Heidelberg Institute for Theoretical Studies

HITS

Gravitational waves and the EoS:

Collapse behavior and postmerger gravitational wave emission of neutron star mergers

EMMI Rapid Reaction Task Force: the physics of neutron star mergers at GSI/FAIR, 05/06/2018

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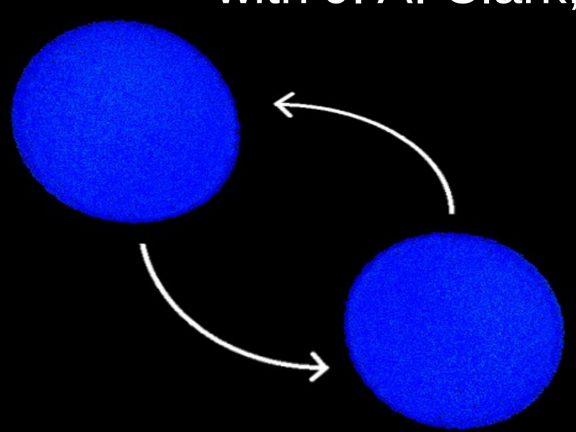
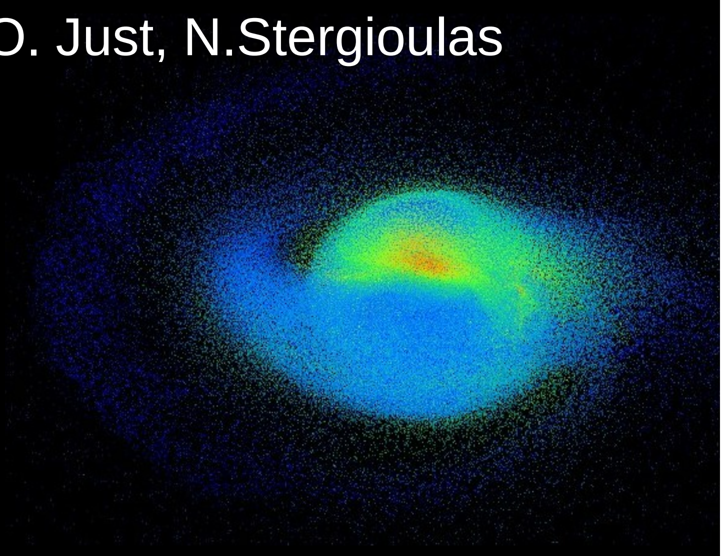
with J. A. Clark, K. Chatziioannou, H.-T. Janka, O. Just, N.Stergioulas





Outline

Focus of this talk on EoS impact / constraints

- Simulations and ejecta masses
- Collapse behavior
- NS radius constraints from GW170817 *
- dominant postmerger GW emission

  → NS radius measurements

  → maximum mass and other EoS constraints
- Unified picture of postmerger dynamics and GW emission

  → secondary GW peaks

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

Importance of EoS

- Understand properties of high-density matter (hardly accessible by laboratory experiments – theoretically challenging)

  → e.g. nuclear parameter (also important for nucleosynthesis models)

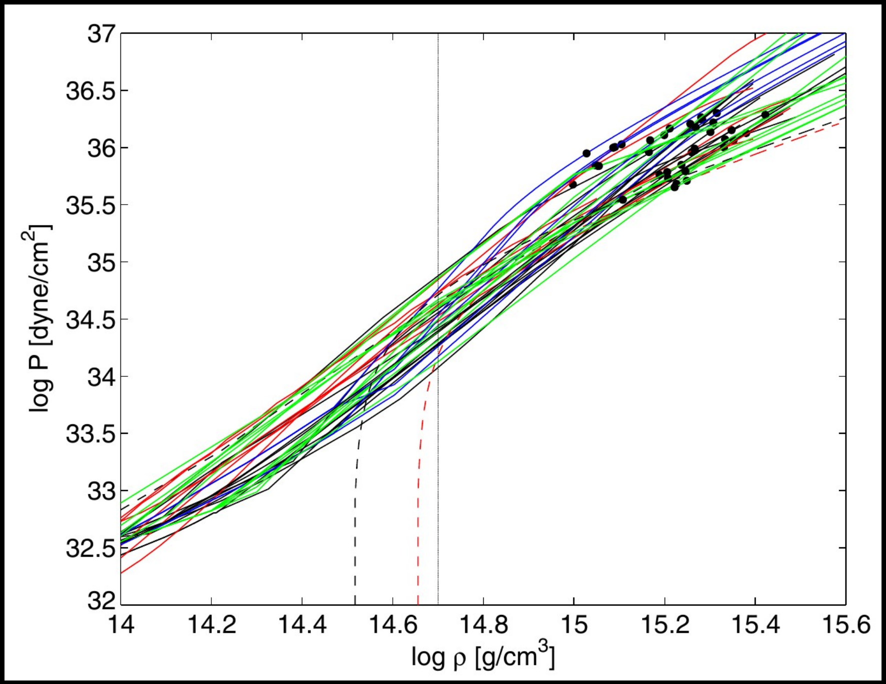
  → phase transition to hyperonic matter? Quark matter?

- Stellar properties of NS (observationally challenging)

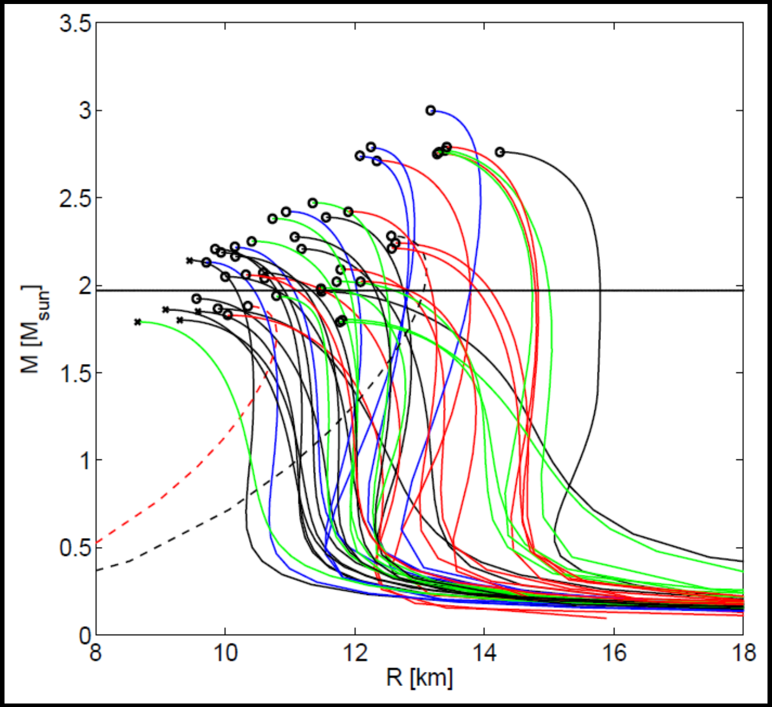
  → EoS affects dynamics/phenomenology of mergers (e.g em counterparts, nucleosynthesis, GRBs), supernovae, NS cooling, ….

Introductory remark

- Mass-radius relation (of non-rotating NSs) and EoS are uniquely linked through Tolman-Oppenheimer-Volkoff (TOV) equations



TOV ⟷



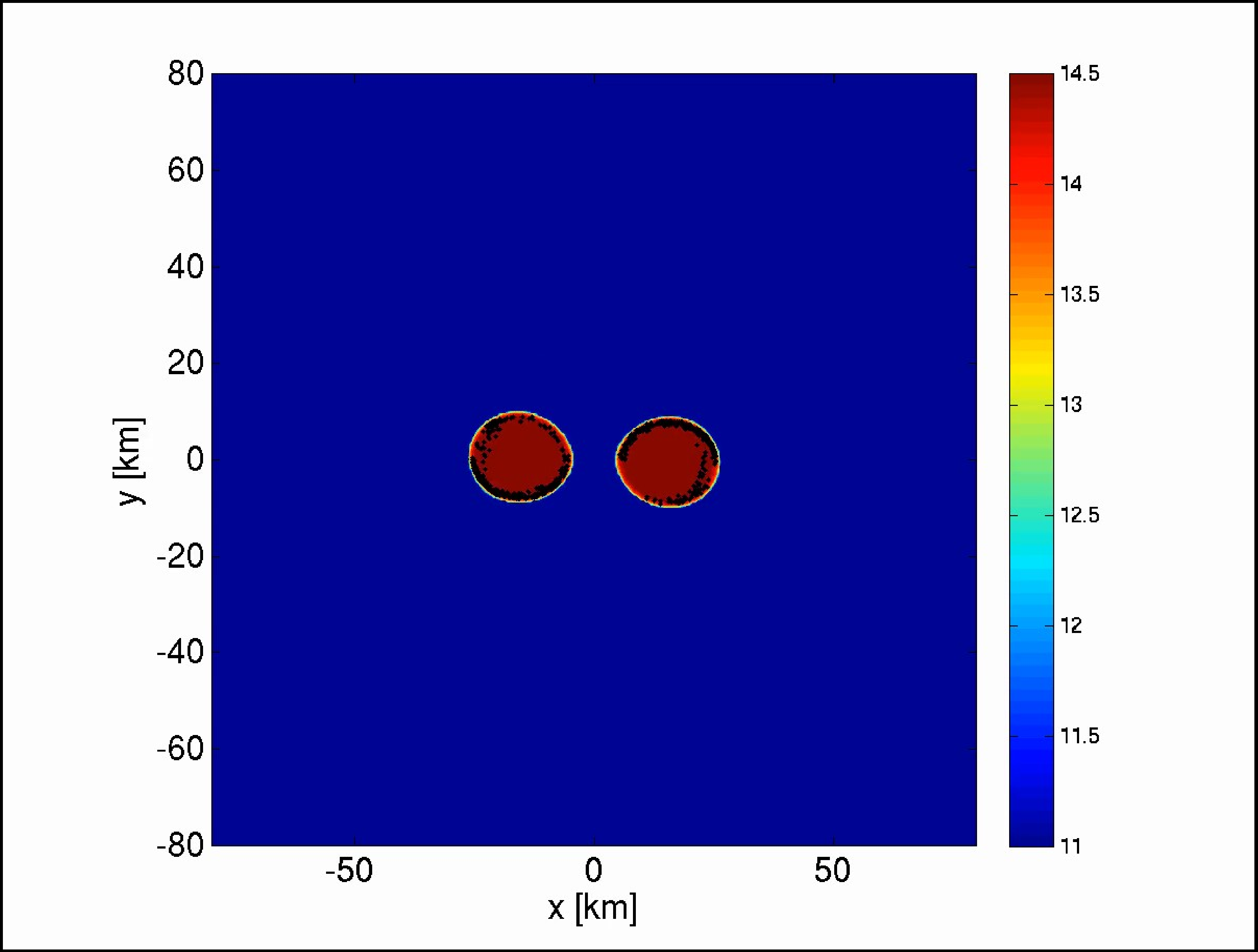
Theory: P(ρ) ⟵ currently / future ⟶ Observation: R(M)

→ NS properties (of non-rotating stars) and EoS properties are equivalent !!!

(not all displayed EoS compatible with all current constraints)

Simulation results – ejecta

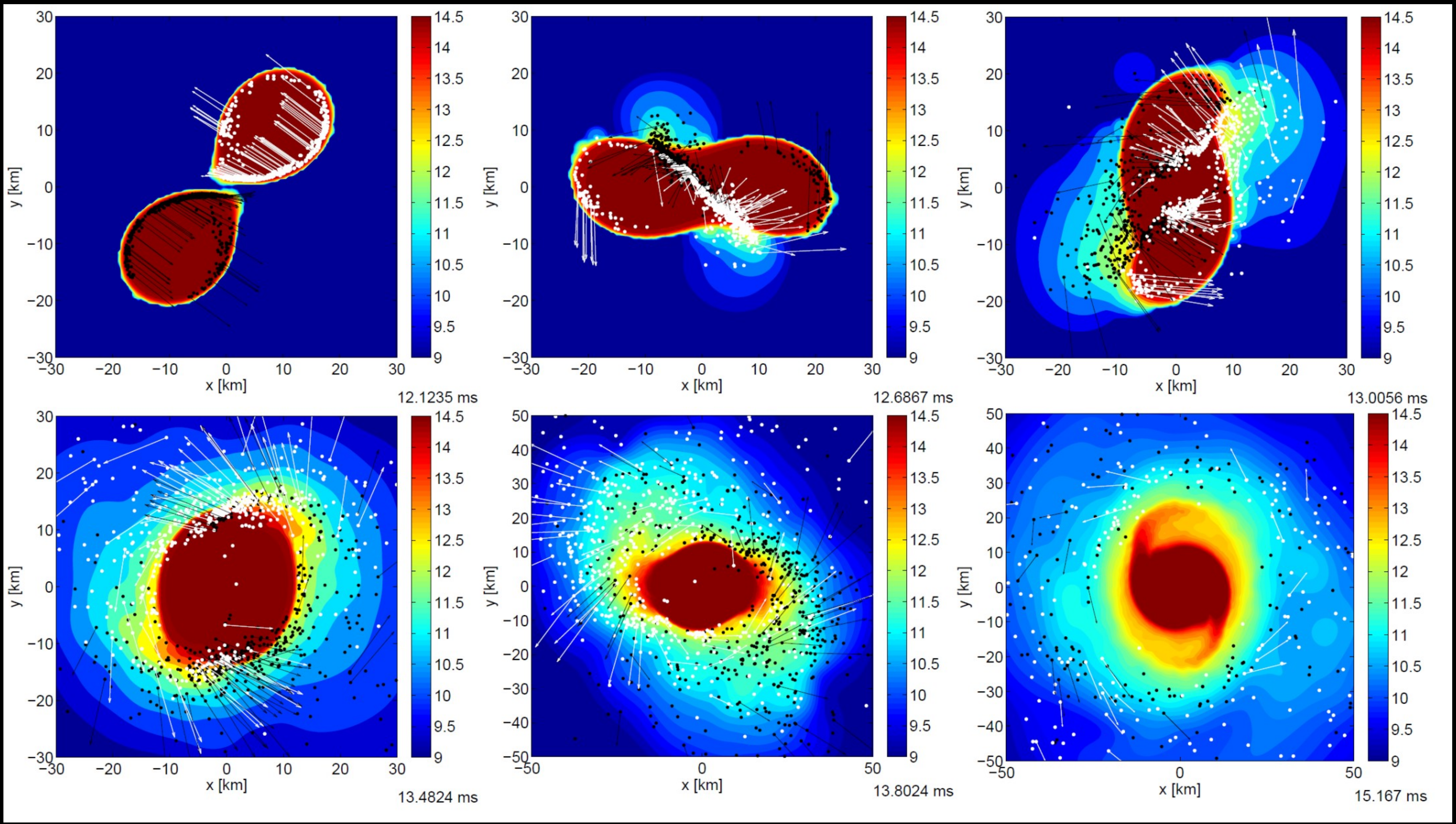
(EoS and binary mass dependence)



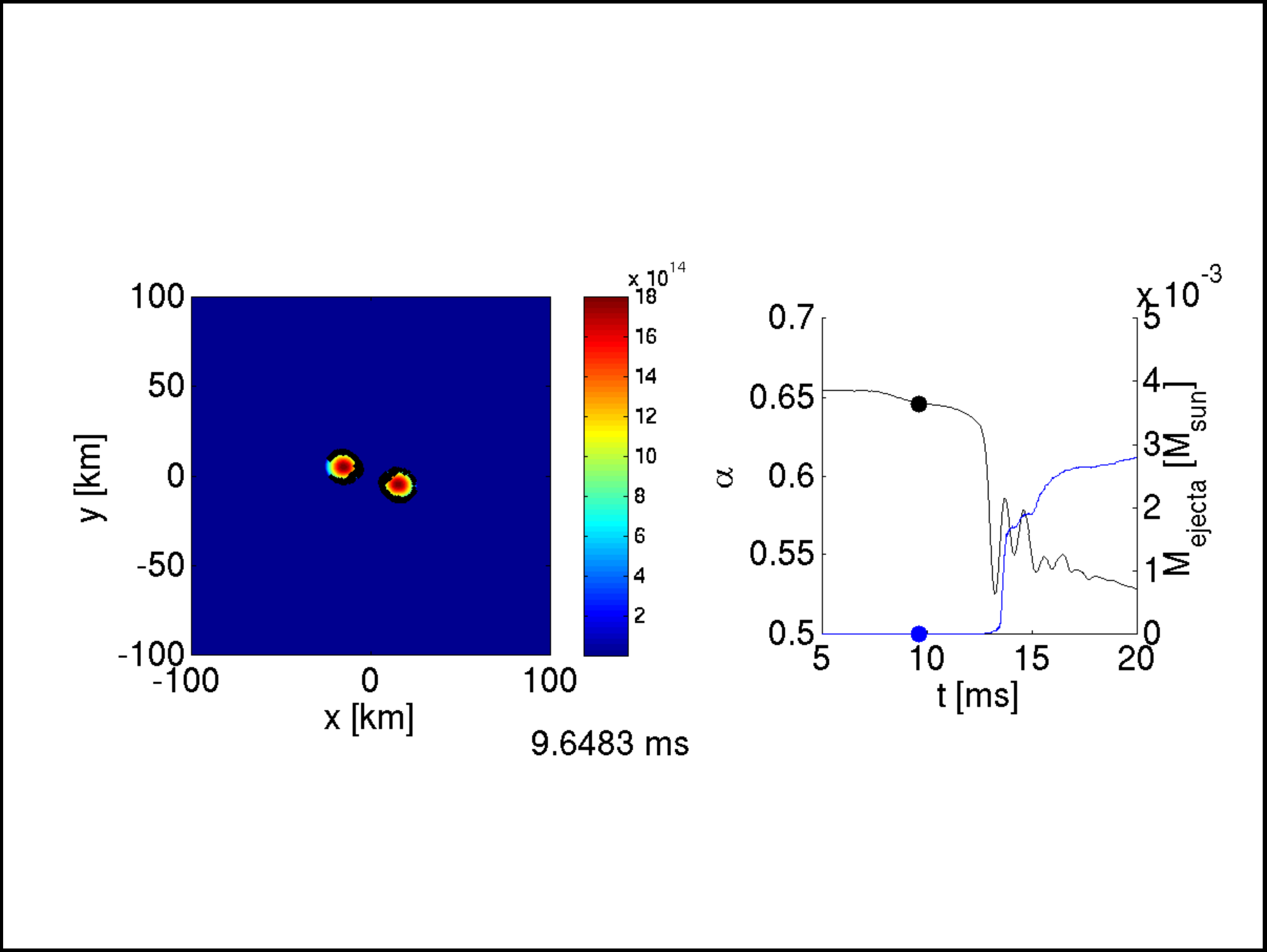
DD2 1.35-1.35 M_{sun}, representative ejecta particles (white unbound)

Simulations

Dots trace ejecta (DD2 EoS 1.35-1.35 M_{sun})



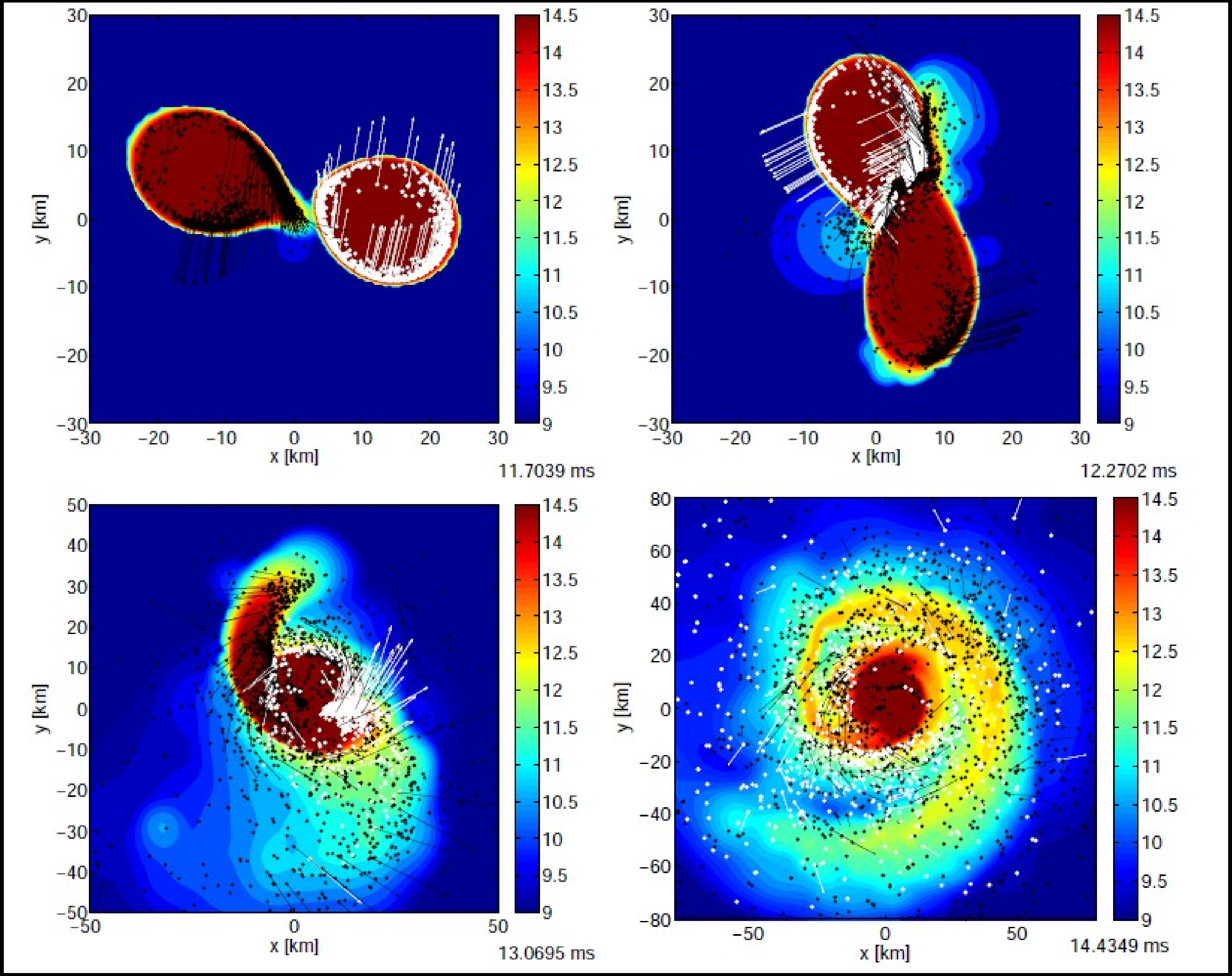
Bauswein et al. 2013



Black: bound; white: unbound (formally)

Central lapse: measure for compactness

Asymmetric mergers

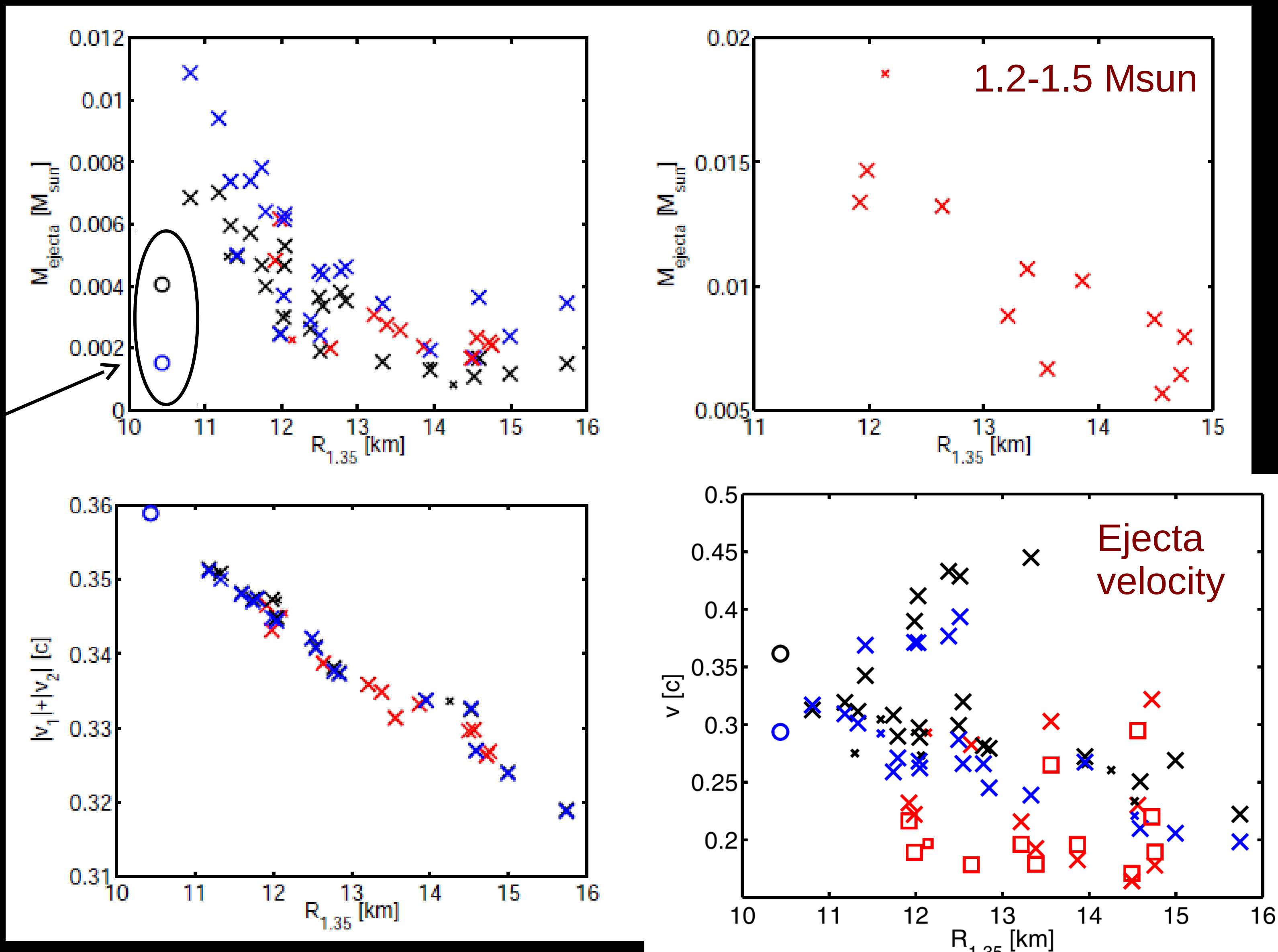


→ larger tidal component, larger total ejecta masses

Bauswein et al. 2013

Ejecta mass dependence

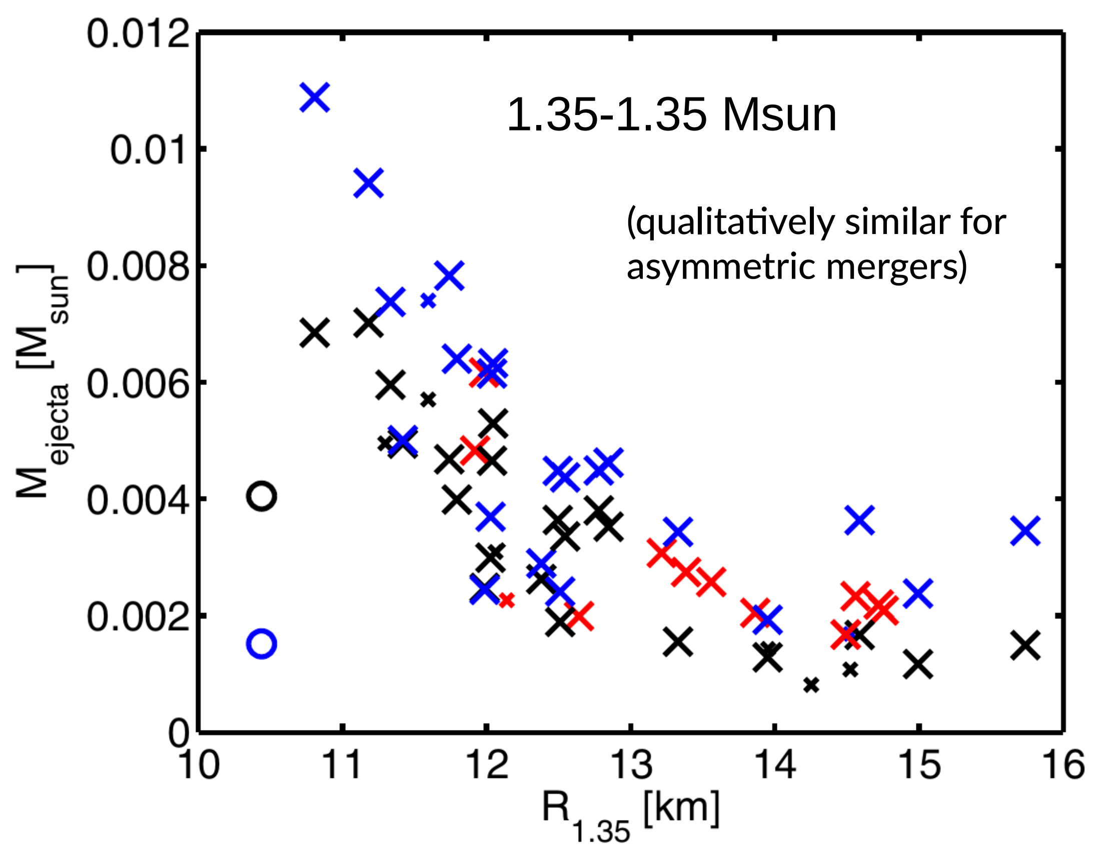
Prompt collapse



Different EoSs characterized by radii of 1.35 M_{sun} NSs (note importannce of thermal effects)

Coarse picture: EoS dependence of ejecta mass

- Ejecta mass 0.03-0.05 Msun in GW170817
- Excludes tentatively very stiff EoSs
- Excludes tentatively very soft EoSs – prompt collapse !!!



Bauswein et al 2013, see also Hotokezaka et al 2013

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)	$0.002 - 0.03$	$0.03 - 0.1$
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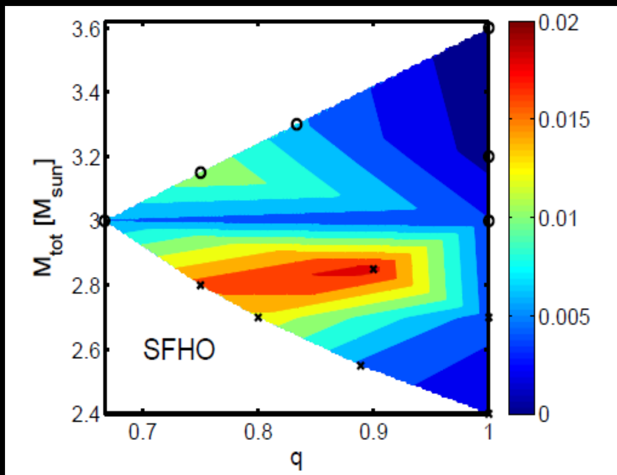
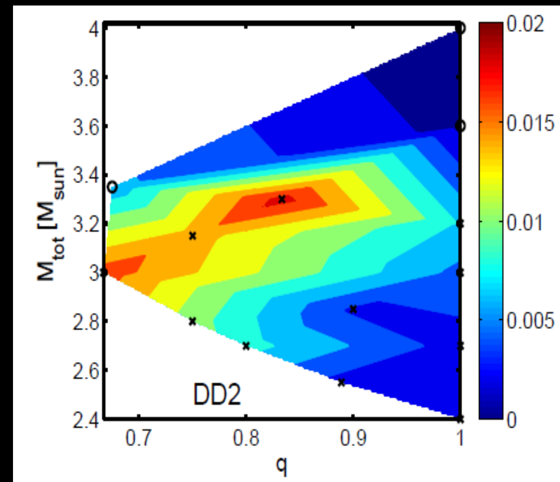
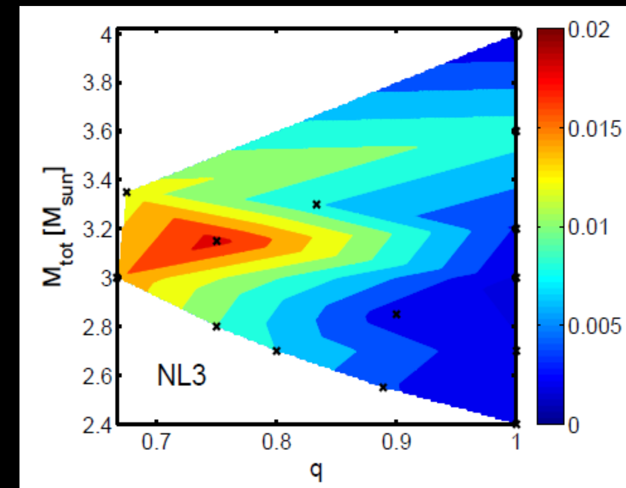
Smartt et al. (2017)	$0.03 - 0.05$	0.018
Tanaka et al. (2017a)	0.01	0.03
Tanvir et al. (2017)	$0.002 - 0.01$	0.015
Troja et al. (2017)	$0.001 - 0.01$	$0.015 - 0.03$

Compilation in Cote et al 2018

Ejecta mass dependencies: binary para.

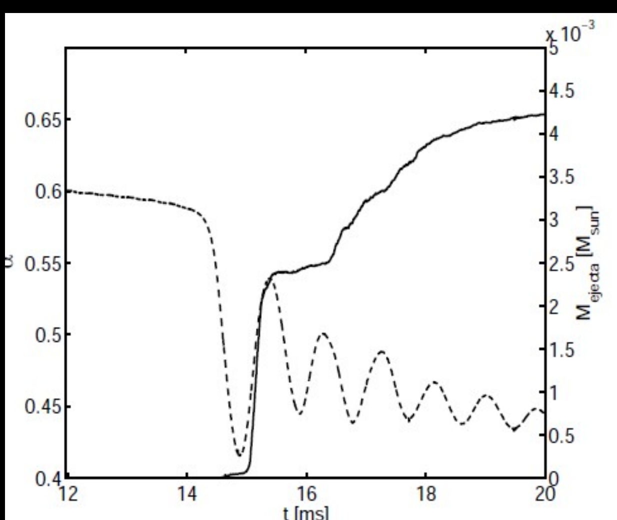


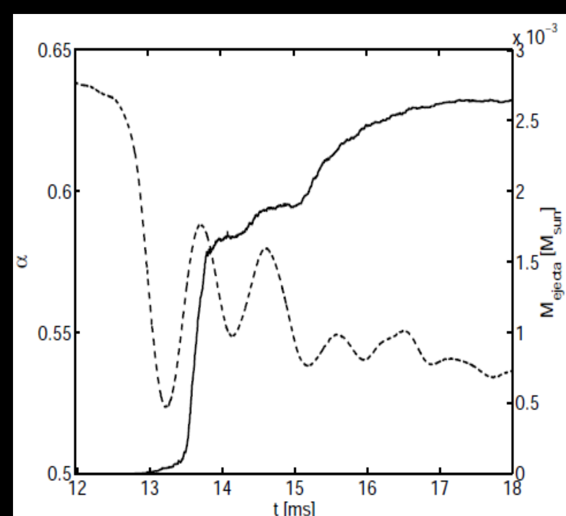


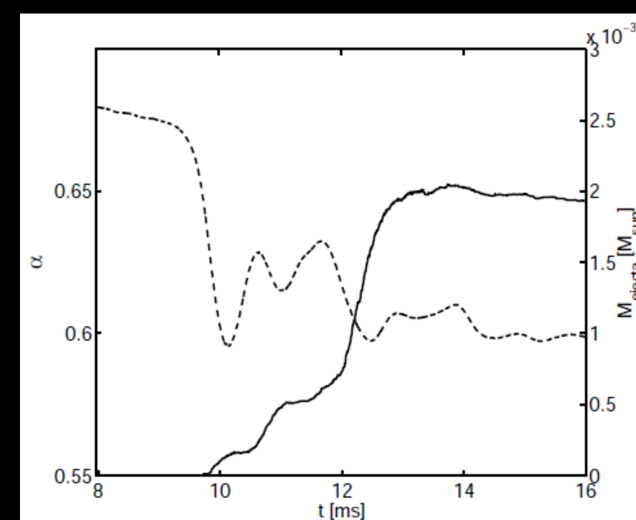


Stiffness

understandable by different dynamics / impact velocity / postmerger oscillations



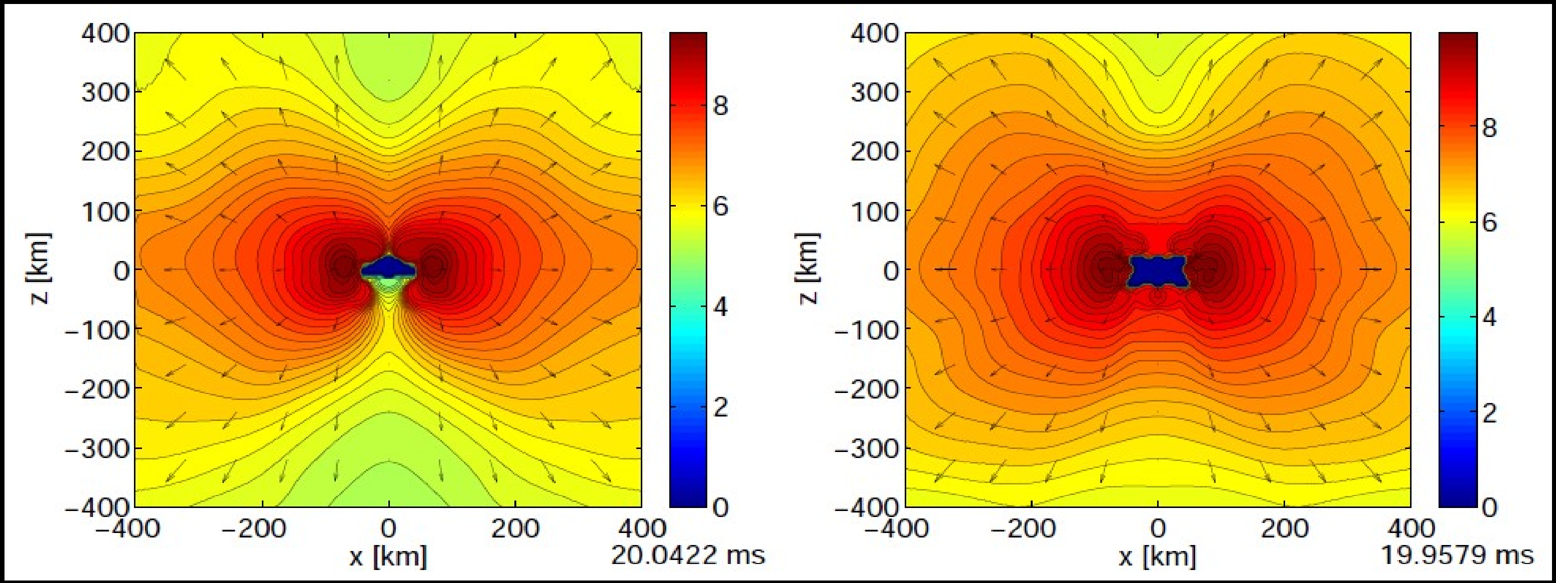




Central lapse α traces remnant compactness / oscillations / dynamics (dashed lines)

Ejecta morphology

- Rather isotropic ejection → dynamical ejecta obsurcs secular ejecta (?) → early blue component puzzling? → strong neutrino effects such that no heavy r-process elements (high opacity material is produced)?



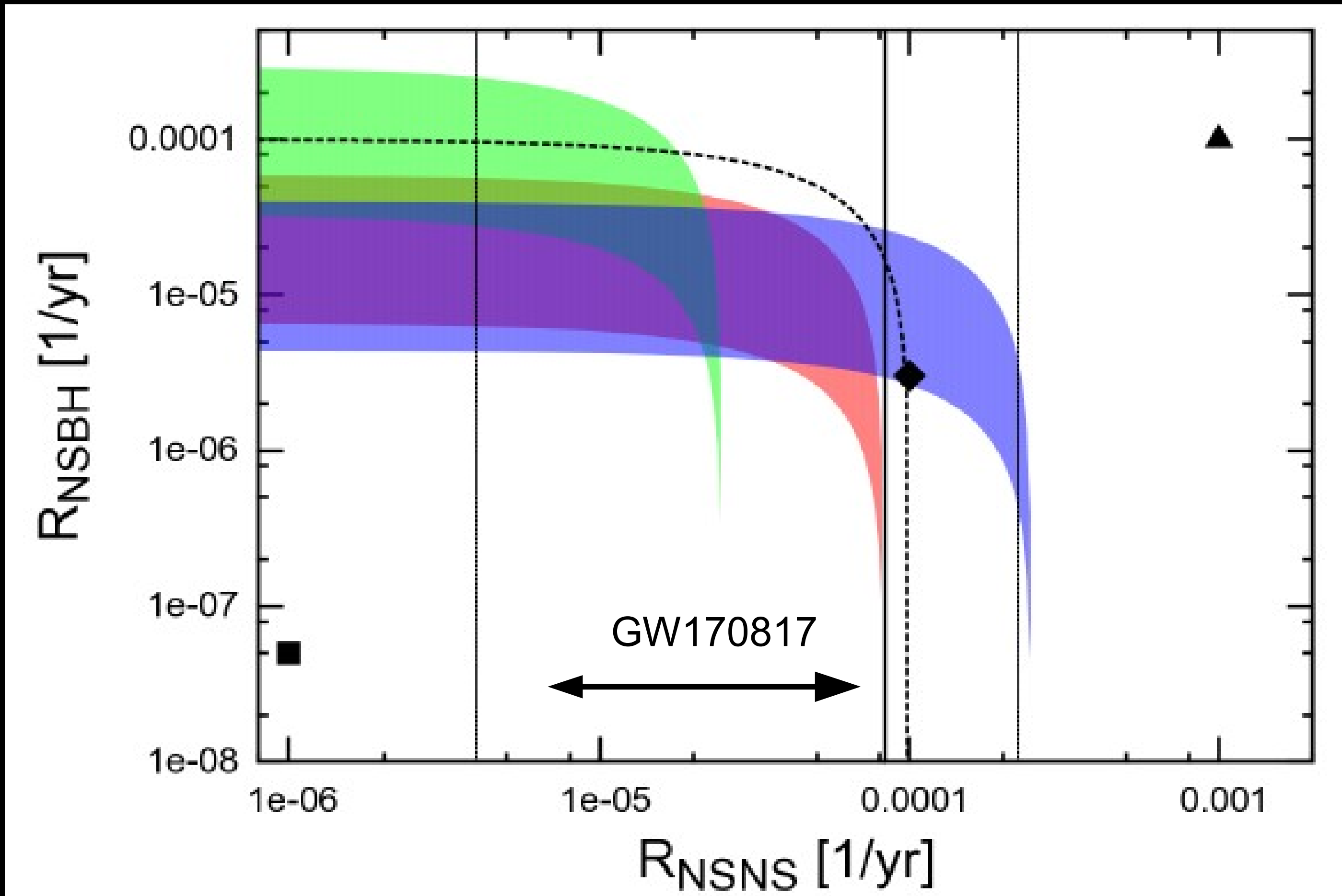
Symmetric

asymmetric

Bauswein et al. 2013

Considering only heavy elements with A > 140

=> not clear how much of this material in GW170817 !!!



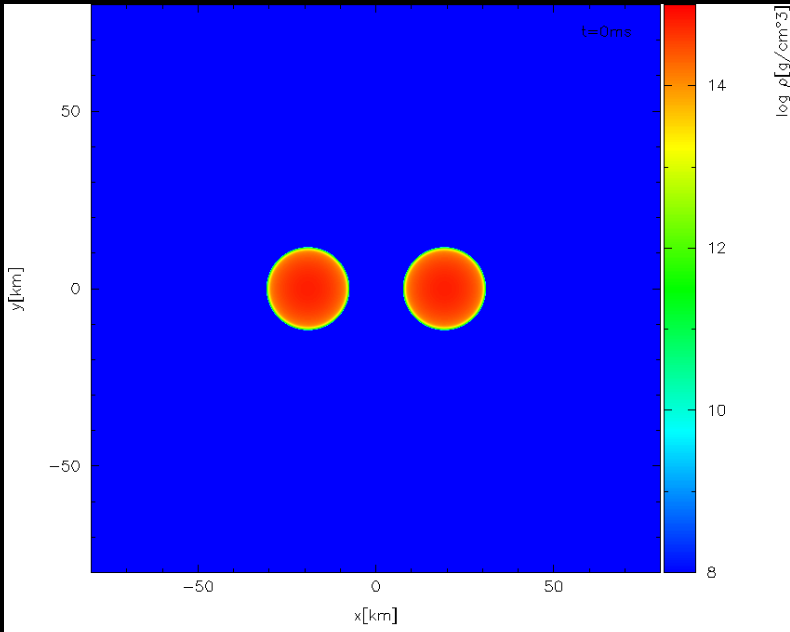
M_{ej}(NSNS):

Blue: $10^{-3}\ M_{sun}$

Red: $3*10^{-3}\ M_{sun}$

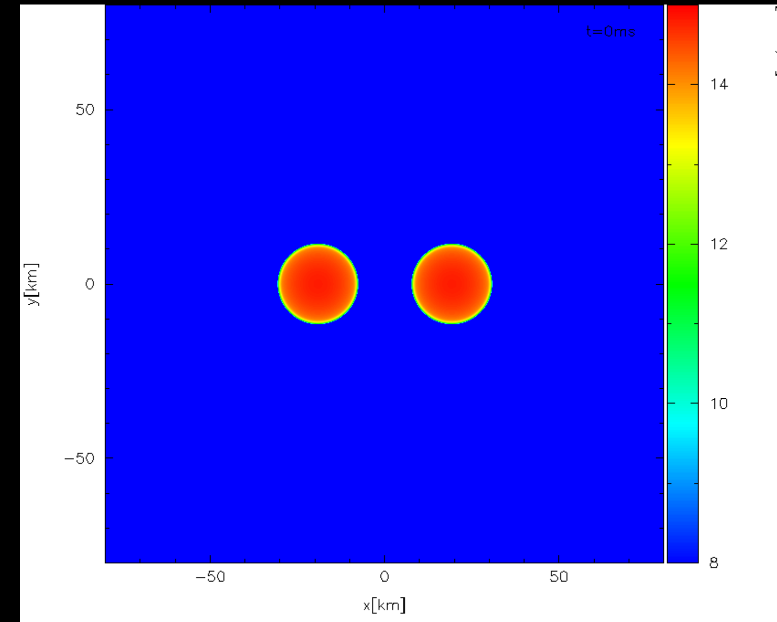
Green: $10^{-2}\ M_{sun}$

- Colored bands: rates for different EoSs
- Symbols: population synthesis predictions (Abadie et al. 2010)
- Vertical lines: pulsar observations (Kalogera et al. 2004)
- Dashed curve: short GRBs (Berger 2013)
- Arrow: volumetric rate (Abbott et al. 20017) converted to Galactic rate



$M_{\rm tot} = 3.4\ M_\odot$ ←

$M_{\rm tot} = 3.5\ M_\odot$ →



Shen EoS

Collapse behavior: Prompt vs. delayed (/no) BH formation

<u>Relevant for:</u>

EoS constraints through M_{max} measurement

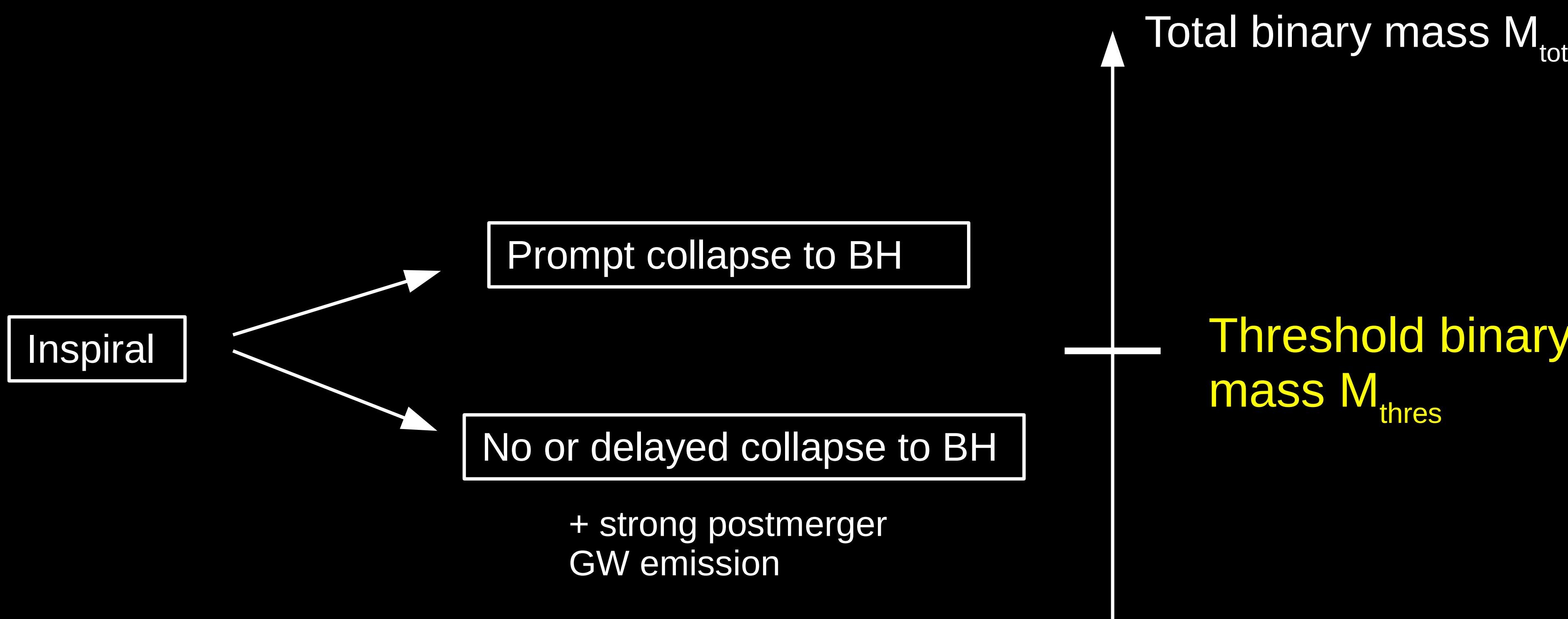
Conditions for short GRBs

Mass ejection

Electromagnetic counterparts powered by thermal emission

And NS radius constraints !!!

Collapse behavior



EoS dependent - somehow M_{max} should play a role

Simulations reveal M_{thres}

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

Bauswein et al. 2013

Smooth particle hydrodynamics + conformal flatness

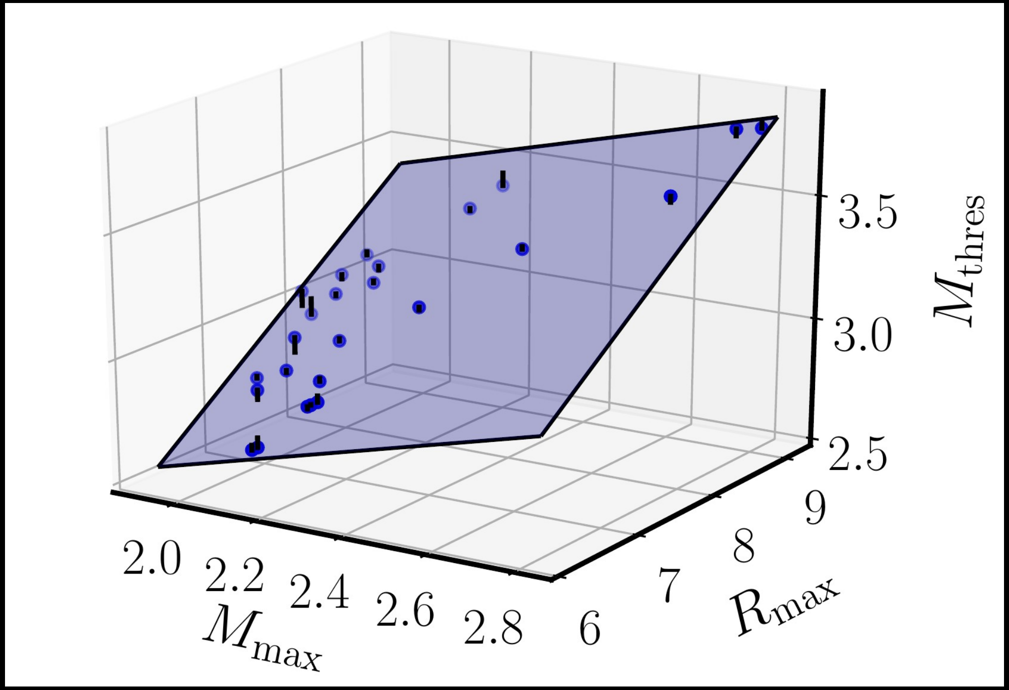
Threshold binary mass

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

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

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

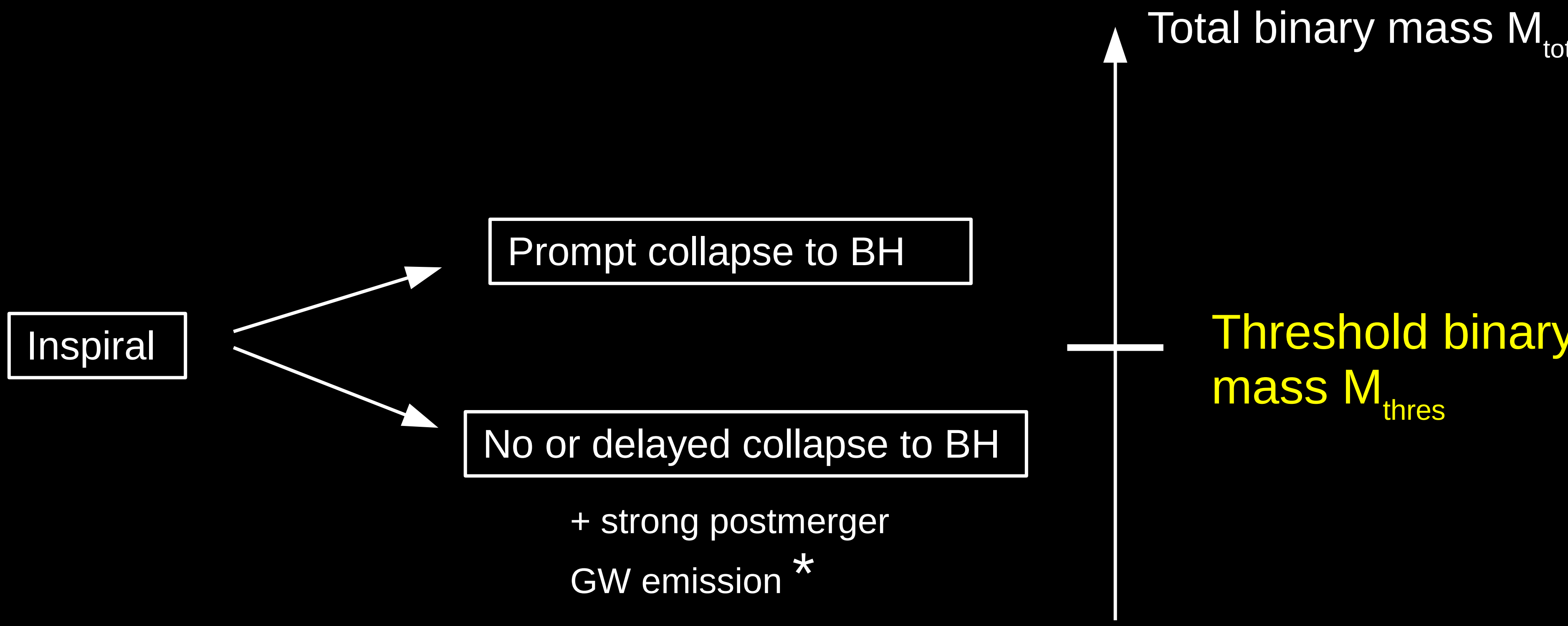
- Both better than 0.06 M_{sun}



EoS constraints from GW170817

→ lower bound on NS radii

Collapse behavior



M_{thres} EoS dependent - somehow M_{max} should play a role

A simple but robust NS radius constraint from GW170817

- High ejecta mass inferred from electromagnetic transient

  → 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)	$0.001 - 0.01$	–
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Compilation in Cote et al 2018

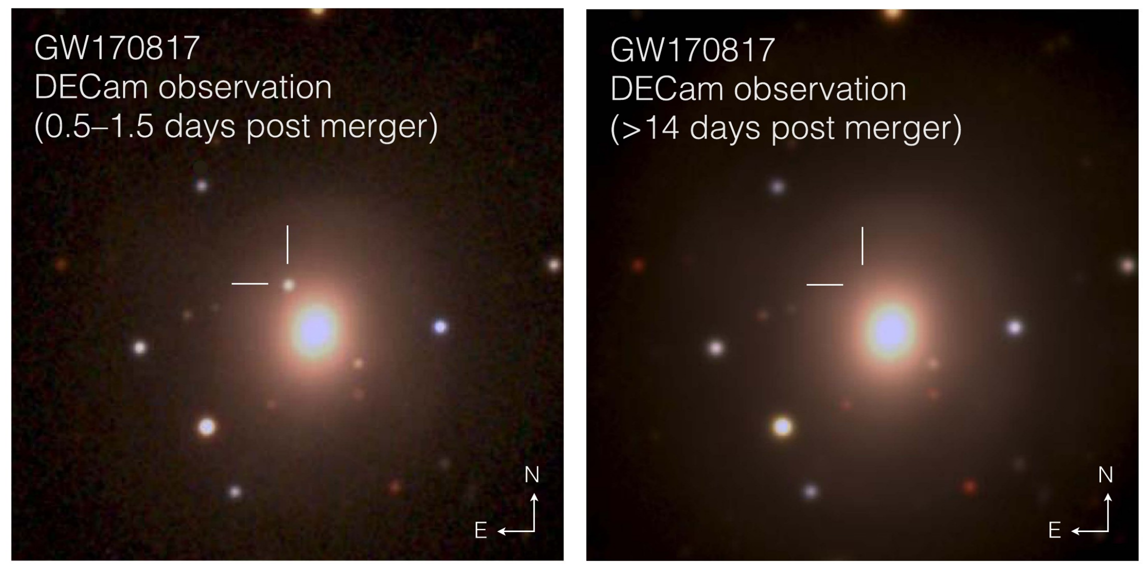


Figure 1. NGC4993 *grz* color composites (1.′5 × 1.′5). Left: composite of detection images, including the discovery *z* image taken on 2017 August 18 00:05:23 UT and the g and r images taken 1 day later; the optical counterpart of GW170817 is at R.A., decl. =197.450374, −23.381495. Right: the same area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

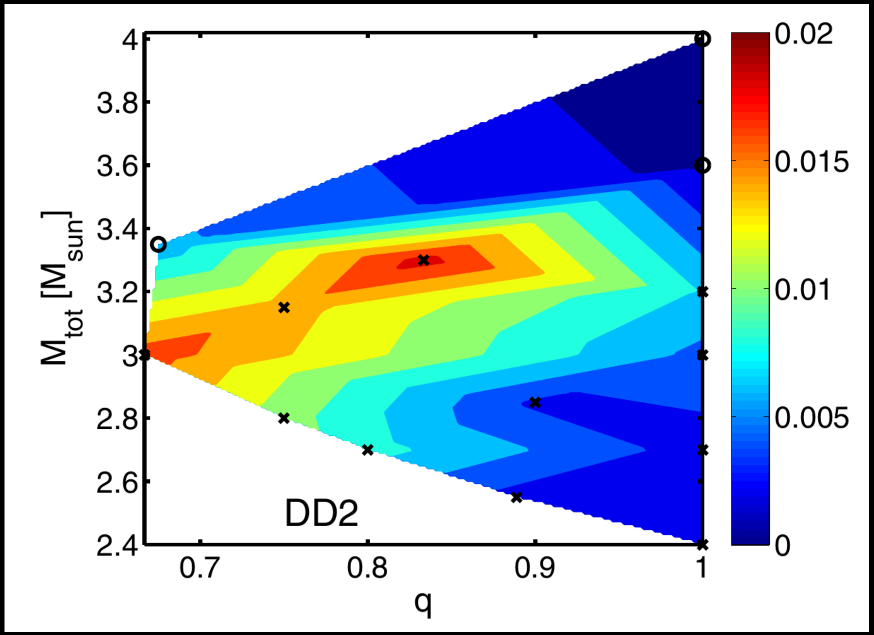
Soares-Santos et al 2017

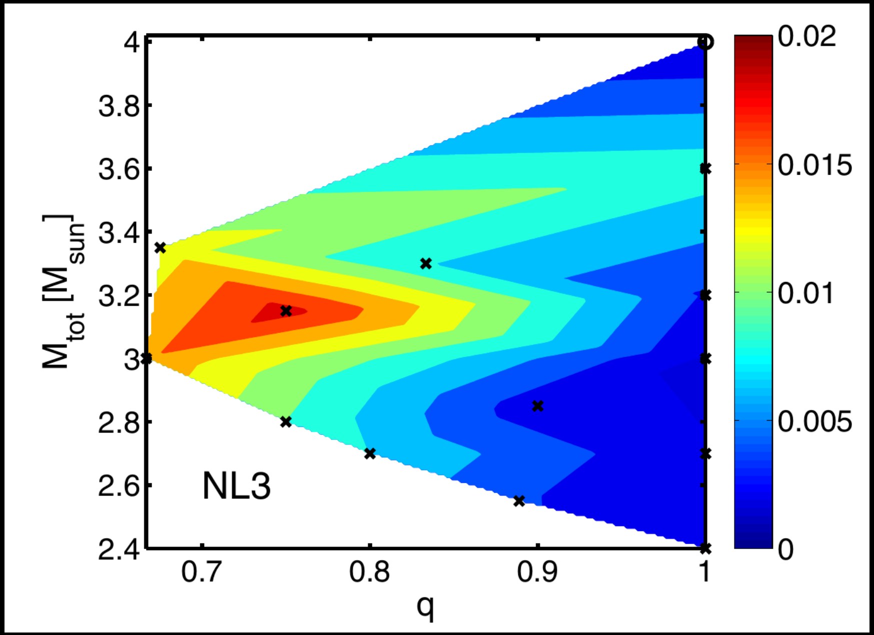
- Ejecta masses depend on EoS and binary masses
- Note: high mass points already to soft EoS (tentatively/qualitatively)
- Prompt collapse leads to reduced ejecta mass
- Light curve depends on ejecta mass:

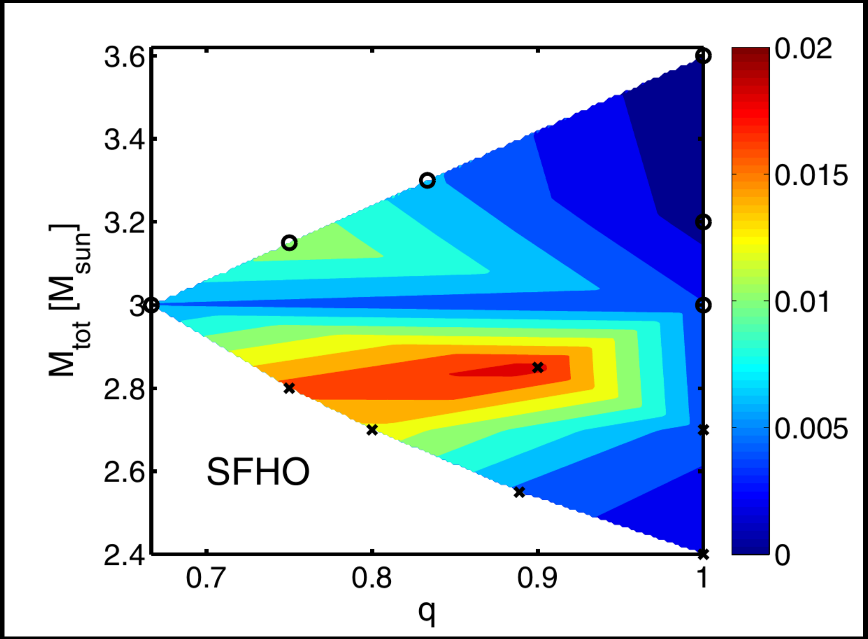
  → 0.02 - 0.05 M_{sun} point to delayed collapse

- Note: here only dynamical ejecta

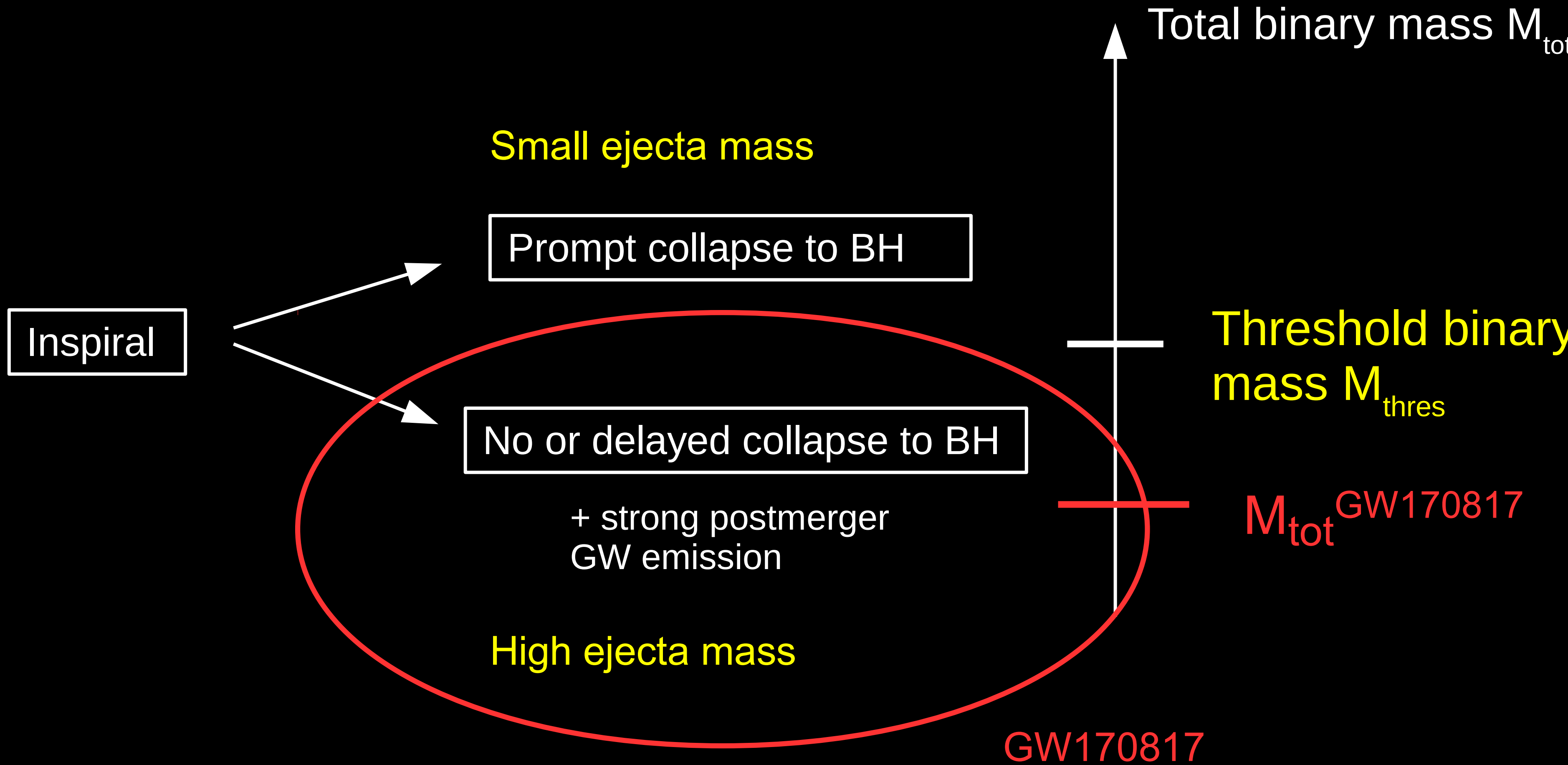
Only dynamical ejecta







Collapse behavior



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

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

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

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

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

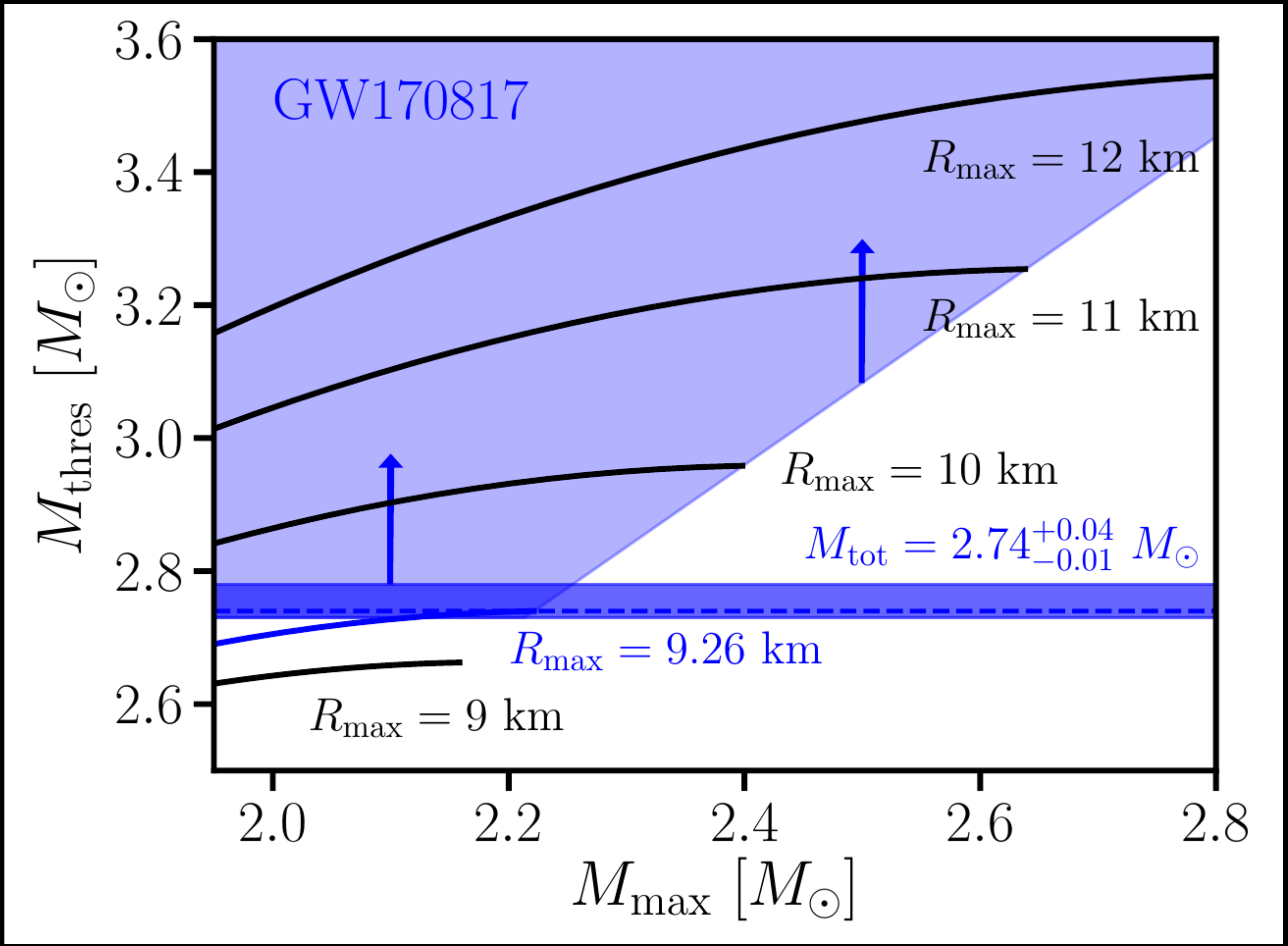
(3) Causality: speed of sound $v_S \leq c$ $\Rightarrow M_{\rm max} \leq \frac{1}{2.82}\frac{c^2\,R_{\rm max}}{G}$

- Putting things together:

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

→ Lower limit on NS radius

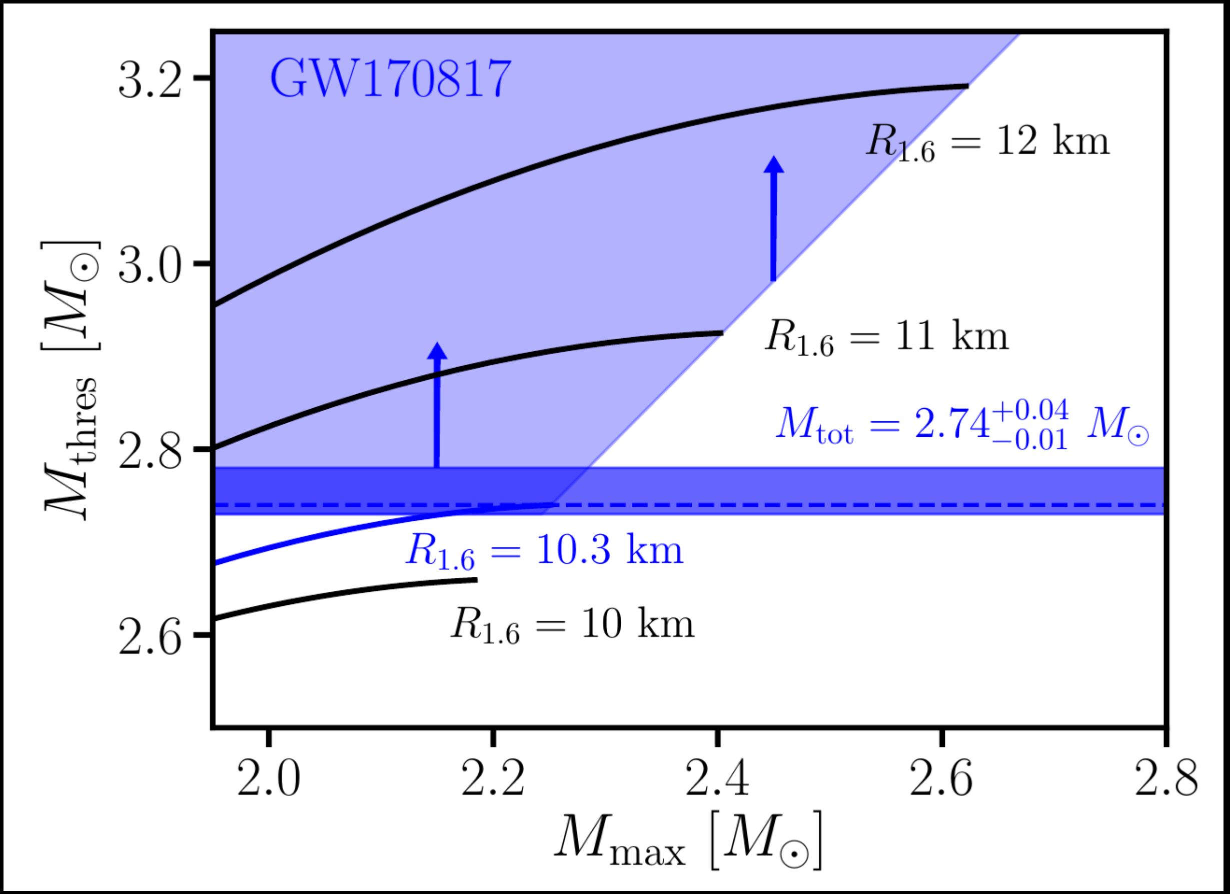
Bauswein et al. 2017



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

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

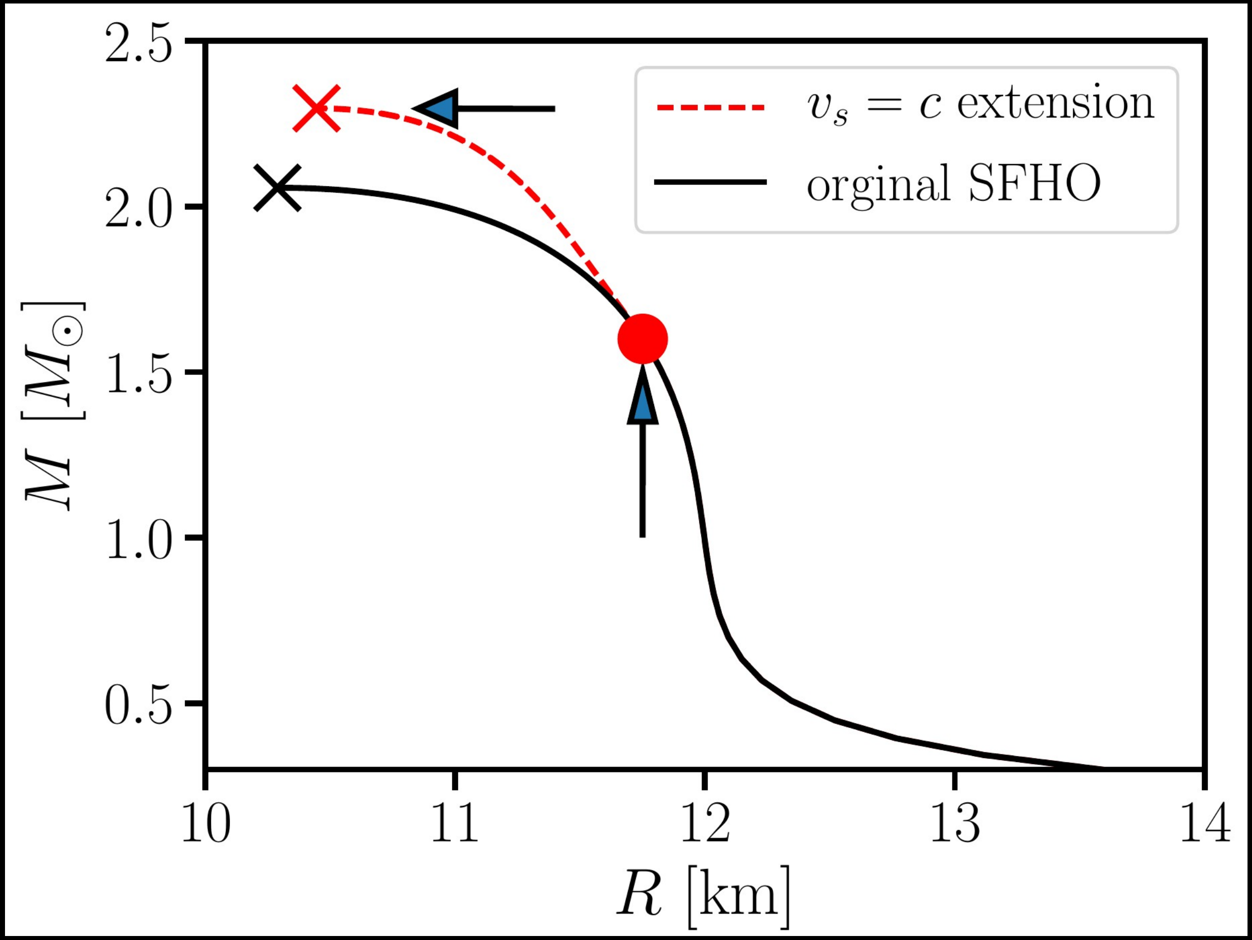
Bauswein et al. 2017



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

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

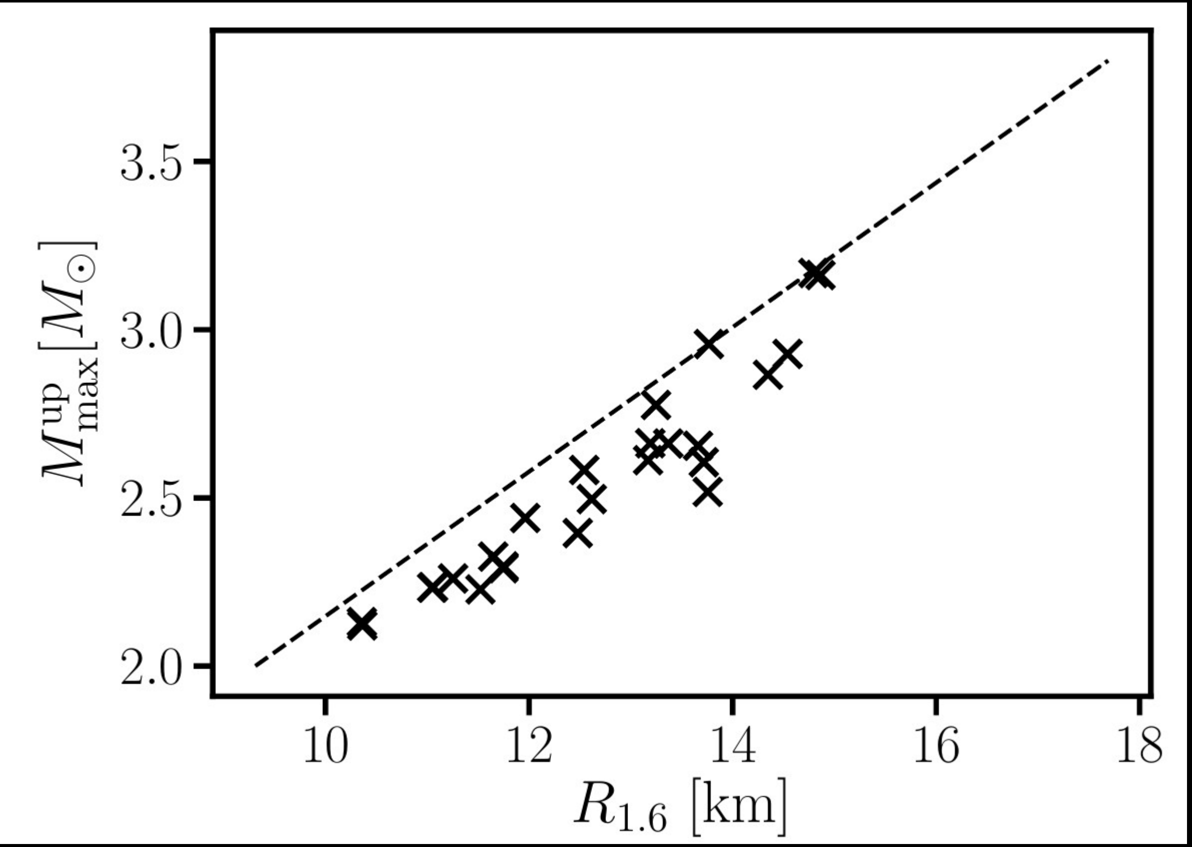
Causal limit

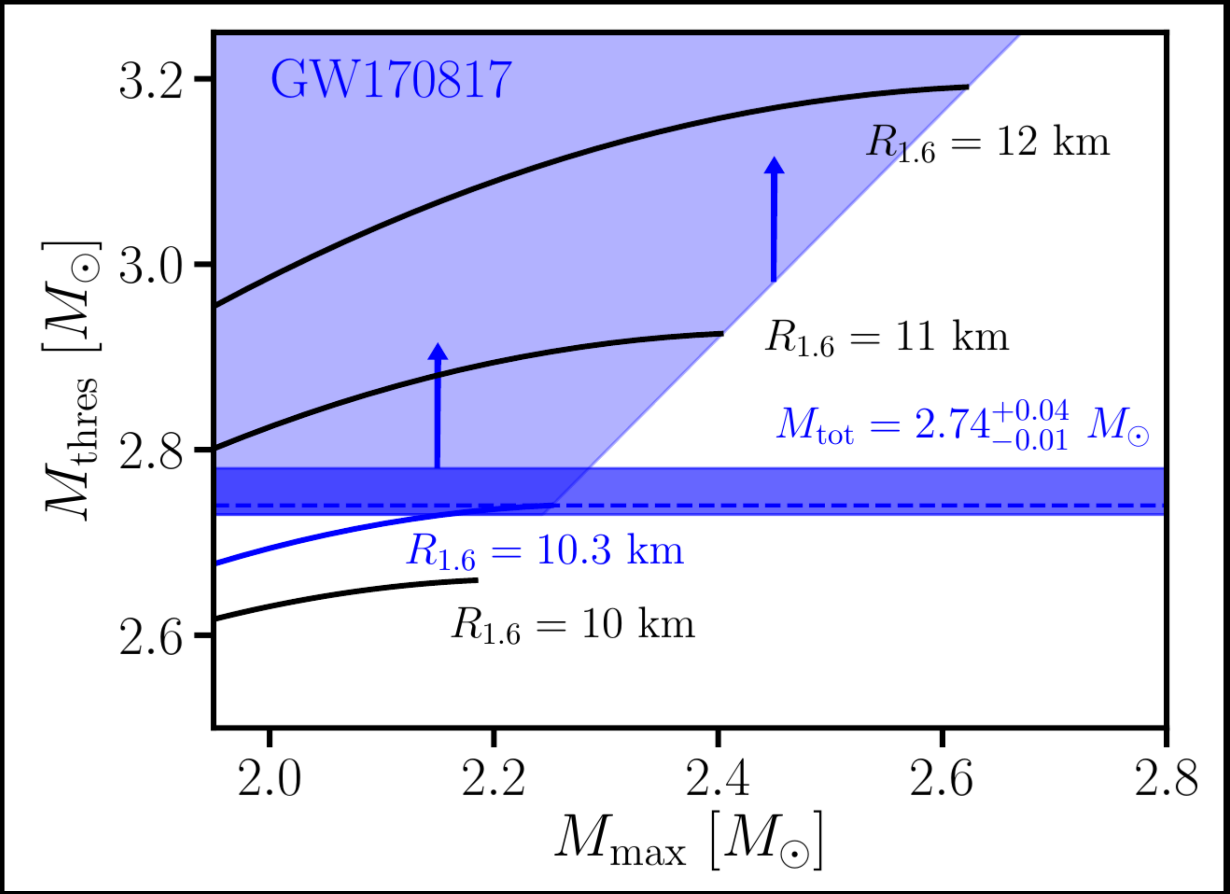


- Extend a large sample of EoS with v_s=c beyond central density of 1.6 Msun NS

$\rightarrow$ $$v_S = \sqrt{\frac{dP}{de}} \leq c \;\rightarrow\; M_{\max} \leq \kappa R_{1.6}$$

Causality limit

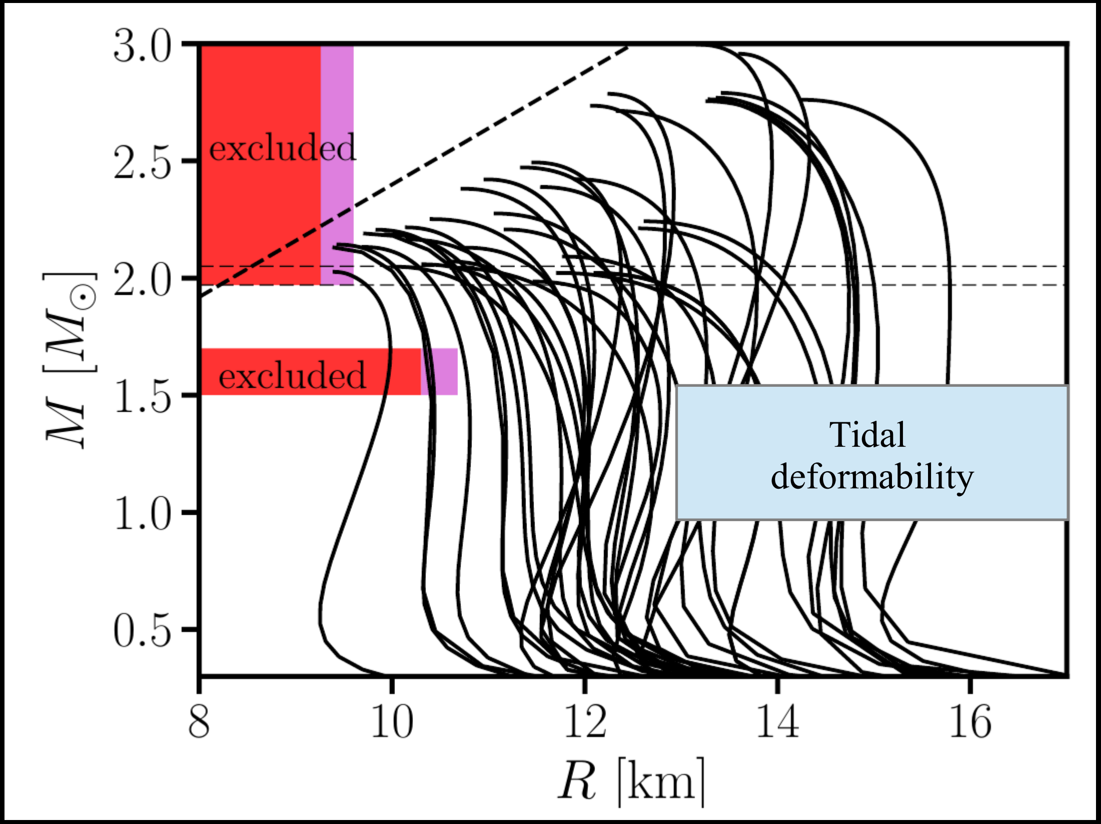




$$M_{\rm thres} = \left(-3.6\frac{G\,M_{\rm max}}{c^2\,R_{1.6}} + 2.38\right)\,M_{\rm max}$$

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

NS radius constraint from GW170817

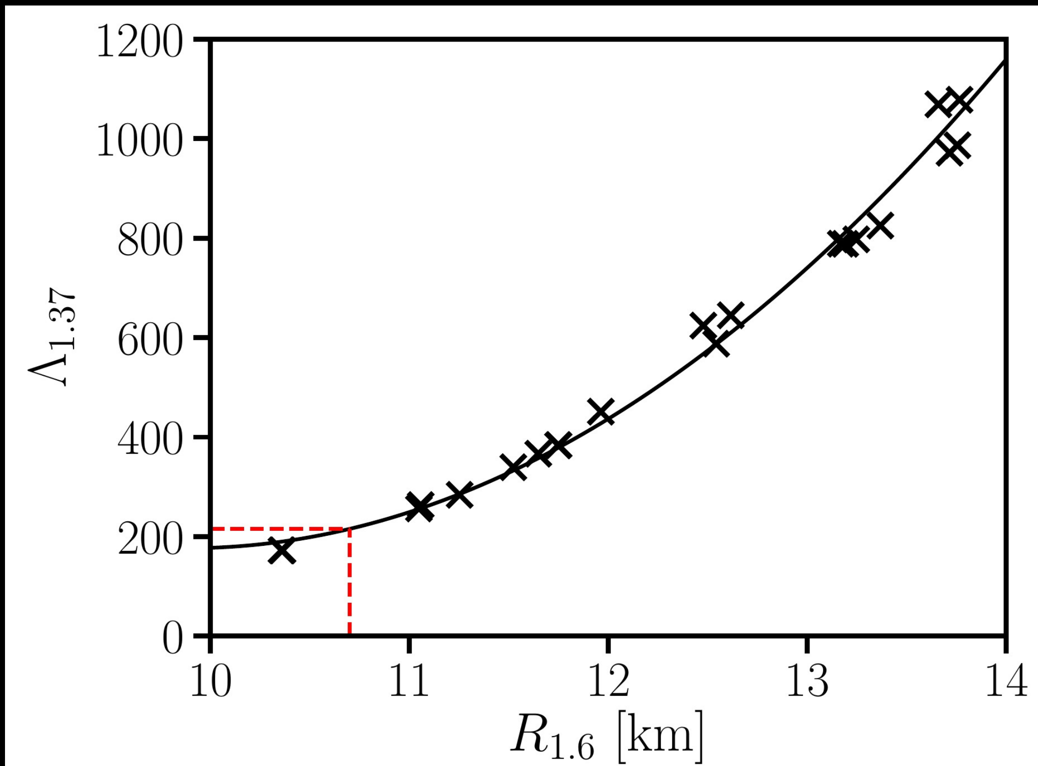


Bauswein et al. 2017

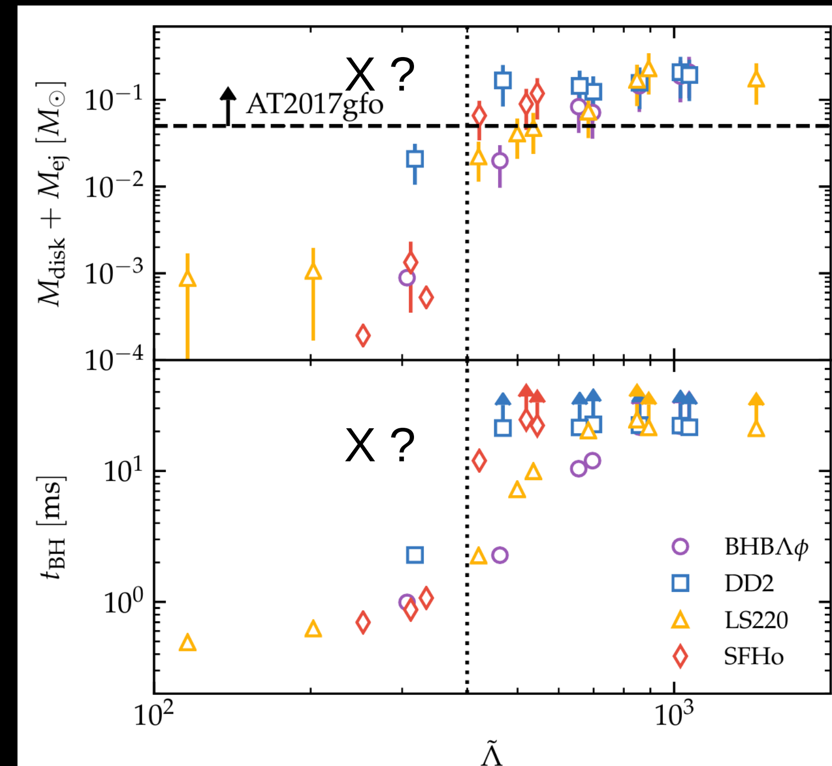
- $R_{1.6}$ > 10.7 km
- Excludes very soft nuclear matter

Radius vs. tidal deformability

Radice et al 2018



Bauswein, unpubl.



- Radius and tidal deformability scale tightly → **Lambda > 210**
- Radice et al. 2018 followed a very similar approach claiming Lambda > 400

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

  → no argument why the fifth EoS shouldn't lie at Lambda<400 → full EoS dependence has to be investigated via Mthres

Discussion - robustness

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

  → testable by refined emission models

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

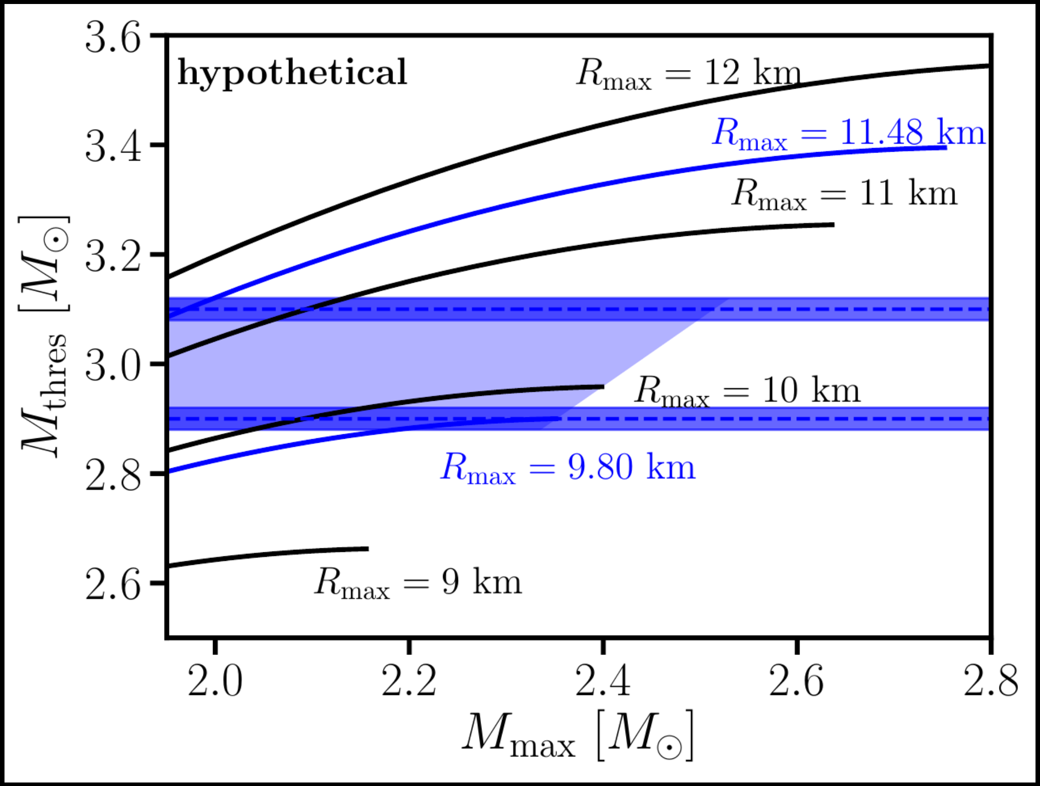
Future

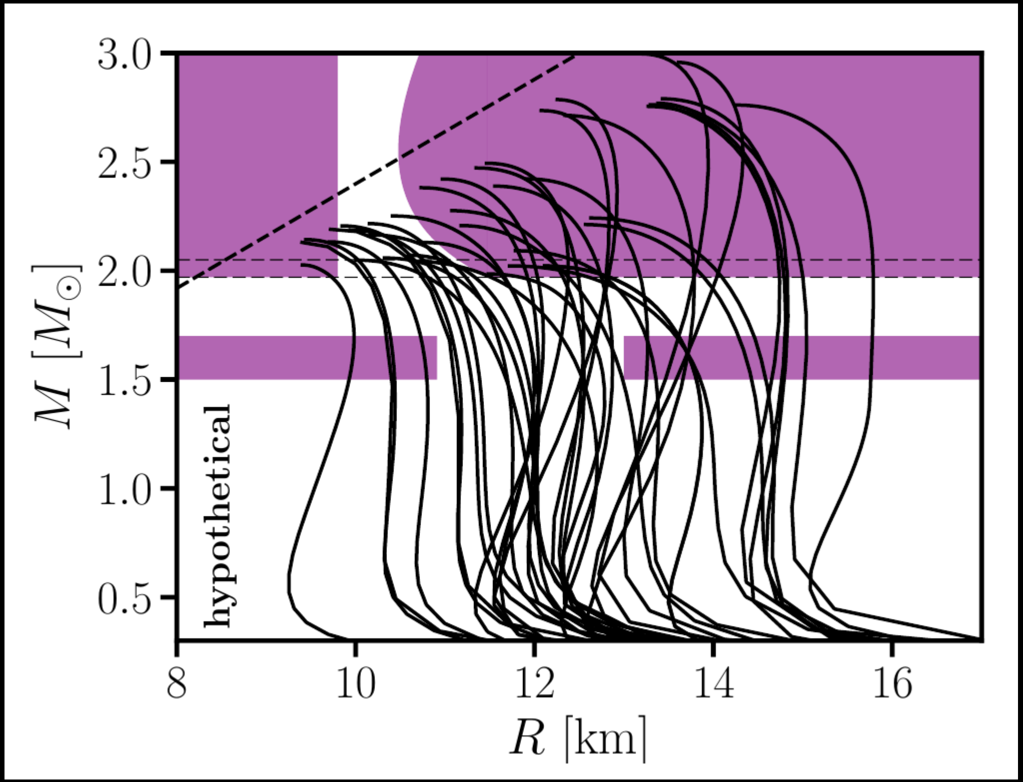
- Any new detection can be employed if it allows distinction between prompt/delayed collapse
- With more events in the future our comprehension of em counterparts will grow → more robust discrimination of prompt/delayed collapse events
- Low-SNR detections sufficient !!! → that's the potential for the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

  → we don't need louder events, but more

  → complimentary to existing ideas for EoS constraints

Future detections (hypothetical discussion)

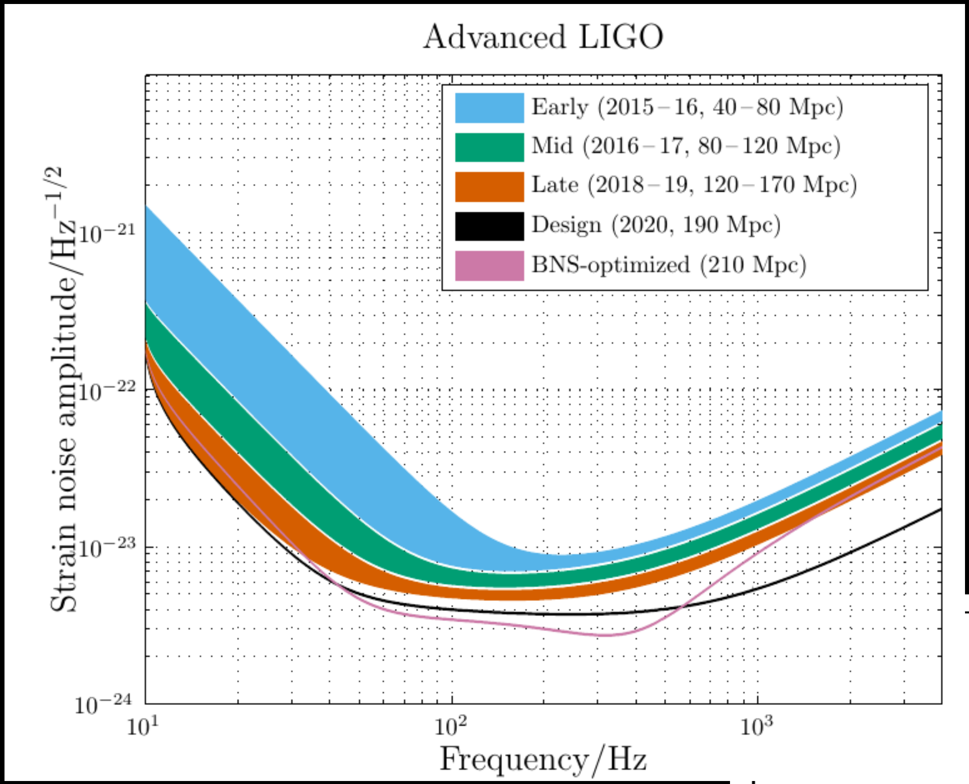




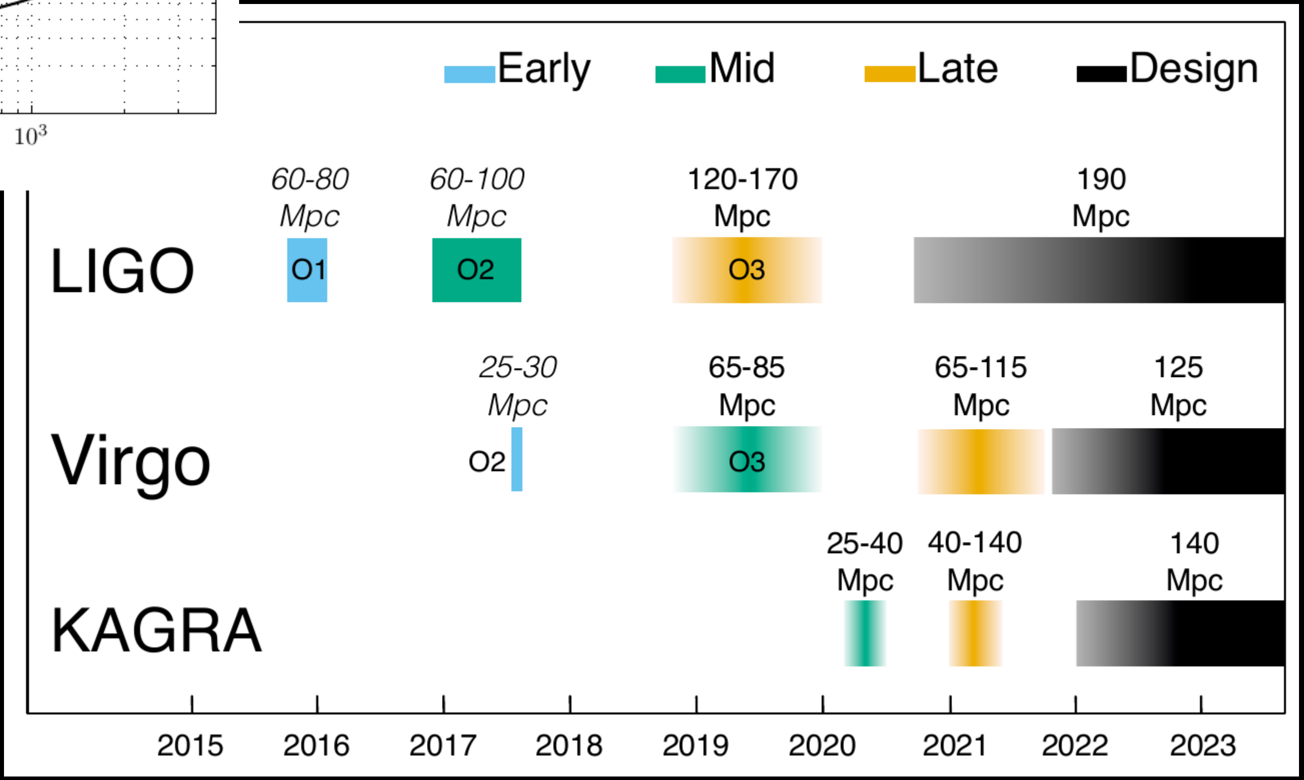
→ as more events are observed, bands converge to true M_{thres}
→ prompt collapse constrains M_{max} from above

Bauswein et al. 2017

Future plans

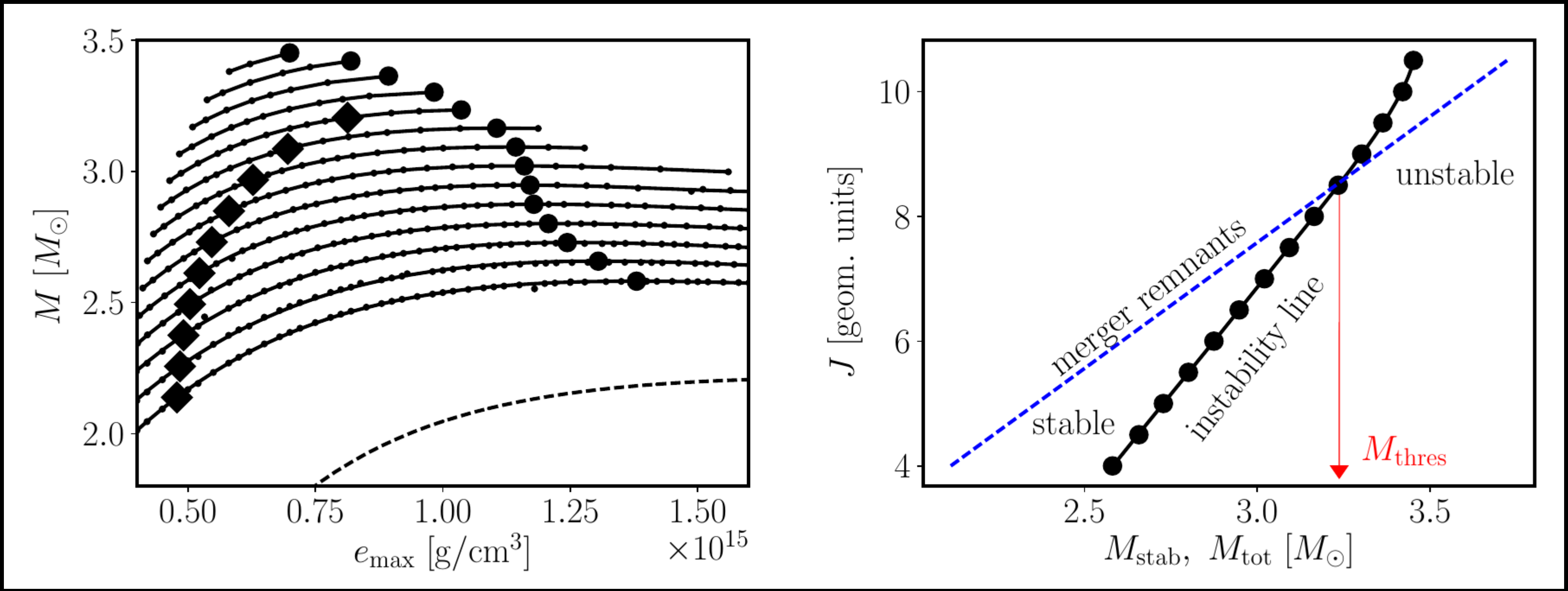


Abbott et al. 2017



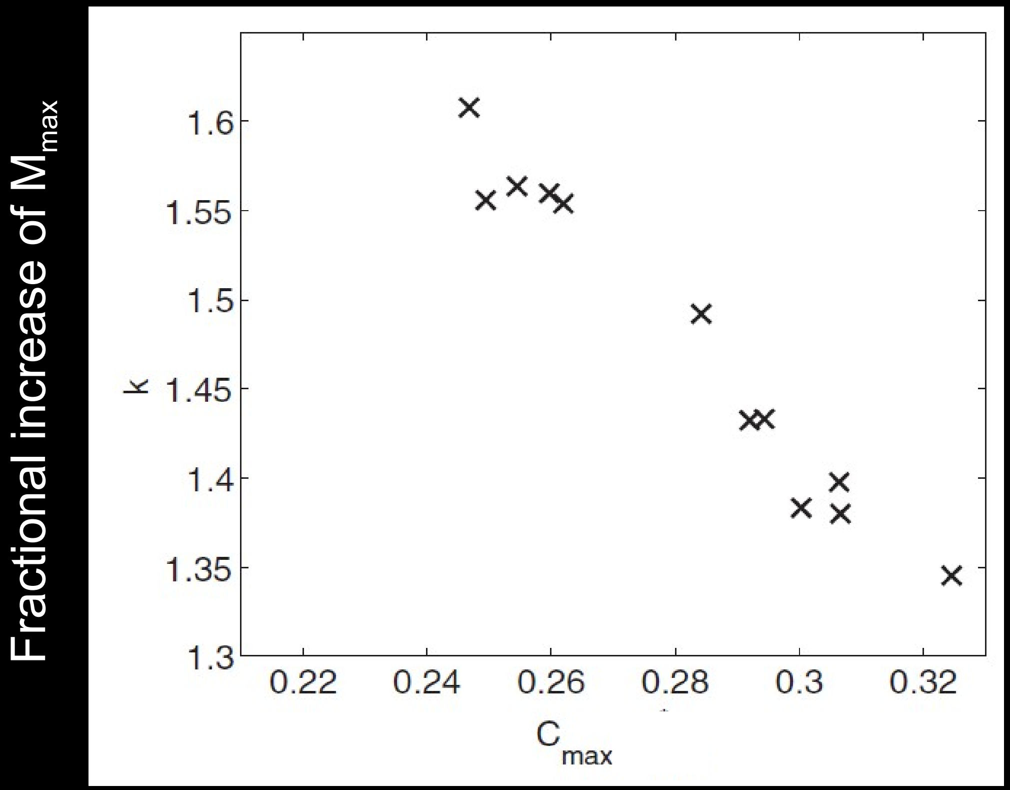
Semi-analytic model: details

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

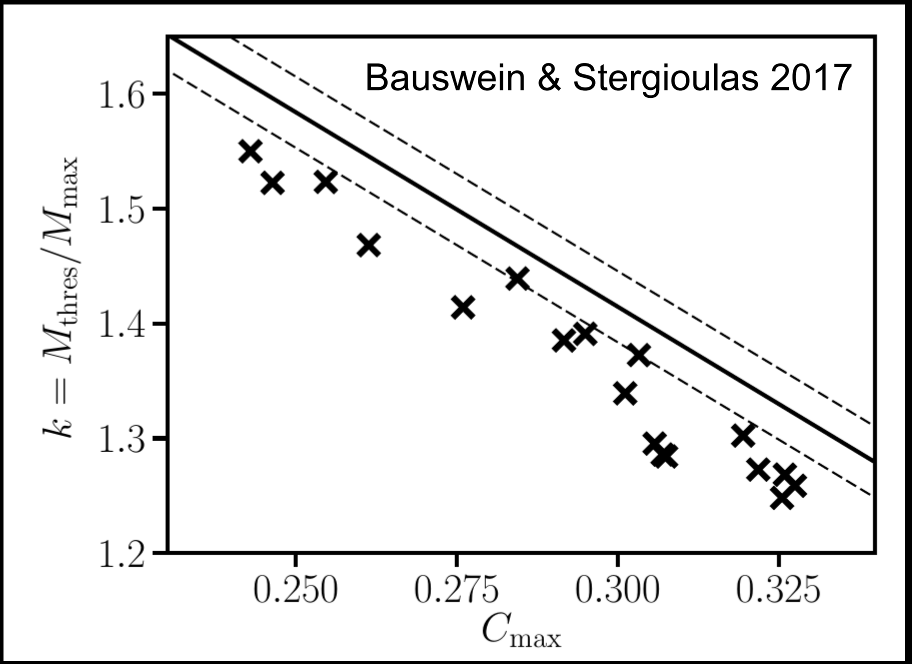


Bauswein & Stergioulas 2017

Semi-analytic model reproducing collapse behavior



Bauswein et al 2013: numerical determination of collapse threshold through hydrodynamical simulations



Solid line fit to numerical data

Crosses stellar equilibrium models:

- prescribed (simplistic) diff. rotation
- many EoSs at T=0
- detailed angular momentum budget !

=> equilibrium models qualitatively reproduce collapse behavior

- even quantitatively good considering the adopted approximations

Future: Maximum mass

- Empirical relation

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

- Sooner or later we'll know $R_{1.6}$ (e.g. from postmerger) and M_{thres} (from several events – through presense/absence of postmerger GW emission or em counterpart)

  => direct inversion to get precise estimate of M_{max}

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

Postmerger GW emission*

(dominant frequency of postmerger phase)

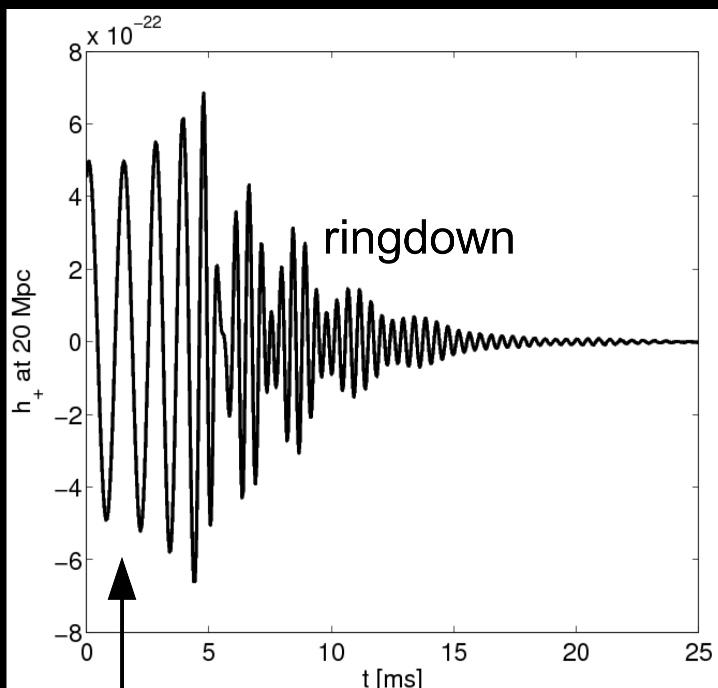
→ determine properties of EoS/NSs

→ postmerger GW spectrum reveals dynamics

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

Postmerger

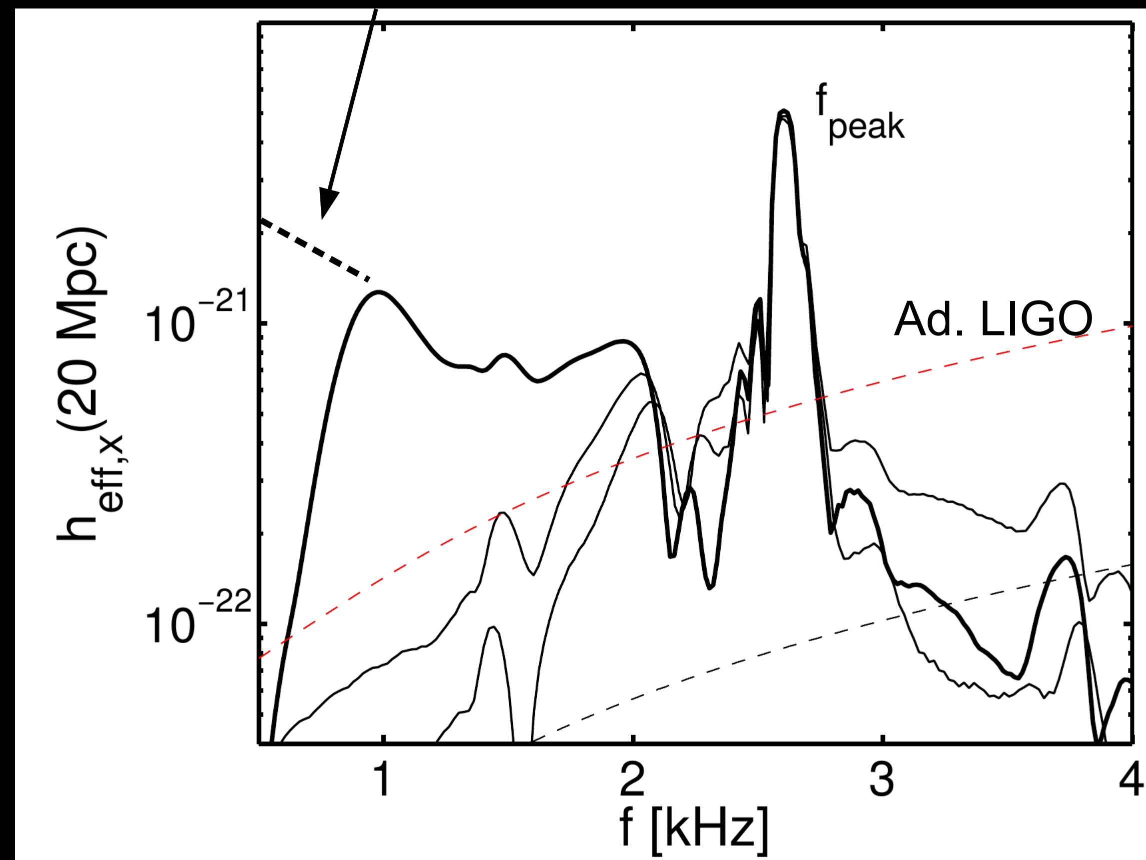
1.35-1.35 M_{sun} , 20 Mpc



inspiral

Earlier inspiral

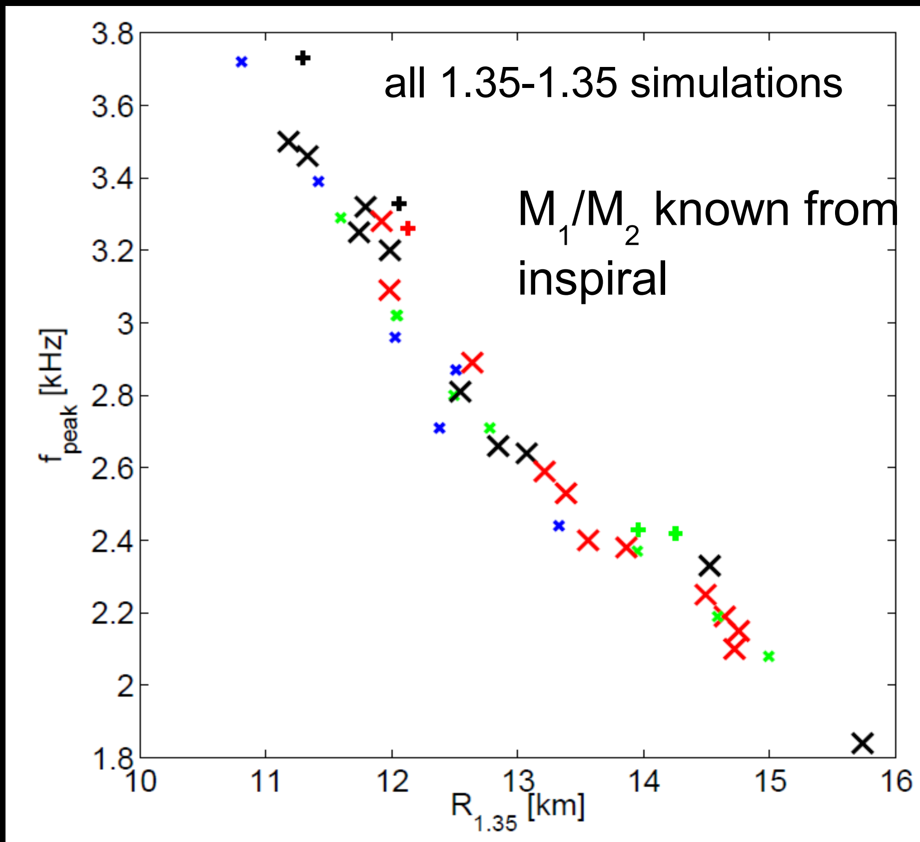
EoS

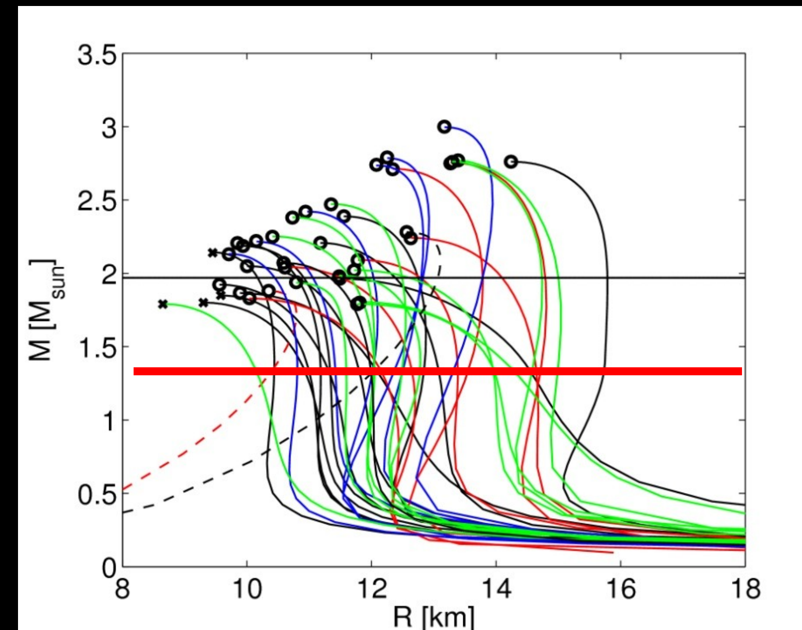


Dominant postmerger oscillation frequency f_{peak}

Very characteristic (robust feature in all models)

Gravitational waves – EoS survey





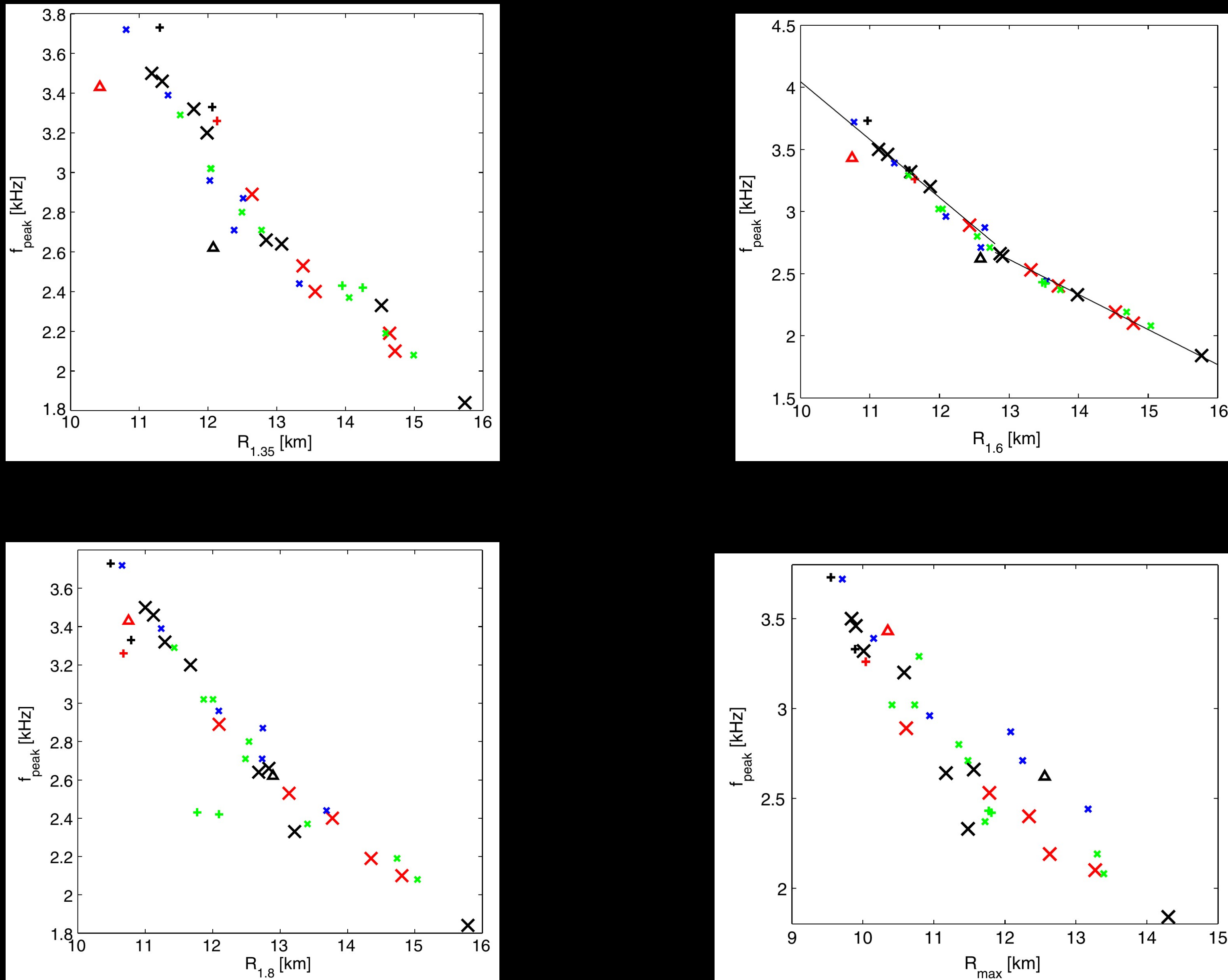
characterize EoS by radius of nonrotating NS with 1.35 M_{sun}

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

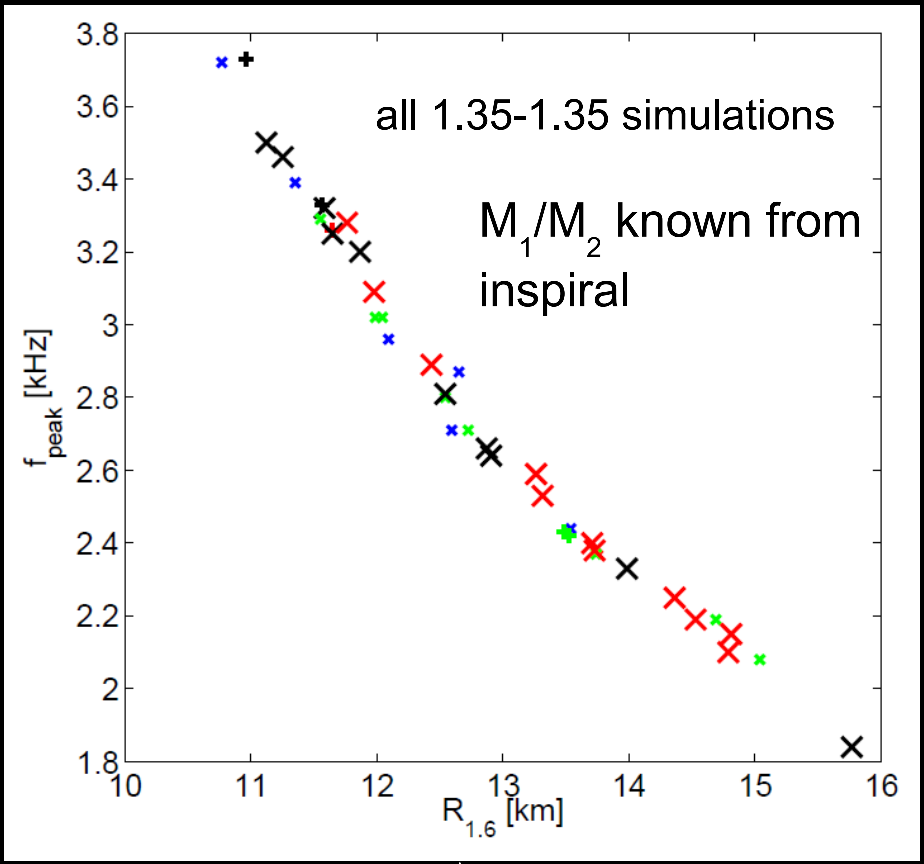


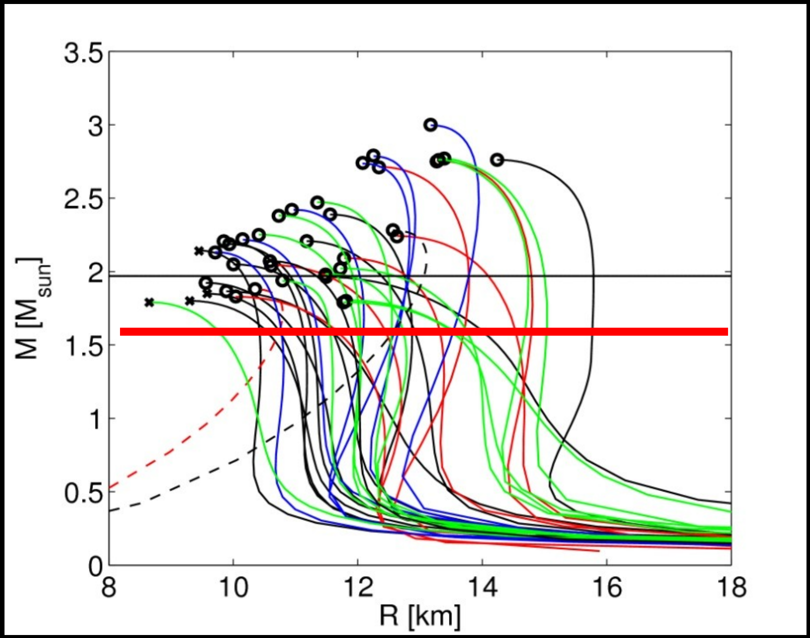
Bauswein et al. 2012

Assess quality of empirical relation relation – only infinity norm meaningful !!!

→ as many EoS models as possible !!!

Gravitational waves – EoS survey





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

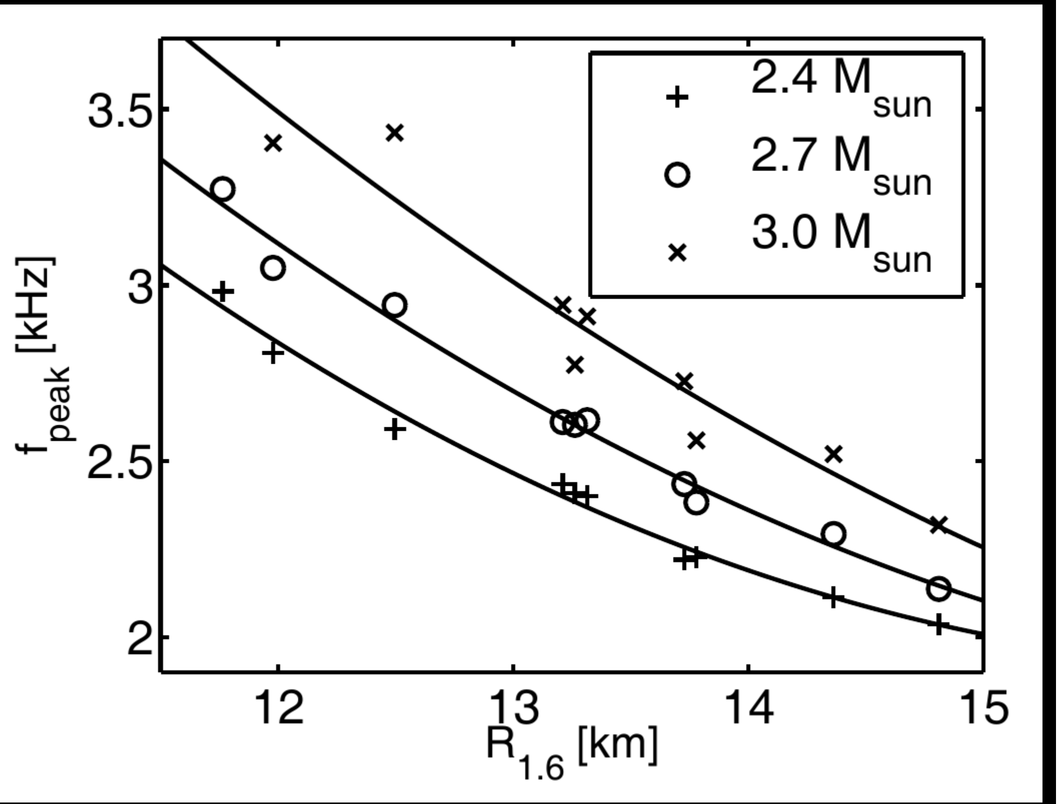
Bauswein et al. 2012

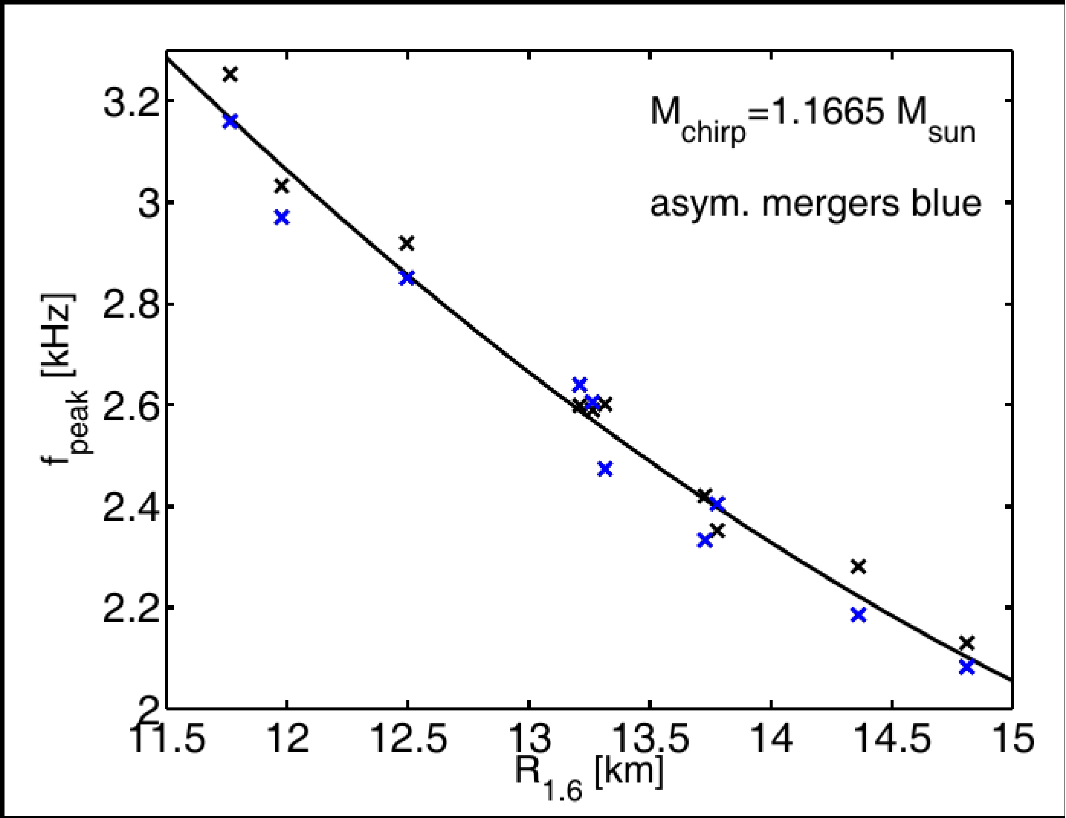
Pure TOV/EoS property => Radius measurement via f_{peak}

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)

Binary mass variations





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

→ f_{peak} precisely measurable !!!

Bauswein et al. 2012, 2016

Strategy for radius measurements

- Measure binary masses from inspiral
- Construct f_{peak} – R relation for this fixed binary masses and (optimally) chosen R
- Measure f_{peak} from postmerger GW signal
- Obtain radius by inverting f_{peak} – R relation
- (possibly restrict to fixed mass ratios if mergers with high asymmetry are measured)

- Final error of radius measurement:

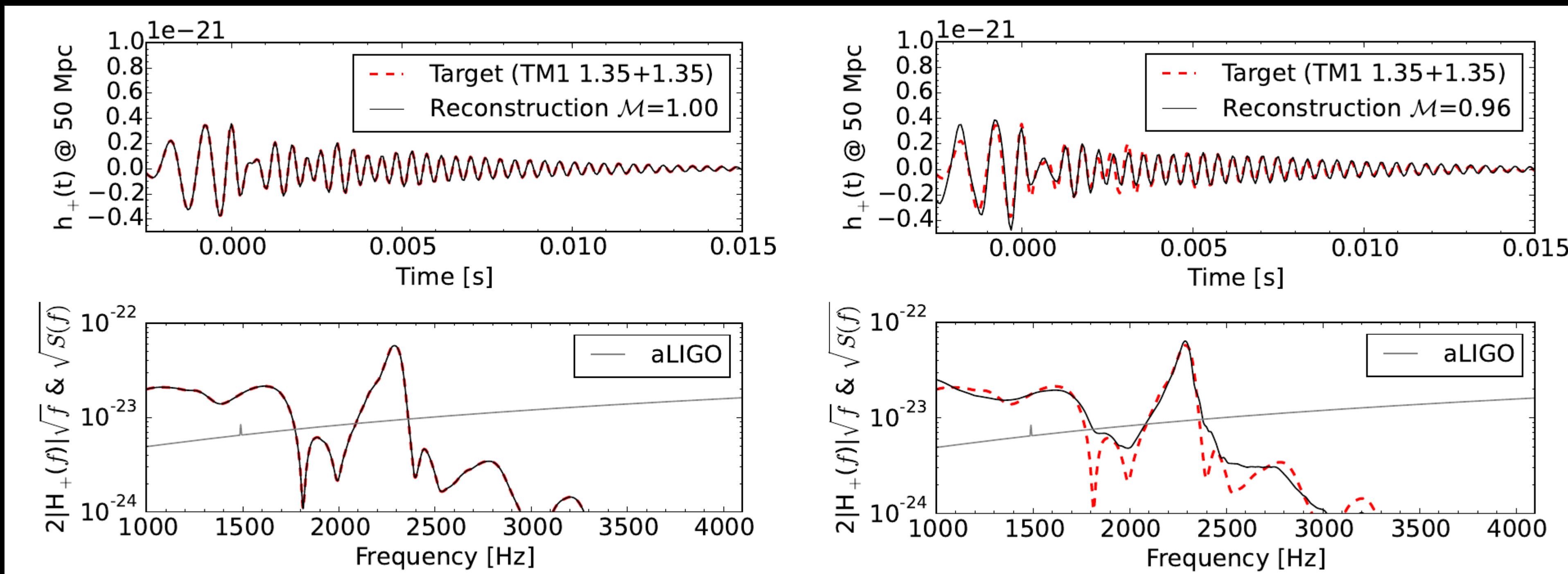
  - accuracy of f_{peak} measurement (see Clark et al. 2014, Clark et al. 2016)

  - maximum scatter in f-R relation (important to consider very large sample of EoSs)

  - systematic error in f-R relation

Data analysis

- Principal Component analysis



Excluding recovered waveform from catalogue

Clark et al. 2016, see also Clark et al 2014, Chatziioannou et al 2017, Bose et al. 2018

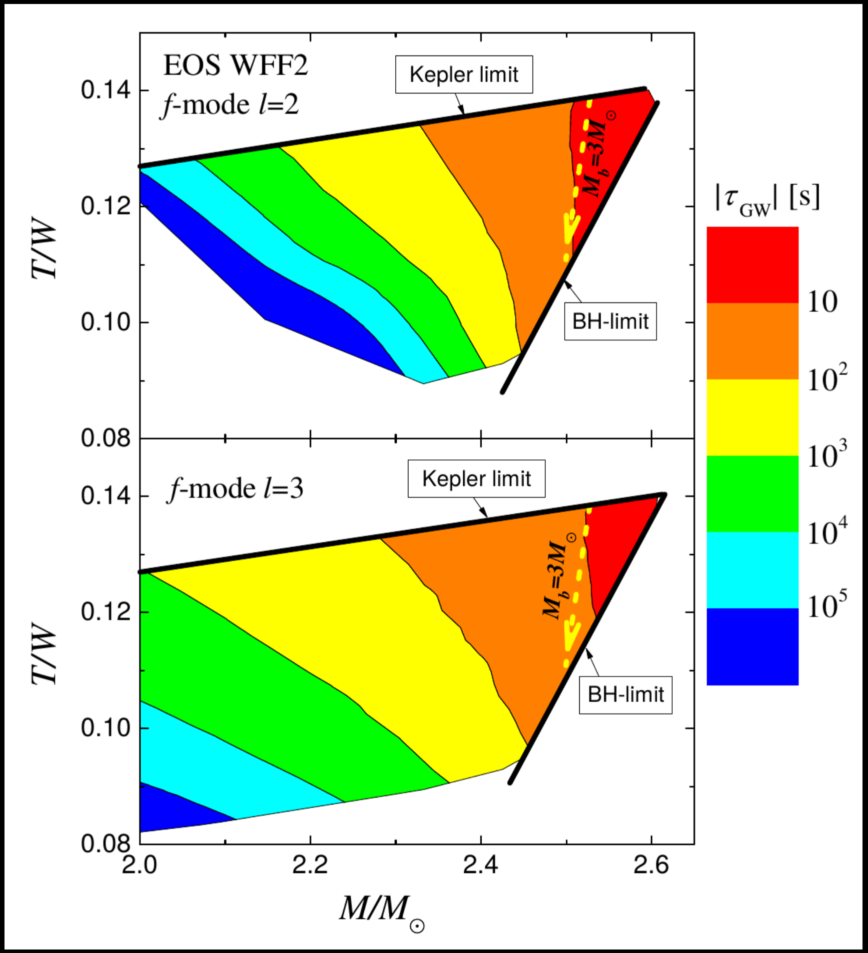
Instrument	$\mathrm{SNR}_{\mathrm{full}}$	D_{hor} [Mpc]	$\dot{N}_{\mathrm{det}}$ [year^{-1}]
aLIGO	$2.99^{3.86}_{2.37}$	$29.89^{38.57}_{23.76}$	$0.01^{0.03}_{0.01}$
A+	$7.89^{10.16}_{6.25}$	$78.89^{101.67}_{62.52}$	$0.13^{0.20}_{0.10}$
LV	$14.06^{18.13}_{11.16}$	$140.56^{181.29}_{111.60}$	$0.41^{0.88}_{0.21}$
ET-D	$26.65^{34.28}_{20.81}$	$266.52^{342.80}_{208.06}$	$2.81^{5.98}_{1.33}$
CE	$41.50^{53.52}_{32.99}$	$414.62^{535.221}_{329.88}$	$10.59^{22.78}_{5.33}$

Outdated!!!

→ possible at Ad. LIGO's design sensitivity !

Secular instability

- F-modes become secular unstable (CFS)
- Linear perturbation → saturation?
- Growth time scale may be sufficiently short to affect long-term remnant evolution



Doneva et al. 2015

Conclusions

- NS radius must be larger than 10.7 km (very robust)
- 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}
- Different mechanisms generate subdominant GW peaks
- Classification scheme of postmerger GW spectra based on presence/strength of secondary peaks (physically motivated)
- Secondary features reveal dynamics of postmerger remnant