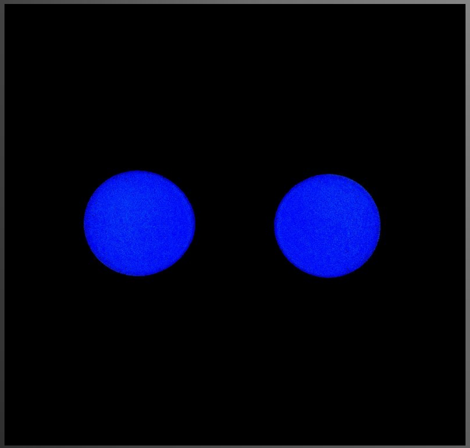
Inferring neutron-star properties from the gravitational-wave emission of binary mergers



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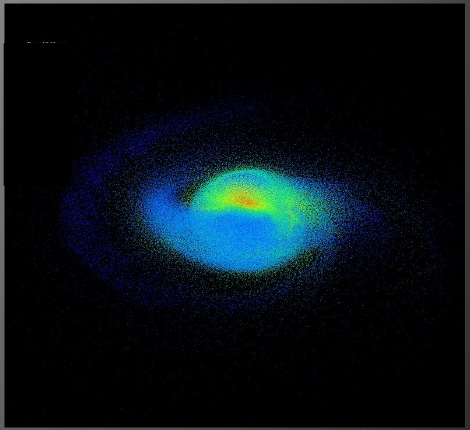

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Outline

General overview and motivation

Gravitational wave emission

NS radius measurements

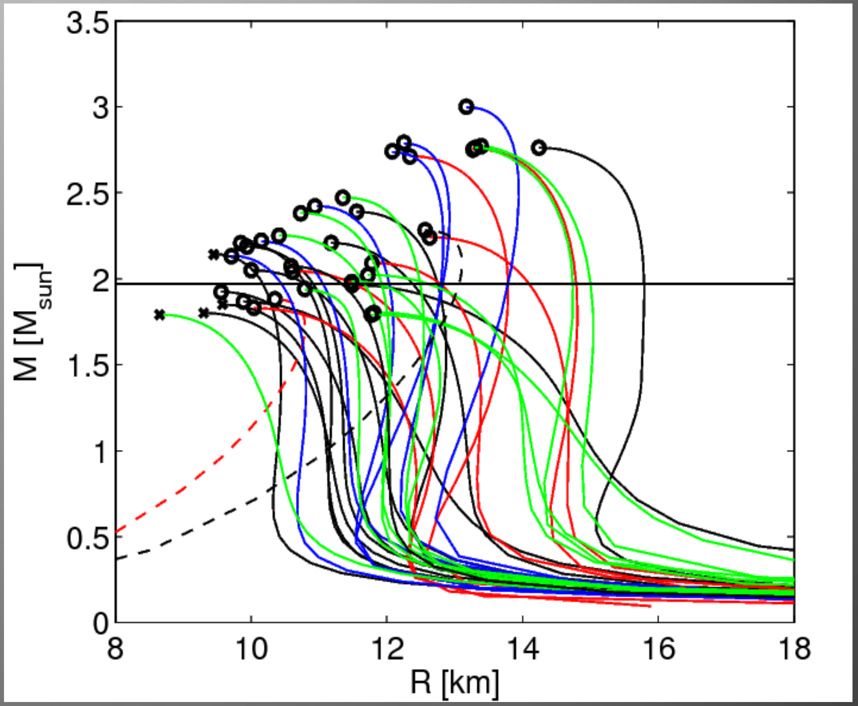
Collapse behavior and the maximum mass of NSs

Summary and conclusions

Motivation

Ad. Ligo Livingston (Louisiana)

- NS mergers are prime target of existing and upcoming GW detectors (Ad. LIGO, Ad. Virgo, Kagra, ET, ...)



- The properties (EoS) of high-density matter only incompletely known (many candidate EoSs)
- Unique relation between NS stellar properties and EoS (M-R relation and EoS are equivalent)

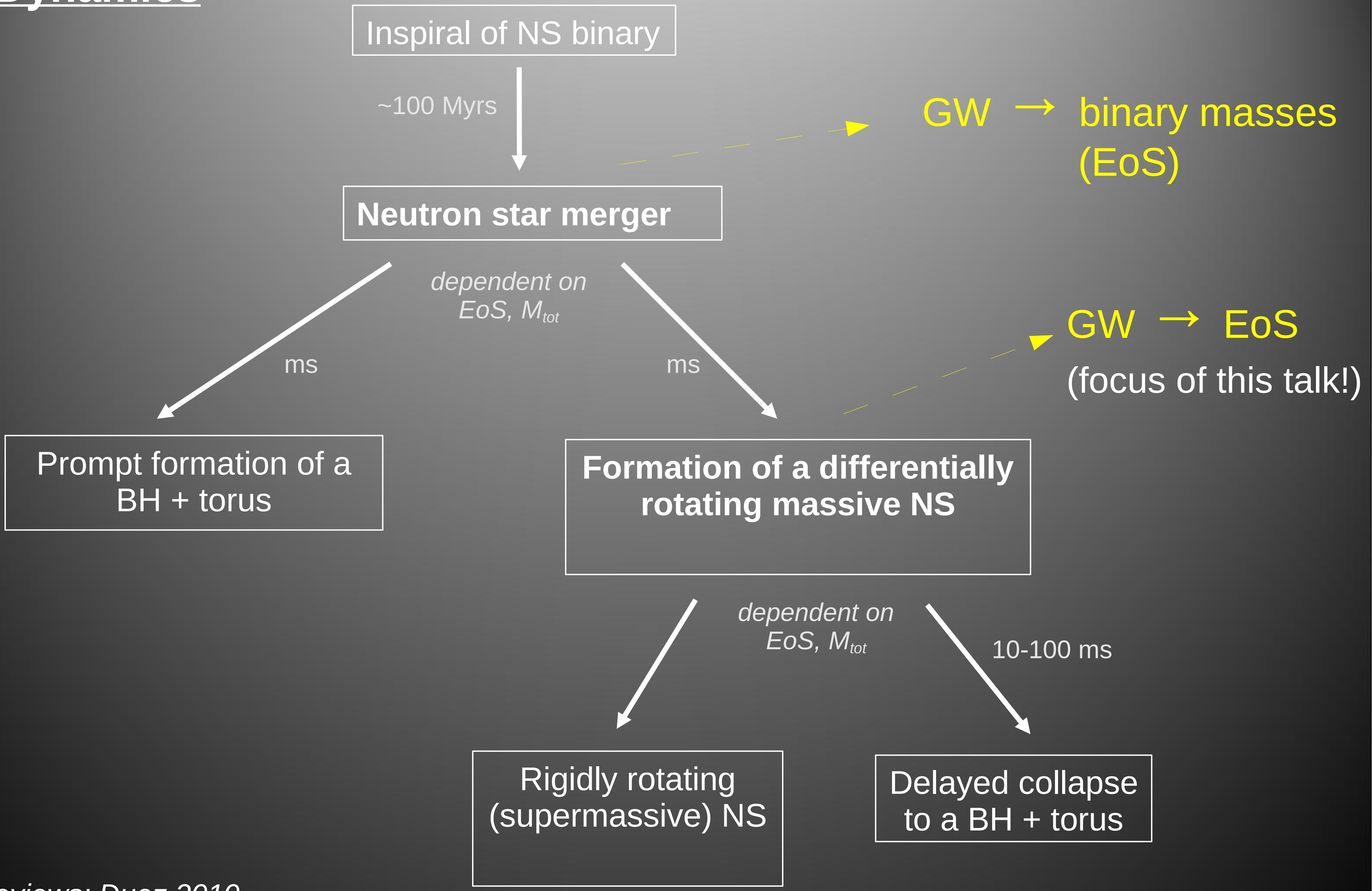
Merger dynamics depend on EoS => GW signal encodes EoS

Motivation

Moreover:

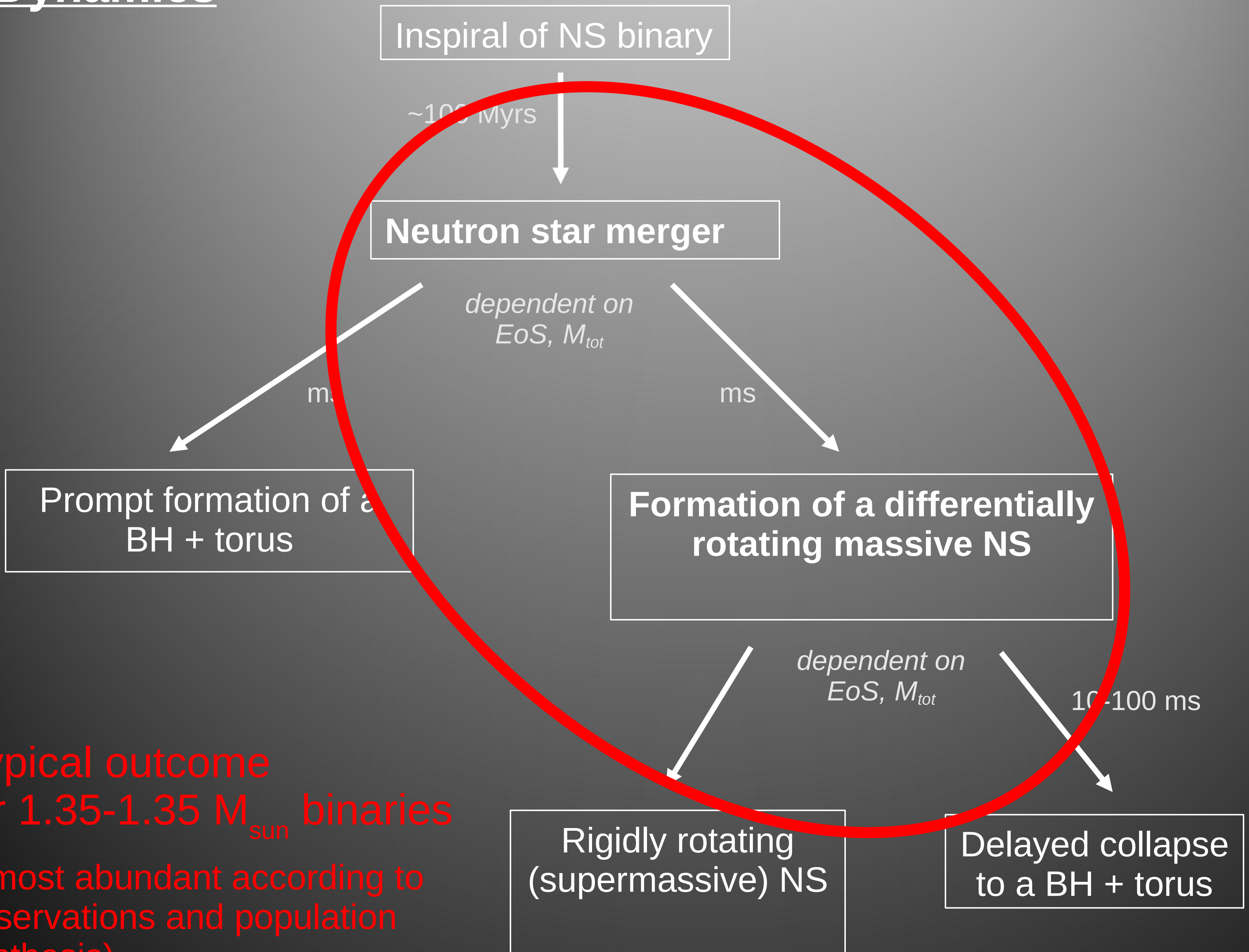
- Ejecta of NS mergers relevant for r-process nucleosynthesis (heavy neutron-rich elements)
- Electromagnetic counterparts (~isotropic; powered by radioactive decays)
- Plausible progenitors for short gamma-ray bursts

Dynamics



Reviews: Duez 2010, Faber & Rasio 2012

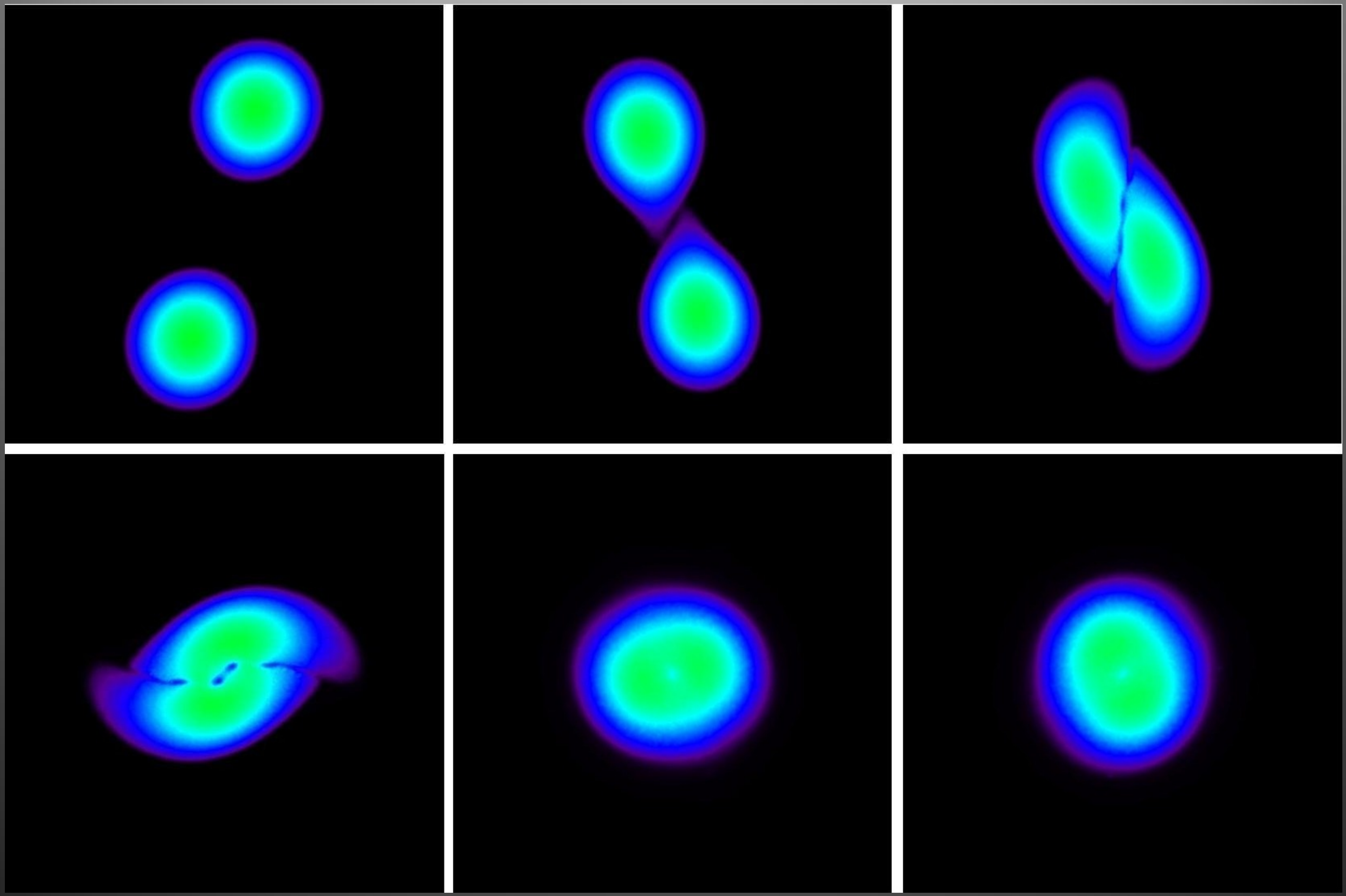
Dynamics



Typical outcome
for 1.35-1.35 M_{sun} binaries

(~most abundant according to observations and population synthesis)

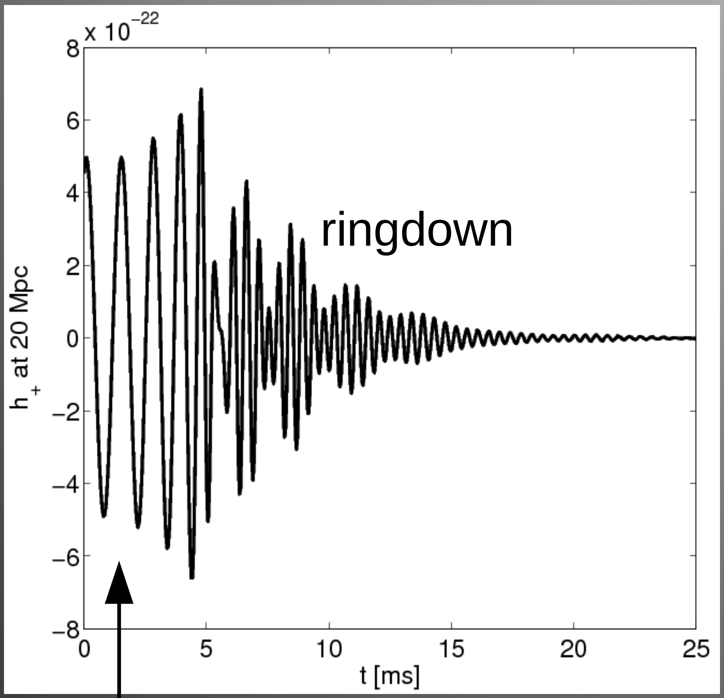
Simulation: snapshots



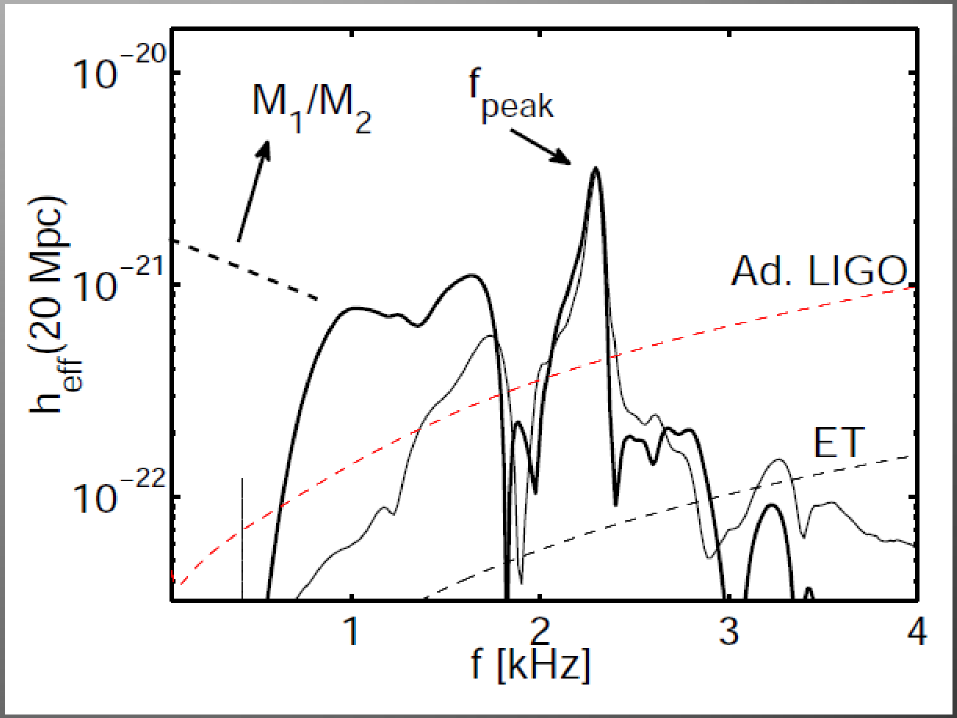
Rest-mass density evolution in equatorial plane: 1.35-1.35 M_{sun} Shen EoS

Gravitational-wave spectrum

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



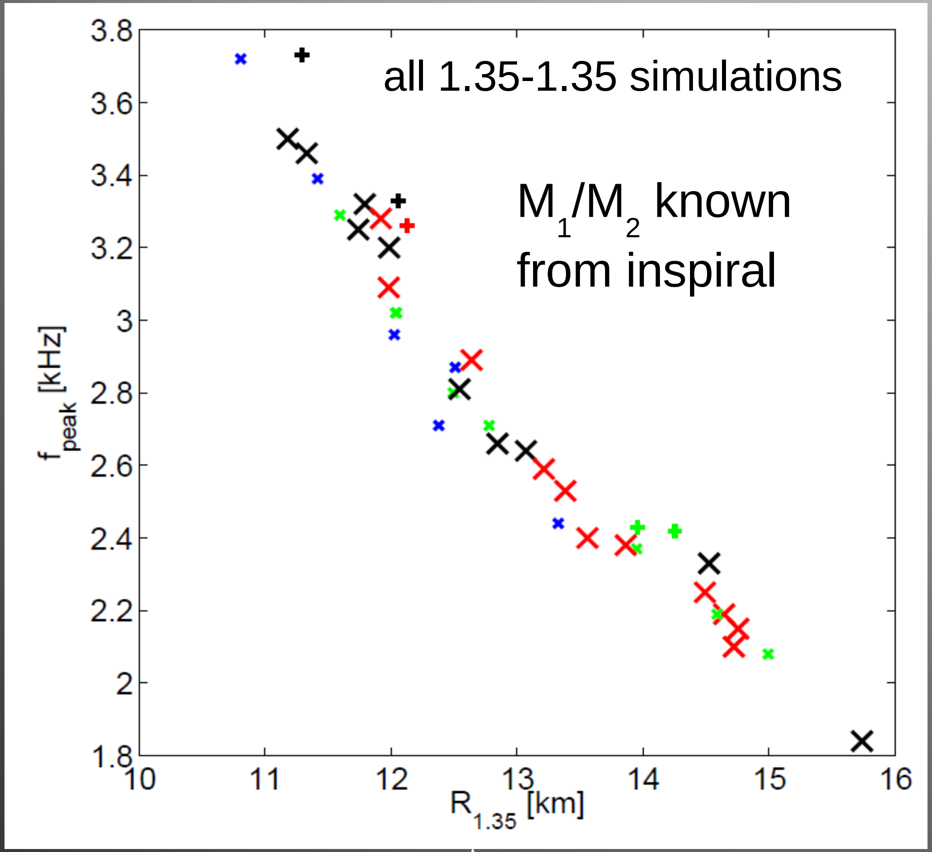
inspiral

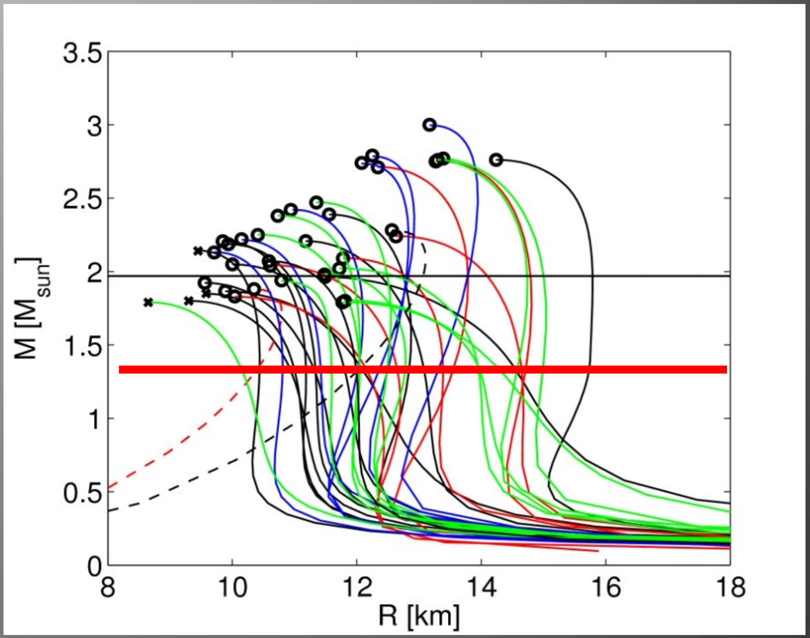


- Pronounced peak in the kHz range as a robust feature of all models forming a differentially rotating NS
- Characteristic GW feature: f_{peak}
- Binary masses M_1/M_2 are measurable from GW inspiral signal (most of the inspiral not covered by simulation)

Gravitational waves – EoS survey

observable





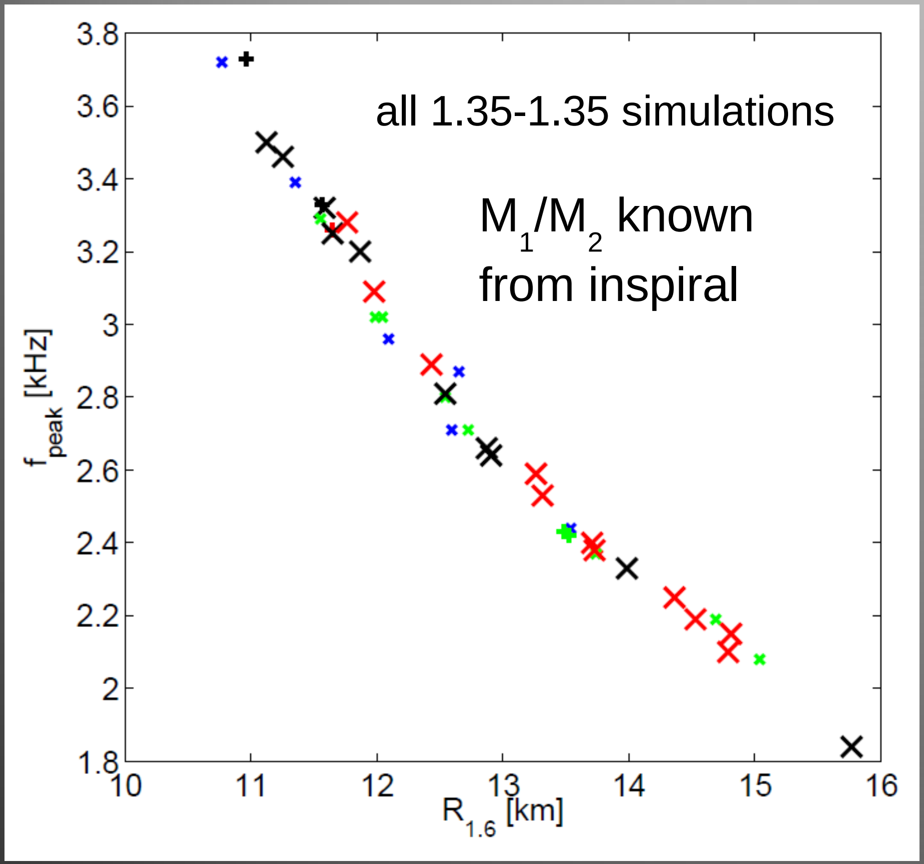
characterize EoS by radius of nonrotating NS with 1.35 M_{sun}

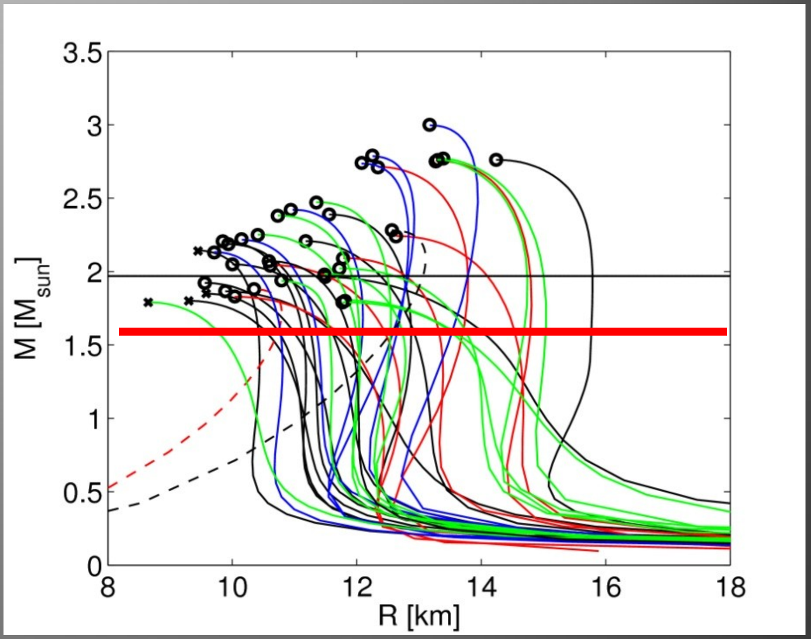
pure TOV property => Radius measurement via f_{peak}

Relation established from relativistic hydrodynamical merger simulations

Bauswein et al. 2012

Gravitational waves – EoS survey





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

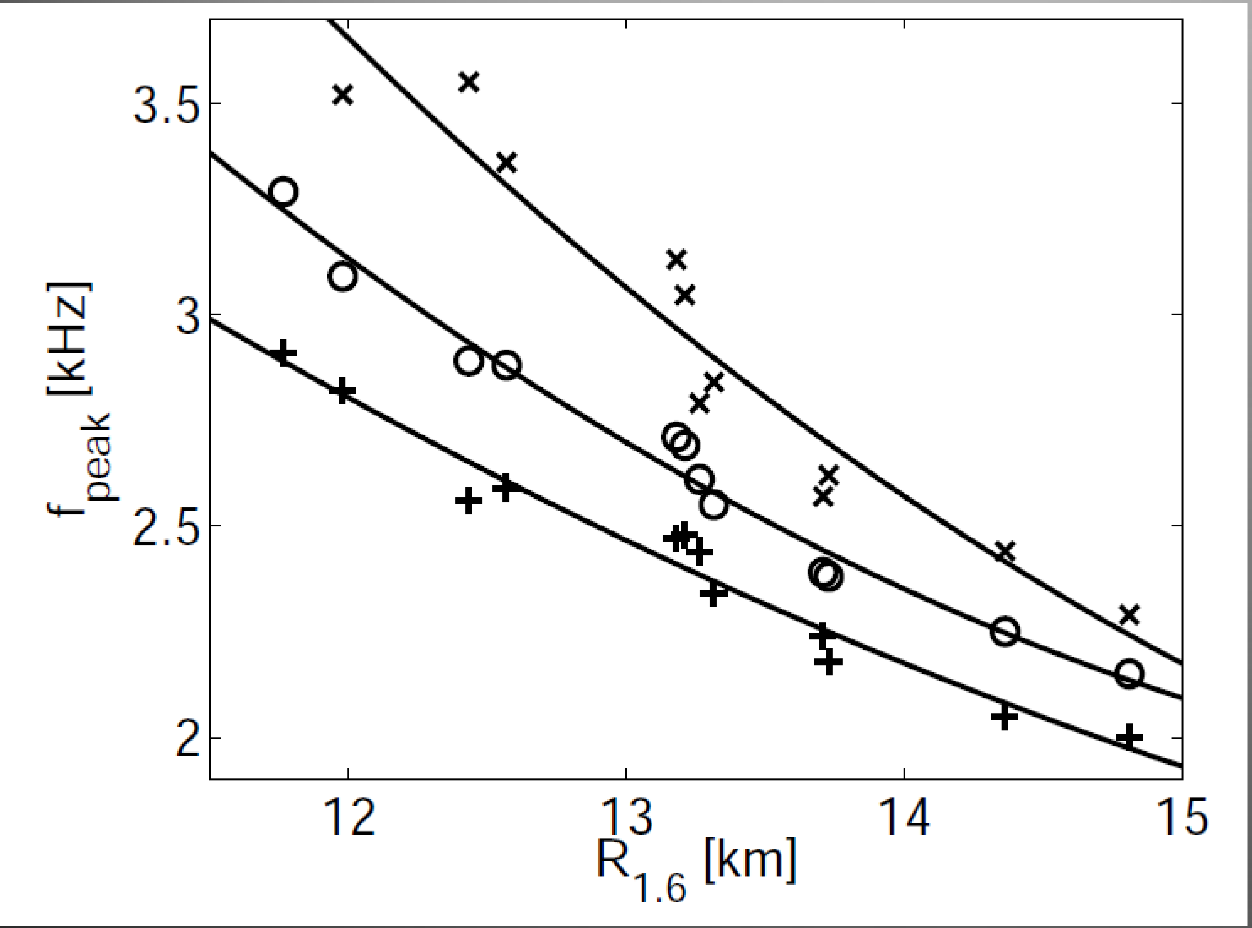
pure TOV property => Radius measurement via f_{peak}

Error: 100-200 m !!!

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

Bauswein et al. 2012

Strategy: Different binary masses



+ 1.2-1.2 M_{sun}
o 1.35-1.35 M_{sun}
x 1.5-1.5 M_{sun}

Maximum deviation determines error:

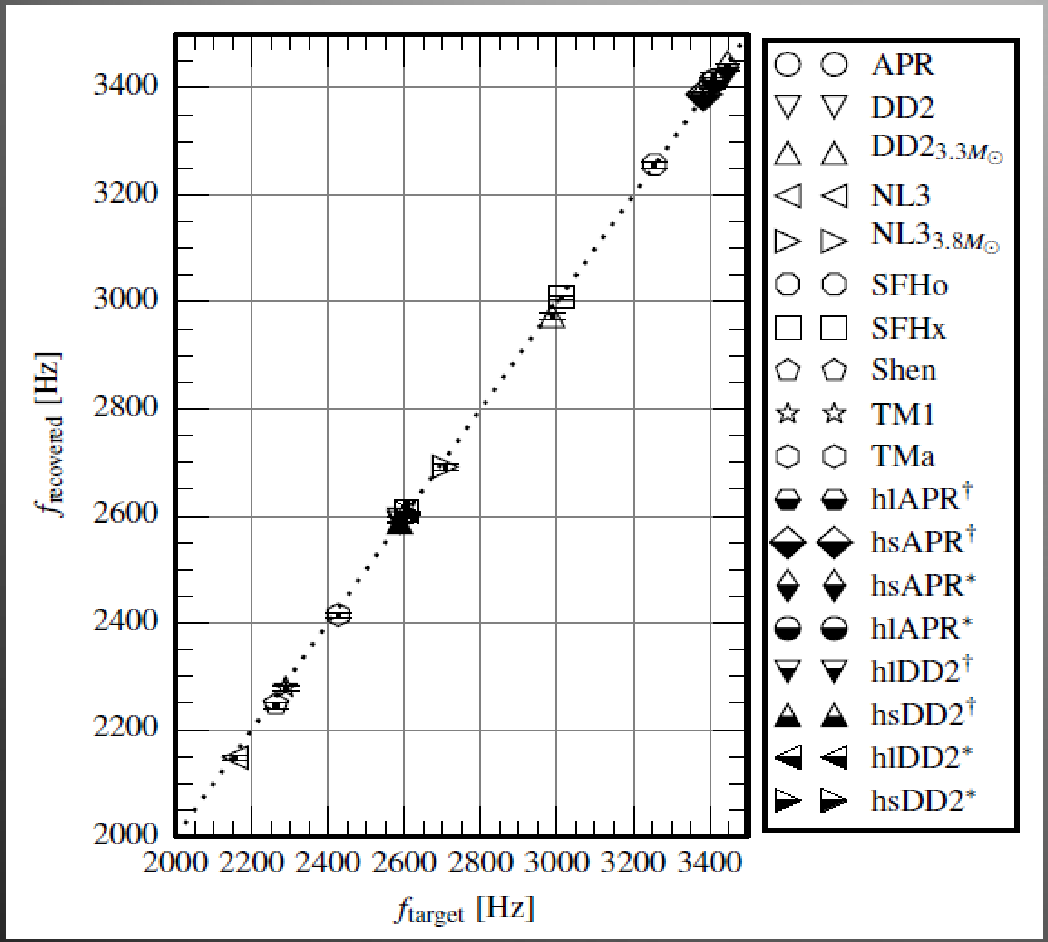
2.4 M_{sun}: 300 m
2.7 M_{sun}: 200 m
3.0 M_{sun}: 300 m

(can be further minimized)
(very similar relations for unequal masses)

Strategy: → Measure binary masses from inspiral GW signal
→ Choose relation depending on binary mass
→ Invert relation to obtain NS radius

Binary mass asymmetry has only small impact !

Measuring the dominant GW frequency



Clark et al. 2014

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

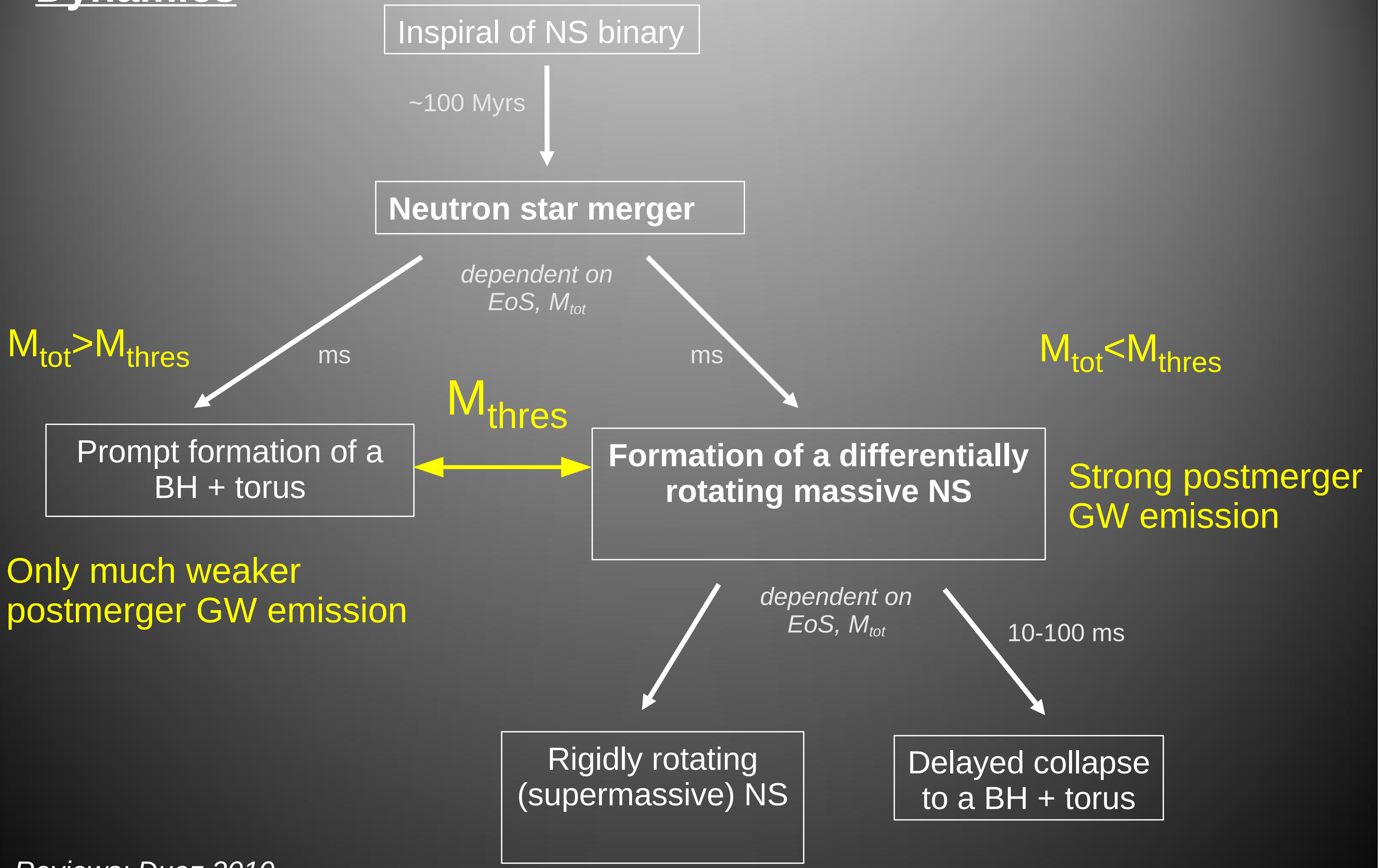
(Binary mass measurable with sufficient accuracy for such distances, e.g. Arun et al. 2005, Hannam et al. 2013, Rodriguez et al. 2014)

Collapse behavior

and the maximum mass M_{max} of nonrotating NSs

Key quantity: threshold binary mass M_{thres} for prompt BH formation

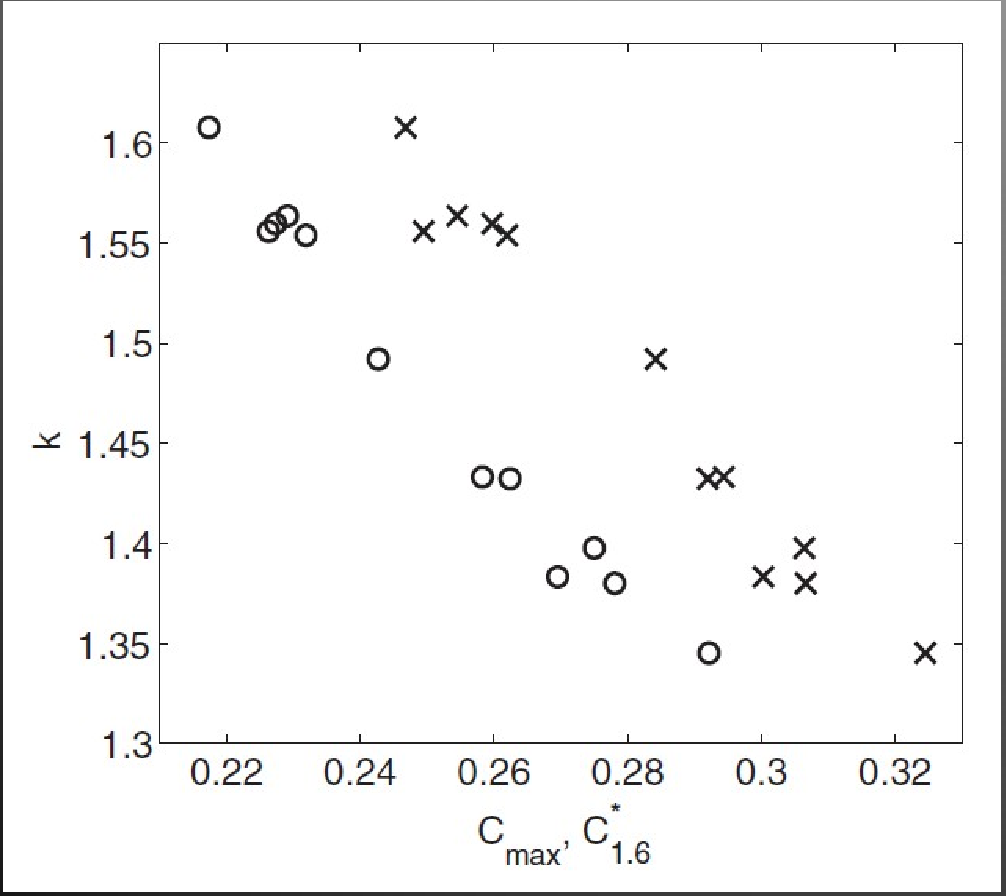
Dynamics



Reviews: Duez 2010,
Faber & Rasio 2012

Estimates of maximum NS mass (nonrotating)

- Key quantity: Threshold binary mass M_{thres} for prompt BH collapse (can be determined observationally !!!)
- 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)



Observable via GWs

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

Pure TOV properties

Estimates of maximum NS mass (nonrotating)

- Key quantity: Threshold binary mass M_{thres} for prompt BH collapse (can be determined observationally !!!)
- 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 M_{thres}/M_{max}:

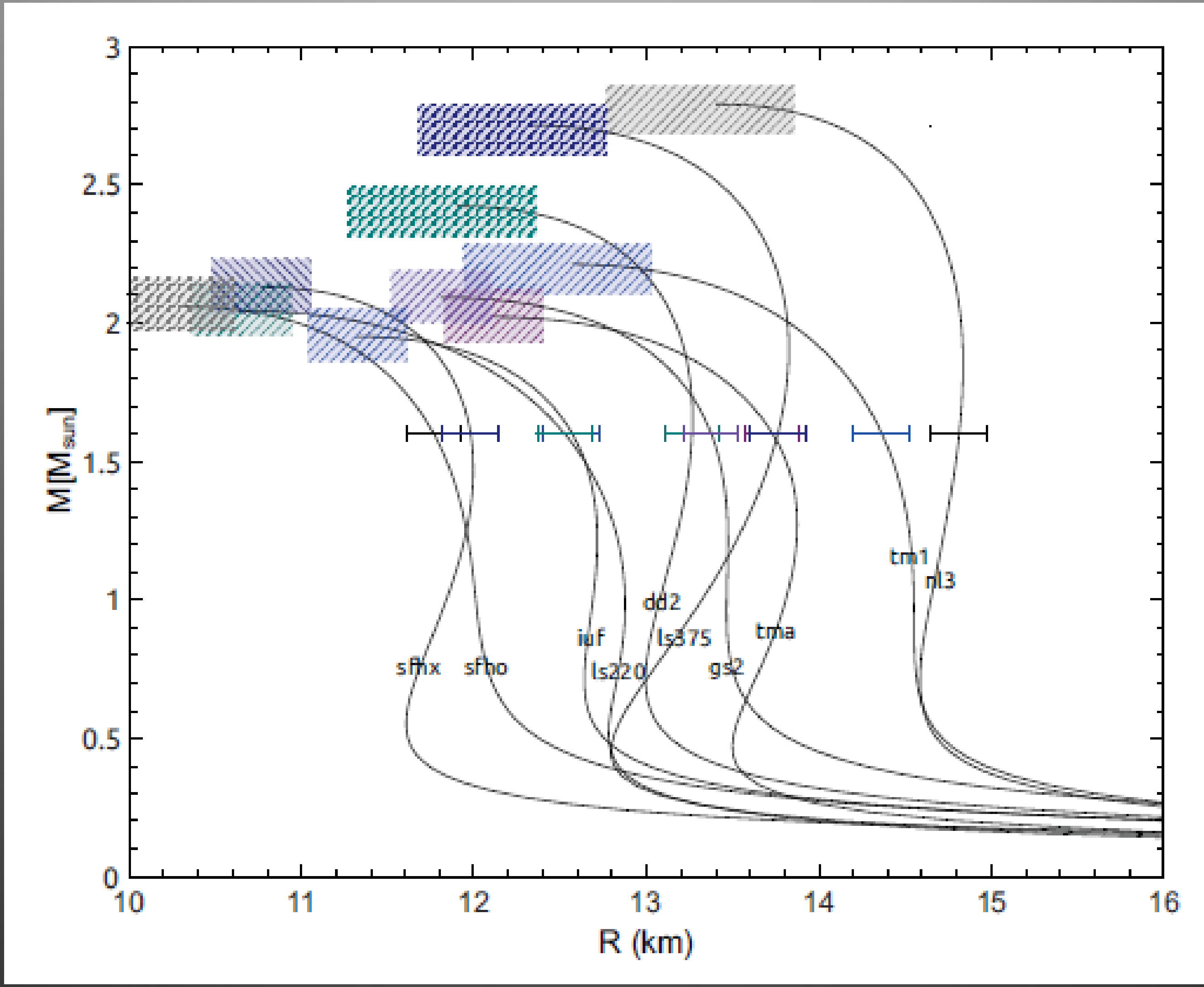
- Determine M_{thres} by direct observations of delayed and prompt collapse for different M_{tot} (Bauswein et al. 2013)

- 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)

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

Summary and conclusions

- NS merger leads (typically) to oscillating NS merger remnant
- Dominant postmerger GW peak frequency scales tightly with NS radii

  => NS radii can be accurately measured

- Threshold binary mass of prompt BH formation depends in particular way on stellar properties (pure TOV properties, i.e. EoS)

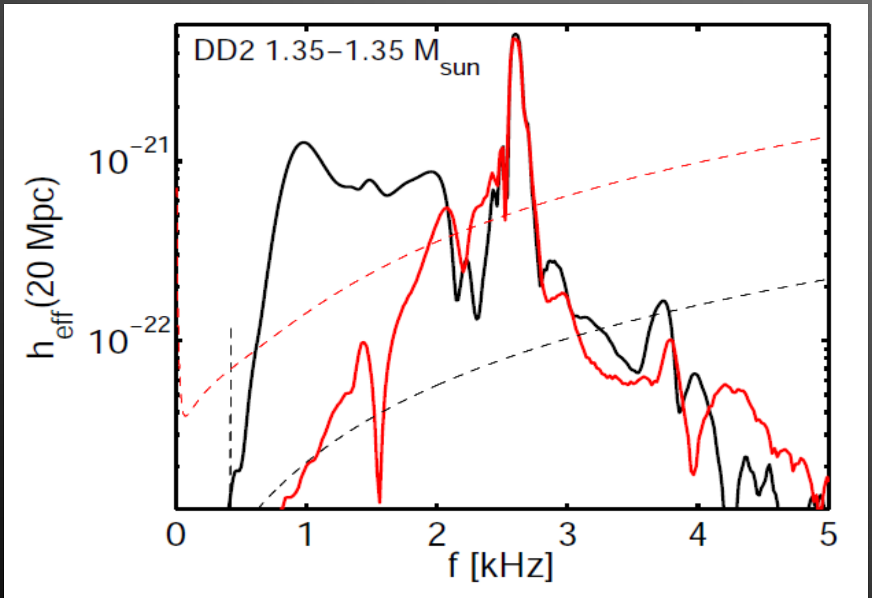
  => Maximum mass of NS can be estimated

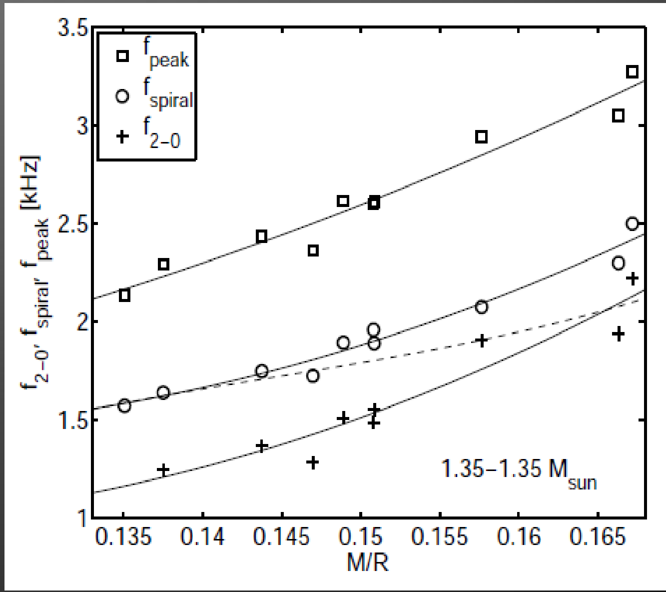
Details:

Bauswein & Stergioulas, PRD 91, 124056 (2015)
Clark, Bauswein, Cadonati, Janka, Pankow, Stergioulas, PRD 90, 062004 (2014)
Bauswein, Stergioulas, Janka, PRD 90, 023022 (2014)
Bauswein, Baumgarte, Janka, PRL 111, 131101 (2013)
Bauswein, Janka, Hebeler, Schwenk, PRD 86, 063001 (2012)
Bauswein & Janka, PRL 108, 011101 (2012)

Secondary peaks in the GW spectrum

- Two distinct mechanism produce secondary peaks: oscillation mode coupling and orbital motion of tidal bulges
- Presence / strength depends on the exact binary system
- → classification scheme of the postmerger dynamics and GW emission (see Bauswein & Stergioulas 2015 – arXiv:1502.03176)
- For fixed binary mass relations of secondary frequencies with radii of inspiralling stars (Bauswein & Stergioulas 2015)
- But for representative range of binary masses no universal mass-independent relation (as in Takami et al. 2014)





Are ejecta masses and current rate estimates compatible with mergers as dominant source of r-process elements?

(similar estimates: Lattimer & Schramm 1974, Freiburghaus et al. 1999, Qian 2000, Metzger et al. 2010, Goriely et al. 2011, Korobkin et al. 2012, Rosswog et al. 2013, Bauswein et al. 2013, Piran et al. 2014)

Consider observed amount of r-process elements → derive merger rates from know ejecta masses (for NS-NS and NS-BH) → uncertainty factor of a few (detailed analysis, Bauswein et al. 2014)

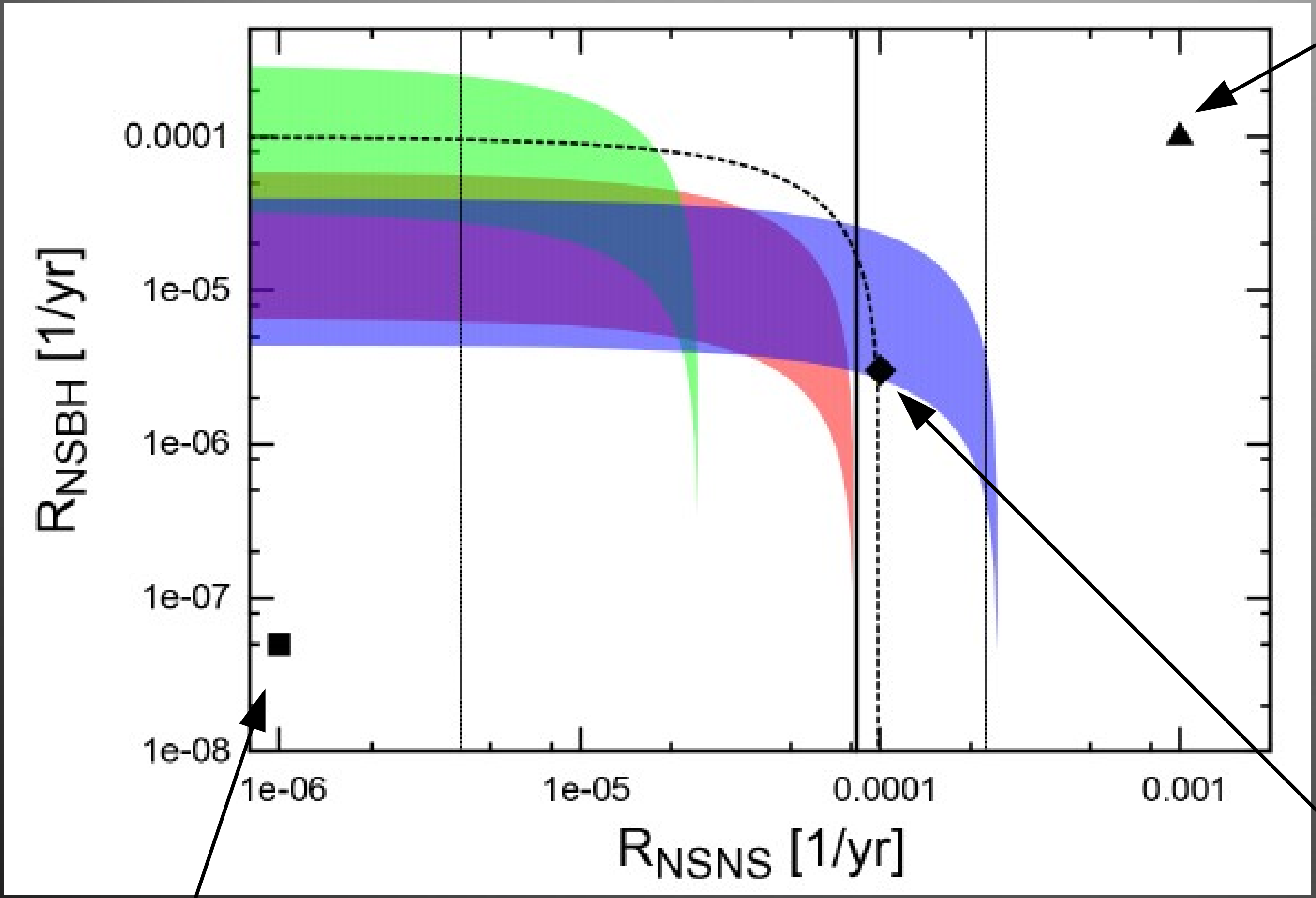
→ mergers are compatible with being the dominant source of r-process elements

→ in turn one can estimate merger rates assuming that most r-process matter was produced by mergers (→ GW and counterpart detection rates)

(keeping in mind that also other sources may contribute, e.g. MHD jets, see Friedel's talk)

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)

Symbols taken from Abadie et al. (2010) (complied mostly from pop. synthesis studies)