Revealing the high-density equation of state through binary neutron star mergers

Andreas Bauswein

(Heidelberg Institute for Theoretical Studies)

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

MITP program: NSkins of Nuclei

MITP Mainz, 18/05/2016

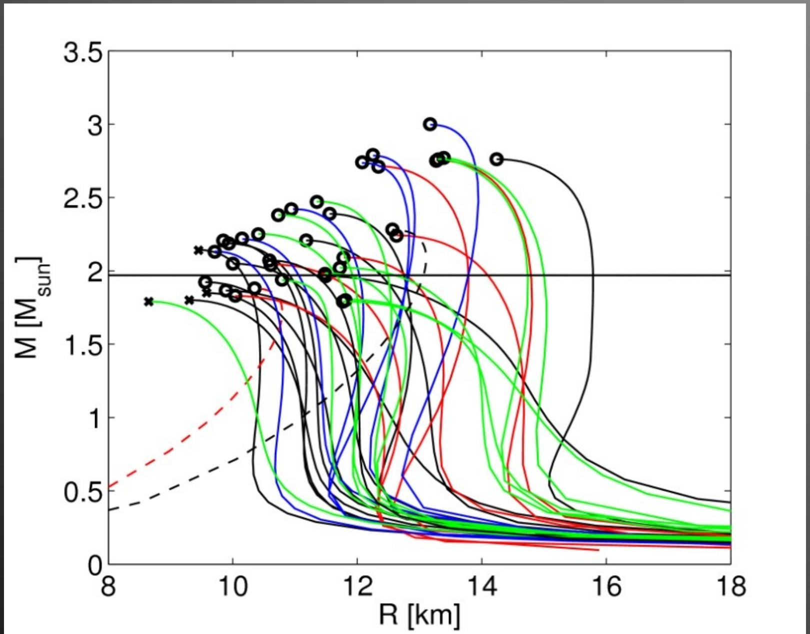
Heidelberg Institute for
Theoretical Studies

HITS

Motivation: understanding the GW emission

Focus on postmerger phase:

- constrain NS / EoS properties from GW measurements (in particular at very high densities)
- Construct templates (analytic model) → boost detectability



Mass-radius relations of Nss for different EoSs

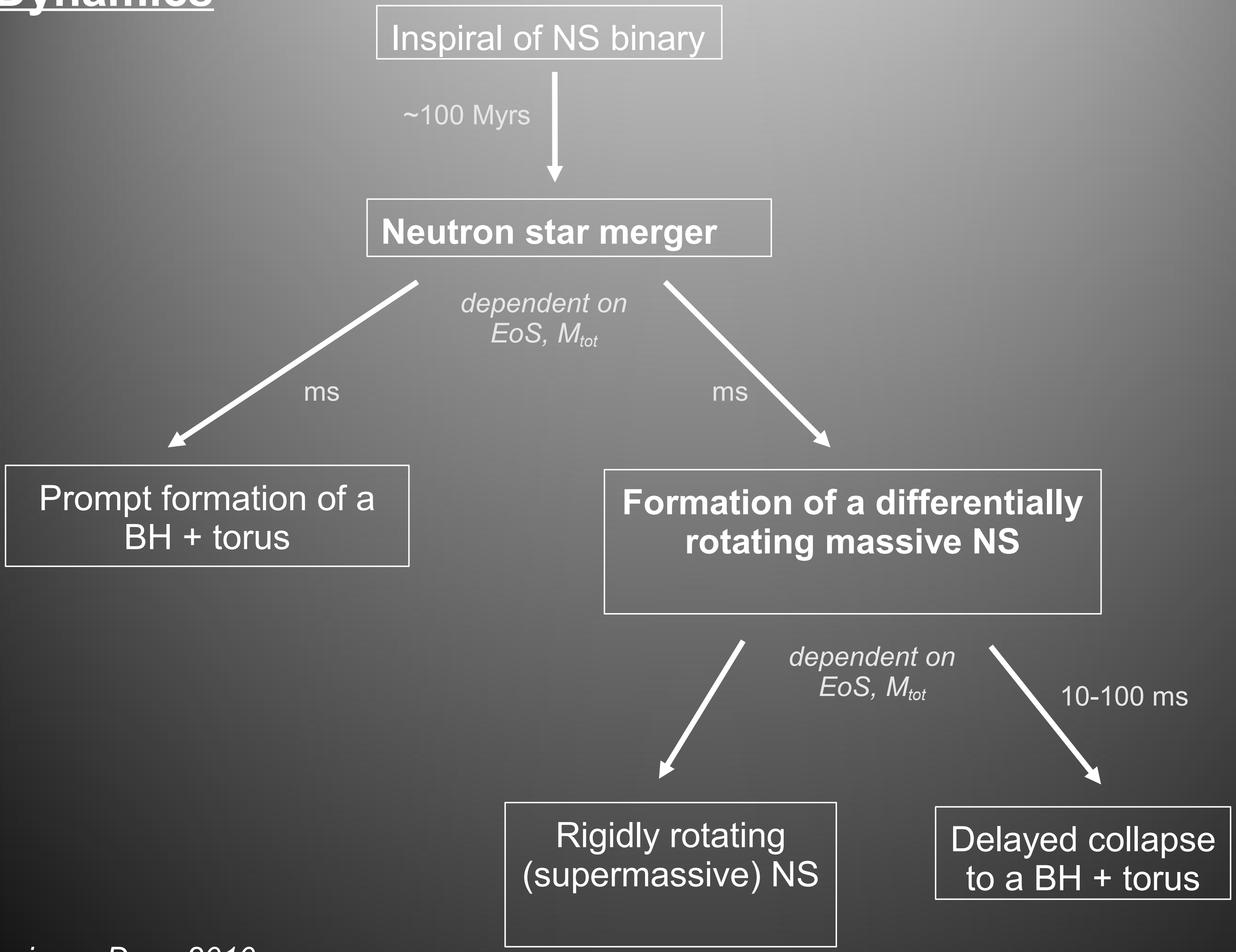
Advanced LIGO

Outline

- Overview
- Mass measurements
- Dominant postmerger GW emission

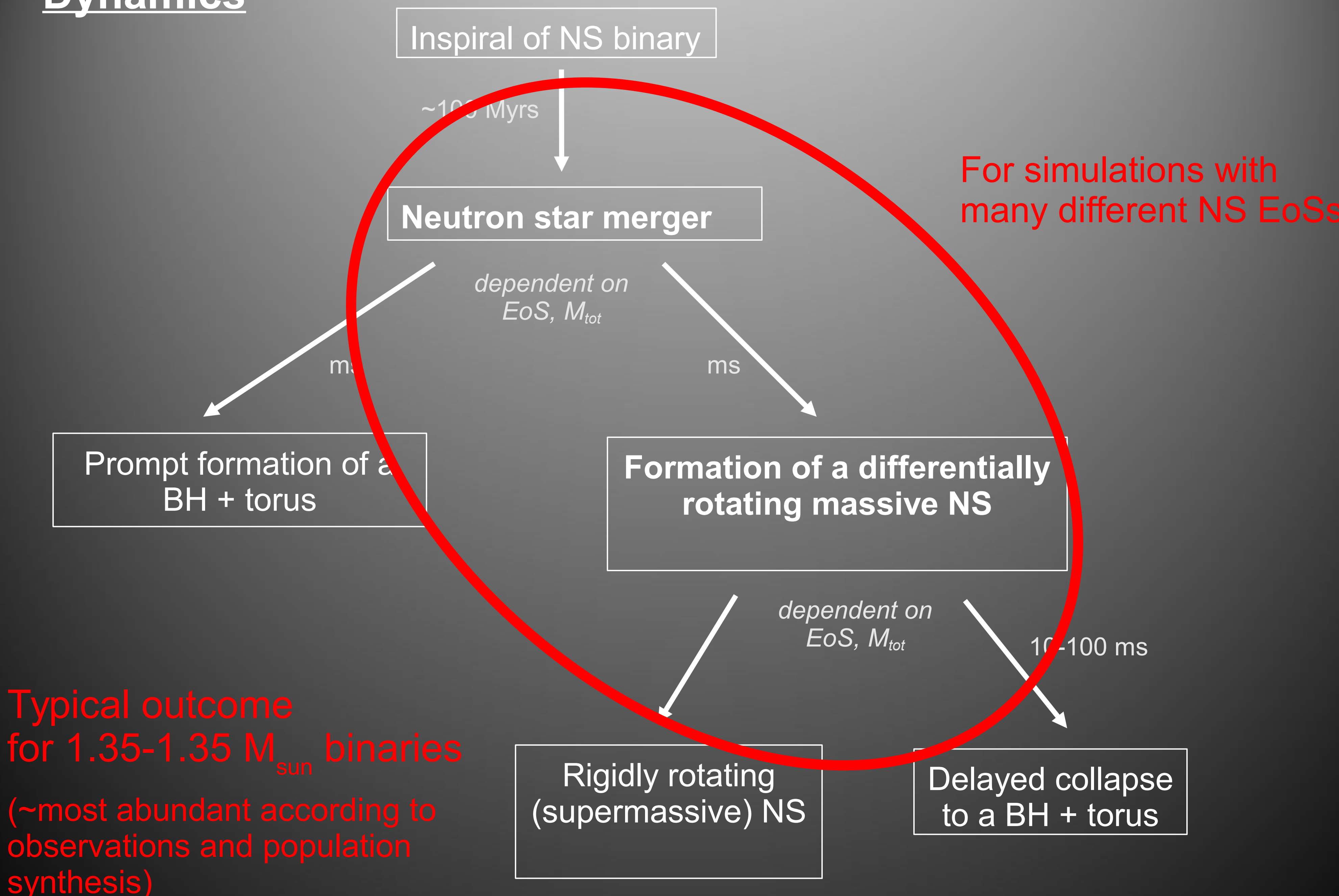
  - NS radius measurements + ...
- Maximum mass of NS via collapse behavior of remnant
- possibly a bit on ejecta

Dynamics

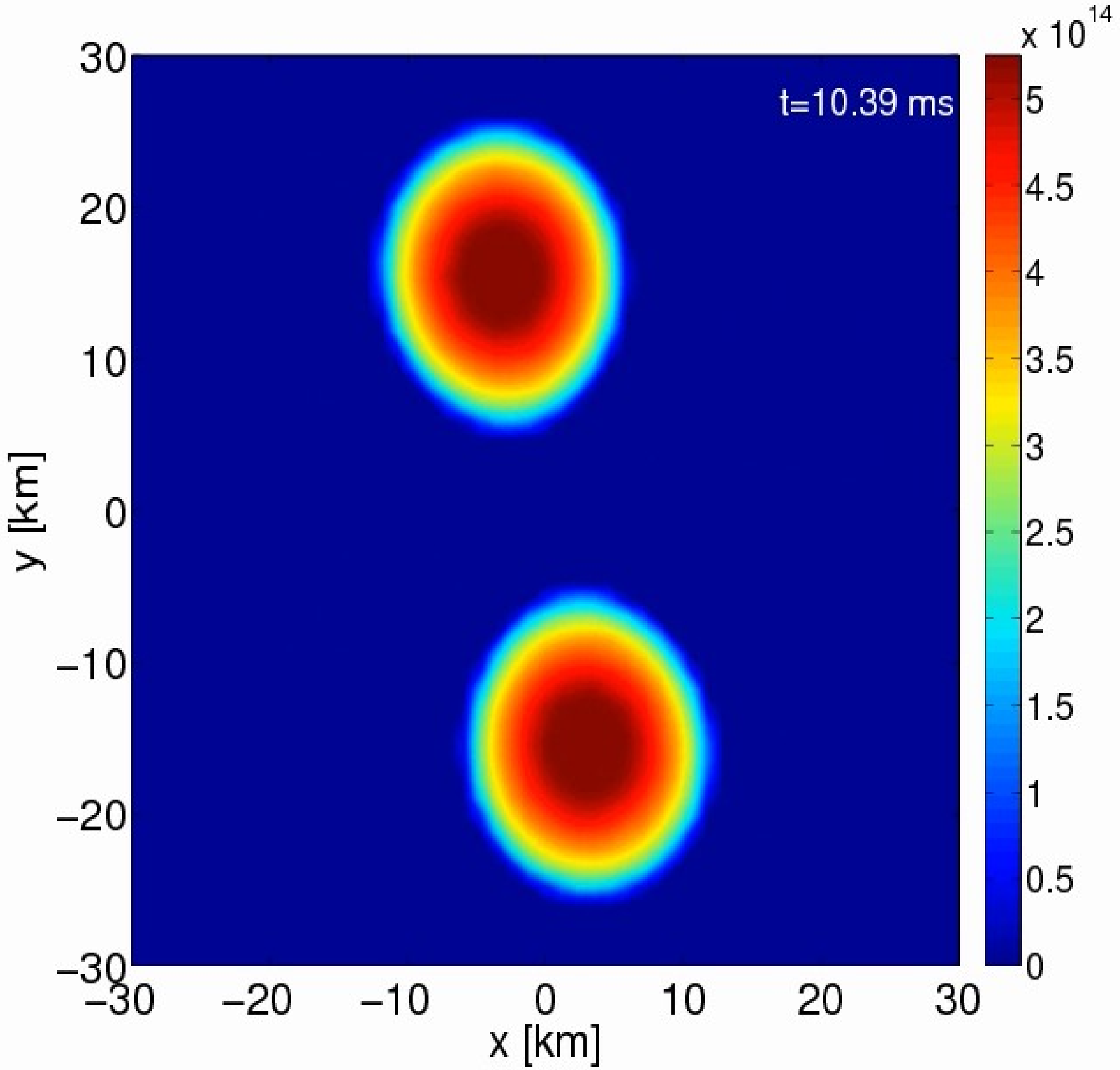


Reviews: Duez 2010, Faber & Rasio 2012

Dynamics

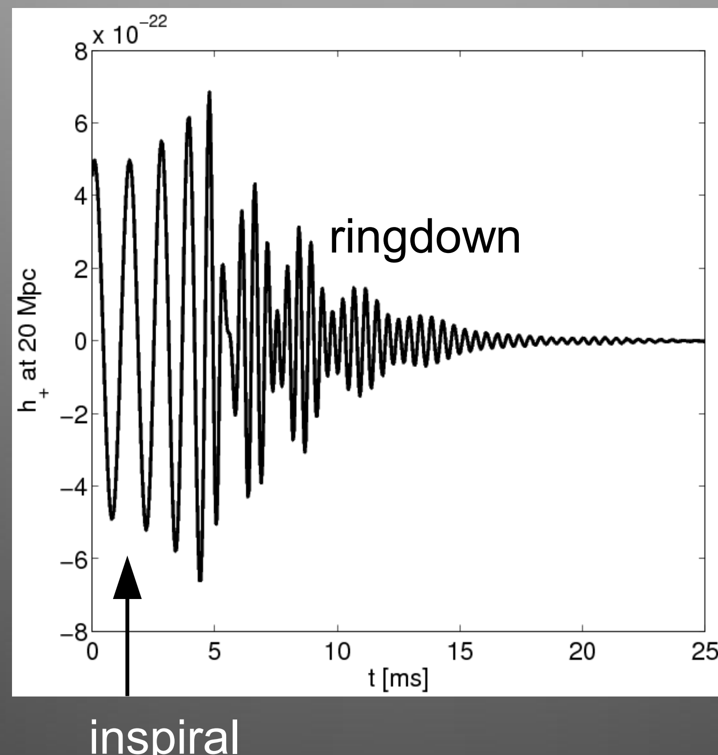


Inspiral of NS binary
~100 Myrs
Neutron star merger
dependent on EoS, M_{tot}
ms
ms
Prompt formation of a BH + torus
Formation of a differentially rotating massive NS
dependent on EoS, M_{tot}
10-100 ms
Rigidly rotating (supermassive) NS
Delayed collapse to a BH + torus
For simulations with many different NS EoSs
Typical outcome for 1.35-1.35 M_{sun} binaries
(~most abundant according to observations and population synthesis)



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

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)

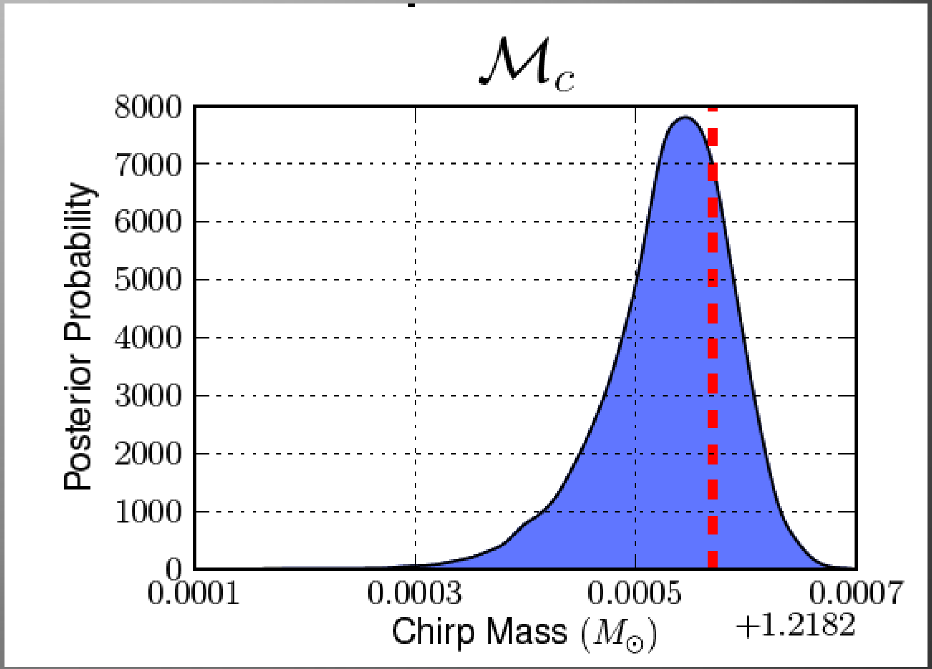
  - dynamics of the inspiral mostly determined by masses

- 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"

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

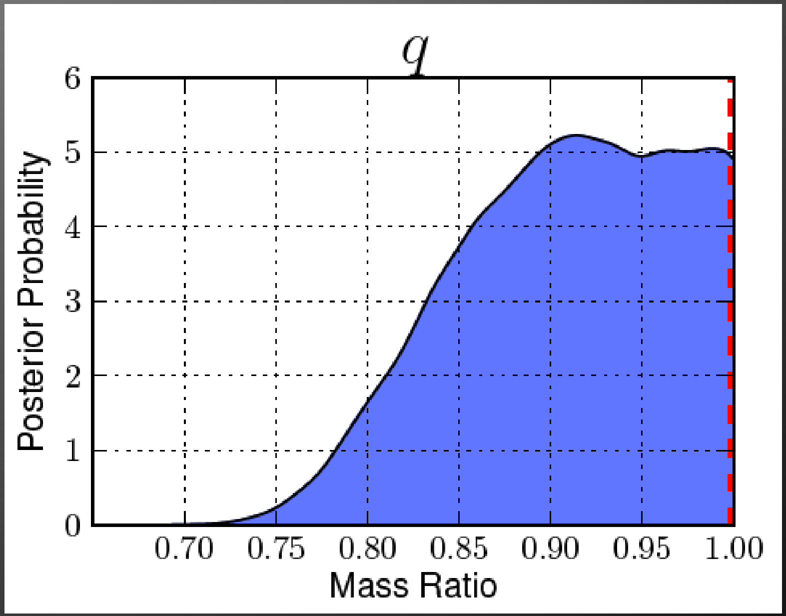


Mass ratio with larger error

$$q = M_1/M_2$$

i.e. q only for near-by mergers

Dashed red line = injected signal
Distribution function of recovered signals in blue



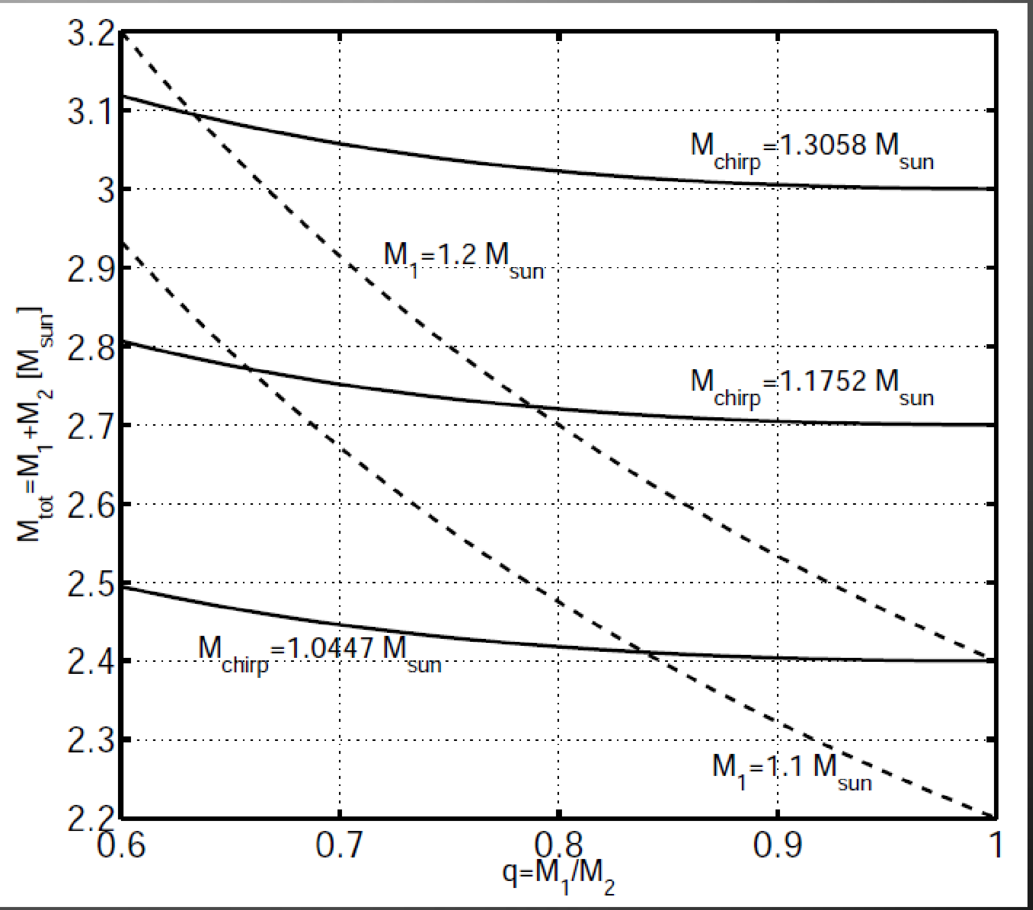
Rodriguez et al 2014 – injected at 100 Mpc

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

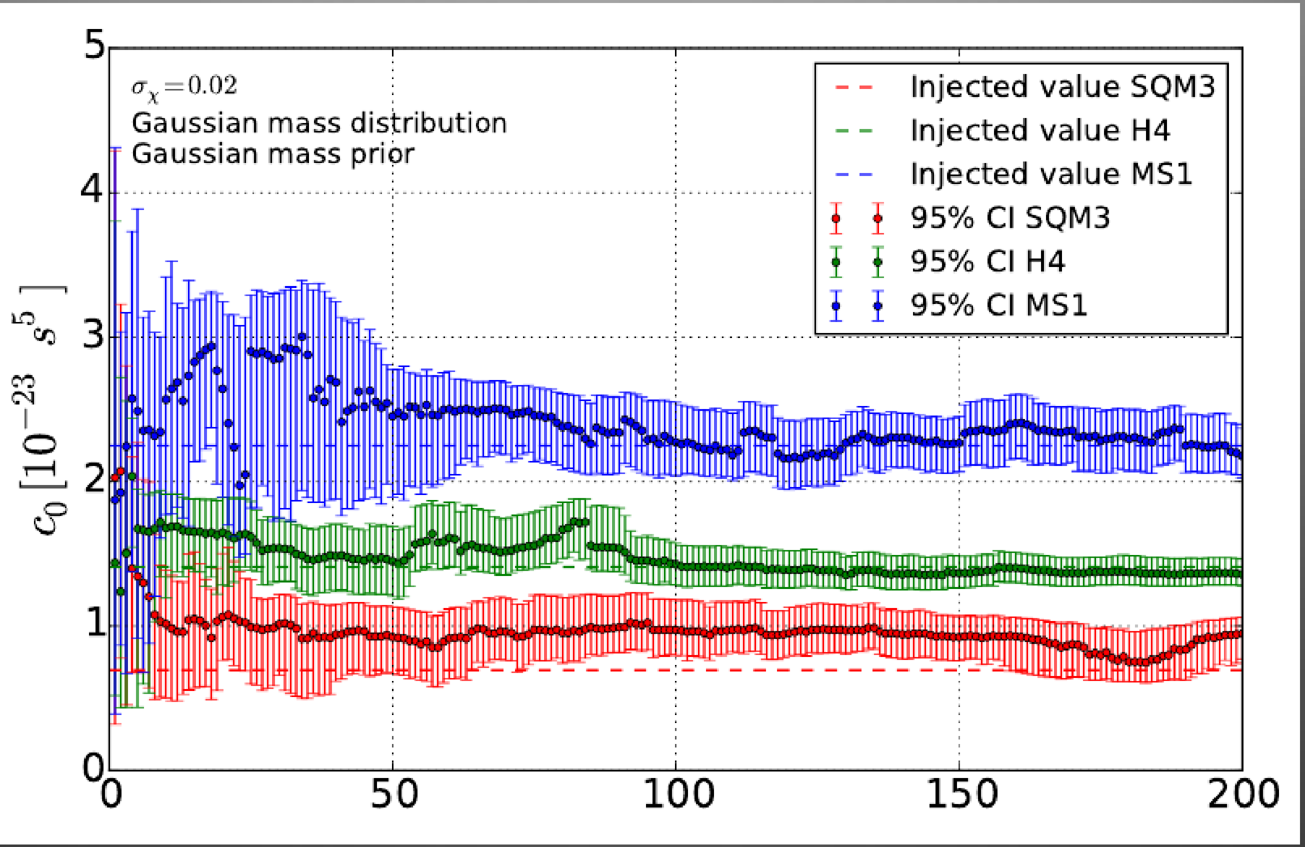
  (e.g. Read et al. 2013 → ~1 km @ 100 Mpc; e.g. Flanagan & Hinderer 2008, Hinderer et al. 2010, Damour et al. 2012, Maselli et al. 2013, Del Pozzo et al 2013, Yagi & Yunes 2014, Wade et al. 2014, Agathos et al. 2015, Hinderer et al. 2016, ...) - accurate templates not yet available

  Note: actually tidal deformability is measured (scales tightly with Ns radius, also "TOV-quantity")

- Postmerger oscillations:

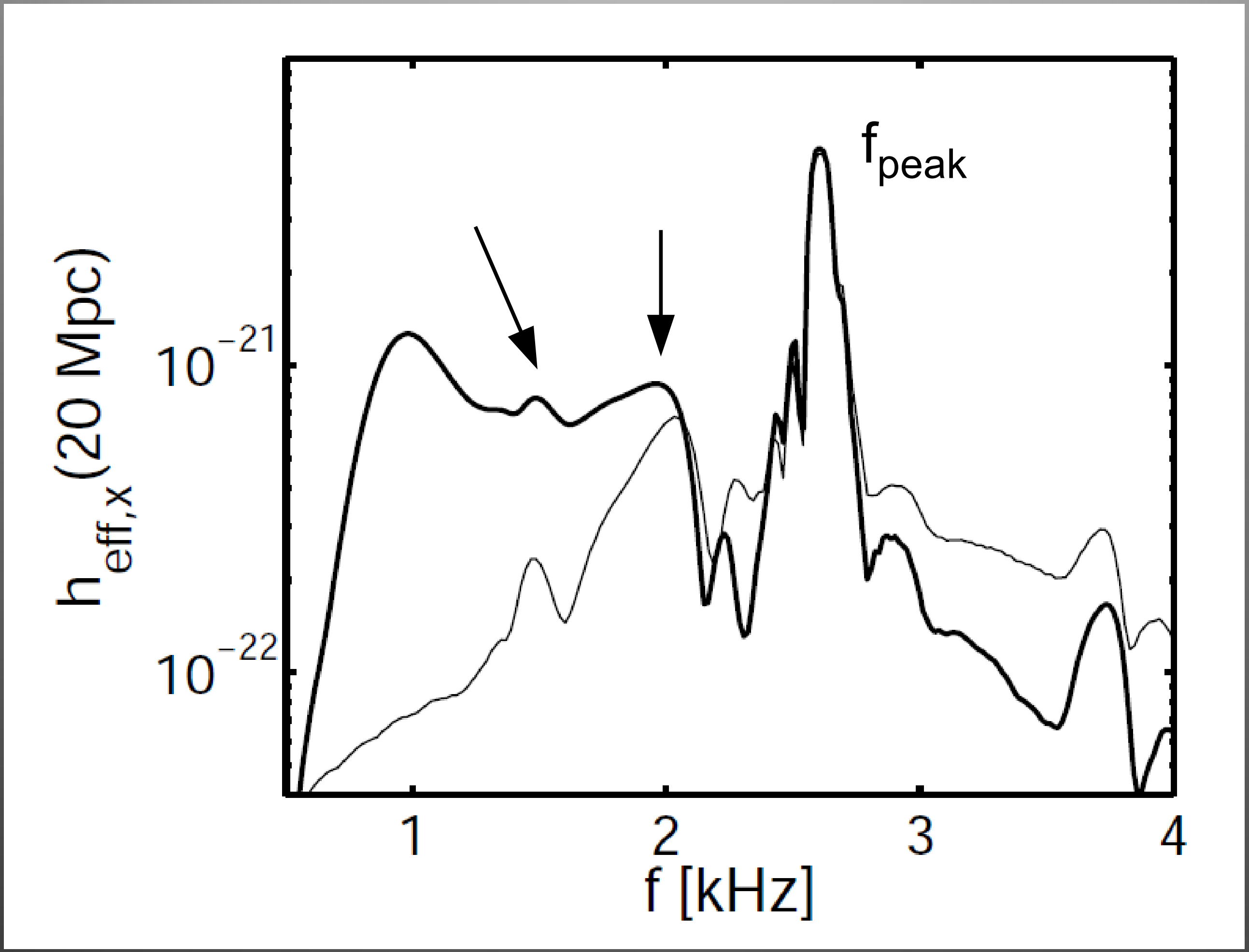
  weak signal – robust strong EoS effect

Combining several measurements for tidal deformability



Agathos et al. 2015

Generic GW spectrum



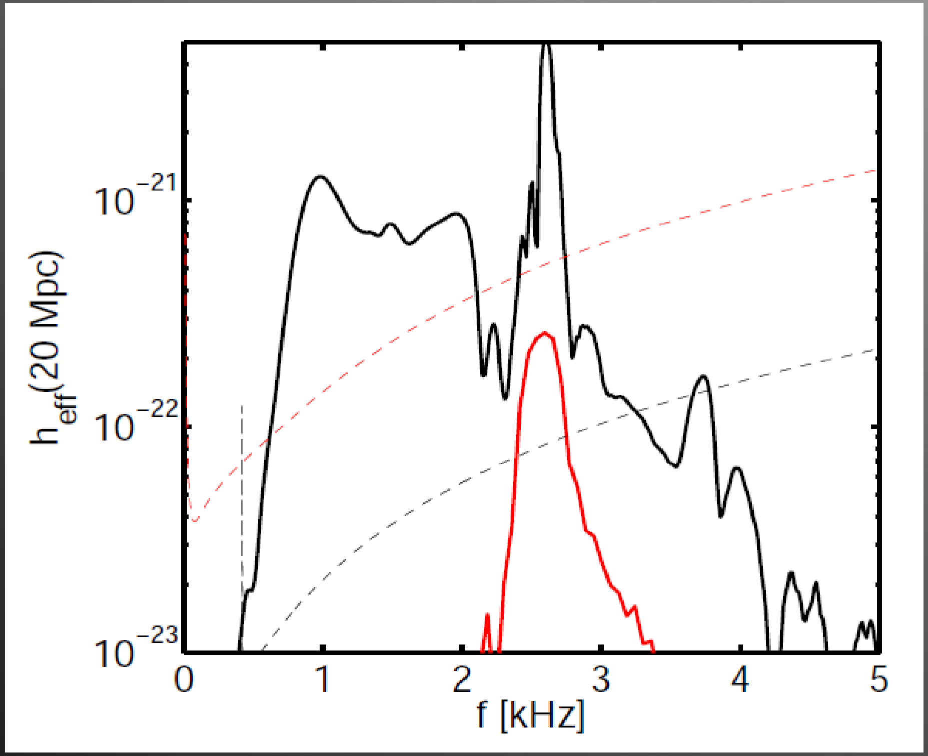
Thin line postmerger only

- 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.)

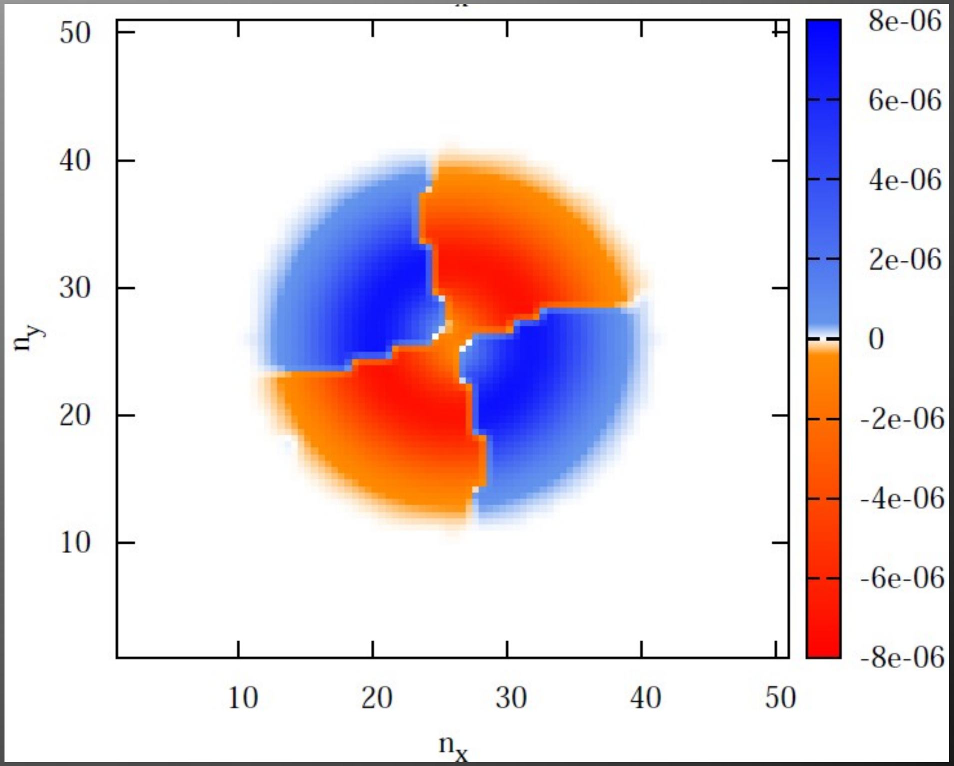
In the literature f_{peak} is also called f_2

Dominant oscillation frequency

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

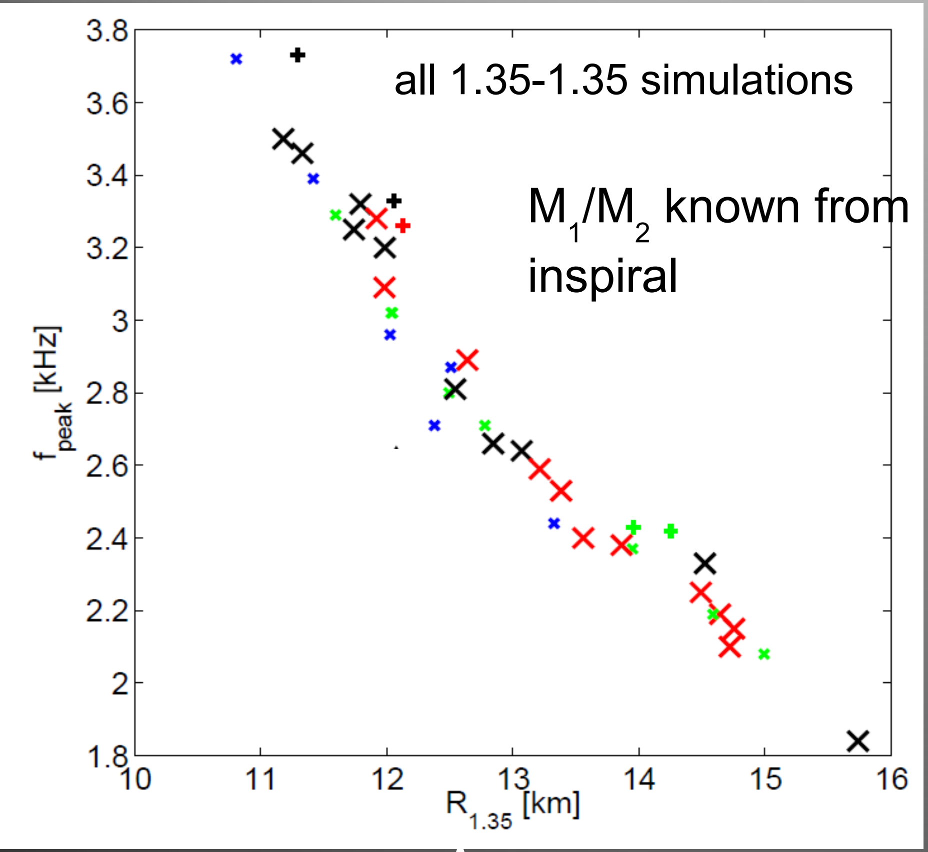


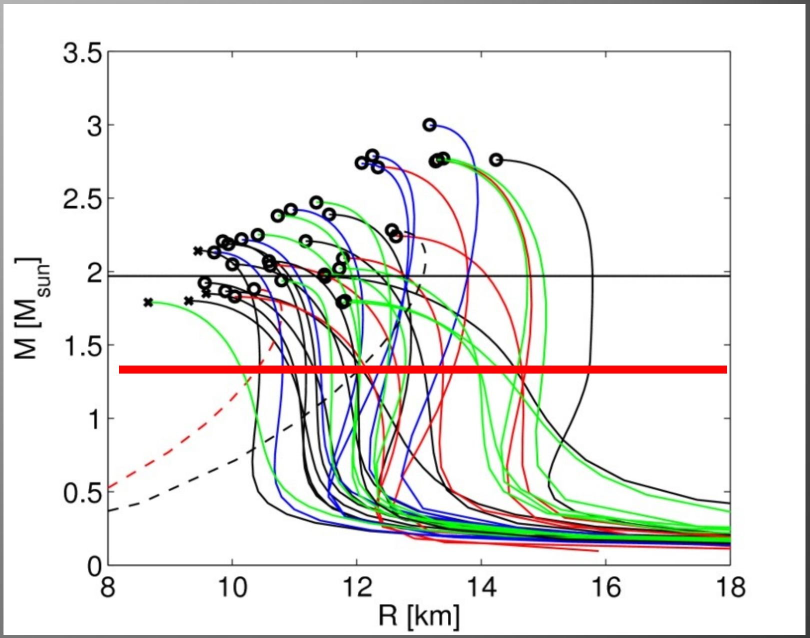
Re-excitation of f-mode (l=|m|=2) in late-time remnant, Bauswein et al. 2015



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}

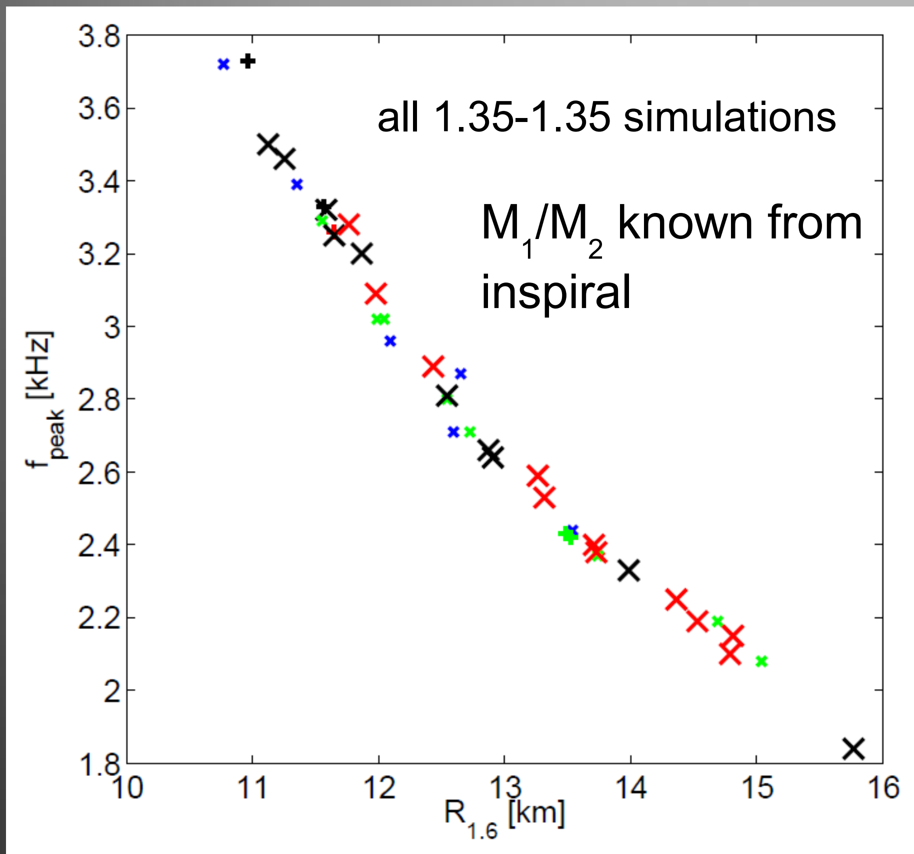
Pure TOV property => Radius measurement via f_{peak}

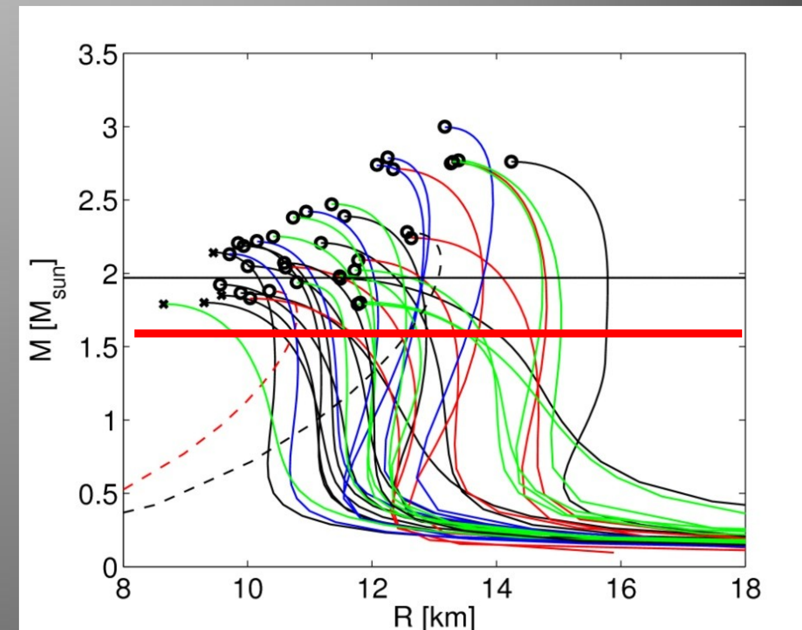
→ Empirical relation between GW frequency and radius of non-rotating NS

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}

Error: maximum scatter in empirical relation ~ 150 m

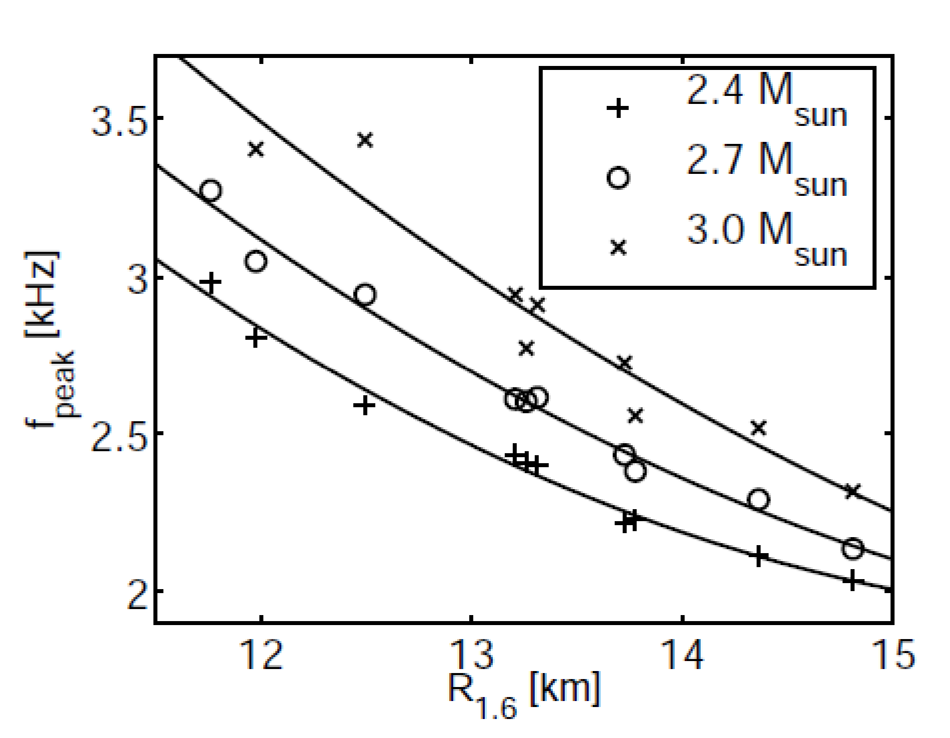
Note: R of 1.6 M_{sun} NS scales with f_{peak} from 1.35-1.35 M_{sun} mergers (density regimes comparable)

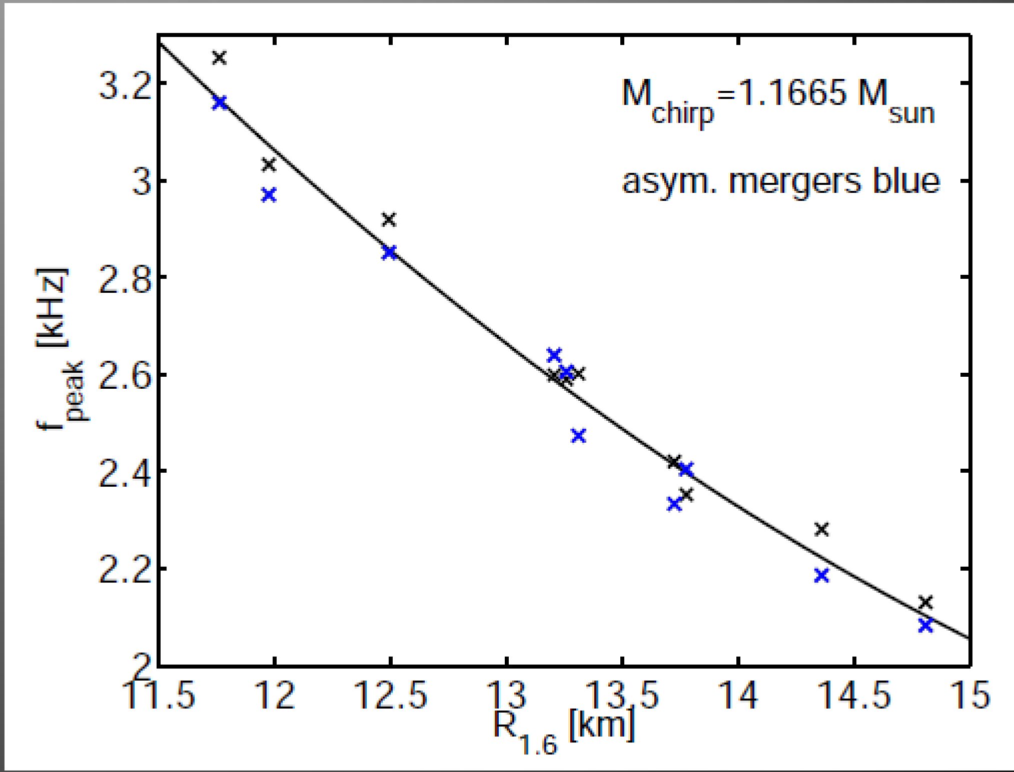
Final strategy - Variations of binary masses

1.) measure binary masses

2.) measure fpeak

2.) choose fpeak relation for inversion depending on mass



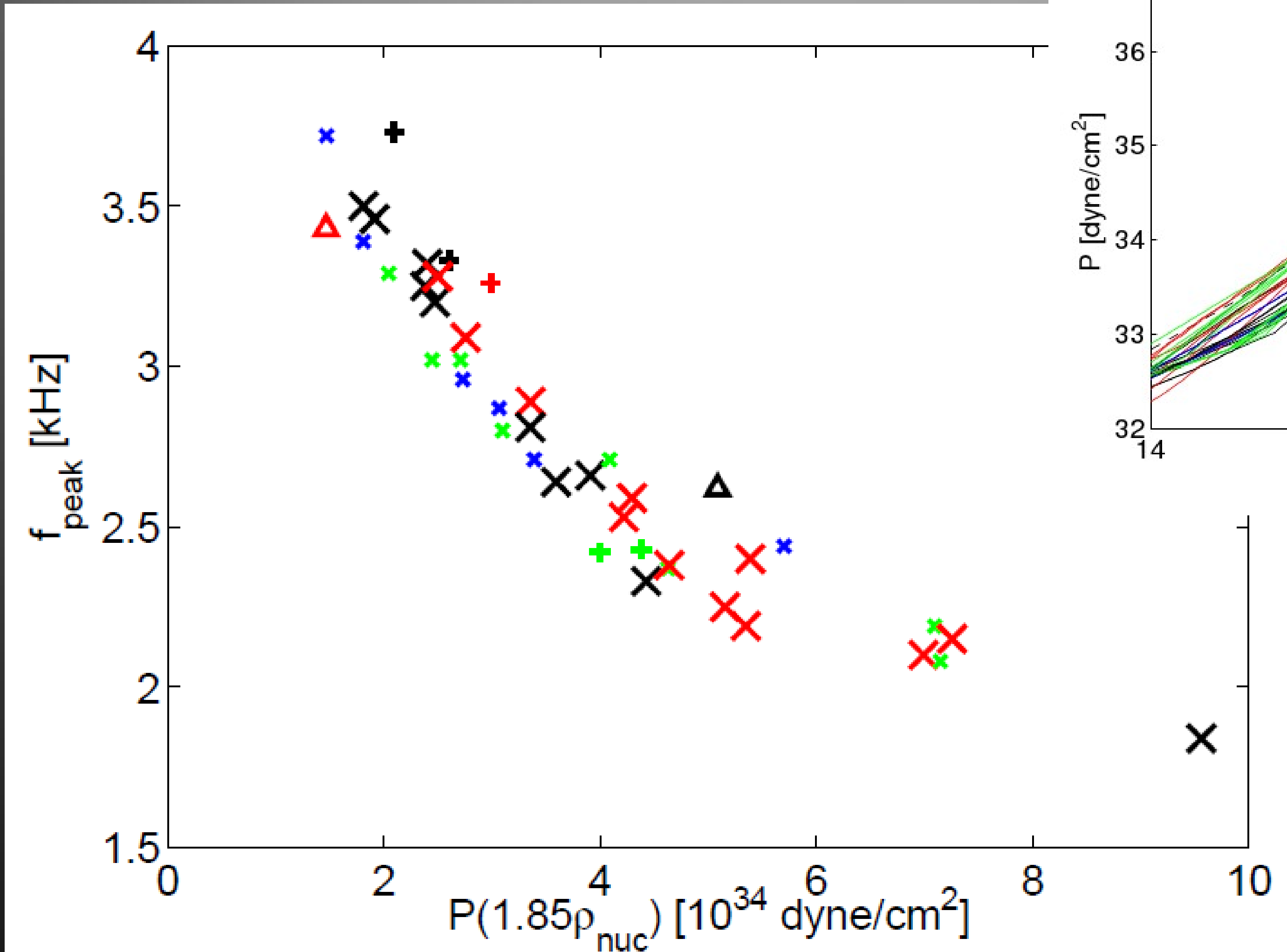


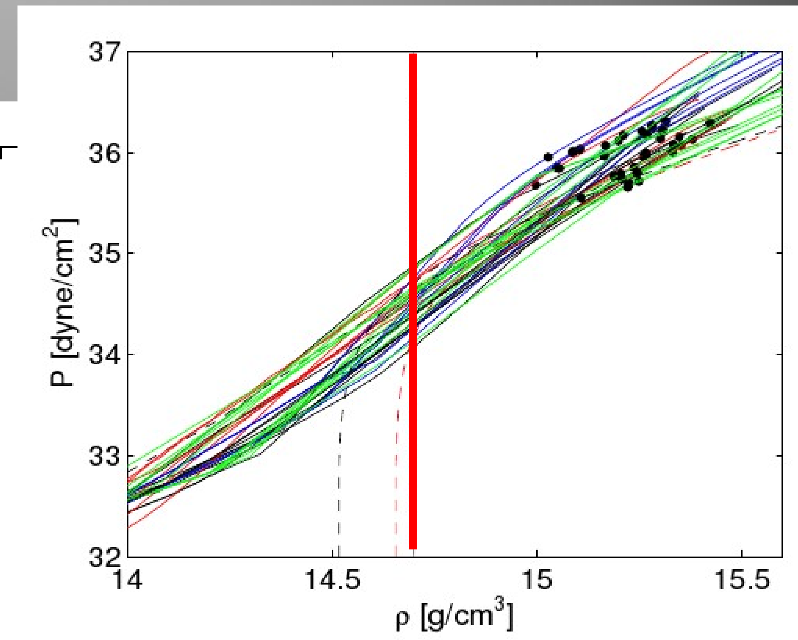
Bauswein et al. 2015

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

Pressure at 1.85 nuclear density

all 1.35-1.35 simulations



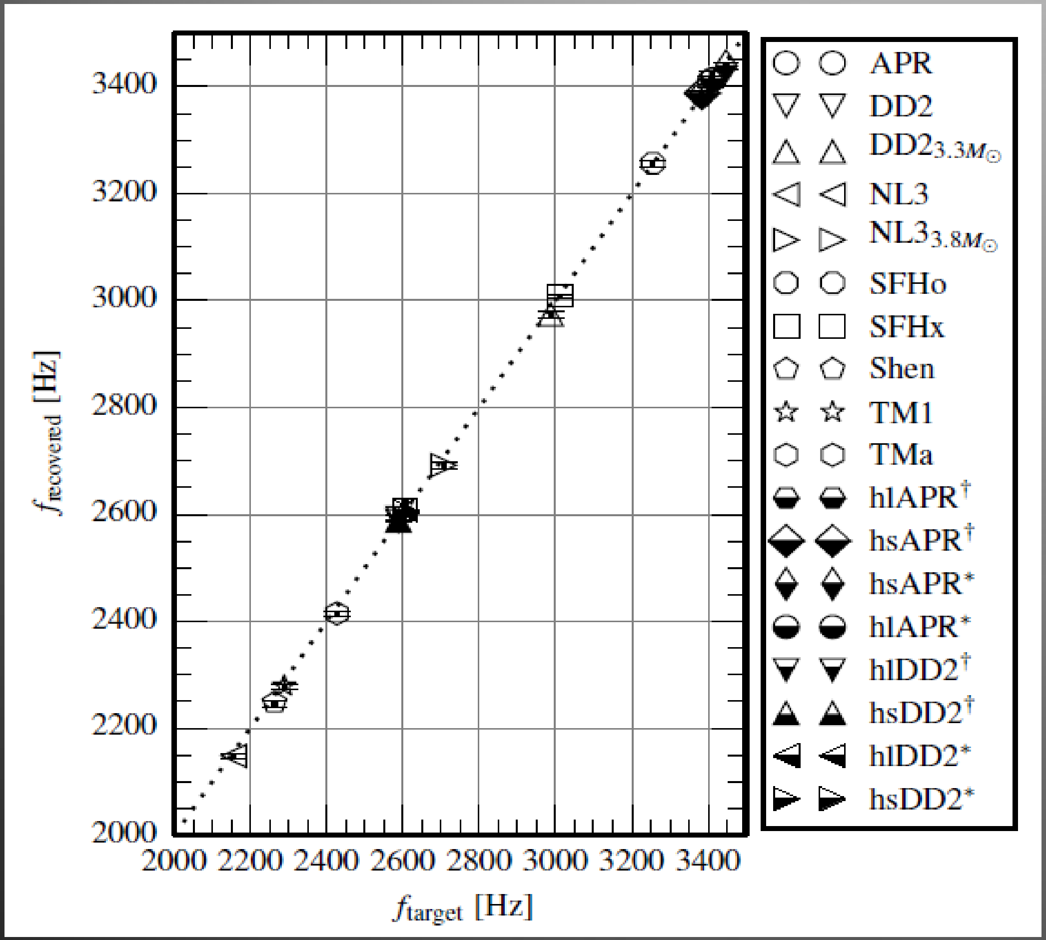


Triangle: strange quark matter (distinguishable by other observations)

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); Hotokezaka et al. 2013, Takami et al. 2014, Foucart et al. 2016, ...
- 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

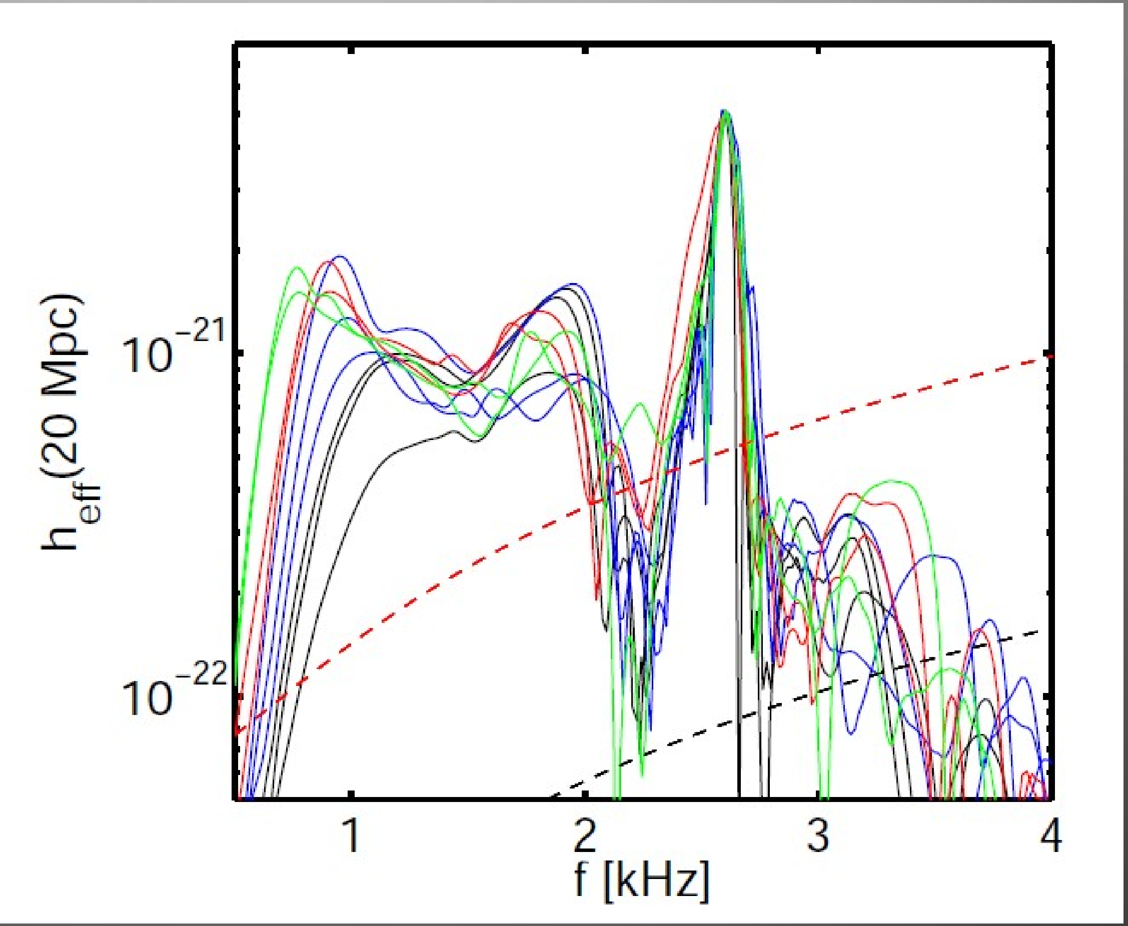
=> for near-by event radius measurable with high precision (~0.01-1/yr)

Proof-of-principle study
→ improvements likely

Clark et al. 2014

Universality of GW spectra

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



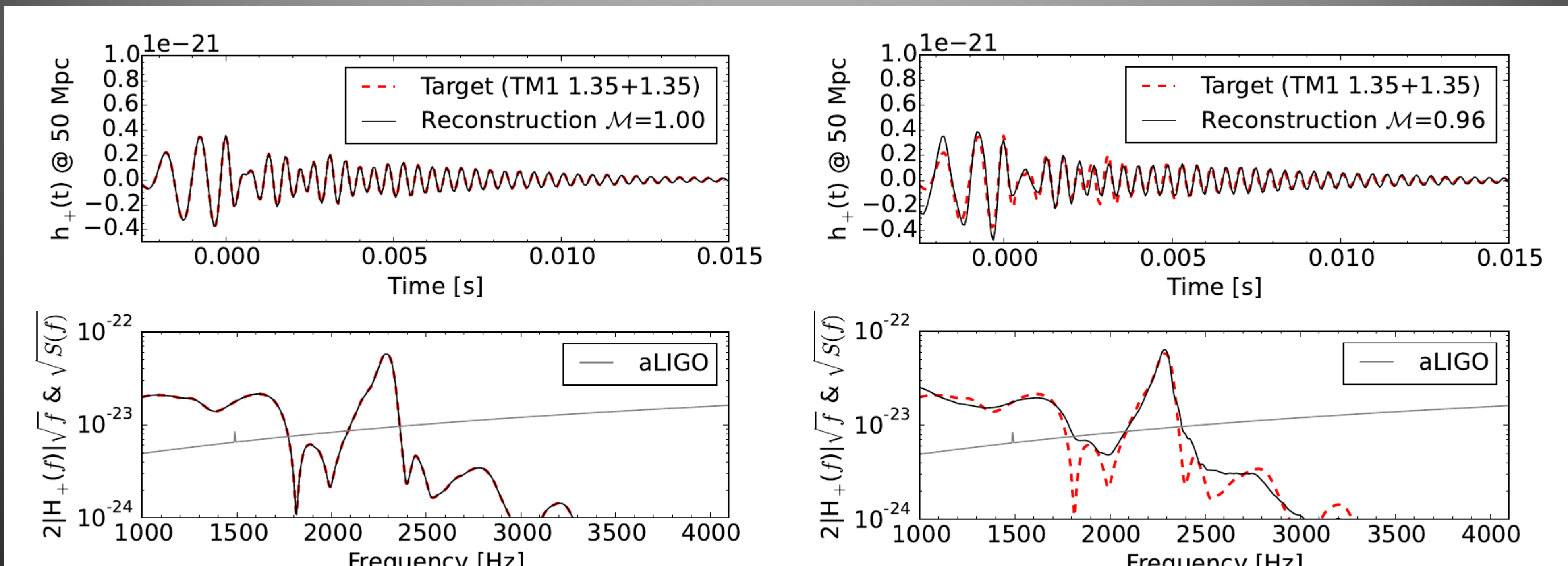
GW spectra shifted to reference frequency → Universality

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

PCA and universality



Instrument	SNR_{full}	D_{hor} [Mpc]	$\dot{\mathcal{N}}_{det}$ [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	$41.50^{53.52}_{32.99}$	$414.62^{535.221}_{329.88}$	$10.59^{22.78}_{5.33}$

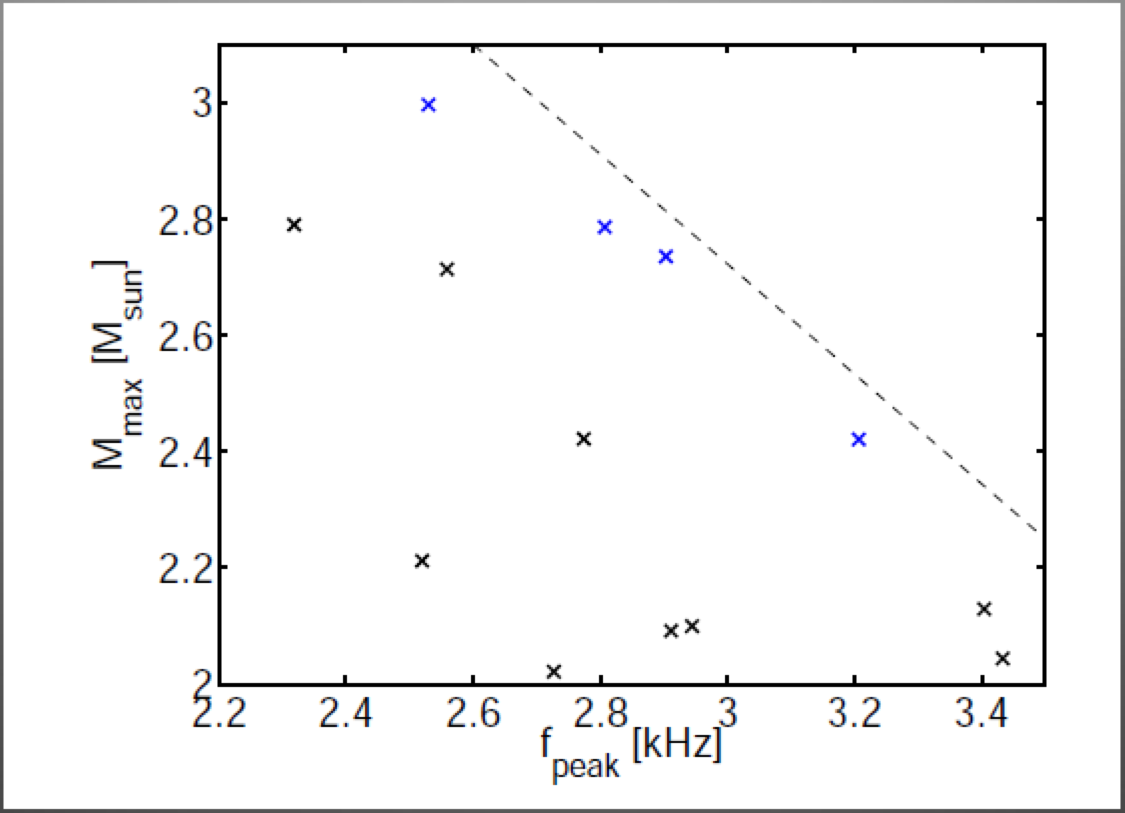
Clark et al. 2015

Maximum mass

Three methods:

- Directly from f_{peak} → only constraint
- Threshold mass
- Extrapolation method for fpeak

Maximum mass from one (high-mass) observation



Bauswein et al. 2015

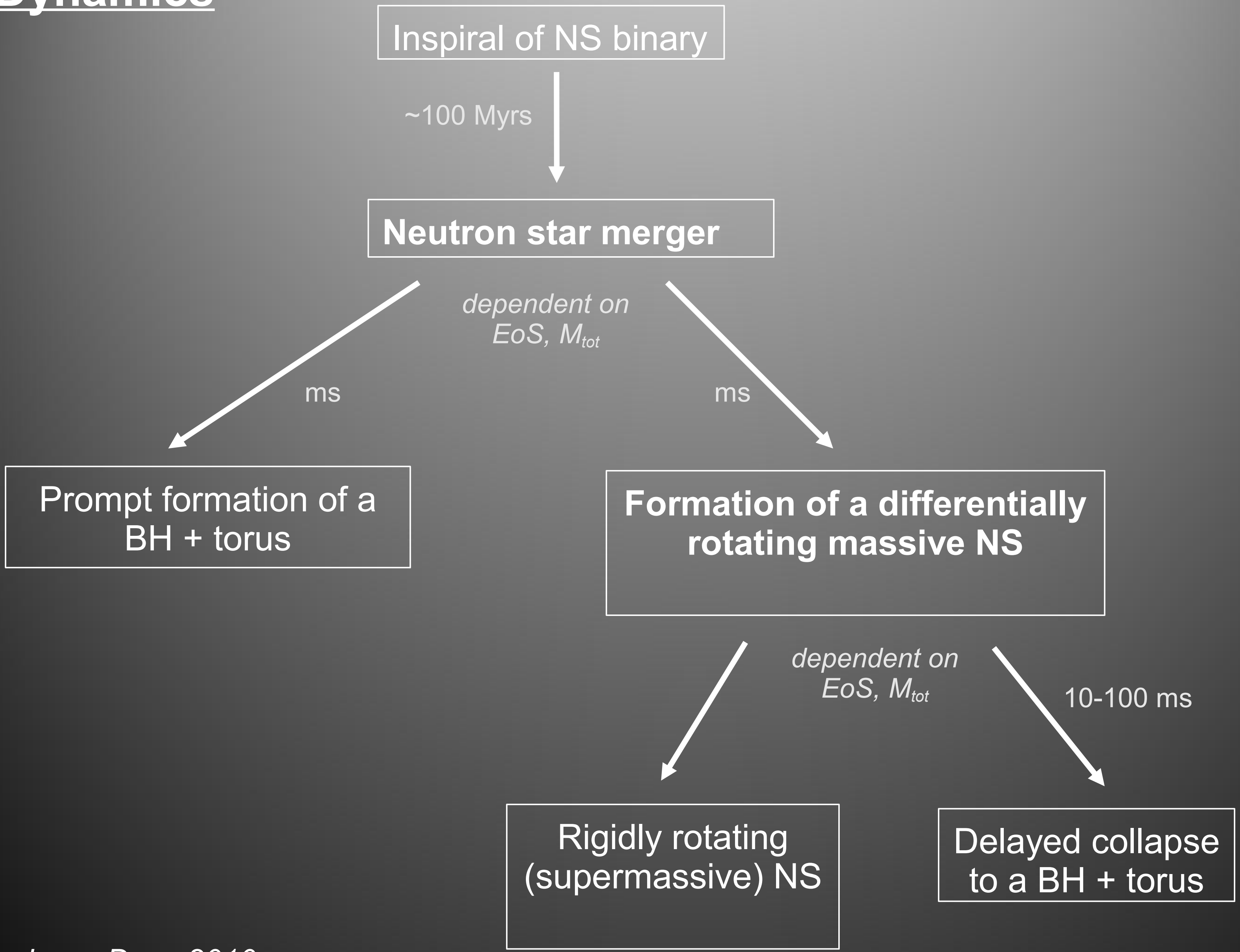
f_{peak} from 1.5-1.5 M_{sun} simulations → constraint on M_{max}

Collapse behavior of NS mergers

(prompt vs. delayed/stable)

and the maximum mass of nonrotating NSs

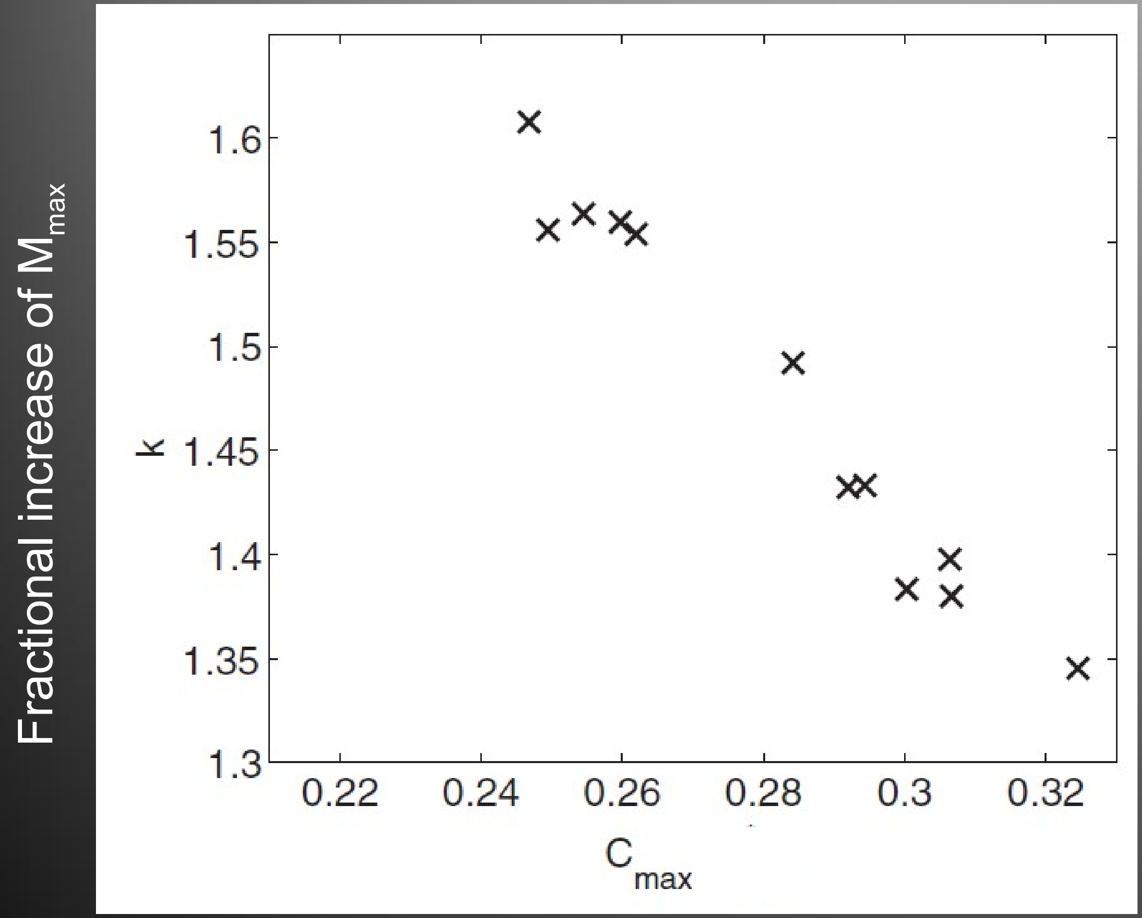
Dynamics



Reviews: Duez 2010, Faber & Rasio 2012

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

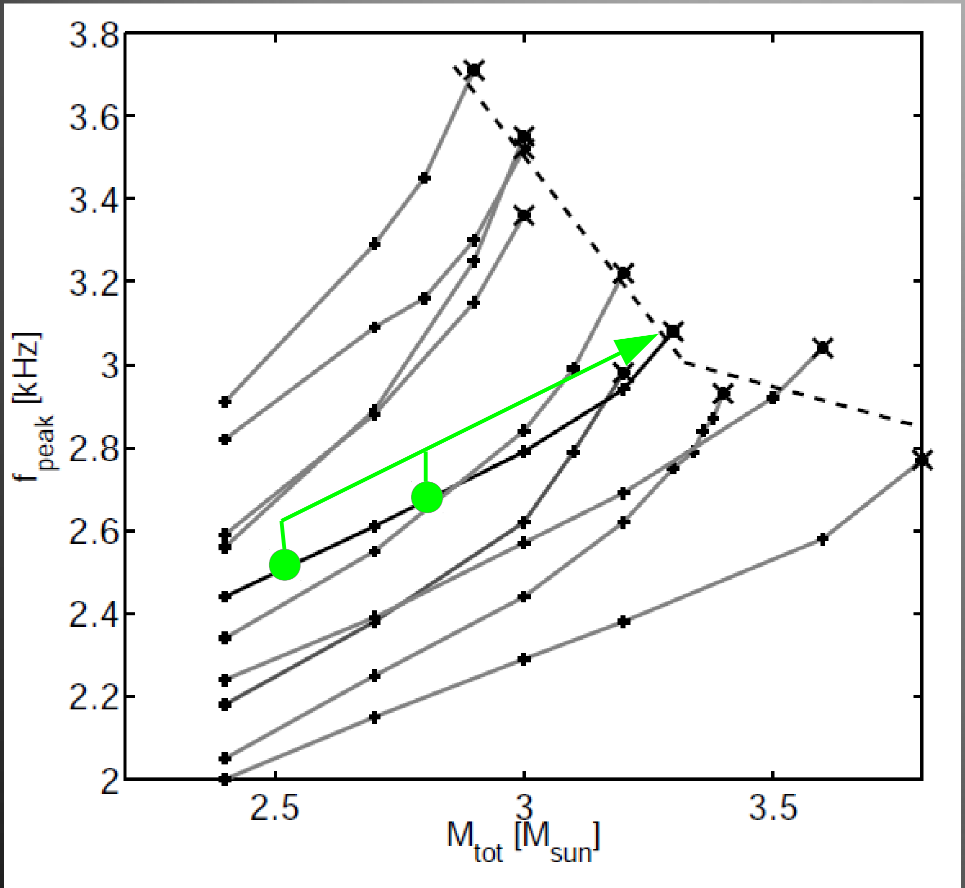
observable

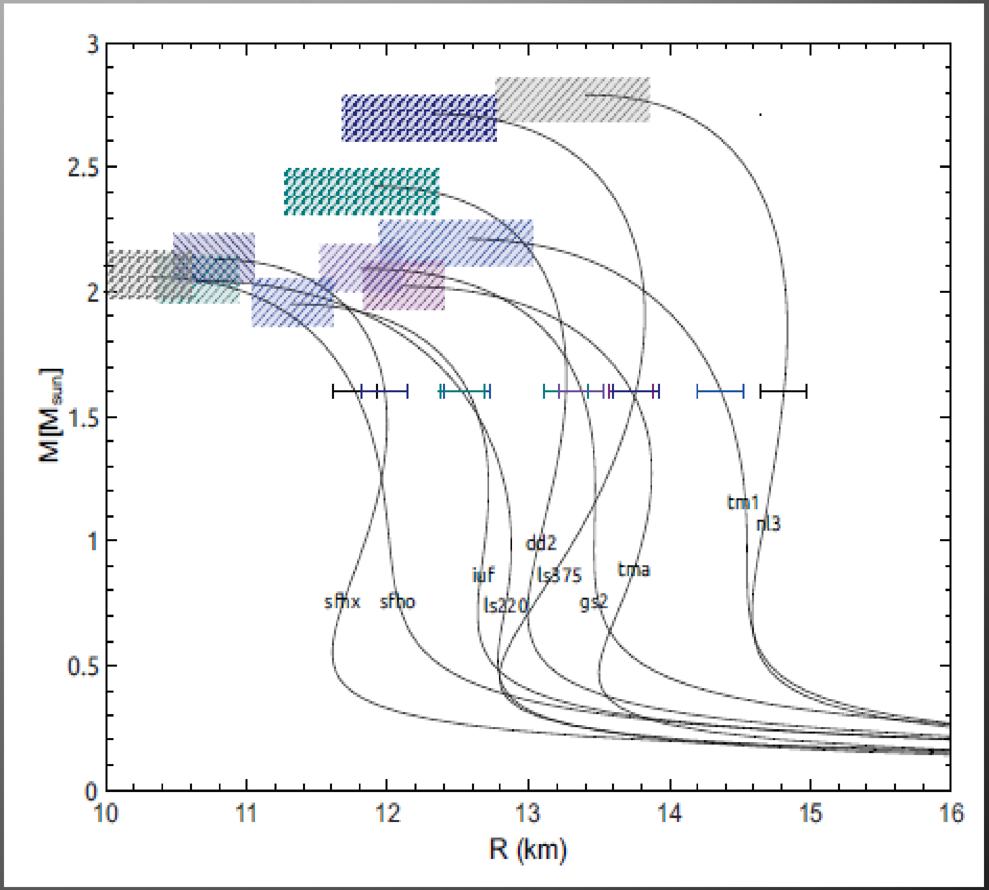
$$M_{thres} = M_{thres}(M_{max}, R_{max}) = M_{thres}(M_{max}, R_{1.6})^{*}$$

Pure TOV properties

* Radii from GW frequency

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



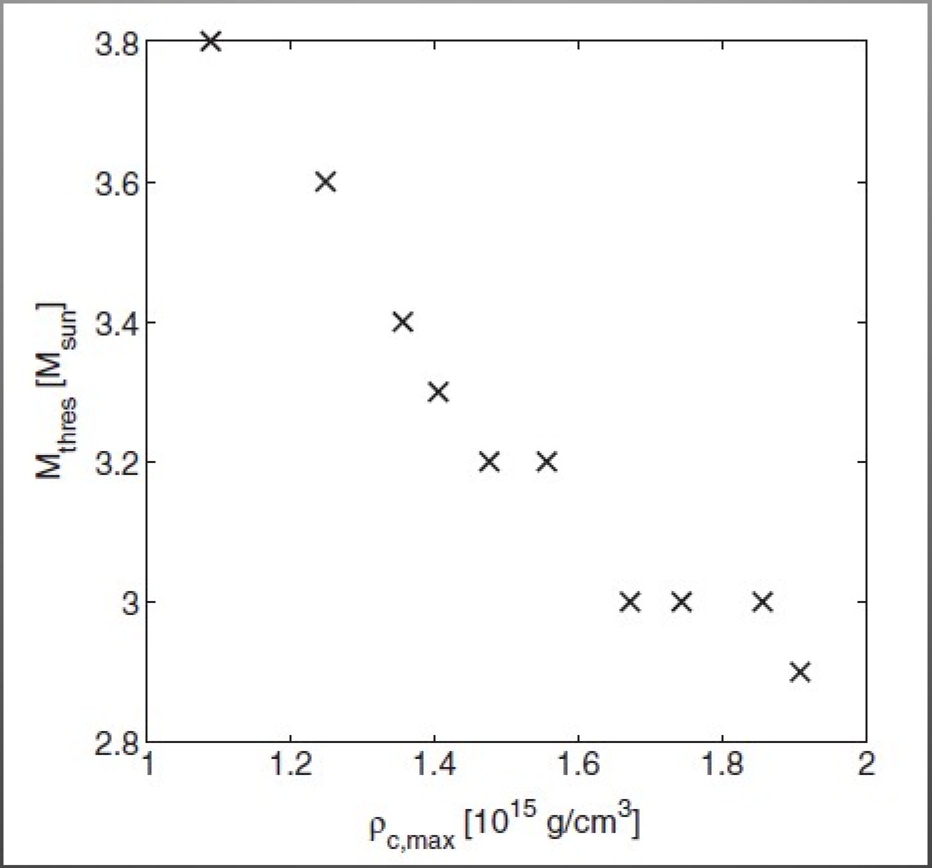


Bauswein et al. 2014

Dashed line: Universal relation between threshold mass and GW frequency

Advantage: we only need detections at lower/moderate binary masses (which are expected to be more frequent)

Maximum central density

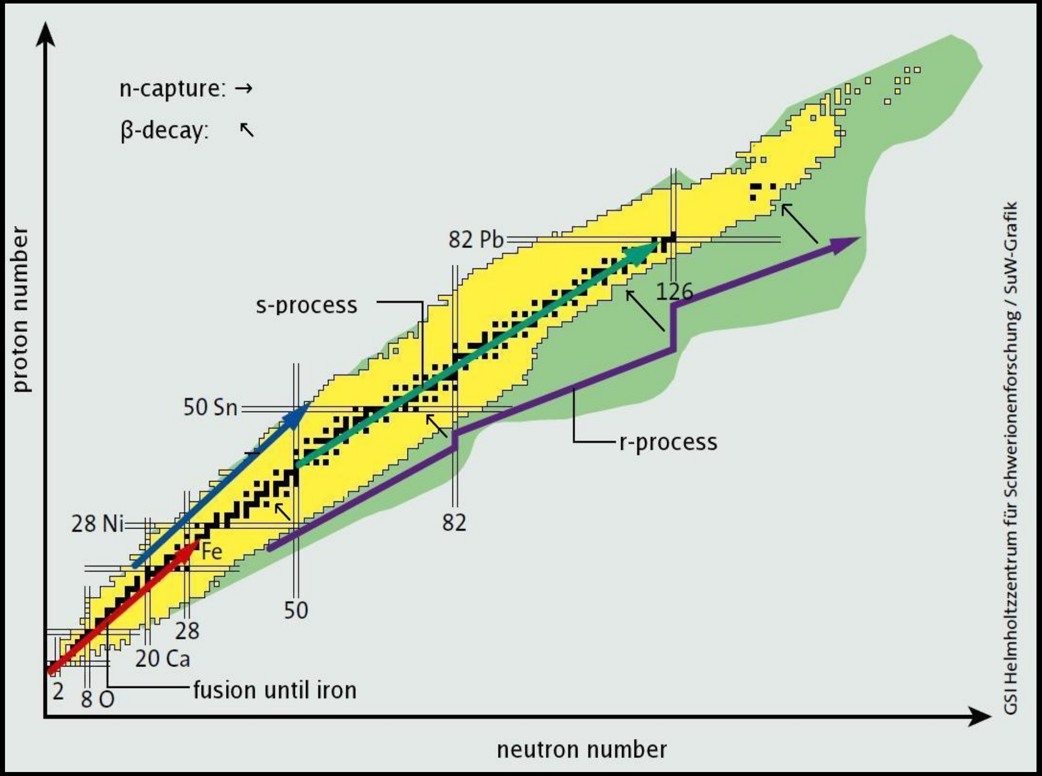


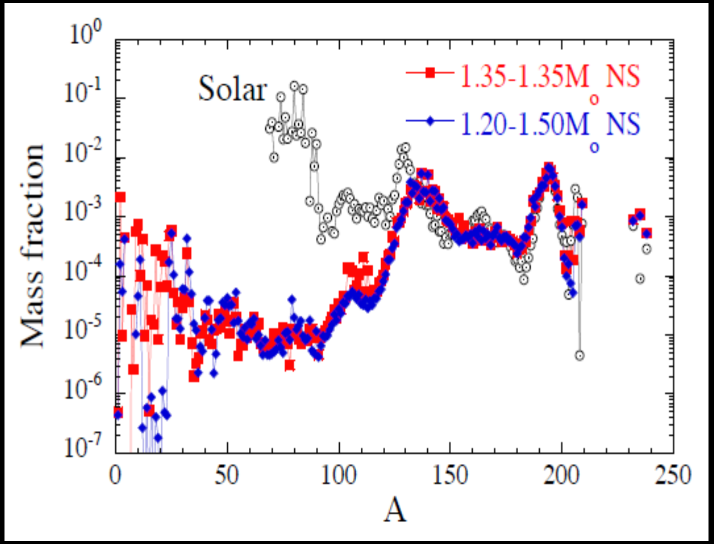
Similar frequency relations for maximum central density for same detection scenario

Bauswein et al. 2014

R-process elements

- NS mergers and their ejecta: formation of heavy elements (rapid neutron-capture elements)
- Note: astrophysical production site(s) currently unclear, (recent supernovae models not overly encouraging)





Abundance pattern from simulations matches observations (Goriely et al. 2011)

Contribution from GWs

- Direct access to merger rate in local universe (including binary mass information)
- Quantify contribution/importance of mergers for overall abundance
- Note: merger rate (from theoretical grounds) not well known → order of magnitude estimates welcome

Merger rate estimate

$$M_{\mathrm{Galaxy,\,tot}} = M_{\mathrm{ejecta}} \times \dot{N}_{NSNS} \times T_{\mathrm{Galaxy}}$$

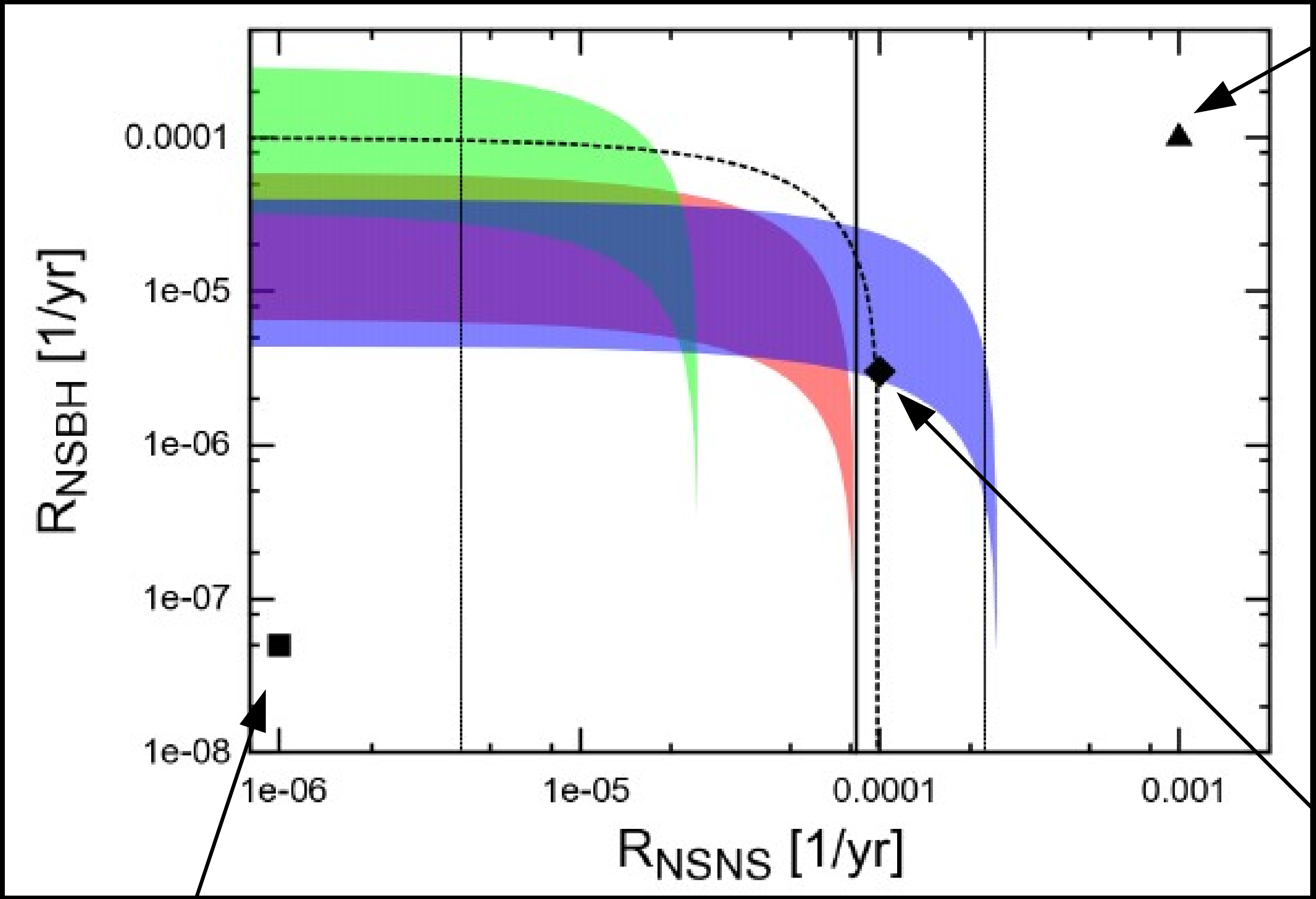
Total Galactic amount of heavy r-process elements (known from observations)

Average ejecta mass of NS merger (known from simulations)

Age of the Galaxy (known)

Galactic merger rates

40 detections per yr (with Ad. LIGO-Virgo network)



Optimistic detection rate (ruled out by our study, but compatible with constraints from recent science runs)

10 detections per yr

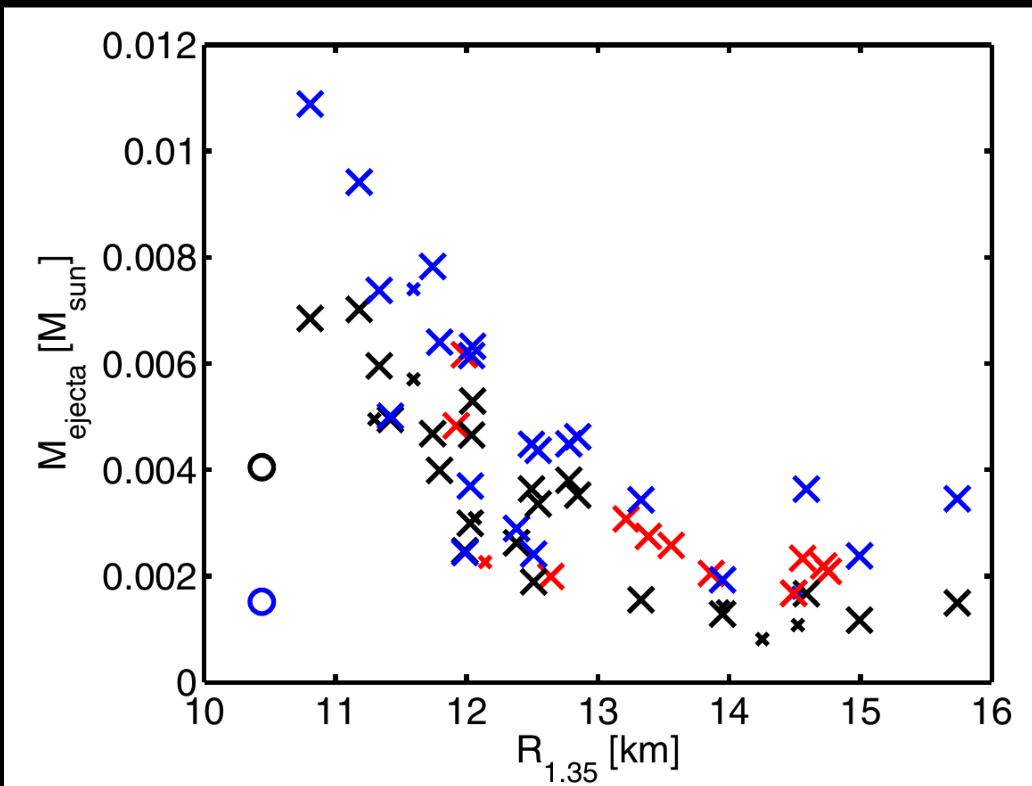
Blue: stiff EoS
Green: soft EoS

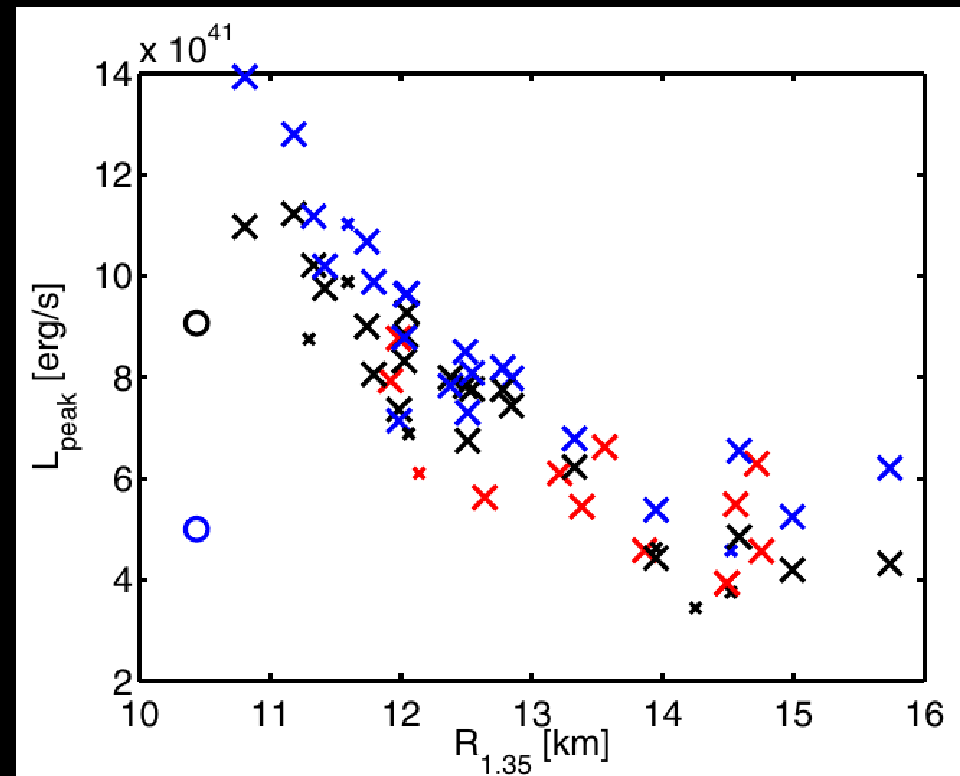
“realistic” detection rate

Bauswein et al. 2014

Pessimistic detection rate (only if additional r-process source)

Ejecta mass – dependence on EoS





Bauswein et al. 2013

Summary

- NS radii scale tightly with dominant postmerger GW frequency
- Dominant postmerger frequency is measurable for near-by events → radius measurement (~200 m) (unmodelled burst search, PCA)
- Pressure at fixed density measurable
- Maximum mass from collapse behavior
- Maximum mass from $f_{peak}(M_{tot})$
- Maximum central density accessible