What can we learn from prompt collapse events in binary neutron star mergers? A numerical study

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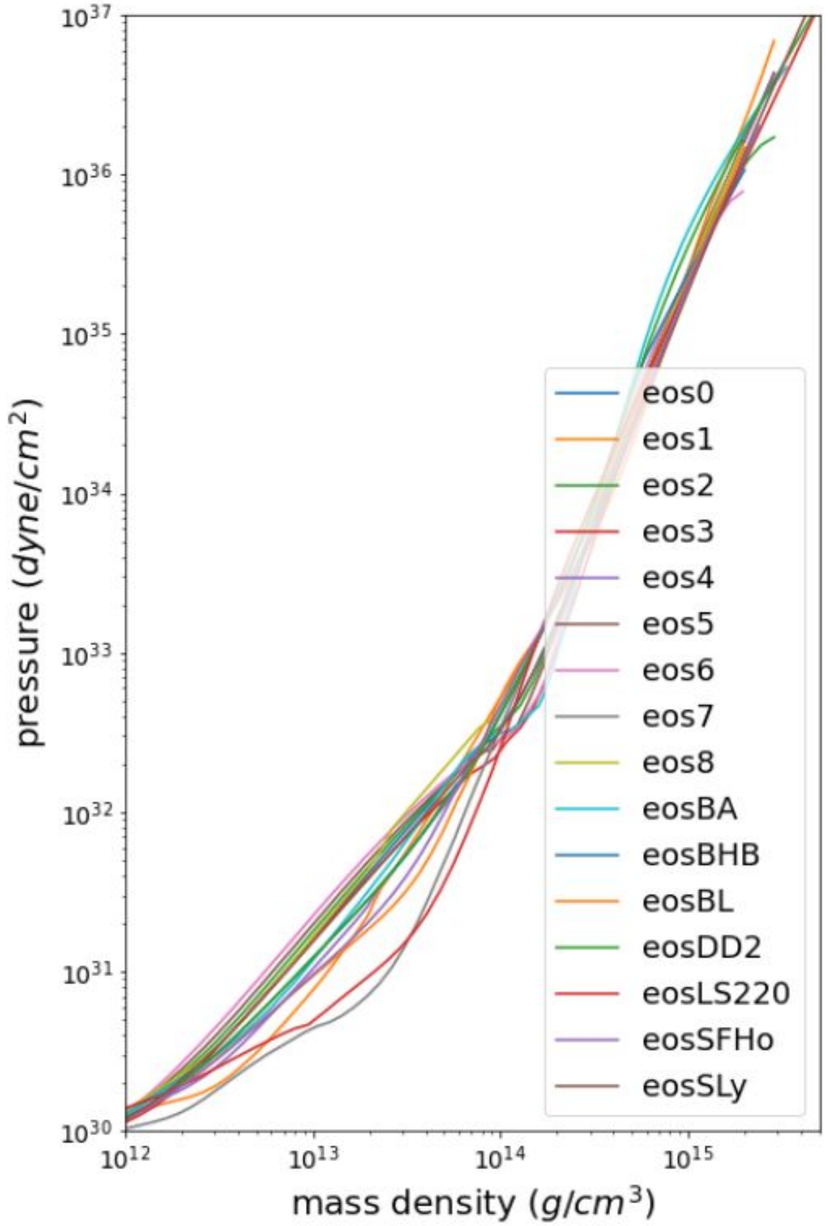
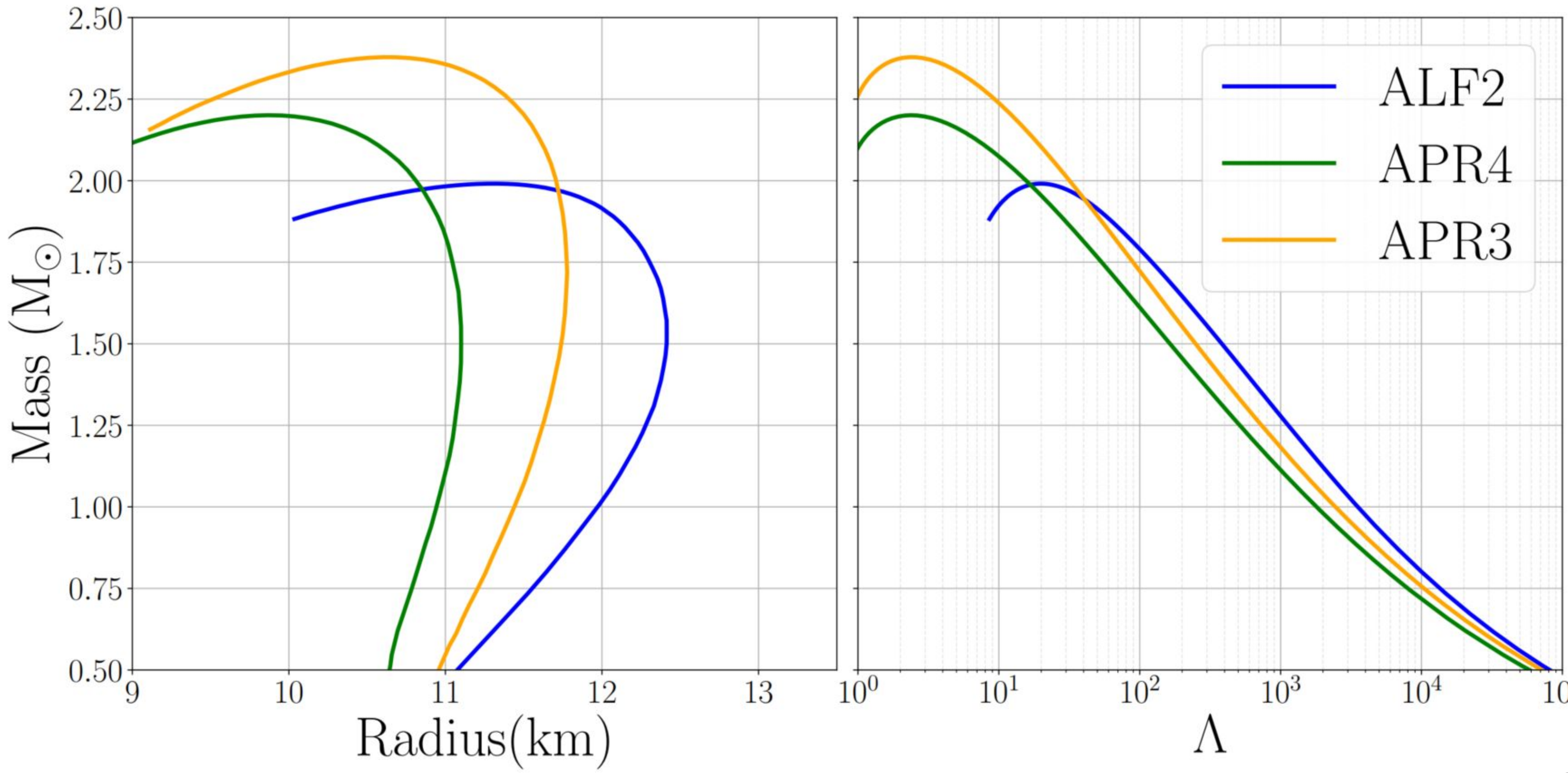
Tolman-Oppenheimer-Volkoff (TOV) description of spherically symmetric static Neutron Star

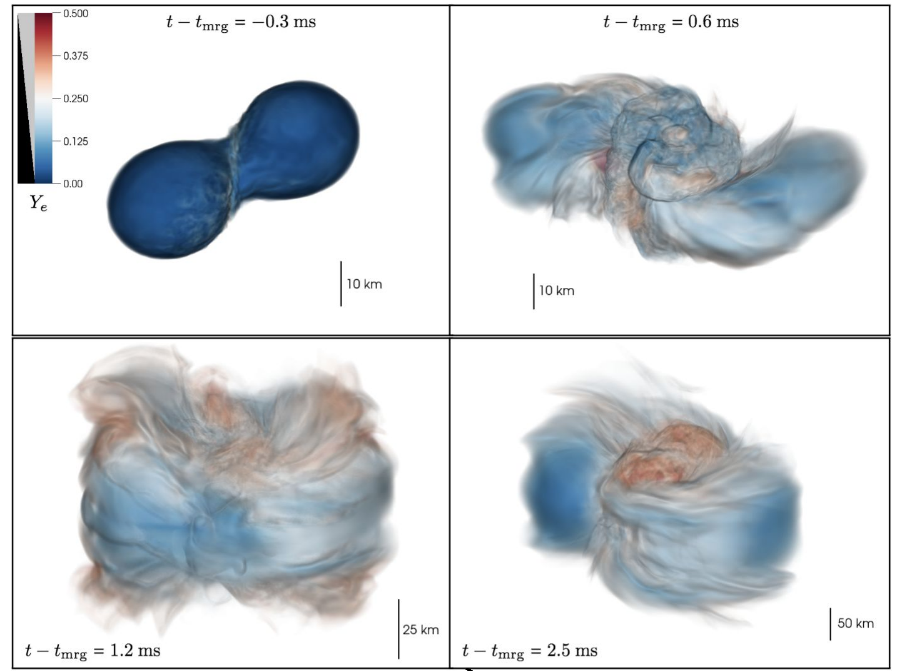




CAVEAT: No Rotation

- EOS is the description of matter w.r.t. density and temperature sometime loosely taken to be as just pressure-density curve at zero temperature

Numerical and observational studies of Binary Neutron Star Mergers

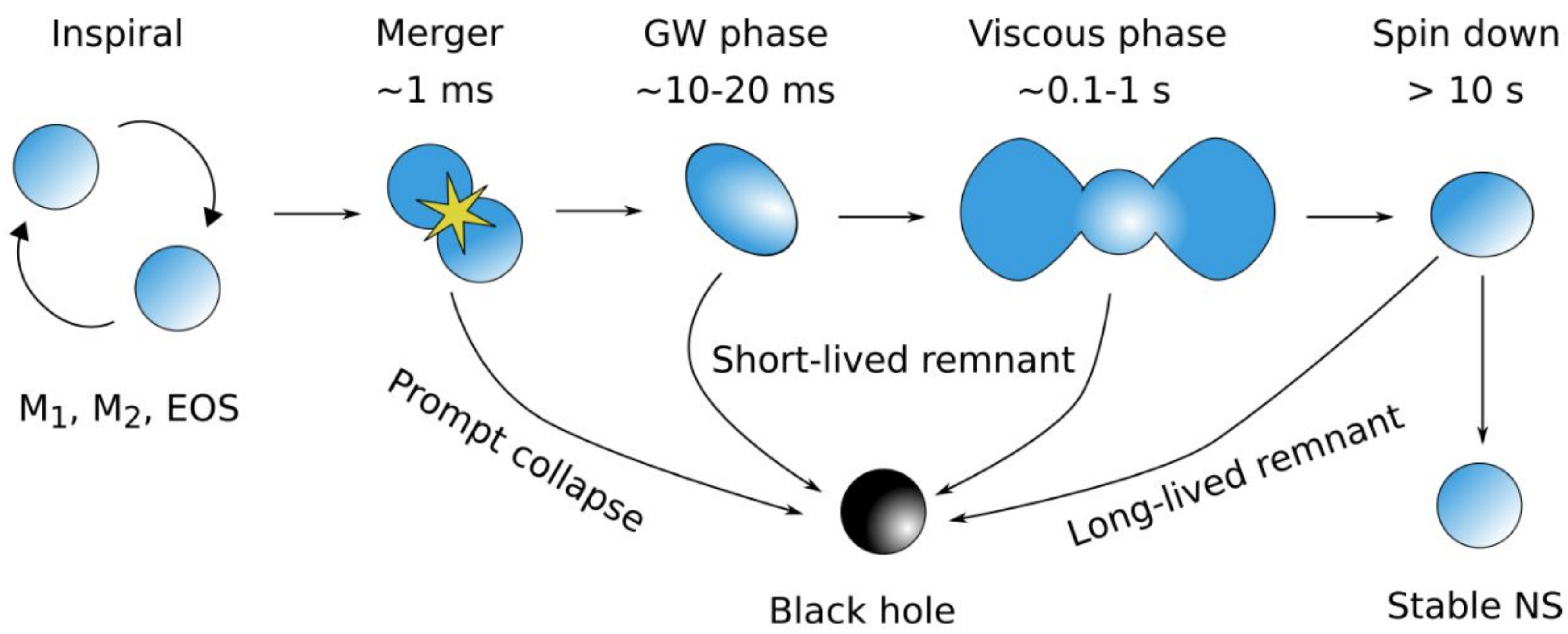


Radice et al 2018

- It enters LIGO bang few minutes before merger.
- Within 3-4 seconds these processes occur:
  - Plunge (either prompt collapse or, collapse after single/multiple bounce) ~ ms
    - dynamical ejection of tidal tail
    - Large amount of initial release of energy due to shock created by the bounce: GRB, jet
  - Shock induced ejection (jet, wind ejecta): ~ 100 ms
  - Disk evaporation within ~1 s or longer (NR simulation results on viscous ejecta)
- r-process heating will be available on days to weeks timescale powering the light curve (Arnett 1982, Chatzopoulos 2012)
- Ejecta interacting with interstellar medium (~months): X-ray, Radio
- Amazing success of this picture by GW-EM observations of GW170817 (LVC and others 2017)

Classification of outcomes

Various outcomes are possible for the merger products (Hotokezaka+2011, Radice+2020)

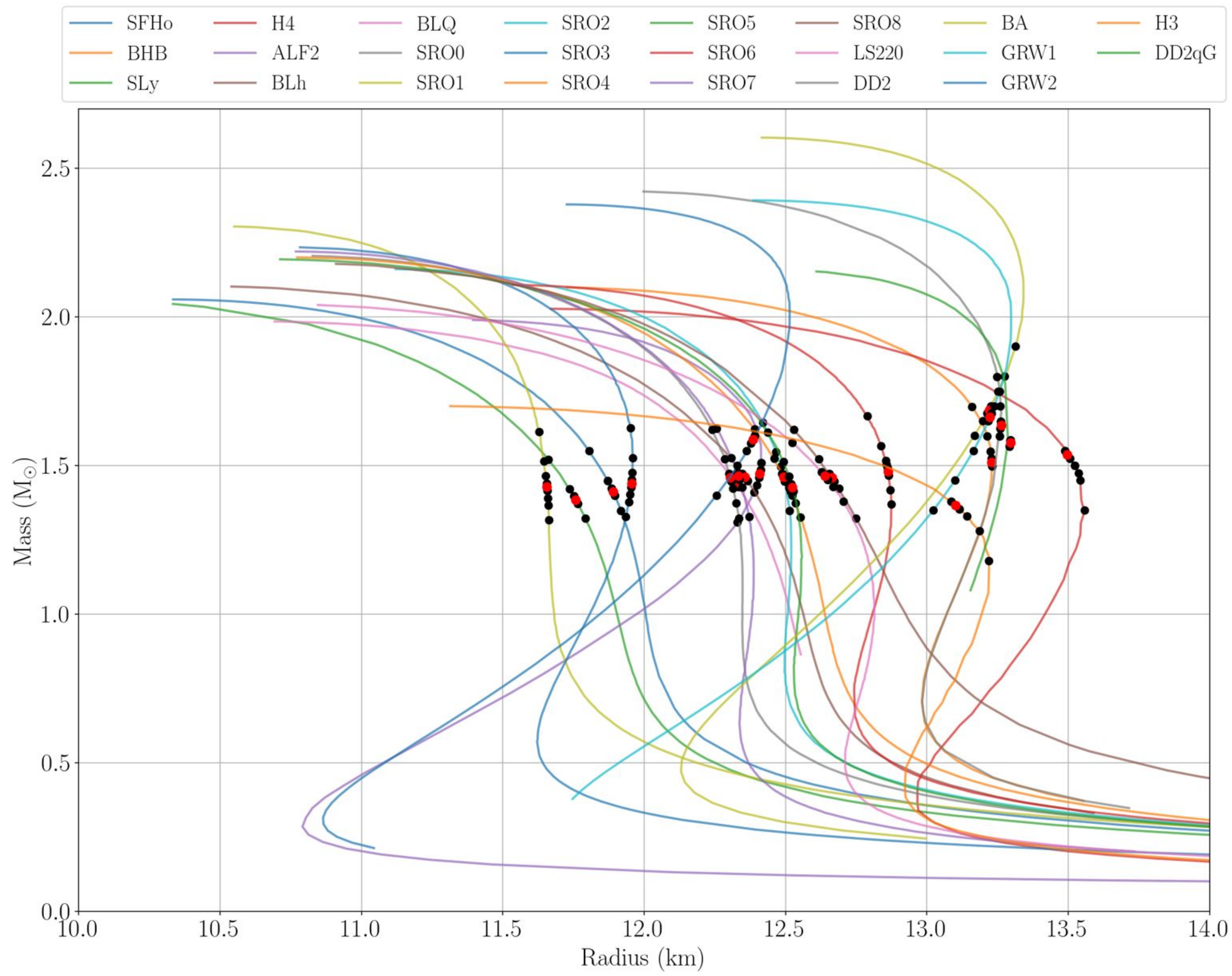


Radice et. al. 2020

Q: What are the conditions on EOS for prompt collapse?
Q: Can we infer the properties of EOS and component NSs by observation of prompt collapse by various classes of observations (GW,EM)?

Simulation details

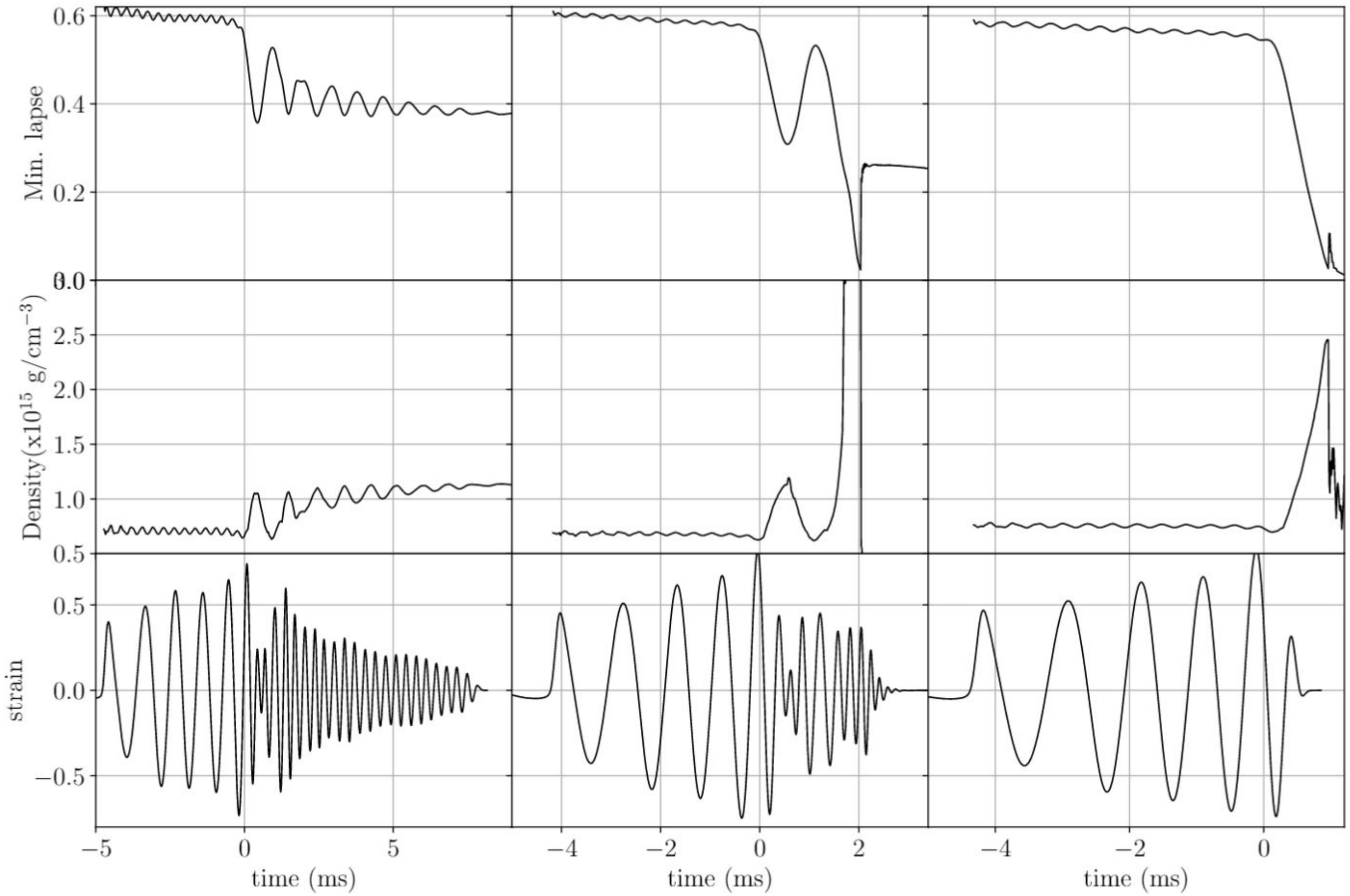
- Whisky-THC: Full GR code in 3+1, Z4C formalism with neutrino leakage (2nd order convergence used here) (Radice+2012,2014,2015,2018)
- A collection of EoS with varying properties including phase transition has been used.
- We use bisection method to reach to a desired accuracy of 0.05 $M_\odot$ for total baryonic masses of the system.



Kashyap, Das et. al. 2021

Classification of outcomes

1. **Direct Collapse** (Our focus here)
2. Collapse after single bounce
3. A highly perturbed rotating neutron stars (*with(out) mass exceeding the maximum TOV mass supported by the EOS*)



CAVEAT: lapse below 0.2 correctly captures the results as verified by high resolution in time capture of apparent horizon (**Bernuzzi et. al.**)

Kashyap, Das et. al. 2021

Ejecta Mass: Prompt vs Non-prompt Collapse

- Variation of amount of ejecta points towards sensitivity on bounce (needs further studies).
- Dimmer EM counterpart for prompt collapse events with no bounce.

Correlations

- Details of collapse must depend on properties of matter and supranuclear densities i.e. parameters of QCD in construction of EOS.
- One can assume (Hotokezaka+2011,Bauswein et. al. 2013, 2020) **linear fit with respect to properties of TOV sequences as a proxy (more on correlations with nuclear parameters later) --**

$$\mathrm{M_{th}} = \mathrm{k_{th} M_{max}}$$

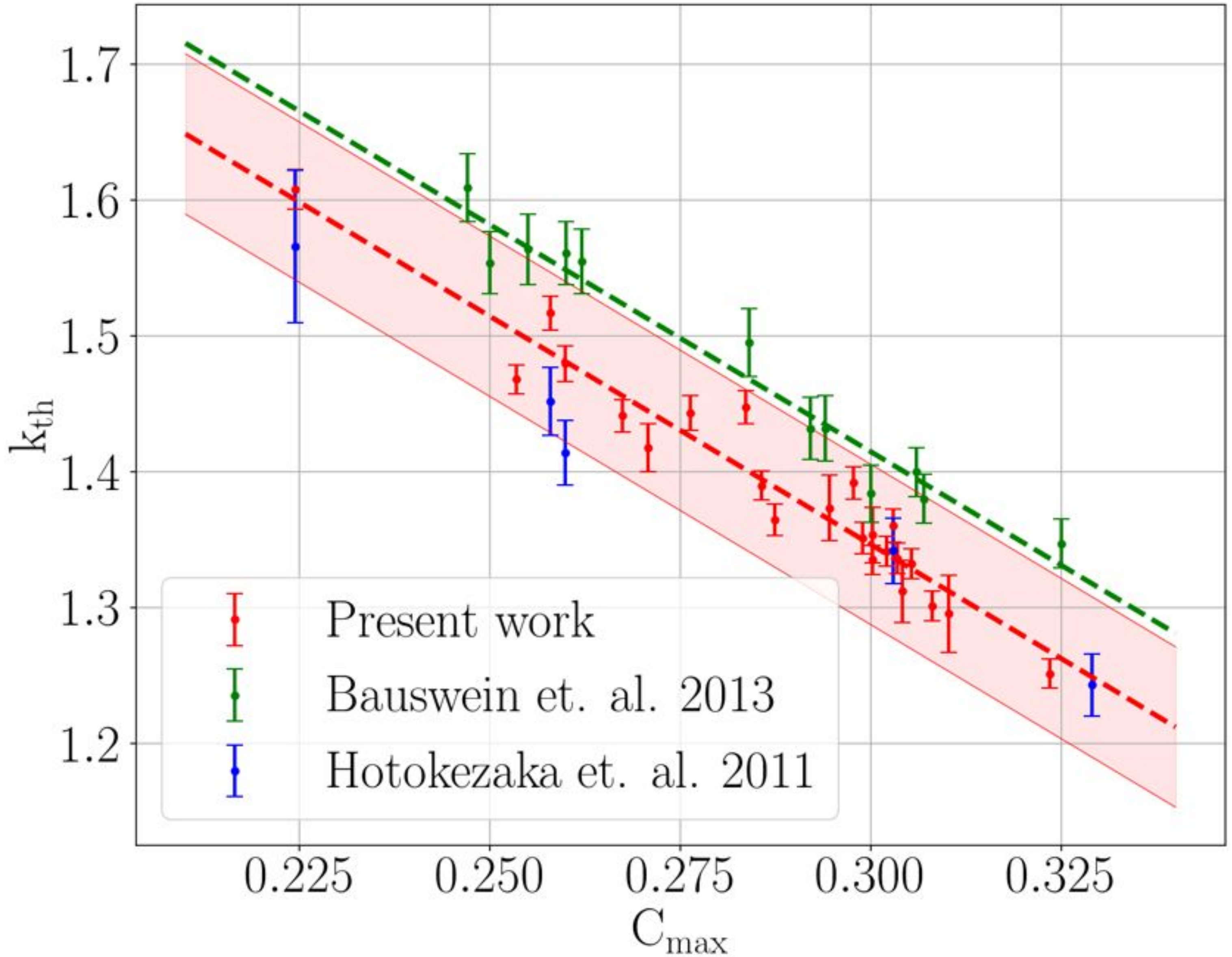
$$\mathrm{k_{th}} = \mathrm{aC_{max} + b}$$

$$\mathrm{M_{th}} = \mathrm{(aC_{max} + b) M_{max}}$$

Results on threshold mass

- We observe a discrepancy in comparison with literature.
- Bauswein et. al. 2013 results using relativistic SPH code in conformally flat spacetime with conservation equation up to 2PN order (Appx. - A, Oechslin et. al. 2001)
- Results differ from full GR in strong gravity (see Shibata+2004 for core-collapse results).

dataset	a	b
Bauswein *et al.* [17]	-3.342	2.42
Bauswein *et al.* [25]	-3.38	2.43
Current work	-3.36 ± 0.20	2.35 ± 0.06



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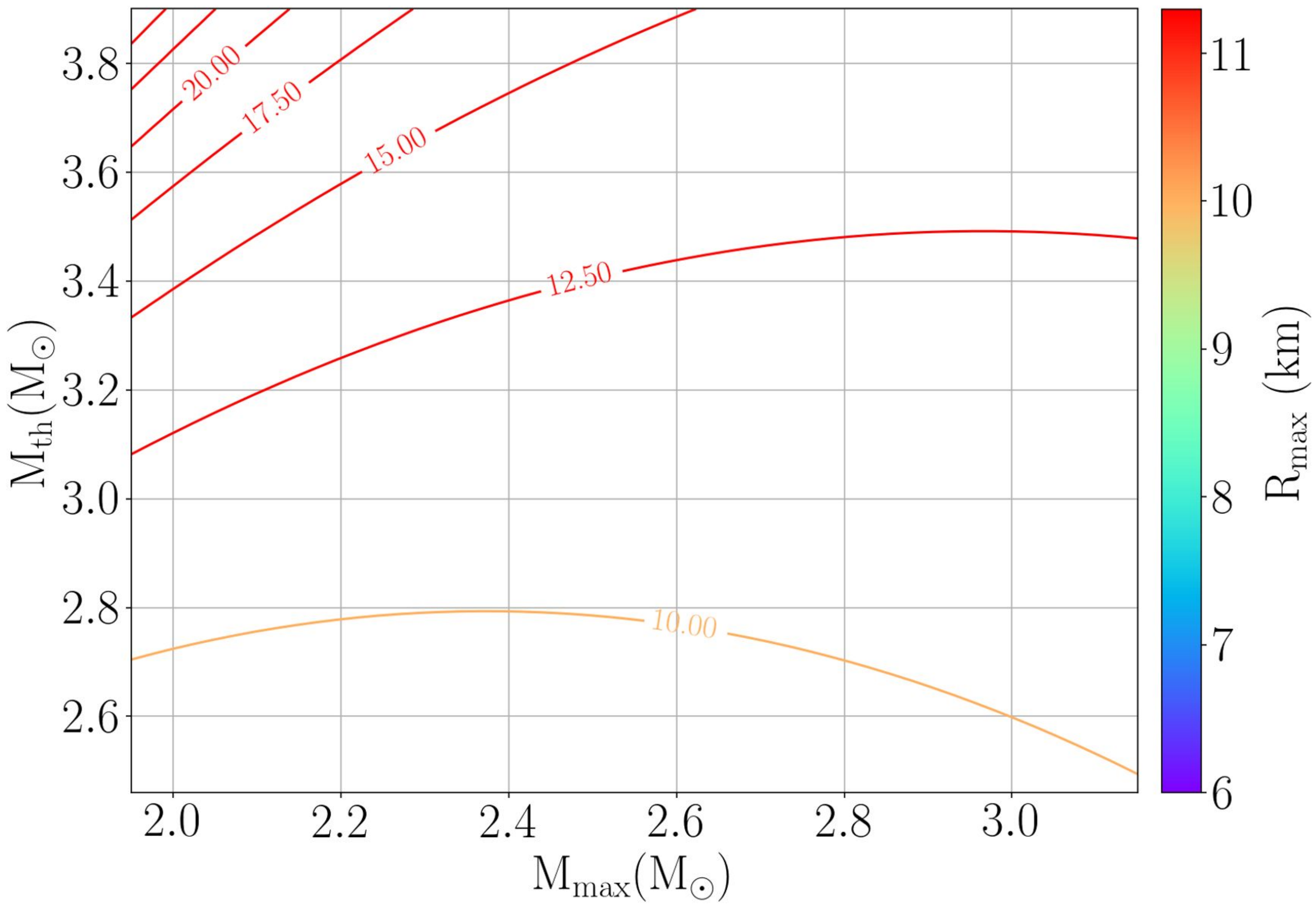
Correlations

$$M_{th} = k_{th} M_{max}$$
$$k_{th} = aC_{max} + b$$
$$M_{th} = (aC_{max} + b) M_{max}$$

$$C_{max} := \frac{G M_{max}}{c^2 R_{max}}$$

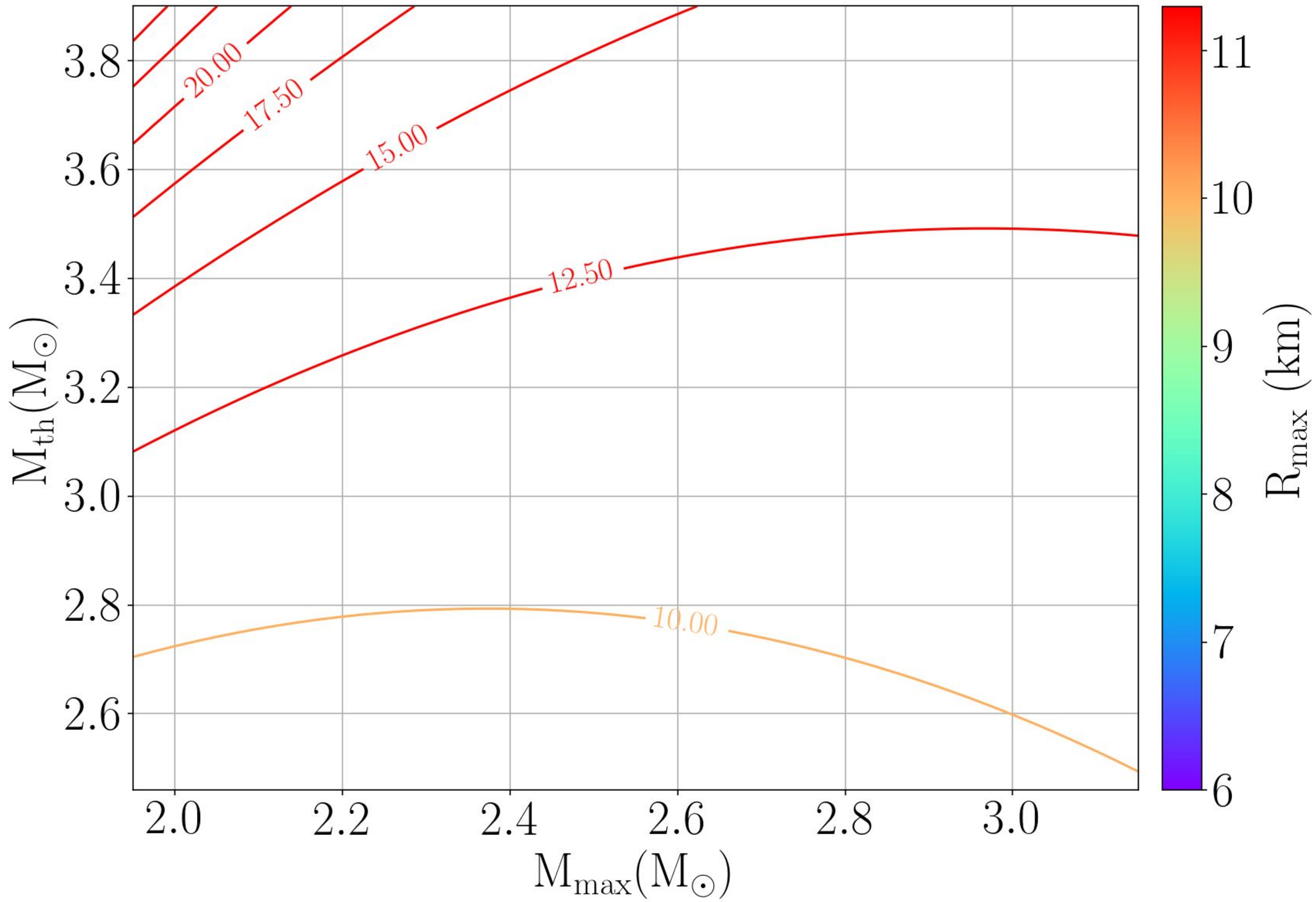
$$R_{max} = \frac{G}{c^2} \left[\frac{a M_{max}^2}{M_{th} - b M_{max}} \right]$$



CAVEAT: No Rotation

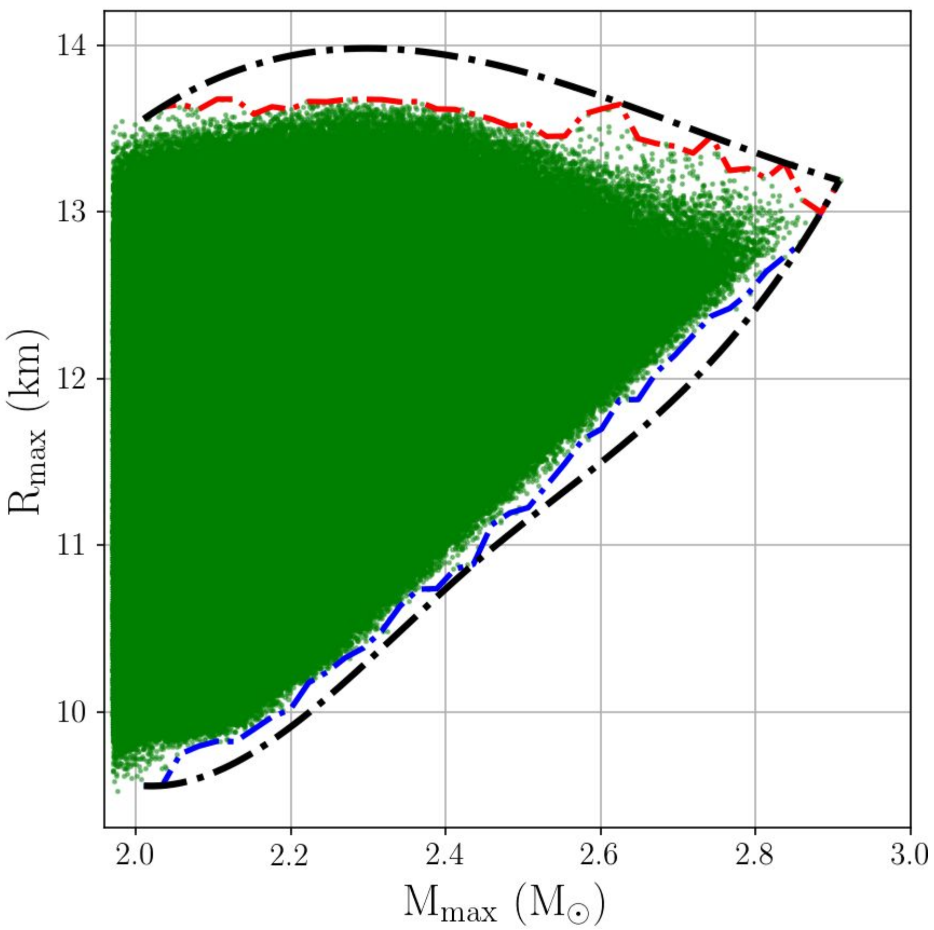
Rmax as a function of threshold mass and maximum mass

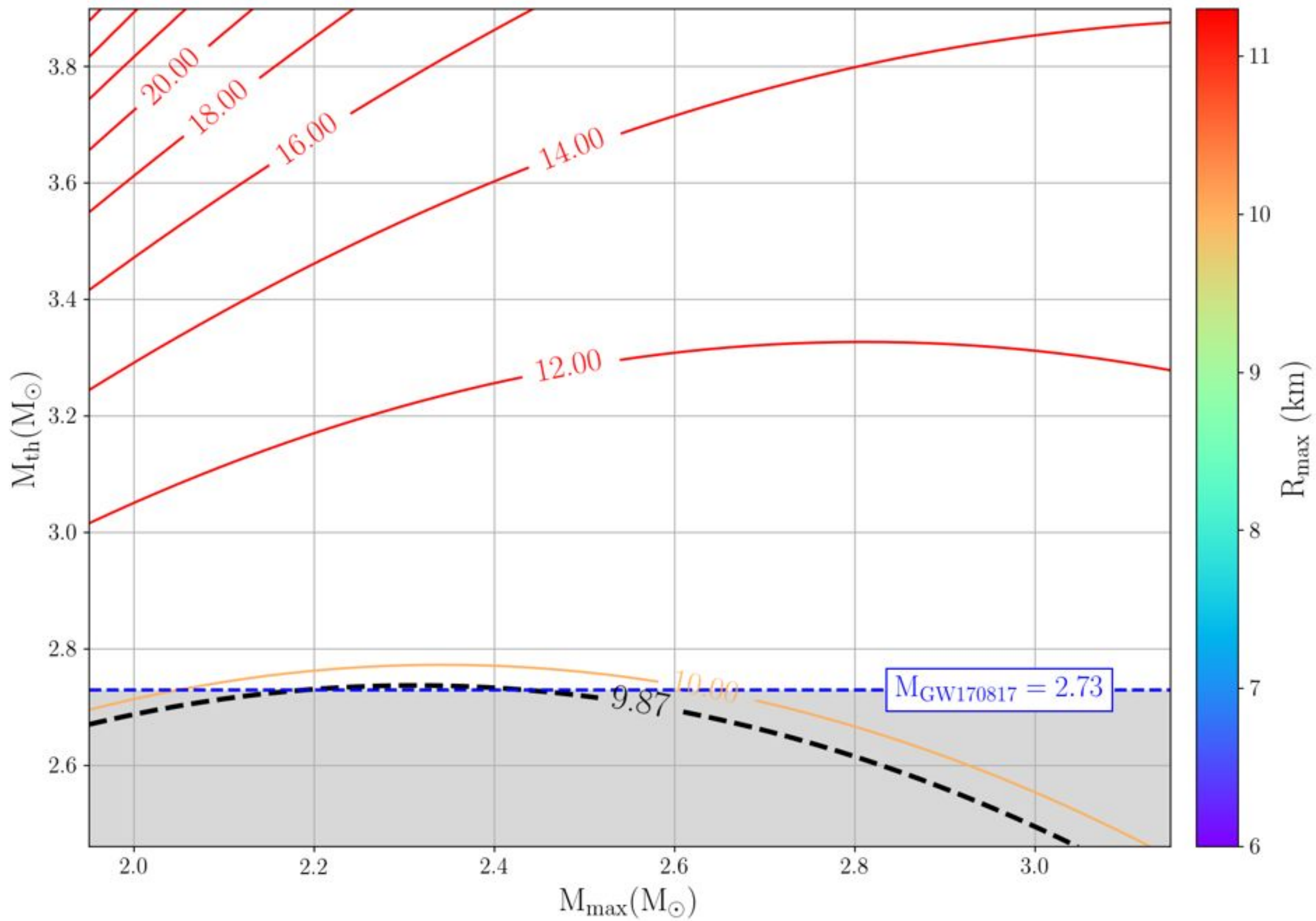
$$R_{max} = \frac{G}{c^2}\left[\frac{aM_{max}^2}{M_{th} - bM_{max}}\right]$$



Constraints on threshold mass (~3.61 M☉) from constraints on compactness

- The upper limit on binary mass will be two times maximum mass but, the minimum total mass at which it'll collapse will be lower than that.





Phenomenological constraint on NS sequences

- Subject to GW170817 analysis, causality and 1.97 for lower limit of maximum mass
- There exist a maximum and minimum compactness for NS

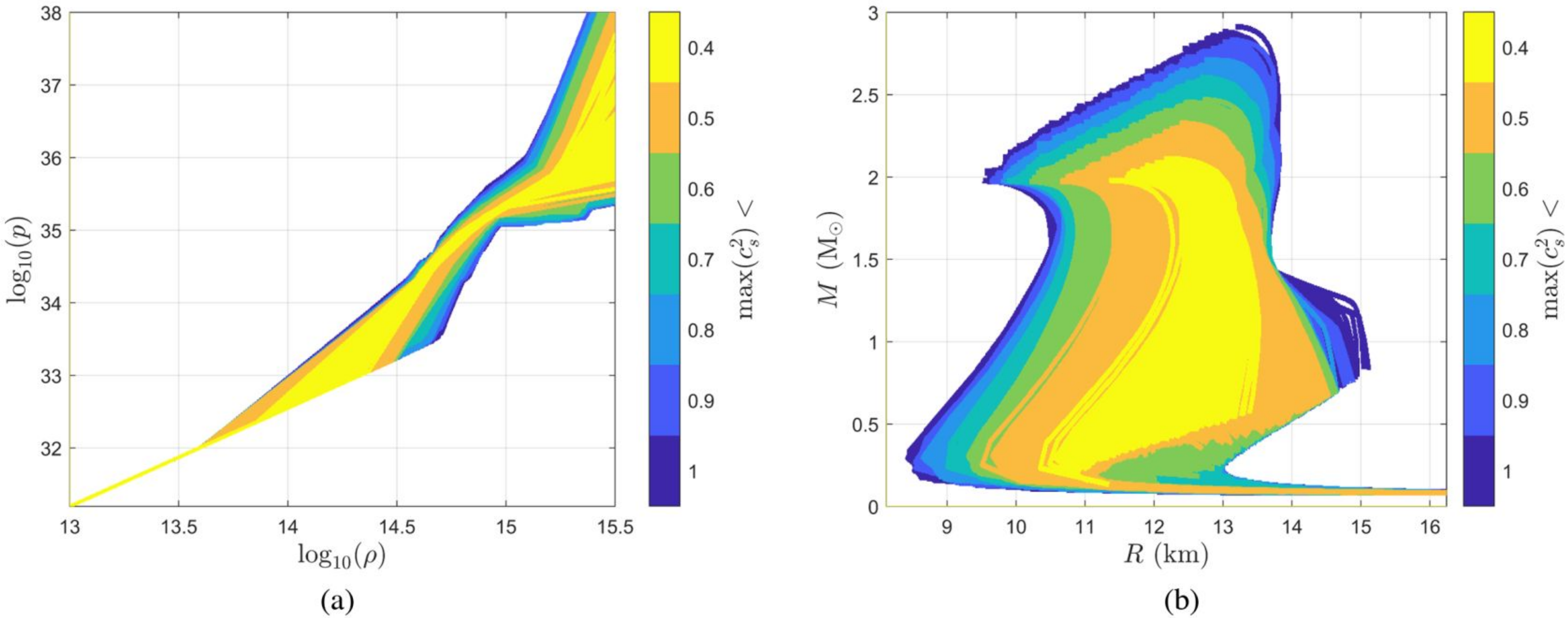
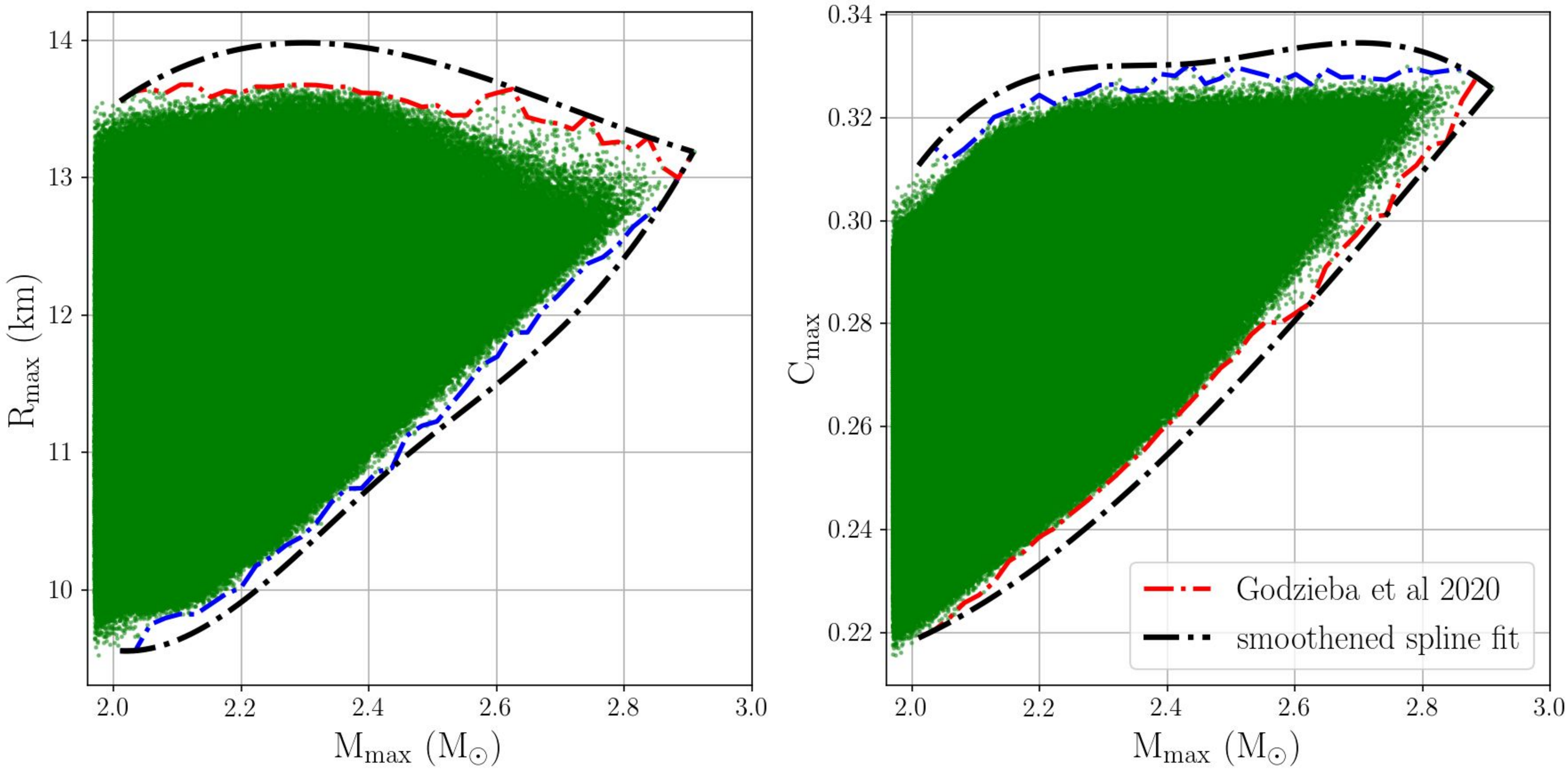


FIG. 2. The collection of 1,966,225 phenomenological EOSs (a) and associated mass-radius curves (b) computed using the MCMC algorithm. Color here is used to indicate the maximum sound speed c_s reached within the maximum mass NS of each EOS [EOSs with smaller $\max(c_s^2)$ are drawn on top of ones with larger $\max(c_s^2)$]. The collection reveals the approximate shape of the EOS band. The most extreme EOSs that reach the edges of the band are those where $c_s = 1$.

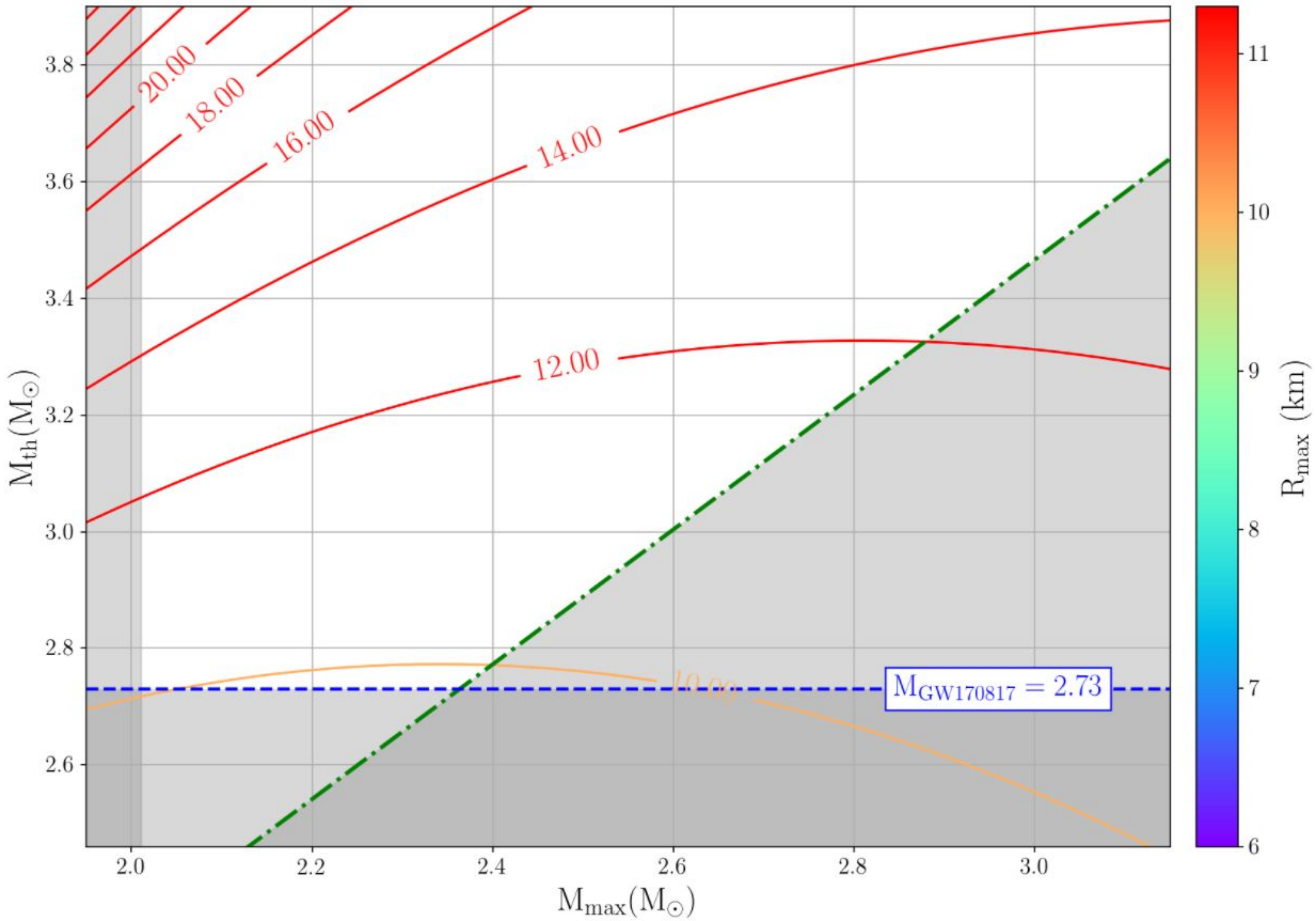
Godzieba et. al. 2021

Phenomenological constraint on NS sequences



Rmax as a function of threshold mass and maximum mass

$$R_{max} = \frac{G}{c^2}\left[\frac{aM_{max}^2}{M_{th} - bM_{max}}\right]$$



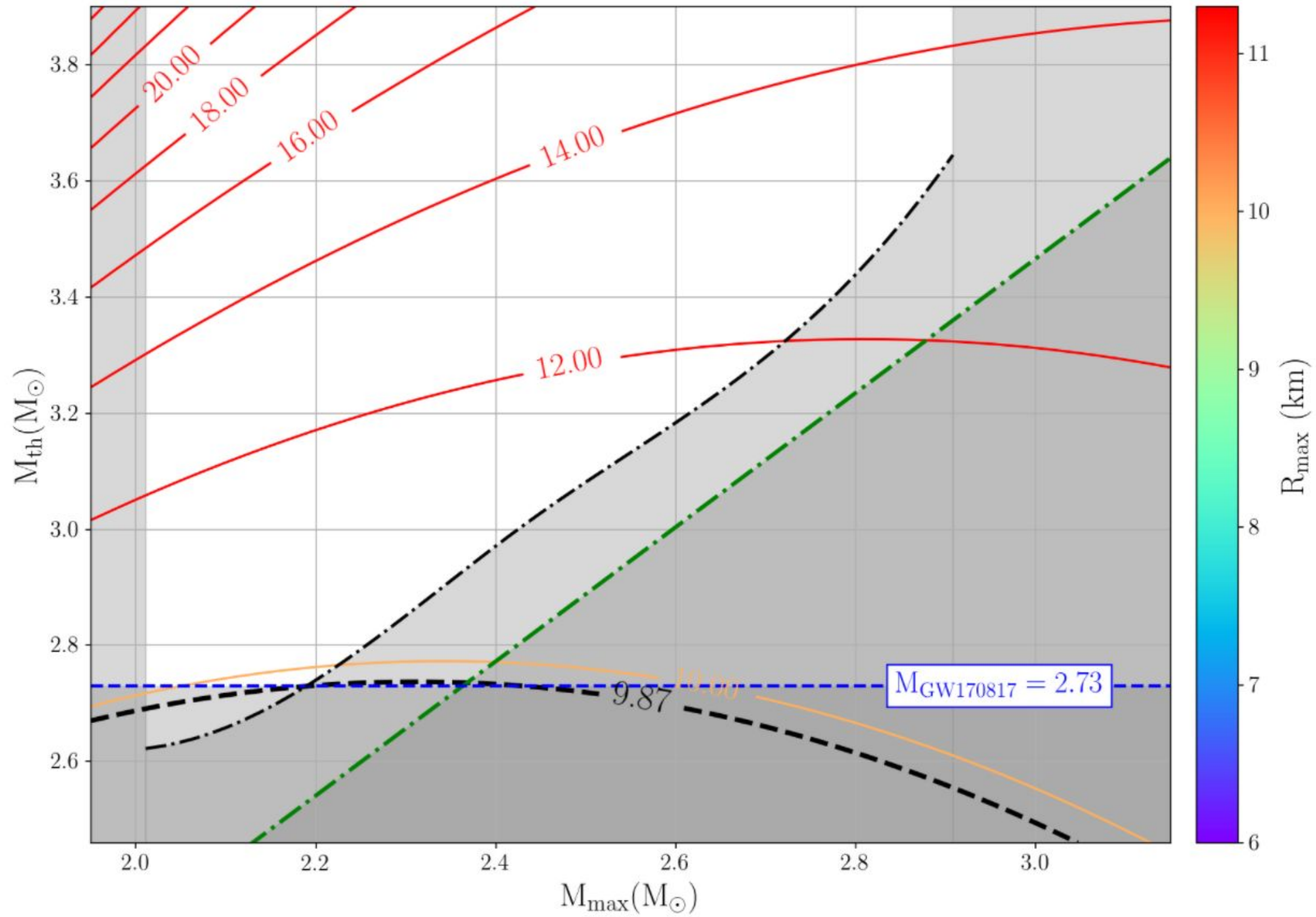
1. Heaviest pulsar observed is 2.01 solar masses.
2. There exist a maximum compactness ($R_{max} \geq \frac{1}{C^*}\frac{GM_{max}}{c^2}$ ssible EOS of NS

$$M_{thres} \geq (aC^* + b)M_{max}$$

3. GW170817 was a delayed collapse.

Rmax as a function of threshold mass and maximum mass

$$R_{max} = \frac{G}{c^2}\left[\frac{aM_{max}^2}{M_{th} - bM_{max}}\right]$$



1. Heaviest pulsar observed is 2.01 solar masses.
2. GW170817 was a delayed collapse.
3. There exist a maximum compactness of all possible EOS of NS

$$R_{max} \geq \frac{1}{C^*}\frac{GM_{max}}{c^2}$$

$$M_{thres} \geq (aC^* + b)M_{max}$$

4. Mmax dependent constrain on maximum compactness

Constraints on threshold mass and maximum mass from Rmax constraints

$$R_{max} = \frac{G}{c^2}\left[\frac{aM^2_{max}}{M_{th} - bM_{max}}\right]$$

1. Heaviest pulsar observed is 2.01 solar masses.
2. GW170817 was a delayed collapse.
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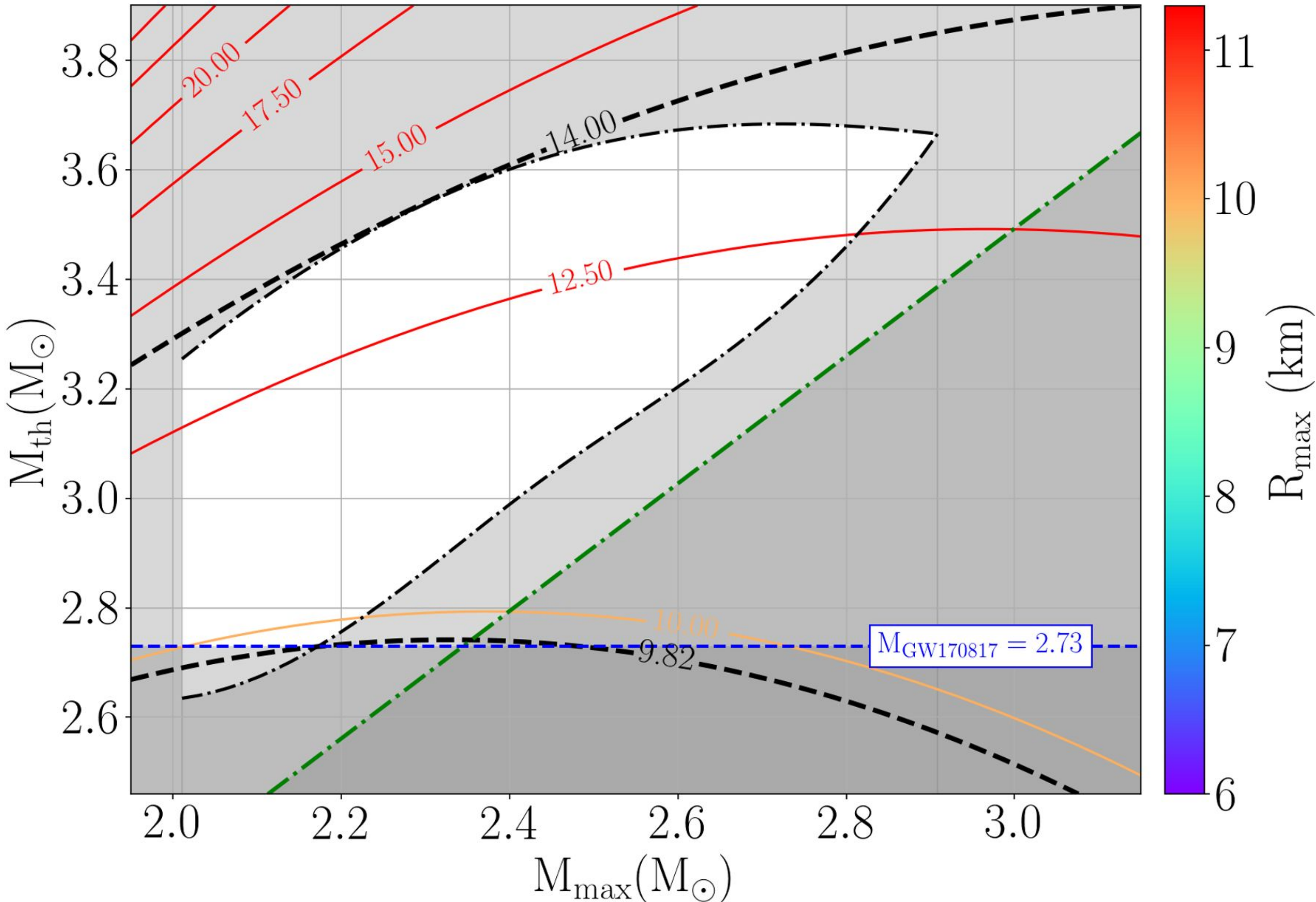
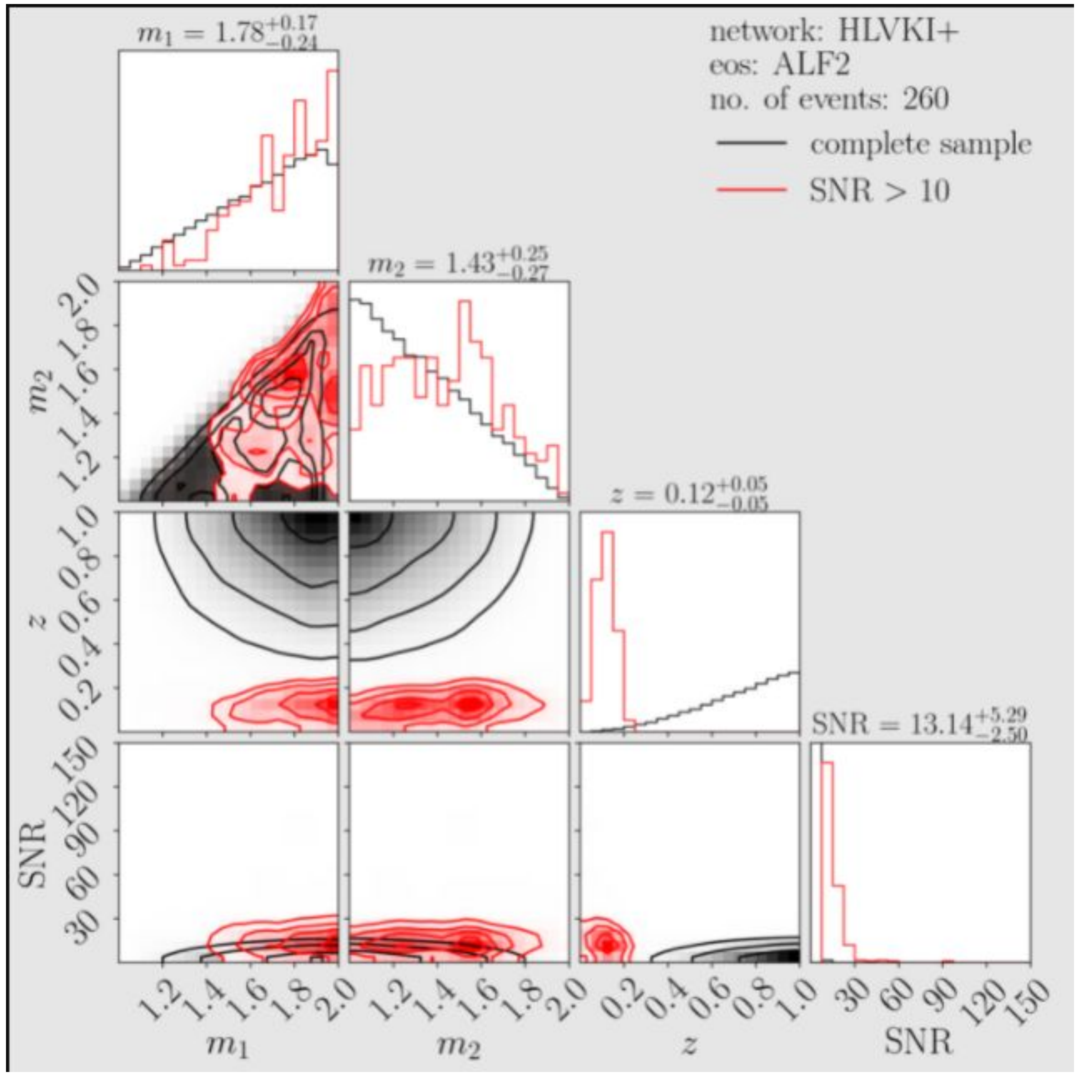


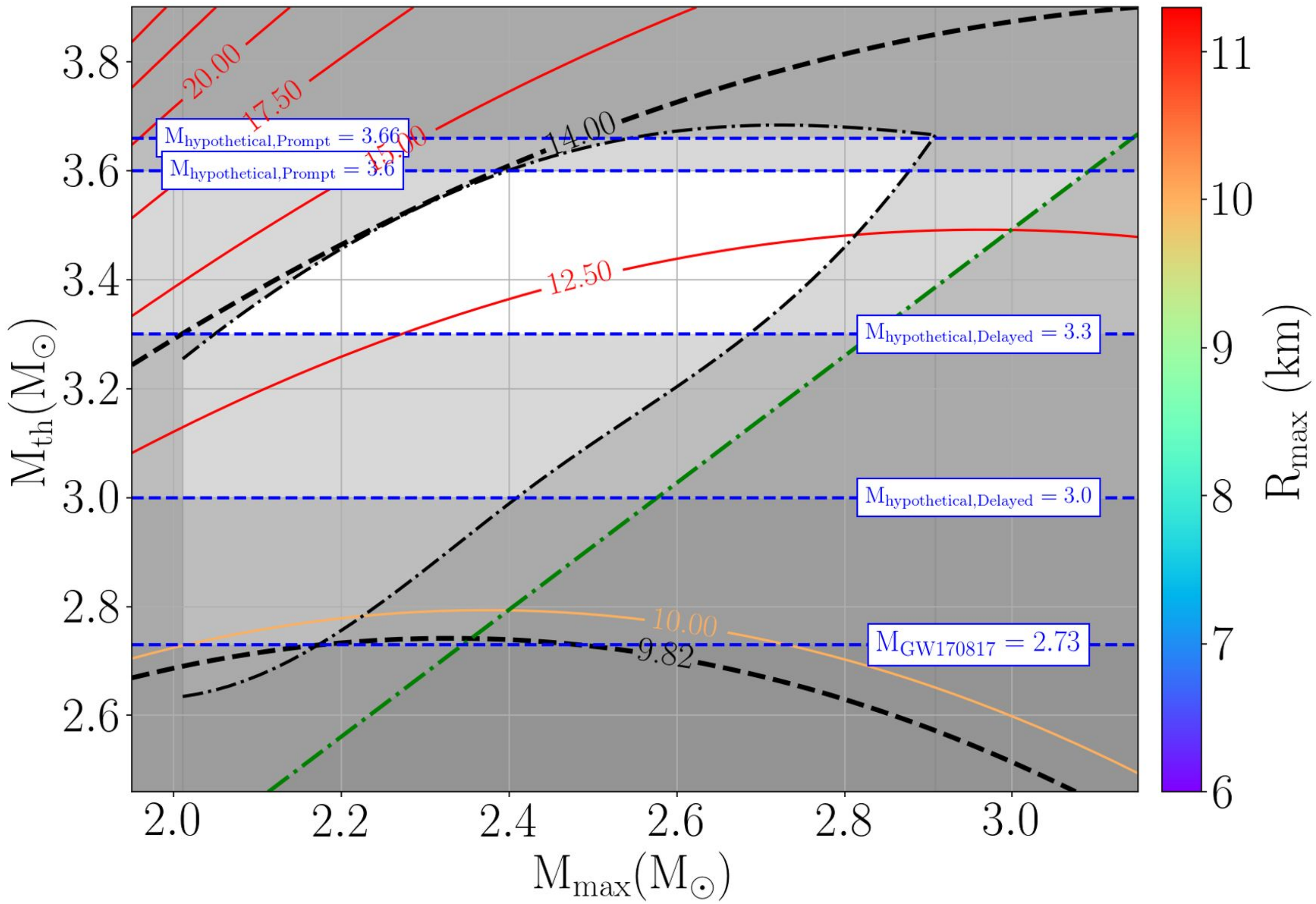
4. Mmax dependent constrain on minimum compactness

$$(aC_{low}(M_{max}) + b)M_{max} \leq M_{th}(M_{max}) \leq (aC_{high}(M_{max}) + b)M_{max}$$

Bounds on maximum mass using future BNS events



Cosmic Explorer Horizon Study (https://cosmicexplorer.org/)



Summary of Constraints

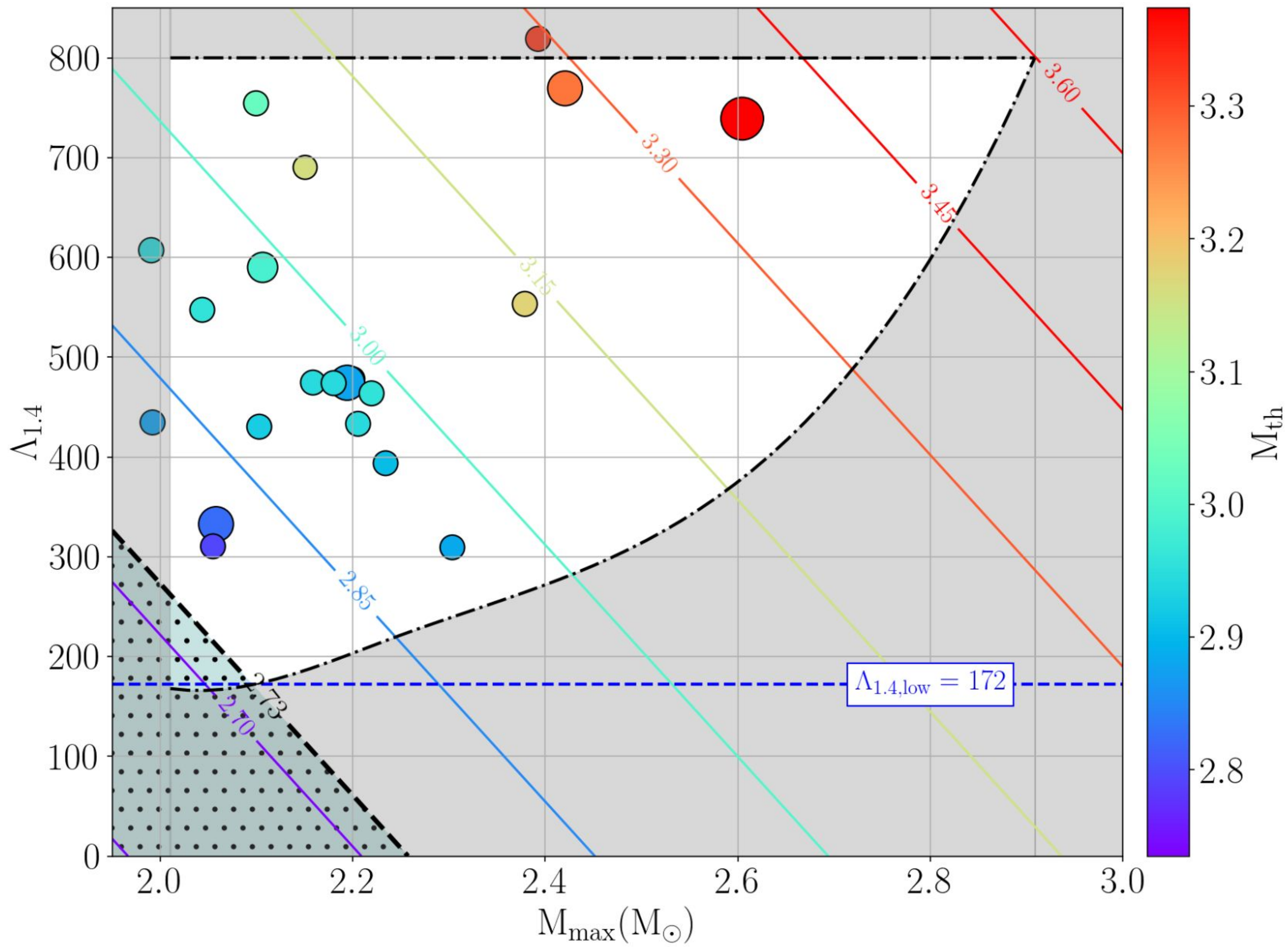
- Observation of either delayed (prompt) collapse will constrain lower (upper) values of maximum mass of NS.

Correlation	$\max(M_{th})$ $(M_\odot)$	$M_{total,\mathbf{Delayed}}$ to constrain $\min(M_{max})$ $(M_\odot)$	$M_{total,\mathbf{Prompt}}$ to constrain $\max(M_{max})$ $(M_\odot)$
k_{th}-C_{max}	3.67	> 3.25	< 3.64
k_{th}-$C^*_{1.4}$	3.38	> 3.05	< 3.20
k_{th}-$C^*_{1.6}$	3.35	> 3.05	< 3.22
M_{th}-$(\Lambda_{1.4}, M_{max})$	3.62	-	-

Dependence of Mth on Mmax and tidal deformability

- Interesting constraints on tidal deformability of 1.4 solar mass NS (**> 180**).
- Maximum threshold mass
- Potential for ruling out EOS

$$M_{th}(\Lambda_{1.4}, M_{max}) = s_0 M_{max} + s_2 \Lambda_{1.4} + s_3$$



Constraints on Radius of a canonical mass NS

Existing constraints (from direct GW, EM observations) (in km)

- LIGO:
  - **GW alone (LVC+2017):**

    $R1 = [9.1, 12.8]$ for $m1 = [1.36, 1.62]$

    $R2 = [9.2, 13.3]$ for $m2 = [1.15, 1.36]$

  - **NICER (Raaijmakers+2019, Miller+2019)**

    $R = 12.71^{+1.14}_{-1.19}$ km ($13.89^{+1.23}_{-1.38}$)

    for $M = 1.34^{+0.15}_{-0.16}$

Indirectly from the knowledge of threshold mass (in km)

- Earlier work (Bauswein+2013)

  $R_{1.6} \geq 10.68^{+0.15}_{-0.04}$

  $R_{max} \geq 9.60^{+0.14}_{-0.03}$

- Our work:

  $R_{max} \geq 9.81^{+1.20}_{-1.09}$

  $R_{1.6} \geq 10.90^{+1.85}_{-1.42}$

  $R_{1.4} \geq 10.74^{+1.86}_{-1.61}$

Implications and future studies

- One may observe prompt collapse (BNS signal with sharp GW cutoff) above the upper limit of threshold mass shown in figure but an observation below the maximum limit would be very useful.
- With every observation signalling prompt or delayed collapse and with total mass below the upper limit, the gap of allowed maximum mass of NS will also get smaller.
- Upper limit on maximum mass will be constrained; will shed light on events such as GW190425.

Upcoming work: GW group Penn State (Rahul Kashyap, Arnab Dhani, B. Sathyaprakash)

- Measurement of NS radii and model selection using inspiral GW modeling and upcoming sensitive GW observations

Conclusions

- New threshold mass from full general relativistic code confirms some of the previous results obtained using full-GR.
- Shows some differences with respect to results obtained using simulations with conformally flat approximations.
- Phenomenological constraints on TOV sequences provide novel method to constraint EOS.

Future Directions

➢ What happens during final moment of collapse?
➢ Relative role of nuclear parameters for the formation of Event (or, Apparent) horizon; Does matter actually matter?
➢ Mass ratio not equal to 1; Effect of asymmetries.

Thank You, be safe