Heidelberg Institute for
Theoretical Studies

HITS

Equation of state constraints from postmerger gravitational-wave emission

Neutron star mergers: From gravitational waves to nucleosynthesis

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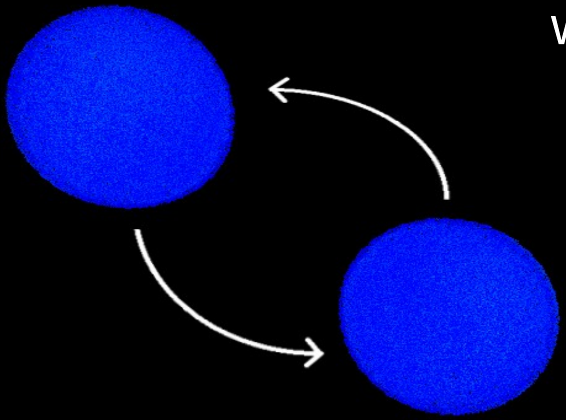
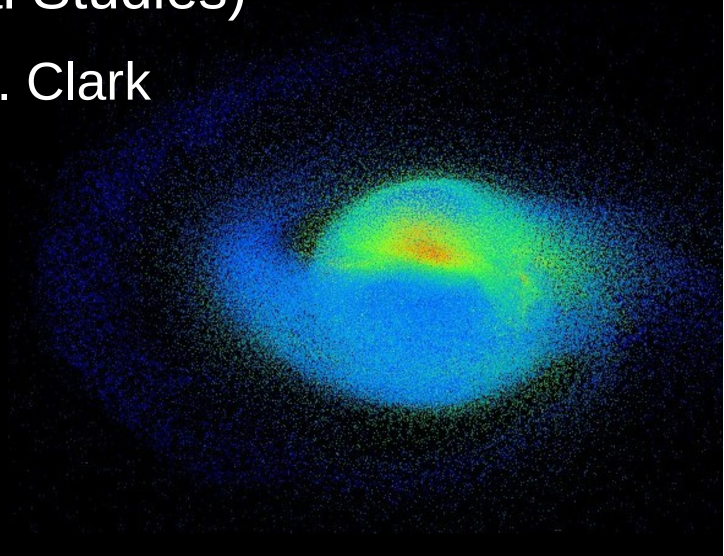
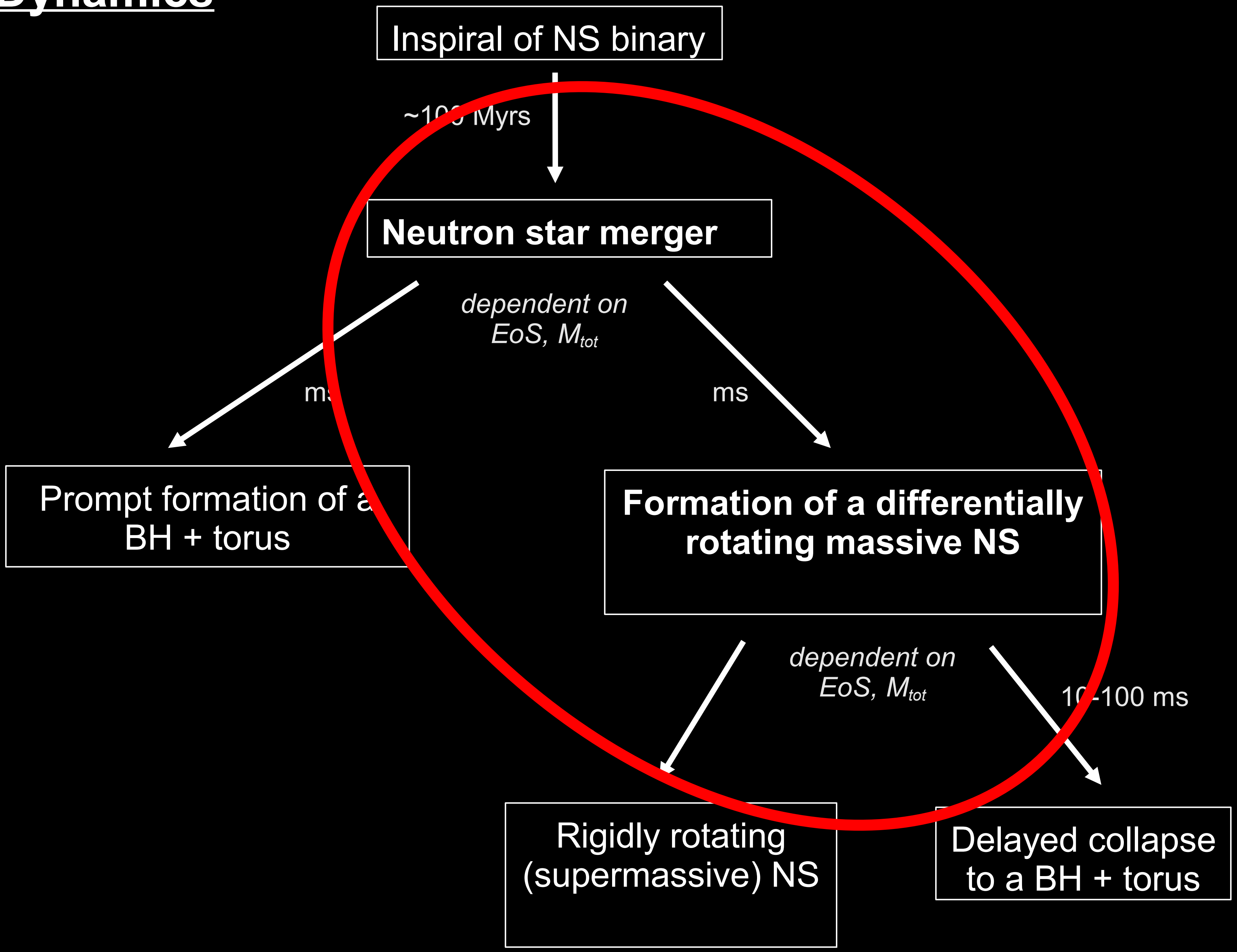




Outline: Neutron-star mergers

- Overview
- Binary mass measurements
- Dominant postmerger oscillation
- Radius measurements
- Data analysis
- Estimates of the maximum mass – collapse behavior of merger remnants
- Secondary features of the postmerger spectrum

Dynamics



Inspiral of NS binary

~100 Myrs

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}

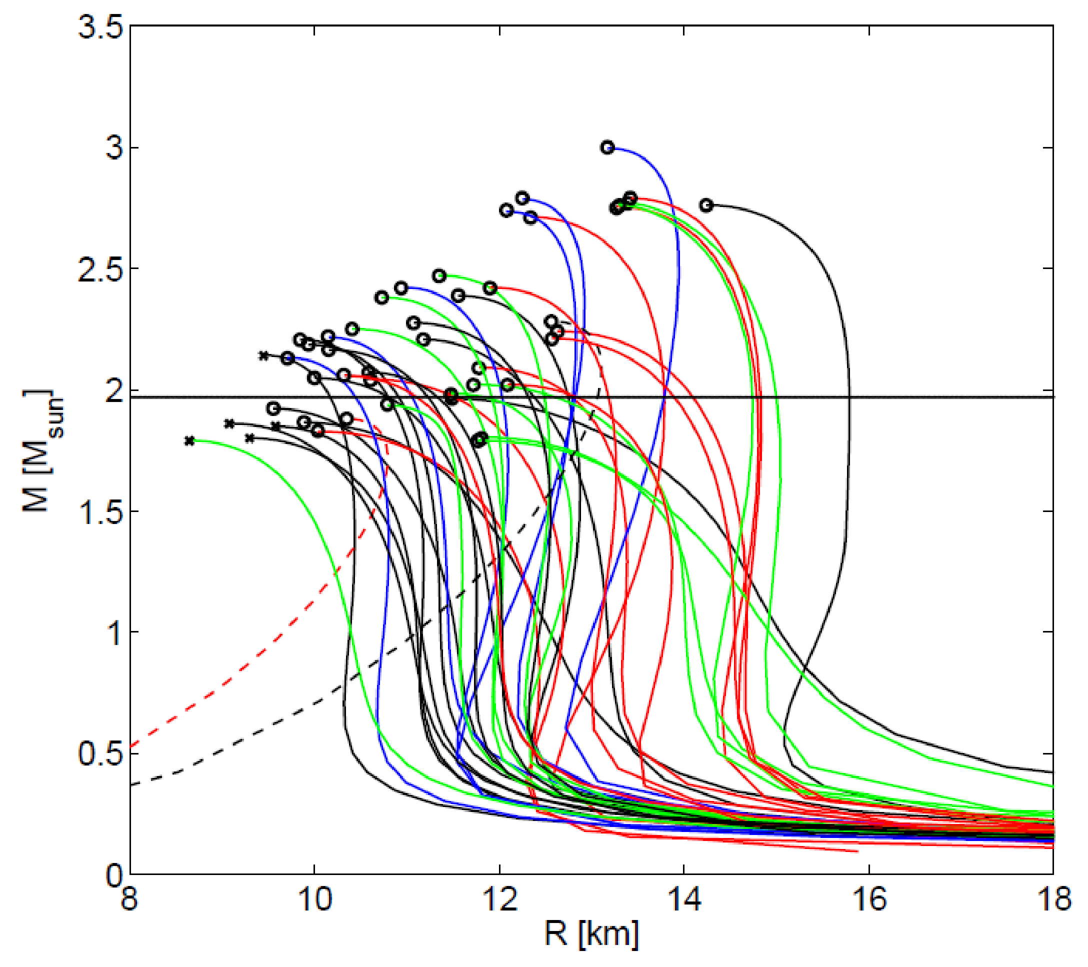
10-100 ms

Rigidly rotating
(supermassive) NS

Delayed collapse
to a BH + torus

General outcome

for 1.35-1.35 M_{sun} binaries

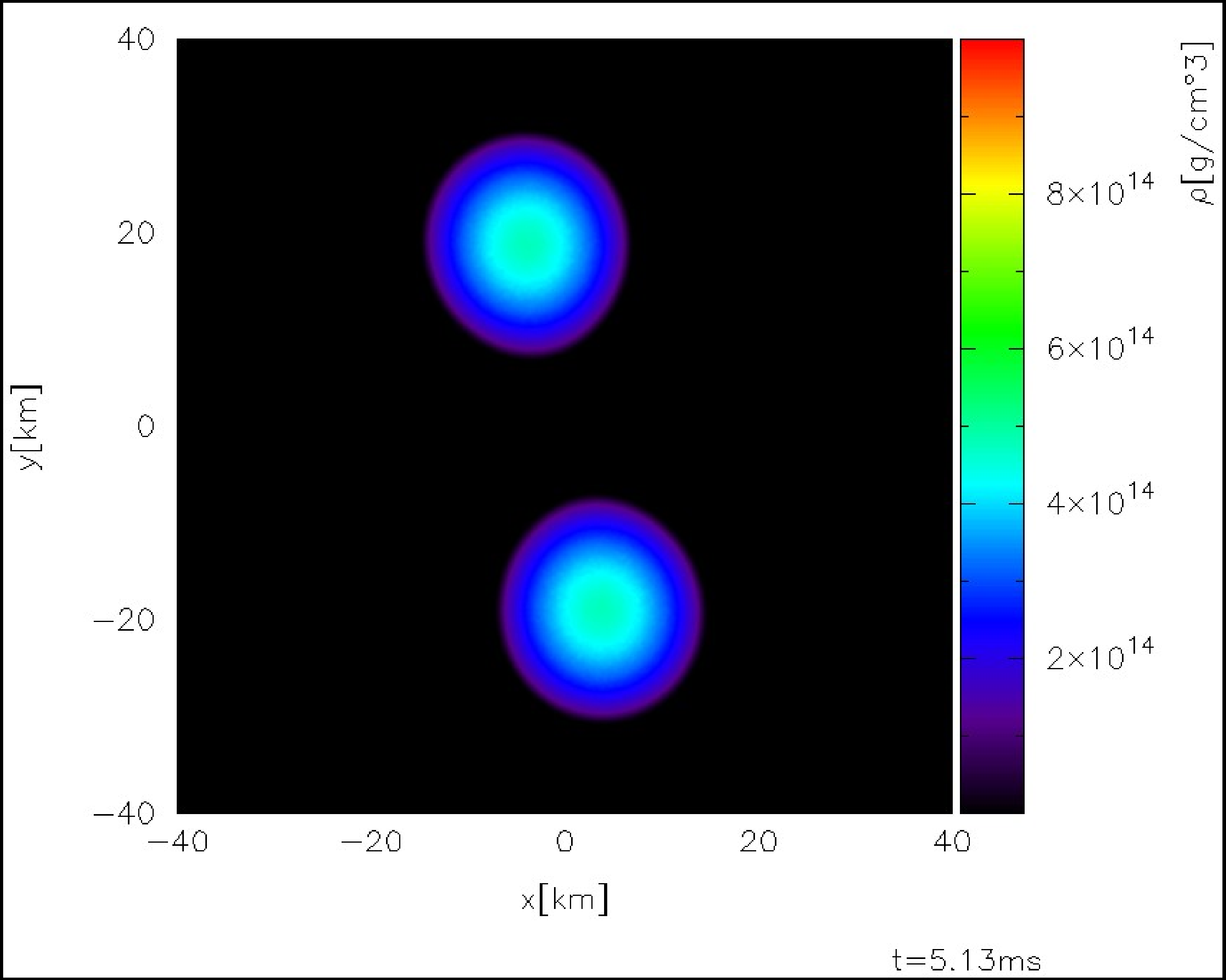


M_{max} with circle: rotating NS merger remnant

M_{max} with cross: direct BH formation

42 out of 47 models lead to the formation of a differentially rotating NS

(only one accepted EoS leads to prompt collapse)



1.35-1.35 Msun, Shen EoS, rest-mass density in equatorial plane

Smooth Particle Hydrodynamics, conformally flat spatial metric

Binary mass measurements

Masses from inspiral

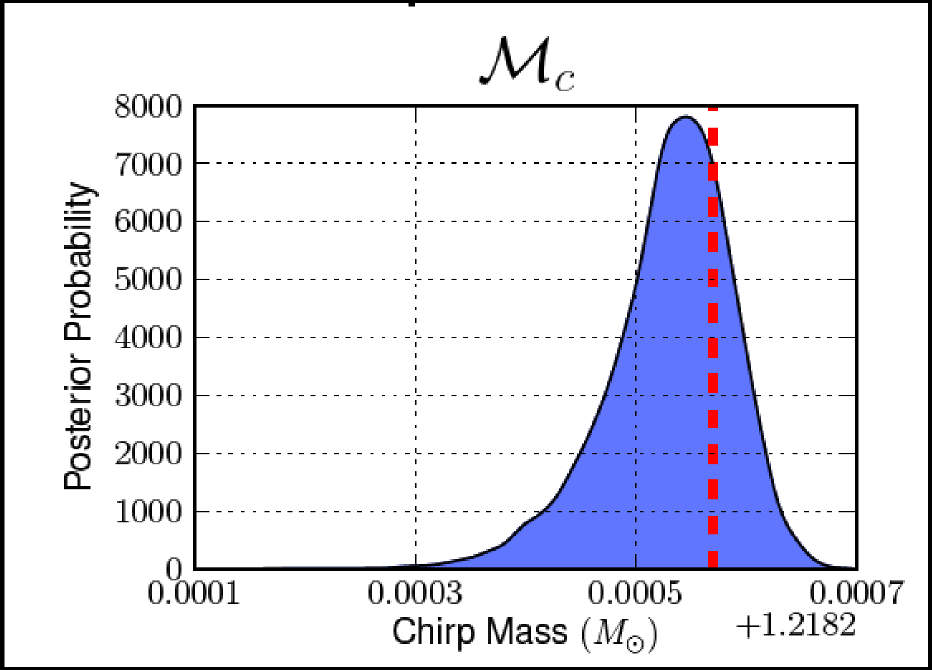
- Accurately measured "chirp mass"

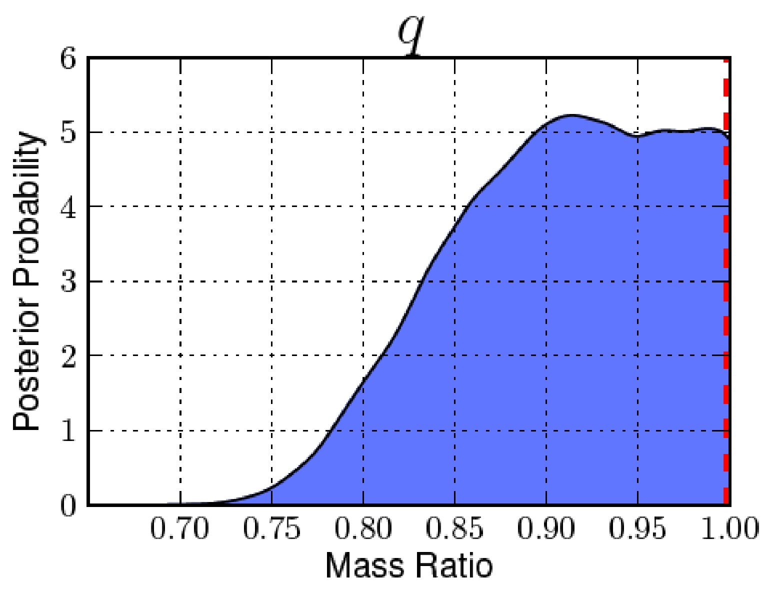
$$M_{chirp} = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}}$$

- Mass ratio with larger error

$$q = M_1/M_2$$

- i.e. q only for near-by mergers
- the closer the more accurate





Dashed red line = injected signal

Distribution function of recovered signals in blue

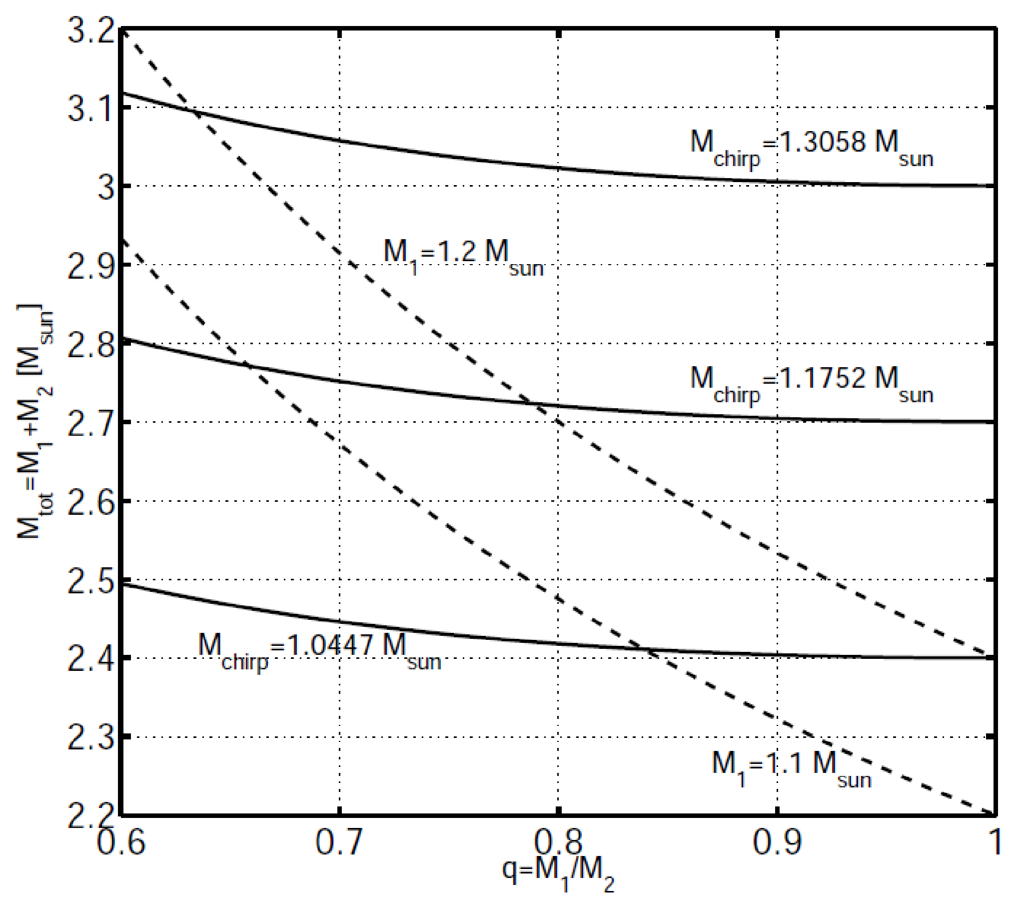
Rodriguez et al 2014 – injected at 100 Mpc

Total mass from chirp

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

$$M_{tot} = M_1 + M_2$$

→ Chirp mass determines M_{tot} quite well



Minimum NS mass 1.1 - 1.2 Msun (e.g. Ertl et al. 2015 or measured masses)

EoS from gravitational waves

GWs: an oversimplified picture

Two complementary approaches to infer EoS properties:

- GW inspiral:

  strong signal - weak EoS effect

  (Jim's talk, Sanjay's talk; e.g. Read et al. 2013 → ~1 km @ 100 Mpc)

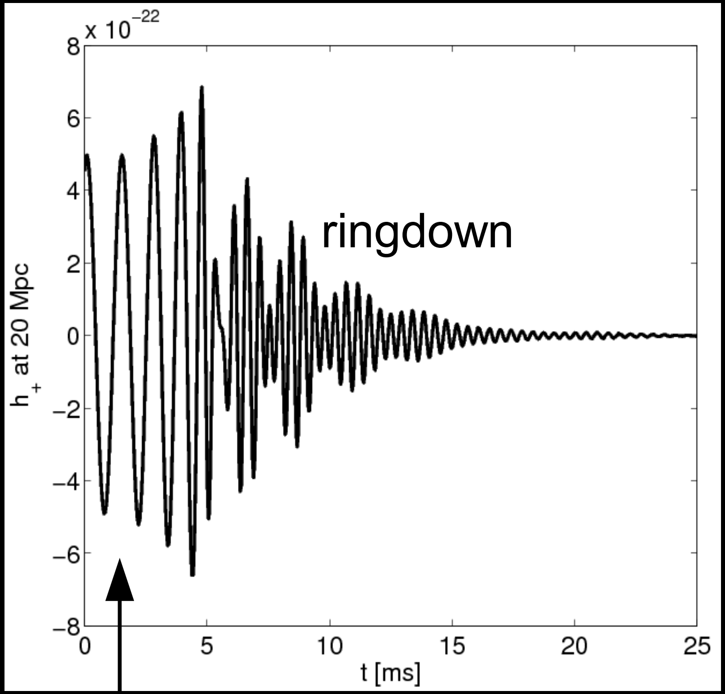
- Postmerger oscillations:

  weak signal – robust strong EoS effect

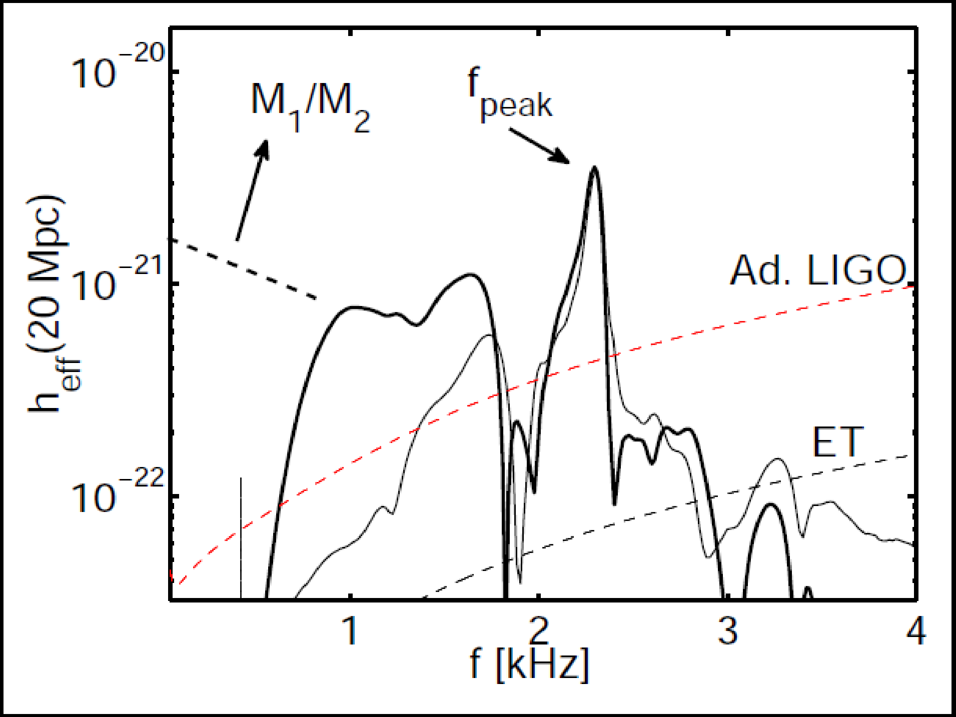
Postmerger gravitational-wave emission

Gravitational-wave spectrum

1.35-1.35 M_{sun} TM1 equation of state (EoS), 20 Mpc

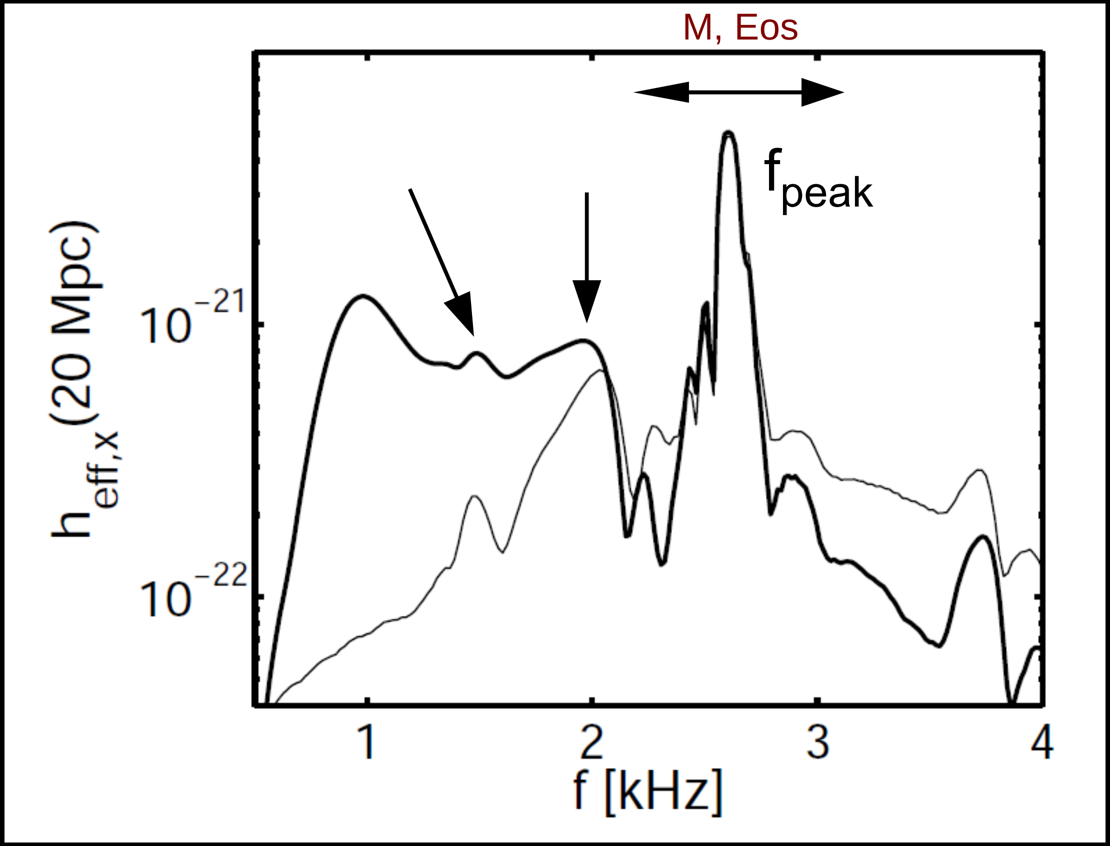


inspiral



- Pronounced peak in the kHz range as a robust feature of all models forming a differentially rotating NS
- Characteristic GW feature: f_{peak}
- Binary masses M_1/M_2 are measurable from GW inspiral signal (most of the inspiral not covered by simulation)

Generic GW spectrum



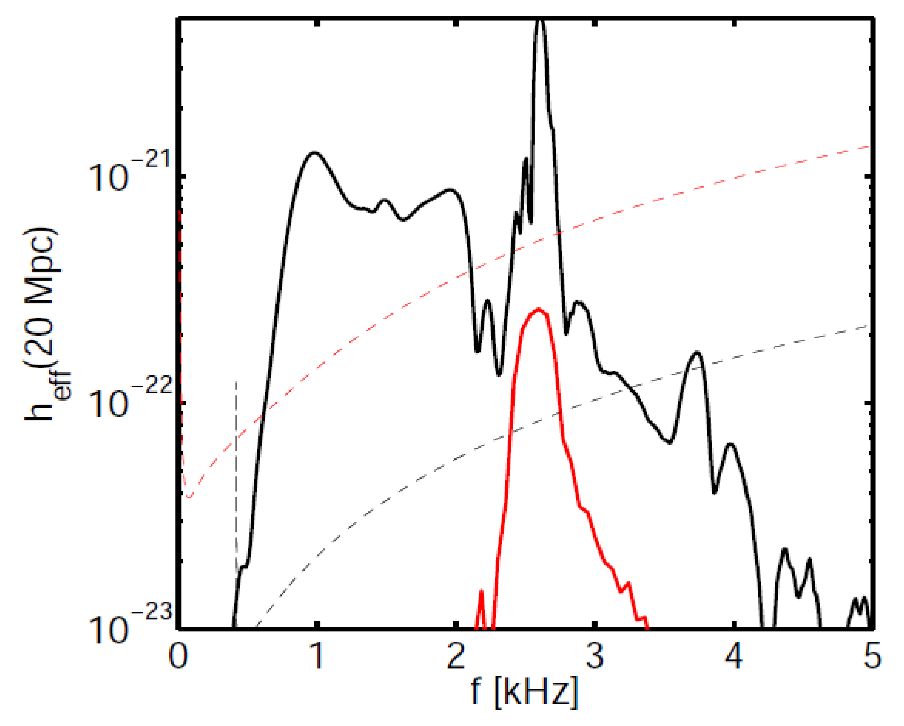
Thin line postmerger only

Note: no unique nomenclature in the literature, e.g. f_{peak} is also called f_2 ...

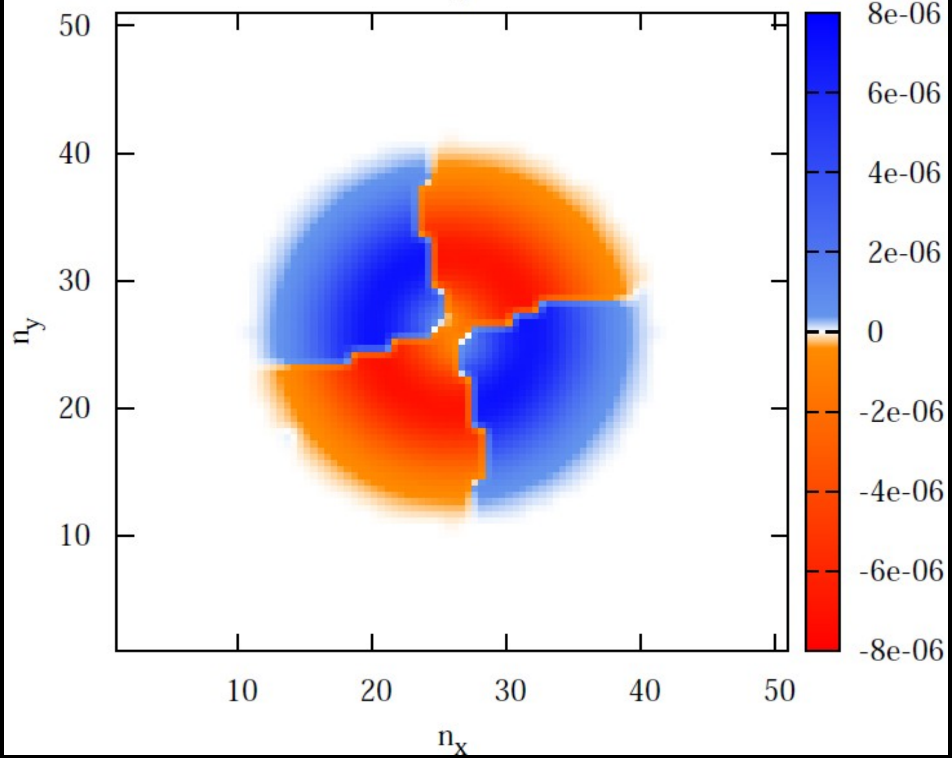
- Up to two ssecondary features at lower frequencies in the postmerger spectrum (subdominan wrt to sensitivity curve) + structure at higher frequencies
- Simulation: 1.35-1.35 M_{sun} DD2 EoS, Smooth Particle Hydro, Conformal Flatness
- Generic in the sense that not all secondary peaks are necessarily present
- Classification scheme of postmerger emission and dynamics depending on presence/strength of secondary peaks (Bauswein et al. 2015)

Dominant oscillation frequency

- Robust feature, which occurs in all models (which don't collapse promptly to BH)
- f_{peak} = fundamental quadrupolar fluid mode of the remnant



Re-excitation of f-mode (l=|m|=2) in late-time remnant (Bauswein et al. 2016)

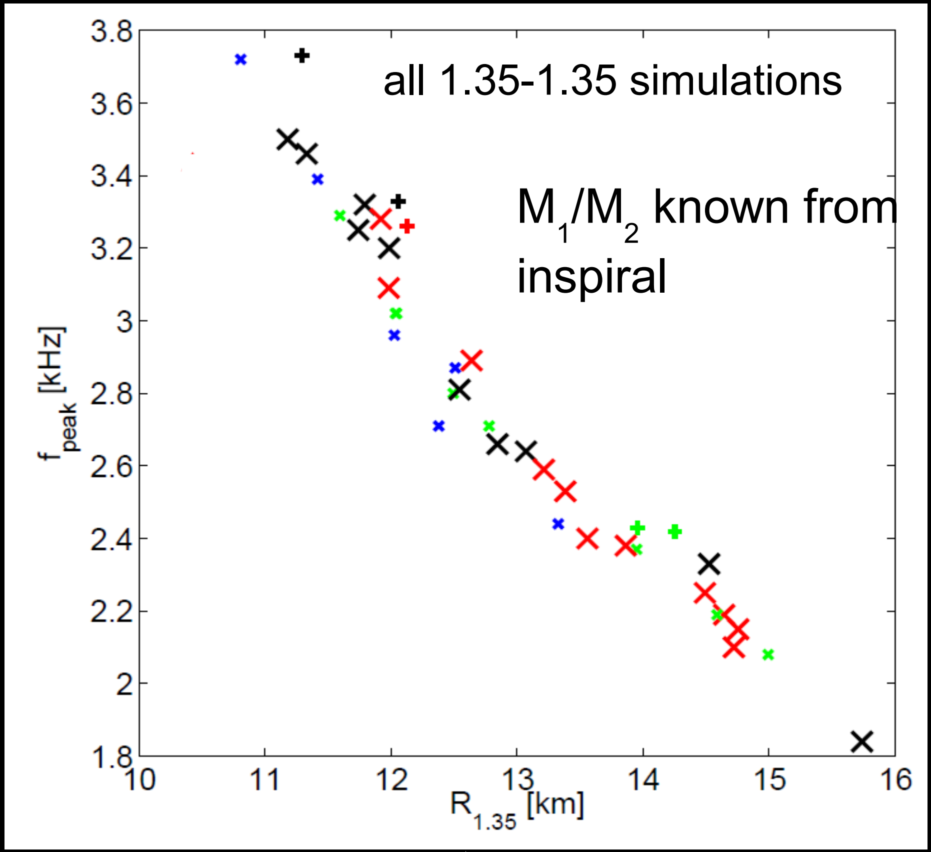


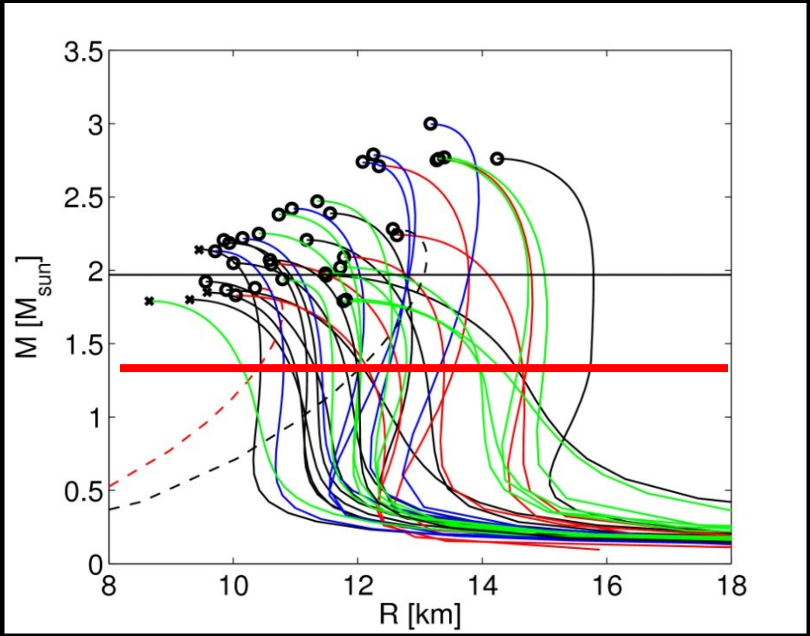
Mode analysis at $f=f_{peak}$
Stergioulas et al. 2011

EoS dependence of f_{peak}

- we consider relations with fixed binary masses
- masses can be well measured from inspiral
- in particular for distances that allow measurement of postmerger emission

Gravitational waves – EoS survey





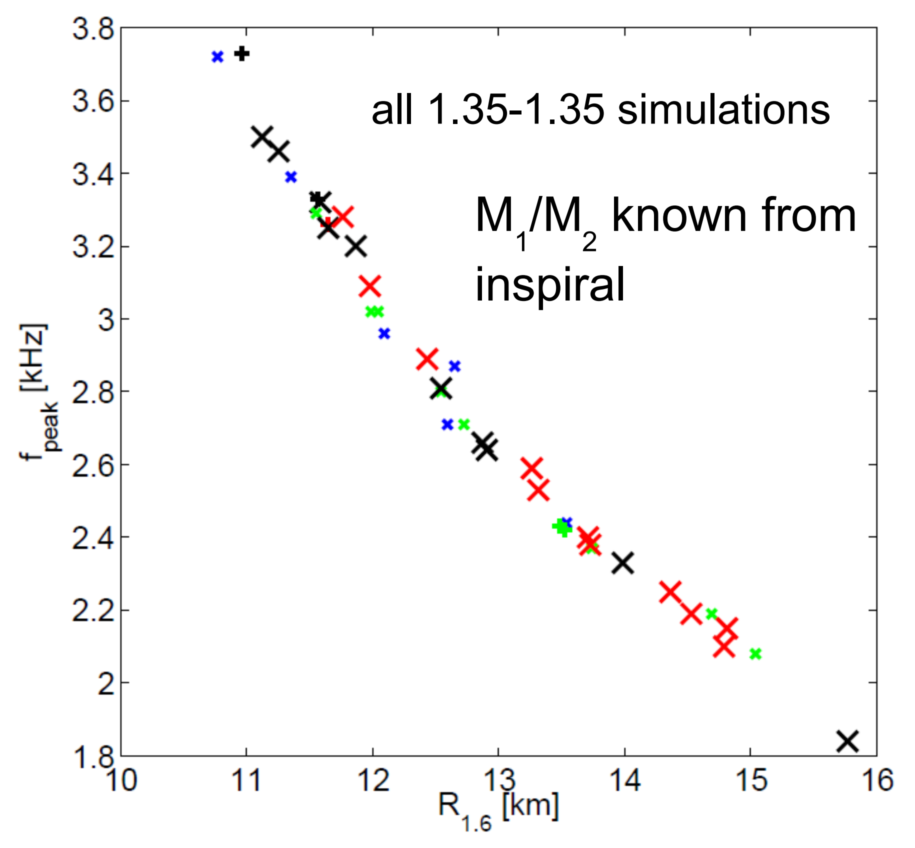
characterize EoS by radius of nonrotating NS with 1.35 M_{sun}

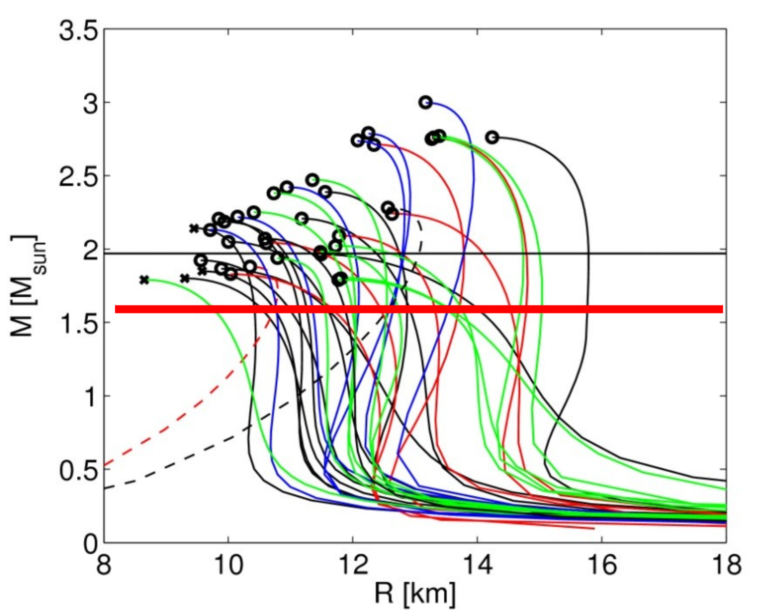
Pure TOV/EoS property => Radius measurement via f_{peak}

Important: Simulations for the same binary system, just with varied EoS

Bauswein et al. 2012

Gravitational waves – EoS survey





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

Bauswein et al. 2012

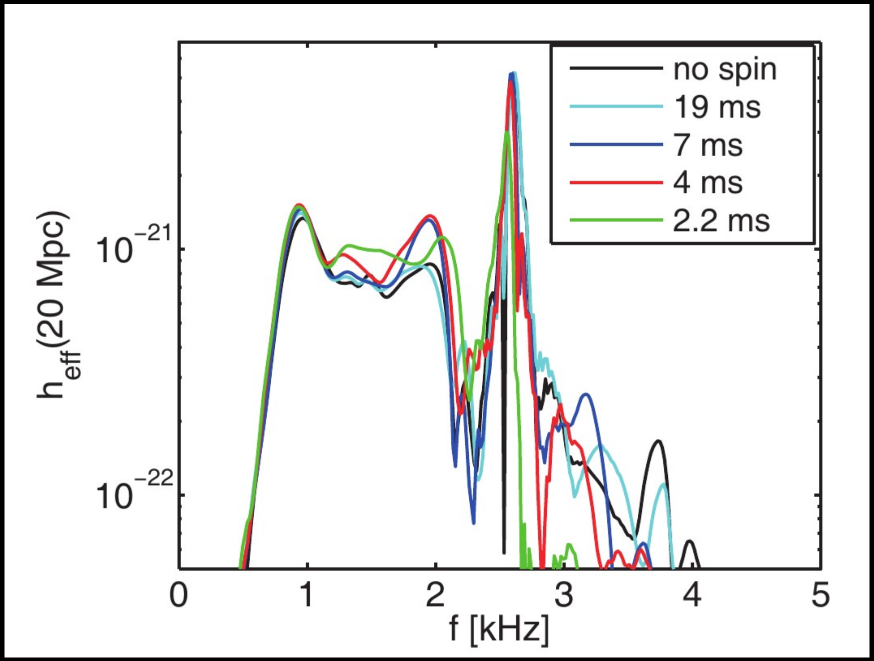
Pure TOV/EoS property => Radius measurement via f_{peak}

Important: Simulations for the same binary system, just with varied EoS

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

Remarks

- Similar relations for asymmetric binaries and other binary masses
- (mass will be measured by inspiral)
- Initial intrinsic NS rotation unimportant
- Agreement with different groups (Kyoto, Caltech, Frankfurt, Parma, e.g. Hotokezaka et al 2013, Bernuzzi et al. 2015, Takami et al. 2015, De Pietri et al. 2015, Foucart et al. 2016)



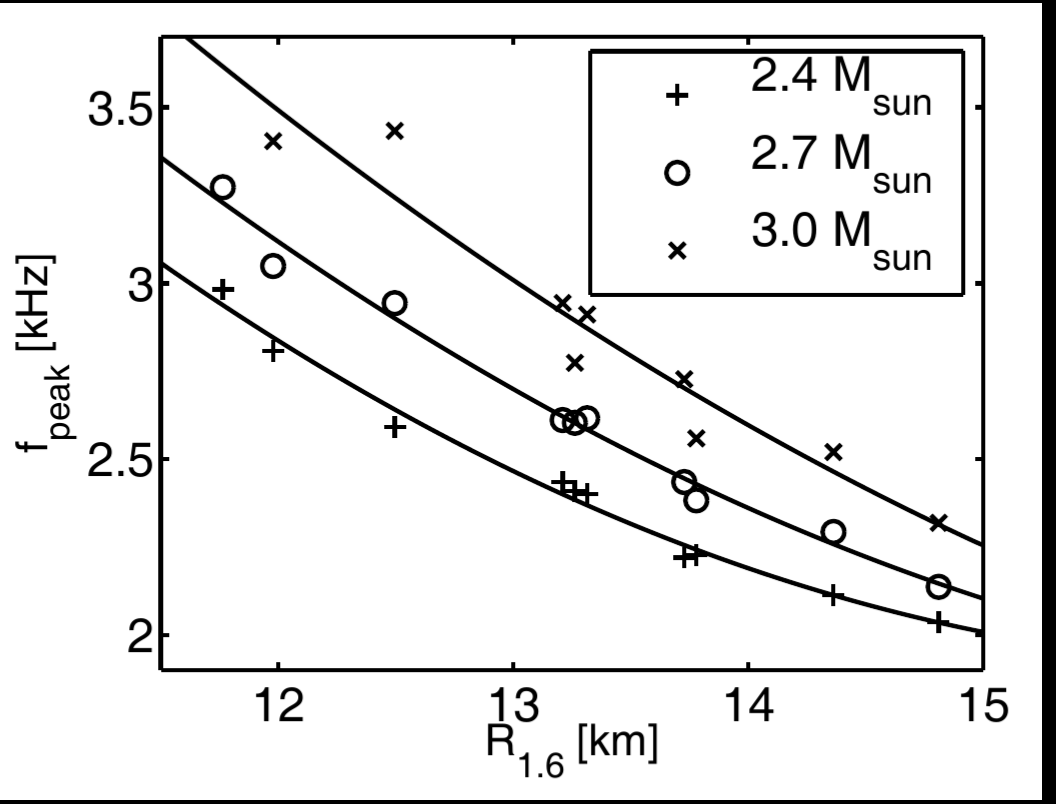
→ No impact on f_{peak}

Bauswein et al. 2016

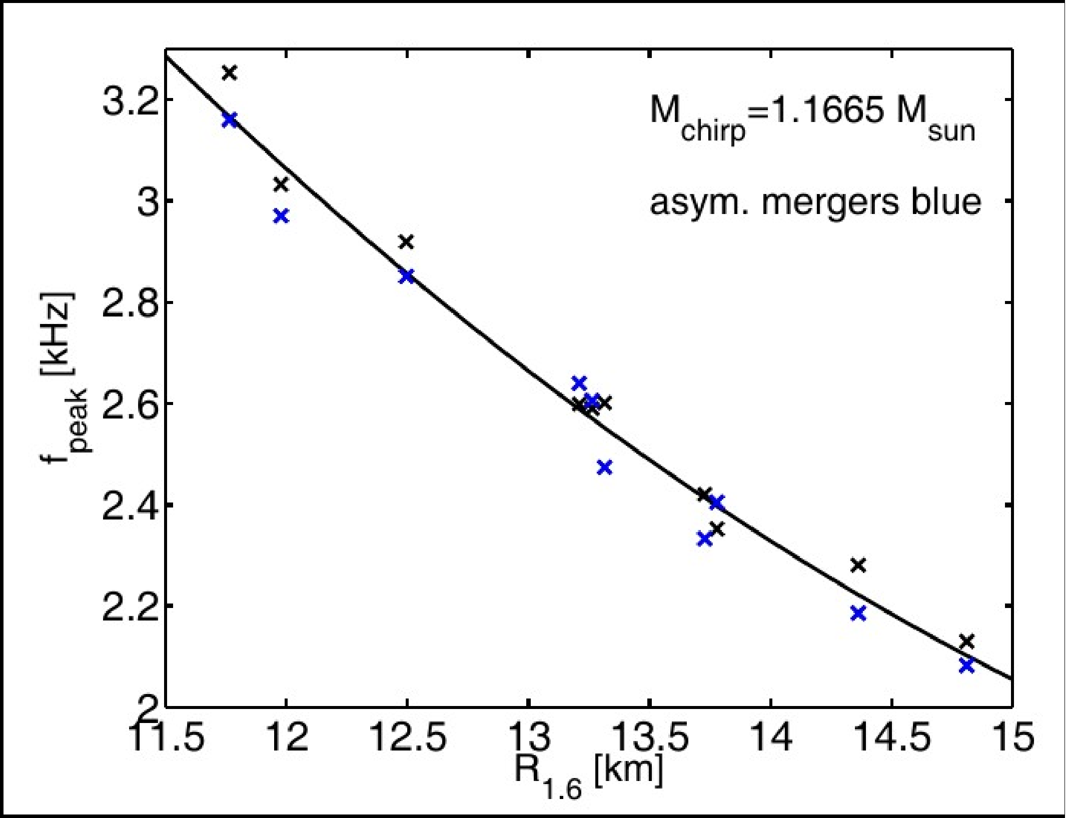
Strategy

- Measure binary masses from inspiral
- Construct f_{peak} – R relation for fixed binary mass
- Measure f_{peak} from postmerger GW signal
- Obtain radius by inverting f_{peak} – R relation

Binary mass variations



Different total binary masses (symmetric)

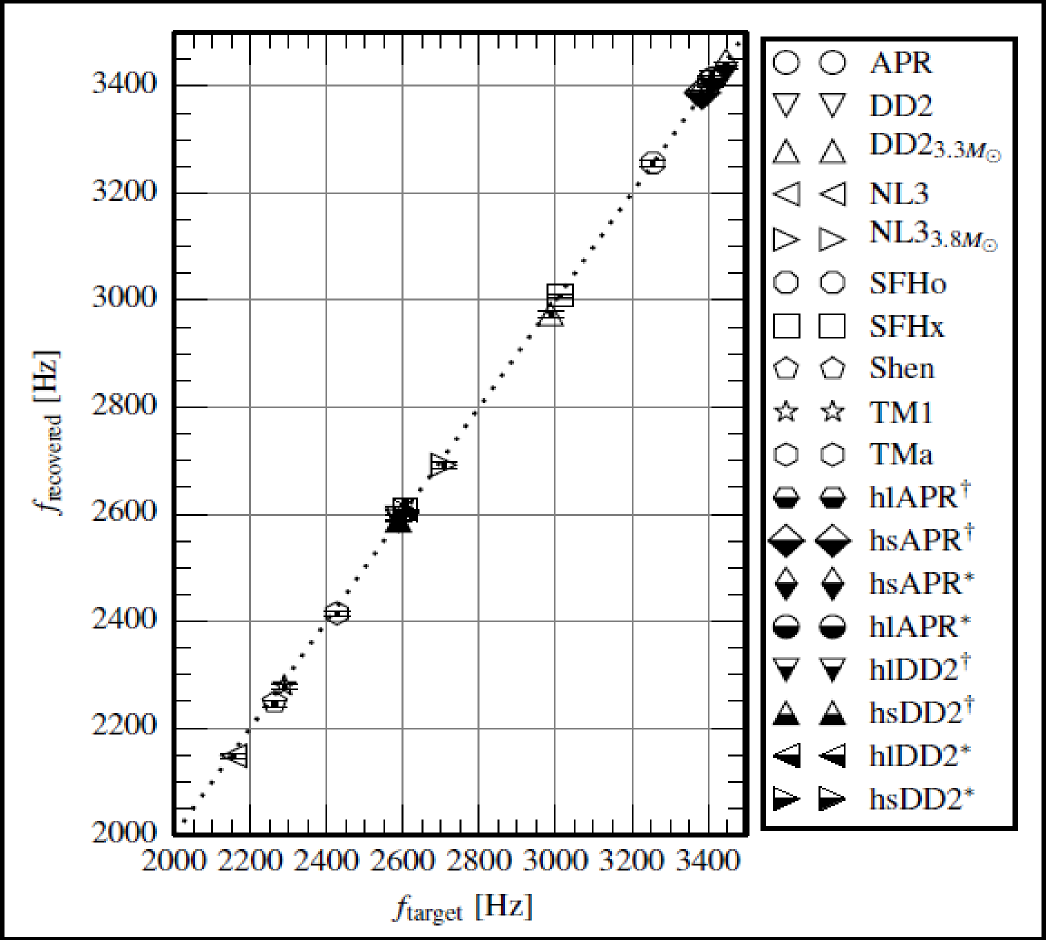


Fixed chirp mass (incl. Asymmertic binaries)

Bauswein et al. 2016

Detectability

Unmodeled searches: Measuring the dominant GW frequency



Model waveforms hidden in rescaled LIGO noise

Peak frequency recovered with burst search analysis

Error ~ 10 Hz

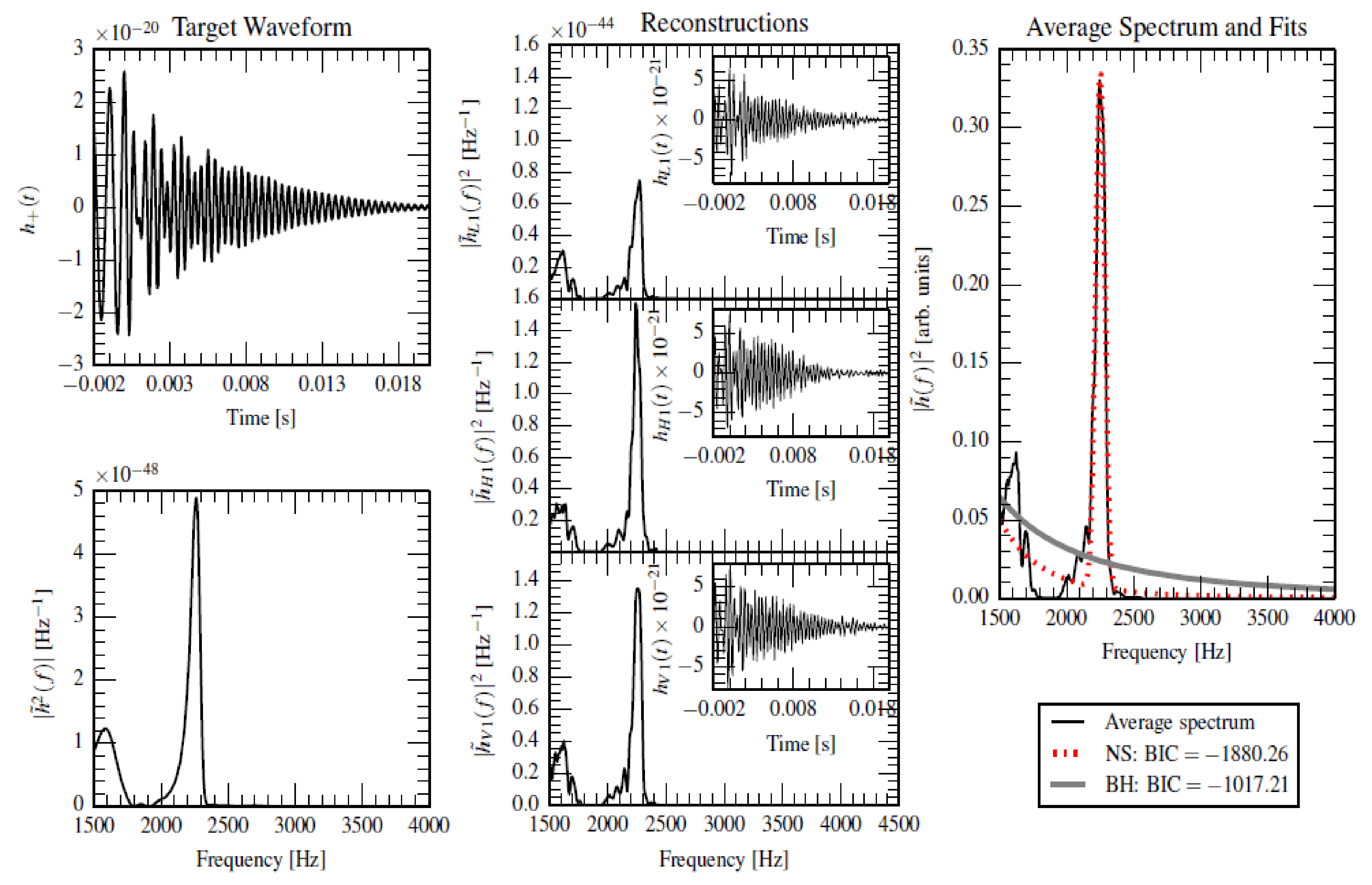
For signals within ~10-25 Mpc

=> for near-by event radius measurable with high precision (~0.01-1/yr)

Proof-of-principle study
→ improvements likely

Clark et al. 2014

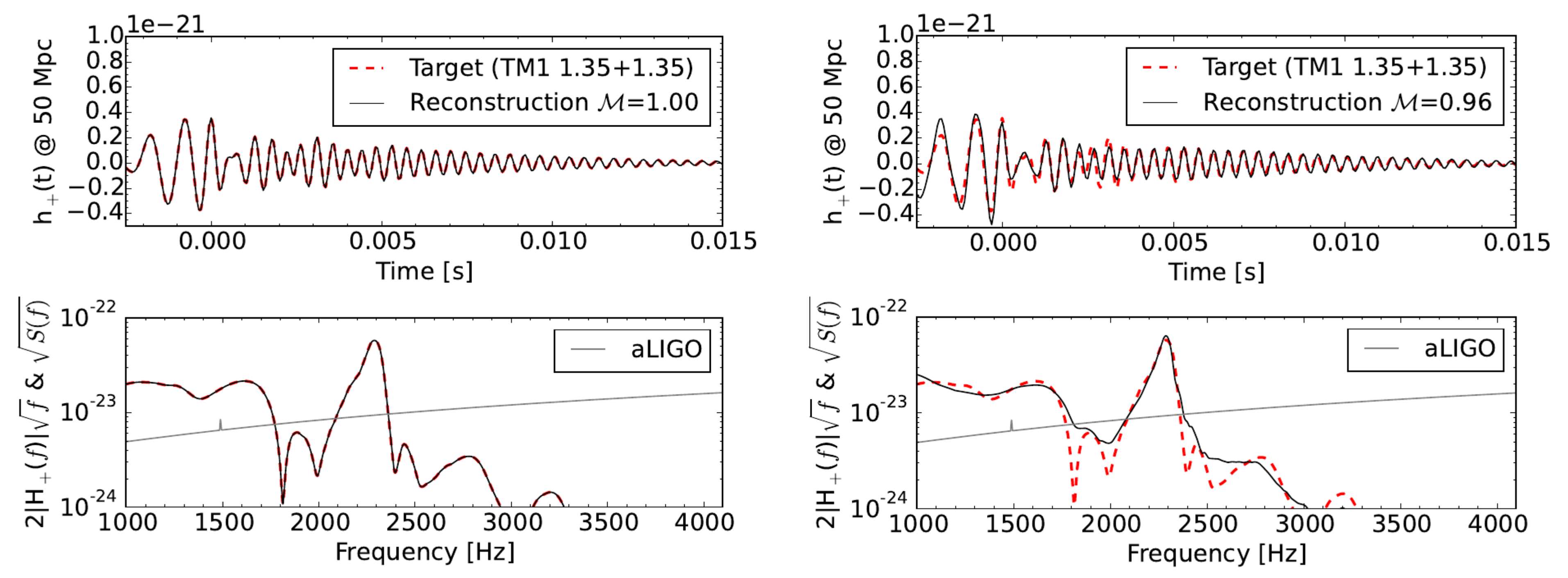
Unmodeled search – less sensitive



Discrimination between prompt collapse and delay/no collapse possible

Shen 1.35-1.35; Clark et al. 2014

Principal Component Analysis

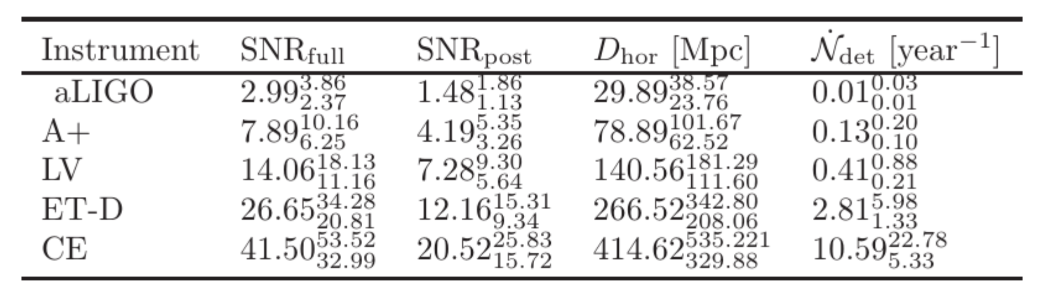


Only first component

Excluding the reconstructed waveform from catalogue

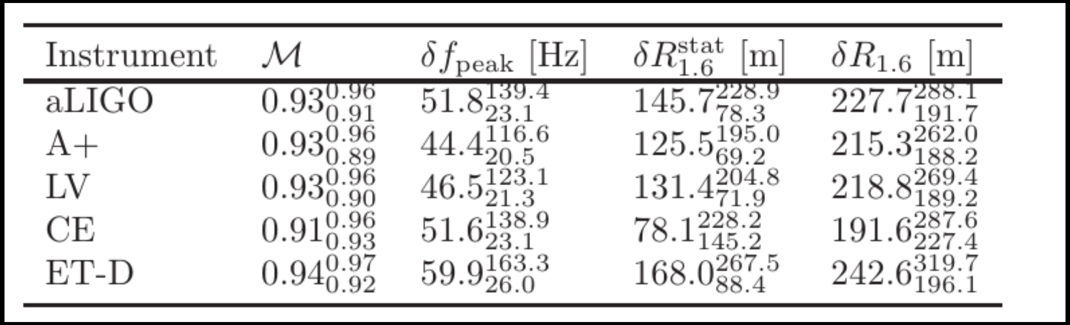
Clark et al 2016

PCA - prospects



Instrument	$\mathrm{SNR}_{\mathrm{full}}$	$\mathrm{SNR}_{\mathrm{post}}$	D_{hor} [Mpc]	$\dot{\mathcal{N}}_{\mathrm{det}}$ [year^{-1}]
aLIGO	$2.99_{2.37}^{3.86}$	$1.48_{1.13}^{1.86}$	$29.89_{23.76}^{38.57}$	$0.01_{0.01}^{0.03}$
A+	$7.89_{6.25}^{10.16}$	$4.19_{3.26}^{5.35}$	$78.89_{62.52}^{101.67}$	$0.13_{0.10}^{0.20}$
LV	$14.06_{11.16}^{18.13}$	$7.28_{5.64}^{9.30}$	$140.56_{111.60}^{181.29}$	$0.41_{0.21}^{0.88}$
ET-D	$26.65_{20.81}^{34.28}$	$12.16_{9.34}^{15.31}$	$266.52_{208.06}^{342.80}$	$2.81_{1.33}^{5.98}$
CE	$41.50_{32.99}^{53.52}$	$20.52_{15.72}^{25.83}$	$414.62_{329.88}^{535.221}$	$10.59_{5.33}^{22.78}$

$$\delta R_{1.6} = \sqrt{(\delta R_{1.6}^{\mathrm{stat}})^2 + (\delta R_{1.6}^{\mathrm{sys}})^2}.$$



Instrument	$\mathcal{M}$	δf_{peak} [Hz]	$\delta R_{1.6}^{\mathrm{stat}}$ [m]	$\delta R_{1.6}$ [m]
aLIGO	$0.93_{0.91}^{0.96}$	$51.8_{23.1}^{139.4}$	$145.7_{78.3}^{228.9}$	$227.7_{191.7}^{288.1}$
A+	$0.93_{0.89}^{0.96}$	$44.4_{20.5}^{116.6}$	$125.5_{69.2}^{195.0}$	$215.3_{188.2}^{262.0}$
LV	$0.93_{0.90}^{0.96}$	$46.5_{21.3}^{123.1}$	$131.4_{71.9}^{204.8}$	$218.8_{189.2}^{269.4}$
CE	$0.91_{0.93}^{0.96}$	$51.6_{23.1}^{138.9}$	$78.1_{145.2}^{228.2}$	$191.6_{227.4}^{287.6}$
ET-D	$0.94_{0.92}^{0.97}$	$59.9_{26.0}^{163.3}$	$168.0_{88.4}^{267.5}$	$242.6_{196.1}^{319.7}$

Clark et al. 2016

Note:

- rate unclear, could be much higher
- Conservative estimate – numerical damping and finite duration→ underestimation of signal strength

Systematics error:

- Intrinsic scatter in relation
- Uncertainties in simulations

Better error for closer systems

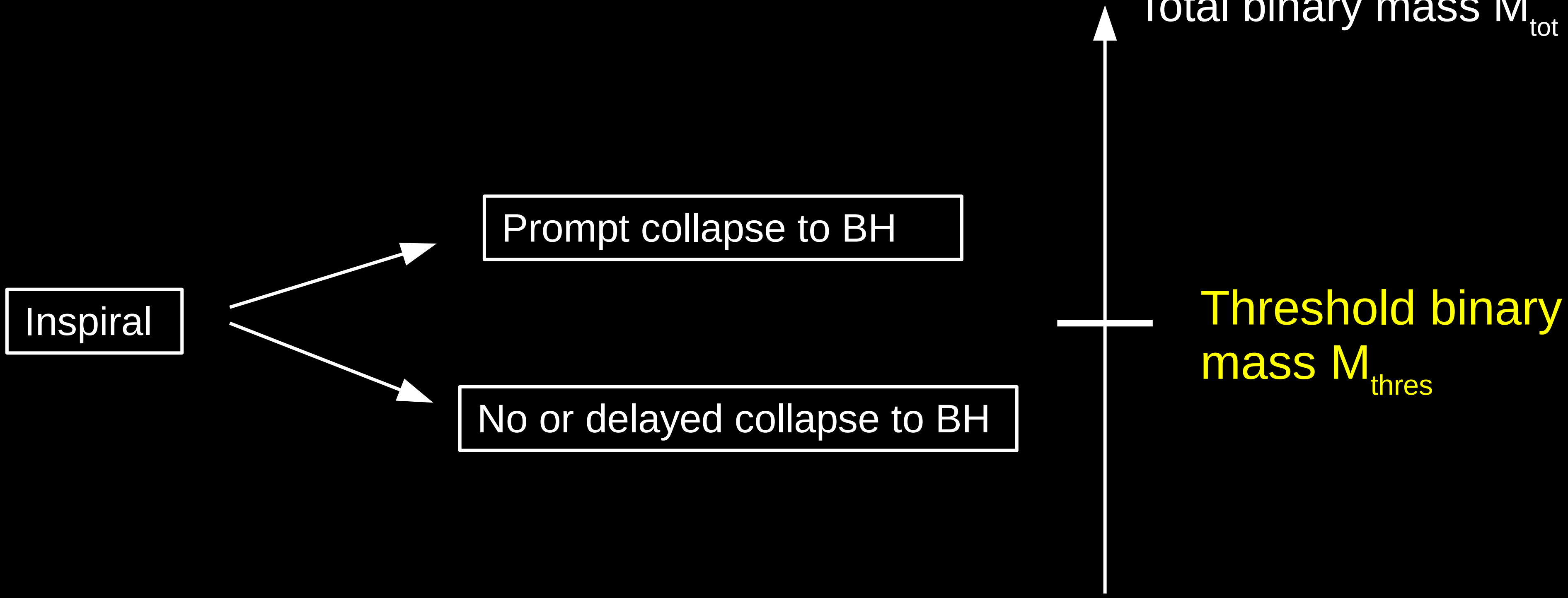
→ improvements possible

Collapse behavior and the maximum mass of (non-rotating) neutron stars

Key quantity: Threshold binary mass for prompt collapse

Note: Collapse behavior important for nucleosynthesis, kilonovae and short gamma-ray bursts !!!

Collapse behavior



Inspiral

Prompt collapse to BH

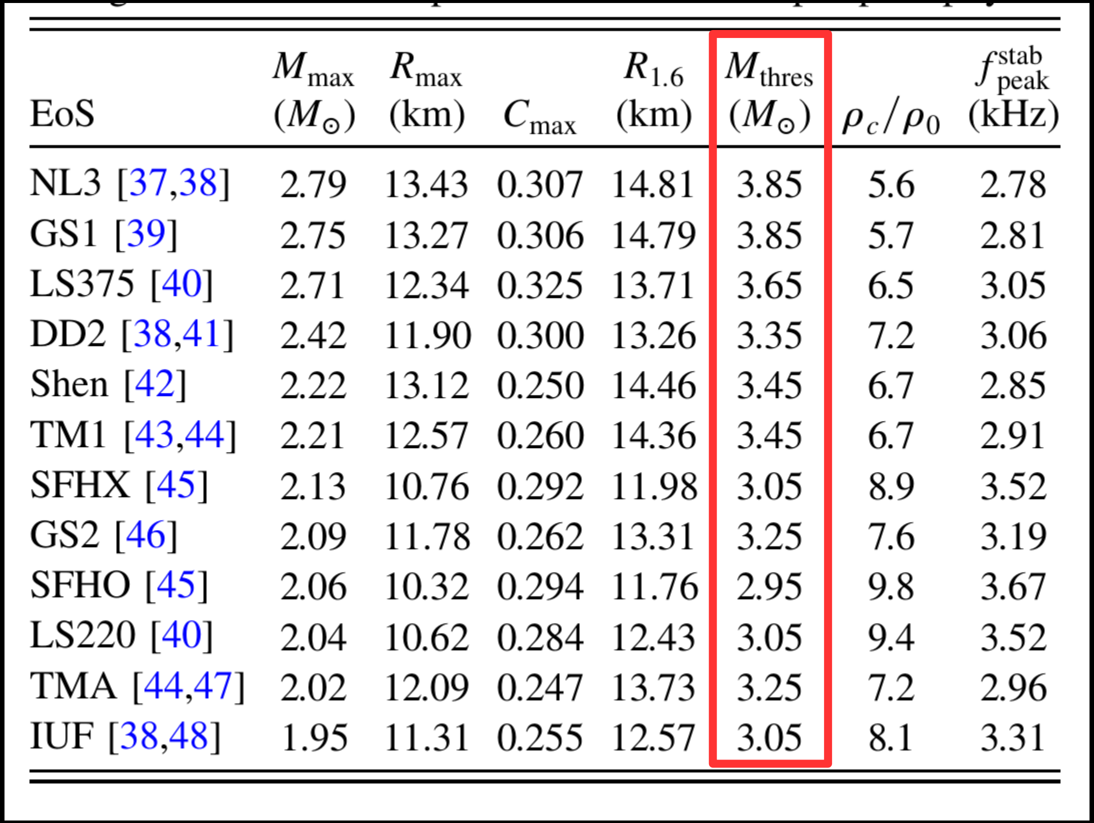
No or delayed collapse to BH

Total binary mass M_{tot}

Threshold binary mass M_{thres}

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

Simulations



EoS	M_{max} ($M_\odot$)	R_{max} (km)	C_{max}	$R_{1.6}$ (km)	M_{thres} ($M_\odot$)	ρ_c/ρ_0	$f_{\mathrm{peak}}^{\mathrm{stab}}$ (kHz)
NL3 [37,38]	2.79	13.43	0.307	14.81	3.85	5.6	2.78
GS1 [39]	2.75	13.27	0.306	14.79	3.85	5.7	2.81
LS375 [40]	2.71	12.34	0.325	13.71	3.65	6.5	3.05
DD2 [38,41]	2.42	11.90	0.300	13.26	3.35	7.2	3.06
Shen [42]	2.22	13.12	0.250	14.46	3.45	6.7	2.85
TM1 [43,44]	2.21	12.57	0.260	14.36	3.45	6.7	2.91
SFHX [45]	2.13	10.76	0.292	11.98	3.05	8.9	3.52
GS2 [46]	2.09	11.78	0.262	13.31	3.25	7.6	3.19
SFHO [45]	2.06	10.32	0.294	11.76	2.95	9.8	3.67
LS220 [40]	2.04	10.62	0.284	12.43	3.05	9.4	3.52
TMA [44,47]	2.02	12.09	0.247	13.73	3.25	7.2	2.96
IUF [38,48]	1.95	11.31	0.255	12.57	3.05	8.1	3.31

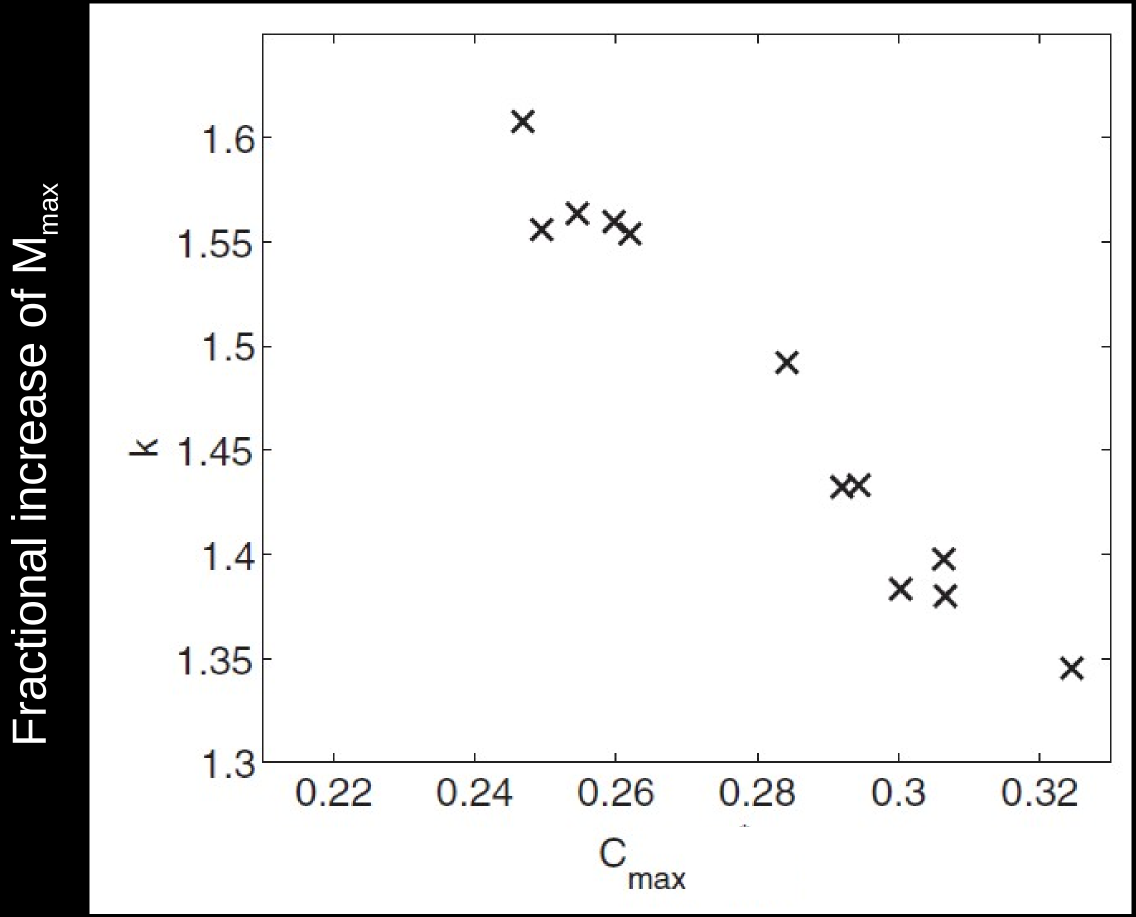
Simulations with many different binary masses

$$k = \frac{M_{thres}}{M_{max}}$$

from simulations

TOV property of employed EoS

Key quantity: Threshold binary mass M_{thres} for prompt BH collapse



$$M_{thres} = k * M_{max}$$

with $k = k(C_{max})$

$$C_{max} = G\, M_{max} / (c^2\, R_{max})$$

(compactness of TOV maximum-mass configuration)

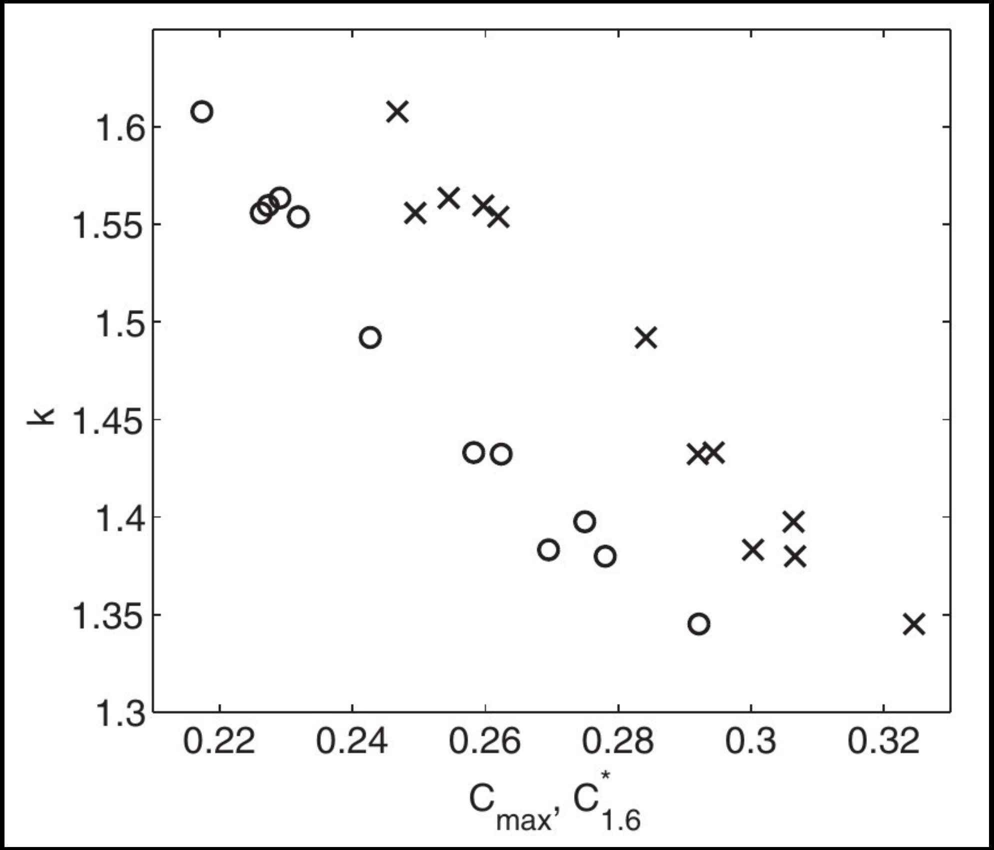
$\Rightarrow M_{thres} = M_{thres}(M_{max}, R_{max})$

Bauswein et al. 2013

$$k = \frac{M_{thres}}{M_{max}}$$

← From simulations with different M_{tot}

← TOV property of employed EoS



Fit: $k = \frac{M_{thres}}{M_{max}} = -3.6 \frac{G M_{max}}{c^2 R_{1.6}} + 2.38$

e.g. from f_{peak} measurement

M_{max} - Method 1

- Measure several NS mergers – check if postmerger GW emission present

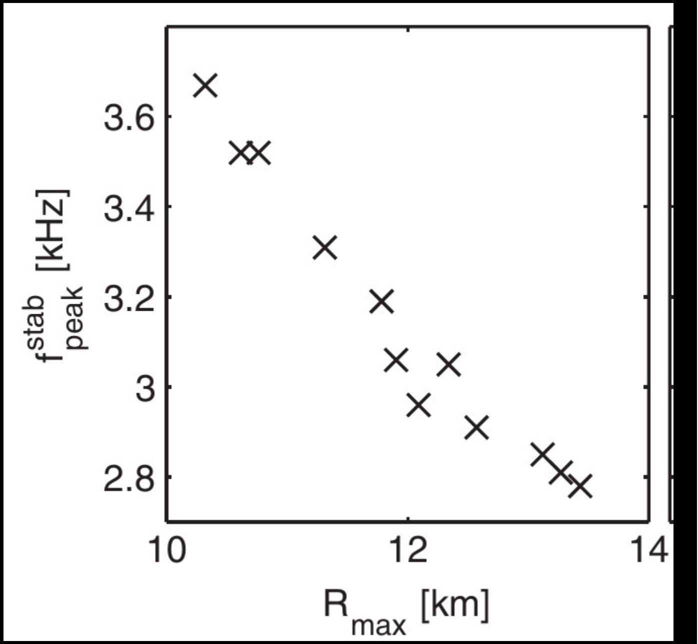
  → M_{thres} estimate

- (We ~ know radii at that point)
- Invert fit

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

  → M_{max}

- Note: already a single/few measurement could provide interesting constraints !!!

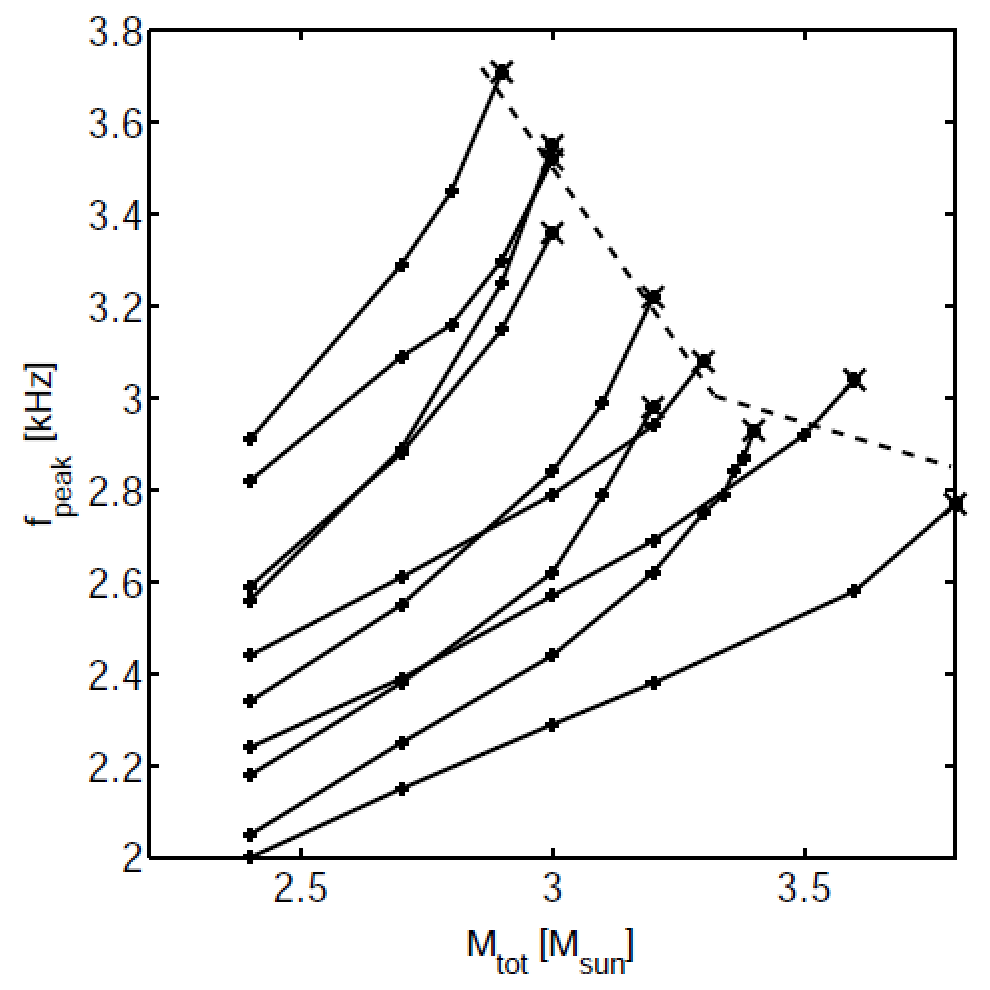


M_{max} – Method 2

- Possibly there are not many binaries with M_{tot} ~ M_{thres}
- May be hard to measure M_{thres}

- Method 2: extrapolate from observations as “moderate” binary masses
- e.g. two events: one with 1.25-1.25 M_{sun} and one with 1.4-1.4 M_{sun}

f_{peak} dependence on total binary mass



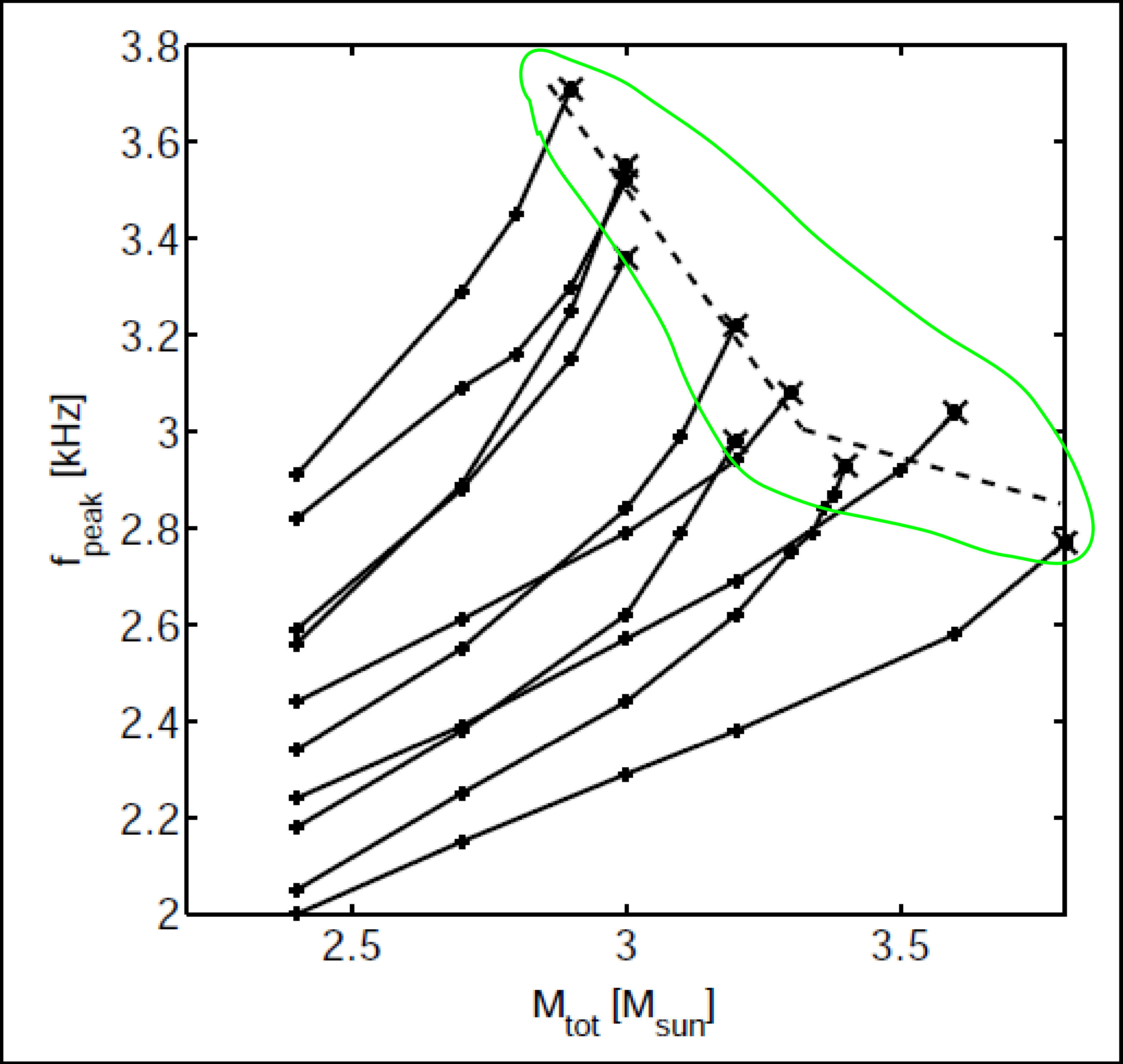
(every single line corresponds to a specific EoS
→ only one line can be the true EoS)

$$f_{peak} \sim \sqrt{\frac{M}{R^3}}$$

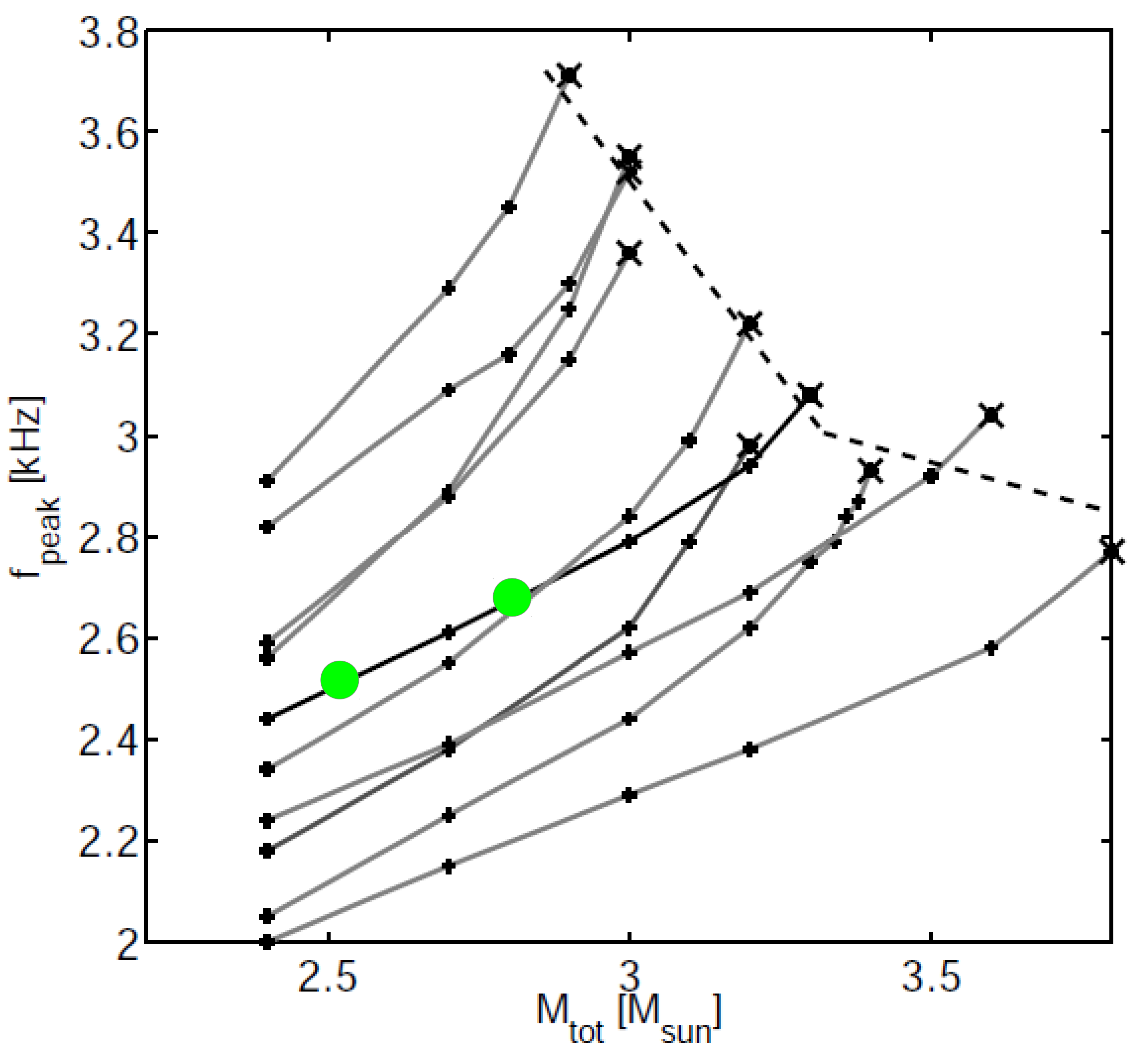
Dominant GW frequency monotone function of M_{tot}

Threshold to prompt BH collapse shows a clear dependence on M_{tot} (dashed line)

Threshold to prompt BH collapse



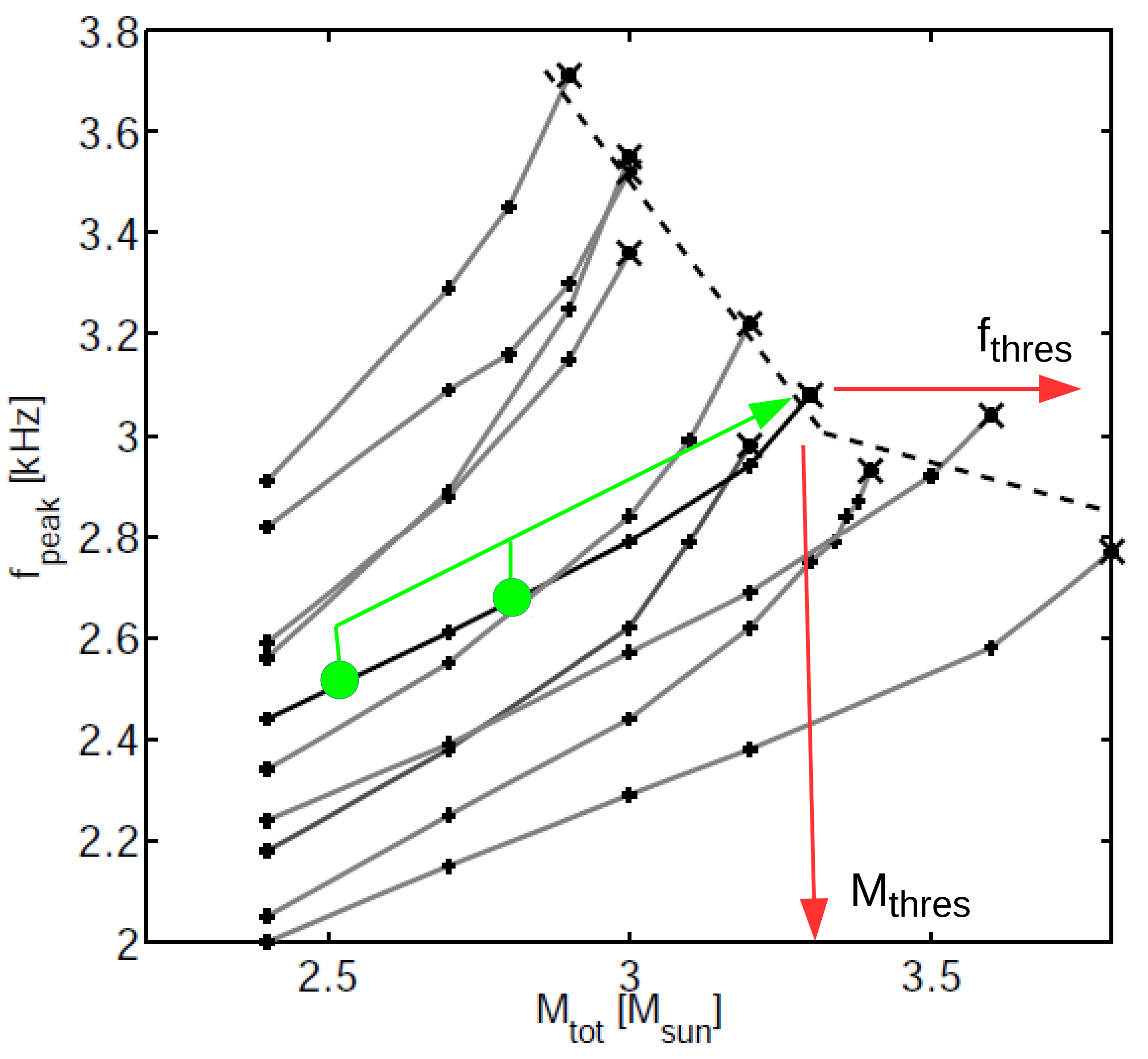
Extrapolation procedure



Details in Bauswein et al. 2014

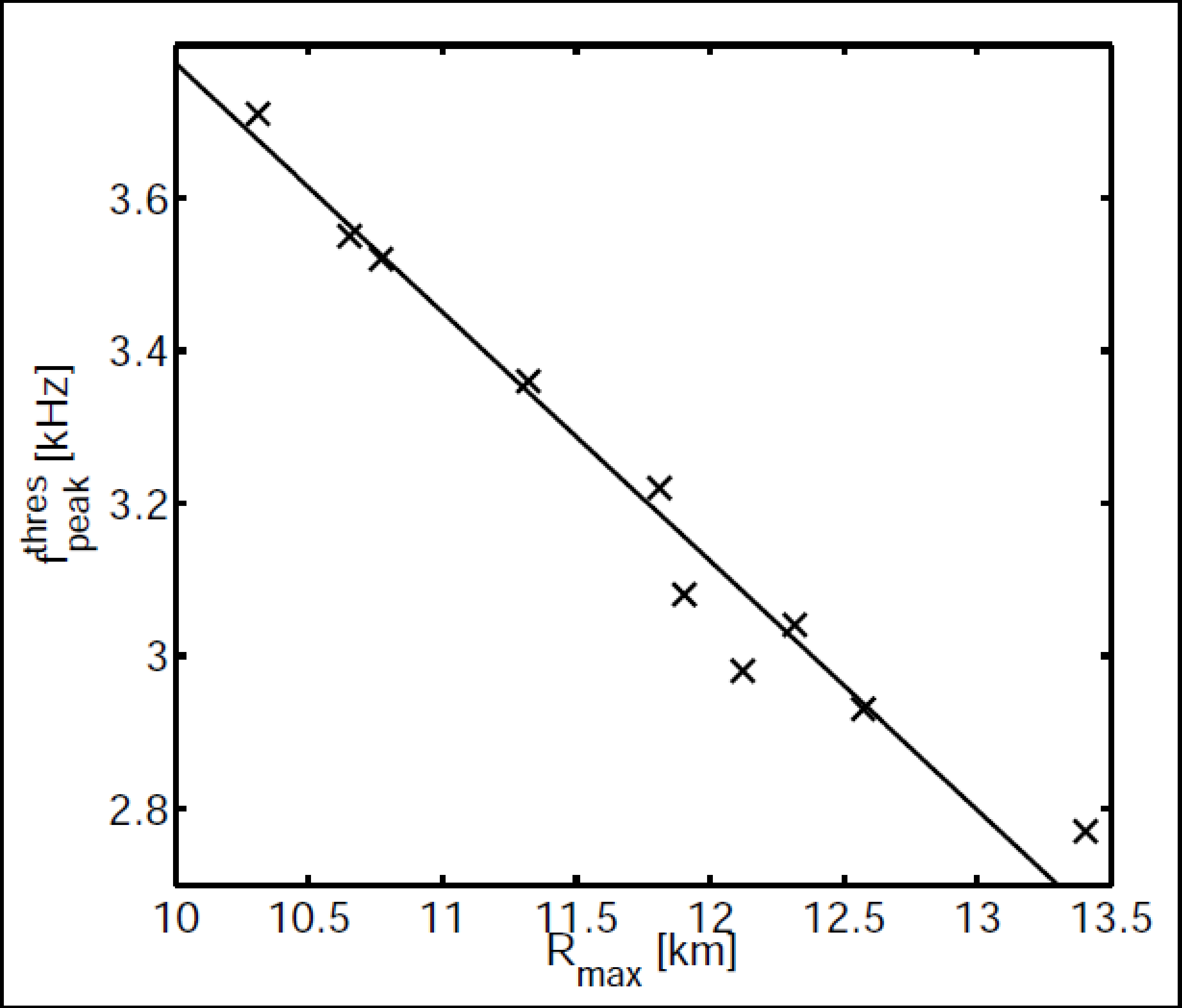
Two f_{peak} measurements at different M_{tot} yield threshold mass and “threshold frequency” !!!

Extrapolation procedure



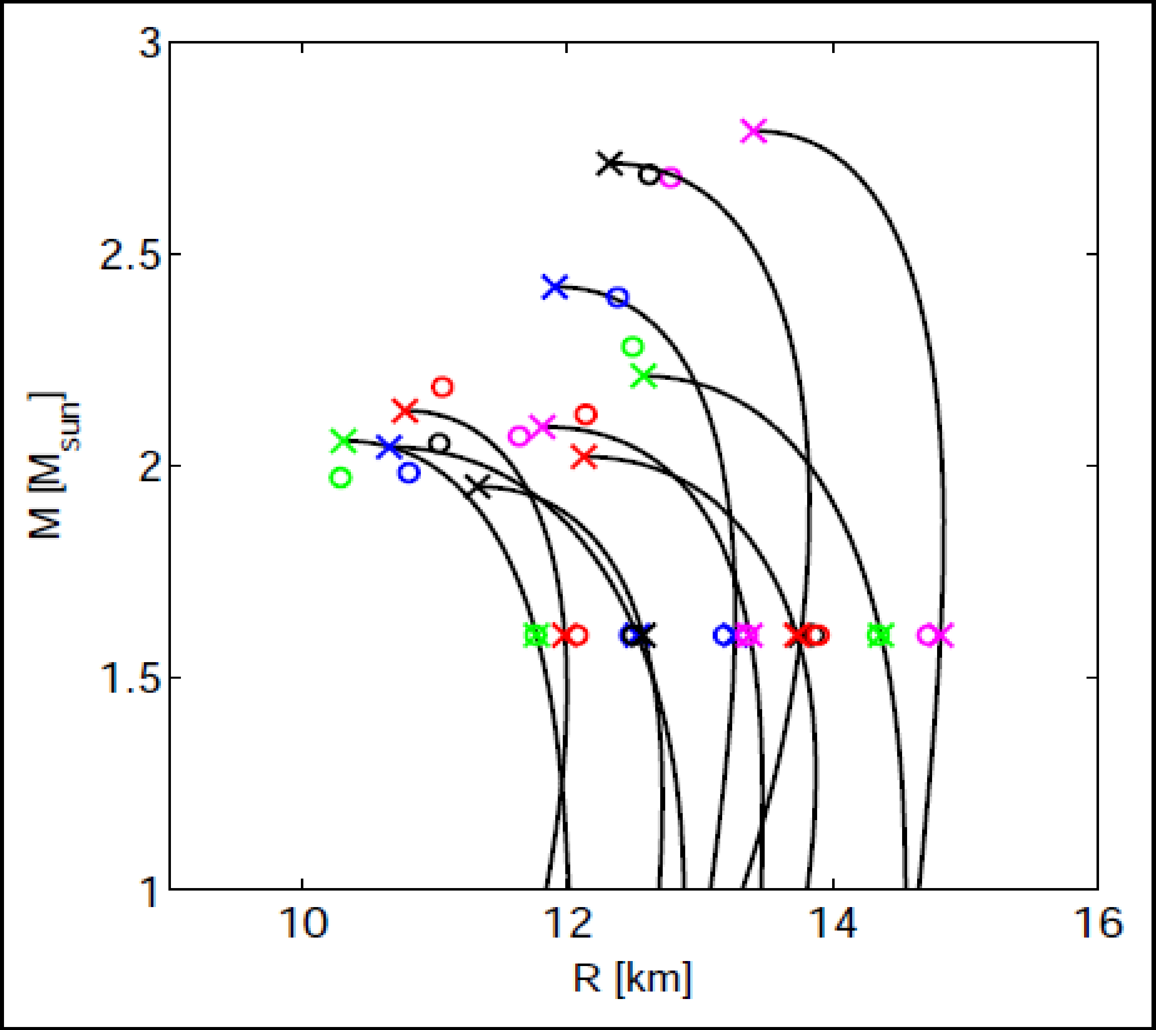
Two f_{peak} measurements at different M_{tot} yield threshold mass and “threshold frequency” !!!

R_{max} determination via extrapolation



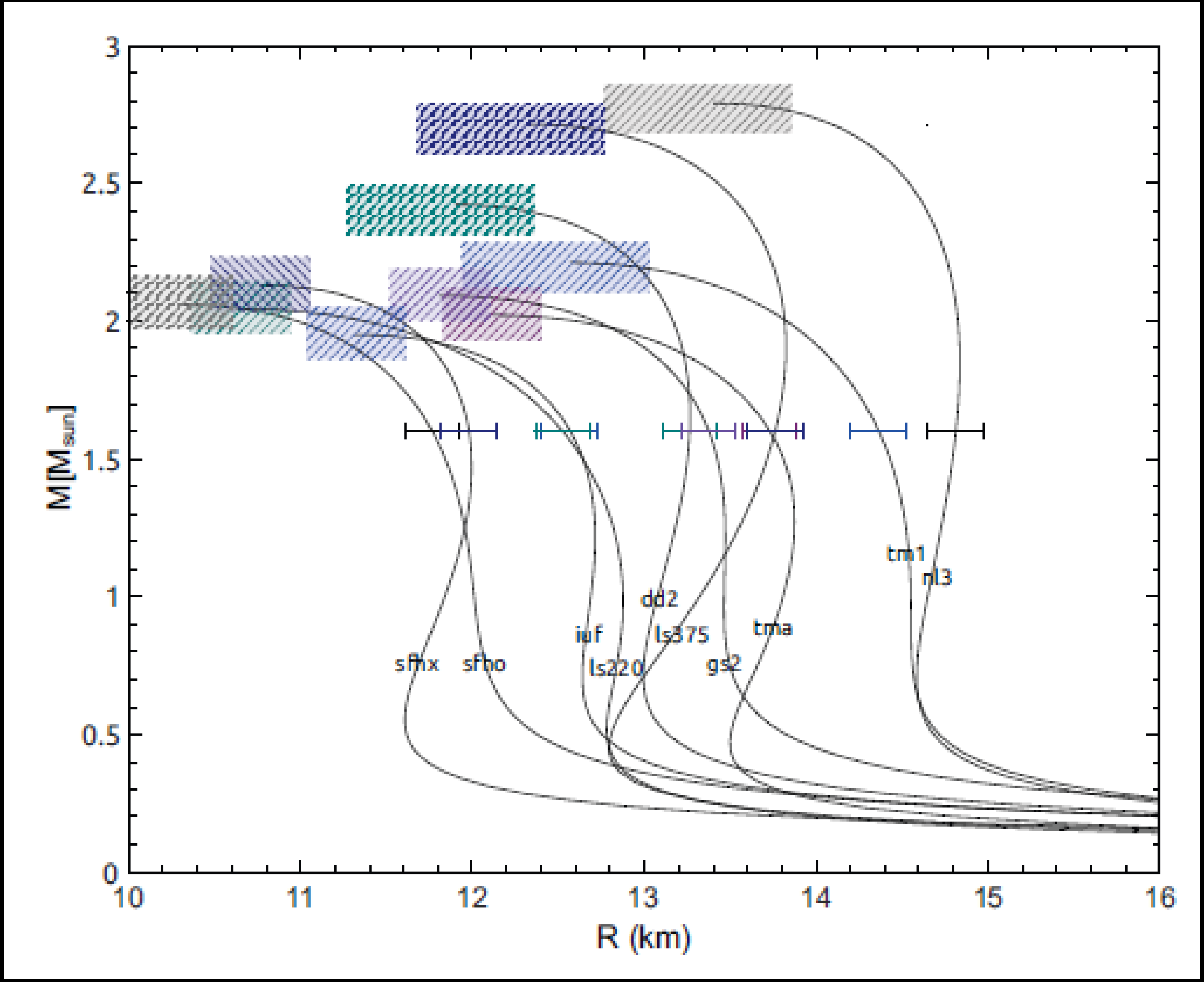
Threshold frequency f_{thres} yields a good estimate of the radius of the TOV maximum mass configuration (a few 100 meters)

Maximum mass via extrapolation



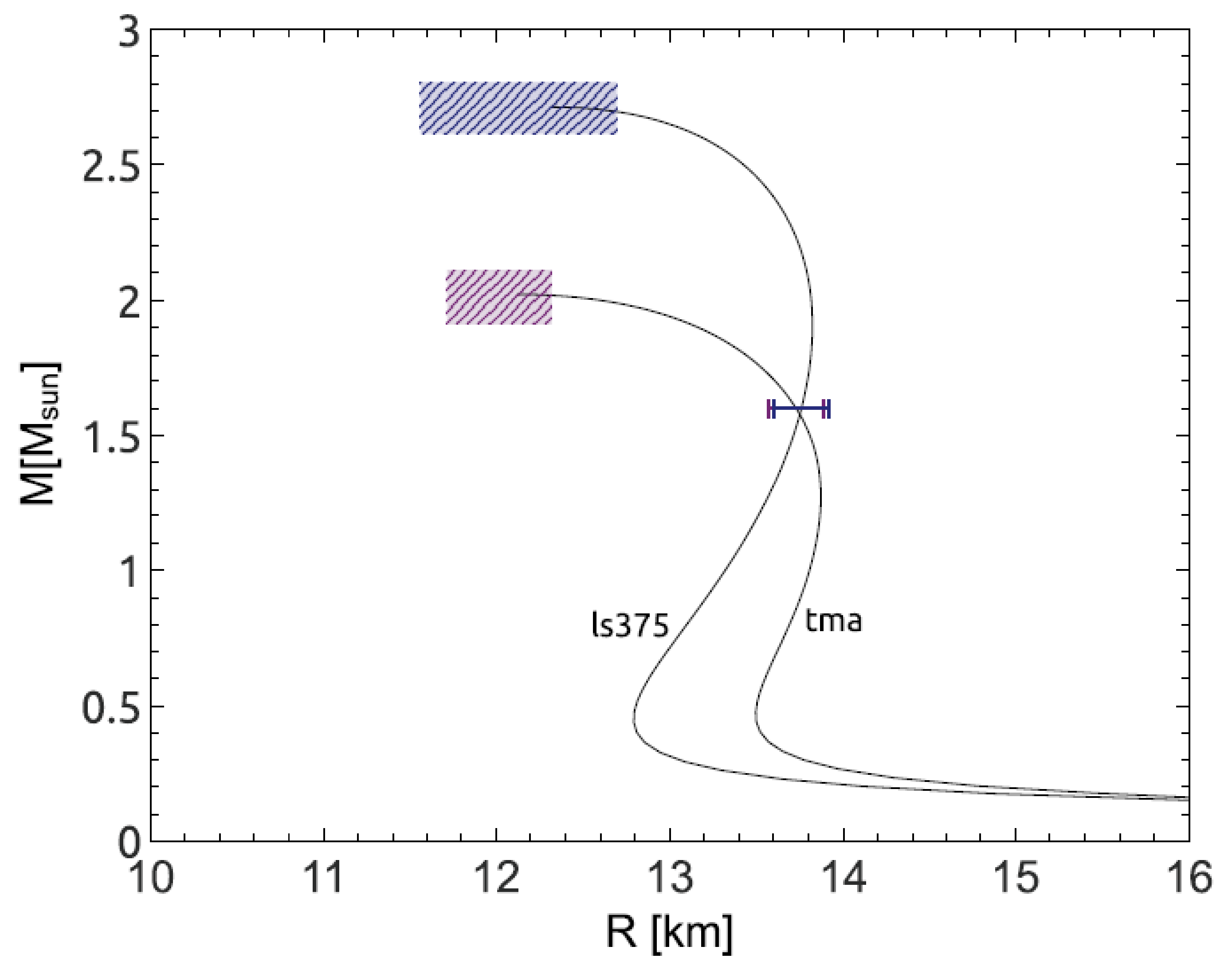
M_{max} within 0.1 M_{sun}, R_{max} within a few 100 m
(from f_{peak} detections at common M_{tot})

from two measurements of f_{peak} at moderate M_{tot}

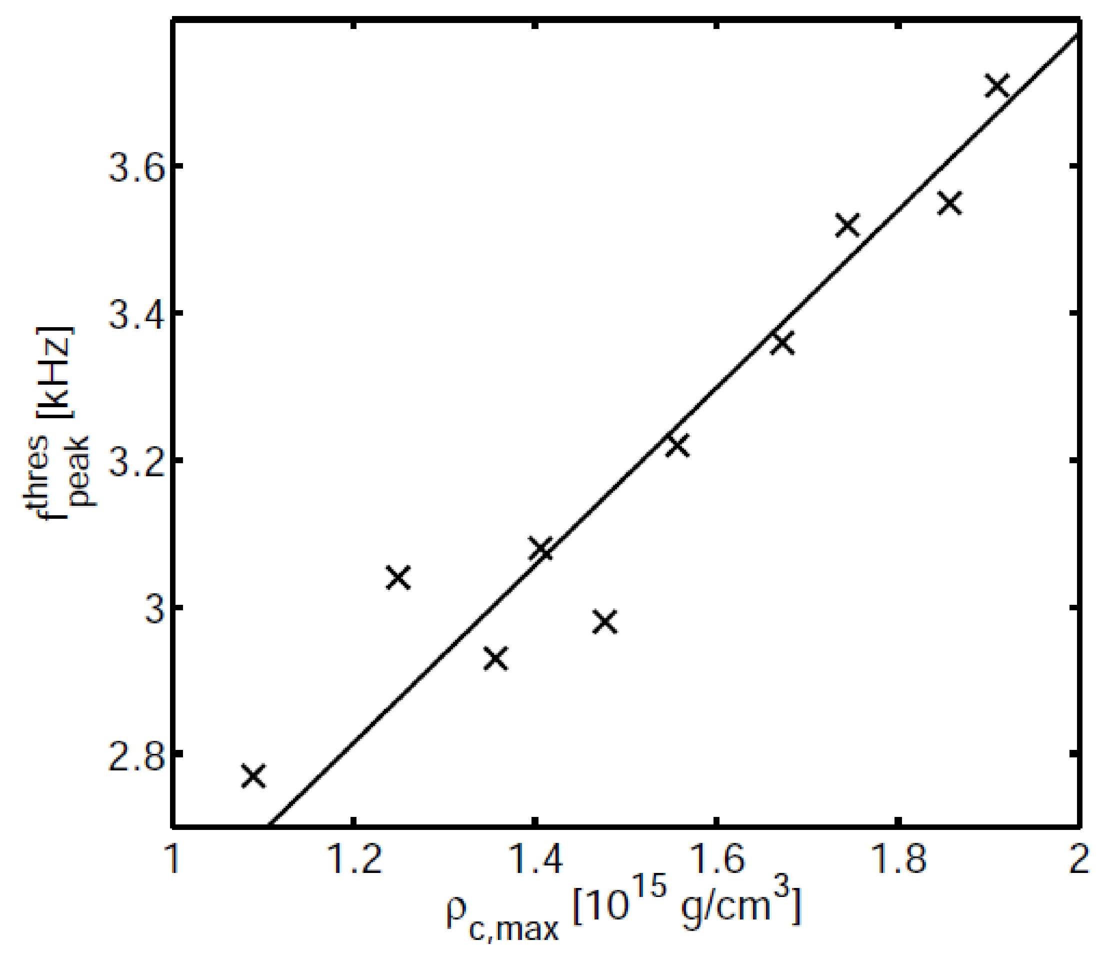


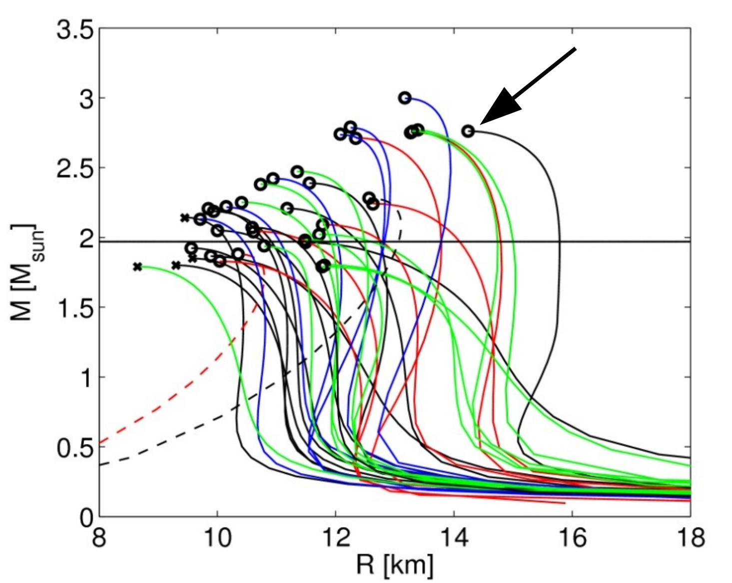
(final error will depend on EoS and extact systems measured)

Note: M_{thres} may also be constrained from prompt collapse directly


M[M$_{sun}$]
R [km]
0
0.5
1
1.5
2
2.5
3
10
11
12
13
14
15
16
ls375
tma

Maximum density via extrapolation

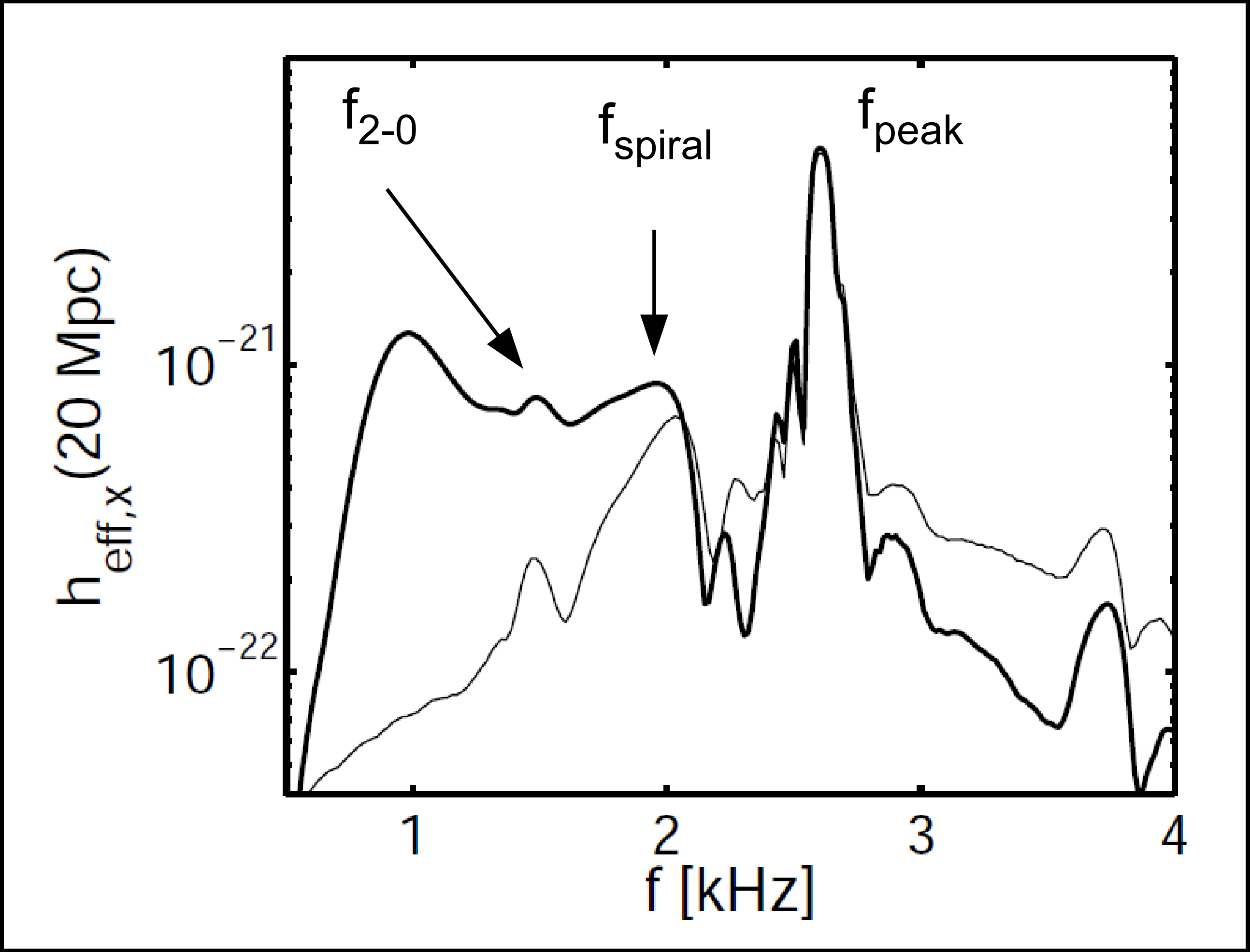


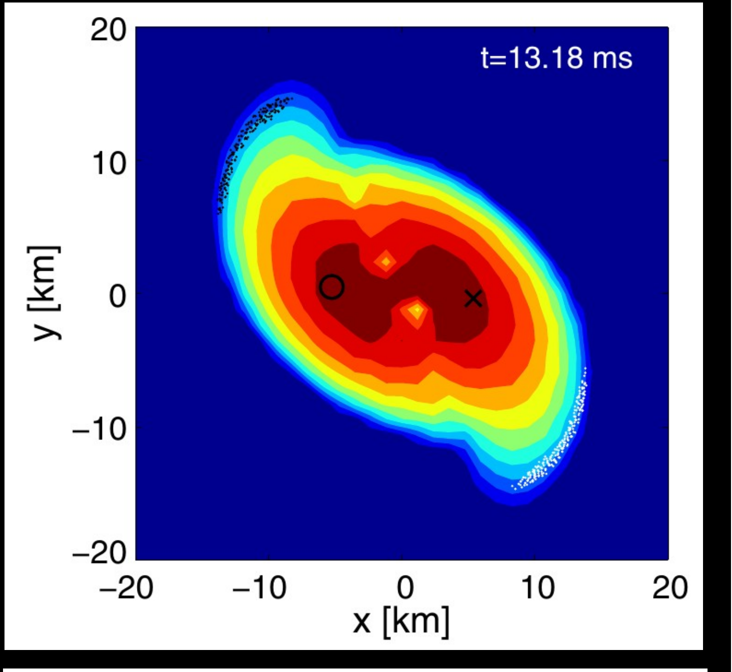


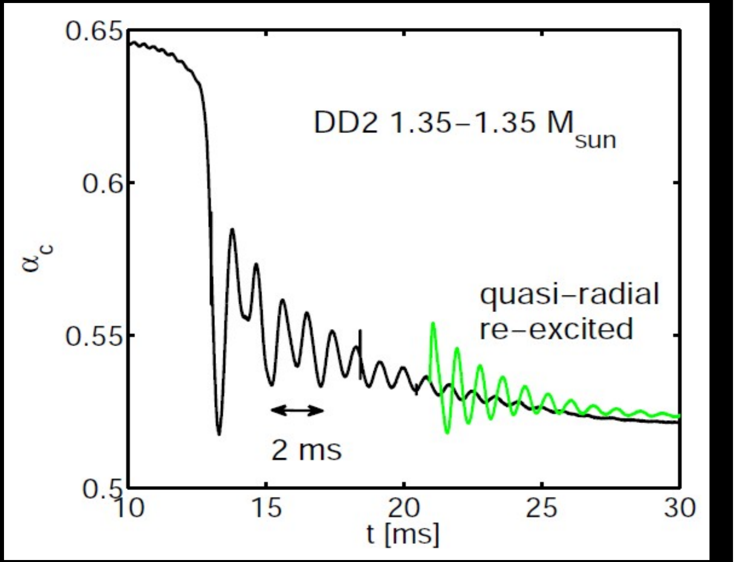
Maximum density of non-rotating NS within 10 per cent

Secondary GW peaks

Generic GW spectrum



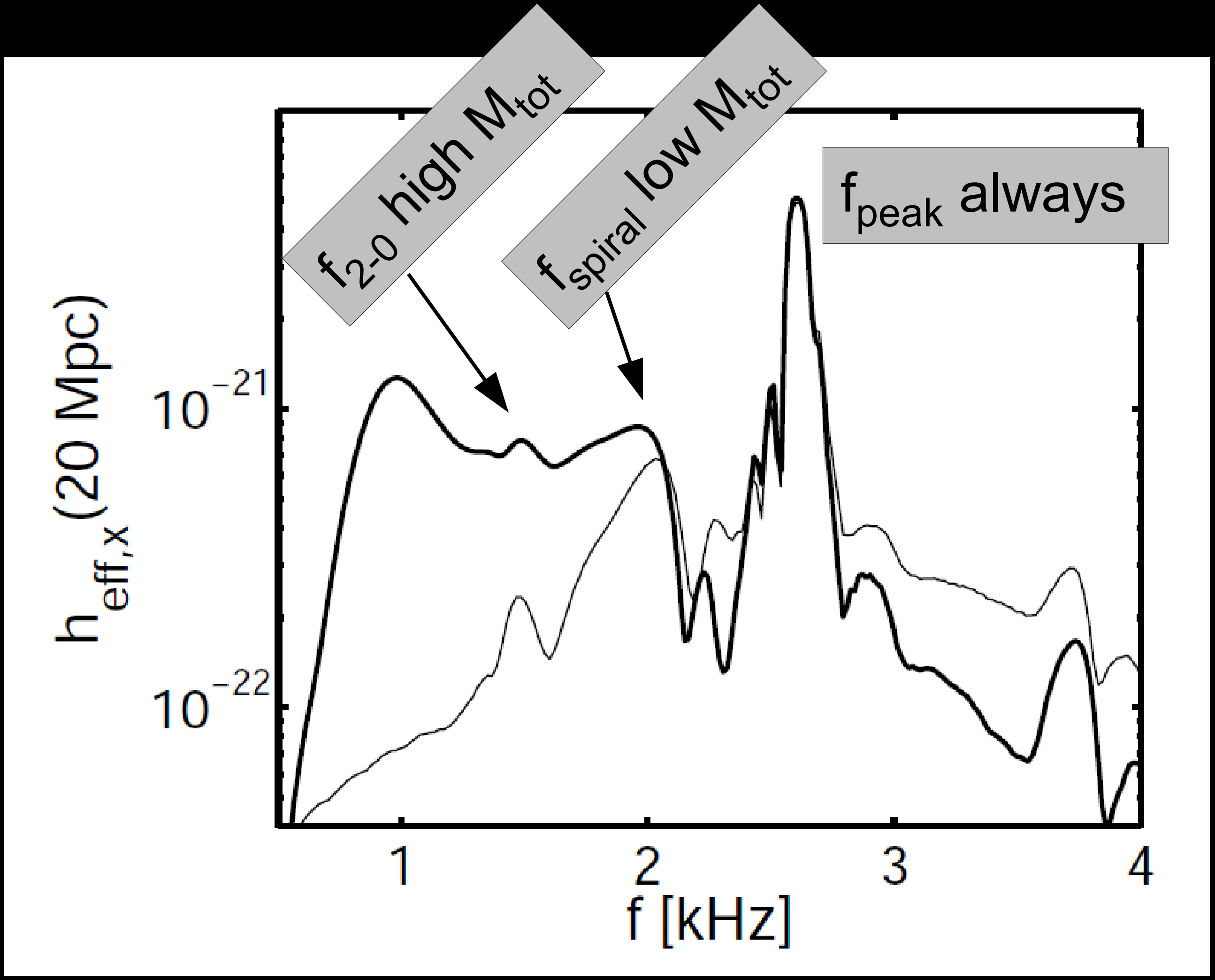




- Orbital motion of antipodal bulges generate peak at f_{spiral}
- Coupling between quasi-radial and quadrupolar mode

Bauswein & Stergioulas 2015

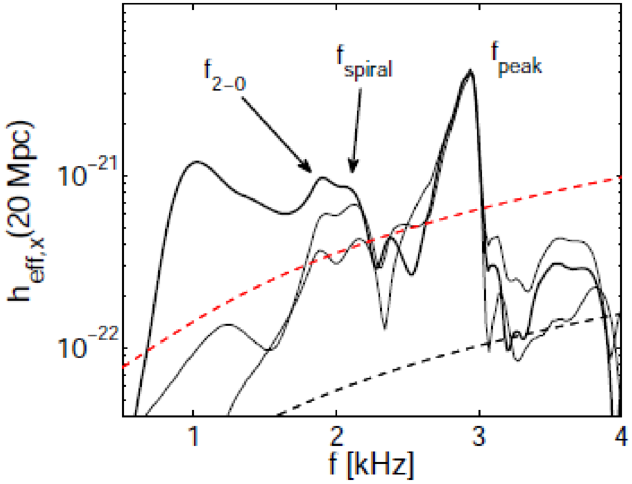
Survey of GW spectra



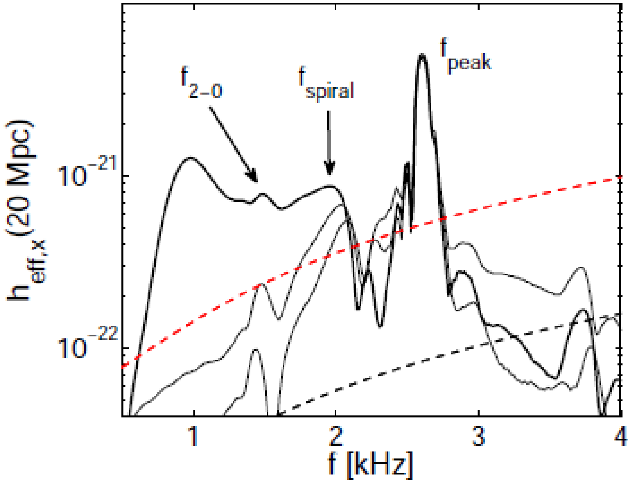
- Considering different models (EoS, M_{tot}): 3 types of spectra depending on presence of secondary features (dominant f_{peak} is always present)
- Secondary frequencies depend on EoS (similar as f_{peak})

Bauswein & Stergioulas 2015

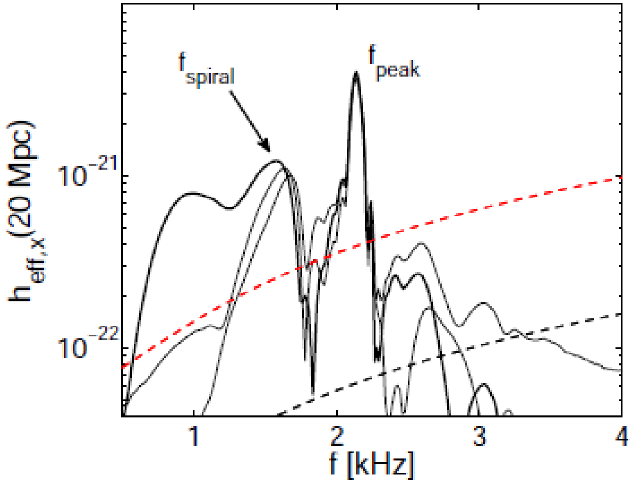
Survey of GW spectra



Type I



Type II



Type III

LS220, DD2, NL3 EoS all with M_{tot} = 2.7 M_{sun} → consider M_{tot} relative M_{thres}

=> Depending on binary model (EoS, M1/2) either one or the other or both features are present / dominant (if you measure a secondary peak you should always think whether it is $f_{2\text{-}0}$ or f_{spiral})

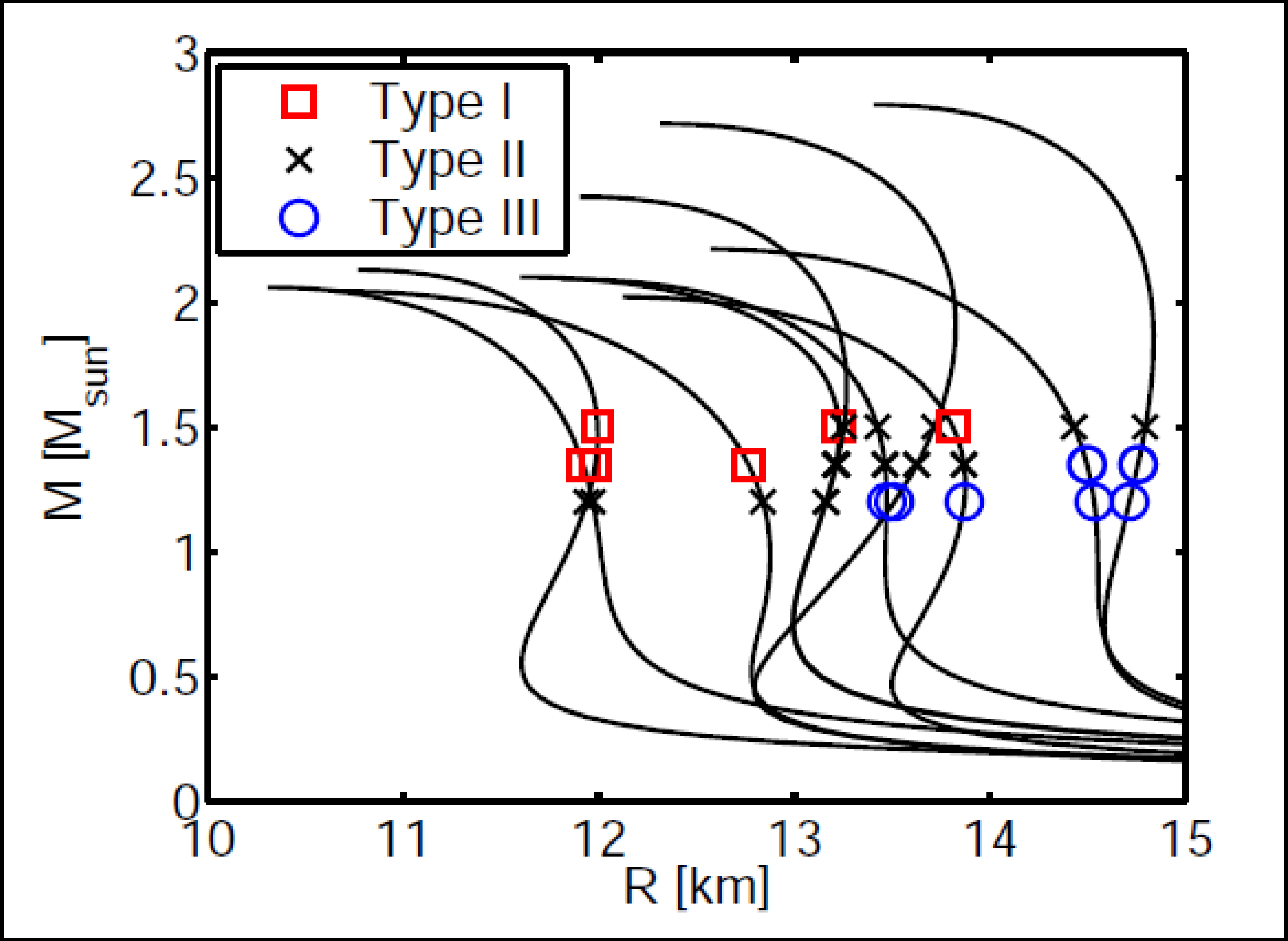
Classification scheme

- **Type I:** 2-0 feature dominates, f_{spiral} hardly visible, radial mode strongly excited, observed for soft EoS, relatively high M_{tot}
- **Type II:** both secondary features have comparable strength, clearly distinguishable, moderate binary masses
- **Type III:** f_{spiral} dominates, $f_{2\text{-}0}$ hardly visible, found for stiff EoS, relatively low binary masses, (central lapse, GW amplitude, rhomax show low-frequency modulation in addition to radial oscillation)

- Different types show also different dynamical behavior, e.g. in central lapse, maximum density, GW amplitude, ….
- High mass / low mass relative to threshold binary mass for prompt BH collapse (→ EoS dependent)
- Continuous transition between different types: a given EoS shows all types depending on M_{tot}: Type III for low M_{tot} → Type I towards M_{thres}

Bauswein & Stergioulas 2015

Classification scheme



Type of M_1-M_2 merger indicate at $M_{tot}/2 = M_1$

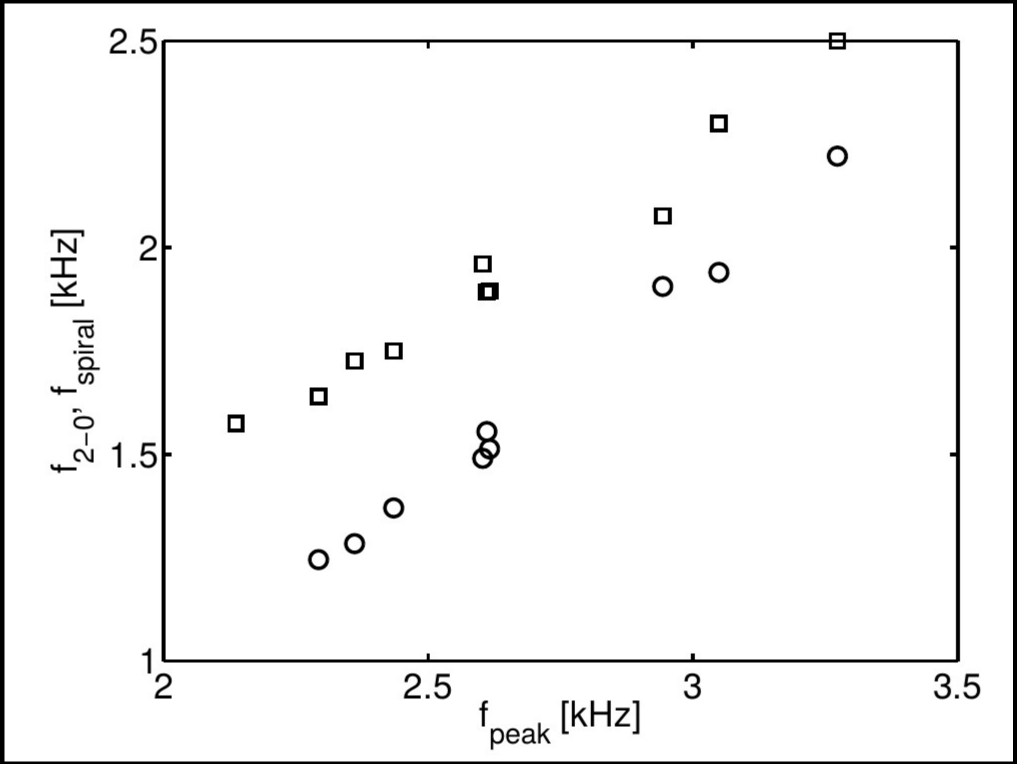
Bauswein et al. 2015

(Continuous transition between types → tentative association)

For M_{tot} = 2.7 M_{sun} all Types are possible depending on EoS

Classification intuitive: merger dynamics affected by compactness

Dependencies of secondary frequencies



1.35-1.35 Msun

Clark et al. 2016

→ secondary frequencies are essentially given by dominant frequency

Conclusions

- NS radii scale tightly with dominant postmerger GW frequency
- GW data analysis → radii measurable with precision of a few 100 m
- a single measurement of only the dominant frequency is sufficient
- Collapse behavior determined by EoS → maximum mass M_{max} of non-rotating NSs

  - directly determine M_{thres} by several merger events

  - extrapolation method: 2 events with “moderate” binary masses
- Radius R_{max} of maximum-mass TOV star
- Maximum density in NSs
- Secondary peaks generated by distinct mechanisms, EoS dependent, classification scheme based on presence of secondary features