Supported by ERC through Starting Grant no. 759253

European Research Council

Established by the European Commission

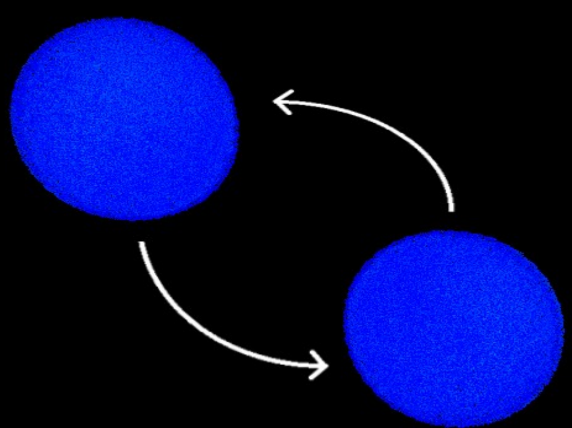
EoS from neutron star mergers

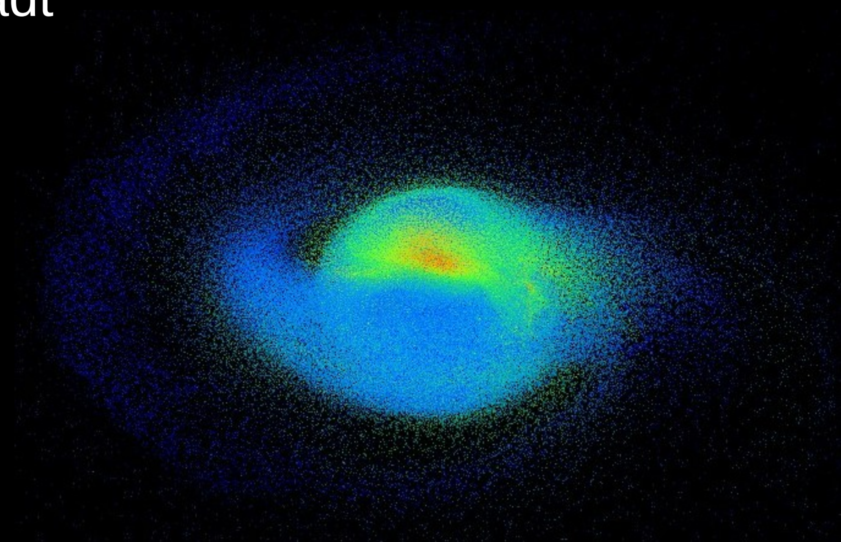
ECT* workshop: Challenges of Transport Theory for Heavy-Ion Collisions

Trento, 23/05/2019

Andreas Bauswein (from Arenzano – Scusi !!!)

GSI Darmstadt





Outline

- Overview: NS mergers and GW170817
- EoS constraints from NS mergers

  - finite-size effects during the inspiral

  - multi-messenger interpretation

  - postmerger GW emission
- Signatures of the QCD phase transition
- Summary and conclusions

presence

future

A break-through in astrophysics

- GW170817 first unambiguously detected NS merger
- Mutli-messenger observations: gravitational waves, gamma, X-rays, UV, optical, IR, radio

Detection August 17, 2017 by LIGO-Virgo network

→ GW data analysis

→ follow-up observations - probably largest coordinated observing campaign in astronomy (observations/time)

Announcement October 2017

Ligo and Virgo take data again → already some new events at larger distances !!!

Scientific aspects of NS mergers

- NS mergers likely progenitors of short gamma-ray bursts (observed since the 70ies)
- NS mergers as sources of heavy elements forged by the rapid neutron-capture process
- Electromagnetic transient powered by nuclear decays during/after r-process (“kilonova”, “macronova”, ...)

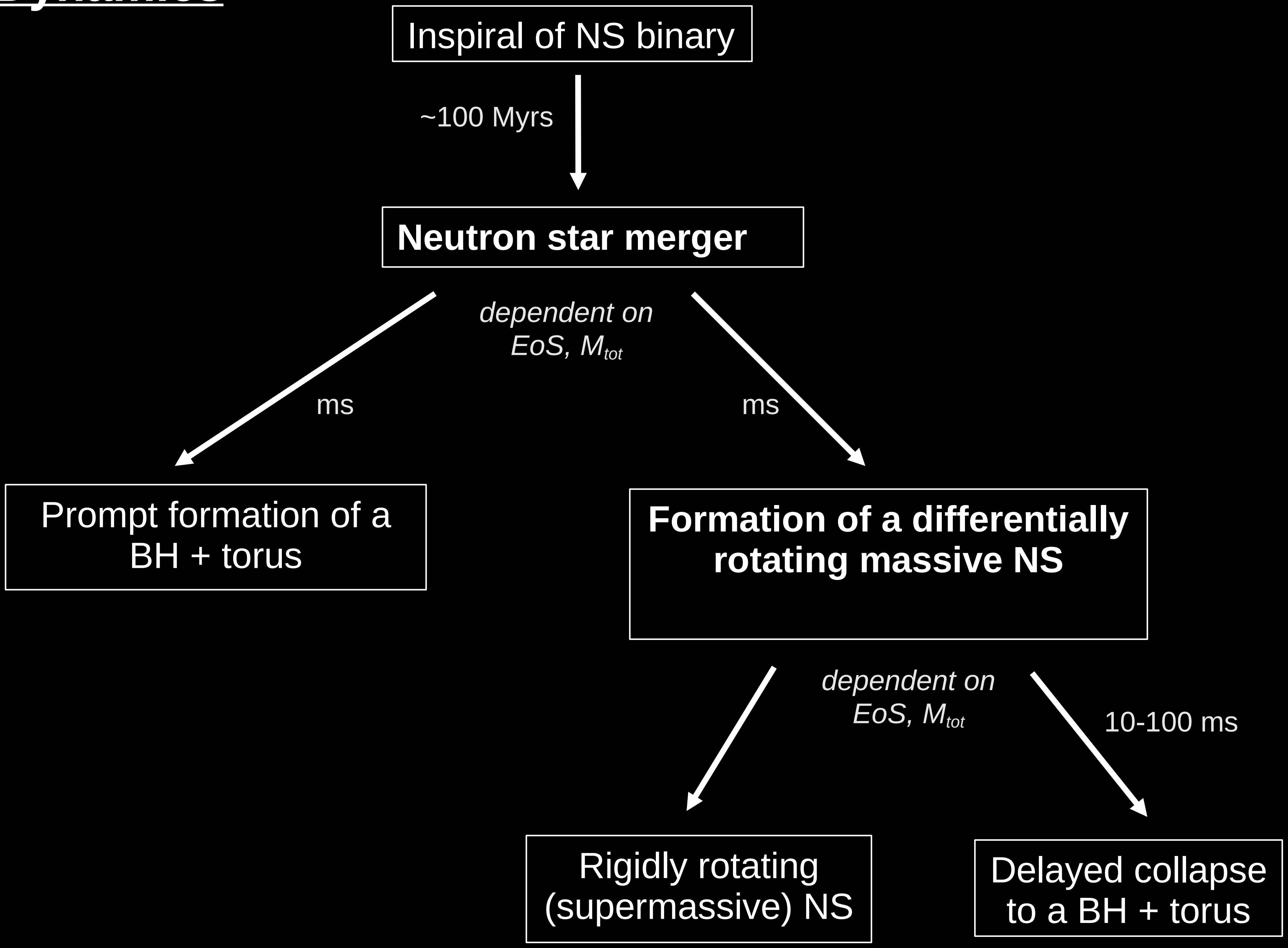
  → UV, optical, IR → targets for triggered or blind searches (time-domain astronomy)
- Various other types of em counterparts
- Strong emitters of GWs

  → population properties: rates, masses, ... → stellar astrophysics

  → EoS of nuclear matter / stellar properties of NSs

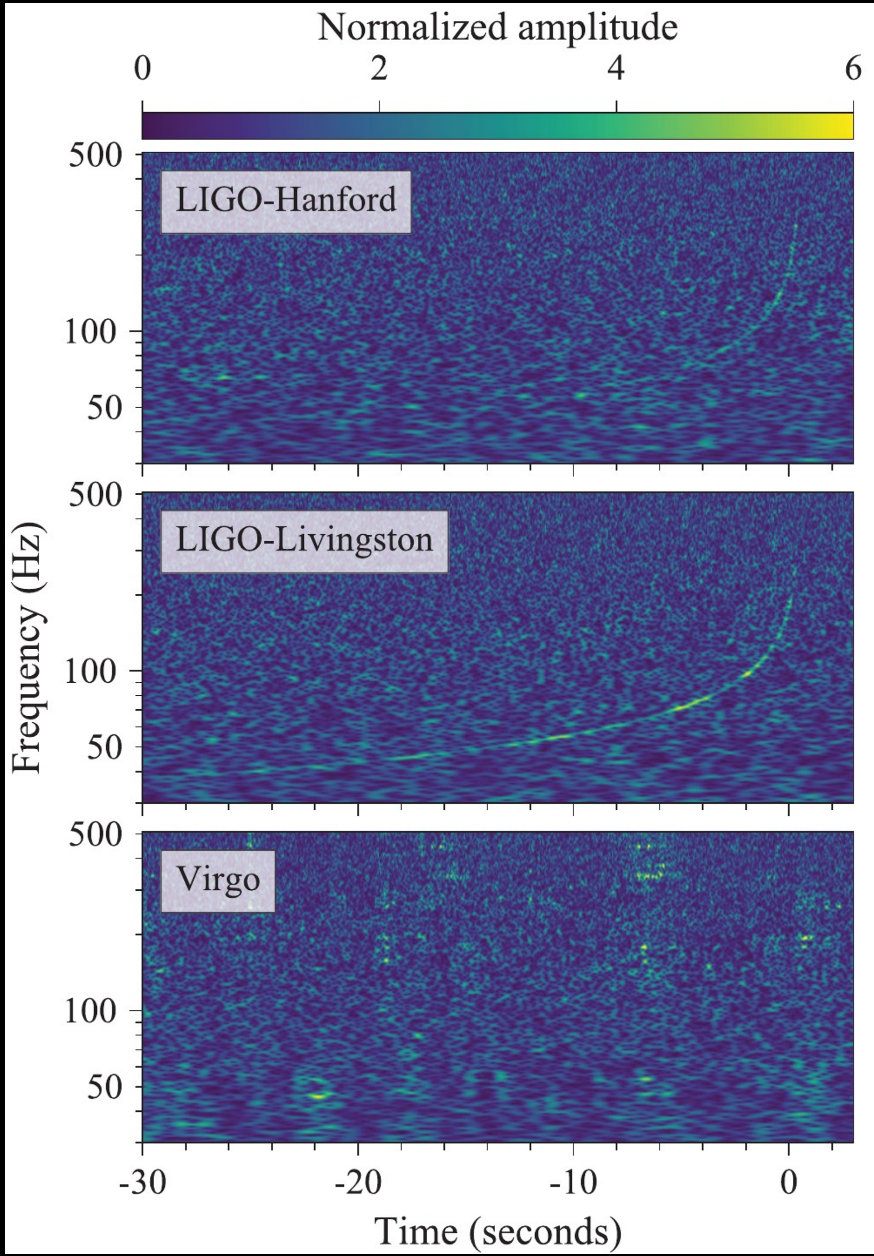
  (NS mergers probe cold and hot matter – pre- and post-merger)
- ...

Dynamics


Inspiral of NS binary
~100 Myrs
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
Delayed collapse
to a BH + torus

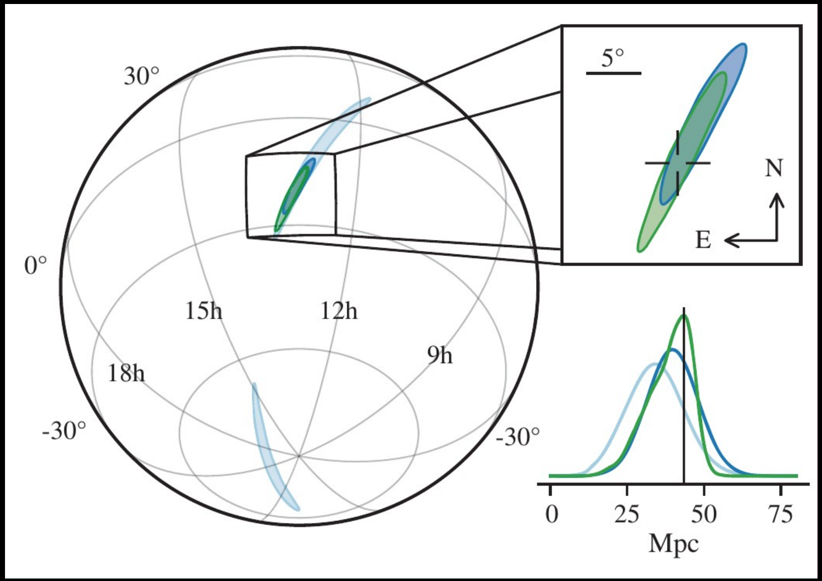
Abbott et al 2017

GW170817



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



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

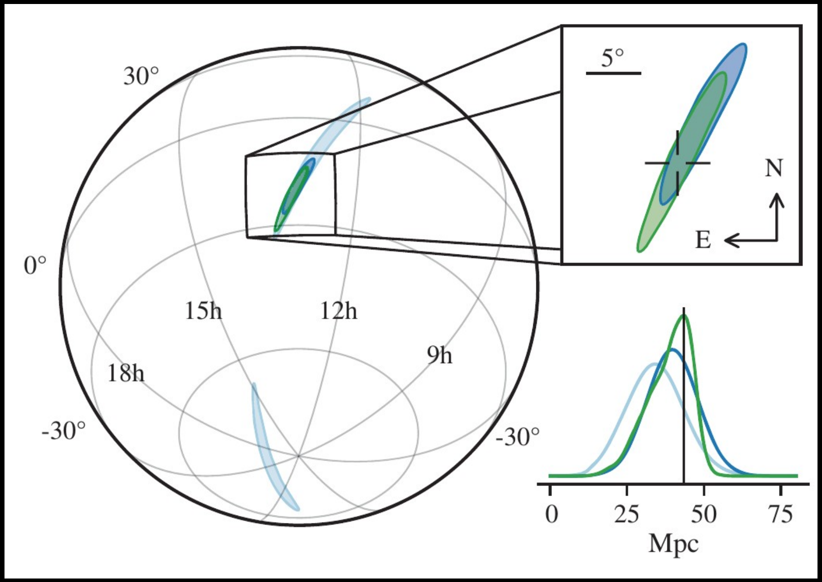
Abbott et al. 2017

	Low-spin priors ($\lvert\chi\rvert \le 0.05$)	High-spin priors ($\lvert\chi\rvert \le 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\le 55°$	$\le 56°$
Using NGC 4993 location	$\le 28°$	$\le 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

Observations

- 1.7 sec after gamma-rays (→ short GRB ???)
- Follow up observation (UV, optical, IR) starting ~12 h after merger

  → ejecta masses, velocities, opacities
- Several days later X-rays, radio (ongoing)



Abbott et al. 2017

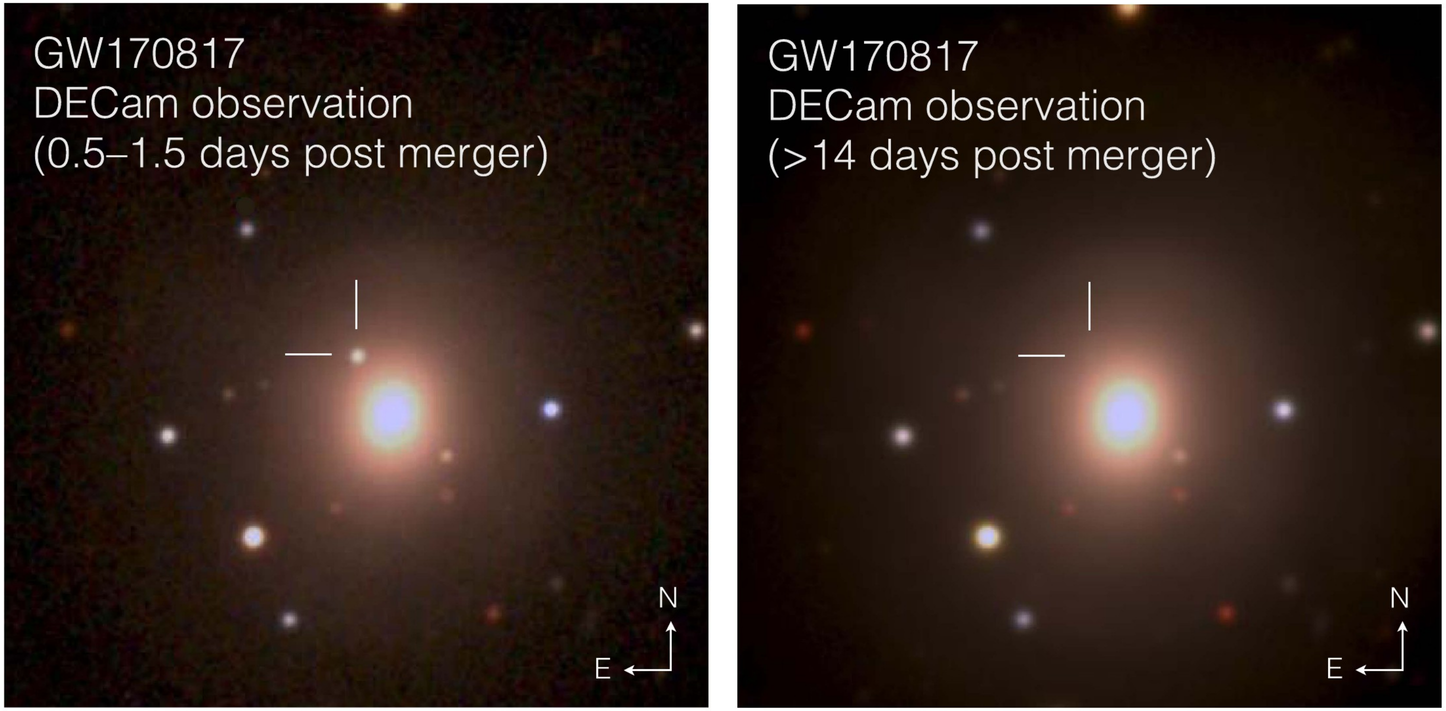


Figure 1. NGC4993 *grz* color composites (1.′5 × 1.′5). Left: composite of detection images, including the discovery *z* image taken on 2017 August 18 00:05:23 UT and the g and r images taken 1 day later; the optical counterpart of GW170817 is at R.A., decl. =197.450374, −23.381495. Right: the same area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

Soares-Santos et al 2017

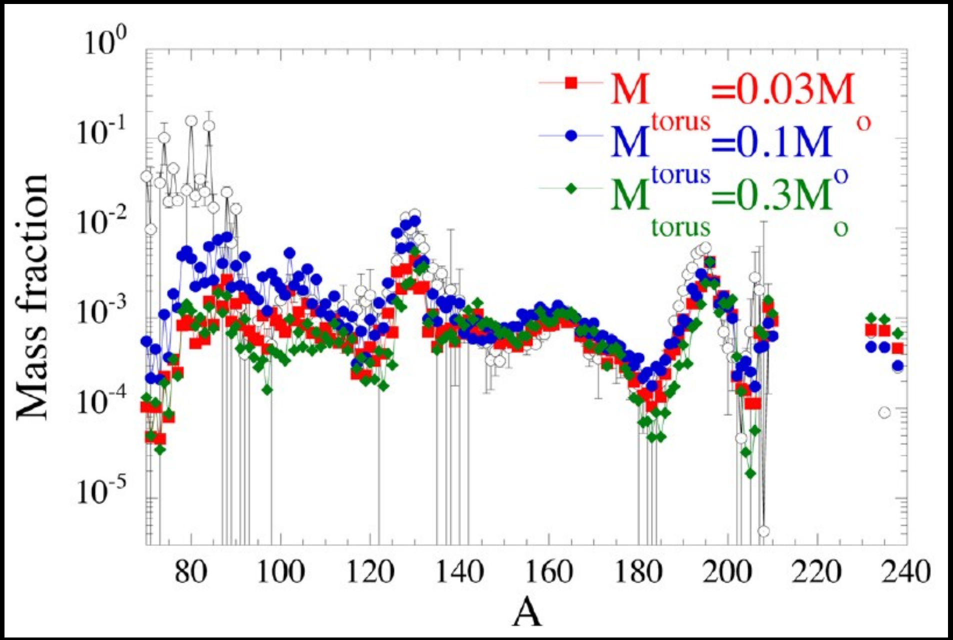
Interpretation - implications

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

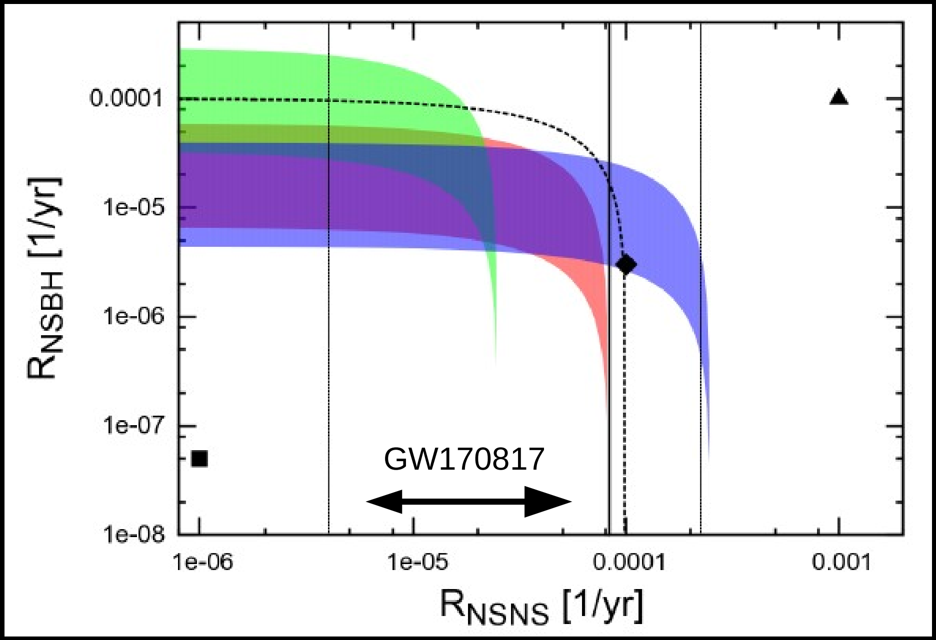
  (not surprising for a theorist, see earlier work on r-process and em counterparts)
- 0.02 – 0.05 Msun ejecta (red and blue component) – somewhat model-dependent
- Ejecta velocities and masses in ballpark of simulation results
- Derived ejecta masses are compatible with mergers being the main source of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

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

Only A>130



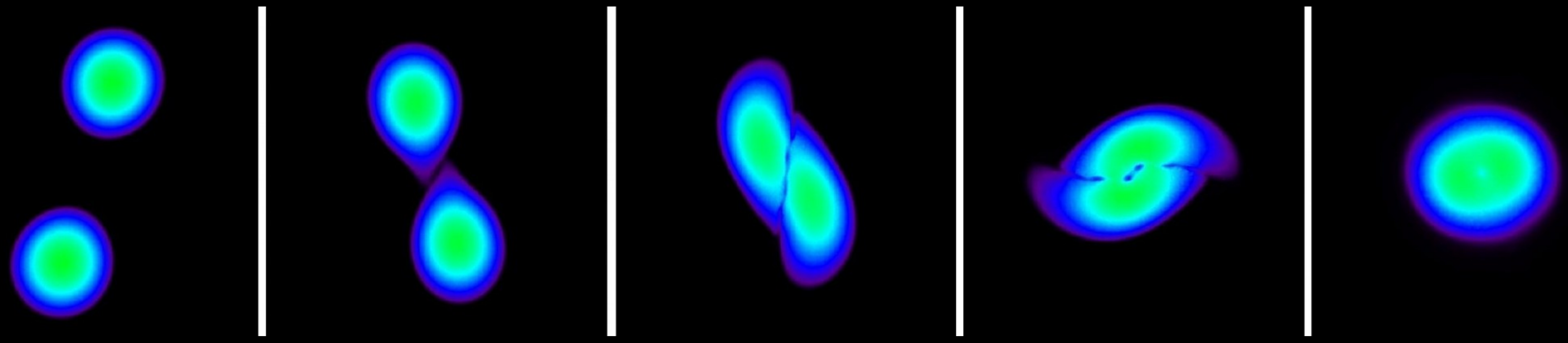
Just et al. 2015



Bauswein et al. 2014

EoS / NS constraints

Finite-size effects during late inspiral



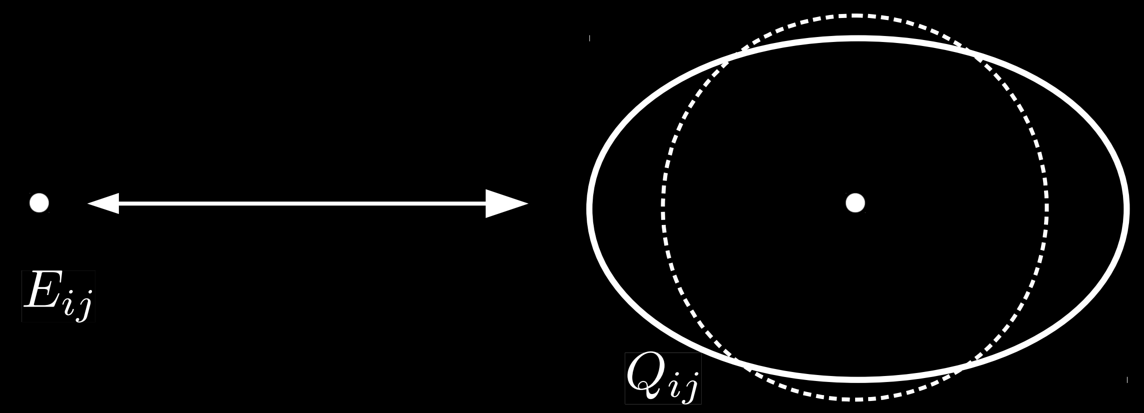
Description of tidal effects during inspiral

- Tidal field E_{ij} of on star induces change of quadrupole moment Q_{ij} of other component
- Changed quadrupole moment affects GW signal, especially phase evolution

  → inspiral faster compared to point-particle inspiral
- Strength of induced quadrupole moment depends on NS structure / EoS:

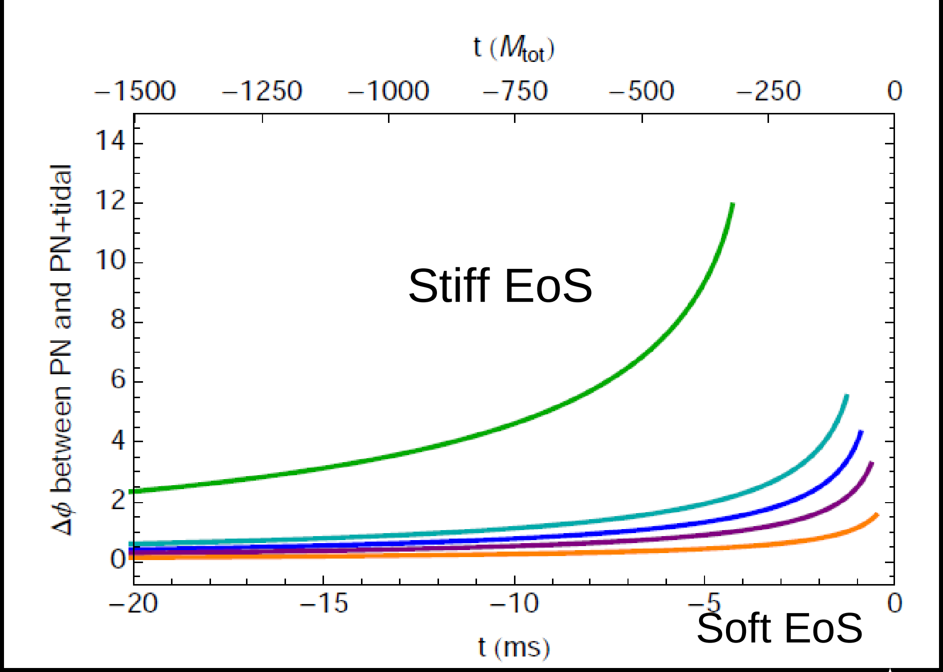
$$Q_{ij} = -\lambda(M)\, E_{ij} \qquad\qquad \lambda(M) = \frac{2}{3} k_2(M) R^5$$

- Tidal deformability depends on radius (clear – smaller stars are harder to deform) and "Love number" k_2 (~"TOV" properties)
- k_2 also depends on EoS and mass



Inspiral

- Orbital phase evolution affected by tidal deformability – only during last orbits before merging
- Inspiral accelerated compared to point-particle inspiral for larger Lambda
- Difference in phase between NS merger and point-particle inspiral:



EoS impact measured by tidal deformability

$$\Lambda(M) = \frac{2}{3} k_2(M) \left(\frac{c^2 R}{G M} \right)^5$$

e.g. Read et al. 2013

Merger time of point particle

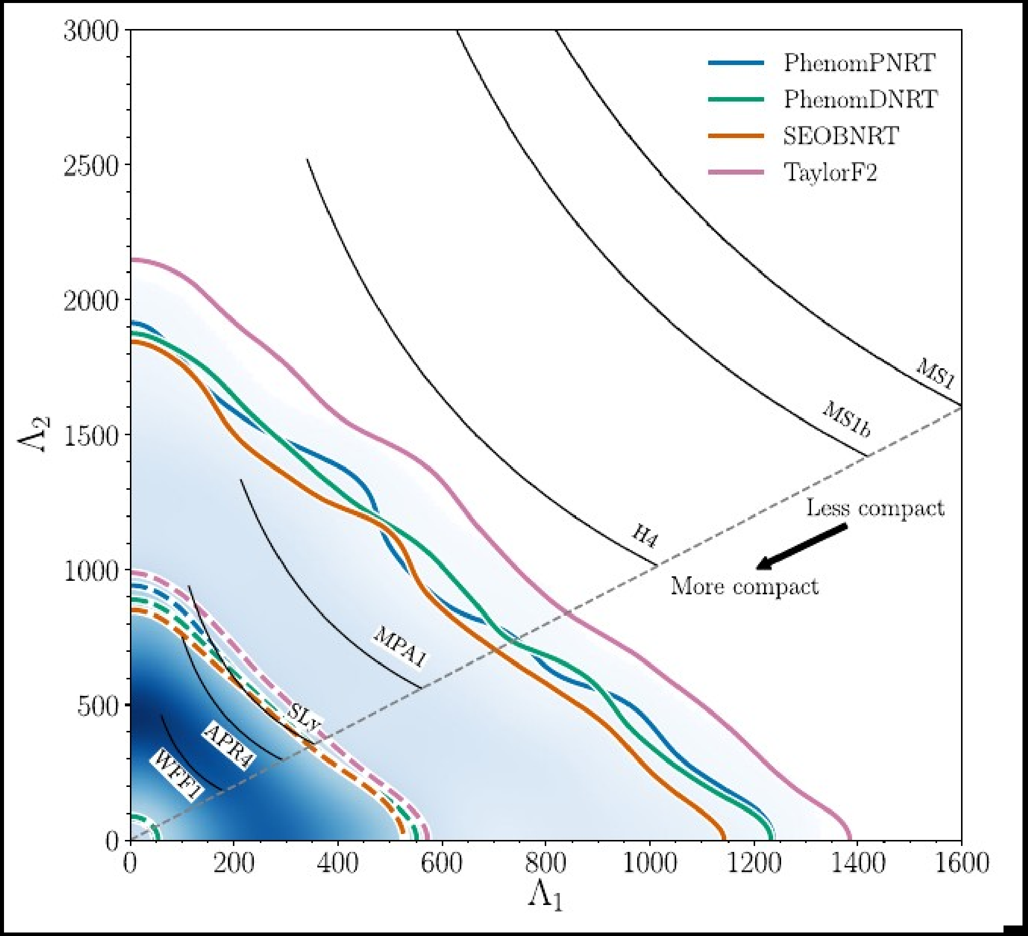
Challenge: construct faithful templates for data analysis

Measurement

- Lambda < ~800 (reanalysis: < 650)

  → Means that very stiff EoSs are excluded
- Recall uncertainties in mass measurements (only Mchirp accurate)
- systematic errors in waveform model

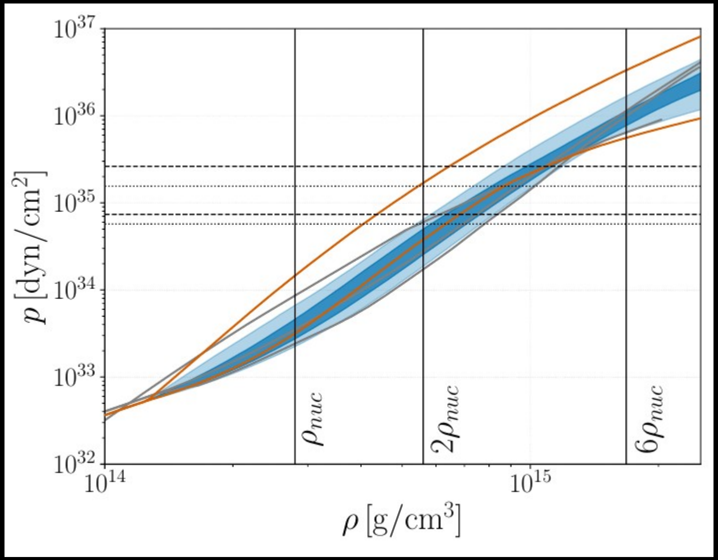
  → ongoing research
- Better constraints expected in future as sensitivity increases



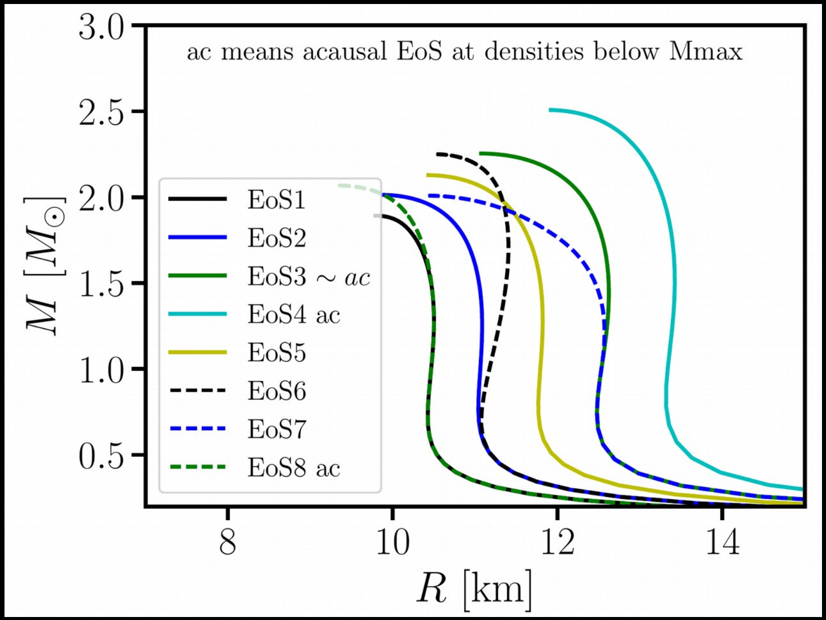
$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}$$

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

Finite-size effects – future prospects

- Measurements of Lambda (~to within several per cent)
- Two caveats:

  - at some point systematics will play a role (better waveform models required)

  - more massive NSs harder to measure because tidal deformability and finite-size effects smaller

Multi-messenger constraints

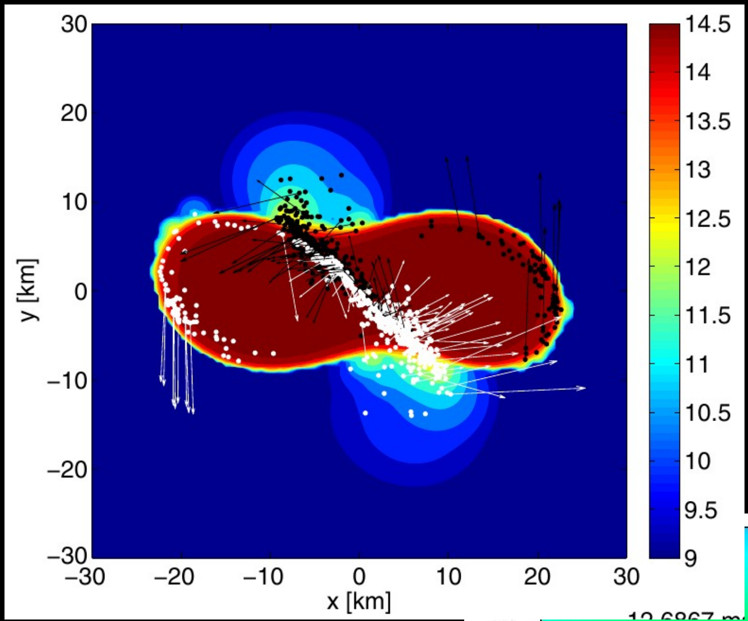
More information – more constraints – but typically model-dependence

Different ideas (some similar) – for Mmax and radii

Basic picture

- Mass ejection → rapid neutron-capture process → heating the ejecta

  → (quasi-) thermal emission in UV – optical – IR observable (time scales ~ hours)
- Different ejecta components: dynamical ejecta, secular ejecta from merger remnant
- Mass ejection depends on binary masses and EoS → imprinted on electromagnetic emission

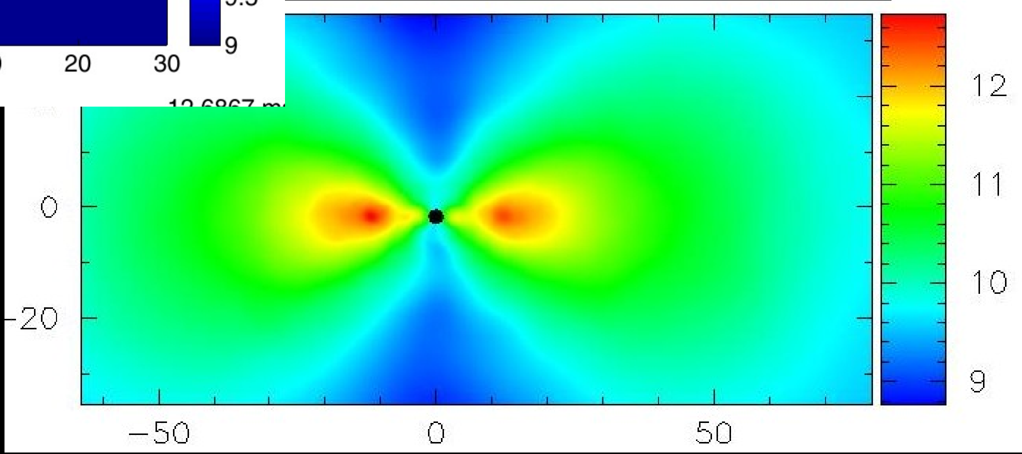


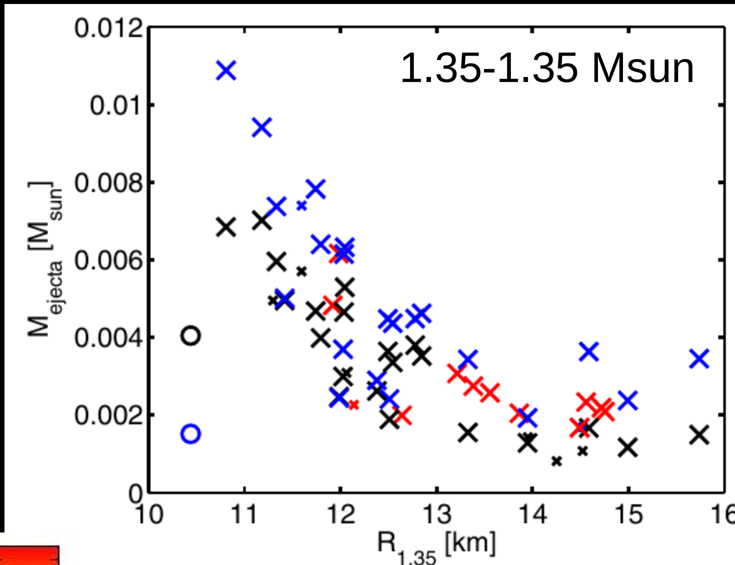
Dynamical ejeca

Luminosity:

$$L \propto \sqrt{v}\sqrt{M_{ejecta}}$$

Remnant: BH torus





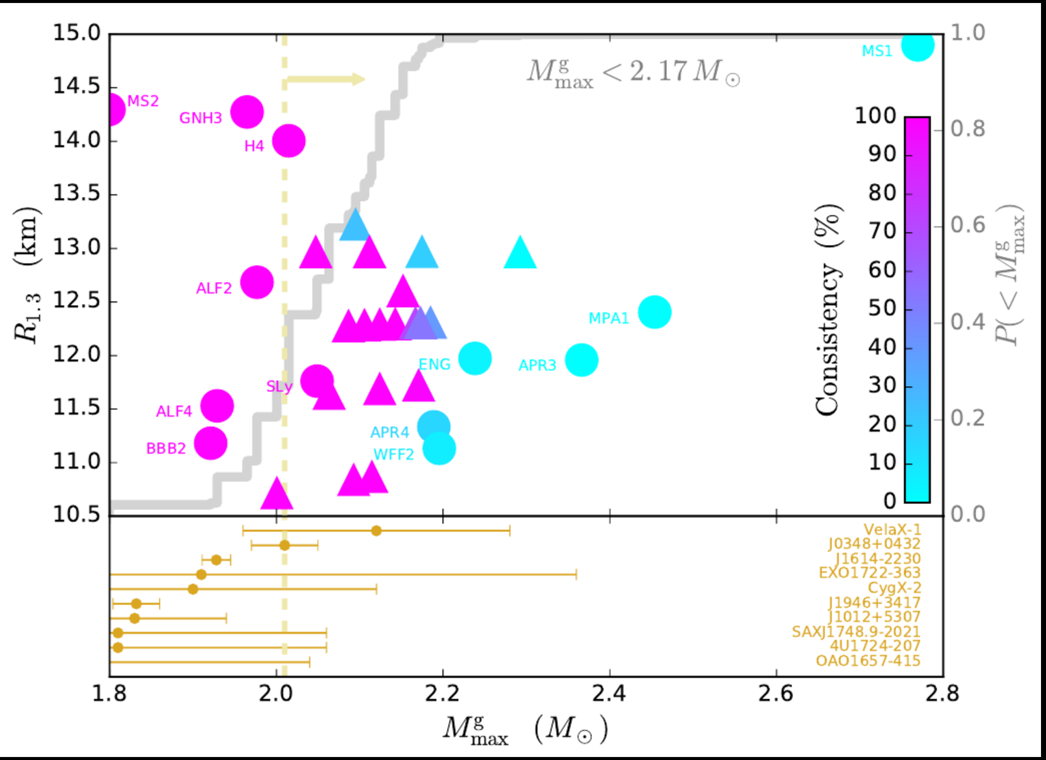
EoS dependence

Secular ejecta form BH torus or NS remnant by viscous effects and neutrino wind

M_{max} from GW170817

- Arguments: no prompt collapse; no long-lasting pulsar spin-down (too less energy deposition)
- If GW170817 did not form a supramassive NS (rigidly rotating > M_{max})

  → M_{max} < ~2.2-2.4 M_{sun} (relying on some assumption)



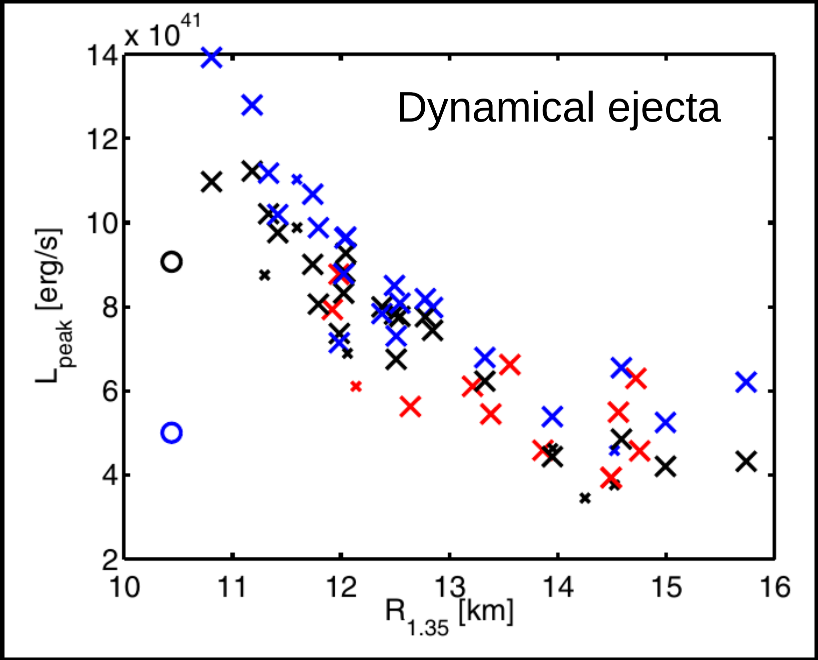
Margalit & Metzger 2017

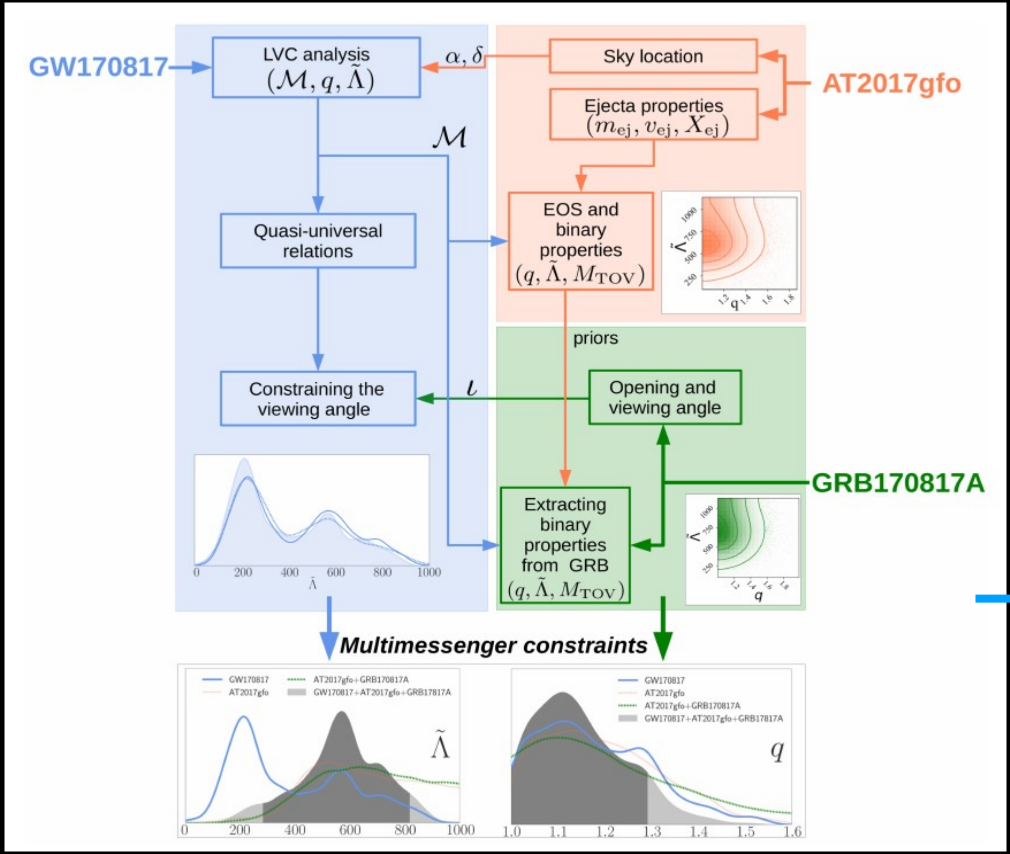
See also Shibata et al 2017, Fujibajshi et al. 2017, Rezzolla et al 2018, Ruiz & Shapiro 2018, Shibata et al 2018 ...

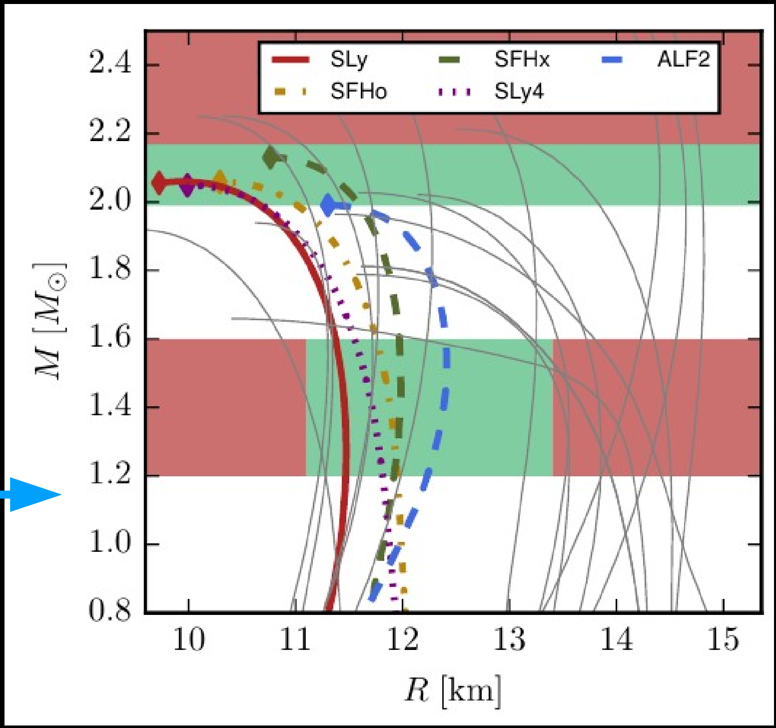
Bauswein et al 2013

Combing all information

- Bayesian analysis: employing EoS dependence of em emission
- Hard to assess systematic uncertainties
- Exact em display difficult to compute: radiative transfer, nucleosynthesis, opacities, uncertainties in hydro-simulation results, GRB mechansim, ... (relying on assumptions)

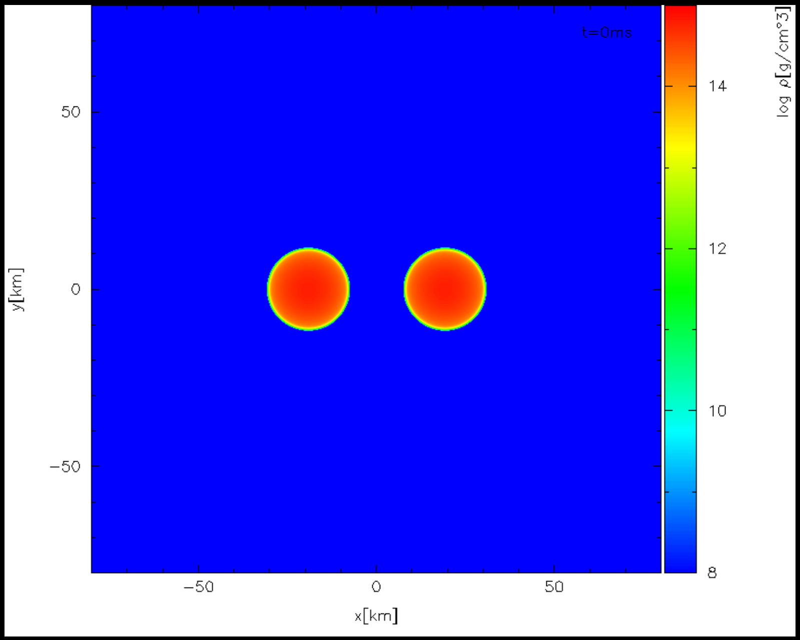






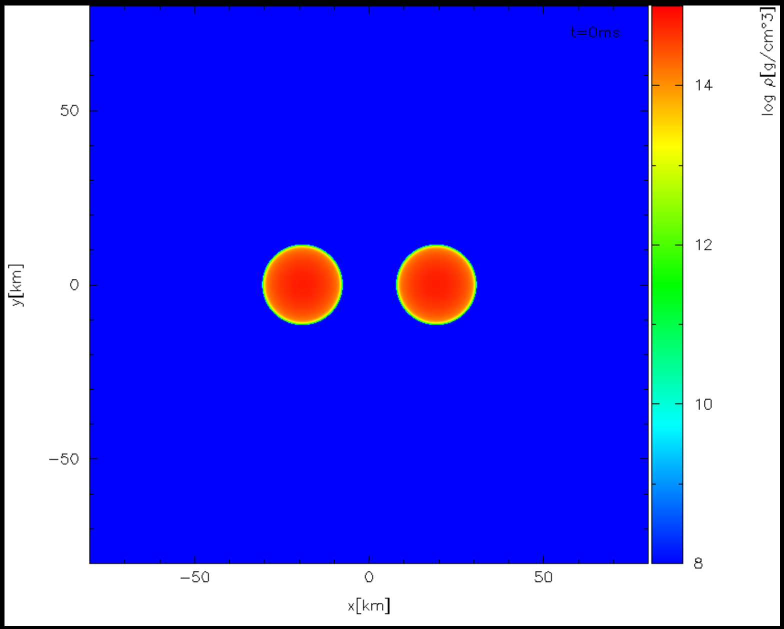
Coughlin et al. 2018

Constraint from collapse behavior



$M_{\rm tot} = 3.4\ M_\odot$

$M_{\rm tot} = 3.5\ M_\odot$



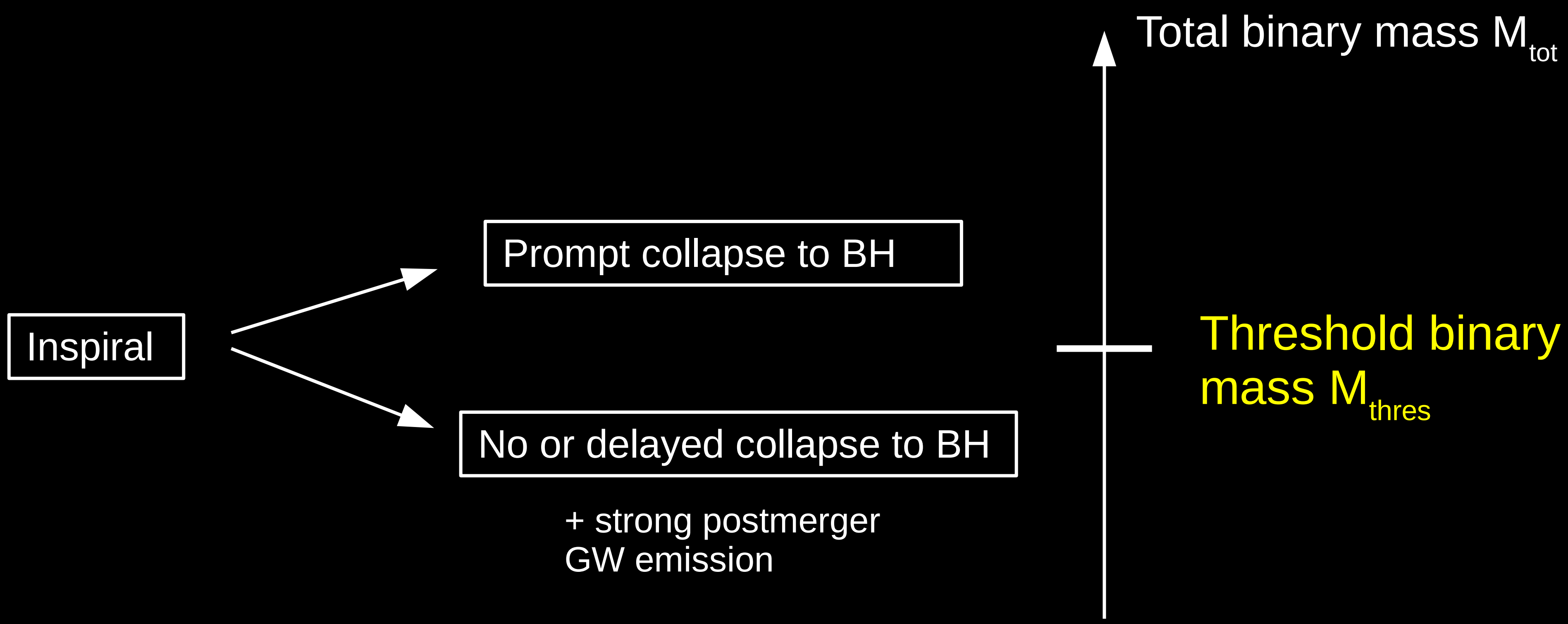
Shen EoS

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

Collapse behavior: Prompt vs. delayed (/no) BH formation
→ distinguishable by presence of postmerger GWs
and brightness of em counterpart

Relevant for: 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

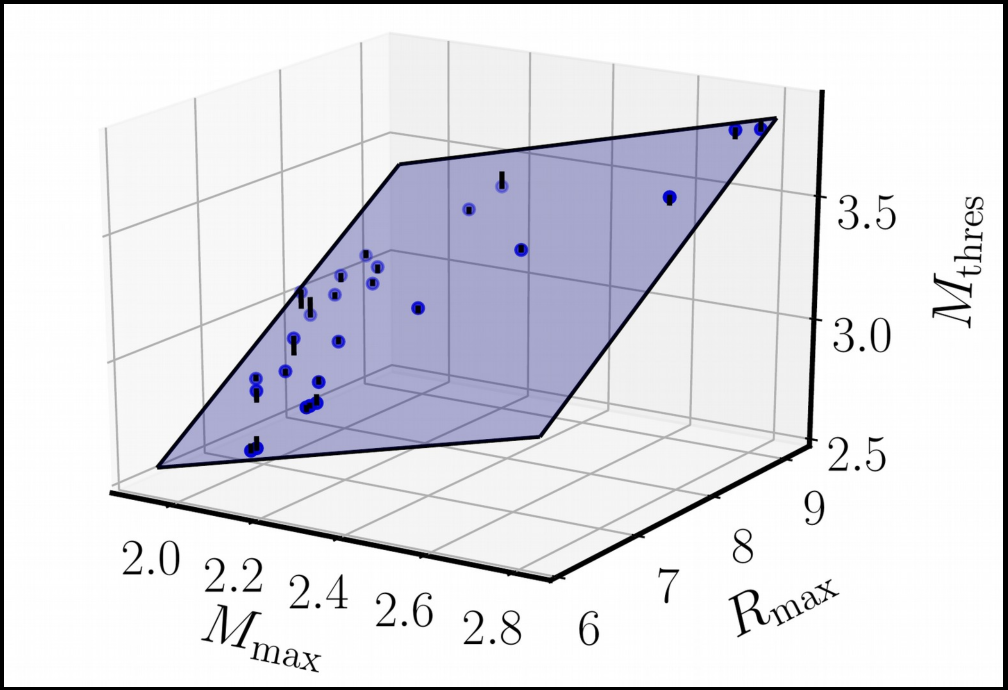
Threshold binary mass

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

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

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

- Both better than 0.06 M_{sun}



EoS constraints from GW170817*

→ lower bound on NS radii

(recall: upper bound from tidal deformability)

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

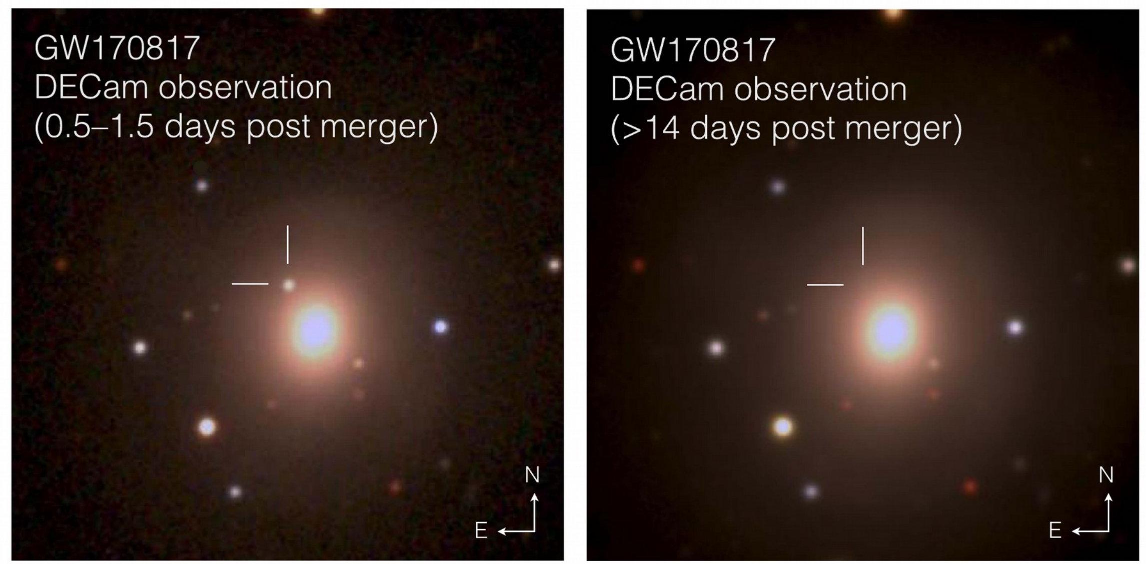
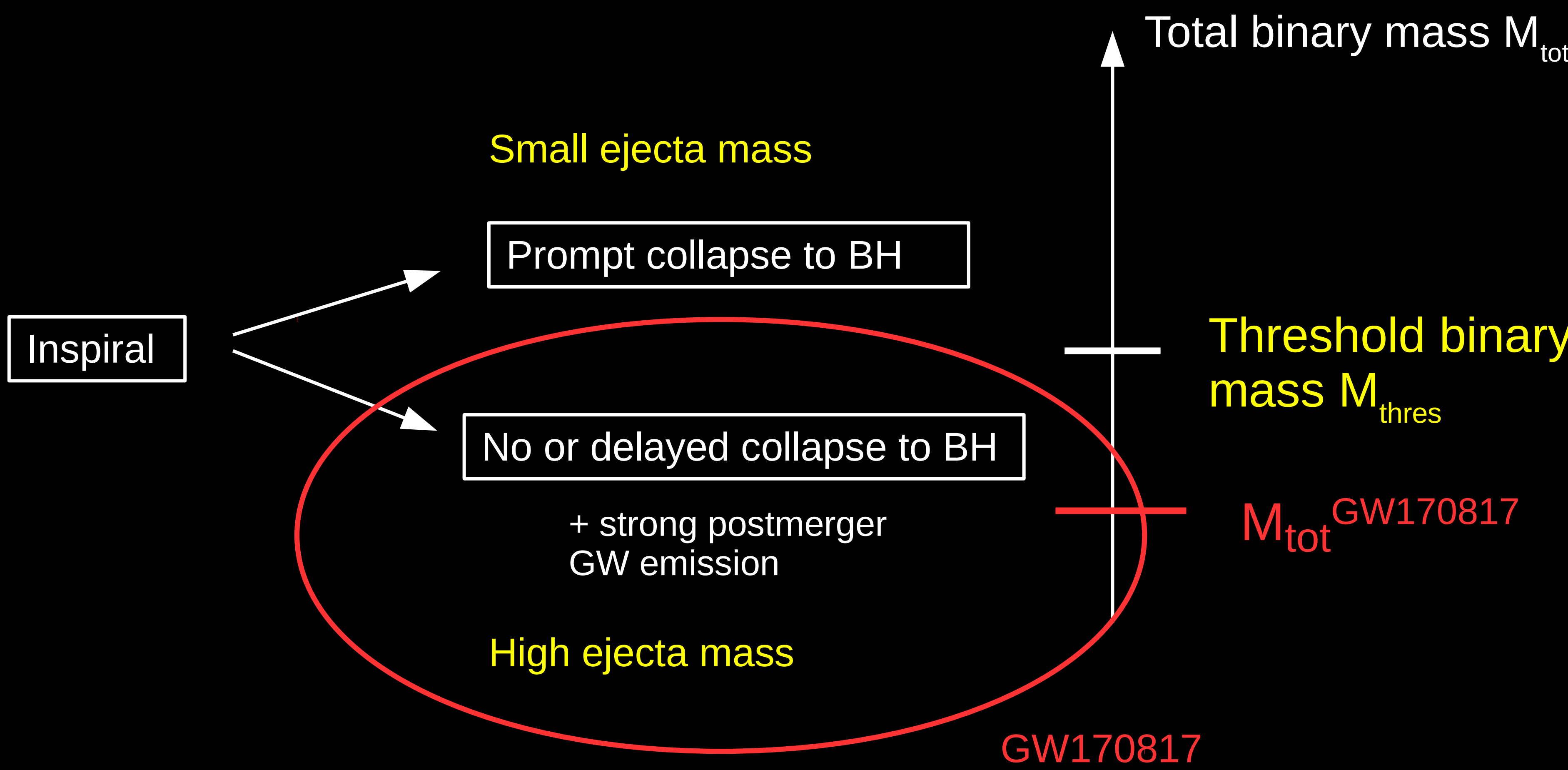


Figure 1. NGC4993 *grz* color composites (1$'$.5 × 1$'$.5). Left: composite of detection images, including the discovery *z* image taken on 2017 August 18 00:05:23 UT and the g and r images taken 1 day later; the optical counterpart of GW170817 is at R.A., decl. =197.450374, −23.381495. Right: the same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

Soares-Santos et al 2017

Collapse behavior



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

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

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

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

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

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

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

- Putting things together:

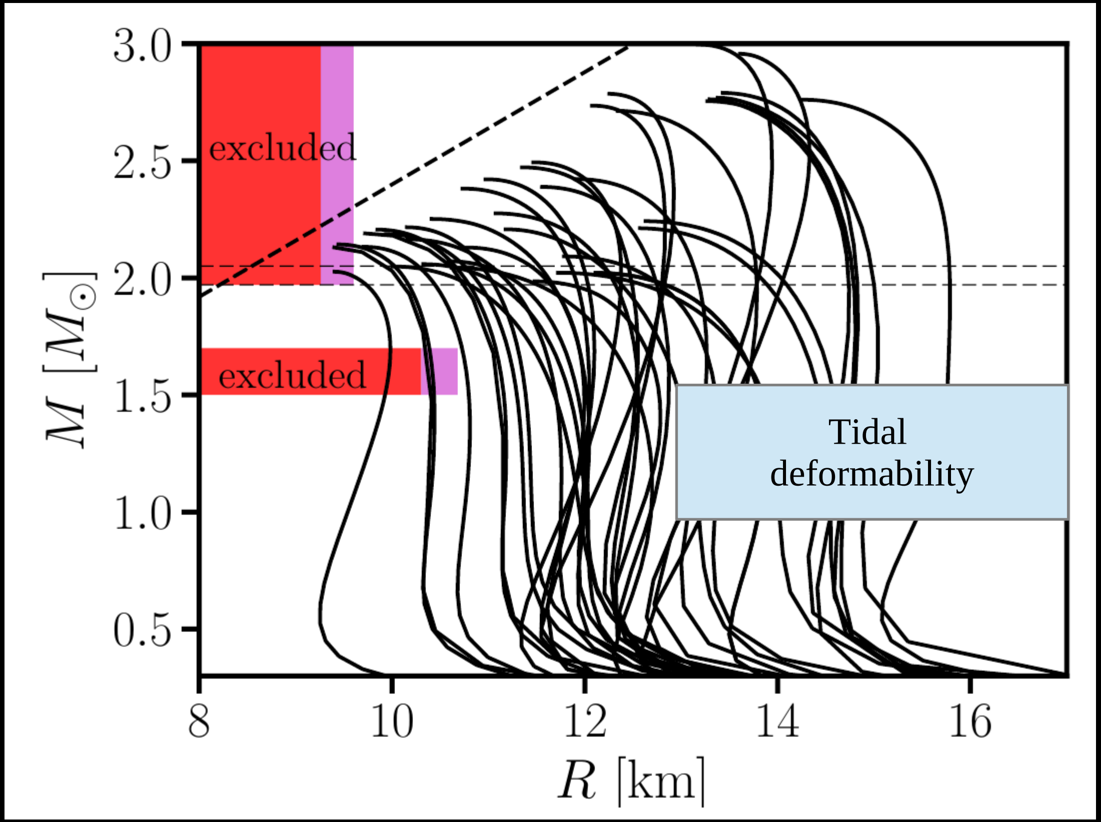
$$M_{\mathrm{tot}}^{GW170817} \leq \left(-3.38\frac{G\,M_{\mathrm{max}}}{c^2\,R_{\mathrm{max}}} + 2.43\right)M_{\mathrm{max}} \leq \left(-\frac{3.38}{2.82} + 2.43\right)\frac{1}{2.82}\frac{c^2\,R_{\mathrm{max}}}{G}$$

→ Lower limit on NS radius

Bauswein et al. 2017

NS radius constraint from GW170817

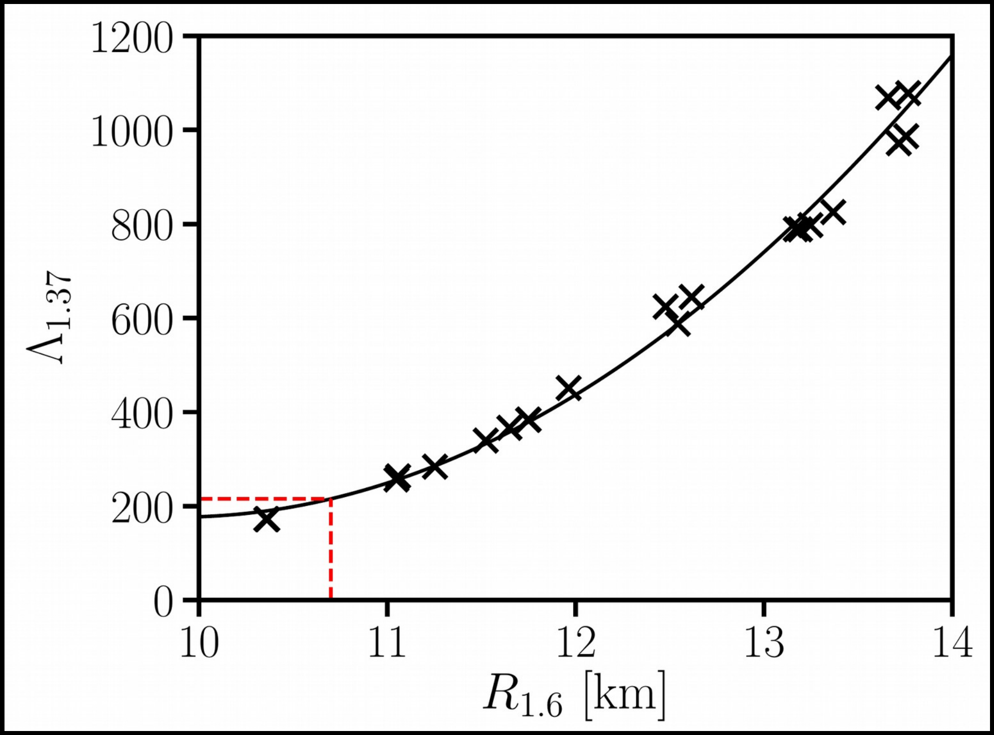
- R_{max} > 9.6 km
- $R_{1.6}$ > 10.7 km
- Excludes very soft nuclear matter
- follow-up Koeppel et al 2019 (same idea) arriving at similar constraints of 10.7 km



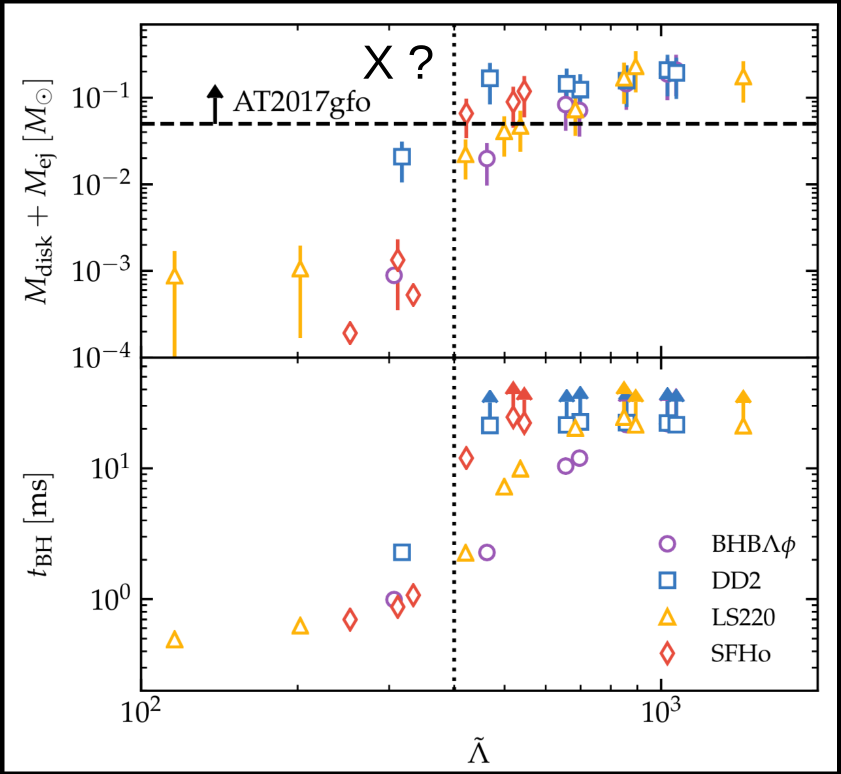
Bauswein et al. 2017

Radius vs. tidal deformability

Radice et al 2018



unpublished



- Radius and tidal deformability scale tightly → **Lambda > 210**
- Compared to Lambda > 400 / 300 in Radice et al 2018/2019 following similar arguments
- limit cannot be much larger than 200 because there are EoSs (with somewhat larger Lambda) that do NOT result in a prompt collapse and thus in a bright em counterpart (see also Kiuchi et al. 2019) !!

  → full EoS coverage essential !!!

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 !!!

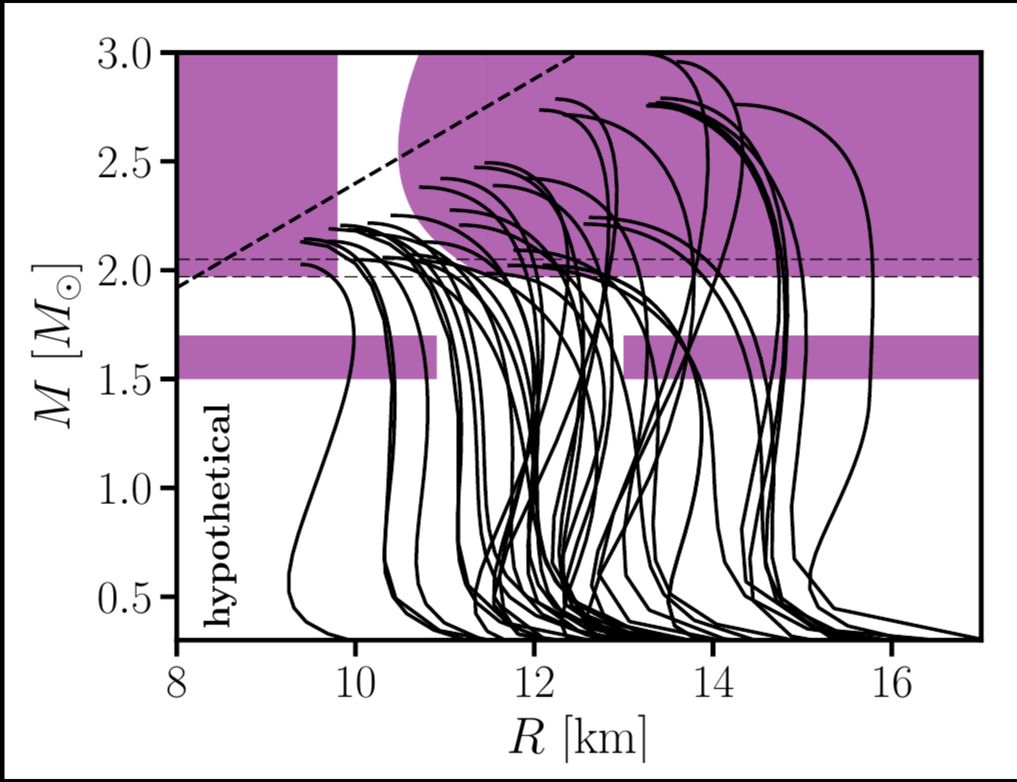
Future

- 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

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 2017, Shibata et al 2017, Rezzolla et al 2018, Ruiz & Shapiro 2018, Shibata et al. 2019, ...)

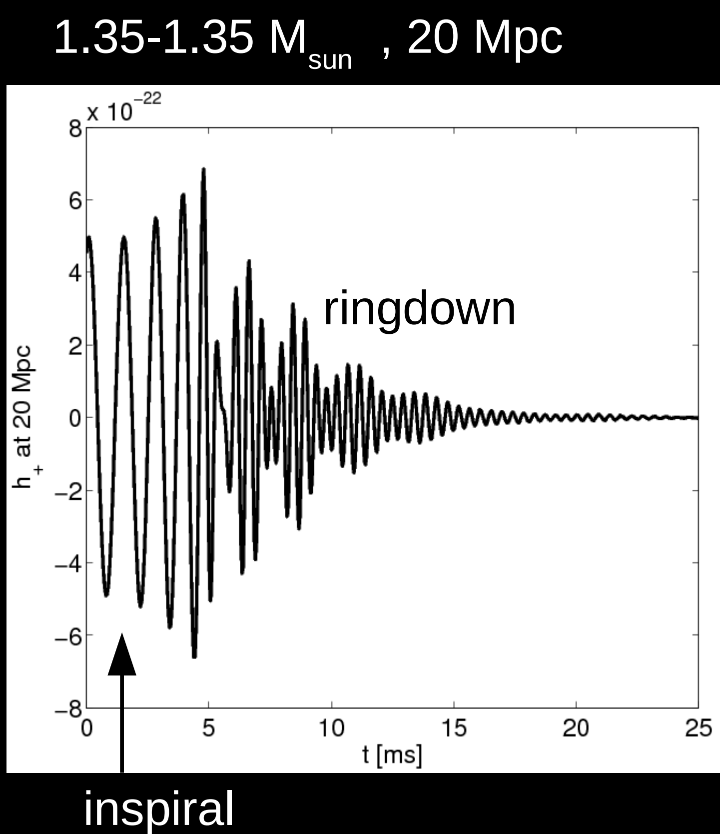
Future: Postmerger GW emission*

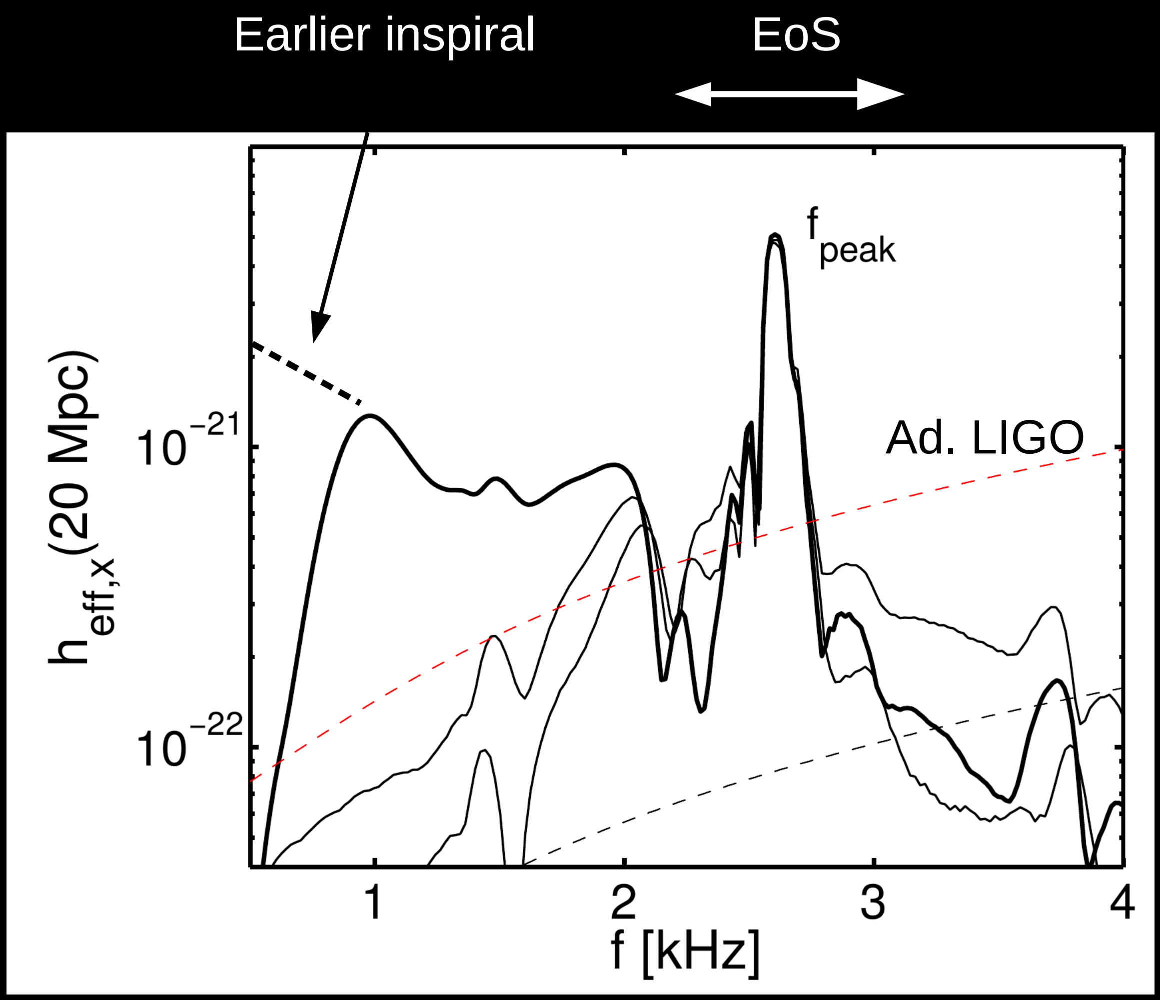
(dominant frequency of postmerger phase)

→ determine properties of EoS/NSs
→ complementary to inspiral

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

Postmerger

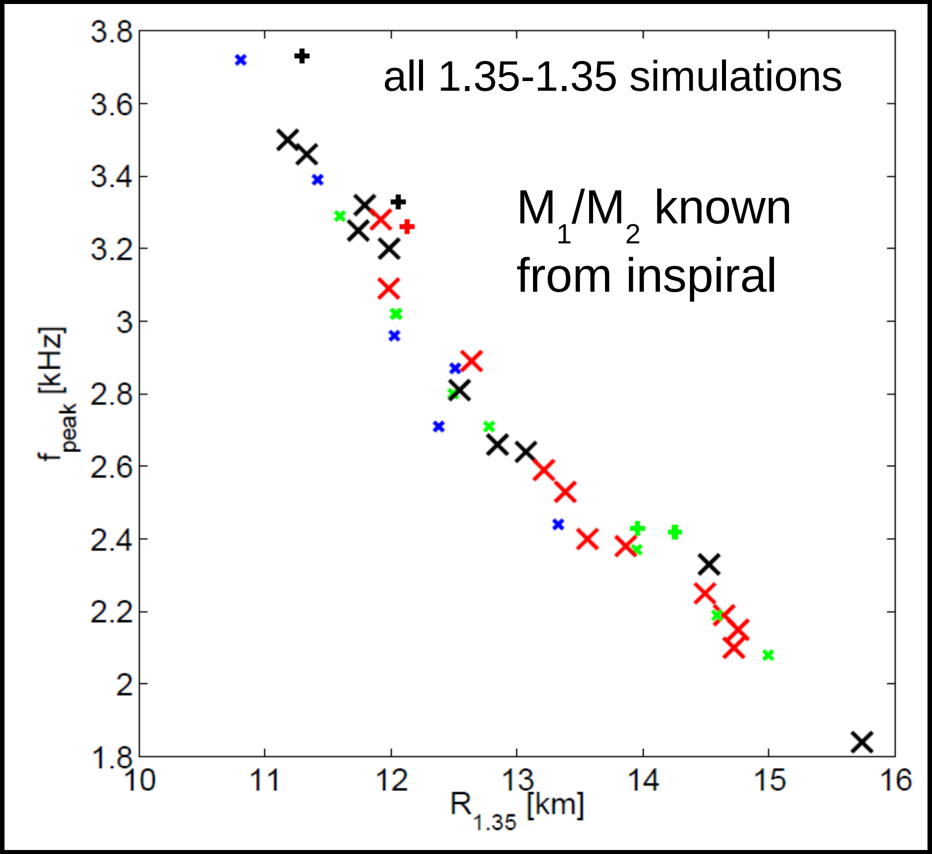


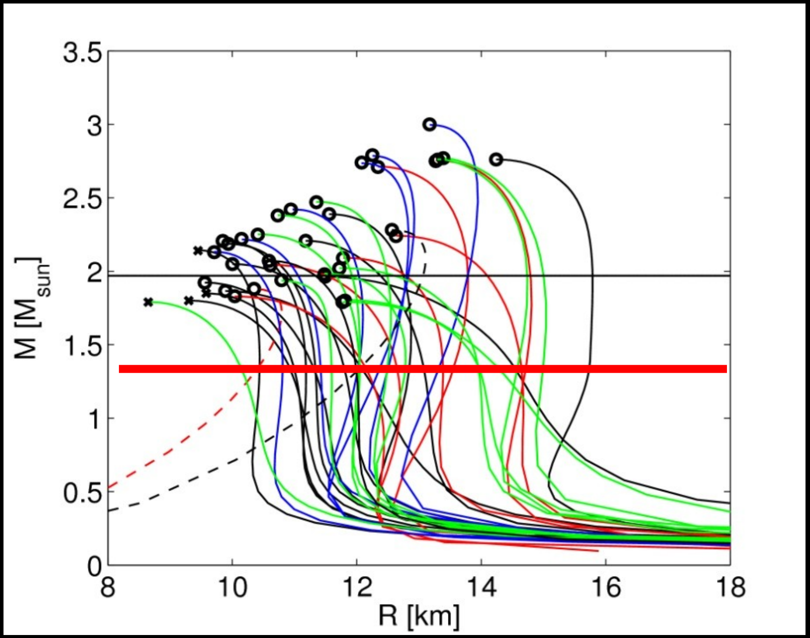


Dominant postmerger oscillation frequency f_{peak}

Very characteristic (robust feature in all models)

Gravitational waves – EoS survey





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

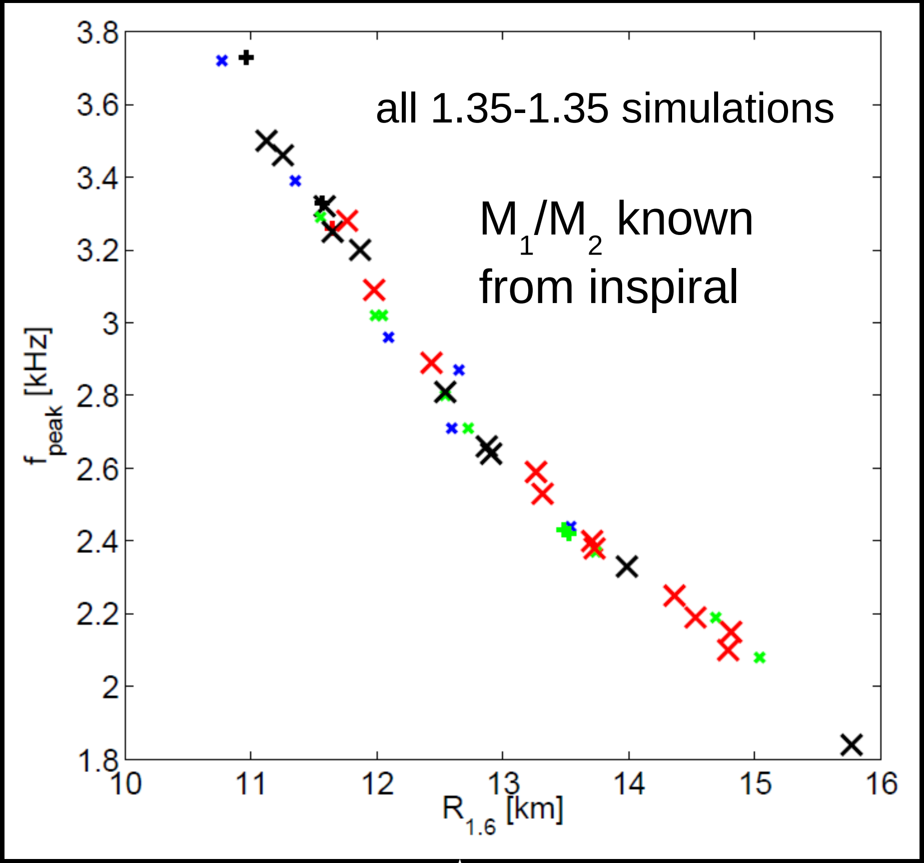
Bauswein et al. 2012

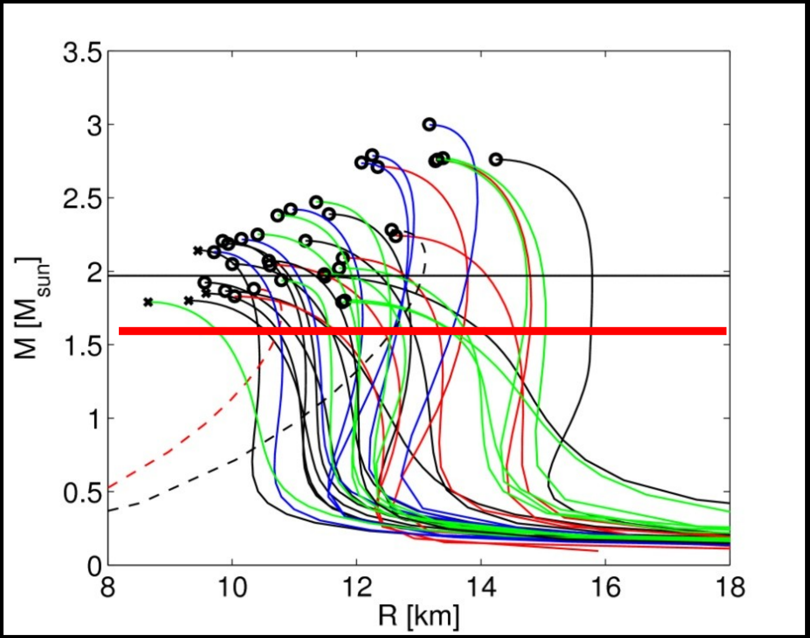
Pure TOV/EoS property => Radius measurement via f_{peak}

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

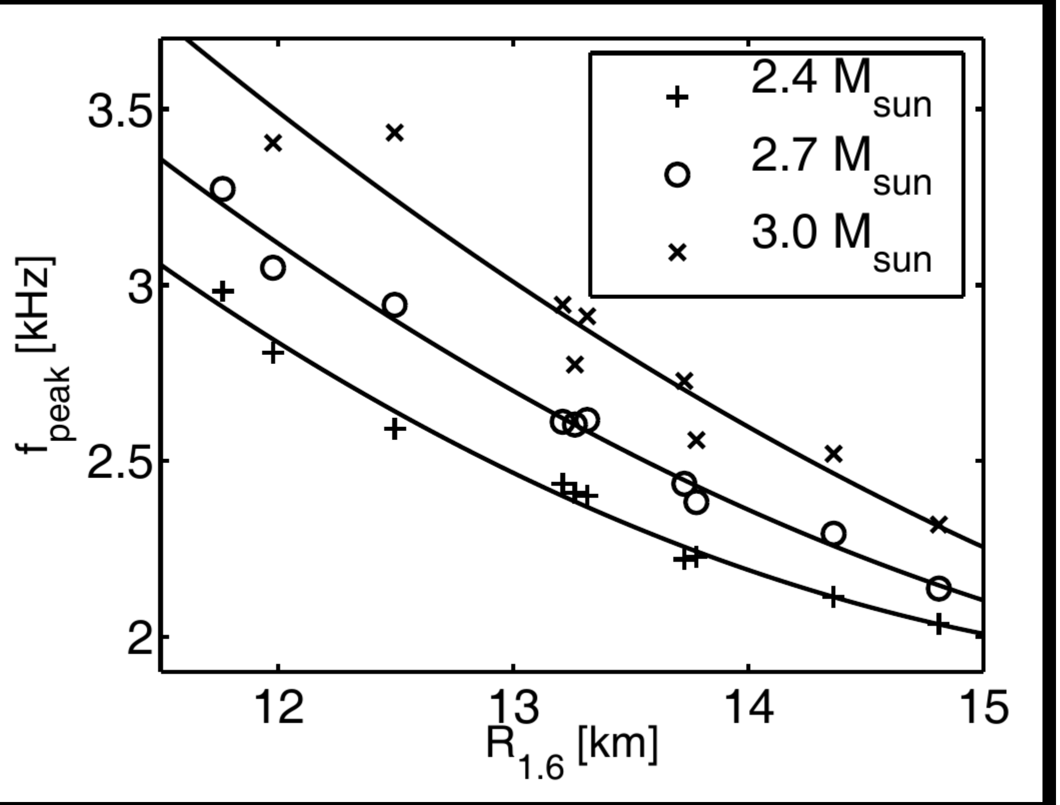
Note: R of 1.6 M_{sun} NS scales with f_{peak} from 1.35-1.35 M_{sun} mergers (density regimes comparable)

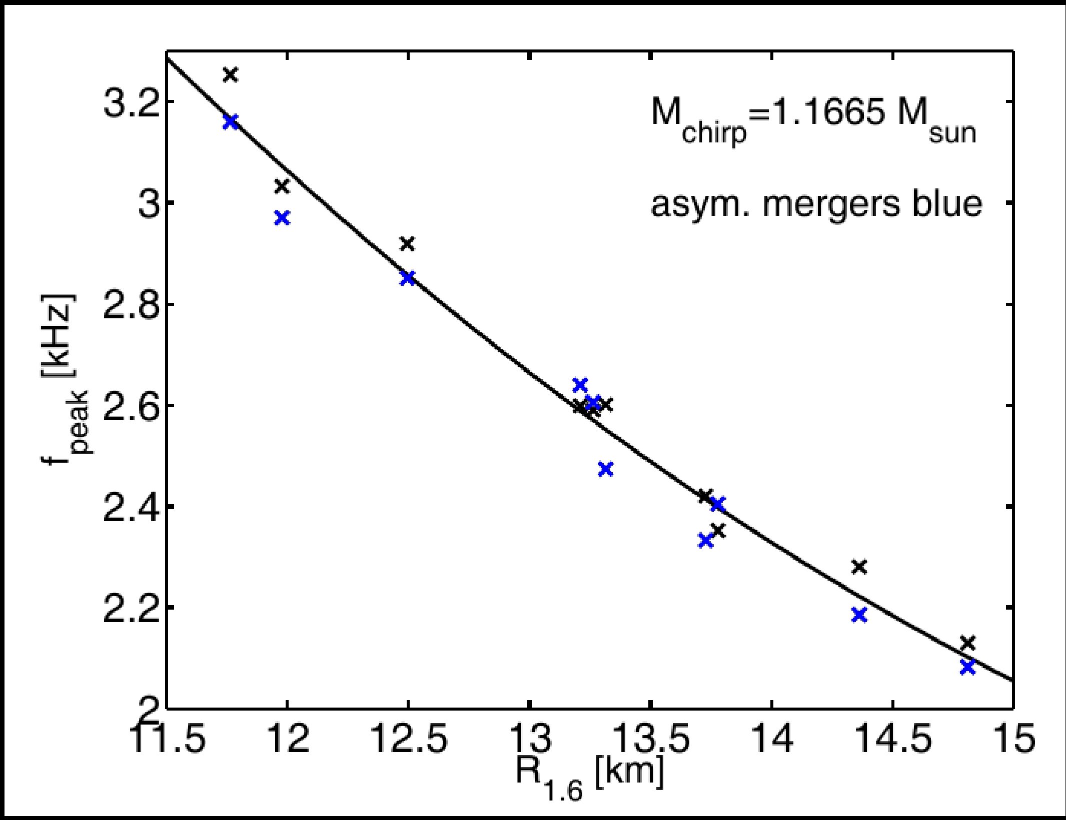
GW data analysis: Clark et al 2014, Clark et al 2016, Chatziioannou et al 2017, …

→ detectable at a few 10 Mpc

Binary mass variations

Bauswein et al. 2012, 2016





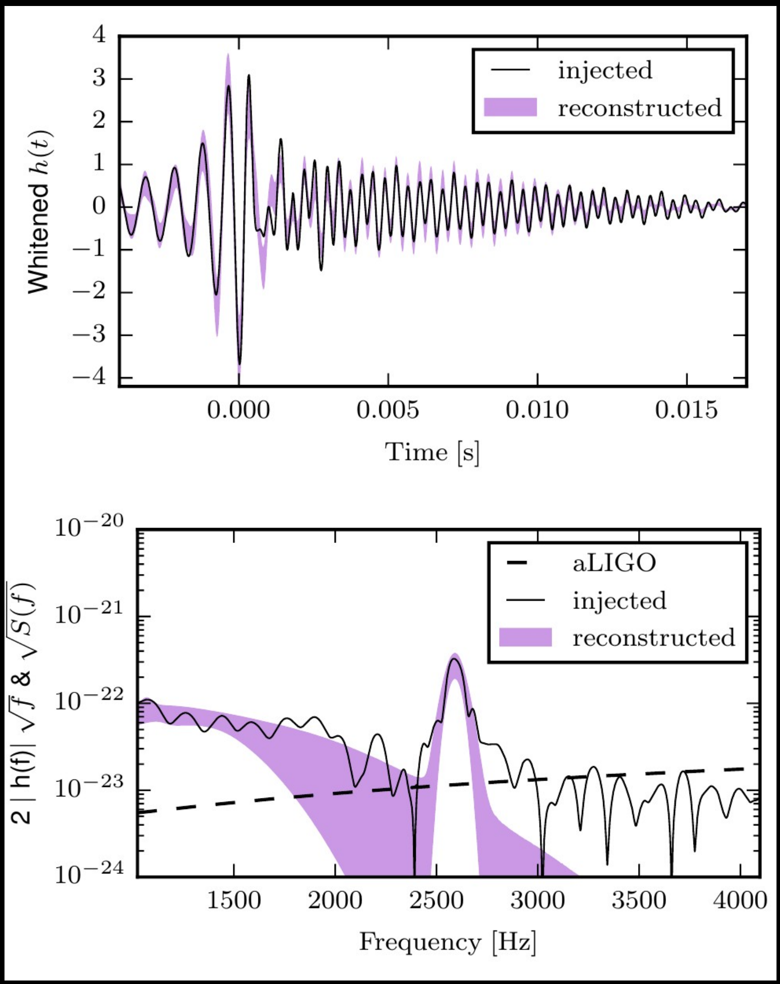
Different total binary masses (symmetric)

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

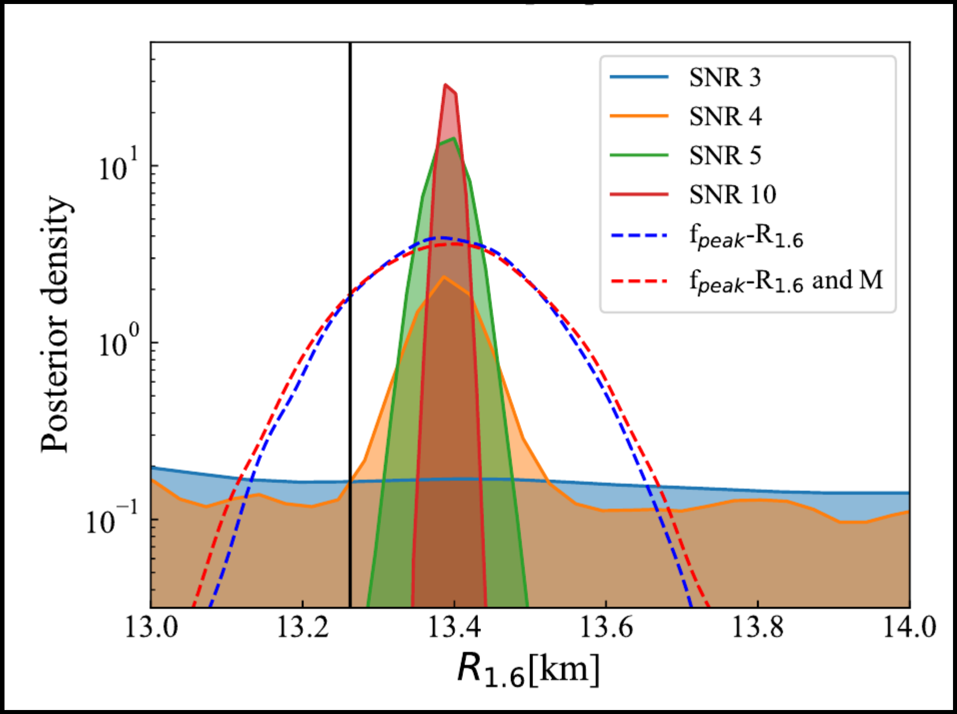
Data analysis: see e.g. Clark et al. 2016 (PCA), Clark et al. 2014 (burst search), Chatziioannou et al 2017, Torres-Riva et al 2019

→ f_{peak} precisely measurable !!!

Model-agnostic data analysis



Based on wavelets



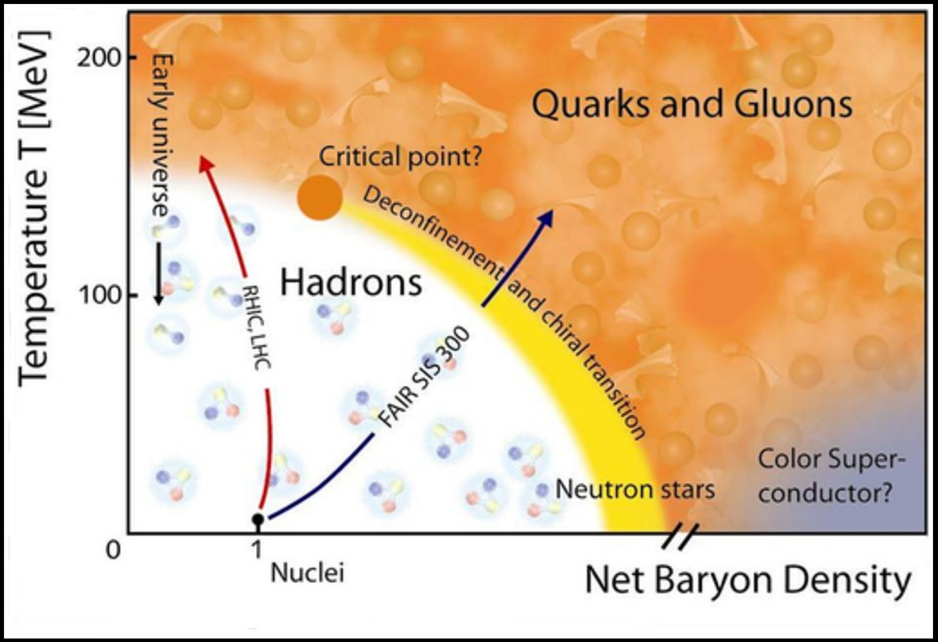
Chatziioannou et al. (2017), Torres-Riva et al 2019

Impact of QCD phase transition detectable

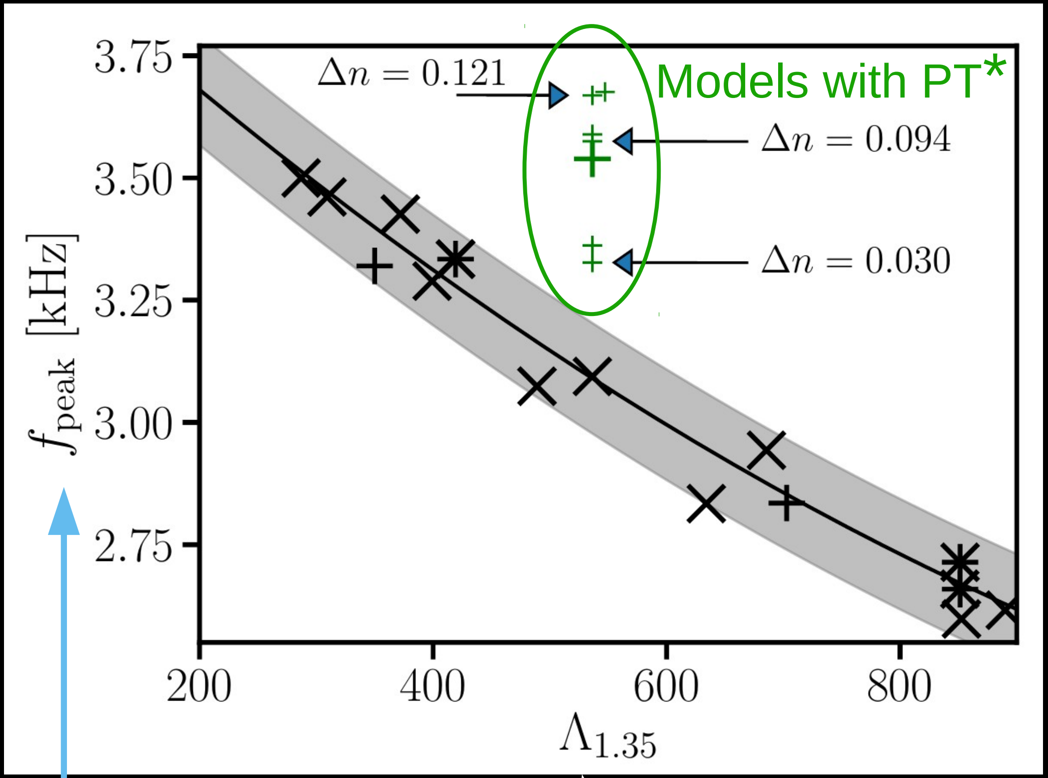
- 1st order phase transition leads to characteristic increase of postmerger frequency relative to tidal deformability

  → presence of phase transition at NS / nuclear densities can be identified or excluded !!

GSI/FAIR



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



Measurable from postmerger

Measurable from inspiral

* a set of hybrid quark matter equations of state computed by Wroclaw group (Bastian, Blaschke, Fischer)

Summary and conclusions

- Tidal deformability from inspiral phase: NS radius must be smaller then ~13.5 km

  → nuclear matter not extremely stiff
- NS radius must be larger than 10.7 km (very robust and conservative)

  → nuclear matter not extremely soft
- 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}

  → high-density regime accessible
- Strong 1st order phase transitions leave characteristic imprint on GW (postmerger frequency higher than expected from inspiral)