Supported by ERC through Starting Grant no. 759253

European Research Council
Established by the European Commission

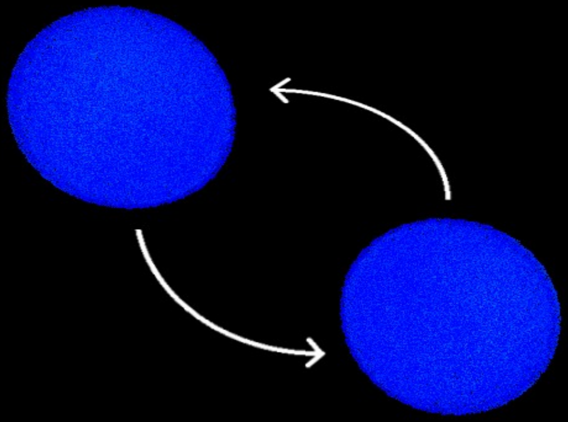
Gravitational waves and neutron star mergers

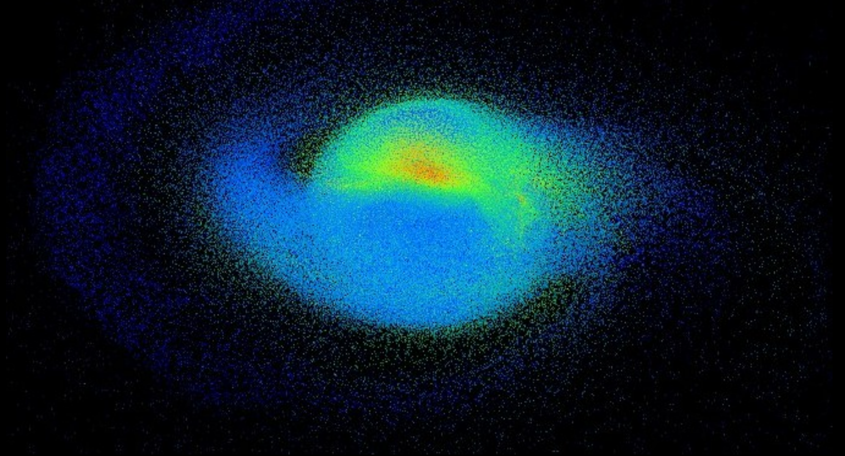
International School of Nuclear Physics: 41st Course - Star Mergers, Gravitational Waves, Dark Matter and Neutrinosin Nuclear, Particle and Astro-Physics, and in Cosmology

Erice, 17/09/2019

Andreas Bauswein

GSI Darmstadt





A break-through in astrophysics

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

Detection August 17, 2017 by LIGO-Virgo network

→ GW data analysis

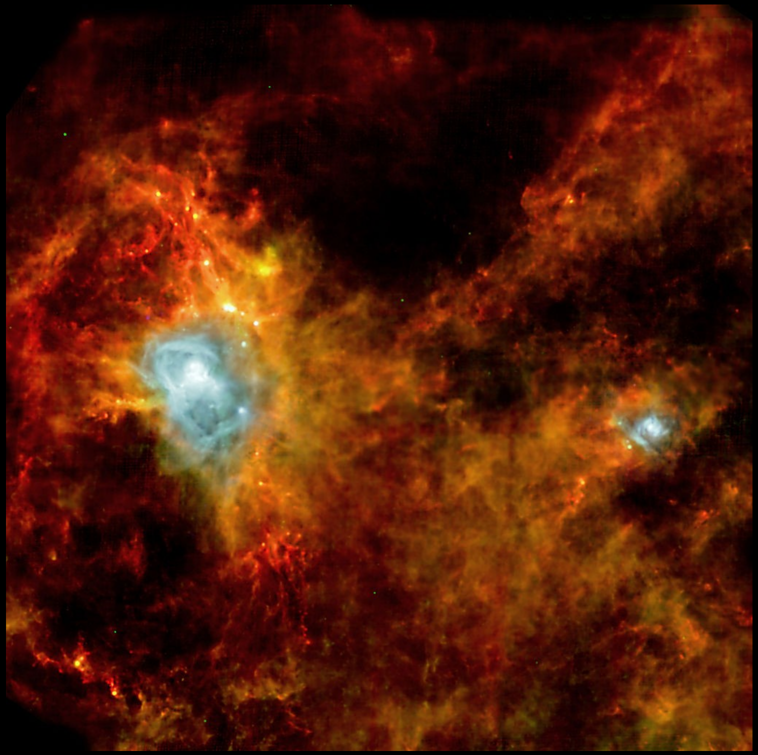
→ follow-up observations - probably largest coordinated observing campaign in astronomy (observations/time)

Announcement October 2017

Meanwhile several more detections at larger distances

NS mergers - what can be learned (from this and future events)

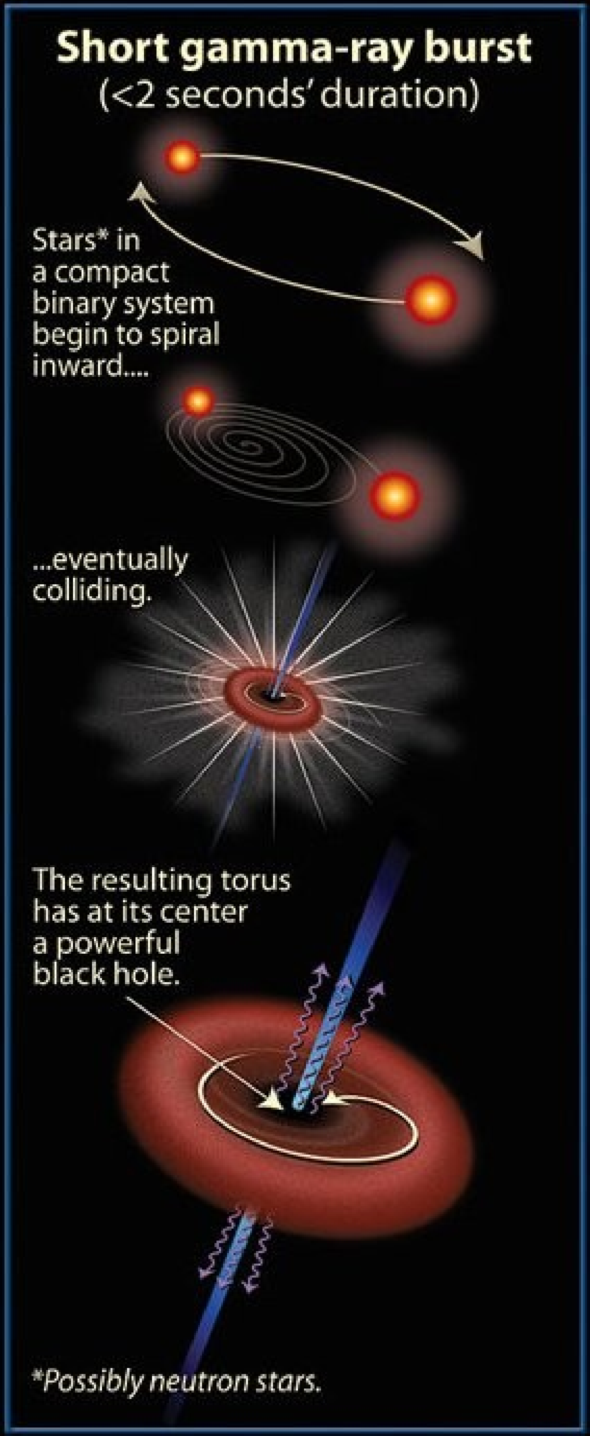
- Properties of NS and NS binary population, host galaxies
- Origin of short gamma-ray bursts (and related emission)
- Origin of heavy elements like gold, uranium, platinum
- Origin of electromagnetic transient (kilonova, marconova)
- Properties of nuclear matter / NS structure
- Occurrence of QCD phase in NS
- Independent constraint on Hubble constant
- … !!!



Star-forming region, ESA/Spire

NS mergers - what can be learned (from this and future events)

- Properties of NS and NS binary population, host galaxies
- Origin of short gamma-ray bursts (and related emission)
- Origin of heavy elements like gold, uranium, platinum
- Origin of electromagnetic transient (kilonova, marconova)
- Properties of nuclear matter / NS structure
- Occurrence of QCD phase in NS
- Independent constraint on Hubble constant
- … !!!

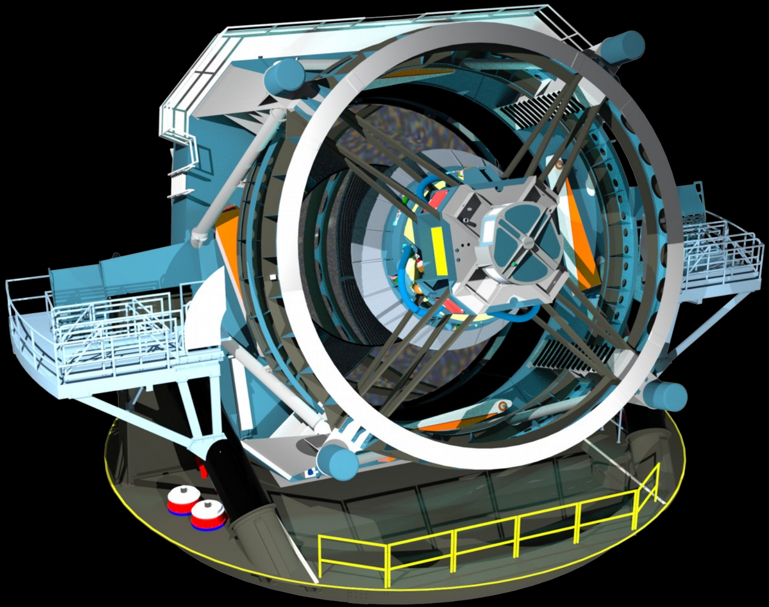


NS mergers - what can be learned (from this and future events)

- Properties of NS and NS binary population, host galaxies
- Origin of short gamma-ray bursts (and related emission)
- Origin of heavy elements like gold, uranium, platinum formed through r-process
- Origin of electromagnetic transient (kilonova, marconova)
- Properties of nuclear matter / NS structure
- Occurrence of QCD phase in NS
- Independent constraint on Hubble constant
- … !!!

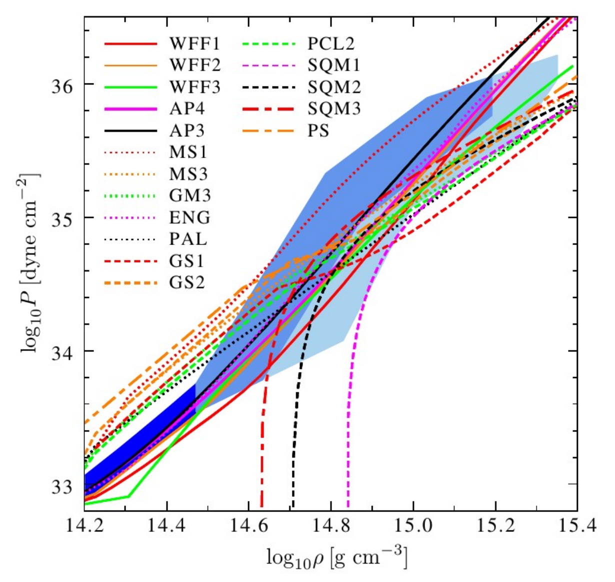
NS mergers - what can be learned (from this and future events)

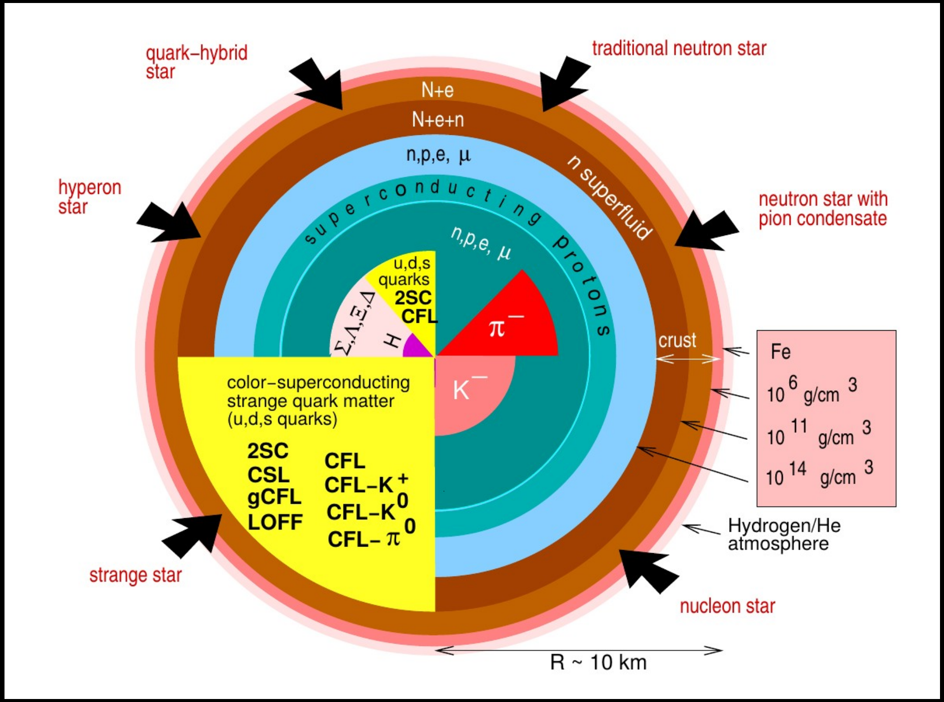
- Properties of NS and NS binary population, host galaxies
- Origin of short gamma-ray bursts (and related emission)
- Origin of heavy elements like gold, uranium, platinum
- Origin of electromagnetic transient (kilonova, marconova) powered by r-process
- Properties of nuclear matter / NS structure
- Occurrence of QCD phase in NS
- Independent constraint on Hubble constant
- … !!!



NS mergers - what can be learned (from this and future events)

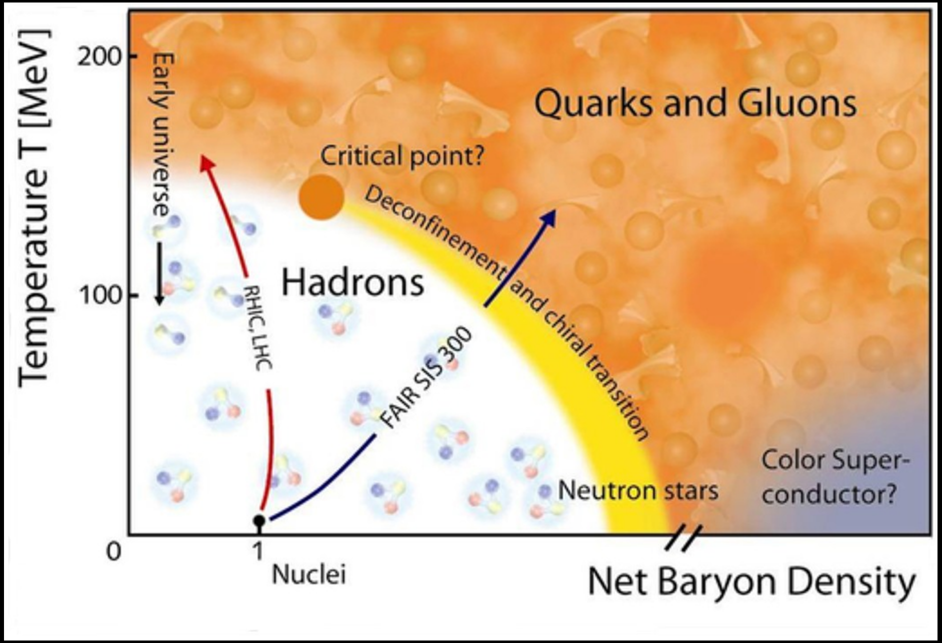
- Properties of NS and NS binary population, host galaxies
- Origin of short gamma-ray bursts (and related emission)
- Origin of heavy elements like gold, uranium, platinum
- Origin of electromagnetic transient (kilonova, marconova)
- Properties of nuclear matter / NS structure
- Occurrence of QCD phase in NS
- Independent constraint on Hubble constant
- … !!!





NS mergers - what can be learned (from this and future events)

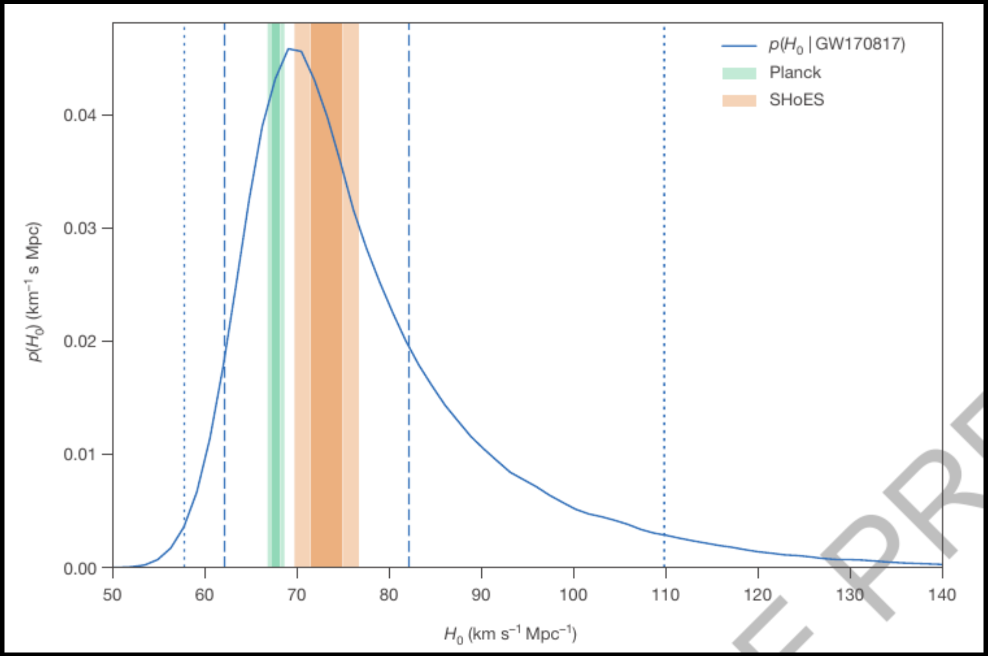
- Properties of NS and NS binary population, host galaxies
- Origin of short gamma-ray bursts (and related emission)
- Origin of heavy elements like gold, uranium, platinum
- Origin of electromagnetic transient (kilonova, marconova)
- Properties of nuclear matter / NS structure
- Occurrence of QCD phase in NS
- Independent constraint on Hubble constant
- … !!!



NS mergers - what can be learned (from this and future events)

- Properties of NS and NS binary population, host galaxies
- Origin of short gamma-ray bursts (and related emission)
- Origin of heavy elements like gold, uranium, platinum
- Origin of electromagnetic transient (kilonova, marconova)
- Properties of nuclear matter / NS structure
- Occurrence of QCD phase in NS
- Independent constraint on Hubble constant
- … !!!

Abbott et al 2017

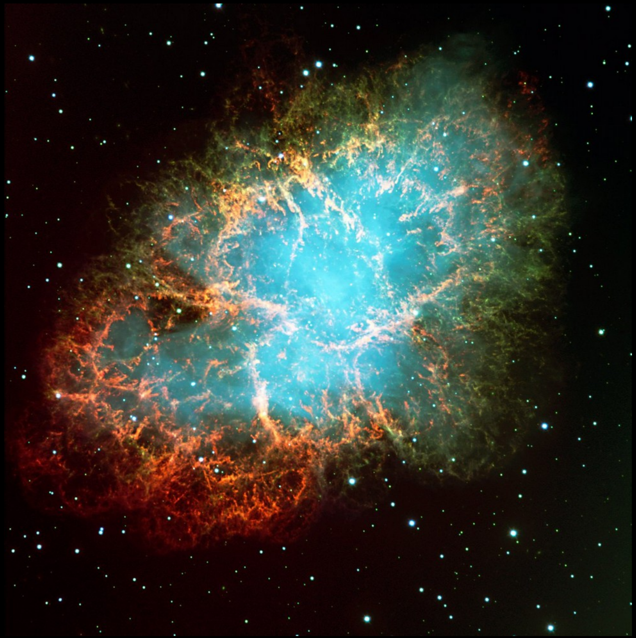


Outline

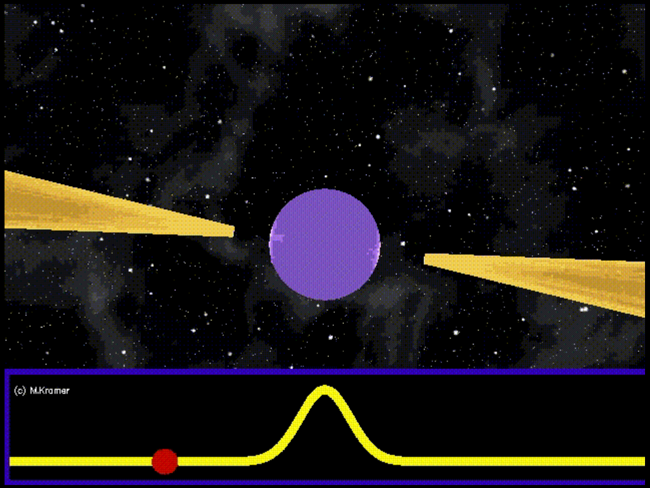
- Overview: NS mergers and GWs
- Gravitational waves and (unknwon) properties of high-density matter
  - finite-size effects during the premerger phase
  - multi-messenger constraints
  - postmerger GW emission
- Signature of strong phase transitions
- Summary and conclusions

Background: NS and NS binaries

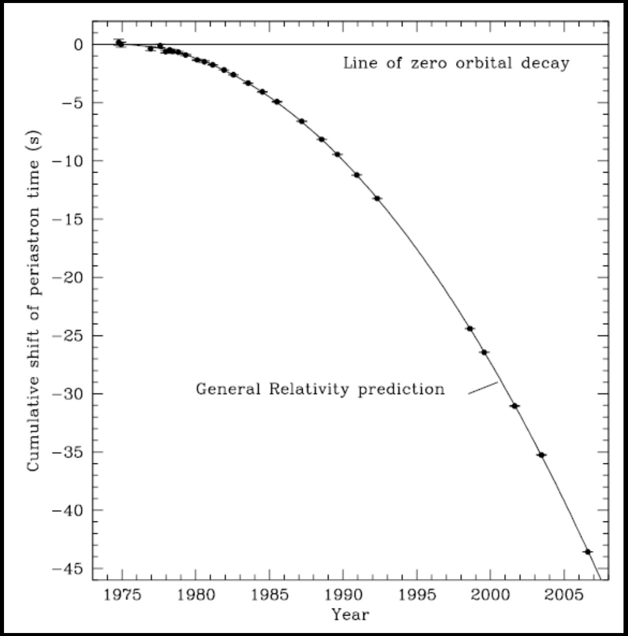
- NSs are end products of massive star evolution
- Compact stars of typically 1.4 Msun, 10-15 km radius → supra-nuclear densities
- EoS of NS matter / nuclear matter not known → stellar structure not known
- NS have a maximum mass (not precisely known) beyond which a black hole forms
- A few 1000 NSs observed mostly as radio pulsars (~100 million expected in our Galaxy)
- Many in binary systems with sufficiently “small” orbits (~ 15 known)
- Decaying orbit measured !! (Nobel prize for Hulse and Taylor)
- Merger driven by GW emission: point-particle inspiral → dynamical merger phase



ESO/VLT

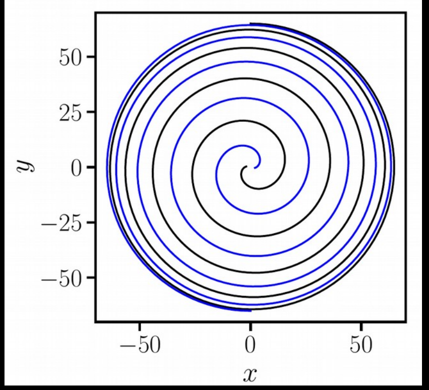


M. Kramer



Weisberg et al.

Background: NS and NS binaries



- Merger driven by GW emission: trajectory = spiral → "inspiral"

  point-particle inspiral continuously speeds up → dynamical merger phase

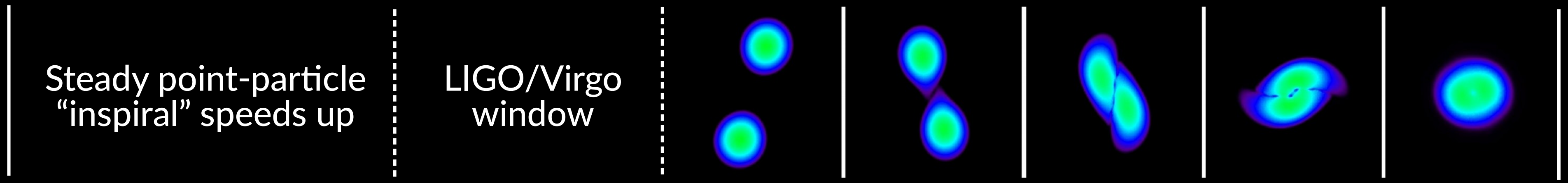
$$E_{orb} = -\frac{1}{2}\frac{M_1 M_2}{a}$$

$$\frac{dE_{orb}}{dt} = -L_{GW}$$

$$f_{orb} = \sqrt{\frac{G(M_1 + M_2)}{4\pi^2 a^3}} = \frac{1}{2} f_{GW}$$

Frequencies

~1/10 h → 10 Hz → 0.5 kHz → ~2kHz



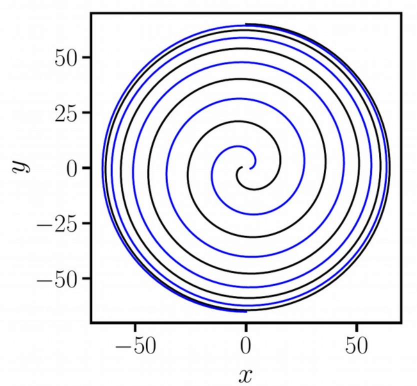
Steady point-particle "inspiral" speeds up

LIGO/Virgo window

~100 Myrs → 10 sec → ms → ~10 ms

Time scales

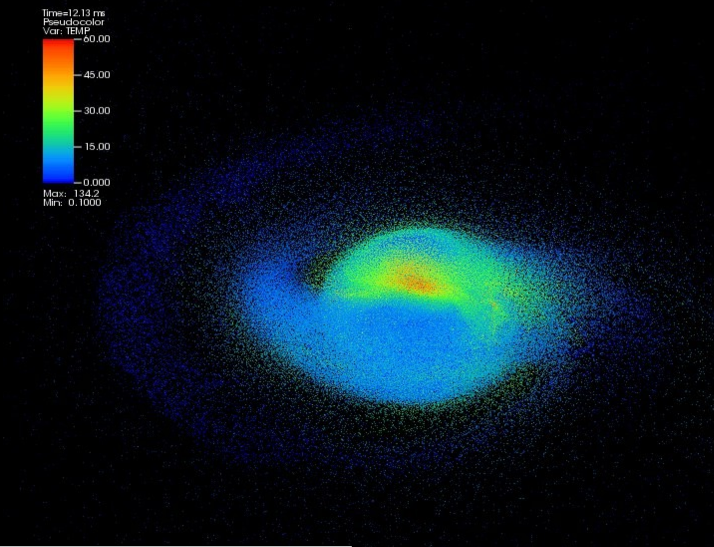
Newtonian point particles + GW emission time → $t_{\text{merger}} \propto a^4$



$P_{orb} \sim 10\,h$

Inspiral of NS binary

~100 Myrs



$P_{orb} \sim 1\,ms$

Neutron star merger

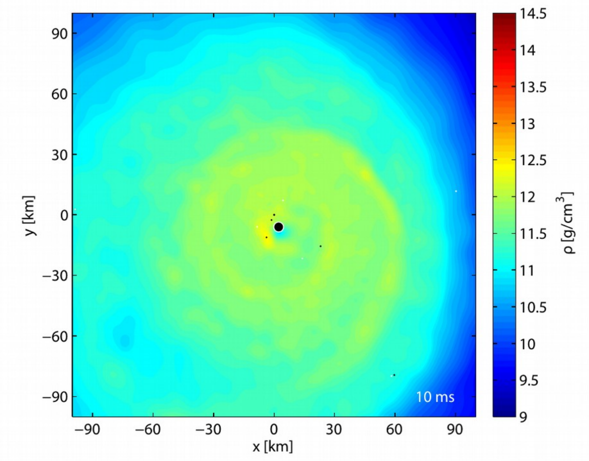
dependent on EoS, M_{tot}

ms

ms

Prompt formation of a BH + torus

Formation of a differentially rotating massive NS

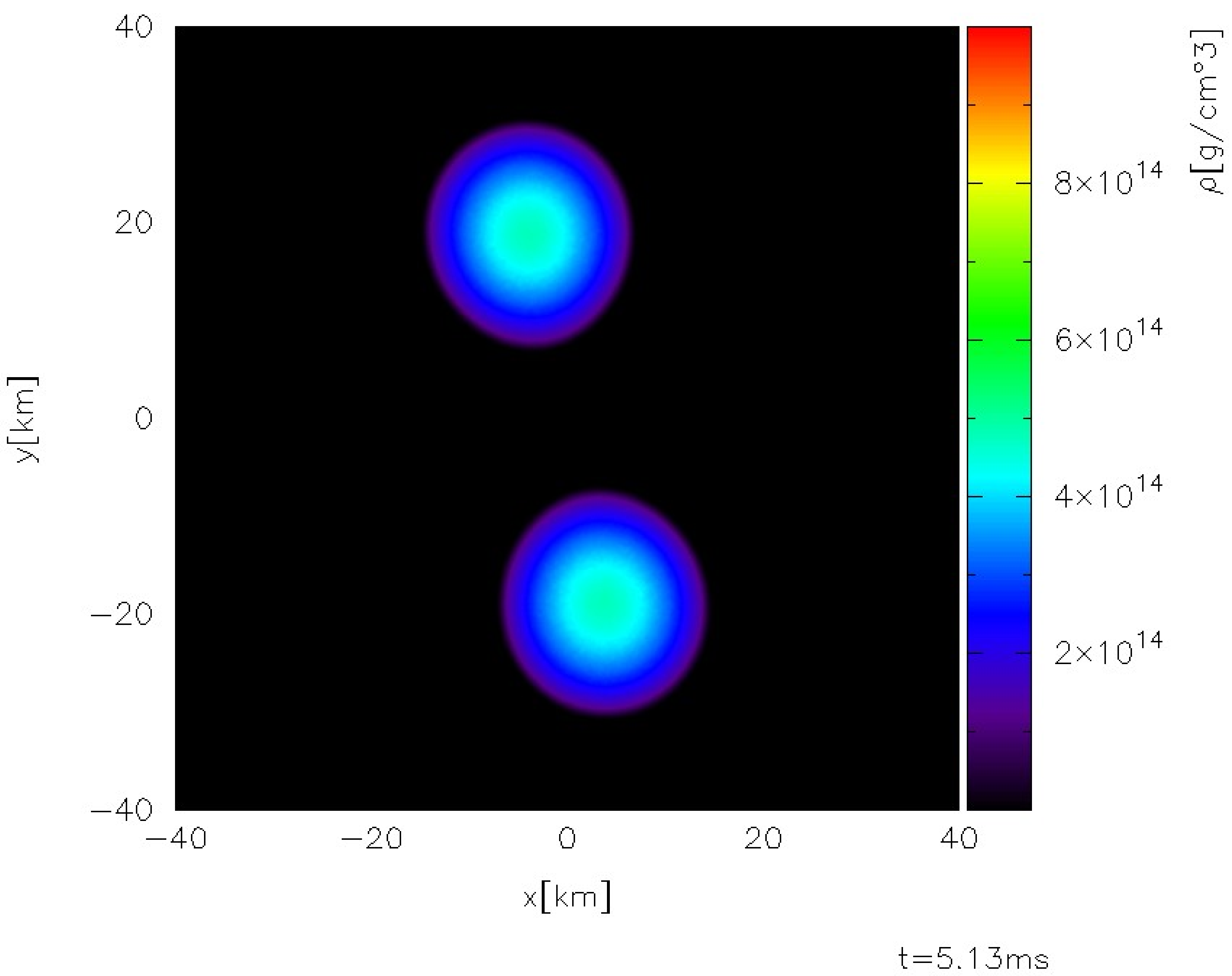


dependent on EoS, M_{tot}

10-100 ms

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

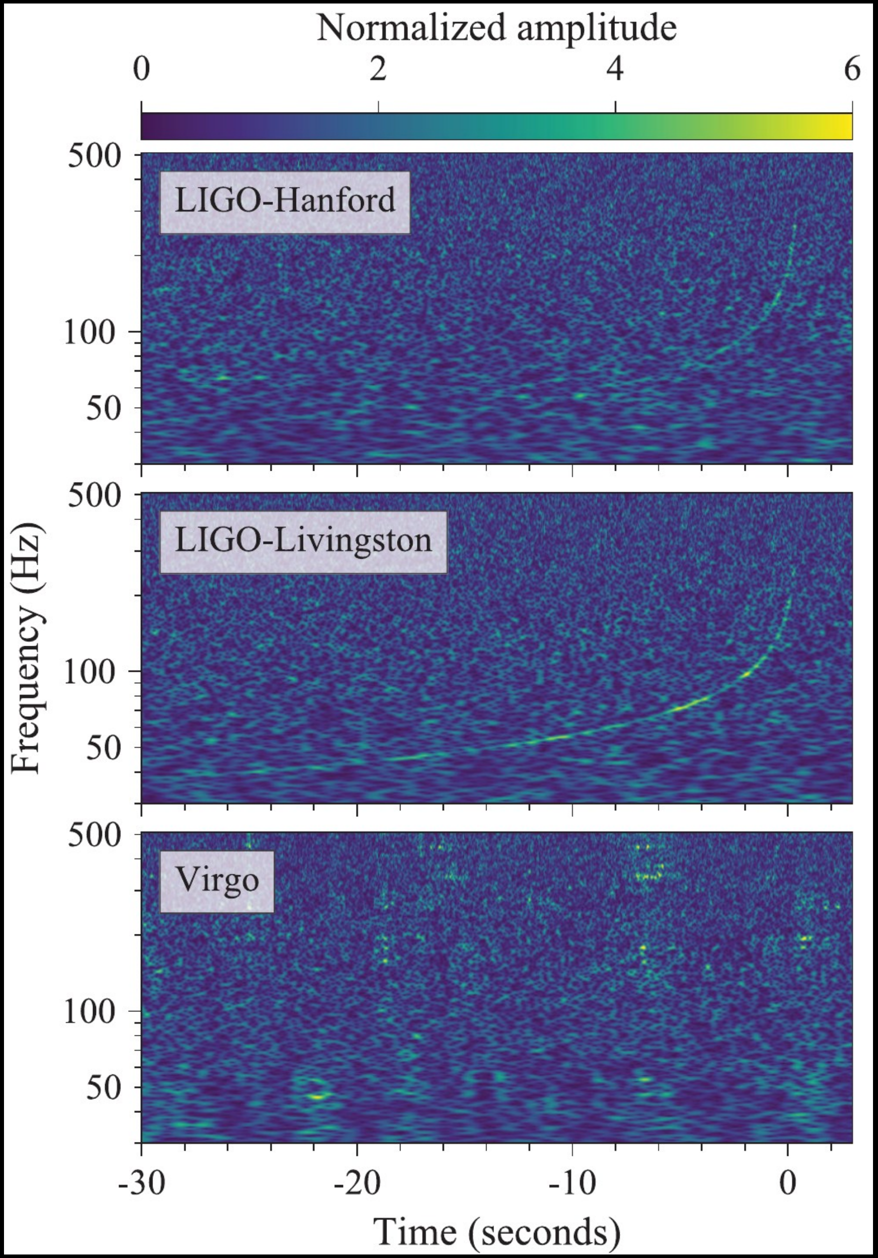
Delayed collapse to a BH + torus



1.35-1.35 Msun, Shen EoS

GW170817

Abbott et al 2017



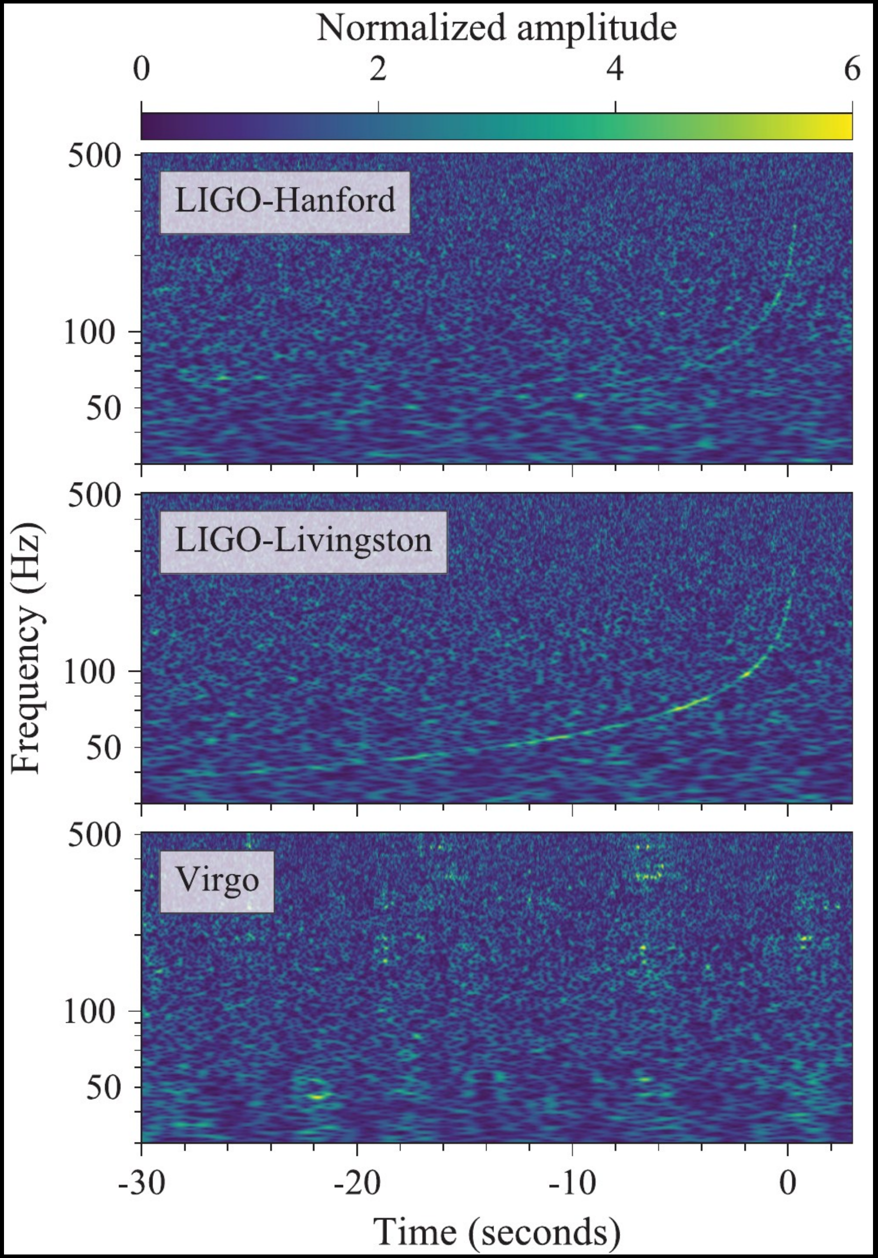
GW170817

Point-particle dynamics + GW emission (quadrupole formula)

$$\frac{dE_{orb}}{dt} = -L_{GW}$$

$$\rightarrow \quad \frac{df}{dt} = \frac{96}{5}^{8/3}\frac{G\mathcal{M}}{c^3} f^{11/3}$$

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



Abbott et al 2017

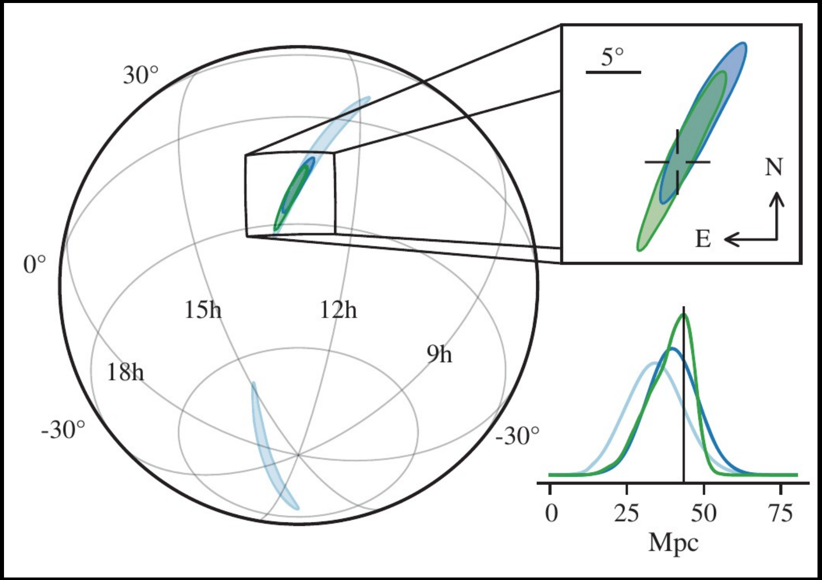
Some insights from GW170817

- From chirp-like inspiral GW signal:

  → Binary masses

  → distance 40 Mpc → rate is presumably high !

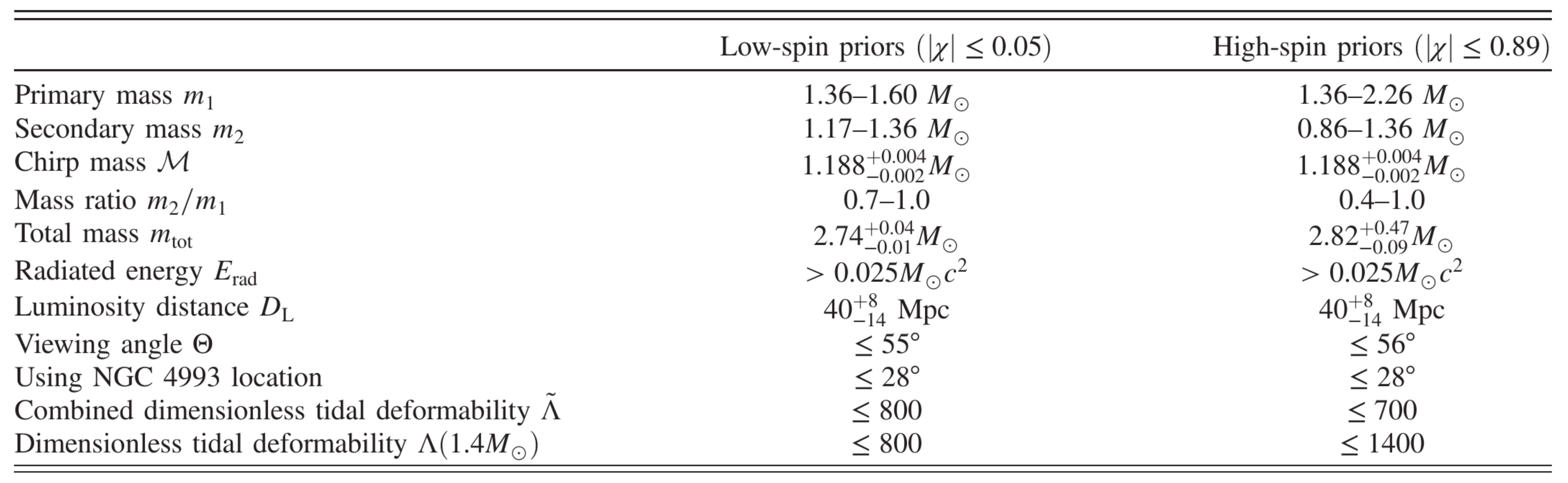
  → Approximate sky location
- Triggered follow-up observations



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

$$q = M_1/M_2$$

Abbott et al. 2017

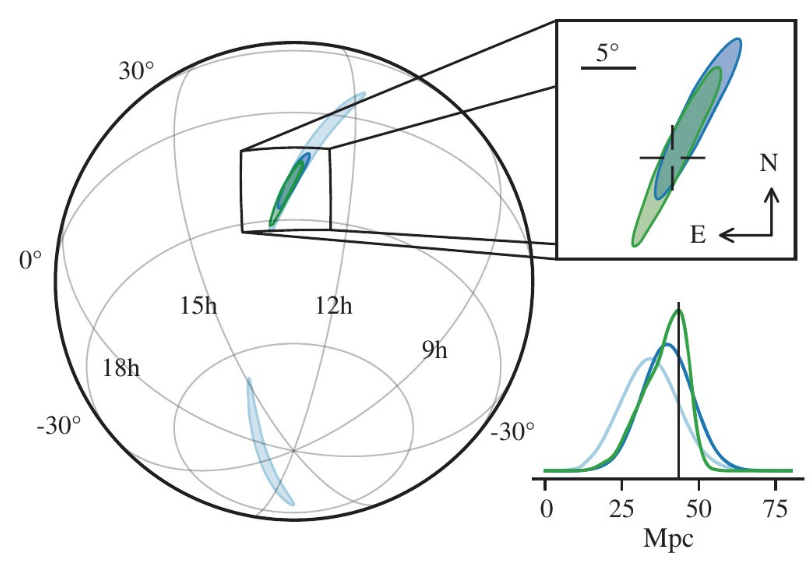


	Low-spin priors ($|\chi| \leq 0.05$)	High-spin priors ($|\chi| \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1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

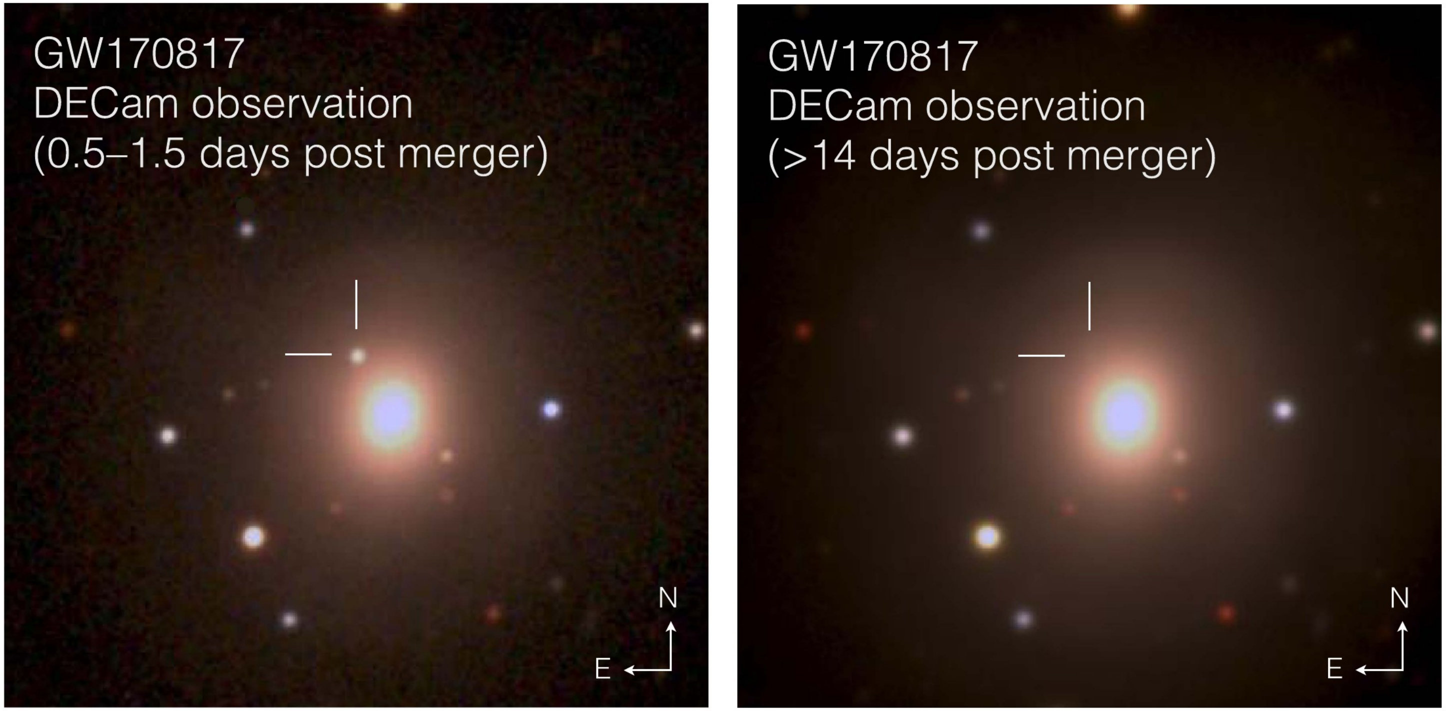


Figure 1. NGC4993 *grz* color composites ($1'.5 \times 1'.5$). Left: composite of detection images, including the discovery *z* image taken on 2017 August 18 00:05:23 UT and the g and r images taken 1 day later; the optical counterpart of GW170817 is at R.A., decl. =197.450374, −23.381495. Right: the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

Soares-Santos et al 2017

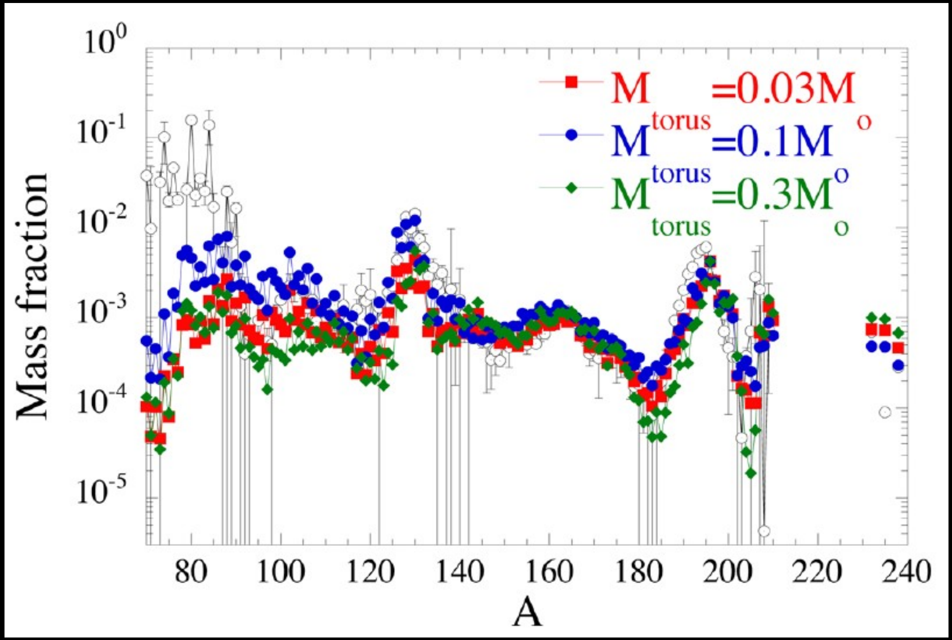
Interpretation of UV/opt/IR - implications

- heating and derived opacities are compatible with r-processing ejecta (composition not known) !!!

  (not surprising for a theorist, see earlier work on r-process and em counterparts)

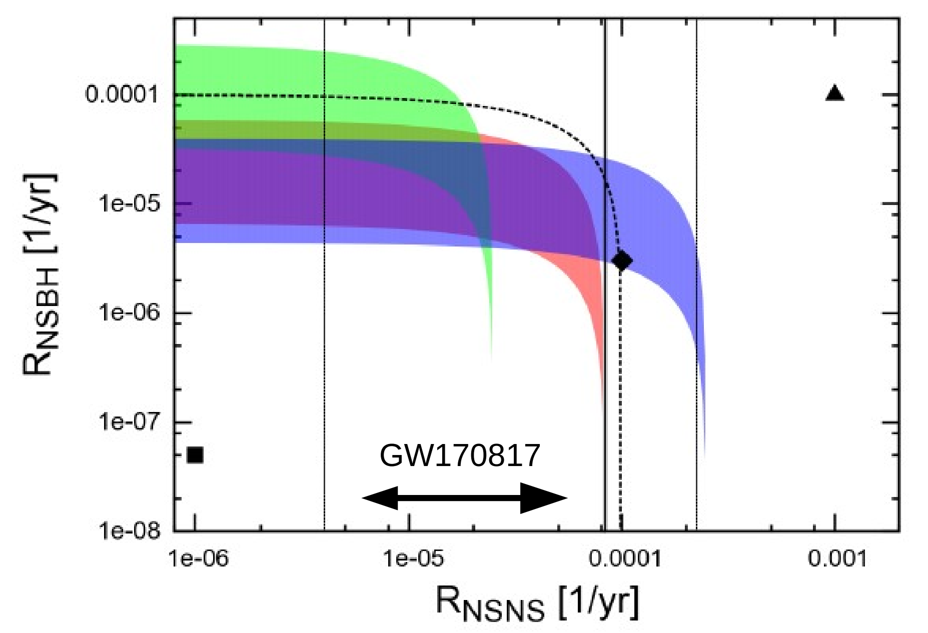
  → first and only confirmed site of rapid neutron capture process !
- 0.02 – 0.05 Msun ejecta (red and blue component) – somewhat model-dependent
- Ejecta velocities and masses in ballpark of simulation results
- Derived ejecta masses are compatible with mergers being the main source of heavy r-process elements in the Universe

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



Just et al. 2015, see also Goriely’s talk

Only A>130



Bauswein et al. 2014

(Future) gravitational wave observations of NSMs

- Interpretation of multi-messenger observations (GW → masses, dynamics, EoS)

- Properties of binary (populations): masses and rates, possibly environment
  → host galaxy demography
  → Relevant to understand enrichment by heavy elements
  → Are mergers the dominant/only source of r-process elements

- Problem: only merger rate in local Universe accessible
  - rate follows star formation rate with some delay (inspiral time > stellar evolution)
  - can be used to gauge population synthesis models and chemical evolution models
  - delay time distribution from host galaxy association (tentatively)

$$M_{r-process\,Galaxy} = \bar{M}_{NSNS}\,R_{NSNS}\,\tau_{Galaxy}$$

+ contribution by NS-BH

EoS / NS constraints

Motivation: Neutron stars and the EoS

- Nuclear many-body problem has to be solve
- 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

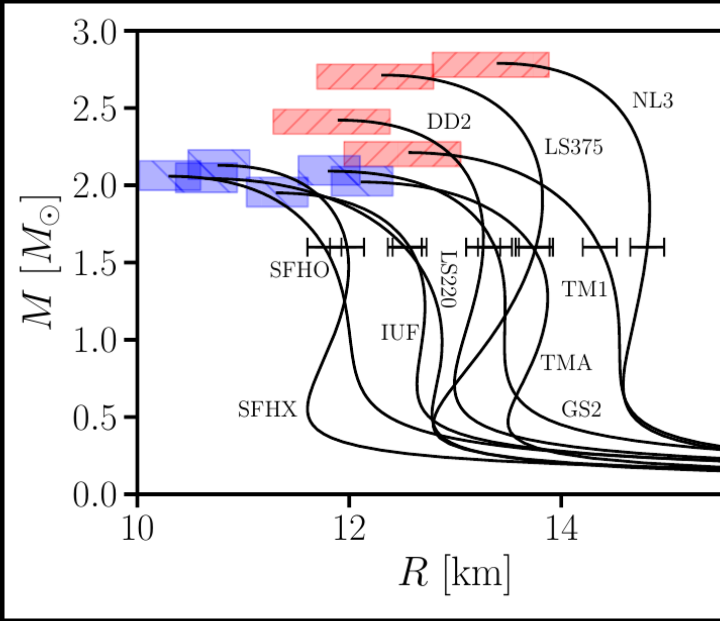
→ high-density EoS P(rho) not precisely known

$$\frac{dm(r)}{dr} = 4\pi r^2 \rho(P)$$

$$G = c = 1$$

$$\frac{dP(r)}{dr} = -\frac{\rho(P)m}{r^2}\left(1+\frac{P}{\rho(P)}\right)\left(1+\frac{4\pi P r^3}{m}\right)\left(1-\frac{2m}{r}\right)^{-1}$$

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



Mass-radius relations for different EoS models

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

EoS constraints from NS mergers and GWs

- GW robust messenger of dynamics

$$h_{ij}^{TT} = \frac{2G}{c^4\, r}\ddot{Q}_{ij}^{TT}$$

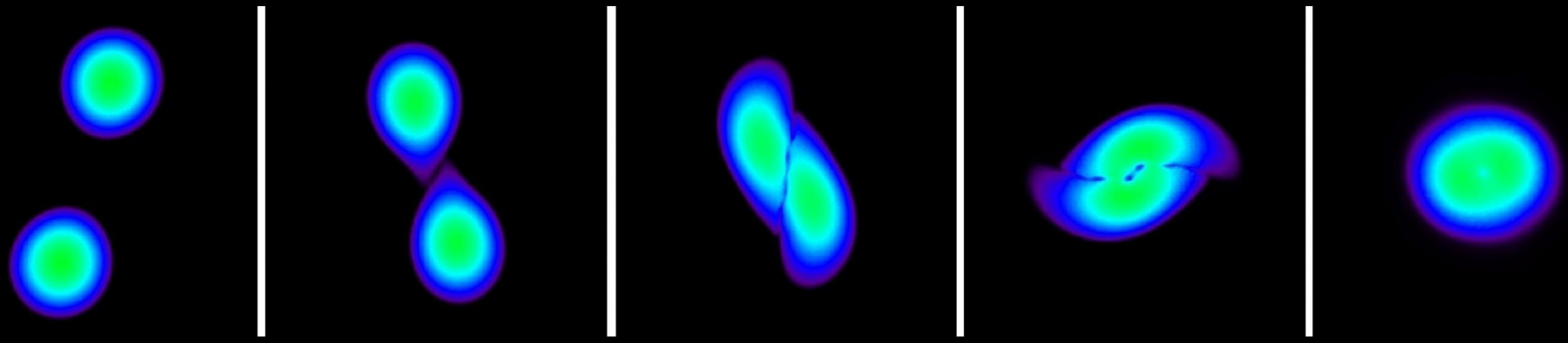
- Finite-size effects during the inspiral
- Multi-messenger interpretation

presence

- Postmerger GW emission

future

Finite-size effects during late inspiral



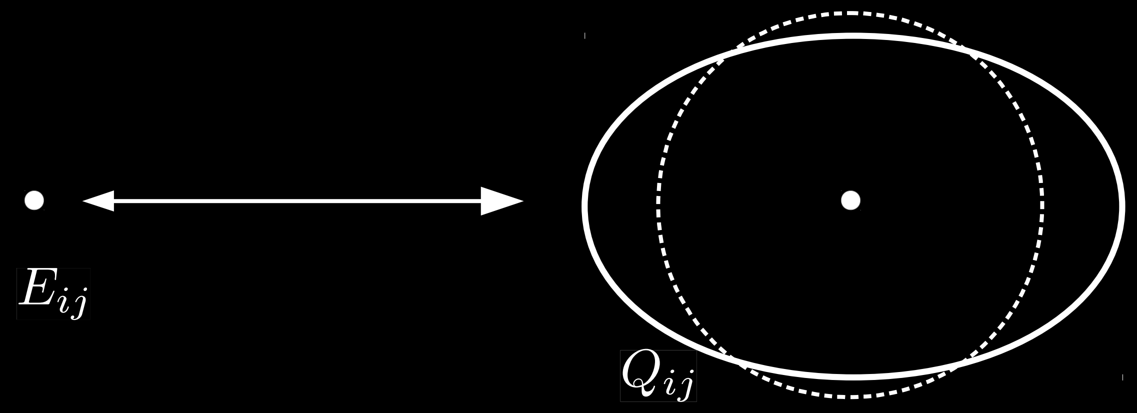
Description of tidal effects during inspiral

- 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:

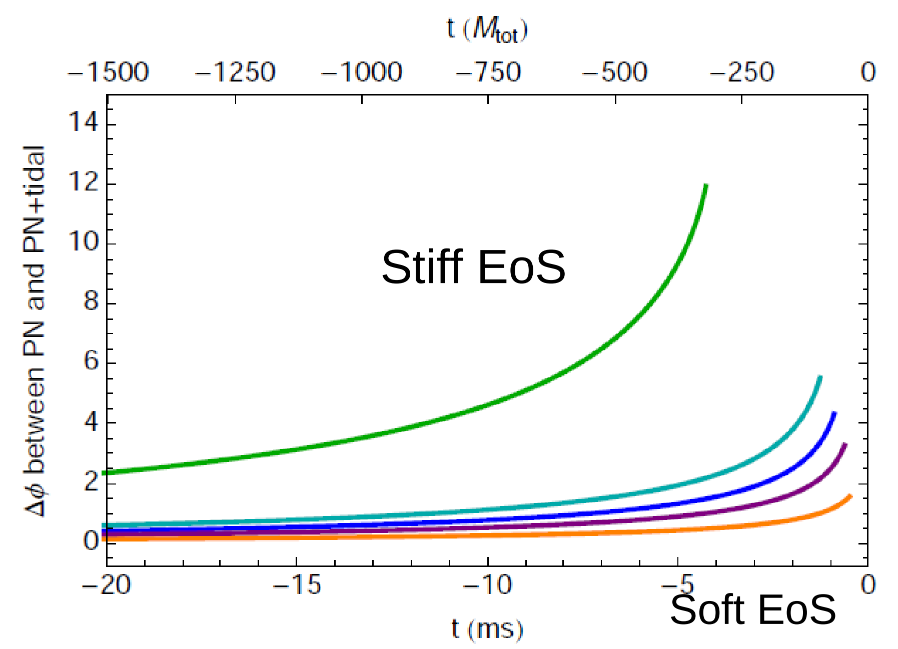
$$Q_{ij} = -\lambda(M)\, E_{ij} \qquad \lambda(M) = \frac{2}{3} k_2(M) R^5$$

- 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

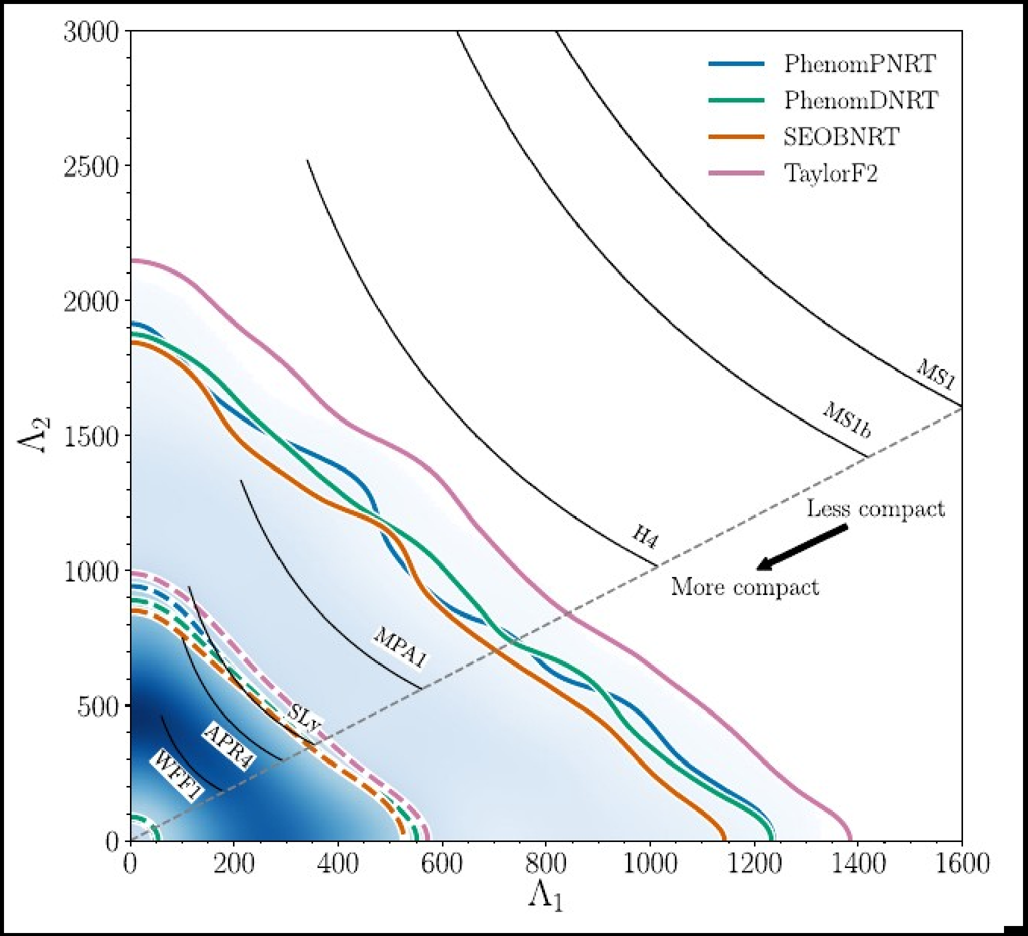
- Lambda < ~800 (reanalysis: < 650)

  → Means that very stiff EoSs are excluded

  → NS radii < ~13.5 km
- Recall uncertainties in mass measurements (only Mchirp accurate)
- Template waveforms somewhat model-dependent

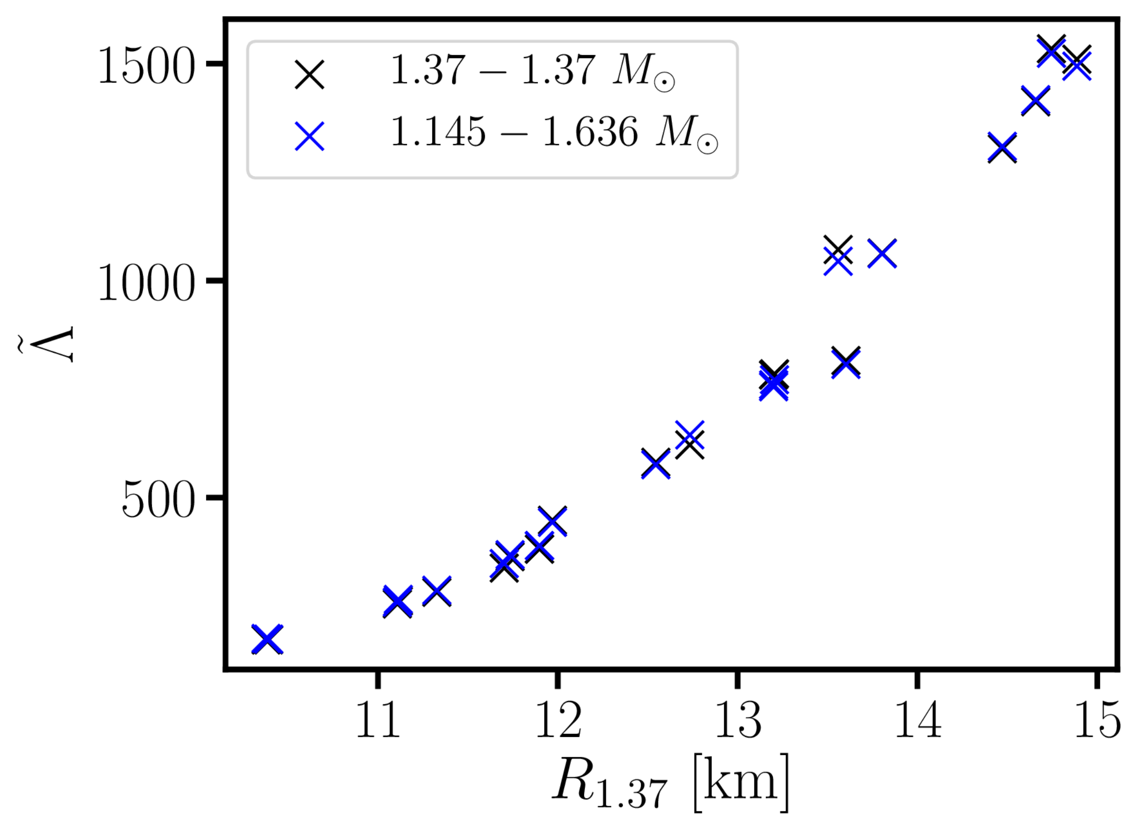
  → ongoing research
- Better constraints expected in future as sensitivity increases

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



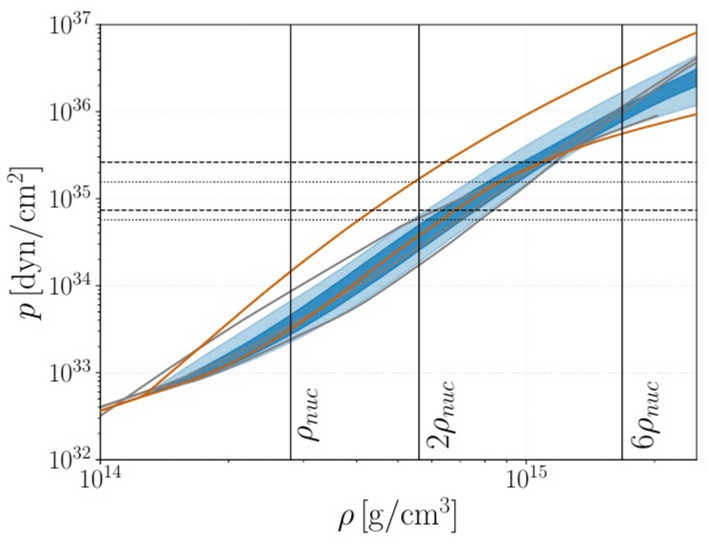
Abbott et al. 2017, 2019
see also later publications by Ligo/Virgo collaboration, De et al. 2018

- Combined tidal deformability vs. radius (for constant chirp mass)

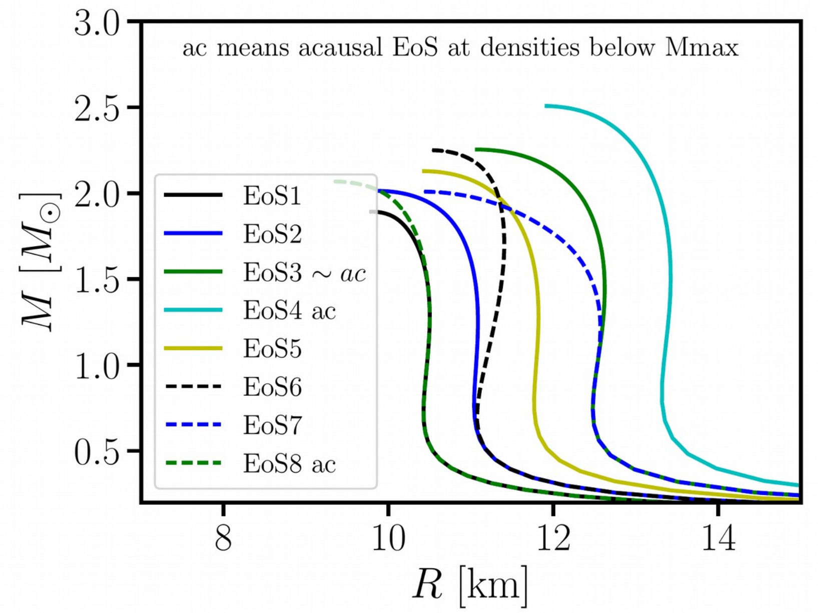


→ GW170817 constrains NS radii from above

- 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

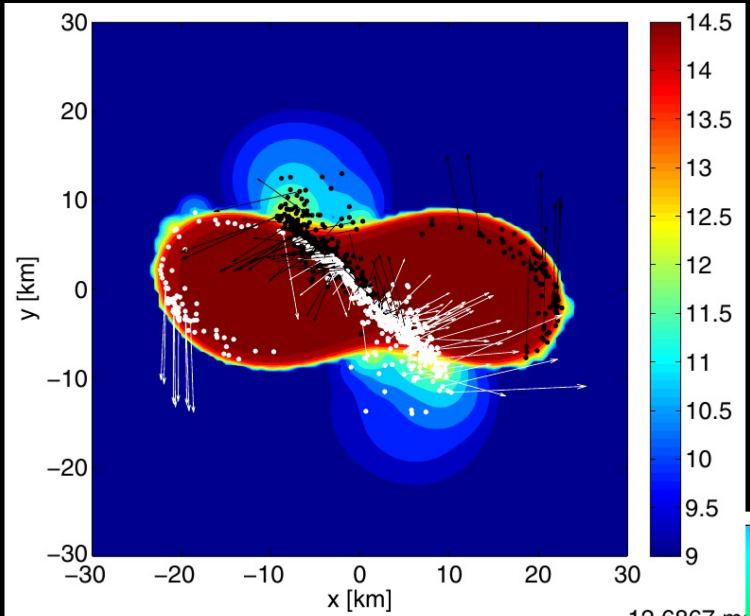
Multi-messenger constraints

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

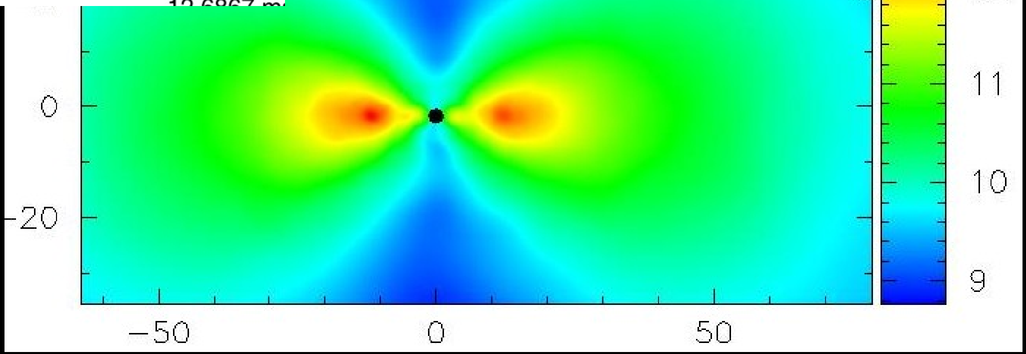


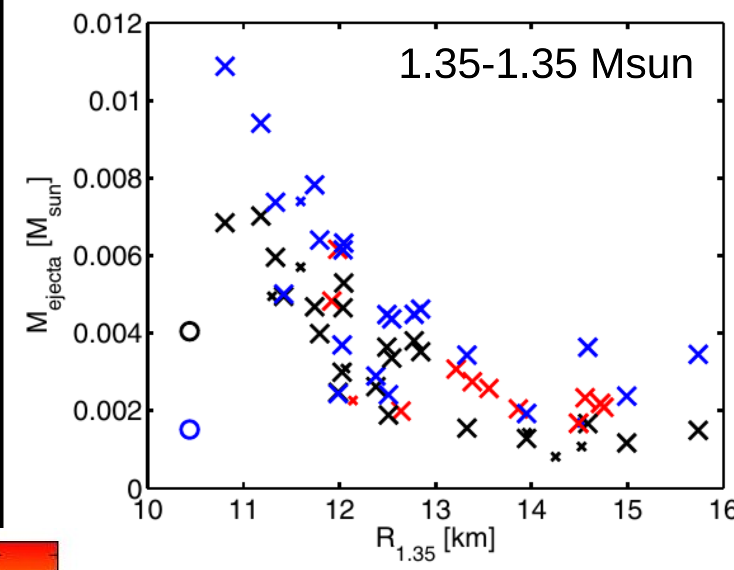
Dynamical ejeca

Luminosity:

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

Remnant: BH torus





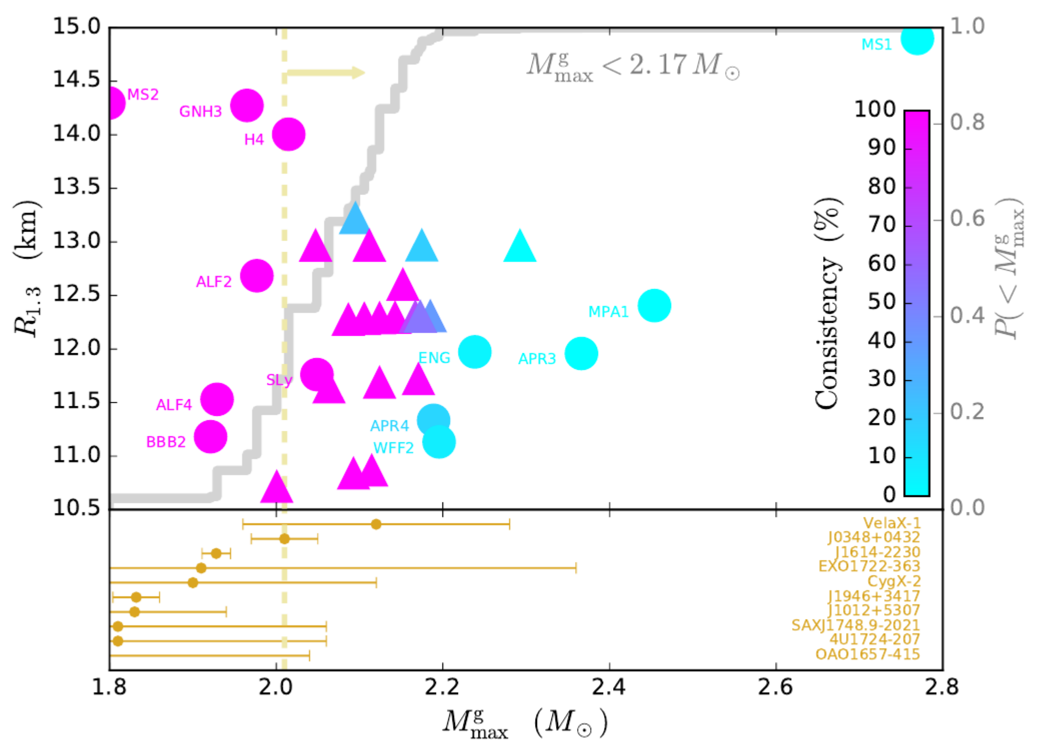
EoS dependence

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})

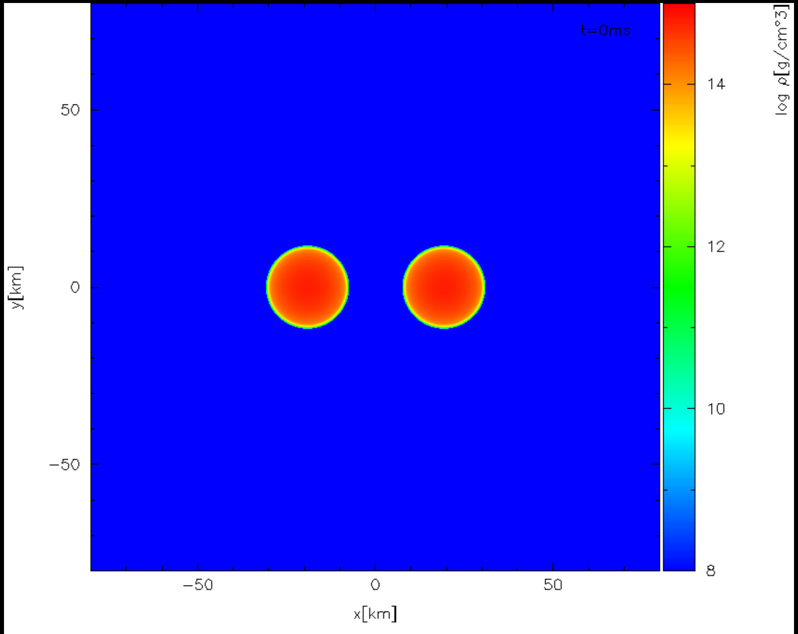
  → M_{max} < ~2.2-2.4 M_{sun} (relying on some assumption)



Margalit & Metzger 2017

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

Constraint from collapse behavior

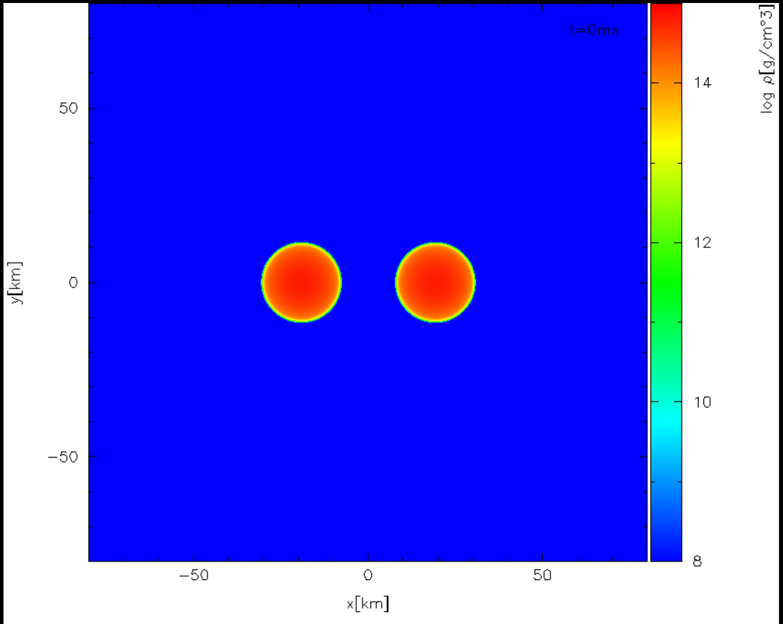


$M_{\mathrm{tot}} = 3.4\ M_\odot$

←

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

→



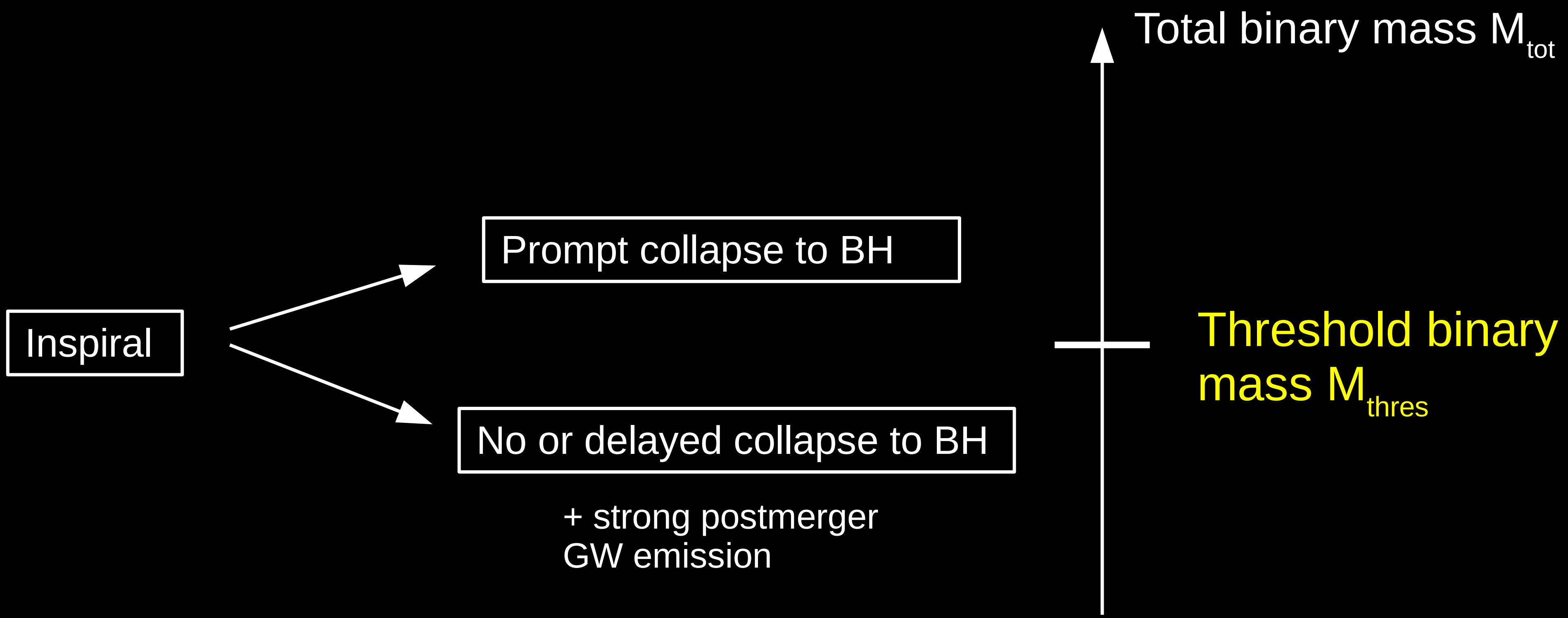
Shen EoS

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

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

<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



Total binary mass M_{tot}

Inspiral

Prompt collapse to BH

No or delayed collapse to BH

+ strong postmerger
GW emission

Threshold binary mass M_{thres}

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):

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

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

- Both better than 0.06 M_{sun}

EoS constraints from GW170817

→ lower bound on NS radii

(recall: upper bound from tidal deformability)

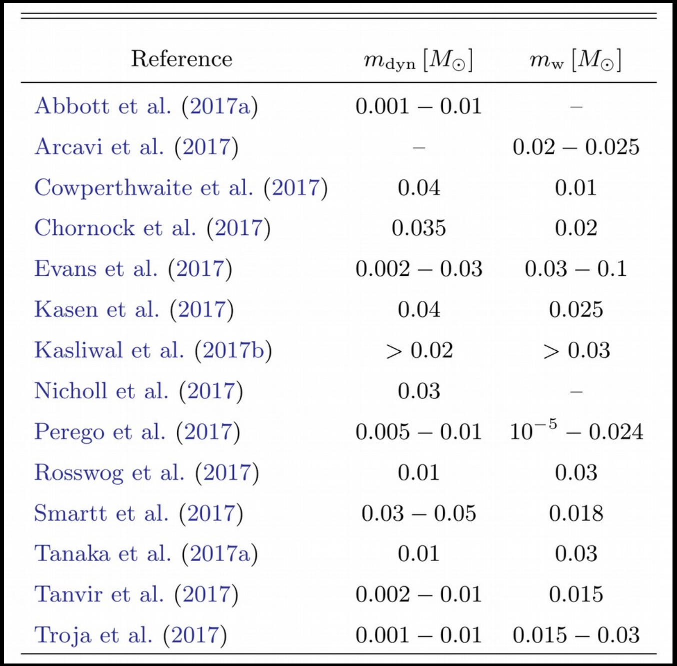
A simple but robust NS radius constraint from GW170817

- 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

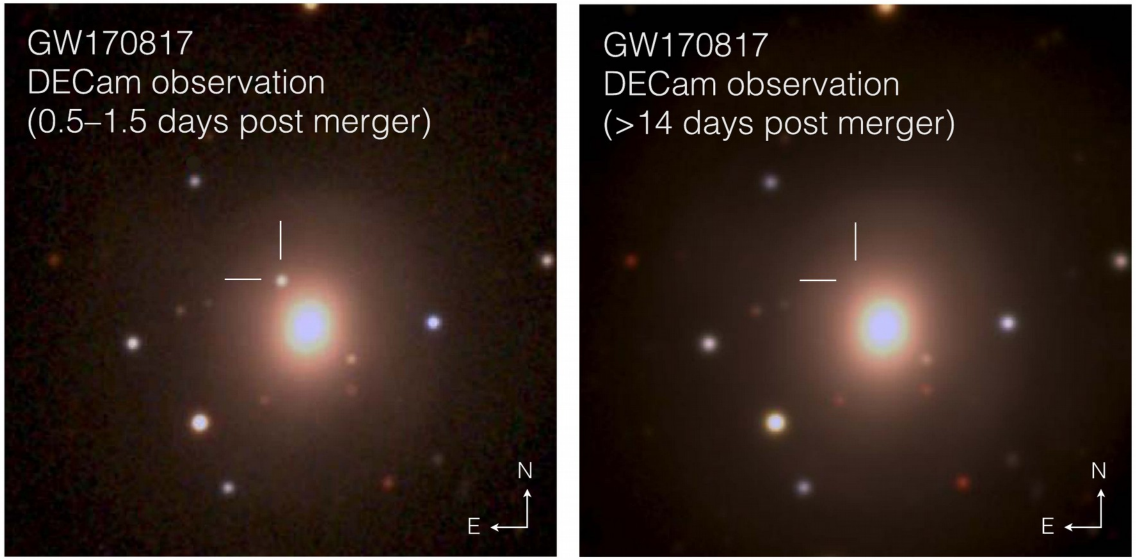


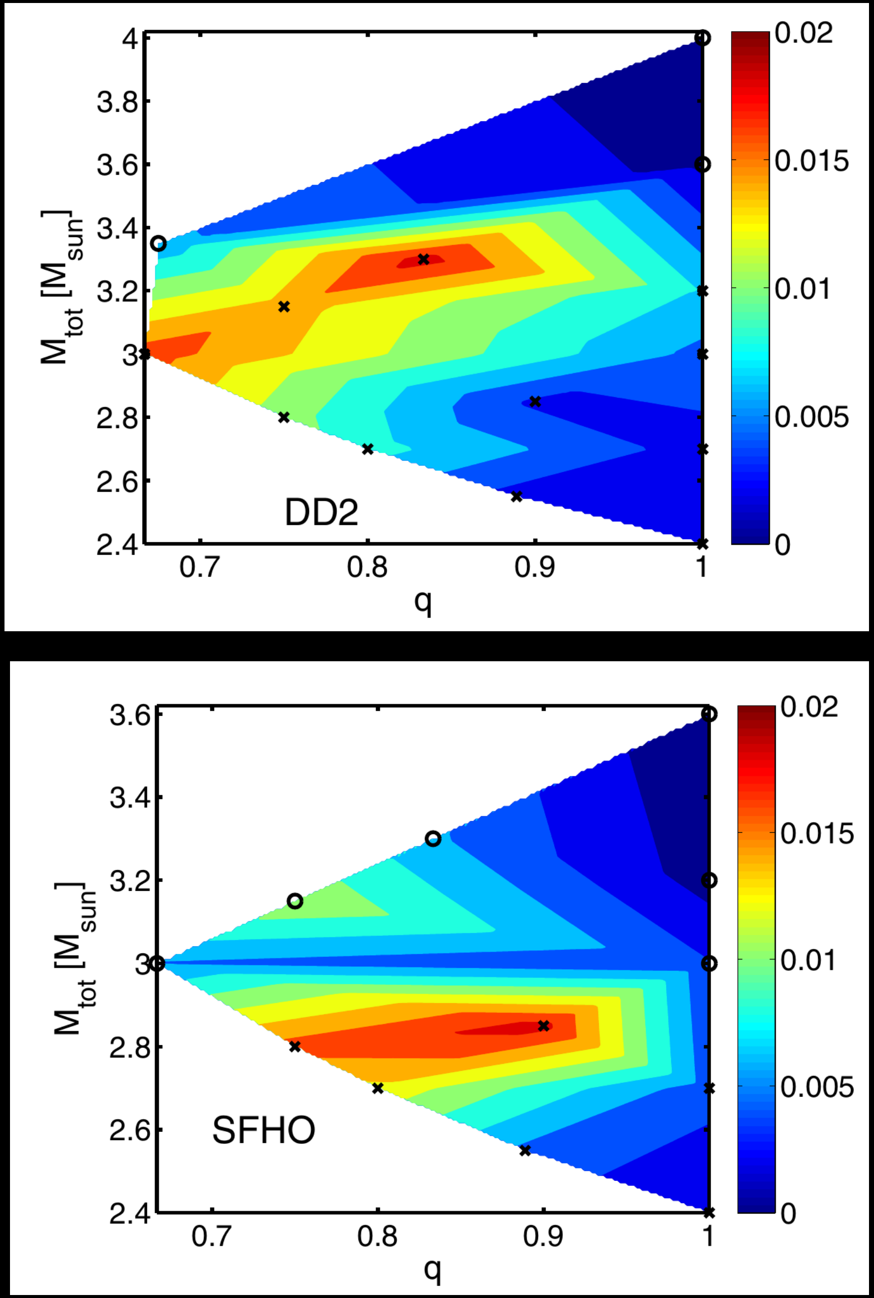
Figure 1. NGC4993 *grz* color composites ($1'.5 \times 1'.5$). Left: composite of detection images, including the discovery *z* image taken on 2017 August 18 00:05:23 UT and the g and r images taken 1 day later; the optical counterpart of GW170817 is at R.A., decl. =197.450374, −23.381495. Right: the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

Soares-Santos et al 2017

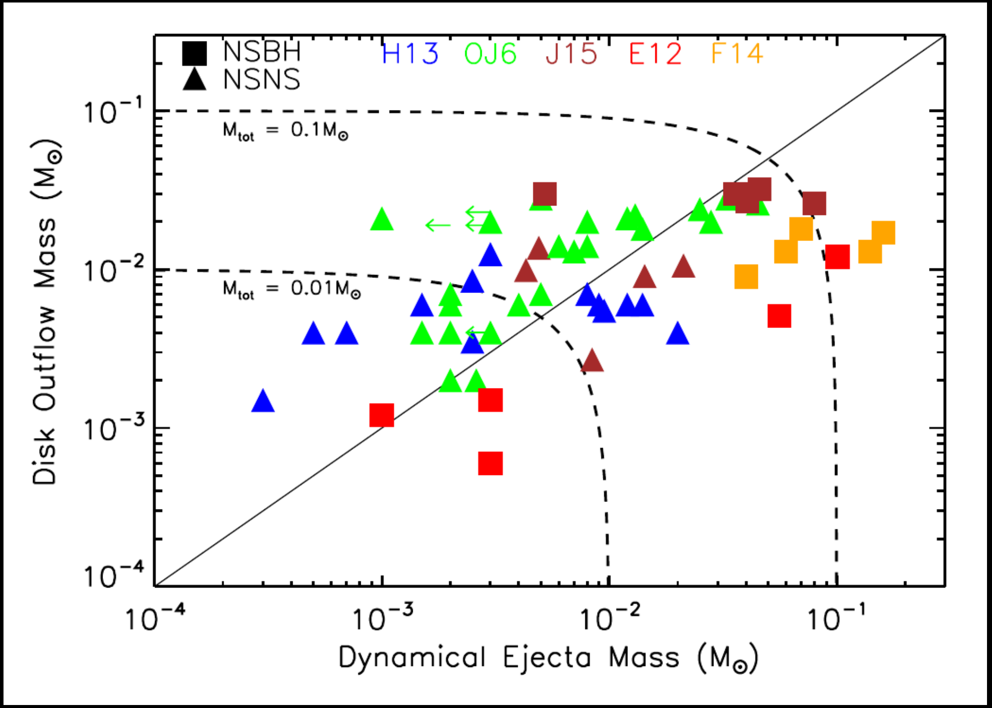
- Ejecta masses depend on EoS and binary masses
- Note: high mass points already to soft EoS (tentatively/qualitatively)
- Prompt collapse leads to reduced ejecta mass
- Light curve depends on ejecta mass:

  → 0.02 - 0.05 M_{sun} point to delayed collapse
- Note: here only dynamical ejecta

Only dynamical ejecta

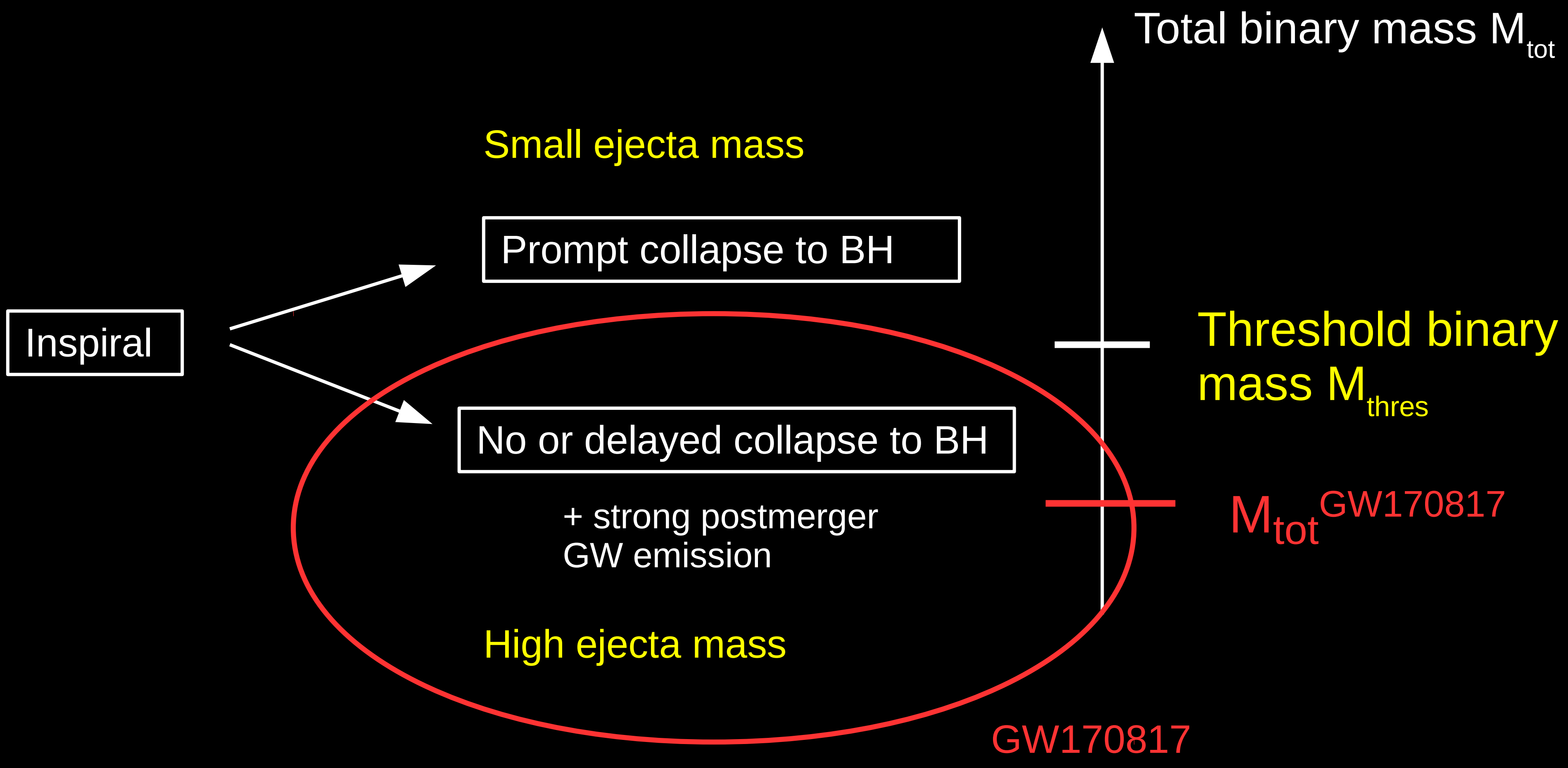


Bauswein et al. 2013



Compilation Wu et al 2016: dynamical and secular ejecta comparable

Collapse behavior



Total binary mass M_{tot}

Small ejecta mass

Prompt collapse to BH

Inspiral

Threshold binary mass M_{thres}

No or delayed collapse to BH

+ strong postmerger
GW emission

$M_{tot}^{GW170817}$

High ejecta mass

GW170817

(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 $M_{\rm max}$, $R_{\rm max}$ 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:

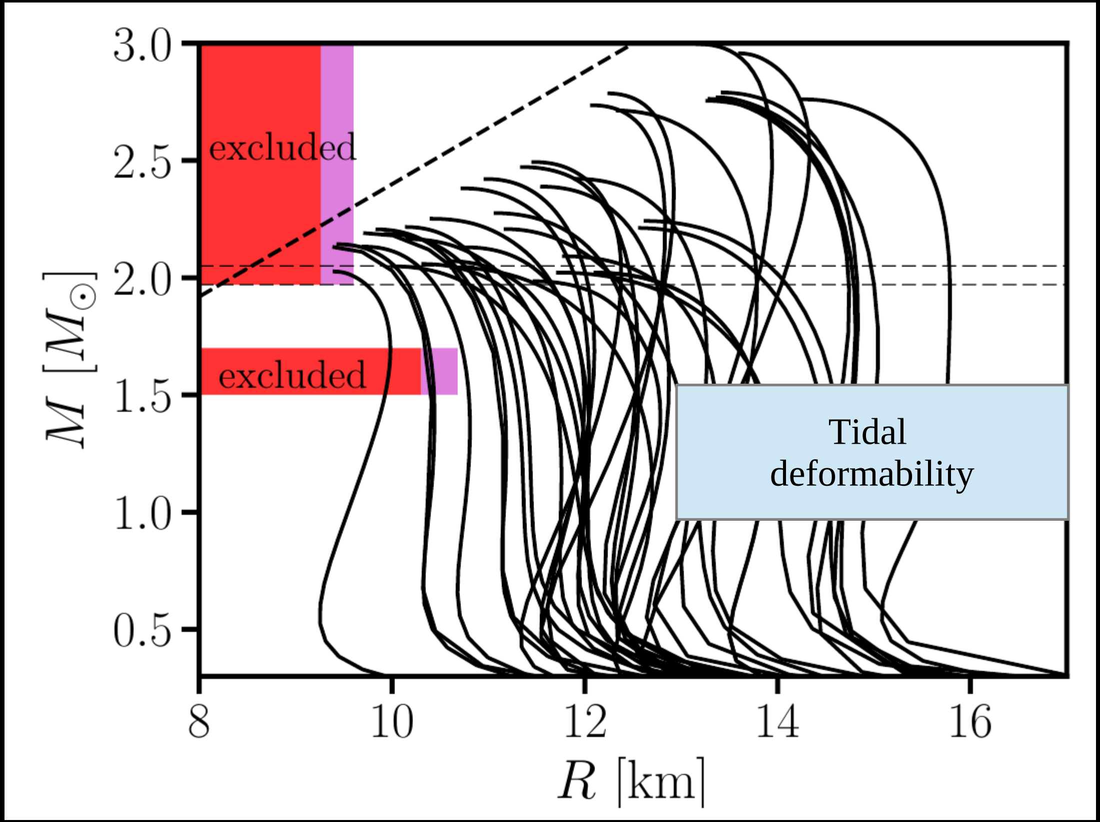
$$M_{\rm tot}^{GW170817} \leq \left(-3.38\frac{G\,M_{\rm max}}{c^2\,R_{\rm max}} + 2.43\right)M_{\rm max} \leq \left(-\frac{3.38}{2.82} + 2.43\right)\frac{1}{2.82}\frac{c^2\,R_{\rm max}}{G}$$

→ Lower limit on NS radius

Bauswein et al. 2017

NS radius constraint from GW170817

- R_{max} > 9.6 km
- $R_{1.6}$ > 10.7 km
- Excludes very soft nuclear matter
- Similar idea for Lambda in Radice et. al 2018
- follow-up Koeppel et al 2019 (same idea) arriving at similar constraints of 10.7 km



Bauswein et al. 2017

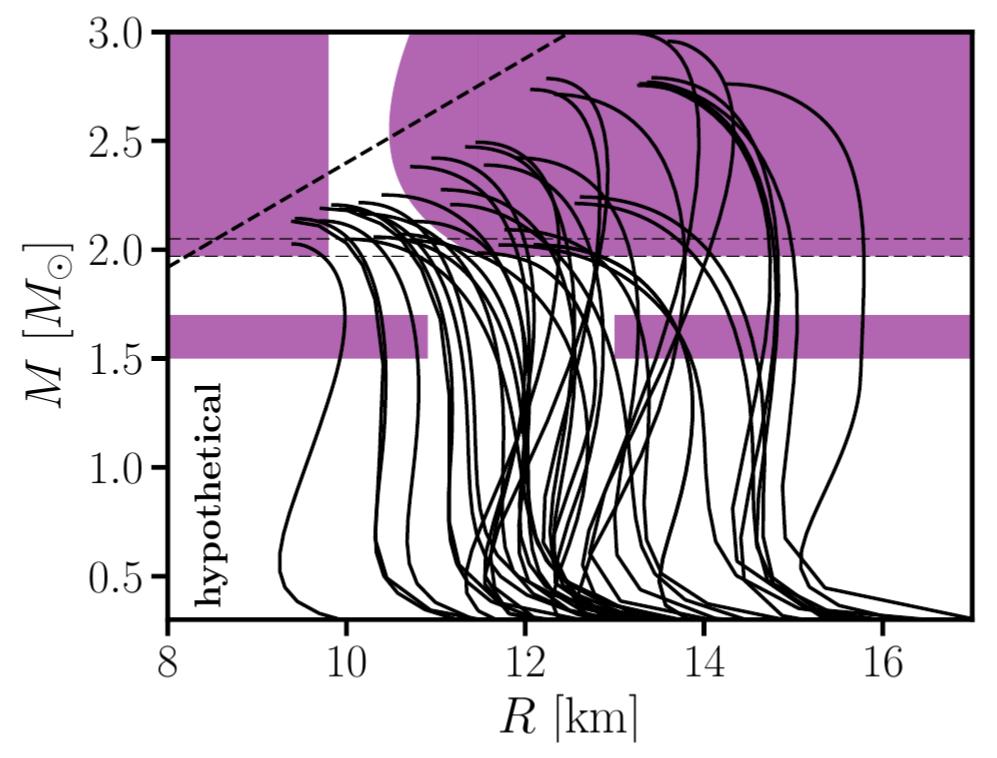
Future

- 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
- In particular: upper bound on M_{max} can be obtained

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*

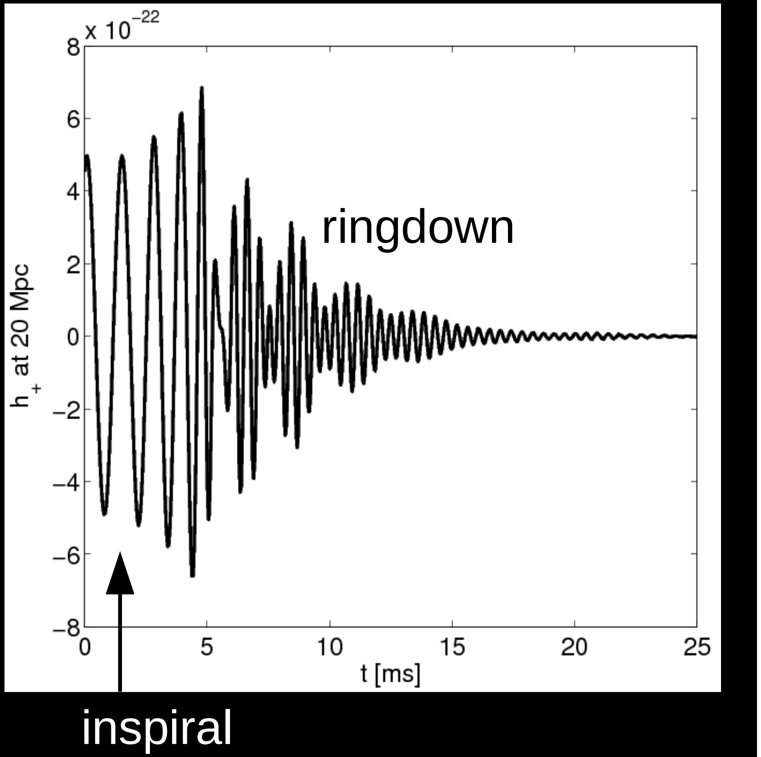
(dominant frequency of postmerger phase)

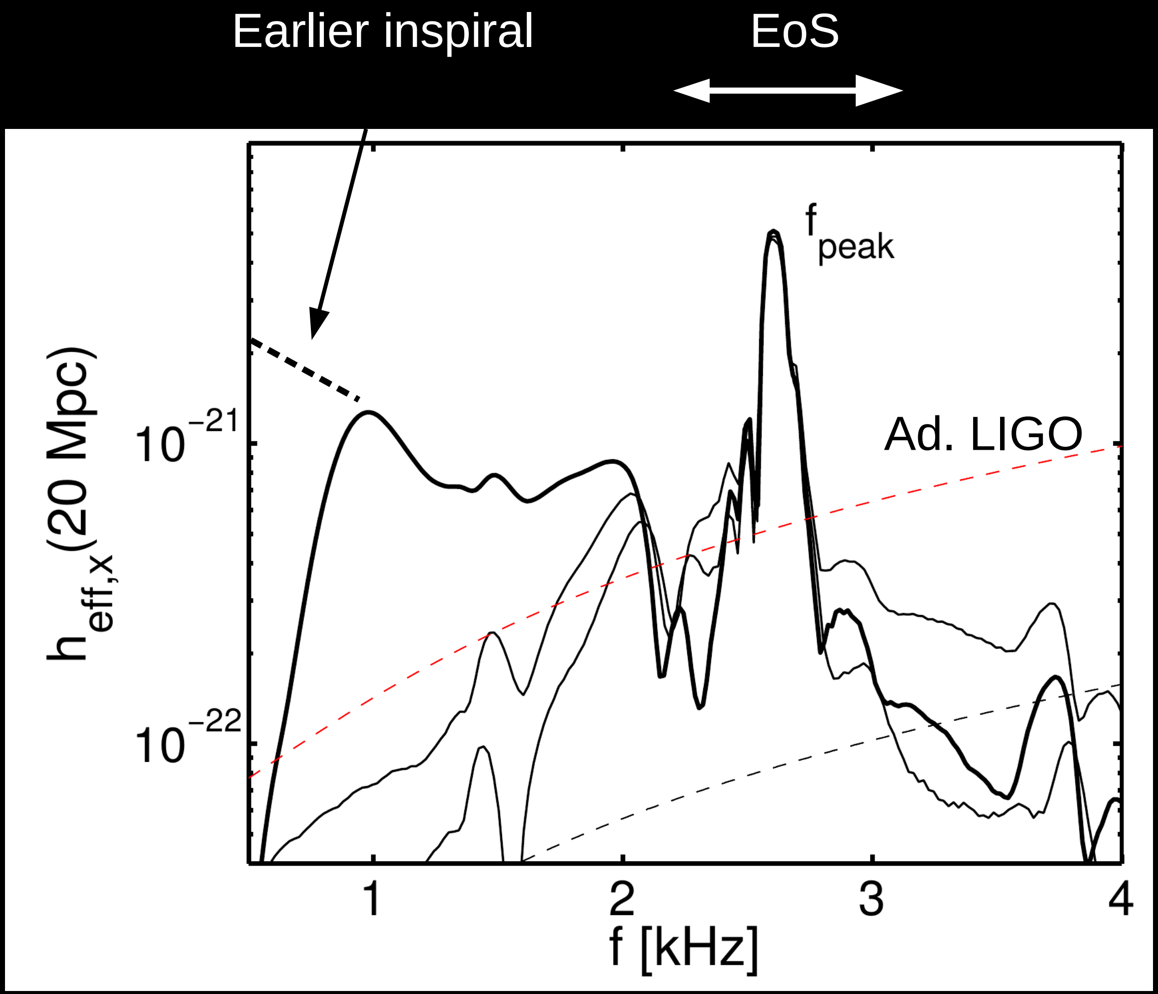
→ determine properties of EoS/NSs
→ complementary to inspiral

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

Postmerger

1.35-1.35 M_{sun} , 20 Mpc

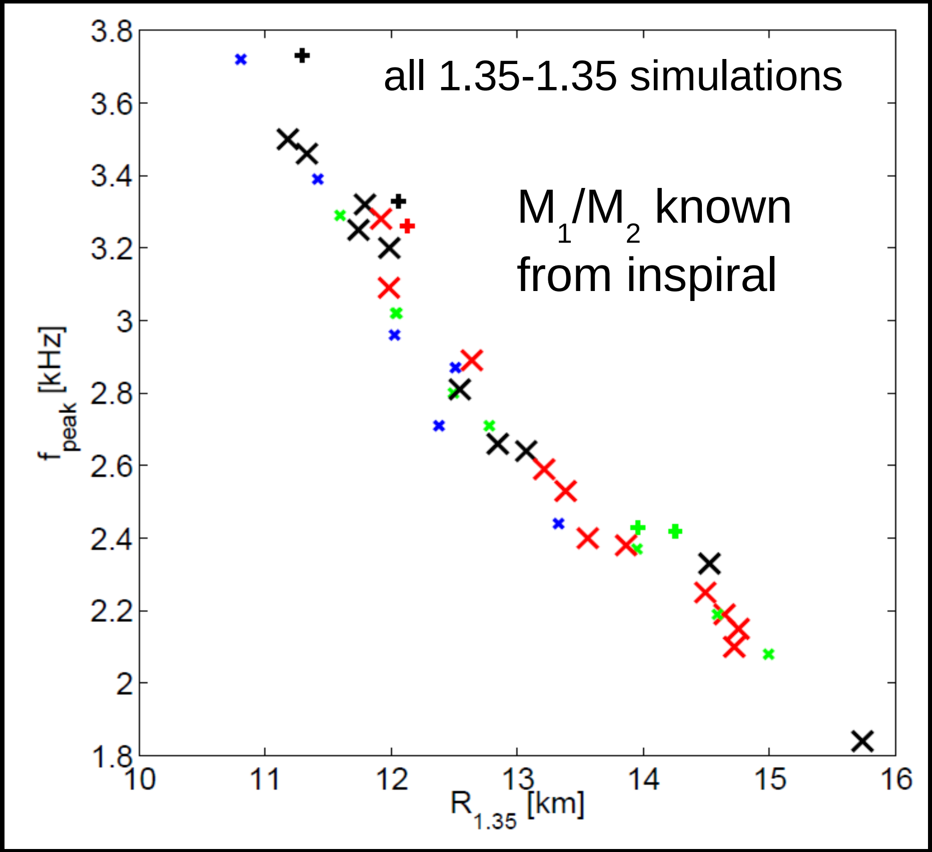




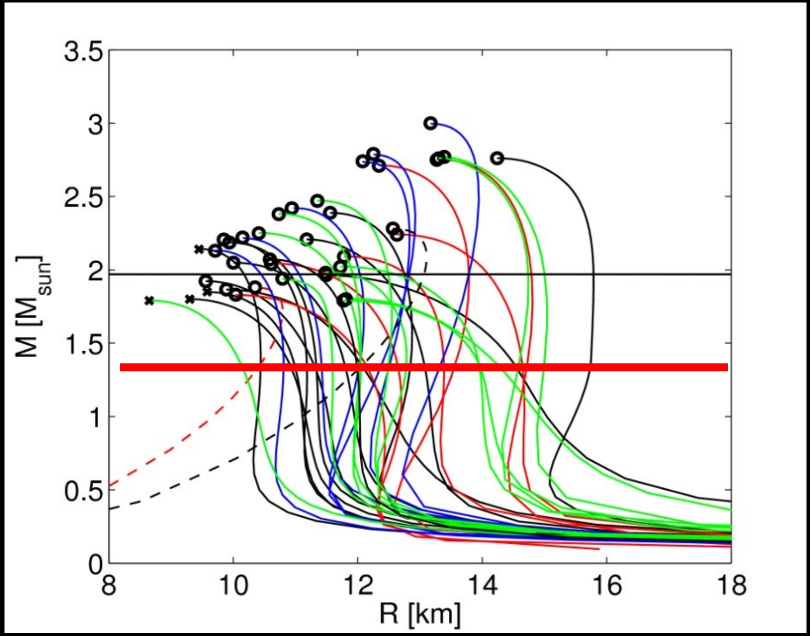
Dominant postmerger oscillation frequency f_{peak}

Very characteristic (robust feature in all models)

Gravitational waves – EoS survey


all 1.35-1.35 simulations

M_1/M_2 known from inspiral



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

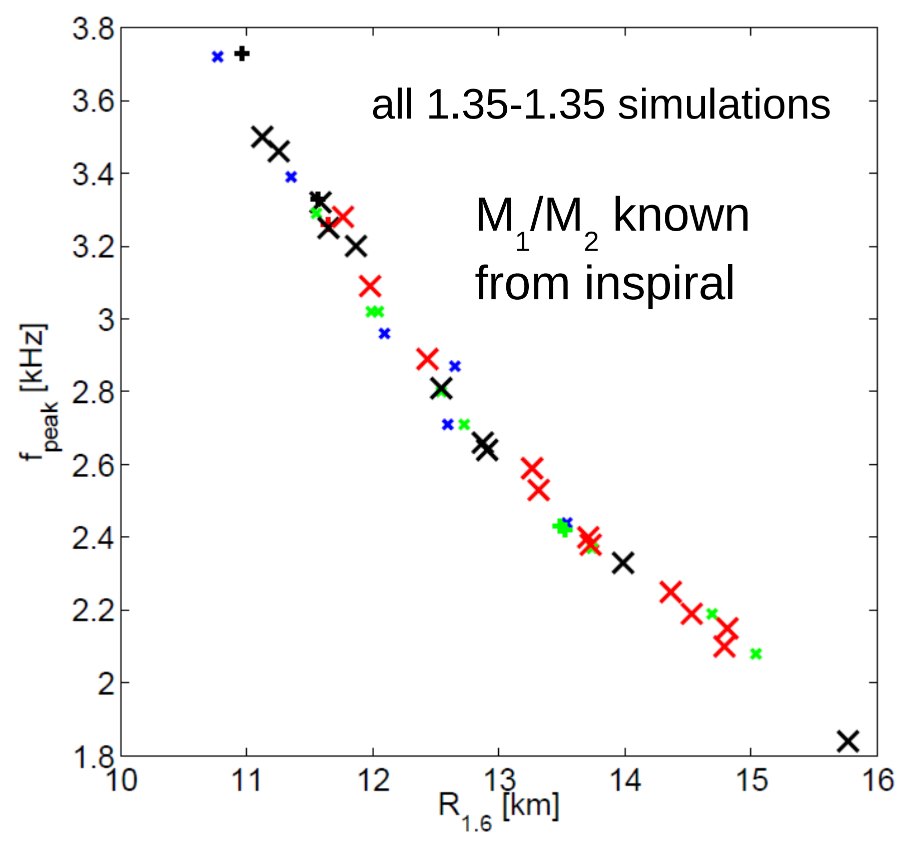
Bauswein et al. 2012

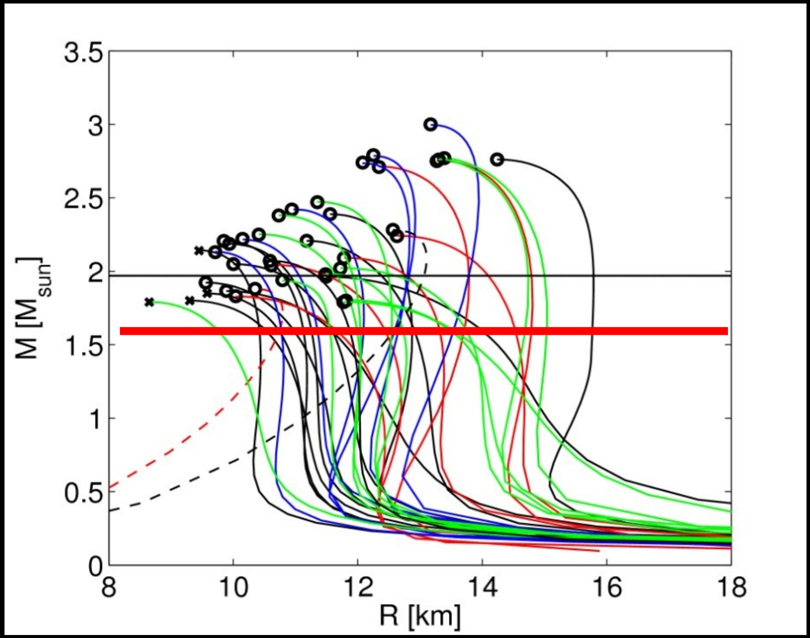
Pure TOV/EoS property => Radius measurement via f_{peak}

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

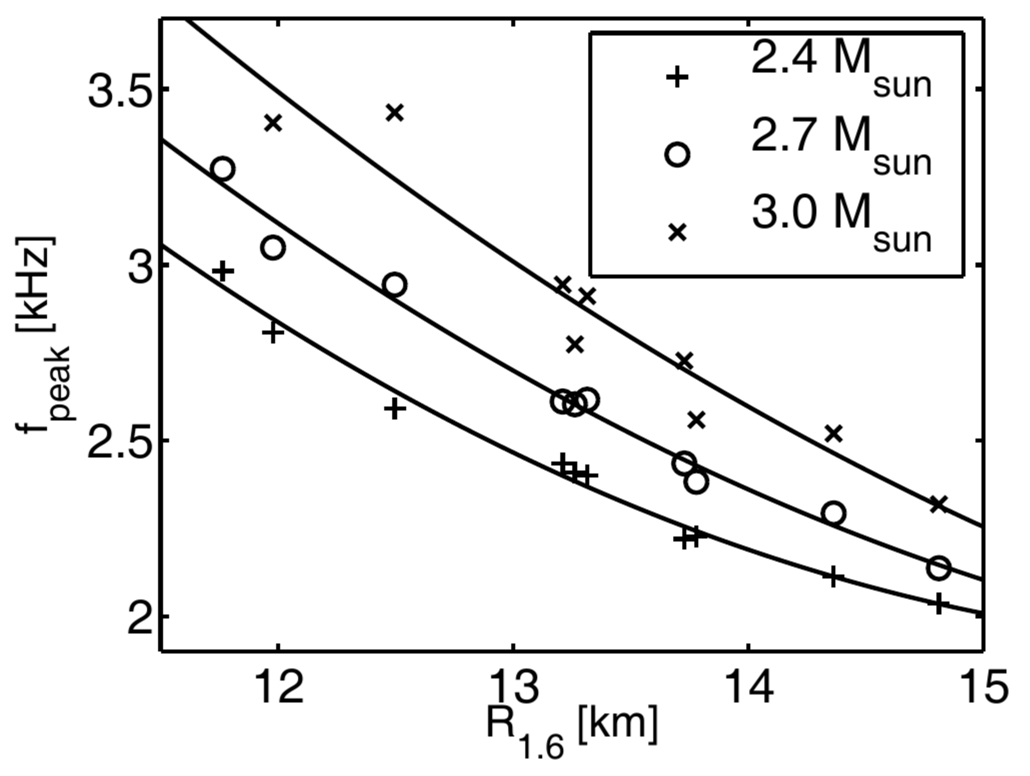
Note: R of 1.6 M_{sun} NS scales with f_{peak} from 1.35-1.35 M_{sun} mergers (density regimes comparable)

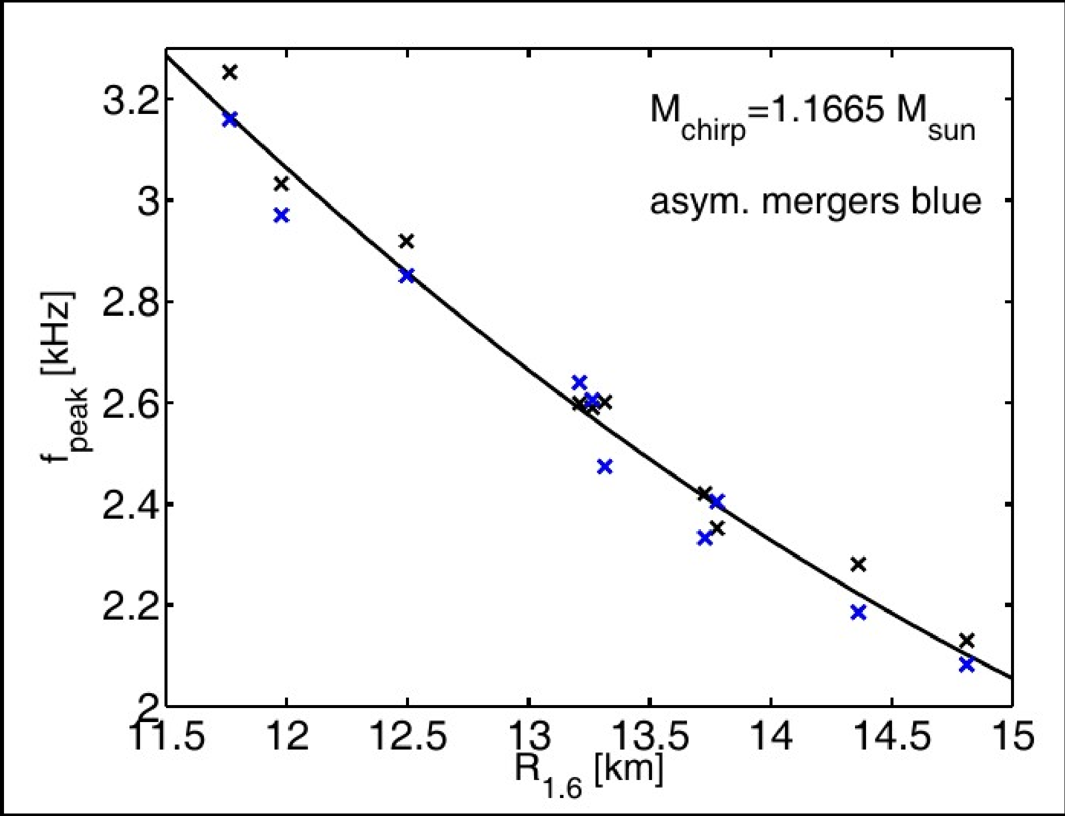
GW data analysis: Clark et al 2014, Clark et al 2016, Chatziioannou et al 2017, …

→ detectable at a few 10 Mpc

Binary mass variations

Bauswein et al. 2012, 2016





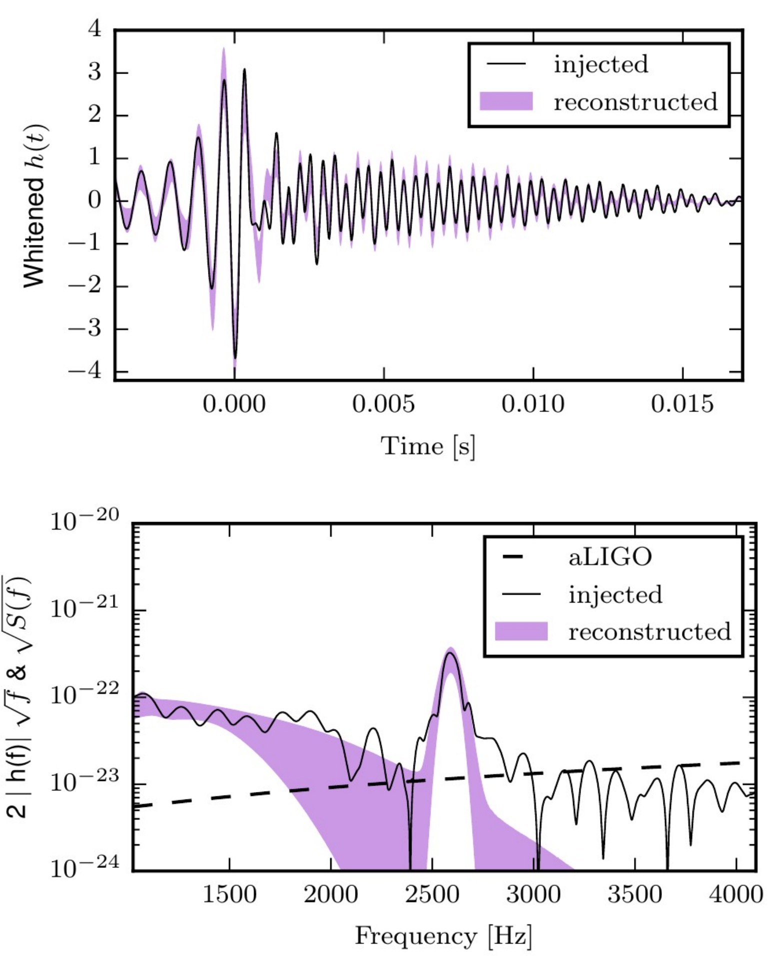
Different total binary masses (symmetric)

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

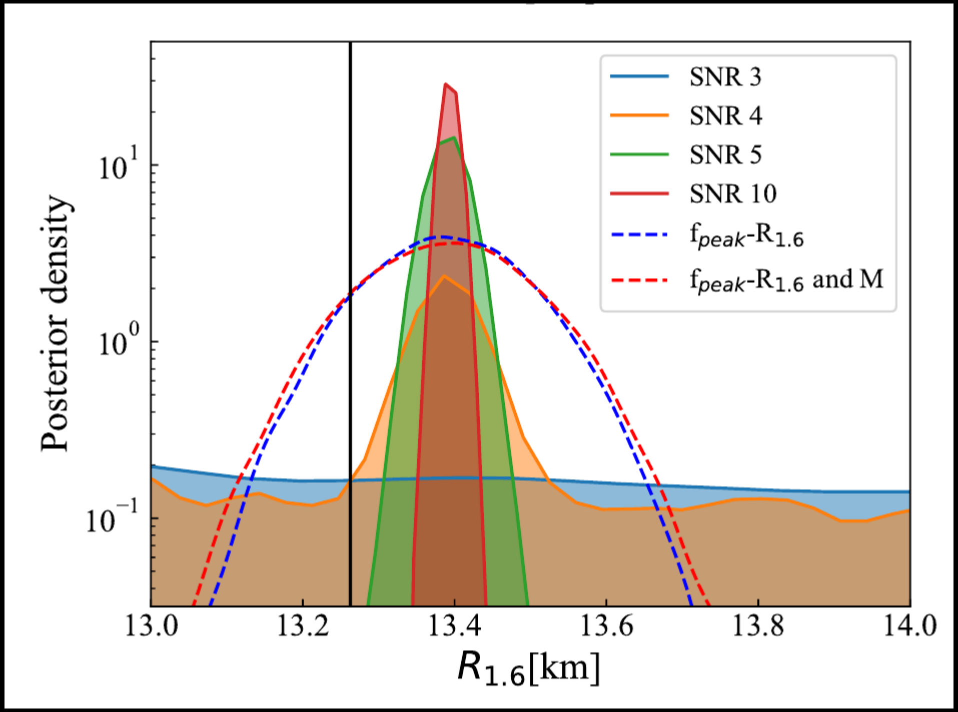
Data analysis: see e.g. Clark et al. 2016 (PCA), Clark et al. 2014 (burst search), Chatziioannou et al 2017, Torres-Riva et al 2019

→ f_{peak} precisely measurable !!!

Model-agnostic data analysis



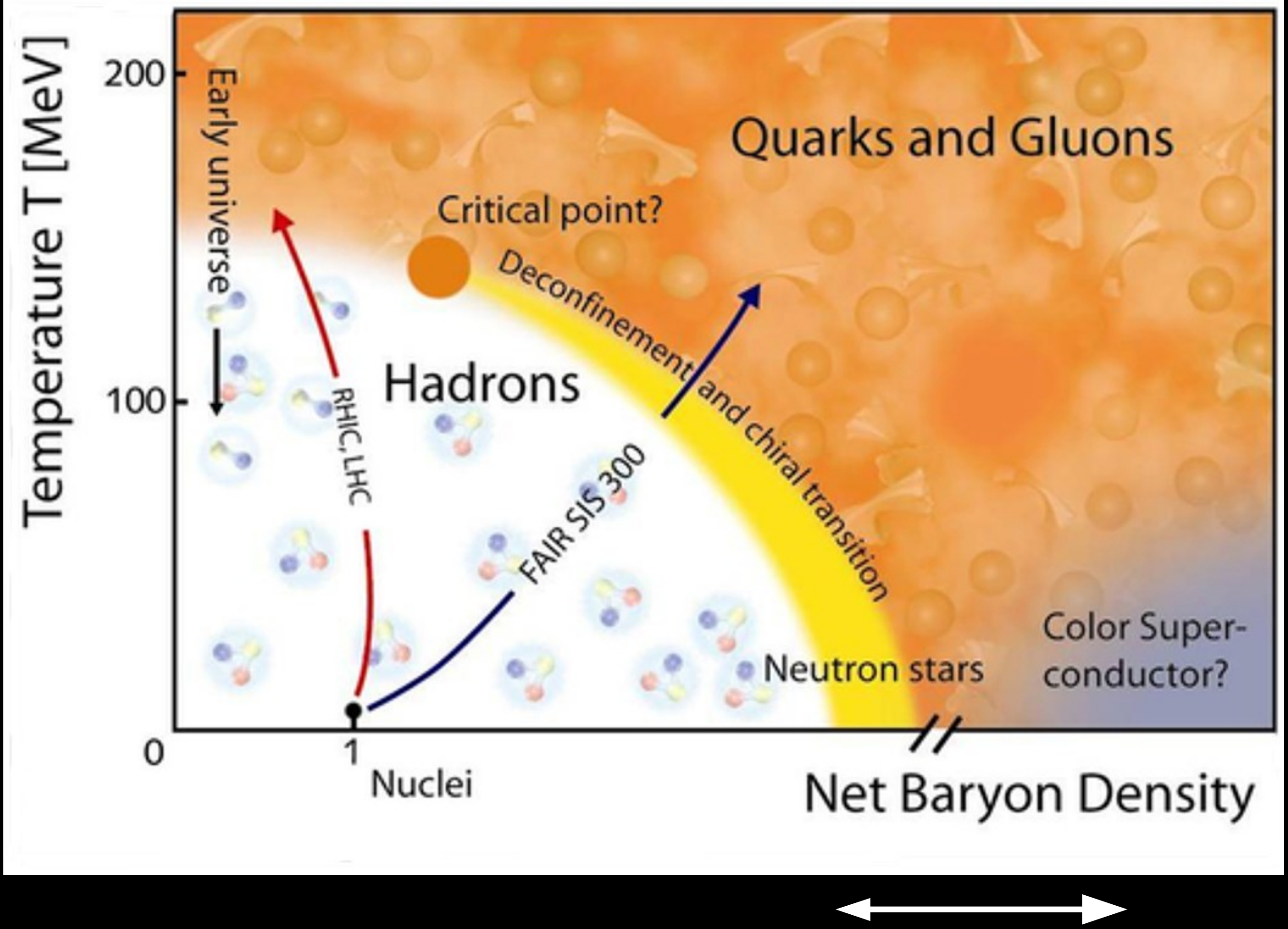
Based on wavelets



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

Observable signature of (QCD) phase transition

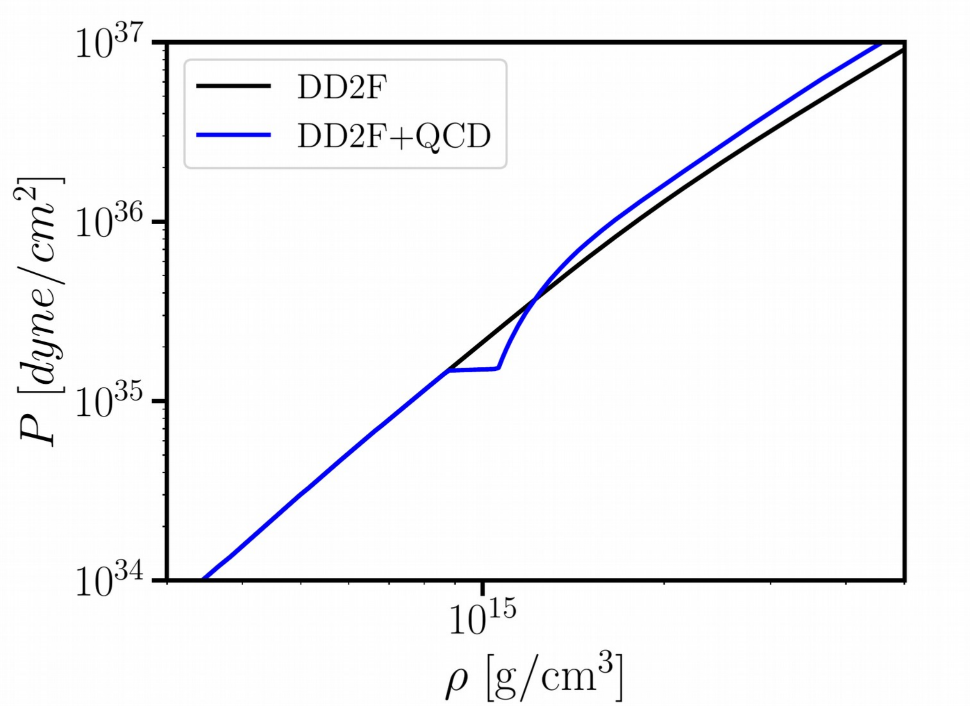
Phase diagram of matter

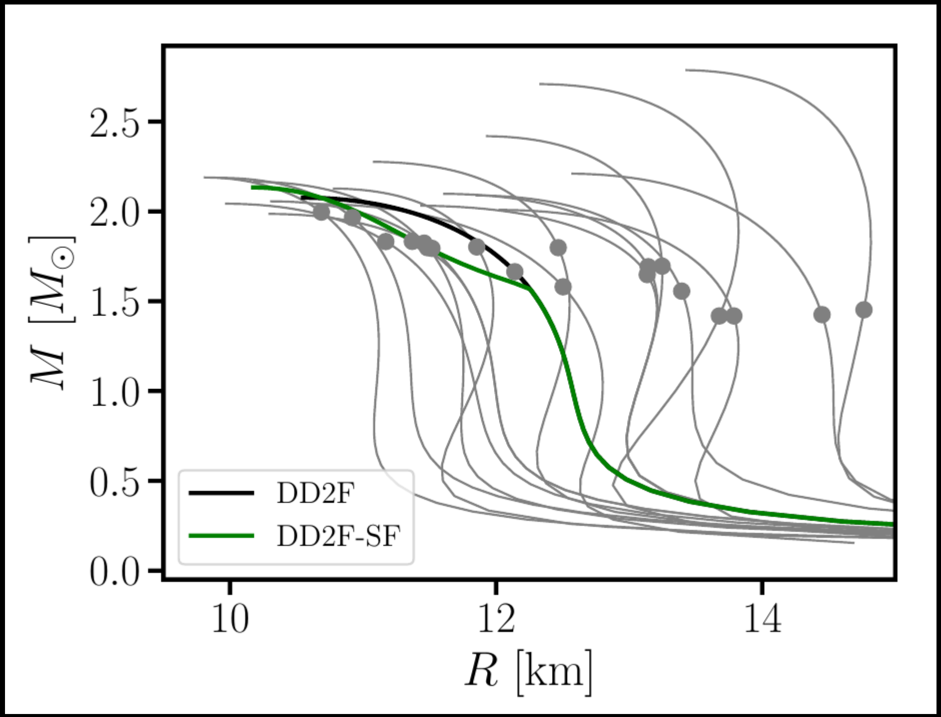


Does the phase transition to quark-gluon plasma occur (already) in neutron stars or only at higher densities ?

EoS with 1st-order phase transition to quark matter

Bauswein et al. 2018

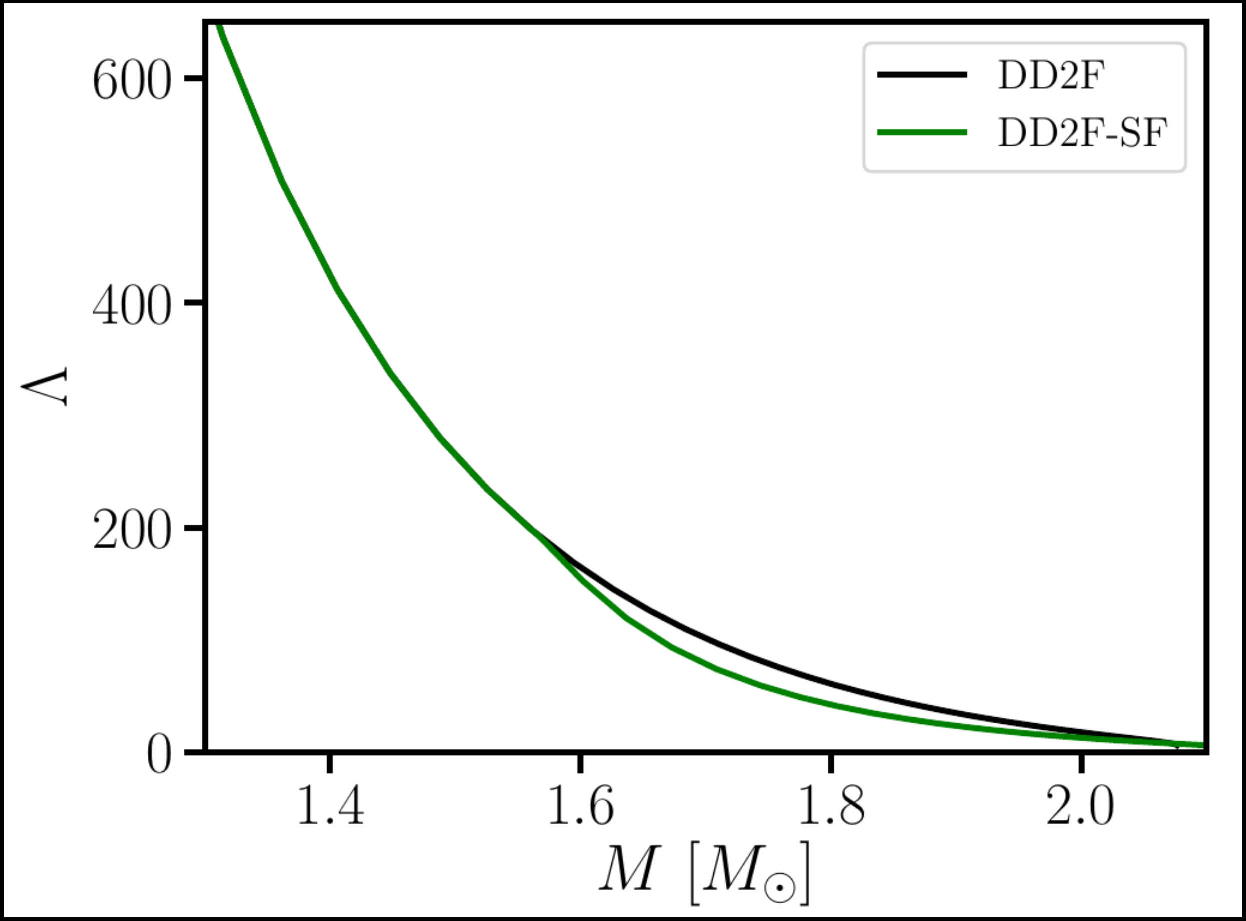




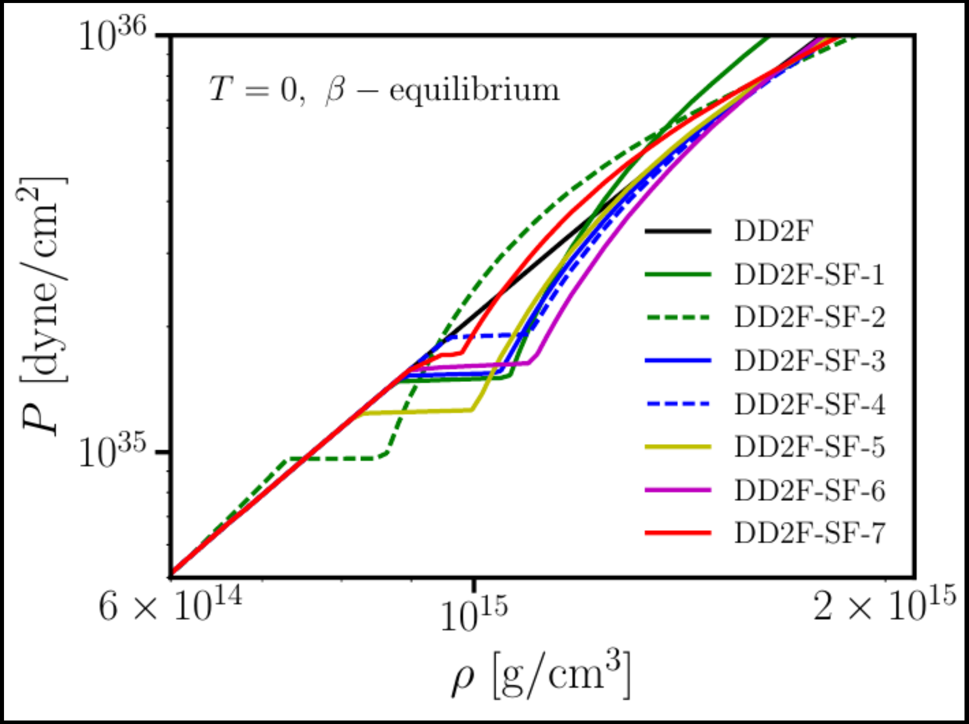
- EoS from Wroclaw group (Fischer, Bastian, Blaschke; Fischer et al. 2018) – as one example for an EoS with a strong 1st-order phase transition to deconfined quarks
- Difficult to measure transition in mergers through inspiral: Lambda very small, high mass star probably less frequent

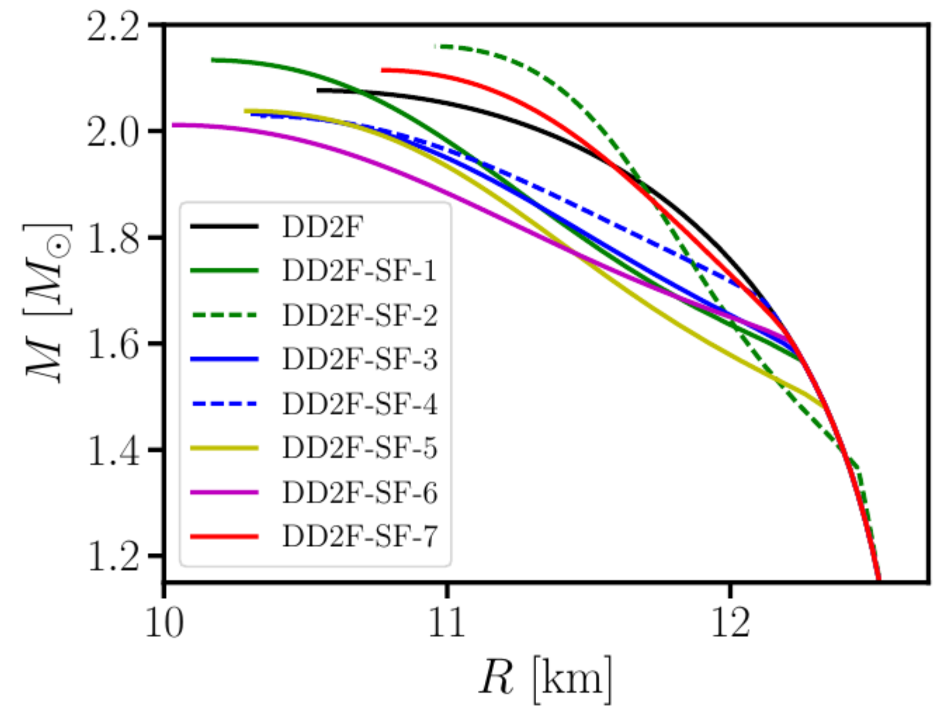
Phase transition

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

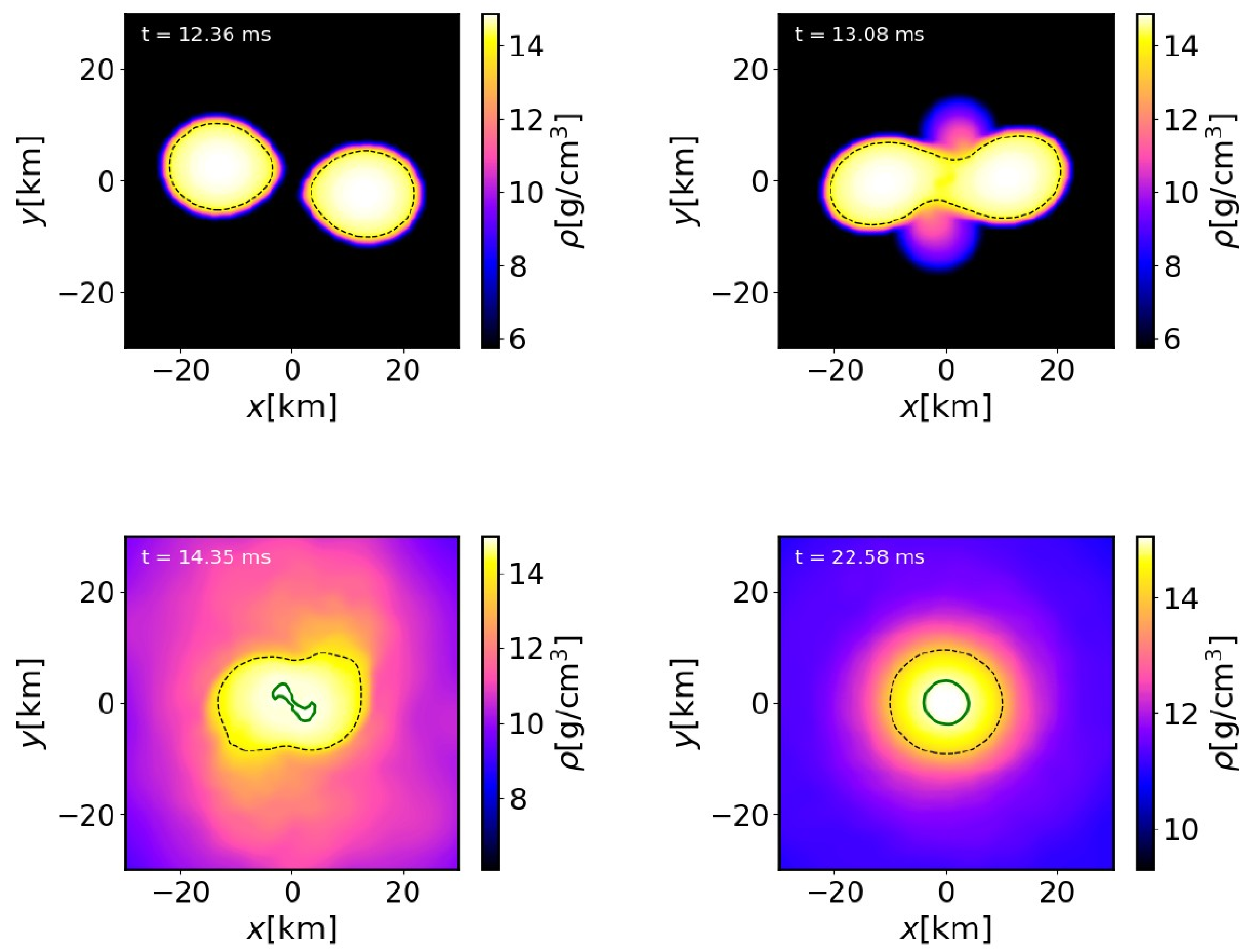


- 7 different models for quark matter: different onset density, different density jump, different stiffness of quark matter phase





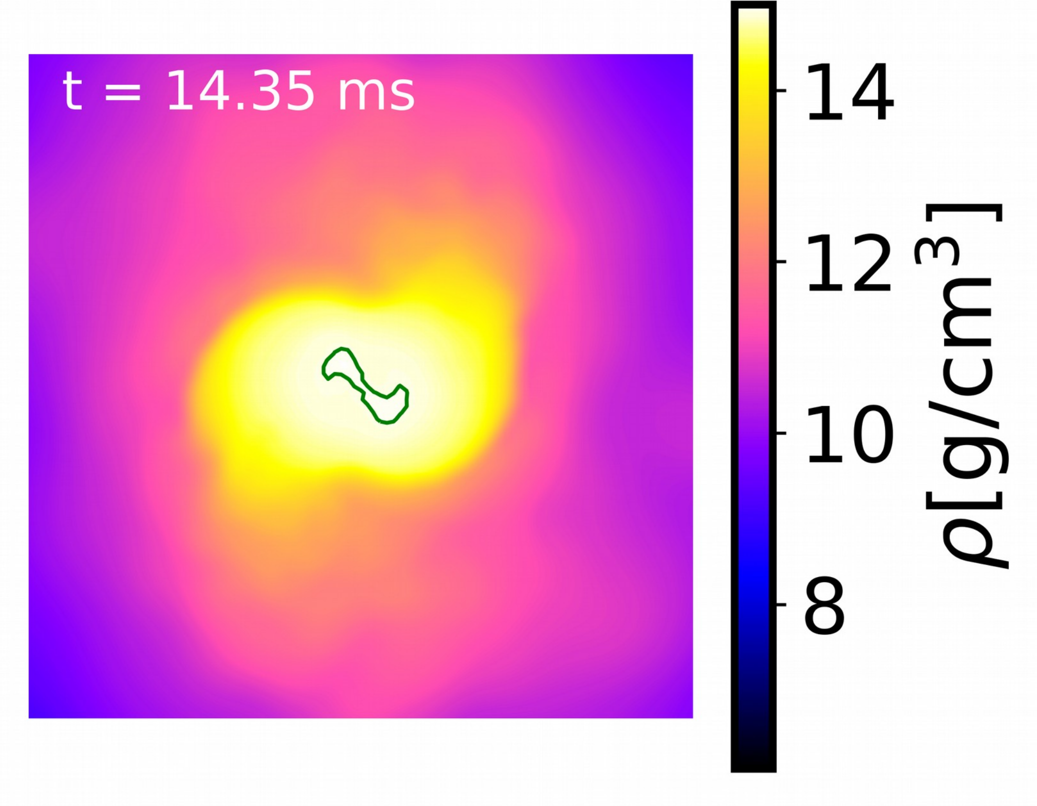
Bauswein et al. 2019

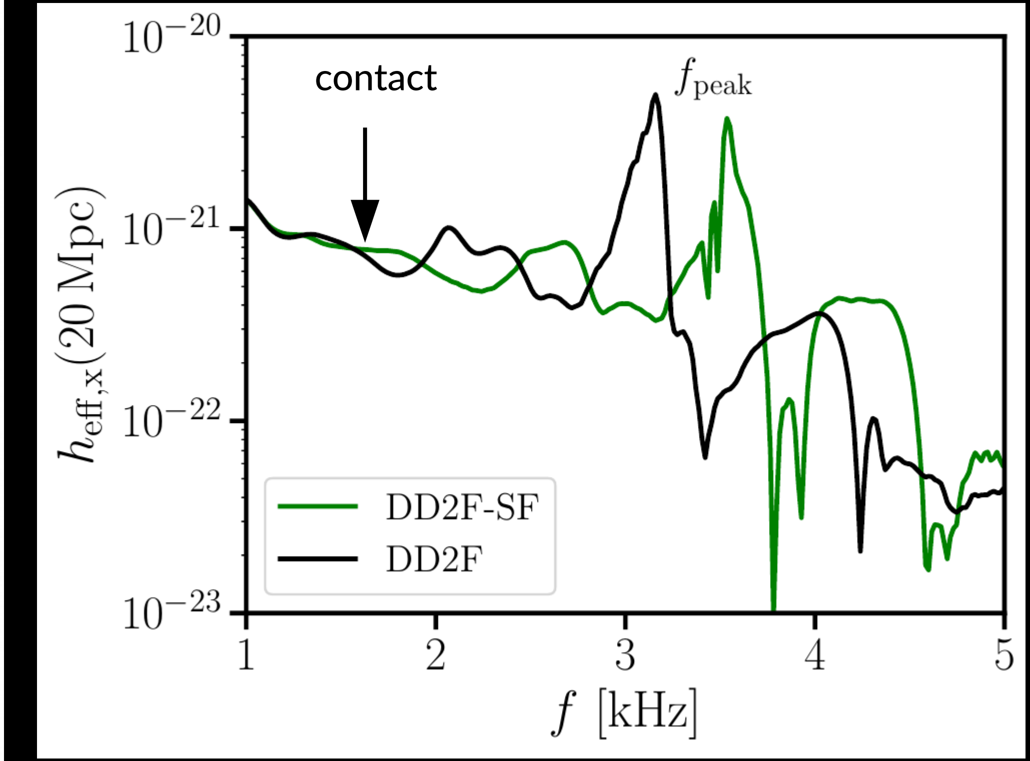


1.35-1.35 Msun - DD2F-SF-1

Merger simulations

- GW spectrum 1.35-1.35 Msun





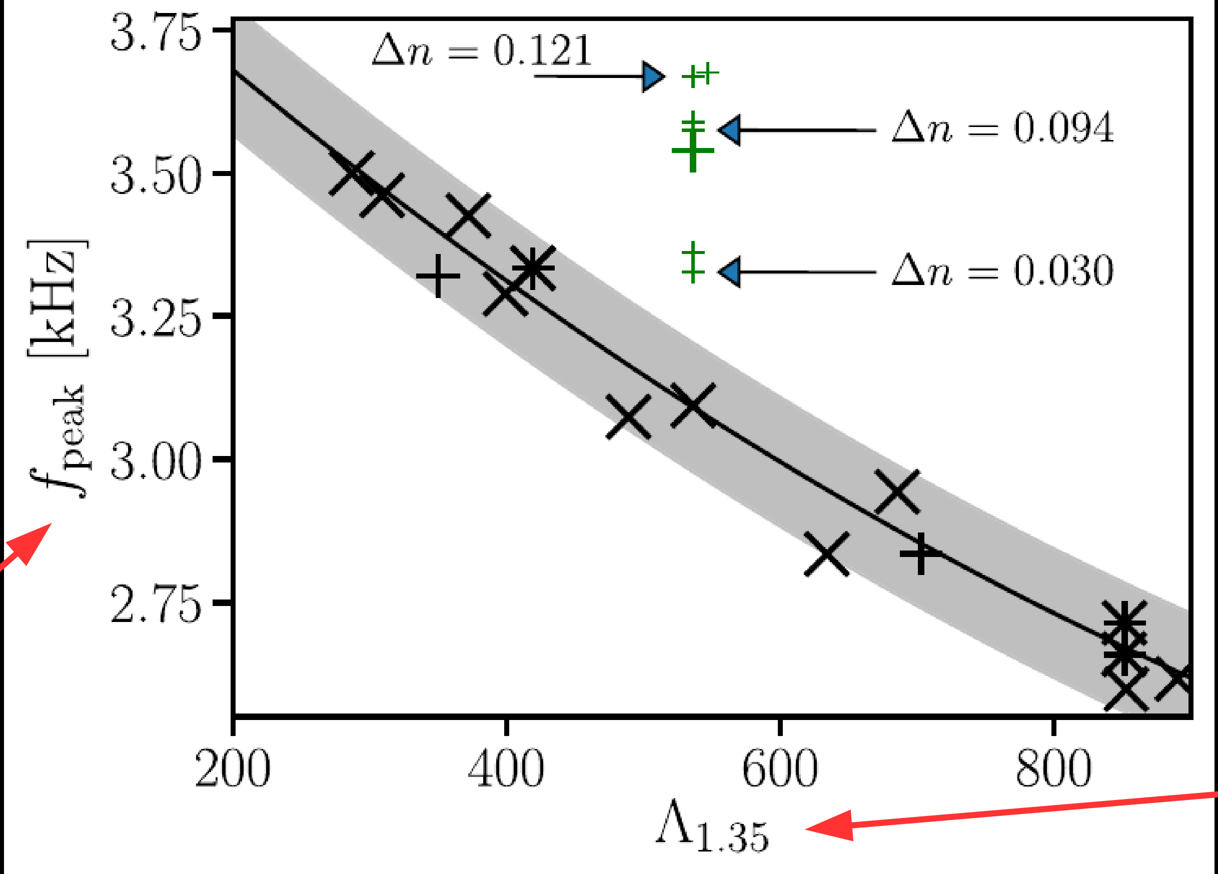
Bauswein et al. 2019

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



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

Discussion

- Consistency with fpeak-Lambda relation points to

  - purely baryonic EoS

  - (or an at most weak phase transition → no strong compactification)

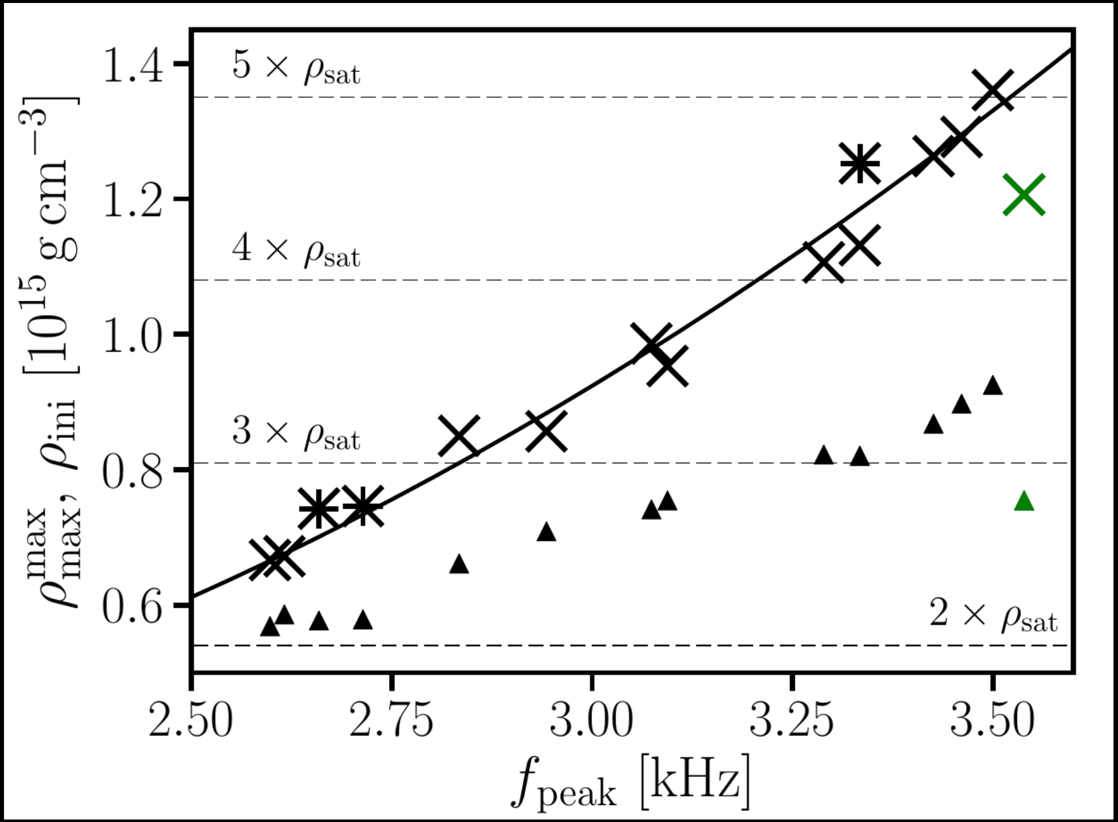
  in the tested (!) density regime

- fpeak also determines maximum density in postmerger remnant

- postmerger GW emission provides complimentary information to inspiral

  → probes higher density regime

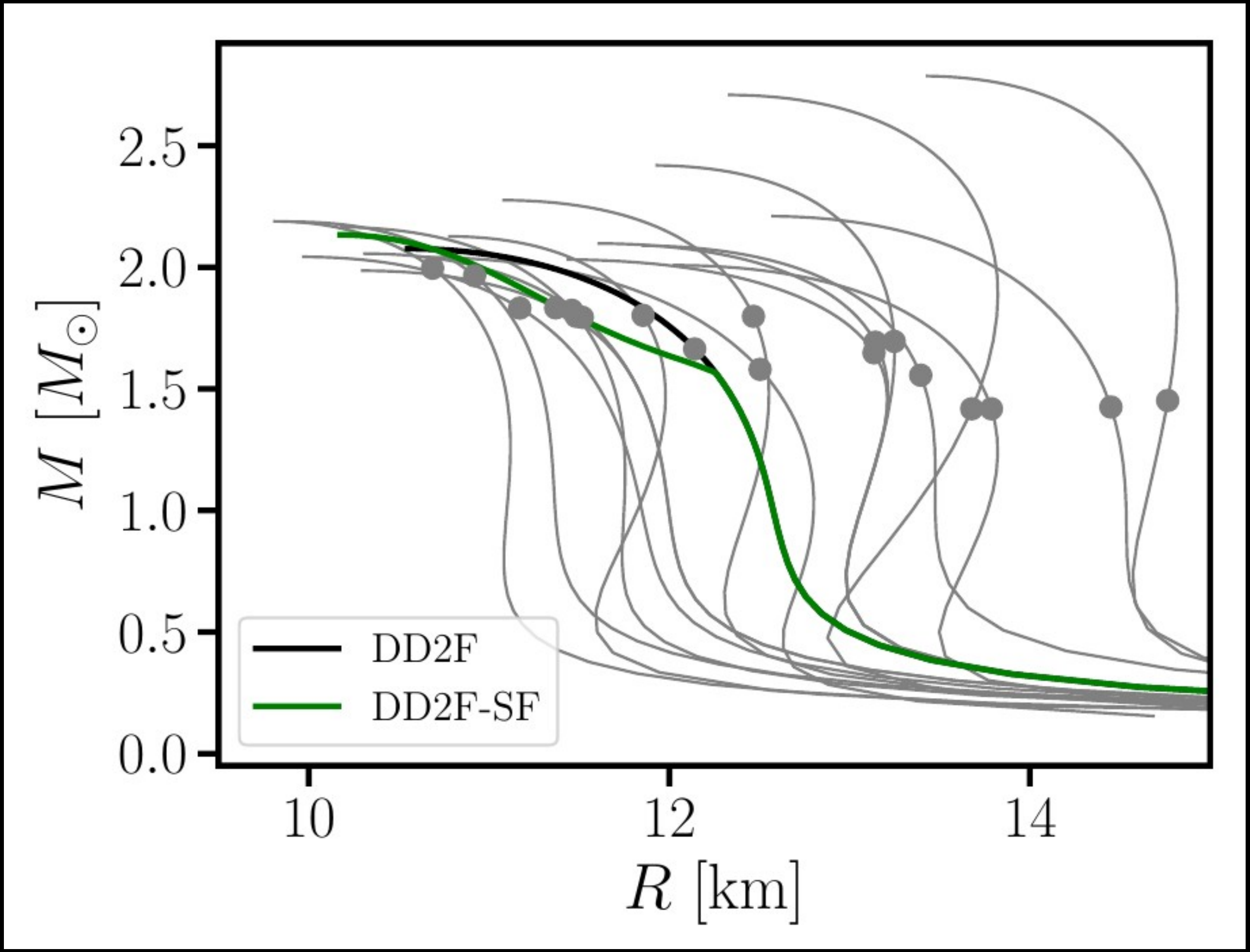
Bauswein et al. 2019



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

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)