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Signals of quark deconfinement in gravitational waves from binary merger events

A Virtual Tribute to Quark Confinement and Hadron Spectrum 2021, (virtual), 05/08/2021

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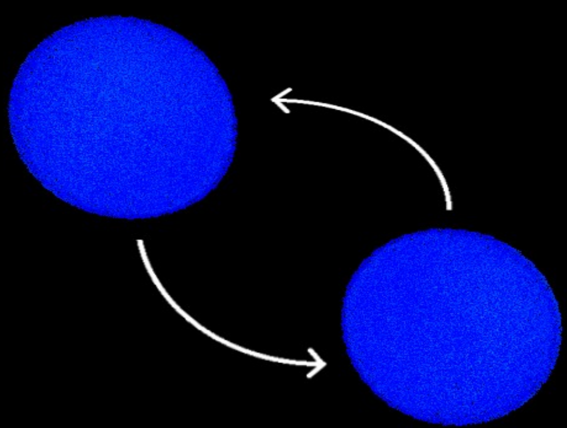
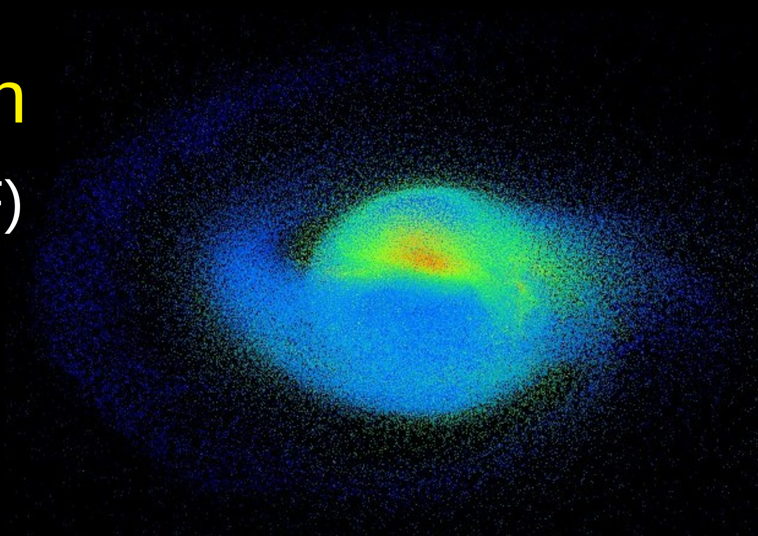




with N. Bastian, S. Blacker, D. B. Blaschke, K. Chatziioannou, M. Cierniak, J. A. Clark, T. Fischer, G. Lioutas, M. Oertel, T. Soultanis, N. Stergioulas, S. Typel, V. Vijayan

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”

Introduction

- 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 ?

Introduction

- 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:

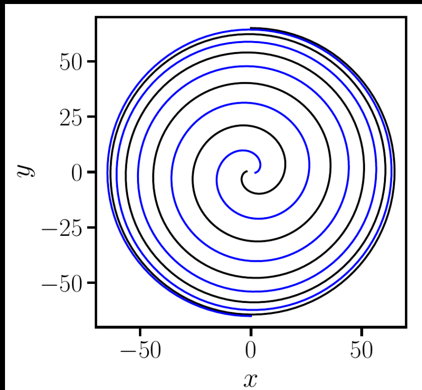
  → impact on stellar structure, e.g. kink or jump in mass-radius relation

  → 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

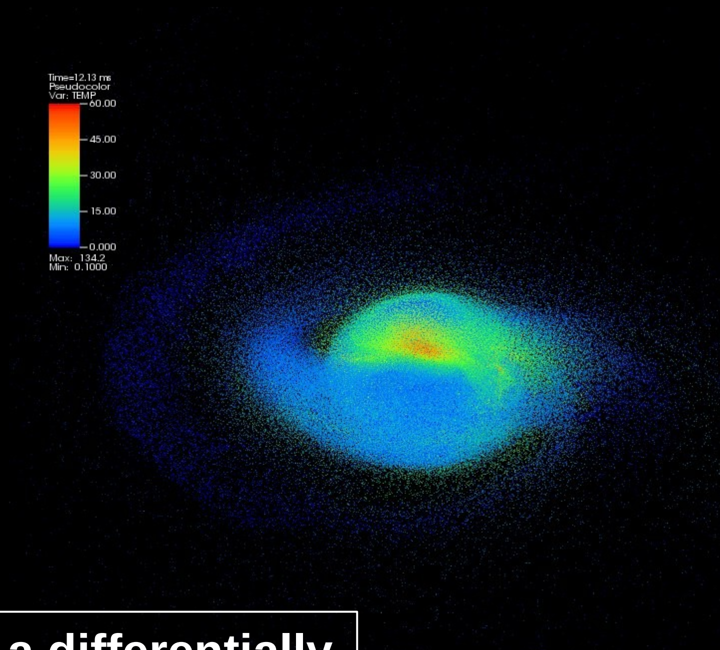
$P_{orb} \sim 1\,ms$

Neutron star merger

dependent on EoS, M_{tot}

ms

ms

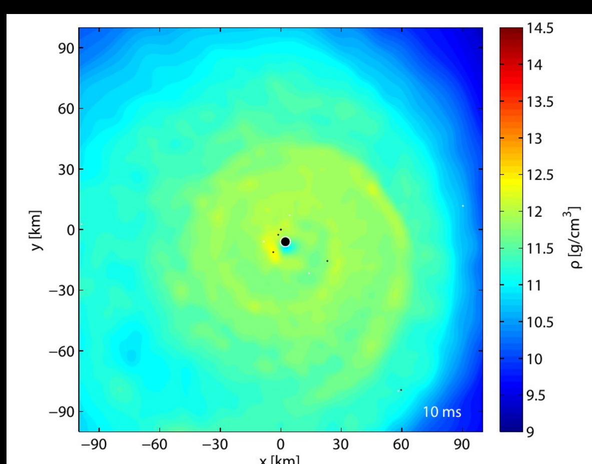


Prompt formation of a BH + torus

Formation of a differentially rotating massive NS

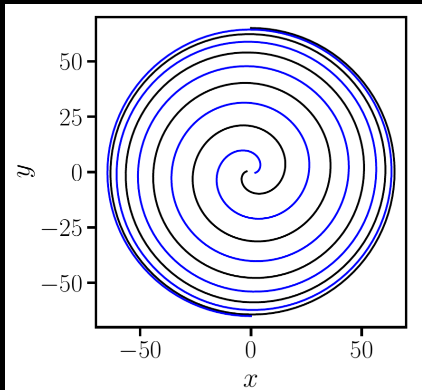
dependent on EoS, M_{tot}

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

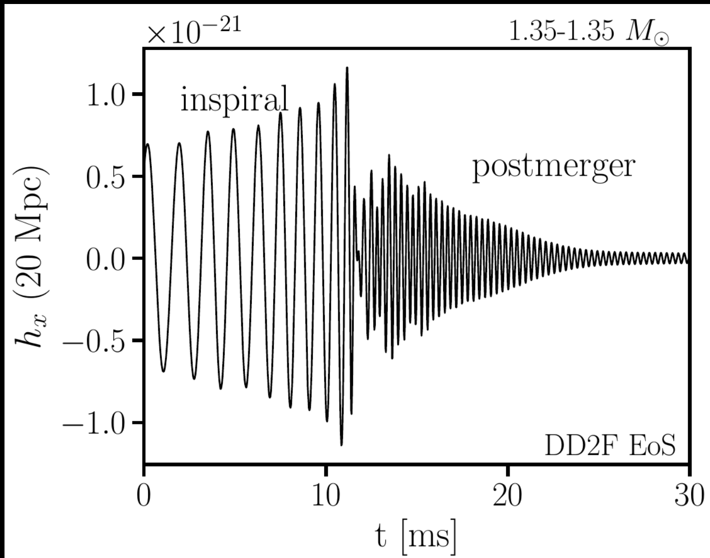
dependent on EoS, M_{tot}

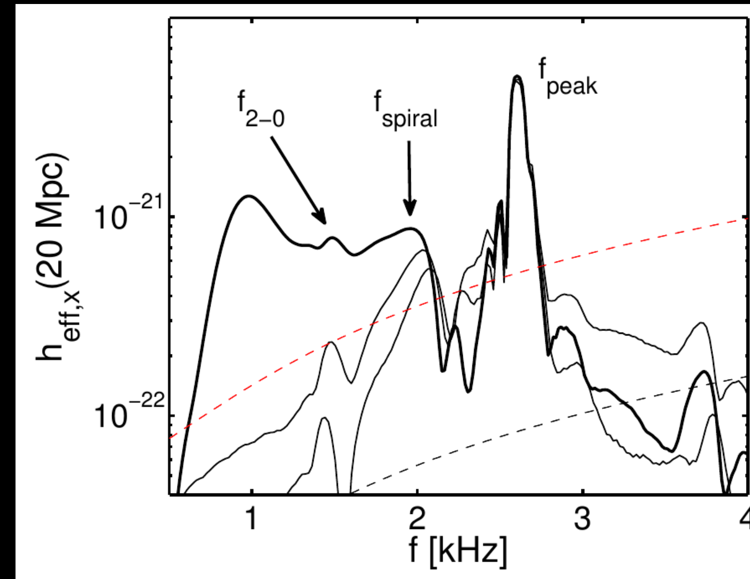
10-100 ms

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

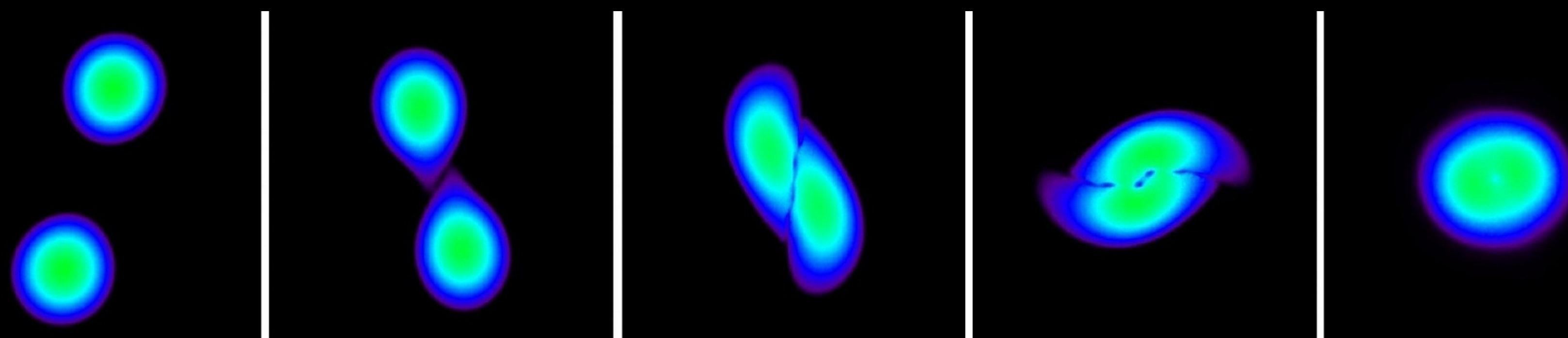
Delayed collapse to a BH + torus

Simulations





Bauswein et al. 2016



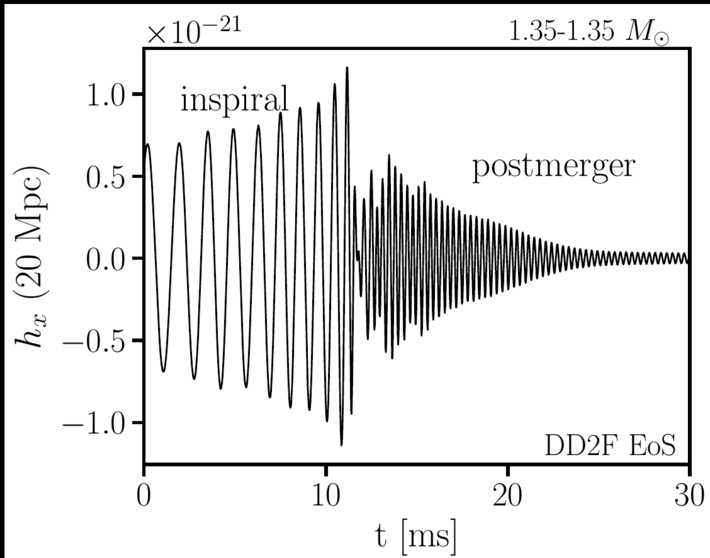
Finite-size effects, i.e. EOS impact, during inspiral described by tidal deformability Λ

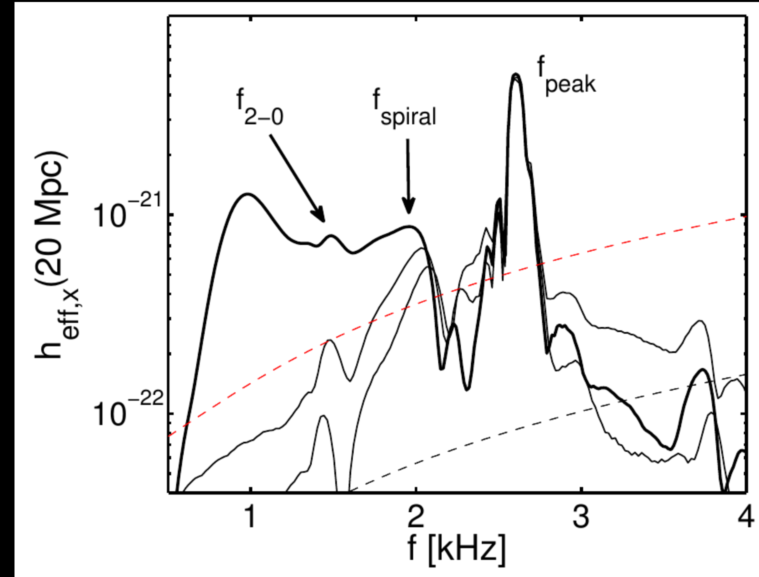
Larger stars /stiffer EOS accelerate inspiral

Dominant remnant oscillation generates pronounced GW peak f_{peak}

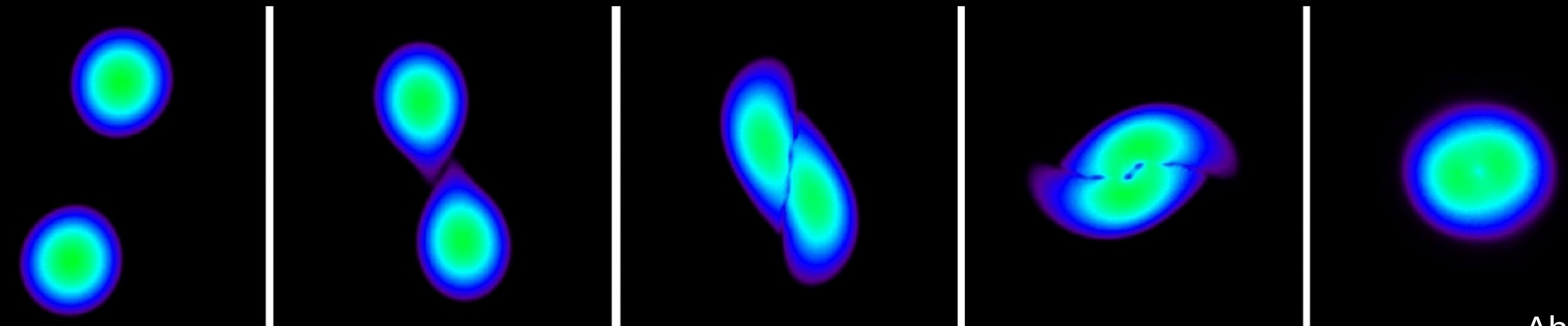
More compact remnants/softer EOS higher f_{peak}

Simulations

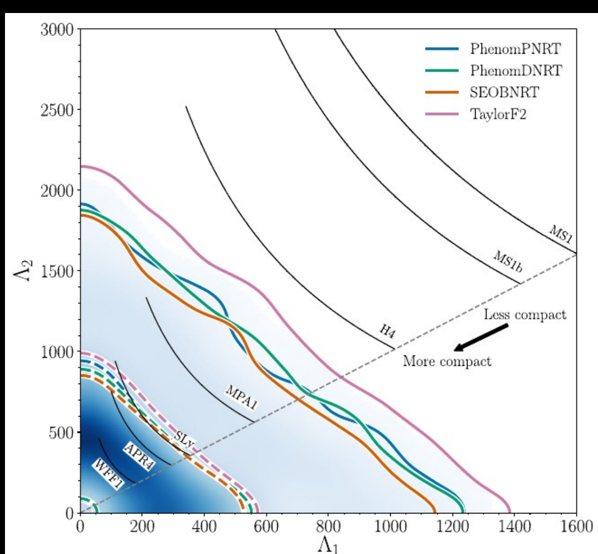




Bauswein et al. 2016



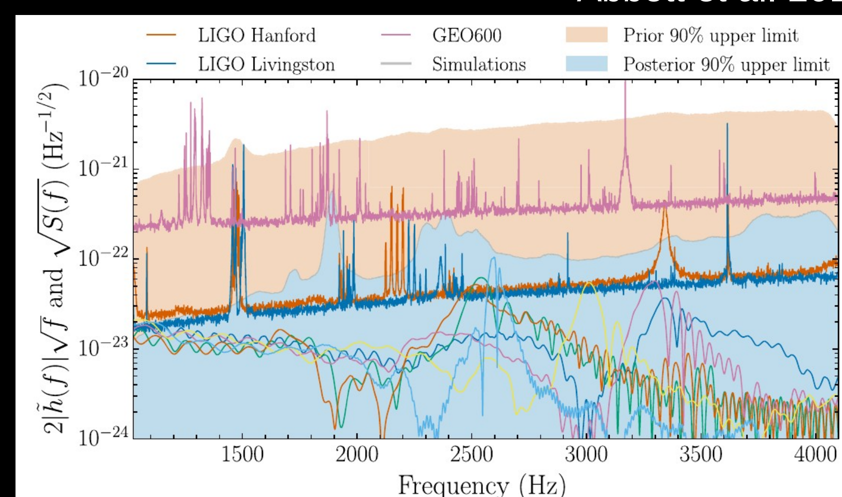
Observations



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

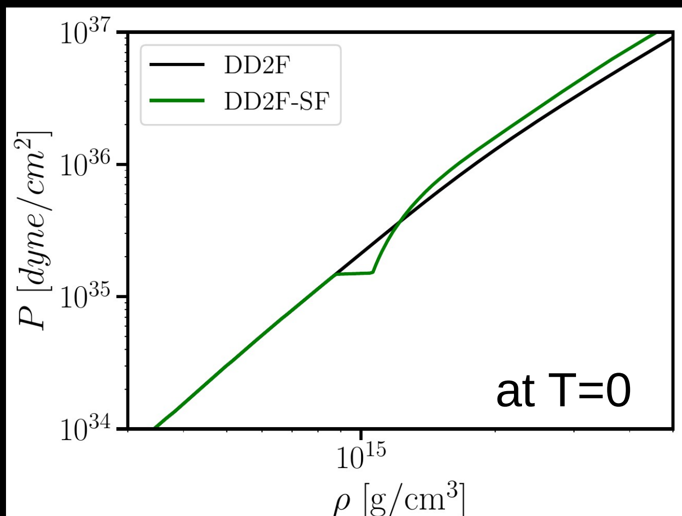
Impact of quark matter on GW signal

→ we test EoS models in simulations and identify signatures

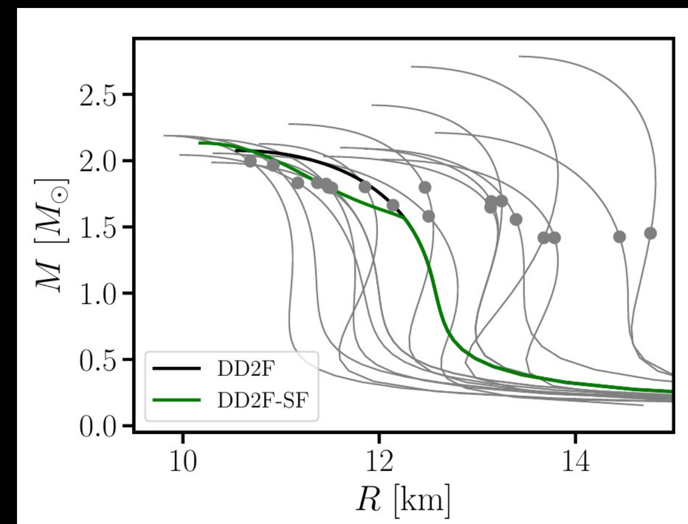
EoS with 1st-order phase transition to quark matter

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

  → relativistic hydrodynamical simulations adopting (temperature dependent) EoS



TOV eq. ⟷



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

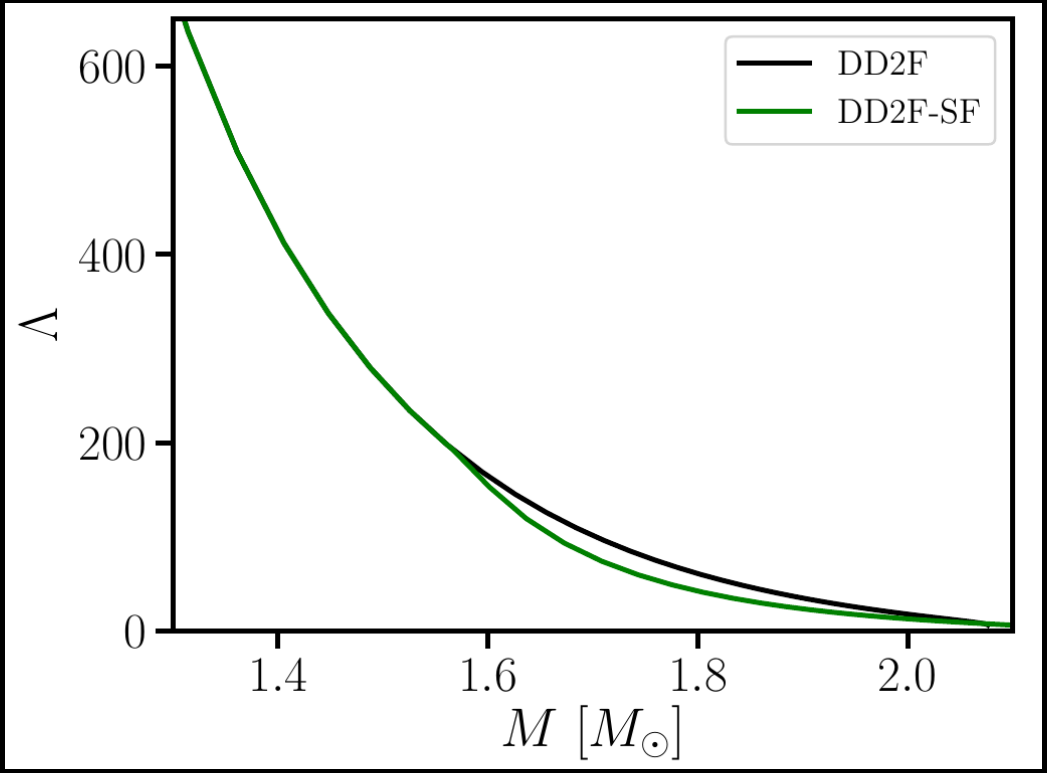
  → many different models available with differently strong impact on stellar structure

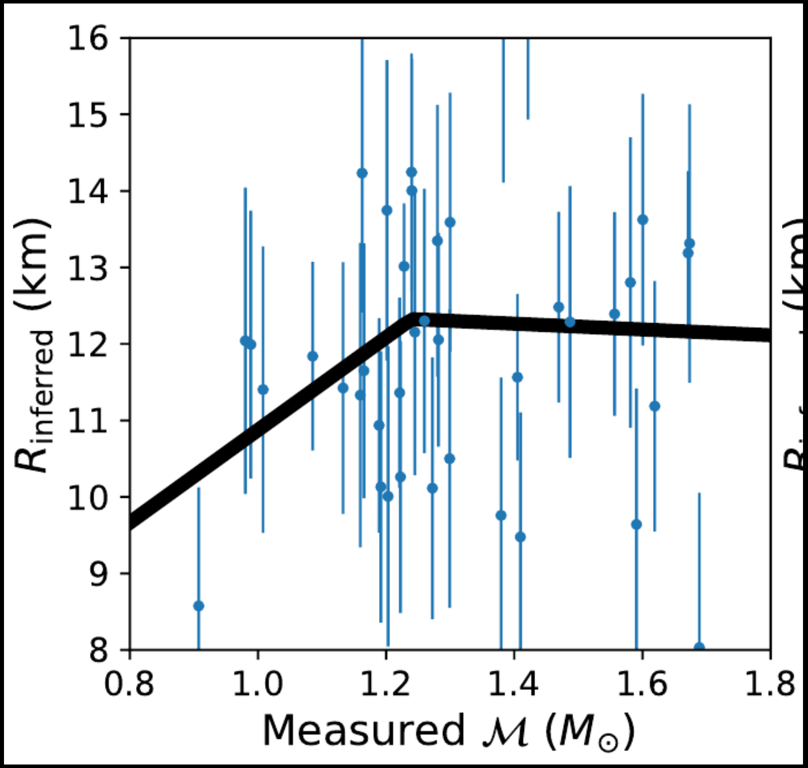
- RMF (density -dependent couplings) + two-flavor string flip model (Maxwell construction), temperature dependent (important: thermal pressure, temperature-dep. phase boundary)
- Compatible with recent constraints from GW170817 and pulsar measurements

Phase transition and the GW inspiral

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

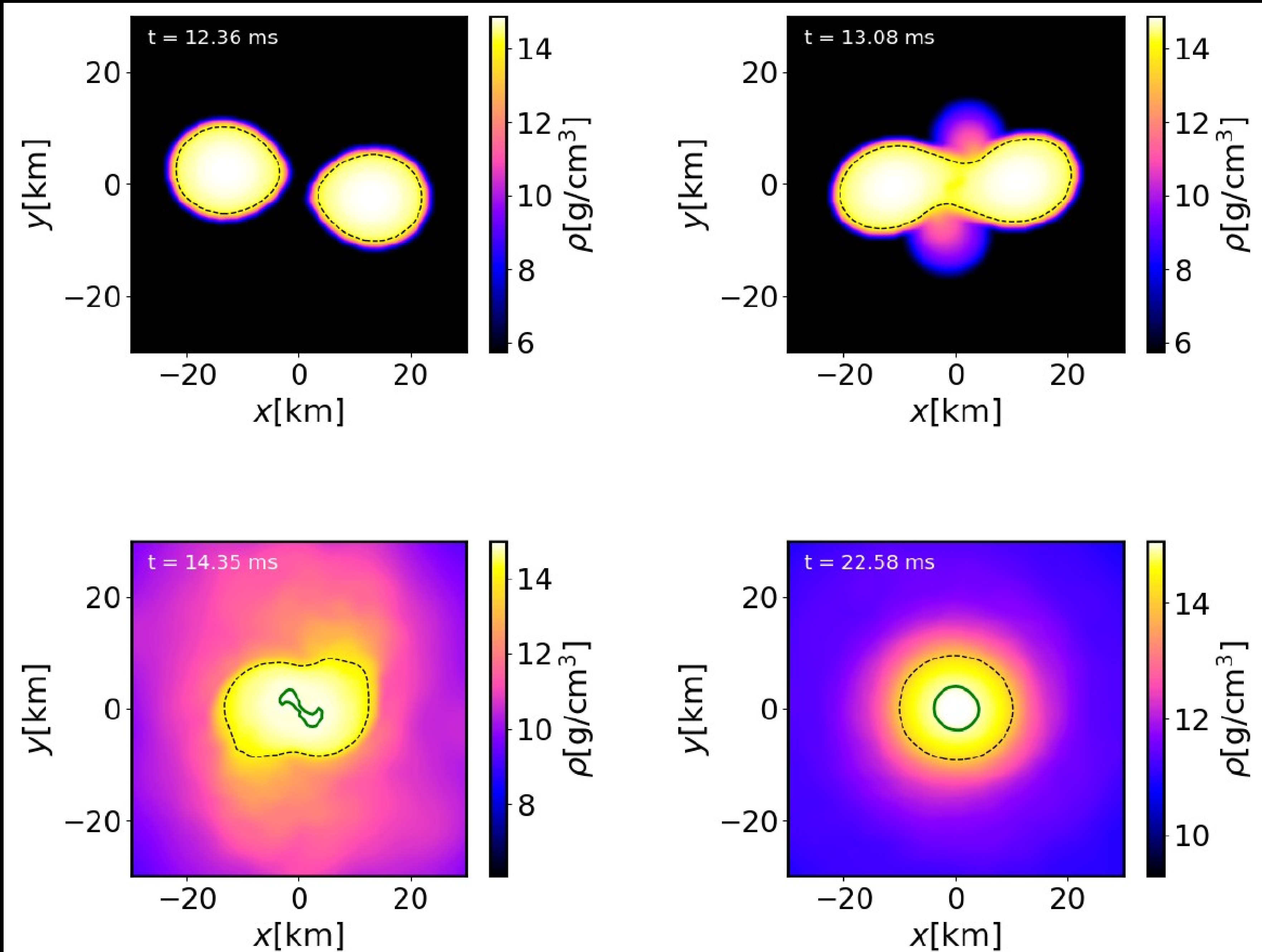
  → challenging to measure transition in mergers through inspiral: Kink weak, Lambda generally very small, high mass star probably less frequent





Chen et al 2020

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

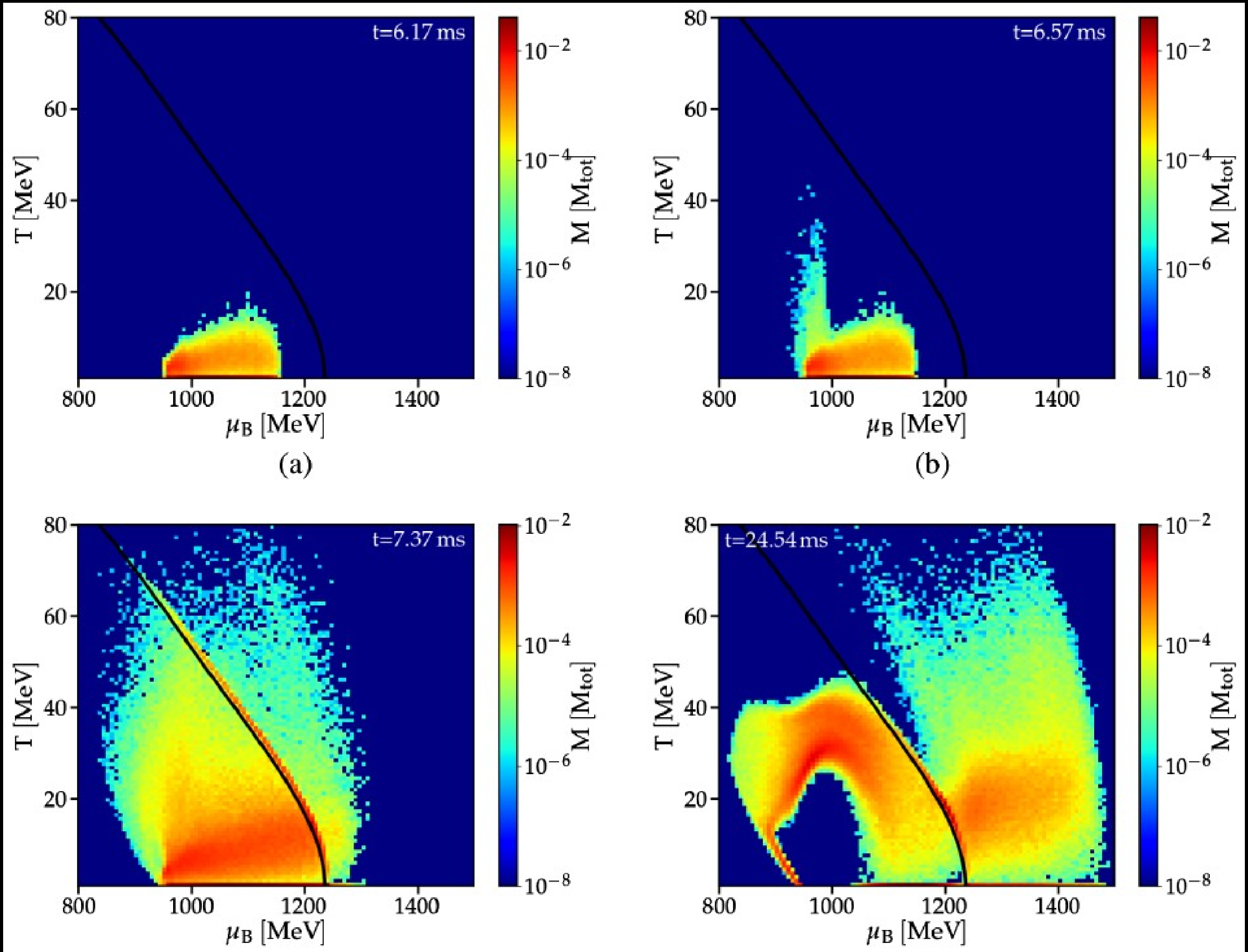


1.35-1.35 Msun - DD2F-SF-1

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

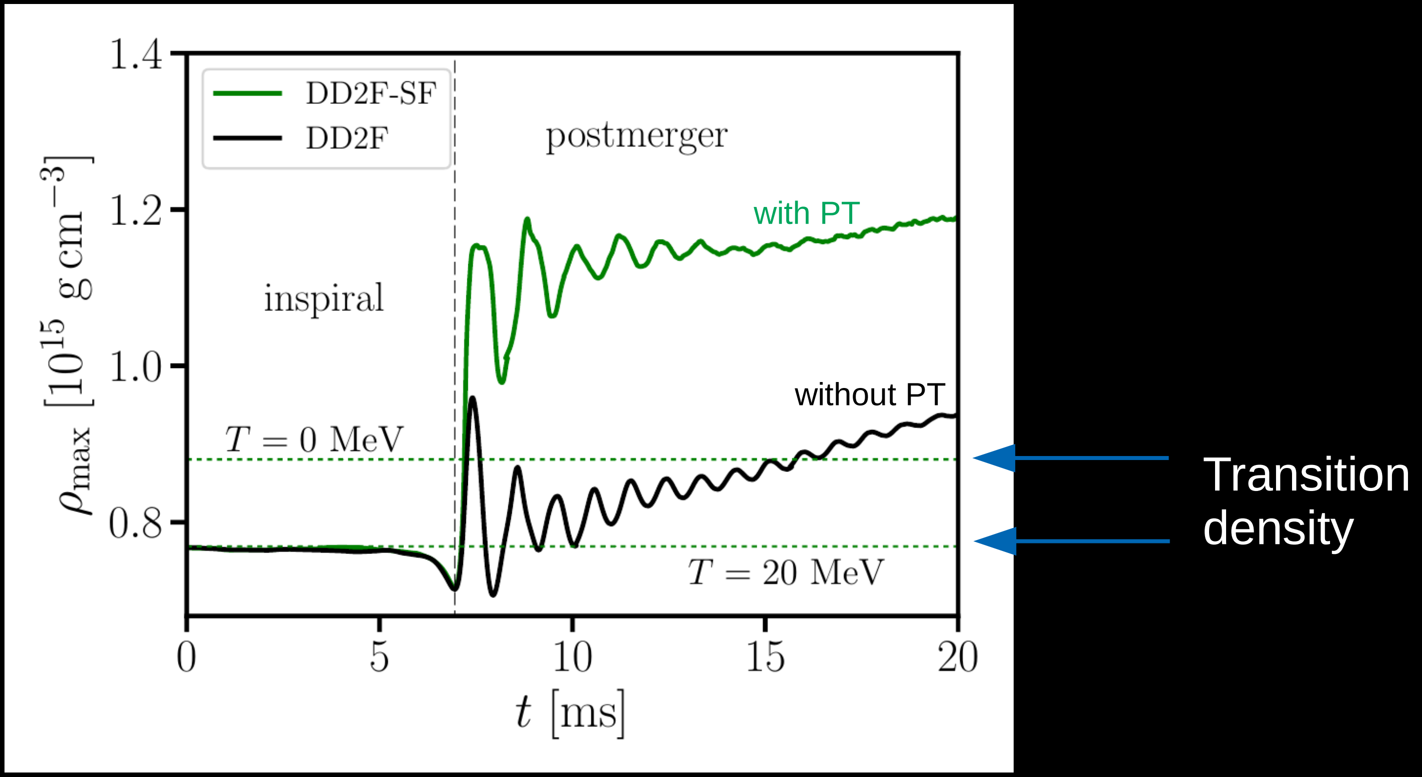
NS merger in the phase diagram

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

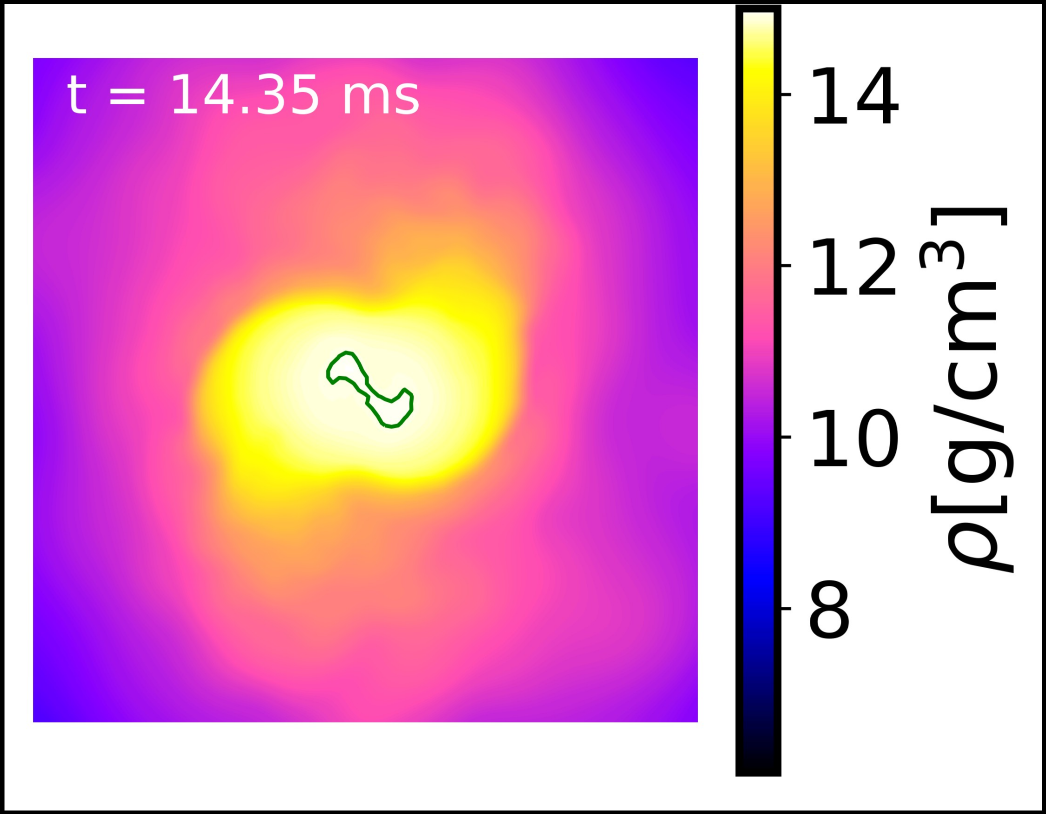


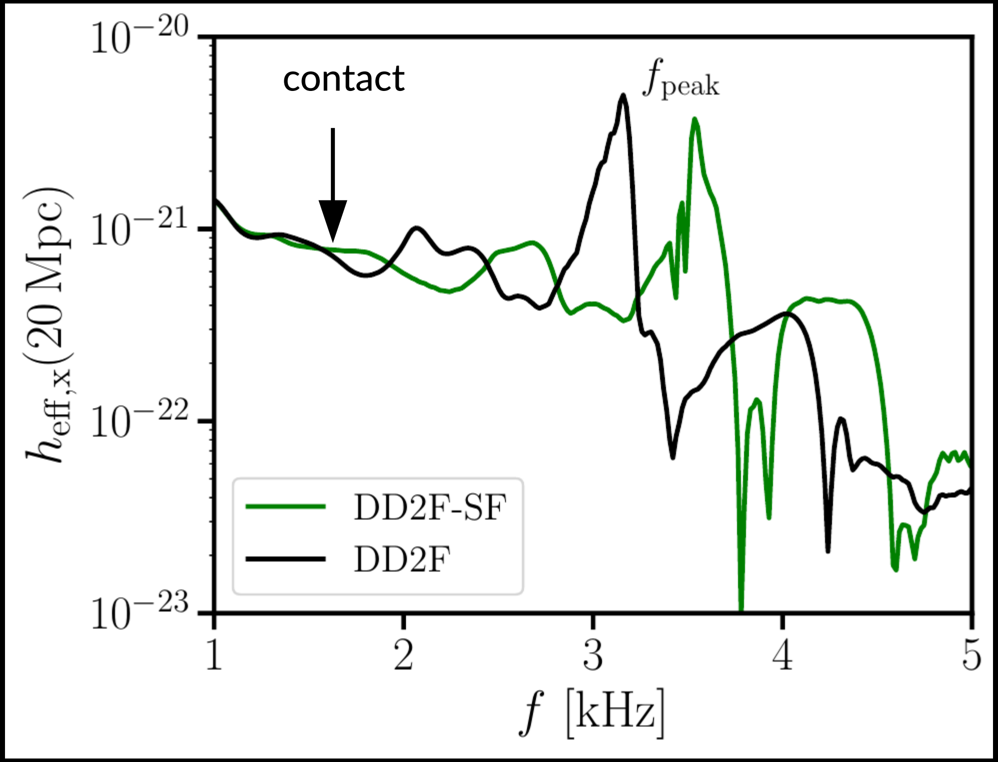
Bauswein et al. 2019

- Softer EoS "needs more density" to provide sufficient pressure support

Merger simulations

- GW spectrum 1.35-1.35 Msun



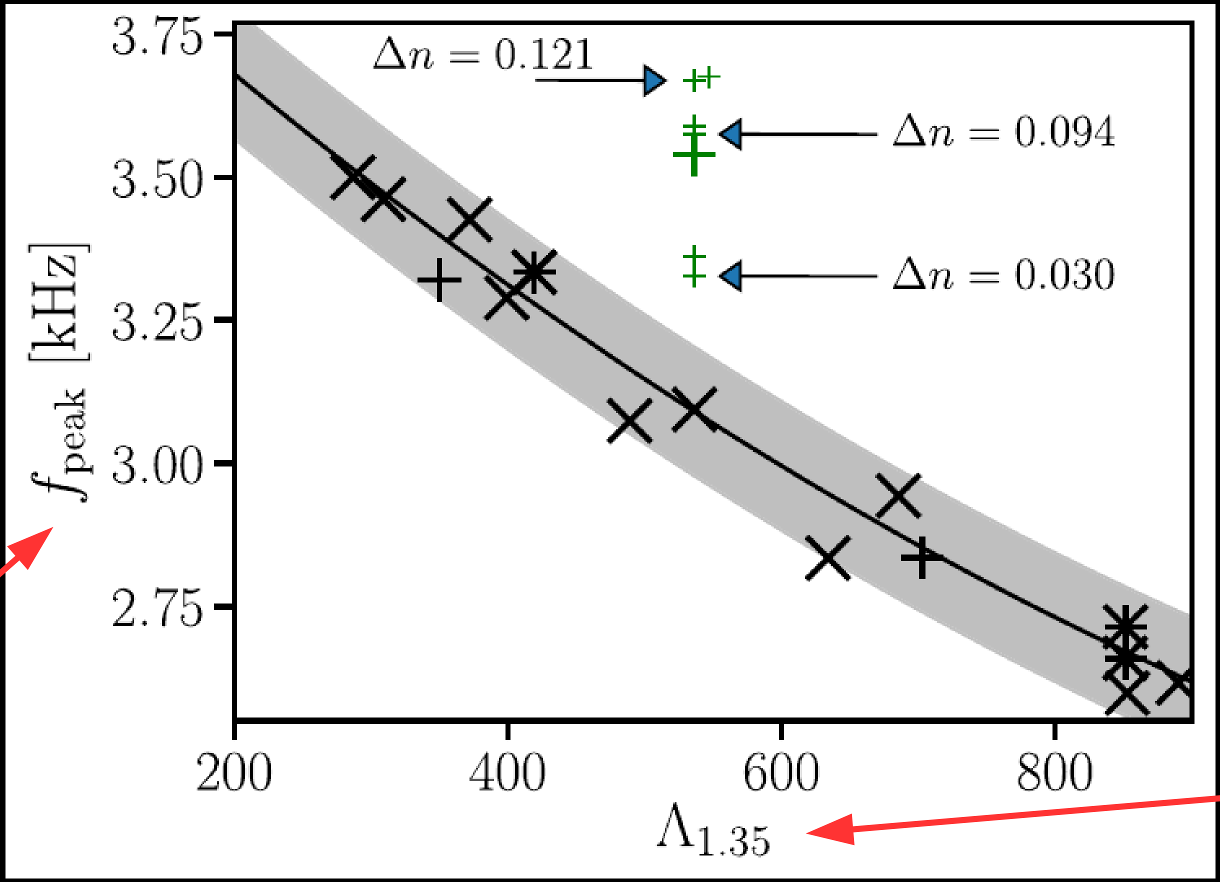


Bauswein et al., PRL 122 (2019)

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

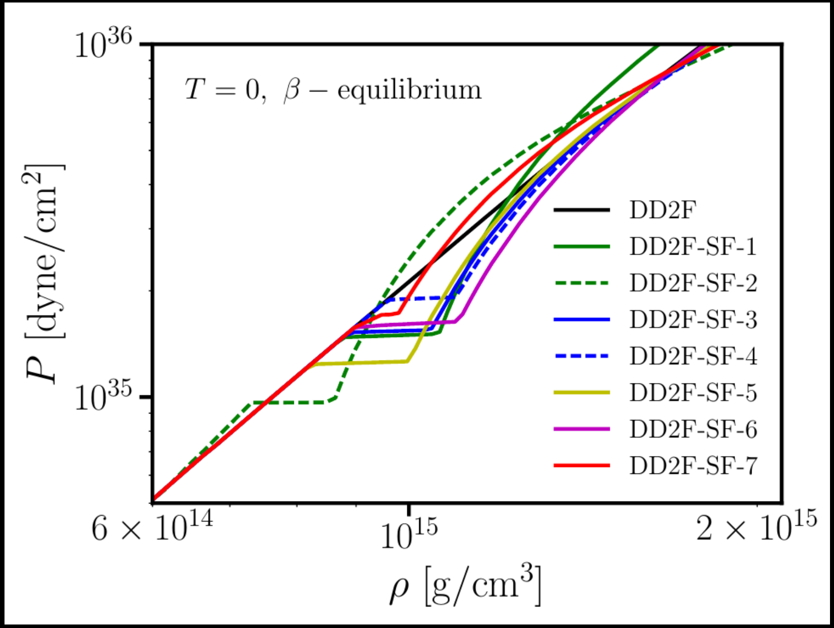
from the inspiral

Bauswein et al., PRL 122 (2019)

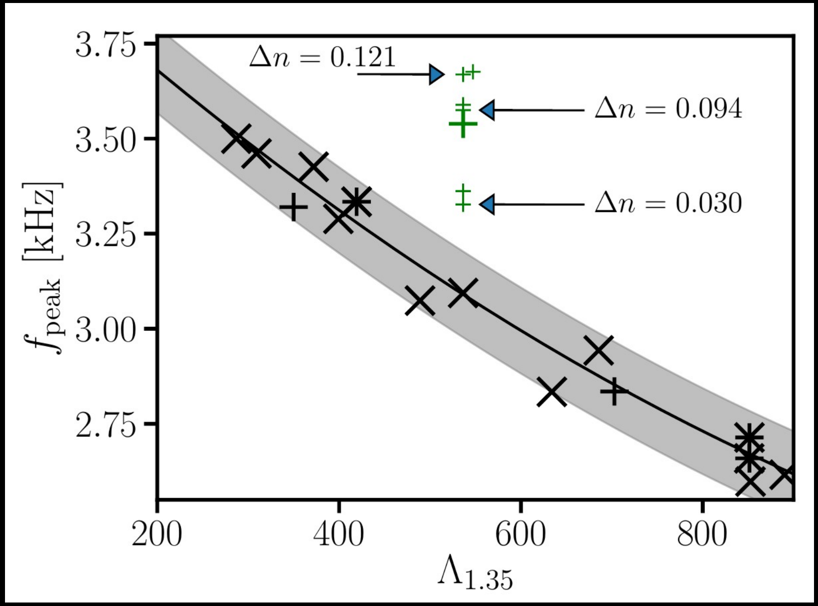
- Tidal deformability measurable from inspiral to within 100-200 (Adv. Ligo design)
- Postmerger frequency measurable to within a few 10 Hz @ a few 10 Mpc (either Adv. Ligo or upgrade: e.g Clark et al. 2016, Chatzioannou et al 2017, Bose et al 2018, Torres-Rivas et al 2019)
- Important: "all" purely 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., PRL 122 (2019)

Constraints on the onset density

- Summary: Compare fpeak and Lambda

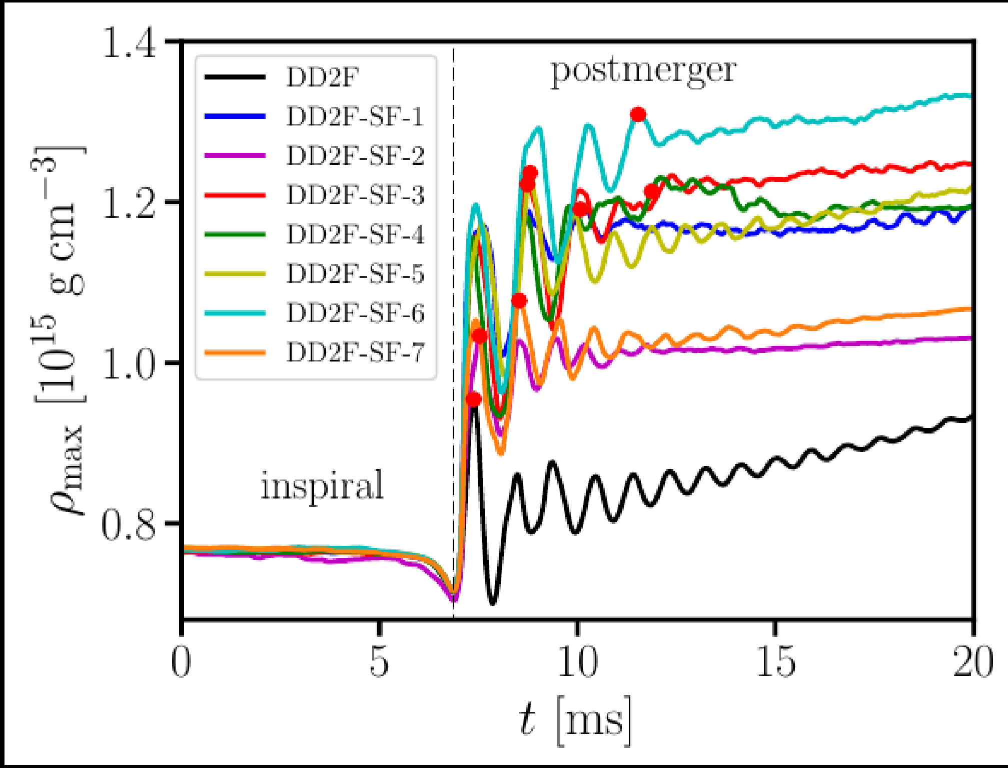
  - fpeak compatible with hadronic (gray band) → No PT (for measured binary masses)

  - 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 !!!

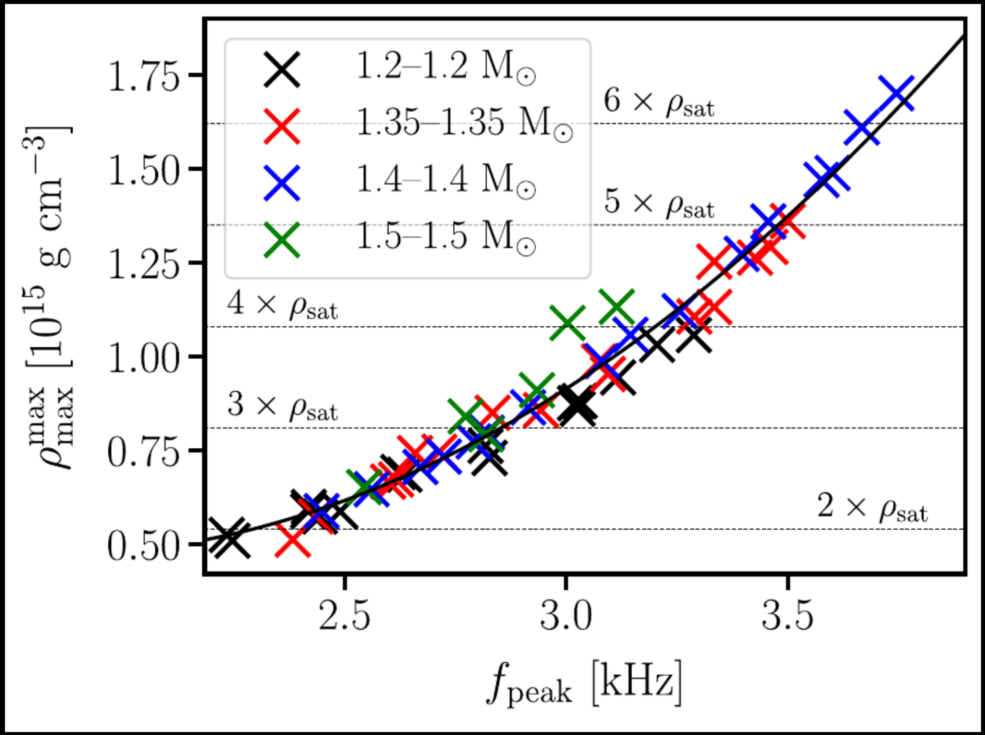
→ Hence we can exclude PT up to this density - or the PT must have occurred below that density !!!

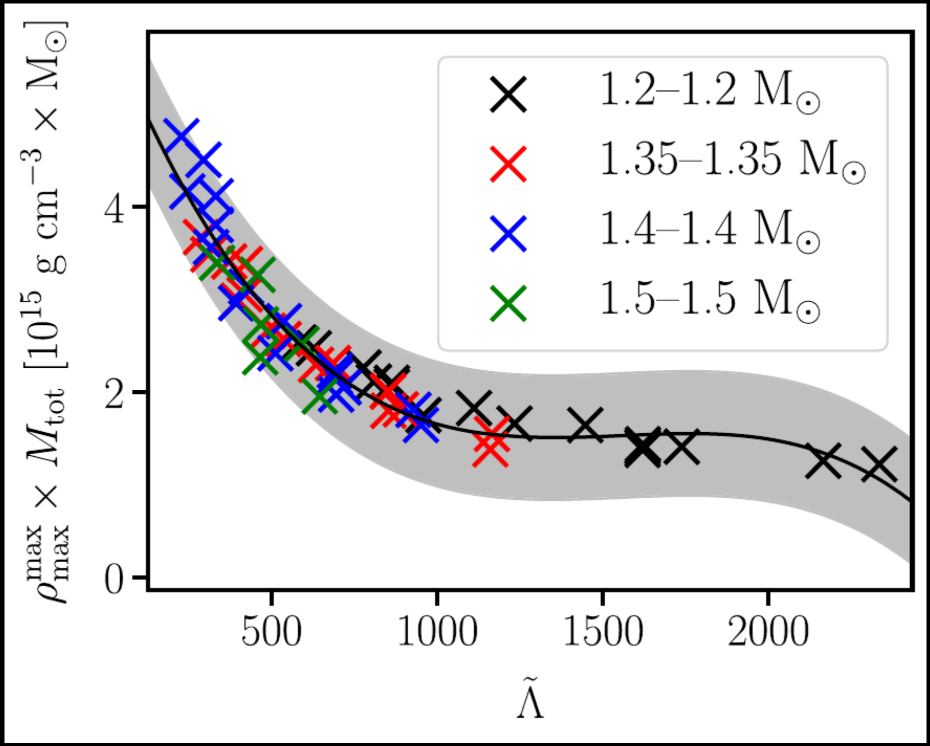


Blacker et al. (2020)

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

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



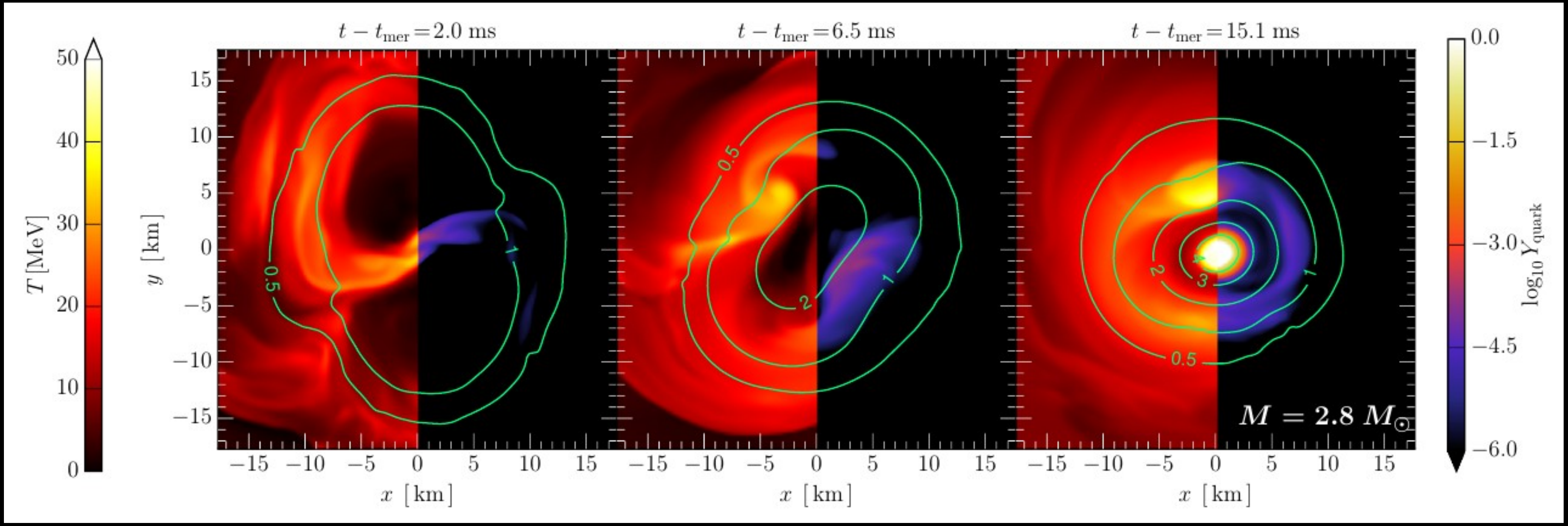


Postmerger frequency fpeak

tidal deformability from inspiral

More EoS models

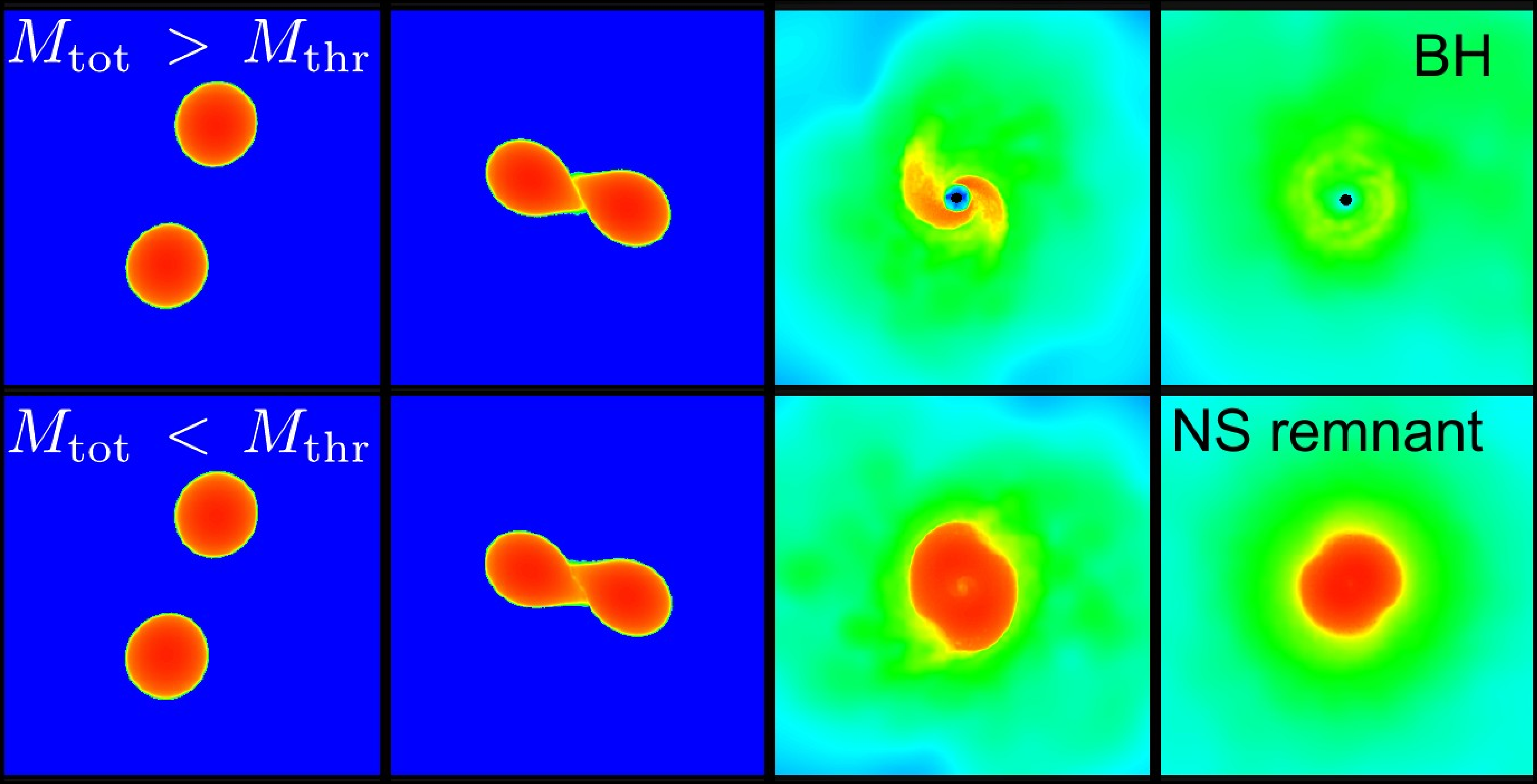
- Hybrid mergers, i.e. PT before merger, similarly show frequency increase (Bauswein & Blacker 2020)
- Also for other hadronic models frequency shifts expected (Bauswein & Blacker 2020, Prakash et al 2021)
- Possibly delayed occurrence of PT (shown for piecewise polytrope; Weih et al. 2020)
- PT can lead to faster delayed collapse during postmerger (Most et al. 2019)



Most et al 2019

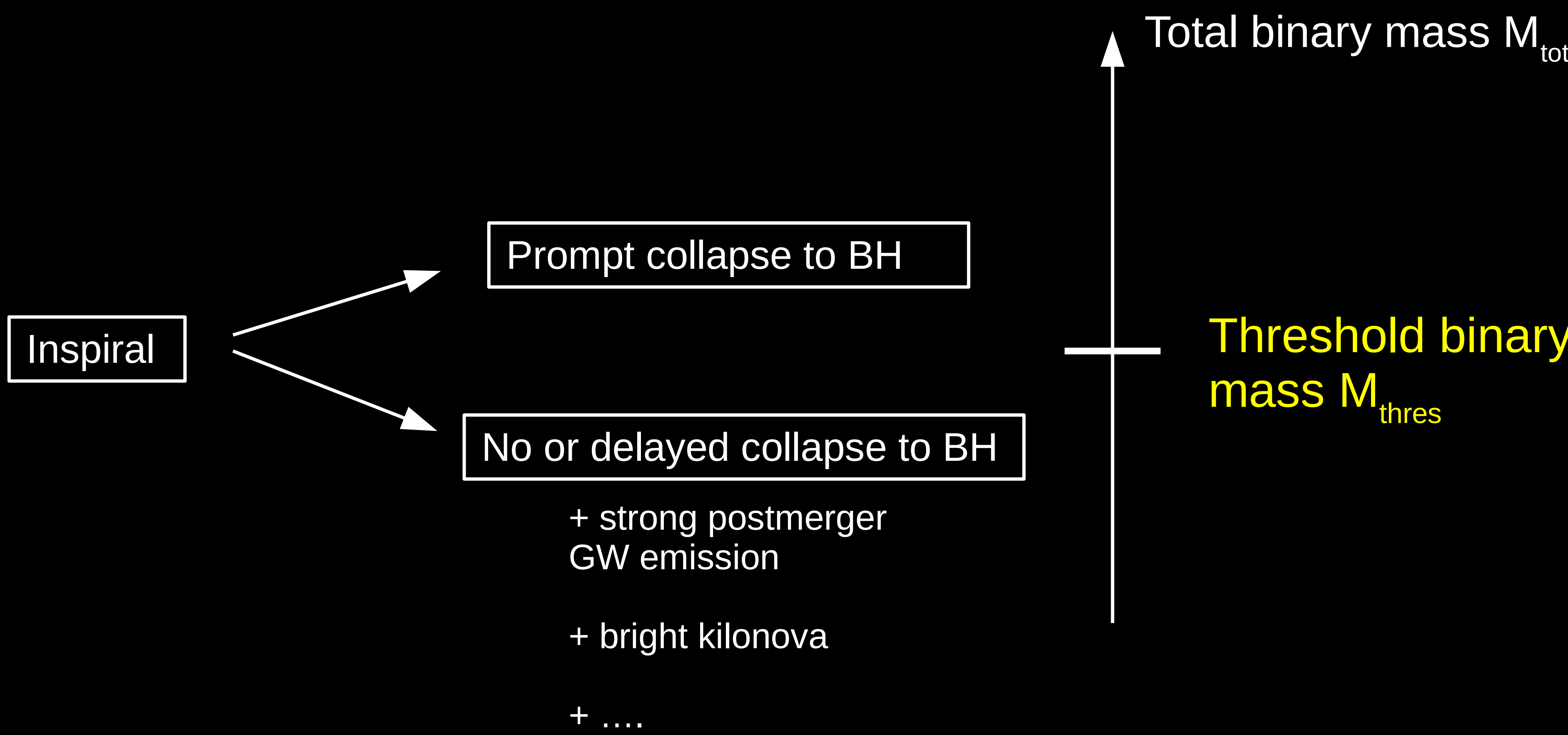
Collapse behavior

Collapse behavior



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

Collapse behavior



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

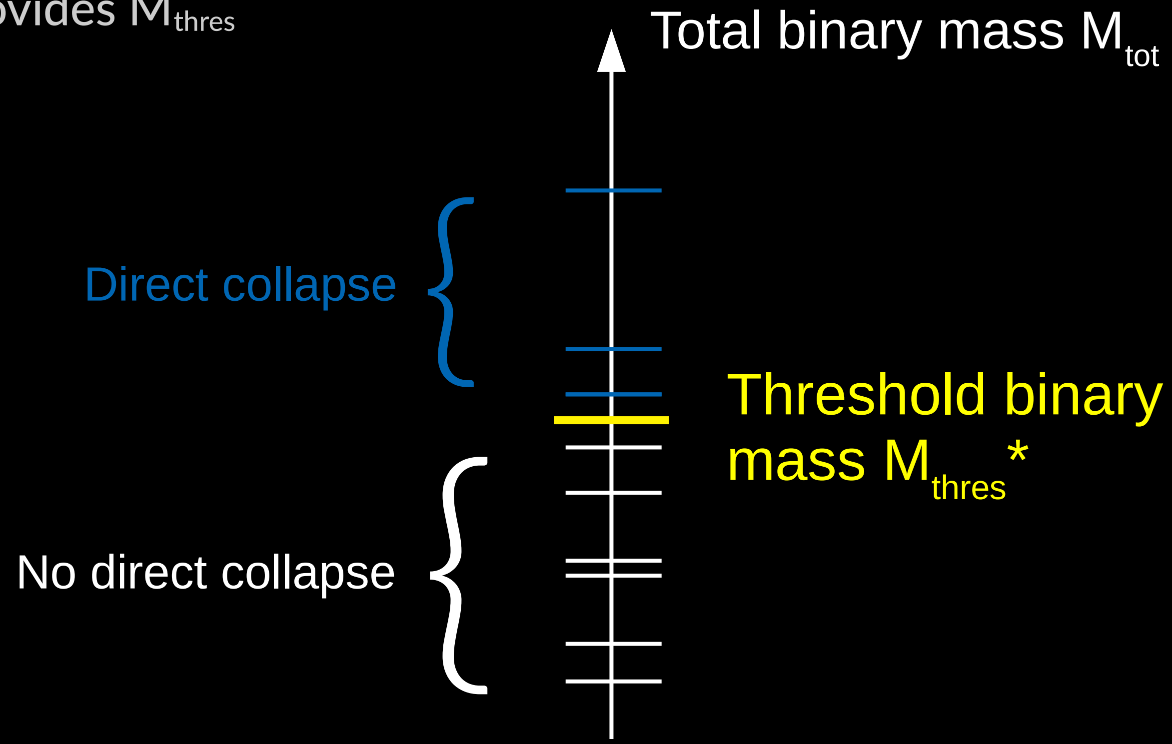
Future determination of M_{thres}

- M_{tot} accurately measured during inpiral

  (from chirp mass and mass ratio q)
- Combing several detections provides M_{thres}
- Merger product NS vs BH

  - kilonova properties

  - postmerger GWs



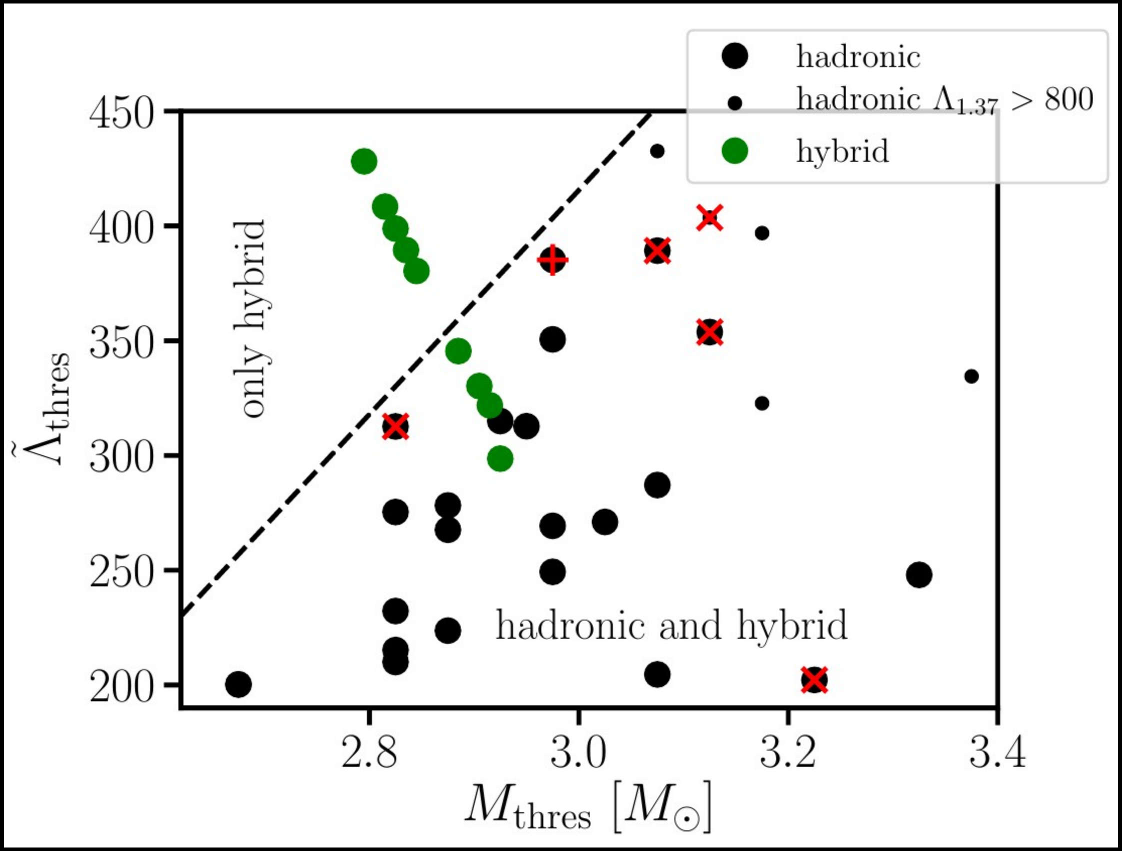
* determined by highest binary mass with no collapse and lowest mass with direct collapse

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

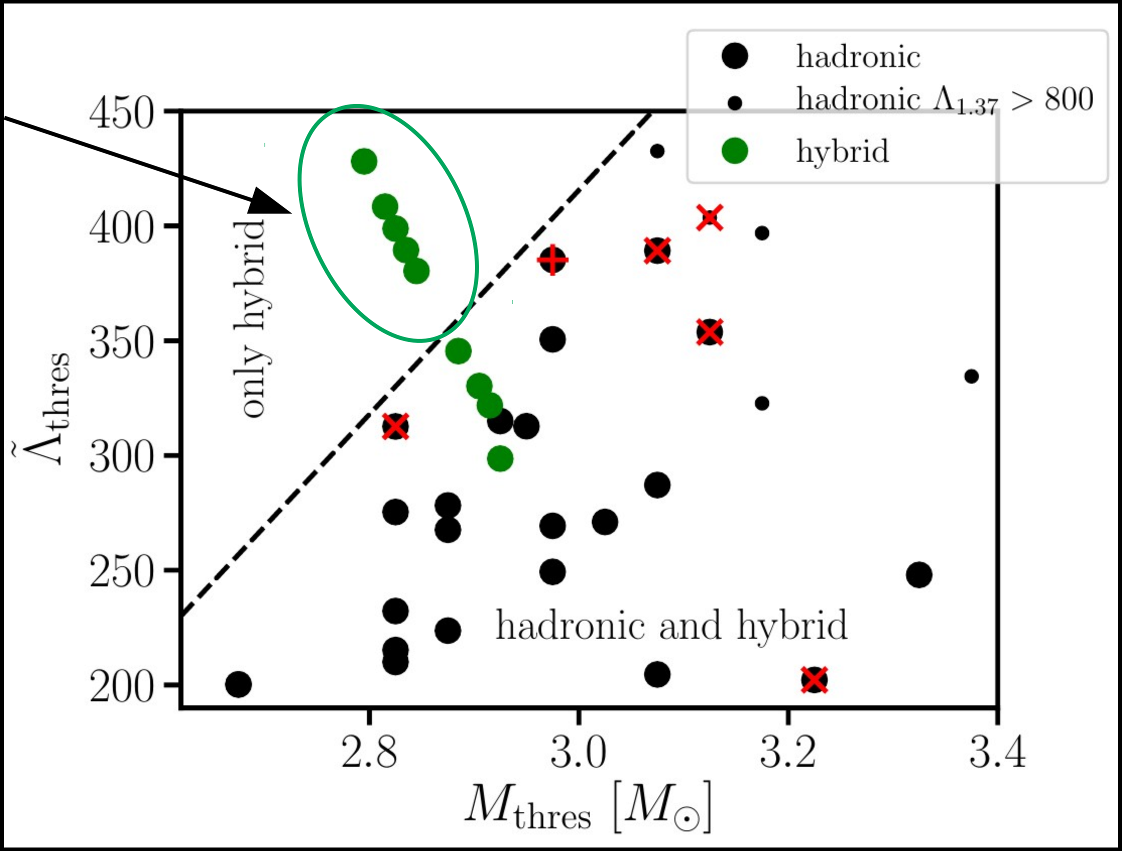
$$\tilde{\Lambda}_{\rm thres} = \Lambda(M_{\rm thres}/2) \ \text{ for } \ q = 1$$

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 !!



Measurable from GW inspiral

Bauswein et al., PRL 125 (2020)

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

Measurable from inspiral + information on merger product

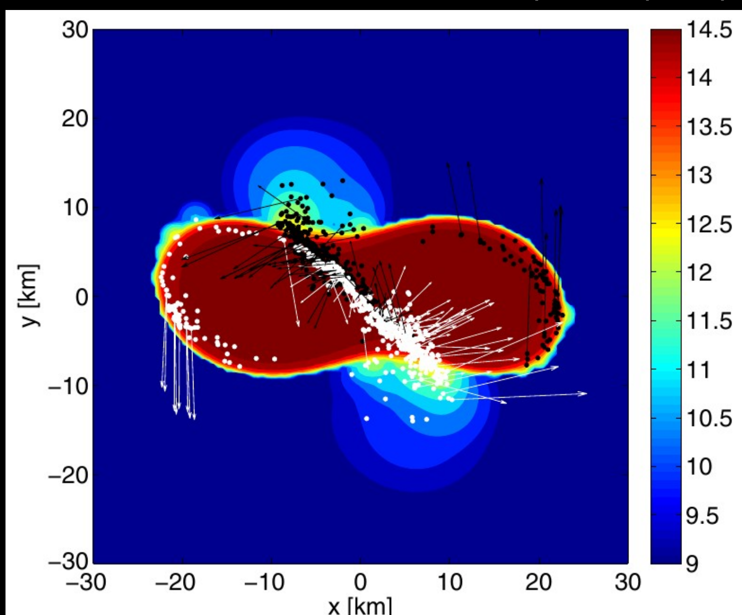
Optical counterpart generated by mass ejection

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

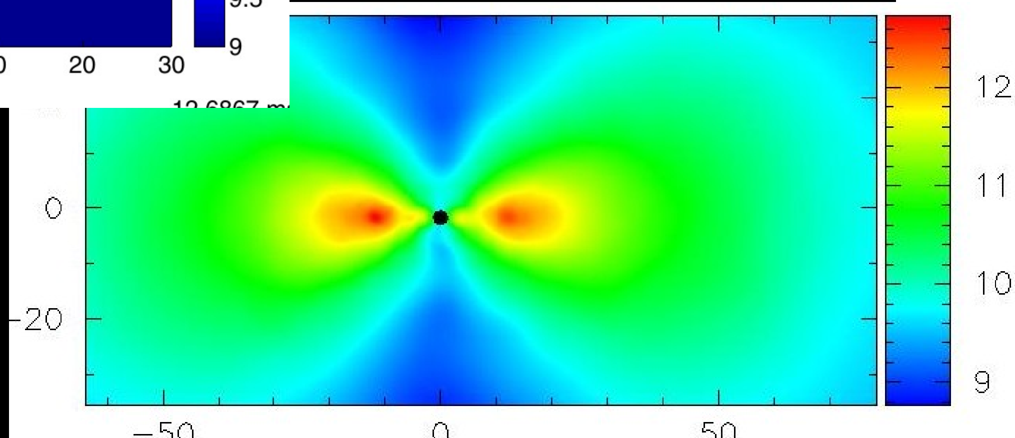
ApJ 773 (2013)



Dynamical ejecta

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

Remnant: BH torus



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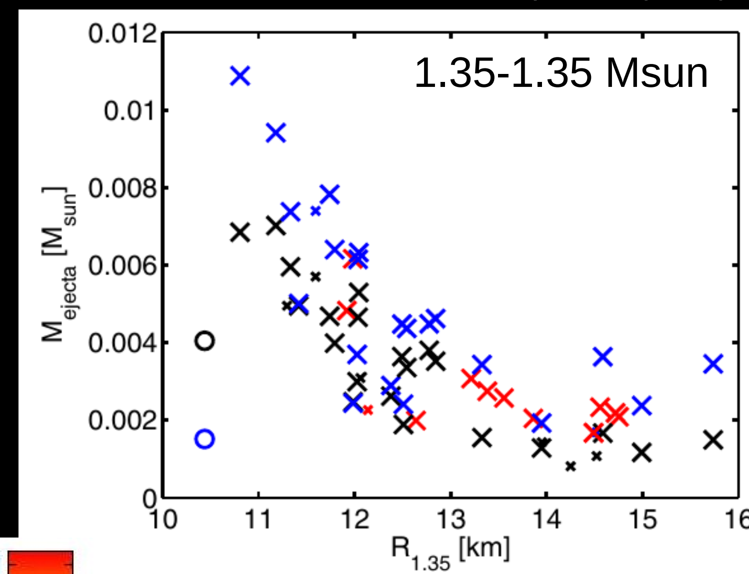


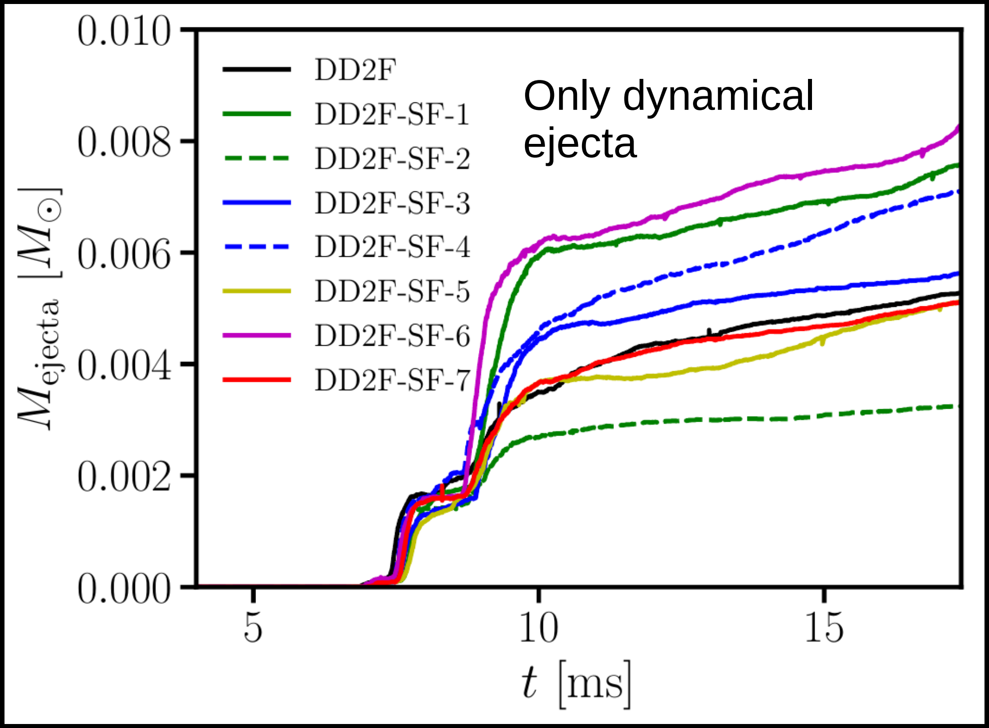
EoS dependence

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

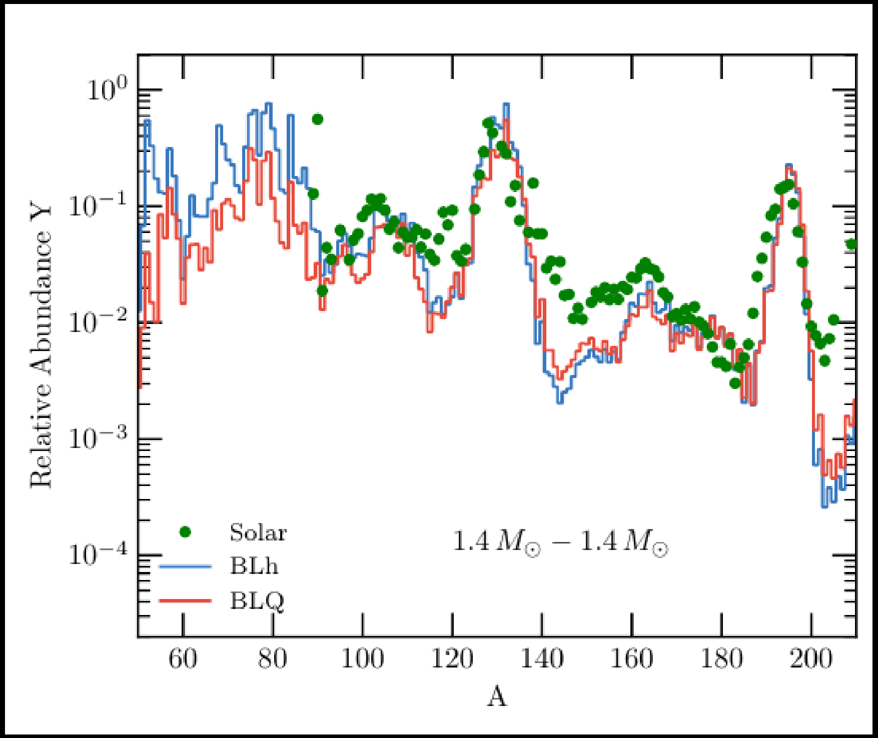
Em counterpart / nucleosynthesis

- 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)



Bauswein et al. 2019



Prakash et al. 2021

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 inpsiral 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