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Strong phase transitions in neutron star mergers

Polish-German WE-Heraeus Seminar & Max Born Symposium Many-particle systems under extreme conditions, 05/12/2023

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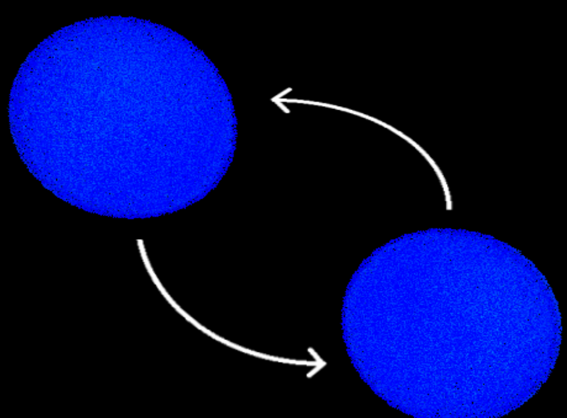
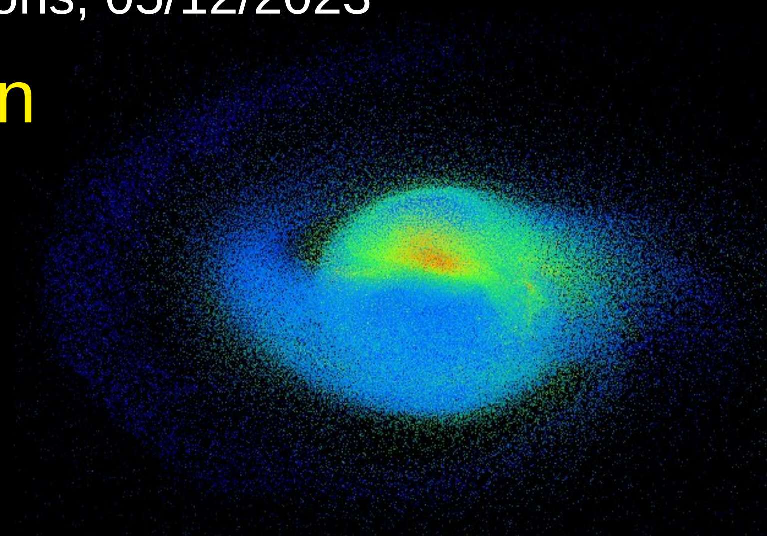
(GSI Darmstadt)





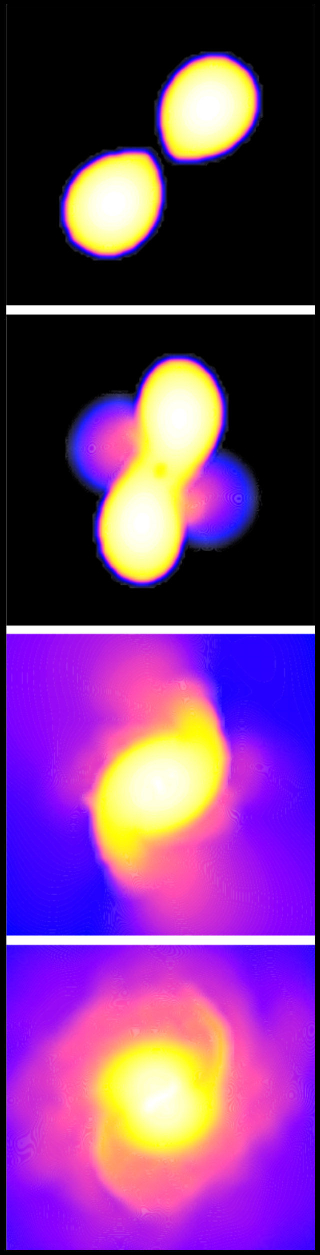
with N. Bastian, S. Blacker, D. B. Blaschke, K. Chatziioannou, M. Cierniak, J. A. Clark, T. Fischer, O. Ivanytskyi, G. Lioutas, M. Oertel, T. Soultanis, N. Stergioulas, S. Typel, V. Vijayan

Outline

- Overview NS mergers
- Postmerger gravitational-wave signal of NS mergers → signature of phase transition
- Constraints on onset density of phase transition
- Black hole formation NS mergers → signature of phase transition
- Electromagnetic counterparts = “kilonovae”
- Thermal properties of hybrid EoSs

NS mergers as probes for fundamental physics

- Properties of NS and NS binary population, host galaxies
- Origin of short gamma-ray bursts (and related emission)
- Origin of heavy elements like gold, uranium, platinum
- Origin of electromagnetic transient (kilonova, marconova)
- Properties of nuclear matter / NS structure
- Occurrence of QCD phase in NS
- Independent constraint on Hubble constant
- ... !!!

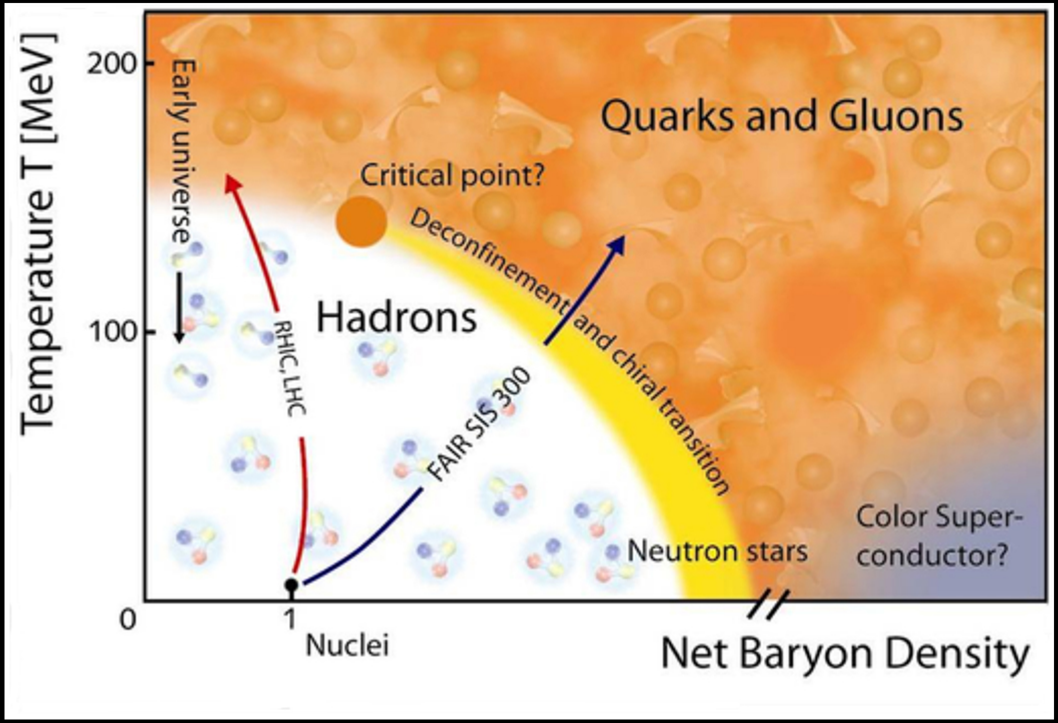


Motivation

- Does the phase transition to deconfined quark matter occur in NSs ?

  i.e. at densities of a few times nuclear saturation ?

- Can we possibly even learn something about the properties of this phase transition and the properties of (hot) quark matter ?



GSI

Motivation

- Does the phase transition to deconfined quark matter occur in NSs ?

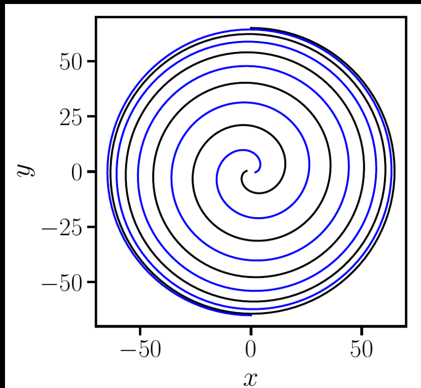
  i.e. at densities of a few times nuclear saturation ?
- Can we possibly even learn something about the properties of this phase transition and the properties of (hot) quark matter ?

- Generally:

  → impact on stellar structure, e.g. kink or jump in mass-radius relation

  → cooling, transport coefficients
- core-collapse supernovae, e.g. Fischer et al., Nature Astronomy (2018), ...
- In mergers:

  → impact on dynamics and thus on GW signal, BH formation, em counterparts, ...



$P_{orb} \sim 10\,h$

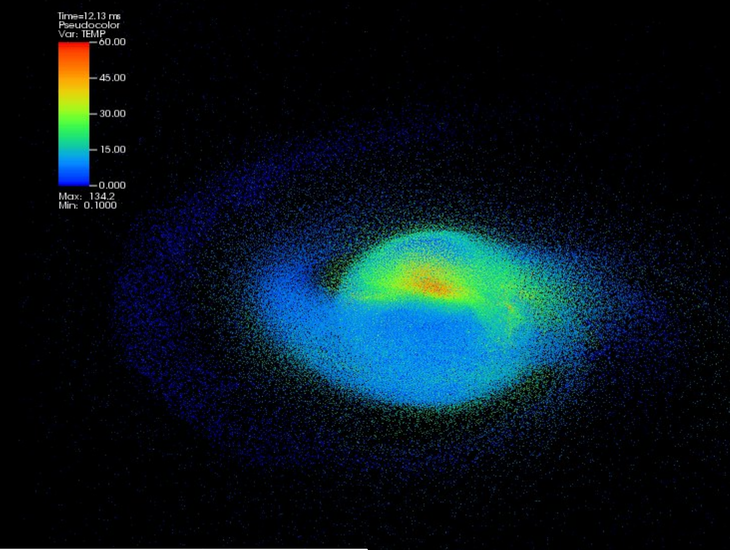
Inspiral of NS binary

~100 Myrs

$P_{orb} \sim 1\,ms$

Neutron star merger

dependent on EoS, M_{tot}

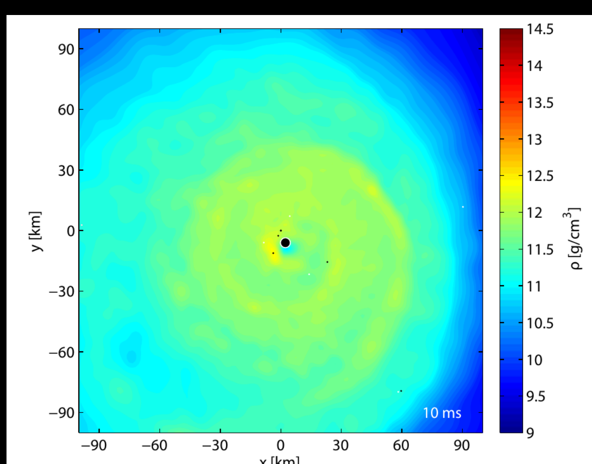


ms

ms

Prompt formation of a BH + torus

Formation of a differentially rotating massive NS

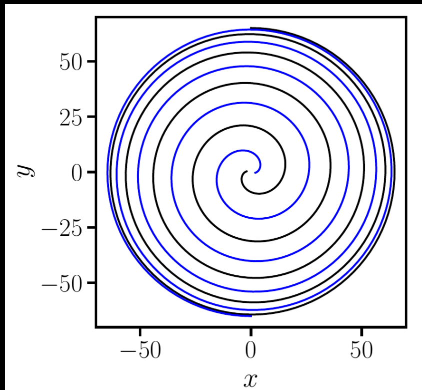


dependent on EoS, M_{tot}

10-100 ms

Rigidly rotating (supermassive) NS (stable or long-lived)

Delayed collapse to a BH + torus



$P_{orb} \sim 10\,h$

Inspiral of NS binary

~100 Myrs

GW (~100 Hz)

Binary masses, …

Tidal deformability

$P_{orb} \sim 1\,ms$

Neutron star merger

dependent on EoS, M_{tot}

ms

ms

GW (~kHz)

Oscillations of remnant

(not yet in 170817)

Prompt formation of a BH + torus

Formation of a differentially rotating massive NS

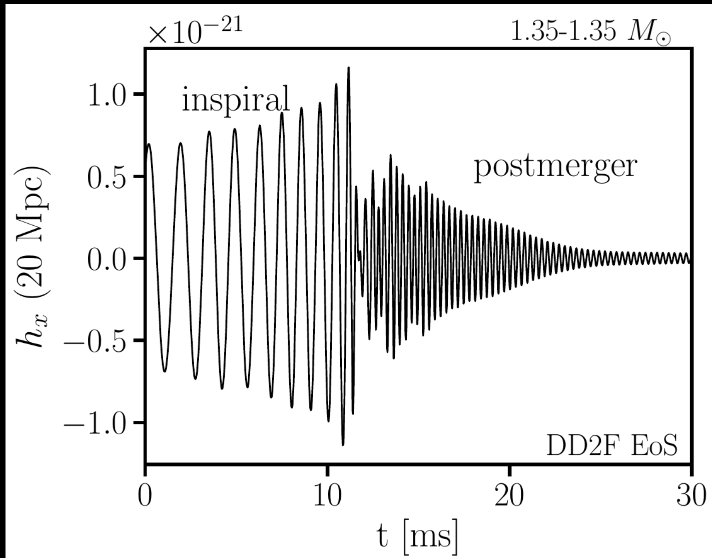
dependent on EoS, M_{tot}

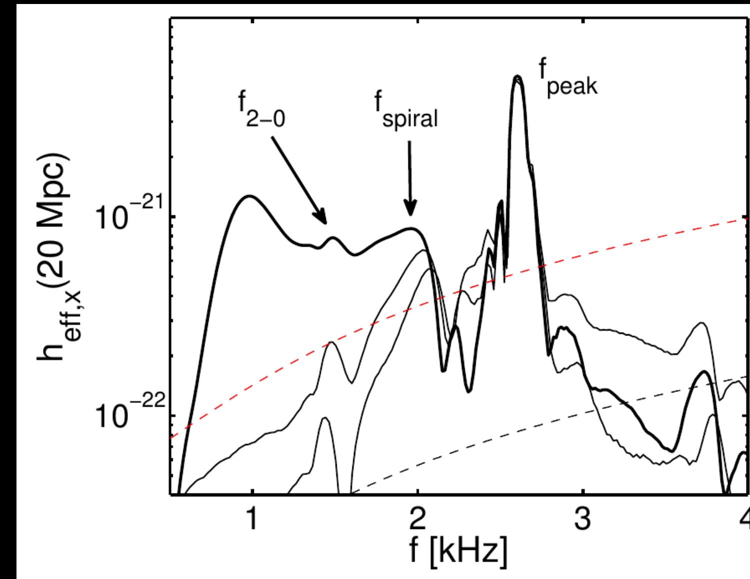
10-100 ms

Rigidly rotating (supermassive) NS (stable or long-lived)

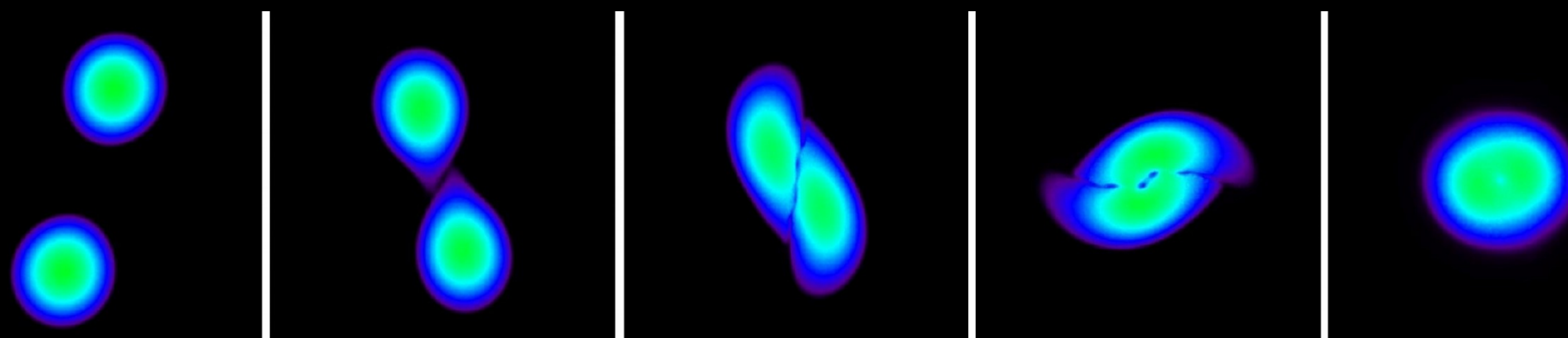
Delayed collapse to a BH + torus

Simulations





Bauswein et al. 2016



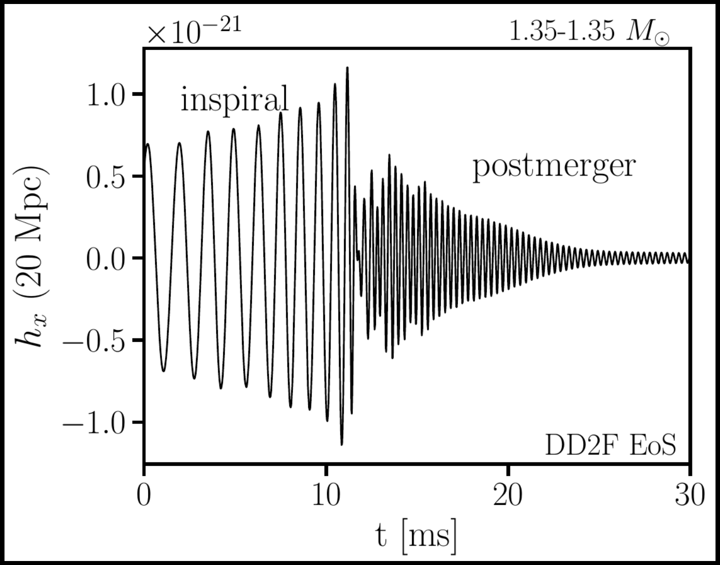
Finite-size effects, i.e. EOS impact, during insprial described by tidal deformability Λ

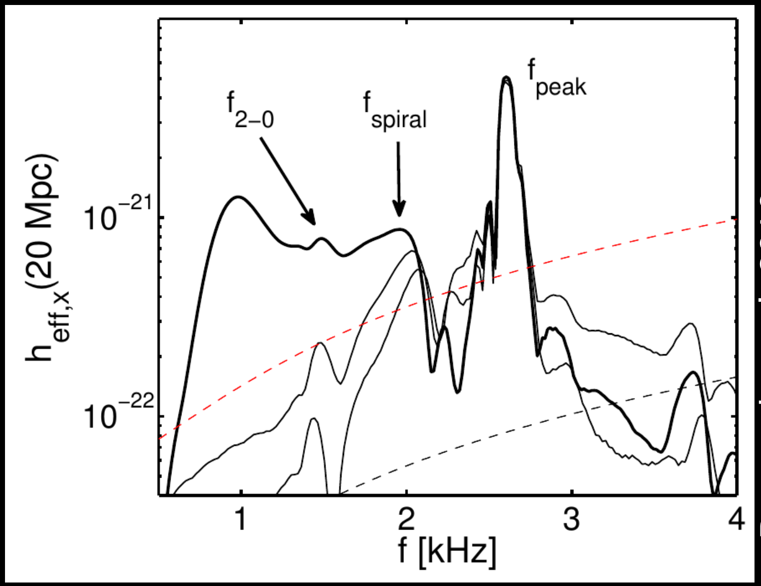
Larger stars /stiffer EOS accelerate inspiral

Dominant remnant oscillation generates pronounced GW peak f_{peak}

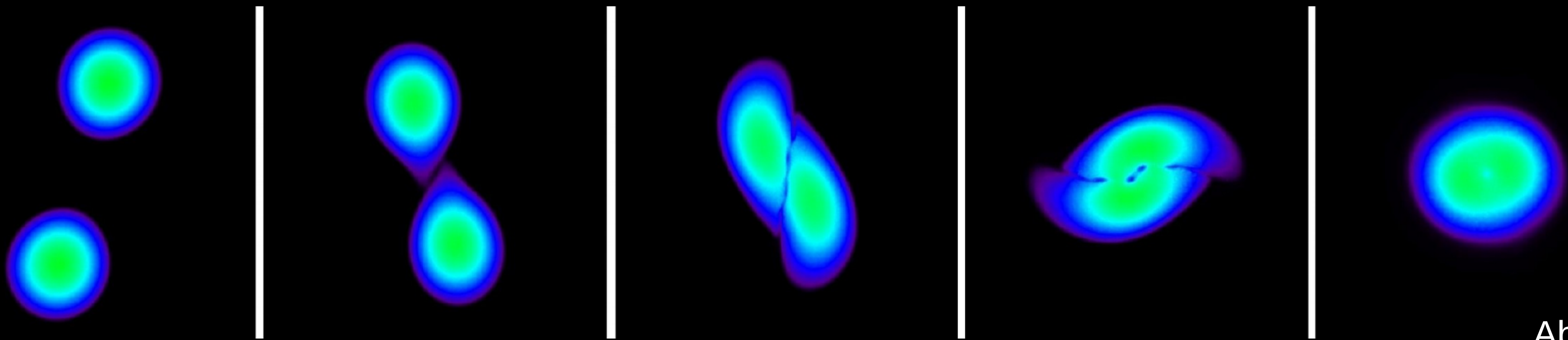
More compact remnants/softer EOS higher f_{peak}

Simulations

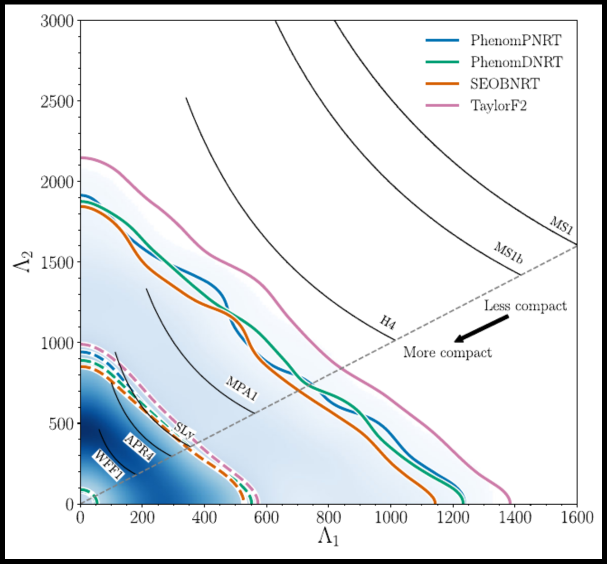




Bauswein et al. 2016



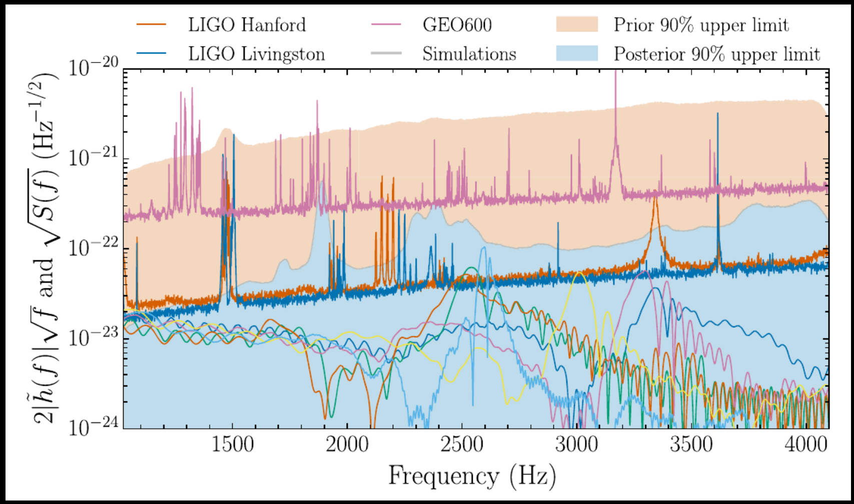
Observations



Abbott et al. 2019

GW170817:
EoS constraint
from GW inspiral:
tidal deformability
Λ<650; R<13.5 km

Abbott et al. 2019



GW170817: postmerger not yet measured but within reach

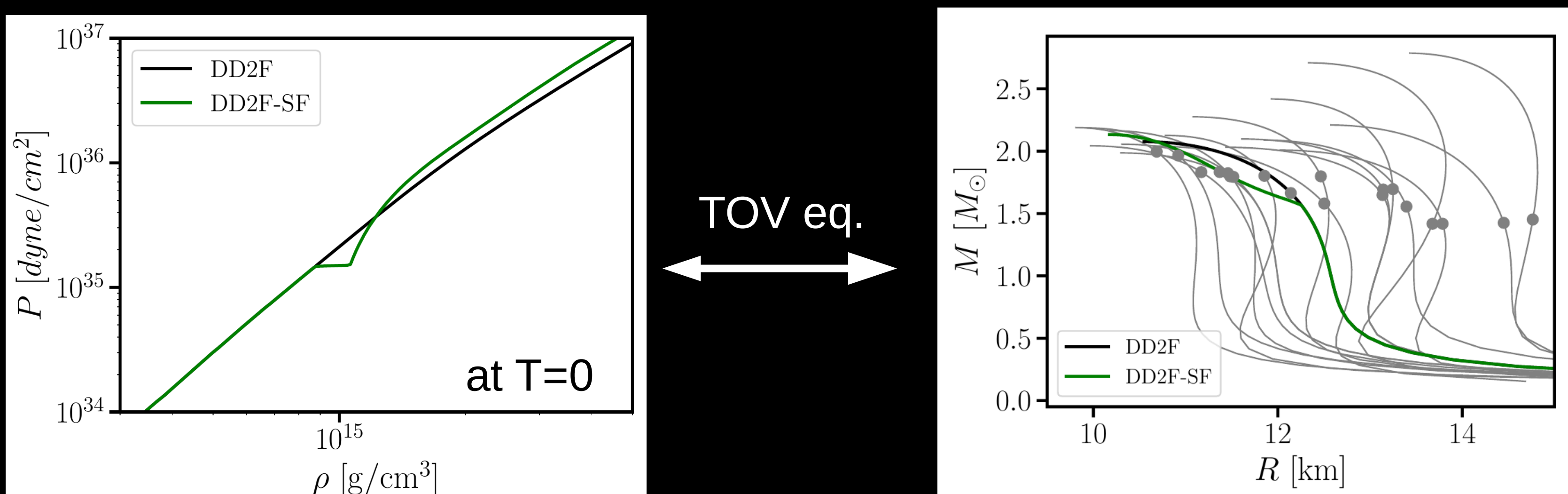
Impact of quark matter on GW signal

$\rightarrow$ we test EoS models in simulations and identify signatures

EoS with 1st-order phase transition to quark matter

- Which impact has a PT to deconfined quark matter on NS mergers ?

  → relativistic hydrodynamical simulations adopting (temperature dependent) EoS



Bauswein et al., PRL 122 (2019)

- EoS from Wroclaw group (Fischer, Bastian, Blaschke; see Kaltenborn et al 2017, Fischer et al. 2018, Bastian et al 2018, Bastian 2020) – as one example for an EoS with strong 1st-order phase transition to deconfined quarks

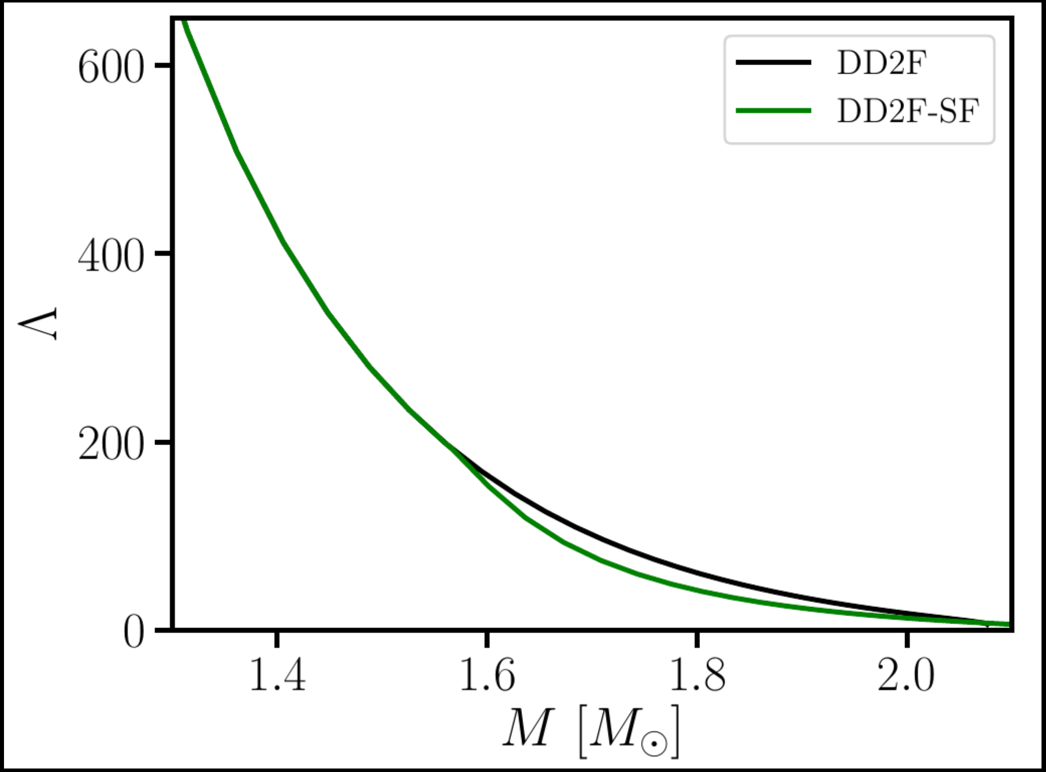
  → many different models available with differently strong impact on stellar structure

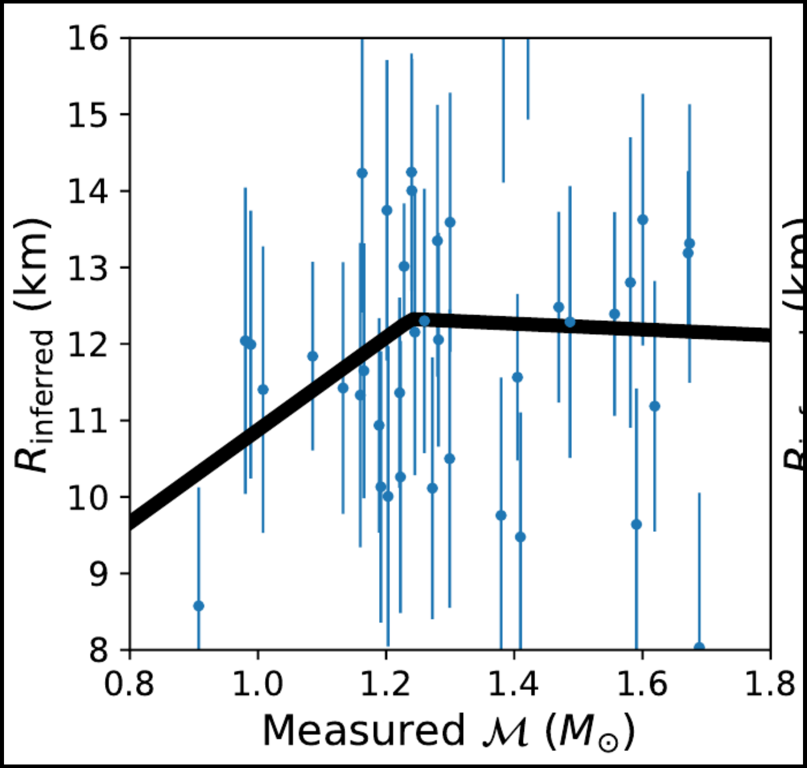
- RMF (density -dependent couplings) + two-flavor string flip model (Maxwell construction), temperature dependent (important: thermal pressure, temperature-dep. phase boundary)
- Compatible with recent constraints from GW170817 and pulsar measurements

Phase transition and the GW inspiral

- Even strong phase transitions leave relatively weak impact on tidal deformability

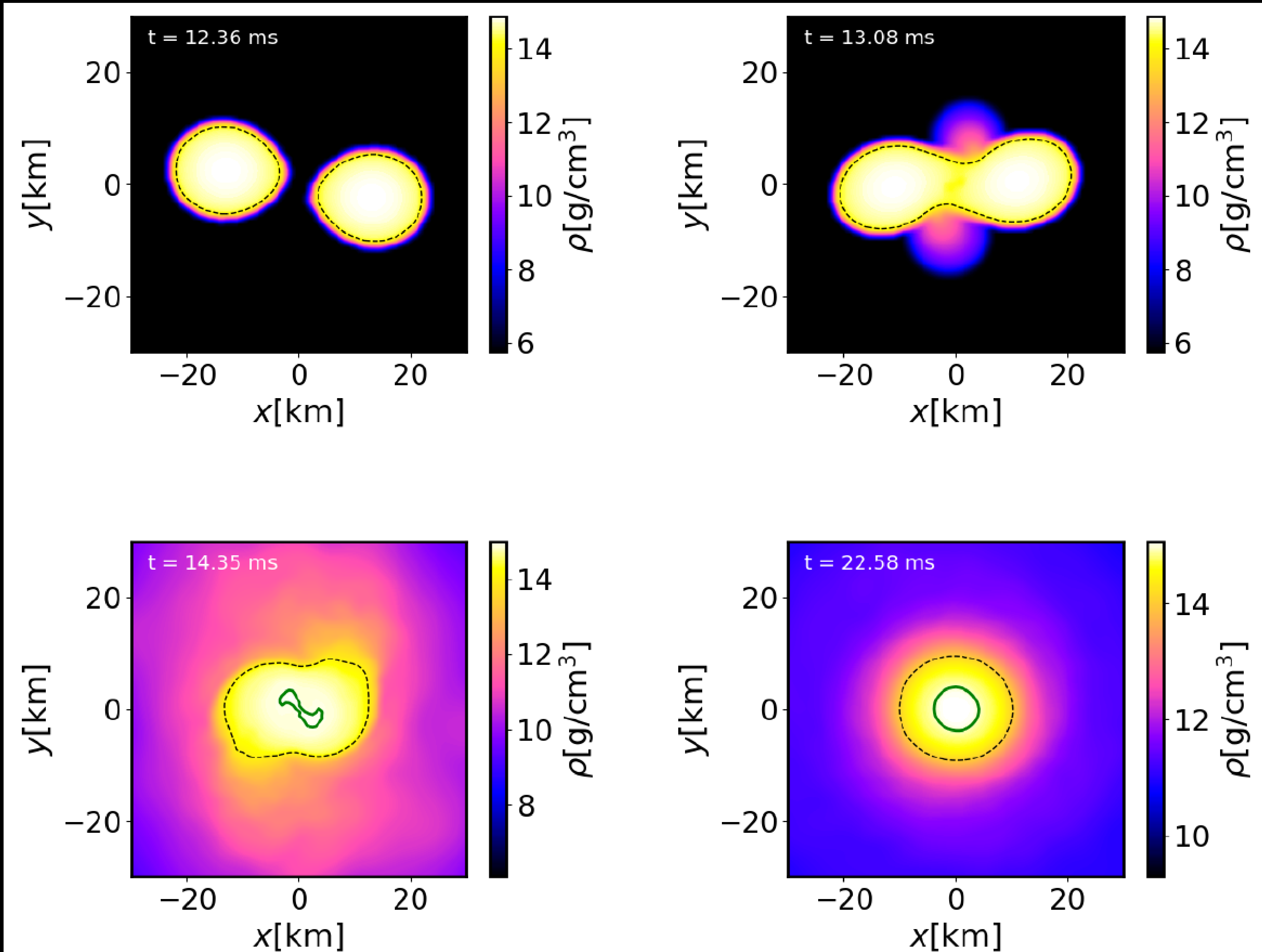
  → challenging to measure transition in mergers through inspiral: Kink weak, Lambda generally very small, high mass star probably less frequent





Chen et al 2020

→ see e.g. Chen et al. 2020, Chatzioannou & Han 2020 using multiple (~100) events

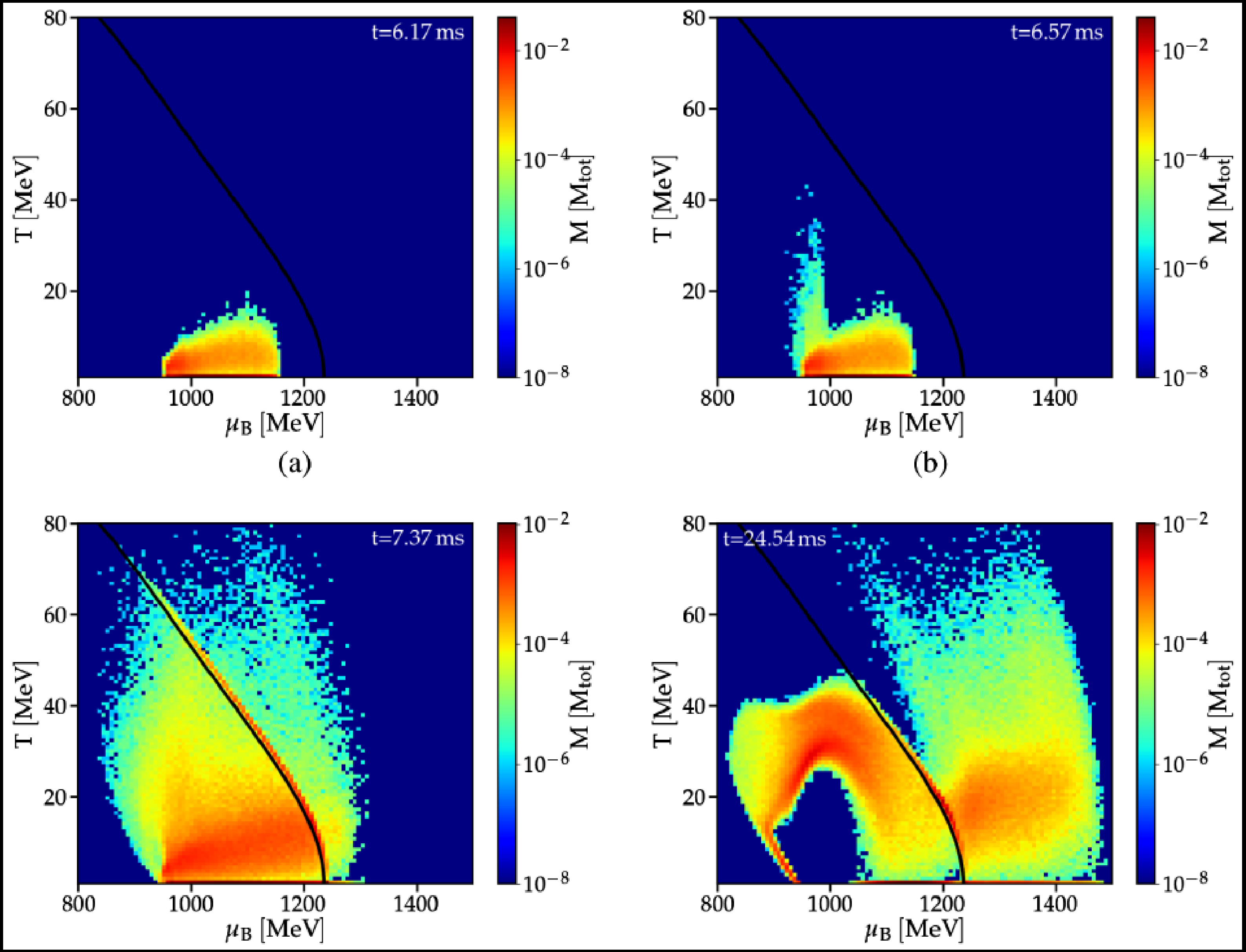


1.35-1.35 Msun - DD2F-SF-1

Bauswein et al., AIP (2019)
ArXiv:1904.01306

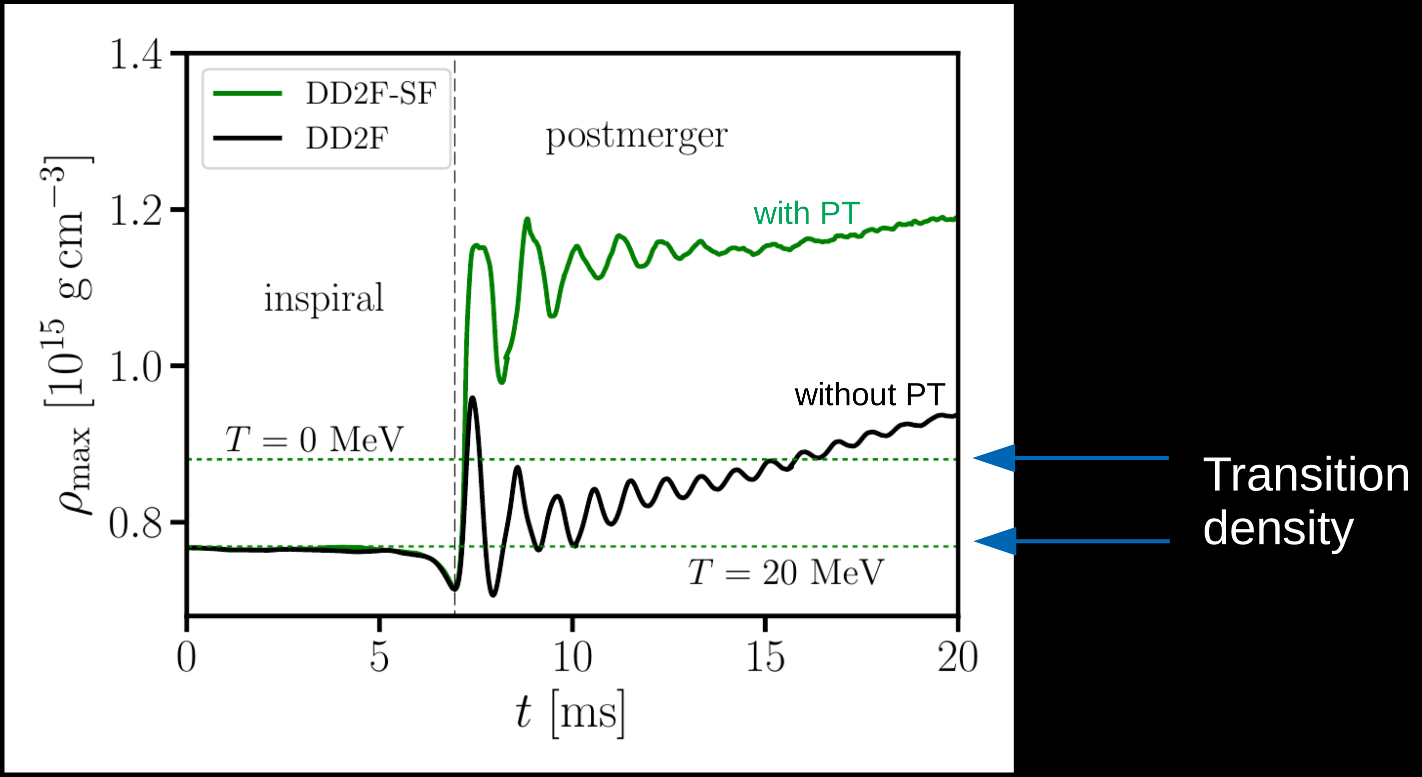
NS merger in the phase diagram

Blacker et al. 2020



- Simulation: 1.35-1.35 Msun merger, EoS model with 1st order phase transition (EoS from Wroclaw group); see also, e.g., Most el al. 2019, Hanauske et al. 2021

Merger simulations

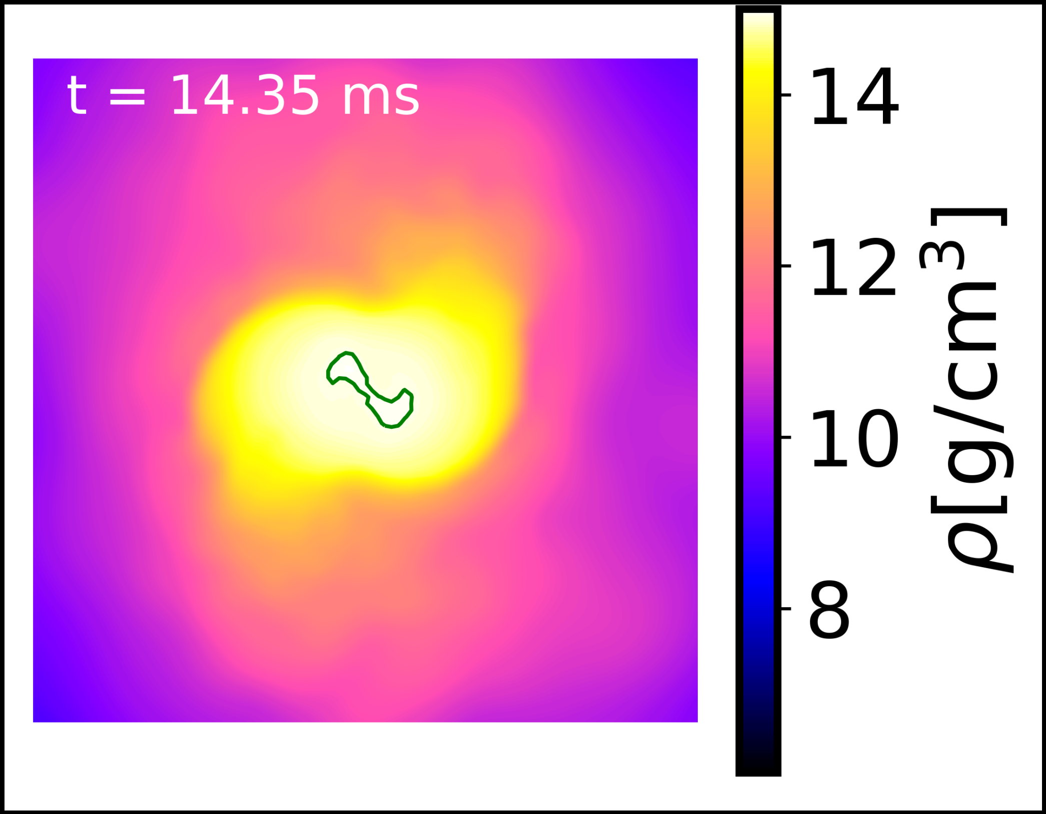


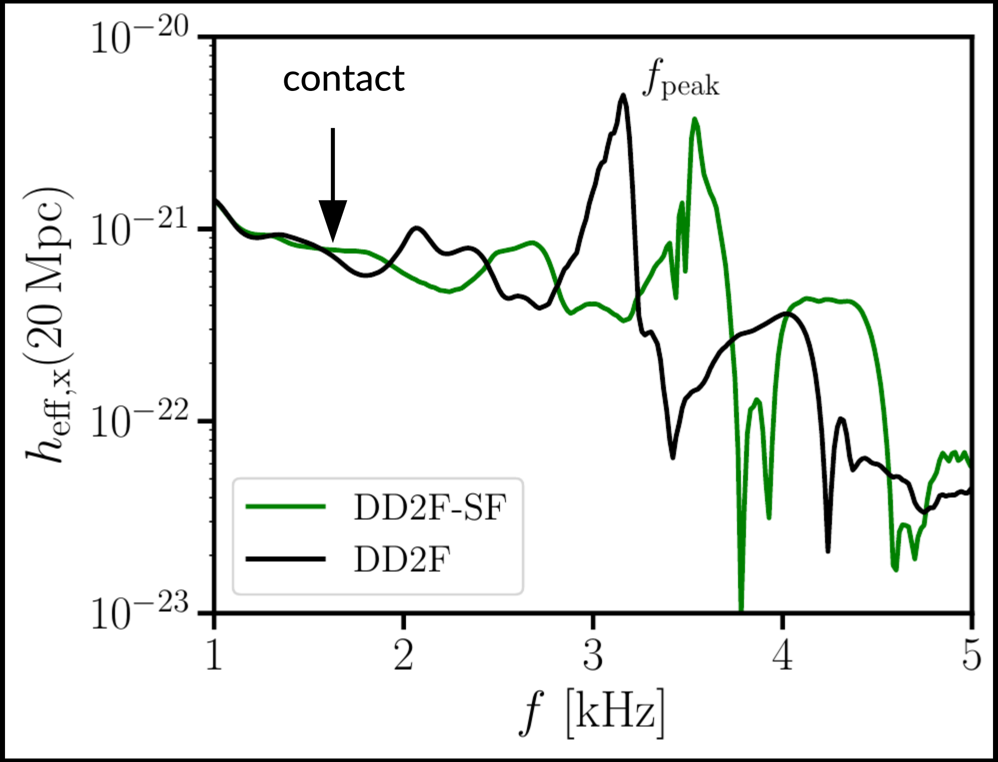
Bauswein et al. 2019

- Softer EoS “needs more density” to provide sufficient pressure support

Merger simulations

- GW spectrum 1.35-1.35 Msun





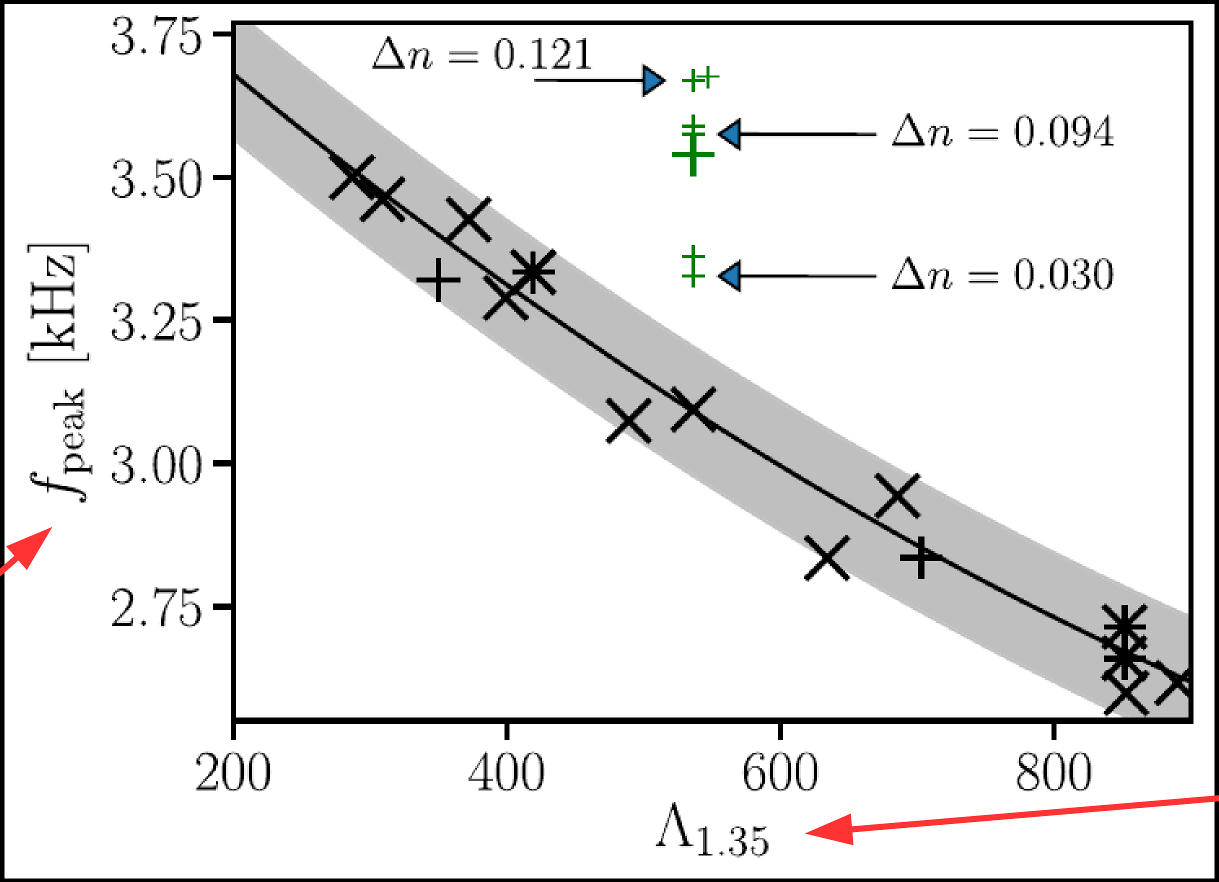
Bauswein et al. (2019)

But: GW frequencies are generally affected by EOS – Is it unambiguous for quark matter ?

(→ show that all purely baryonic EoS behave differently)

Signature of 1st order phase transition

from postmerger



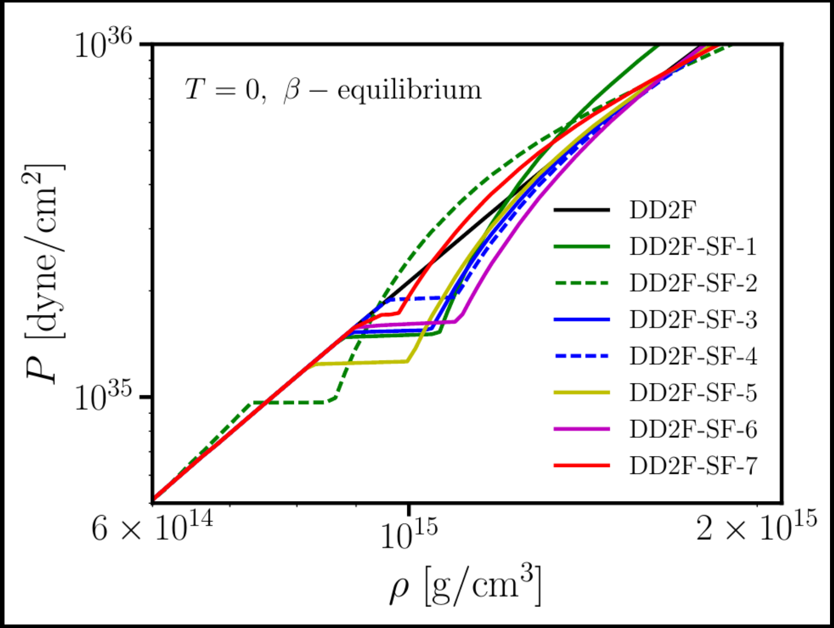
from the inspiral

Bauswein et al. (2019)

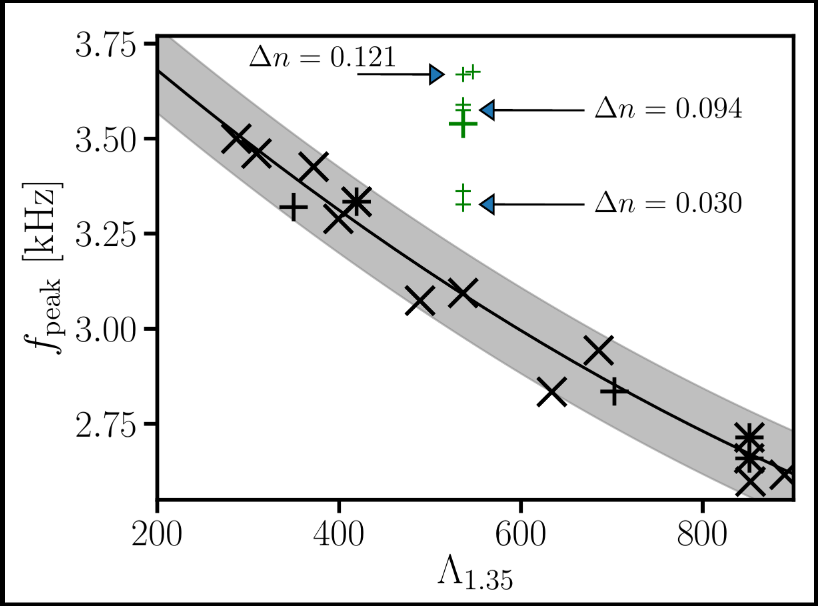
- Tidal deformability measurable from inspiral to within 100-200 (Adv. Ligo design)
- Postmerger frequency measurable to within a few 10 Hz @ a few 10 Mpc (either Adv. Ligo or upgrade: e.g Clark et al. 2016, Chatzioannou et al 2017, Bose et al 2018, Torres-Rivas et al 2019)
- Important: “all” purely hadronic EoSs (including hyperonic EoS) follow fpeak-Lambda relation → deviation characteristic for strong 1st order phase transition

More models

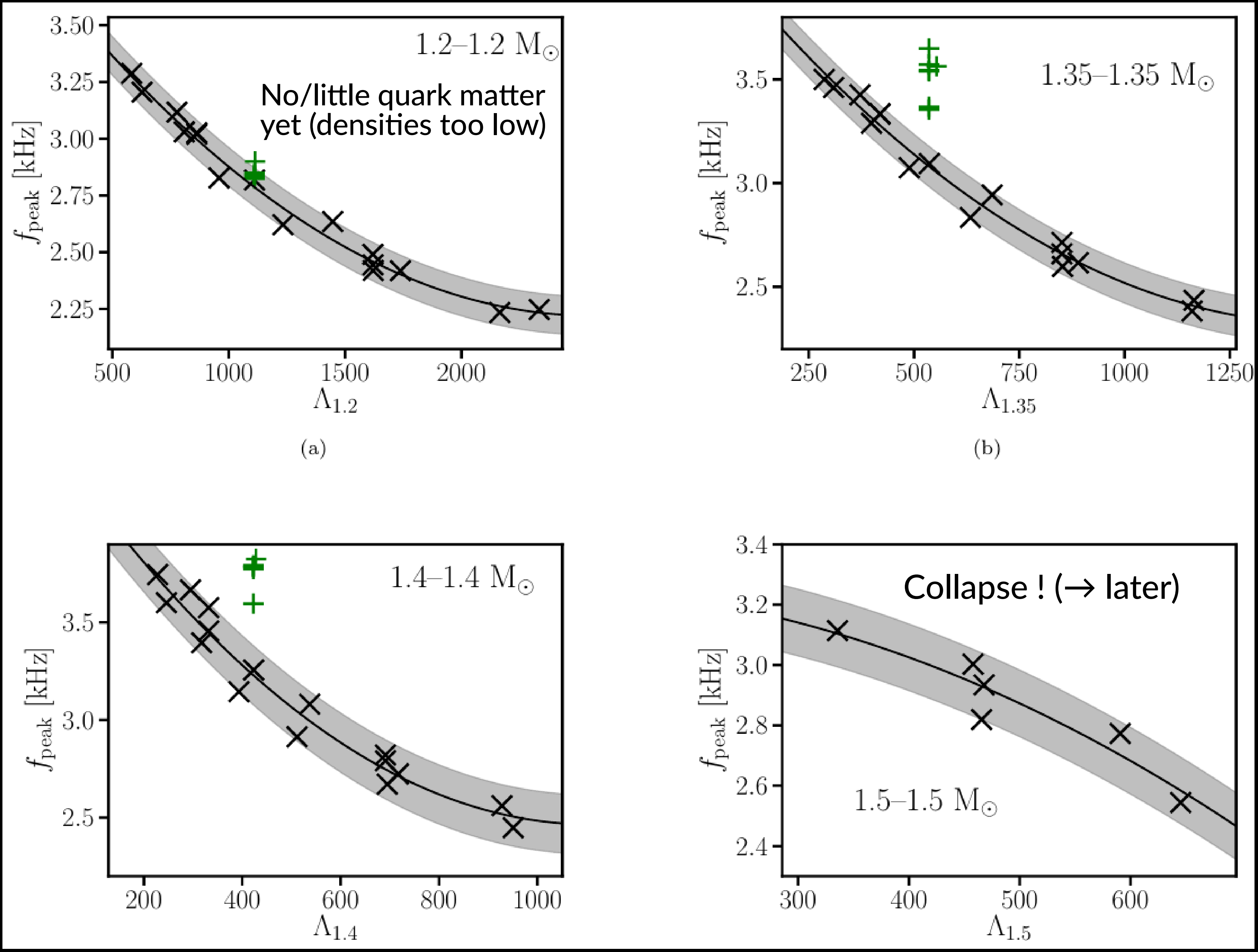
- Larger density jump → stronger compactification → more significant increase of fpeak (keeping other EoS parameters fixed)
  → generally effect depends on “strength” of phase transition
- unequal-mass mergers lead to similar behavior, higher total binary mass



Different parametrization of quark phase

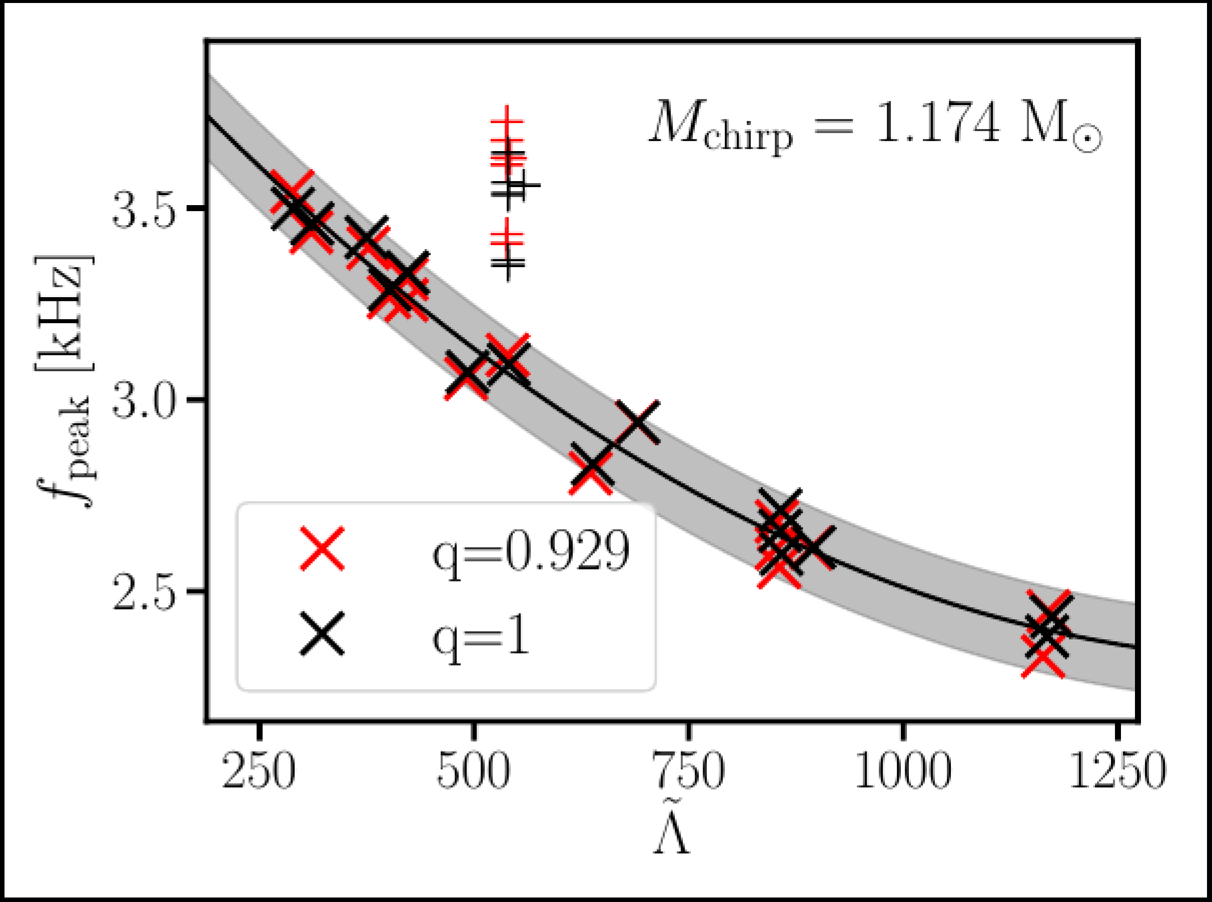


Bauswein et al. (2019)



Blacker et al. (2020), arXiv:2006.03789

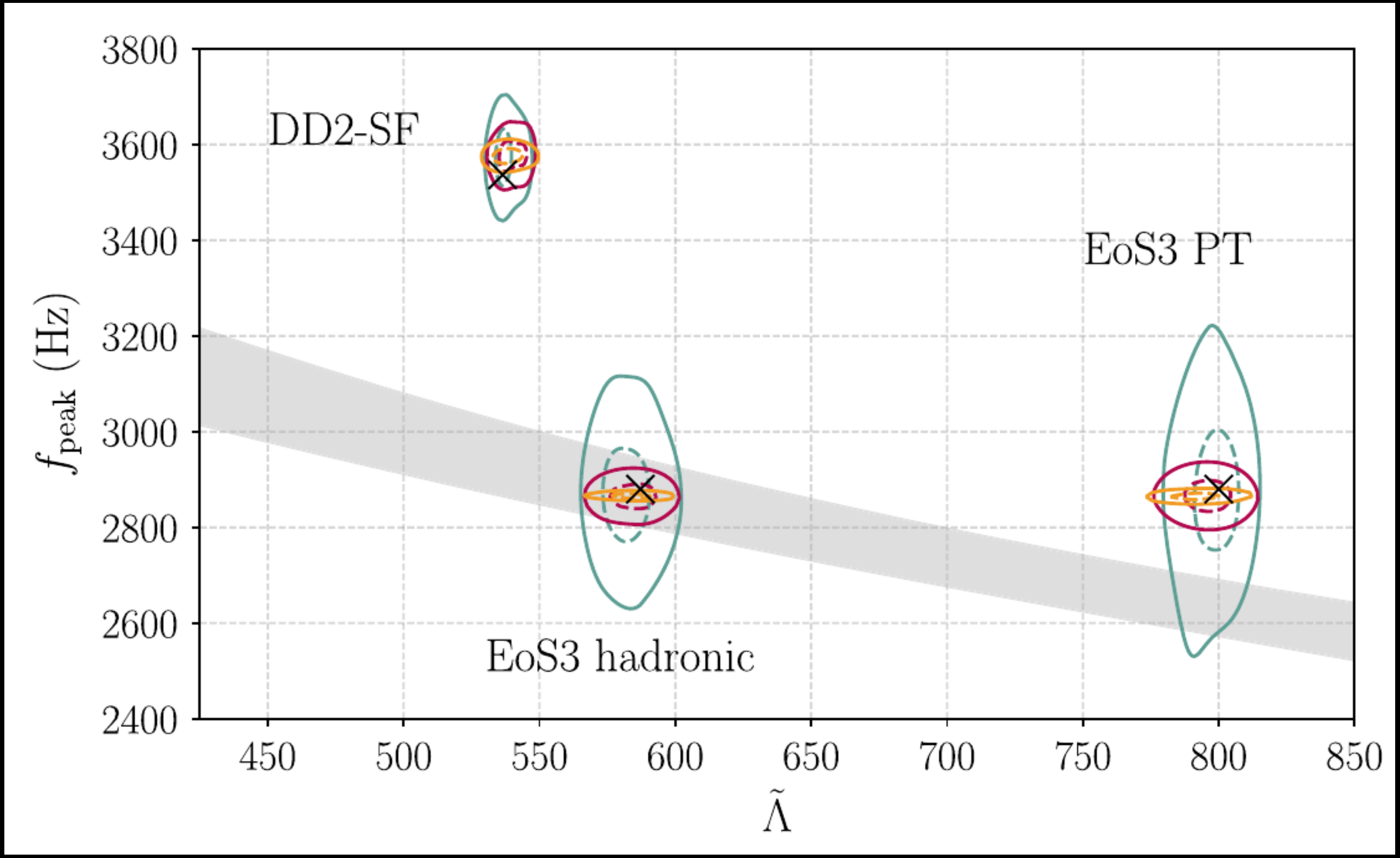
- Signature also present in asymmetric mergers



Blacker et al. 2020

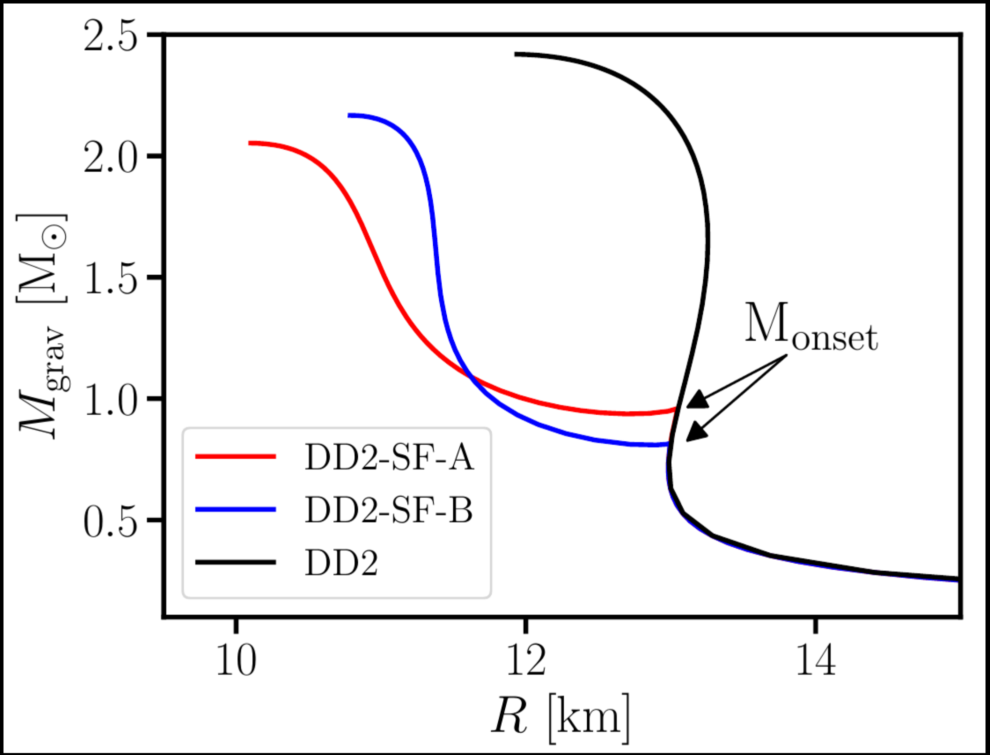
GW data analysis

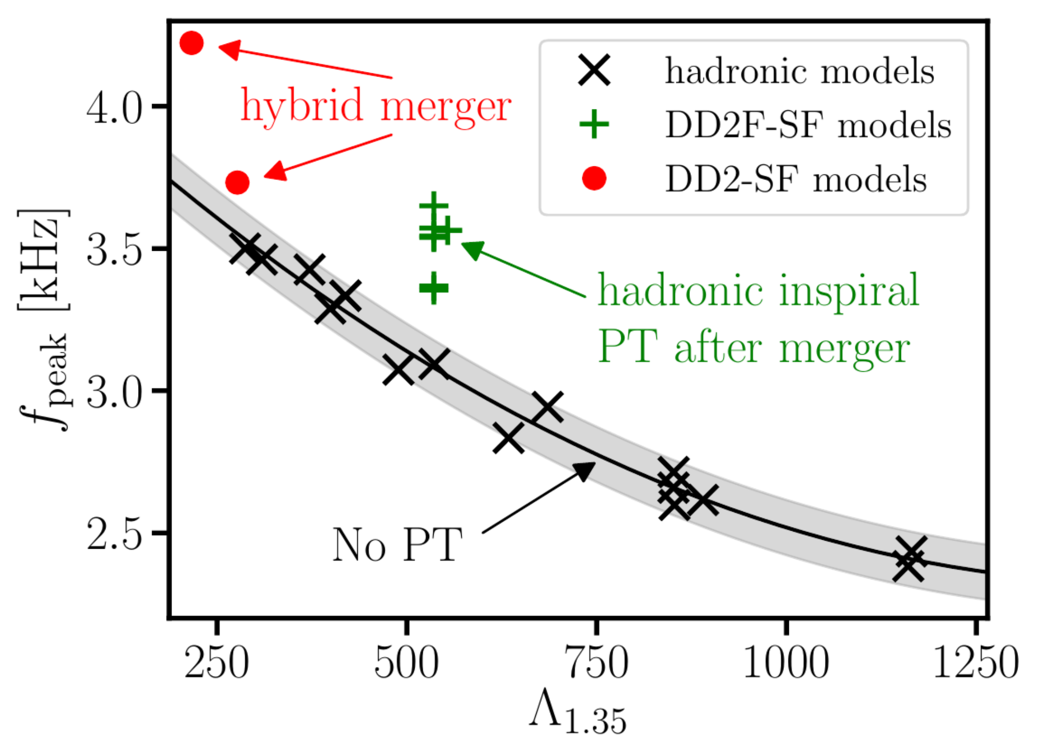
- Recovery of injected waveforms as proof of principle for GW data analysis
  → signature of quark matter measurable



Wijngaarden et al., PRD 2022

- Hybrid star mergers → similar signature
- Finally only relevant for very low onset-density





Bauswein & Blacker, EPJ ST (2020), arXiv:2006.16183

Constraints on the onset density

- Summary: Compare fpeak and Lambda

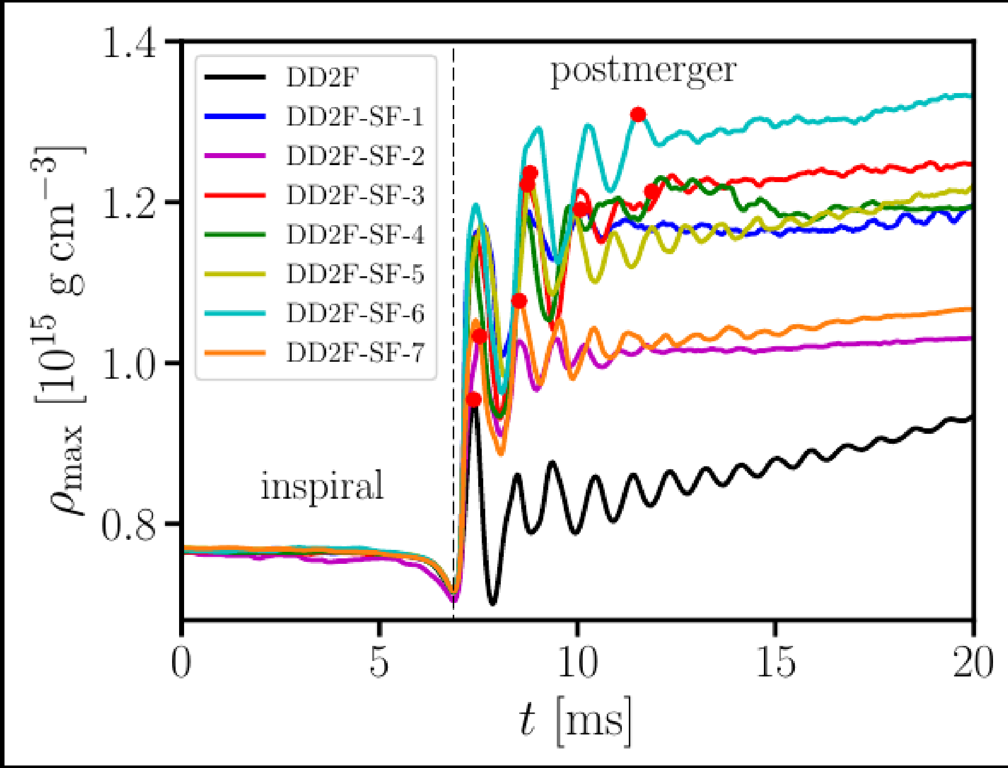
  - fpeak compatible with hadronic (gray band) → No PT (for measured binary masses)

  - fpeak increased → PT

- What does this imply for the onset density of the phase transition ?

Merger probes EoS only up to maximum density in remnant !!!

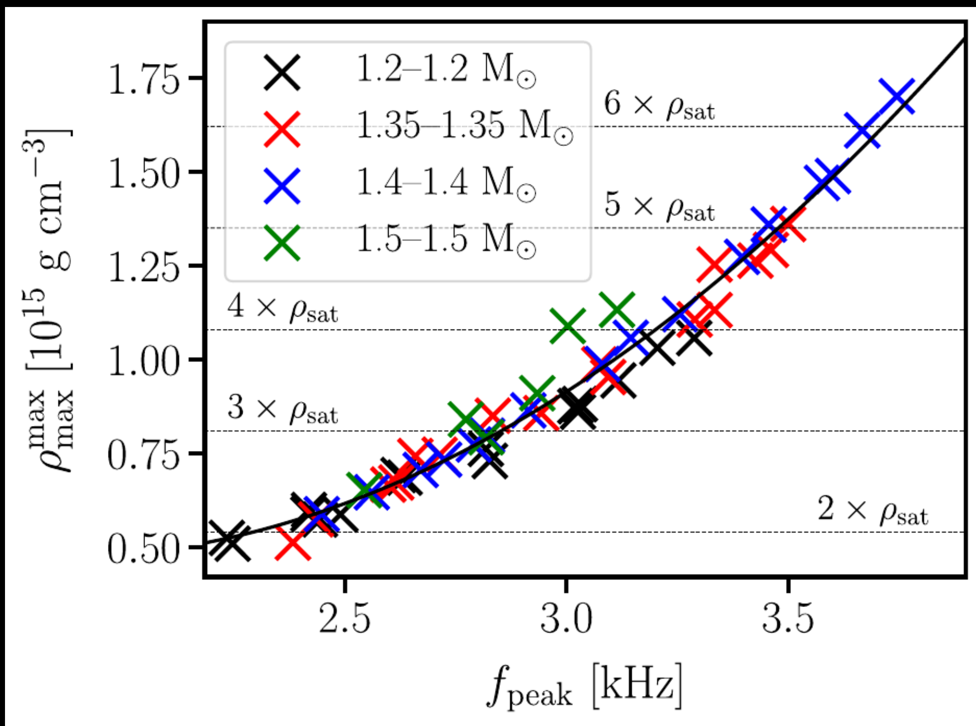
→ Hence we can exclude PT up to this density - or the PT must have occurred below that density !!!

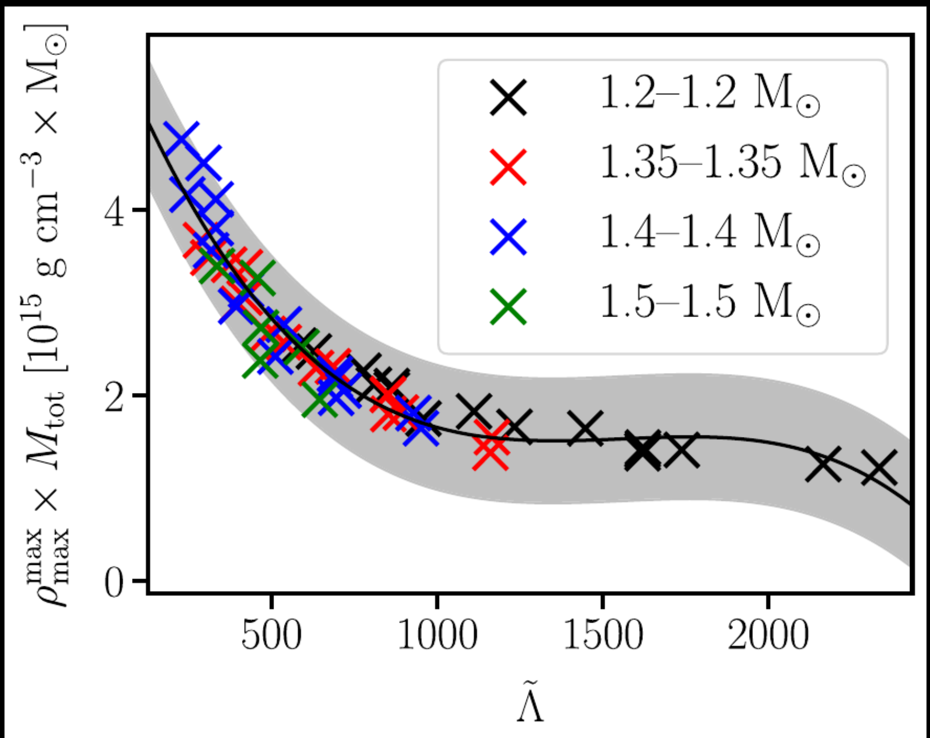


Blacker et al. (2020)

- GWs inform about highest density in the remnant !!!

  → constraint on onset density (if PT is present or not)





Postmerger frequency fpeak

tidal deformability from inspiral

Blacker et al. (2020)

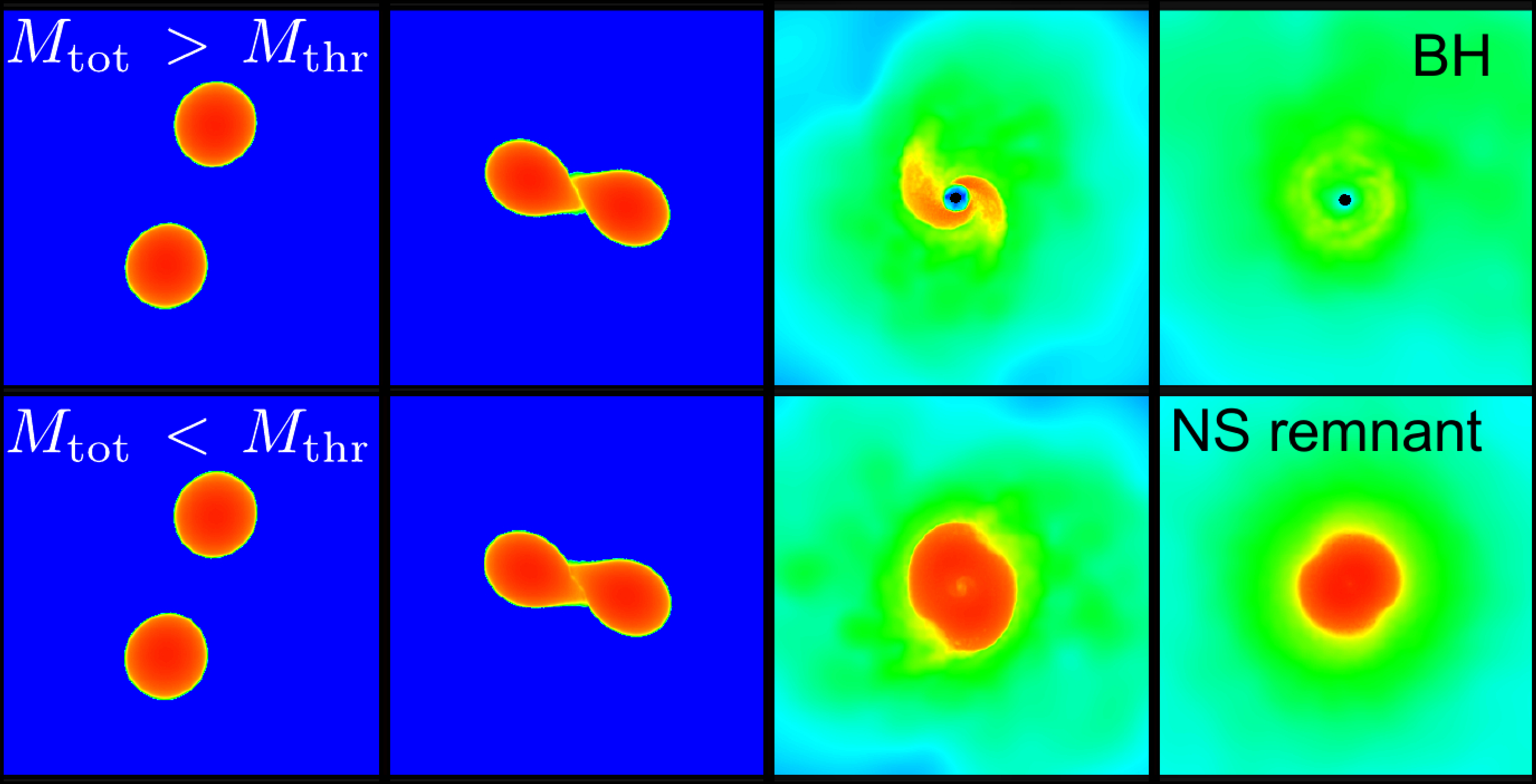
More EoS models

- Hybrid mergers, i.e. PT before merger, similarly show frequency increase (Bauswein & Blacker 2020)
- Also for other hadronic models frequency shifts expected (Bauswein & Blacker 2020, Prakash et al 2021)
- Possibly delayed occurrence of PT (shown for piecewise polytrope and simplistic thermal treatments; Weih et al. 2020)
- PT can lead to faster delayed collapse during postmerger (Most et al. 2019)
- Cross-over (but with simplistic thermal treatment; Huang et al 2022, Fujimoto et al. 2023)

- In general: “masquerade” problem challenging (Alford et al 2005)

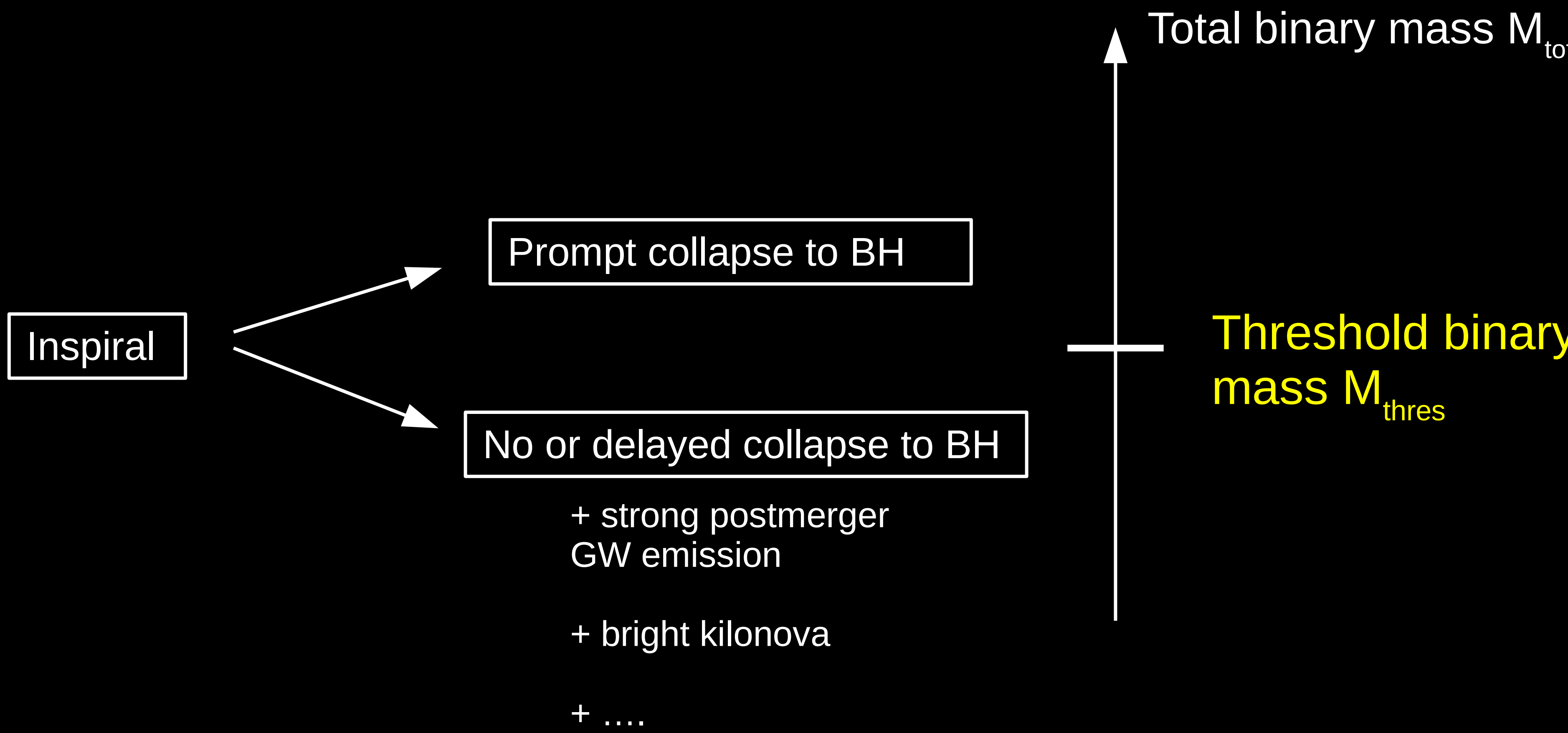
Collapse behavior

Collapse behavior



Central quantity describing BH formation and carrying EOS information: M_{thres}

Collapse behavior



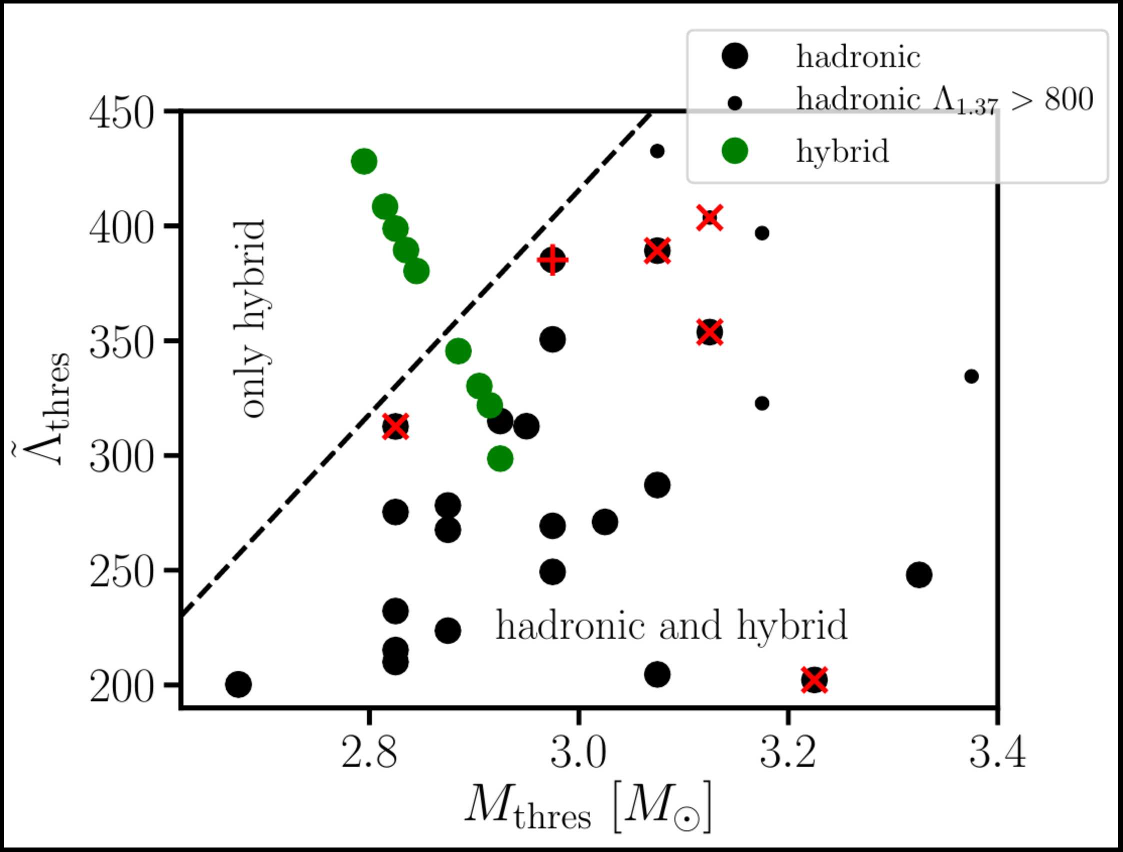
M_{thres} - EoS dependent (weakly on mass ratio) !!!

Does a phase transition have an impact on the collapse behavior ?

QCD phase transition from collapse behavior

- Directly measurable from events around M_{thres}
- Already single events yielding constraints may indicate presence of quark matter

With M_{max} > 1.97 !!



Bauswein et al., PRL 125 (2020)

Measurable from GW inspiral

Measurable from inspiral + information on merger product

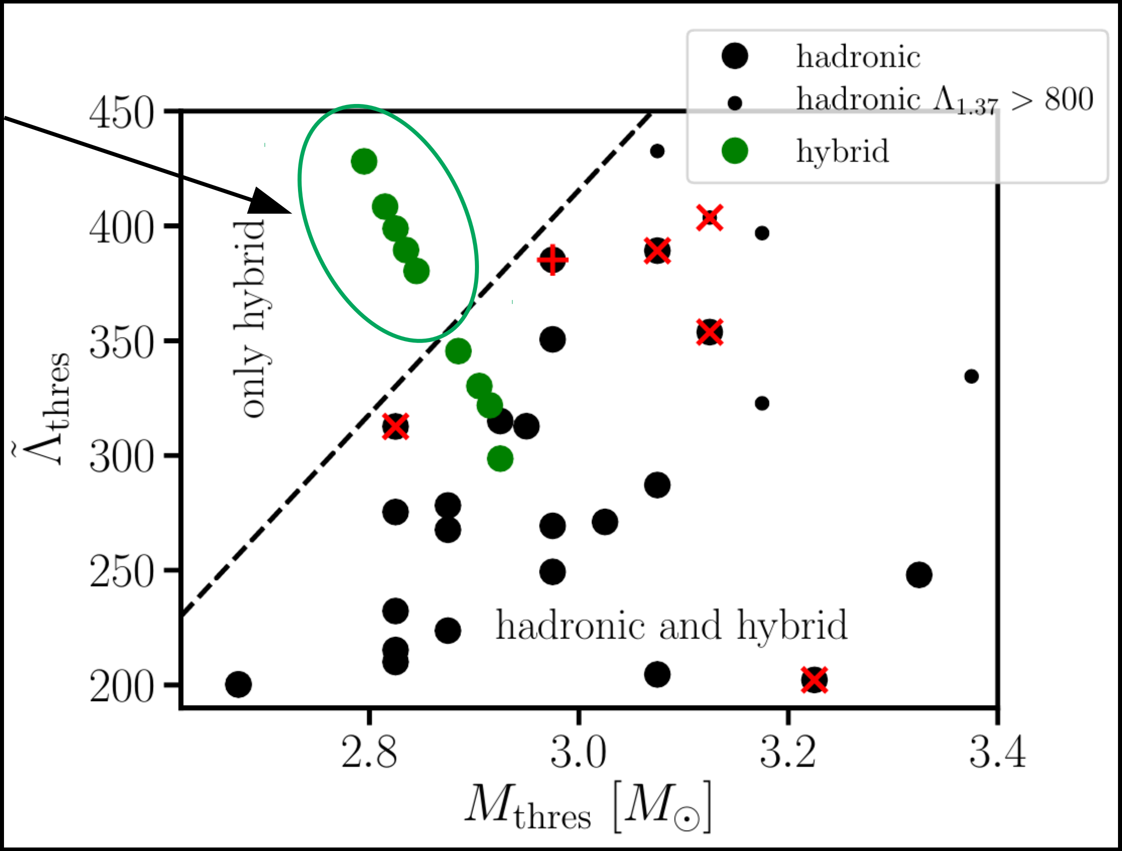
$$\tilde{\Lambda}_{\rm thres} = \Lambda(M_{\rm thres}/2)\ \ \text{for}\ \ q = 1$$

QCD phase transition from collapse behavior

- Directly measurable from events around M_{thres}
- Already single events yielding constraints may indicate presence of quark matter

Evidence for quark matter

With M_{max} > 1.97 !!



Bauswein et al., PRL 125 (2020)

Measurable from GW inspiral

Measurable from inspiral + information on merger product

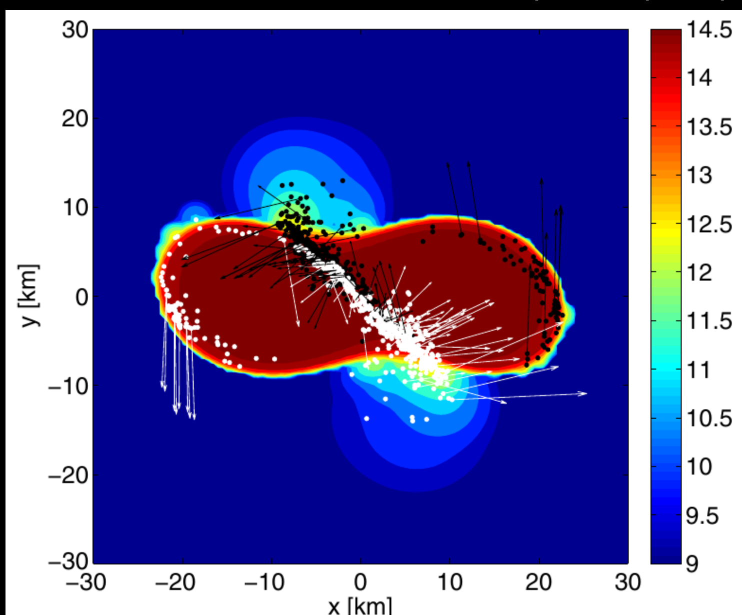
$$\tilde{\Lambda}_{\mathrm{thres}} = \Lambda(M_{\mathrm{thres}}/2) \ \text{for} \ \ q = 1$$

Optical counterpart generated by mass ejection

Basic picture

- Mass ejection → rapid neutron-capture process → heating the ejecta
  → (quasi-) thermal emission in UV – optical – IR observable (time scales ~ hours)
- Different ejecta components: dynamical ejecta, secular ejecta from merger remnant
- Mass ejection depends on binary masses and **EoS** → imprinted on electromagnetic emission

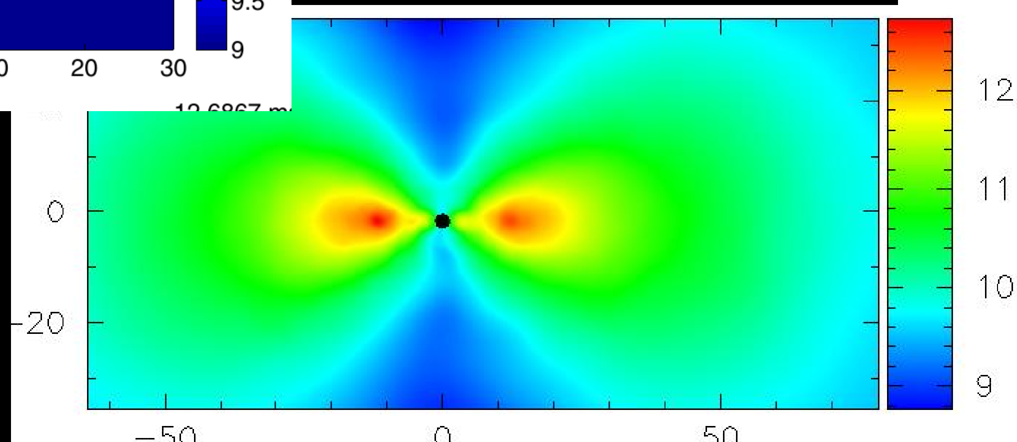
ApJ 773 (2013)



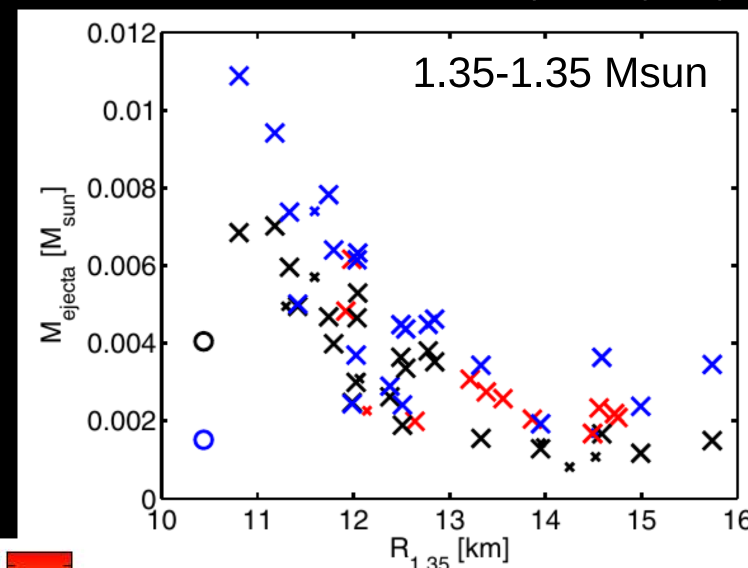
Dynamical ejecta

$$L \propto \sqrt{v}\sqrt{M_{ejecta}}$$

Remnant: BH torus



ApJ 773 (2013)



EoS dependence

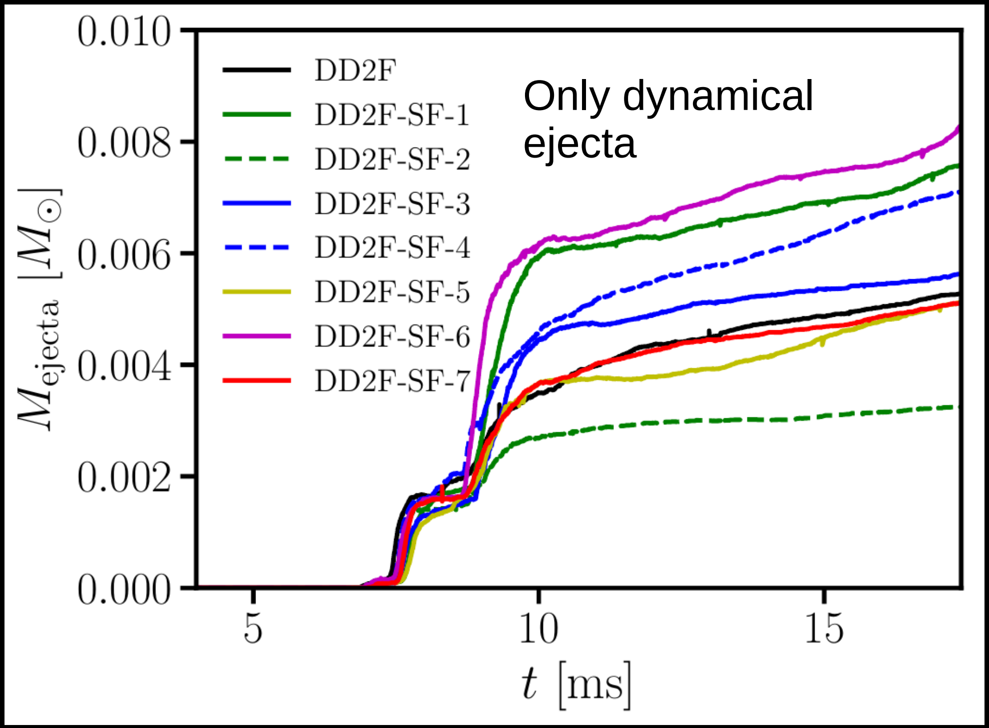
Secular ejecta form BH torus or NS remnant by viscous effects and neutrino wind

Em counterpart / nucleosynthesis

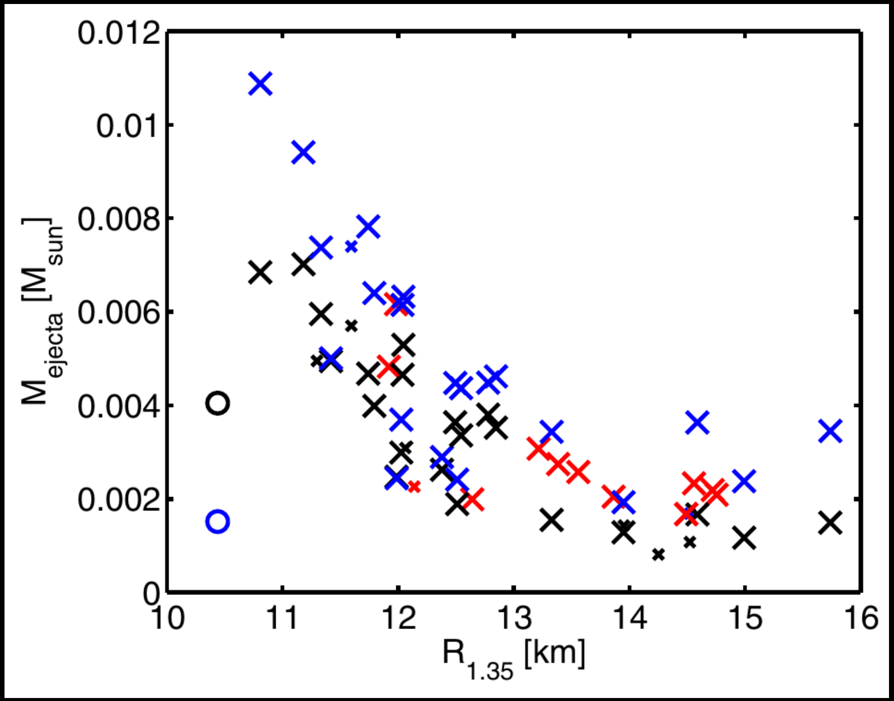
- Electromagnetic transient powered by radioactive decays (during / after r-process)

  → quasi-thermal emission in UV, optical, infrared

- Different ejecta components: dynamical, disk ejecta
- No obvious qualitative differences differences – quantitaive differences within expected "hadronic" scatter (simplistic considerations)
- More subtle impact possible, but unlikely (simple model wo neutrinos, network, disk evolution ...) - also other characteristic similar: outflow velocity, disk mass, ...



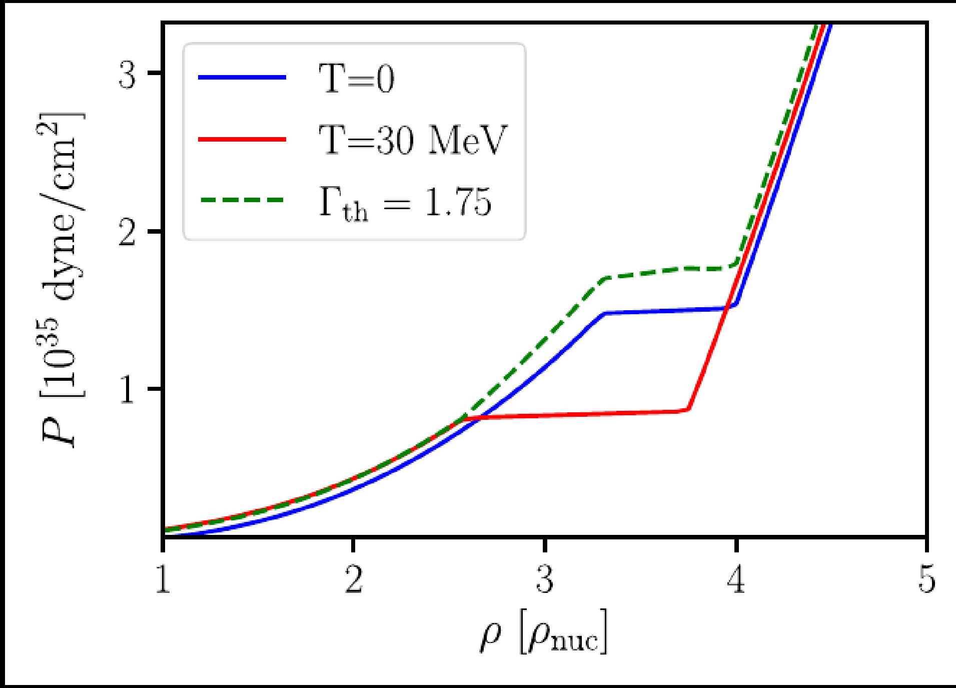
Bauswein et al. AIP 2019, arXiv:1904.01306

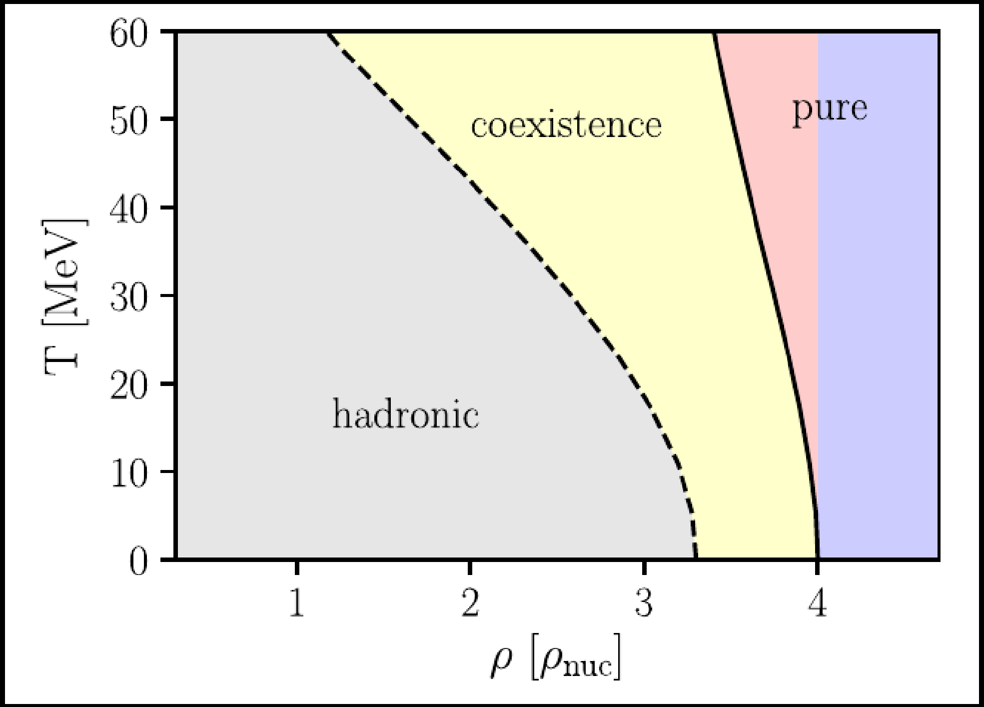


Bauswein et al., ApJ 2013

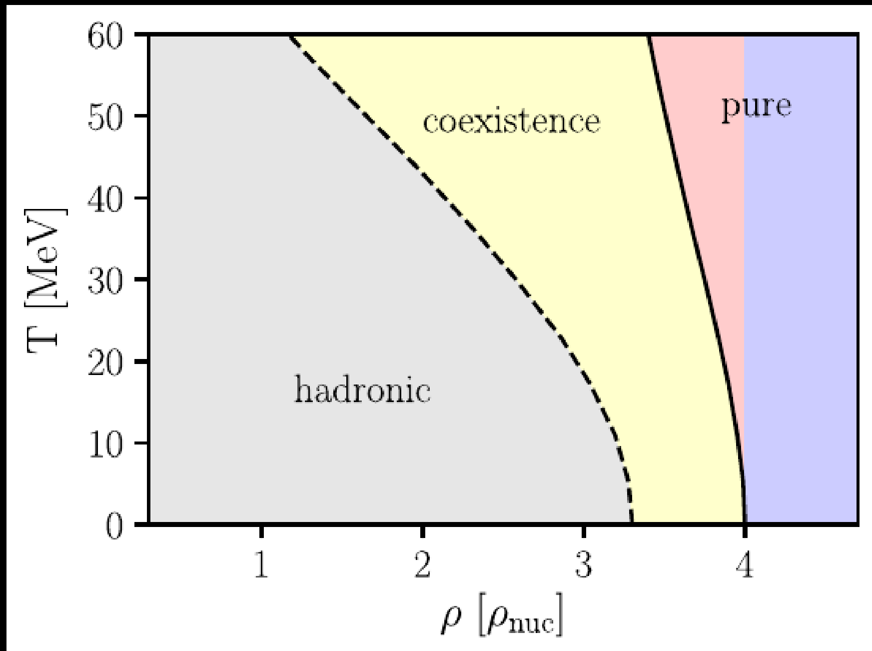
Thermal behavior of hybrid EoSs

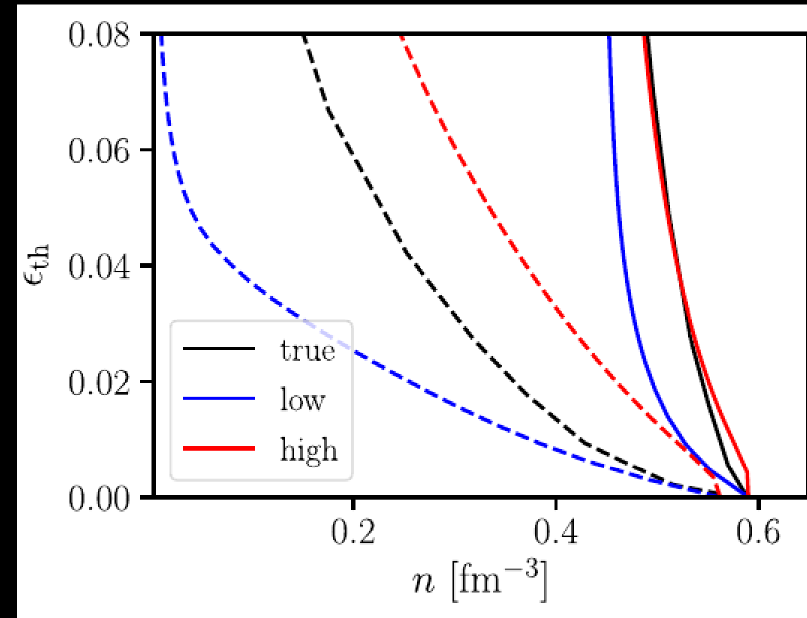
- T dependent phase boundaries lead to rich phenomenology
- Caution: common thermal approximations do not work for hybrid EoSs
- Exemplifies need for consistent 3d hybrid tables



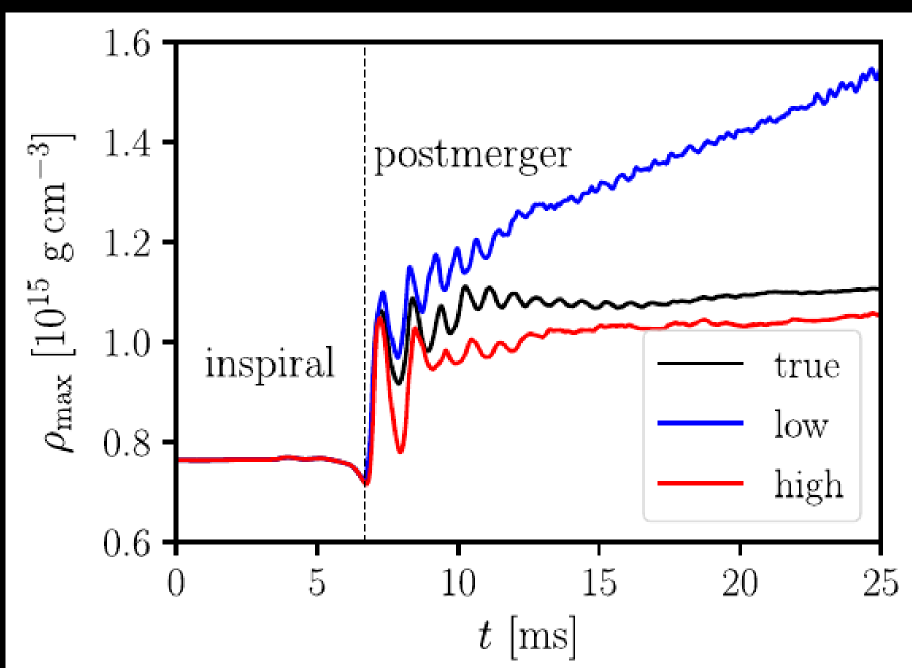


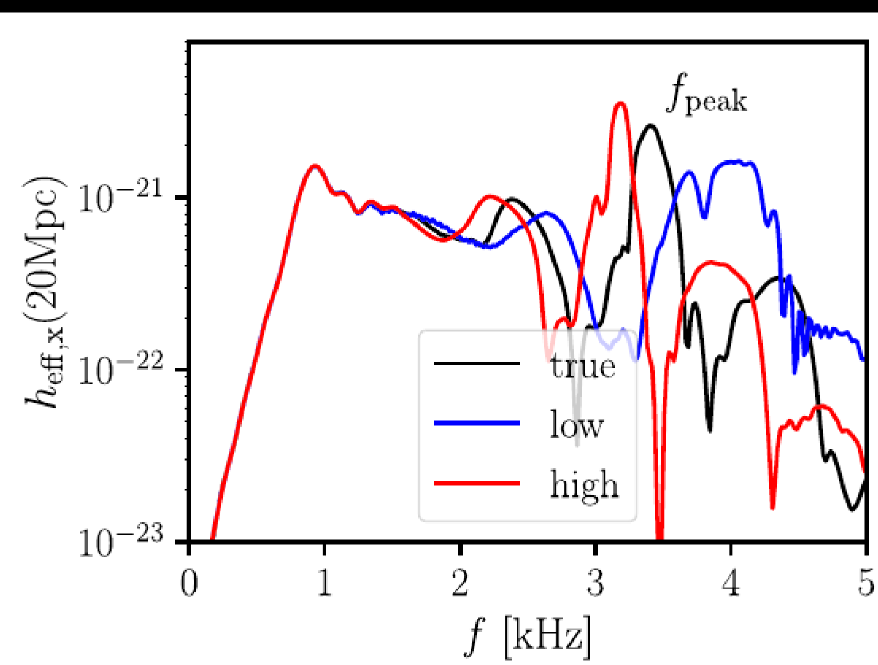
Blacker et al. 2023



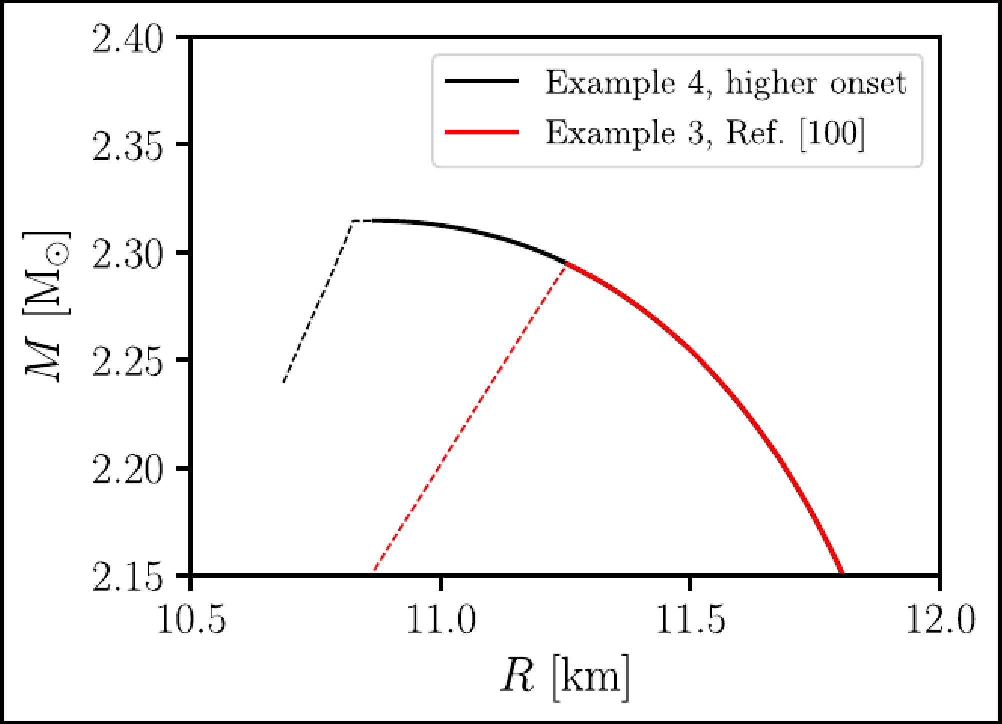


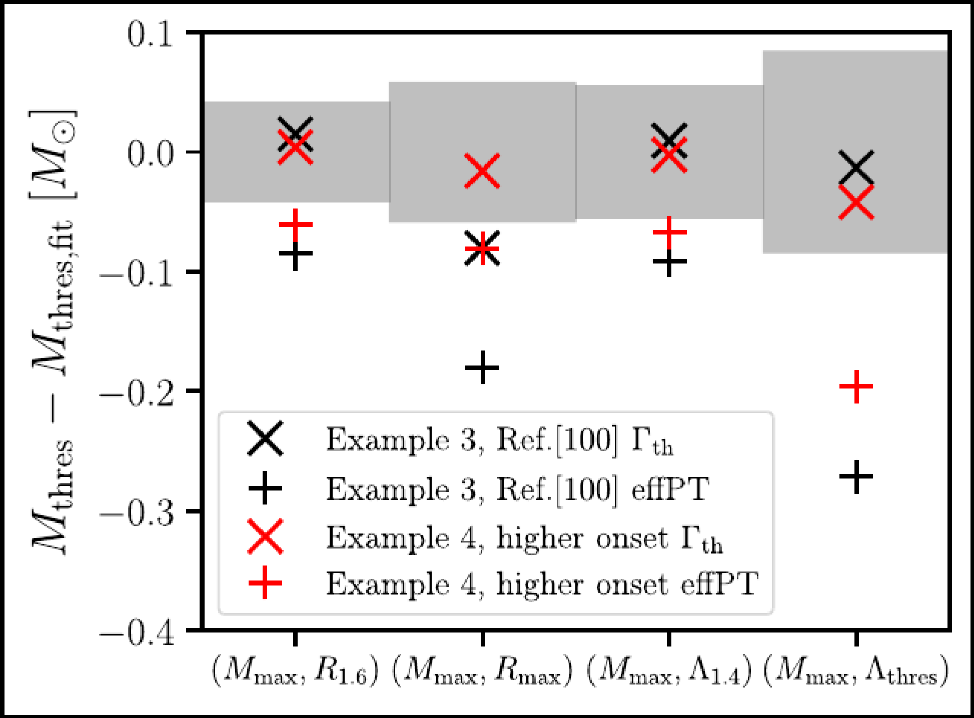
Blacker et al. 2023





- Thermal behavior in the postmerger phase could reveal traces of QM under unfavorable conditions
- For instance, QM only detectable in merger by thermal effects (not in cold stars)





Blacker et al. 2023

Summary

- Sufficiently “strong” PT leaves characteristic and unambiguous impact on GW postmerger frequency → frequency shift due to “compactification” of remnant
- Postmerger generally interesting because it probes highest densities (in comparison to inspiral phase)
- In any case constraint on the onset density (since maximum postmerger density is strongly correlated with postmerger frequency)
- Collapse behavior can (but does not necessarily need to) carry imprint of hadron-quark phase transition

  → low threshold mass for BH formation in comparison to tidal deformability
- Influence on em counterpart less obvious
- Thermal behavior of hybrid EoSs → rich phenomenology

Check also Vimal’s poster on pions in NS mergers