Binary neutron stars: from gravitational to particle physics

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Workshop I: Computational Challenges in MMA

Plan of the talk

- The richness of merging binary neutron stars
- GW spectroscopy: EOS from frequencies
- GW170817: a game changer:
  - maximum mass
  - threshold mass
  - radii and deformabilities
- Signatures of quark-hadron phase transitions
- Accretion disks from BH-NS simulations
- Fast ejecta in BH-NS simulations
- GW190425

The two-body problem in GR

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

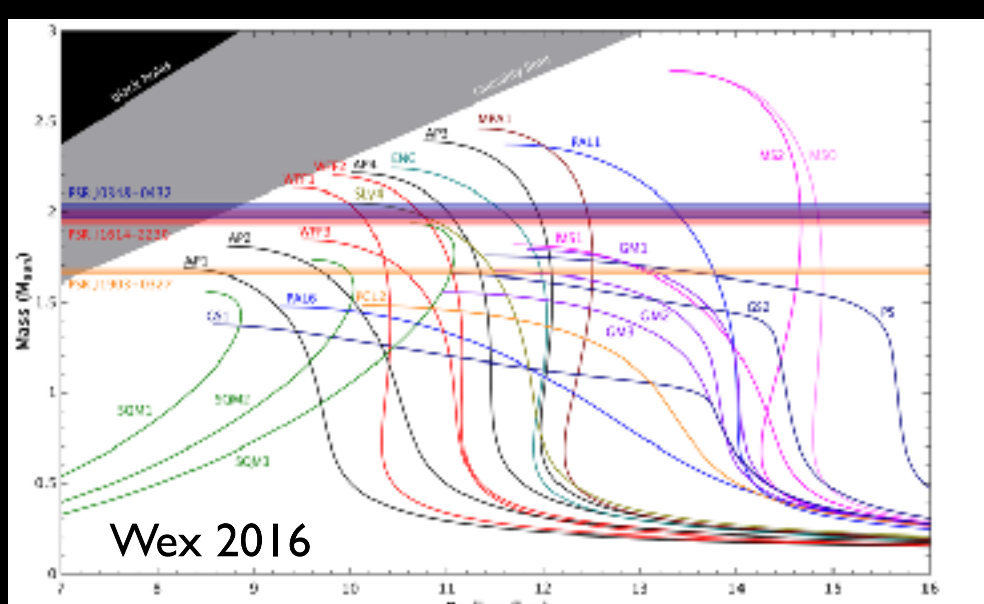
BH + BH → BH + GWs

- For NSs the question is more **subtle:**

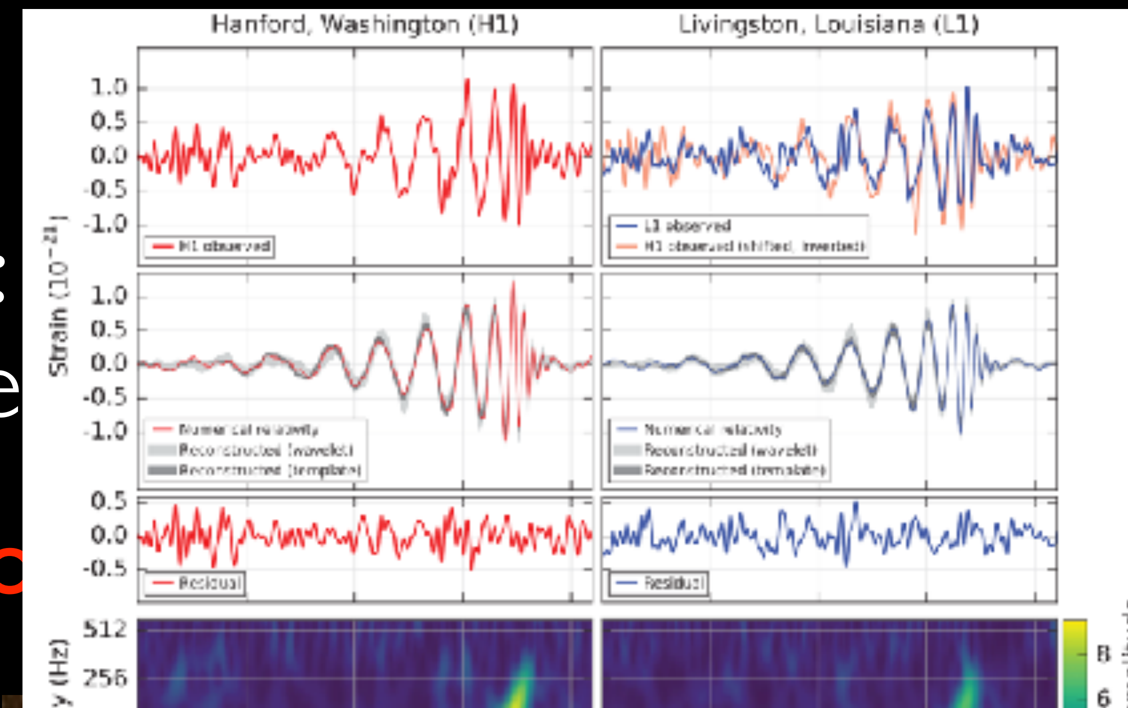
hyper-massive neutron star (HMNS), ie

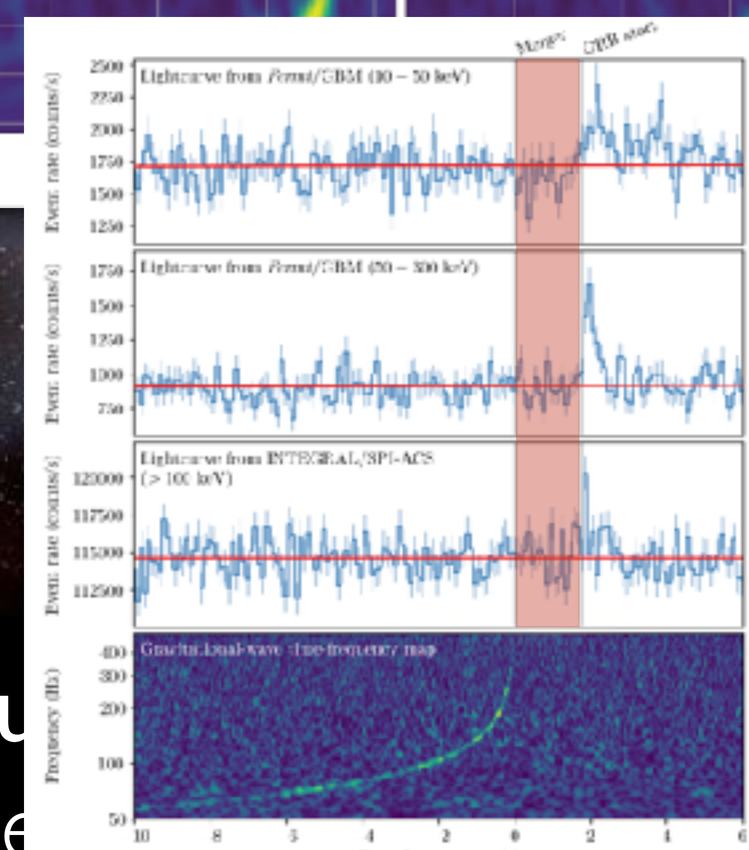
NS + NS → HMNS+... ? → BH+to

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



GW150914





- BH+toru ... us

on the ce ... RBs

GW170817

The two-body problem in GR

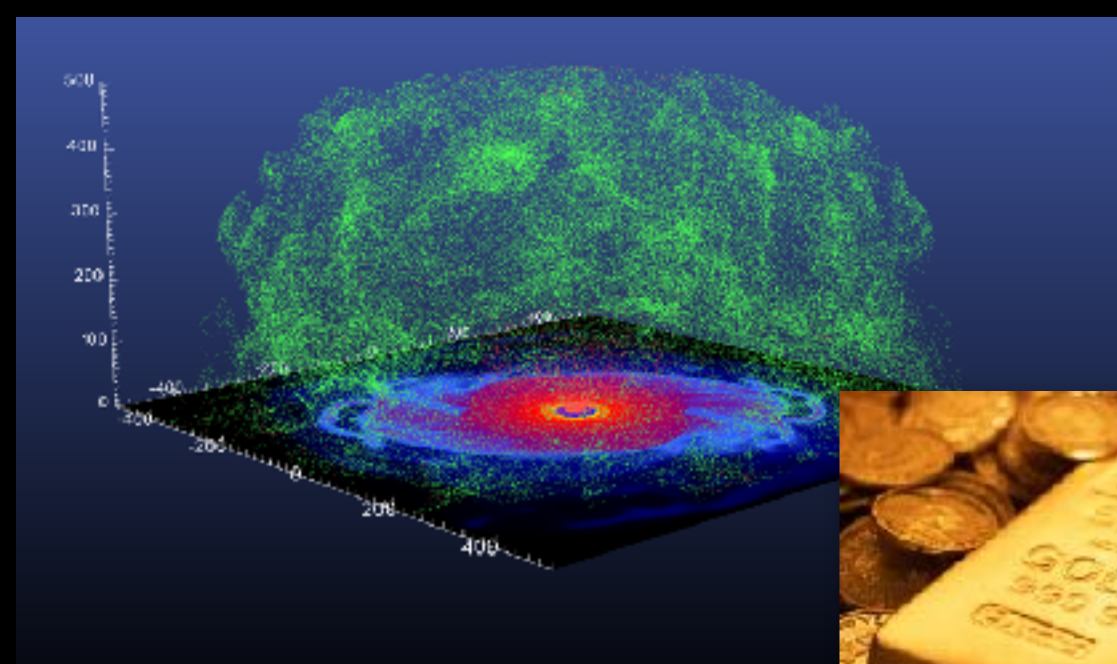
- For black holes the process is very **simple**:

BH + BH $\longrightarrow$ BH + GWs

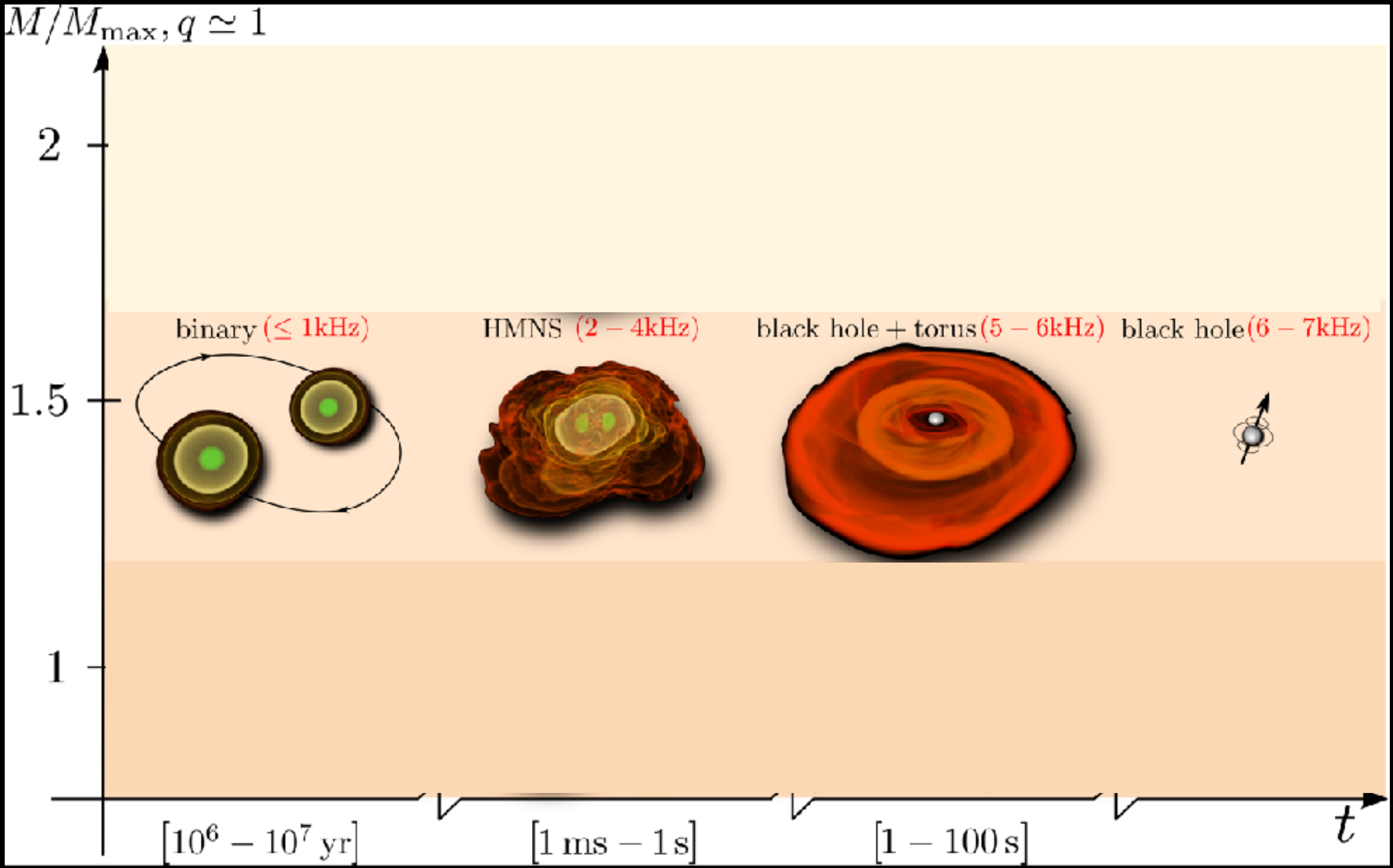
- For NSs the question is more **subtle:** the merger leads to an hyper-massive neutron star (HMNS), ie a metastable equilibrium:

NS + NS $\longrightarrow$ HMNS+... ? $\longrightarrow$ BH+torus+... ? $\longrightarrow$ BH + GWs

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



Broadbrush picture



Qualitatively, this is what normally happens:

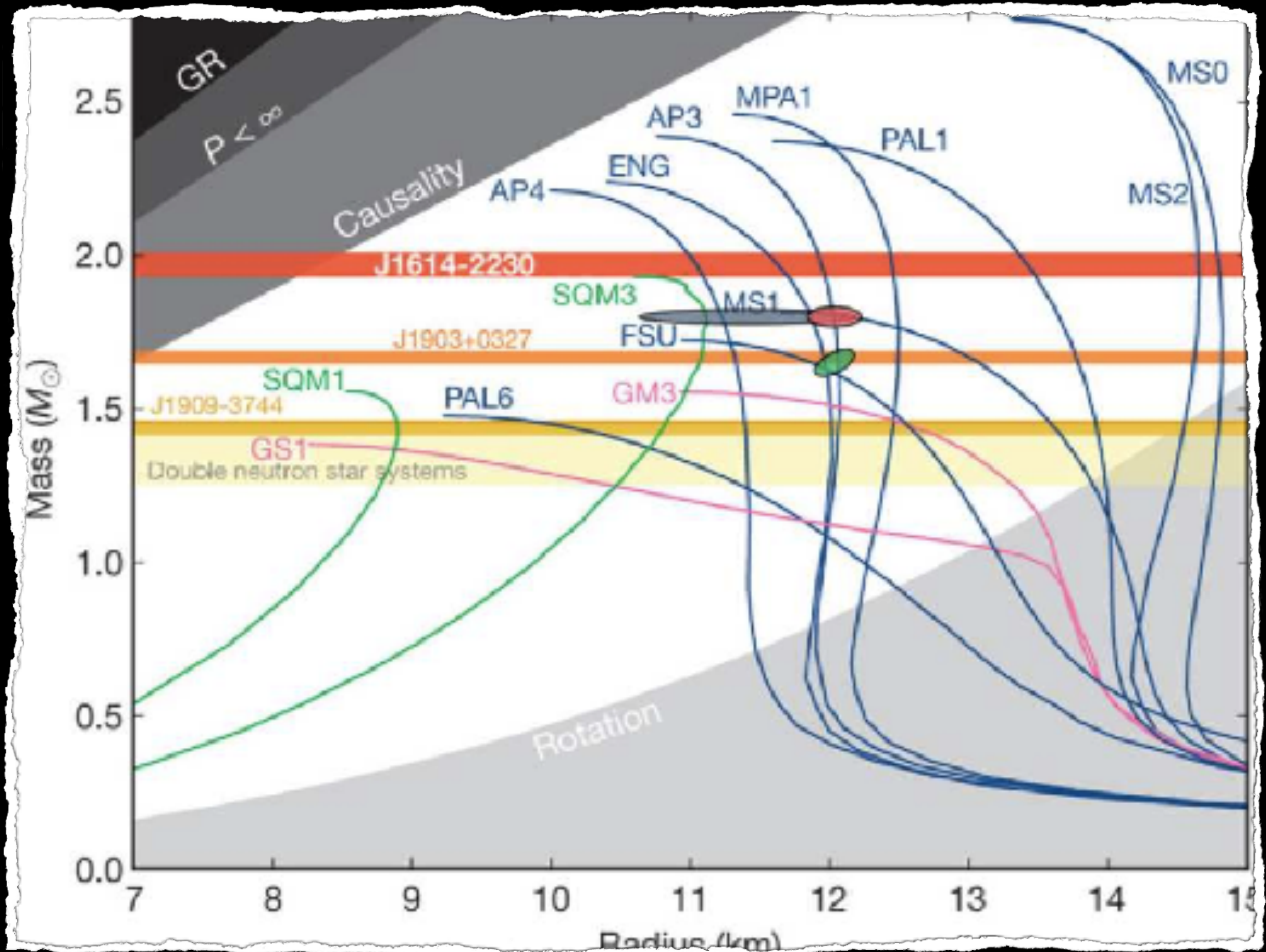
merger $\longrightarrow$ HMNS $\longrightarrow$ BH + torus

Quantitatively, differences are produced by:

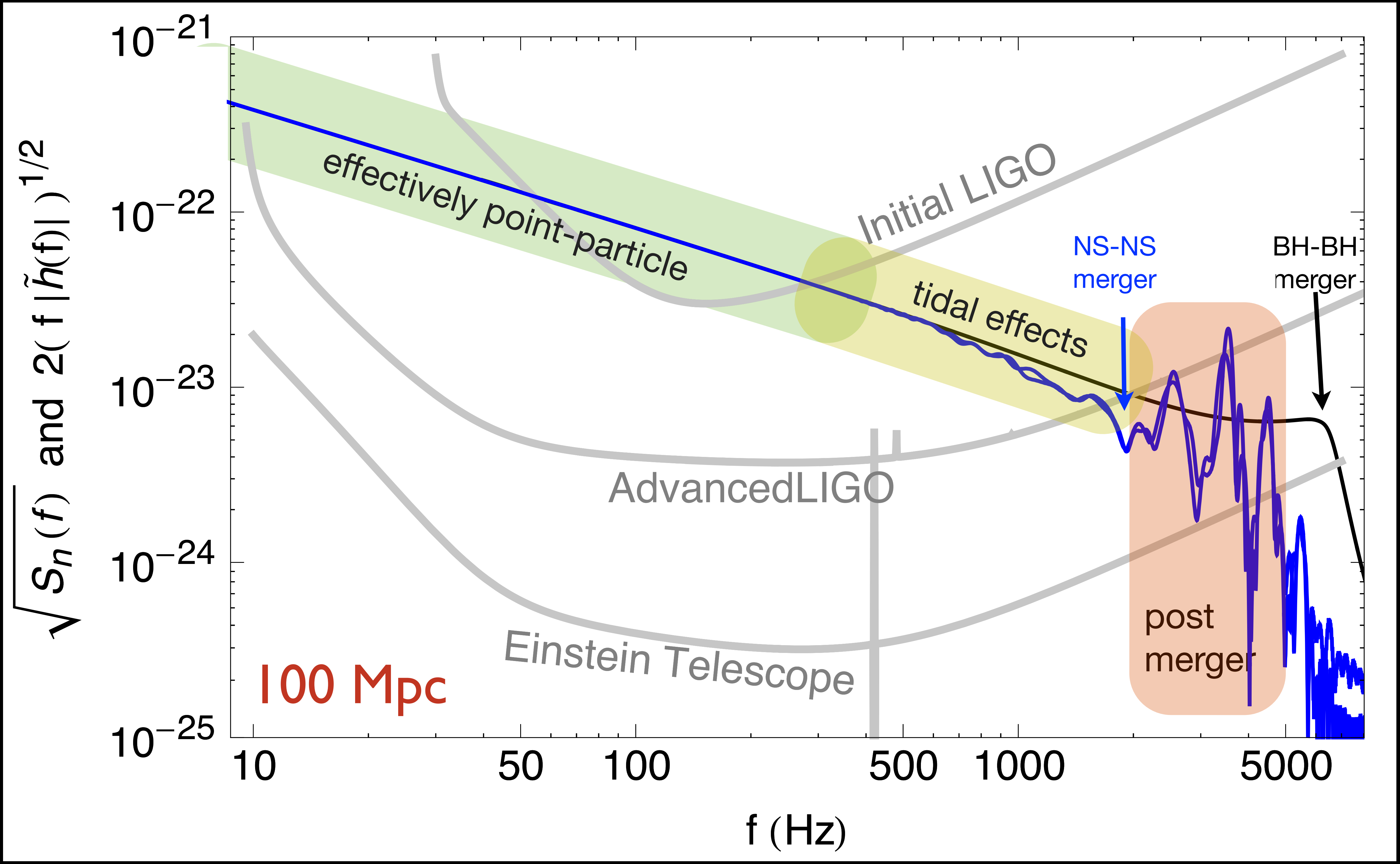
- total mass (prompt vs delayed collapse)
- mass asymmetries (HMNS and torus)
- soft/stiff EOS (inspiral and post-merger)
- magnetic fields (equil. and EM emission)
- radiative losses (equil. and nucleosynthesis)

GW spectroscopy and how to constrain the EOS

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



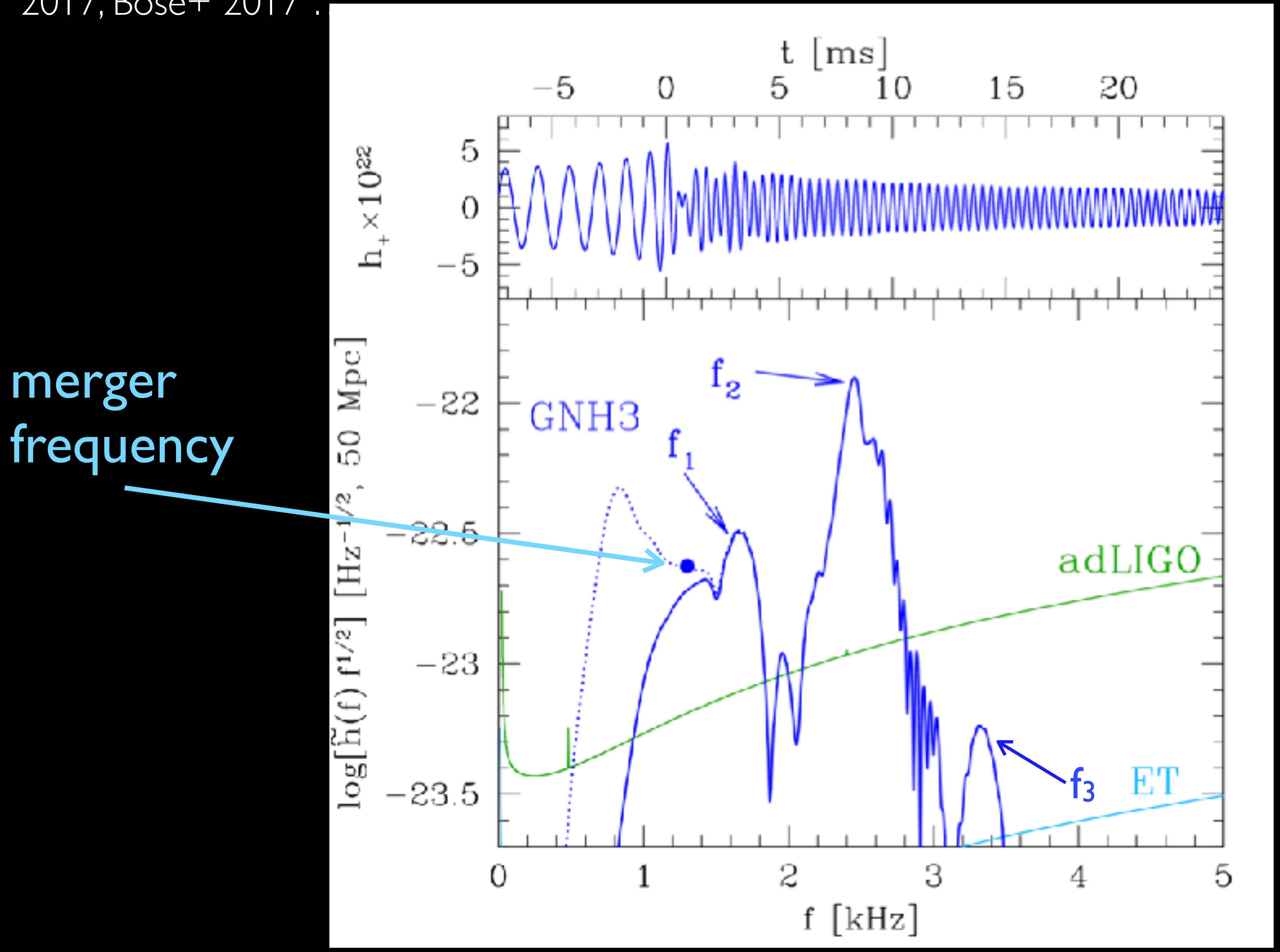
In frequency space



Read et al. (2013)

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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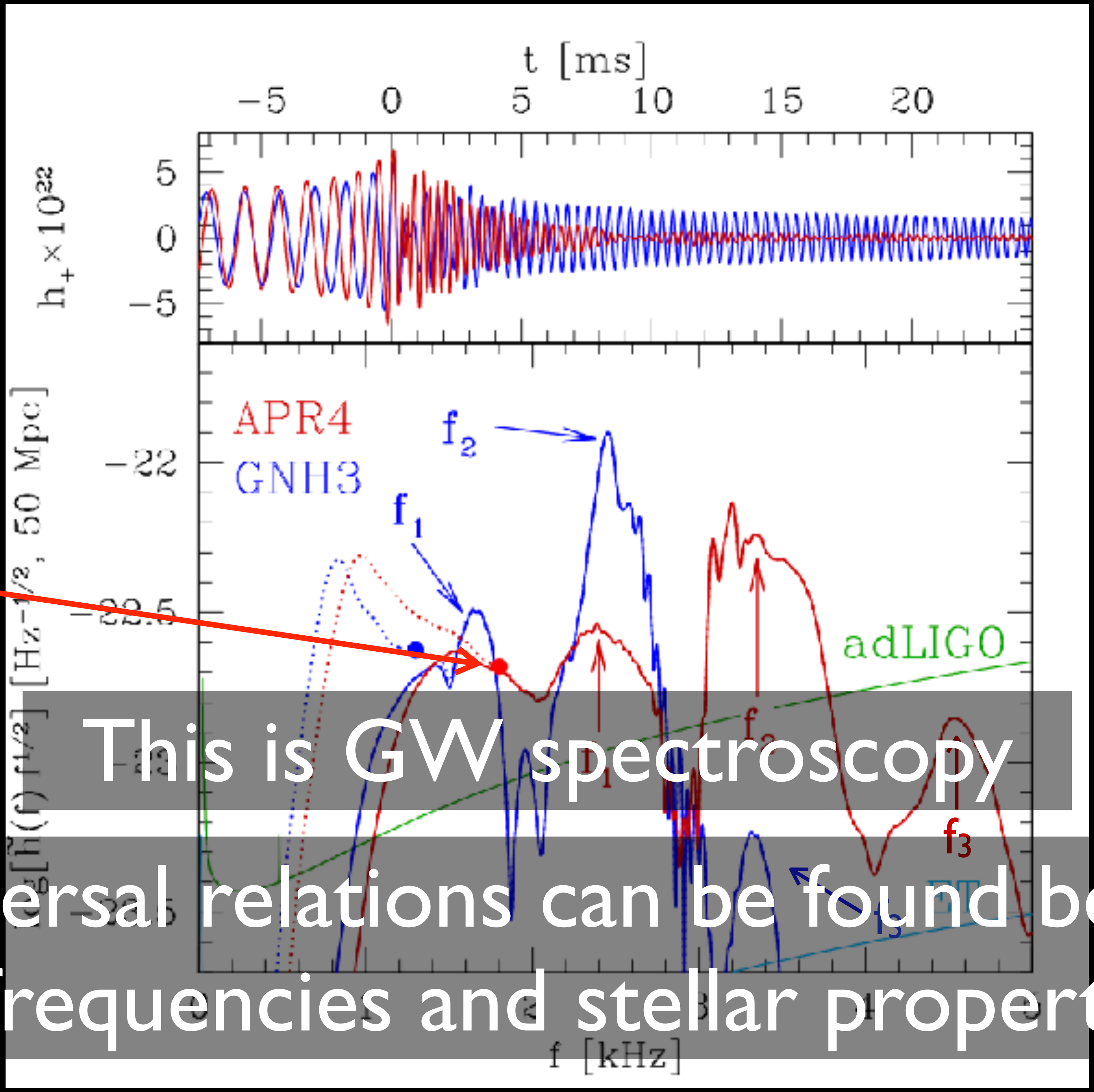
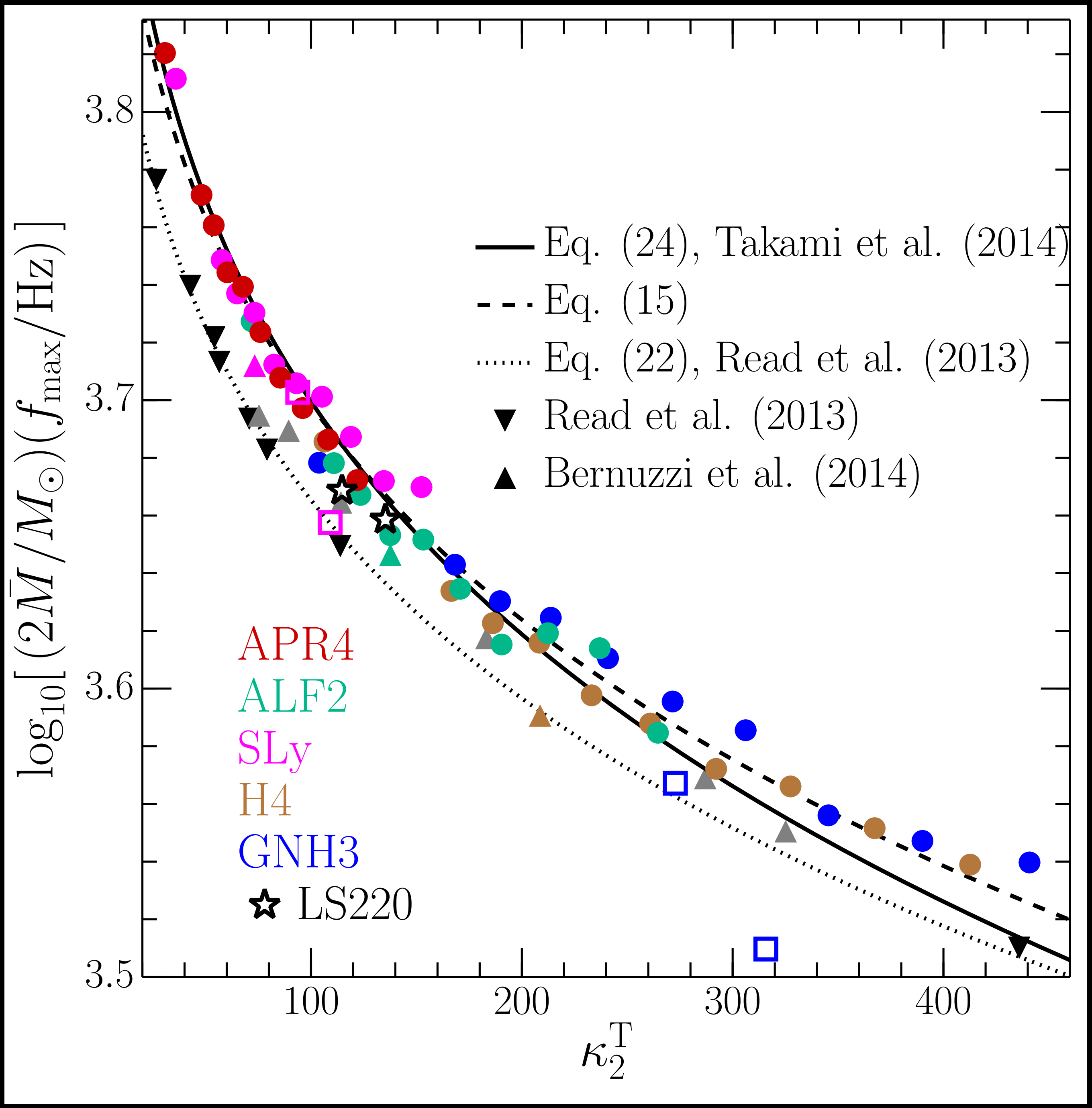
merger frequency



This is GW spectroscopy

Universal relations can be found between frequencies and stellar properties

Quasi-universal behaviour: **inspiral**



Quasi-universal behaviour of GW frequency at amplitude peak (Read+2013, Bernuzzi+ 2014, Takami+ 2015, LR+2016, …)

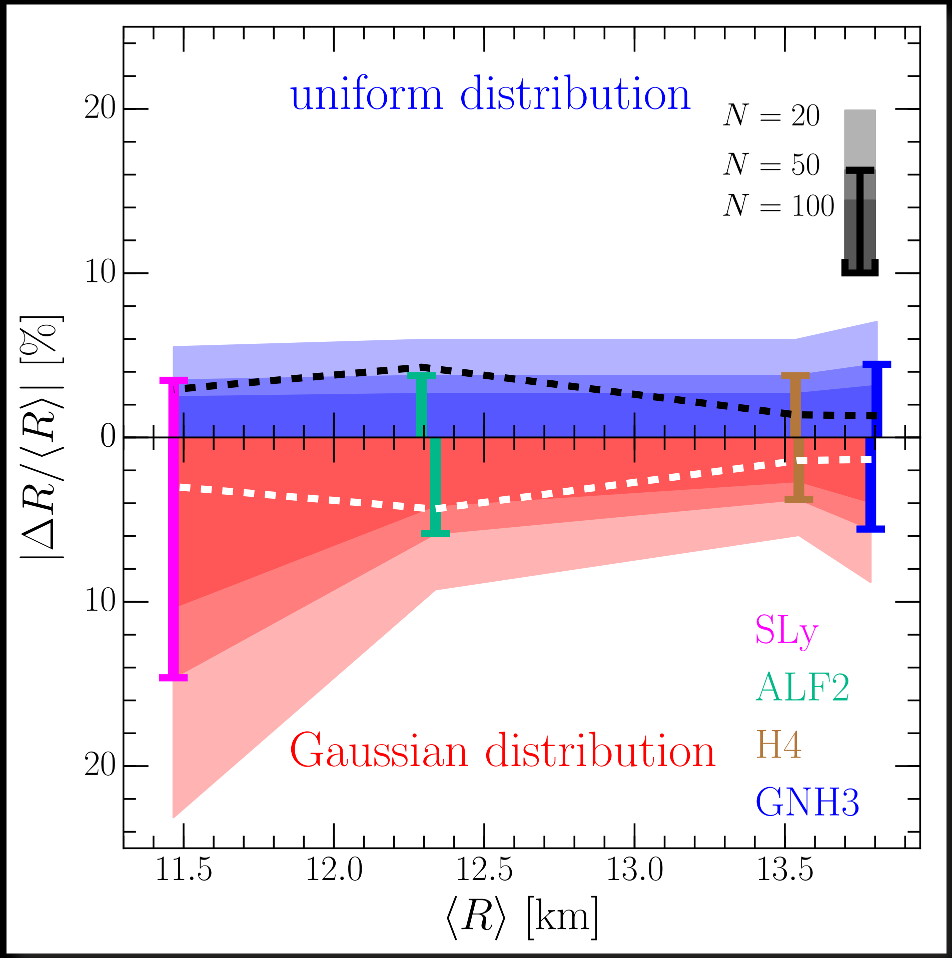
Quasi-universality implies that once $f_{\max}$ is measured, so is the tidal deformability, hence $I, Q, M/R$

Similar quasi-universal relations also for f_1, f_2, f_3

These relations can be used for a spectroscopic approach to the EOS

A spectroscopic approach to the EOS

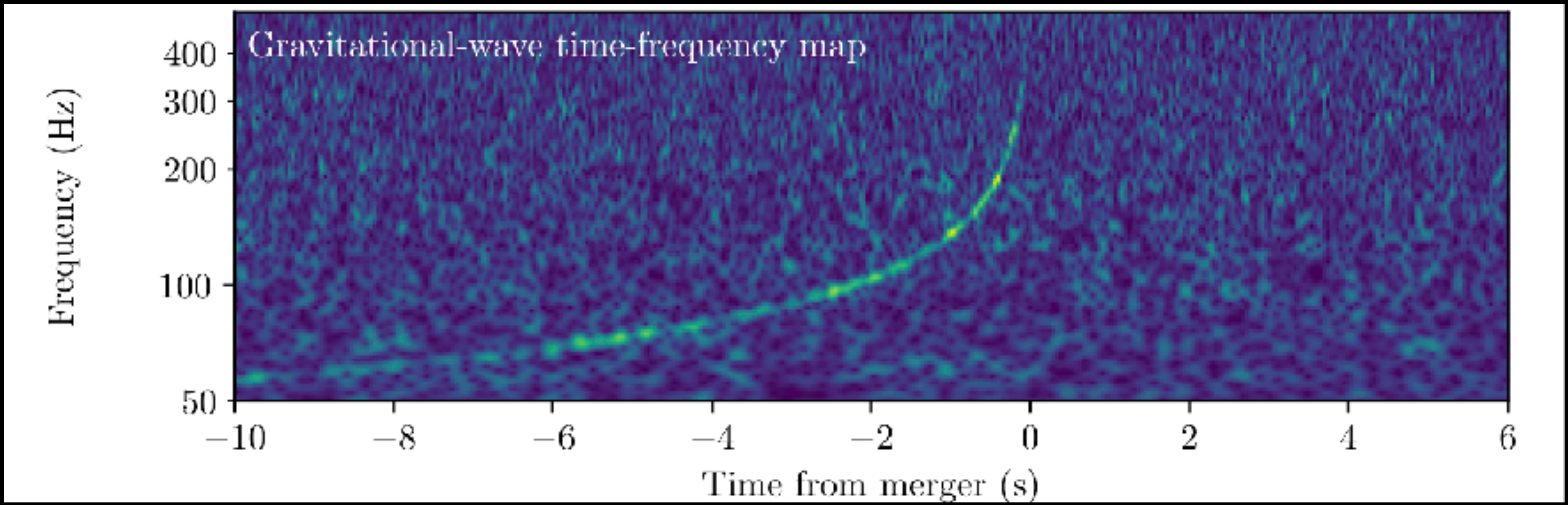
- **Universal behaviour** and **analytic modelling** of post-merger relates position of these peaks with the EOS.
- Question: how well can we constrain the EOS (radius) given ***N* detections?**



- discriminating stiff/soft EOSs possible even with moderate ***N~10***
- stiff EOSs: $|\Delta R/\langle R\rangle| < 10\%$ for ***N~20***
- soft EOSs: $|\Delta R/\langle R\rangle| \sim 10\%$ for ***N~50***
- golden binary: **SNR ~ 6** at **30 Mpc** $|\Delta R/\langle R\rangle| \simeq 2\%$ at 90% confidence

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

GW170817: a game changer

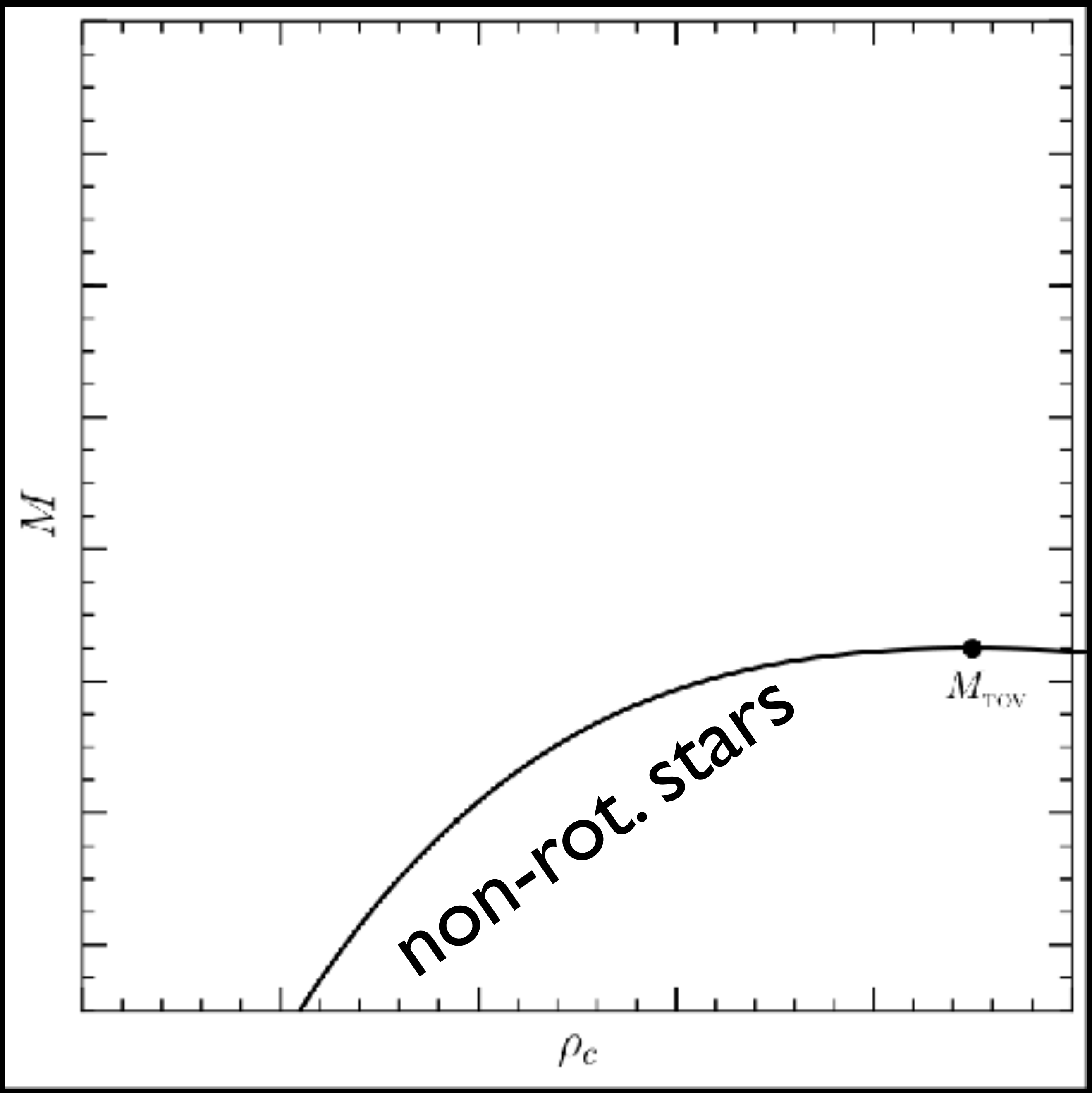


LR, Most, Weih, ApJL (2018)
Most, Weih, LR, Schaffner-Bielich, PRL (2018)
Köppel, Bovard, LR, ApJL (2019)
Tootle, Papenfort, Most, LR ApJL (2021)

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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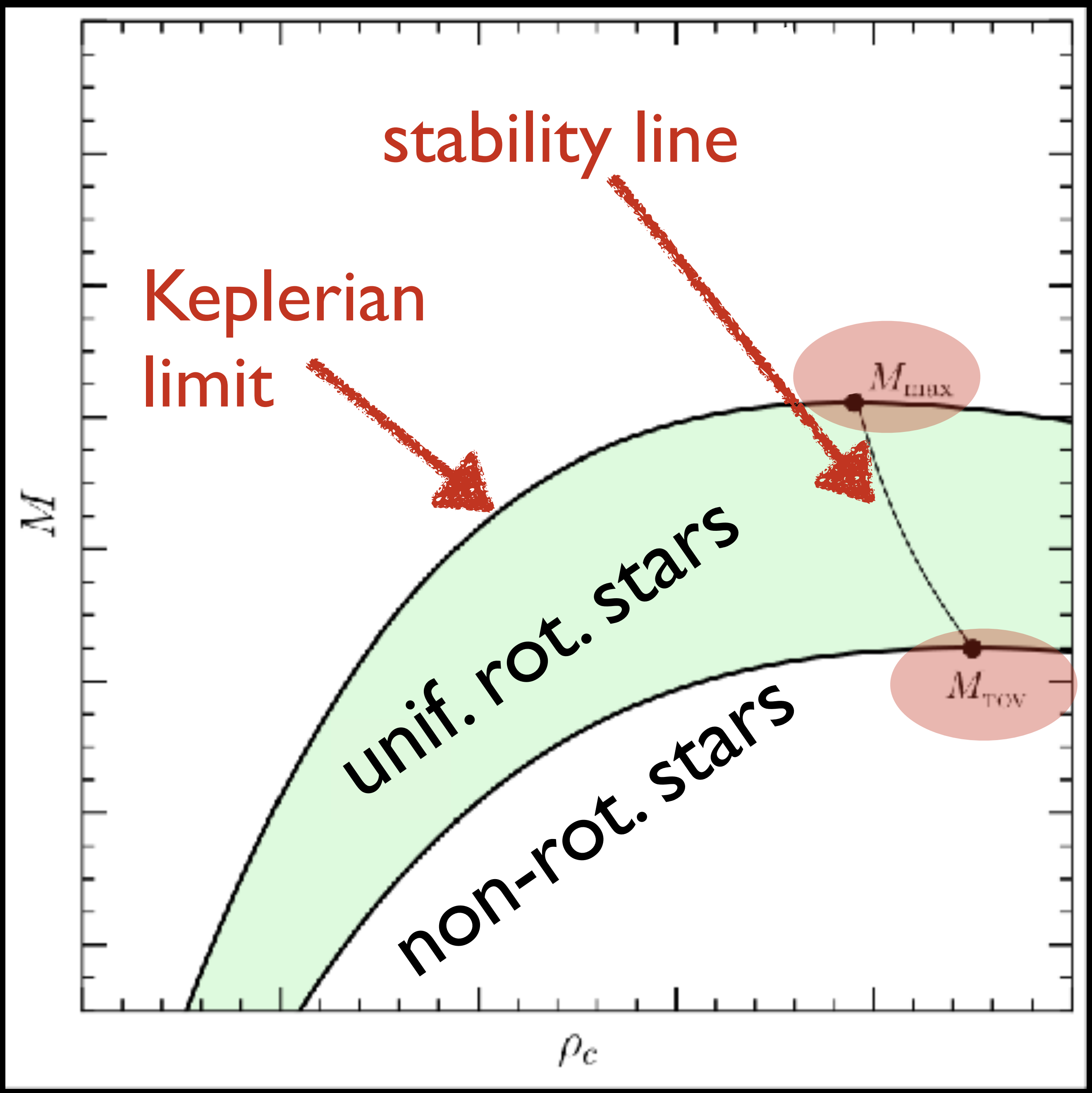

- Sequences of equilibrium models of **nonrotating** stars will have a maximum mass: $M_{\rm TOV}$
- This is true also for **uniformly** rotating stars at mass shedding limit: $M_{\max}$
- $M_{\max}$ simple and **quasi-universal** function of $M_{\rm TOV}$ (Breu & LR 2016)

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

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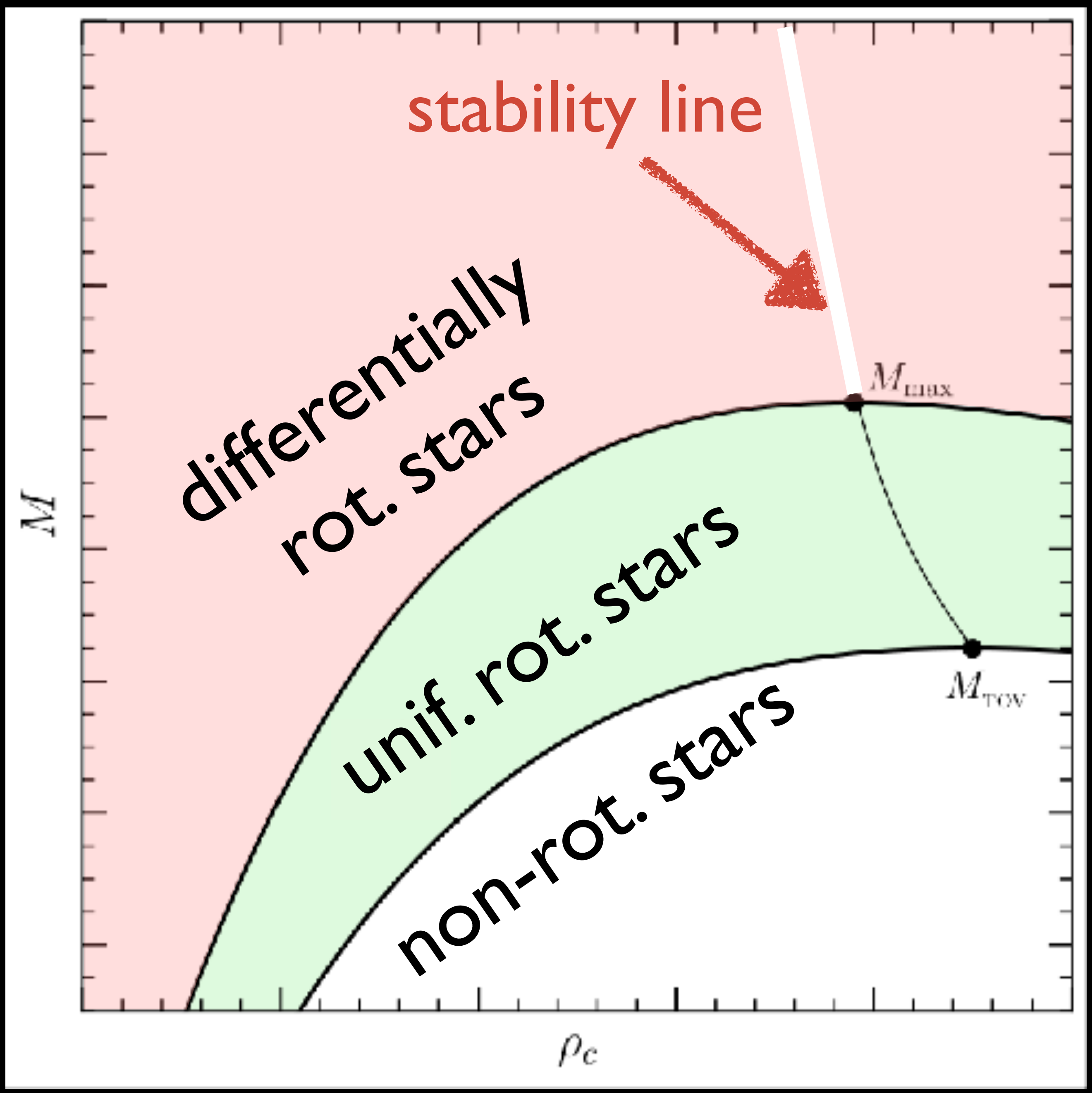


- Green region is for **uniformly** rotating equilibrium models.
- Salmon region is for **differentially** rotating equilibrium models.
- Stability line is simply extended in larger space (Weih+18)

Limits on the maximum mass

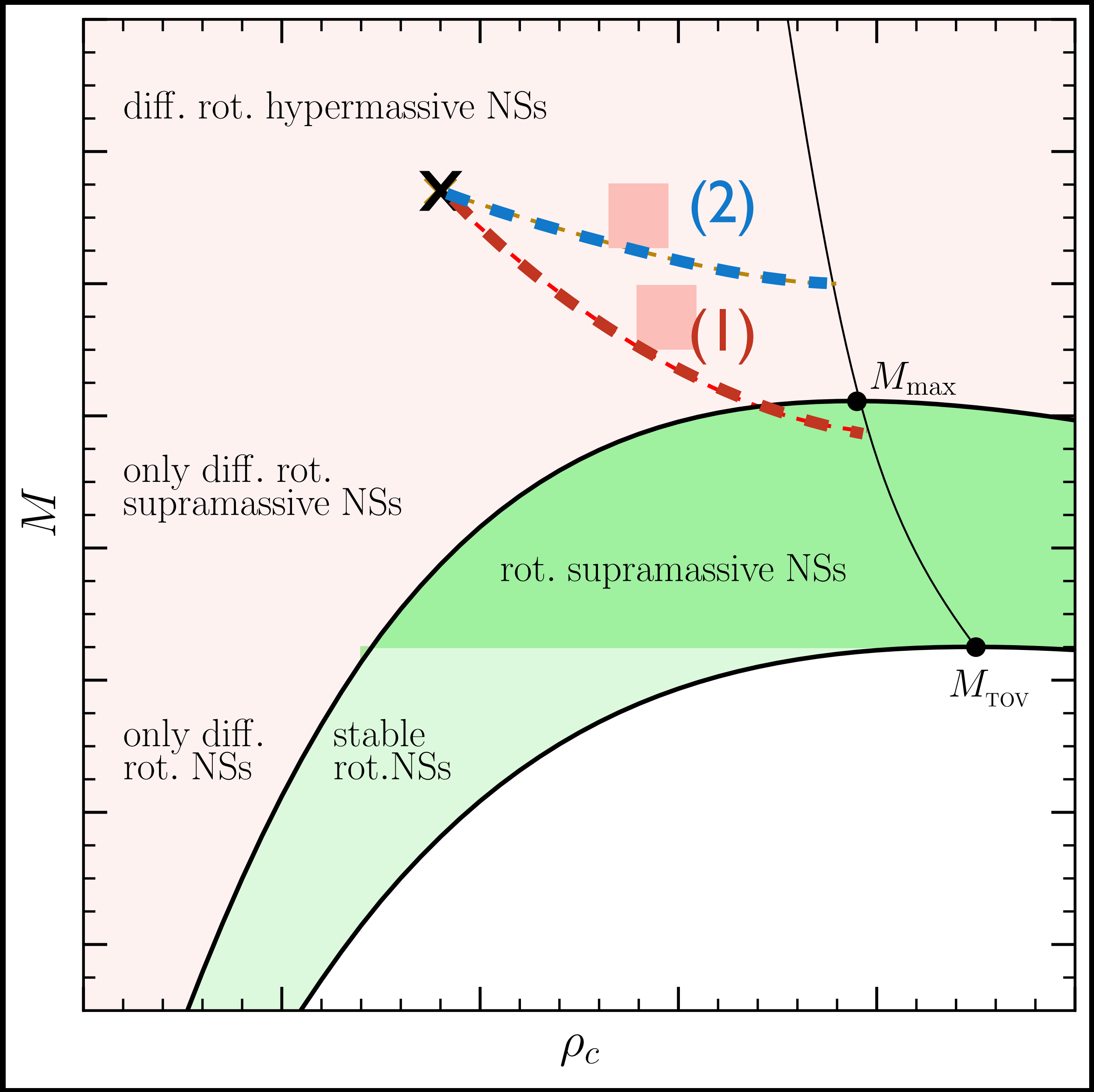
- GW170817 produced object **"X"**; GRB implies a BH has been formed: **"X"** followed two possible tracks: **fast (2)** and **slow (1)**

- 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 $M_{\max}$ and we know this is universal!



let's recap…

- Consider **evolution track (2)**
- Use measured **gravitational mass** of GW170817
- Remove **rest-mass** deduced from kilonova emission (need conversion baryon/gravitational)
- Use **universal relations,** account for errors to obtain

pulsar timing

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

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

Tension on the maximum mass

Nathanail, Most, LR (2021)

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

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

$$M_2 = 2.50 - 2.67\, M_\odot$$

smallest BH or heaviest NS!

- If secondary in GW190814 was a NS, all previous results on the maximum mass are incorrect.
- No EM counterpart was observed with GW190814 and no estimates possible for ejected matter or timescale for survival.
- **How do we solve this tension?**

Tension on the maximum mass

- We can nevertheless explore impact of larger maximum mass, i.e., what changes in the previous picture if

$$M_{\rm TOV}/M_{\odot} \gtrsim 2.5\ ?$$

- In essence, this is a multi-dimensional parametric problem satisfying **conservation** of **rest-mass** and **gravitational mass.**
- Observations provide limits on **gravitational** and **ejected mass.**
- Numerical relativity simulations provide limits on **emitted GWs**
- All the rest is contained in **10 parameters** that need to be varied within suitable ranges.

Genetic algorithm

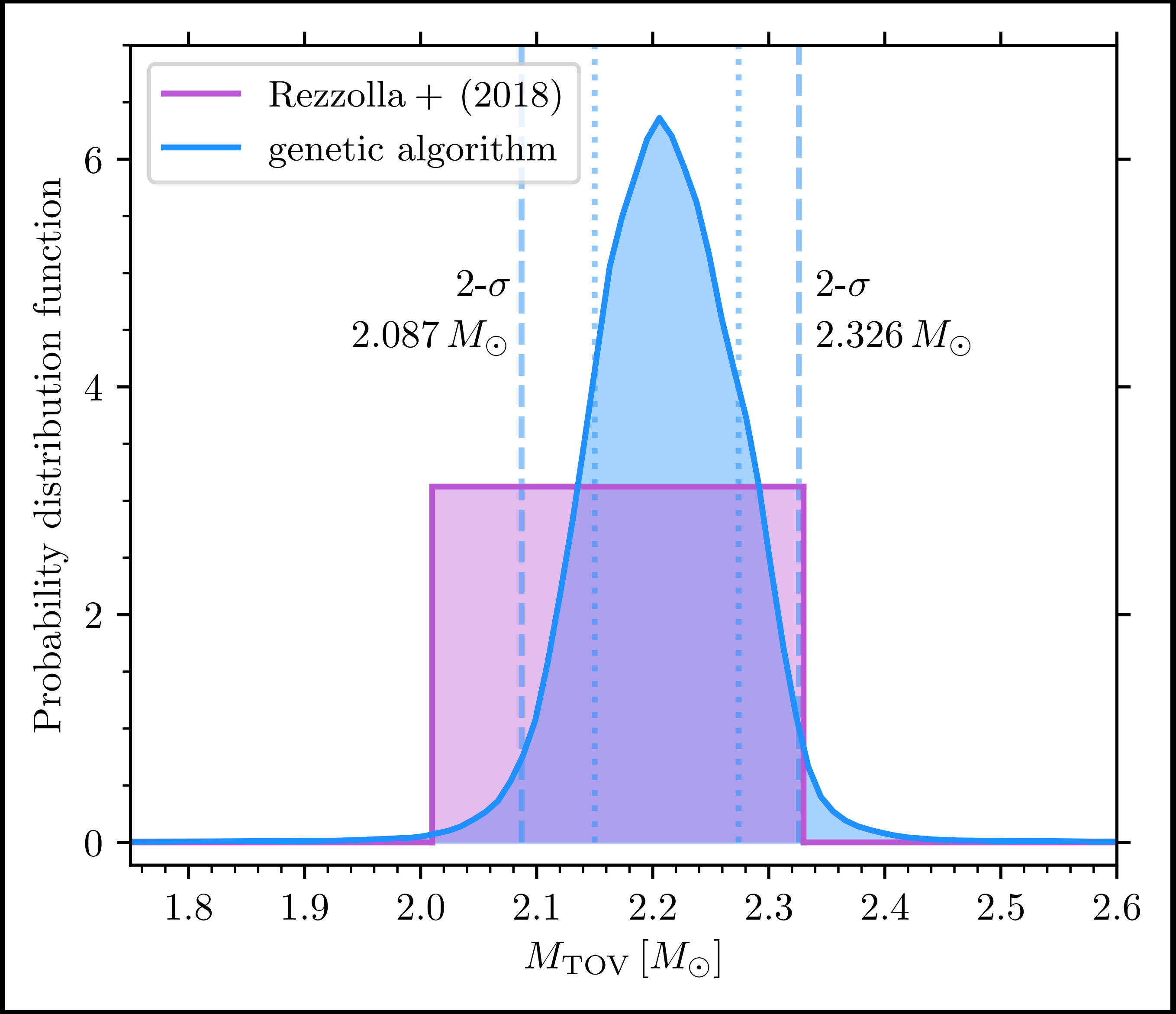
- A **genetic algorithm** is used to sample through the parameter space of the 10 free parameters.

- The algorithm reflects genetic adaptation: given a mutation (i.e. change of parameters) it will be adopted if it provides a better fit to data.

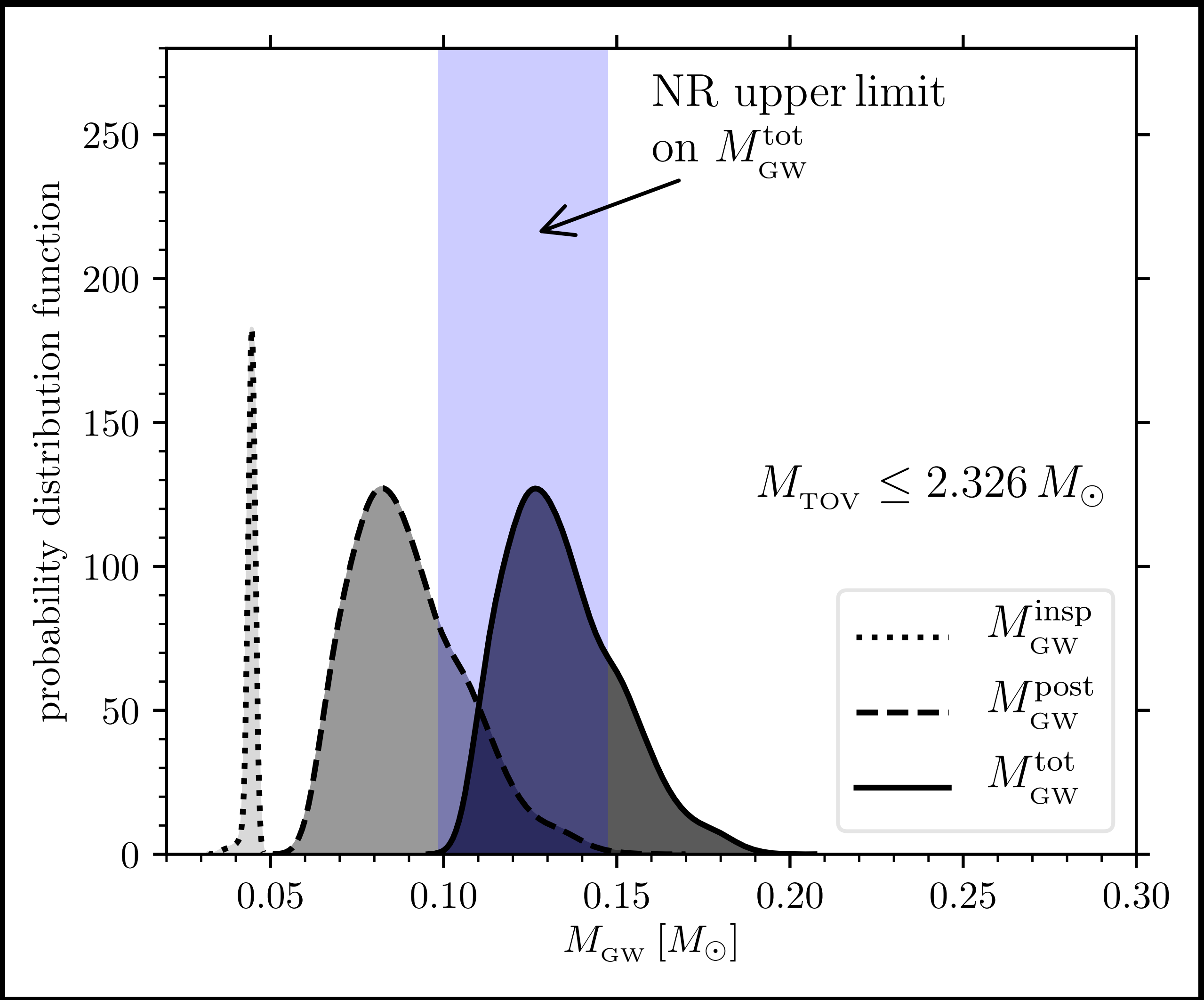
- Consider first previous estimate:

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

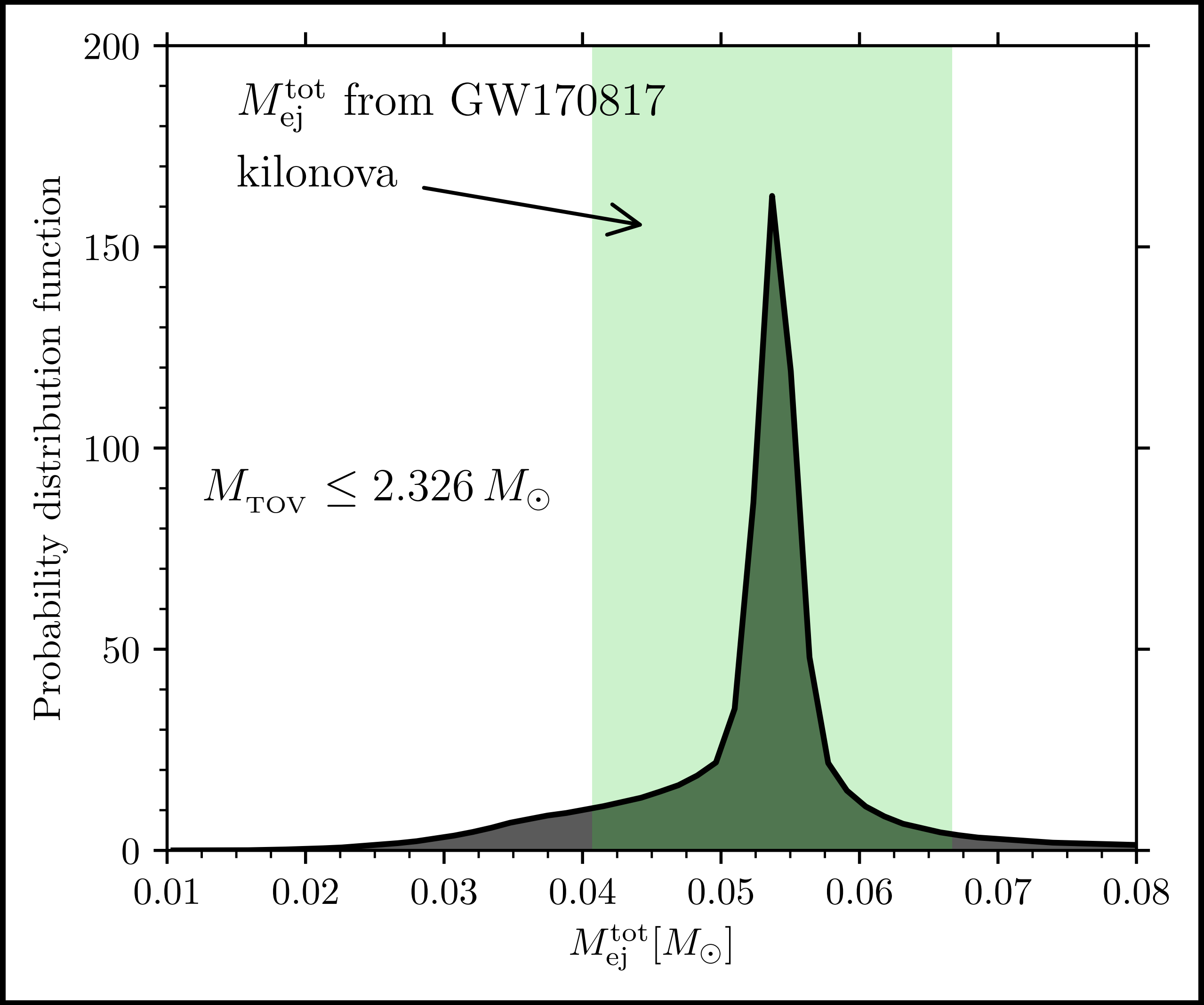
$$M_{\rm TOV}/M_\odot \le 2.16^{+0.17}_{-0.15}$$



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

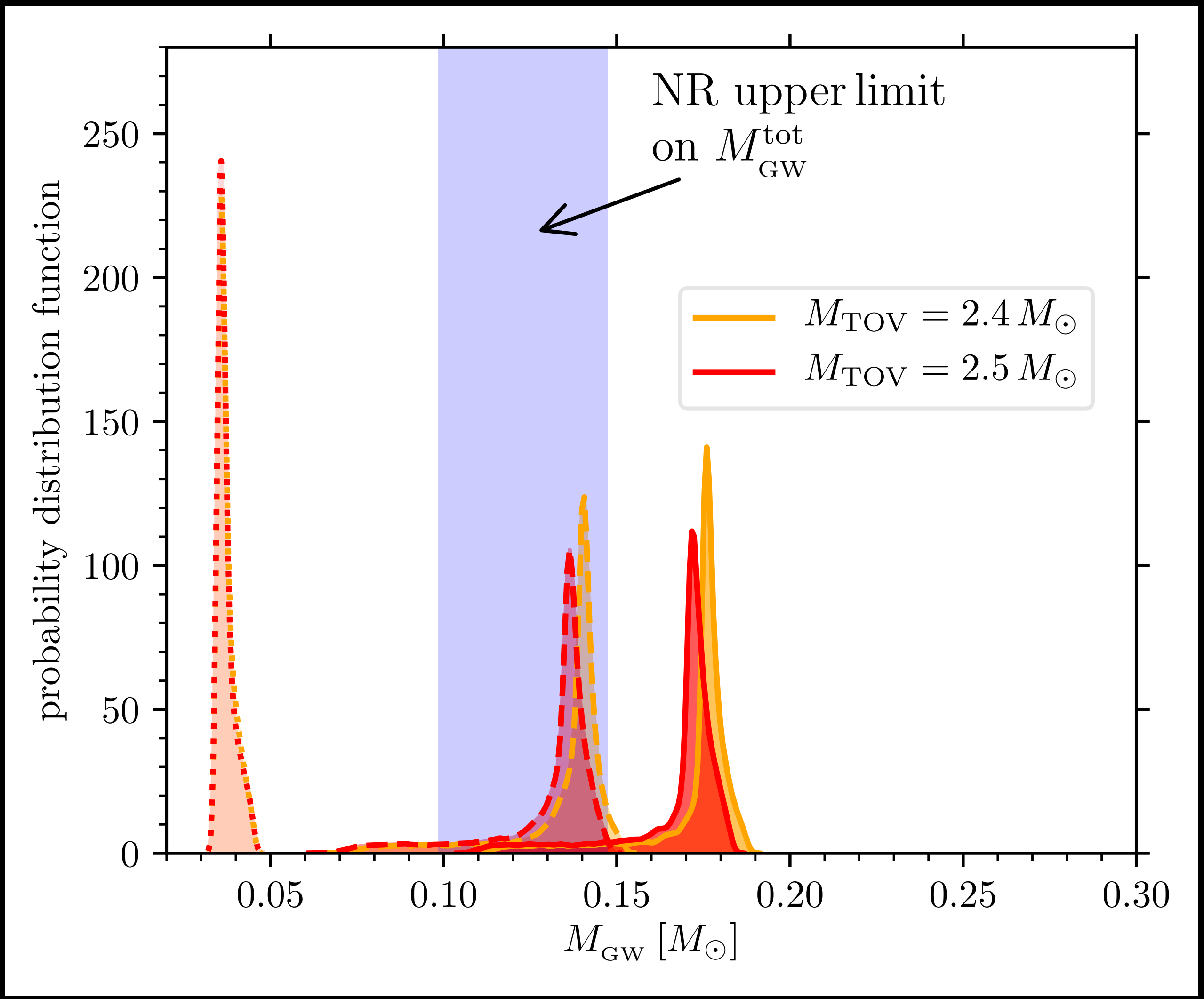


- Total mass emitted in GWs is in perfect **agreement** with predictions from numerical relativity

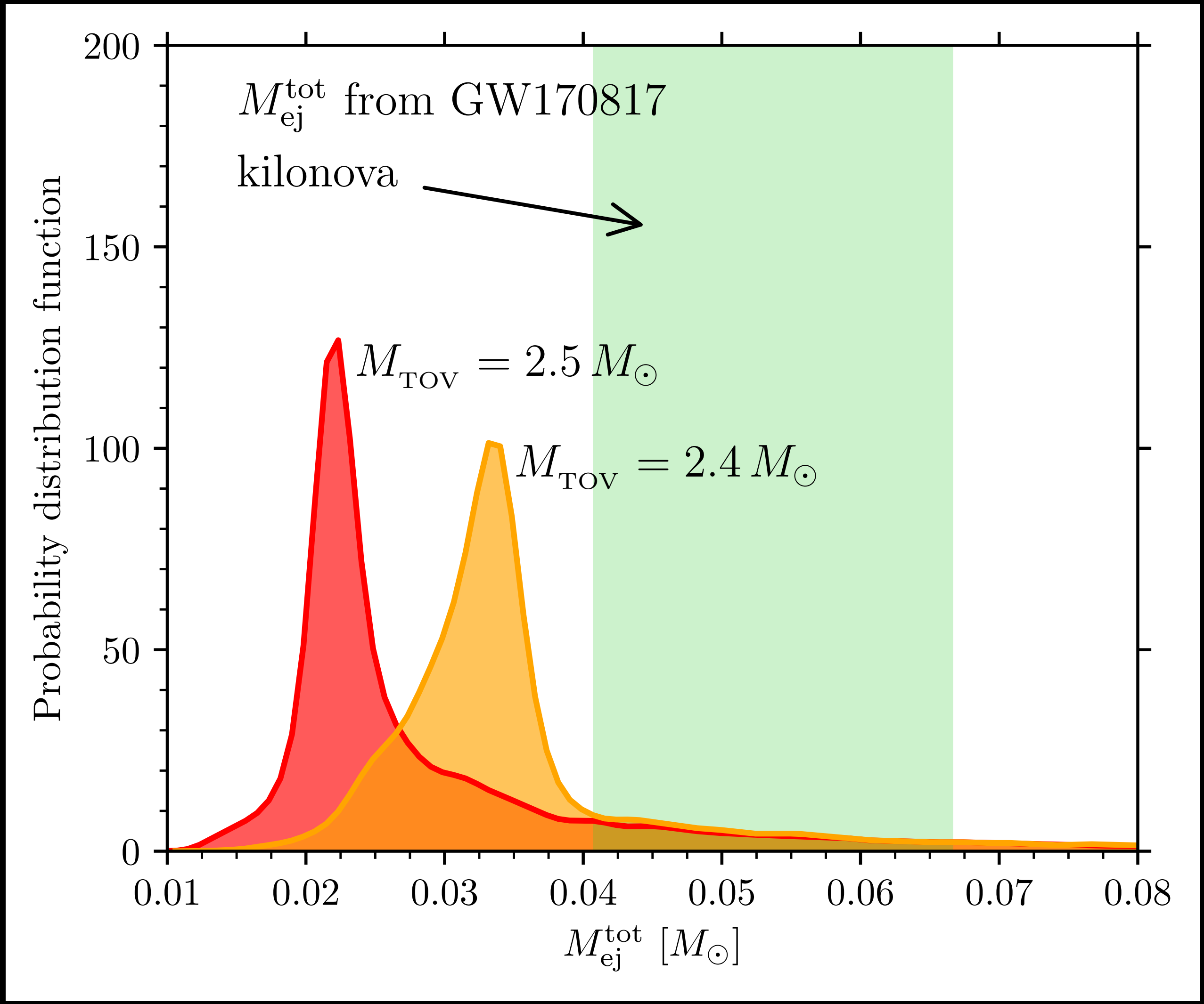


- Total mass ejected is in perfect **agreement** with predictions from kilonova signal

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.

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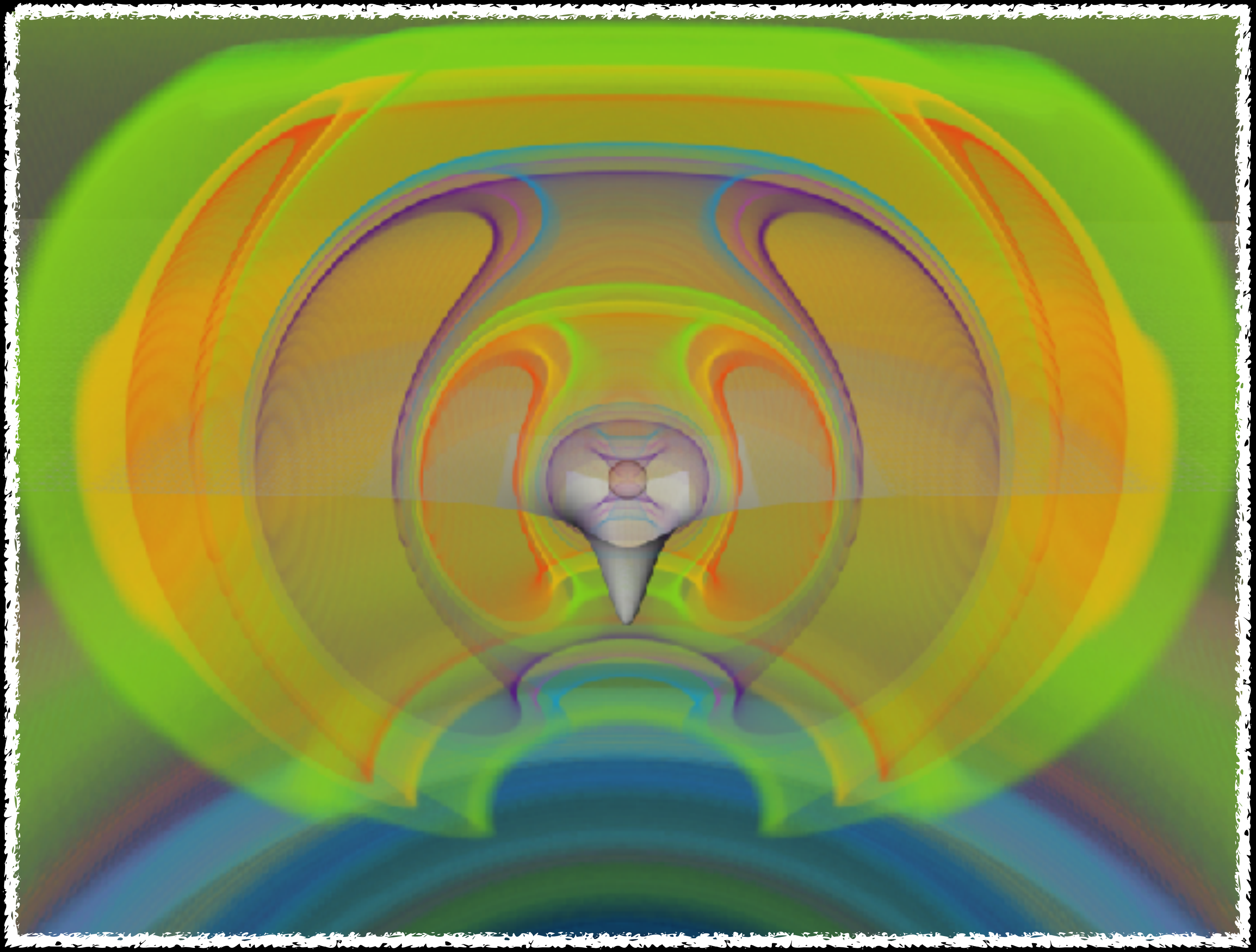
- **How do we solve this tension?**

- Solution: secondary in GW190814 **was a BH at merger** but could have been a NS before

Threshold Mass to prompt collapse

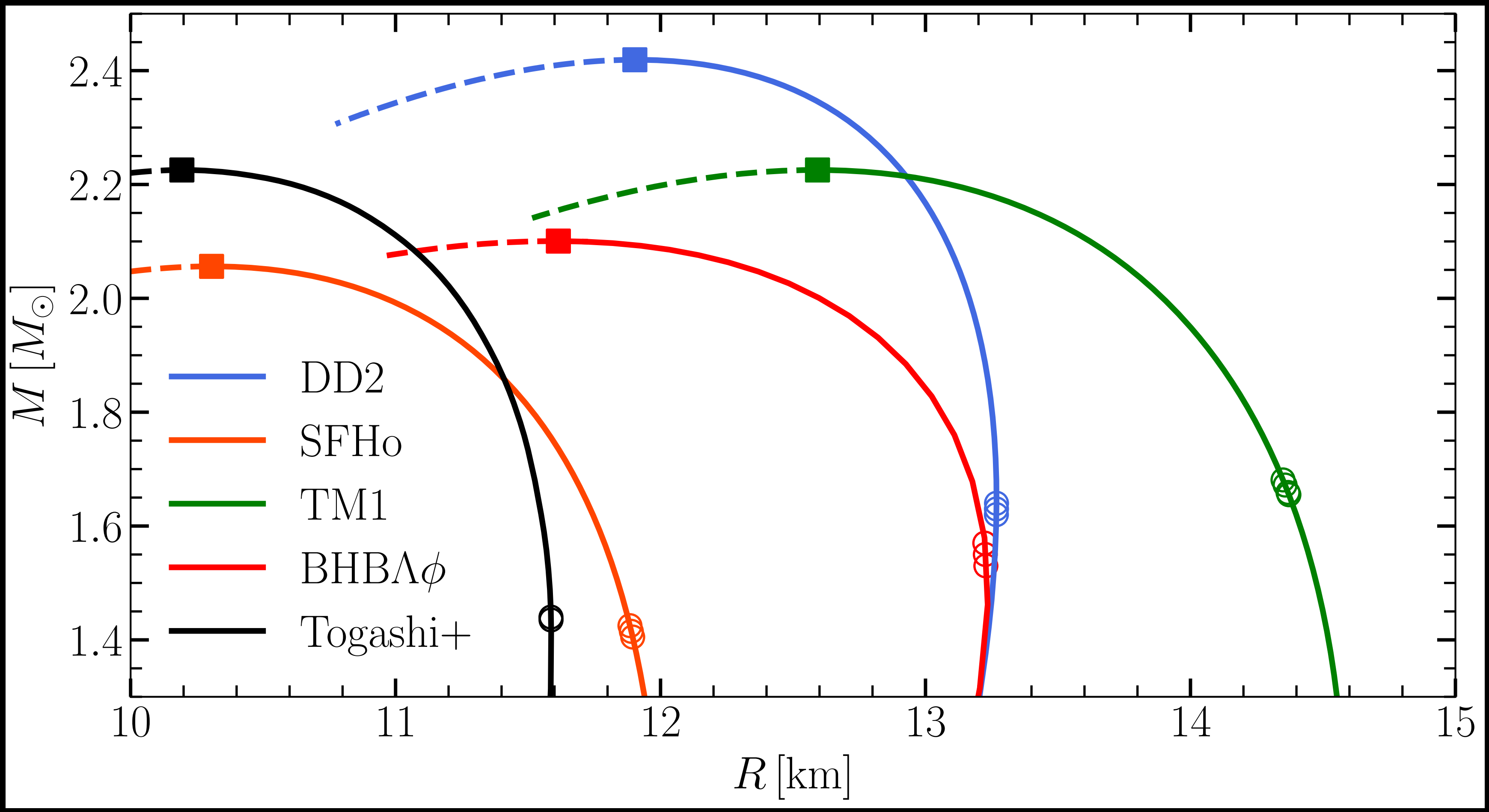


Another universal behaviour

- Interestingly, a **universal behaviour** can be found also when computing the **threshold mass** to prompt collapse.

But what is the **threshold mass?**

1. Select useful EOSs that self-consistently incorporate ***finite-temperature effects***.



Another universal behaviour

- Interestingly, a **universal behaviour** can be found also when computing the **threshold mass** to prompt collapse.

2. Determine rigorous definition of ***"prompt"*** collapse and produce dimensionless quantity

$$t_{\rm coll} := t_{\rm BH} - t_{\rm merg}$$

$$t_{\rm merg}: \quad \min(\alpha) = \alpha_{\rm merg} := 0.35\,,$$

$$t_{\rm BH}: \quad \min(\alpha) = \alpha_{\rm BH} := 0.2\,.$$

extremely robust and EOS independent

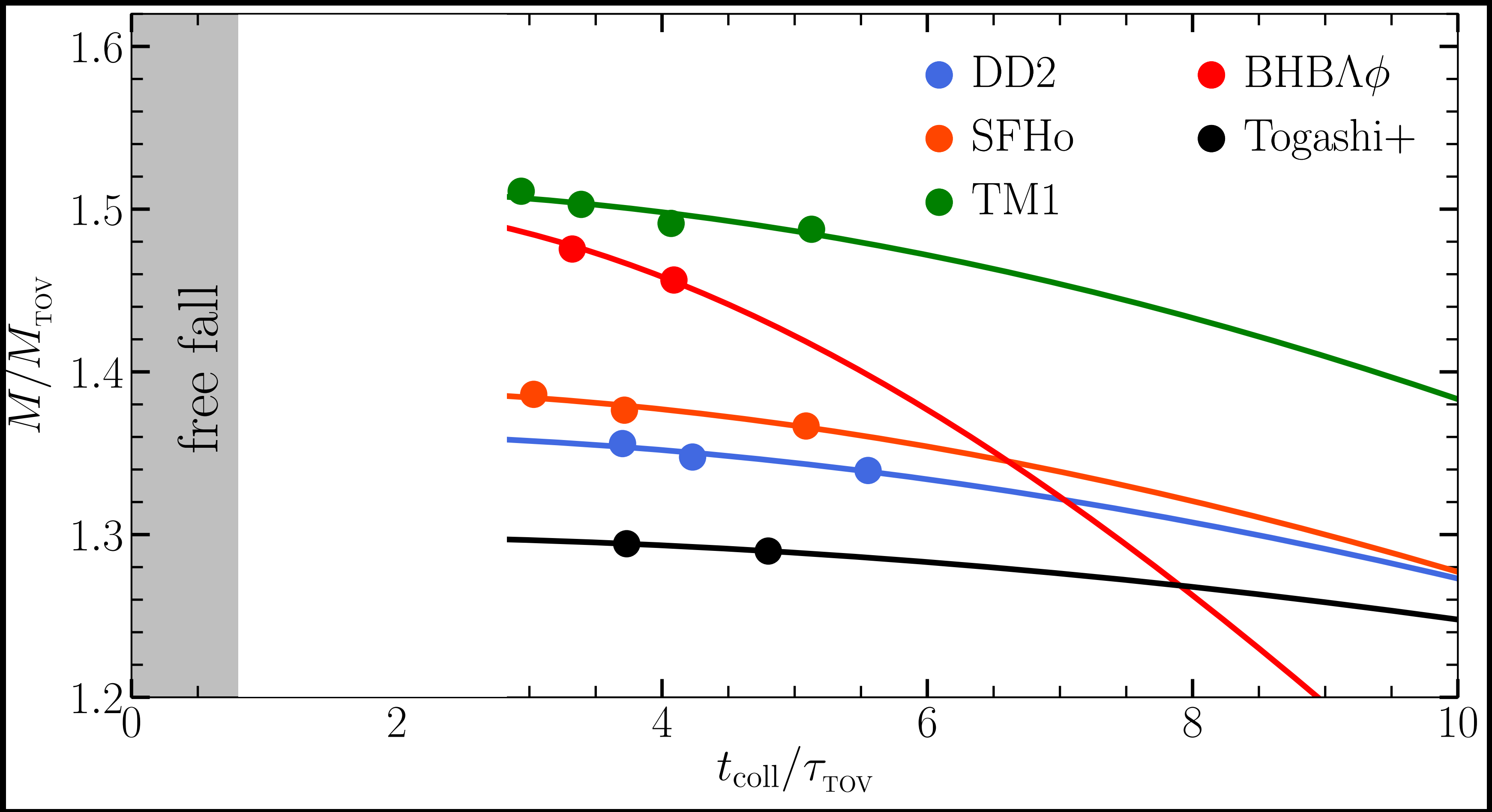
$$\tau_{\rm ff}(M,R) := \frac{\pi}{2}\sqrt{\frac{R^3}{2M}}\,.$$

free-fall timescale in Oppenheimer-Snyder collapse

Another universal behaviour

- Interestingly, a **universal behaviour** can be found also when computing the **threshold mass** to prompt collapse.

3. Express measured values in terms of dimensionless collapse time.



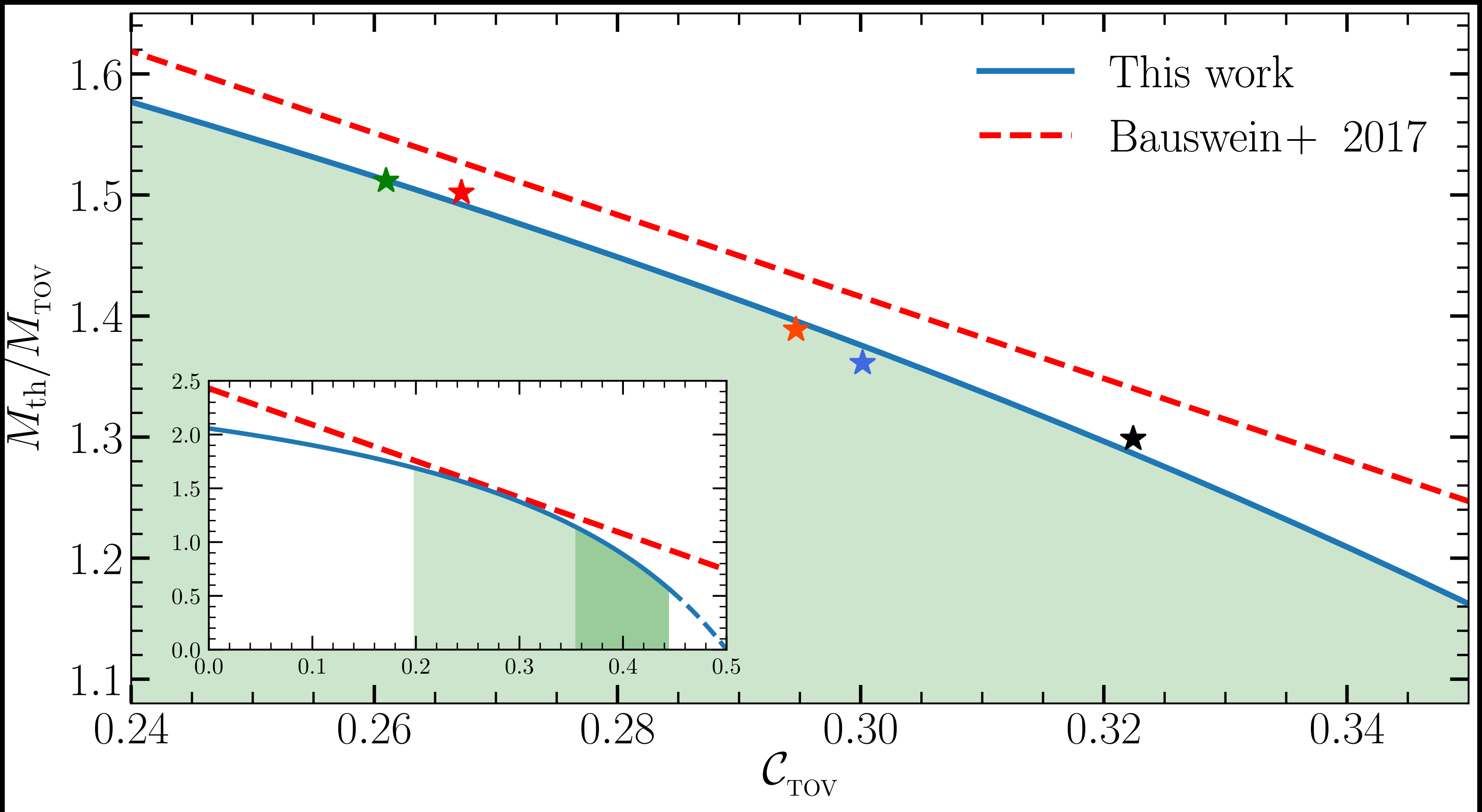
$$\frac{M_{\rm th}}{M_{\rm TOV}} \approx 1.415$$

first rough estimate

Another universal behaviour

- Interestingly, a **universal behaviour** can be found also when computing the **threshold mass** to prompt collapse.

4. Seek universal behaviour via maximum compactness. $\mathcal{C}_{\rm TOV} := (M/R)_{\rm TOV}$. A **linear** fit is possible but not satisfactory. A **nonlinear** fit obtained by requiring that



$$\frac{M_{\rm th}}{M_{\rm TOV}} \to 0$$

for

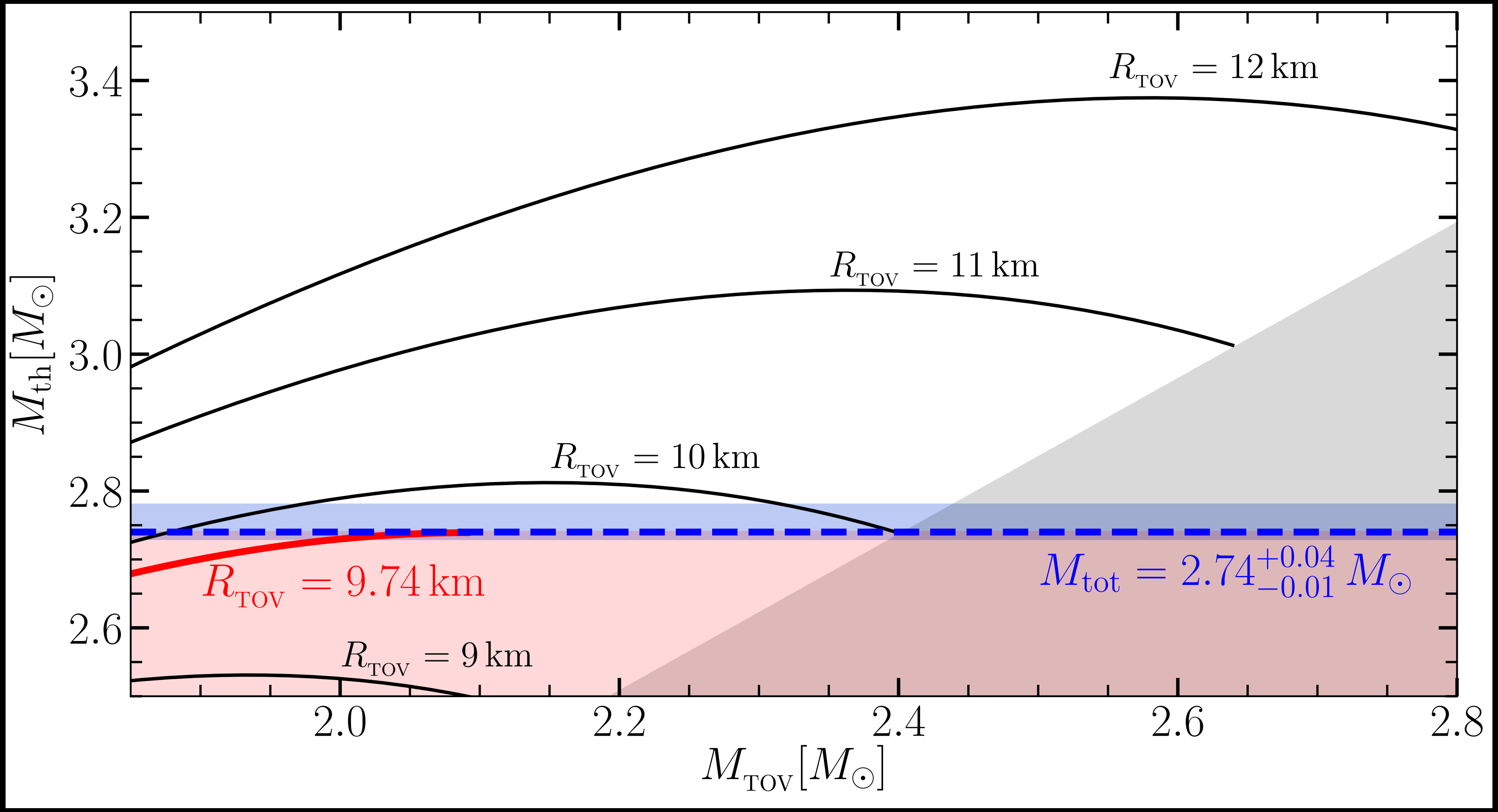
$$\mathcal{C}_{\rm TOV} \to 1/2$$

$$\frac{M_{\rm th}}{M_{\rm TOV}} = a - \frac{b}{1 - c\,\mathcal{C}_{\rm TOV}}$$

Another universal behaviour

- Interestingly, a **universal behaviour** can be found also when computing the **threshold mass** to prompt collapse.

5. The detection of a merger not leading to prompt collapse constraints the radius from below



GW170817

$$M_{\rm tot} = 2.74^{+0.04}_{-0.01}\,M_\odot$$

so that

$$R_{\rm TOV} \geq 9.74^{+0.14}_{-0.04}\,{\rm km}$$

Another universal behaviour

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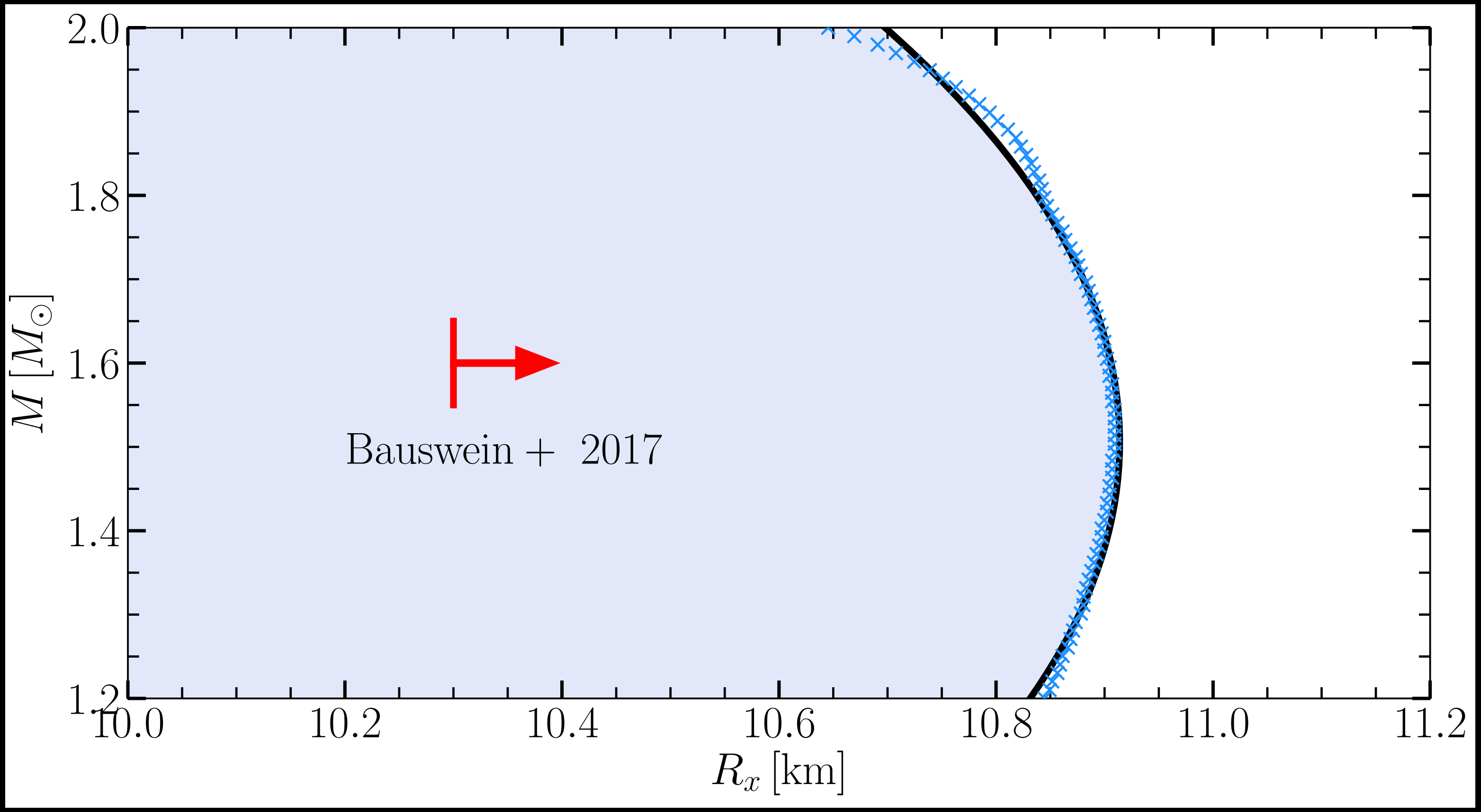
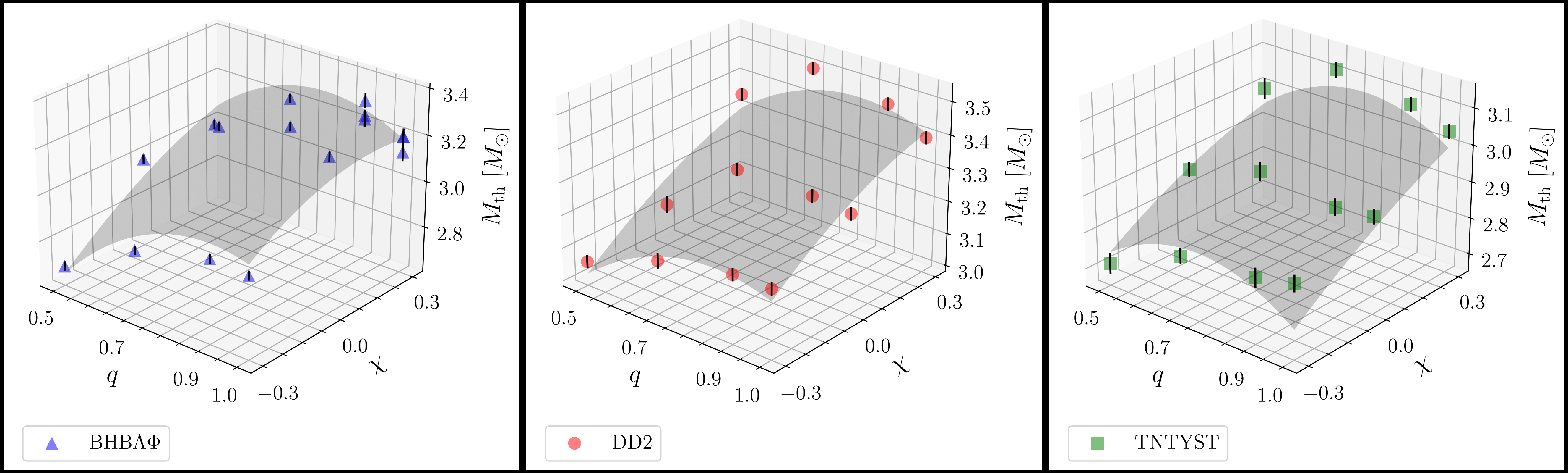
5. The detection of a merger not leading to prompt collapse constraints the radius from below



$$R_x = -0.88\, M^2 + 2.66\, M + 8.91$$

A more general behaviour

- All results so far true for **irrotational equal-mass** binaries
- $M_{\rm th}$ will depend also on **mass ratio** and **spin**
- Intuitively, $M_{\rm th}$ increases with **positive spin** and **mass ratio**
- We have considered **40** configurations, **360** simulations



Clearly, $M_{\rm th} = M_{\rm th}(\mathrm{EOS}, q, \chi)$

A more general behaviour

Is this behaviour **universal?**

Assume separable ansatz

$$M_{\rm th} = M_{\rm th}(\mathrm{EOS}, q, \chi) = \kappa(\mathrm{EOS})\, f(q, \chi)$$

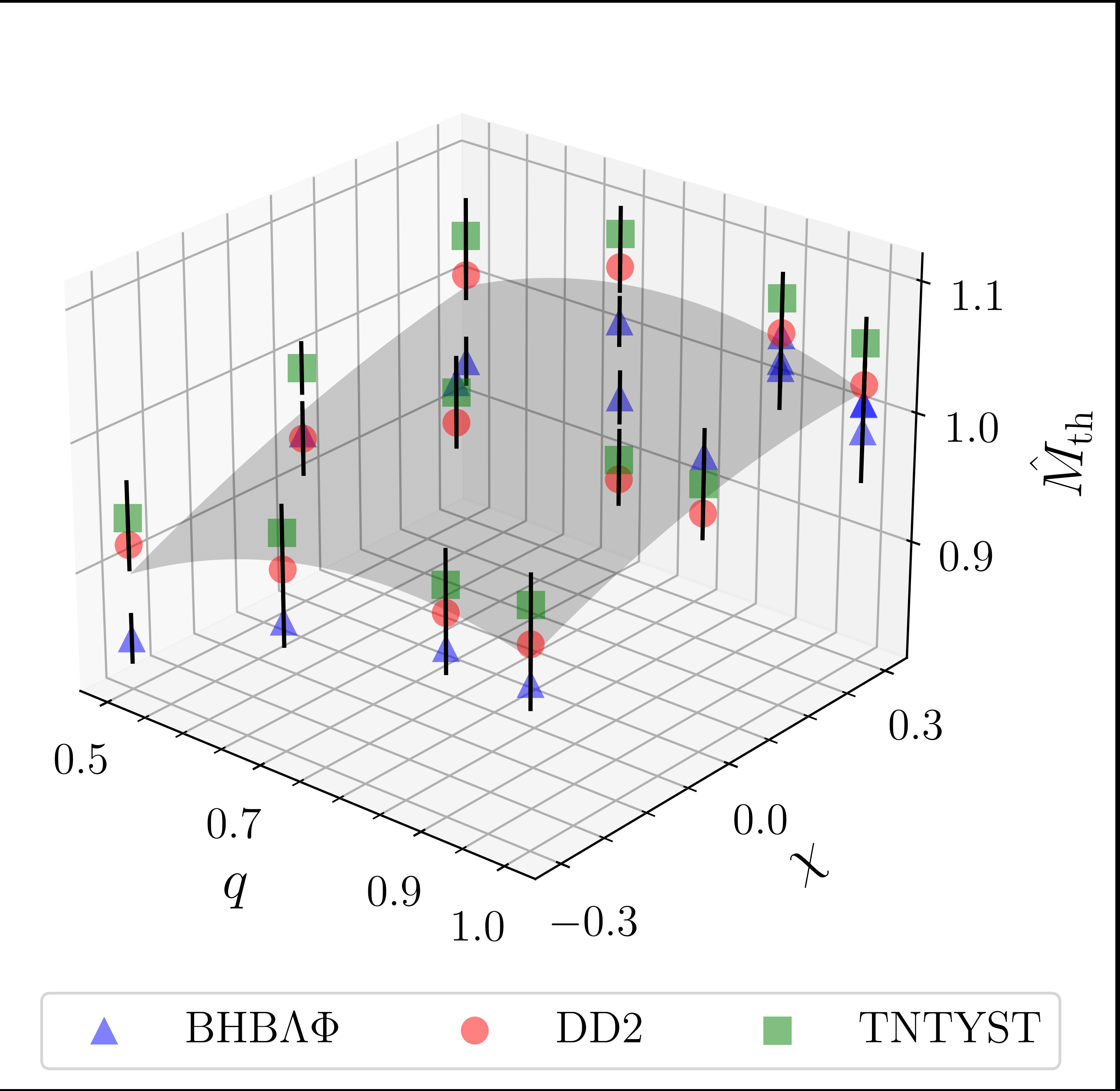
where $\kappa(\mathrm{EOS})$ comes from $q = 1, \chi = 0$ (Köppel+ 2019)

$$\kappa(\mathrm{EOS}) := \left(a - \frac{b}{1 - c\,\mathcal{C}_{\rm TOV}}\right) M_{\rm TOV}$$

and $f(q, \chi)$ is a quadratic function of q and χ

$$f(q, \chi) := a_1 + a_2(1-q) + a_3\chi + a_4(1-q)\chi + a_5(1-q)^2 + a_6\chi^2$$

Does this work?



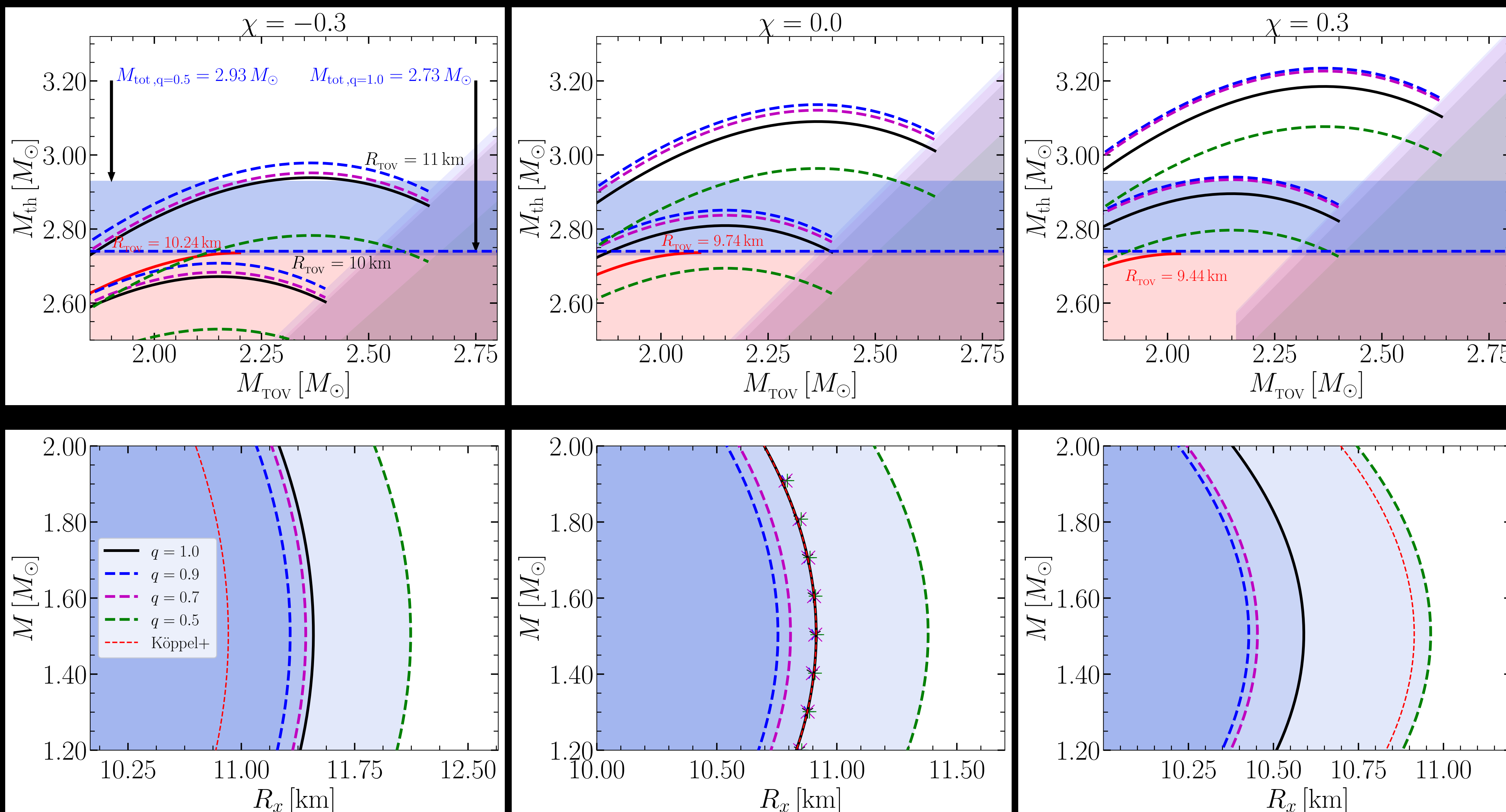
Indeed a **universal relation** exists and yields:

- **average deviation** from fit of ~2%, and **largest deviation** below ~6%.
- $M_{\rm th}$ **increases** by ~10% for **aligned** spins
- $M_{\rm th}$ **decreases** by ~5% for **antialigned** spins

Note: dependence on q **not monotonic:** balance between larger "discs" for small q and increased stability for large q yields **local maximum**

Possible to extend logic for lower limit on radius:

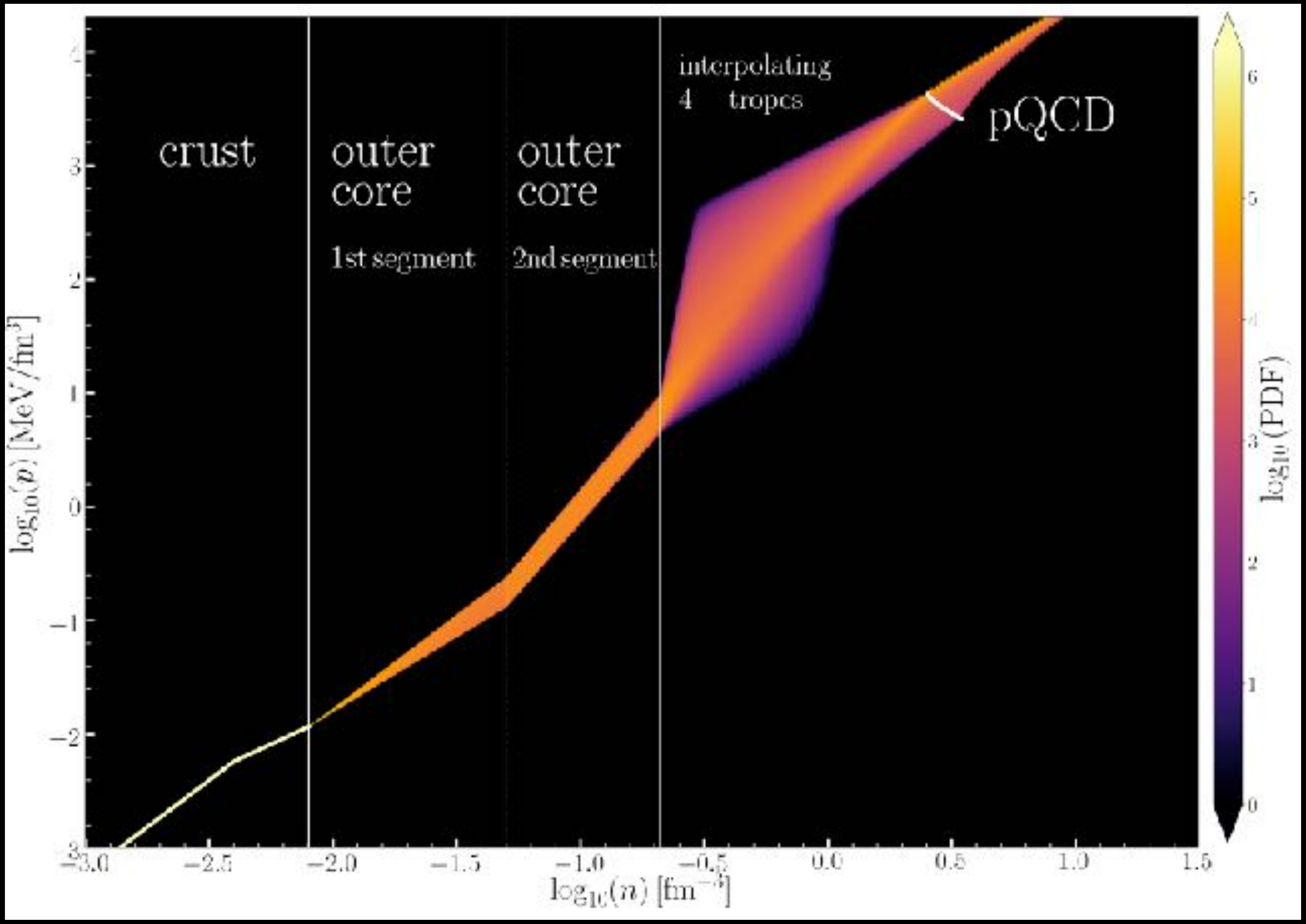
$$R_x(M,q,\chi) = \frac{R_x(M)}{f(q,\chi)}$$ where $R_x(M)$ is from Köppel+ 2019 and $f(q,\chi)$ is the same as for $M_{\rm th}$



Antialigned binaries provide significantly tighter constraints:

$R_{\rm TOV} \geq 10.24\,{\rm km}$ for $\chi = -0.3$ **vs** $R_{\rm TOV} \geq 9.44\,{\rm km}$ for $\chi = 0.3$

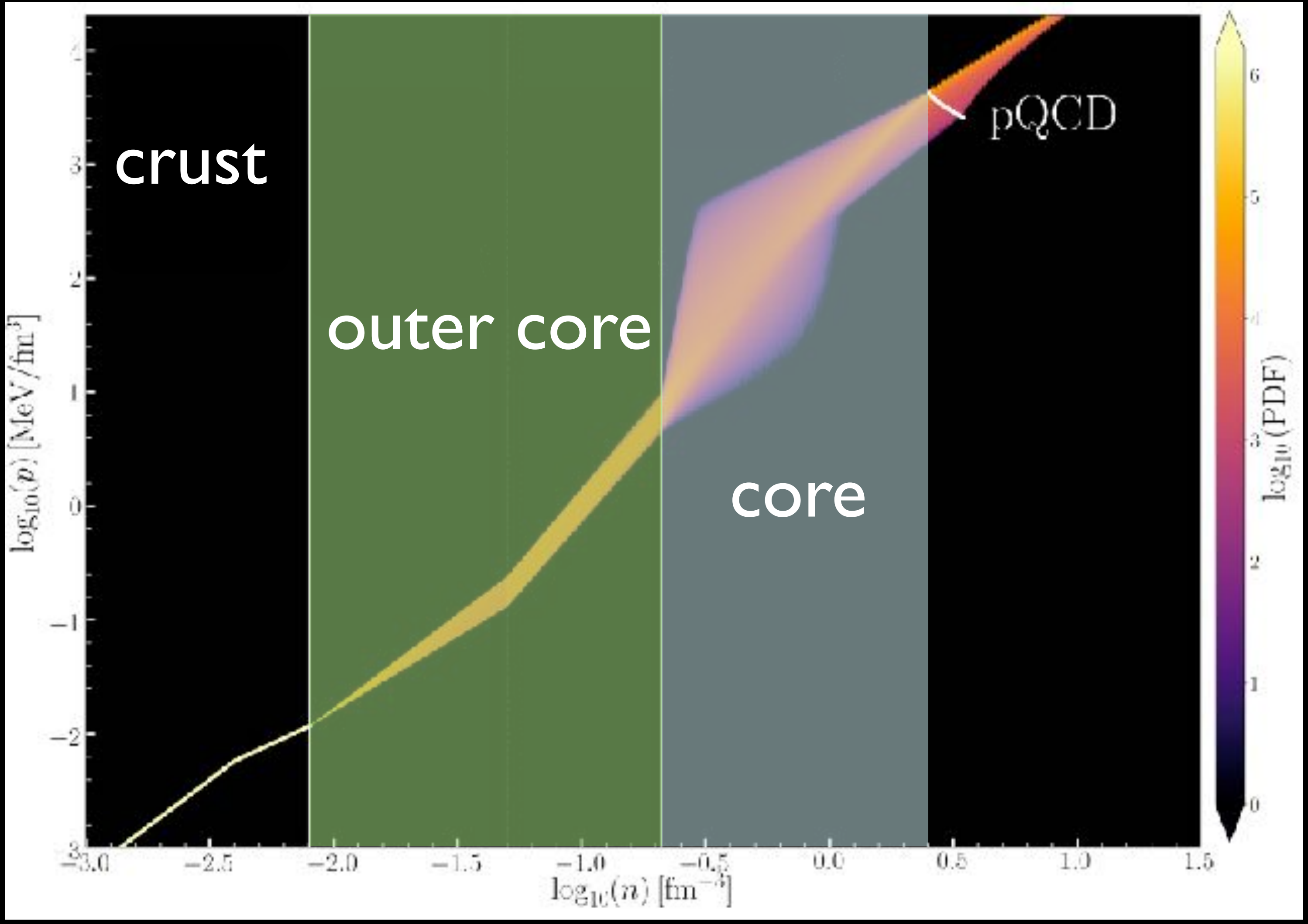
Limits on radii and deformabilities



Limits on radii and deformabilities

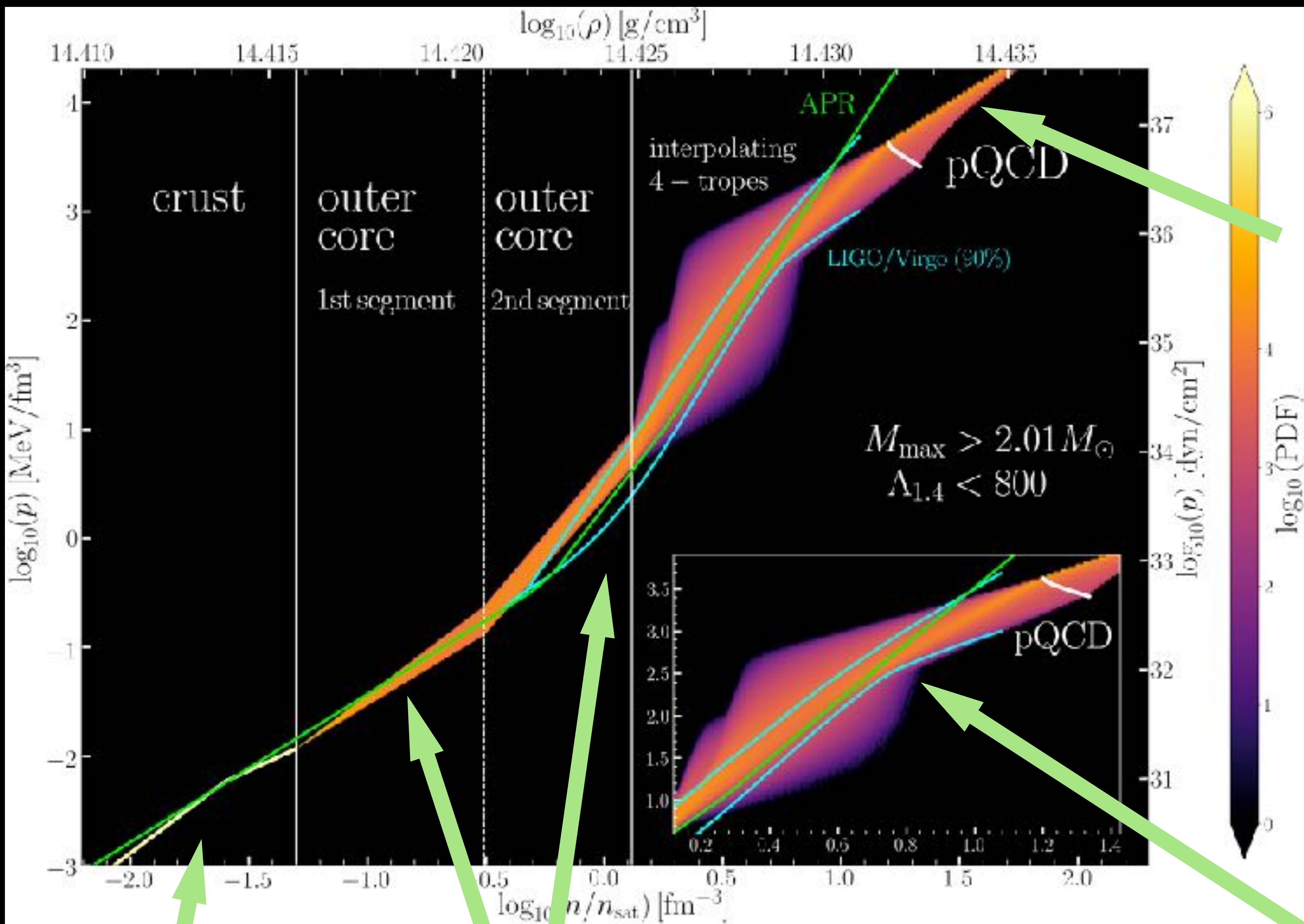
- Can new constraints be set on typical radius and tidal deformability by using GW170817?

- **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)

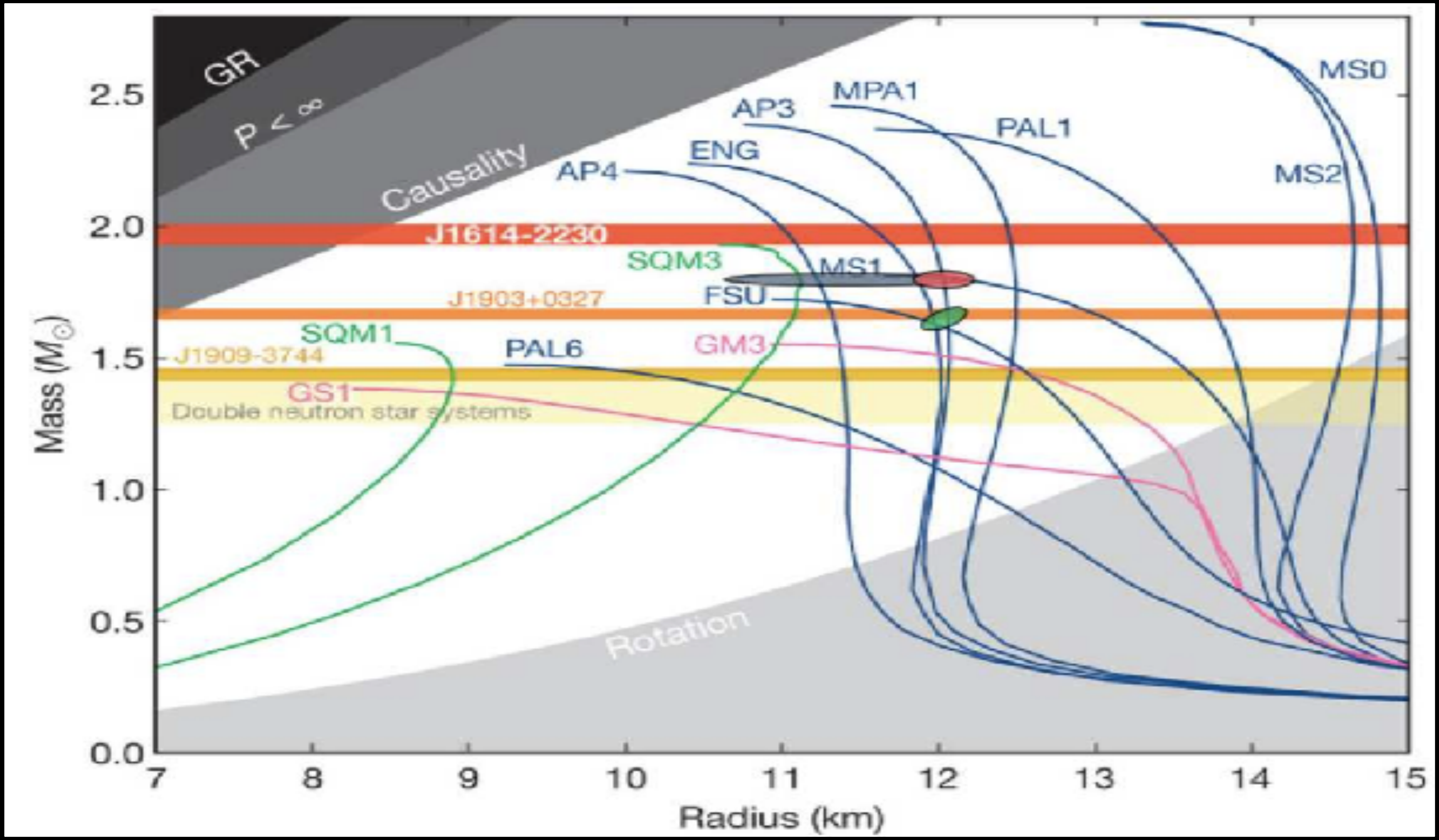
interpolation by matching 4 polytropes

BPS

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

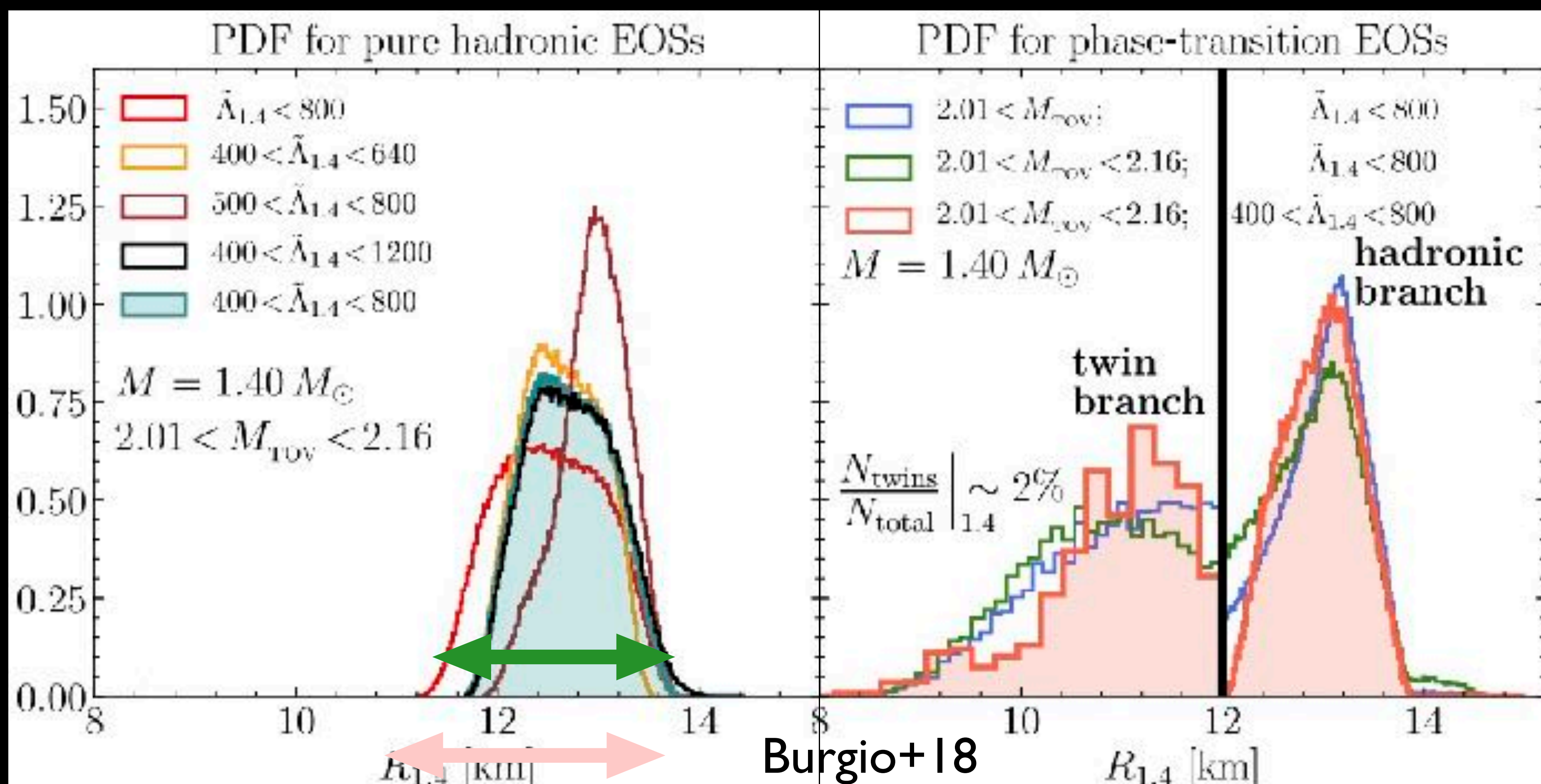
Mass-radius relations

- 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 $M = 1.40\,M_\odot$
- Play with different constraints on M_{TOV} and tidal deformability
- Overall distribution is very robust



Tews+18

De+18

LVC+18

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

Constraining tidal deformability

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

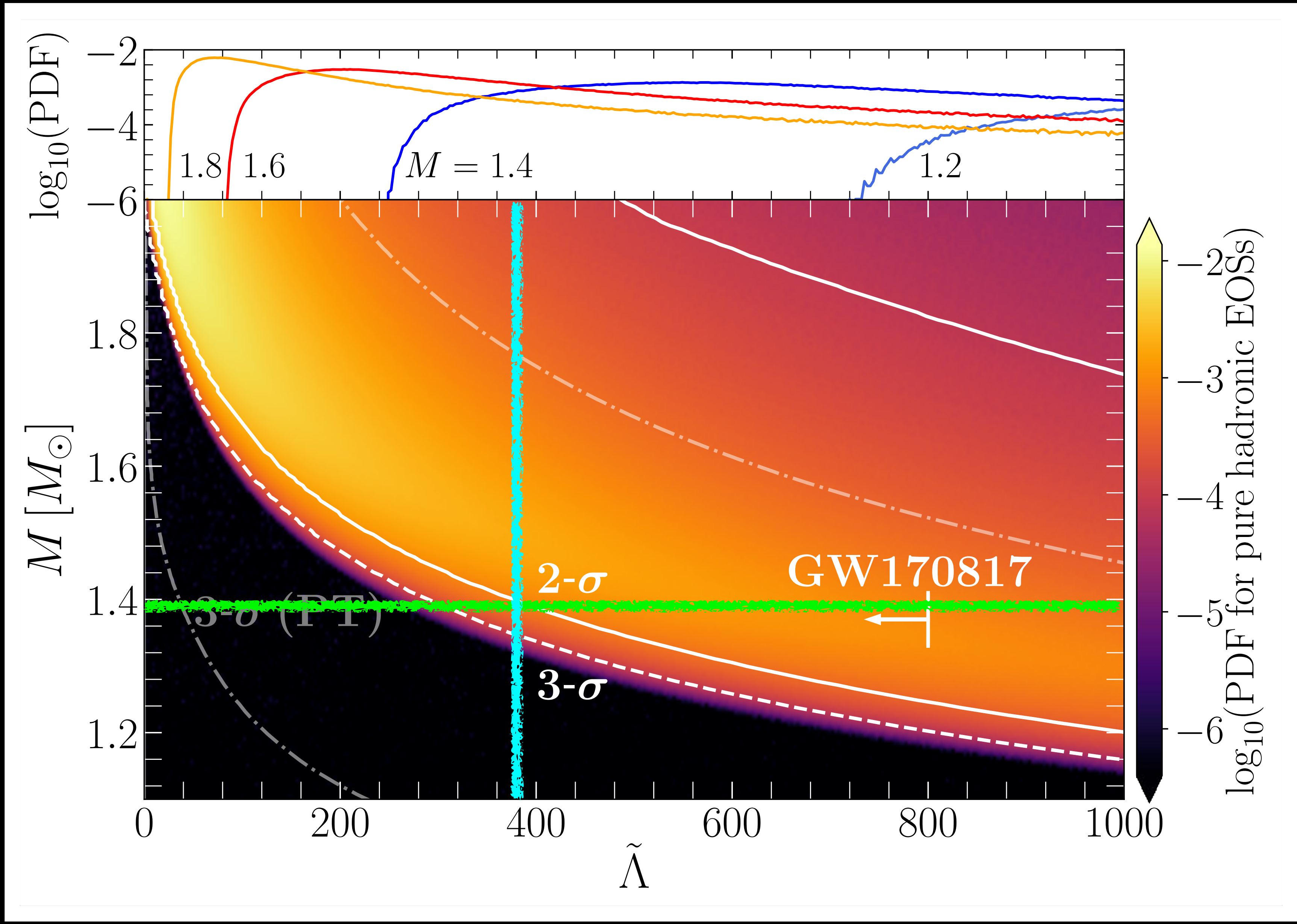
- LIGO has already set upper limit:

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

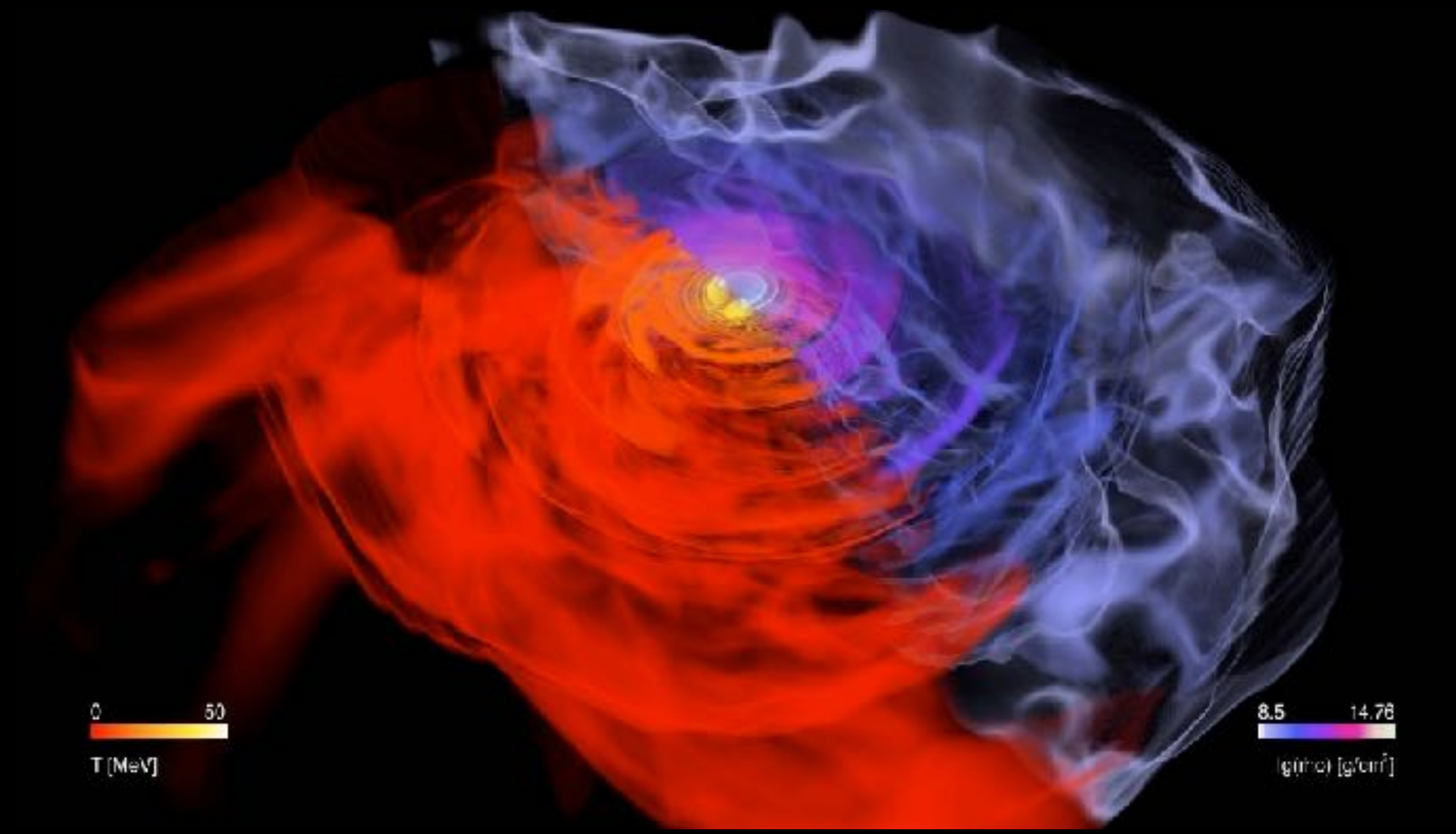
- Our sample sets a lower limit:

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

the largest so far.

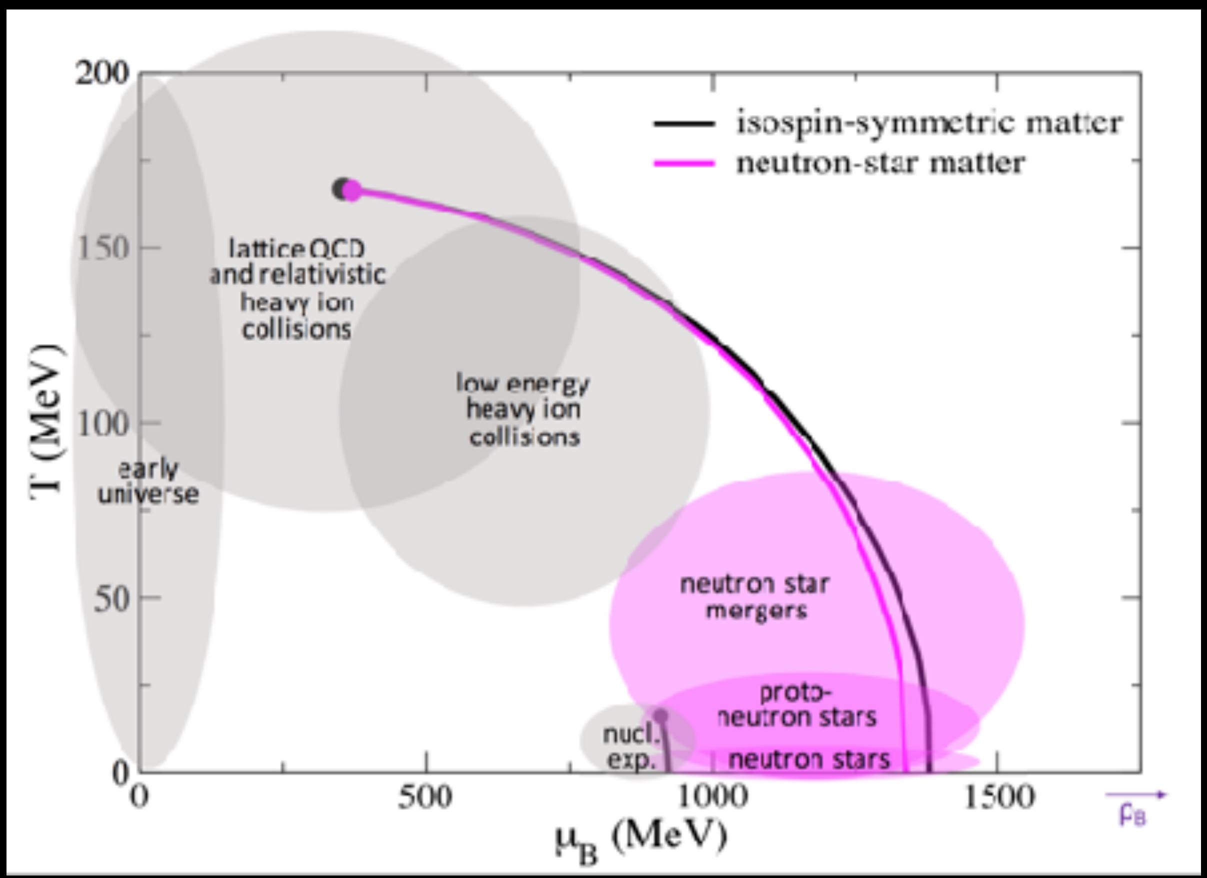


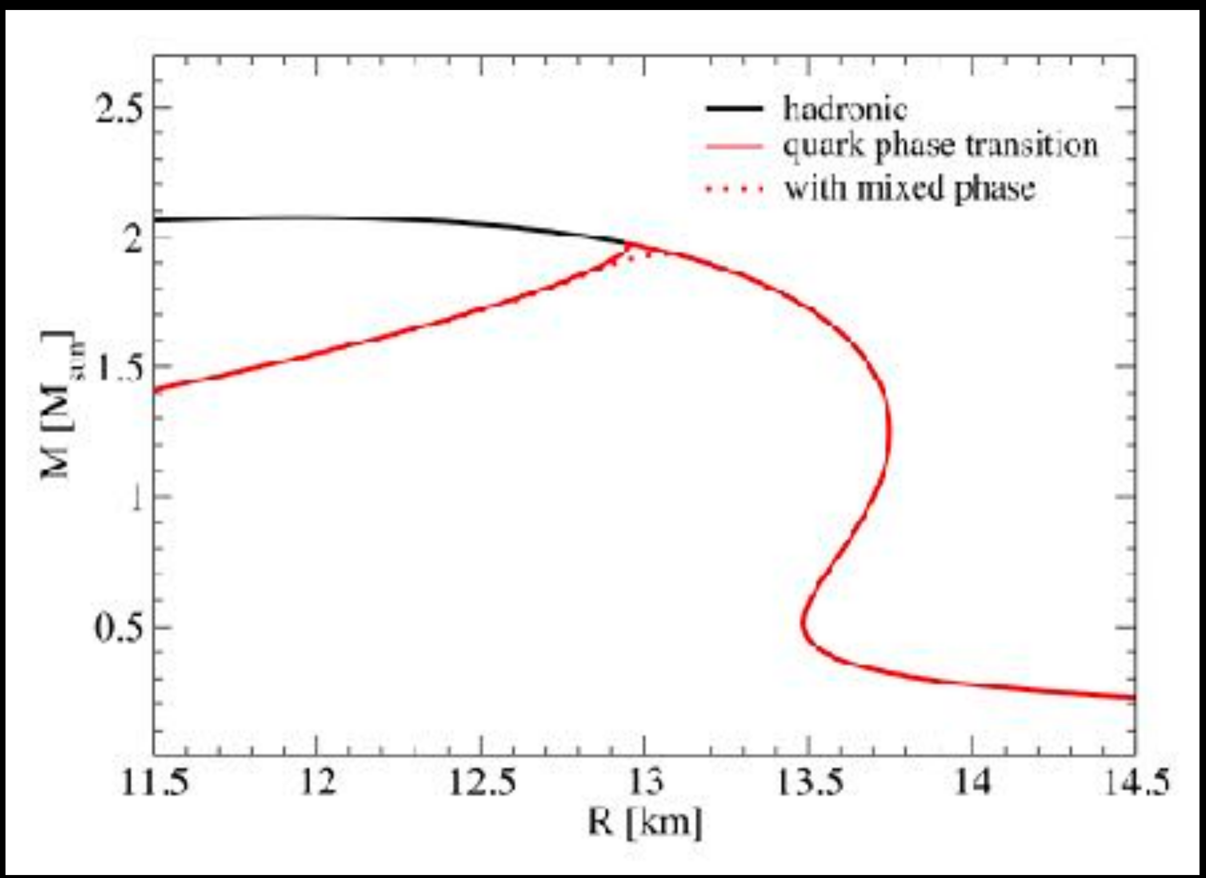
Phase transitions and their signatures



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

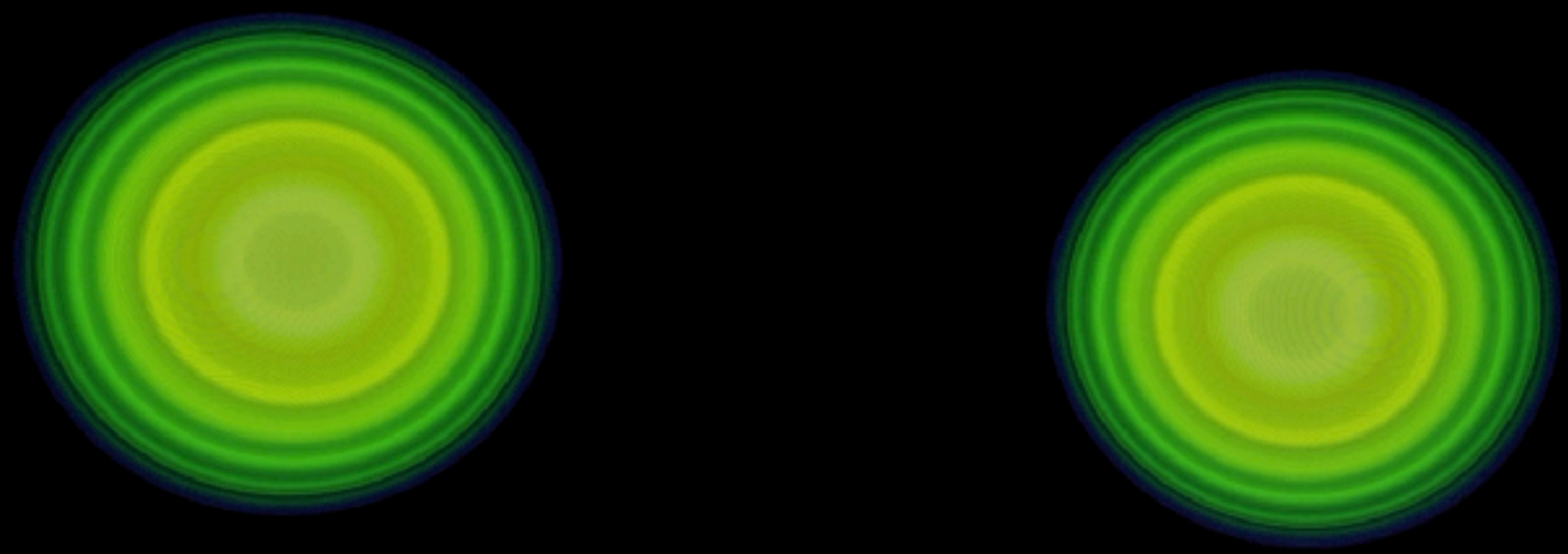
- **Isolated** neutron stars probe a small fraction of phase diagram.
- Neutron-star **binary** mergers reach temperatures up to 80 MeV and probe regions complementary to experiments.

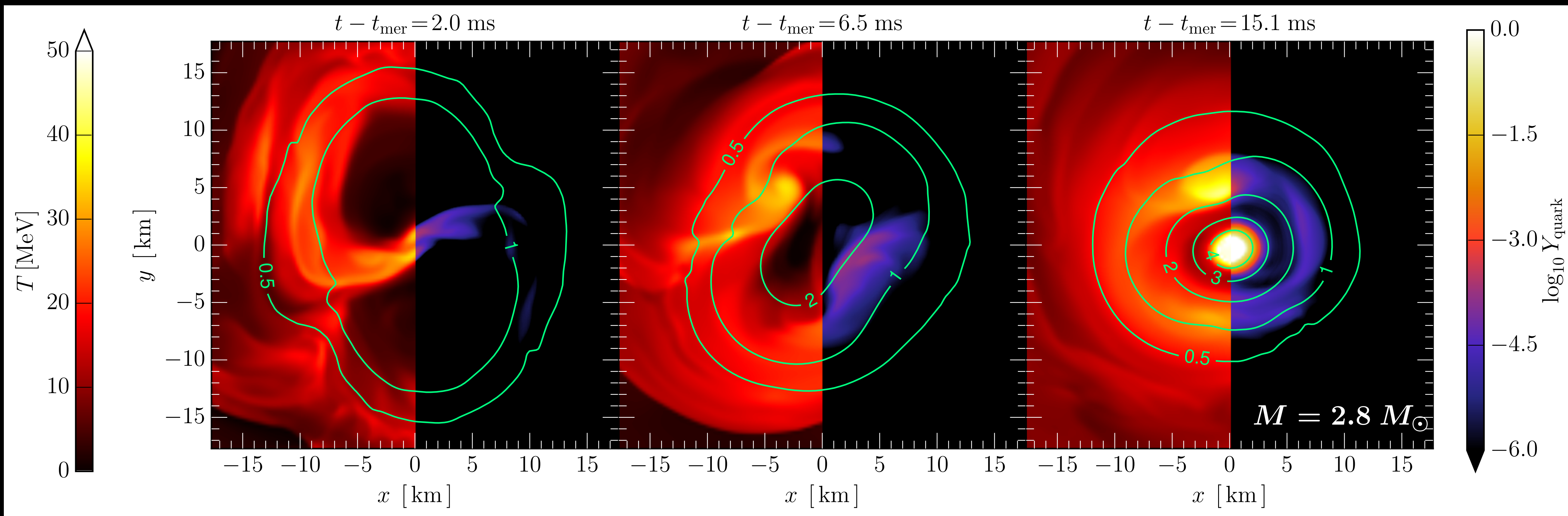




- Considered EOS based on Chiral Mean Field (CMF) model, based on a nonlinear SU(3) sigma model.
- Appearance of quarks can be introduced naturally.

Animations: Weih, Most, LR

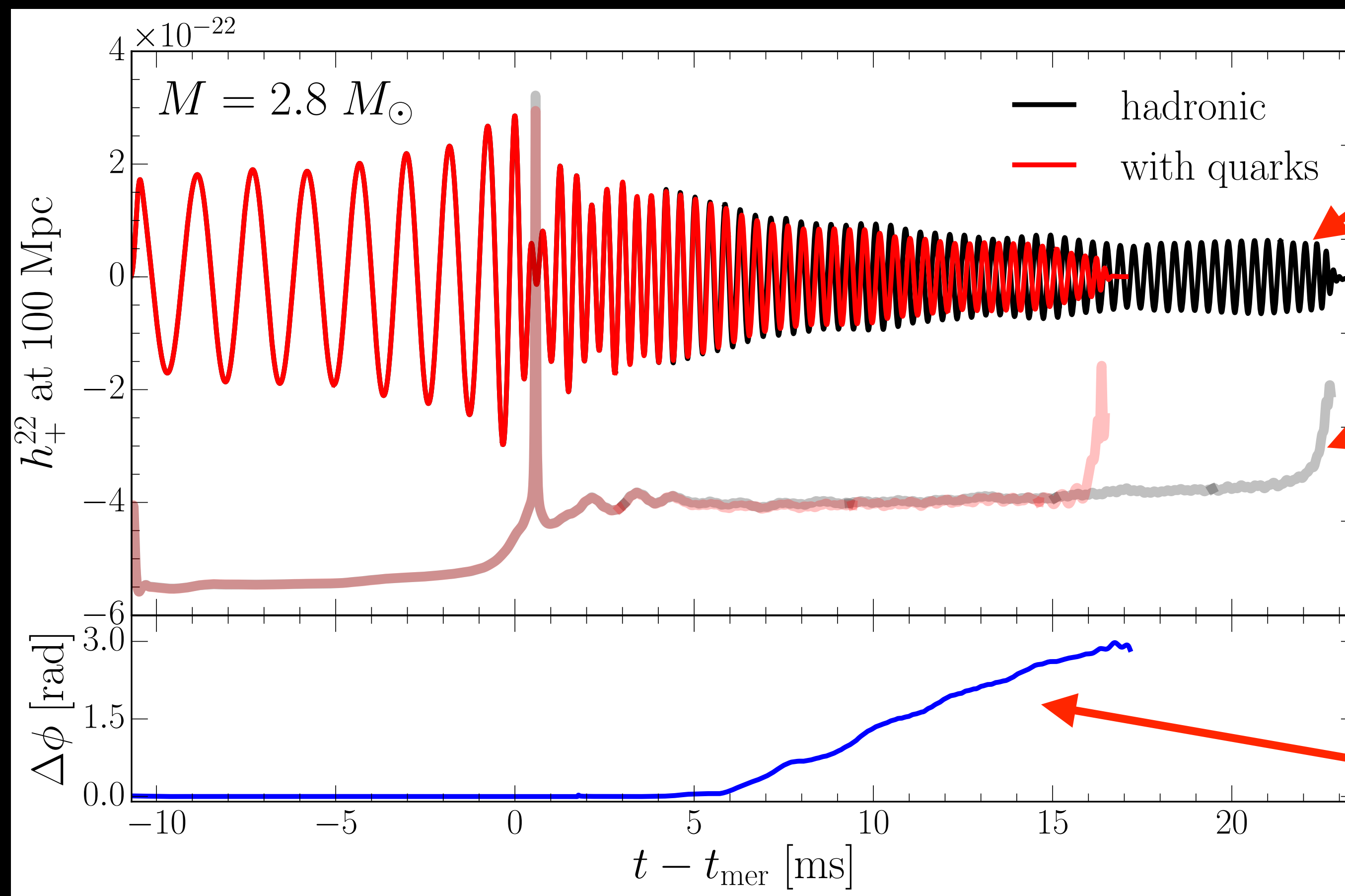




Quarks appear at sufficiently large temperatures and densities.

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

Gravitational-wave emission



waveforms

GW frequencies

phase difference

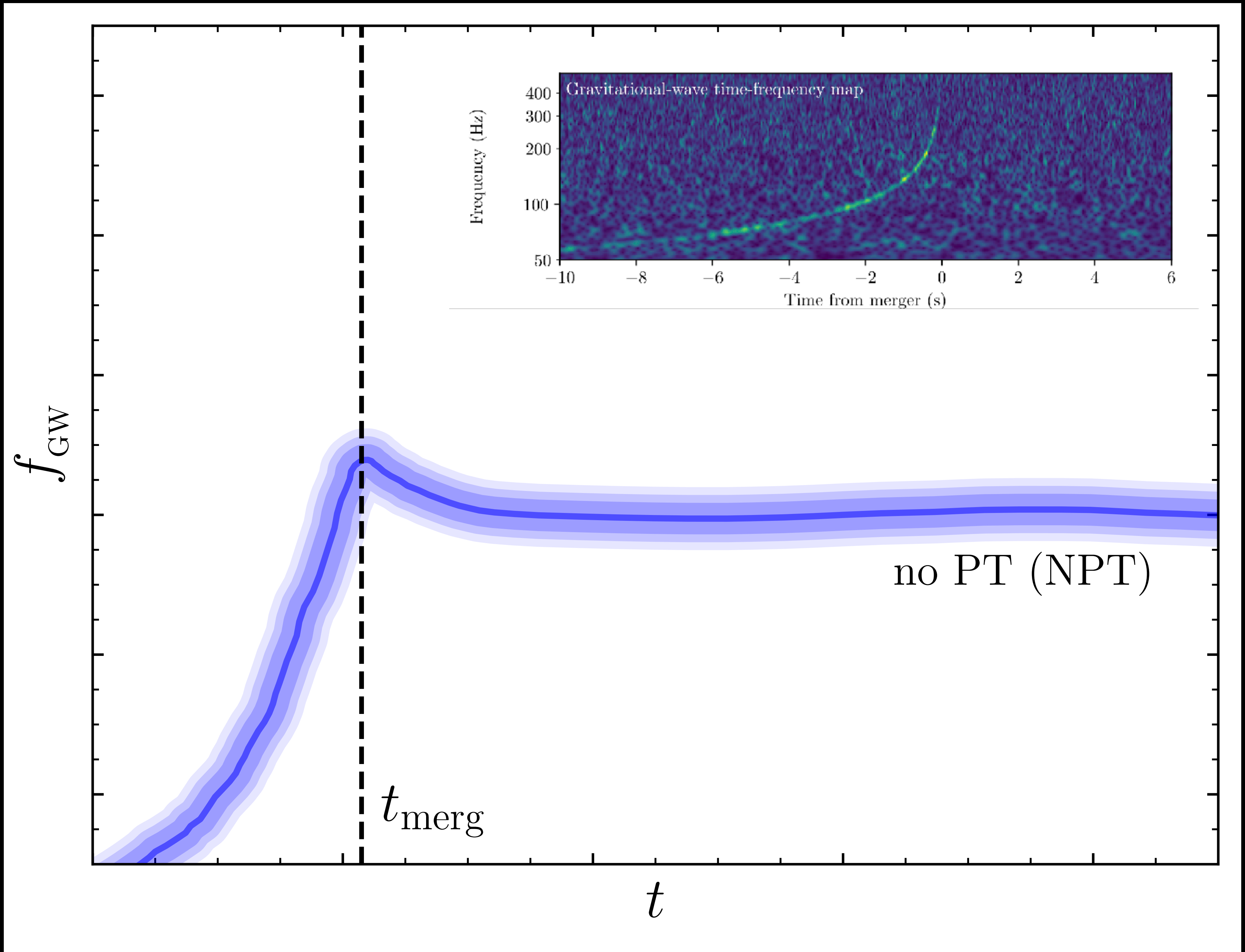
- After ~ 5 ms, quark fraction is large enough to change quadrupole moment and yield differences in the waveforms.
- Sudden softening of the phase transition leads to collapse and **large difference** in phase evolution.

Observing mismatch between **inspiral** (fully hadronic) and **post-merger** (phase transition): clear **signature** of a **PT**

Animations: Weih, Most, LR

A more comprehensive picture

We have recently added another possible scenario for a post-merger **PT,** which completes the picture of possible scenarios (Weih, Hanauske, LR 2020).



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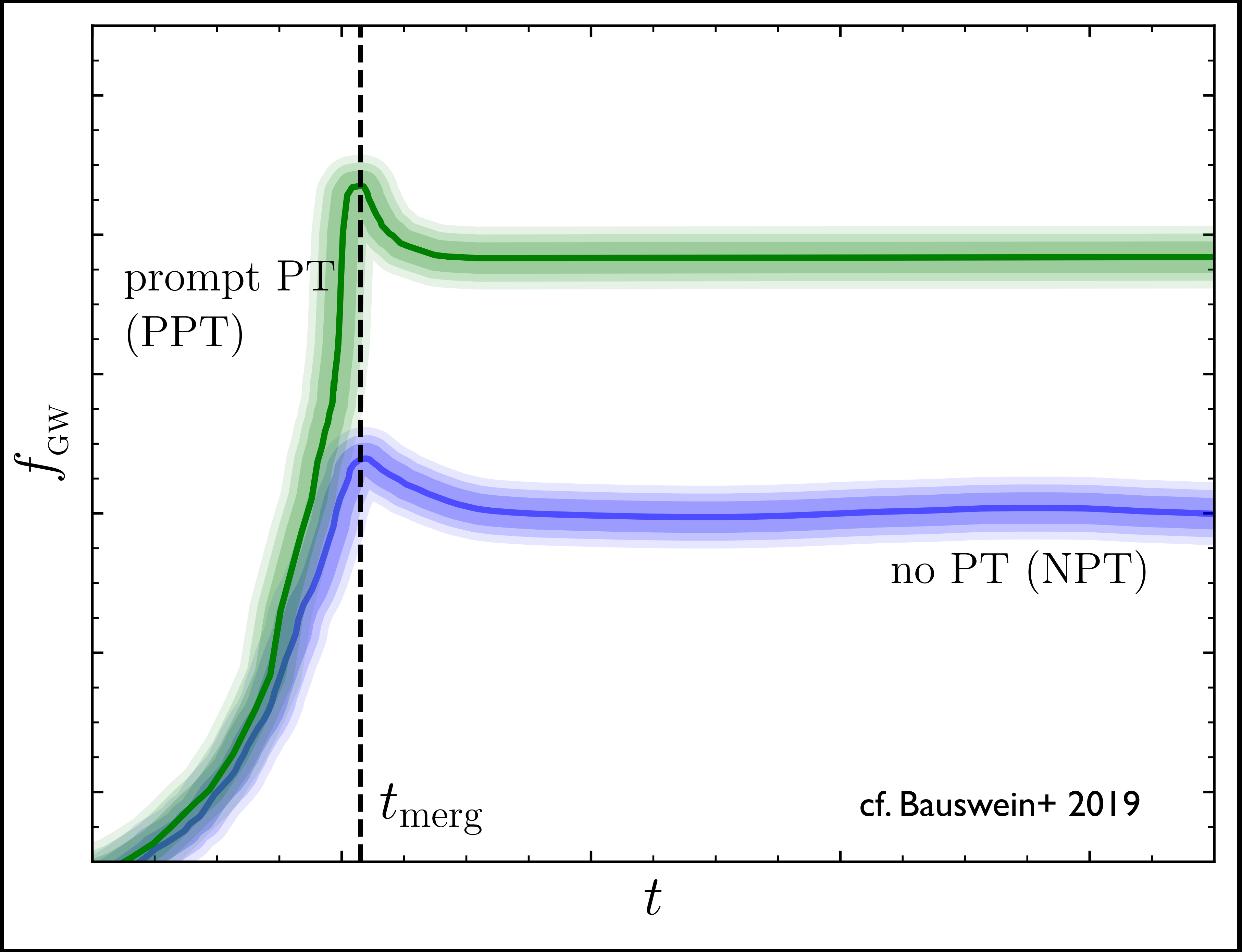

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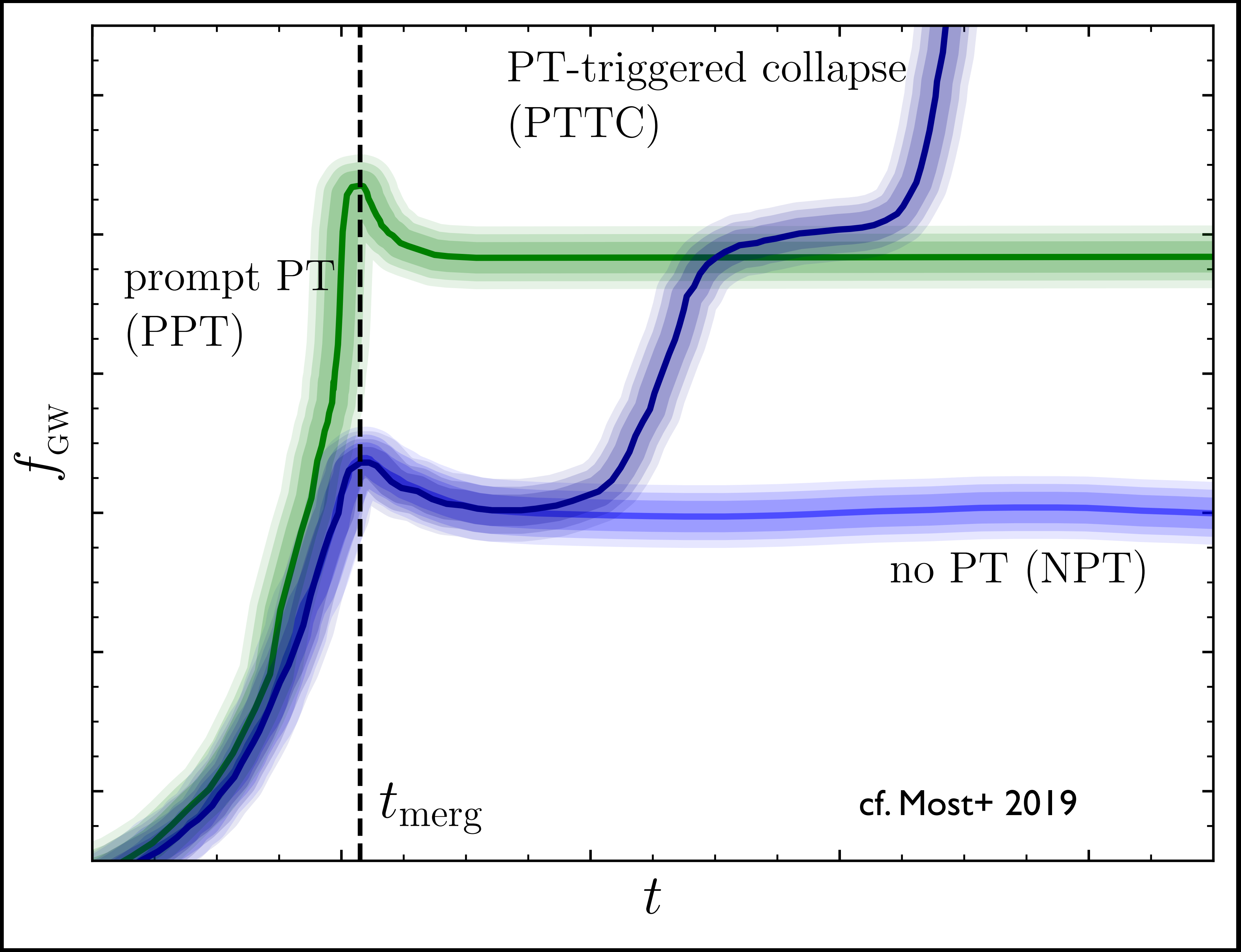

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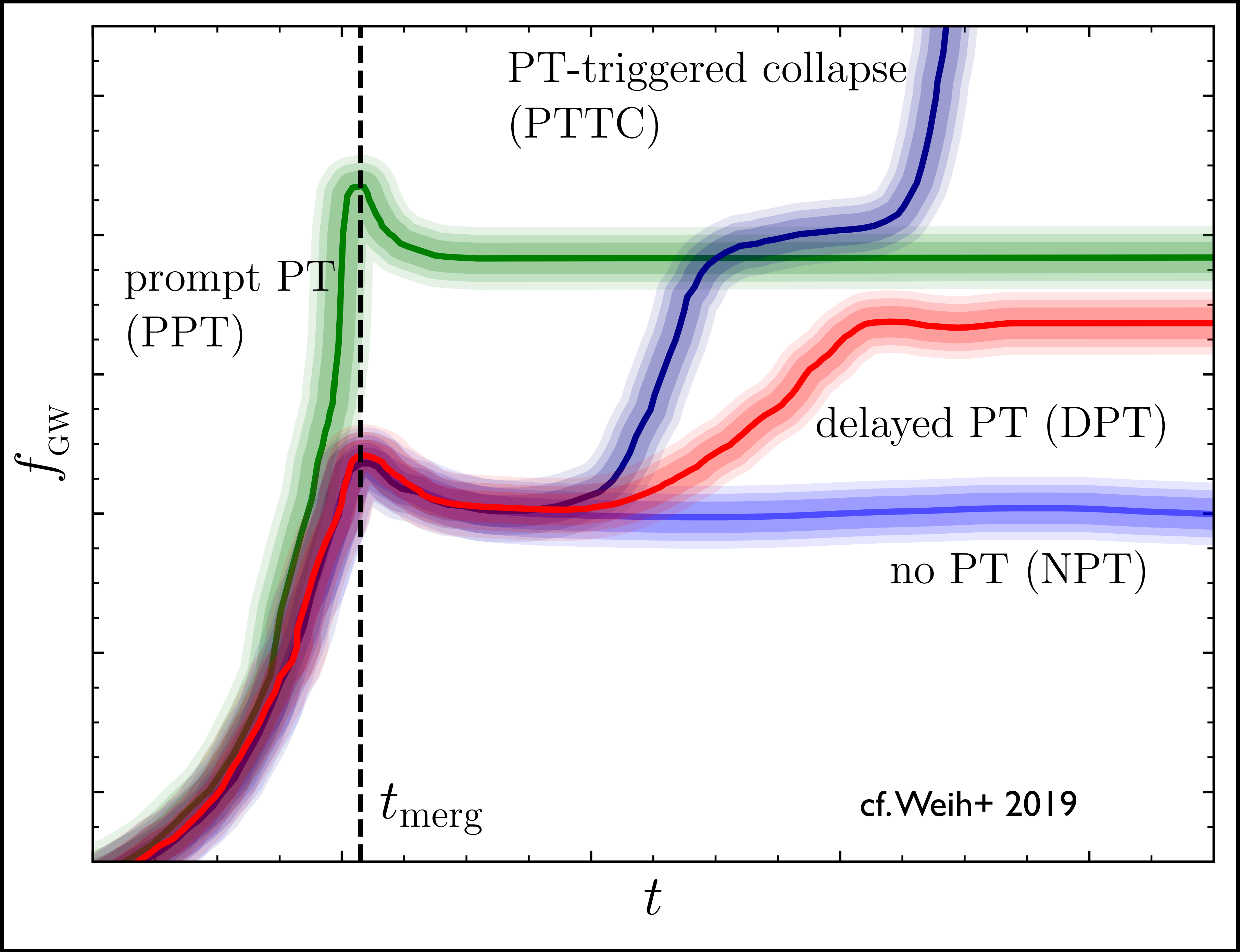
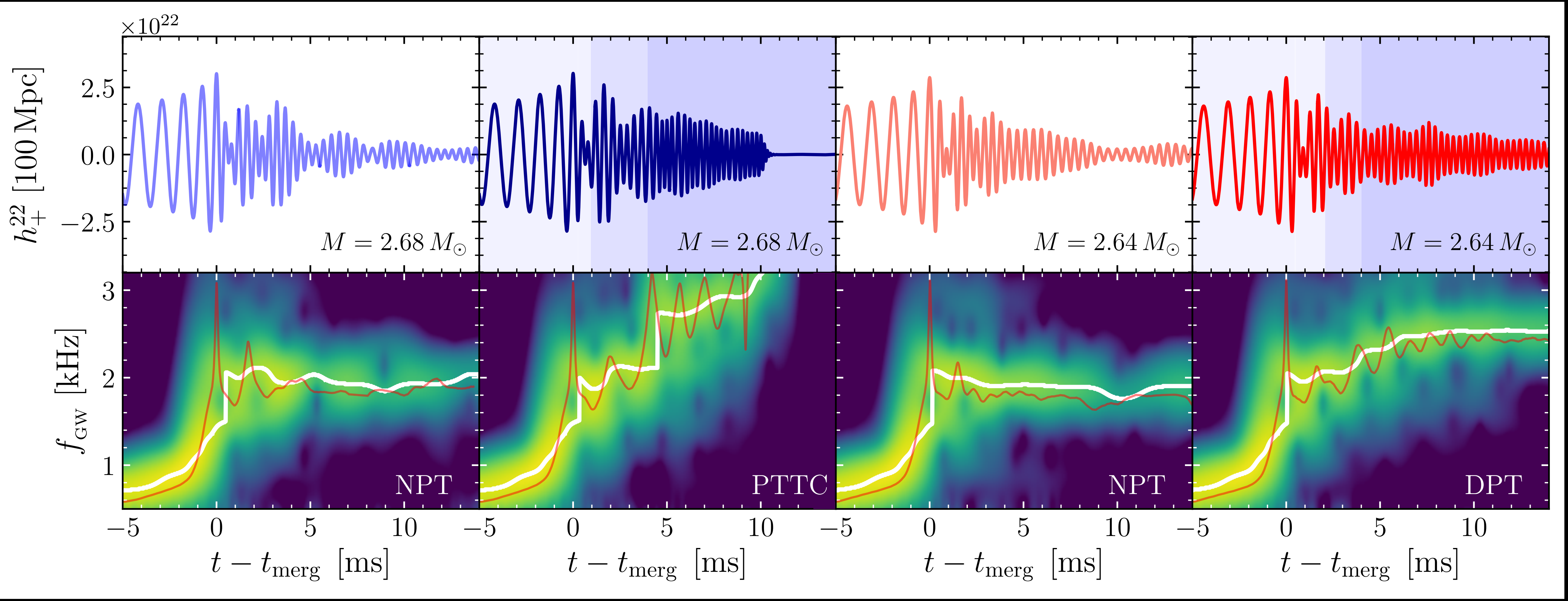


A more comprehensive picture

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



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

A more comprehensive picture

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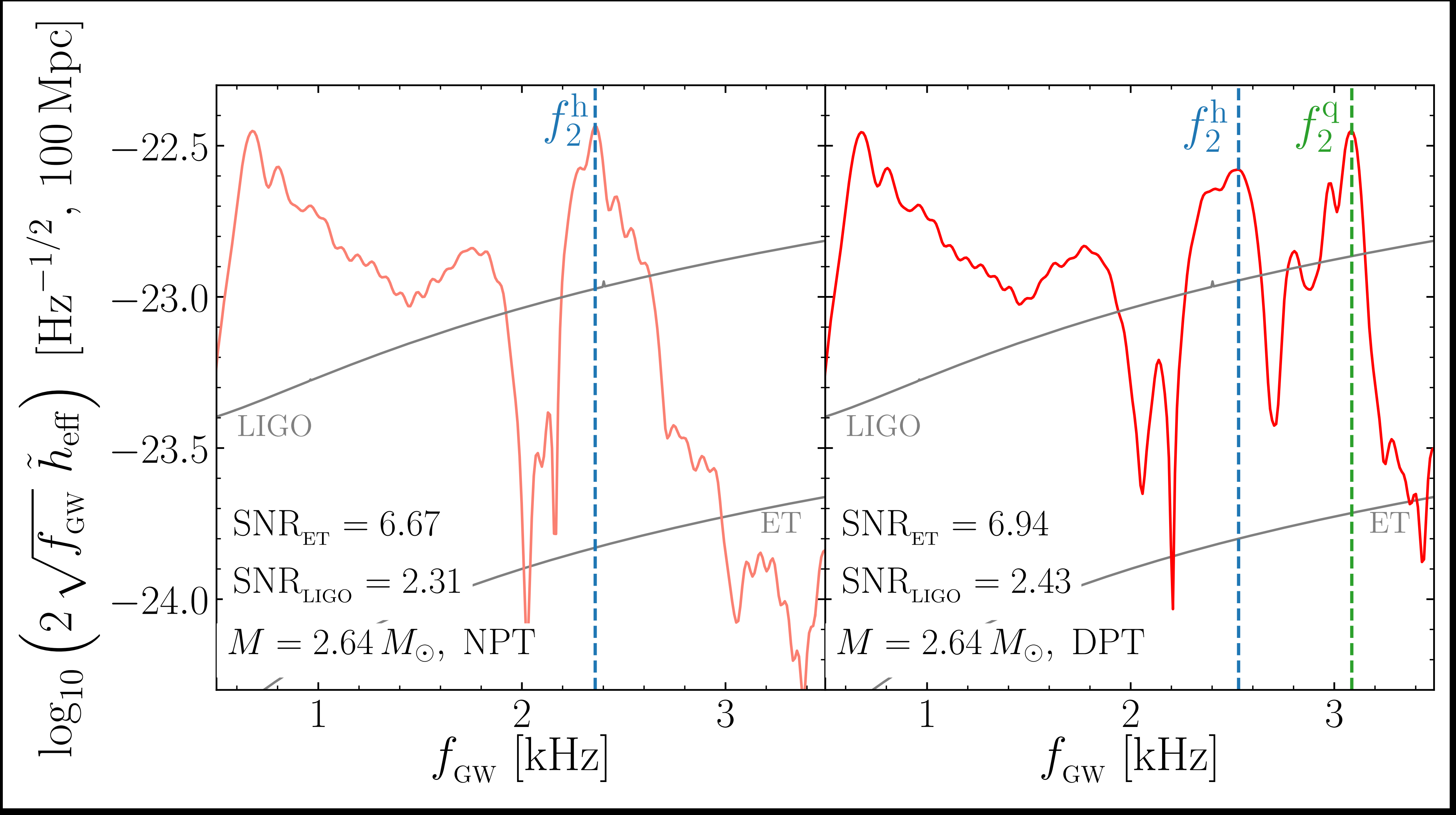
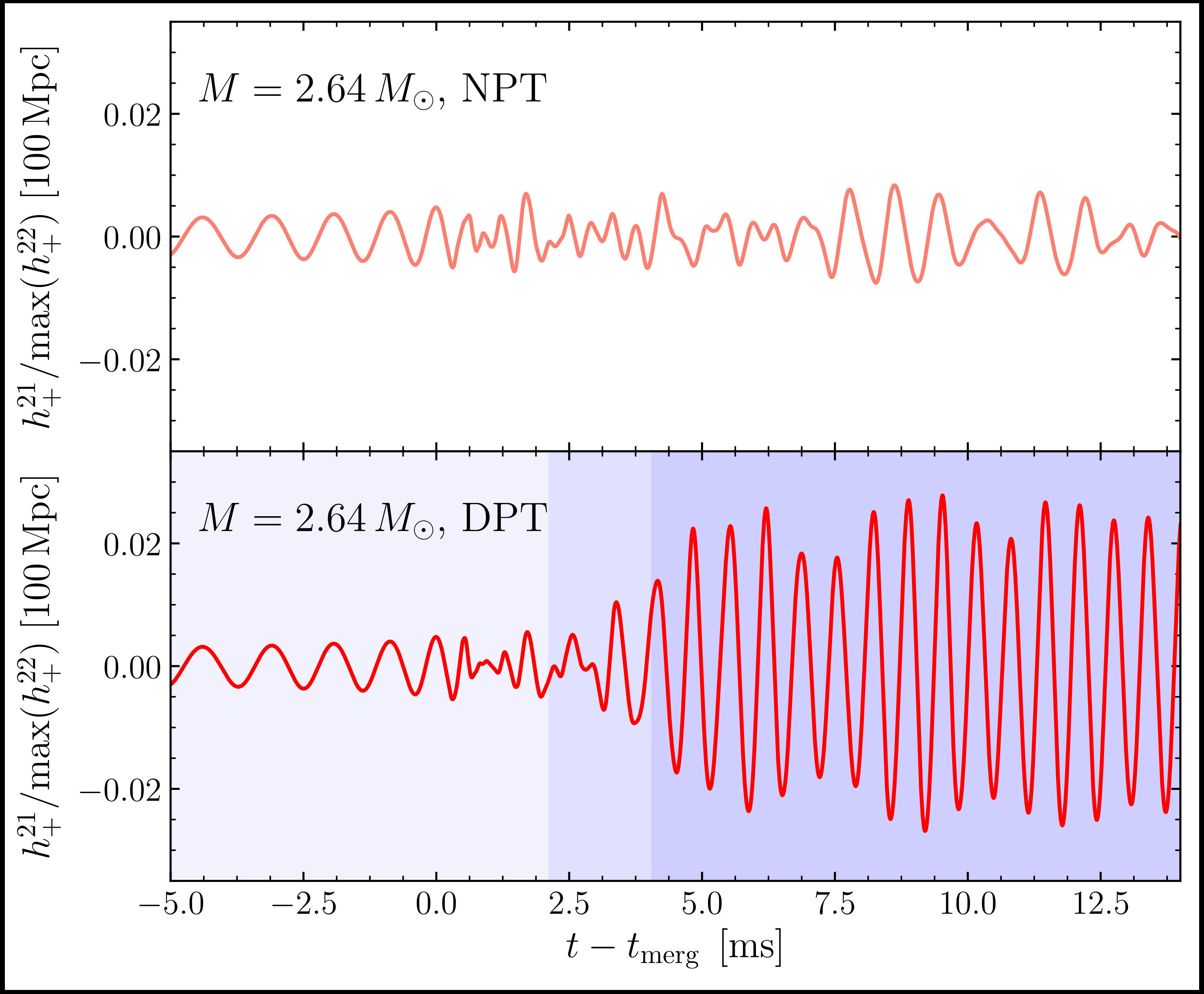


Importance of **DPT** is that it leads to **two** different "stable" f_2 **frequencies** that are easily distinguishable in the PSD

A more comprehensive picture

Another signatures is appearance of an $\ell = 2, m = 1$ mode



The mode is triggered by the PT and the non-axisymmetric deformations it produces.

Conclusions

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

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

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

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

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

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

$M_{\rm th}/M_{\rm TOV} \approx 1.41 \quad R_{\rm TOV} \geq 9.74^{+0.14}_{-0.04}\,{\rm km}$ **threshold mass**

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