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EoS influence on neutron star mergers

Advances on Giant Nuclear Monopole Excitations and Applications to Multimessenger Astrophysics, ECT* Trento (virtual), 14/07/2022

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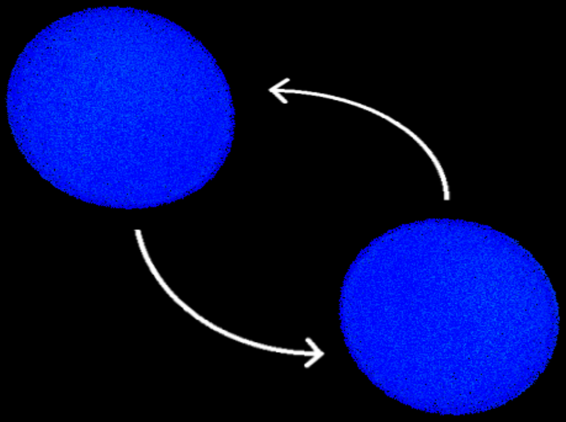
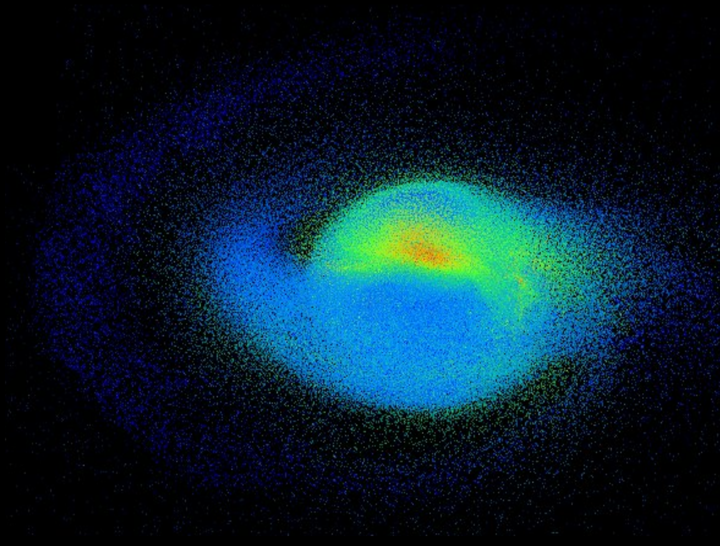




Outline

- Overview
- EoS influence on mergers → EoS constraints

  - GW inspiral signal
  - multi-messenger interpretation
  - postmerger GW emission

  Present (GW inspiral signal, multi-messenger interpretation)

  Future (postmerger GW emission)
- Quark matter in neutron stars

First NS merger in GWs

= 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

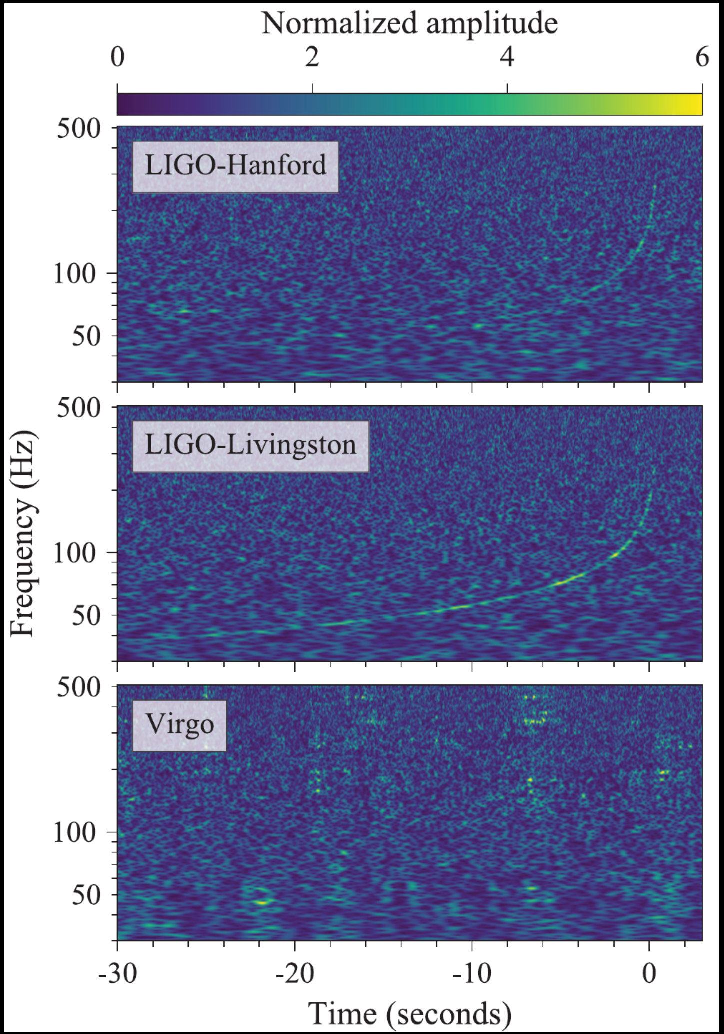
→ settled many open/tentative/speculative ideas in the context of NS mergers !!!

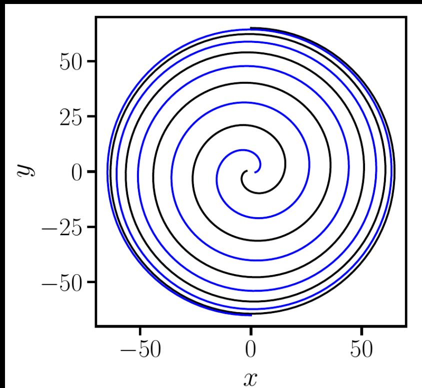
→ a few more detections meanwhile

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

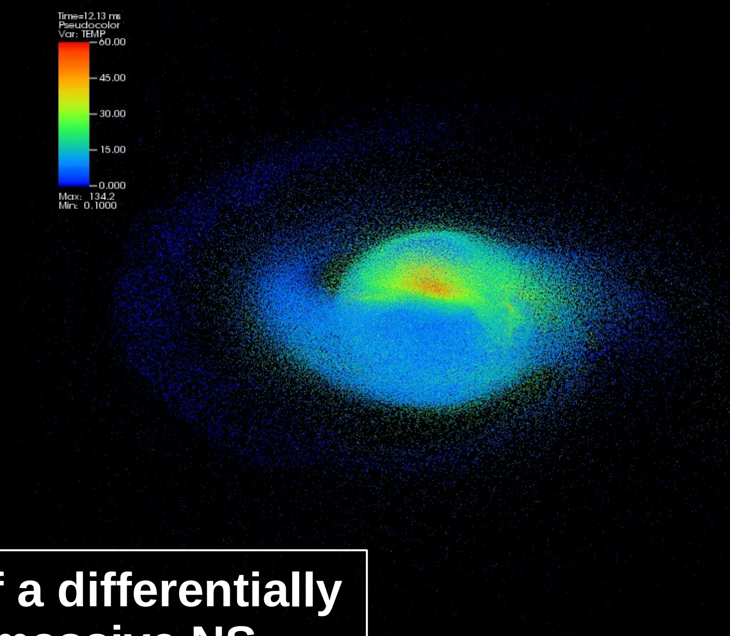
$P_{orb} \sim 1\,ms$

Neutron star merger

dependent on EoS, M_{tot}

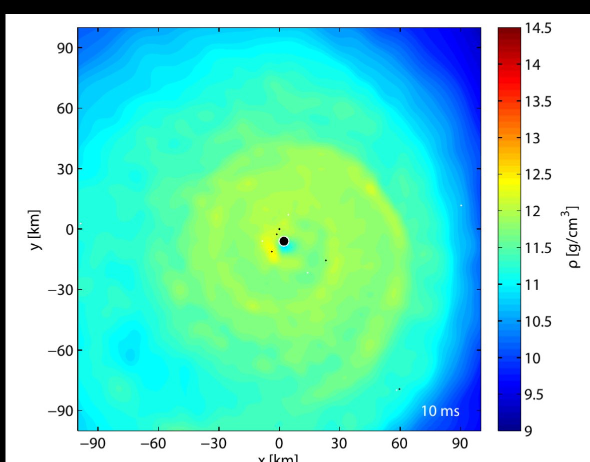
ms

ms



Prompt formation of a BH + torus

Formation of a differentially rotating massive NS



dependent on EoS, M_{tot}

10-100 ms

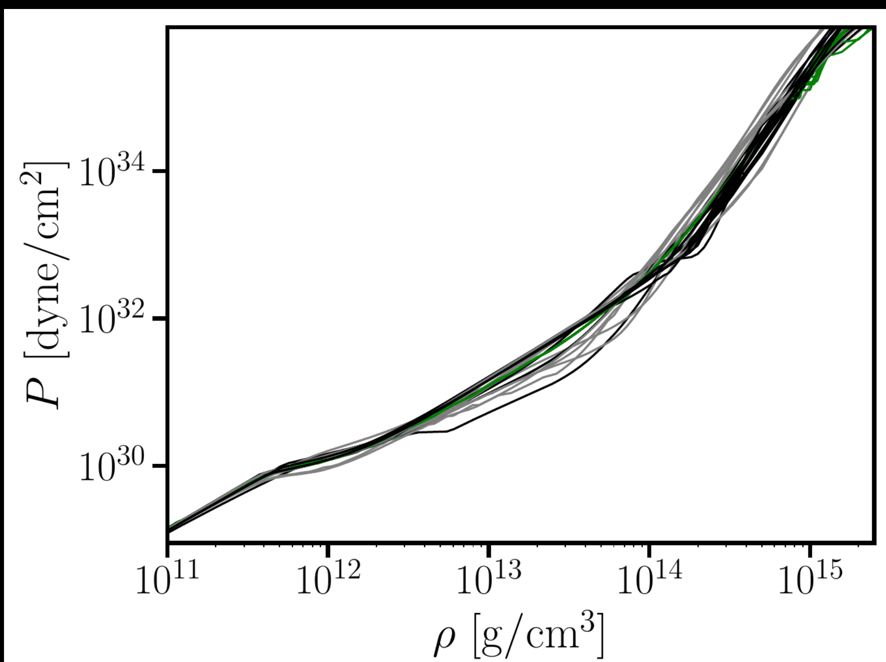
Rigidly rotating (supermassive) NS (stable or long-lived)

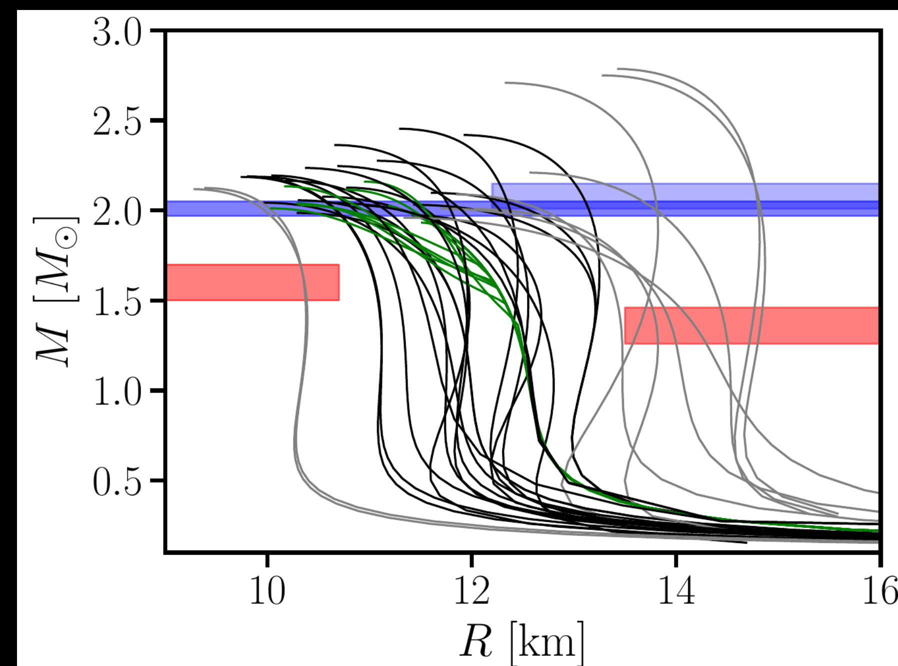
Delayed collapse to a BH + torus

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)

Observation: R(M) → Theory: P(ρ)

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

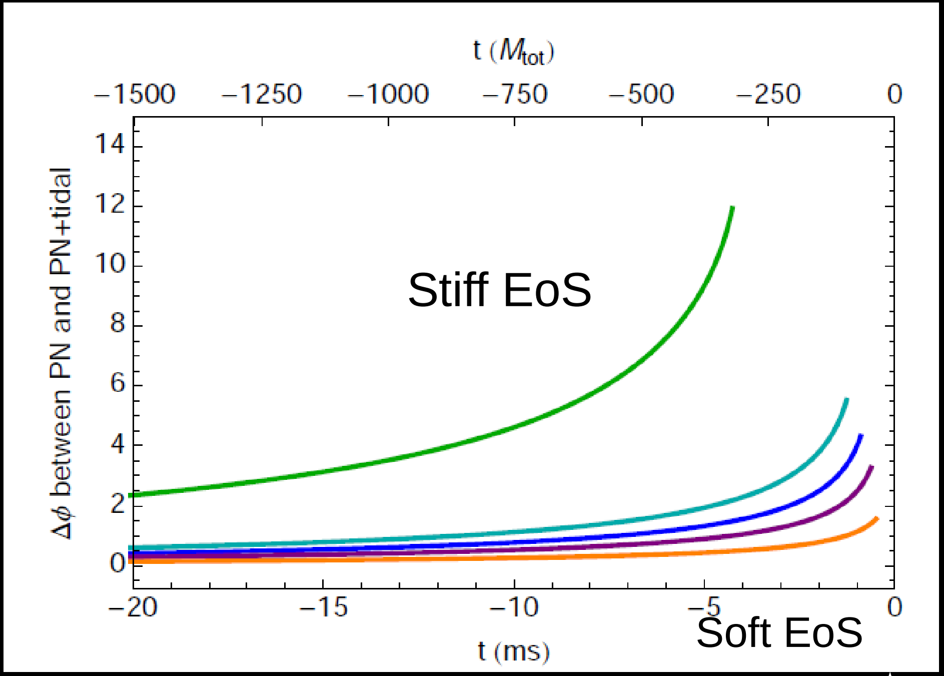
Goal: EoS from NS mergers/GWs

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:



e.g. Read et al. 2013

Merger time of point particle

EoS impact measured by tidal deformability

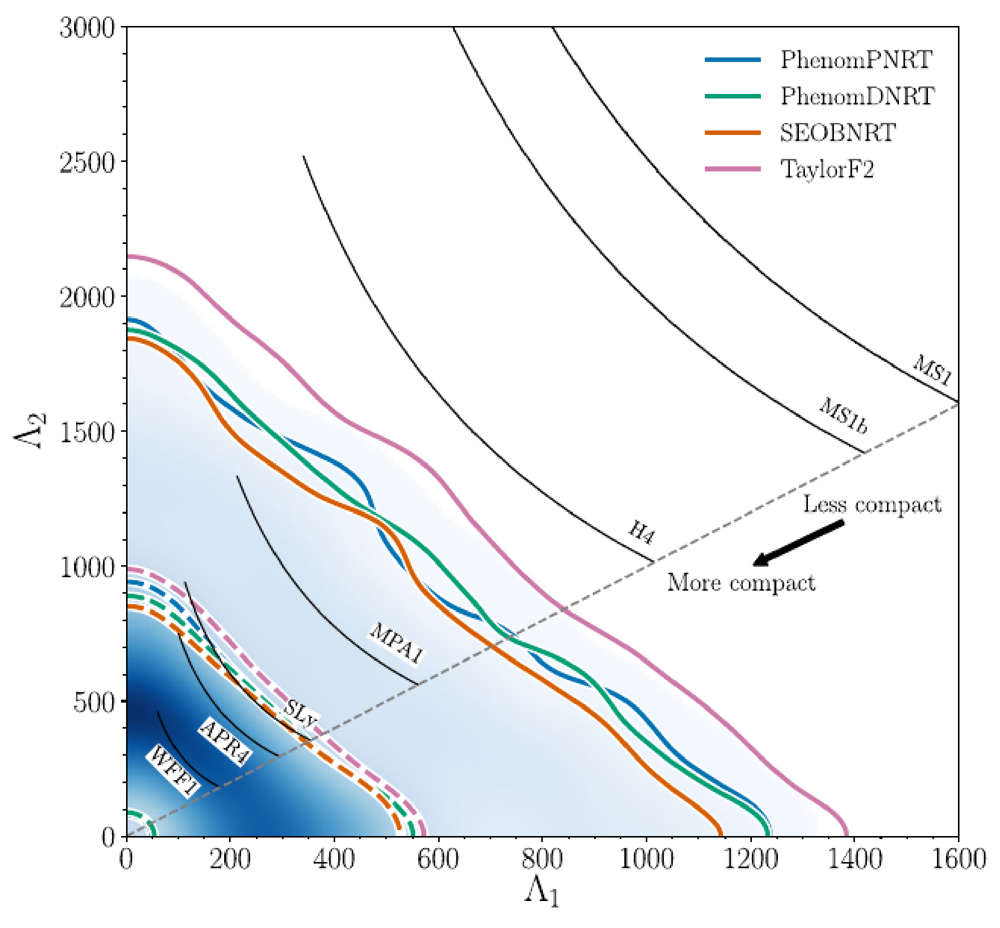
$$\Lambda(M) = \frac{2}{3} k_2(M) \left(\frac{c^2 R}{G M} \right)^5$$

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, …

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

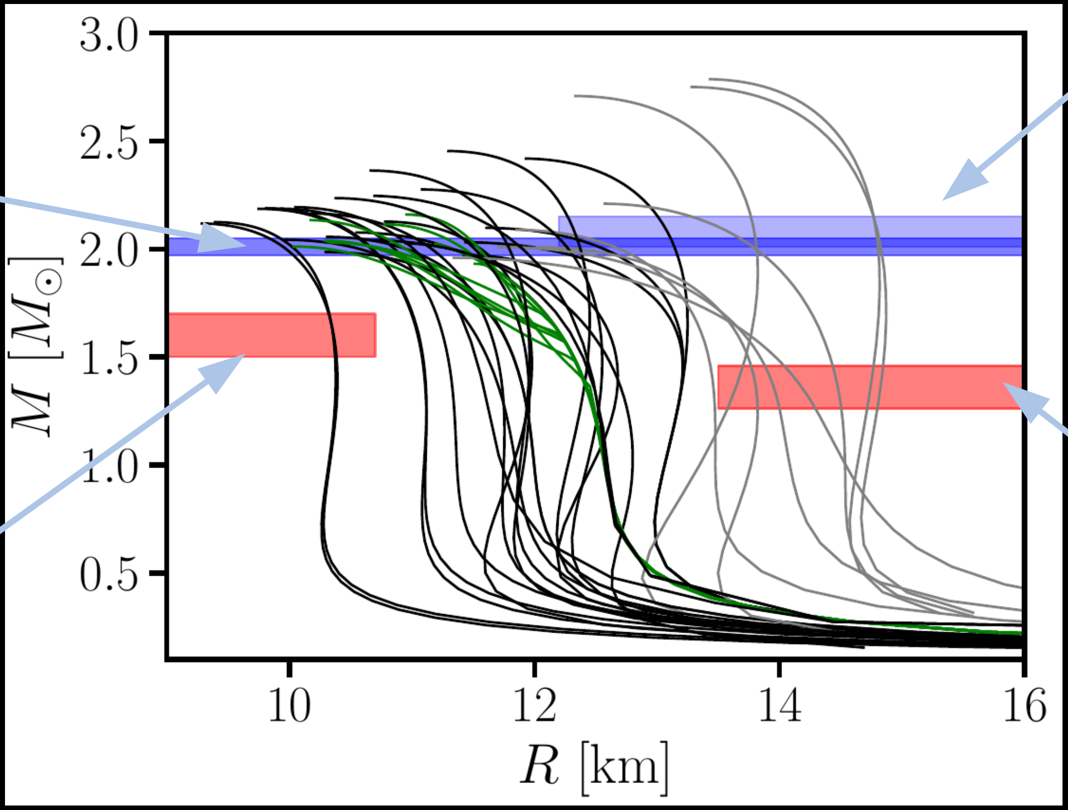
See e.g. Hinderer et al., PRD 2010

EoS / NS constraints

- Narrow down stellar properties of NSs

Pulsar mass measurements

Multi-messenger interpretation of GW170817



X-ray timing NICER

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

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

Multi-messenger constraints

More information – more constraints – but typically model-dependence

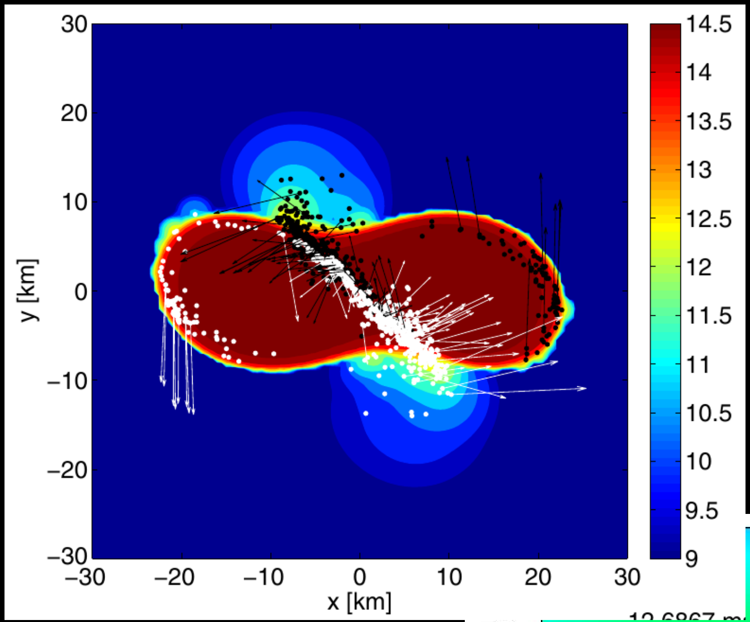
Different ideas (some similar) – for M_{max}, radii and tidal deformability

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

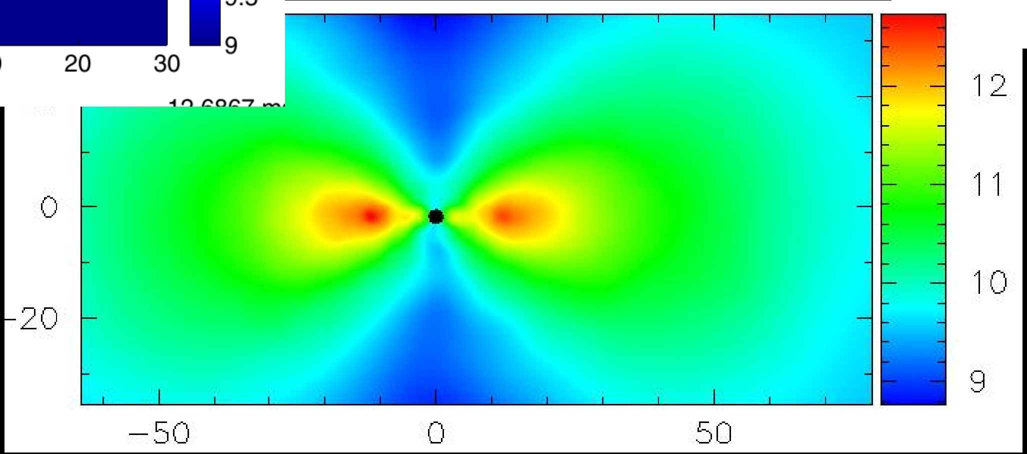
ApJ 773 (2013)



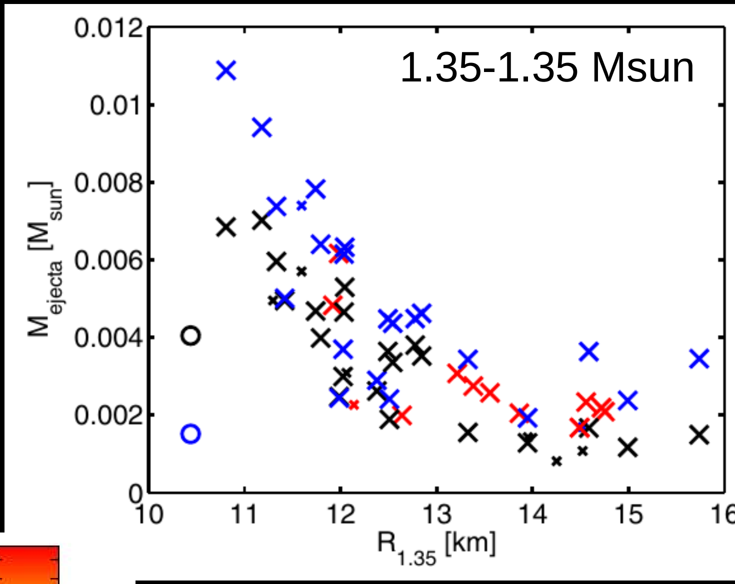
Dynamical ejecta

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

Remnant: BH torus



ApJ 773 (2013)



EoS dependence

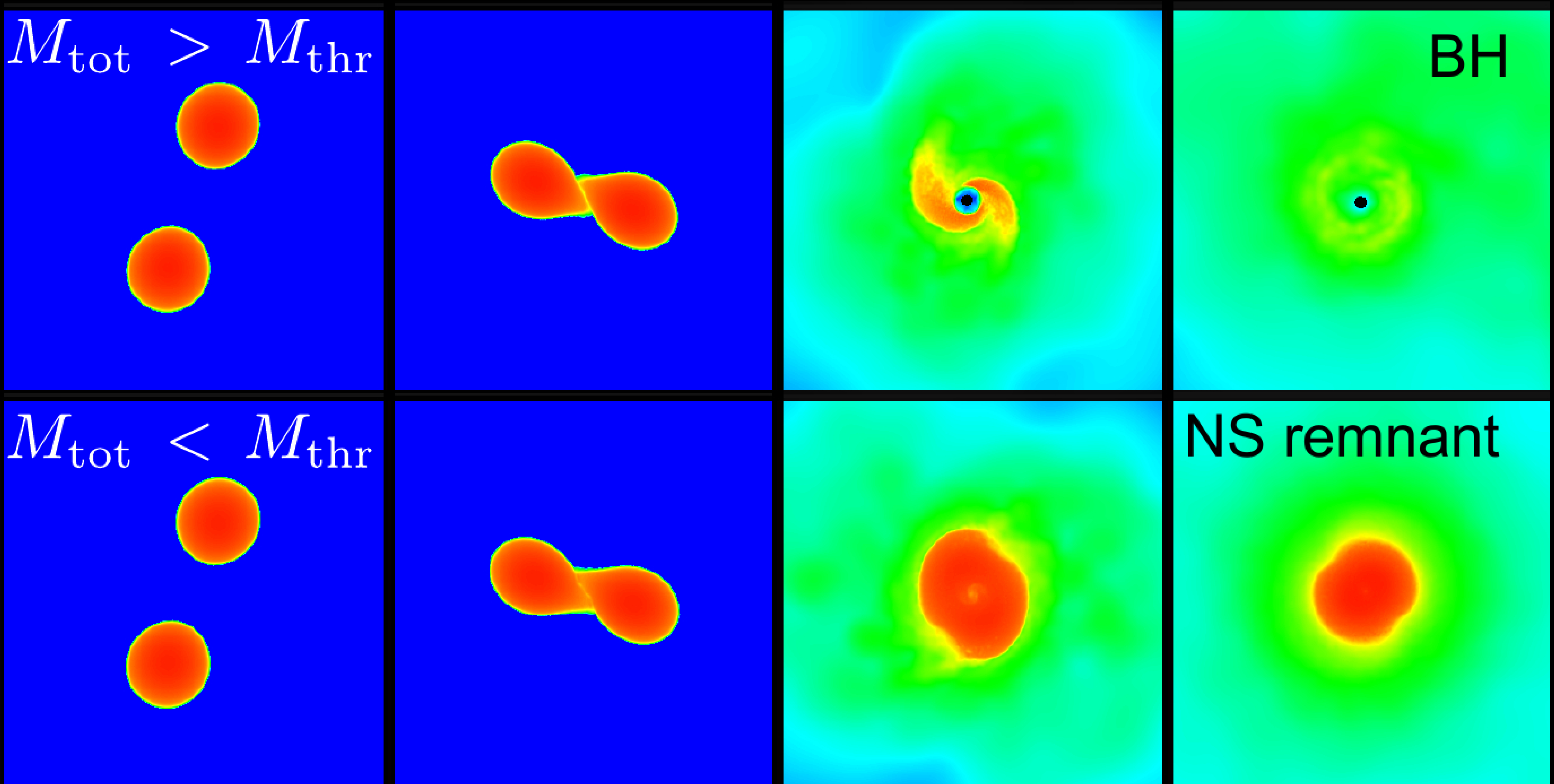
Secular ejecta form BH torus or NS remnant by viscous effects and neutrino wind

Multi-messenger constraints

- Prompt collapse behavior (→ details in a moment)
- Linking em emission to arguments about collapse/evolution of hyper/supermassive NSs, i.e. collapse after a specific evolution path involving mass loss and angular momentum redistribution/loss

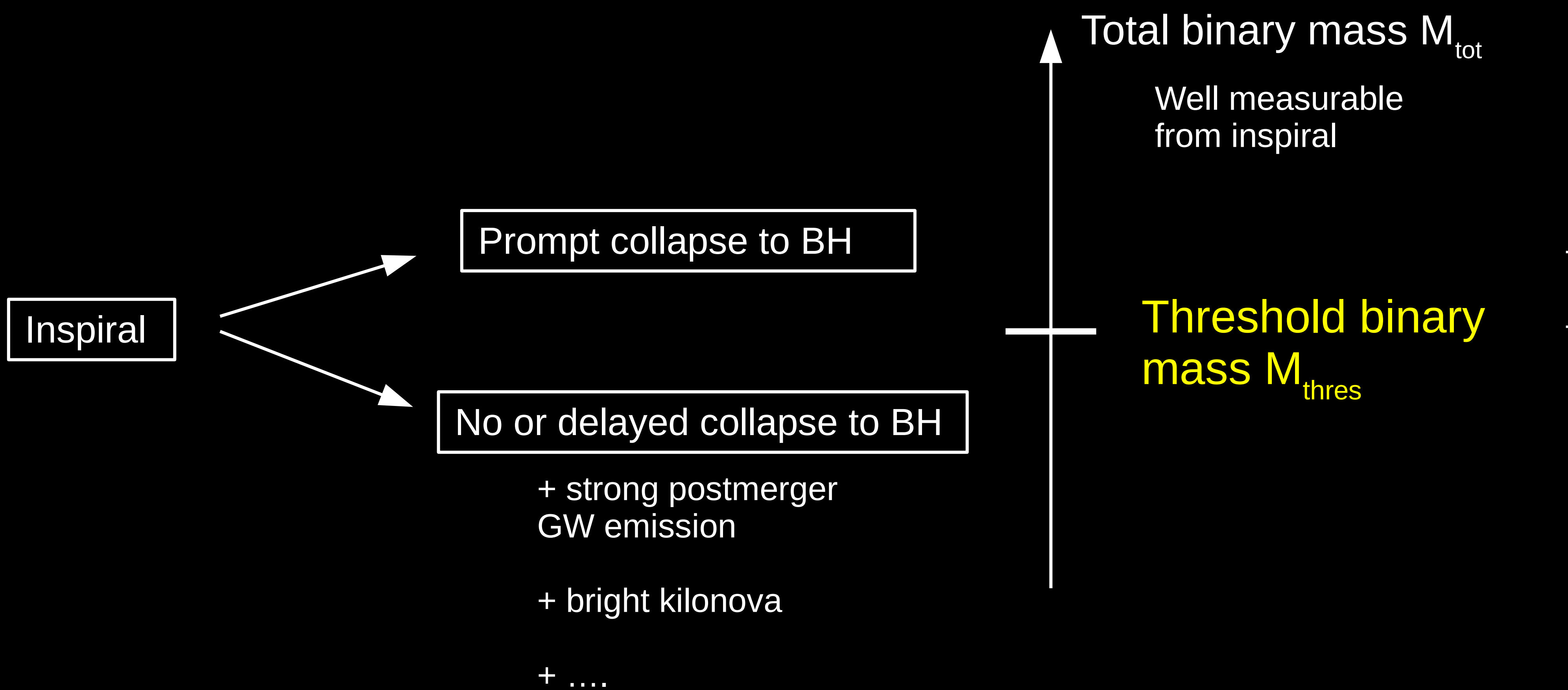
  → Mmax < ~2.2 Msun (e.g. Margalit&Metzger 2017, Shibata et al 2017, Rezzolla et al 2018, Ruiz et al 2018, Khadkikar et al 2021 ,...)
- Direct relations between kilonova/ejecta properties and NS parameters (significant uncertainties: simulations, radiative transfer, opacities, ...) (e.g. Coughlin et al 2018, Radice et al 2018, Dietrich et al 2020,)

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

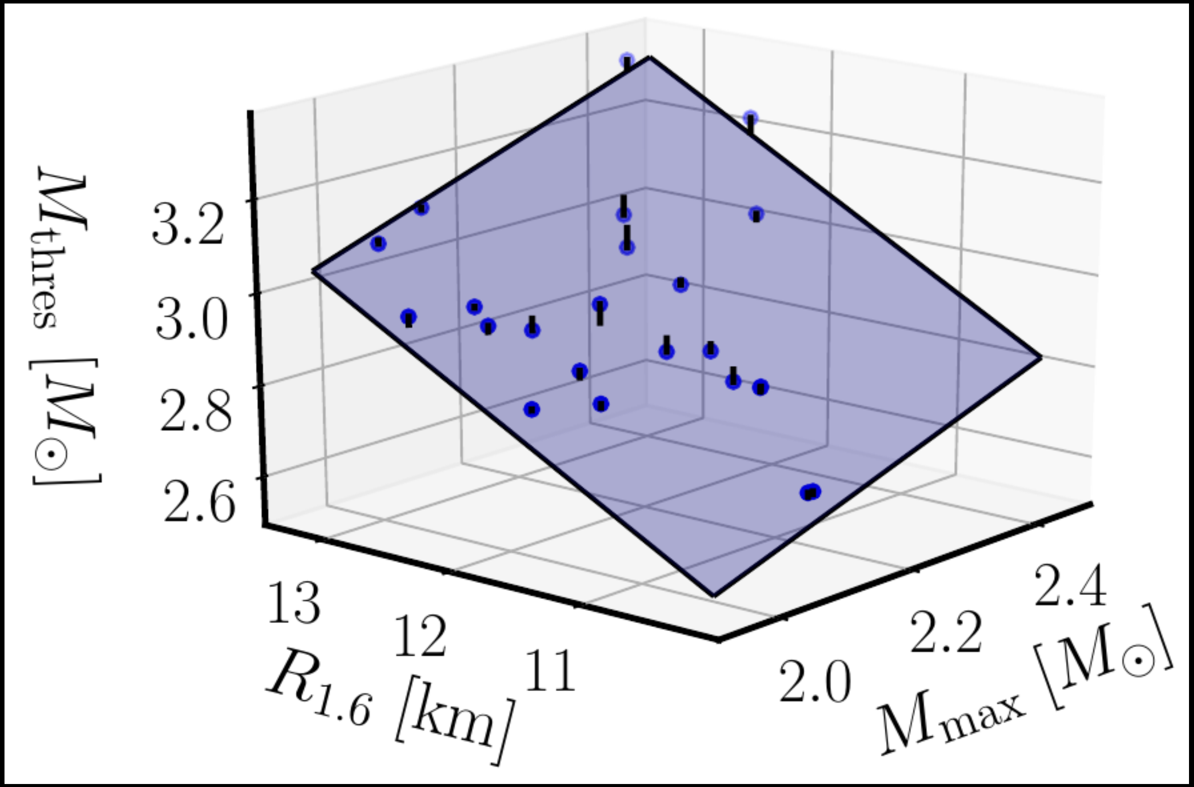


M_{thres} - EoS dependent !!!

EoS	T/B	$M_{\max}$ ($M_{\odot}$)	$R_{1.6}$ (km)	$\Lambda_{1.4}$	$M_{\mathrm{thres}}(q=1)$ ($M_{\odot}$)	$\tilde{\Lambda}_{\mathrm{thres}}(q=1)$	$M_{\mathrm{thres}}(q=0.7)$ ($M_{\odot}$)	$\tilde{\Lambda}_{\mathrm{thres}}(q=0.7)$	sample	Ref.
BHBLP	T	2.098	13.192	691.0	3.125	353.8	2.975	512.8	b	[18]
DD2Y	T	2.031	13.169	691.0	3.075	389.2	2.875	622.1	b	[19, 20]
DD2	T	2.419	13.247	694.8	3.325	248.0	3.275	300.3	b	[14, 15]
DD2F	T	2.077	12.220	423.1	2.925	315.0	2.850	427.7	b	[15, 21, 22]
APR	B	2.187	11.253	245.9	2.825	232.2	2.825	260.2	b	[23]
BSK20	B	2.165	11.648	317.4	2.875	267.6	2.875	300.3	b	[24]
eosUU	B	2.189	11.057	227.9	2.825	215.2	2.825	241.1	b	[25]
LS220	T	2.041	12.478	537.0	2.975	350.6	2.875	519.0	b	[26]
LS375	T	2.709	13.767	950.8	3.575	223.5	3.575	248.5	e	[26]
GS2	T	2.089	13.369	717.2	3.175	322.7	3.025	487.3	e	[27]
NL3	T	2.787	14.795	1360.3	3.775	228.5	3.775	257.9	e	[14, 28]
Sly4	B	2.043	11.523	292.4	2.825	275.4	2.775	352.8	b	[29]
SFHO	T	2.056	11.751	331.5	2.875	278.2	2.825	352.9	b	[30]
SFHOY	T	1.986	11.748	331.5	2.825	312.6	2.725	441.5	b	[19, 20]
SFHX	T	2.127	11.963	393.1	2.975	269.3	2.925	328.3	b	[30]
TM1	T	2.210	14.347	1142.0	3.375	334.5	3.225	525.0	e	[16, 31]
TMA	T	2.008	13.660	928.0	3.175	396.9	2.975	698.1	e	[16, 32]
BSK21	B	2.276	12.543	511.4	3.075	287.1	3.075	317.7	b	[24]
GS1	T	2.750	14.864	1392.1	3.775	229.6	3.775	260.4	e	[27]
eosAU	B	2.125	10.357	149.9	2.675	200.3	2.675	222.2	b	[25]
WFF1	B	2.118	10.362	150.0	2.675	200.2	2.675	220.1	b	[25, 33]
WFF2	B	2.186	11.048	222.4	2.825	210.0	2.825	235.3	b	[25, 33]
MPA1	B	2.454	12.448	475.9	3.225	202.2	3.225	224.6	b	[33, 34]
ALF2	B	1.973	12.616	565.1	2.975	385.2	2.875	510.1	b	[33, 35]
H4	B	2.010	13.716	846.4	3.125	403.6	2.925	699.6	e	[33, 36]
DD2F-SF-1	T	2.134	12.141	423.1	2.845	380.4	2.770	497.8	h	[9, 10, 37, 38]
DD2F-SF-2	T	2.160	12.061	421.2	2.925	298.6	2.870	399.3	h	[9, 10, 37, 38]
DD2F-SF-3	T	2.032	12.189	423.1	2.825	398.8	2.720	570.1	h	[9, 10, 37, 38]
DD2F-SF-4	T	2.029	12.220	423.1	2.835	389.5	2.725	566.9	h	[9, 10, 37, 38]
DD2F-SF-5	T	2.038	11.928	423.1	2.815	408.4	2.725	539.2	h	[9, 10, 37, 38]
DD2F-SF-6	T	2.012	12.219	423.1	2.795	428.1	2.675	635.5	h	[9, 10, 37, 38]
DD2F-SF-7	T	2.115	12.220	423.1	2.905	330.2	2.825	451.2	h	[9, 10, 37, 38]
DD2F-SF-8	T	2.025	12.216	422.3	2.915	321.9	2.810	467.3	h	[9, 10, 37, 38]
VBAG	T	1.932	12.214	422.3	2.885	345.5	2.775	505.4	h	[39]
ENG	B	2.236	11.899	367.5	2.975	249.3	2.975	279.7	b	[33, 40]
APR3	B	2.363	11.954	364.8	3.075	204.6	3.075	228.1	b	[23, 33]
GNH3	B	1.959	13.756	850.4	3.075	432.6	2.875	799.3	e	[33, 41]
SAPR	T	2.194	11.462	265.7	2.875	223.7	2.875	254.5	b	[42]
SAPRLDP	T	2.247	12.369	449.3	3.025	271.0	3.025	309.4	b	[42]
SSkAPR	T	2.028	12.304	442.6	2.950	312.7	2.875	420.8	b	[42]

Bauswein et al., PRL 2020

Simulation results → $M_{\mathrm{thres}} = M_{\mathrm{thres}}(X,Y) = aX + bY + c$ ← EoS/TOV properties

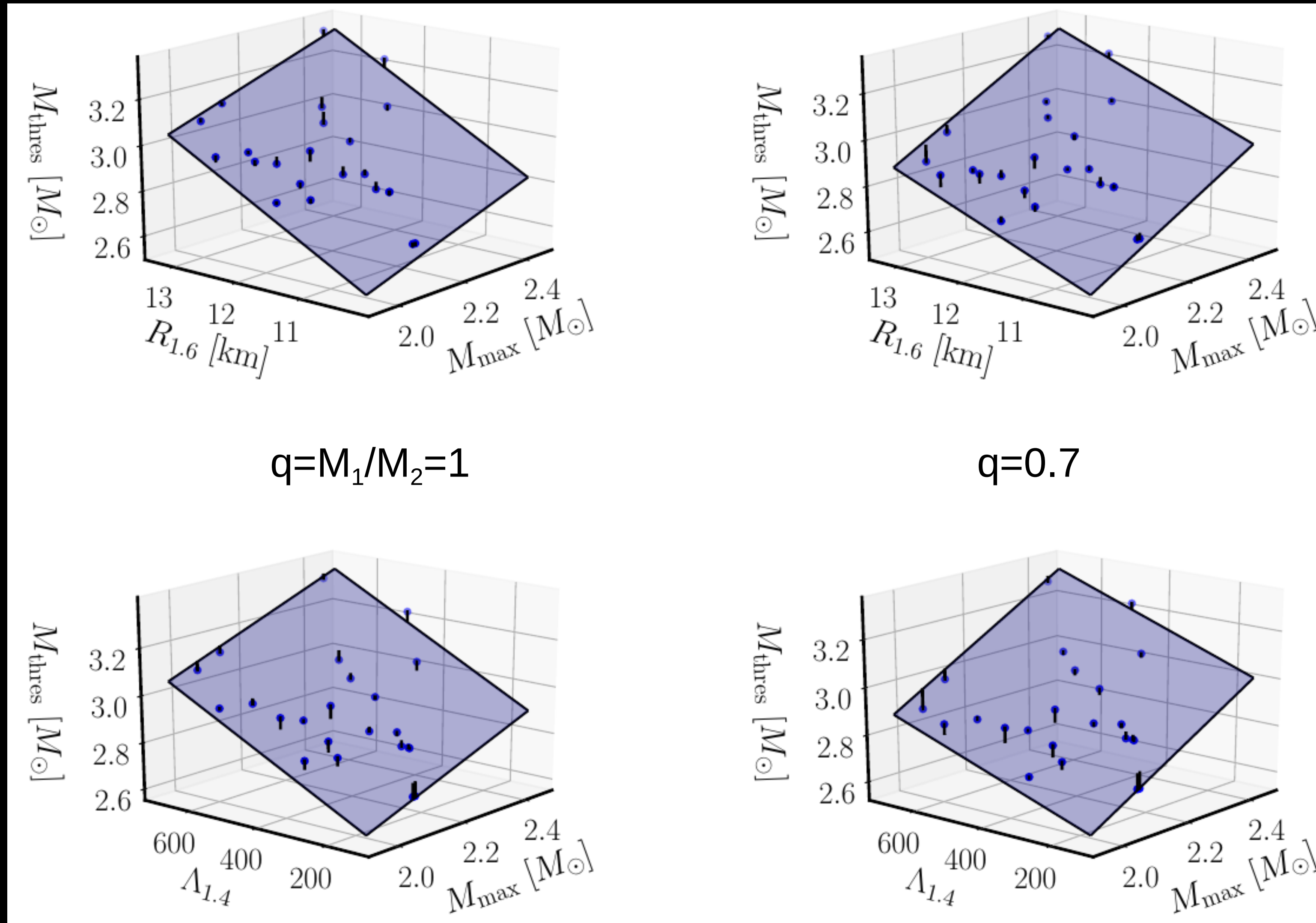


arXiv:2010.04461

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

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

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



arXiv:2010.04461

- Similarly tight fits for asymmetric mergers

Other independent variables like Λ(1.4), R_{max}, Λ_thres

- Bi-linear relations → simple to invert
- Similar relations for chirp mass

EoS constraints, i.e. NS TOV parameter

measurable

Unknown EoS/TOV properties

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

$$\text{e.g.} \quad M_{\mathrm{thres}} = M_{\mathrm{thres}}(M_{\mathrm{max}}, R_{1.6}) = aM_{\mathrm{max}} + bR_{1.6} + c$$

- Either measure X as well and get Y
- Or impose a relation between X and Y (empirical relations or causality link eg R16 and Mmax)

$$X = M_{\mathrm{max}}; \quad Y = \{R_{1.6}, R_{\mathrm{max}}, \Lambda_{1.4}, \tilde{\Lambda}_{\mathrm{thres}}, ...\}$$

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

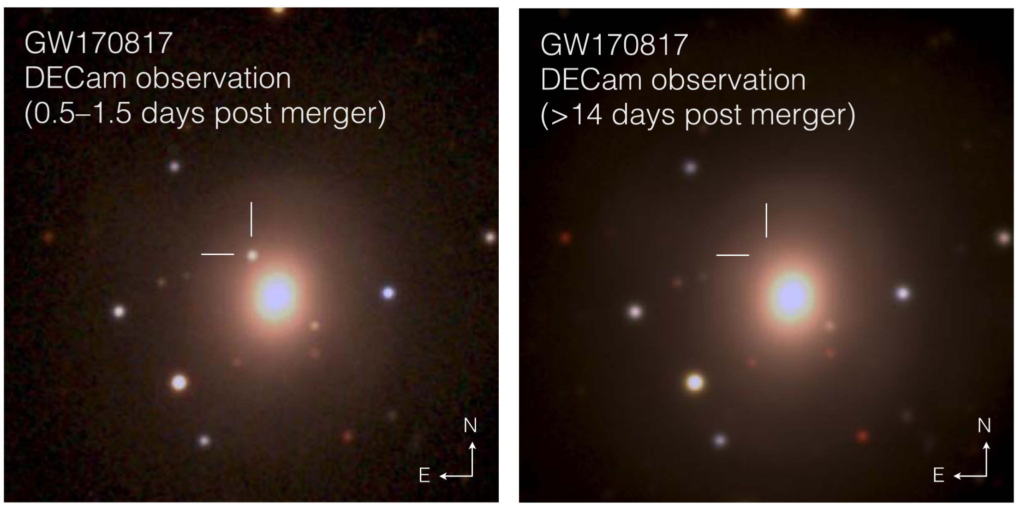
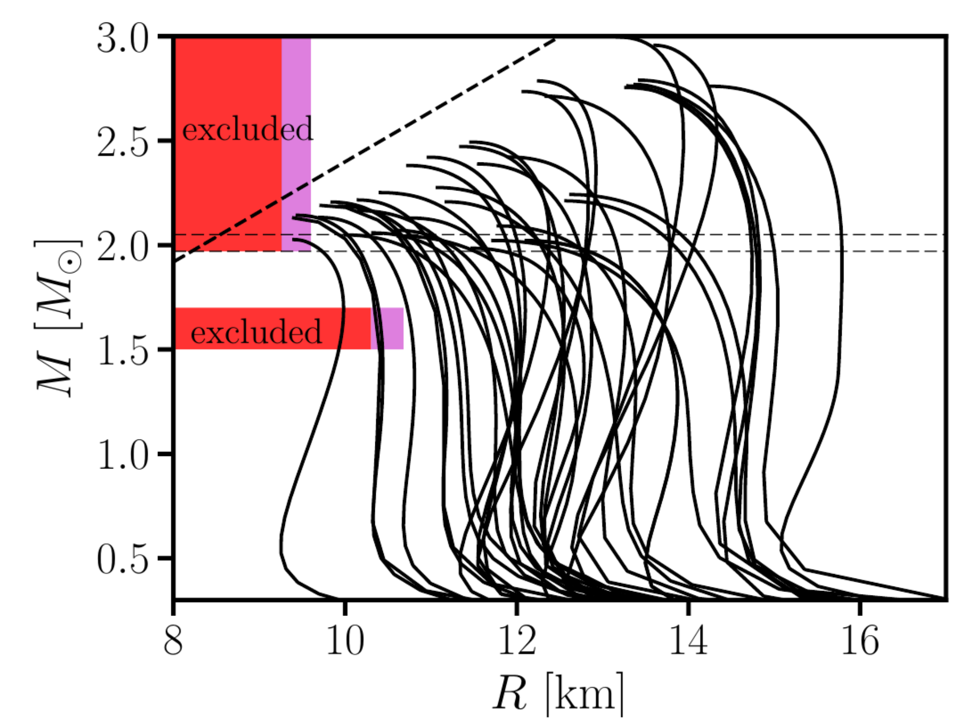


Figure 1. NGC4993 *grz* color composites (1.'5 × 1.'5). Left: composite of detection images, including the discovery *z* image taken on 2017 August 18 00:05:23 UT and the g and r images taken 1 day later; the optical counterpart of GW170817 is at R.A., decl. =197.450374, −23.381495. Right: the same area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

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

→ Inferred ejecta mass 0.02-0.05 Msun

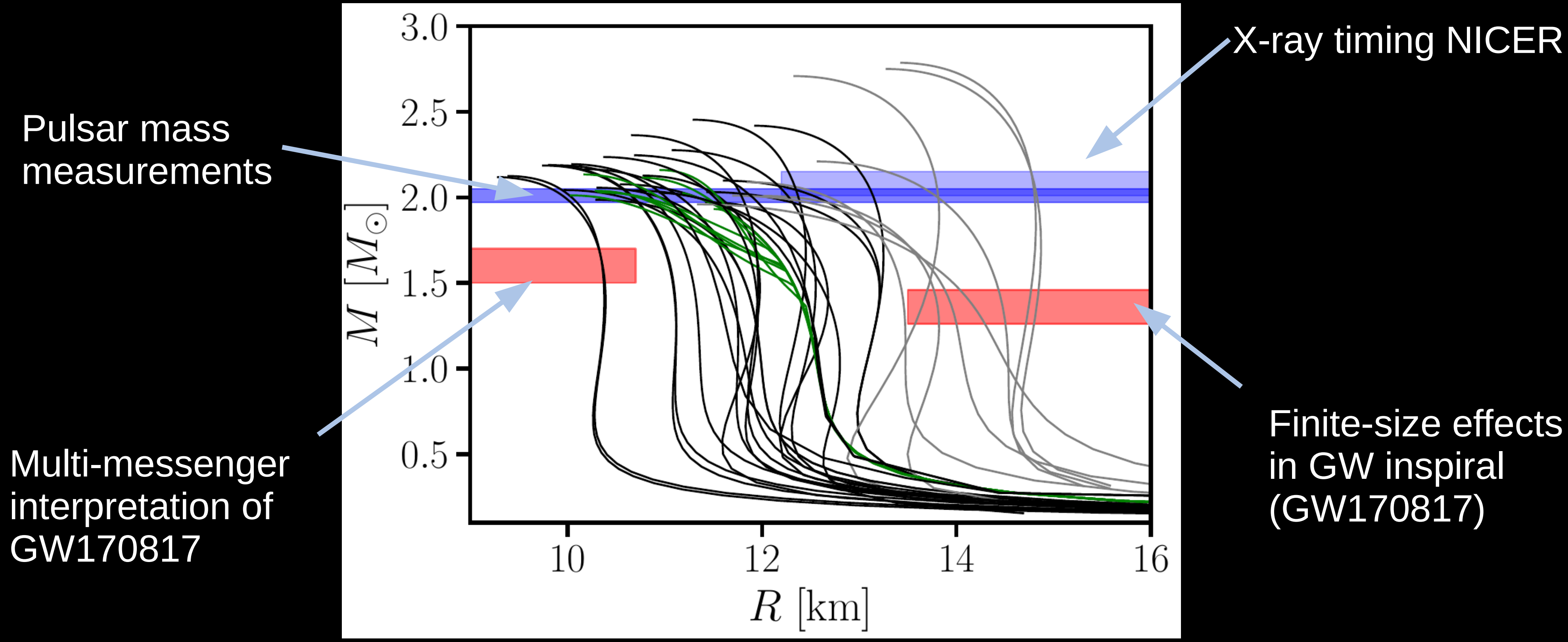


Bauswein et al. 2017

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

EoS / NS constraints

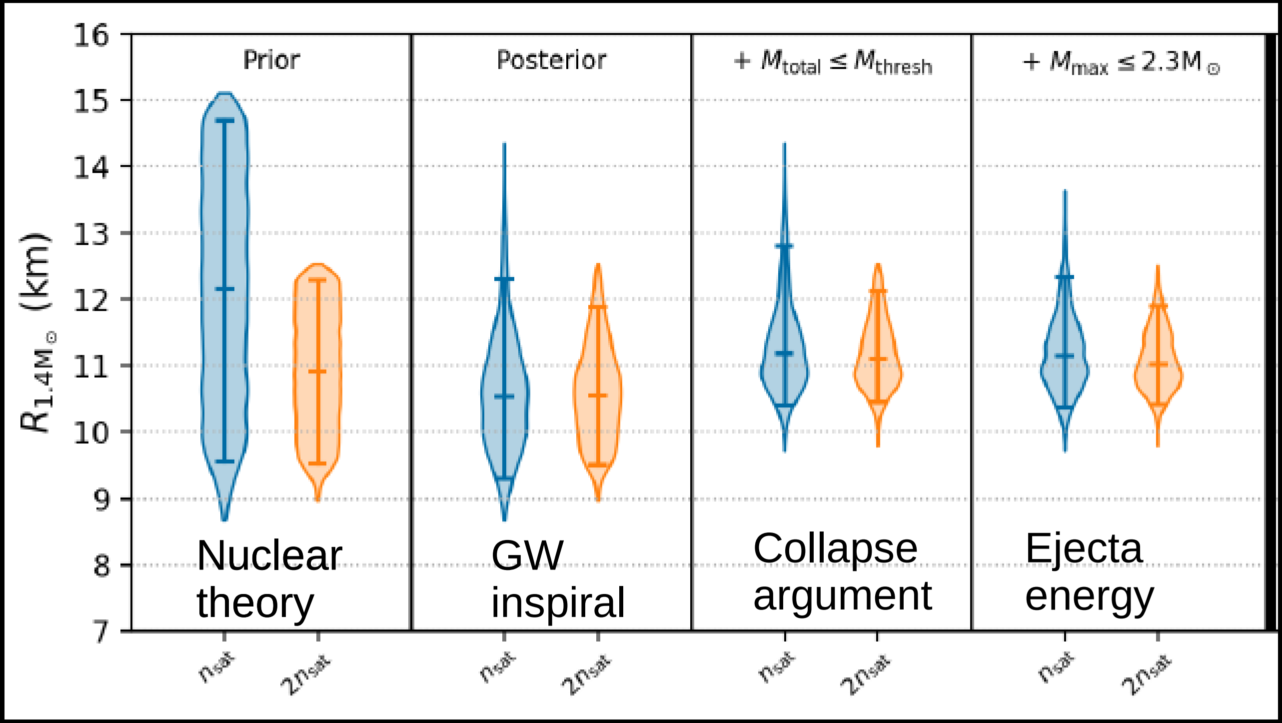
- Narrow down stellar properties of NSs



Reddish bands = excluded

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

Combining information

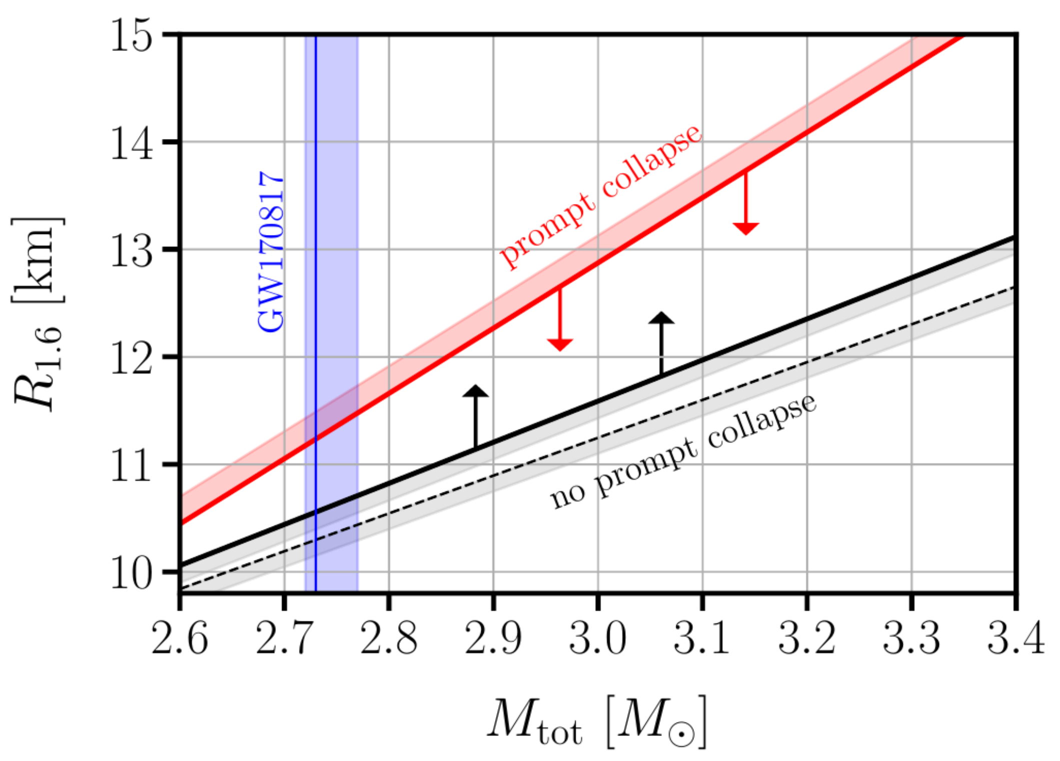


Capano et al 2020; many other similar approaches

Current and future multi-messenger constraints

- For GW170817 we obtain   R > 10.6 km
- Applicable to any new observation with information on the outcome

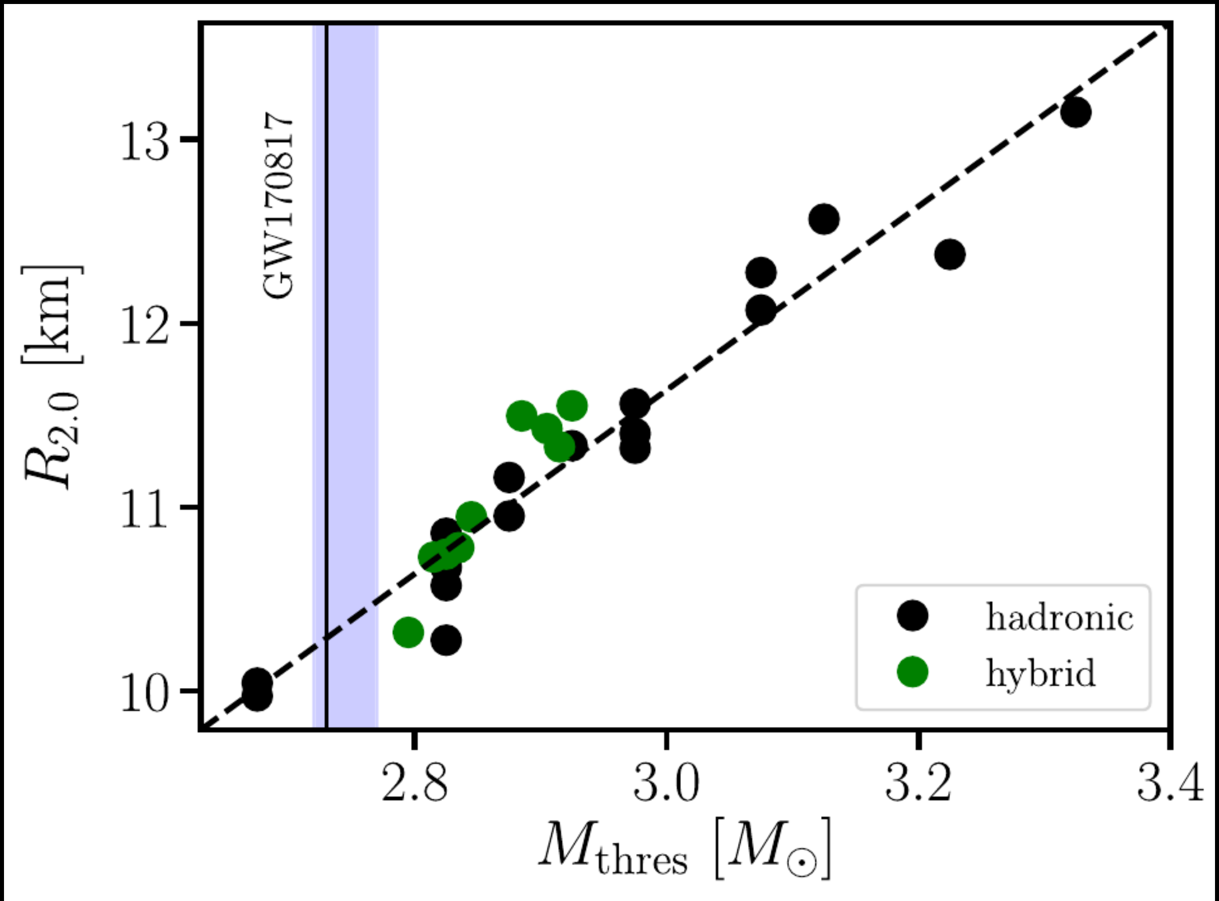
  → a lot of potential for future – complementary and independent of inspiral finite-size effects



arXiv:2010.04461

(cf. R /Λ limits from Bauswein et al. 2017, Radice et. al 2018, Most et al. 2018, Koeppel et al. 2019, Bauswein et al. 2019, Capano et al. 2020, ...)

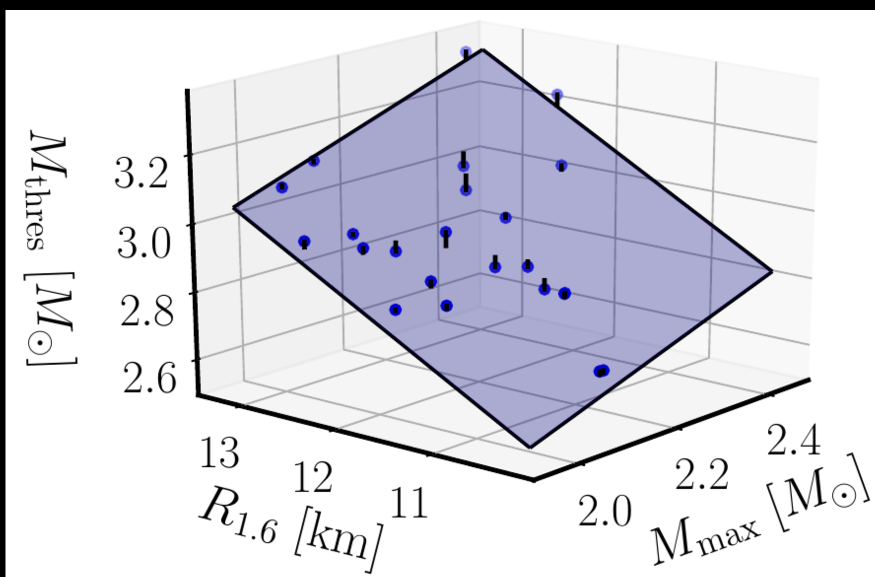
- Simple constarint through direct relation between high-mass NS property and Mthres

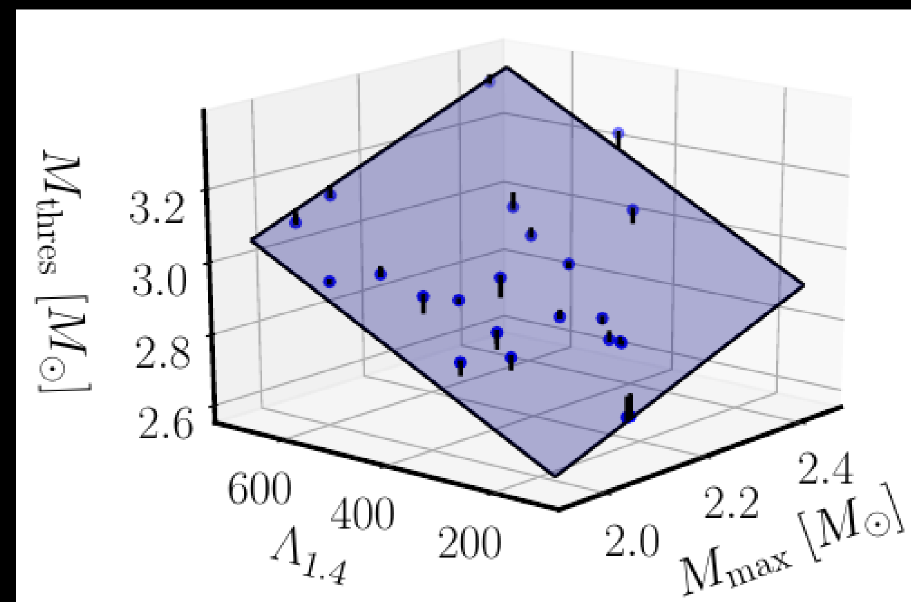


AB et al 2021

M_{max} from M_{thres}

- M_{thres} + another NS property (radius or Lambda from other observations) → very accurate and robust M_{max}





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

arXiv:2010.04461

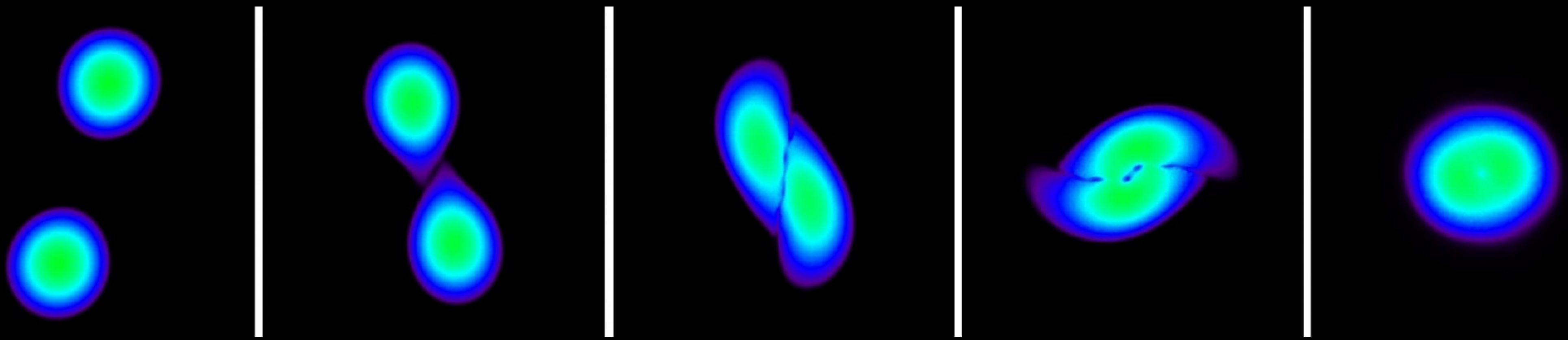
see also current estimates e.g. by Margalit & Metzger 2017, Shibata et al. 2017, Rezzolla et al 2018, Ruiz & Shapiro 2018, Shibata et al. 2019, … (employing GW170817) and Lawrence et al 2015, Fryer et al. 2015, …

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

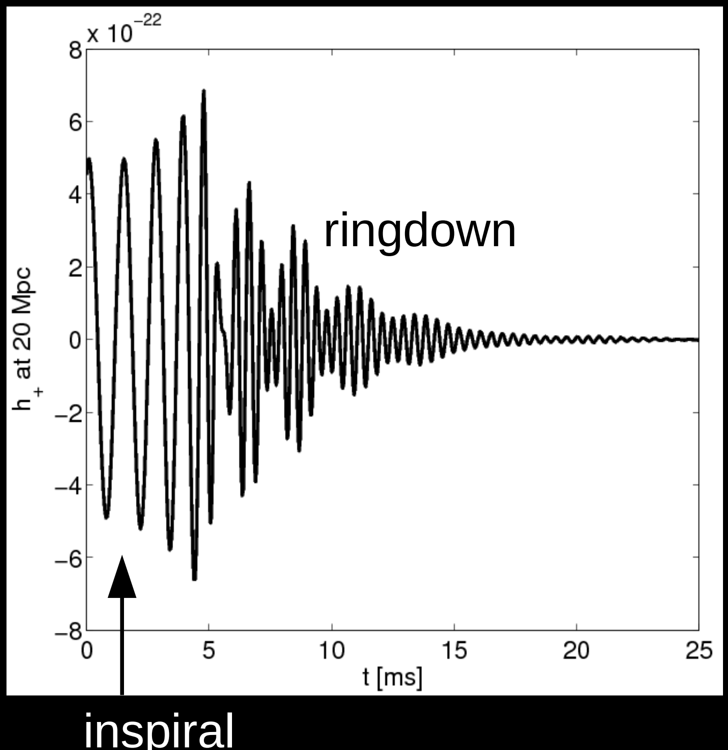
Postmerger GW oscillations

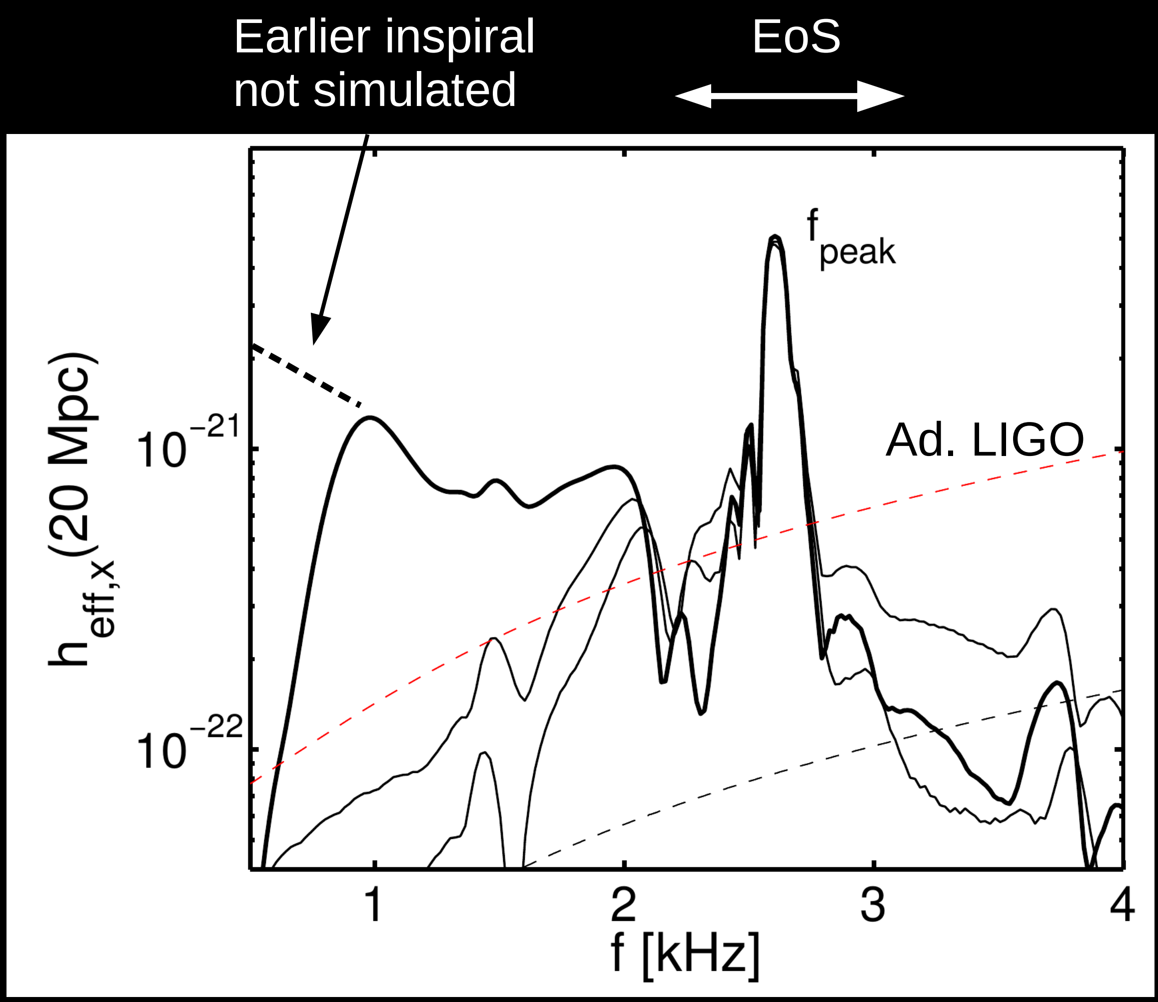


Not yet observed (but possible in future events, shown by simulated injections)

Postmerger

1.35-1.35 M_{sun} , 20 Mpc

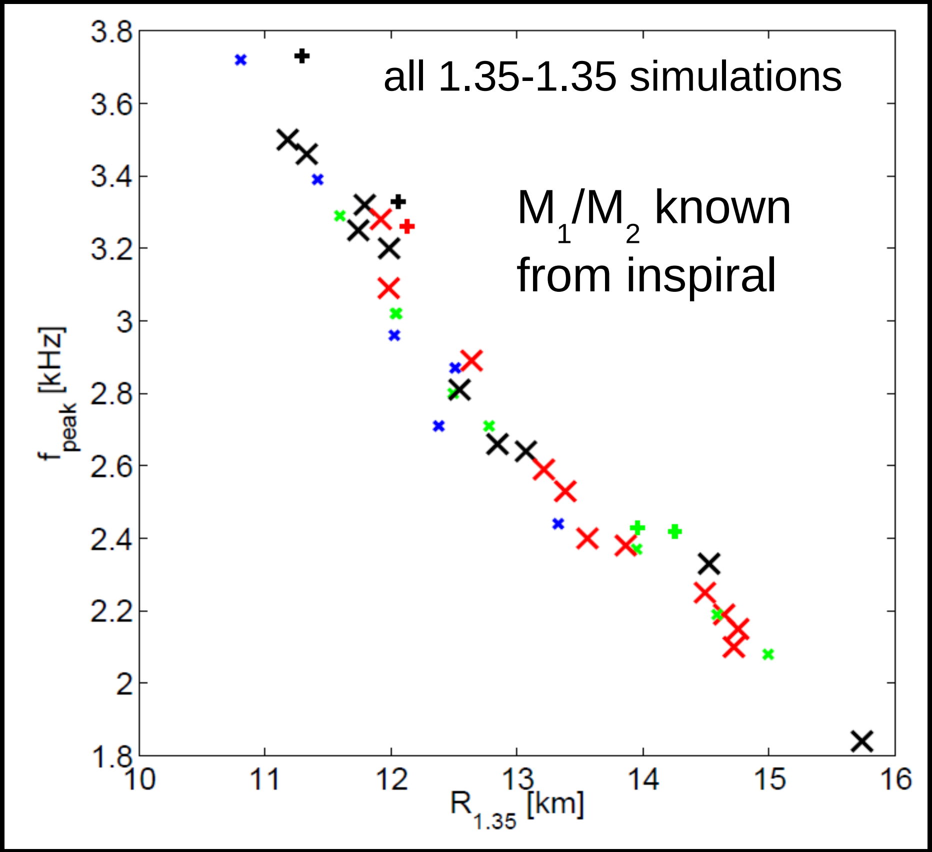


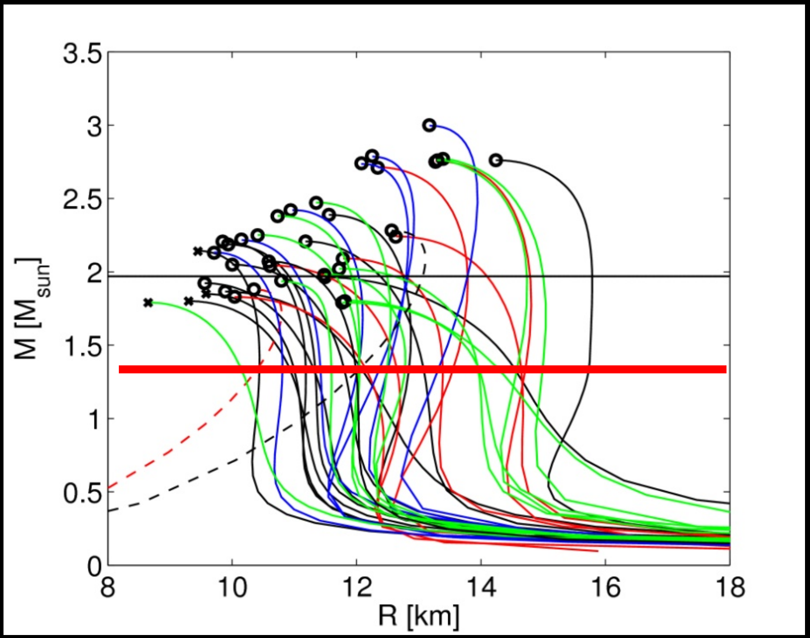


Dominant postmerger oscillation frequency f_{peak} (robust feature in all models)

Postmerger frequencies depend in specific 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





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

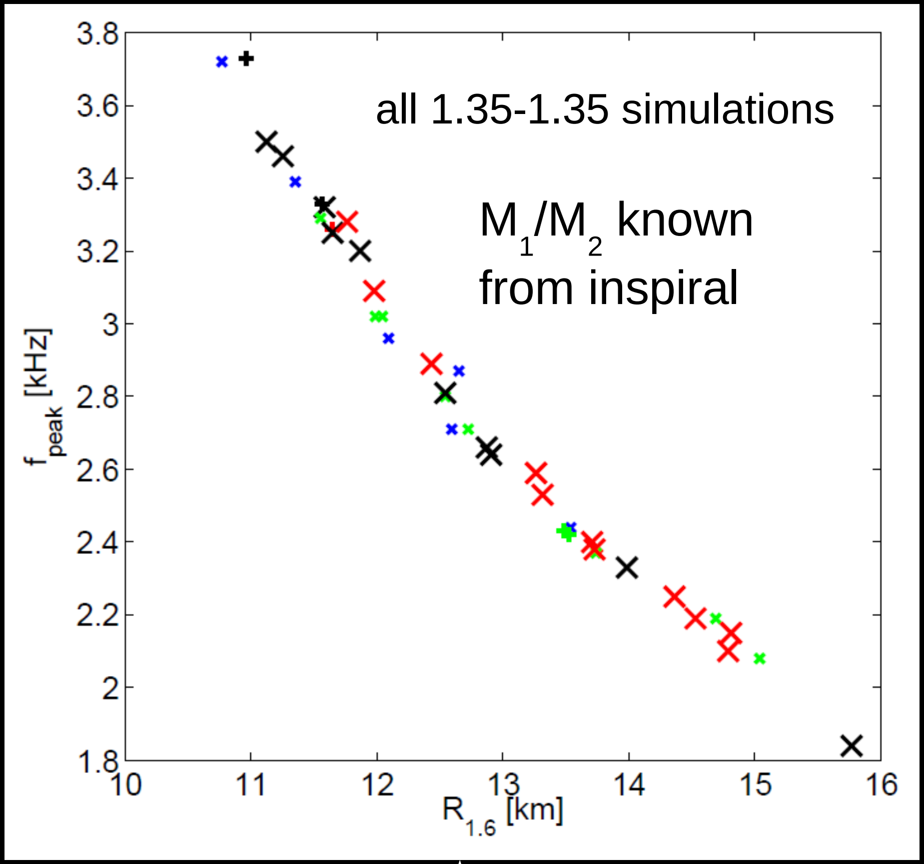
Bauswein et al. 2012

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

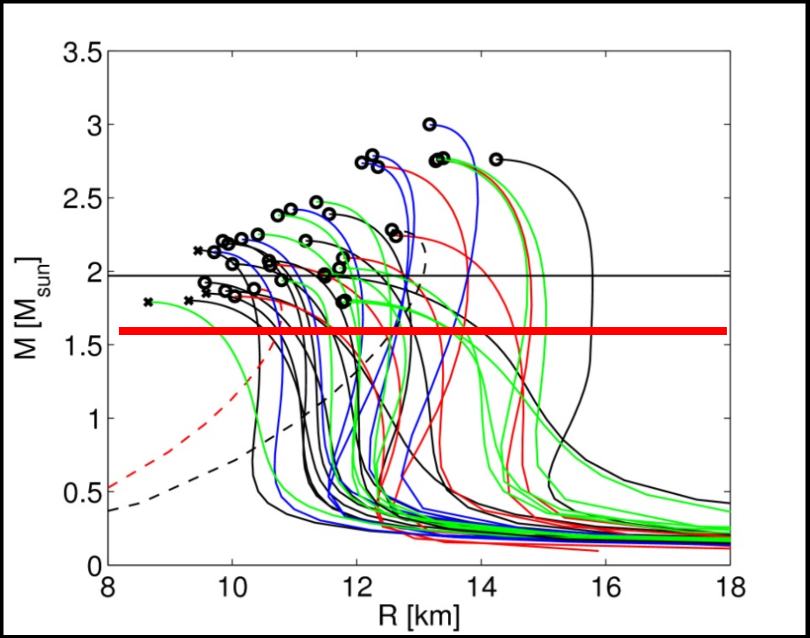
Here only 1.35-1.35 Msun mergers (binary masses measurable) – similar relations exist for other fixed binary setups !!!

~ 40 different NS EoSs

Gravitational waves – EoS survey



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}

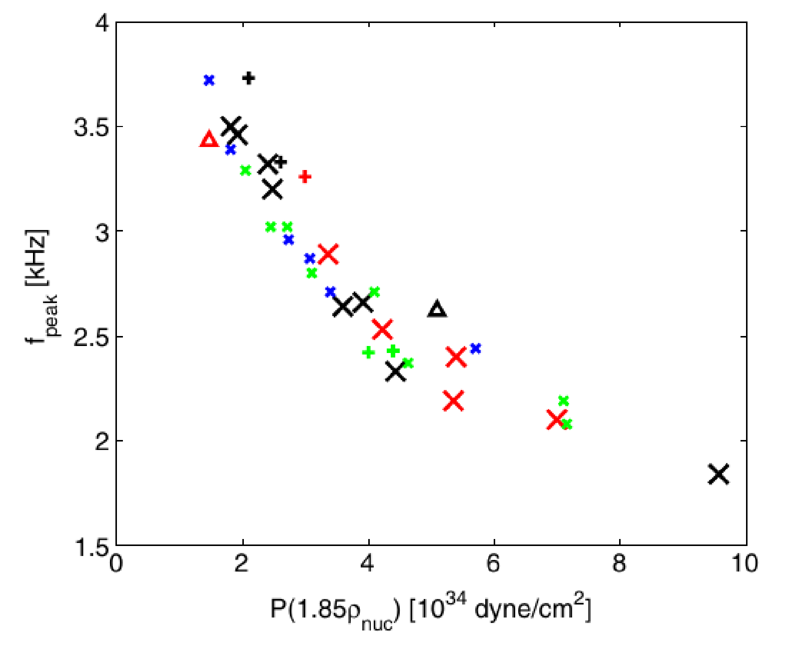
Note: similar relatiosn for other binary masses (measurable from inspiral)

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

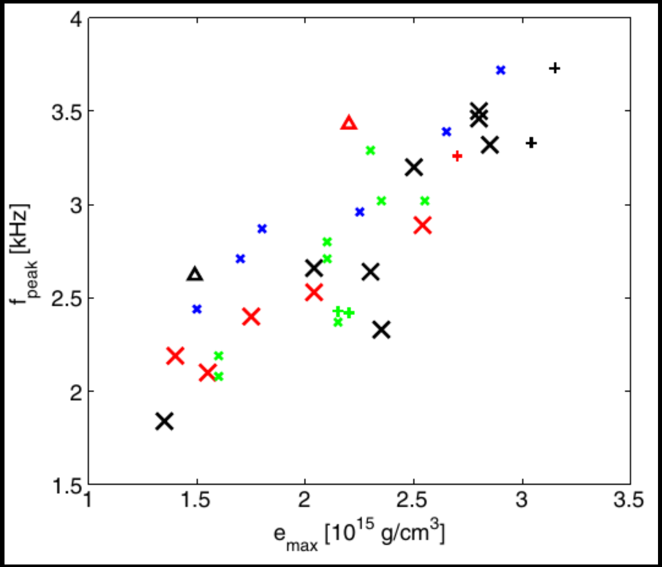
[A.B. & Janka, PRL 2012, A.B. et al., PRD 2012]

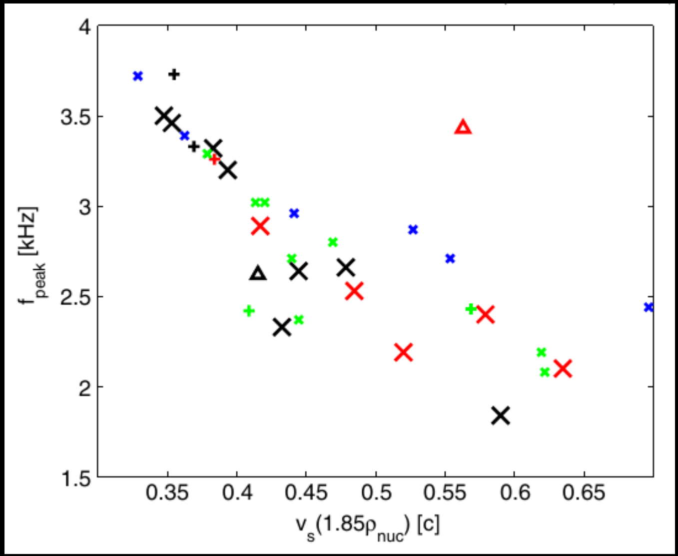
EoS constraints from postmerger GW emission

- Rely on empirical relations between frequency and **any** EoS (which can in principle be freely chosen) for a **chosen** set of candidate EoSs
- Some are more some are less tight



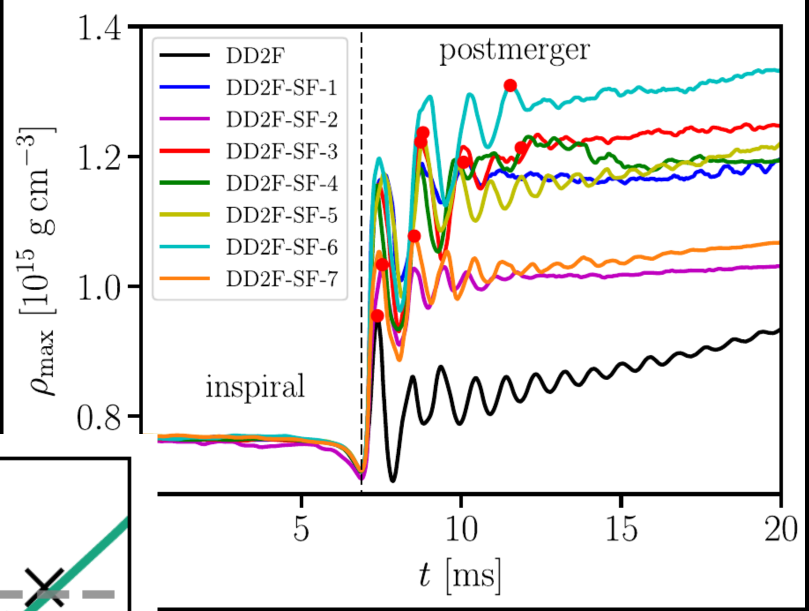
A.B. et al., PRD 2012



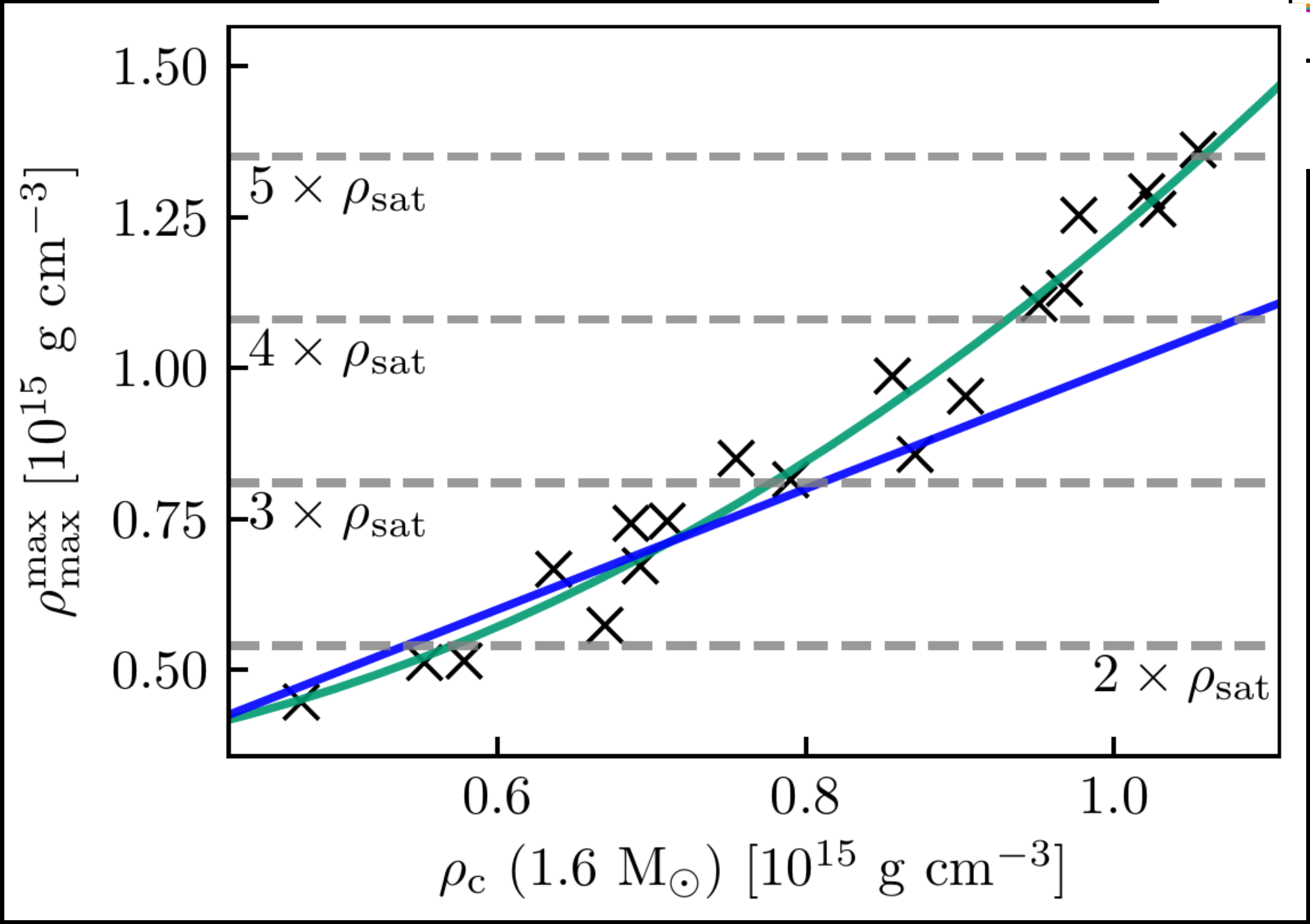


Recall relation between P(nsat) and slope of symmetry energy (and symmetry energy itself)

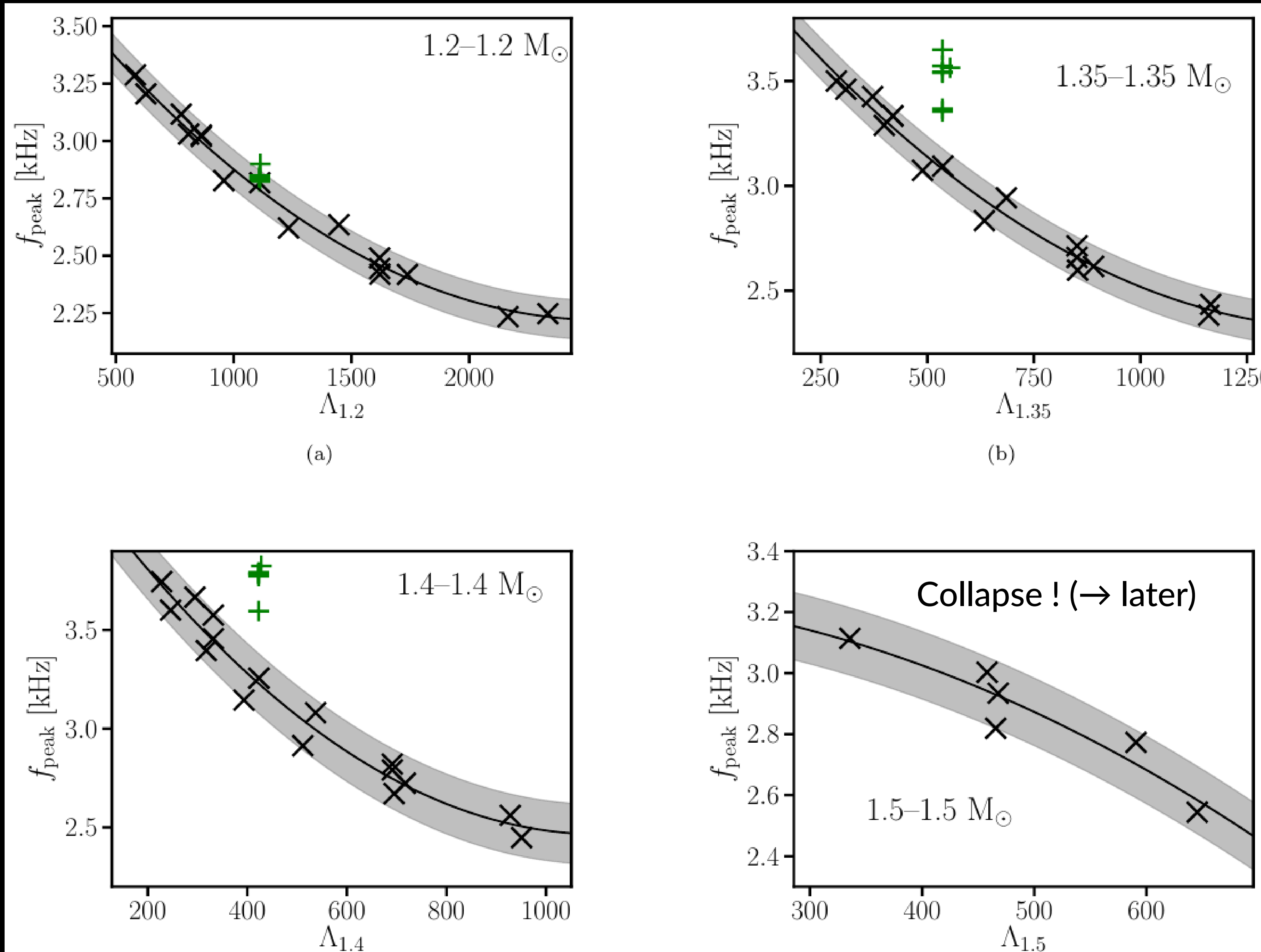
- Maximum density in postmerger remnant (time dependent) vs central density of isolated start - note: very different masses



Blacker et al. (2021)



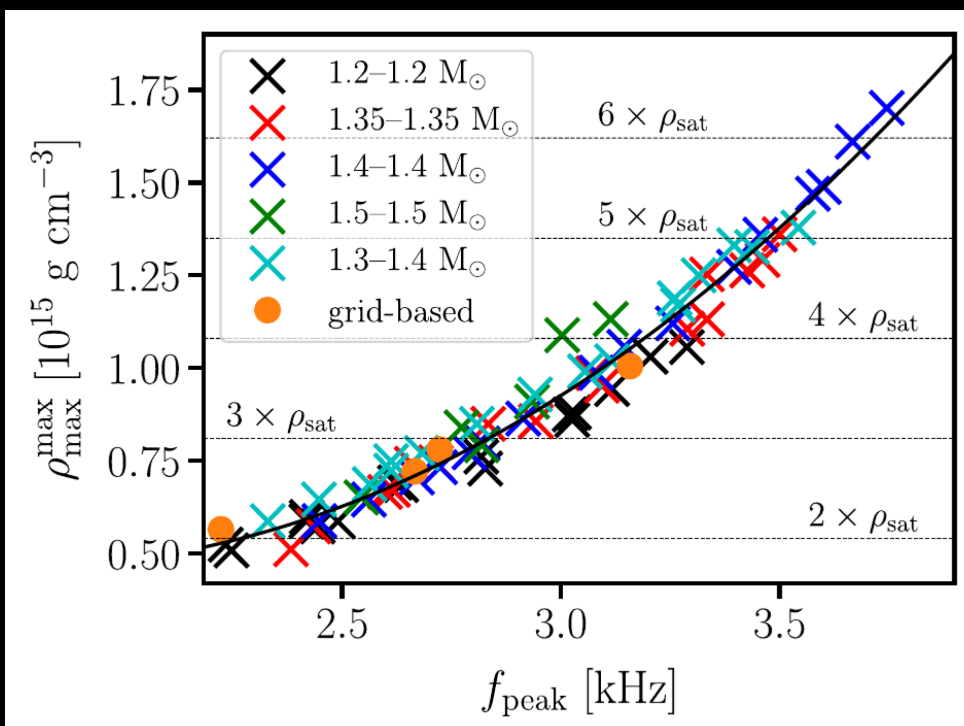
Lioutas et al, PRD, 2021; blue line $\rho_{\max}^{\max} = \rho_{\rm c}$

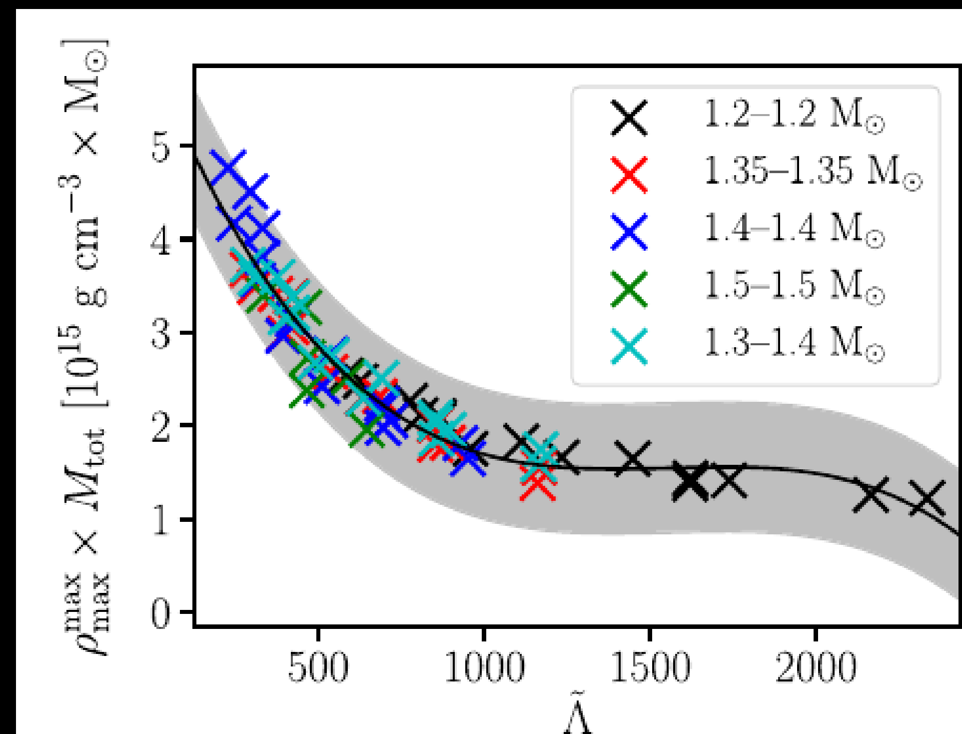


Blacker et al. (2020), arXiv:2006.03789

Density regime of mergers

- GW parameters inform about density regime of remnant, i.e. which density regime of EoS is actually probed

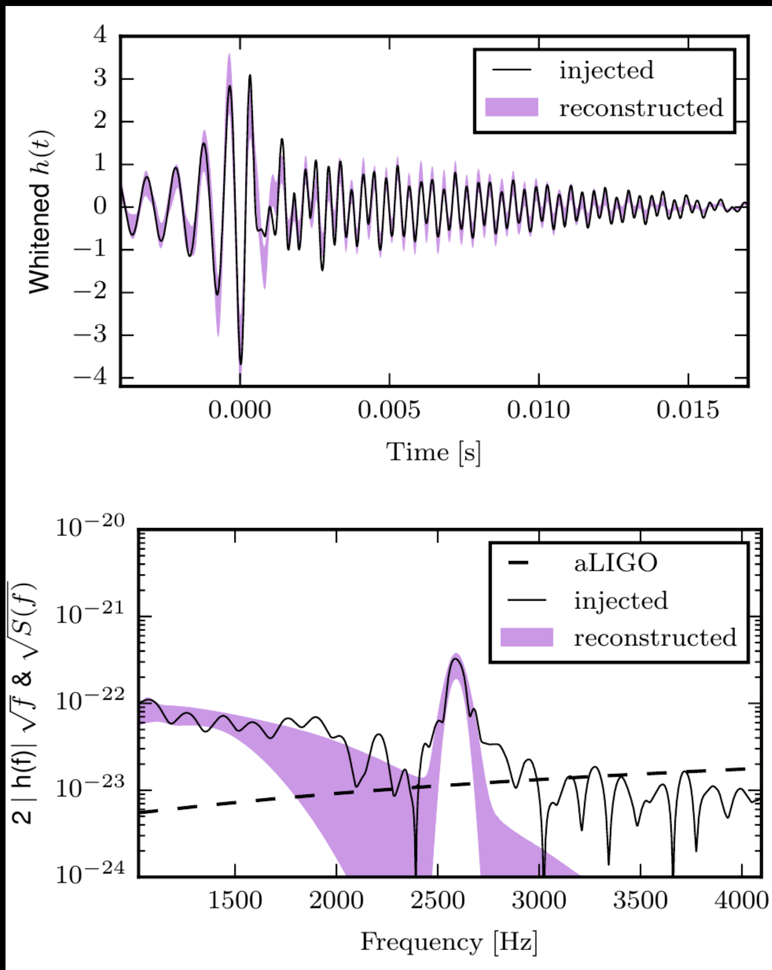


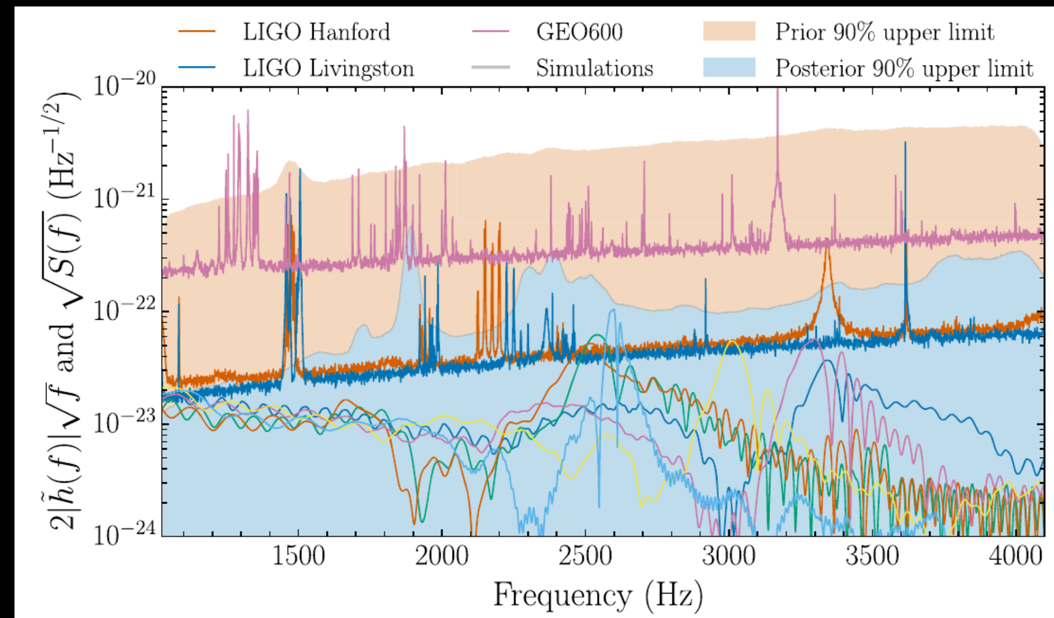


Blacker et al. 2020

GW data analysis: Model-agnostic data analysis

Based on wavelets





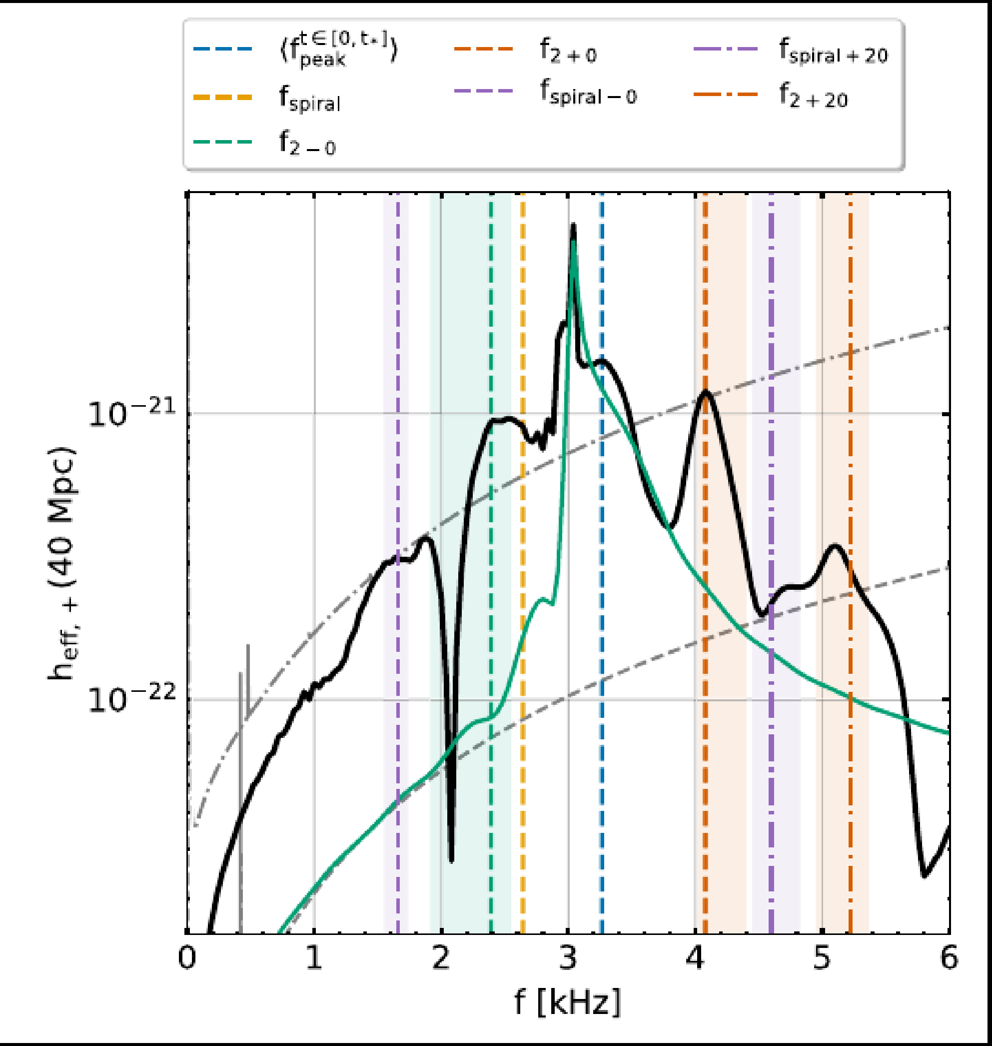
Abbott et al., PRX (2019)

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, …

Secondary features → asteroseismology

- Subdominat features enocde dynamics and additional EoS information

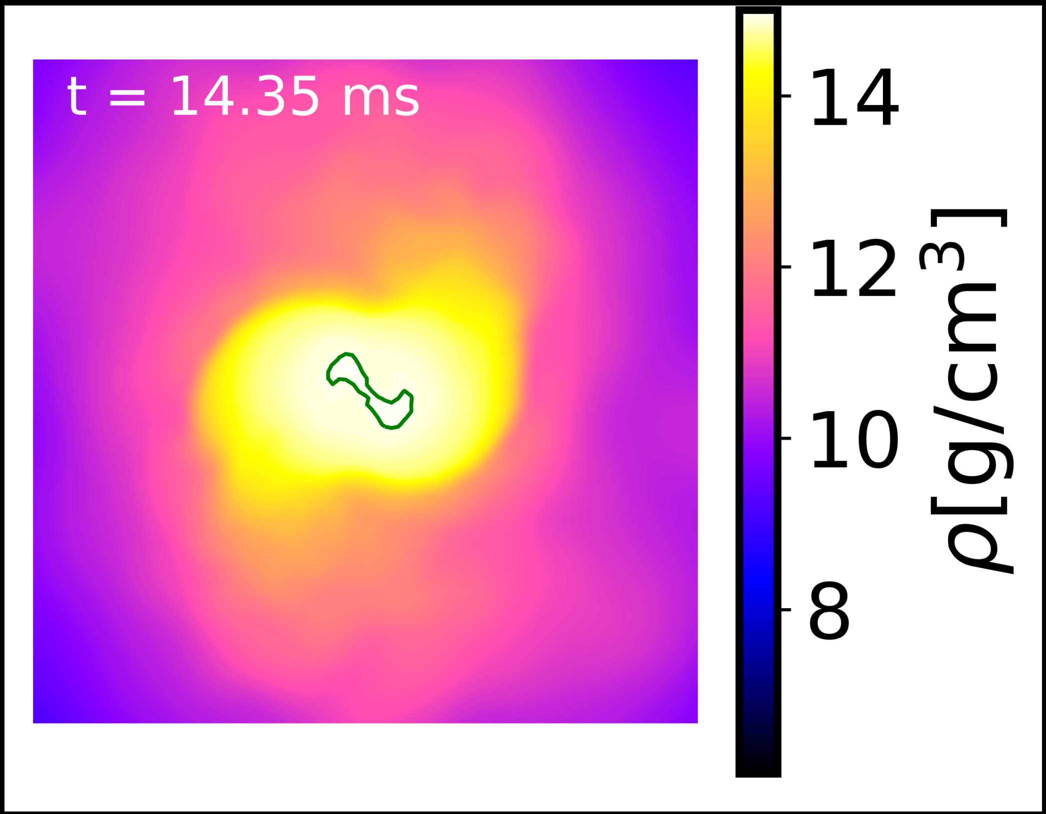


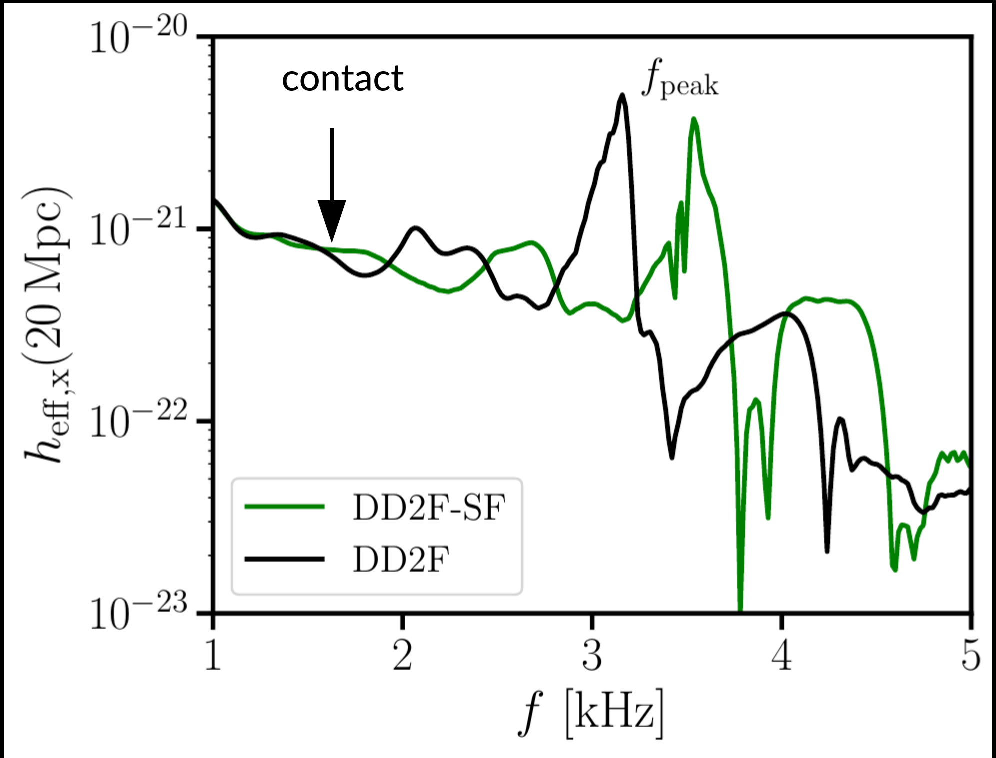
Soultanis et al 2022

Quark matter in NS mergers

Merger simulations with quark matter core

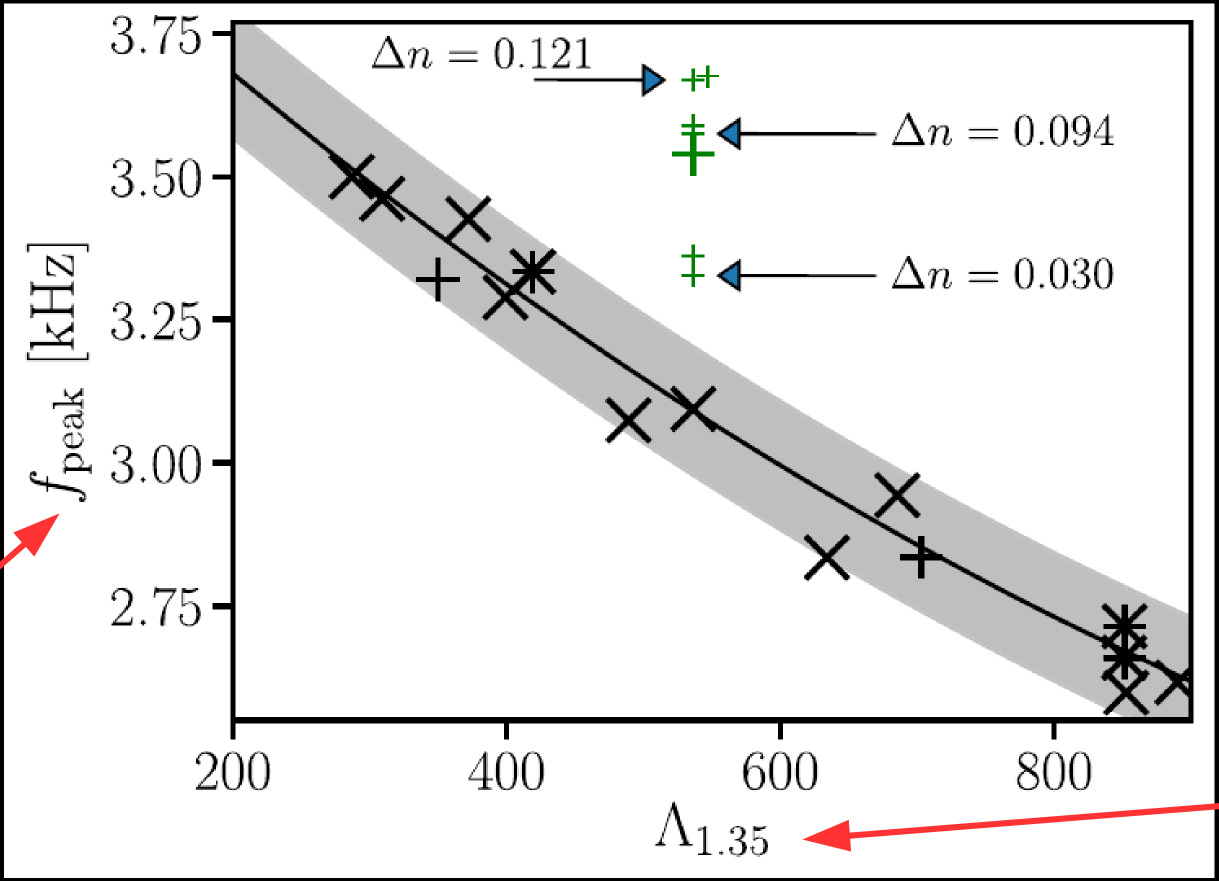
- GW spectrum 1.35-1.35 Msun





A.B. et al. 2019

Signature of 1st order phase transition



from postmerger

from the inspiral

A.B. et al 2019

- Characteristic increase of postmerger frequency compared to tidal deformability
  → evidence of presence of quark matter core
  → in any case constraint on onset density of hadron-quark phase transition

Summary

- Different possibilities to learn about high-density matter
- GW inspiral → finite size effects → nuclear matter cannot be too stiff
- Many different ideas for multi-messenger interpretation

  → collapse behavior (robust interpretation) → nuclear matter cannot be too soft

  → potential for future: Mmax
- future: postmerger GW oscillations
- QCD phase transition detectable