Gravitational-Wave Emission from Neutron Star Mergers

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NAVI Physics Days

GSI Darmstadt, 19/01/2016

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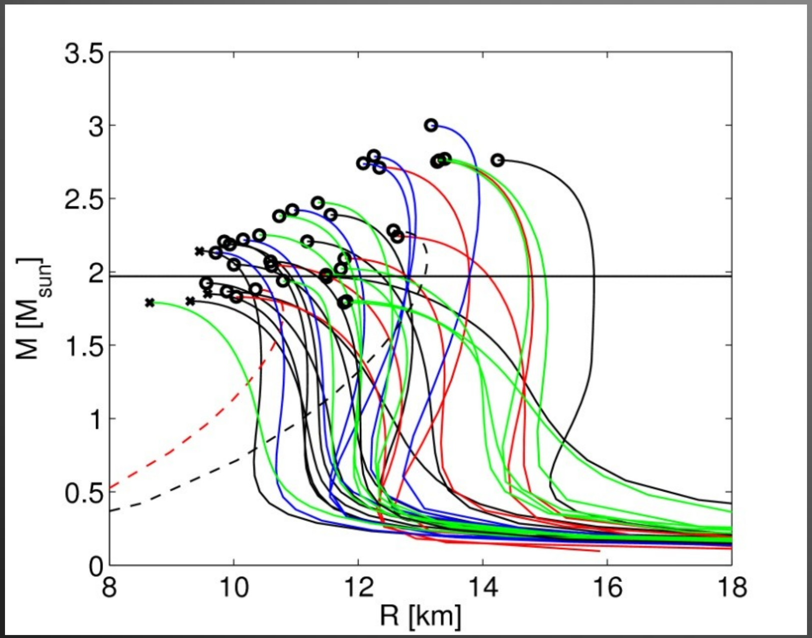
Motivation: understanding the GW emission

Focus on postmerger phase:

- constrain NS / EoS properties from GW measurements
- Construct templates (analytic model) → boost detectability



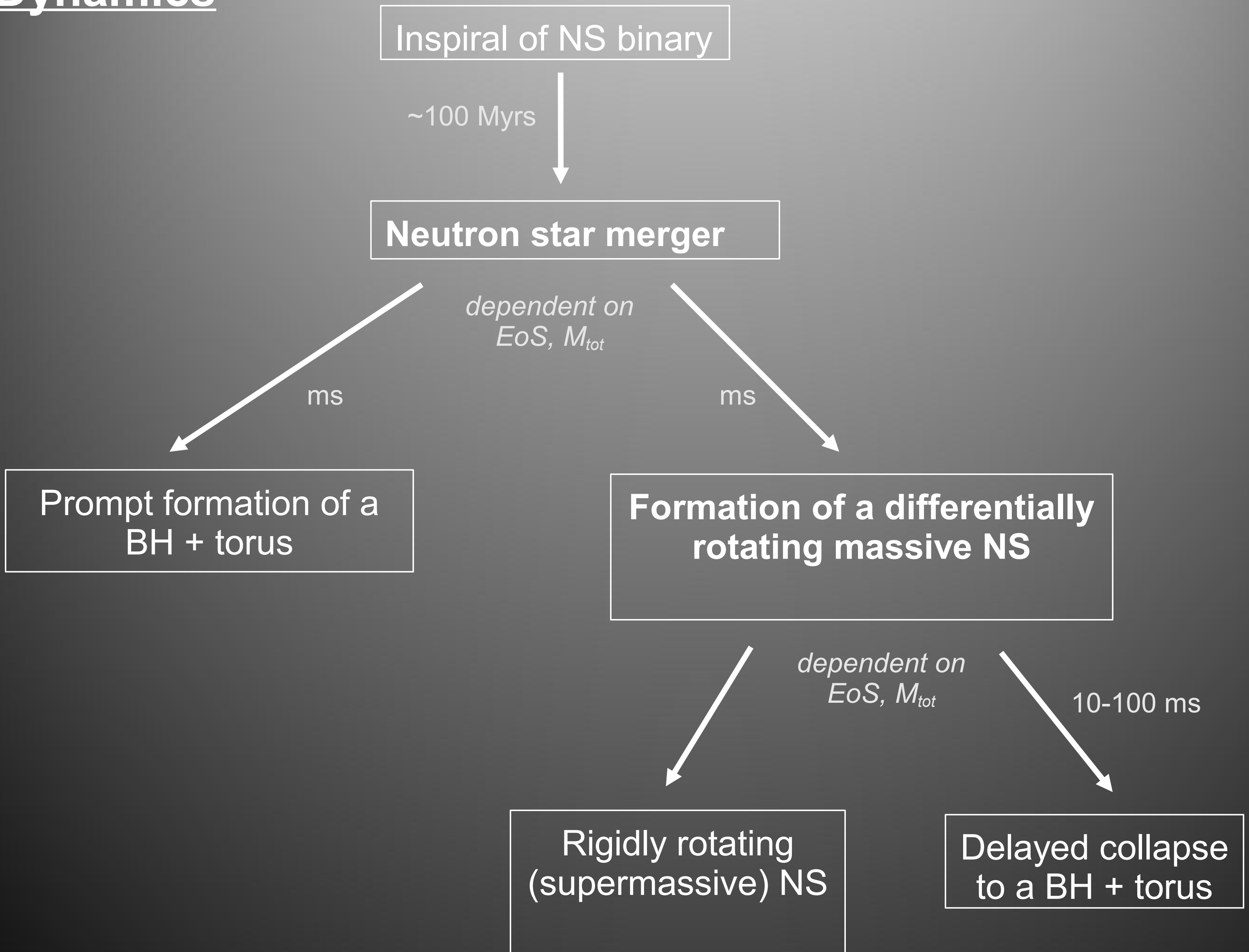
Advanced LIGO

Outline

- Overview
- Mass measurements
- Dominant postmerger GW emission

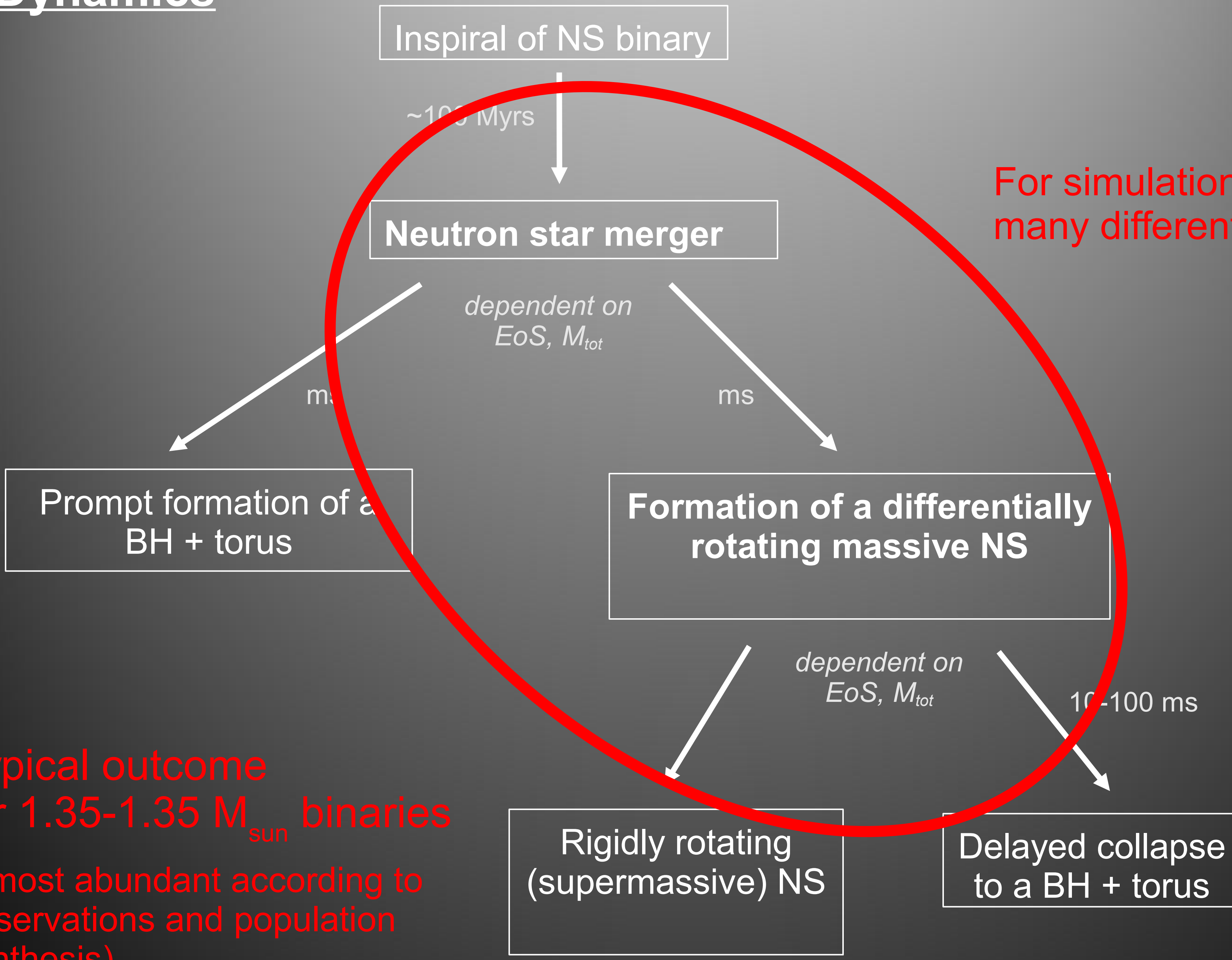
  - NS radius measurements
- Maximum mass of NS via collapse behavior of remnant
- Secondary features: Classification scheme of GW spectra / dynamics, universality of GW spectra, analytic model

Dynamics



Reviews: Duez 2010, Faber & Rasio 2012

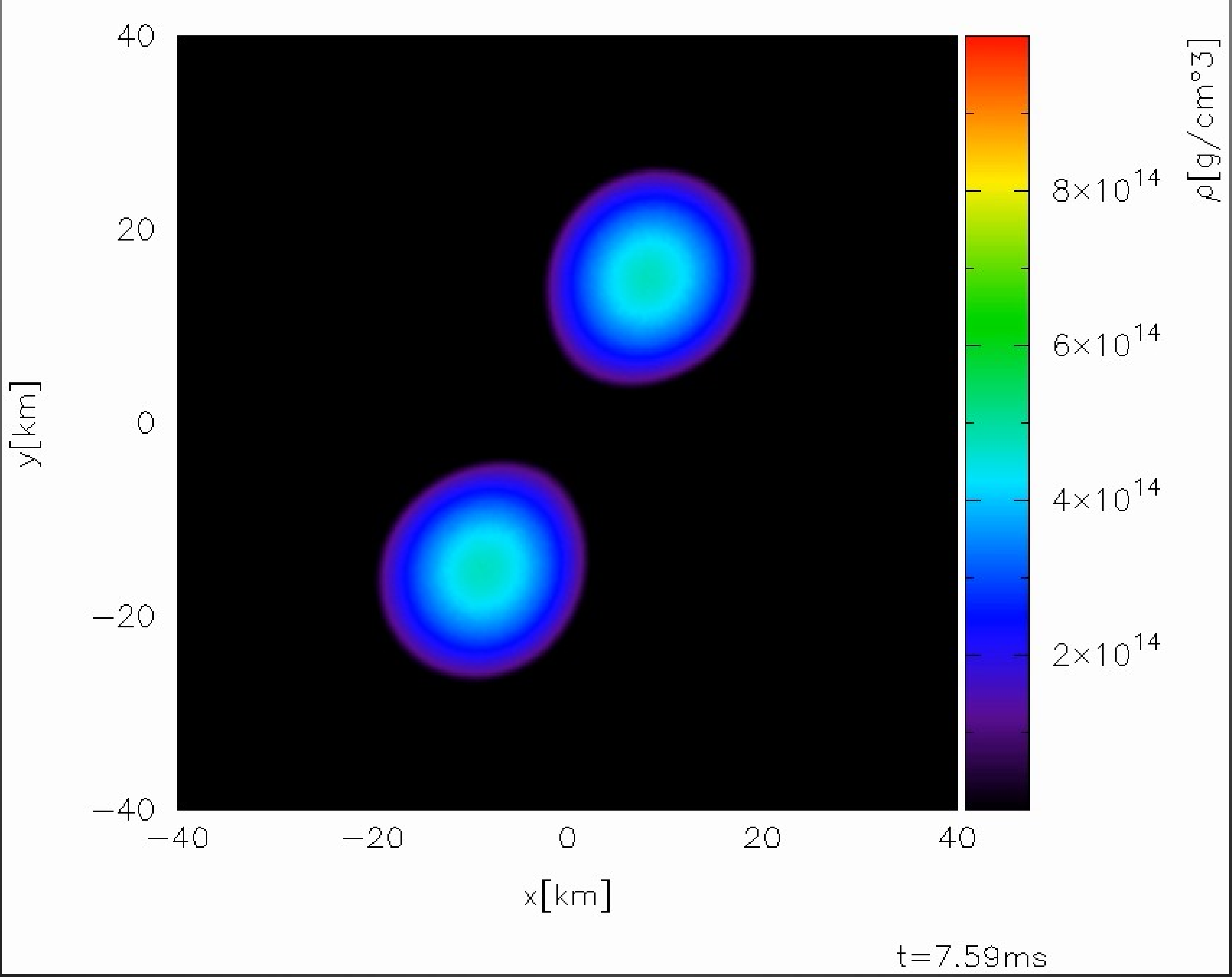
Dynamics



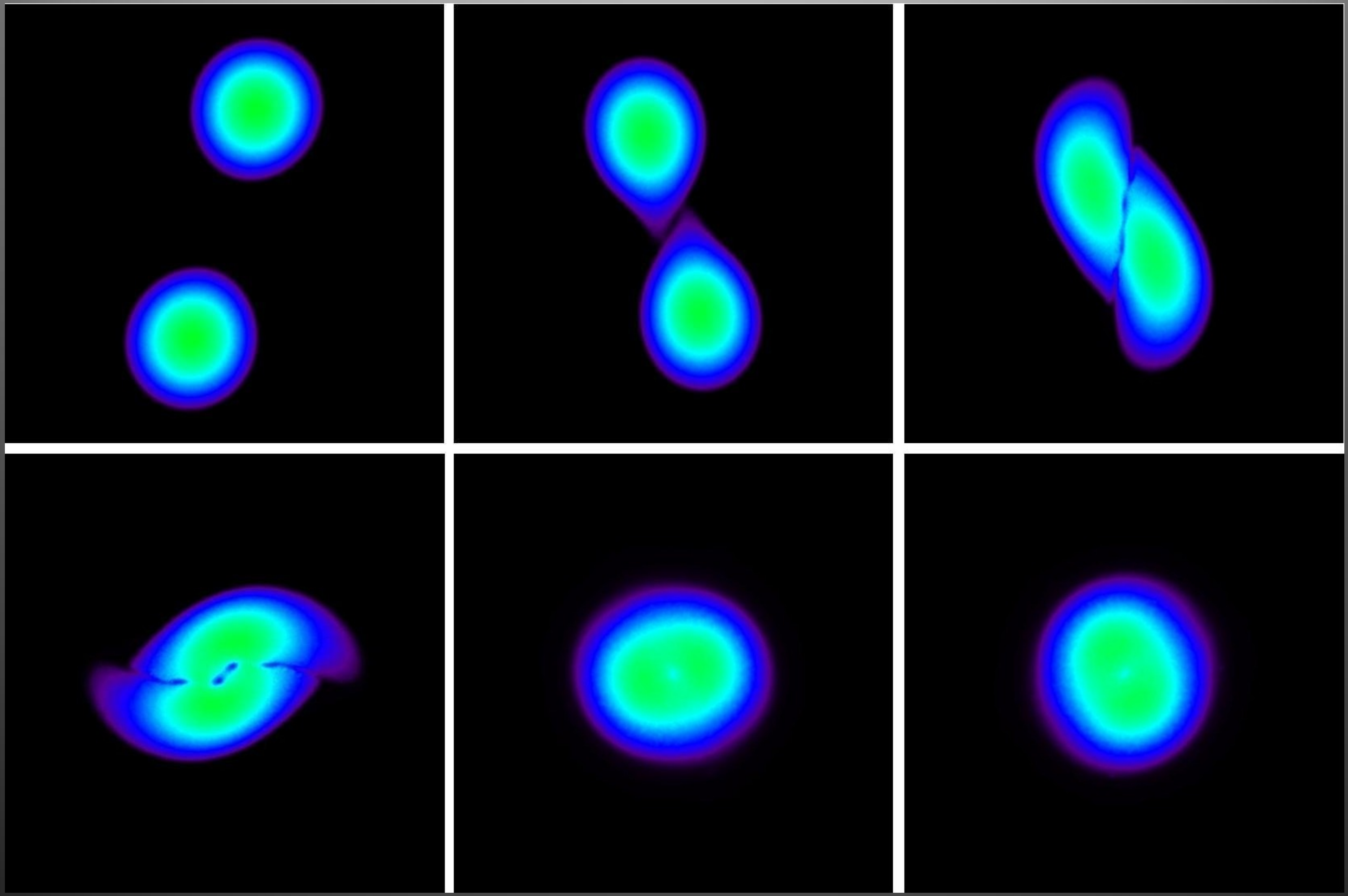
For simulations with many different NS EoSs

Typical outcome for 1.35-1.35 M_{sun} binaries

(~most abundant according to observations and population synthesis)

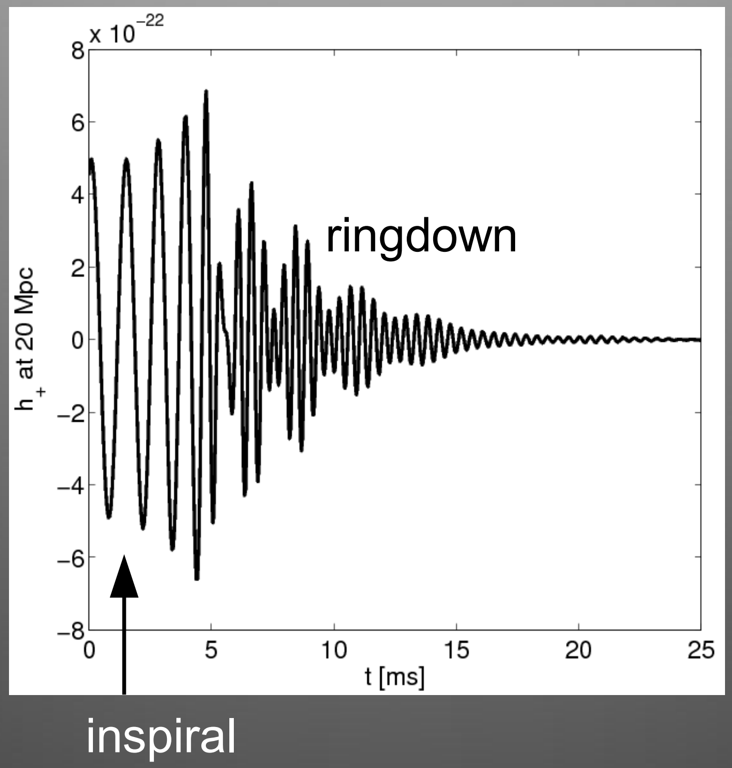

40
20
0
−20
−40
y[km]
−40
−20
0
20
40
x[km]
8×10^14
6×10^14
4×10^14
2×10^14
ρ[g/cm^3]
t=7.59ms

Simulation: snapshots



Rest-mass density evolution in equatorial plane: 1.35-1.35 M_{sun} Shen EoS

GW signal



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

What can be learned from the GW signal?

- Binary masses - easiest to measure via matched filtering (template bank)

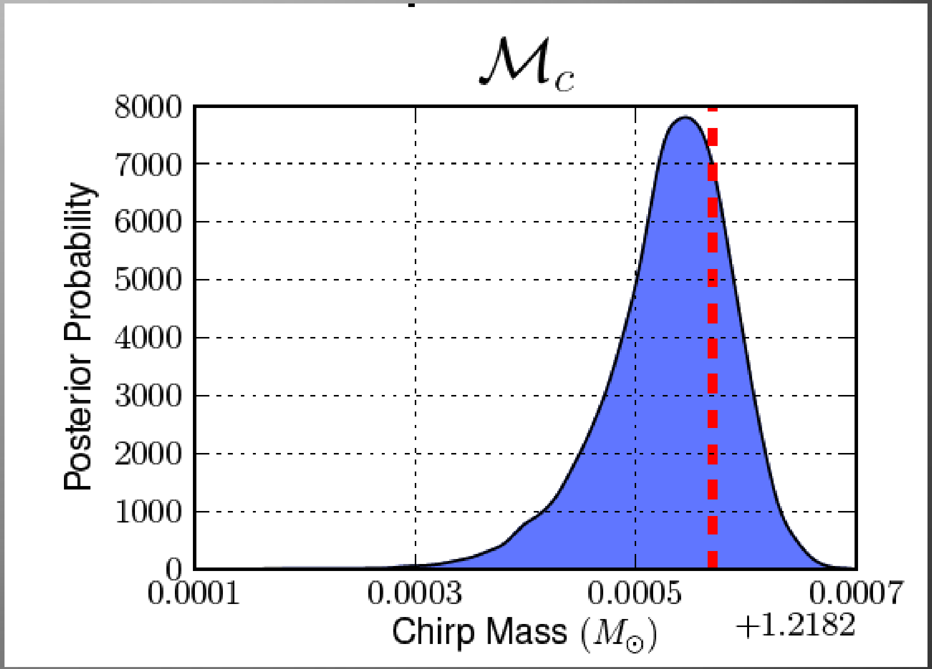
  - dynamics of the inspiral mostly determined by masses

- EoS via NS properties (more difficult to measure, i.e. near-by event required) → different complementary approaches (tidal effects in the late inspiral, oscillations of the postmerger remnant)

Masses from the inspiral

Accurately measured "chirp mass"

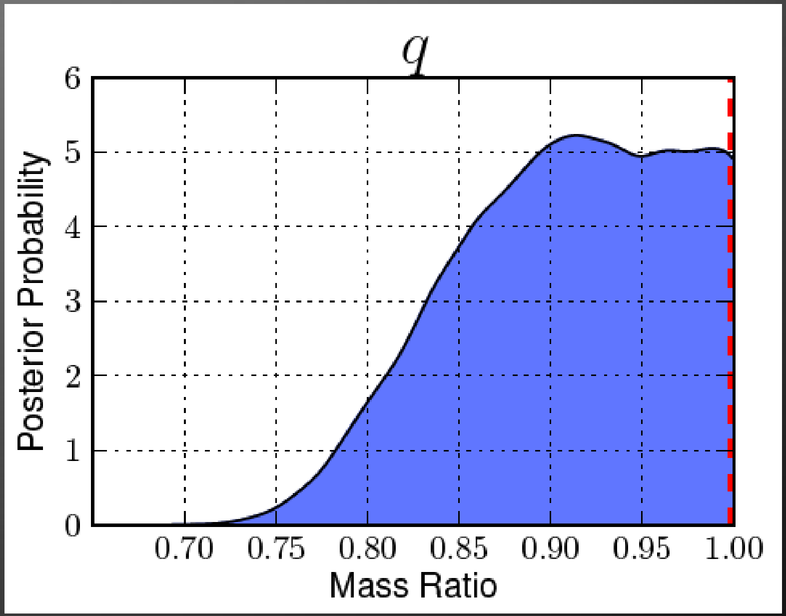
$$M_{chirp} = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}}$$



Mass ratio with larger error

$$q = M_1/M_2$$

i.e. q only for near-by mergers



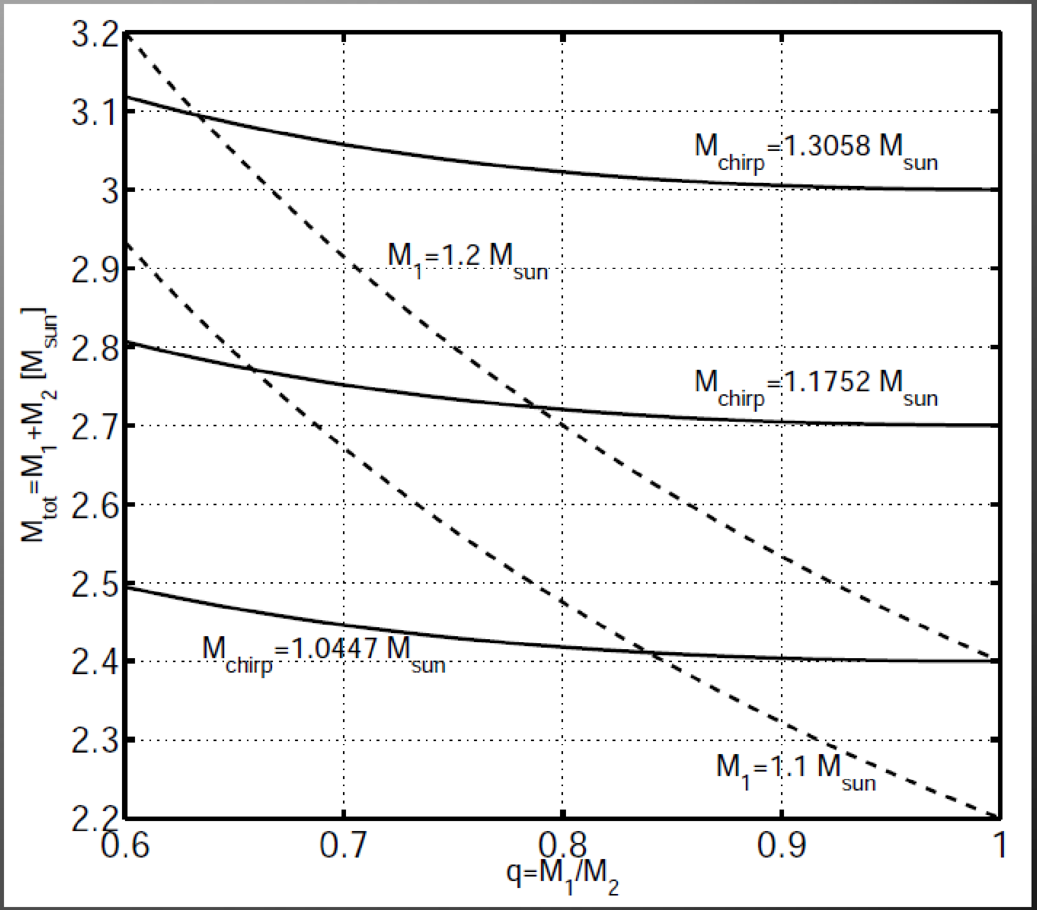
Rodriguez et al 2014 – injected at 100 Mpc

Total mass from chirp mass

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

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

→ Chirp mass determines M_{tot} quite well



Bauswein et al. 2015

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

EoS from GWs: an oversimplified picture

Two complementary approaches to infer EoS properties:

- GW inspiral:

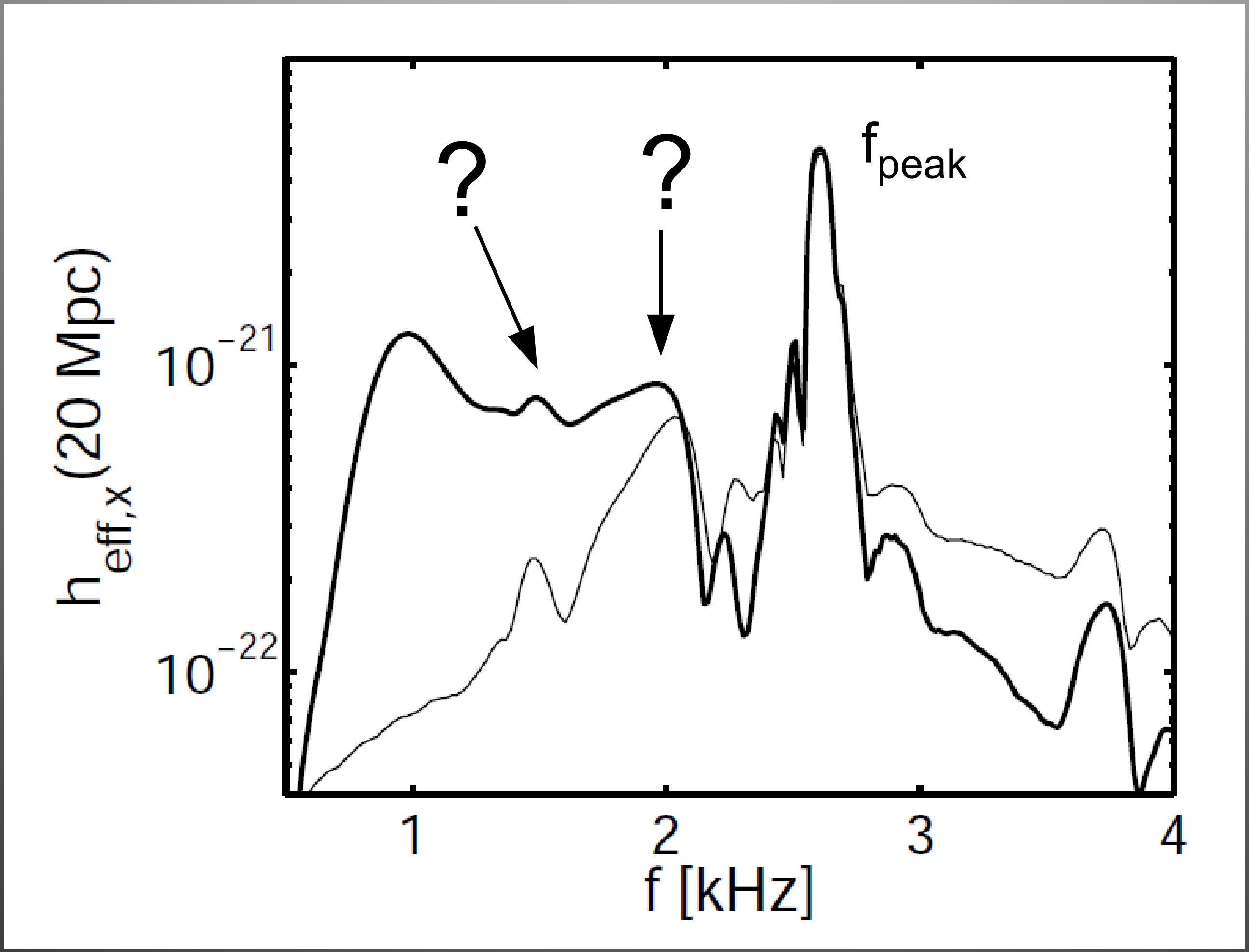
  strong signal - weak EoS effect

  (e.g. Read et al. 2013 → ~1.3 km @ 100 Mpc; e.g. Flanagan & Hinderer 2008, Hinderer et al. 2010, Damour et al. 2012, Maselli et al. 2013, Del Pozzo et al 2013, Yagi & Yunes 2014, Wade et al. 2014, ...) - accurate templates not yet available

- Postmerger oscillations:

  weak signal – robust strong EoS effect

Generic GW spectrum



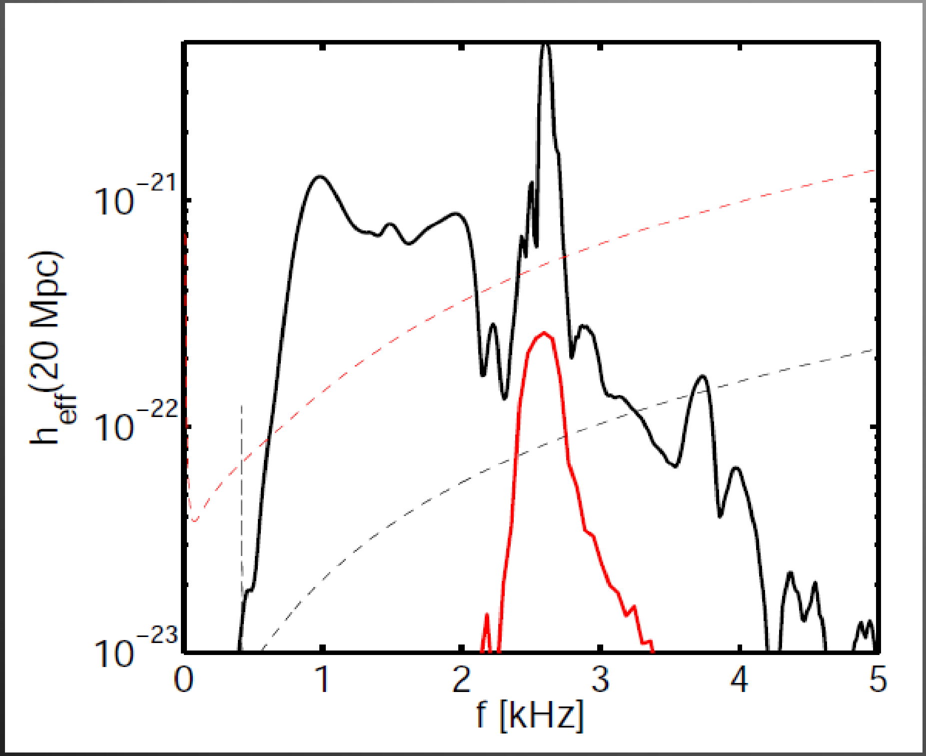
Thin line
postmerger only

- Up to three pronounced features in the postmerger spectrum (+ structure at higher frequencies)
- Simulation: 1.35-1.35 M_{sun} DD2 EoS (table from Hempel et al.)

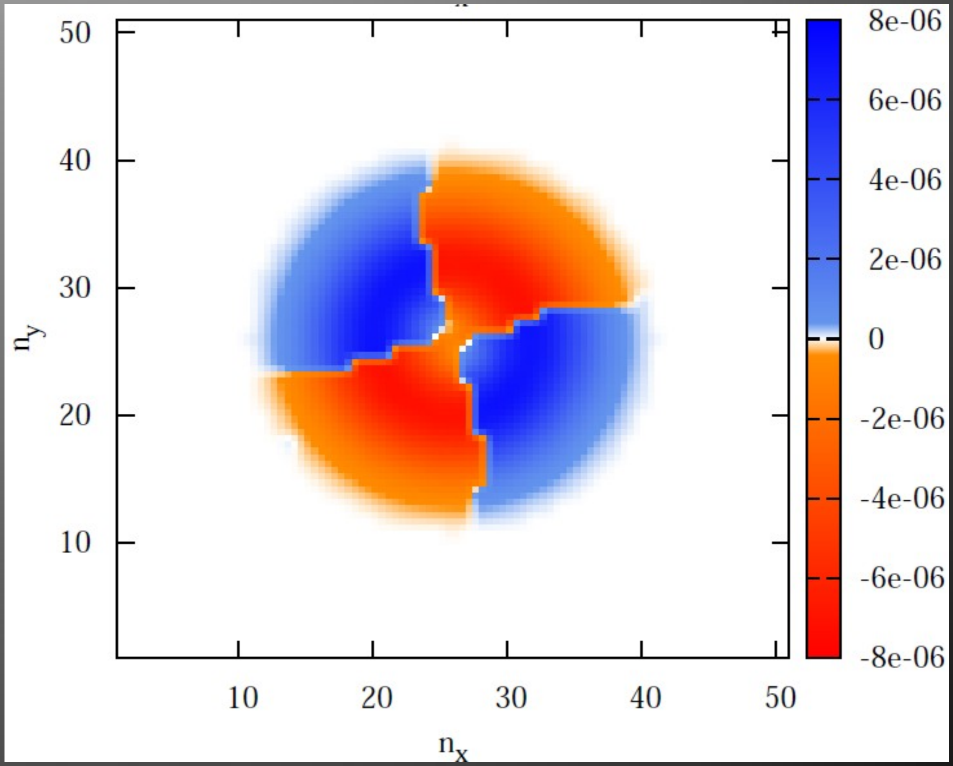
In the literature f_{peak} is also called f_2

Dominant oscillation frequency

- Robust feature, which occurs in all models (which don't collapse promptly to BH)
- Fundamental quadrupolar fluid mode of the remnant

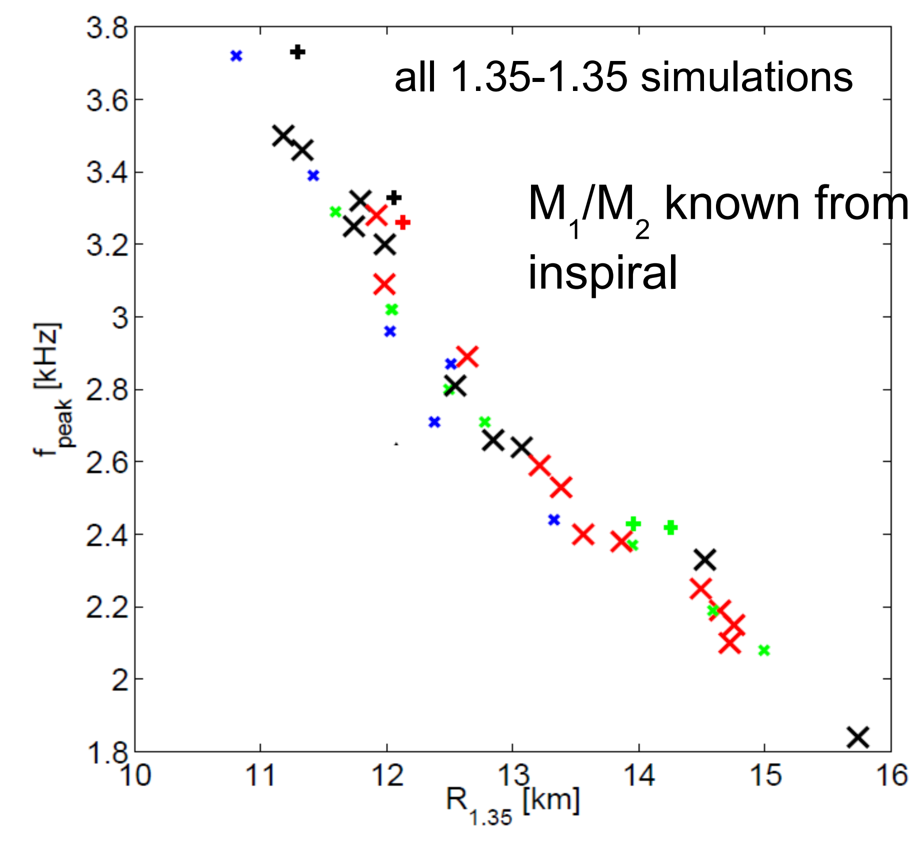


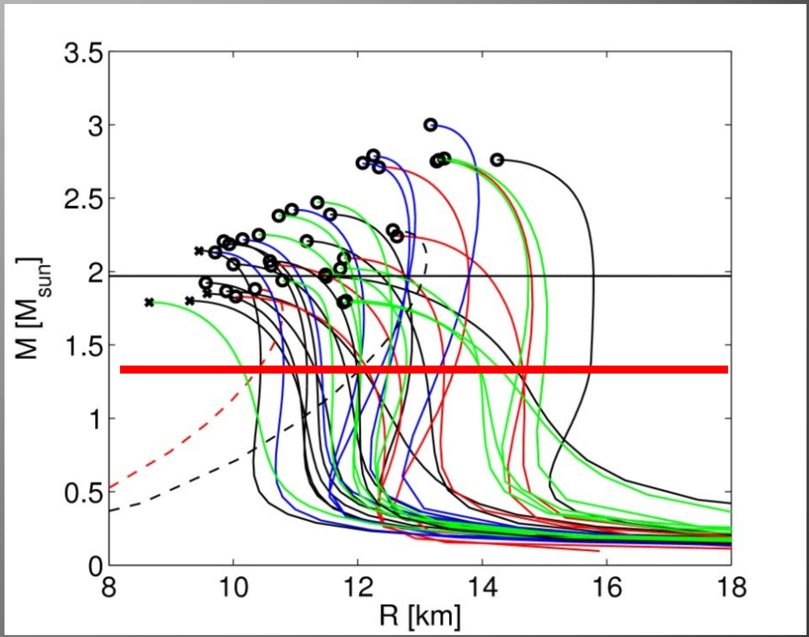
Re-excitation of f-mode (l=|m|=2) in late-time remnant, Bauswein et al. 2015



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

Gravitational waves – EoS survey





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

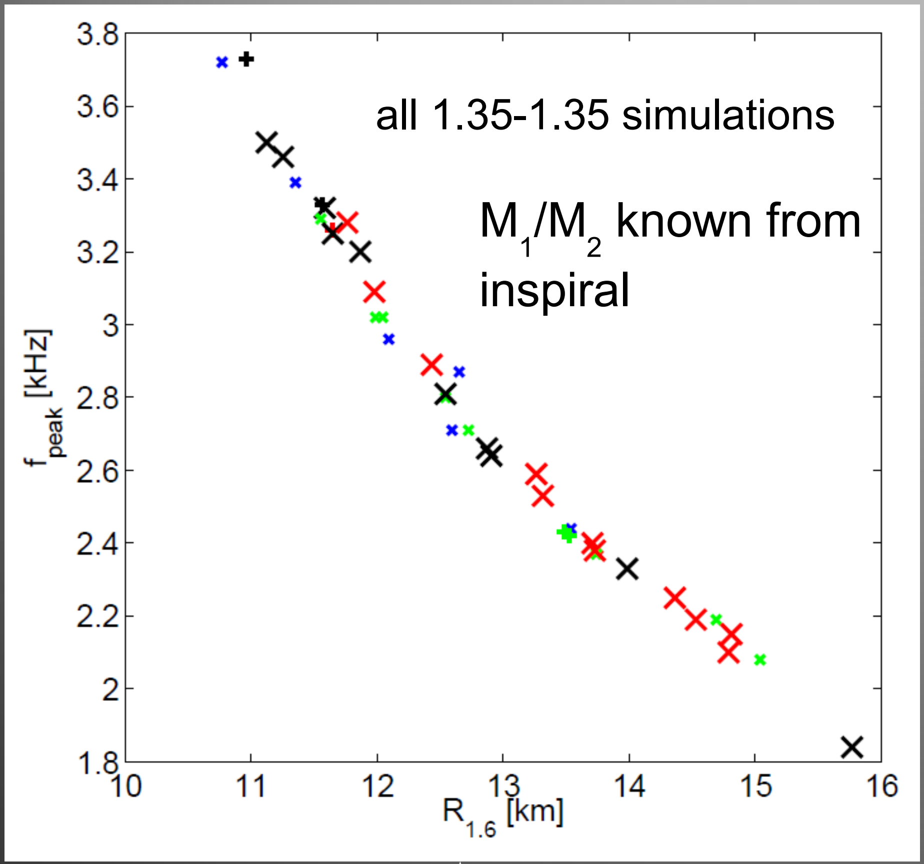
Pure TOV property => Radius measurement via f_{peak}

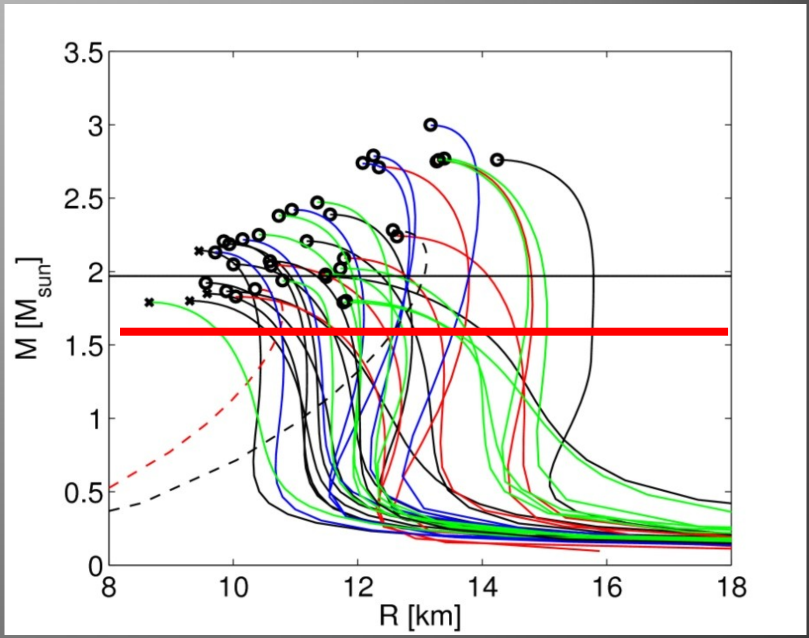
→ Empirical relation between GW frequency and radius of non-rotating NS

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

Triangles: strange quark matter; red: temperature dependent EoS; others: ideal-gas for thermal effects

Gravitational waves – EoS survey





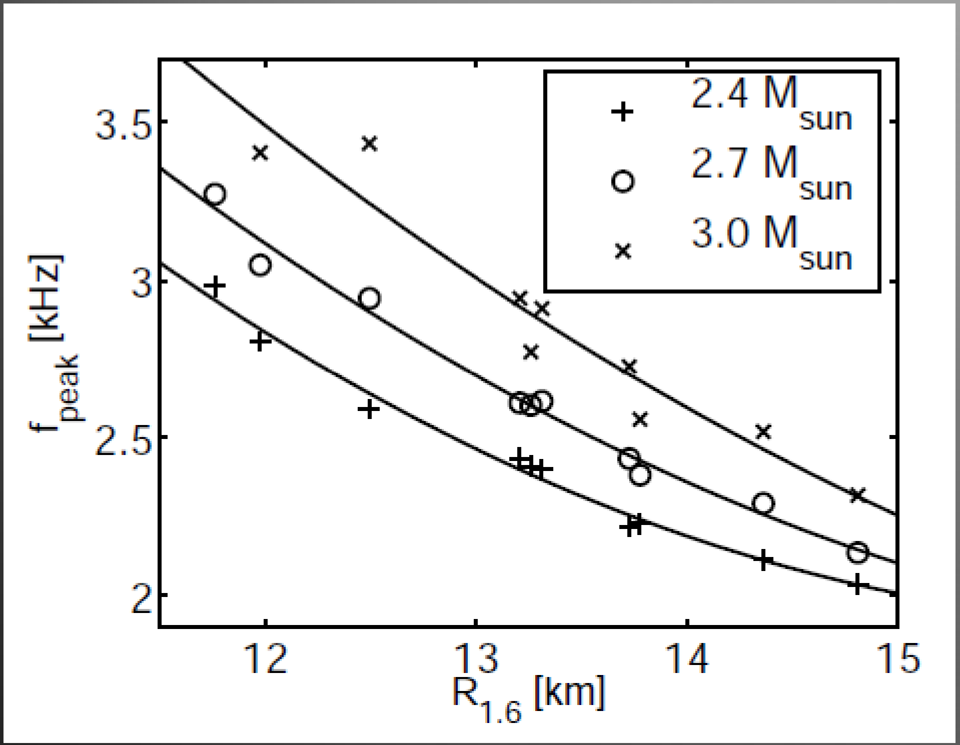
characterize EoS by radius of nonrotating NS with 1.6 M_{sun}

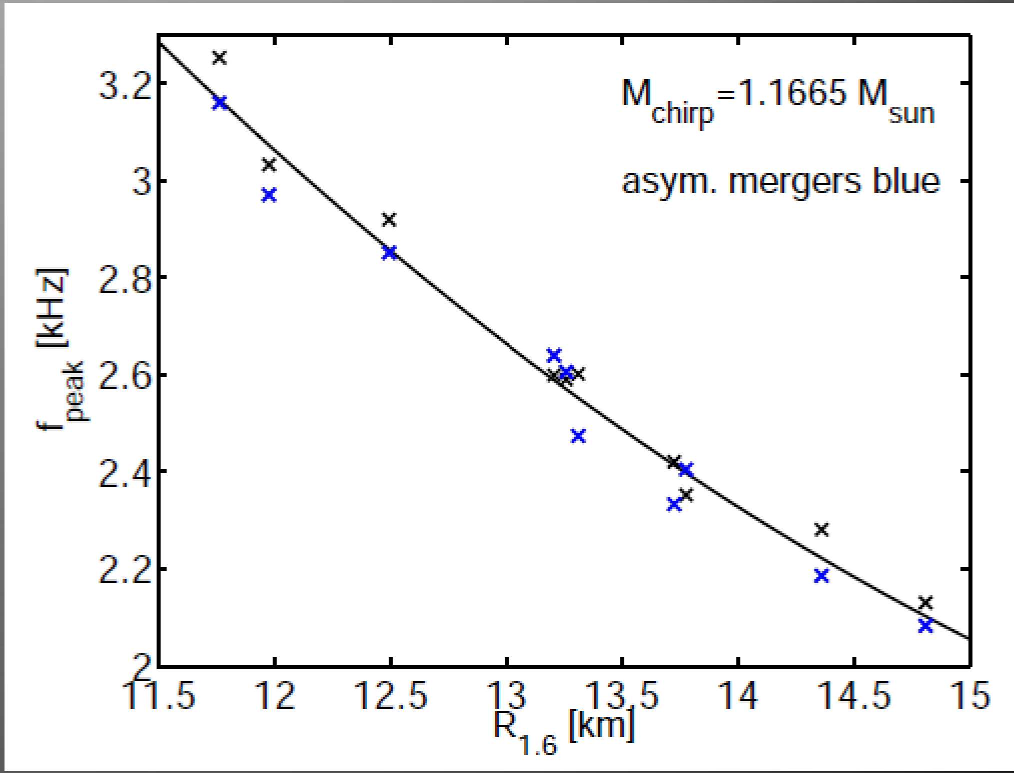
Pure TOV/EoS property => Radius measurement via f_{peak}

Important: Simulations for the same binary mass, 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)

Variations of binary masses



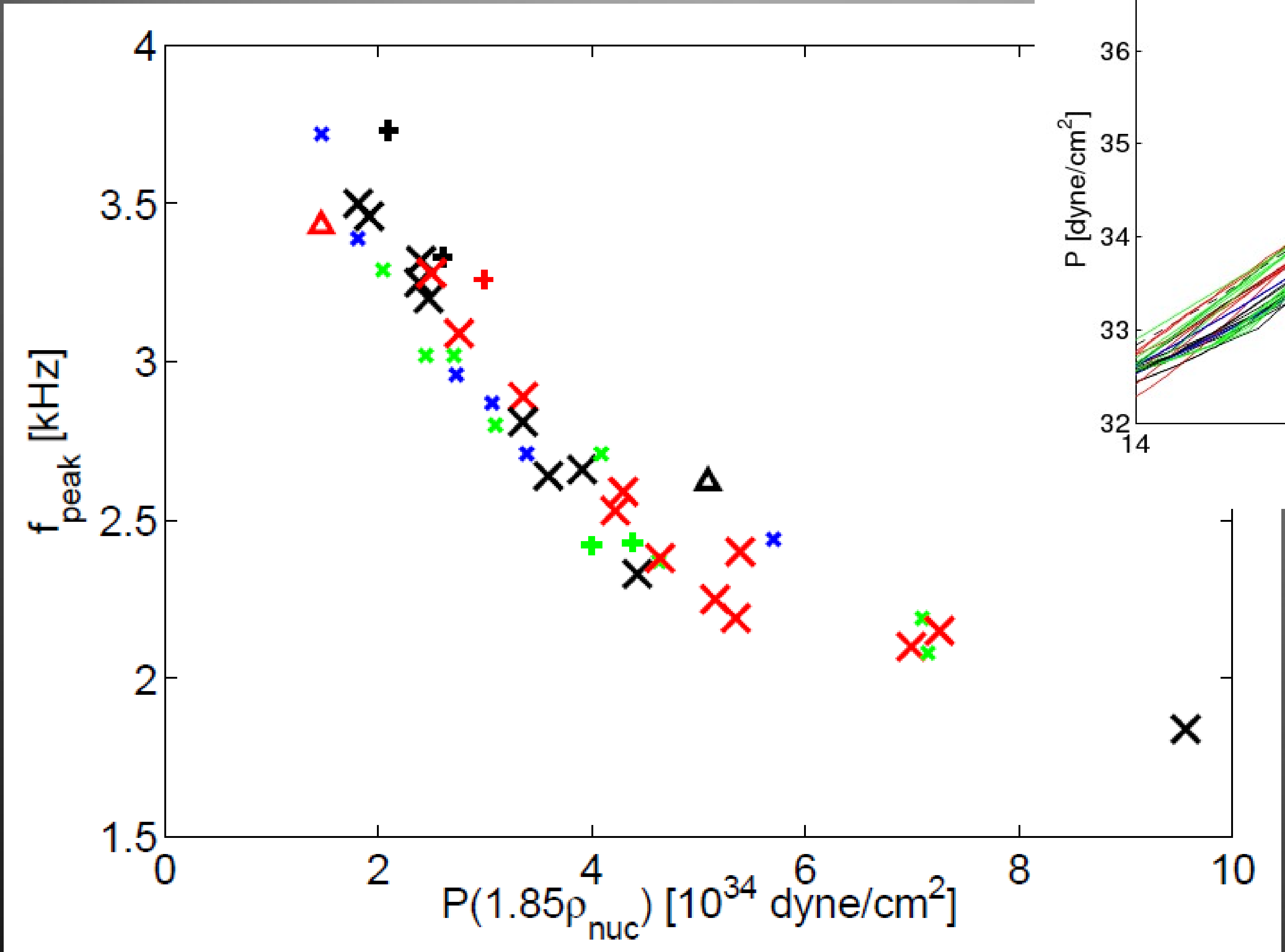


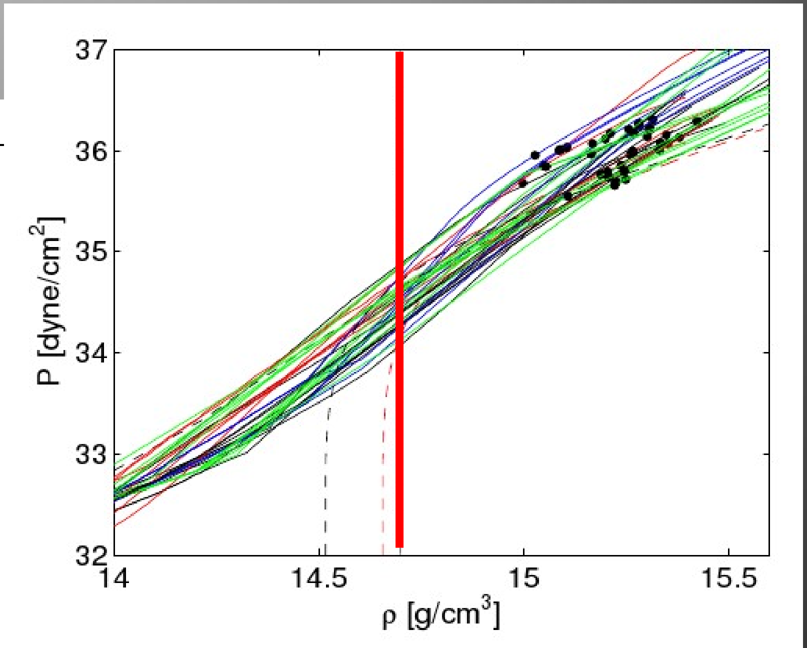
Bauswein et al. 2015

Recall: chirp mass precisely measured – good proxy for total mass

Pressure at 1.85 nuclear density

all 1.35-1.35 simulations



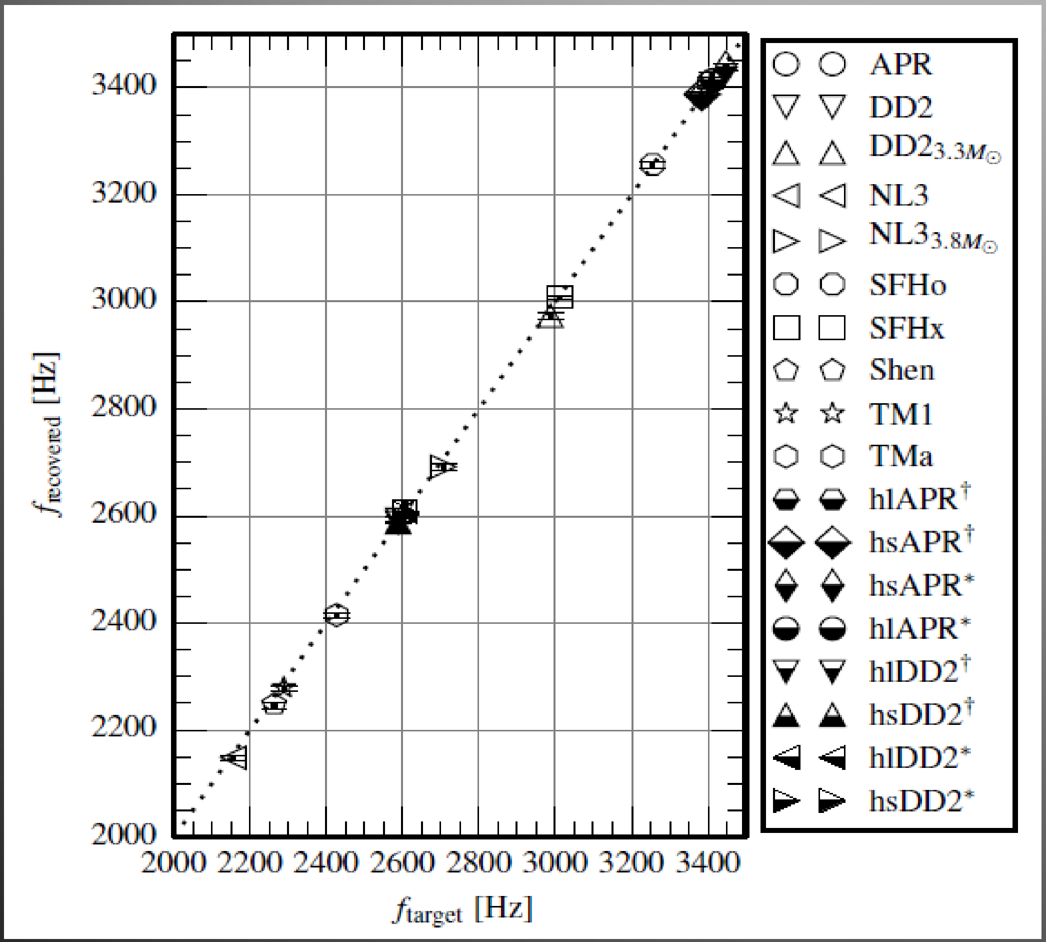


Triangle: strange quark matter (distinguishable by other observations)

Remarks: radius measurements

- Equivalent relations exist for other total binary masses
- Binary masses are measurable at distance which allow f_{peak} determination (e.g. Rodriguez et al. 2014)
- Asymmetric binaries of the same M_{tot} alter f_{peak} only slightly
- Intrinsic rotation has negligible impact for observed spin rates
- Simulations within conformal flatness but frequencies agree well with results from Kyoto / Frankfurt / Caltech group (full GR)
- Dominant frequency detectable for near-by events e.g. via morphology-independent burst analysis with ~10 Hz accuracy (Cark et al. 2014) or Principal Component Analysis (PCA) at larger distances with larger uncertainties (Clark et al. 2015)

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

Clark et al. 2015

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

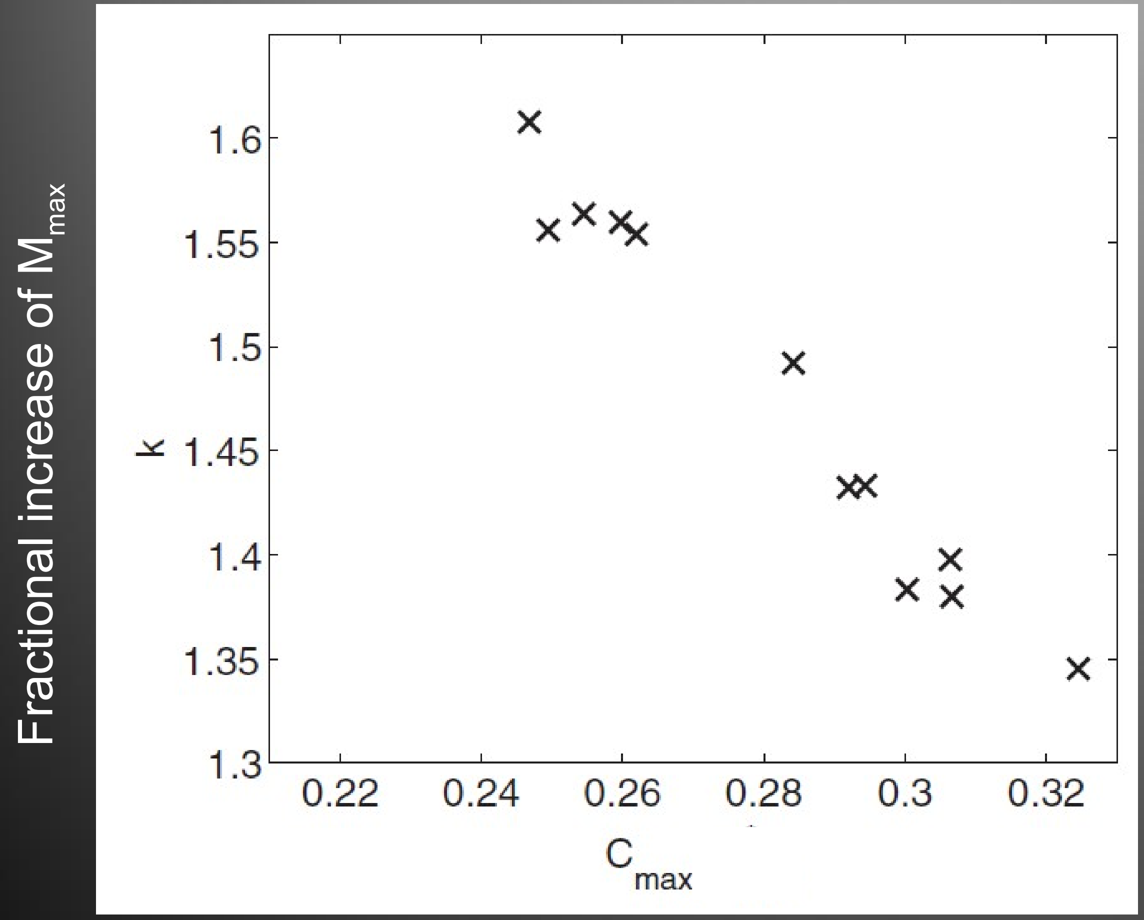
Collapse behavior of NS mergers

(prompt vs. delayed/stable)

and the maximum mass of nonrotating NSs

Estimates of maximum NS mass

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)

=> $M_{thres} = M_{thres}(M_{max},R_{max})$

Bauswein et al. 2013

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

← From simulations with different M_{tot}

← TOV property of employed EoS

M_{max} estimates

observable

$$M_{thres} = M_{thres}(M_{max}, R_{max}) = M_{thres}(M_{max}, R_{1.6})^{*}$$

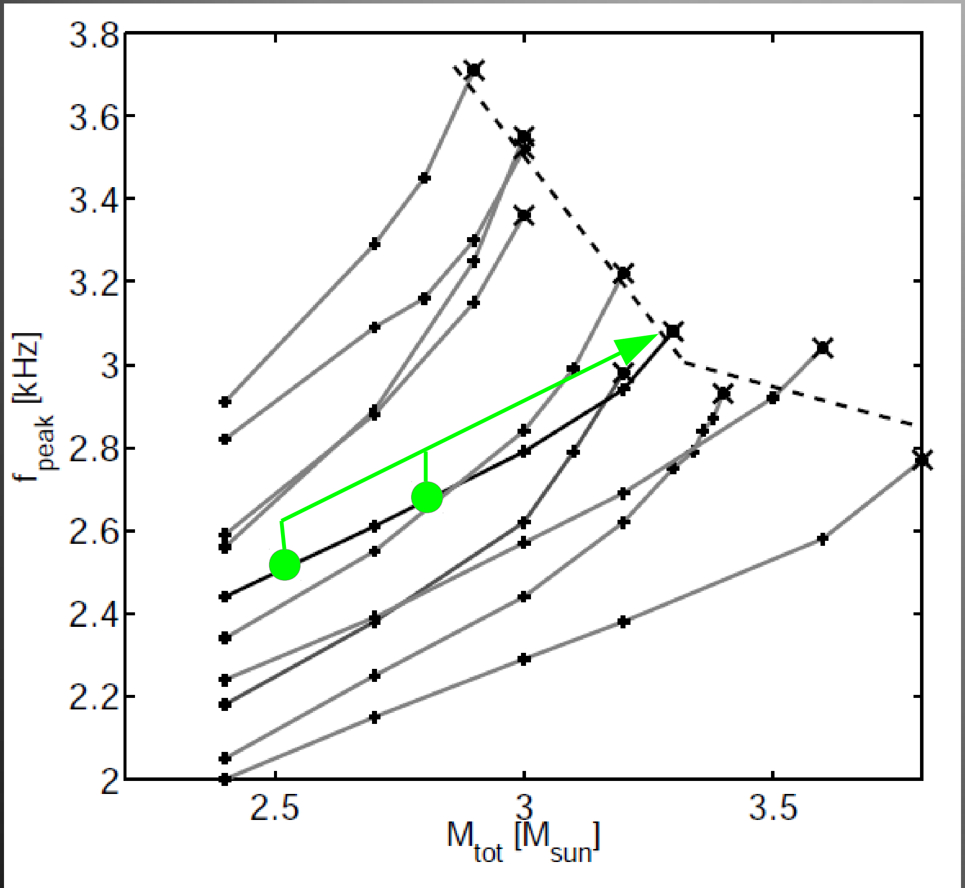
Pure TOV properties

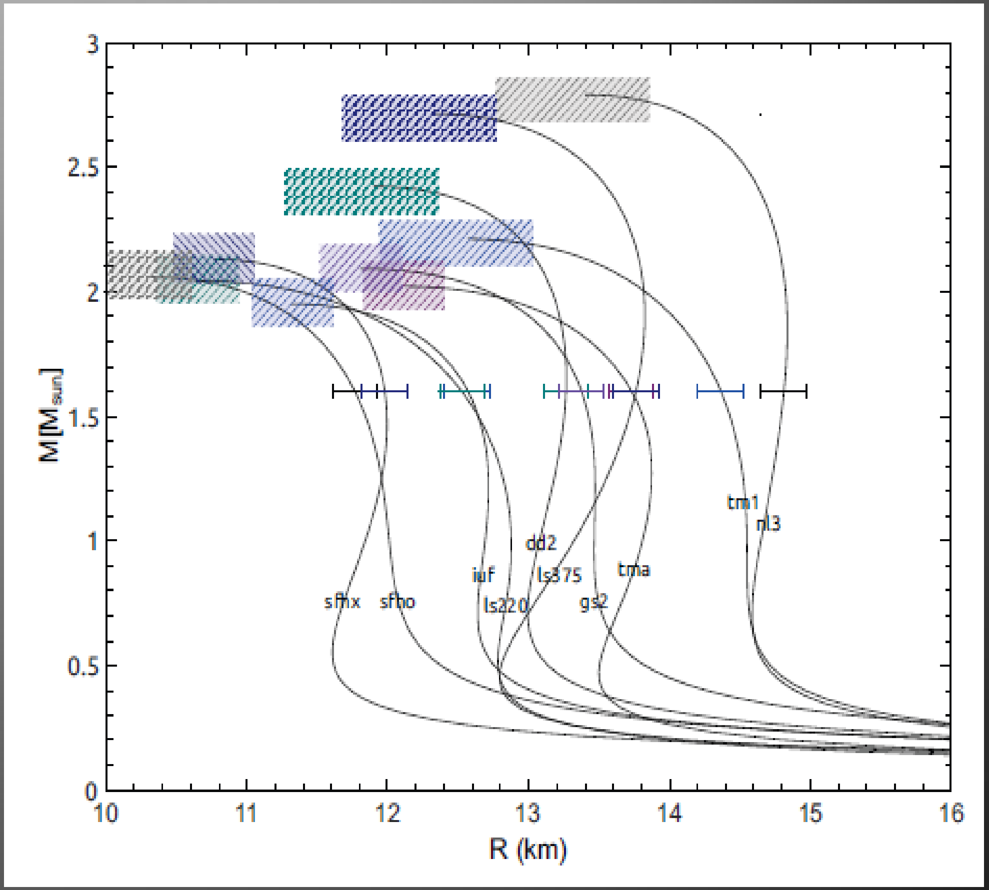
* Radii from GW frequency

Three methods to determine M_{max}:

- Determine M_{thres} by direct observations of delayed and prompt collapse for different M_{tot} (Bauswein et al. 2013) – many detections especially at high masses required
- Extrapolate $f_{peak}(M_{tot}) \rightarrow f_{thres}(M_{thres})$ behavior from several events at lower binary masses (most likely range) (Bauswein et al. 2014)
- f_{peak} (high M_{tot}) directly constrains M_{max}

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

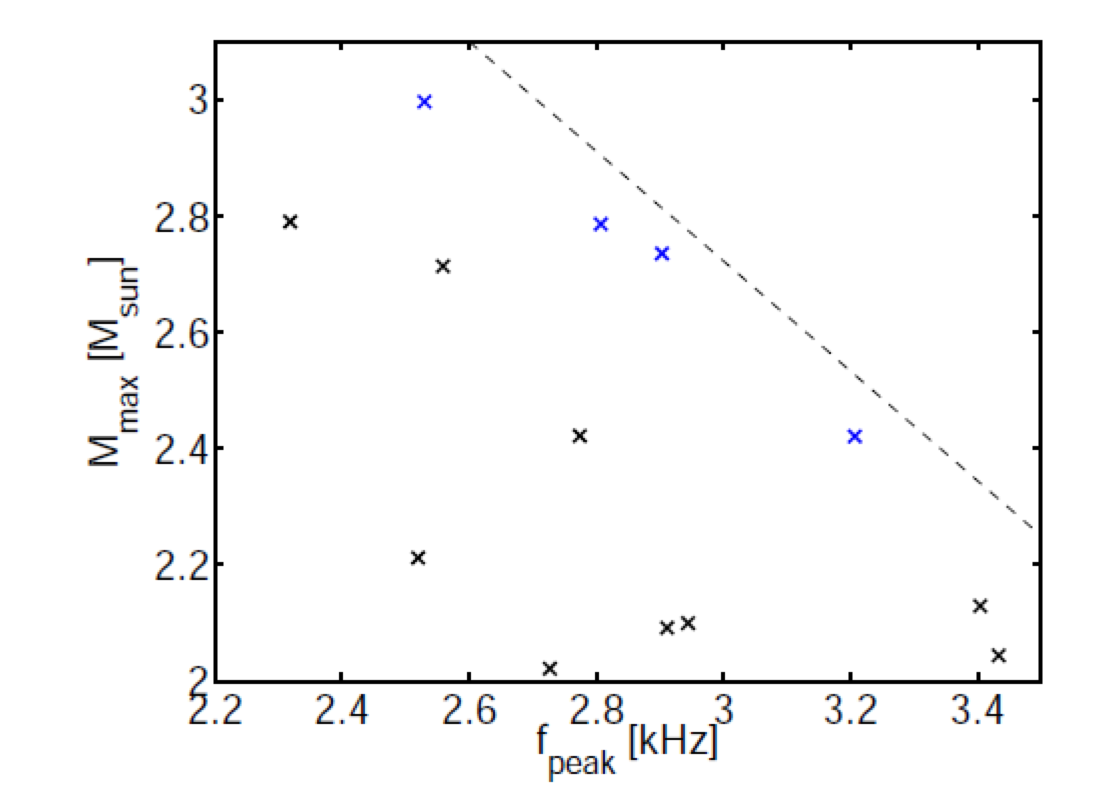




Bauswein et al. 2014

Dashed line: Universal relation between threshold mass and GW frequency

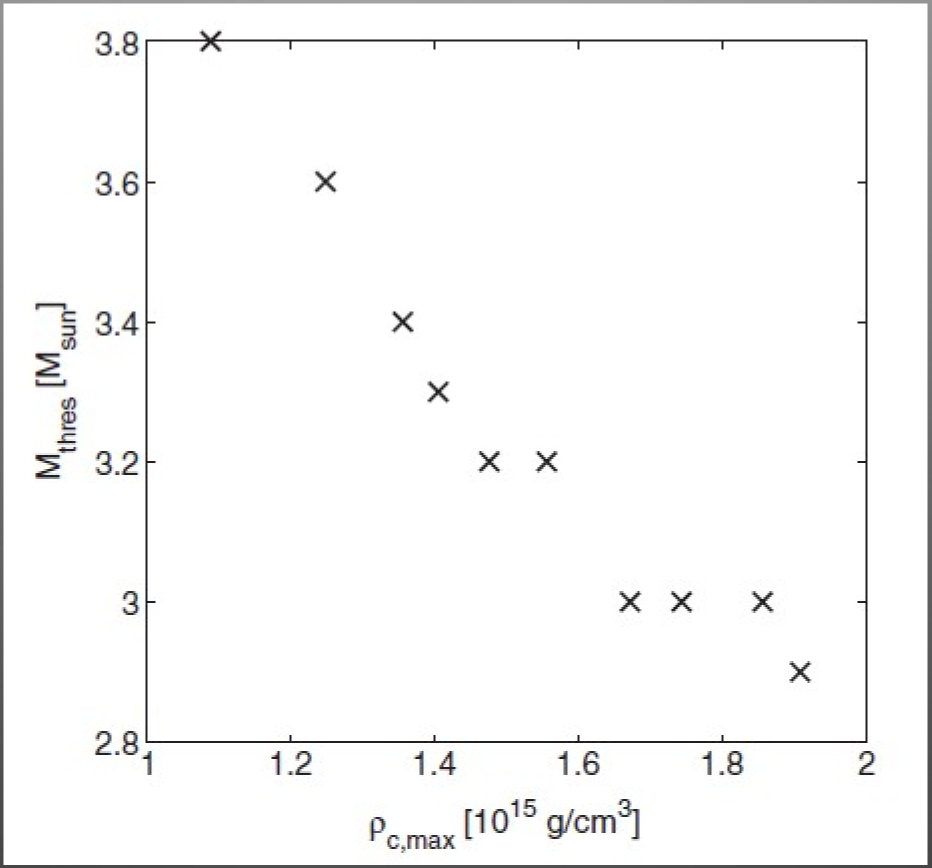
Maximum mass from one (high-mass) observation



Bauswein et al. 2015

f_{peak} from 1.5-1.5 M_{sun} simulations → constraint on M_{max}

Maximum central density

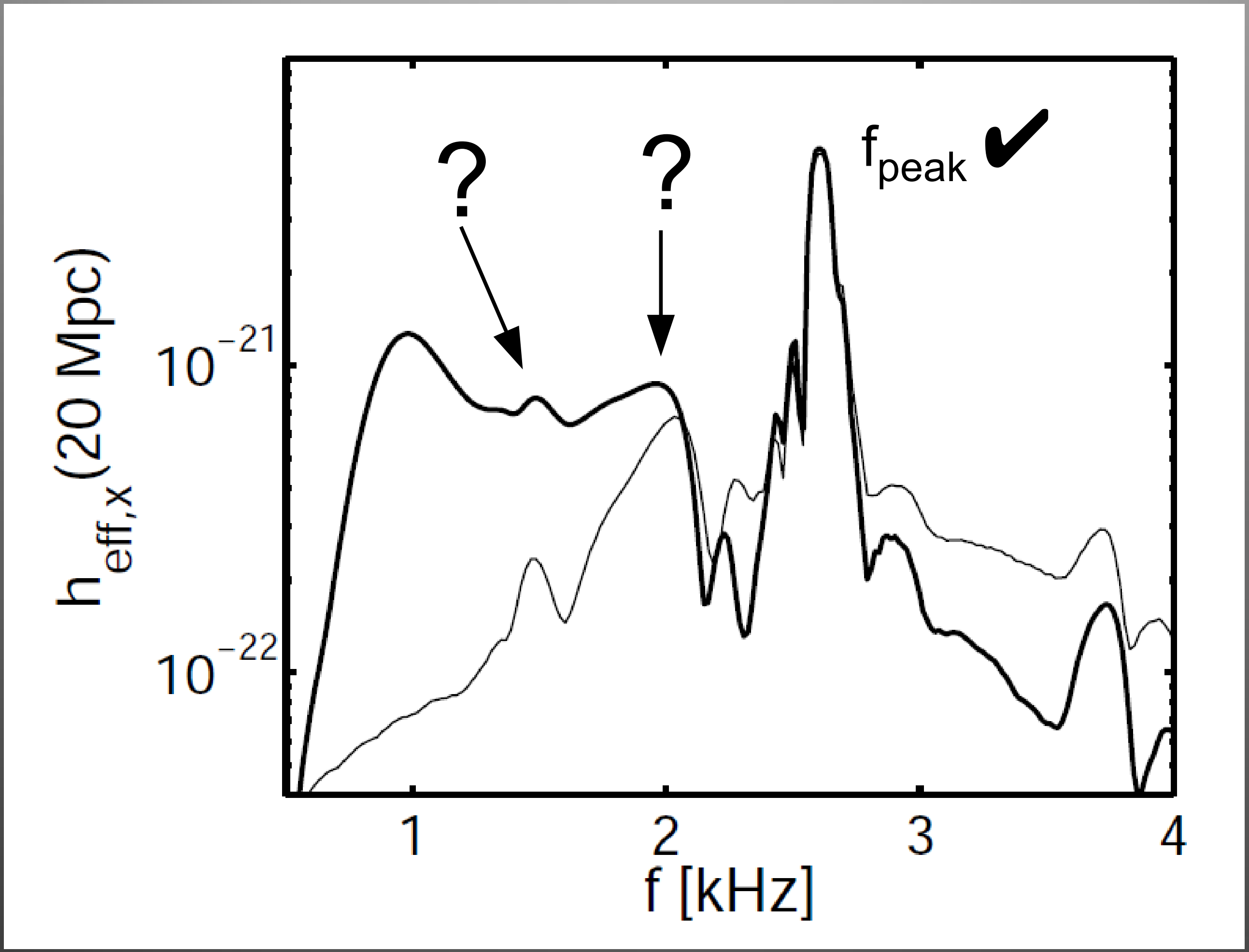


Similar frequency relations for maximum central density for same detection scenario

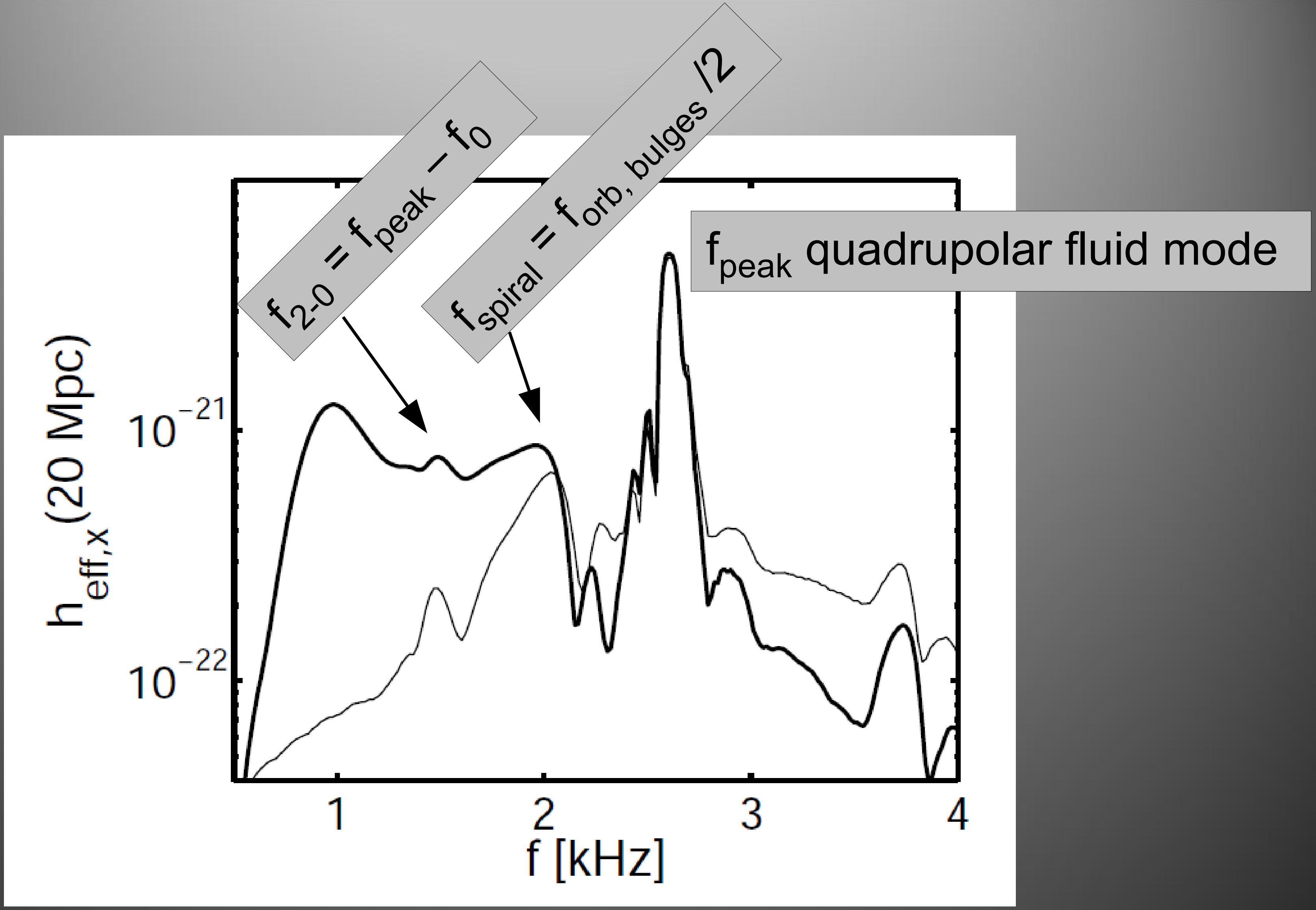
Bauswein et al. 2014

Secondary GW features in the postmerger spectrum

Generic GW spectrum



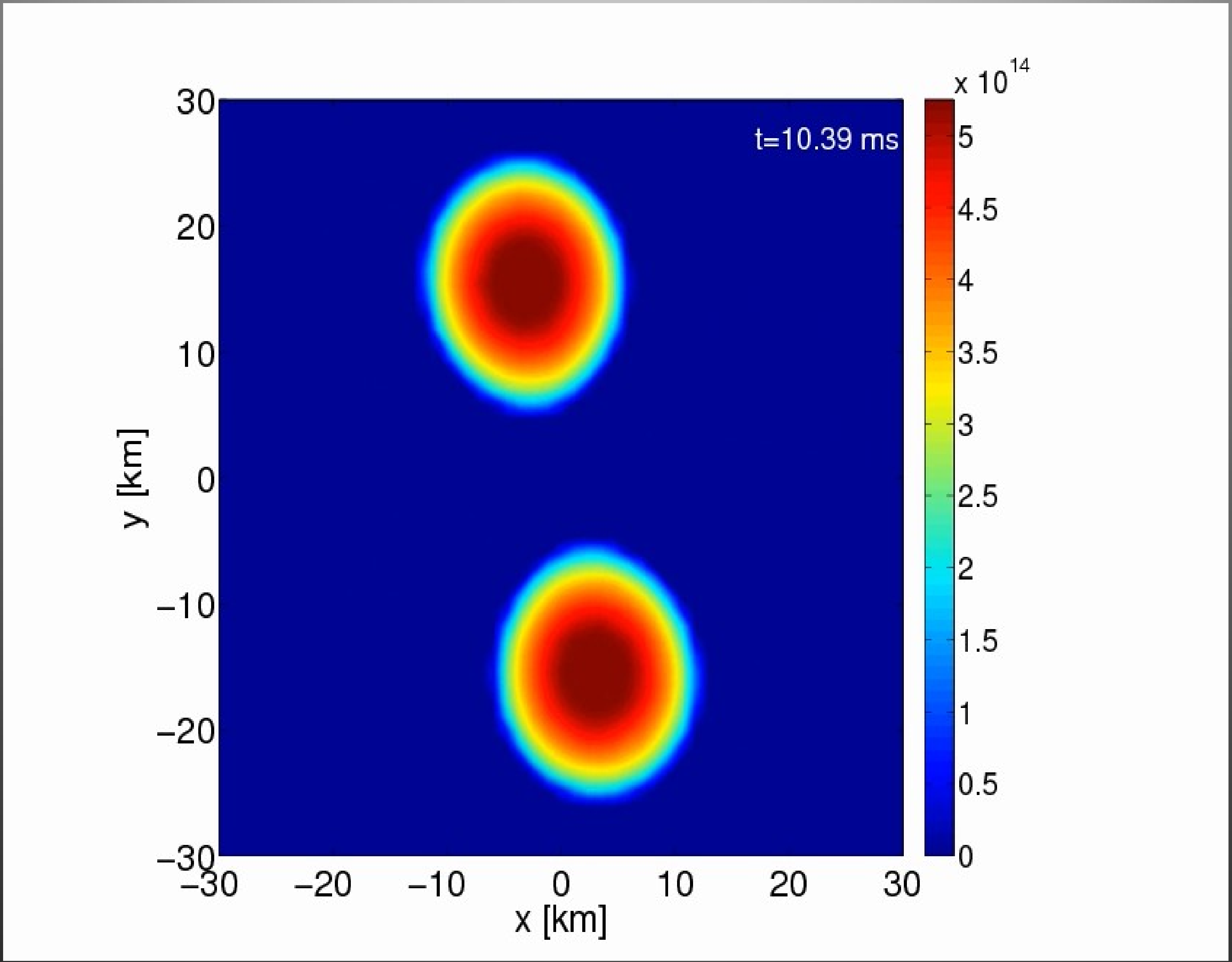
- Up to three pronounced features in the postmerger spectrum (+ structure at higher frequencies)
- 1.35-1.35 Msun DD2 EoS



Bauswein & Stergioulas 2015

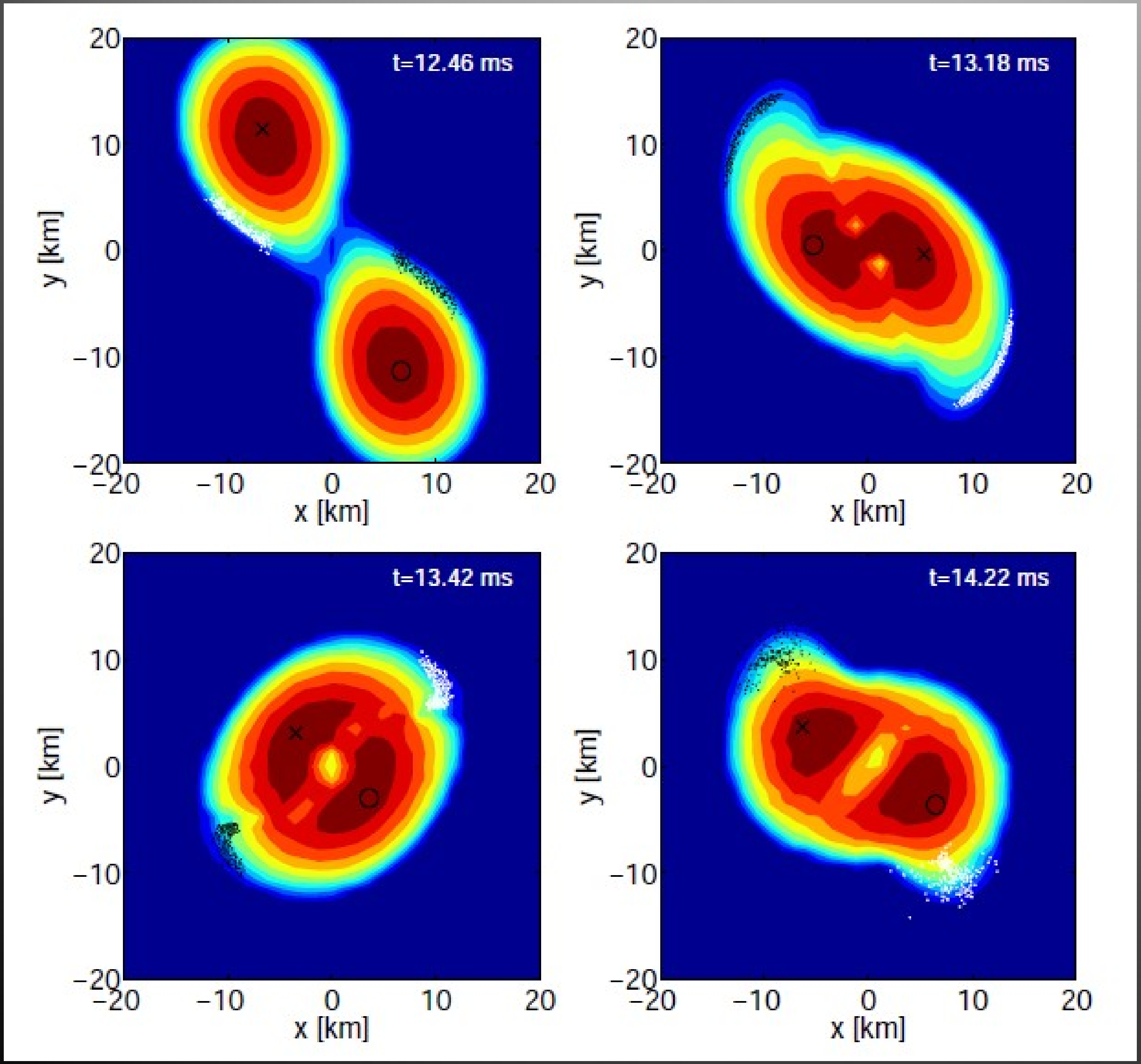
Secondary peaks due to:

- Combination frequency (mode coupling) $f_{2\text{-}0} = f_{peak} - f_0$
- Orbital motion of tidal bulges (outer edges of the remnant)



DD2 1.35-1.35 Msun, rest-mass density in the equatorial plane

Antipodal bulges (spiral pattern)



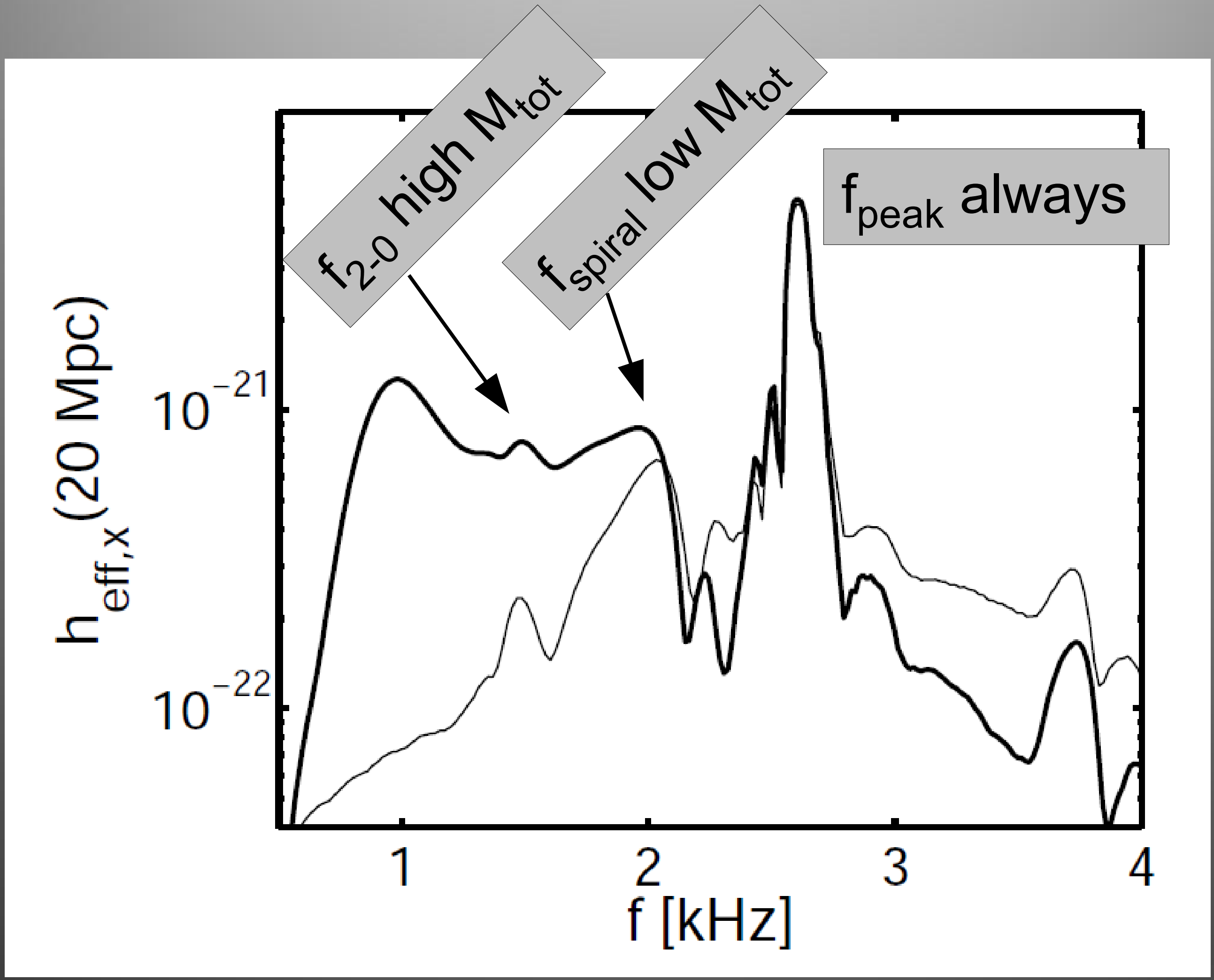
Orbital motion of antipodal bulges slower than inner part of the remnant (double-core structure)

Spiral pattern, created during merging lacks behind

Orbital frequency: 1/1ms → generates GW at 2 kHz !!!

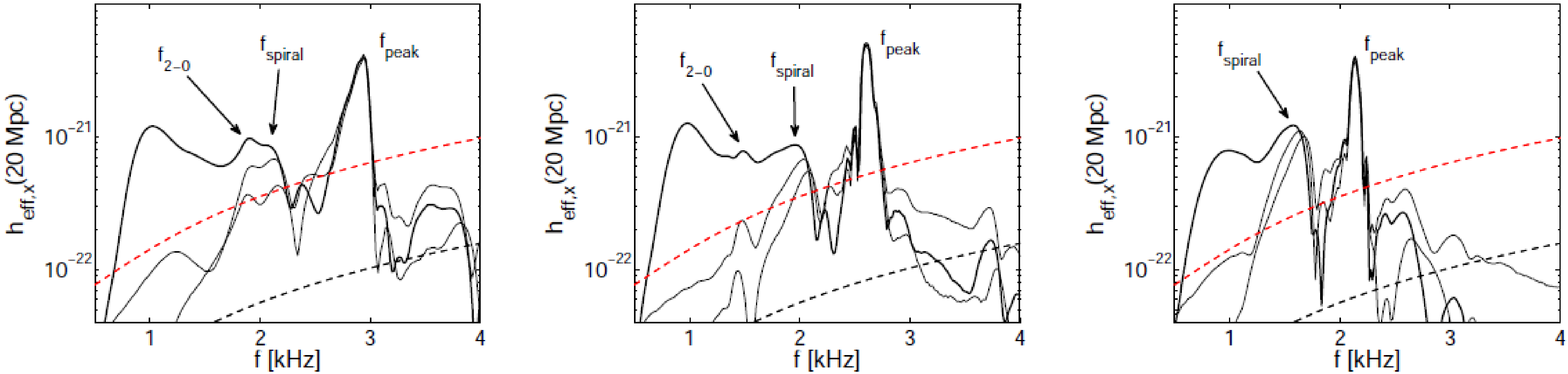
Present for only a few ms / cycles

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)

Survey of GW spectra



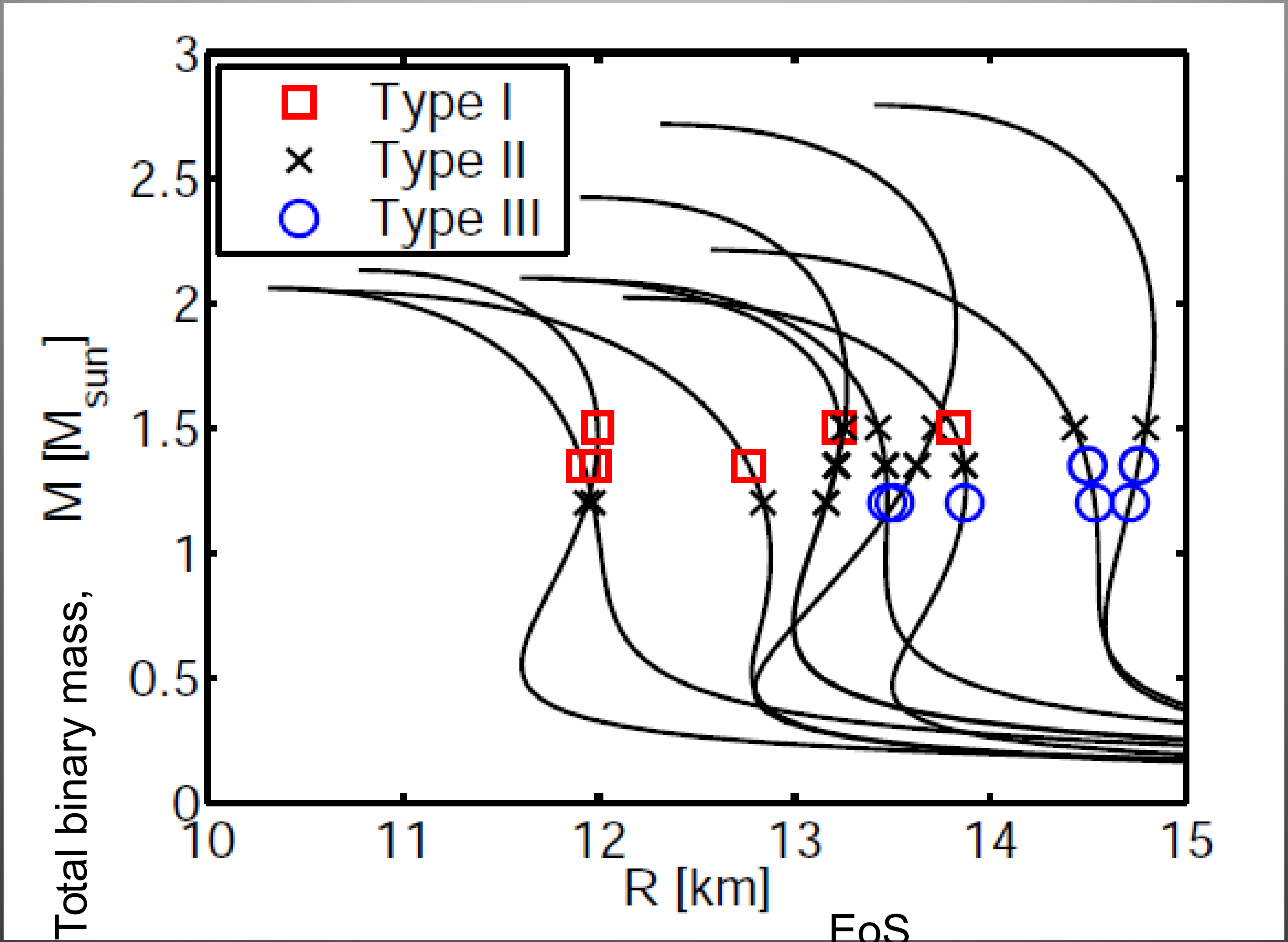
Type I

Type II

Type III

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

Classification scheme



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

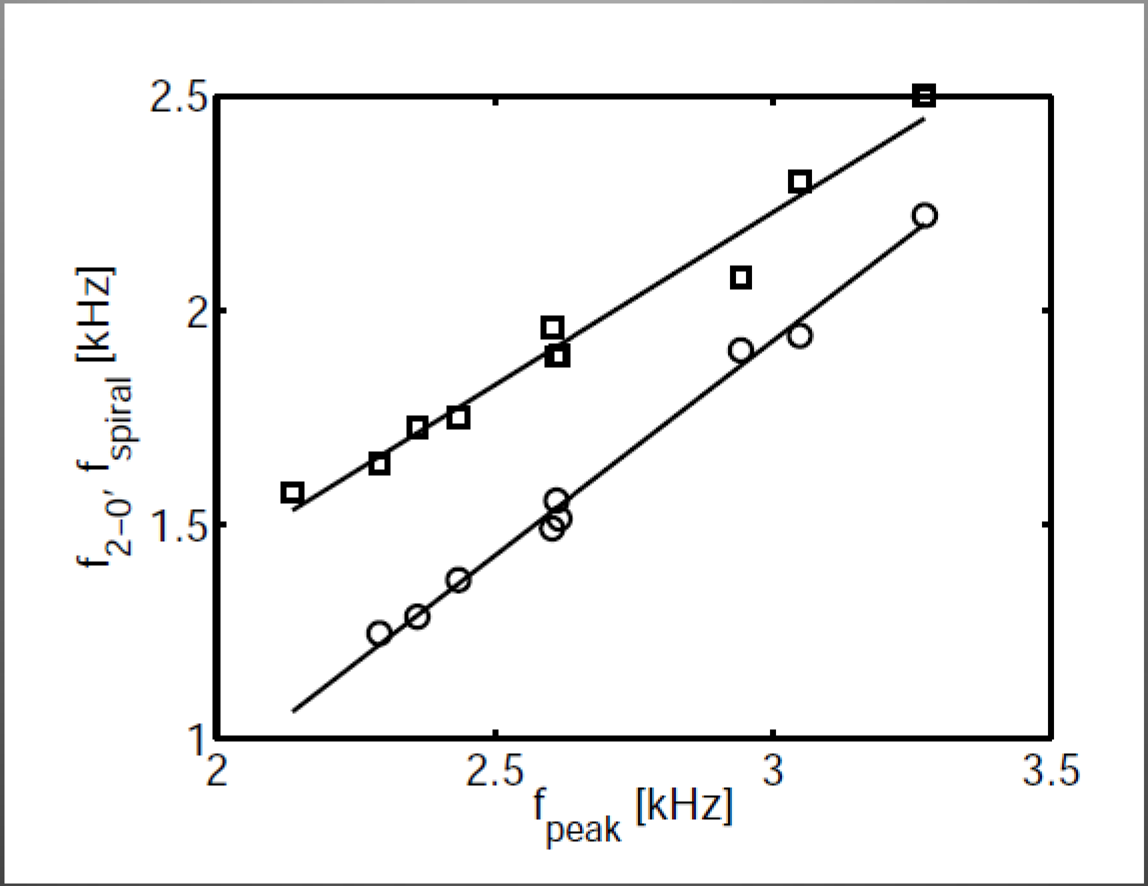
(Continuous transition between types → tentative association)

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

Classification scheme

Behavior reasonable:

- Type I: compact NSs merge → high impact velocity / violent collision => radial oscillation strongly excited (2-0 dominant); higher compactness → formation of tidal bulges suppressed (f_{spiral} weaker)
- Type III: less compact NSs merge → lower impact velocity / smooth merging => radial mode suppressed (no 2-0); pronounced tidal bulges (strong f_{spiral} feature)

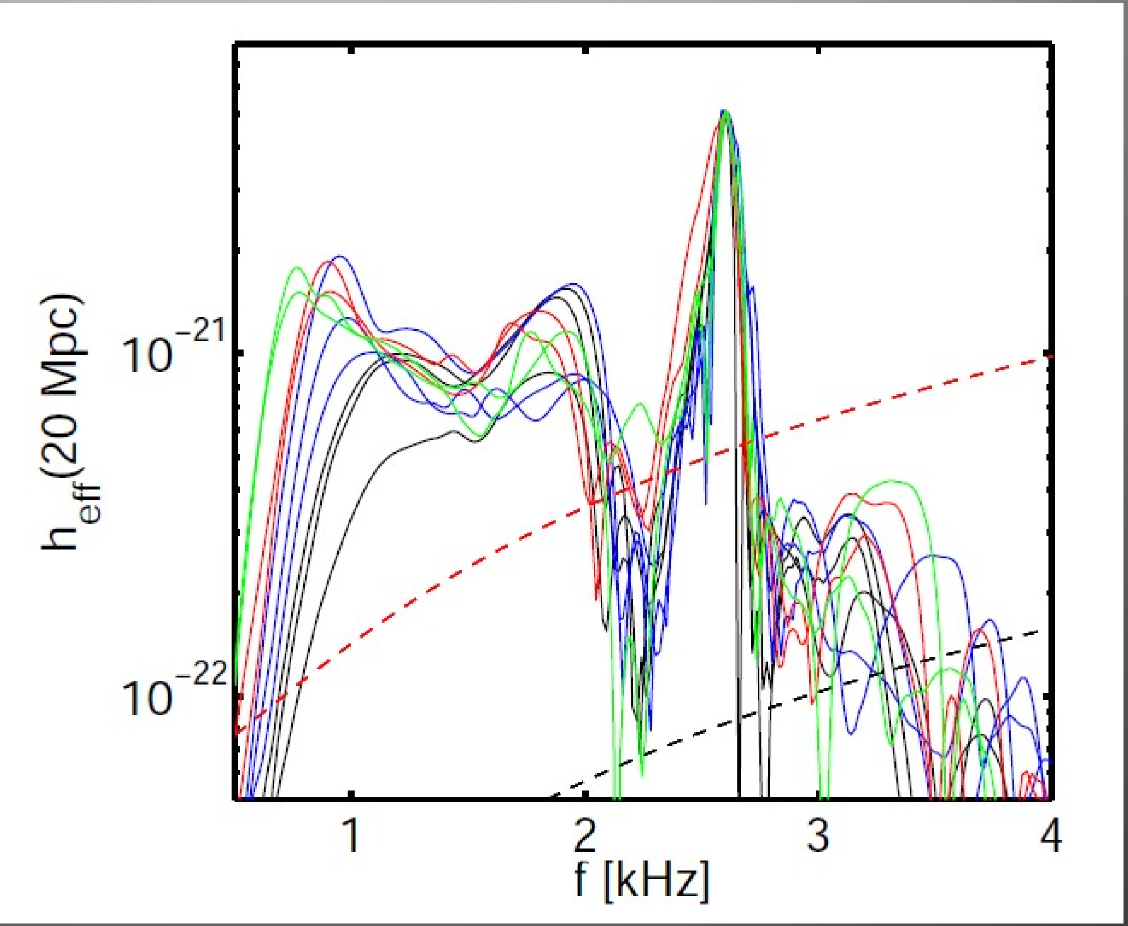


1.35-1.35 Msun simulations: secondary frequencies scale well with dominant frequency (→ contain redundant information)

Bauswein et al 2015

Universality of GW spectra

$$f \rightarrow f \times \frac{f_{reference}}{f_{peak}}$$



GW spectra shifted to reference frequency → Universality

Reason: $f_{spiral\,/\,2-0} \propto f_{peak}$

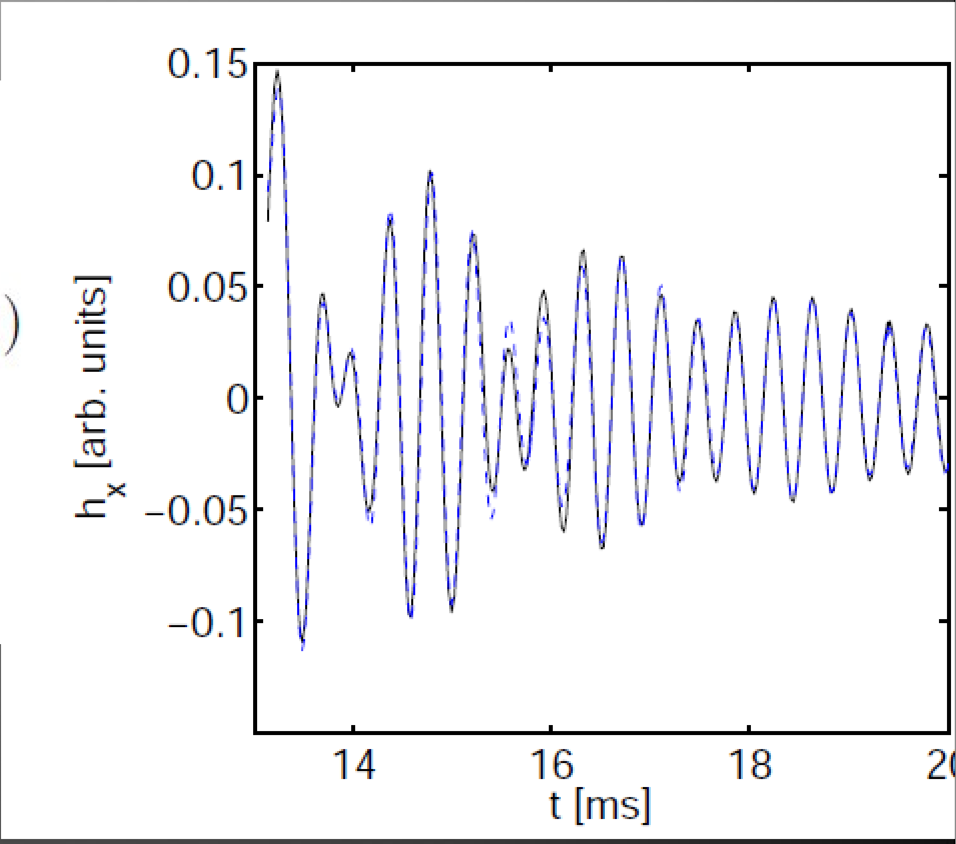
→ Very useful property for Principal Component Analysis for GW data analysis (Clark et al. 2015) → low number of principal components suffices

→ construction of templates seems possible

Analytic model

Motivated by understanding of different emission mechanisms:

$$
\begin{aligned}
h_\times \propto Q_{xy} = & A_{\rm peak} \exp\left(-(t-t_0)/\tau_{\rm peak}\right) \\
& \sin\left(2\pi f_{\rm peak}(t-t_0)+\phi_{\rm peak}\right) \\
& + A_{\rm spiral} \exp\left(-(t-t_0)/\tau_{\rm spiral}\right) \\
& \sin\left(2\pi f_{\rm spiral}(t-t_0)+\phi_{\rm spiral}\right) \\
& + A_{2-0} \exp\left(-(t-t_0)/\tau_{2-0}\right) \\
& \sin\left(2\pi f_{2-0}(t-t_0)+\phi_{2-0}\right),
\end{aligned}
$$



→ very good match for this model (open question: how does model perform for other simulations?)

Bauswein et al. 2015

→ construction of templates

Summary

- Inspiral GW signal determines chirp mass / total mass (and component masses for near-by mergers)
- Dominant postmerger oscillation frequency tightly constrains NS radii (single detection of fpeak sufficient)
- Collapse behavior constrains maximum mass of Nss
- Maximum central density can be estimated
- Two distinct mechanisms generate secondary features in GW spectrum: mode interaction between quadrupolar and radial mode; orbital motion of antipodal bulges
- three different types of spectra / dynamics (depending on total binary mass for given EoS) → classification scheme
- Secondary and dominant frequencies show very similar dependence on NS compactness / radius
- Universality of GW spectra, analytic model of postmerger phase → GW data analysis