Supported by ERC through Starting Grant no. 759253

European Research Council
Established by the European Commission

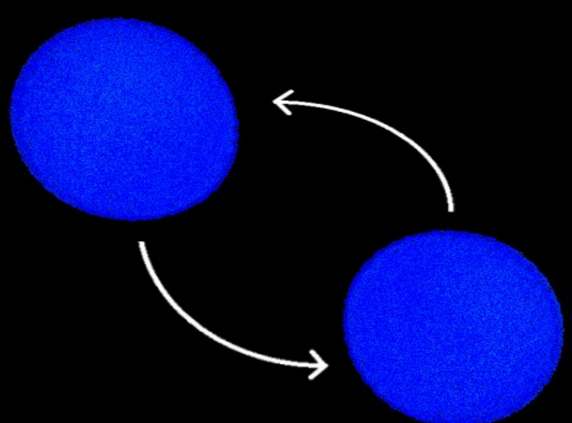
Mass Ejection from Neutron Star Mergers

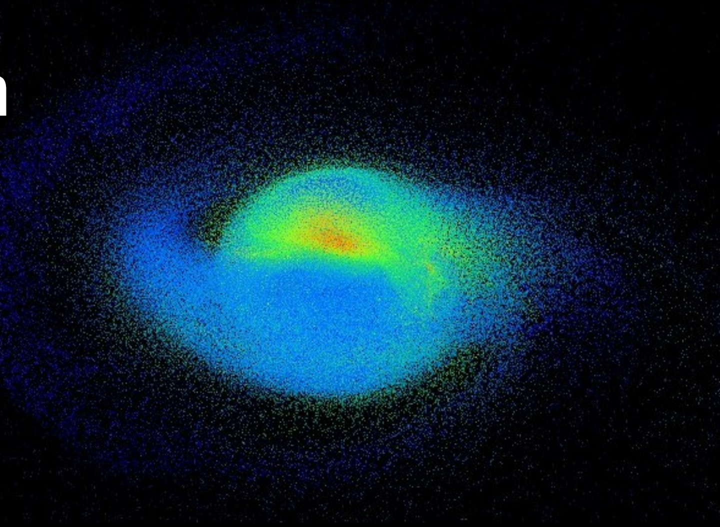
Nuclear and astrophysics aspects for the rapid neutron-capture process in the era of multimessenger observations

ECT*, Trento, 04/07/2019

Andreas Bauswein

(GSI Darmstadt)





Outline

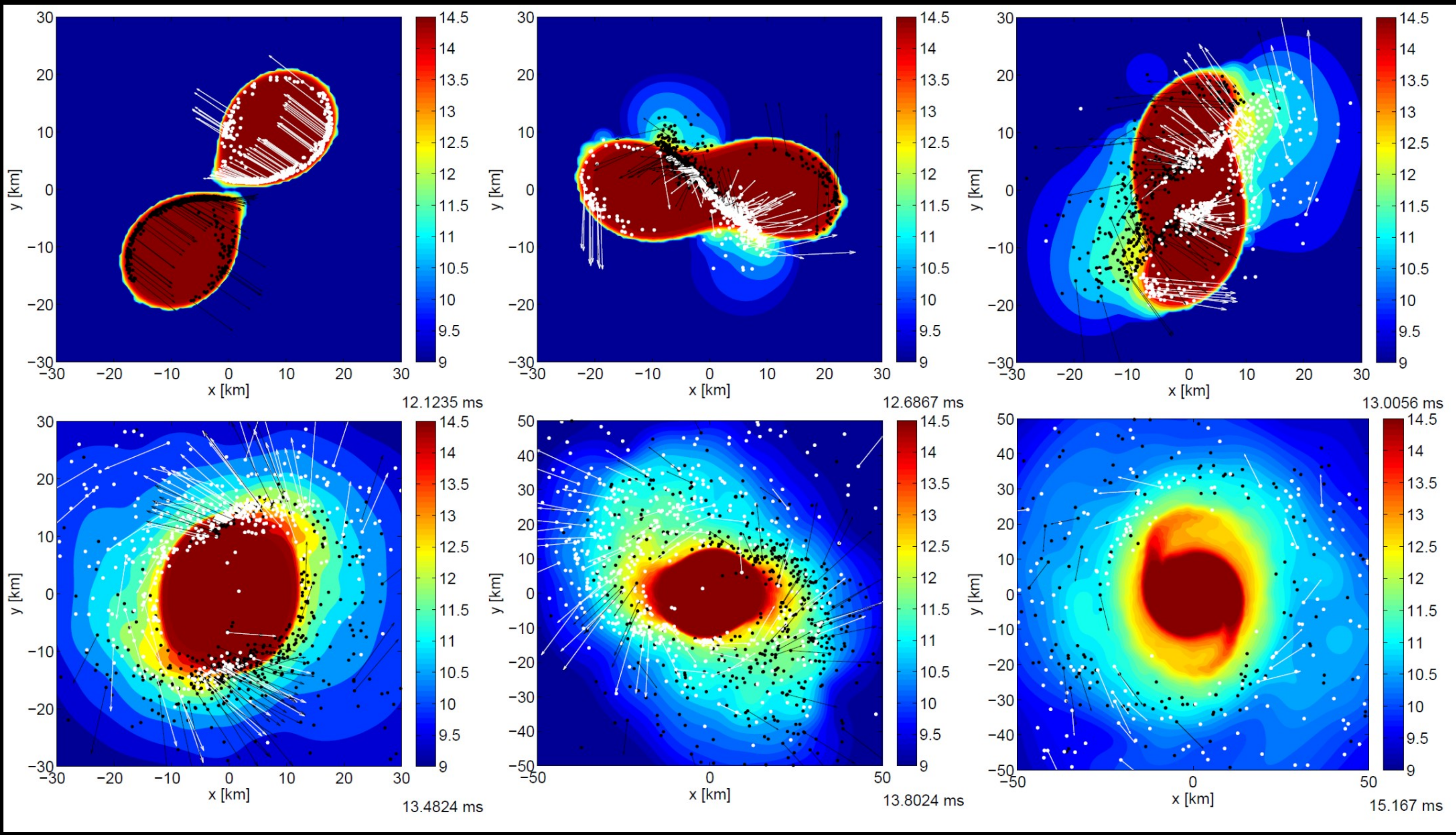
- Simulations and ejecta masses – dependence on EoS and binary parameter (focus on dynamical ejecta)
- Rate estimates
- Collapse behavior – prompt collapse leads to reduction of mass rejection
- NS radius / EoS constraints from GW170817
- Observing strategy
- Mass ejection with QCD phase transition
- Neutron decay ejecta

Simulation results – dynamical ejecta

(EoS and binary mass dependence)

Simulations

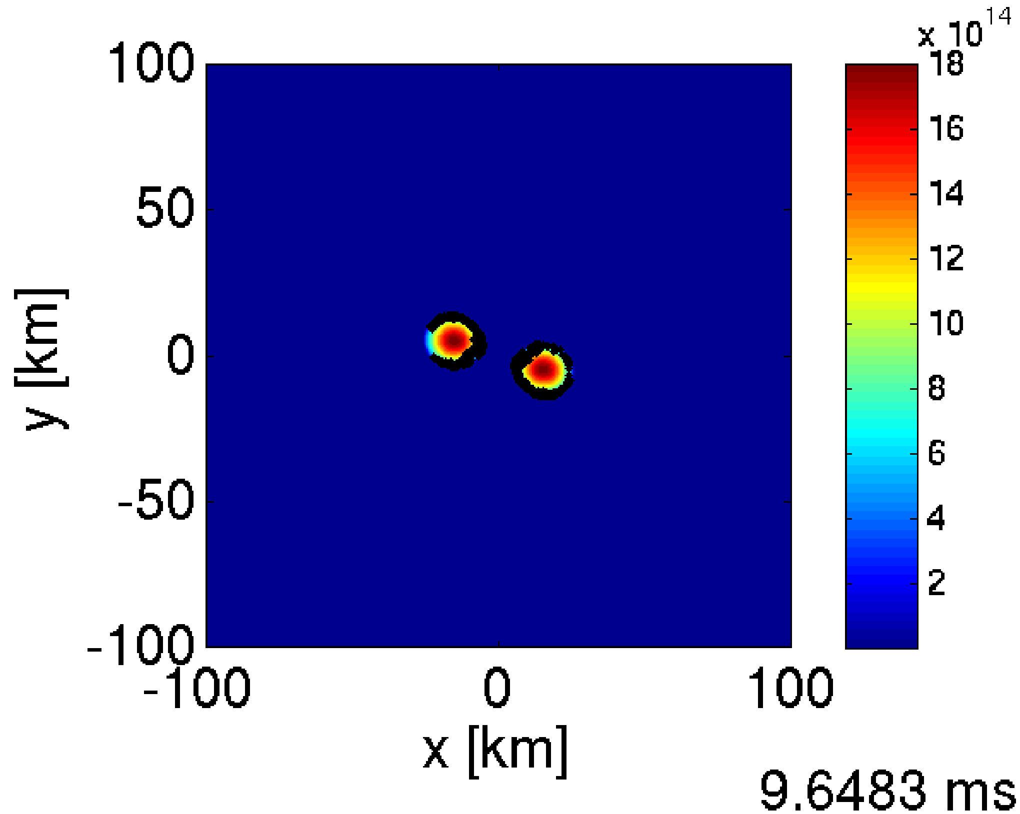
Dots trace ejecta (DD2 EoS 1.35-1.35 M_{sun})

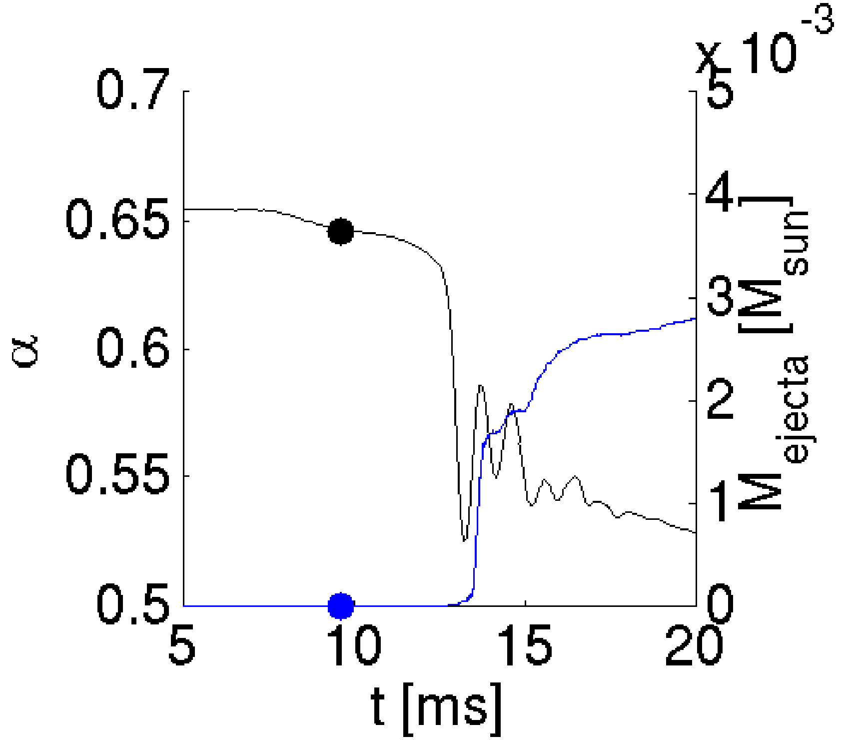


Bauswein et al. 2013

Black: bound but eventually unbound; white: unbound (formally)

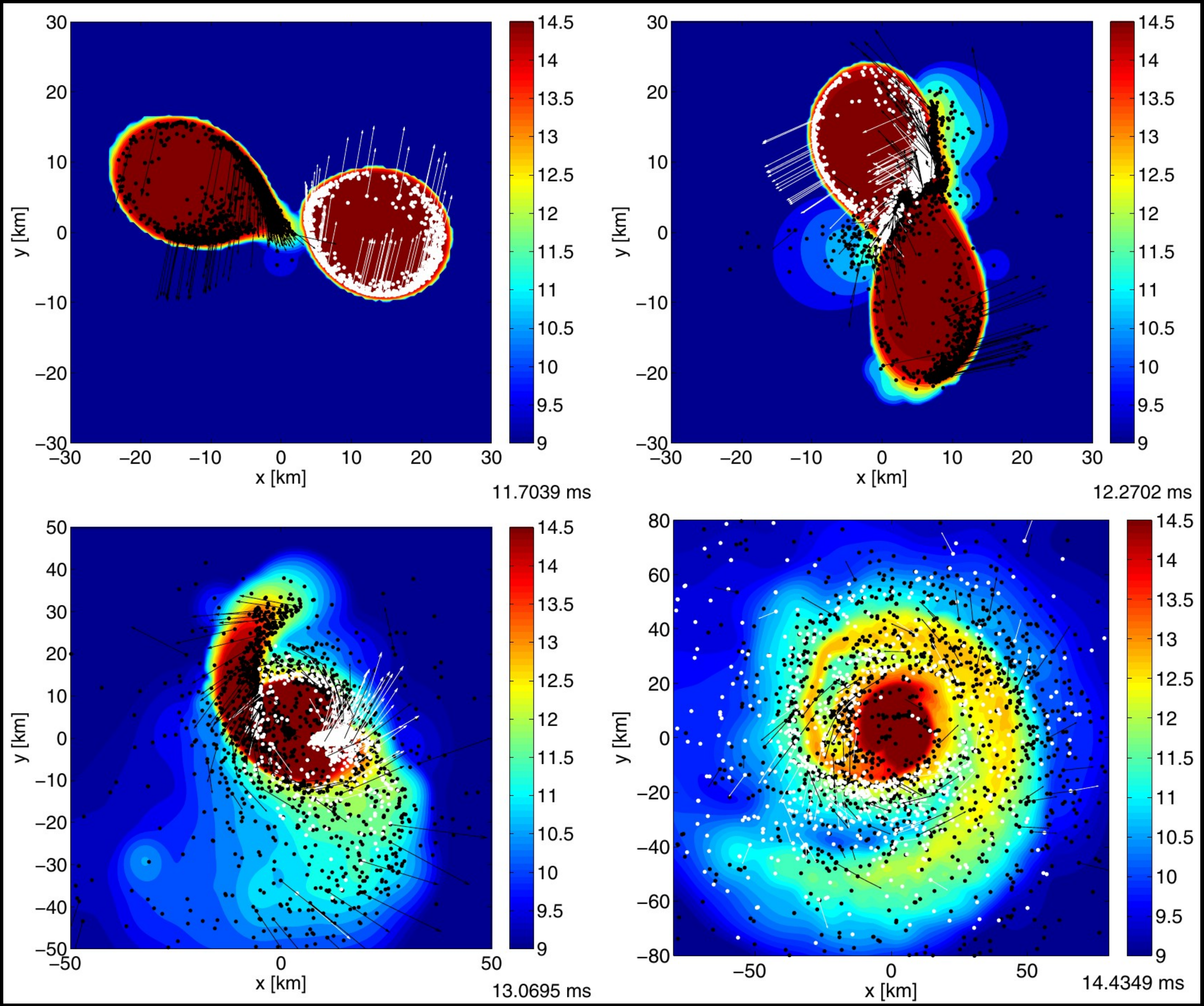
Central lapse: measure for compactness





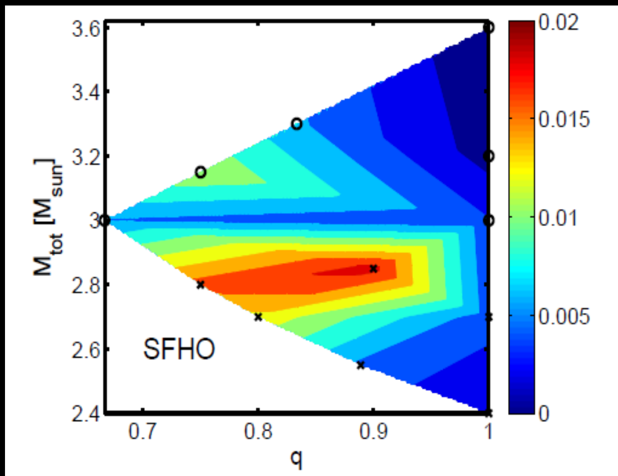
Fair fraction ejecta gets unbound during the first rebounce/expansion of remnant

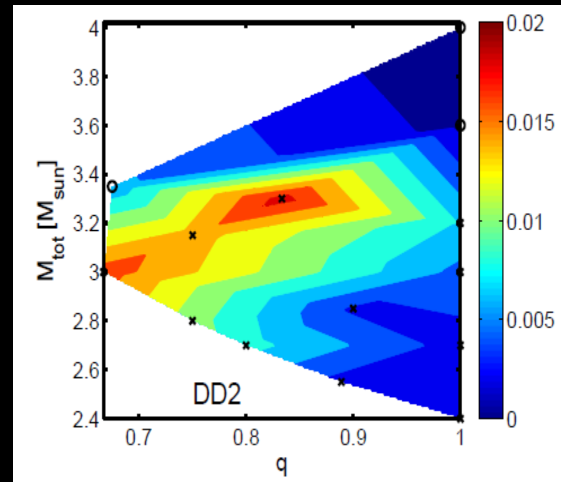
Asymmetric mergers: 1.2-1.5 M_{sun}

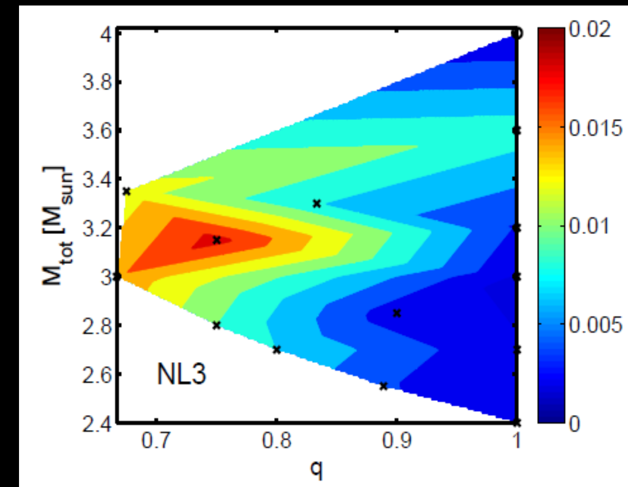


→ larger tidal component, larger total ejecta masses

Ejecta mass dependencies: binary para.

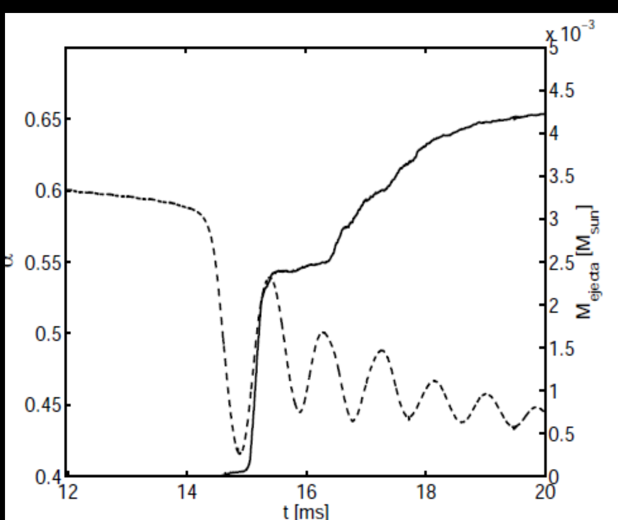


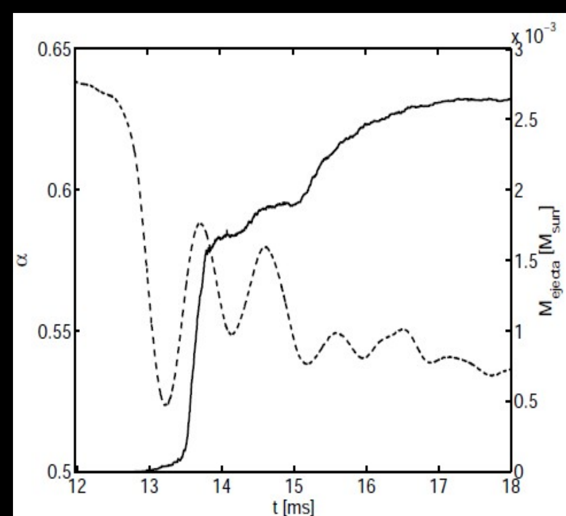


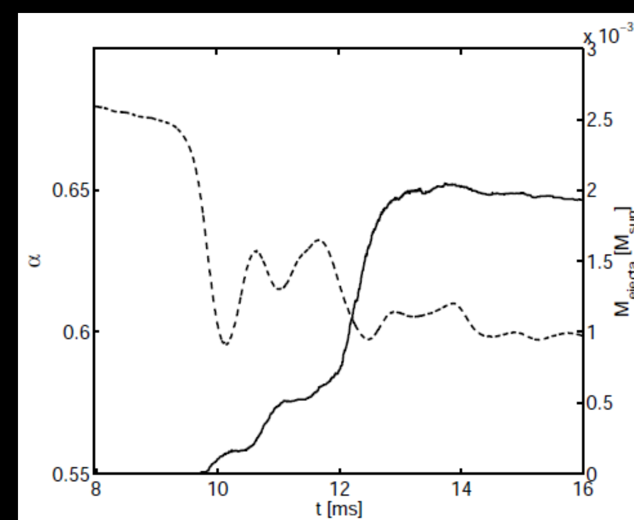


Stiffness

understandable by different dynamics / impact velocity / postmerger oscillations

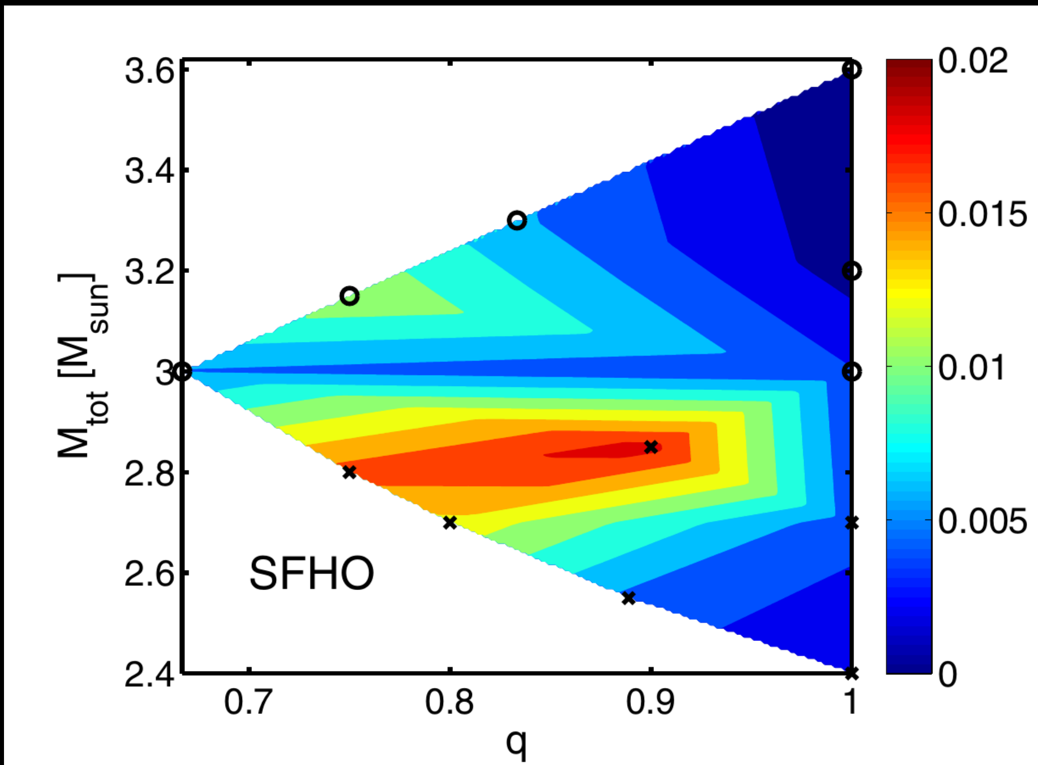


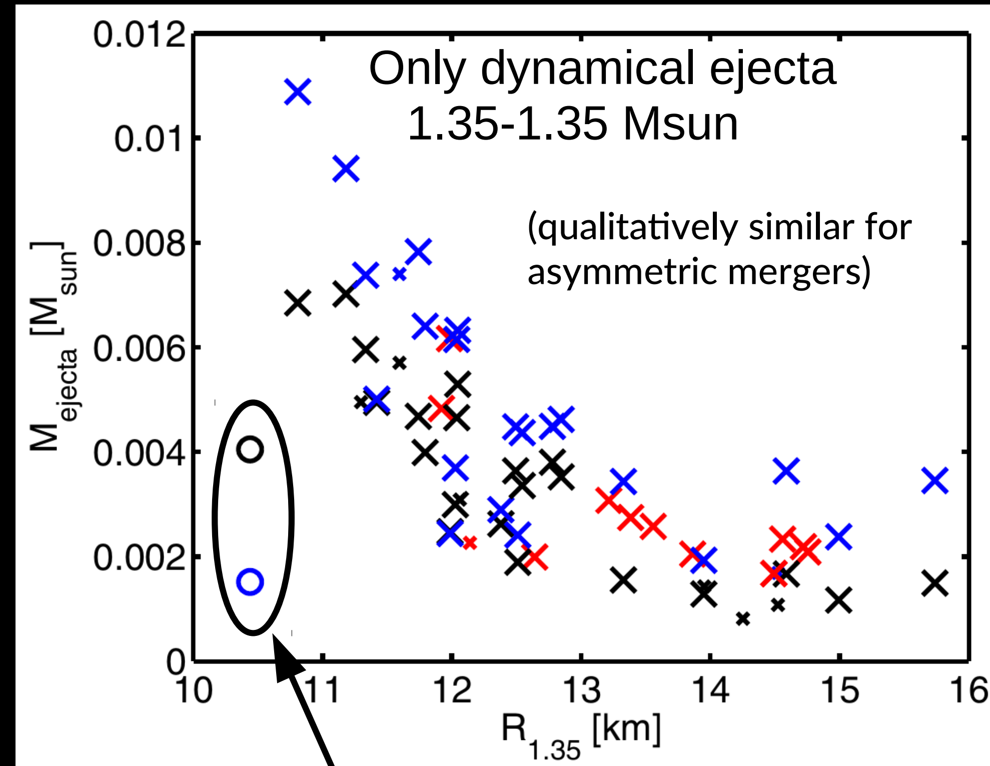




Central lapse α traces remnant compactness / oscillations / dynamics (dashed lines)

Ejecta dependencies



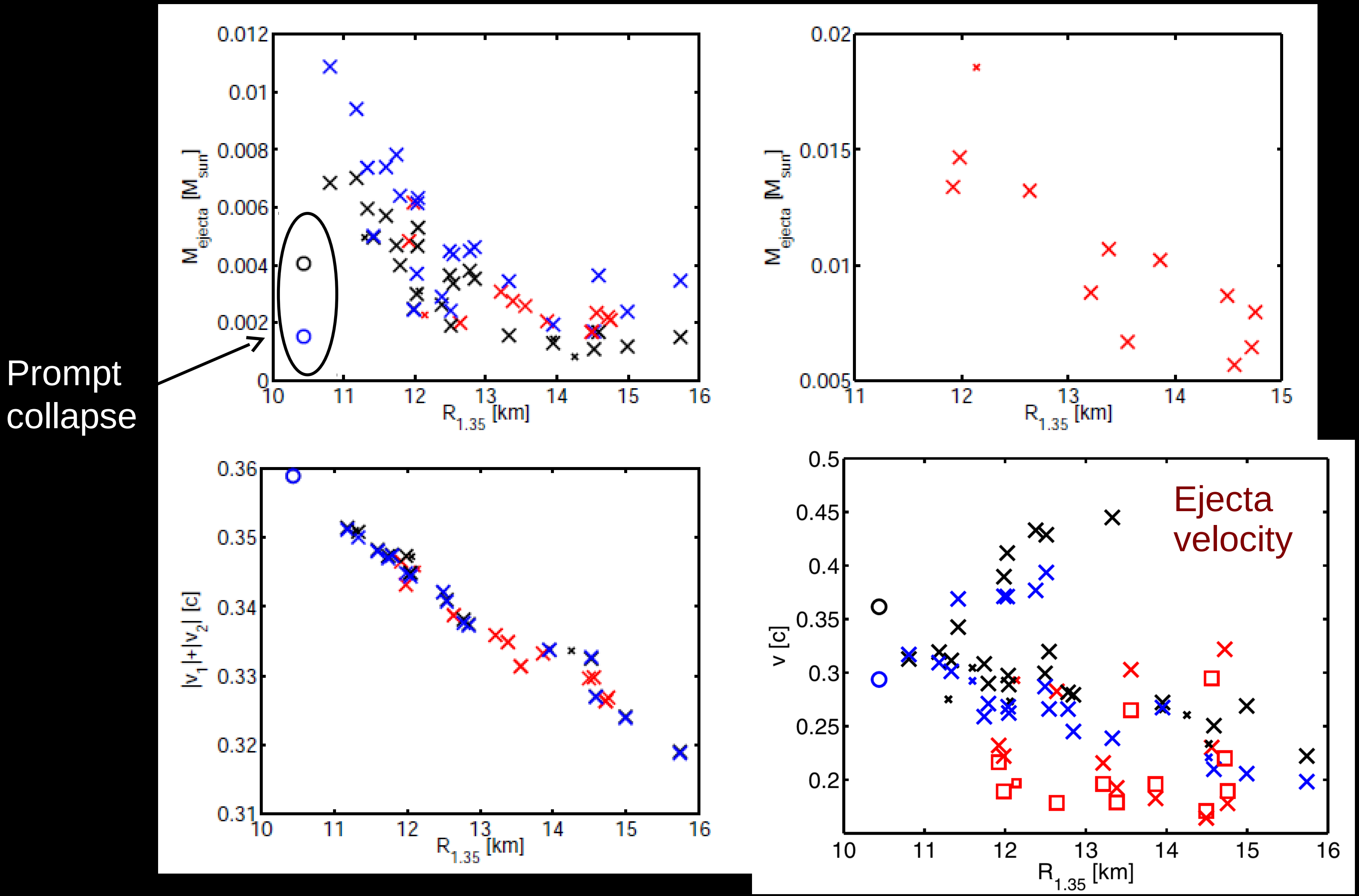


Prompt collapse

Bauswein et al 2013, see also Hotokezaka et al 2013, Rosswog et al 2013, Sekiguchi et al 2015, Palenzuela et al 2015, Radice et al. 2016, Foucart et al. 2016, Dietrich et al. 2017, Bovard et al. 2017, ...

- Note 1: do not take numbers literally; generally okayish agreement between different codes / numerical methods / physical models; uncertainties of at least several 10 %
- Note 2: significant amounts of ejecta from postmerger evolution (NS-torus or BH-torus)
- Note 3: generally robust r-process in dynamical and secularmerger ejecta

Ejecta mass dependence



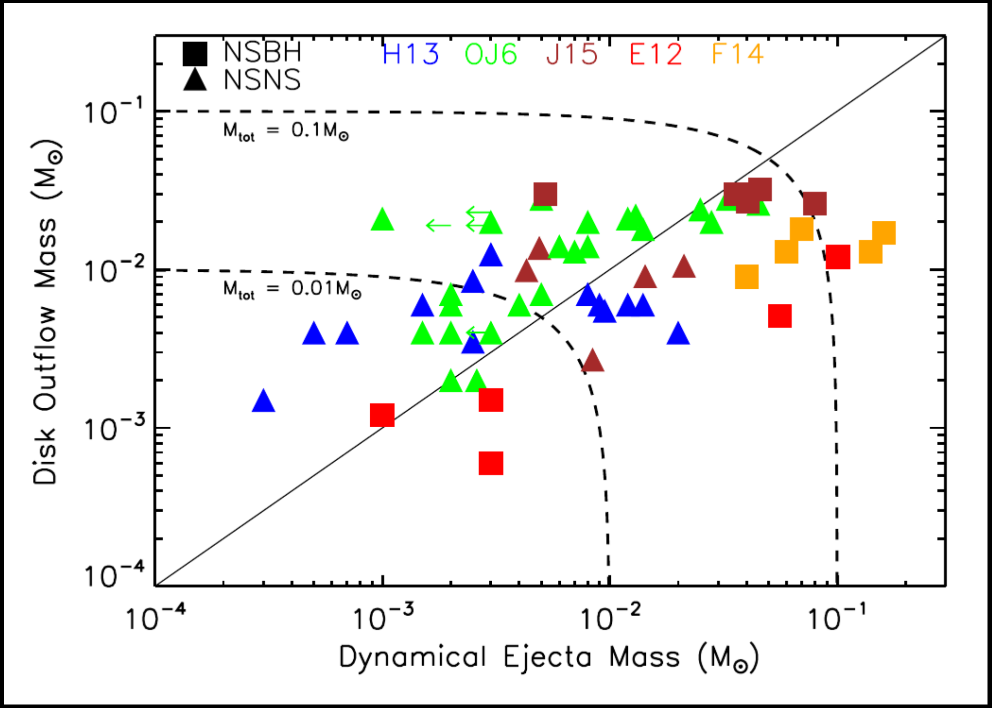
Different EoSs characterized by radii of 1.35 M_{sun} NSs (note importannce of thermal effects)

- Postmerger simulations show: 10-40% of remnant disk get unbound (somewhat slower, possibly more neutron-rich); see e.g. talk by O. Just
- Ejecta mass 0.03-0.05 Msun in GW170817

  → compatible with simulations (also other properties)
- Excludes tentatively very stiff EoSs, excludes tentatively very soft EoSs – prompt collapse !!!

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



Compilation Wu et al 2016: dynamical and secular ejecta comparable

Consistency - simple estimate

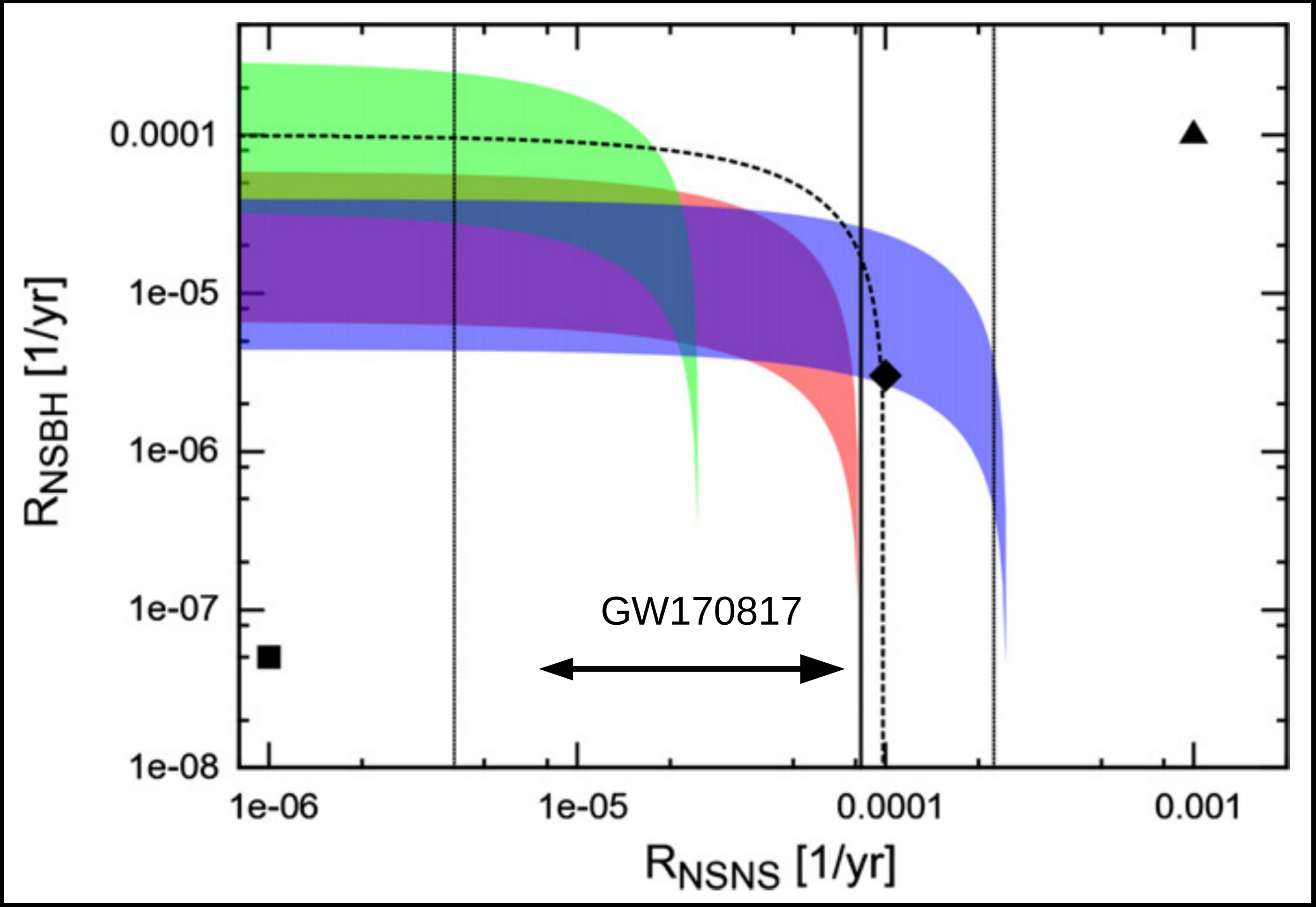
- In GW170817 a few 0.01 M_{sun} of ejecta
- Composition not known
- Red/blue component, but not know what was dynamical/secular ejecta
- Simple estimate (no GCE, many uncertainties) for nuclei with A > 140:

$$M_{A>140,\,Galaxy} = \left(\bar{M}_{NSNS} R_{NSNS} + \bar{M}_{NSBH} R_{NSBH}\right) \tau_{Galaxy}$$

- Given the known sensitivity of LIGO and the observing time → low-number statistics rate estimate

Considering only heavy elements with A > 140

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



M_{ej}(NSNS), A>140:

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

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

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

Bauswein et al. 2014, see Rosswog et al. for required rate dependent on minimum A

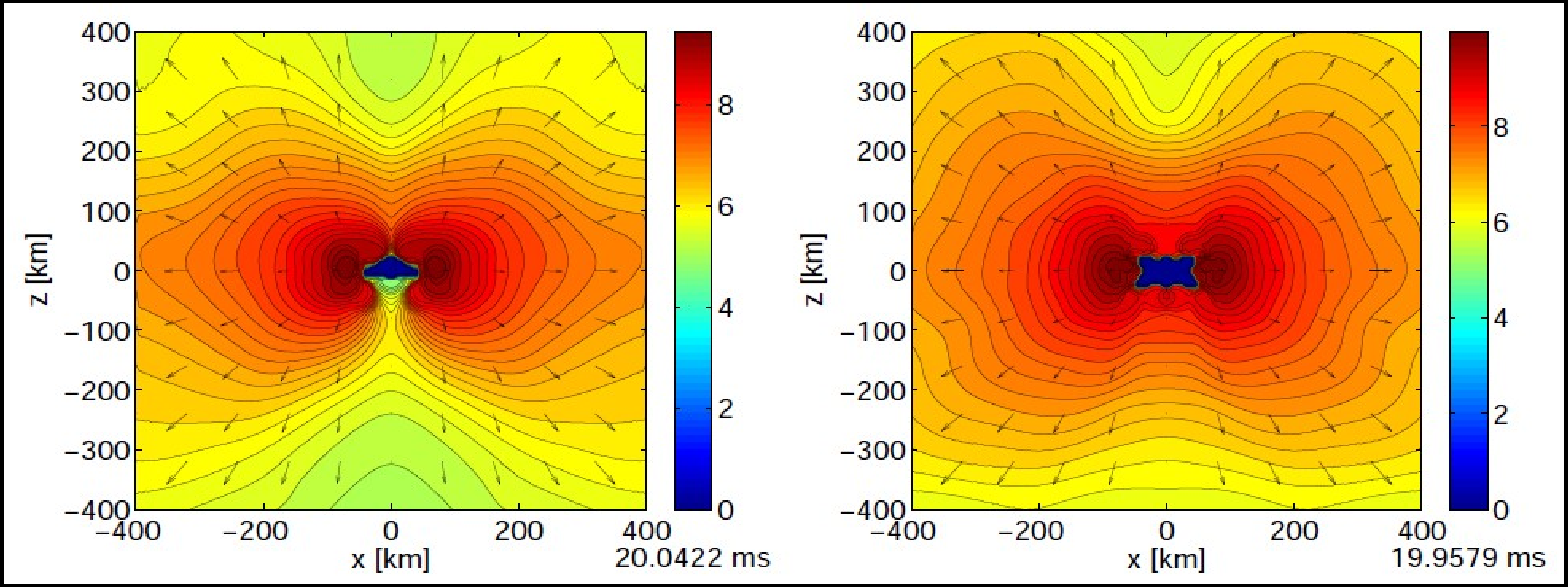
- Colored bands: rates for different EoSs / amount of ejecta with A>140
- Symbols: population synthesis predictions (Abadie et al. 2010)
- Vertical lines: pulsar observations (Kalogera et al. 2004)
- Dashed curve: short GRBs (Berger 2013)
- Arrow: volumetric rate (Abbott et al. 20017) converted to Galactic rate

Ejecta morphology

- Rather isotropic ejection → dynamical ejecta obsurcs secular ejecta → early blue component / dynamical ejecta must have a window → strong neutrino effects such that no heavy r-process elements (high opacity material is produced)?
- Disk ejecta is produced later and with lower velocity

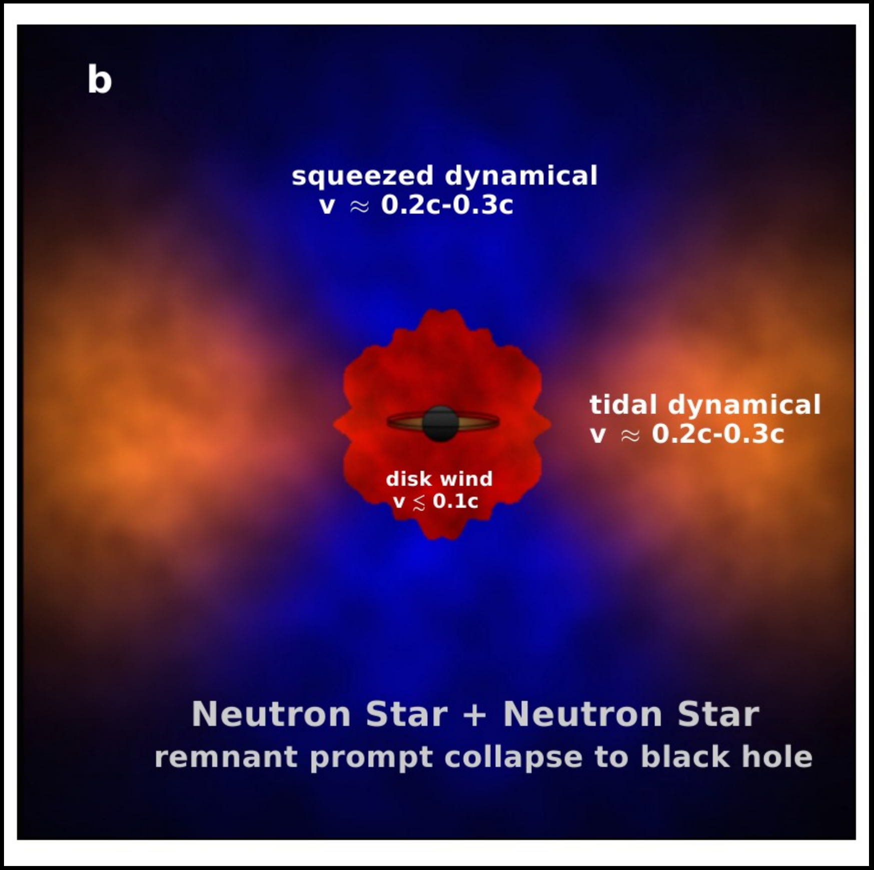
1.35-1.35 Msun

1.2-1.5 Msun



Bauswein et al. 2013, see also Hotokezaka et al 2013

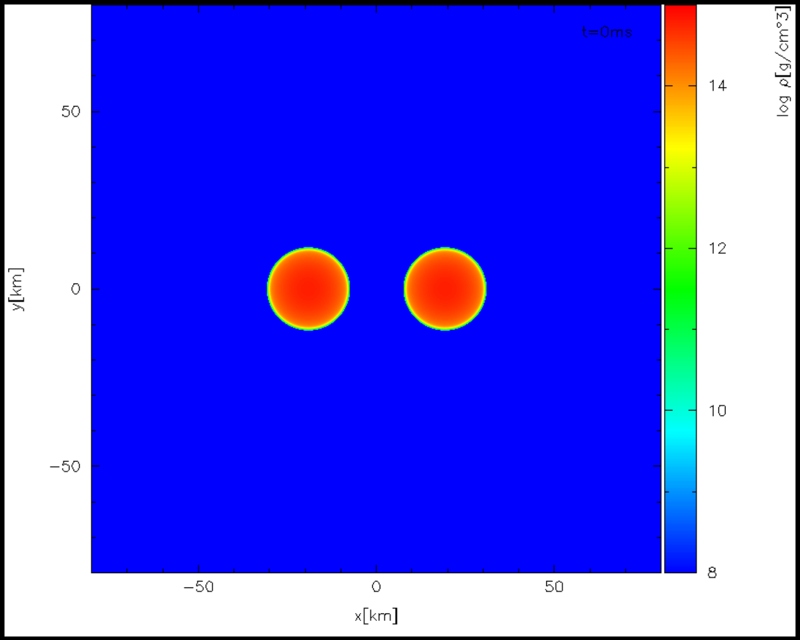
Possible interpretation



→ At least there should be a transparent window in the dynamical ejecta

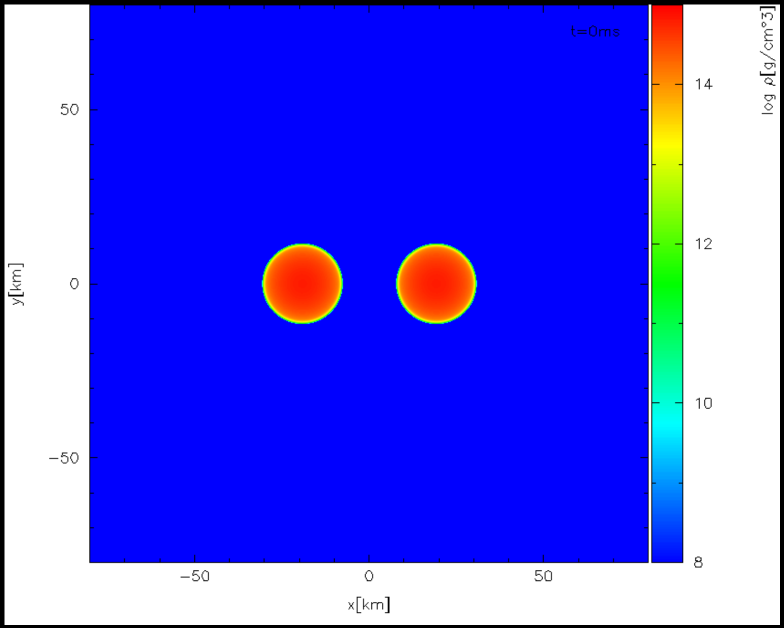
Kasen et al. 2017

Prompt black hole formation
and multi-messenger EoS constraints



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

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



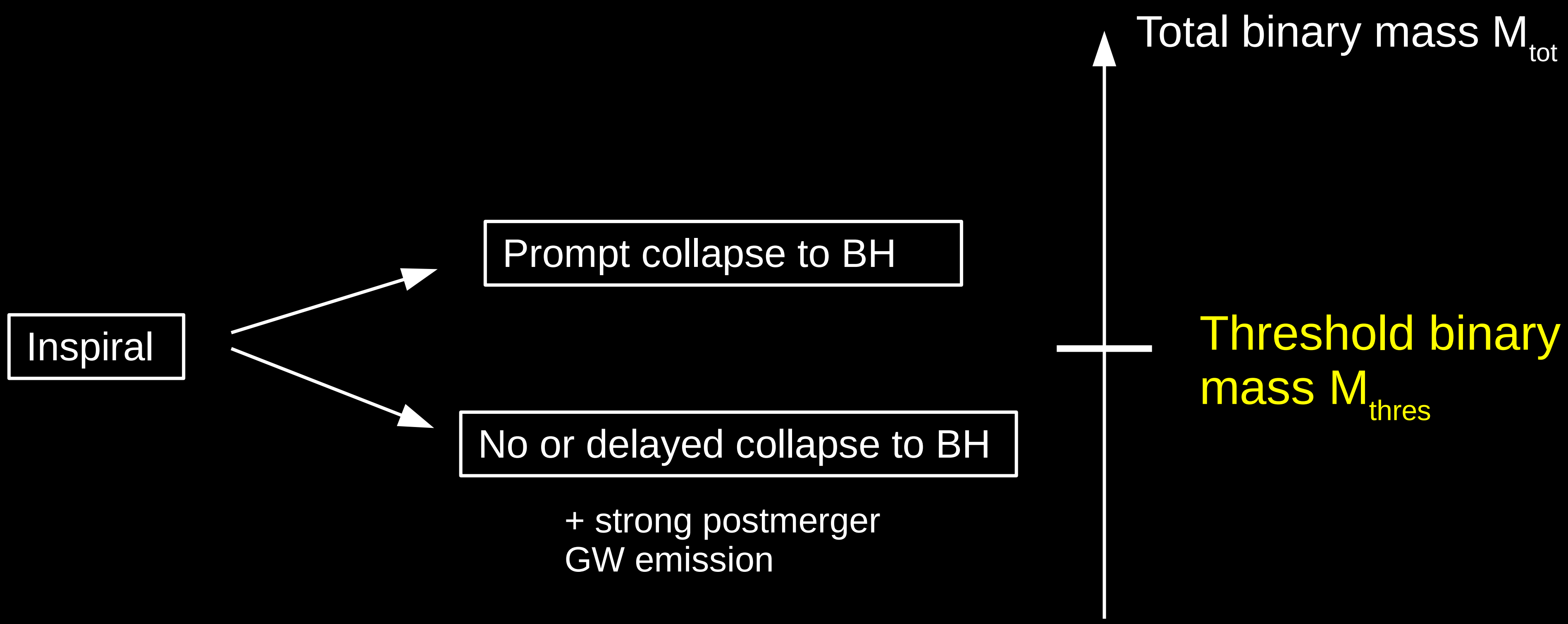
Shen EoS

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

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

Relevant for: EoS constraints through M_{max} measurement, Conditions for short GRBs, Mass ejection, Electromagnetic counterparts powered by thermal emission, NS radius constraints !!!

Collapse behavior



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

Simulations reveal M_{thres}

TOV properties of nonrotating stars, i.e. EoS characteristics

Merger property from simulations

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

Code: Smooth particle hydrodynamics + conformal flatness + T-dependent EoS

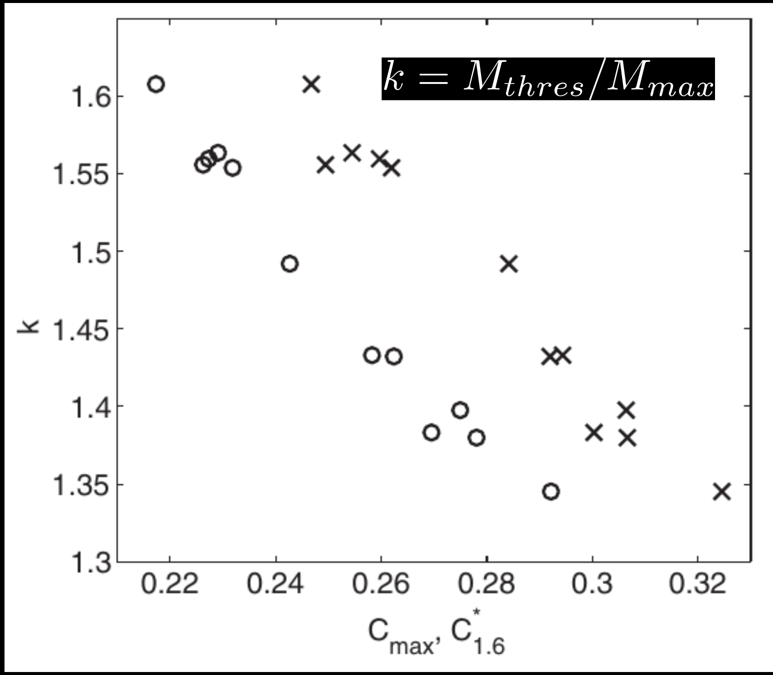
Threshold binary mass for prompt BH formation

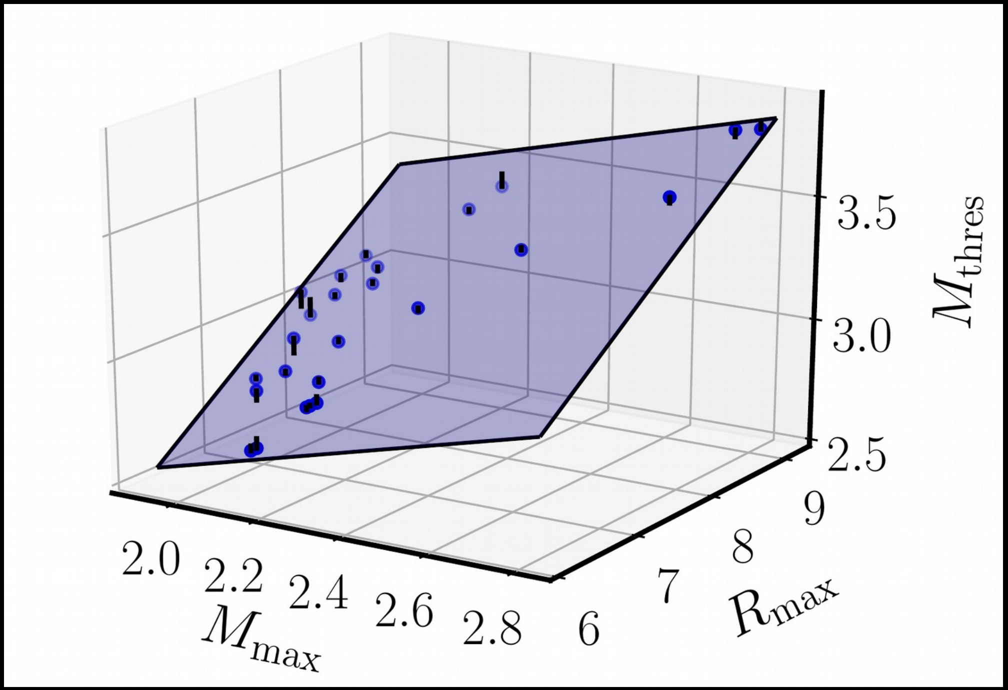
- Empirical relation from simulations with different M_{tot} and EoS
- Fits (to good accuracy):

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

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

- Both better than 0.06 M_{sun}





Remarks

- Prompt collapse or not leads to very strong impact on observables

  → potential to constrain EoS, mass ejections, properties of kilonova, conditions for short gamma-ray bursts

  → Mthres relatively insensitive to mass ratio and robust

EoS constraints from GW170817*

→ lower bound on NS radii

* See also Margalit & Metzger 2017, Shibata et al. 2017, Rezzolla et al. 2018, Radice et al. 2018, Ruiz & Shapiro 2018, Coughlin et al 2018, Shibata et al 2019, ... for other EoS constraints in the context of GW170817

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 no direct collapse in GW170817
  → even asymmetric mergers that directly collapse do not produce very 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
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Compilation in Cote et al 2018

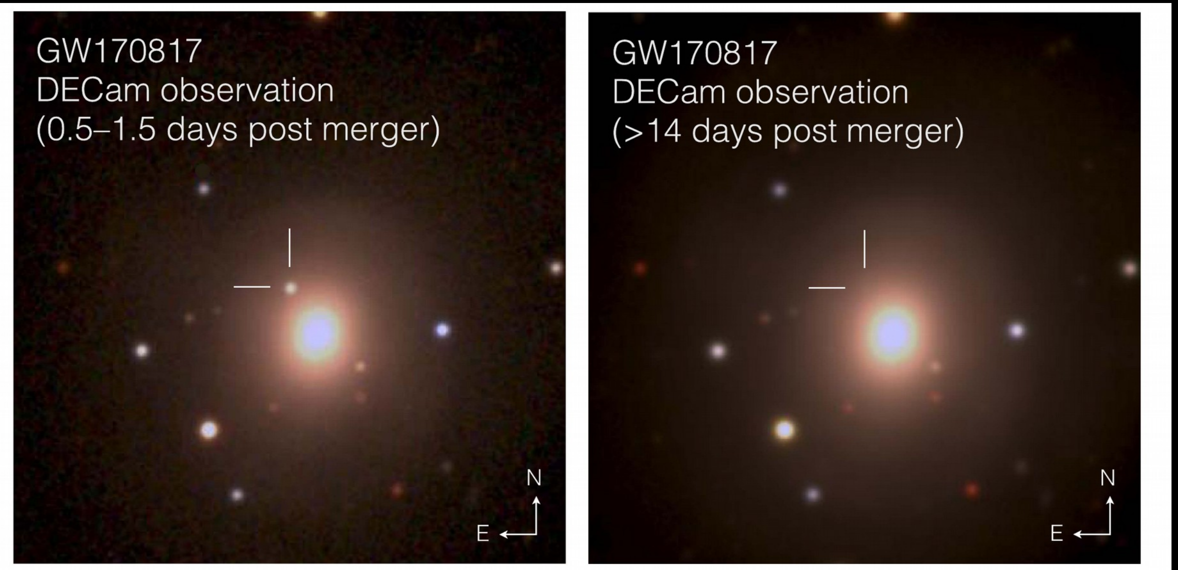
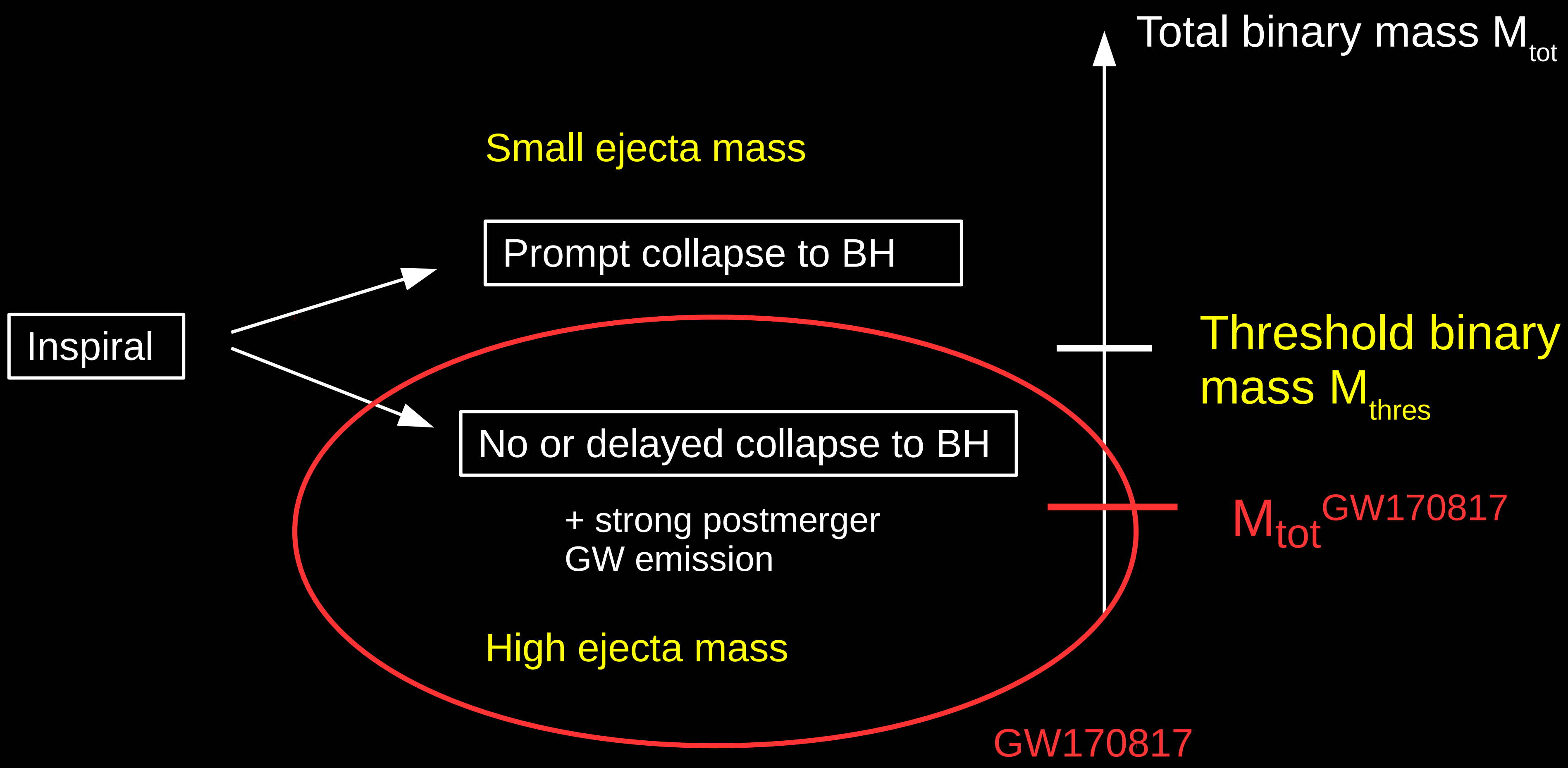


Figure 1. NGC4993 *grz* color composites (1.′5 × 1.′5). Left: composite of detection images, including the discovery *z* image taken on 2017 August 18 00:05:23 UT and the g and r images taken 1 day later; the optical counterpart of GW170817 is at R.A., decl. =197.450374, −23.381495. Right: the same area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

Soares-Santos et al 2017

Collapse behavior



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

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

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

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

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

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

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

- Putting things together:

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

→ Lower limit on NS radius

NS radius constraint from GW170817

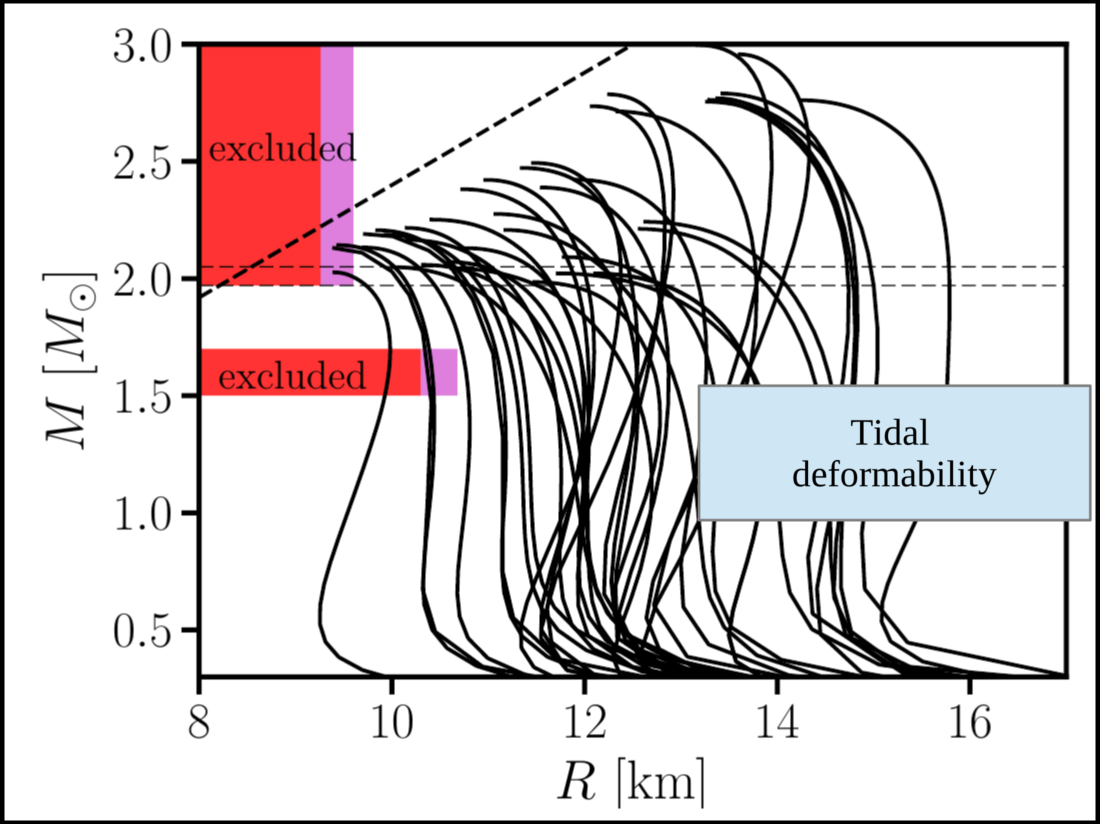
- R_{max} > 9.6 km
- $R_{1.6}$ > 10.7 km
- Excludes very soft nuclear matter
- Not yet very restrictive, but potential for future

  → stronger constraints

  → upper limit on Mmax (and R) through prompt collapse !!!
- Multi-messenger EoS constraints complementary to GWs

  → low SNR constraint !!!

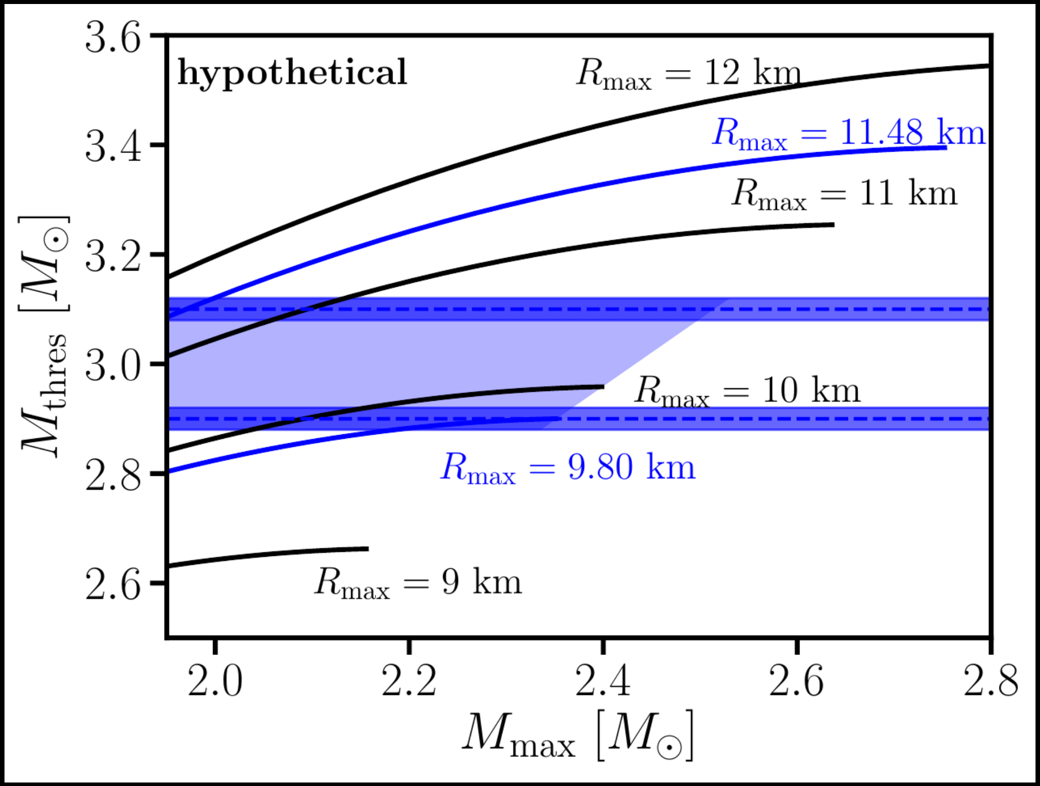
  → more follow-up obseravtions needed

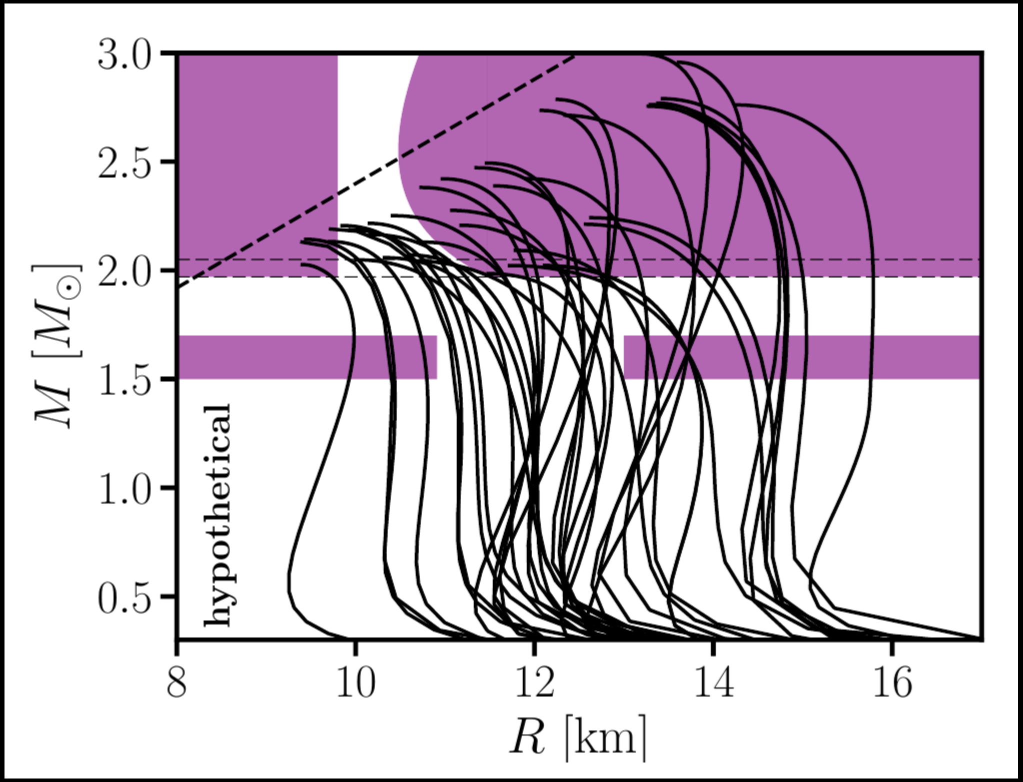


Bauswein et al. 2017

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

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

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

- 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}

(relatively robust and model-independent)

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, …

Strategy for follow-up observations

- As argued: determining Mthres important for EoS constraints/mass ejection/r-process:

  - radius constraints from above and below

  - Mmax if NS radius known with some precision

  - Mthres is also important for clues on em signature/ GRB conditions

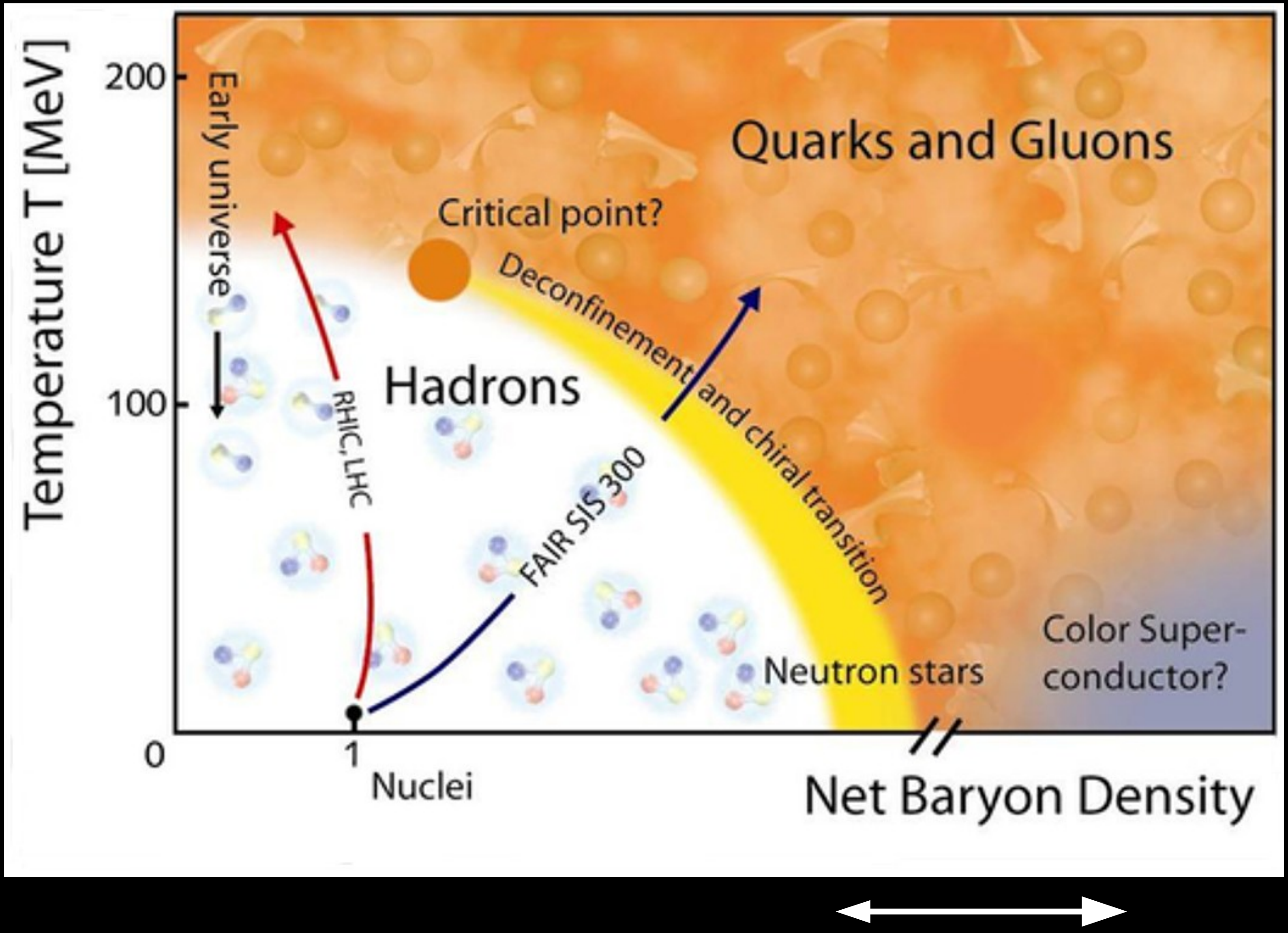
- Not for all GW triggers extensive searches possible / meaningful

  → Which are the most promising events to determine Mthres ?

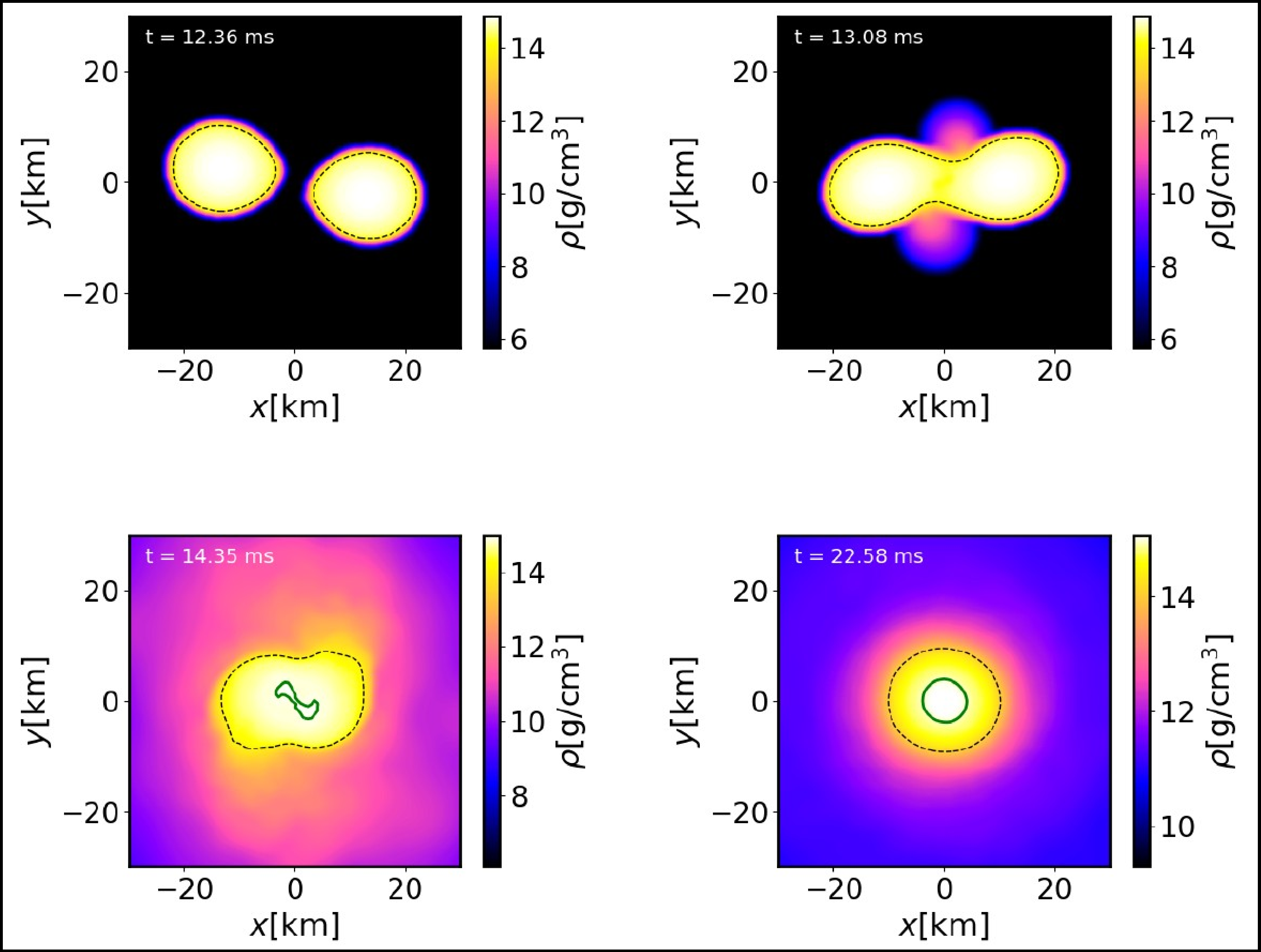
  → Which events are nearly hopeless to find / which instruments to choose ?

Observable signature of (QCD) phase transition

Phase diagram of matter

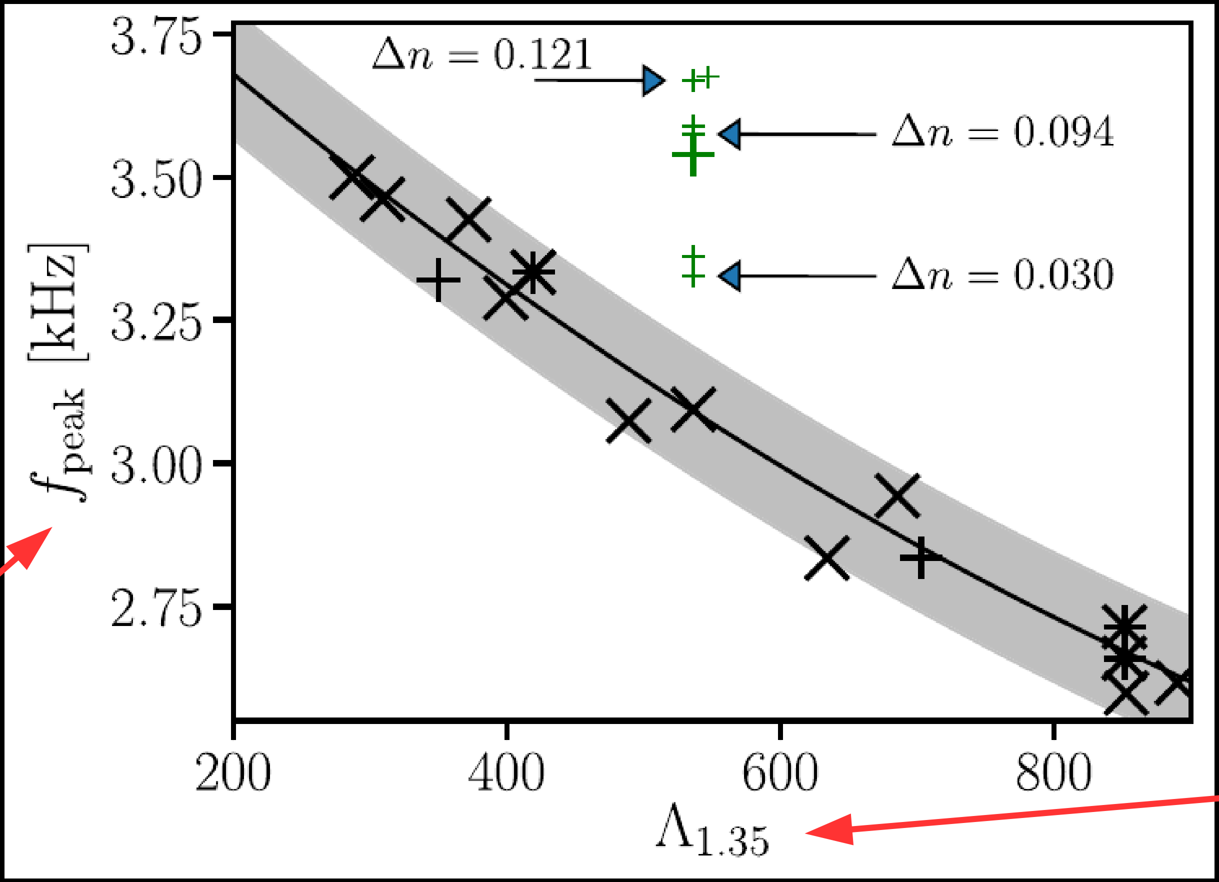


Does the phase transition to quark-gluon plasma occur (already) in neutron stars or only at higher densities ?



1.35-1.35 Msun – DD2F-SF-1, EoS model from Wroclaw: Bastian, Blaschke, Fischer

Signature of 1st order phase transition



from postmerger

from the inspiral

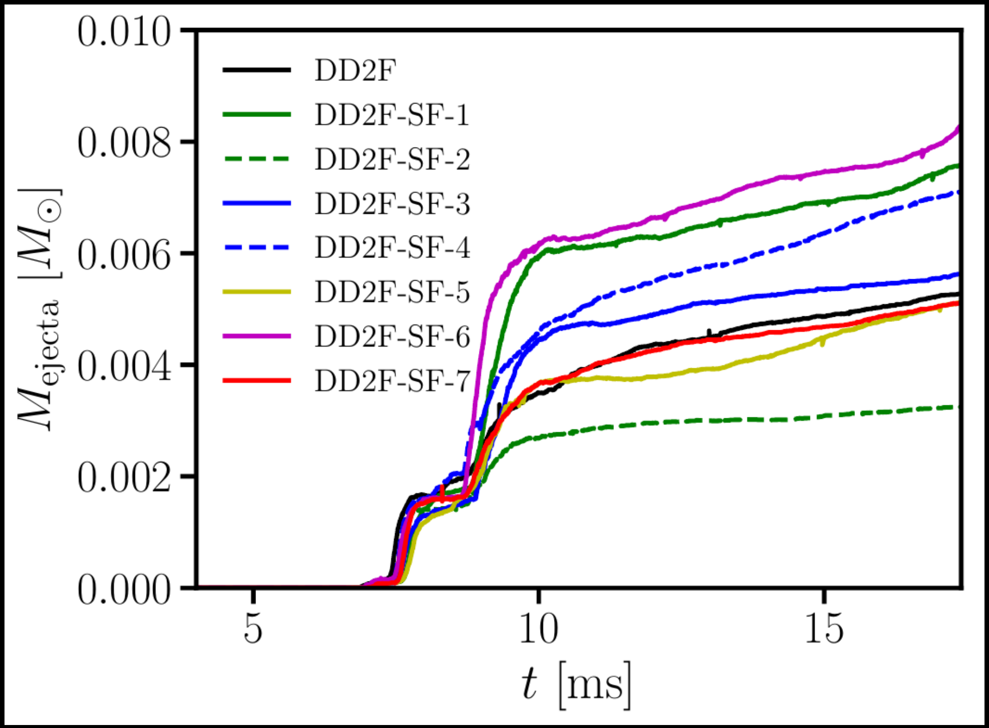
Bauswein et al. 2019

- 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, 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

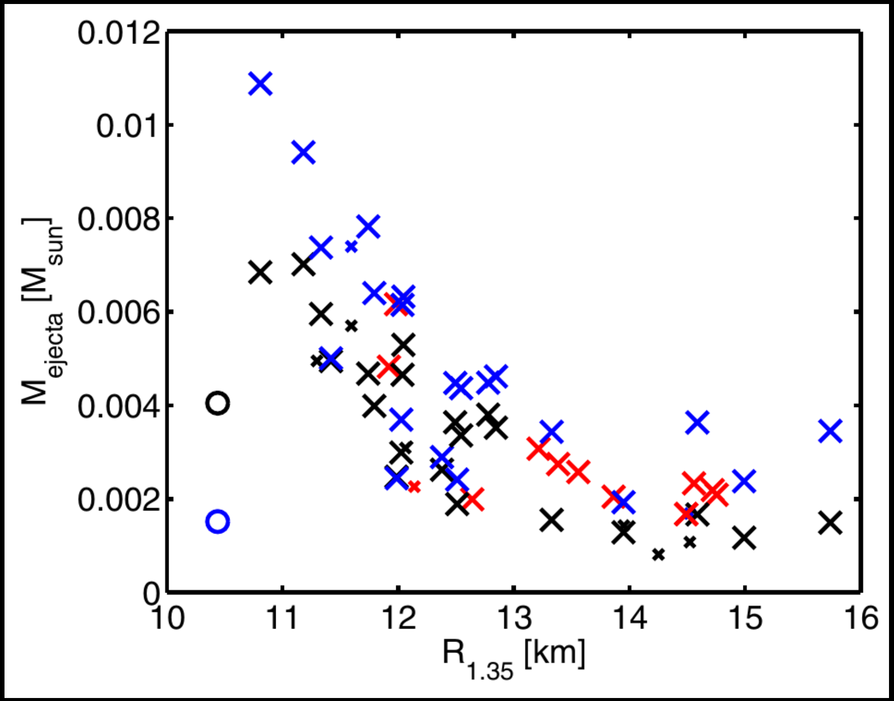
Em counterpart / nucleosynthesis

- No obvious qualitative differences differences – quantitaive differences within expected "hadronic" scatter (simplistic considerations)
- More subtle impact possible (simple model wo neutrinos, network, disk evolution ...) - also other characteristic similar: outflow veocity, disk mass, ...

  see also Fischer's talk for core-collapse



Bauswein et al 2019 – only dynamical ejecta

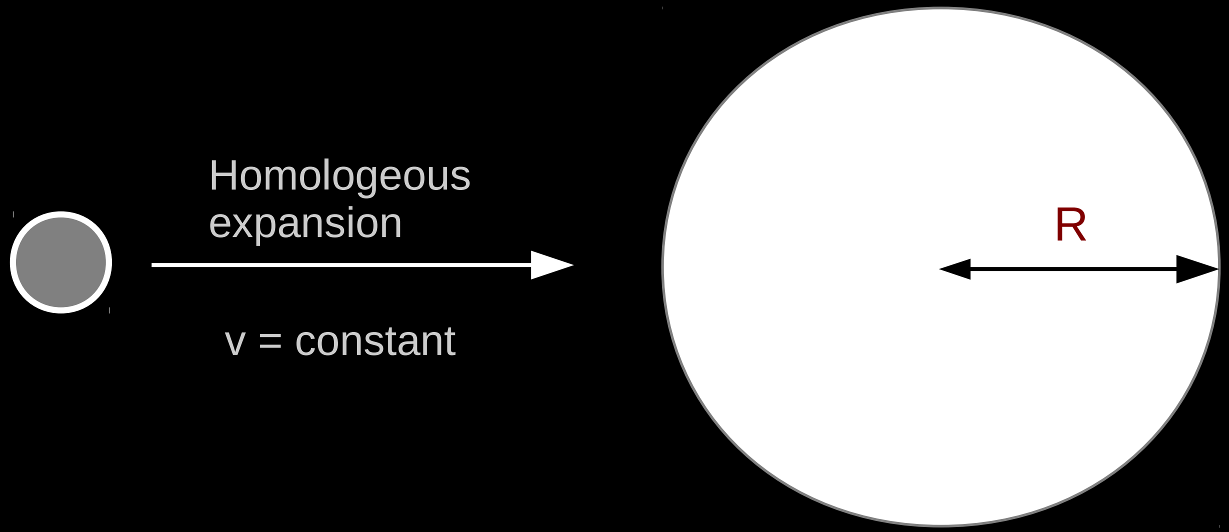


Bauswein et al 2013

Neutron decay ejecta

Standard picture

Metzger et al. 2010, Arnett 1982



$R = v \cdot t_{ex}$

Homologeous expansion (justified by numerical simulation)

t_{ex} measures size of expanding bubble

$$t_{diff} = \frac{0.07 \kappa M_{ej}}{c\, R}$$

Photon diffusion time (0.07 numerical factor for this geometry; kappa = opacity)

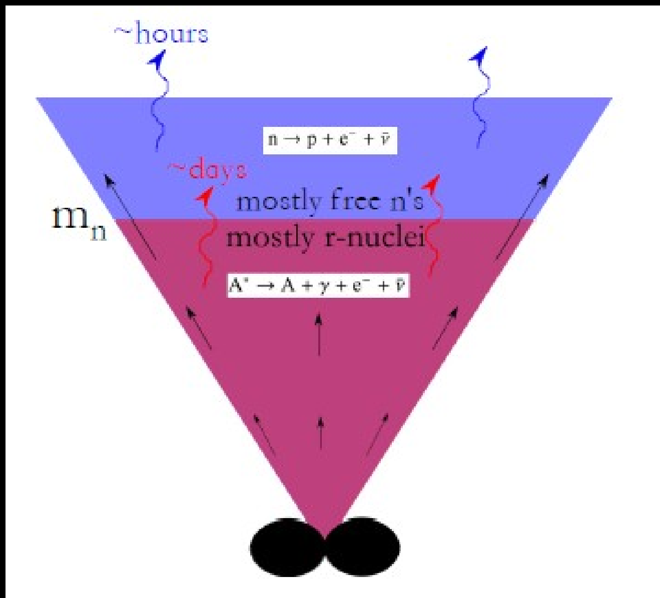
→ decreasing since R grows (all other quantities constant)

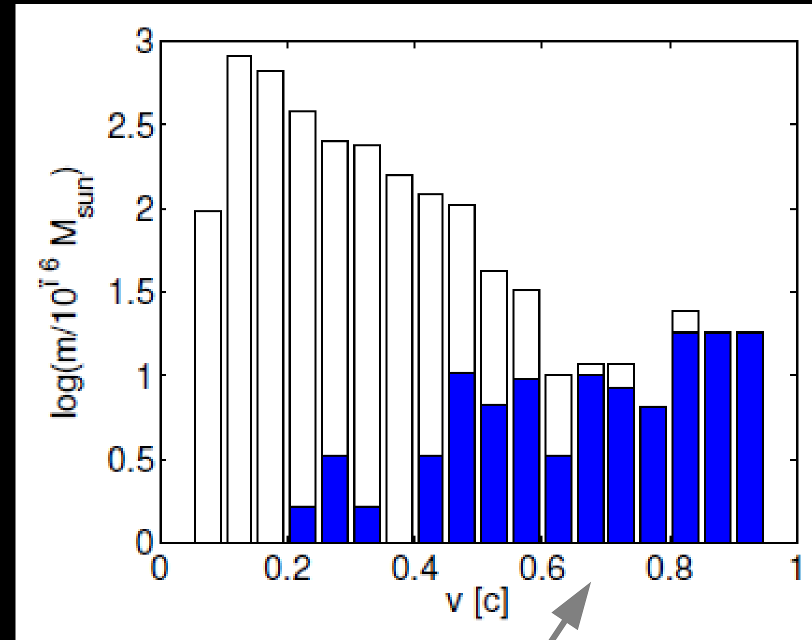
Initially only a few photons from the surface can escape

At $t_{ex} = t_{diff}$ photons from the center have enough time to diffuse out

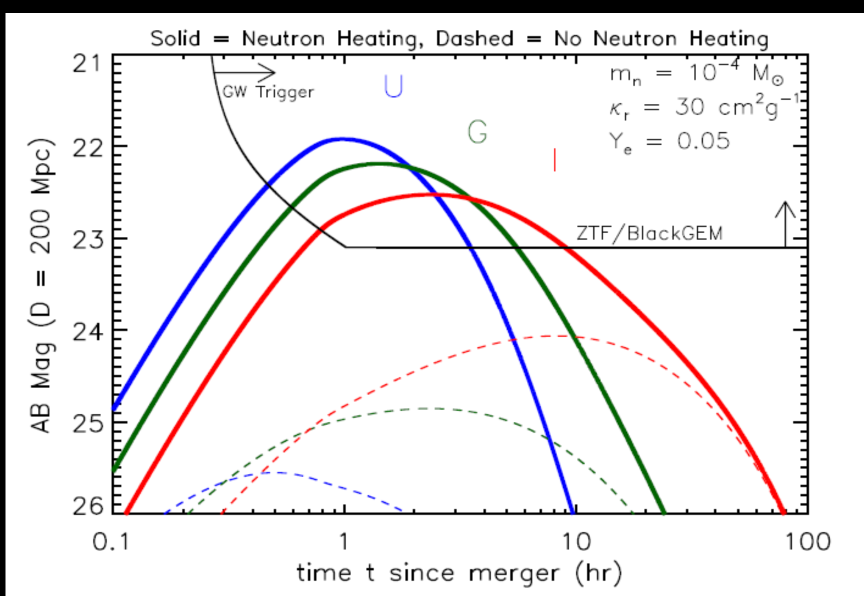
→ peak of luminosity since we start seeing the whole bubble

Kilonova precursors





Neutrons left about 10^{-4} M_{sun}



Metzger et al. 2015

- Fast ejecta: r-process at low densities
- Neutron decay leads to early, bright, optical emission
- Easier to detect, interesting for GW follow up and as trigger for deeper observations of the later lightcurve
- Very promising but hard to resolve numerically (model uncertainties)
- May also be interesting for synchrotron emission in radio (Hotokezaka et al 2018)

Summary

- Mass ejection in simulations compatible with inferred ejecta properties of GW170817
- NS merger are compatible with being main source of heavy elements
- Prompt collapse incompatible with GW170817

  $\rightarrow$ lower limit on NS radii
- Importance to determine Mthres - strategy to constrain threshold mass for prompt BH formation
- Mass ejection of hybrid stars similar to purely nucleonic stars
- Fast mass ejection leads to neutron decay ejecta