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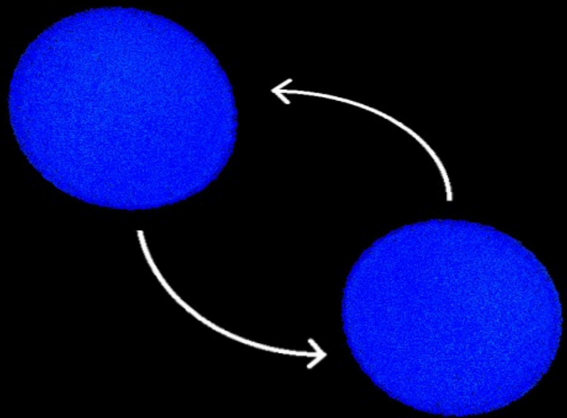
QCD, EoS and neutron star mergers

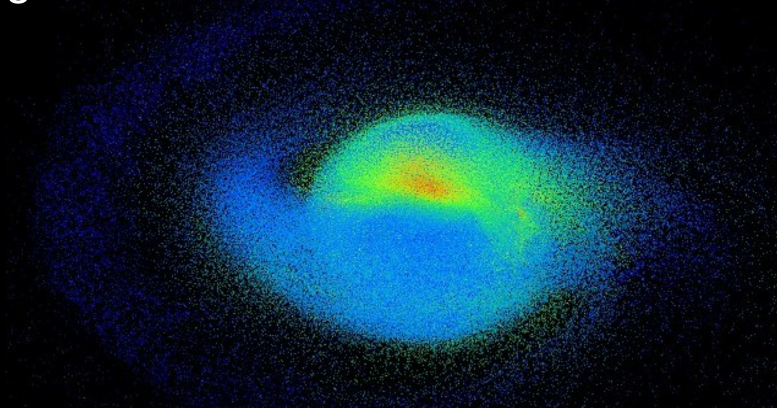
QCD at FAIR, Darmstadt 11/11/2024

Andreas Bauswein

(GSI Darmstadt)

with N. Bastian, S. Blacker, D. B. Blaschke, K. Chatziioannou, C. Collins, R. Damgaard, T. Fischer, H. Kochankovski, G. Lioutas, G. Martinez-Pinedo, M. Oertel, A. Ramos, L. Shingles, S. Sim, A. Sneppen, T. Soultanis, L. Tolos, S. Typel, V. Vijayan, D. Watson, Z. Xiong



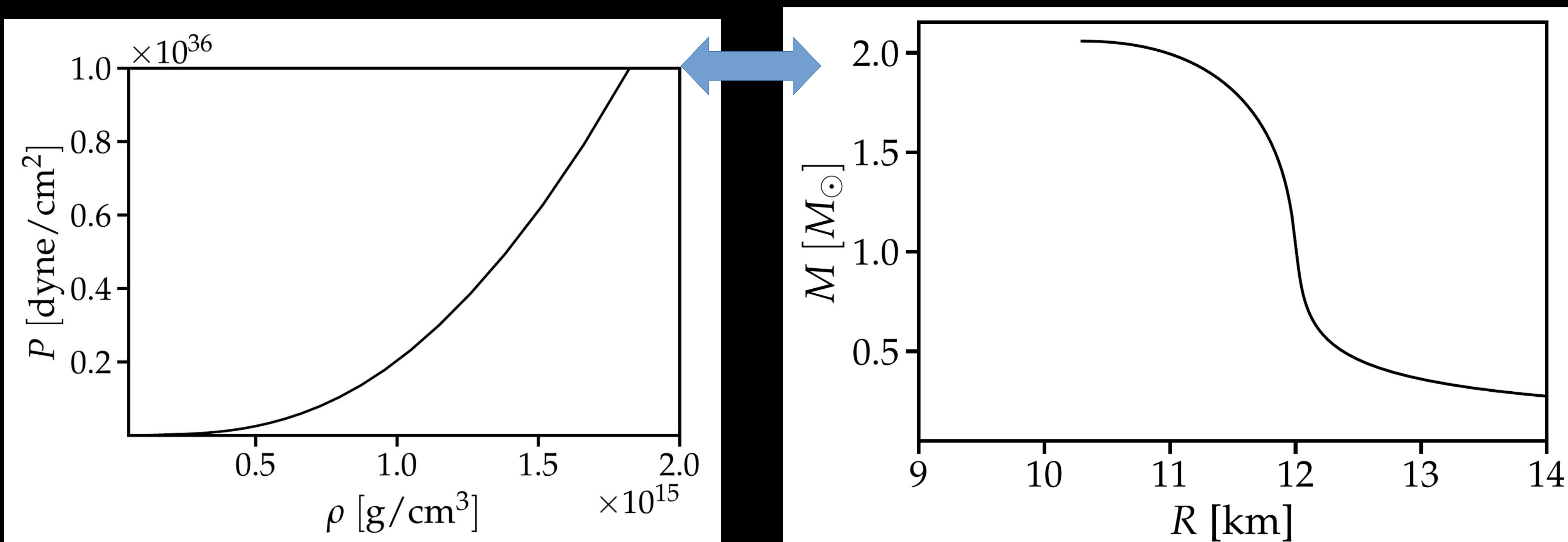


Outline

- EoS and neutron stars
- Neutron star mergers and their observables
- Quark matter
- (Hyperons)
- EoS constraints from He
- Conclusions

EoS and neutron stars

- Constituents and interactions of neutron star matter not exactly known
- Relativistic stellar structure equations (TOV): P(rho)* ↔ M(R)



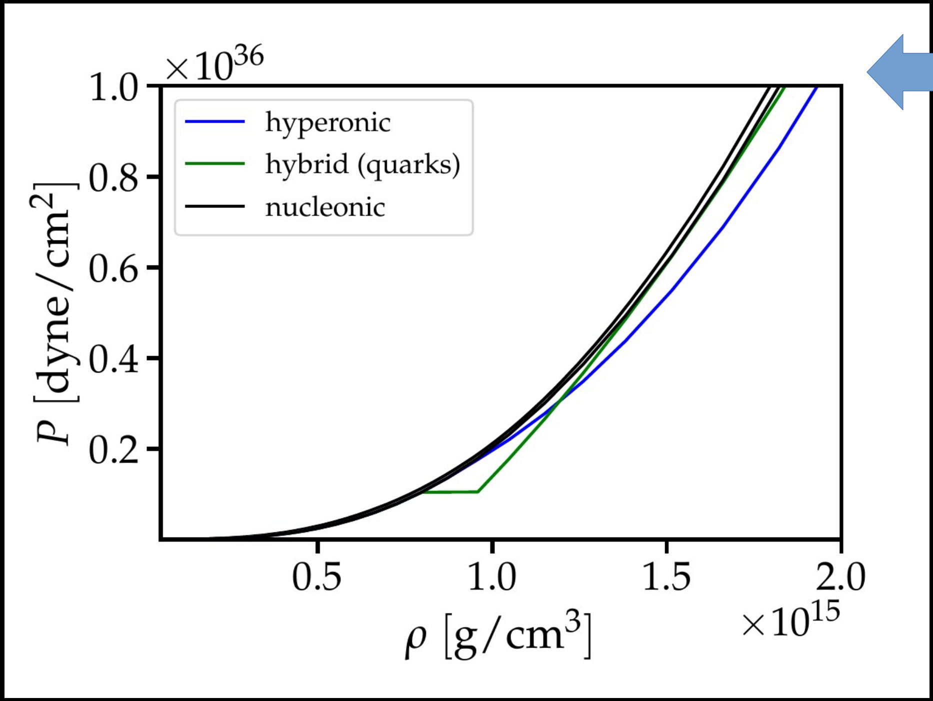
obviously many more EoS models available

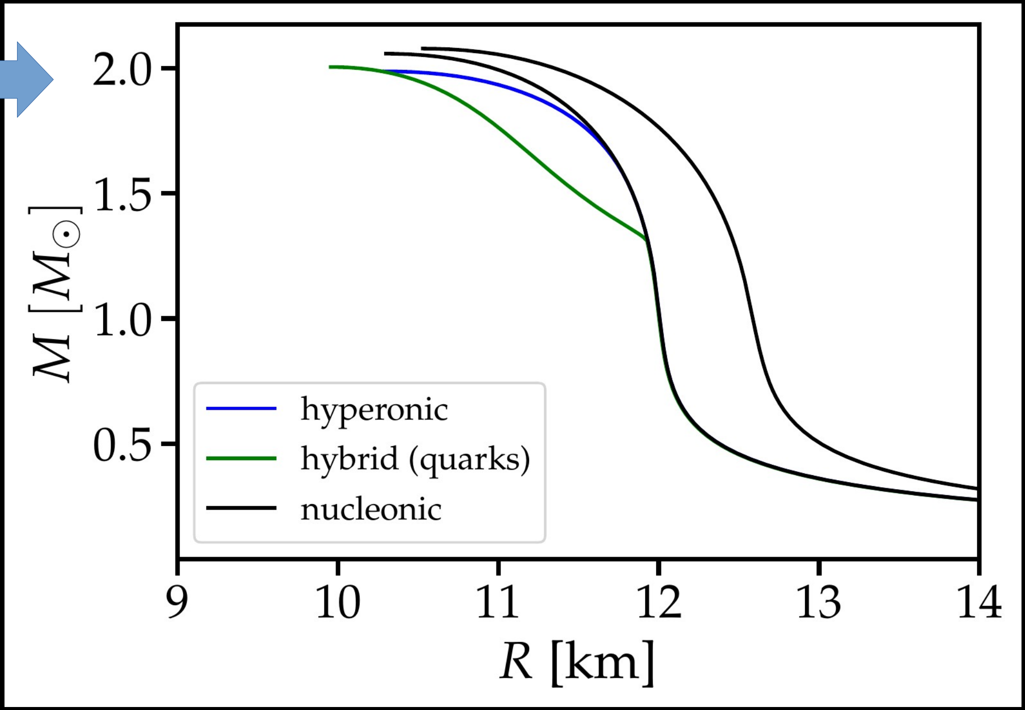
- Many ideas to measure M(R) but in practice hard to control errors

* at T=0 and beta equilibrium

EoS and neutron stars

- Constituents and interactions of neutron star matter not exactly known
- Relativistic stellar structure equations (TOV): P(rho) ↔ M(R)





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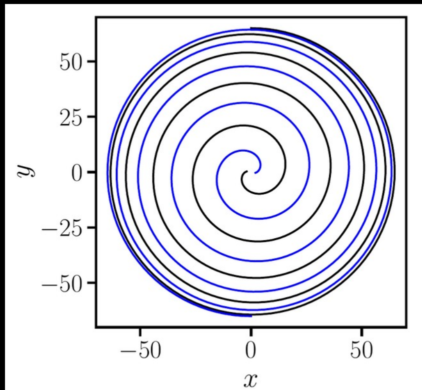


$P_{orb} \sim 10\,h$

Inspiral of NS binary

~100 Myrs

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

Neutron star merger

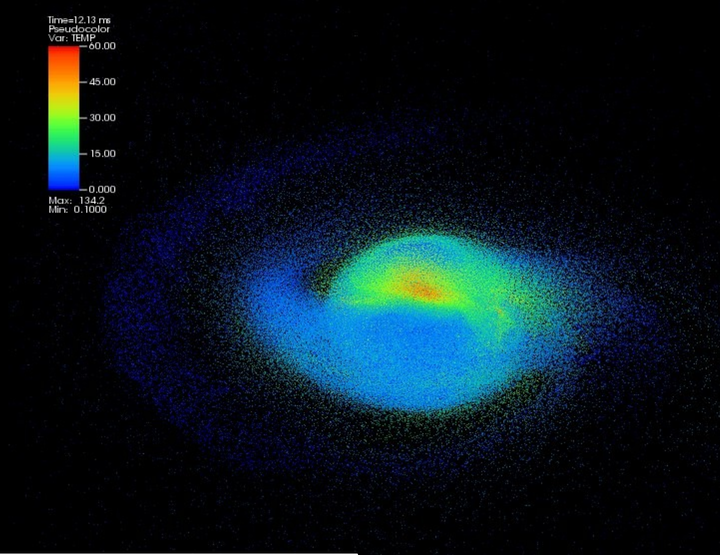
dependent on EoS, M_{tot}

ms

ms

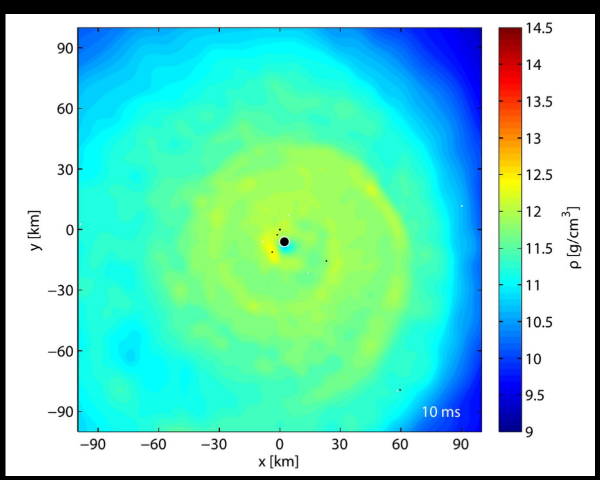
Prompt formation of a BH + torus

Formation of a differentially rotating massive NS



dependent on EoS, M_{tot}

10-100 ms

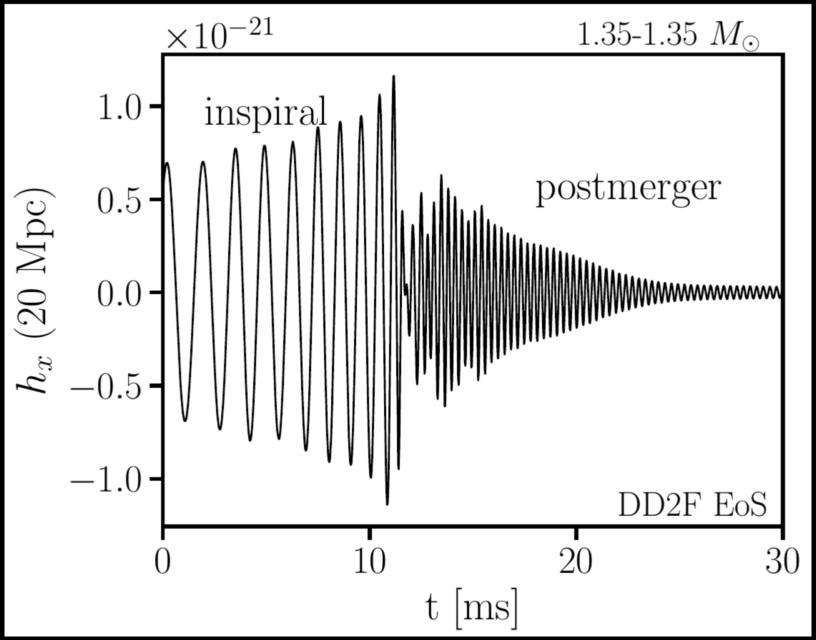


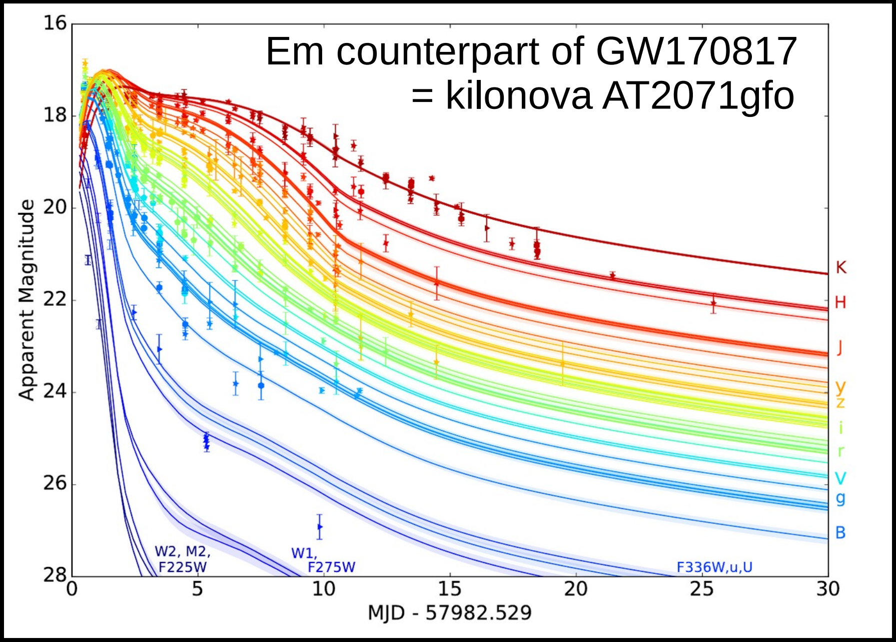
Rigidly rotating (supermassive) NS (stable or long-lived)

Delayed collapse to a BH + torus

Merger observables

- GW signal: inspiral and postmerger (latter only in future events)
- Kilonova and mass ejection: radioactive decays during rapid-neutron capture heat outflow leading to quasi-thermal emission in optical
- Gamma-ray bursts, X-ray and radio emission (probably less informative with regards to EoS)
- Generally: EoS affects dynamics of merger and thus observables





Villar et al. 2017

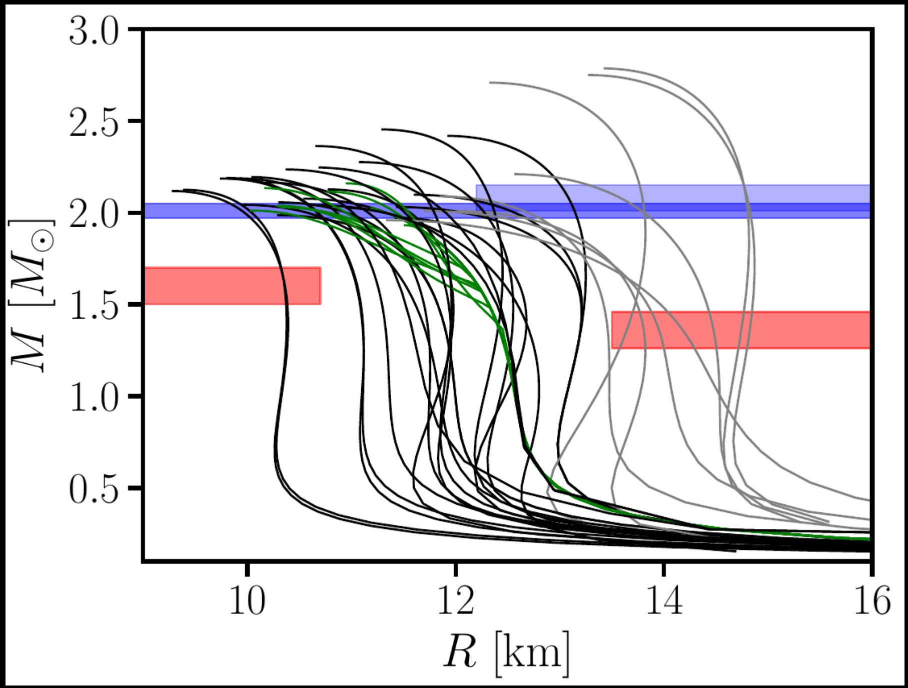
EoS constraints from GW170817

- Constraints on the tidal deformability from GW inspiral → R < 13.5 km
- General arguments about the collapse of the remnant (via em radiation)

  - no prompt collapse → minimum stiffness / radius required → R > 10.5 km

  - collapse to BH (because of GRB) → tentative M_{max} limit ~2.3 M_{sun}
- Modeling of kilonova light curve → M_{ej} → EoS via fit formulae (suffers from various uncertainties)
- Note: coarse classification with vast amount of literature (partly overlapping, partly in combination with other constraints)

  → different arguments, different model assumptions/uncertainties/robustness



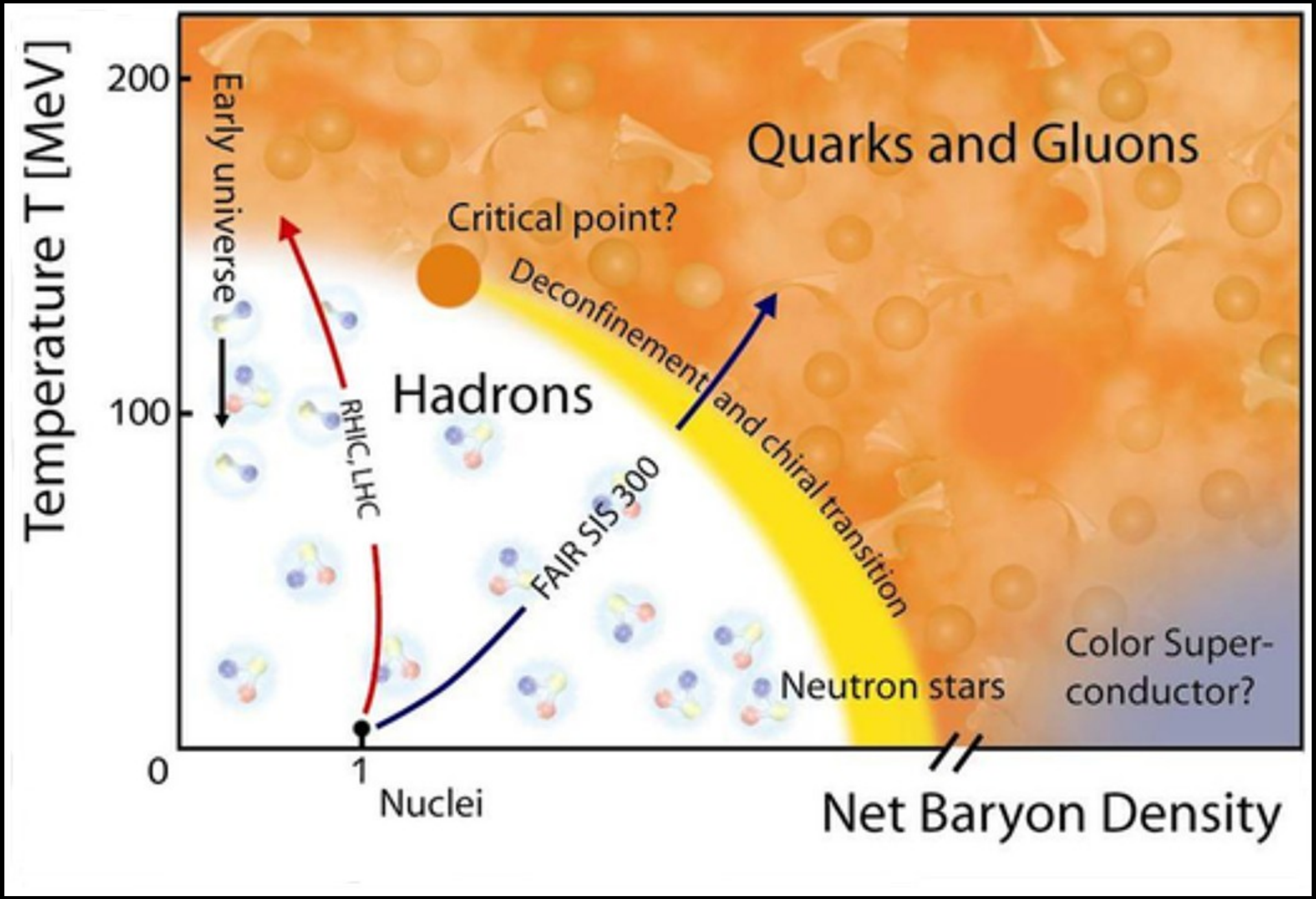
Quark matter in NS mergers

Bauswein et al 2019, Bauswein & Blacker 2020, Bauswein et al 2020, Blacker et al. 2020, Blacker et al. 2023, Blacker & Bauswein 2024

Phase diagram of matter of strongly interacting matter

GSI/FAIR

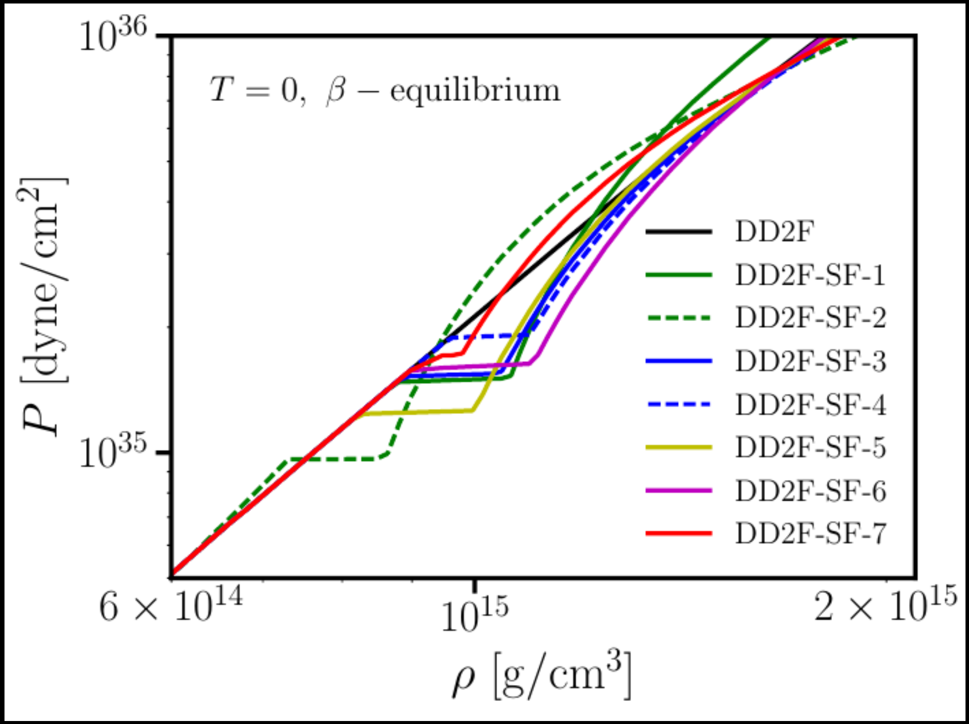
High T, low μ: experiments and lattice QCD

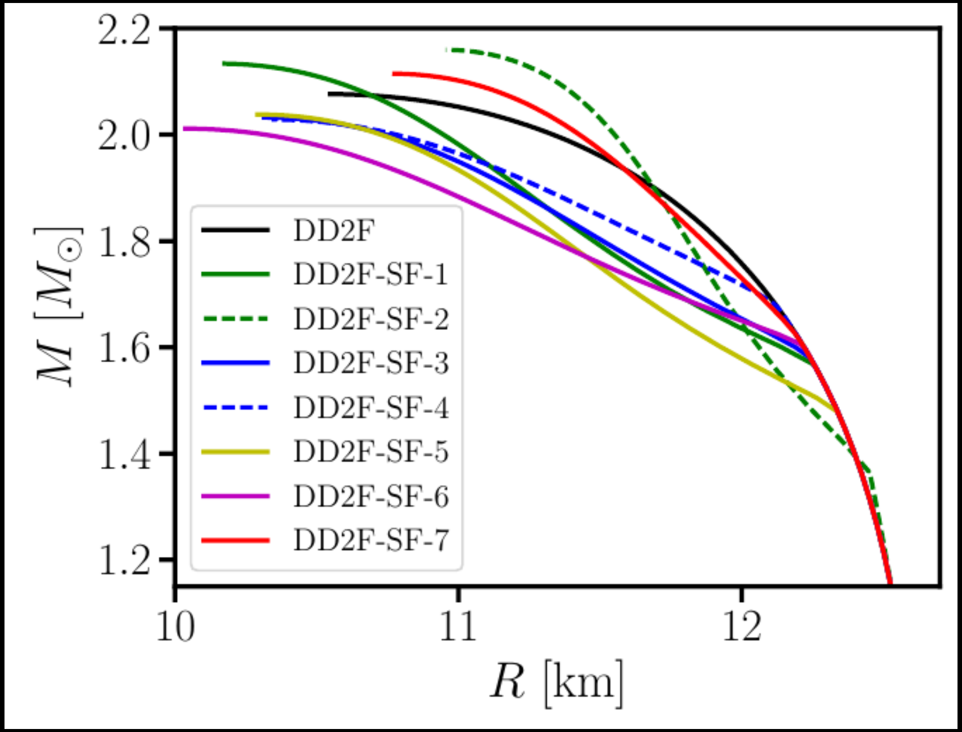


Does the phase transition to quark-gluon plasma occur (already) in neutron stars or only at higher densities?

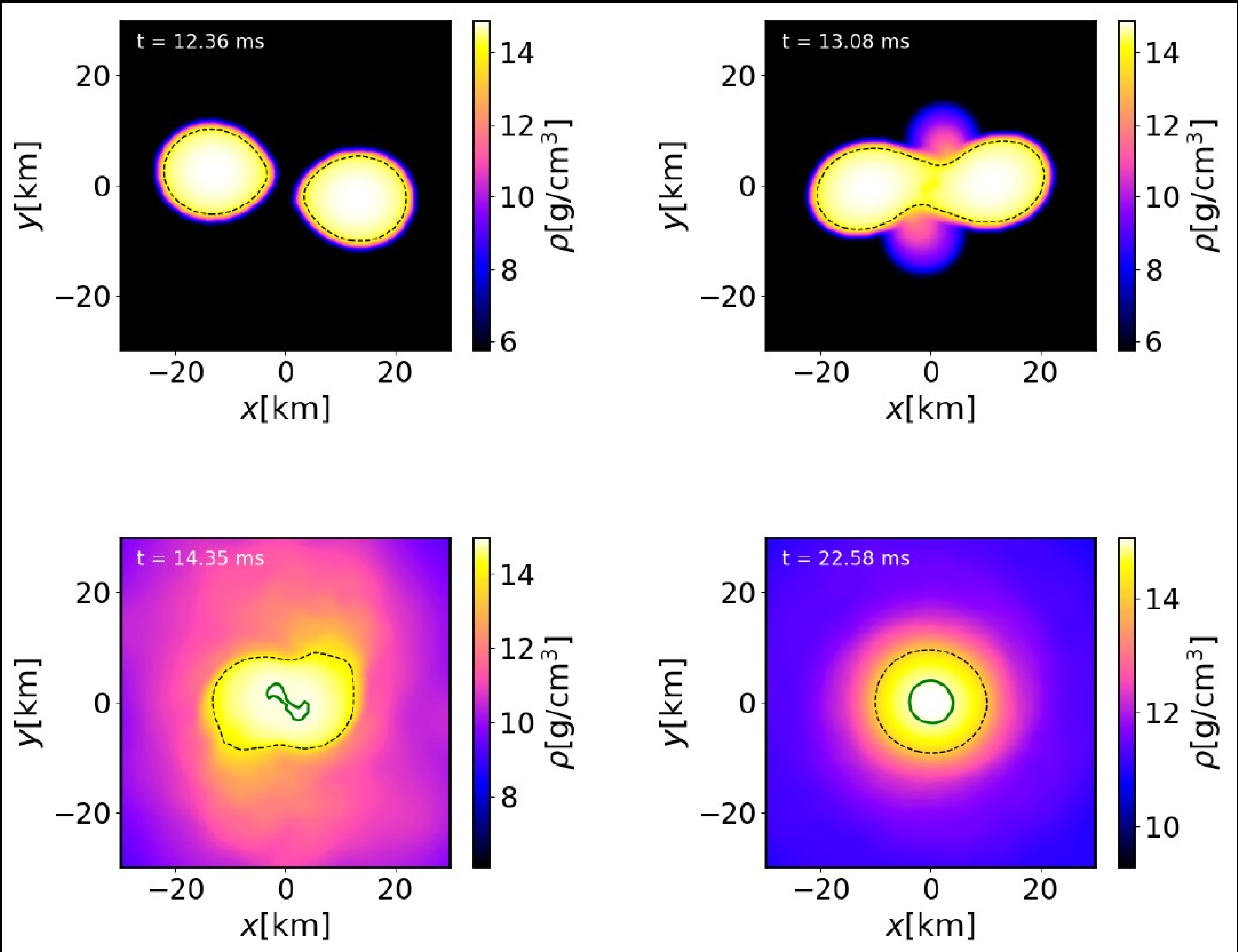
(low T, high rho not accessible by experiments or ab-initio models)

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

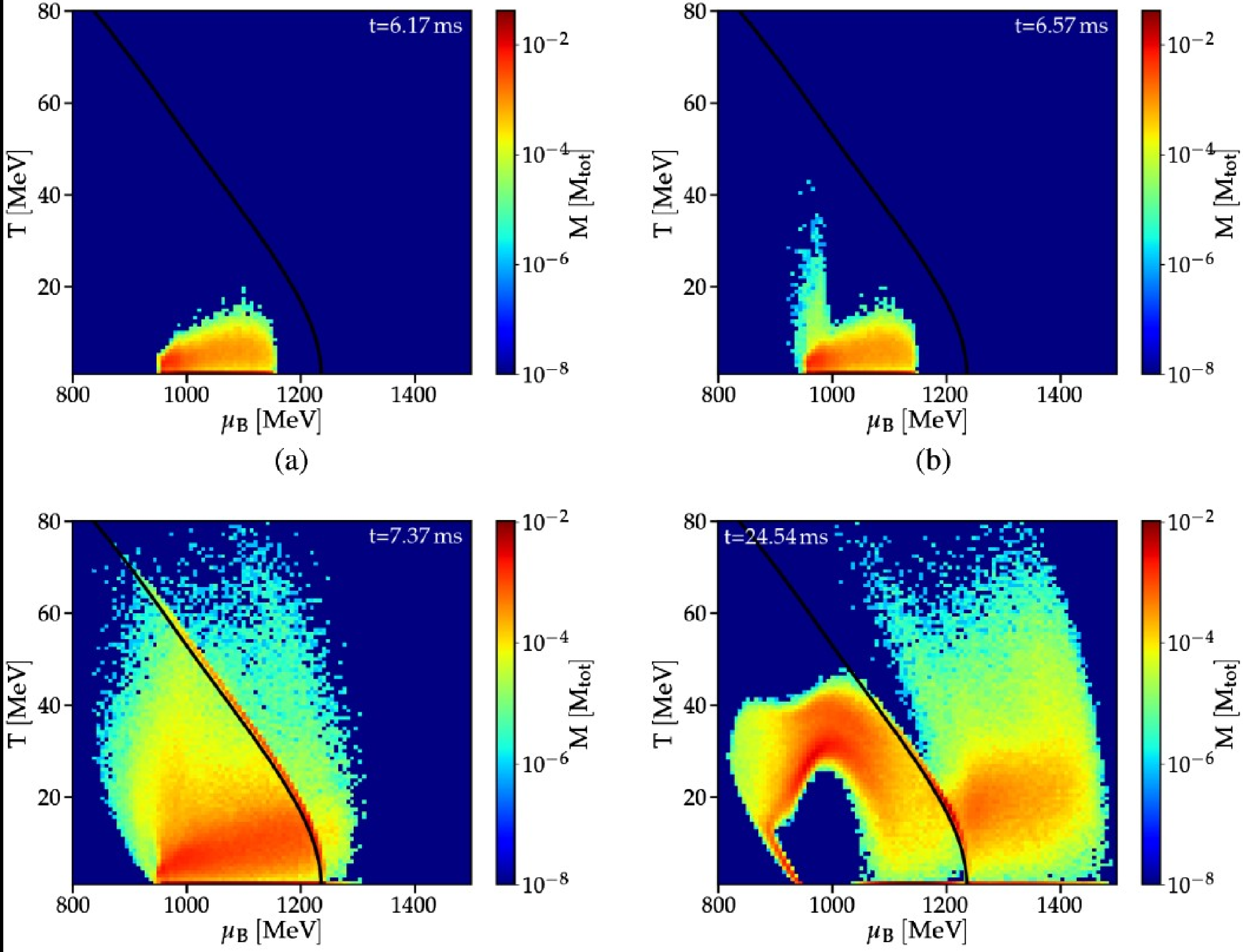




Bastian 2020, Bauswein et al. 2019

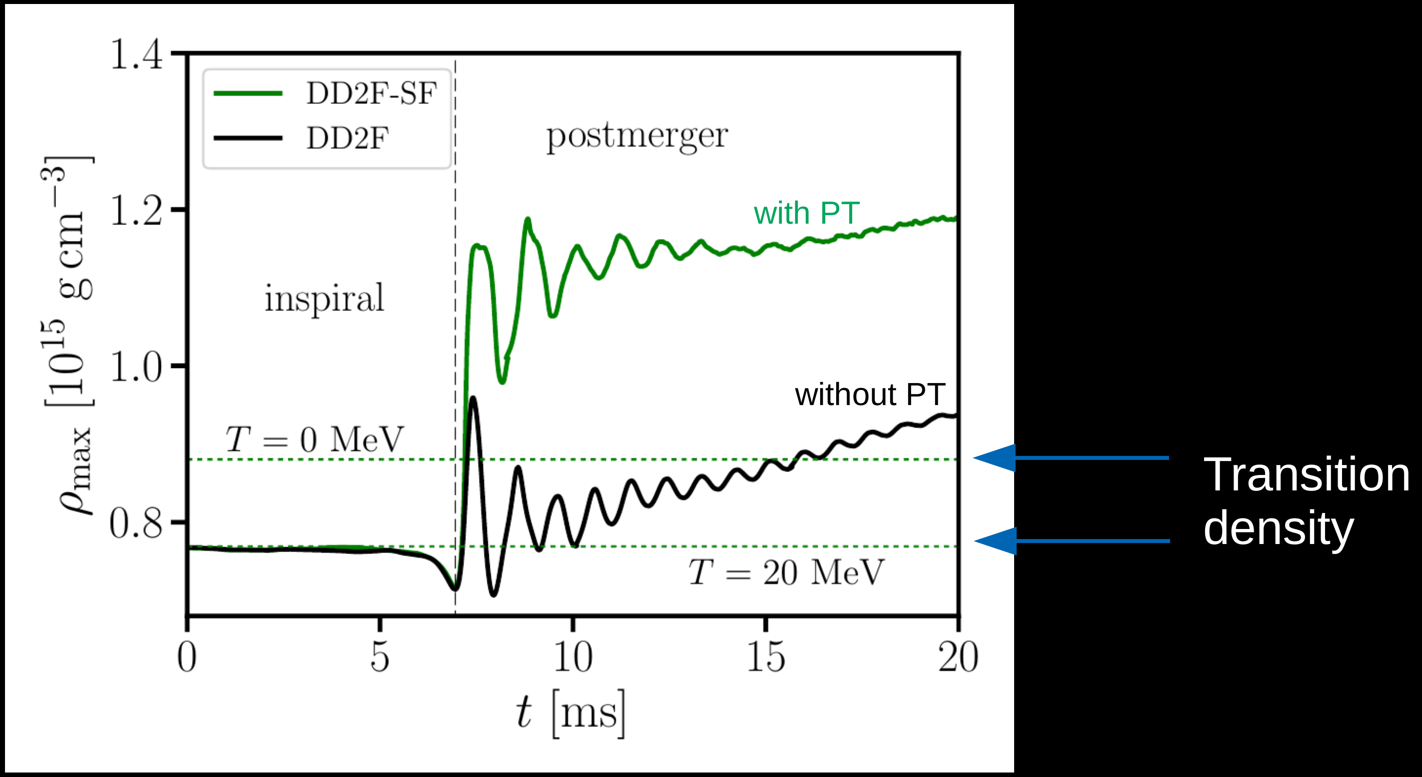


Bauswein et al. 2019



Blacker et al. 2020

Merger simulations

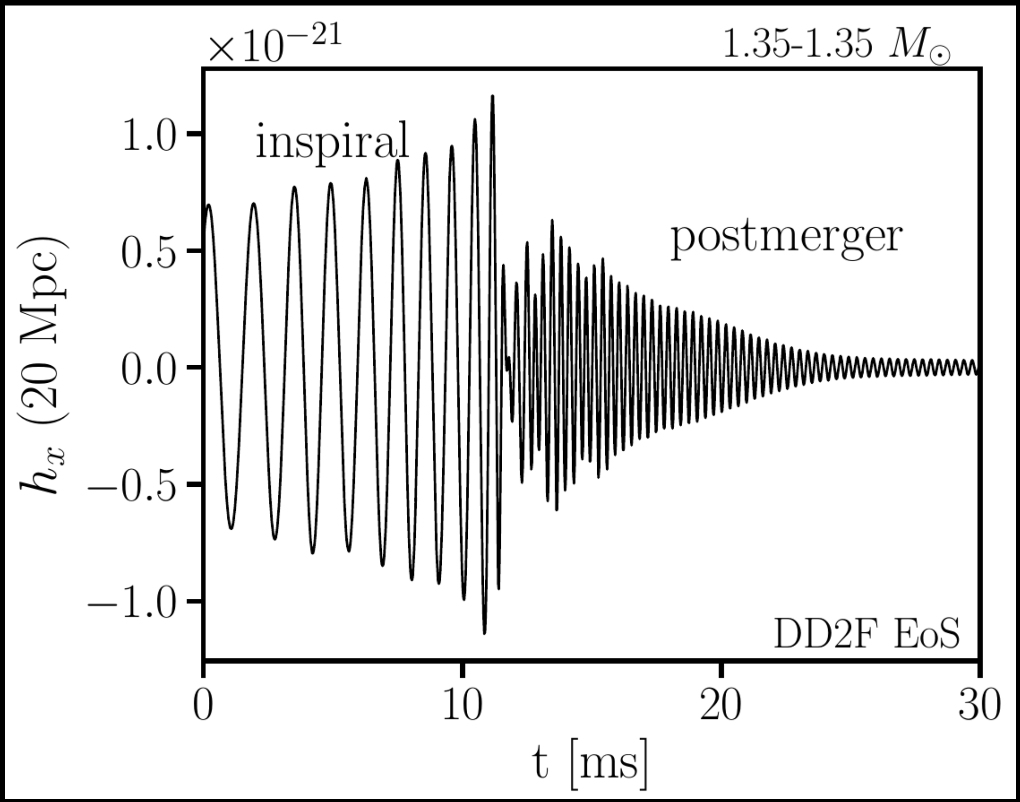


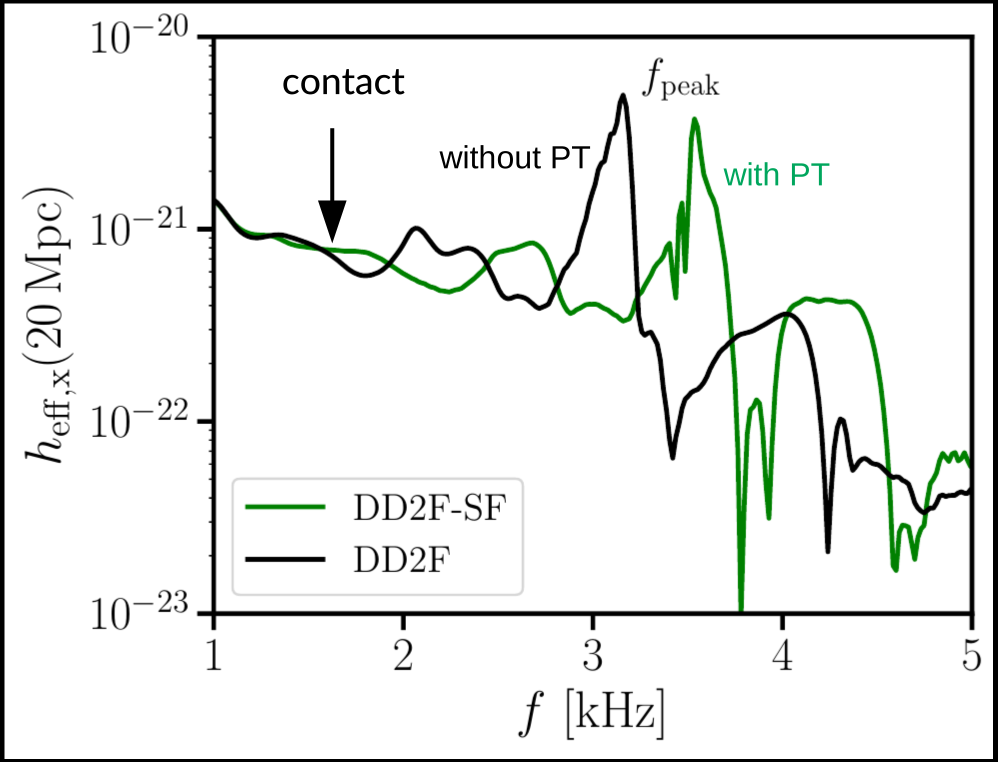
Bauswein et al. 2019

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

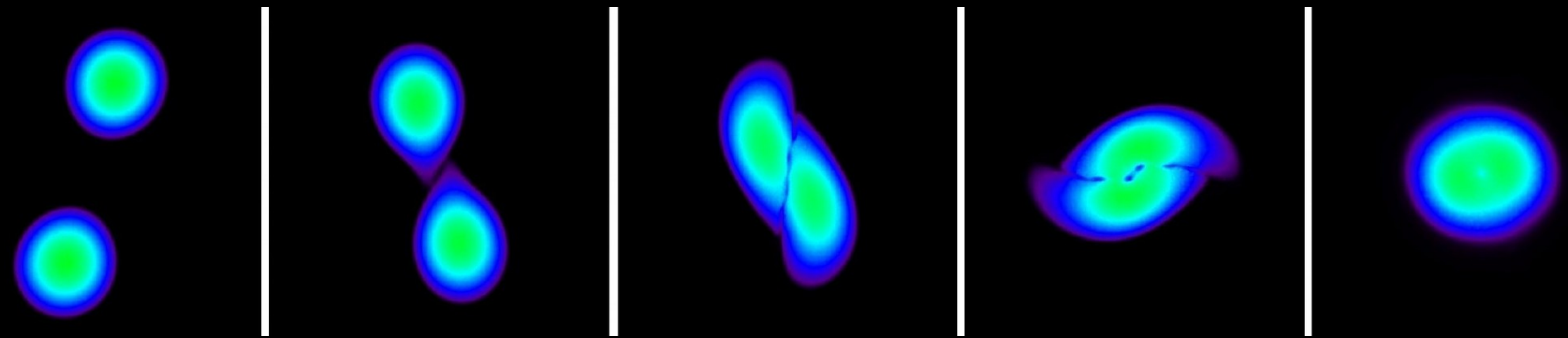
Merger simulations

- GW spectrum 1.35-1.35 Msun



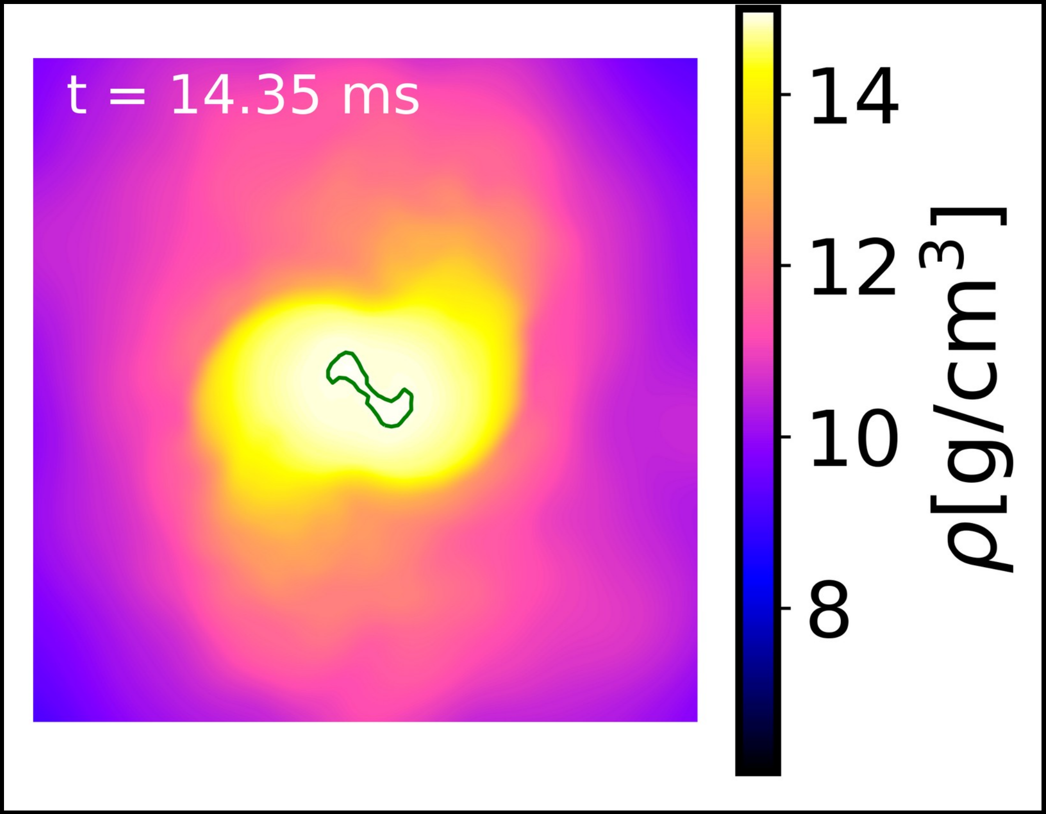


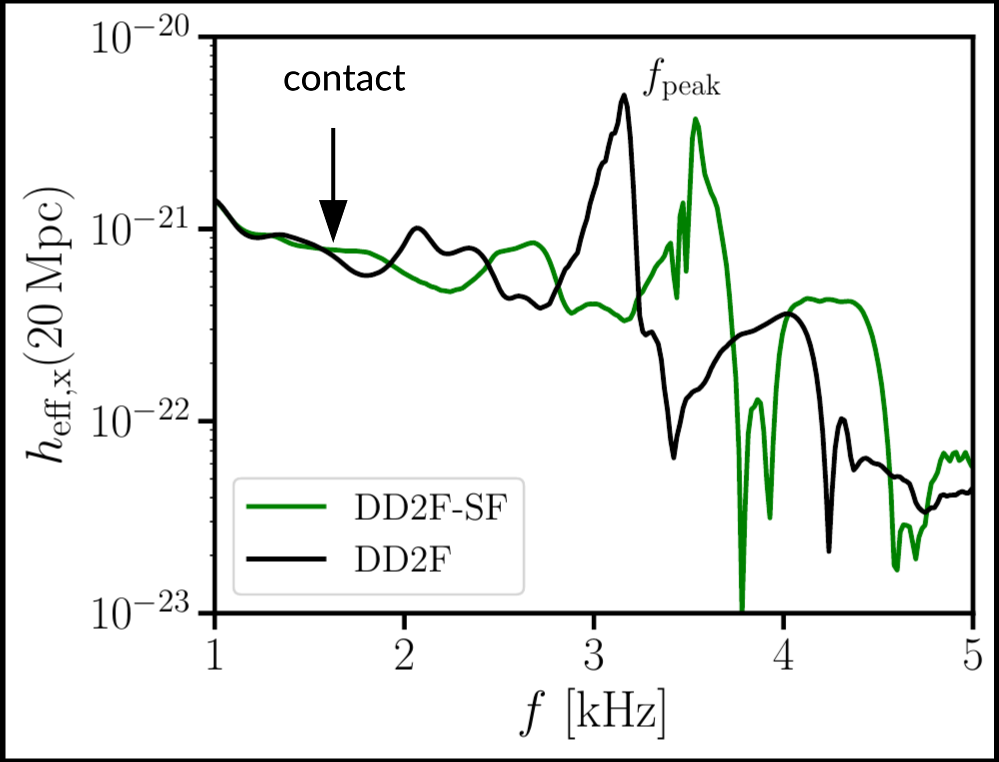
Bauswein et al. 2019



Merger simulations with quark matter core

- GW spectrum 1.35-1.35 Msun



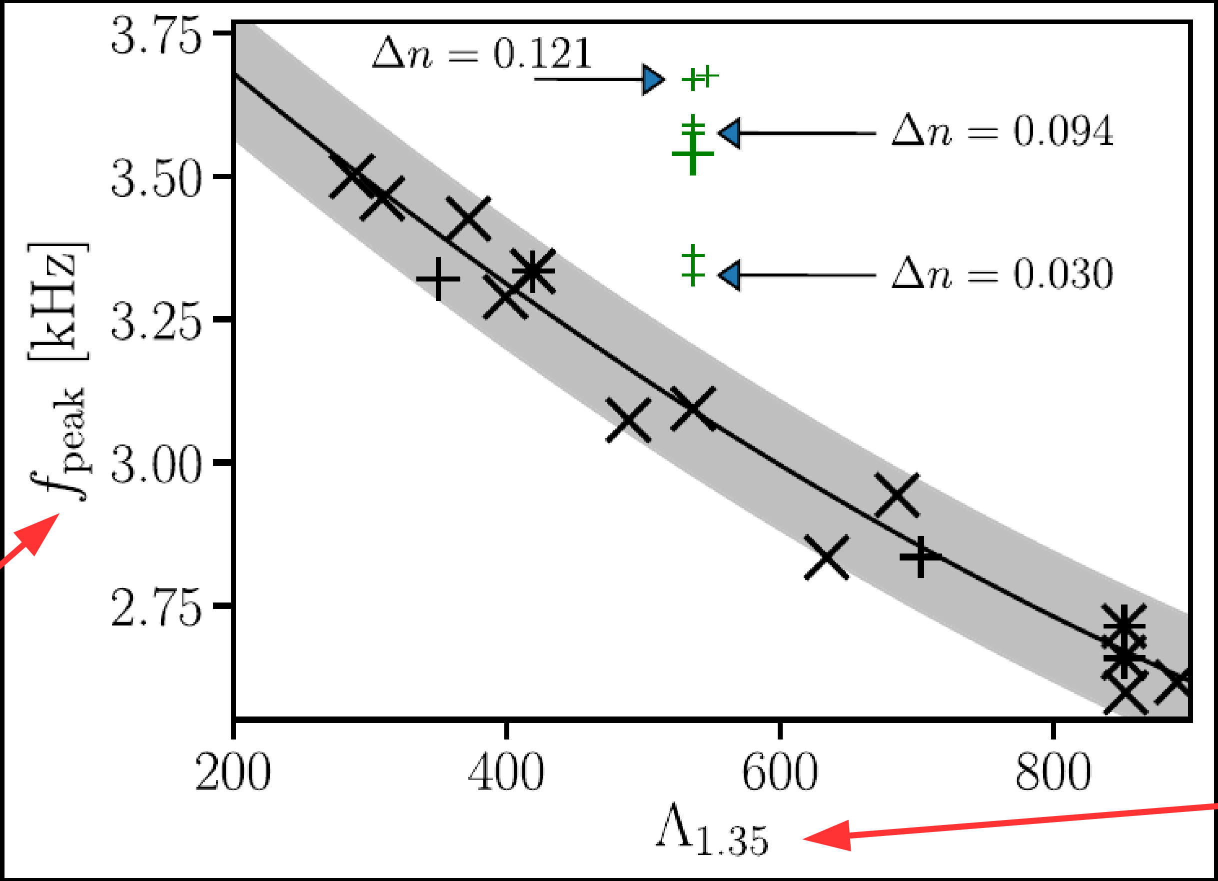


A.B. et al. 2019

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

→ unambiguous signature

Signature of 1st order phase transition



from postmerger

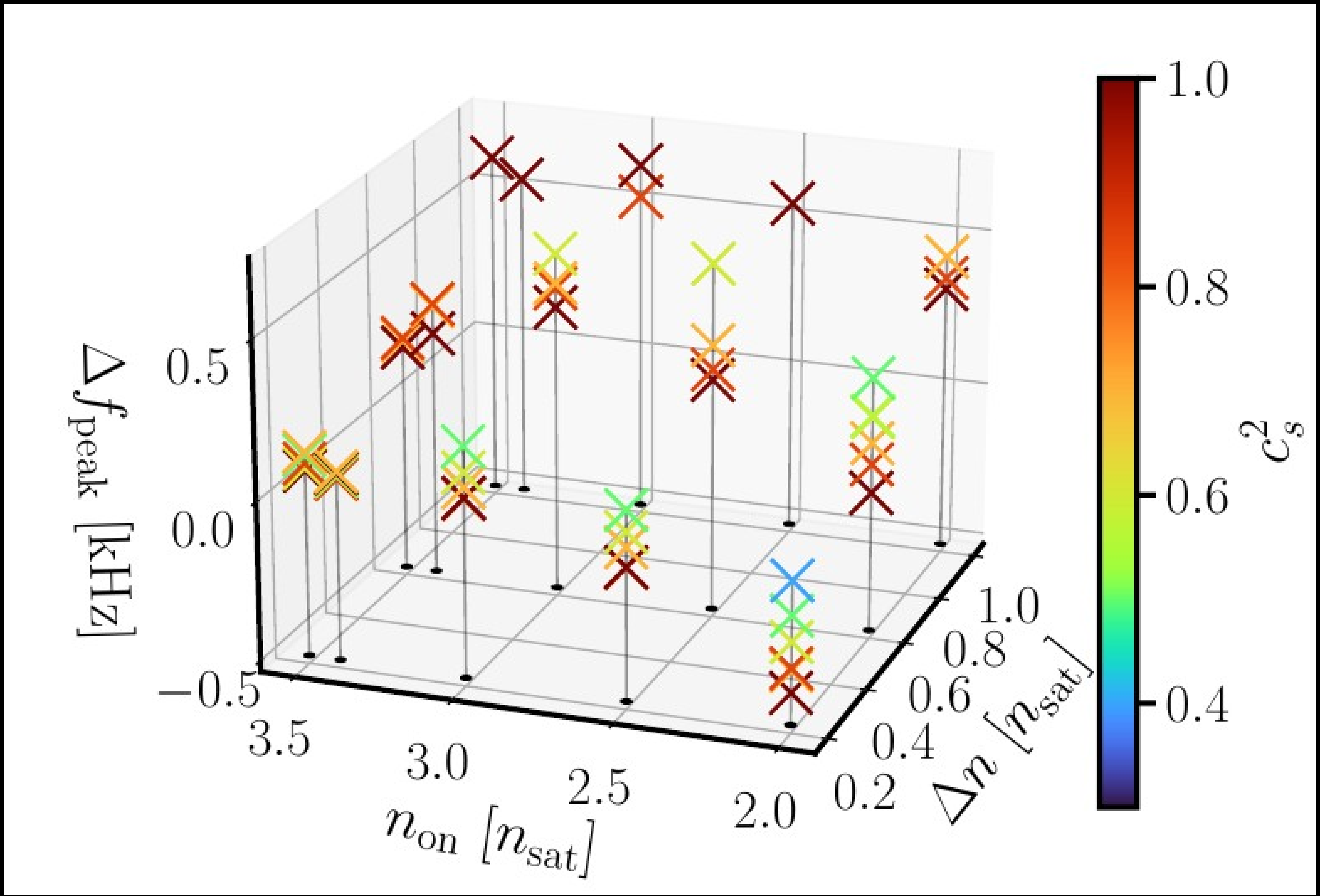
from the inspiral

A.B. et al 2019

- Characteristic increase of postmerger frequency compared to tidal deformability
  → evidence of presence of quark matter core
  → in any case constraint on onset density/properties of hadron-quark phase transition

See also Most+ 2019, Blacker+ 2020, Weih +2020, Bauswein+2020, Prakash+ 2021, Liebling+ 2021, Hanauske+ 2021, Fujimoto+2022, Tootle+ 2022, Huang+ 2022, Blacker+ 2023,...

- Parameter study with simple QM model and different nucleonic base EoSs
- Characterized by nucleonic EoS, Delta n, n_{on} and c_s
- More than 250 EoS models provide quantitative dependencies

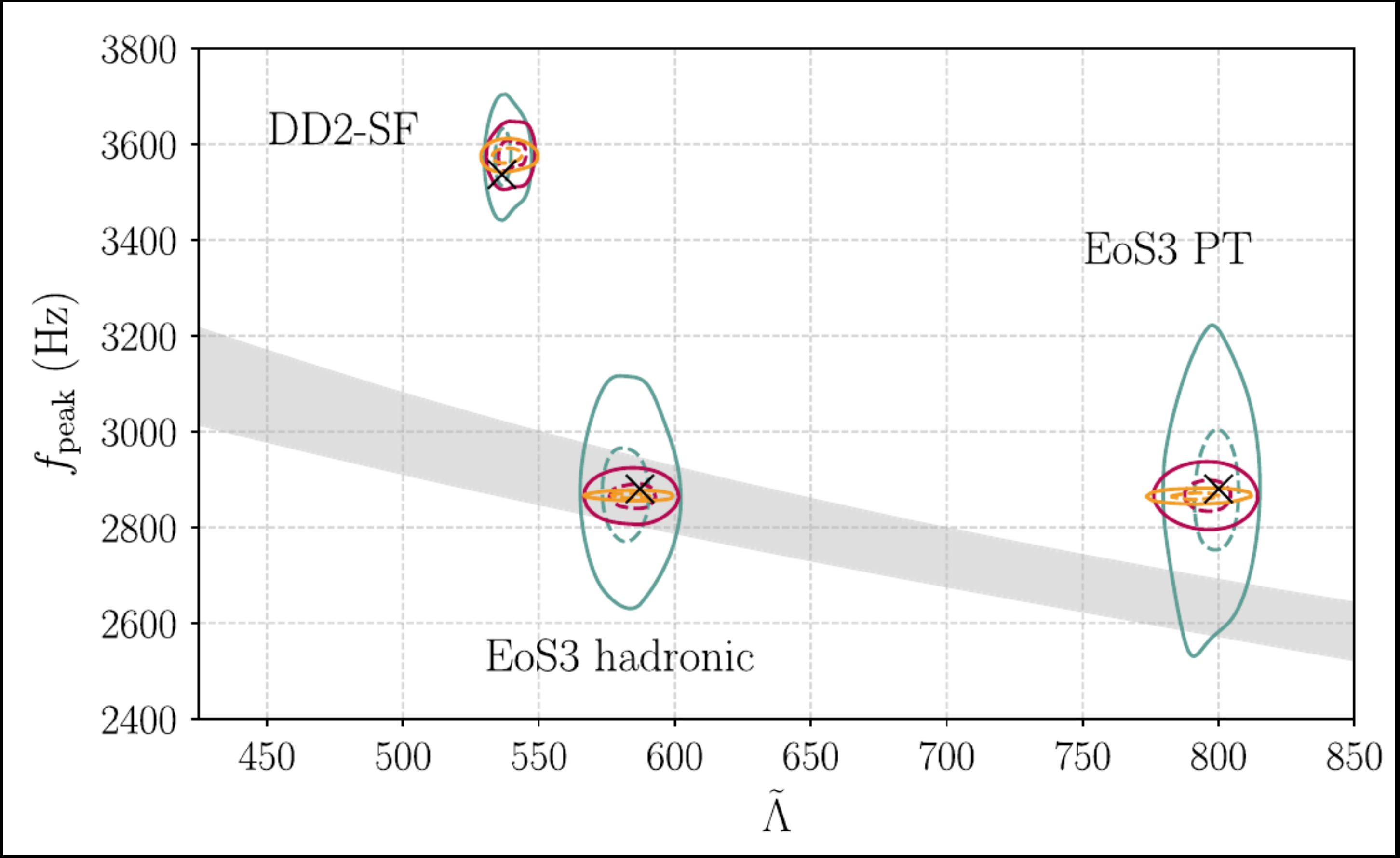


Blacker & Bauswein 2024, arXiv:2406.14669

GW data analysis

- Recovery of injected waveforms as proof of principle for GW data analysis with BayesWave, i.e. morphology-independent search, combined with pre-merger templates

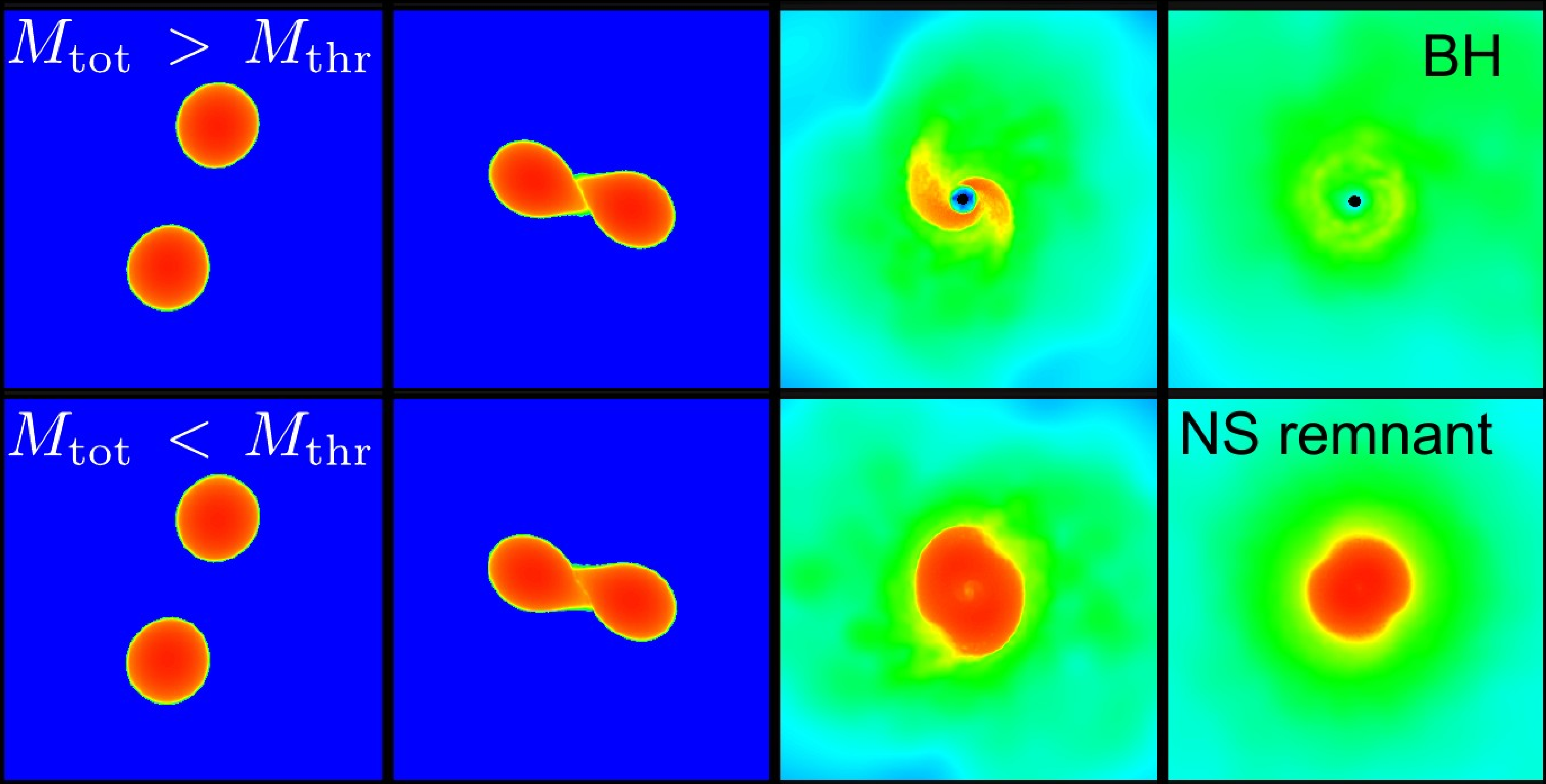
  → signature of quark matter measurable



Wijngaarden et al., PRD 2022

40 Mpc, 2x, 4x, 6x design sensitivity

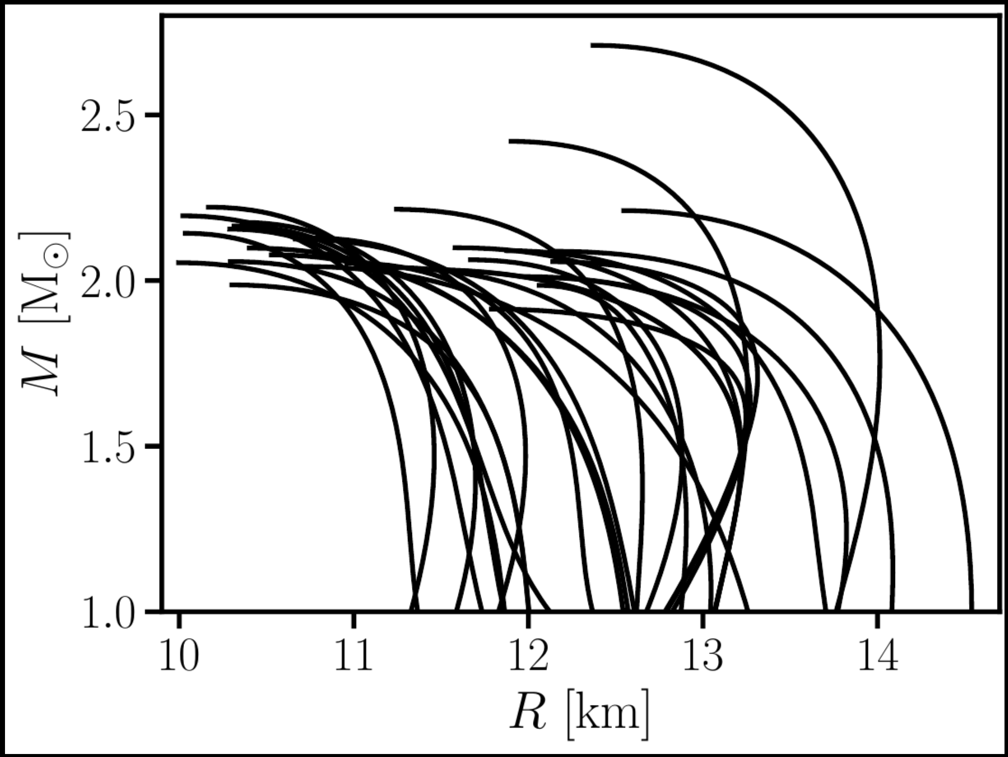
Collapse behavior – M_{thres} measurable



Understanding of BH formation in mergers [e.g. Shibata 2005, Baiotti et al. 2008, Hotokezaka et al. 2011, Bauswein et al. 2013, Bauswein et al 2017, Koeppel et al 2019, Agathos et al. 2020, Bauswein et al. 2020, Bauswein 2021, Kashyap et al 2022, Koelsch et al 2022]

Discussion

- Masquerade problem: hybrid EoS may look nucleonic if PT is very weak
- More general: exact determination of P(rho) or M(R) does not reveal physics generating this EoS



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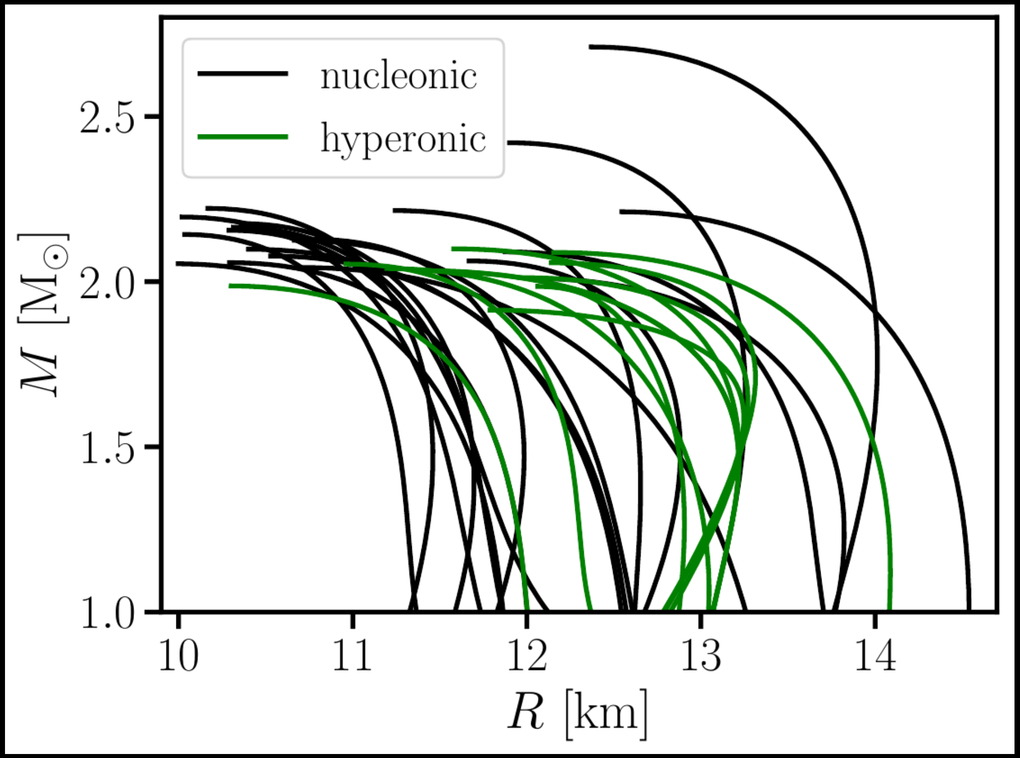
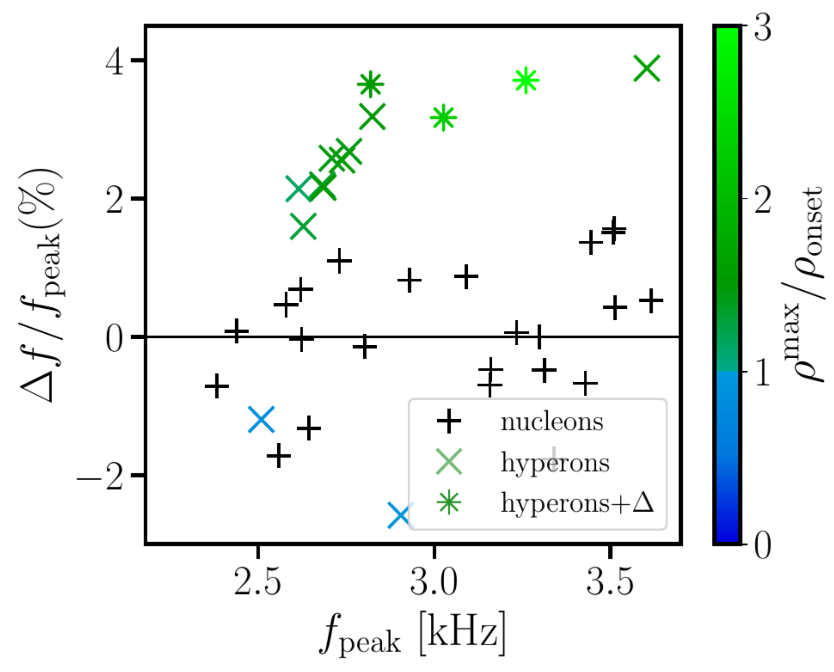


Discussion

- Masquerade problem: hybrid EoS may look nucleonic if PT is very weak
- More general: exact determination of P(rho) or M(R) does not reveal physics generating this EoS
- Details: thermal behavior of hyperonic matter leads to small but characteristic shift of postmerger GW frequency (Blacker et al. 2024)



(a) $\Delta f / f_{\rm peak}(f_{\rm peak})$

Kochankovski et al., in prep

Helium as an indicator of the neutron star merger remnant lifetime and its potential for equation of state constraints

arXiV:2411.03427

in brief: new EoS constraints from GW170817 (old data)

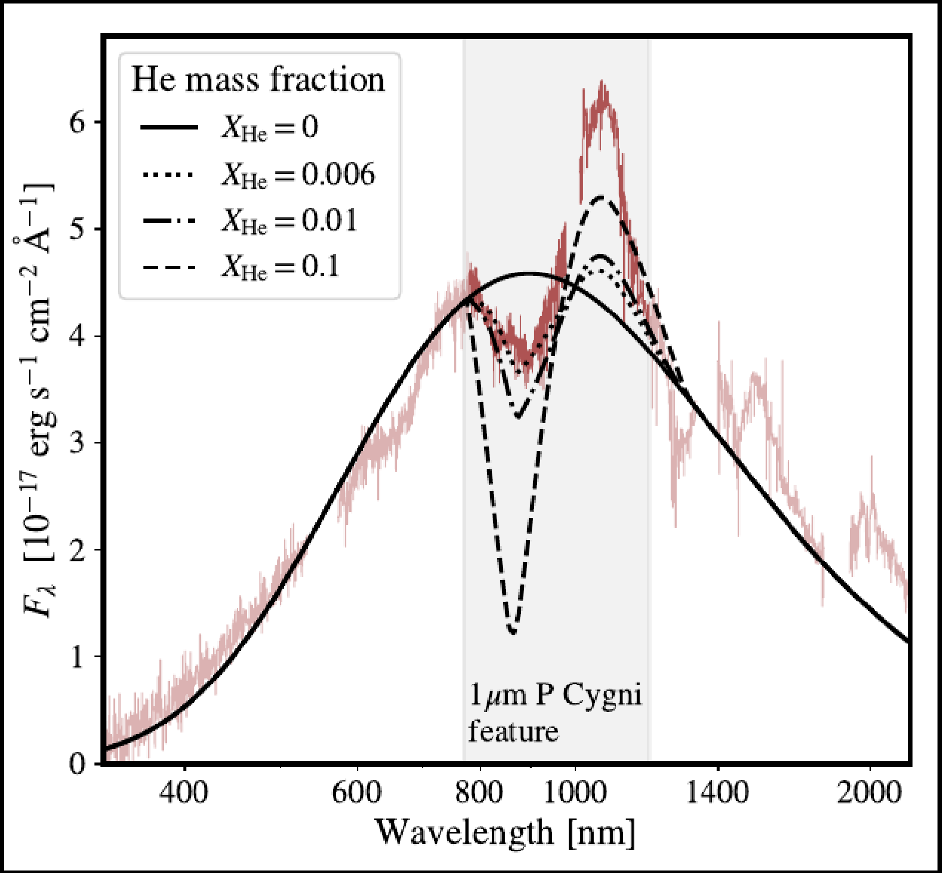
New EoS constraint from GW170817/AT2017gfo

- Exploting so far unused information in 3 major steps
  - Limits on He abundance in ejecta from kilonova spectrum
  - theoretically expected He enrichment from simulations limits lifetime
  - Lifetime limit constrains M_{thres} → EoS/NS constraints

Sneppen, Just, AB et al. 2024, arXiv:2411.03427

He spectral features in spectrum

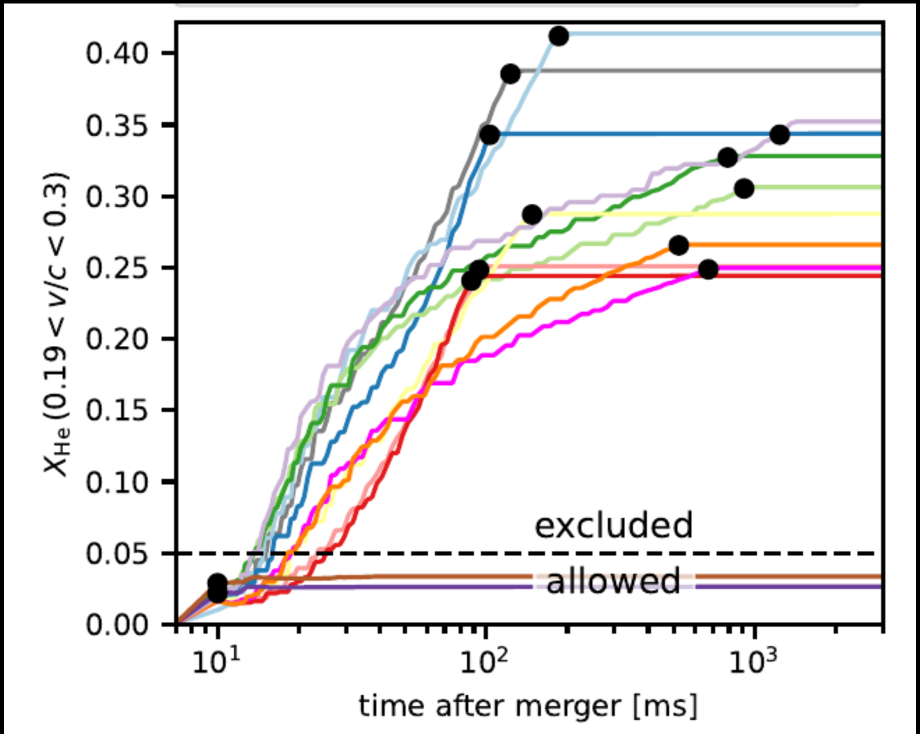
- Already tiny amounts of He would produce strong absorption feature
  → mass fraction X(He) < 0.006 ... 0.05



Sneppen, Just, AB et al. 2024, arXiv:2411.03427

He production in merger simuations

- Efficient He production only by long-lived merger remnants (producing neutrino driven wind with less neutron-rich outflows – after BH formation He production shuts off)
- Low He abundance → remnant in GW170817 collapse latest after 20-30 ms (short-lived)

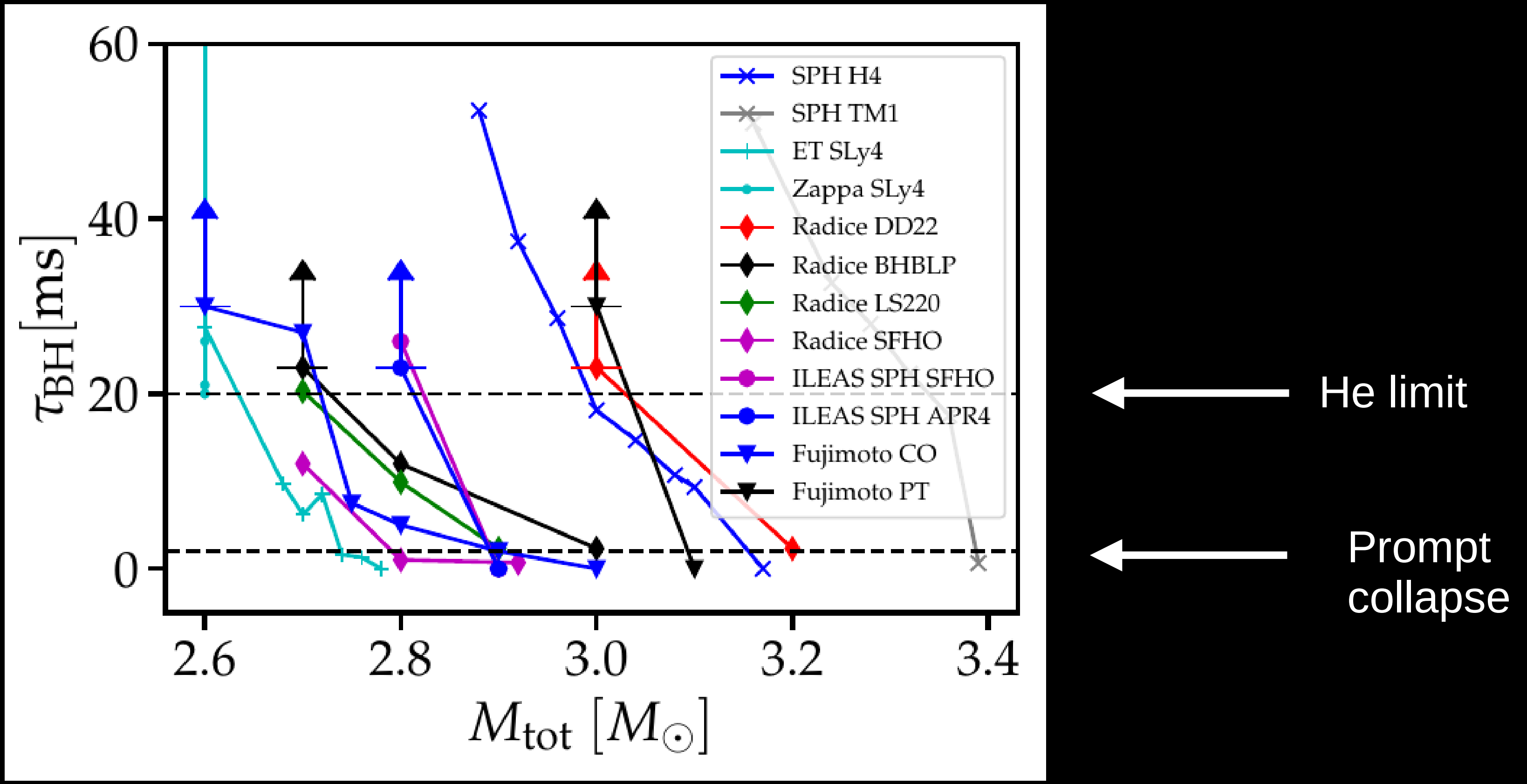


Sneppen, Just, AB et al. 2024, arXiv:2411.03427

Short-lived remnant constraints M_{thres}

- Lifetime steeply declines with total binary mass reaching ~0 at M_{thres}
- Lifetime of ~20 ms implies that GW170817 was “close” to prompt collapse

  → M_{tot}=2.73 M_{sun} => M_{thres} < 2.93 M_{sun}

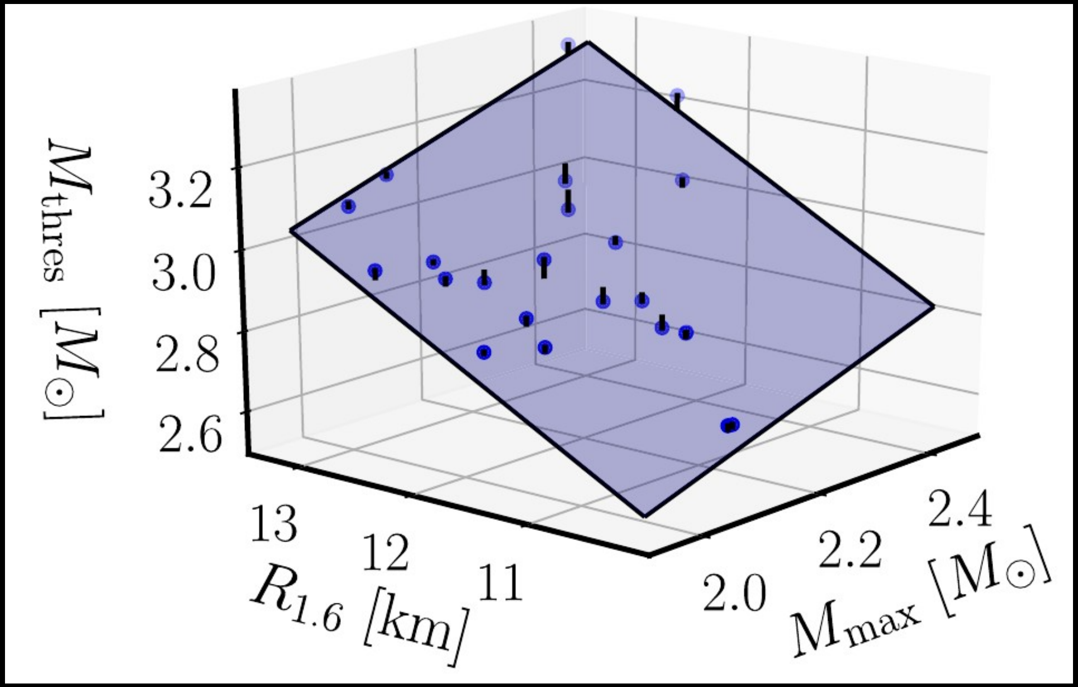


Most studies avoid concrete limits for tau or favor long-lived model – recall GRB after 1700 ms

Sneppen, Just, AB et al. 2024, arXiv:2411.03427

Threshold mass for prompt collapse

- Empirical relations: M_{thres} (M_{max},$R_{1.6}$) from simulations for large set of EoSs
  → Mthres limit simultaneously constrains R and M_{max}
- R16 can be replaced by R_{14}, Lambda_14, R_{max}

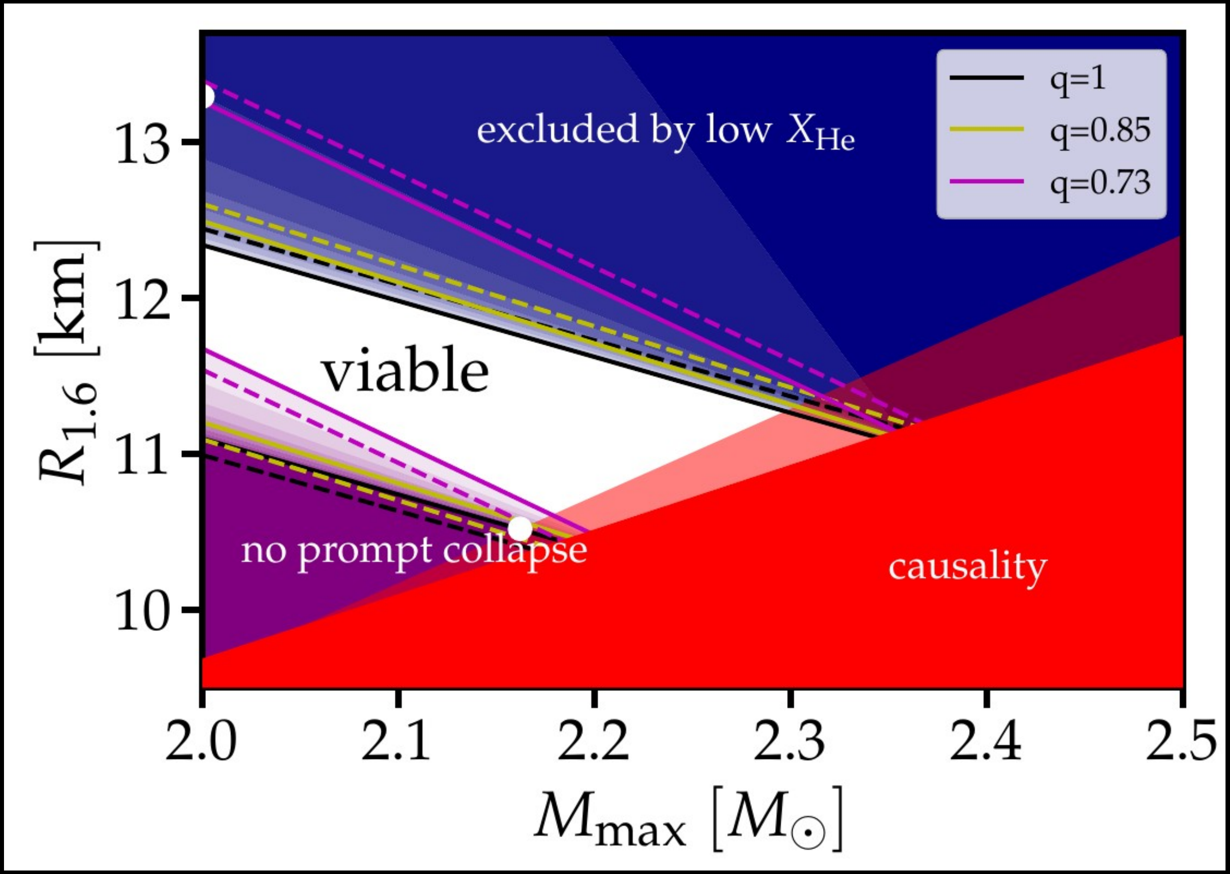


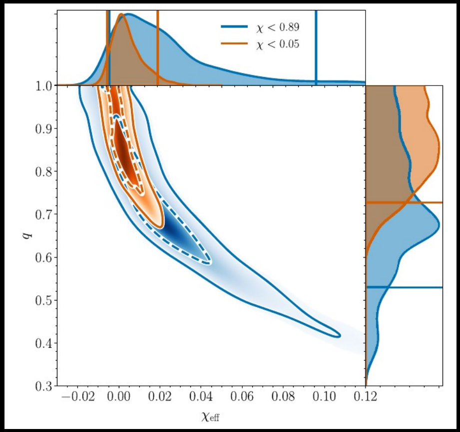
Here only equal-mass shown, but extension to asymmetric binaries possible; Bauswein et al. 2021

$$M_{\rm thres}(q, M_{\rm max}, R_{1.6}) = c_1 M_{\rm max} + c_2 R_{1.6} + c_3 + c_4 \delta q^3 M_{\rm max} + c_5 \delta q^3 R_{1.6} + c_6 \delta q^3. \quad (10)$$

Constraints on EoS/NS parameters

- Low He fraction provides upper limits on R – dependent on M_{max}
- Significant dependence on binary mass ratio (0.7<q<1 for GW170817)
- Causality limits stiffness and no prompt collapse argument provides lower limit on R



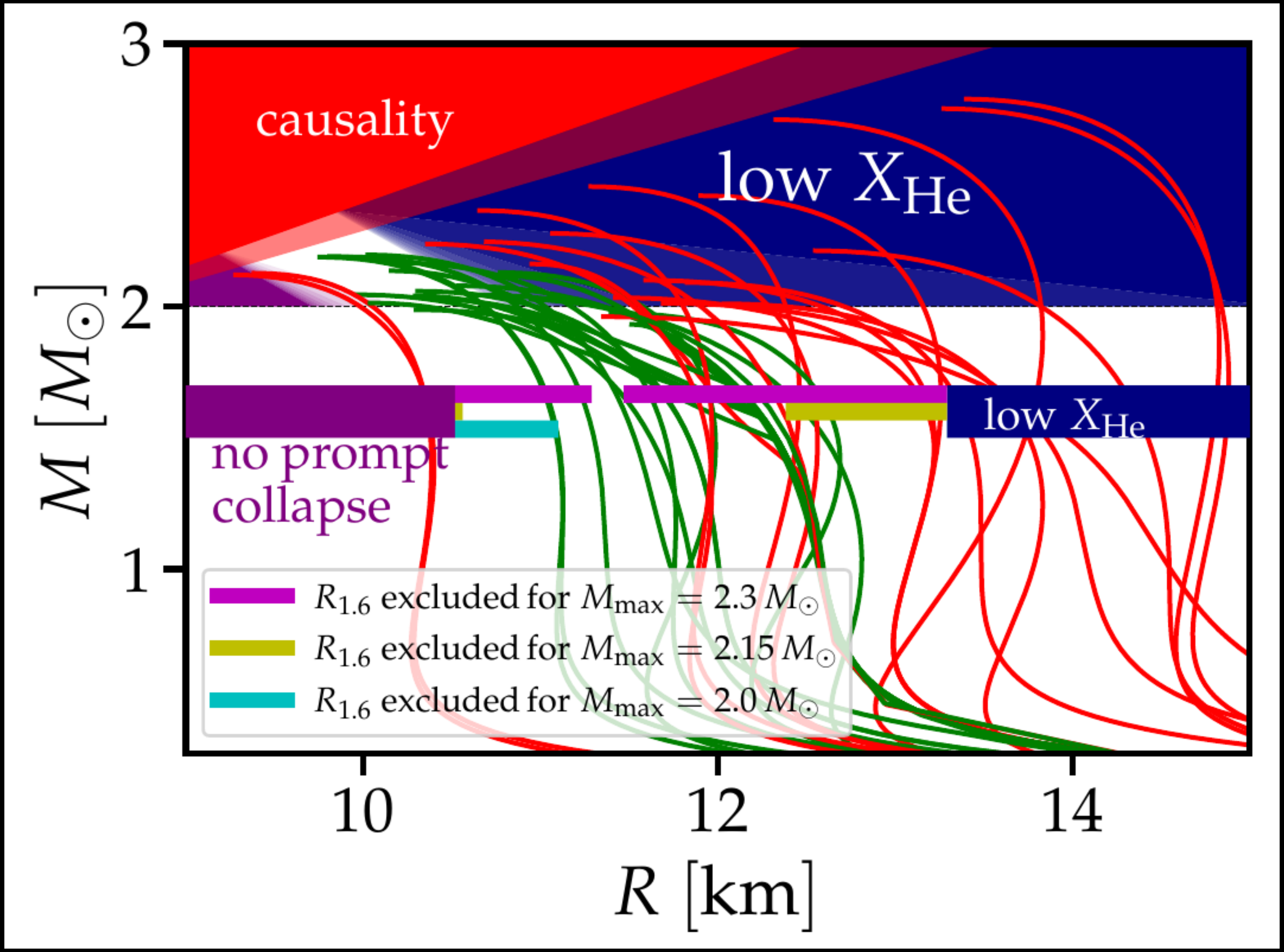


Abbott et al 2019

Sneppen, Just, AB et al. 2024, arXiv:2411.03427

Constraints on EoS/NS parameters

- $M_{max} < 2.3\ M_{sun}$
- Radii limited to narrow range (sliding window)
- Rules out a number of current EoS models



Sneppen, Just, AB et al. 2024, arXiv:2411.03427

Outlook

- Clear and testable (!) predictions for which binary should show He features or undergo prompt collapse (dim kilonova)
- GRB in GW170817 was powered by black hole (not a magnetized NS)
- Very potential method exploiting so far unused information

  → future events can further tighten constraints
- However, still connected with uncertainties (ongoing work)

Summary

- Postmerger phase particularly interesting (higher densities, higher temperatures)
- Sufficiently strong phase transition leads to characteristic shift of postmerger GW frequency
- M_{thres} may carry imprint as well
- Hyperons may be detectable from thermal behavior of EoS
- General masquerade problem
- New EoS constraint: absence of He limits NS radii and M_{max} from above