Constraints on neutron star properties from GW170817

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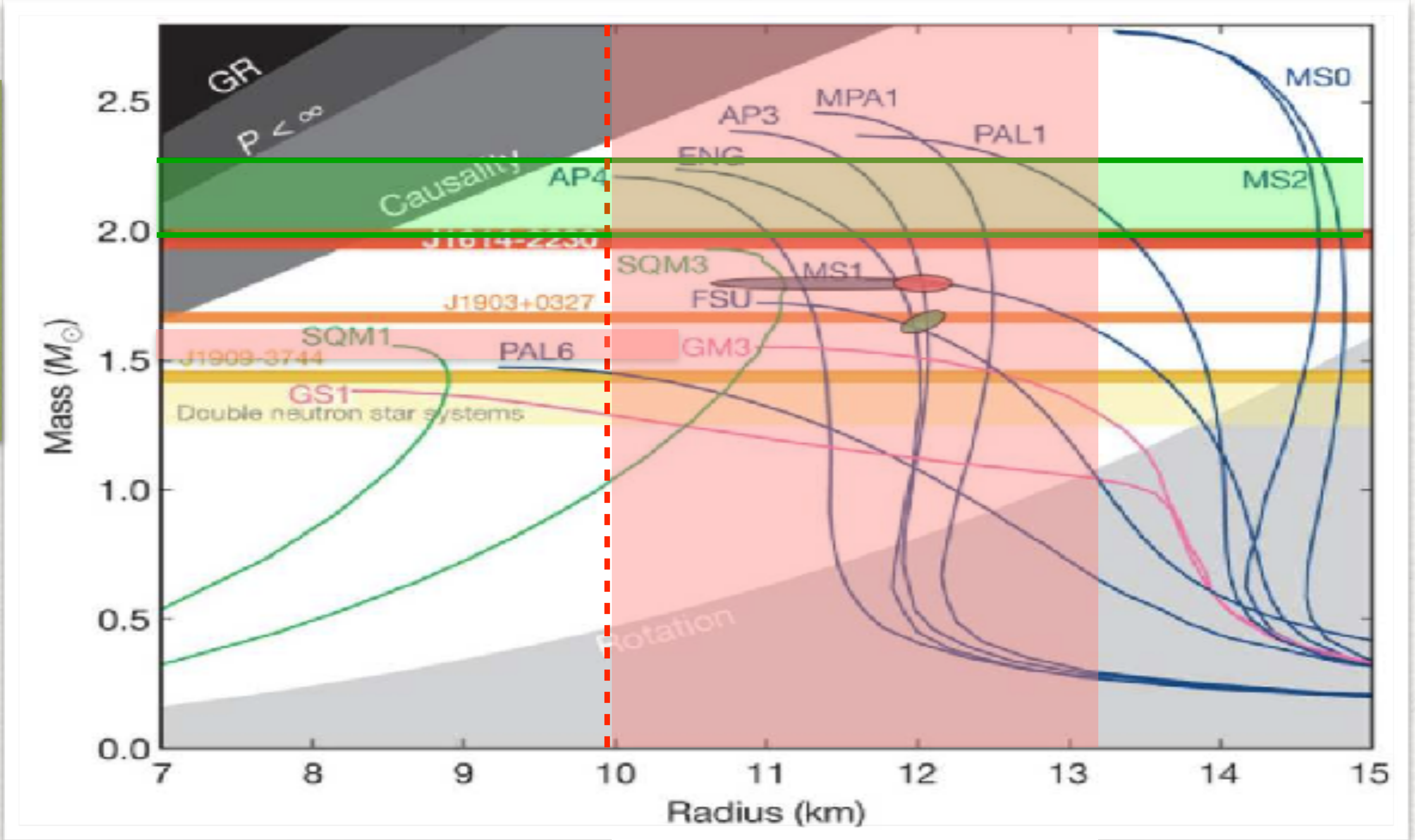
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

ITP Institute for Theoretical Physics

HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research

Can we translate GW170817 to constraints on the EOS?

maximum mass



lowest/largest radius

Demorest+ 2010

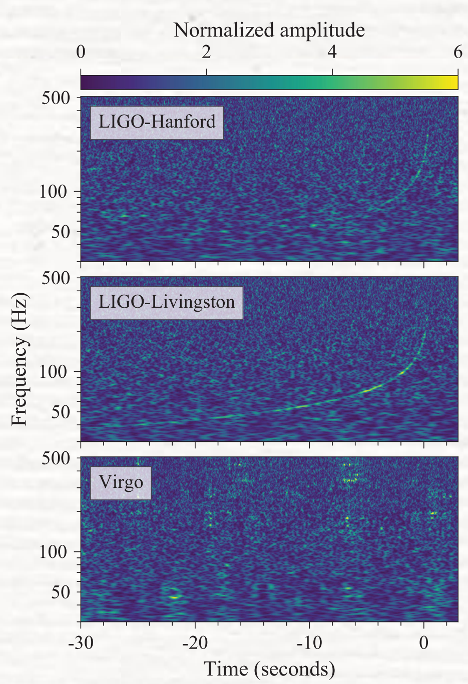
Ingredients to constrain EOS

Numerical relativity

Physics modelling

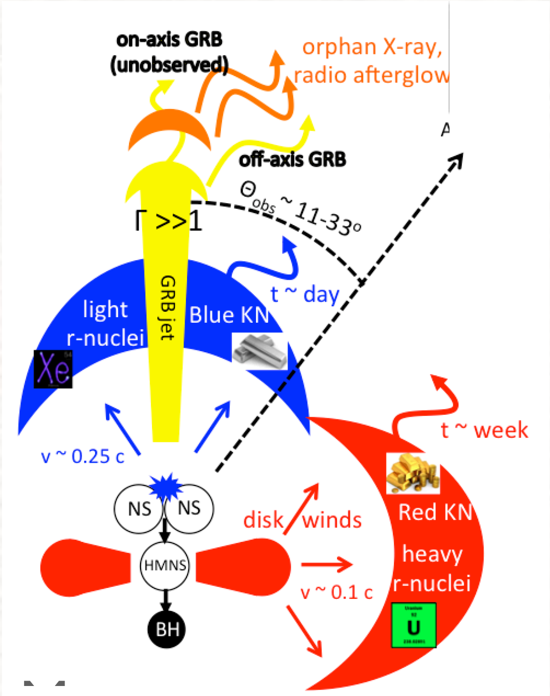
EOS CONSTRAINTS

Observation GW170817

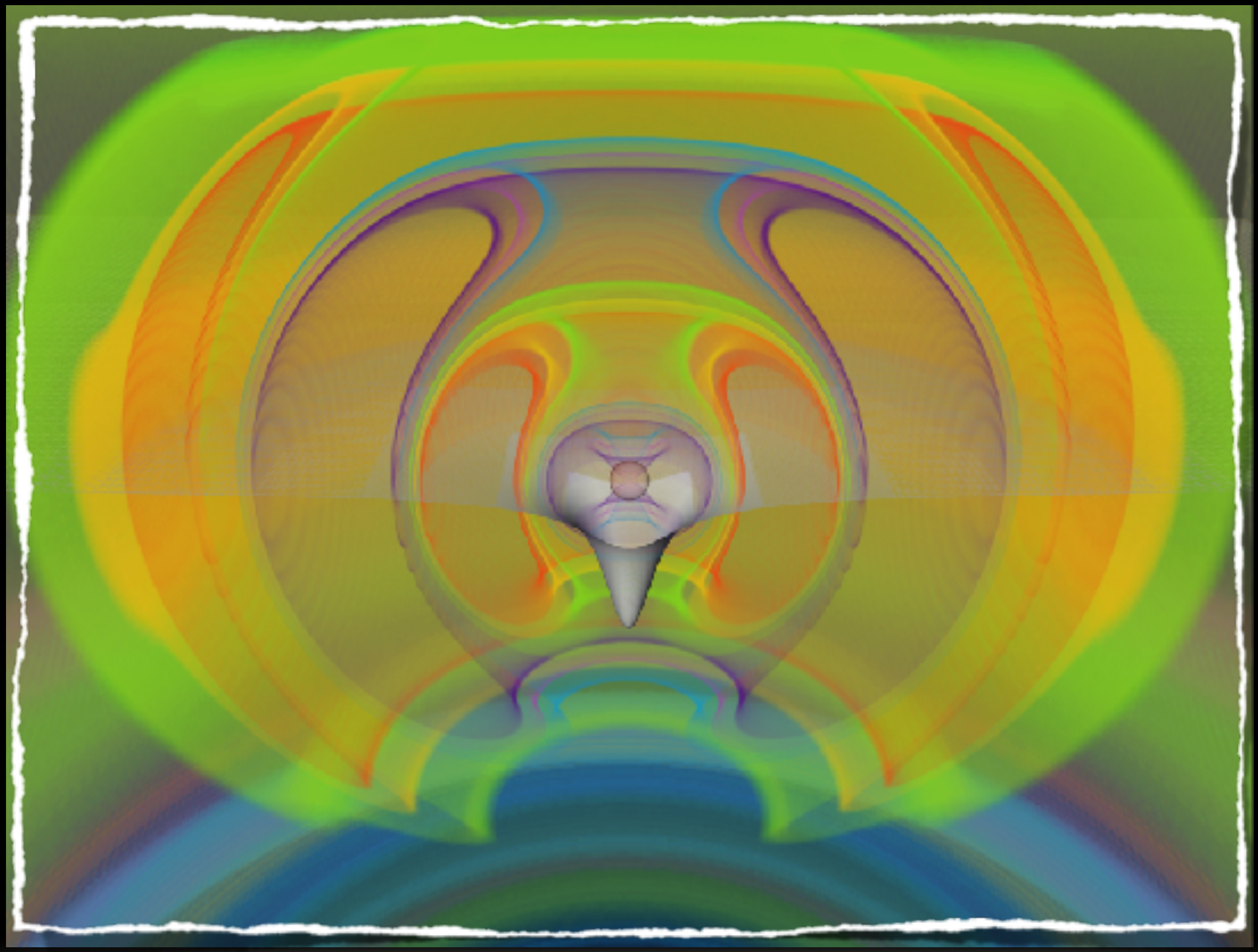


Abbott+ 2017

Metzger 2017

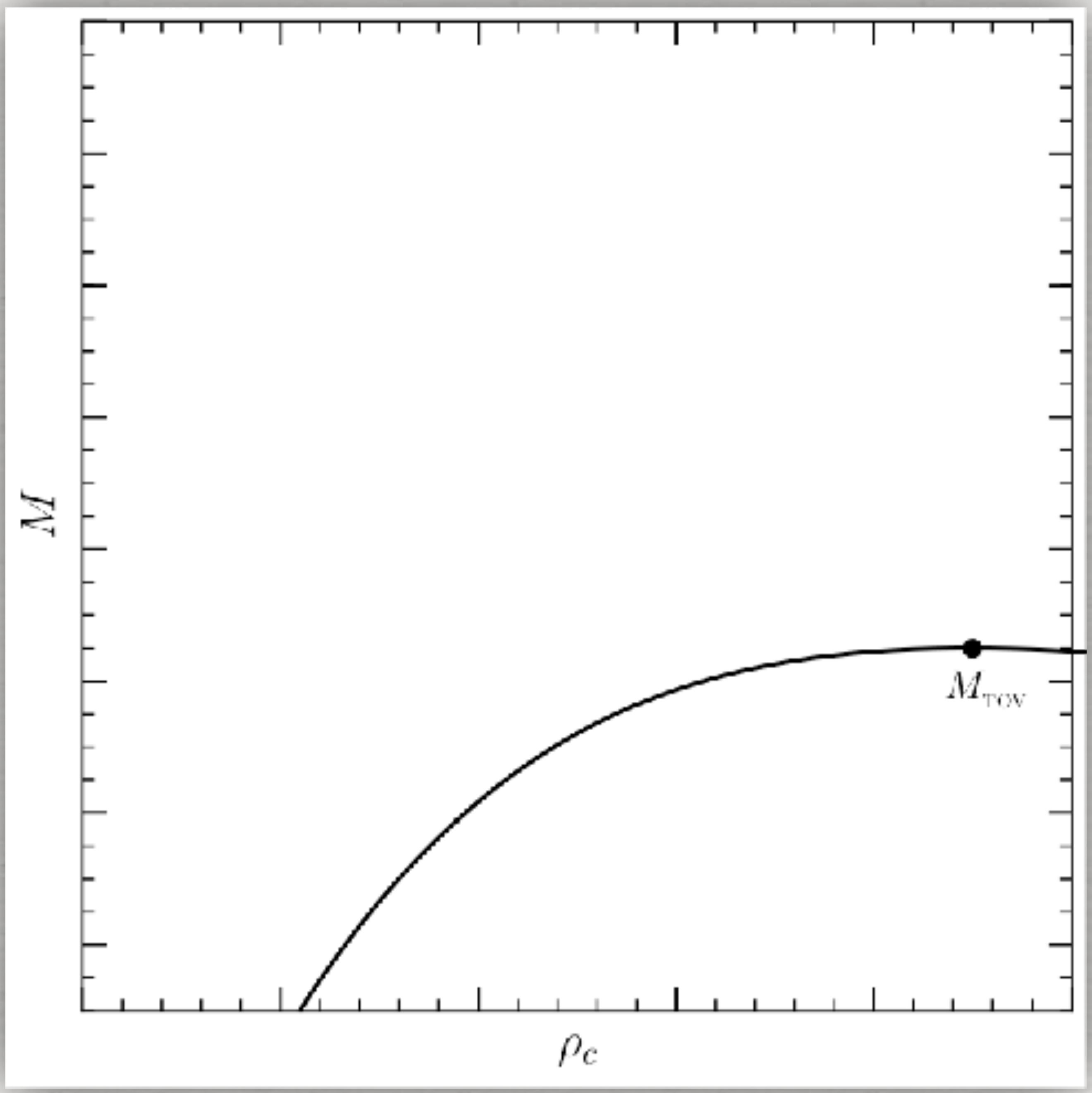


Maximum mass constraints from GW170817



The outcome of GW170817

- The product of GW170817 was likely 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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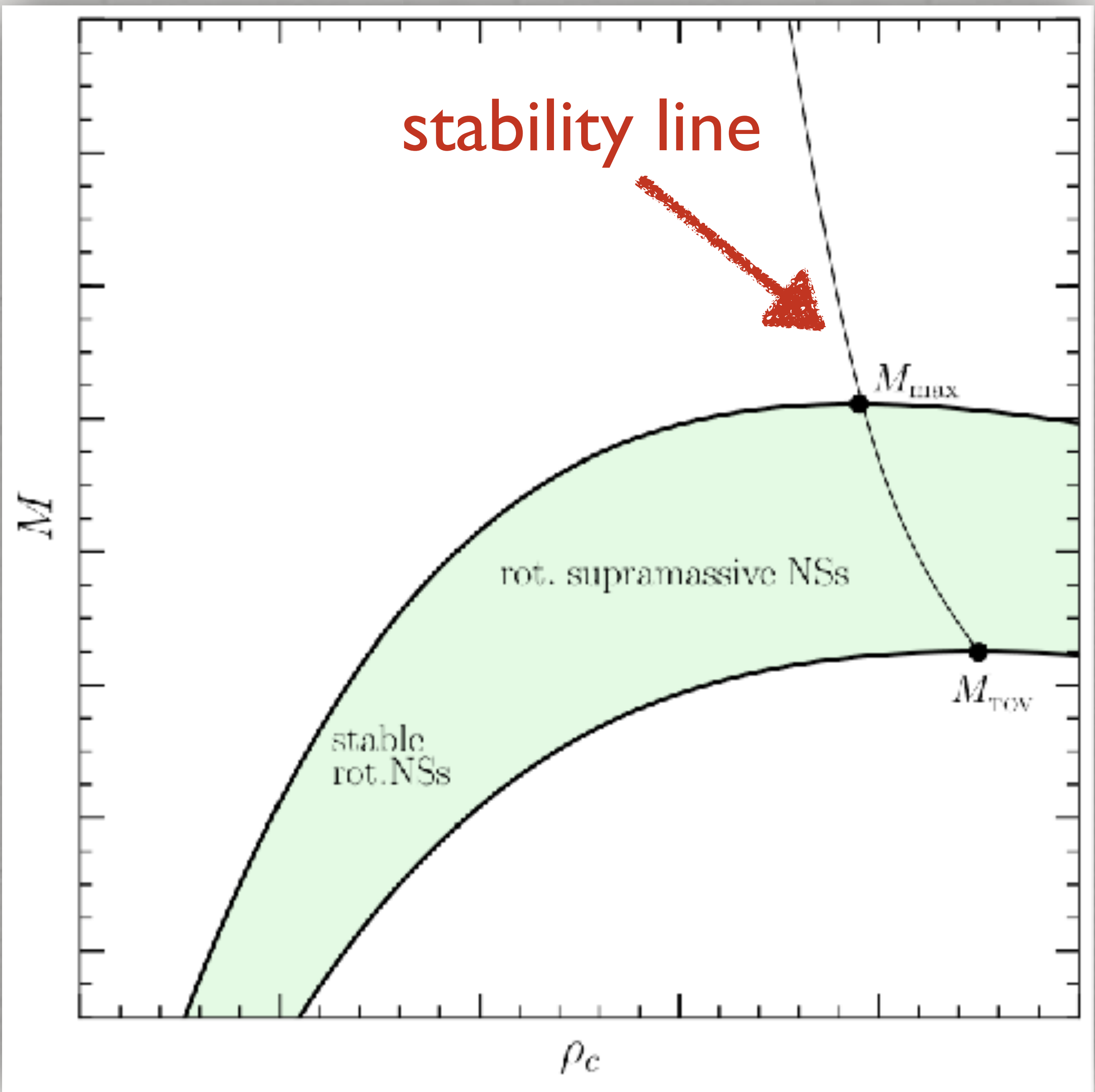

- Sequences of equilibrium models of **nonrotating** stars will have a maximum mass: $M_{\rm TOV}$
- This is true also for **uniformly** rotating stars at mass shedding limit: $M_{\rm max}$
- $M_{\rm max}$ simple and **quasi-universal** function of $M_{\rm TOV}$ (Breu & Rezzolla 2016)

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

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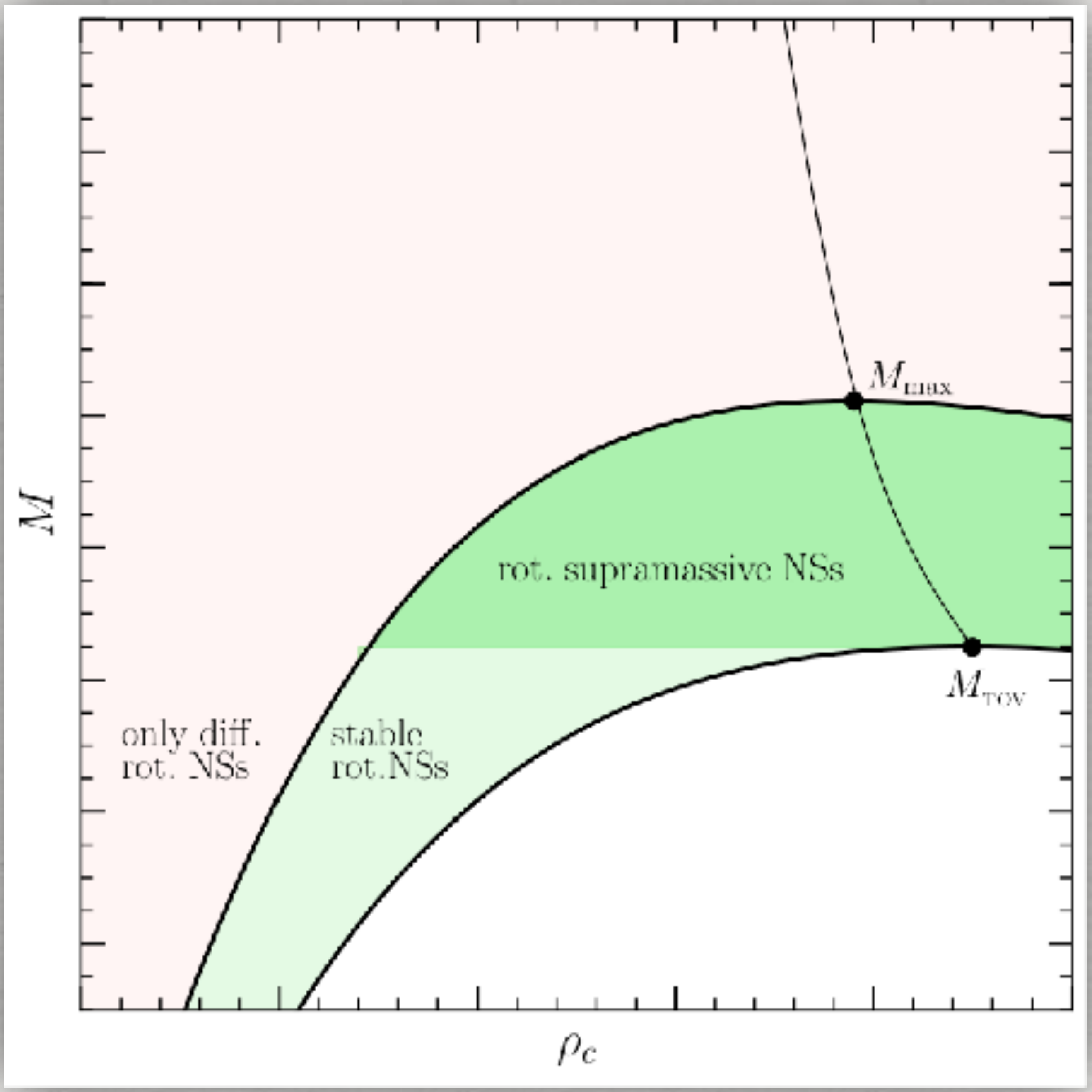

- Green region is for **uniformly** rotating equilibrium models.
- Salmon region is for **differentially** rotating equilibrium models.

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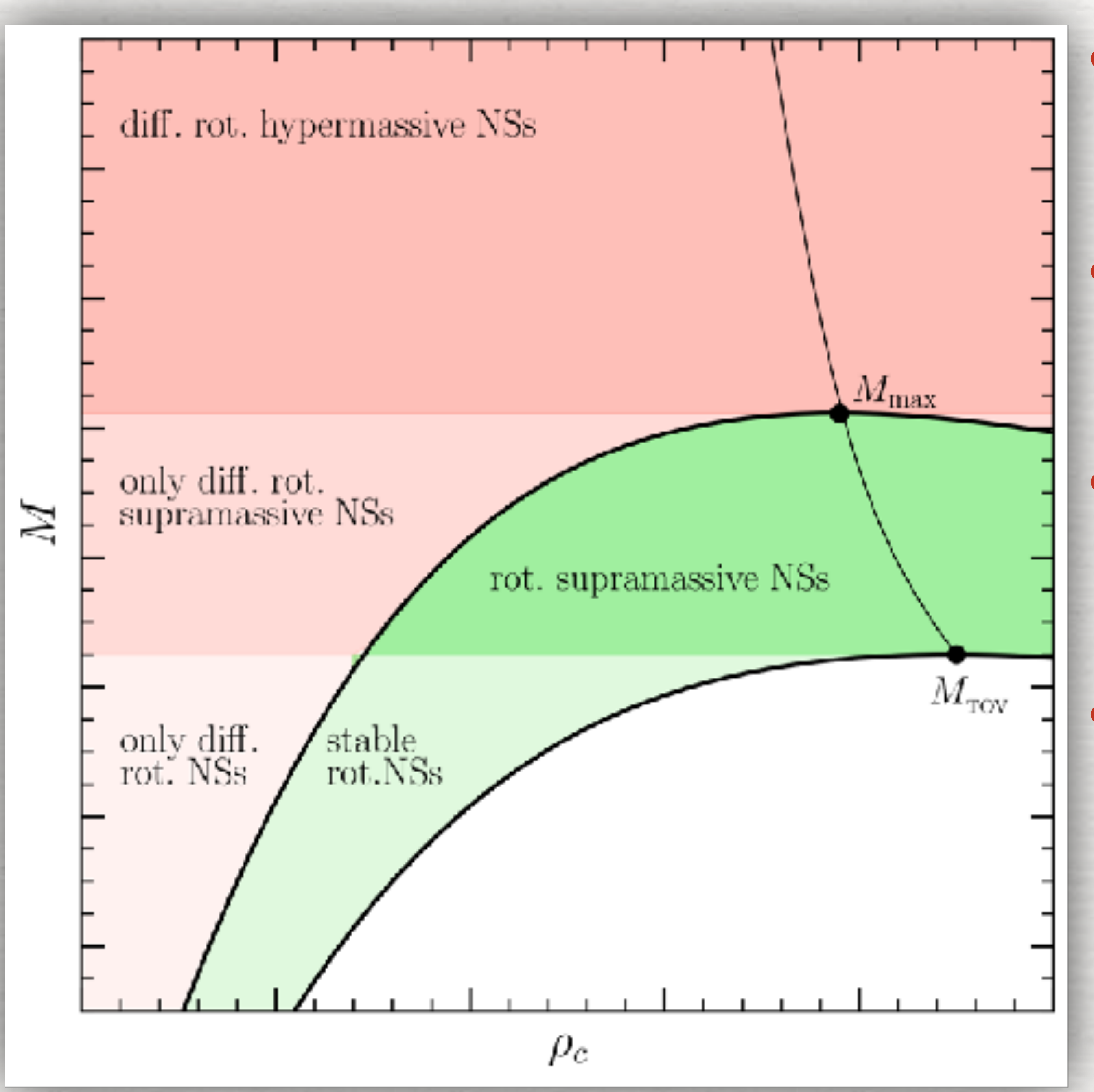


- Green region is for **uniformly** rotating equilibrium models.
- Salmon region is for **differentially** rotating equilibrium models.
- **Supramassive** stars have

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

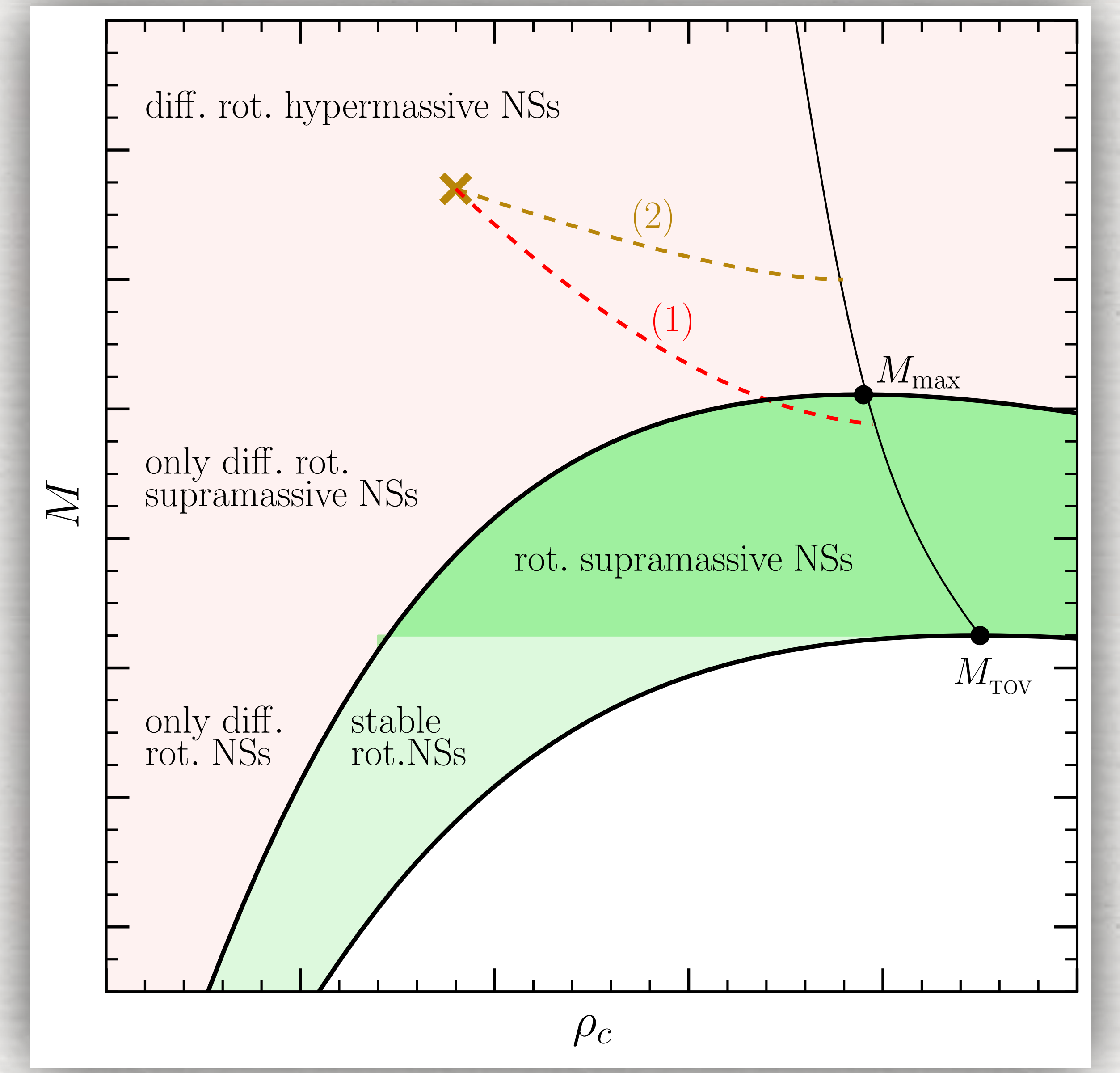
- **Hypermassive** stars have

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

The outcome of GW170817

- Merger product in GW170817 could have followed two possible tracks in diagram: **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 more likely because of large ejected mass (long lived).
- Final mass is near $M_{\max}$ and we know this is universal!



Maximum mass constraint

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

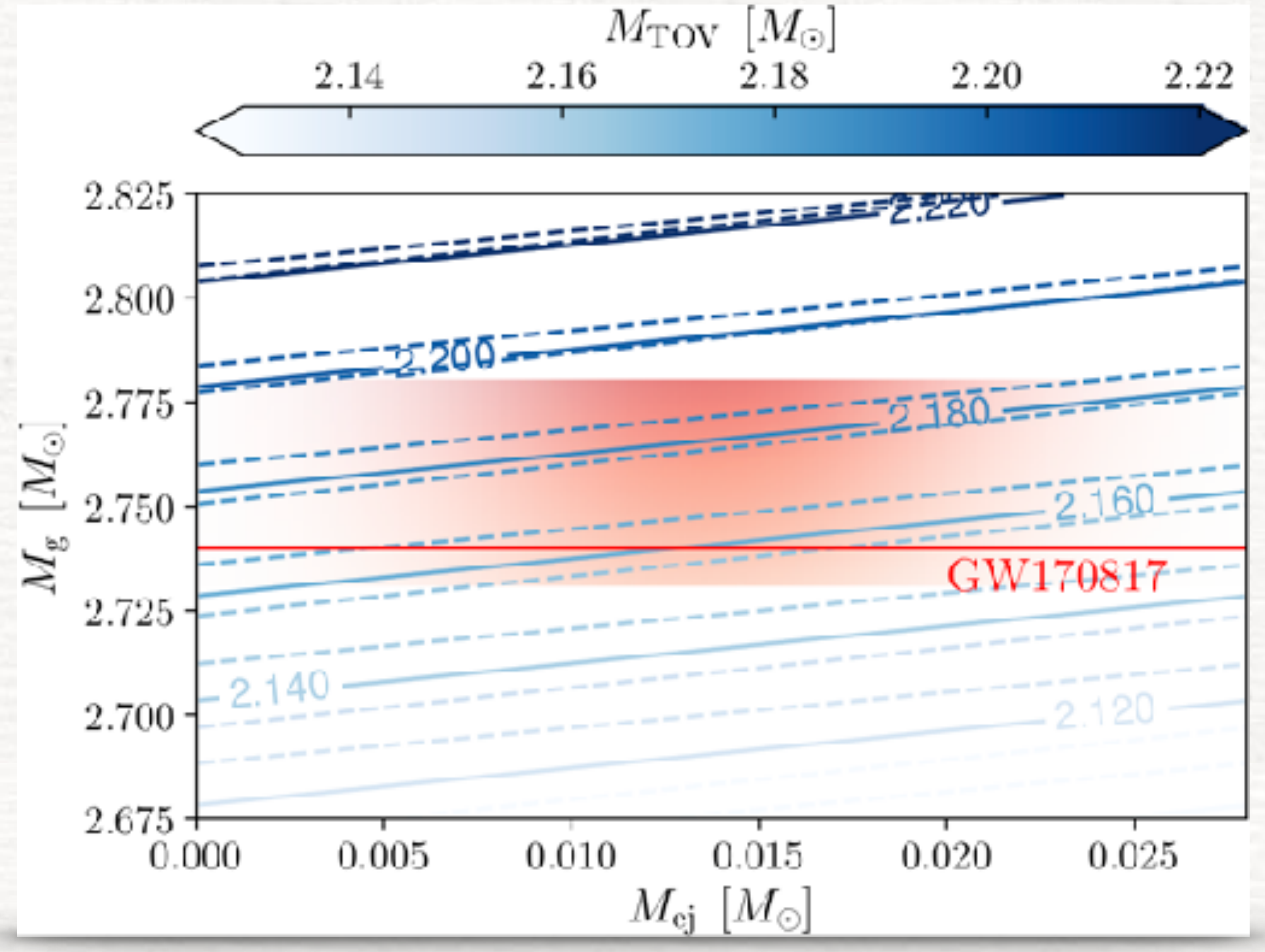
- HMNS core has about 95% **gravitational** mass of

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

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

$$M_{\rm ej}^{\rm blue} = 0.014^{+0.010}_{-0.010} M_\odot$$

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



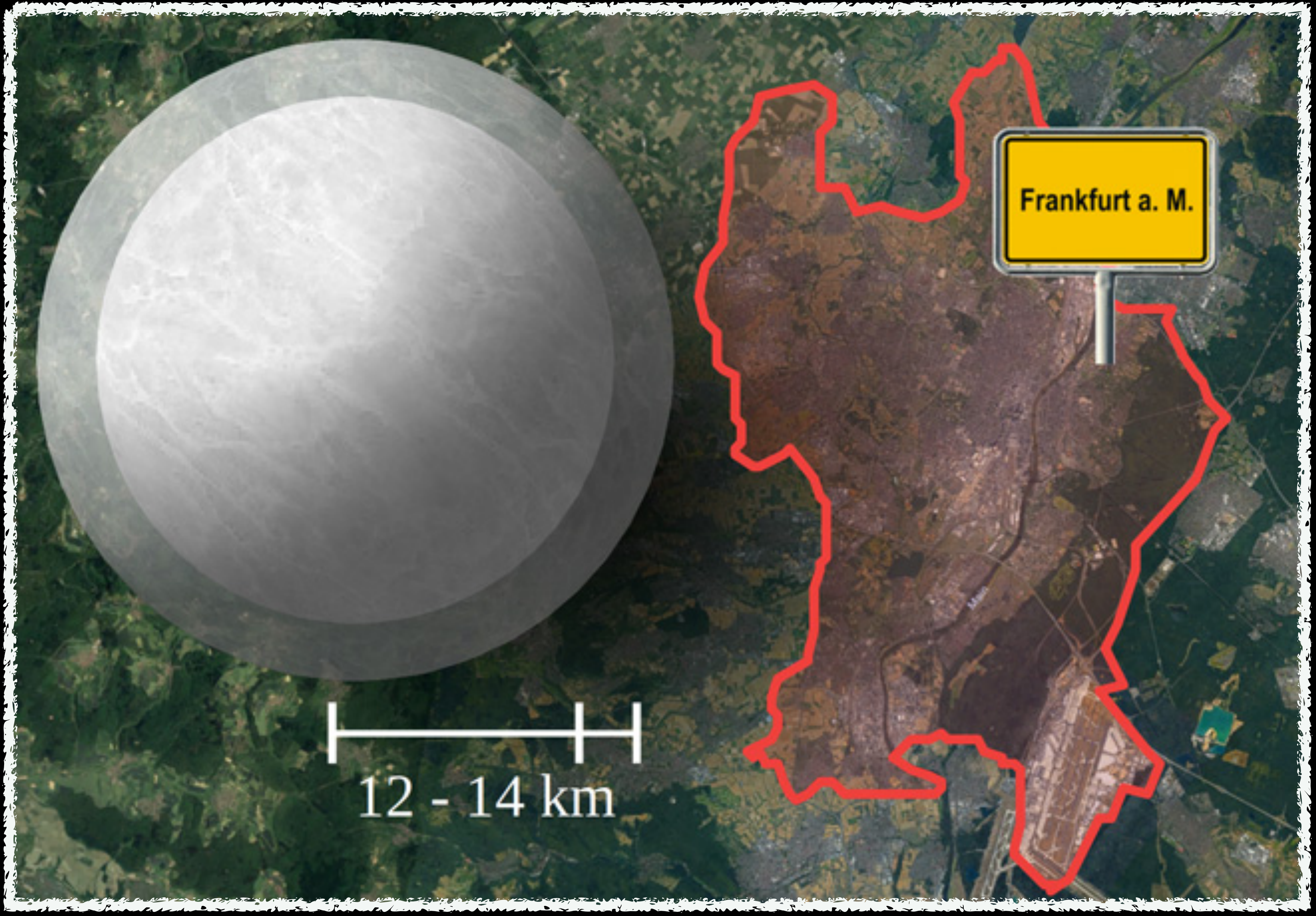
Rezzolla, ERM, Weih (ApJL 2018)

pulsar timing

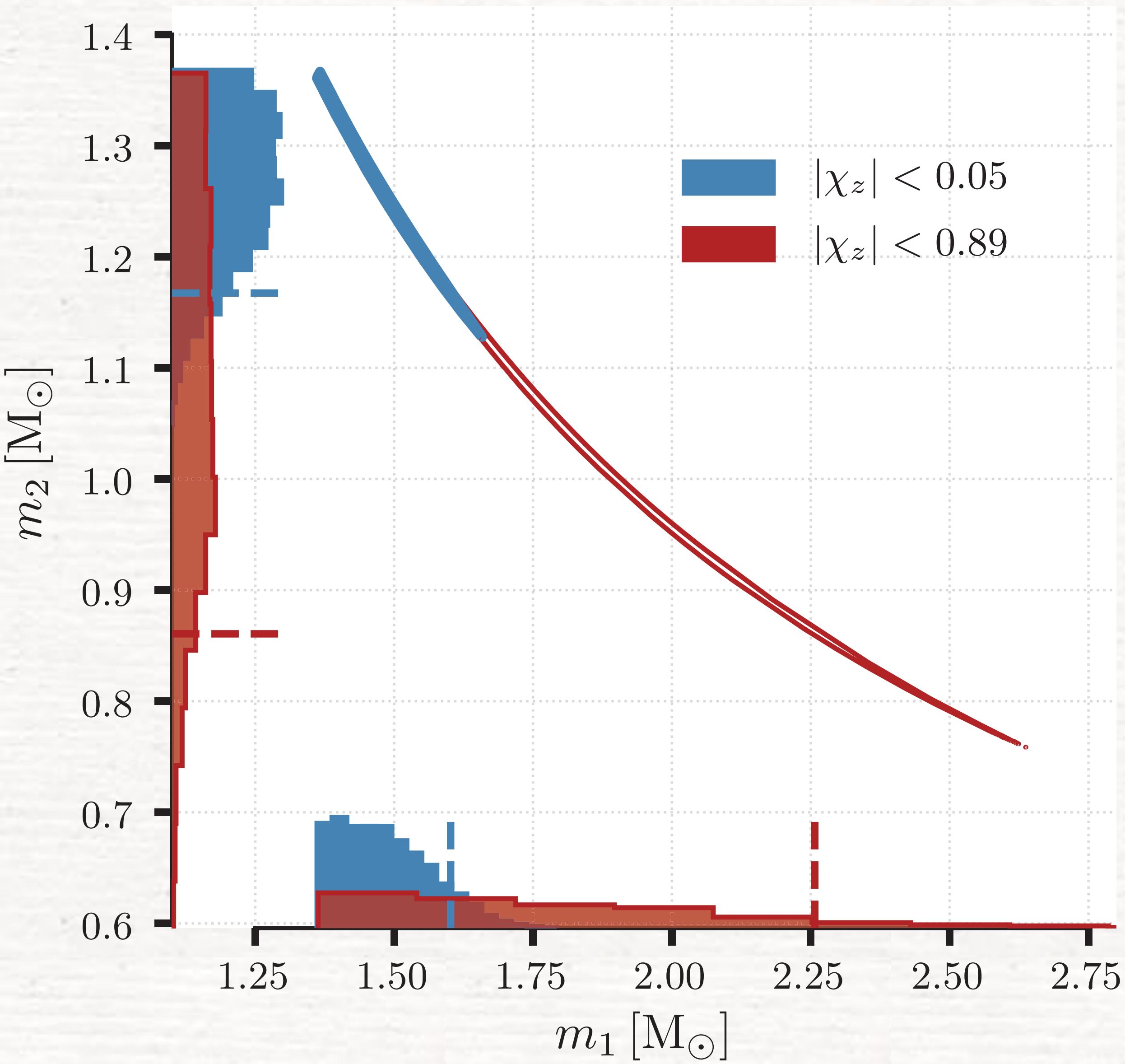
$$2.01^{+0.04}_{-0.04} \leq M_{\rm TOV}/M_\odot \lesssim 2.16^{+0.17}_{-0.15}$$

universal relations and GW170817; similar estimates by other groups

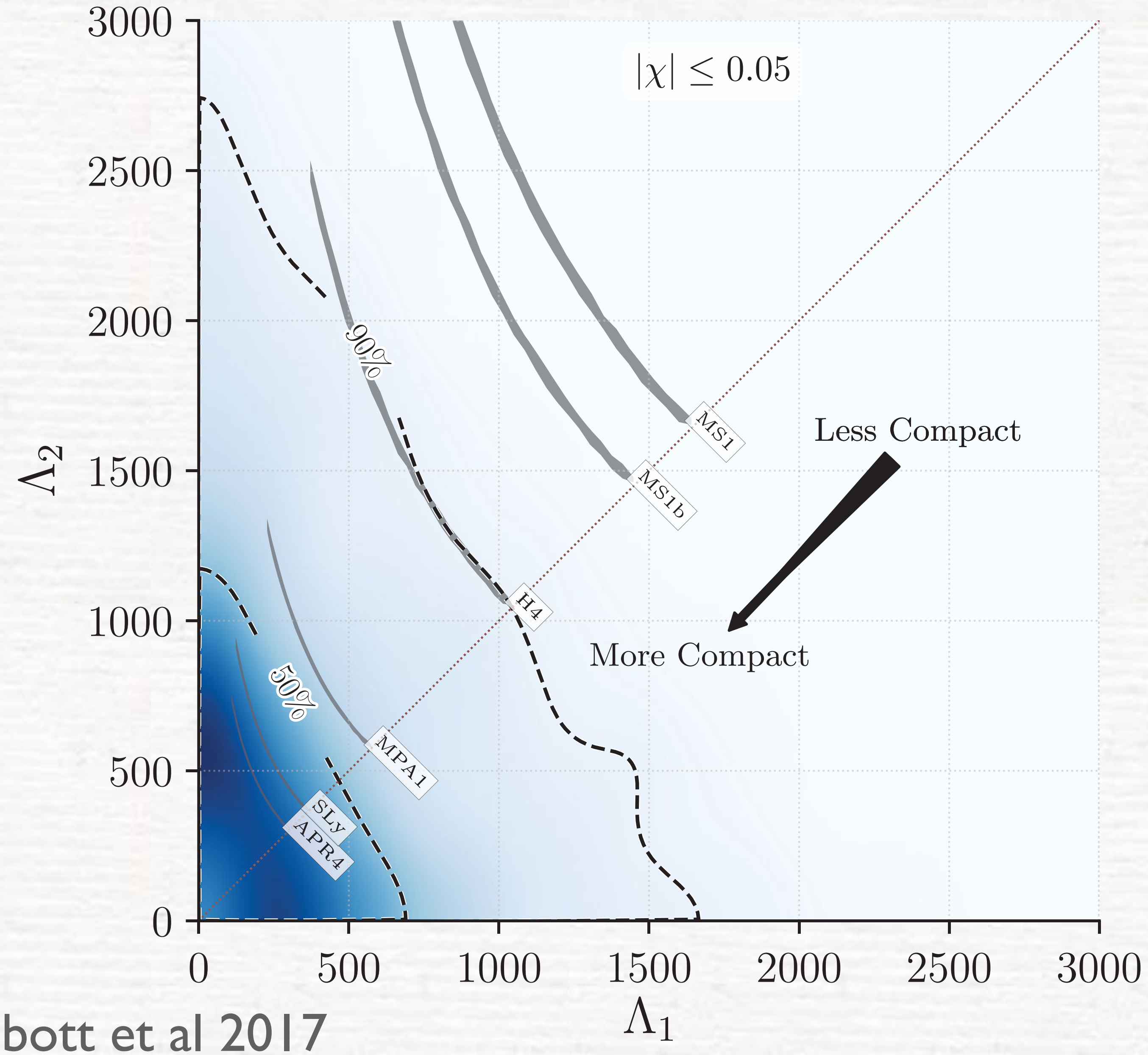
Radius constraints from GW170817:
A Frankfurt perspective



GW170817: What do we know?



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



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

$$M_1 = 1.36 - 1.60 M_\odot$$

$$M_2 = 1.17 - 1.36 M_\odot$$

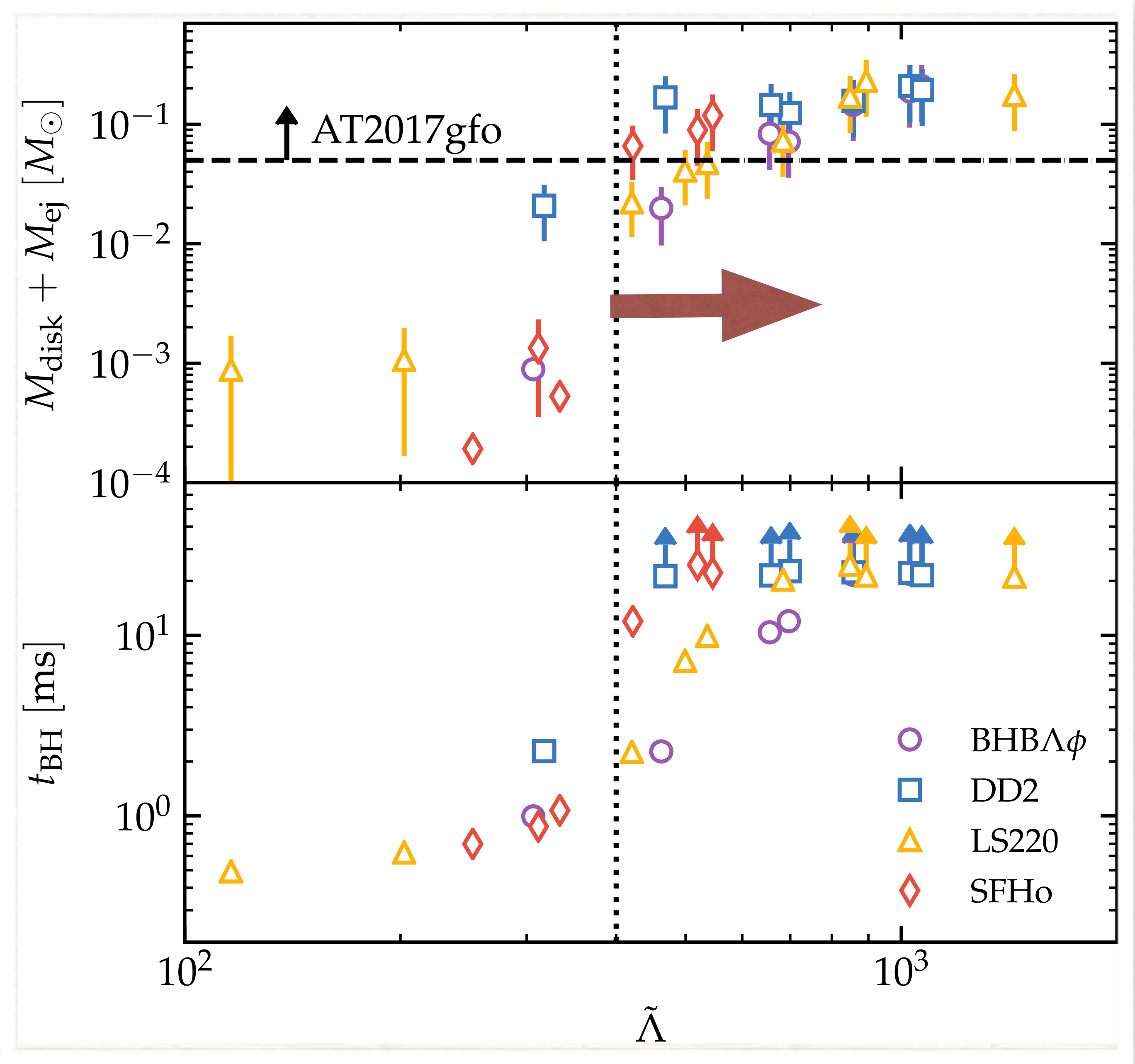
Abbott et al 2017

Kilonova constraints on the tidal deformability

- Consistency with kilonova modelling (mass ejection) requires lower limit on tidal deformability

$$\tilde{\Lambda} = \frac{16}{13}\left[\frac{(M_A + 12M_B)M_A^4\Lambda_2^{(A)}}{(M_A+M_B)^5} + (A \leftrightarrow B)\right],$$

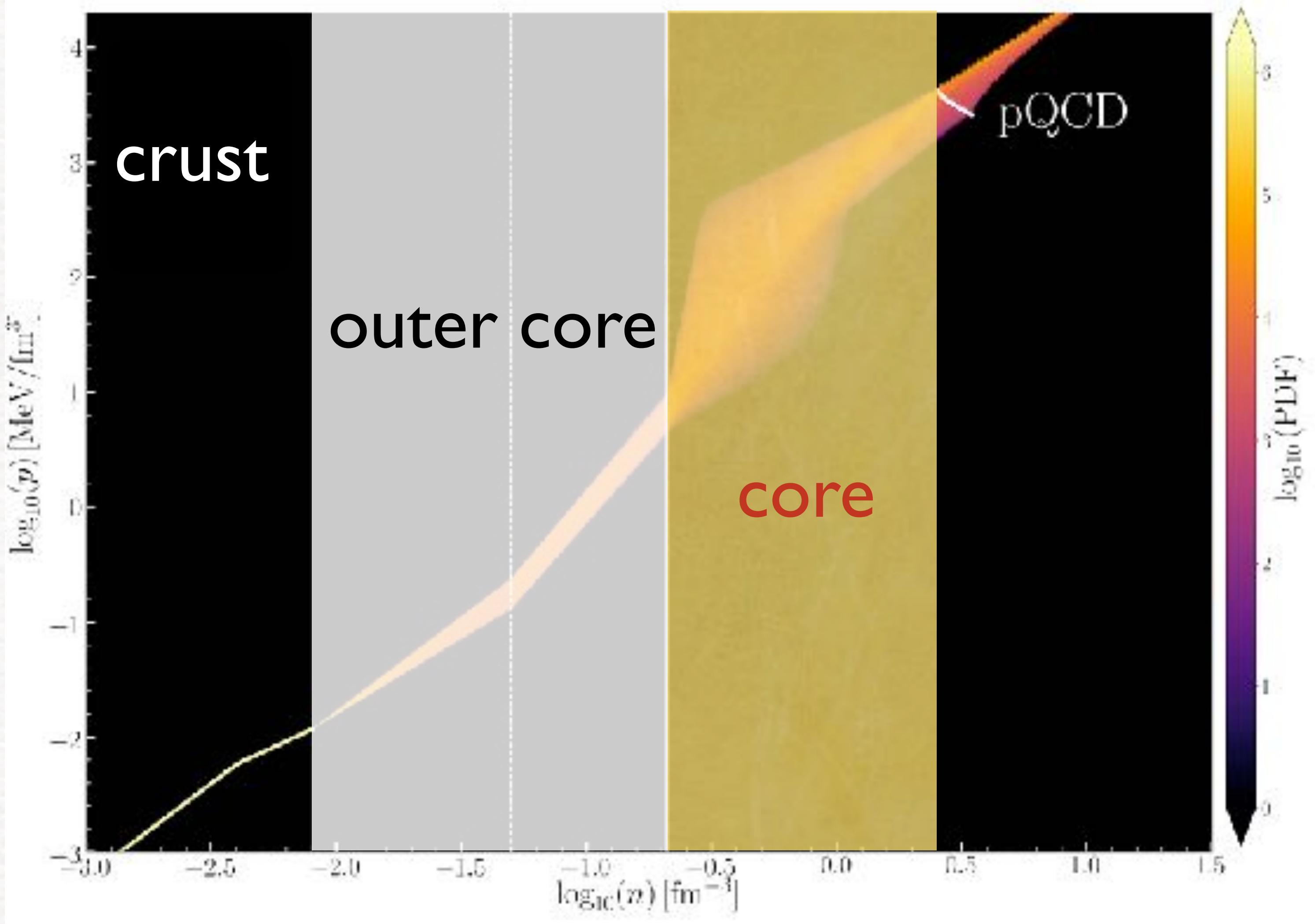
Errors unclear
Might be as low as ~200
(Coughlin+ 2018)



Radice et al 2018

Limits on radii and deformabilities

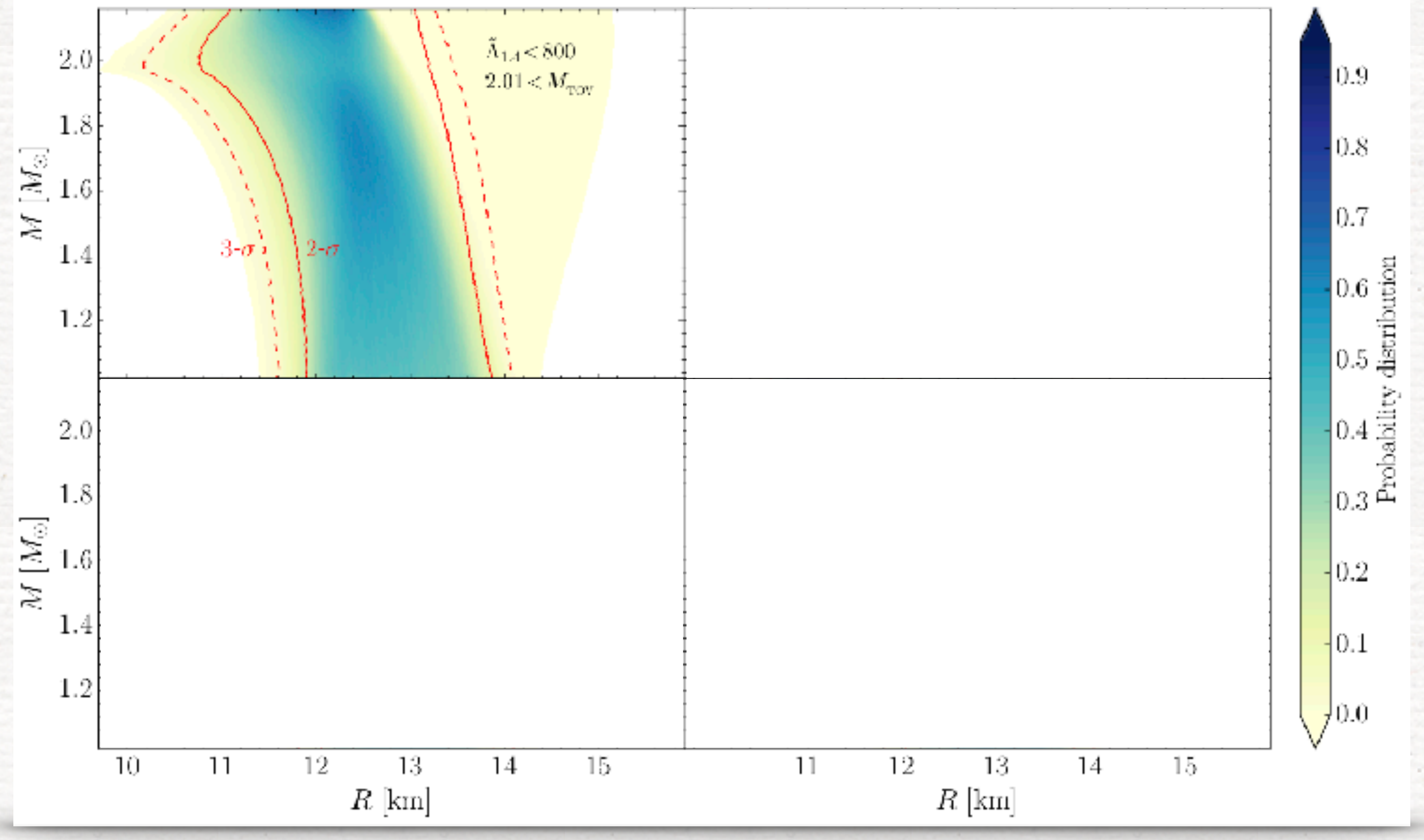
- Constraining NS radii of neutron stars is an effort with thousands of papers published over the last 40 years.
- Question is deeply related with EOS of nuclear matter.
- Can new constraints be set by GW170817?
- Ignorance can be parameterised and EOSs can be built arbitrarily as long as they satisfy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



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**



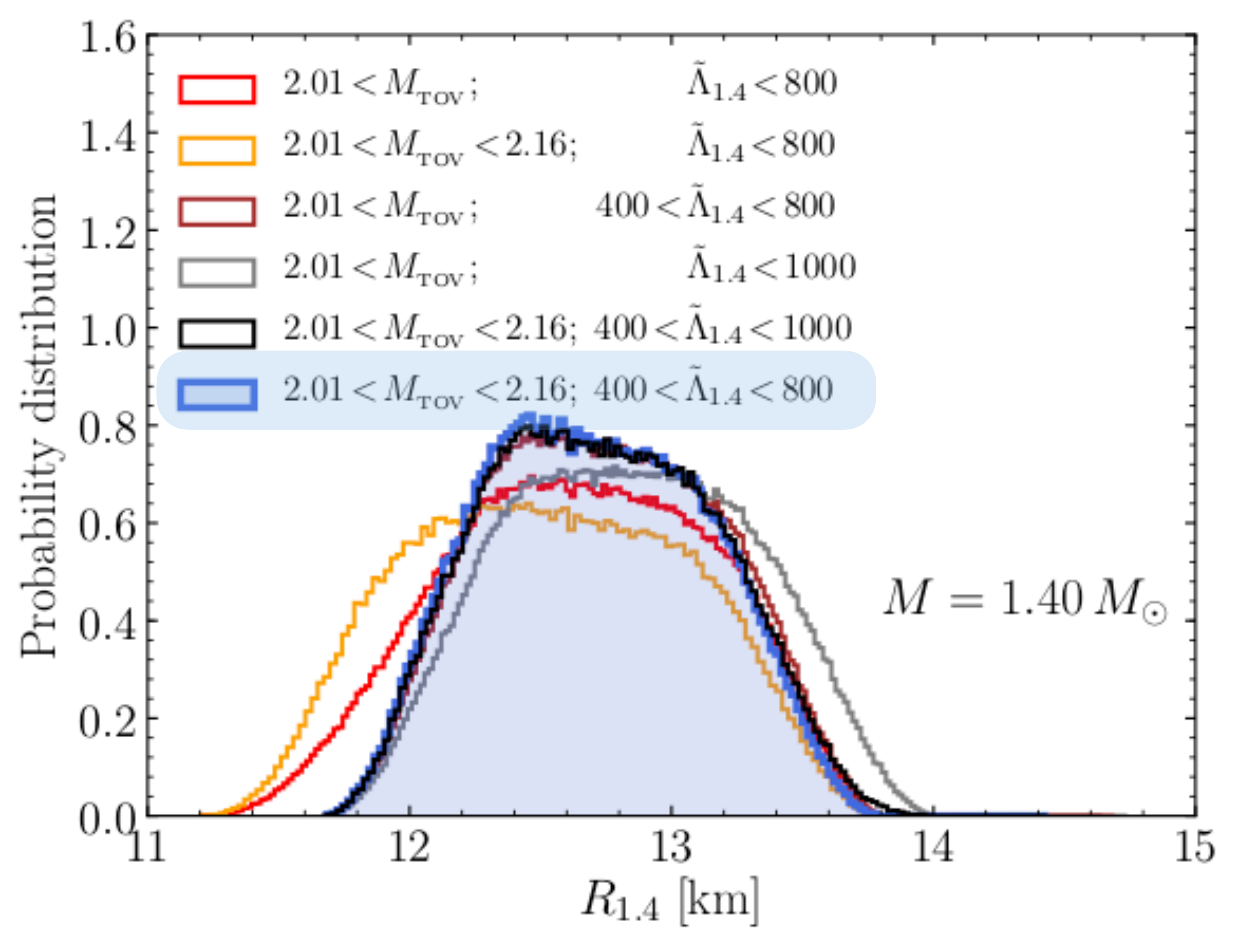
ERM+(PRL 2018)

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

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

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



ERM+(PRL 2018)

Constraining tidal deformability

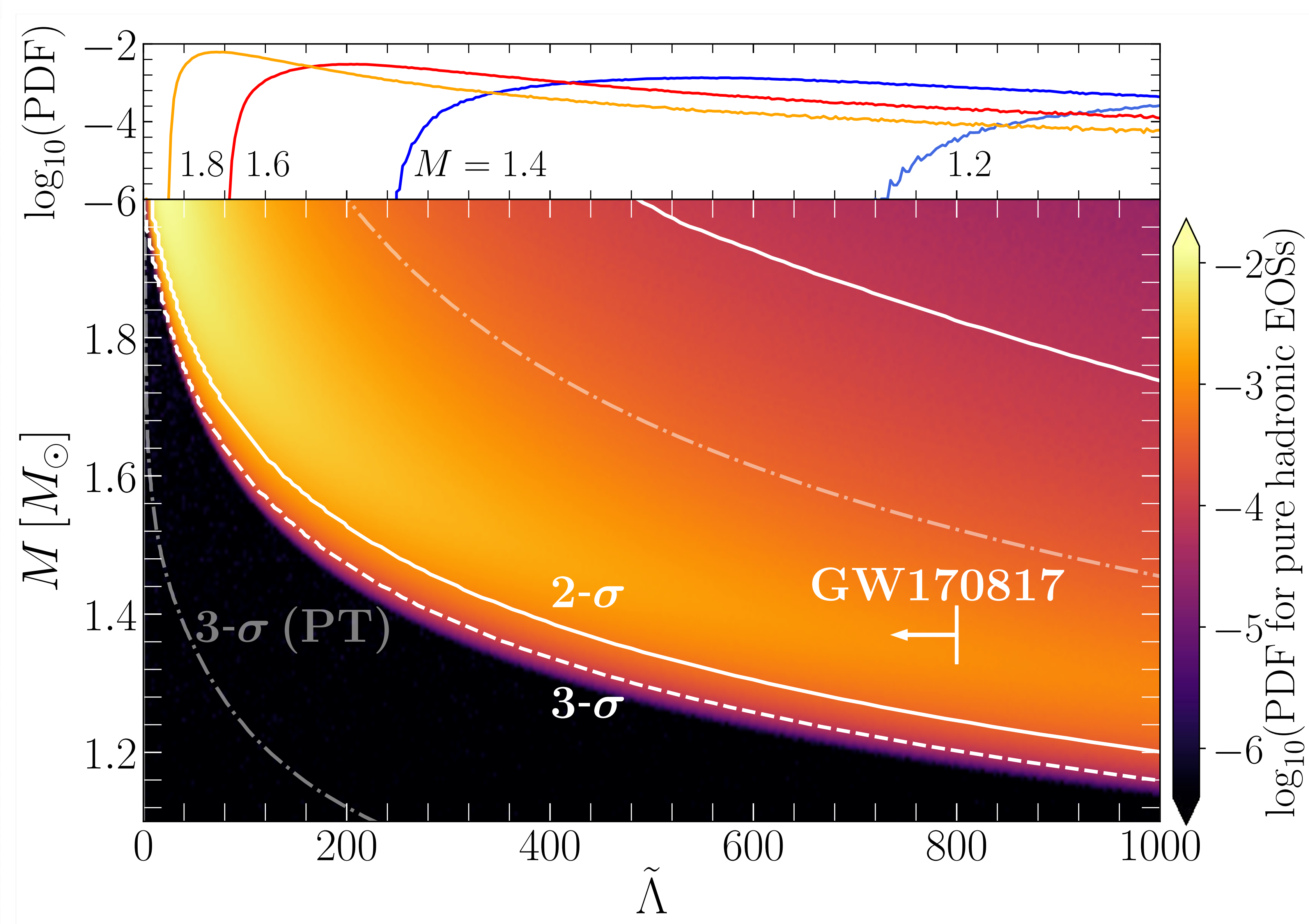
- Can explore statistics of all properties of our 10^9 models.
- In particular can study PDF of tidal deformability: $\tilde{\Lambda}$

- LIGO has already set upper limit:

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

- Our sample naturally sets a lower limit:

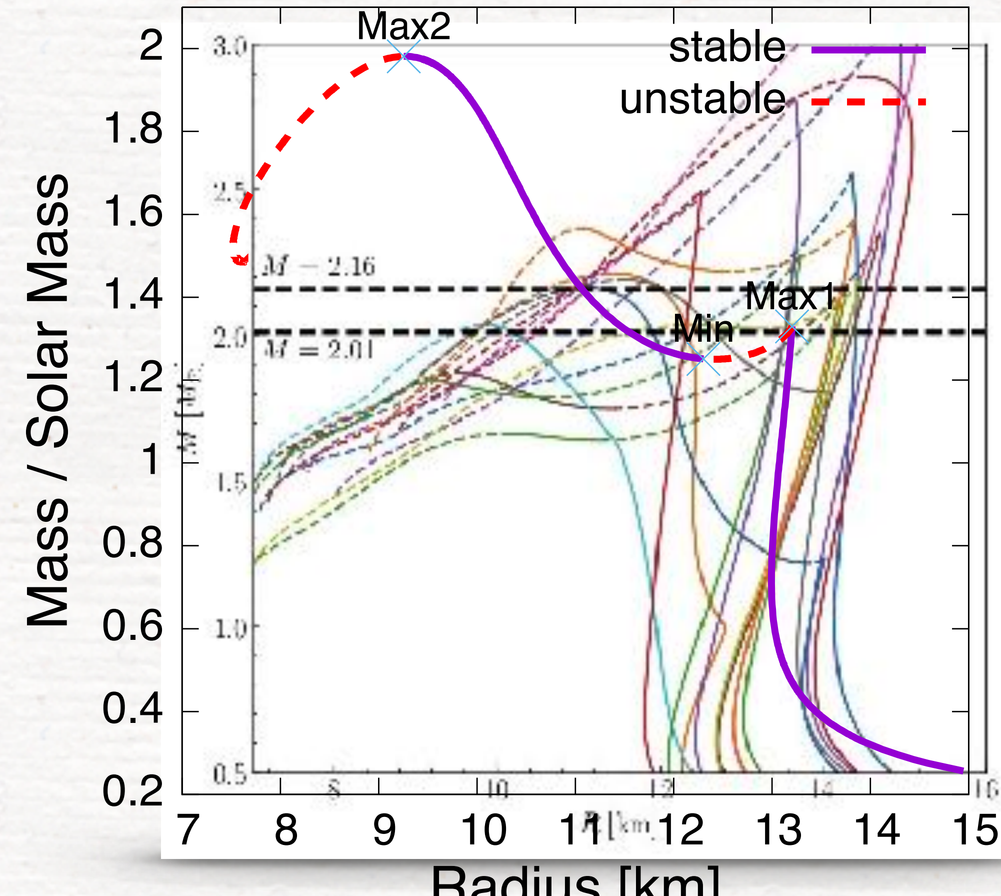
$$\tilde{\Lambda}_{1.4} > 375$$



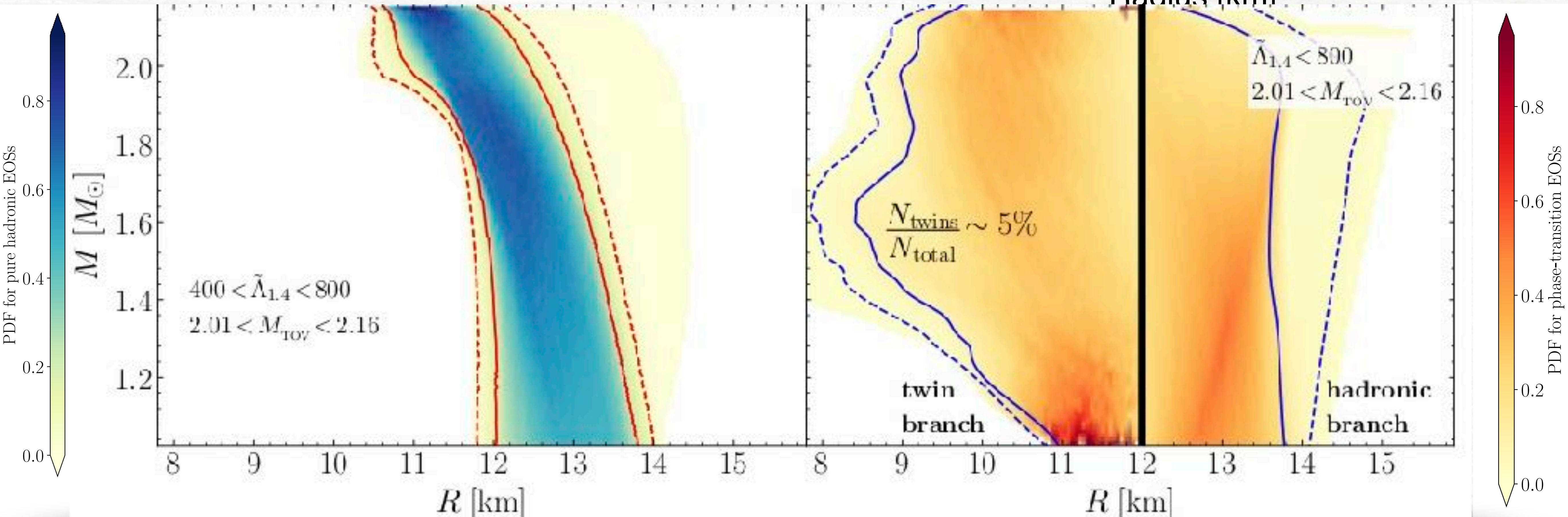
Mass-radius relations

Christian+ (2018)

- Presence of a phase transition leads to second stable branch and "**twin-star**" models.



ERM+(PRL 2018)

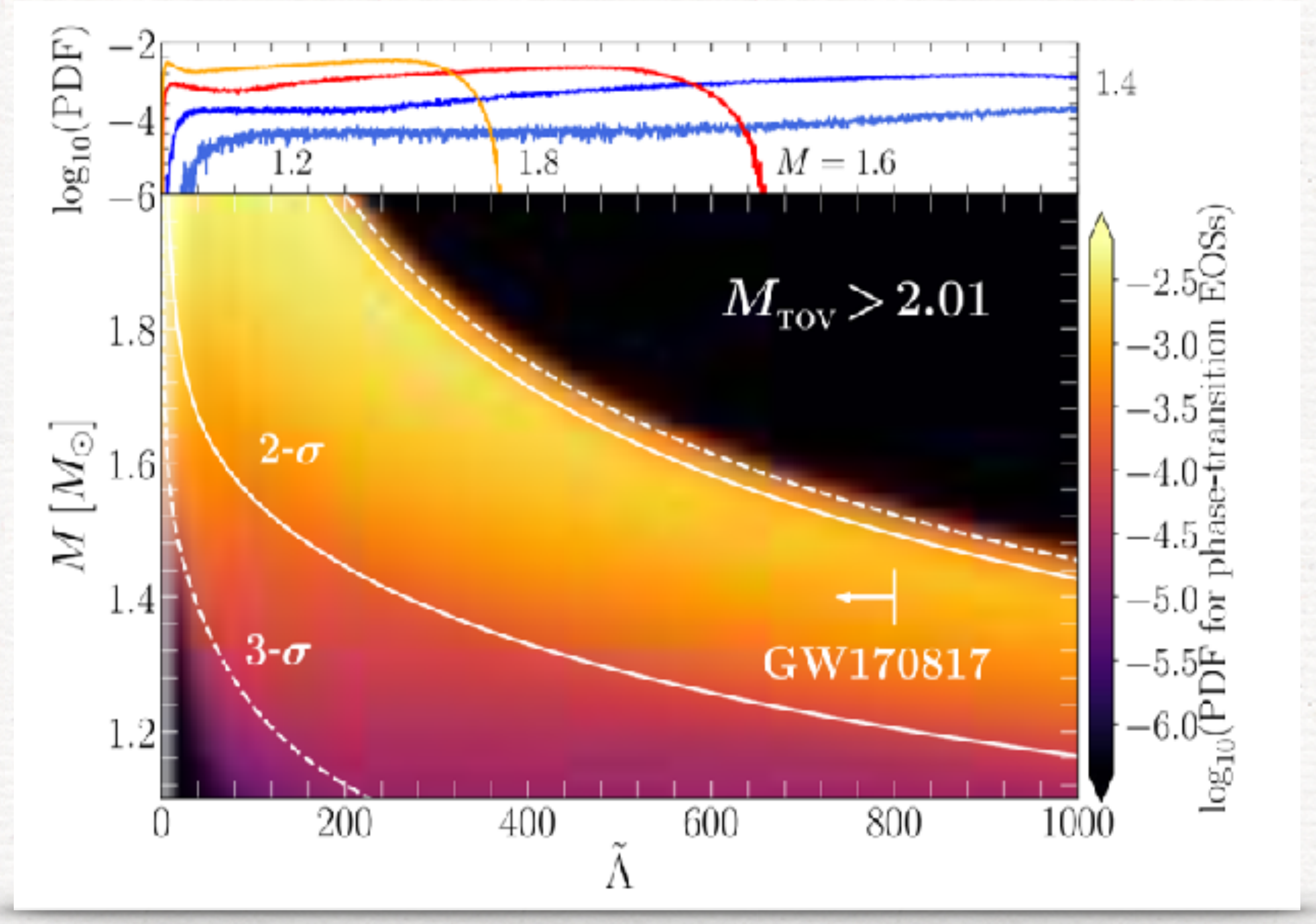


Constraining tidal deformability: **PT**s

- Can repeat considerations with EOSs having PTs
- Lower limit much weaker: $\tilde{\Lambda}_{1.4} \gtrsim 35$
- Large masses have sharp cut-off on upper limit:

$$\tilde{\Lambda}_{1.7} \lesssim 460$$

GW detection with $\tilde{\Lambda}_{1.7} \sim 700$ would rule out twin stars!



Conclusions

✴**GW170817** provides new limits on **maximum mass** and **radii:**

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

$$12.00 < R_{1.4}/{\rm km} < 13.45 \qquad \bar{R}_{1.4} = 12.45\,{\rm km}$$

hadronic EOS

$$8.53 < R_{1.4}/{\rm km} < 13.74 \qquad \bar{R}_{1.4} = 13.06\,{\rm km}$$

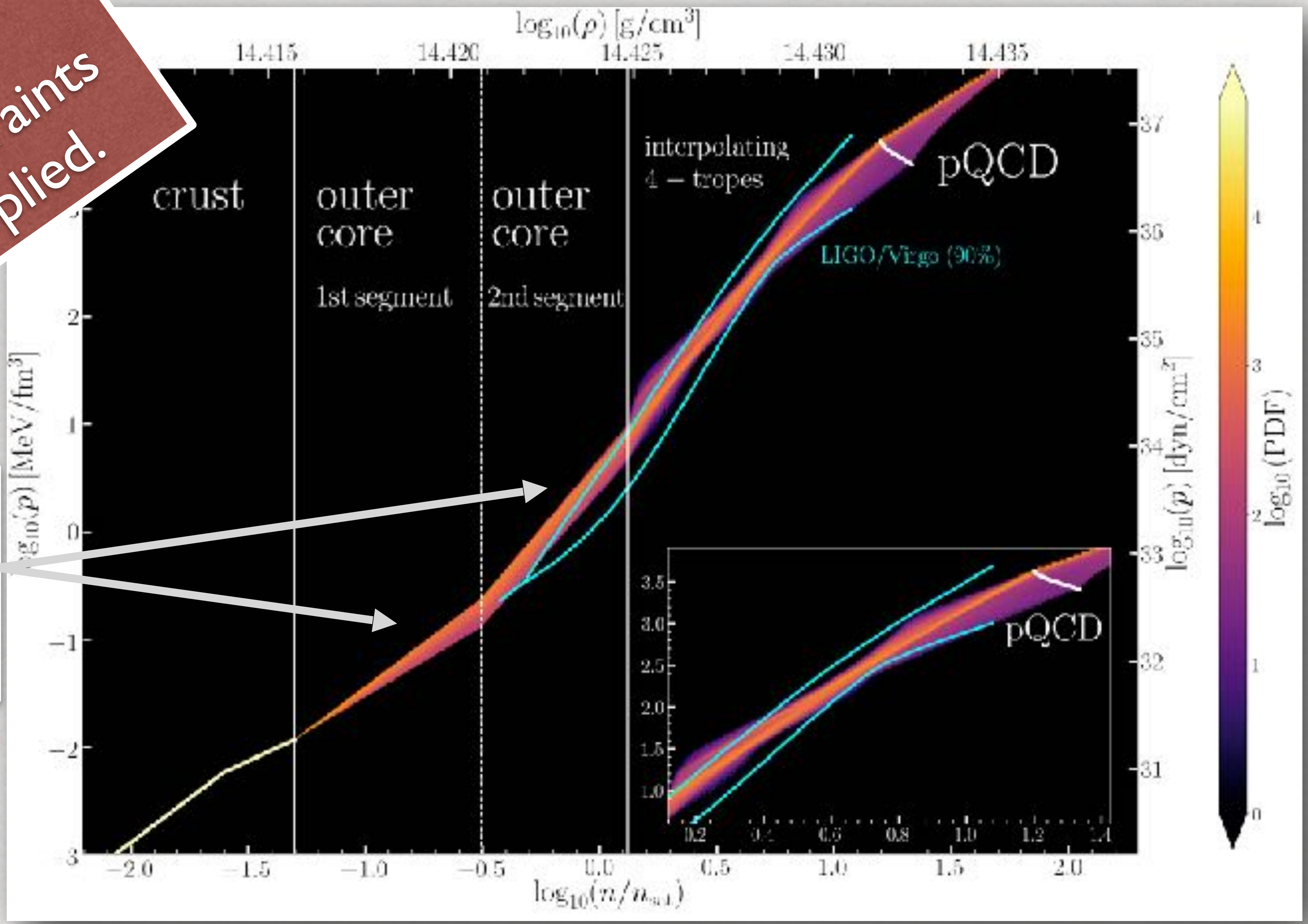
phase transitions

$$\tilde{\Lambda}_{1.7} \lesssim 460$$

Upper limit on deformability can rule out twin stars

What do we now know about the EOS?

All constraints applied.



Outer core determines radius