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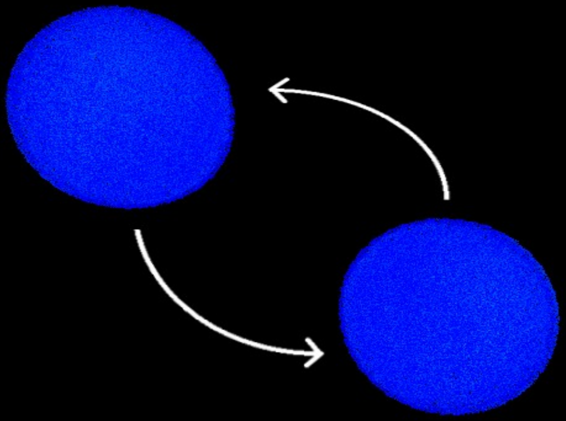
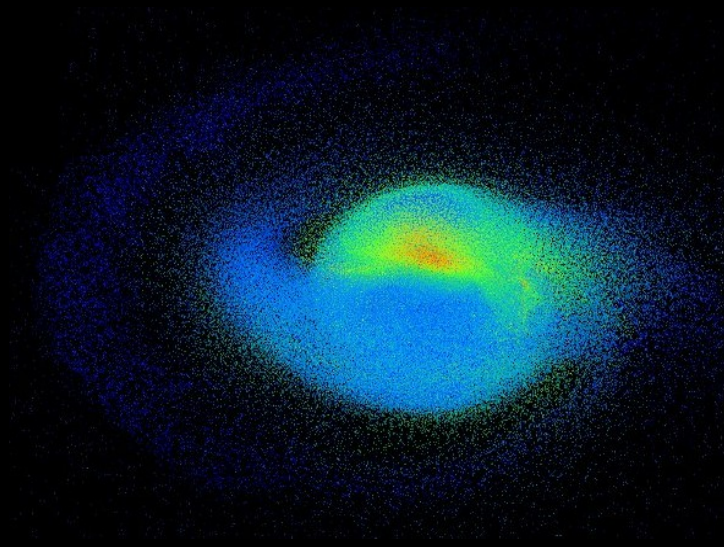
Neutron star binary mergers

Hadron2021, Mexico City (virtual), 28/07/2021

Andreas Bauswein

(GSI Darmstadt)





A break-through in astrophysics

= gravitational wave event on August 17, 2017

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

Detection August 17, 2017 by LIGO-Virgo network

→ GW data analysis providing approximate sky location

→ follow-up observations - probably largest coordinated observing campaign in astronomy (observations/time); starting immediately after – still ongoing in X-rays and radio

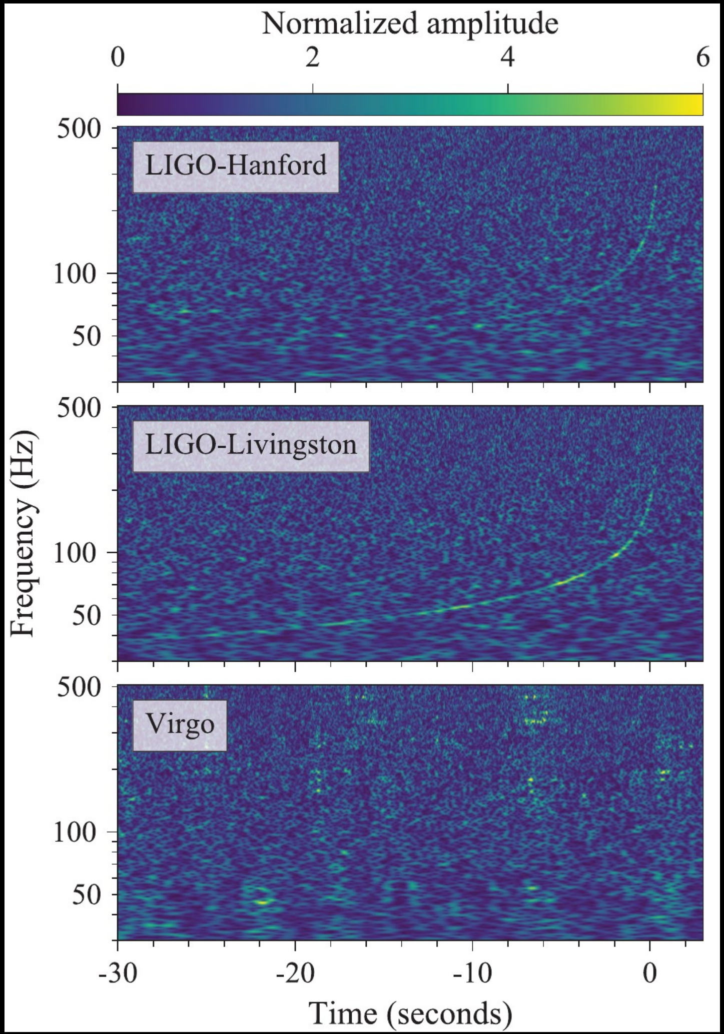
→ settled many open/tentative/speculative ideas in the context of NS mergers !!!

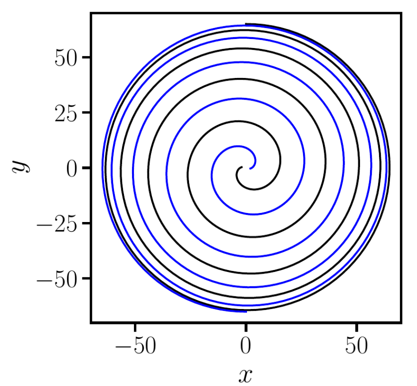
→ a few more detections meanwhile

NS mergers as probes for fundamental physics

- 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
- … !!!

GW signal in time-frequency map (Abbott et al 2017)





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

Inspiral of NS binary

~100 Myrs

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

Neutron star merger

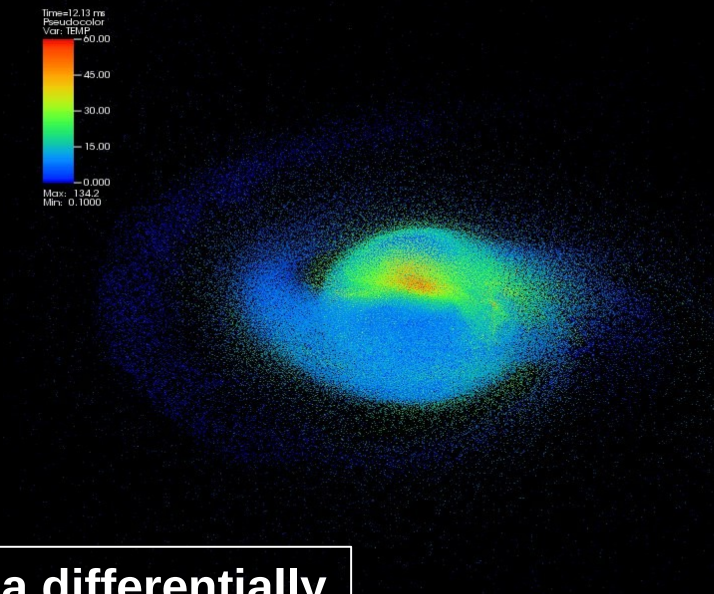
dependent on EoS, M_{tot}

ms

Prompt formation of a BH + torus

ms

Formation of a differentially rotating massive NS

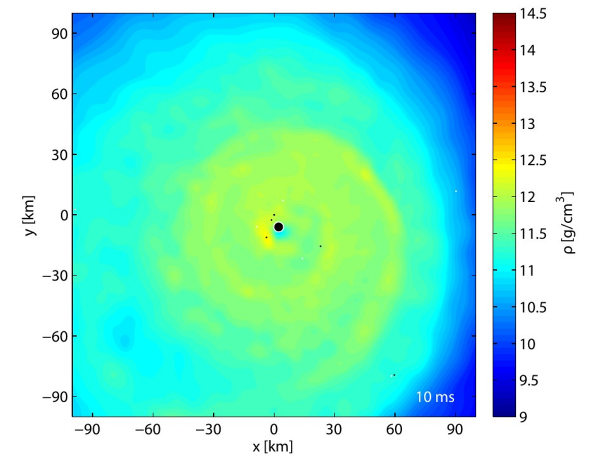


dependent on EoS, M_{tot}

10-100 ms

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

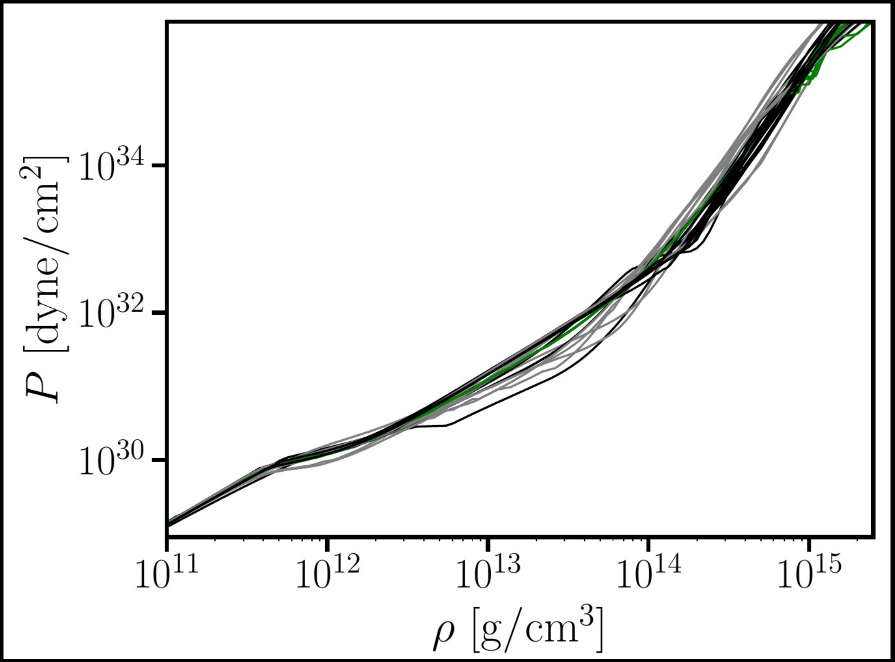
Delayed collapse to a BH + torus

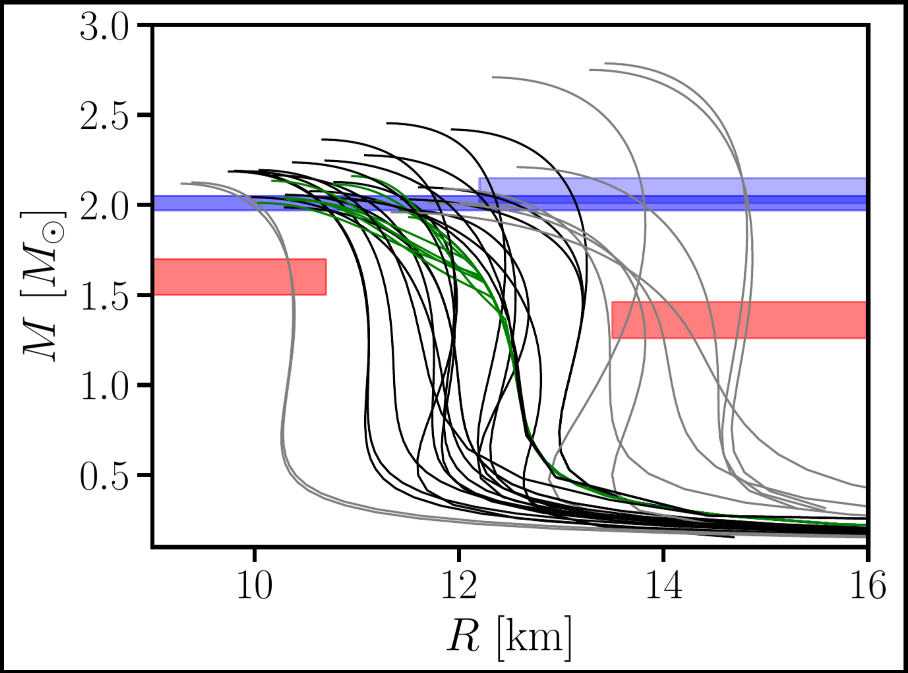


Gravitational waves and properties of high-density matter

NSs and the equation of state

- Many models for the unique (!) equation of state of high-density matter on the market
- Tolman-Oppenheimer-Volkoff eqs. uniquely link EoS to stellar structure






Theory: P(ρ)

Observation: R(M)

future

Certain contraints exist – dynamics and thus observables of NS merger depend sensitively on EoS

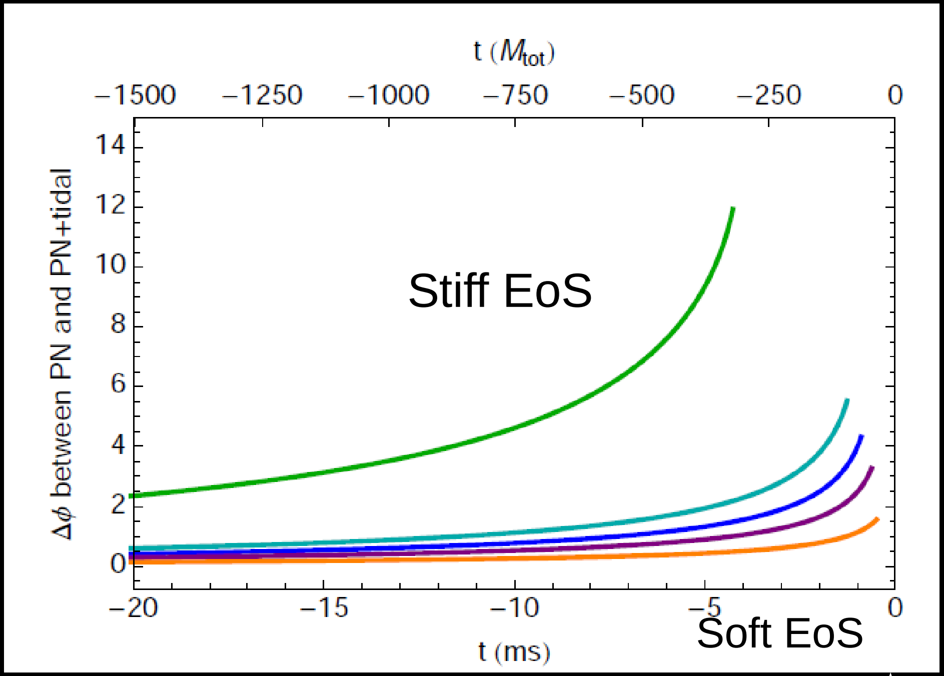
Goal: EoS from NS mergers/GWs

Three complementary strategies:

- Tidal effects during the inspiral → accelerate inspiral compared to BH-BH
- Multi-messenger interpretation (different ideas - some pretty model dependent)
- Postmerger GW emission

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

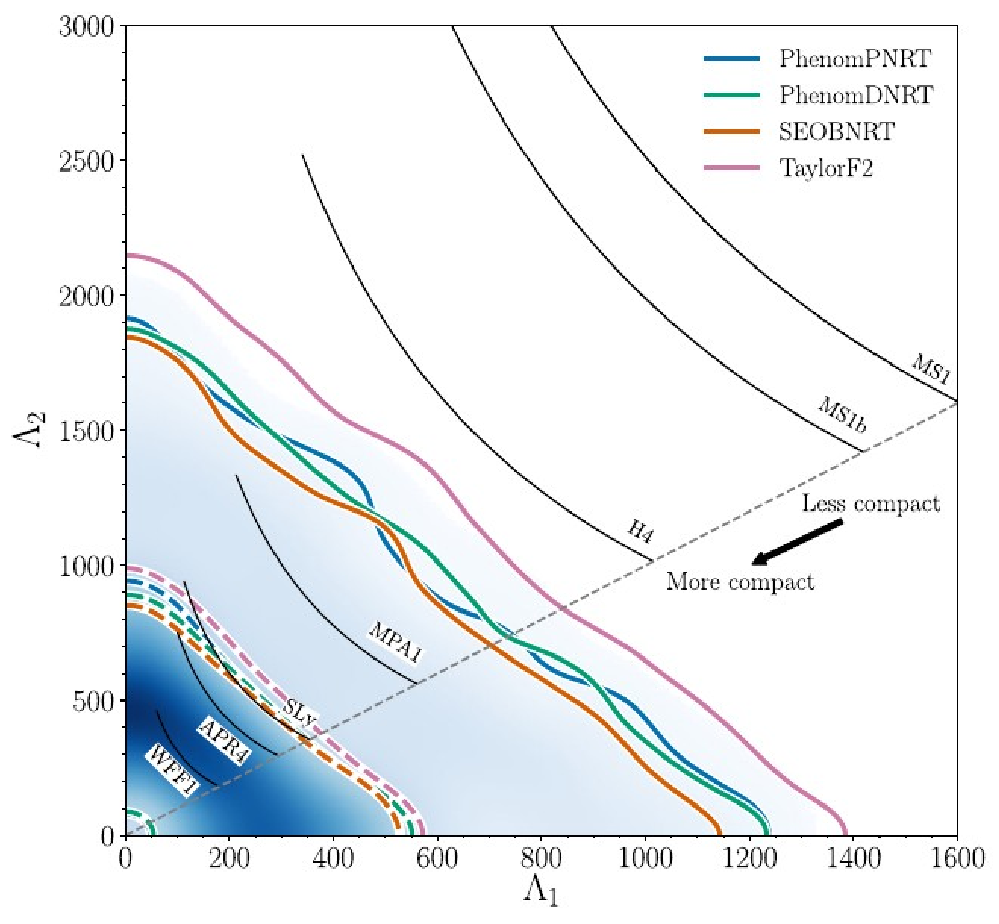
Merger time of point particle

Measurement - GW170817

- EoS impact dominated by combined tidal deformability
- Tidal deformability Lambda < ~650

  → NS radii < 13.5 km

  → Means that very stiff EoSs are excluded
- Exact limit depends on waveform model and assumptions about common EoS, spins, EoS parametrization and adopted additional constraints
- Better constraints expected in future



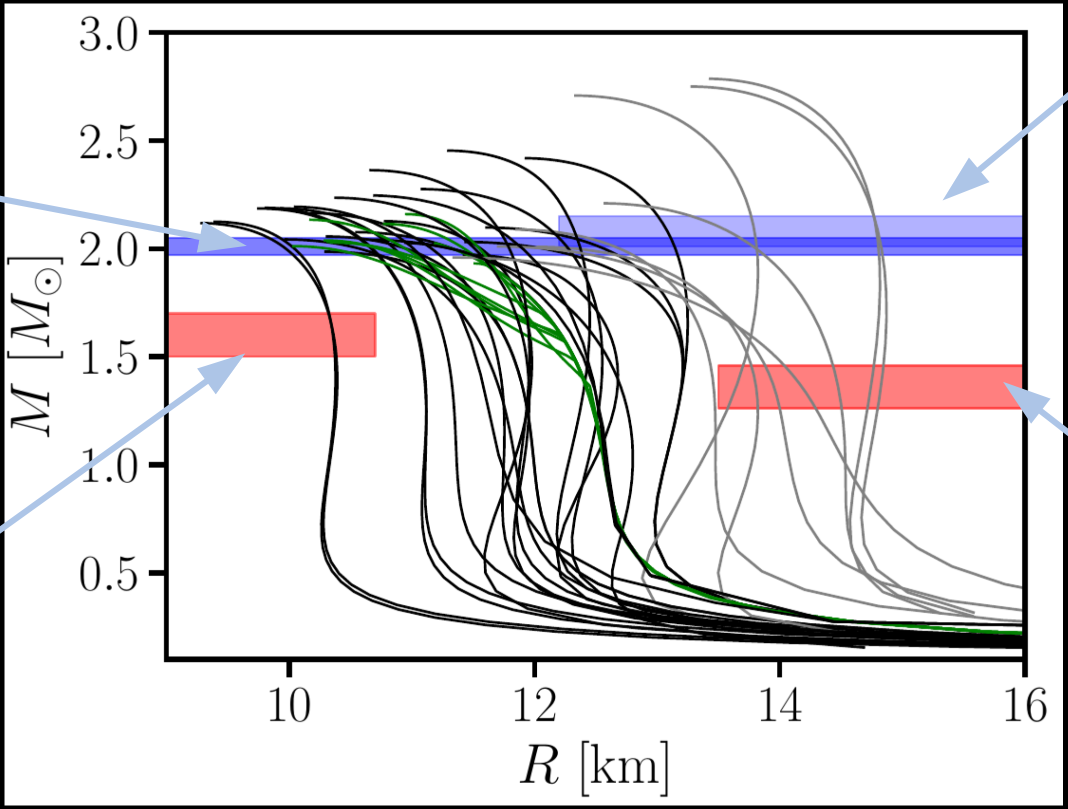
Abbott et al., PRX 2019, ...

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

See e.g. Hinderer et al., PRD 2010

EoS / NS constraints

- Narrow down stellar properties of NSs



X-ray timing NICER

Pulsar mass measurements

Multi-messenger interpretation of GW170817

Finite-size effects in GW inspiral (GW170817)

Reddish bands = excluded

- Many more ideas and measurements
- Include different uncertainties / usually hard to assess all uncertainties

Goal: EoS from NS mergers/GWs

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Multi-messenger constraints

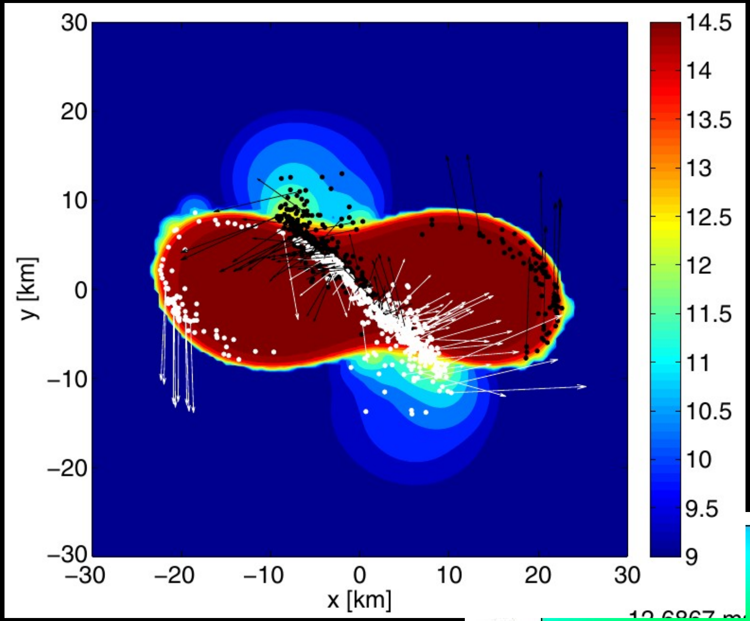
More information – more constraints – but typically model-dependence

Different ideas (some similar) – for M_{max}, radii and tidal deformability

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

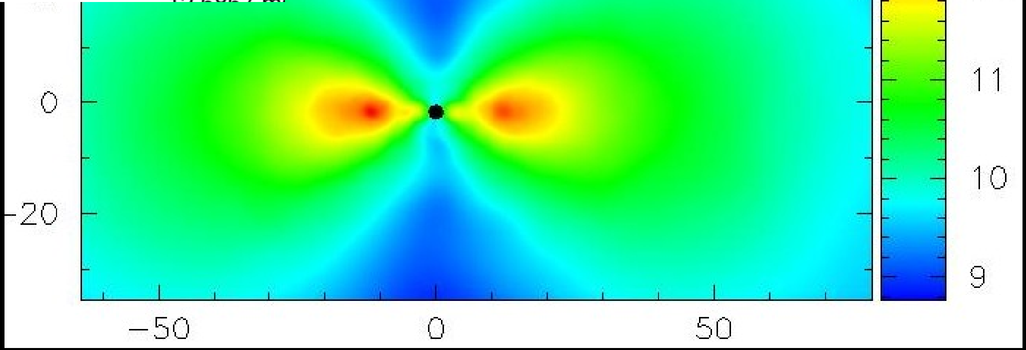
ApJ 773 (2013)



Dynamical ejecta

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

Remnant: BH torus



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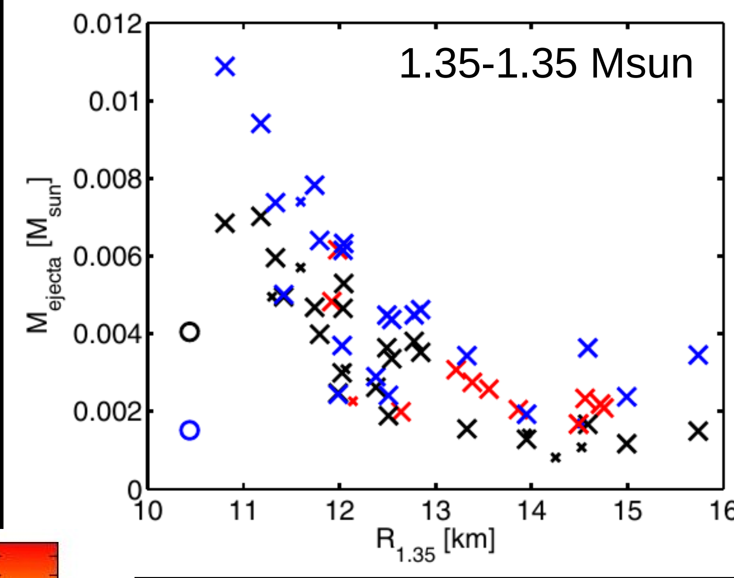


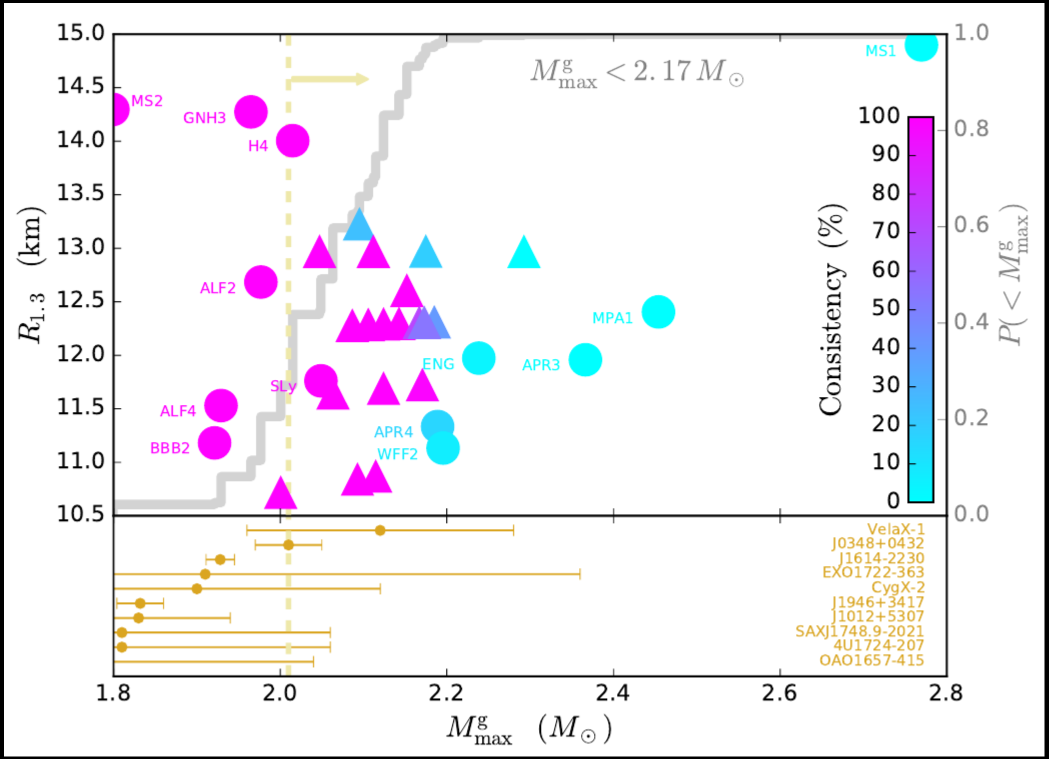
EoS dependence

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})

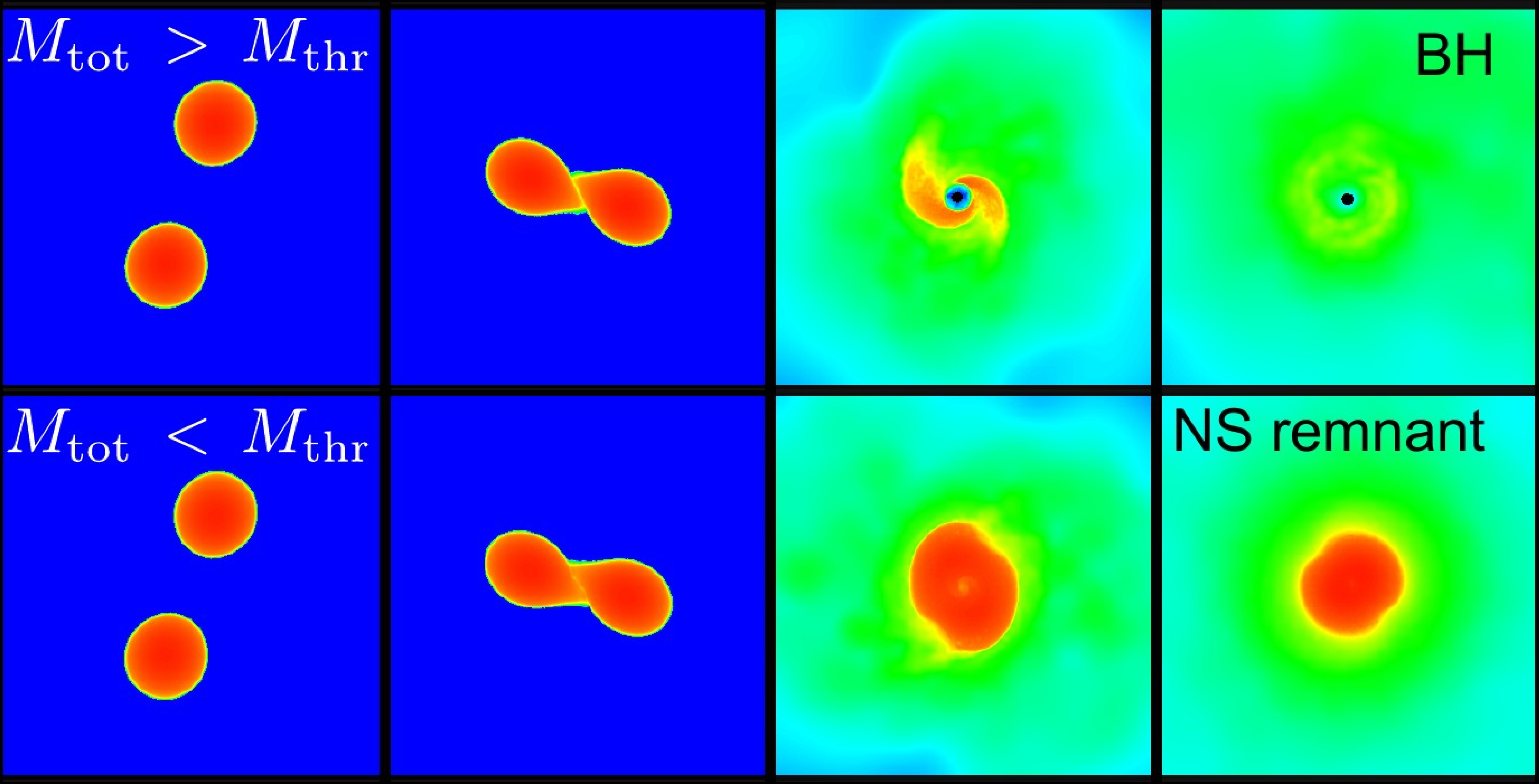
→ M_{max} < ~2.2-2.4 M_{sun}



Margalit & Metzger 2017

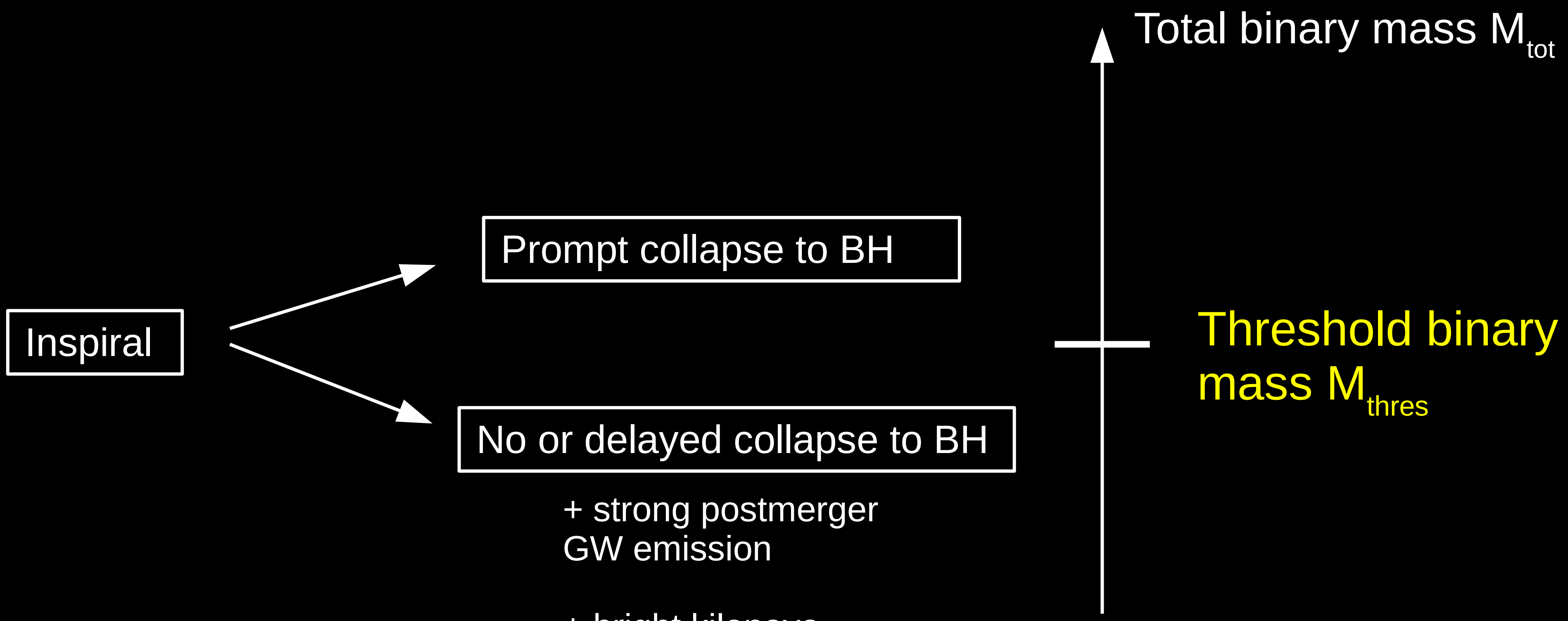
See also Shibata et al 2017, Fujibajshi et al. 2017, Rezzolla et al 2018, Ruiz & Shapiro 2018, Shibata et al

Collapse behavior



Understanding of BH formation in mergers [e.g. Shibata 2005, Baiotti et al. 2008, Hotokezaka et al. 2011, Bauswein et al. 2013, Bauswein et al 2017, Agathos et al. 2020, Bauswein et al. 2020]

Collapse behavior



Total binary mass M_{tot}

Inspiral

Prompt collapse to BH

No or delayed collapse to BH

+ strong postmerger
GW emission

+ bright kilonova

+ ….

Threshold binary mass M_{thres}

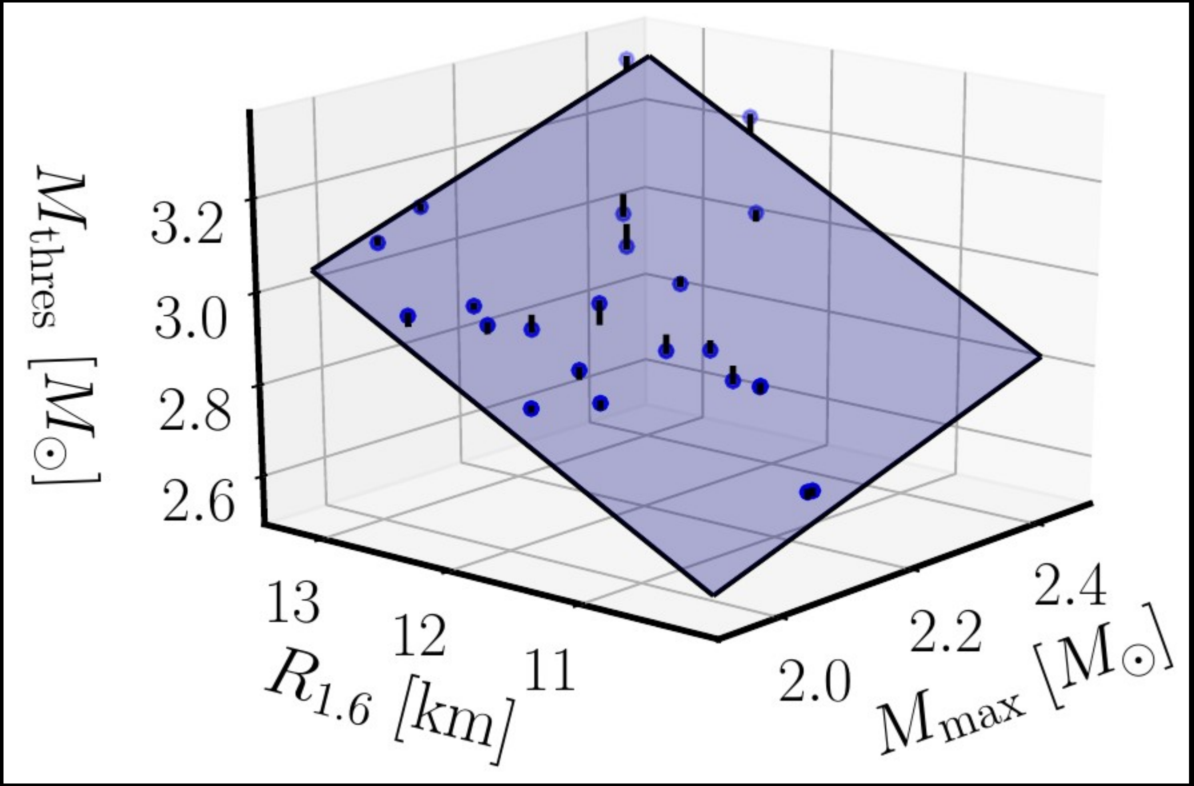
M_{thres} - EoS dependent !!!

Simulation results

EoS/TOV properties

$$M_{\mathrm{thres}} = M_{\mathrm{thres}}(X, Y) = aX + bY + c$$

Merger feature
/observable



EoS property

EoS property

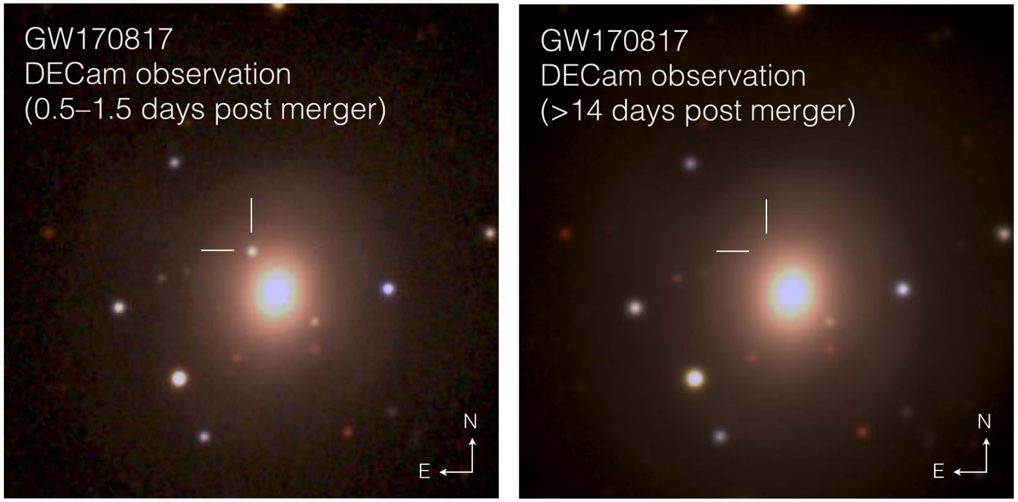
$$M_{\mathrm{thres}} = M_{\mathrm{thres}}(M_{\mathrm{max}}, R_{1.6}) = aM_{\mathrm{max}} + bR_{1.6} + c$$

Very clear dependence on stellar / EoS properties

(Maximum residual 0.04 M_{sun}, on average 0.02 M_{sun} deviation!)

NS radius constraint from GW170817

- If GW170817 did not directly form BH as indicated by relatively bright kilonova
- NSs cannot be too small/ EoS too soft because this resulted in a prompt collapse
- Relatively simple and robust: Quantitatively based on threshold binary mass for prompt collapse → a lot of potential for stronger future constraints

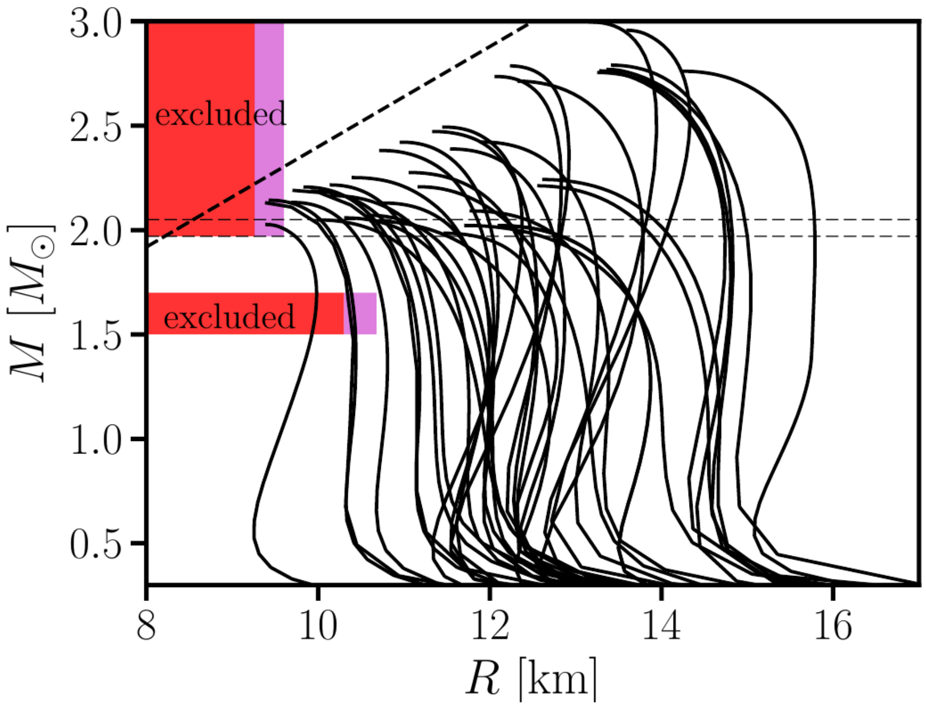


Soares-Santos et al 2017

Figure 1. NGC4993 *grz* color composites ($1\overset{\prime}{.}5 \times 1\overset{\prime}{.}5$). 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.

$$L_{\mathrm{bol}} \propto \sqrt{M_{\mathrm{ejecta}}}$$

→ Inferred ejecta mass 0.02-0.05 Msun

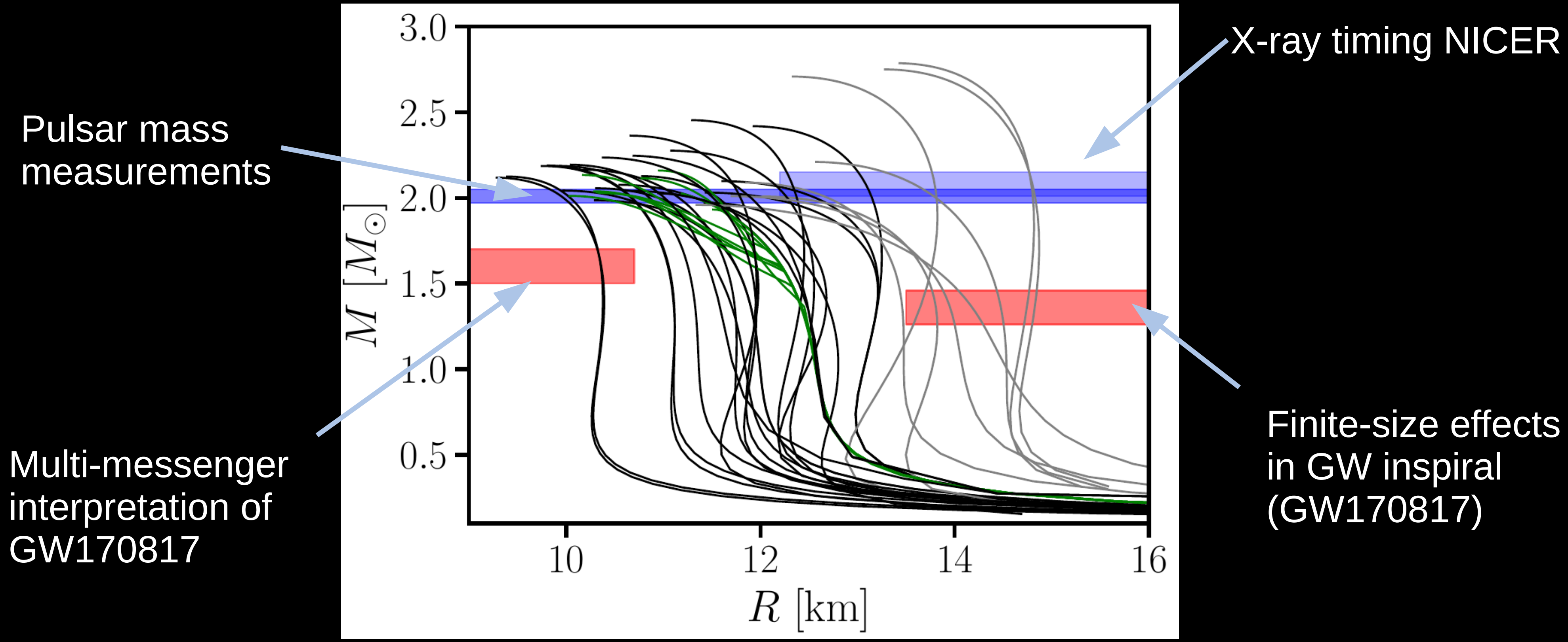


Bauswein et al. 2017

See also Radice et al 2018, Koeppel et al 2019, ... for similar constraints on radius/ tidal deformability

EoS / NS constraints

- Narrow down stellar properties of NSs



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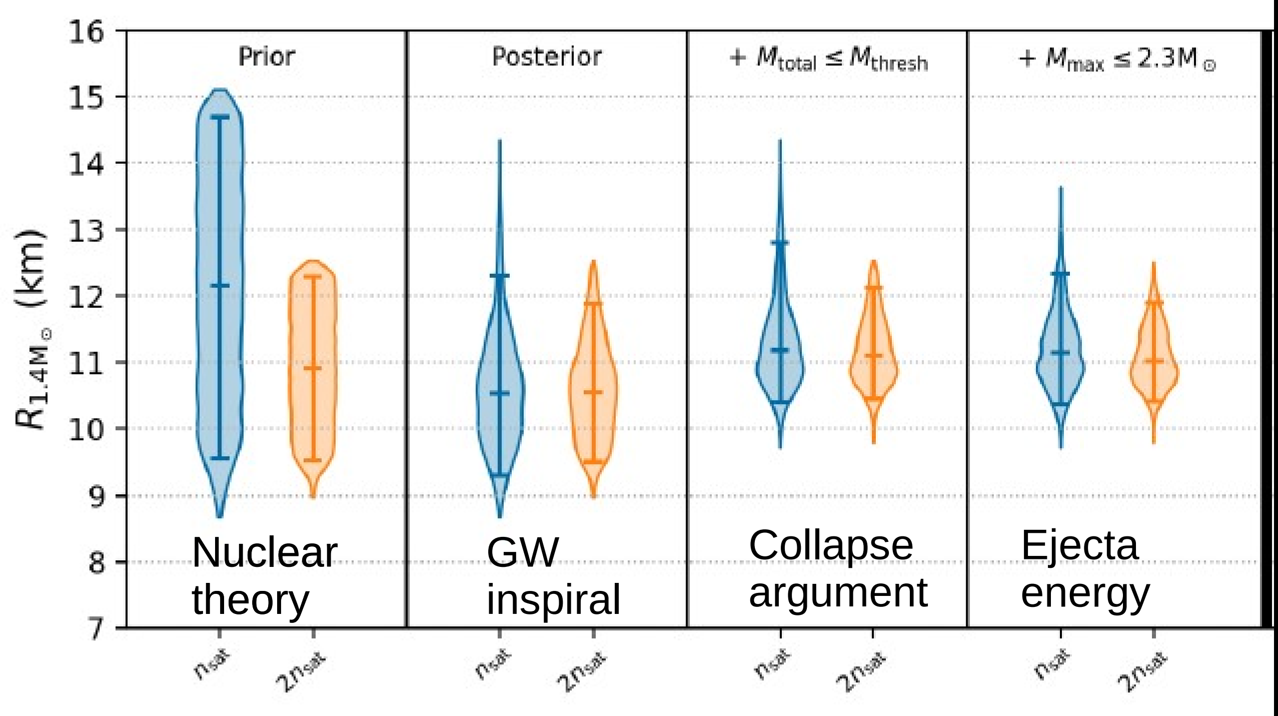
Combining information



Capano et al 2020; many other similar approaches

Goal: EoS from NS mergers/GWs

Three complementary strategies:

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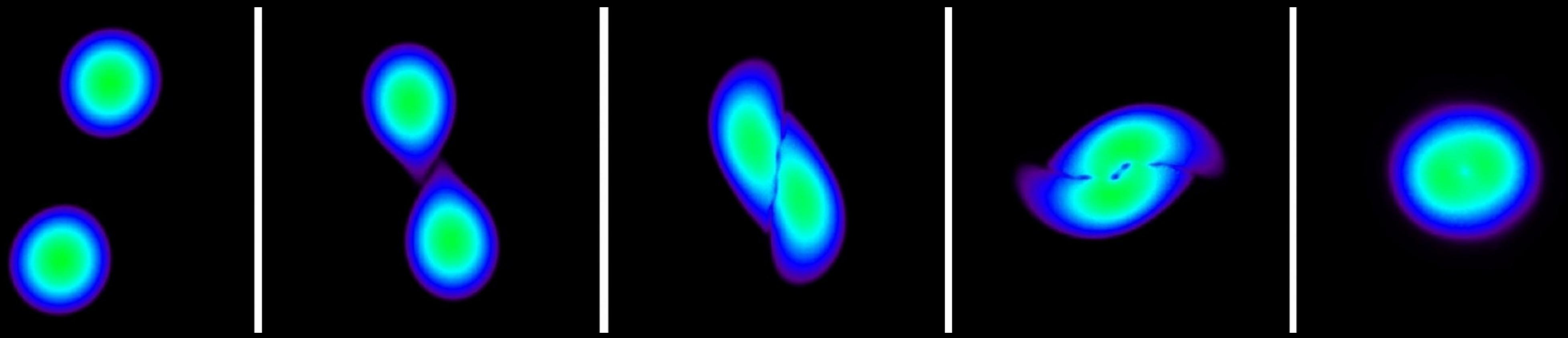
- Postmerger GW emission

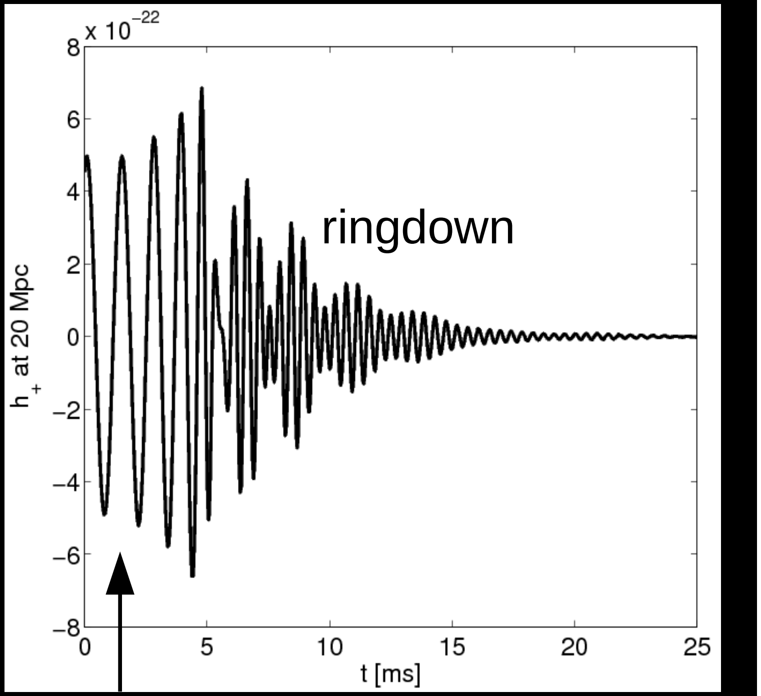
Postmerger GW oscillations



Not yet observed (but possible in future events, shown by simulated injections)

Postmerger

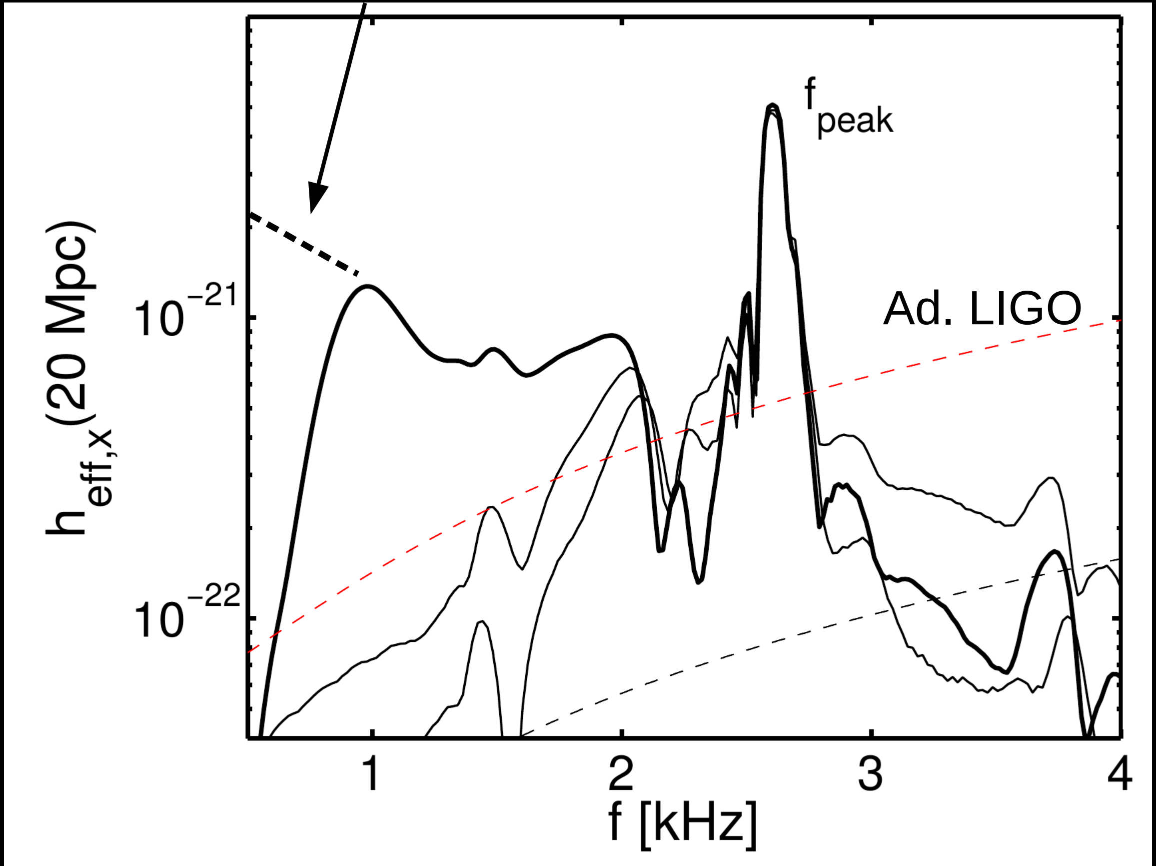
1.35-1.35 M_{sun} , 20 Mpc



inspiral

Earlier inspiral not simulated

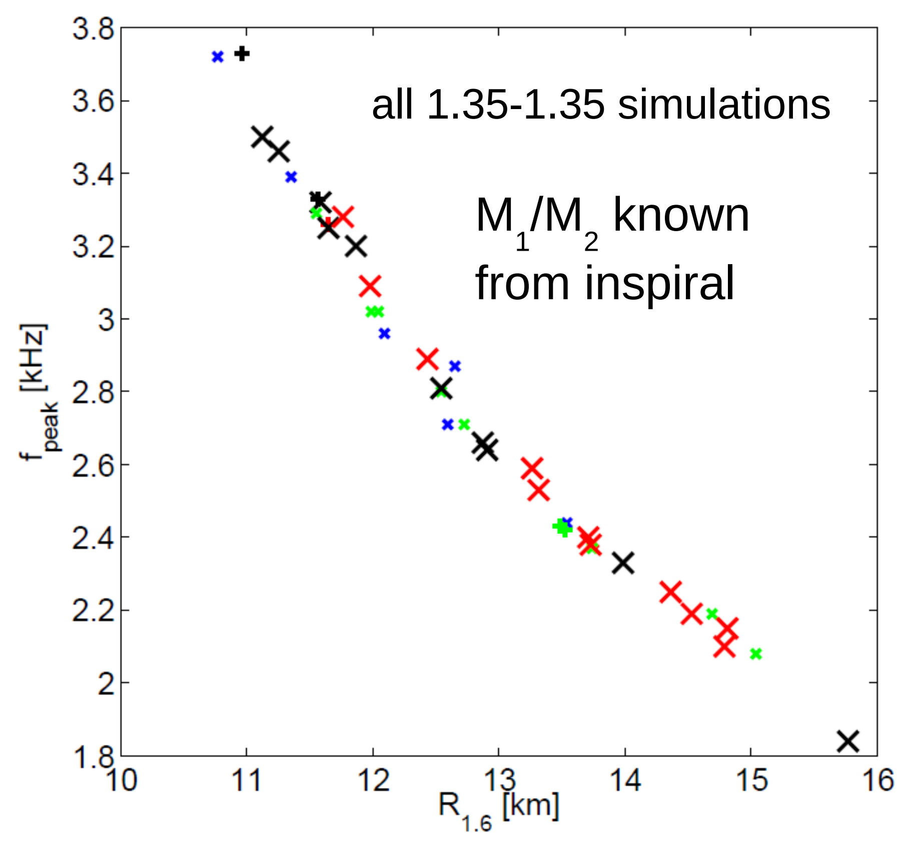
EoS



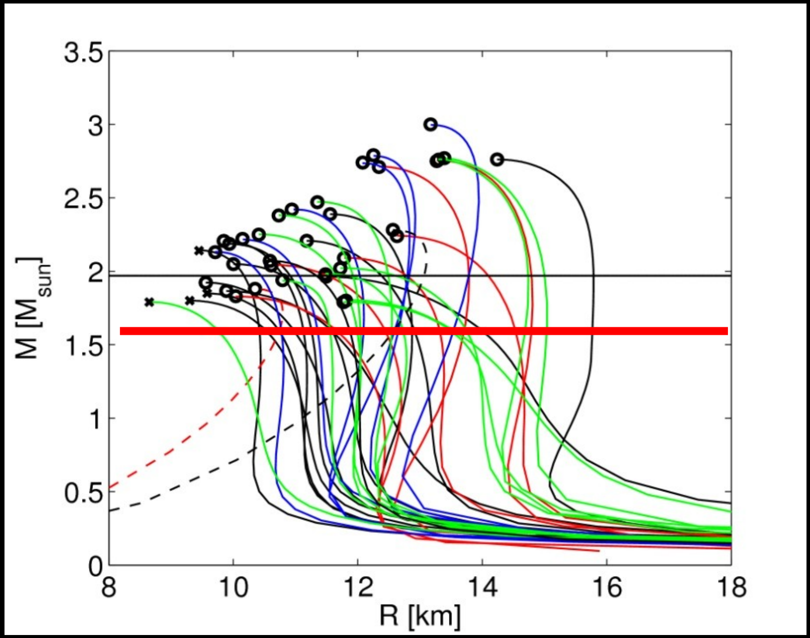
Dominant postmerger oscillation frequency f_{peak} (robust feature in all models)

Postmerger frequencies depend in <u>specific</u> way on EoS [Bauswein & Janka, PRL 2012, Bauswein et al., PRD 2012, Hotokezaka et al., PRD 2013, Takami et al. PRL 2014, Bernuzzi et al. PRL 2015, Bauswein et al. PRD 2015, ..] → EoS constraints !!!

Gravitational waves – EoS survey



A.B. et al. PRD 2012



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

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

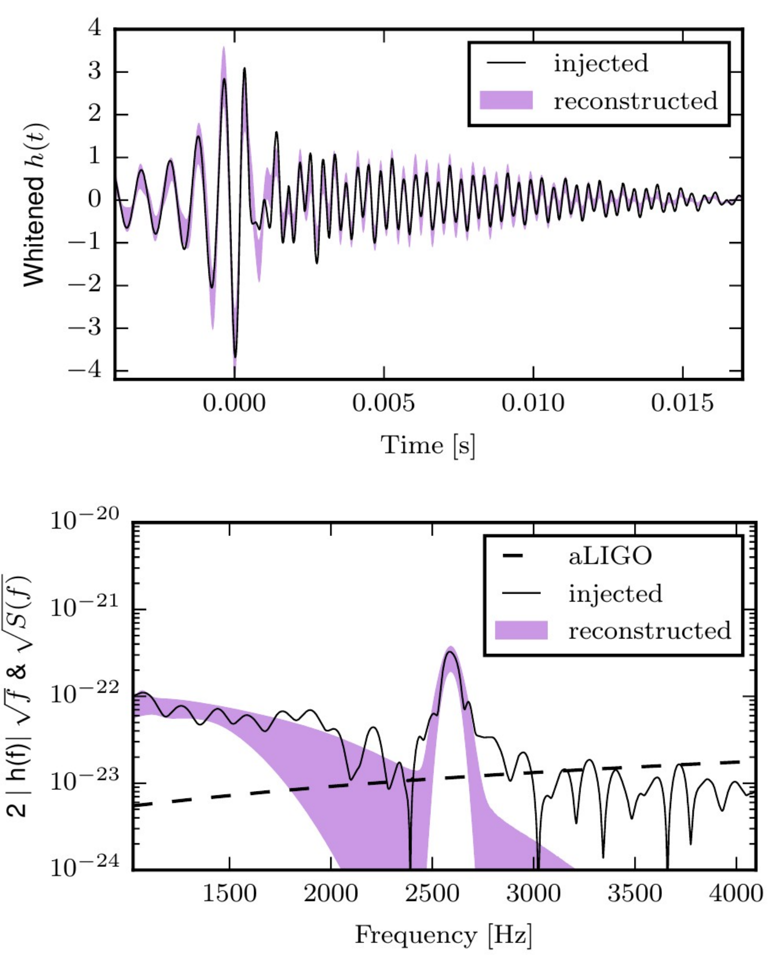
Note: similar relatiosn for other binary masses (measurable from inspiral)

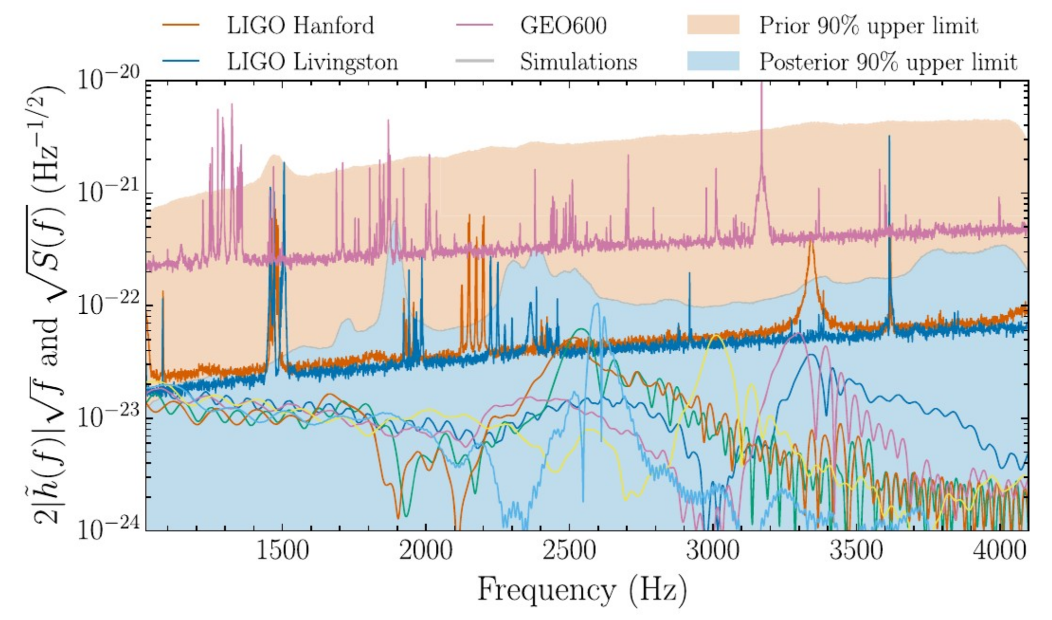
R of 1.6 M_{sun} NS scales with f_{peak} from 1.35-1.35 M_{sun} mergers (density regimes comparable)

[A.B. & Janka, PRL 2012, A.B. et al., PRD 2012]

GW data analysis: Model-agnostic data analysis

Based on wavelets





Abbott et al., PRX (2019)

Simulated injections → detectable at a few 10 Mpc
→ within a few 10 Hz

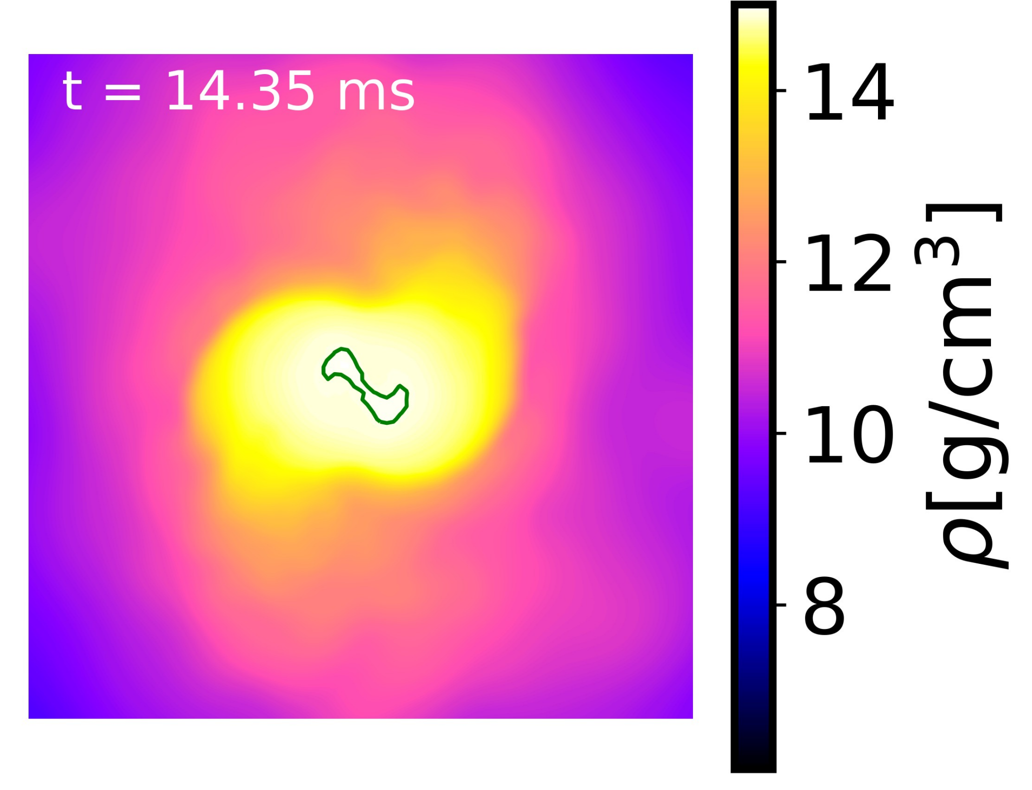
Chatziioannou et al., PRD 2017, see also Clark et al., PRD 2014, Clark et al., Class. Quantum Grav. 2016, Bose et al. PRL 2018, Yang et al. PRD 2018 Torres-Riva et al., PRD 2019, …

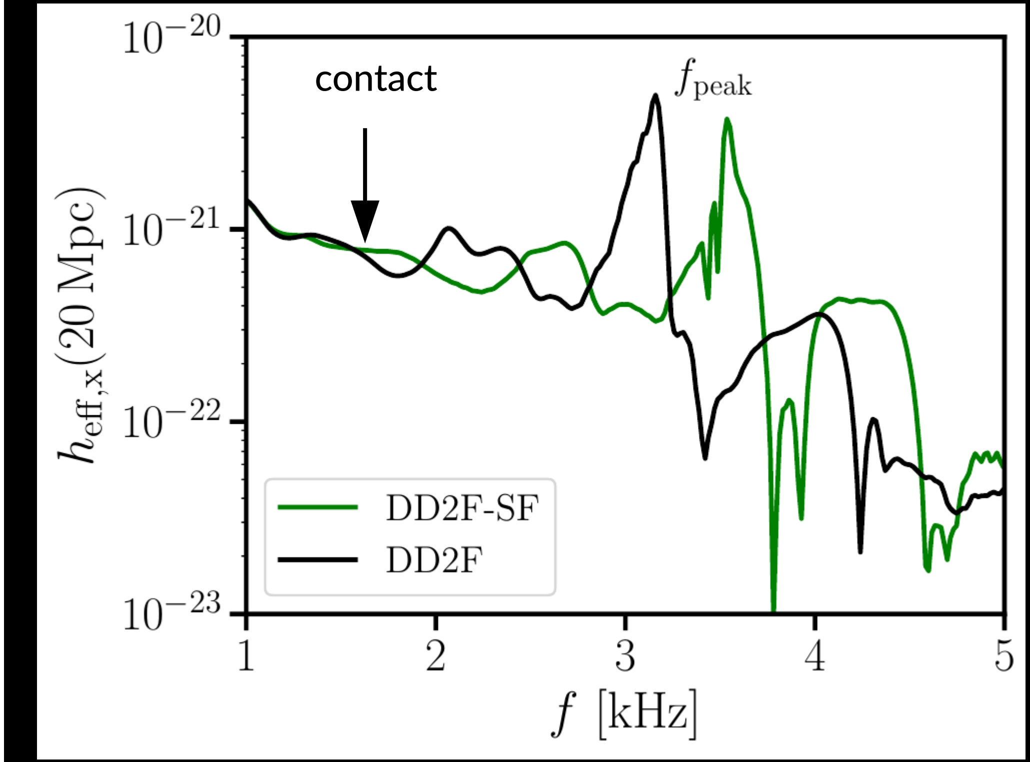
Quark matter in NS mergers

→ round table on Friday

Merger simulations with quark matter core

- GW spectrum 1.35-1.35 Msun





A.B. et al. 2019

But: a high frequency on its own may not yet be characteristic for a phase transition

→ unambiguous signature

Summary

- NS mergers as laboratory for fundamental physics (not only EoS): stellar astrophysics, nucleosynthesis, cosmoslogy, ….
- Different possibilities to learn about high-density matter

  - GW inspiral → finite size effects → nuclear matter cannot be too stiff

  - multi-messenger effects → nuclear matter cannot be too soft

  - future: postmerger GW oscillations