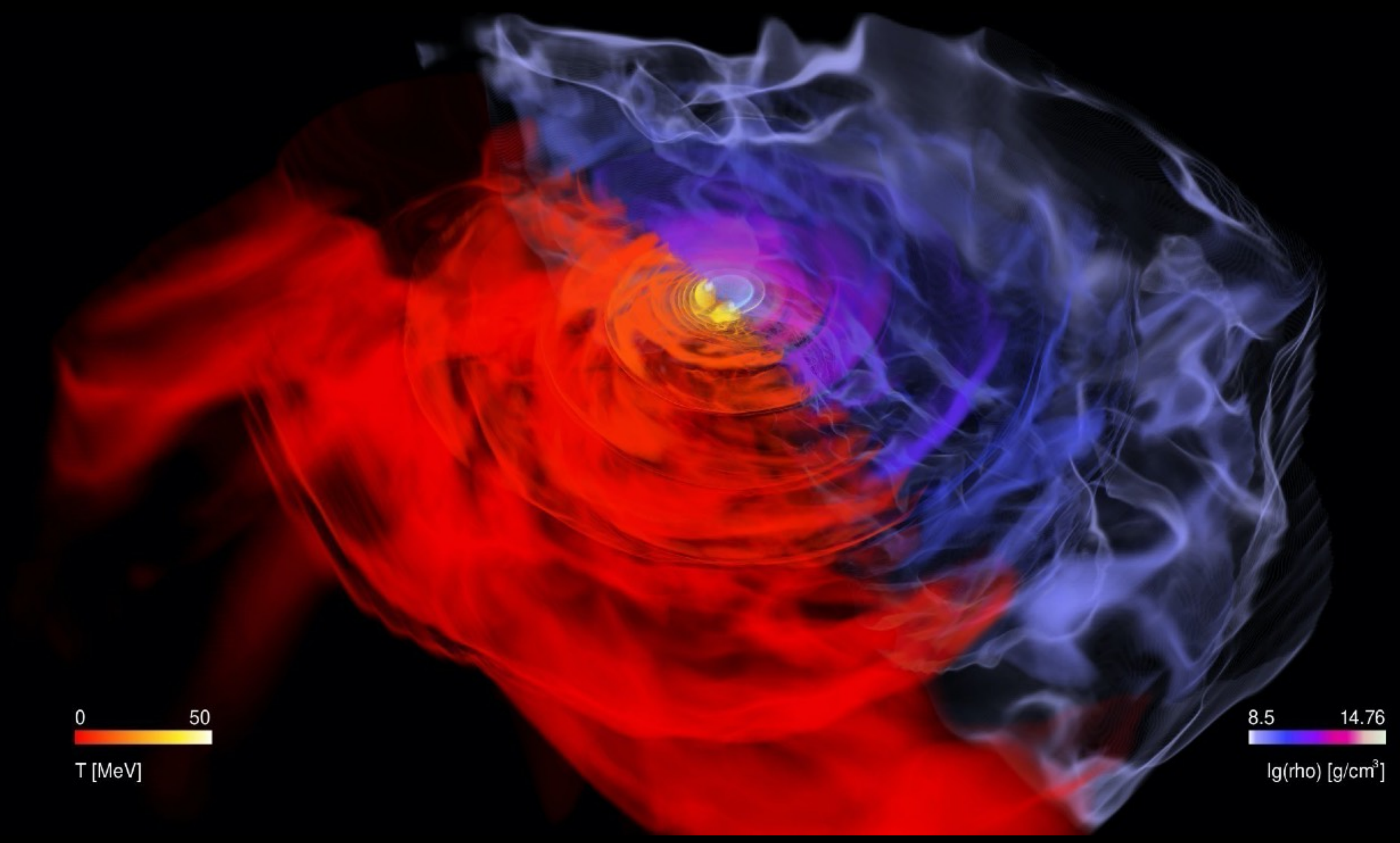
- Overall distribution is very robust

$$12.00 < R_{1.4}/\mathrm{km} < 13.45$$
$$\langle R_{1.4} \rangle = 12.45\,\mathrm{km}$$

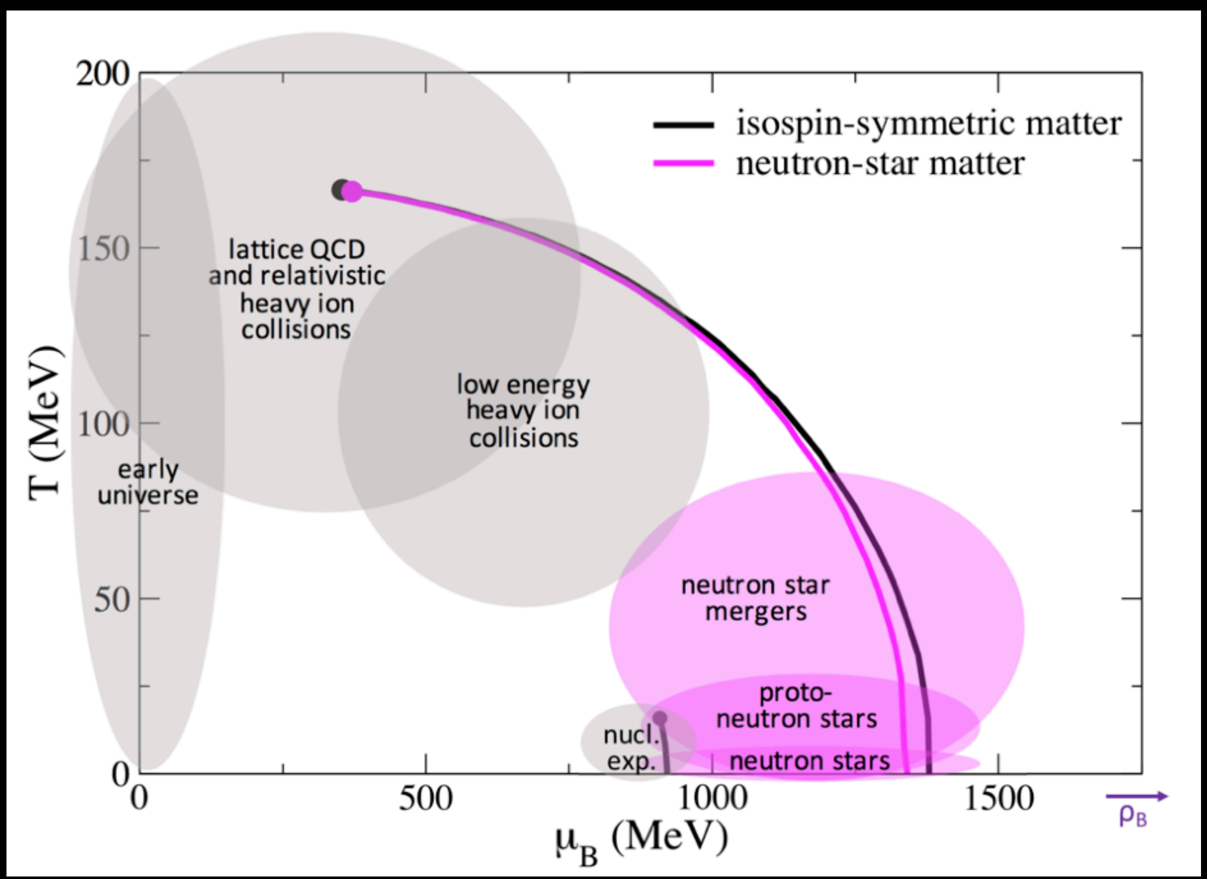


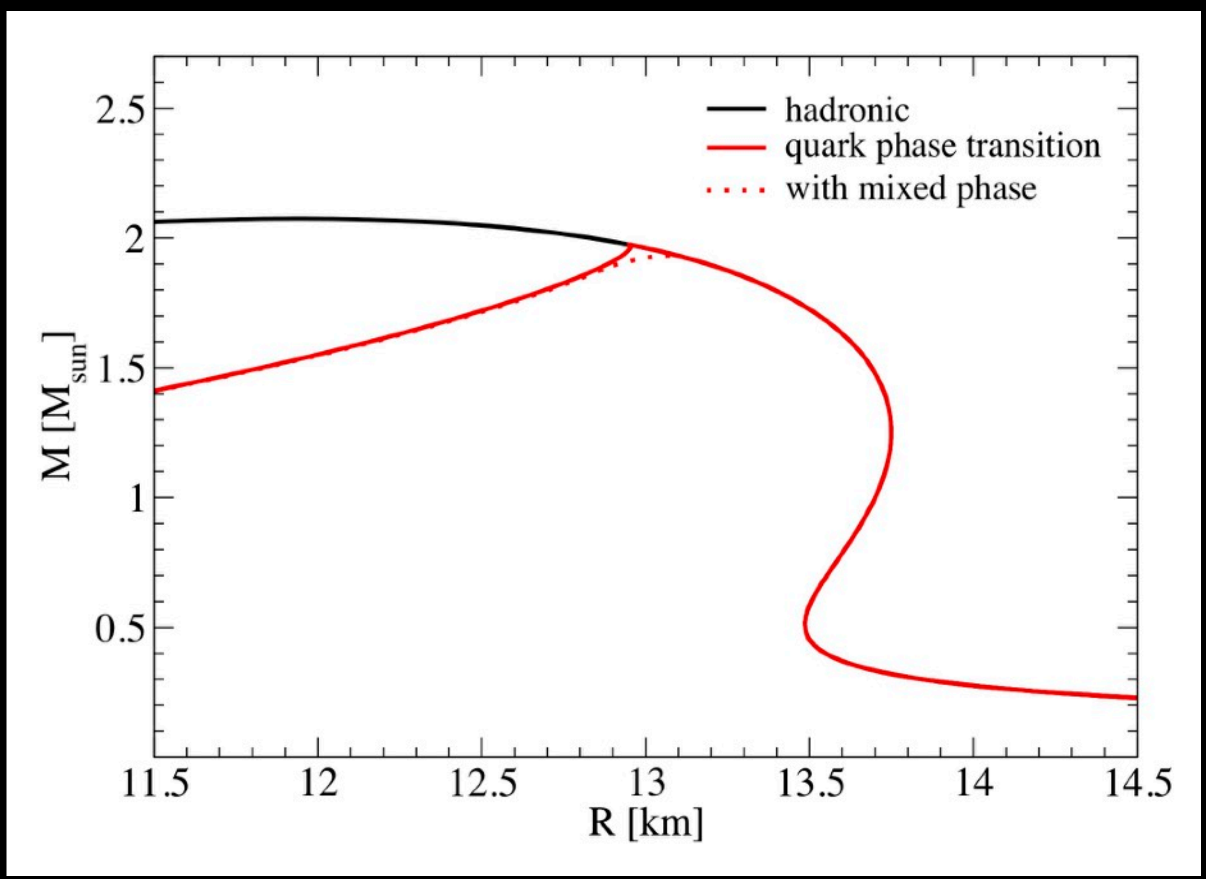
Phase transitions and their signatures

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



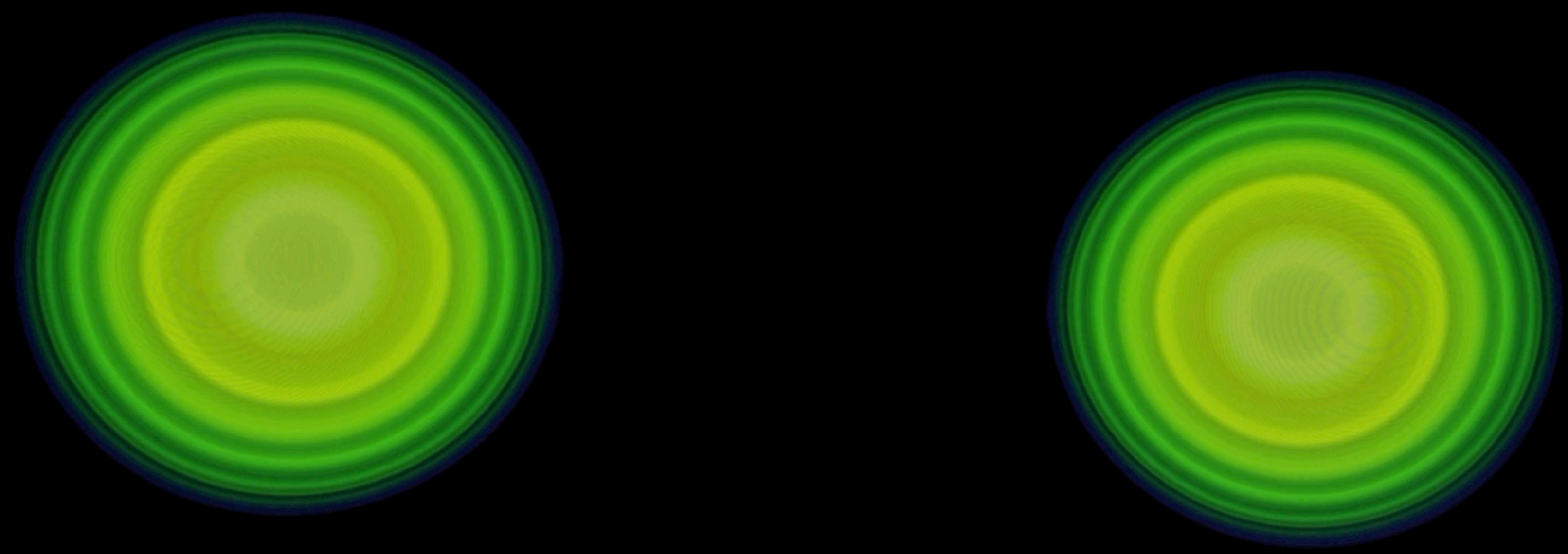
- **Isolated** neutron stars probe a small fraction of phase diagram.
- Neutron-star **binary** mergers reach temperatures up to **80 MeV** and probe regions complementary to experiments.

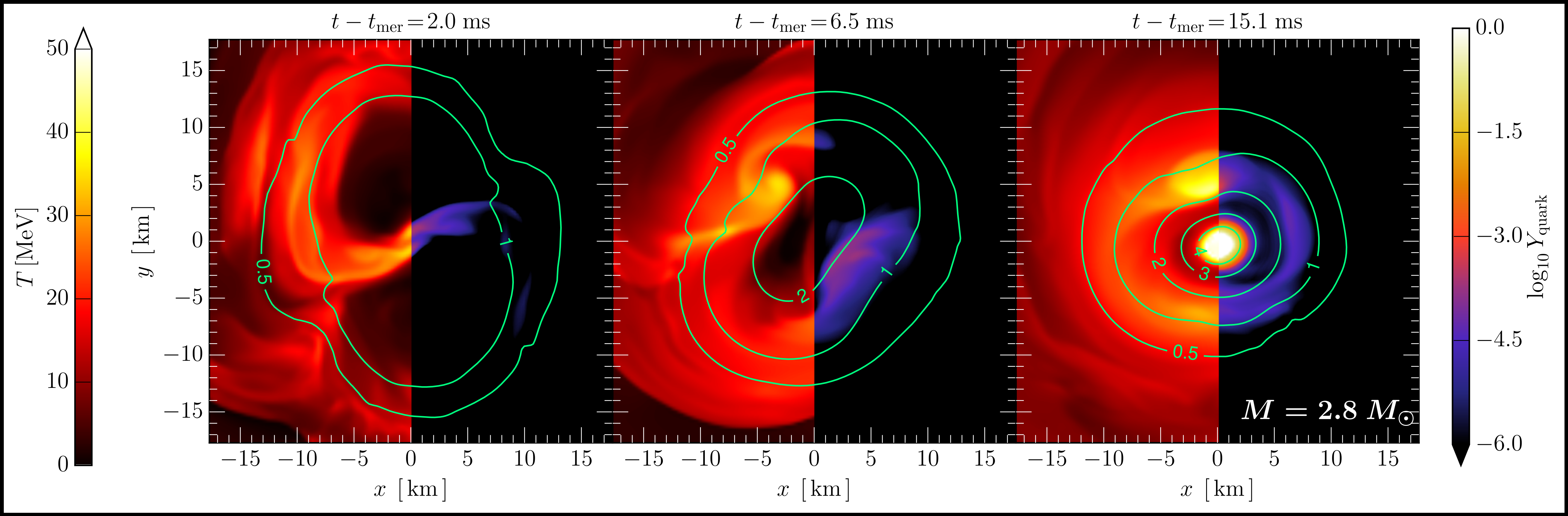




- Considered EOS based on Chiral Mean Field (CMF) model, based on a nonlinear SU(3) sigma model.
- Appearance of quarks can be introduced naturally.

Animations: Weih, Most, LR

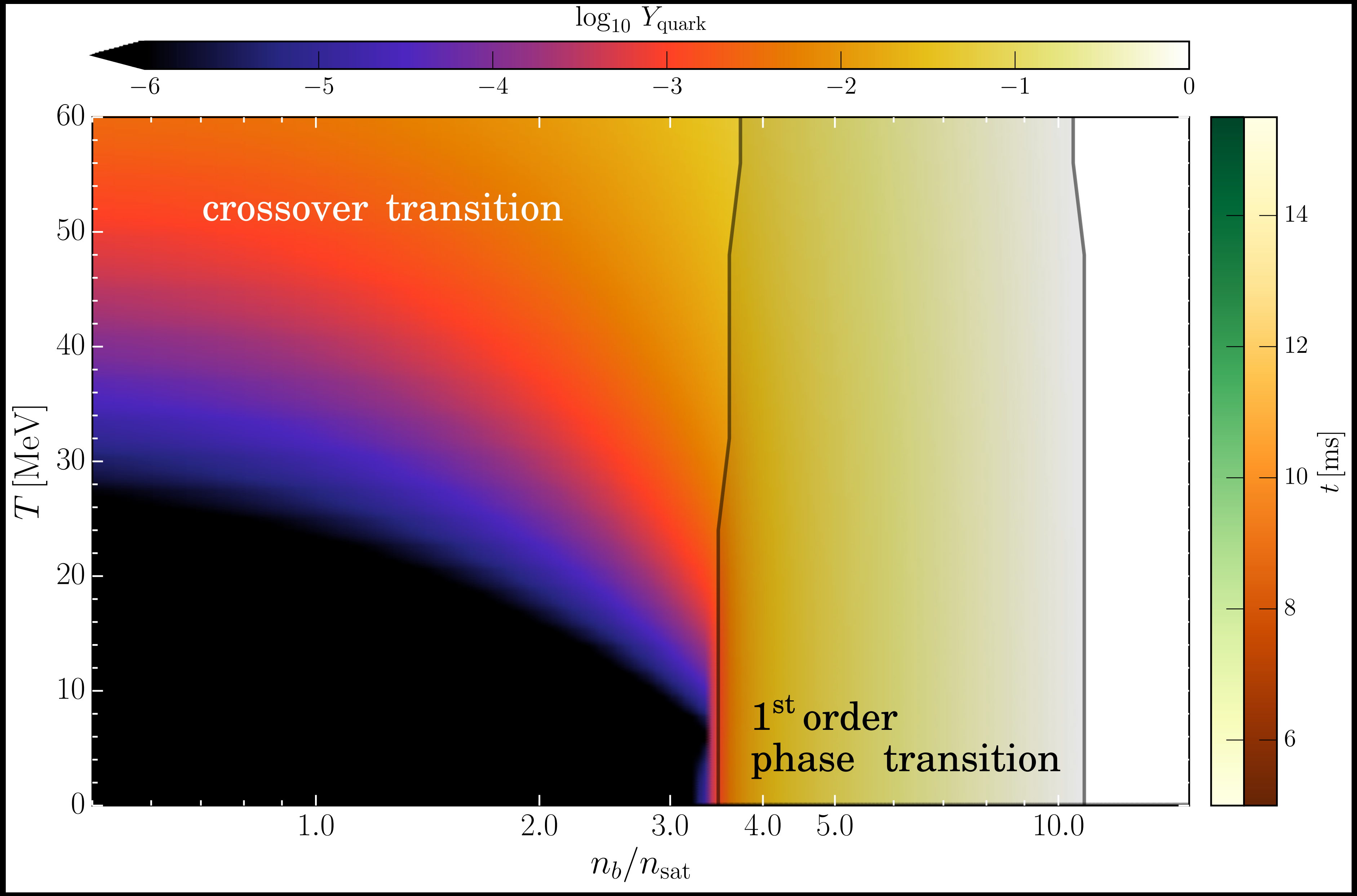




Quarks appear at sufficiently large temperatures and densities.

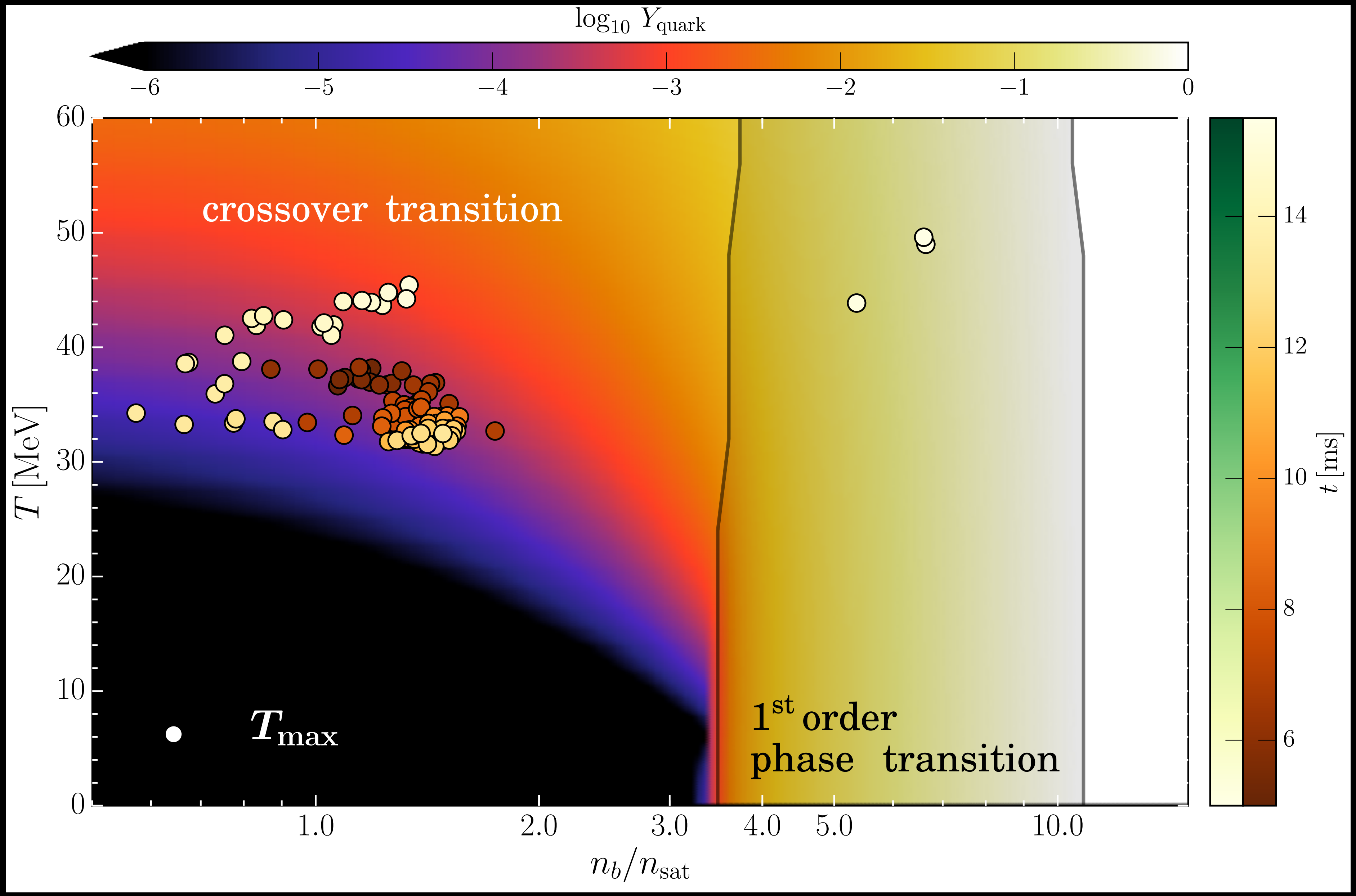
When this happens the EOS is considerably softened.

Comparing with the phase diagram



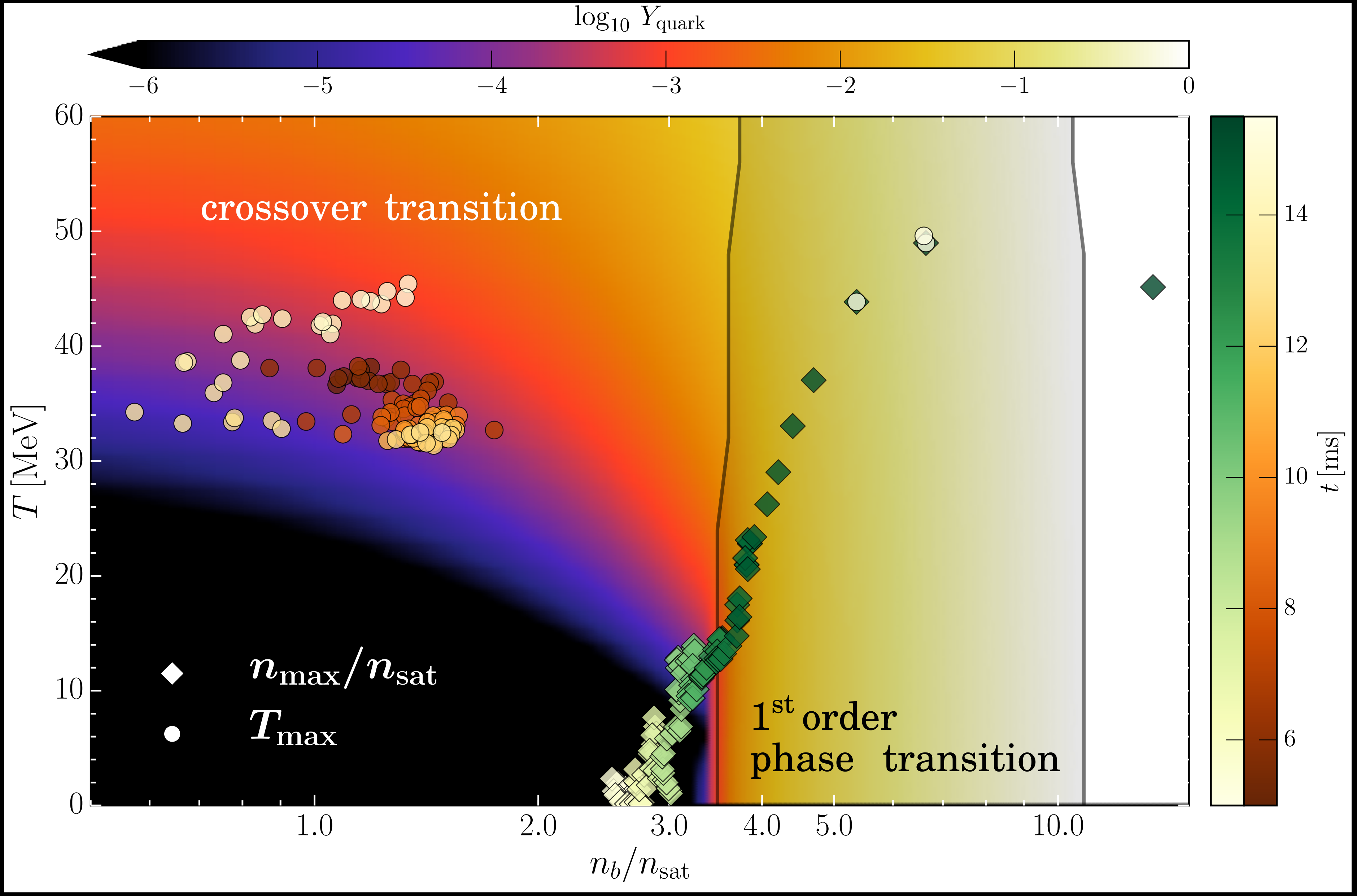
- Phase diagram with quark fraction

Comparing with the phase diagram



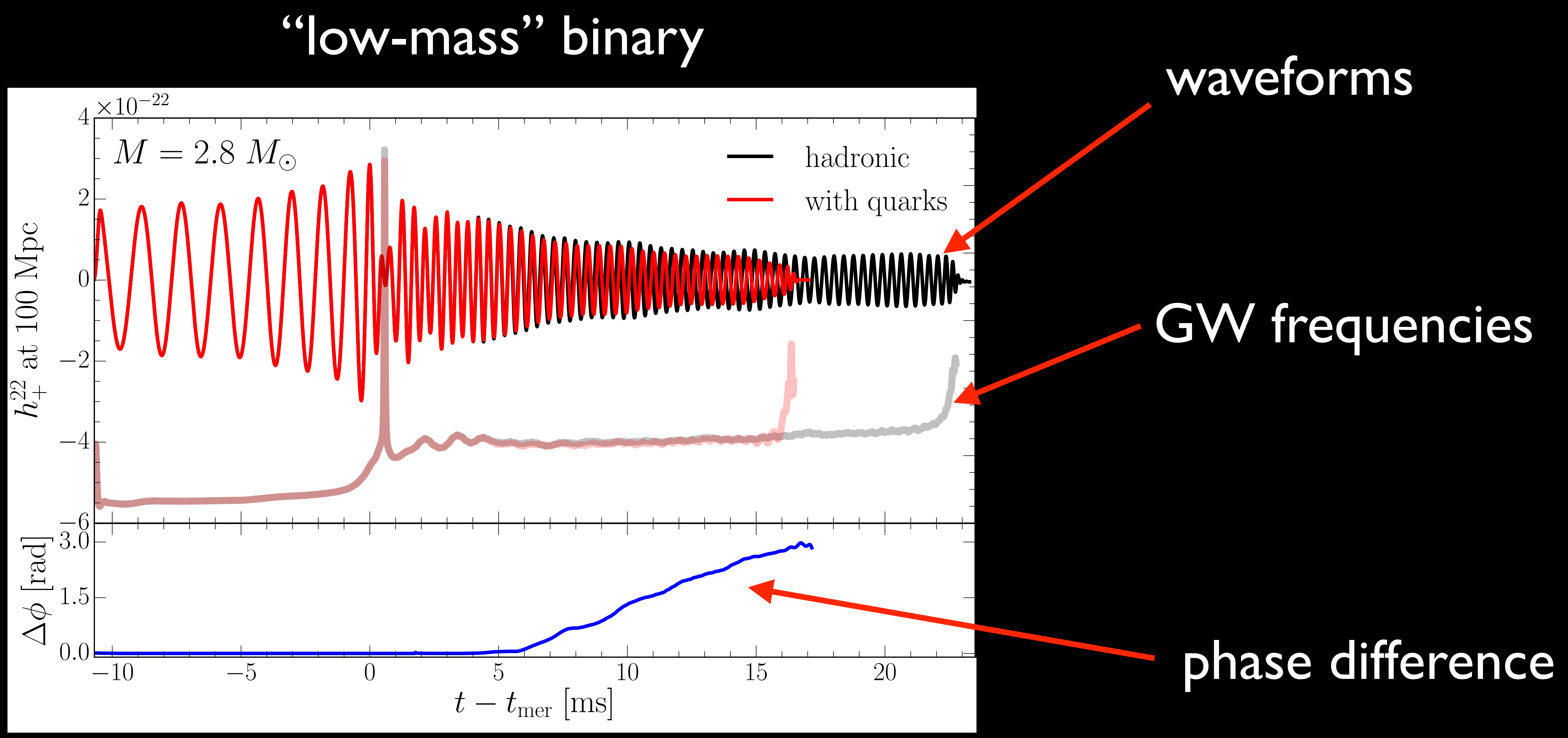
- Phase diagram with quark fraction
- Circles show the position in the diagram of the maximum temperature as a function of time

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.

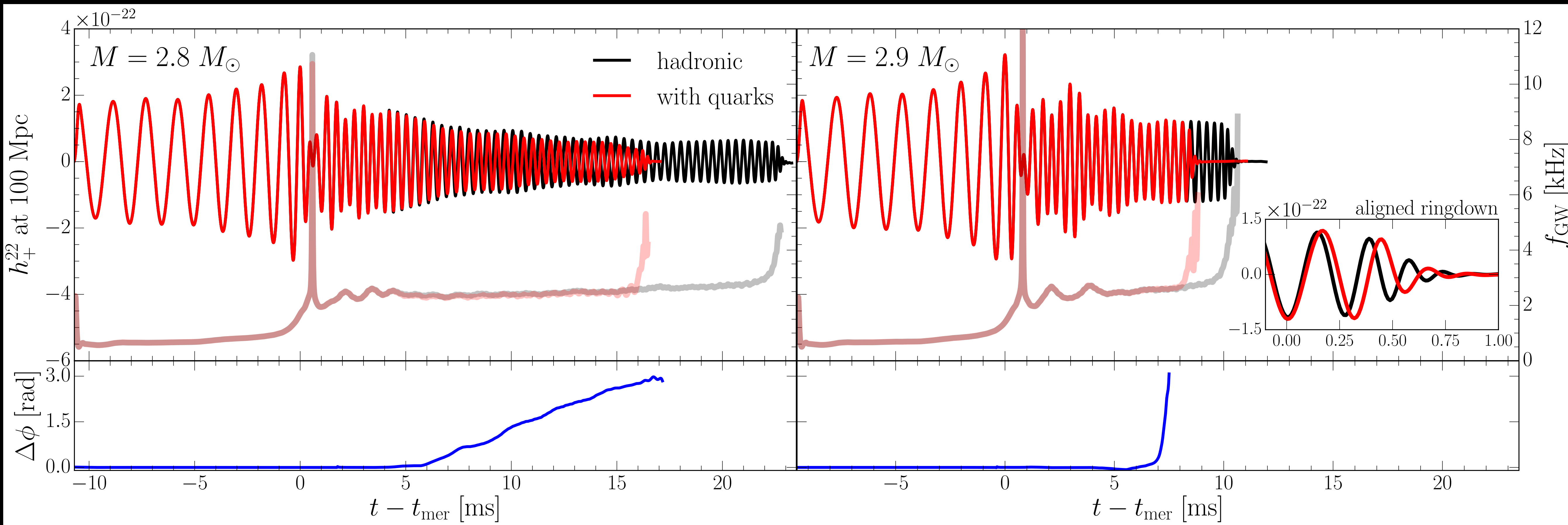
Gravitational-wave emission



- In **low-mass binary**, 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.

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**

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