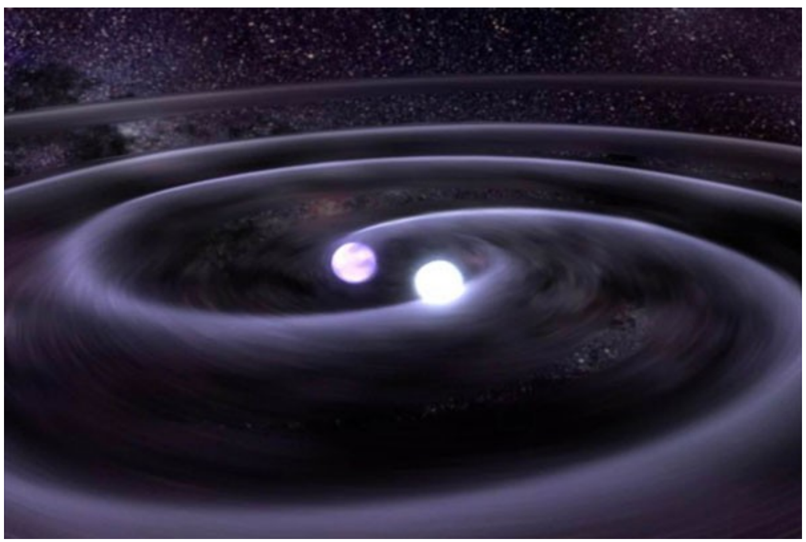
Impact of a first order phase transition on neutron star merger simulations

Sebastian Blacker



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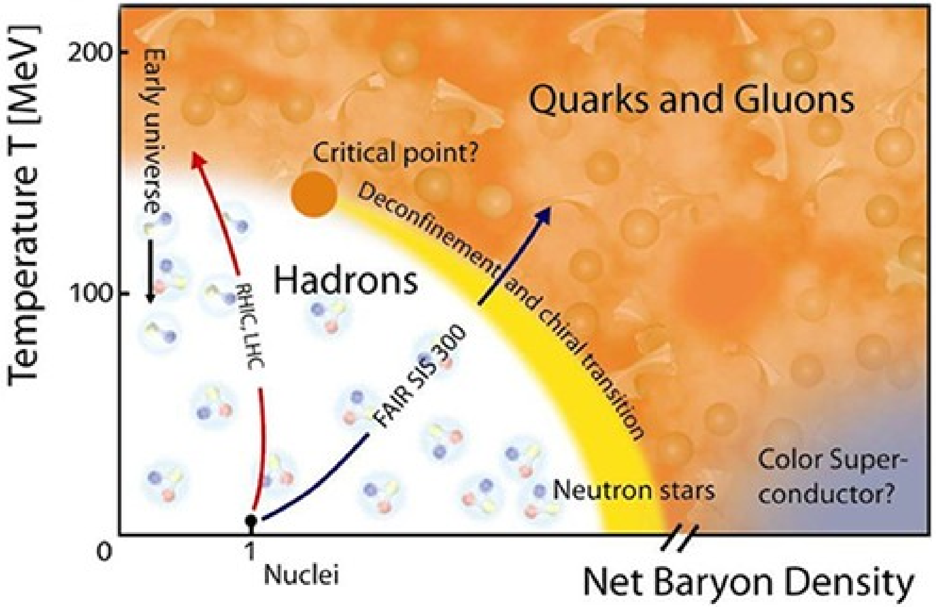

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Outline

- **Introduction**
  - Neutron stars and their equation of state
  - Gravitational waves
- **Neutron star mergers**
  - Constrains on the equation of state
- **Effects of a first order phase transition on mergers**
  - Results from simulations

Neutron stars (NS)

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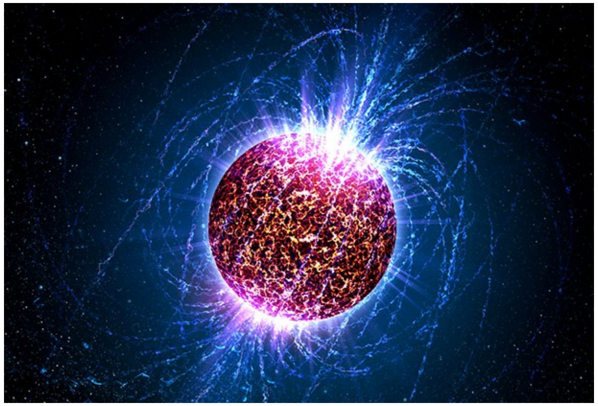
- Possible remnants of supernovae
- Typical masses about 1.4-2.0 M_{sun}
- Typical radii 10-15 km

➡ Densities are above nuclear saturation density ~$3*10^{14}$g/cm^3)!!

- Offer possibility to study properties of extremely dense, cold matter
- First merger of two NS detected in 2017 (GW170817, Abbott et. al 2017)



Casey Reed, Penn State University

TOV-Equations (1)

- General Relativistic equations of stellar structure
- Assumptions: System is static and spherically symmetric

$$\frac{\mathrm{d}M}{\mathrm{d}r} = 4\pi r^2 \rho$$

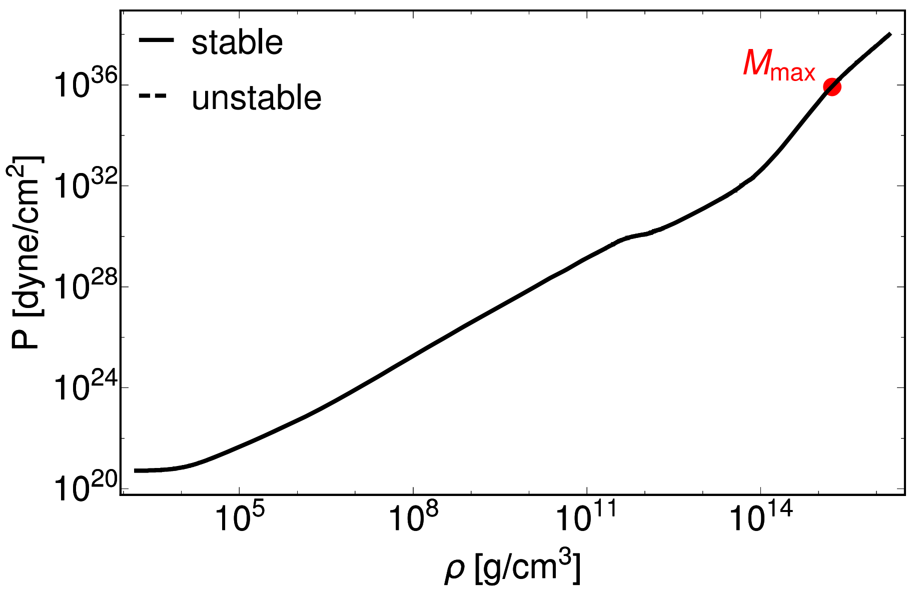
$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{GM\rho}{r^2}\left(1+\frac{P}{c^2\rho}\right)\left(1+\frac{4\pi r^3 P}{c^2 M}\right)\left(1-\frac{2GM}{c^2 r}\right)^{-1}$$

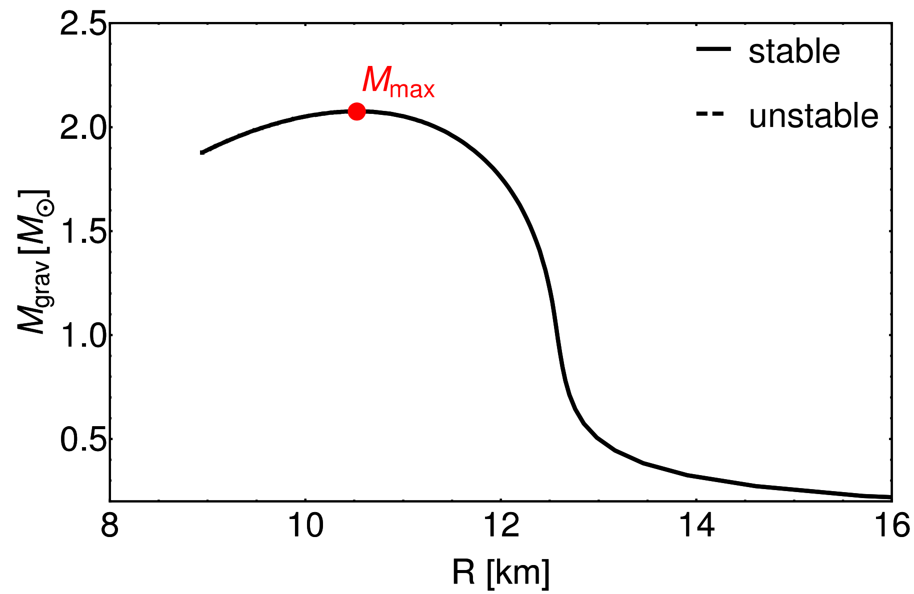
P :pressure, ρ : total energy density, M: Mass in the sphere of Radius r

- To close the system the equation of state (EoS) is needed:

  $P(\rho)$ (zero temperature, beta-equilibrium)

TOV-Equations (2)





TOV-equations

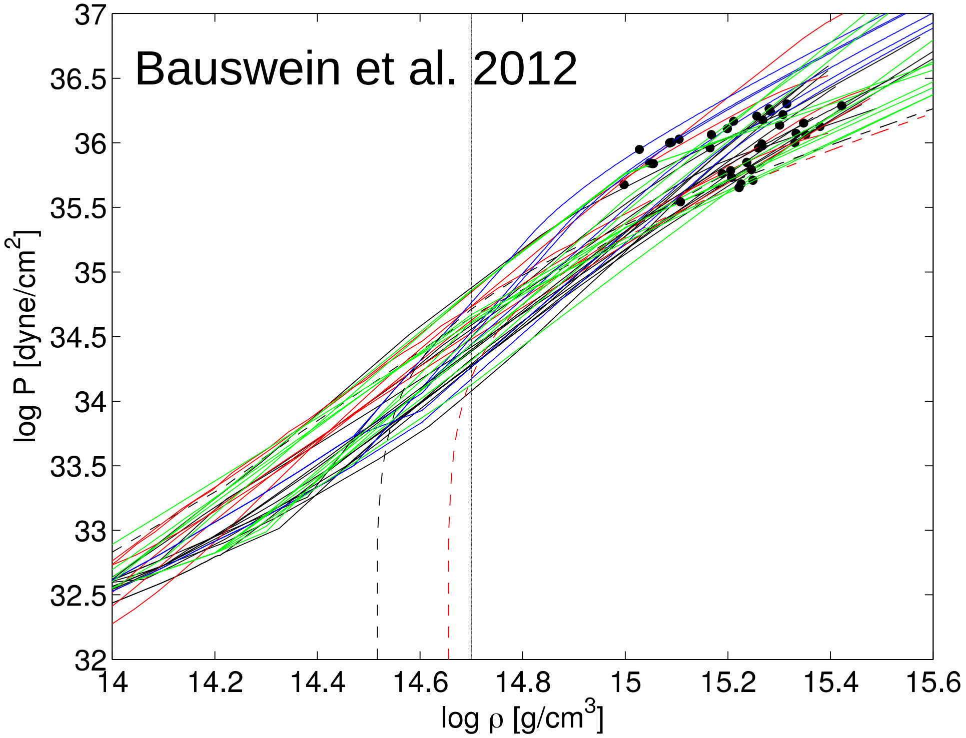
Microphysical EoS ⟷ Mass-radius relation

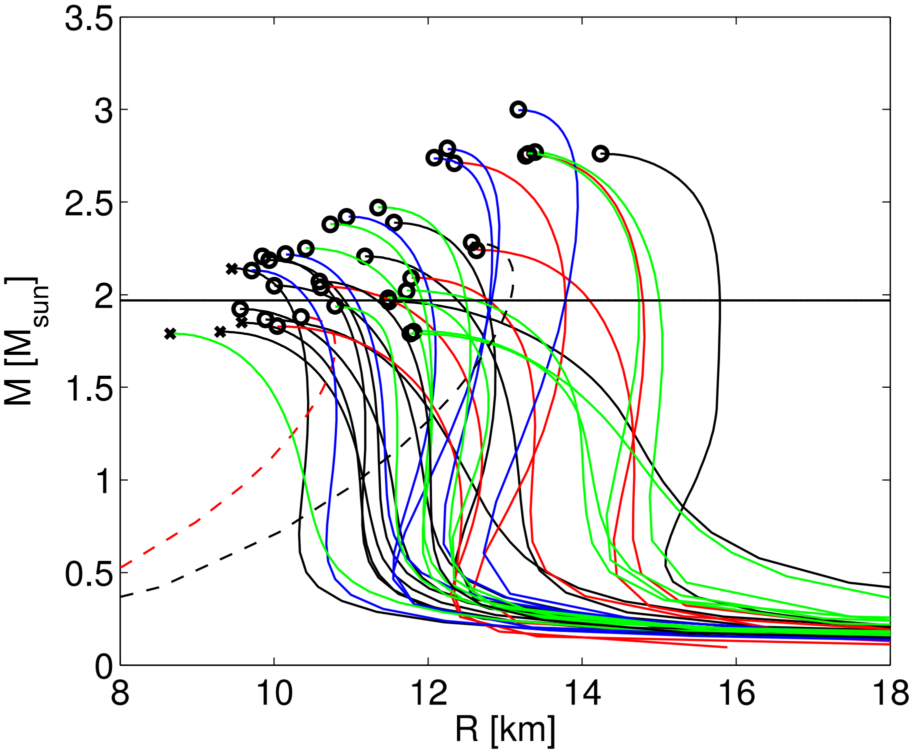
Unique solutions (Mass, Radius,...) for every EoS!

Neutron star equation of state (2)

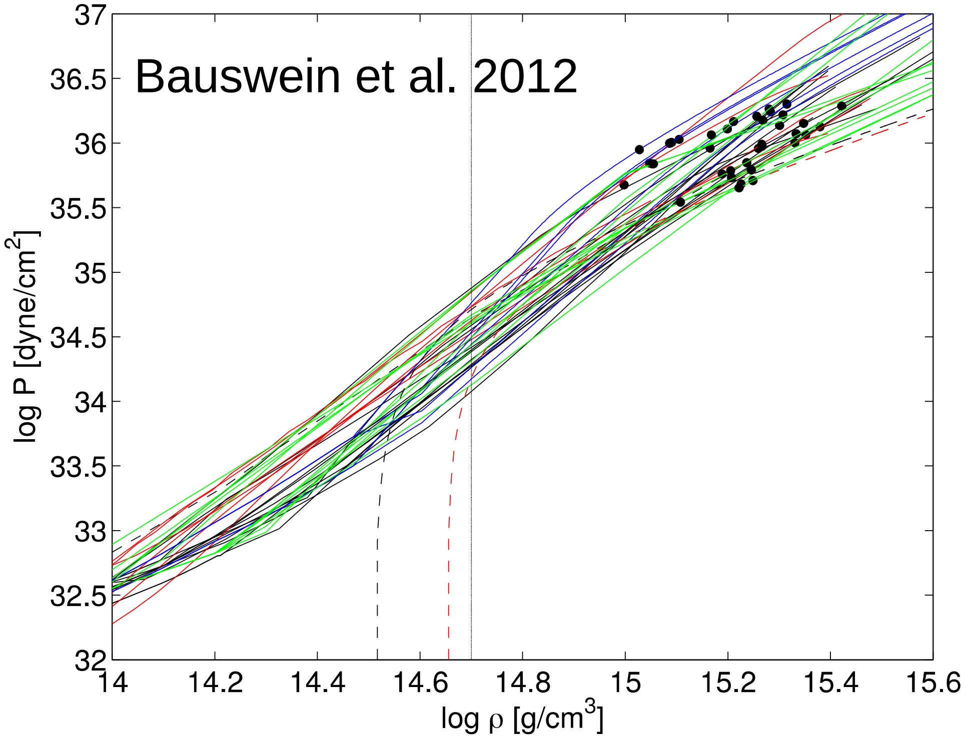
- Not well known at densities above nuclear saturation density ➡ Many different models!!

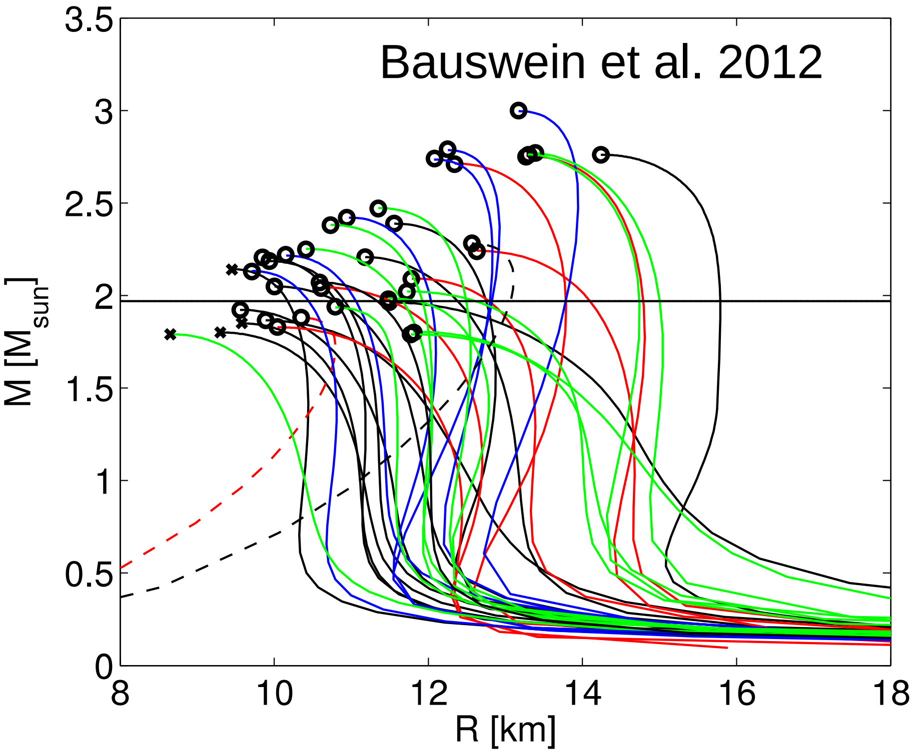
Bauswein et al. 2012





Neutron star equation of state (3)





Which is the correct one??

Gravitational waves (GW)

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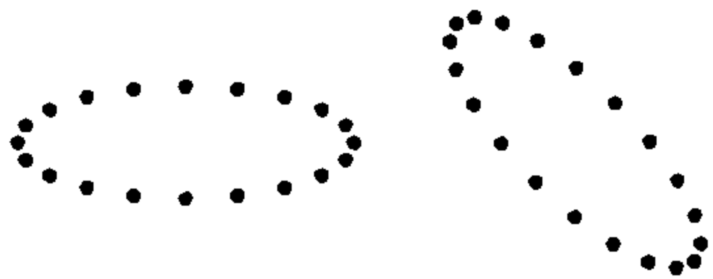
- Prediction of GR and experimentally confirmed (GW150914, Abbott et al. 2016)
- Distortions of spacetime itself moving at the speed of light
- Contain information on matter motion
- Carry energy and angular momentum
- Interaction with matter

  is extremely weak

  ➡ No absorption



https://brilliant.org/wiki/gravitational-waves

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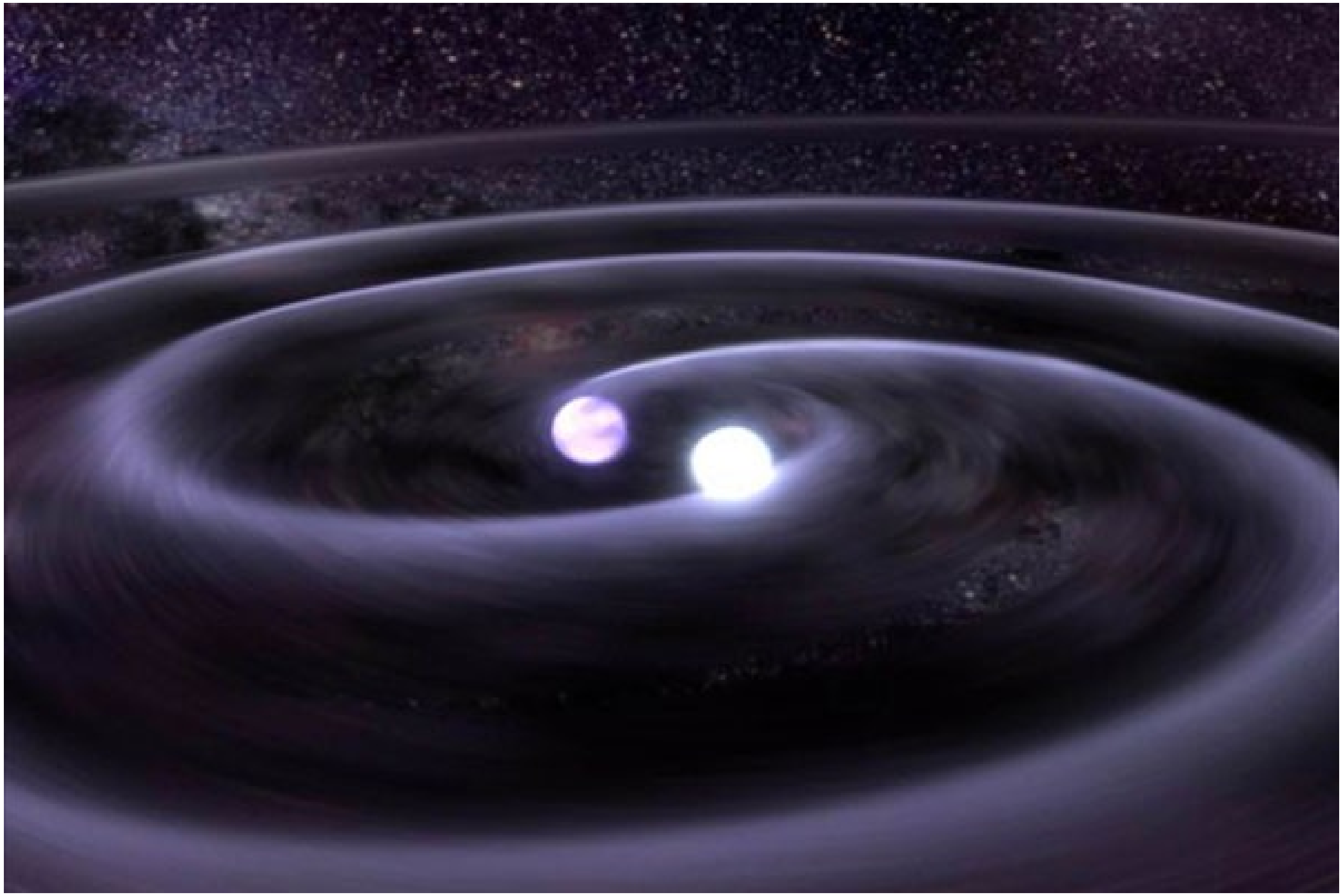
Neutron star binaries (1)



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Neutron star mergers

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- GWs carry away energy and angular momentum

➡ Orbits decrease and NS will eventually merge

EoS constraints via tidal effects

Inspiral

↓

Merger

Outcome depends on the mass and the EoS!!

$M_{tot} \geq M_{thres}$ → Prompt collapse to black hole

$M_{tot} < M_{thres}$ → Formation of a (temporary) stable differentially rotating massive NS

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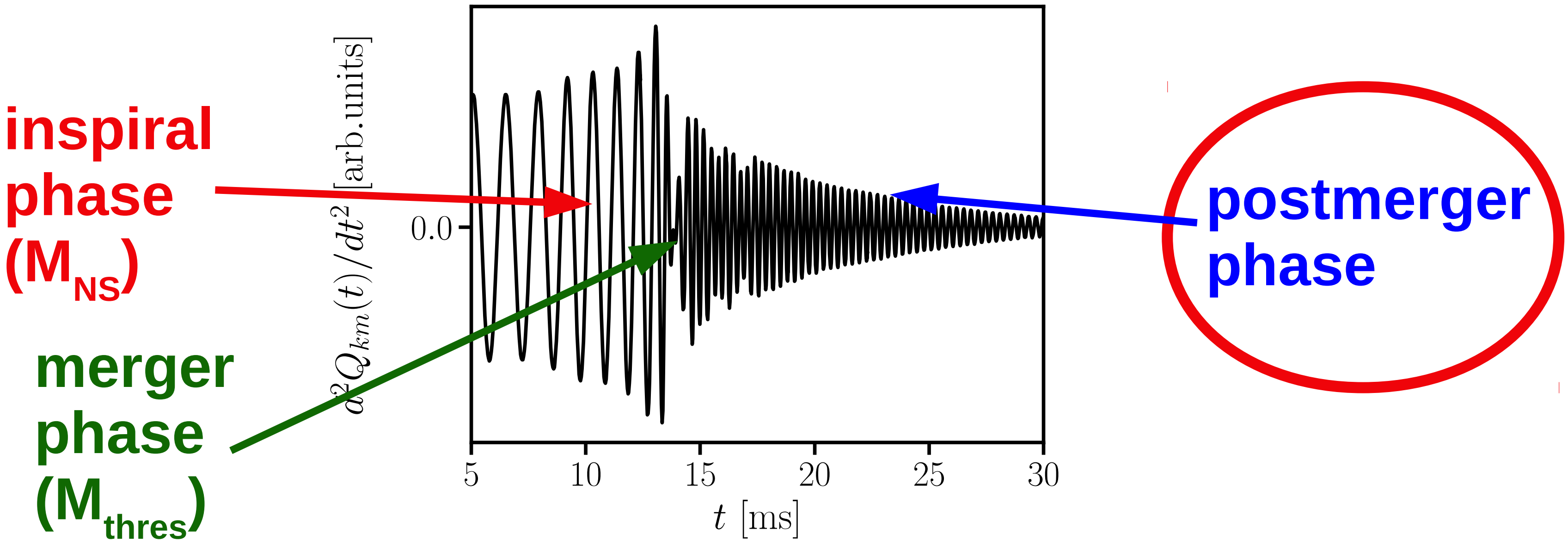
GW from neutron star mergers

- 3 phases:
  - Inspiral: EoS constraints via tidal effects
  - Merger: EoS constraints via collapse behaviour
  - Postmerger: EoS constraints via remnant oscillations



Below the threshold mass

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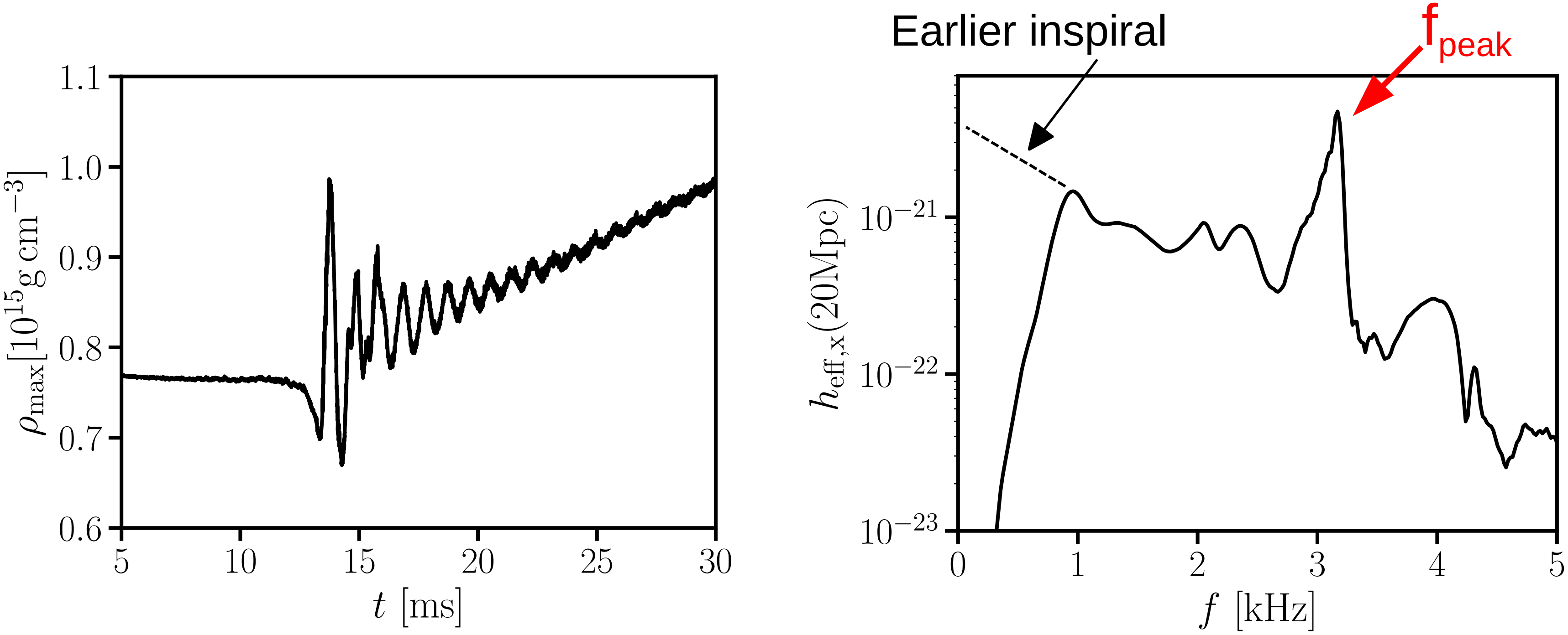
- The remnant is (temporarily) stable and oscillates
- ➡ Produces a postmerger gravitational wave signal



Oscillation frequency depends on EoS!

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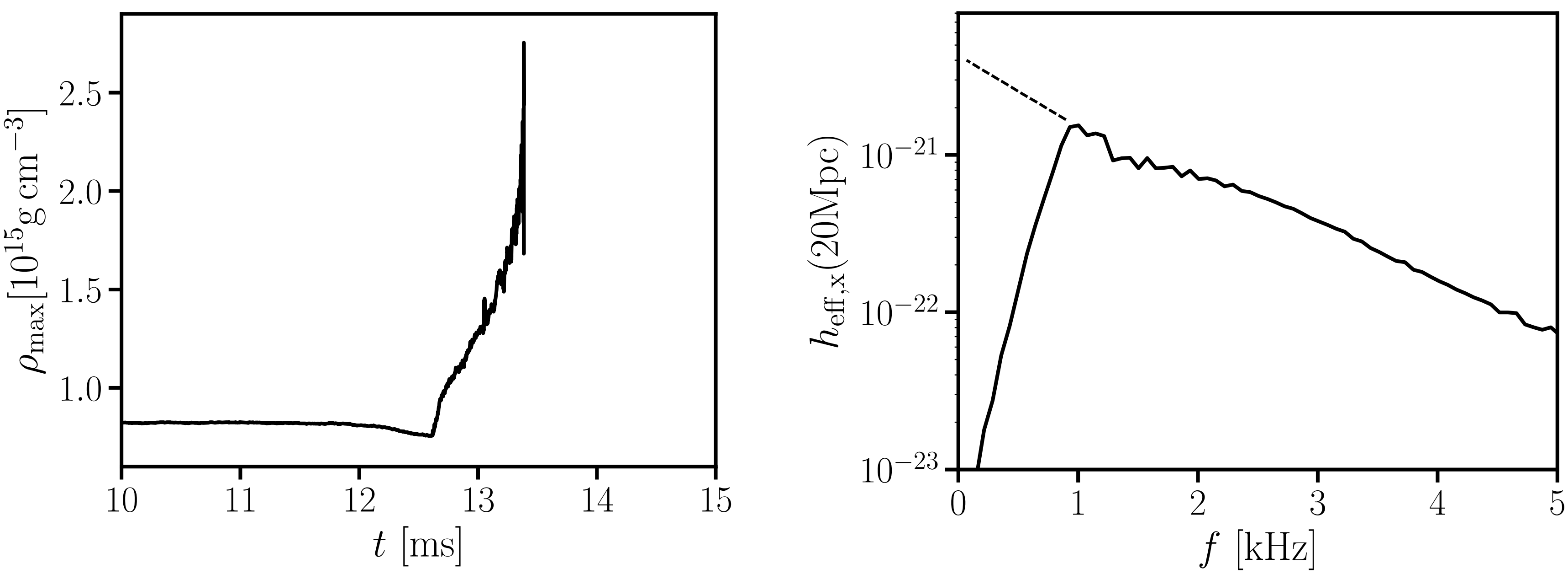
Above the threshold mass

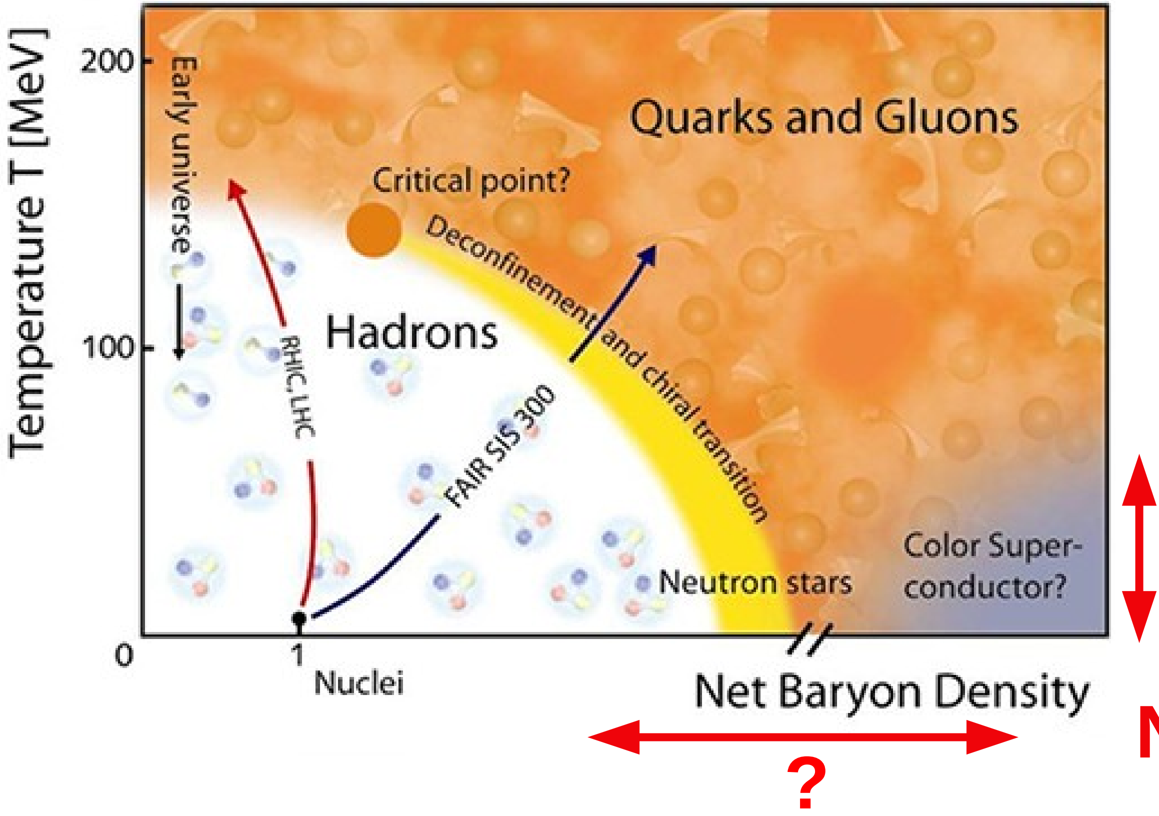
- The remnant collapses promptly to a black hole
- ➡ Much weaker postmerger gravitational wave signal



Collapse behavior gives constraints on the EoS!

Phase diagram of matter

- QCD predicts a phase transition from hadronic to deconfined quark matter, but at what density?



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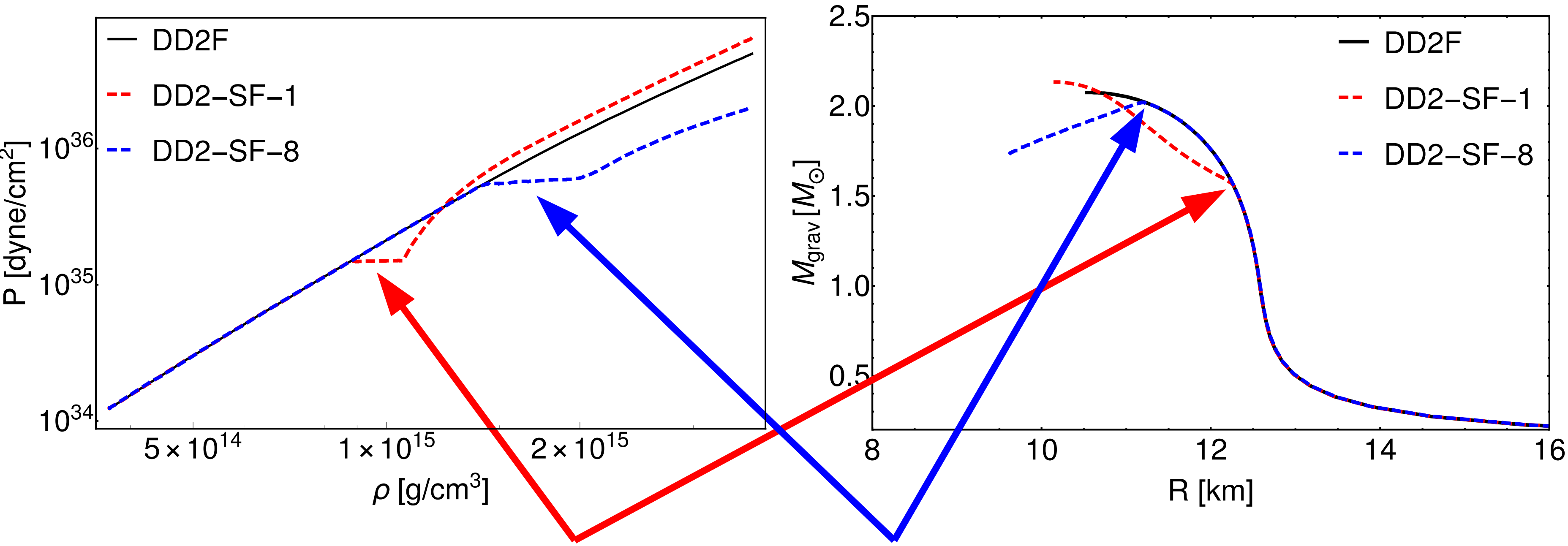
NS-mergers

EoS with phase transition to deconfined quark matter

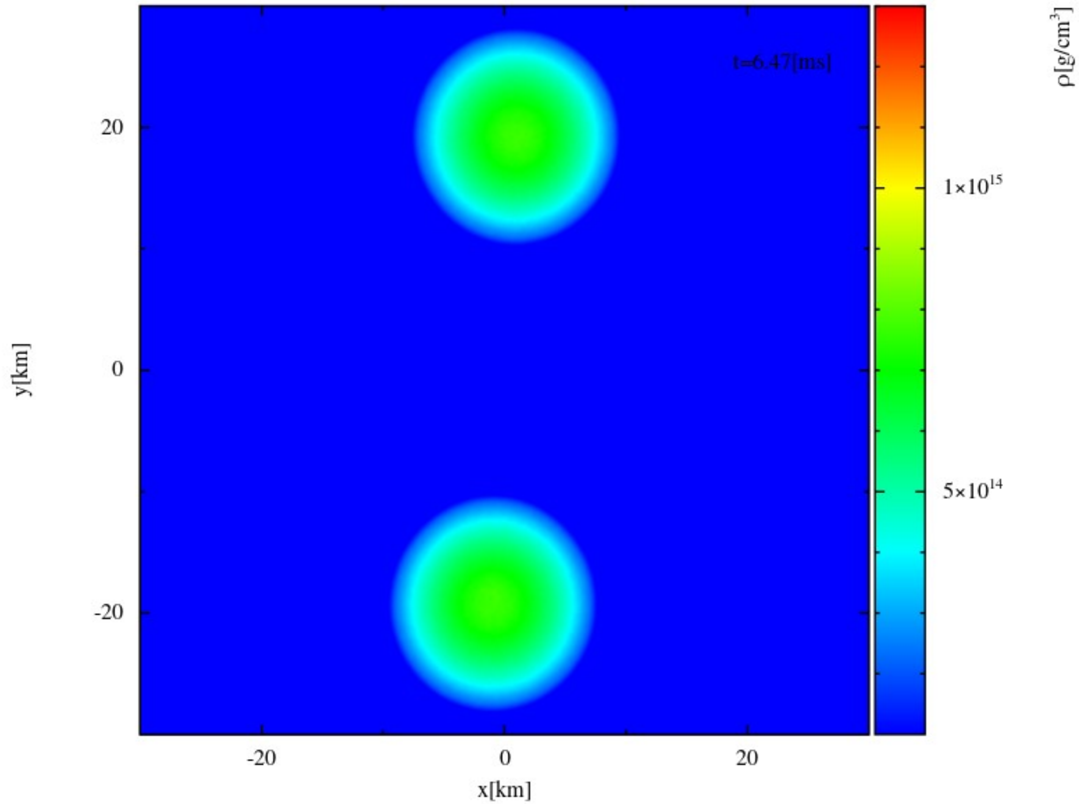


First order phase transition

See Bauswein et al. 2019 for the hybrid EoS names and Fischer et al. 2018, Bastian et al. 2018 and references therein for underlying EoS model

Impact of 1st order phase transition on merger simulations (1)

simulation with 2*1.35 M_{sun}



Density in the equatorial plane using the DD2f-SF-6 EoS

Impact of 1st order phase transition on merger simulations (3)

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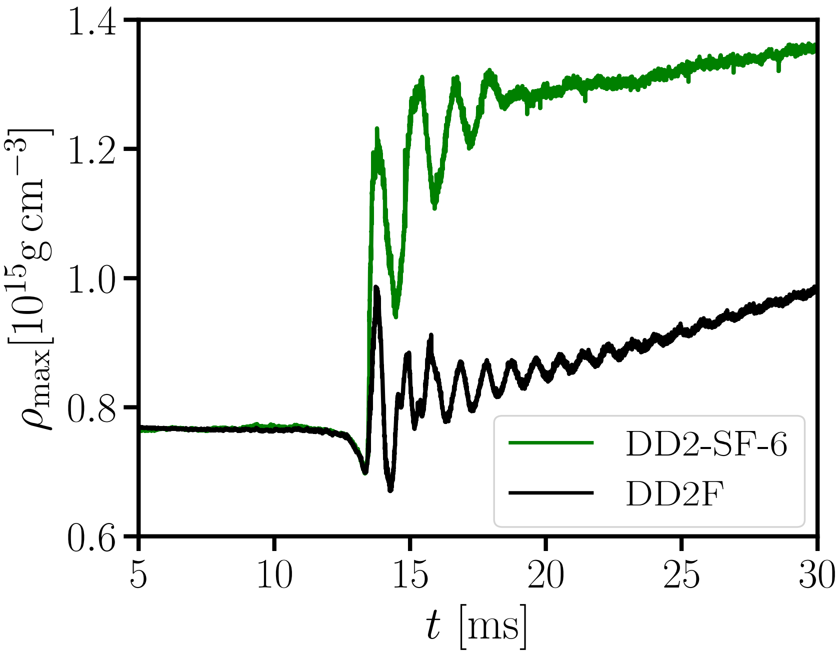
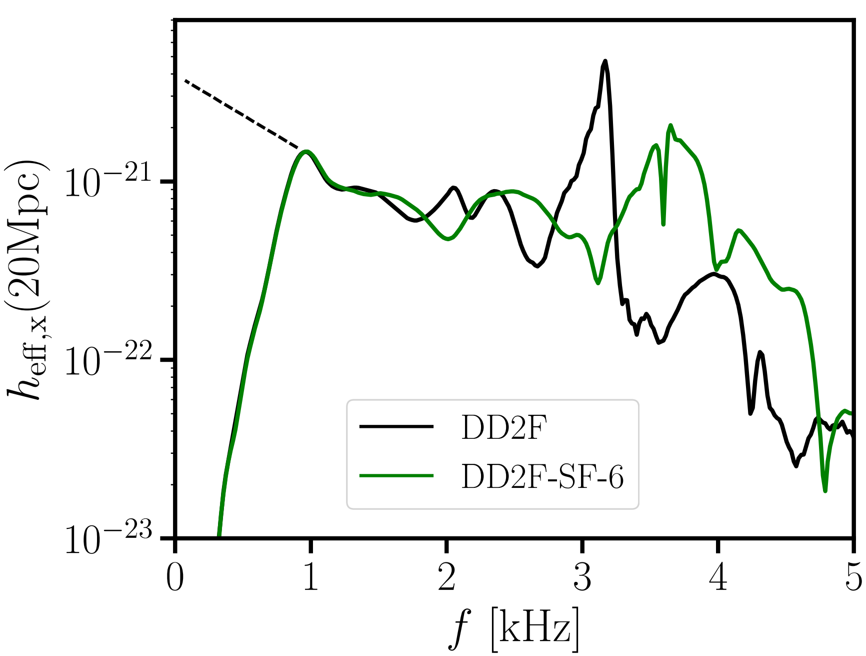




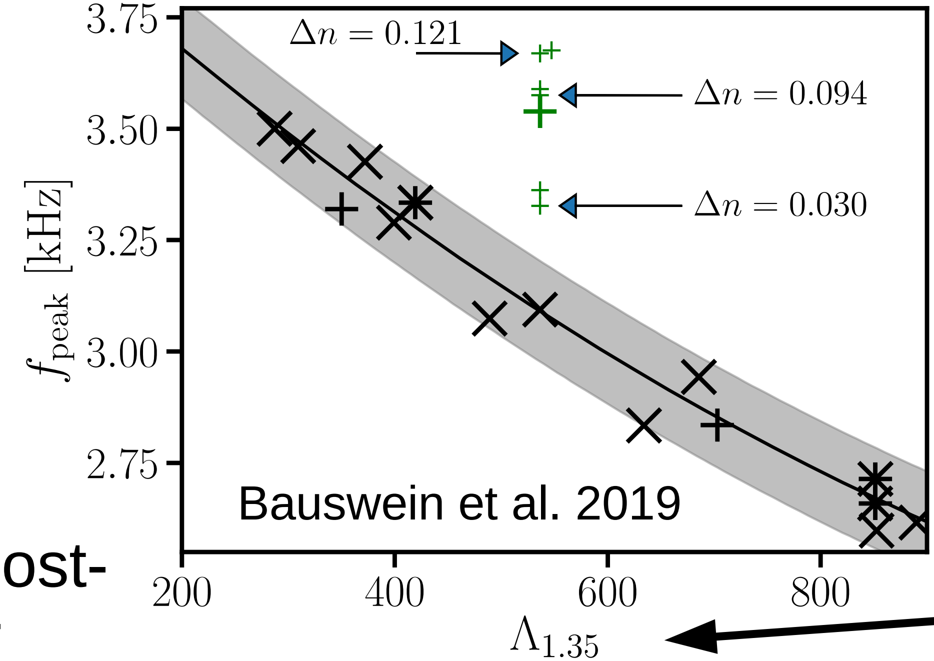
High densities (frequencies) alone not unambiguous signature of a phase transition!

➡ **Need behaviour different from all hadronic EoS**

Impact of 1st order phase transition on merger simulations (4)

- If the transitions happens during the merger:

➡ **Inspiral signal will behave 'hadronicly', while postmerger signal will not!!**



From post-merger

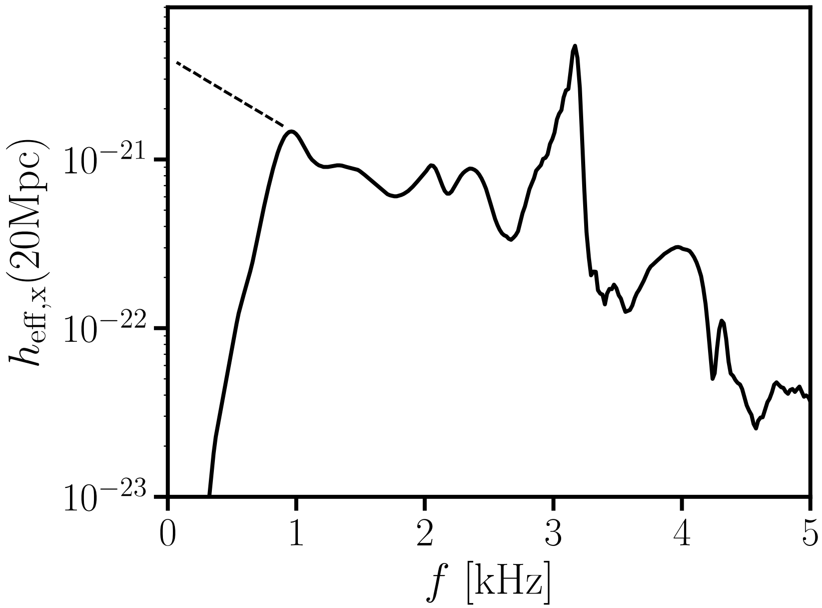
From inspiral

- Feature of EoS with 1st order phase transition
- Size of deviation depends on density jump!

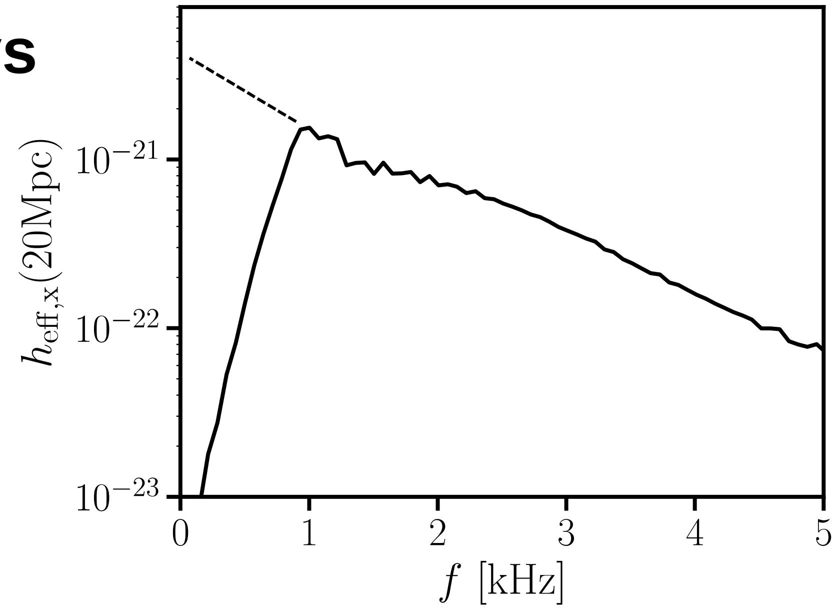
M_{thres} for hybrid EoS

- Mergers below or above M_{thres} distinguishable via postmerger GW-signal

➡ **M_{thres} detectable with enough events!**



vs



Does a first order phase transition affect M_{thres}?

f_{Peak}-M_{thres}-relation for hybrid EoS

M_{thres}-relations for hybrid- and hadronic-EoS similar!

Summary

- **GW from NS mergers give constraints on the EoS via**
  - Inspiral phase (tidal effects)
  - Merger phase (collapse behavior)
  - Postmerger phase (oscillations of the remnant, f_{peak})
- **Effects of a first order phase transition**
  - Larger densities and peak frequencies
  - Deviations from empirical relation between tidal deformability and f_{peak}
  - No clear deviation from M_{thres}-relations

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Thank you for your attention!!