Bulk viscosity in Hybrid Stars

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Astro-ph/0312009

The problem

- R-modes in Compact Stars
- Gravitational waves , viscosity and Stability
- Quark Matter in Compact Stars and Color Superconductivity
- Instability of pure Quark Stars
- Hybrid stars. Are they stable?

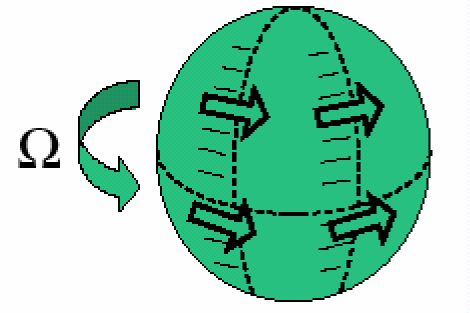
Bulk viscosity

- Bulk viscosity: dissipative process in which a perturbation of the pressure of a fluid element is converted into heat.
- R-modes vary the pressure and densities of the various particles.

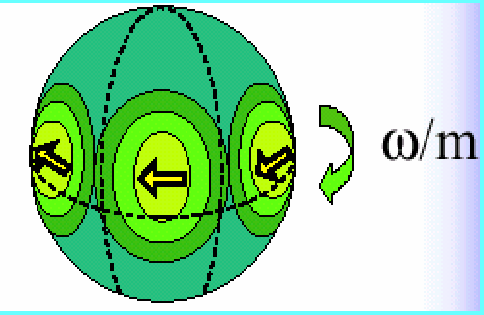
  Beta equilibrium is lost.
- Reactions between different particles drive the system back to the equilibrium with a delay depending on the characteristic time scale of the interaction.
- Bulk viscosity is dominated by the processes having time scale comparable with the period of the perturbation.
- “Fast” and “Slow” processes

R-modes in Compact stars

R-modes are solution of the perturbed Euler equation for the fluid composing a rotating star



A rotating neutron star



Perturbation in rotating frame

If $\Omega - \omega/m > 0$, star “drags” perturbations in opposite direction

Perturbations create rotating mass and momentum multipoles which emit GW which caries away positive angular momentum ⟺ Additive negative angular momentum to the perturbations. The mode amplitude increases

The r-modes are unstable to the emission of GWs at all rotation rates

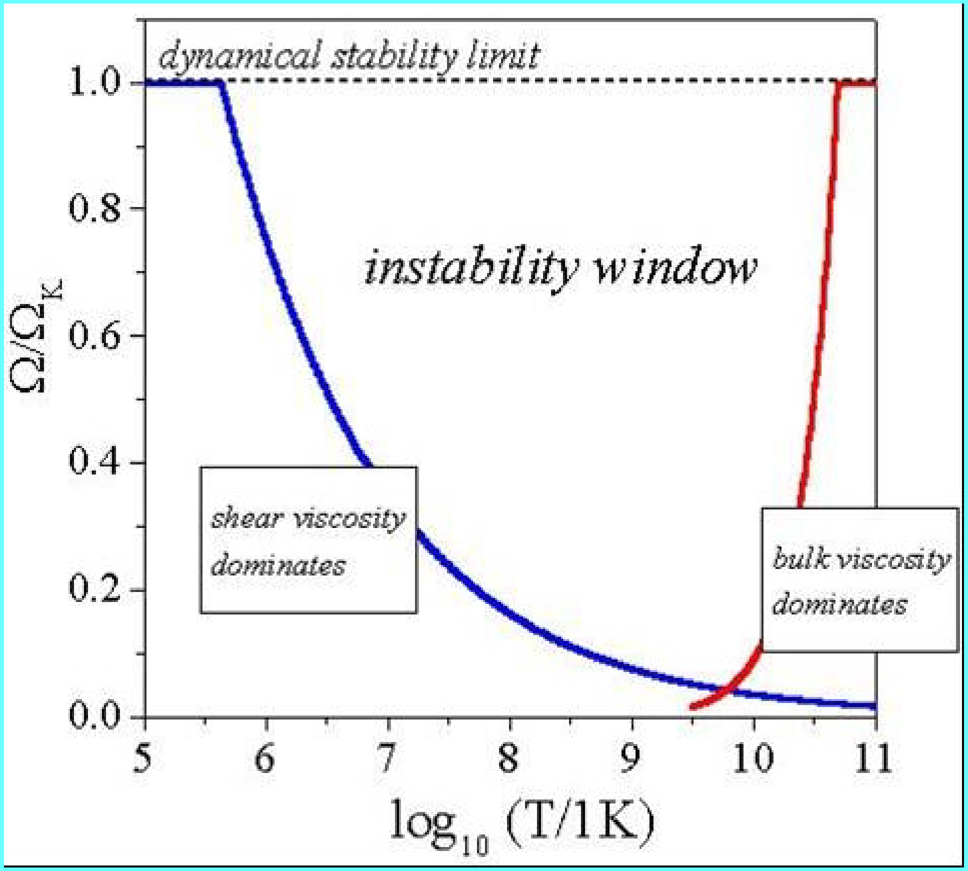
Possible effects in the frequency of Pulsars

R-modes in Neutron Stars

- Stability of a neutron star respect to r-modes: τ_{GR} and $\tau_{viscous}$
- Two type of viscosity:

  Shear viscosity (scattering processes) at low T

  Bulk viscosity (modified URCA processes) at high T
- There is a large window of T and Ω in which a Neutron star is unstable and loses a huge amount of its angular momentum in GWs.



L. Lindblom et al. Phys. Rev. Lett 80 (1998) 4843

R-mode instability put sever limits on the frequency of rotating neutron stars

R-modes in Hyperon Stars

At the high densities reached in a compact star it is possible to form hyperonic matter

With Λ and Σ hyperons various non-leptonic weak processes which produce a rather large bulk viscosity

$$n + n \xleftrightarrow{H_W} p + \Sigma^-$$

$$n + p \xleftrightarrow{H_W} p + \Lambda$$

L. Lindblom, Phys. Rev. D (2002) 063006

R-modes instability is suppressed at T ~ 10^9 K. A small window of instability is still open for T~10^{10}K and for Ω larger than 0.3 $\Omega_{\text{Keplerian}}$

R-modes in Quark Stars

Strange quark matter has a large bulk viscosity due to the weak process:

$$\boxed{d + u \overset{H_W}{\longleftrightarrow} u + s}$$

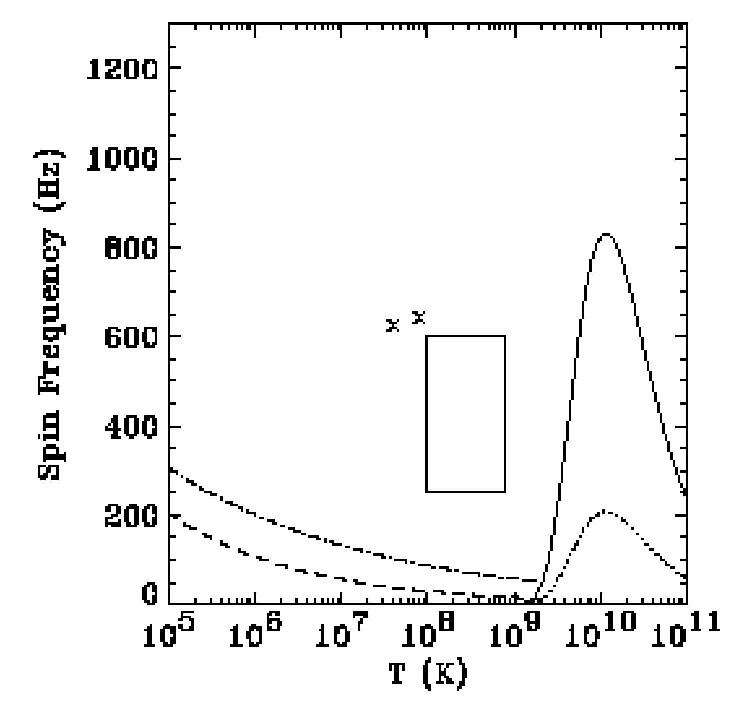
QCD at high density:

Color Superconducting Phase in

Compact Stars

Color Flavor Locking (CFL) :
all 9 quarks pair with energy
gap ~ 100 MeV

2SC : 4 quark pair



J. Madsen , Phys. Rev. Lett. 85 (2000) 10

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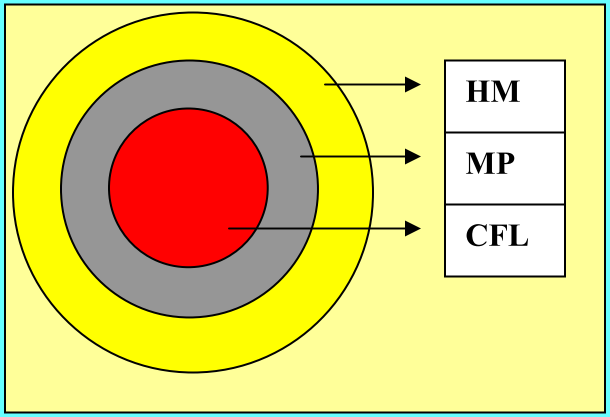
Bulk viscosity is strongly reduced by the energy gap.

CFL stars are instable

What about Hybrid Stars ?



Mixed phase : nuclear (hadronic) – quark (superconducting quark) phases

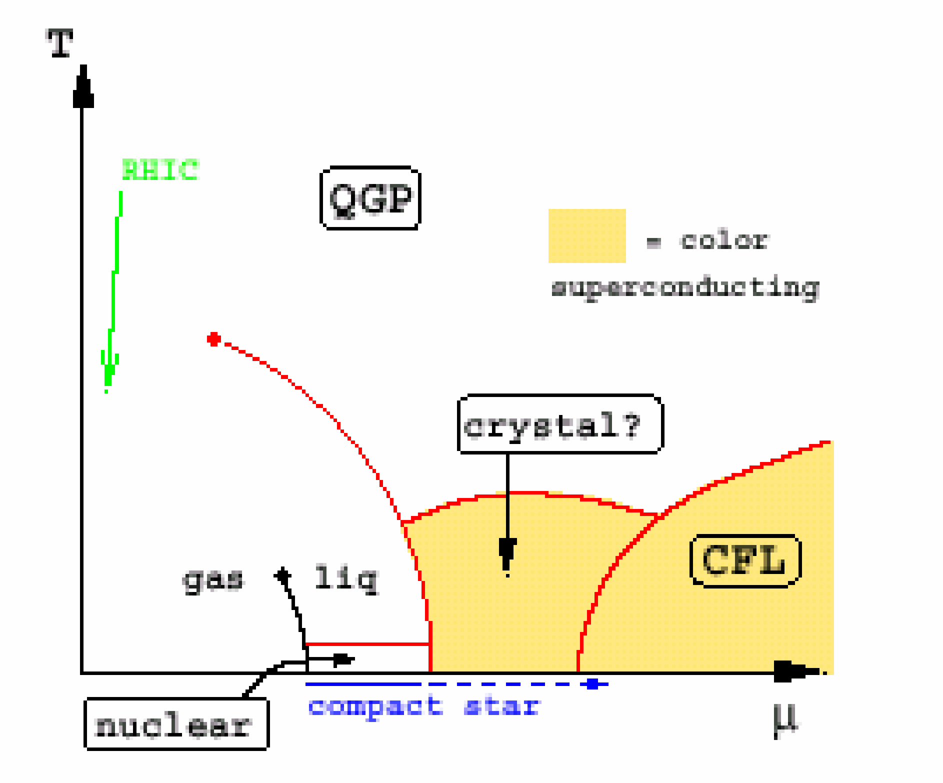
In presence of Color Superconductivity

How large is bulk viscosity of the mixed phase ?

Are Hybrid Stars stable respect to r-modes?

QCD at High Density

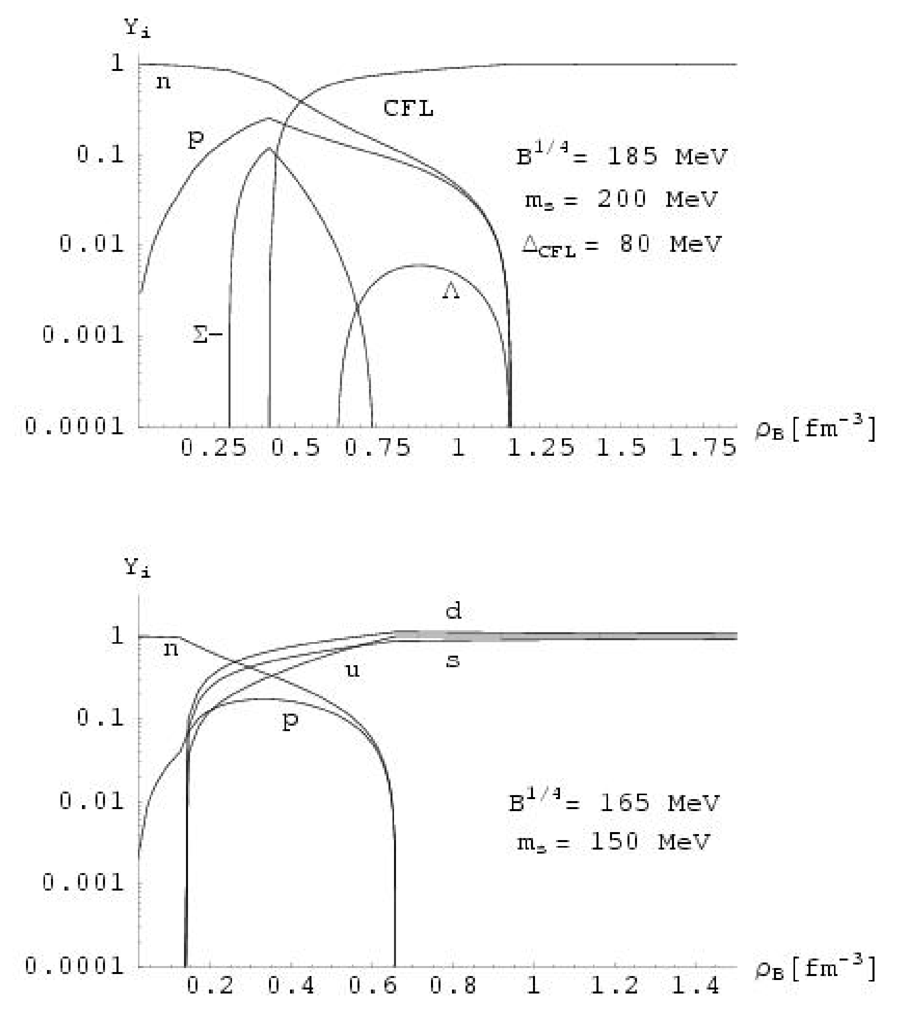
- Direct Hadrons-CFL transition.
- At low density:
  - Unpaired QM
  - 2SC
  - Gapless CFL
  - Crystalline CS
  - Mixed CS phases



M. Alford hep-ph/0209287

Equation of State of mixed phase

- Hadronic phase: Walecka type model with inclusion of Hyperons
- Quark phase: Color Flavor Locking phase (CFL) quark matter – Unpaired quark matter in MIT bag model
- Gibbs conditions for mixed phase
- Two possible scenarios depending on the value of the critical density.



First scenario: CFL - Hyperons MP

$n + n \Leftrightarrow \Sigma^- + p$

$n + p \Leftrightarrow p + \Lambda$

Slow processes mediated by weak interaction

$n + \Lambda \Leftrightarrow p + \Sigma^-$

$\Lambda + \Lambda \Leftrightarrow 2\,(u\,d\,s)_{CFL}$

Fast processes mediated by strong interaction

Second scenario: Quark - Nucleon MP

$d + u \Leftrightarrow u + s$

Slow process mediated by weak interaction

$n \Leftrightarrow u\,d\,d$

$p \Leftrightarrow u\,u\,d$

Fast processes mediated by strong interaction

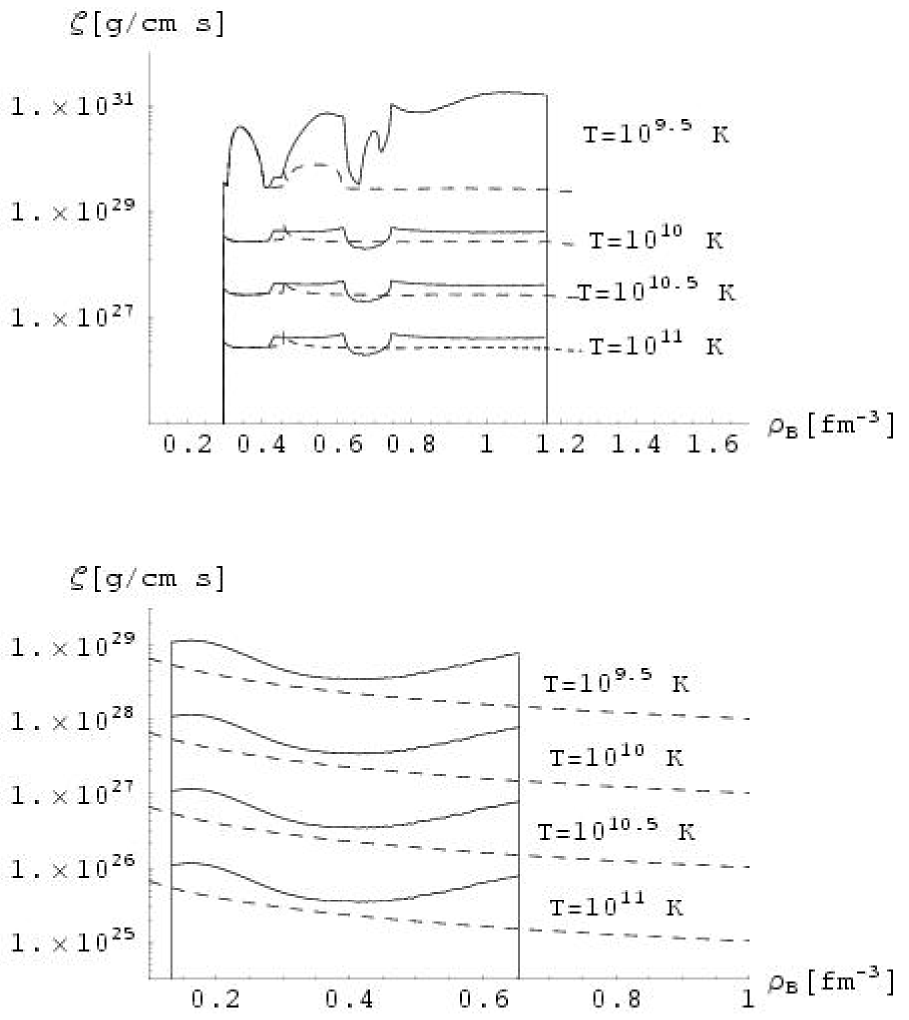
Baryon number conservation, charge neutrality and mechanical equilibrium have to be imposed during the perturbation

Relaxation associated to the weak reactions:

$$\frac{1}{\tau} = \left(\frac{\Gamma_\Lambda}{\delta\mu} + 2\frac{\Gamma_\Sigma}{\delta\mu}\right)\frac{\delta\mu}{\delta\rho_n}$$

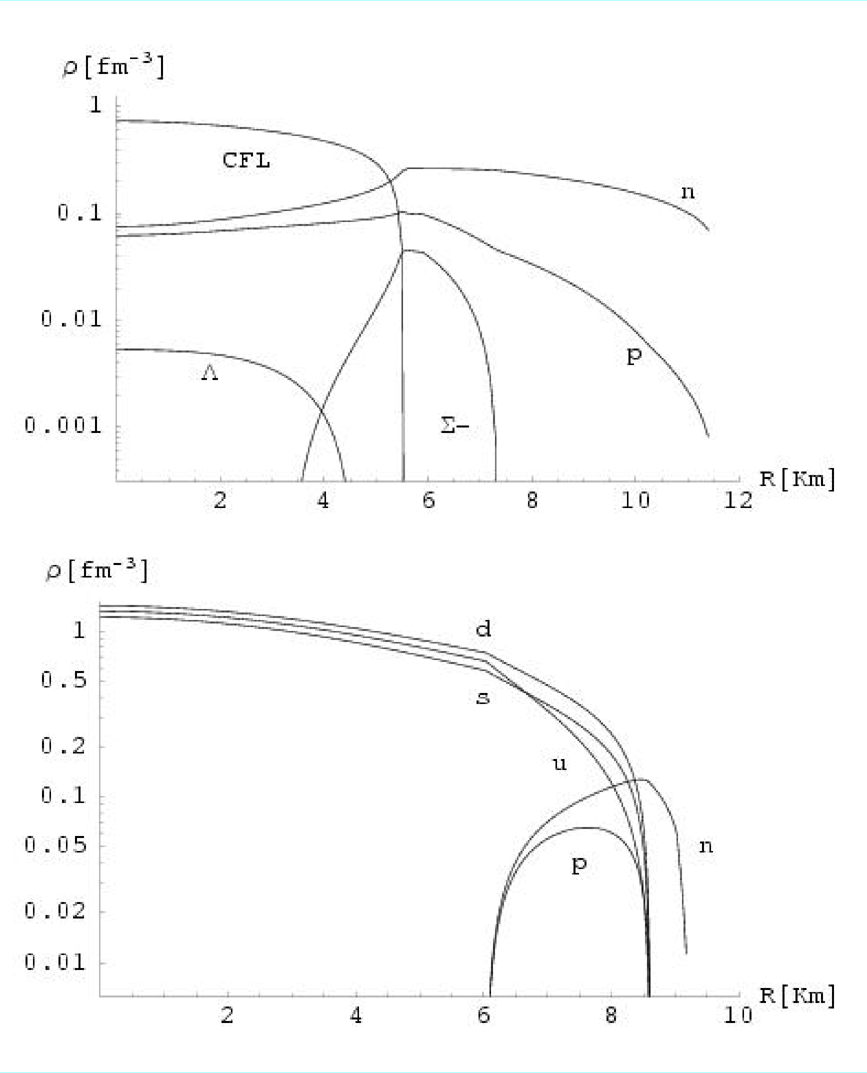
Bulk viscosity:

$$\zeta = \frac{P(\gamma_\infty - \gamma_0)\tau}{1+(\omega\tau)^2}$$



Hybrid stars structure

Particle densities profiles for a 1.46 M_{sun} star in the two possible scenarios

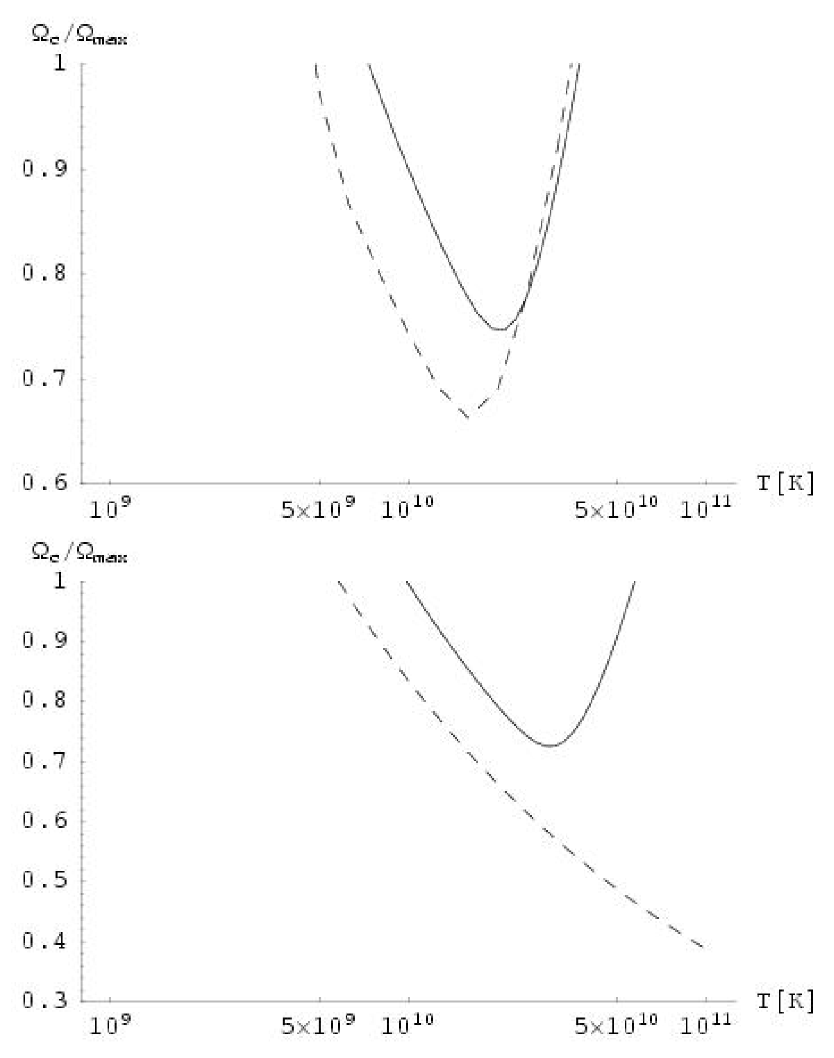


Hybrid stars stability

The critical angular velocity is the value of Ω for which the imaginary part of the r-mode frequency vanishes:

$$\boxed{-1/\tau_{GR} + 1/\tau_B + 1/\tau_{B(URCA)} = 0}$$

Times scales associated to the GW emission and to dissipative processes due to bulk viscosity



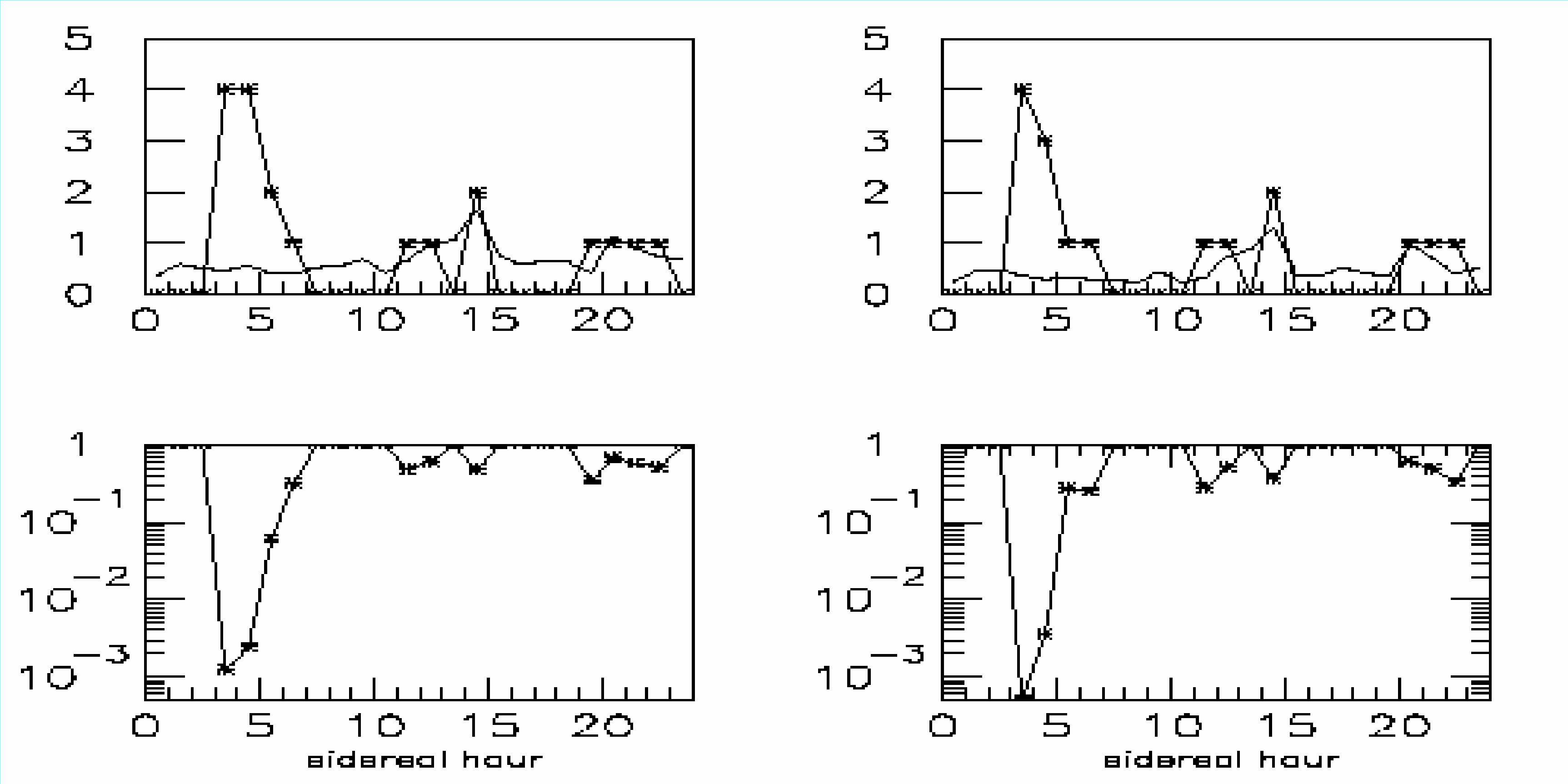
Gravitational Waves emission

- R-modes instability is an efficient mechanism to produce GWs
- The stability depends strongly on the composition of the star
- GWs as probe of internal composition, GW Astronomy.
- New GW detectors LIGO VIRGO

Some interesting data:
data from EXPLORER and NAUTILUS in years 1998 and 2001

- Search for 1 msec GW bursts (Integrating on all the frequencies).
- Total measuring time 90 days.
- Analysis of the coincidences between events detected by the two Antennas.

Data of 2001



Excess of coincidences at the sidereal hour 4 .

Bars oriented perpendicuraly to direction of the center of the Galaxy

Maximum of sensitivity for galactic sources.

Results

- From 3 - 5 sidereal hour, 6 coincidence excesses in 5 days.
- Correlation between the energies deposited in the bars
- Temporal clustering of events.
- GW burst lasting 1msec with $h \sim 2 \times 10^{-18}$
- No neutrinos in coincidence (LVD)

$$\Delta E_{\rm rad} \simeq 10^{-2} M_\odot c^2 \left(\frac{E_s}{100\,{\rm mK}}\right)\left(\frac{r}{8\,{\rm kpc}}\right)^2\left(\frac{f_{\rm max}}{1{\rm kHz}}\right)^3.$$

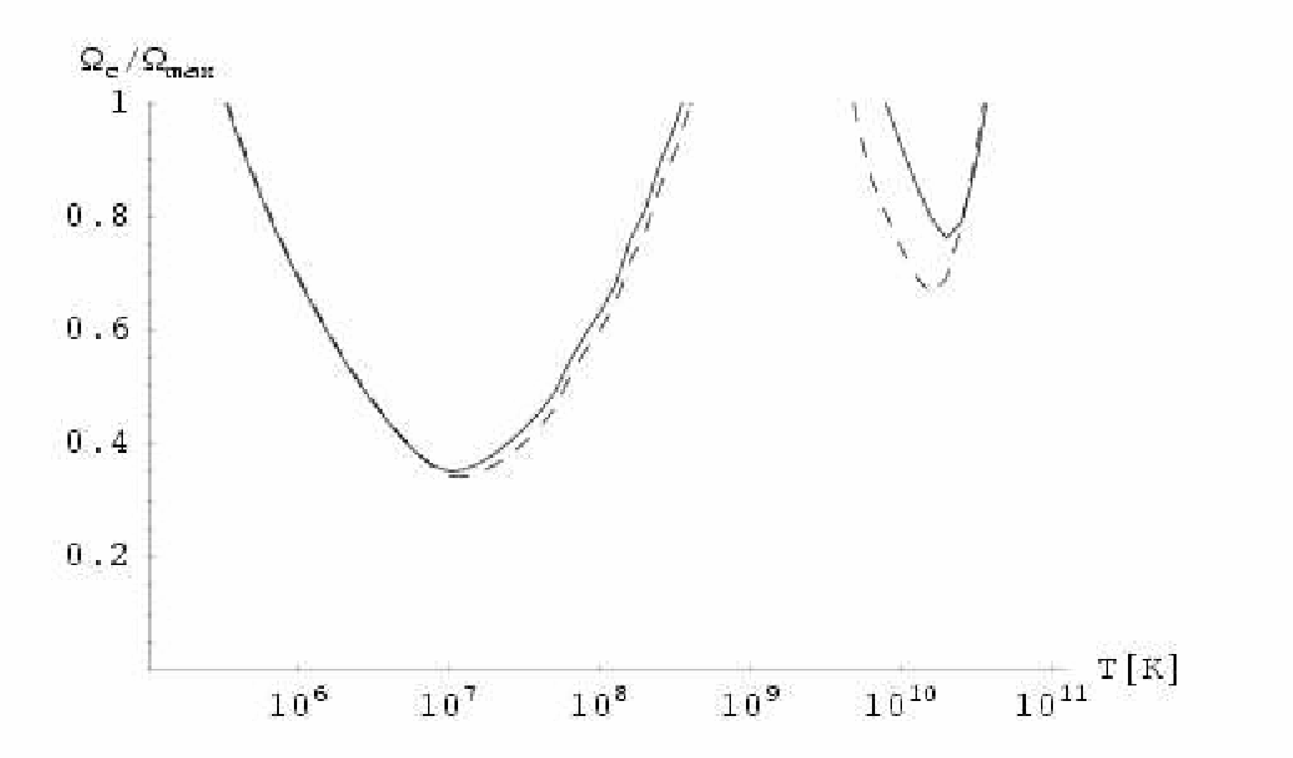
Energy deposited in the bar $E_s \sim 100$mK.

New data of 2003 seem to confirm (and support) these results

Our model ingredients :

- GW emission by Rotating Compact Stars
- R-modes induced Spin down
- Hybrid Star containing a core of Mixed Phase
- Surface tension and phase transitions induced by Spin down
- Sudden changes in composition and structure
- Mini collapses generating highly energetic GW bursts

Two Instabilty Windows



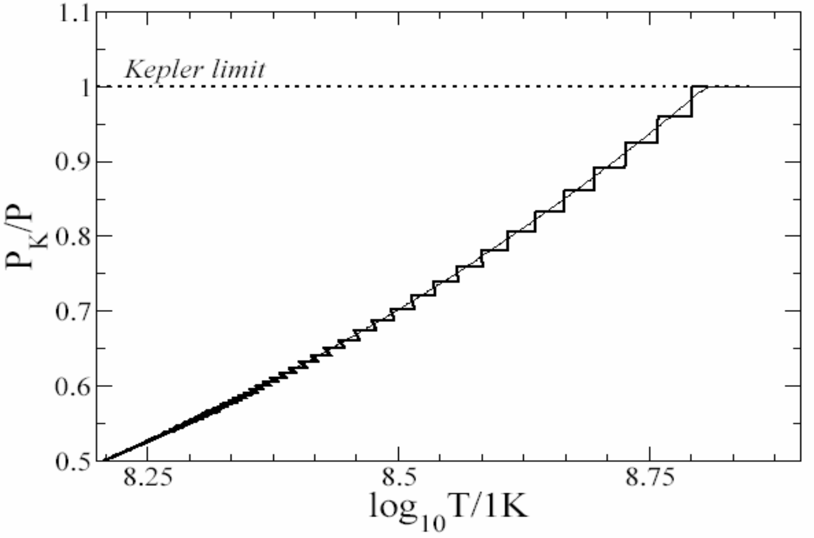
In Compact Stars containing hyperons or quark, the r-mode instability window is splitted into two windows at low and high temperature

Time evolution of Ω α T:

$$\frac{\dot{\alpha}}{\alpha} = \frac{-1}{t_g} - \left(1 - \frac{3\alpha^2 \tilde{J}}{2\tilde{I}}\right)\left(\frac{1}{t_v}\right) - \frac{\dot{M}}{2\tilde{I}\Omega}\left(\frac{G}{MR^3}\right)^{\frac{1}{2}} \quad (1)$$

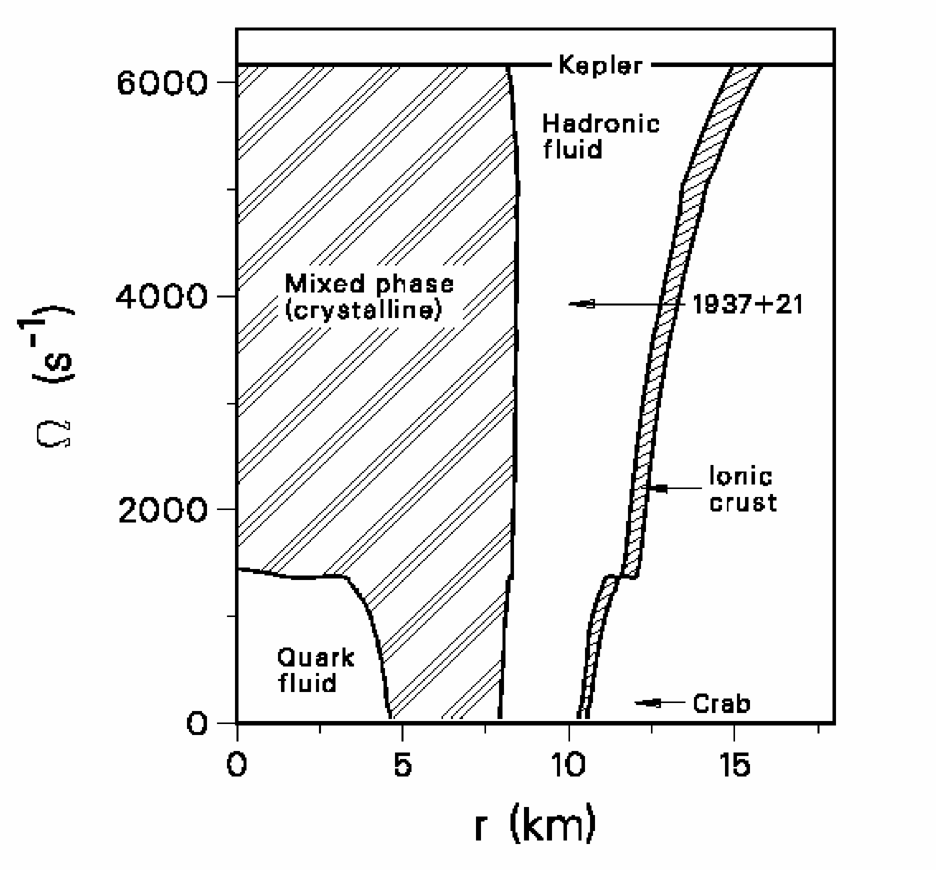
$$\dot{\Omega} = \frac{\dot{M}}{\tilde{I}}\left(\frac{G}{MR^3}\right)^{1/2} - \frac{\dot{M}\Omega}{M} - 3\Omega\alpha^2\frac{\tilde{J}}{\tilde{I}}\left(\frac{1}{t_v}\right) \quad (2)$$

$$\dot{E}_{\text{thermal}} = \dot{E}_{\text{accretion}} + \dot{E}_{\text{viscosity}} - \dot{E}_{\text{neutrino}} \,. \quad (3)$$



Phase transition induced by Spin Down

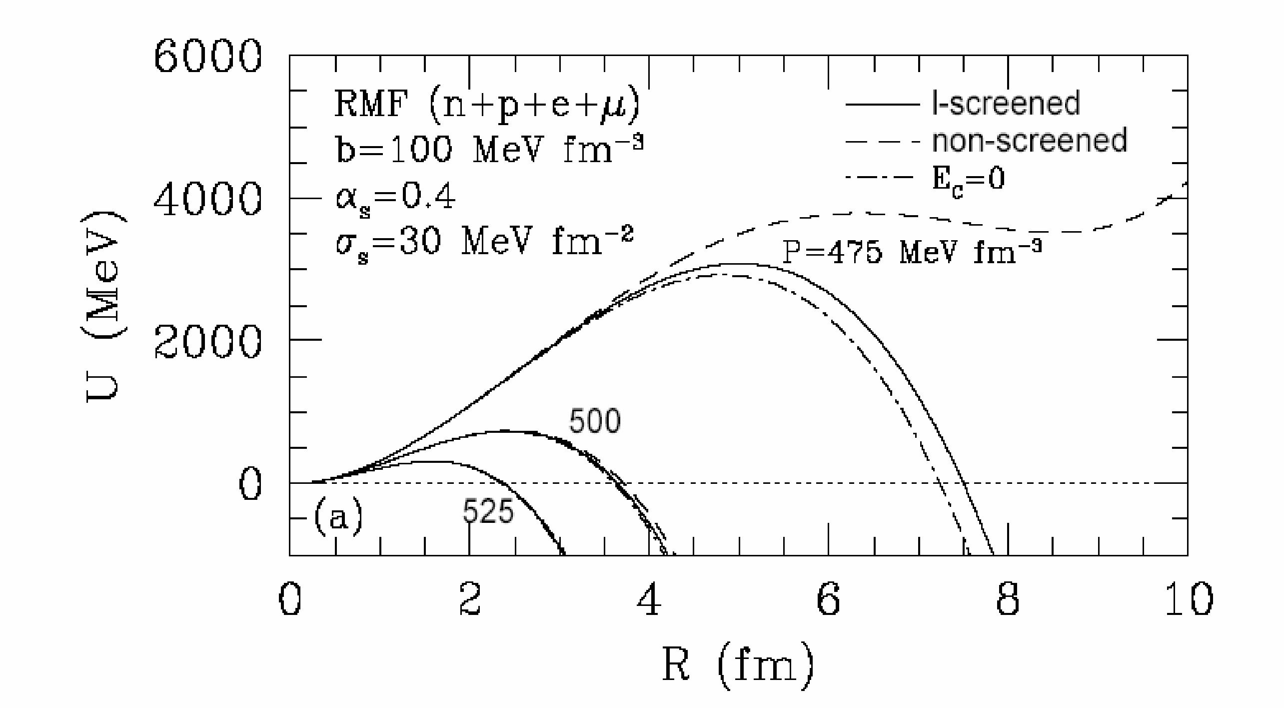
- During spin down the central density increases until reach the critical density
- Phase transition
- Changes in composition and structure
- ΔR ~ 5 km



N.Glendenning PRL 79,1603

The effect of Surface Tension:

The phase transition does not occur until a critical value of the over pressure is reached



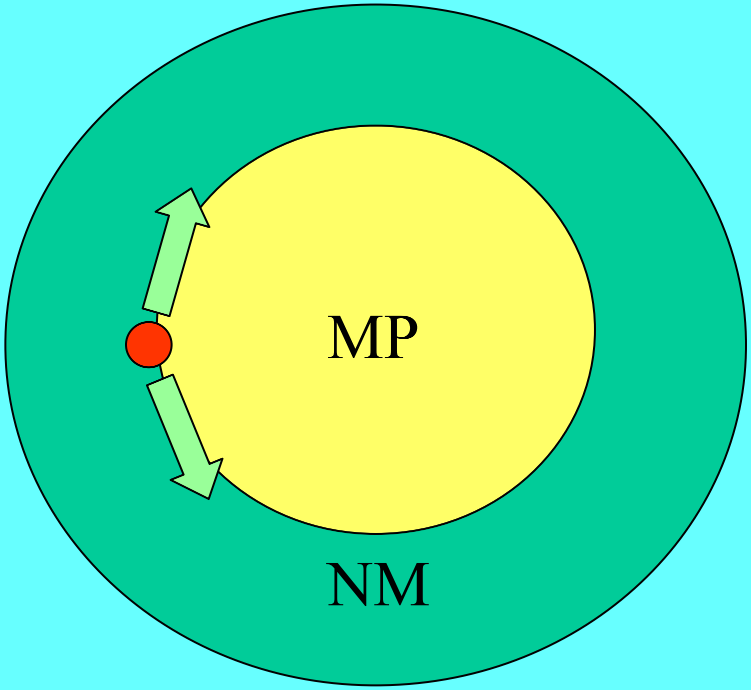
K.Iida & A.Sato, Phys.Rev.C 58,2538

Collecting the ingredients:

- R-mode instability is a very efficient mechanism for a Compact Star to slow down (10 – 20 % in 10 years)
- Spin down triggers phase transitions
- The structure modification are discontinous due to the metastability if σ is considered
- Sudden variation of Radius of the star and GW burst emission. Starquake activity.

GW bursts

The process of conversion in one site into the star propagates with a finite velocity inside the star and a sudden modification of the radius occurs. Non radial modes develops and GW bursts can be emitted before a new equilibrium configuration is reached



- Total $\Delta\Omega/ \Omega \sim 20\%$ in ten years by r-mode instability
- Increase of the pressure of roughly the same amount
- A few periods of "GW burst activity" in ten years

Energy of GW bursts

$E = M\,(\Delta R/R)^2$

M mass in quadrupole motion

For each mini-collapses $\Delta R/R \sim 2 - 3 \times 10^{-3}$

$E \sim 0.5\ \text{-}1 \times 10^{-5}$ Solar masses

(It can be one order of magnitude larger in more realistic calculations)

Four order of magnitude larger respect to SGR

Energy scale of hadronic physics vs atomic nuclear physics

For a flat distribution
of frequencies

$$E_{GW} = \frac{4\pi^2 d^2 \tilde{h}^2}{3G}\left(f^3_{\max} - f^3_{\min}\right)$$

$$\begin{aligned} \tilde{h} &= \frac{\sqrt{3}}{2\pi d}\frac{1}{f^{3/2}_{\max}}\frac{\Delta R}{R}\sqrt{GM} \\ &= 2\times 10^{-19}\frac{\Delta R}{R}\left(\frac{1\mathrm{kHz}}{f_{\max}}\right)^{3/2}\left(\frac{1\mathrm{kpc}}{d}\right)\left(\frac{M_\odot}{M}\right)^{1/2} \end{aligned}$$

The measured value of the amplitude is 2.5 × 10^{-22} sec

In agreement with the model for ΔR/R ~ 10^{-2}

D = 1 kpc

A. Drago, G. Pagliara, Z. Berezhiani gr-qc/0405145

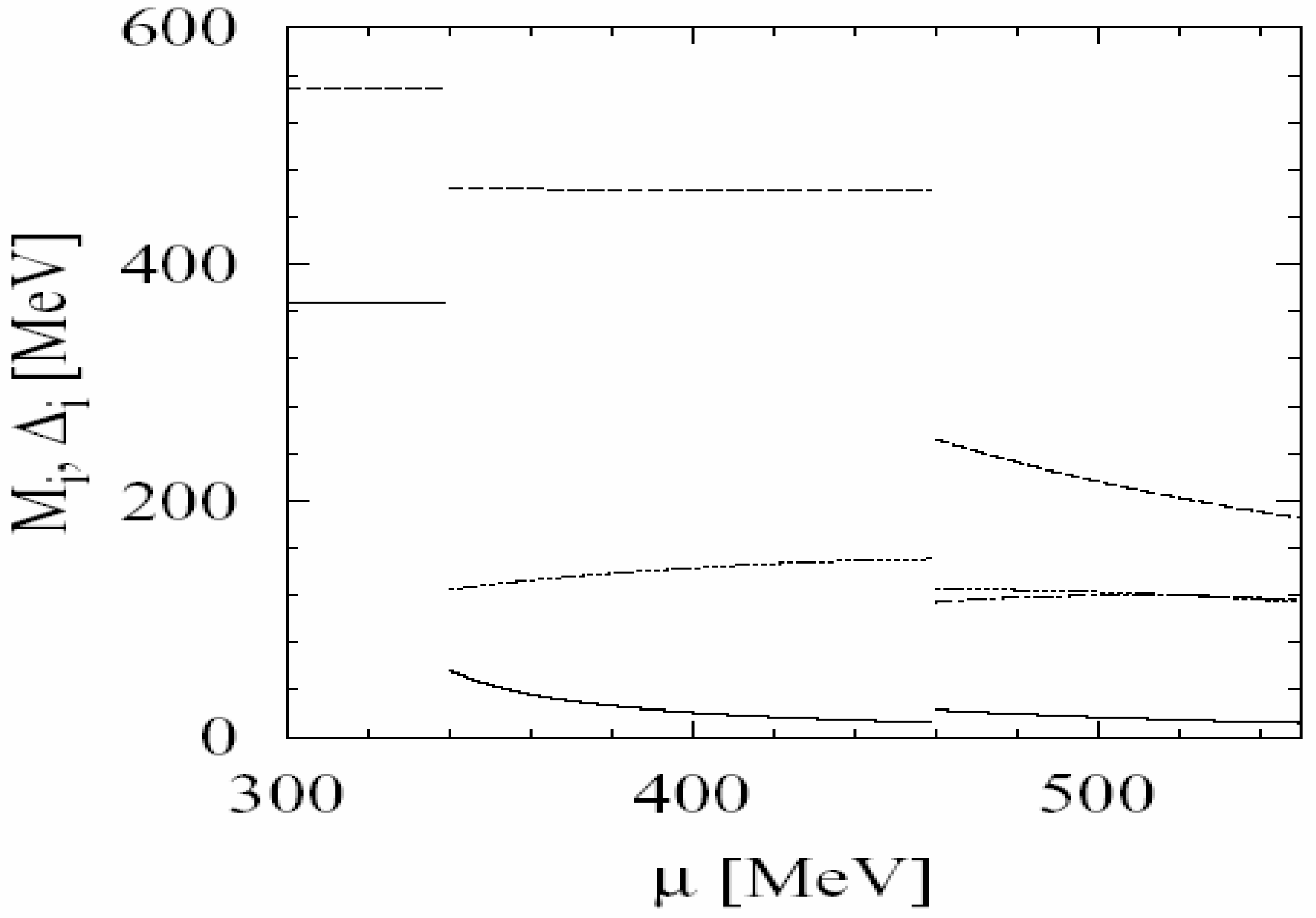
Conclusions

Hybrid Stars, containing a Color Superconducting phase, are generally stable respect to r-modes at high T.

Hybrid Stars spinning down by r- mode instability can be powerful sources of GW bursts.

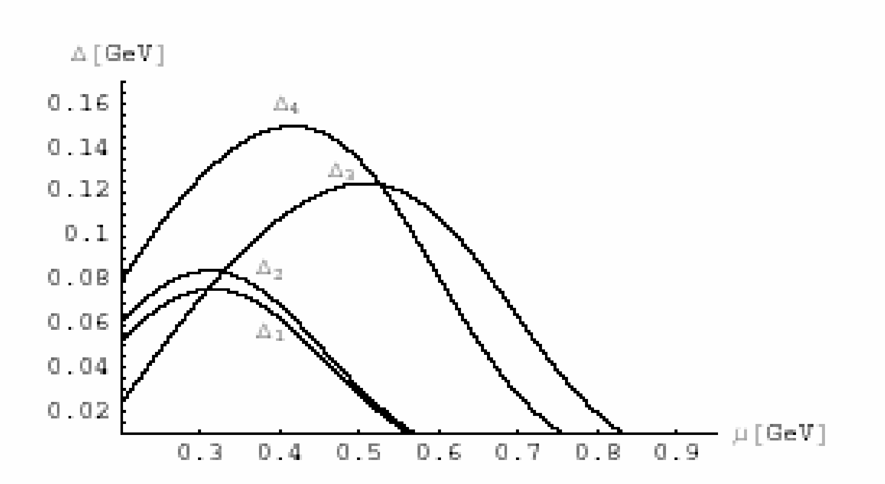
Chiral and CS gaps

Neumann, Buballa, Oertel, NPA 714 (2003) 481



Effects of CS in compact stars

From QCD at high density: u,d,s form Cooper pairs with binding energy ~ 100 MeV in the CFL phase.

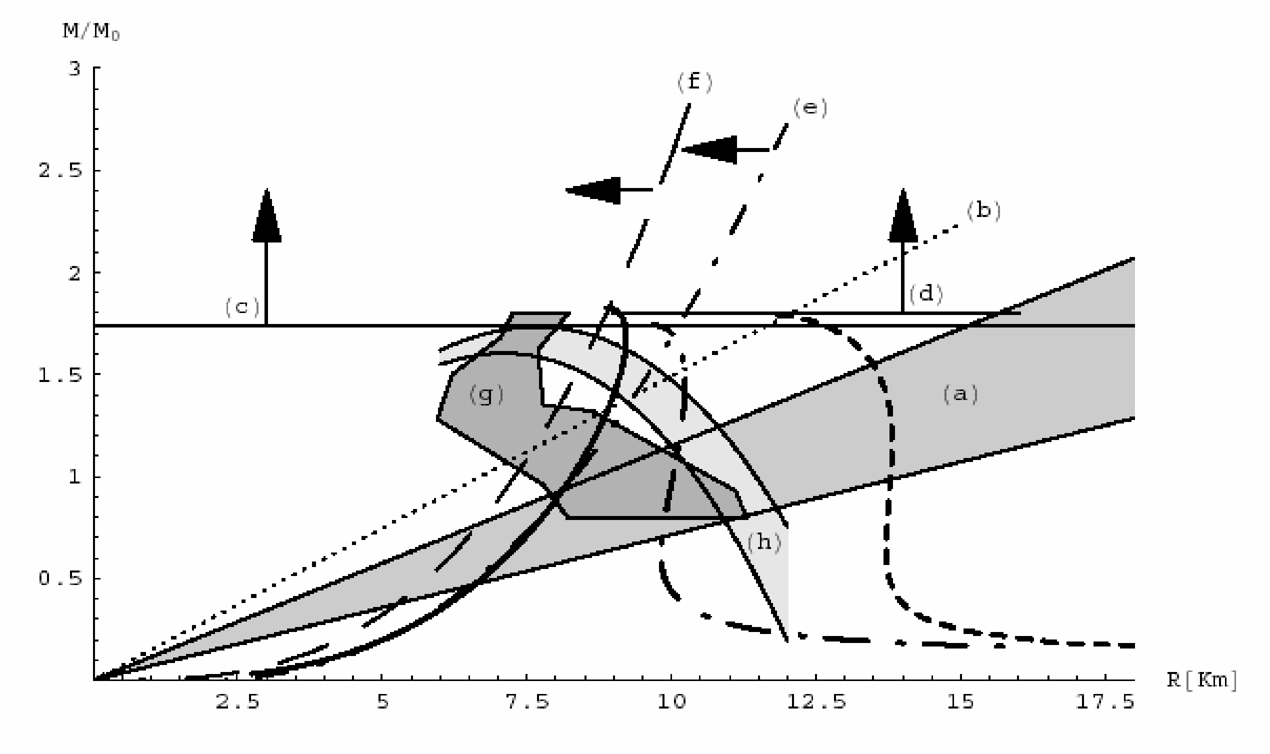


The changes in the EOS of quark phase are important at the energy scale involved in NS.

$$\begin{aligned}\Omega_{CFL} &= \frac{6}{\pi^2}\int_0^{\nu} k^2(k-\mu)\,\mathrm{d}k \\ &+ \frac{3}{\pi^2}\int_0^{\nu} k^2(\sqrt{k^2+m_s^2}-\mu)\,\mathrm{d}k - \frac{3\Delta^2\mu^2}{\pi^2}\end{aligned}$$

Mass – Radius relation of compact stars

A.Drago, G.Pagliara and A.Lavagno, PRD 69 (2004) 057505



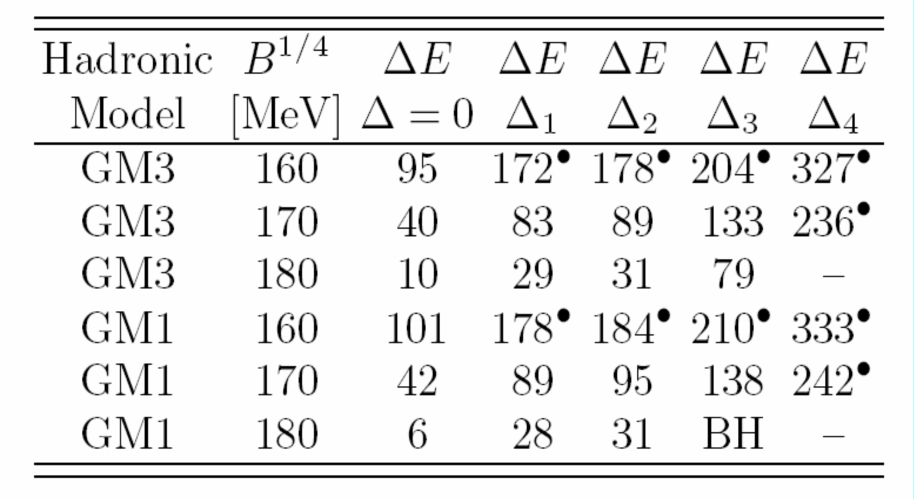
Two families of Compact Stars: (metastable) hadronic stars and stable stars containg deconfined quark matter.

Conversion processes

The energy released in the conversion process from a (metastable) HS into a (stable) HyS or QS is strongly increased by the presence of the Color Superconducting Phase

First Scenario

The conversion takes place immediately after deleptonization of PNS.

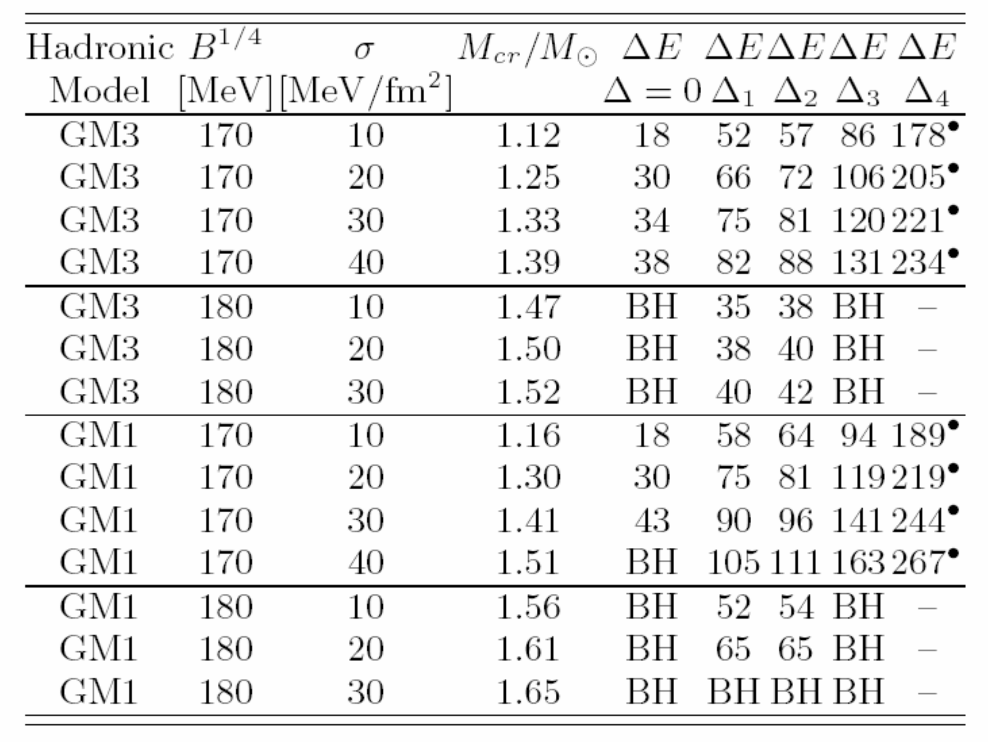


Hadronic Model	$B^{1/4}$ [MeV]	ΔE $\Delta = 0$	ΔE Δ_1	ΔE Δ_2	ΔE Δ_3	ΔE Δ_4
GM3	160	95	$172^\bullet$	$178^\bullet$	$204^\bullet$	$327^\bullet$
GM3	170	40	83	89	133	$236^\bullet$
GM3	180	10	29	31	79	–
GM1	160	101	$178^\bullet$	$184^\bullet$	$210^\bullet$	$333^\bullet$
GM1	170	42	89	95	138	$242^\bullet$
GM1	180	6	28	31	BH	–

The huge amount of energy released could help Supernovae to explode!

Second Scenario

If the surface tension of Quark Matter is taken into account, the conversion can be delayed (1 year in table)



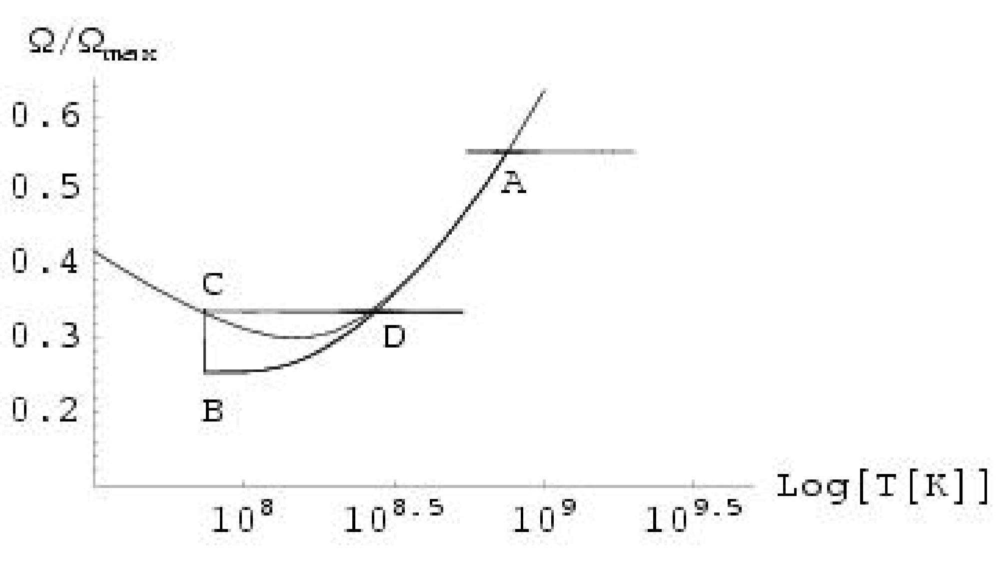
Hadronic Model	$B^{1/4}$ [MeV]	σ [MeV/fm^2]	$M_{cr}/M_\odot$	ΔE $\Delta=0$	ΔE Δ_1	ΔE Δ_2	ΔE Δ_3	ΔE Δ_4
GM3	170	10	1.12	18	52	57	86	$178^\bullet$
GM3	170	20	1.25	30	66	72	106	$205^\bullet$
GM3	170	30	1.33	34	75	81	120	$221^\bullet$
GM3	170	40	1.39	38	82	88	131	$234^\bullet$
GM3	180	10	1.47	BH	35	38	BH	–
GM3	180	20	1.50	BH	38	40	BH	–
GM3	180	30	1.52	BH	40	42	BH	–
GM1	170	10	1.16	18	58	64	94	$189^\bullet$
GM1	170	20	1.30	30	75	81	119	$219^\bullet$
GM1	170	30	1.41	43	90	96	141	$244^\bullet$
GM1	170	40	1.51	BH	105	111	163	$267^\bullet$
GM1	180	10	1.56	BH	52	54	BH	–
GM1	180	20	1.61	BH	65	65	BH	–
GM1	180	30	1.65	BH	BH	BH	BH	–

Possible engine for GRB subsequent to SN explosions

Physical Interpretation

- Soft Gamma Repeaters:
  - high magnetic field of “magnetars”
  - breaking of the Crust and GW bursts emission
  - low values of rigidity of the Crust
  - energy released $\sim 10^{-9}$ solar masses
  - density in our Galaxy ?

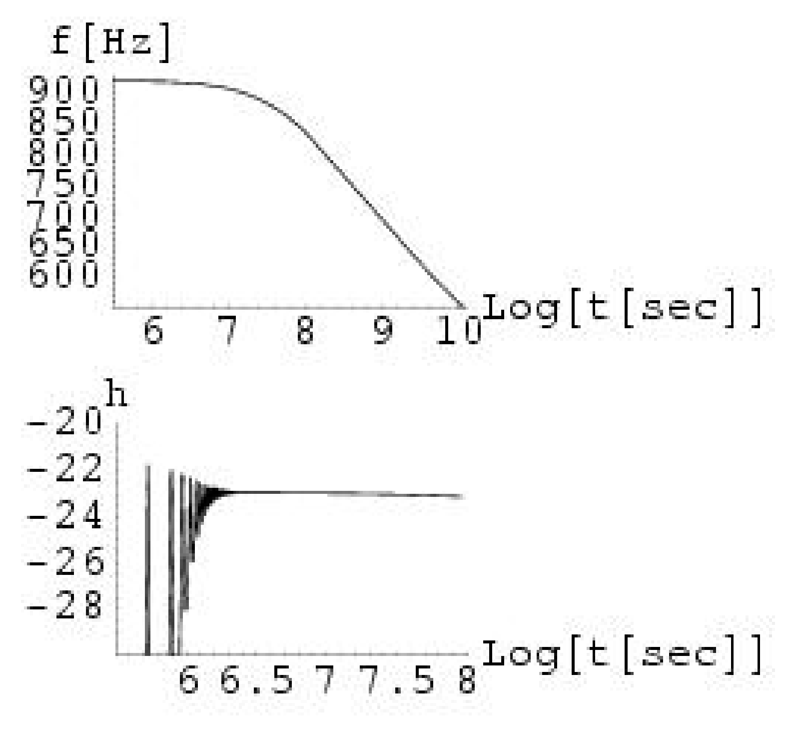
$\Omega - T$ plane:



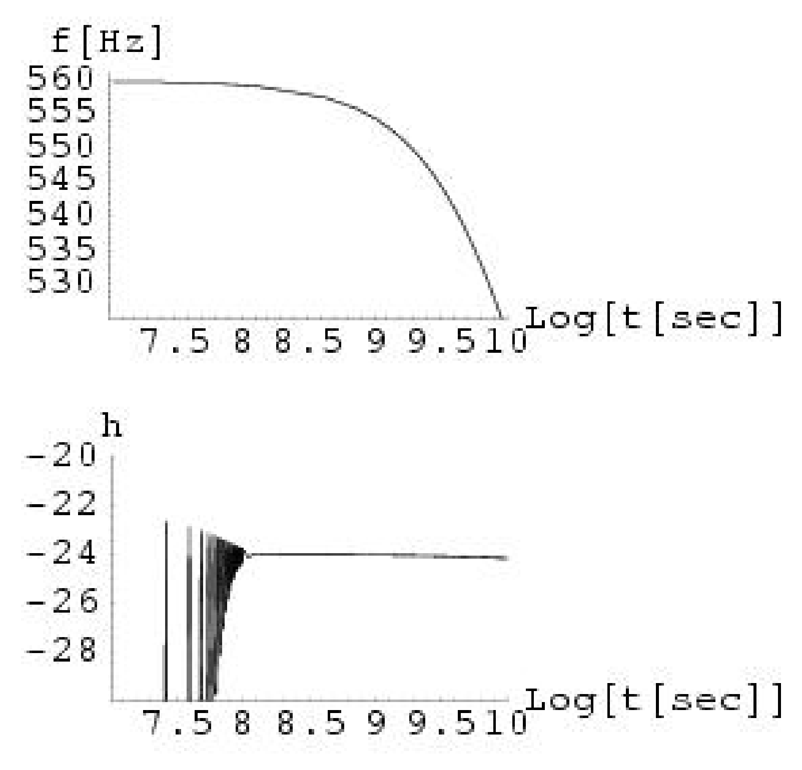
- Young Compact Stars spinning down

- Old Compact Stars “recycled” by mass accretion from a companion. LMXB.

Steady emission of GW



First scenario



Second scenario

It is not the type of signal searched by the bar antennas

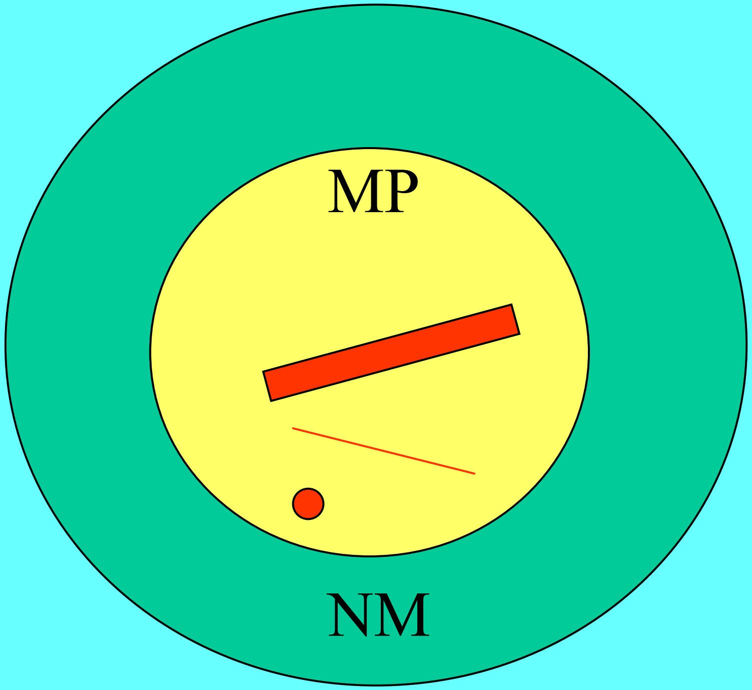
It can be detected by Interferometers

A toy model:

The star is modeled as a spheroid with a core of uniform density ρ1 of Mixed Phase and a crust of Nuclear Matter of uniform density ρ2

$$\frac{1}{\rho}\frac{dP}{da} = -G\frac{m(a)}{a^2} + \frac{2}{3}\Omega^2 a$$

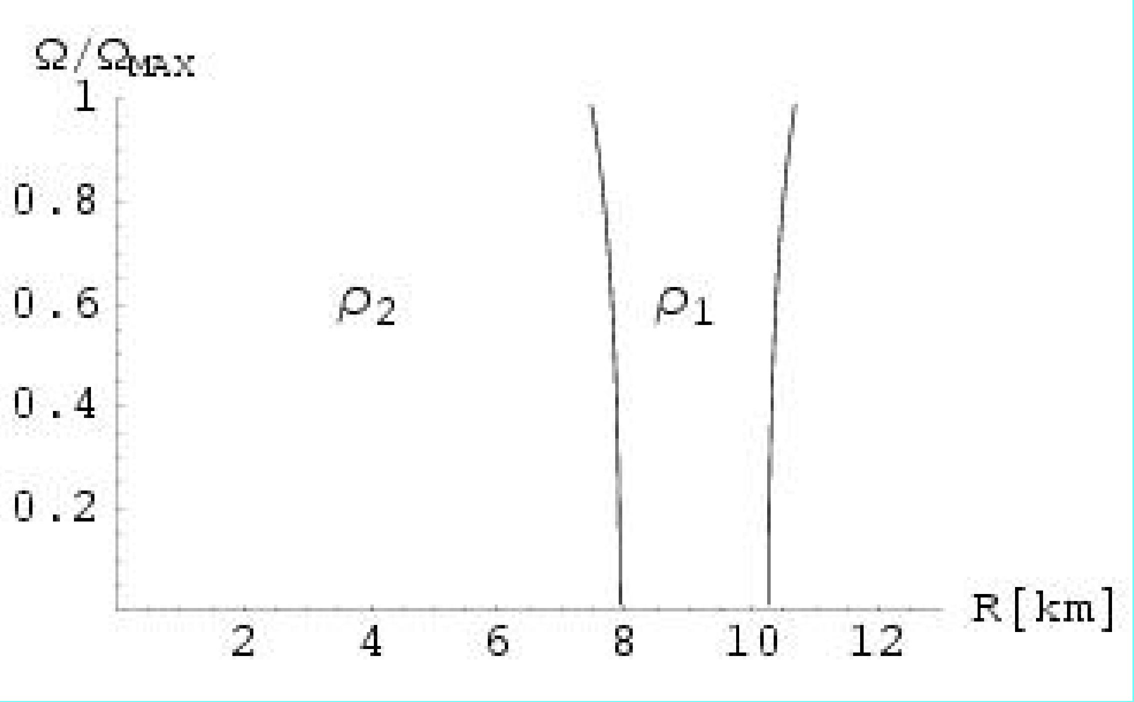
$$m(a) = 4\pi \int_0^a \rho(a')a'^2 da'$$



In a realistic scenario drops, rods and slabs are present.

New degree of freedom which can be exited during spin down

Structure and Composition



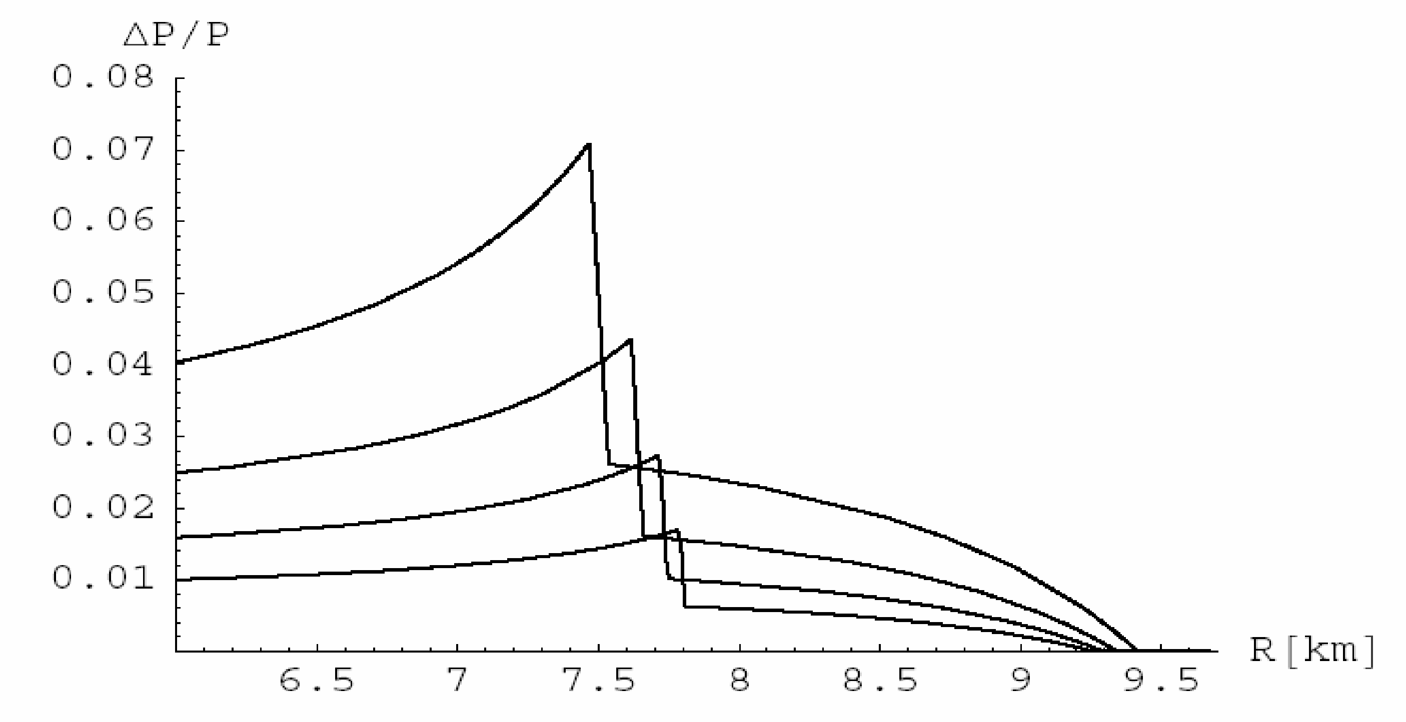
A reduction of the radius ΔR of ~ 0.5 km is obtained in a complete spin down.

More realistic calculation gives ΔR up to on order of magnitude larger.

Which is the critical OverPressure ?

- For a choice of EoS and a fixed value of σ which is the variation of angular velocity $\Delta\Omega/\Omega$ large enough to trigger the formation of a new drop of QM ?
- Overpressure: $P(r, \Omega- \Delta\Omega)- P(r, \Omega)$

OverPressure



Ω from 8000 to 5000 rad/sec, $\Delta\Omega/\Omega = 0.05$

$\Delta P/P \sim \Delta\Omega/\Omega$

Using typical values of $\sigma \sim$ few MeV/fm^2 the

Nucleation time is of order of days for $\Delta P/P \sim$ few %

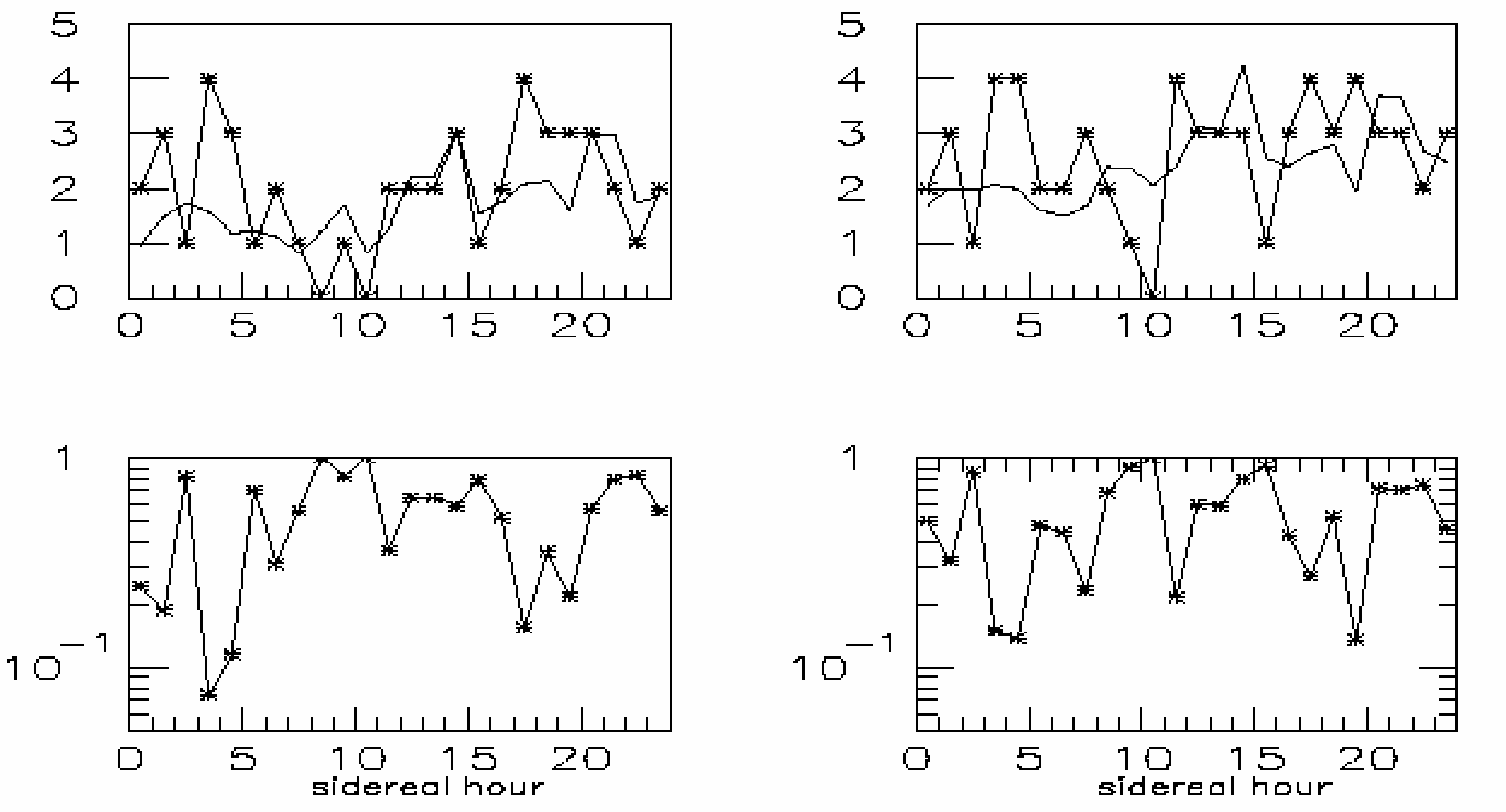
Candidates

- All newborn NSs are rapidly spinning until they enter the instability window
- Rate of NS production ~ 0.02 per year in our galaxy
- Observed distance 1 kpc (1/100 galactic volume)
- Total duration of GW bursts activity ~ 50 years
- Probability for one of this object to be detected is of order % (larger if recycling is considered or the bursts are more energetic)

Predictions:

- The frequency of the bursts activity will decrease from a few emissions per 10 years to a few emissions per 100 years
- The amplitude should decrease, because the angular velocity is reduced
- Both feautures reflect the progressive draining of the energy source wich, in this model, is the Rotational Energy

Data of 1998



- Starquake activity : after a first mini-collapse subsequent reassesments of the star produce GWs in a few days
- Long period (years) of quiescence
- Similar behaviour in soft gamma repeaters
- Temporal Clustering of the events measured by NAUTILUS and EXPLORER

Nucleation times