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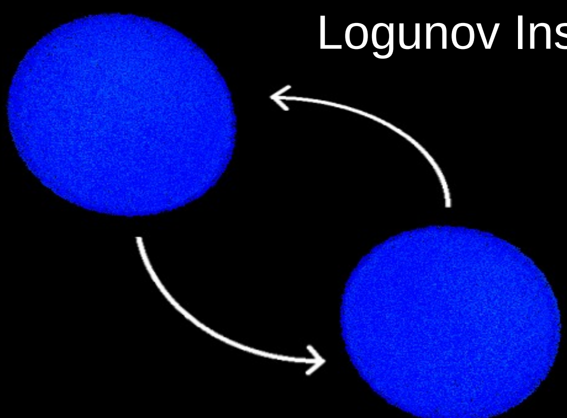
The hadron-quark phase transition and neutron star mergers

XXXII International Workshop on High Energy Physics

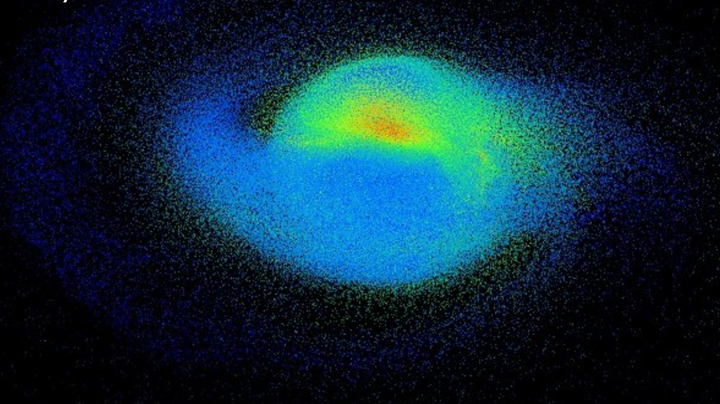
“Hot problems of Strong Interactions”

Logunov Institute for High Energy Physics, virtual, 10/11/2020



Andreas Bauswein

(GSI Darmstadt, HFHF)



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

- NS mergers with hadron-quark phase transition
- Postmerger gravitational-wave signal of NS mergers → signature of phase transition
- Constraints on onset density of phase transition
- Collapse behavior of NS mergers → signature of phase tranition
- Note on em counterparts

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 ?

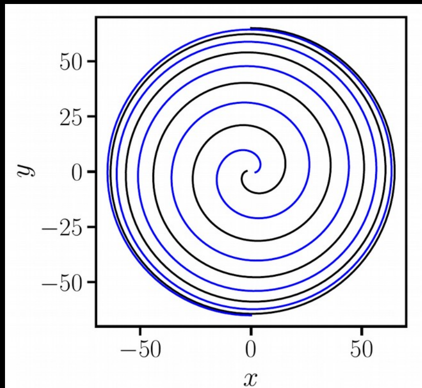
  i.e. at densities of a few times nuclear saturation ?
- Can we possibly even learn something about the properties of this phase transition and the properties of (hot) quark matter ?

- Generally:

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

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

  → impact on dynamics and thus on GW signal, collapse behavior, em counterparts, ...



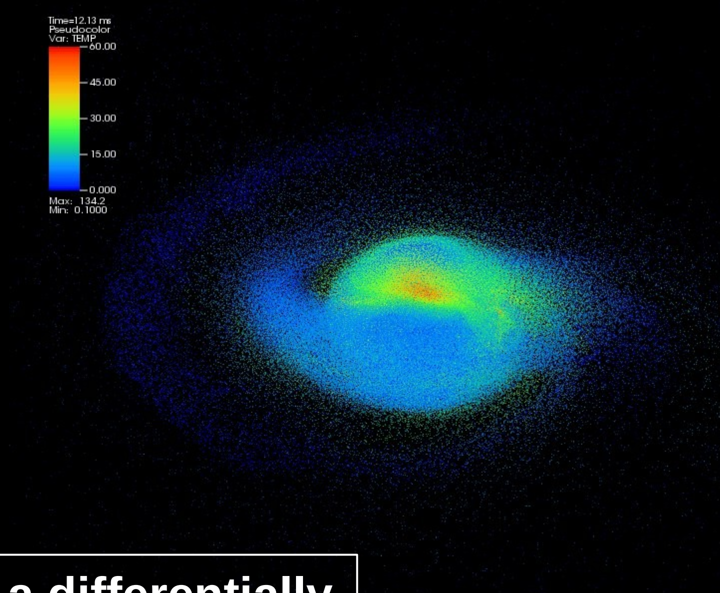
$P_{orb} \sim 10\,h$

Inspiral of NS binary

~100 Myrs

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

Neutron star merger



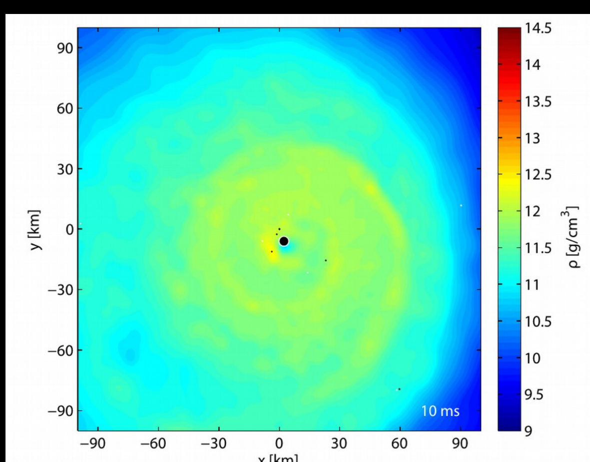
dependent on EoS, M_{tot}

ms

ms

Prompt formation of a BH + torus

Formation of a differentially rotating massive NS

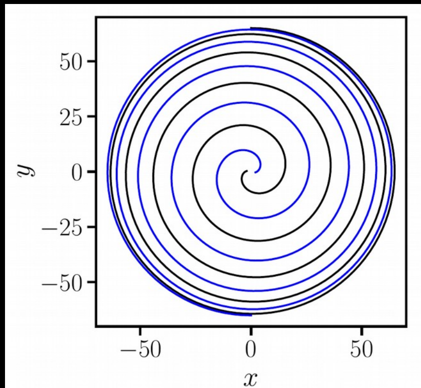


dependent on EoS, M_{tot}

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

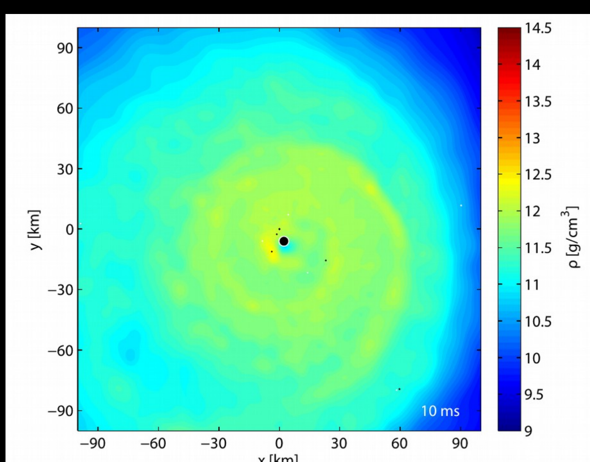
Formation of a differentially rotating massive NS

dependent on
EoS, M_{tot}

10-100 ms

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

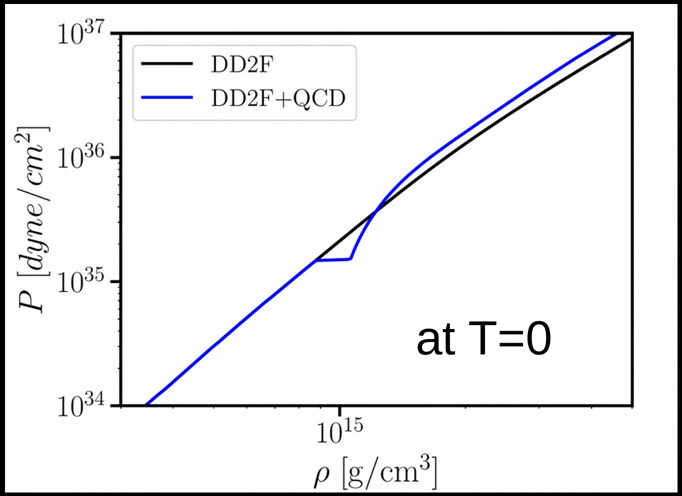
Delayed collapse to a BH + torus



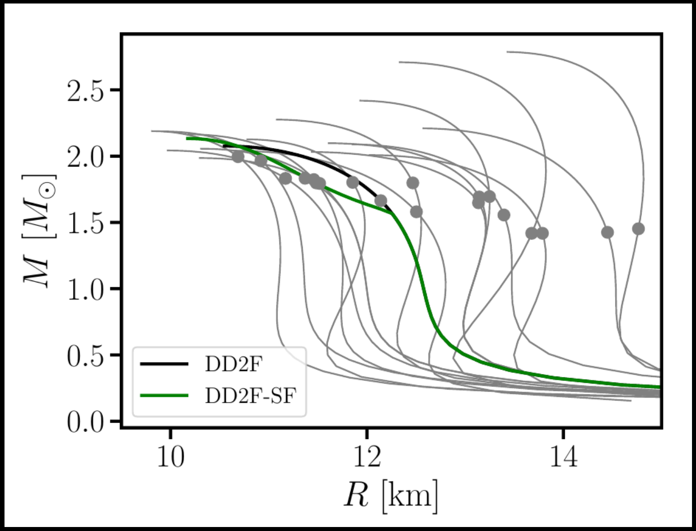
EoS with 1st-order phase transition to quark matter

- 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

  → IMPORTANT: any signature should be unambiguous !!!

- RMF (density -dependent couplings) + two-flavor string flip model (Maxwell construction), temperature dependent (important: thermal pressure, temperature-dep. phase boundary)

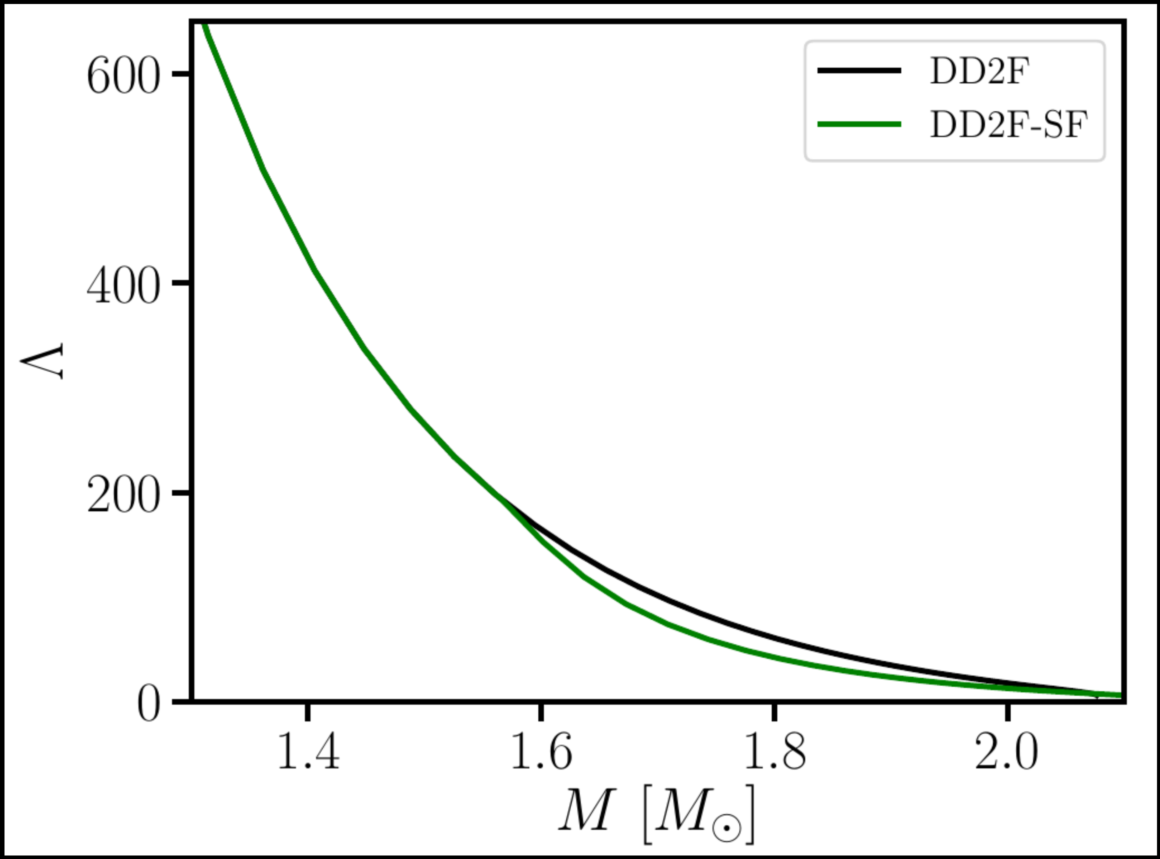
- Compatible with recent constraints from GW170817 and pulsar measurements

Phase transition and the GW inspiral

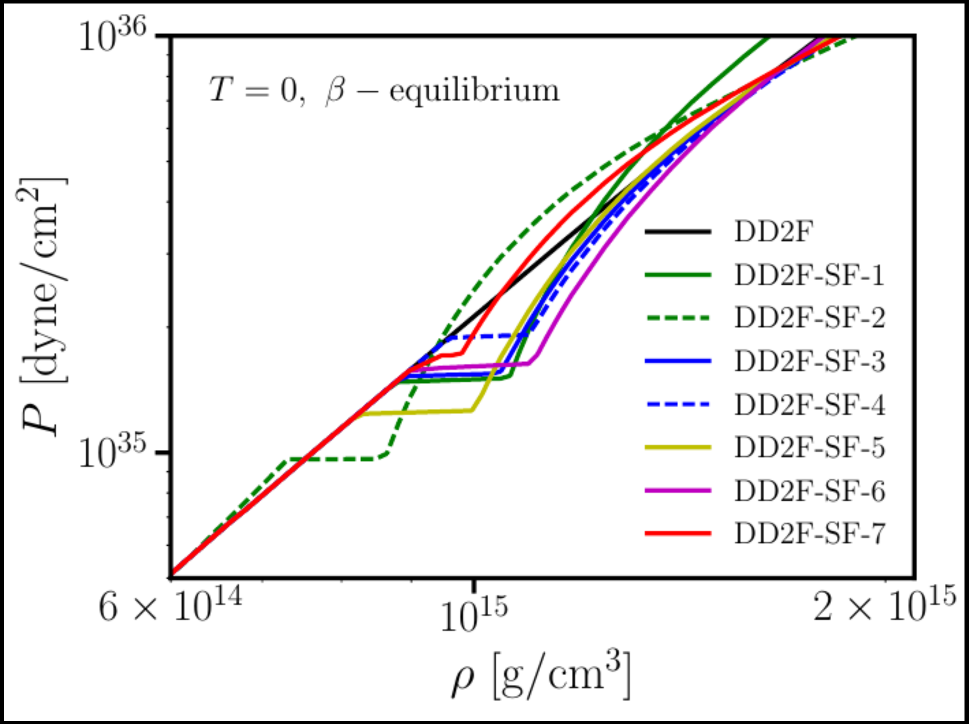
- Even strong phase transitions leave relatively weak impact on tidal deformability

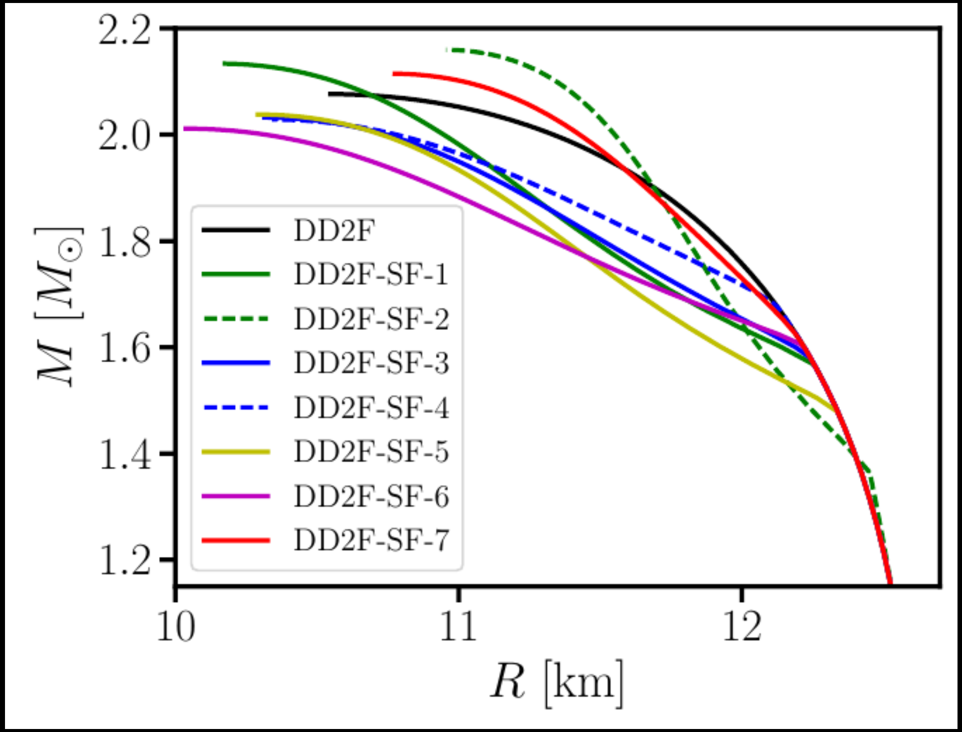
  → Difficult to measure transition in mergers through inspiral: Kink weak, Lambda generally very small, high mass star probably less frequent

  → Postmerger phase only accessible by hydrodynamical simulations



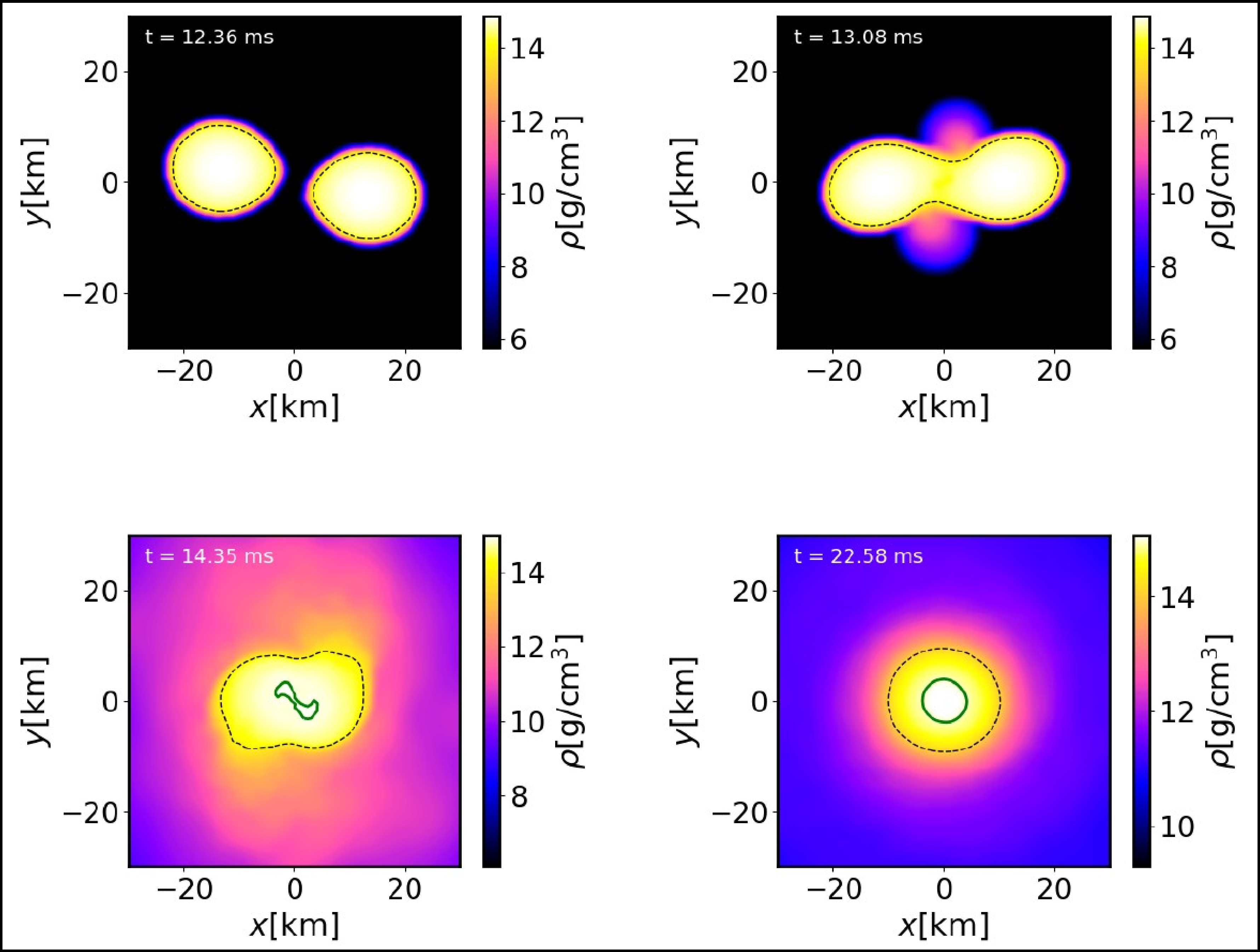
- 7 different models for quark matter: different onset density, different density jump, different stiffness of quark matter phase





Bauswein et al., PRL 122 (2019)

EoSs from Wroclaw group (Kaltenborn et al. 2017, Fischer et al. 2018, Bastian et al. 2018, Bastian 2020)

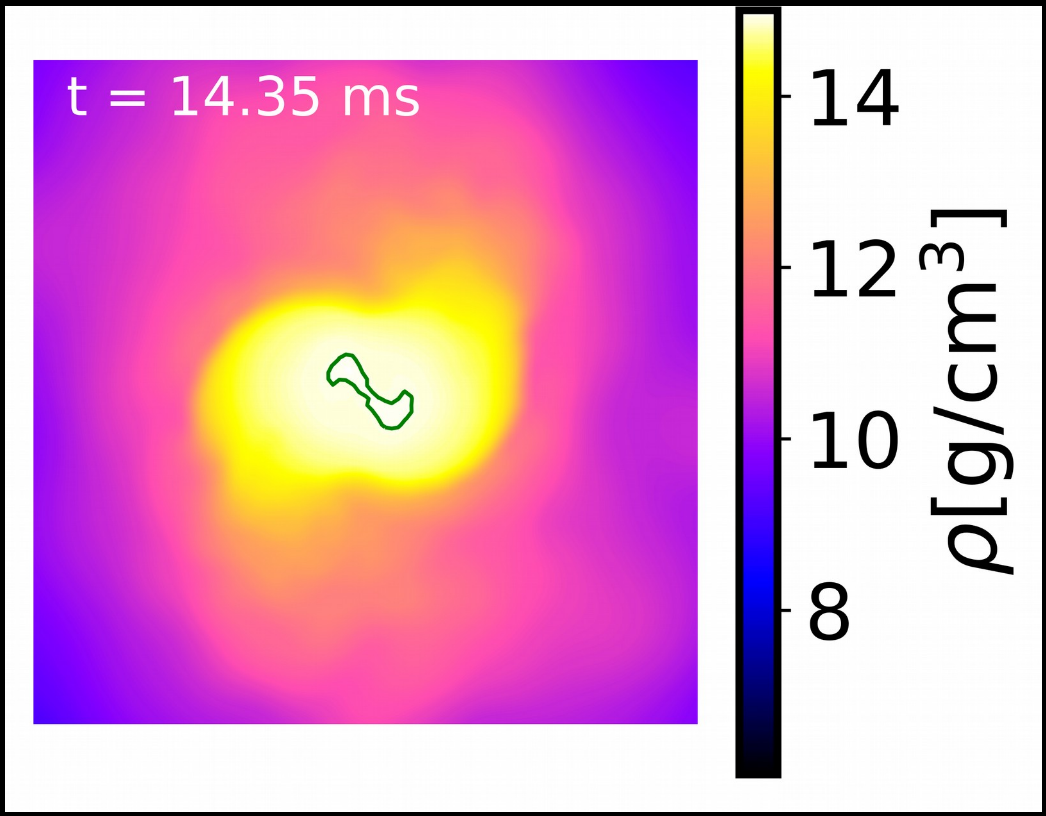


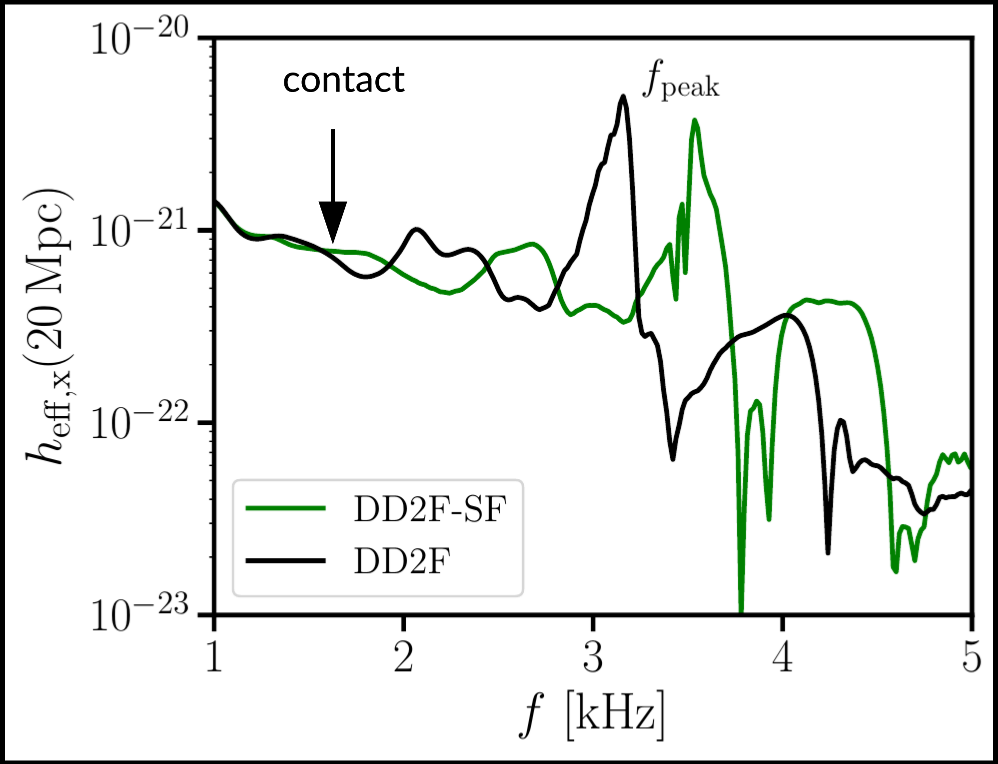
1.35-1.35 Msun - DD2F-SF-1

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

Merger simulations

▸ GW spectrum 1.35-1.35 Msun





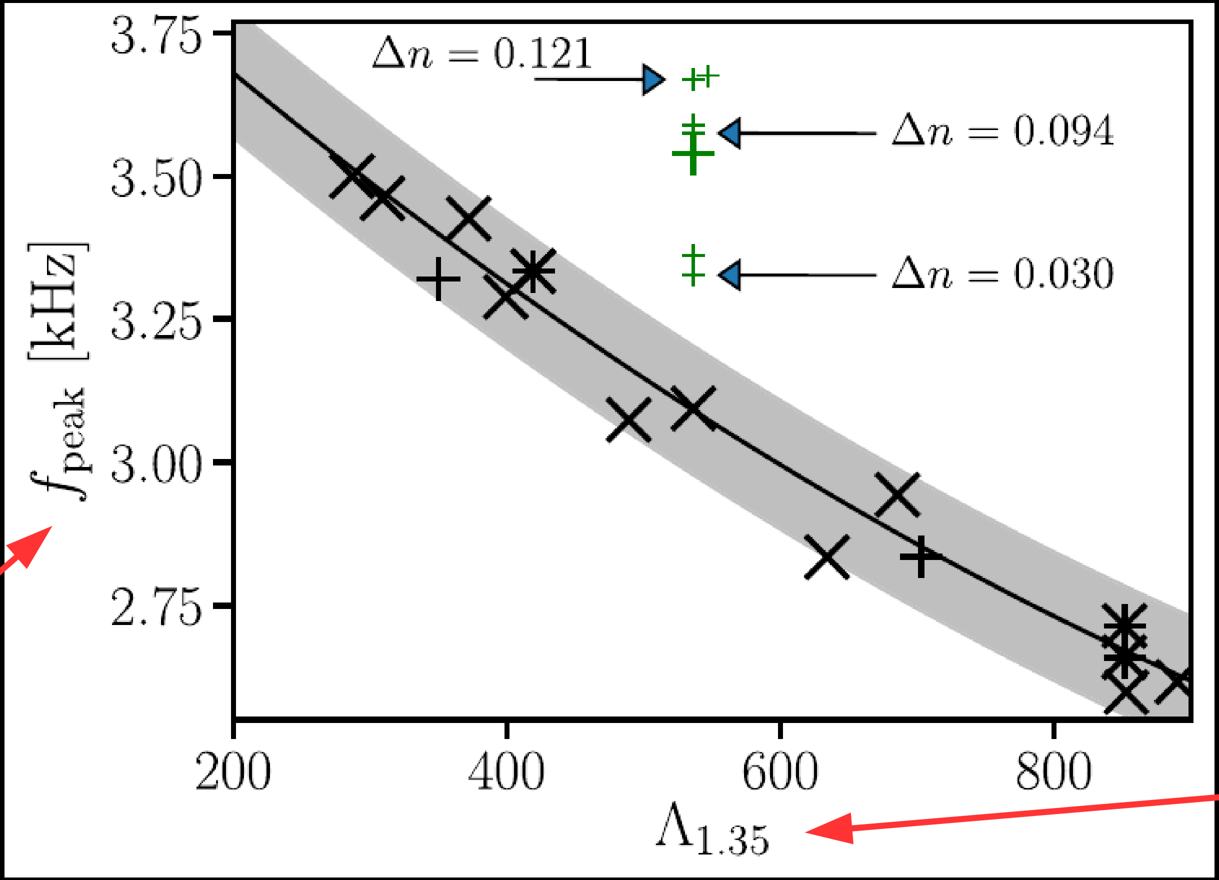
Bauswein et al., PRL 122 (2019)

But: a high frequency on its own may not yet be characteristic for a phase transition

→ unambiguous signature

(→ show that all purely baryonic EoS behave differently)

Signature of 1st order phase transition



from postmerger

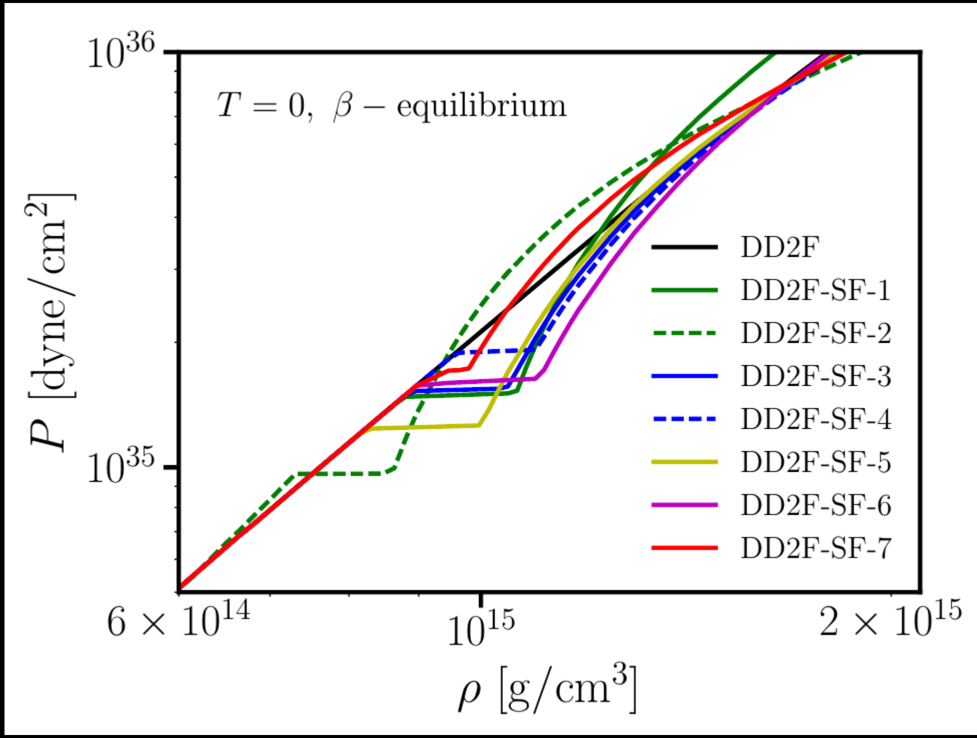
from the inspiral

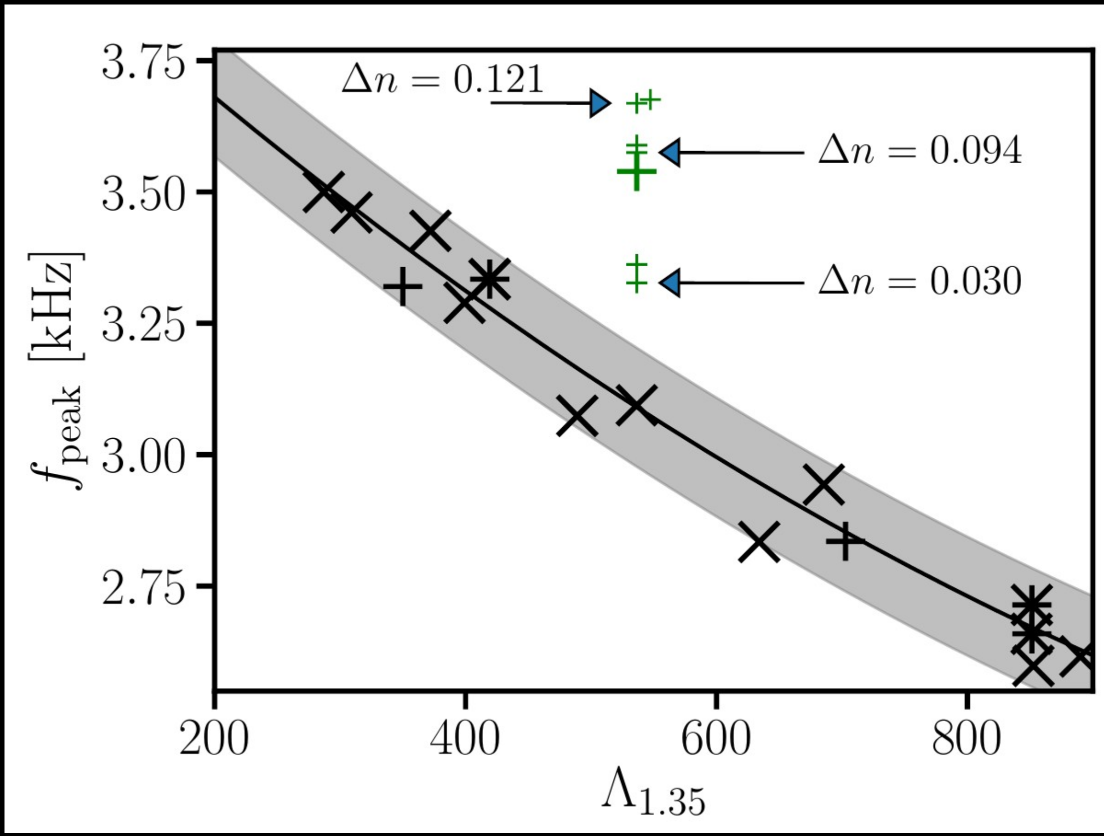
Bauswein et al., PRL 122 (2019)

- 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

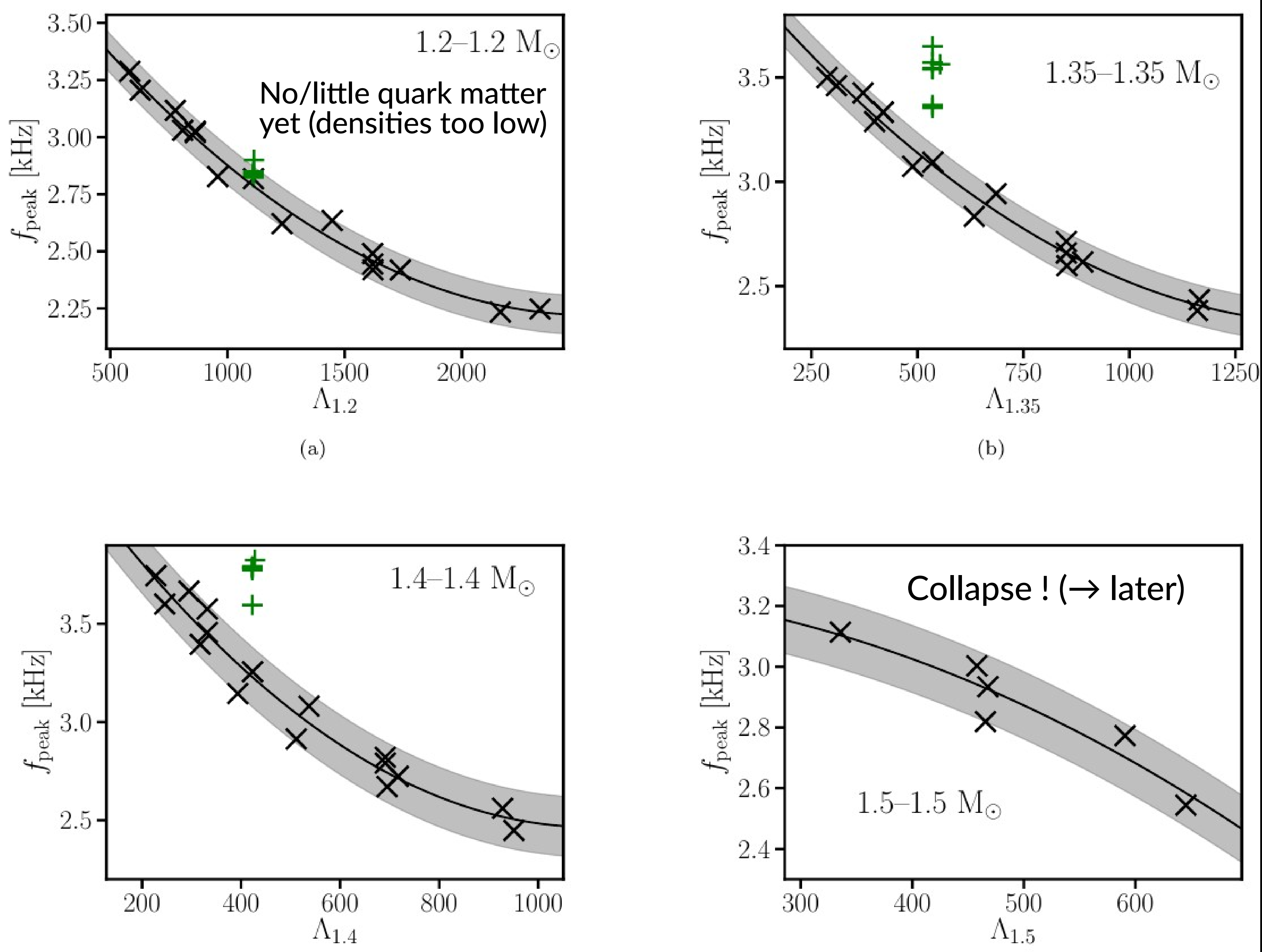
- Larger density jump → stronger compactification → more significant increase of fpeak (keeping other EoS parameters fixed)
- asymmetric mergers lead to similar behavior
- Hybrid mergers also show frequency increase
- For other hadronic base models we expect same effect





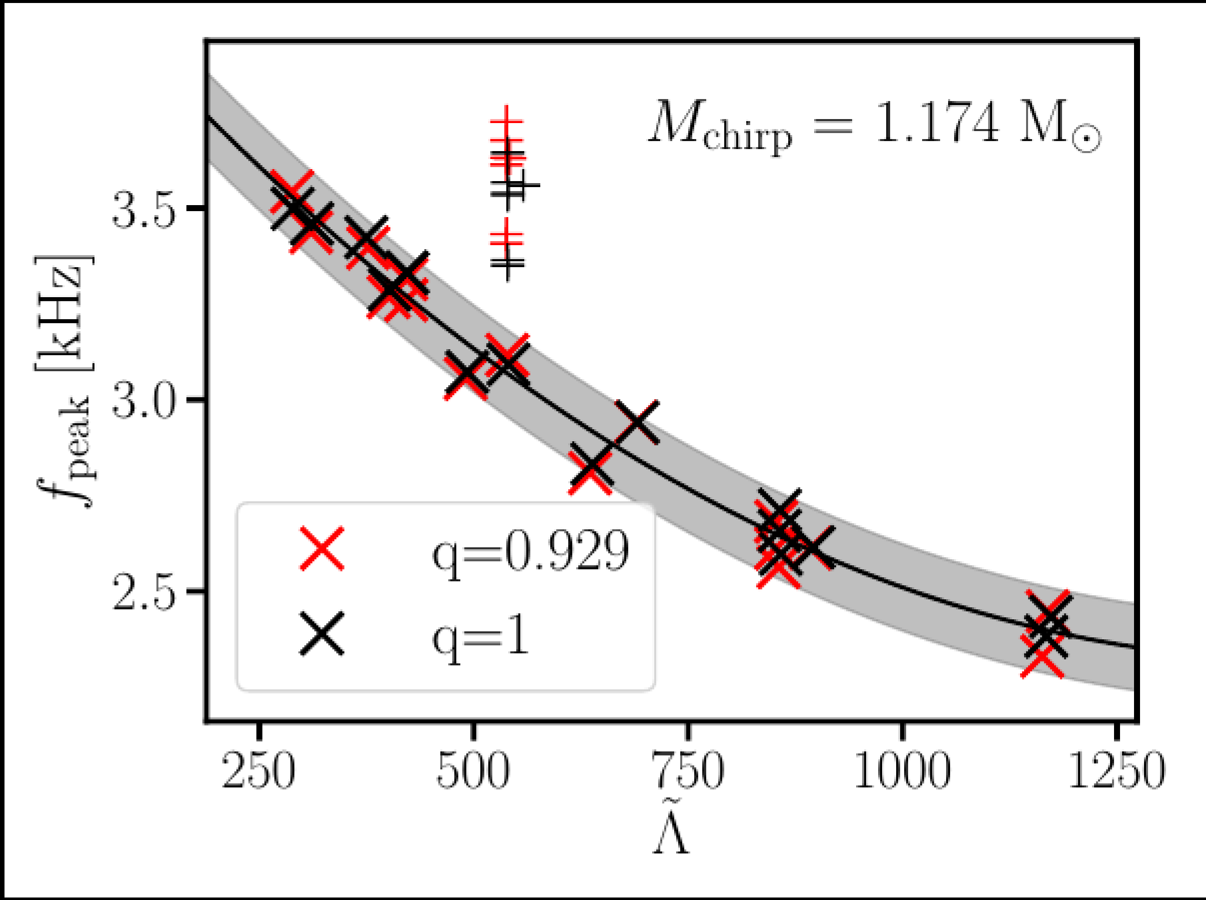
Different parametrization of quark phase

Bauswein et al., PRL 122 (2019)



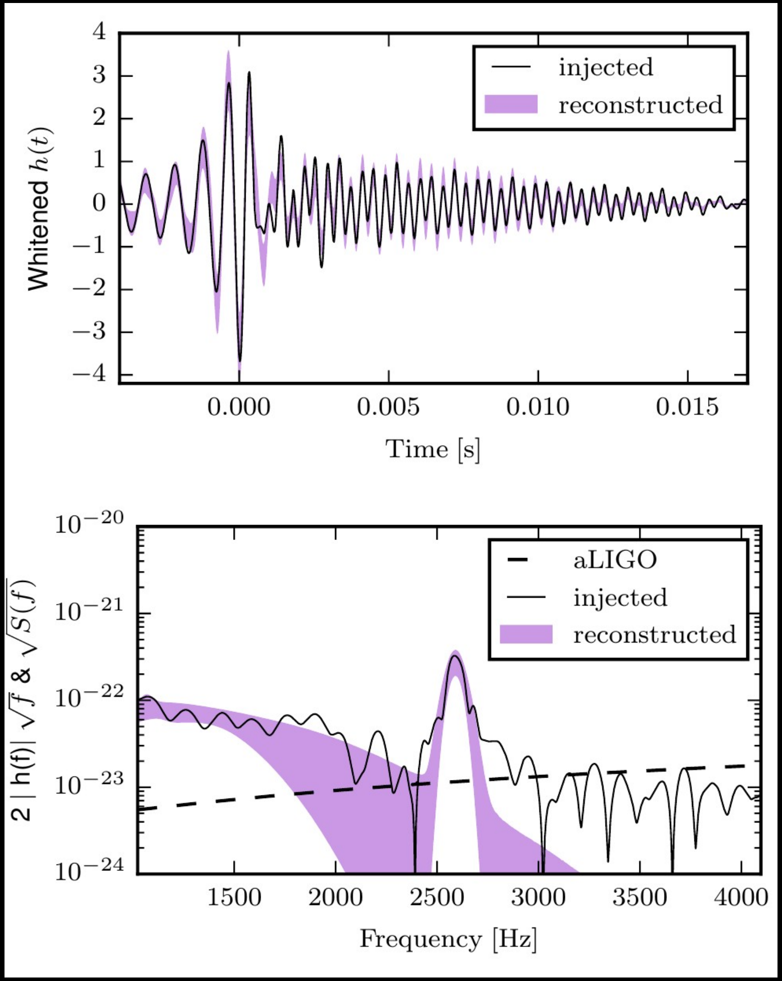
Blacker et al. (2020), arXiv:2006.03789

- Signature also present in asymmetric mergers

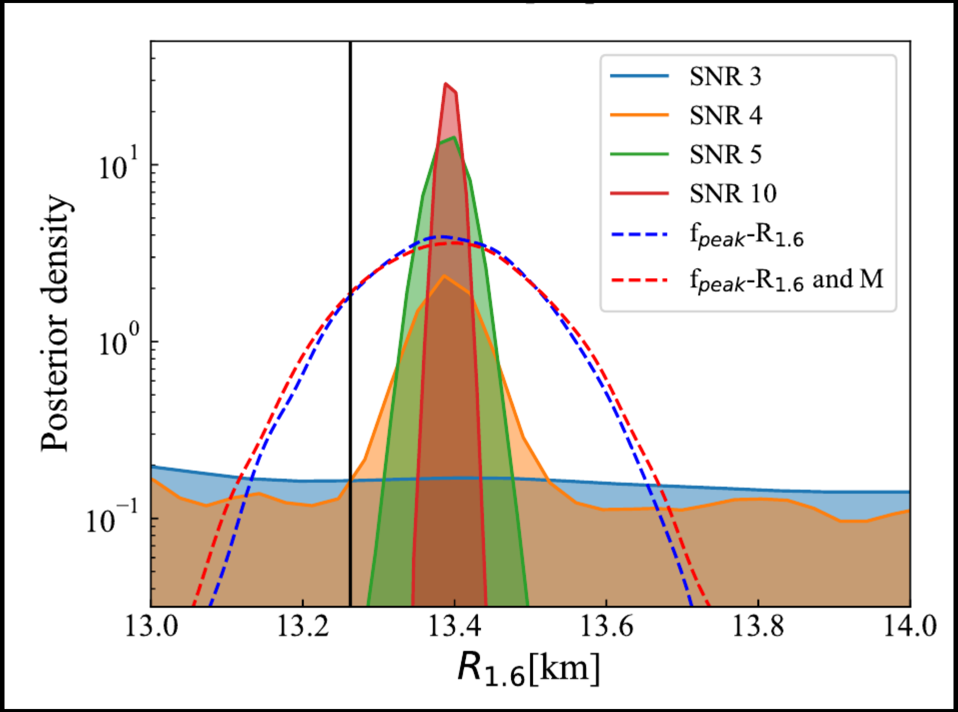


Blacker et al. (2020), arXiv:2006.03789

Model-agnostic data analysis



Based on wavelets



Chatziioannou et al., PRD 96 (2017), Torres-Riva et al., PRD 99 (2019)

→ at a few 10 Mpc detectable

Constraints on the onset density

- Summary: Compare fpeak and Lambda

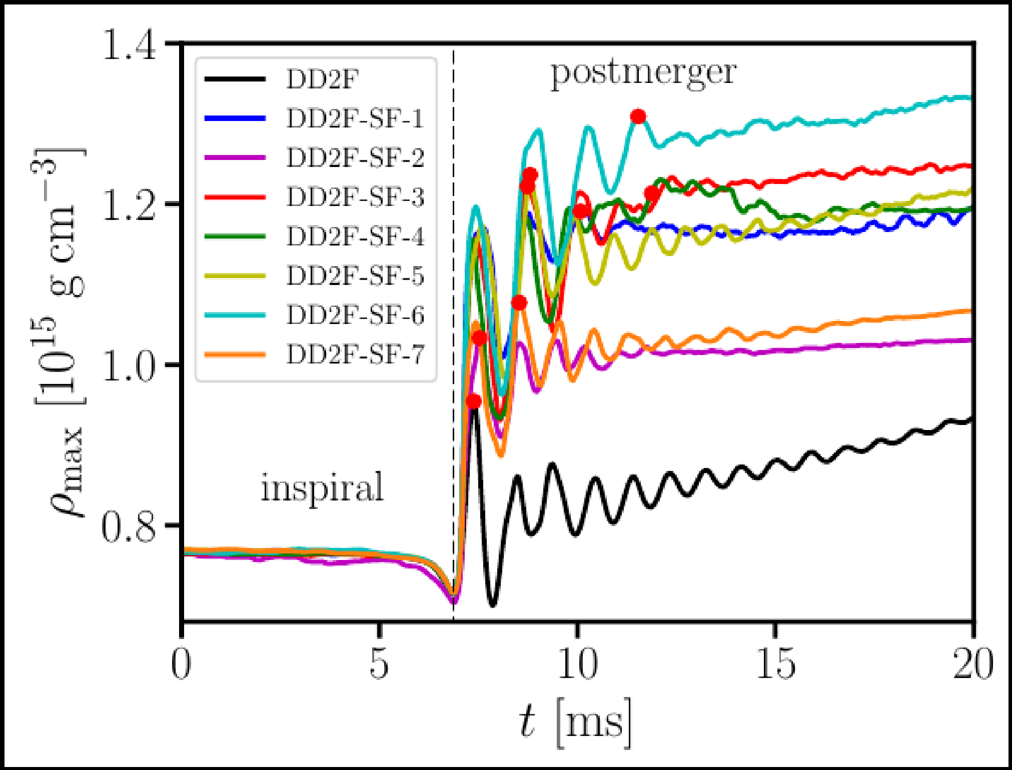
  - fpeak compatible with hadronic (gray band) → No PT (for measured binary masses)

  - 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 !!!

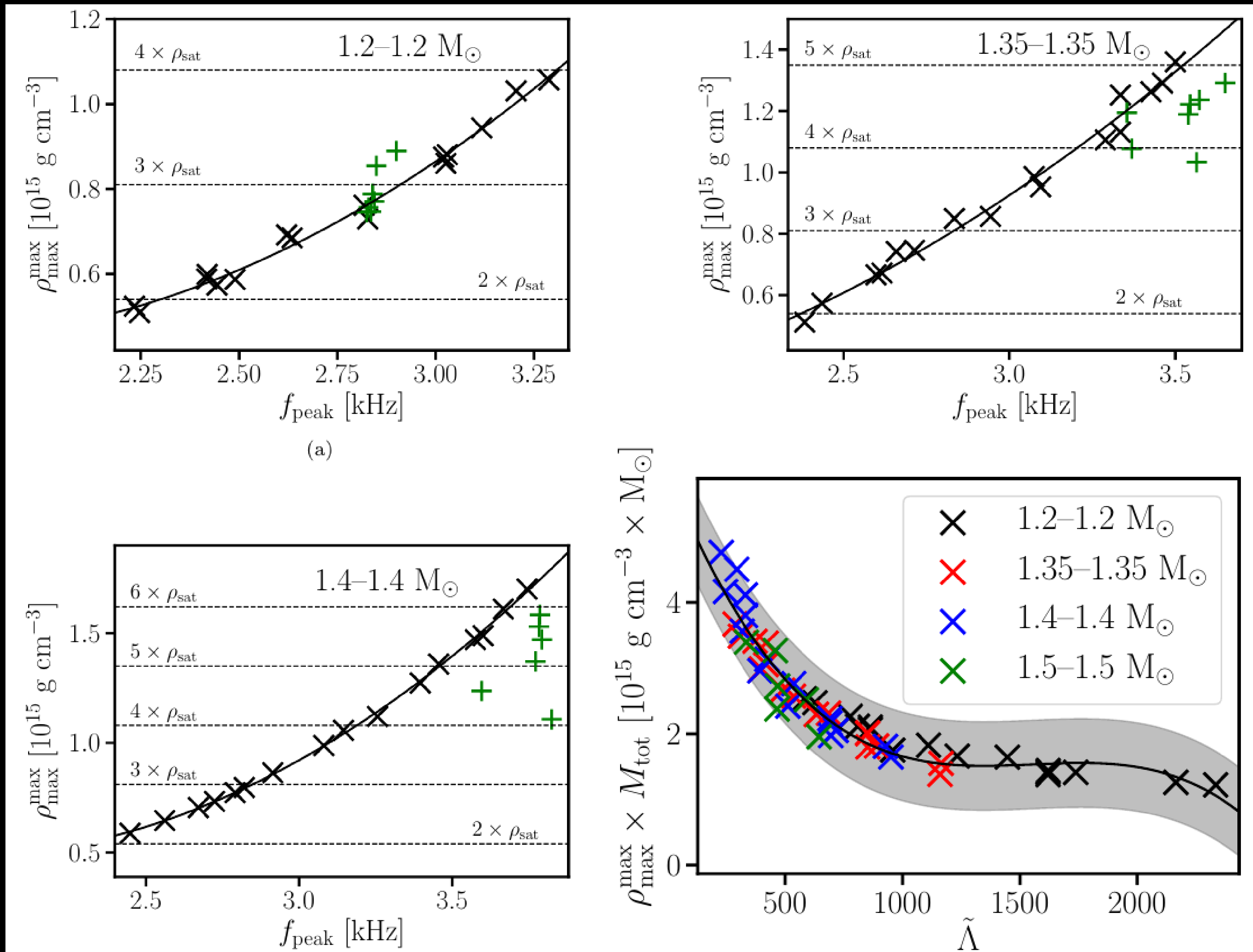
→ Hence we can exclude PT up to this density - or the PT must have occurred below that density !!!



Blacker et al. (2020), arXiv:2006.03789

- 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), arXiv:2006.03789

Bauswein et al., PRL 122 (2019)

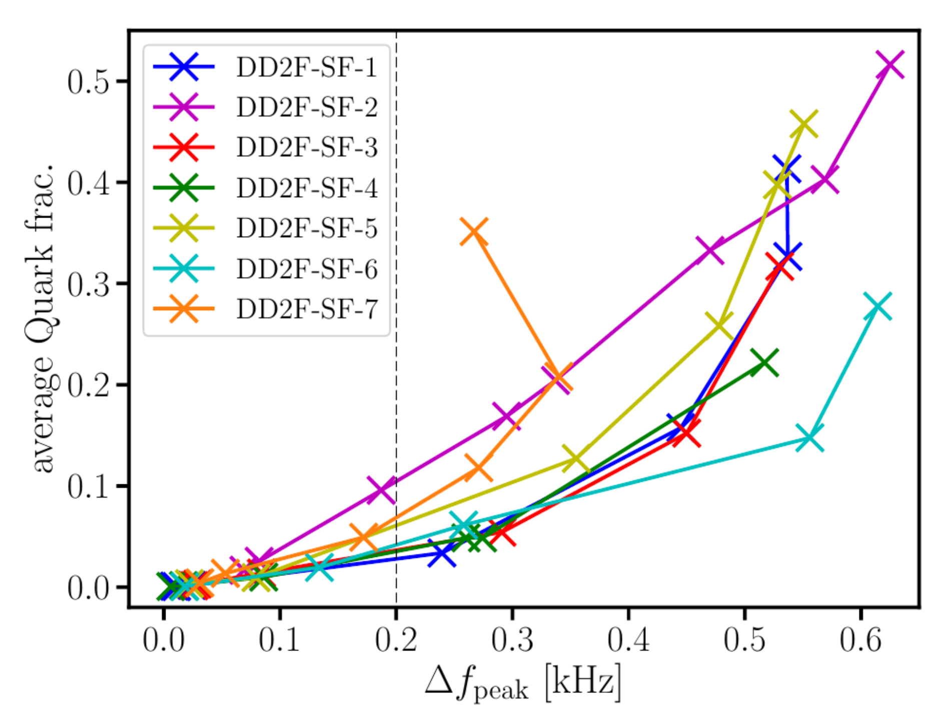
Constraints on onset density

- In detail slightly more complicated → two opposite effects

  - Core quark can be too small to lead to a strong frequency shift → quark matter undetected

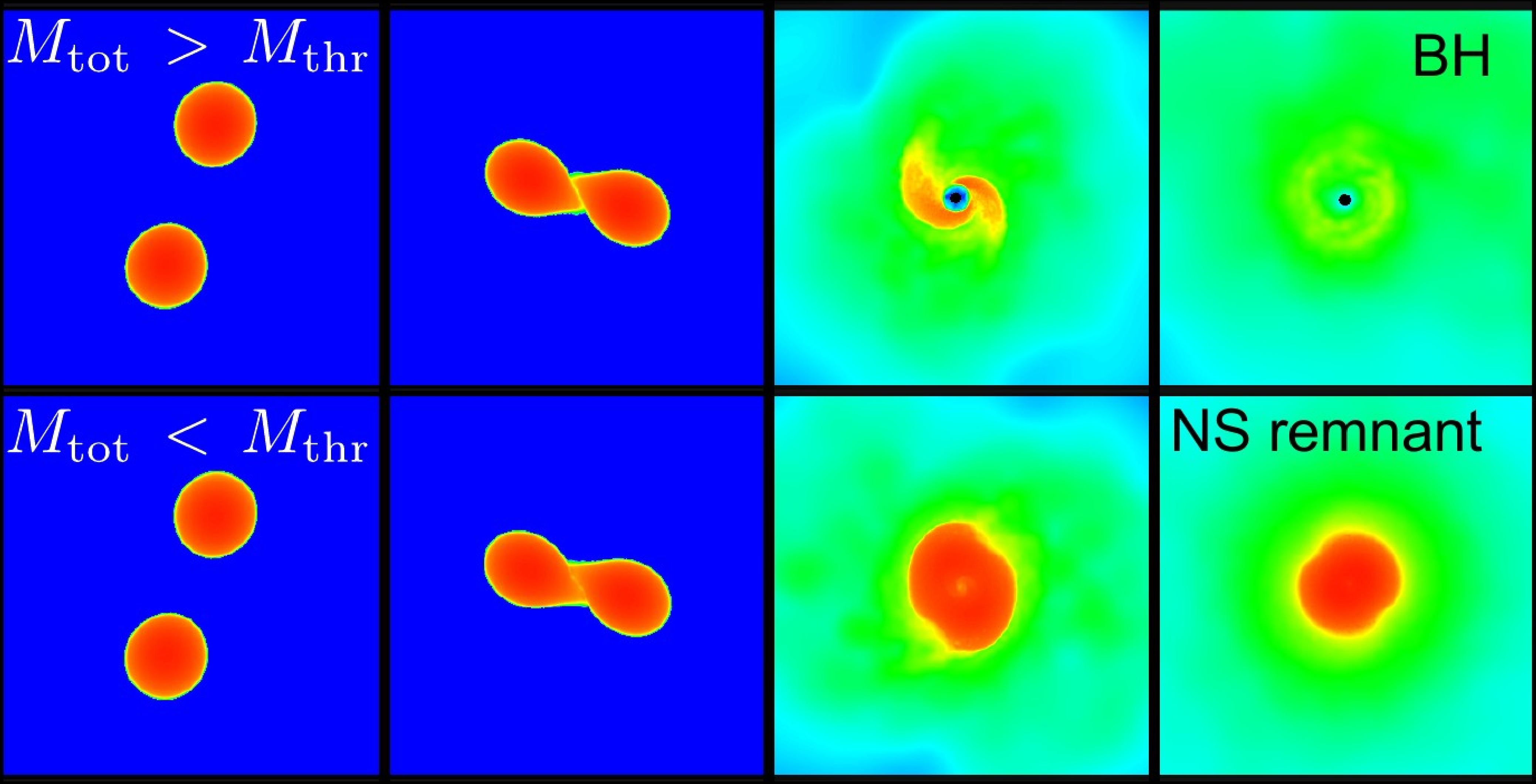
  - Quark matter can occur already at lower densities than the T=0 onset density that we want to constrain (merger probes finite T, we attempt to constrain transition at T=0)

  → both can be captured by effective procedure (Blacker et al. 2020, arXiv:2006.03789)



Collapse behavior

Collapse behavior



Collapse behavior

Total binary mass M_{tot}

Inspiral

Prompt collapse to BH

Threshold binary mass M_{thres}

No or delayed collapse to BH

+ strong postmerger GW emission

+ bright kilonova

+ ….

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

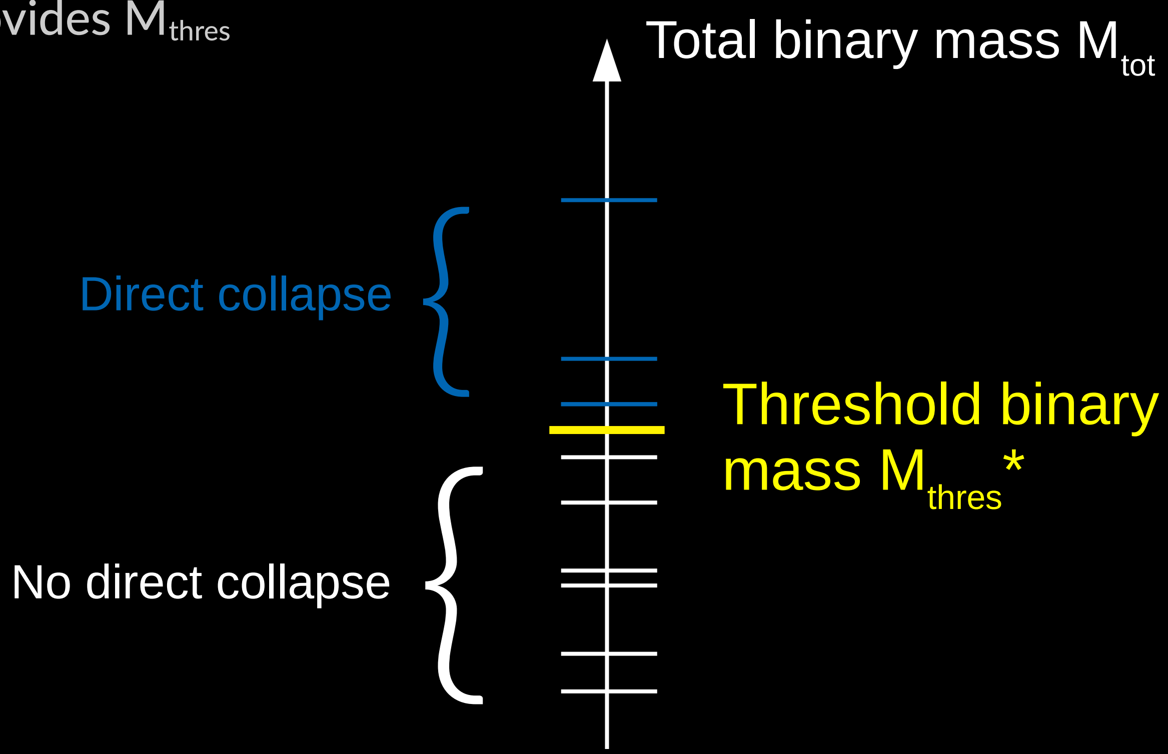
Future determination of M_{thres}

- 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



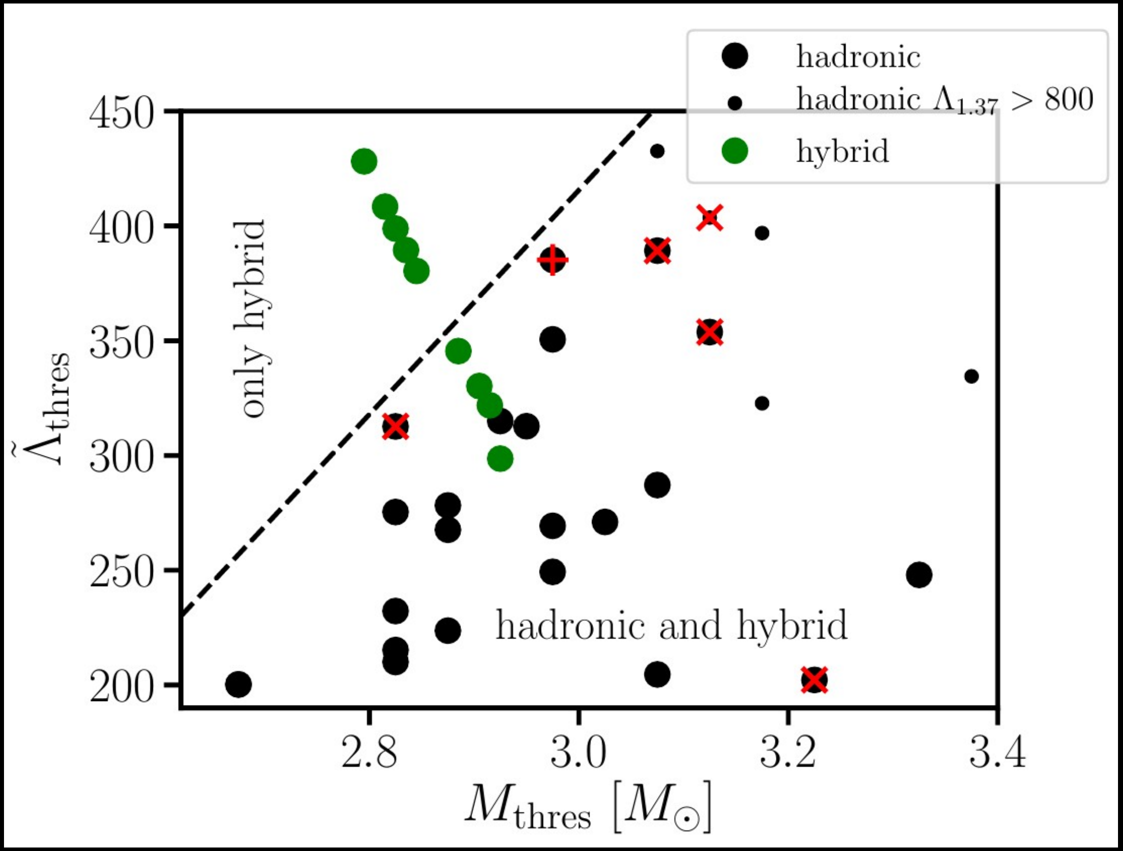
* determined by highest binary mass with no collapse and lowest mass with direct collapse

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

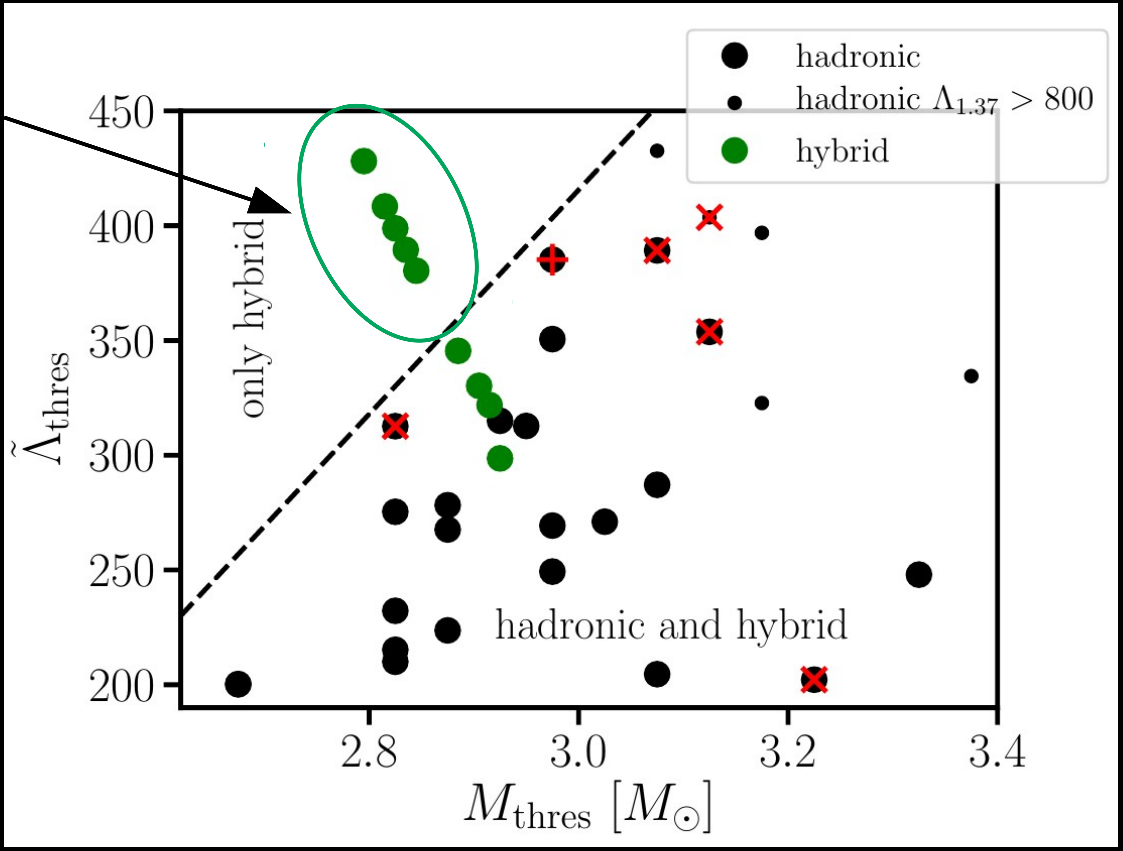
$$\tilde{\Lambda}_{\rm thres} = \Lambda(M_{\rm thres}/2) \ \ \text{for} \ \ q = 1$$

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

Discussion

- Lambda probes low densities during inspiral – Mthres higher densities during merger

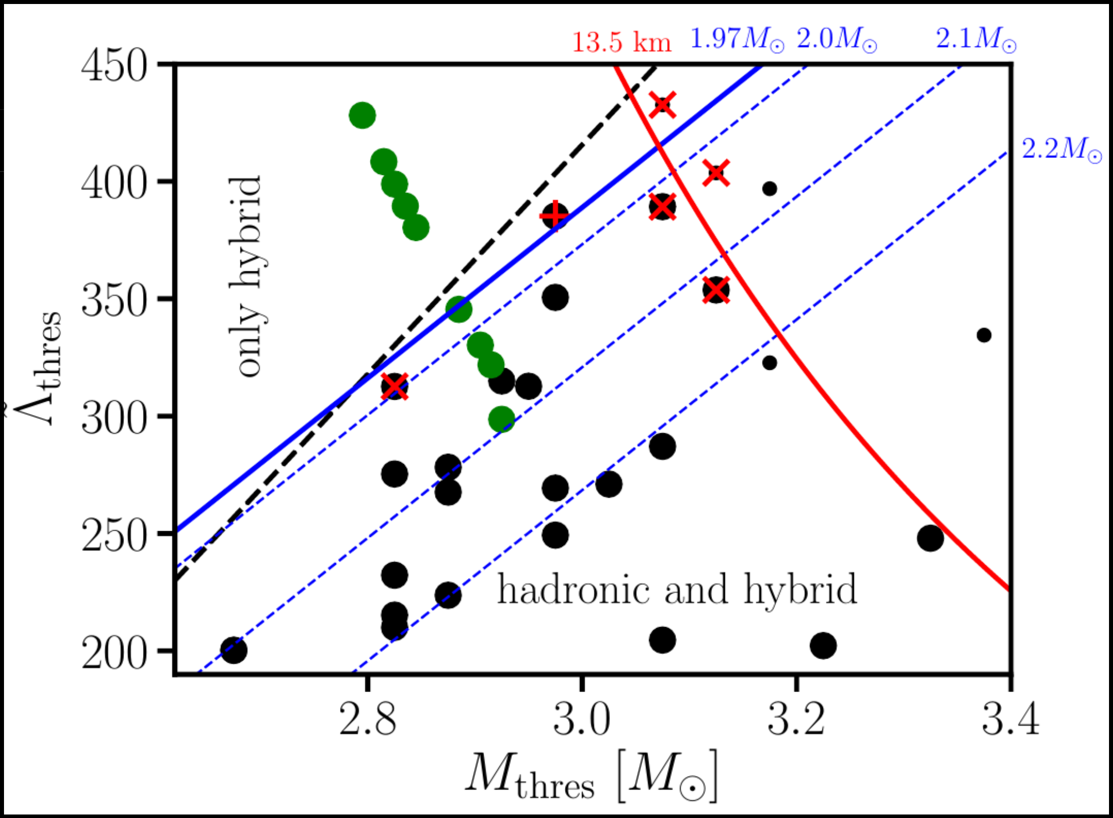
  → PT can* lead to destabilization of the remnant

  → unexpectedly low Mthres (though compatible with Mmax constraints)

  (subtlety: lowering Mthres automatically increases Lambda_thres by definition)

  → PT can push models to upper left corner

$$\tilde{\Lambda}_{\text{thres}} = \Lambda(M_{\text{thres}}/2)$$



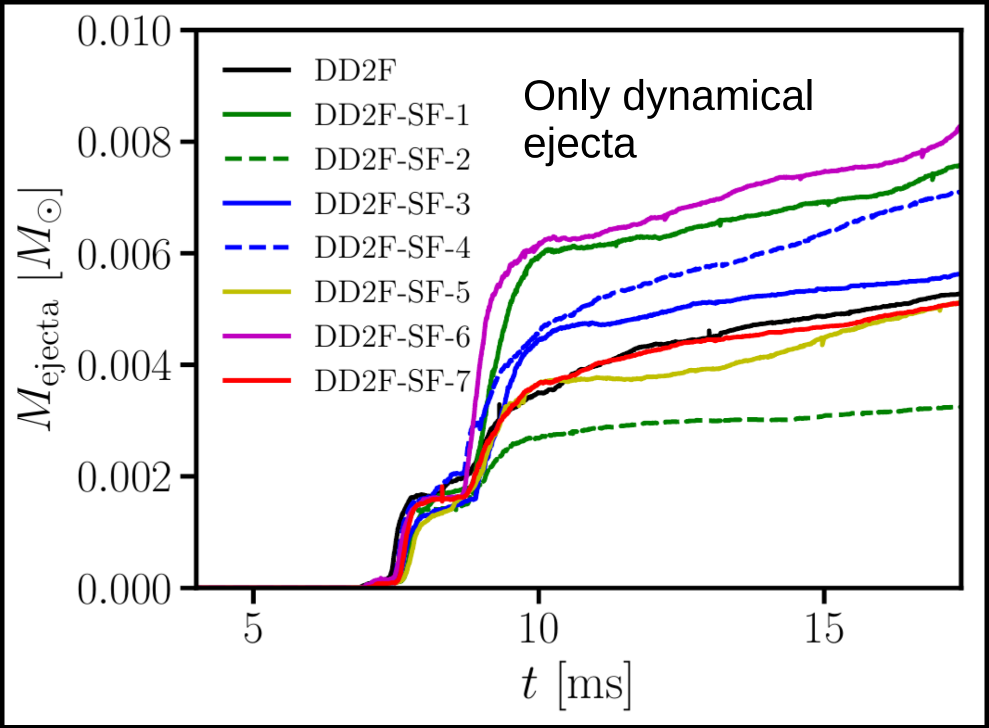
arXiv:2010.04461

* for some models quark matter can lead to stabilization depending on quark EoS

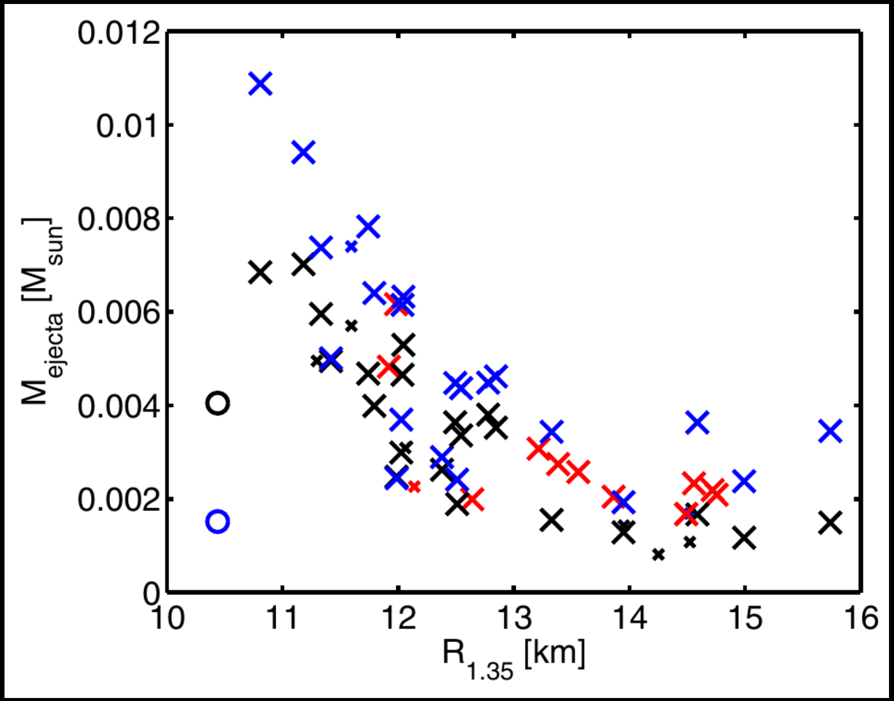
Note on em counterpart / nucleosynthesis

- 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 veocity, disk mass, …



Bauswein et al. AIP 2019, arXiv:1904.01306



Bauswein et al., ApJ 2013

Summary

- 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 may carry imprint of hadron-quark phase transition

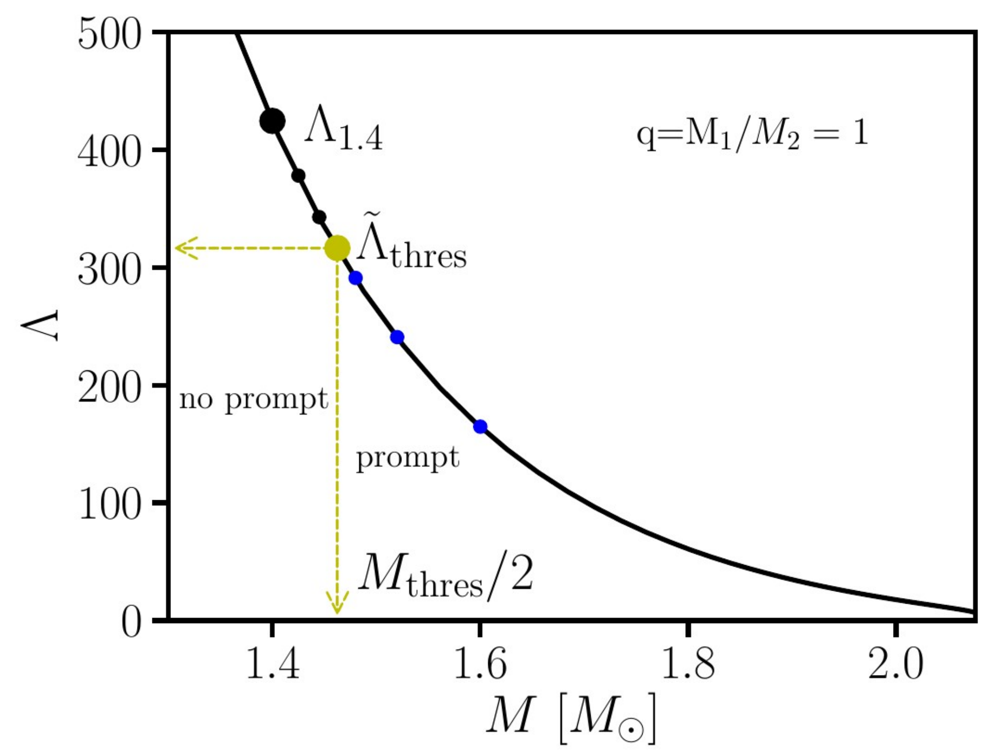
  → low thershold mass for BH formation in comparison to tidal deformability

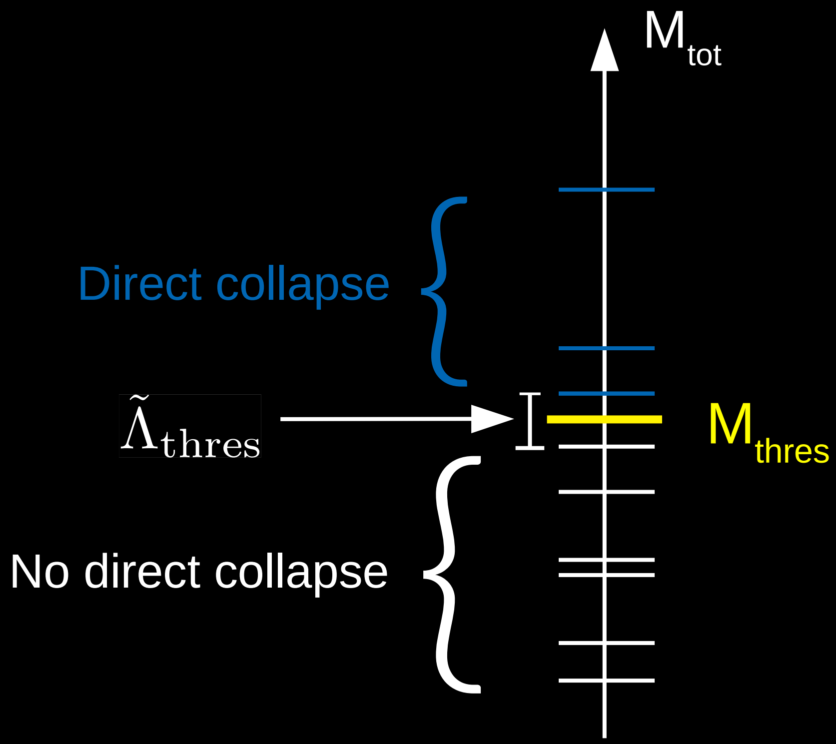
- Detection of postmerger GW emission very important (instruments and data analysis); similarly em follow up

Literature:
Bauswein et al., PRL 122, 061102 (2019), arXiv:1809.01116
Bauswein et al., AIP Conf. Proc. 2127, 020013 (2019), arXiv:1904.01306
Blacker et al., submitted to PRD (2020), arXiv:2006.03789
Bauswein & Blacker, accepted EPJ ST (2020), arXiv:2006.16183
Bauswein et al., PRL 125, 141103 (2020), arXiv:2004.00846

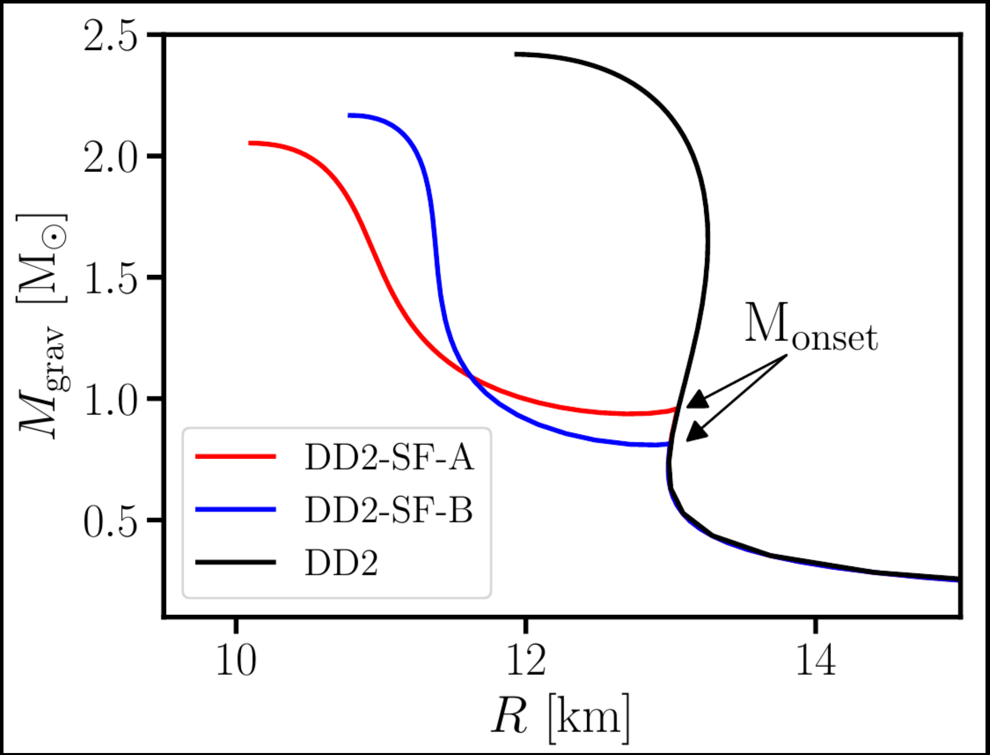
Λ_{thres} and Mthres

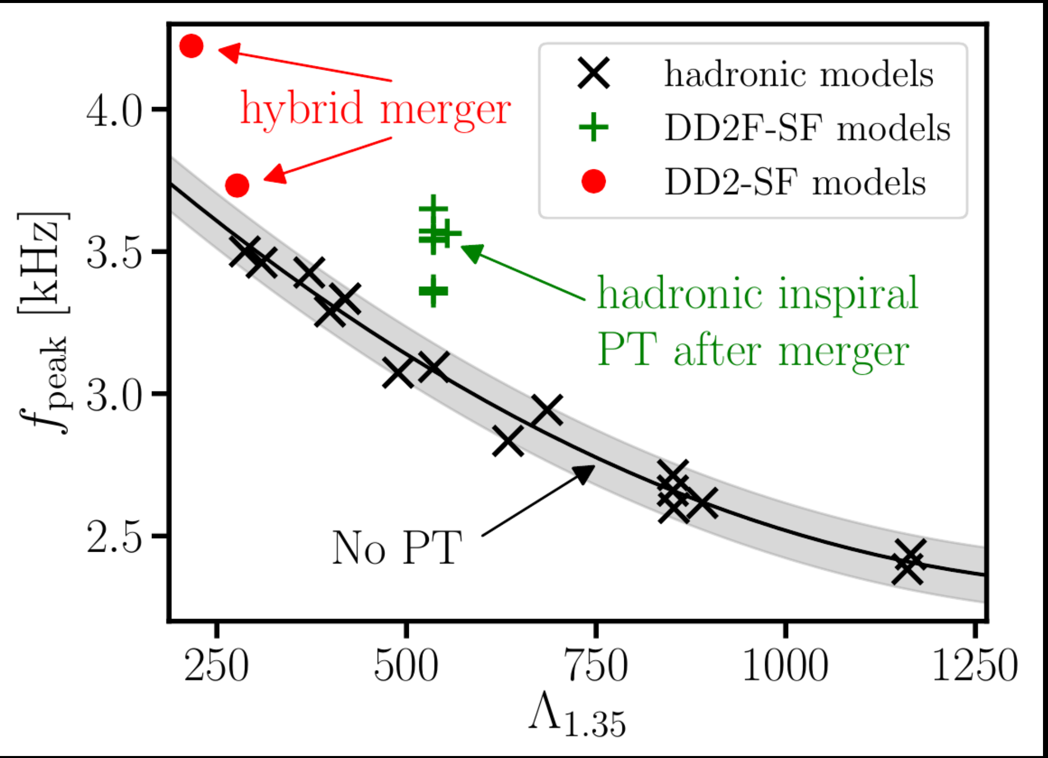
$$\tilde{\Lambda}_{\rm thres} = \tilde{\Lambda}(M_{\rm thres}/2, M_{\rm thres}/2) = \Lambda(M_{\rm thres}/2) \quad \text{for } q = 1$$





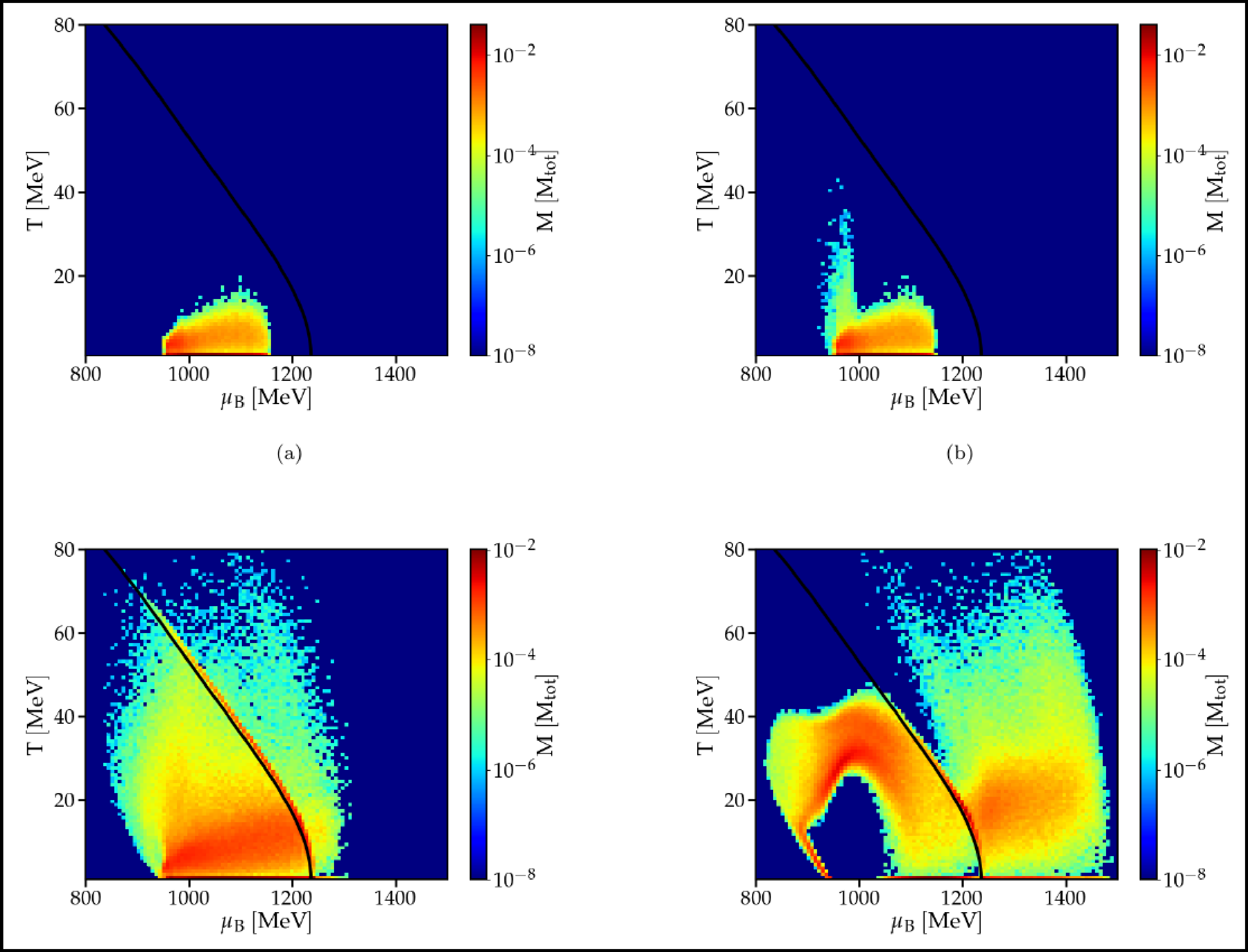
- Hybrid star mergers → similar signature
- Finally only relevant for very low onset-density

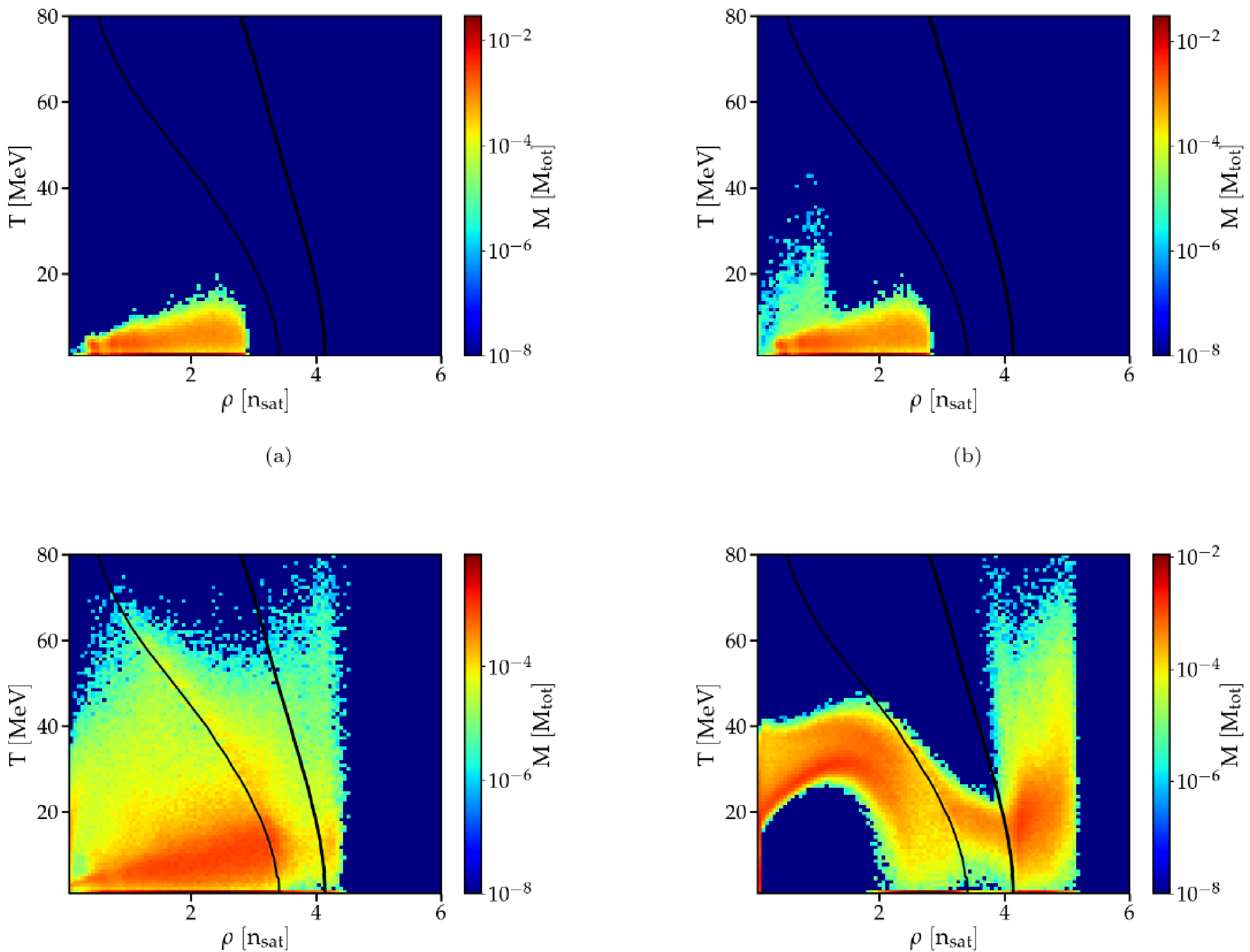




Bauswein & Blacker, EPJ ST (2020), arXiv:2006.16183

- Phase diagram





80
60
40
20
T [MeV]
2
4
6
ρ [n_sat]
10^−2
10^−4
10^−6
10^−8
M [M_tot]
(a)
(b)