Materia a quark nelle stelle e in laboratorio: segnature e limiti

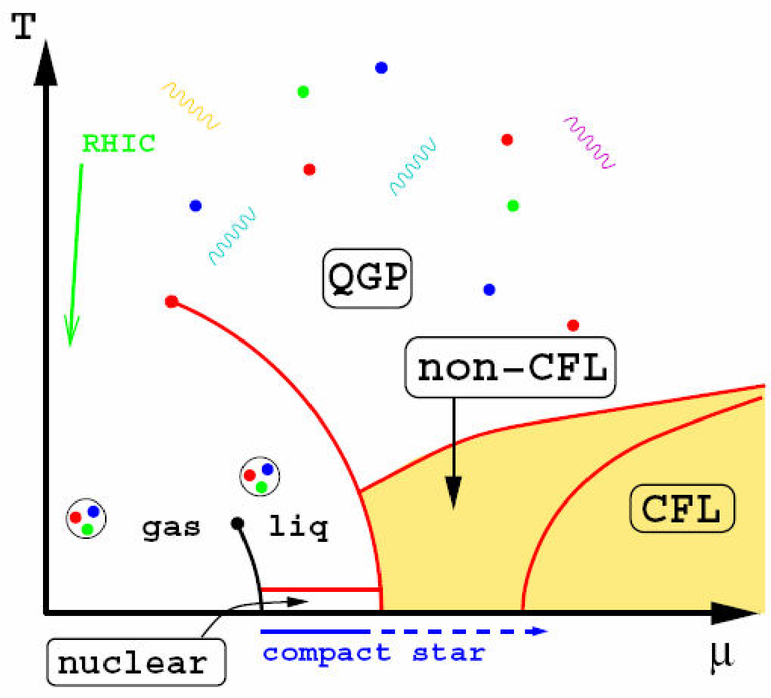
Alessandro Drago

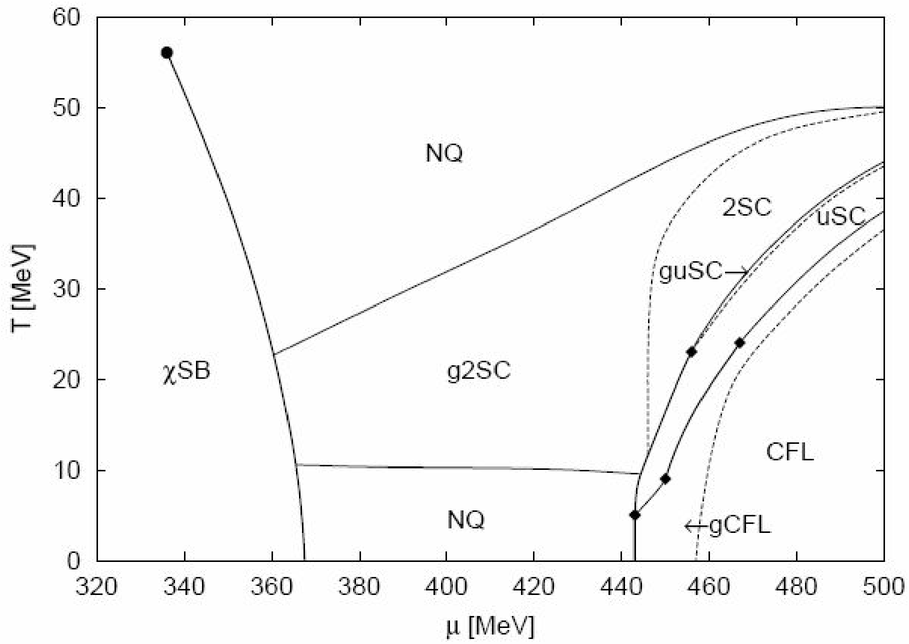
Università di Ferrara

Pavia, 6 Dicembre 2007

- Theory of matter at large densities
- Limits on masses and radii
- Cooling curves
- Millisecond pulsars
- Other observations (glitches, QPO in soft gamma repeaters)
- Implications for explosive phenomena (SNs and GRBs)
- Connection with lab experiments
- Conclusions

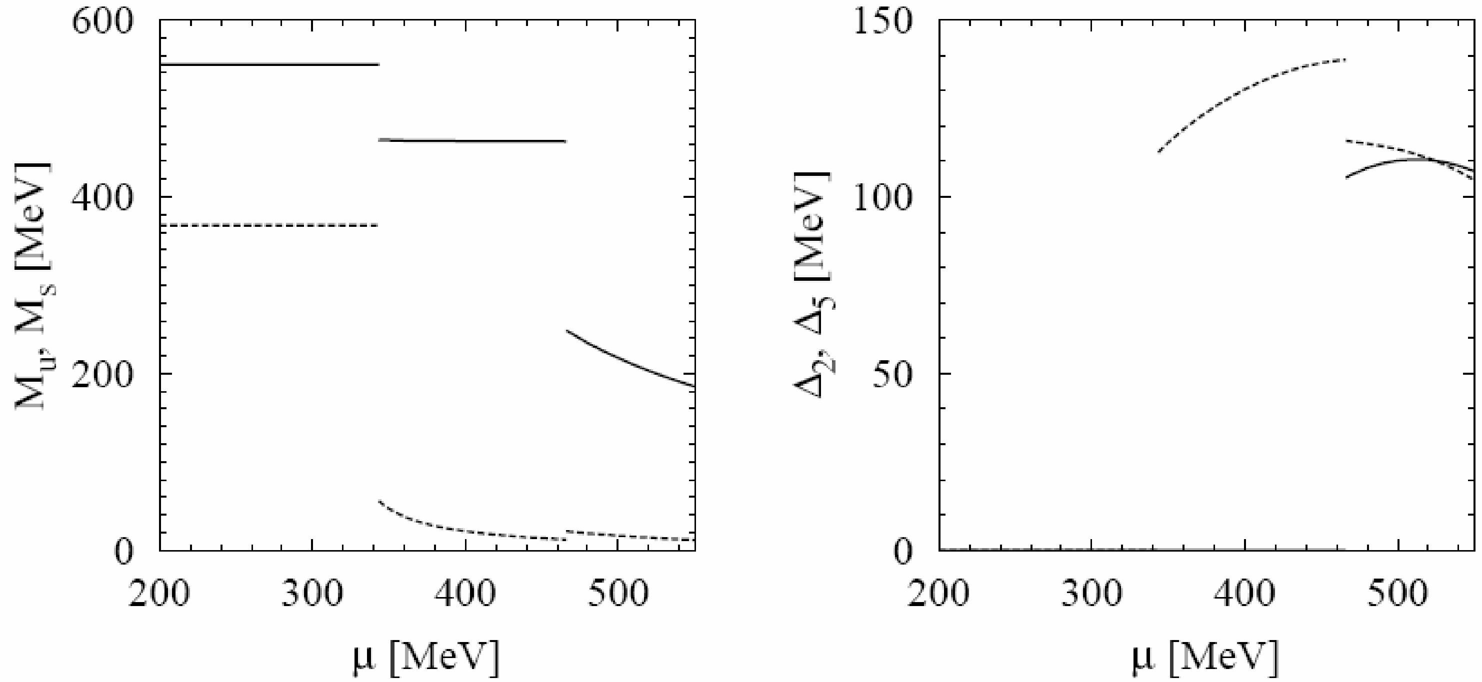
Phase diagram of high density matter



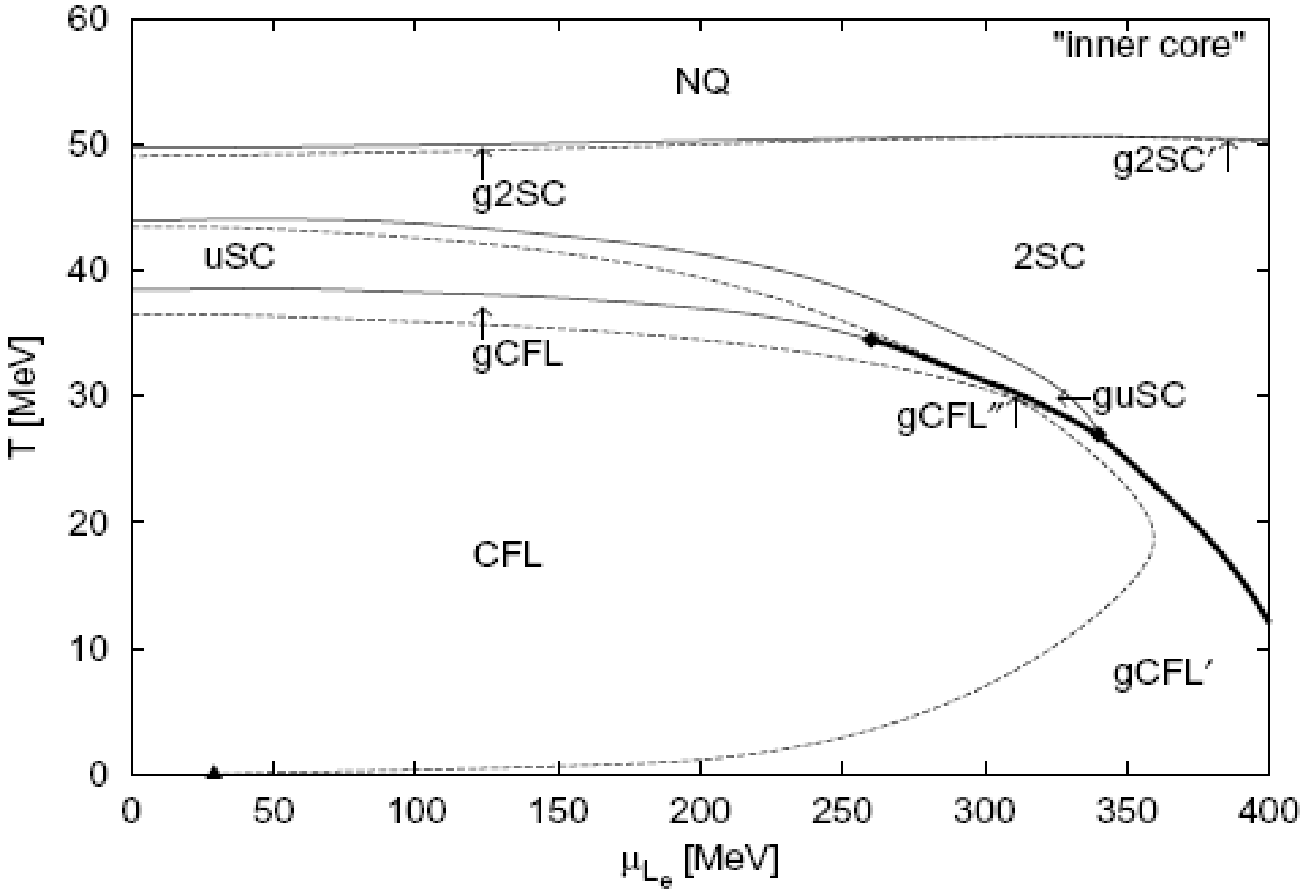


NJL model
Ruster et al. 2005

Constituent masses and gaps in NJL
Buballa 2004



Phase diagram of neutral quark matter: effect of neutrino trapping
Ruster et al. PRD73 (2006) 034025



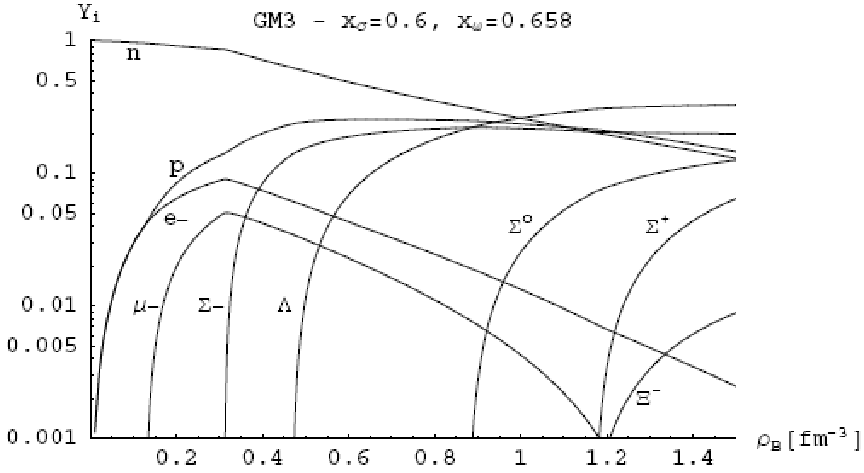
Formation of color superconducting quark matter from normal quark matter takes place through a first order transition.

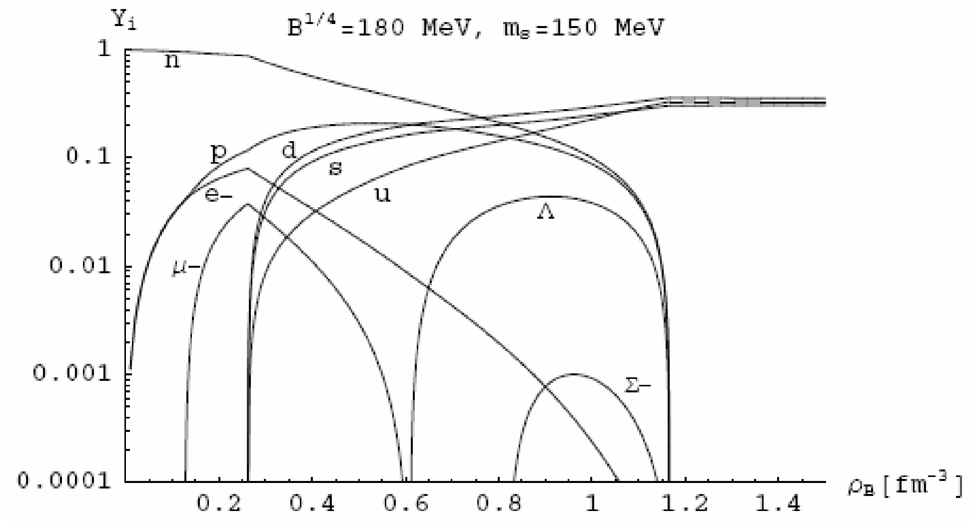
The energy released in the second transition is larger than in the first!

Open questions in the theory of high density matter

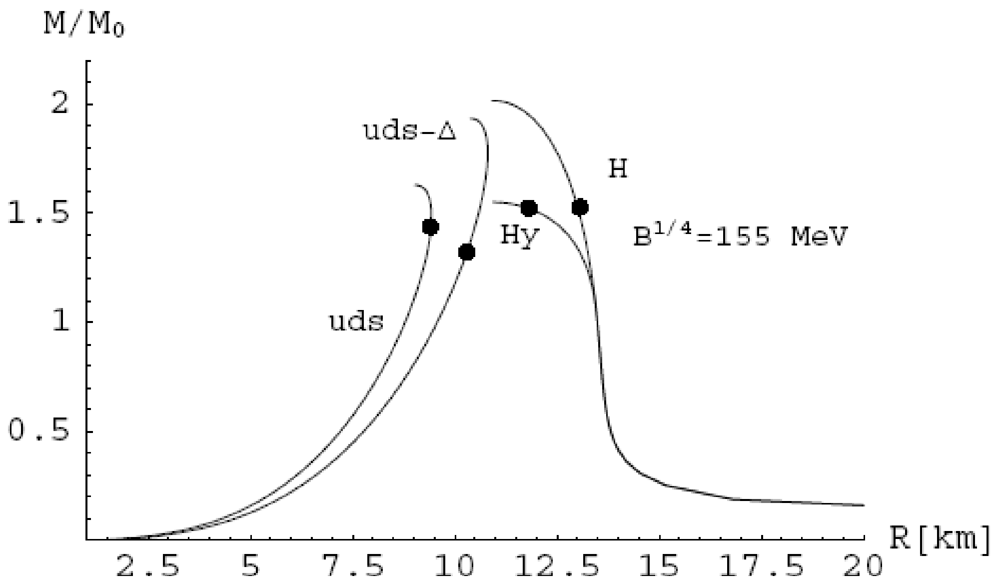
- Which phases between HM and CFL? NQ? 2SC? Gapless 2SC? Gapless CFL? Crystalline phases?...
- Discrepancy between MIT-like and NJL calculations due to large m_s in NJL: in NJL it is difficult to produce strange quark matter
- Large density repulsion: gluon exchange? Vector mesons? Which parameter values?

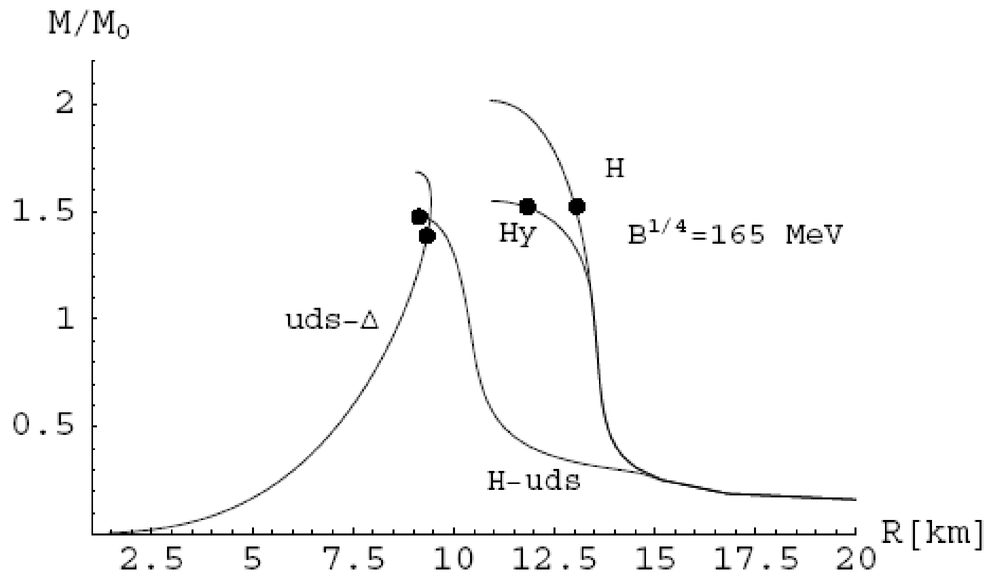
Composition of high density matter: hyperons and (ungapped) quarks





Masses and radii: effect of hyperons and quarks





How many quark stars? (if any…)

If quark stars exist → all compact stars are quark stars (Madsen, Olinto et al.)

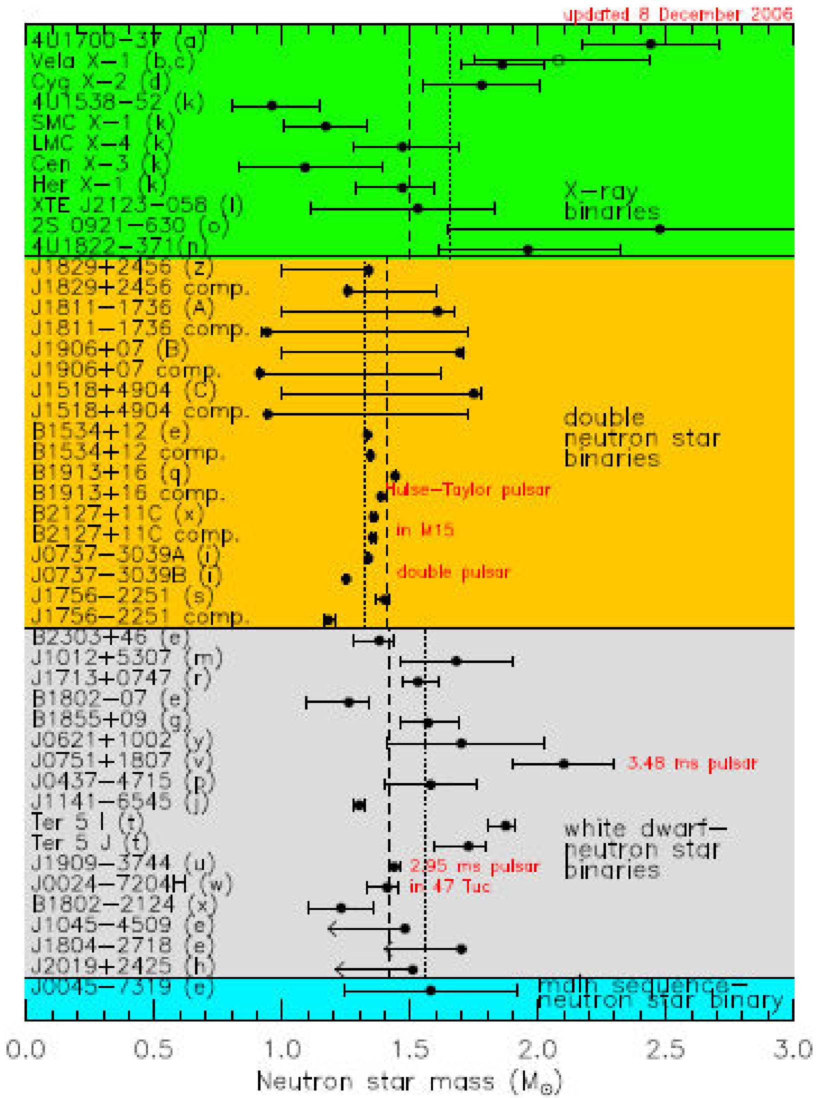
But…

- Quark nugget contamination maybe overestimated
- Mechanism providing the formation of quark matter unclear

Maybe quark and neutron stars can both exist!

Masses

Lattimer and Prakash 2007

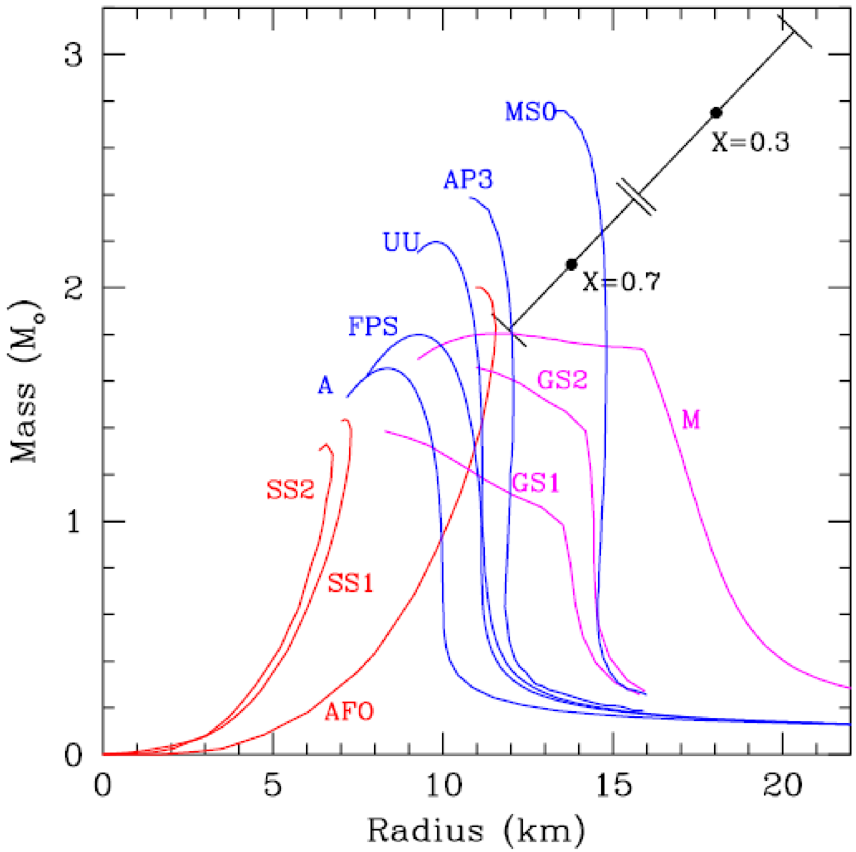


Limits on masses and radii
Ozel 2006

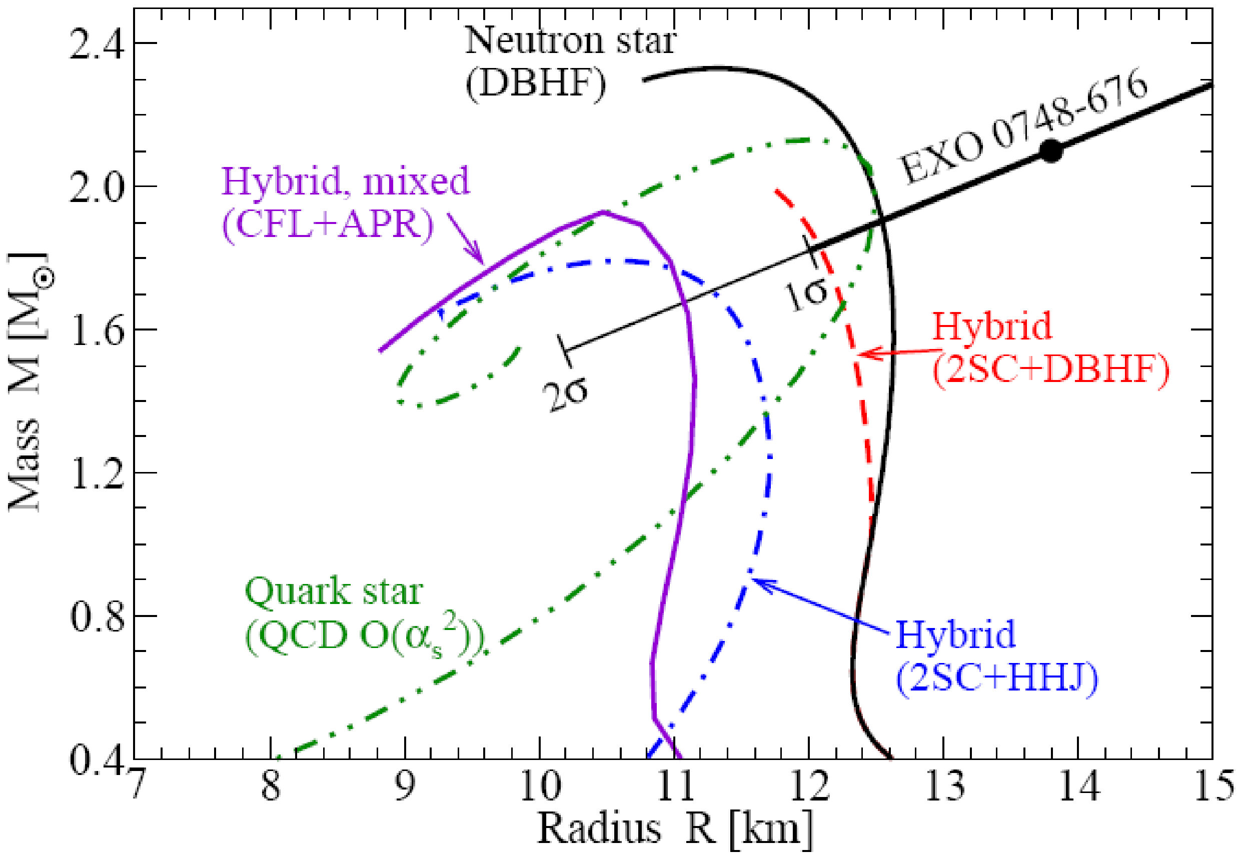
Observable	Measurement	Dependence on NS Properties
$F_{\rm Edd}$	$(2.25 \pm 0.23) \times 10^{-8}$ erg cm^{-2} s^{-1}	$\frac{1}{4\pi D^2}\frac{4\pi GMc}{\kappa_{\rm es}}\left(1-\frac{2GM}{c^2R}\right)^{1/2}$
z	0.35	$\left(1-\frac{2GM}{Rc^2}\right)^{-1/2}-1$
$F_{\rm cool}/\sigma T_{\rm c}^4$	1.14 ± 0.10 (km/kpc)^2	$f_\infty^2\frac{R^2}{D^2}\left(1-\frac{2GM}{Rc^2}\right)^{-1}$

NS Property	Dependence on Observables	Constraint
M	$\frac{f_\infty^4 c^4}{4G\kappa_{\rm es}}\left(\frac{F_{\rm cool}}{\sigma T_{\rm c}^4}\right)\frac{[1-(1+z)^{-2}]^2}{(1+z)^3}F_{\rm Edd}^{-1}$	$2.10 \pm 0.28 M_\odot$
R	$\frac{f_\infty^4 c^2}{2\kappa_{\rm es}}\left(\frac{F_{\rm cool}}{\sigma T_{\rm c}^4}\right)\frac{1-(1+z)^{-2}}{(1+z)^3}F_{\rm Edd}^{-1}$	13.8 ± 1.8 km
D	$\frac{f_\infty^2 c^2}{2\kappa_{\rm es}}\left(\frac{F_{\rm cool}}{\sigma T_{\rm c}^4}\right)^{1/2}\frac{1-(1+z)^{-2}}{(1+z)^3}F_{\rm Edd}^{-1}$	9.2 ± 1.0 kpc

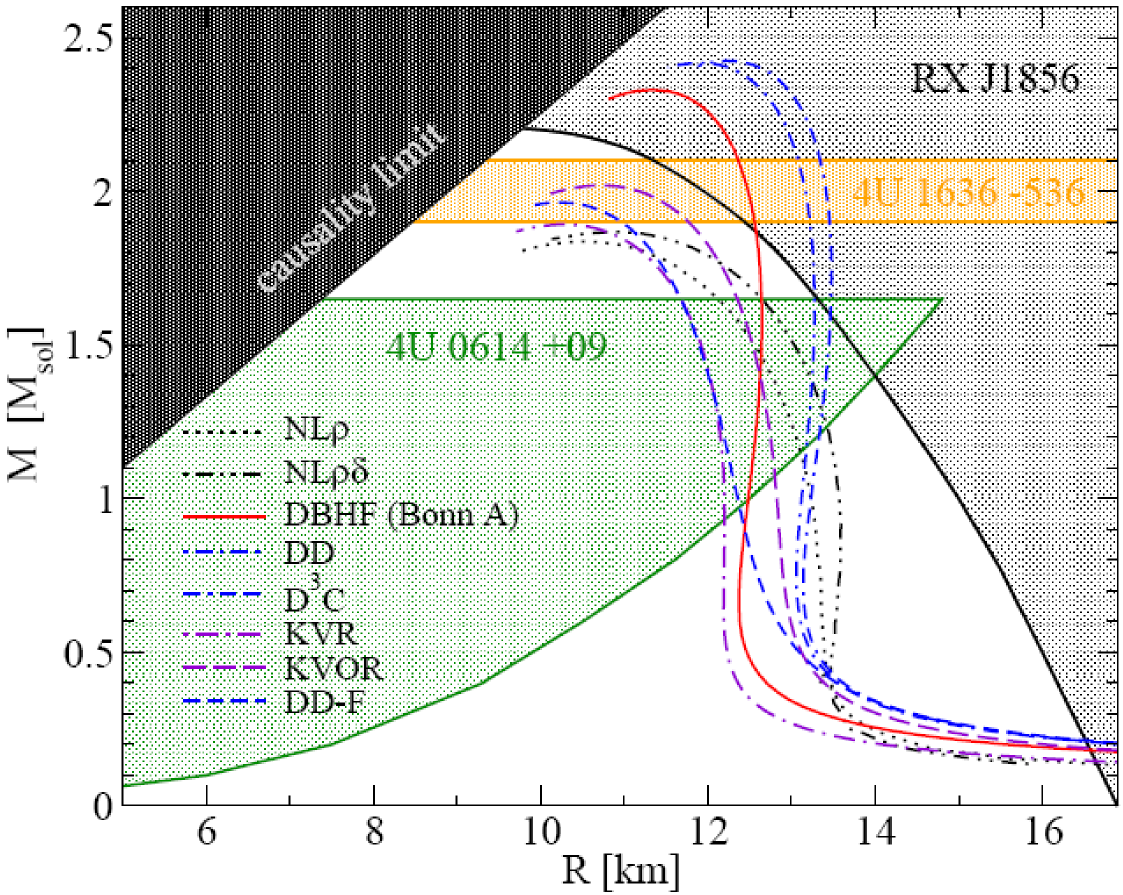
Limits on masses and radii
Ozel 2006



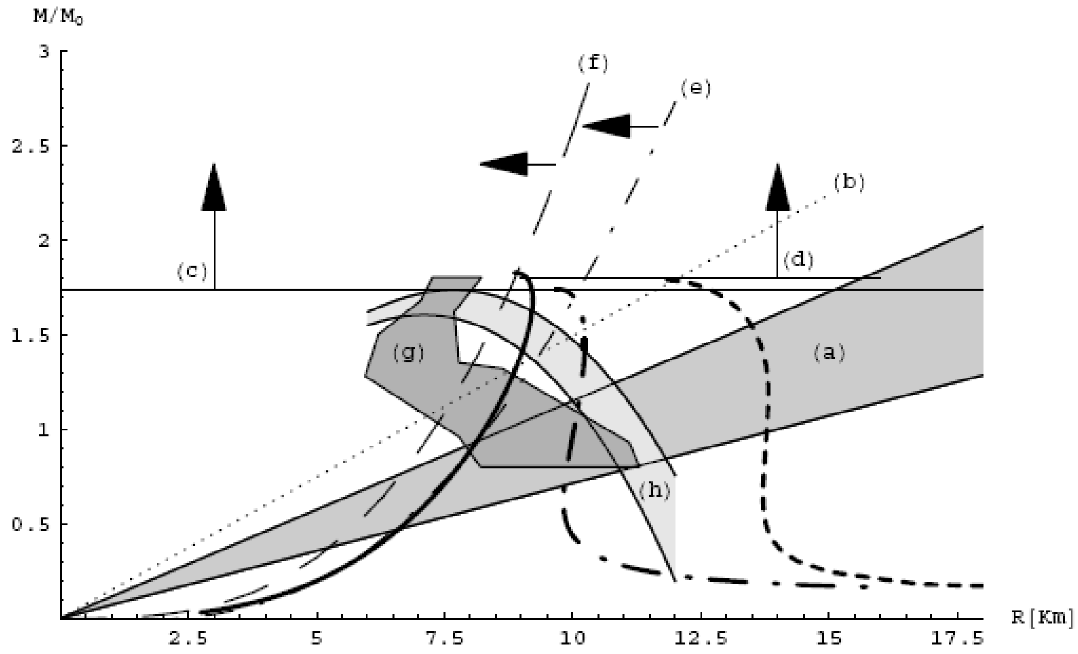
Limits on masses and radii
Alford et al. 2007



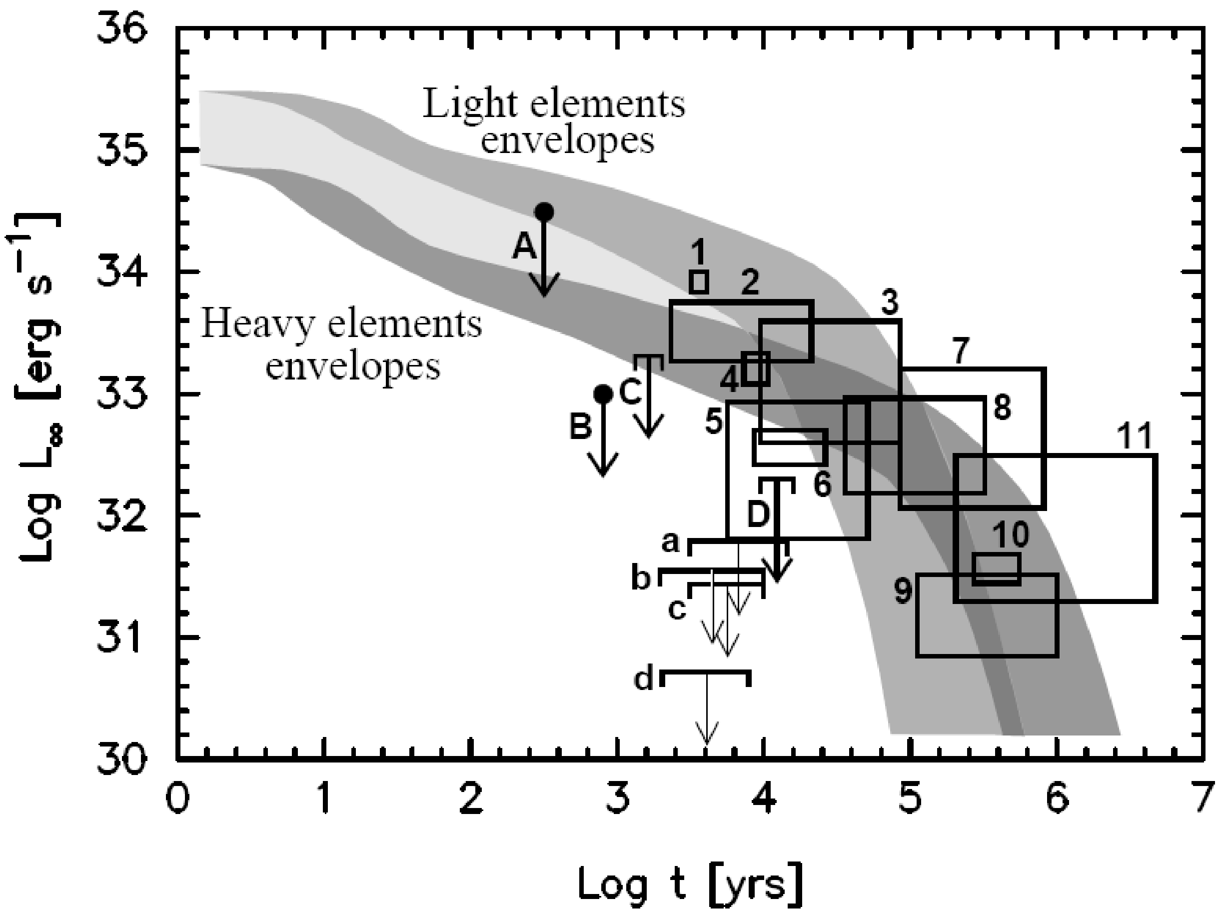
Various limits on masses and radii
Klahn et al. 2006



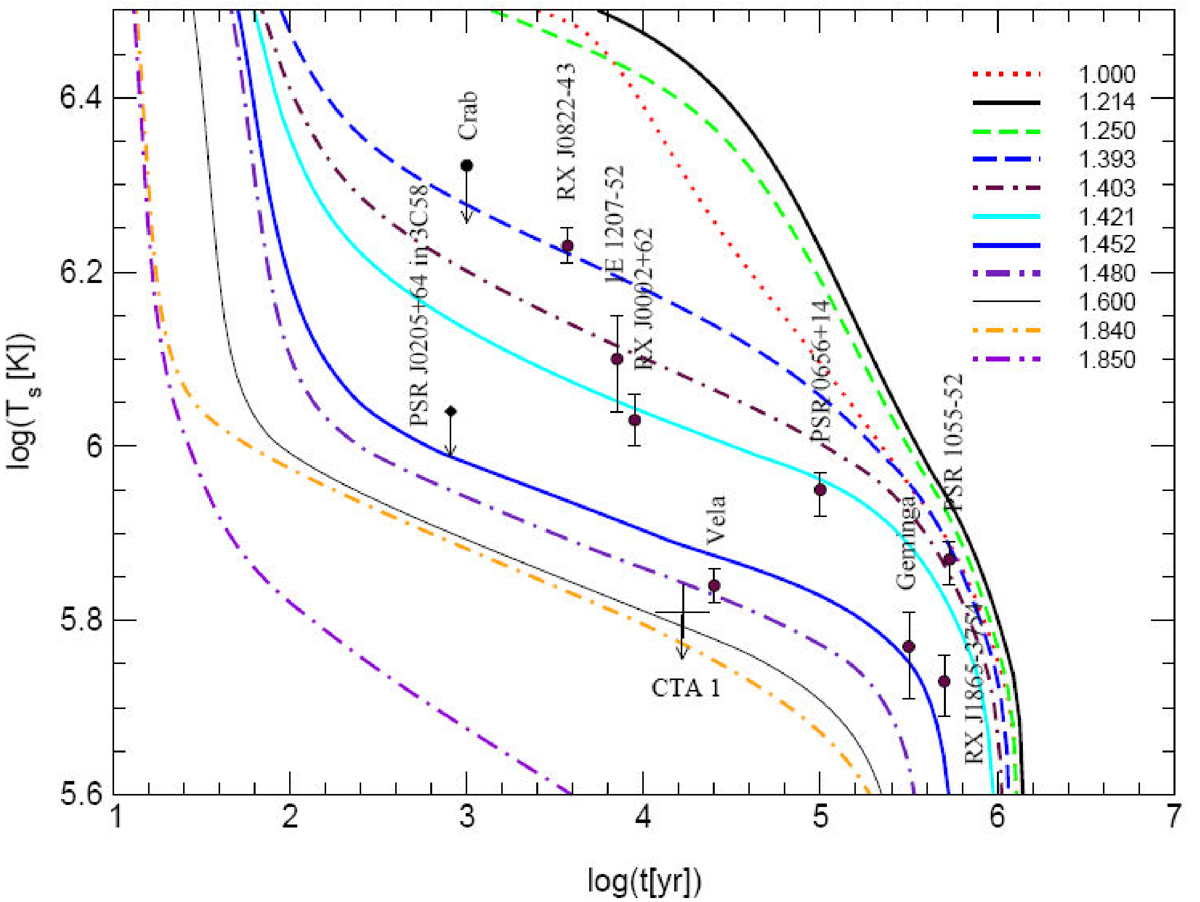
Thermal radii (obsolete…)



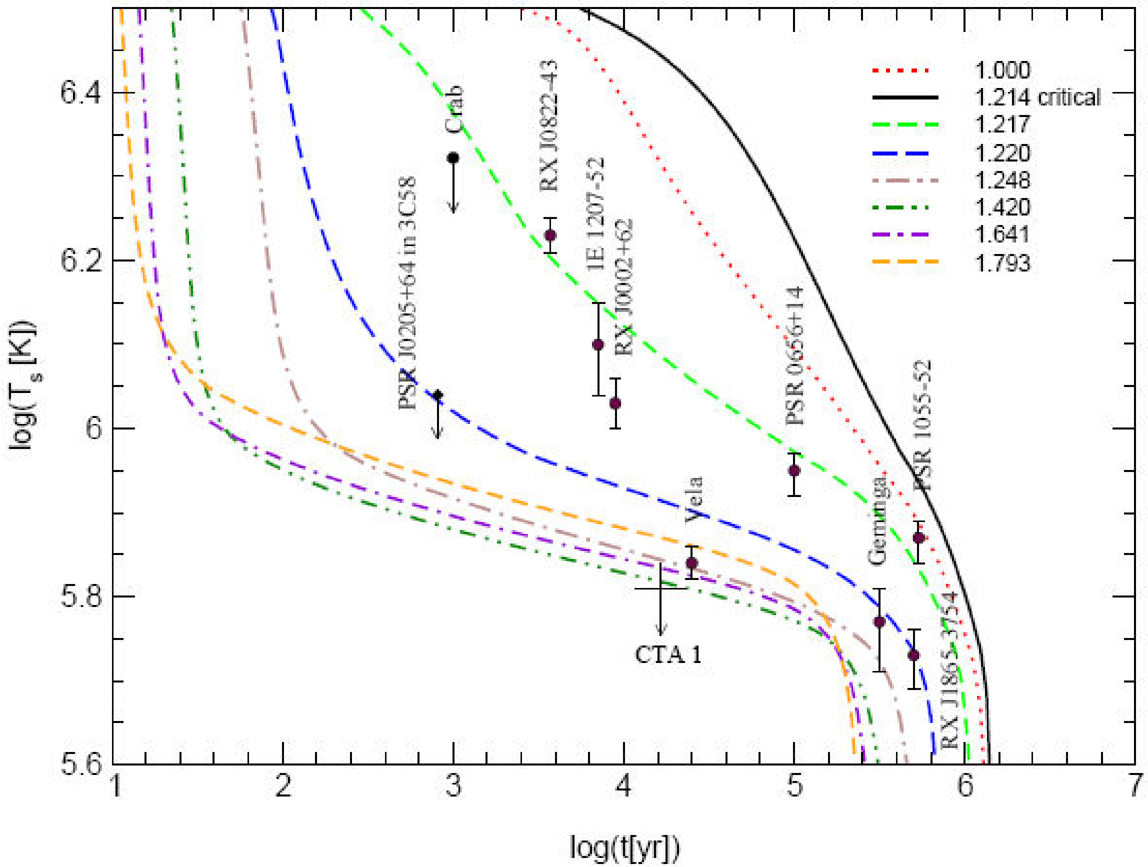
Cooling curves: minimal model vs data
Page et al. 2005



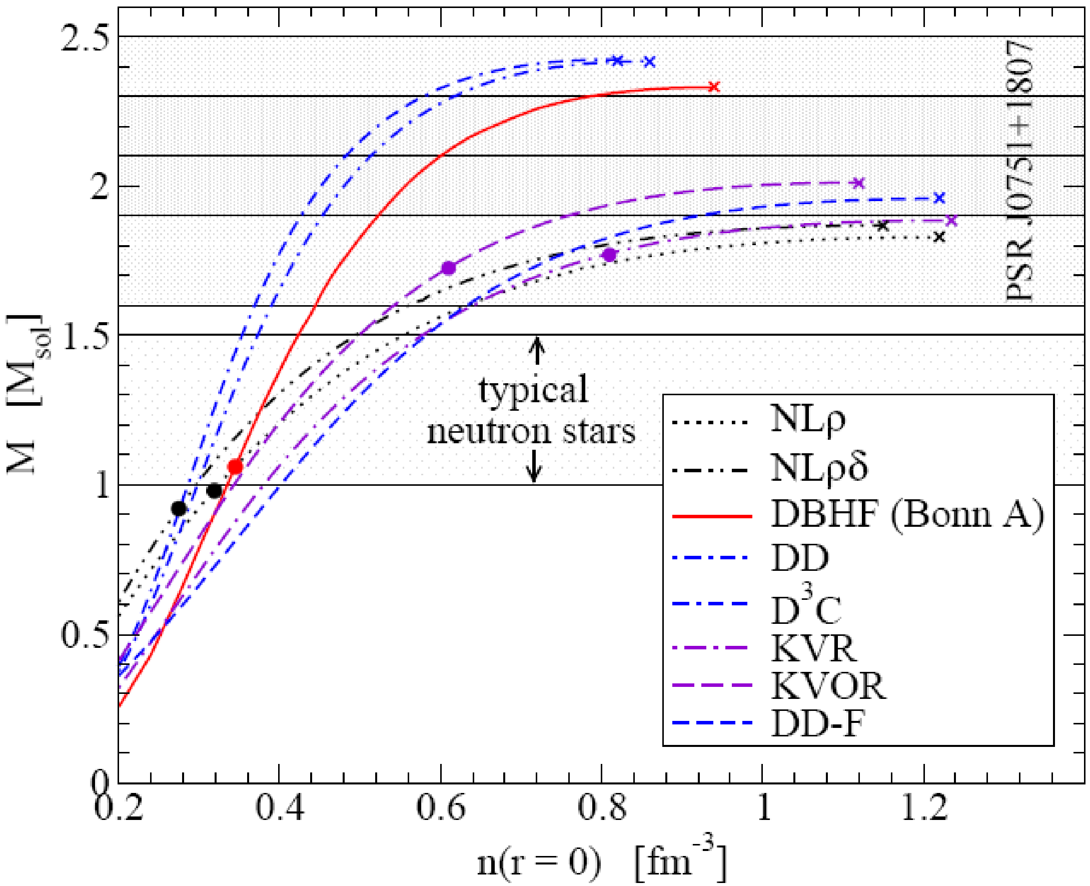
Cooling curves in a hadronic scenario
Grigorian et al. 2005



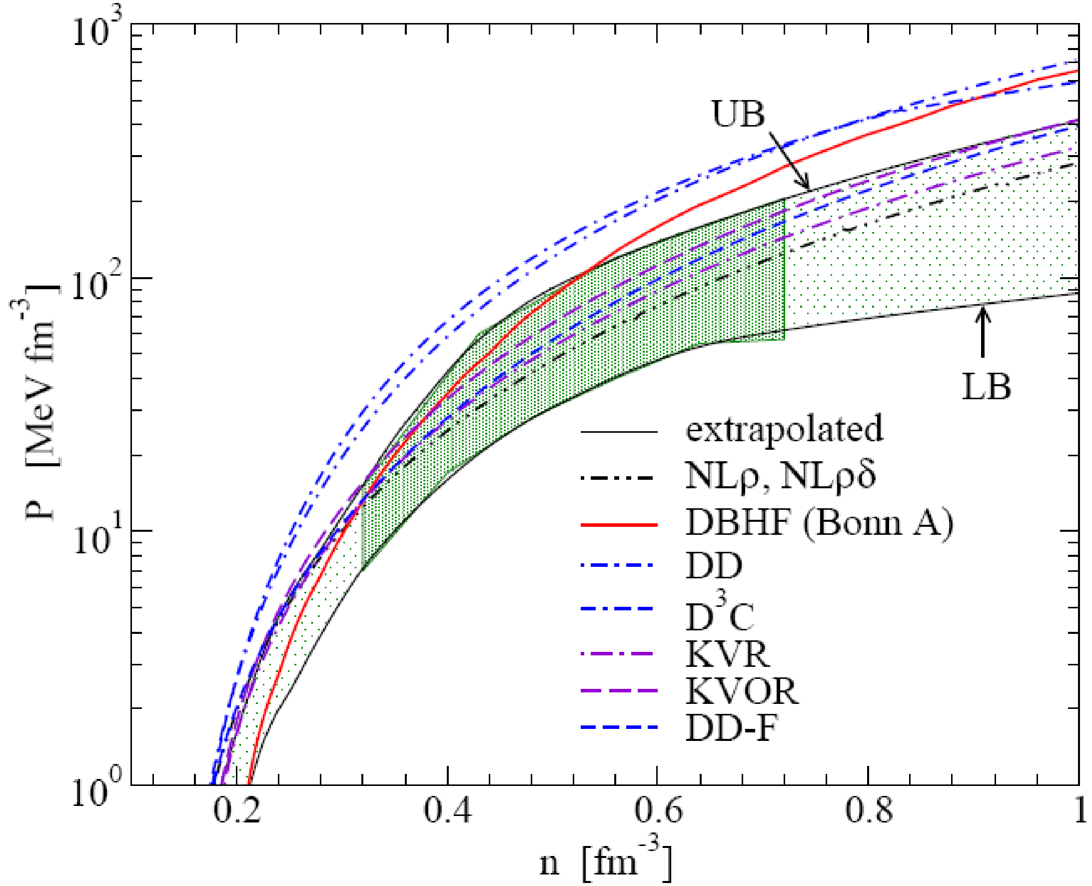
Cooling curves for a hybrid star
Grigorian et al. 2005



Maximum mass and direct Urca threshold
Klahn et al. 2006



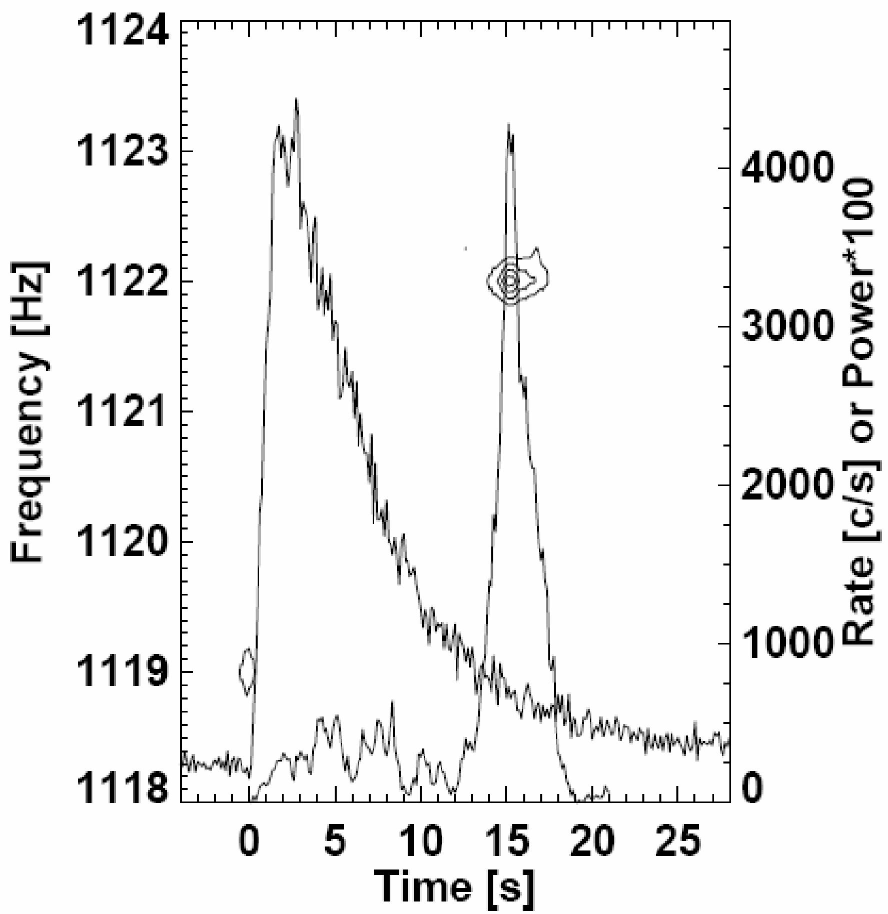
Extrapolated limits on pressure from lab experiments



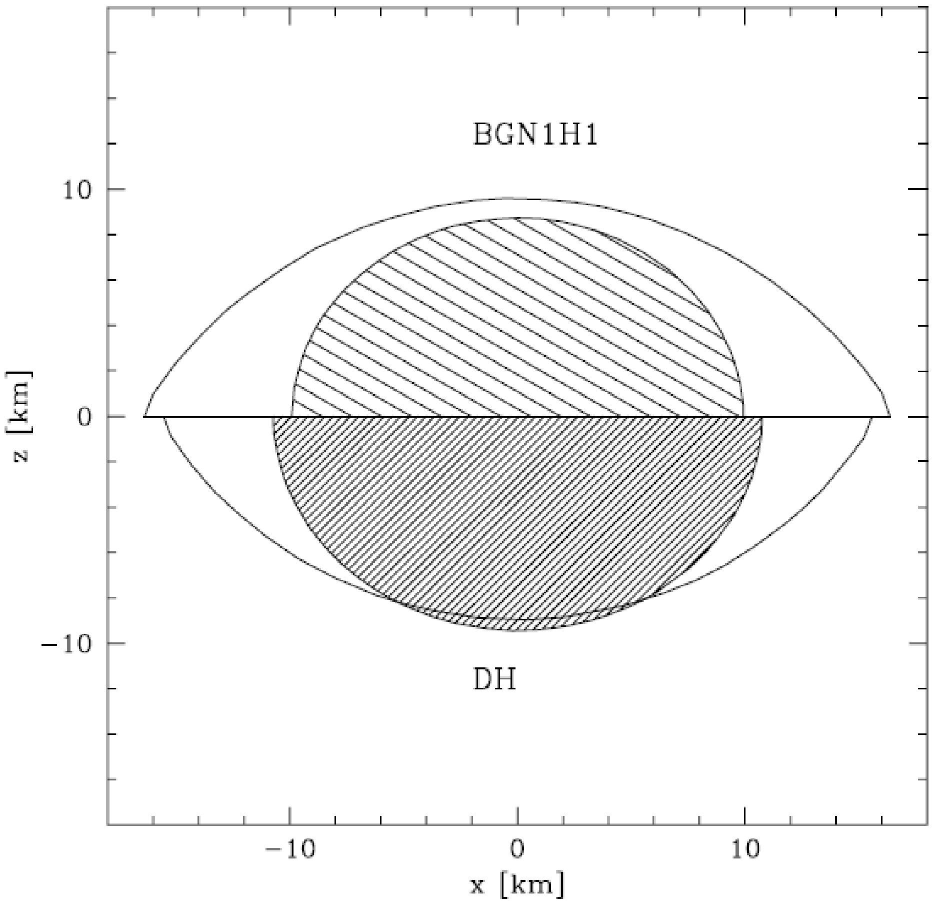
Summary of constraints from masses, radii, cooling and lab experiments Klahn et al 2006

Model	$M_{max} \geq 1.9\ M_\odot$	$M_{max} \geq 1.6\ M_\odot$	$M_{DU} \geq 1.5\ M_\odot$	$M_{DU} \geq 1.35\ M_\odot$	4U 1636-536 (u)	4U 1636-536 (l)	RX J1856 (A)	RX J1856 (B)	J0737 (no loss)	J0737 (loss 1% $M_\odot$)	SIS+AGS flow constr.	SIS flow+ K^+ constr.	No. of passed tests	(out of 6)
NLρ	−	+	−	−	−	−	−	−	−	−	+	+	1	2
NL$\rho\delta$	−	+	−	−	−	−	−	−	−	−	+	+	1	2
DBHF	+	+	−	−	+	+	−	+	−	+	−	+	2	5
DD	+	+	+	+	+	+	−	+	−	−	−	−	3	4
D^3C	+	+	+	+	+	+	−	+	−	−	−	−	3	4
KVR	○	+	+	+	−	○	−	−	−	+	+	+	3	5
KVOR	+	+	+	+	−	+	−	−	−	○	+	+	3	5
DD-F	+	+	+	+	−	+	−	−	−	+	+	+	3	5

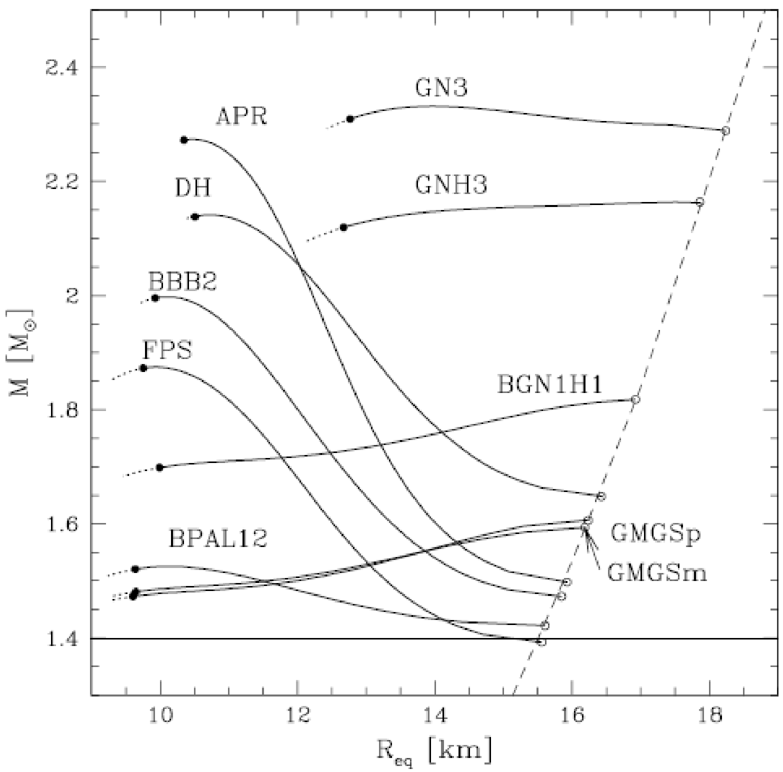
Evidence of a 1122Hz pulsation in a transient of a LMXB
Kaaret et al. 2006

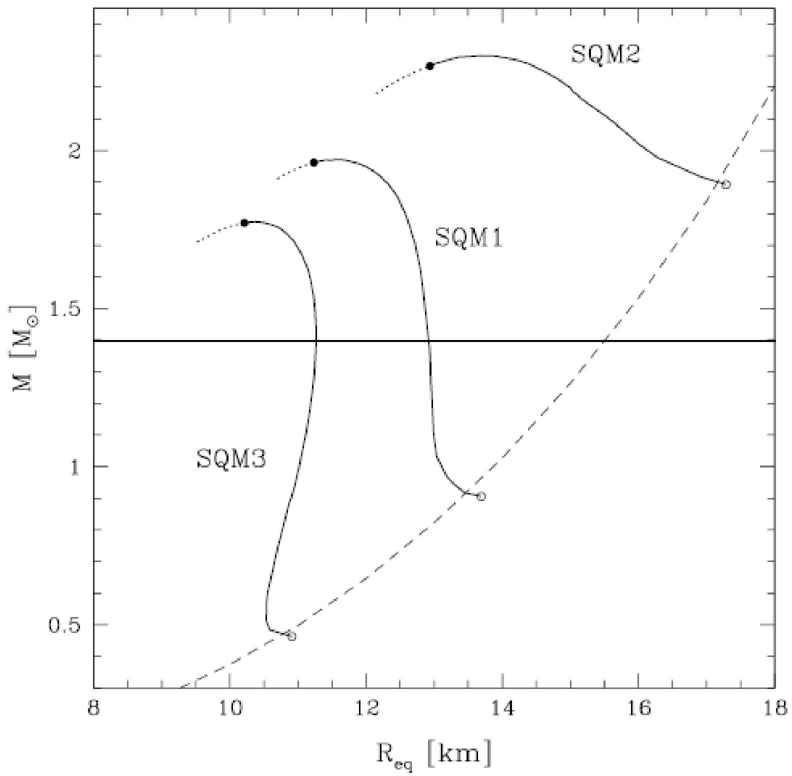


Stability of a 1122 Hz rotator
Beiger et al. 2007



Stability of a 1122 Hz rotator
Beiger et al. 2007





R-mode instabilities

Discovered by Andersson and Friedman&Morsink in 1998

Rapidly drain angular momentum from a rotating compact star

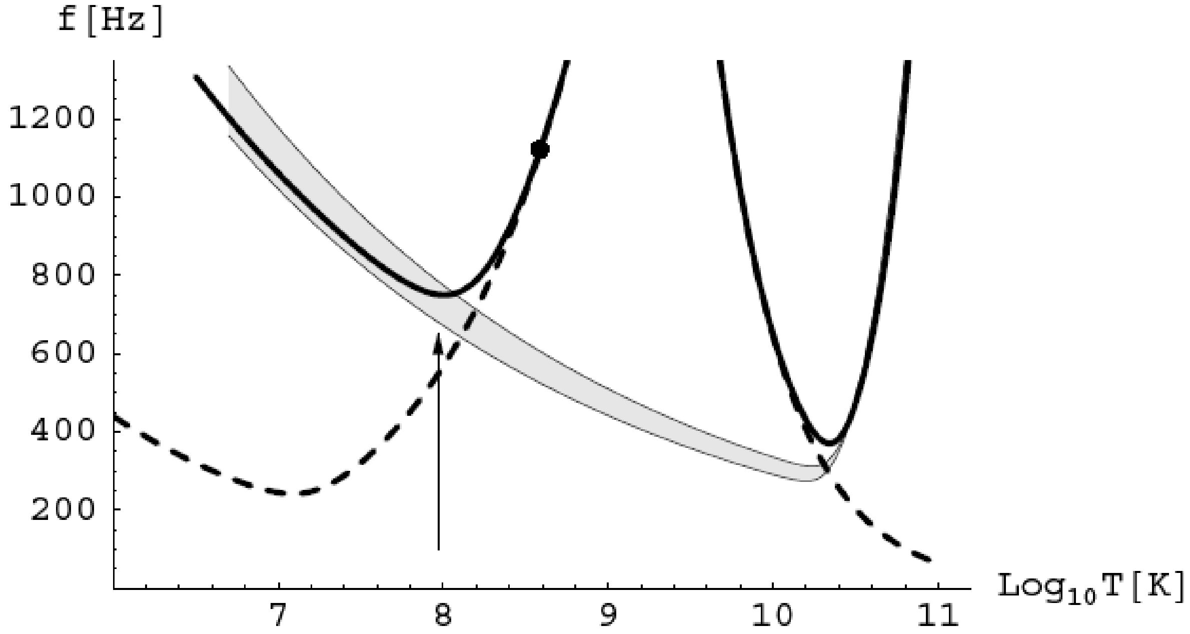
Suppressed by bulk and shear viscosity

$$\dot{\alpha} = -\alpha \left[\frac{1}{t_g} + \left(1 - \frac{3\alpha^2 \tilde{J}}{2\tilde{I}} \right) \left(\frac{1}{t_s} + \frac{1}{t_b} \right) + \frac{\dot{M}}{2\tilde{I}\Omega} \left(\frac{G}{MR^3} \right)^{1/2} \right] \quad (23)$$

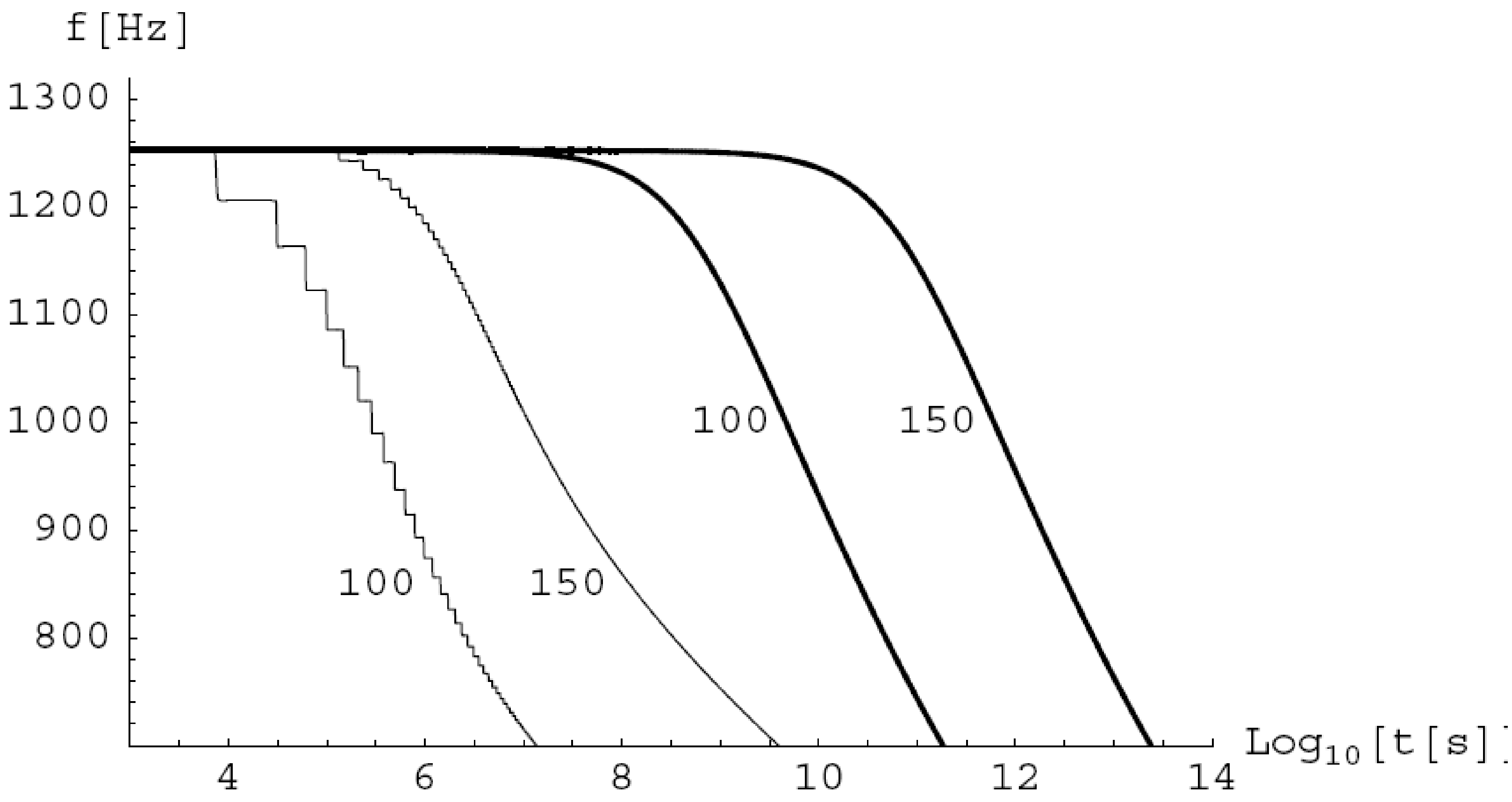
$$\dot{\Omega} = \frac{\dot{M}}{\tilde{I}} \left(\frac{G}{MR^3} \right)^{1/2} - \frac{\dot{M}\Omega}{M} - 3\Omega\alpha^2 \frac{\tilde{J}}{\tilde{I}} \left(\frac{1}{t_{\rm sv}} + \frac{1}{t_{\rm bv}} \right) \quad (24)$$

$$\dot{E}_{\rm thermal} = \dot{E}_{\rm accretion} + \dot{E}_{\rm viscosity} - \dot{E}_{\rm neutrino}$$

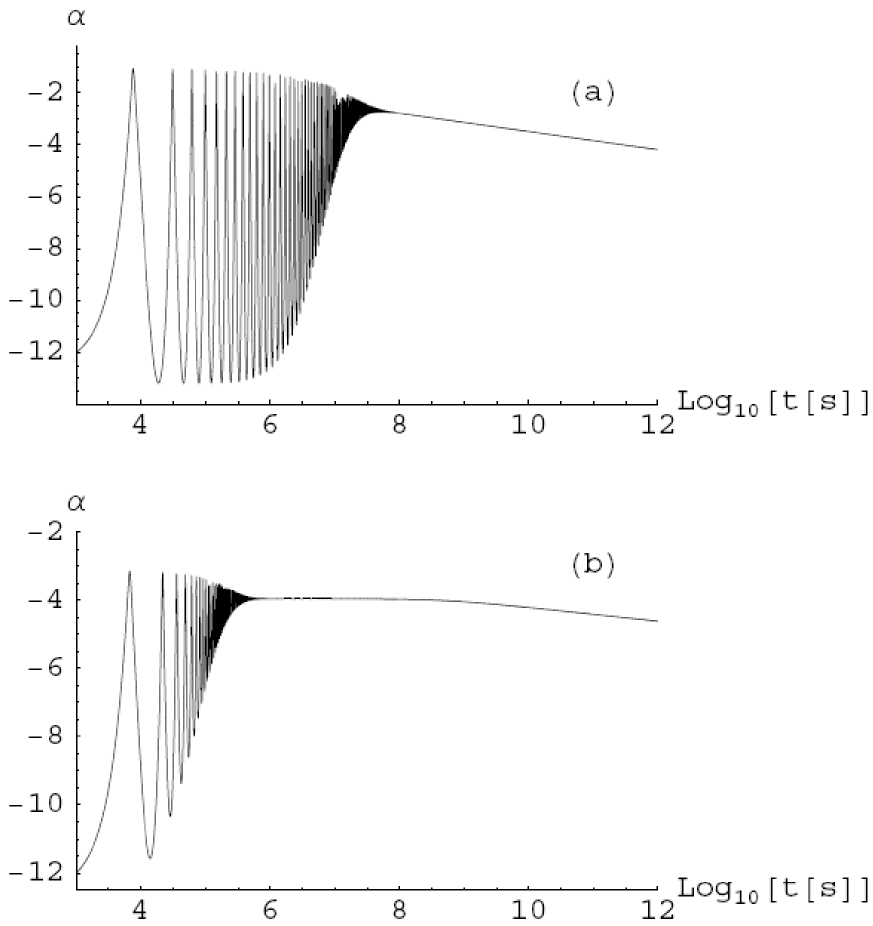
Stability windows due to r-modes adapted from Andersson et al.



Time evolution of rotational frequency
Drago et al. 2007



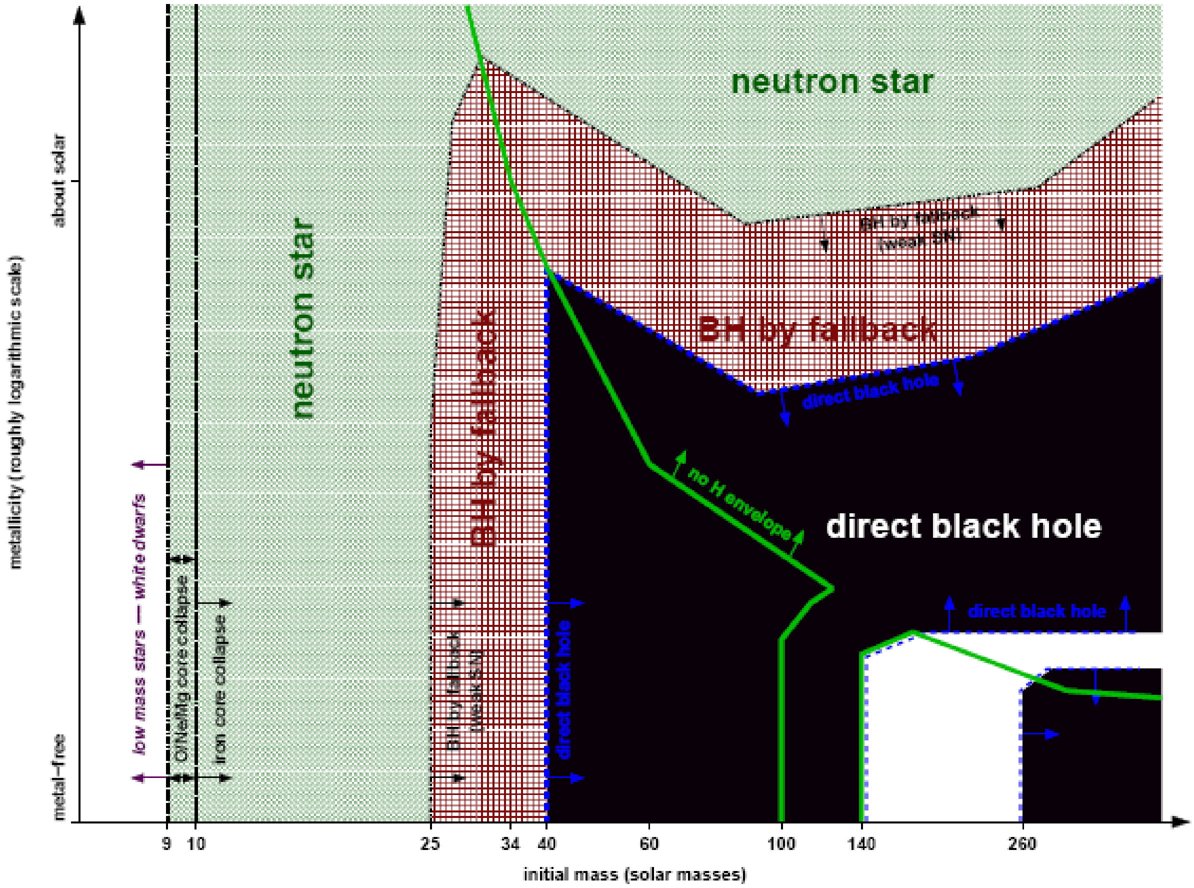
R-mode amplitudes
Drago et al. 2007



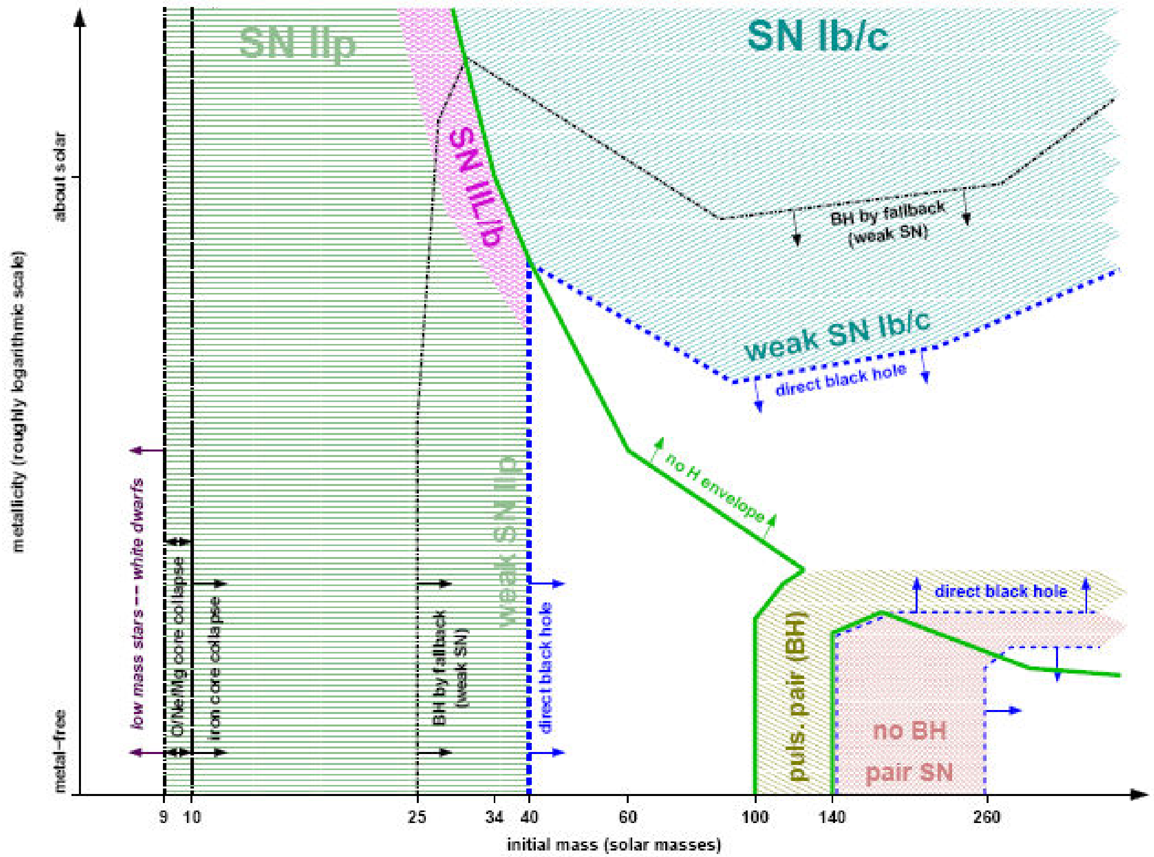
Other limits

- Glitches (temporary speeding-up of neutron stars). Crystalline phases in compact stars: can exist also in stars containing deconfined quark matter
- QPO in soft gamma repeaters: indication of frequencies of thoroidal modes of the crust of the star. Incompatible with pure quark star surfaces (Watts and Reddy 2006)

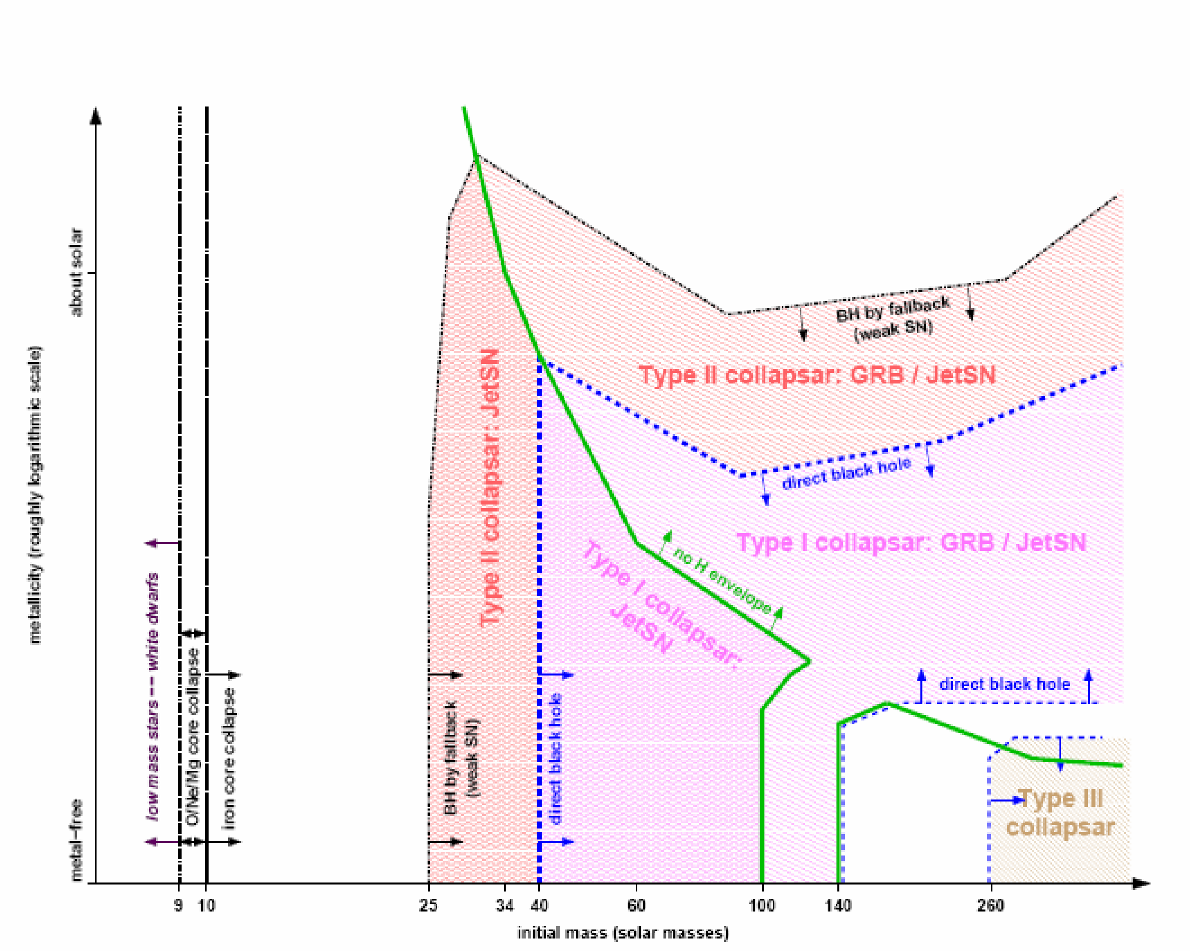
Fate of massive stars
Fryer et al. 2003



Fate of massive stars: SN types
Fryer et al. 2003



Fate of massive stars: GRB and collapsars
Fryer et al. 2003



Hypernova model (Collapsars)

Rotating massive stars, whose central region collapses to a black hole surrounded by an accretion disk.

Outflows are collimated by passing through the stellar mantle.

Detailed numerical analysis of jet formation.

Fits naturally in a general scheme describing collapse of massive stars.

Large angular momentum needed.

SN – GRB time delay: less then 100 s.

Hadronic Stars → Hybrid or Quark Stars

Z.Berezhiani, I.Bombaci, A.D., F.Frontera, A.Lavagno, ApJ586(2003)1250

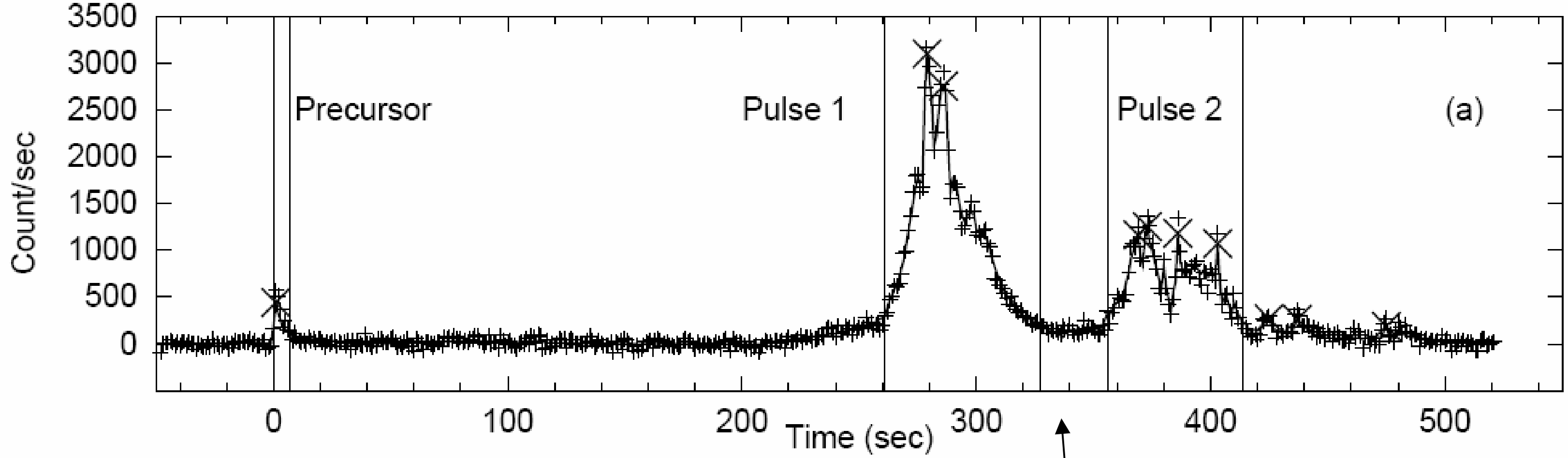
Metastability due to delayed production of Quark Matter.

1) conversion to Quark Matter (it is NOT a detonation)
2) cooling (neutrino emission)
3) neutrino – antineutrino annihilation
4)(possible) beaming due to strong magnetic field and star rotation

Fits naturally into a scheme describing QM production.
Energy and duration of the GRB are OK.

No calculation of beam formation, yet.

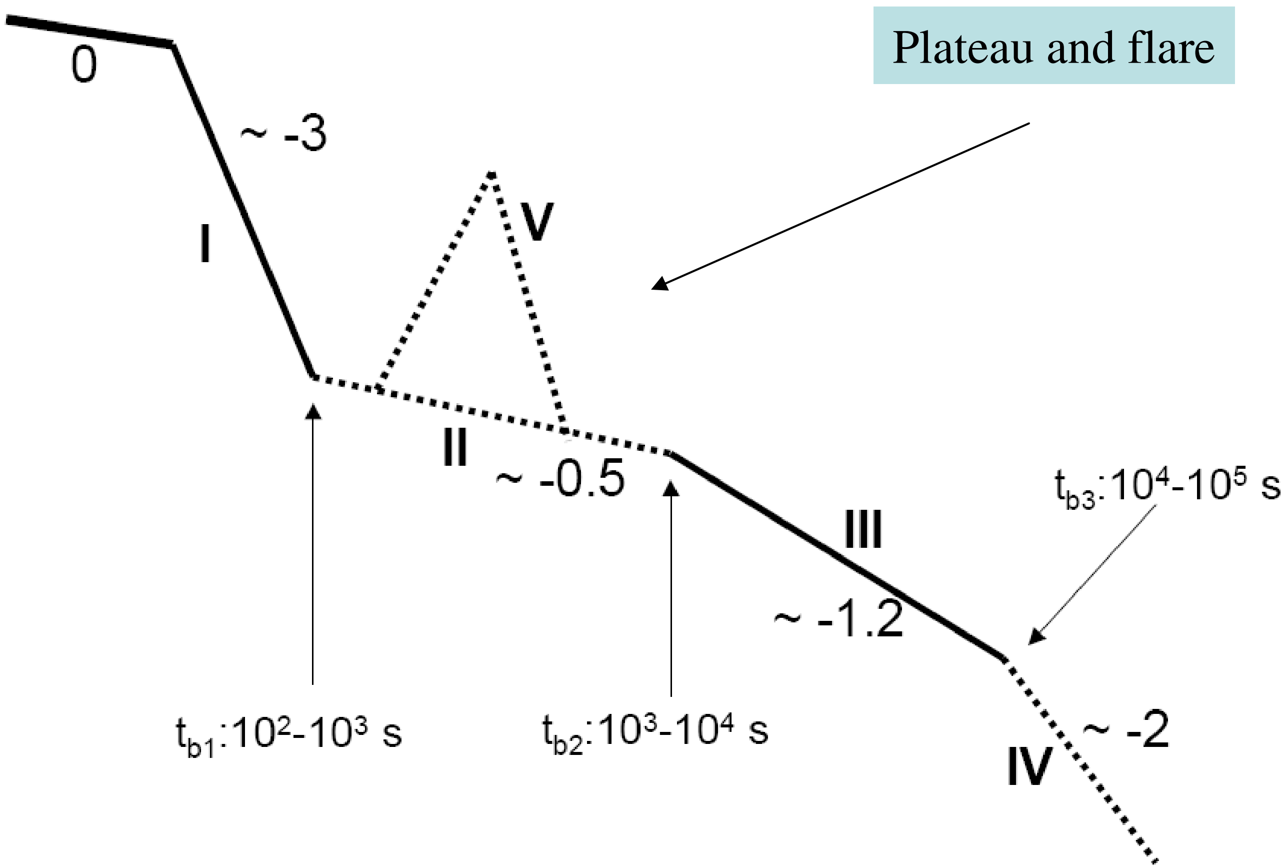
SN – GRB time delay: minutes → years
depending on mass accretion rate



Quiescent time

Early x-ray afterglow

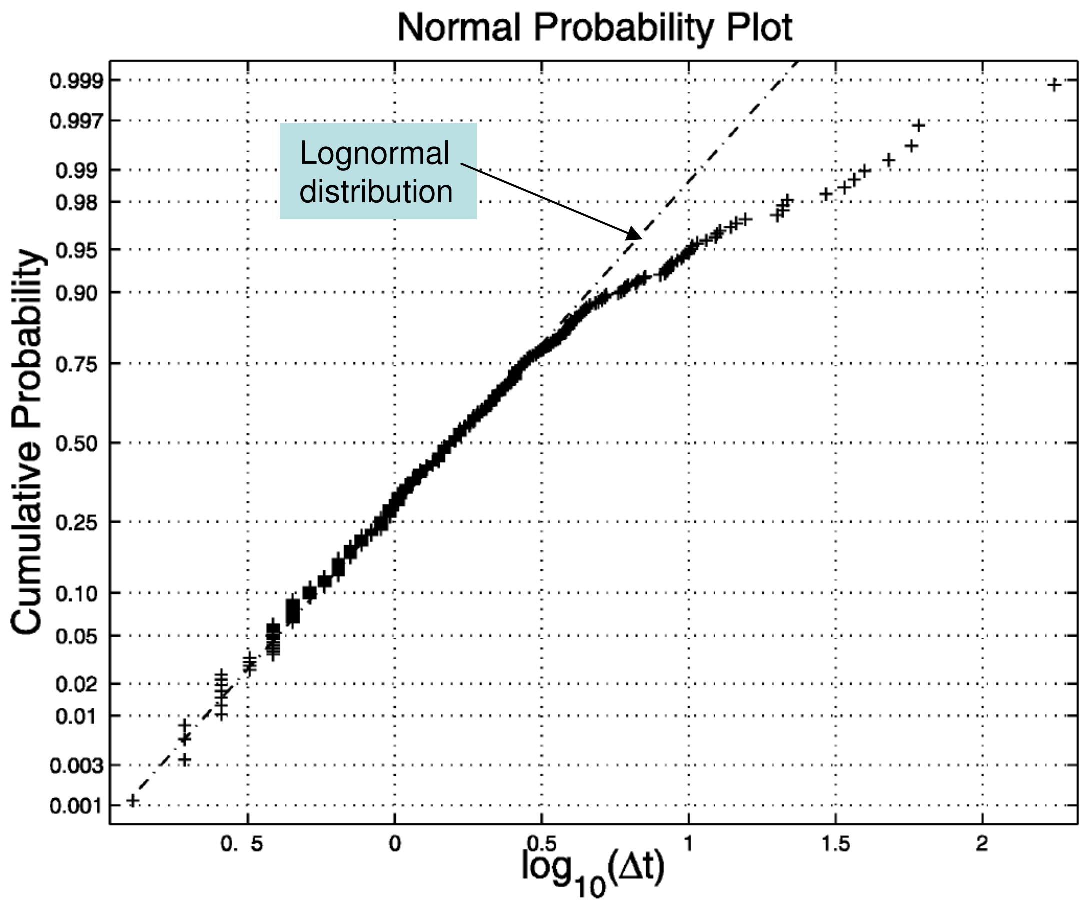
Zhang et al. astro-ph/0508321



Cumulative distribution of quiescent times

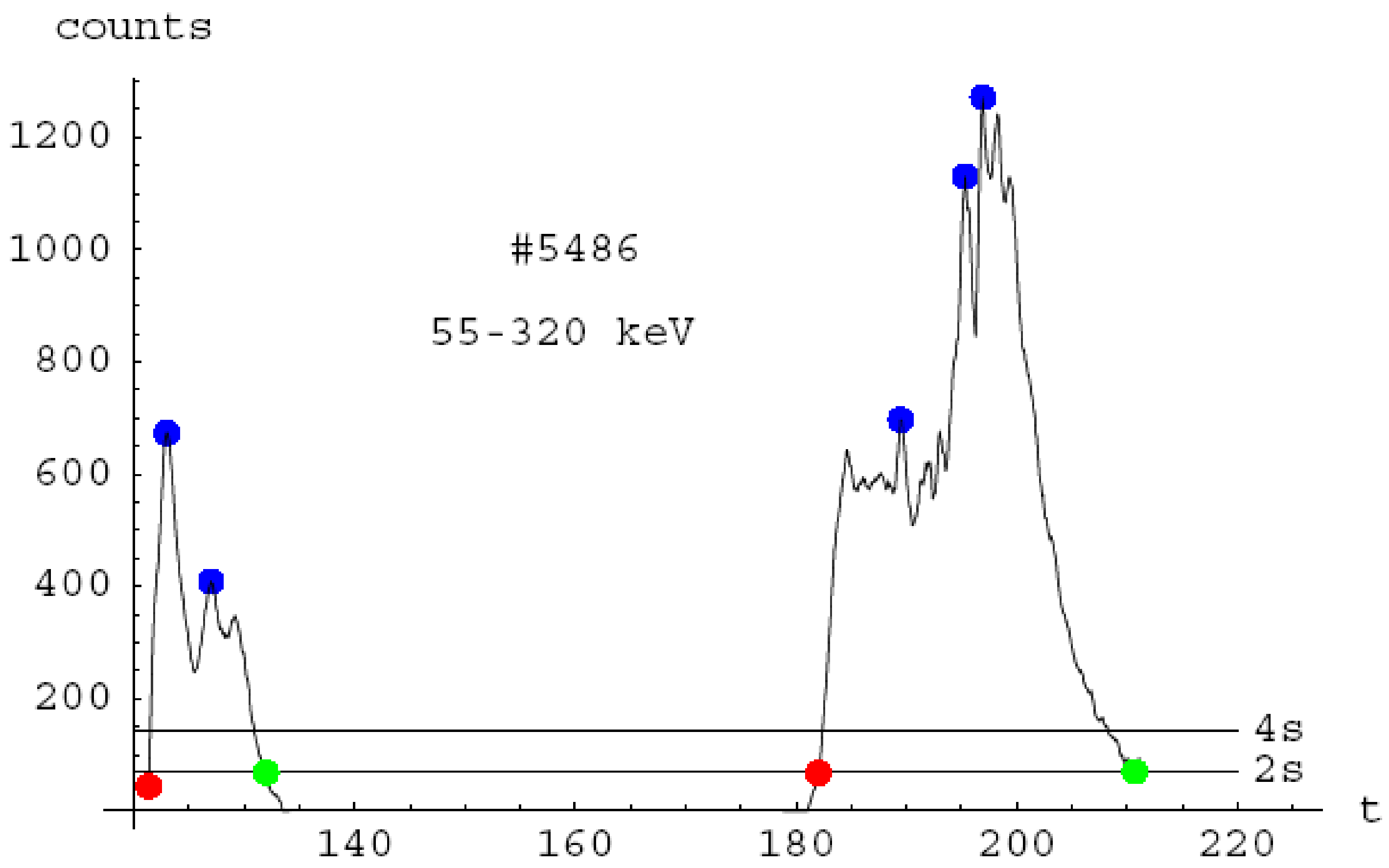
E.Nakar and T.Piran, MNRAS 331 (2002) 40

data from Batse catalog



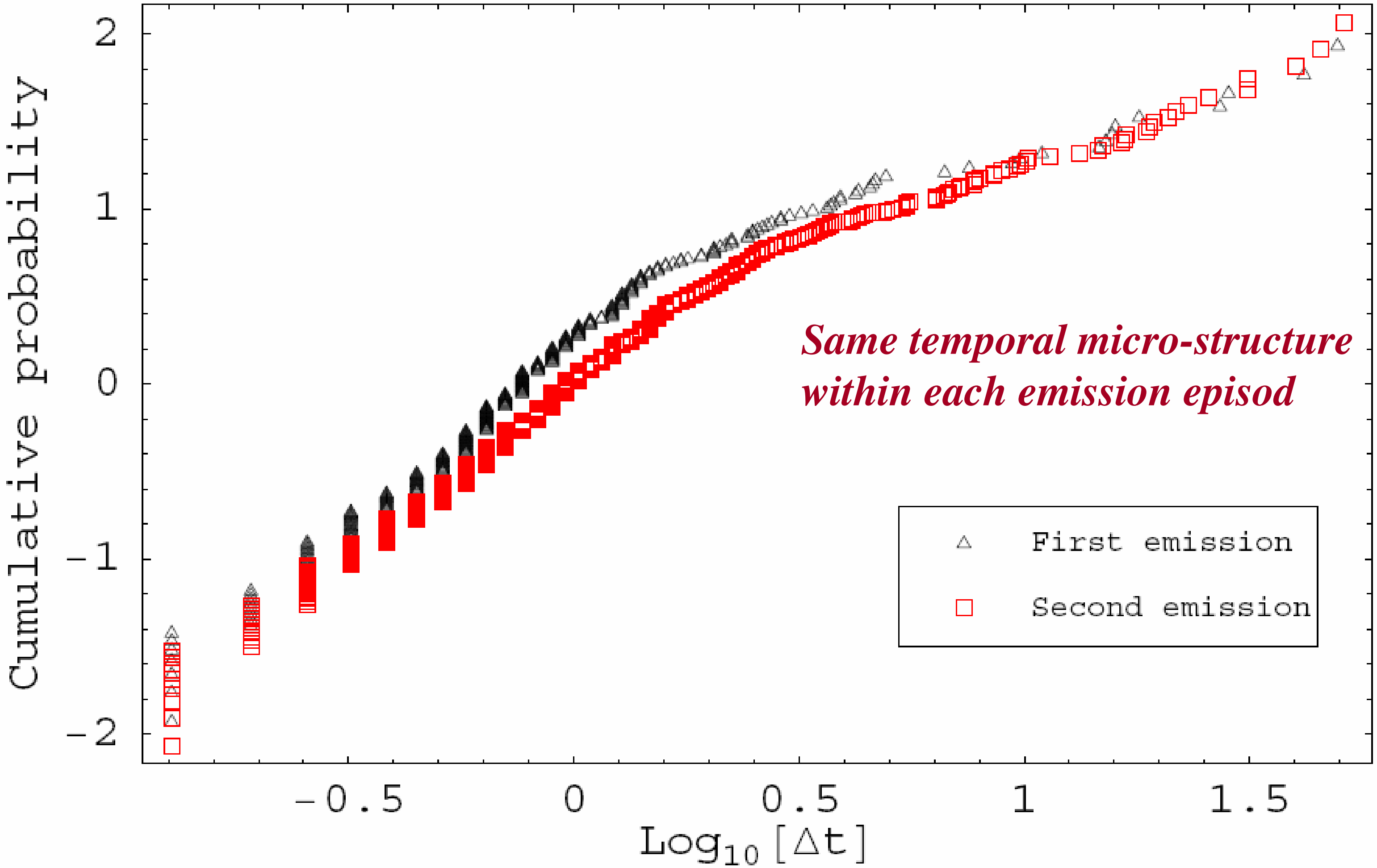
"… the quiescent times are made by a different mechanism then the rest of the intervals"
Nakar and Piran 2002

Temporal structure of BATSE 5486

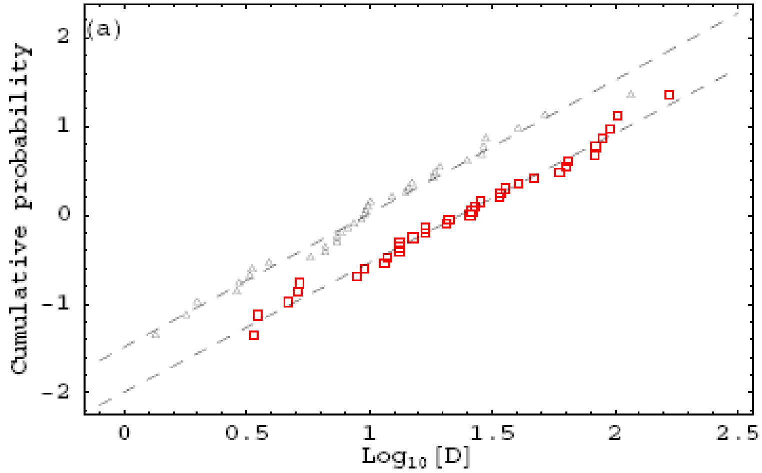


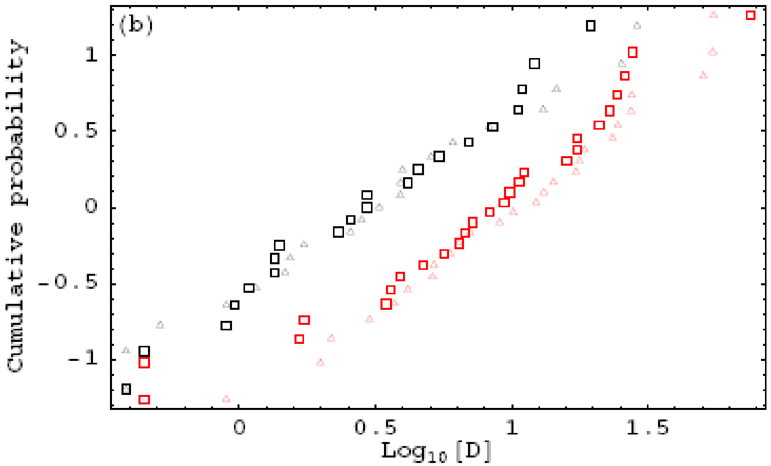
Analysis of time intervals between peaks within each emission episod

A.D., G.Pagliara, astro-ph/0512602



Analysis of durations of the two emission episods a) and within each episode b)





The second active period lasts on the average twice the first active period

Why?

In the collapsar model this would imply that the second fragment of the disk is larger than the first…

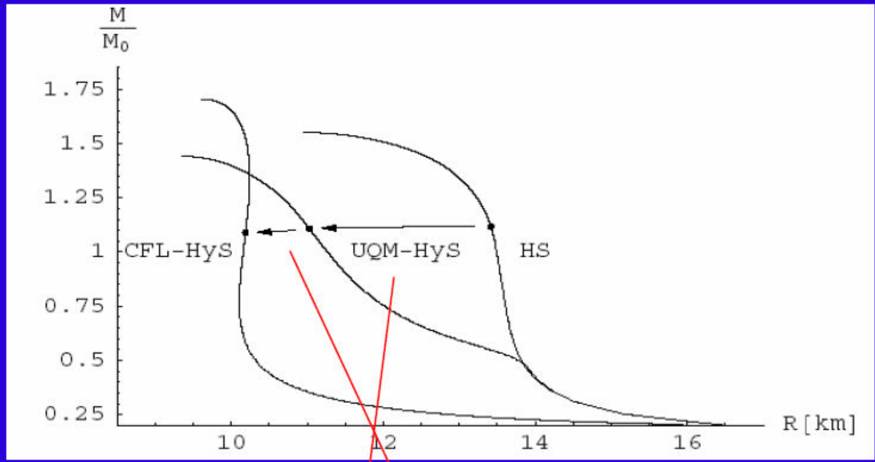
What sets the scale??

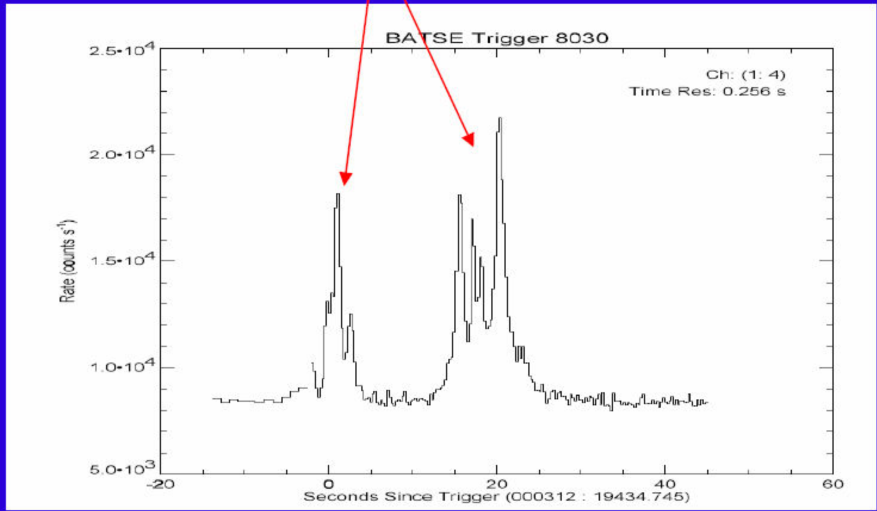
Double GRBs generated by double phase transitions

Two steps:

1) transition from hadronic matter to unpaired or 2SC quark matter. “Mass filtering”

2) The mass of the star is now fixed. After strangeness production, transition from 2SC to CFL quark matter. Decay time scale τ few tens of second





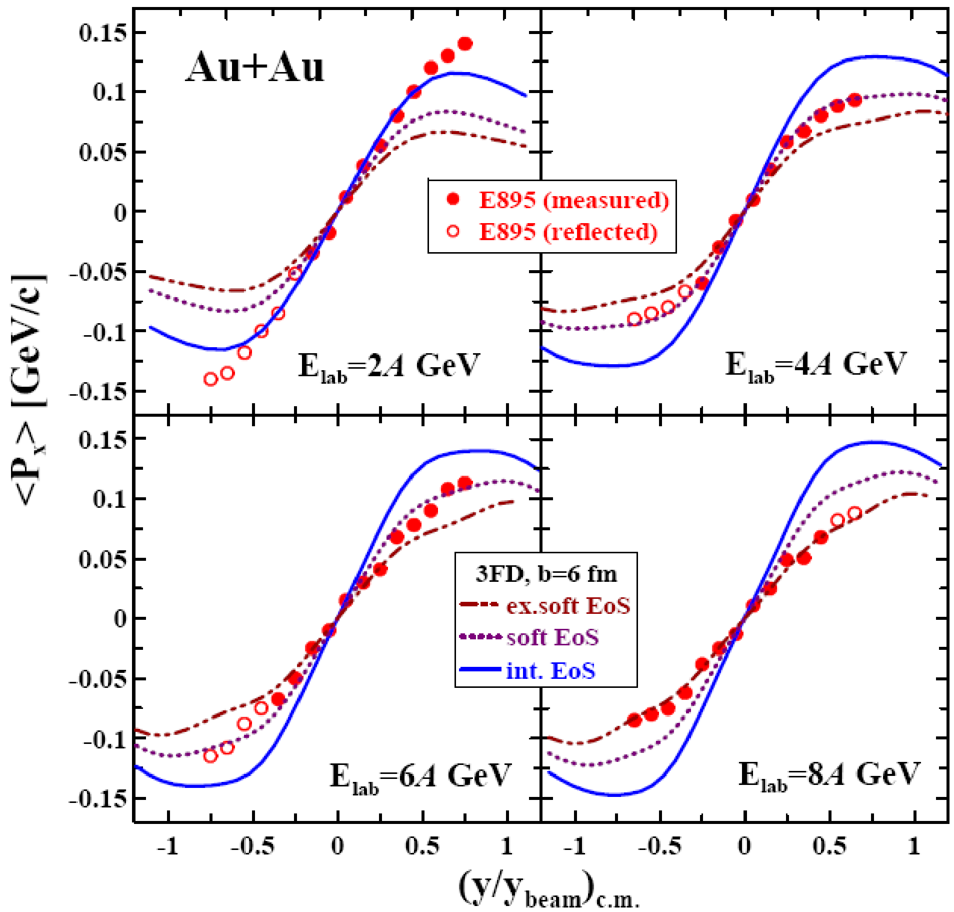
Temporal structure of GRBs
in the **quark deconfinement model**

0. Supernova explosion → **neutron-proton star**
   and then… (delay, **mass accretion**)

1. Precursor (**formation of strangeness**) → delay…
2. Main event (**formation of normal quark matter**),
   quiescent time, then...
   formation of superconducting quarks
   No need to inject energy continously during the precursor and the main event!

3. Early X-ray afterglow, plateau and flares (**differential rotation, expulsion of the toroidal magnetic field**, Haensel et al. in preparation)

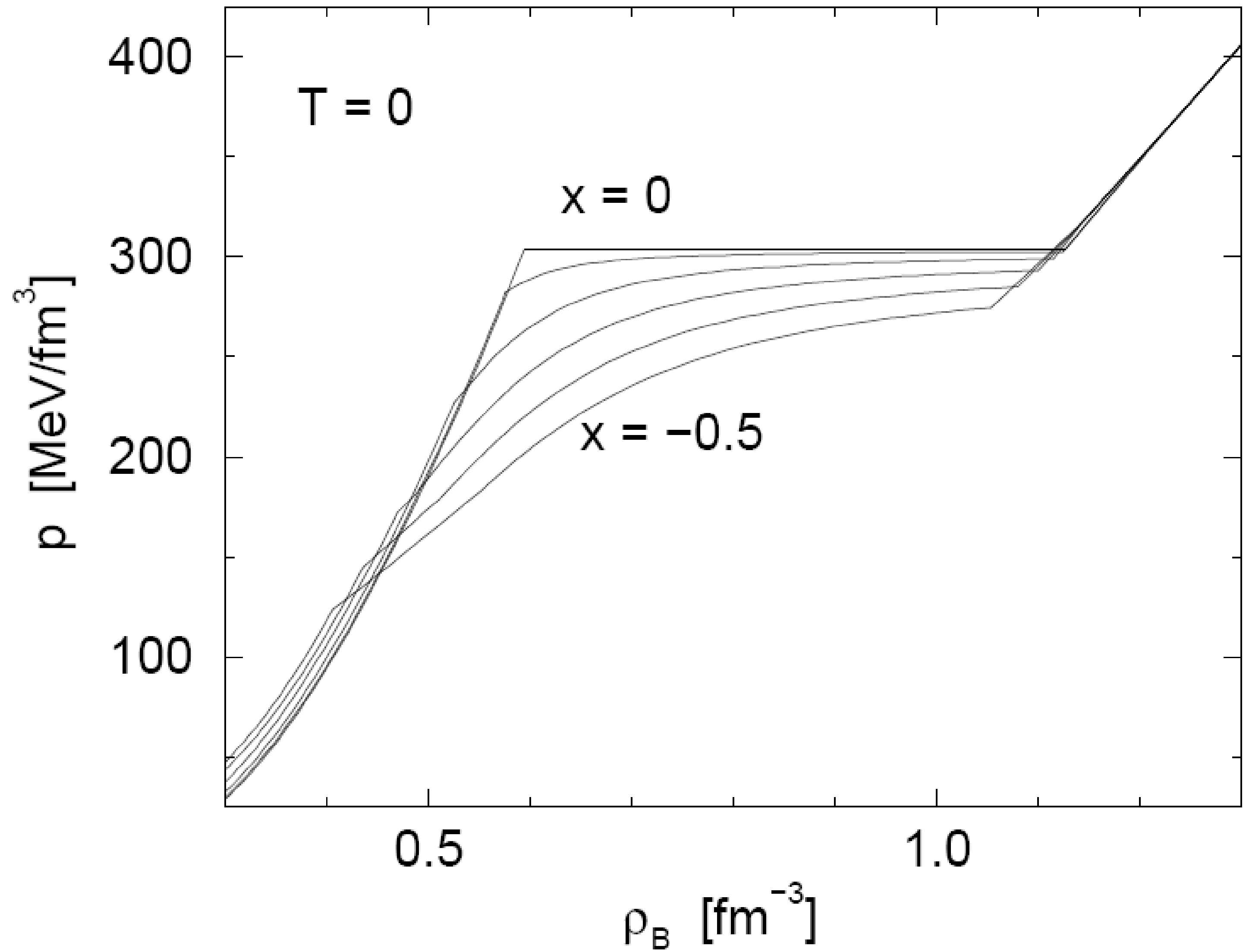
Softening at intermediate energies in heavy ion scattering?
Russkikh and Ivanov 2006



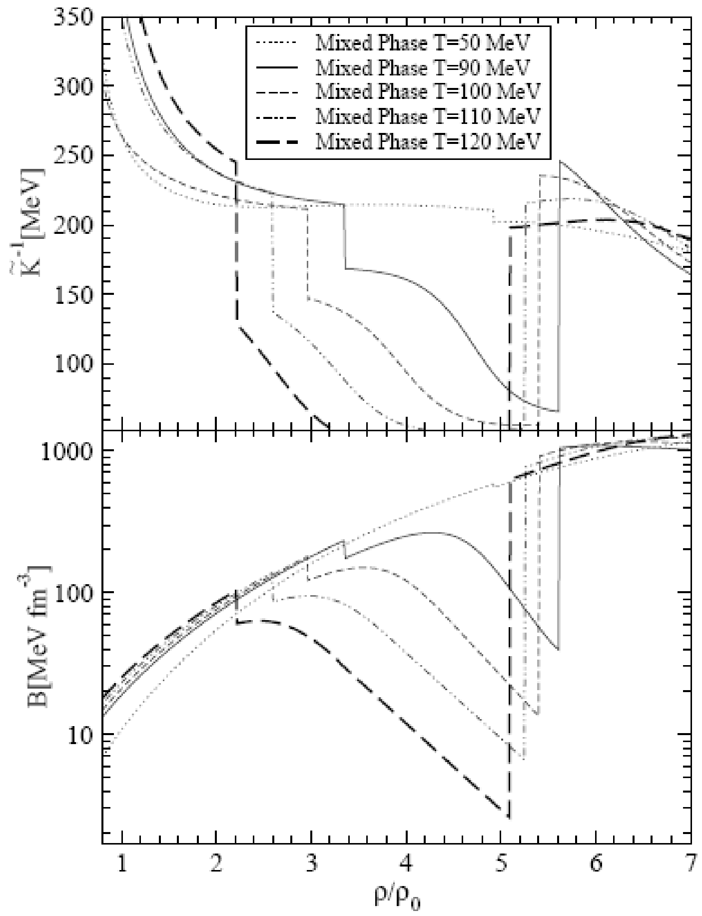
A model for the mixed hadron-quark phase: Gibbs construction with two conserved charges

- Experiments in heavy ion scattering are perfomed with nuclei having Z/A ~ 0.4
- Conserved charges: baryon, isospin, strangeness
- When more than one charge is conserved pressure is not constant in the mixed phase (Glendenning 1992, Muller & Serot 1995)
- Toneev et al. 2003 conserves baryon and strangeness charges.
  Pressure almost constant in the mixed phase
- We conserve baryon and isospin charges

Muller 1997



Bulk modulus in a mixed phase of quarks and hadrons with two conserved charges Bonanno et al. 2007



Conclusions

Good news!

- X-ray satellites are providing lot of new data
- Analysis of lab experiments can provide important information
- Explosive phenomena suggest new problems and possibilities

Bad news!

- Data analysis is often complicated and model dependent
- Data are often contradictory (or seem to be)
- The connection between matter tested in labs and in stars is rather weak

Also bad “news”

Still extremely difficult to interact with most of the astrophysical community! (at least in the case of explosive phenomena…)