Binary Neutron Stars: from macroscopic collisions to microphysics

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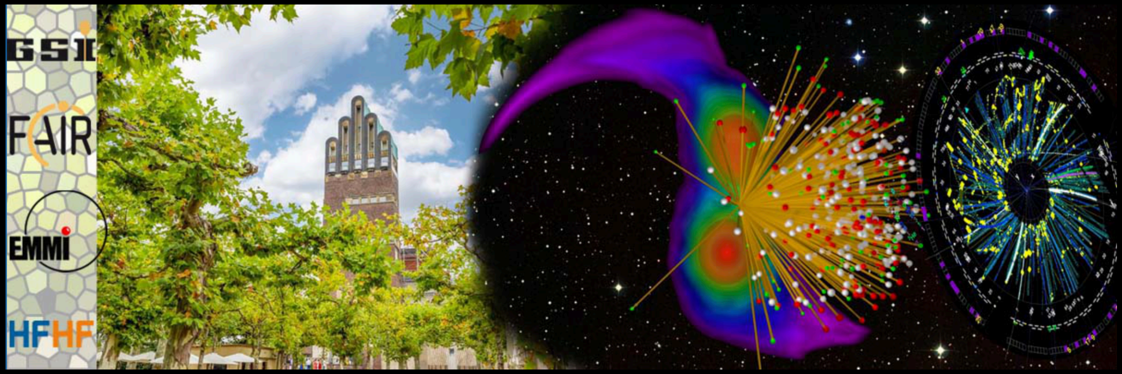


Plan of the talk

- The richness of merging binary neutron stars
- GW spectroscopy: EOS from frequencies
- GW170817, GW190814 and maximum mass
- Signatures of quark-hadron phase transitions
- On the sound speed in neutron stars

The two-body problem in GR

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

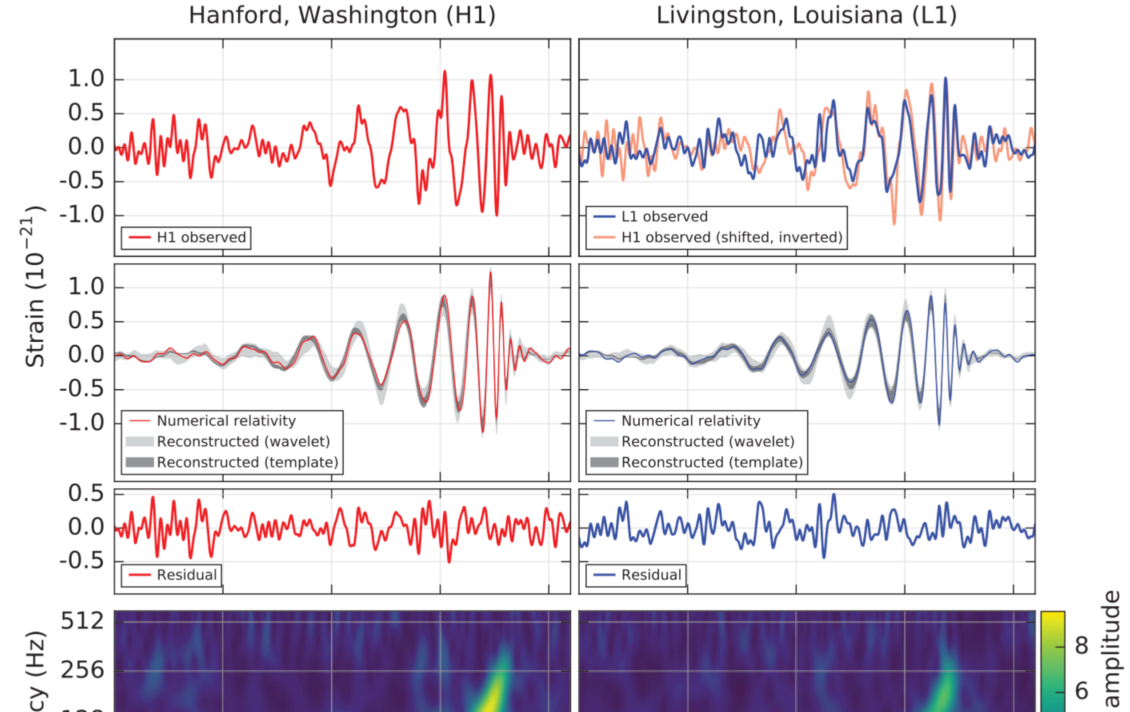
BH + BH → BH + GWs

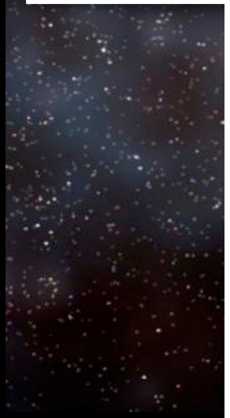
- For NSs the question is more **subtle:** hyper-massive neutron star (HMNS), ie

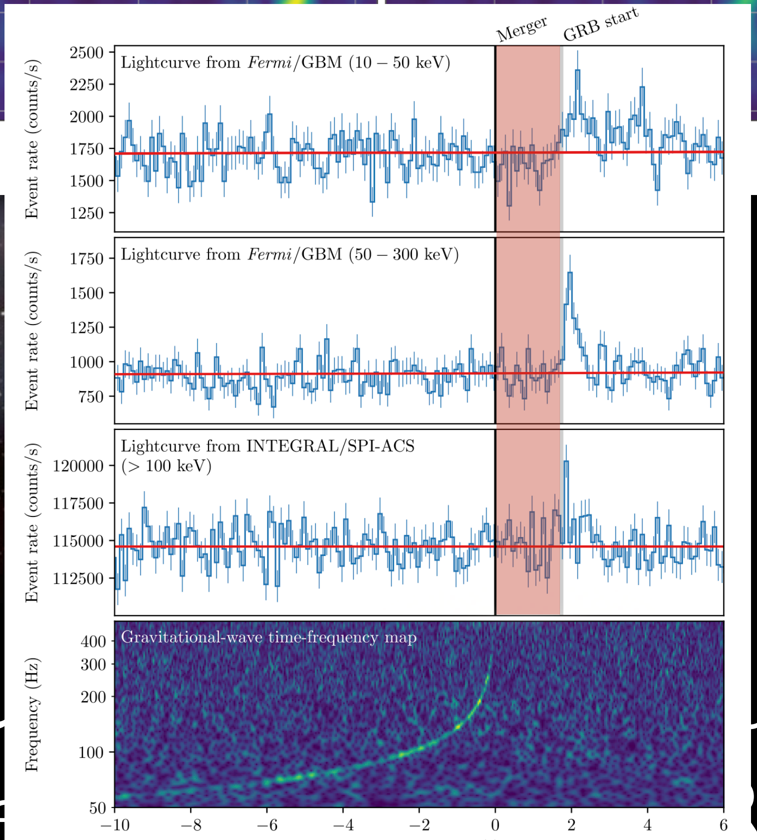
NS + NS → HMNS+... ? → BH+to

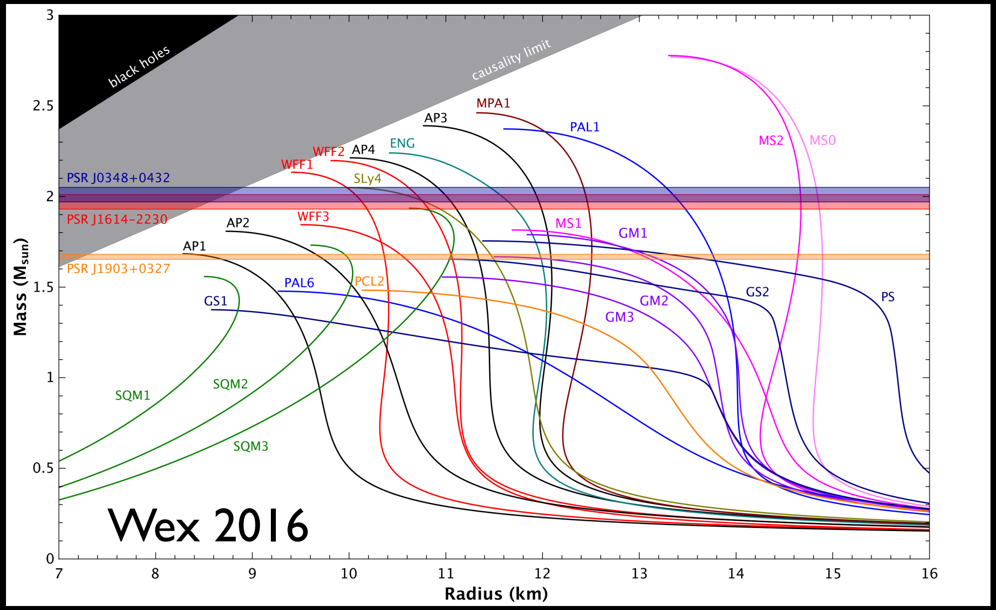
- **HMNS** phase can provide clear information on **EOS**

GW150914









Wex 2016

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

GW170817

The two-body problem in GR

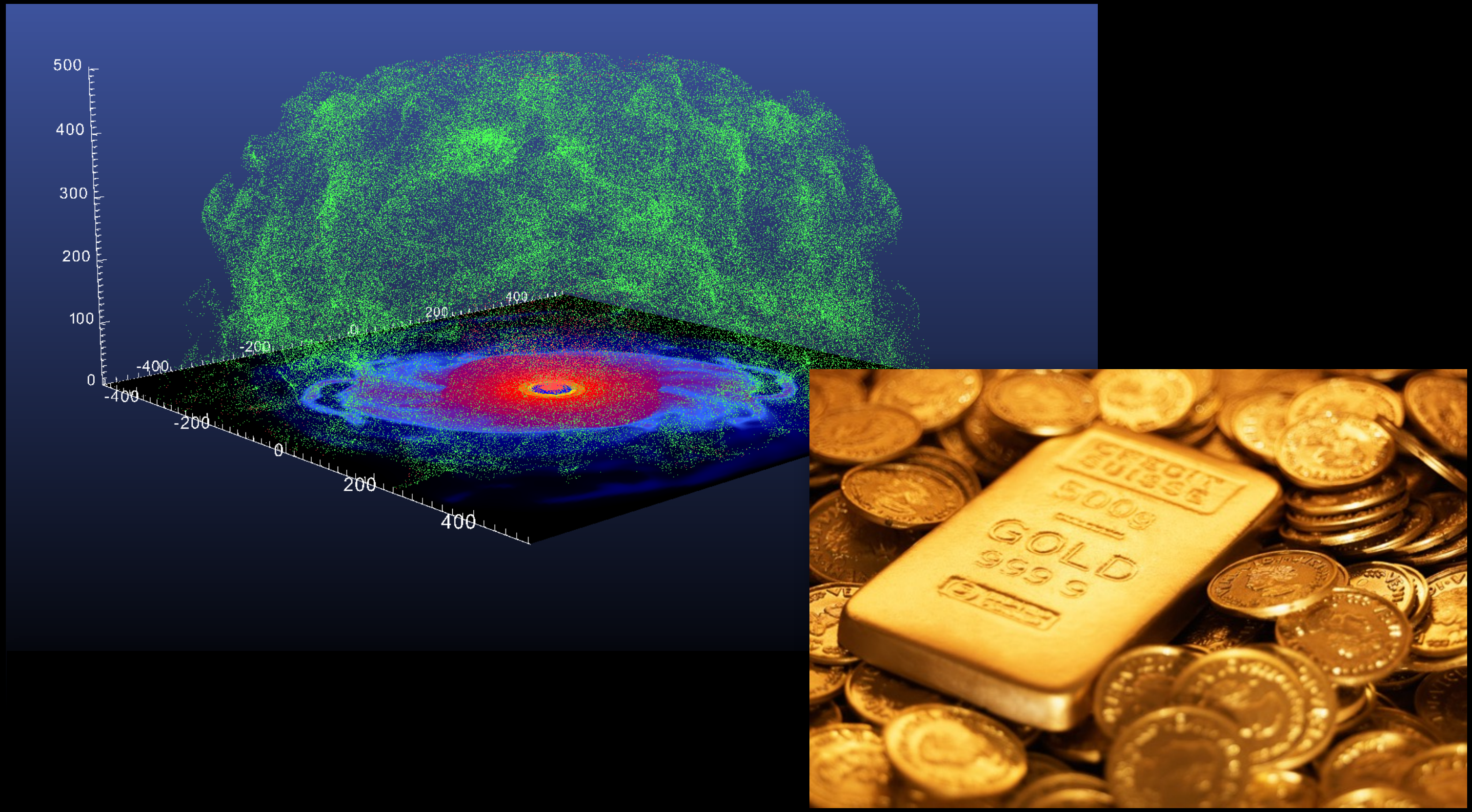
- For black holes the process is very **simple**:

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

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

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

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

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

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

$$\nabla_\mu T^{\mu\nu}_{\rm rad} = S^\nu\,, \quad \text{(radiative losses)}$$

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

Animations: Breu, Radice, LR

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

merger → HMNS → BH + torus

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

timescale for all this is 0.01-1 sec

LS220 EOS

Qualitatively, this is what normally happens:

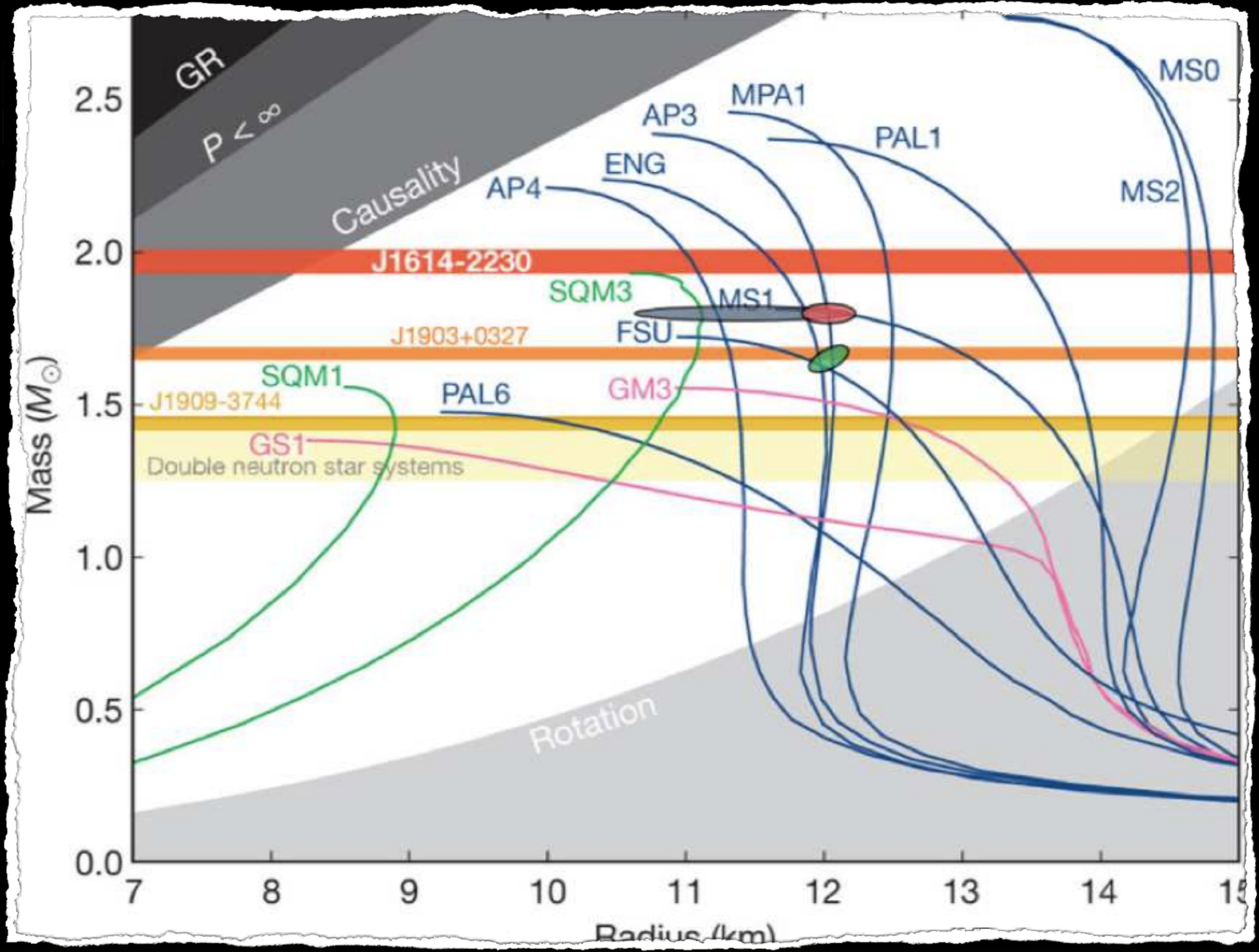
merger → HMNS → BH + torus

Quantitatively, differences are produced by:

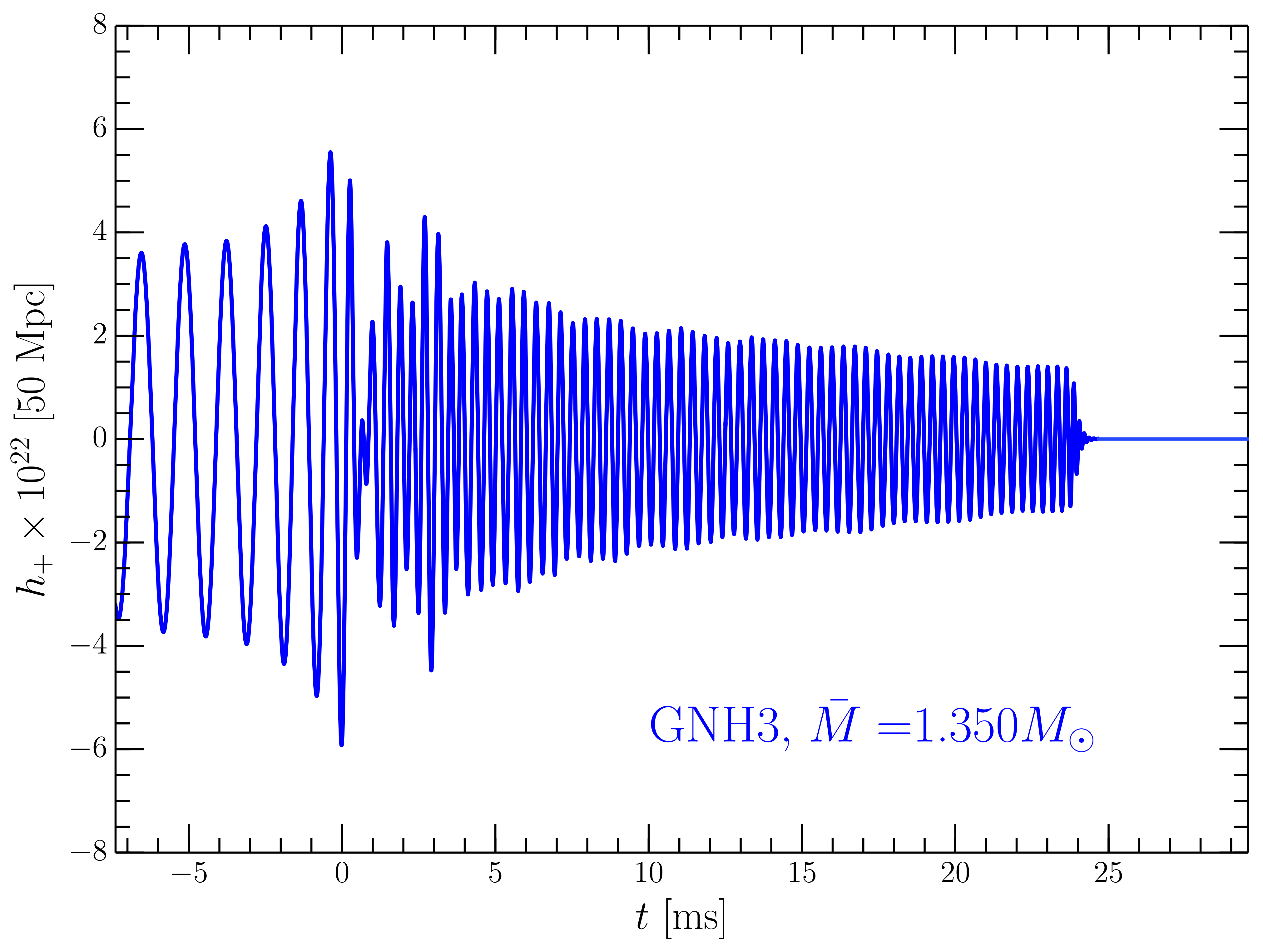
- total mass (prompt vs delayed collapse)
- mass asymmetries (HMNS and torus)
- soft/stiff EOS (inspiral and post-merger, PT)
- magnetic fields (equil. and EM emission)
- radiative losses (equil. and nucleosynthesis)

GW spectroscopy: EOS from frequencies

Takami, LR, Baiotti 2014; Takami, LR, Baiotti 2015; LR, Takami 2016; Bose, LR, + 2017; Zhu, LR 2020,+…



Anatomy of the GW signal



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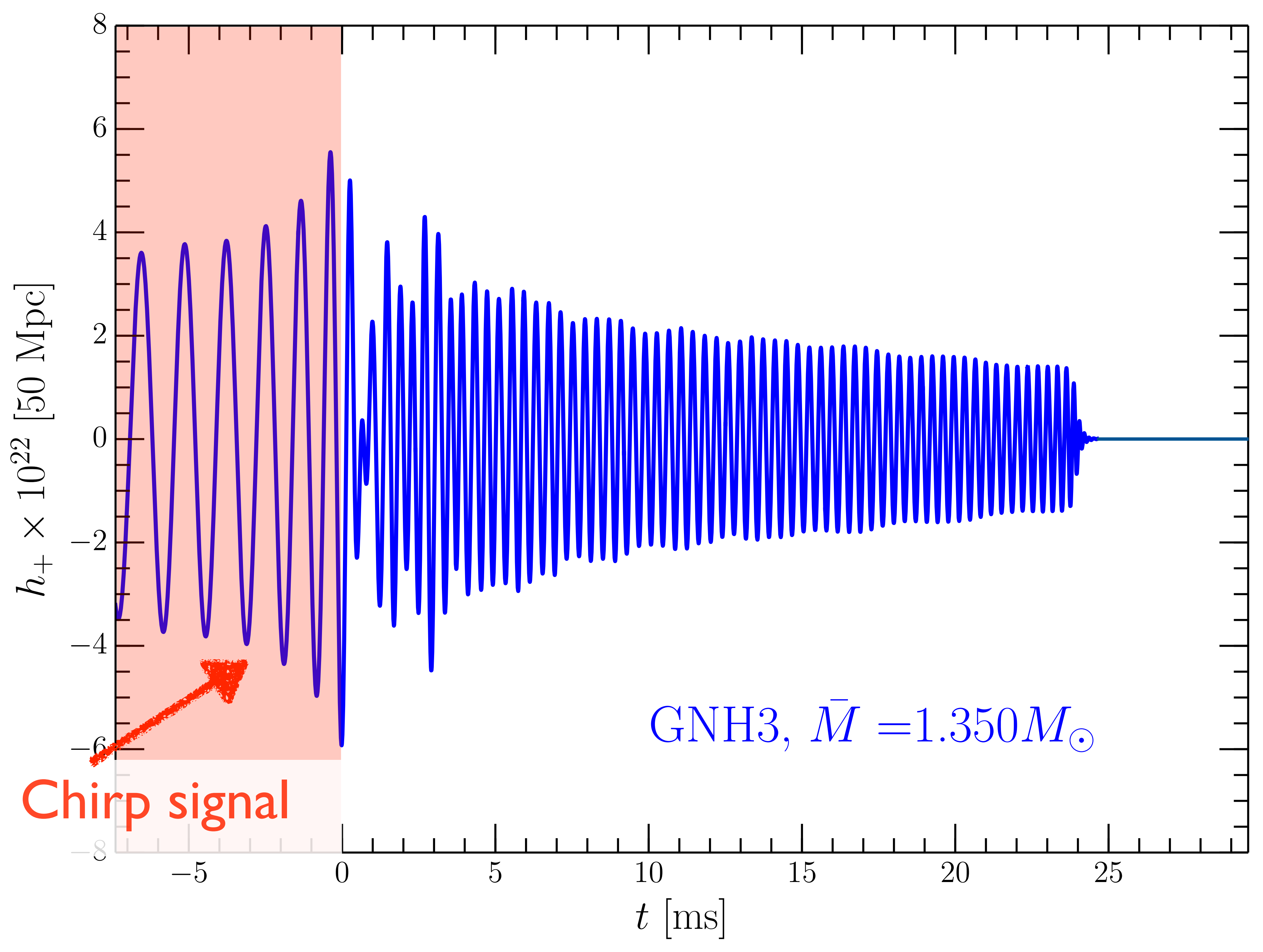
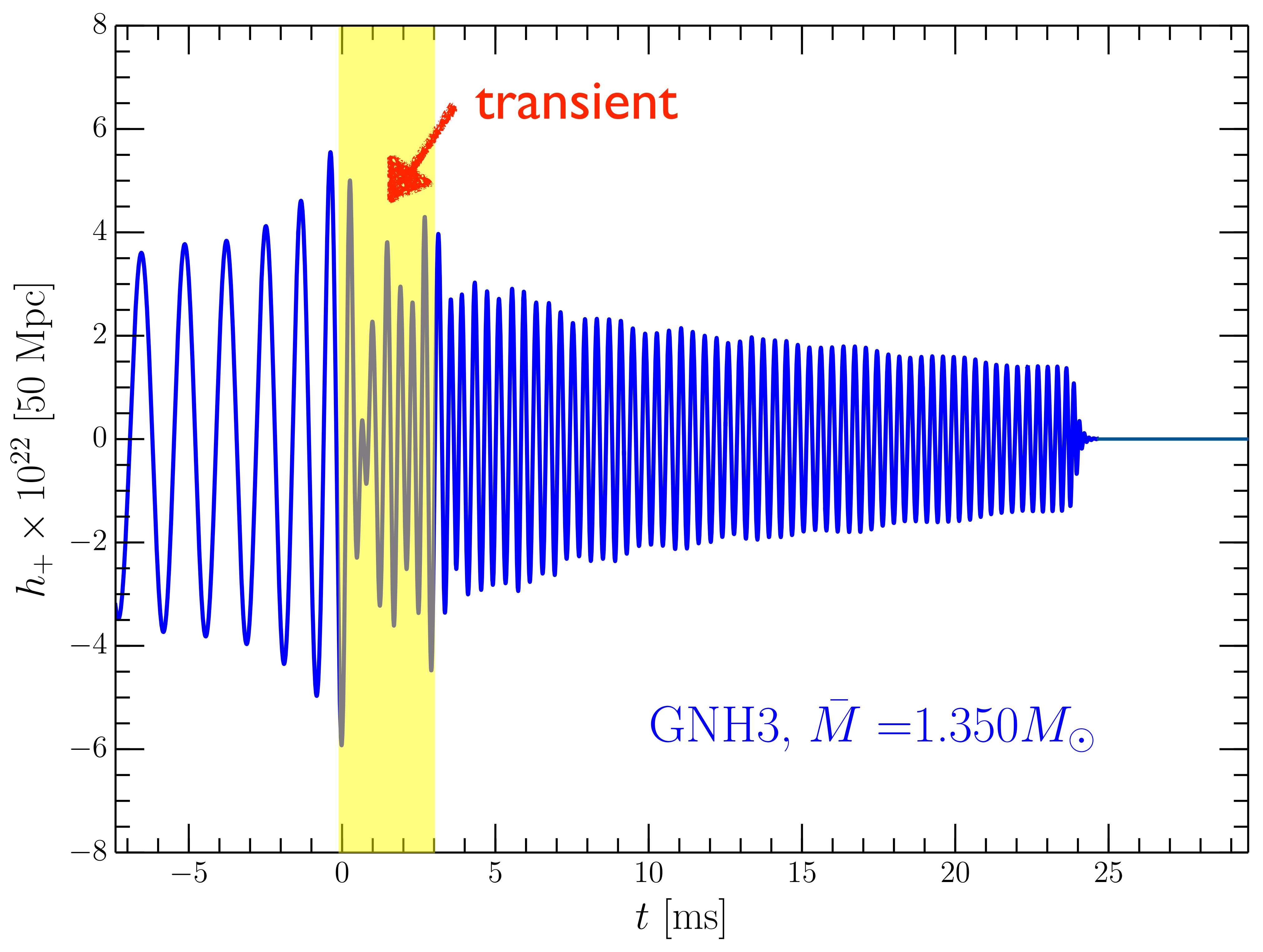


Chirp signal

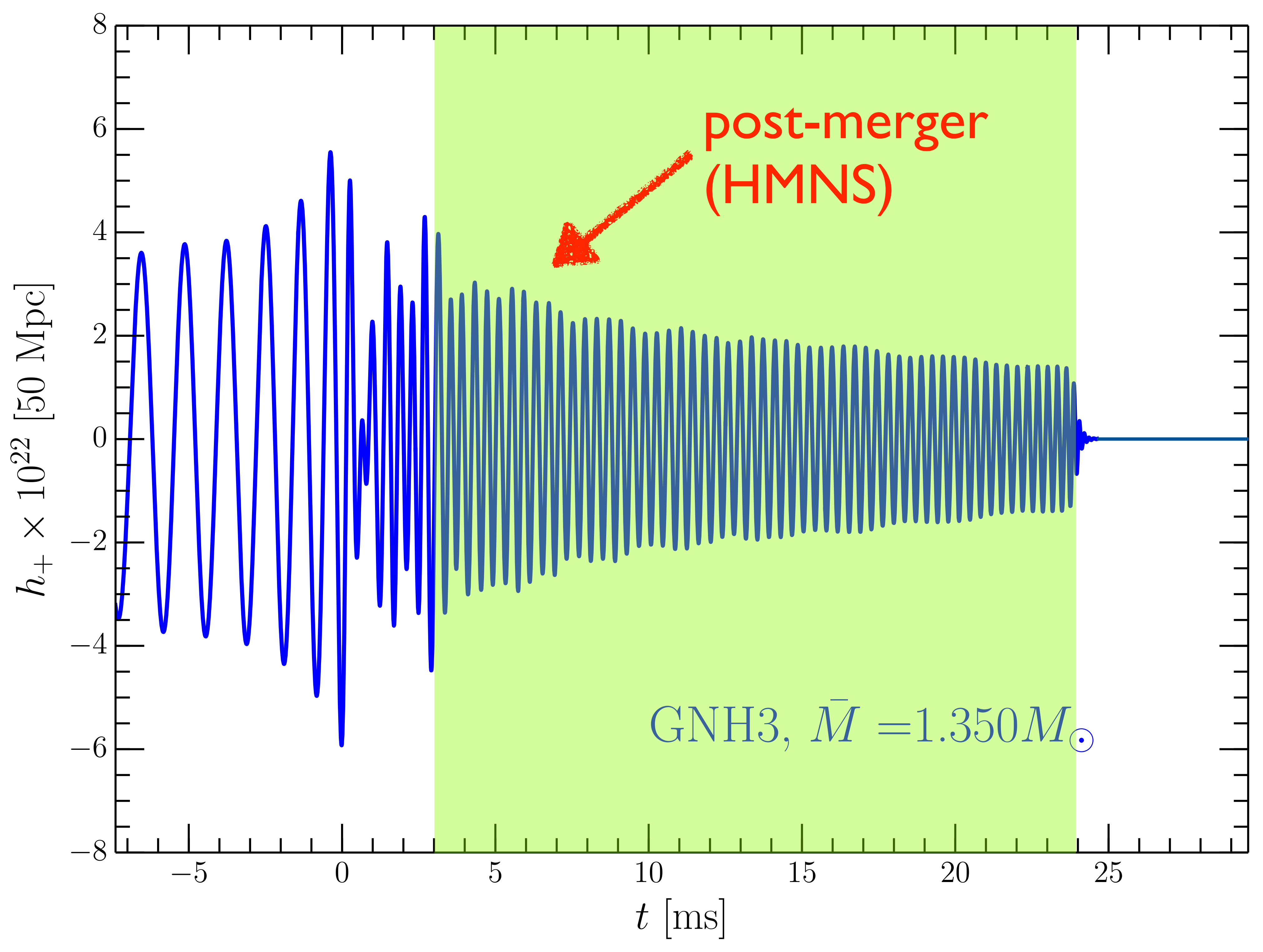
Inspiral: well approximated by PN/EOB; tidal effects important

Anatomy of the GW signal



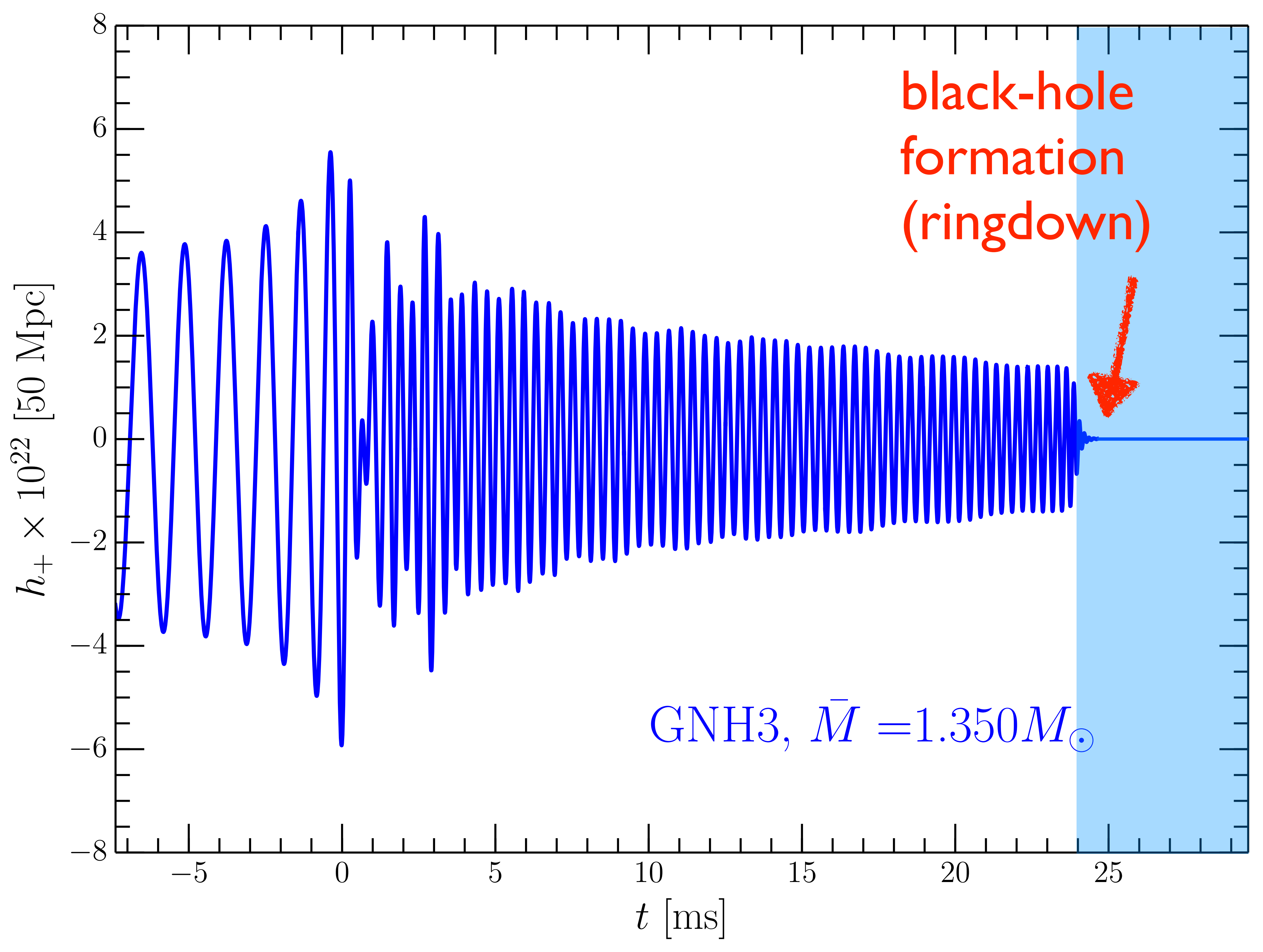
Merger: highly nonlinear but analytic description possible

Anatomy of the GW signal



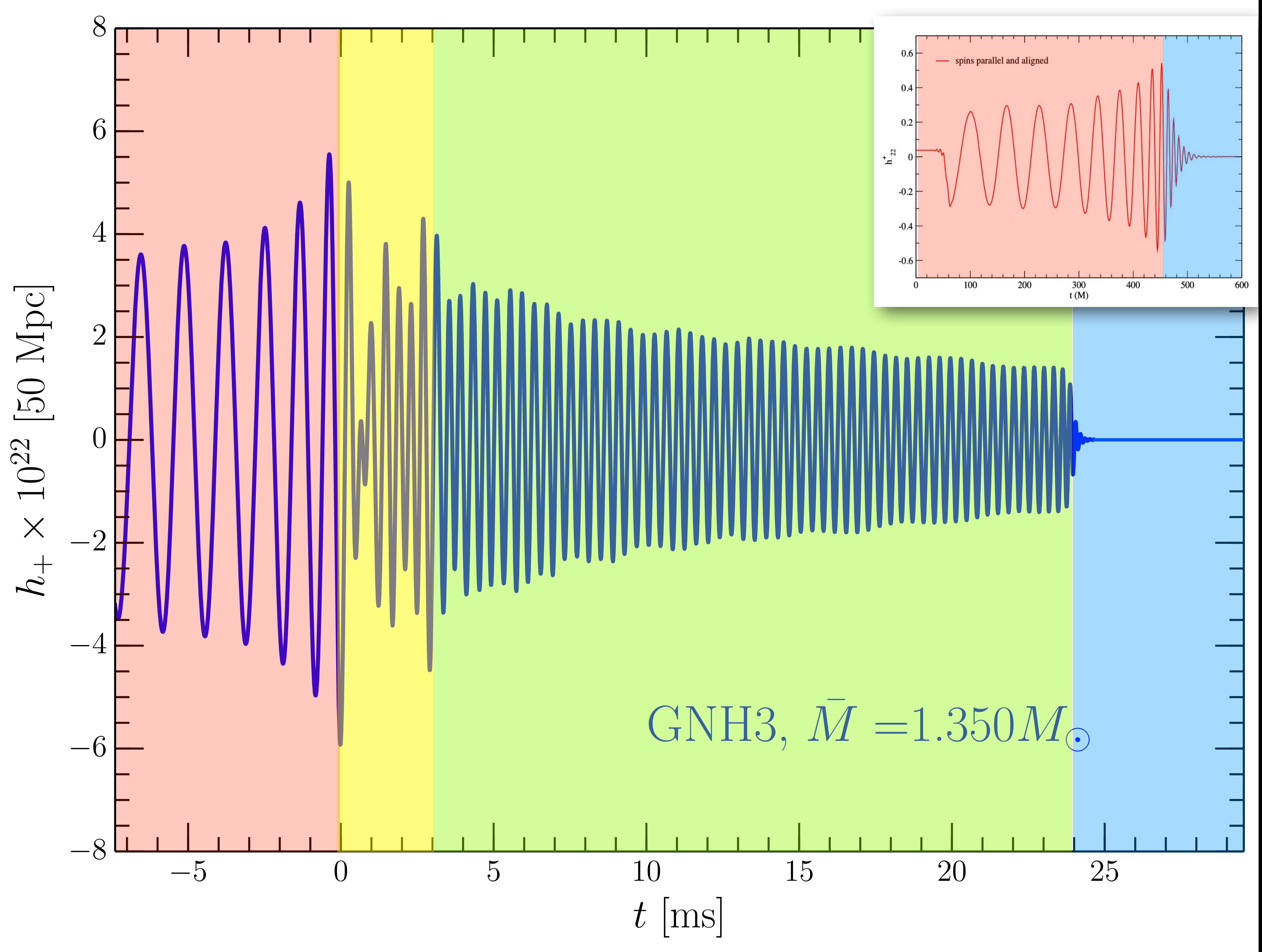
post-merger: quasi-periodic emission of bar-deformed HMNS

Anatomy of the GW signal



Collapse-ringdown: signal essentially shuts off

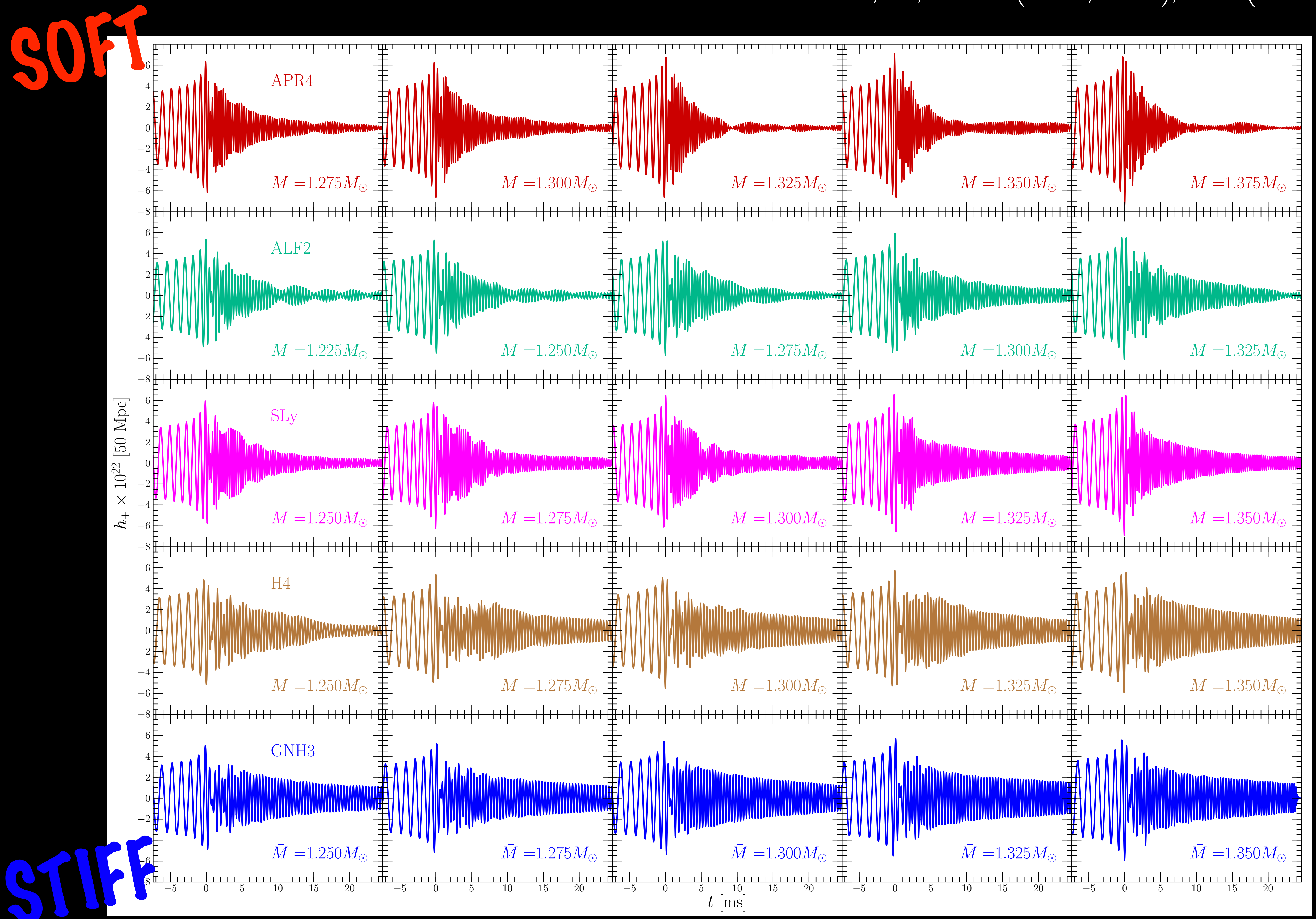
Anatomy of the GW signal



Postmerger signal: peculiar of binary NSs

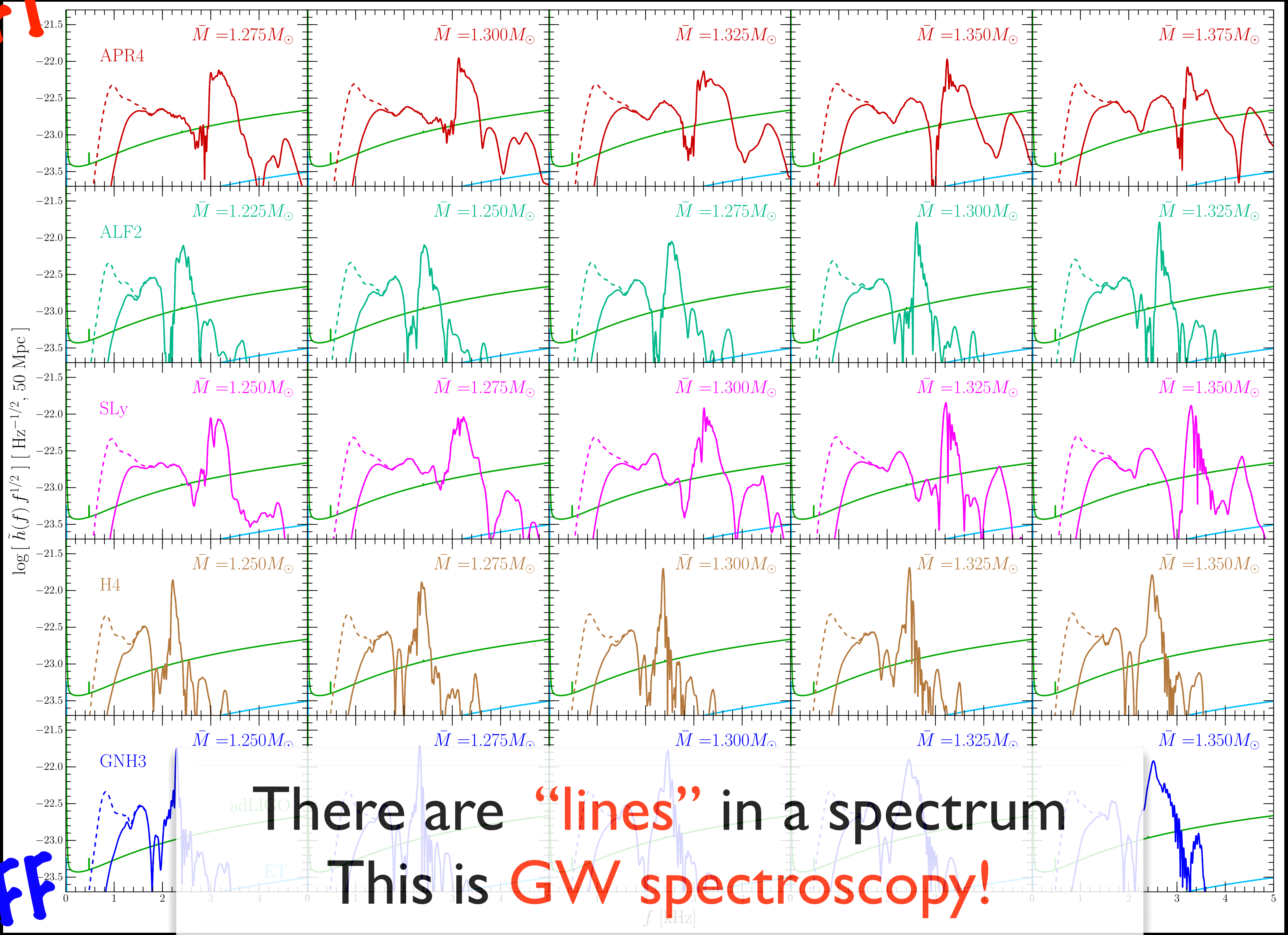
What we can do nowadays

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



Extracting information from the EOS

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

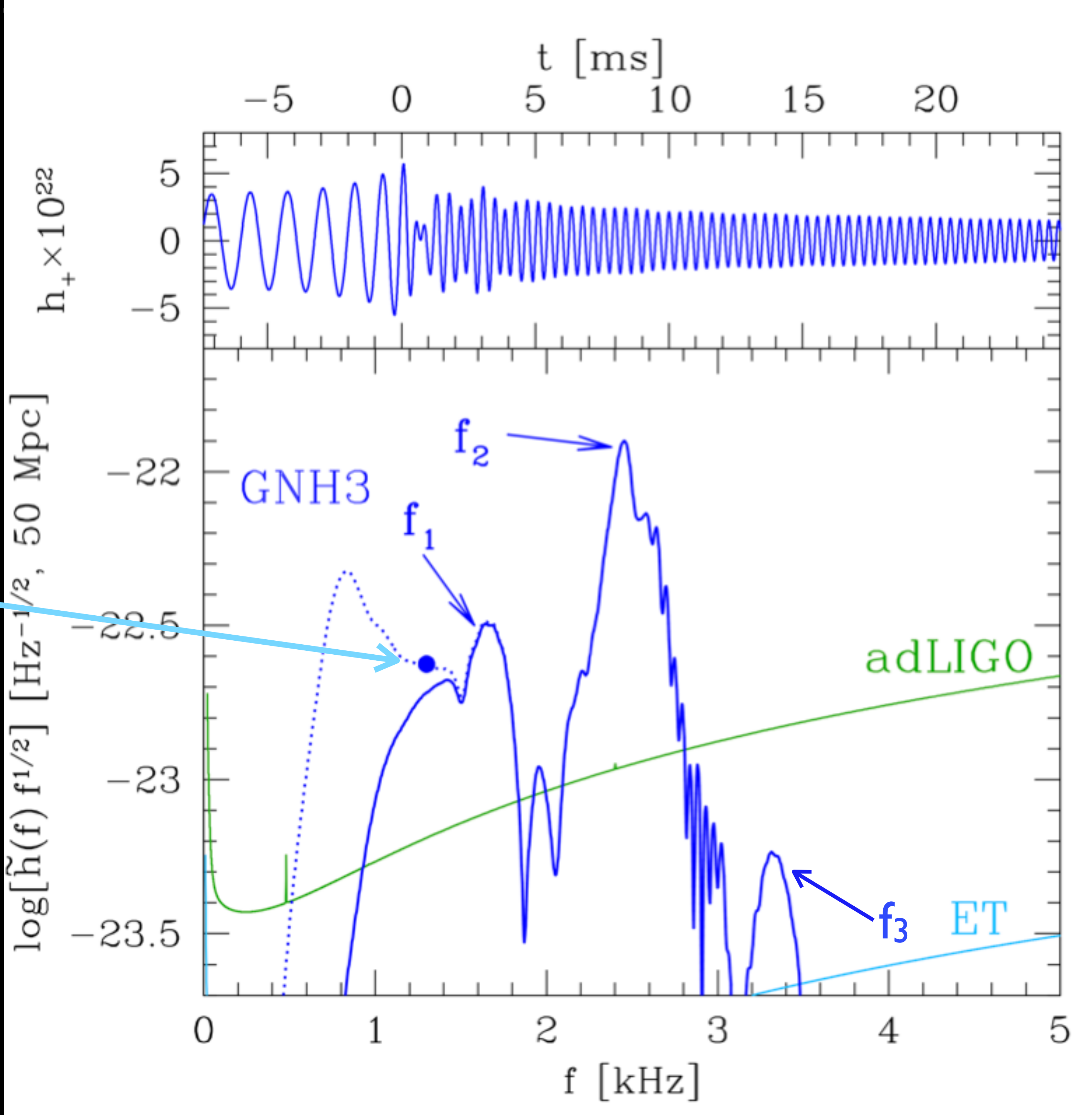


There are "lines" in a spectrum

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 .



merger frequency

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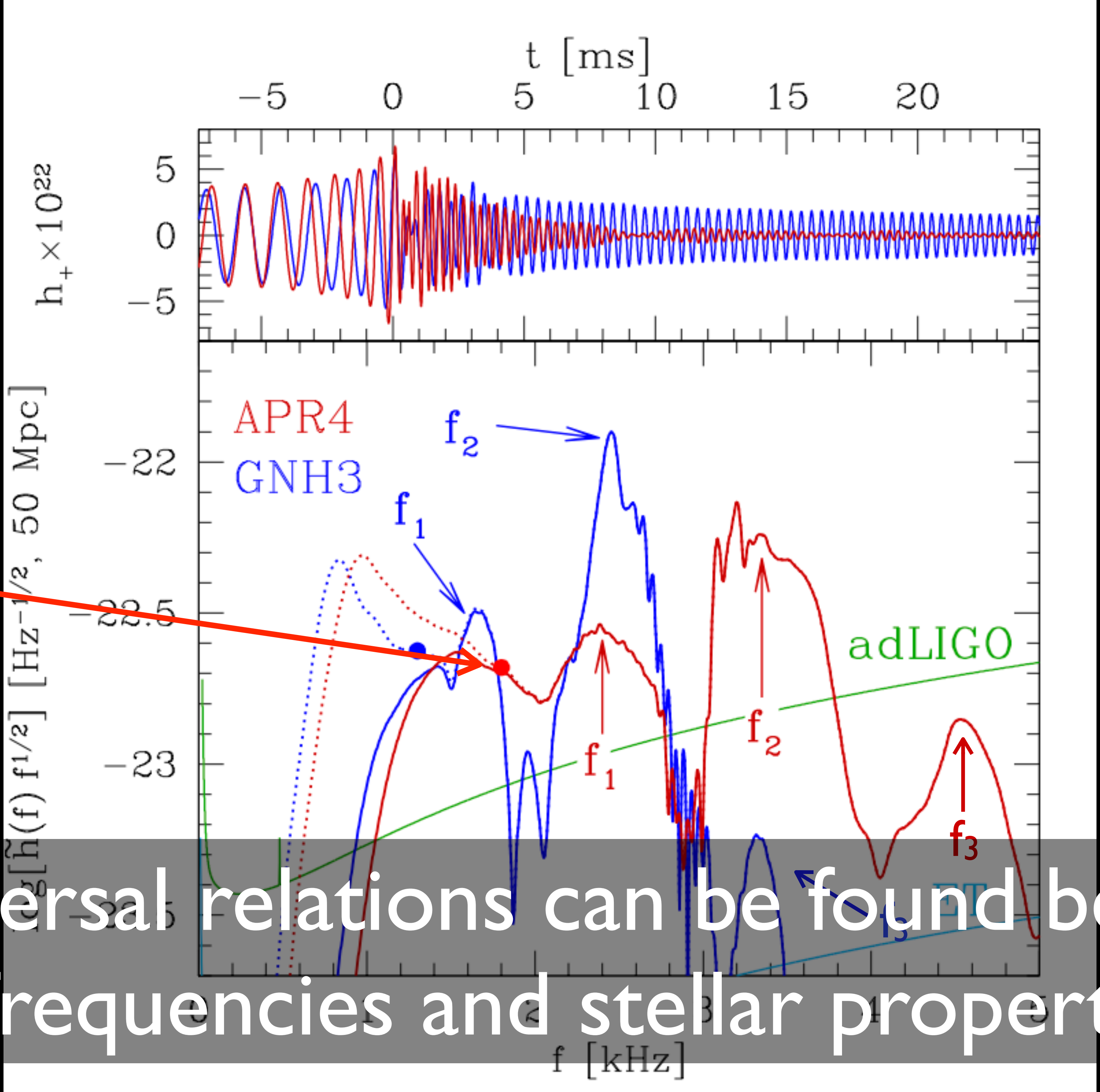
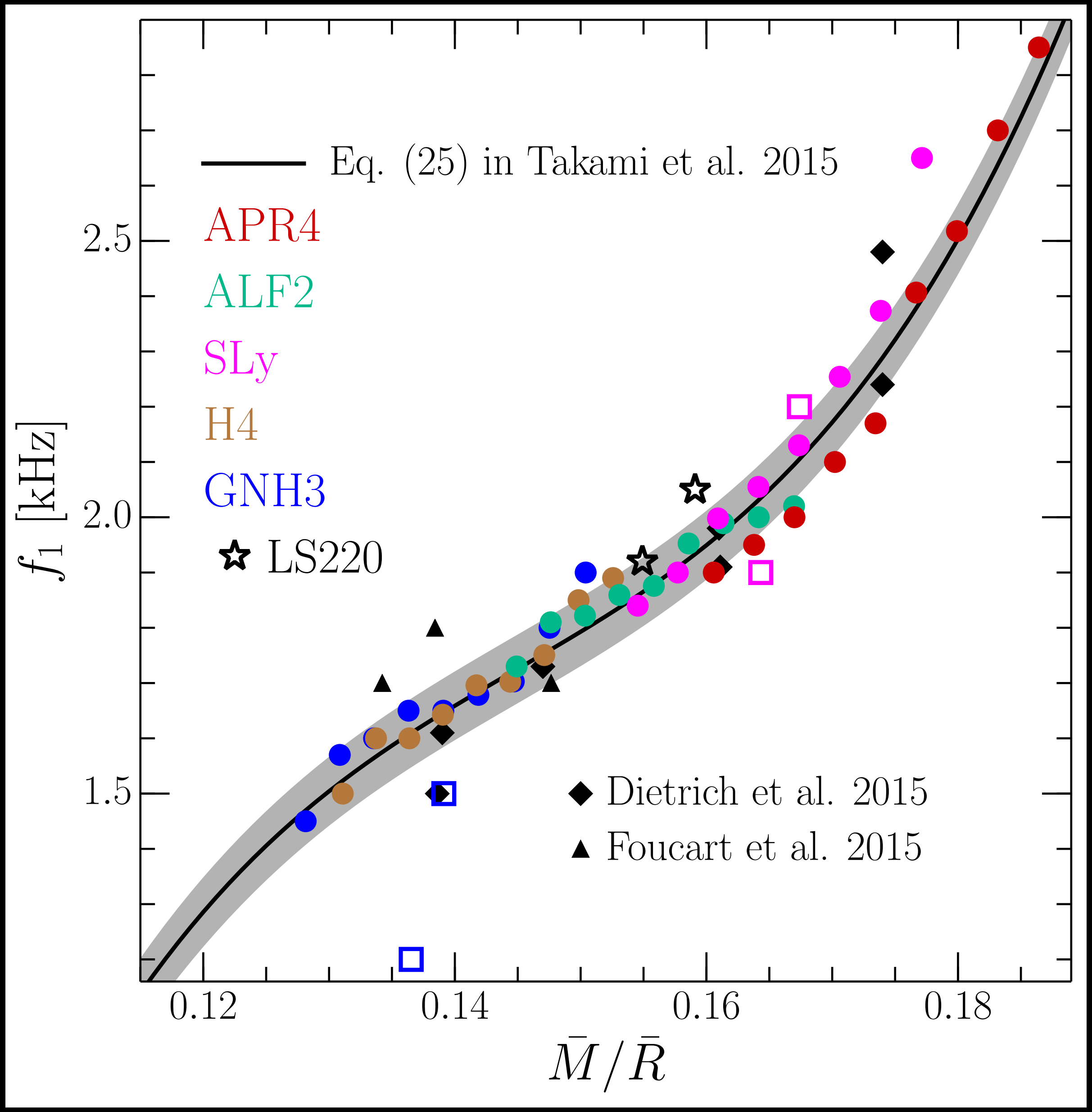
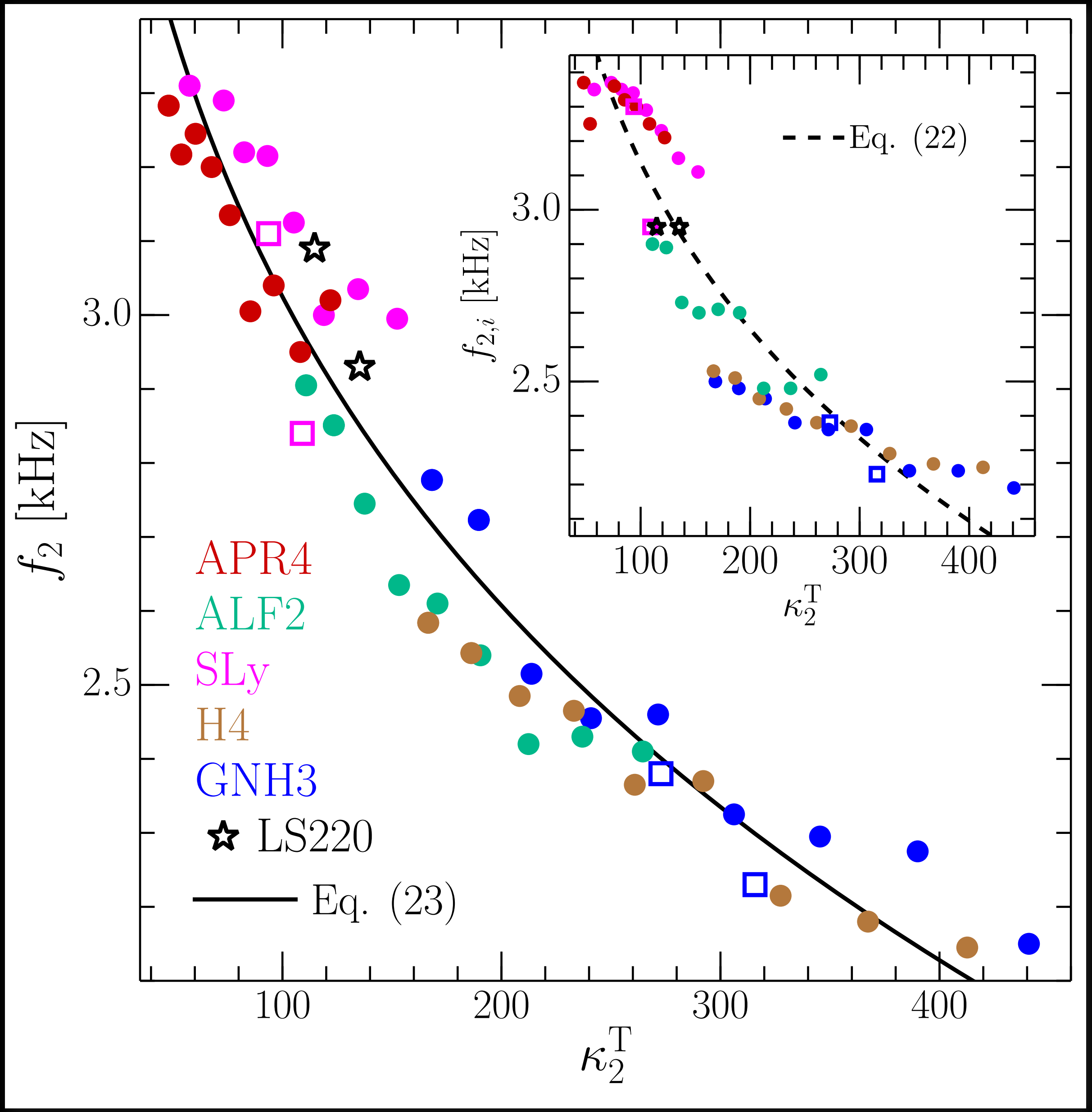


merger frequency

Universal relations can be found between frequencies and stellar properties

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

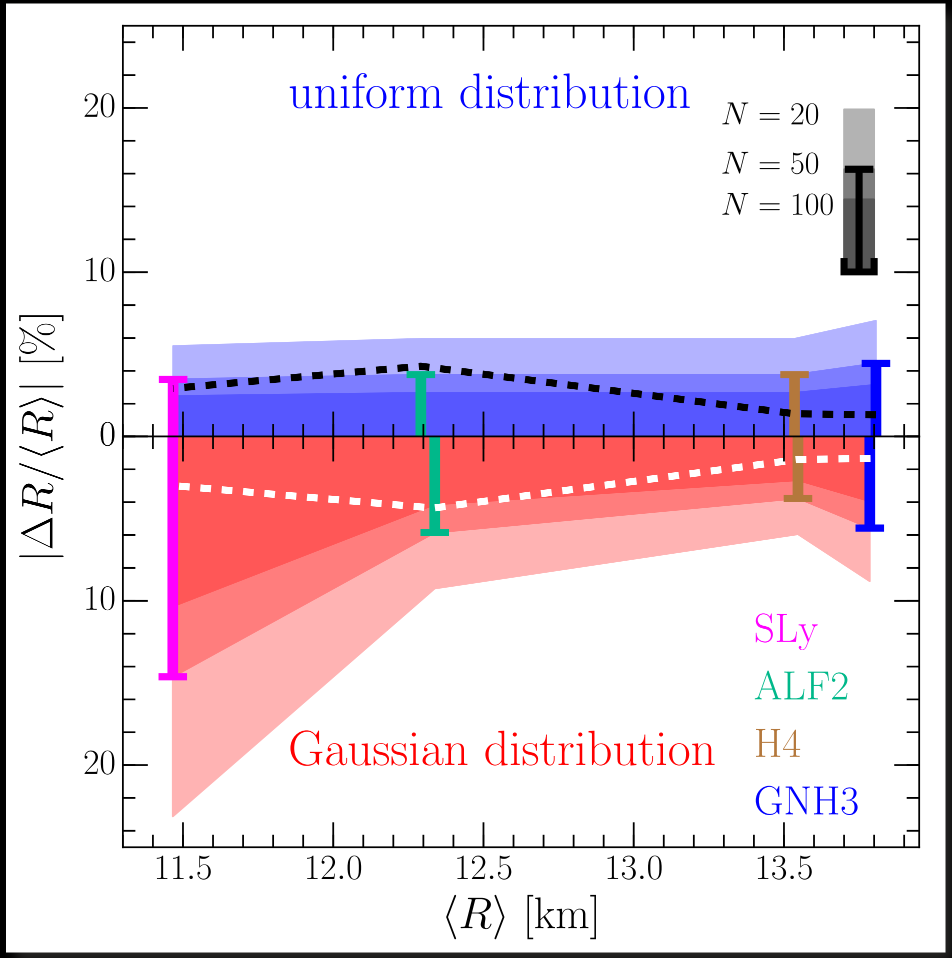




quasi-universal behaviour has profound implications for the analytical modelling of the GW emission: "what we do for one EOS can be extended to all EOSs."

A spectroscopic approach to the EOS

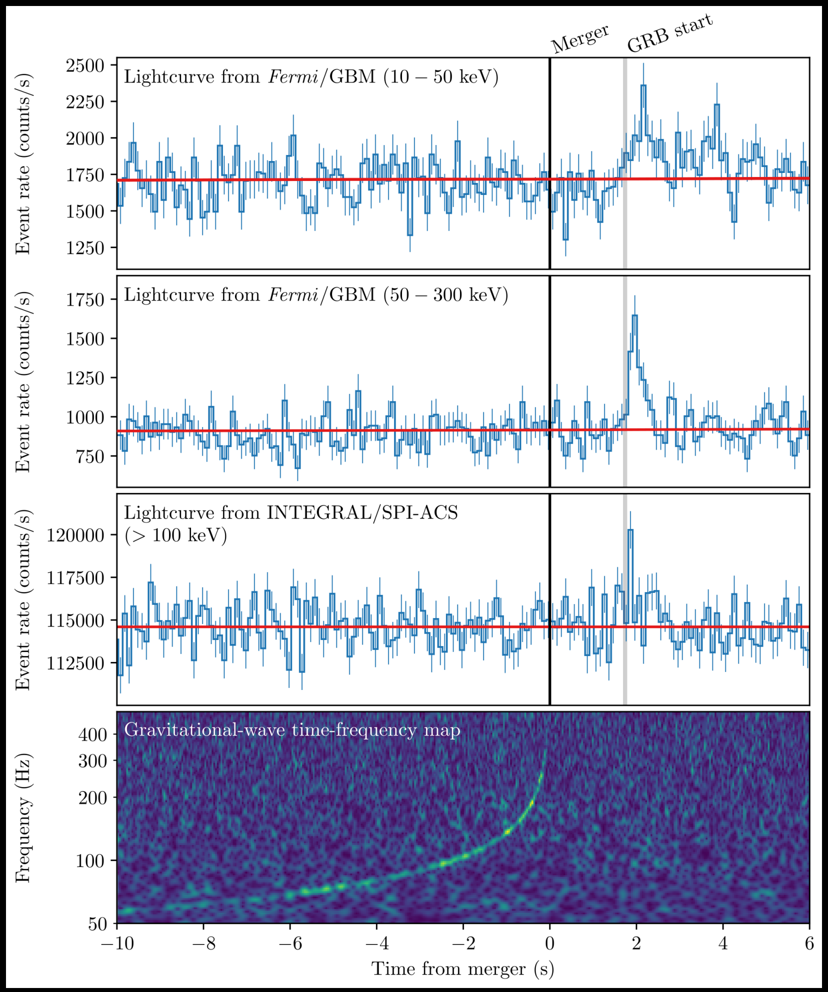
- **Universal behaviour** and **analytic modelling** of post-merger relates position of these peaks with the EOS.
- Question: how well can we constrain the EOS (radius) given ***N* detections?**



- 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, GW190814 and maximum mass

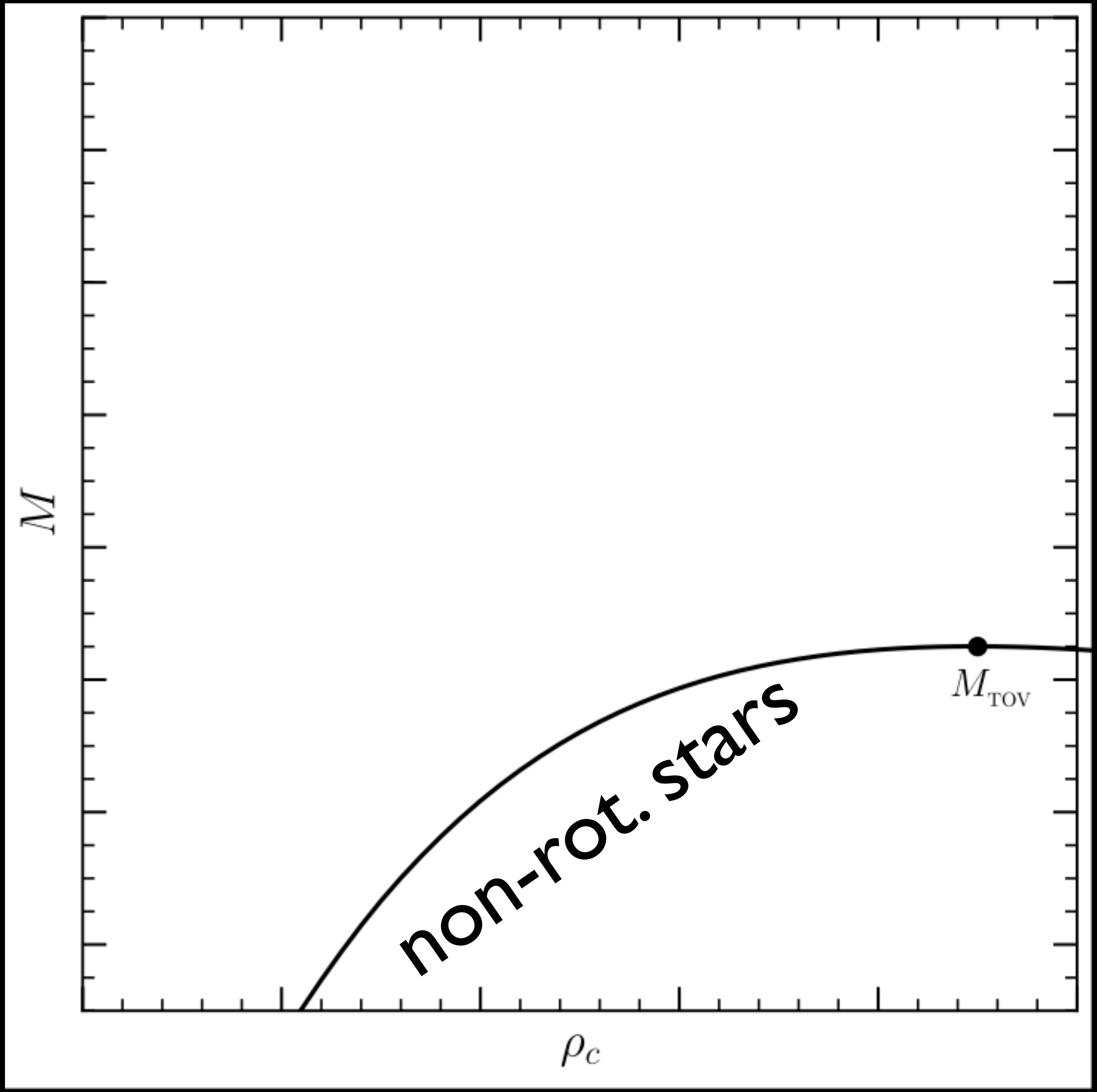


LR, Most, Weih, ApJL (2018)
Most, Weih, LR, Schaffner-Bielich, PRL (2018)
Nathanail, Most, LR, ApJL (2021)
Musolino, Ecker, LR, arXiv (2023)

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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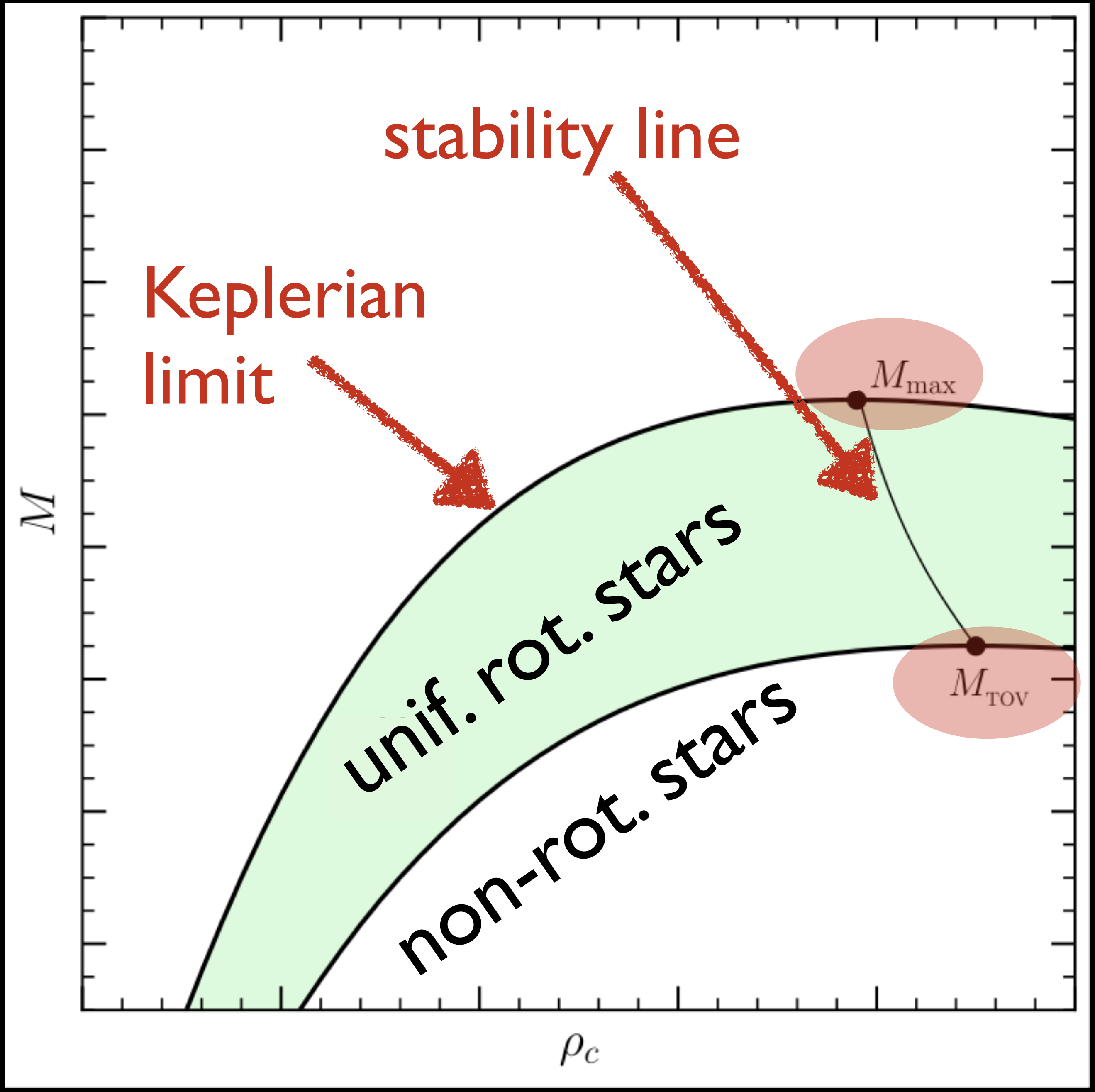

- Sequences of equilibrium models of **nonrotating** stars will have a maximum mass: $M_{\rm TOV}$
- This is true also for **uniformly** rotating stars at mass shedding limit: $M_{\rm max}$
- $M_{\rm max}$ simple and **quasi-universal** function of $M_{\rm TOV}$ (Breu & LR 2016)

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

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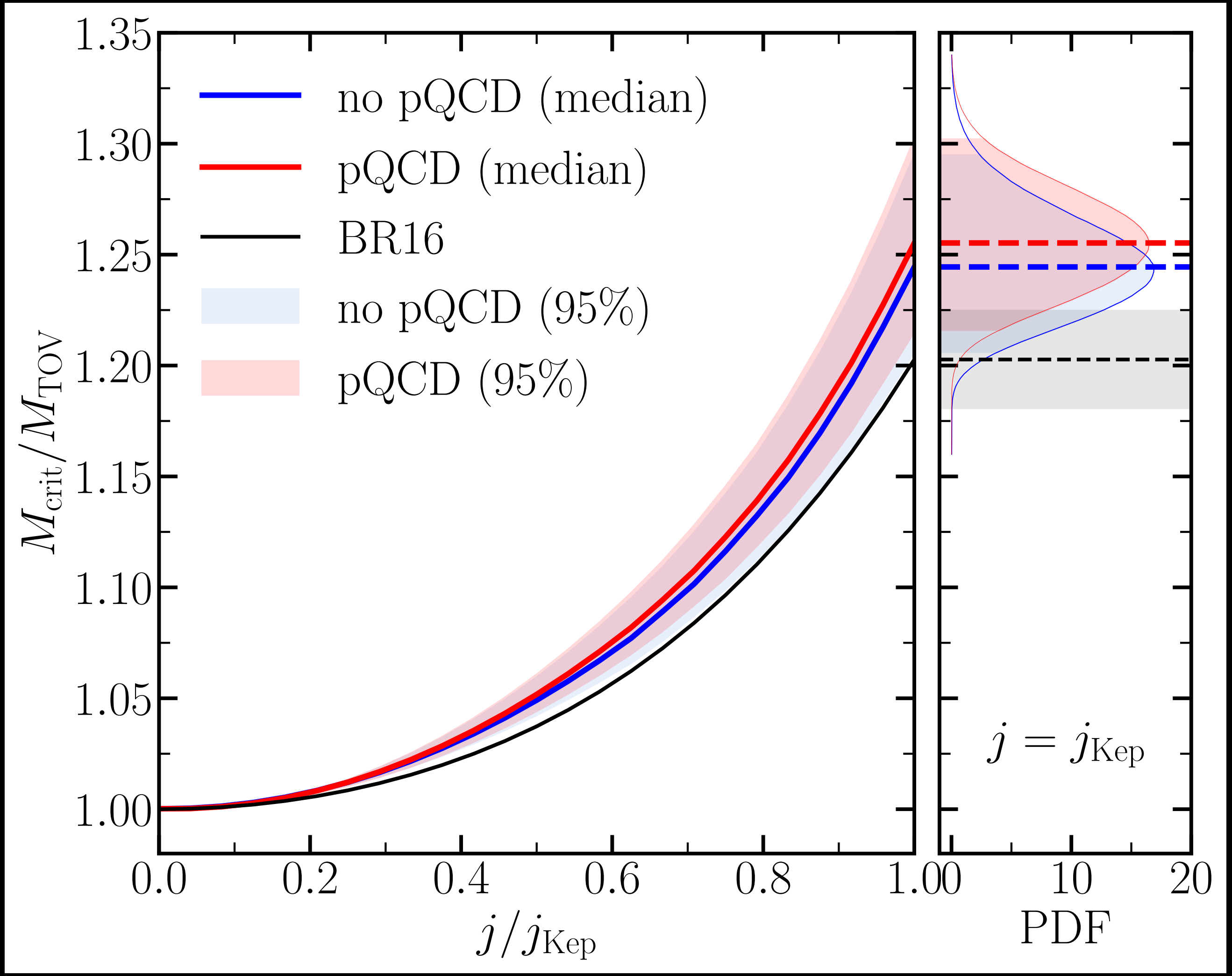

$$\boxed{M_{\rm max} = 1.25^{+0.05}_{-0.04}\,M_{\rm TOV}}$$

Limits on the maximum mass

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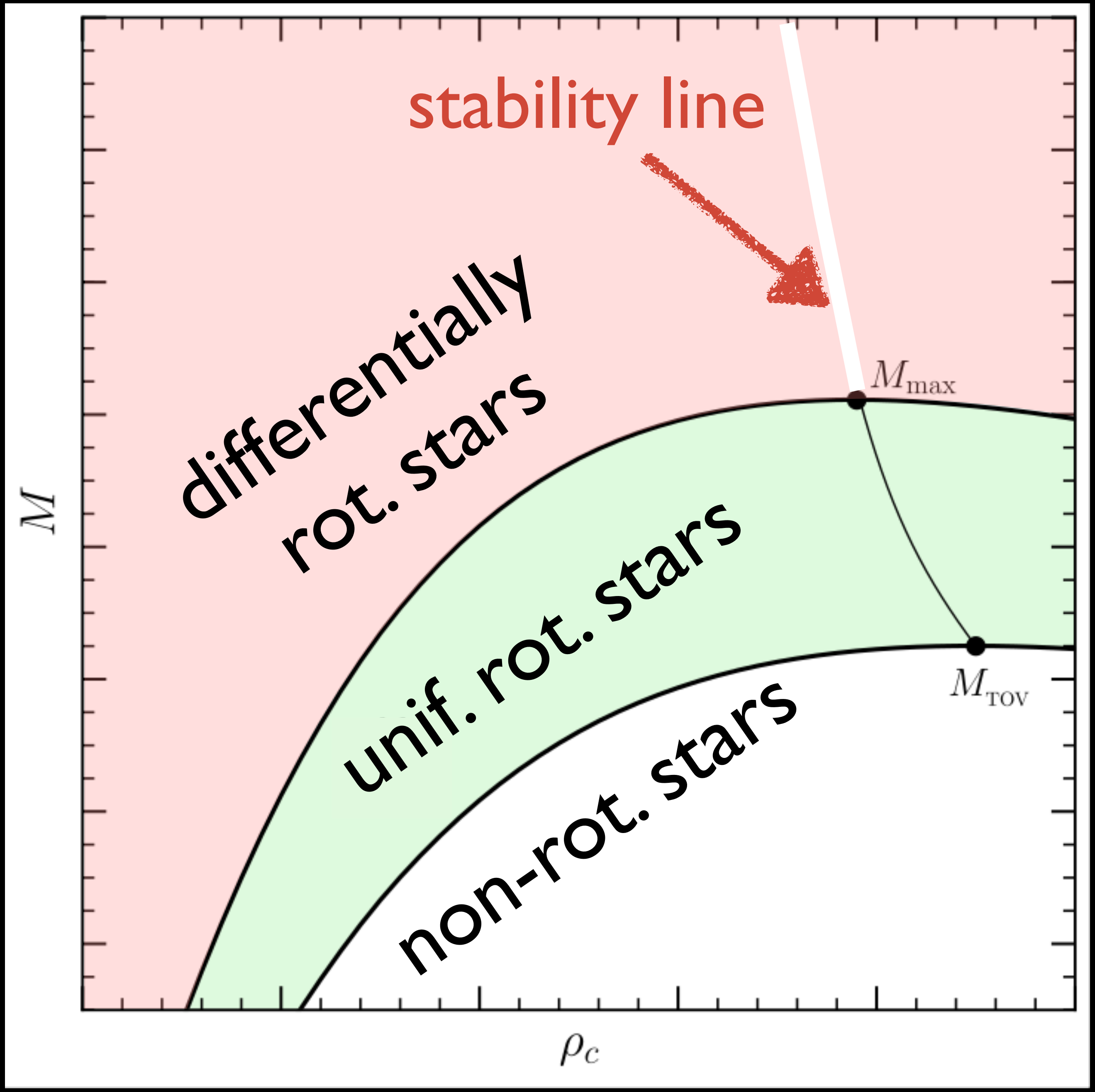
$$M_1 + M_2 = 2.74^{+0.04}_{-0.01}\, M_\odot$$



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

Limits on the maximum mass

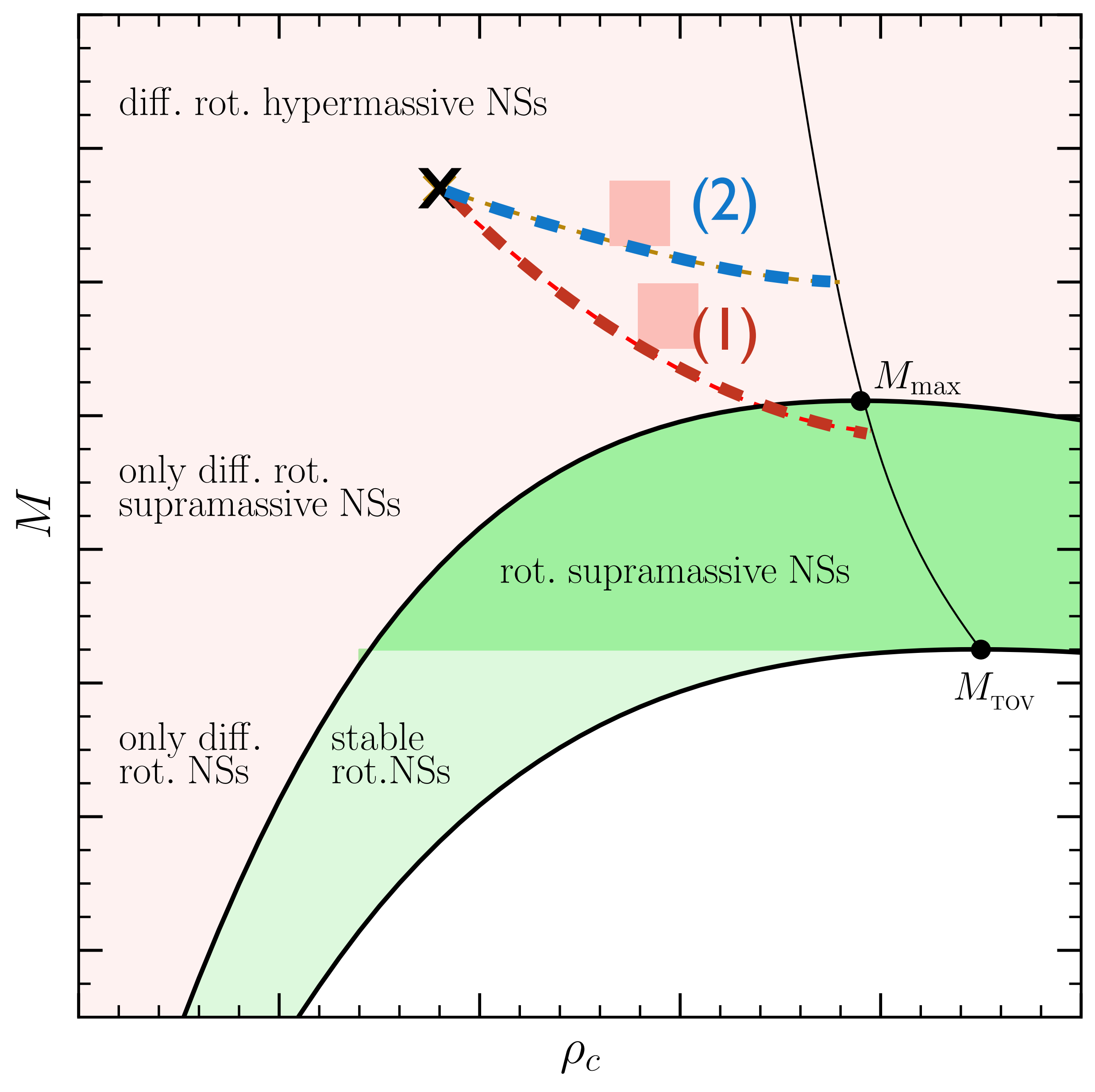
- GW170817 produced object **"X"**; GRB implies a BH has been formed: **"X"** followed two possible tracks: **fast (2)** and **slow (1)**

- 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,** to obtain

pulsar timing

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

GW170817; similar estimates by other groups (Margalit+ 2018, Shibata+ 2018, Ruiz+ 2018)

Tension on the maximum mass

Nathanail, Most, LR (2021)

- The 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

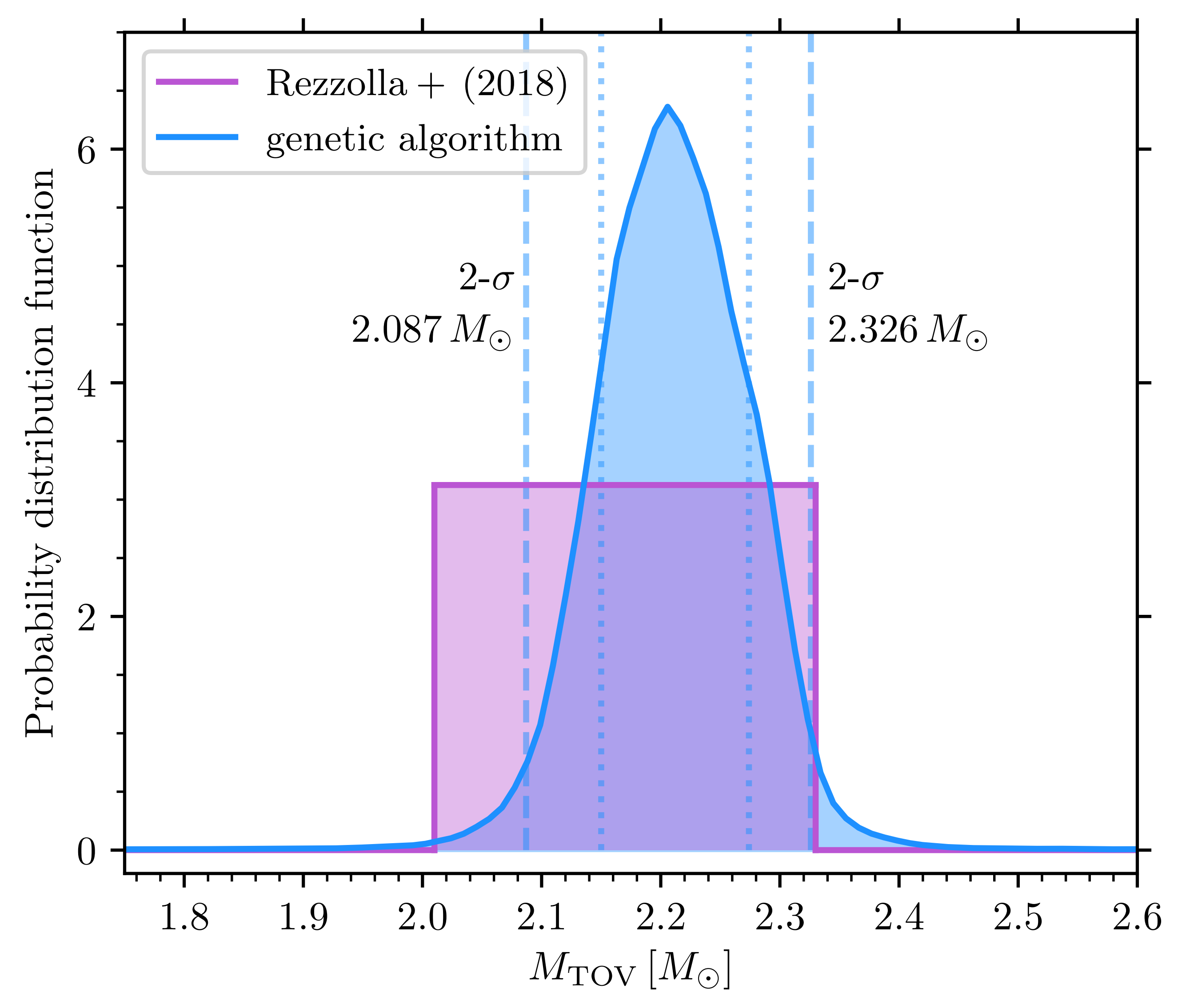
- A **genetic algorithm** is used to sample through the parameter space of the 10 free parameters.

- 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.

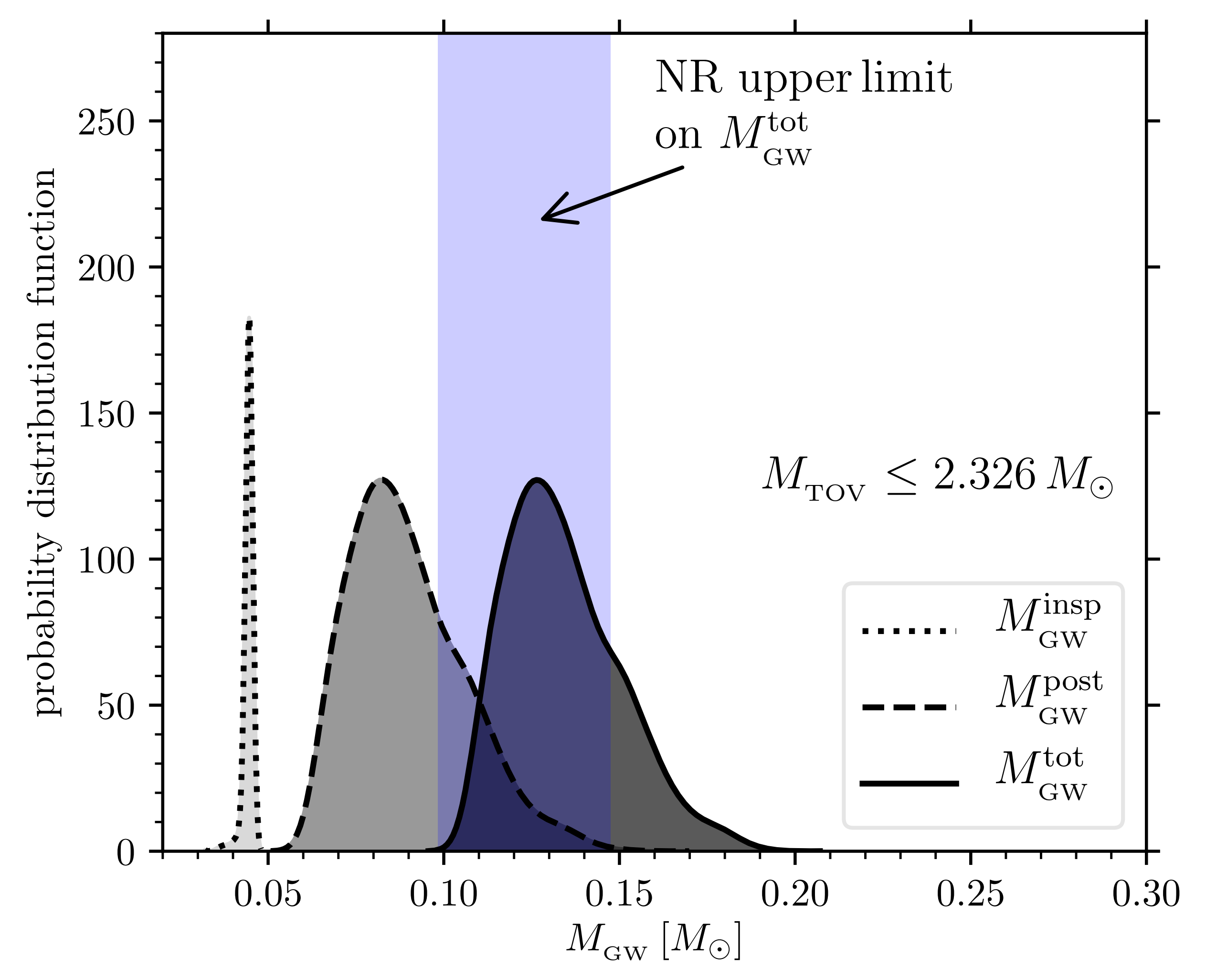
- Consider first previous estimate:

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

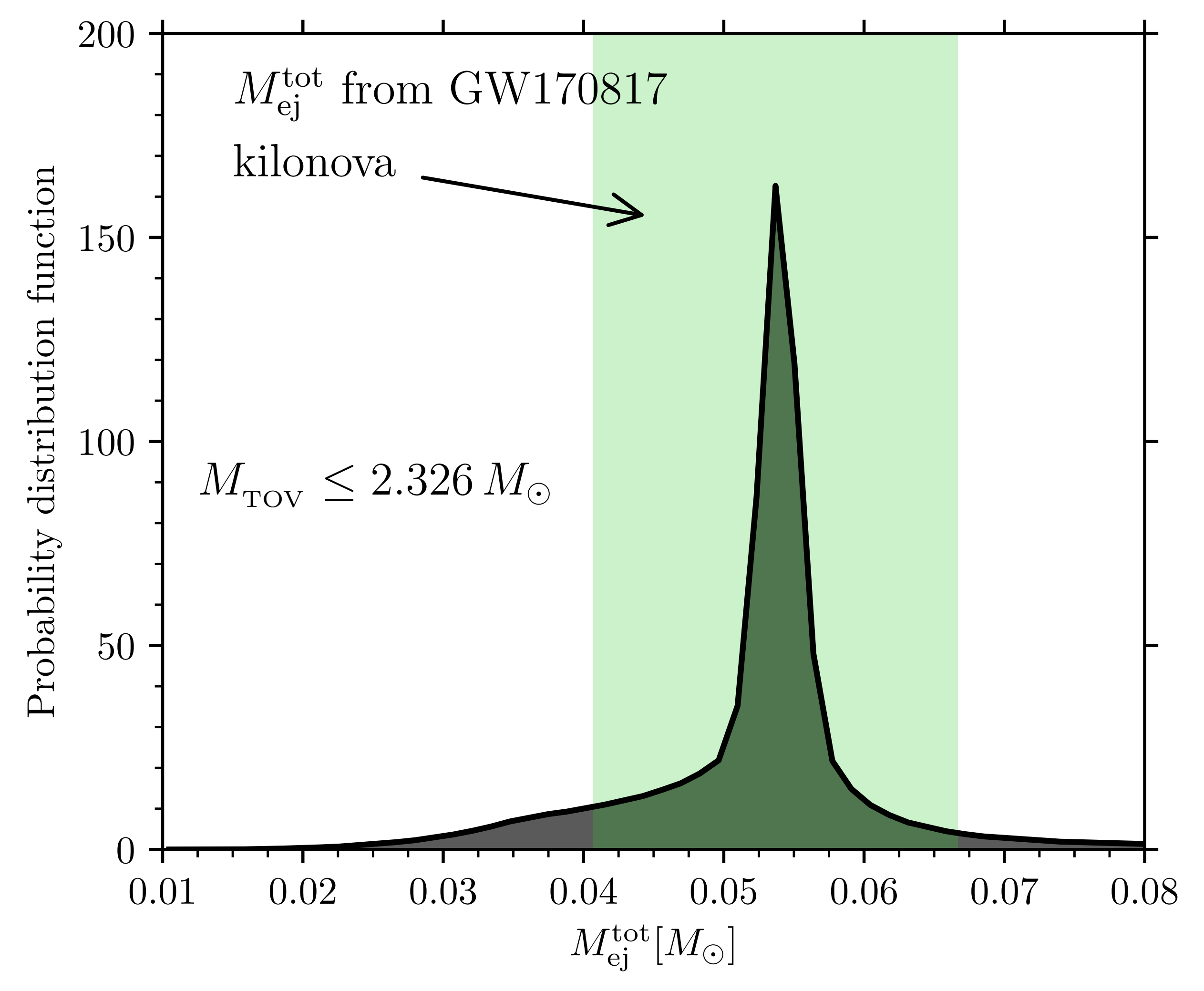
$$M_{\rm TOV}/M_\odot \leq 2.16^{+0.17}_{-0.15}$$



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

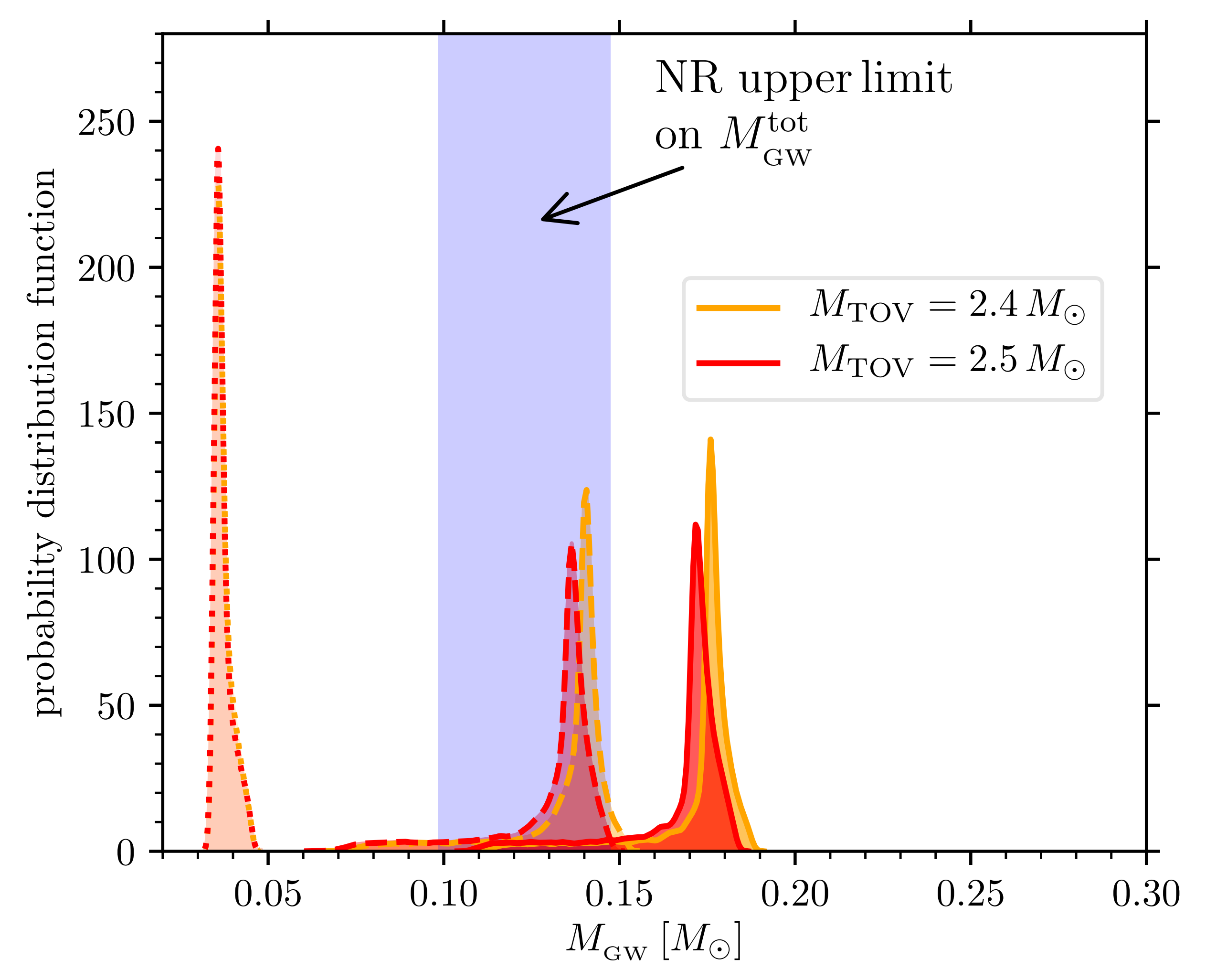


- Total mass emitted in GWs is in perfect **agreement** with predictions from numerical relativity

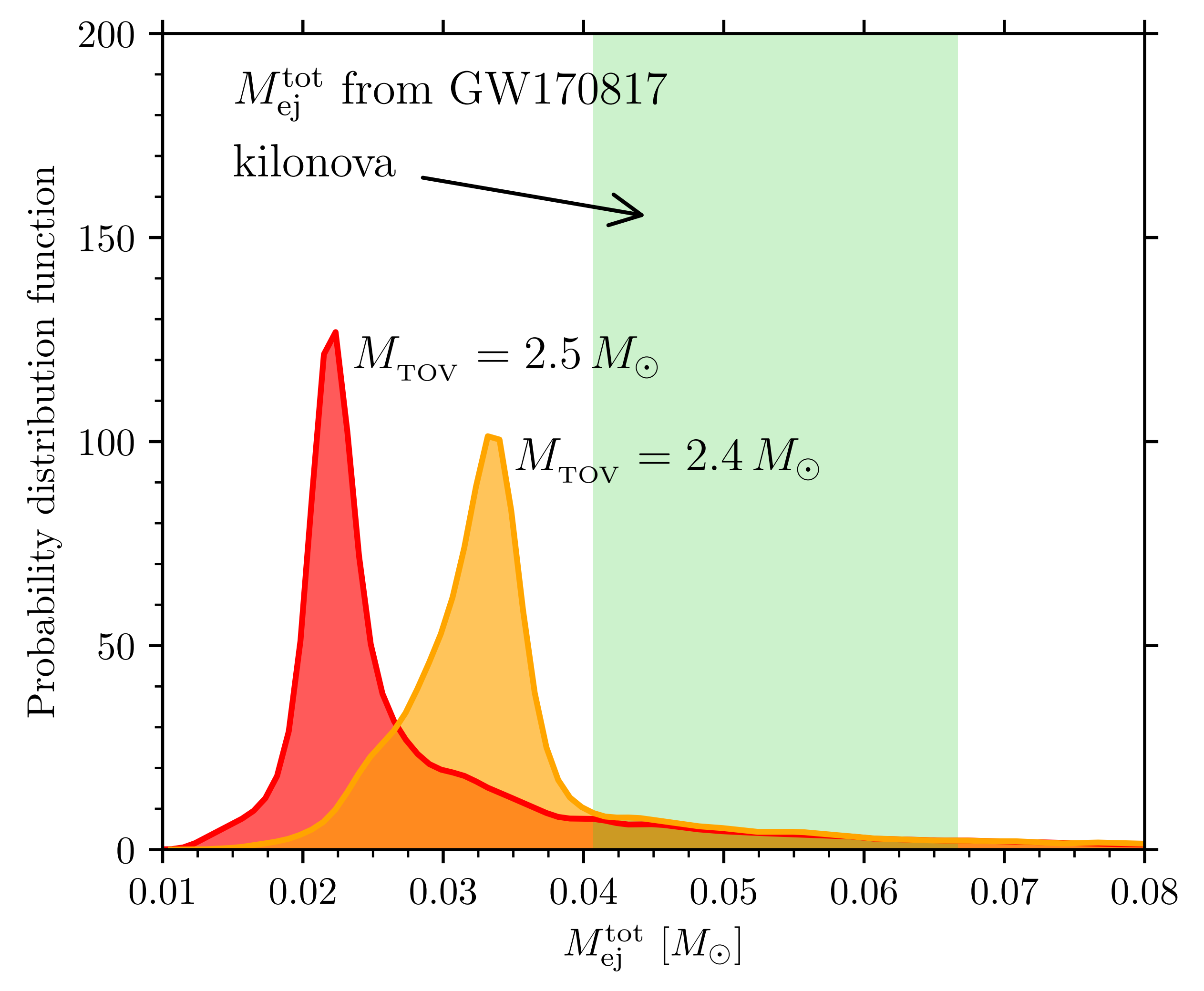


- Total mass ejected is in perfect **agreement** with predictions from kilonova signal

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.

Tension on the maximum mass

Nathanail, Most, LR (2020)

- The recent detection of GW190814 has created a significant tension on the maximum mass

$$M_1 = 22.2 - 24.3\,M_\odot$$

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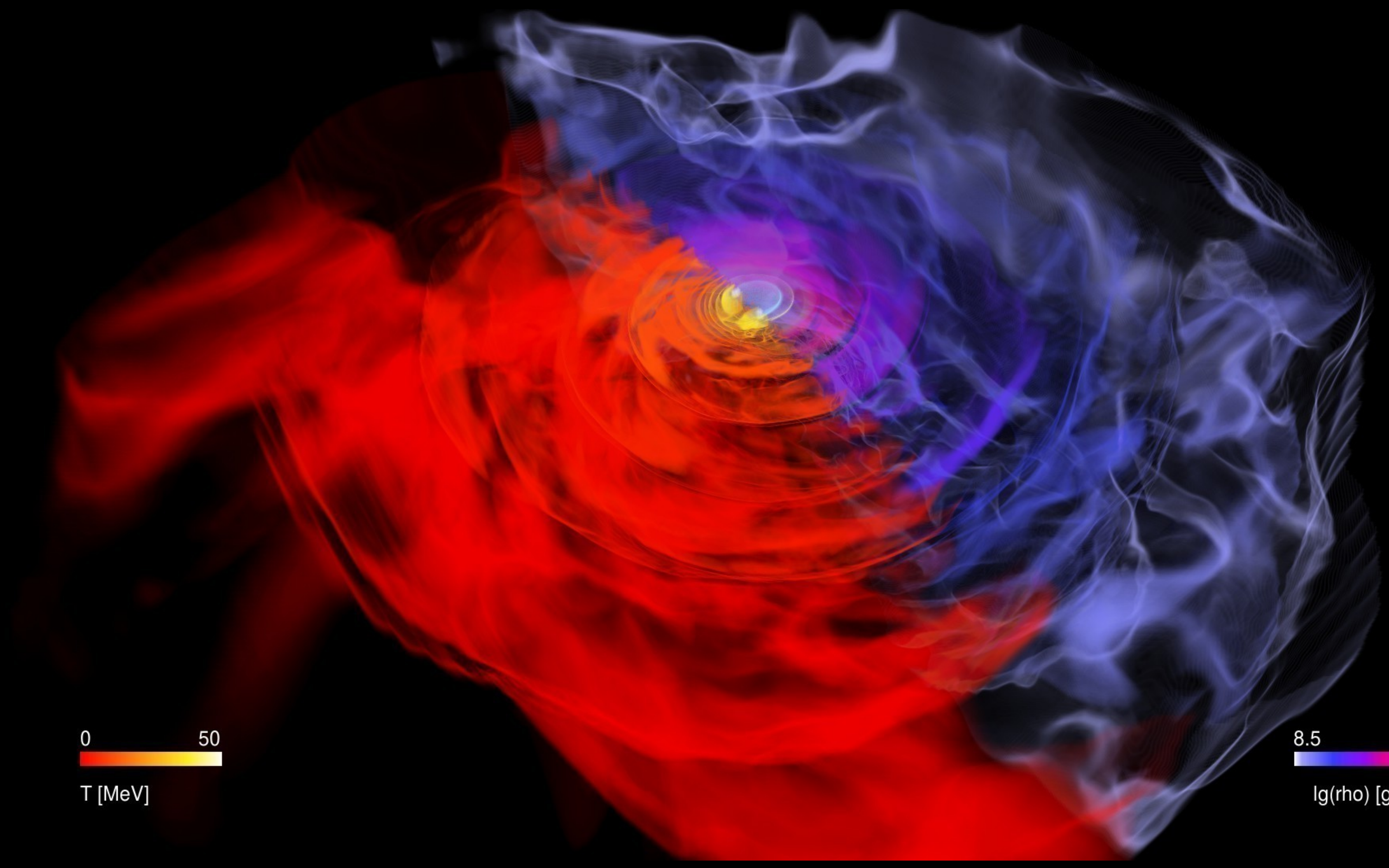
smallest BH or heaviest NS!

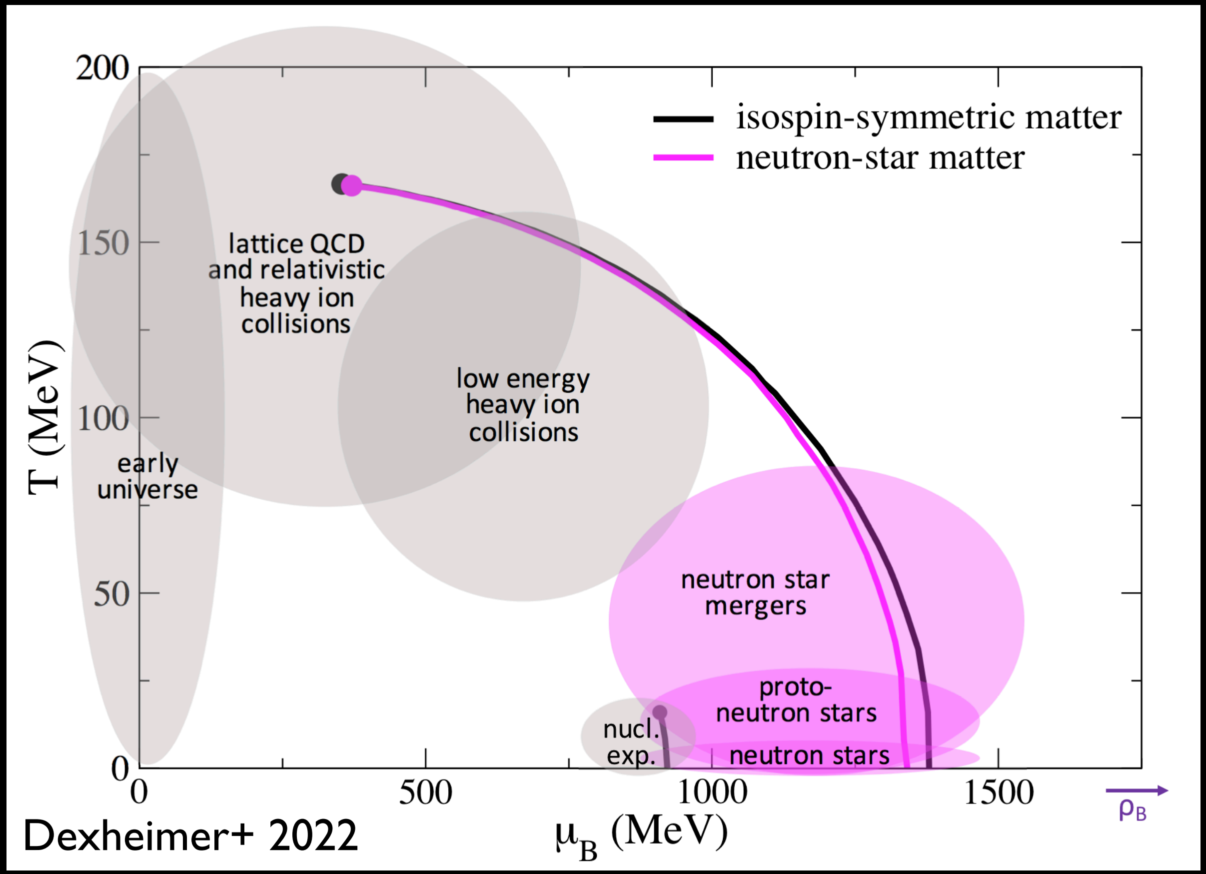
- If secondary in GW190814 was a NS, all previous considerations are incorrect.
- No EM counterpart was observed with GW190814 and no estimates possible on ejected matter or timescale for survival.
- **How do we solve this tension?**
- Solution: secondary in GW190814 **was a BH at merger** but could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

Phase transitions and their signatures

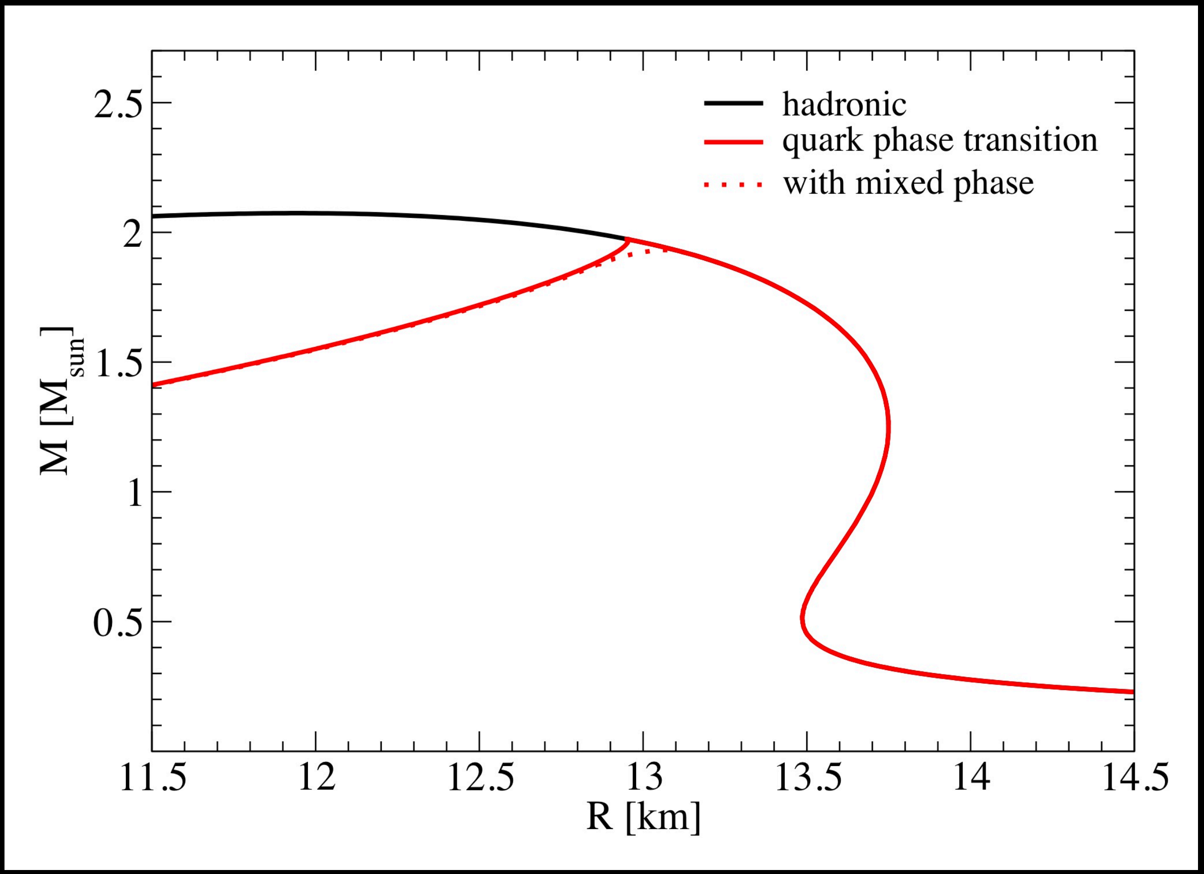


Most, Papenfort, Dexheimer, Hanauske, Schramm, Stoecker, LR (2019)
Weih, Hanauske, LR (2020)
Tootle, Ecker, Topolski, Demircik, Järvinen, LR (2022)

- **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.



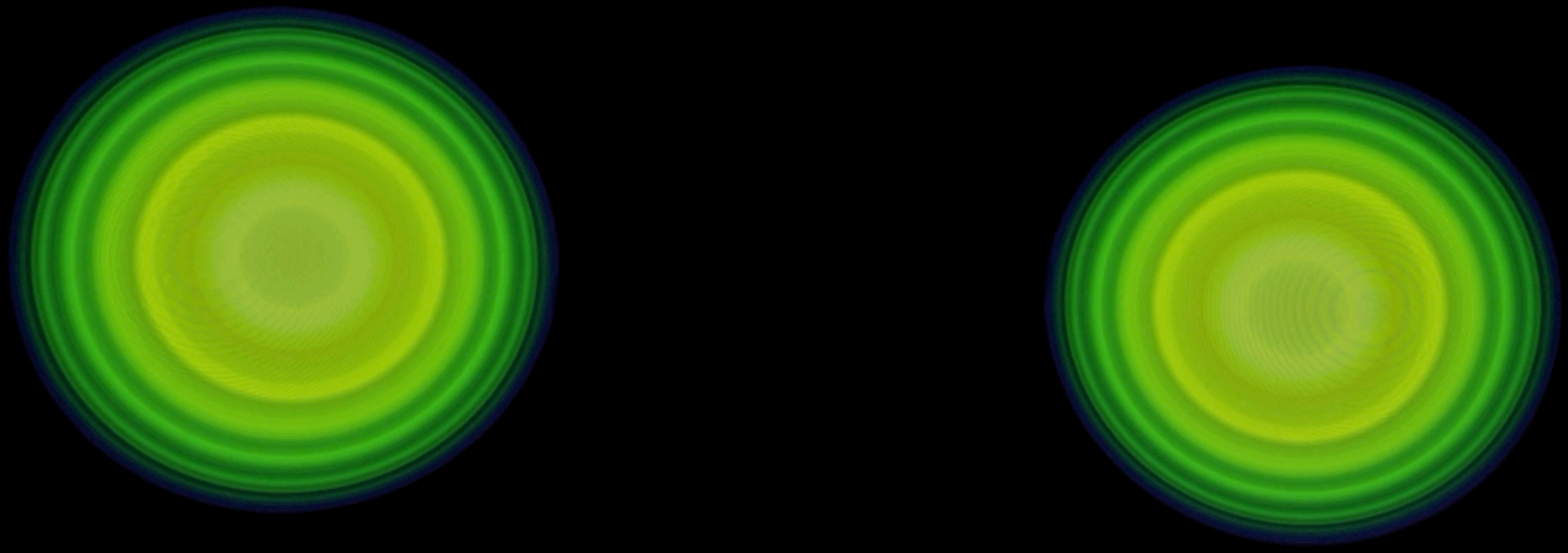
Dexheimer+ 2022

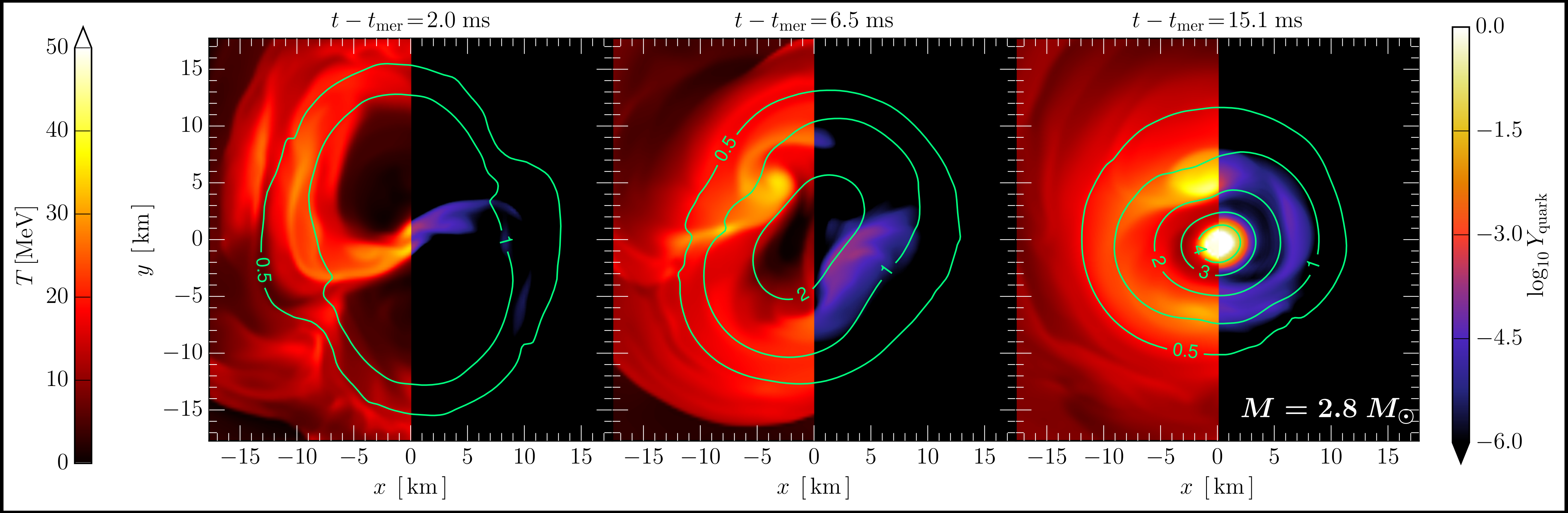


- Considered EOS based on Chiral Mean Field (CMF) model, based on a nonlinear SU(3) sigma model.
- Appearance of quarks can be introduced naturally.

Animations: Weih, Most, LR

Simulation of a phase-transition triggered collapse (PTTC)

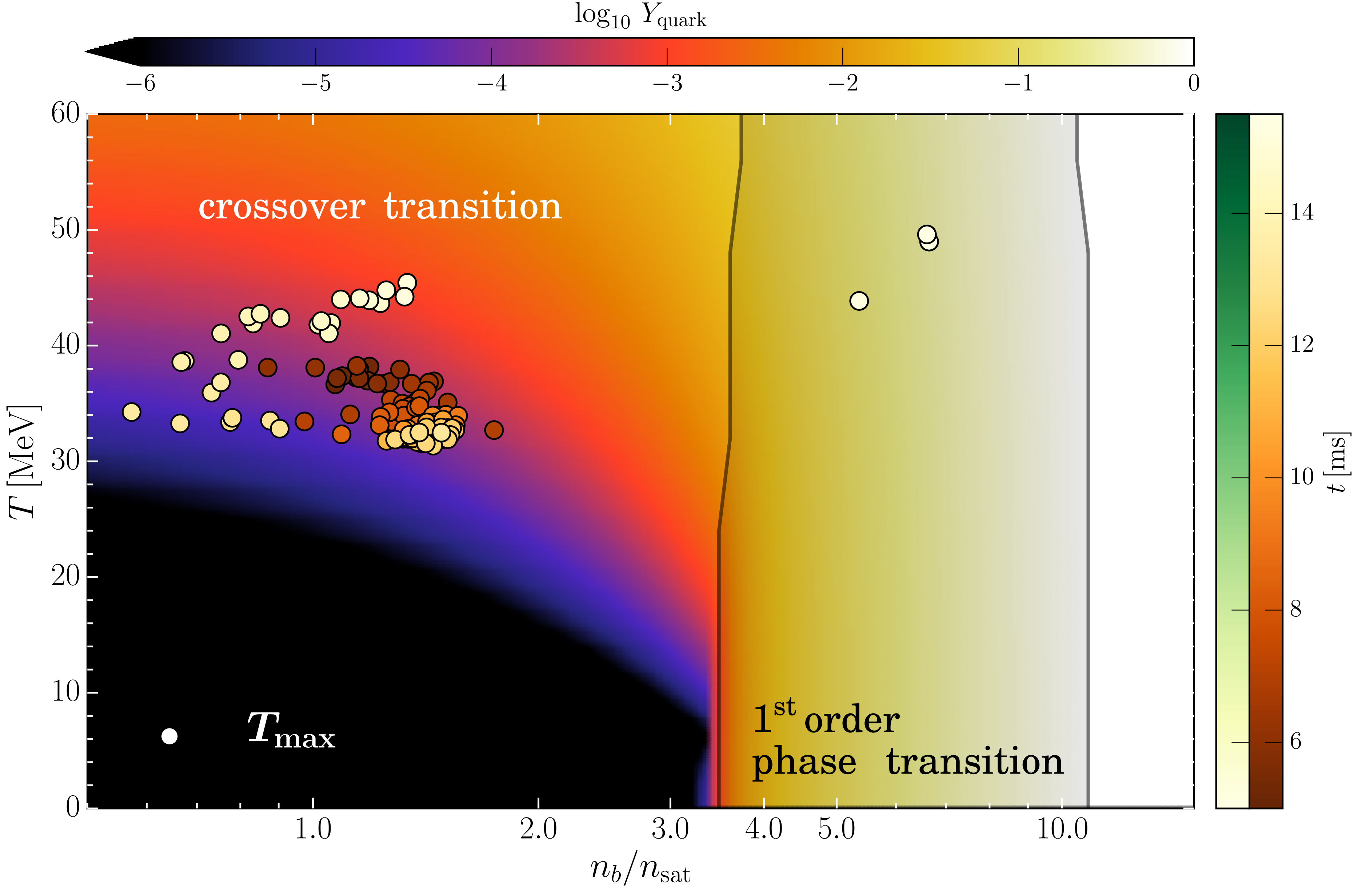




Quarks appear at sufficiently large temperatures and densities.

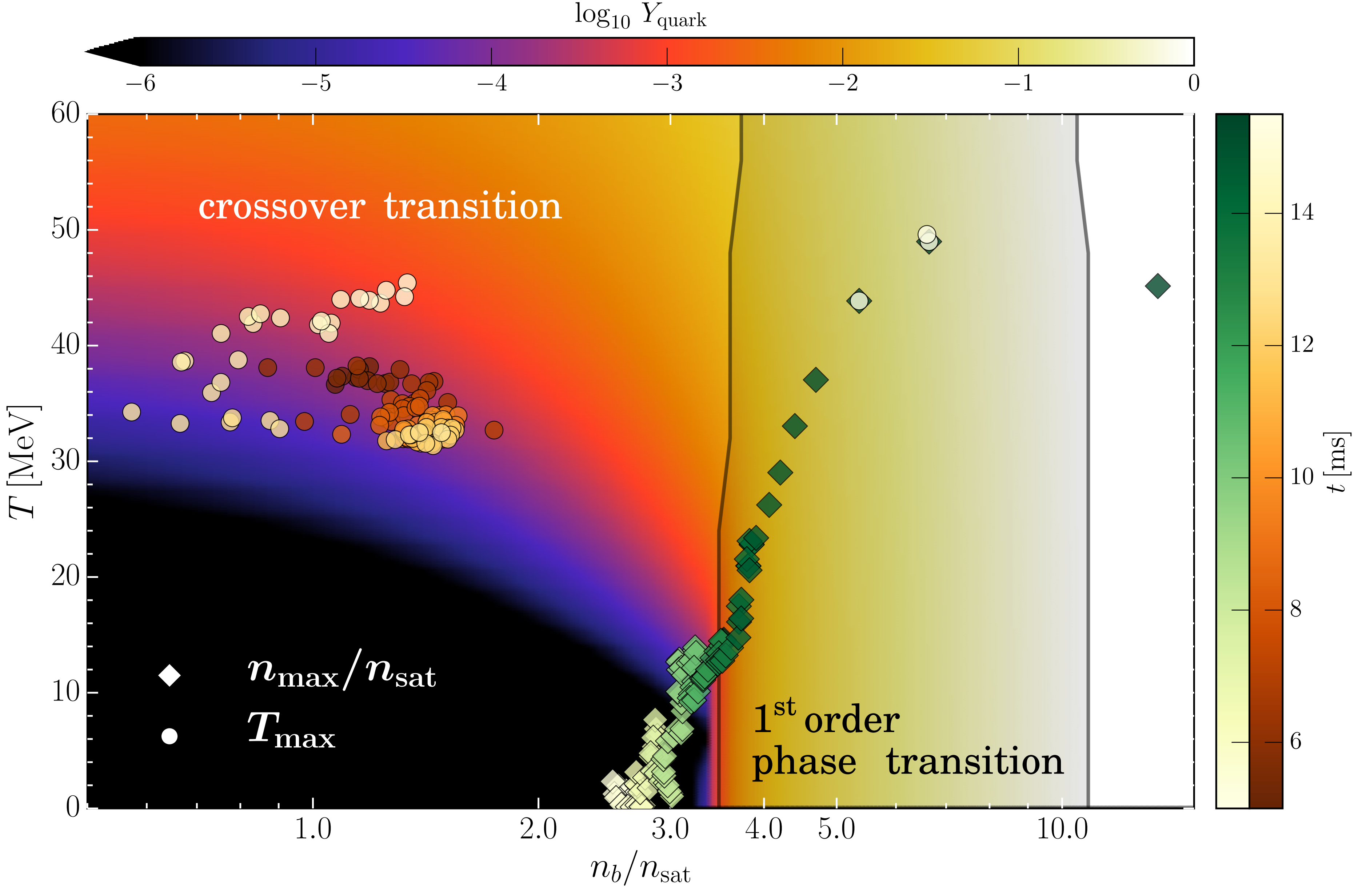
When this happens the EOS is considerably softened and a BH produced.

Comparing with the phase diagram



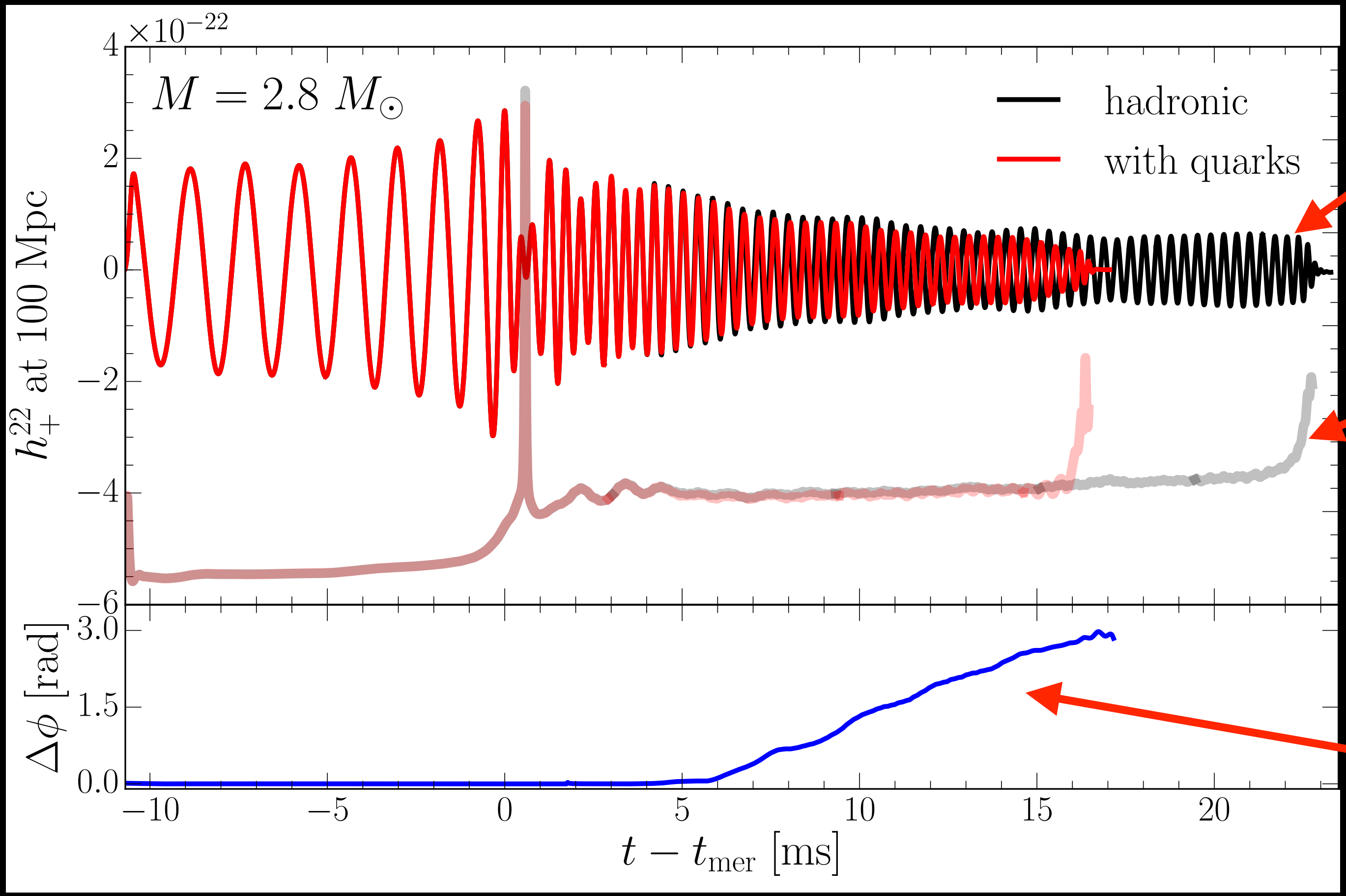
- Phase diagram with quark fraction
- Circles show the position in the diagram of the maximum temperature as a function of time

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

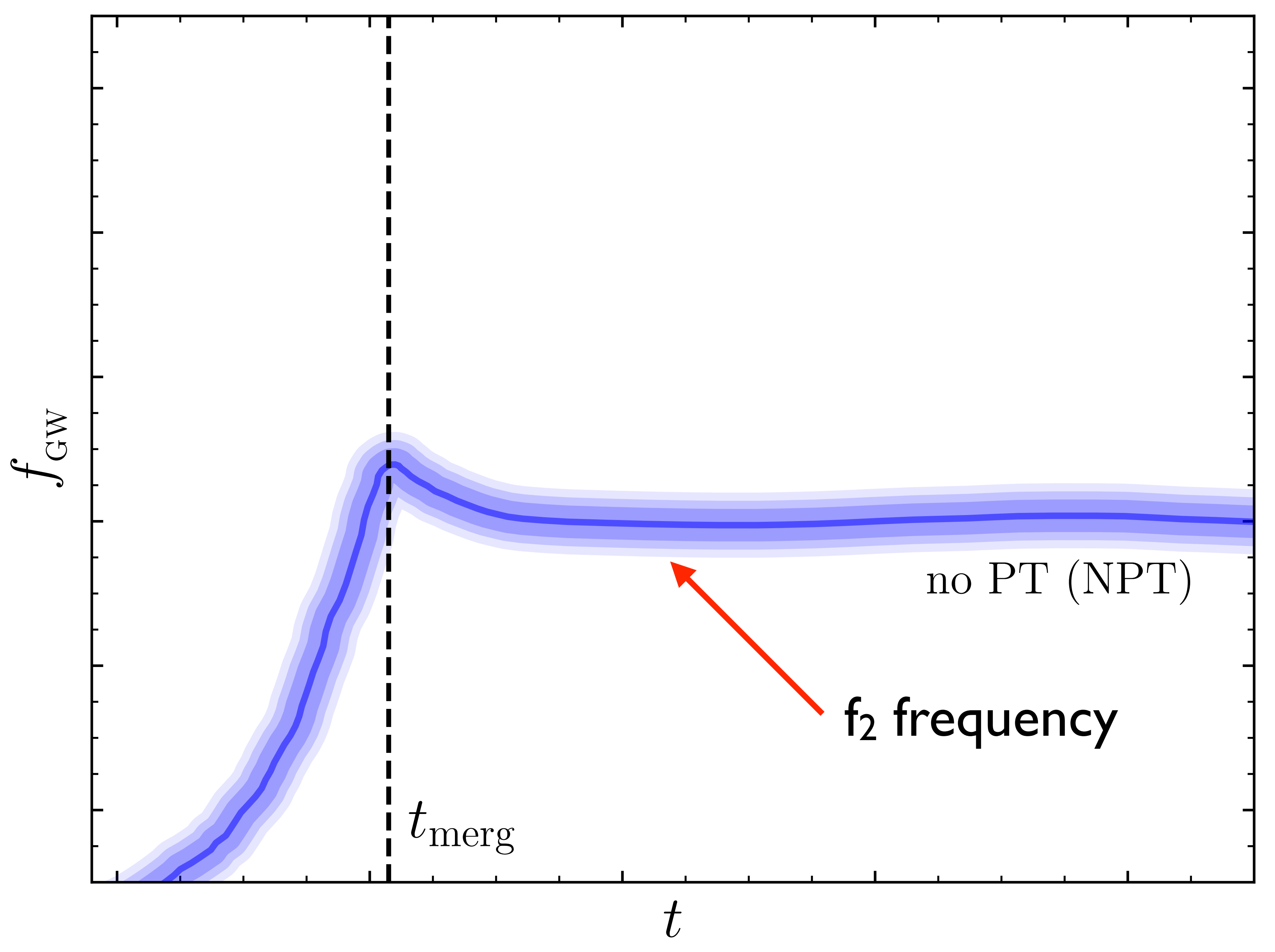
phase difference

- After~5 ms, quark fraction large enough to yield differences in GWs
- 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 zoology of behaviours

The occurrence of a PT considerably enriches the range of possible scenarios in the GW emission



f_2 frequency

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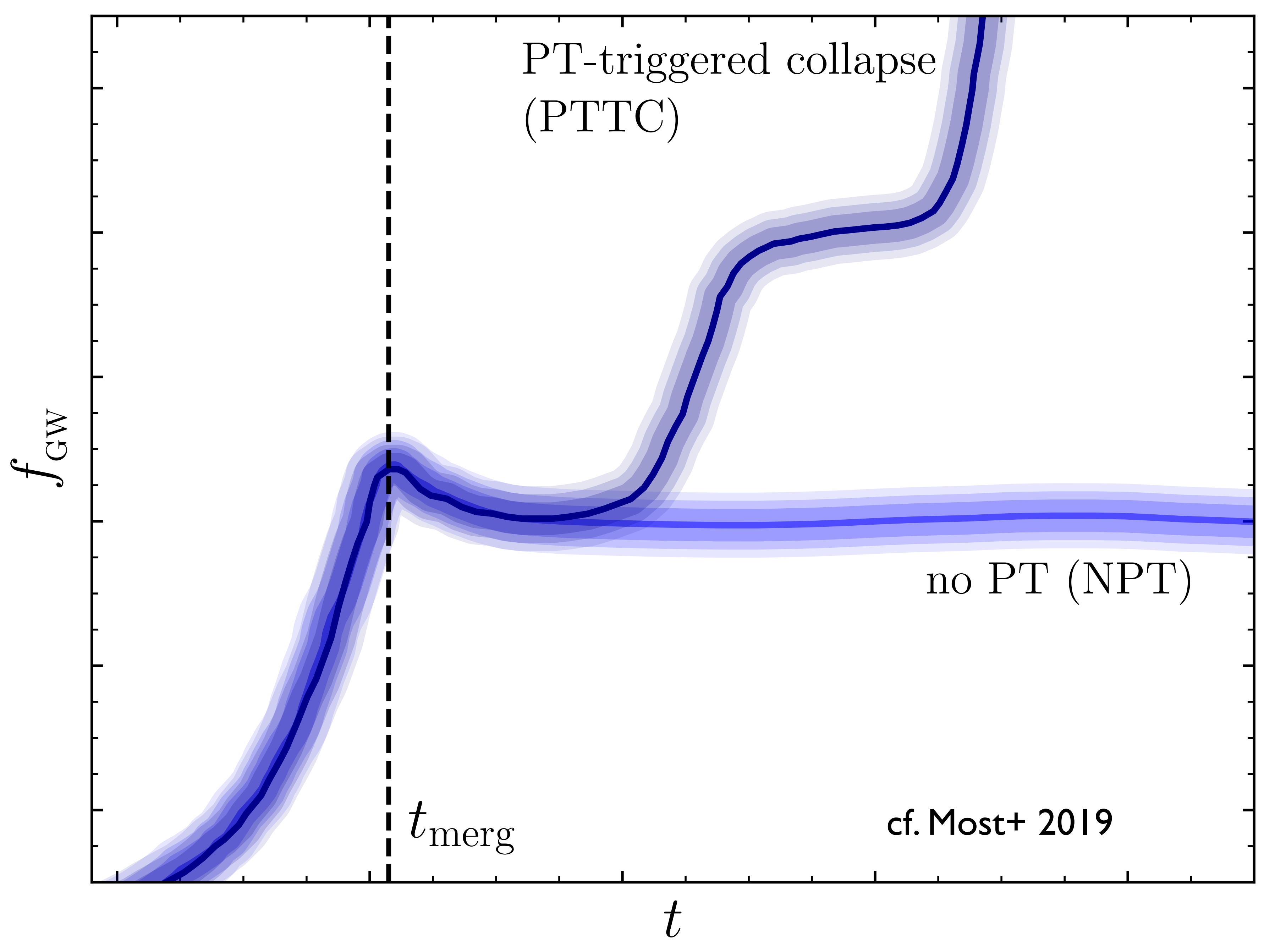

cf. Most+ 2019

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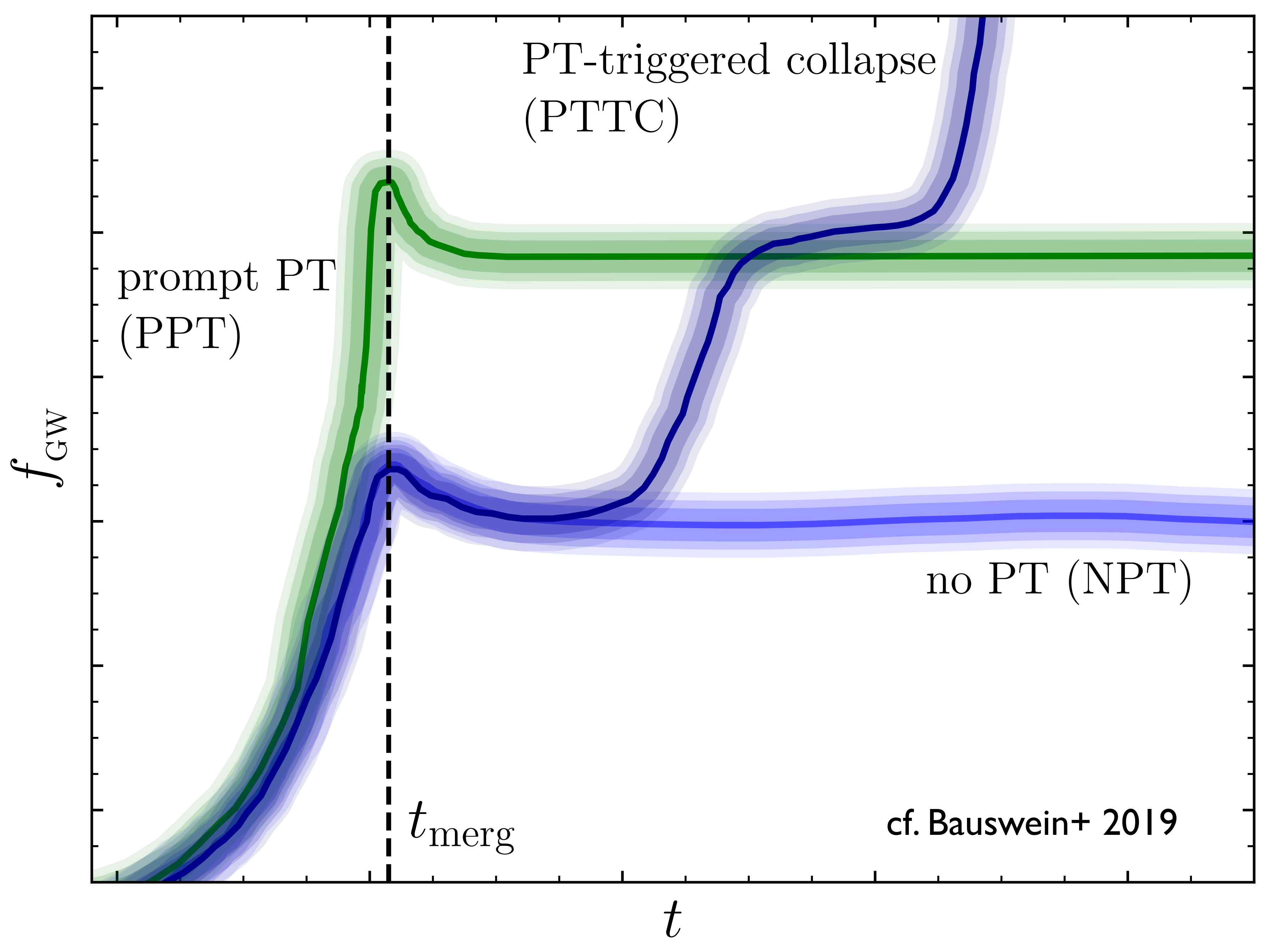
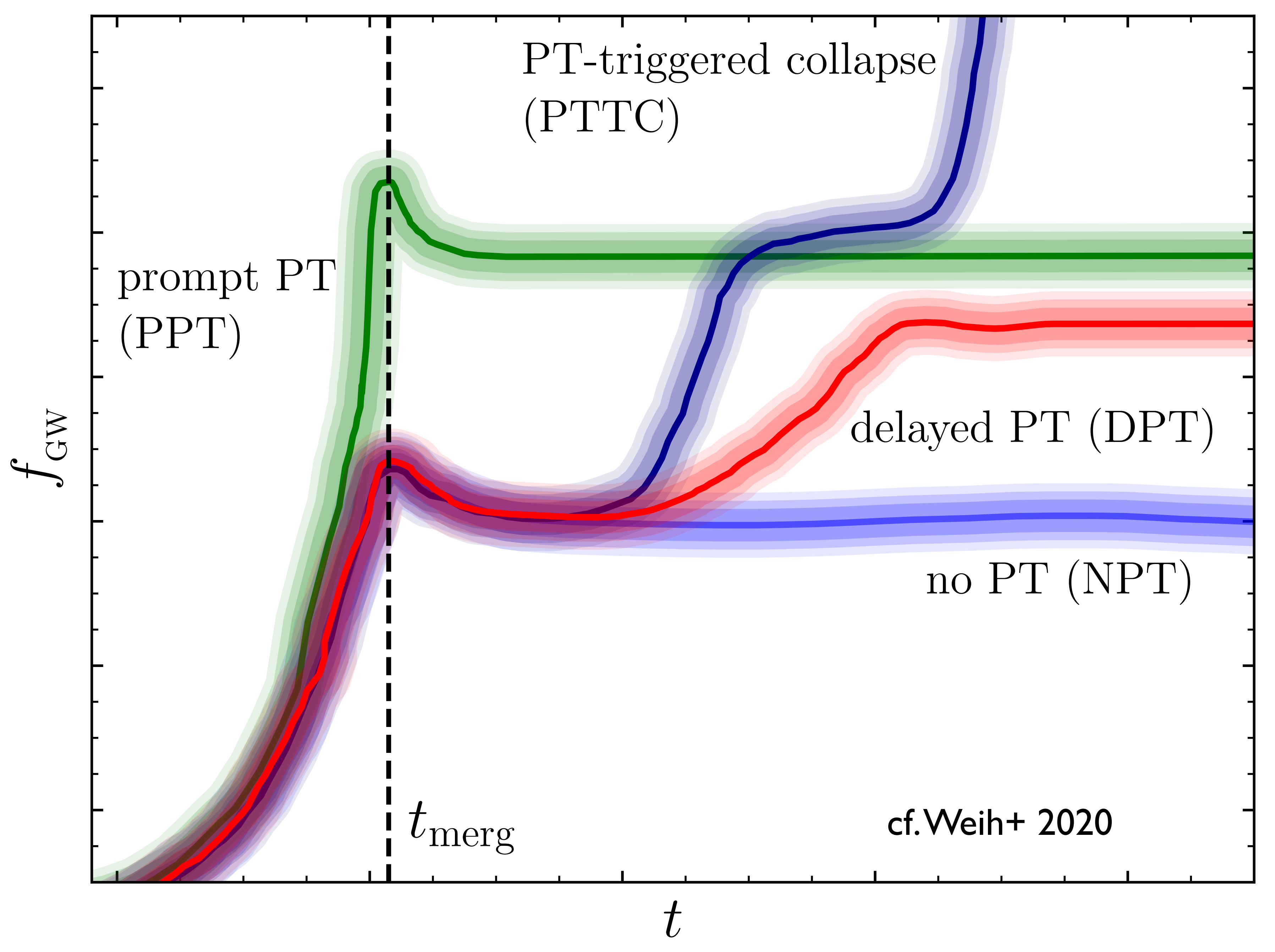


cf. Bauswein+ 2019

A zoology of behaviours

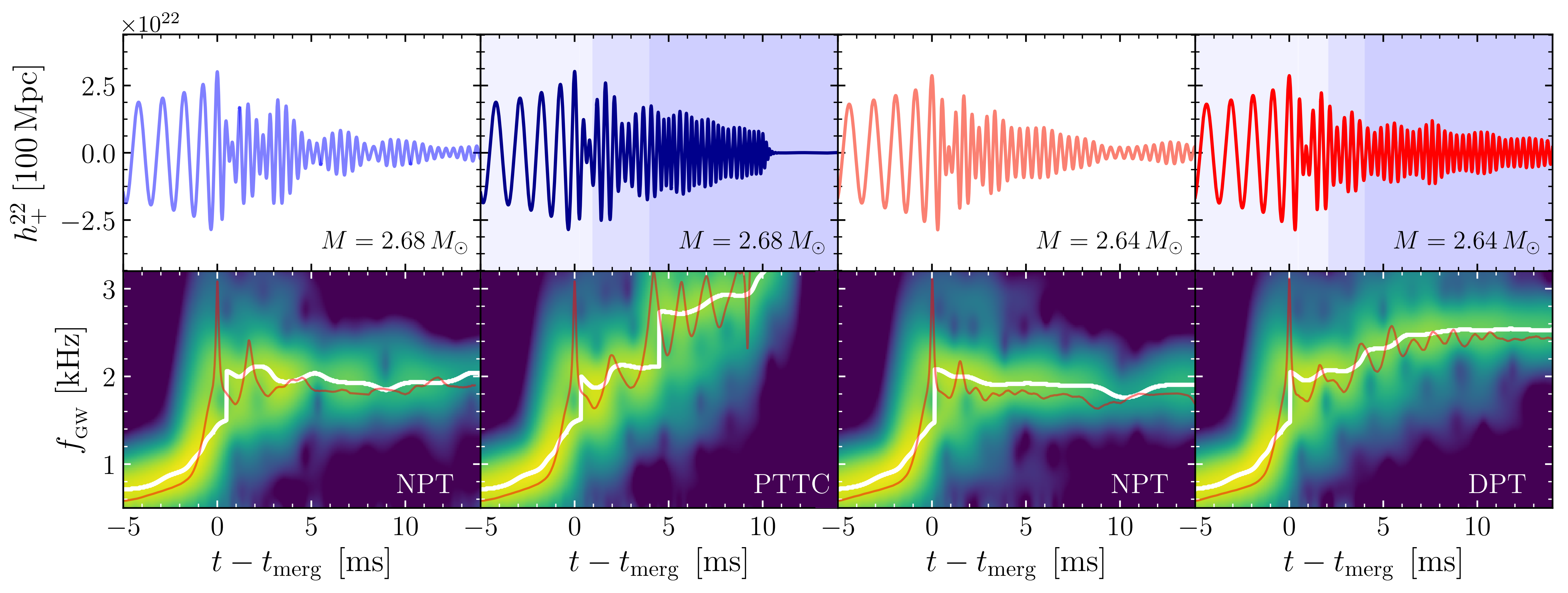
The occurrence of a PT considerably enriches the range of possible scenarios in the GW emission



cf. Weih+ 2020

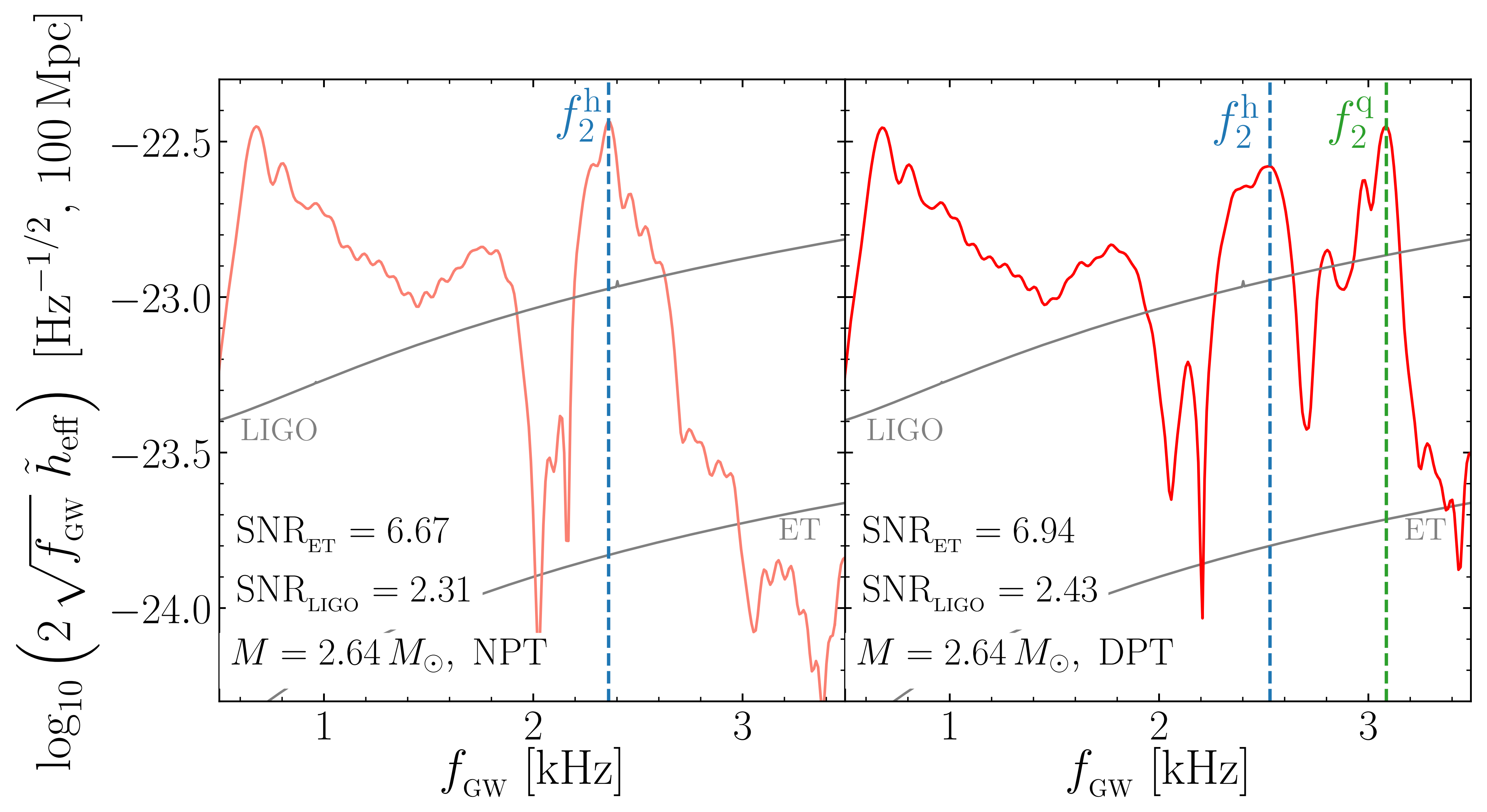
A more comprehensive picture

Zoology discussed above can be recognised when shown in terms of the gravitational waves and their spectrograms.



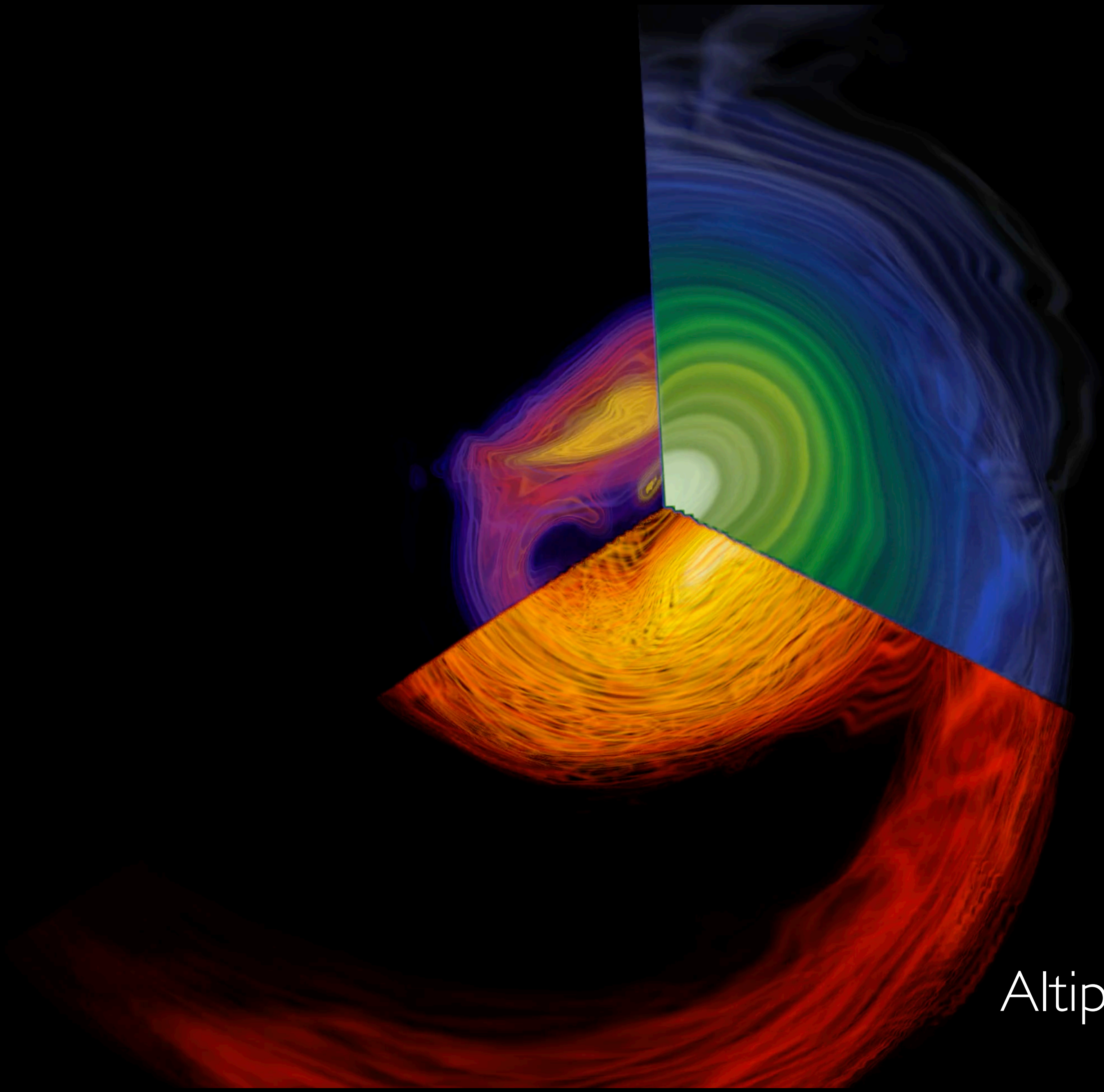
Importance of **DPT** is that it leads to **two** different "stable" f_2 **frequencies** that are easily distinguishable in the PSD

Why DPT is the most interesting case



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

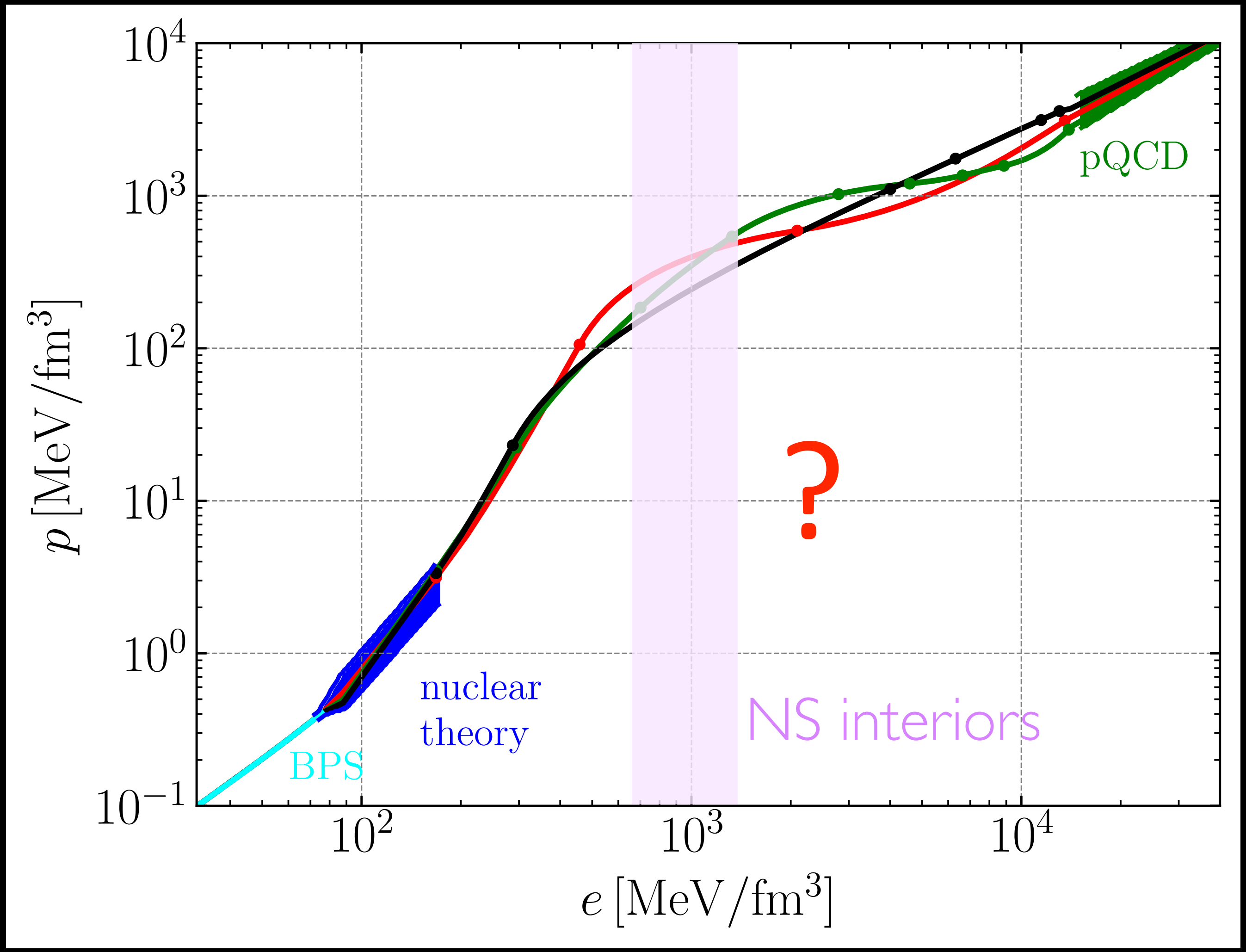
On the sound speed in neutron stars

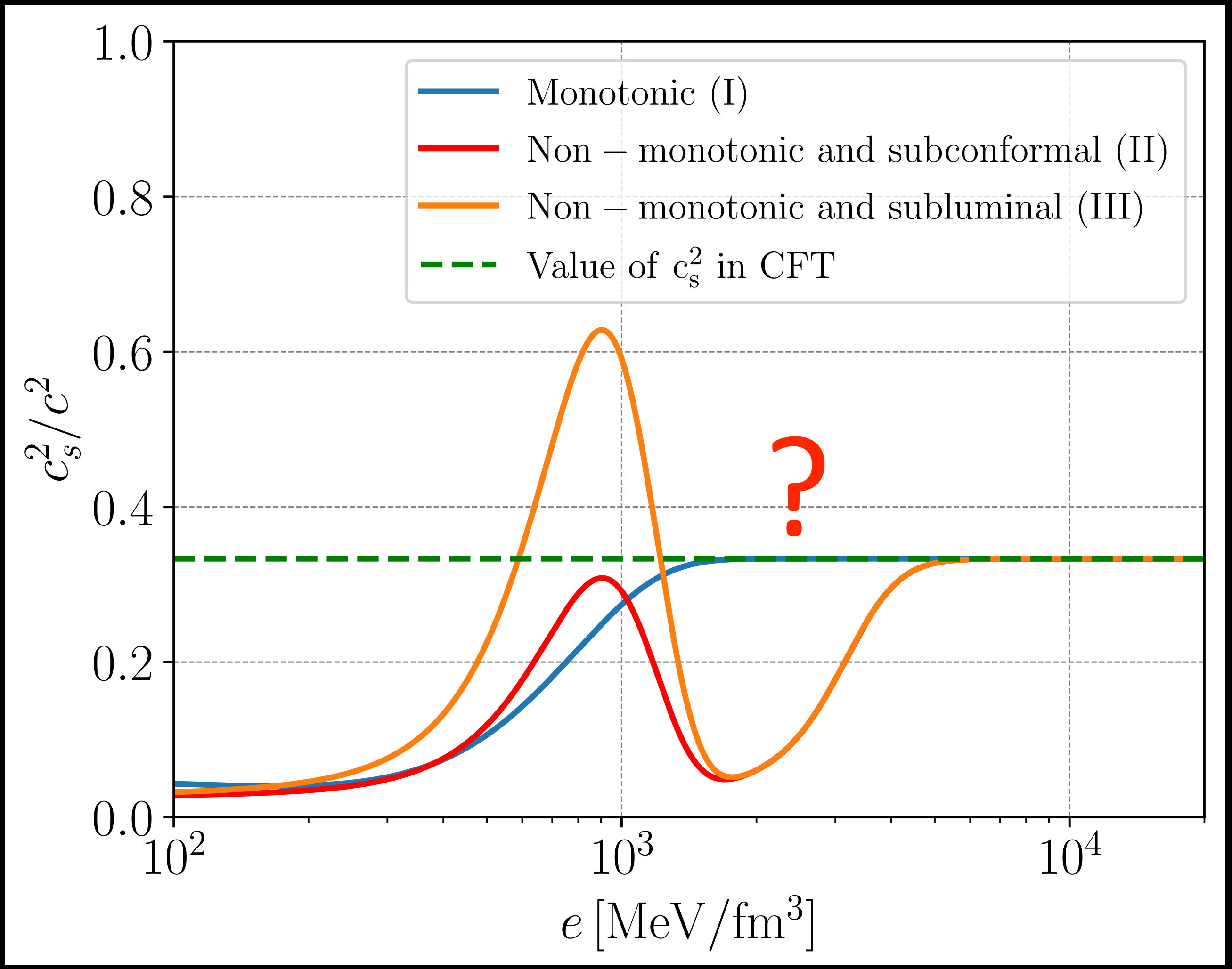


Altiparmak, Ecker, LR (2022a)
Ecker, LR (2022b)
Ecker, LR (2022c)

A very basic question

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





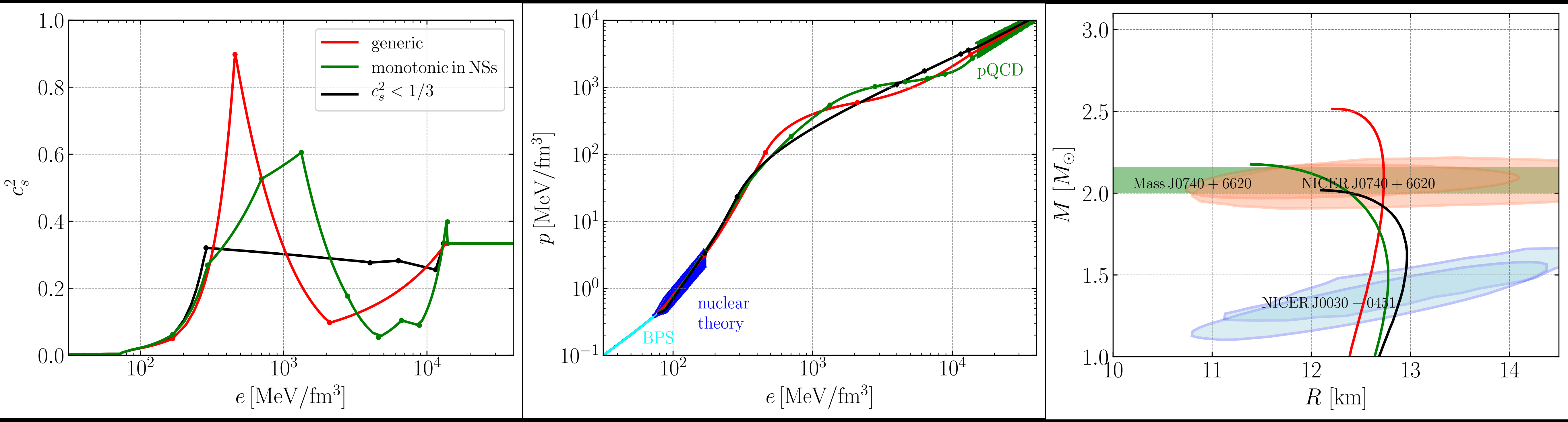
i) monotonic and sub-conformal: $c_s^2 < 1/3$ (blue)

ii) non-monotonic and sub-conformal: $c_s^2 < 1/3$ (orange)

iii) non-monotonic and sub-luminal: $c_s^2 < 1$ (red)

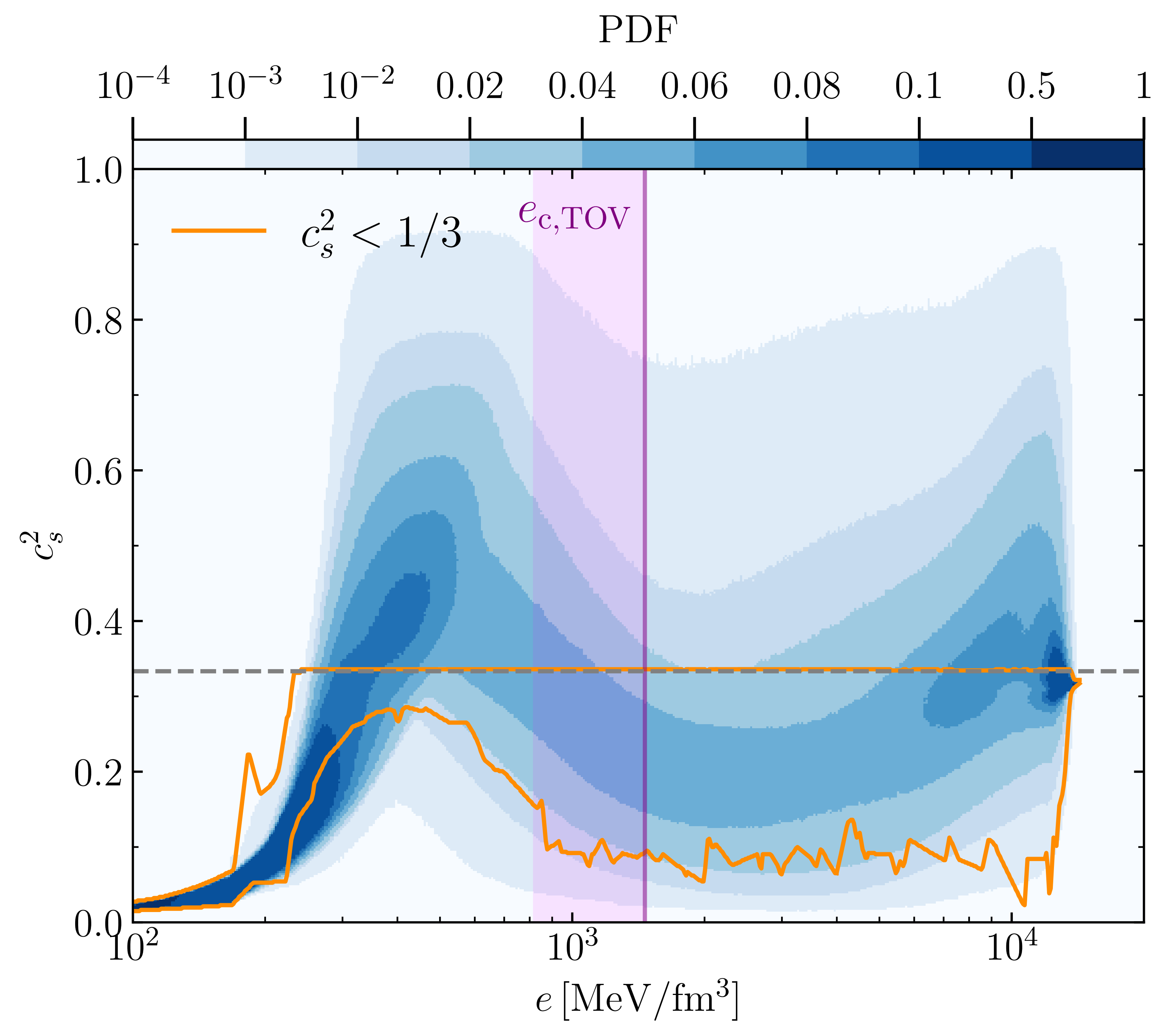
- Lacking stronger constraints, an **agnostic approach** is viable and followed by many (eg piecewise polytropes, Most+ 2018)

- Alternative, we can 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). We repeat 1.5x10^7 times…
- In this way, ~ 10% of our EOSs survives and provides robust statistics from which we compute PDFs.

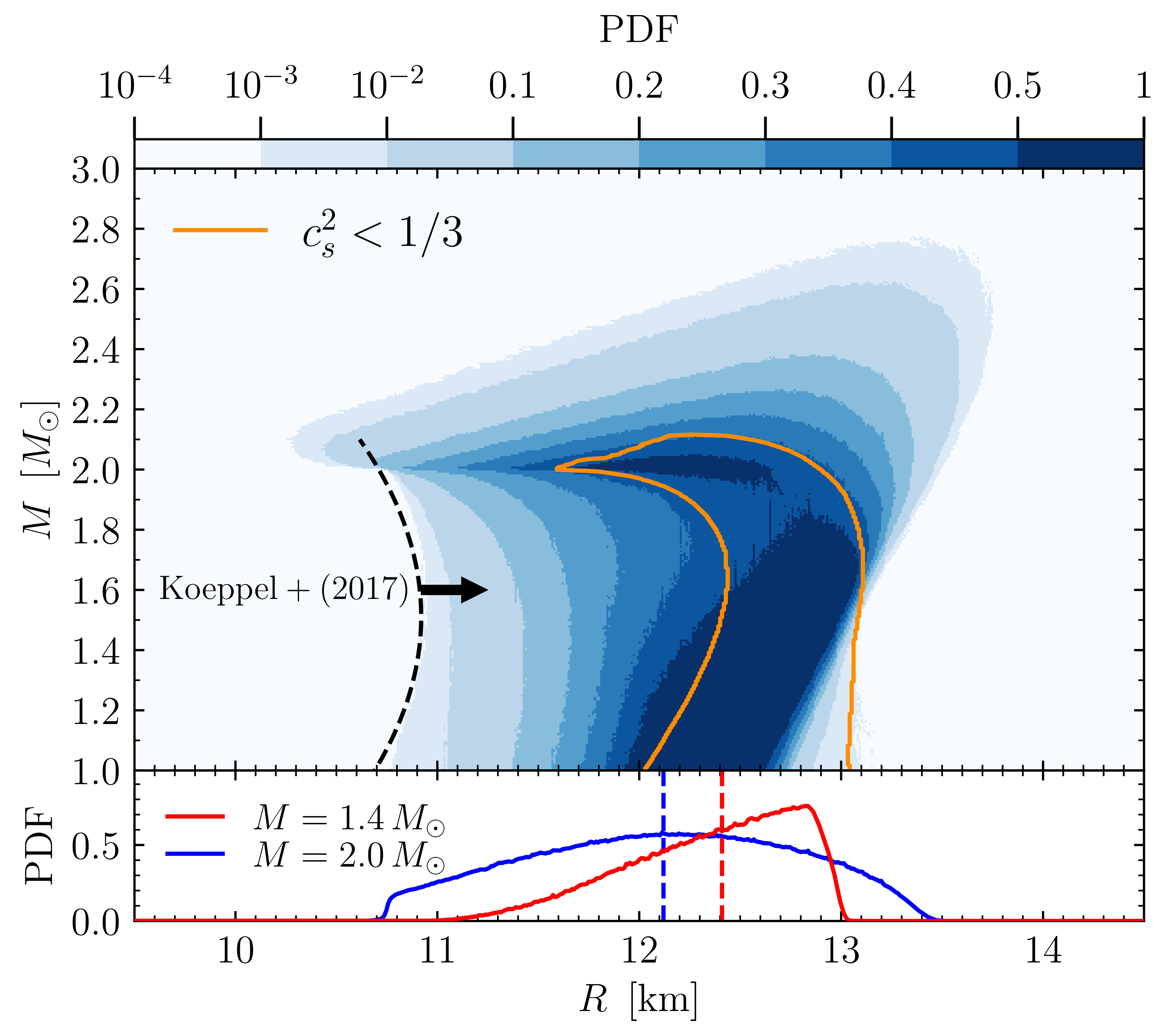
Sound speed PDF



Orange line marks region of sub-conformal EOSs (0.03%).

No monotonic sub-conformal EOS found.

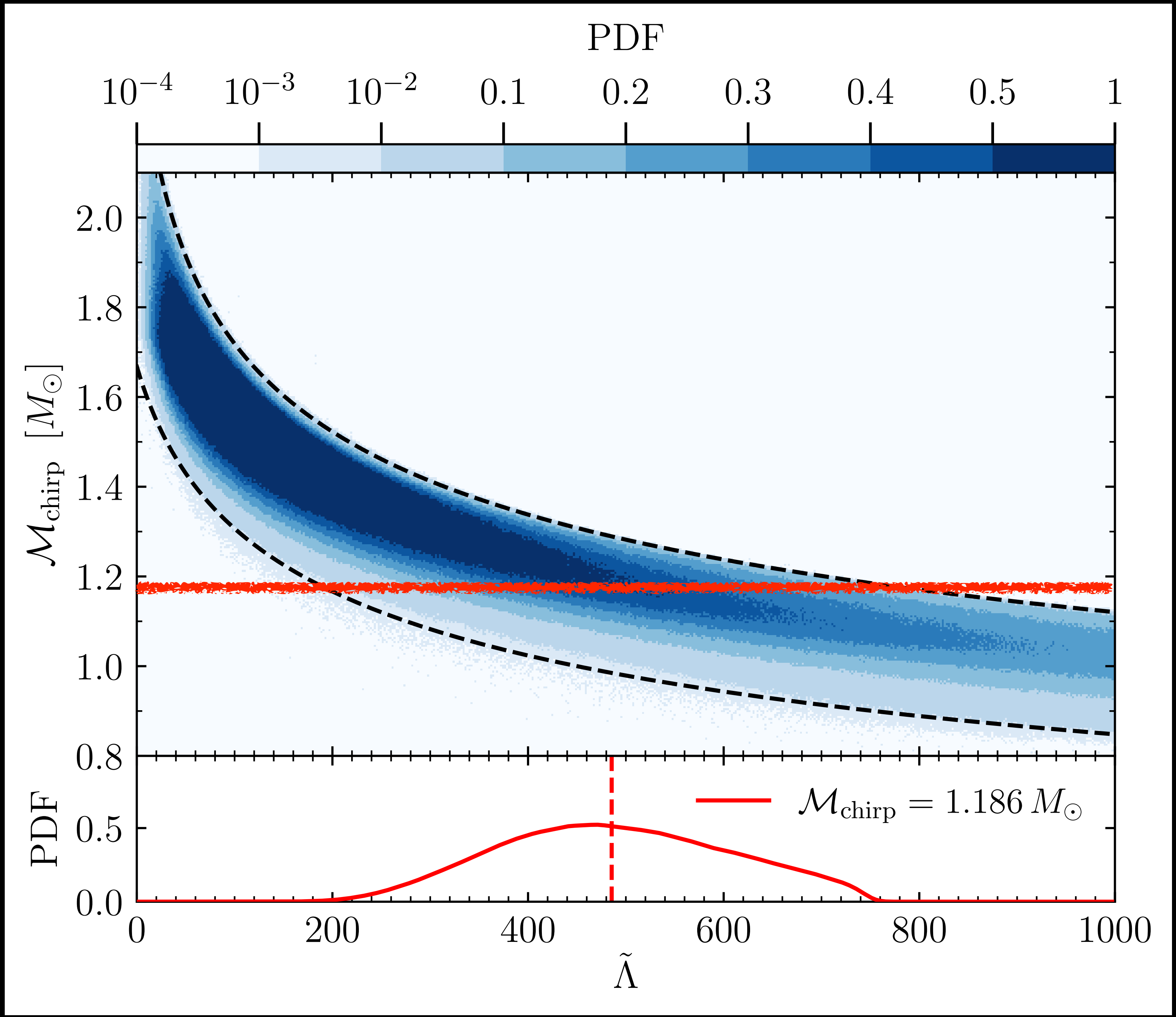
A more comprehensive picture



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

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

A more comprehensive picture



Simple behaviour of binary tidal deformability: $\tilde{\Lambda}_{\rm min\ (max)} = a + b\,\mathcal{M}^c_{\rm chirp}$

Straightforward bounds once a detection is made.

A scale-independent representation

With this large sample one may ask simple but basic questions:

- How does the sound speed vary in a star?
- Is the maximum sound speed at the center of the star?
- Does the maximum value attain a constant value?

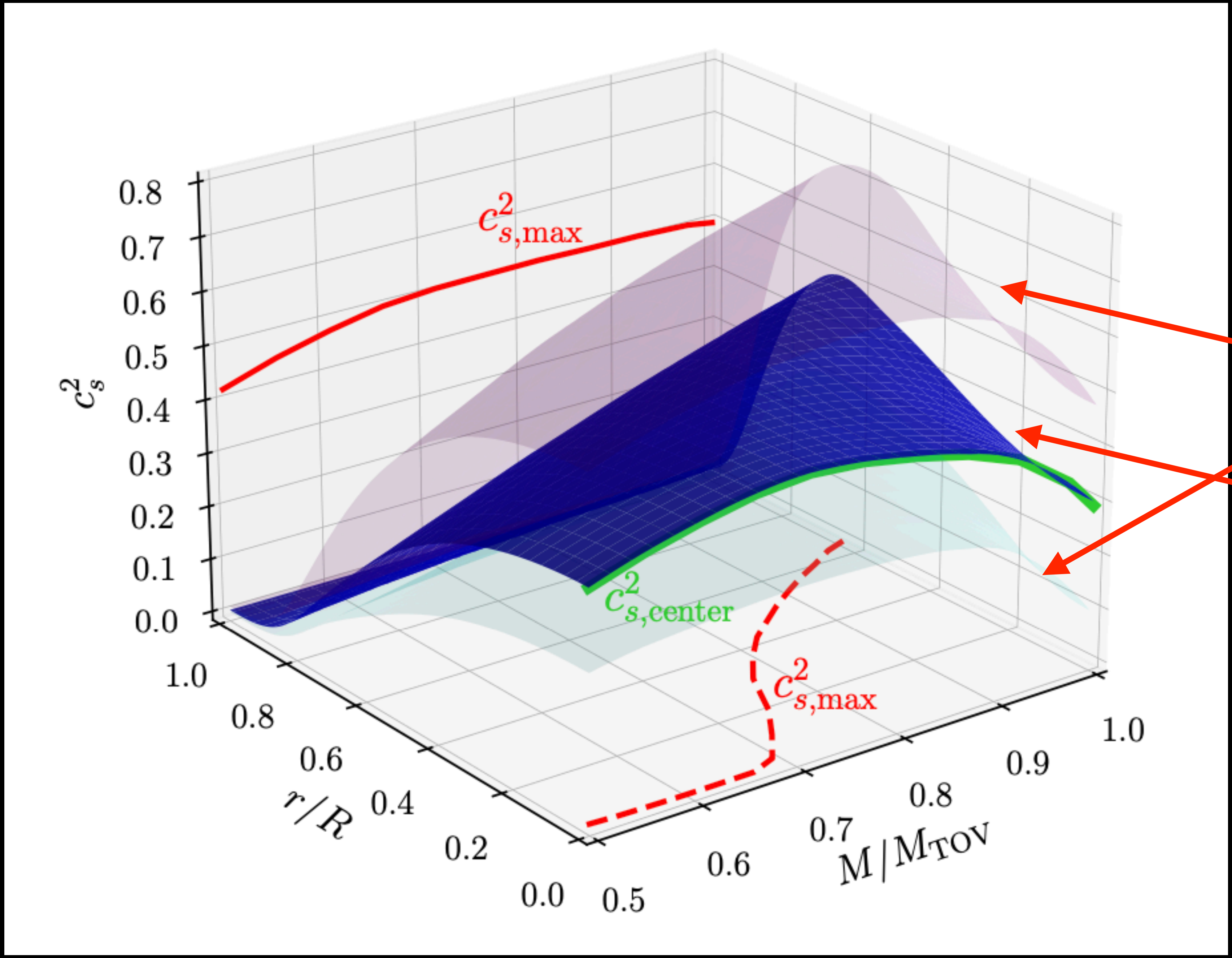
Hard to answer: every EOS will have its own *(M, R)* relation

$c_s \in [0, c], \qquad r \in [0, R], \qquad M \in [0, M_{\mathrm{TOV}}]:$ **EOS dependent**

$c_s/c \in [0, 1], \qquad r/R \in [0, 1], \qquad M/M_{\mathrm{TOV}} \in [0, 1]:$ **EOS independent**

A scale-independent representation

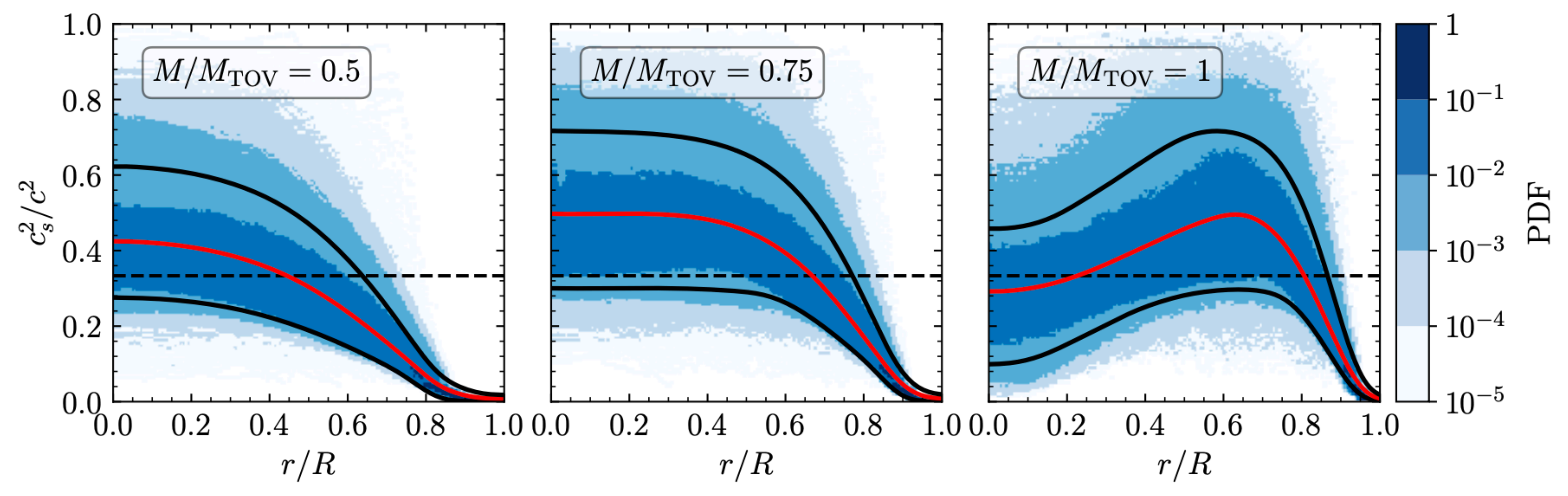
All information contained in a unit cube: $(c_s/c,\ r/R,\ M/M_{\rm TOV})$



95% confidence

median

A scale-independent representation



"Light" stars: sound speed monotonic with maximum at stellar center

"Heavy" stars: sound speed non-monotonic with maximum far from stellar center (*r*/*R*~0.7)

In other words:

“Light” stars: stiff core, soft mantle

“Heavy” stars: soft core, stiff mantle

Press release: “*…neutron stars behave like chocolate pralines. Light stars have stiff core and soft exterior; heavy stars have soft core and hard exterior…*"

The *”sweetest”* discovery of the year

Conclusions

✳Spectra of post-merger shows peaks, some **”quasi-universal”**.

✳**GW170817, GW190814** 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**

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

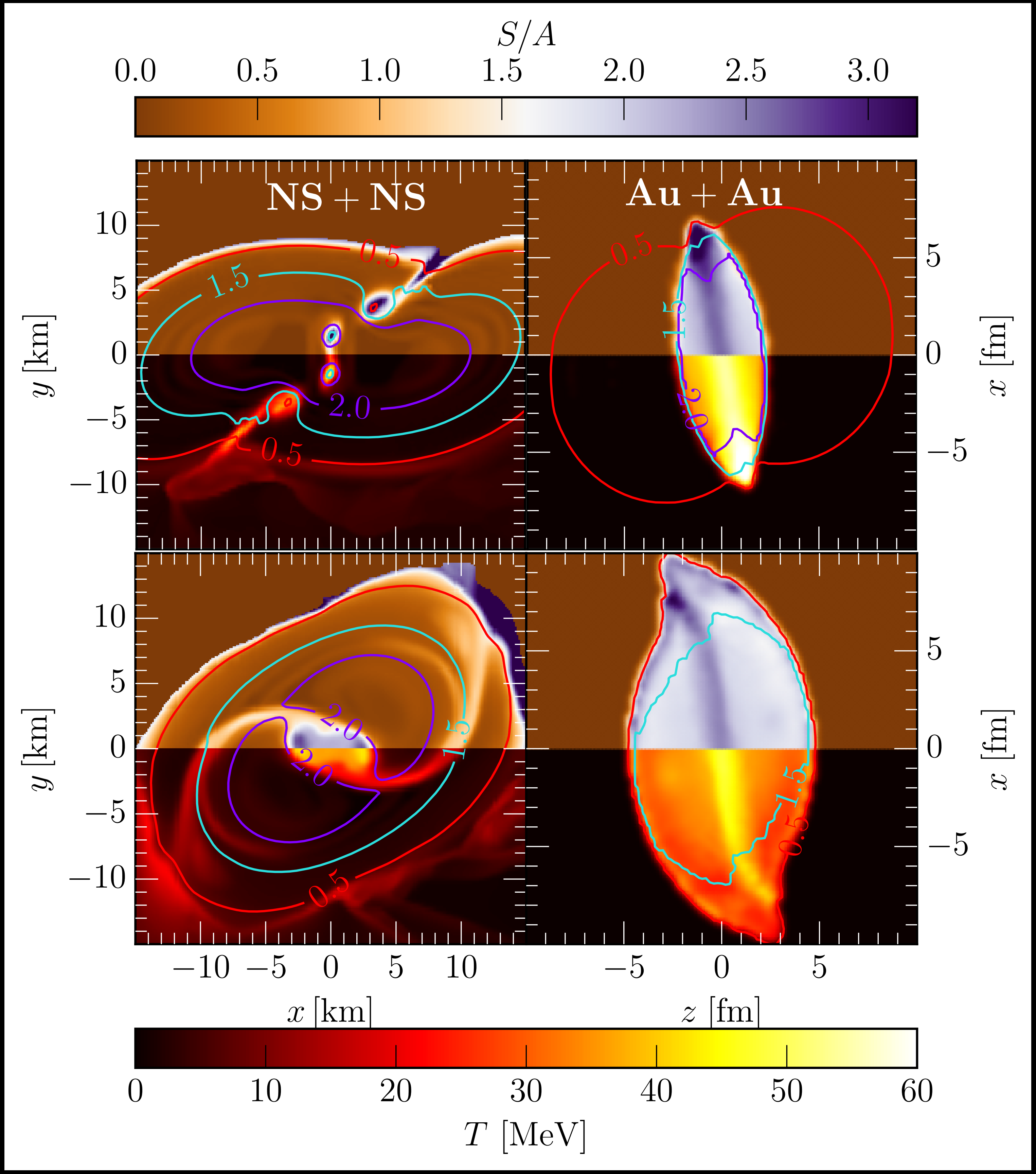
✳**Sound speed** in neutron stars cannot be sub-conformal and monotonic; likely to be super-conformal somewhere in the interior.

✳**Sound speed** monotonic in light stars (max at centre), non-monotonic in heavy stars (max in mantle)

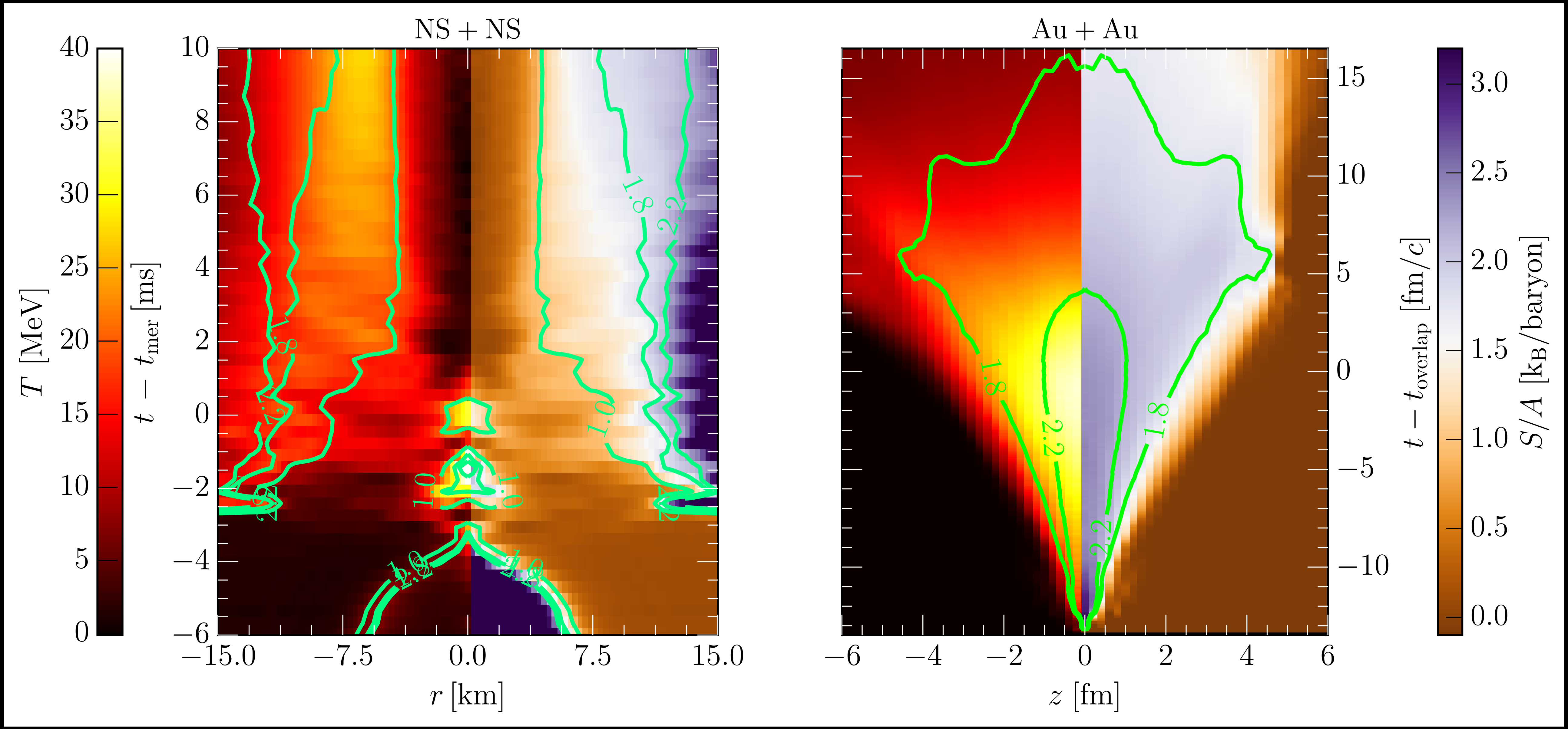
EXTRAS

Probing neutron-star matter in the lab

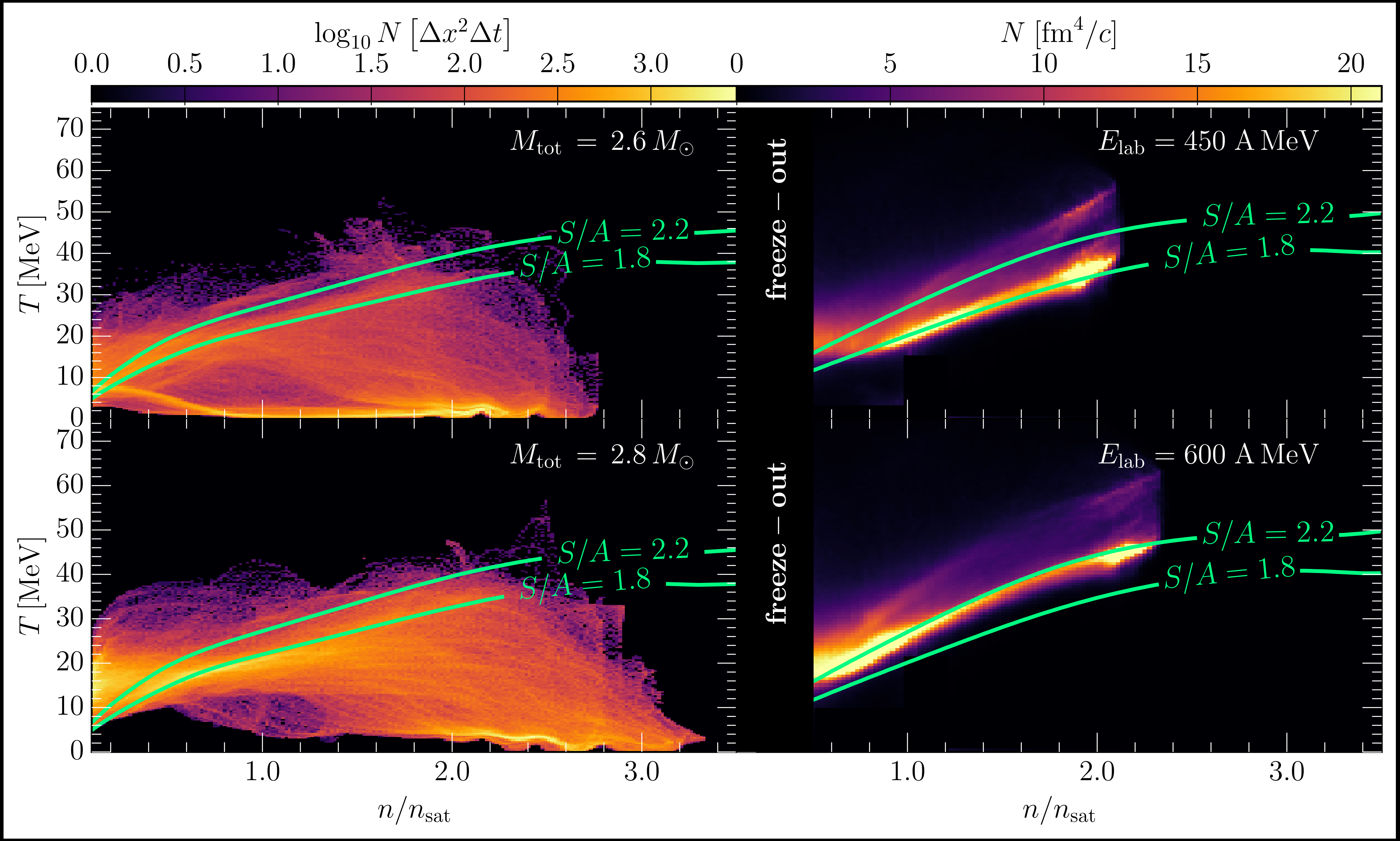
BNS mergers vs HICs



- We have explored the dynamics of BNS mergers and HIC using the same EOS.
- Chiral Mean Field model, based on the three-flavor chiral Lagrangian for hadronic matter.
- Crossover transition for deconfinement occurs at both, finite and zero temperature



- **BNSs**: core is hot and with high entropy; hot and high entropy ring is formed. Remnant is gravitationally bound.
- **HICs**: collision product is hot and with high entropy but expands rapidly cooling isentropically.



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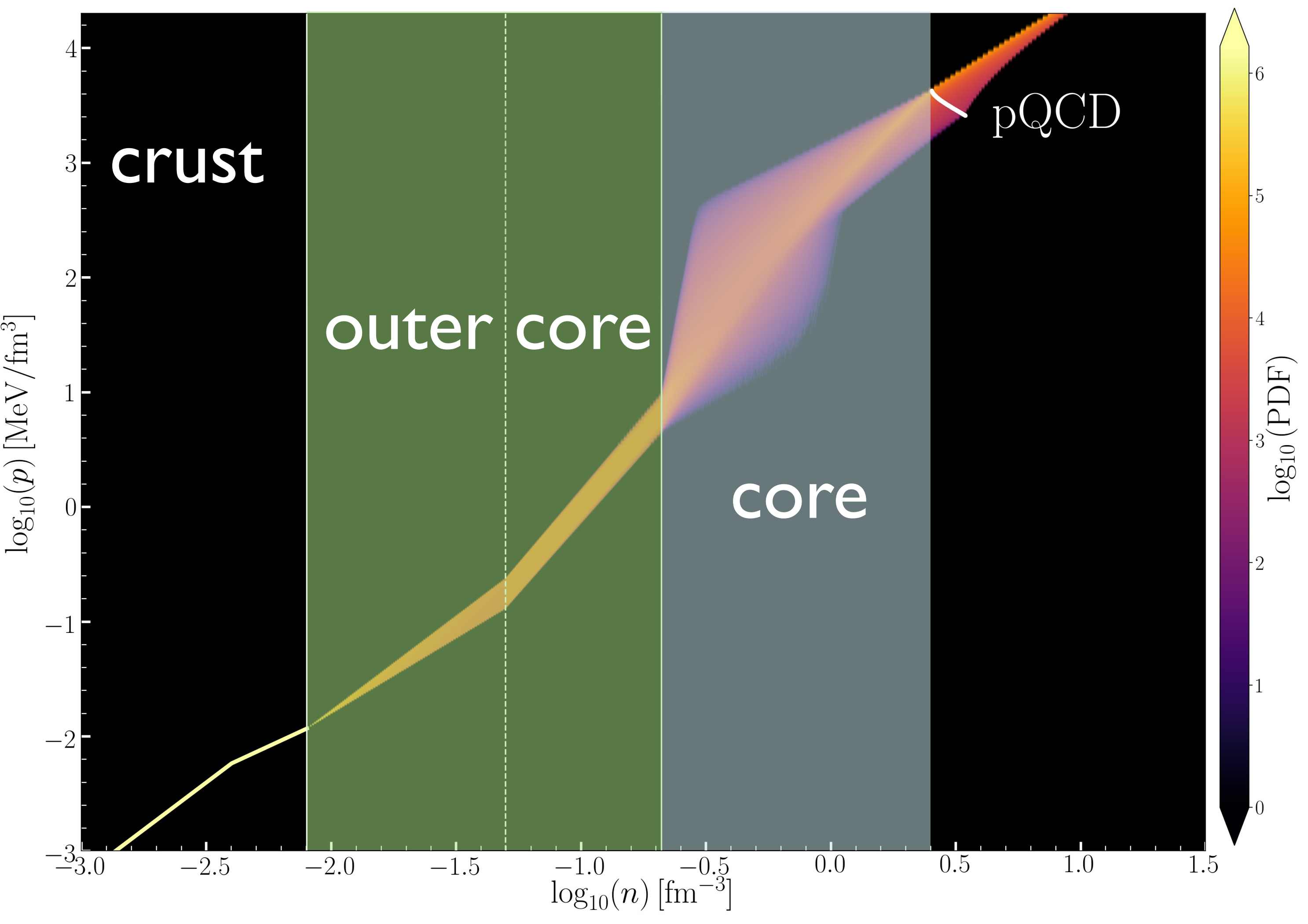
- **HICs**: collision product is hot and with high entropy but expands rapidly cooling isentropically.

Limits on radii and deformabilities

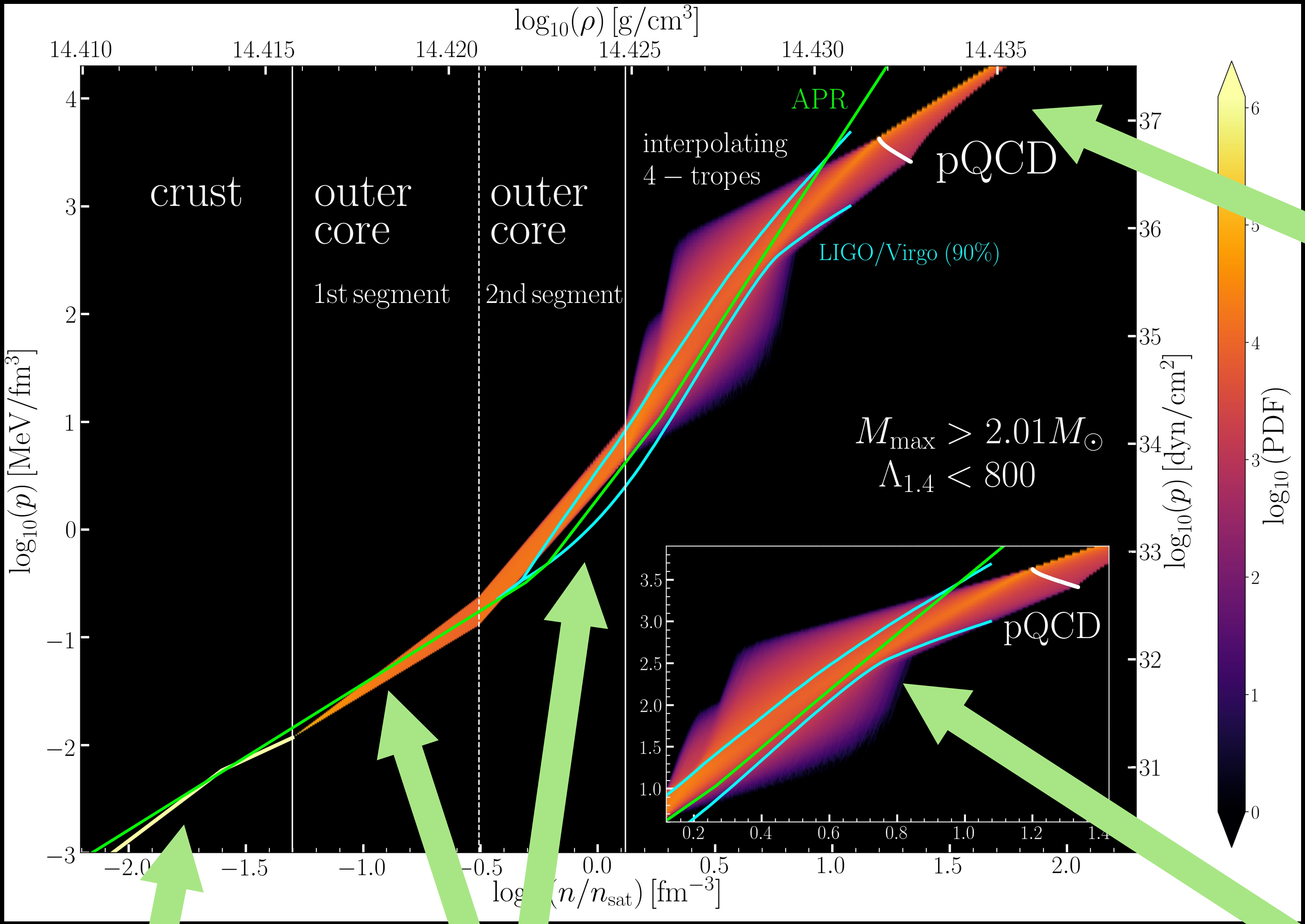
- Can new constraints be set on typical radius and tidal deformability by using GW170817?

- **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)

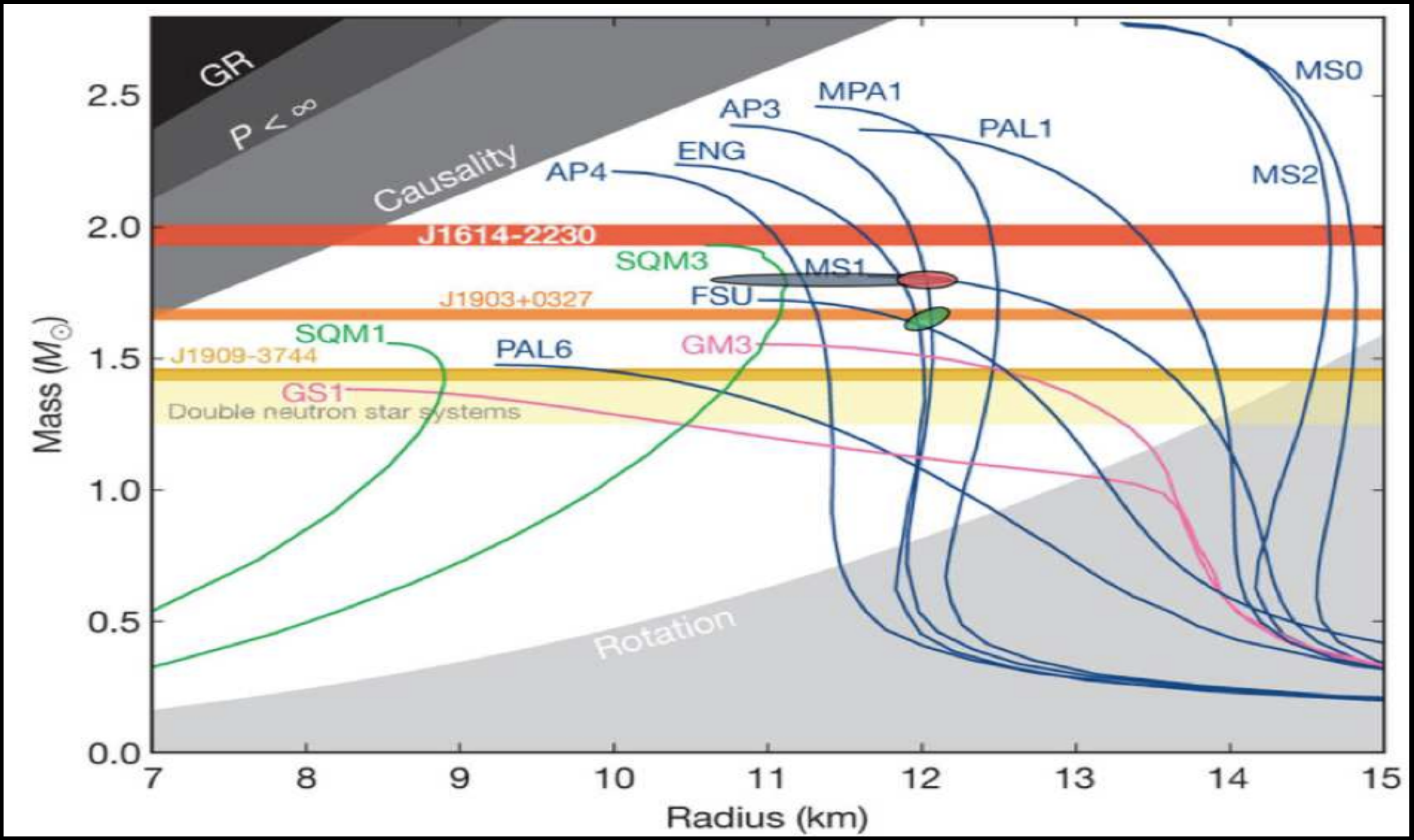
interpolation
by matching 4
polytropes

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

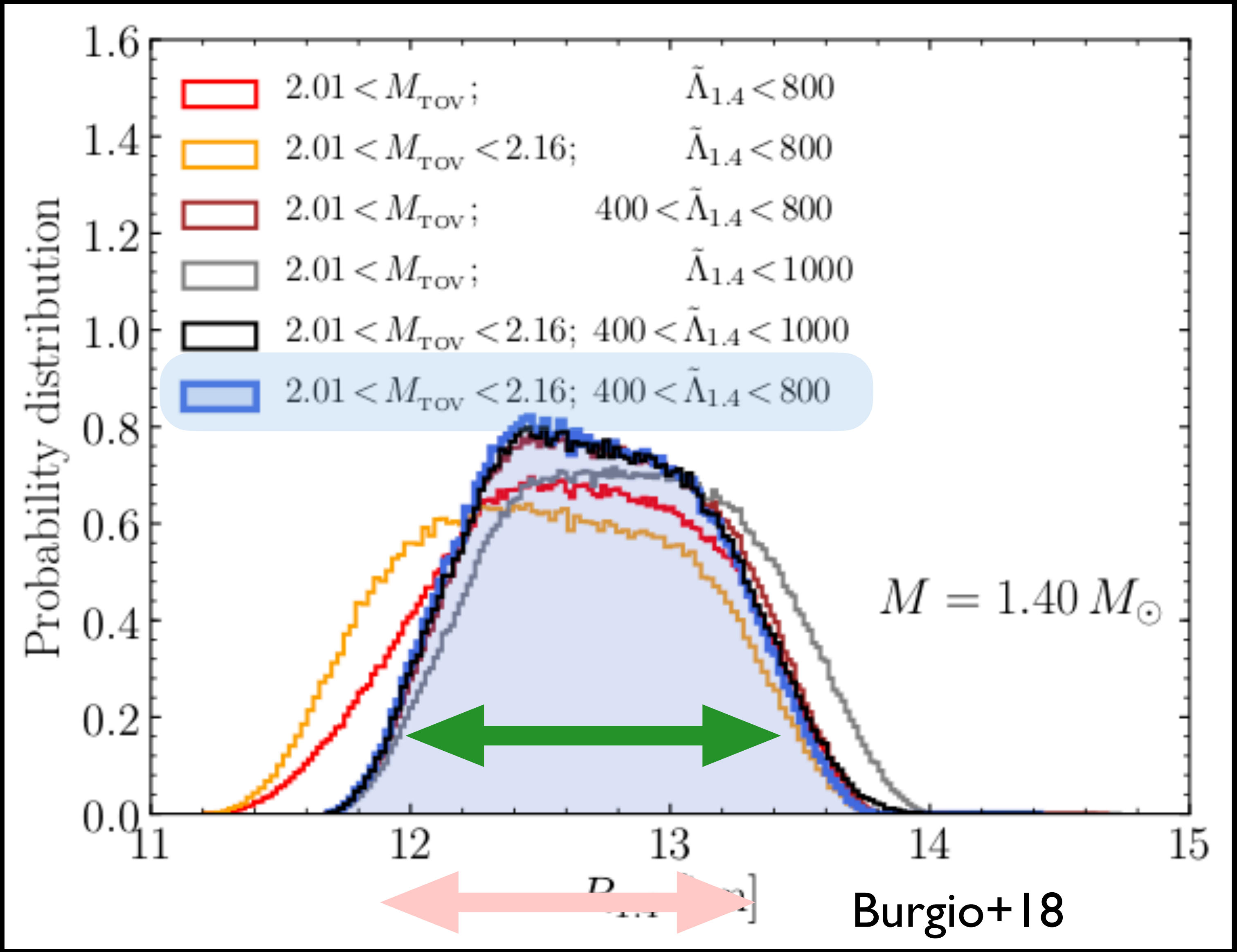


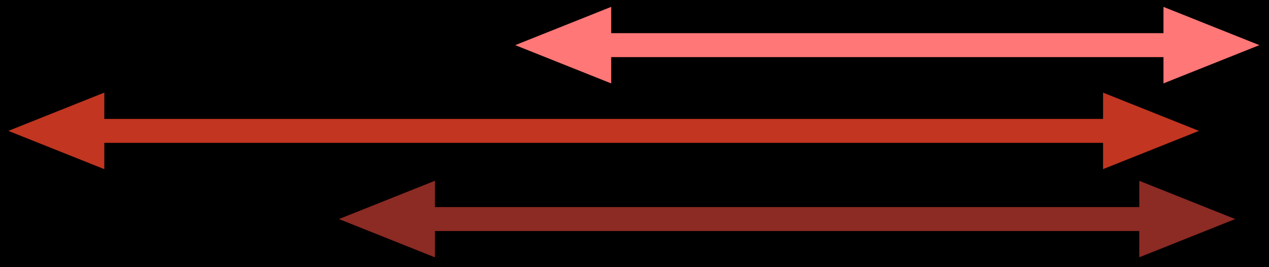
one-dimensional cuts

- 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

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

$$\langle R_{1.4} \rangle = 12.45\,\mathrm{km}$$





Constraining tidal deformability

- Can explore statistics of all properties of our **10^9** models.
- In particular can study PDF of tidal deformability:

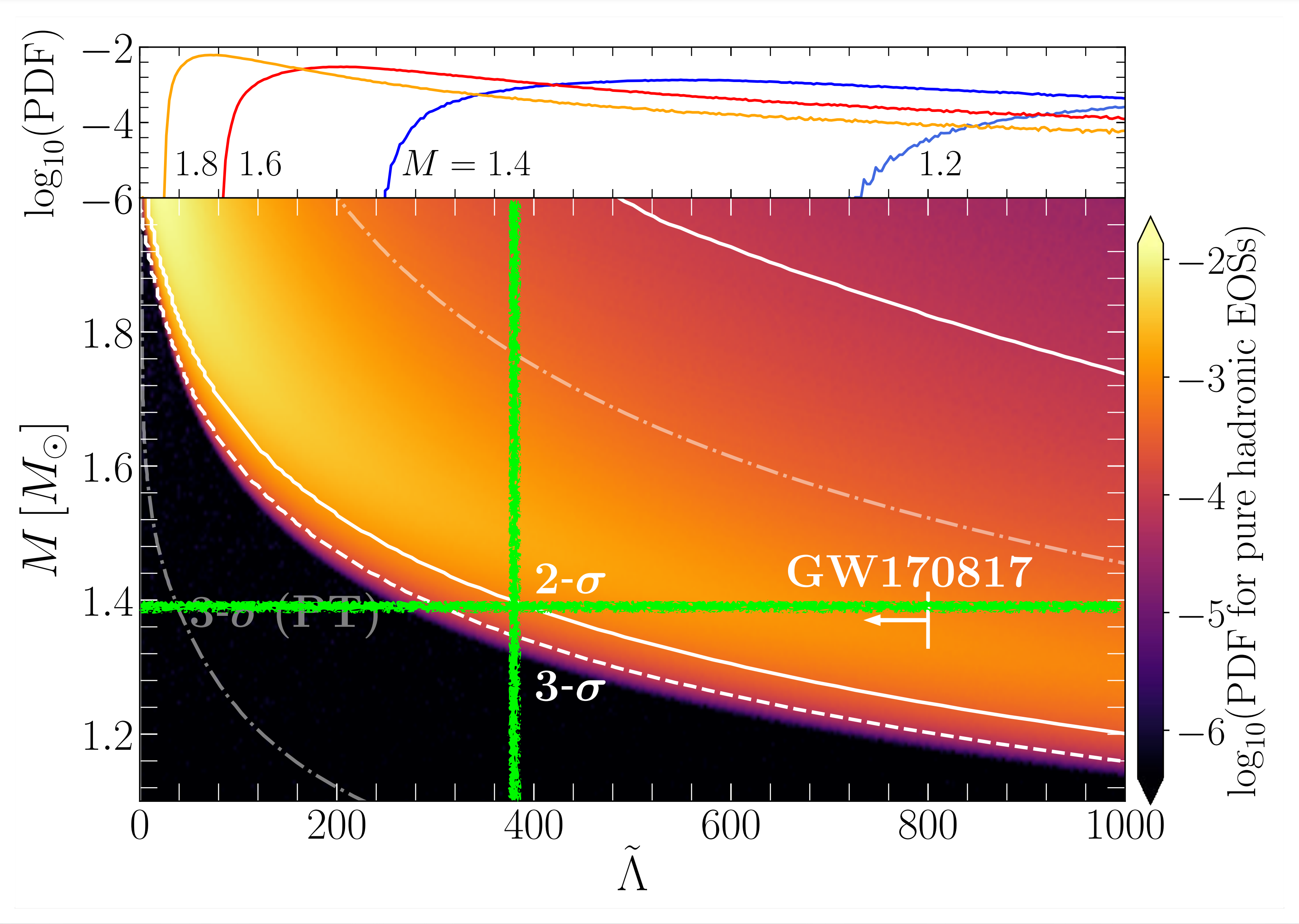
- LIGO has already set upper limit:

$$70 < \tilde{\Lambda}_{1.4} < 720$$

- Our sample sets a lower limit:

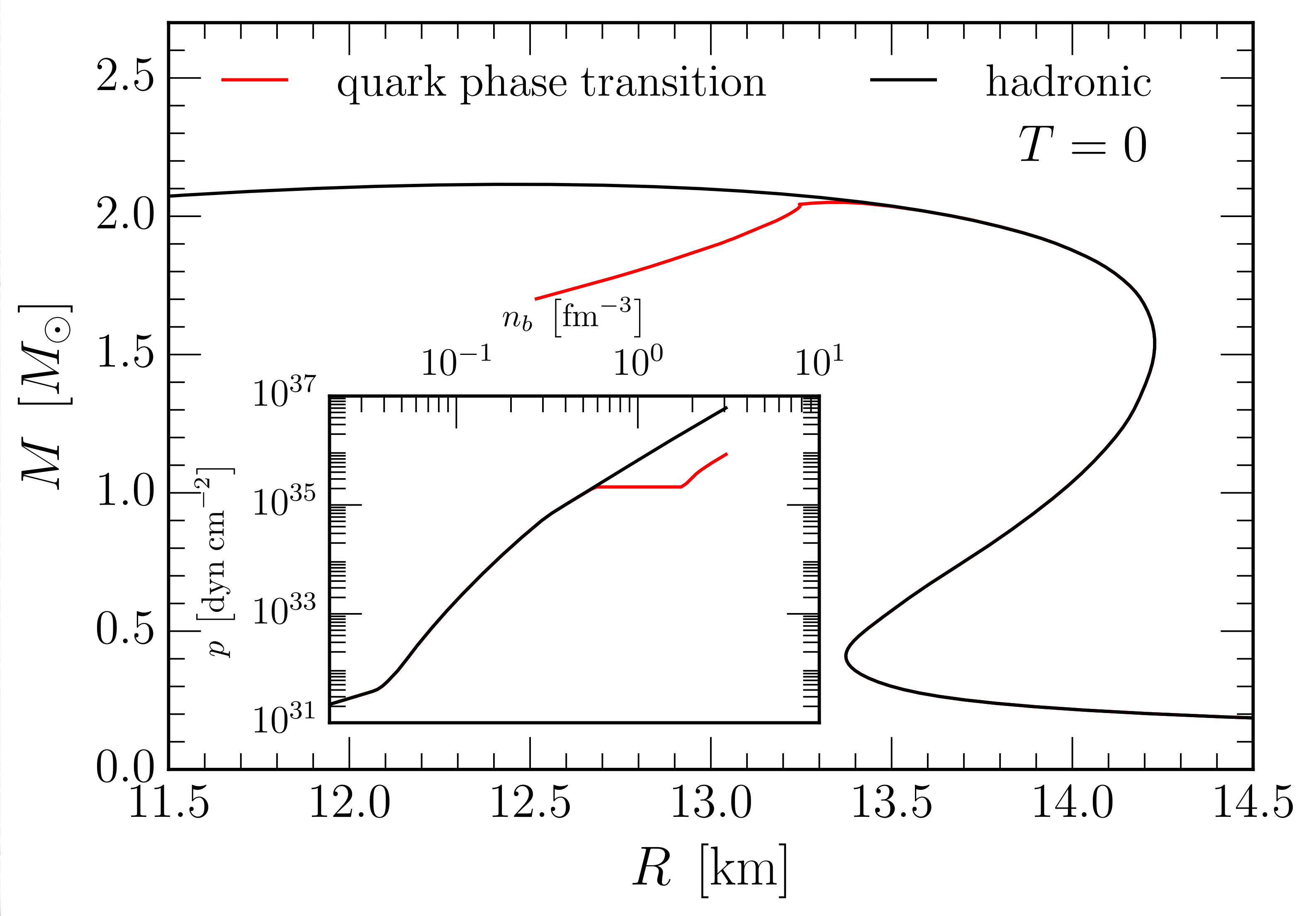
$$\tilde{\Lambda}_{1.4} > 375$$

the largest so far.

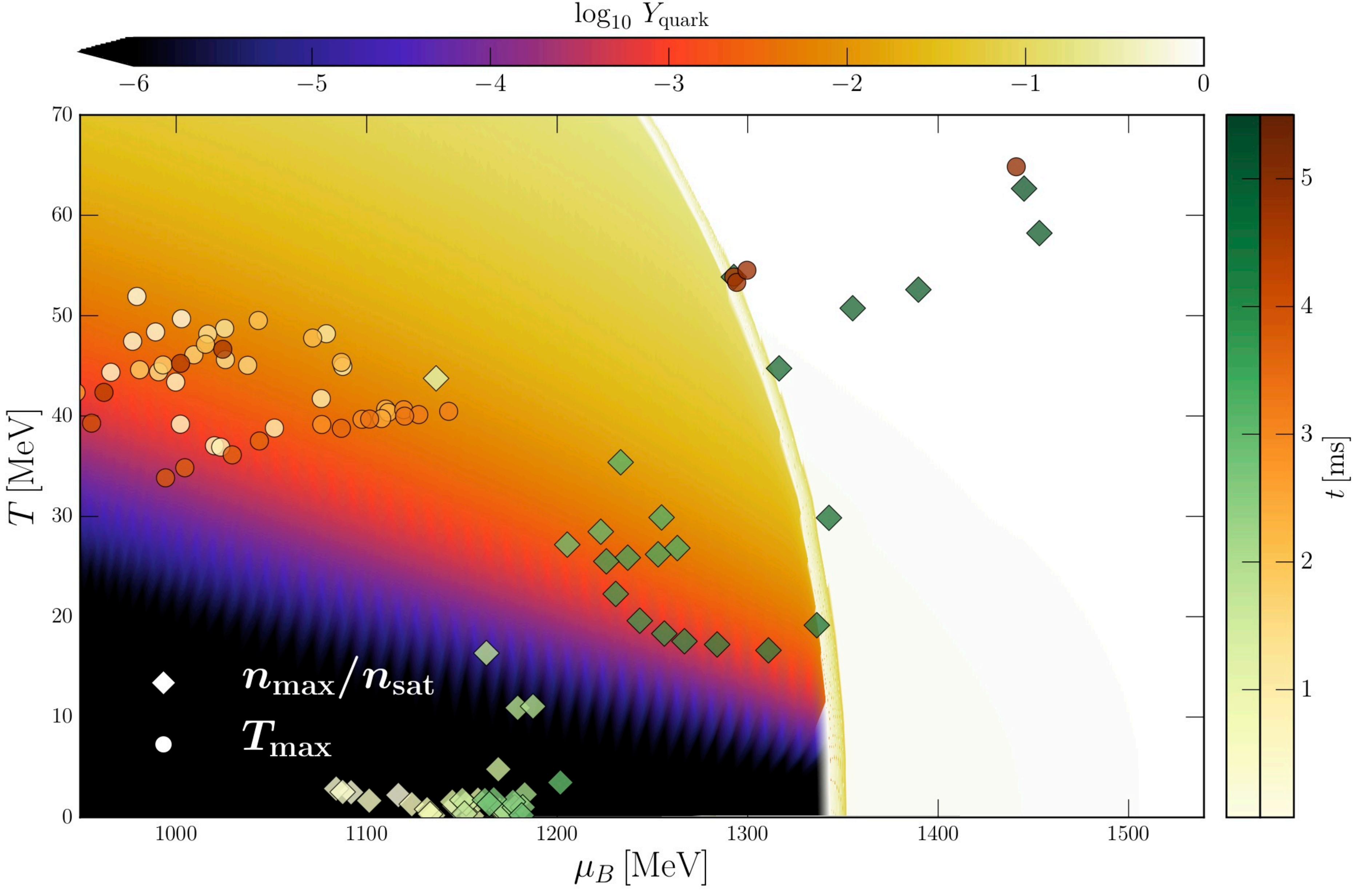


Modelling the EOS

- 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

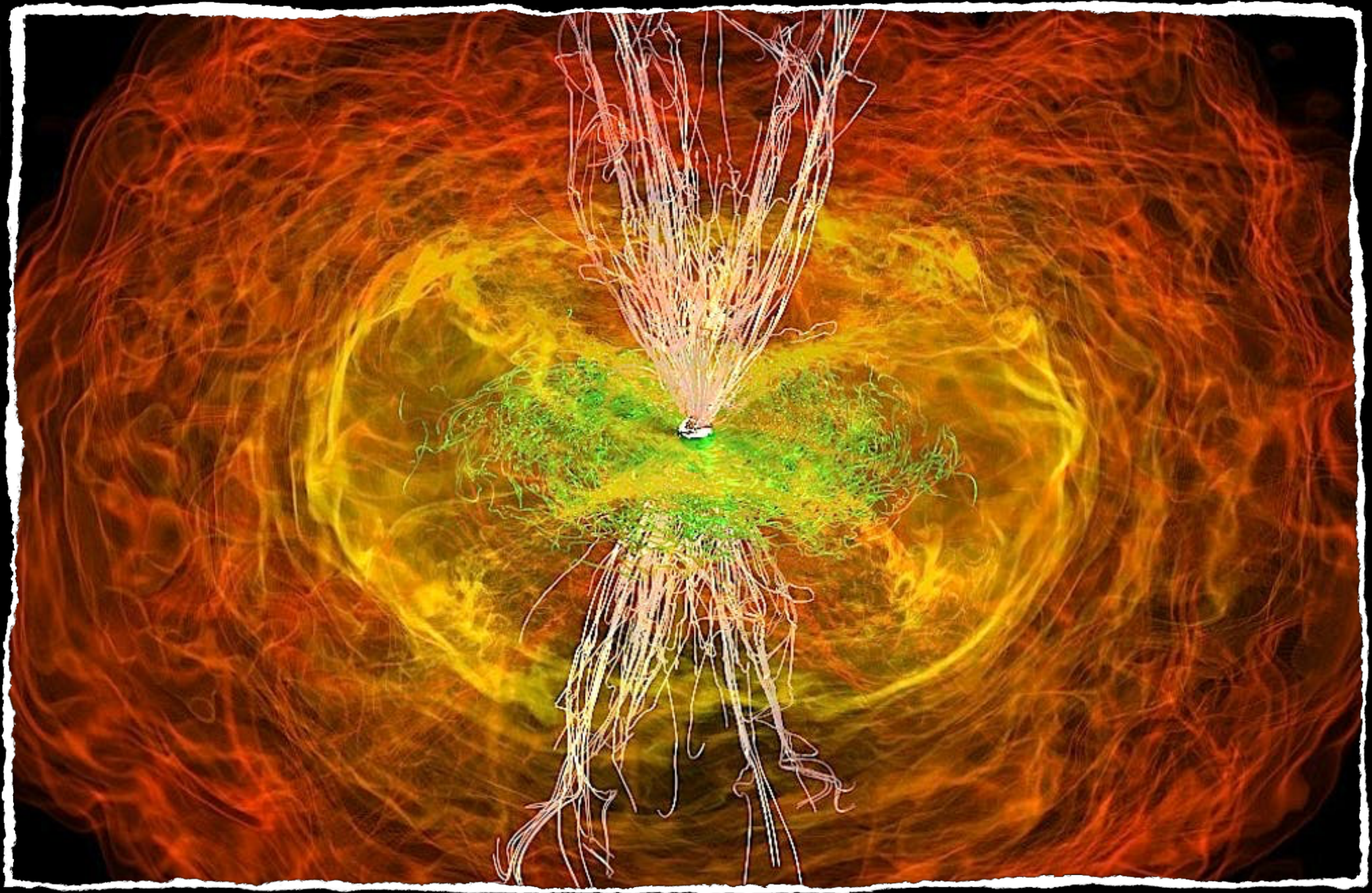


Comparing with the phase diagram



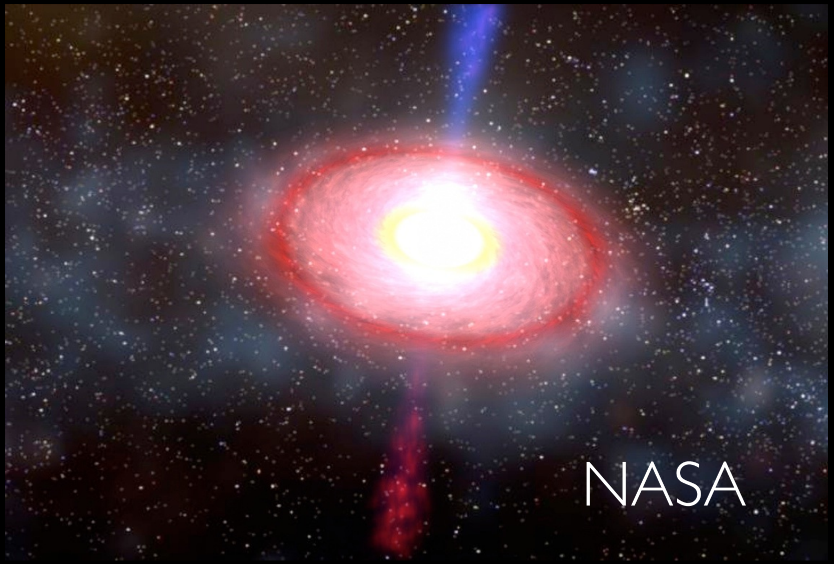
- Reported are the evolution of the max. temperature and density.
- Quarks appear already early on, but only in small fractions.
- Once sufficient density is reached, a full phase transition takes place.

Electromagnetic counterparts



Electromagnetic counterparts

- Since 70's observed flashes of gamma rays observed with energies 10^{50-53} erg: **gamma-ray bursts (GRBs)**
- Two families of GRBs: "**long**" and "**short**"
- **Long:** last **tens-hundreds** of **seconds;** likely due to the collapse of very massive stars
- **Short:** last less than a second; due to NS mergers
- All GRBs show **jets** but how do you produce a jet from a binary merger?



NASA

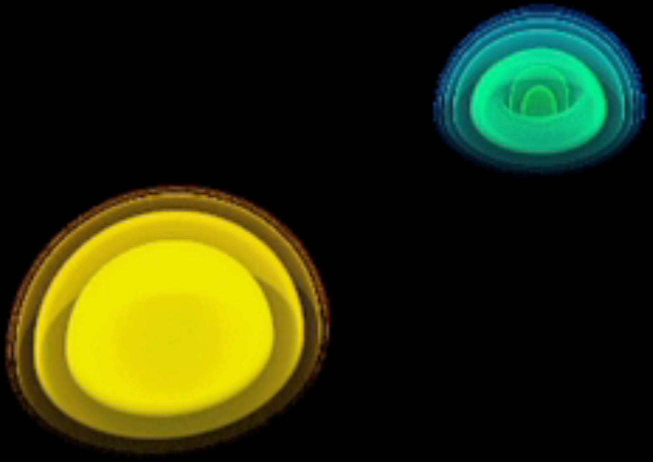
Electromagnetic counterparts

We have now evidence that gamma-ray bursts are associated with neutron star mergers

Presence of jets in gamma-ray bursts implies presence of large-scale magnetic fields

What happens when magnetised stars collide?

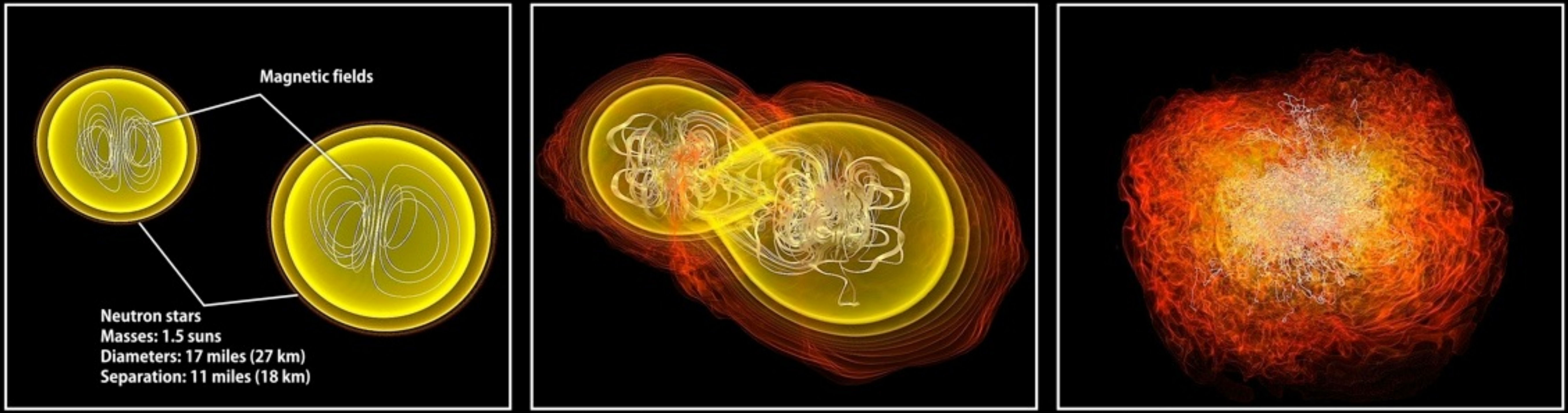
Need to solve equations of magnetohydrodynamics in addition to the Einstein equations



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

Animations:, LR, Koppitz

What happens when magnetised stars collide?

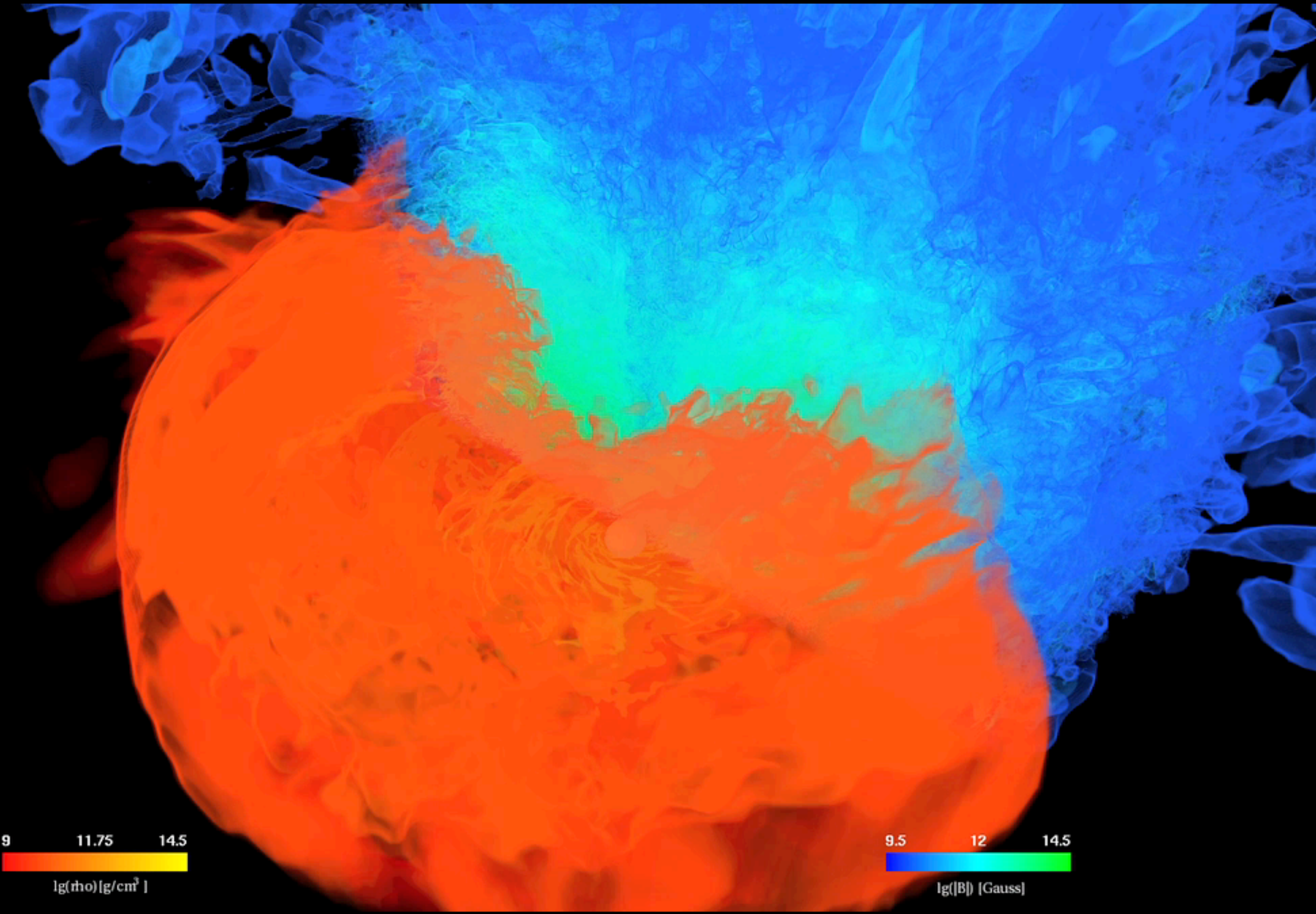


Simulation begins

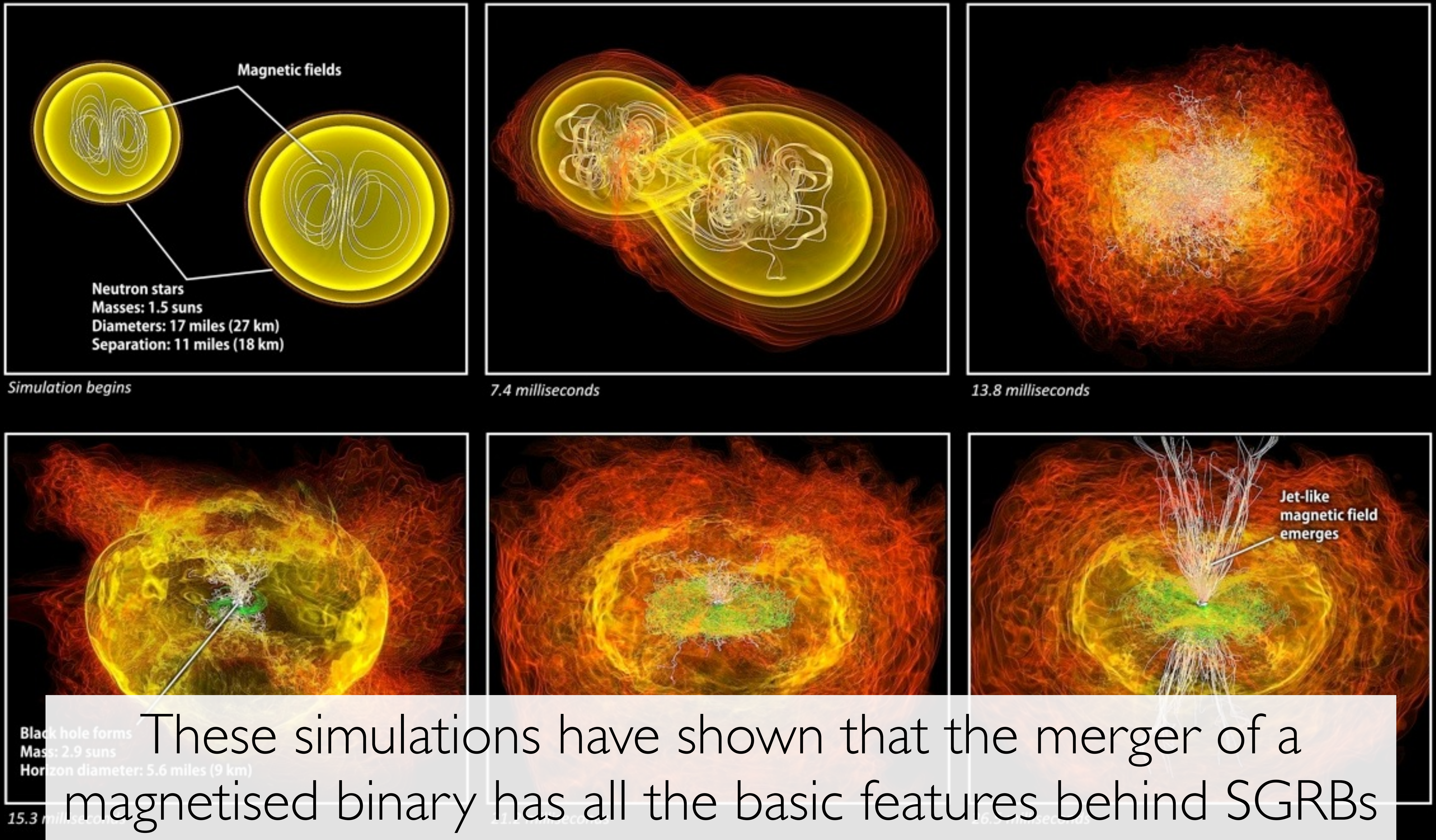
7.4 milliseconds

13.8 milliseconds

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

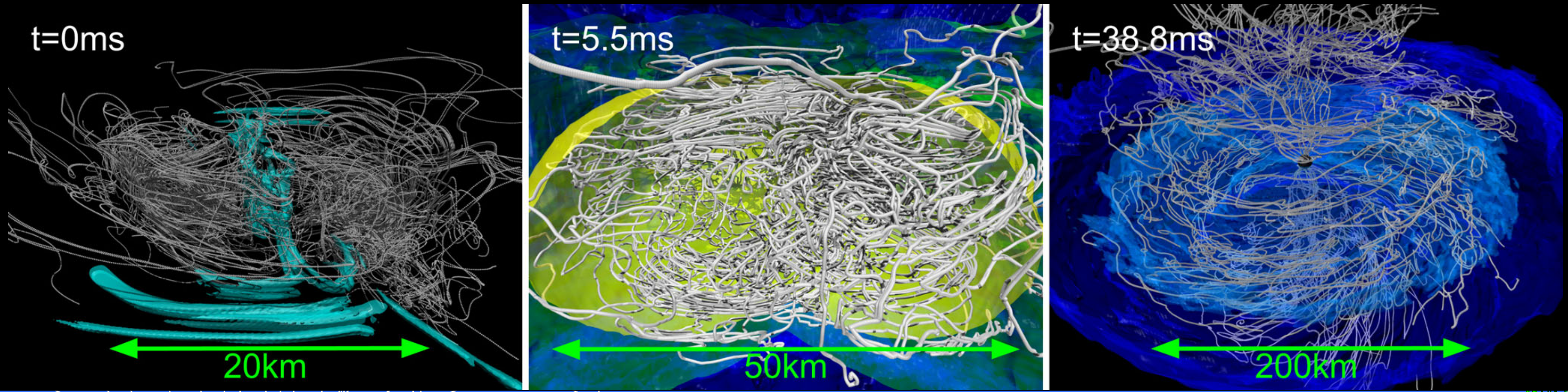


These simulations have shown that the merger of a magnetised binary has all the basic features behind SGRBs

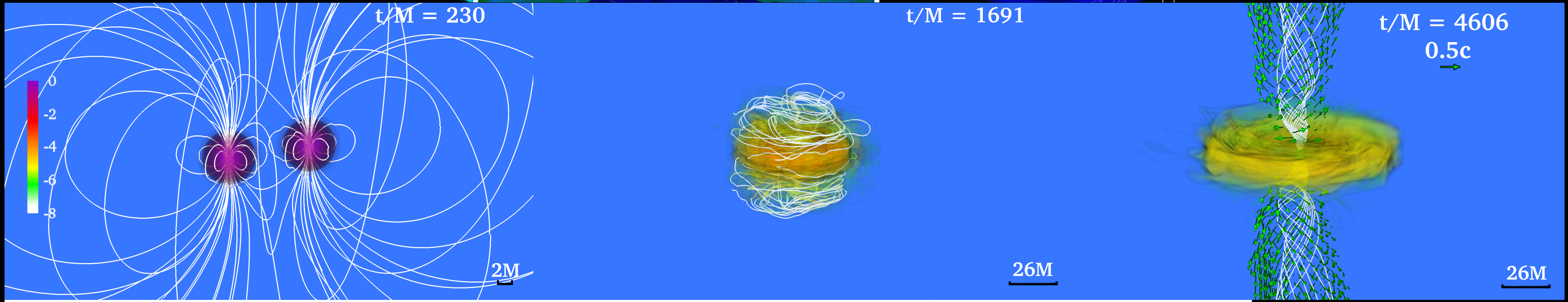
Credit: NASA/AEI/ZIB/M. Koppitz and L. Rezzolla

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

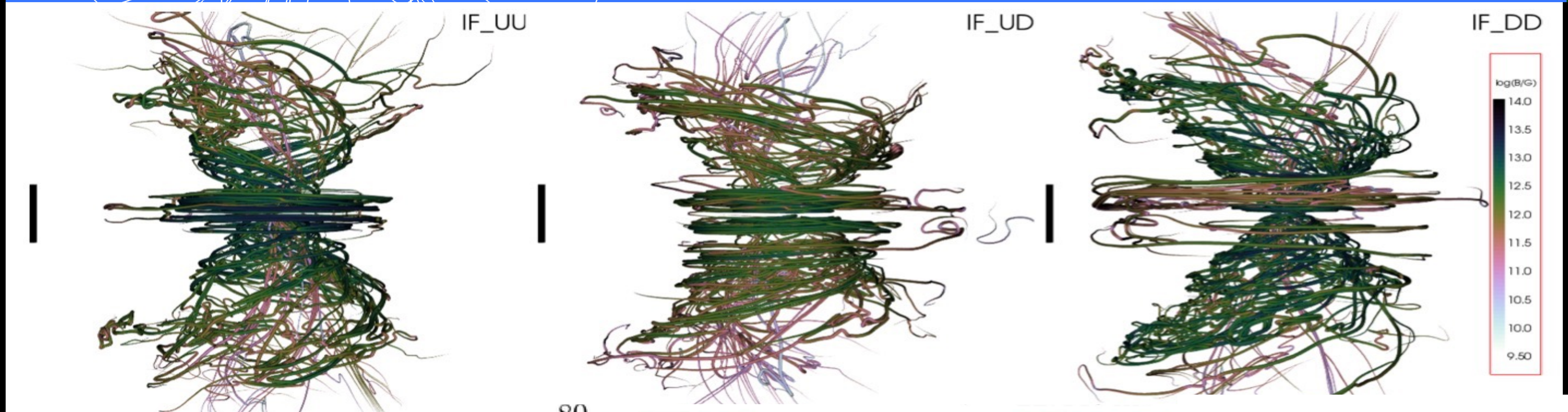
With due differences, other groups confirm this picture



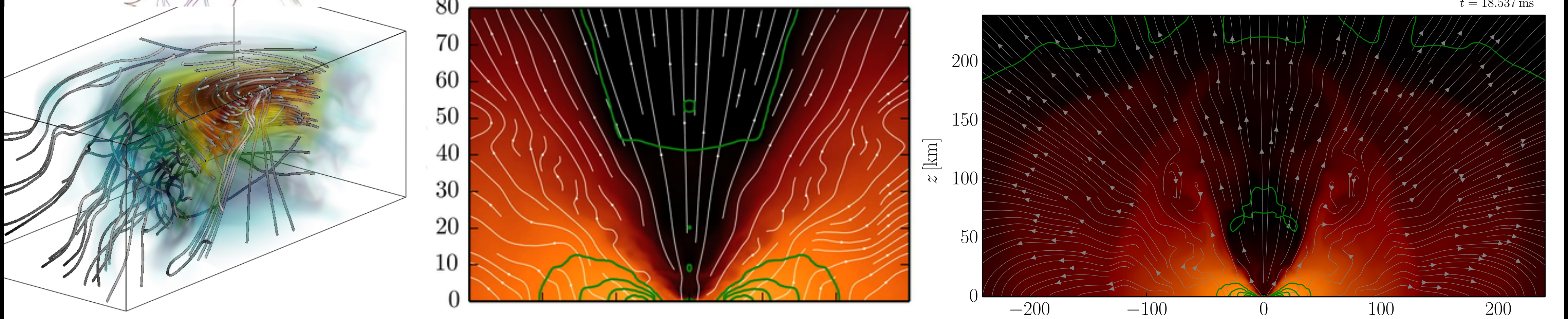
Kiuchi+ 2014



Ruiz+ 2016



Kawamura+2016

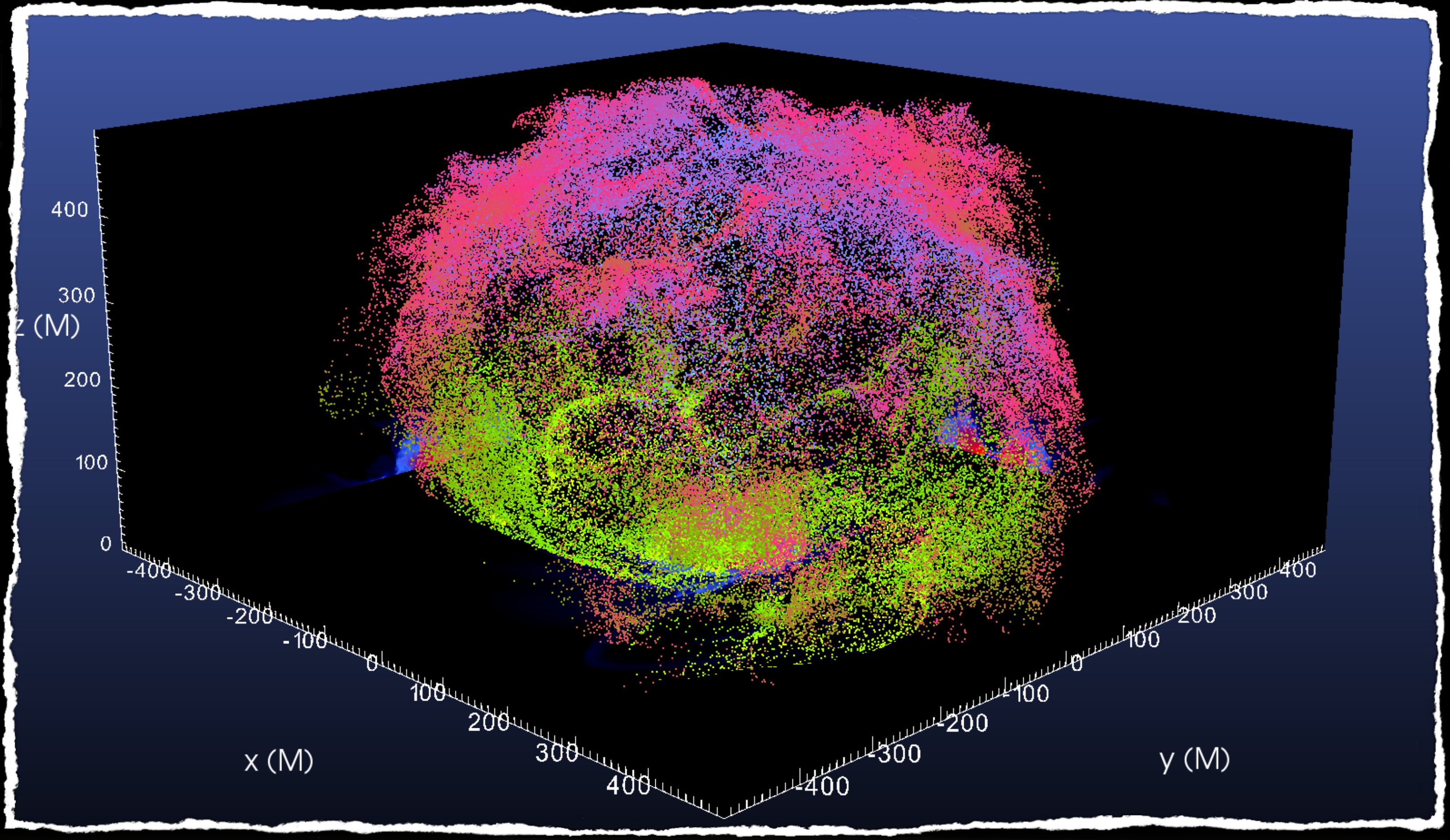


Dionysopoulou+ 2015

RMHD

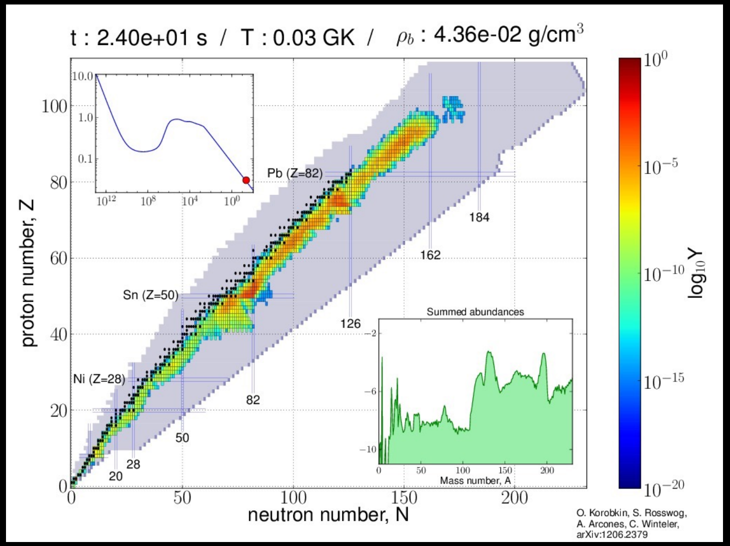
Ejected matter and nucleosynthesis

Bovard+ (2017)

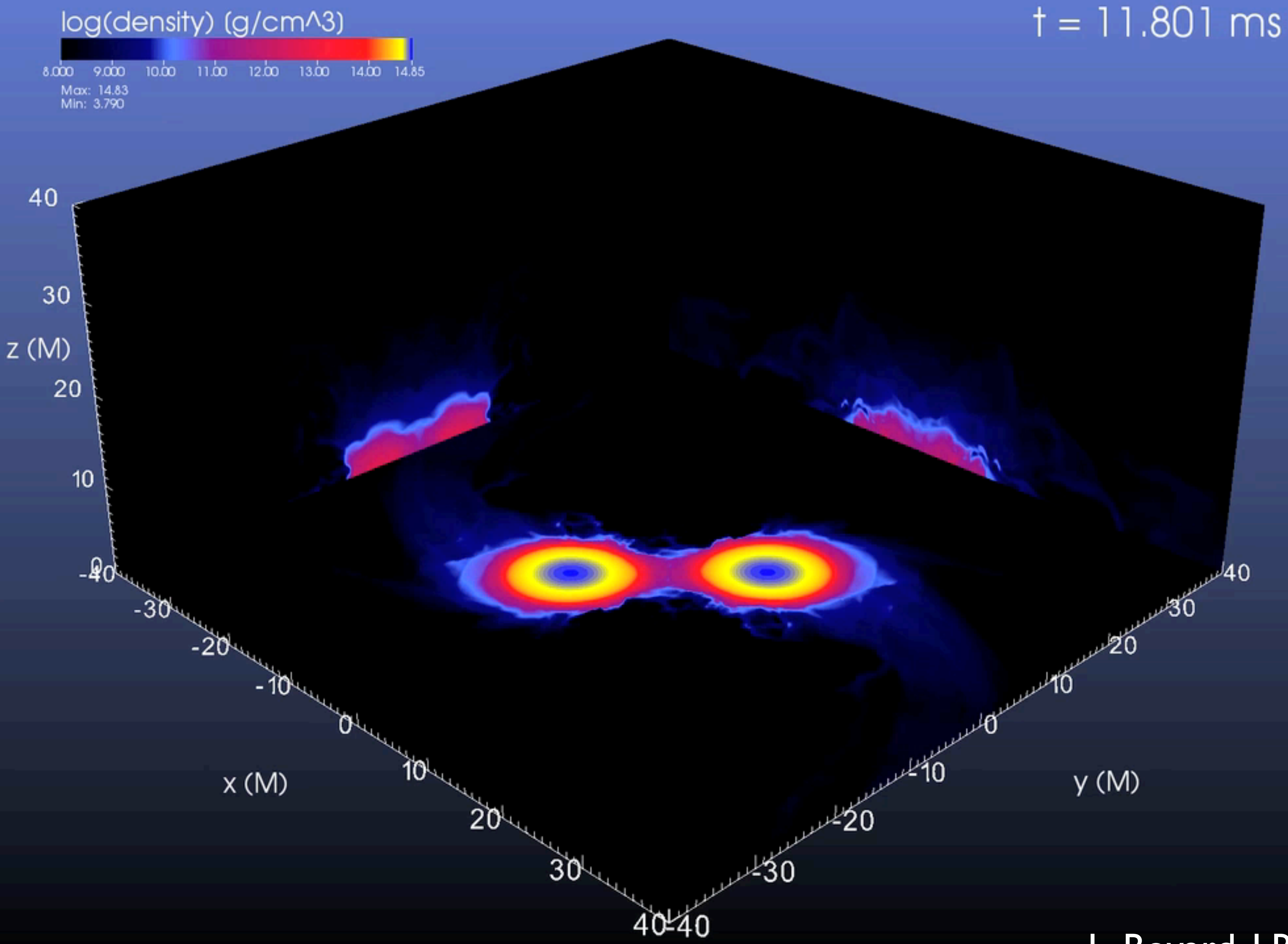


Nucleosynthesis

- 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!



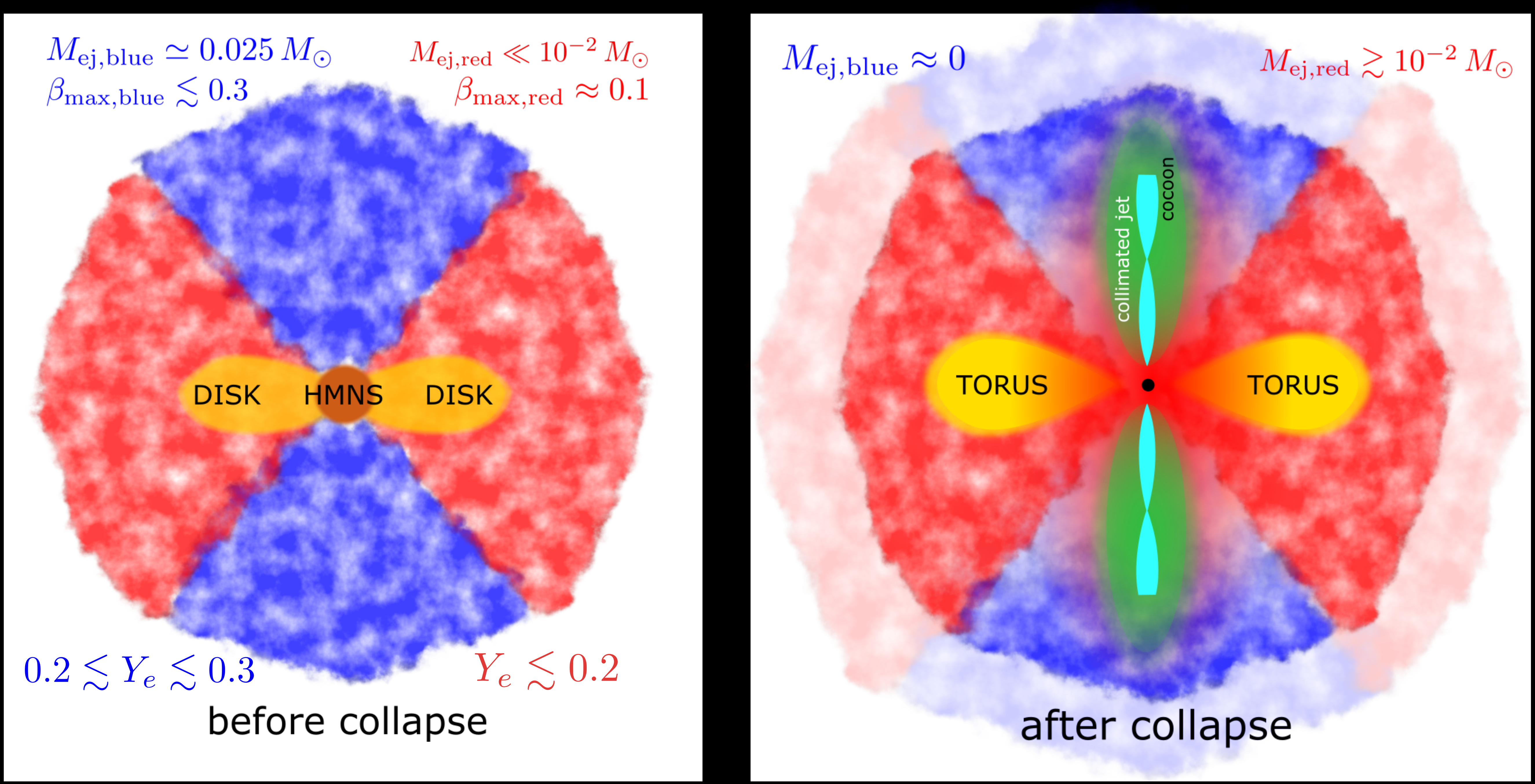
O. Korobkin, S. Rosswog, A. Arcones, C. Winteler, arXiv:1206.2379


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)
40
30
20
10
0
x (M)
-40
-30
-20
-10
0
10
20
30
40
y (M)
-40
-30
-20
-10
0
10
20
30
40

L. Bovard, LR

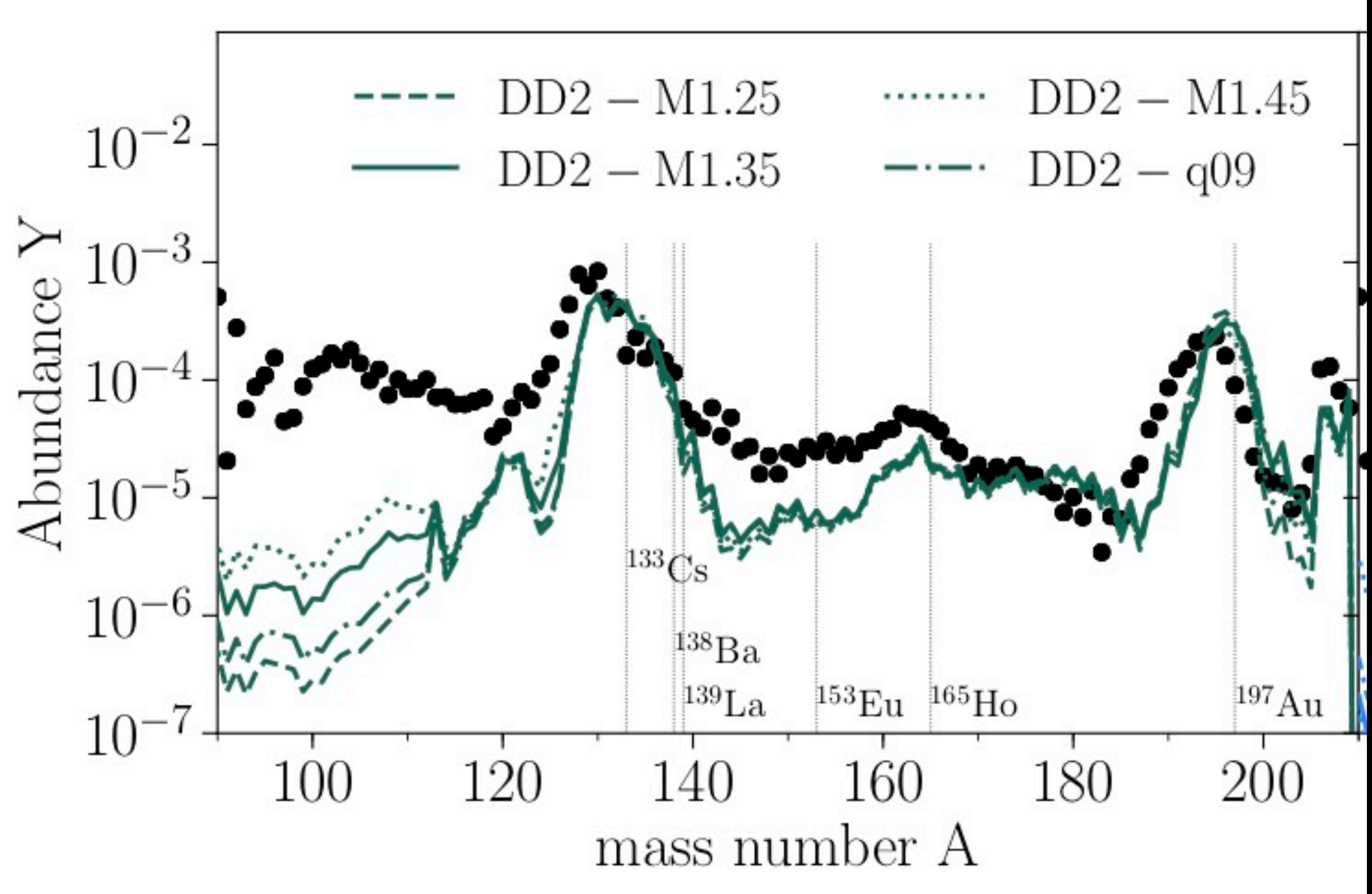
Ejection of mass

- After merger mass is lost in many different **channels** (shock heating, neutrino or magnetic-driven winds) and on very different **timescales** (**dynamical** and **secular**).



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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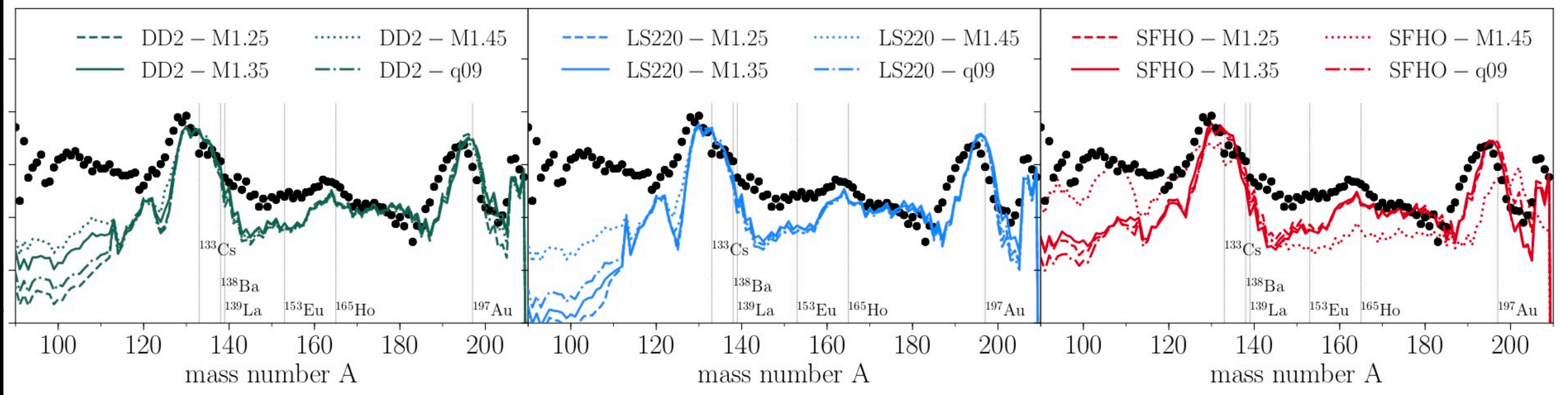

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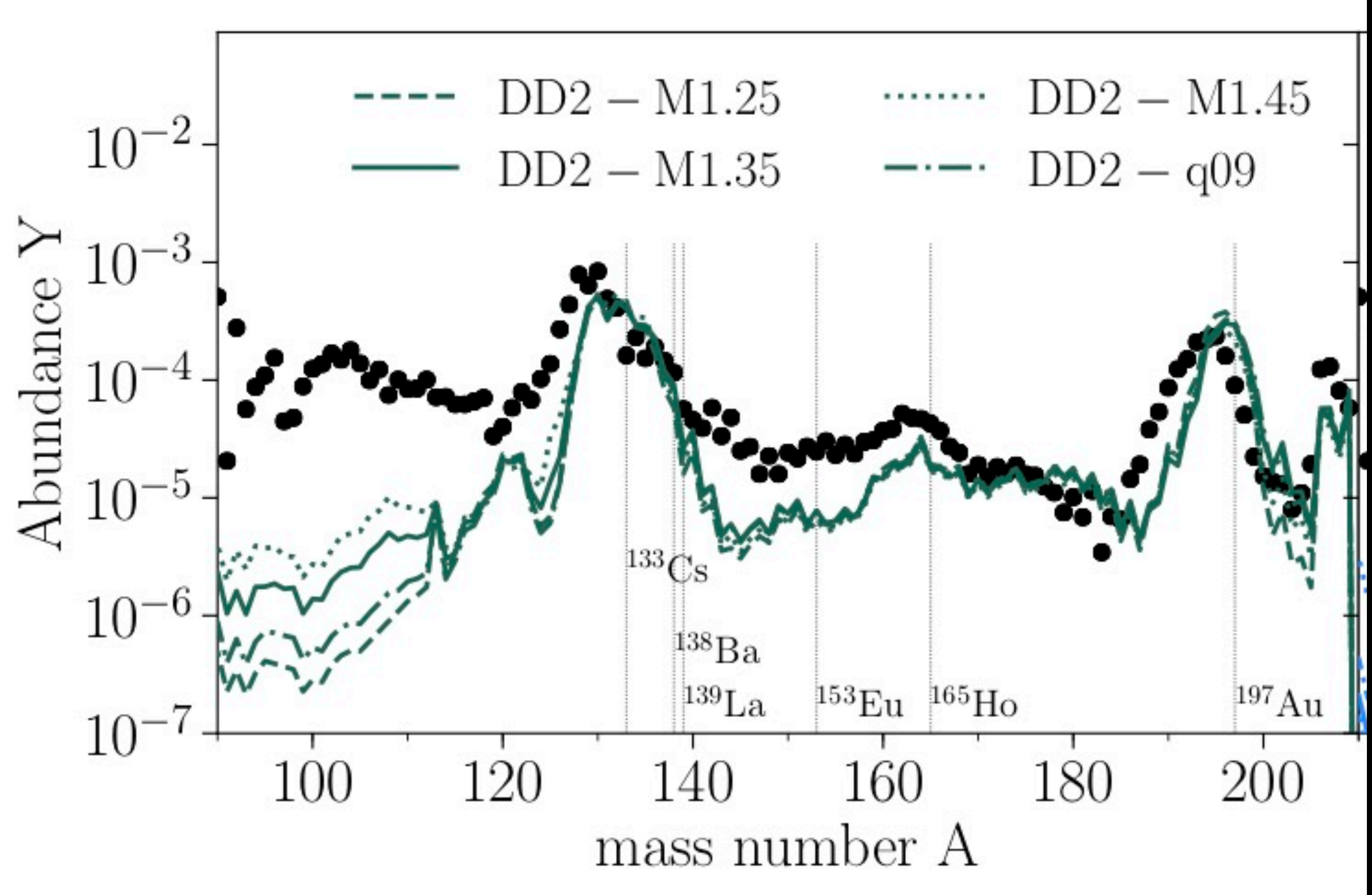
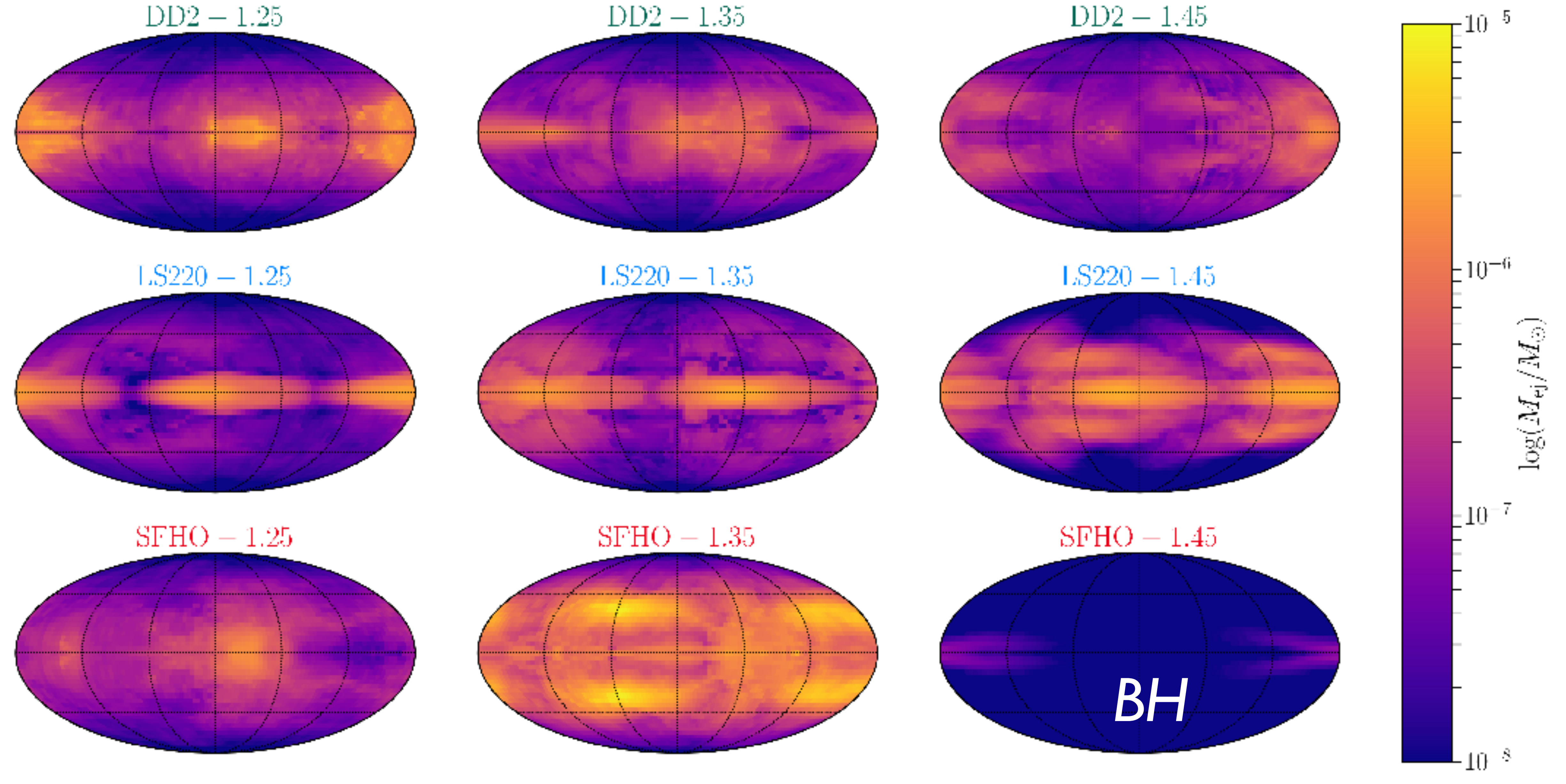


- GW170817 produced total of **16,000** times the mass of the Earth in heavy elements (**10** Earth masses in **gold/platinum**)
- We are not only **stellar dust** but also **neutron-star dust!**

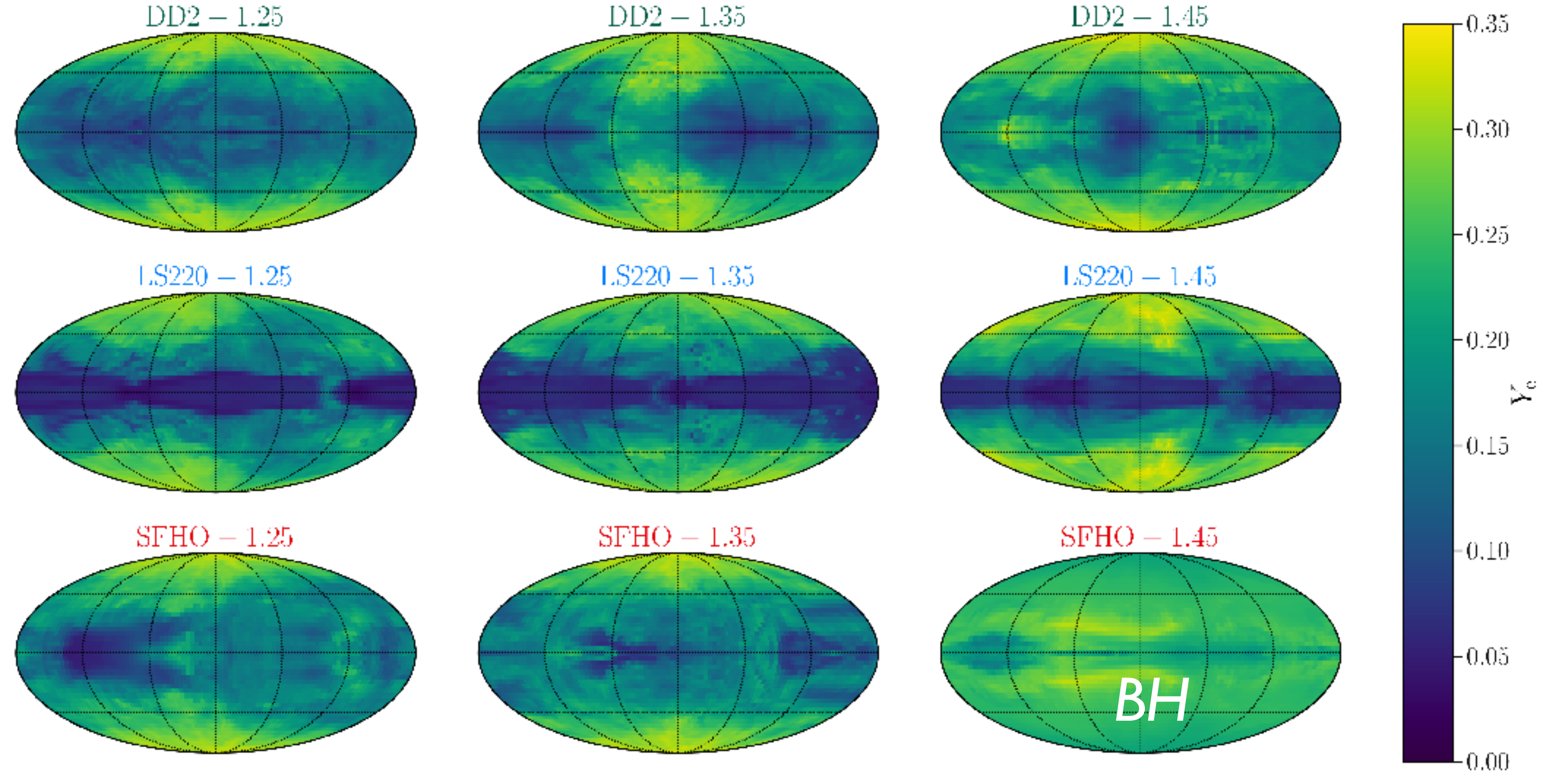
Spatial distributions: M_{ej} Bovard+ 17



Spatial distribution of M_{ej} impacts detectability of EM counterpart:

- ★ most of M_{ej} lost at low latitudes;
- ★ depending on EOS/mass, contamination also in polar regions

Spatial distributions: Y_e



Spatial distribution of Y_e impacts detectability of EM counterpart:

- ★ **high** Y_e in **polar** regions: **blue** (optical) macronova
- ★ **low** Y_e in **equatorial** regions: **red** (FIR) macronova