# Quasiequilibrium sequences of binary strange stars

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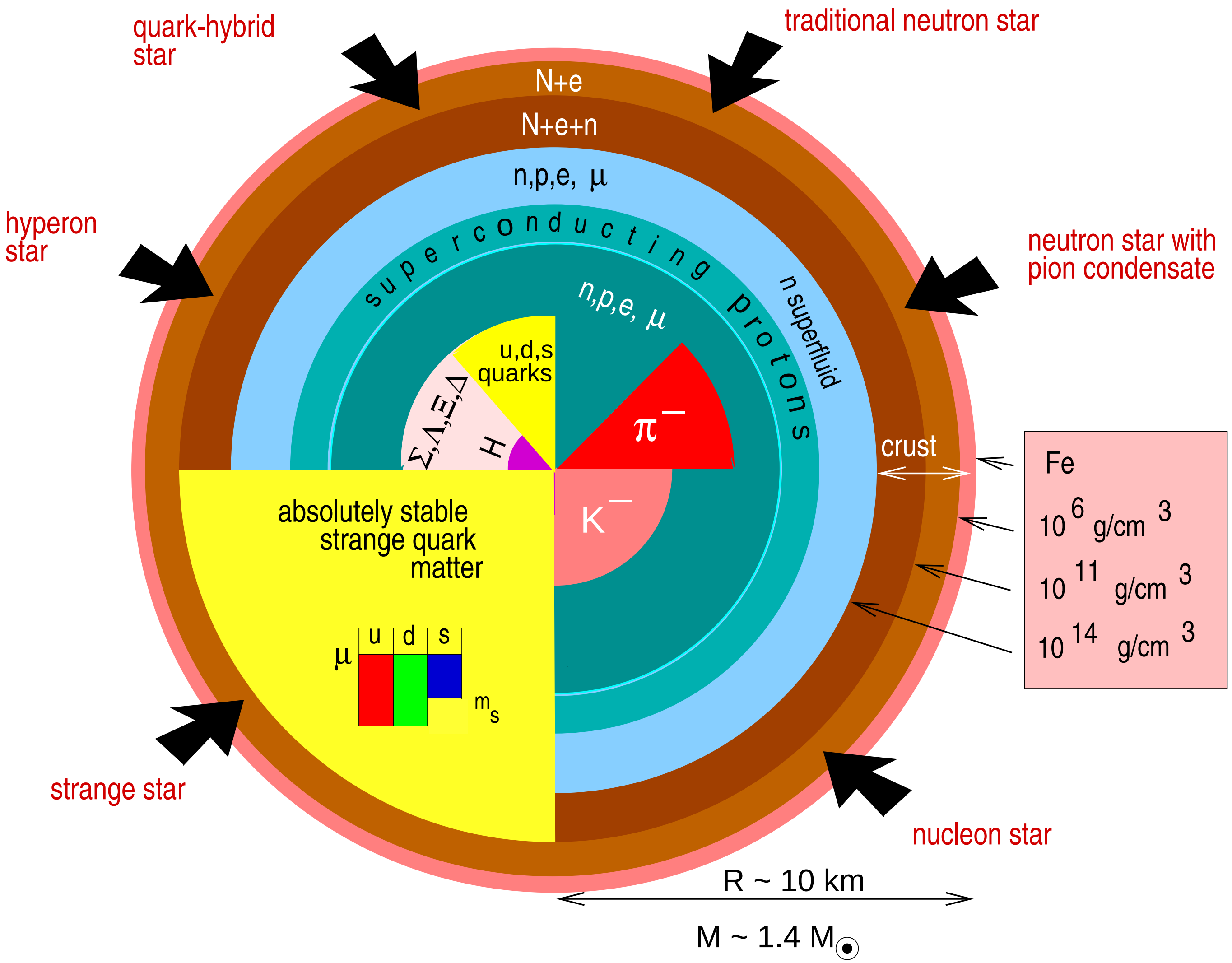
# Strange quark stars




Different models of the interior of a neutron star

[Weber, J. Phys. G **27**, 465 (2001)]

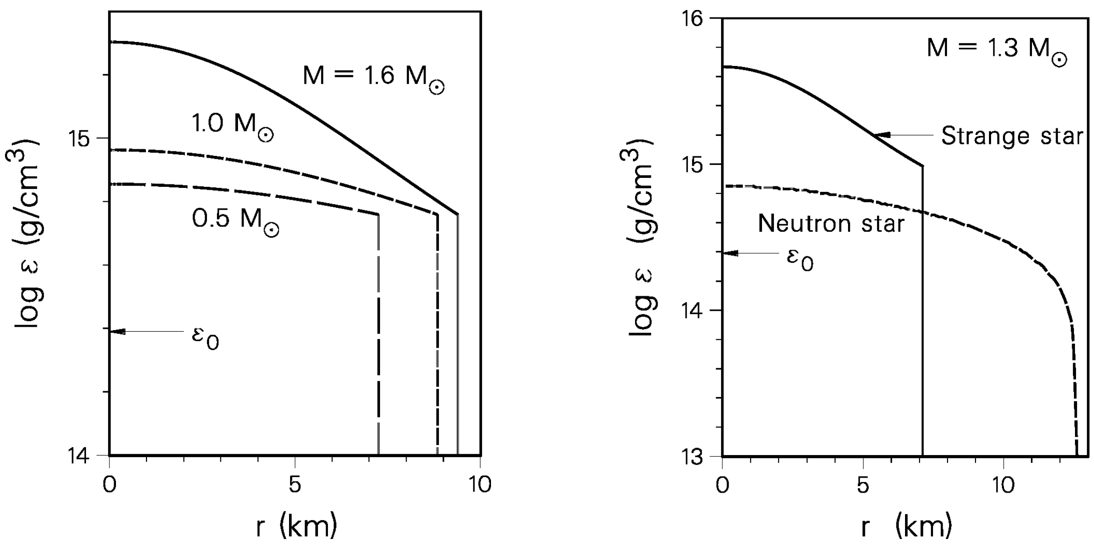
# Static strange stars

First numerical models computed by Haensel, Zdunik & Schaeffer [A&A **160**, 121 (1986)] and Alcock, Fahri & Olinto [ApJ **310**, 261 (1986)] by integration of the **Tolman-Oppenheimer-Volkoff equations** with MIT bag-model EOS.

Basic features :

- **finite density at the surface** (zero pressure)

- for small mass (weak gravity) : almost constant density profile

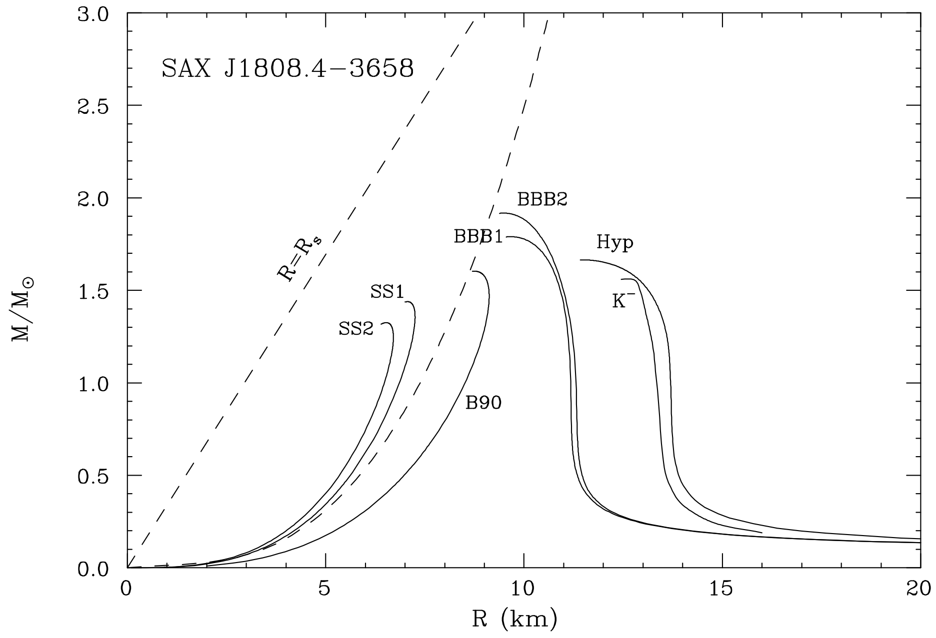



[from Glendenning (1997)]

# Comparison with neutron stars

*neutron stars = gravitationally bound objects*

*strange quark stars ∼ self-bound objects*



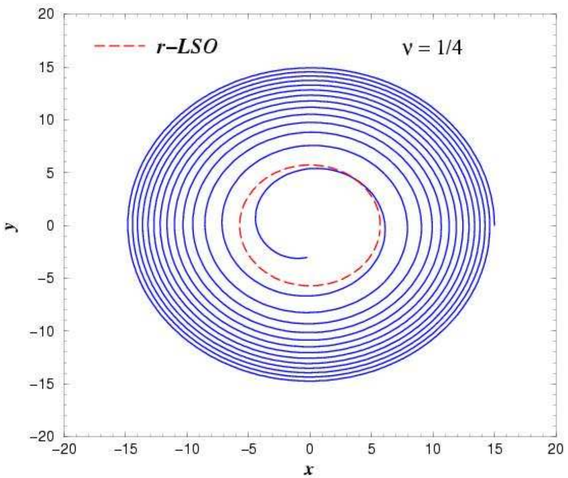

Gravitational mass as a function of the areal radius for nonrotating neutron stars (BBB1, BBB2, Hyp and $\mathrm{K}^-$) and nonrotating strange stars in the MIT bag model (B90) and Dey et al model (SS1 and SS2) [from Bombaci (2002)]

# Quasiequilibrium sequences

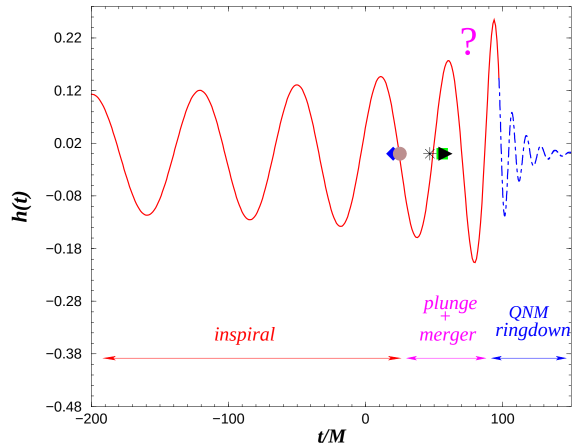
- Evolution of binary systems entirely driven by the emission of gravitational waves.

  We consider sequences of **circular** orbits with smaller and smaller radius, keeping the baryon mass constant, imitating the inspiral phase.

- The innermost stable circulat orbit (ISCO) is defined as the minimum of the binding energy of the system. It could be observed by laser interferometers in the gravitational waveforms.




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




Buonanno & Damour, PRD 62, 064015 (2000)

# Methods

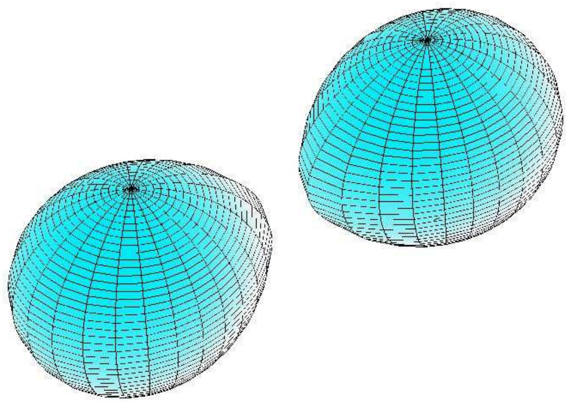
- Resolution of Einstein equations using 3+1 formalism :

$$\boxed{g_{\mu\nu}\, dx^\mu\, dx^\nu = -N^2\, dt^2 + \gamma_{ij}\,(dx^i + \beta^i dt)\,(dx^j + \beta^j dt)}$$

We assume that the spatial part of the metric is conformally flat ( *Isenberg-Wilson-Mathews approximation).*

Numerical methods :

- Multi-domain spectral methods
- The entire space ($\mathbb{R}^3$) is covered : compactification of the external domain
- Adaptatives coordinates
- Numerical implementation based on LORENE



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

**Coordinates adapted to the surface of the stars**

# Equation of state

We compute sequences of binary systems for :

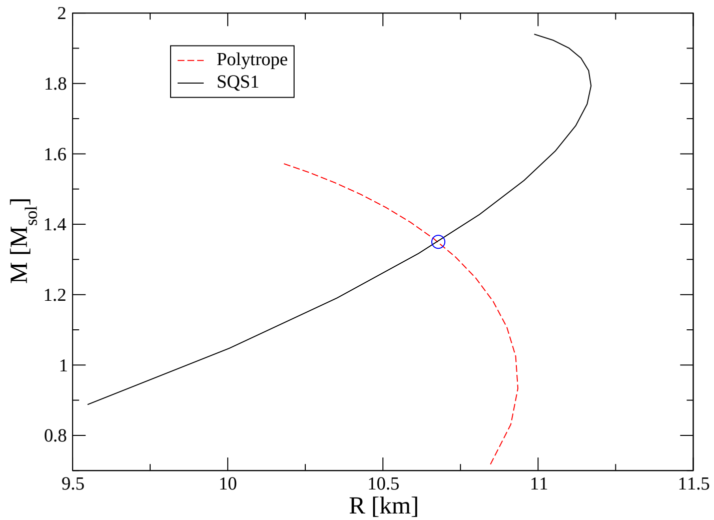
- three differents equation of state of MIT bag model :
  - ⋆ **SQS0** - the standard MIT bag model: $m_{\rm s}c^2 = 200\ \mathrm{MeV}$, $\alpha = 0.2$, $B = 56\ \mathrm{MeV/fm^3}$,
  - ⋆ **SQS1** - the simplified MIT bag model : $m_{\rm s} = 0$, $\alpha = 0$, $B = 60\ \mathrm{MeV/fm^3}$,
  - ⋆ **SQS2** - the "extreme" MIT bag model (relatively low strange quark mass and $B$ but high $\alpha$) : $m_{\rm s}c^2 = 100\ \mathrm{MeV}$, $\alpha = 0.6$, $B = 40\ \mathrm{MeV/fm^3}$.
- one equation of state of **Dey et al.** (derived from microscopic QCD calculations). Stars computes within this model are much more compact.

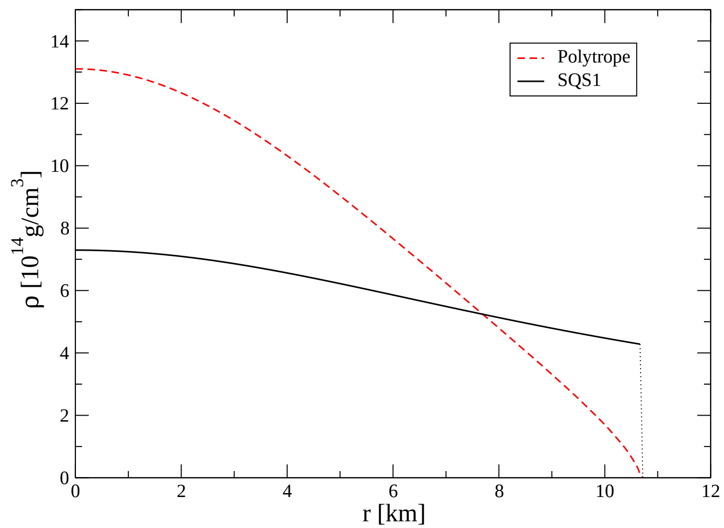
For all these EOS, we can approximate with a very well approximation :

$$P(\rho) = a(\rho - \rho_0).$$

# Comparison with a polytropic EOS

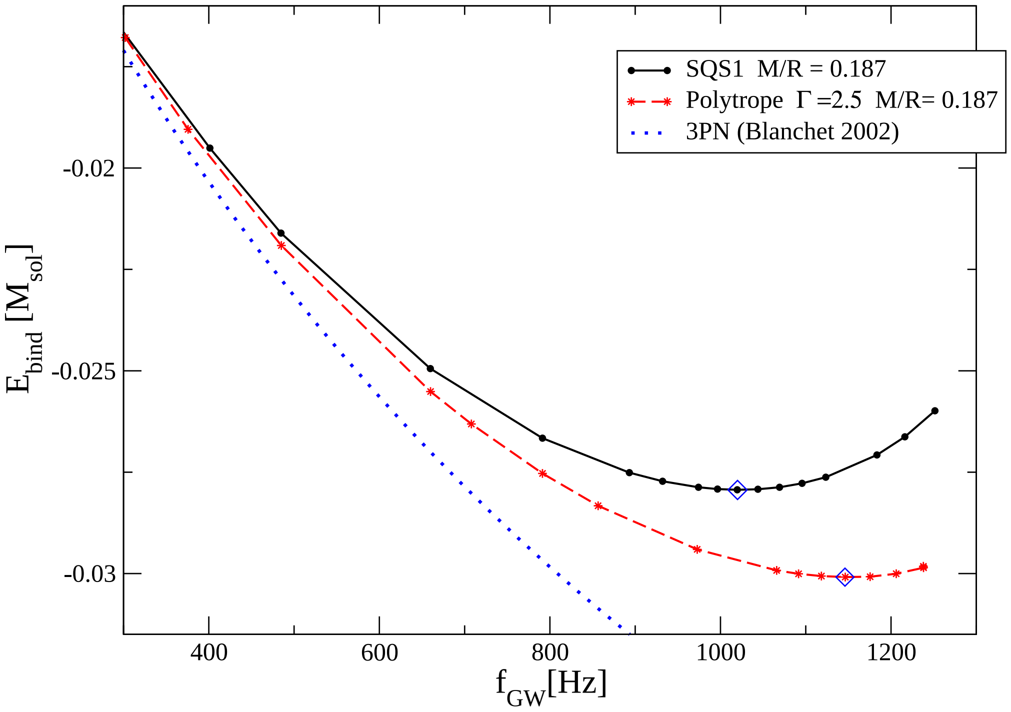
- Computation of quasiequilibrium sequences for corotational and irrotational case with equal mass $M = 1.35M_\odot$, $R = 10.7$ km and $M/R = 0.187$ at infinite separation.
- We compare our results for the simplified MIT bag model (SQS1) with neutron stars.
- We choose for the neutron stars a polytropic equation of state $P = \kappa n^\Gamma$ with $\Gamma = 2.5$ and $\kappa$ chosen so that the compacity and the radius of the star at infinite separation is the same as for SQS1.



# Corotational case

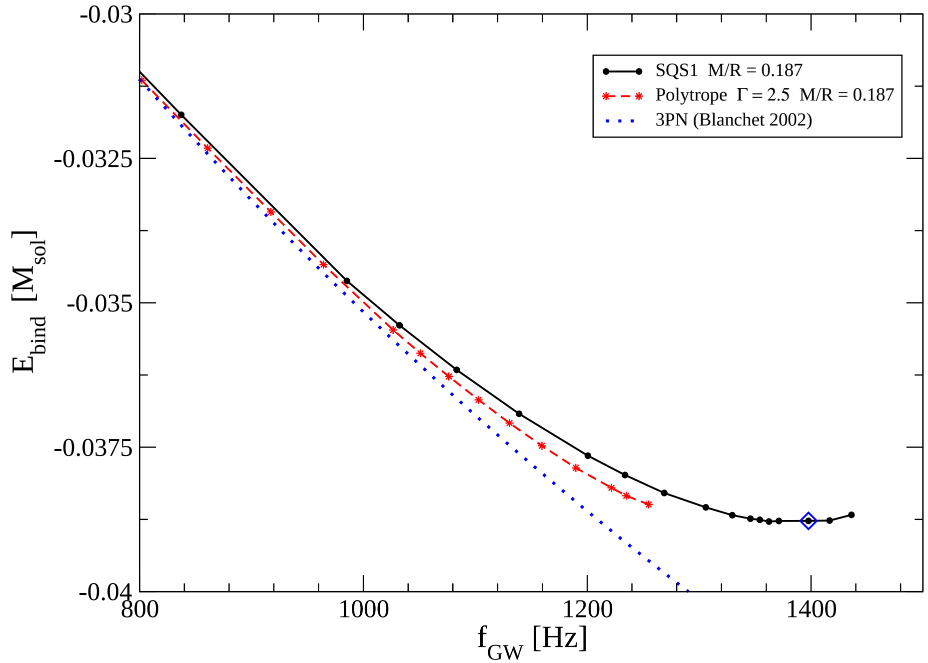
Rigid rotation is not realistic, the viscosity of the star is far too low to ensure synchronisation between the spin of the star and its orbital motion




- An ISCO is found for both NS and SS, but it appears for different frequencies.
- SS lose less energy than NS.
- Both agrees with 3PN results for large distances.

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

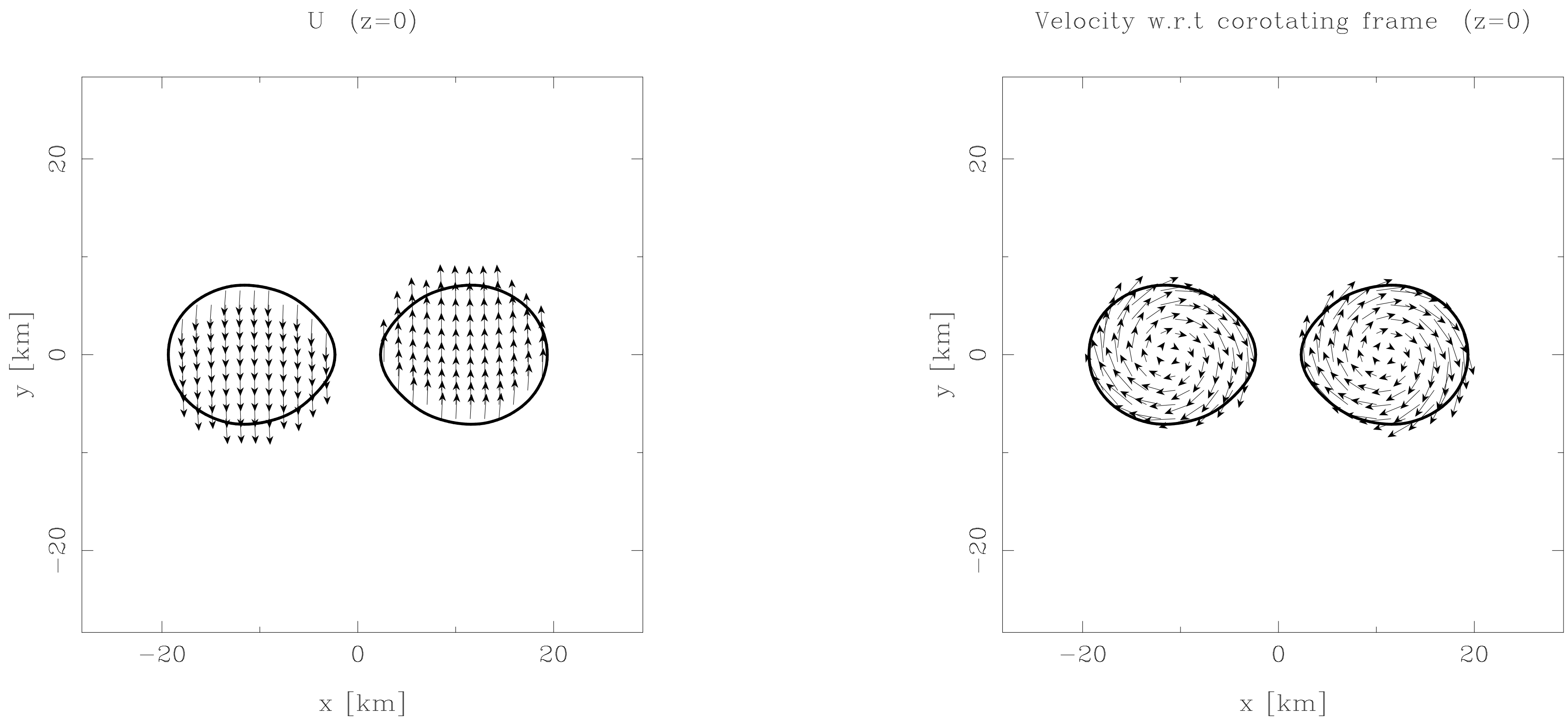
# Irrotational case




Gravitational mass at infinity : $M_0 = 1.35\,M_\odot$
($M/R = 0.187$)

- An ISCO is found for SS around 1400 Hz.
- Sequence of NS terminates by the mass-shedding limit (exchange of matter).
- For the same distance, SS are less deformed than NS. Due to the additional strong interaction between quarks.

# Velocity field



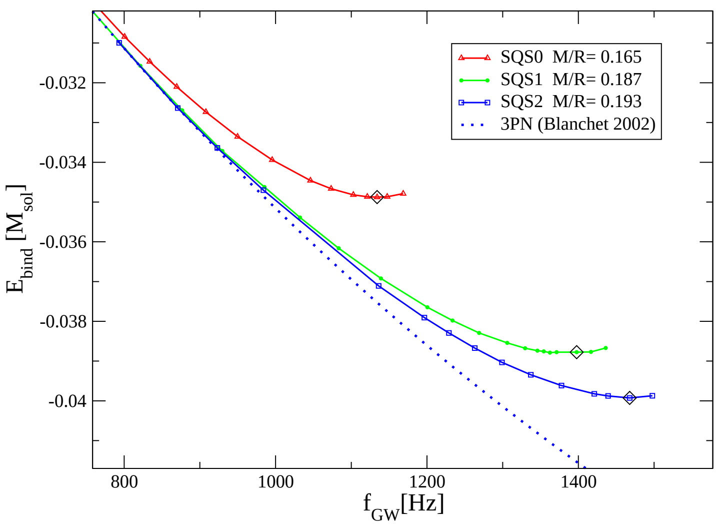

Velocity field in the reference frame and in the corotating frame for irrotational stange stars (SQS1) binaries at the ISCO.

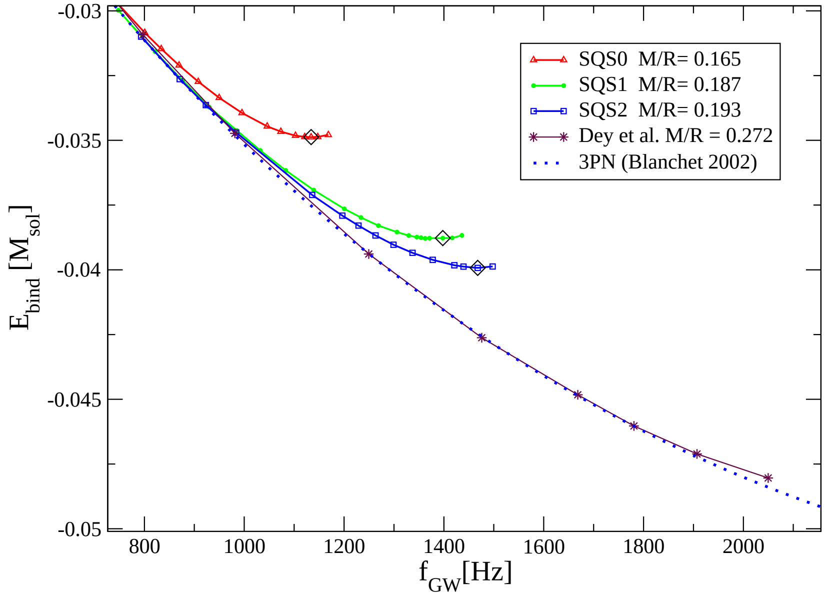
The fluid velocity at the surface of the star has no components orthogonal to this surface in the corotating frame.

No cusp (angular point) appears before dynamical instability.

# Influence of the equation of state

- An ISCO is found for the 3 different MIT bag model EOS.
- The frequency of the ISCO **depends strongly on the EOS**. The higher the compaction parameter is, the higher the frequency at the ISCO.
- For Dey et al., frequency higher than 2kHz.



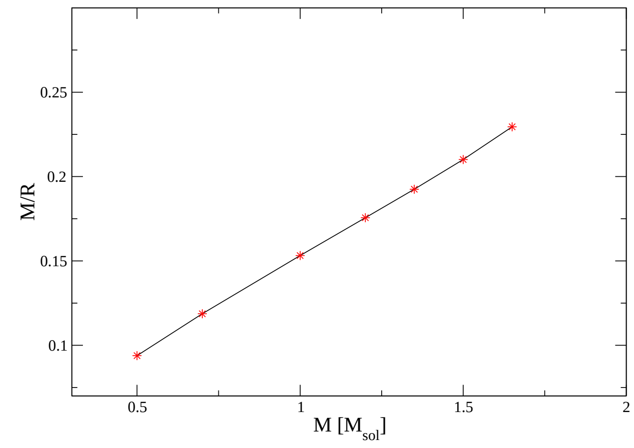



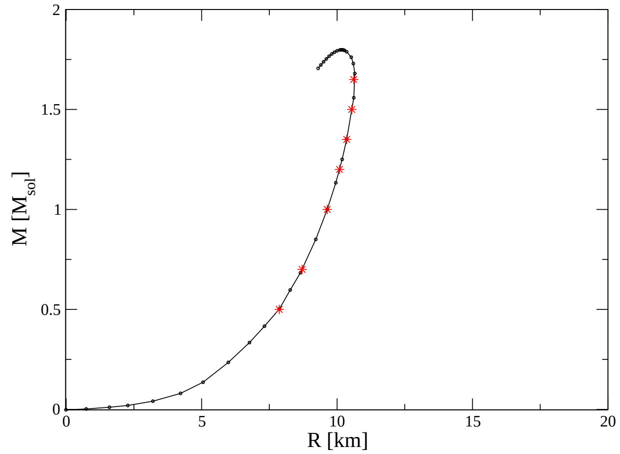

Gravitational mass at infinity : $M_0 = 1.35\ M_\odot$

# Influence of the mass

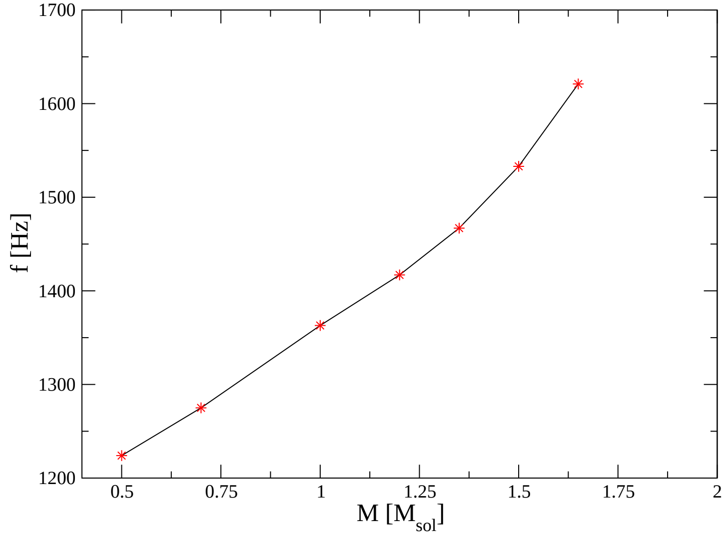
Computation of sequences for SQS0 EOS with mass 0.5, 0.7, 1.0, 1.2, 1.35, 1.5 and 1.65 $M_\odot$.

The GW frequency of the ISCO increase with the mass, and is quasi-linear in this range of mass. Behavior very similar for the compaction parameter.




Mass versus radius of the star for SQS0 EOS.




Frequency of the ISCO versus mass of the stars.

# Conclusion

- In each of the rotation states, corotational or irrotational, the sequence of quasiequilibrium configurations for strange stars terminate with an ISCO, contrary to irrotational neutron stars.

- Depending of the equation of state for the strange quark matter, for the same gravitational mass at infinity, we obtain different frequency for the ISCO.

- The frequency of the ISCO increase with the mass of the stars. And is strongly dependant on the compaction parameter.

- The observation of gravitational waves by laser interferometers (LIGO, VIRGO...) could lead to the determination of the frequency of the ISCO. Impose constraints on the EOS of neutron stars.