Equation-of-state influence on neutron-star mergers

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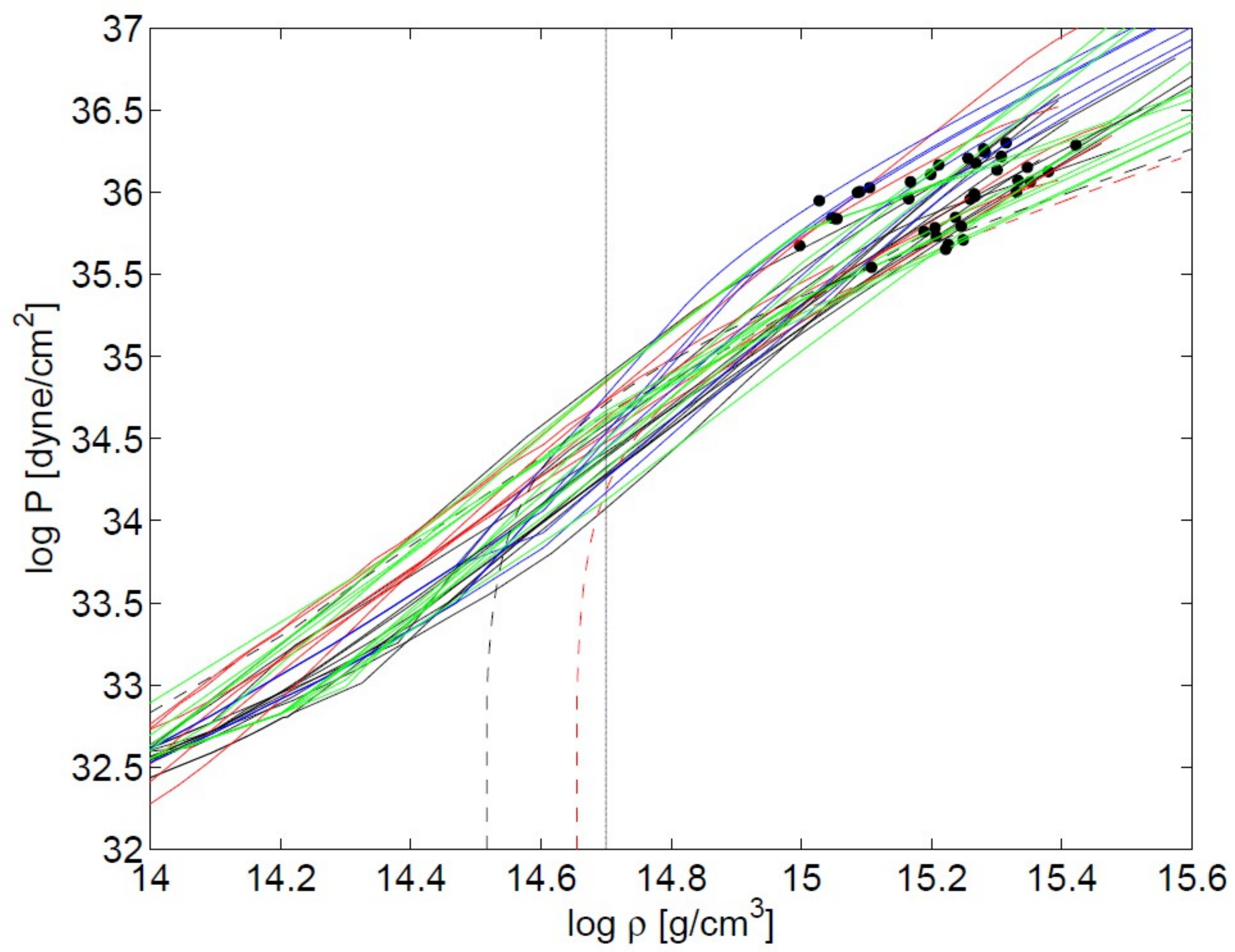
GRAVITATIONAL WAVE ASTRONOMY
GARCHING HANNOVER JENA POTSDAM TÜBINGEN

Outline

- Motivation
- Equation of state of high-density matter and the mass-radius relation of neutron stars
- Code details
- Neutron star mergers: general outcome
- Gravitational waves → Advanced LIGO, Advanced Virgo
- Results: equation of state dependence of the GW signal
- Interpretation
- Summary and conclusions

Equation of state of high-density matter



Beta equilibrium, zero temperature

Motivation

Equation of state of high-density matter only incompletely known

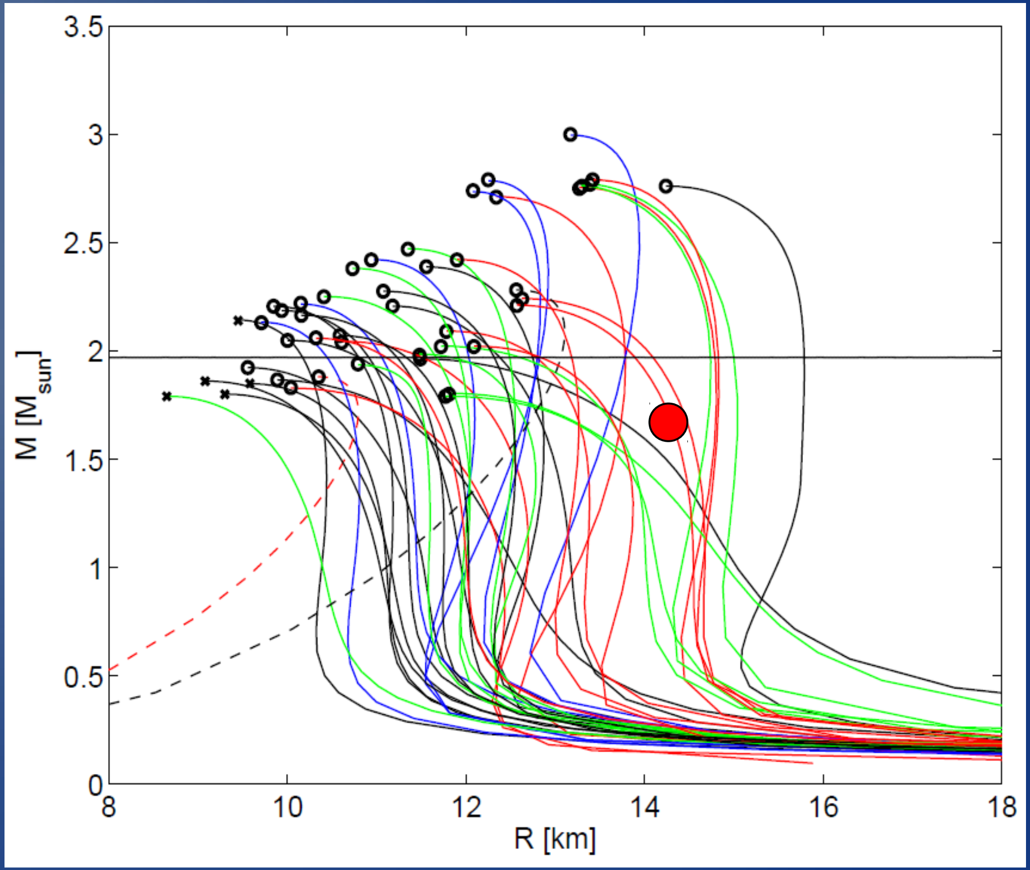
→ neutron star properties unknown

→ survey of EoS dependence of neutron-star mergers

→ measure EoS from gravitational-wave signal of neutron-star mergers

→ **functional dependence !!!!**

EoS ← TOV eqs. → M-R relation

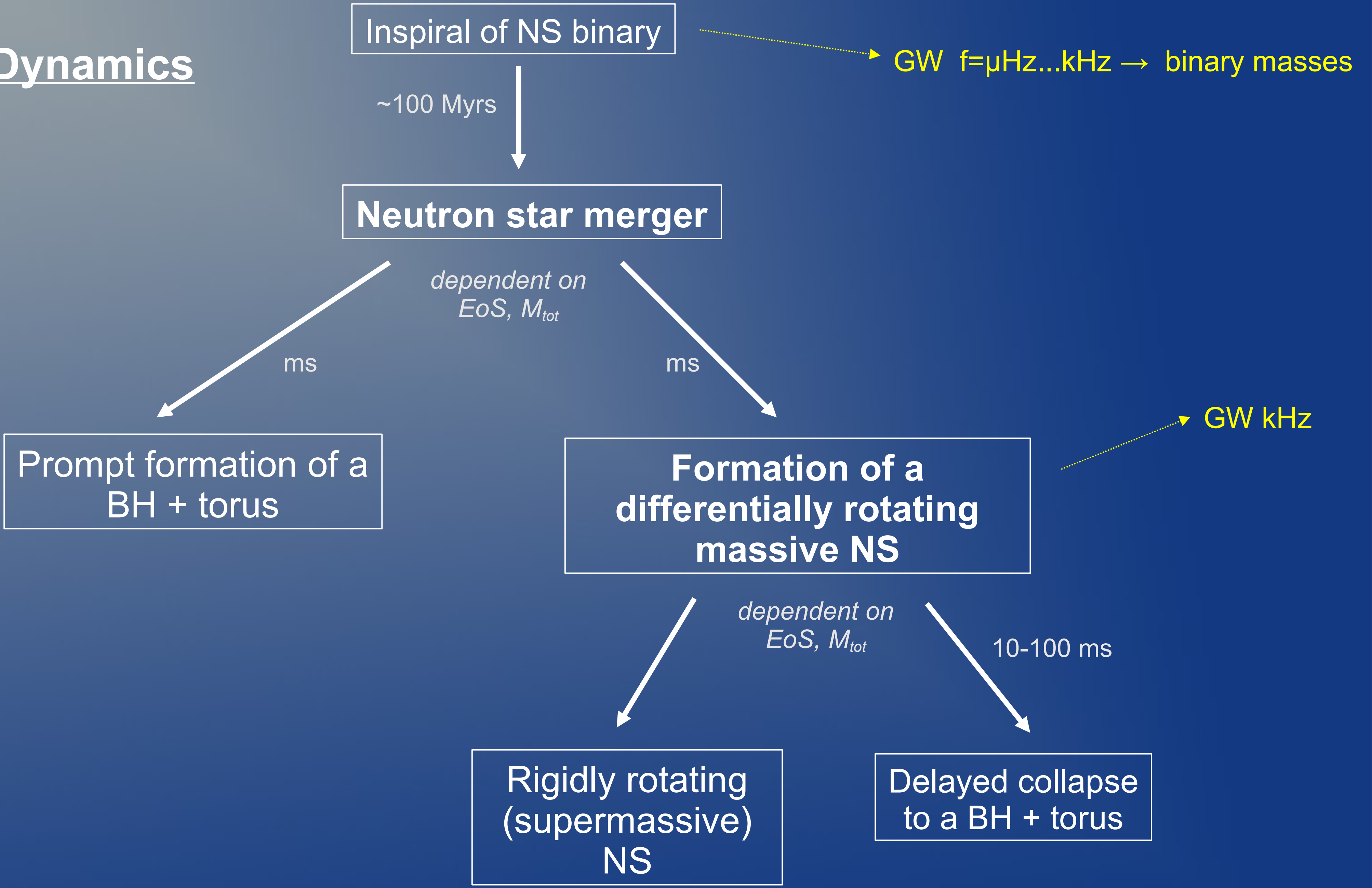


Horizontal line: 1.97 M_{sun} (Demorest et al. 2010)

Code details

- 47 microphysical EoS (12 include thermal effects consistently), including two strange quark matter EoSs (distinguishable by other observational features)
- without any selection procedure
- 3D Relativistic Smooth Particle Hydrodynamics
- spatial conformal flatness (+ postNewtonian backreaction)
- from quasi-equilibrium oribt about three revolutions before merging
- inially cold neutron stars in neutrinoless beta-equlibrium
- nonrotating velocity profile
- default resolution of 340,000 SPH particle

Dynamics



Inspiral of NS binary

GW f=μHz...kHz → binary masses

~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

GW kHz

dependent on EoS, M_{tot}

10-100 ms

Rigidly rotating (supermassive) NS

Delayed collapse to a BH + torus

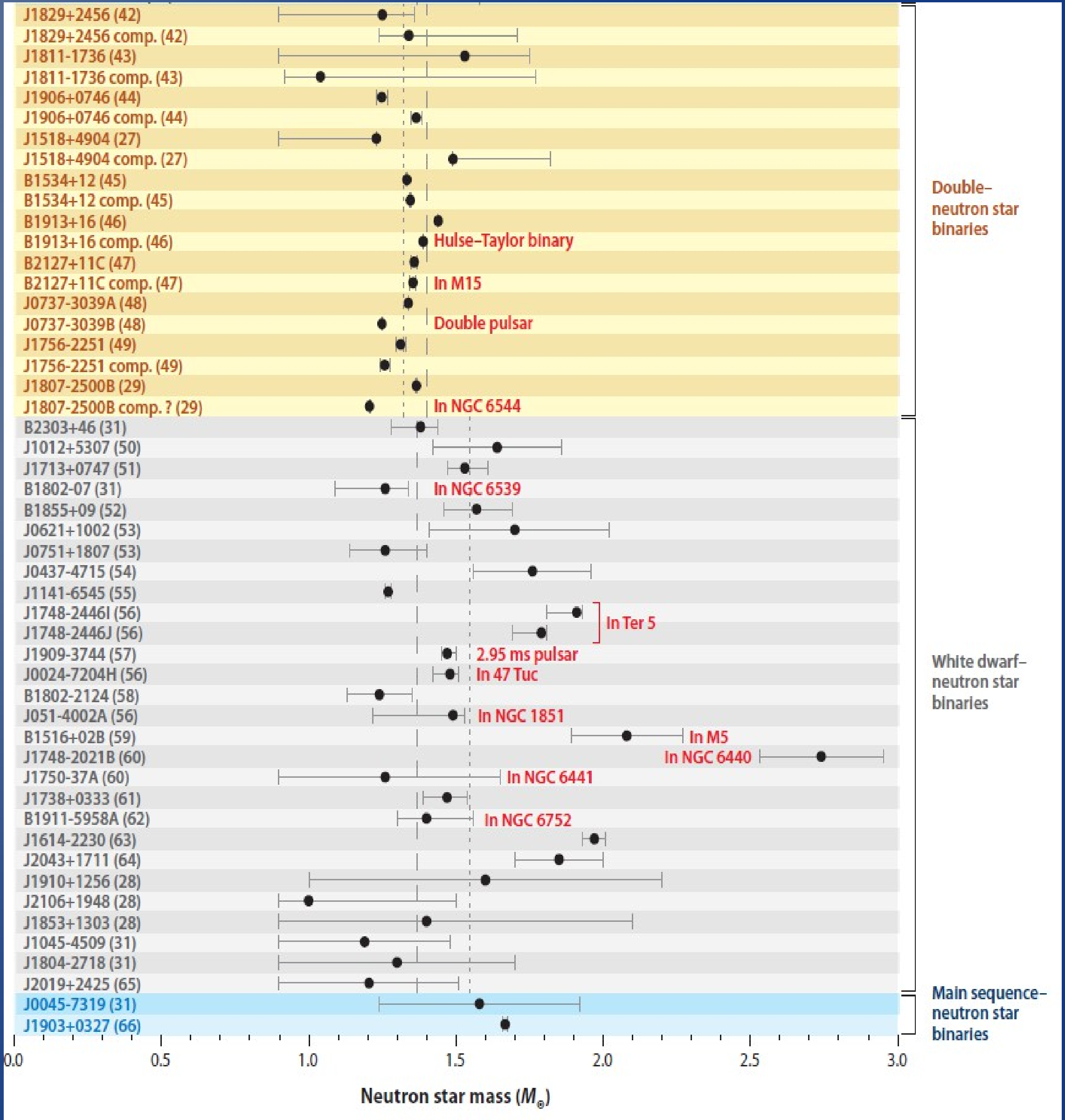
Expected binary parameters

Observations suggest:

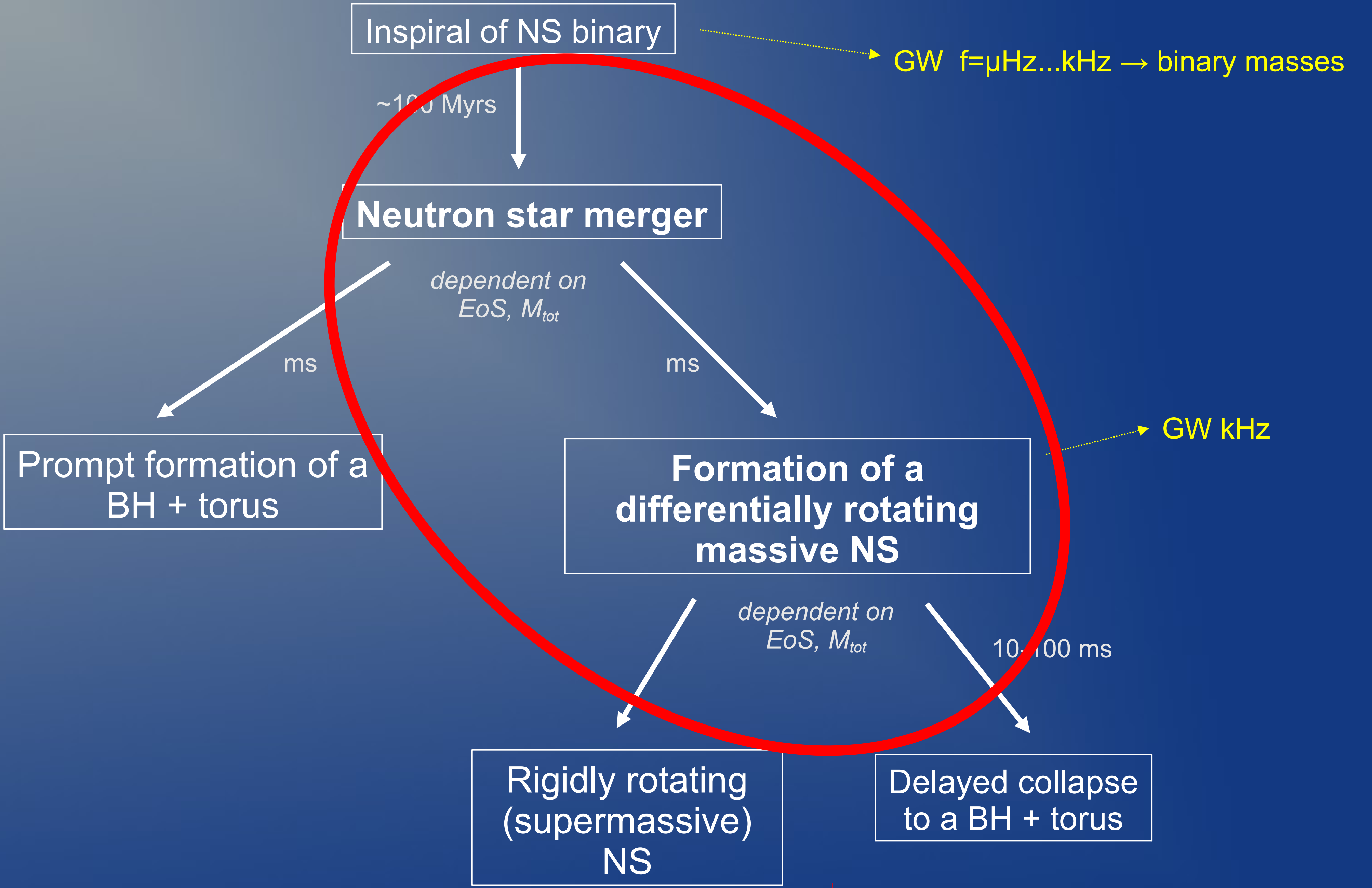
~ equal-mass binaries with $M_{tot} \approx 2.6\ M_{sun}$ most abundant in binary population

(in agreement with population synthesis studies)

=> focus on 1.35-1.35 M_{sun}



Lattimer 2012



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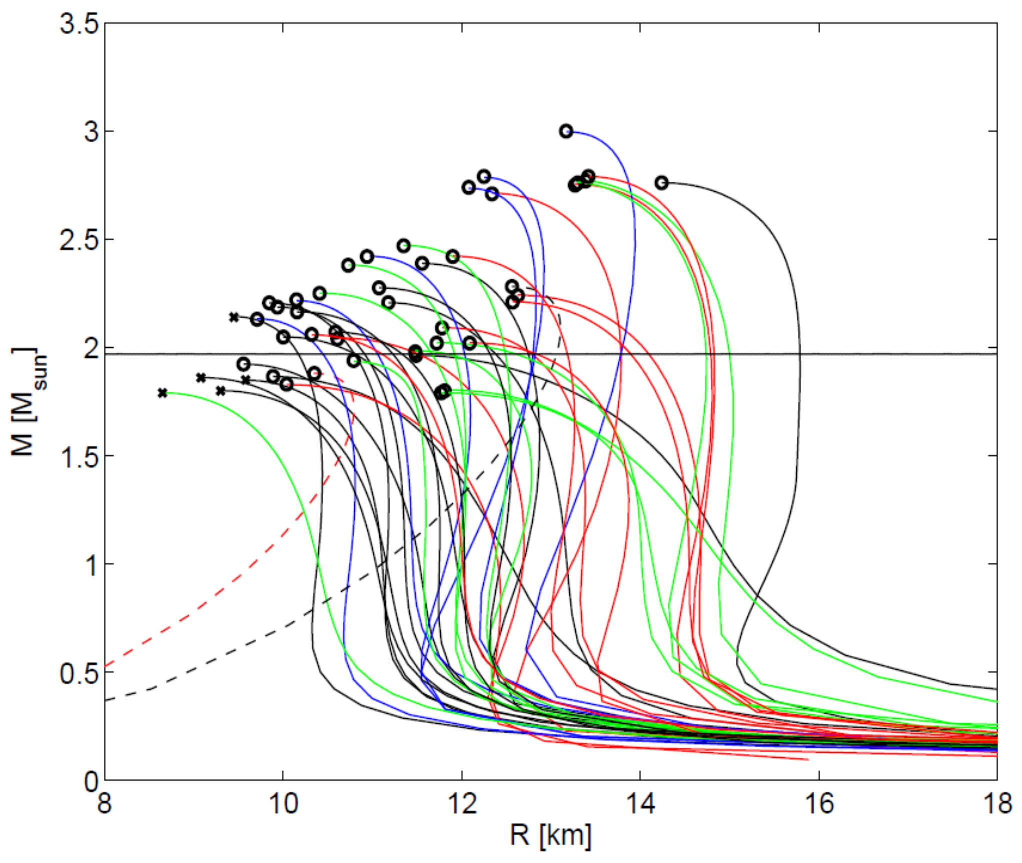
- Movie 1.2-1.35 (Temperature)

Movie 1.35-1.35 (density, equatorial plane)

General outcome

for 1.35-1.35 M_{sun} binaries

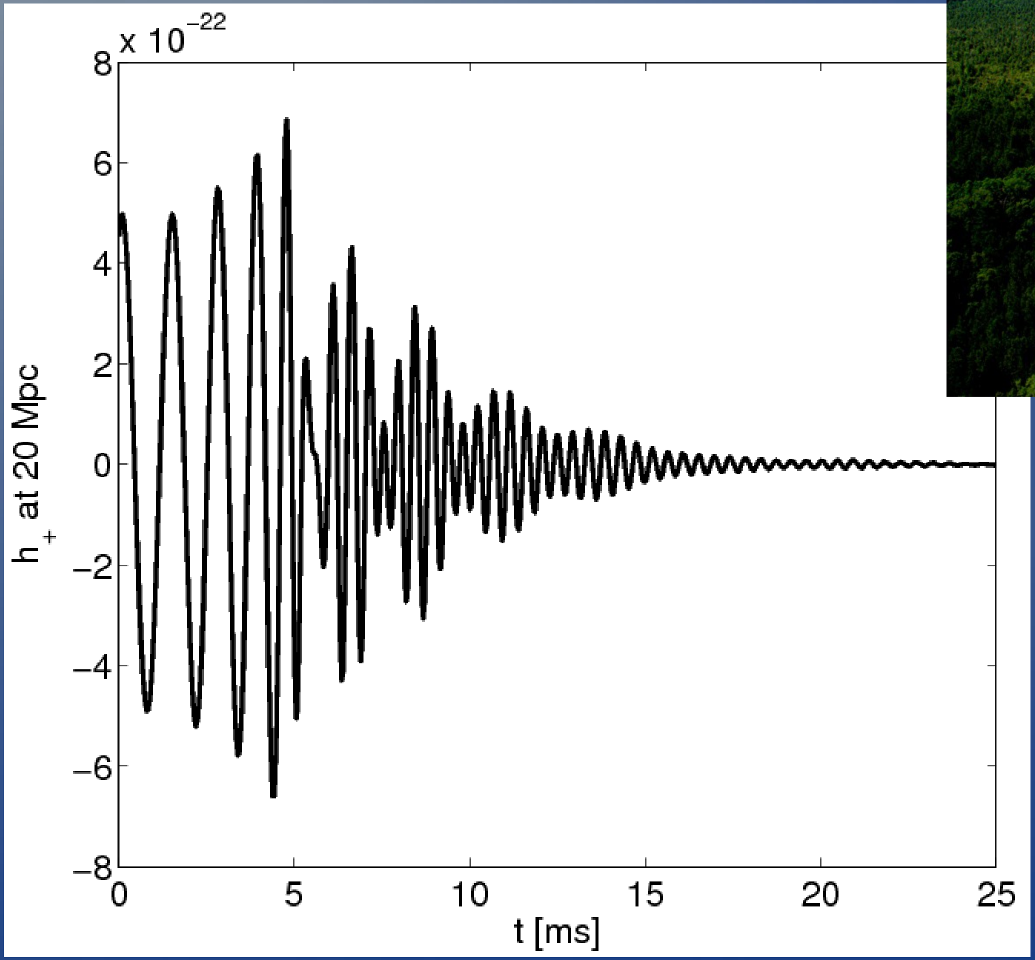
(most abundant according to population synthesis studies)



42 out of 47 models lead to the formation of a differentially rotating object

Gravitational-wave amplitude

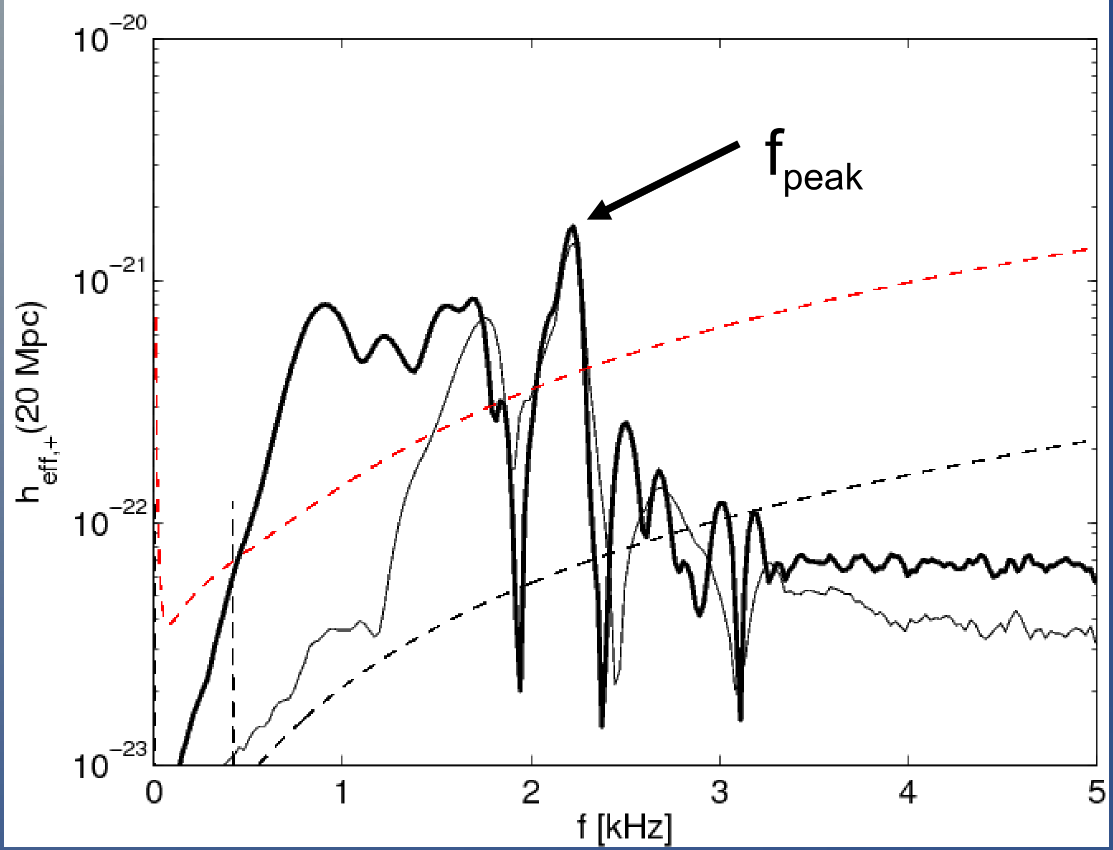
via quadrupole formula



Advanced LIGO

1.35-1.35 M_{sun}, Shen EoS

Gravitational-wave spectra



Sensitivity curves:

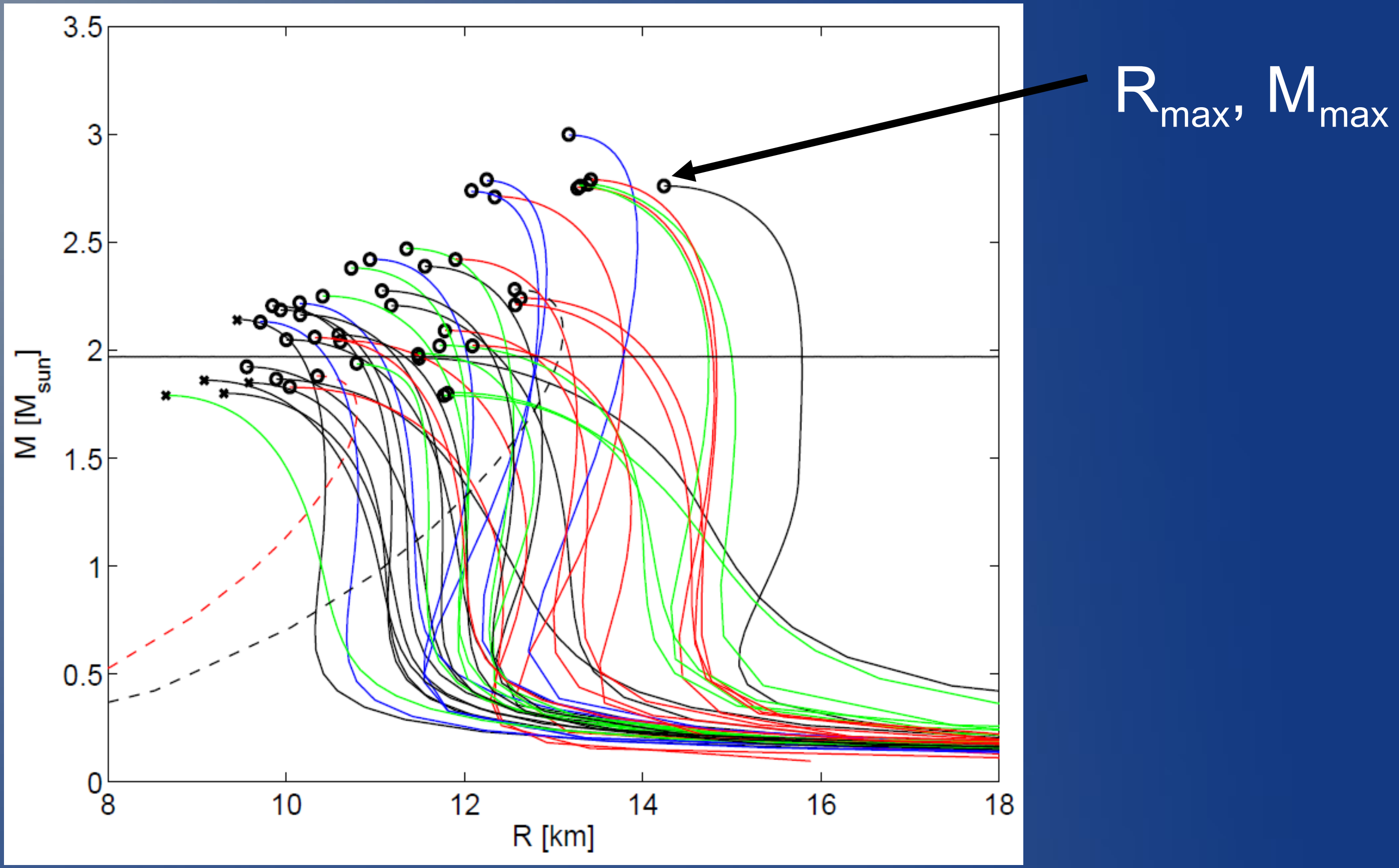
Red dashed:
Advanced LIGO

Black dashed:
Einstein Telescope

thick line: full signal
thin line: postmerger signal

- Pronounced peak in the kHz range as a robust feature of all models forming a differentially rotating NS

Connect EoS and GW signal:



Mass-radius relations of nonrotating neutron stars

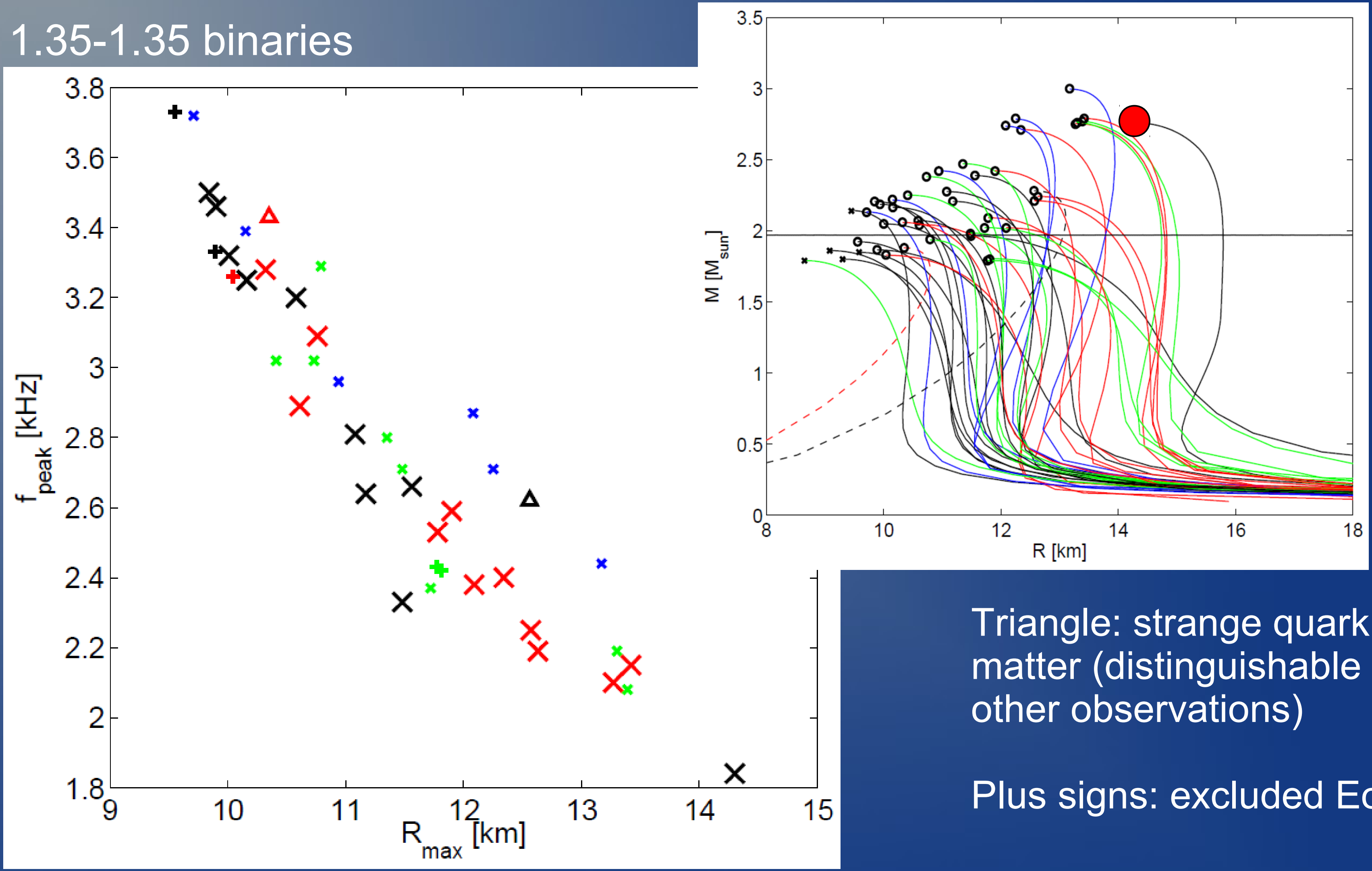
Stellar parameters of nonrotating NSs = integral EoS property

Candidate EoS cover the full range of stellar parameters for all EoS 1.35-1.35 M_{sun} binaries:

f_{peak} vs. properties of nonrotating NS

Radius of the maximum-mass configuration

1.35-1.35 binaries

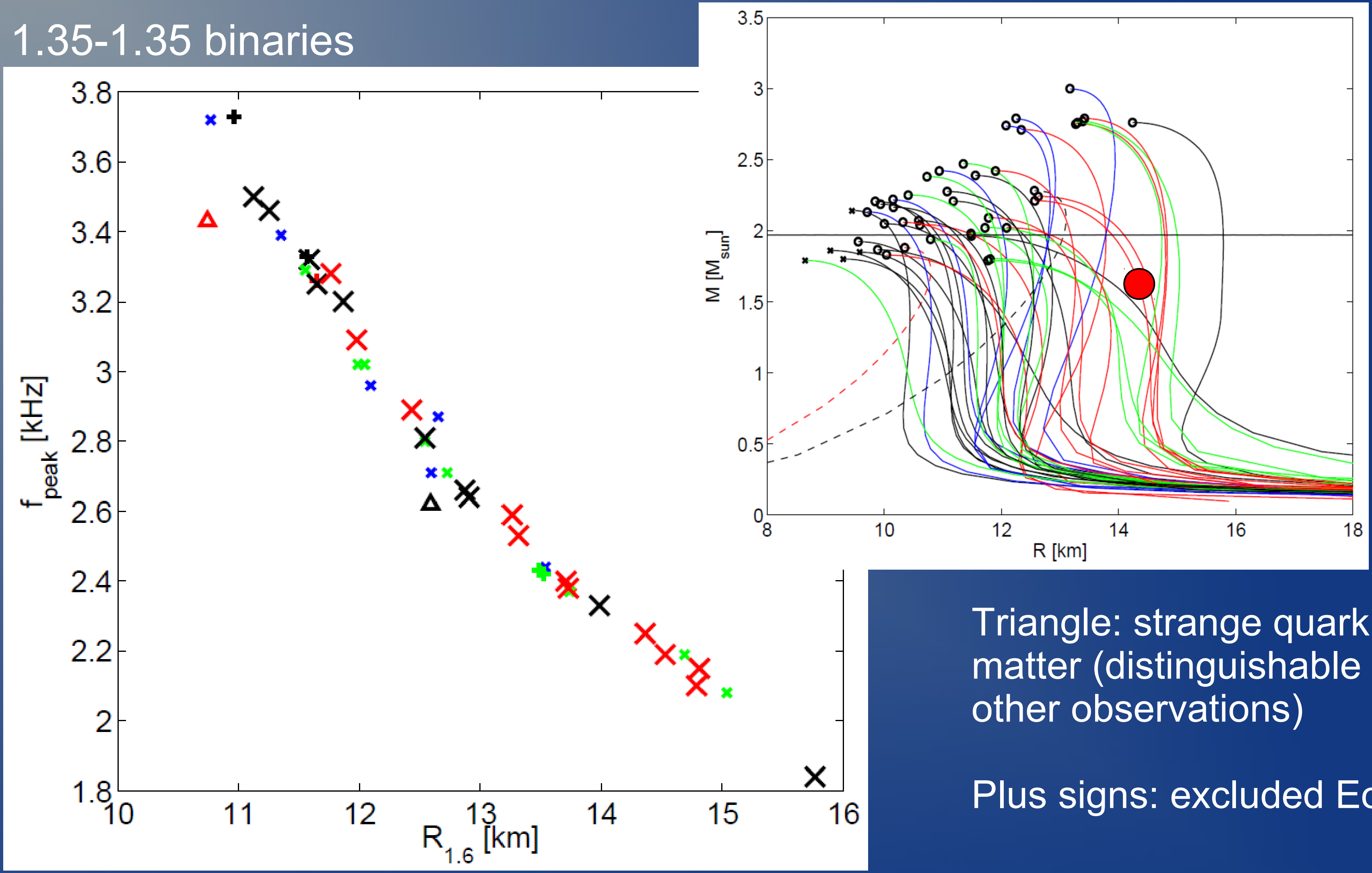


Triangle: strange quark matter (distinguishable by other observations)

Plus signs: excluded EoSs

Red: temperature dependent EoS, remaining: ideal-gas for thermal effects

Radius of a 1.6 M_{sun} star


1.35-1.35 binaries

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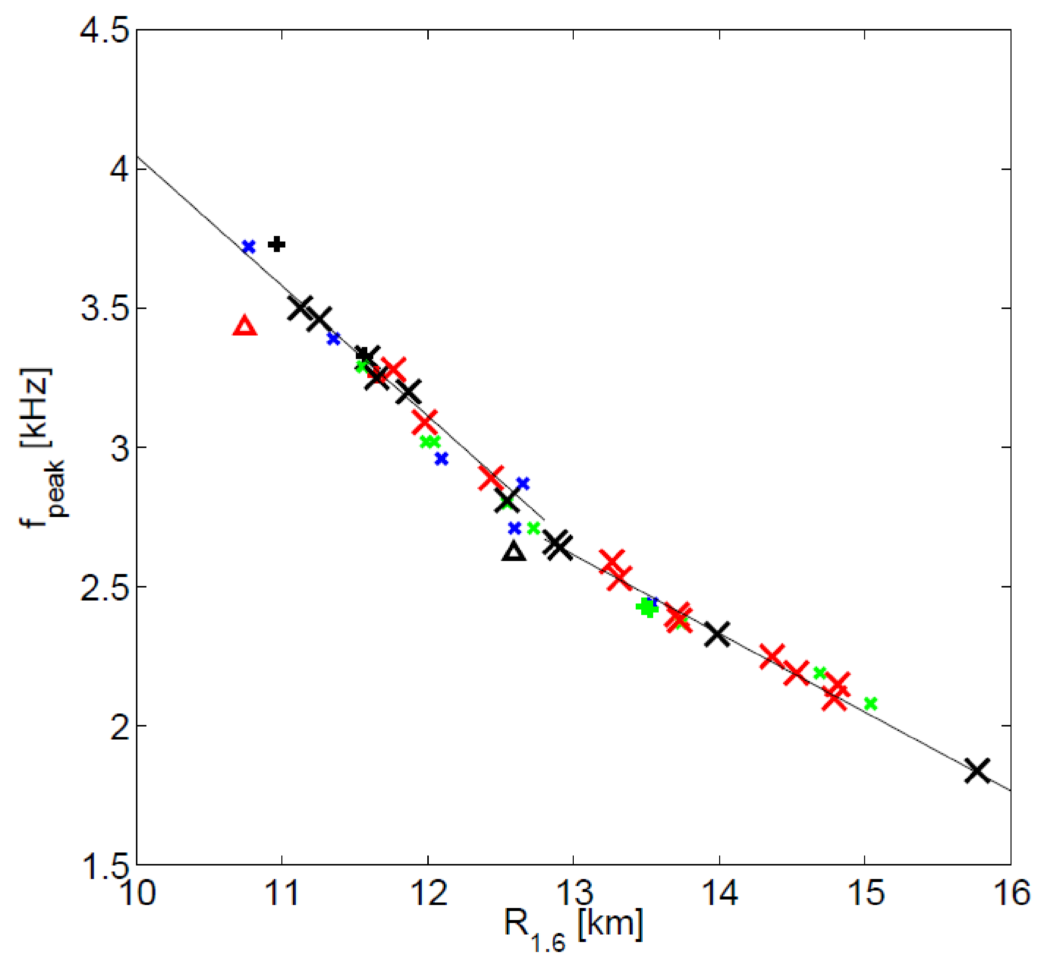
Radius of a 1.6 M_{sun} star



For the accepted models:
Maximum scatter from fit:

~ 100 meters

Triangle: strange quark matter (distinguishable by other observations)

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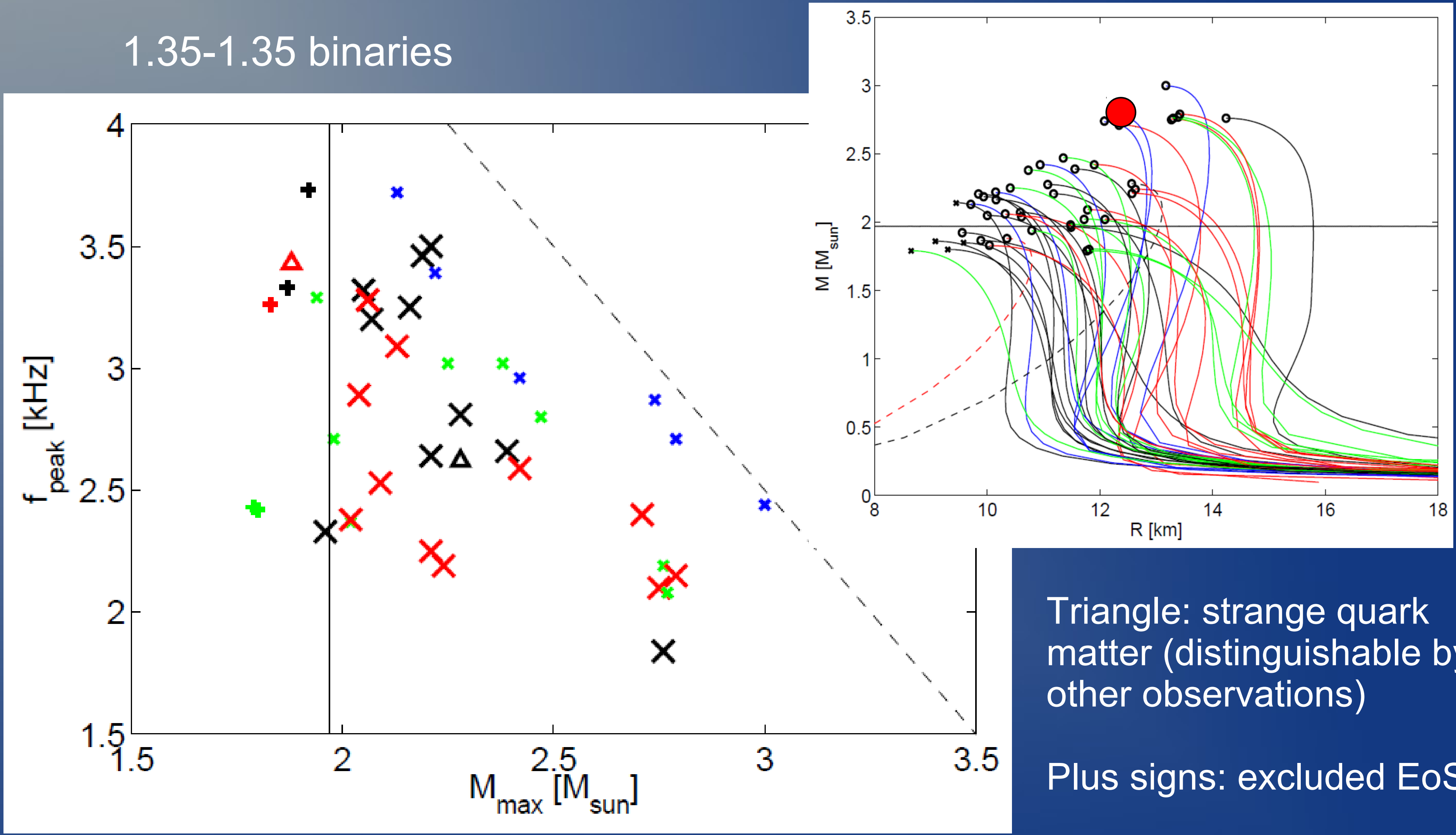
Maximum-mass (of nonrotating NSs)

1.35-1.35 binaries



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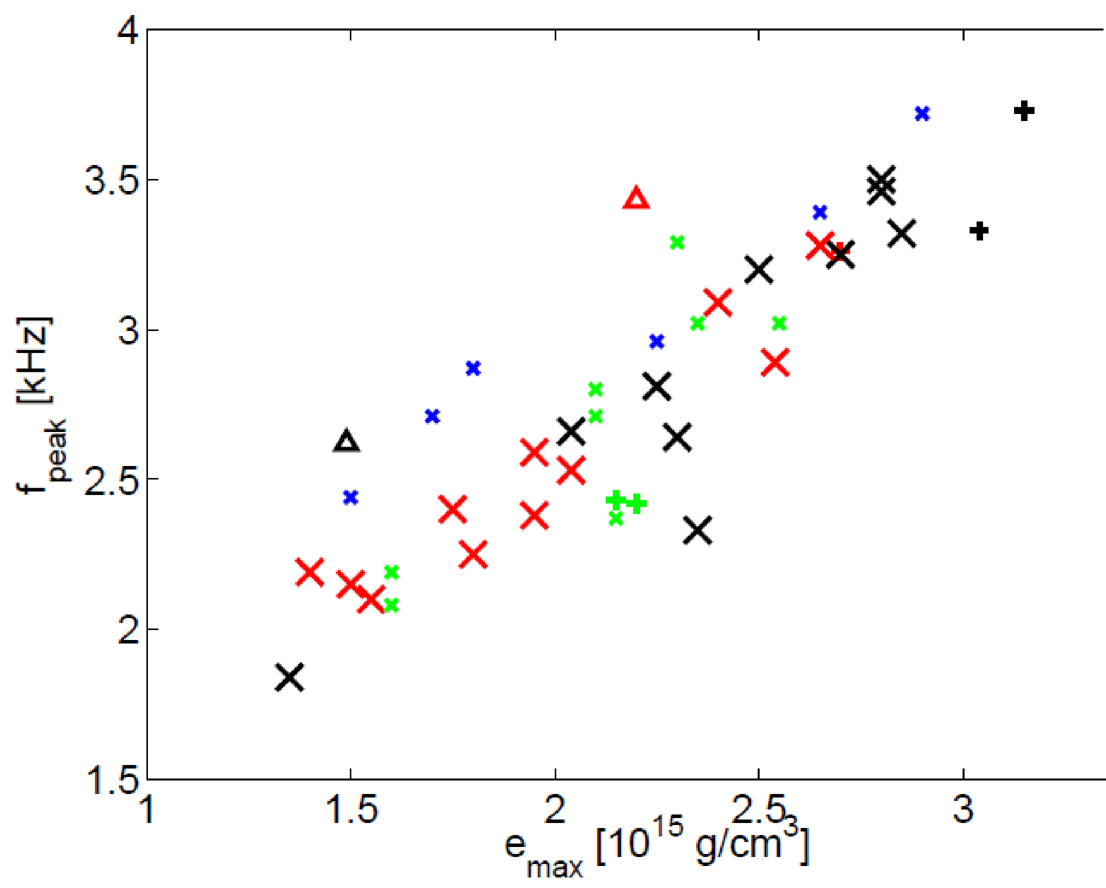
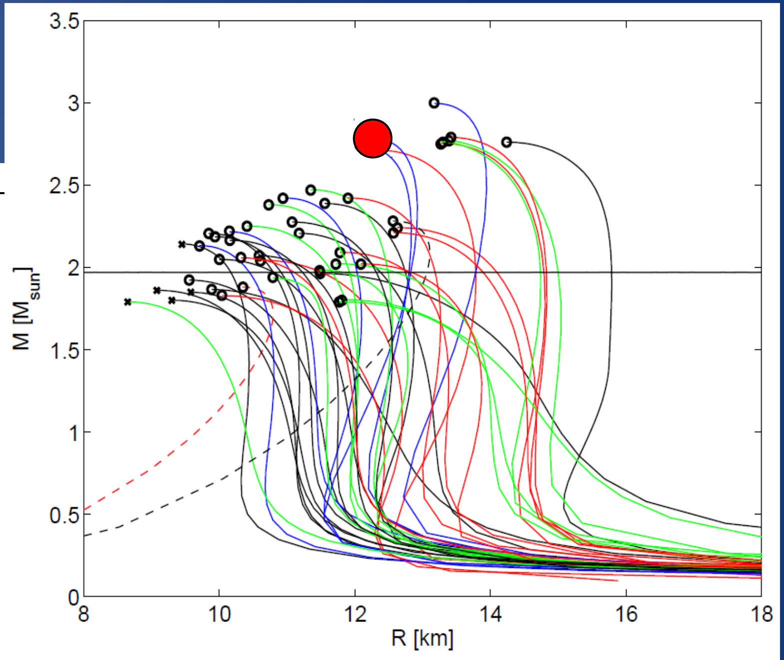
Central density of maximum-mass NS

1.35-1.35 binaries





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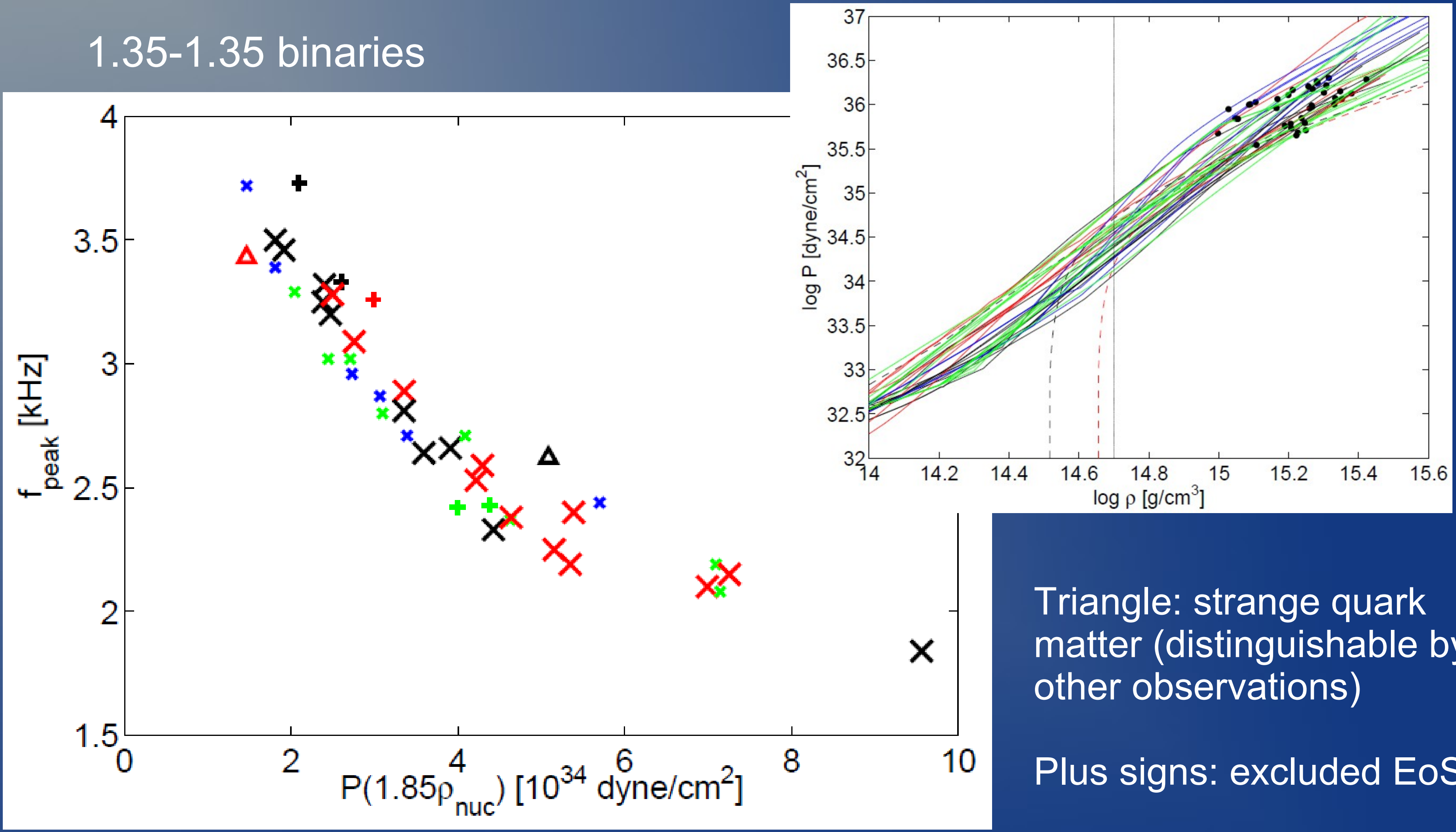
Pressure at 1.85 nuclear density

1.35-1.35 binaries



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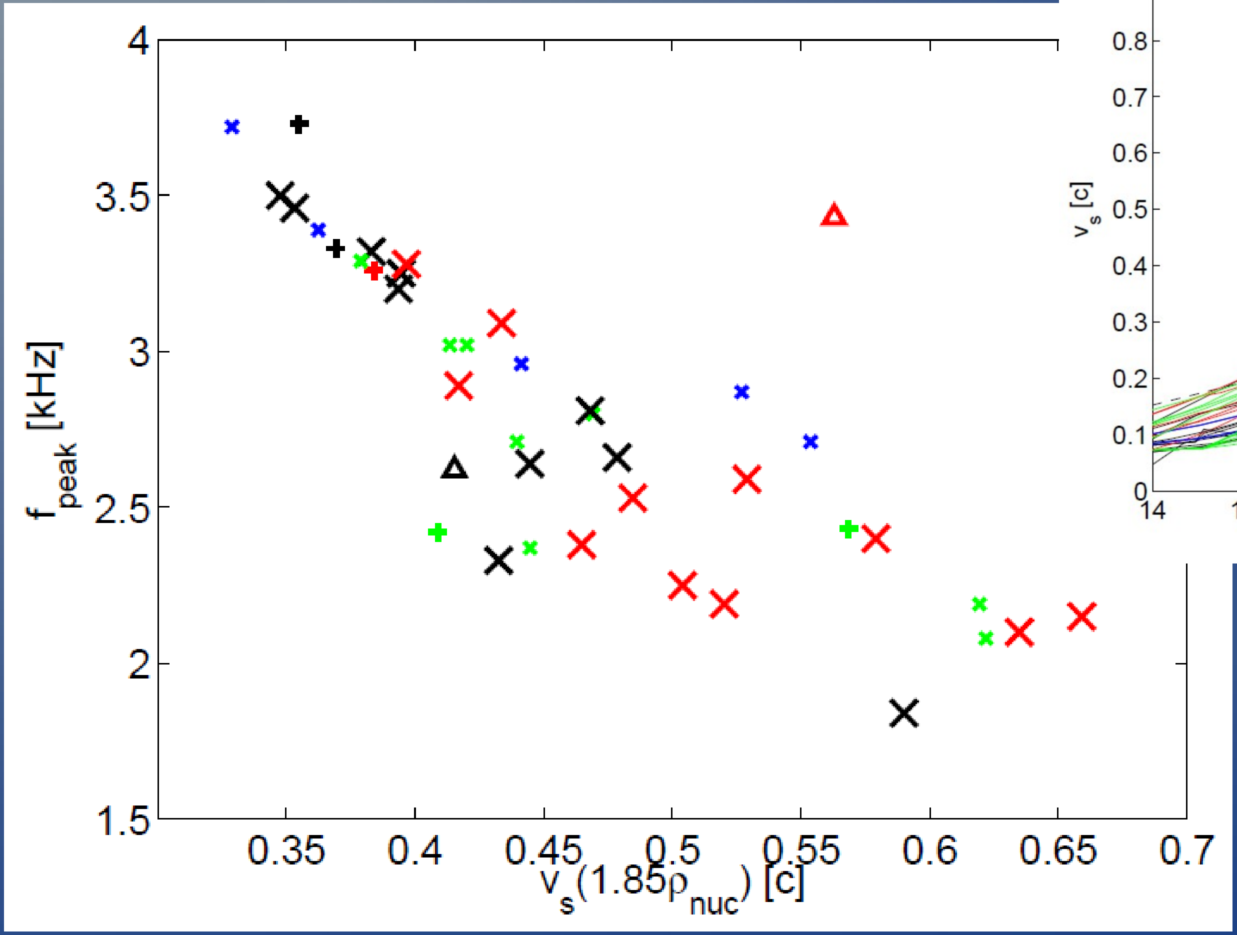
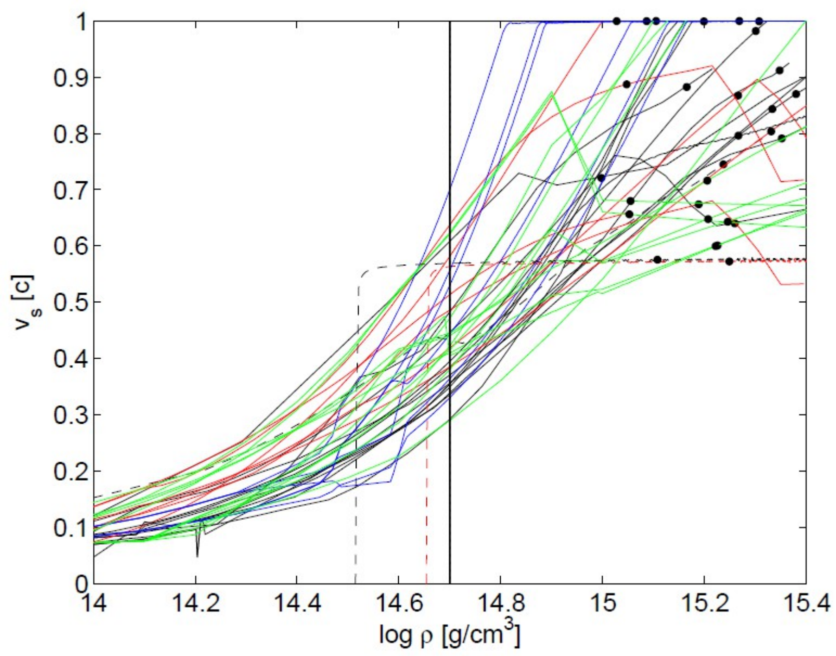
Sound speed at 1.85 nuclear density

1.35-1.35 binaries





Triangle: strange quark matter (distinguishable by other observations)

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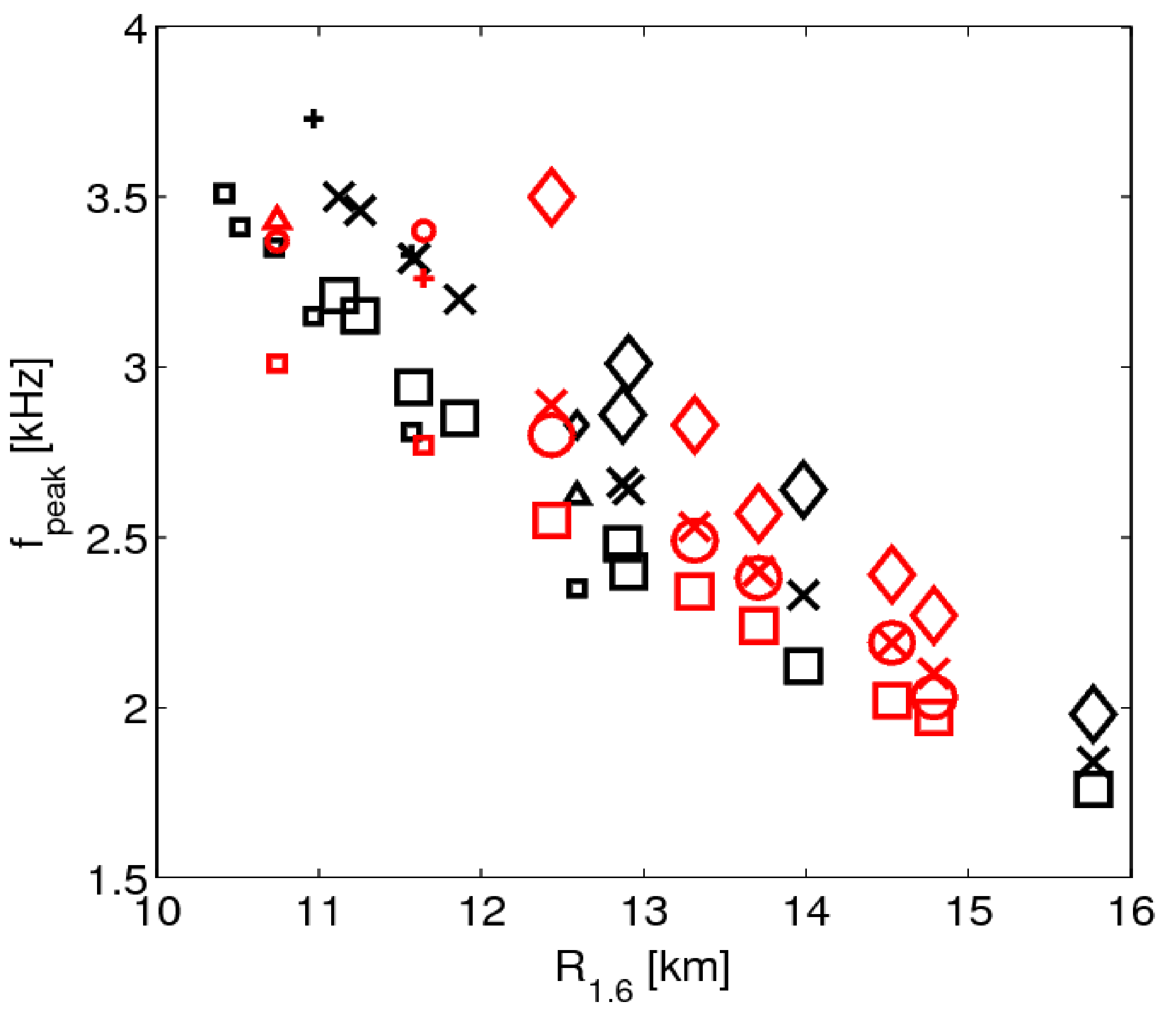
Variation of binary parameter

M_1 and M_2 measurable from GW inspiral signal



Squares: 1.2 - 1.2

Circles: 1.2 – 1.5

Crosses: 1.35 - 1.35

Diamonds: 1.5 - 1.5

(subset of EoSs)

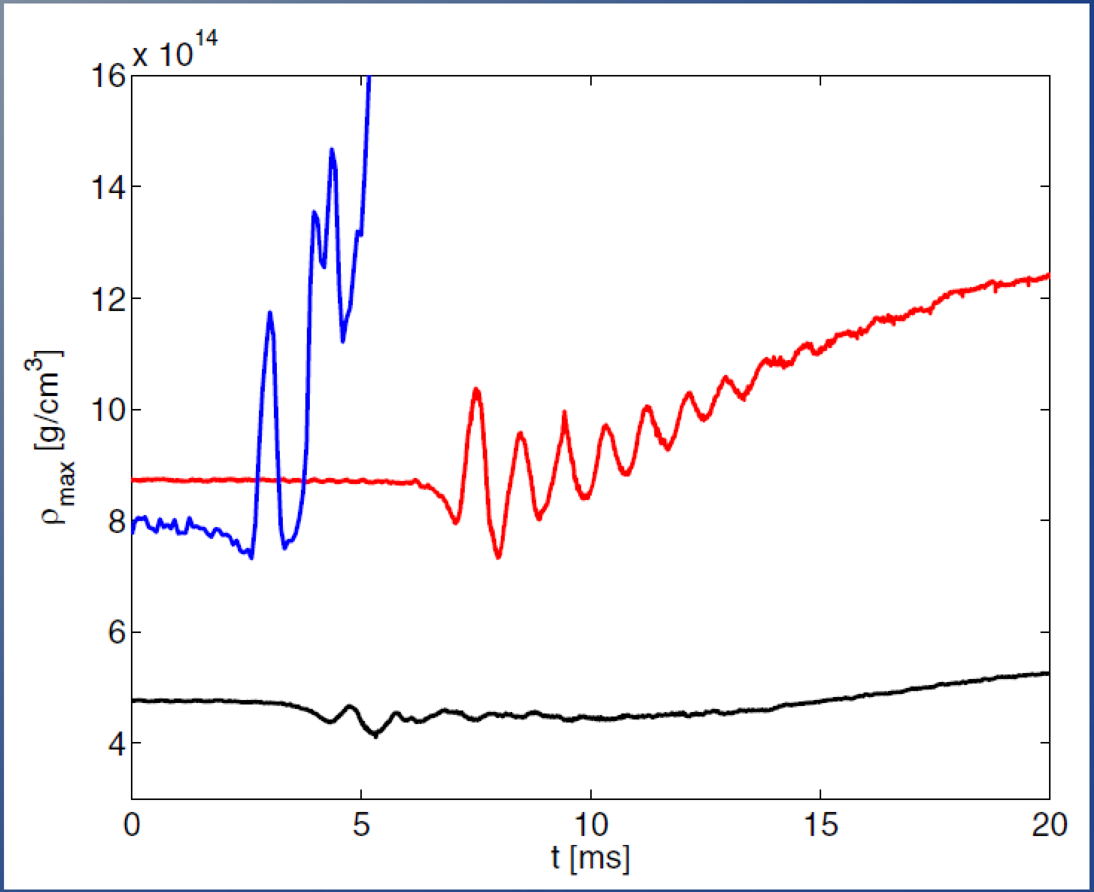
Note: for the different total binary masses different radii of nonrotating NSs represent better choice (involved density regimes)

Evolution of maximum density

Sly4

1.35 M_{sun}

Shen



Remnant ~2.6 M_{sun}

Crucial for usability:

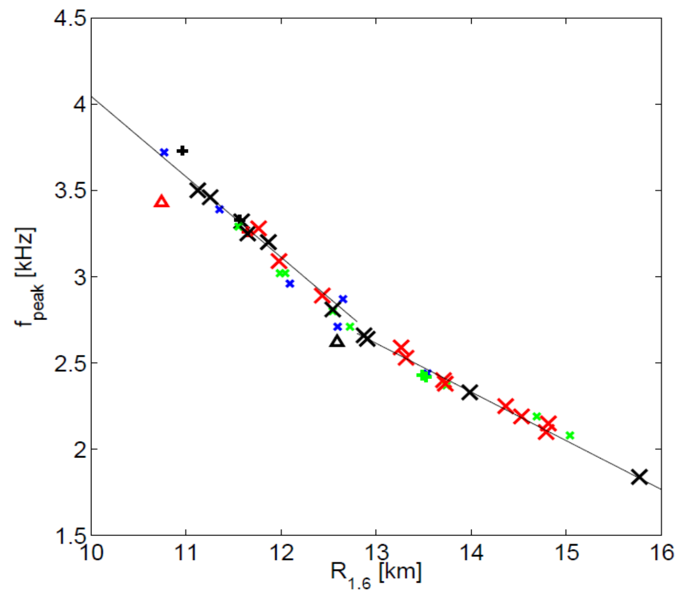
- Out to which distance the postmerger signal can be detected?

→ 20-45 Mpc with Advanced LIGO → 0.01 – 1 events/yr (conservative)

→ much more with late inspiral signal

- To which accuracy f_{peak} can be determined?

→ about 30-50 Hz (from Fisher information matrix)



- (binary masses, merger time, distance … known from inspiral)

Remarks:

- Peak frequency coincides within a few per cent with results of fully relativistic calculations (without trend, depends also on exact implementation of EoS)
- Some EoS might be ruled out by nuclear physics → reduces scatter
- Our method is robust with respect to uncertainties in the determination of the binary masses
- Alternative: EoS from GW inspiral signal: ~1 km accuracy but higher event rate (Read et al. 2009)
- Multiple detections with different total binary masses highly interesting

Why such a scaling?

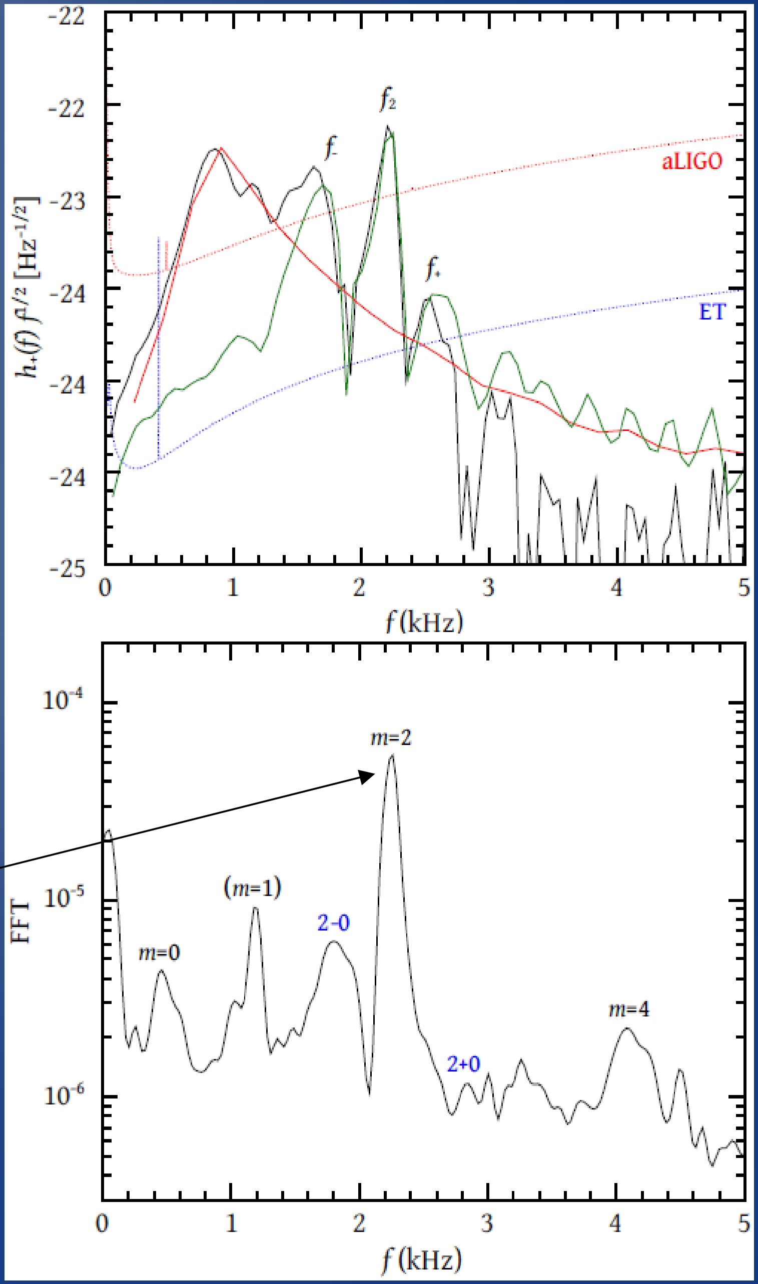
GW spectrum (pre- and post-merger)

1.35-1.35 M_{sun}, Shen EoS

Fourier transform of the pressure

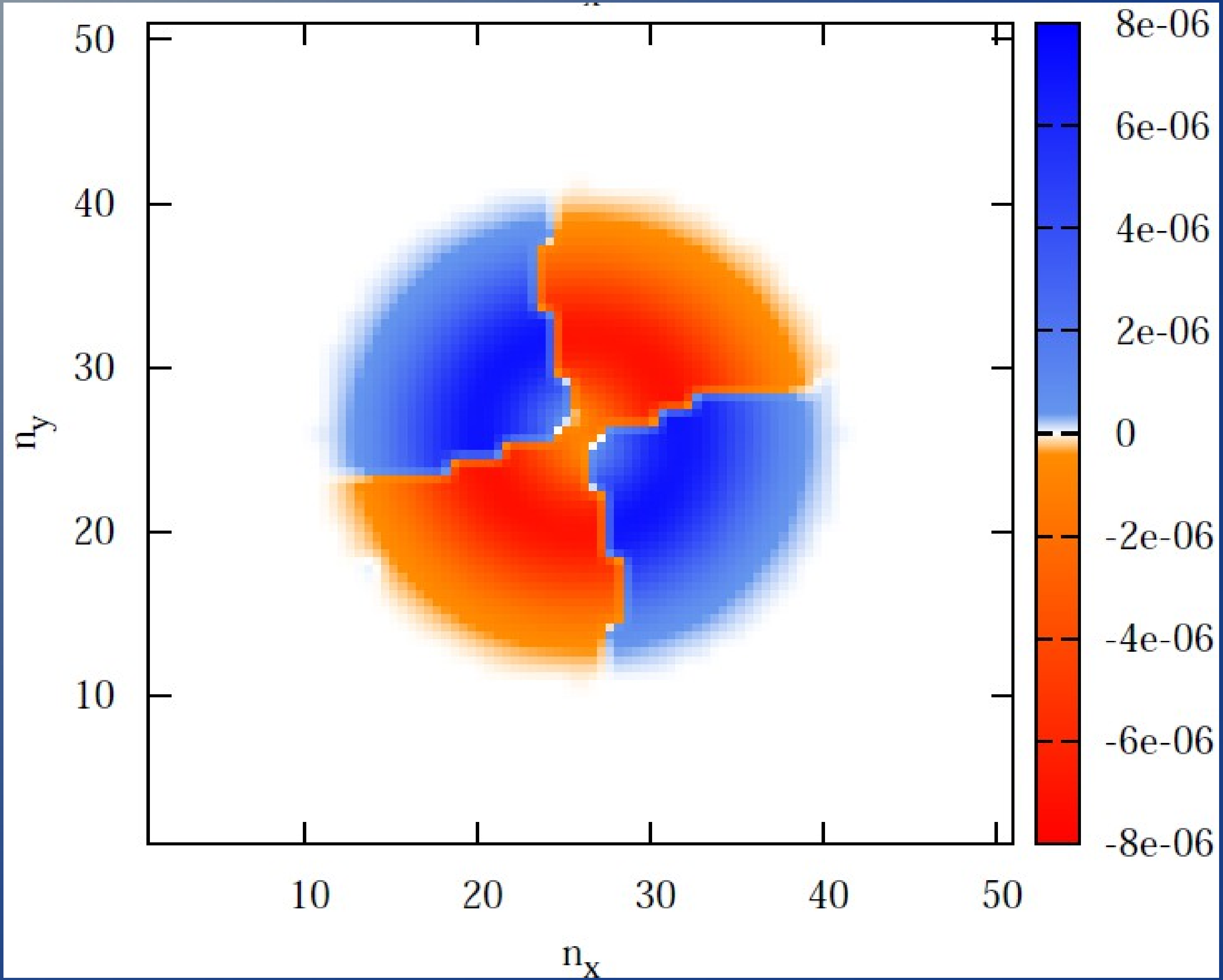
in the equatorial plane

Stergioulas et al. (2011)



f_{peak}

Eigenfunction of the pressure at f_{peak}



Fundamental quadrupolar fluid mode

for Newtonian uniform-density stars:

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

still valid for relativistic, rotating stars with arbitrary EoS

$$\Rightarrow f_{\mathrm{peak}} \propto R_{\mathrm{remnant}}^{-3/2}$$

if remnant size correlates with the radius of nonrotating stars

$$\Rightarrow f_{\mathrm{peak}} \propto R_{\mathrm{TOV}}^{-3/2}$$

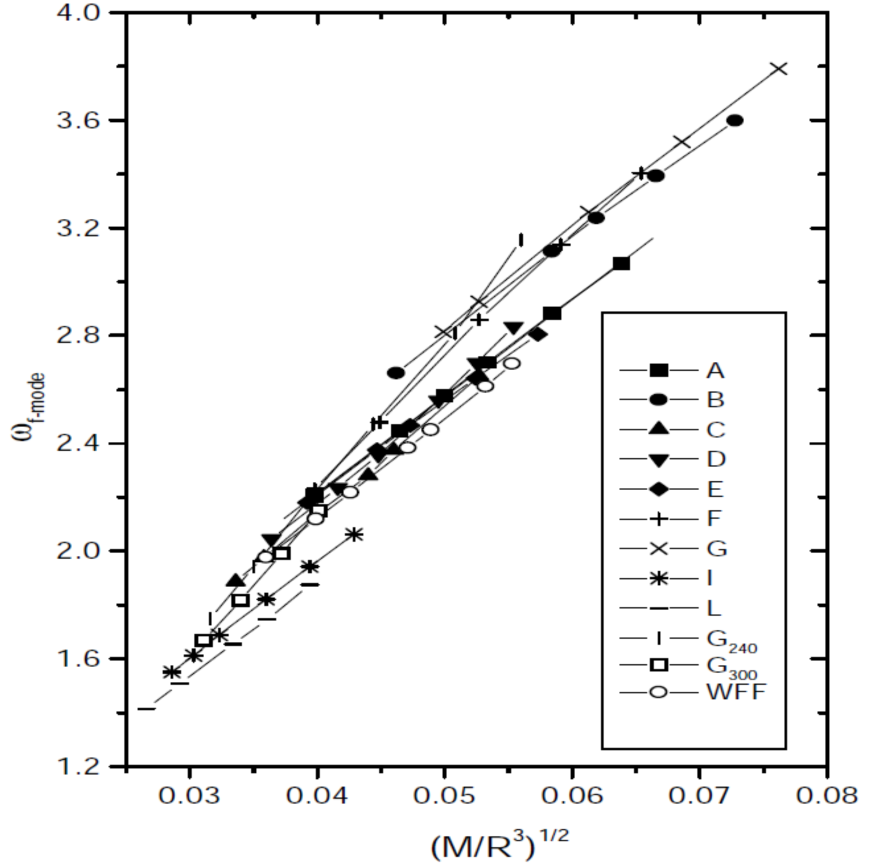
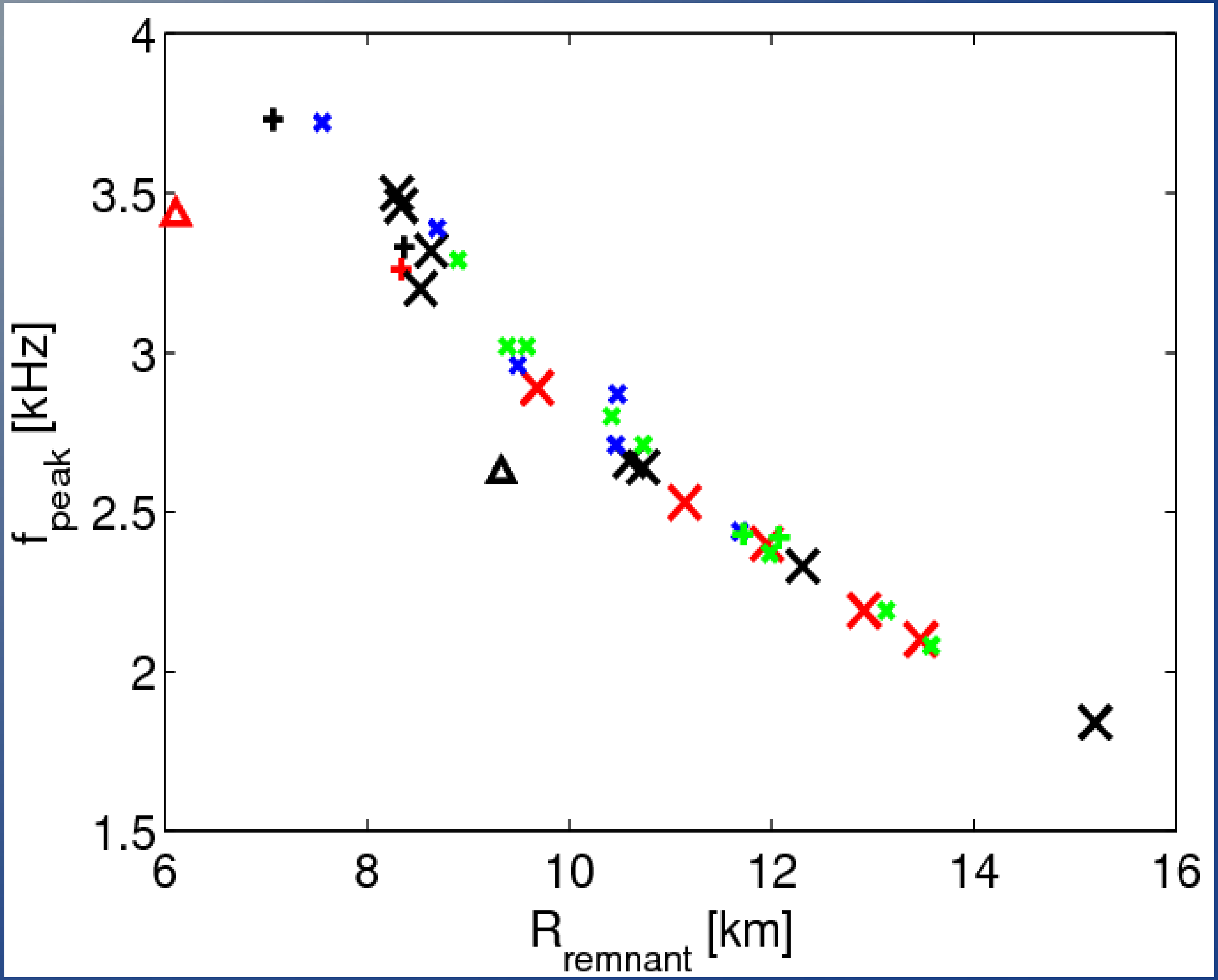


Figure 1. The numerically obtained f-mode frequencies plotted as functions of the mean stellar density (M and R are in km and ω_{f-mode} in kHz).

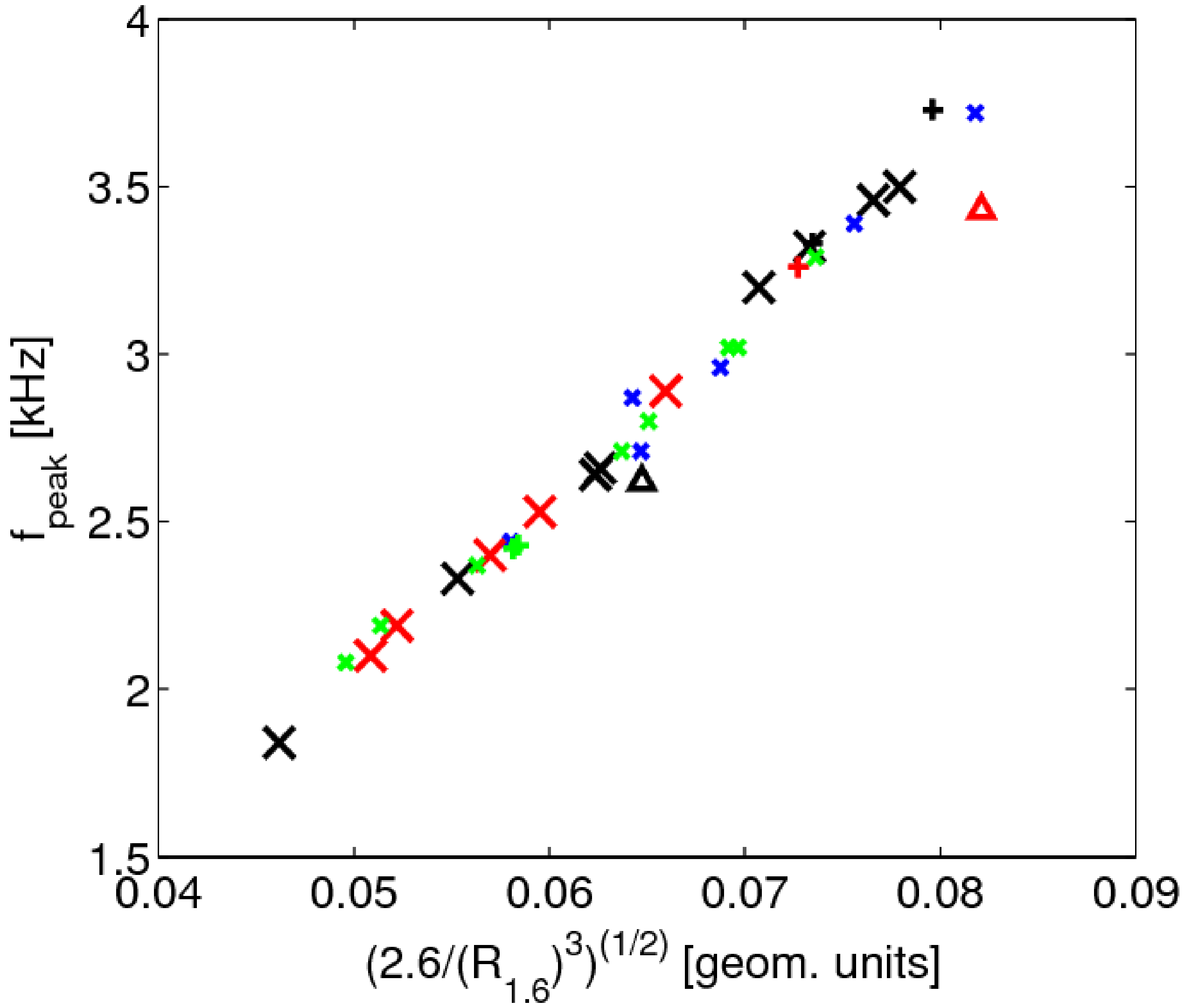
Andersson & Kokkotas 1998

Radius of the remnant

1.35-1.35 binaries



$R_{remnant}$ = sphere enclosing 2.6 M_{sun} rest mass



→ linear scaling

Summary and conclusions

- Survey of equation of state influence on neutron star mergers
- Generic outcome of 1.35-1.35 M_{sun} merger: formation of a differentially rotating NS
- Pronounced peak in the GW spectrum
- Peak frequency scales very well with the radius of a nonrotating NS with 1.6 M_{sun}
- Neutron star radii can be measure with an accuracy of 100-200 meters
- Correlations / constraints for other EoS properties

Details: Bauswein & Janka, PRL 108, 011101 (2012)

Bauswein et al., PRD 86, 063001 (2012)

Stergioulas et al., MNRAS 418, 427 (2011)