Heidelberg Institute for Theoretical Studies

HITS

Neutron-star mergers and the high-density equation of state

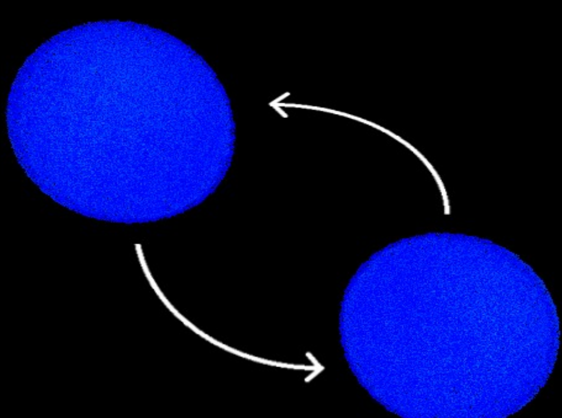
2nd workshop of the SFB 1245

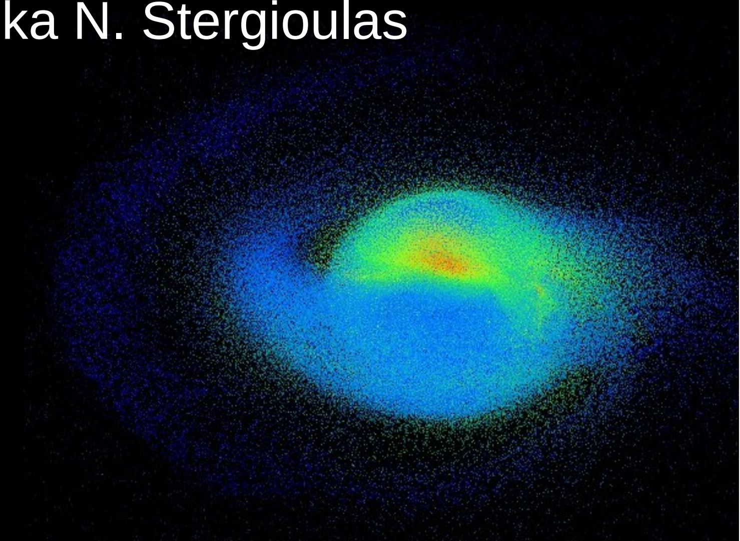
Budenheim, 05/10/2017

Andreas Bauswein

(Heidelberg Institute for Theoretical Studies)

with K. Chatziioannou, J. A. Clark, H.-T. Janka N. Stergioulas



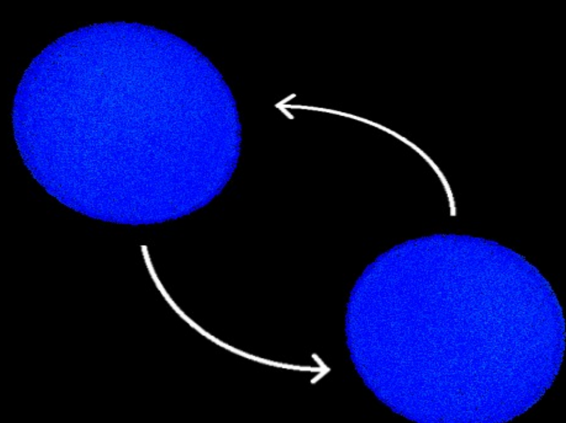


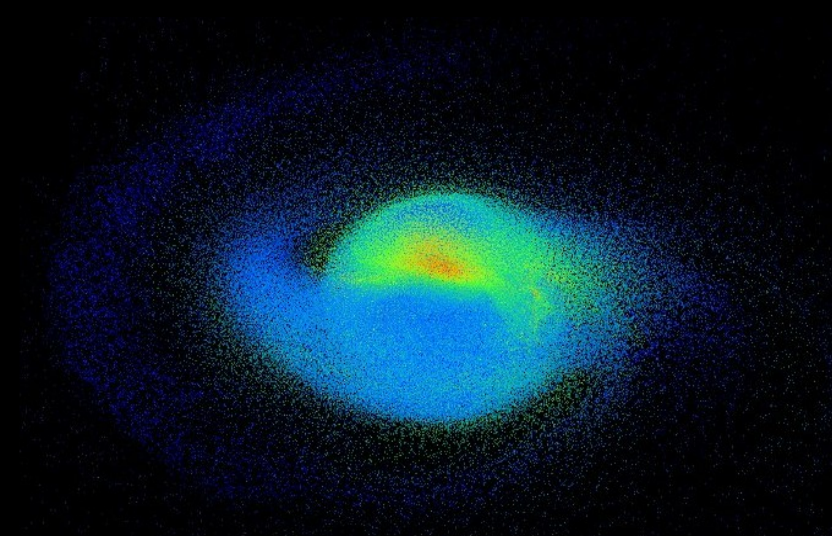
Outline

- NS merger – motivation and overview
- Gravitational waves
- EoS constraints

  → dominant postmerger GW frequency → Radius measurement

  → collapse behavior → Maximum mass of NSs (very high density regime)
- GW data analysis
- Outlook: GW astereoseismology





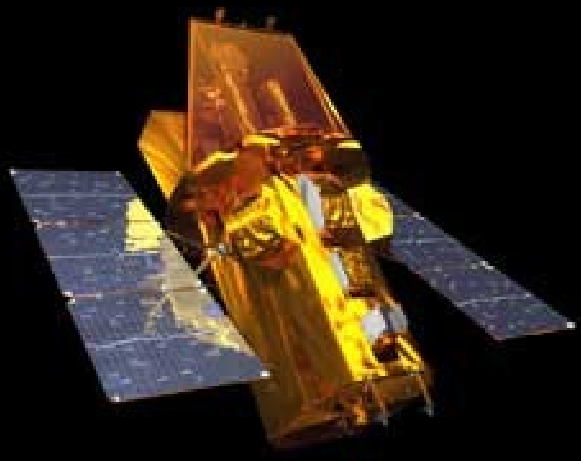
Overview - NS mergers

- Short gamma-ray bursts → high-energy astrophysics / gamma-ray astronomy
- Site for the rapid neutron-capture process → heavy element formation
- Electromagnetic transients → "time-domain astronomy"
- Gravitational wave emitters → EoS of nuclear matter

- Btw: all these aspects are also related to NS-black hole mergers

Short gamma-ray bursts

- Observed since the 70ies
- Intense flashes of gamma rays with duration <~2 secs with 10^{50} … 10^{52} erg/s
- random, non-repeating, isotropic at cosmological distances
- (long GRBs with duration >~2 secs produced by collapse of massive star – confirmed by supernova association = lightcurve observed; tend to be somewhat softer than short bursts)
- produced by jets (baryon-poor relativistic beamed outflow) forming from a BH-torus system after NS merger or NS-BH merger → beamed emission
- Afterglow (=interaction of jet with ambient medium) routinely observed as follow up with X-ray, optical, radio telescopes
- Some GRBs show X-ray plateau emission ~100 … 1000 seconds



Swift

Short gamma-ray bursts

- Arguments for mergers as progenitors:

  - energetics and time scales

  - no supernova association (excluded with very good limits)

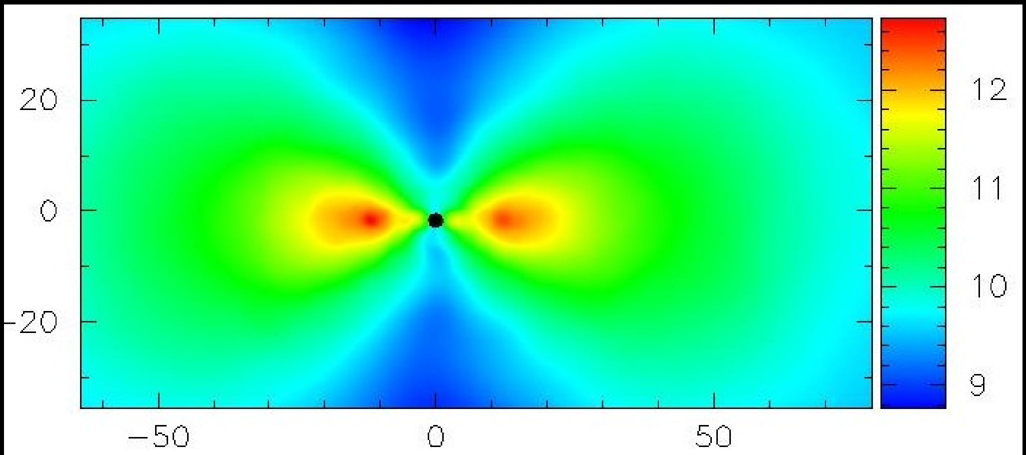
  - occurrence in star-forming and elliptical galaxies

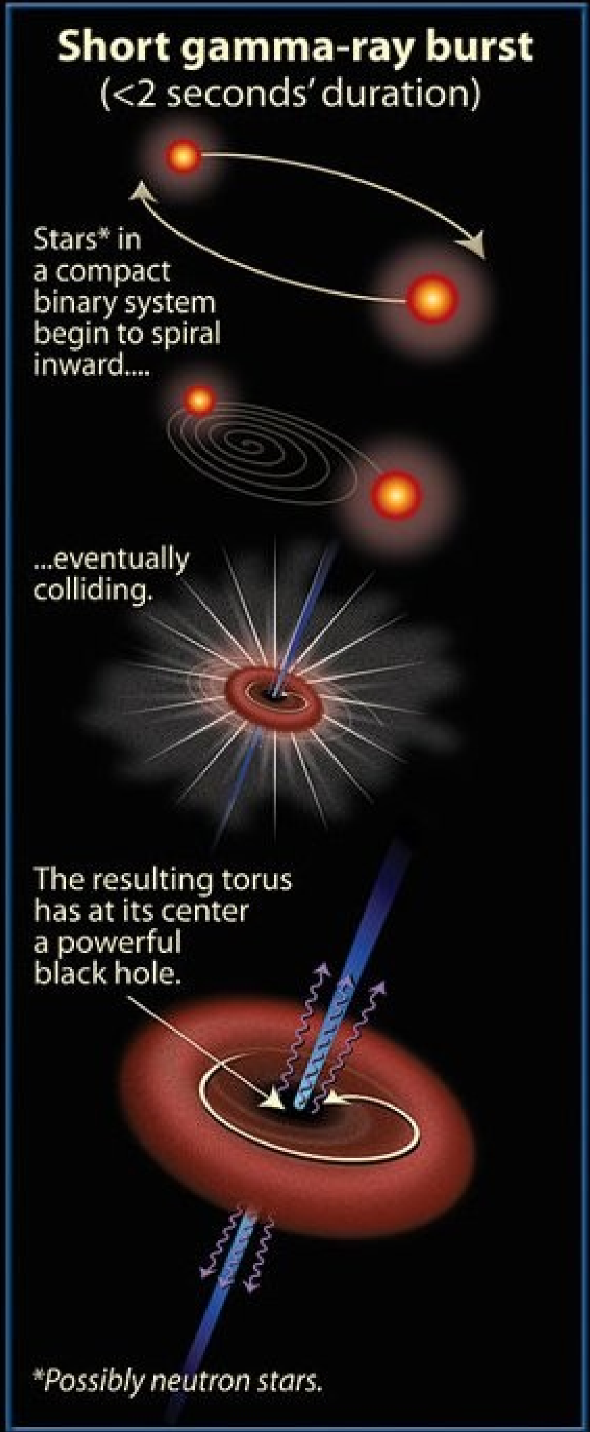
  - off-center from host galaxies

  - rates (as far as we can estimate rates)

- Smoking gun: coincident detection of sGRB and GWs

  → estimate probability to see both simultaneously (assume opening angle ~10 deg.)

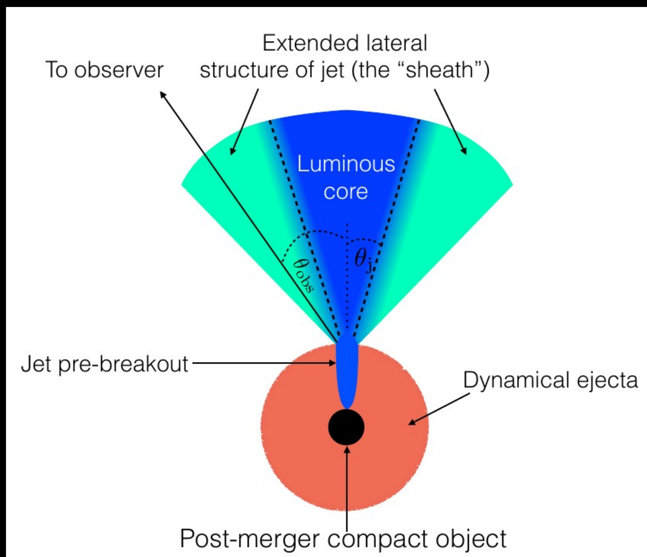


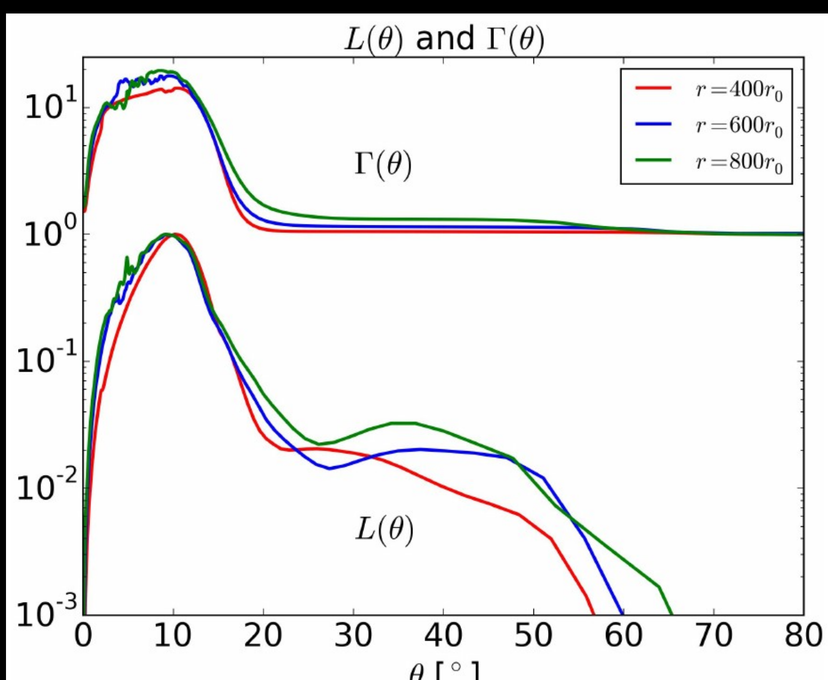


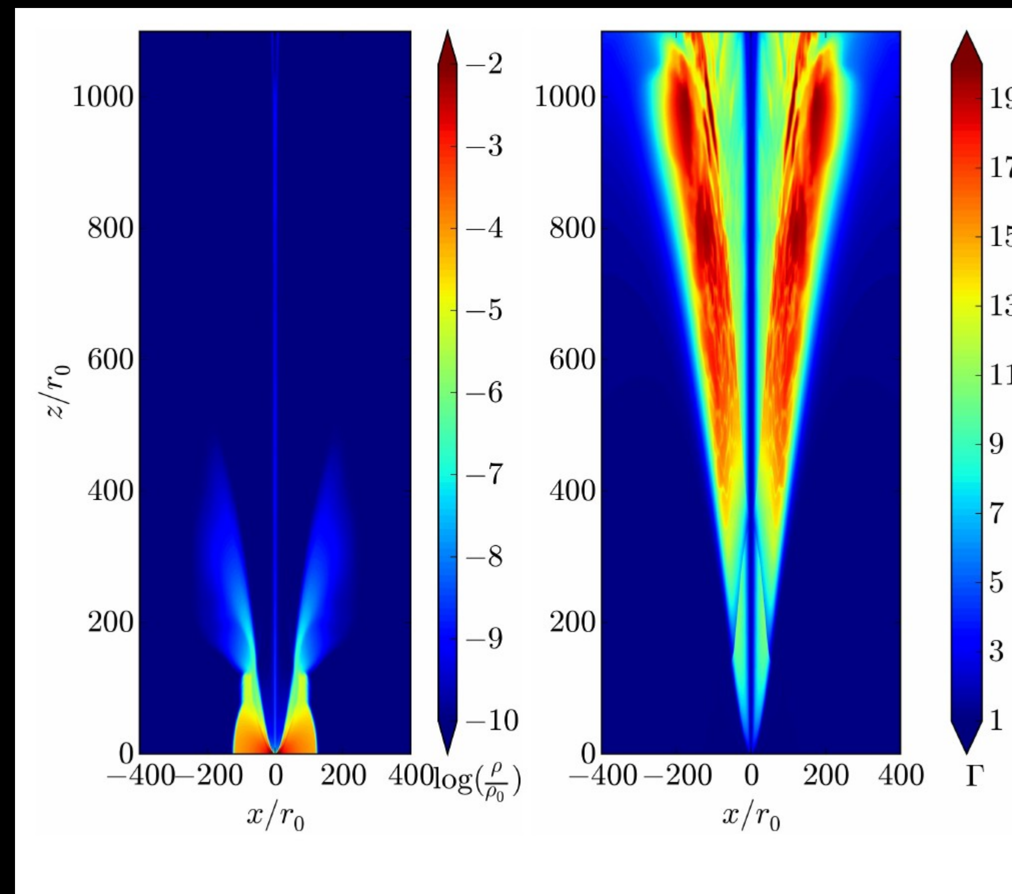
Covino 2007

Off-axis emission

- May increase likelihood of coincident measurements







e.g. Kathirgamaraju et al. 2017

Nucleosynthesis

- Origin of heavy elements formed by rapid-neutron capture process
- Astrophysical production site of rapid neutron-capture elements not yet identified

  - mergers provide favorable conditions: ejecta neutron rich, fast expanding ejecta (typically ~10^{-2} M_{sun})

  - many alternative scenarios, e.g. core-collapse supernovae
- R-process elements observed in stellar spectra of of all metalicities especially metal-poor (=old) stars

  → points to certain robustness and universality of r-process

  → understand galactic chemical evolution
- Open questions

  - details of r-process path (ejecta properties, e.g. masses, temperatures, neutrinos, different types of ejecta: dynamical vs. secular, importance of fission)

  - nuclear physics models

  - overall production / dominant source ? → GW / em observations will settle rate
- Many groups involved from astro side and nuclear physics, e.g. in DA Arcones, Martinez-Pinedo, ...

Electromagnetic transients

- Synonyms: “kilonova”, “macronova”
- Powered by radioactive decays during/after r-process → heat expanding ejecta
- Ejecta initially opaque → transparent on time scale of 1 d → peak luminosity
- Thermal emission in UV, optical, infrared
- Targets for time-domain astronomy

  - blind searched by surveys: Large Synoptic Survey Telescope (LSST), Palomar Transient Factory (PTF), BlackGEM, ...

  - triggered searches (by GW candidate, sGRB): Hubble Space Telescope, Very Large Telescope, ...
- Potential observations of radioactively powered transients in aftermath of sGRBs, e.g. GRB130603b

Electromagnetic transients - outlook

- Electromagnetic counterpart to GW event → increases confidence and sensitivity of GW searches by providing precise sky position
- Understand zoo of astronomical transient phenomena
- Rate of NS mergers
- Reveal details of nucleosynthesis: ejecta masses, velocities, abundances, ...

  → Rate * ejecta mass = total production

  → Is all gold produced in NS mergers?

- Particularly rewarding: multi-messenger astronomy

  - GW → binary masses, possibly EoS

  - em emission (sGRB / kilonova): sky position, dynamics of merger, ejecta masses

Gravitational waves

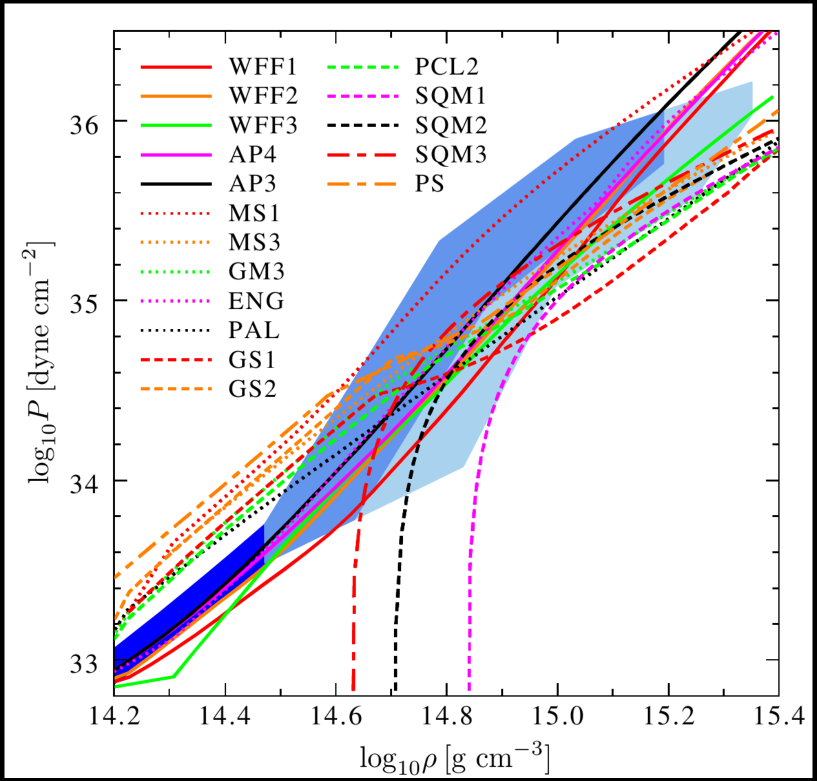
- NS mergers are strong emitters of GWs → next type of source to be detected
- Detections will clarify rate and binary masses of population
- GWs from NS mergers bear potential to constrain EoS of high-density matter

  - stiffness at saturation and beyond

  - hyperon puzzle

  - more exotic phases (QCD phase transition)

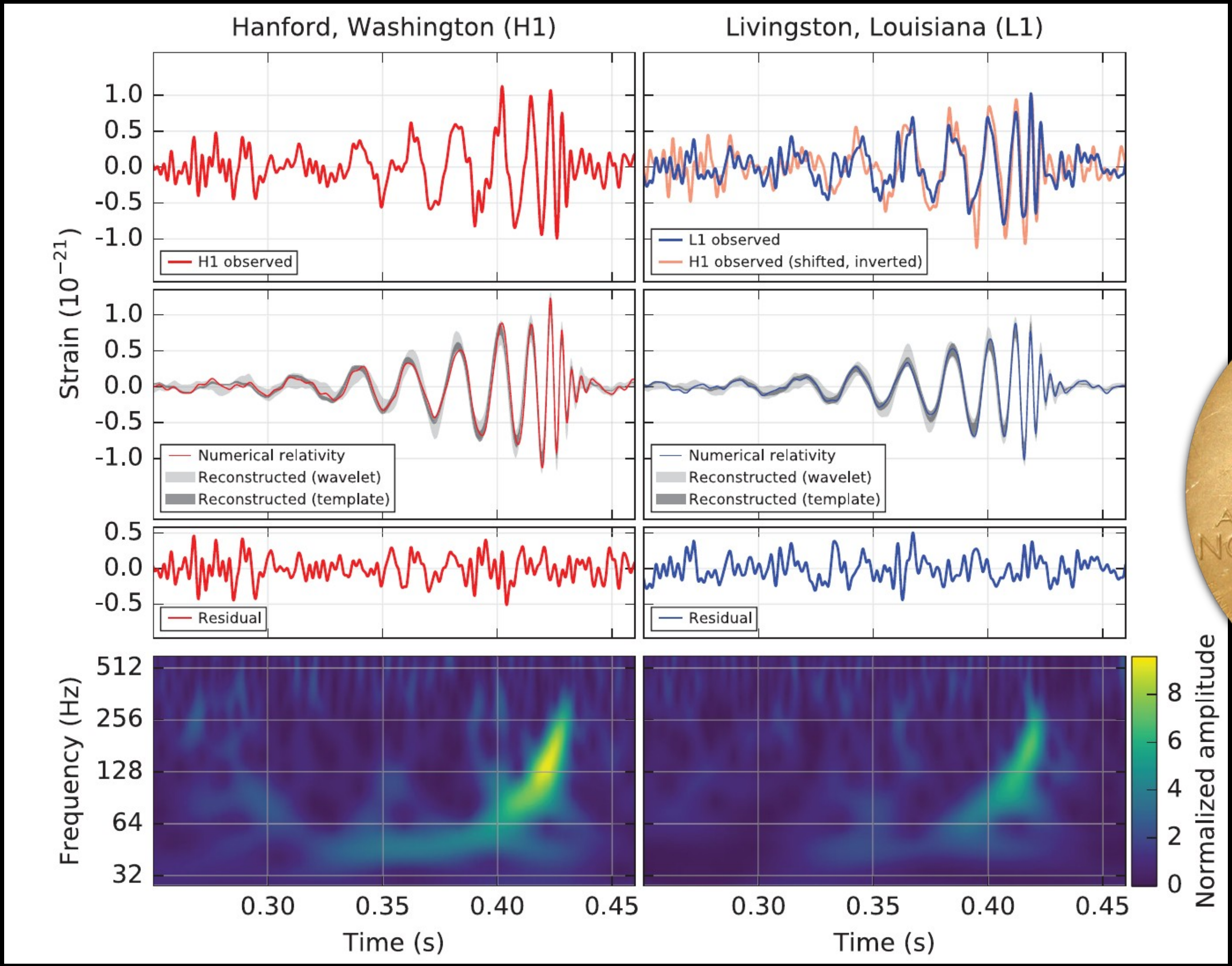
  - ....



Hebeler & Schwenk 2014

Gravitational waves

GW150914: a BH-BH merger – first direct observation of GWs



2017

Abbott et al. 2016

September 14, 2015

Plus three more BH mergers

GWs from BH mergers

- First BH binaries detected
- GW signal reveals masses – orbital motion

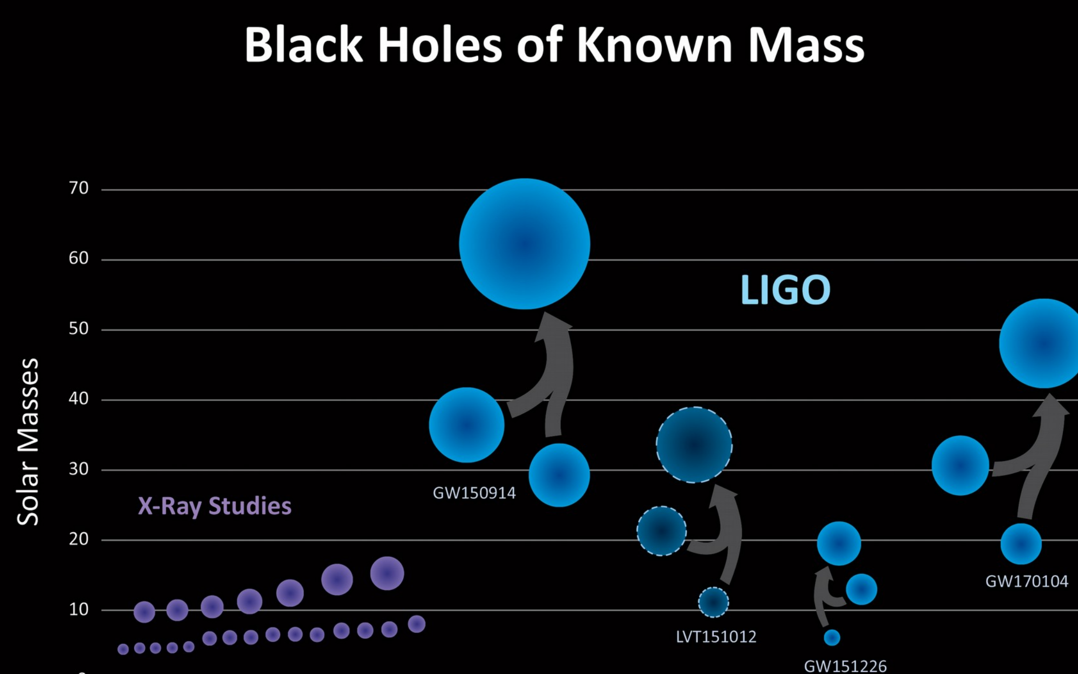
  → any orbiting binary will produce a chirping signal → merger
- Rates

  → 4 BH mergers vs 0 NS mergers does not imply that rate of NS mergers is lower

  → NSM rate per volume is expected to be higher

Primary black hole mass m_1	$31.2^{+8.4}_{-6.0} M_\odot$
Secondary black hole mass m_2	$19.4^{+5.3}_{-5.9} M_\odot$
Chirp mass $\mathcal{M}$	$21.1^{+2.4}_{-2.7} M_\odot$
Total mass M	$50.7^{+5.9}_{-5.0} M_\odot$
Final black hole mass M_f	$48.7^{+5.7}_{-4.6} M_\odot$
Radiated energy $E_{\rm rad}$	$2.0^{+0.6}_{-0.7} M_\odot c^2$
Peak luminosity $\ell_{\rm peak}$	$3.1^{+0.7}_{-1.3} \times 10^{56} \mathrm{erg\,s^{-1}}$
Effective inspiral spin parameter $\chi_{\rm eff}$	$-0.12^{+0.21}_{-0.30}$
Final black hole spin a_f	$0.64^{+0.09}_{-0.20}$
Luminosity distance D_L	880^{+450}_{-390} Mpc
Source redshift z	$0.18^{+0.08}_{-0.07}$

GW170104 (Abbott et al. 2017)

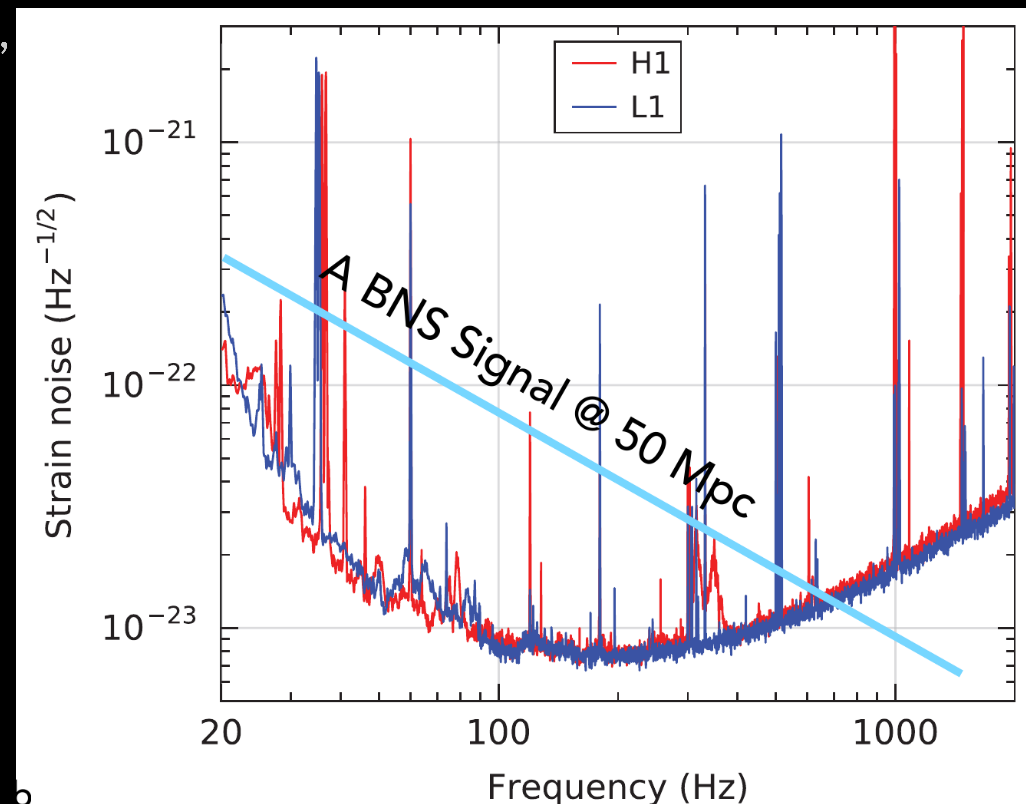


+ GW170814: 25+31 solar masses

Abott et al. 2016

Detector characteristics

Sensitivity (noise) curve of Ad. LIGO detectors during first observing run (O1) in 2016



Seismic noise

Thermal noise

Photon shot

- Fabry-Perot Michelson interferometer
- Different sources of noise: thermal, seismic, shot noise, ...
- Sensitive to GWs with frequencies between a few 10 Hz to a few kHz

  → frequency range determines types of observable sources (orbital/dynamical time scales)

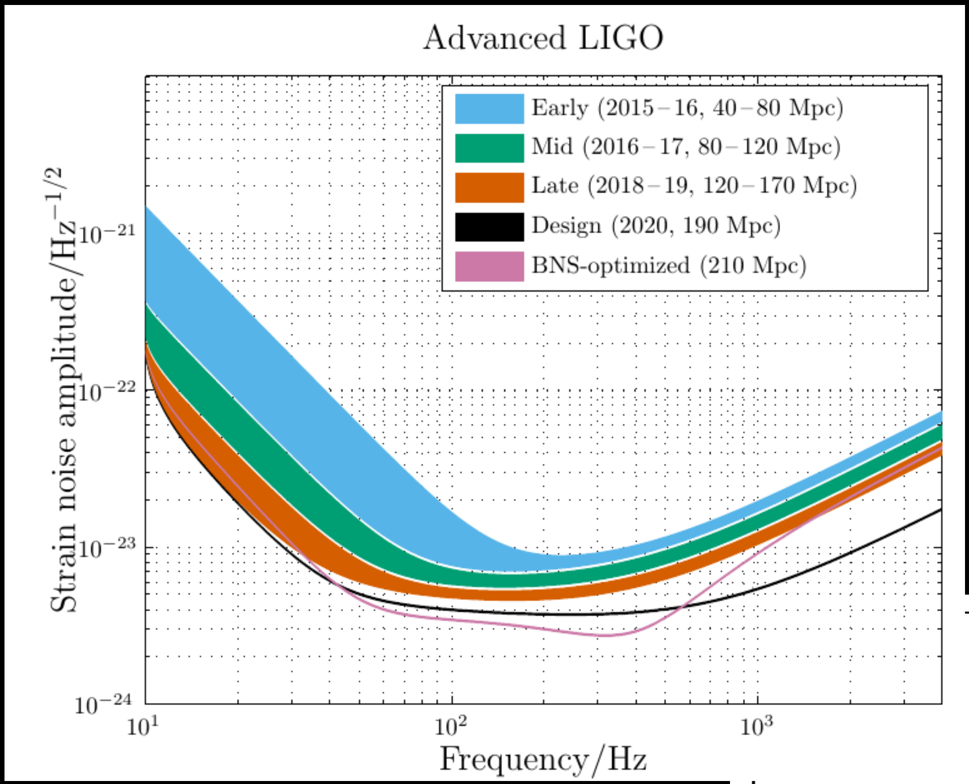
  → stellar compact objects: NS stellar mass BHs
- Design sensitivity within next years (a few factors higher), more instruments become operational
- Challenge: GW data analysis, e.g.,

  - matched filtering: template based → requires complete model of expected signals

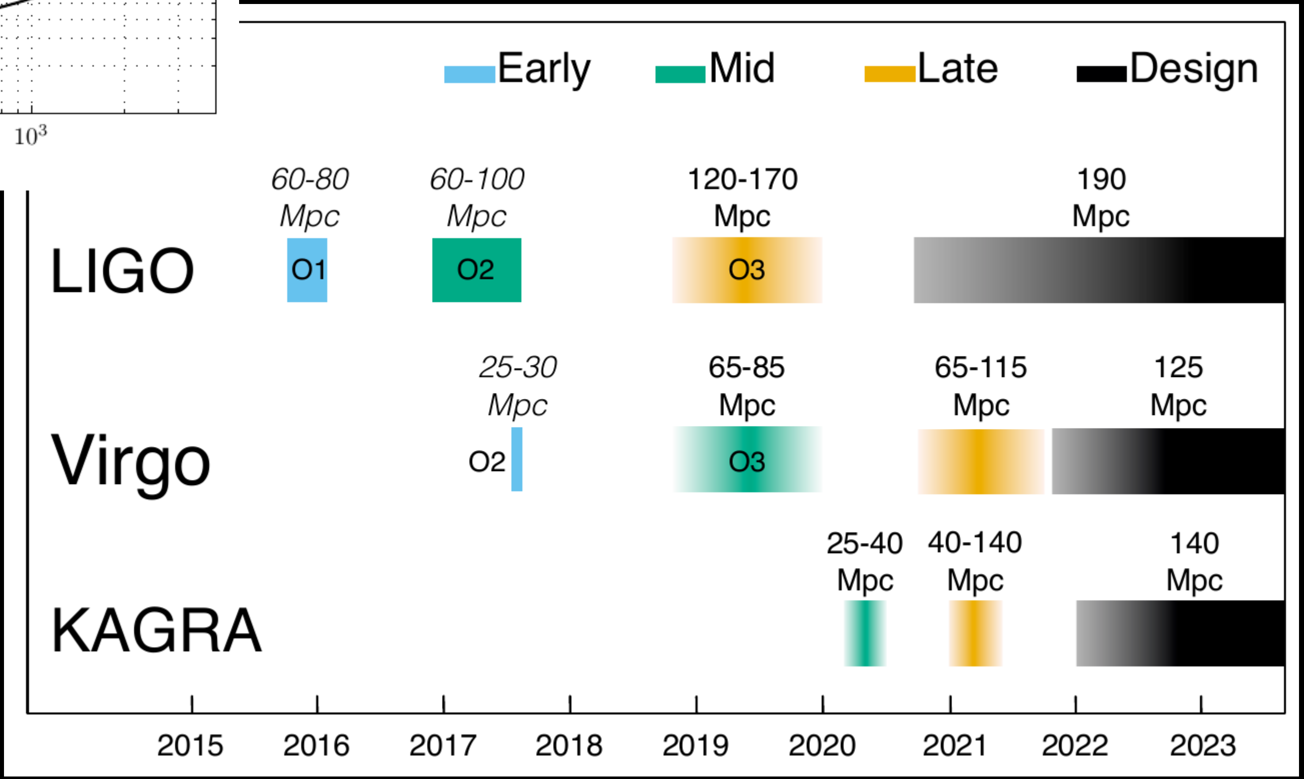
  - unmodelled searches

  → some proper statistical argument that some pattern was not a random fluctuation

Future plans



Abbott et al. 2017



Future

- More detectors become operational with higher sensitivity → network leads to higher overall sensitivity
- Plans for 3rd generation instruments and upgrades of current detectors:

  - Einstein Telescope

  - Voyager

  - Cosmic Explorer

  - LIGO +

  (all similar frequency band: 10 Hz to several kHz, but different sensitivity)
- Laser Interferometer Space Antenna (LISA) not before 2034 → space borne GW detector for low frequencies (0.1 mHz … 1 Hz) → supermassive BHs, white dwarfs, …
- Pulsar Timing Arrays (ongoing efforts) nanoHertz → supermassive BHs

What's next? - NS mergers?


nature International weekly journal of science

Home | News & Comment | Research | Careers & Jobs | Current Issue | Archive | Audio & Video | For Au

News & Comment > News > 2017 > September > Article

NATURE | EXPLAINER

Rumours swell over new kind of gravitational-wave sighting

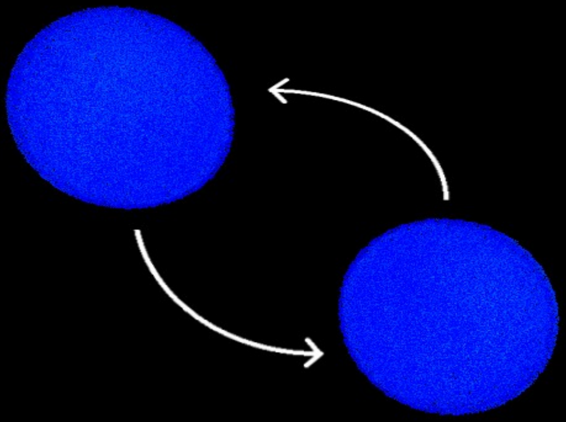
Gossip over potential detection of colliding neutron stars has astronomers in a tizzy.

Davide Castelvecchi

24 August 2017 | Updated: 25 August 2017, 25 August 2017

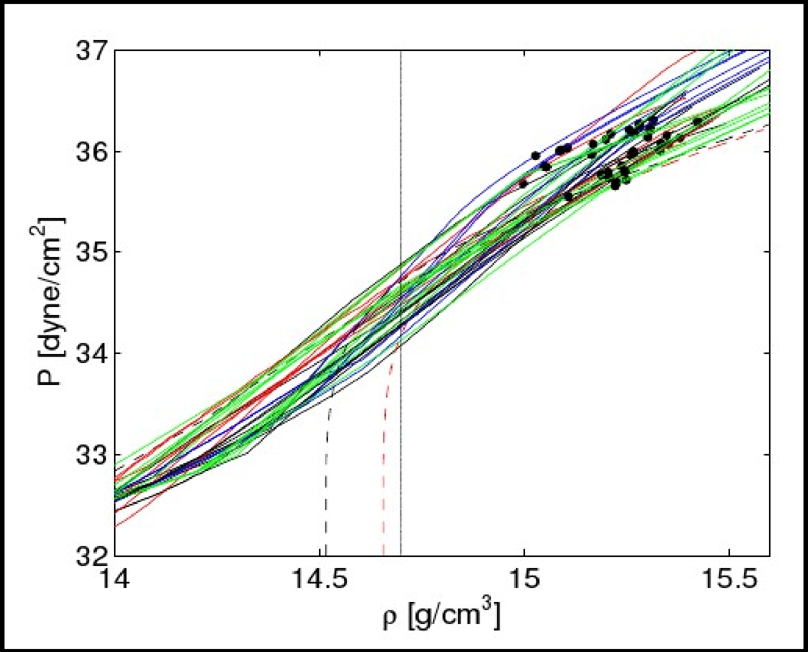
Rights & Permissions

Neutron-star mergers and the nuclear EoS

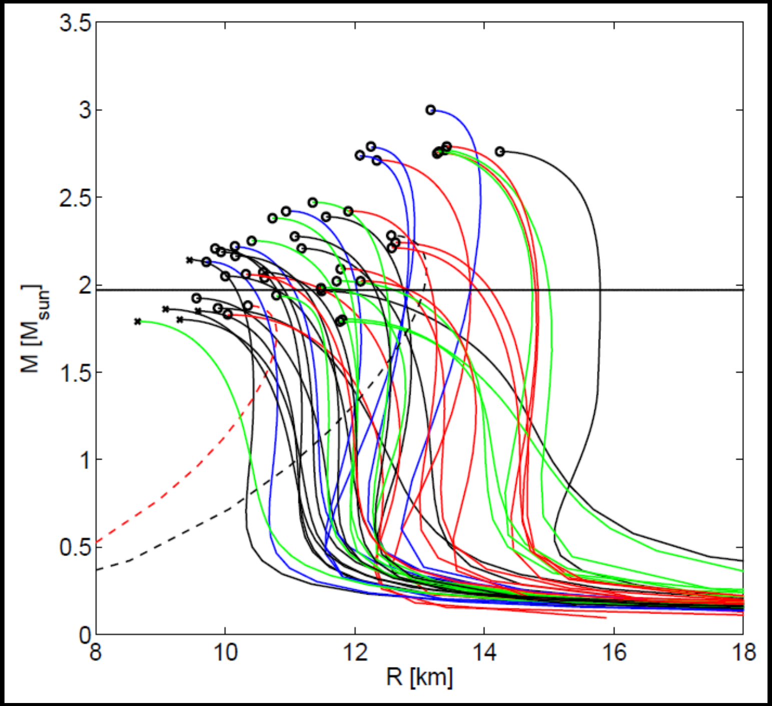


EoS of NS matter

- Mass-radius relation (of non-rotating NSs) and EoS are uniquely linked through Tolman-Oppenheimer-Volkoff (TOV) equations



TOV ⟷



Theory: P(ρ) ⟷ Observation: R(M)

currently

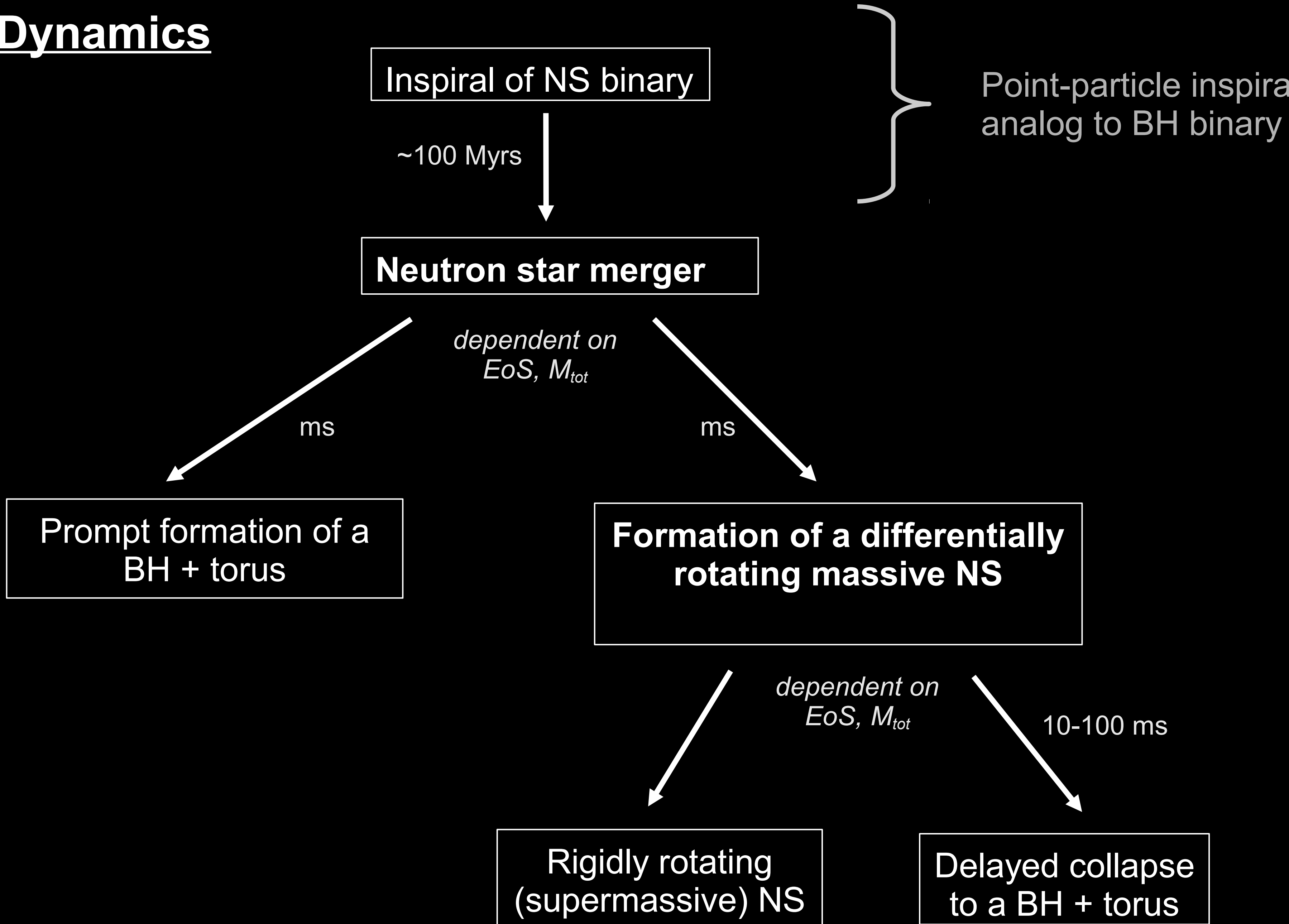
future

=> NS properties (of non-rotating stars) and EoS properties are equivalent !!!

=> in particular we would like to measure radius of fixed mass, e.g. $R_{1.35}$, $R_{1.6}$

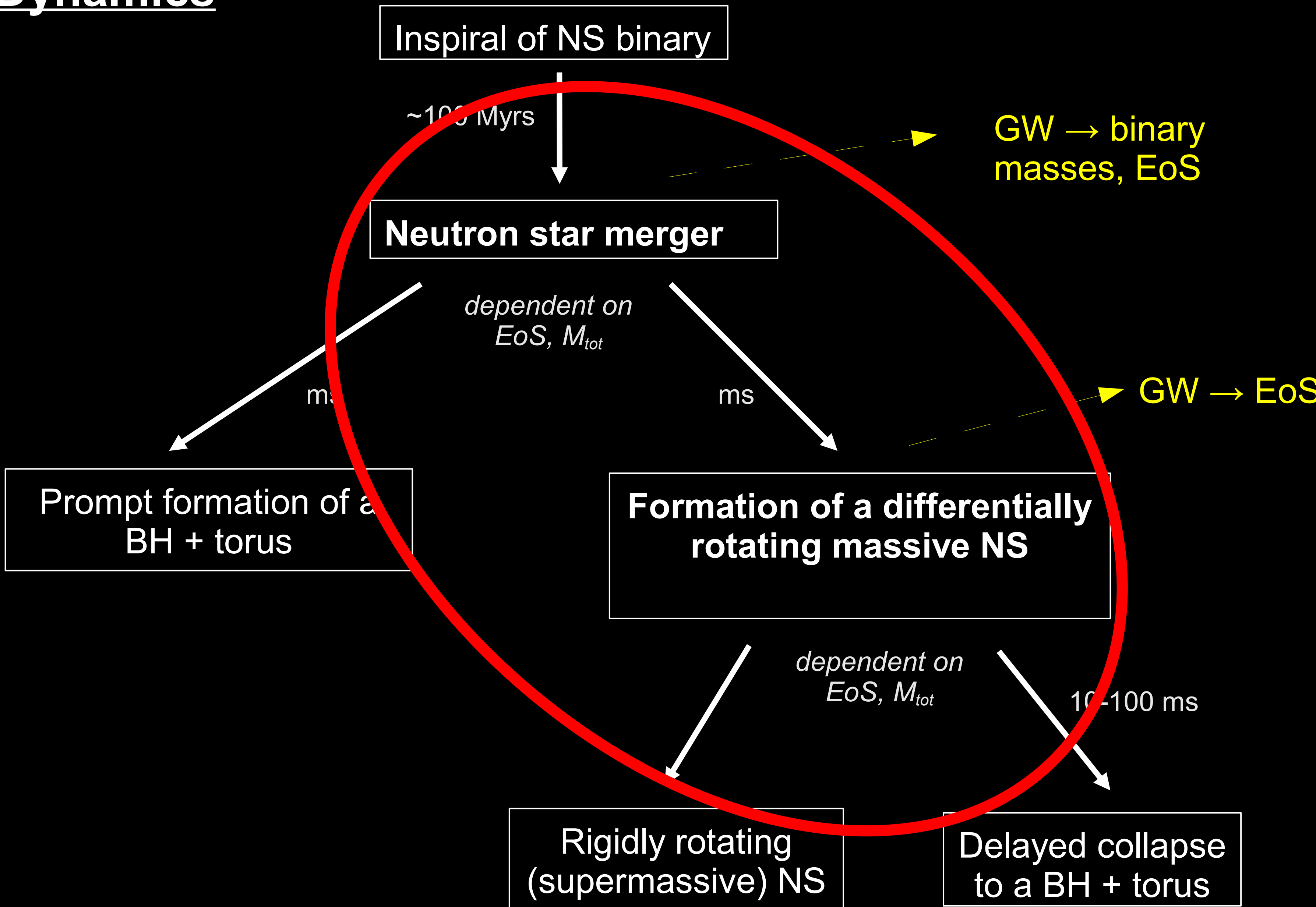
Merger stages

Dynamics



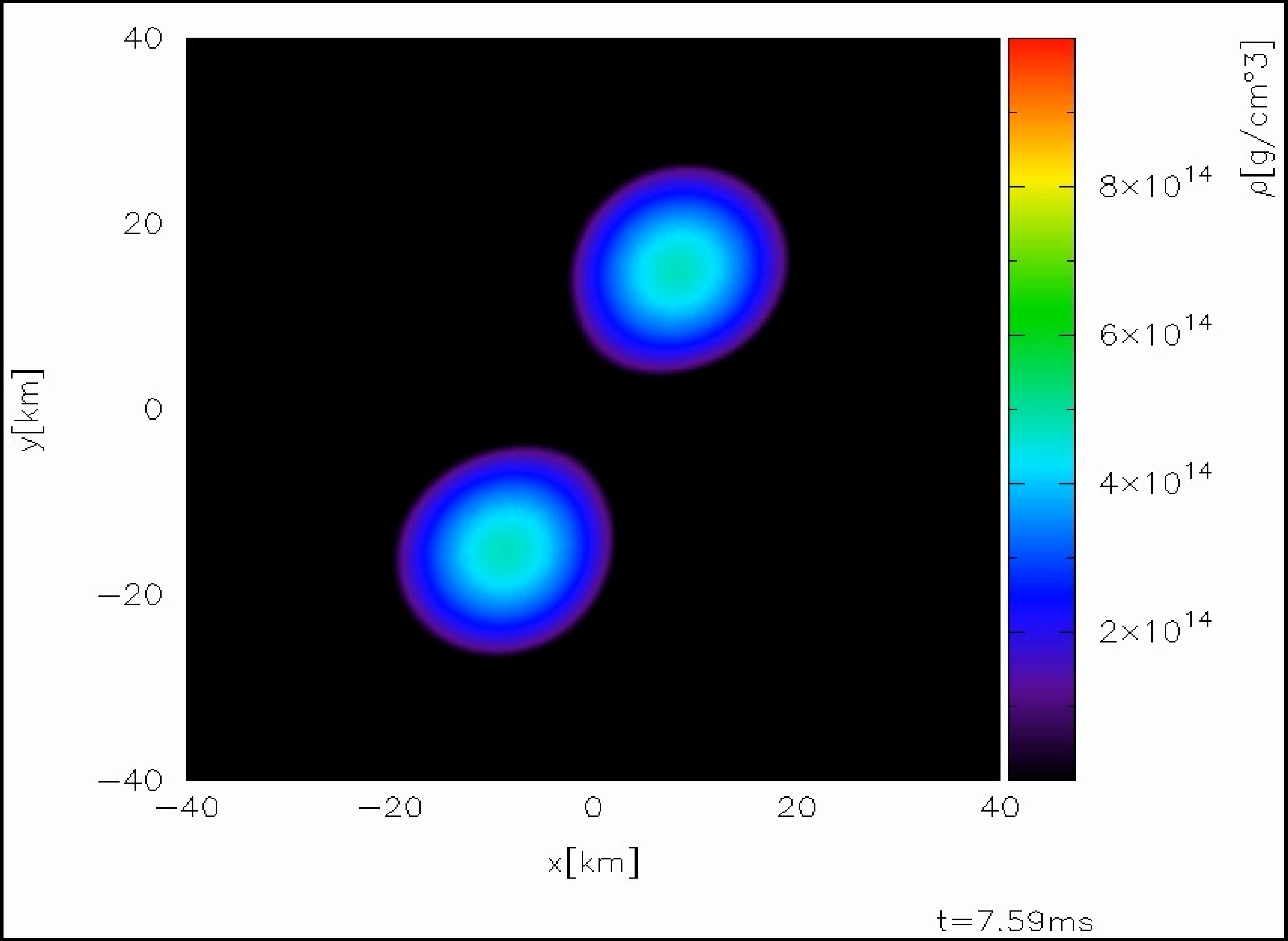
Review: e.g. Faber & Rasio 2012

Dynamics



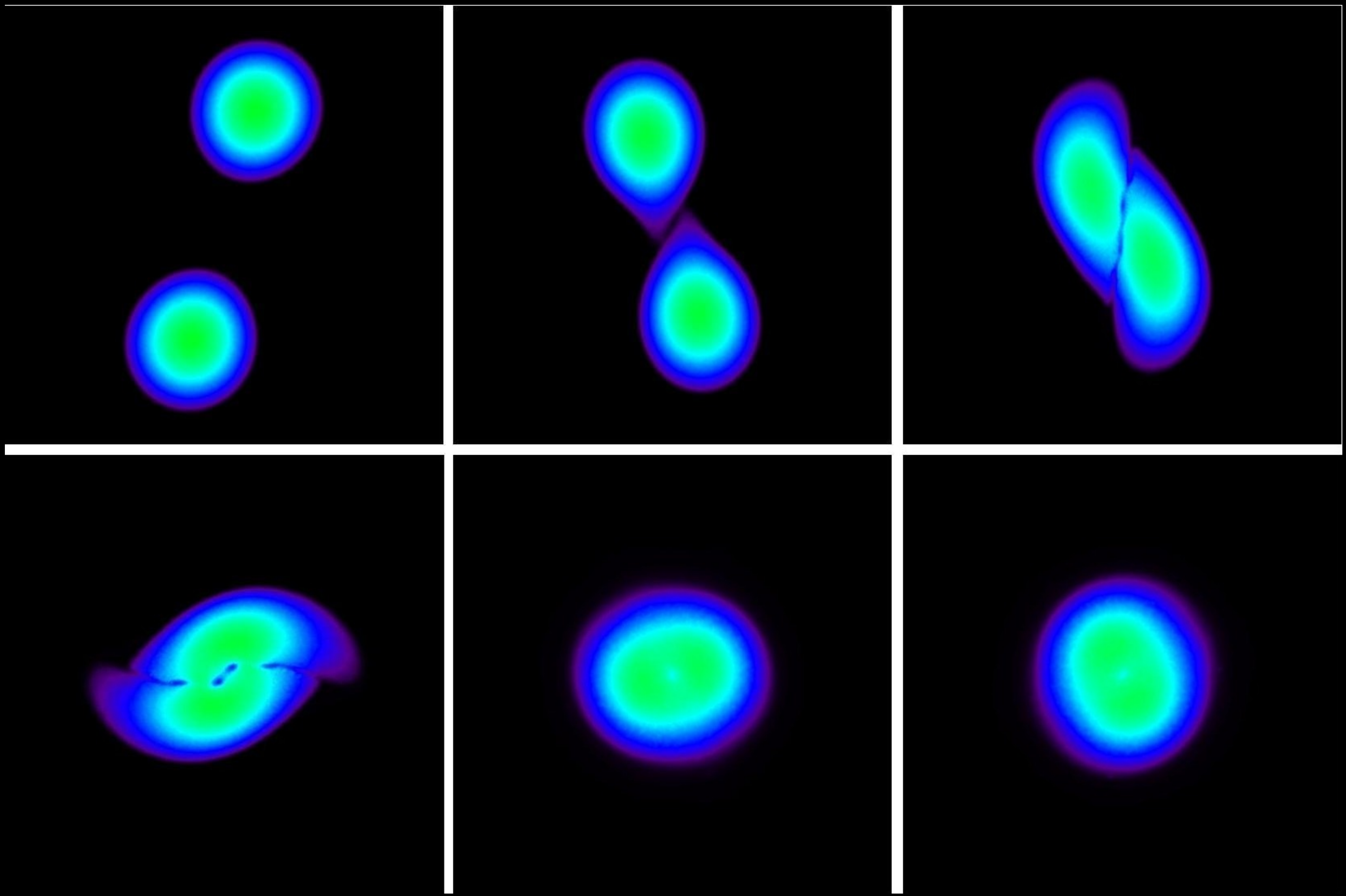
Inspiral of NS binary
~100 Myrs
GW → binary masses, EoS
Neutron star merger
dependent on EoS, M_{tot}
ms
ms
GW → EoS
Prompt formation of a BH + torus
Formation of a differentially rotating massive NS
dependent on EoS, M_{tot}
10-100 ms
Rigidly rotating (supermassive) NS
Delayed collapse to a BH + torus

Simulation: 1.35+1.35 M_{sun}



Density evolution in equatorial plane, Shen EoS

Only late inspiral phase and (post-)merger phase covered by simulation



Goal: EoS from GWs

Two complementary strategies:

- Tidal effects during the inspiral → accelerate inspiral compared to BH-BH

  - strong signal – weaker EoS effect

- Oscillations of the postmerger remnant

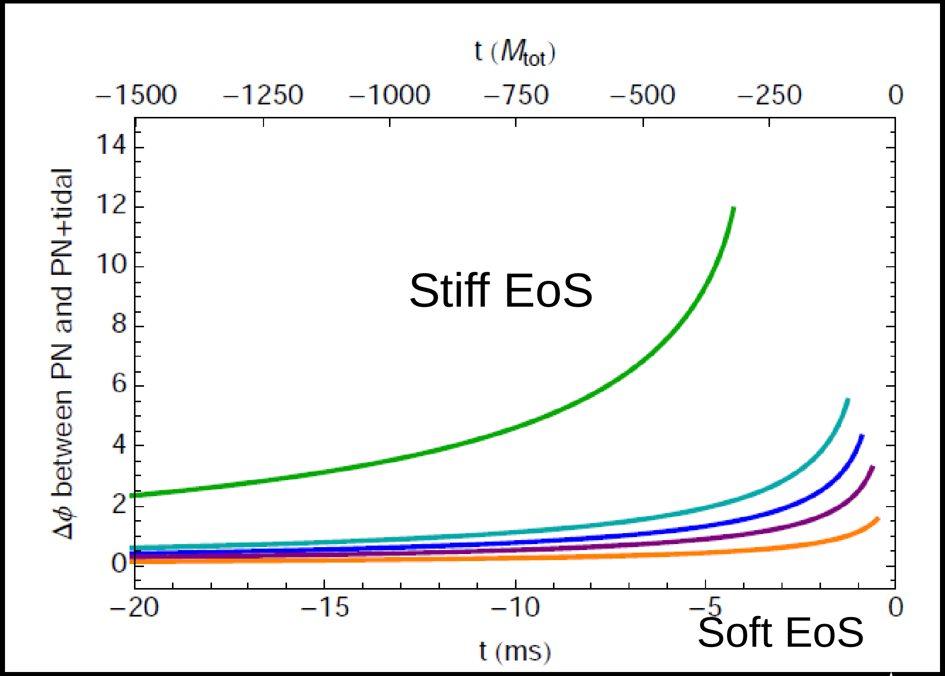
  - strong EoS impact – weaker signal (at higher frequencies)

- Keep in mind: binary masses are easy to measure

EoS effects during inspiral

Inspiral

- Orbital phase evolution affected by NS radius (precisely tidal deformability) – only during last orbits before merging
- Difference in phase between NS merger and point-particle inspiral:



EoS impact measured by tidal deformability

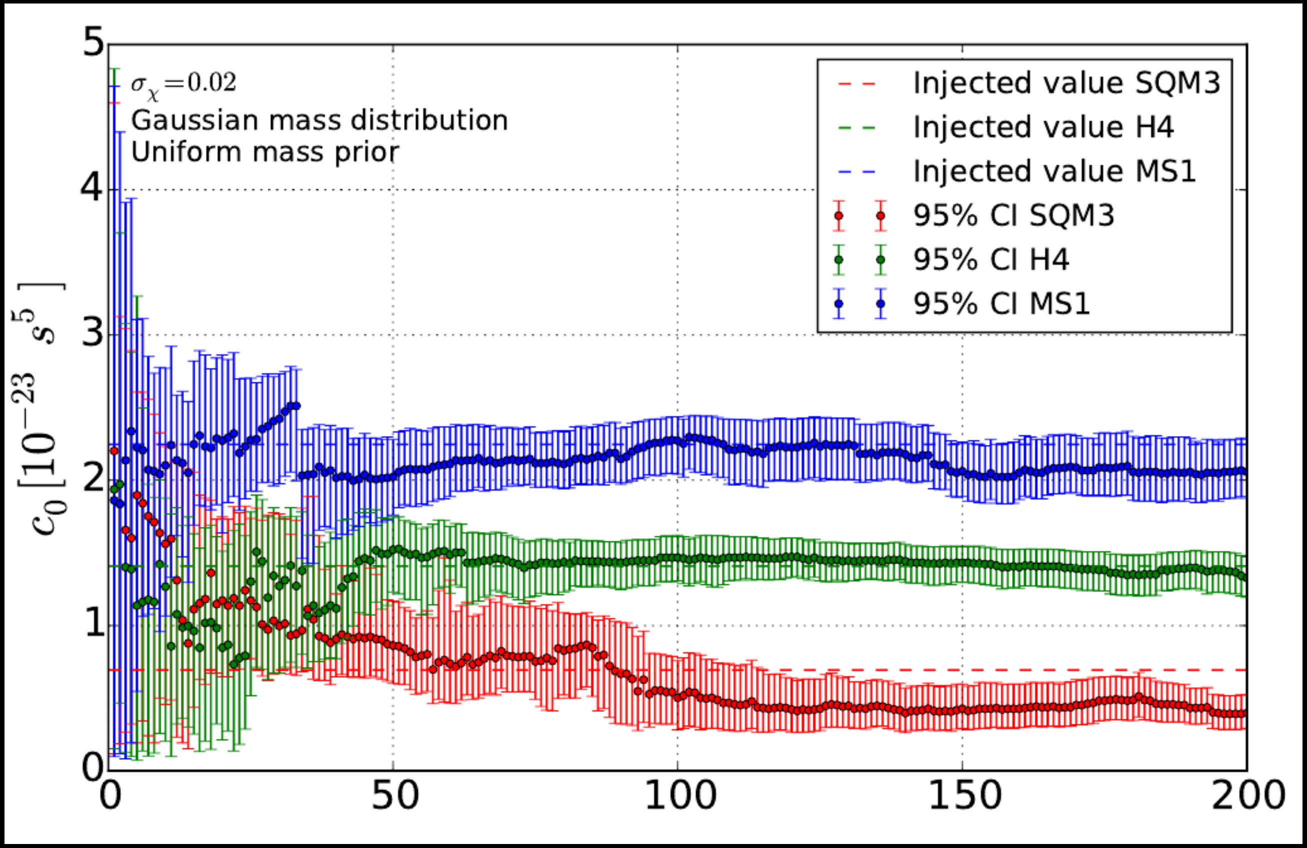
$$\lambda(M) = \frac{2}{3} k_2(M) R^5$$

e.g. Read et al. 2013

Merger time of point particle

Challenge: construct faithful templates for data analysis

Tidal deformability – combining many signals

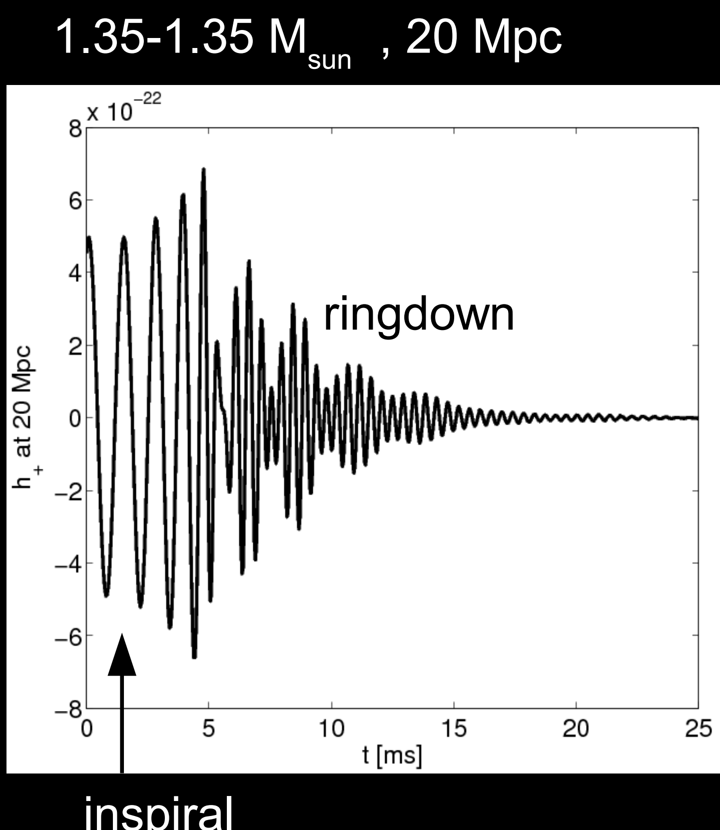


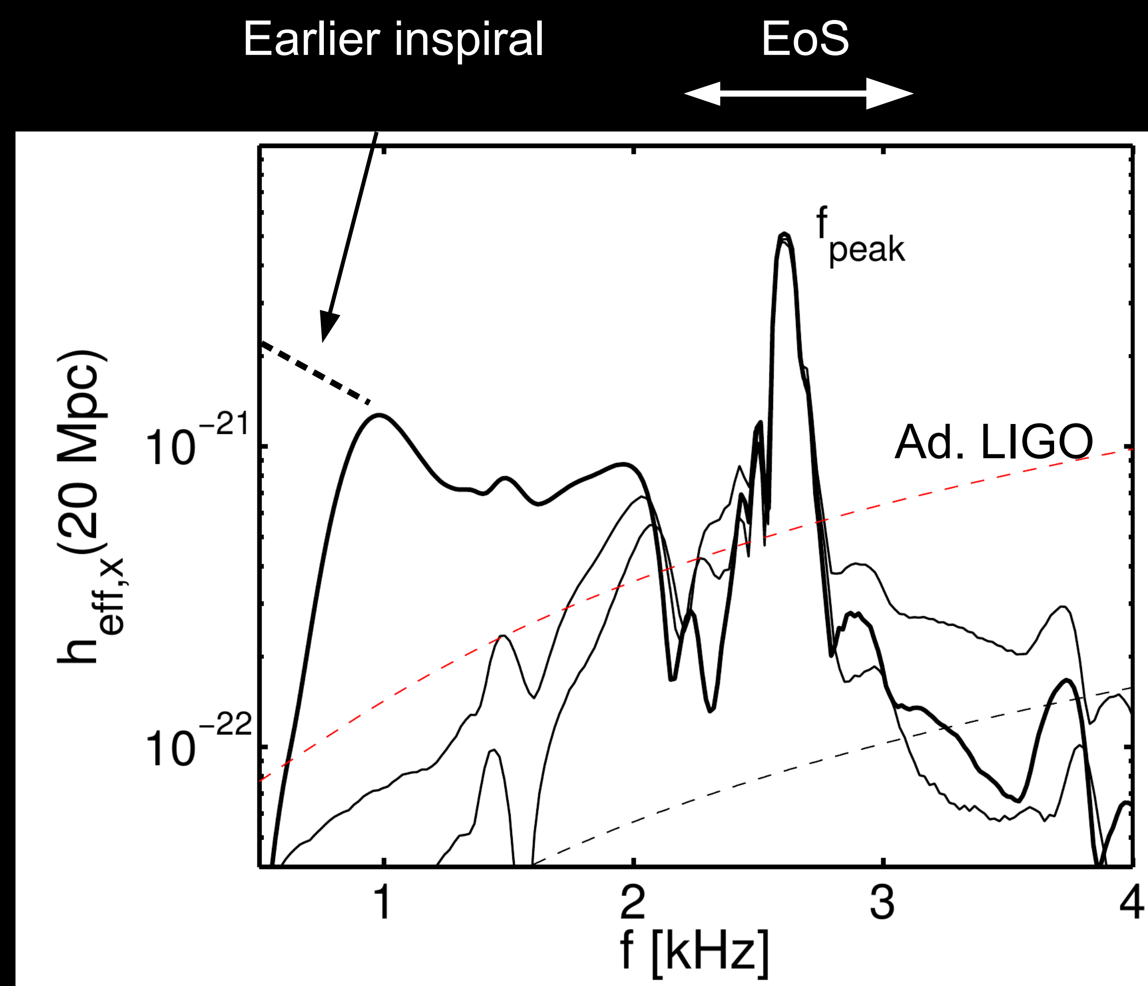
$$\lambda(m) \simeq c_0 + c_1\left(\frac{m-m_0}{M_\odot}\right) + \frac{1}{2}c_2\left(\frac{m-m_0}{M_\odot}\right)^2$$

Agathos et al. 2015

Radius measurements from the postmerger phase

Postmerger

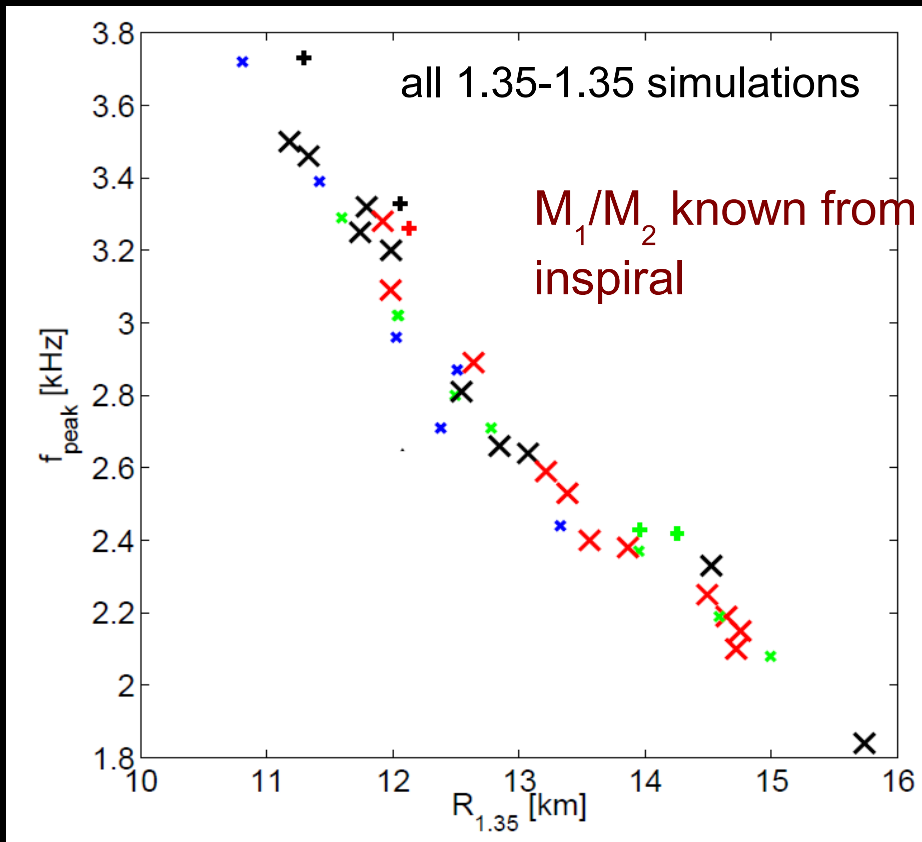




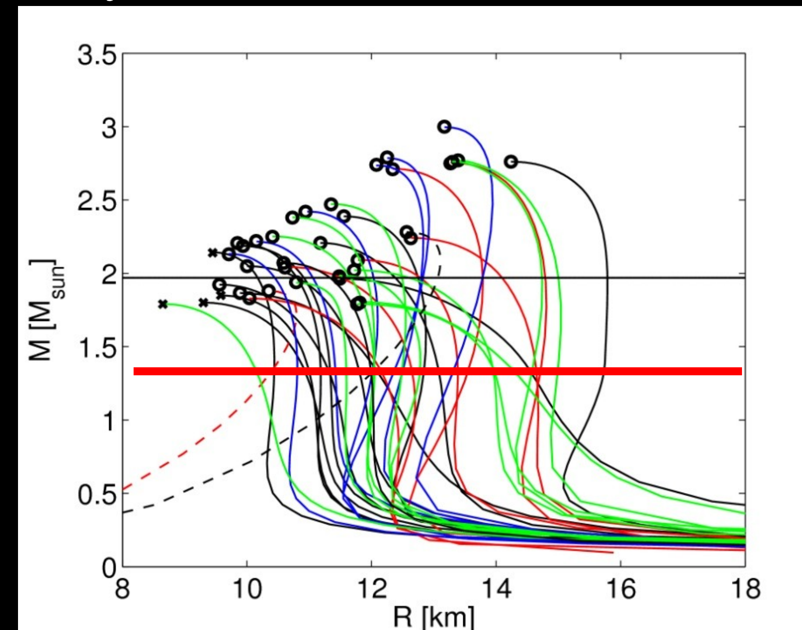
Dominant postmerger oscillation frequency f_{peak}

Very characteristic (robust feature in all models)

Every data point a single simulation of a 1.35-1.35 M_{sun} binary



Bauswein et al. 2012

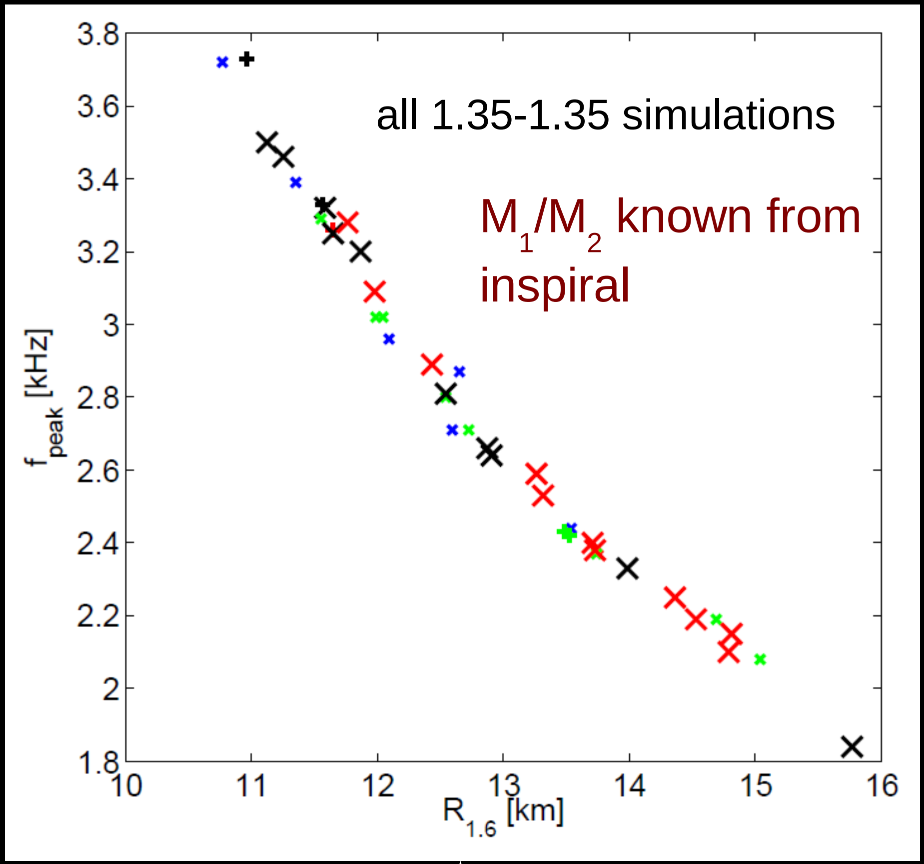


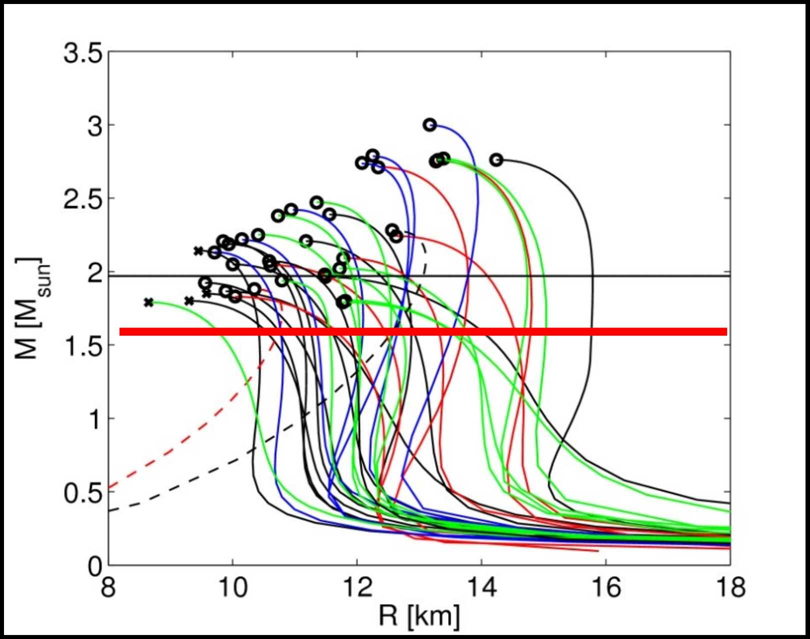
characterize EoS by radius of nonrotating NS with 1.35 M_{sun}

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

→ Empirical relation between GW frequency and NS radius (= our EoS parameter)

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





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

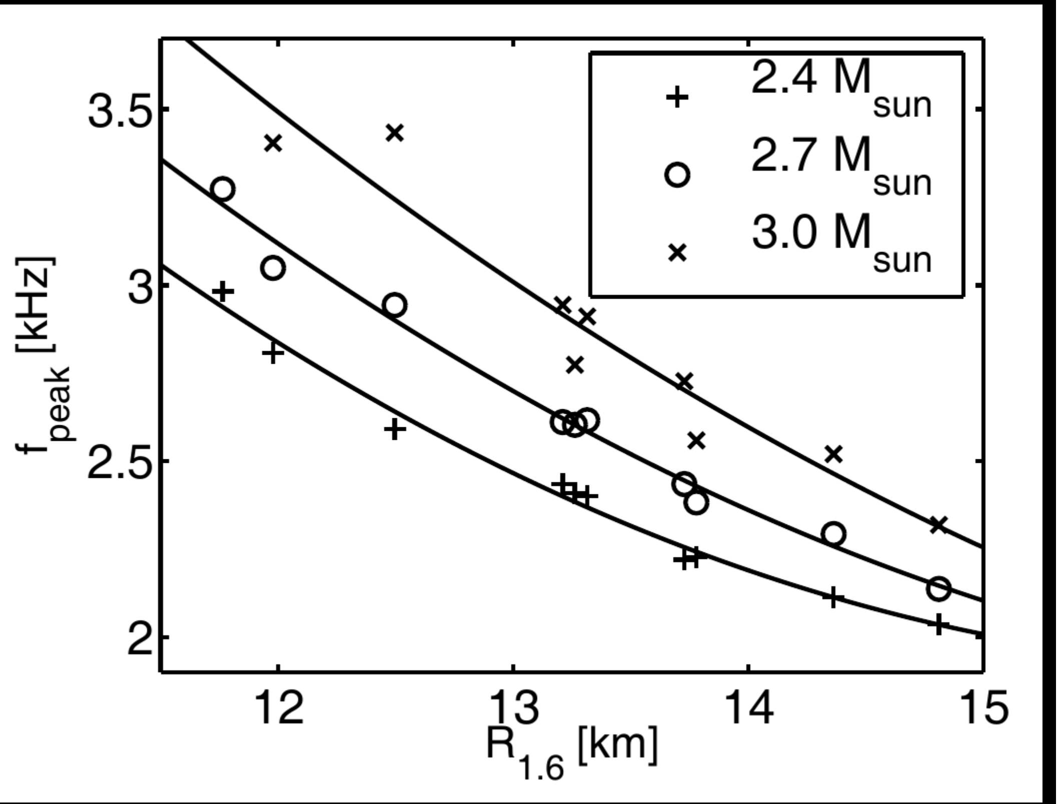
Bauswein et al. 2012

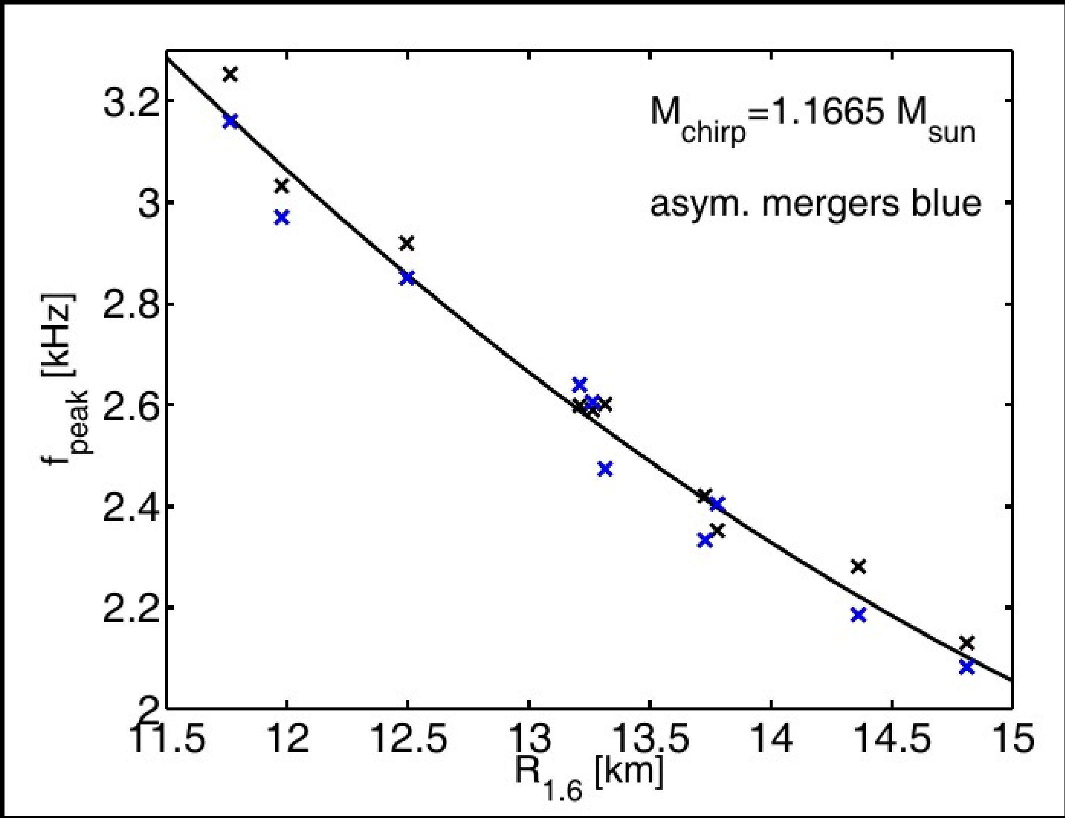
Pure TOV/EoS property => Radius measurement via f_{peak}

Fit: $R(1.6\ M_\odot) = 1.1\, f_{GW}^2 - 8.6\, f_{GW} + 28.$

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

Binary mass variations





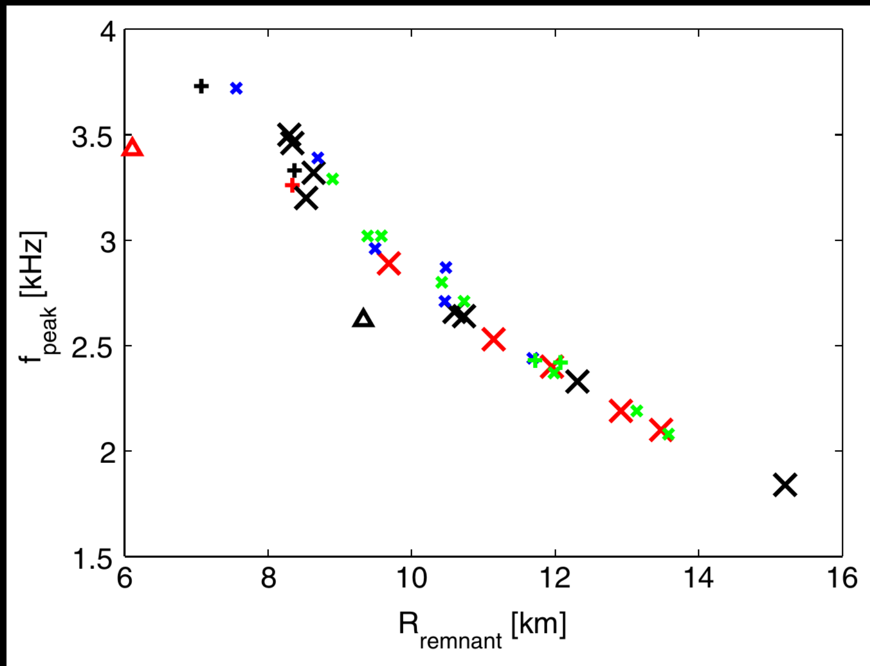
Different total binary masses (symmetric)

Fixed chirp mass (asymmertic 1.2-1.5 M_{sun} binaries and symmetric 1.34-1.34 M_{sun} binaries)

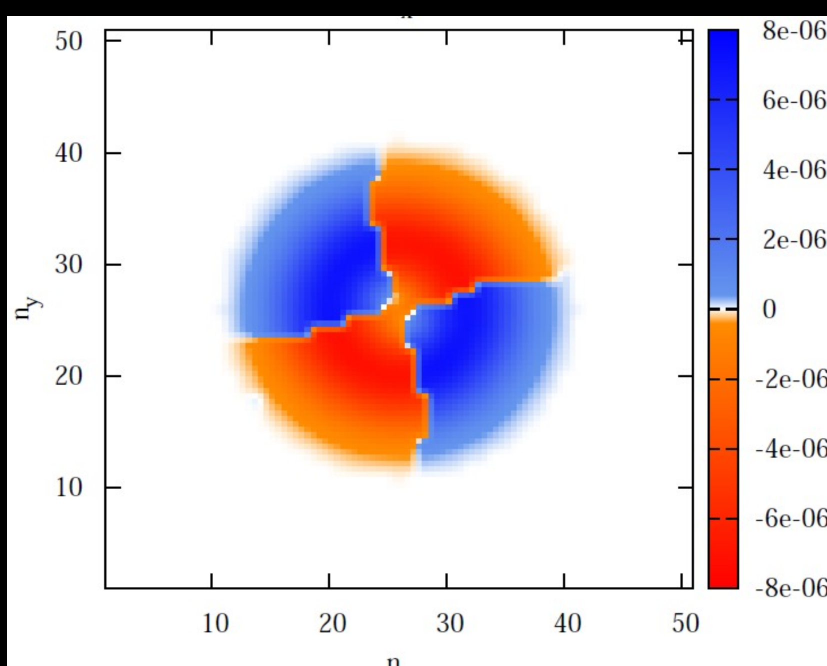
Bauswein et al. 2012, 2016

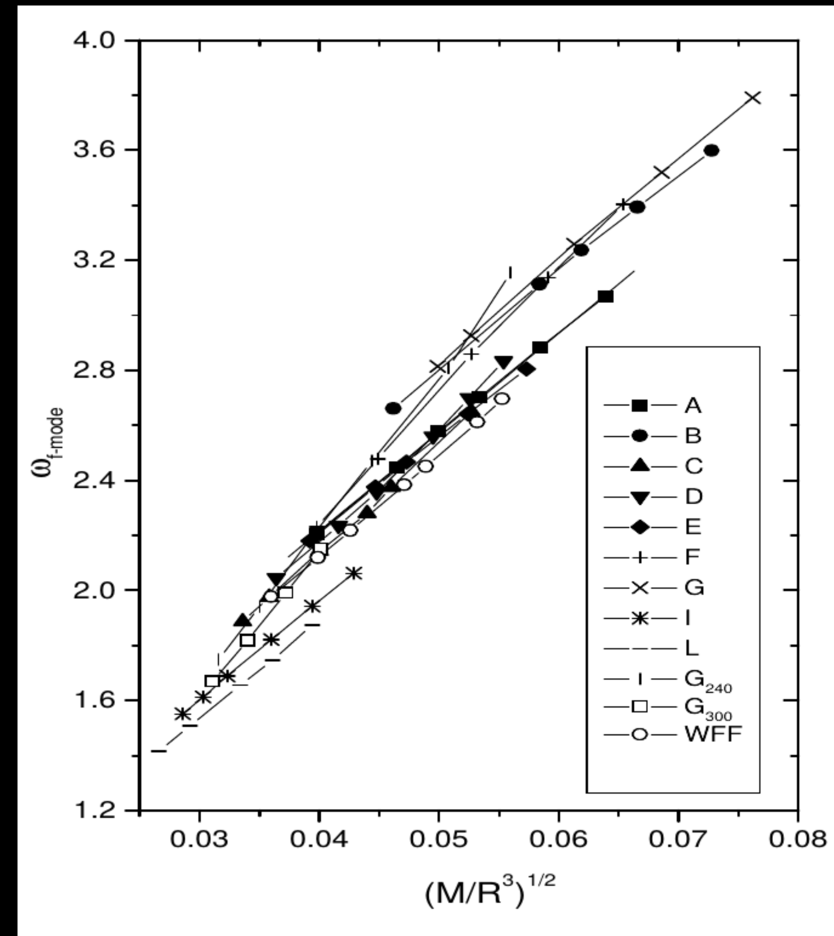
▸ Background

Bauswein et al. 2012



Stergioulas et al. 2011





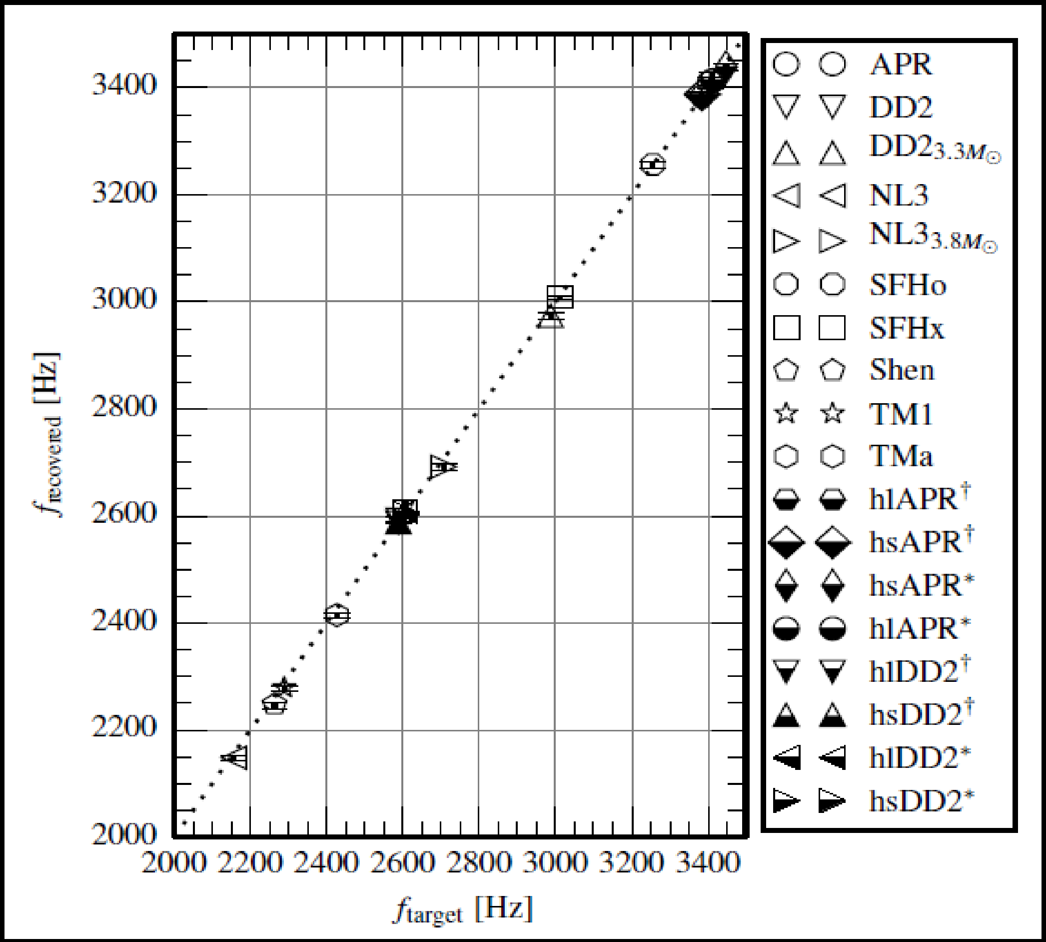
Andersson & Kokkotas 1998

f-mode frequency of nonrotating stars:

$$f \propto \sqrt{\frac{M}{R^3}}$$

Data analysis

Data analysis – prove of principle



Clark et al. 2014

Model waveforms hidden in rescaled LIGO noise

Peak frequency recovered with burst search analysis

Error ~ 10 Hz

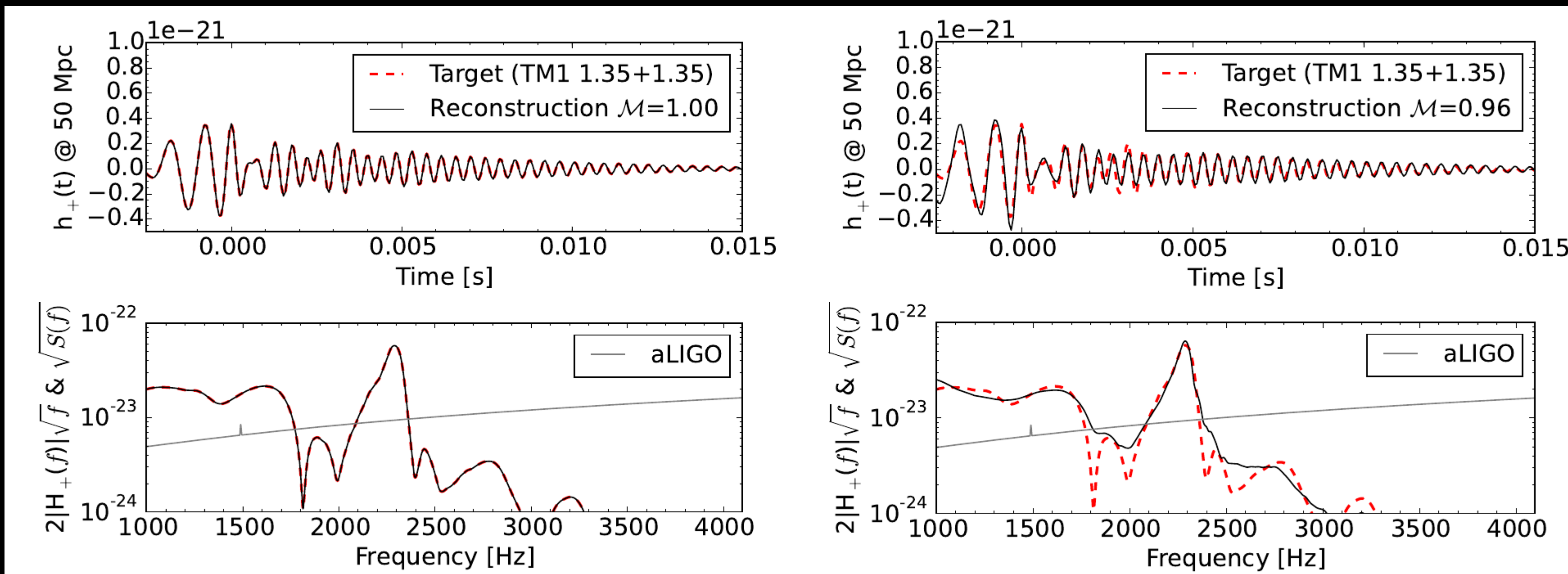
For signals within ~10-25 Mpc

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

Proof-of-principle study
→ improvements likely

Data analysis

- Principal Component analysis



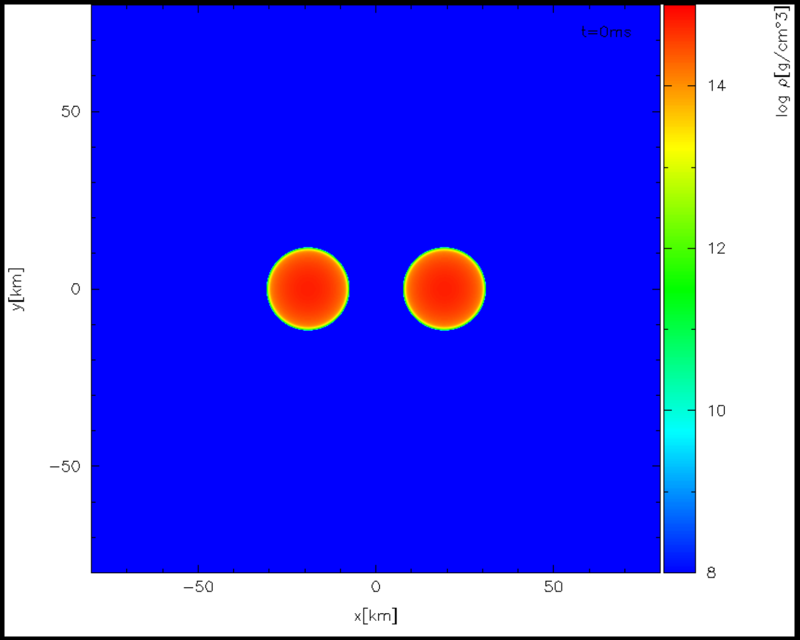
Excluding recovered waveform from catalogue

Clark et al. 2016

(stacking results, e.g. Yang et al., Bose et al.)

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

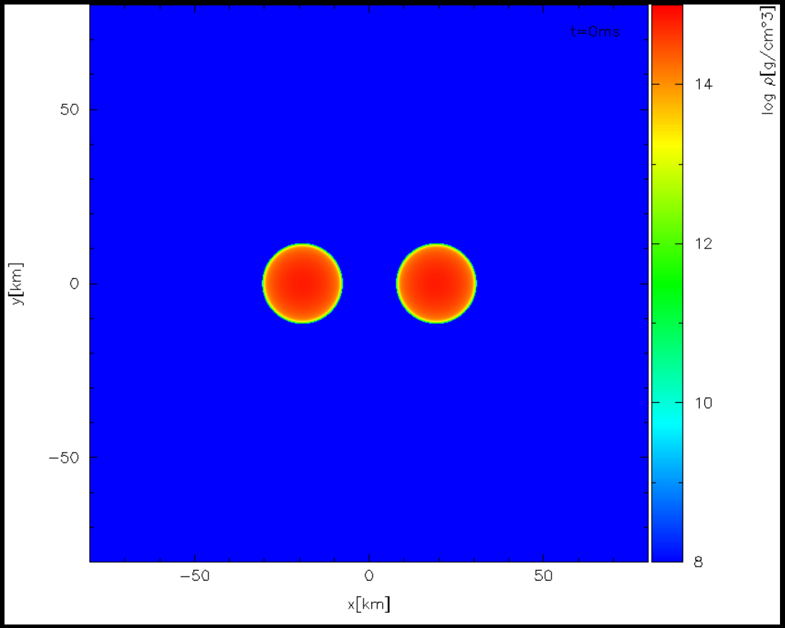
Collapse behavior of the merger remnant



$M_{\rm tot} = 3.4\ M_\odot$

Shen EoS

$M_{\rm tot} = 3.5\ M_\odot$



Collapse behavior:

Prompt vs. delayed (/no) collapse

Relevant for:

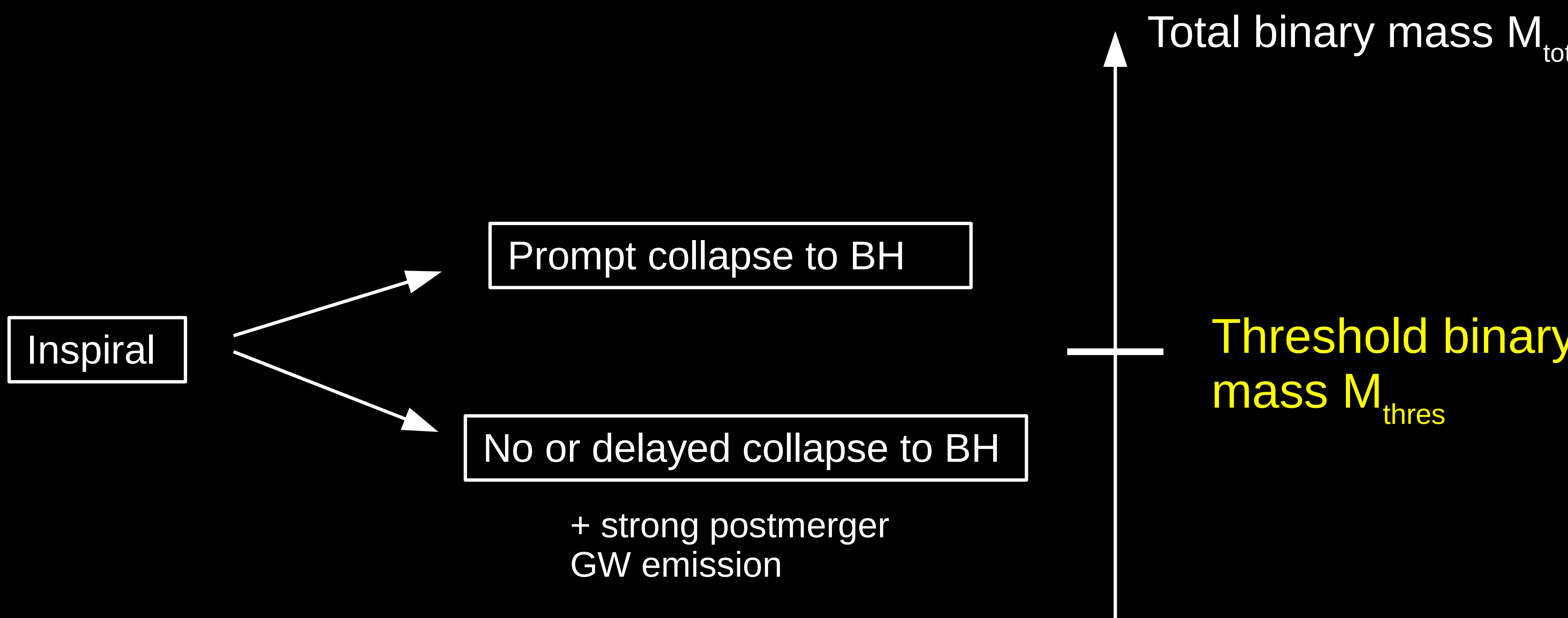
EoS constraints through M_{max} measurement

Conditions for short GRBs

Mass ejection

Electromagnetic counterparts powered by thermal emission

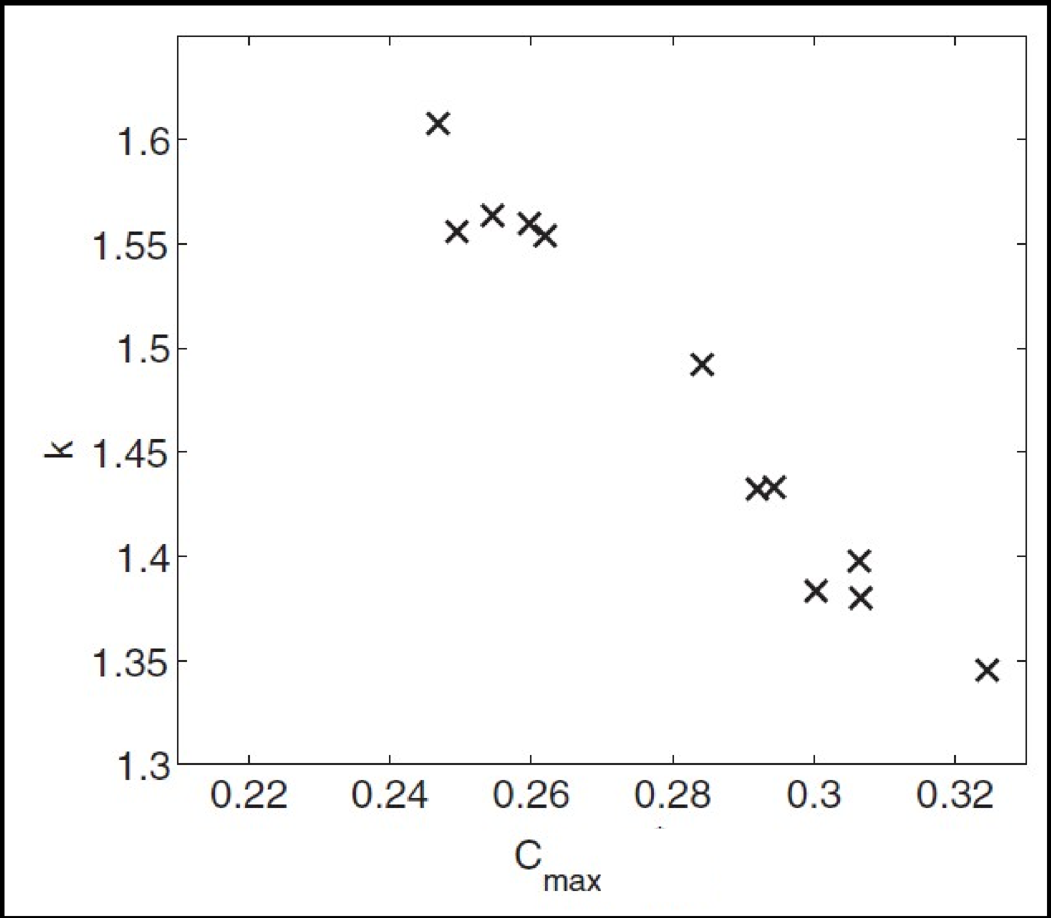
Collapse behavior



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

→ … from observations we can determine M_{max}, R_{max}, ρ_{max}

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

Constrain M_{max}

- Measure several NS mergers with different M_{tot} – check if postmerger GW emission present

  → M_{thres} estimate

$$M_{\rm thres} = \left(-3.38\frac{GM_{\rm max}}{c^2 R_{\rm max}} + 2.43\right) M_{\rm max}$$

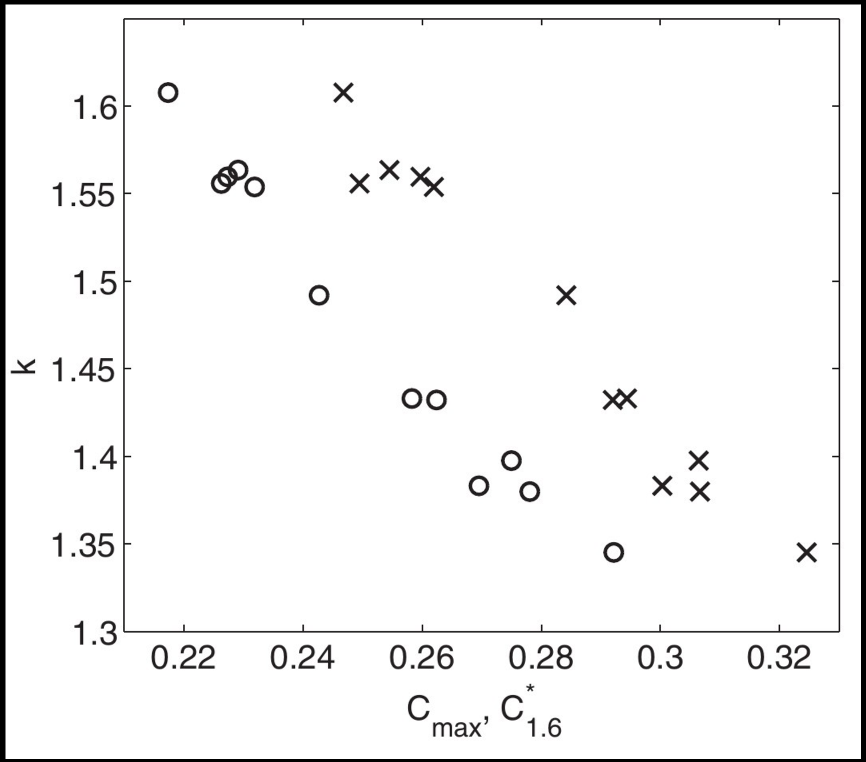
- Radius e.g. from postmerger frequency
- Invert fit

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

→ M_{max}

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

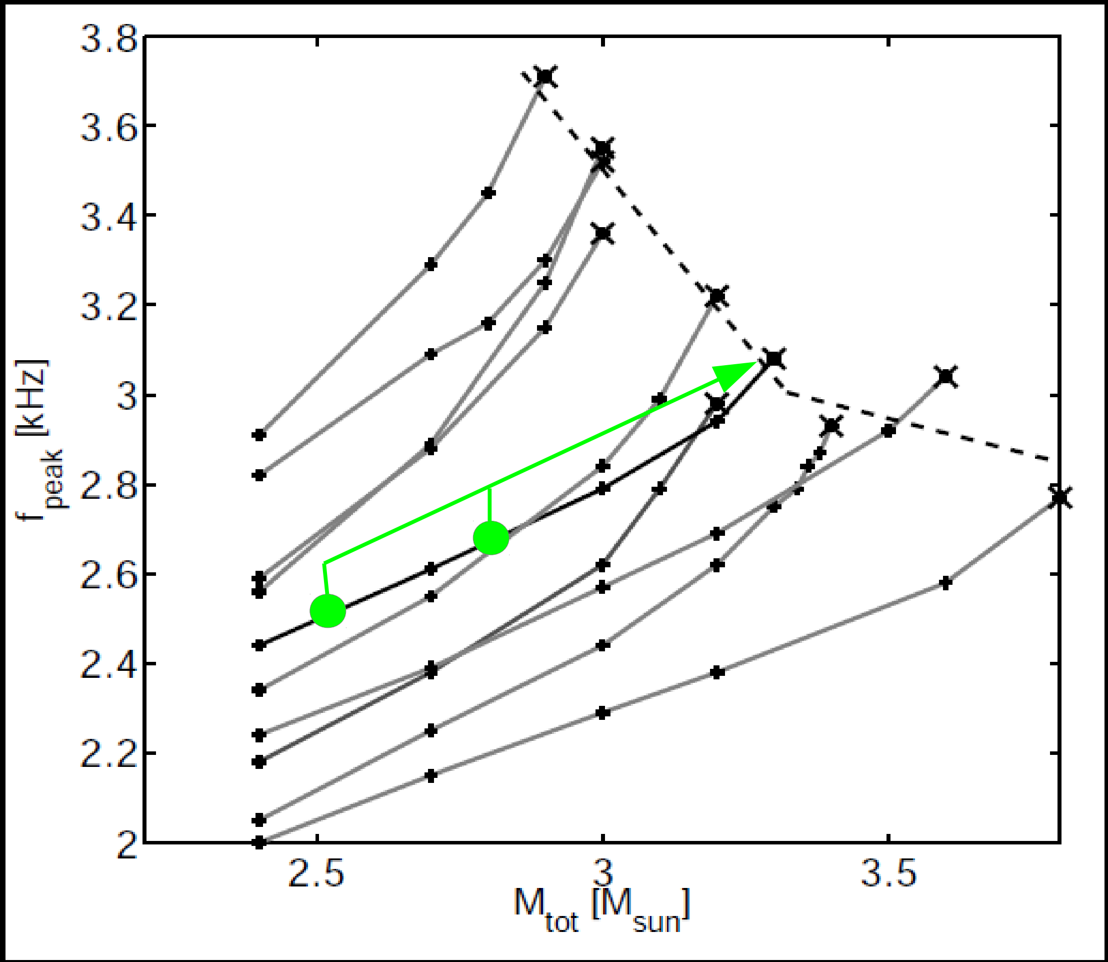
- M_{thres} constraints also from GRB, em counterparts, ...



One more idea:

maybe we get more events but not with high binary masses

Alternative: f_{peak} dependence on total binary mass



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

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

Bauswein et al. 2014

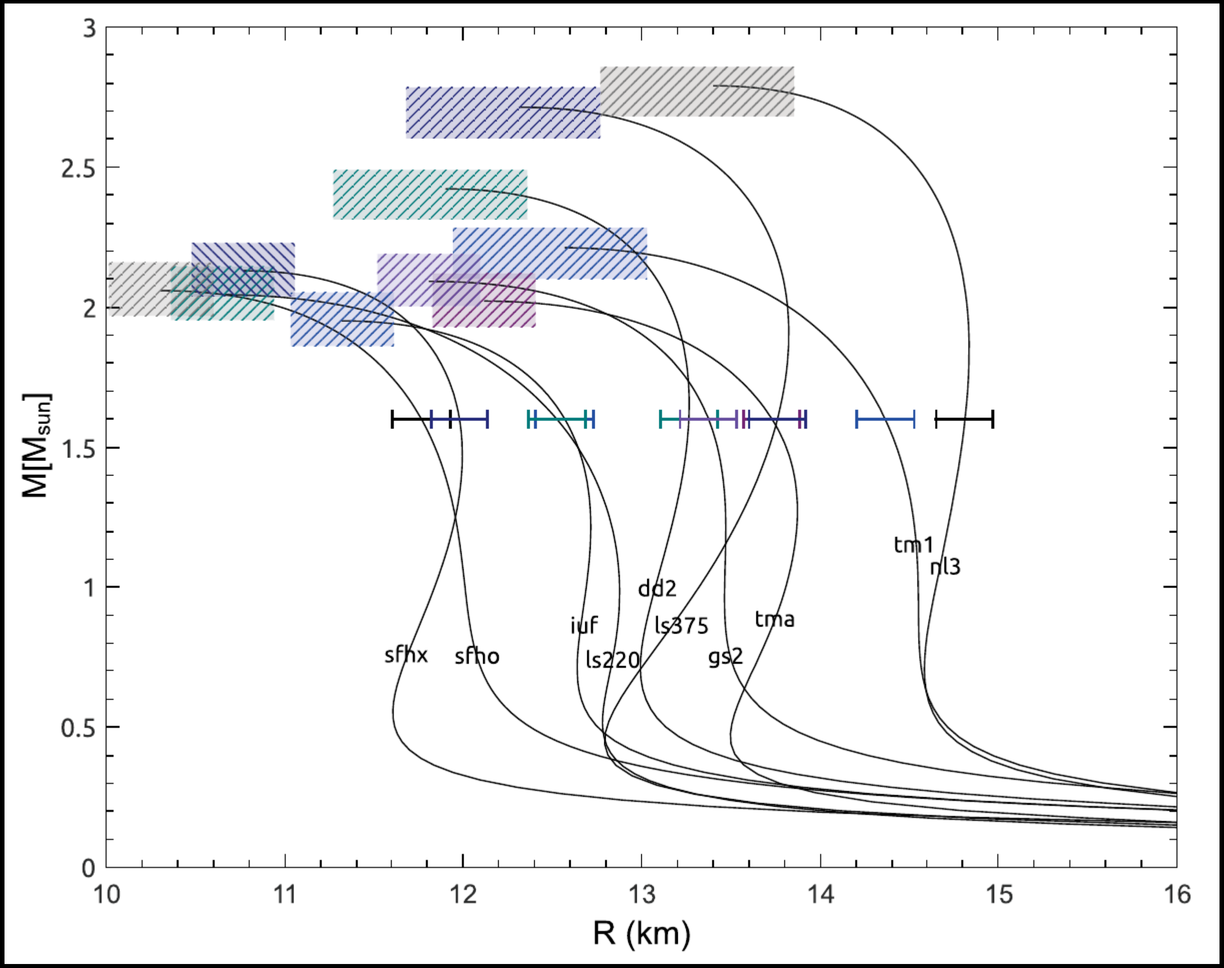
Dominant GW frequency monotone function of M_{tot}

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

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

Maximum-mass TOV properties →

by extrapolation of f_{peak} (M_{tot}



← Radius at lower masses from f_{peak}

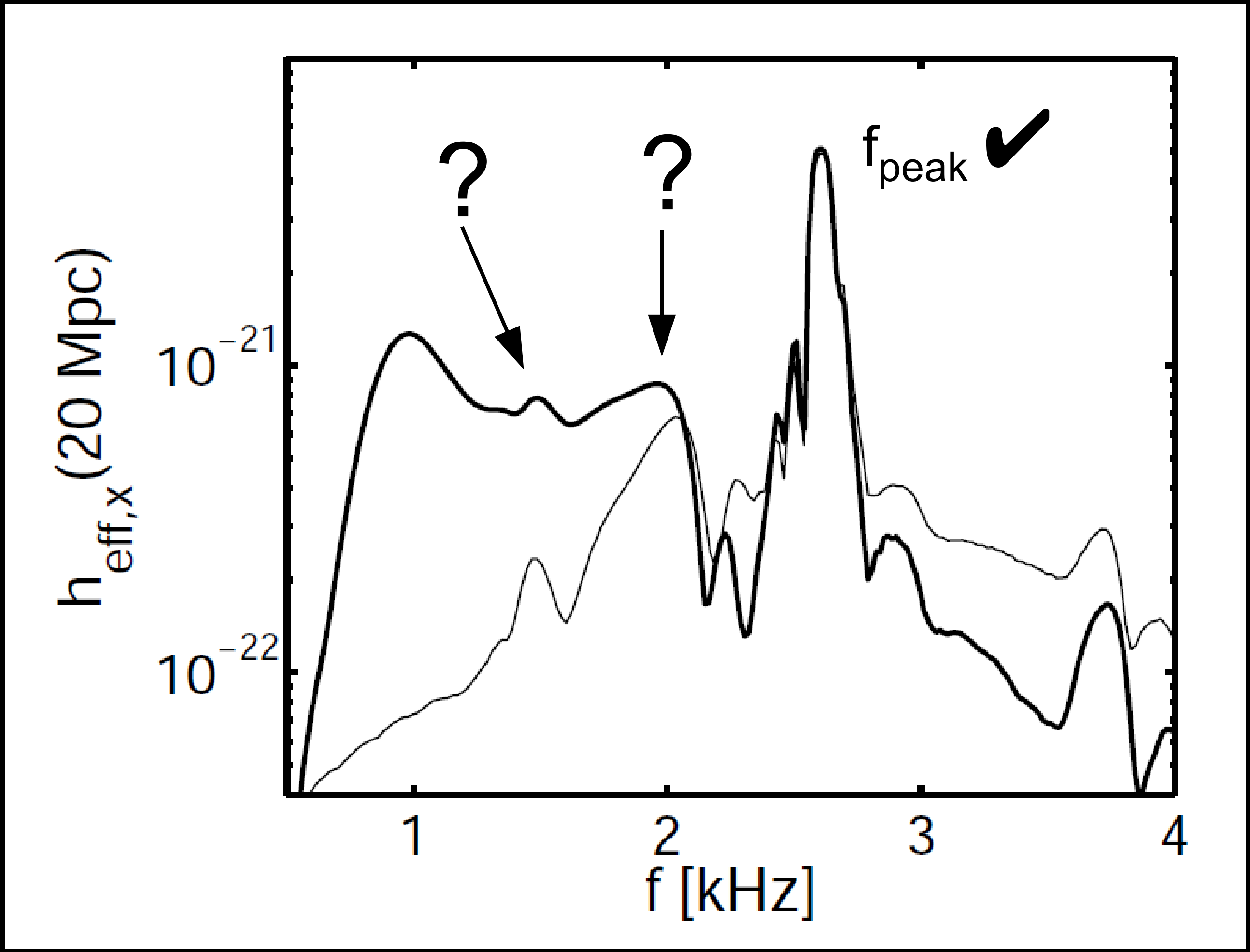
(final error will depend on EoS and extact systems measured)

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

Bauswein et al. 2014

Outlook:
GW astereoseismology

Generic GW spectrum

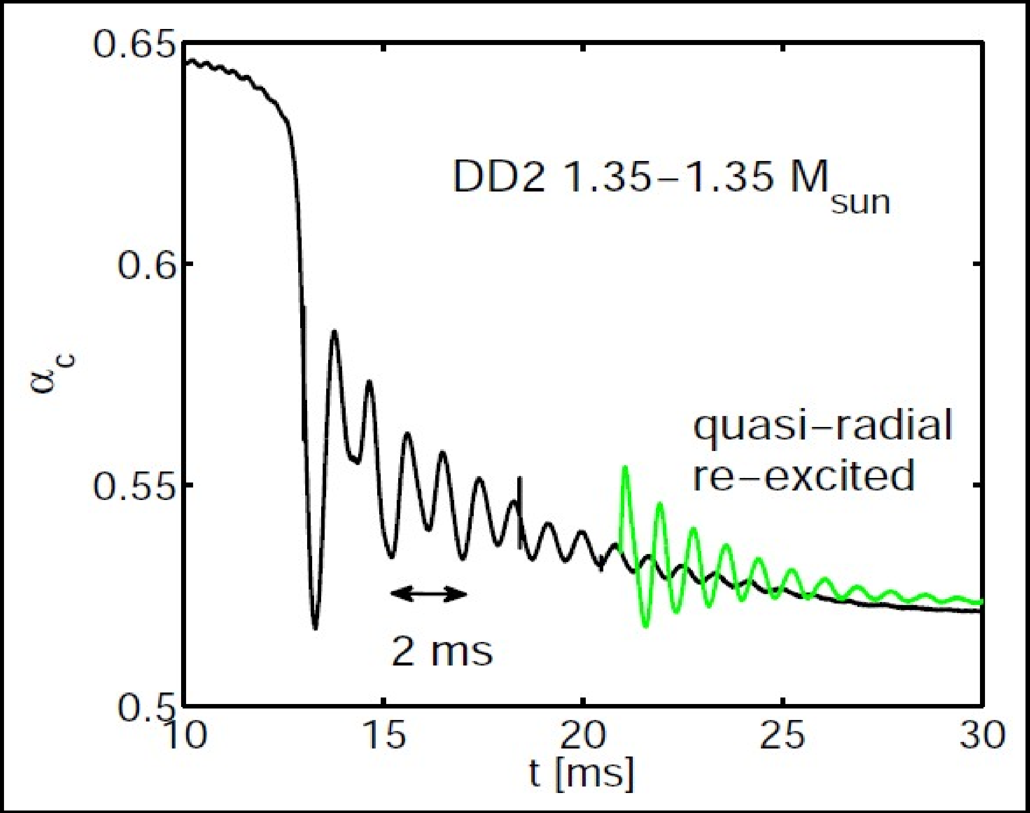


- Up to three pronounced features in the postmerger spectrum (+ structure at higher frequencies)
- 1.35-1.35 Msun DD2 EoS

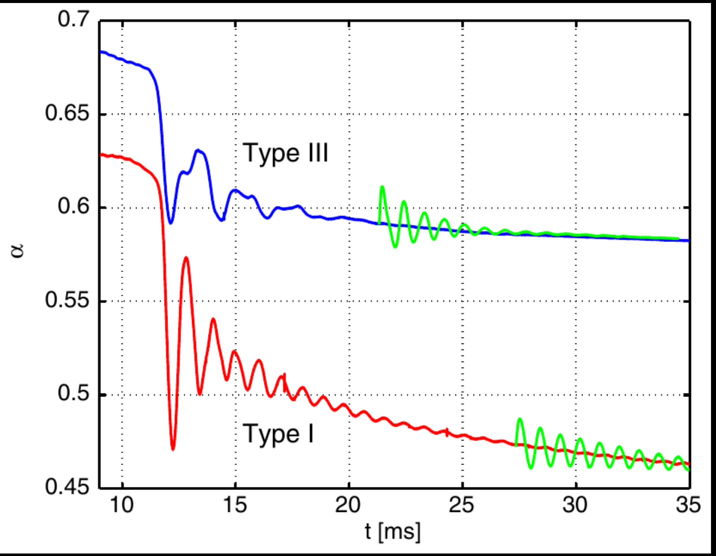
Interpretation and exact dependencies of secondary frequencies still under debate (cf. Frankfurt group)

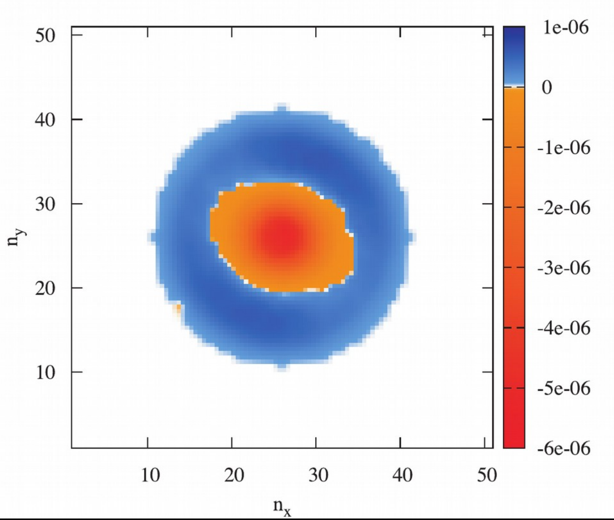
Quasi-radial mode

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



Bauswein et al. 2015



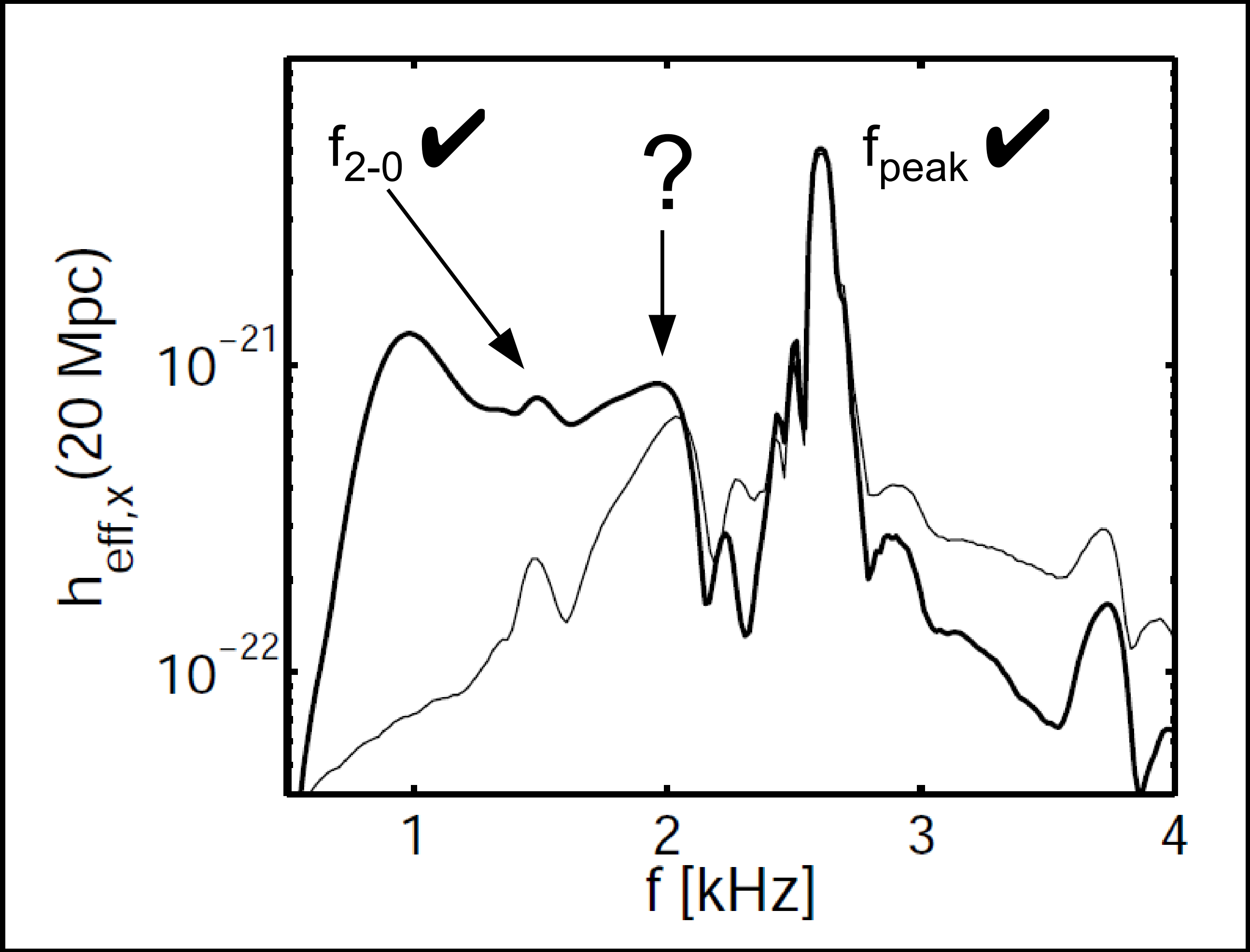


Stergioulas et al. 2011

Could consider also size of the remnant, rhomax, …

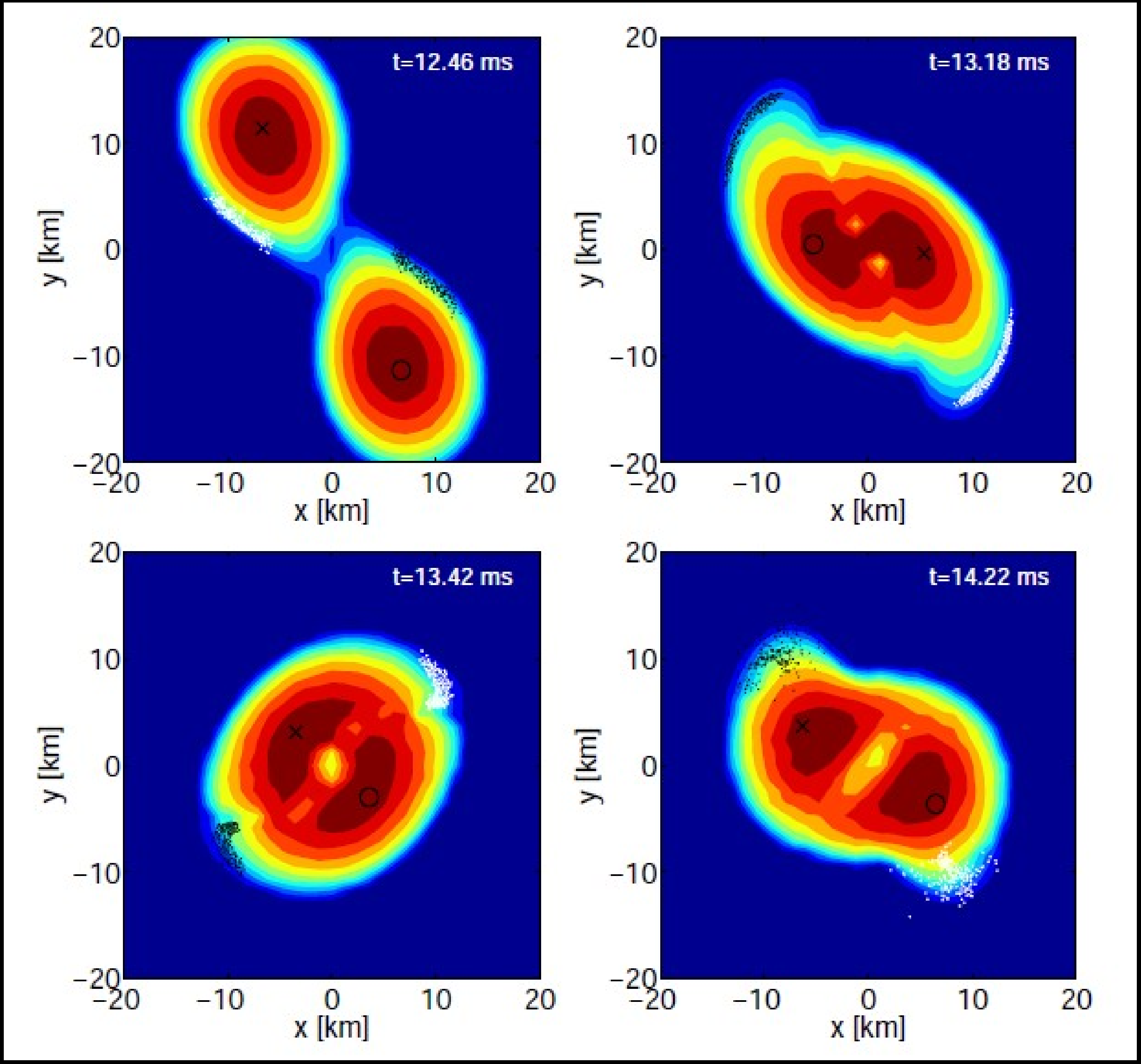
Note: additional low-frequency oscillation (500 Hz) also in GW amplitude (explained later)

Generic GW spectrum



- Interaction between dominant quadrupolar mode and quasi-radial oscillation produced peak at $f_{2\text{-}0} = f_{peak} - f_0$ (see Shibata & Taniguchi 2006, Stergioulas et al. 2011)

Antipodal bulges (spiral pattern)



Bauswein et al. 2015

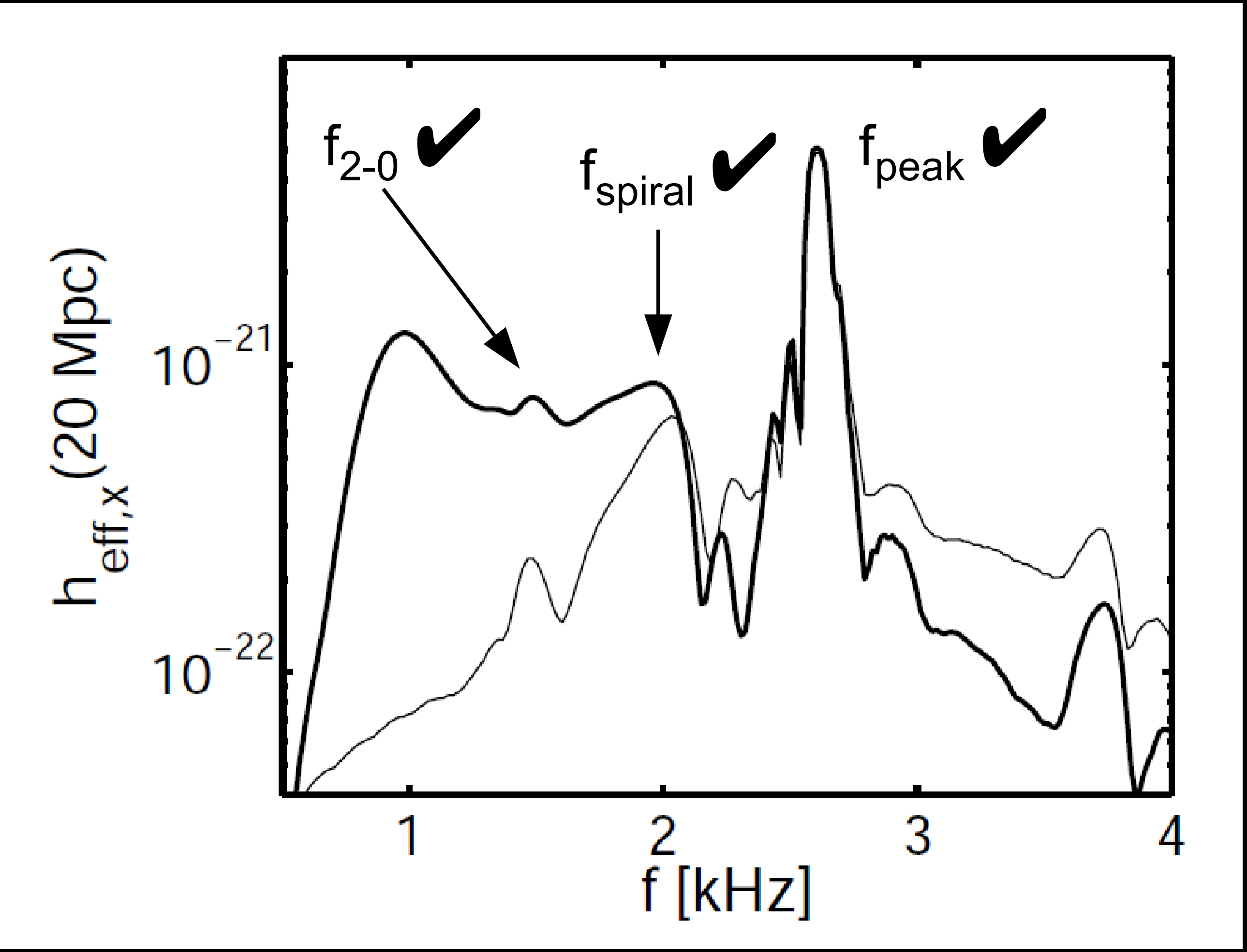
Orbital motion of antipodal bulges slower than inner part of the remnant (double-core structure)

Spiral pattern, created during merging lacks behind

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

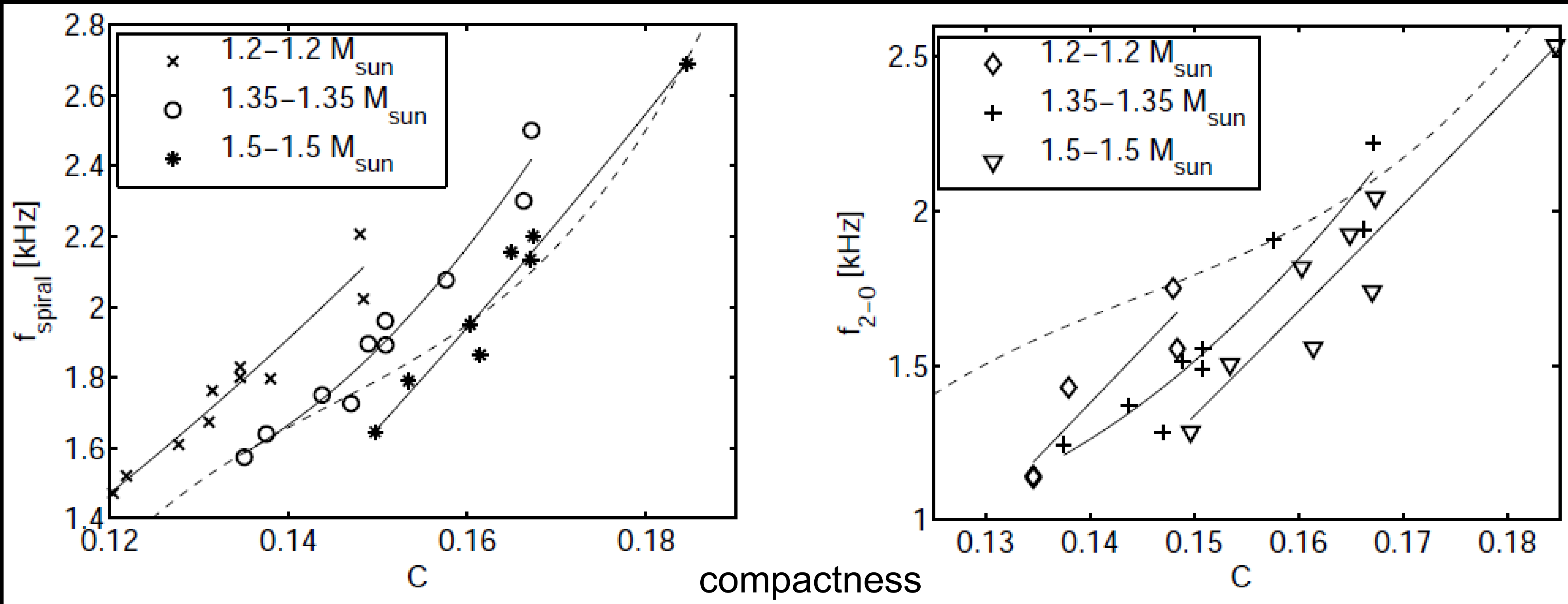
Present for only a few ms / cycles

Generic GW spectrum



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

Different binary masses



Bauswein et al. 2015

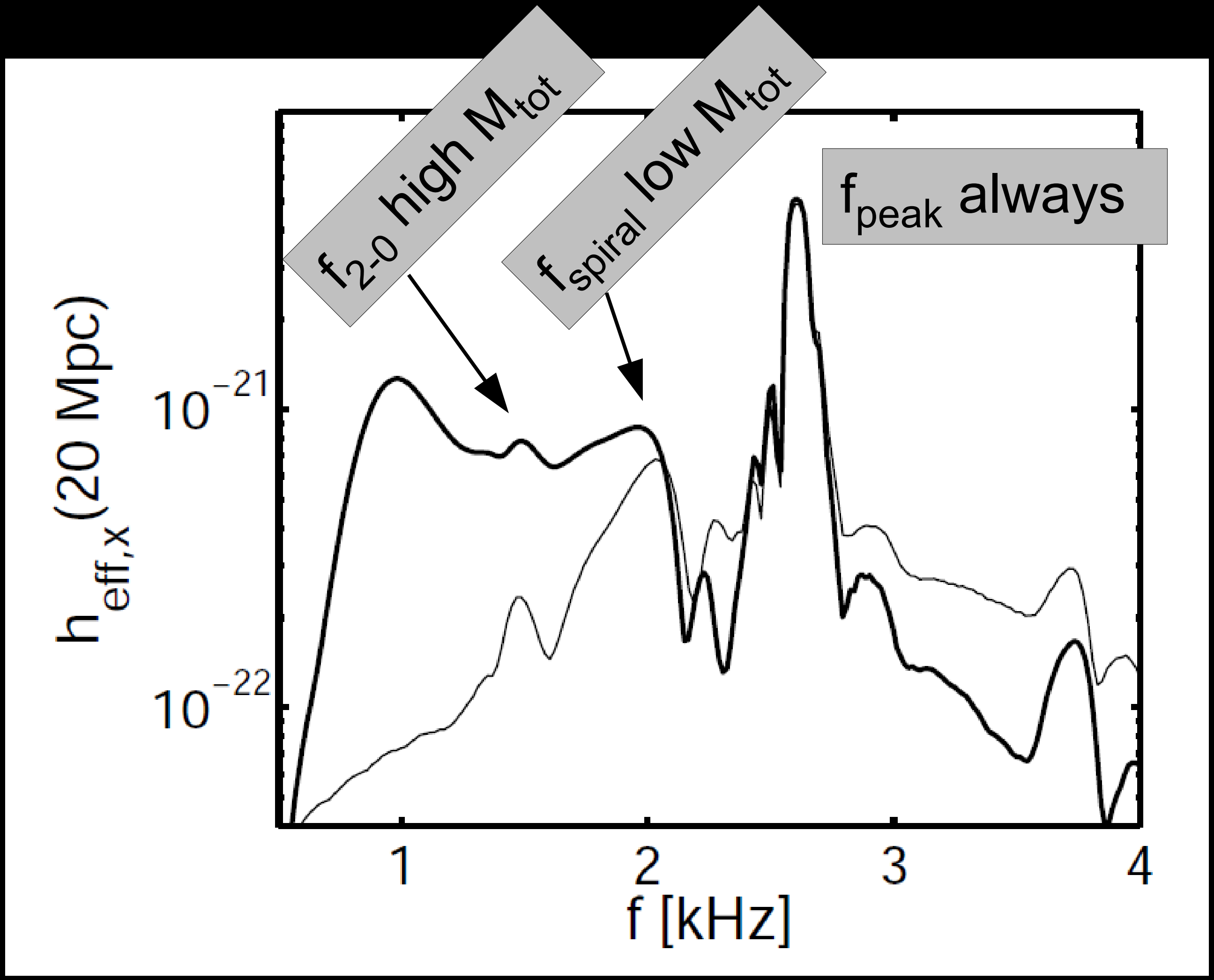
Dashed line from Takami et al. 2014

- 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)
- mass-dependent relations for secondary peaks – not all equally strong!

Secondary peaks

- Strength of secondary peaks leads to classification scheme of postmerger spectra and dynamics → 3 types of spectra
- Origin and dependencies of secondary peaks still under debate
- More features to be identified
- Detection of secondary features challenging

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)

Bauswein & Stergioulas 2015

Summary

- NS mergers are multi-messenger events: r-process nucleosynthesis, kilonovae, short gamma-ray bursts, gravitational waves → highly rewarding
- GWs from NS mergers expected any time
- EoS impact on inspiral
- Dominant postmerger oscillation frequency scales with NS radius → accurate and robust measurements
- GW data analysis ready for the postmerger (still improving)
- Collapse behavior of merger remnant → maximum mass of NSs (+ further properties)
- Secondary peaks towards GW astereoseismology → more details of the EoS