What neutron star mergers can teach us about matter under extreme conditions

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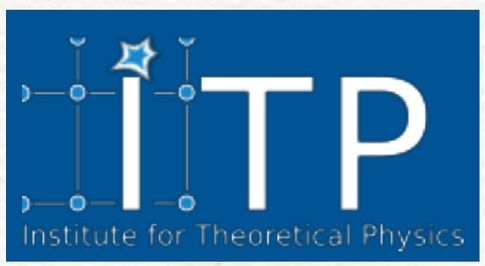


Different states of matter

- Matter comes in different states
- Different physical systems probe different parts
- Neutron stars are at high densities (chemical potentials)

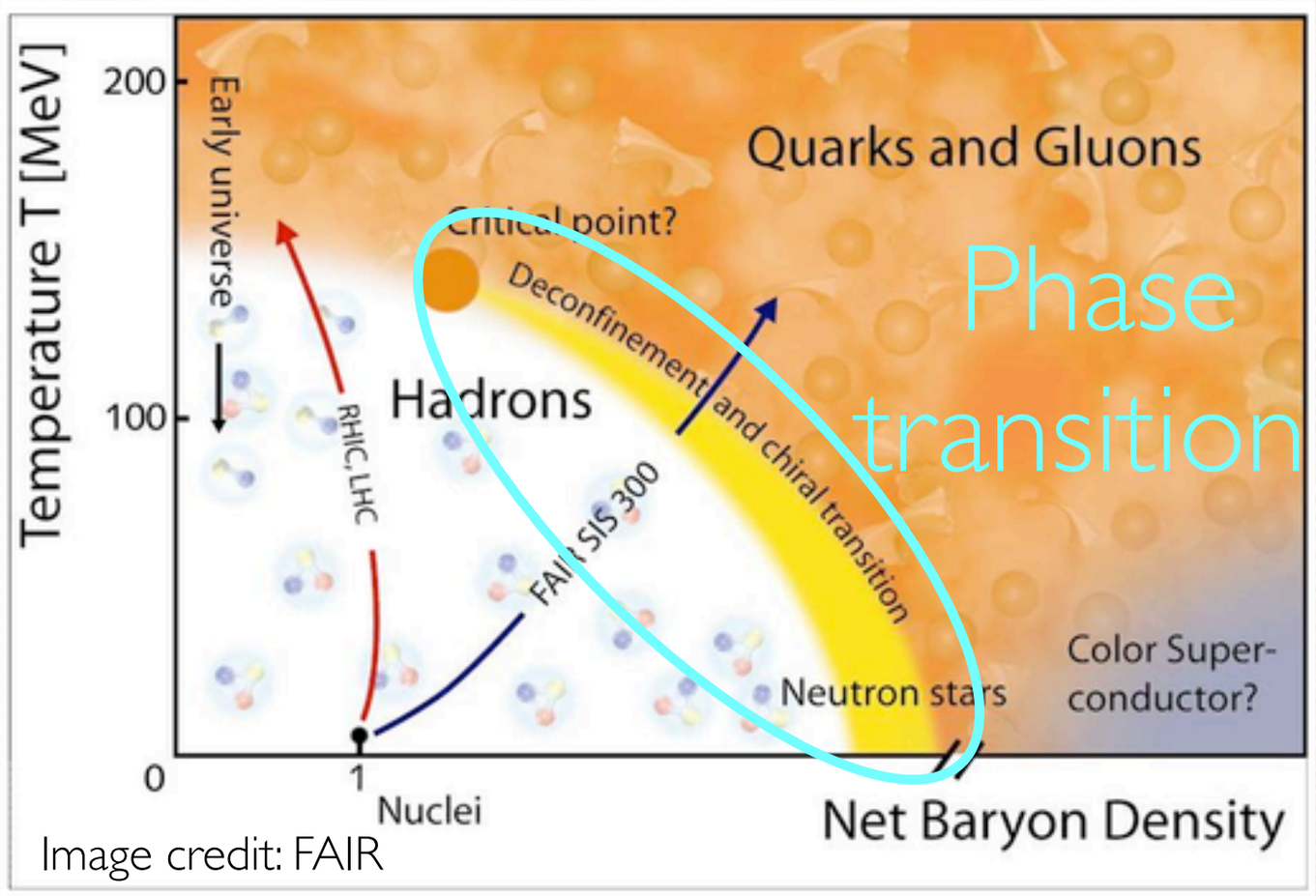
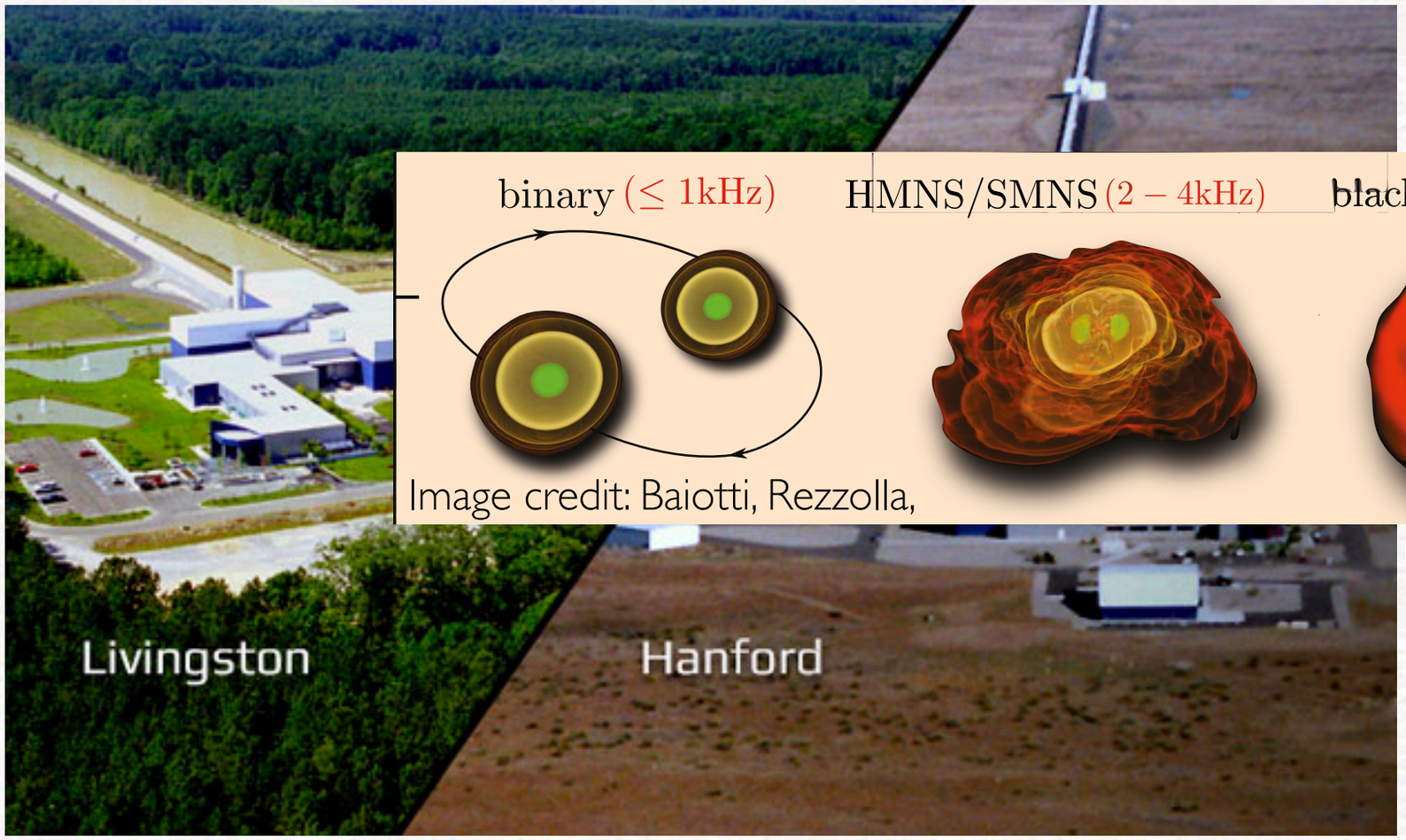


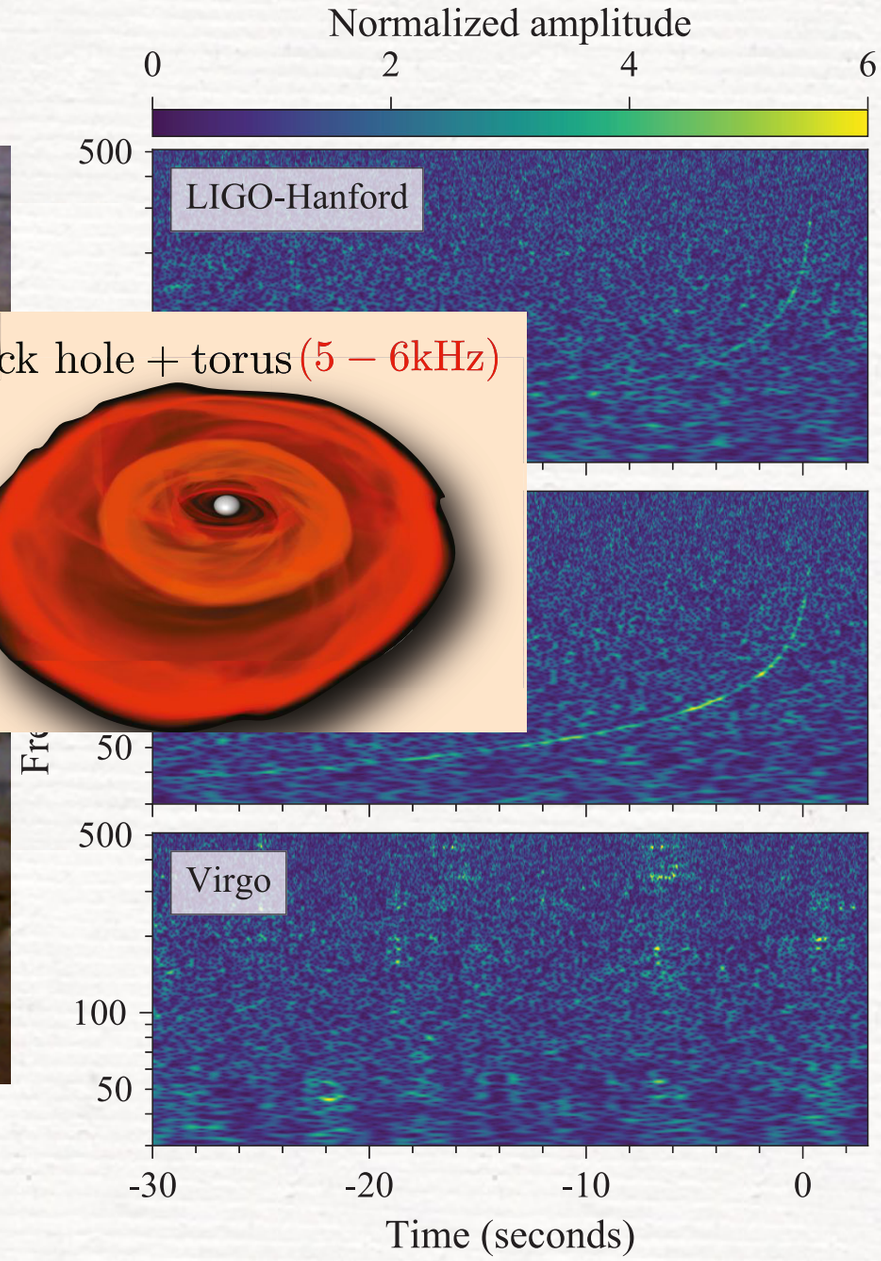
Image credit: FAIR

- Quark gluon plasma formed at high temperature /high density

GW170817

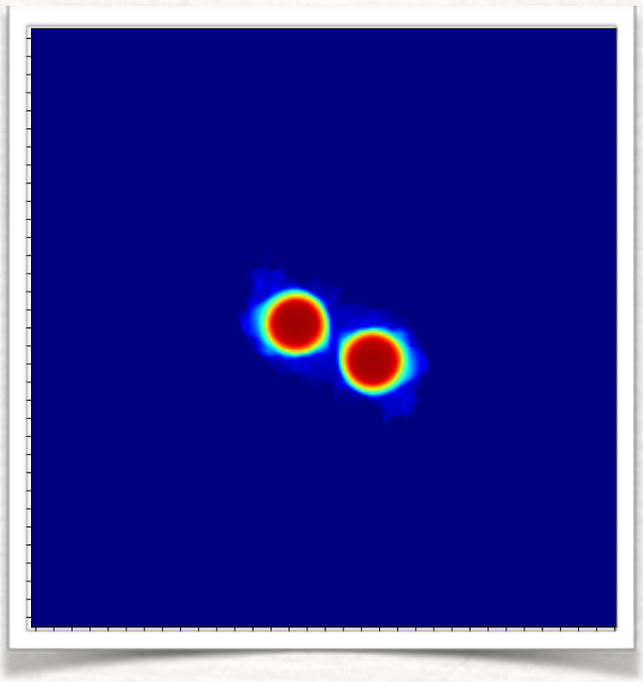


LIGO Lab MIT/Caltech



Abbott et al 2017

Revealing phase transitions from gravitational wave signals

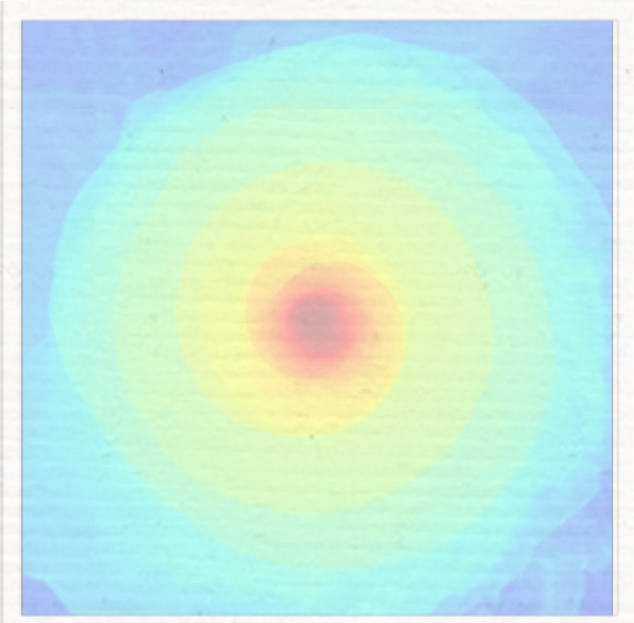


Signals from the inspiral

ERM+ PRL **120**, 261103 (2018)

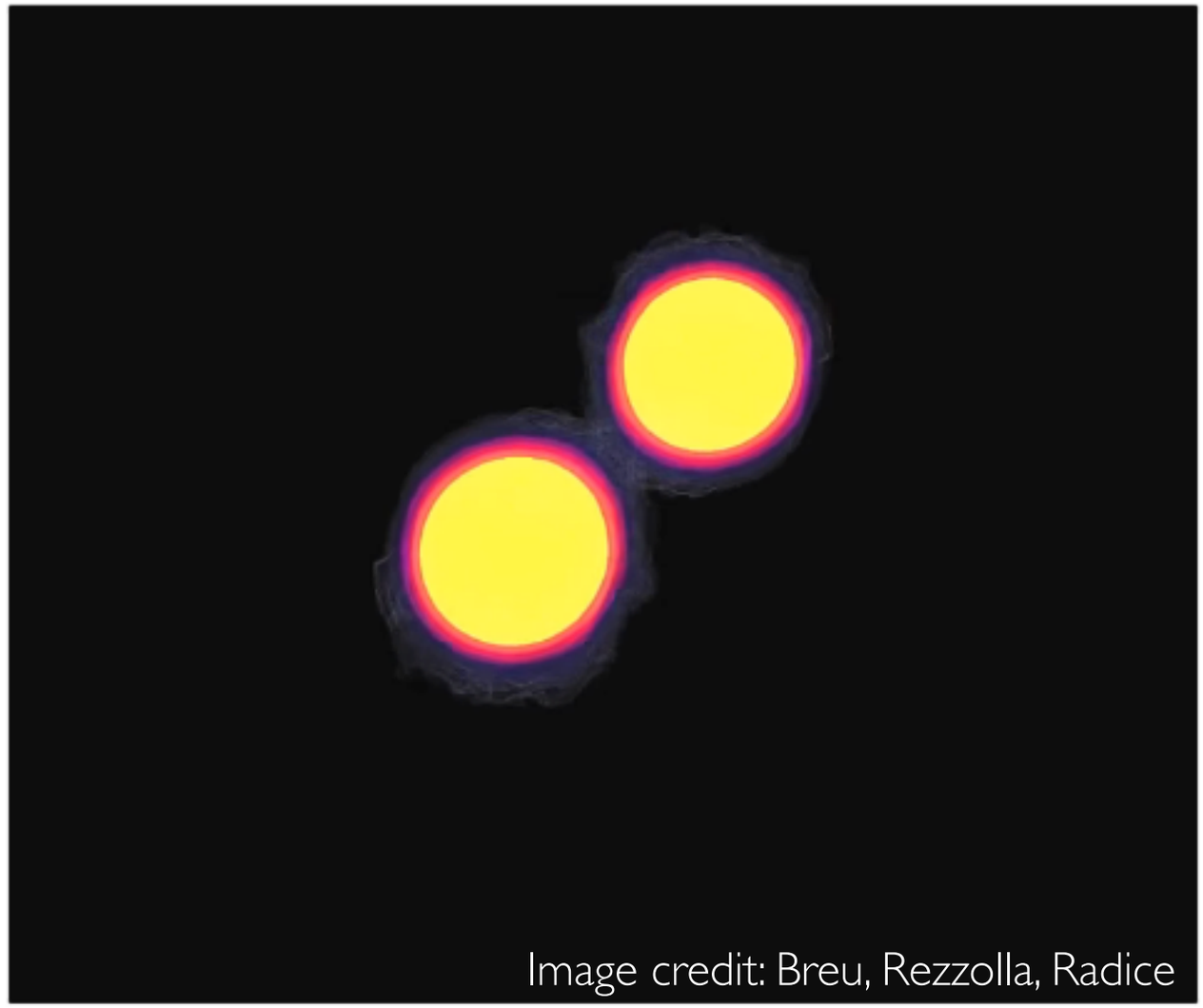
Signals from the post-merger

ERM+ PRL **122**, 061101 (2019)



How is BH-BH different from NS-NS?

Neutron stars in binary are tidally deformed by companion

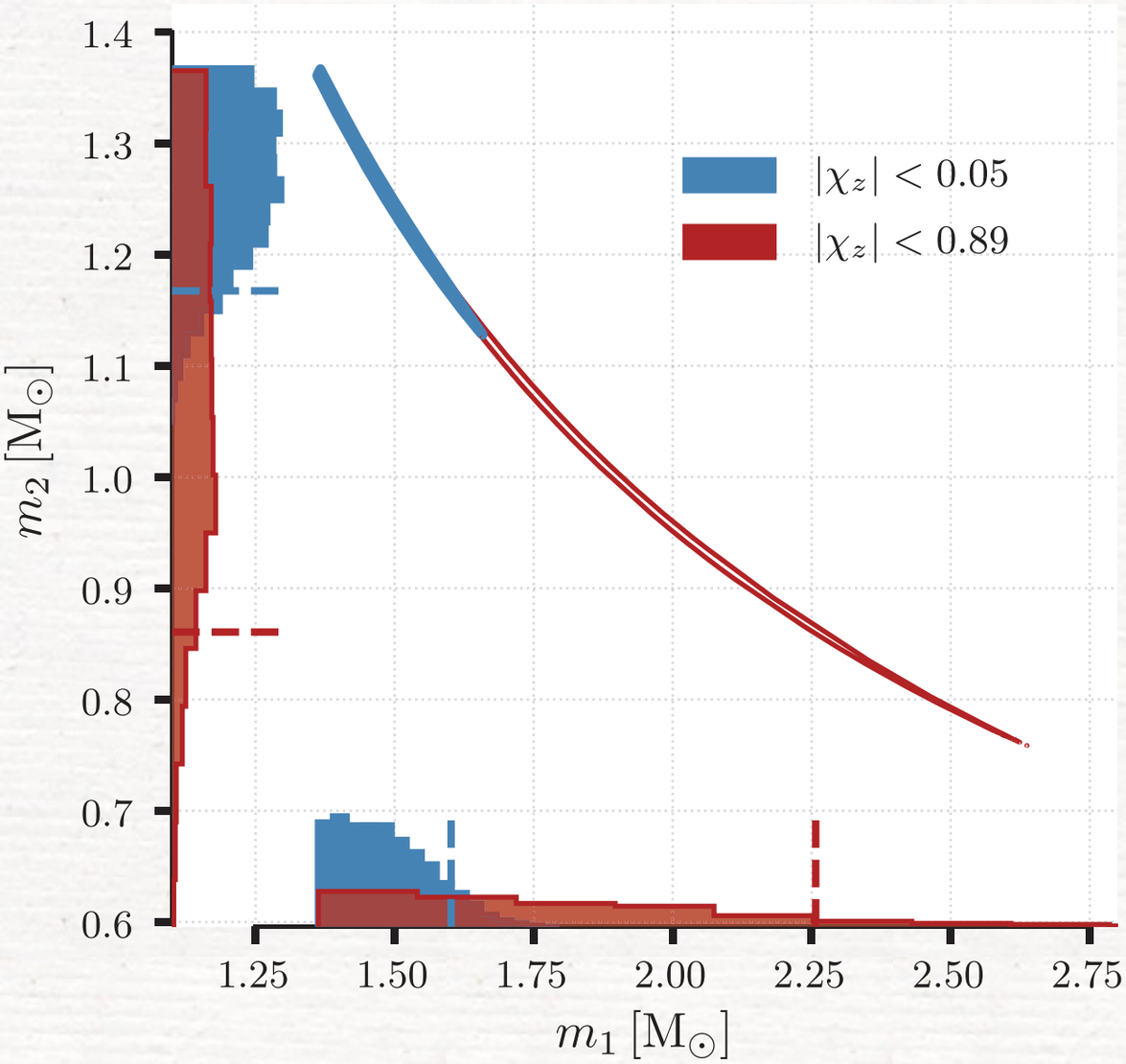


EOS

$$\Lambda = \frac{2}{3}\kappa_2 \left(\frac{Rc^2}{MG} \right)^5$$

Tidal deformability of an isolated neutron star

GW170817: What do we know?

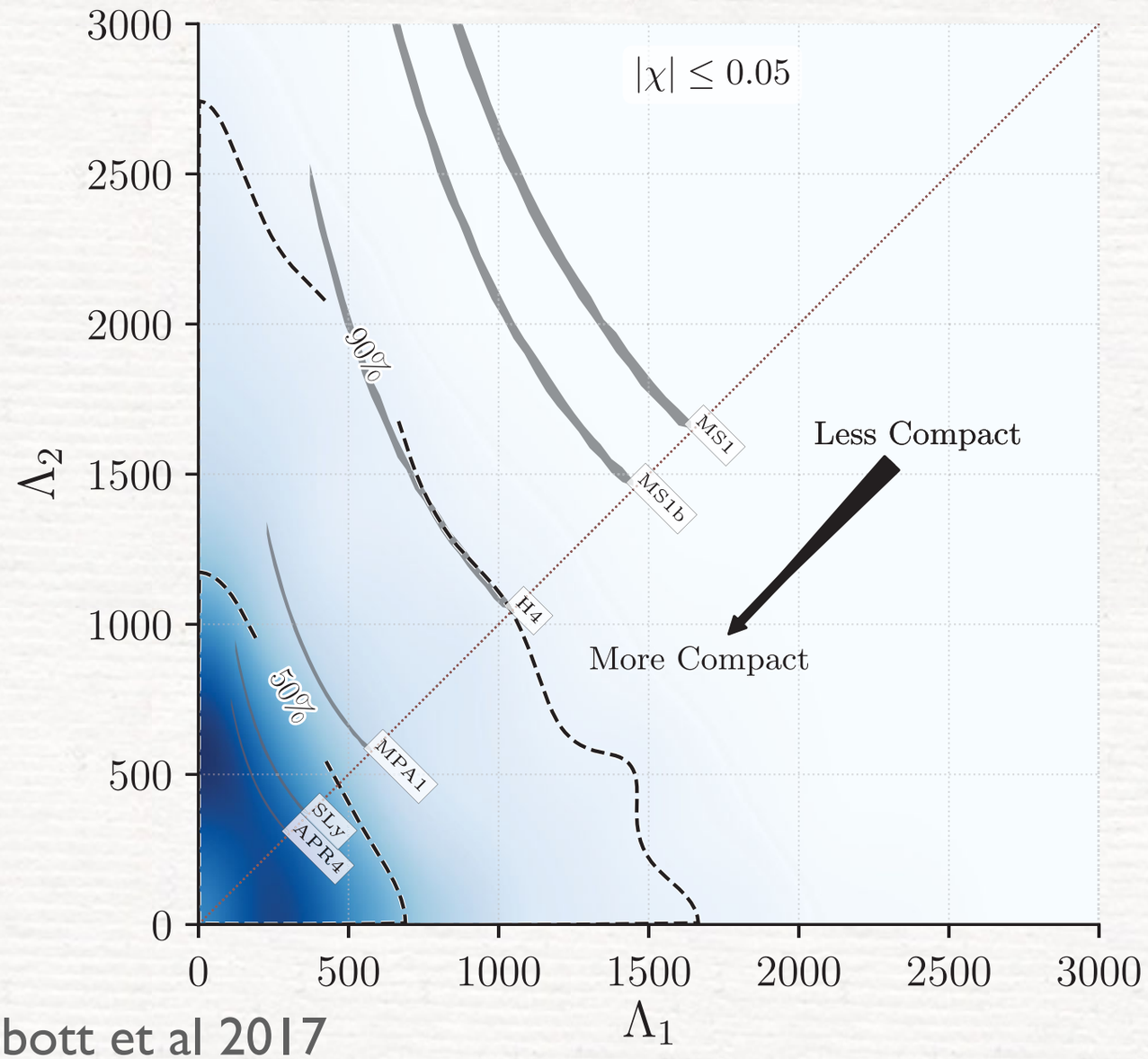


$$M_1 + M_2 = 2.74^{+0.04}_{-0.01} M_\odot$$

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

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

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



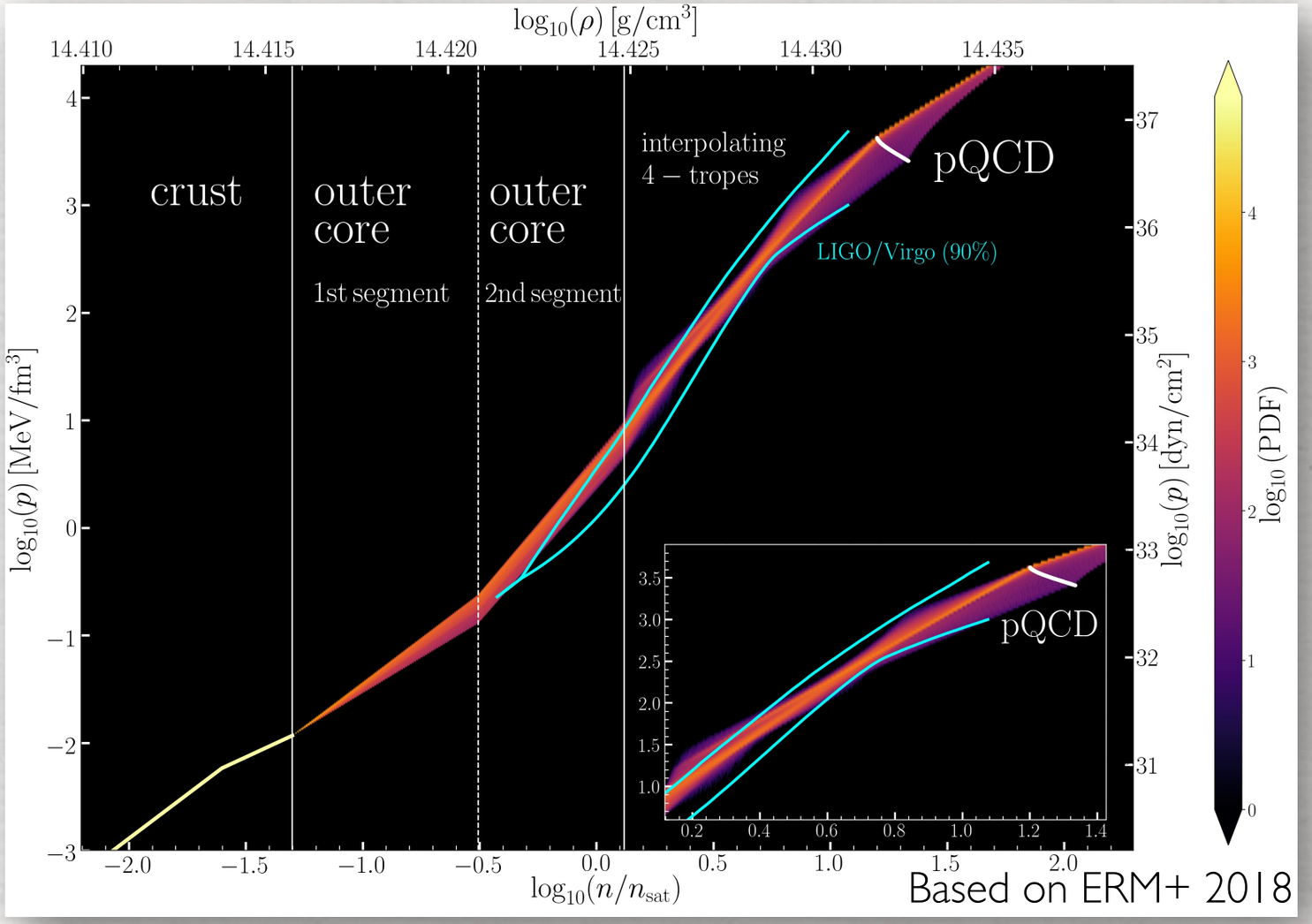
Abbott et al 2017

How does matter behave at extreme densities?

- Understanding the behaviour of matter under extreme conditions is very difficult

- GW170817 has already helped constraining matter at T=0 MeV

See Rezzolla's talk on Monday

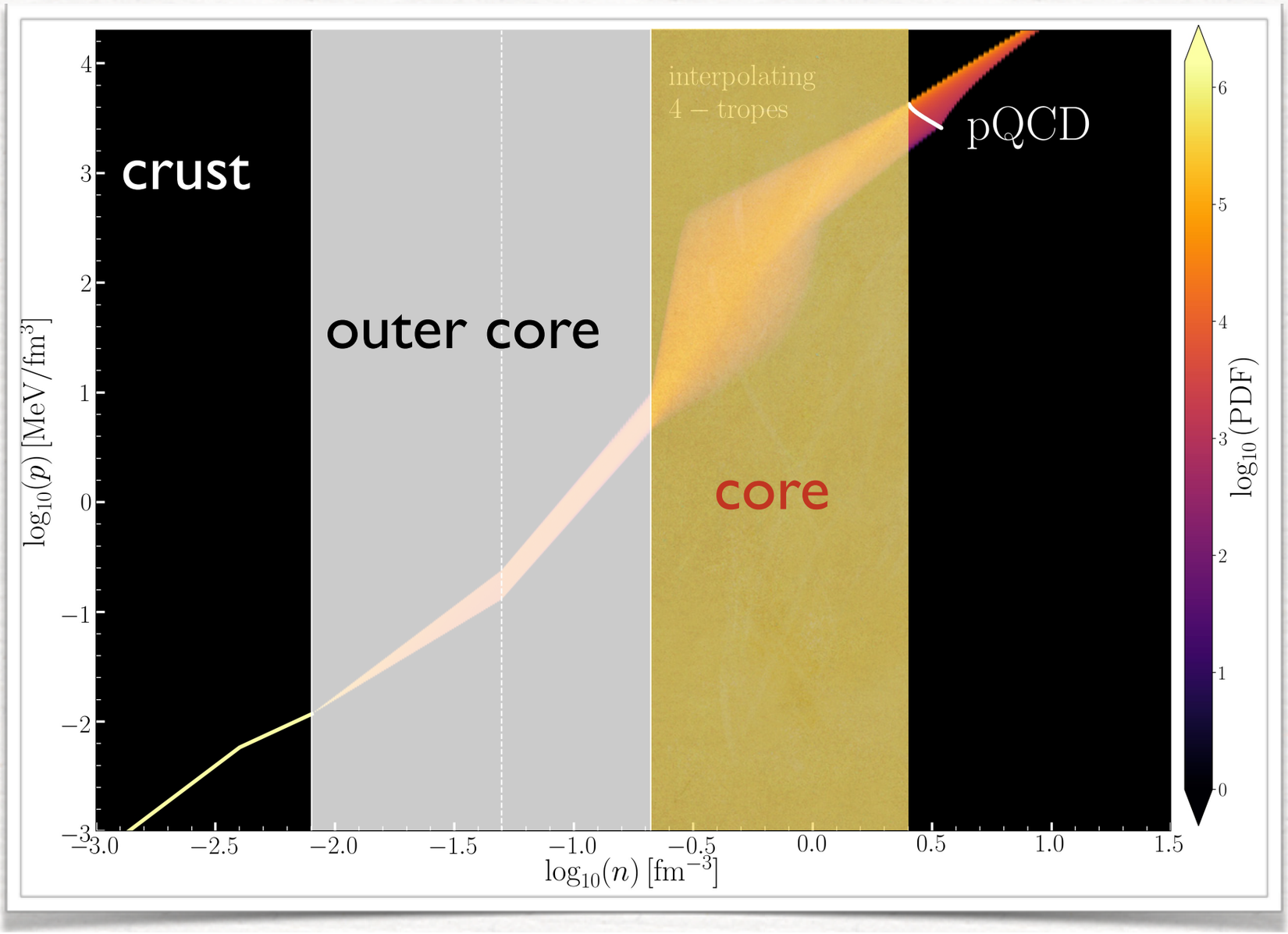


See also De+ (2018), LIGO/VIRGO (2018+) and many more

How can we model a phase transition in the inspiral?

- Parameterise EOS from nuclear saturation to pQCD limit.

- Randomly include strong first order phase transition

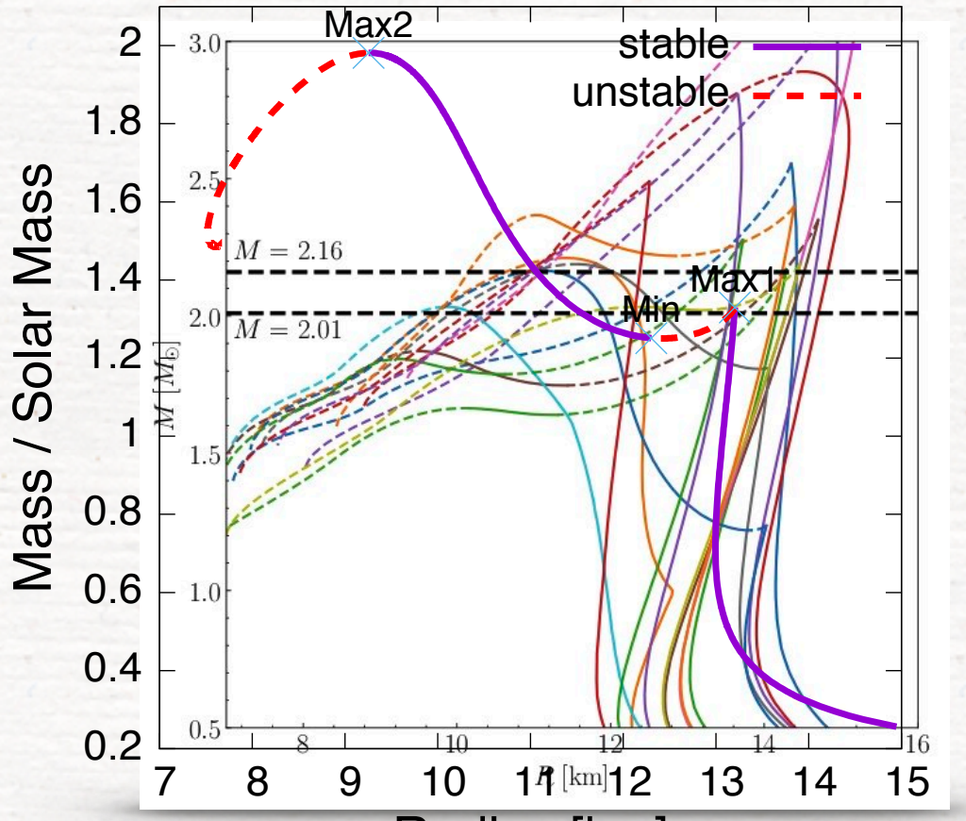


10^6 EOSs with a total of ~10^9 TOV-models

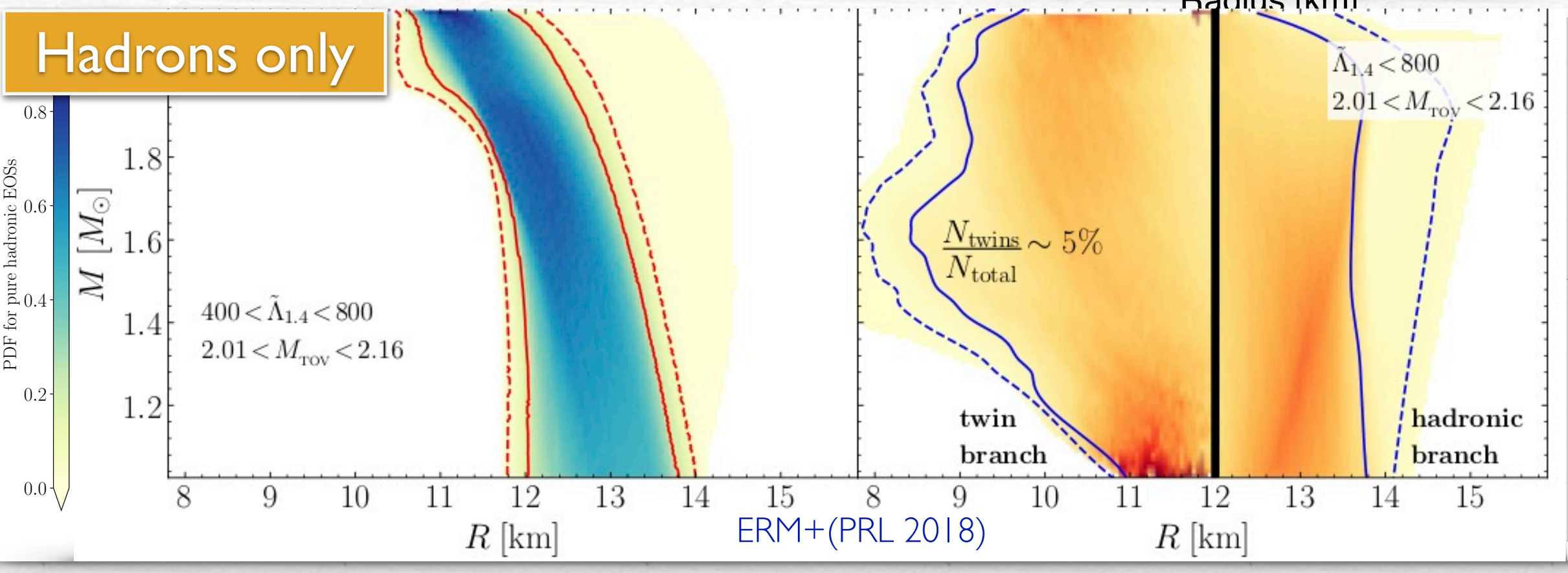
Mass-radius relations

Christian+ (2018)

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



Hadrons only



ERM+(PRL 2018)

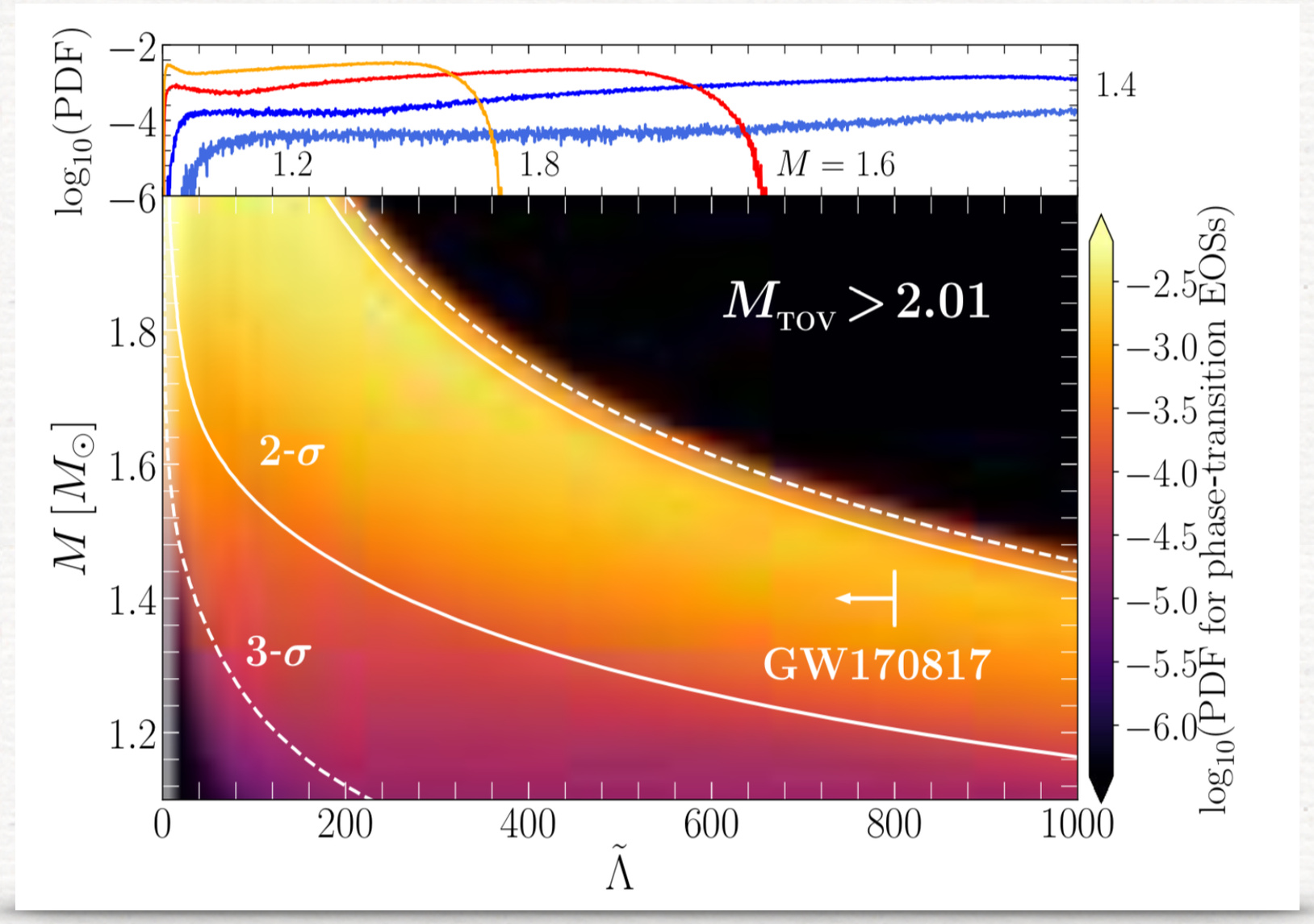
Constraining tidal deformabilities

- Almost no constraint on lower limit: $\tilde{\Lambda}_{1.4} \gtrsim 35$

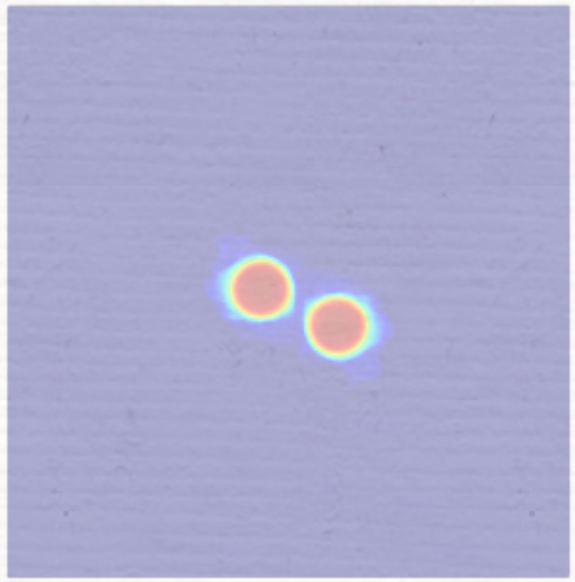
- Large masses have sharp cut-off on upper limit:

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

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



Revealing phase transitions from gravitational wave signals



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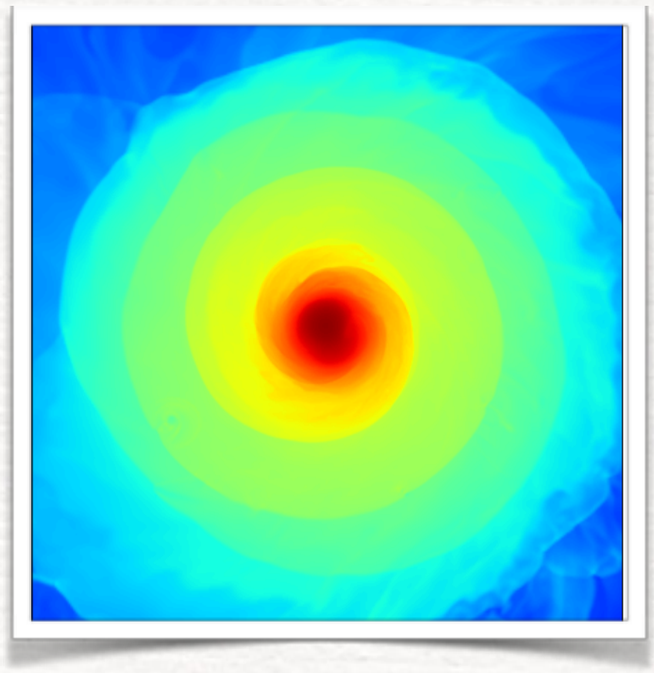
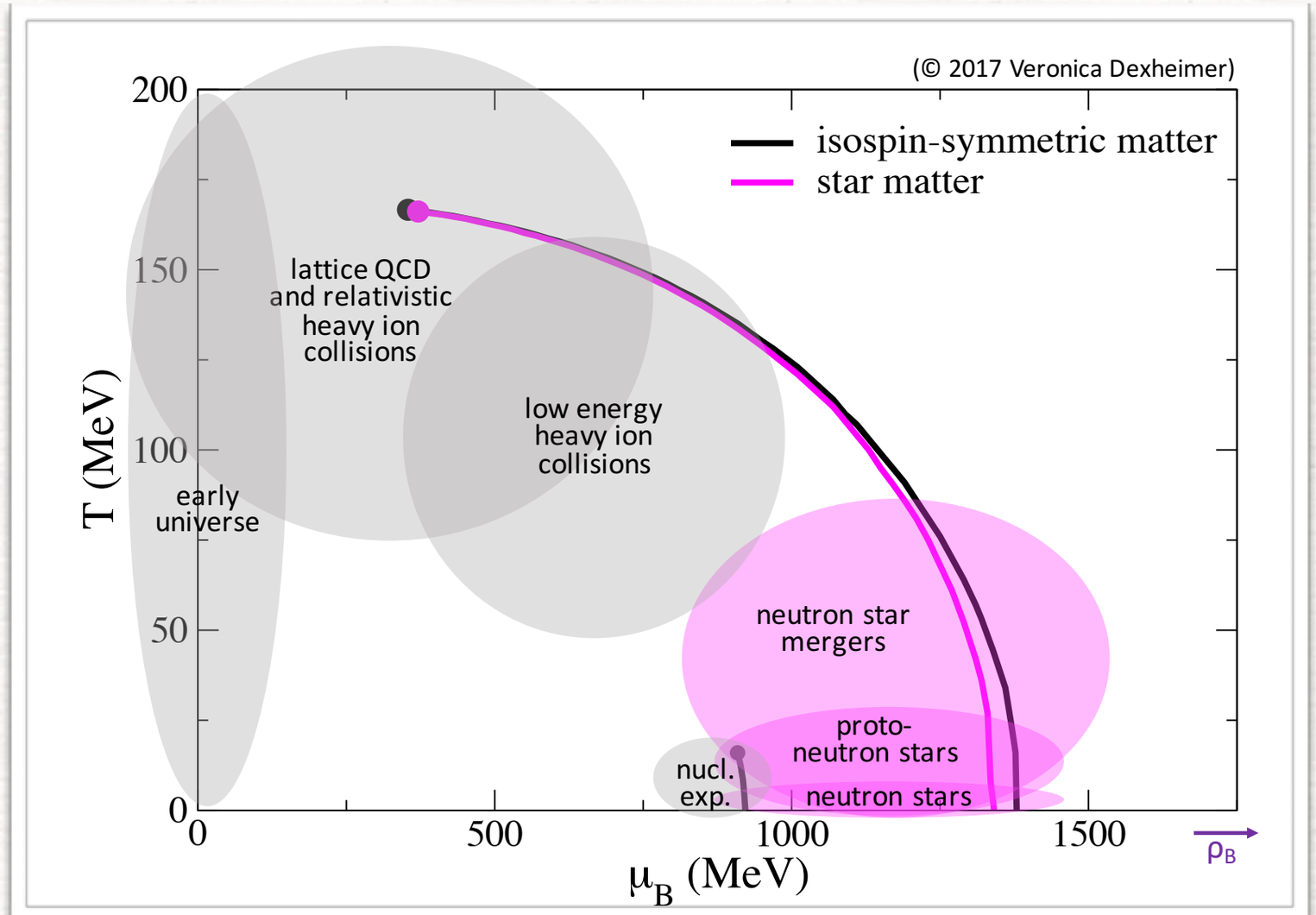


What mergers can tell us

- Cold neutron stars can only probe a tiny fraction of the phase diagram

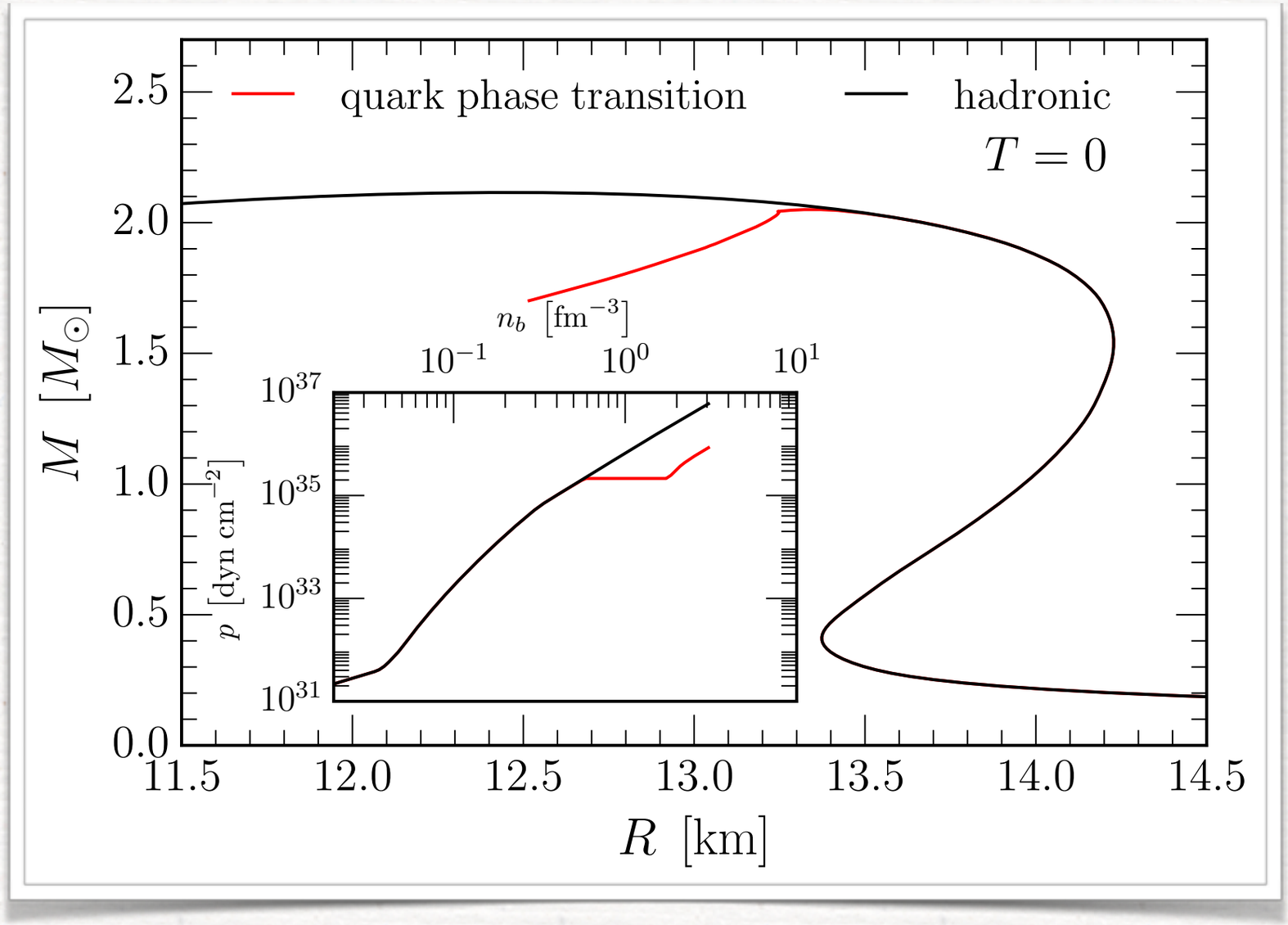
- Neutron star mergers reach temperatures up to 100 MeV and probe regions not reached by any experiment!



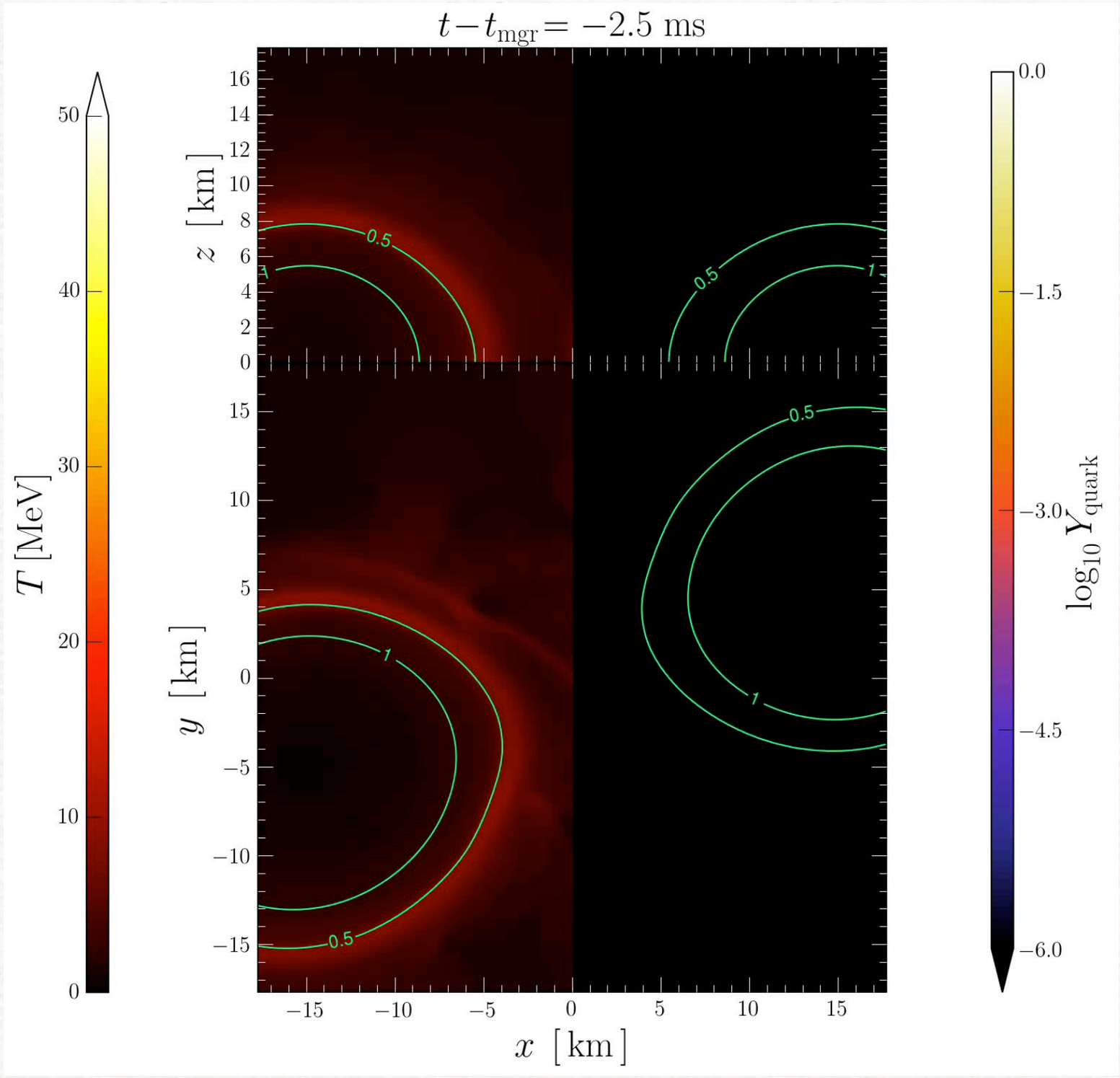
Chiral Mean Field Model

Dexheimer & Schramm

- Includes hyperons and quarks (*can be turned off*)
- Uses Polyakov loop to implement a strong first order phase transition
- Includes a cross-over transition at high temperatures



Quark phase transition in mergers



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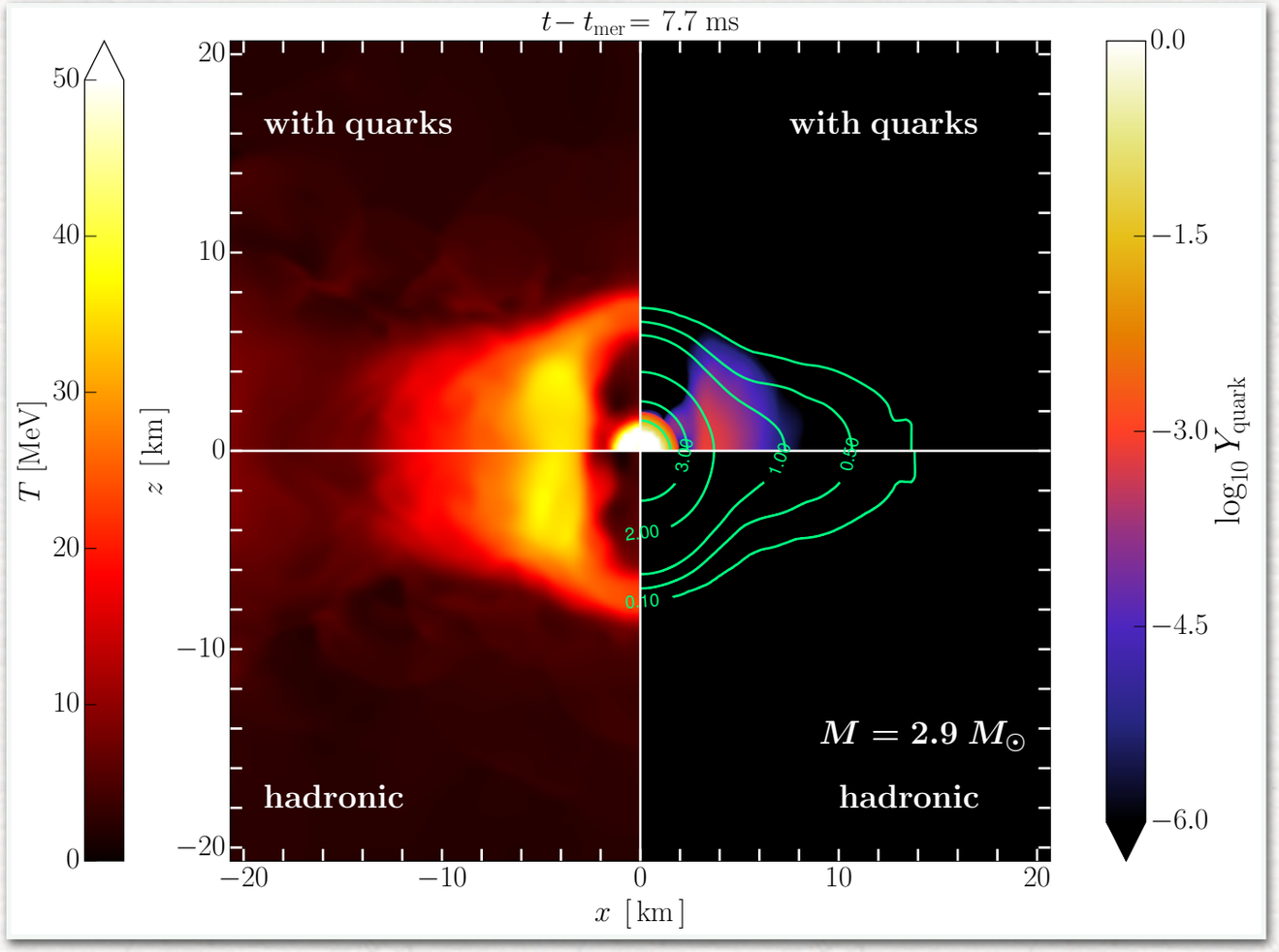


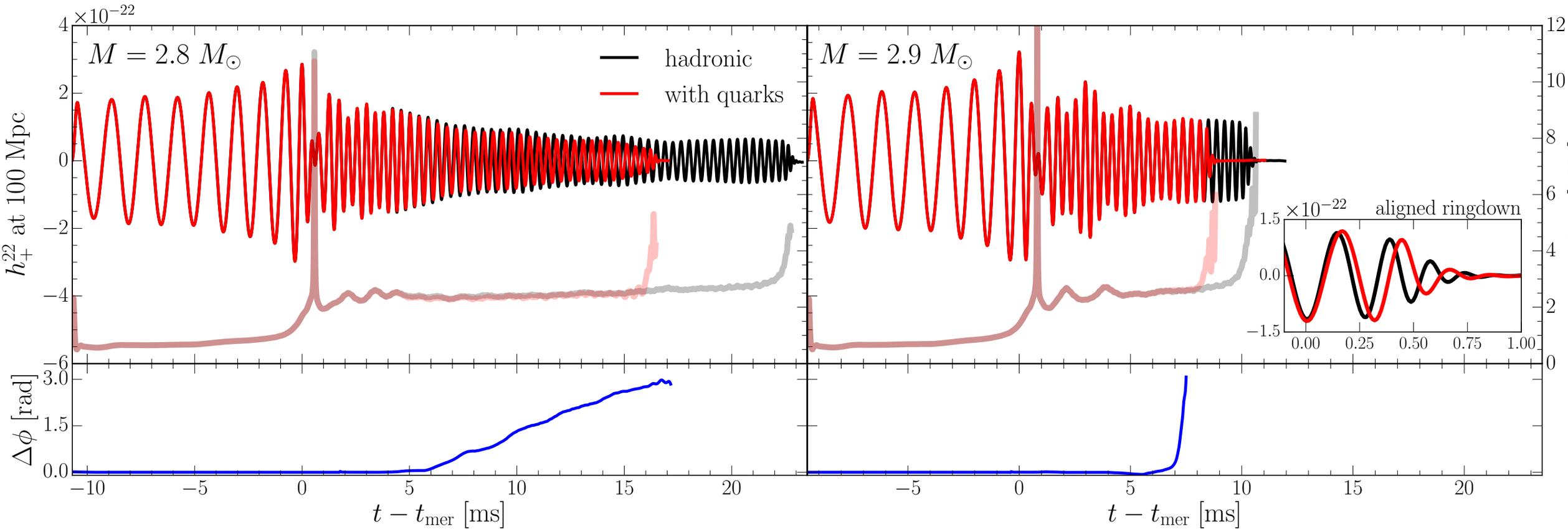
- Small fraction of quarks is present in hot regions at all times (*cross-over transition*)

- Hot quark core is formed as soon as the phase transition sets in

- Quark phase is unstable and triggers early collapse

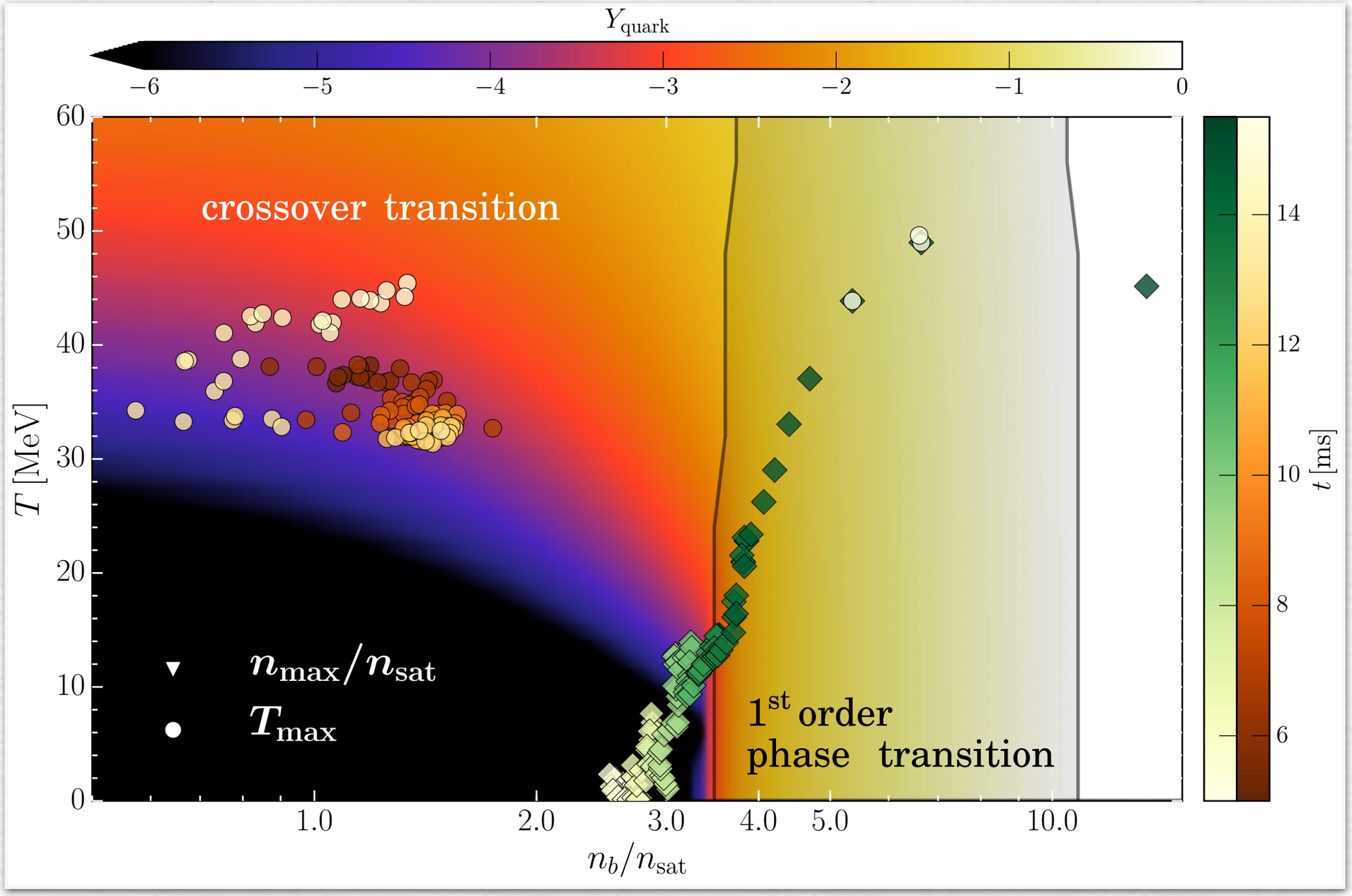
Can quarks be seen in gravitational waves?

- No quarks are present in the inspiral phase !



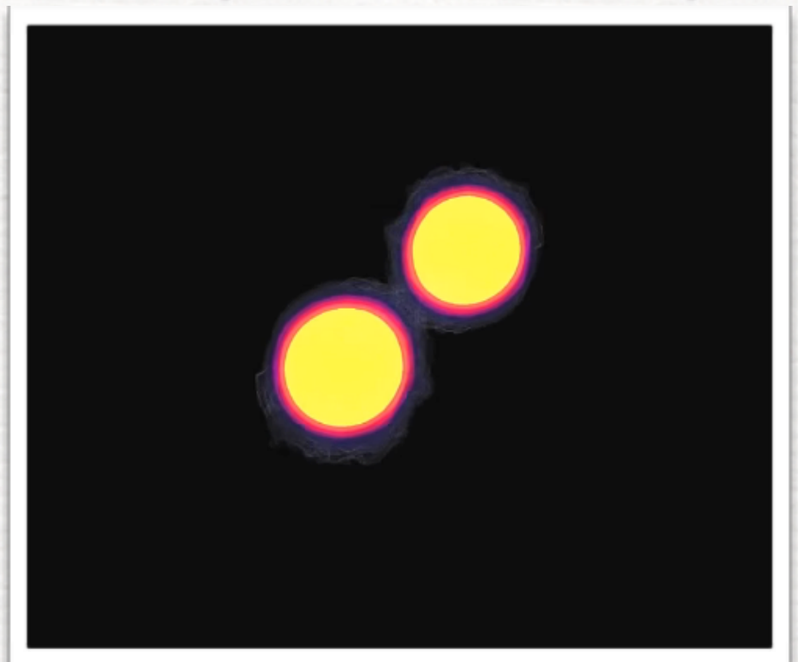
Continued presence of small quark fraction leads to a de-phasing of the waveform in the post merger

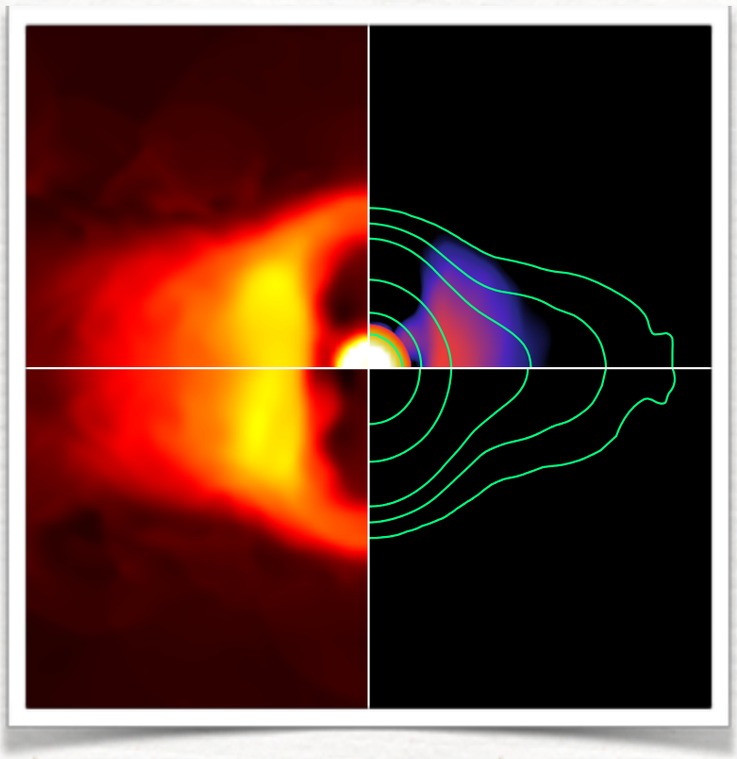
Mergers in the phase diagram



Can quarks be seen in gravitational waves?

- A quark phase transition in the inspiral is hard to spot. If quarks are already present in the stars, they will most likely have small Λ
- Large neutron stars at high masses can rule out such twin solutions!





- Small amounts of quarks in the merger already cause a de-phasing of the waveform
- If the quark phase collapses to a black hole the ringdown is modified