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Neutron star mergers and kHz gravitational-wave emission

Challenges and Opportunities of High Frequency Gravitational Wave Detection

Abdus Salam International Centre for Theoretical Physics, Trieste, 14/10/2019

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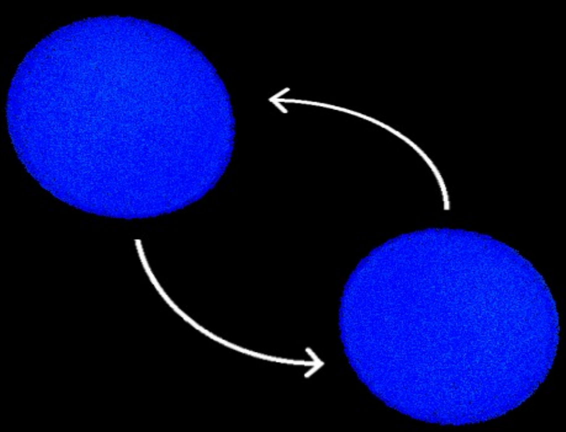
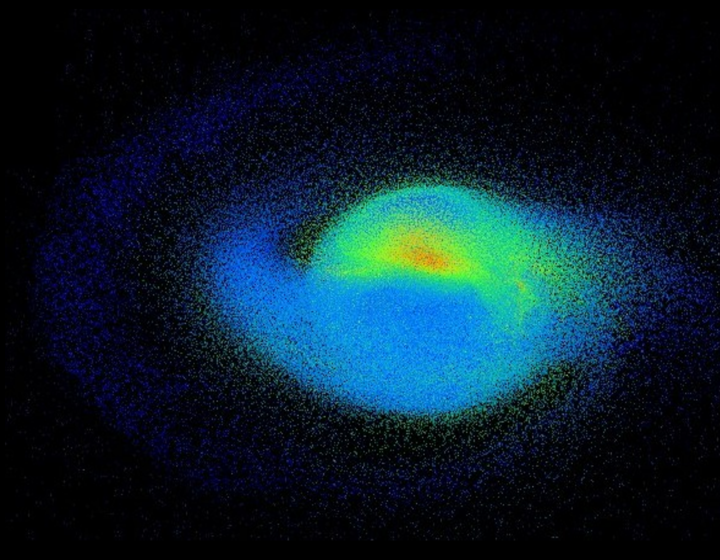




Outline

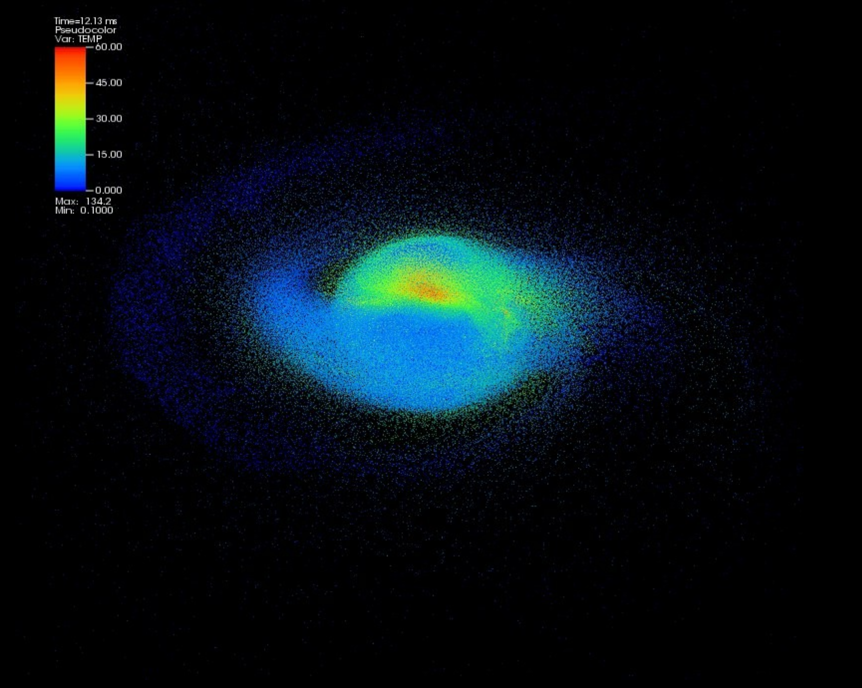
- Overview: NS mergers and GW170817
- Postmerger GW emission (kHz !!!) → NS radius constraints
- GW data analysis
- Maximum mass of NSs – Collapse behavior of NS mergers
- Signatures of the QCD phase transition
- Summary and conclusions

Note: high frequency = a few kHz

$$t_{\rm dyn} = \sqrt{\frac{R^3}{G\,M}} \approx 1\ ms$$

Disclaimer: focus on NS physics ignoring all other interesting stuff at higher frequencies

Dynamics



Inspiral of NS binary

~100 Myrs

Neutron star merger

dependent on EoS, M_{tot}

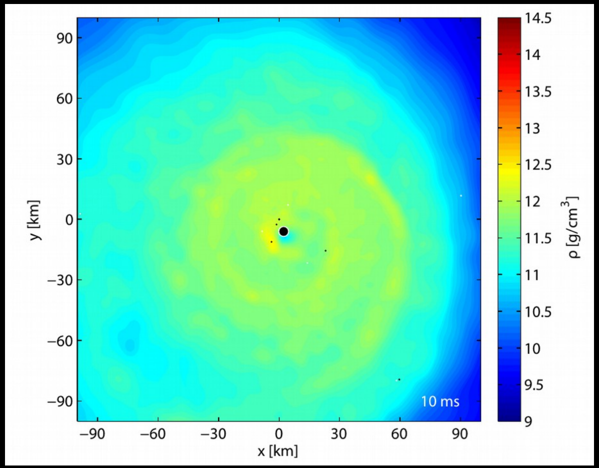
ms → Prompt formation of a BH + torus

ms → **Formation of a differentially rotating massive NS**

dependent on EoS, M_{tot}

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

10-100 ms → Delayed collapse to a BH + torus



Insights from GW170817

- First unambiguously observed NS merger → rate
- Well measured total mass 2.73 Msun, mass ratio M1/M2 between 0.7 .. 1
- Multi-messenger observations: accompanying emission in radio, IR, optical, UV, X-rays and gamma rays
- Connection between short GRBs and NS mergers strengthens / established
- Optical emission compatible with ejecta heated by rapid neutron-capture process → first and only confirmed r-process site !
- Estimated ejecta mass 0.02-0.05 Msun → mergers compatible with being main source of heavy elements
- Independent measurment of Hubble constant
- EoS constraints:

  - Finite-size effects in pre-merger phase → tidal deformability → upper limit on NS radii (smaller than about 13.5 km) → nuclear matter not too stiff

  - Multi-messenger interpretation: bright em transient points to no direct BH formation → lower limit on NS radii (larger than 10.5 km) → nuclear matter not too soft

Motivation: Neutron stars and the EoS

- Nuclear many-body problem hard to solve (some approximations required)
- Nuclear interactions not precisely known, especially at higher densities
- Fundamental contituents of NSs not known: pure nuclear matter, hyperons, ..., possibly phase transition to deconfined quark matter

→ high-density EoS not precisely known

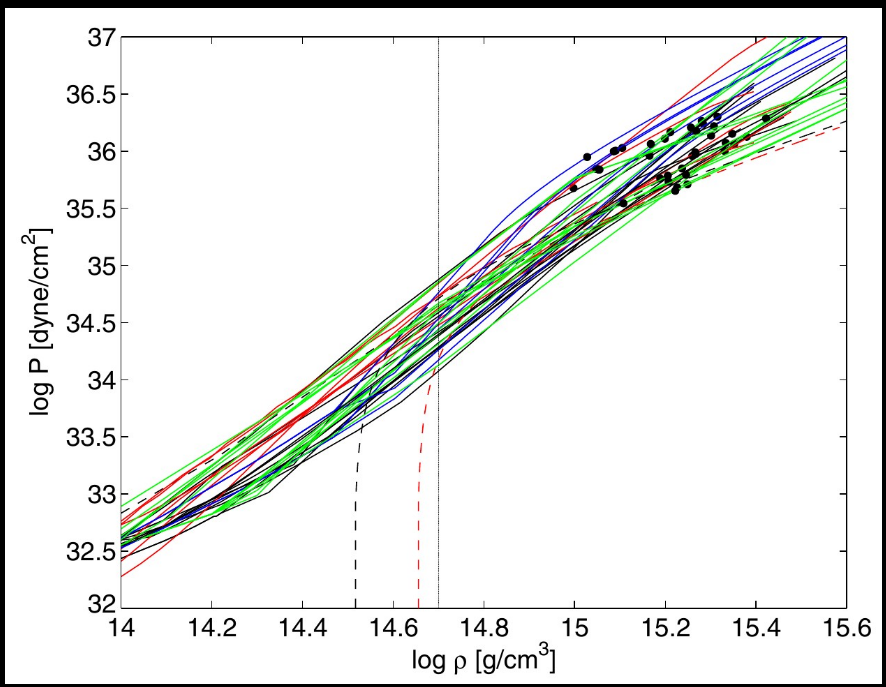
↔ stellar structure of NSs not precisely known - density profile, radii, tidal deformability, maximum mass ??? – uniquely linked through structure eqs.

→ relevant for nuclear/high-denisty matter physics and astrophysics of NS (NS cooling, SN explosions, NS mass distribution, mass gap, cosmology, ...)

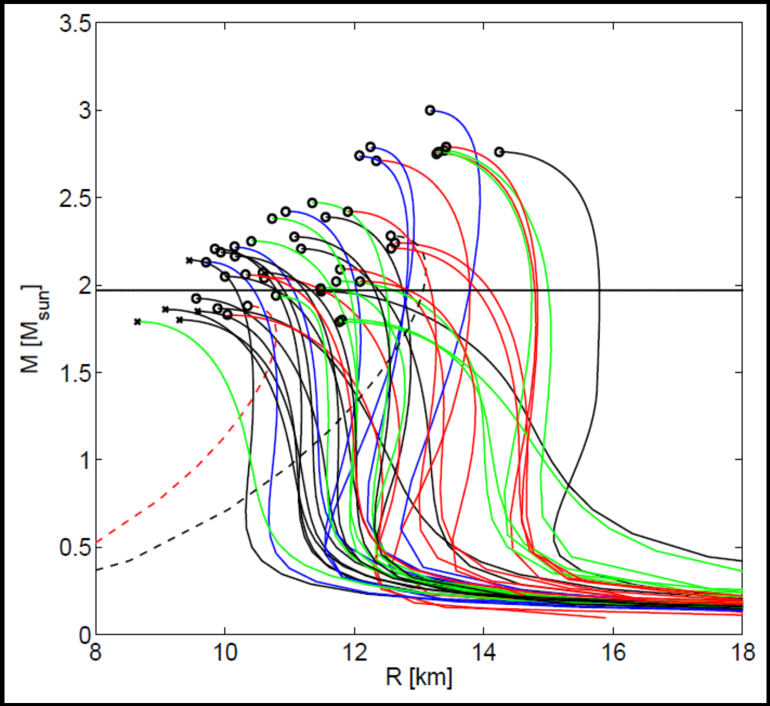
→ it's all about measuring stellar properties (e.g. radius) – GW particularly promising

Introductory remark

- Mass-radius relation (of non-rotating NSs) and EoS are uniquely linked through Tolman-Oppenheimer-Volkoff (TOV) equations



TOV ⟷

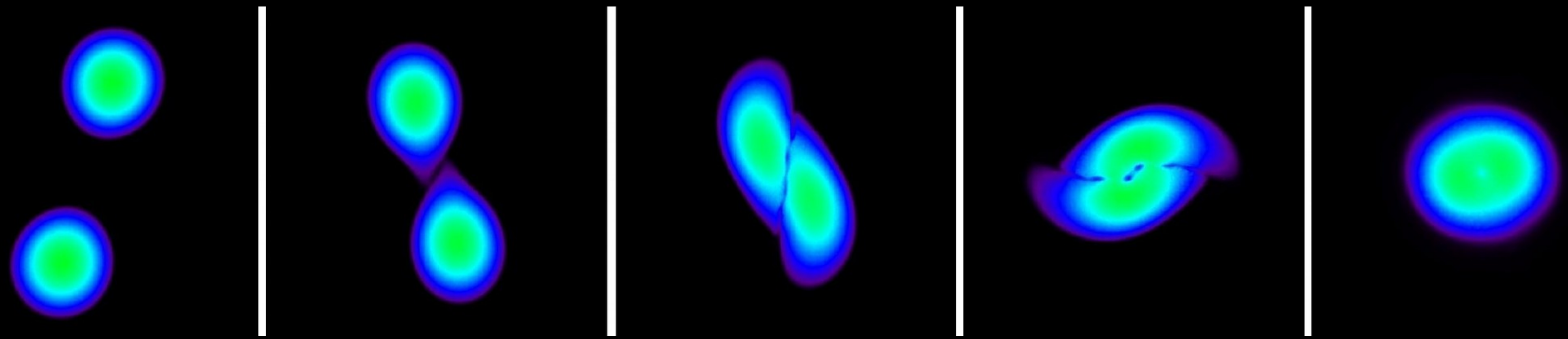


Theory: P(ρ) ⟵ currently / future ⟶ Observation: R(M)

→ NS properties (of non-rotating stars) and EoS properties are equivalent !!!

(not all displayed EoS compatible with all current constraints)

Finite-size effects during late inspiral



Inspiral

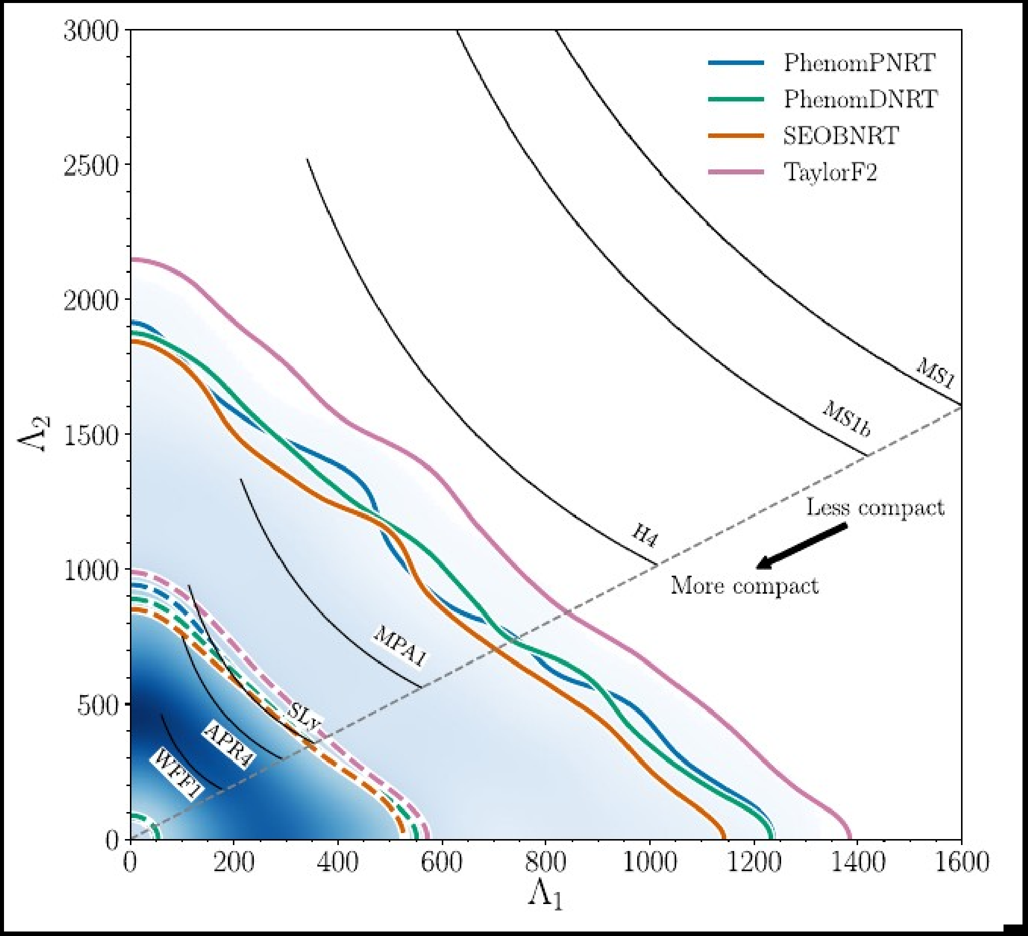
- Lambda < ~650

  → Means that very stiff EoSs are excluded

  → NS radii smaller than ~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

Inspiral

- Waveform models still not fully understood → model dependencies and degeneracies (q,S)

  → complementary measurements desirable (note: em measurements typically very model dependent)

  → Tidal deformability and radii scale tightly but not perfectly

- Finite-size effects harder to measure for more massive systems
- NS mass distribution peaks at 1.3-1.4 Msun

  → high mass NSs / very high density EoS not accessible

  → thermal effects not accessible (inspiral probes cold EoS)

Future: Postmerger GW emission*

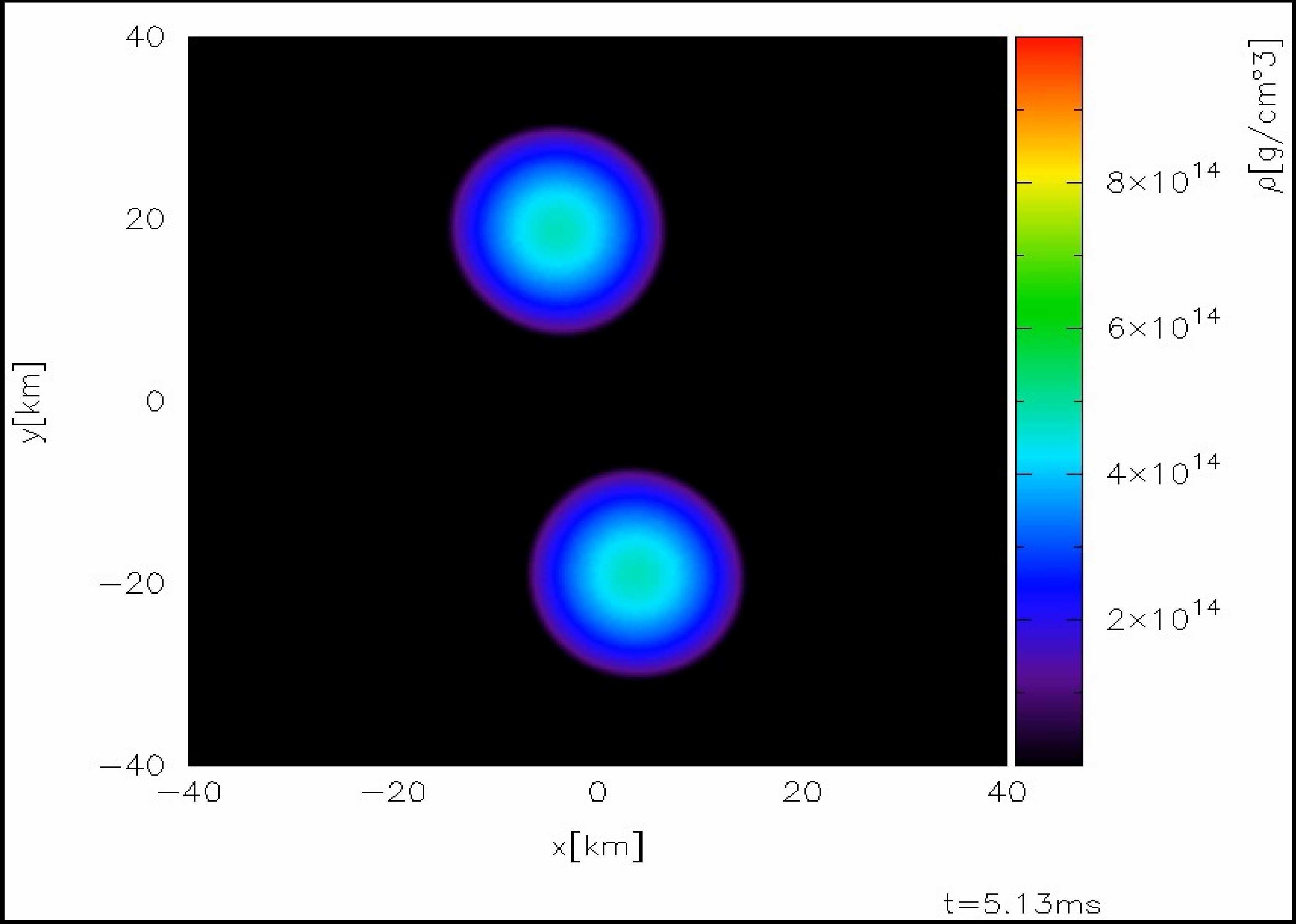
(dominant frequency of postmerger phase)

→ determine properties of EoS/NSs

→ complementary to inspiral

* not detected for GW170817 – expected for current sensitivity and d=40 Mpc (Abbott et al. 2017)

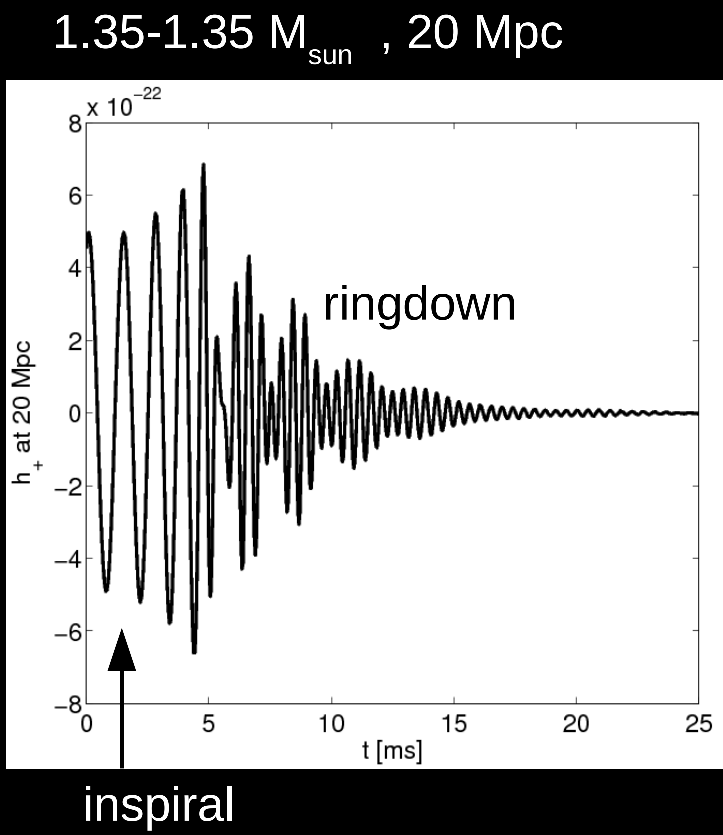
Simulation: 1.35+1.35 M_{sun}

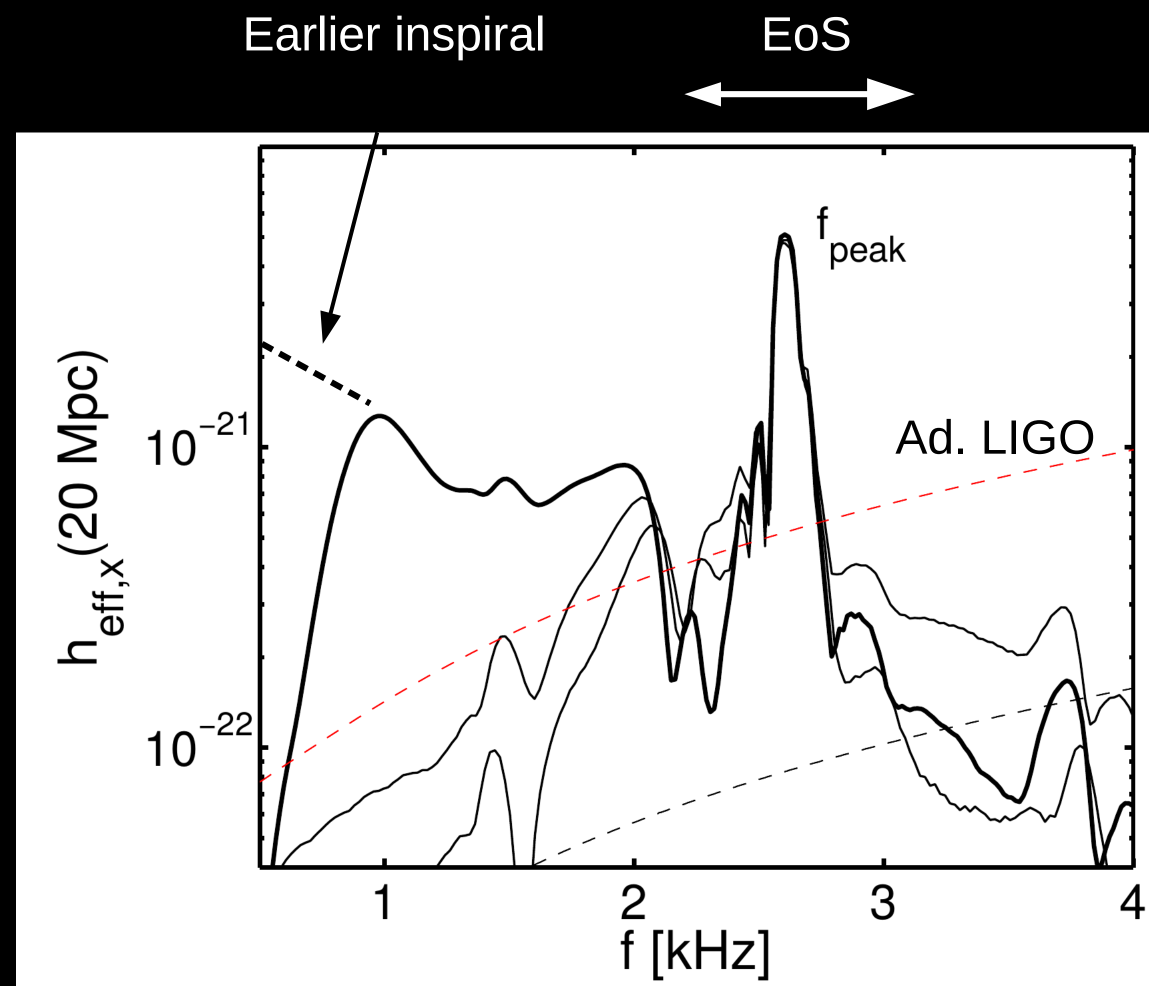


Density evolution in equatorial plane, Shen EoS

Relativistic smooth particle hydrodynamics, conformally flat spatial metric, microphsyical temperature-dependent EoS

Postmerger

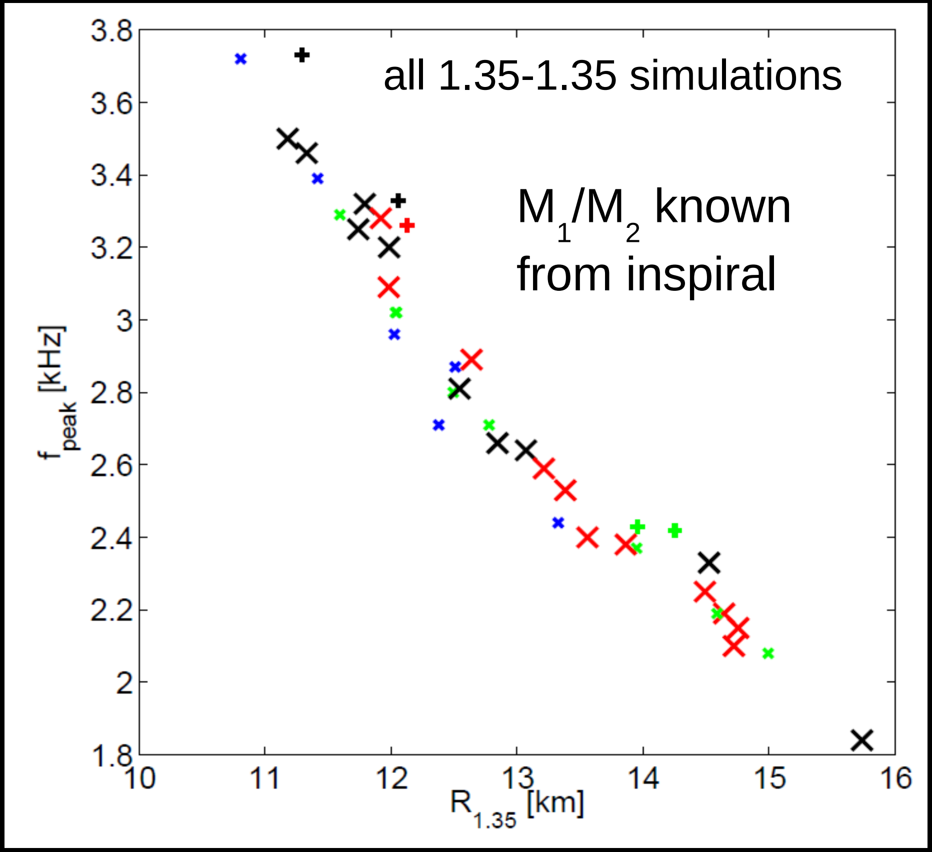


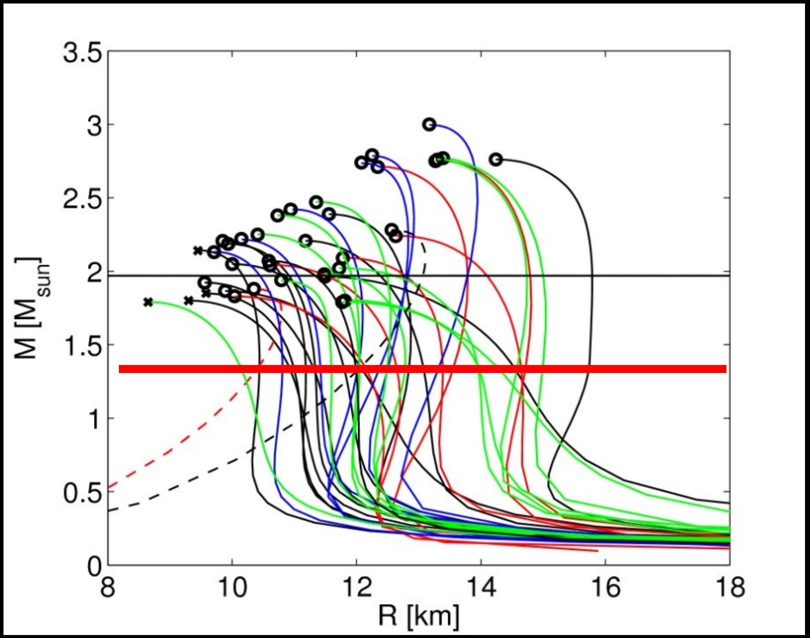


Dominant postmerger oscillation frequency f_{peak}

Very characteristic (robust feature in all models) but kHz regime

Gravitational waves – EoS survey





characterize EoS by radius of nonrotating NS with 1.35 M_{sun}

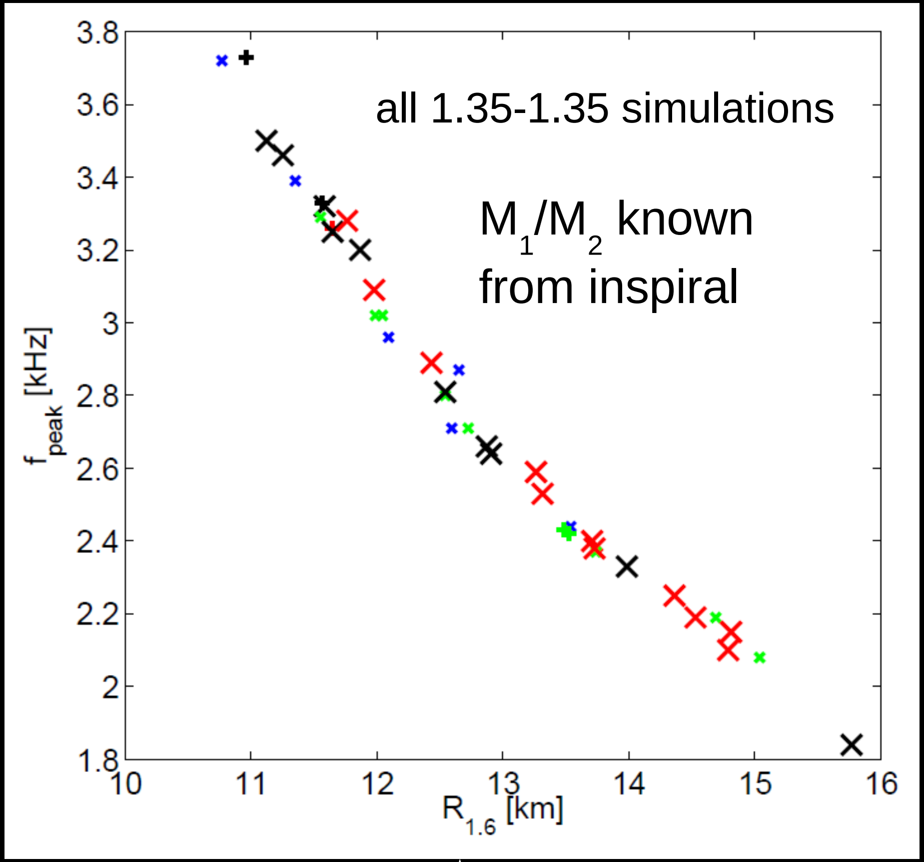
Bauswein et al. 2012

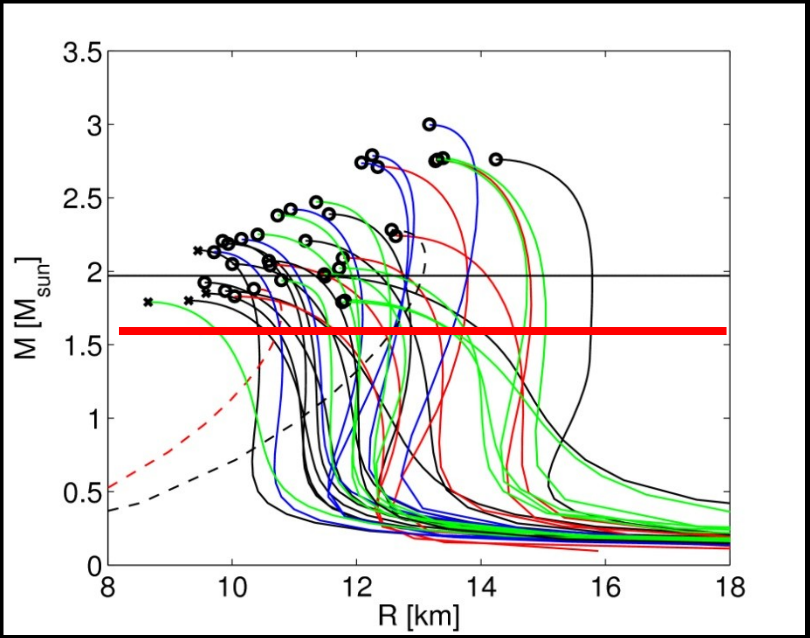
Pure TOV/EoS property => Radius measurement via f_{peak}

Here only 1.35-1.35 Msun mergers (binary masses measurable) – similar relations exist for other fixed binary setups !!!

~ 40 different NS EoSs

Gravitational waves – EoS survey





characterize EoS by radius of nonrotating NS with 1.6 M_{sun}

Bauswein et al. 2012

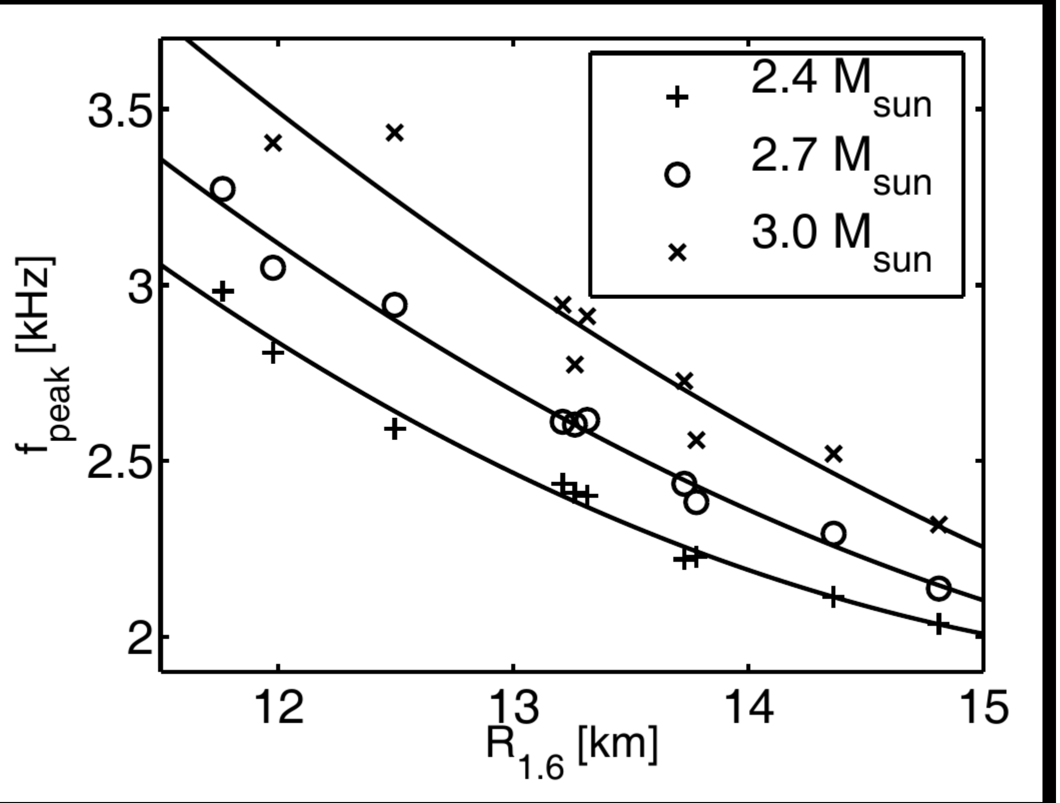
Pure TOV/EoS property => Radius measurement via f_{peak}

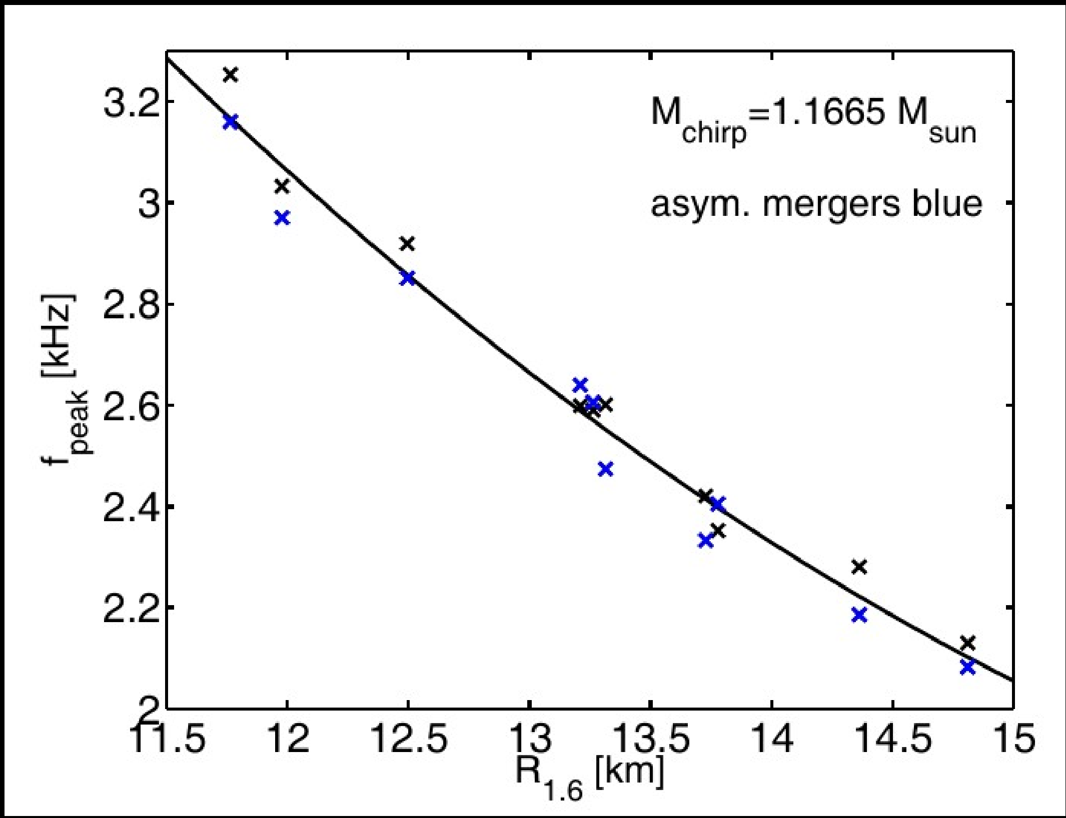
Smaller scatter in empirical relation (< 200 m) → smaller error in radius measurement

Note: R of 1.6 M_{sun} NS scales with f_{peak} from 1.35-1.35 M_{sun} mergers (density regimes comparable)

GW data analysis: Clark et al 2014, Clark et al 2016, Chatziioannou et al 2017, Bose et al. 2018, Yang et al 2017, … → detectable at a few 10 Mpc

Binary mass variations





Different total binary masses (symmetric)

Fixed chirp mass (asymmertic 1.2-1.5 M_{sun} binaries and symmetric 1.34-1.34 M_{sun} binaries)

Data analysis: see e.g. Clark et al. 2016 (PCA), Clark et al. 2014 (burst search), Chatziioannou et al 2017

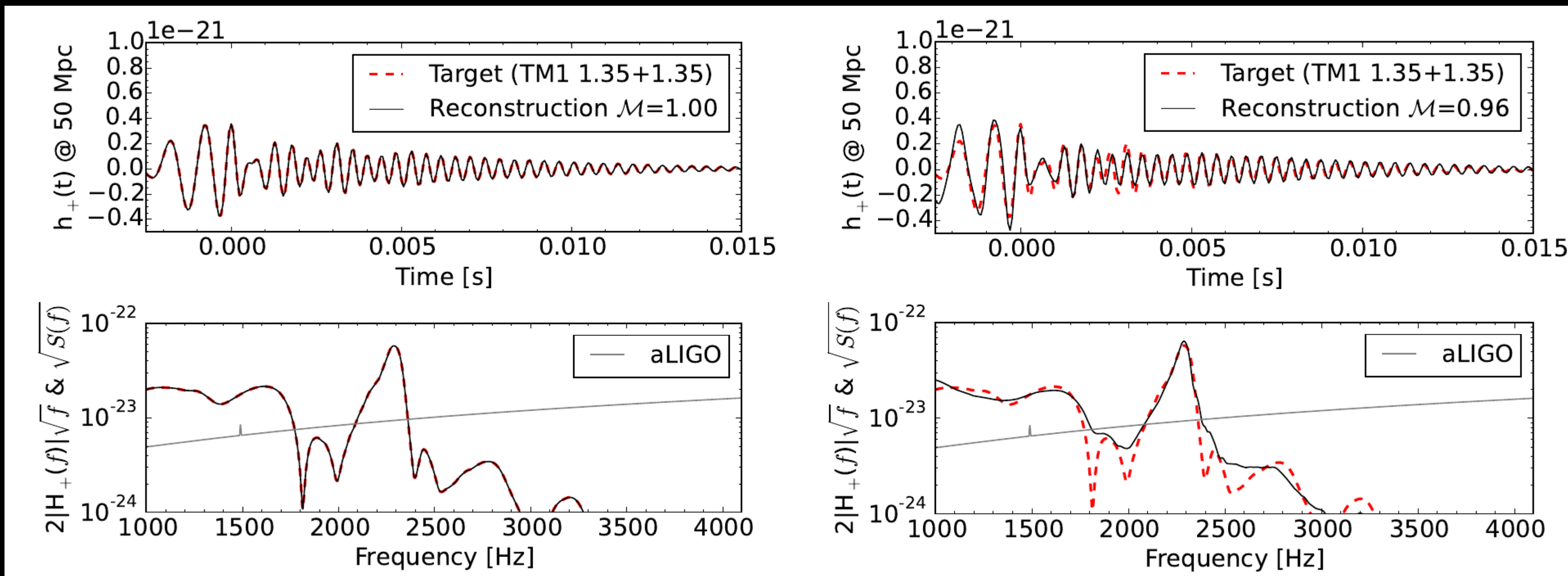
→ f_{peak} precisely measurable !!!

Bauswein et al. 2012, 2016

GW data analysis for postmerger

Data analysis

- Principal Component analysis



Excluding recovered waveform from catalogue

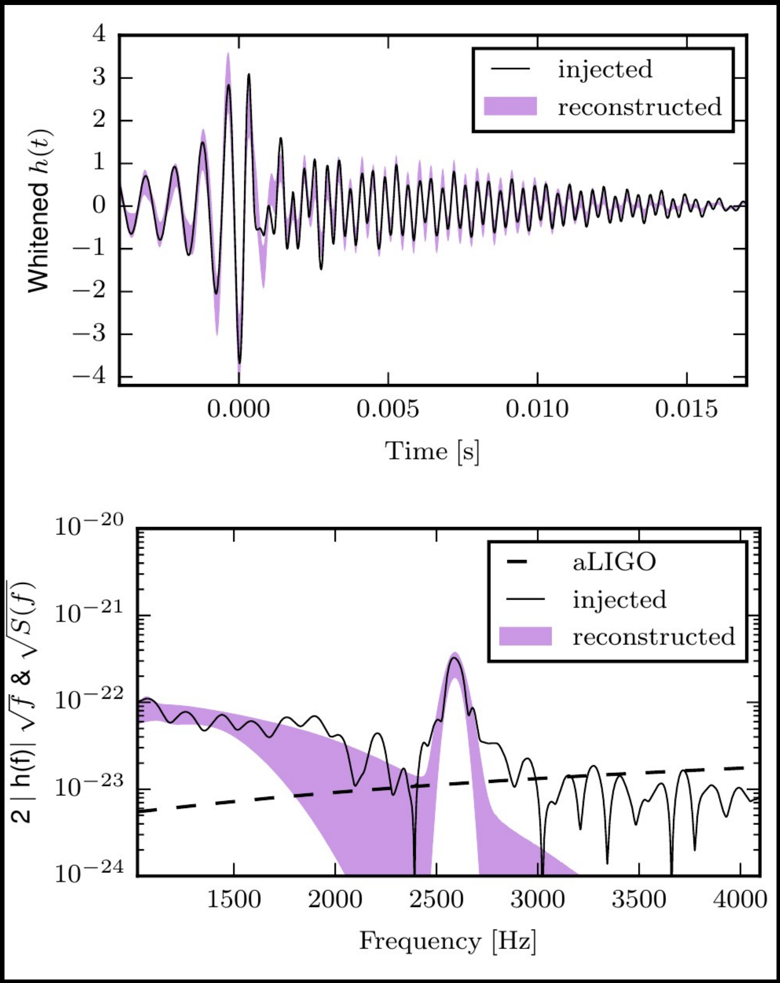
Clark et al. 2016, see also Clark et al 2014, Chatziioannou et al 2017, Bose et al. 2018

Instrument	$\mathrm{SNR}_{\mathrm{full}}$	D_{hor} [Mpc]	$\dot{\mathcal{N}}_{\mathrm{det}}$ [year^{-1}]
aLIGO	$2.99_{2.37}^{3.86}$	$29.89_{23.76}^{38.57}$	$0.01_{0.01}^{0.03}$
A+	$7.89_{6.25}^{10.16}$	$78.89_{62.52}^{101.67}$	$0.13_{0.10}^{0.20}$
LV	$14.06_{11.16}^{18.13}$	$140.56_{111.60}^{181.29}$	$0.41_{0.21}^{0.88}$
ET-D	$26.65_{20.81}^{34.28}$	$266.52_{208.06}^{342.80}$	$2.81_{1.33}^{5.98}$
CE	$41.50_{32.99}^{53.52}$	$414.62_{329.88}^{535.221}$	$10.59_{5.33}^{22.78}$

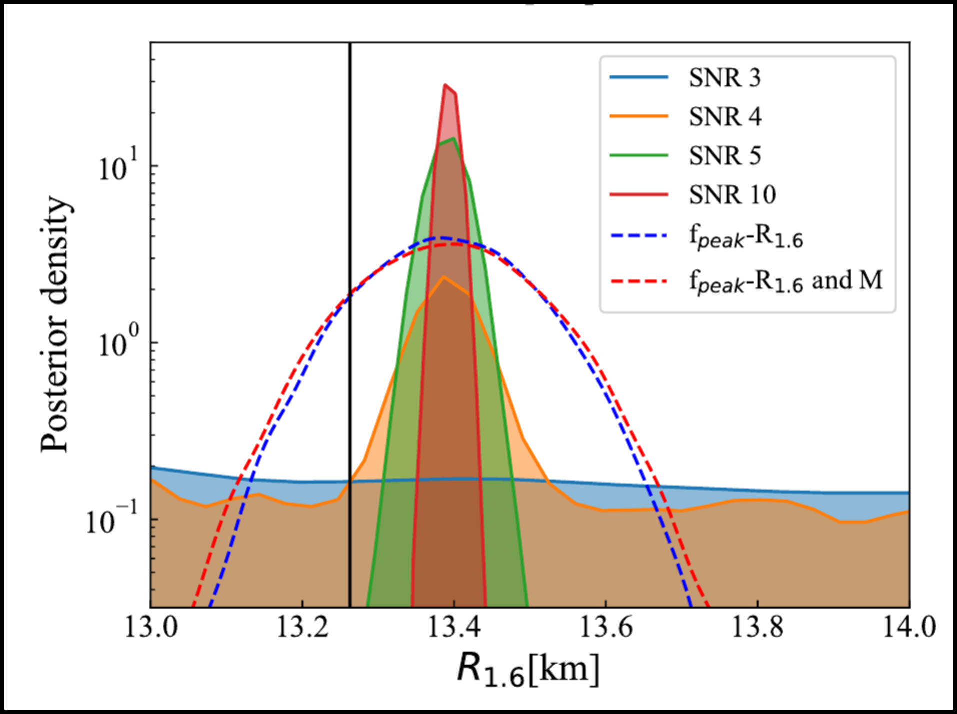
Outdated!!!

→ possible at Ad. LIGO's design sensitivity !

Model-agnostic data analysis

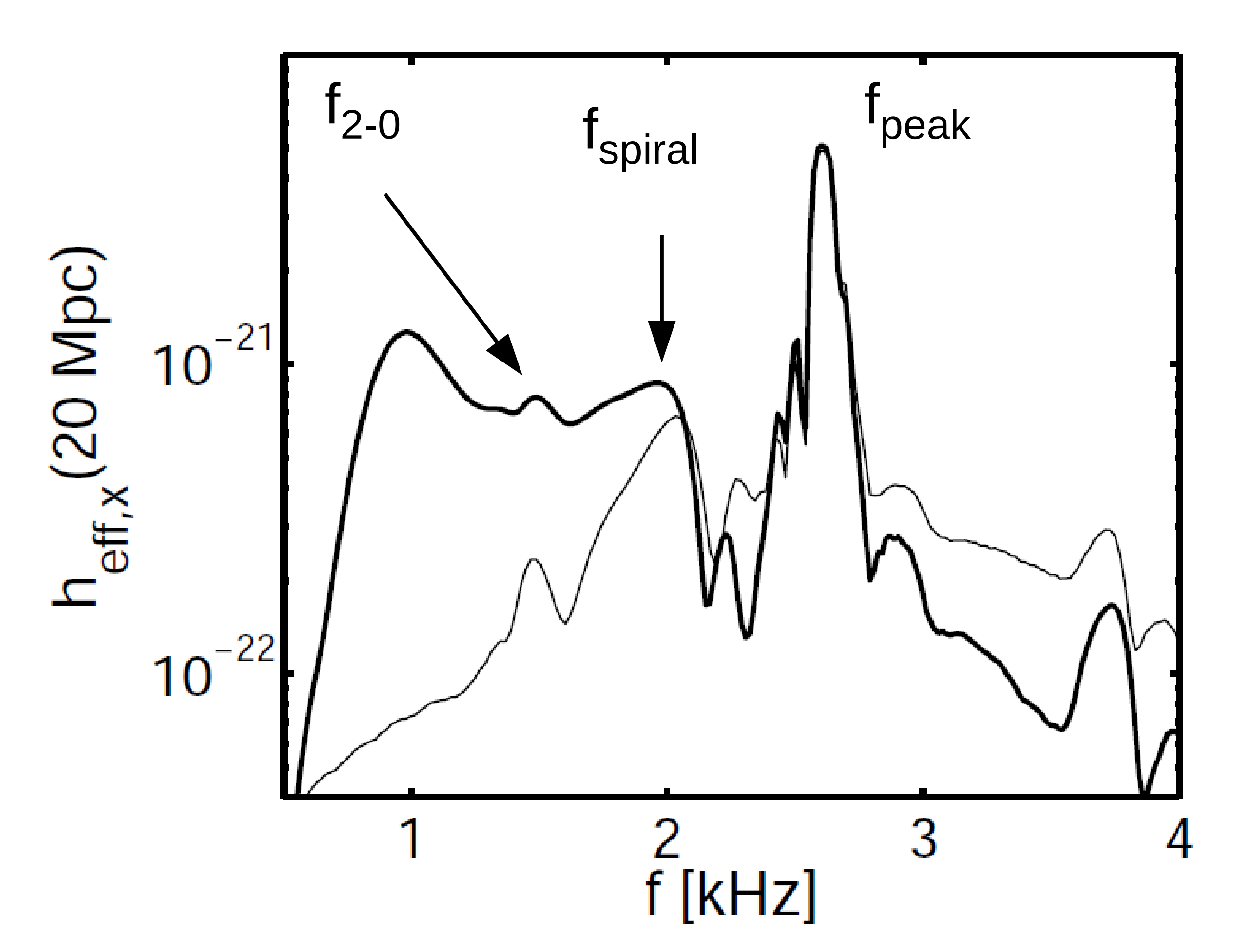


Based on wavelets (BayesWave)



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

Typical GW spectrum – secondary peaks



Two/three secondary peaks identfiied

- coupling between radial and quadrupolar mode
- transient tidal bulges

Secondary peaks

- Ns remnant is a rapidly rotating massive NS – many different oscillation modes excited
- Probe different regimes of the EoS / remnant

  → to date only some understood – linked to dynamical features

  → access dynamics of merger → relevant multi-messenger interpretation

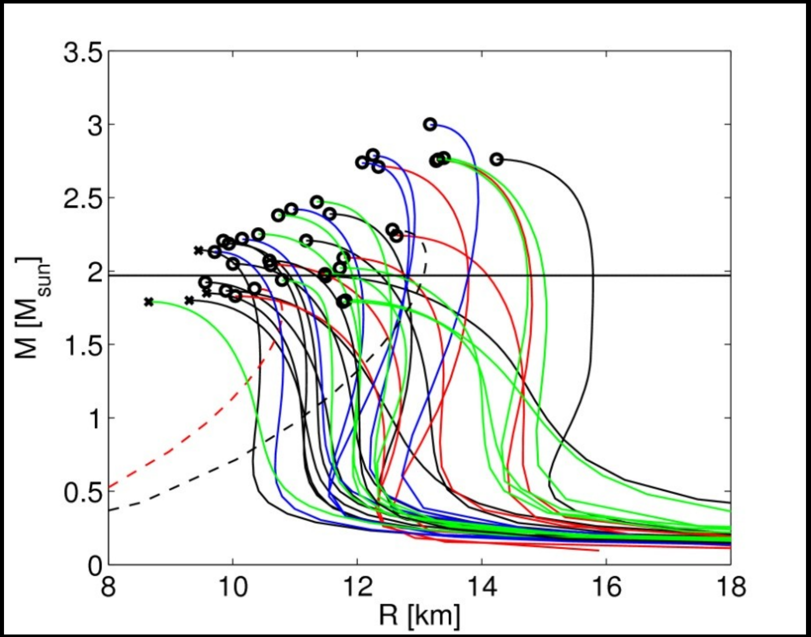
  → Although harder to measure: postmerger contains much richer information (compared to inspiral)

  → future: GW asteroseismology – exploit every measurable mode

  → kHz detectors highly important for NS and high-density matter physics !!

Maximum mass of NSs and collapse behavior of NS mergers

Maximum mass of NSs



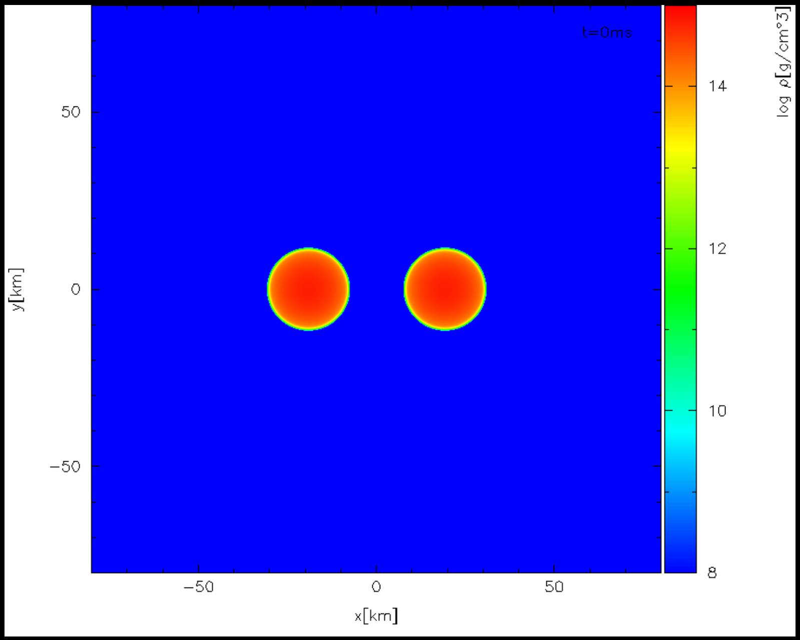
- Mmax* relevant for

  - astrophysics (supernovae, mass gap, …)

  - nuclear physics (probes very high-density regime)

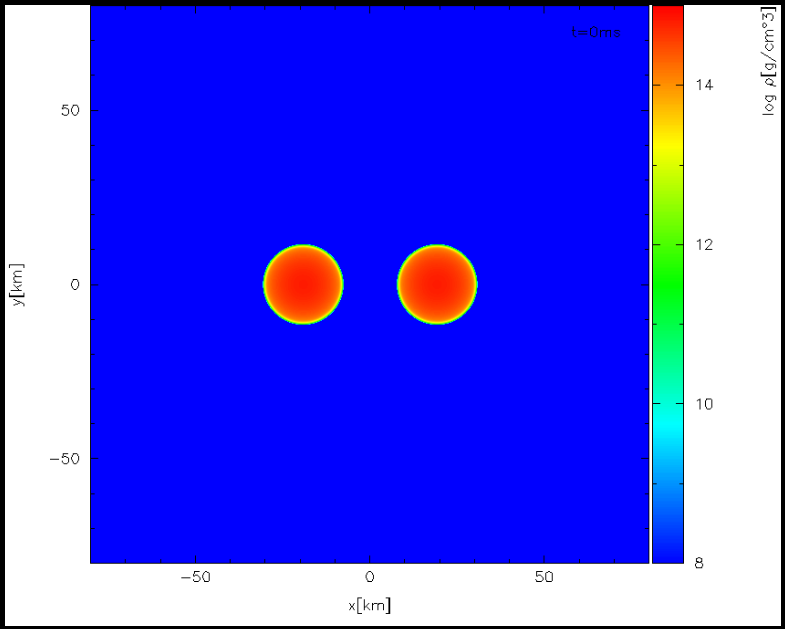
- Pulsar measurements accurate, but can only provide lower bound (current limit ~2 Msun)
- Other ideas to infer Mmax pretty model dependent

* maximum mass of nonrotating NSs (uniquely linked to EoS); fast rotation increases mass that can be supported against collapse (but depends on J)



$M_{\rm tot} = 3.4\ M_\odot$ ←

$M_{\rm tot} = 3.5\ M_\odot$ →



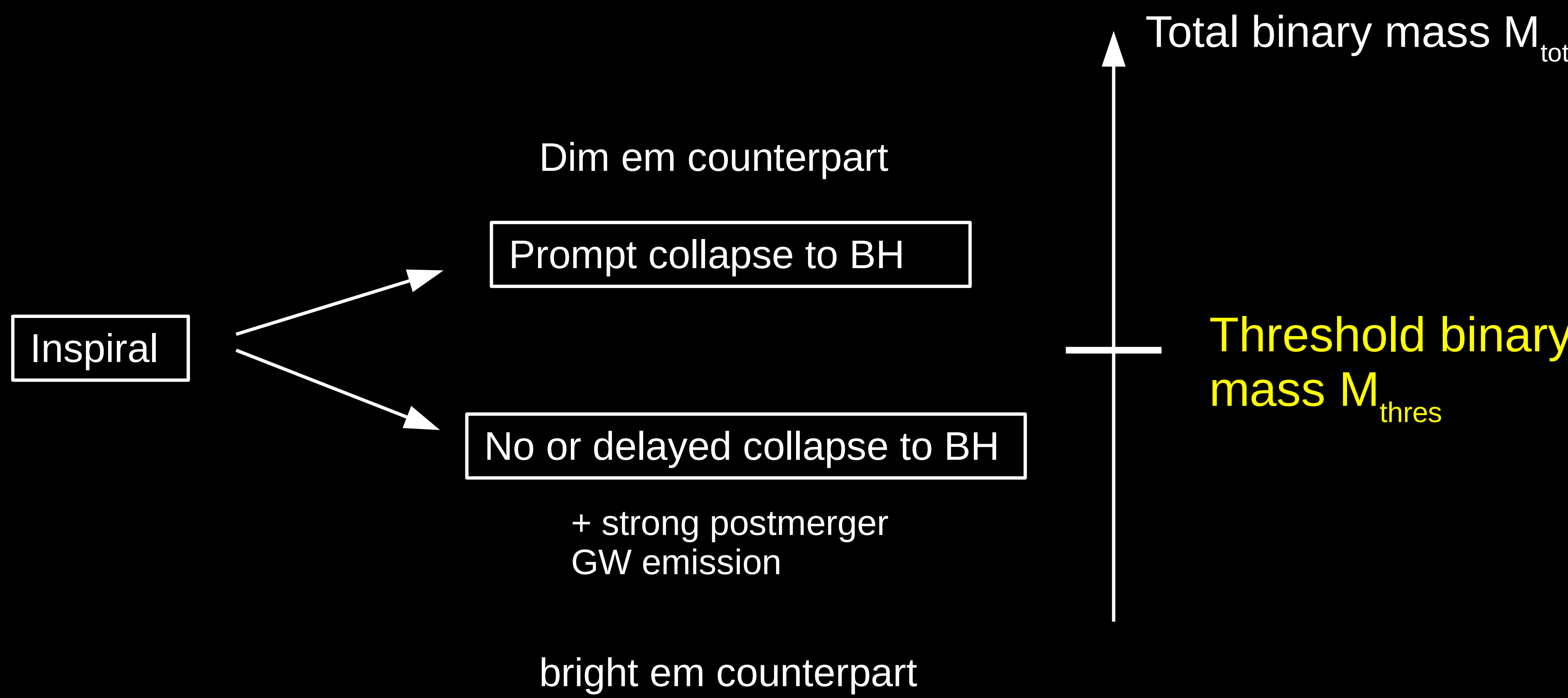
Shen EoS

$\longrightarrow\ M_{\rm thres} = (3.45 \pm 0.05)\ \ M_\odot$ (for this particular EoS)

Collapse behavior: Prompt vs. delayed (/no) BH formation

<u>Relevant for:</u> EoS constraints through M_{max} measurement, Conditions for short GRBs, Mass ejection, Electromagnetic counterparts powered by thermal emission, NS radius constraints !!!

Collapse behavior



EoS dependent - somehow M_{max} should play a role

Threshold binary mass

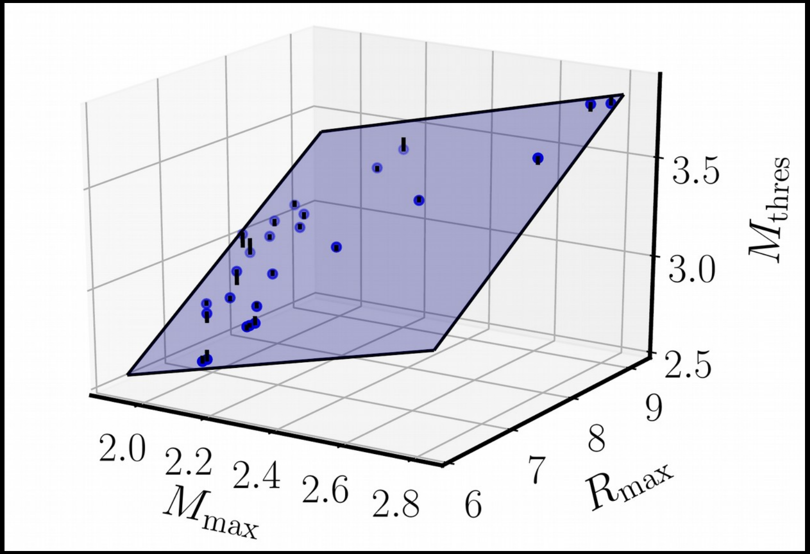
- Empirical relation from simulations with different M_{tot} and EoS
- Fits (to good accuracy):

$$M_{\mathrm{thres}} = M_{\mathrm{thres}}(M_{\mathrm{max}}, R_{\mathrm{max}}) = \left(-3.38\frac{GM_{\mathrm{max}}}{c^2 R_{\mathrm{max}}} + 2.43\right) M_{\mathrm{max}}$$

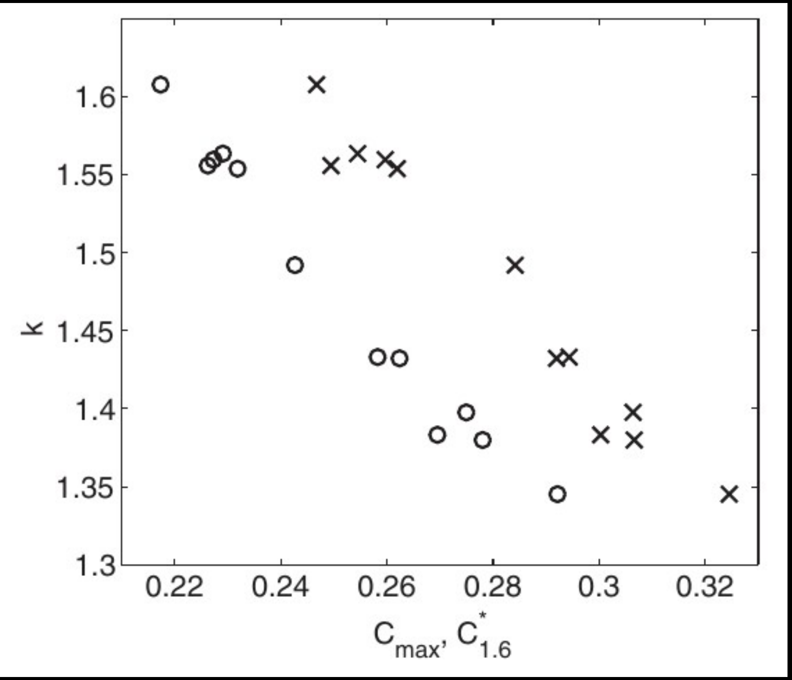
$$M_{\mathrm{thres}} = M_{\mathrm{thres}}(M_{\mathrm{max}}, R_{1.6}) = \left(-3.6\frac{G\,M_{\mathrm{max}}}{c^2\,R_{1.6}} + 2.38\right) M_{\mathrm{max}}$$

Bauswein et al 2013

- Both better than 0.06 M_{sun},



$$k = M_{\mathrm{thres}}/M_{\mathrm{max}}$$



Future: Maximum mass

- Empirical relation

$$M_{\mathrm{thres}} = \left(-3.6 \frac{G\, M_{\mathrm{max}}}{c^2\, R_{1.6}} + 2.38 \right)\, M_{\mathrm{max}}$$

- Sooner or later we'll know $R_{1.6}$ (e.g. from postmerger) and M_{thres} (from several events – through presense/absence of postmerger GW emission or em counterpart)

=> direct inversion to get precise estimate of M_{max}

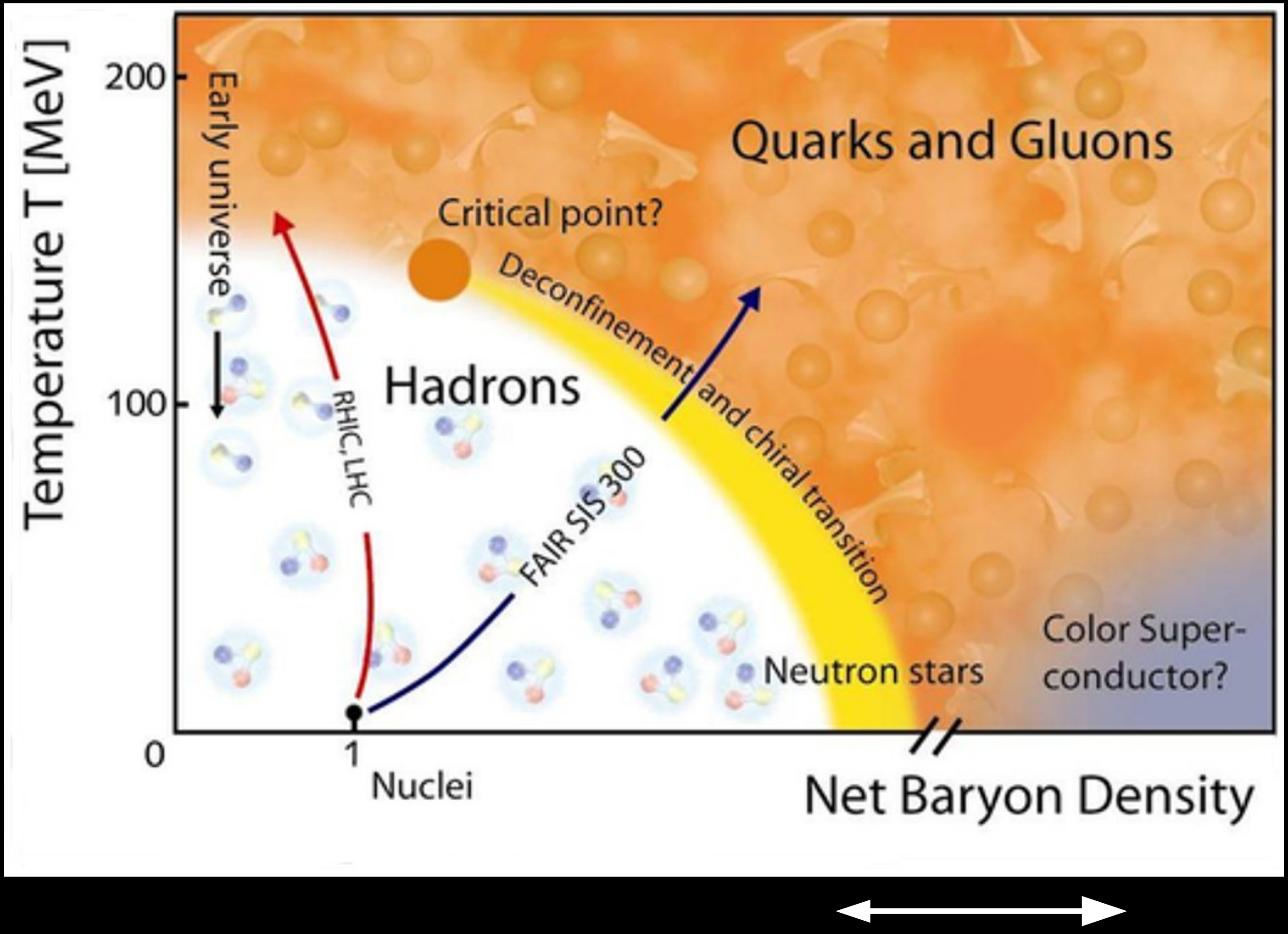
→ unique opportunity to robustly (!) measure M_{max}

→ also important for interpretation of em emission (kilonovae, GRBs, ...)

(see also current estimates e.g. by Margalit & Metzger, Rezzolla et al, Ruiz & Shapiro, Shibata et al., ...)

Signature of QCD phase transition

Phase diagram of matter



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

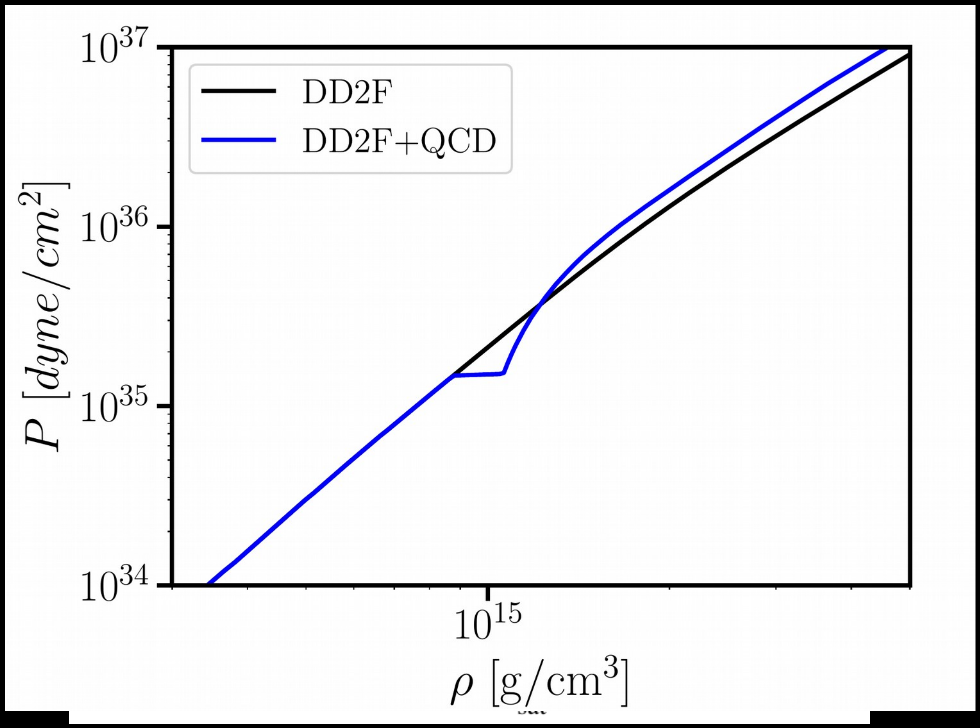
Remark

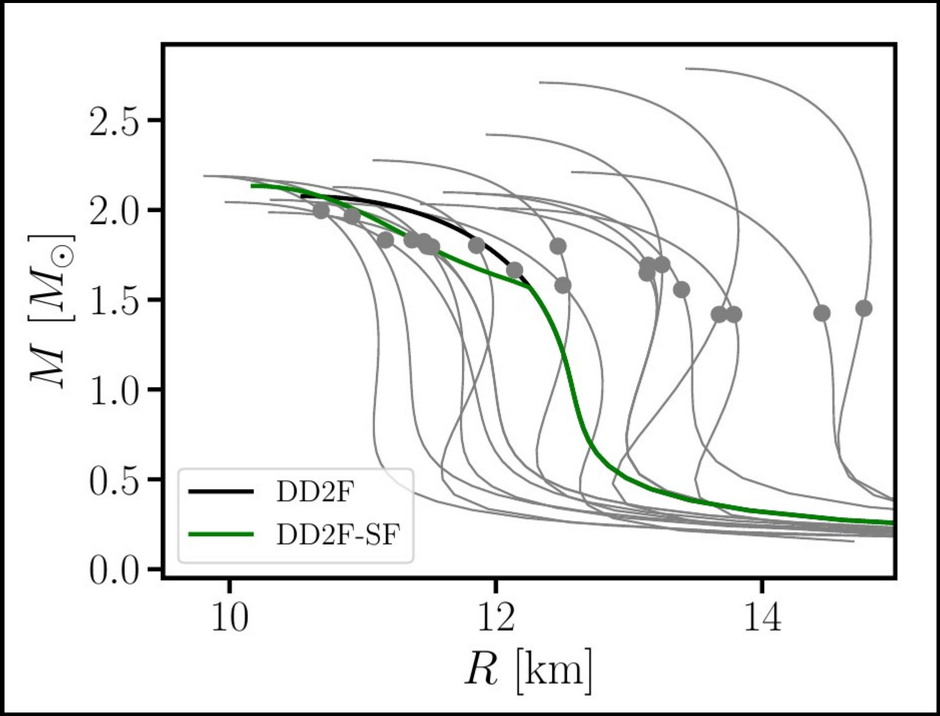
- Not just an academic question, but significant theoretical and experimental efforts !!

e.g. CBM experiment at FAIR (Darmstadt)

EoS with 1st-order phase transition to quark matter

Bauswein et al. 2019





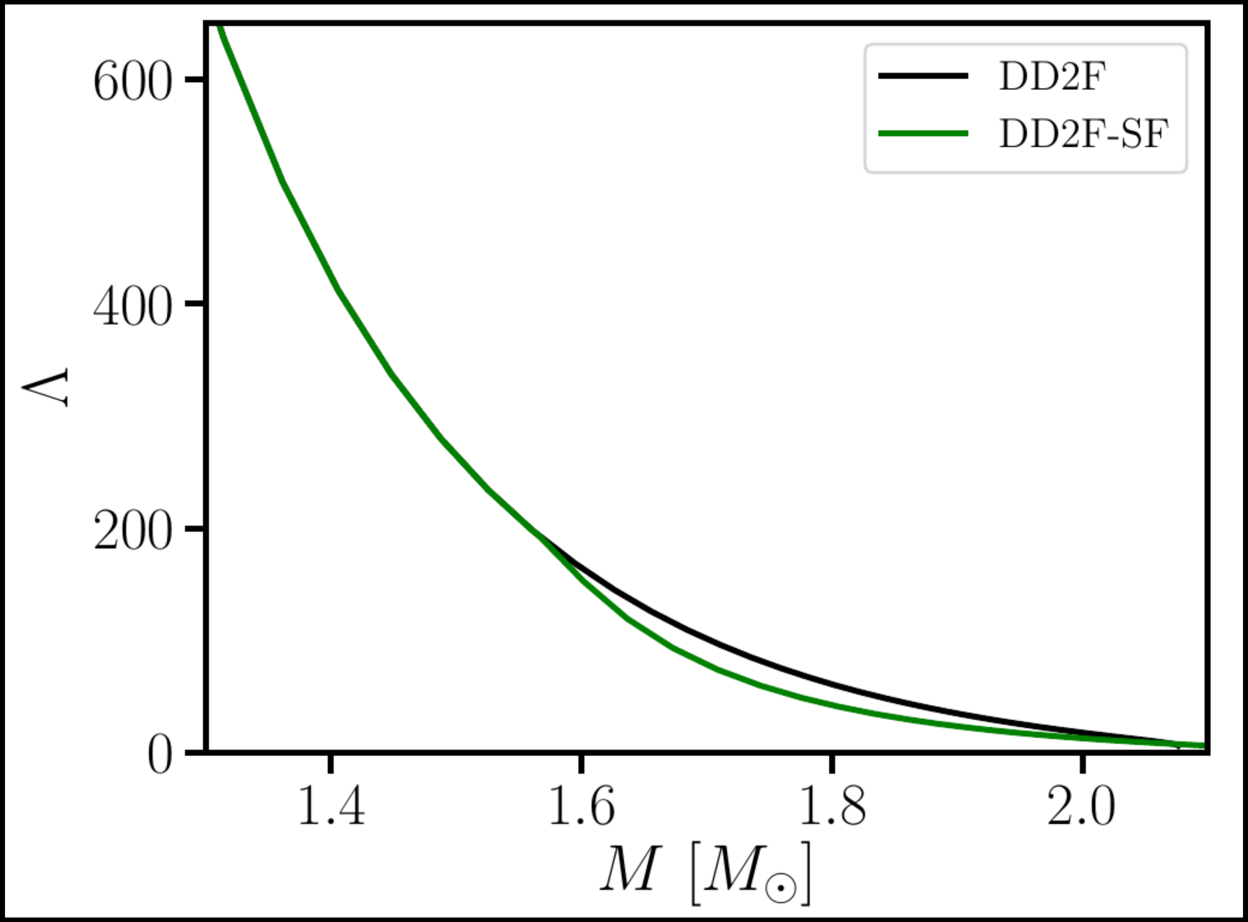
- EoS from Wroclaw group (Fischer, Bastian, Blaschke; see Fischer et al. 2018, Bastian et al 2018) – as one example for an EoS with strong 1st-order phase transition to deconfined quarks
- Phase transition from nuclear matter to deconfined quark matter → kink in mass-radius relation

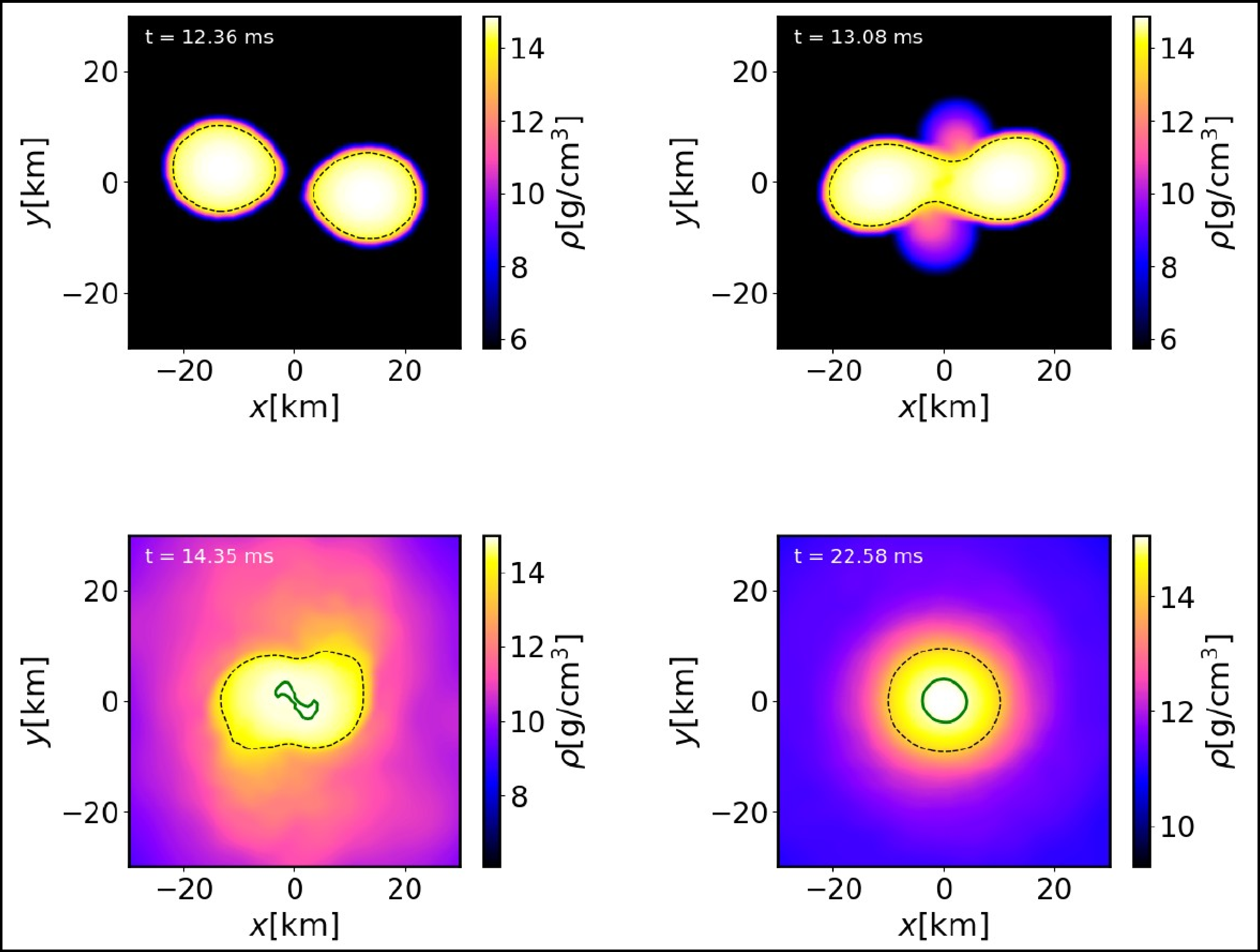
Phase transition

- 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

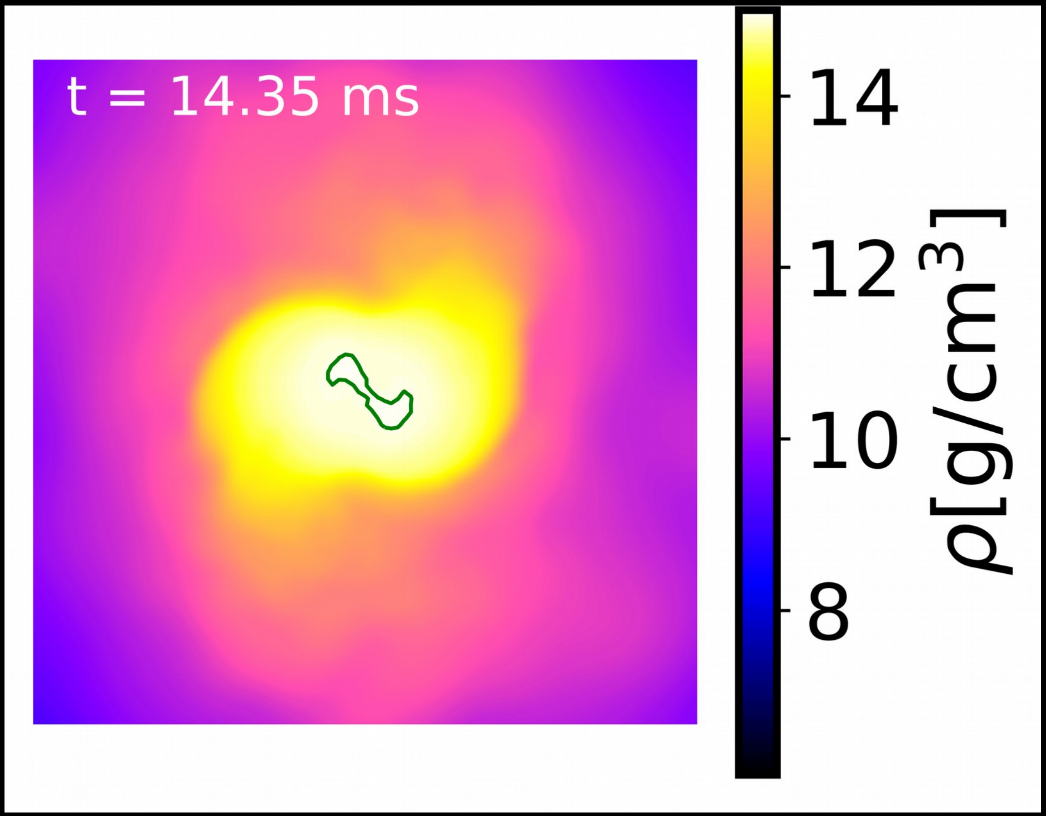


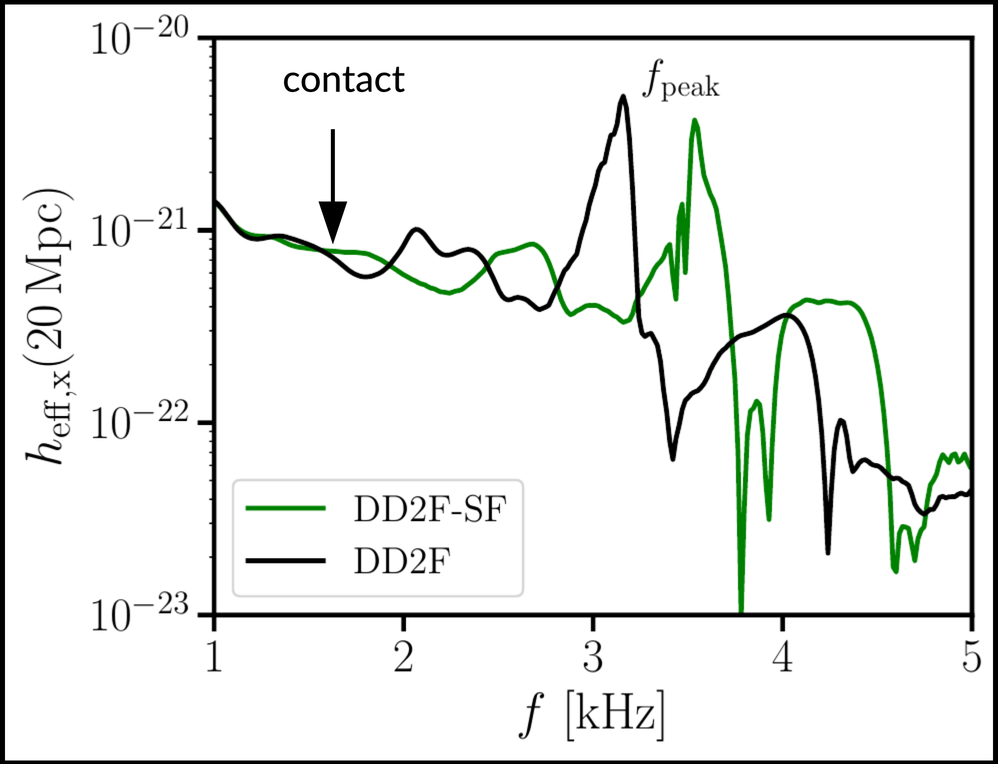


1.35-1.35 Msun - DD2F-SF-1

Merger simulations

- GW spectrum 1.35-1.35 Msun





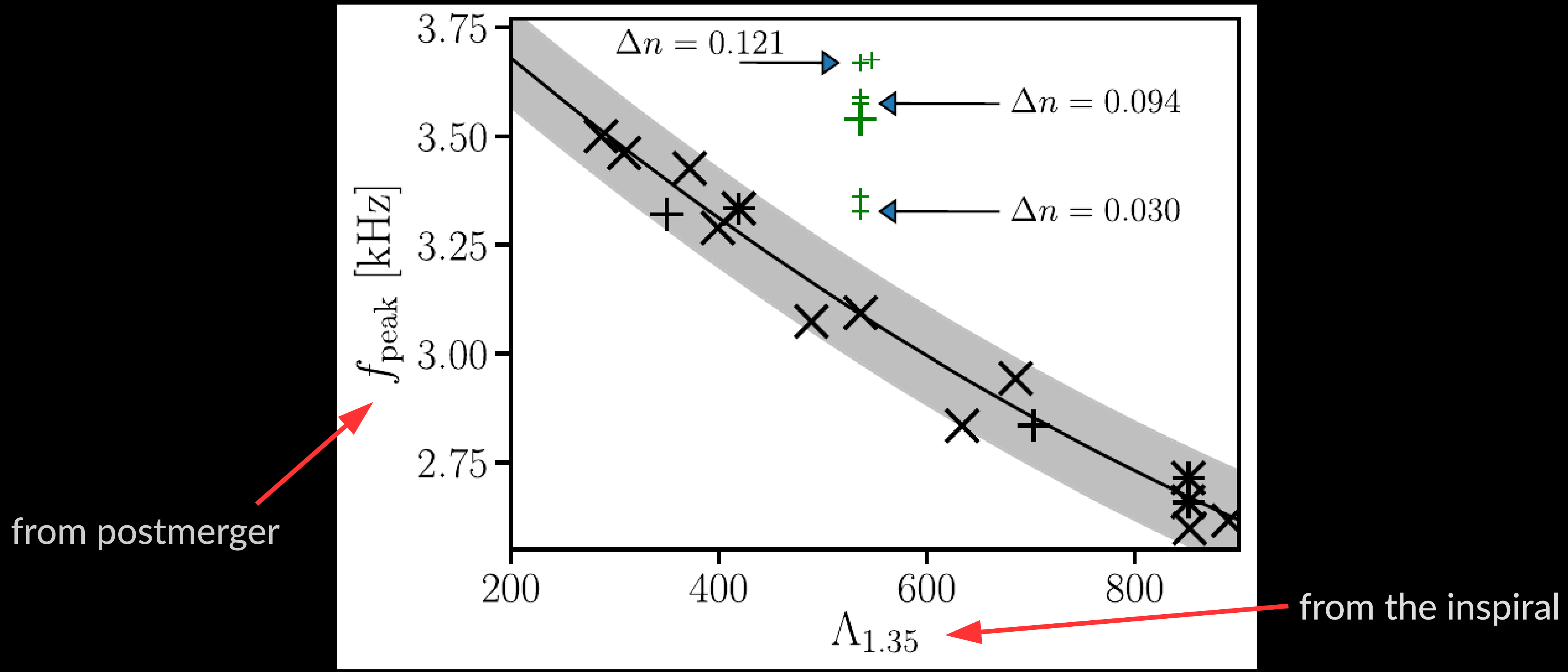
Bauswein et al. 2019

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



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

Discussion

- Consistency with fpeak-Lambda relation points to

  - purely baryonic EoS

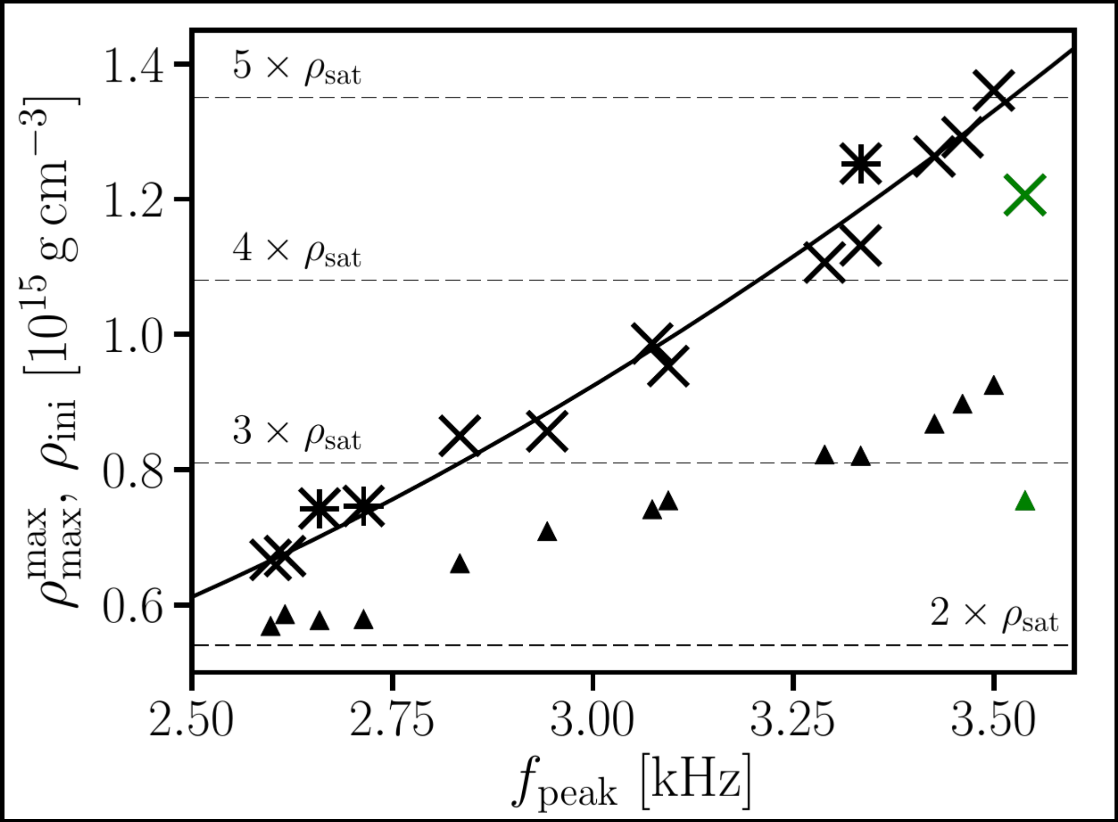
  in the tested (!) density regime $\rightarrow$ lower limit on transition density

- fpeak also determines maximum density in postmerger remnant

- postmerger GW emission provides complimentary information to inspiral

  $\rightarrow$ probes higher density regime

Bauswein et al. 2019



Summary and conclusions

- Postmerger contains rich information on properties of high-density EoS / NSs
- Dominat postmerger GW frequency scales with NS radii

  → robust and accurate radius measurements (especially of high-mass NSs)

  → complementary to inspiral (regarding methods and information)
- Long-term goal: GW asteroseismology understand full content of spectrum → probe different regimes of EoS
- Dynamics of remnant → multi-messenger interpretation, critical for em emission
- kHz emission crucial to determine Mmax (hard otherwise) → very high density regime
- GW data analysis methods available and continuously improved
- Identify or exclude presence of QCD phase transition

→ unique and very important science in the kHz range (not only for astrophysics)