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Phase transitions in neutron star mergers

40th Max Born Symposium – Three Days of Strong Correlations in Dense Matter

Wroclaw, 11/10/2019

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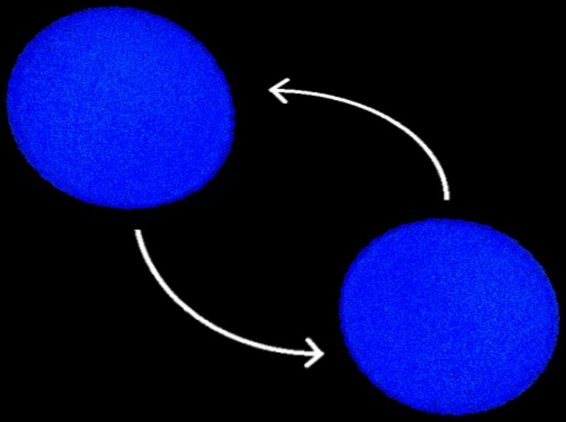
with N.-U. Bastian, S. Blacker, D. Blaschke, K. Chatziioannou, J.A. Clark,T. Fischer, M. Oertel



Some insights from GW170817

- From chirp-like inspiral GW signal:
  - → Binary masses
  - → distance 40 Mpc → rate is presumably high !
  - → Approximate sky location
- Triggered follow-up observations

$$\mathcal{M}_{chirp} = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}} \qquad q = M_1/M_2$$

Abbott et al. 2017

	Low-spin priors $(|\chi| \leq 0.05)$	High-spin priors $(|\chi| \leq 0.89)$

Interpretation of UV/opt/IR - implications

- heating and derived opacities are compatible with r-processing ejecta !!!

  (not surprising for a theorist, see earlier work on r-process and em counterparts)
- 0.02 – 0.05 Msun ejecta (red and blue component) – somewhat model-dependent
- Ejecta velocities and masses in ballpark of simulation results
- Derived ejecta masses are compatible with mergers being the main source of heavy r-process elements in the Universe

  → overall strong evidence that NS mergers play a prominent role for heavy element formation

Only A>130

Just et al. 2015

Bauswein et al. 2014

EoS constraints

- EoS of high-density matter not precisely known ↔ stellar properties of NSs
- Affects dynamics of mergers and thus obseravbles like GWs, em transients

- 3 different complementary ideas

  - finite-size effects during the inspiral affect orbital dynamics and GWs

  - multi-messenger interpretation (different ideas – some pretty model dependent)

  - postmerger GW oscillations (not yet detectable for GW170817 – but a lot of future potential)

Finite-size effects during late inspiral

Measurement

- Lambda < ~650

  → Means that very stiff EoSs are excluded

  → NS radius < ~13.5 km

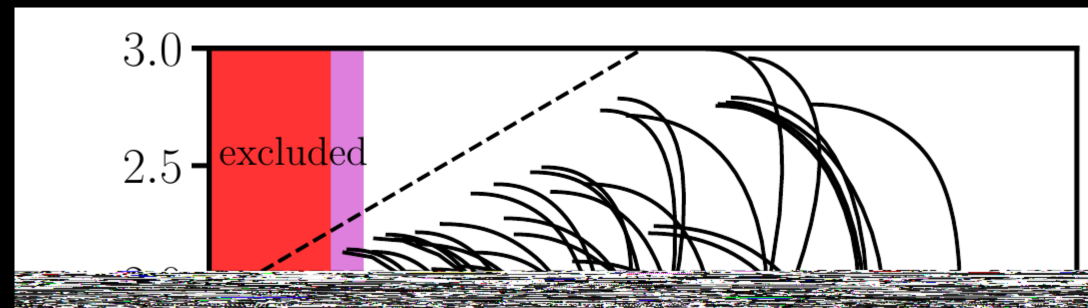
- Somewhat model-dependent
- Better constraints expected in future as sensitivity increases

$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}$$

Abbott et al. 2017, 2019
see also later publications by Ligo/Virgo collaboration, De et al. 2018

NS radius constraint from GW170817

- R_{max} > 9.6 km
- $R_{1.6}$ > 10.7 km
- Excludes very soft nuclear matter
- Based on simple, robust, conservative argument (testable in futrue)



Tidal deformability

- A lot of potential for future when new events become available

  - stronger radius constraints

  - Prompt collapse will constrain Mmax !!!

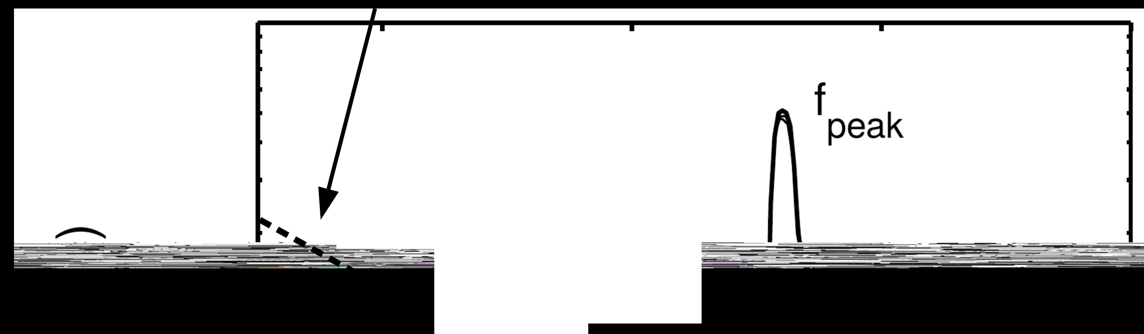
Bauswein et al. 2017

Future: Postmerger GW oscillations

Earlier inspiral

EoS

1.35-1.35 M_{sun} , 20 Mpc



inspiral

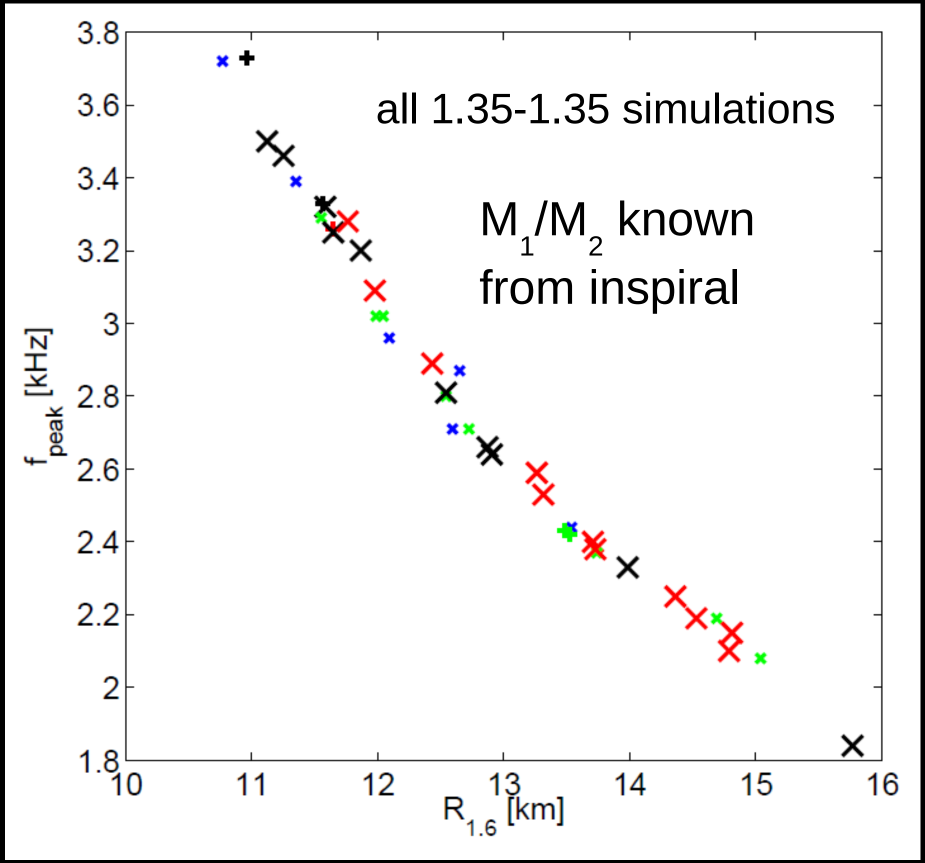
Dominant postmerger oscillation frequency f_{peak}

Very characteristic (robust feature in all models)

Future: postmerger oscillations

- Dominant frequency of postmerger GW oscillations scales tightly with NS radii

  (not yet detected for GW170817, but in reach at design sensitivity for that distance)



Ladek Zdroj 2008, 44th Karpacz Winter School of Theoretical Physics & Compstar:

D.B.: "We give you a hybrid EOS and you run a merger simulation!" → Does a phase transition leave a observable impact on NS mergers?

Answer: A. Bauswein, N.-U. Bastian, D. Blaschke, K. Chatziioannou, J.A. Clark,T. Fischer, M. Oertel, PRL 122, 061102 (2019)

For core-collapse SNe see: T. Fischer, N.-U. F. Bastian, M.-R. Wu, P. Baklanov,E. Sorokina, S. Blinnikov, S. Typel, T. Klähn, and D. B. Blaschke, Nat. Astron. 2, 980 (2018)

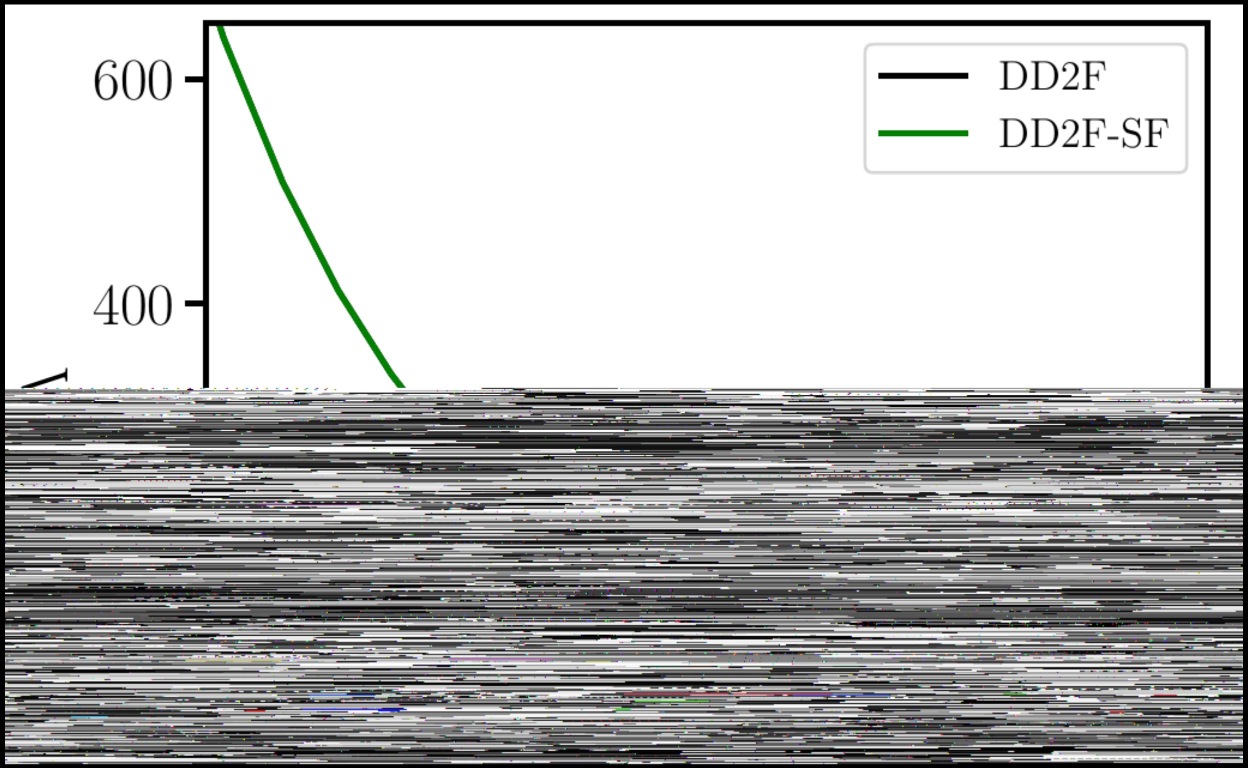
Phase diagram of matter

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

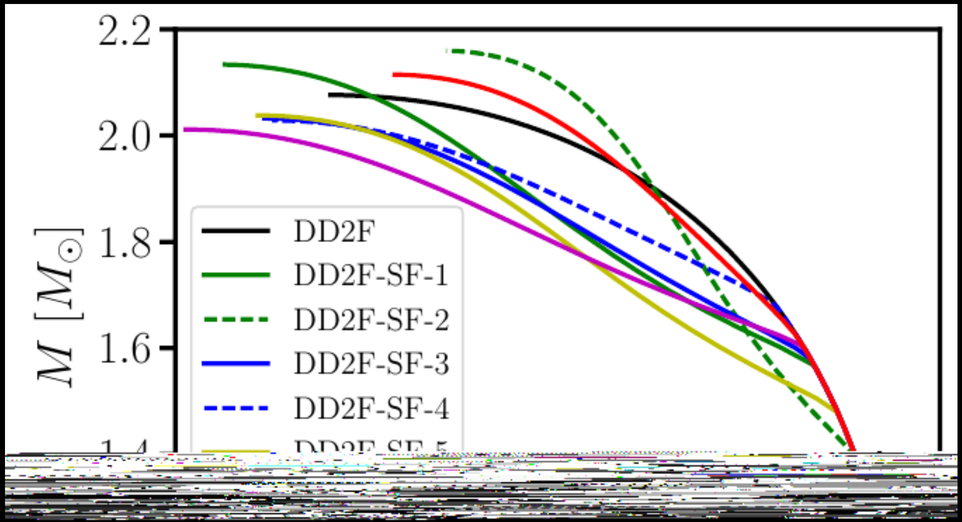
Phase transition

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

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



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

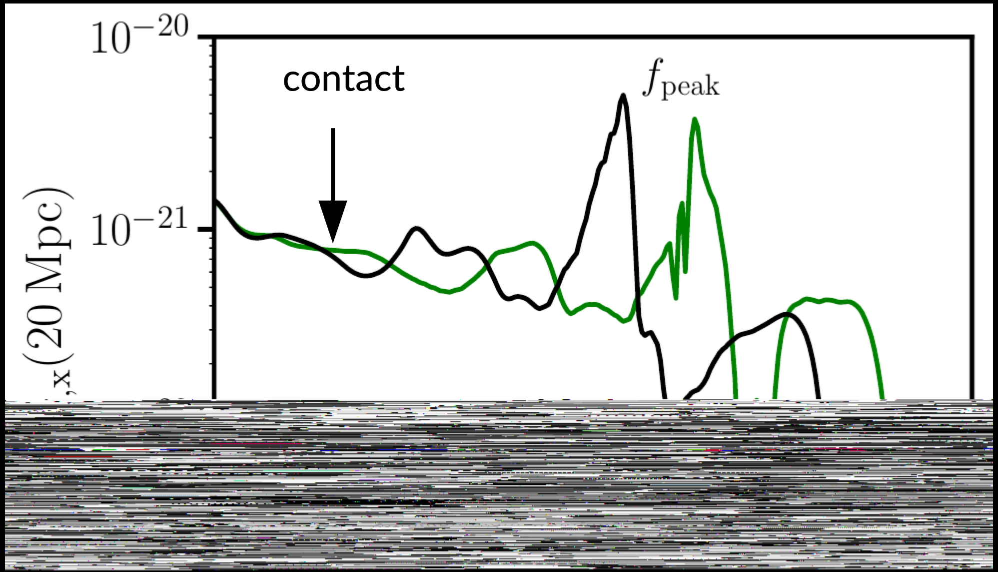


Bauswein et al. 2019

EoSs from Wroclaw group

Merger simulations

- GW spectrum 1.35-1.35 Msun



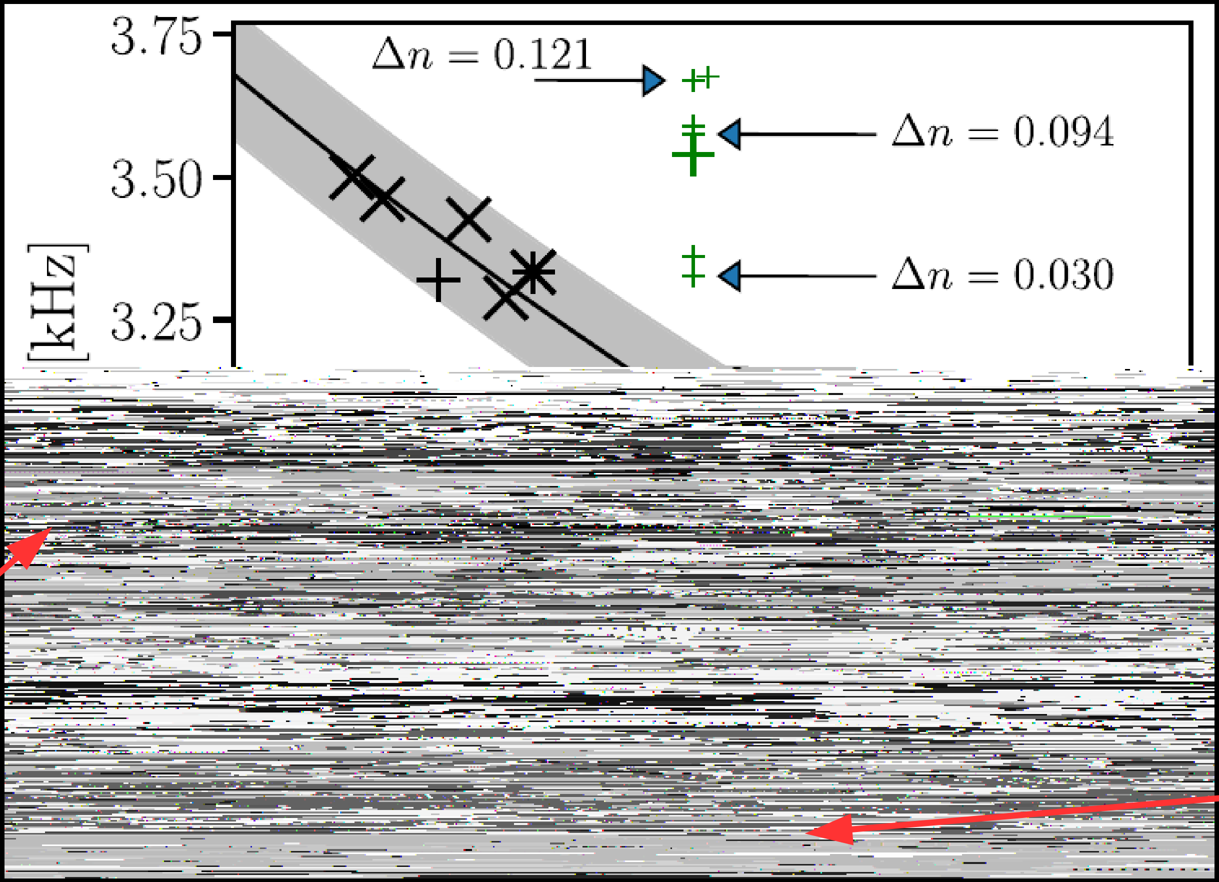
Bauswein et al. 2019

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

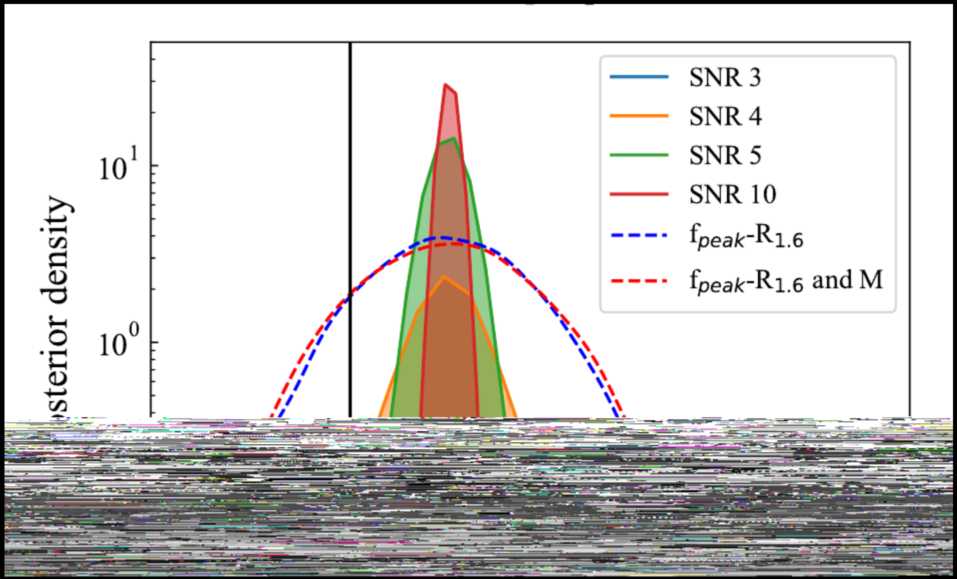
from the inspiral

Bauswein et al. 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

Model-agnostic data analysis

Based on wavelets



Chatziioannou et al. 2017, Torres-Riva et al 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 effectively captured (work in progress)

Probed densities / NS masses

- Dots: NS mass with central density = maximum density during early postmerger evolution

Bauswein et al. 2019

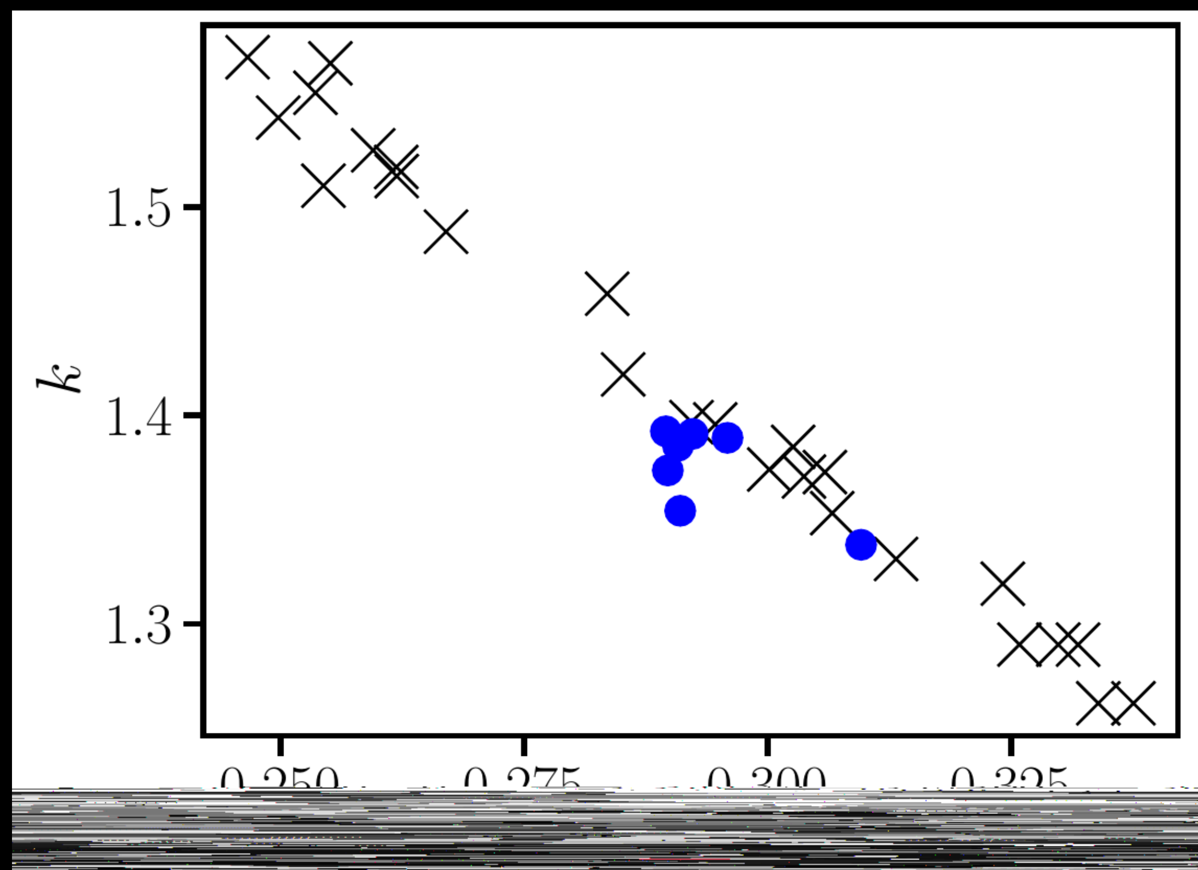
For 1.35-1.35 Msun merger – higher binary masses probe higher densities / NS masses

Impact on collapse behavior - preliminary

- Threshold mass for direct black-hole formation
- Observable by measuring total binary mass during inspiral and check outcome based on em or psotmerger GWs
- Even strong phase transitions do not leave a too strong impact on collapse (in comparison to hadronic EoSs – Bauswein et al. 2013)

$$k = \frac{M_{\rm thres}}{M_{\rm max}}$$

$$C_{\rm max} = \frac{G M_{\rm max}}{c^2 R_{\rm max}}$$



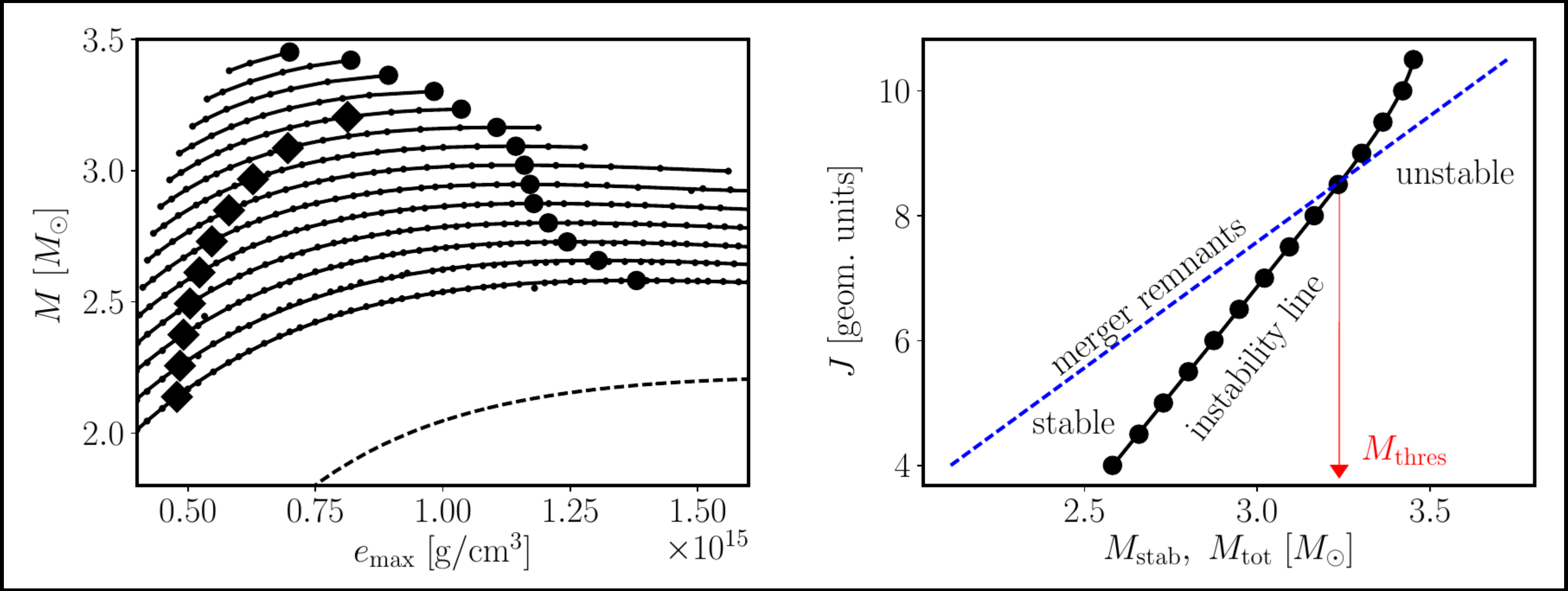
Conclusions

- NS radius smaller than ~13.5 km (from GW inspiral)
- NS radius must be larger than 10.7 km (very robust and conservative)
- More stringent constraints from future detections

- Strong 1st order phase transitions leave characteristic imprint on GW (postmerger frequency higher than expected from inspiral because of “unexpected” effective softening of EoS)
- Postmerger signal detectable in a few years
- Constraints on onset density of phase transition !!!
- Other observables may be more subtly affected by presence of phase transition

Semi-analytic model: details

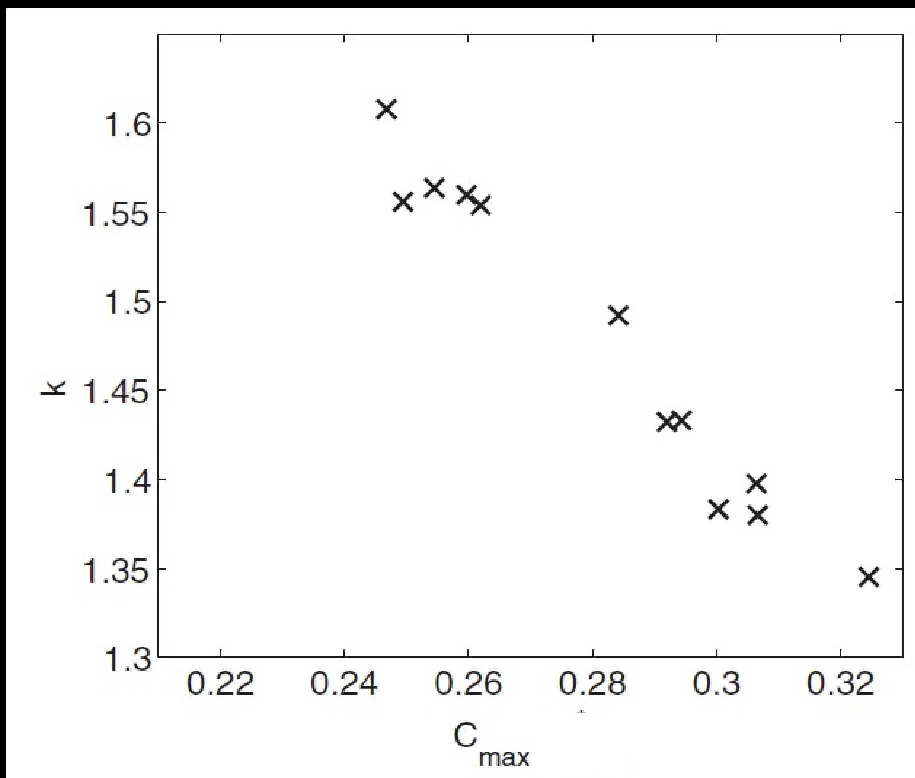
- Stellar equilibrium models computed with RNS code (diff. Rotation, T=0, many different microphysical EoS) => turning points => $M_{stab}(J)$
- Compared to $J(M_{tot})$ of merger remnants from simulations (very robust result) → practically independent from simulations



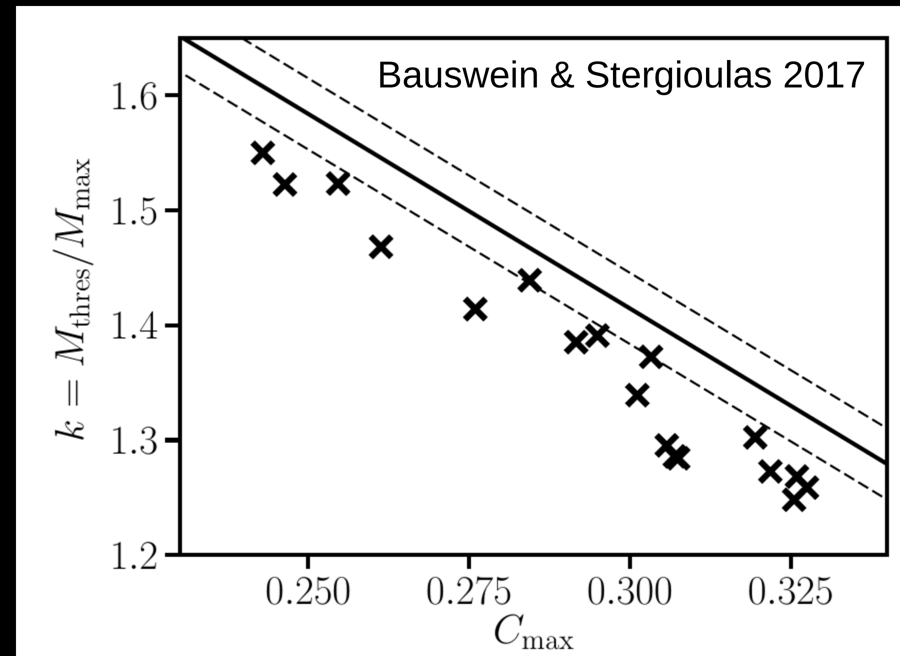
Bauswein & Stergioulas 2017

Semi-analytic model reproducing collapse behavior

Fractional increase of M_{max}



Bauswein et al 2013: numerical determination of collapse threshold through hydrodynamical simulations



Solid line fit to numerical data

Crosses stellar equilibrium models:

- prescribed (simplistic) diff. rotation
- many EoSs at T=0
- detailed angular momentum budget !

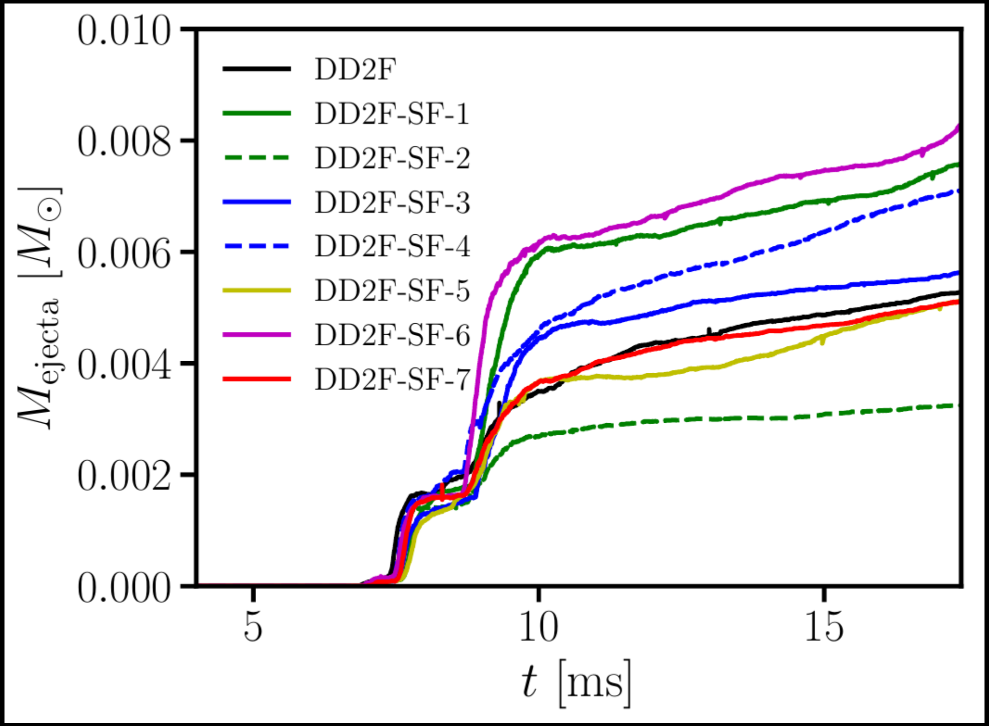
=> equilibrium models qualitatively reproduce collapse behavior

- even quantitatively good considering the adopted approximations

Em counterpart / nucleosynthesi

- 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 2019 – only dynamical ejecta

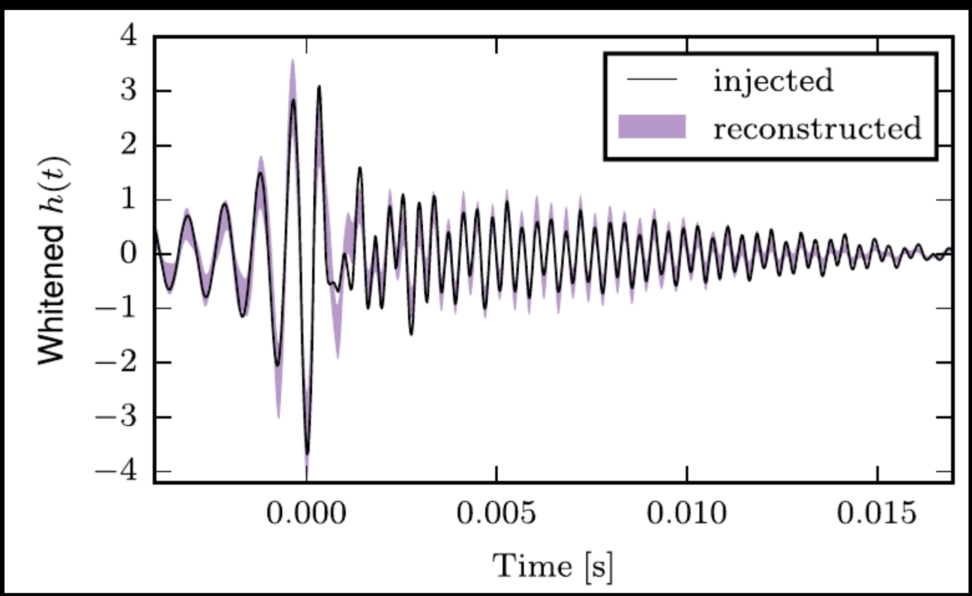
Bauswein et al 2013

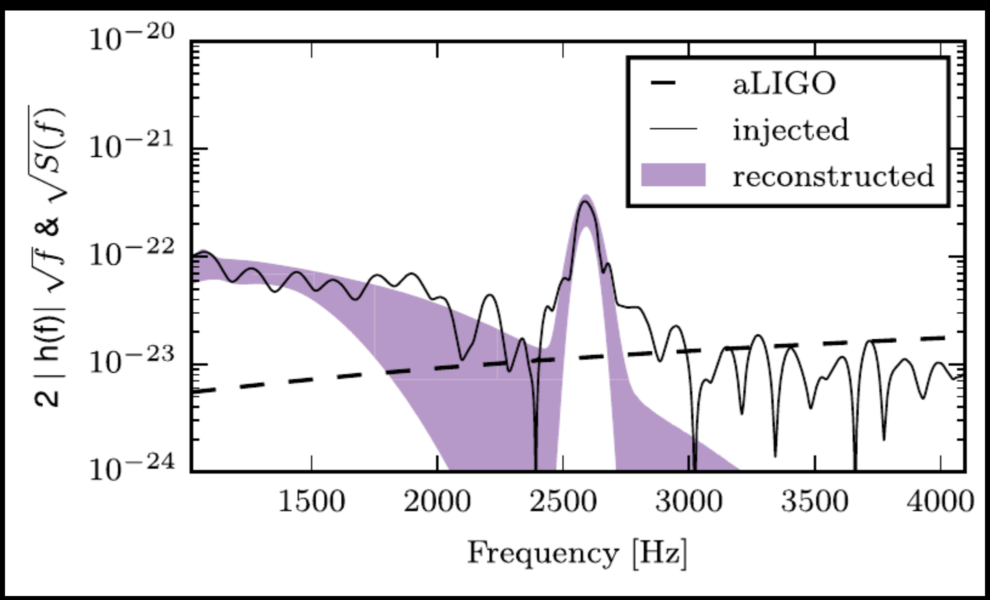
GW data analysis

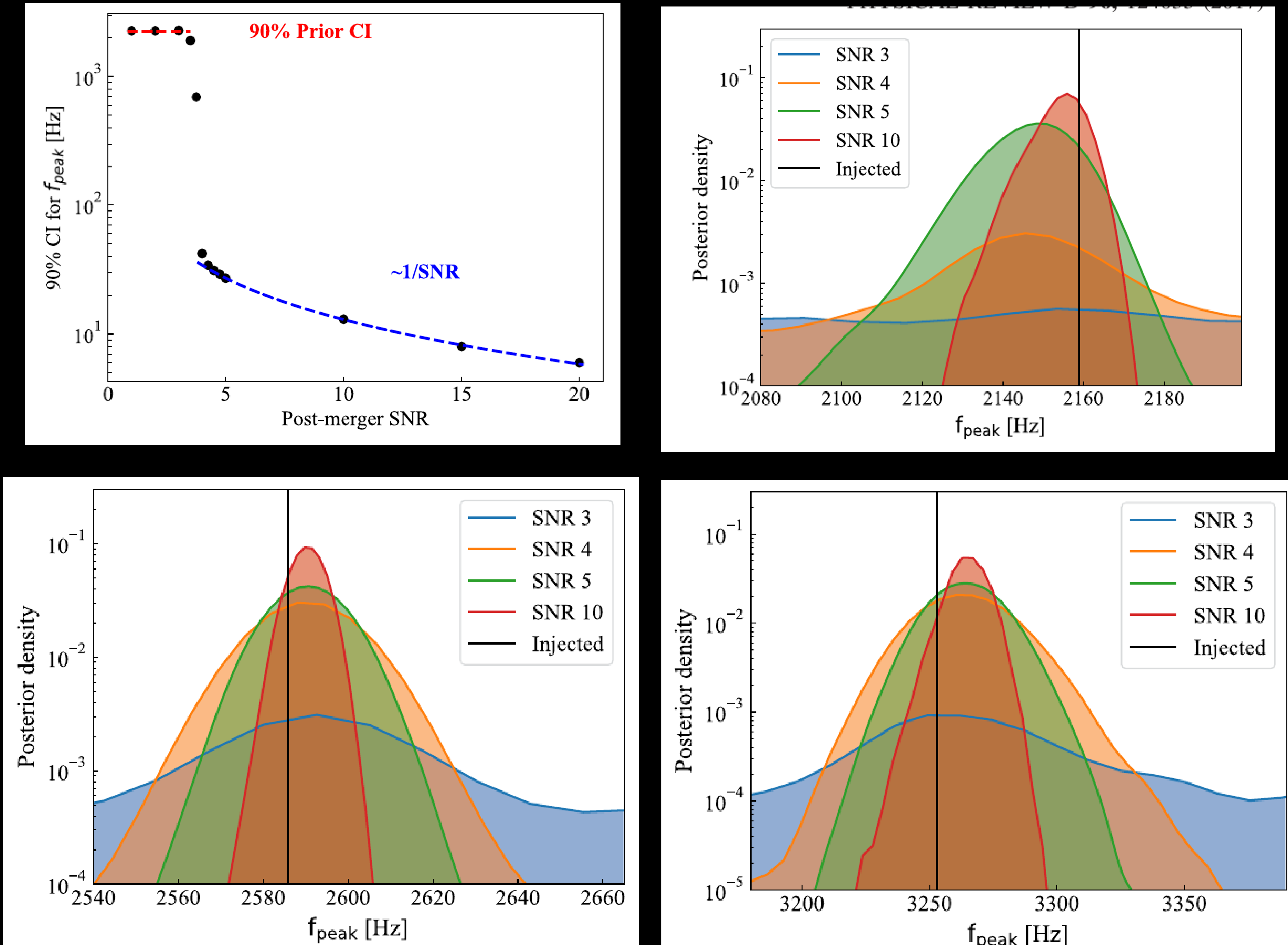
- Injected simulations with SNR 5 (postmerger only, at design sensitivity)

  → recovery through BayesWave (based on wavelets)

  - minimum assumptions about signal morphology
- DD2 1.35-1.35 Msun







Chatzioannou et al 2017