Supported by ERC through Starting Grant no. 759253

European Research Council
Established by the European Commission

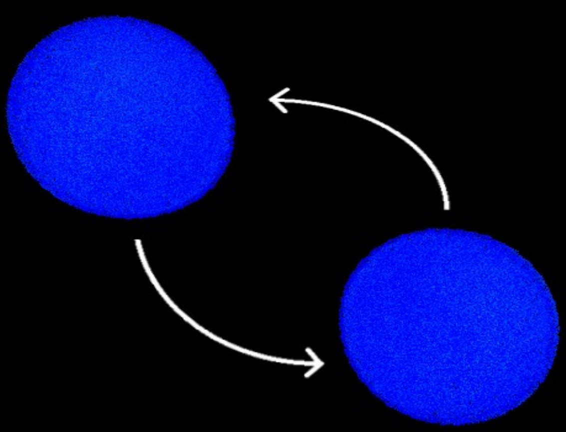
Neutron star mergers and the high-density equation of state

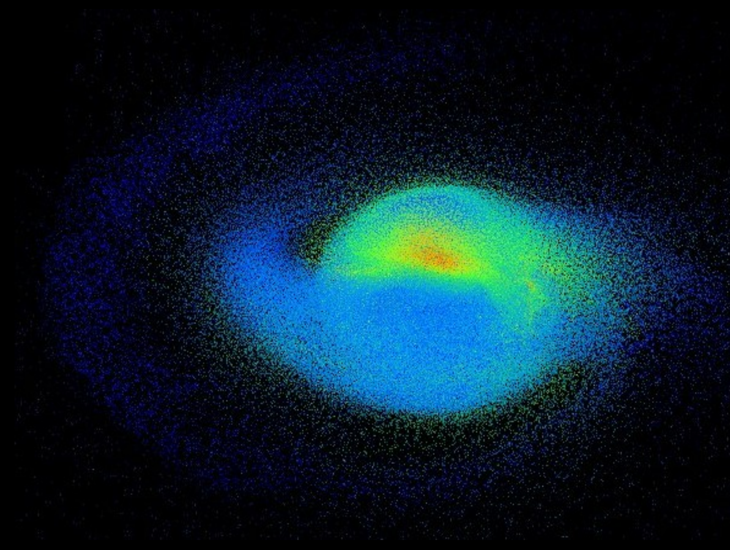
Astrophysics with GW detections

Warsaw, 07/09/2019

Andreas Bauswein

(GSI Darmstadt)





Outline

- Motivation and overview
- Multi-messenger interpretation of GW170817 → lower limit on NS radii

  → Collapse behavior (EoS dependence of BH formation)
- Postmerger GW emission
- Signatures of the QCD phase transition

Motivation: Neutron stars and the EoS

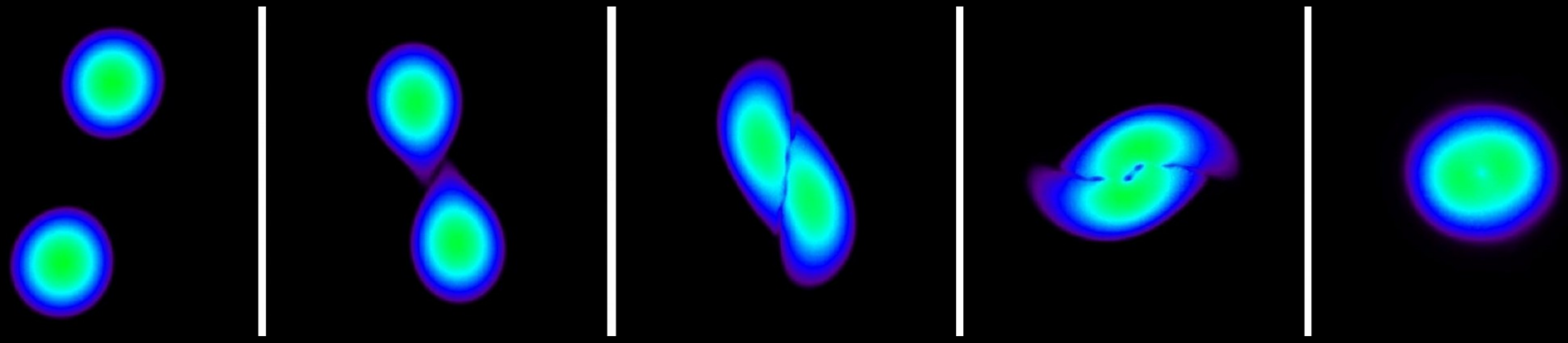
- Nuclear many-body problem hard to solve (some approximations required)
- Nuclear interactions not precisely known, especially at higher densities
- Fundamental contituents of NSs not known: pure nuclear matter, hyperons, ..., possibly phase transition to deconfined quark matter

→ high-density EoS not precisely known

↔ stellar structure of NSs not precisely known - density profile, radii, tidal deformability, maximum mass ???

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

Finite-size effects during late inspiral



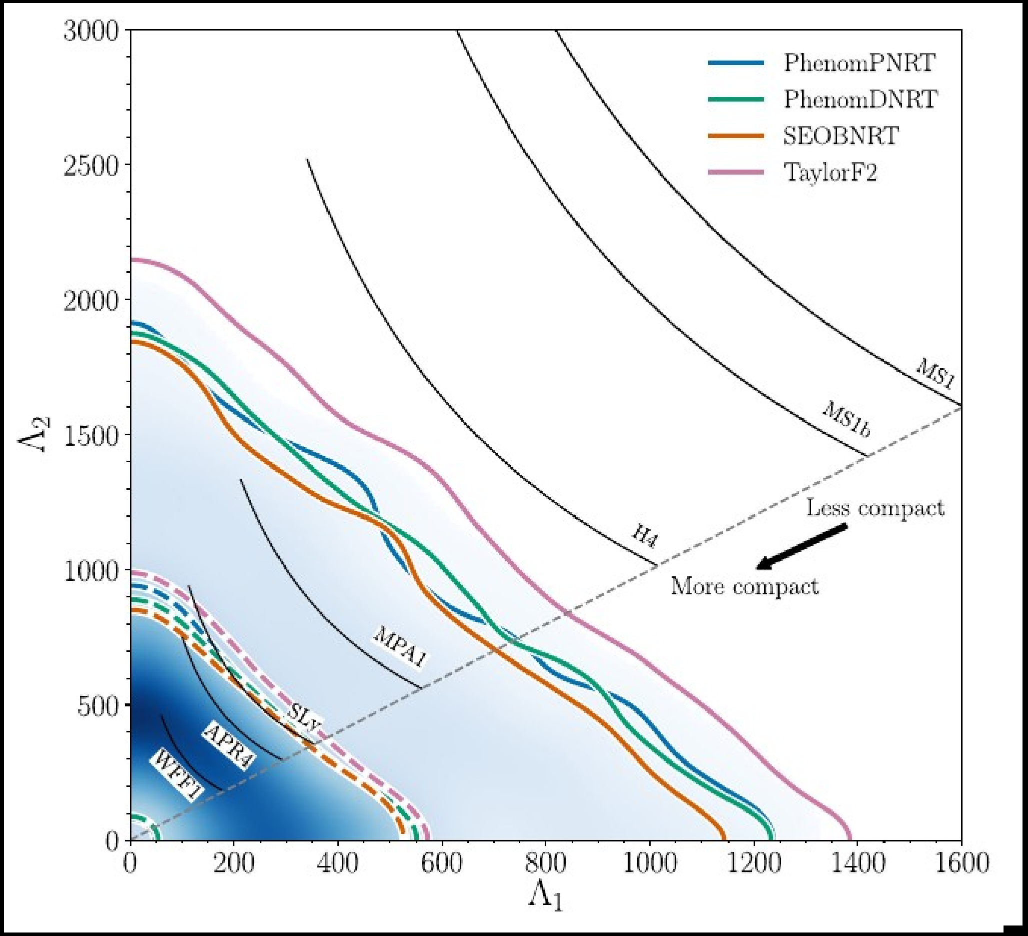
Measurement

- Lambda < ~650

  → Means that very stiff EoSs are excluded

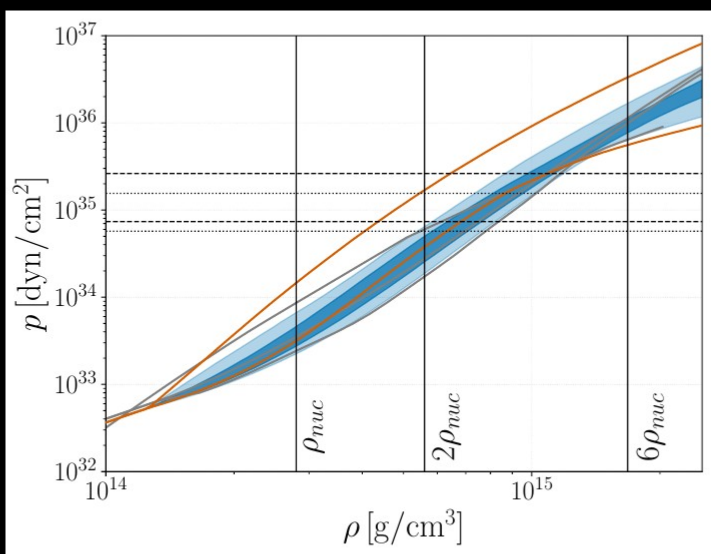
- Somewhat model-dependent
- Better constraints expected in future as sensitivity increases

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

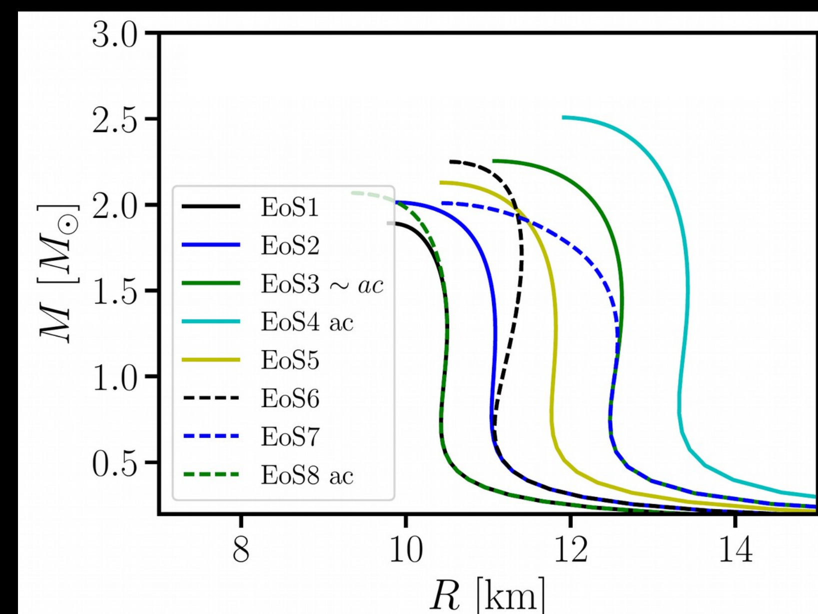


Abbott et al. 2017, 2019
see also later publications by Ligo/Virgo collaboration, De et al. 2018

- Current constraints from LIGO/Virgo through tidal effects during inspiral
- Recall strong correlation between tidal deformability and NS radius
- Current constraints roughly compatible with current knowledge from chiral EFT (depending on cut off, e.g. Tews et al 2018)

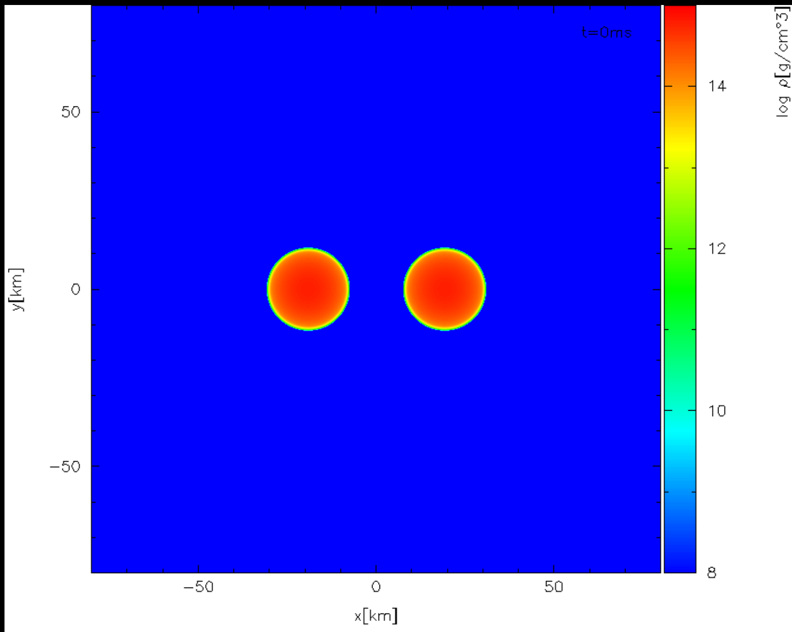


Ligo/Virgo collaboration 2018



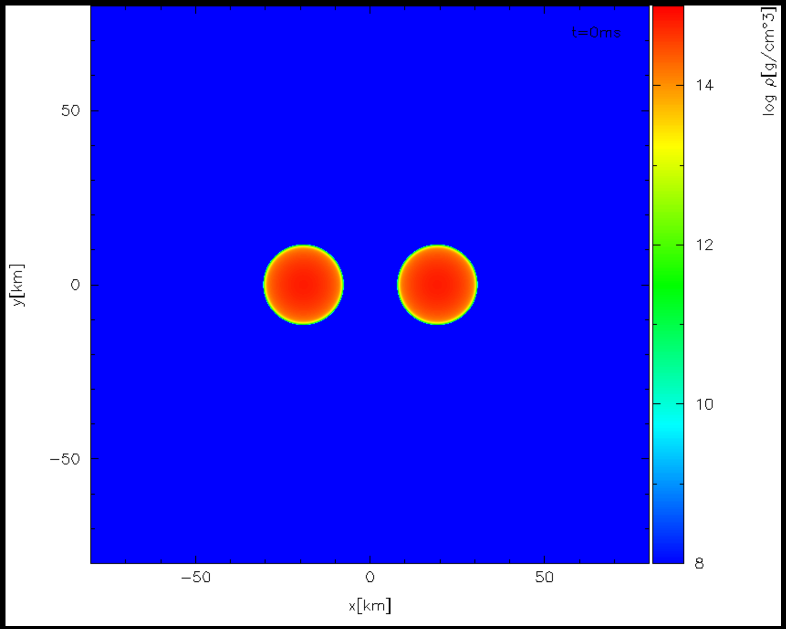
Torres-Riva et al 2019

Collapse behavior and multi-messenger EoS constraints



$M_{tot} = 3.4\ M_\odot$ ←

$M_{tot} = 3.5\ M_\odot$ →



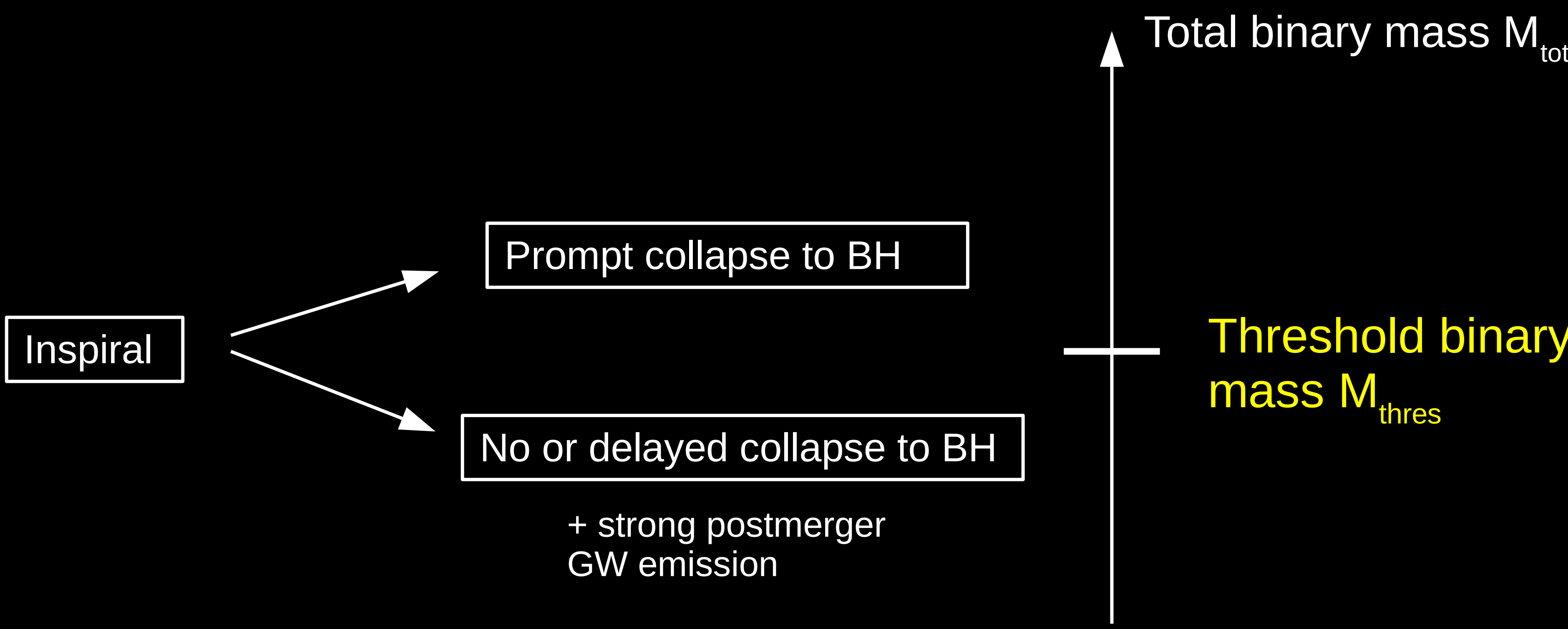
Shen EoS

$\longrightarrow\ M_{thres} = (3.45 \pm 0.05)\ M_\odot$ (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

Simulations reveal M_{thres}

TOV properties of nonrotating stars, i.e. EoS characteristics

Merger property from simulations

EoS	M_{max} ($M_\odot$)	R_{max} (km)	C_{max}	$R_{1.6}$ (km)	M_{thres} ($M_\odot$)
NL3 [37,38]	2.79	13.43	0.307	14.81	3.85
GS1 [39]	2.75	13.27	0.306	14.79	3.85
LS375 [40]	2.71	12.34	0.325	13.71	3.65
DD2 [38,41]	2.42	11.90	0.300	13.26	3.35
Shen [42]	2.22	13.12	0.250	14.46	3.45
TM1 [43,44]	2.21	12.57	0.260	14.36	3.45
SFHX [45]	2.13	10.76	0.292	11.98	3.05
GS2 [46]	2.09	11.78	0.262	13.31	3.25
SFHO [45]	2.06	10.32	0.294	11.76	2.95
LS220 [40]	2.04	10.62	0.284	12.43	3.05
TMA [44,47]	2.02	12.09	0.247	13.73	3.25
IUF [38,48]	1.95	11.31	0.255	12.57	3.05

Bauswein et al. 2013

Smooth particle hydrodynamics + conformal flatness

Threshold binary mass

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

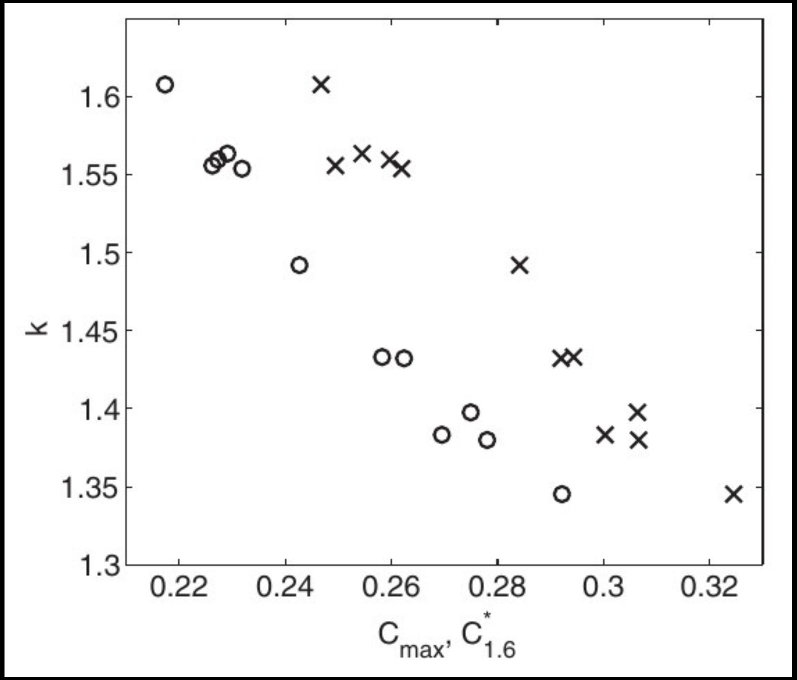
$$M_{\mathrm{thres}} = M_{\mathrm{thres}}(M_{\mathrm{max}}, R_{\mathrm{max}}) = \left(-3.38\frac{GM_{\mathrm{max}}}{c^2 R_{\mathrm{max}}} + 2.43\right) M_{\mathrm{max}}$$

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

- Both better than 0.06 M_{sun},

  (meanwhile more ~20 models)

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



Bauswein et al 2013

EoS constraints from GW170817*

→ lower bound on NS radii

(recall: upper bound from tidal deformability)

* See also Margalit & Metzger 2017, Shibata et al. 2017, Radice et al. 2018, Rezzolla et al. 2018, Ruiz & Shapiro 2018, ... for other EoS constraints in the context of GW170817

A simple but robust NS radius constraint from GW170817

- High ejecta mass inferred from electromagnetic transient
  (high compared to simulations)
  → provides strong support for a delayed/no collapse in GW170817
  → even asymmetric mergers that directly collapse do not produce such massive ejecta

Reference	$m_{\rm dyn}$ $[M_\odot]$	$m_{\rm w}$ $[M_\odot]$
Abbott et al. (2017a)	$0.001 - 0.01$	–
Arcavi et al. (2017)	–	$0.02 - 0.025$
Cowperthwaite et al. (2017)	0.04	0.01
Chornock et al. (2017)	0.035	0.02
Evans et al. (2017)	$0.002 - 0.03$	$0.03 - 0.1$
Kasen et al. (2017)	0.04	0.025
Kasliwal et al. (2017b)	> 0.02	> 0.03
Nicholl et al. (2017)	0.03	–
Perego et al. (2017)	$0.005 - 0.01$	$10^{-5} - 0.024$
Rosswog et al. (2017)	0.01	0.03
Smartt et al. (2017)	$0.03 - 0.05$	0.018
Tanaka et al. (2017a)	0.01	0.03
Tanvir et al. (2017)	$0.002 - 0.01$	0.015
Troja et al. (2017)	$0.001 - 0.01$	$0.015 - 0.03$

Compilation in Cote et al 2018

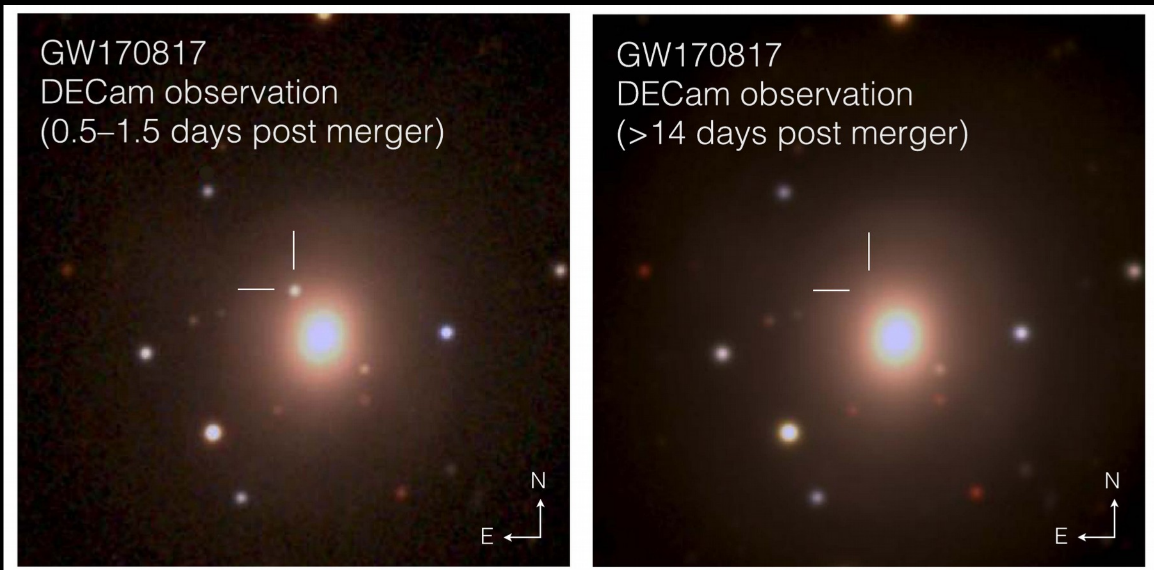
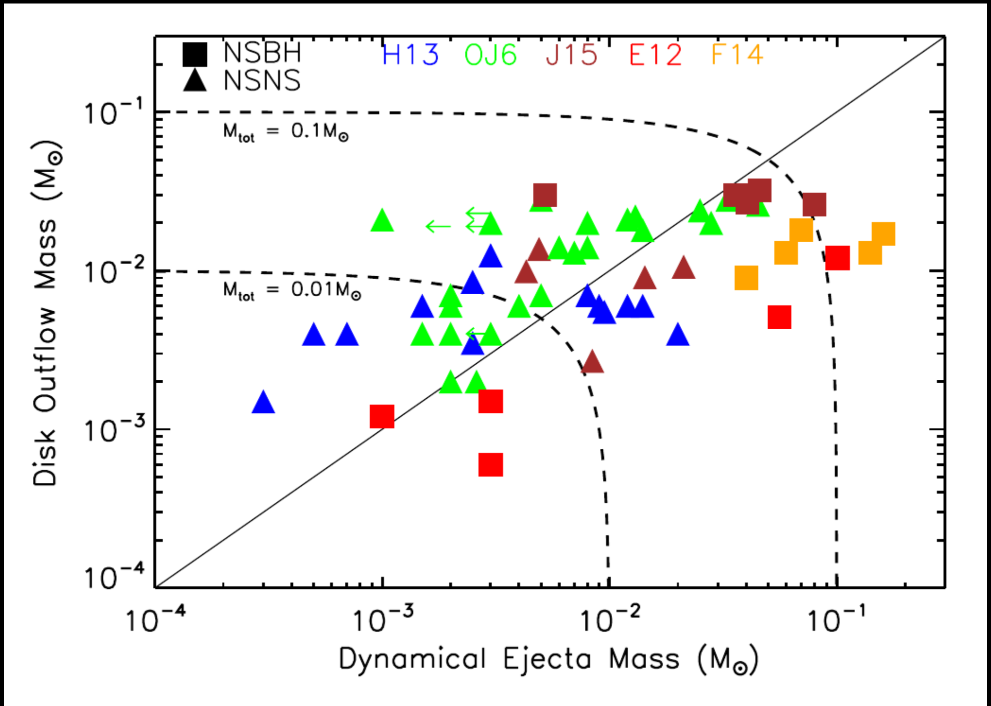


Figure 1. NGC4993 *grz* color composites (1.′5 × 1.′5). Left: composite of detection images, including the discovery *z* image taken on 2017 August 18 00:05:23 UT and the g and r images taken 1 day later; the optical counterpart of GW170817 is at R.A., decl. =197.450374, −23.381495. Right: the same area two weeks later.

Soares-Santos et al 2017

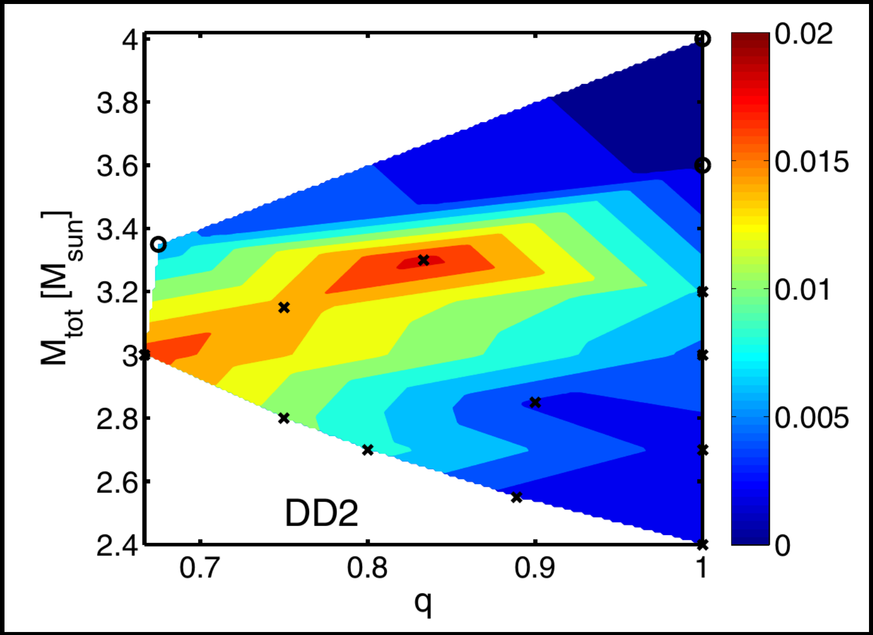
- Ejecta masses depend on EoS and binary masses
- Note: high mass points already to soft EoS (tentatively/qualitatively)
- Prompt collapse leads to reduced ejecta mass
- Light curve depends on ejecta mass:

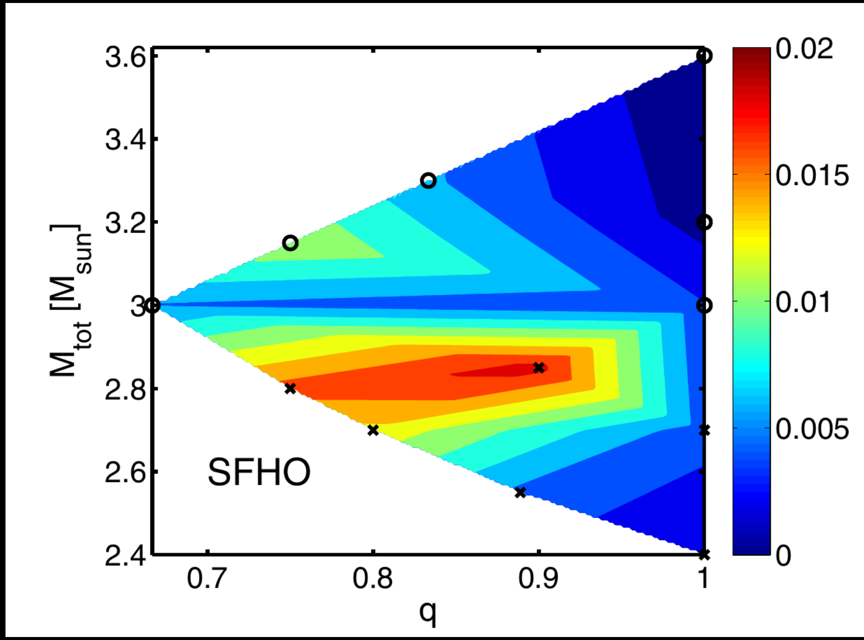
→ 0.02 - 0.05 M_{sun} point to delayed collapse



Compilation Wu et al 2016: dynamical and secular ejecta comparable

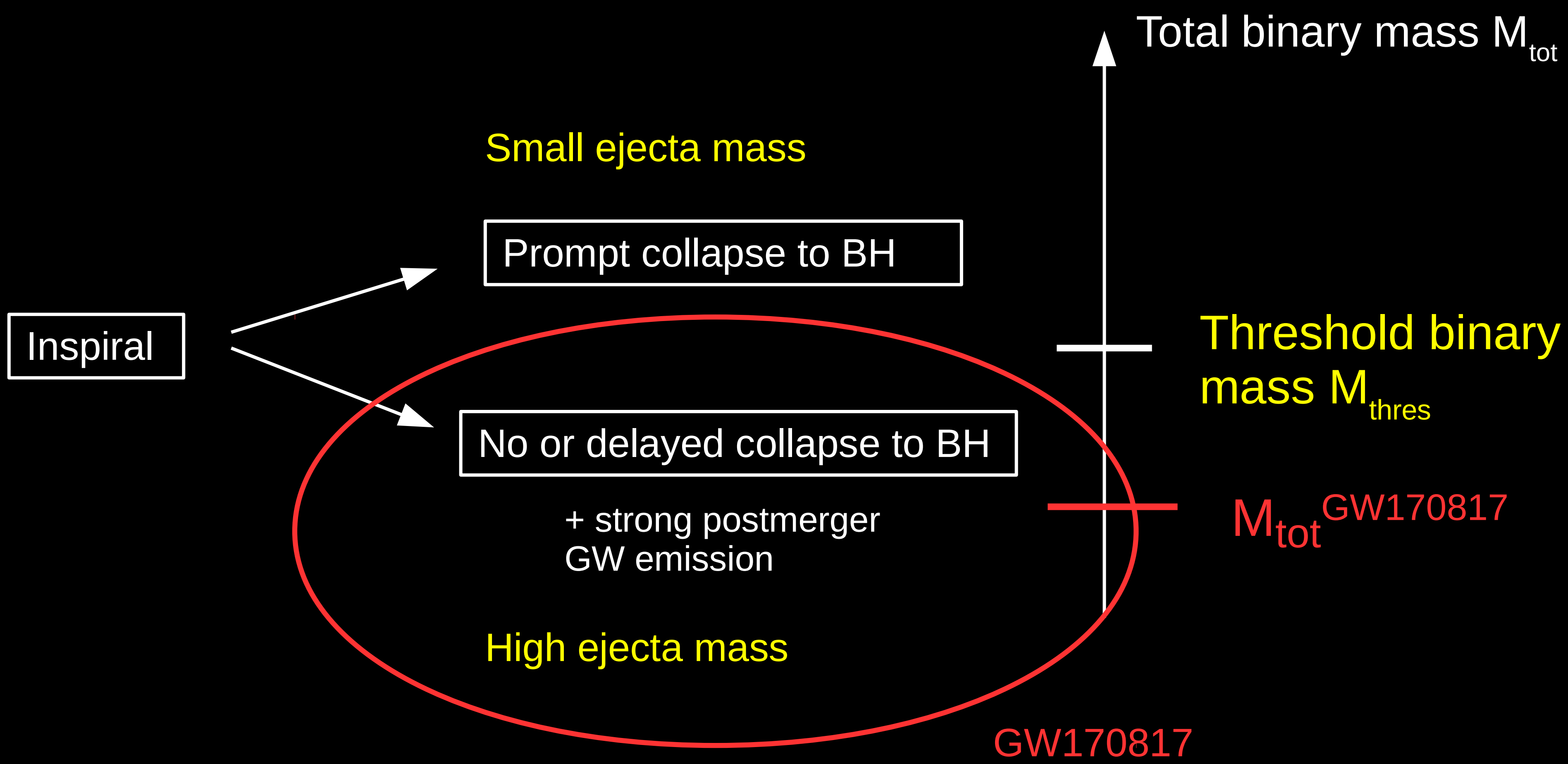
Only dynamical ejecta





Bauswein et al. 2013

Collapse behavior



(1) If GW170817 was a delayed (/no) collapse:

$$M_{\rm thres} > M_{\rm tot}^{GW170817}$$

(2) Recall: empirical relation for threshold binary mass for prompt collapse:

$$M_{\rm thres} = \left(-3.38\frac{G\, M_{\rm max}}{c^2\, R_{\rm max}} + 2.43\right)\, M_{\rm max} > 2.74\ M_\odot$$

(with M_{max}, R_{max} unknown)

(3) Causality: speed of sound $v_S \leq c$

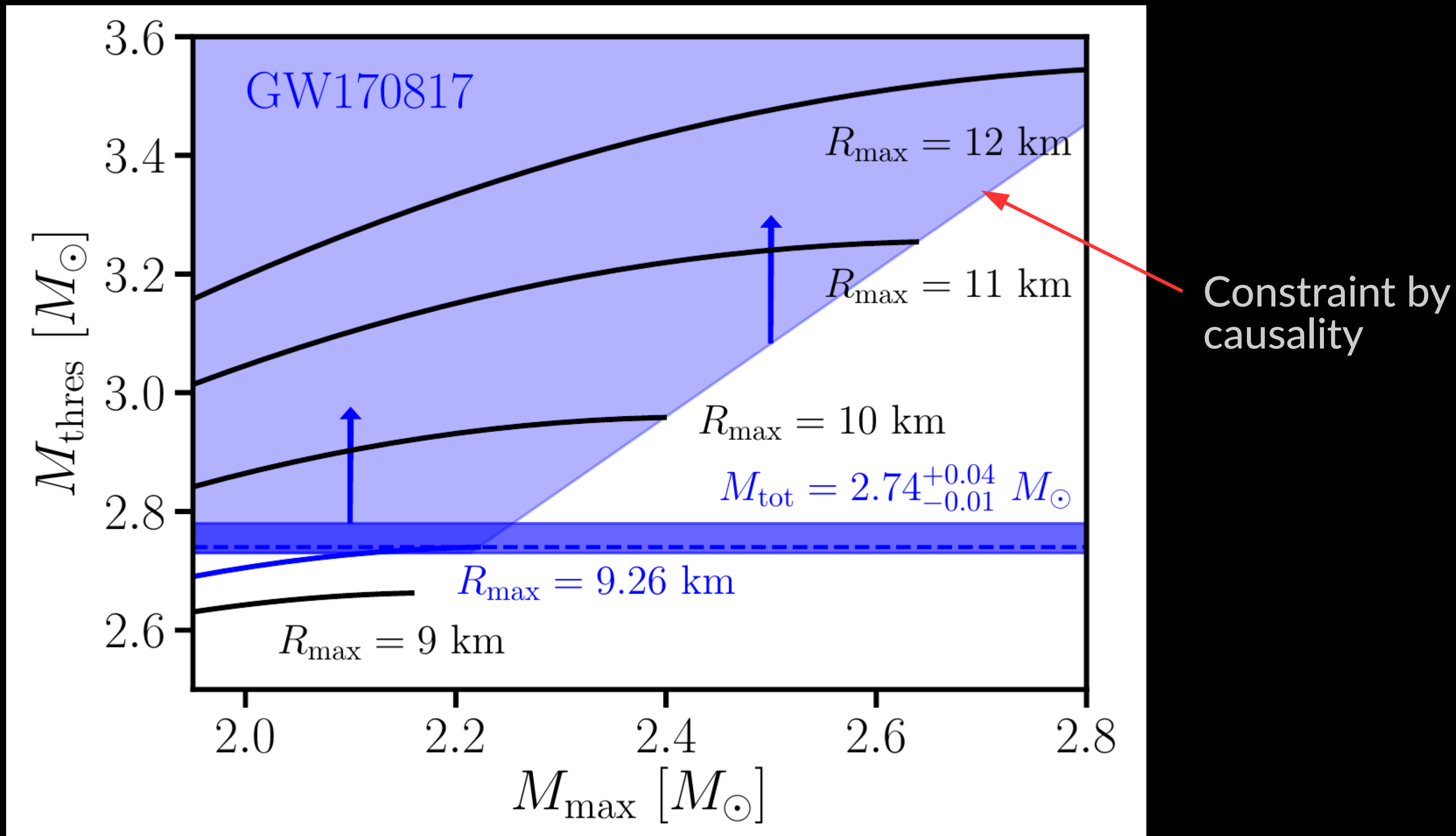
$$\Rightarrow M_{\rm max} \leq \frac{1}{2.82}\frac{c^2\, R_{\rm max}}{G}$$

- Putting things together:

$$M_{\rm tot}^{GW170817} \leq \left(-3.38\frac{G\, M_{\rm max}}{c^2\, R_{\rm max}} + 2.43\right) M_{\rm max} \leq \left(-\frac{3.38}{2.82} + 2.43\right)\frac{1}{2.82}\frac{c^2\, R_{\rm max}}{G}$$

→ Lower limit on NS radius

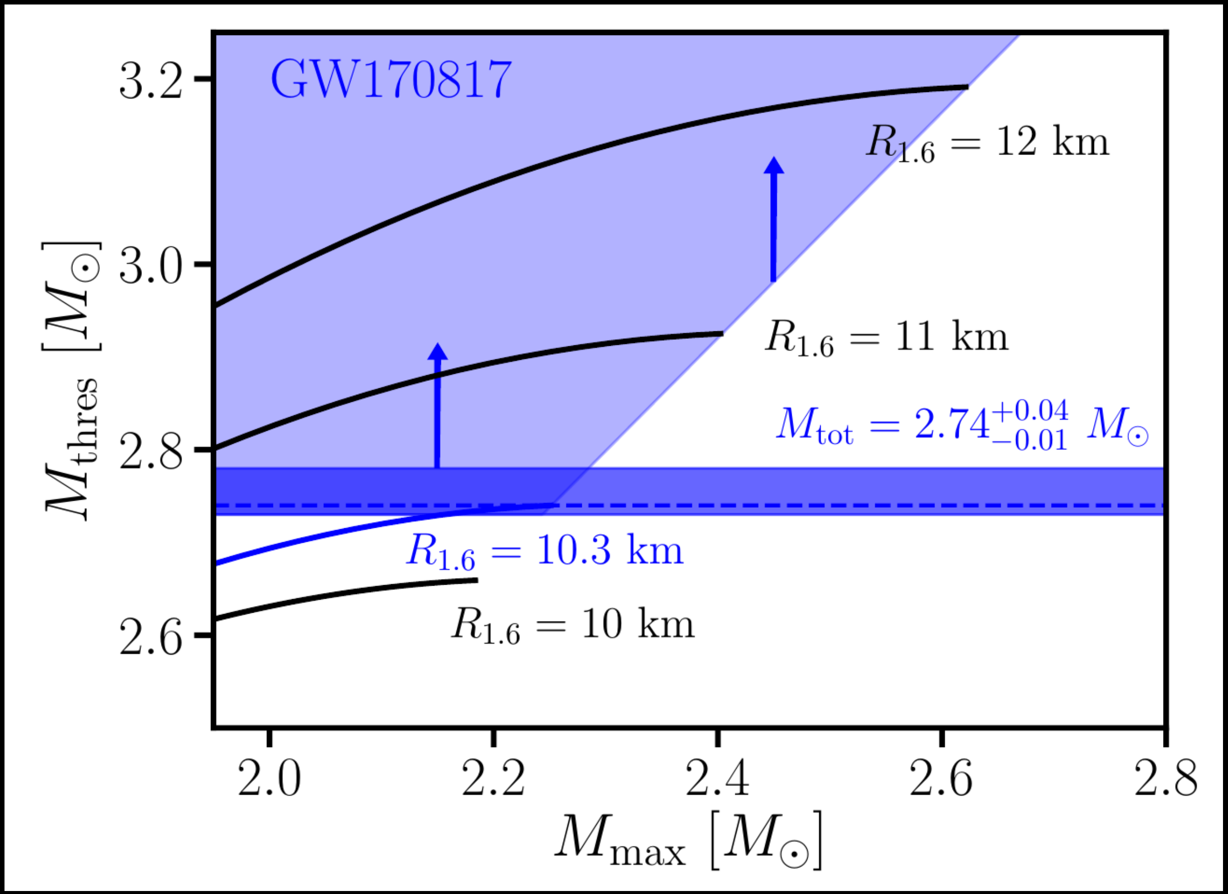
Bauswein et al. 2017



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

$$M_{\rm thres} \geq 1.2 M_{\max}$$

Bauswein et al. 2017

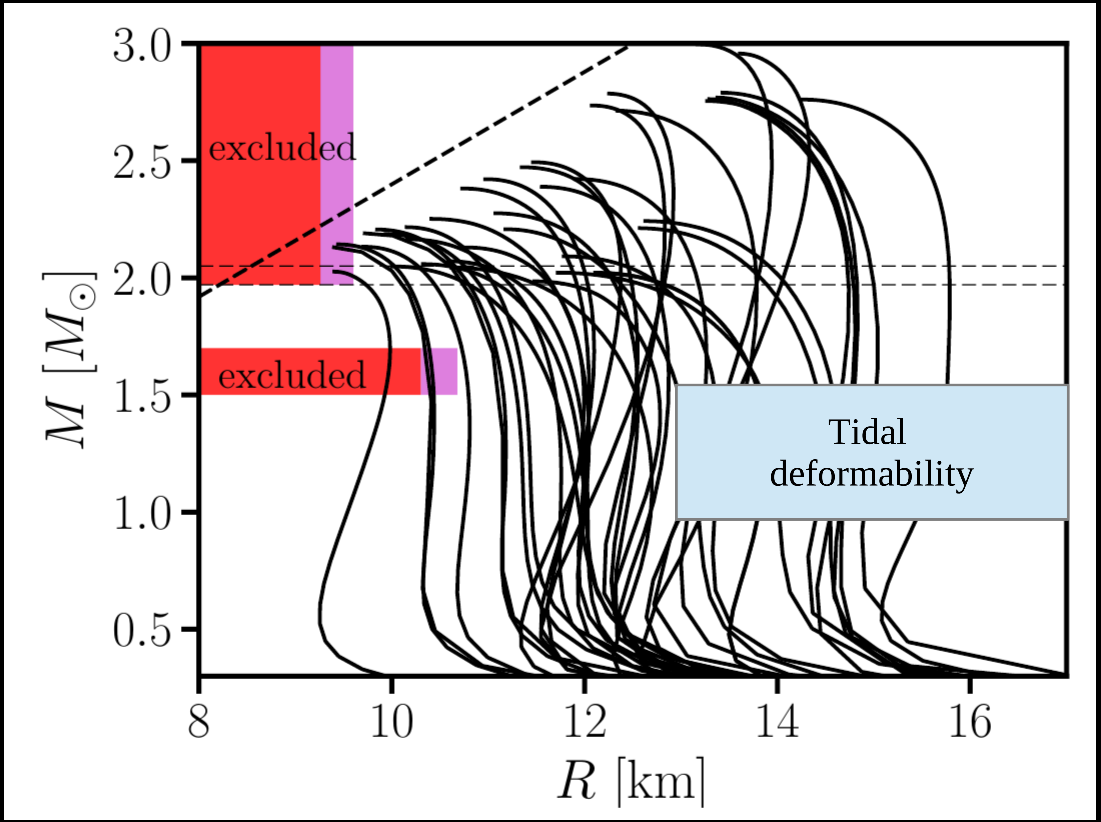


$$M_{\rm thres} = \left(-3.6\frac{G\,M_{\rm max}}{c^2\,R_{1.6}} + 2.38\right)\,M_{\rm max}$$

$$v_S = \sqrt{\frac{dP}{de}} \leq c \;\; \rightarrow \;\; M_{\rm max} \leq \kappa R_{1.6} \;\; \Rightarrow \;\; M_{\rm thres} \geq 1.2 M_{\rm max}$$

NS radius constraint from GW170817

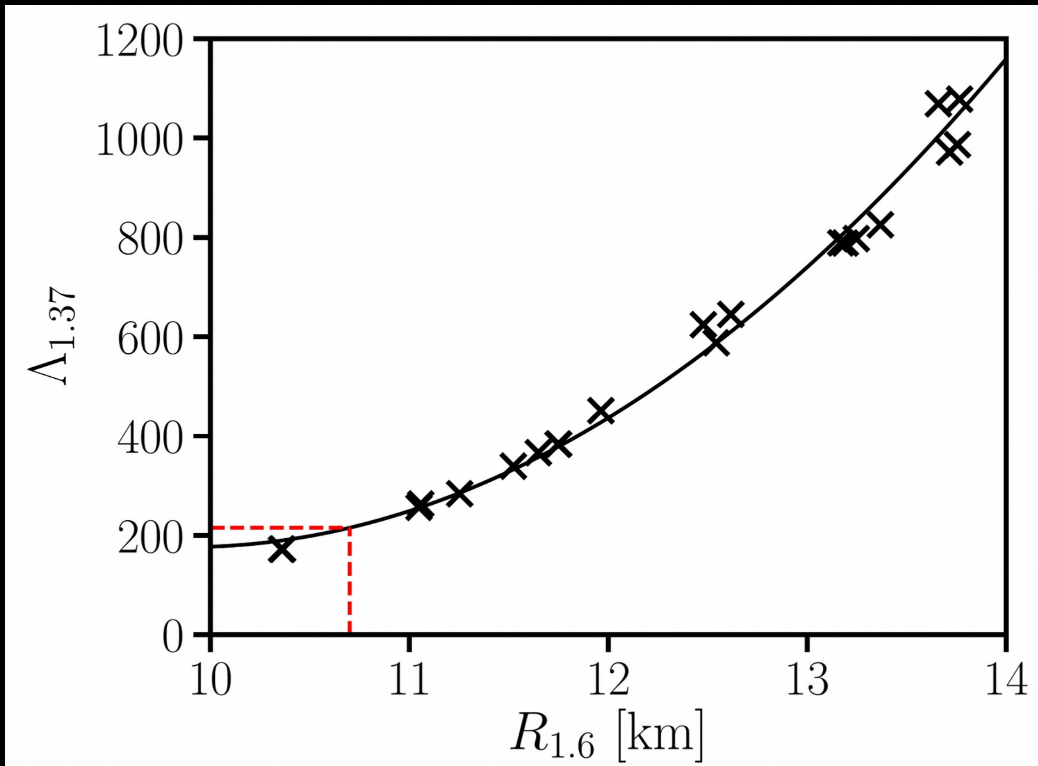
- R_{max} > 9.6 km
- $R_{1.6}$ > 10.7 km
- Excludes very soft nuclear matter

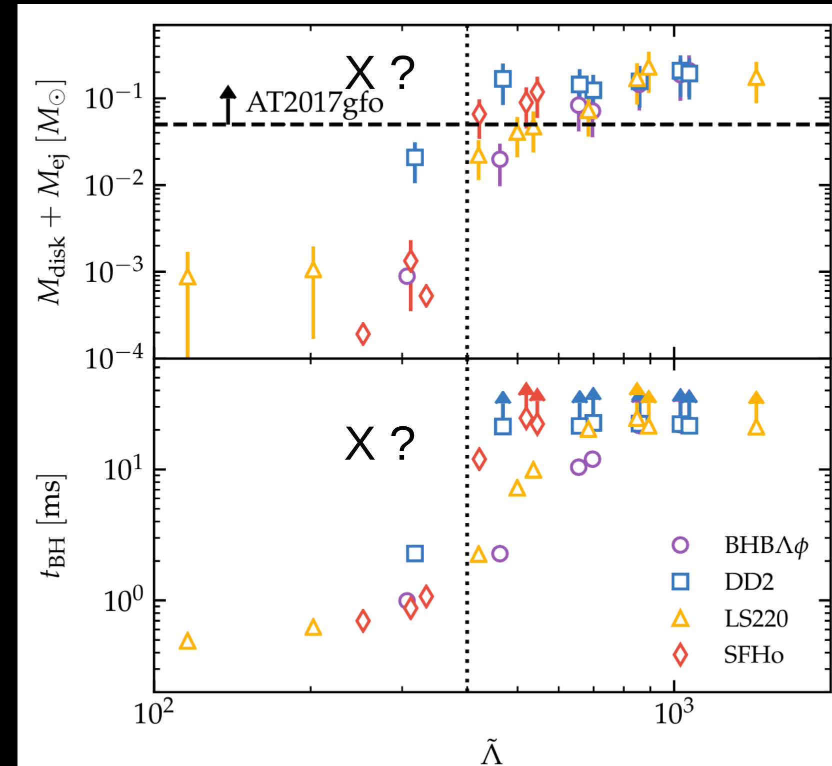


Bauswein et al. 2017

Radius vs. tidal deformability

Radice et al 2018





Bauswein, unpubl.

- Radius and tidal deformability scale tightly → **Lambda > 210**
- Limit cannot be much larger otherwise we could get direct collapse / dim counterpart (unless one weakens some of the conservative assumptions)
- Radice et al. 2018 followed a very similar argument claiming Lambda > 400 (300 in Dai 2019)

  → only 4 EoS considered – no complete coverage existing simulation data/parameter space

  → no argument why the fifth EoS shouldn't lie at Lambda<400 (see also Tews et al. 2018)

  → full EoS dependence has to be investigated via Mthres

Discussion - robustness

- Binary masses well measured with high confidence error bar
- Clearly defined working hypothesis: delayed collapse

  → testable by refined emission models

  → as more events are observed more robust distinction
- Very conservative estimate, errors can be quantified
- Empirical relation can be tested by more elaborated simulations (but unlikely that MHD or neutrinos can have strong impact on M_{thres})
- Confirmed by semi-analytic collapse model
- Low-SNR constraint !!!

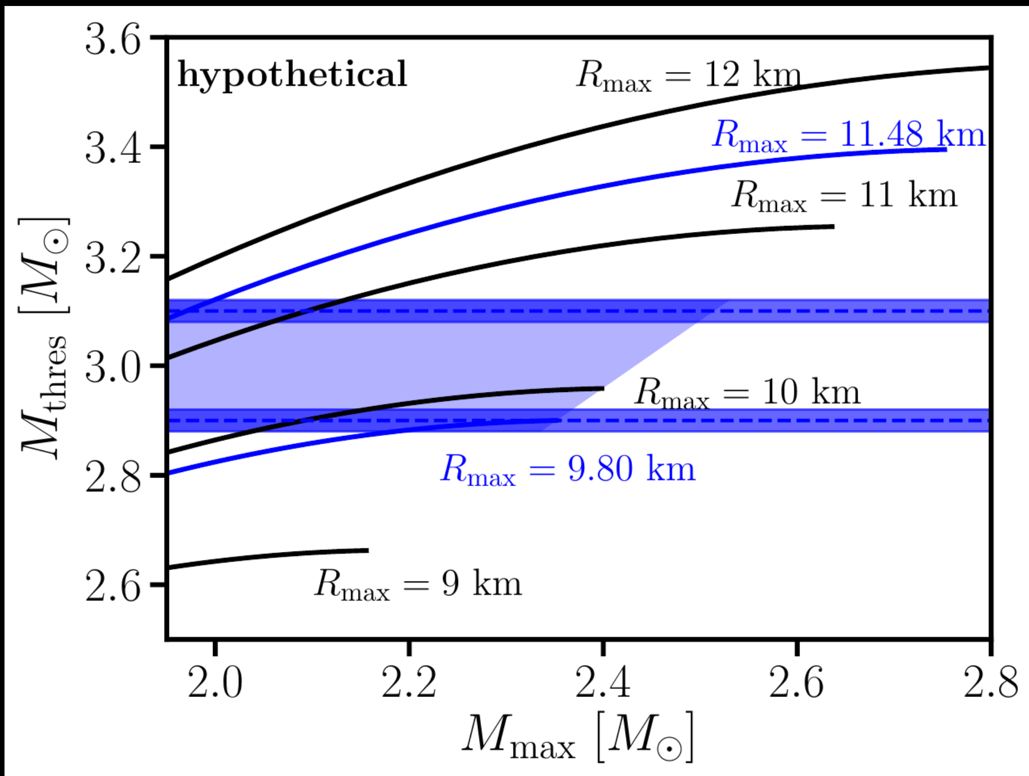
Future

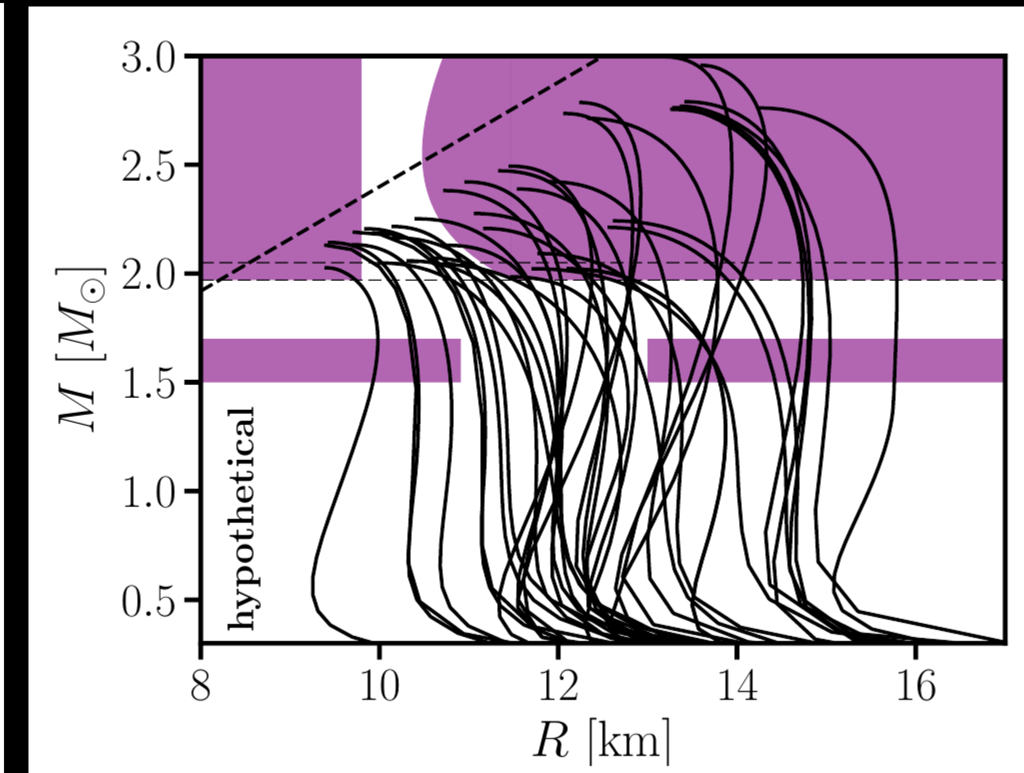
- Any new detection can be employed if it allows distinction between prompt/delayed collapse
- With more events in the future our comprehension of em counterparts will grow → more robust discrimination of prompt/delayed collapse events
- Low-SNR detections sufficient !!! → that's the potential for the future

  → we don't need louder events, but more

  → complimentary to existing ideas for EoS constraints

Future detections (hypothetical discussion)



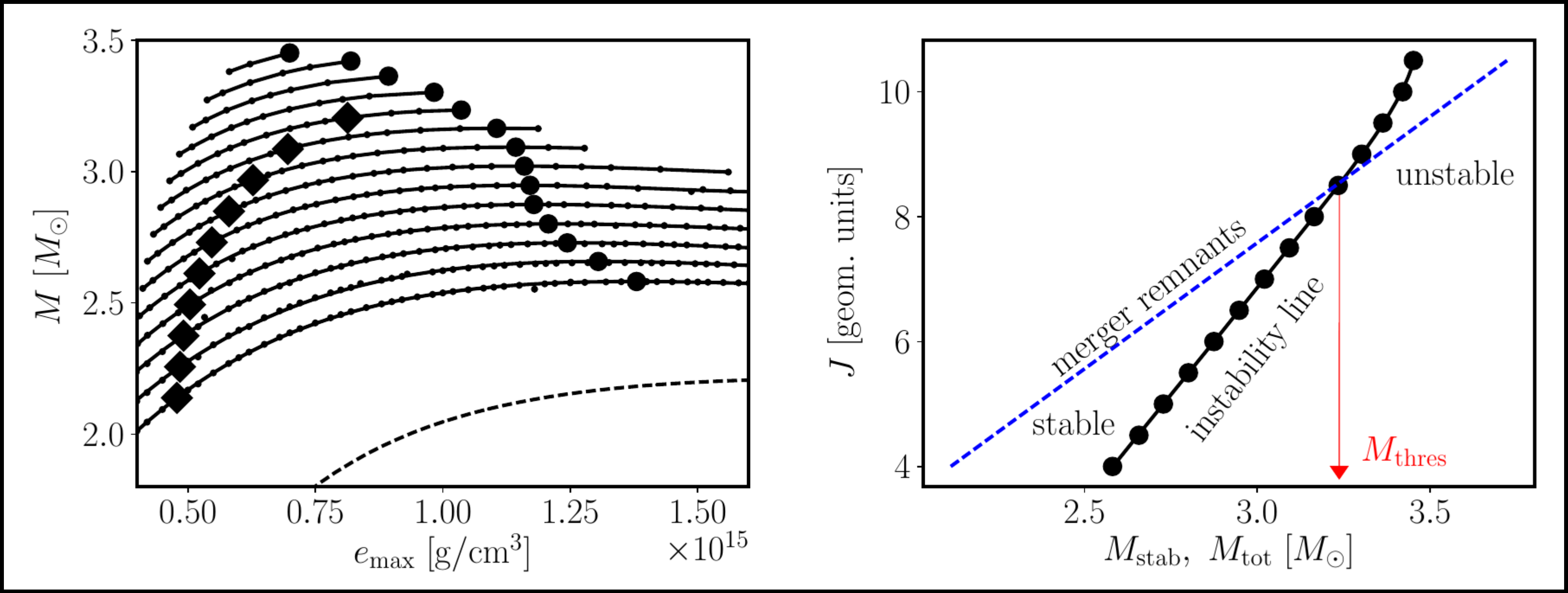


→ as more events are observed, bands converge to true M_{thres}
→ prompt collapse constrains M_{max} from above

Bauswein et al. 2017

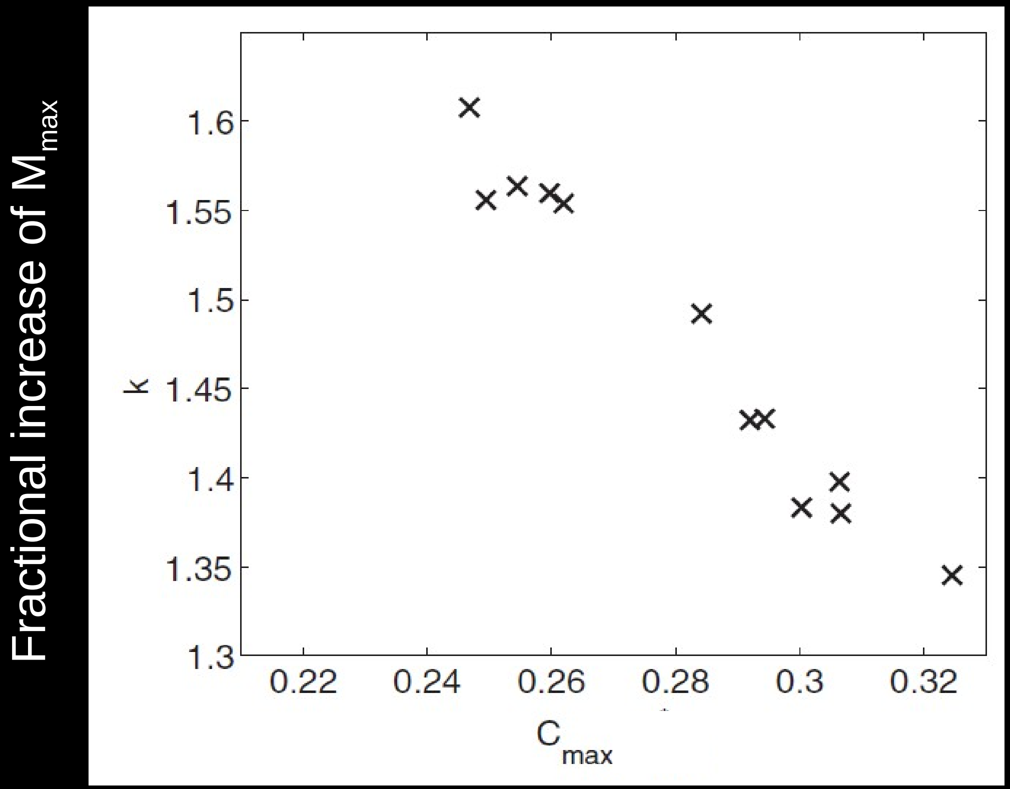
Semi-analytic model: details

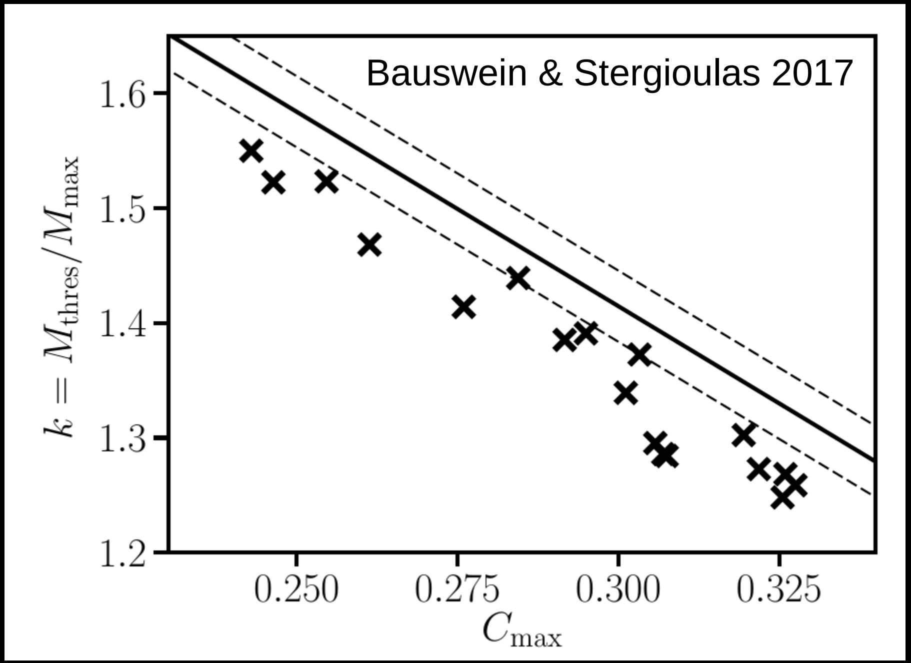
- Stellar equilibrium models computed with RNS code (diff. Rotation, T=0, many different microphysical EoS) => turning points => $M_{stab}(J)$
- Compared to $J(M_{tot})$ of merger remnants from simulations (very robust result) → practically independent from simulations



Bauswein & Stergioulas 2017

Semi-analytic model reproducing collapse behavior





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

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}

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

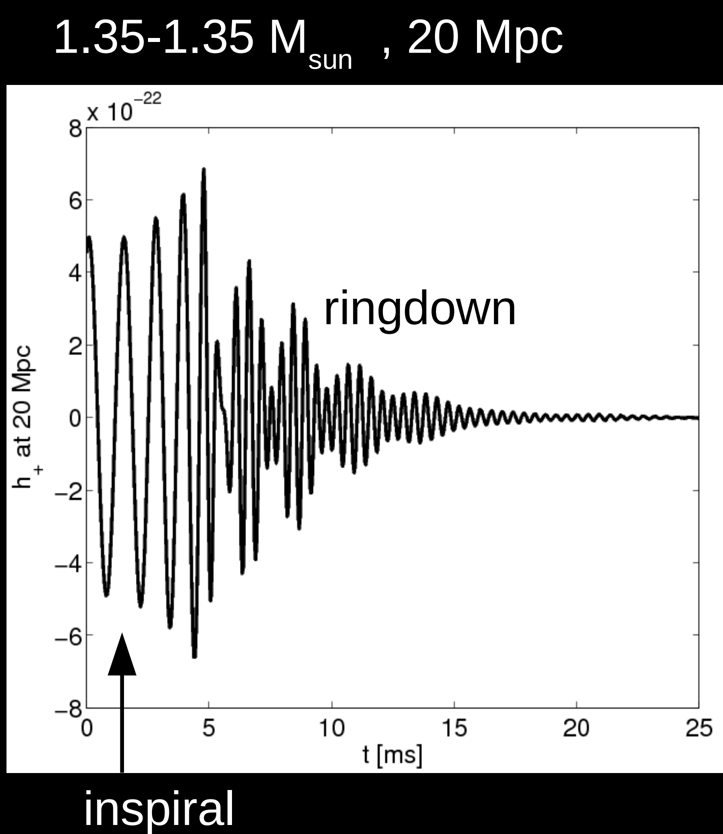
Postmerger GW emission*

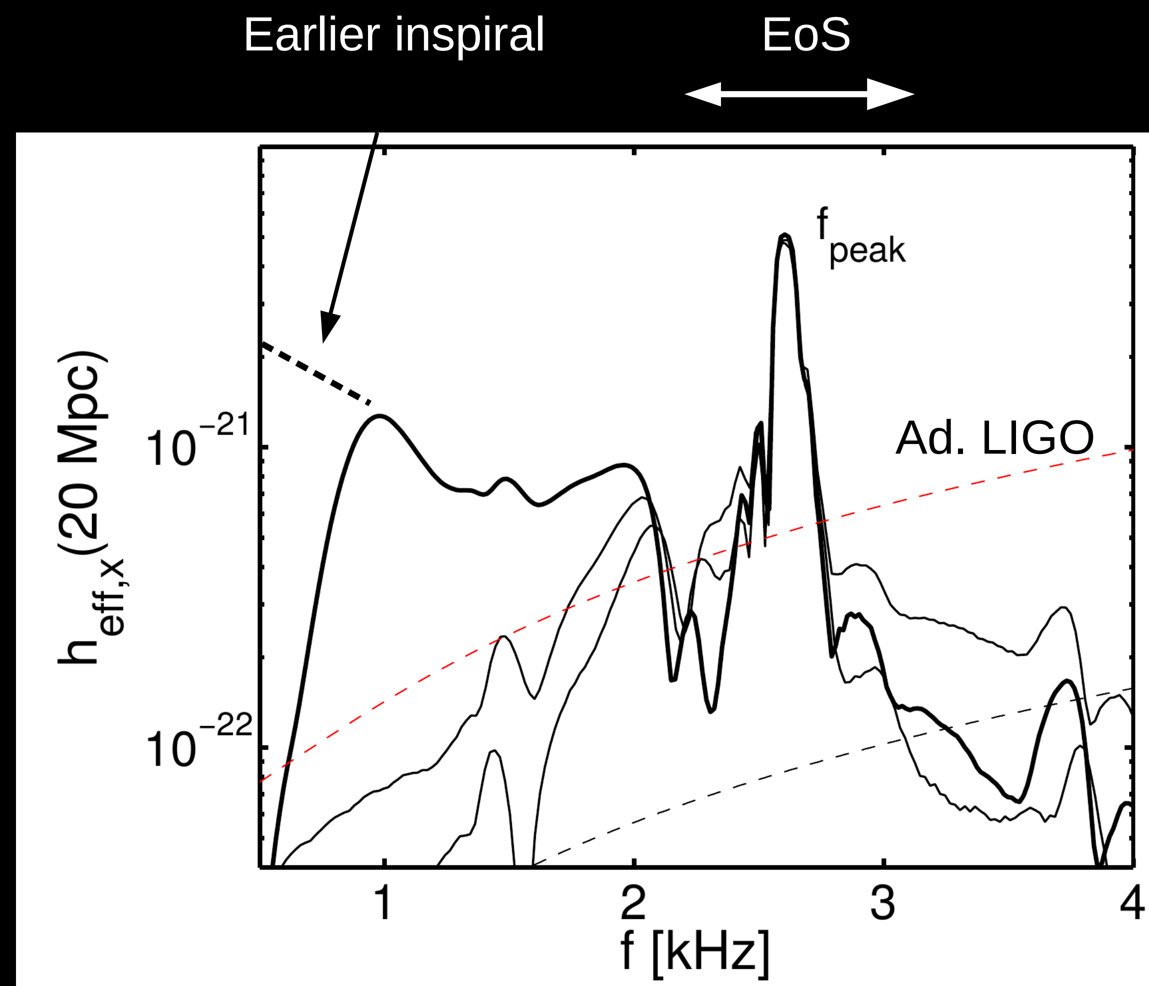
(dominant frequency of postmerger phase)

→ determine properties of EoS/NSs
→ complementary to inspiral

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

Postmerger

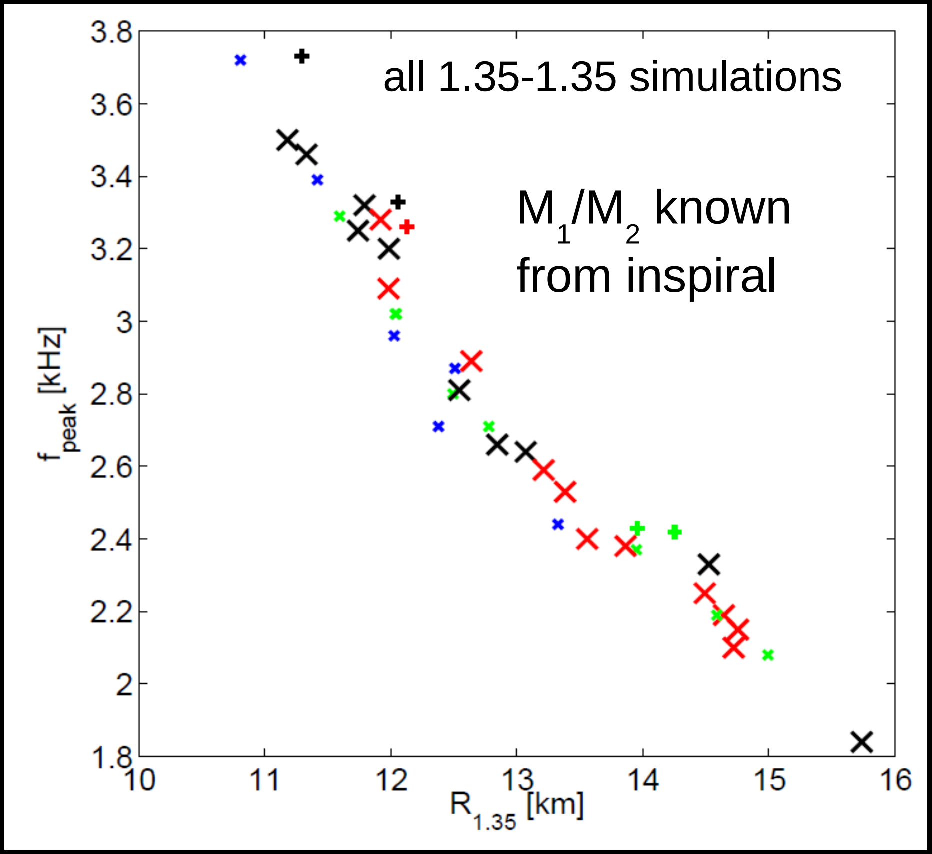


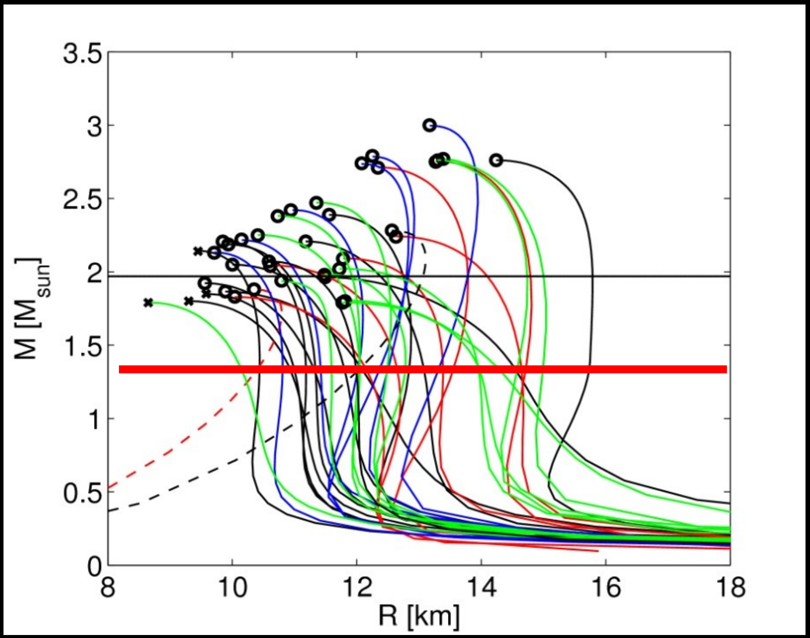


Dominant postmerger oscillation frequency f_{peak}

Very characteristic (robust feature in all models)

Gravitational waves – EoS survey





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

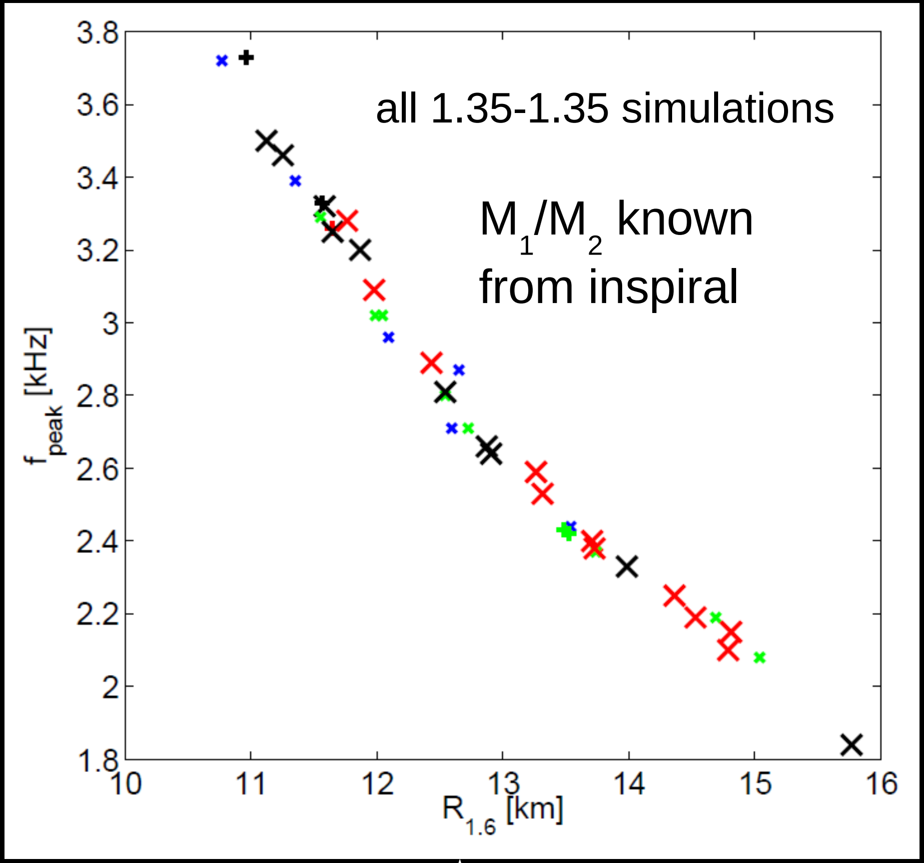
Bauswein et al. 2012

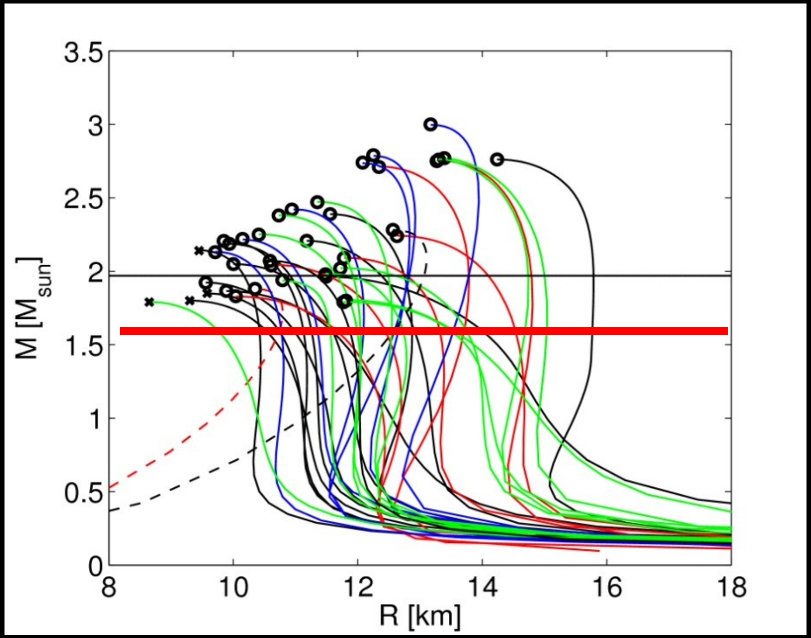
Pure TOV/EoS property => Radius measurement via f_{peak}

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}

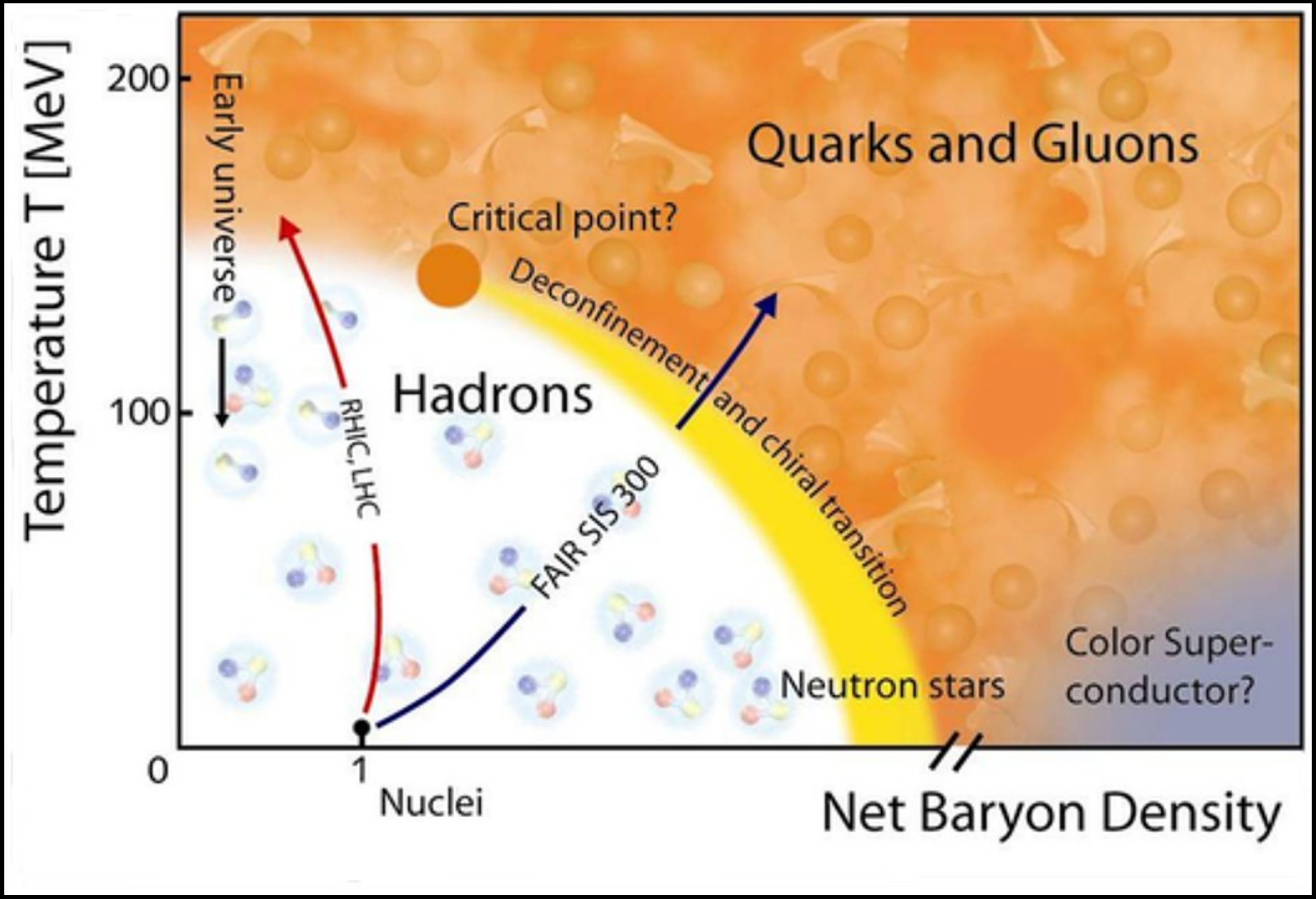
Smaller scatter in empirical relation (< 200 m) → smaller error in radius measurement

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, Breschi et al 2019, … → detectable at a few 10 Mpc

Observable signature of (QCD) phase transition

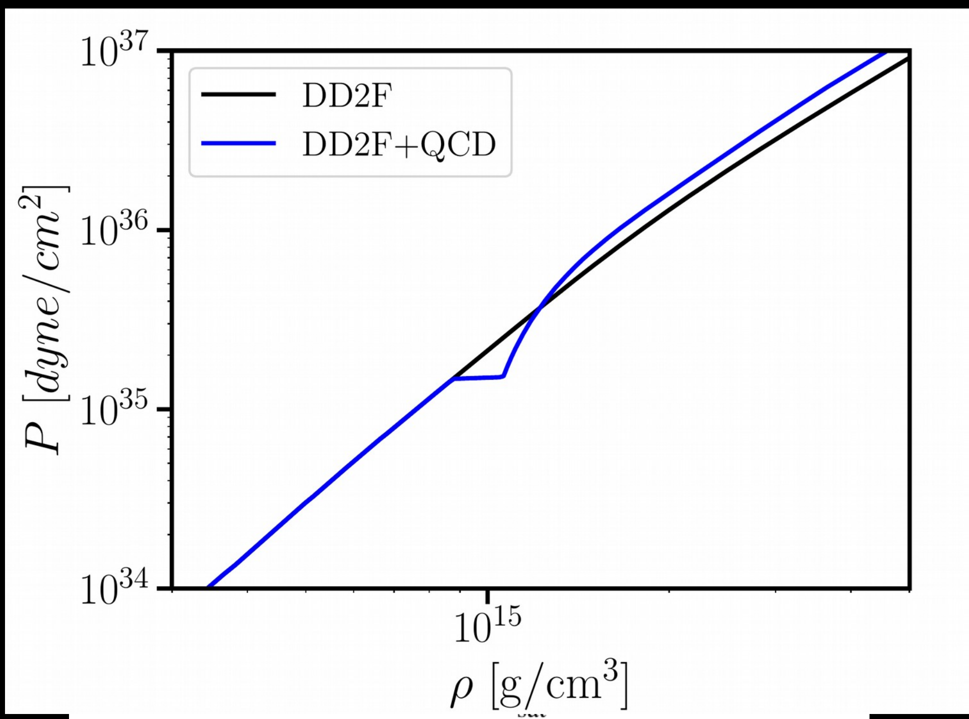
Phase diagram of matter

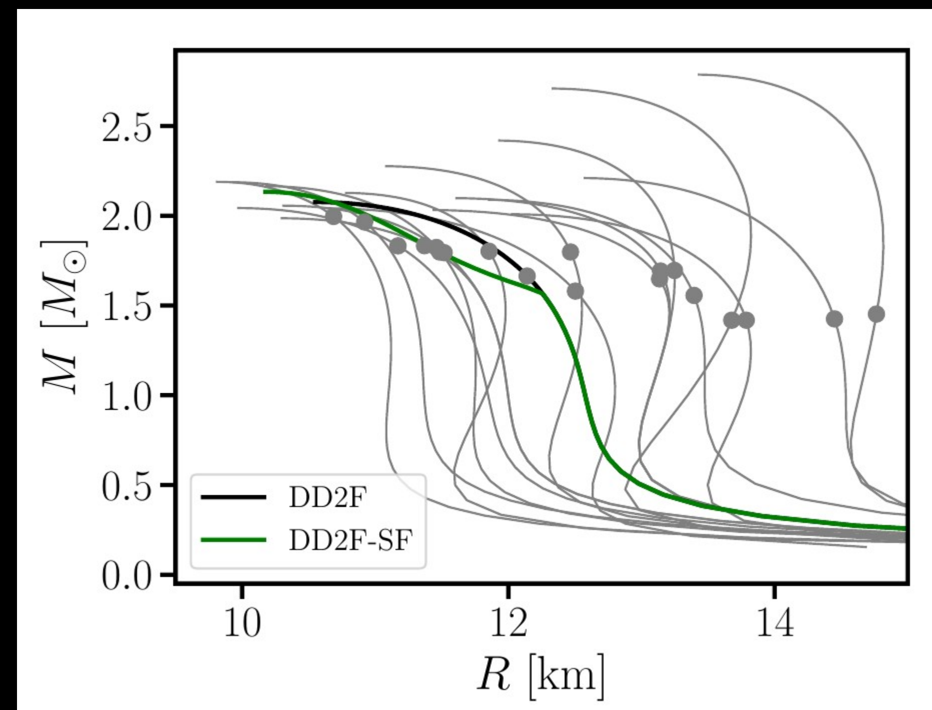


Does the phase transition to quark-gluon plasma occur (already) in neutron stars or only at higher densities ?

EoS with 1st-order phase transition to quark matter

Bauswein et al. 2018

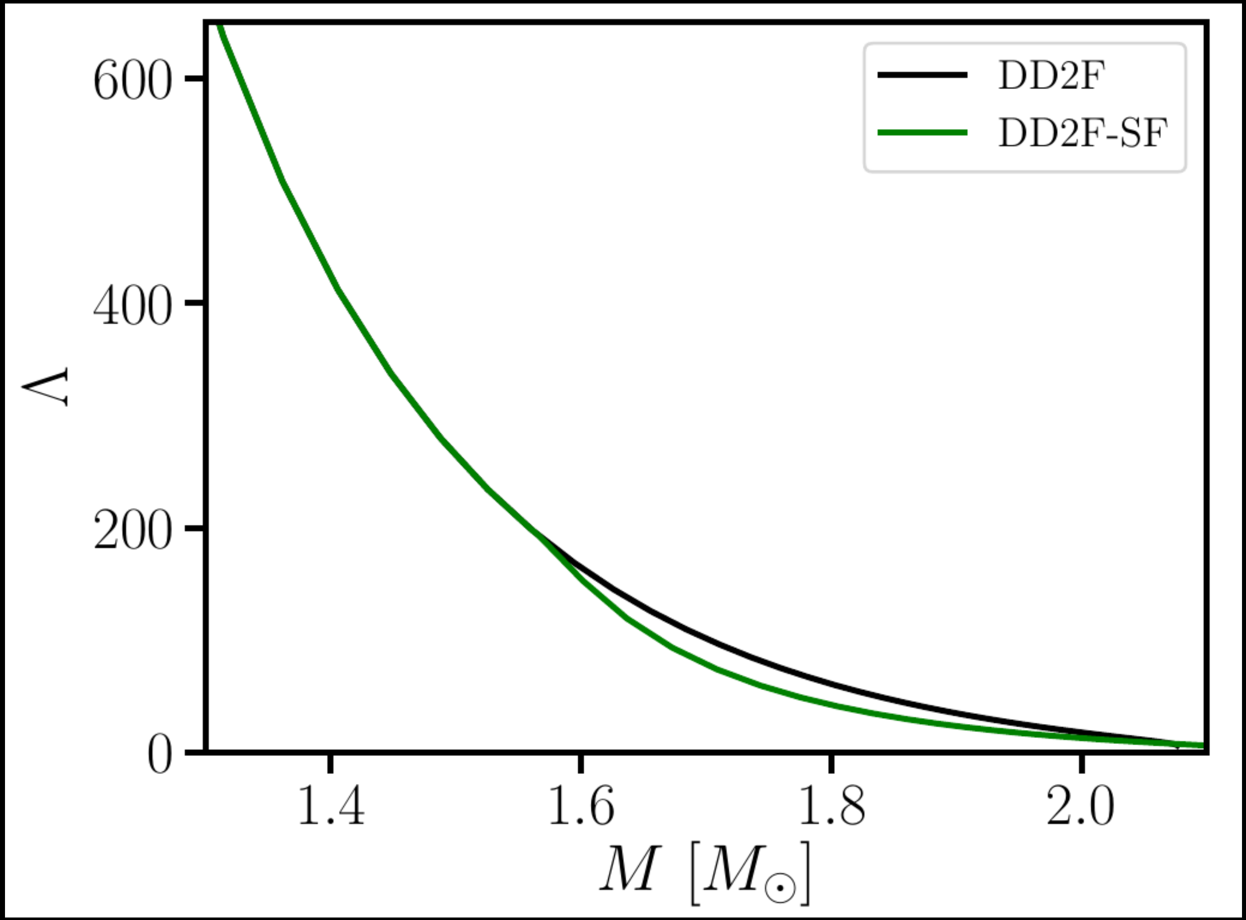




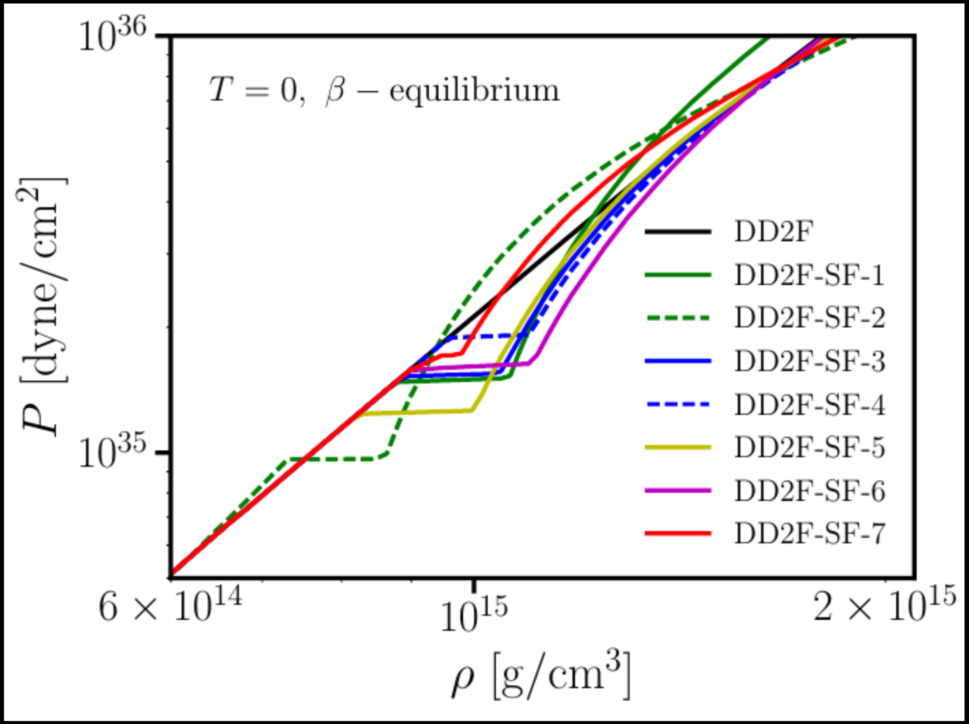
- EoS from Wroclaw group (Fischer, Bastian, Blaschke; Fischer et al. 2018) – as one example for an EoS with a strong 1st-order phase transition to deconfined quarks
- Difficult to measure transition in mergers through inspiral: Lambda very small, high mass star probably less frequent

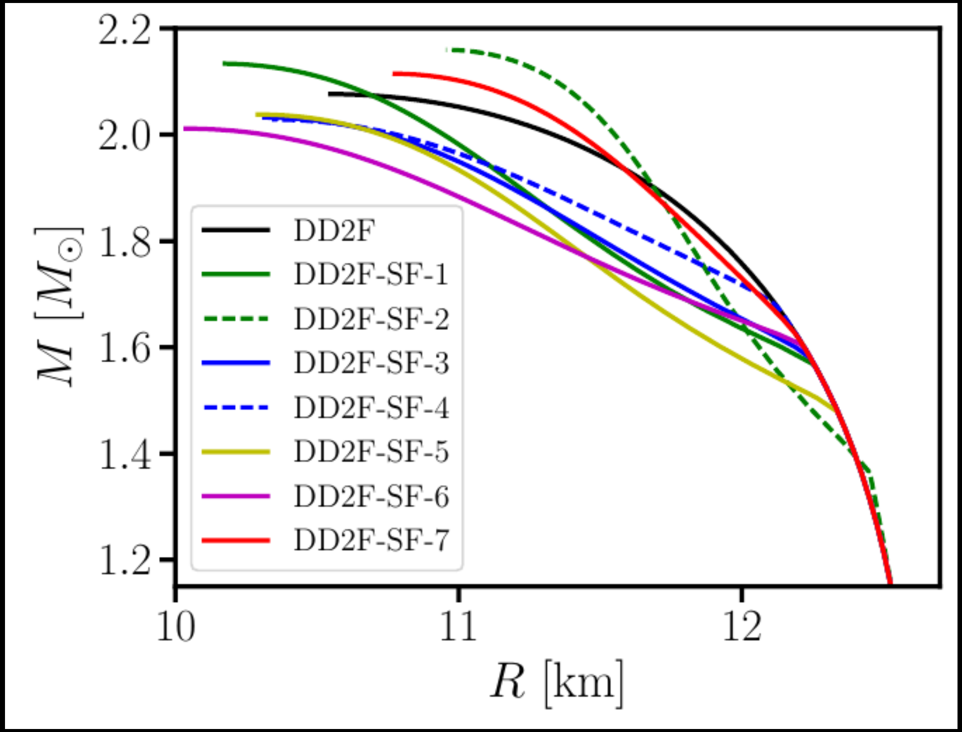
Phase transition

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



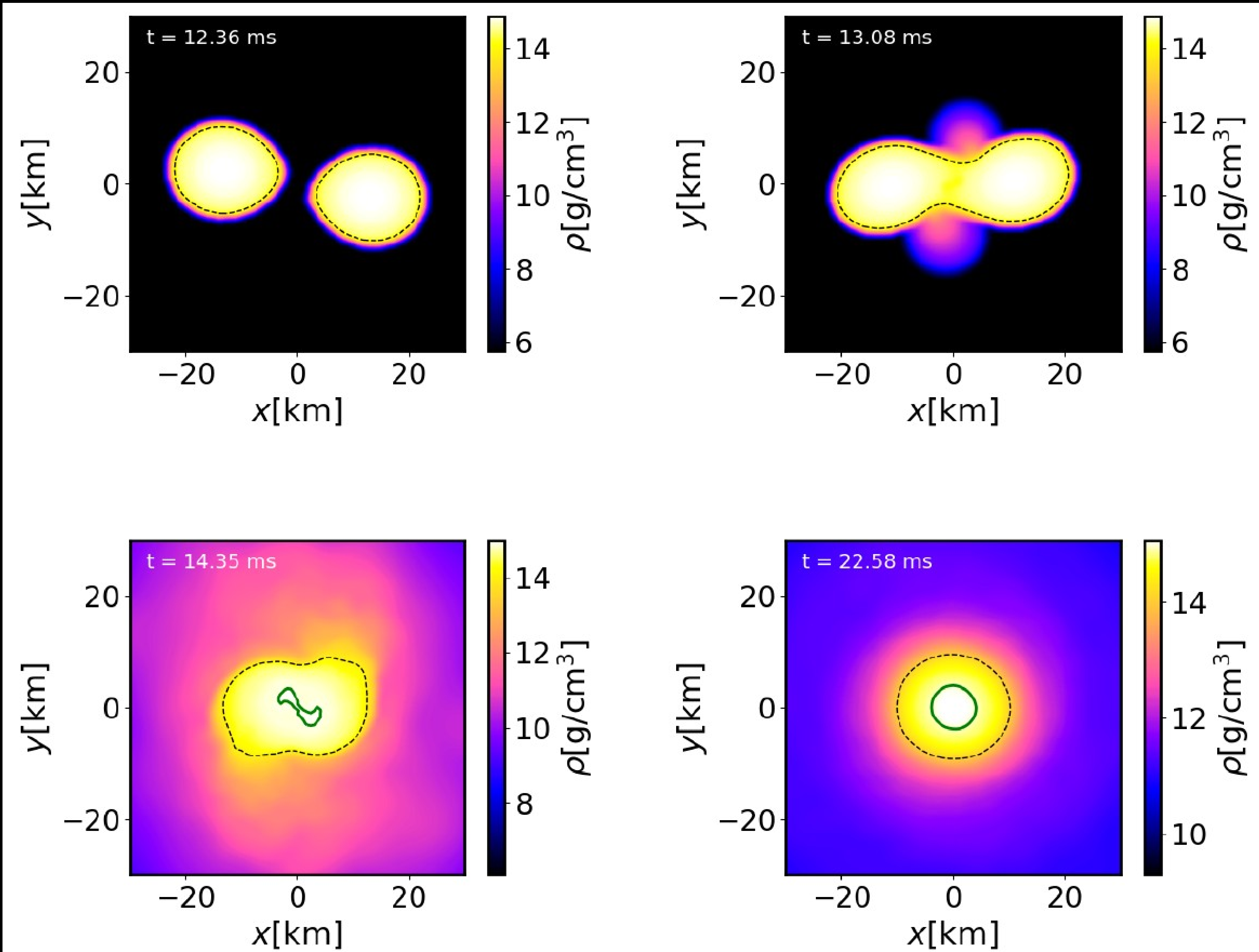
- 7 different models for quark matter: different onset density, different density jump, different stiffness of quark matter phase





Bauswein et al. 2019

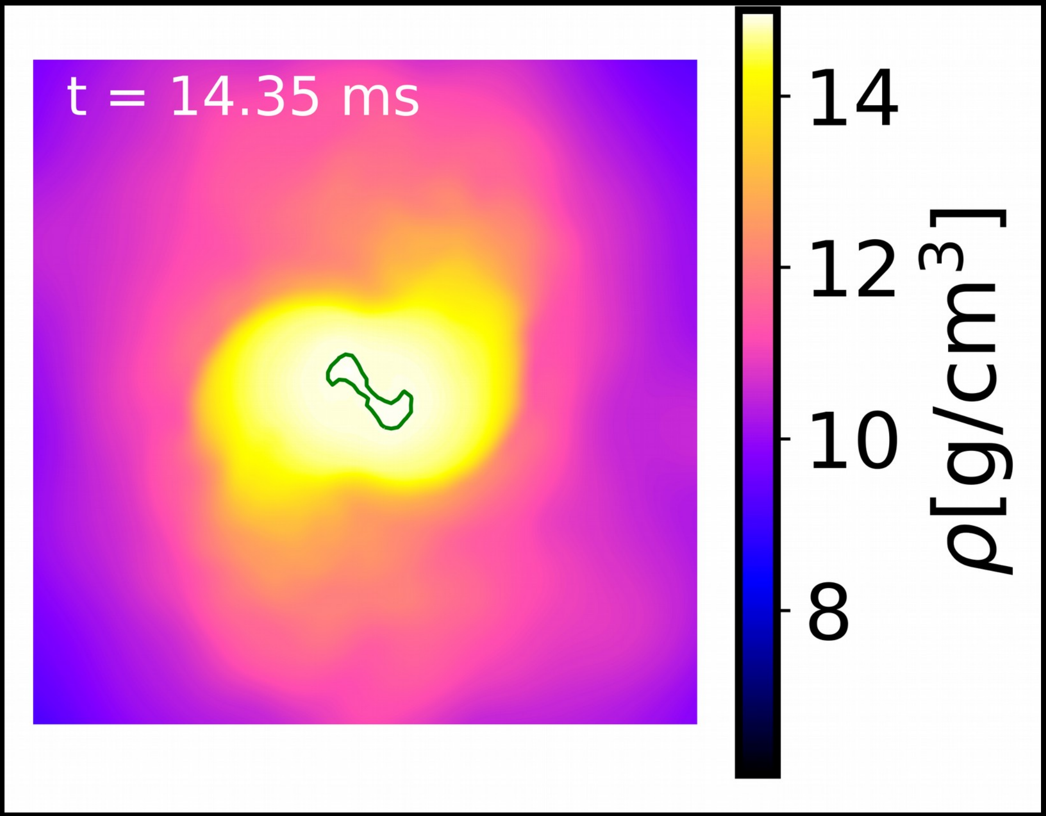
EoSs from Wroclaw group

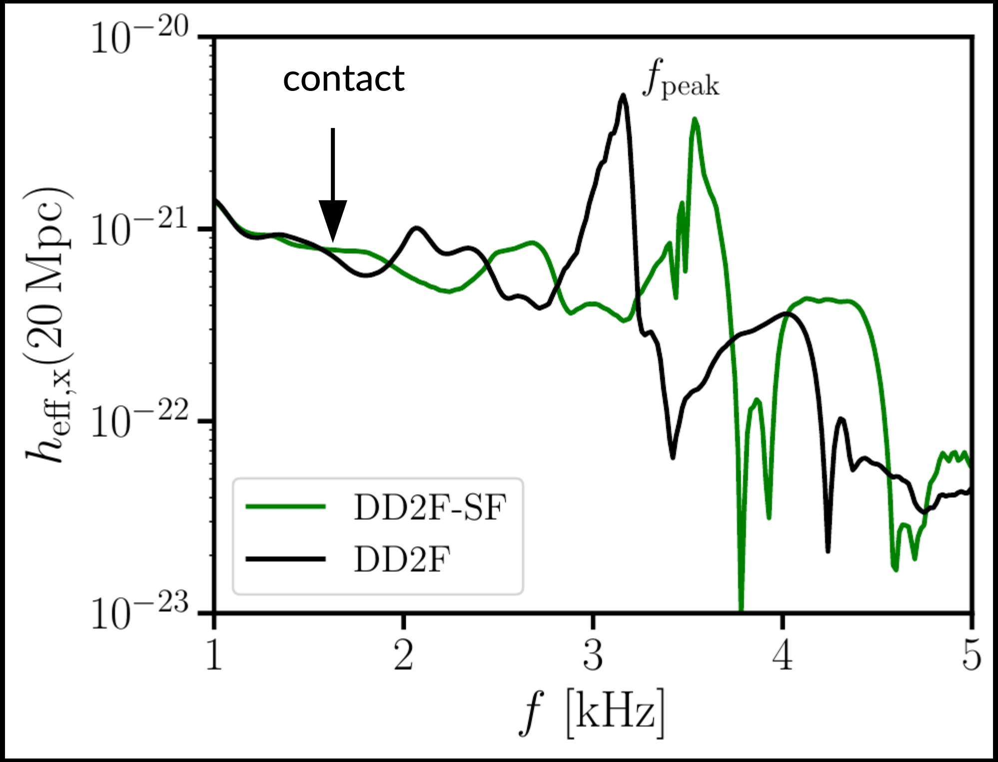


1.35-1.35 Msun - DD2F-SF-1

Merger simulations

- GW spectrum 1.35-1.35 Msun





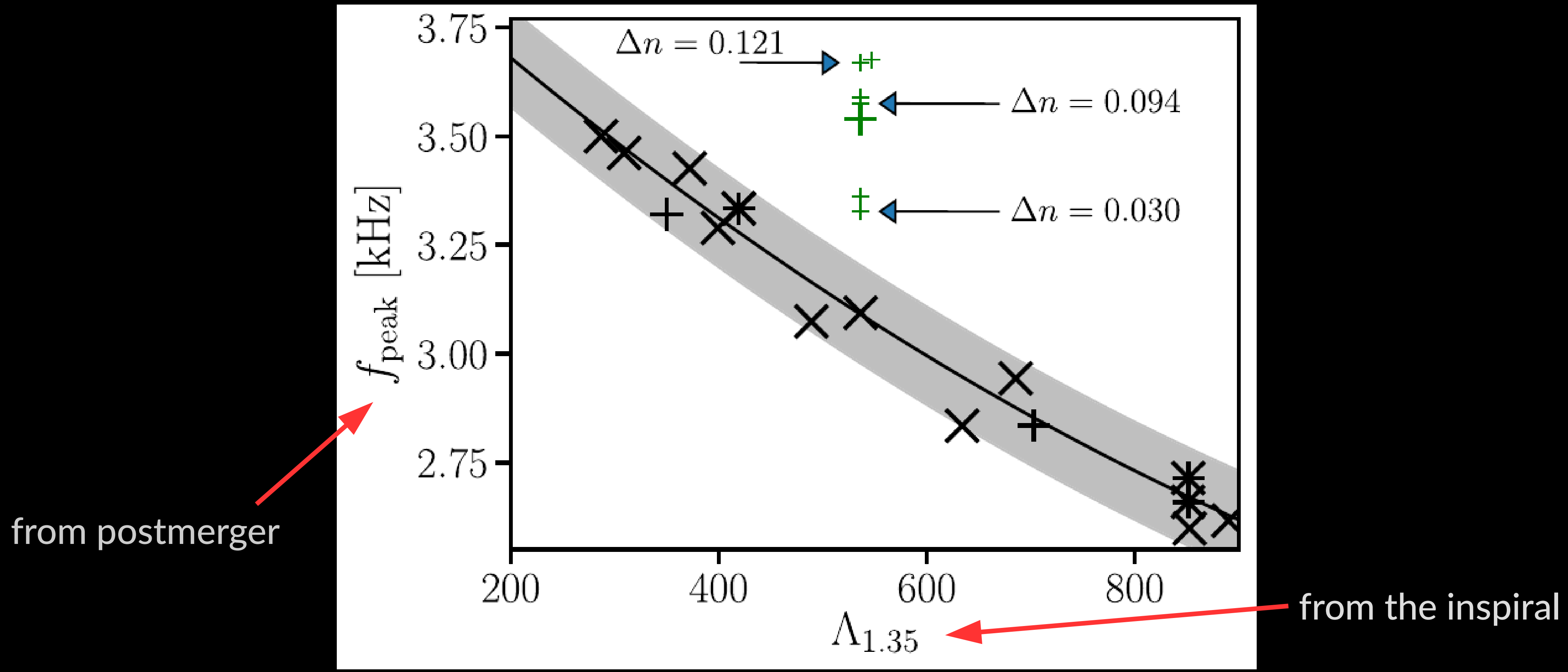
Bauswein et al. 2019

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

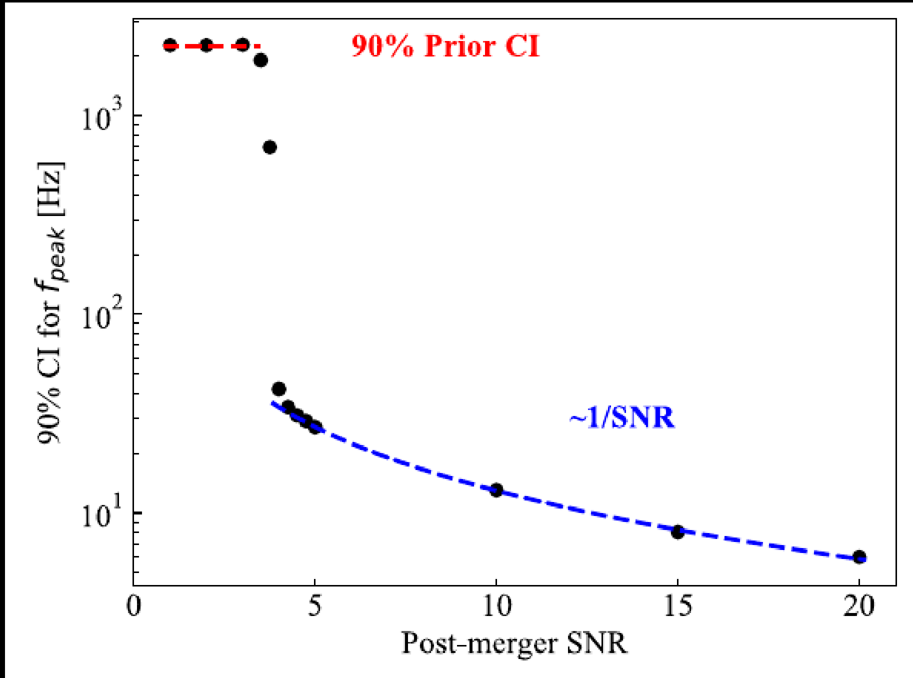


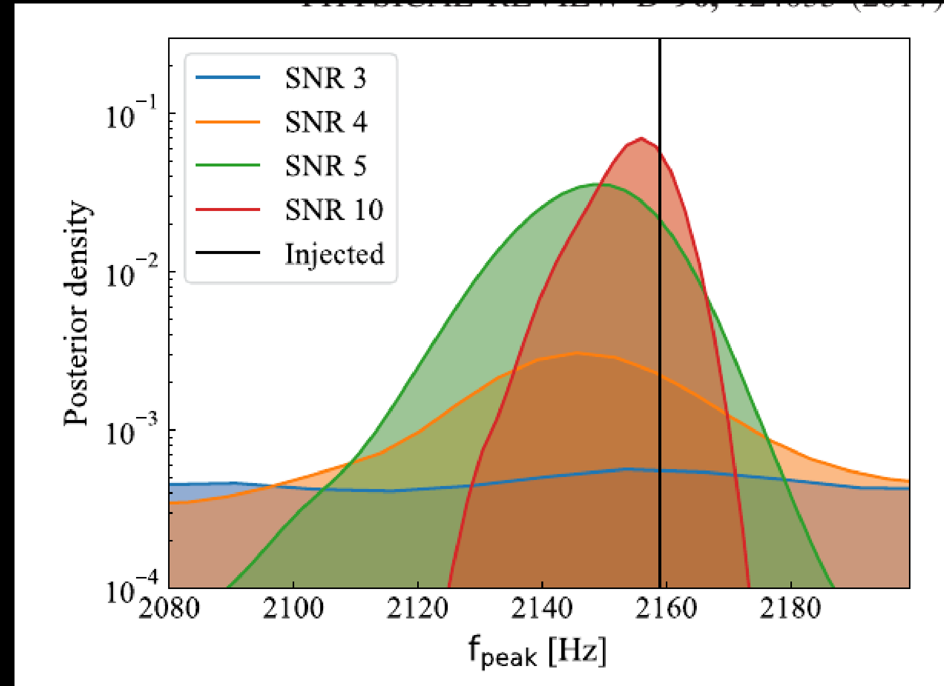
Bauswein et al. 2019

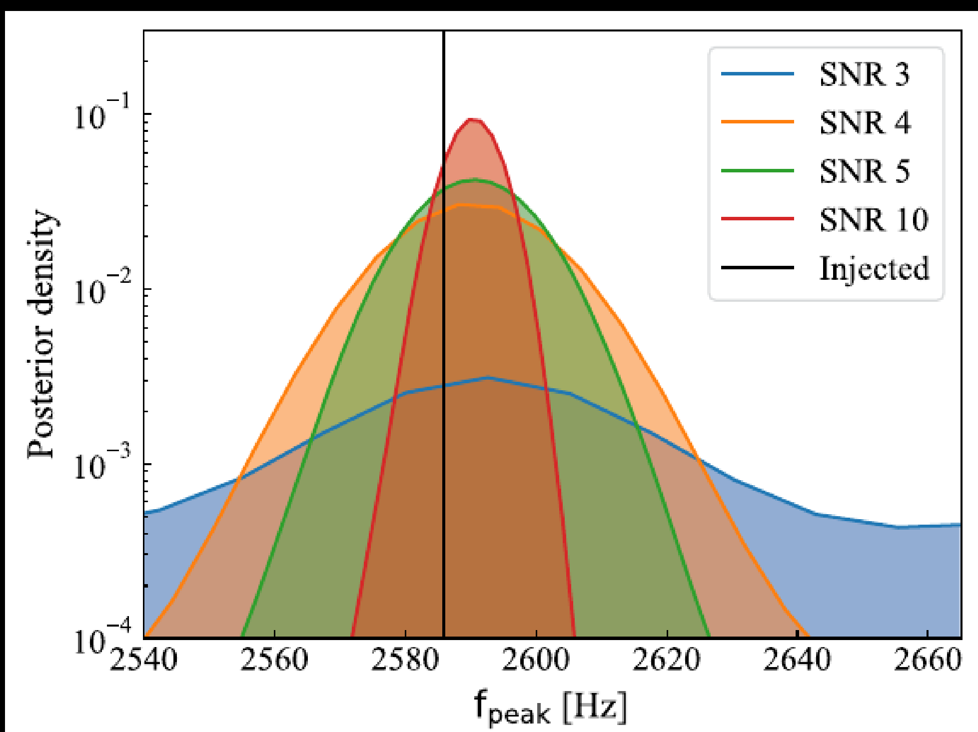
- Tidal deformability measurable from inspiral to within 100-200 (Adv. Ligo design)
- Postmerger frequency measurable to within a few 10 Hz @ a few 10 Mpc (either Adv. Ligo or upgrade: e.g Clark et al. 2016, Chatzioannou et al 2017, Bose et al 2018, Torres-Rivas et al 2019)
- Important: "all" purely hadronic EoSs (including hyperonic EoS) follow fpeak-Lambda relation → deviation characteristic for strong 1st order phase transition

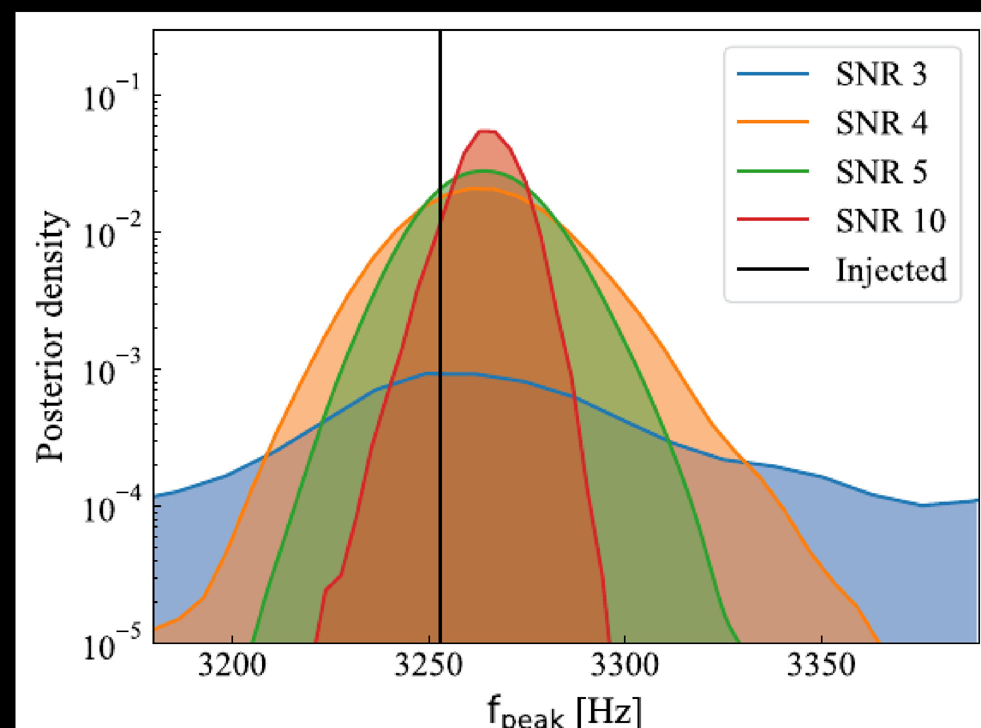
Conclusions

- NS radius must be larger than 10.7 km (very robust and conservative)
- More stringent constraints from future detections
- NS radius measurable from dominant postmerger frequency
- Explicitly shown by GW data analysis
- Threshold binary mass for prompt collapse → maximum mass M_{max}
- Strong 1st order phase transitions leave characteristic imprint on GW (postmerger frequency higher than expected from inspiral)
- Complementarity of inspiral and postmerger phase → postmerger probes higher density regime









Chatzioannou et al 2017