Numerical relativity:

what we knew **before** and what we know **after** GW170817

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Plan of the talk

- The richness of merging binary neutron stars
- GW spectroscopy: EOS from frequencies
- GW170817: a number of lessons
  - Maximum-mass constraints
  - Radius constraints
  - What happened to GW170817's remnant?
- Signatures of quark-hadron phase transitions
- Magnetic fields and EM counterparts
- Ejected mass and nucleosynthesis

see E. Most's talk

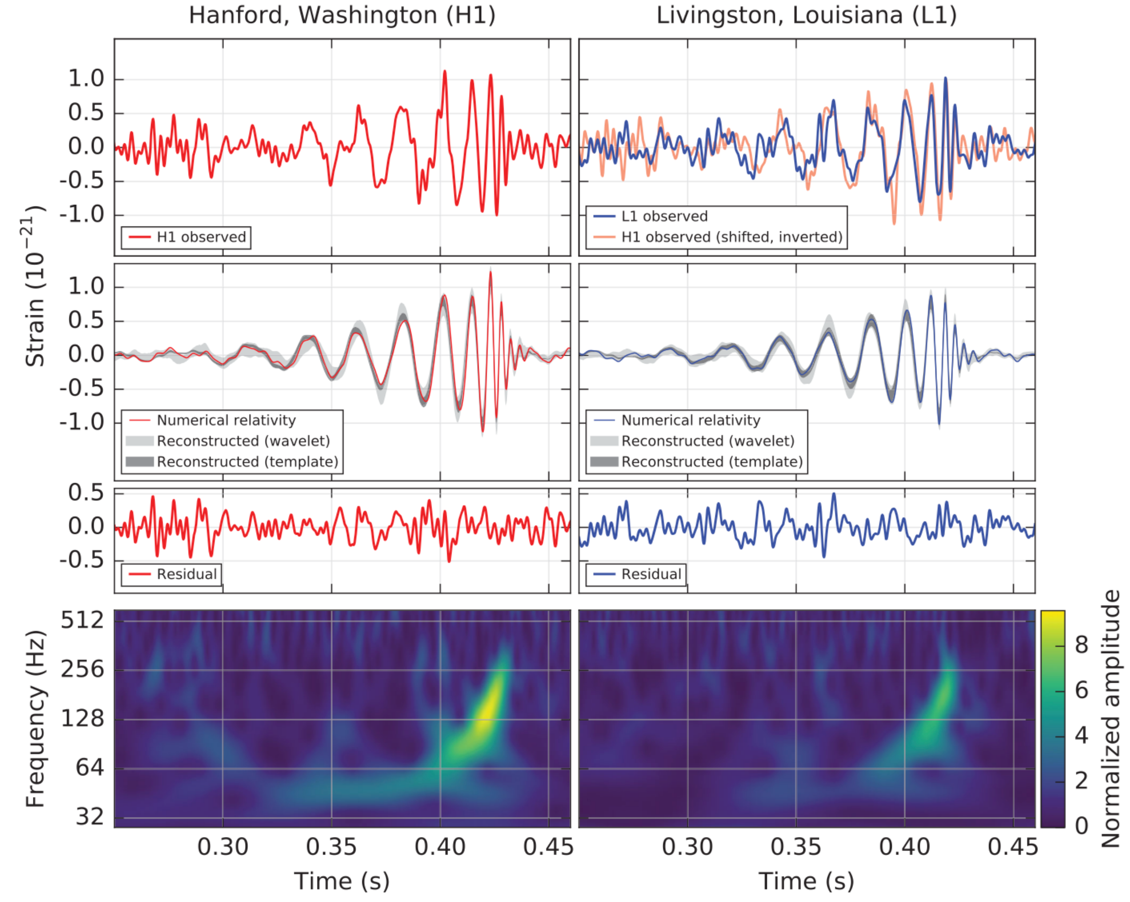
The two-body problem in GR

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

BH + BH ⟶ BH + GWs

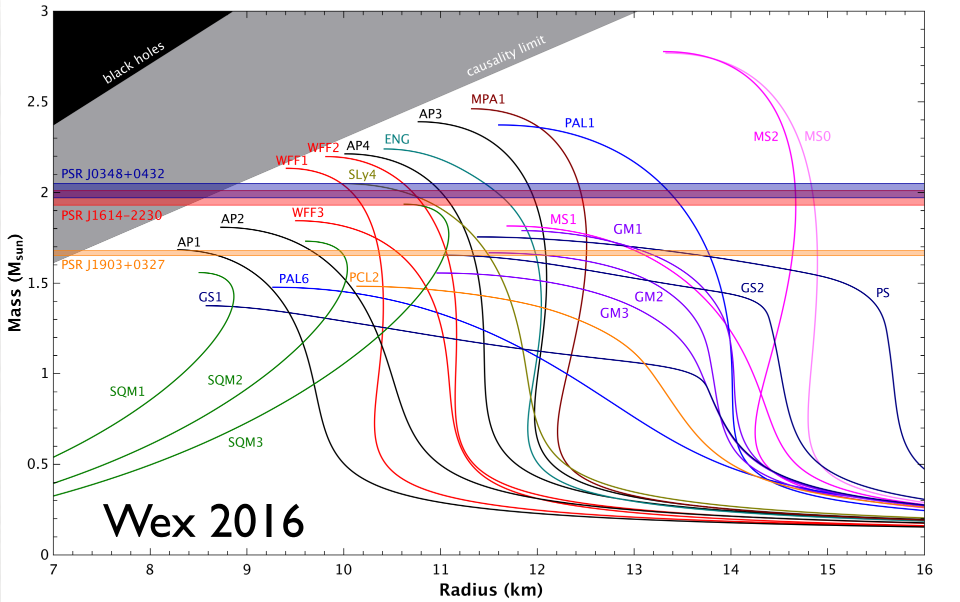
- For NSs the question is more **subtle**: hyper-massive neutron star (HMNS), ie

NS + NS ⟶ HMNS+**… ?** ⟶ BH+t

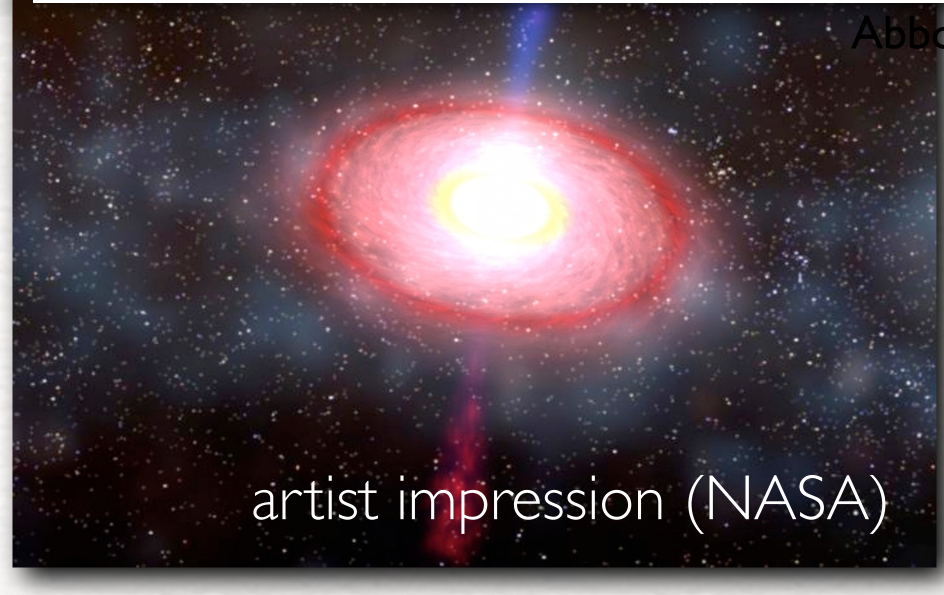


Abbott+ 2016

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



Wex 2016



artist impression (NASA)

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

The two-body problem in GR

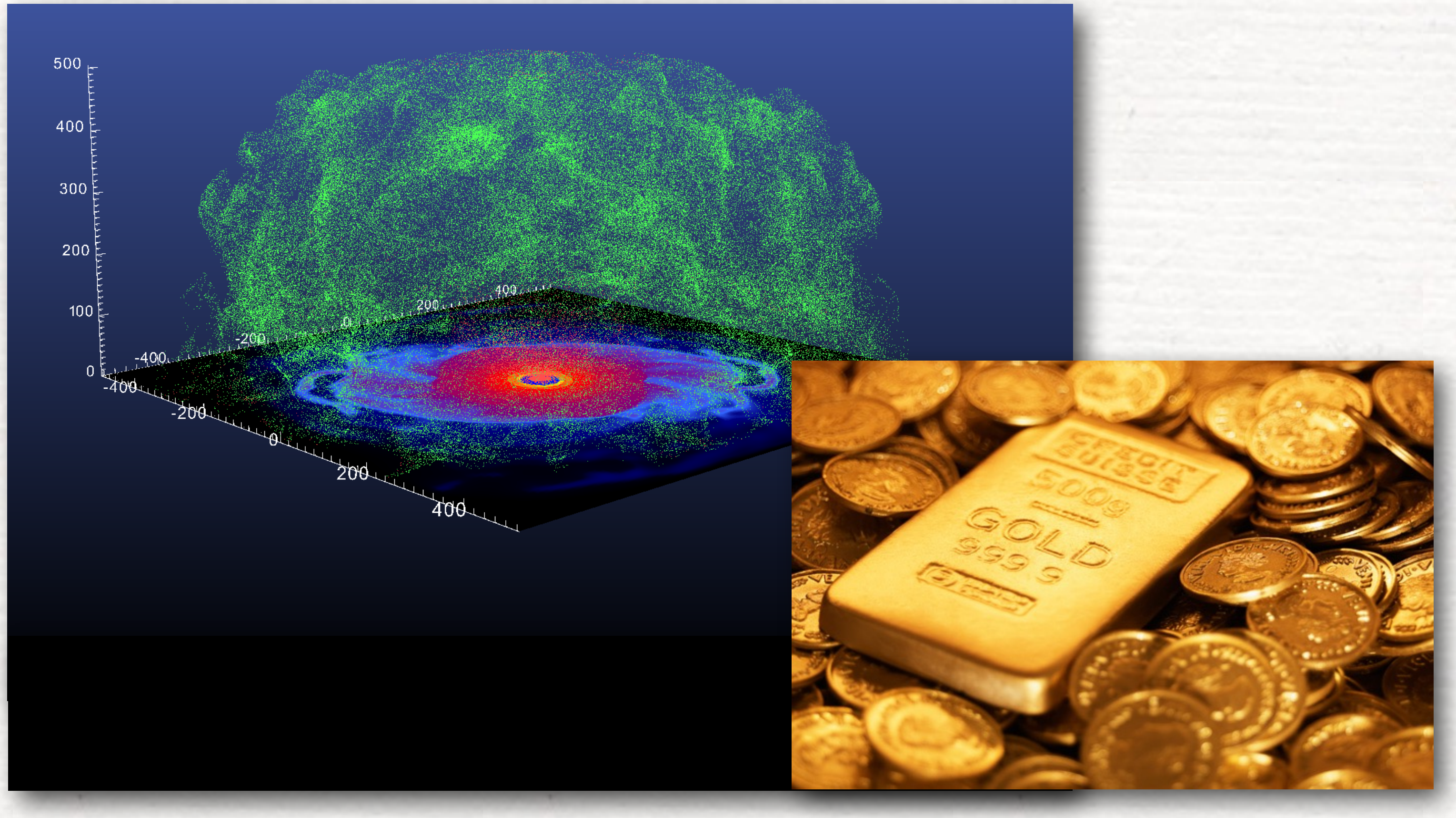
- For BHs we know what to **expect**:

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



Animations: Breu, Radice, LR

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

merger → HMNS → BH + torus

LS220 EOS

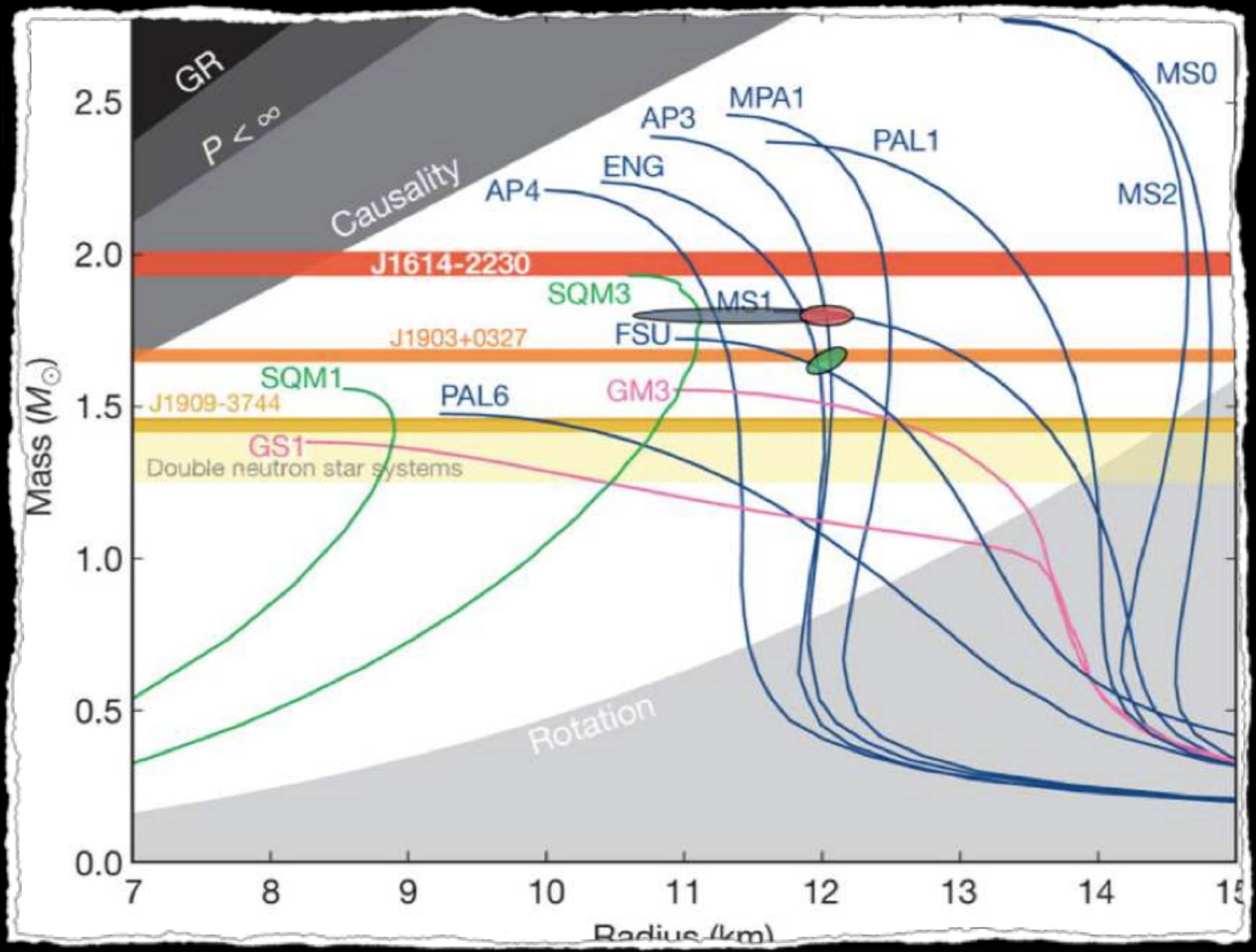
merger → HMNS → BH + torus

Quantitative differences are produced by:

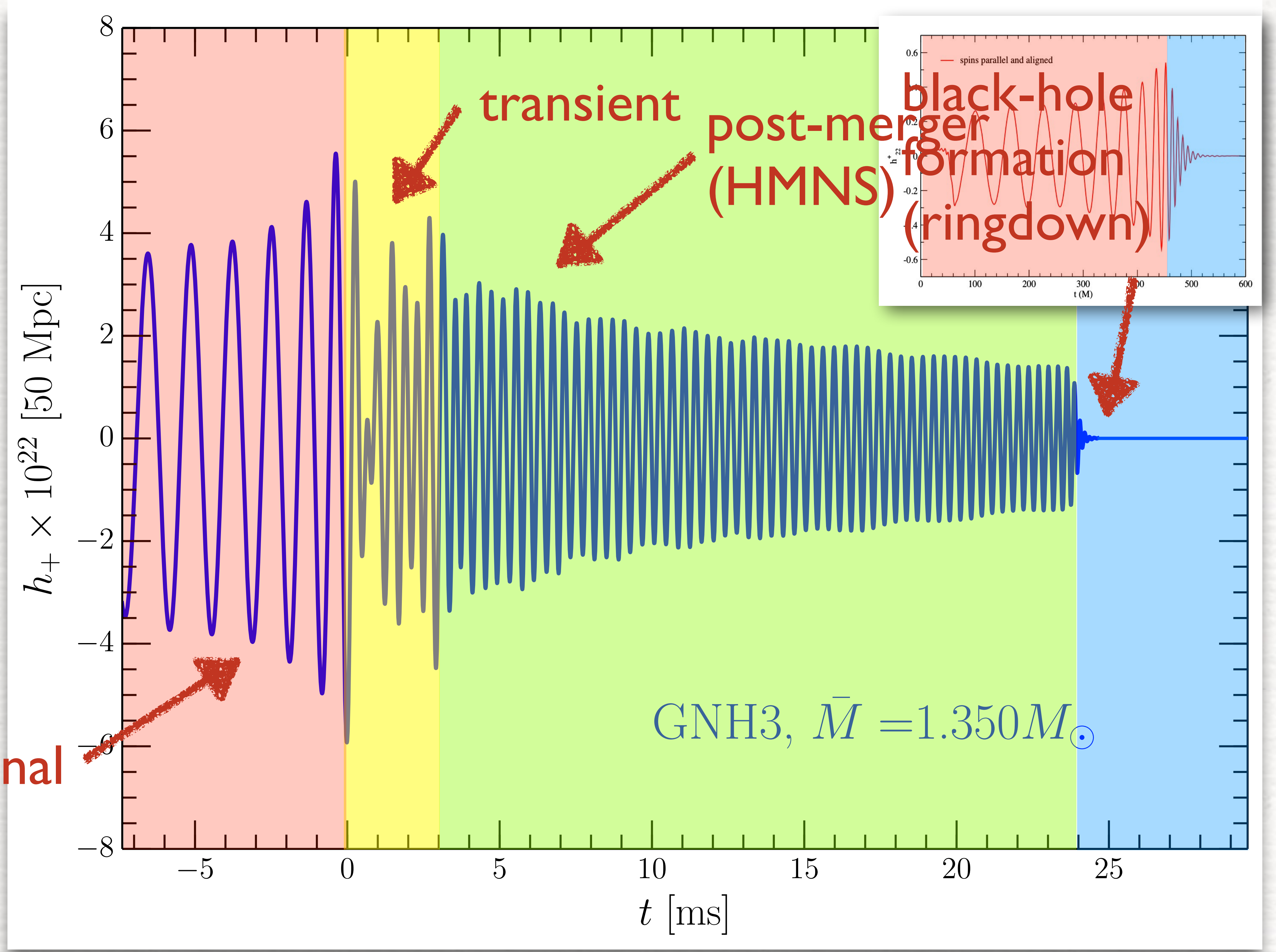
- total mass (prompt vs delayed collapse)
- mass asymmetries (HMNS and torus)
- soft/stiff EOS (inspiral and post-merger)
- magnetic fields (equil. and EM emission)
- radiative losses (equil. and nucleosynthesis)

GW spectroscopy and how to constrain the EOS

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



Anatomy of the GW signal



transient

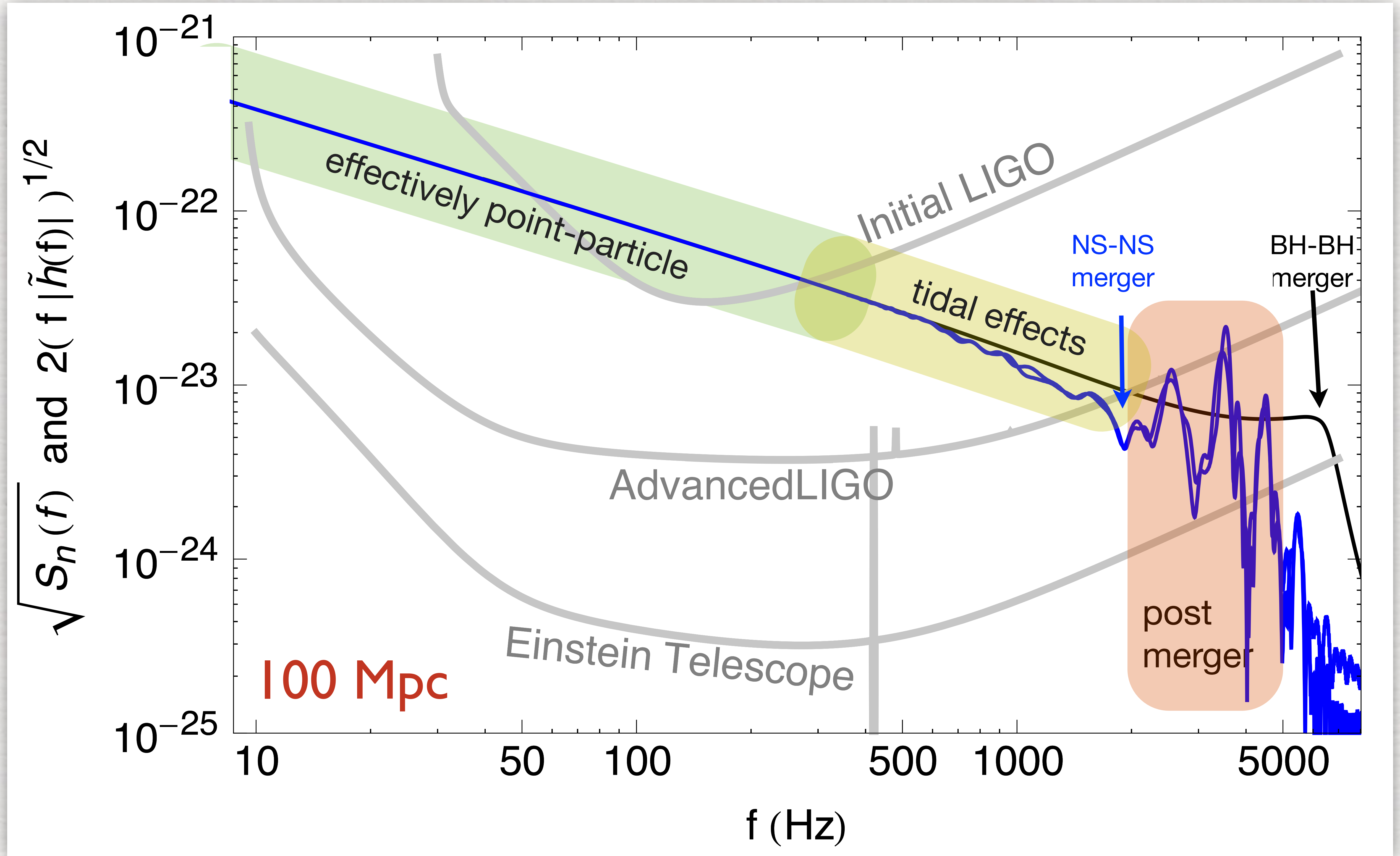
post-merger (HMNS)

black-hole formation (ringdown)

Chirp signal

Postmerger signal: peculiar of binary NSs

In frequency space

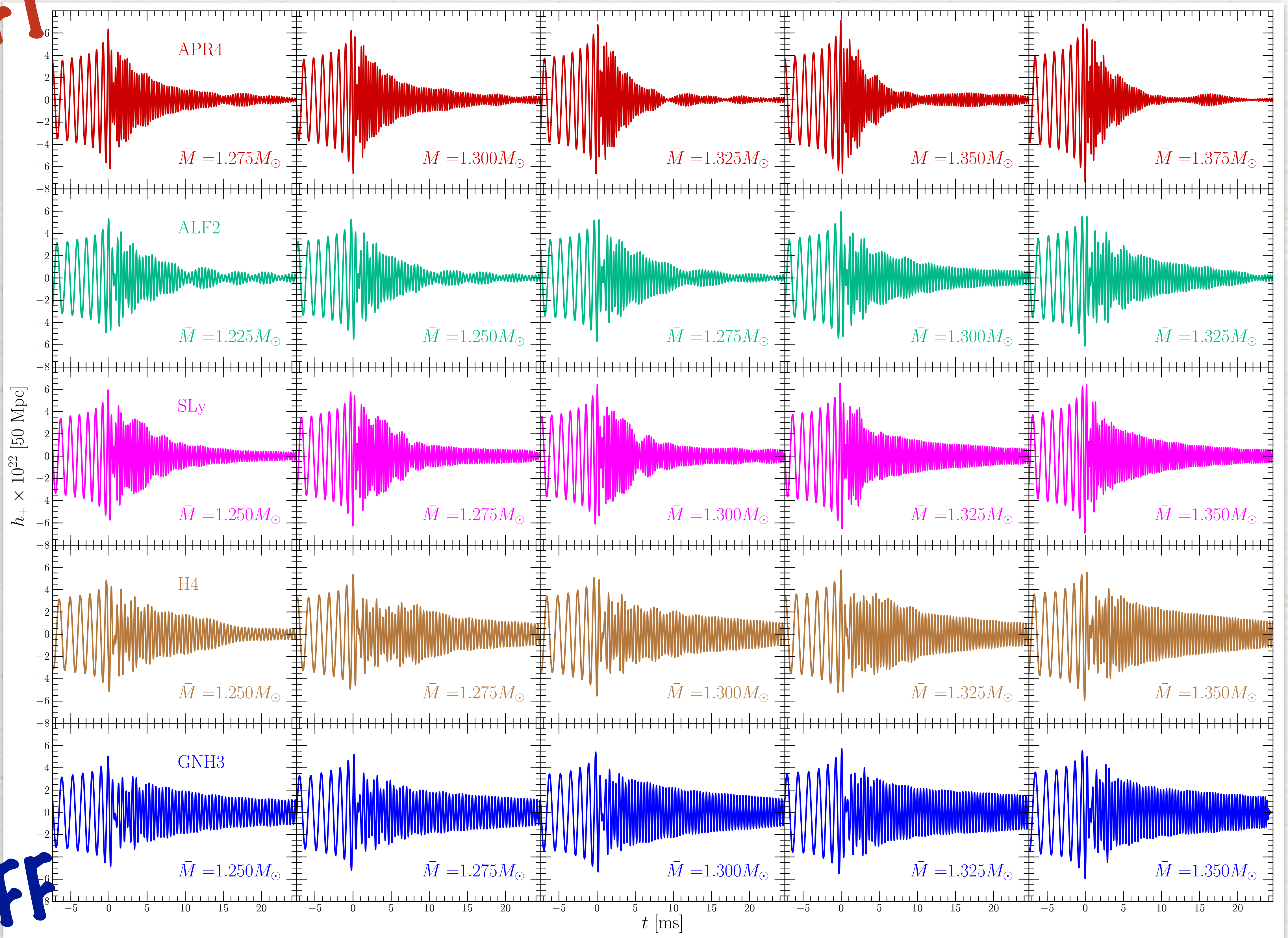


Read et al. (2013)

What we can do nowadays

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

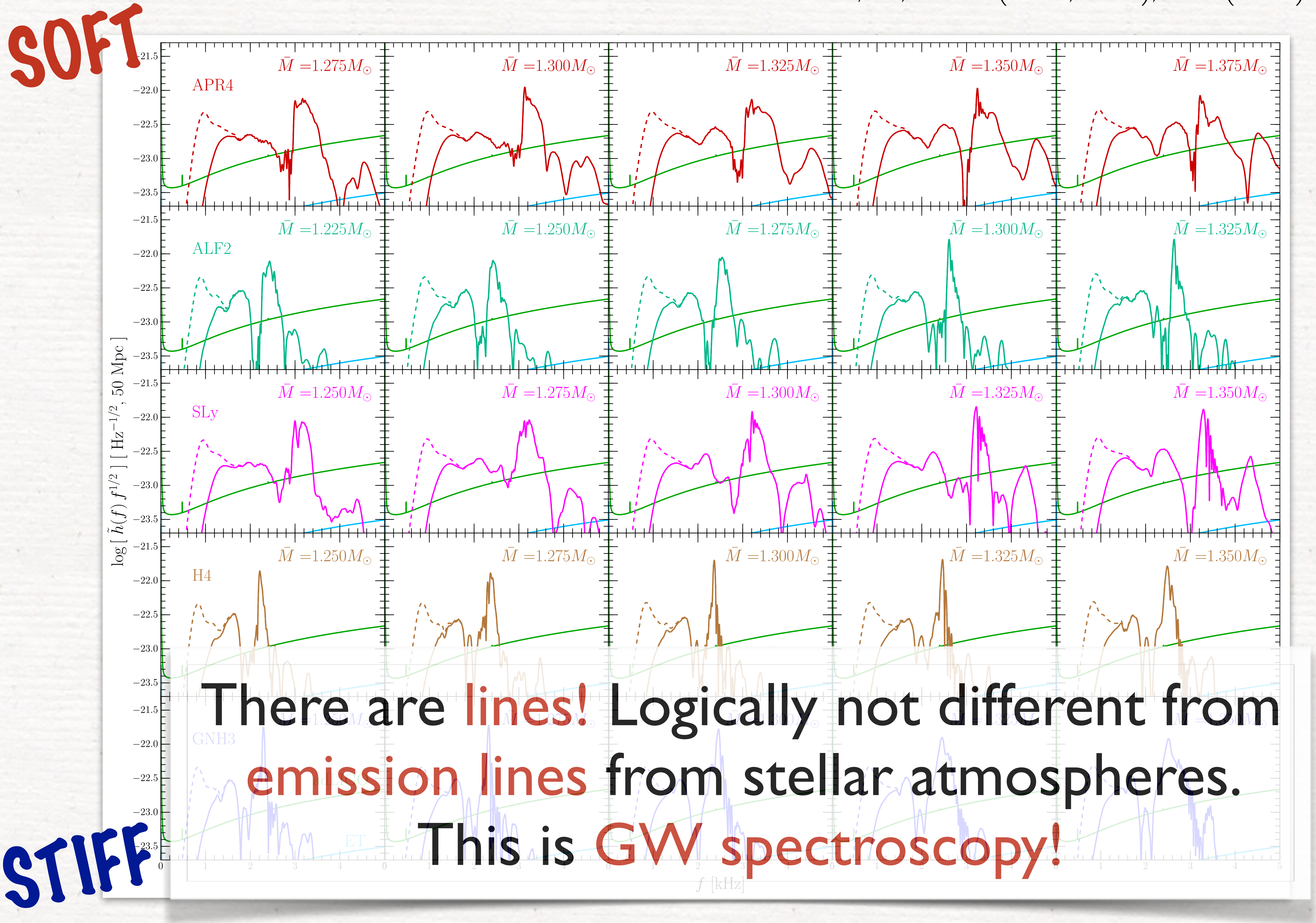
SOFT



STIFF

Extracting information from the EOS

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



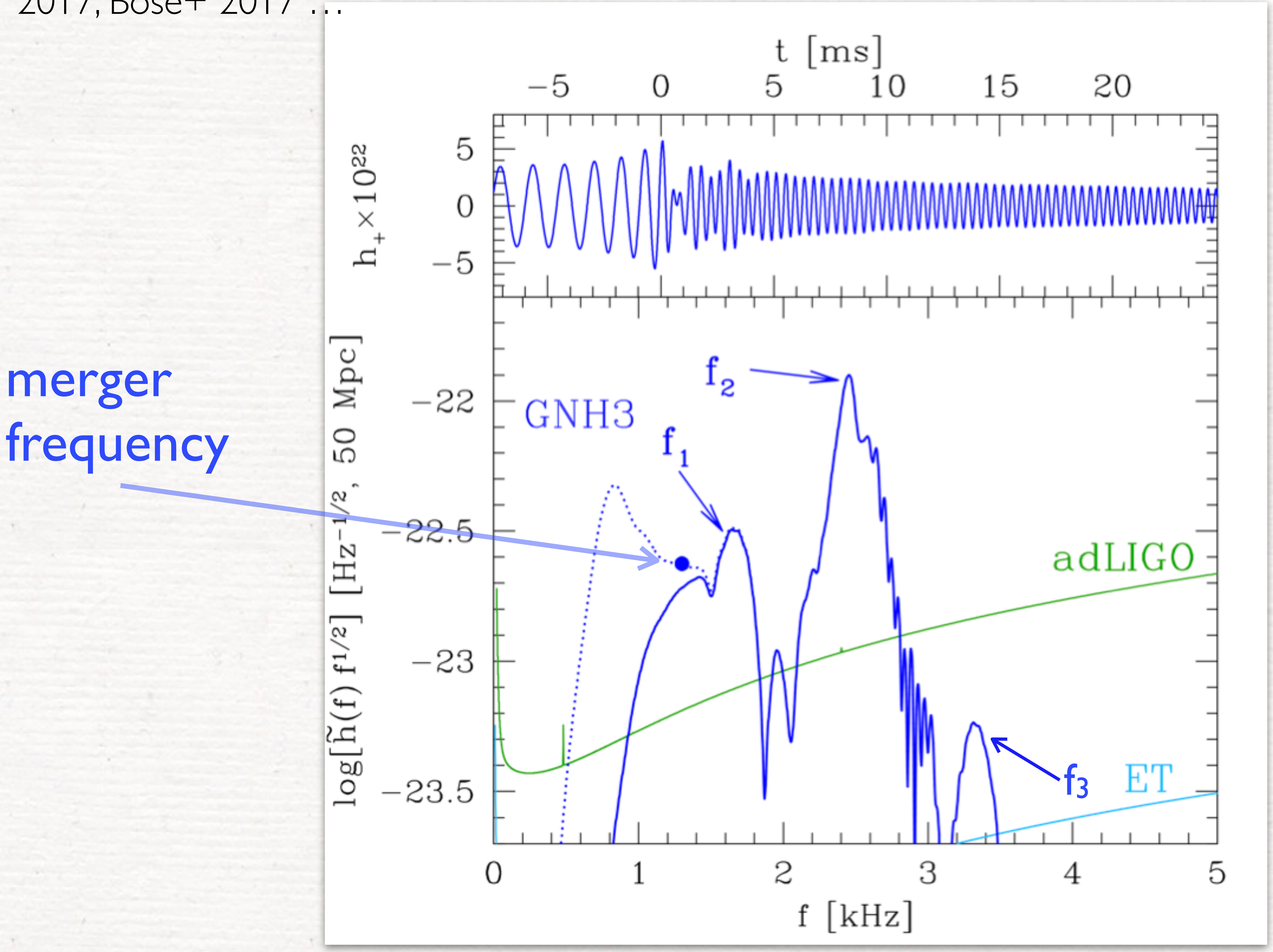
There are **lines!** Logically not different from **emission lines** from stellar atmospheres.

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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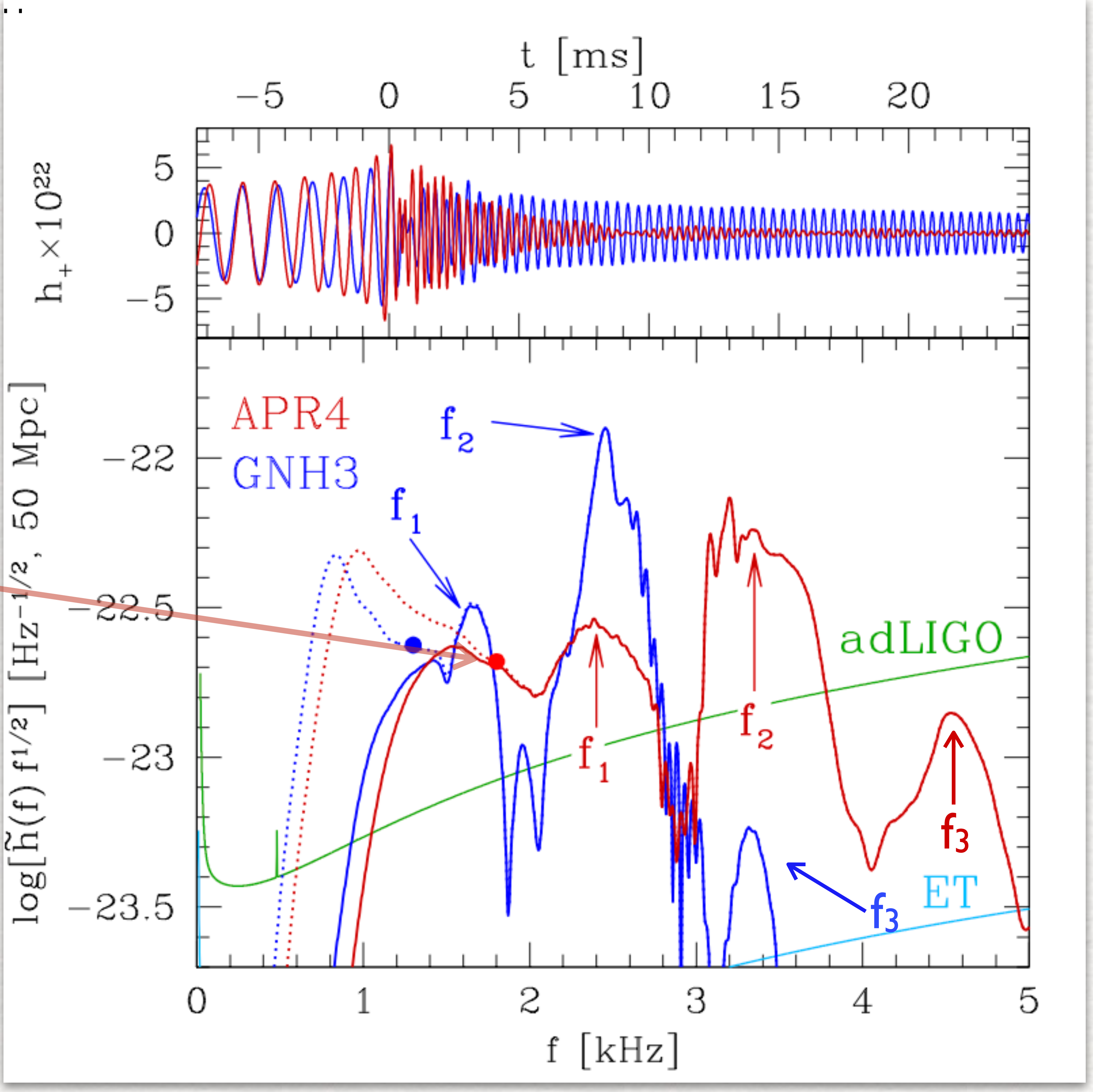
see N. Stergioulas' talk

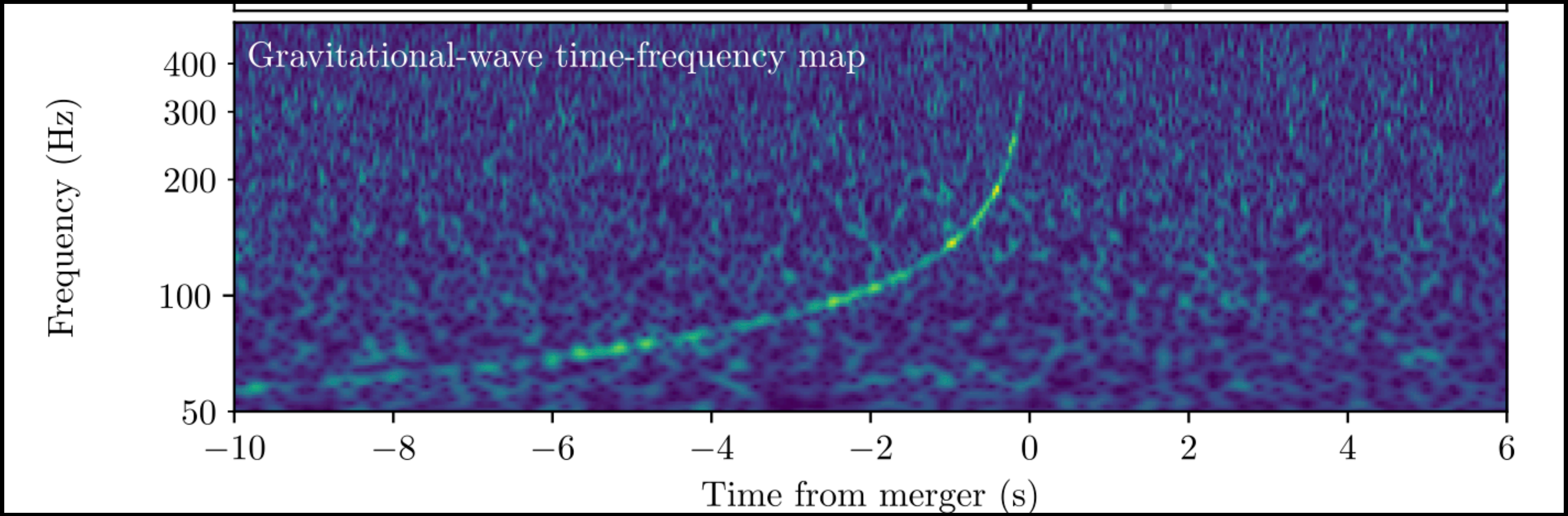


merger frequency

GW170817, maximum mass, radii and tidal deformabilities

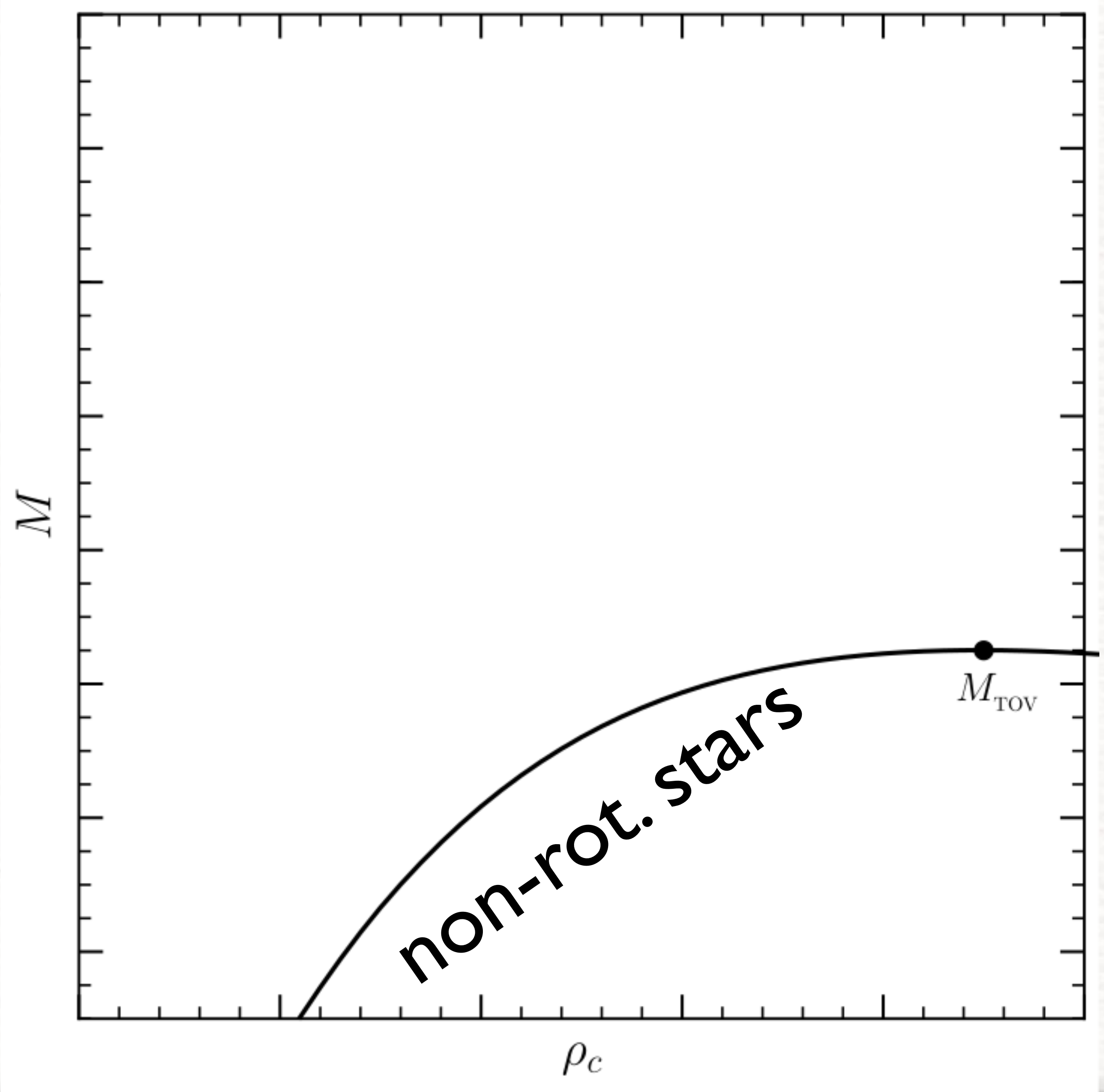
LR, Most, Weih, ApJL (2018)

Most, Weih, LR, Schaffner-Bielich, PRL (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: $M_{\rm TOV}$

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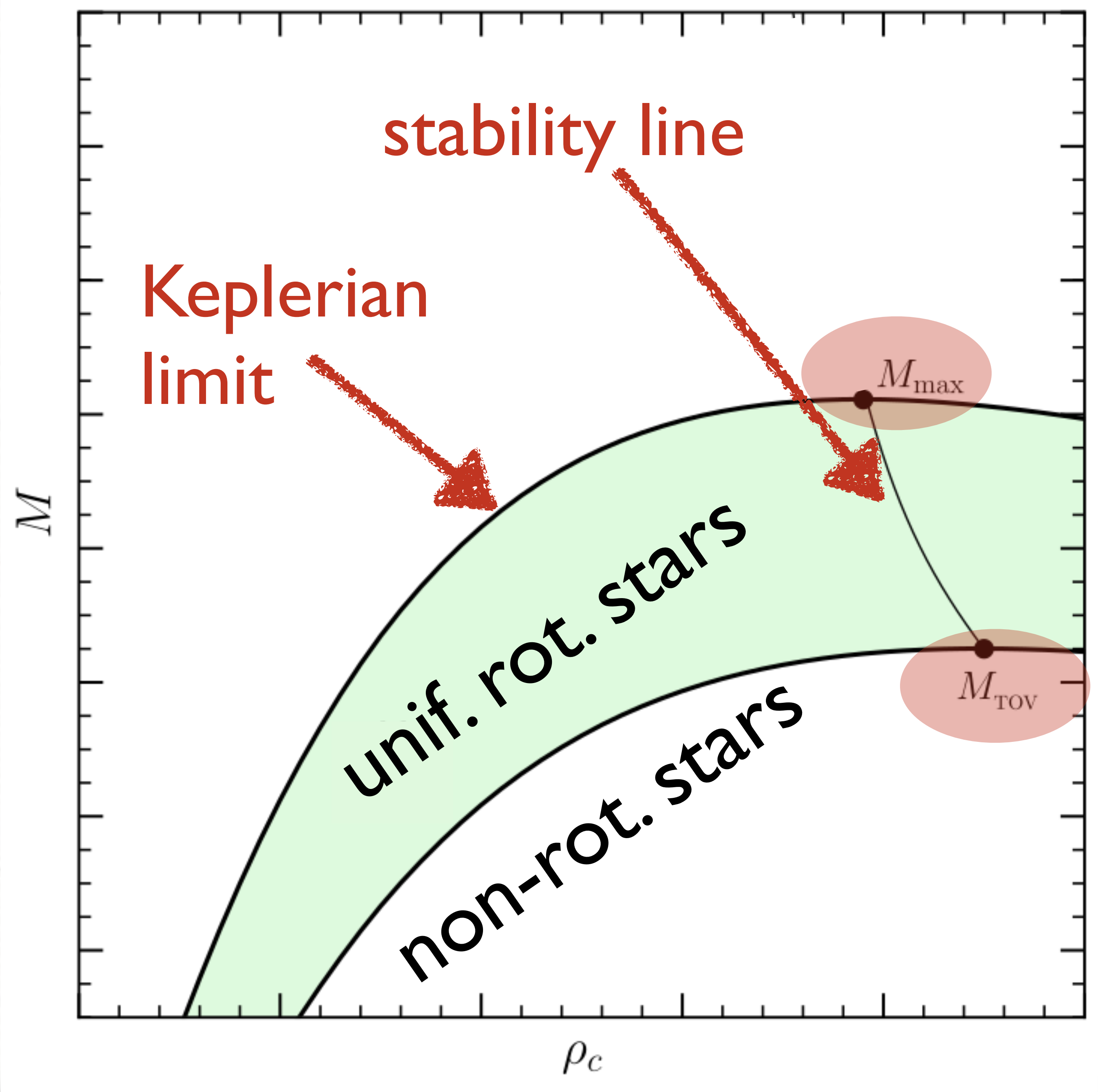

- Sequences of equilibrium models of **nonrotating** stars will have a maximum mass: $M_{\rm TOV}$
- This is true also for **uniformly** rotating stars at mass shedding limit: $M_{\rm max}$
- $M_{\rm max}$ simple and **quasi-universal** function of $M_{\rm TOV}$ (Breu & LR 2016)

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

The outcome of GW170817

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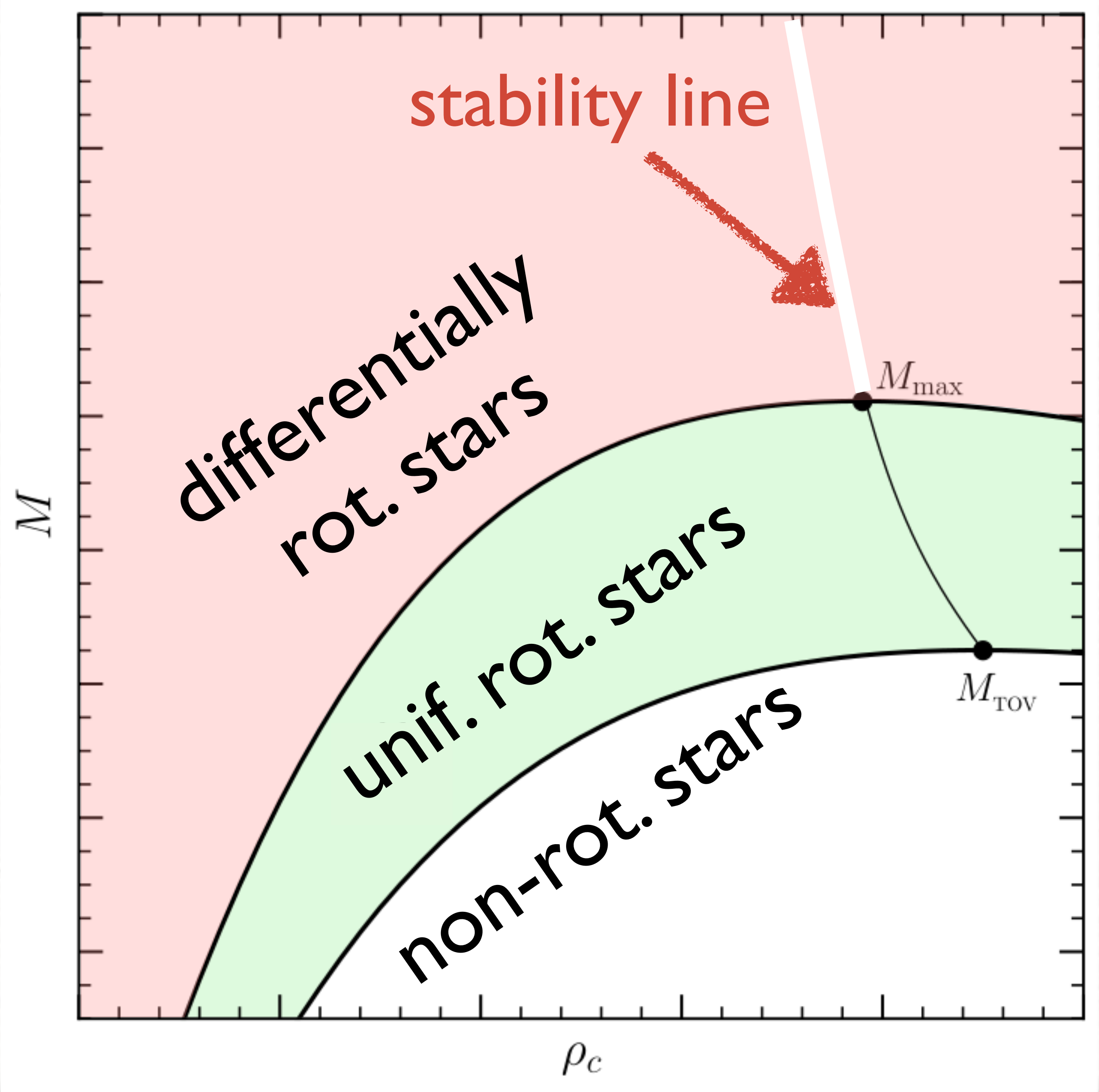
$$M_1 + M_2 = 2.74^{+0.04}_{-0.01} M_\odot$$

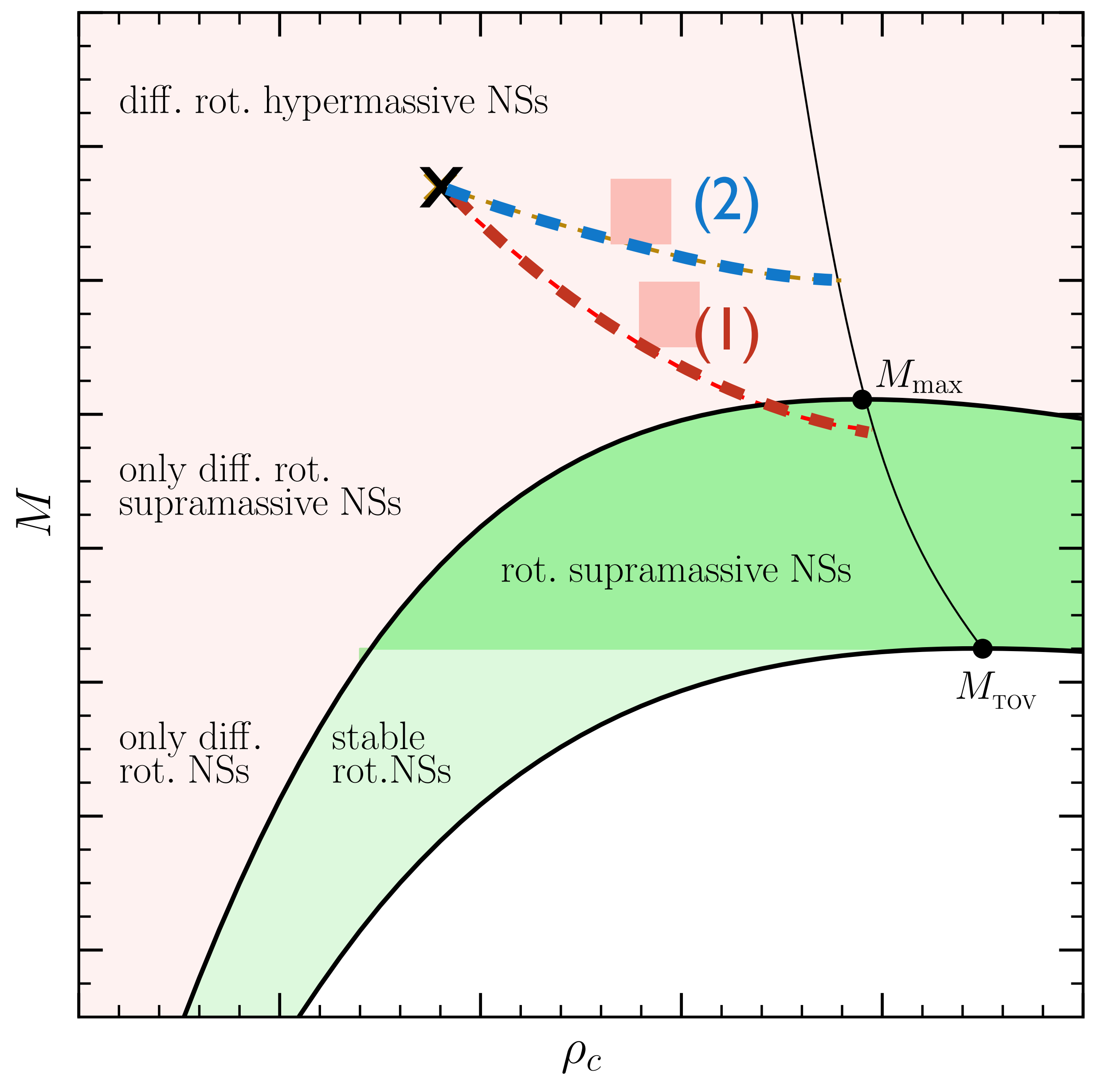


- **Green** region is for **uniformly** rotating equilibrium models.
- **Salmon** region is for **differentially** rotating equilibrium models.
- Stability line is simply extended (Weih+18)

The outcome of GW170817

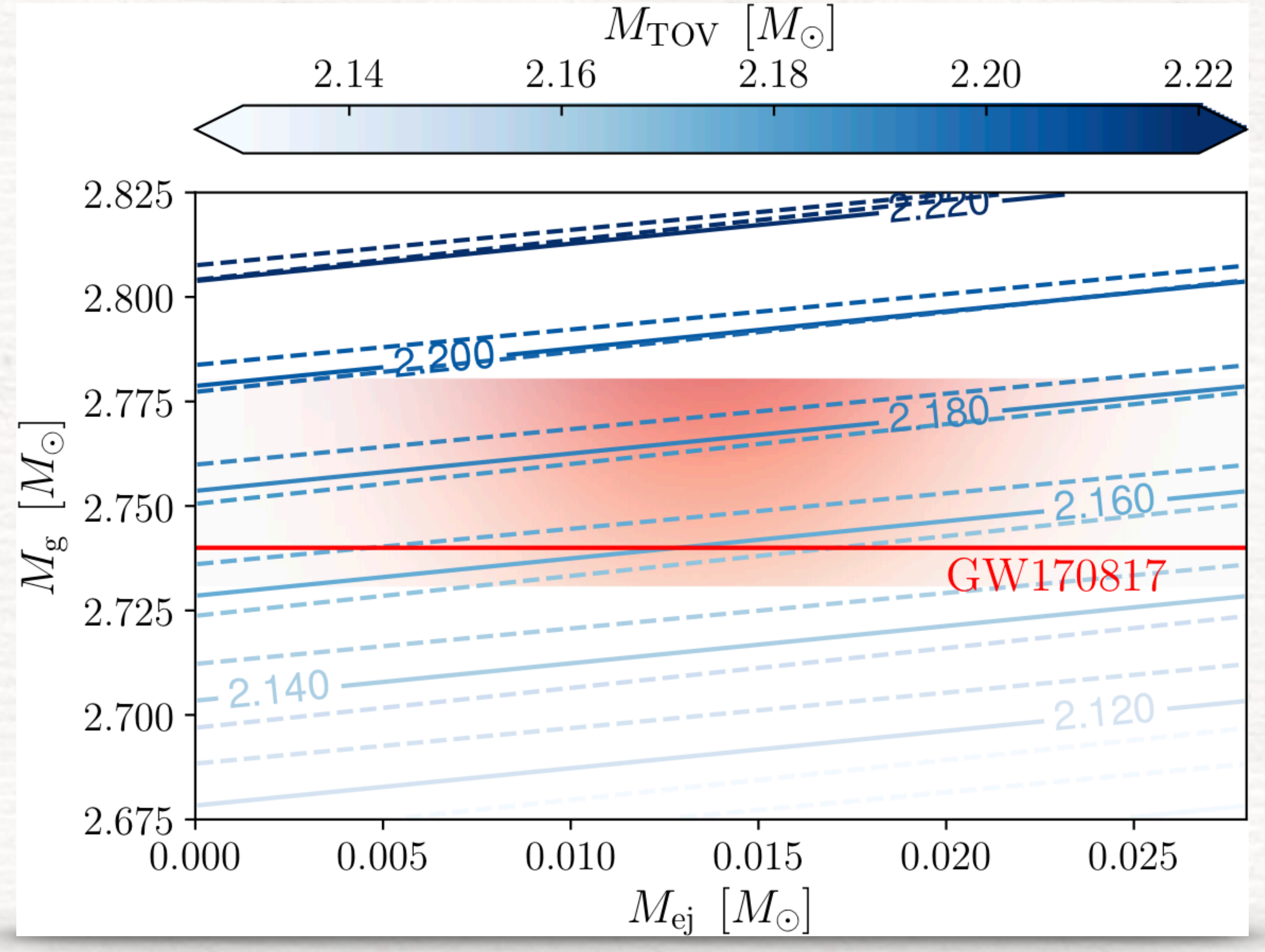
- GW170817 produced object as **"x"**; GRB implies a BH has been formed: **"x"** followed two possible tracks: **fast (2)** and **slow (1)**

- 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 $M_{\rm max}$ 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 errors to obtain

pulsar timing

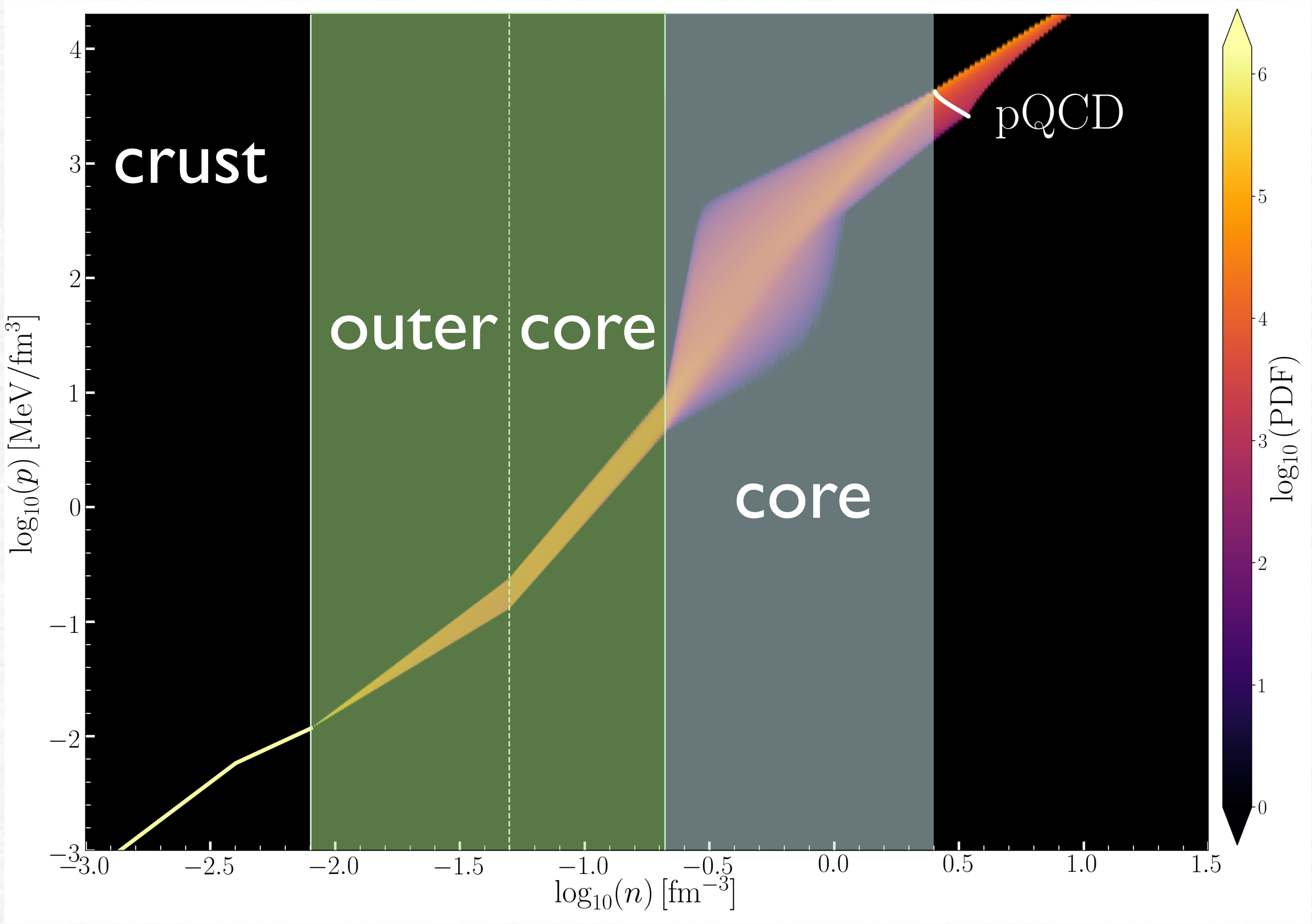
$$2.01^{+0.04}_{-0.04} \leq M_{\rm TOV}/M_\odot \lesssim 2.16^{+0.17}_{-0.15}$$

universal relations and GW170817; similar estimates by other groups

Limits on radii and deformabilities

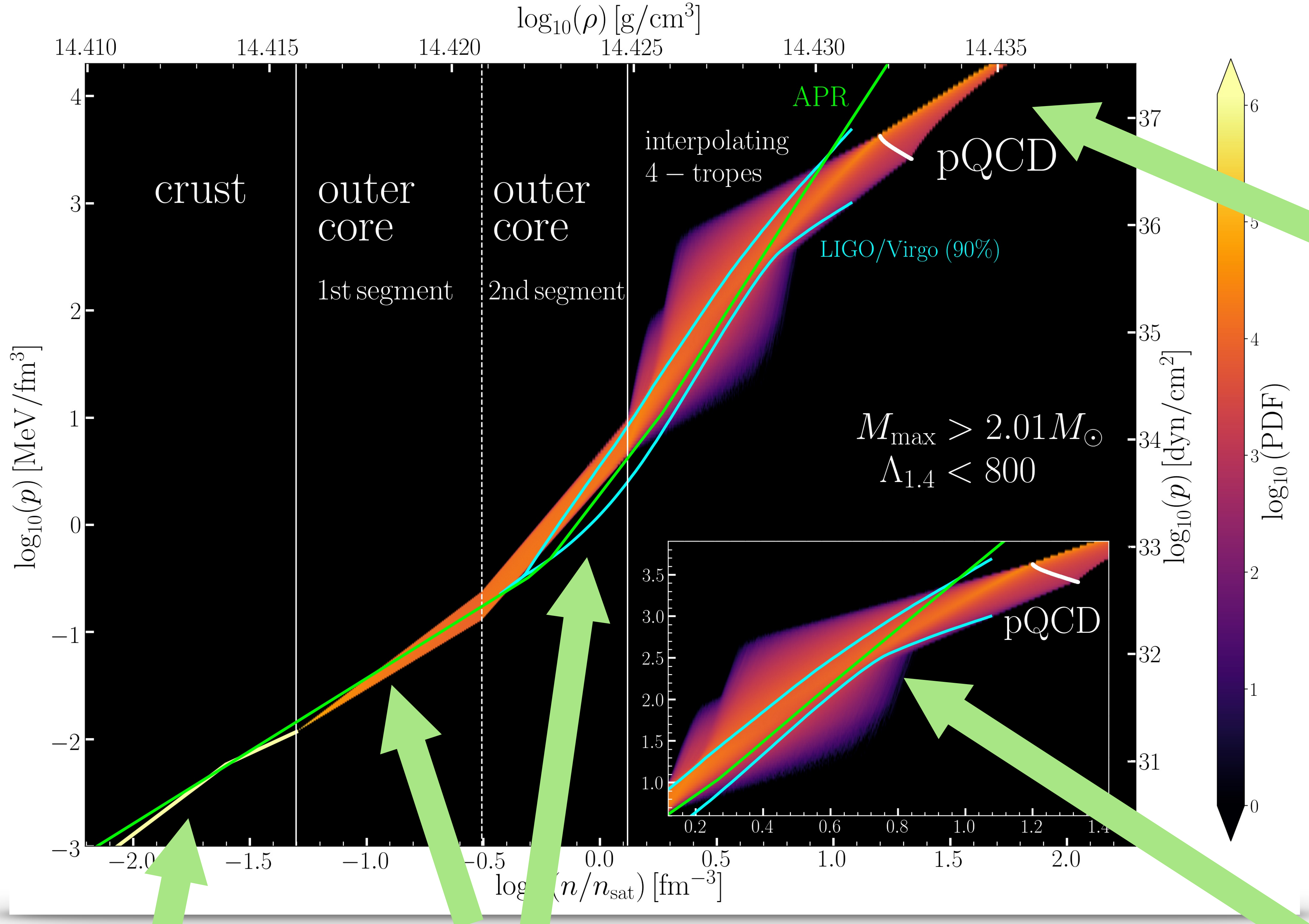
- Can new constraints be set on typical radius and tidal deformability by using GW170817?

- 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)

BPS

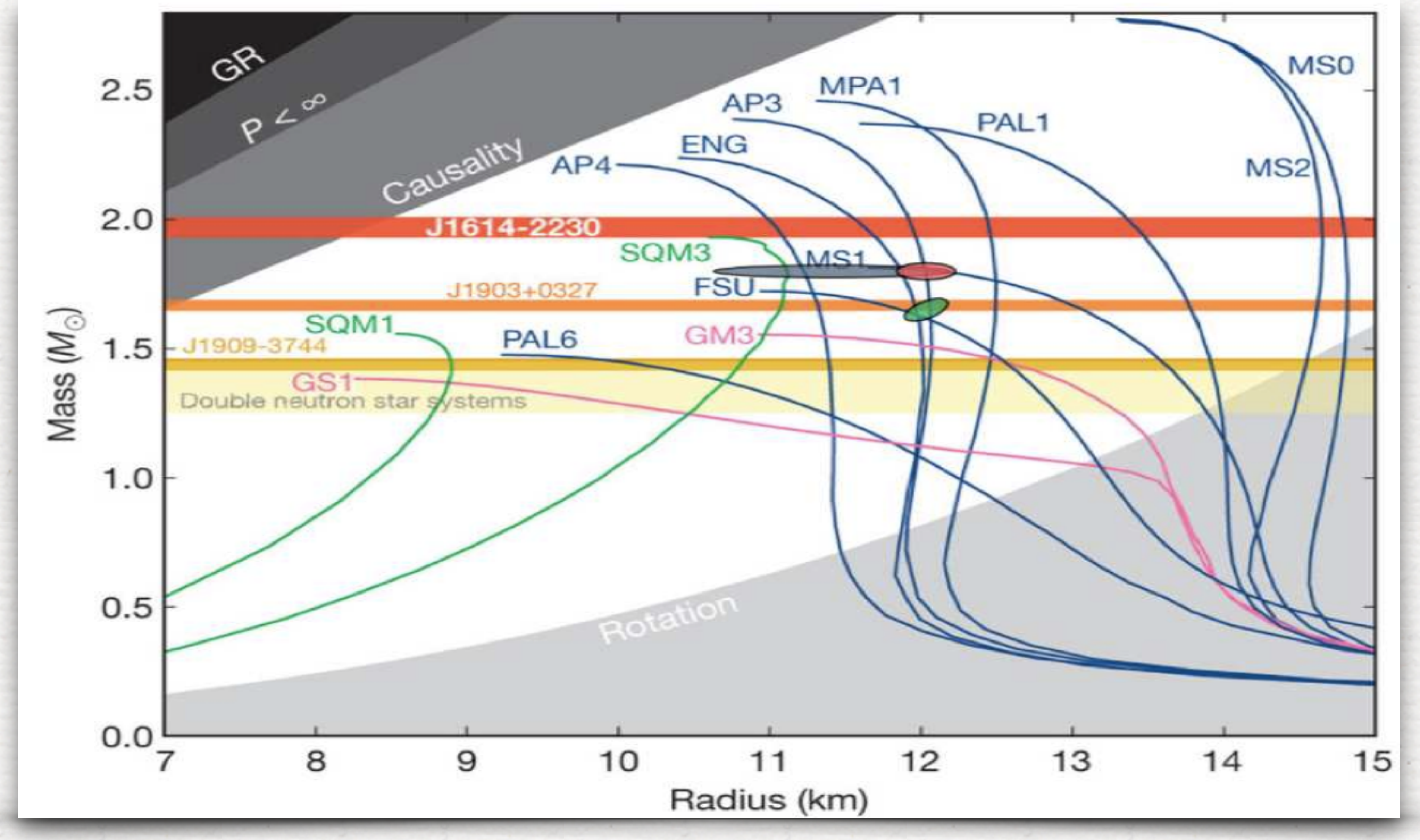
polytropic fit of Drischler+ (2016)
(large impact on results)

interpolation
by matching 4
polytropes

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

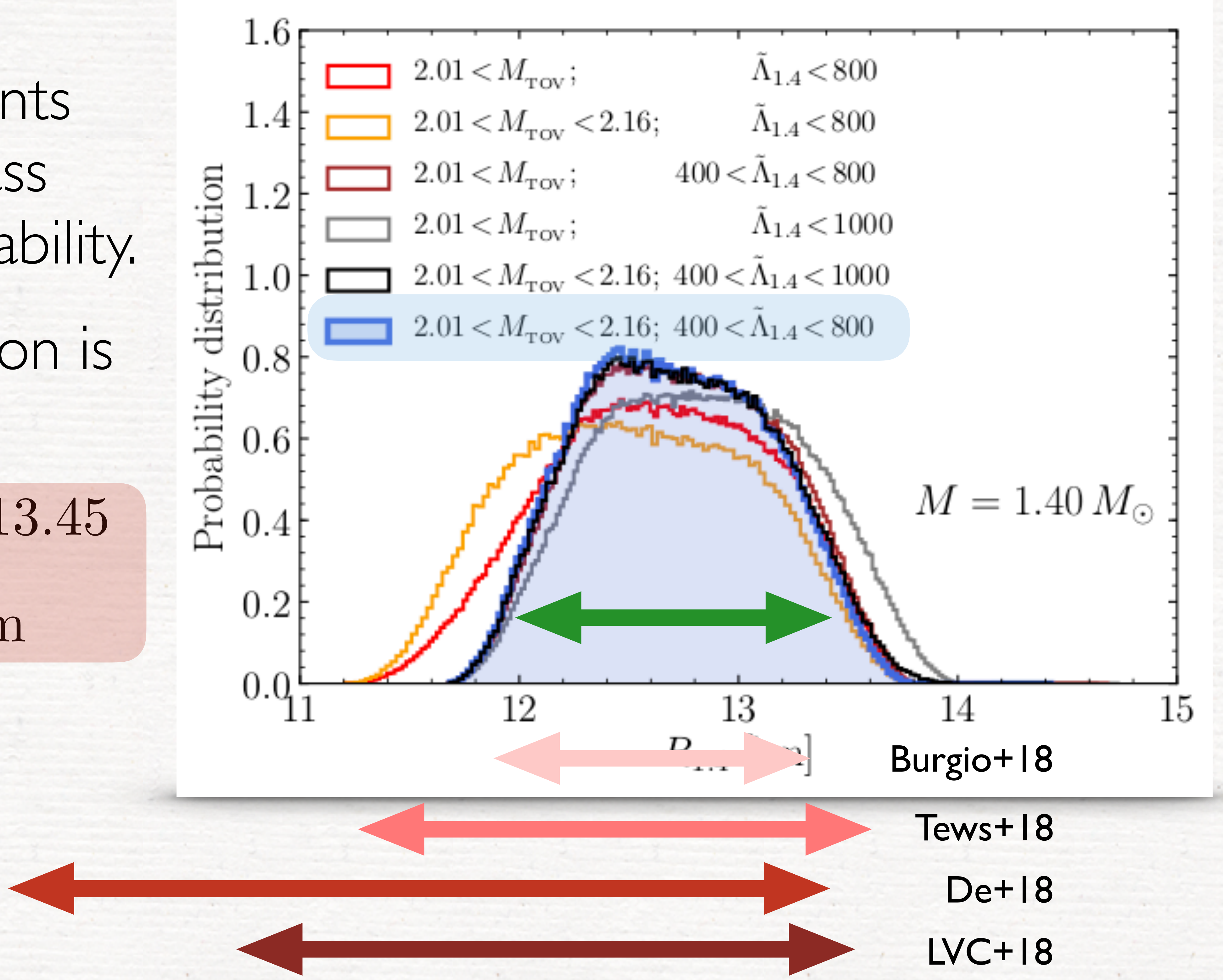


one-dimensional cuts

- 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

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

$$\bar{R}_{1.4} = 12.45\,\mathrm{km}$$



and many more estimates…

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:

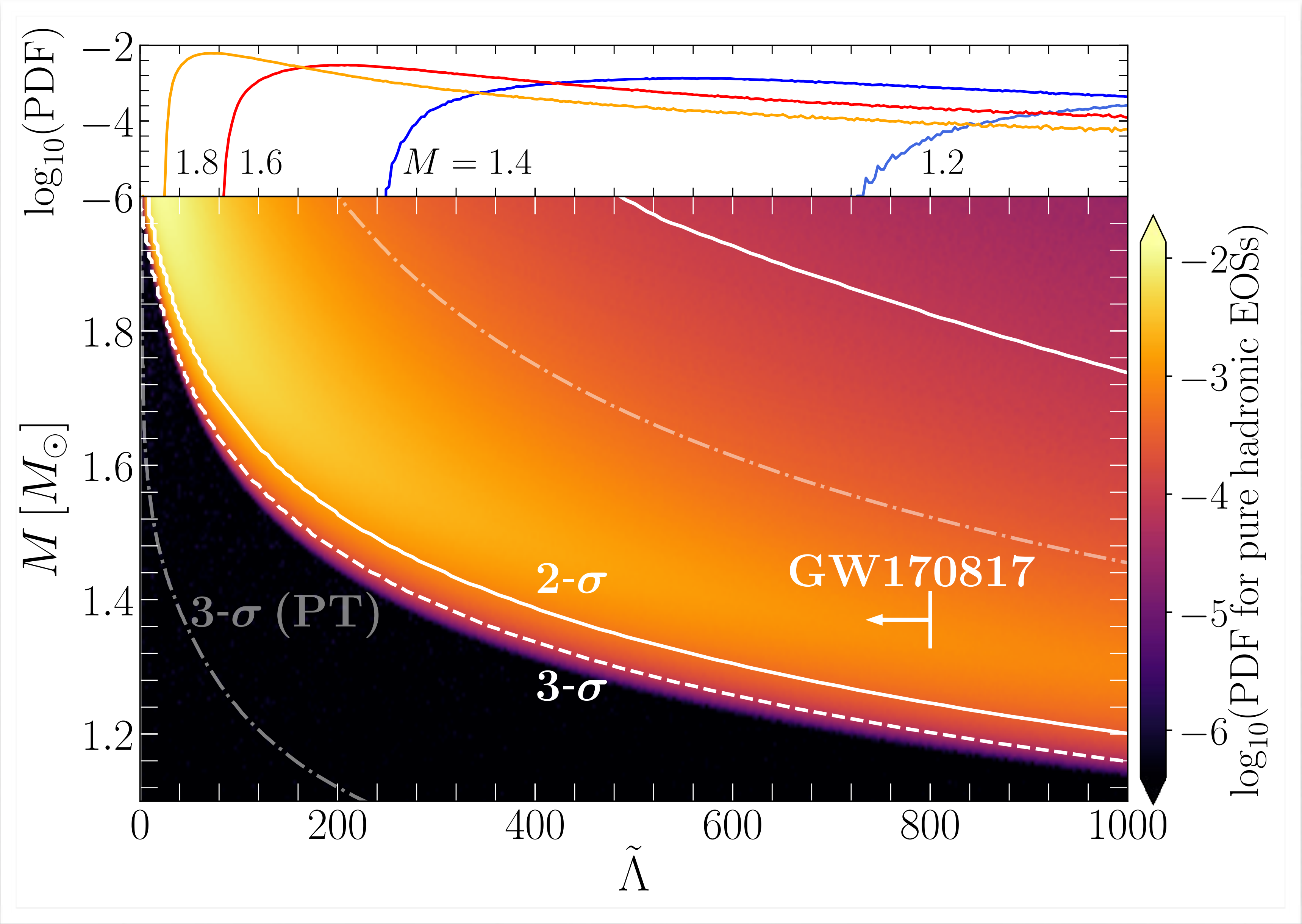
$$\tilde{\Lambda}_{1.4} \lesssim 800$$

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

- Our sample sets a lower limit:

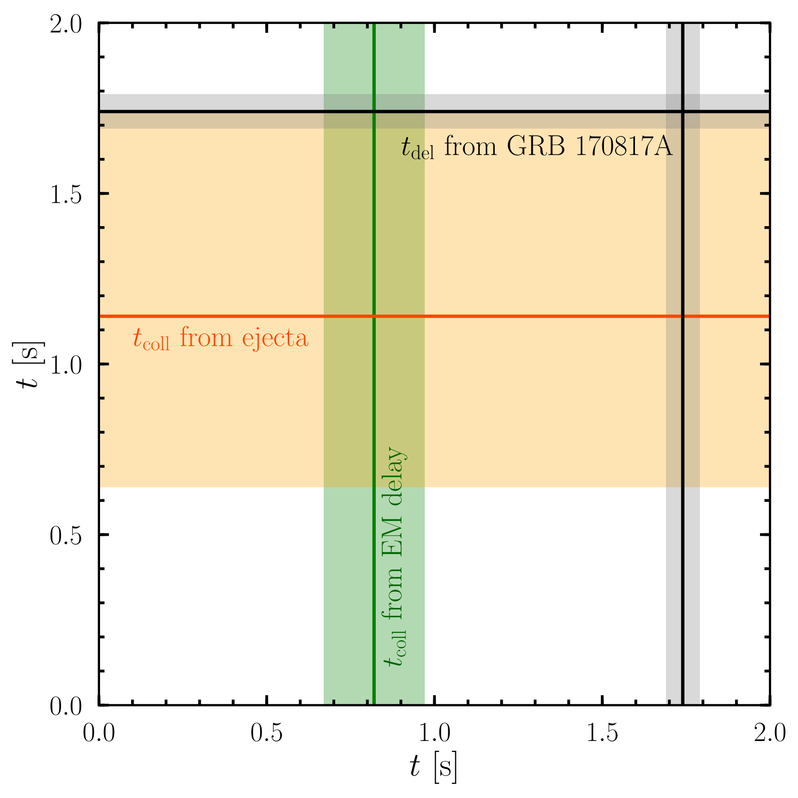
$$\tilde{\Lambda}_{1.4} > 375$$

largest so far.



When did the merger of GW170817 collapse to a BH?

Gill, Nathanail, LR (2019)

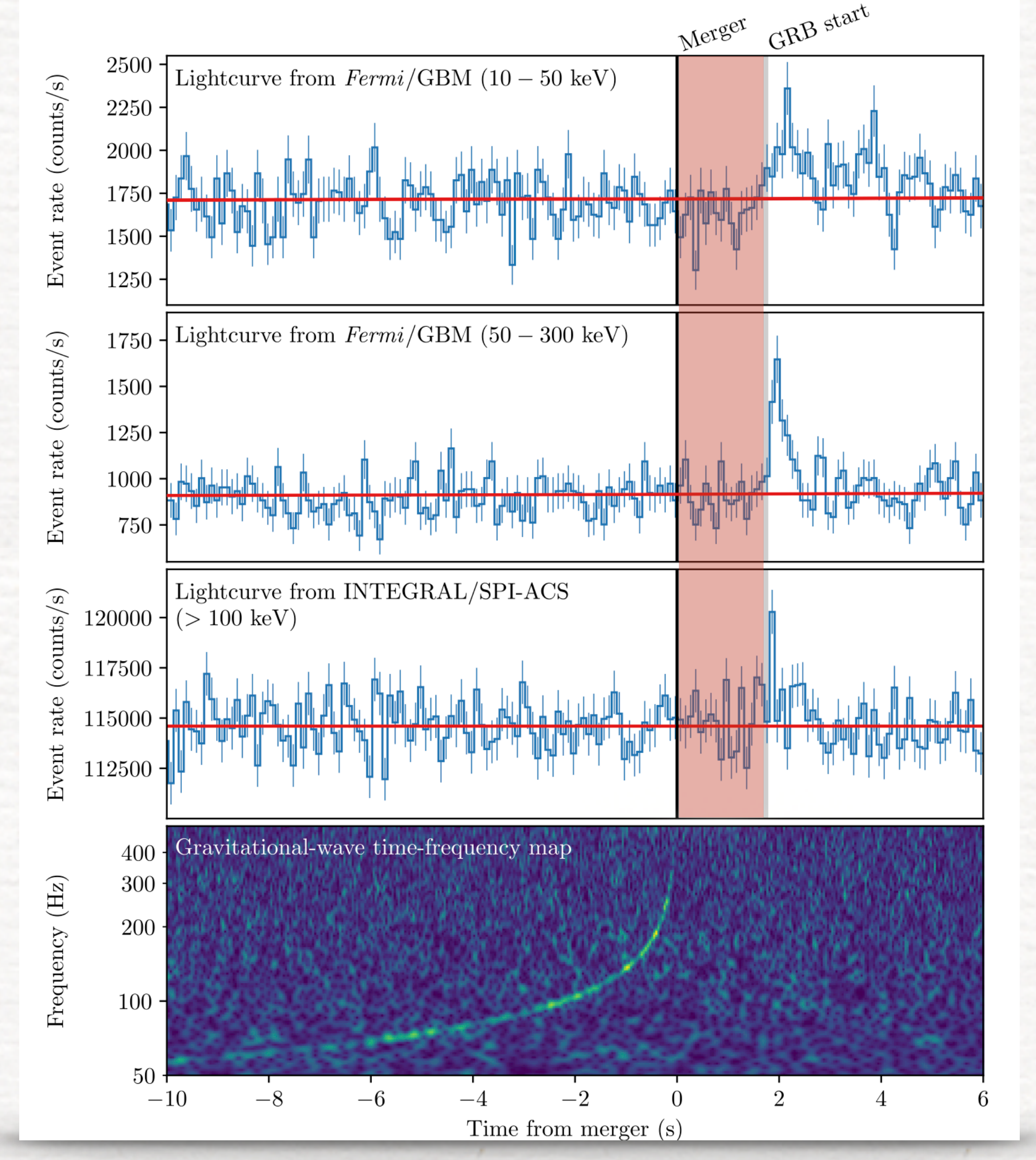


Why is this important?

Conservative assumption: the remnant of GW170817 collapsed to a BH. GRB observed at $t_{\rm del} = 1.74 \pm 0.05\,{\rm s}$

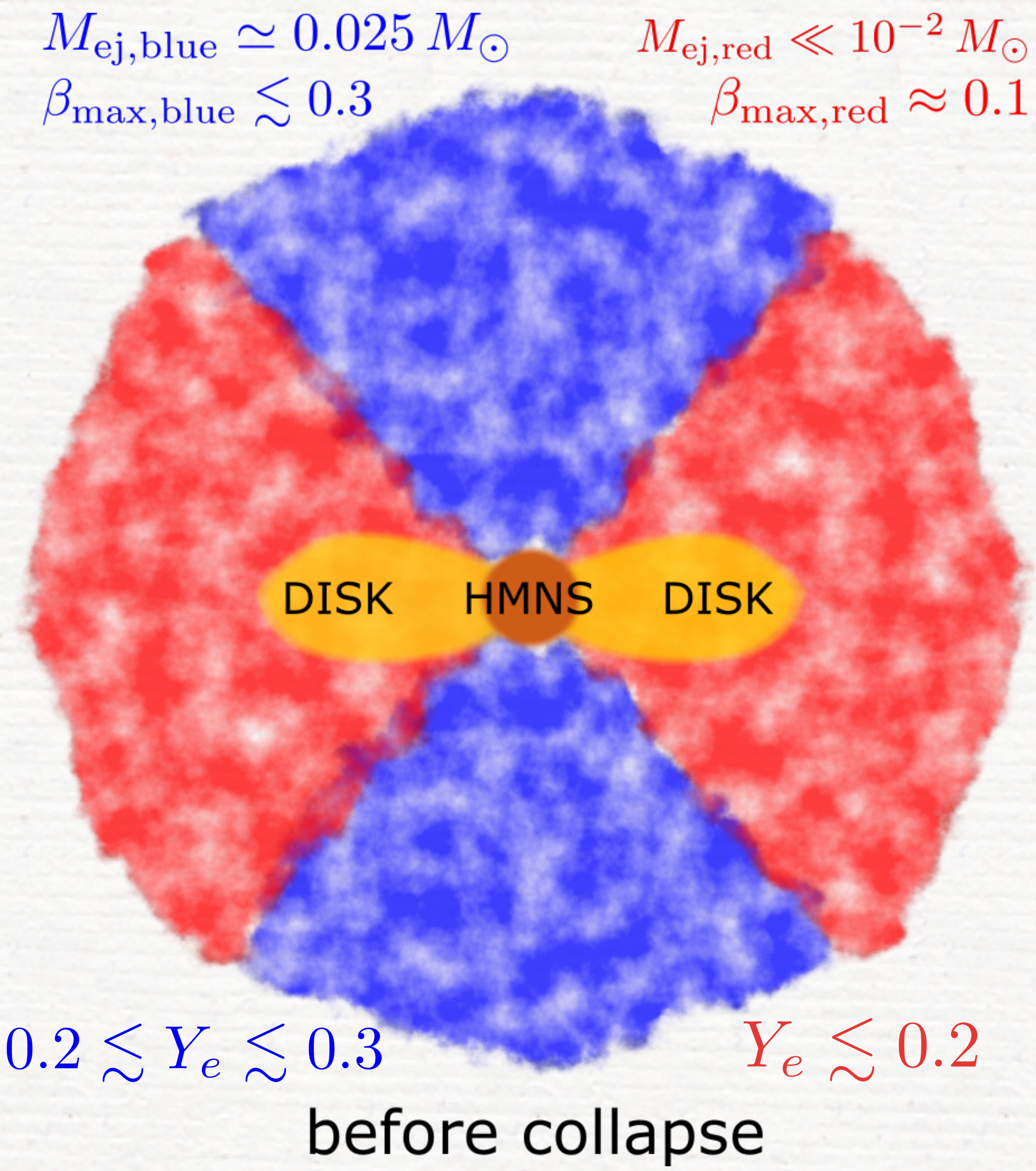
However, when did it actually collapse?

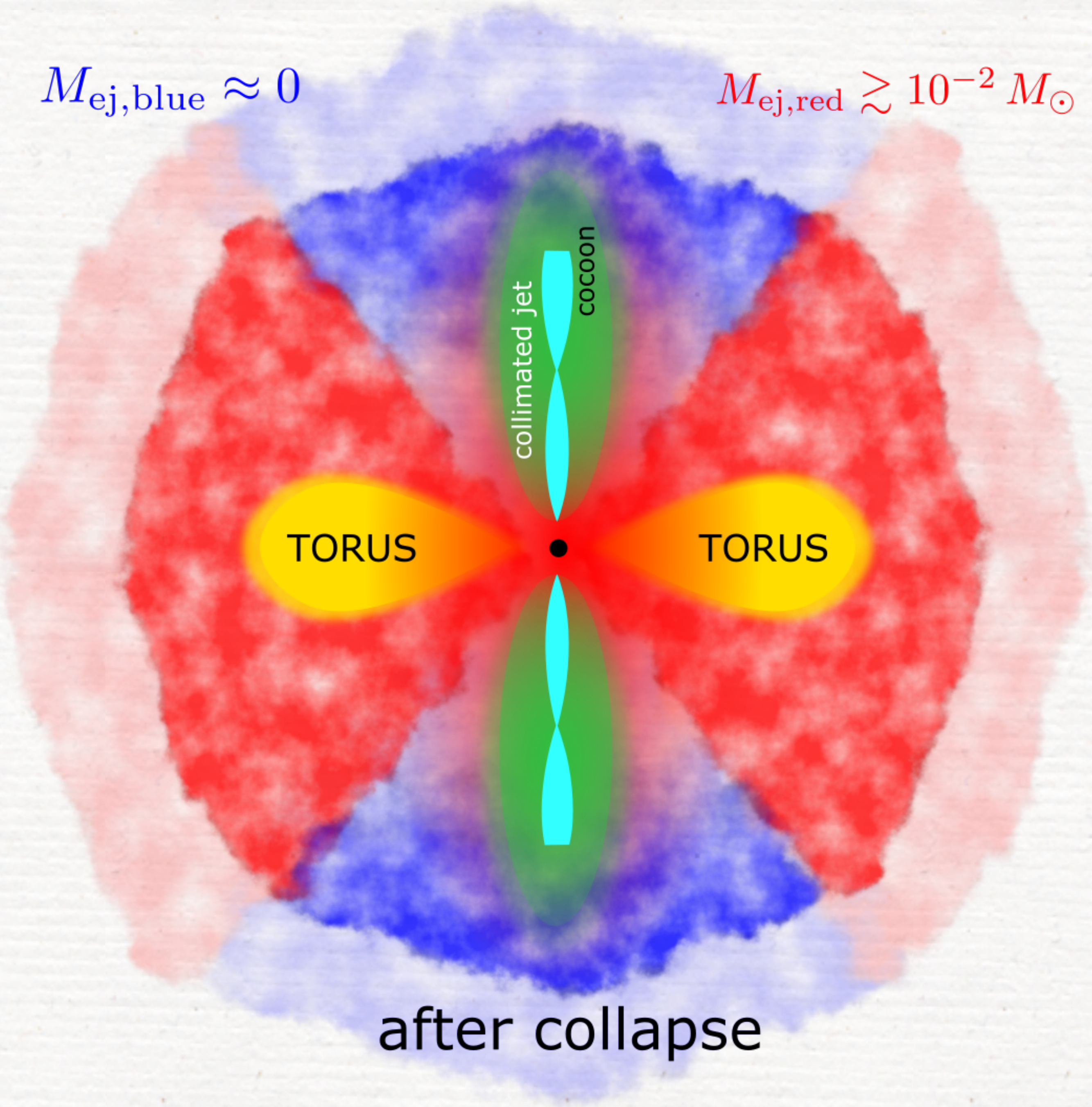
- If collapsed **too early,** not enough matter **ejected** for observed kilonova
- If collapsed **too late,** delay in the GRB would have been **longer** than 1.74 s.
- The more the mass ejected, the longer for the jet to bore its way and **breakout**.



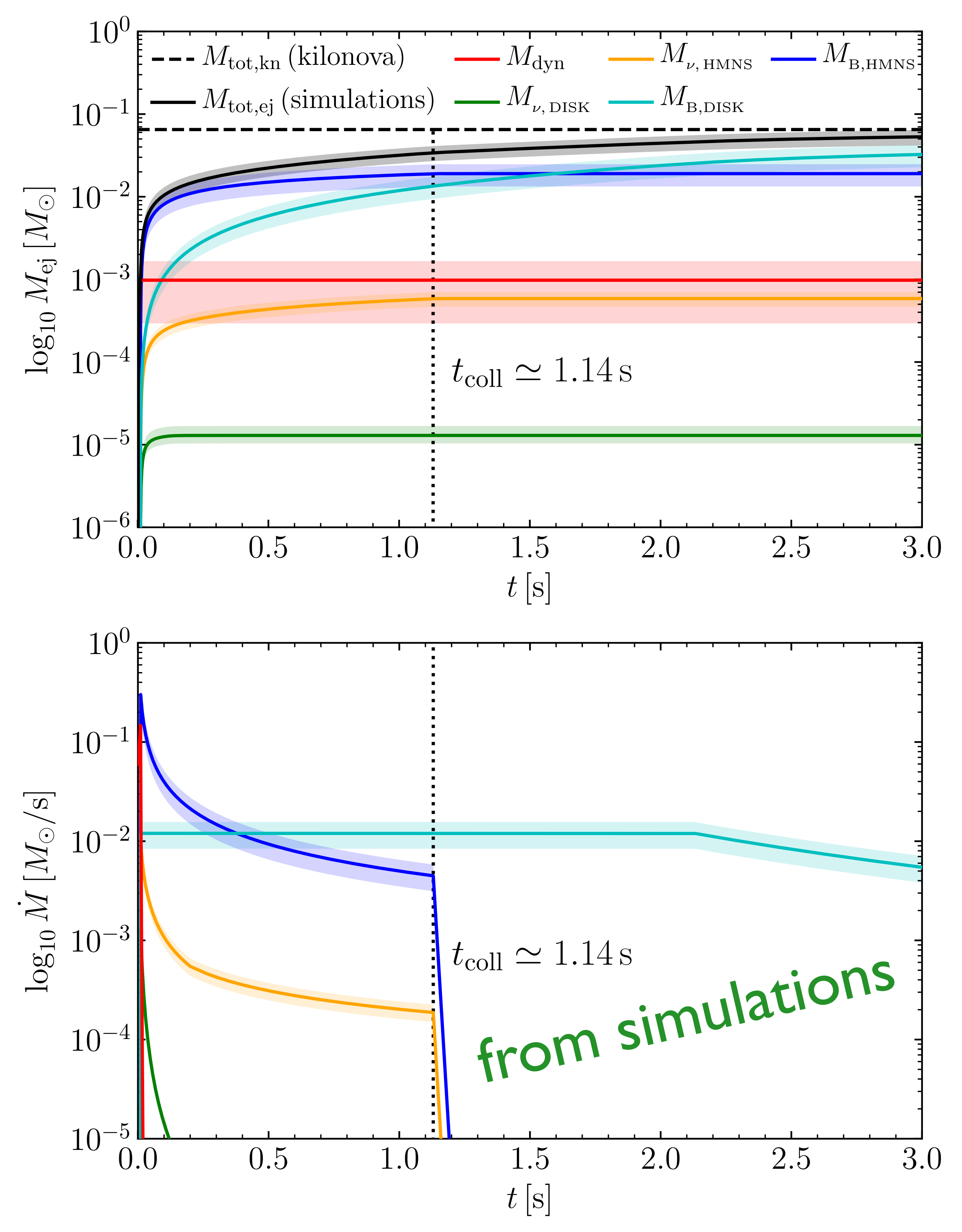
Ejection of mass

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





Ejection of mass



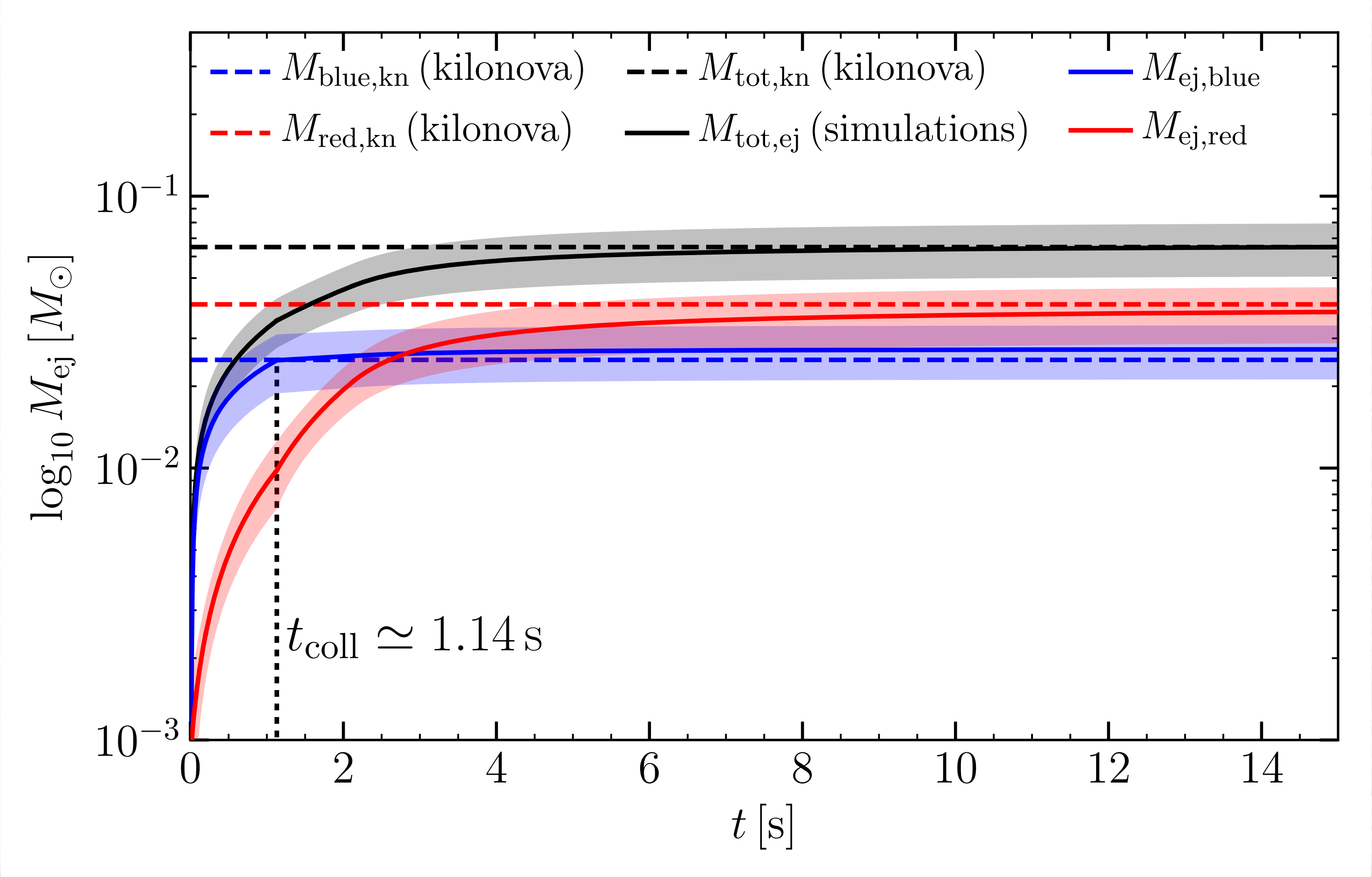
from simulations

- Shown are the mass-ejection rates from numerical simulations.
- $M_{\rm dyn}$: matter ejected dynamically
- M_ν: matter ejected via neutrino-driven winds
- $M_{\rm B}$: matter ejected via magnetically driven winds

All channels have contribution from the central object and the disk.

All channels provide both **blue** or **red** ejecta in different amounts.

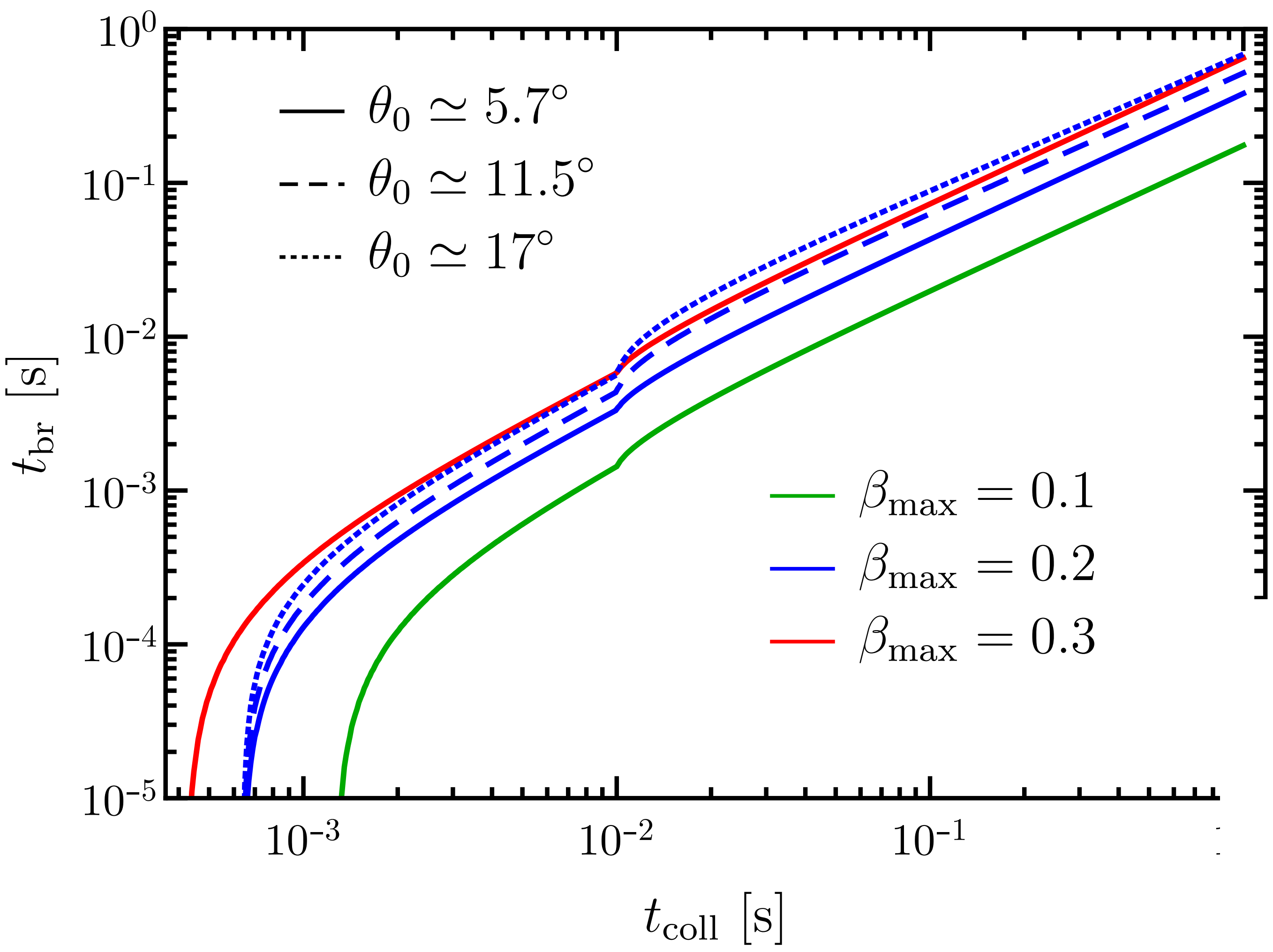
Constraints from mass ejection



- Shown are the mass contributions (blue/red) on "long" timescales.
- Blue ejecta essentially stops after collapse and constraints collapse time **from mass ejection** to be

$$t_{\rm coll} = 1.14^{+0.60}_{-0.50}\ {\rm s}$$

Constraints from breakout

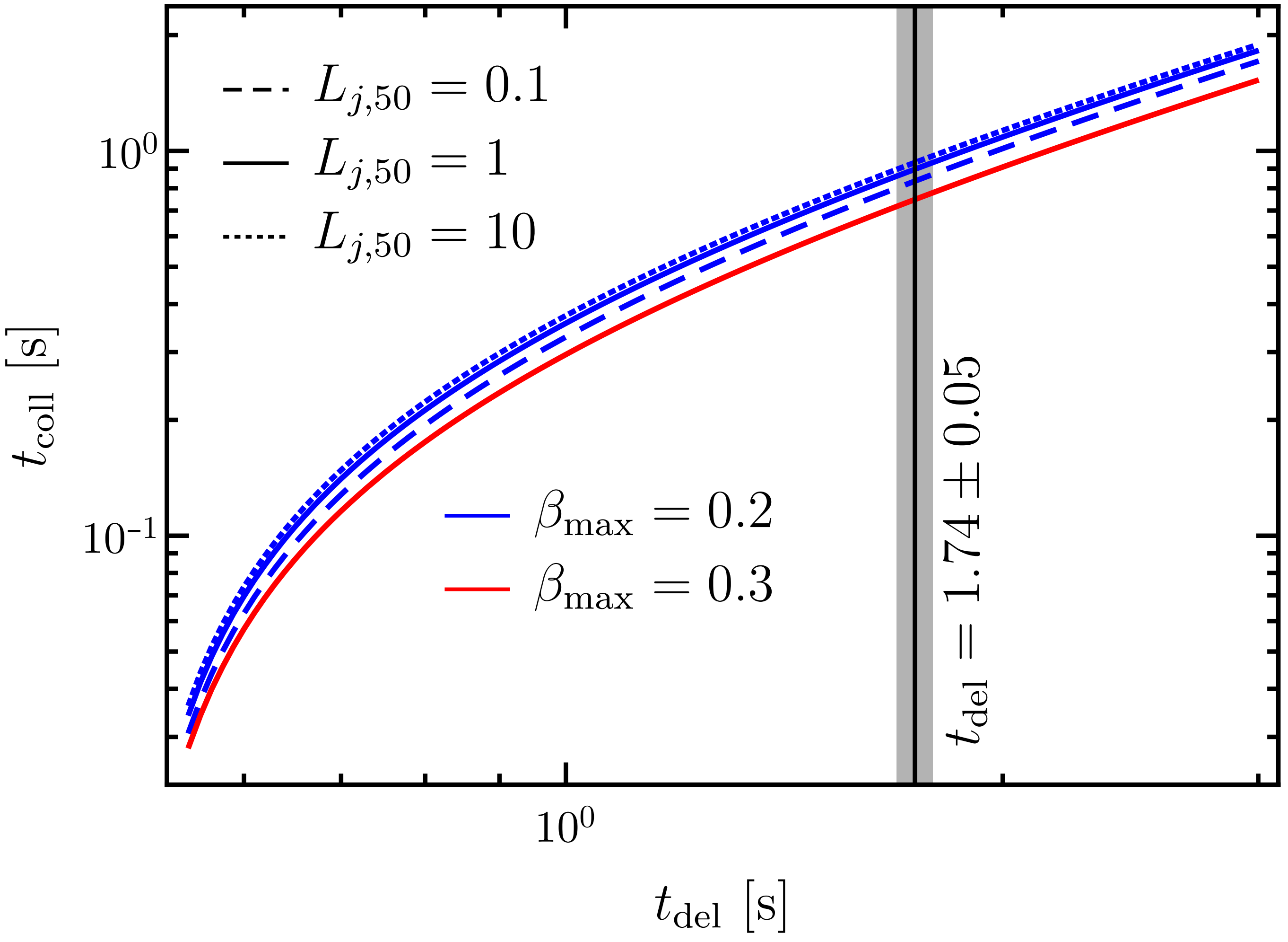


- Breakout time depends on collapse time, speed of ejecta jet opening angle, and energy injected (i.e., more and faster ejecta, longer time to escape).

- Given measured t_{del} we can constrain collapse time **from breakout** to be

$$t_{\mathrm{coll}} = 0.82 \pm 0.15 \text{ s}$$

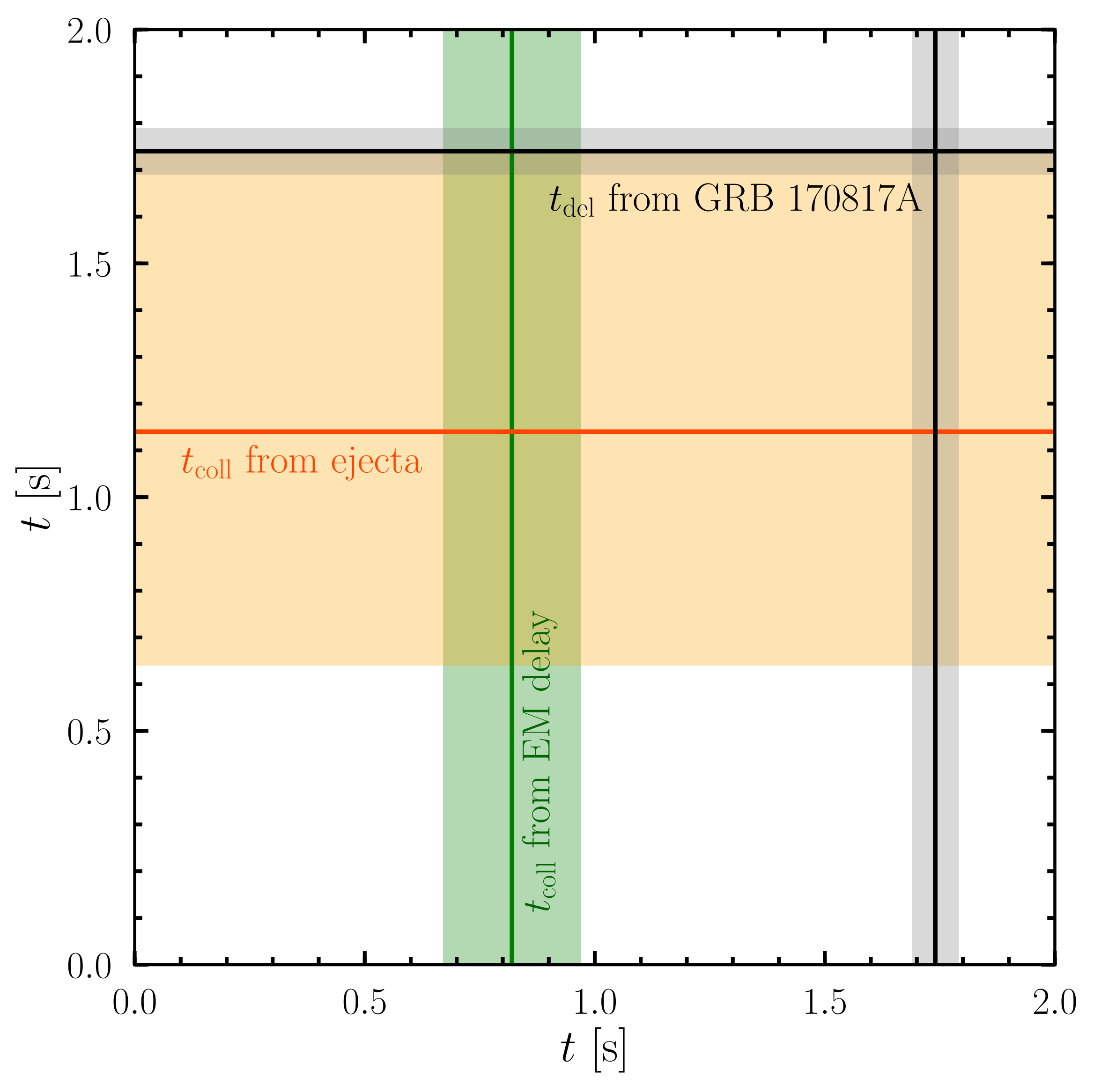
$$t_{\mathrm{del}} = 1.74 \pm 0.05\,\mathrm{s} = t_{\mathrm{coll}} + t_{\mathrm{br}}(t_{\mathrm{coll}}) + t_R$$



Putting things together

- Can combine two constraints and their uncertainties to obtain a single estimate

$$t_{\rm coll} = 0.98^{+0.31}_{-0.26}\ {\rm s}$$



- What are the **implications?**
  - ✳correlates $M_{\rm ej,blue}$ and $t_{\rm coll}$: to be tested new detections
  - ✳much longer than what can be simulated accurately (~0.1 s)
  - ✳mechanisms other than GWs for loss of angular momentum: spin down due to dipolar EM radiation appears reasonable
  - ✳this implies $B \gtrsim 10^{16}$ G need to be produced **after** merger

Conclusions

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

✳When used together with tens of observations, they will set tight constraints on EOS: radius known with ~1 km precision.

✳**GW170817** has already provided new limits on

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

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

✳First constraints on lifetime of **GW170817** remnant

$t_{\rm coll} = 0.98^{+0.31}_{-0.26}\ {\rm s}$

Gravitational physics is living its Renaissance!
Also this time Europe will be its main centre.