



On the rotation and pulsation properties of Proto-neutron stars

José A. Pons

Departament de Física Aplicada
Universitat d'Alacant
SPAIN

- ☐ 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

$M_{\text{core}} > 1 \sim 2 M_{\text{solar}}$

□ $T \approx 10^{10} \text{ K}$, $\rho \approx 5 \times 10^9 \text{ g/cm}^3$,

□ $Y_e \approx 0.42$, $s \approx 1-2 \text{ (k)}$

□ $R \approx 1000 \text{ km}$

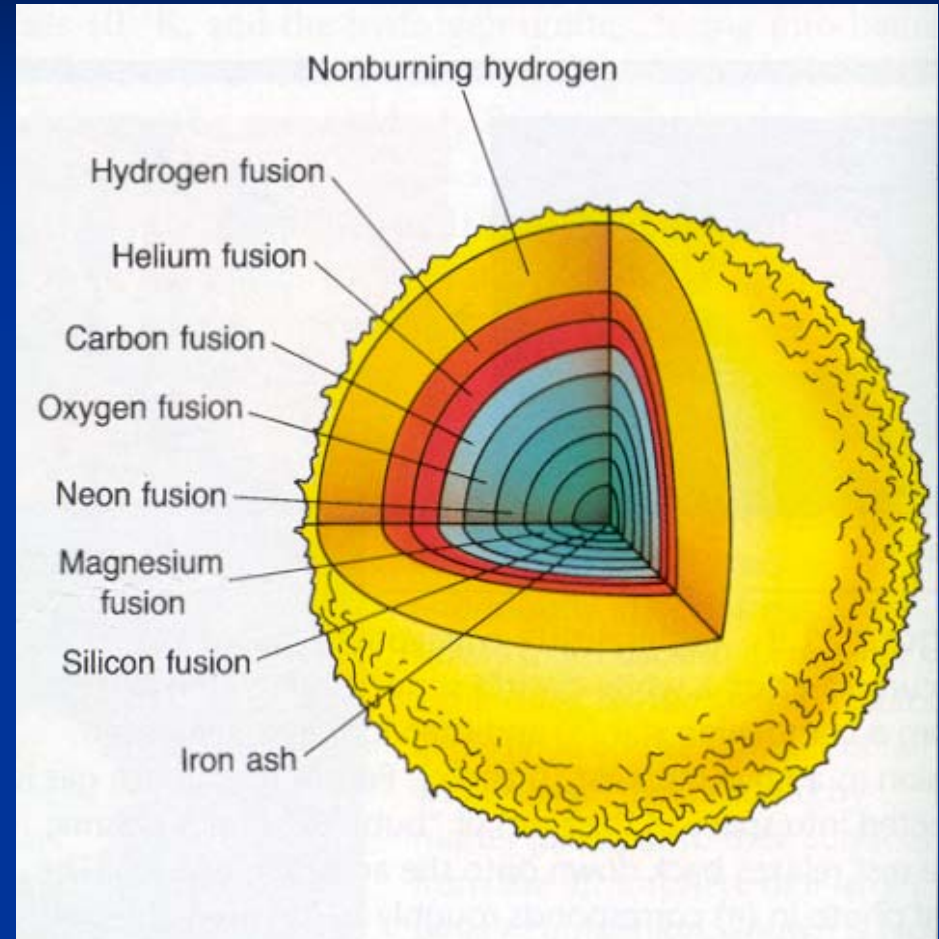
□ Photodesintegration

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

$\gamma + \alpha \rightarrow 2n + 2p$

□ Electron captures

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



Infall and bounce

□ Infall (< 1 s) :

homologous

free fall

neutrinos escape freely

trapping ($\rho > 10^{12} \text{ g/cm}^3$)

□ Bounce

($\rho > 3 \cdot 10^{14} \text{ g/cm}^3$)

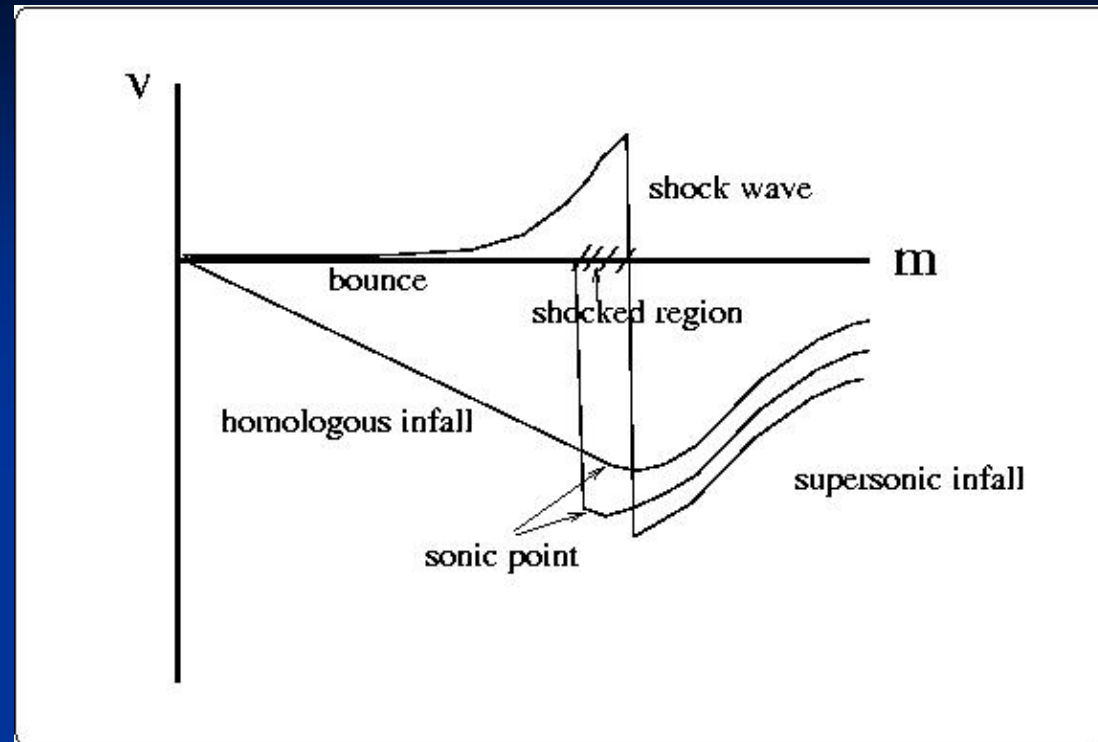
□ Shock wave formation and propagation

nuclei dissociation

neutrino losses

➤ Neutrino reactivation

➤ Convective overturn



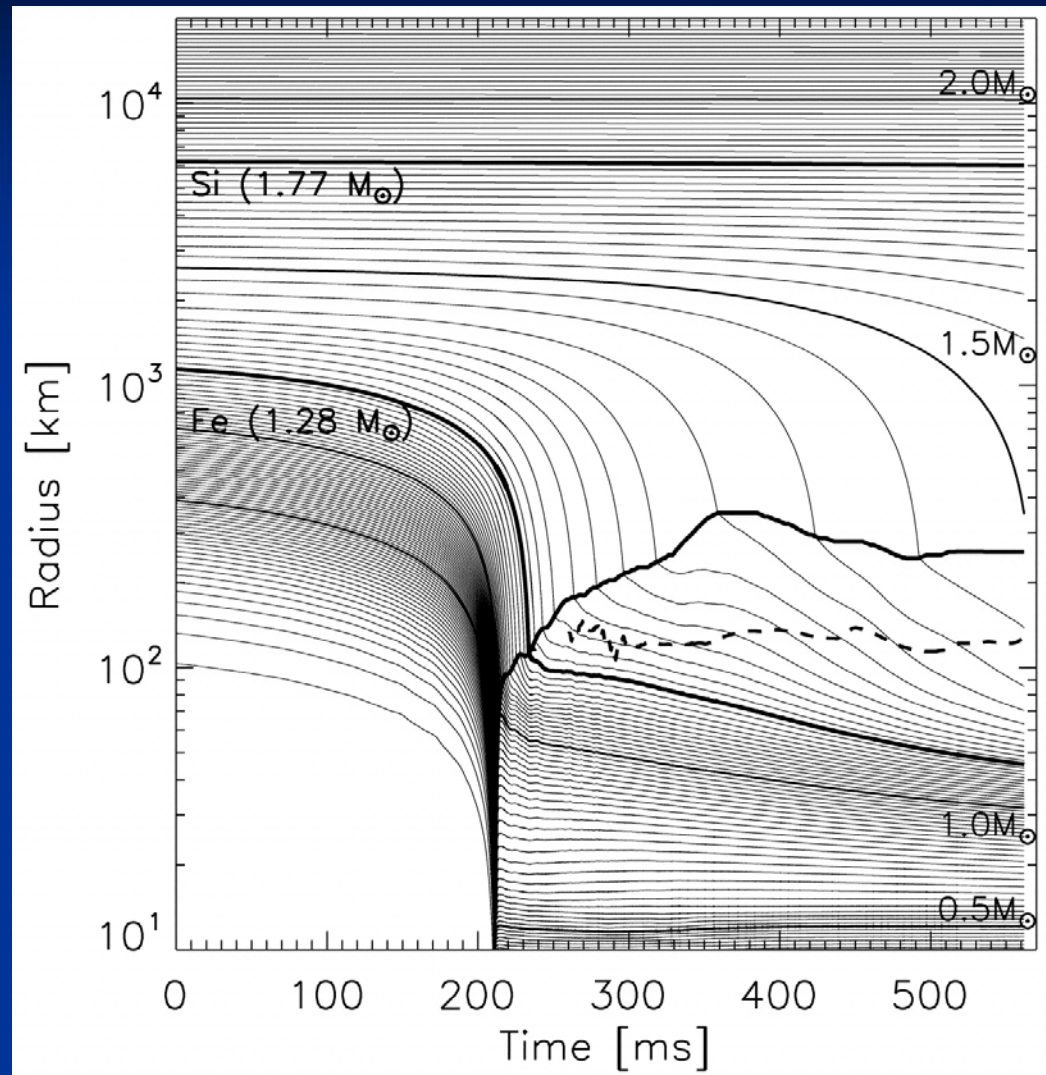
A neutron star is born

➤ $\tau_{\text{dyn}} \ll \tau_{\text{diff}}$

Quasi-stationary
evolution

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

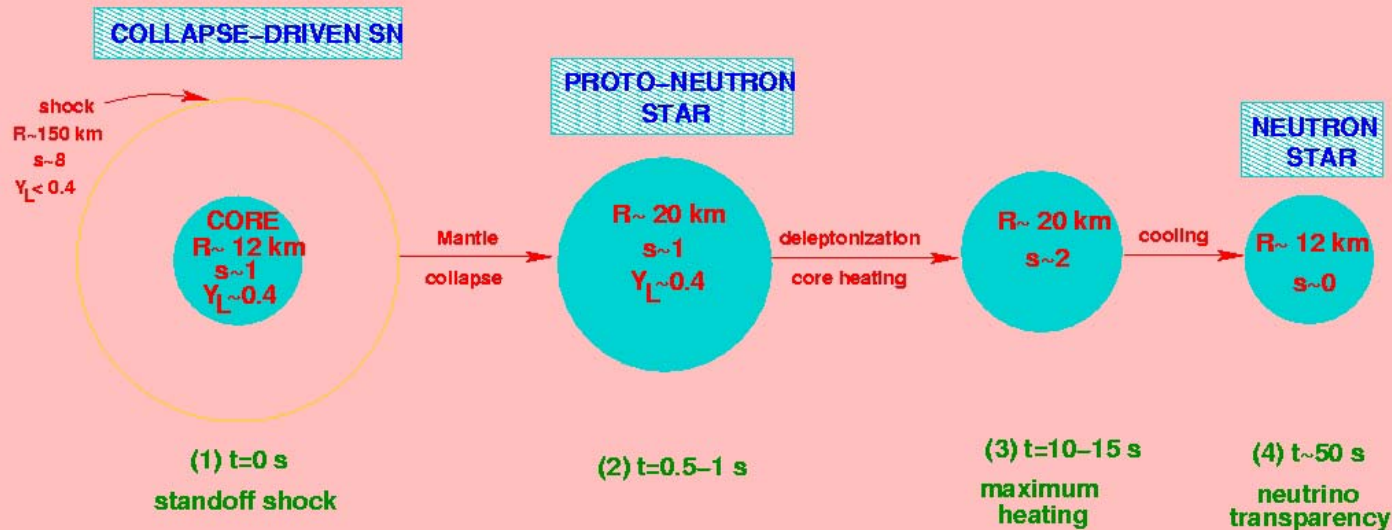
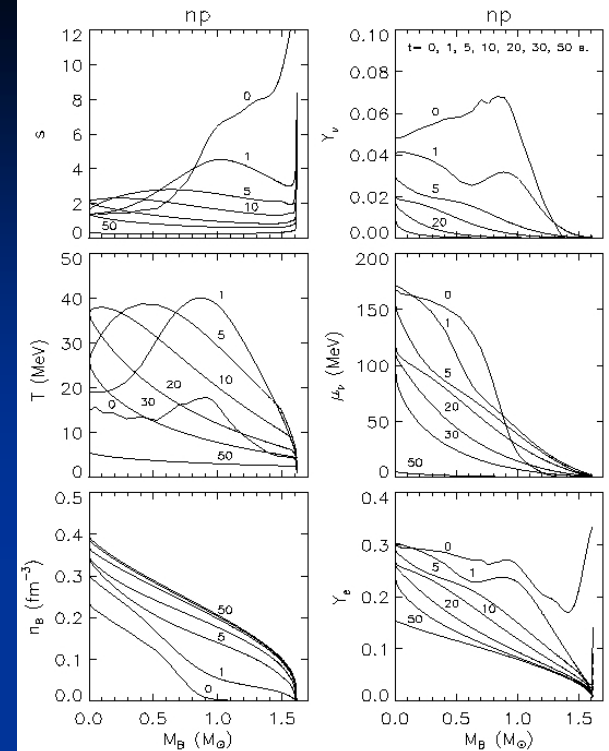
✓ Neutrino diffusion
governs chemical and
thermal evolution



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

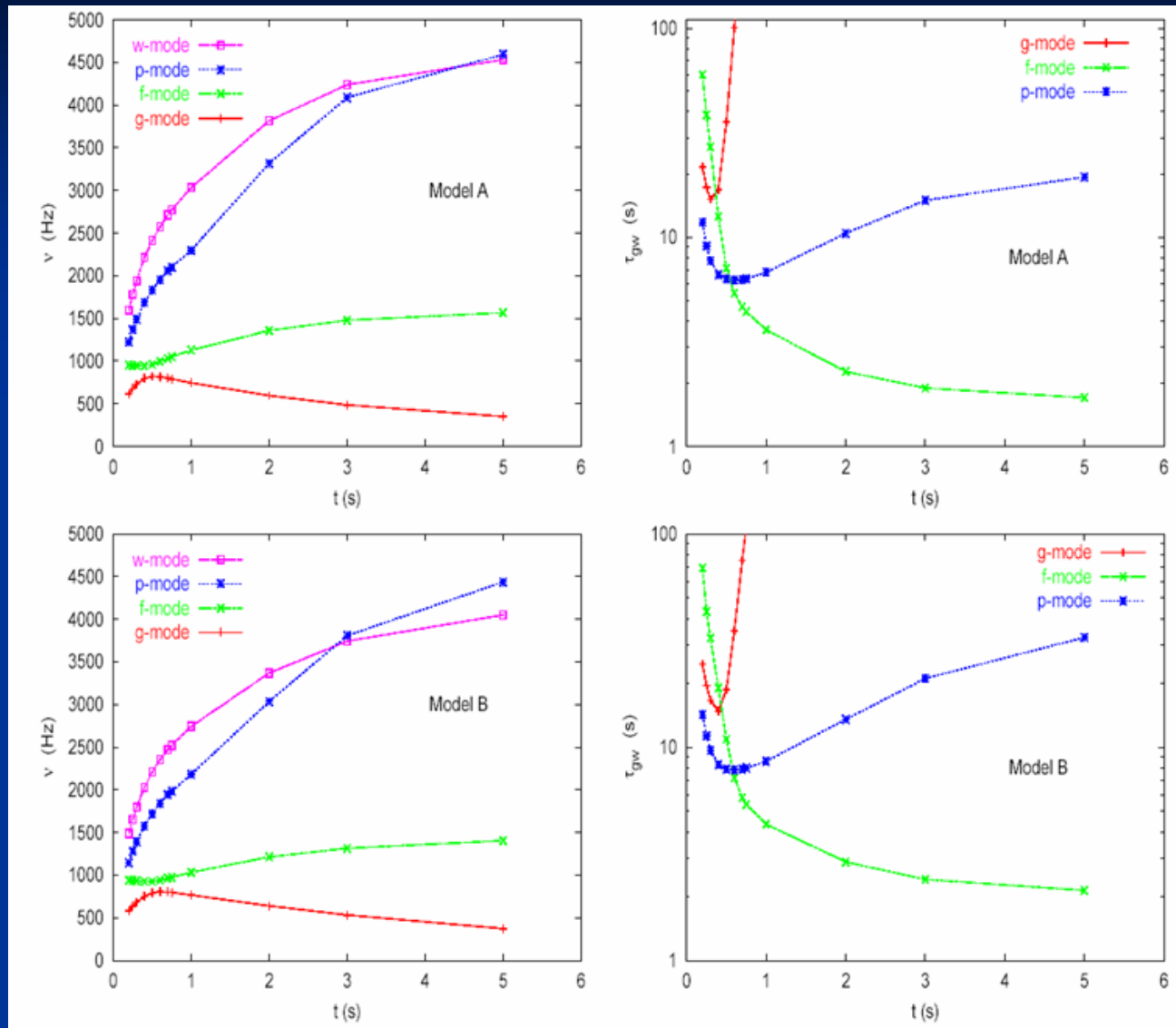
vs.

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)

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

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

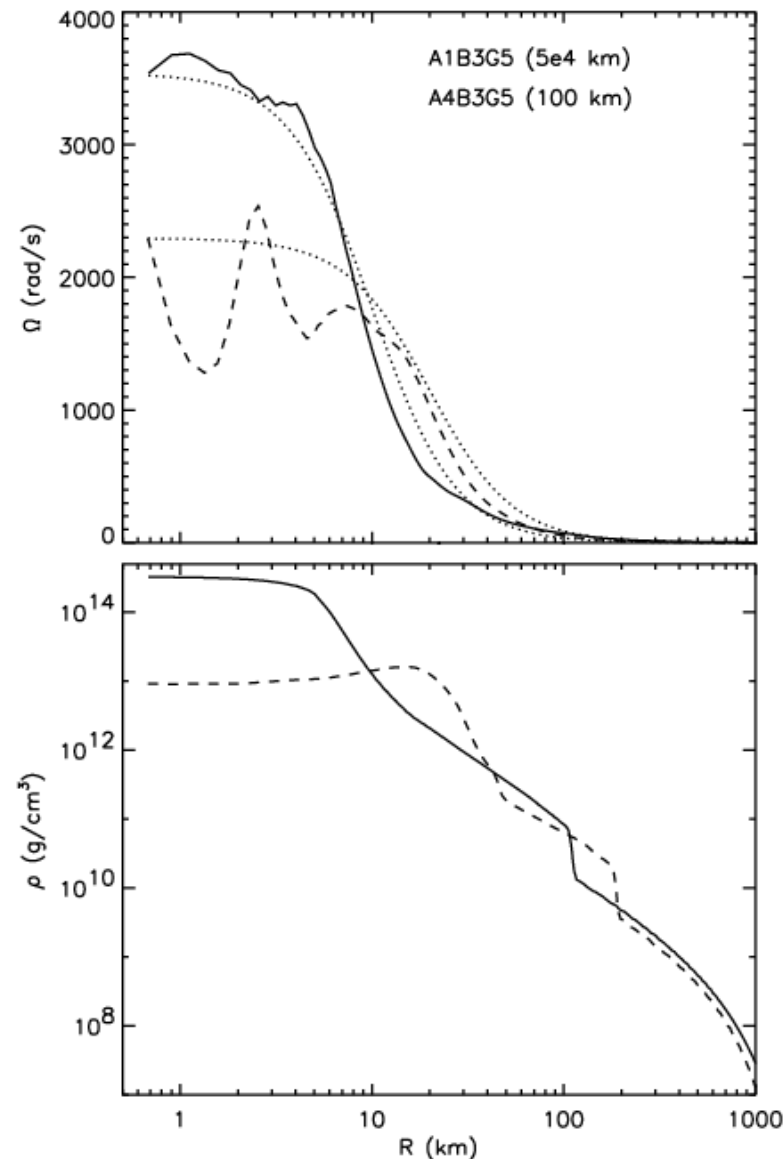
$$F[\Omega] = R_0^2 (\Omega_c - \Omega),$$

(Komatsu, Eriguchi, Hachisu, 1989)

Newtonian limit:

$$\Omega = R_0^2 \Omega_c / (R_0^2 + r^2 \sin^2 \theta)$$

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

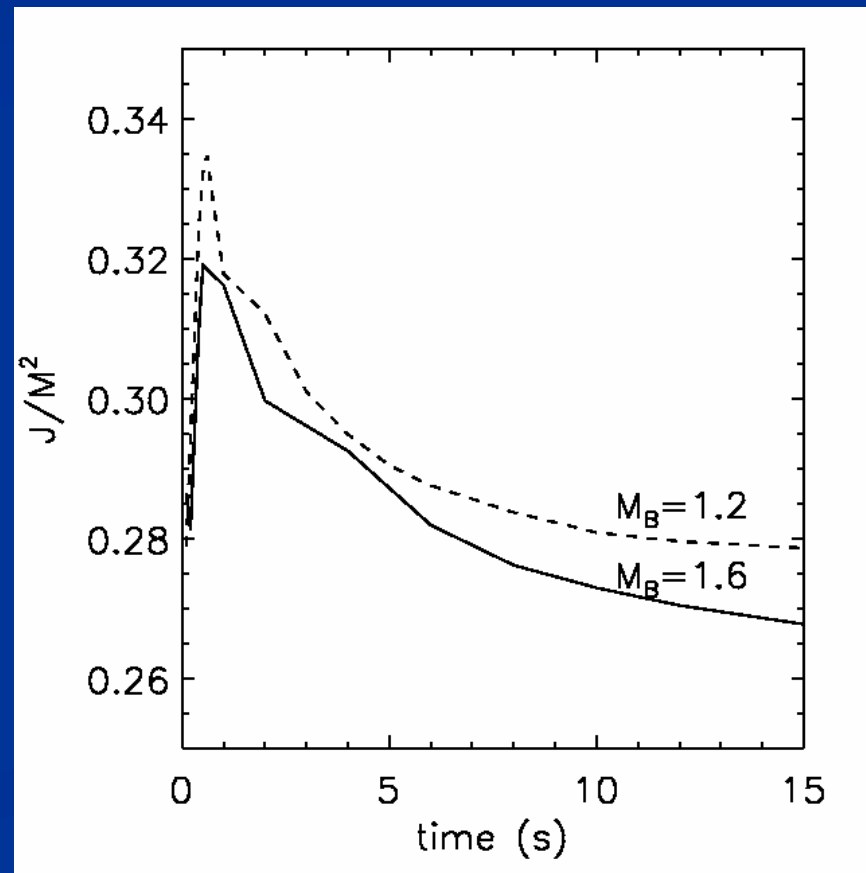
Diff. Rotation max T/W = 0.18

Table 1. Properties of non-rotating PNSs and rigidly rotating PNSs at the limiting frequency, for a fixed baryonic mass $M_B = 1.6 M_\odot$. The models are labeled by the evolutionary time of non-rotating PNSs at which the thermodynamical profile was calculated. The entries in the table are: central baryon number density, n_c ; gravitational mass, M_G ; relative binding energy $(M_G - M_B)/M_B$; circumferential equatorial radius, R_{eq} ; Kepler frequency, Ω_K ; angular momentum, J ; axis ratio r (pole to equator) and the rotation parameter $\beta = T/W$ (rotational energy on absolute value of gravitational energy). For 4 time steps at early times we give results using BPS or LS at low densities for comparison.

Model	$\Omega = 0$					$\Omega = \Omega_K$							
	n_c [fm ⁻³]	M_G [$M_\odot$]	B.E. [%]	R_{eq} [km]		n_c [fm ⁻³]	M_G [$M_\odot$]	B.E. [%]	R_{eq} [km]	Ω_K [rad/s]	J [$GM_\odot^2/c$]	r	T/W
0.1	0.006	1.592	-0.4675	83.5		0.0055	1.593	-0.45	125	332.7	1.598	0.644	0.029
1.5	(0.006)	(1.594)	(-0.288)	(74.0)		(0.0051)	(1.594)	(-0.36)	(117)	(394.1)	(2.175)	(0.624)	(0.049)
0.2	0.014	1.592	-0.467	55.3		0.0128	1.594	-0.34	78.6	430.8	1.569	0.659	0.039
1.5	(0.014)	(1.596)	(-0.588)	(48.6)		(0.0119)	(1.596)	(-0.63)	(72.2)	(765.6)	(2.189)	(0.603)	(0.048)
0.4	0.020	1.587	-0.794	37.0		0.0267	1.584	-0.96	54.0	1174	1.728	0.613	0.059
0.5	0.040	1.585	-0.893	33.3		0.0322	1.583	-1.02	48.4	1384	1.790	0.606	0.066
1.5						(0.0295)	(1.582)	(-1.09)	(45.1)	(1565)	(2.232)	(0.561)	(0.102)
1.0	0.338	1.548	-3.18	20.2		0.0751	1.578	-1.34	37.1	2064	1.764	0.583	0.077
1.5						(0.0616)	(1.577)	(-1.42)	(35.7)	(2239)	(2.278)	(0.535)	(0.123)
2.0	0.373	1.531	-4.305	16.5		0.2006	1.557	-2.72	25.9	3470	1.627	0.587	0.086
4.0	0.399	1.508	-5.76	14.4		0.2618	1.523	-4.82	21.3	4644	1.622	0.565	0.101
6.0	0.407	1.496	-6.51	13.9		0.2891	1.509	-5.70	20.4	4939	1.573	0.568	0.099
8.0	0.410	1.489	-6.94	13.7		0.3043	1.501	-6.21	20.0	5078	1.541	0.569	0.099
10.	0.411	1.483	-7.31	13.6		0.3156	1.495	-6.37	19.7	5154	1.533	0.569	0.099
12.	0.413	1.478	-7.61	13.5		0.3248	1.491	-6.82	19.6	5260	1.509	0.570	0.098
15.	0.415	1.473	-7.94	13.43		0.3346	1.487	-7.07	19.5	5323	1.494	0.570	0.098
20.	0.422	1.466	-8.36	13.36		0.3444	1.483	-7.31	19.4	5364	1.484	0.570	0.097

Table 2. Properties of non-rotating PNSs and rigidly rotating PNSs at the limiting frequency, for a fixed baryonic mass $M_B = 1.2 M_\odot$. The entries in the table are the same as in Table 1.

Model	$\Omega = 0$					$\Omega = \Omega_K$							
	n_c [fm ⁻³]	M_G [$M_\odot$]	B.E. [%]	R_{eq} [km]		n_c [fm ⁻³]	M_G [$M_\odot$]	B.E. [%]	R_{eq} [km]	Ω_K [rad/s]	J [$GM_\odot^2/c$]	r	T/W
0.1	0.0055	1.199	-0.10	78.73		0.00509	1.199	-0.08	117.6	314.7	0.876	0.63	0.0241
0.4	0.038	1.194	-0.405	32.80		0.0302	1.191	-0.72	47.91	1216	1.018	0.63	0.0509
0.5	0.057	1.193	-0.58	29.25		0.0390	1.191	-0.74	43.05	1429	1.043	0.63	0.0631
0.6	0.096	1.191	-0.772	26.36		0.0495	1.190	-0.84	39.71	1614	1.051	0.63	0.0673
0.75	0.248	1.174	-2.08	20.87		0.0673	1.187	-1.04	34.80	1836	1.030	0.60	0.0699
1.	0.260	1.172	-2.337	19.38		0.1078	1.187	-1.42	32.27	2264	0.989	0.60	0.0699
2.	0.286	1.156	-3.63	15.58		0.1893	1.165	-3.00	27.93	3077	0.980	0.59	0.0870
3.	0.295	1.149	-4.267	14.79		0.2136	1.154	-3.72	24.63	3965	0.945	0.58	0.0880
4.	0.298	1.144	-4.648	14.45		0.2271	1.149	-4.25	20.97	4138	0.926	0.58	0.0877
5.	0.299	1.140	-4.98	14.25		0.2362	1.145	-4.59	20.61	4237	0.912	0.58	0.0874
6.	0.300	1.137	-5.25	14.12		0.2439	1.142	-4.84	20.39	4300	0.903	0.58	0.0871
7.	0.301	1.134	-5.46	14.03		0.2498	1.140	-5.04	20.24	4340	0.897	0.58	0.0868
8.	0.302	1.132	-5.64	13.96		0.2553	1.138	-5.19	20.14	4379	0.891	0.58	0.0866
10.	0.306	1.129	-5.93	13.88		0.2638	1.135	-5.39	20.03	4400	0.882	0.58	0.0860
12.	0.311	1.126	-6.16	13.82		0.2698	1.134	-5.48	19.96	4420	0.878	0.58	0.0859



(Villain et al. 2003)
LORENE package

PNS's Convective instability

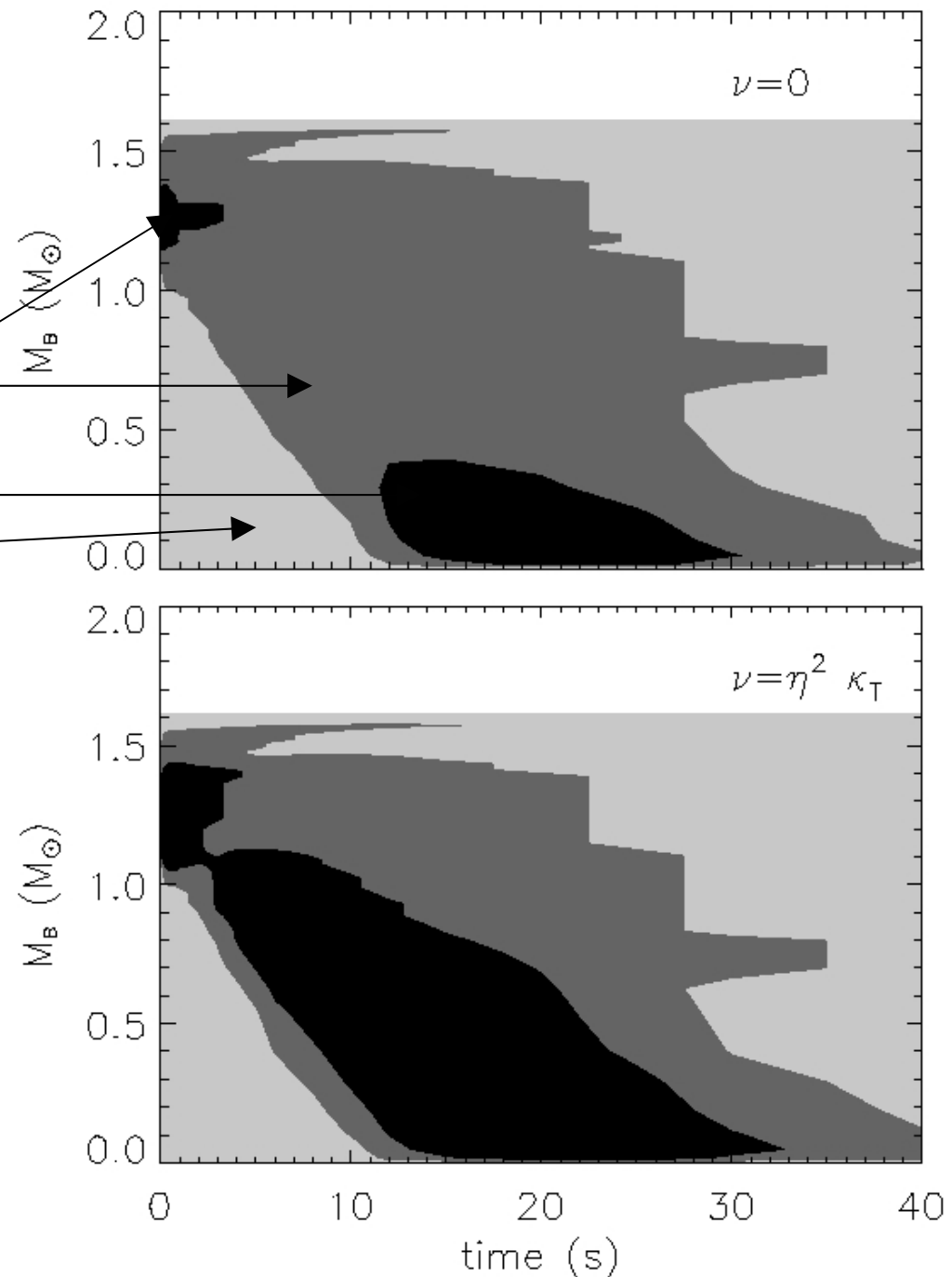
Neutron fingers
Convection
Stable

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

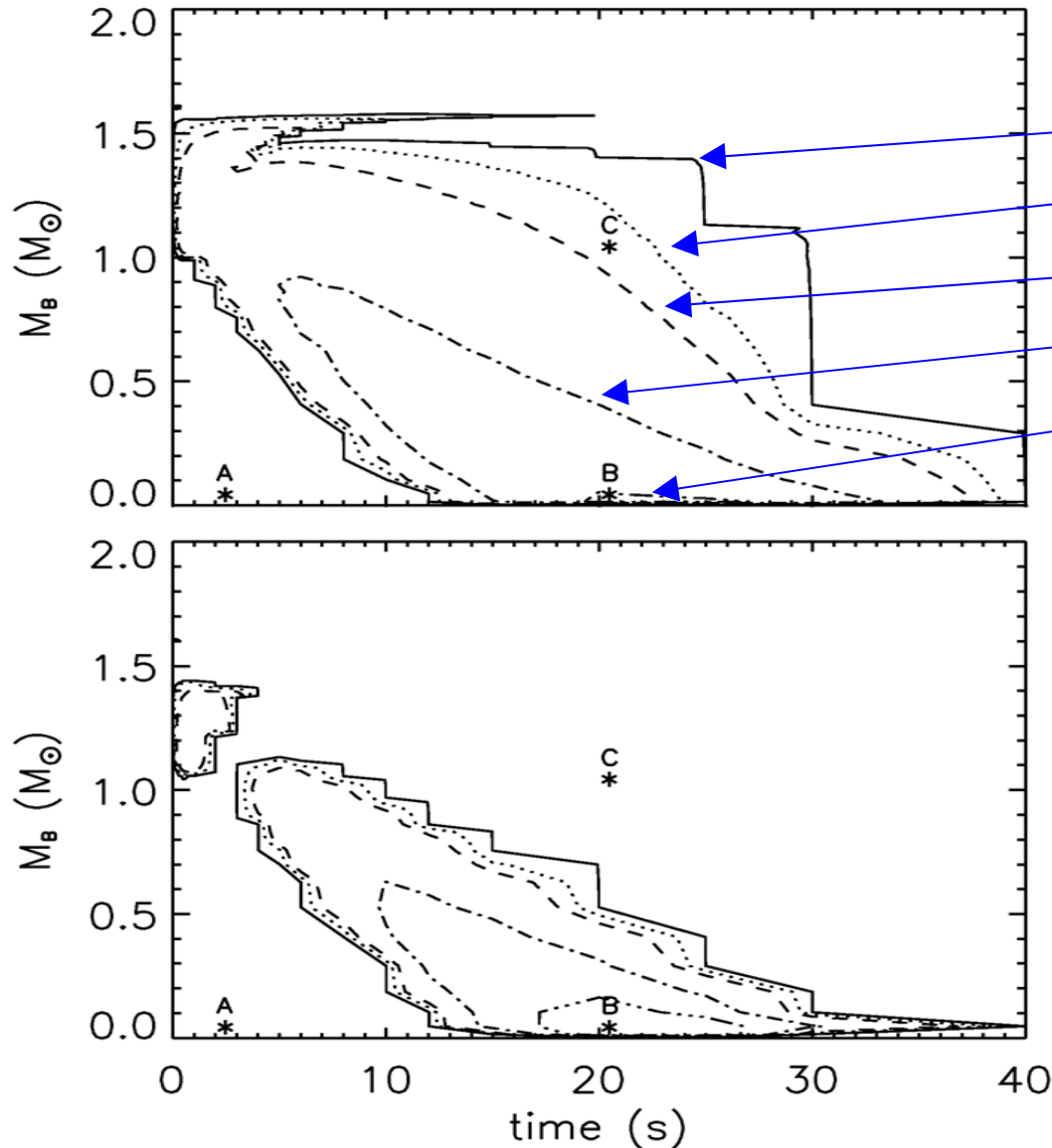
Shear Instability +
convection may lead to

Rigid rotation in few s.

$$\text{Ri} < 1/4 \quad (< 0)$$



Convection in magnetic PNSs



R-T

10^{14} G

$5 \cdot 10^{15}$ G

10^{16} G

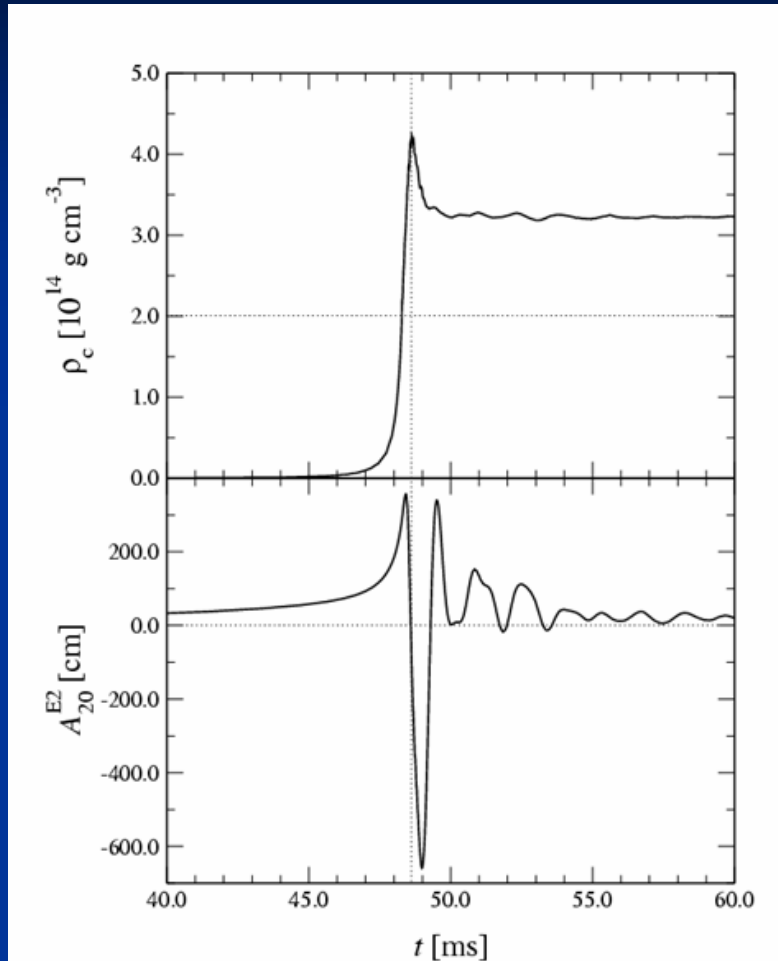
$3 \cdot 10^{16}$ G

$5 \cdot 10^{16}$ G

Schwarzschild

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

Quasinormal mode's damping



Fast damping: almost no ring down observed.

-- GW damping ?

-- Numerical viscosity ?

-- Thermal dissipation ?

Actually, just simple HD:
a PNS is NOT isolated

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

PNS from collapse

vs.

PNS from mergers

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

- ☐ 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 ... ☺