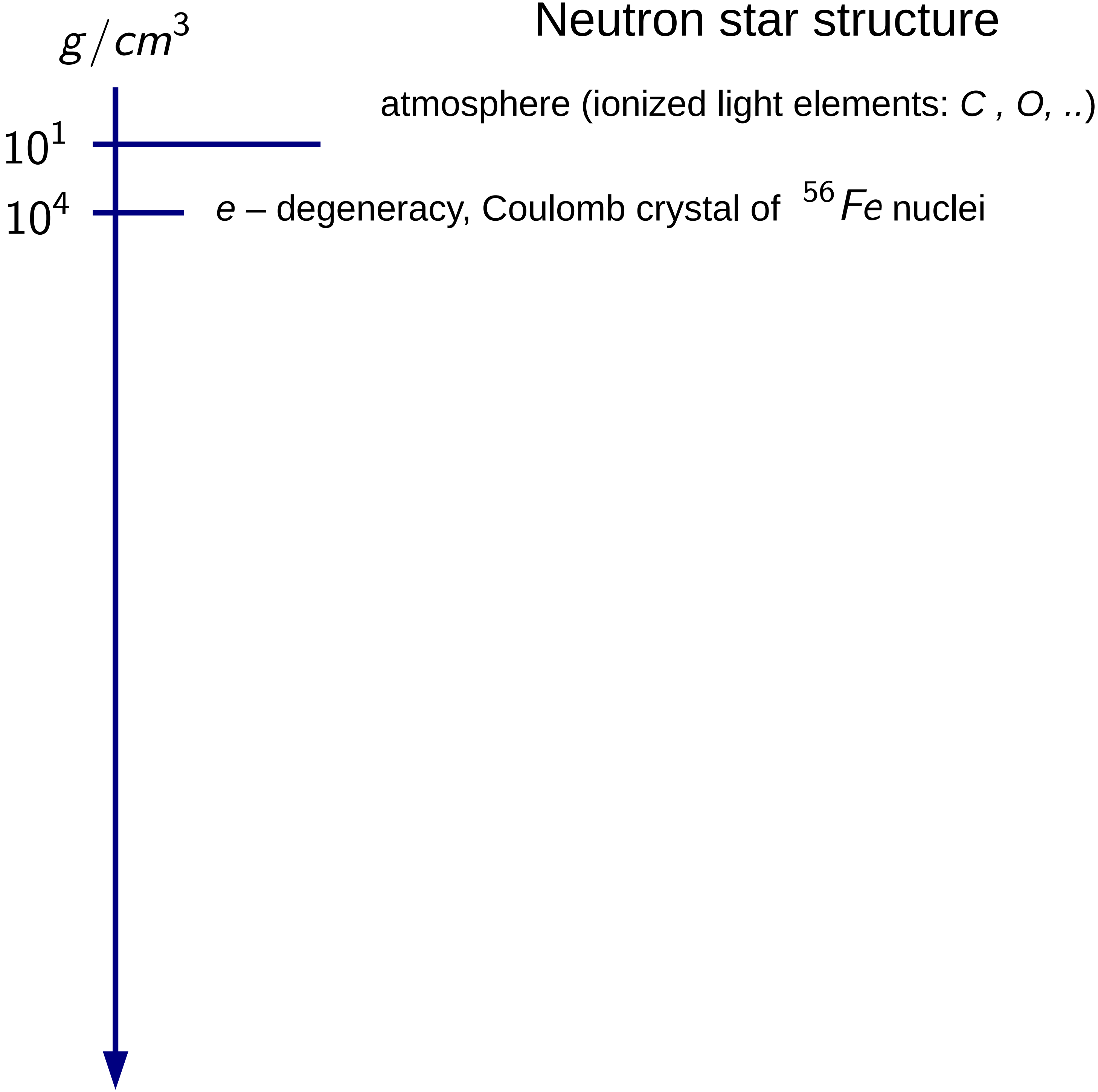
Nuclear EoS
from astrophysical observations

Sebastian Kubis
Cracow University of Technology

- NS structure
- NS cooling
- Pulsar Glitching
- ms Pulsars and GW emission

NUSYM15 , Kraków

Neutron star structure



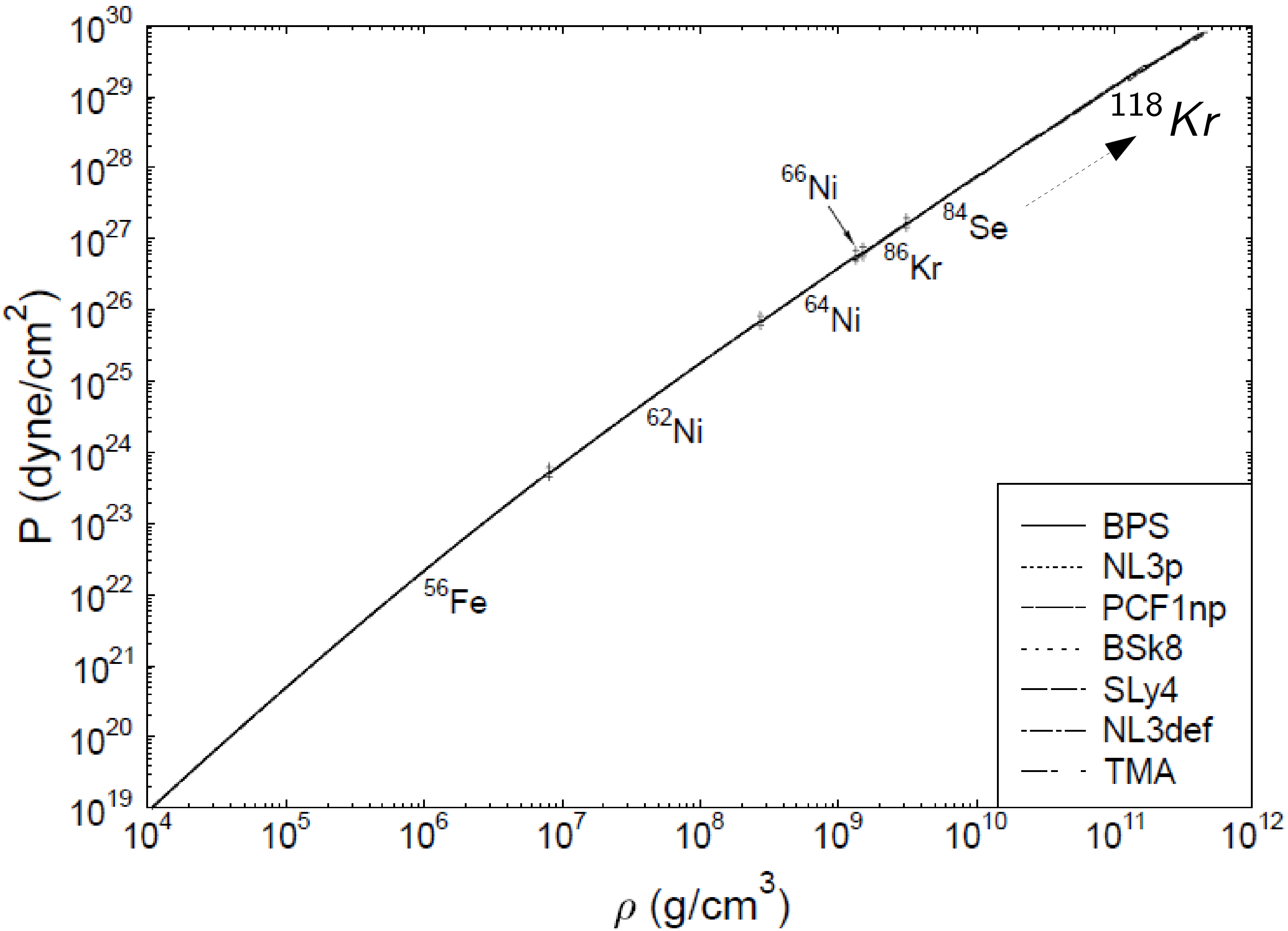
Neutron star structure

g/cm^3

10^1 — atmosphere (ionized light elements: *C* , *O*, ..)

10^4 — *e* – degeneracy, Coulomb crystal of ^{56}Fe nuclei

10^7 — $\mu_e > m_n - m_p = 1.3$ MeV   neutronization of nuclei



$x(^{118}Kr) = 0.3$

Rüster et.al. '06

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10^1

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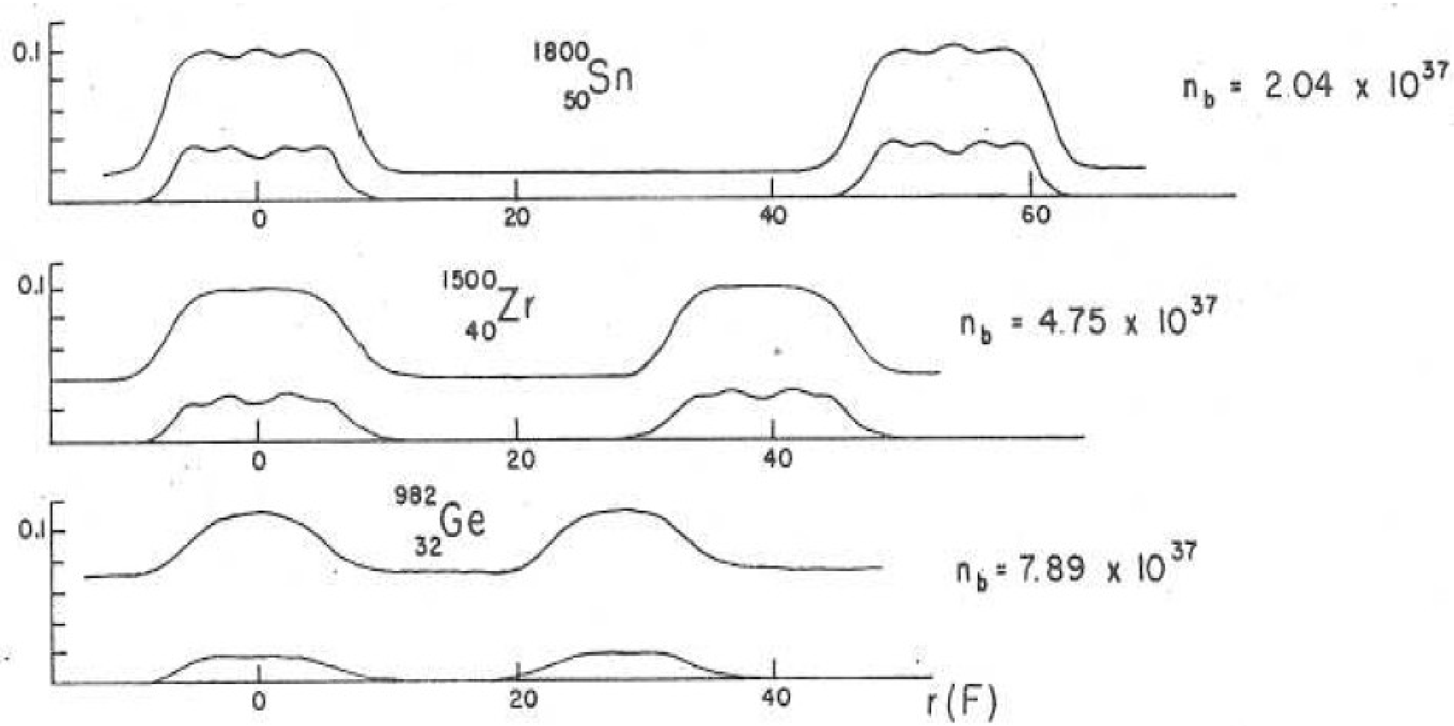
10^{11} — neutron drip → proton clusters in quasi-free neutron liquid



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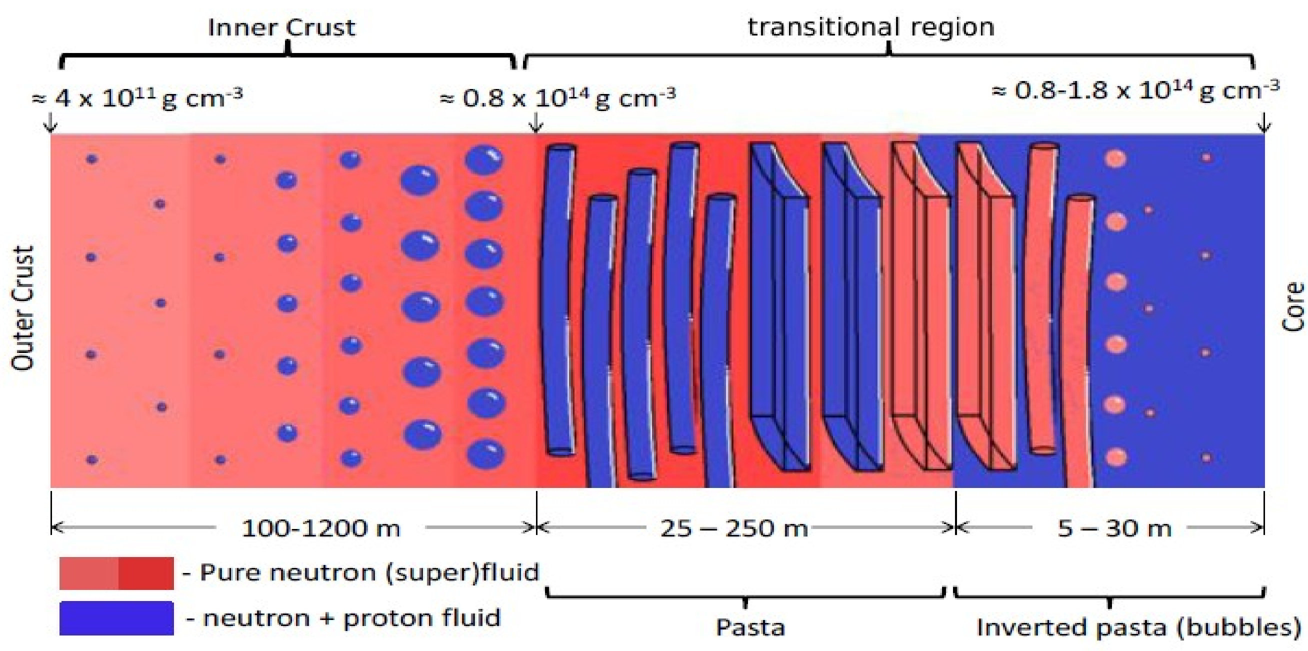
10^{13} — cluster deformation → pasta phases



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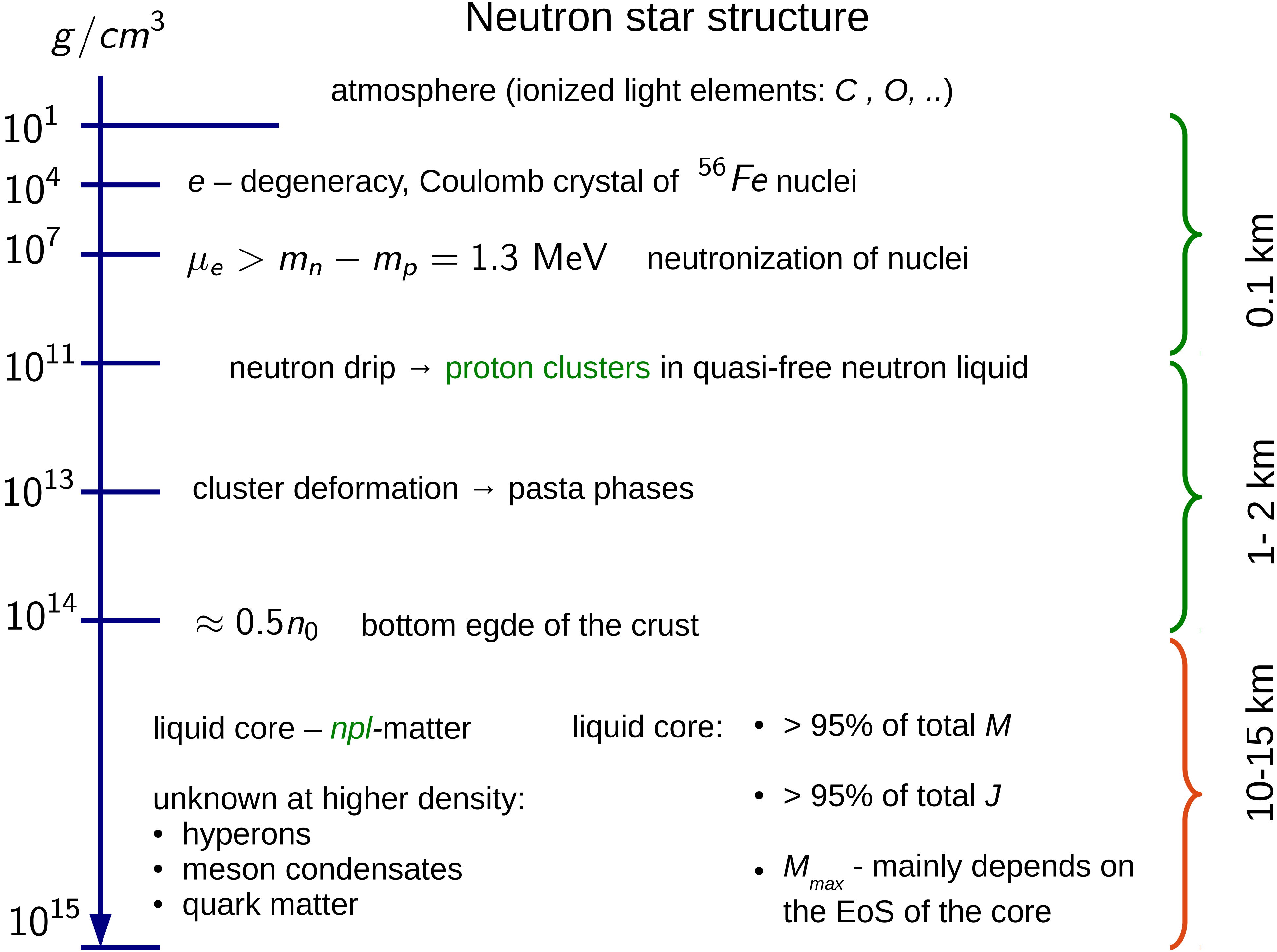
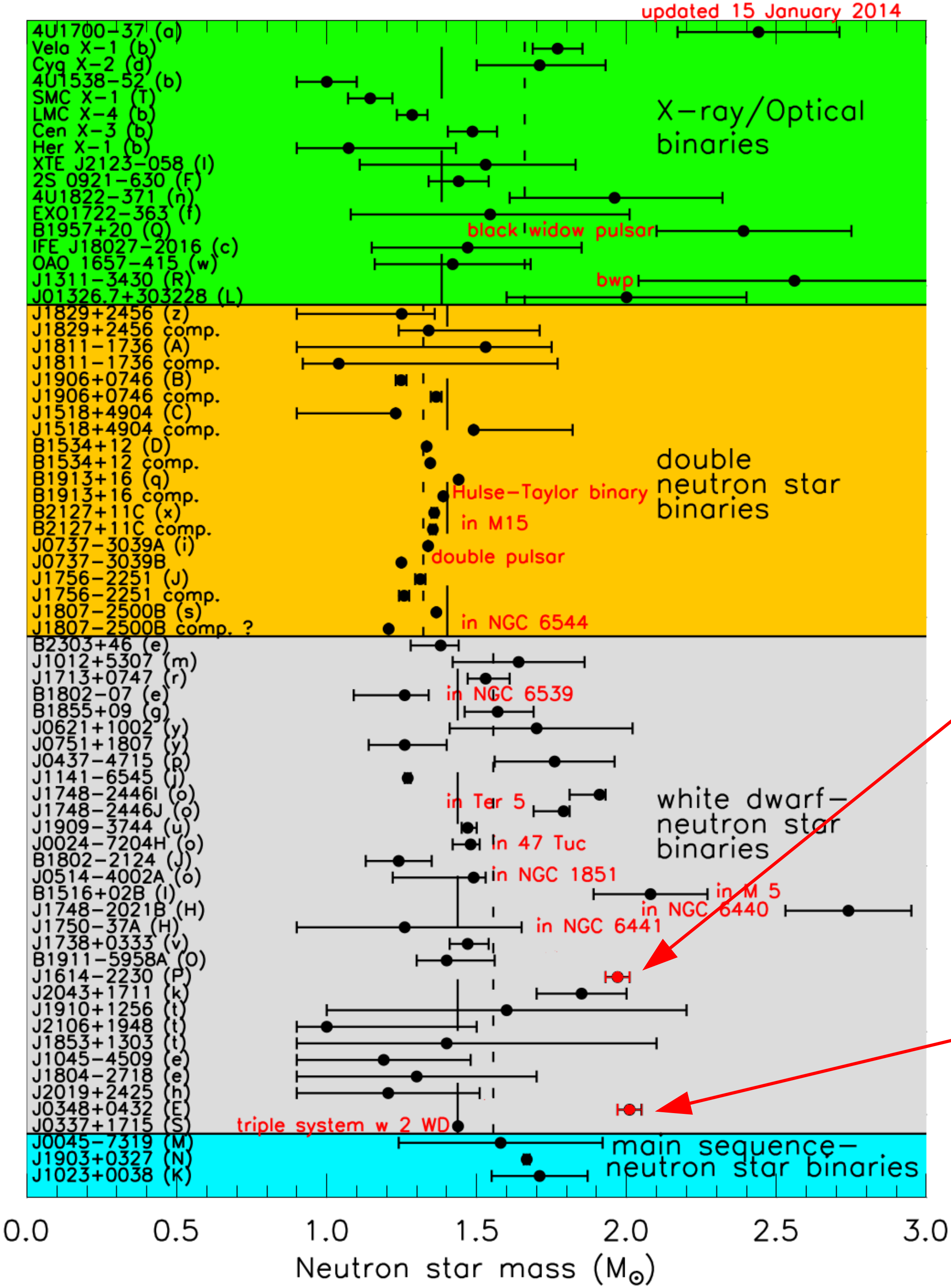




Neutron Star masses

/from binary systems/

typical: 1.5 $M_\odot$

PSR J1614-2230 *Demorest '10*

$1.97 \pm 0.04\ M_\odot$

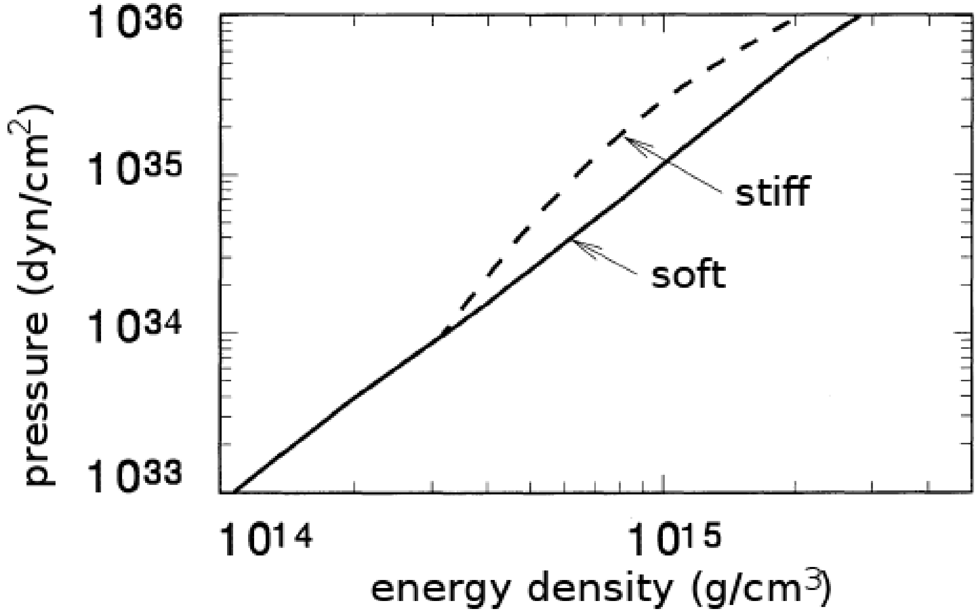
by Shapiro delay

PSR J0348+0432 *Antoniadis '13*

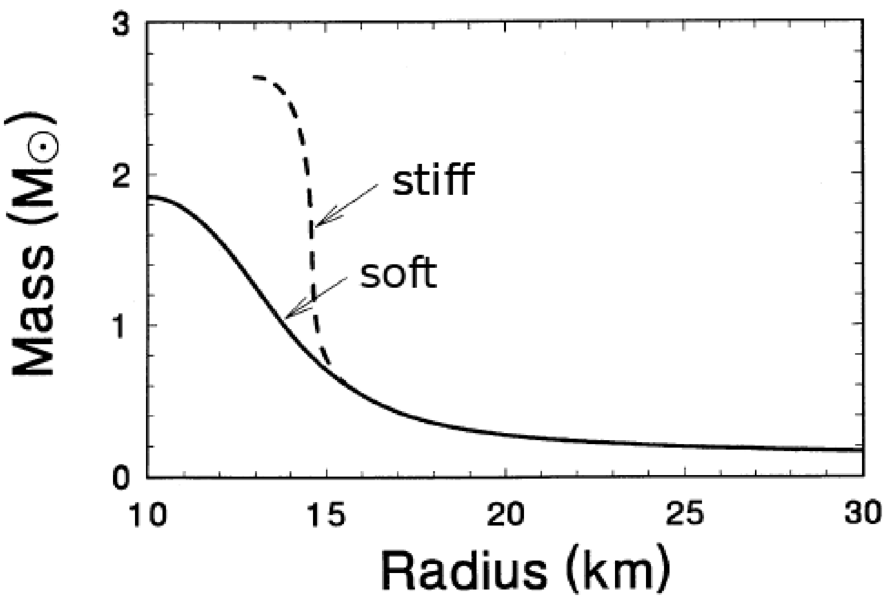
$2.01 \pm 0.04\ M_\odot$

by GR effects in orbital movement

NS masses and EoS



Lindblom '92



non-rotating configuration

Tolman-Oppenheimer-Volkoff equations

$$\frac{dm}{dr} = 4\pi r^2 \rho \ ,$$

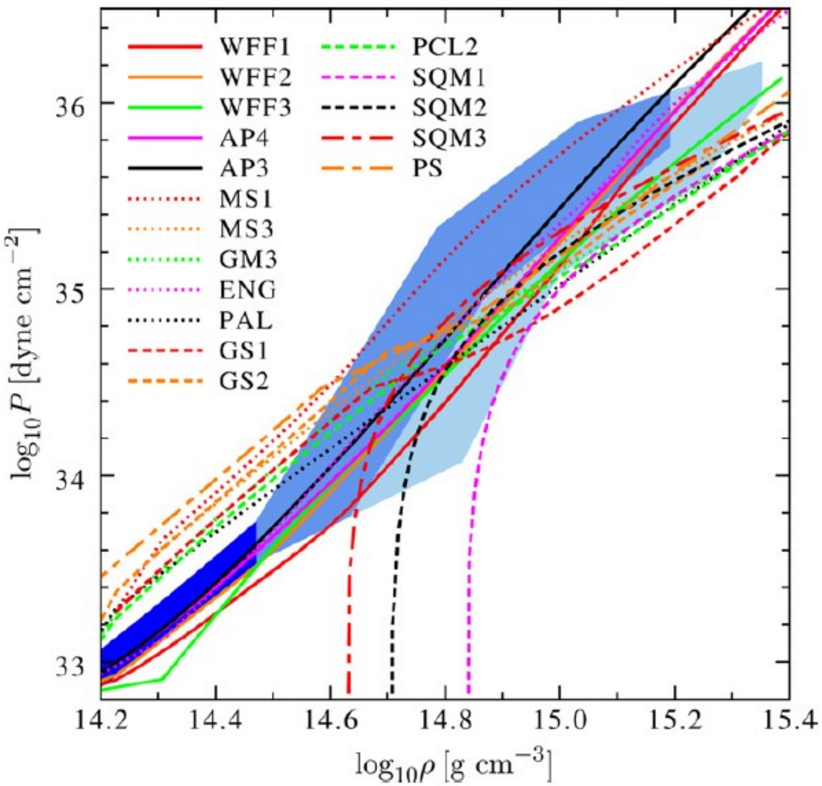
$$\frac{dp}{dr} = -(\rho + p)\frac{m + 4\pi r^3 p}{r(r - 2m)} \ ,$$

$$P(\rho) \longleftrightarrow M(R)$$

stiffer EoS : M $\nearrow$, R $\nearrow$

no simultaneous measurement of *M* and *R*

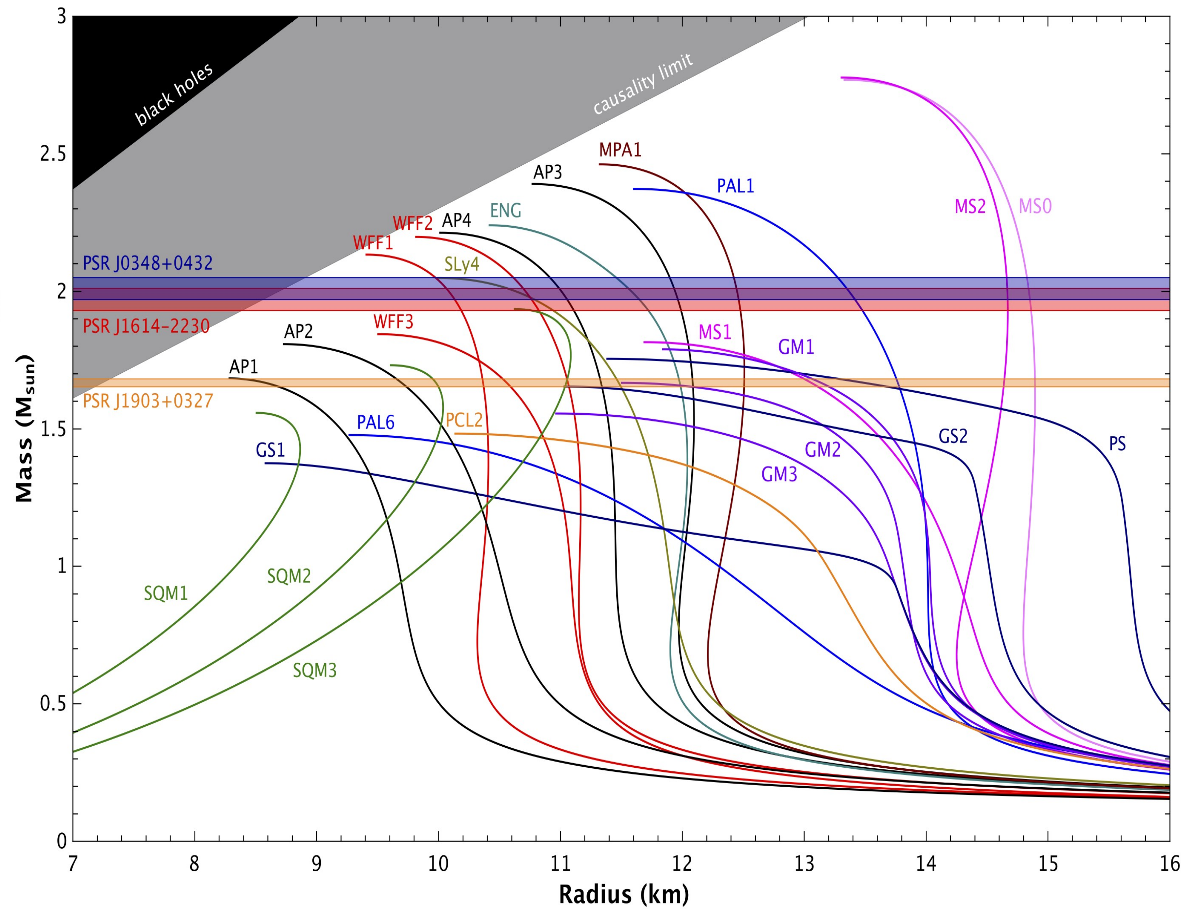
Maximum mass constraint



TOV property : M_{max}

$M_{max} \geq 2M_{\odot}$ too soft EoSs ruled out:

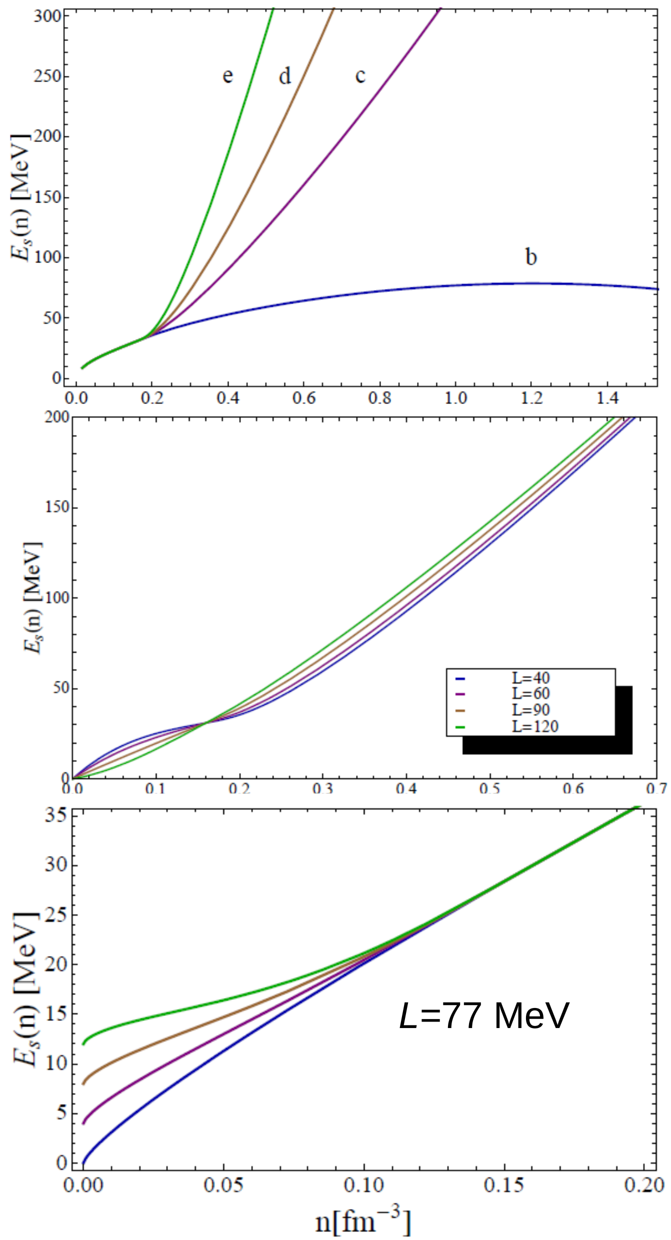
- meson condensates
- hyperons
- quark matter (?)

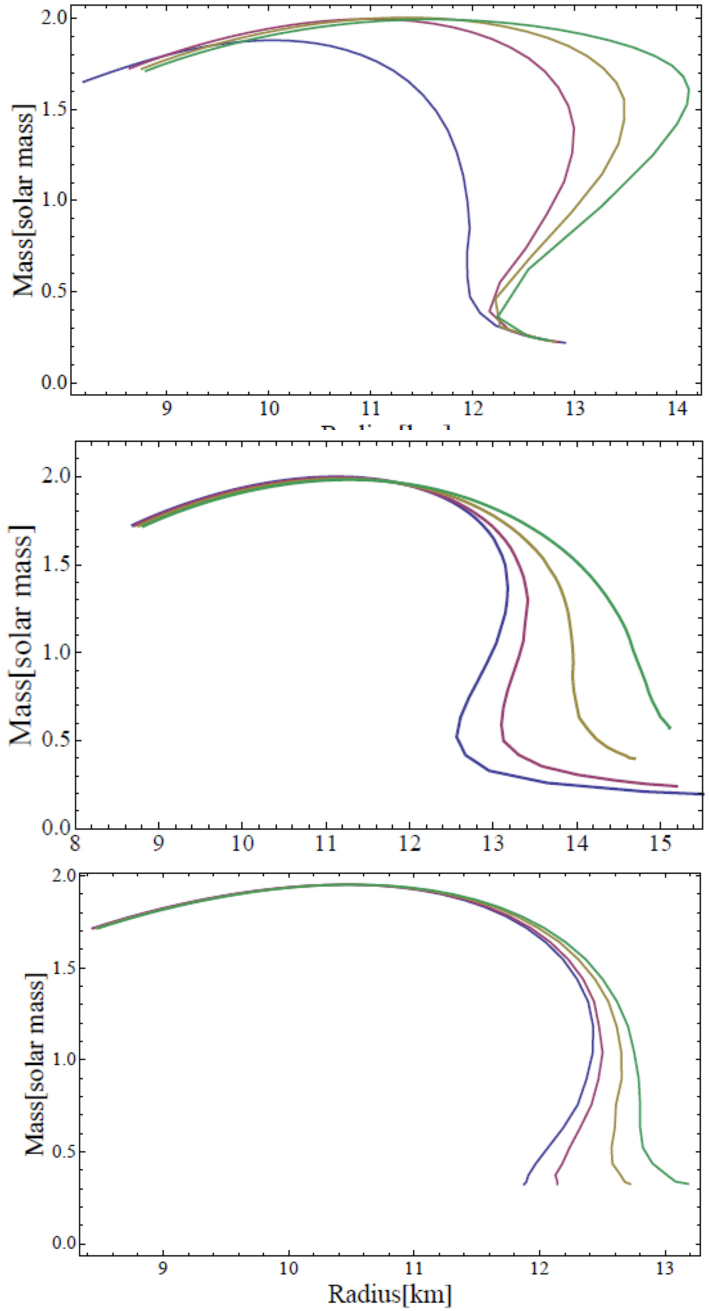


S(n) relation and *M – R*

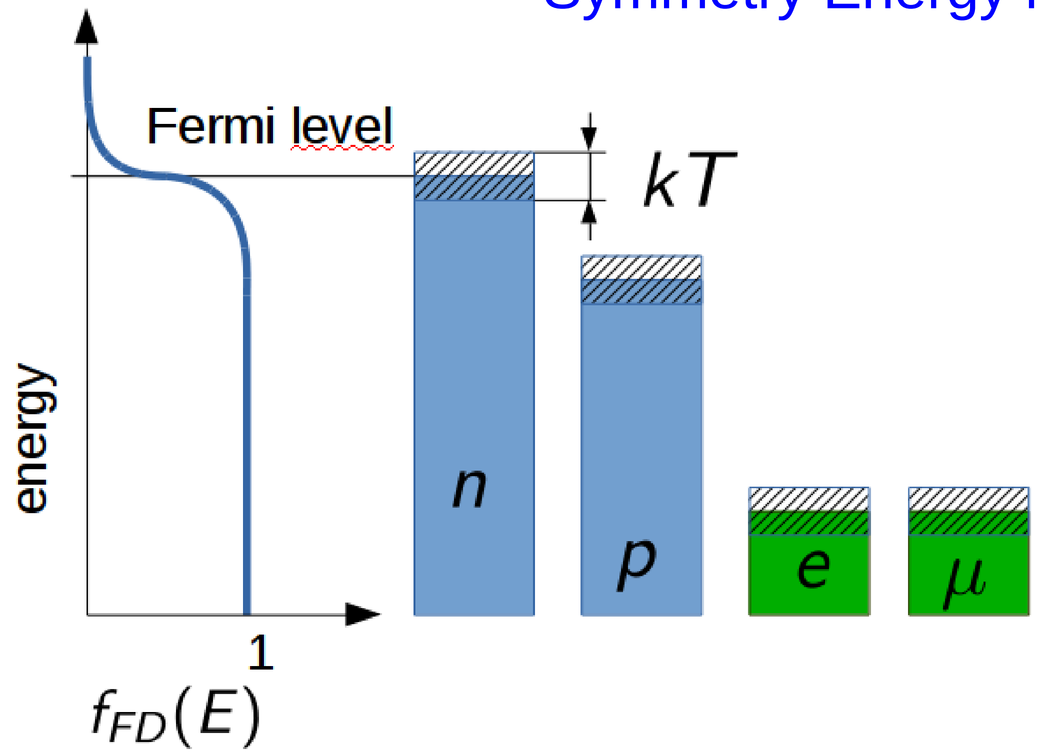
S(n) – Bezier curve parametrization

Alvarez-Castillo & SK '12





Symmetry Energy role



SN explosion, core collapse

degenerated *n, p, e, μ*
at beta equilibrium

$$p + e \rightarrow n + \nu_e$$

$$n \rightarrow e + p + \bar{\nu}_e$$

$$\mu_n - \mu_p = \mu_e = \mu_\mu$$

$$S(n)(1-2x)^2 = \mu_e = k_e$$

$$E_{nuc}(n,x) = V(n) + S(n)(1-2x)^2 + \ldots$$

stiffness of the $P(\rho) \rightarrow M_{max}$

- abundance of ALL species: leptons, hyperons, condensates..
- cooling
- crust-core transition
- radius

Cooling of Neutron Stars

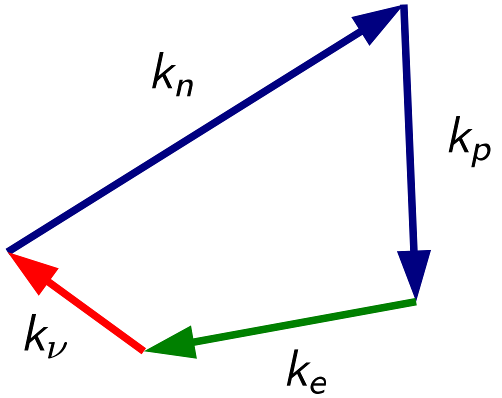
neutrino emission from the whole volume of NS

direct Urca cycle

$$p + e \rightarrow n + \nu_e$$
$$n \rightarrow e + p + \bar{\nu}_e$$

$k_\nu \sim kT \sim 0.01$ MeV

$k_{n,p,e} \sim 100$ MeV



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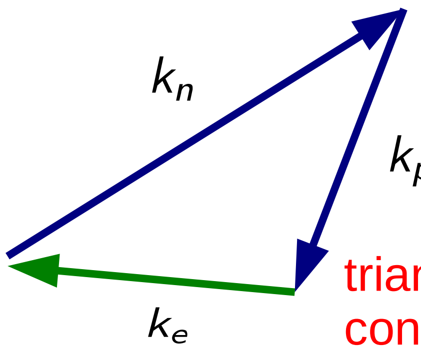


large lepton abundance required!

$x_{dUrca} = 0.11 - 0.14$
$S(n_0) = 30$ MeV $\rightarrow x = 0.04$

exotica (hyperons, kaons..) may help

modified Urca cycle

$$
\begin{aligned}
p + e + N &\rightarrow n + N + \nu_e \\
n + N &\rightarrow e + p + N + \bar{\nu}_e
\end{aligned}
$$

"enhanced" cooling

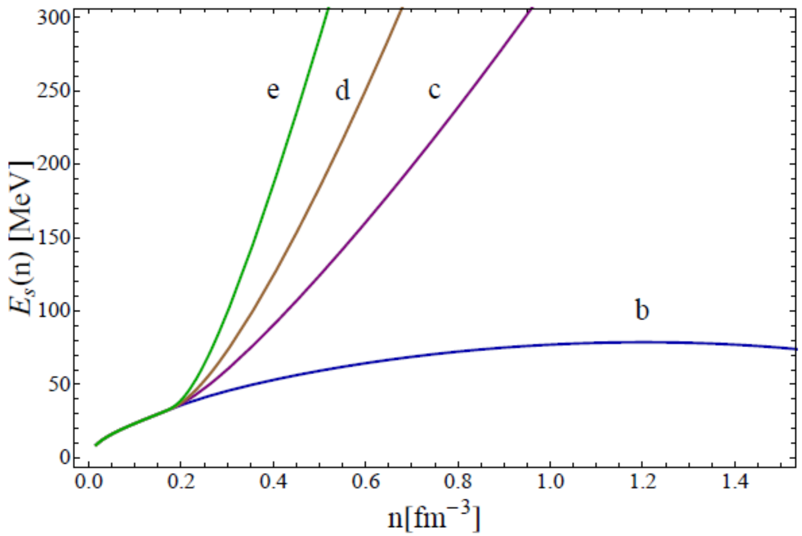
$$Q_{fast} = Q_D T_9^6$$

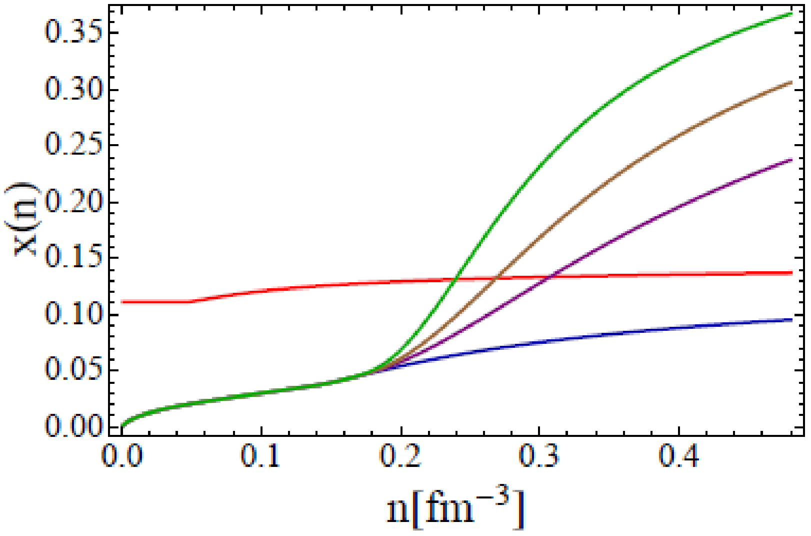
"standard" cooling

$$Q_{slow} = Q_M T_9^8$$

Process			Q_s **[erg cm^{-3} s^{-1}]**
Modified Urca	$nN \rightarrow pNe\bar{\nu}$	$pNe \rightarrow nN\nu$	10^{20}–3×10^{21}
Bremsstrahlung	$NN \rightarrow NN\nu\bar{\nu}$		10^{19}–10^{20}
Nucleon matter	$n \rightarrow pe\bar{\nu}$	$pe \rightarrow n\nu$	10^{26}–3×10^{27}
Pion condensate	$\tilde{N} \rightarrow \tilde{N}e\bar{\nu}$	$\tilde{N}e \rightarrow \tilde{N}\nu$	10^{23}–10^{26}
Kaon condensate	$\tilde{B} \rightarrow \tilde{B}e\bar{\nu}$	$\tilde{B}e \rightarrow \tilde{B}\nu$	10^{23}–10^{24}
Quark matter	$d \rightarrow ue\bar{\nu}$	$ue \rightarrow d\nu$	10^{23}–10^{24}

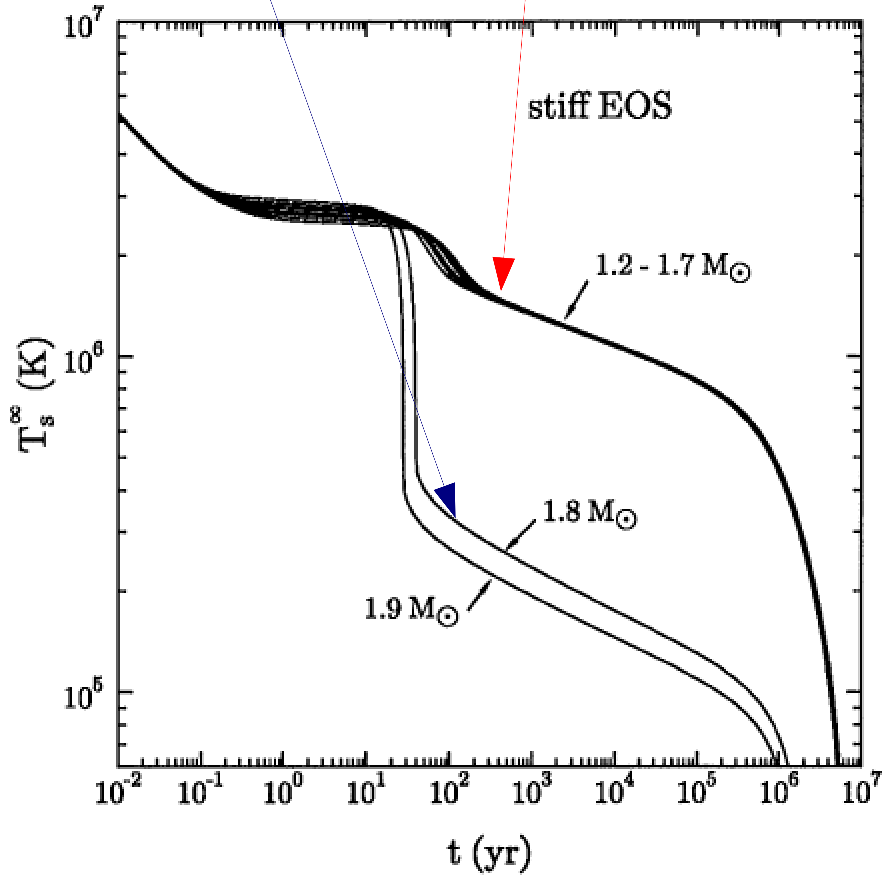
S(n) – cooling regulator





enhanced vs *standard* cooling

Yakovlev '99



S(n) – cooling regulator ?

new era: *XMM Newton* and *Chandra*

Yakovlev '04

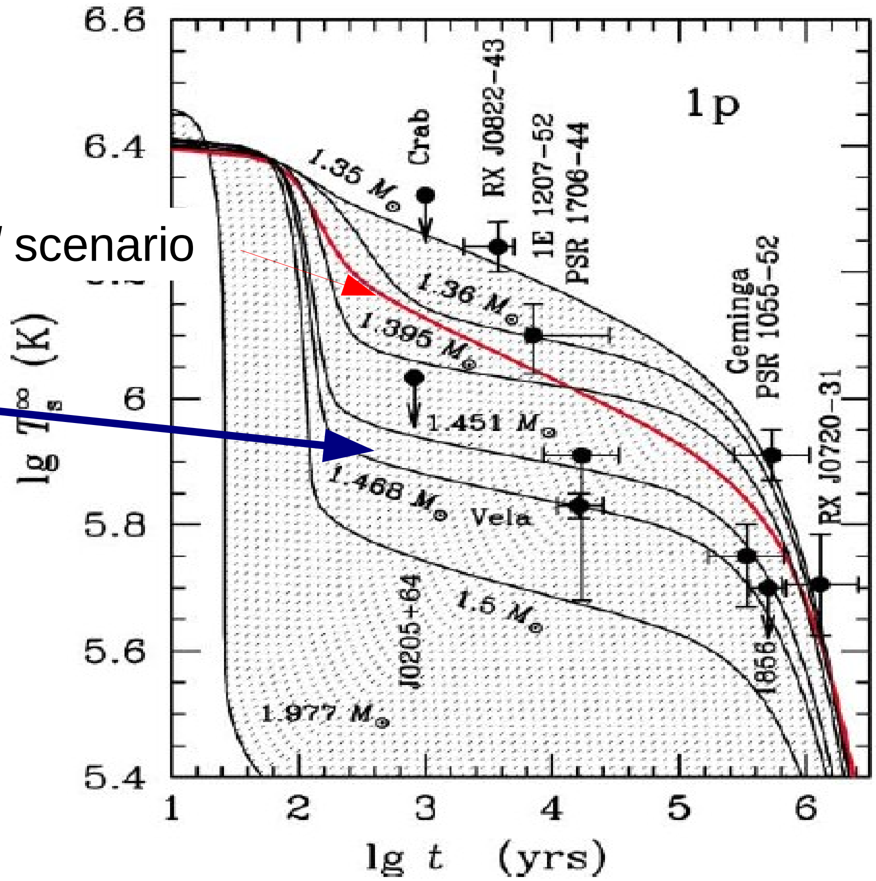
superfluidity: suppresses all neutrino processes

$$Q_\nu \to R(T)Q_\nu \ , \quad R(T) \sim \exp(-a\frac{T_c}{T})$$

enhanced scenario:

- dUrca
- exotic components
- superfluidity

standard scenario



S(n) – cooling regulator ?

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enhanced scenario:

- dUrca
- exotic components
- superfluidity

superfluidity: introduces a new process - Cooper pair breaking and formation (PBF)

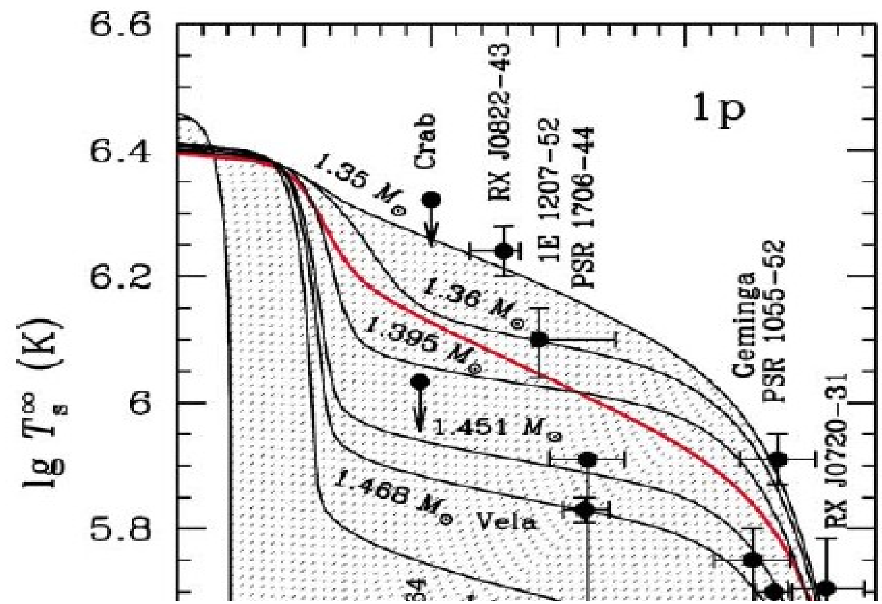
minimal scenario: *Page et al* '04

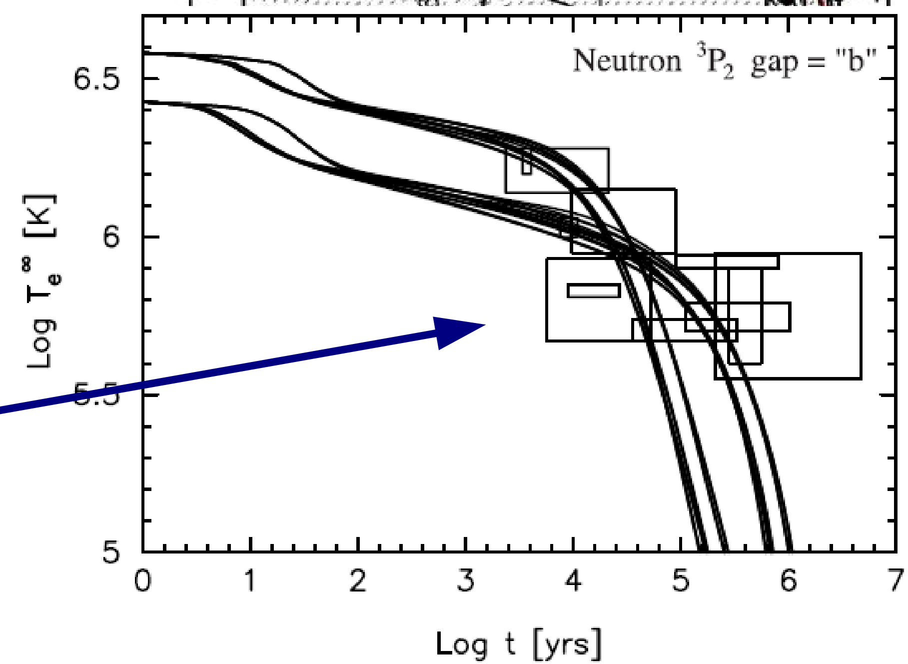
- no exotica
- no dUrca
- emission from Cooper PBF

successfully explained all observational data

new era: *XMM Newton* and *Chandra*

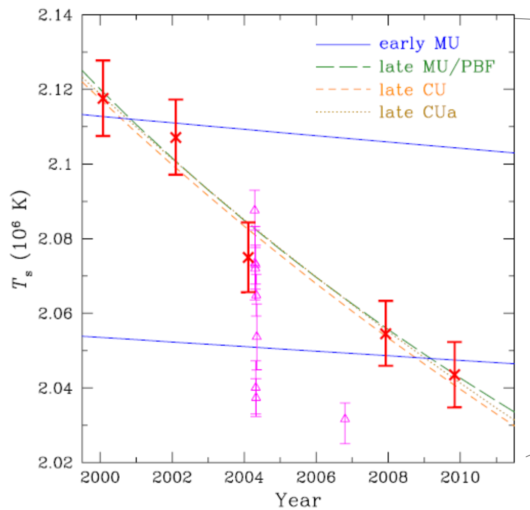
Yakovlev '04



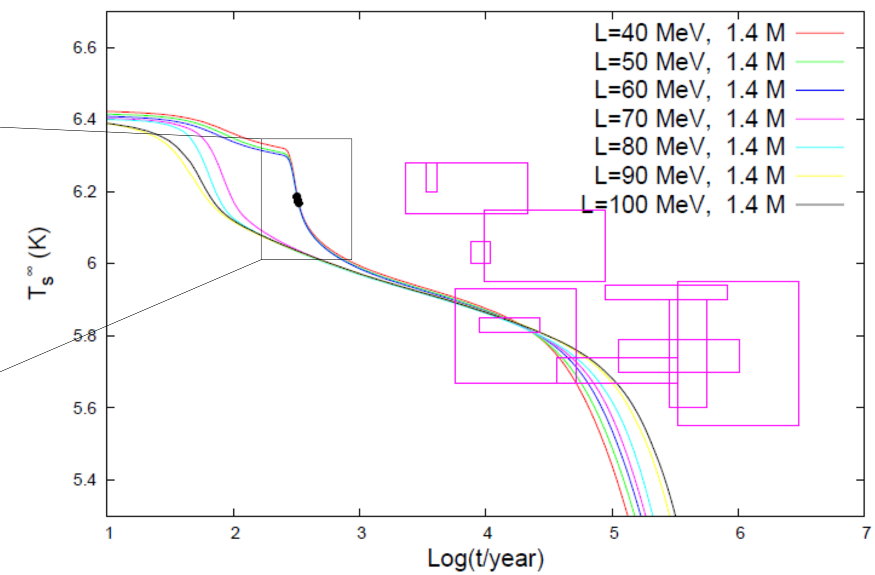


Cas A neutron star – the onset of superfluidity

Chandra archival data:
sudden drop in *T* over 10 years



Lim '13

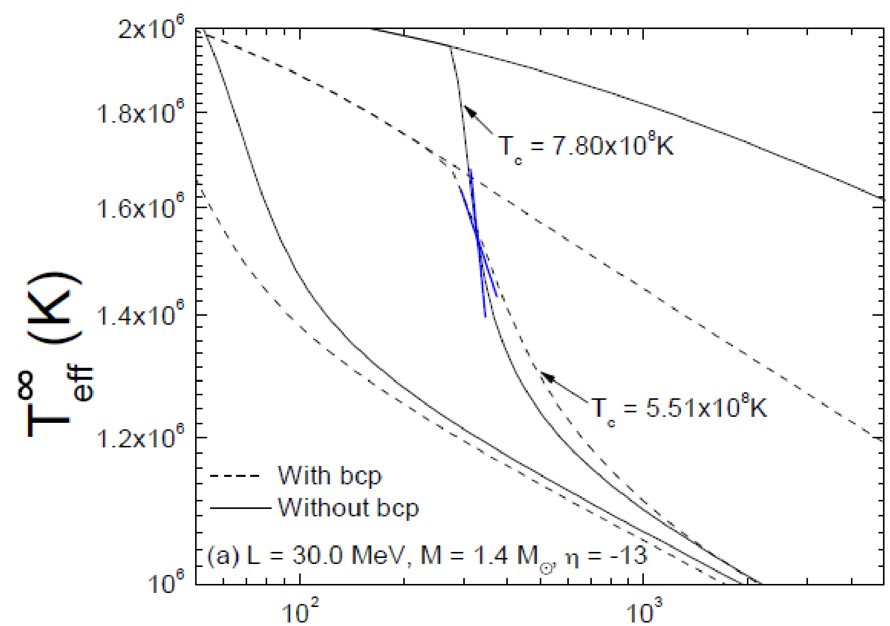


the star enters into the superfluid state
→ intense PBF cooling

minimal cooling scenario allows to probe EoS details

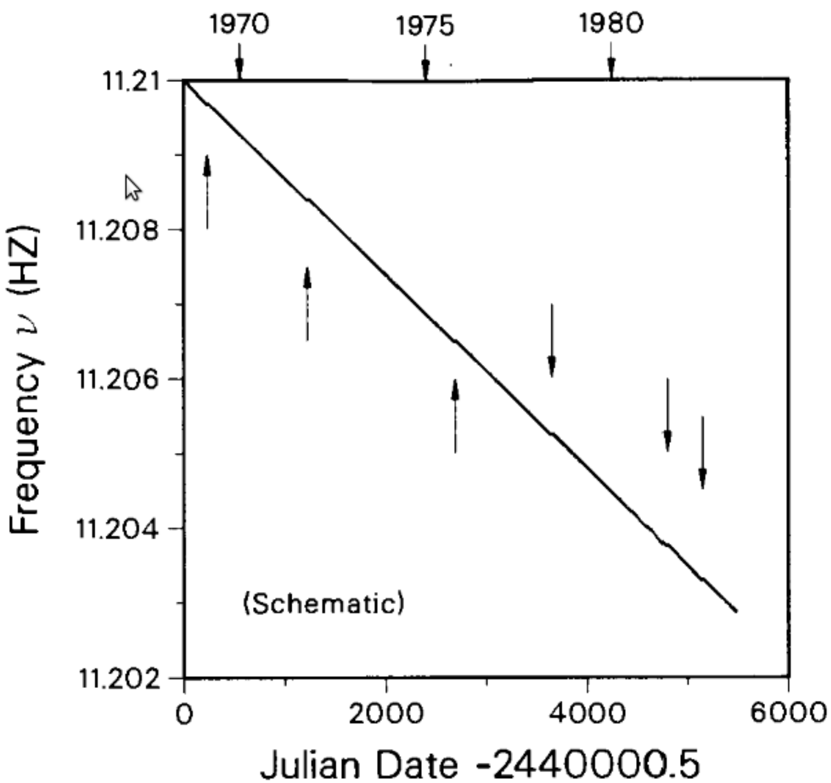
with pasta phases ***L*<70** MeV
with no pasta phases ***L*<45** MeV

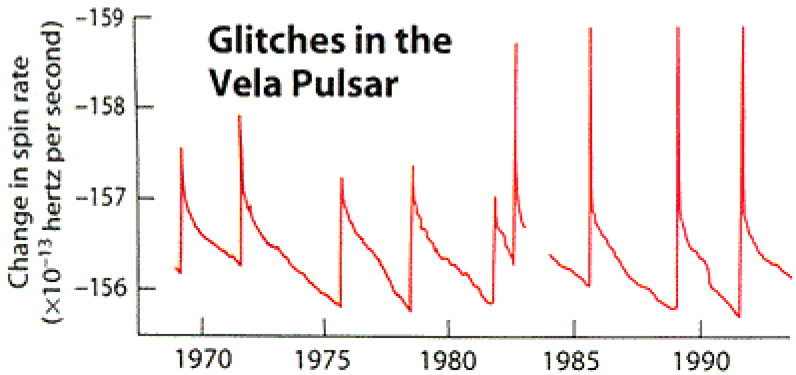
Newton et al '15



Pulsar Glitching

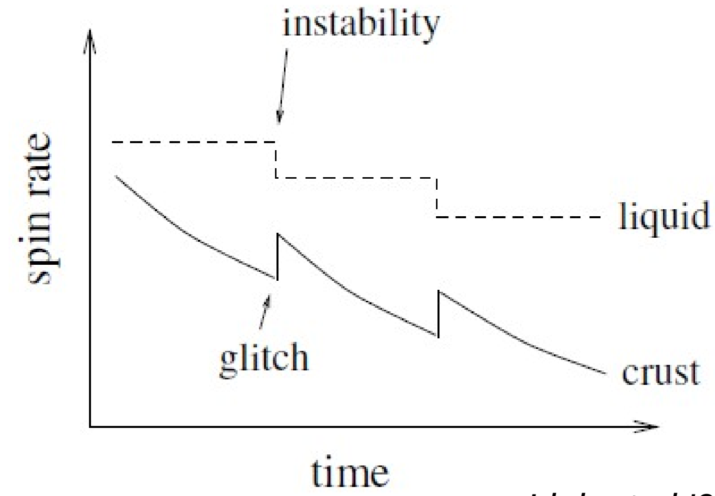
sudden, unexpected increase in Ω



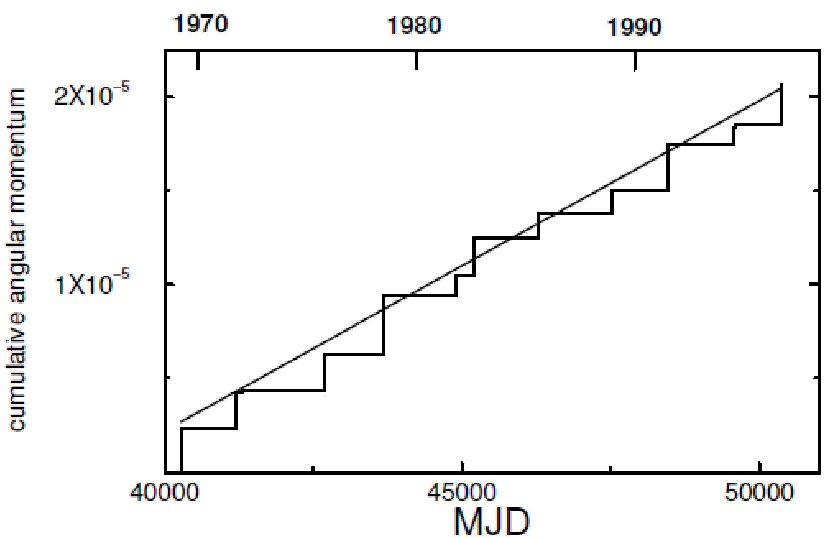


two components:

- superfluid – vortices
- normal - coupled to magnetic field

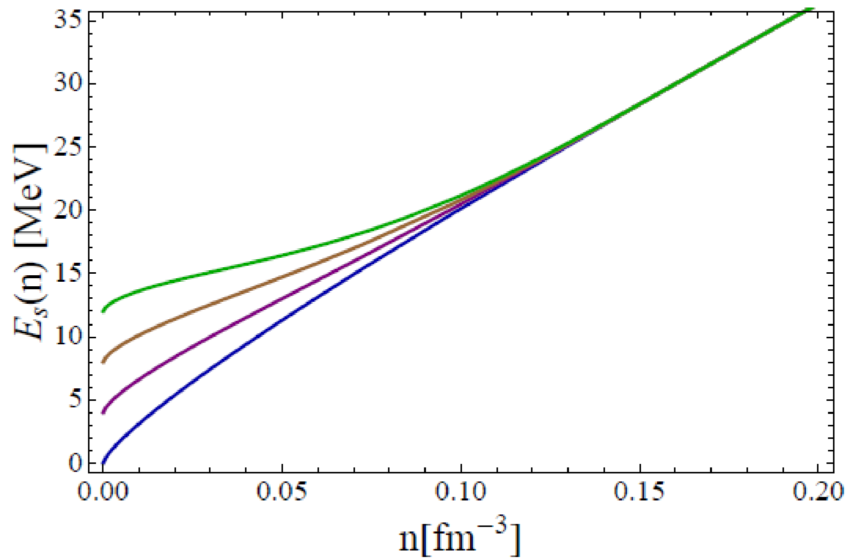


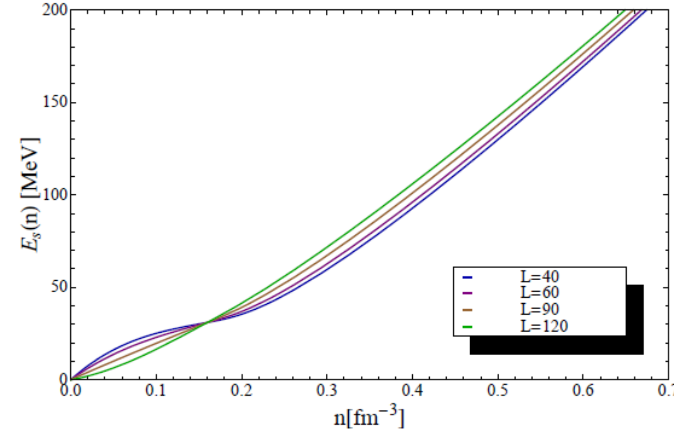
Link et al '99

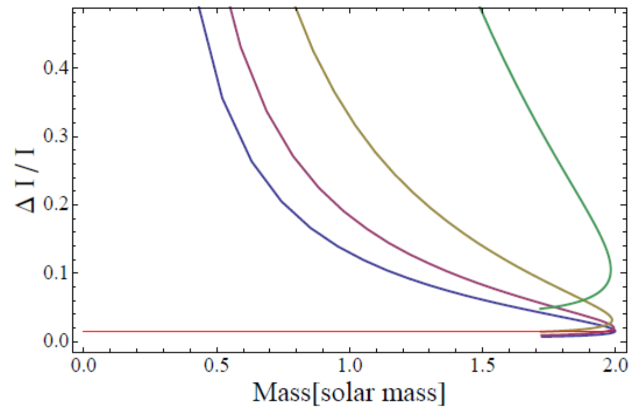


lower limit on I_{crust} : $\frac{I_{crust}}{I} > 1.4\%$

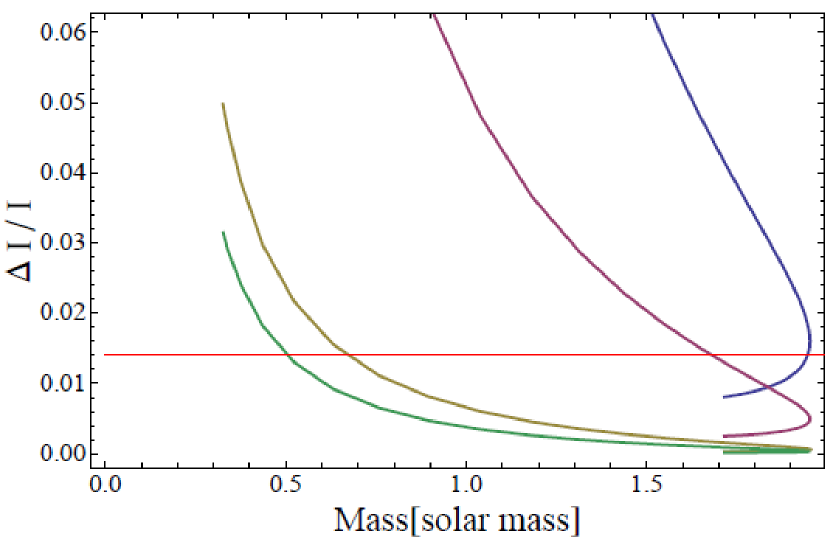
Pulsar Glitching contd







$$\frac{I_{crust}}{I} > 1.4\%$$ for ***L*** not very restrictive



but! – improved analysis by *Newton et al* '15

- neutron entrainment
- reduction of pinning region
- momentum transfer from the core to the crust

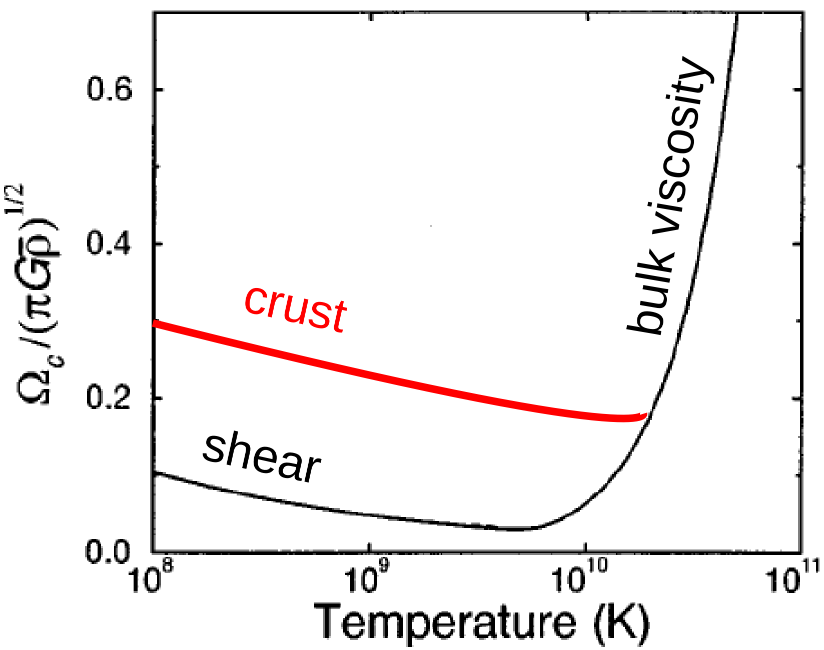
} EoS dependent

L > 100 MeV

r-mode instability and lower limit on spin period of MSP

the fastest pulsar 716 Hz
Keplerian frequency
(shedding mass limit) ~ 2000 Hz

GW emission above Ω_{crit}



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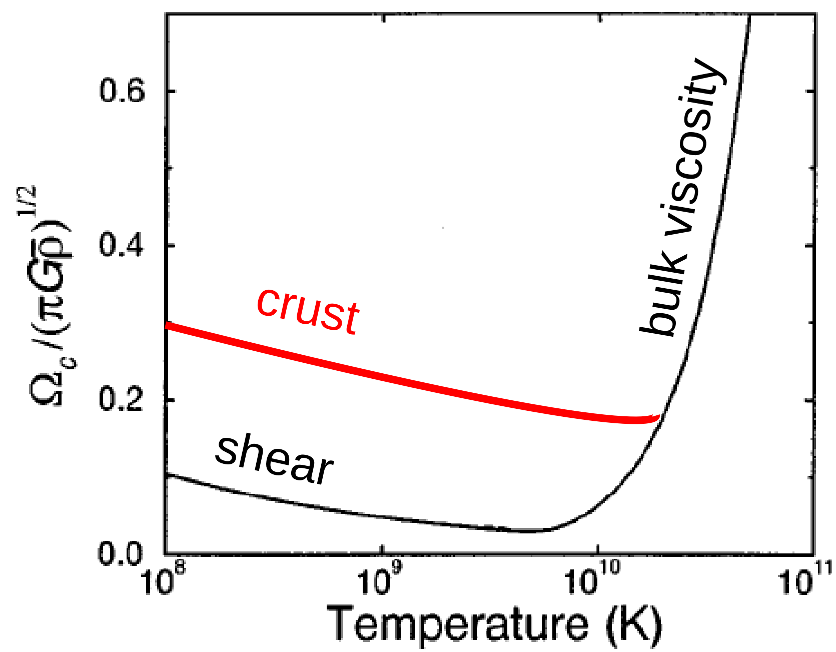
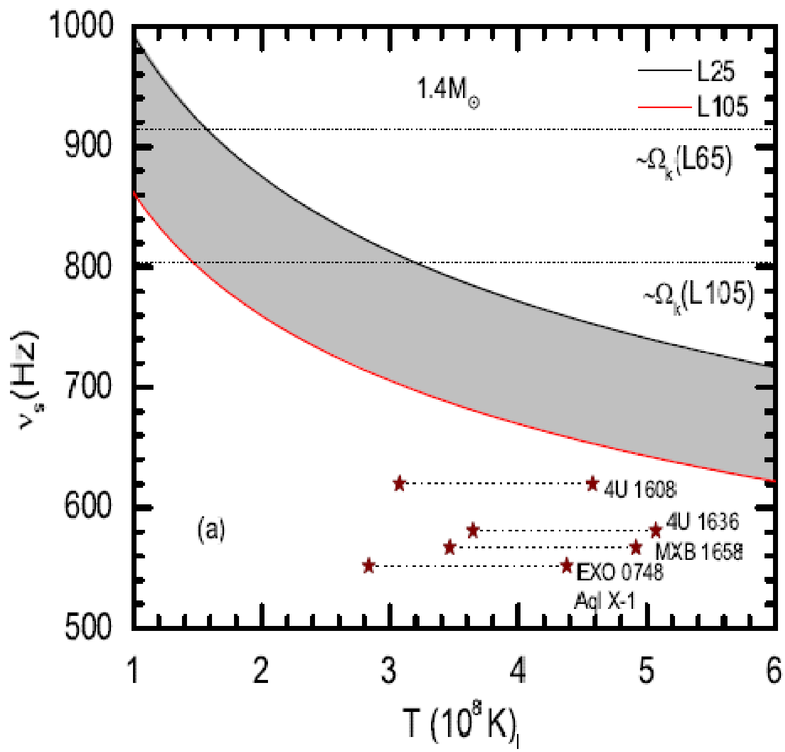
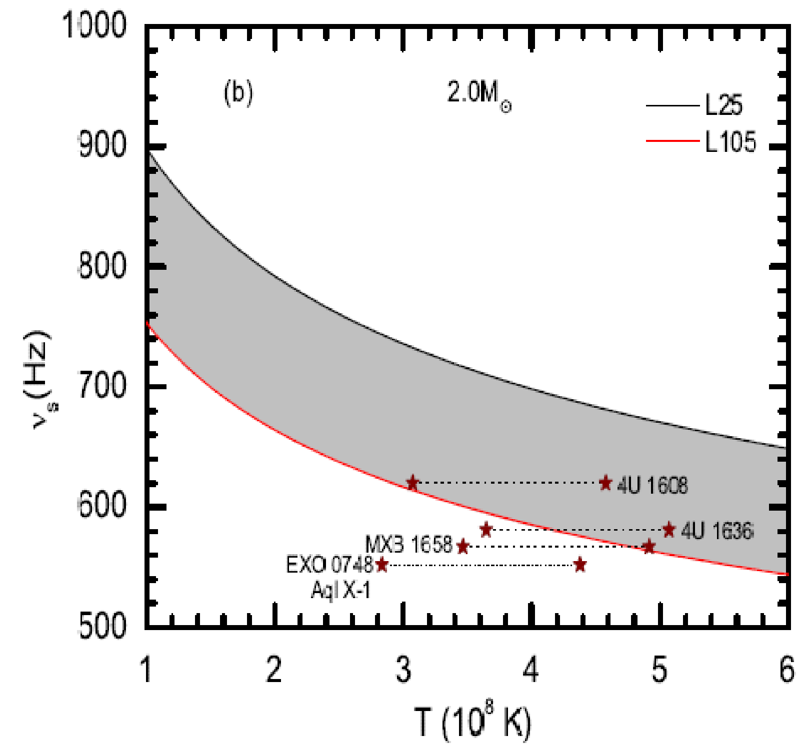


GW emission above Ω_{crit}

Wen et al. '12 L > 65 MeV





Conclusions

- constraining *S(n)* by NS observations - possible and promising
- highly model dependent

... isn't our job to make models ?