GWs from Binary Neutron Stars

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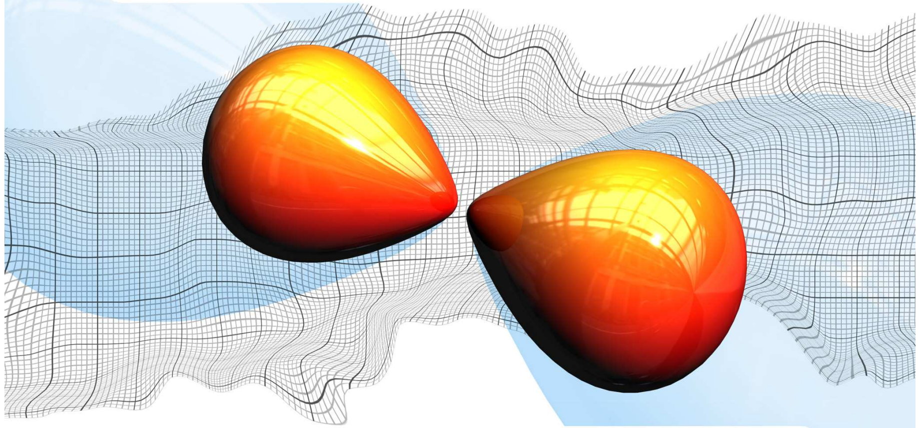

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Motivation

- Large laser interferometers are coming on line: VIRGO, LIGO $(10 \text{ Hz} < f < 1 \text{ kHz})$

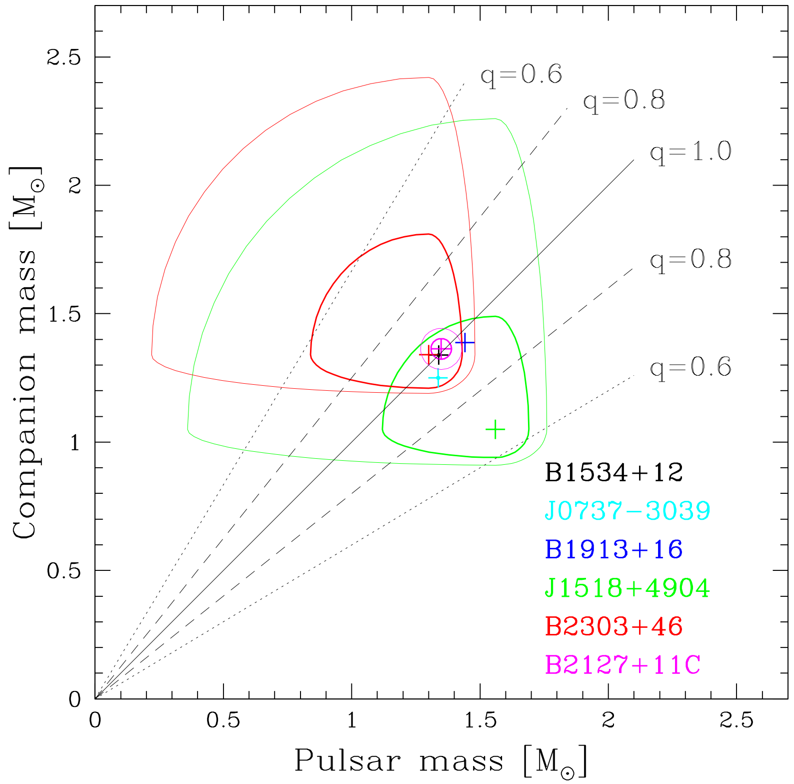
VIRGO, Cascina, Italy

LIGO Livingston Observatory, Louisiana

- Coalescing binary neutron stars are among the most important sources of GW:
  Expected event rate (Kalogera et al. 2004, Belczynski et al. 2002):
  - VIRGO/LIGO: $10^{-3} - 1$ per year
  - LIGO II: $1 - 10^{3}$ per year

- It is necessary to construct accurate templates of expected GW signal to filter out the detectable signal from the background noise

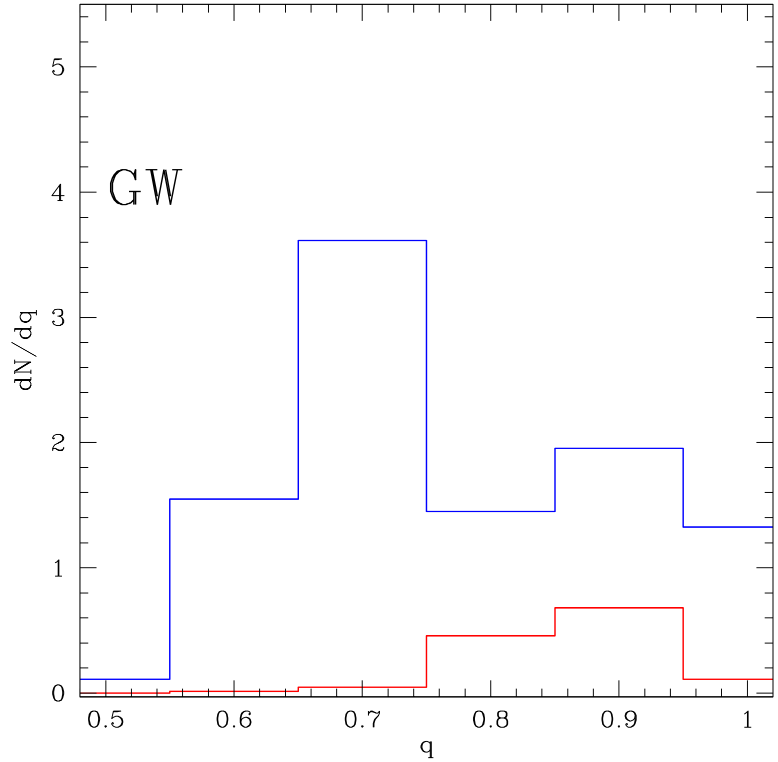
I. Searching for the most realistic masses of coalescing NS - The radio observations



Radio observations provide us with six binary neutron star systems (Thorsett and Chakrabarty 2001, Burgay et al. 2003). We present their masses and uncertainties in the mass determination. Only three of the systems reside in the Galaxy and are coalescing (have shorter lifetime than the Hubble time).

The observed sample exhibits a strong peak for the mass ratio close to unity ($M_{\rm NS} \sim 1.35 M_\odot$), and a possible long tail stretching down to smaller values ($q \sim 0.7$) ...but the radio selected sample includes the long lived pulsars while a significant fraction of the merging binary neutron star population do not satisfy these conditions (Belczynski Kalogera 2001). It is necessary to perform the population synthesis calculations to find the most realistic masses of NS in binary systems (see the next page)

II. Searching for the most realistic masses of coalescing NS - The expected masses of BNS observed in gravitational waves

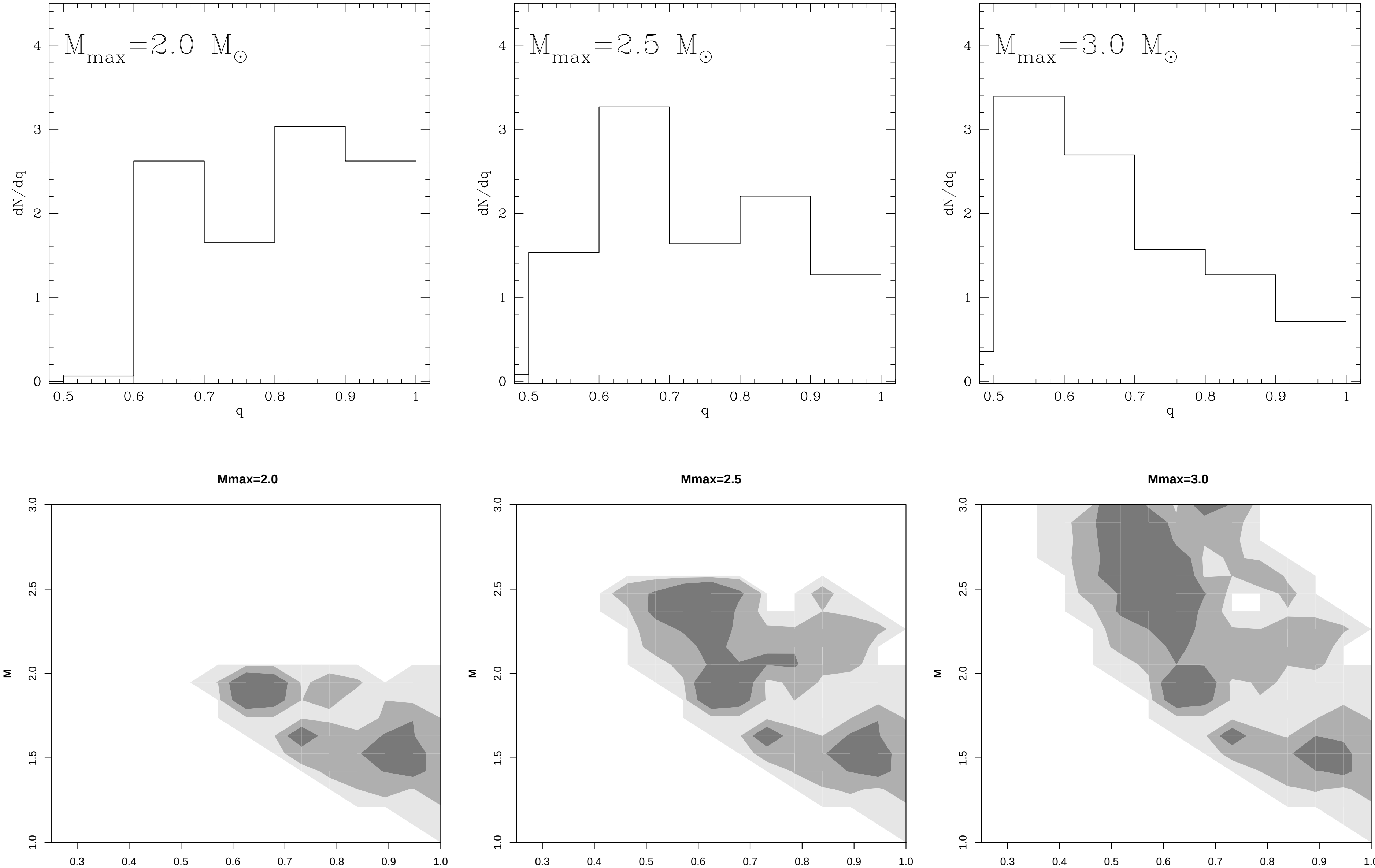


The results of the population synthesis calculations obtained with the standard model of stellar evolution (using StarTrack population synthesis code developed by Belczyński, Bulik and Kalogera)

The blue line corresponds to all binary neutron stars to be observed in GW while the red line shows the contribution of the population of binary radio pulsars.

The population of neutron star binaries observed in gravitational waves are dominated by the systems with small mass ratio $q \sim 0.7$, containg a star with canonical mass and a star with the mass close to the maximal mass. The observations of several double neutron star mergers should yield an estimate of the maximum mass of a neutron star and help to impose constraints on equation of state of neutron stars in supranuclear densities.

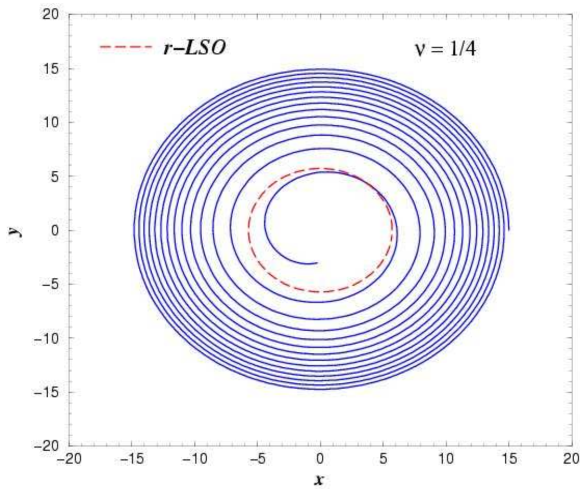
Expected masses of merging neutron star binaries observed in gravitational waves



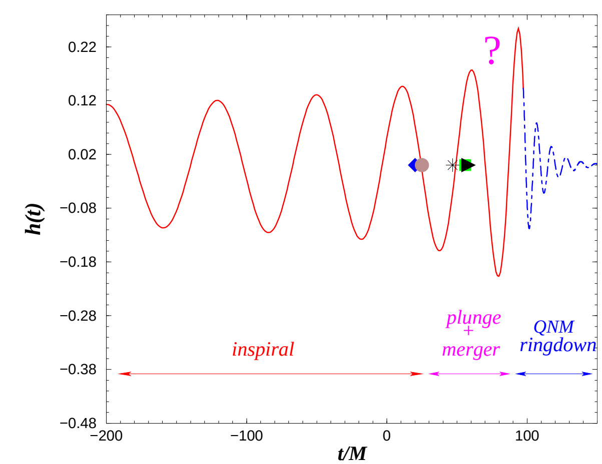
[Gondek-Rosińska, Bulik, Belczyński, 2004, submitted to A& A]

Evolution of binary neutron stars - inspiraling motion

- Evolution of binary black holes or neutron stars entirely driven by gravitational radiation reaction
- There are three phases of the evolution of binary neutron stars: point-like inspiral, hydrodynamical inspiral and merger.
- Observation of the hydrodynamical inspiral or the merger phase $\longrightarrow$ constraints on EOS
- The hydrodynamical inspiral $\longrightarrow$ the initial conditions for the merger phase



2.5-PN Effective One Body computation
[Buonanno & Damour, PRD **62**, 064015 (2000)]



Buonanno & Damour, PRD 62, 064015 (2000)

Defining an evolutionary sequence of binary NS

The inspiral phase can be studied by constructing quasi-equilibrium sequences of close NS binaries in the conformal flatness approximation of general relativity.

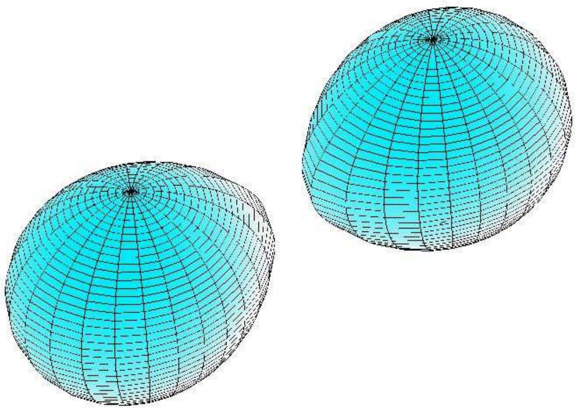
The quasi-stationary evolution of binary NS is modelled by computing a sequence of HKV (helical Killing vector) configurations with decreasing separation and fixed total baryon number of each star

The fluid in NS has zero vorticity in the inertial frame (irrotational case)

The end of quasi-equilibrium : the last stable orbit ISCO or mass-shed limit

The numerical method :

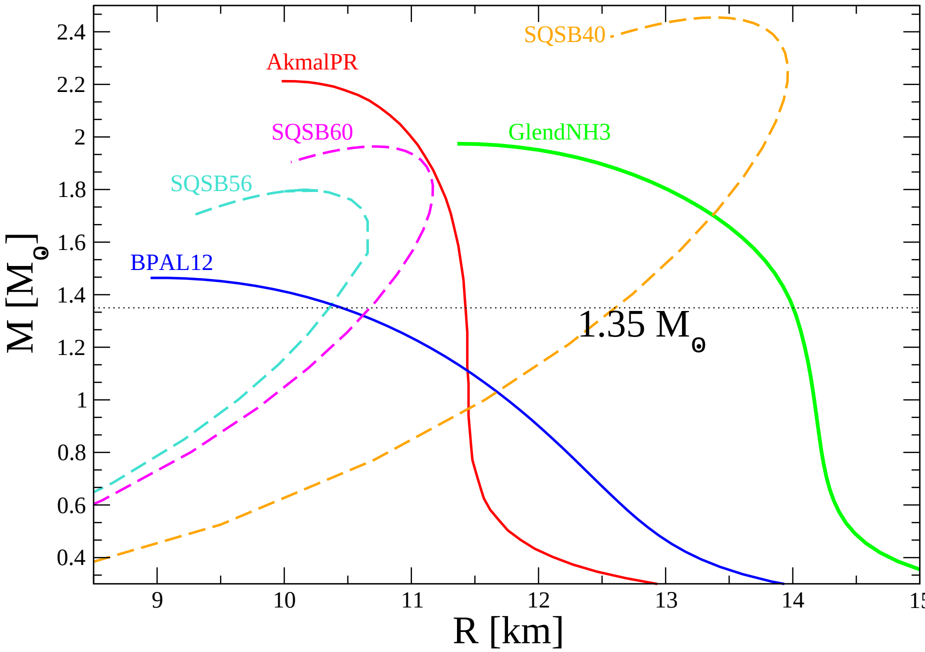
- A multi-domaines 3D spectral method
- Surface fitted cordinates
- Codes C++ LORENE (http://www.lorene.obspm.fr)



[Taniguchi, Gourgoulhon & Bonazzola, Phys. Rev. D **64**, 064012 (2001)]

Surface fitted cordinates

Static neutron star and strange quark star models



Neutron Stars EOS - solid lines

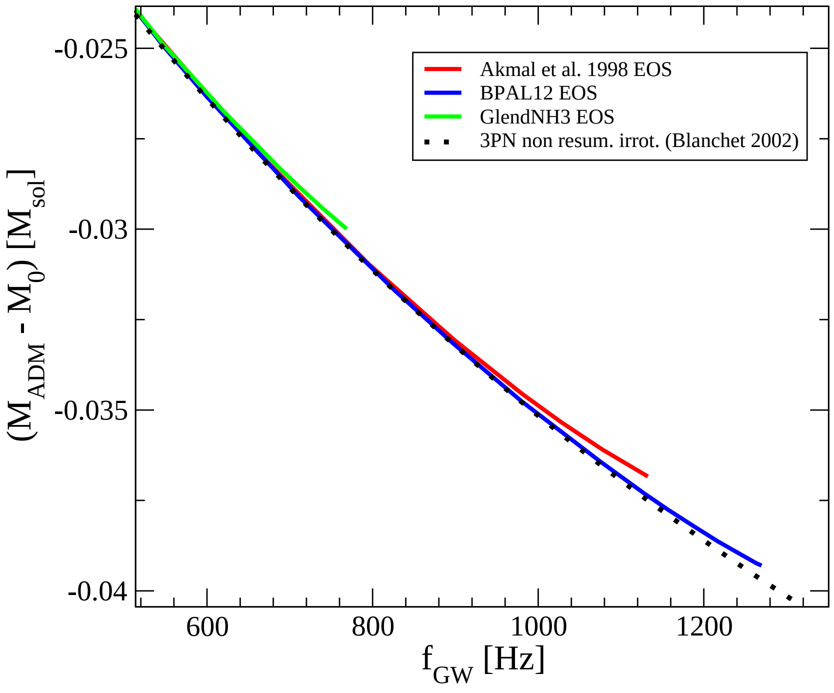
AkmalPR: neutrons, protons, electrons and muons described by the A18+dv+UIX* model of Akmal et al. 1998
BPAL12: n, p, e, muons Bombaci et al 1995
GlendNH3: nucleons + hyperons Glendenning 1985

Strange Quark Stars MIT Bag model - dashed lines

The MIT Bag model parameters: B - the bag constant, $\sim$ density at the stellar surface; m_s - the strange quark mass; α - the coupling constant;

SQSB40 - B=40 MeV/fm^3 $\mathrm{m_s}$=100 MeV,$\alpha = 0.6$; **SQSB56** B=56 MeV/fm^3 $\mathrm{m_s}$=200 MeV,$\alpha = 0.2$; **SQSB60** B=60 MeV/fm^3 $\mathrm{m_s}$=0 ,$\alpha = 0$

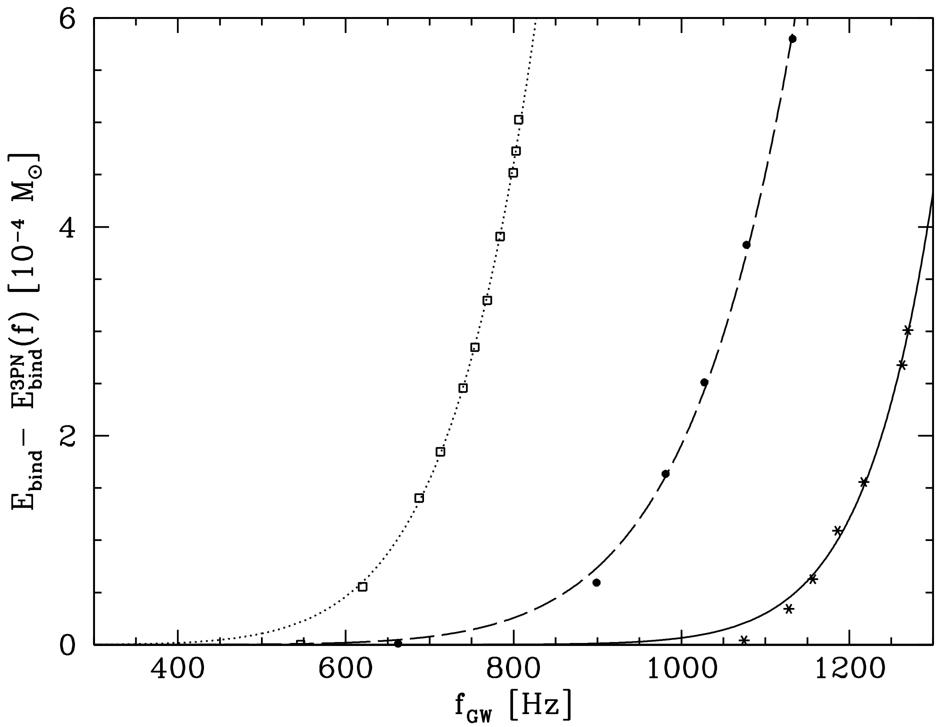
Nuclear EOS and the last orbits of binary neutron stars with masses $1.35 M_{\odot}$



Energy emitted in gravitational waves vs frequency of GW (twice the orbital frequency) for binary neutron stars described by three different EOS of nuclear matter. The end of each sequence - a mass transfer between stars.

The end of quasiequlibrium sequence strongly depend on the compaction parameter M/R of NS (0.14; 0.176; 0.19)

The difference between 3PN and our results

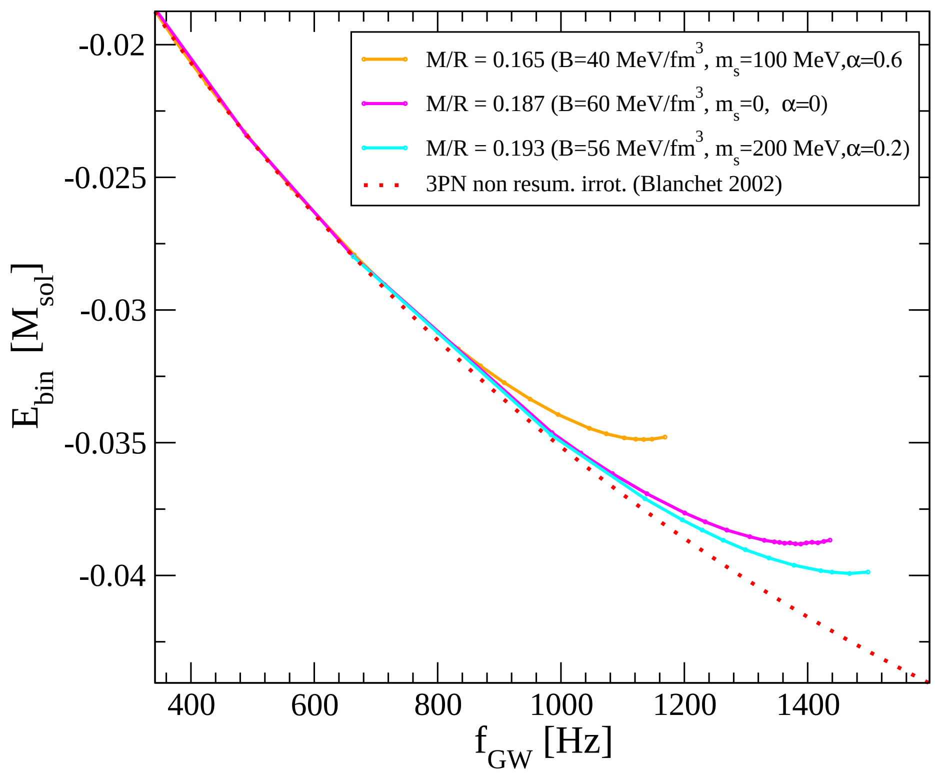


[Bejger, Gondek-Rosińska, Gourgoulhon, Haensel, Taniguchi & Zdunik, [astro-ph/0406234]]

We can determine the individual masses of the two neutron stars in the system taking into account the frequency evolution of the gravitational signal at the inspiral phase and high-order PN effects on the phase evolution of the signal (Cutler and Flanagan 1994).

In addition we can get the compactness parameter M/R of neutron stars based on the observed deviation of the gravitational energy spectrum from point-mass behavior at the end of inspiral (Faber, Grandclement and Rasio 2002, Bejger et al. 2004).

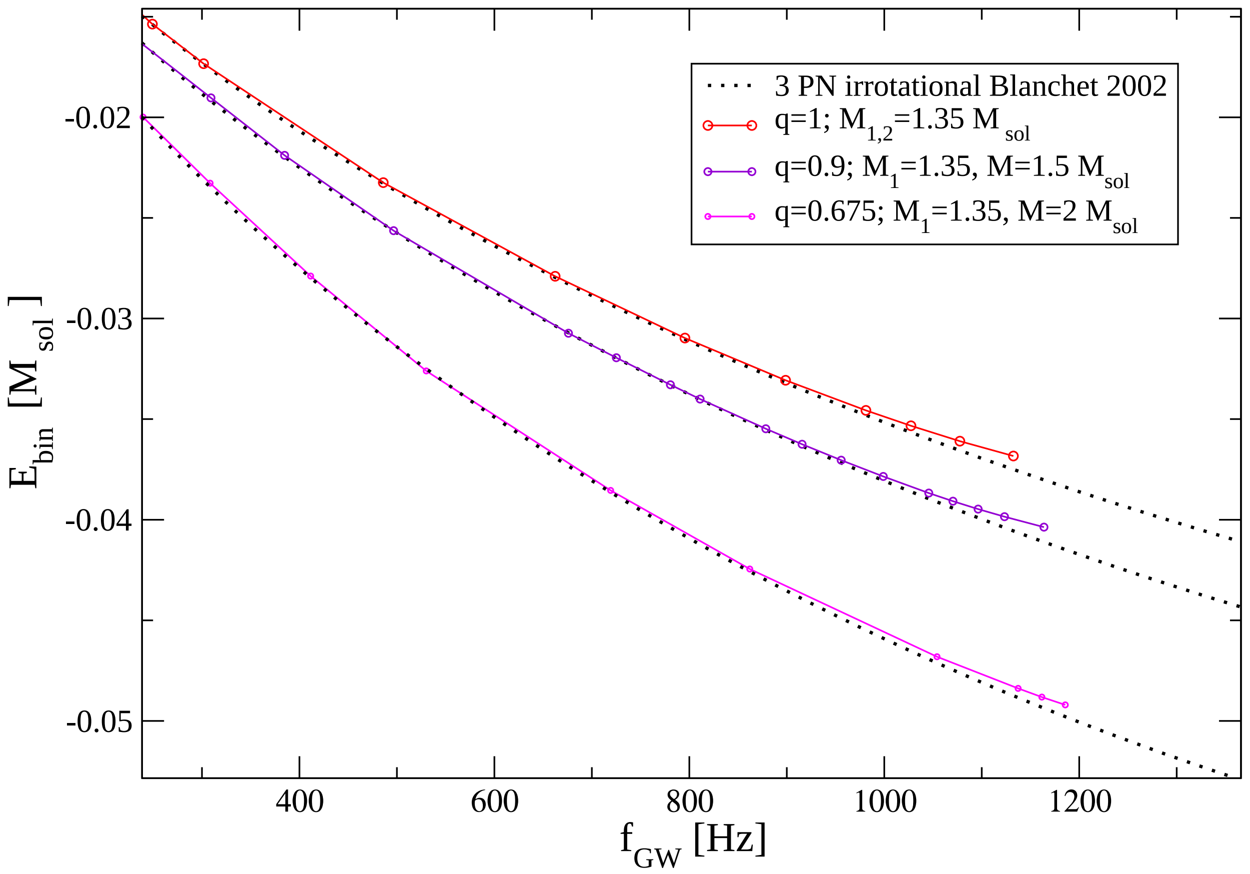
The last orbits of binary strange stars with masses $1.35 M_{\odot}$



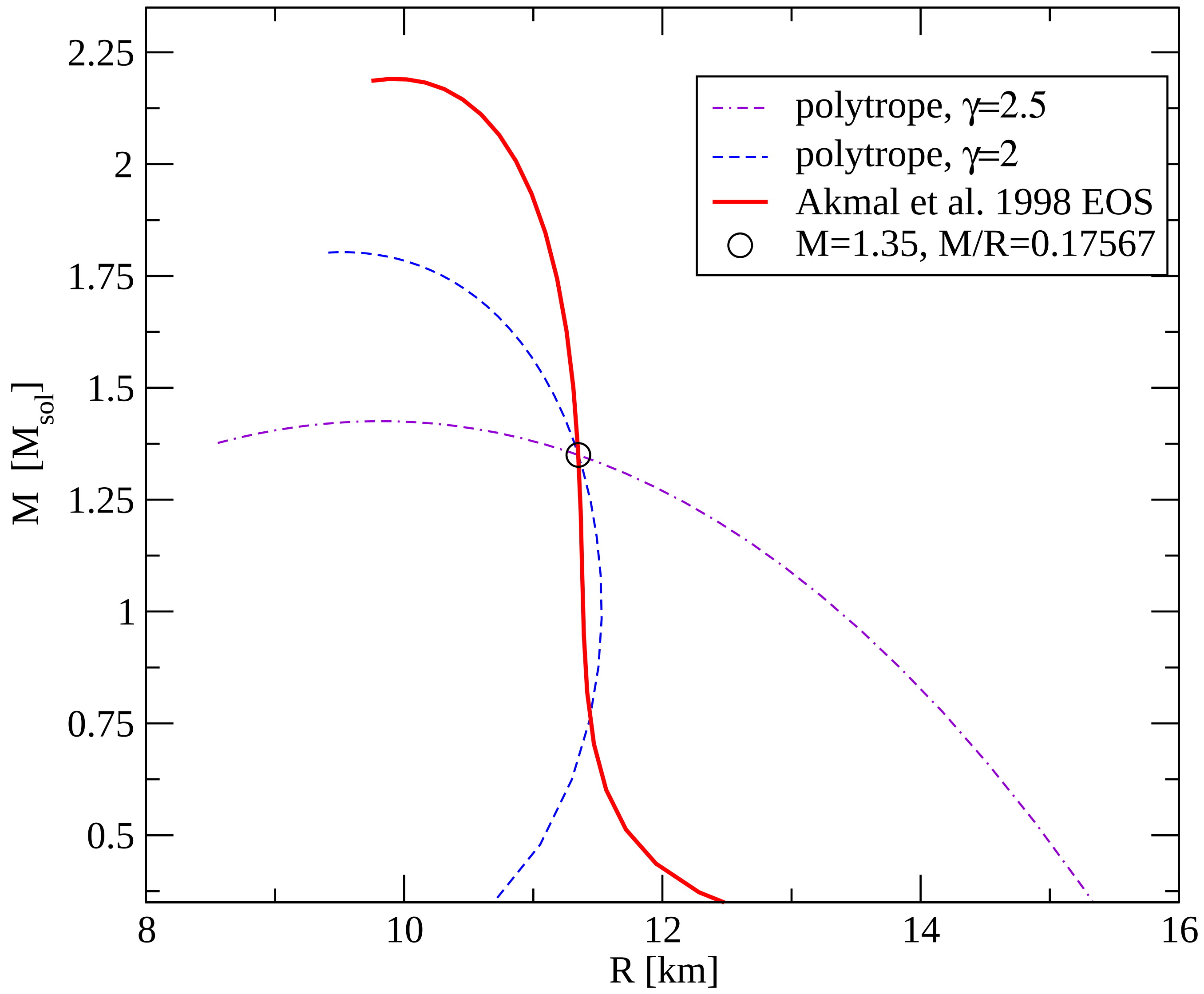
Energy emitted in gravitational waves vs frequency of GW for binary strange quark stars described by three different EOS of MIT Bag model. The turning points correspond to marginally stable orbit, which may be observed in gravitational waveforms

The frequency of GW at ISCO strongly depends on the compaction parameter M/R - it would be possible to determine M and R from GW signal and make constraints on EOS of dense matter. The GW frequency at the merger is higher for strange stars than for neutron stars

Sequences for different mass ratios: 0.675, 0.9, 1

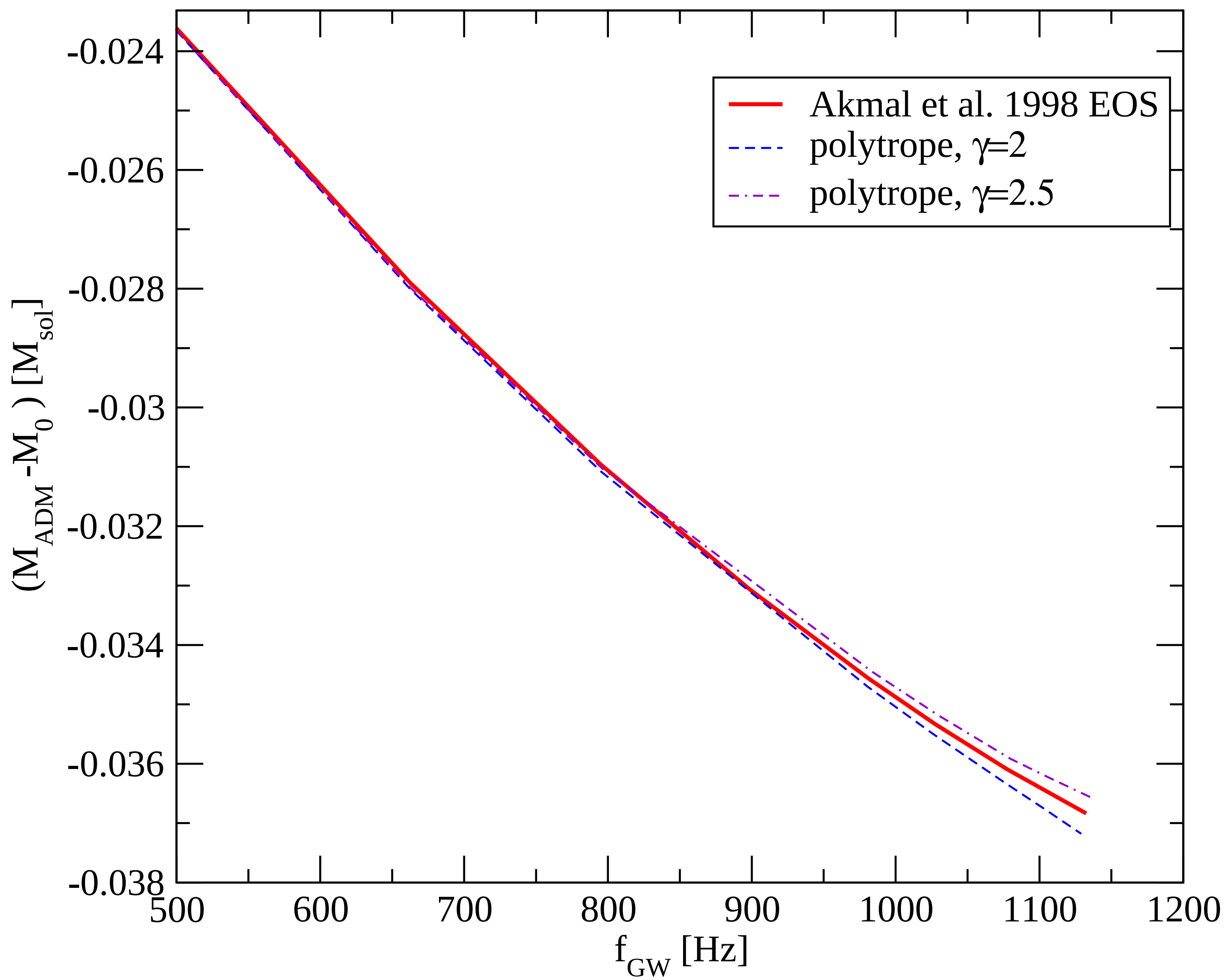


A binary neutron star system with small mass ratio $q \sim 0.7$ (which contains a neutron star with mass close to maximum mass of neutron star) is emitting more energy in gravitational waves than a system containing stars with the same masses



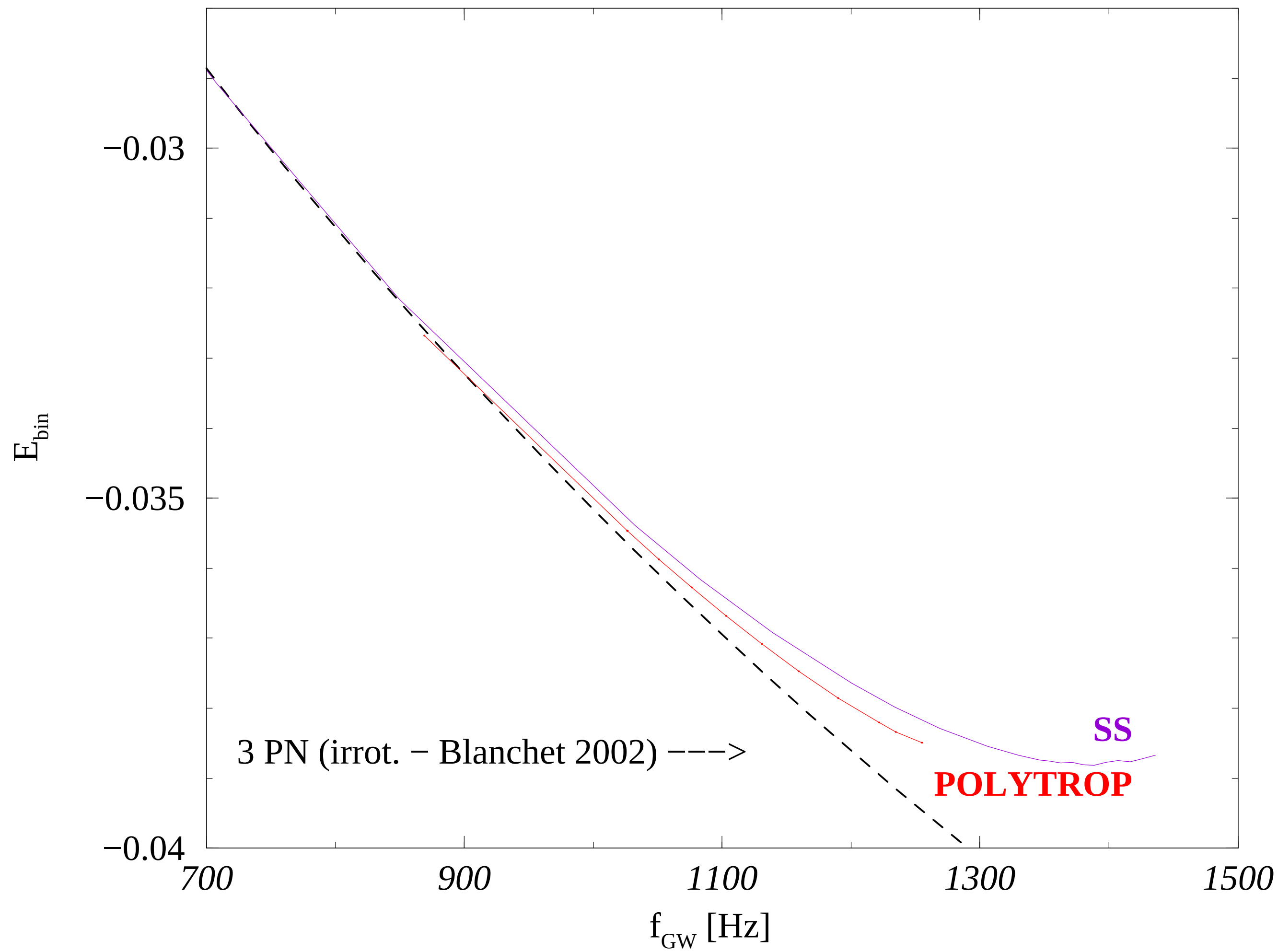
Mass-radius relation of static models in isolation

AkmalPR EOS and polytropic EOS: evolutionary sequences



Gravitational mass at infinite separation : $M_0/2 = 1.35\,M_\odot$ ($M/R = 0.176$)

Strange quark stars: evolutionary sequences



Gravitational mass at infinite separation : $M_0/2 = 1.35\ M_\odot$ ($M/R = 0.187$)

[Gondek-Rosińska, Gourgoulhon, Limousin, in preparation]

Our studies

- Using the well tested StarTrack binary population synthesis code we show that a significant franction of the observed binary neutron stars in gravitational waves will have mass ratios $q < 0.7$ and ~ 0.9. Binary neutron stars observed in radio (having mass ratio close to unity) are a small fraction (less 10 $\%$) of all binary systems containing two neutron stars.

- We performed calculations of the last orbits of binary neutron star described by realistic equations of state (a standard model of nuclear matter, a model with hyperons, MIT bag model of strange quark matter) in general relativity - up to now, all calculations (except Oechslin et al. 2004) of the hydrodynamical inspiral and merger phases have been done for the simplified equation of state of dense matter, for the polytropic EOS.

- The merger process of binary neutron stars and the gravitational waveforms depend strongly on the stellar mass ratio (Shibata, Taniguchi and Uryu 2003). We extended current equal mass binary NS calculations (K. Tanigouchi and E. Gourgoulhon 2003, Uryu and Eriguchi 2000,Uryu et al. 2000) to include the most realistic masses of components (mass ratio q=0.675; 0.9; 1)