The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

SMR/1842-14

International Workshop on QCD at Cosmic Energies III

28 May - 1 June, 2007

Lecture Notes

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Astrophysical limits on quark matter

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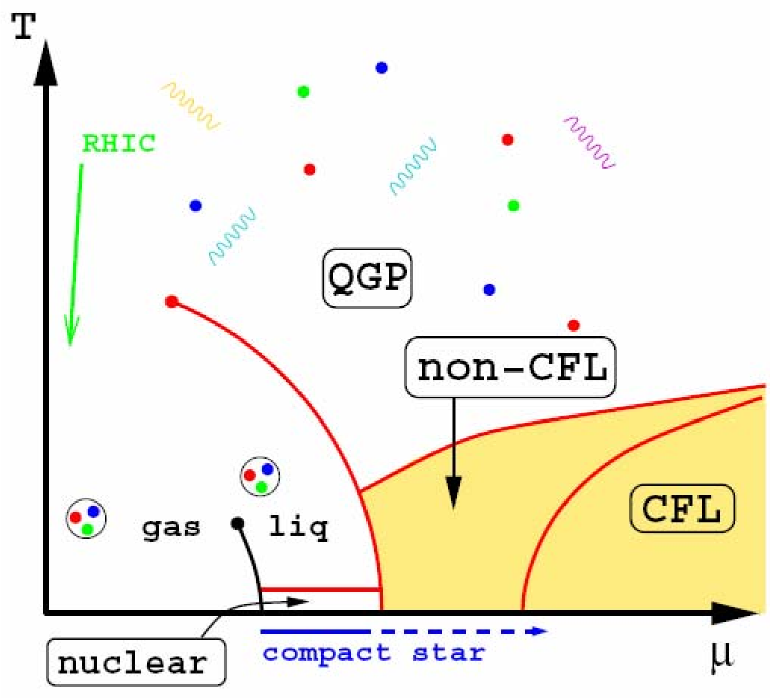
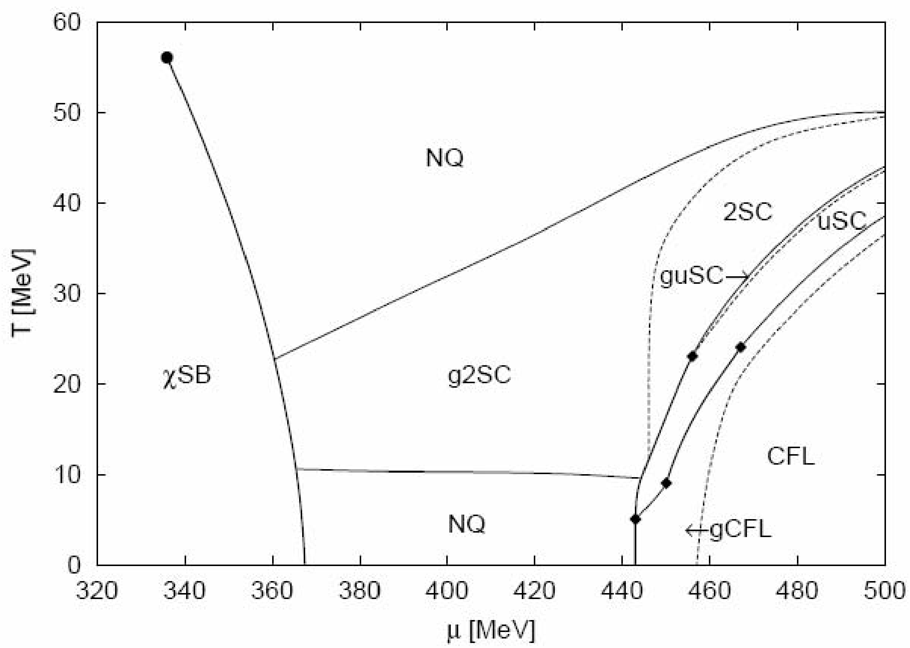
- Theory of matter at large densities
- Limits on masses and radii
- Cooling curves
- Millisecond pulsars
- Other observations (glitches, QPO in soft gamma repeaters)
- Implications for explosive phenomena (SNs and GRBs)
- Connection with lab experiments
- Conclusions

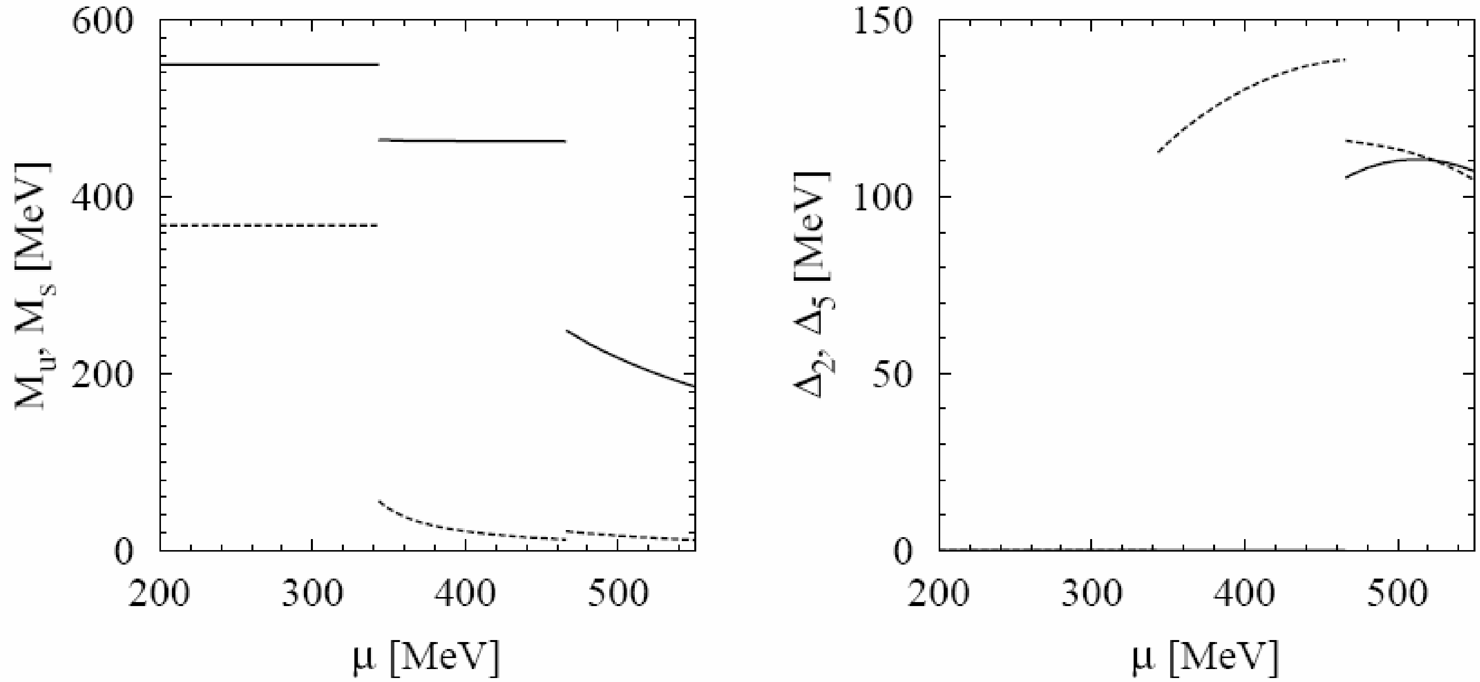
Phase diagram of high density matter



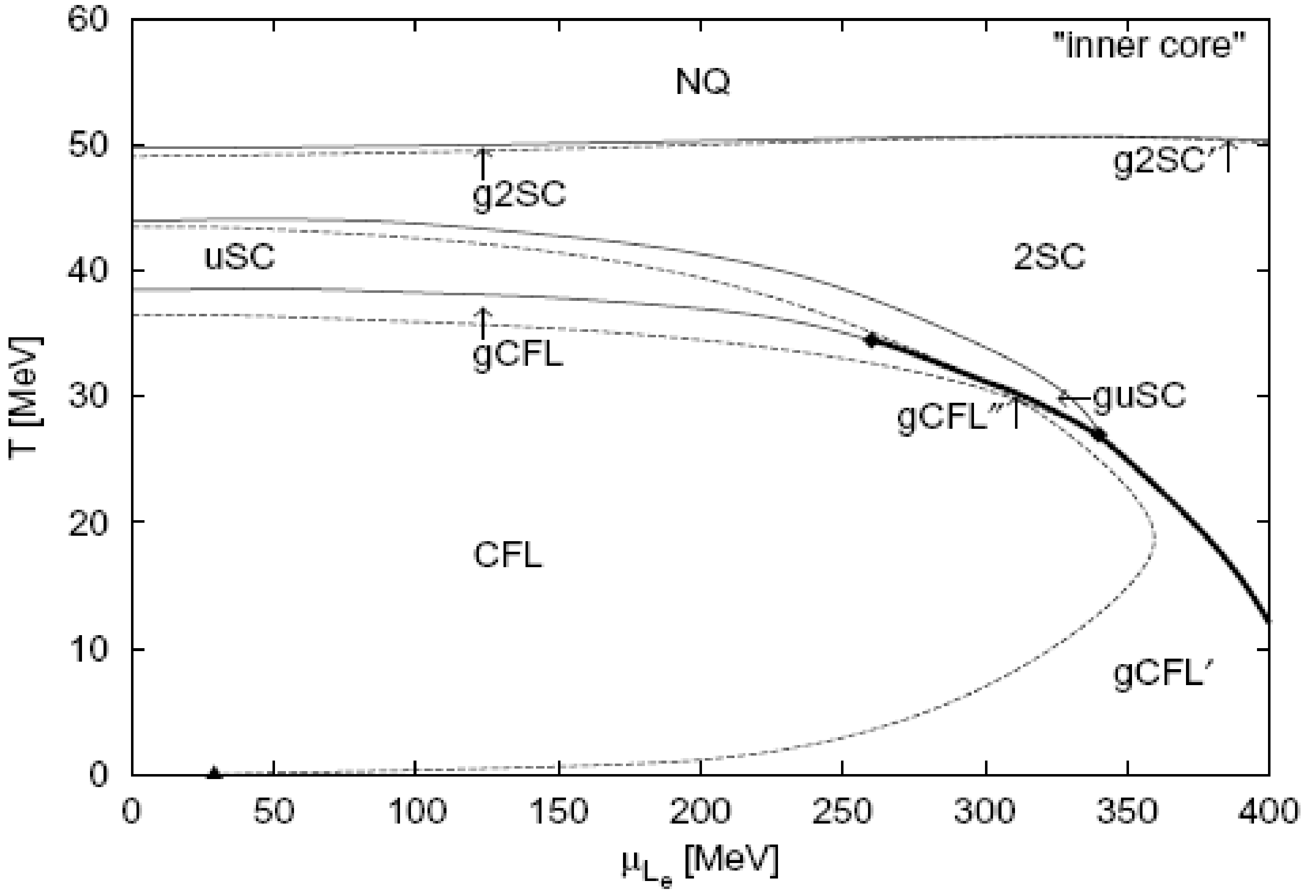


NJL model
Ruster et al. 2005

Constituent masses and gaps in NJL
Buballa 2004



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

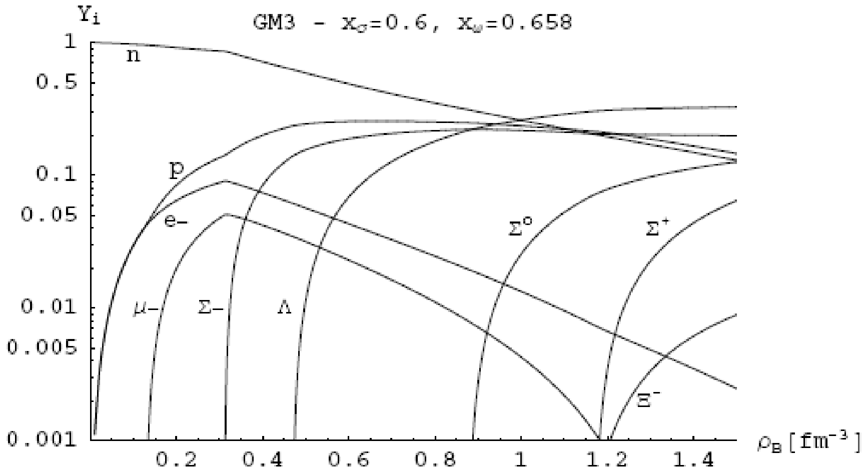


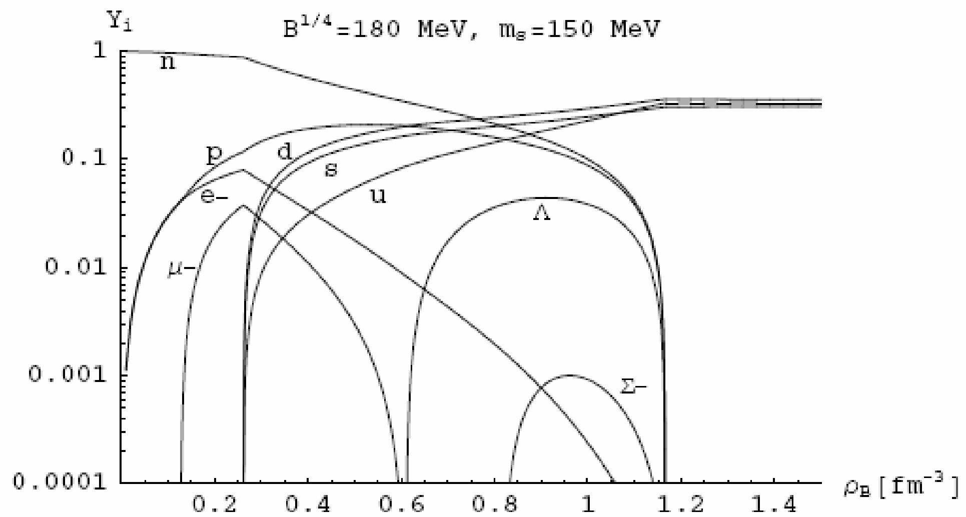
Formation of color superconducting quark matter from normal quark matter takes place through a first order transition.
The energy released in the second transition is larger than in the first!

Open questions in theory of high density matter

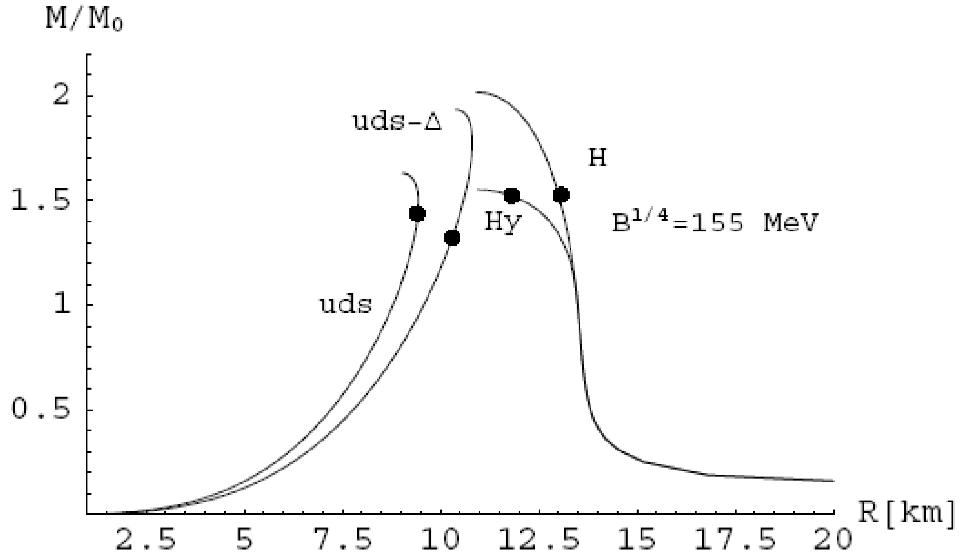
- Which phases between NQ and CFL? NQ? 2SC? Gapless 2SC? Gapless CFL? Crystalline phases?...
- Discrepancy between MIT-like and NJL calculations due to large m_s in NJL: in NJL it is difficult to produce strange quark matter
- Large density repulsion: gluon exchange? Vector mesons? Which parameter values?

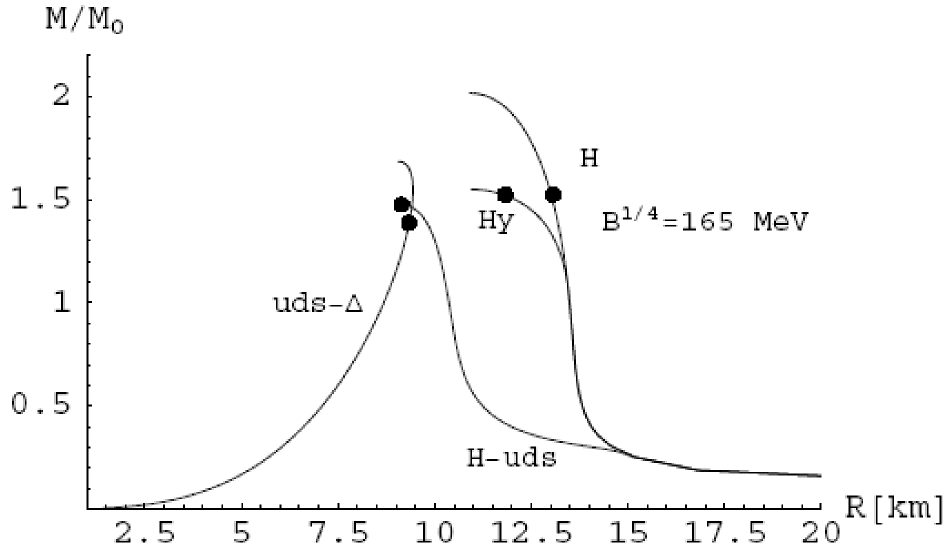
Composition of high density matter: hyperons and quarks





Masses and radii: effect of hyperons and quarks





How many quark stars? (if any…)

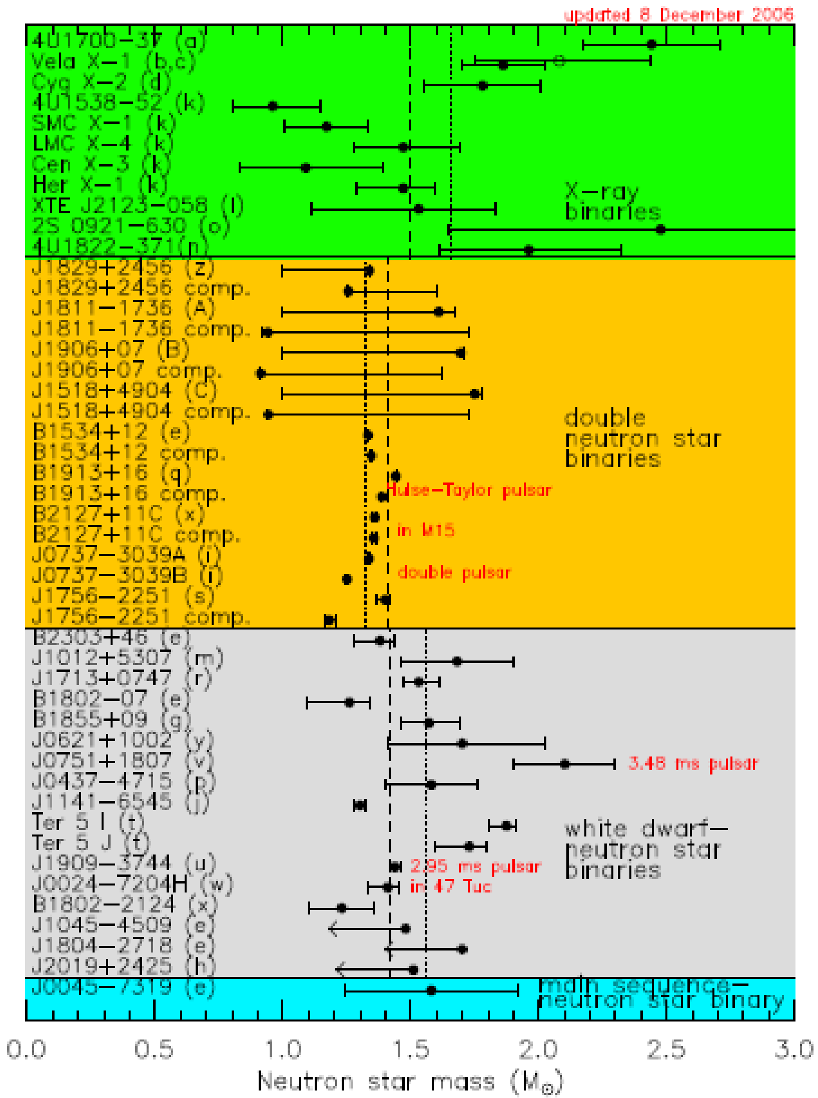
If quark stars exist → all compact stars are quark stars (Madsen, Olinto et al.)

But…

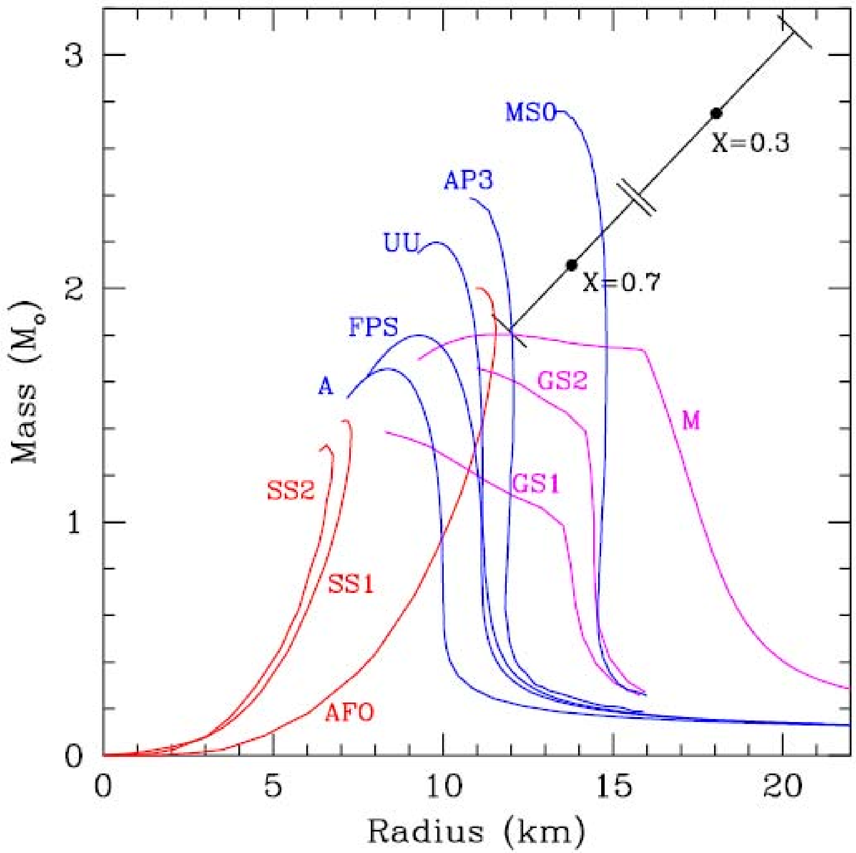
- Quark nugget contamination maybe overestimated
- Mechanism providing the formation of quark matter unclear

Maybe quark and neutron stars can both exist!

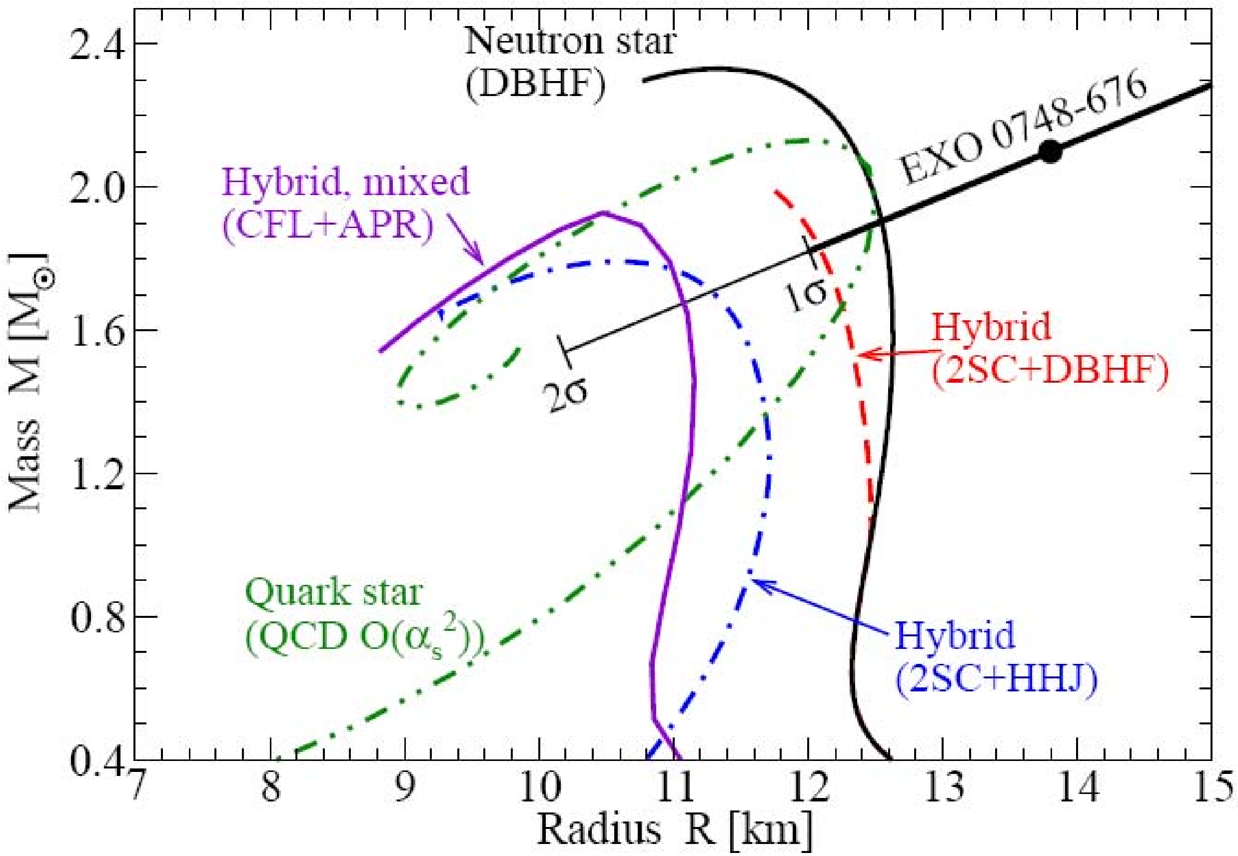
Masses
Lattimer and Prakash 2007



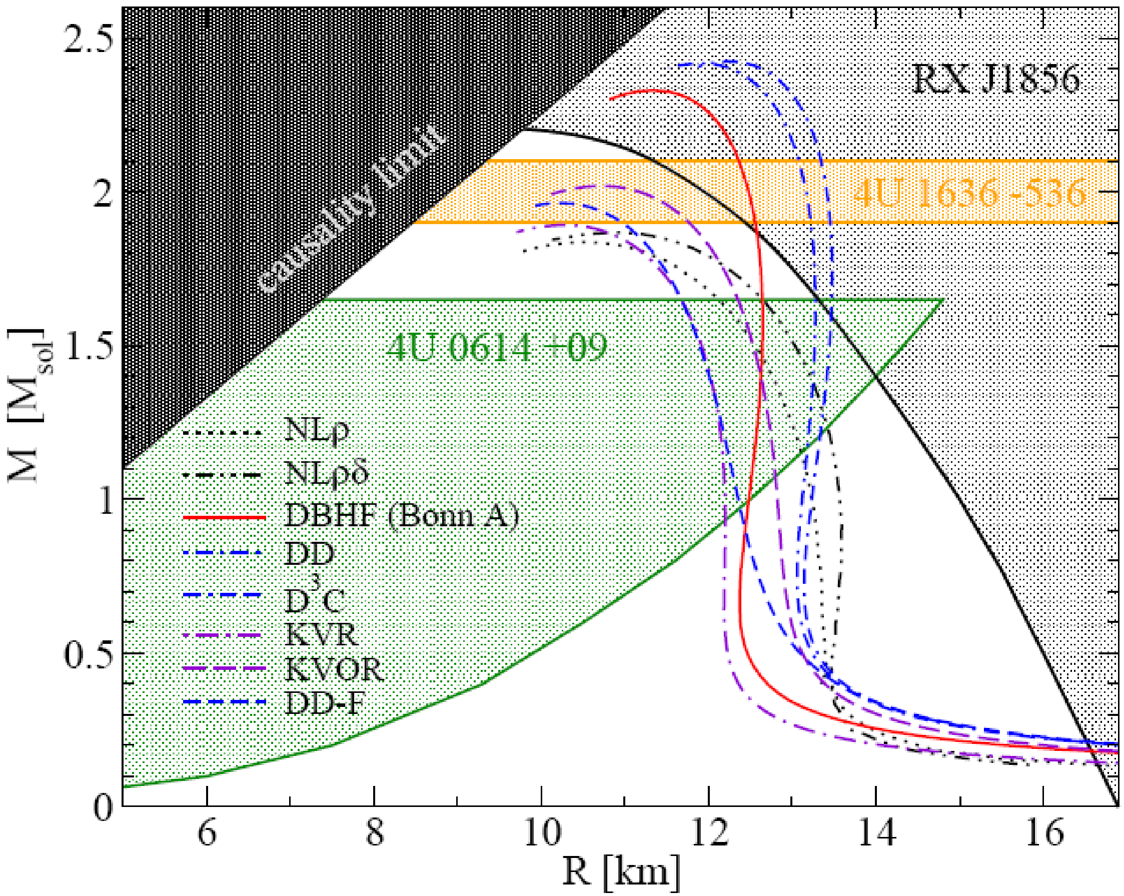
Limits on masses and radii
Ozel 2006



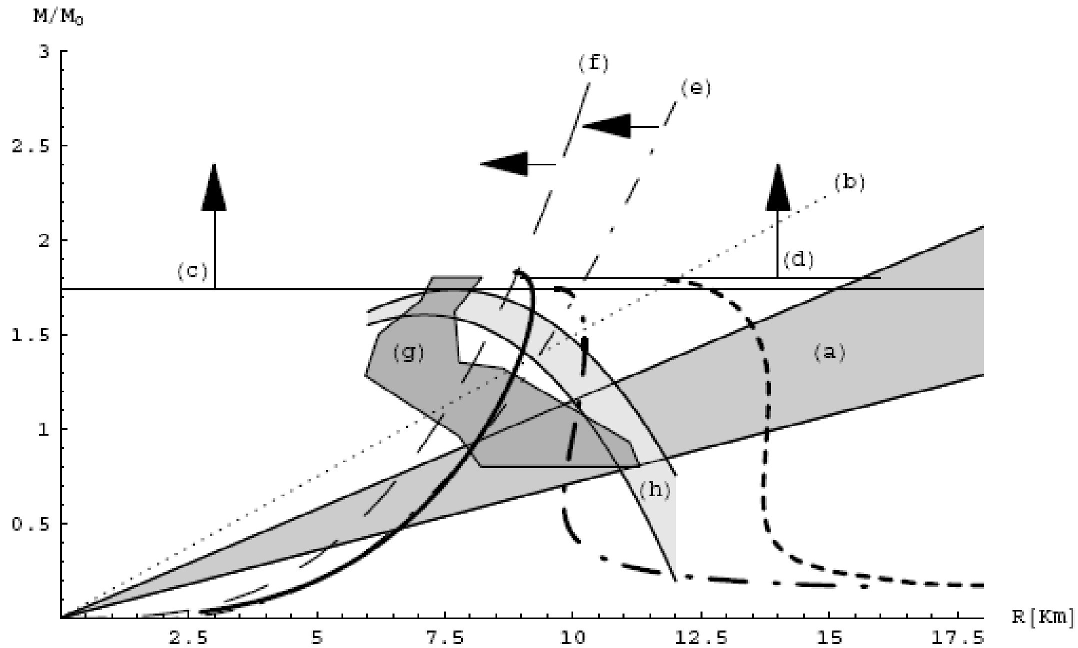
Limits on masses and radii
Alford et al. 2007



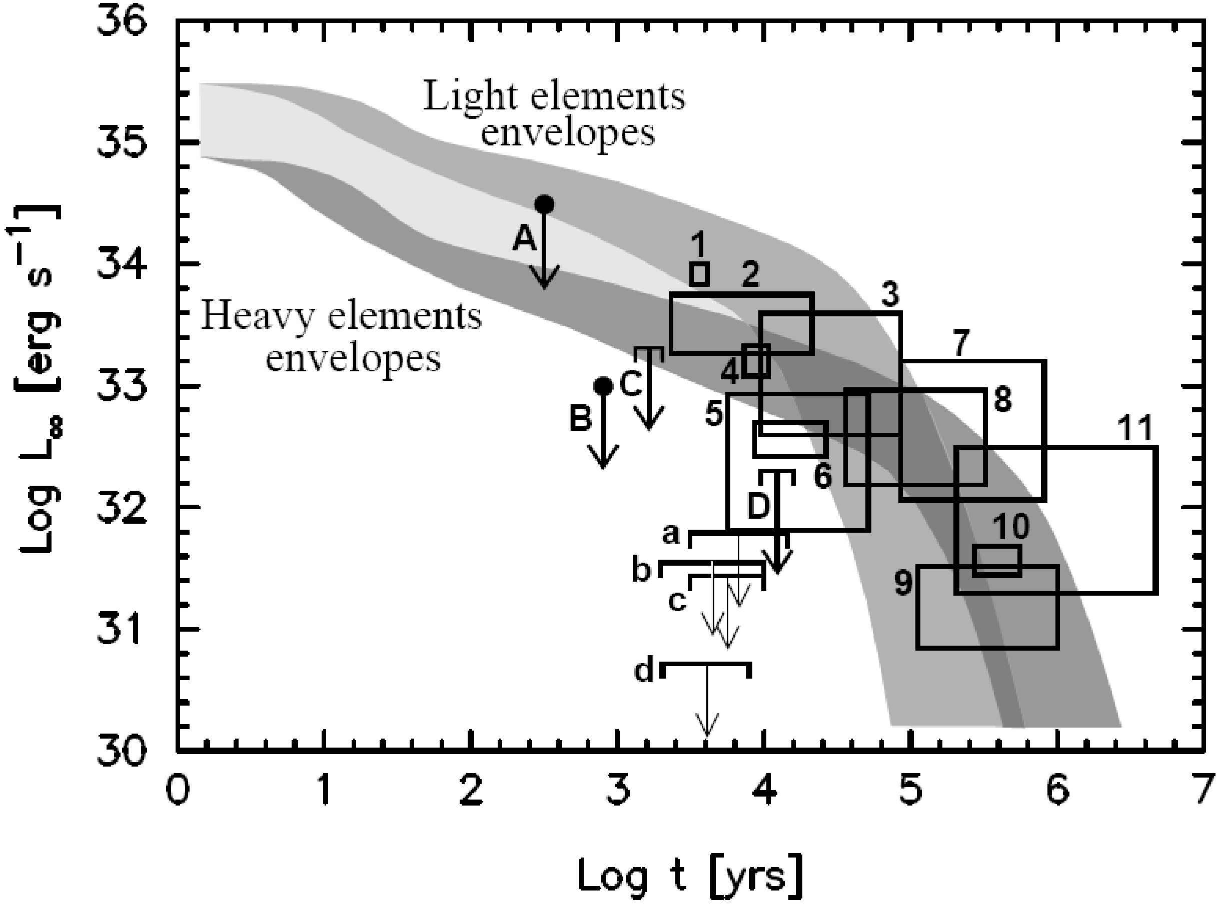
Various limits on masses and radii
Klahn et al. 2006



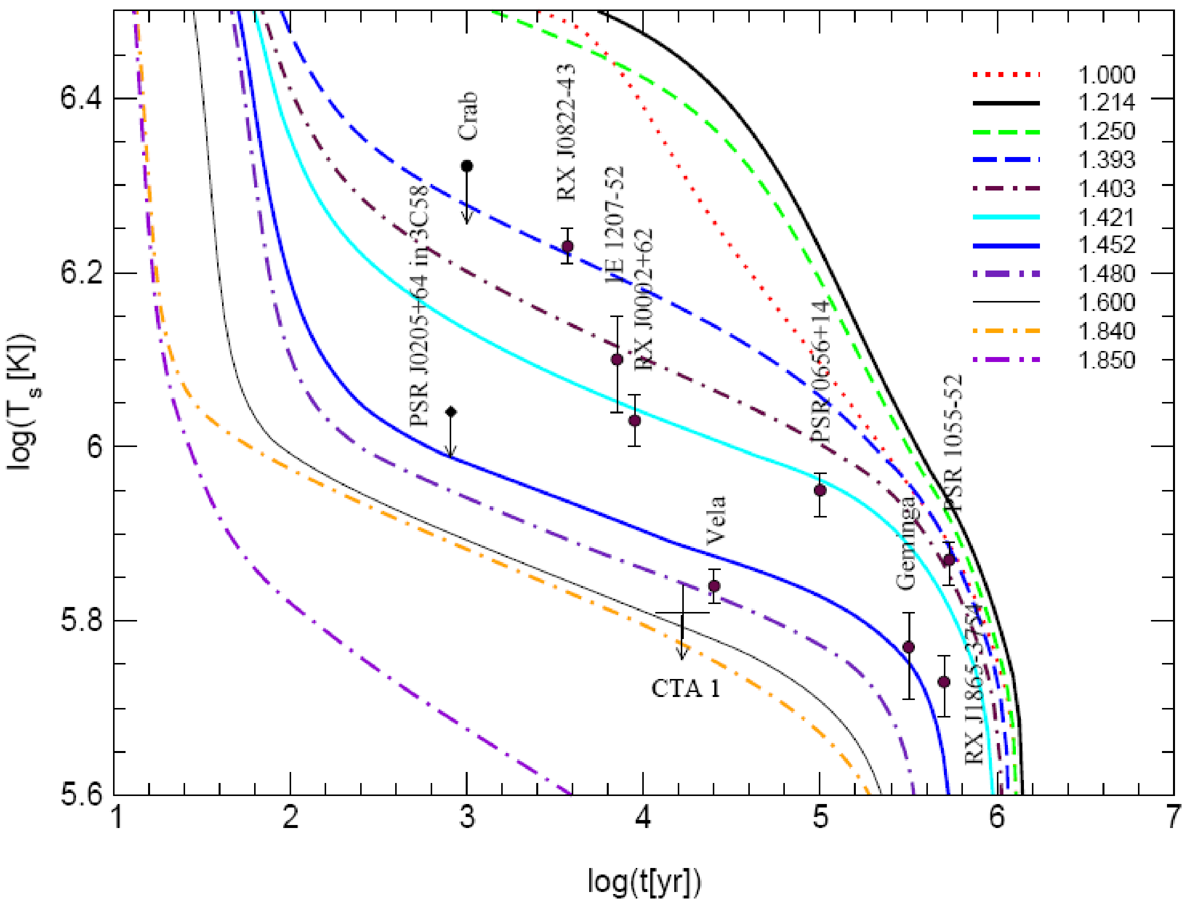
Thermal radii (obsolete…)



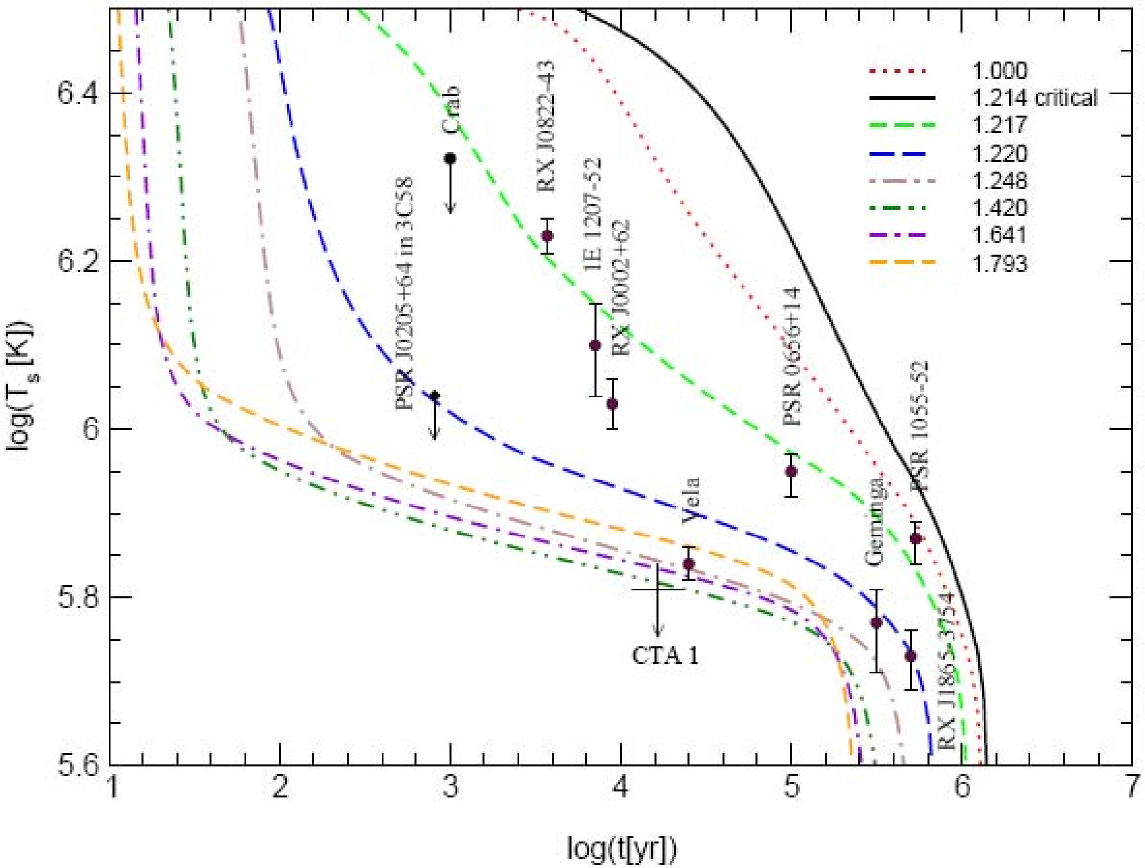
Cooling curves: minimal model vs data
Page et al. 2005



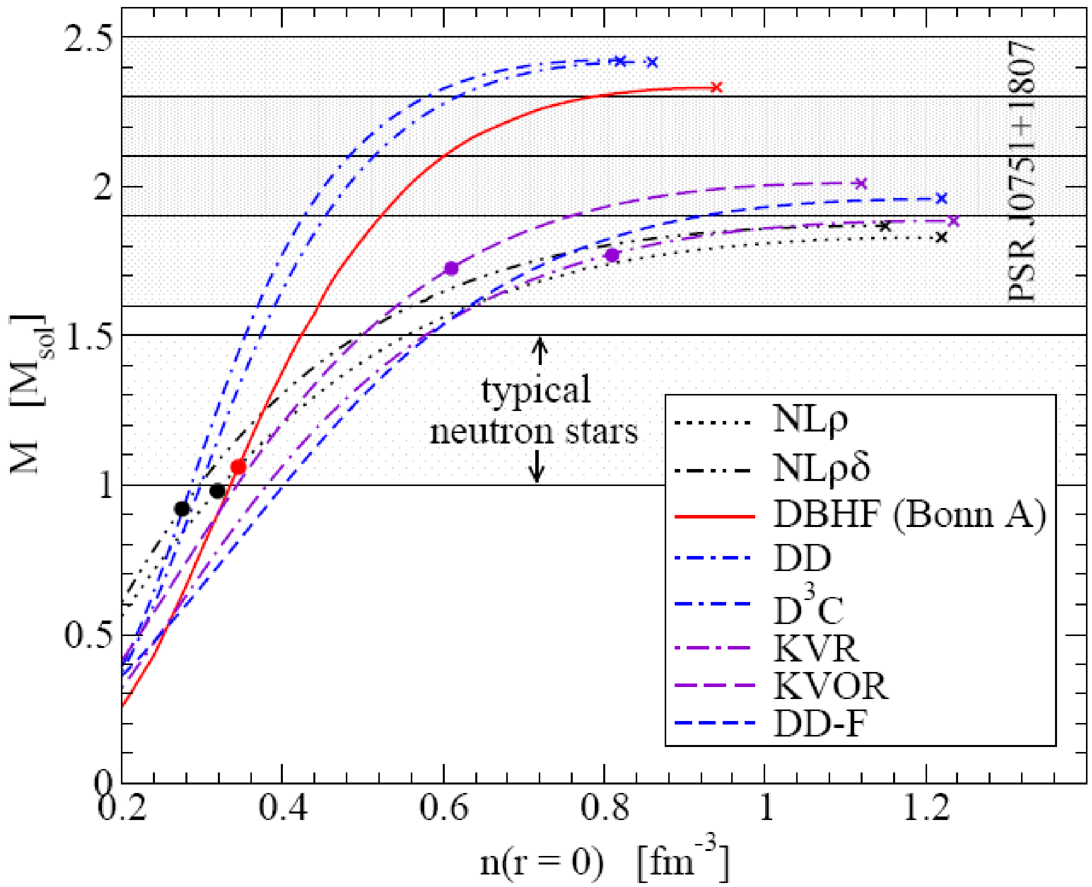
Cooling curves in a hadronic scenario
Grigorian et al. 2005



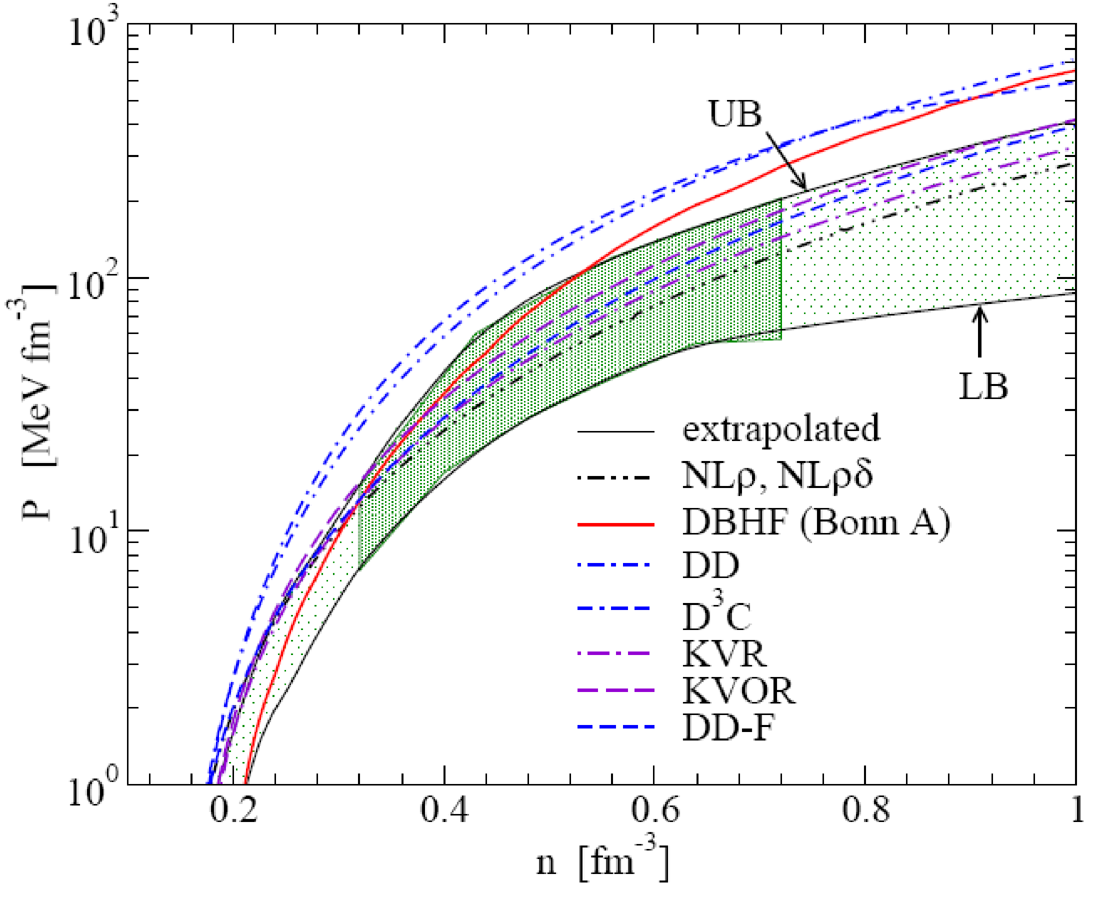
Cooling curves for a hybrid star
Grigorian et al. 2005



Maximum mass and direct Urca threshold
Klahn et al. 2006



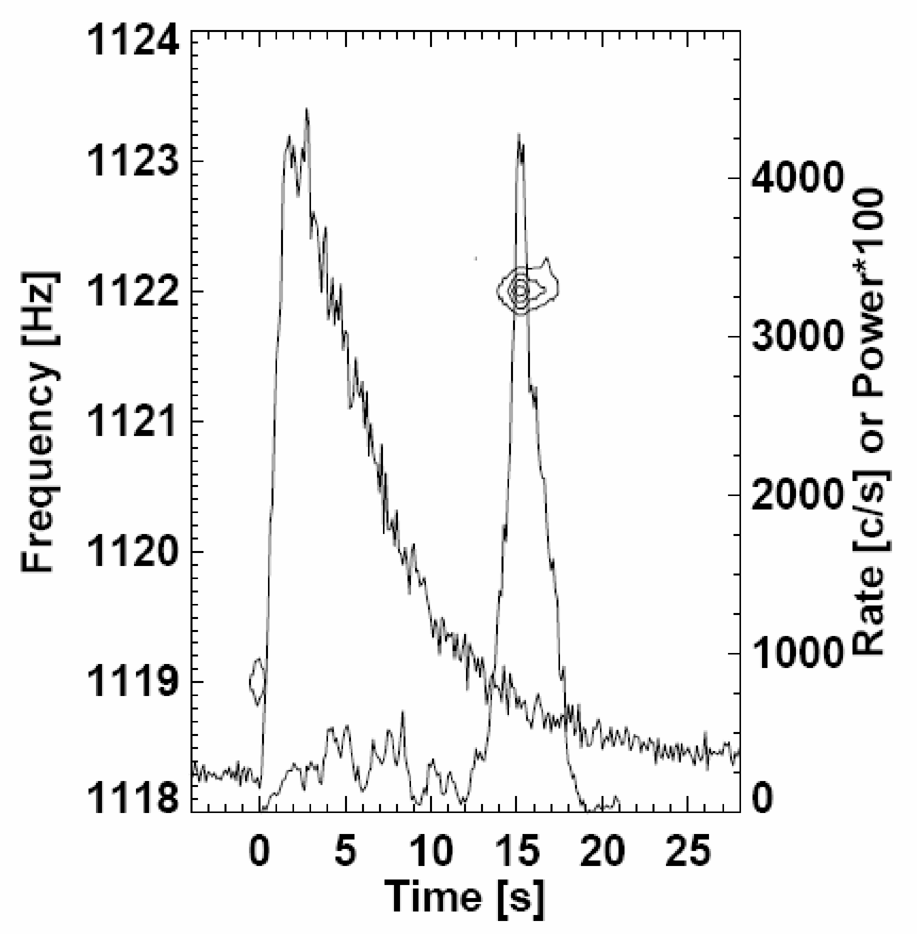
Extrapolated limits on pressure from lab experiments



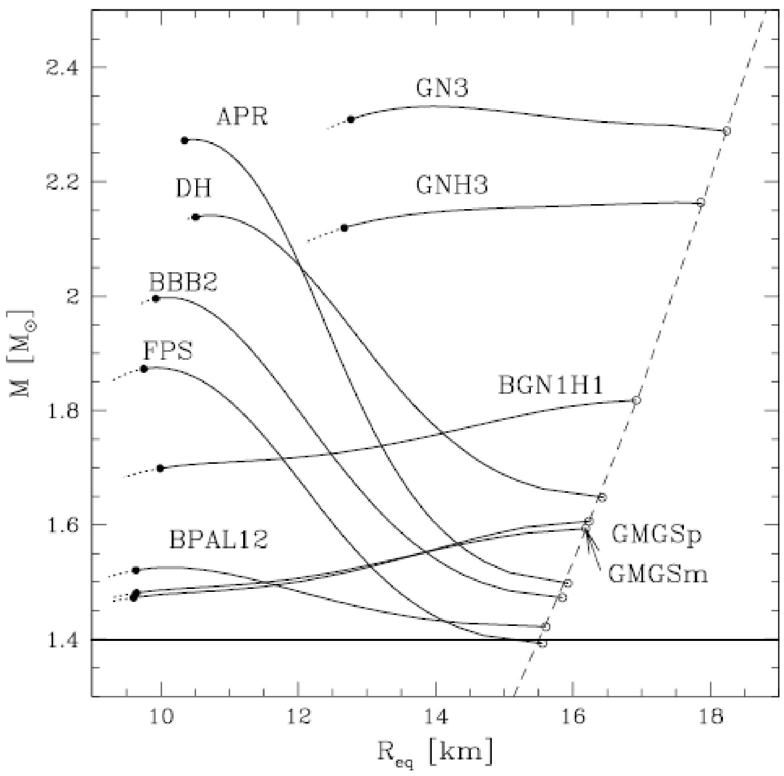
Summary of constraints from masses, radii, cooling and lab experiments
Klahn et al 2006

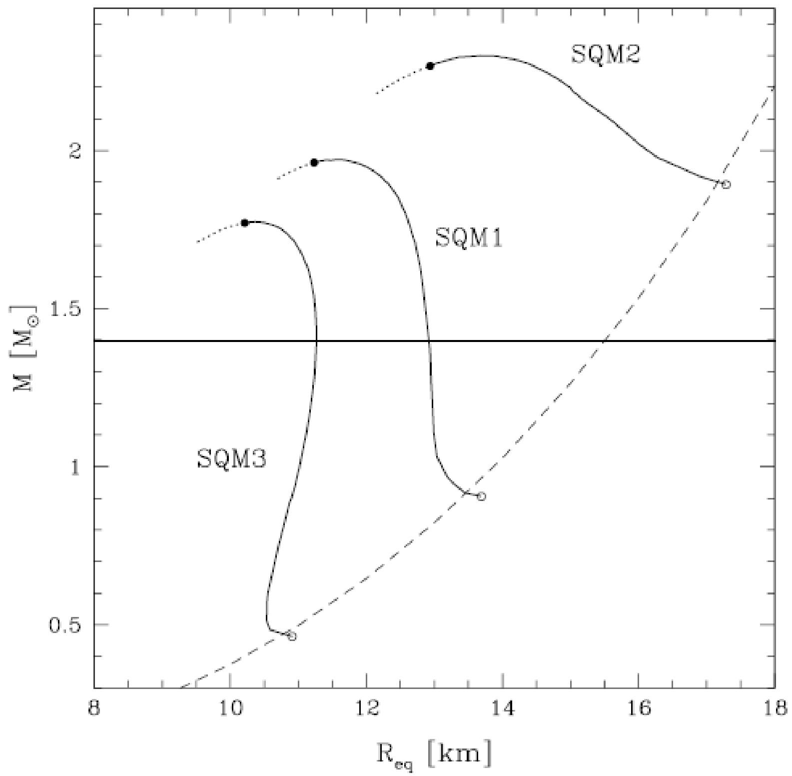
Model	$M_{\max} \geq 1.9\ M_\odot$	$M_{\max} \geq 1.6\ M_\odot$	$M_{DU} \geq 1.5\ M_\odot$	$M_{DU} \geq 1.35\ M_\odot$	4U 1636-536 (u)	4U 1636-536 (l)	RX J1856 (A)	RX J1856 (B)	J0737 (no loss)	J0737 (loss 1% $M_\odot$)	SIS+AGS flow constr.	SIS flow+ K^+ constr.	No. of passed tests	(out of 6)
NLρ	−	+	−	−	−	−	−	−	−	−	+	+	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





R-mode instabilities

Discovered by Andersson and Friedman&Morsink in 1998

Rapidly drain angular momentum from a rotating compact star

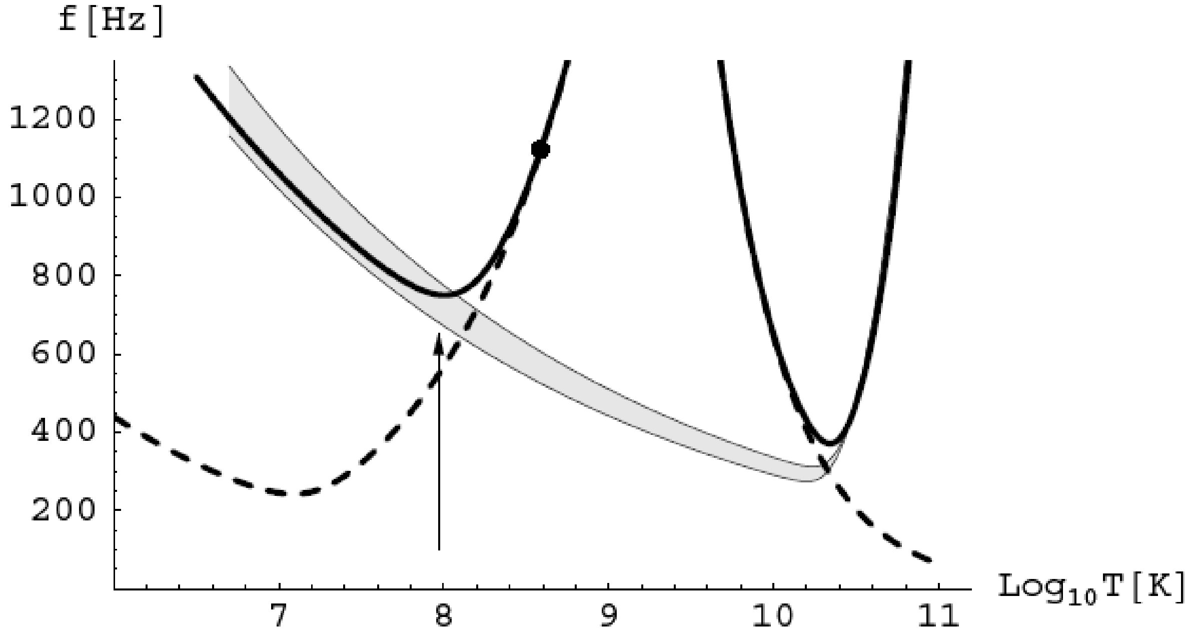
Suppressed by bulk and shear viscosity

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

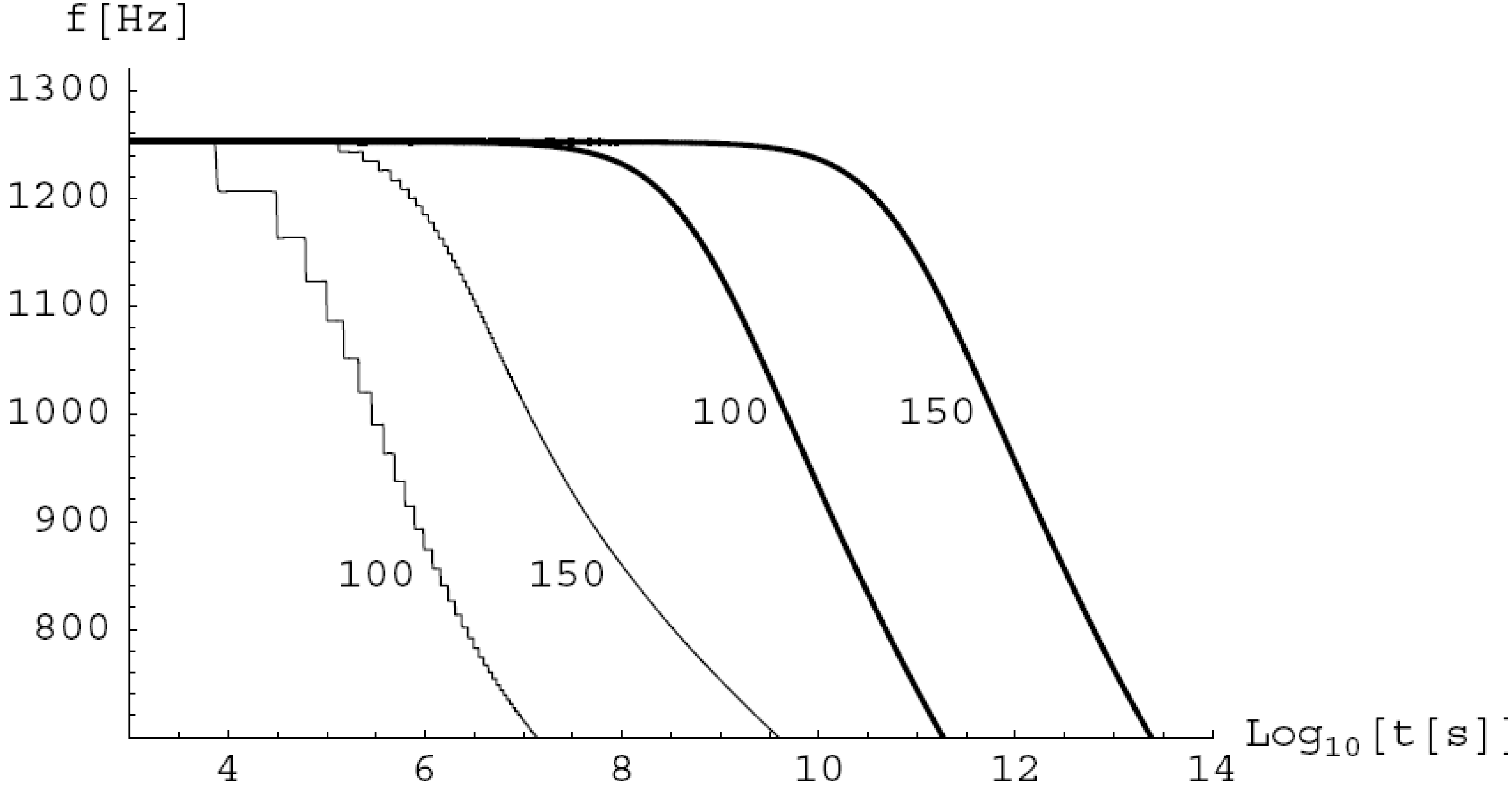
$$\dot{\Omega} = \frac{\dot{M}}{\tilde{I}} \left(\frac{G}{MR^3} \right)^{1/2} - \frac{\dot{M}\Omega}{M} - 3\Omega\alpha^2 \frac{\tilde{J}}{\tilde{I}} \left(\frac{1}{t_{\mathrm{sv}}} + \frac{1}{t_{\mathrm{bv}}} \right) \quad (24)$$

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

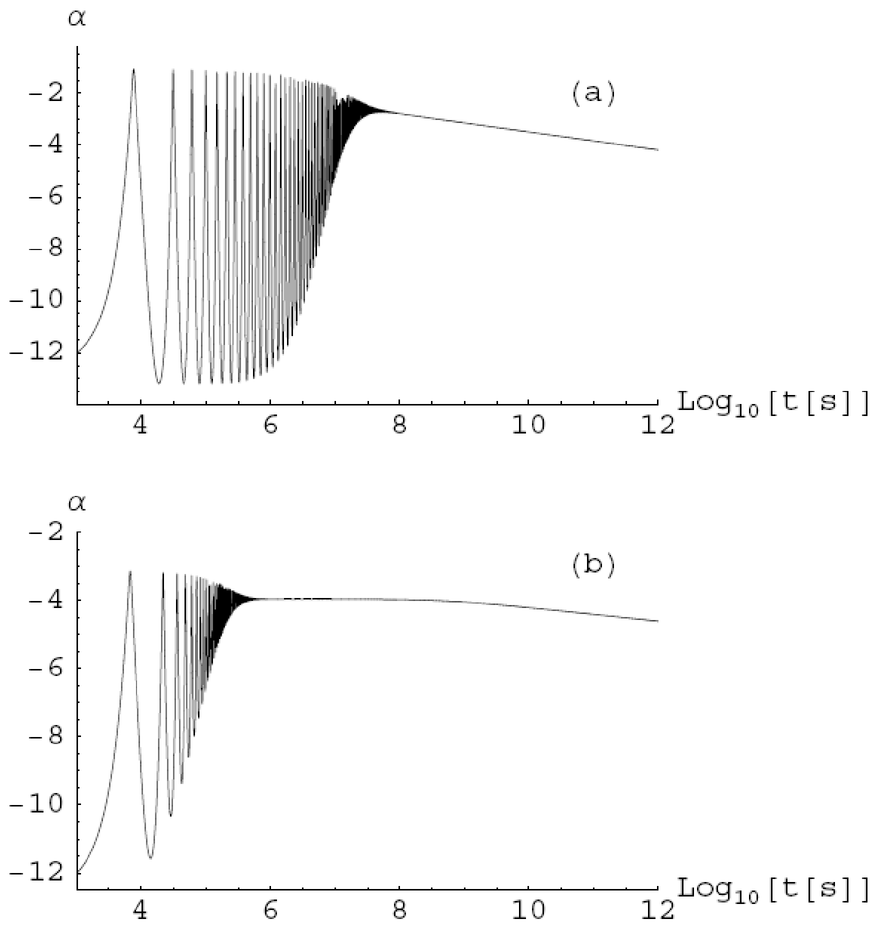
Stability windows due to r-modes adapted from Andersson et al.



Time evolution of rotational frequency
Drago et al. 2007



R-mode amplitudes
Drago et al. 2007

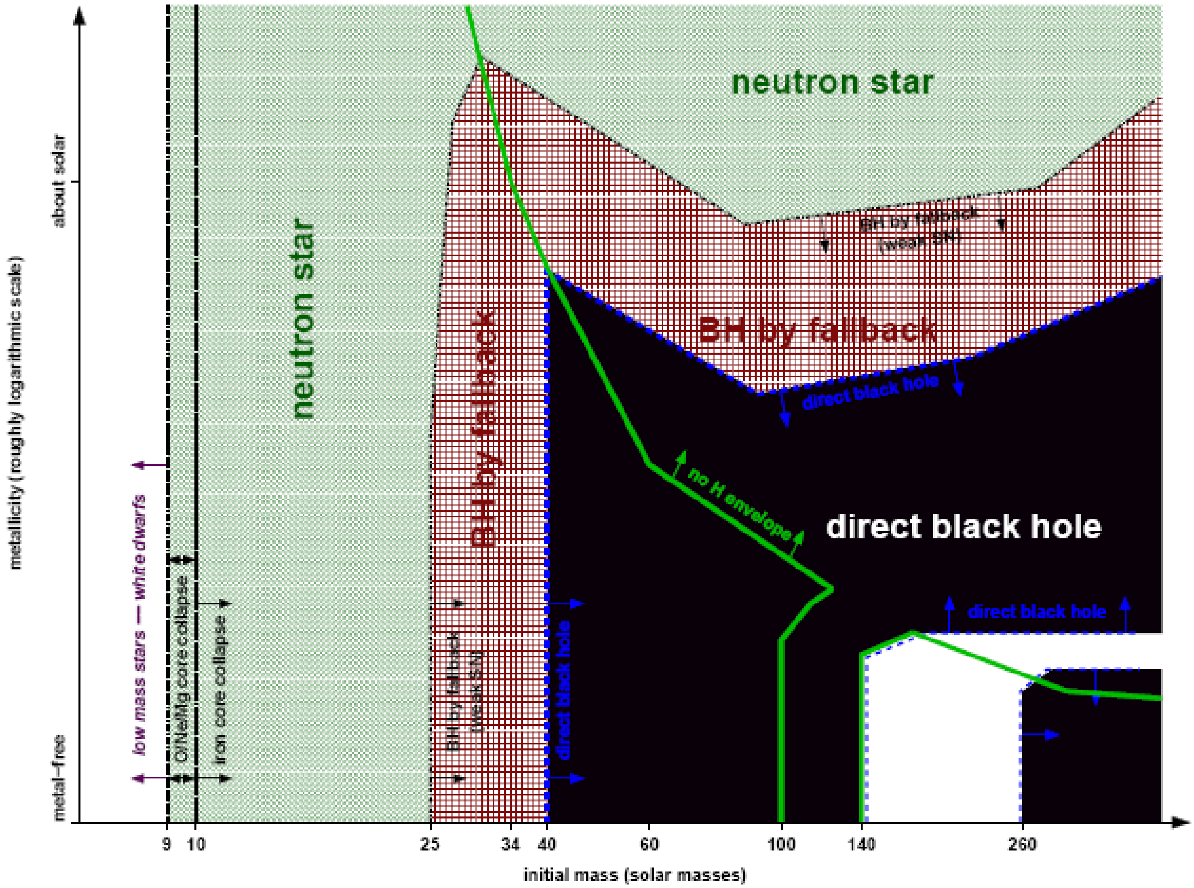


Other limits

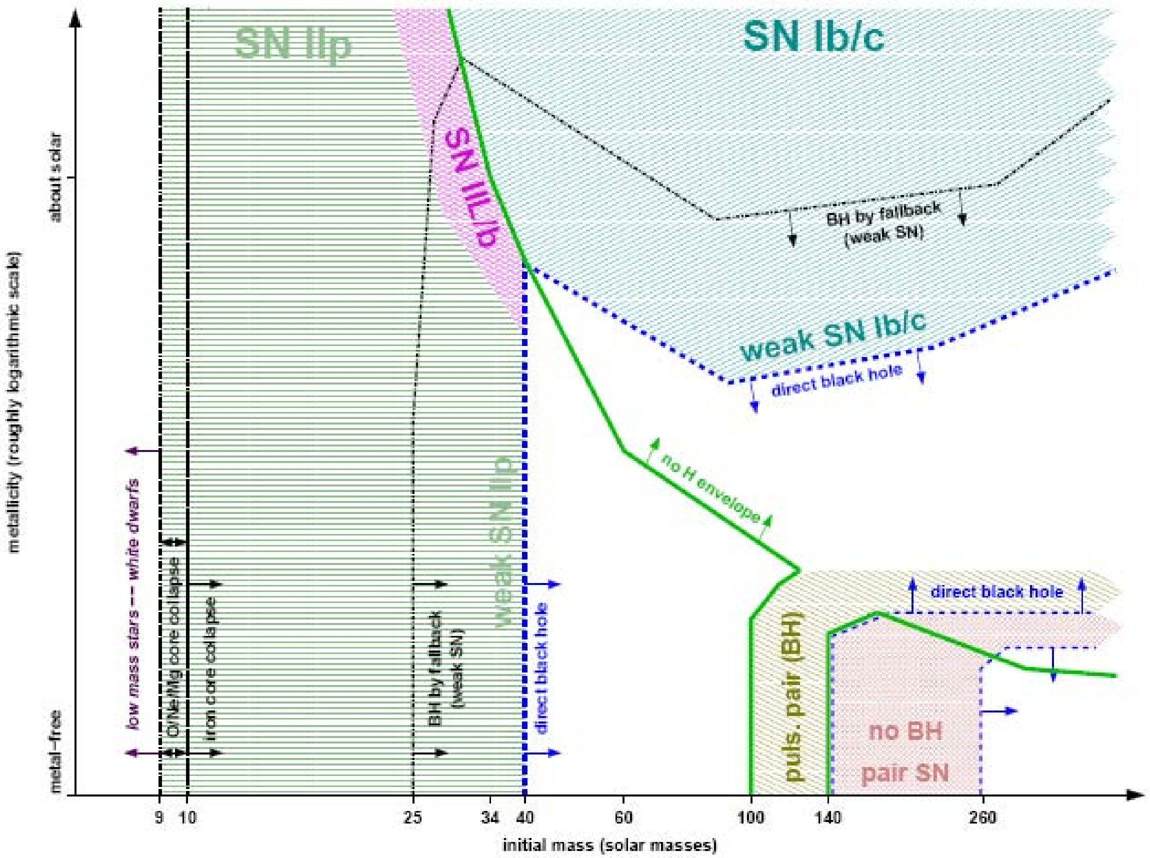
- Glitches (temporary speeding-up of neutron stars). Crystalline phases in compact stars: can exist also in stars containing deconfined quark matter

- 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)

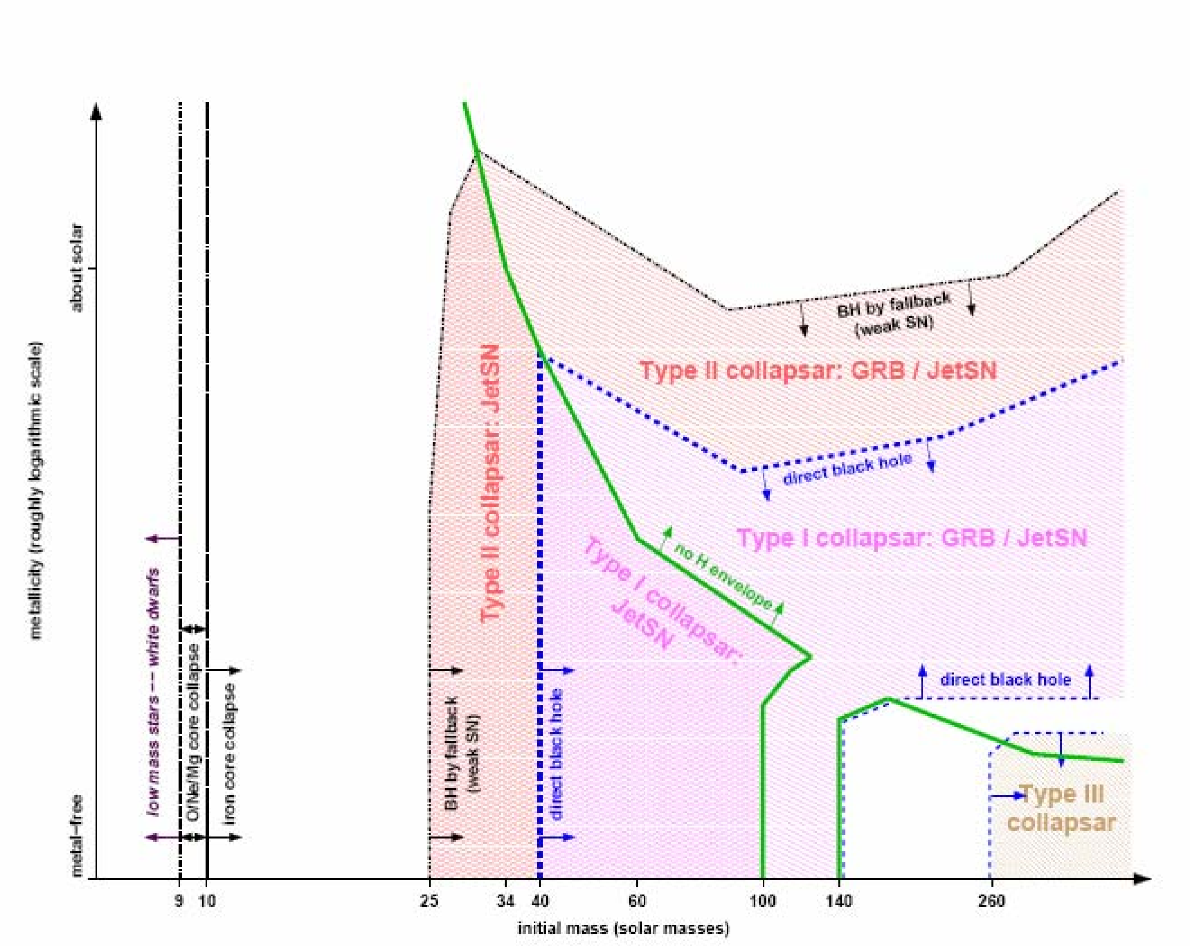
Fate of massive stars
Fryer et al. 2003



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

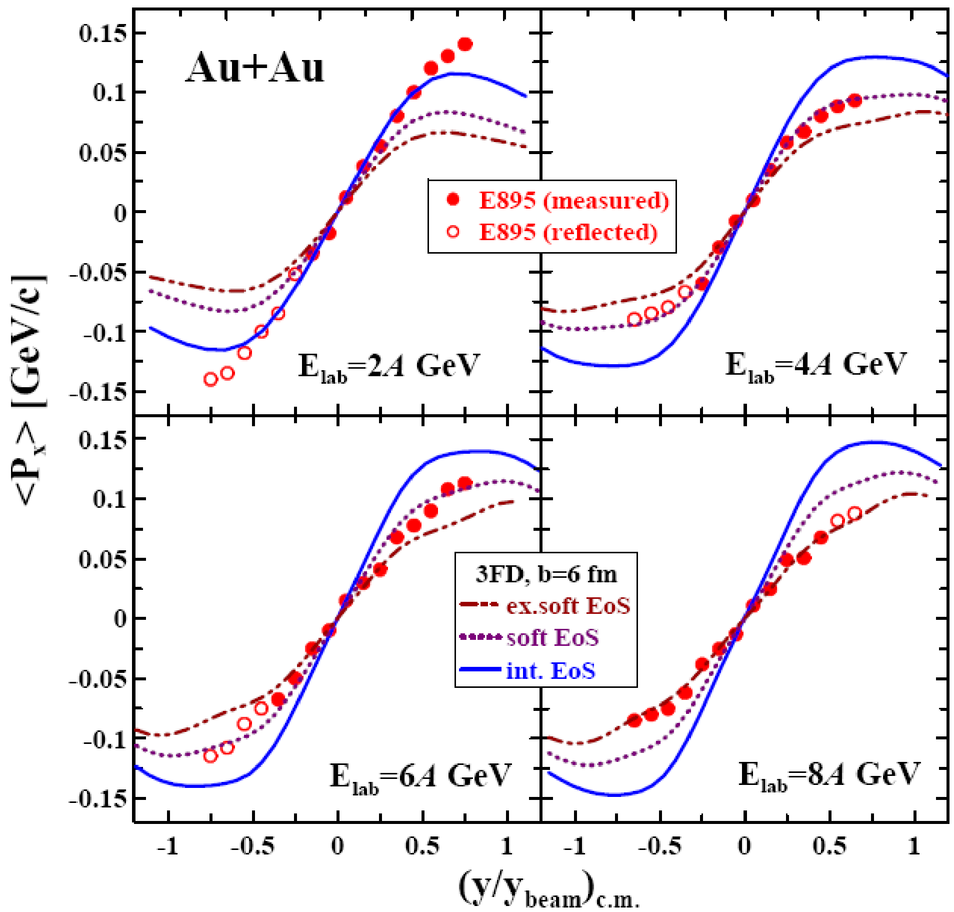
Fits naturally into a scheme describing QM production.

Energy and duration of the GRB are OK.

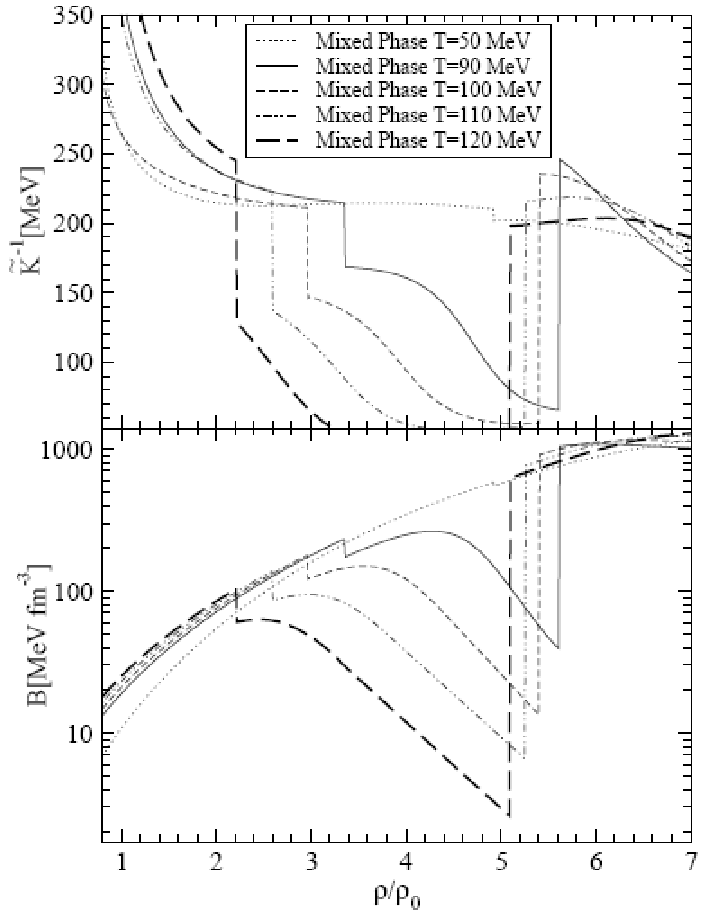
No calculation of beam formation, yet.

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

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



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…)