On the rotation and pulsation properties of Proto-neutron stars

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- The birth of a neutron star
- ProtoNS vs. old NS
- Properties of rotating PNS
- Quasi-normal modes and GW signal
- g-modes and convective instabilities

Core collapse

Mcore >1≈2 **M**solar

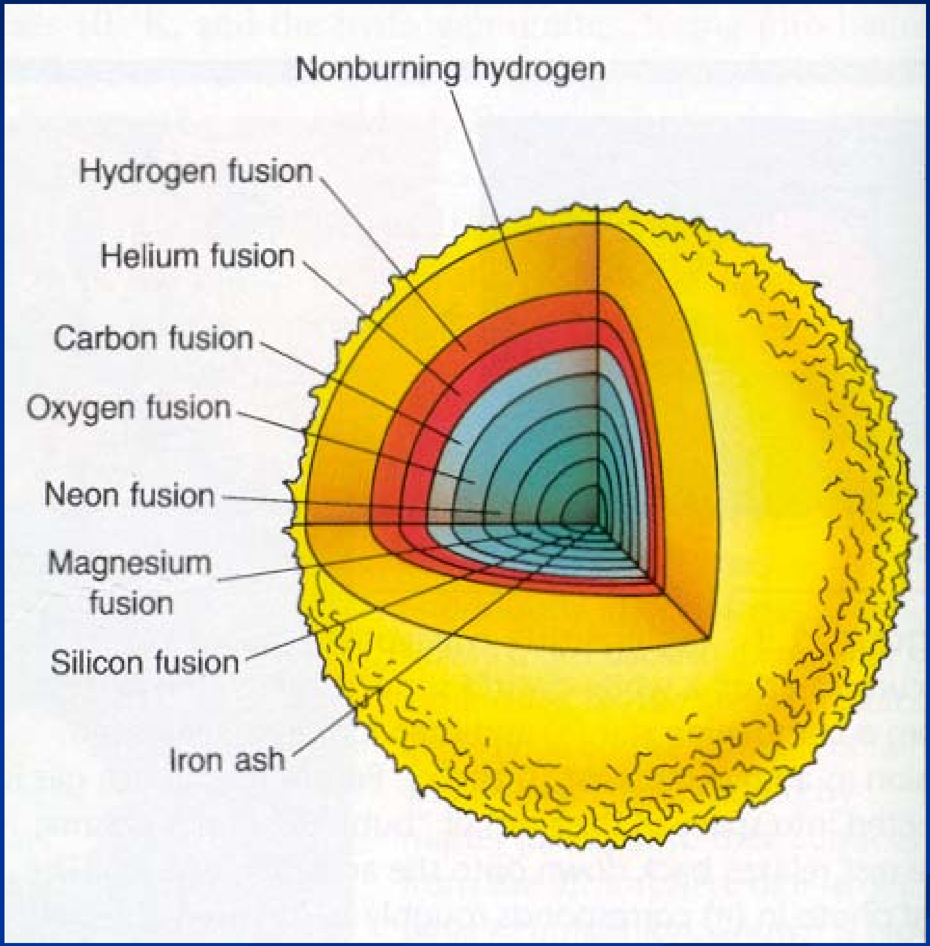
- $T \approx 10^{10}$ K, $\rho \approx 5\times10^{9}$ g/cm^3 ,
- $Y_e \approx 0.42$, s ≈1–2 (k)
- R≈1000 km
- Photodesintegration

$\gamma + (A,Z) \longrightarrow (A-4, Z-2) + \alpha$

$\gamma + \alpha \longrightarrow 2\,n + 2\,p$

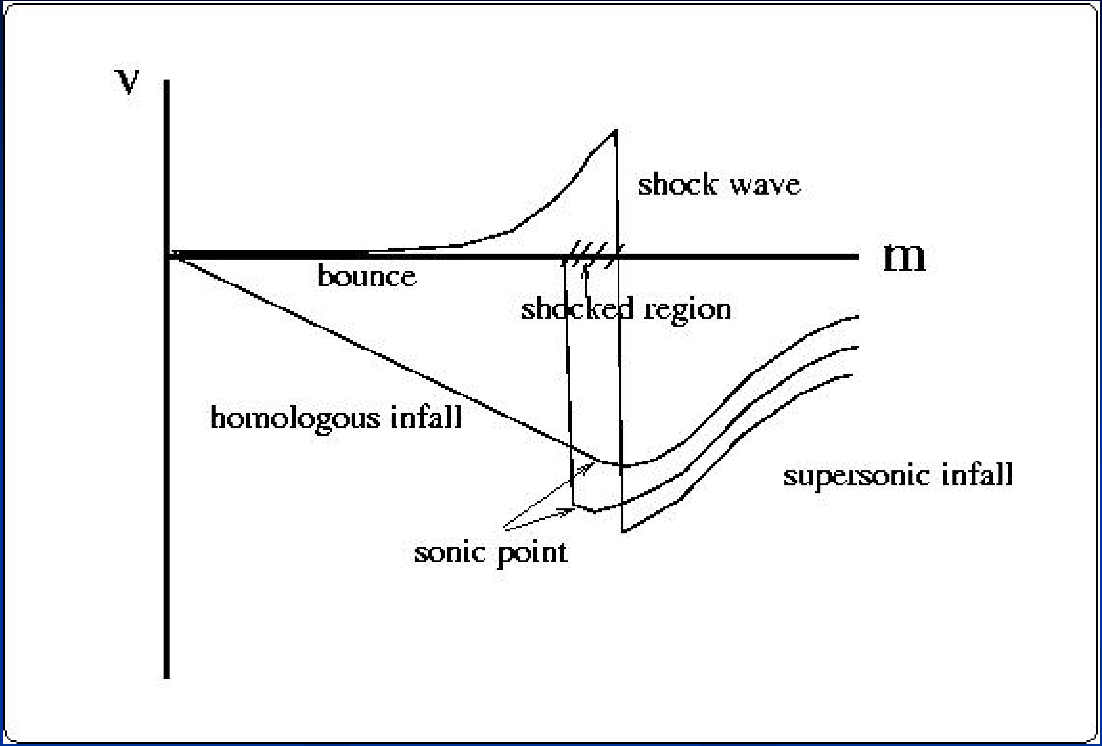
- Electron captures

$e^- + (A,Z) \longrightarrow (A, Z-1) + \nu$



Infall and bounce

- **Infall** (< 1 s) :
  - homologous
  - free fall
  - neutrinos escape freely
  - trapping ($\rho > 10^{12}$ g/cm^3)
- **Bounce**
  - ($\rho > 3\ 10^{14}$ g/cm^3)
- **Shock wave formation and propagation**
  - nuclei dissociation
  - neutrino losses



- **Neutrino reactivation**
- **Convective overturn**

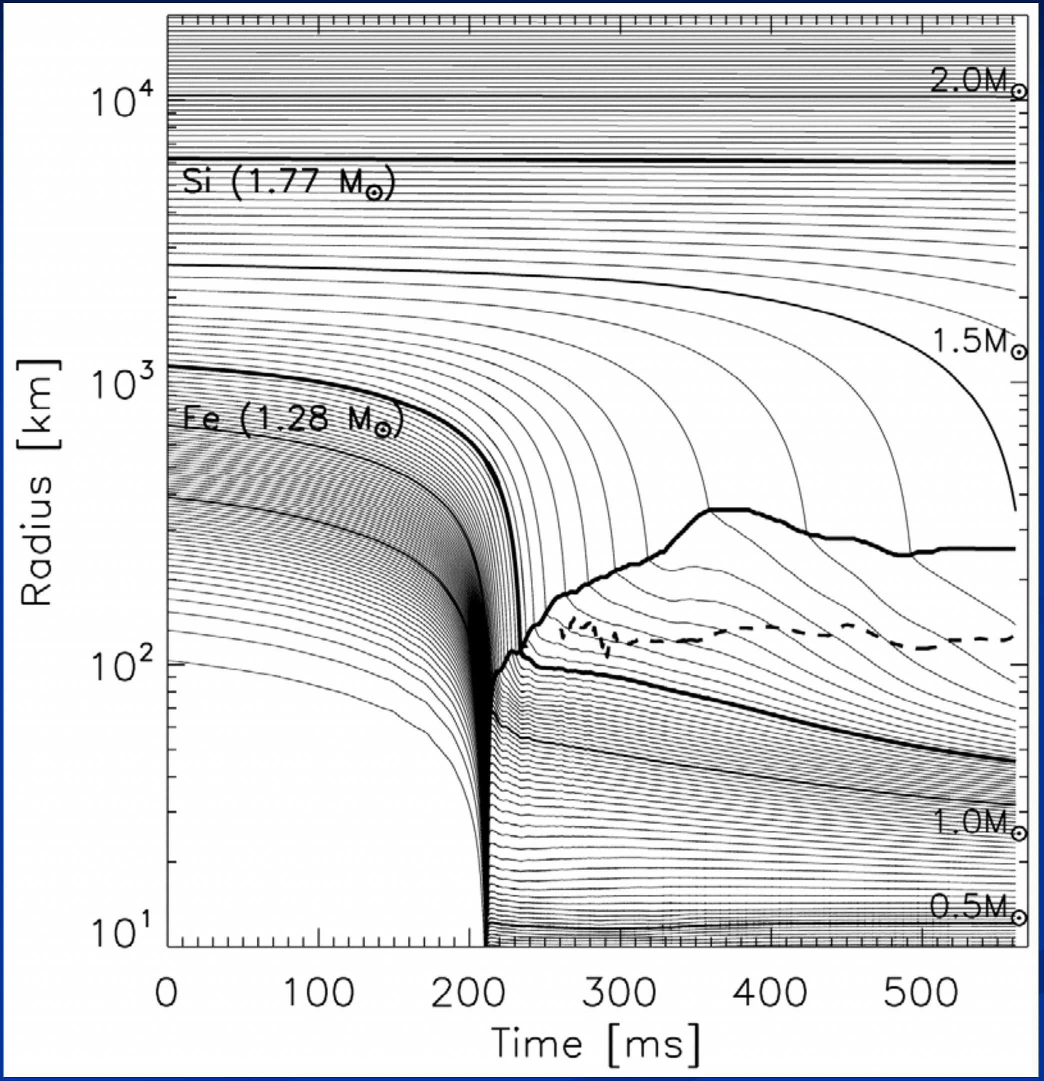
A neutron star is born

- $\tau_{dyn} \ll \tau_{diff}$

  Quasi-stationary evolution

- High entropy accreting mantle
- Lepton rich (Y_L=0.4)
- Low entropy core

✓ Neutrino diffusion governs chemical and thermal evolution

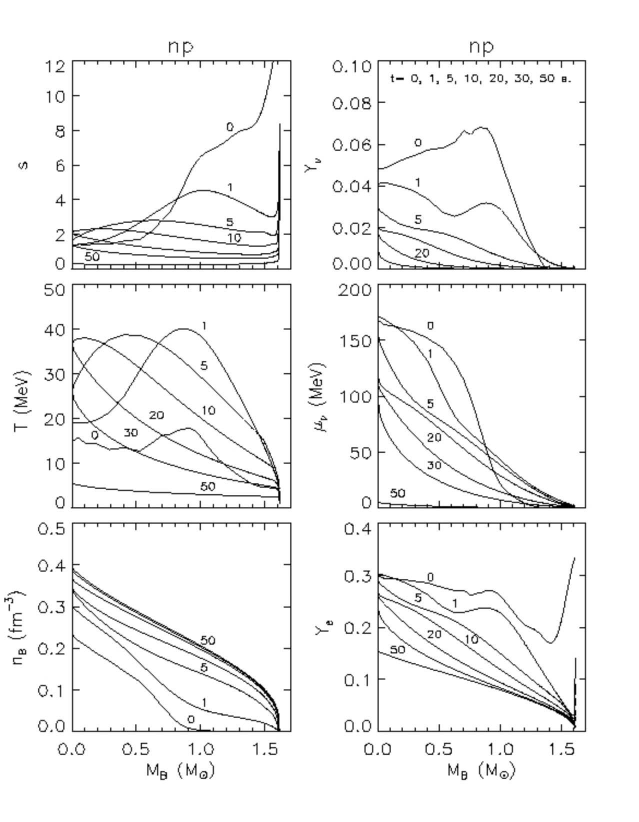


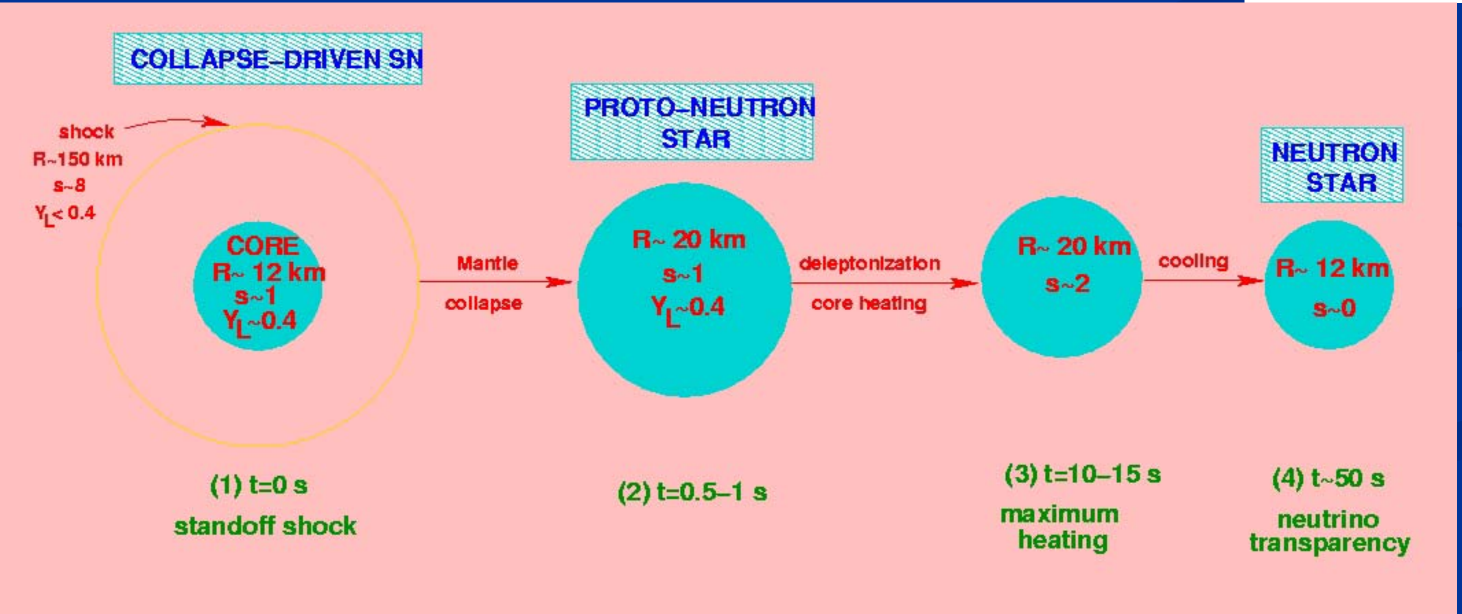
Rampp & Janka, (2000) ApJ 539, L33

Evolution

The first minute of life

- **Mantle collapse**
  0.1-1 s, heating, compression
- **Deleptonization**
  with *Joule* heating,
  maximum central T
- **Cooling**
  basically thermal neutrinos,
  from 50 MeV down to 1 MeV





Pons et al., 1999

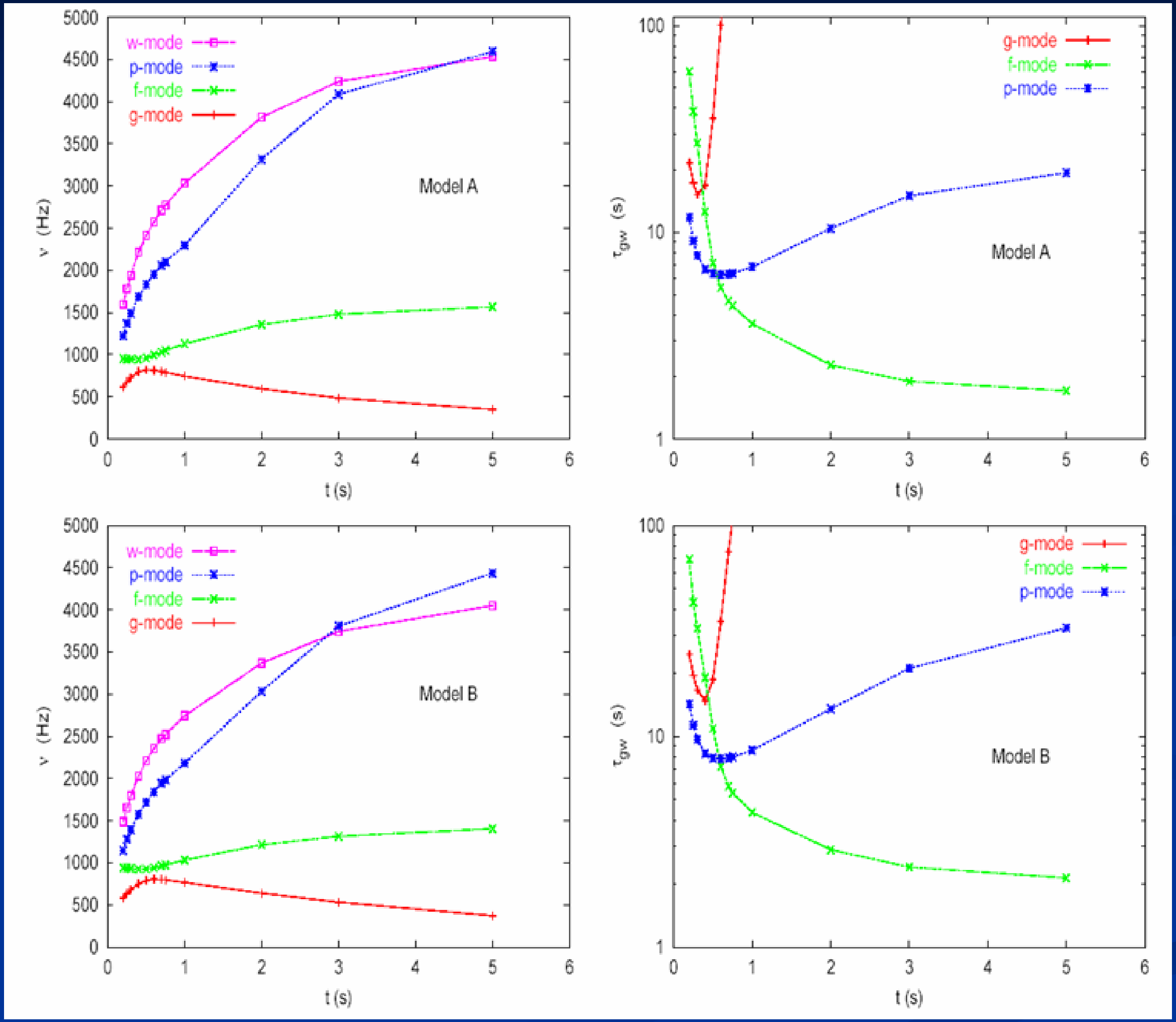
ApJ 513, 780

PNS vs. old NS

- ❑ Hot (≈10-50 MeV), lepton rich
- ❑ Large chemical and thermal gradients
- ❑ Less compact (≈100 km)
- ❑ No crust, no superfluid

- ❑ Cold (T<1 MeV), $Y_e<0.1$
- ❑ Essentially isothermal
- ❑ More compact (R=10-15 km)
- ❑ Solid crust, superfluid interior

Quasinormal modes of PNSs



Ferrari, Miniutti & Pons, MNRAS (2003)

Rotating PNSs : Initial profiles ?

Stationary motion of rotating NS in GR

(BGSM, 1993, A&A 278, 421)

$$\frac{\partial_i P}{e + P} + \partial_i \ln\left[\frac{N}{\Gamma}\right] = - F\,\partial_i \Omega\,,$$

$$F[\Omega] = \frac{A^4 B^2 r^2 \sin^2\vartheta\,(\Omega - N^\varphi)}{N^2 - A^4 B^2 r^2 \sin^2\vartheta\,(\Omega - N^\varphi)^2}$$

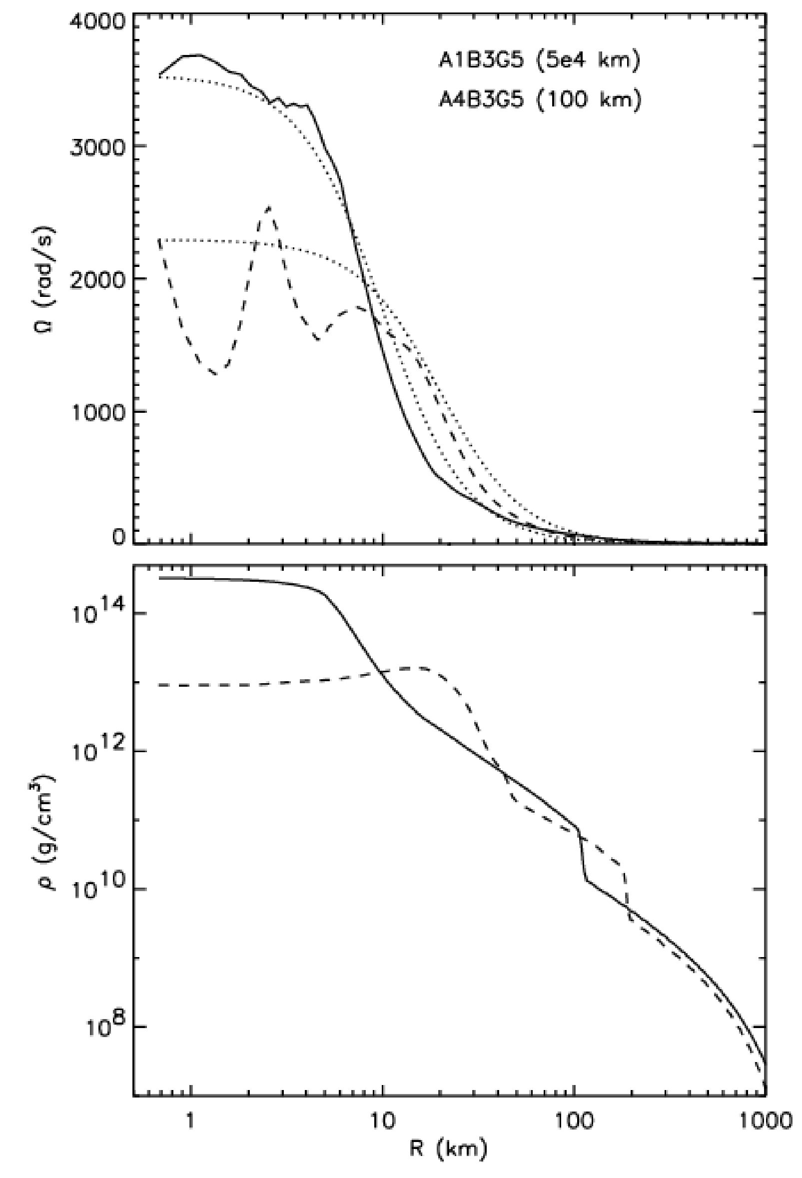
$$F[\Omega] = R_0^2\,(\Omega_c - \Omega)\,,$$

(Komatsu, Eriguchi, Hachisu, 1989)

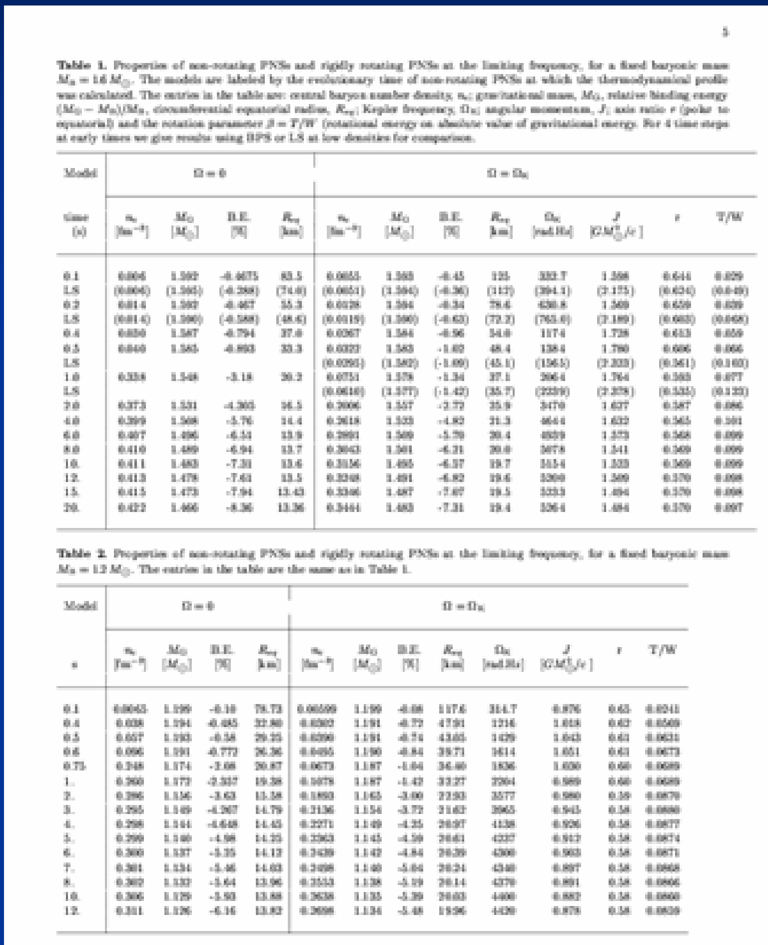
Newtonian limit:

$\Omega = R^2_0\, \Omega c \,/\, (R^2_0 + r^2 \sin^2\theta)$

Acceptable approximation ? R_0 ?



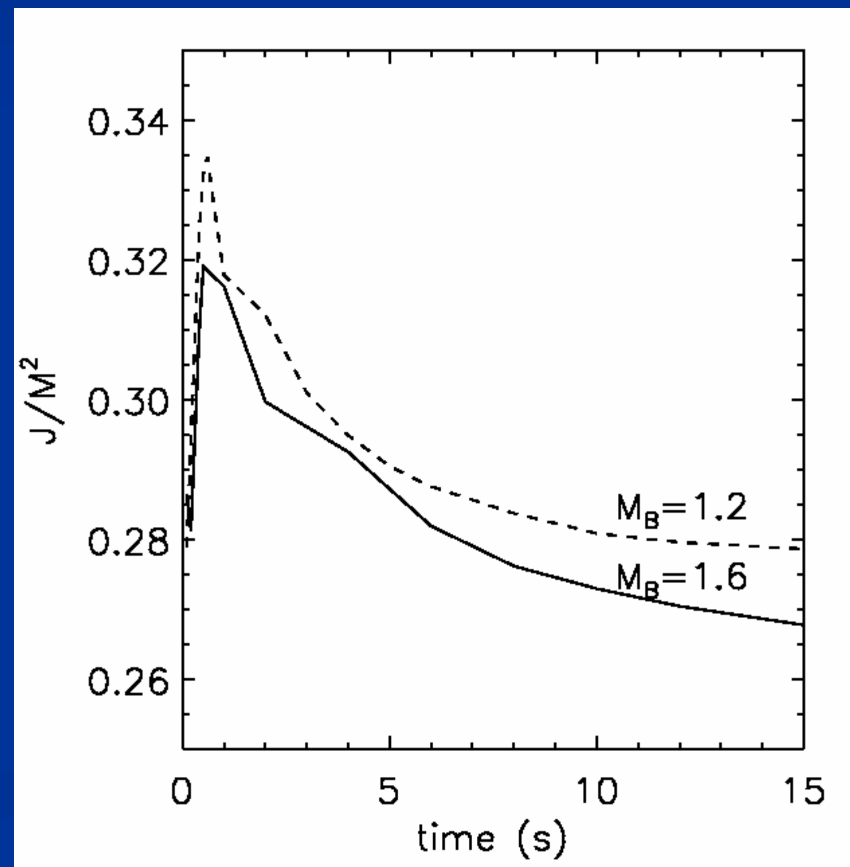
Properties of rotating PNSs



Rigid rotation $\Omega_K \sim 0.58\ (M/R^3)^{1/2}$

max T/W = 0.12

Diff. Rotation max T/W = 0.18



(Villain et al. 2003)

LORENE package

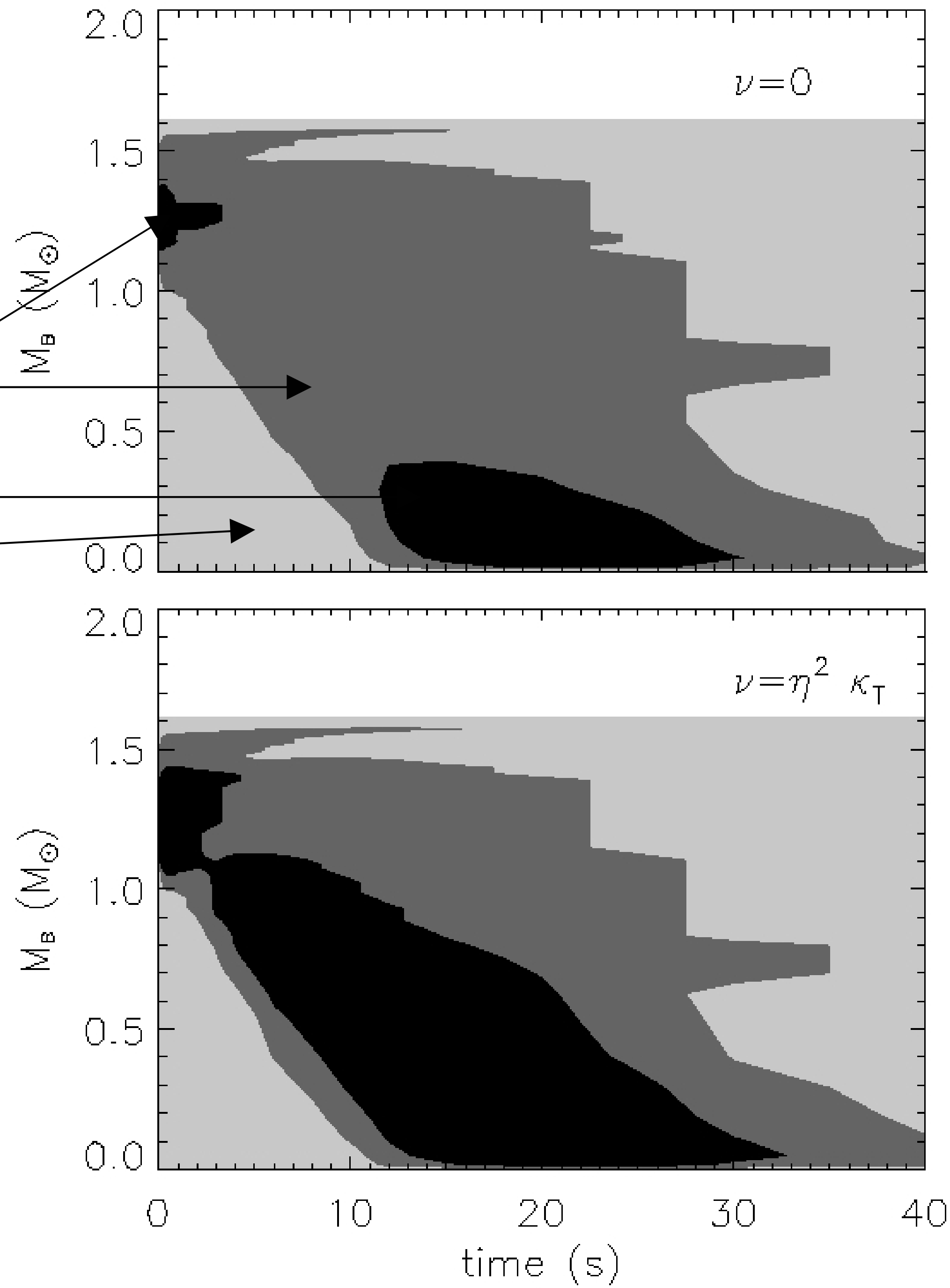
PNS's Convective instability

Neutron fingers

Convection

Stable

Miralles, Pons, Urpin
ApJ 543, 1001 (2000)

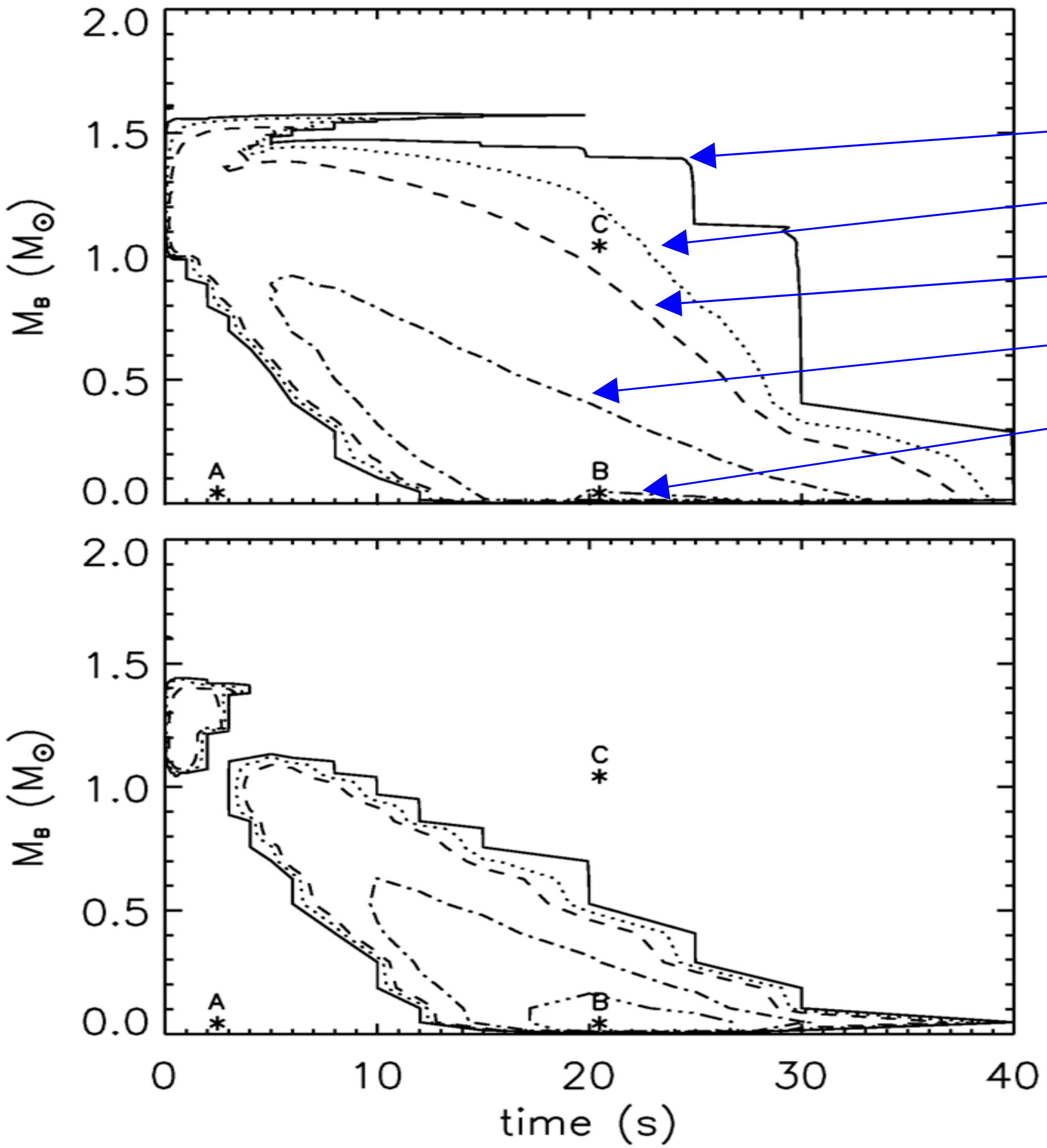


Shear Instability +
convection may lead to

Rigid rotation in few s.

Ri < ¼ (<0)

Convection in magnetic PNSs



R-T

10^{14} G

$5\ 10^{15}$ G

10^{16} G

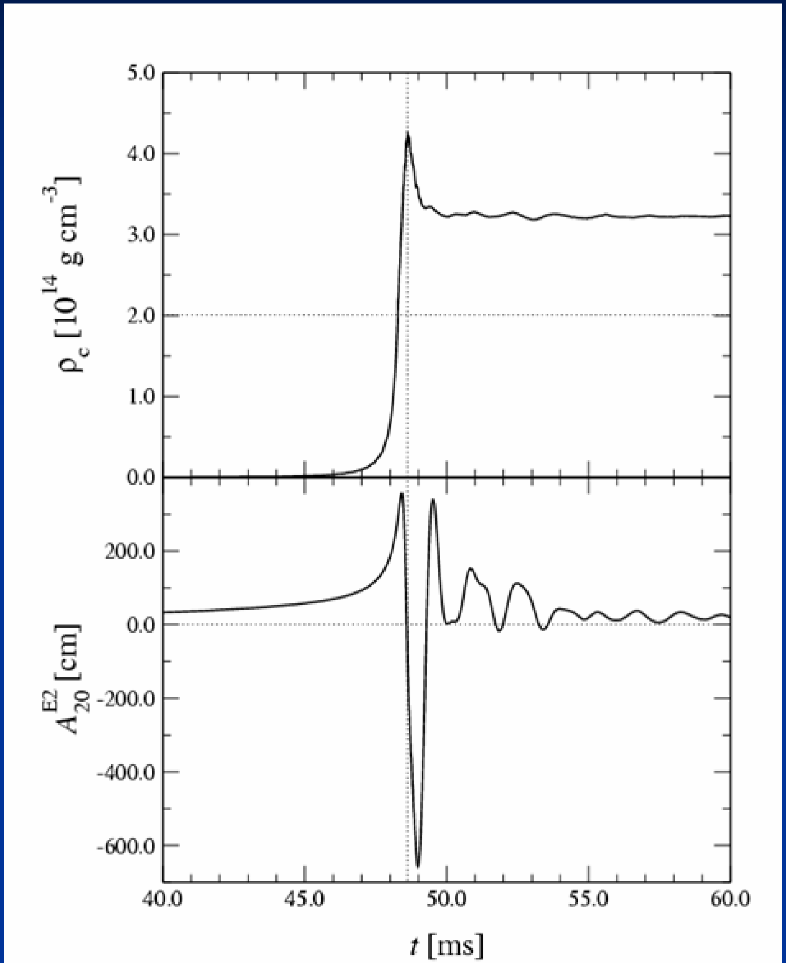
$3\ 10^{16}$ G

$5\ 10^{16}$ G

Schwarzschild

(Miralles, Pons, Urpin ApJ, 574, 356, 2002)

Quasinormal mode's damping



Dimmelmeier, Font, Müller
A&A 393, 523 (2002)

Fast damping: almost no ring down observed.

-- GW damping ?

-- Numerical viscosity ?

-- Thermal dissipation ?

Actually, just simple HD:

a PNS is NOT isolated

PNS from collapse vs. PNS from mergers

PNS from collapse

- ❑ Hot (≈10-50 MeV)
- ❑ lepton rich $Y_L \approx 0.4$
- ❑ Non isolated !
- ❑ Moderate diff. rotation
- ❑ Supramasive only after accretion
- ❑ T/W = 0.10-0.12
- ❑ Rotation induced instabilities may appear after diffusion timescale

PNS from mergers

- ❑ Hot (≈10 MeV)
- ❑ Deleptonized $Y_e < 0.1$
- ❑ PNS + disk
- ❑ ???
- ❑ Probably always supramasive (short lived)
- ❑ Larger T/W possible ?
- ❑ Collapse to BH after diffusion/gravitational instabilities timescale

Conclusions

- Thermodynamics does matter, macroscopic properties of NS and PNS are quite different.
- Moderate diff. rotation after core collapse, $R_0 = 10$ km
- Maximal Ω (instabilities) only immediately following bounce or after diffusion timescales.
- Convective + shear instabilities may result in early rigid rotation
- GW signal during first second highly unknown, most probably dominated by non-linear dynamics (convection, accretion). No clear peak + ringdown expected.
- Later (t>0.5-1 s) pulsations may be visible
- Failed SN can also reveal information of PNS structure.
- Much to be done … not to mention magnetic field … ☺