Meudon Group

Physics of compact objects and sources of gravitational waves

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Graduate students:

- Nicolas Chamel
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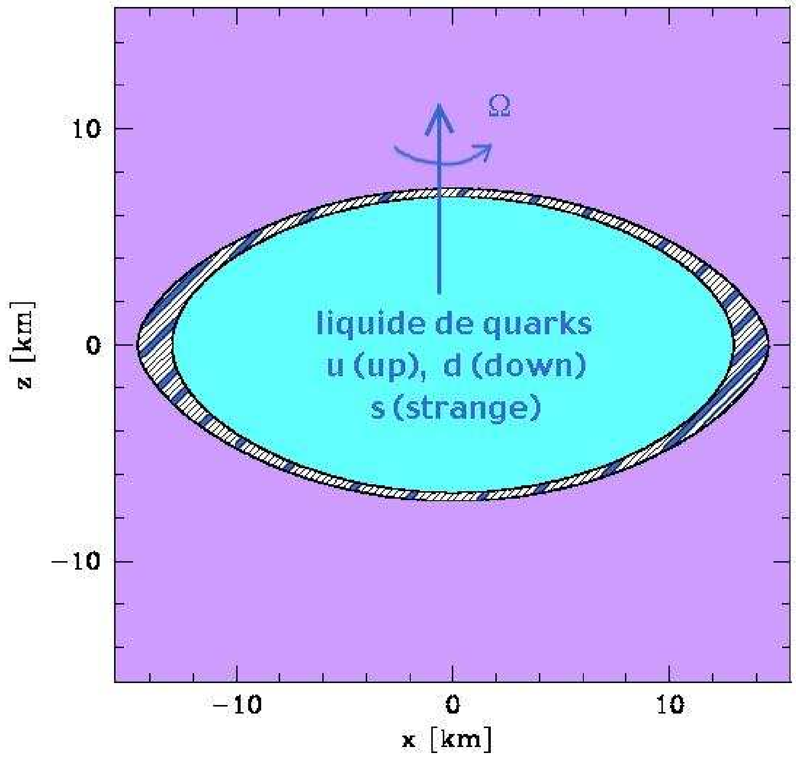
Rapidly rotating strange stars

D. Gondek-Rosińska & E. Gourgoulhon

Collaborations: Warsaw (Poland), Thessaloniki (Greece)



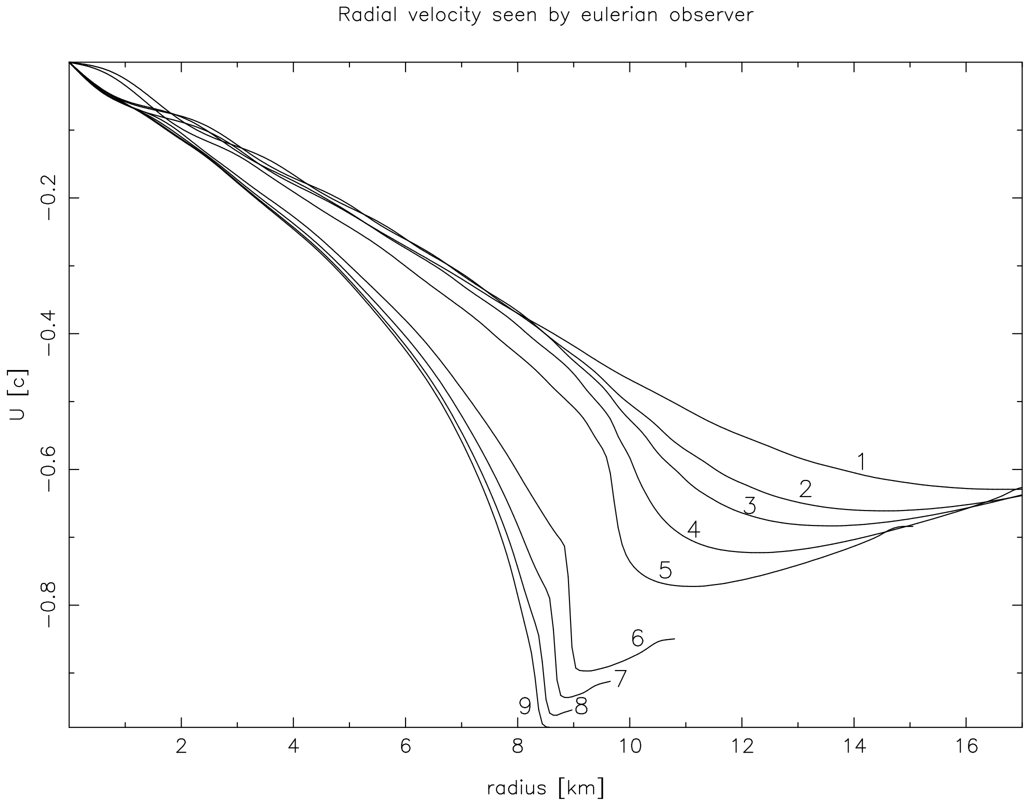
Recent results:

- Constraints on strange quark matter lead by QPO observations in X-ray binaries
- Viscosity-driven bar-mode instability in rapidly rotating strange stars and prospect for gravitational wave detection

Gravitational collapse

J. Novak

Collaborations: Valencia University (Spain)



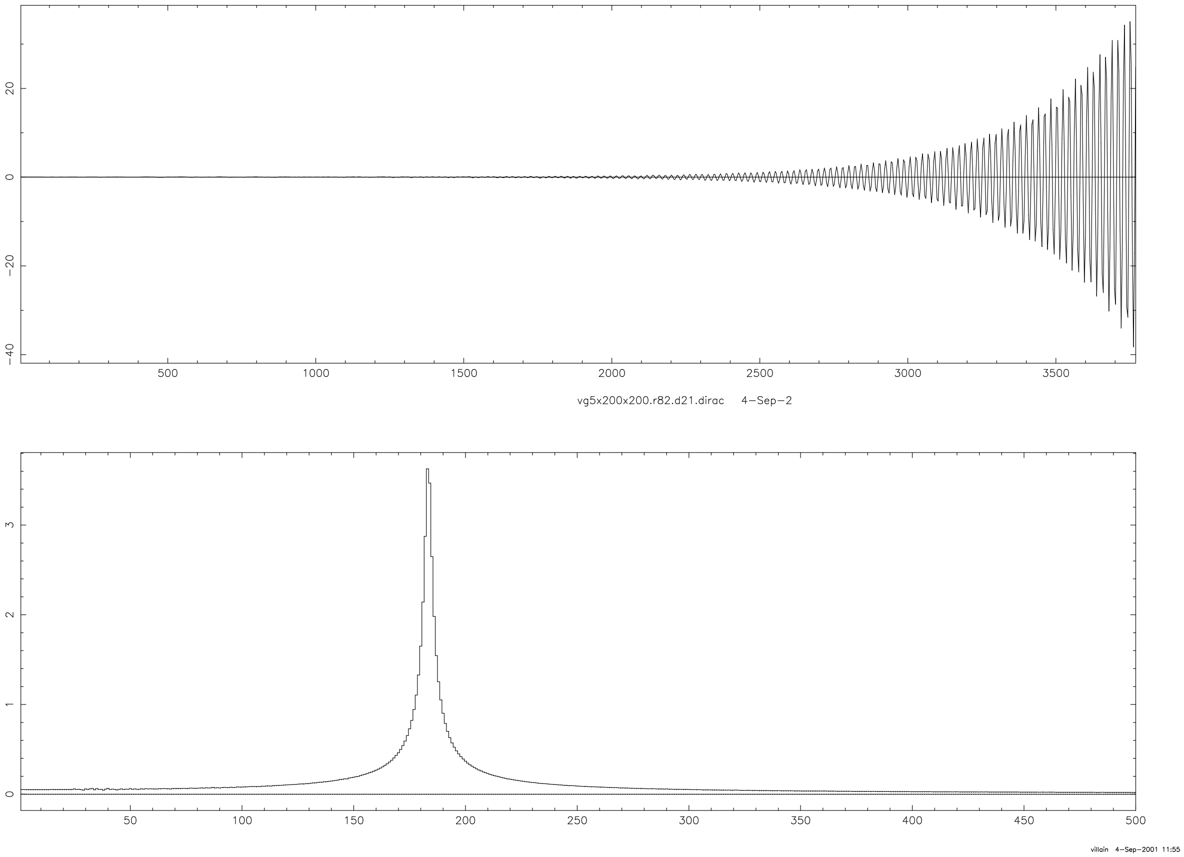
Recent results:

- Computation of the monopolar gravitational waves emitted by a supernova in the framework of tensor-scalar theory of gravitation
- Minimal mass of a black hole formed in the gravitational collapse of a neutron star

Instabilities in rotating neutron stars

S. Bonazzola & L. Villain

Computation of the inertial modes in the non-linear regime

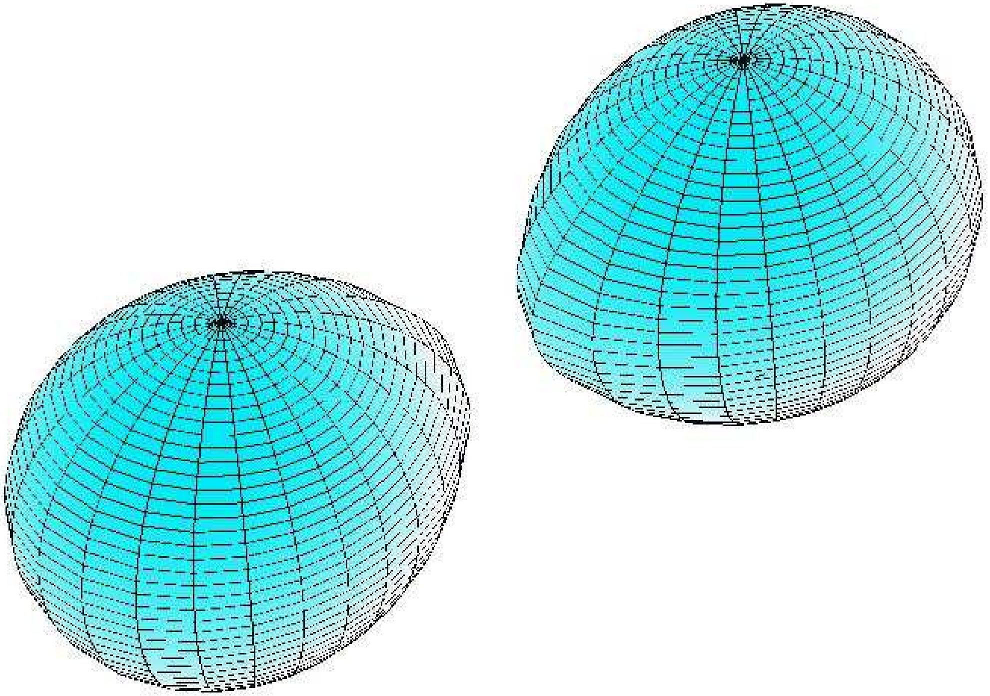


Binary neutron stars

S. Bonazzola, E. Gourgoulhon & P. Grandclément

Collaborations: Albert-Einstein Institut, Golm (Germany)

Quasi-equilibrium configuration of binary stars in general relativity (5/10 Einstein equations)



Multi-domain spectral methods (C++/LORENE)

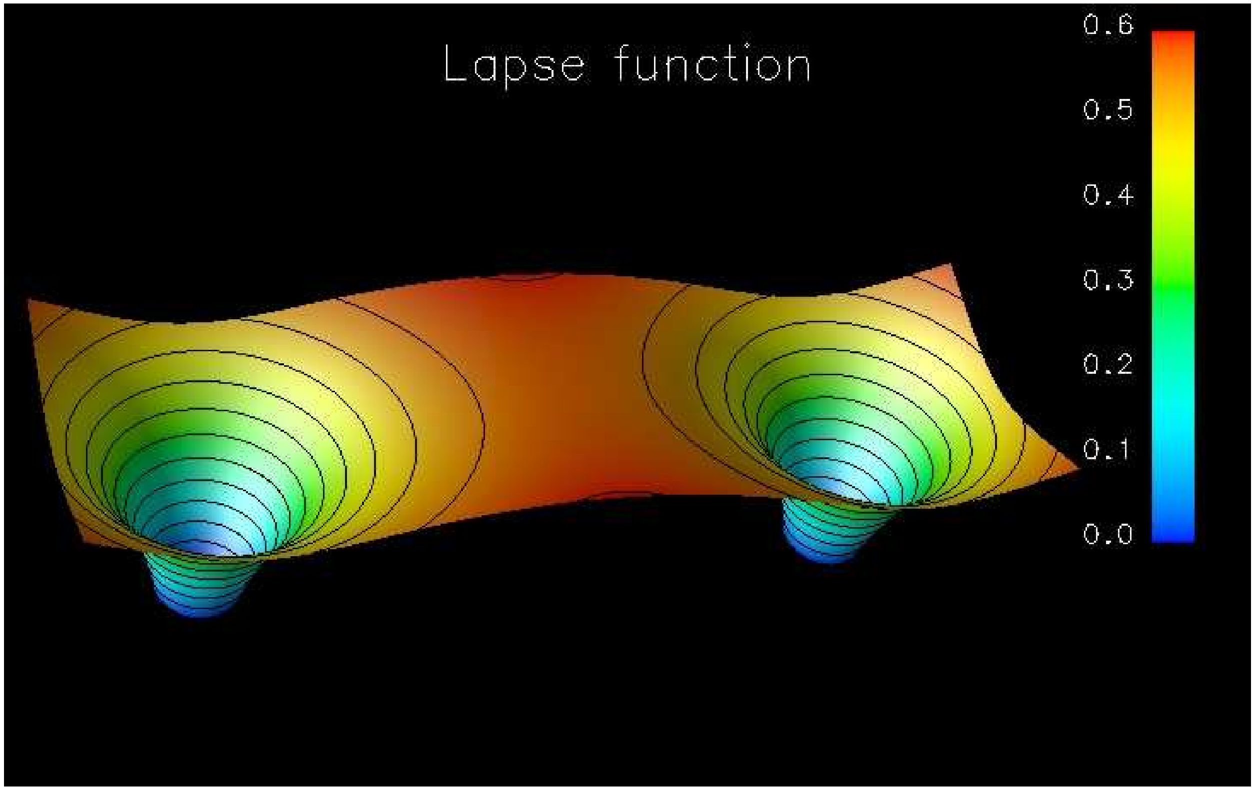
Irrotational binary neutron stars

$\Longrightarrow$ initial data for dynamical evolution

Binary black holes

S. Bonazzola, E. Gourgoulhon & P. Grandclément

First realistic computations of quasiequilibrium configurations of a black hole binary system

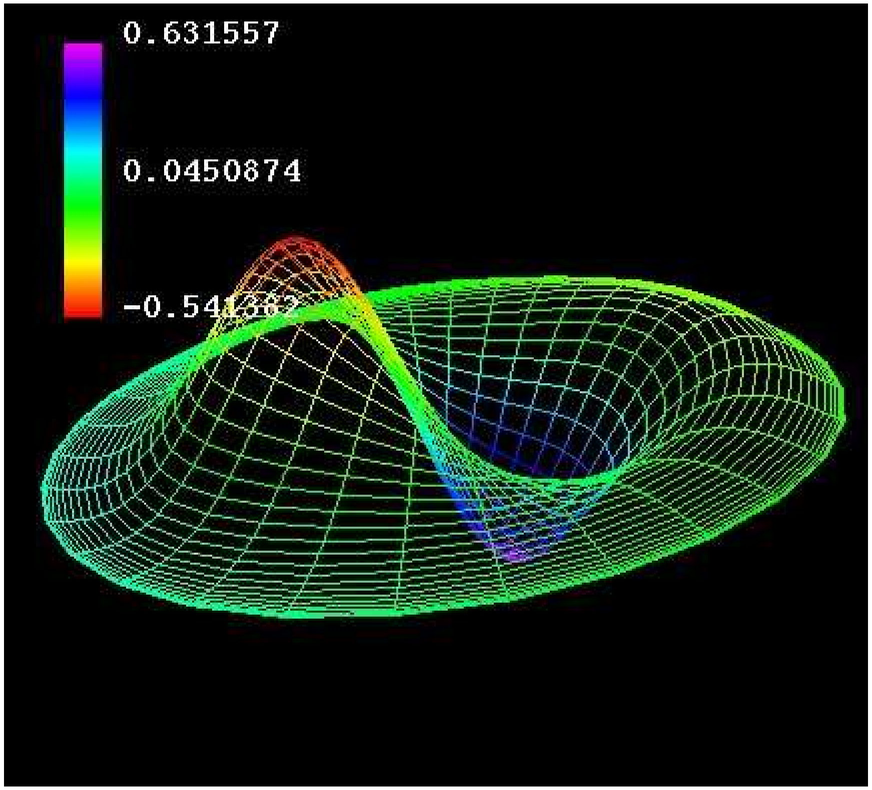


$\Longrightarrow$ Initial data for dynamical simulations

Spectral method for the wave equation

J. Novak

New numerical method with accurate outgoing boundary conditions



Gravitational waves from *supernovæ*

Jérôme Novak

SUPERNOVAE FORUM

Orsay, March 21st 2002

1. Gravitational waves
2. Detectors
3. Some astrophysical sources
4. Simulations of core collapses

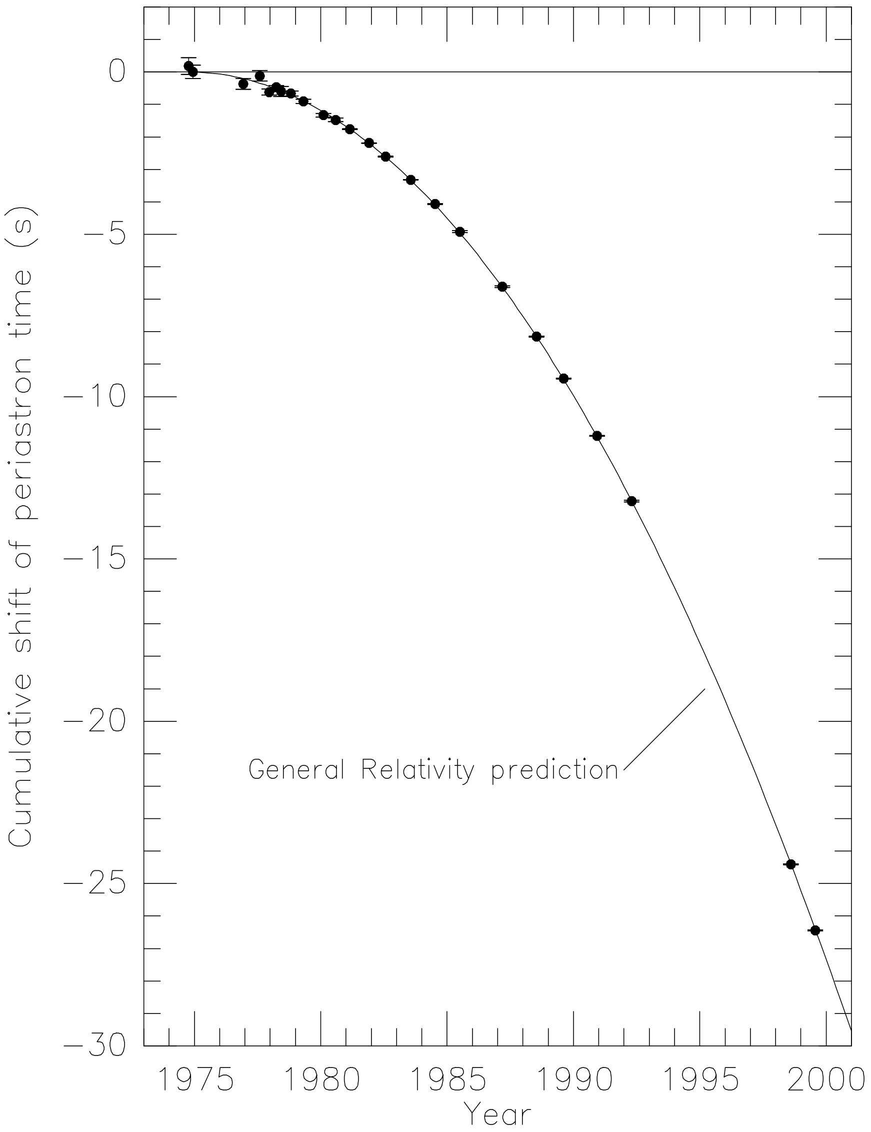
Gravitational waves

Within the theory of General Relativity, concentration of mass (or energy) warps spacetime. If this mass moves/changes shape, the warpage propagates
$\Rightarrow$ Gravitational Waves (in weak field).

Using linearised Einstein equations, one finds that:

- at first order, $h \sim \ddot{Q}$ (source quadrupole momentum);
- the effect of a wave on 2 test particles is their relative time-dependent displacement $\Delta l/l \simeq h$;
- to be efficient, a gravitational wave source needs to be compact $(R \sim R_S)$, relativistic $(v \sim c)$ and highly asymmetric.

$\Rightarrow$ astrophysical sources



Indirect detection of gravitational waves has been done by the timing of binary pulsars (PSR1913+16 by Hulse & Taylor, Nobel Prize in 1993).

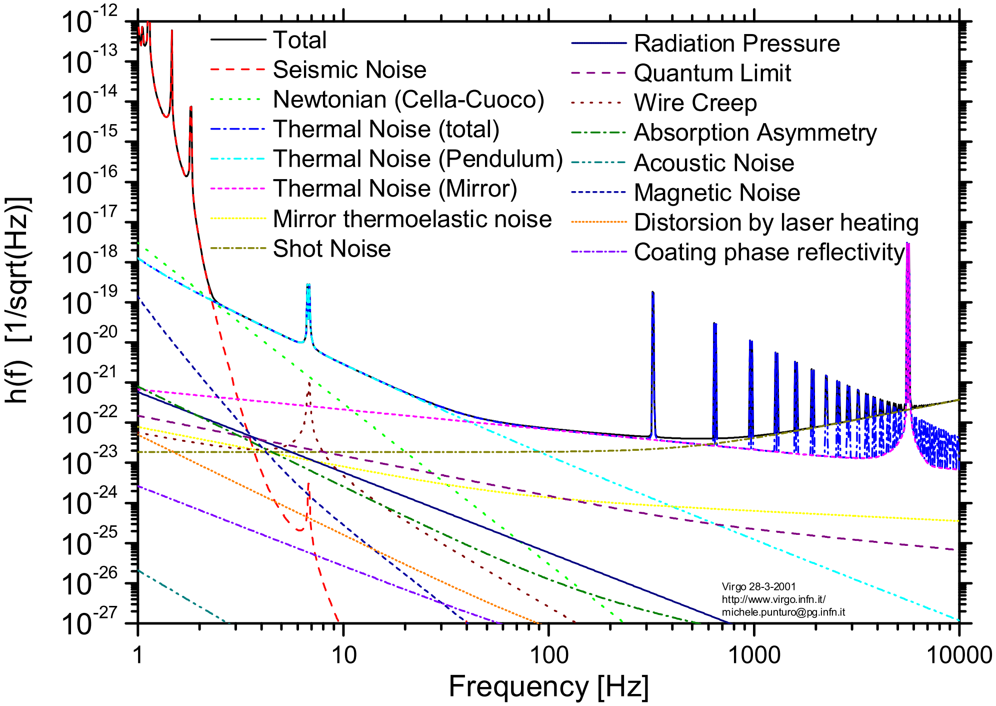
⇒ the system is loosing angular momentum exactly at the rate predicted by GR gravitational wave emission.

Detectors

2 types of detectors:

1. Resonant bars: resonant masses made of Al alloy, cooled cryogenically around 1 K. Five currently operating: EXPLORER, AURIGA, NAUTILUS (Italy); ALLEGRO (USA) and NIOBE (Australia). Very narrow bandwidth ($\sim 1Hz$) around $900\,Hz$ (NIOBE $\rightarrow 700\,Hz$). Network aimed at detecting stochastic background or burst signals in coïncidence.
2. Laser interferometers: Michelson type interferometers that measure the relative distance variation between both arms (test particles are the mirrors). One is currently operating: TAMA (Japan). Four are under construction: GEO600 (Germany), LIGO (2 detectors in USA) and VIRGO (Italy). Large bandwidth ($10 \rightarrow 6000\,Hz$ for VIRGO) which enables to follow a quasi-periodic source (binary systems of compact objects).

VIRGO



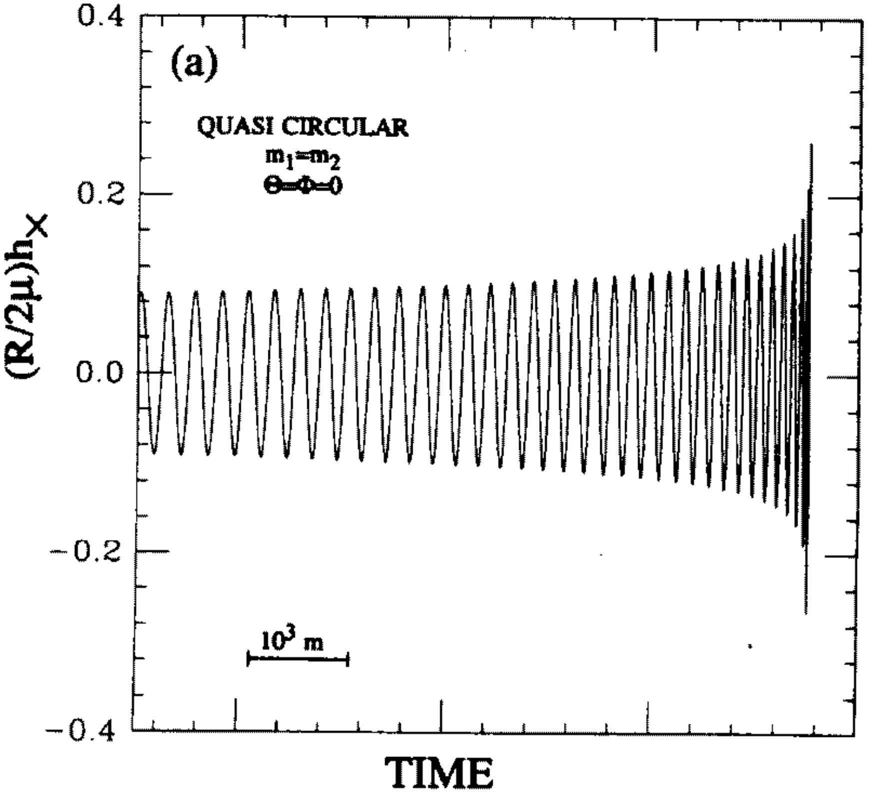
Virgo 28-3-2001
http://www.virgo.infn.it/
michele.punturo@pg.infn.it

Astrophysical sources

Compact objects moving with a relativistic speed, not too spherical.

For high frequencies (10 $Hz \longrightarrow$ 10 kHz):

- coalescing compact binaries (neutron stars, black holes)
- instabilities and deformations of neutron stars
- $supernov\ae$



$$h \sim 10^{-21}\,\frac{1\text{Mpc}}{r}\left[\frac{M}{M_\odot}\right]^{5/3}\left[\frac{f}{1\,kHz}\right]^{2/3}\,.$$

If integrating over n cycles, the signal-to-noise ratio increases as $\sqrt{n}$.

Numerical simulations of core collapses

Studies cannot be spherically symmetric – complicated physical phenomenon.

gravitational wave emission $\Longleftrightarrow$ bulk motion of matter

Simplifying assumptions: only hydro and gravitational evolutions are considered + analytical EOS

No calculation in full General Relativity. Up to very recently only Newtonian calculations:

- Bonazzola & Marck (1993) performed the first 3D simulation, stopping at the bounce. $\Rightarrow$ emitted GW is almost only sensitive to initial deformation and amplitude is very low: not detectable further than few kpc.
- Axisymmetric models (followed after the bounce) studied by Zwerger & Müller (1997) hardly more optimistic: radiated energy $6 \times 10^{-11} M_\odot c^2 \lesssim E_{GW} \lesssim 8 \times 10^{-8} M_\odot c^2$. Largest signals from rapidly and strongly differentially rotating cores.

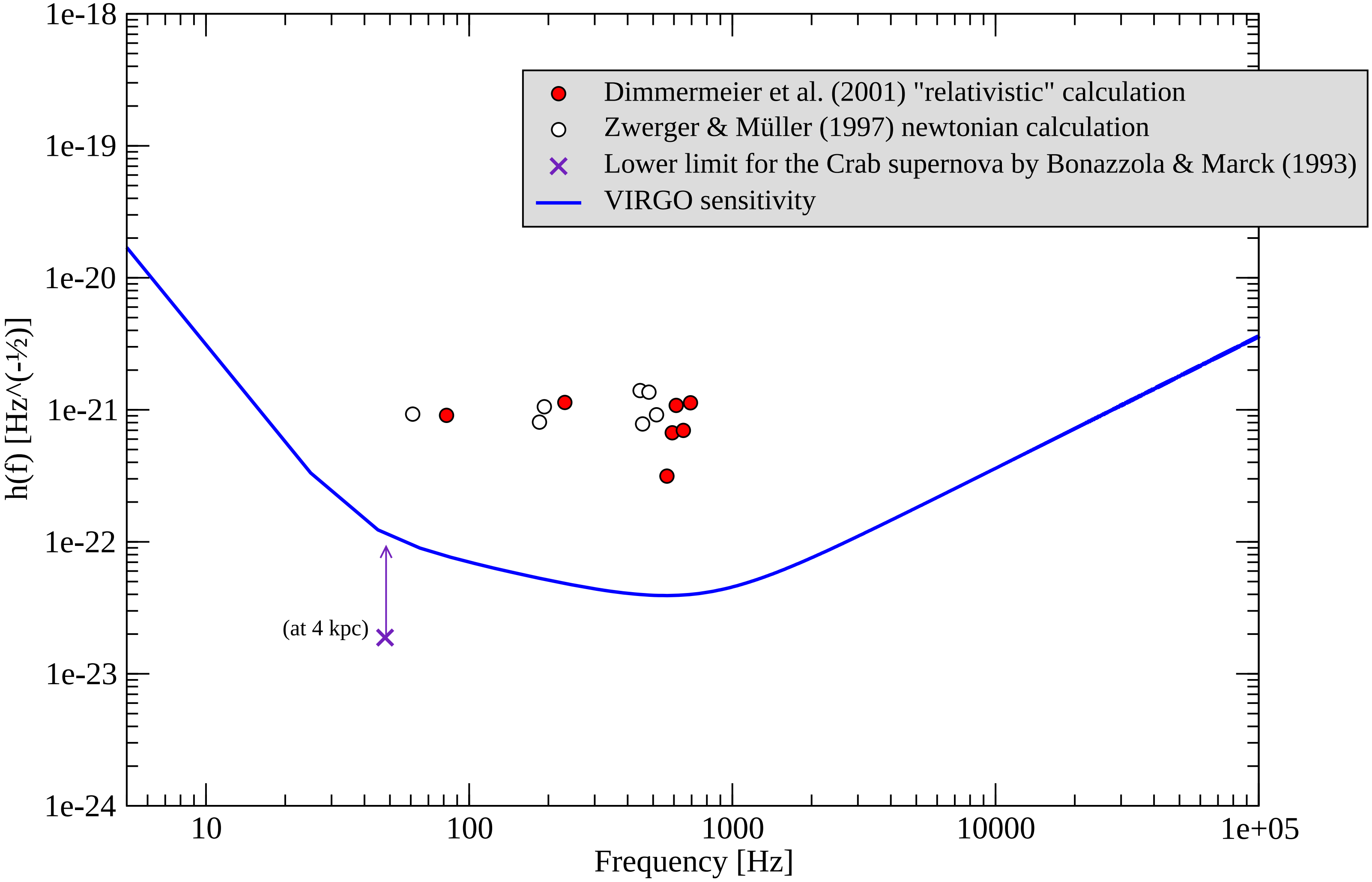
- Dimmelmeier *et al.* (2001) have considered models in General Relativity: GR hydro + Wilson approximation for the gravitational field ⇒ extraction of the wave by the quadrupole formula.

→ SN core dynamics are quite sensitive to GR effects.
→ Uncertainties on the progenitor (iron core) are greater than the GR effects.
→ Emitted energy in the range $2 \times 10^{-10} M_\odot c^2 \lesssim E_{GW} \lesssim 3 \times 10^{-7} M_\odot c^2$.
→ Change in the characteristic frequency of the emitted wave, but little change in the overall amplitude.

Relativistic gravitational potential is deeper than Newtonian:
⇒ central density is higher and the resulting object more compact.
BUT outer parts of the core a less dense.

Numerical simulations of core collapses

For a source situated at 10 kpc



Conclusions

- *Supernovæ* are rather spherically symmetric events and do not seem to be very efficient sources of gravitational radiation (we have to be lucky to get an explosion "sufficiently" close to us...).
- They result in "burst" signals, more difficult to detect than quasi-periodic ones.
- Optical and neutrino counterpart are interesting features.
- Can provide tests for General Relativity (looking for monopolar waves).
- Gravitational waves can provide us with informations from the most dense regions of a *supernova*.
- If models of the stellar progenitor could be improved ...