Neutron stars: from astrophysics to nuclear physics

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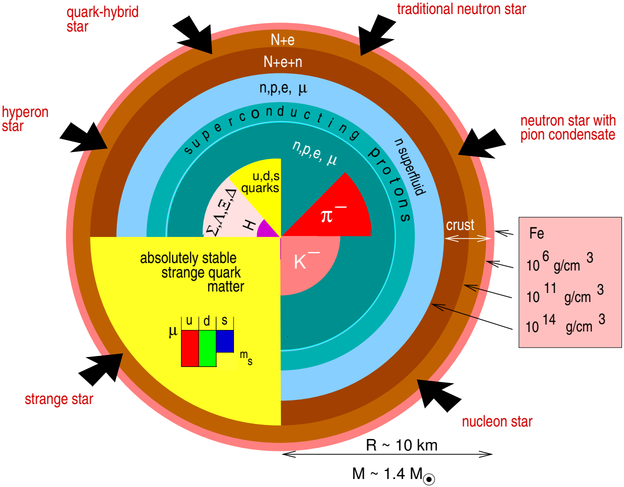
Our (poor) knowledge of matter at supernuclear densities

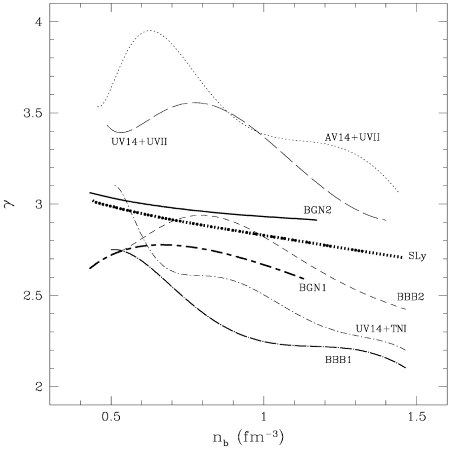
Internal structure of compact stars



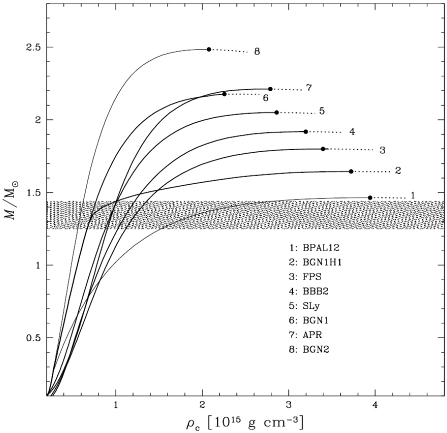
[Weber, J. Phys. G **27**, 465 (2001)]

Large discrepancies...

adiabatic index



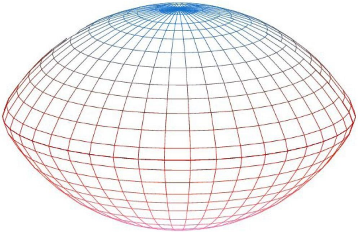
neutron star mass



[Haensel, Potekhin & Yakovlev (2007)]

Computation of rotating neutron star models

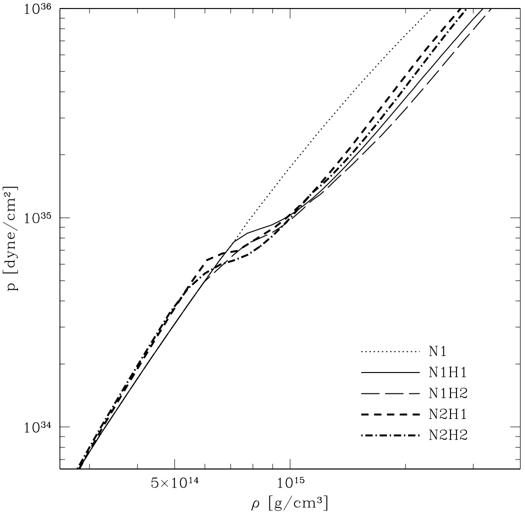
Framework: **RotStar** code based on LORENE C++ library
http://www.lorene.obspm.fr/



Resolution of Einstein equations for stationary axisymmetric rotating stars

Numerical technique: spectral methods
$\Rightarrow$ high accuracy
Microphysics input: equation of state (EOS)

Search for an indicator of hyperonization of matter (1/2)

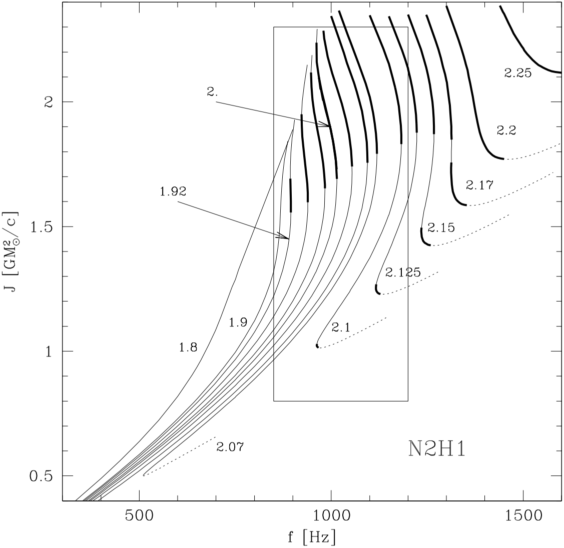


Hyperon = baryon (i.e. hadron + fermion) made of 3 quarks, with at least one strange quark:

- Λ_0 = uds
- Σ^- = dds
- Ξ^0 = uss
- etc...

Should appear at high density ($\rho > 2\rho_{\rm nuc}$)
$\Rightarrow$ EOS softening

N1 = np, N1H1,N2H1 = np$\Lambda\Sigma$,
N1H2,N2H2 = np$\Lambda\Sigma\Xi$
Balberg & Gal (1997)

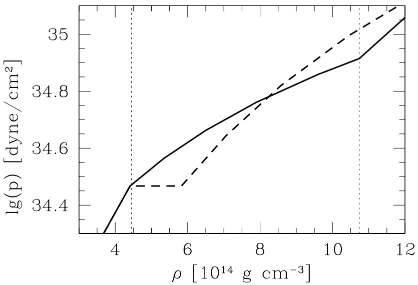


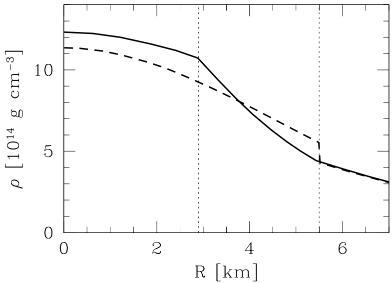
Hyperon softening of the EOS ⇒ back-bending : spin-**up** by angular momentum **loss**

Detectability: pulsar with $\dot{P} < 0$

[Zdunik, Haensel, Gourgoulhon & Bejger, A&A **416**, 1013 (2004)]

Phase transitions in dense matter (1/2)





At high density, phase transition to an *exotic* state:

- meson (pion, kaon) condensate
- deconfined quarks

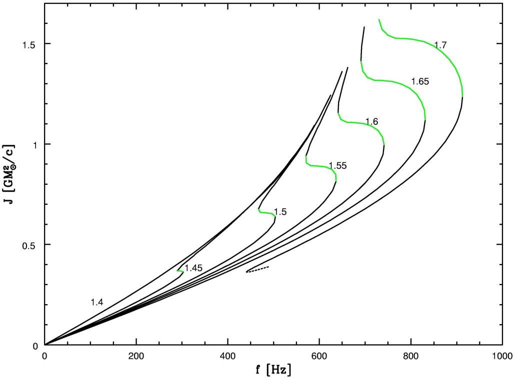
Various kinds of phase transitions:

- — — — Constant pressure phase transition
- —— Mixed-phase state

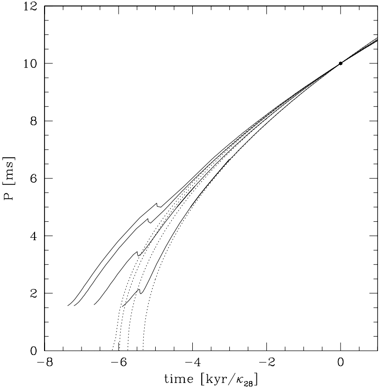
Both yield EOS softening

[Zdunik, Bejger, Haensel & Gourgoulhon, A&A **450**, 747 (2006)]

Back-bending phenomenon: spin-up by angular momentum loss



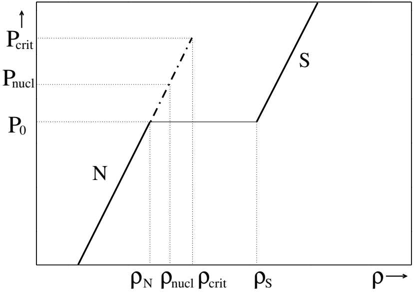
$\Rightarrow$ pulsar age inferred from spin-down formula $P/(2\dot{P})$ is underestimated



[Zdunik, Bejger, Haensel & Gourgoulhon, A&A **450**, 747 (2006)]

Energy release due to a phase transition (1/3)

First-order phase transition



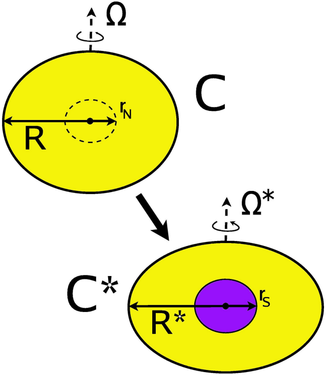
N : normal phase (nucleons)

S : superdense phase (exotic matter)

$P_{\rm nucl}$: pressure at which compression timescale = nucleation timescale

central overpressure:

$\delta \bar{P} = (P_{\rm nucl} - P_0)/P_0$

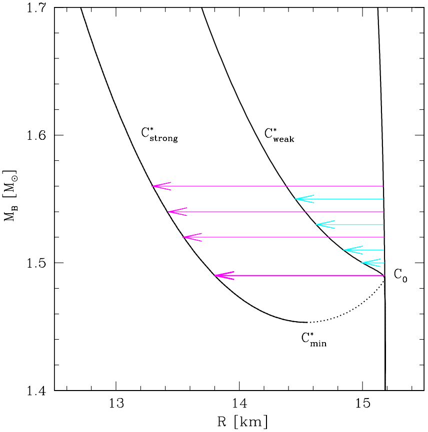


conservation of baryon number : $A^* = A$

conservation of angular mom. : $J^* = J$

energy release :

$$\Delta E = [M(C) - M(C^*)]c^2$$

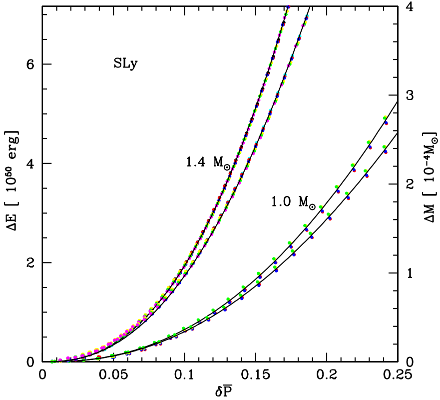


[Zdunik, Bejger, Haensel & Gourgoulhon, arXiv:0707.3691]

Two types of phase transitions:

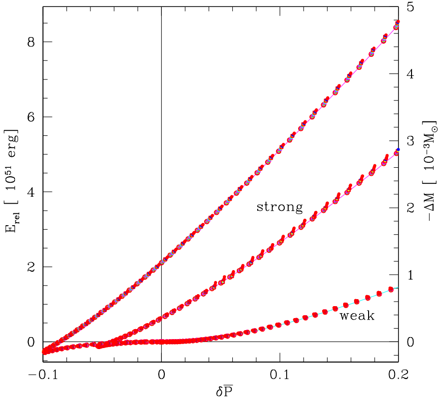
- **weak**: $\rho_S < \frac{3}{2}(\rho_N + P_0/c^2)$
  configurations with arbitrarily small S cores are stable
  phase transition $\Rightarrow$ small corequake
- **strong**: $\rho_S > \frac{3}{2}(\rho_N + P_0/c^2)$
  configurations with small S core are unstable and collapse to configurations with large S core
  phase transition $\Rightarrow$ large corequake

Weak phase transitions



[Zdunik, Bejger, Haensel & Gourgoulhon, A&A **465**, 533 (2007)]

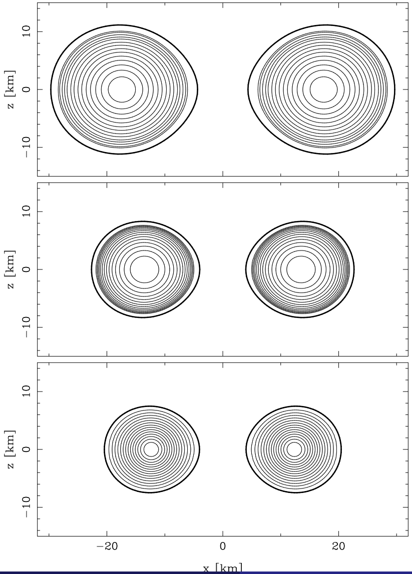
Strong phase transitions



[Zdunik, Bejger, Haensel & Gourgoulhon, arXiv:0707.3691]

ΔE depends only on $\delta \bar{P}$, not on the rotation state

Constraints on EOS from gravitational radiation (1/2)



GW from inspiraling binary neutrons stars

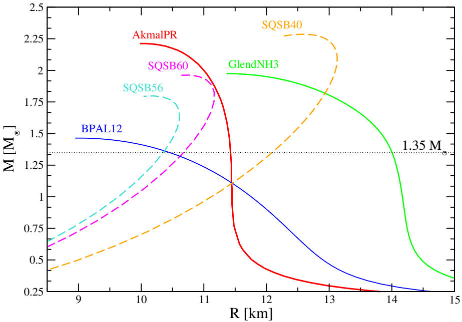
Primary target for VIRGO / LIGO

← Irrotational binary configurations close to mass-shedding limit for GlendNH3, AkmalPR and BPAL12 EOS

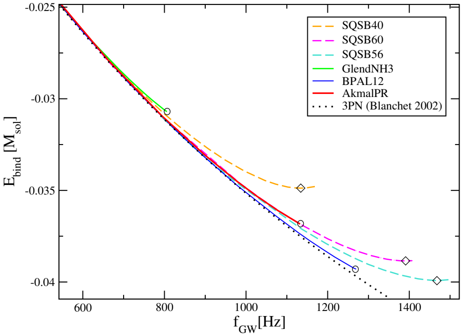
[Bejger, Gondek-Rosińska, Gourgoulhon, Haensel, Taniguchi & Zdunik, A&A **431**, 297 (2005)]

Constraints on EOS from gravitational radiation (2/2)

3 nuclear matter EOS
3 strange matter EOS



Inspiraling sequences

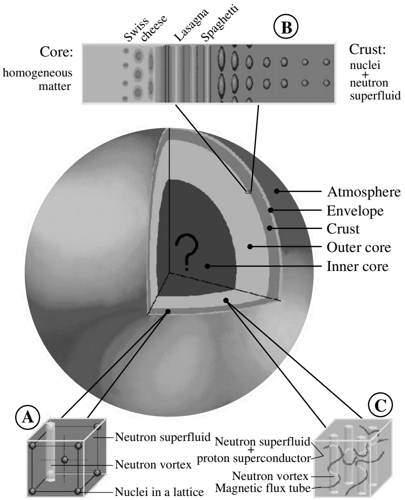


[Bejger, Gondek-Rosińska, Gourgoulhon, Haensel, Taniguchi & Zdunik, A&A **431**, 297 (2005)]

[Limousin, Gondek-Rosińska & Gourgoulhon, PRD **71**, 064012 (2005)]

[Gondek-Rosińska, Bejger, Bulik, Gourgoulhon, Haensel, Limousin, Taniguchi & Zdunik, ASR **39**, 271 (2007)]

Neutron star crust



Page & Reddy ARNPS **56**, 327 (2006)

- Entrainment coefficient and effective mass for conduction neutrons in the crust:
  – microscopic models :
  [Carter, Chamel & Haensel, Nucl. Phys. **A748**, 675 (2005)]
  – macroscopic treatment :
  [Carter, Chamel & Haensel, I.J.M. Phys. D **15**, 777 (2006)]
- BCS mesoscopic treatment of neutron superfluidity in the crust
  [Carter, Chamel & Haensel, Nucl. Phys. **A759**, 411 (2005)]