# Unified Picture of the Postmerger Dynamics and Gravitational-Wave Emission

Andreas Bauswein

(AUTH Thessaloniki)

with N. Stergioulas, J. Clark, H.-T. Janka

Workshop on Binary Neutron Star Mergers

Thessaloniki, 29/05/2015

supported by Marie-Curie Intra-European Fellowship (IEF 331873) within the Seventh European Community Framework Programme

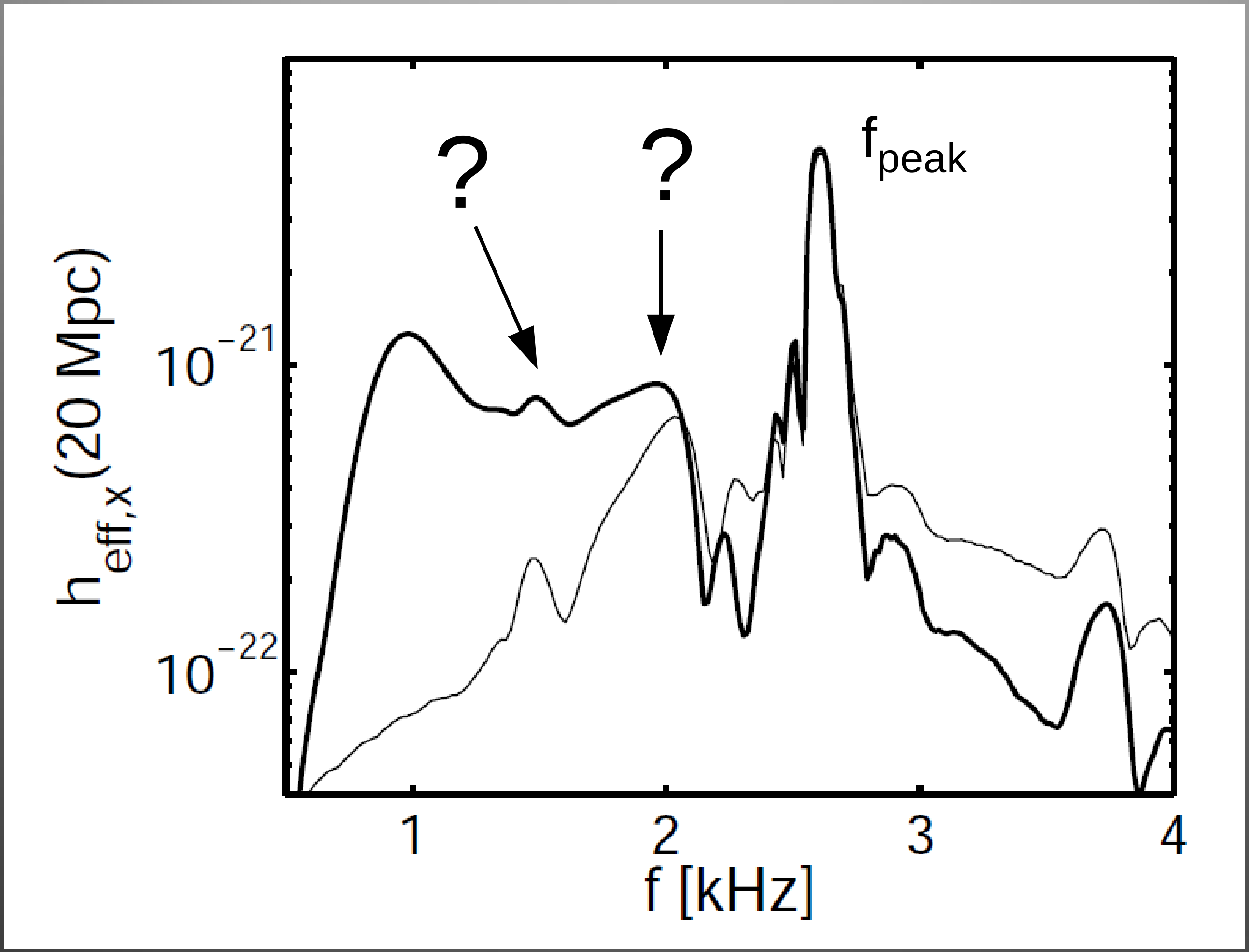
# Outline

- Dominant postmerger GW emission

  - NS radius measurements

  - estimates of the NS maximum mass
- Origin of secondary features
- Classification of postmerger GW emission and dynamics
- Dependencies of secondary frequencies

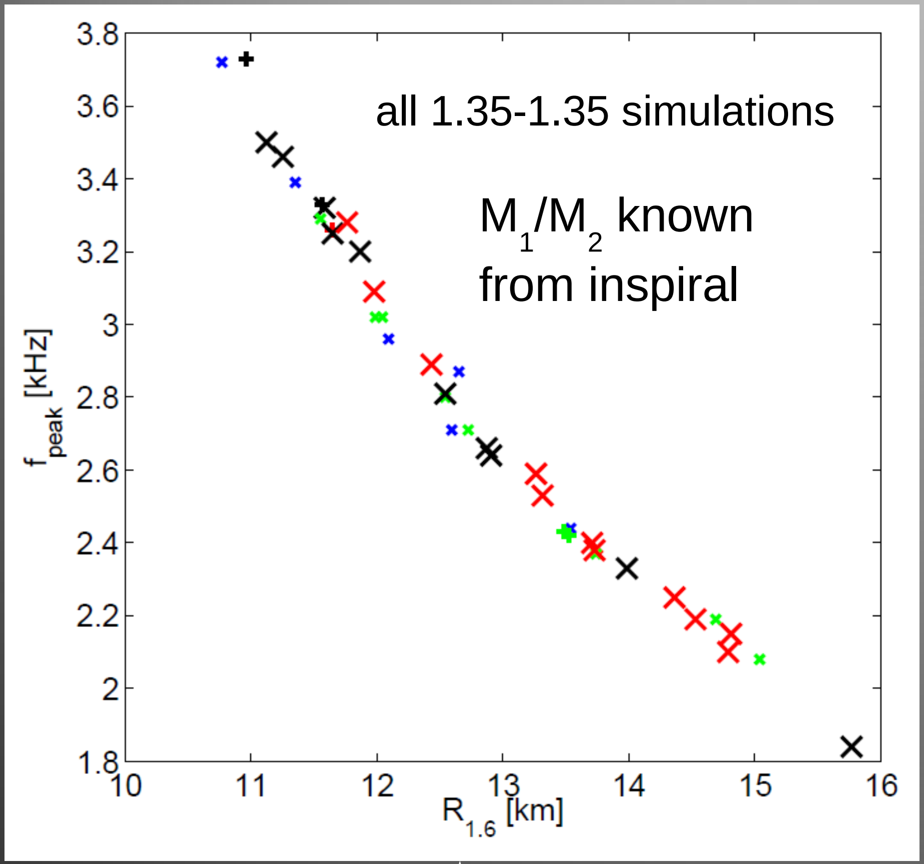
# Generic GW spectrum

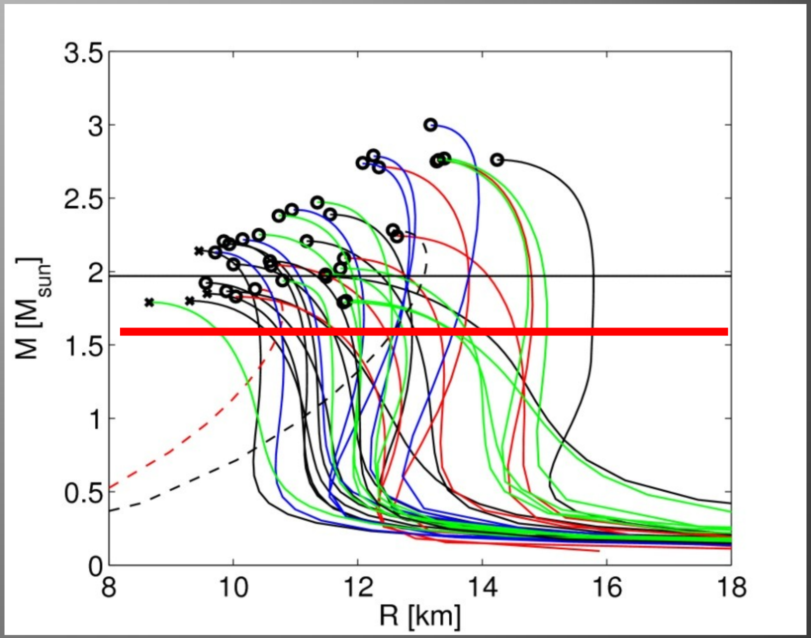



- Up to three pronounced features in the postmerger spectrum (+ structure at higher frequencies)
- 1.35-1.35 $M_{sun}$ DD2 EoS

In the literature $f_{peak}$ is also called $f_2$

# Gravitational waves – EoS survey




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

*Bauswein et al. 2012*

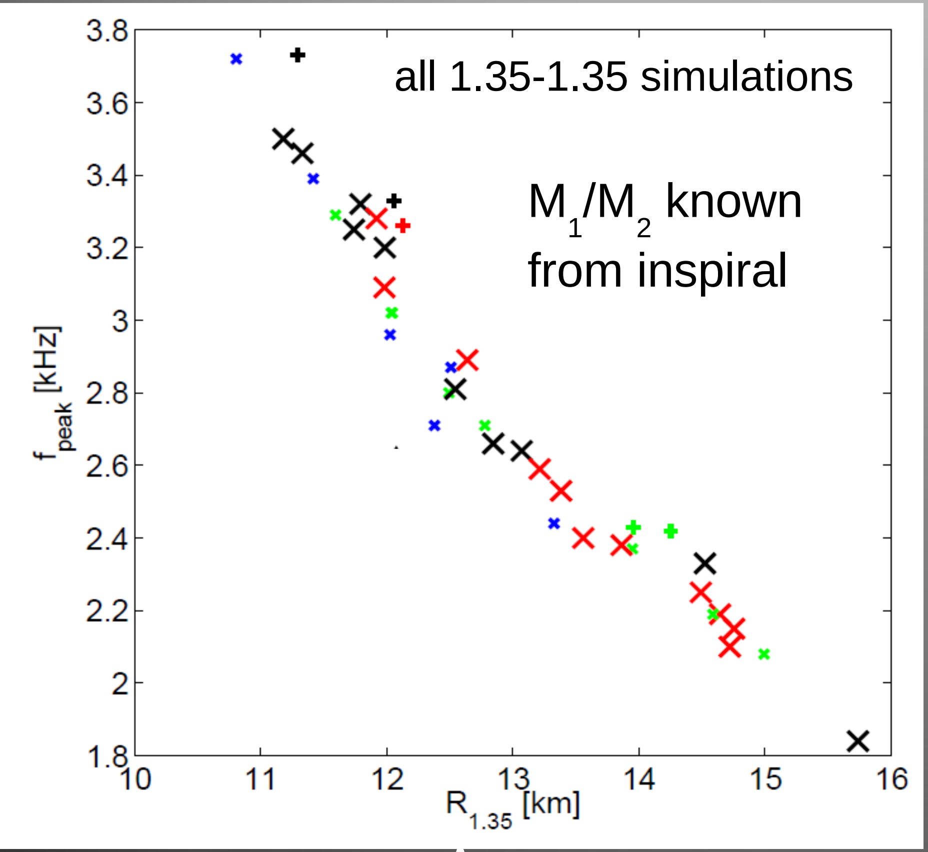
Pure TOV/EoS property => Radius measurement via $f_{peak}$

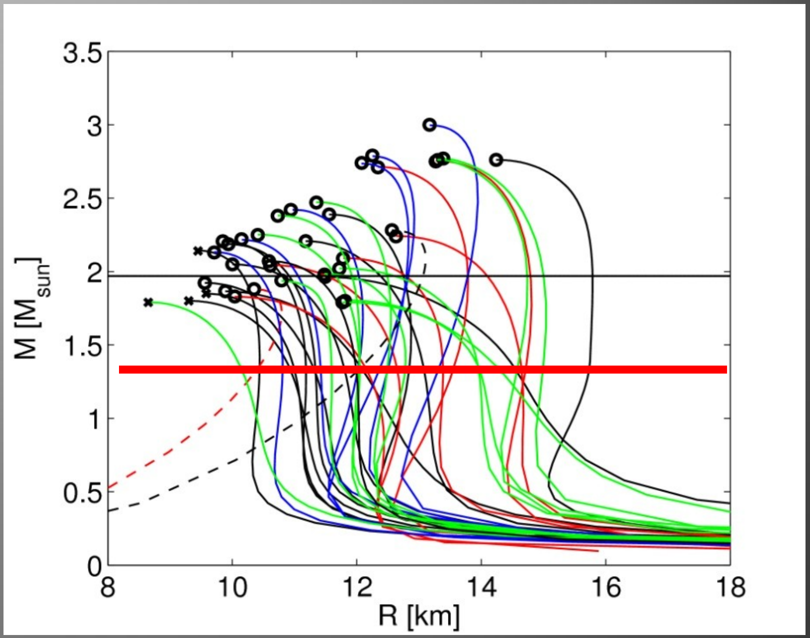
*(Triangles: strange quark matter; red: temperature dependent EoS; others: ideal-gas for thermal effects)*

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

See also Clark's talk

# Gravitational waves – EoS survey




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

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

(or equivalently compactness)

*Bauswein et al. 2012*

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

# 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 (see also talk by Kastaun)
- Frequencies agree with results from Kyoto / Frankfurt group
- Dominant frequency detectable for near-by events e.g. via morphology-independent burst analysis (Clark's talk) with ~10 Hz accuracy

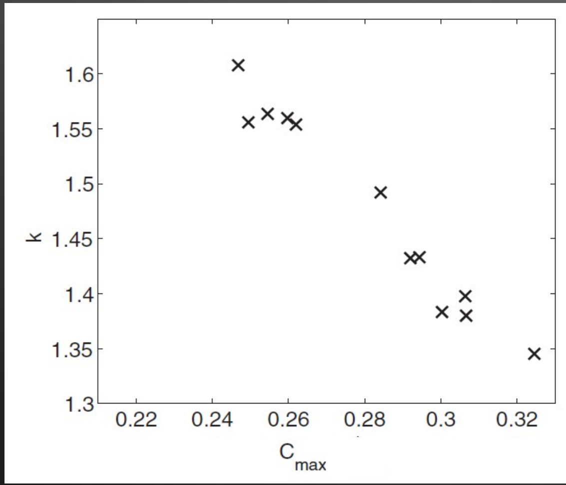
# Estimates of maximum NS mass (nonrotating)

- Key quantity: Threshold binary mass $M_{thres}$ for prompt BH collapse
- Important: depends in particular way EoS/TOV properties
  $M_{thres} = M_{thres}(R_{max}, M_{max}) = M_{thres}(R_{1.6}, M_{max})$ (Bauswein et al. 2013)
- 2 ways of estimating Mthres/Mmax:

  - Determine $M_{thres}$ either by direct observations of delayed and prompt collapse for different $M_{tot}$ (Bauswein et al. 2013)

  - Or extrapolate behavior from several events at lower binary masses $f_{peak}(M_{tot}) \rightarrow f_{thres}(M_{thres})$ , i.e. using observations of events in the most likely range of binary masses (Bauswein et al. 2014)

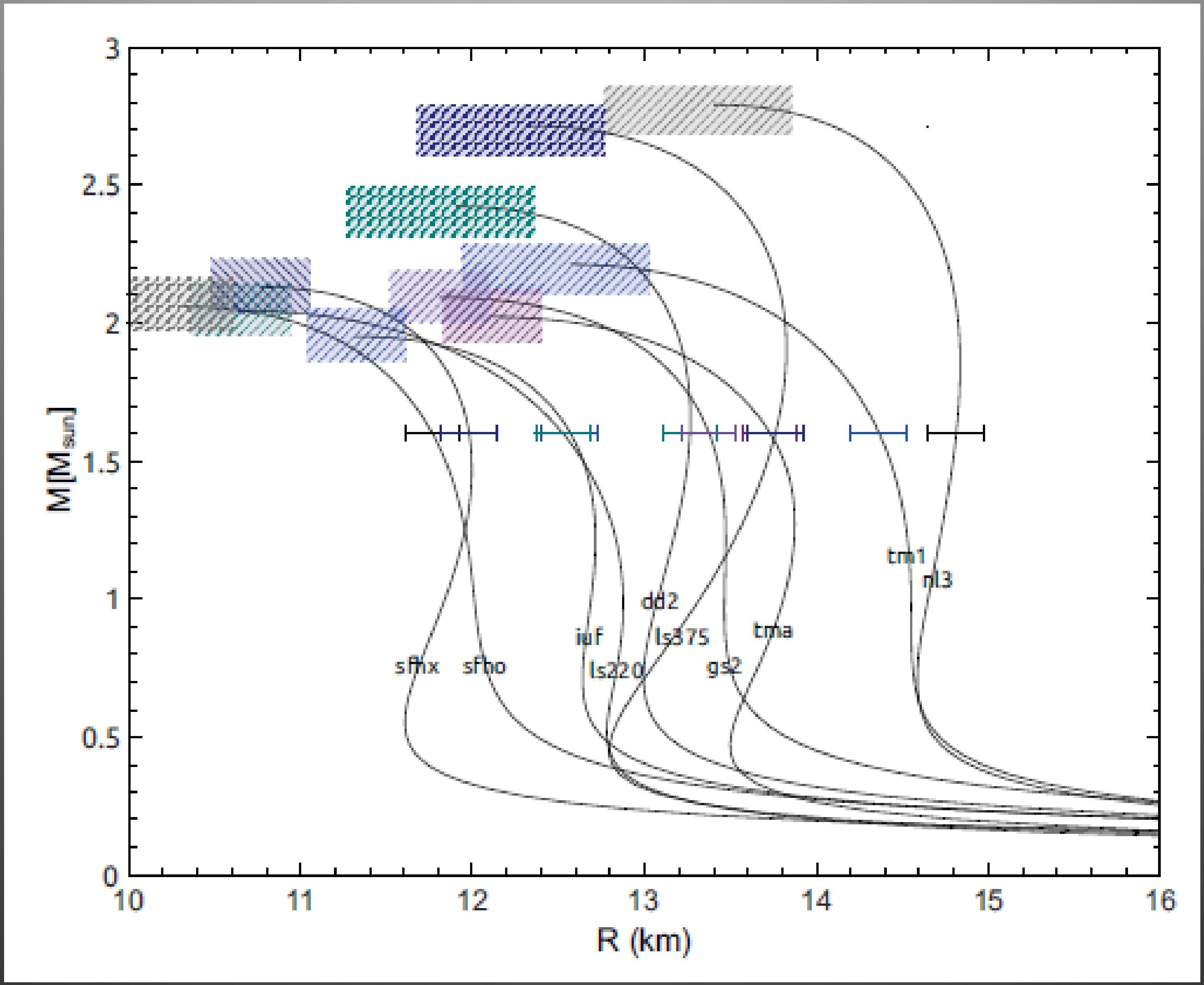
k




$C_{max}$

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

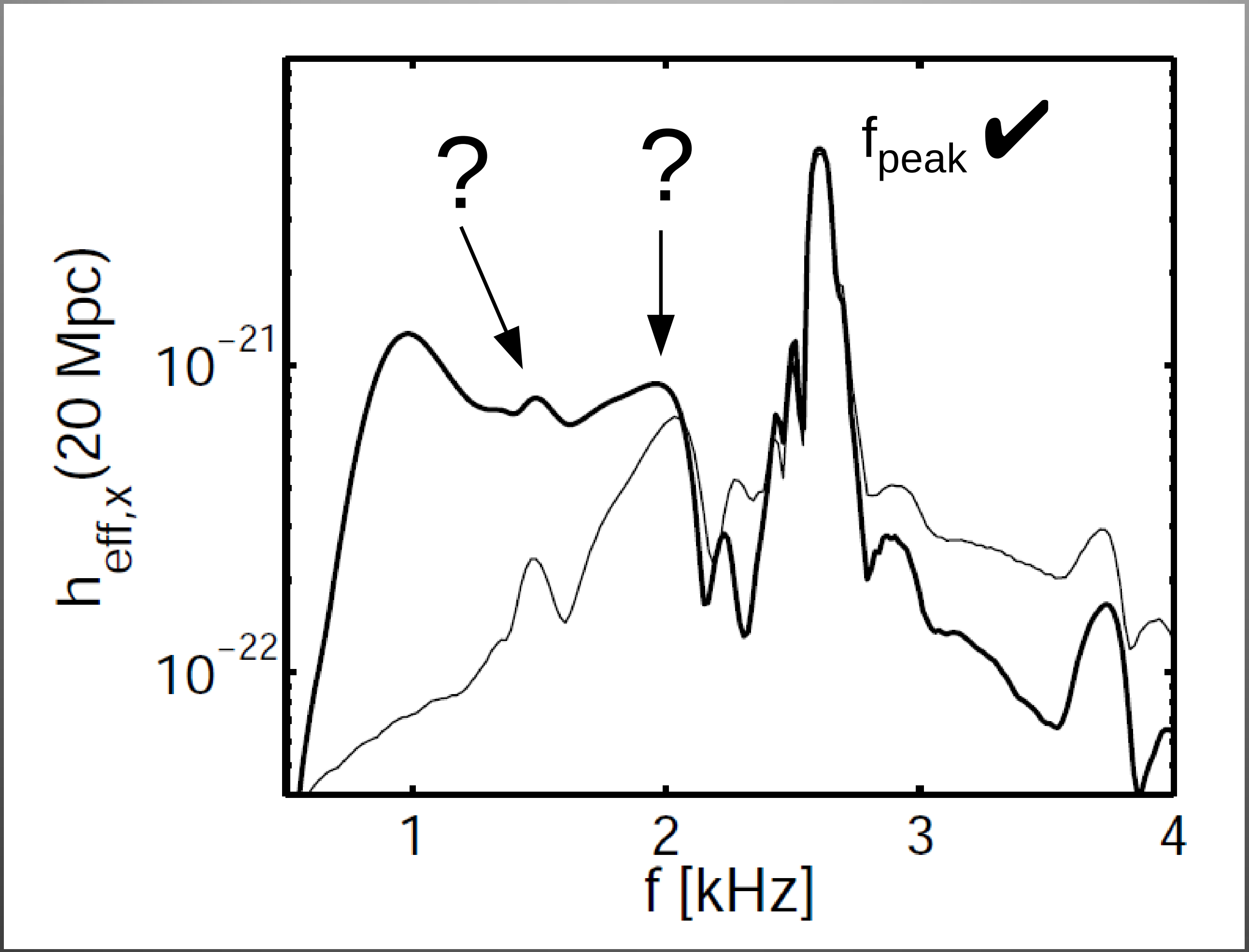
# from two measurements of $f_{peak}$ at moderate $M_{tot}$




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

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

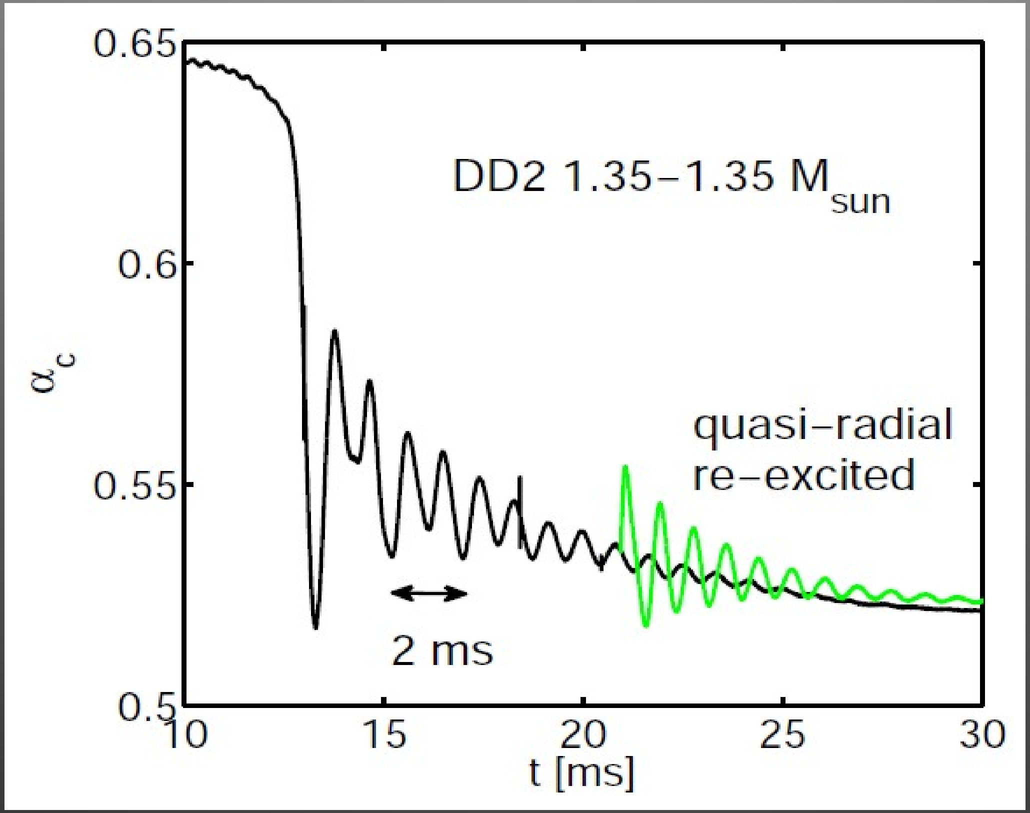
# Generic GW spectrum




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

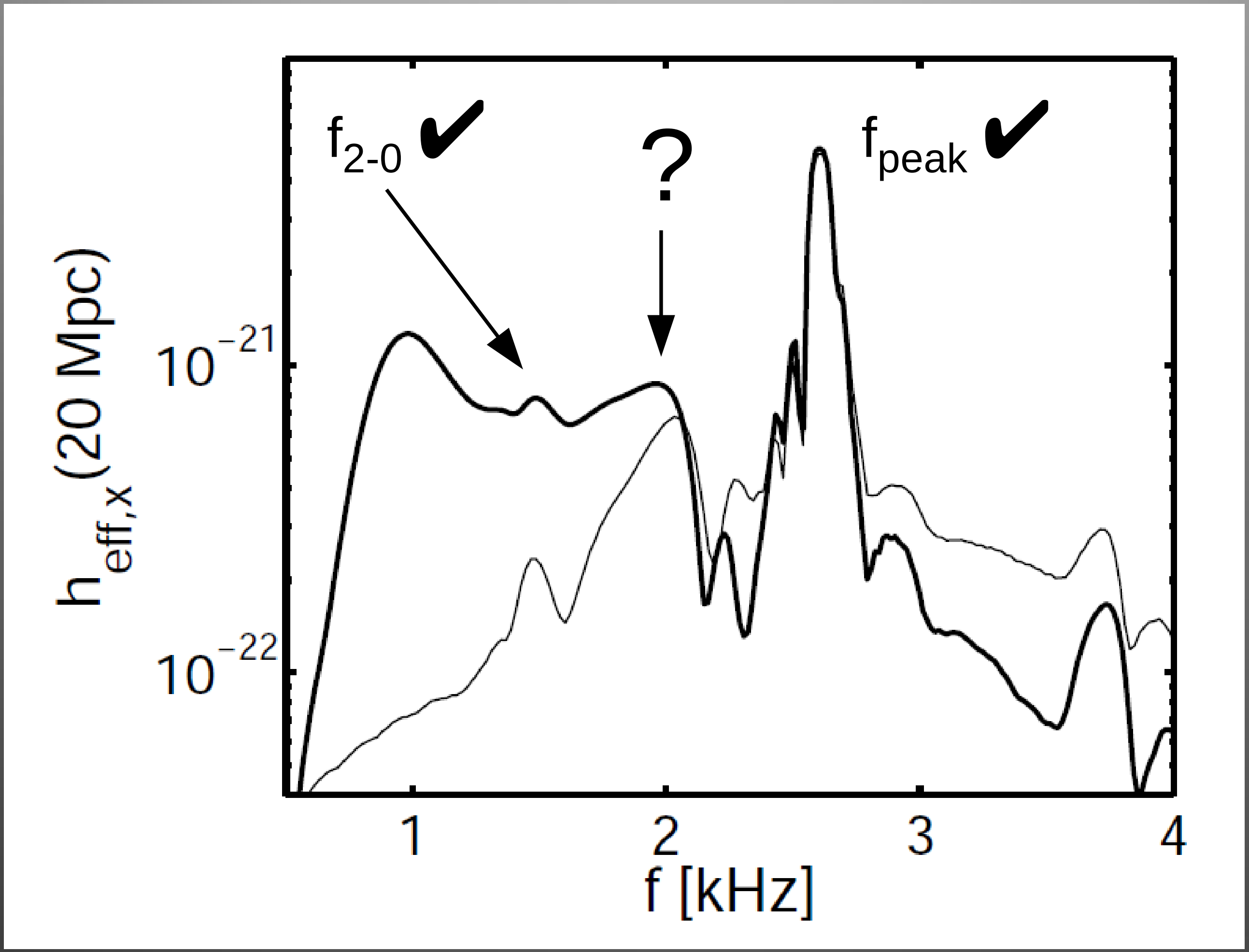
# Quasi-radial mode

- Central lapse function shows two frequencies (~500 Hz and ~1100 Hz)
- Add quasi-radial perturbation → re-excite quasi-radial mode
  => $f_0$ = 1100 Hz
- Confirmed by mode analysis → radial eigen function at $f_0$

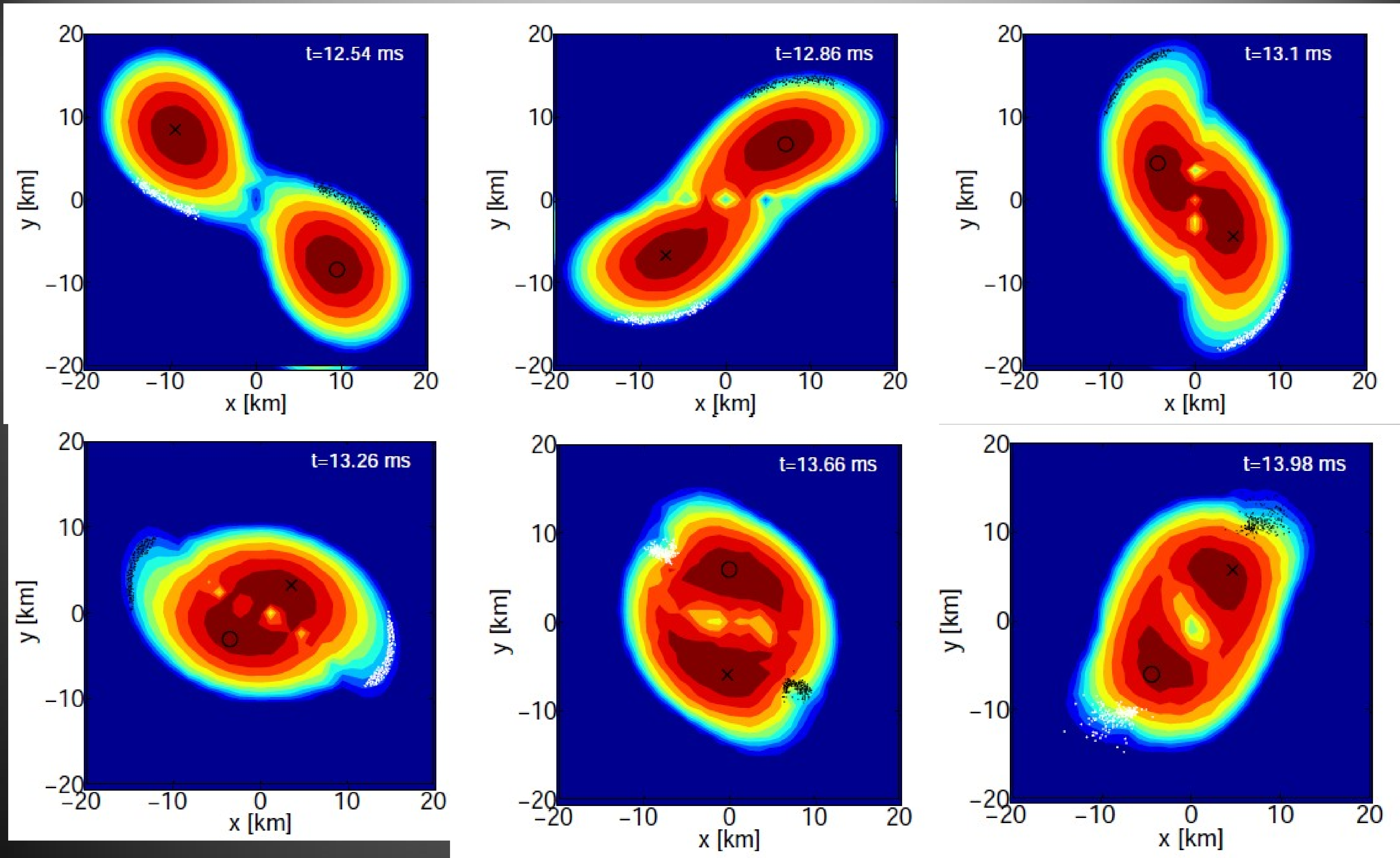



Could consider also size of the remnant, rhomax, …
Note: additional low-frequency oscillation (500 Hz) also in GW amplitude (explained later)

# Generic GW spectrum




- Interaction between dominant quadrupolar mode and quasi-radial oscillation produced peak at $f_{2\text{-}0} = f_{peak} - f_0$ (see Stergioulas et al. 2011)

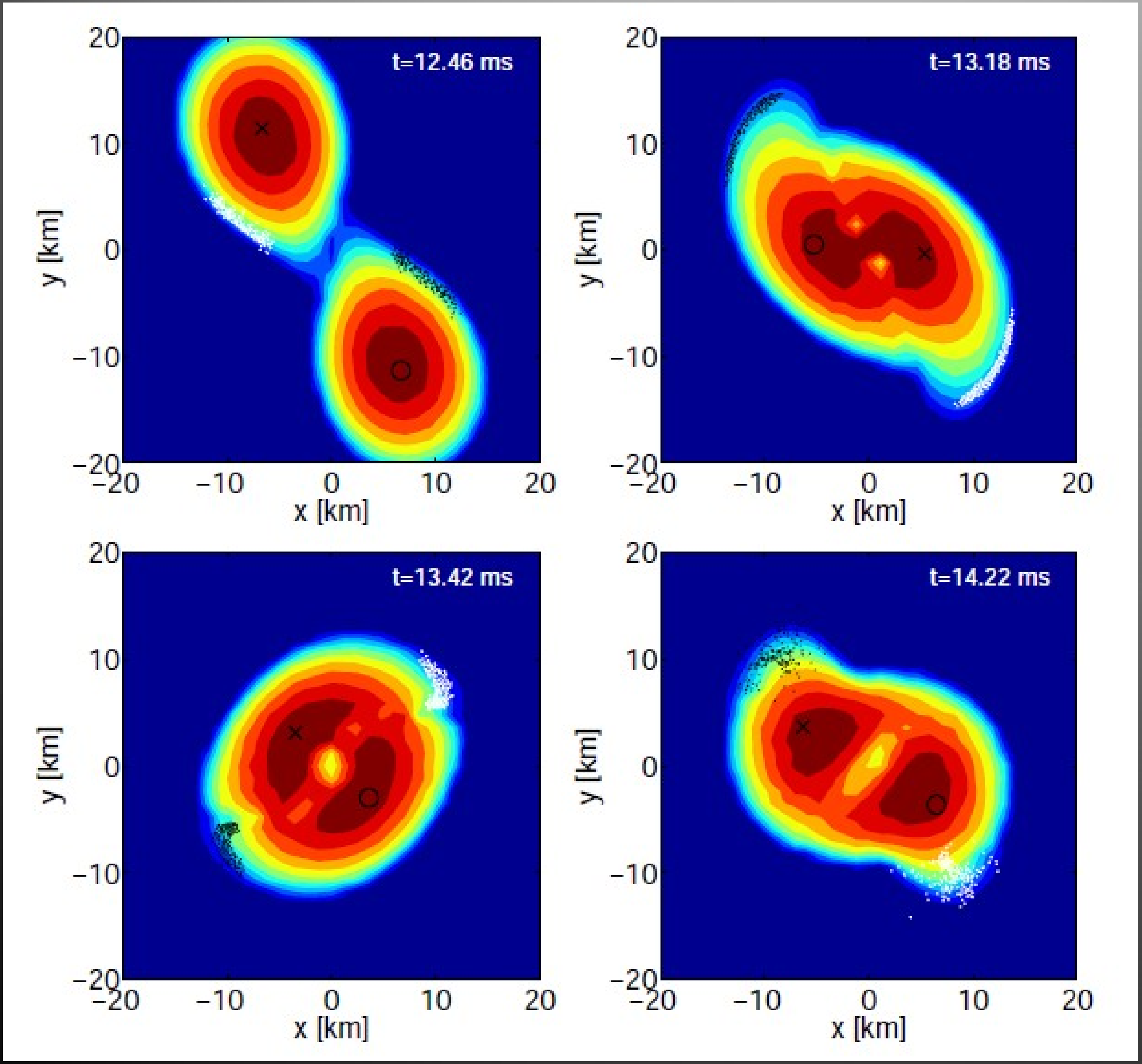



Rest-mass density (equatorial plane) – linear scale !

DD2 EoS, 1.35-1.35 Msun

=> Second component of the remnant

# Antipodal bulges (spiral pattern)



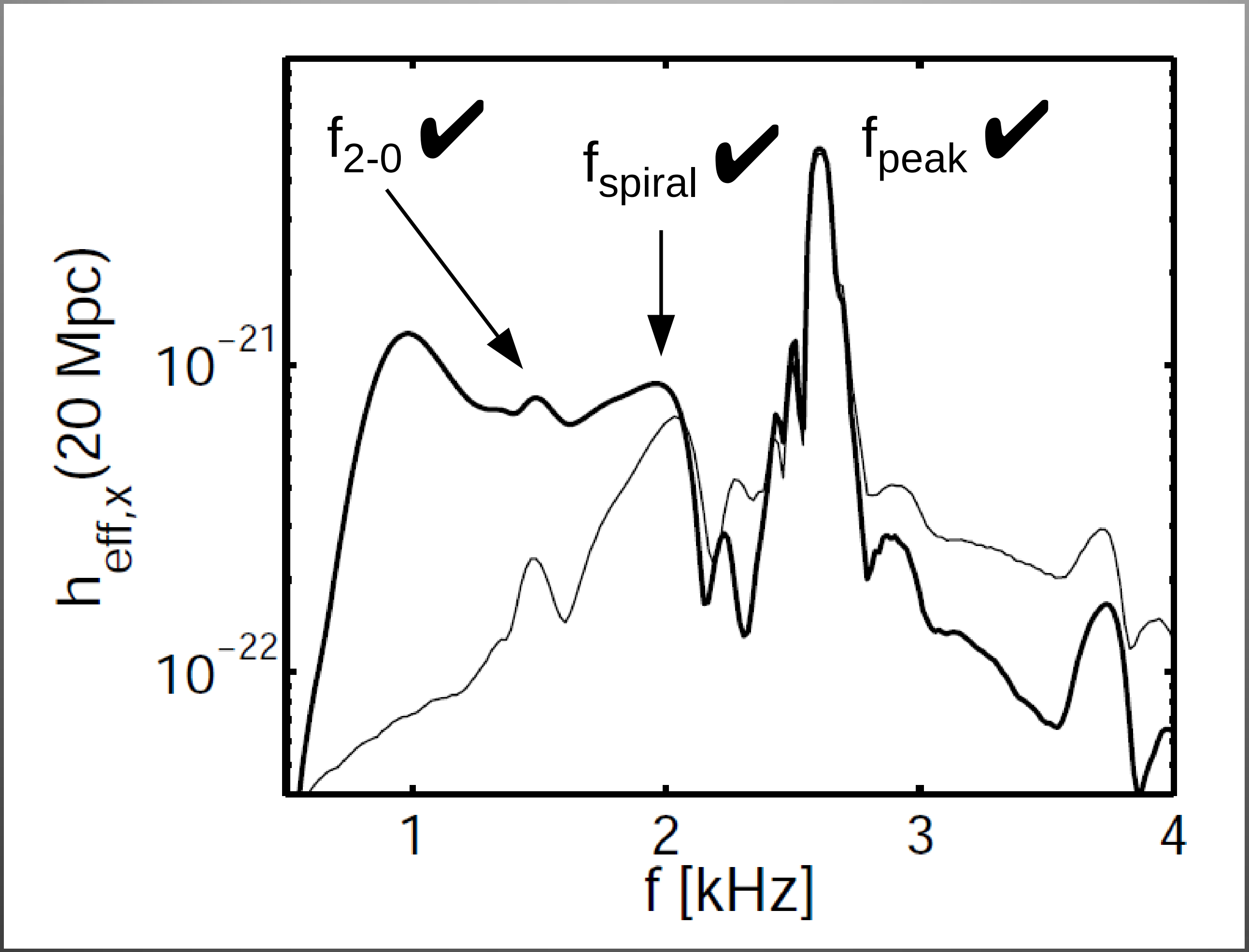

Orbital motion of antipodal bulges slower than inner part of the remnant (double-core structure)

Spiral pattern, created during merging lacks behind

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

Present for only a few ms / cycles

# Generic GW spectrum



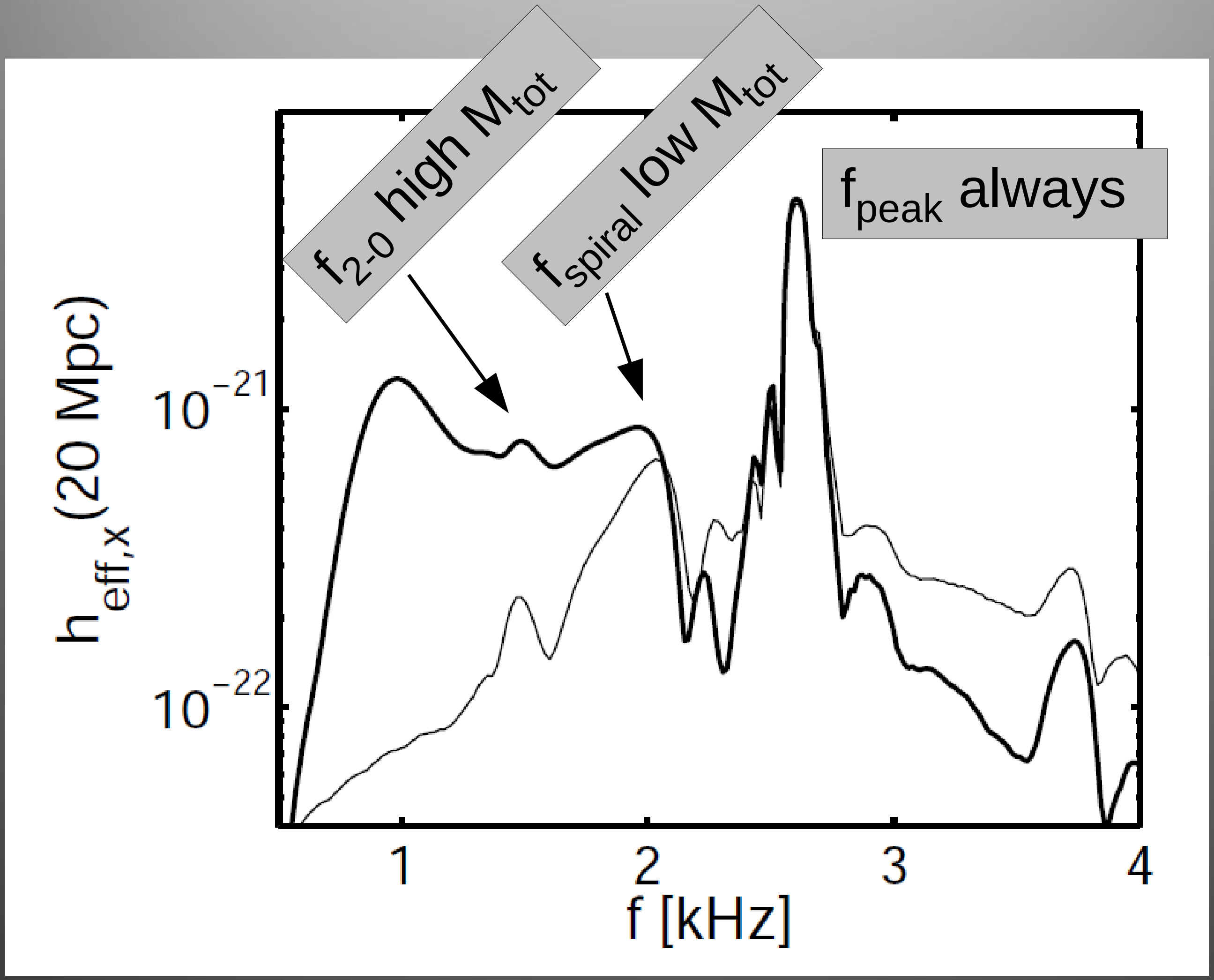

- Orbital motion of antipodal bulges generate peak at $f_{spiral}$

# Further evidence

- Presence of spiral pattern coincides with presence of peak in GW spectrum
- Mass of bulges (several 0.1 $M_{sun}$) can explain strength of the peak by toy model of point particles the central remnant for a few ms
- Tracing dynamics / GW emission by computing spectra for “outer” and “inner” remnant → $f_{spiral}$ emission is produced outside
- (Dynamics of double cores fail to explain this emission)

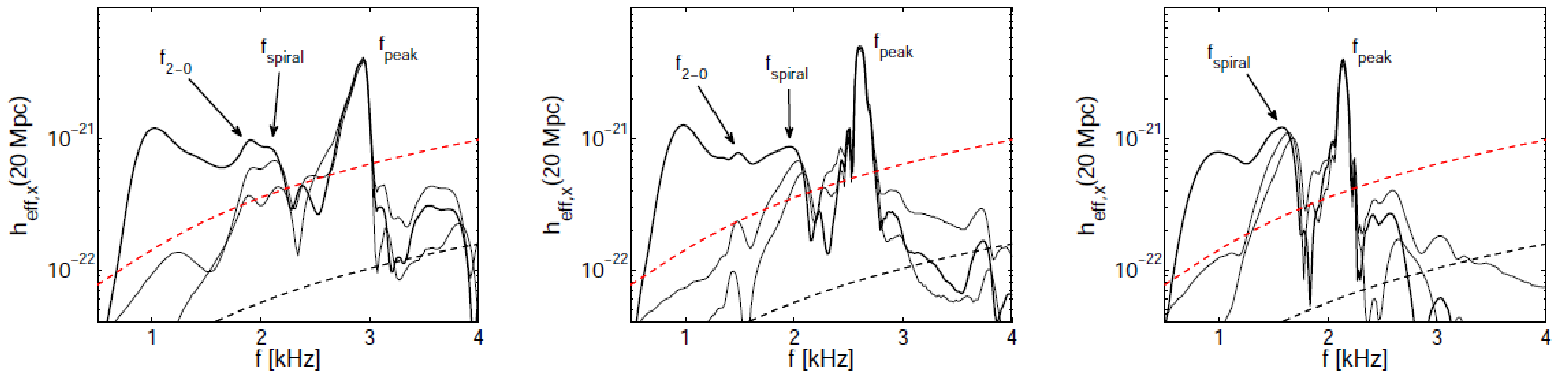
=> orbital motion => $f_{spiral}$ peak

# 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 $M_{thres}$

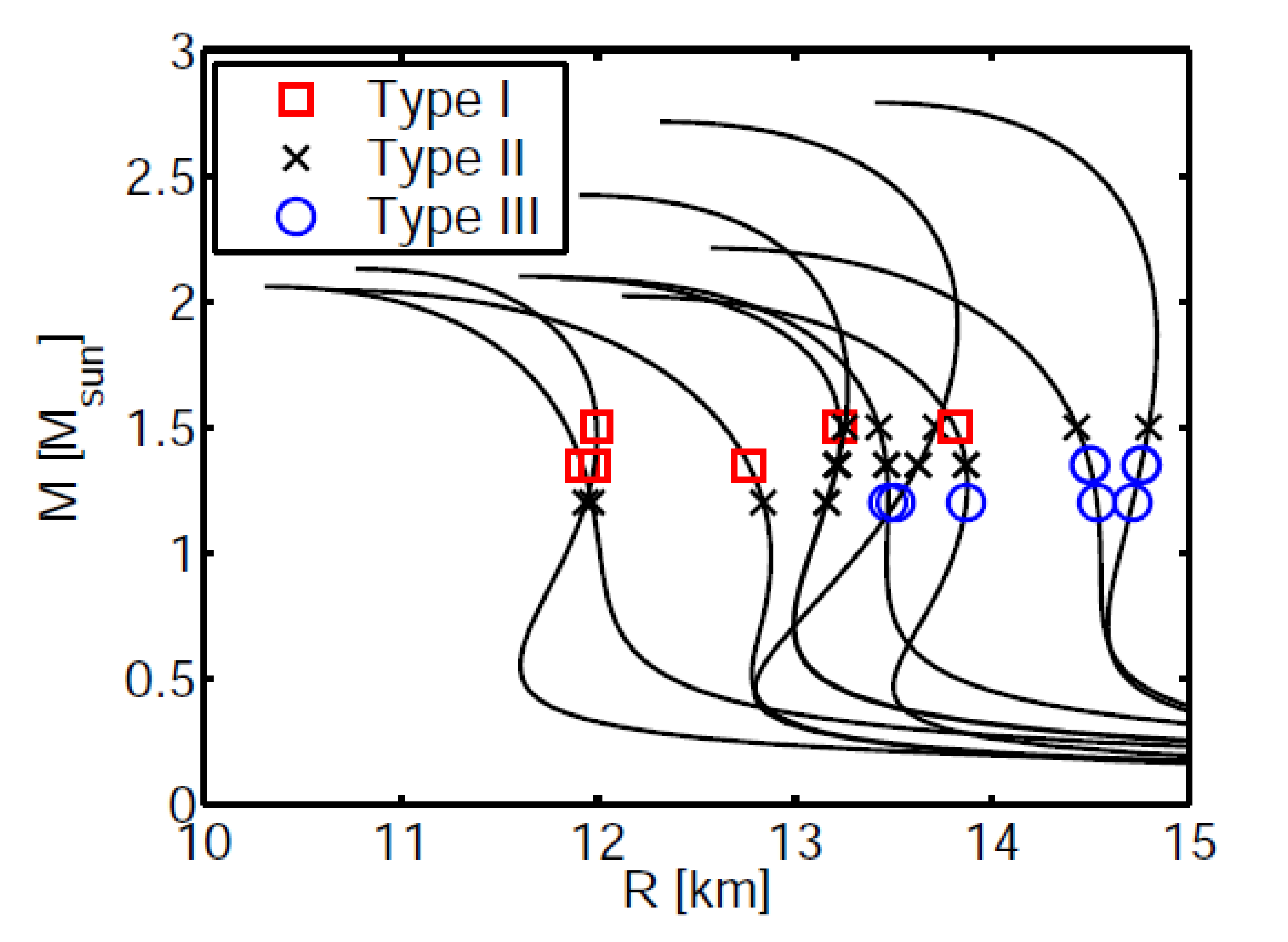
# Classification scheme

- Type I: 2-0 feature dominates, $f_{spiral}$ hardly visible, radial mode strongly excited, observed for 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 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, rhomax, ….
- High mass / low mass relative to threshold binary mass for prompt BH collapse (→ EoS dependent)
- Continuous transition between different types

=> Depending on binary model (EoS, M1/2) either one or the other or both features are there / dominant (if you measure a secondary peak you should always think whether it is f2-0 or fspiral)

# 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

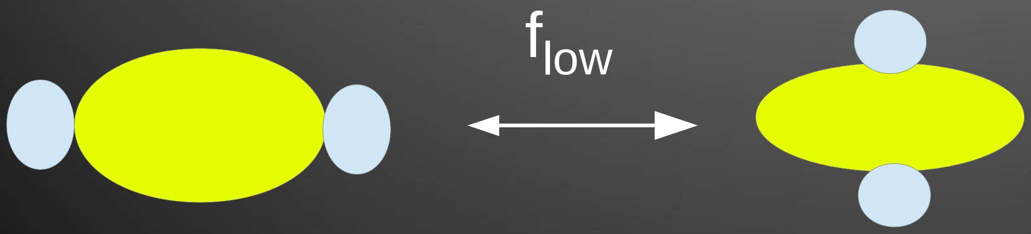
# Classification scheme

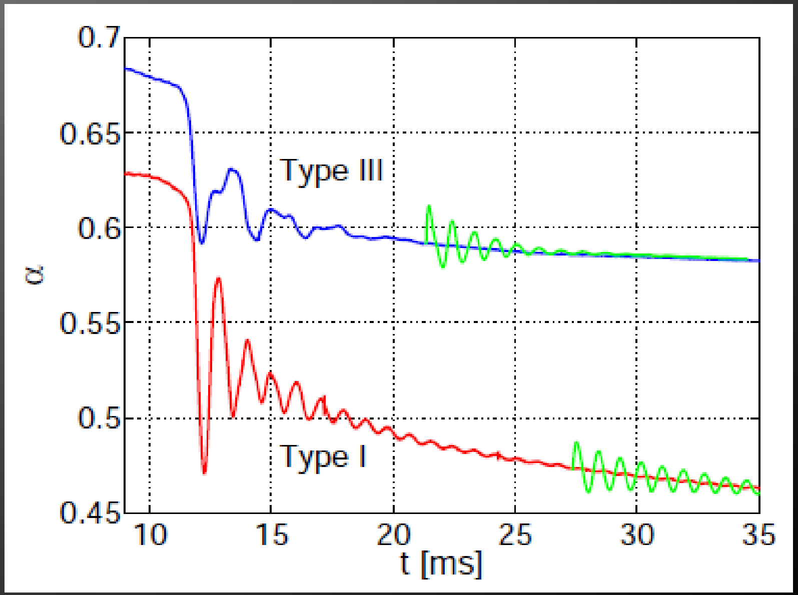
Behavior reasonable:

- 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)

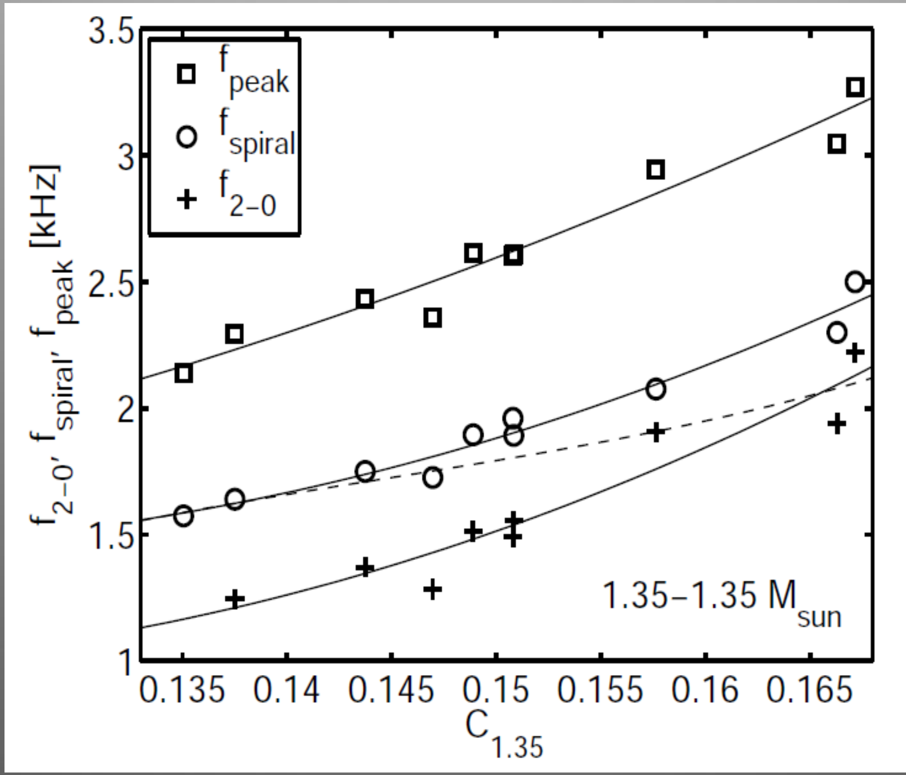
For Type III and Type II low-frequency modulation with $f_{low} = f_{peak} - f_{spiral}$ by orientation of bulge w. r. t. inner double-core/bar

(seen in lapse, GW amp., rhomax, ...)



# Dependencies of secondary frequencies




For fixed $M_{tot}$ = 2.7 $M_{sun}$

Dashed line from Takami et al. 2014

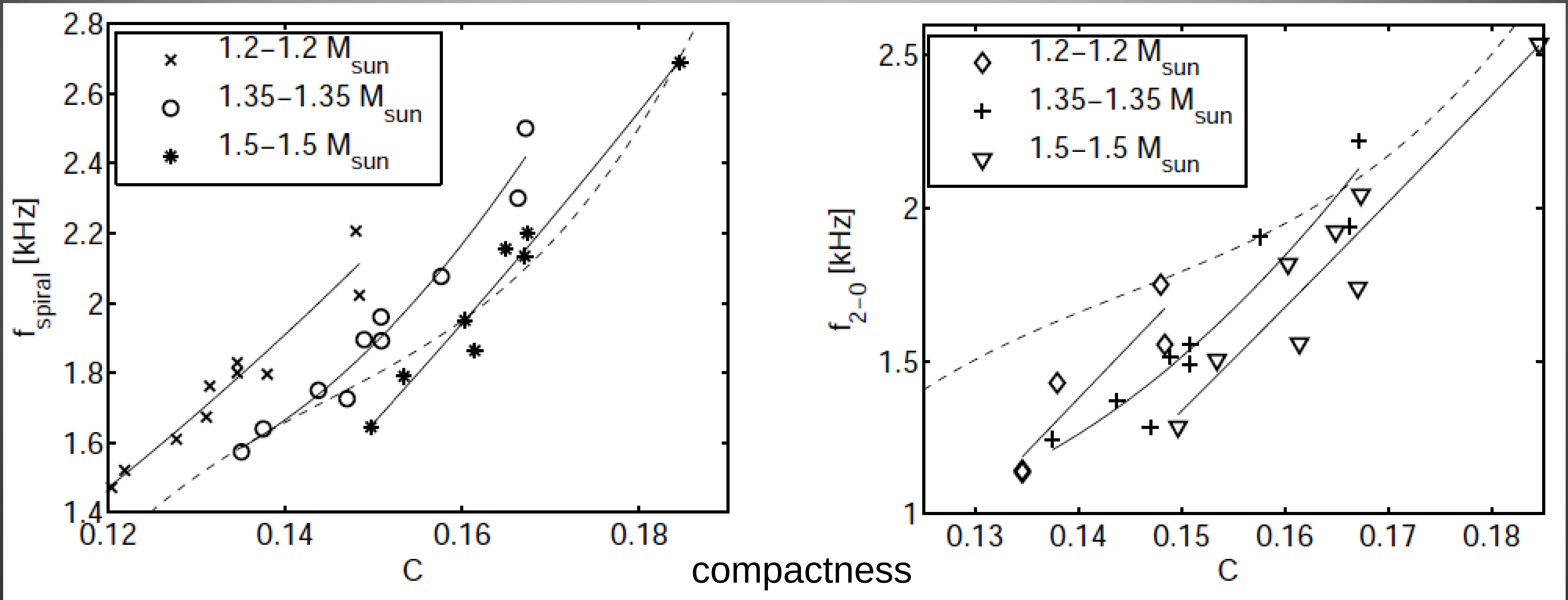
EoS characterized by compactness C=M/R of inspiralling stars (equivalent to radius as before)

All three frequencies scale similarly with compactness (equivalently radius since M = $M_{tot}$/2 = fixed here)

Here: only temperature-dependent EoS to avoid uncertainties/ambiguities due to approximate treatment of thermal effects (Gamma_th)

For small binary mass asymmetry only small quantitative shifts

# Different binary masses




Dashed line from Takami et al. 2014

- for the individual secondary frequencies there are relations between C and the frequency for fixed binary masses (solid lines)

- (binary masses will be known from GW inspiral signal)

- there is no single, universal, mass-independent relation (for a expected range of binary masses), also when choosing the strongest secondary peak

- no conflict with Takami et al.'s data (frequencies agree when comparing same models), but here constant binary mass range for every EoS, more EoSs (larger, more representative parameter range (EoS, $M_{tot}$))

# Summary

- Dominant postmerger oscillation frequency tightly constrains NS radii and NS maximum mass
- Two distinct mechanisms generate secondary features in GW spectrum: interaction between quadrupolar and radial mode; orbital motion of antipodal bulges (explain also low-frequency modulation)
- Depending on presence of secondary features GW emission and dynamics can be classified: three different Types (depending on total binary mass for given EoS)
- Secondary and dominant frequencies show very similar dependence on NS compactness / radius
- Mass-dependent relations for different frequency peaks (but no universal mass-independent relation)

Details: Bauswein & Stergioulas: arXiv:1502.03176