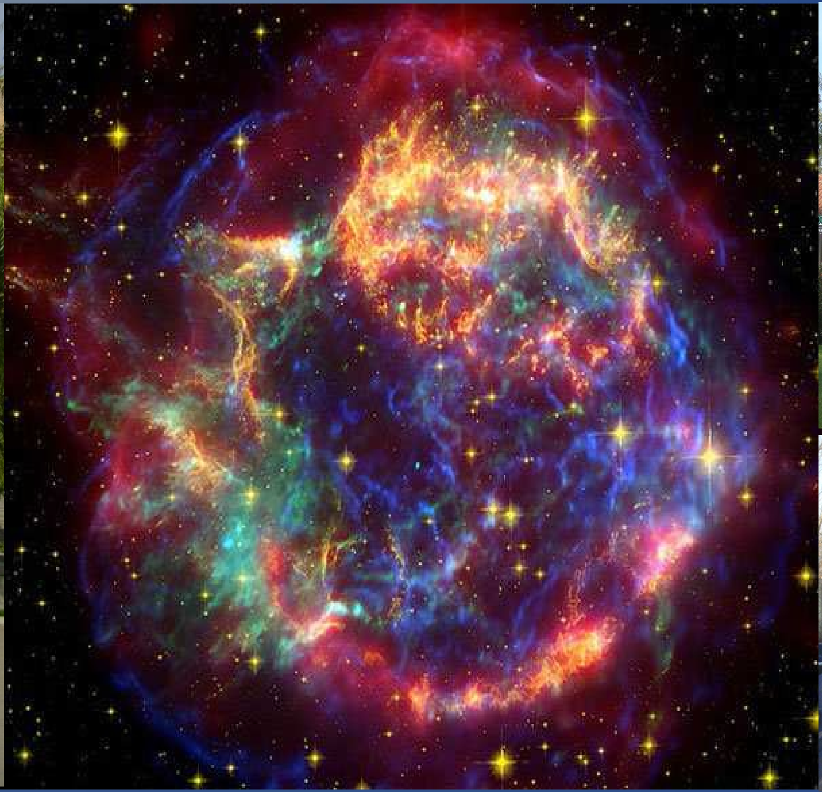
Structure and Cooling of Compact Stars - an update after J1614-2230 and Cas A

David Blaschke (Wroclaw University, JINR Dubna)

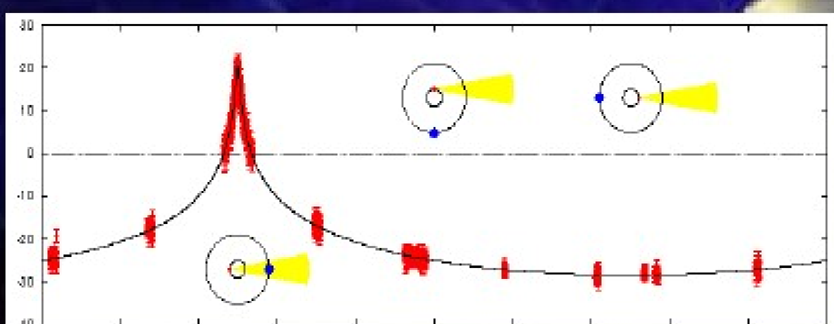
Thanks to 'cool' coauthors:
Hovik Grigorian, Fridolin Weber, Dima Voskresensky

EMMI Workshop "Dense Baryonic Matter ...", Tübingen, 12.10.12

comp star

PSR J1614-2230 - A new constraint for the Compact Star EoS

- NS-WD binary in Scorpius
- NS is recycled MSP with $P = 3.15$ ms
- almost edge-on, inclination 89.17^o
- Shapiro delay measured!
- $M_{WD} \sim 0.5\ M_\odot$
- $M_{NS} = (1.97 \pm 0.04)\ M_\odot$



Demorest et al., Nature 467, 1081 (2010)

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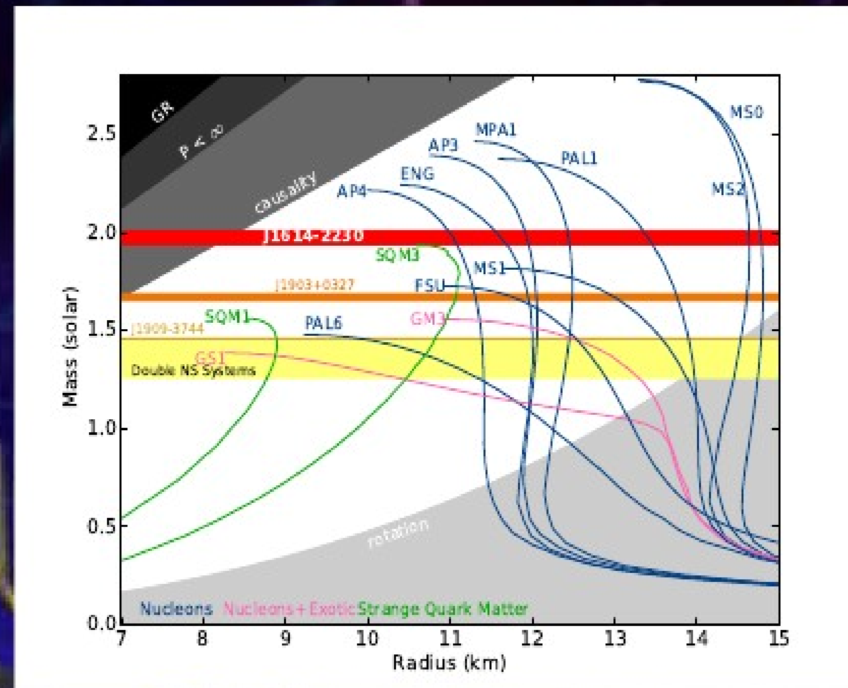

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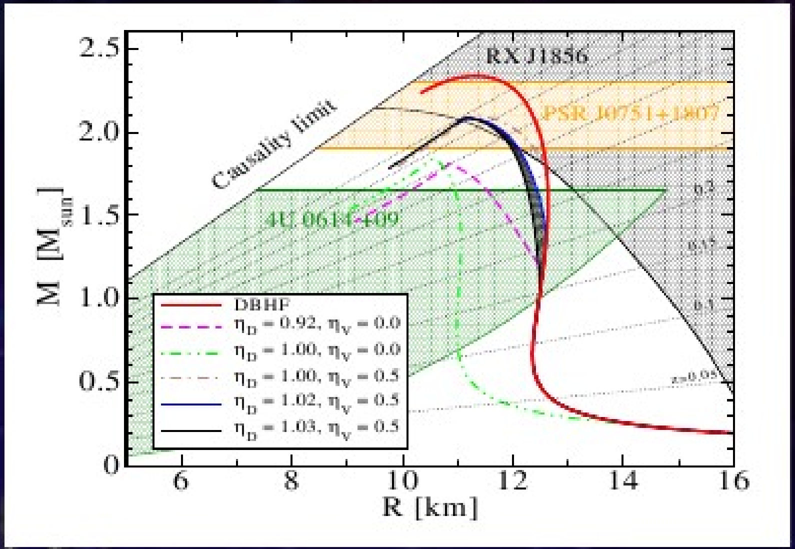
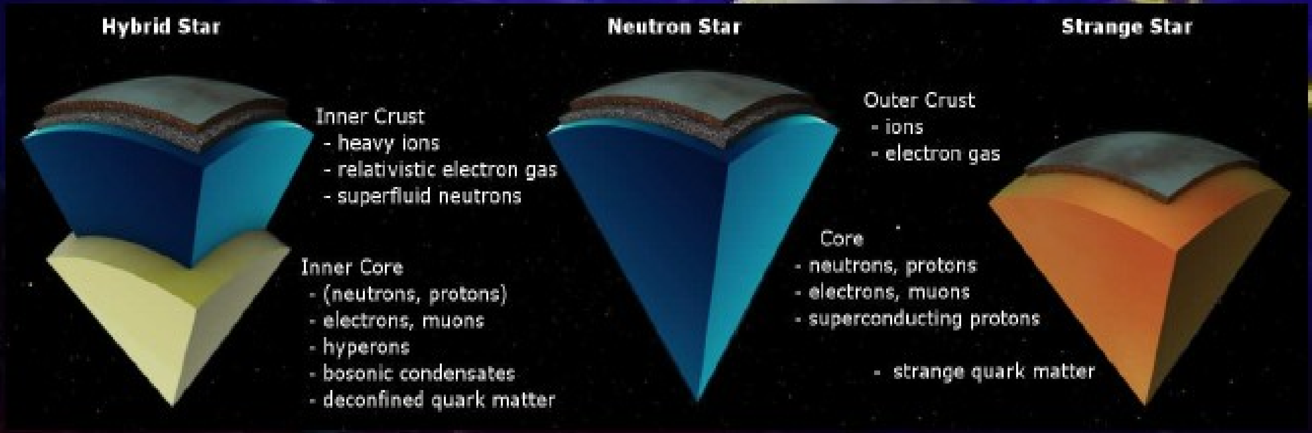


Klähn et al., PLB 654, 170 (2007)



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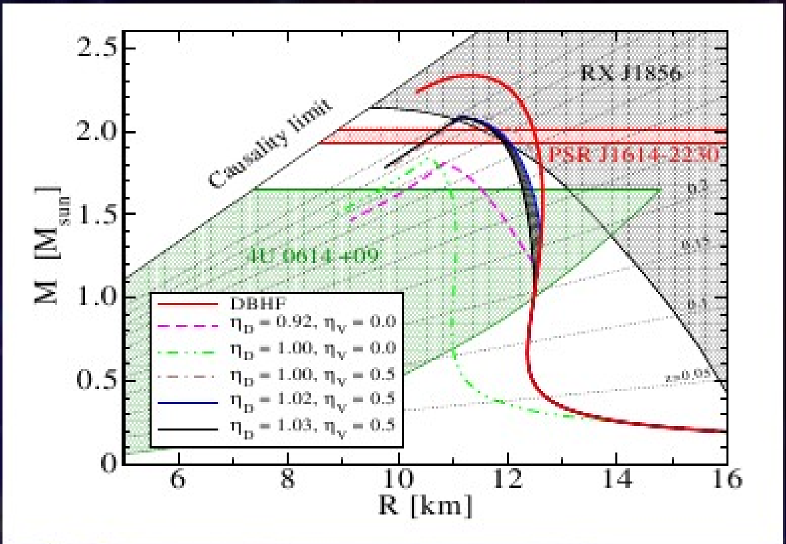
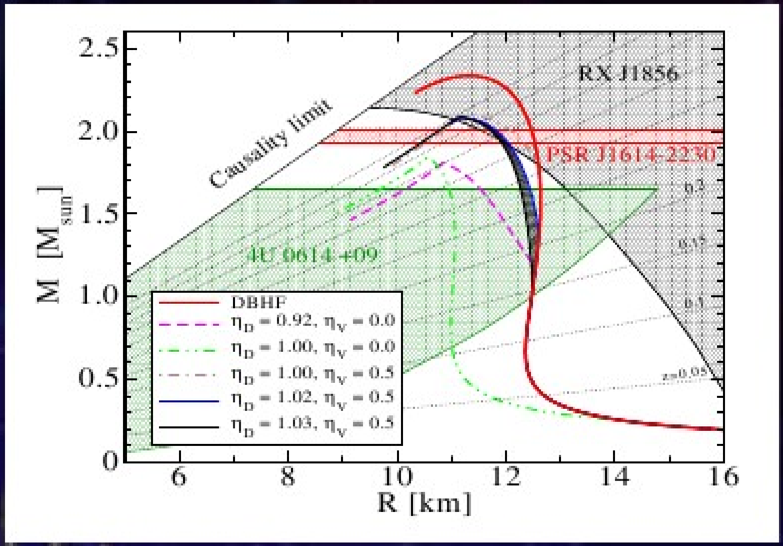


CompStar, in preparation (2010)

State-of-the-art hybrid EoS model:

- Chiral symmetry restoration
- Color superconductivity
- Vector meanfield “stiffening”

PSR J1614-2230 - A new constraint for the Compact Star EoS



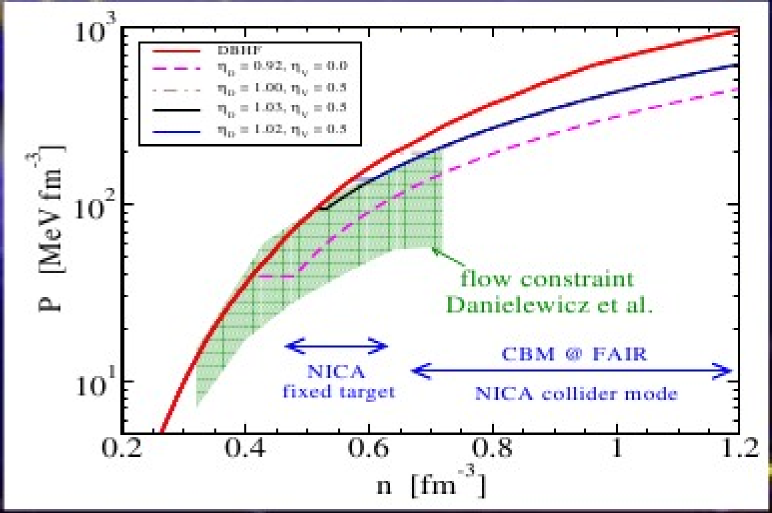
State-of-the-art hybrid EoS model:

- Chiral symmetry restoration
- Color superconductivity
- Vector meanfield “stiffening”

Constraints from heavy-ion collisions:

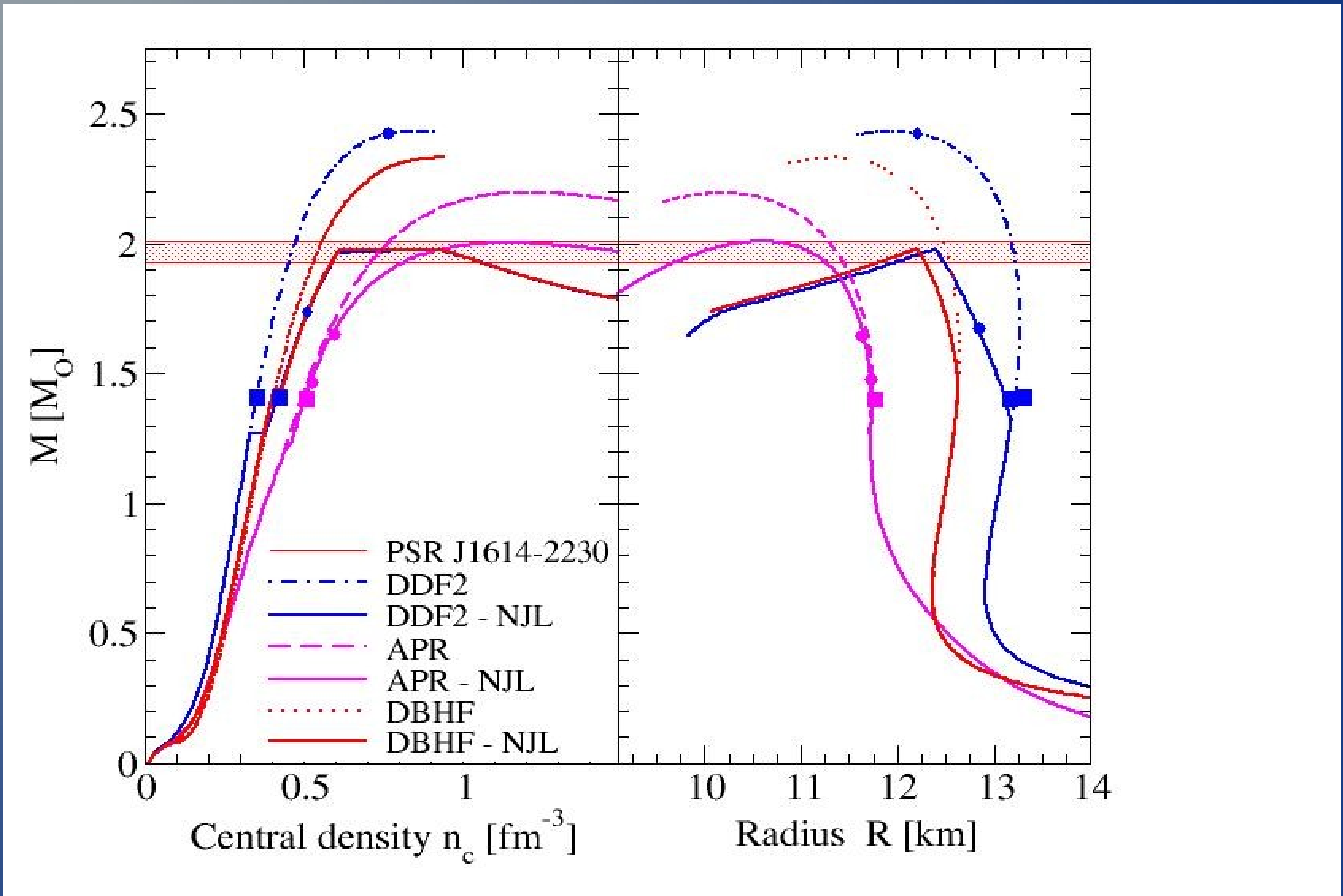
- Flow constraint at high densities
- Not too early onset of quark matter

⟹ **QCD phase diagram**

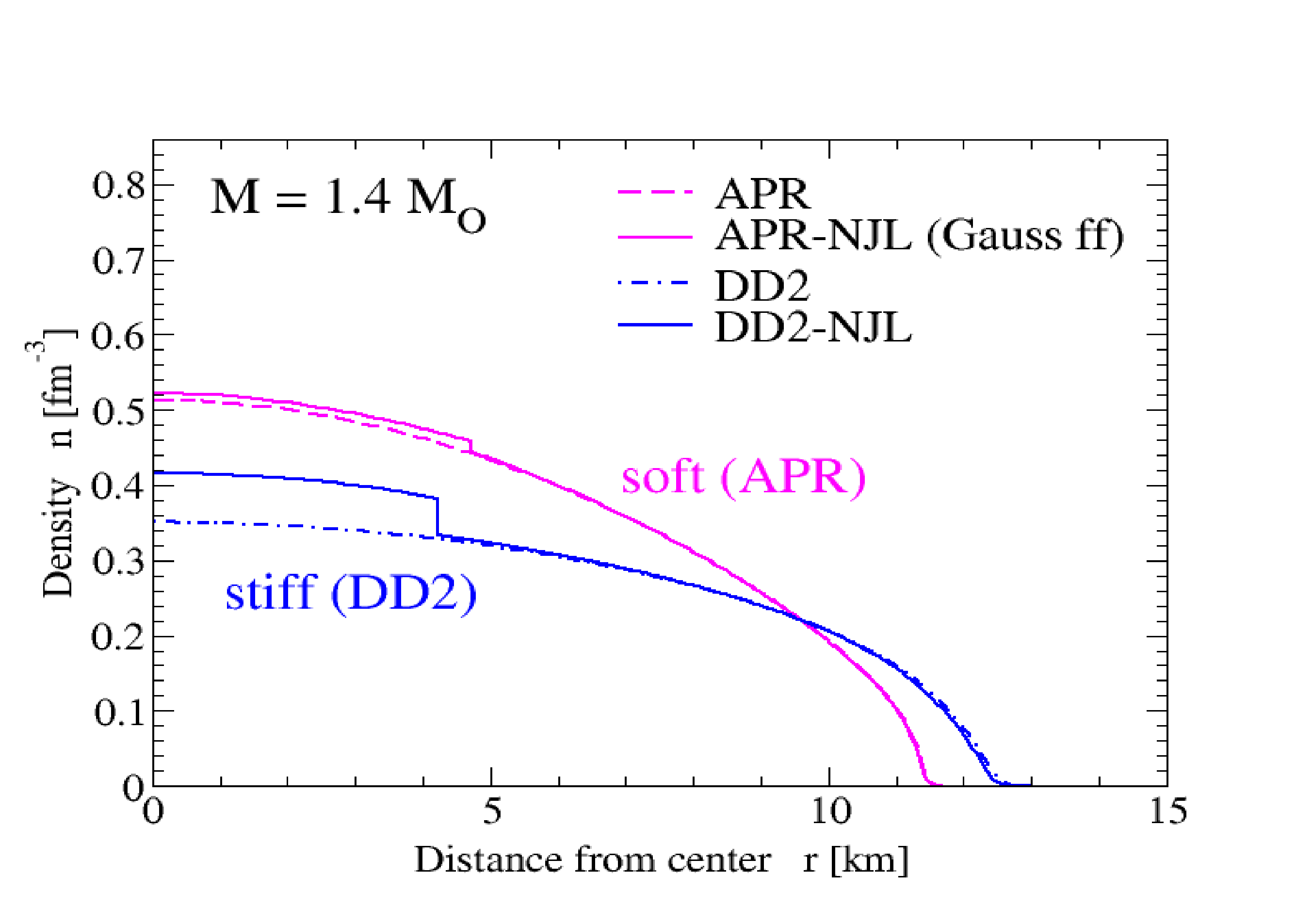


Klähn et al., PLB (2007), arxiv:1101.6061

Hybrid star configuration sequences



Hybrid star structure



Larger Mmax → stiffer EoS → lower central densities, flatter profiles → slower cooling

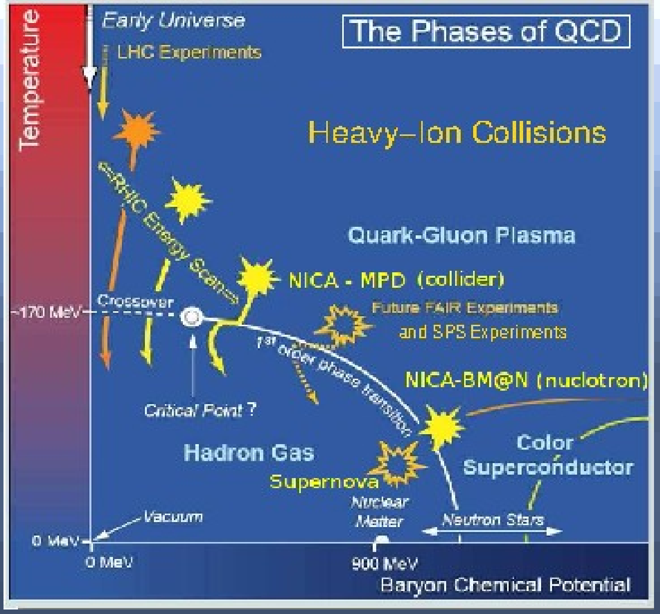
QCD Phase Diagram

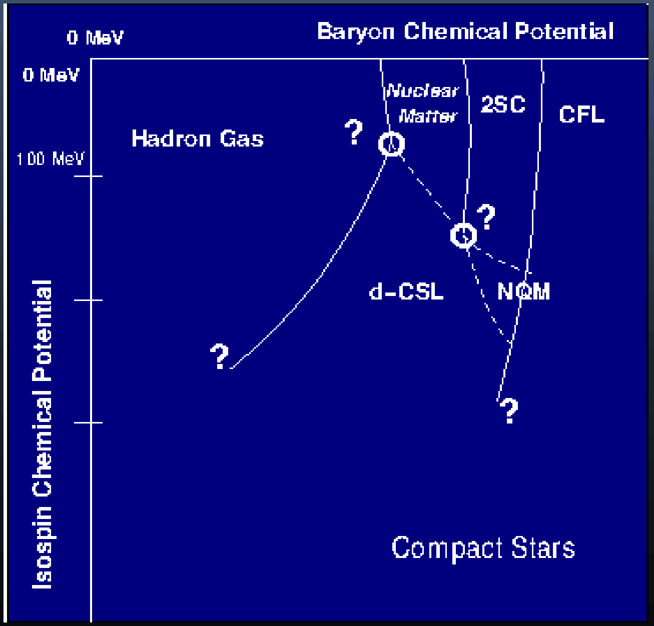
Heavy-Ion Collisions

Chemical freeze-out
(Hadron Resonances)

Flow data (EoS)

Compact Stars





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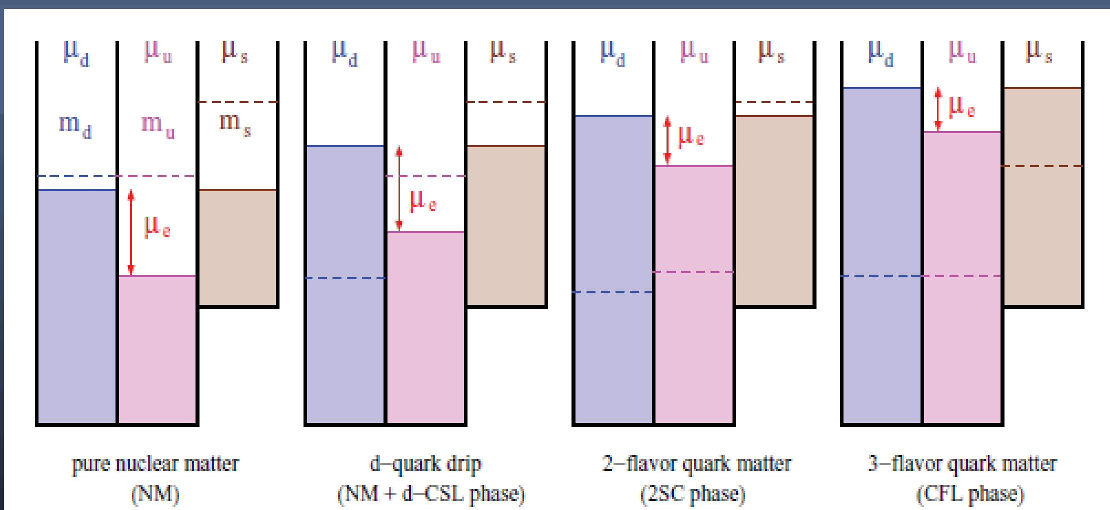
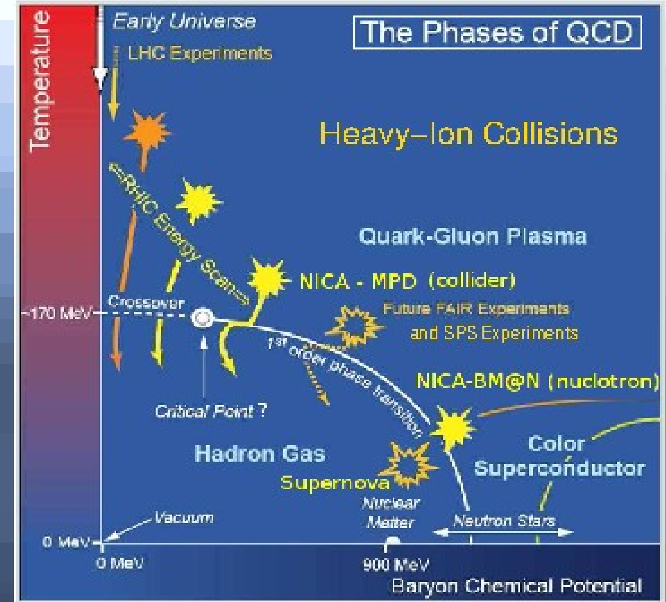
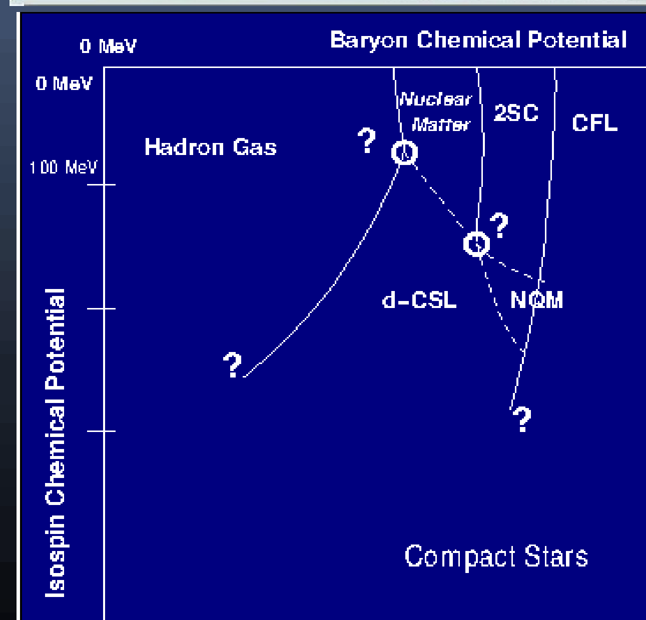


→ increasing baryon density

d-Quark dripline effect (asymmetric matter only!
D.B., Klahn, Sandin, Berdermann, PRC 80 (2009)





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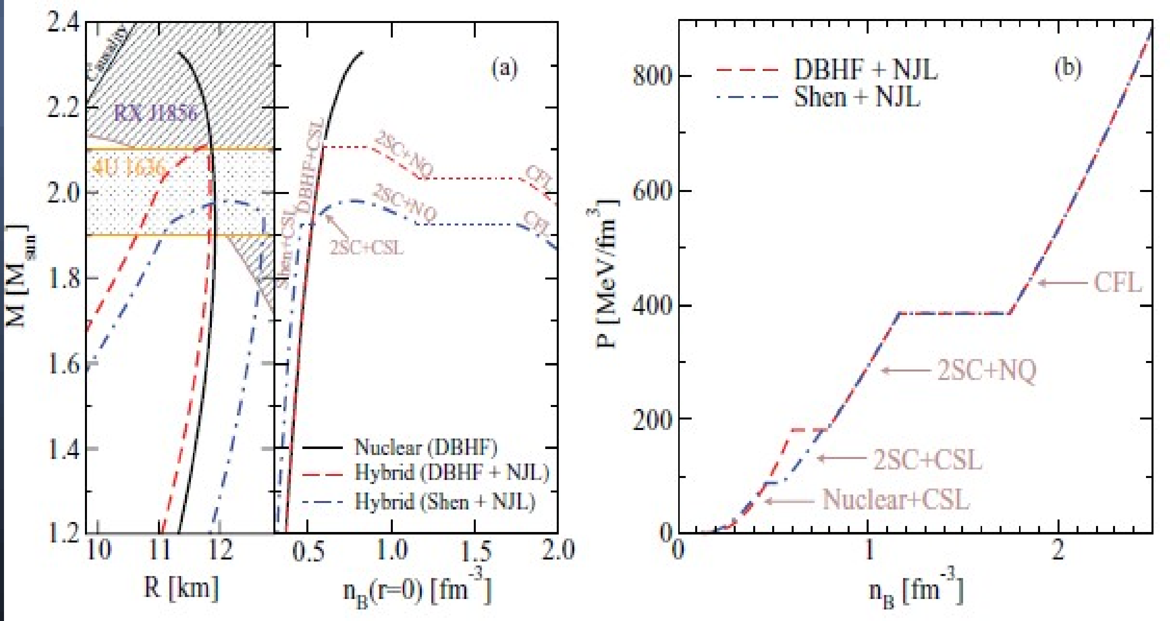

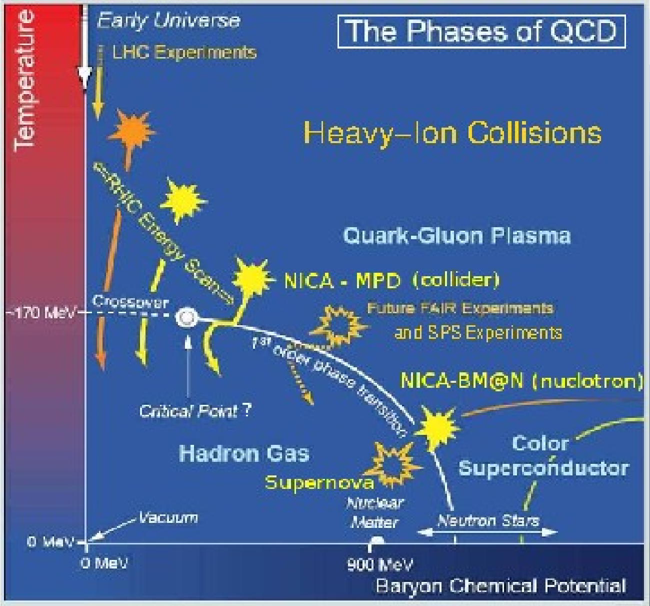

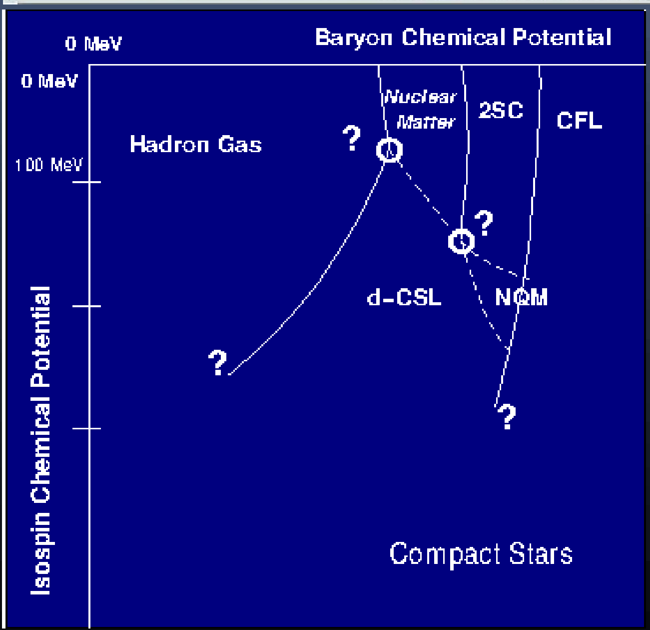

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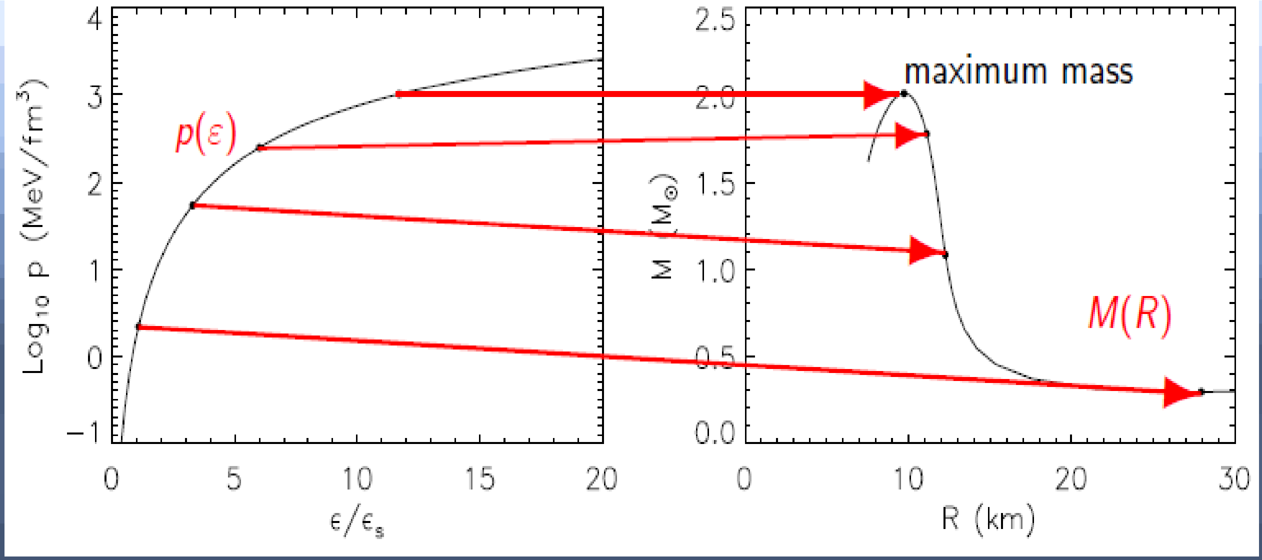

Bayesian TOV inversion [Steiner, Lattimer, Brown (2010)]

Tolman-Oppenheimer-Volkov equations

$$\frac{dp}{dr} = -\frac{G}{c^2}\frac{(m + 4\pi p r^3)(\varepsilon + p)}{r(r - 2Gm/c^2)}$$

$$\frac{dm}{dr} = 4\pi \frac{\varepsilon}{c^2} r^2$$

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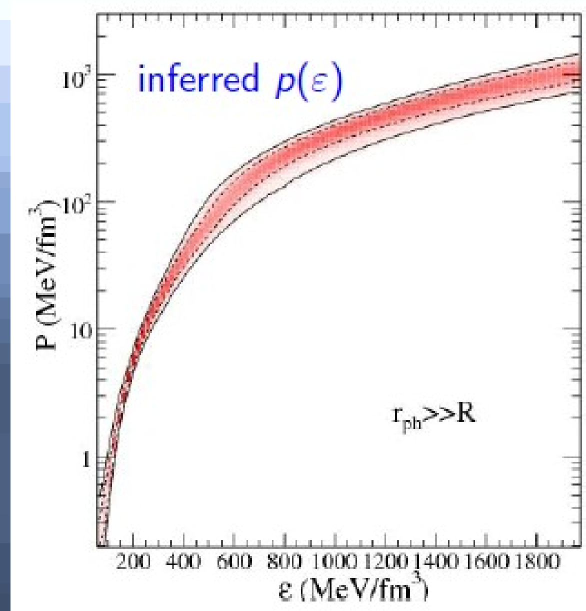
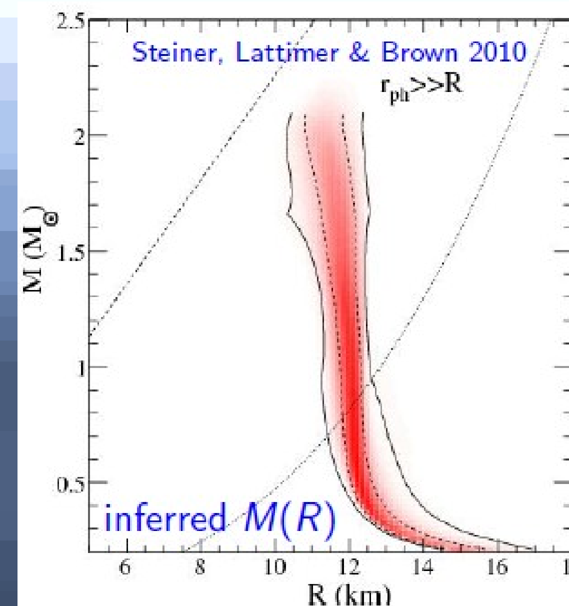
M(R) ↔ P(epsilon)





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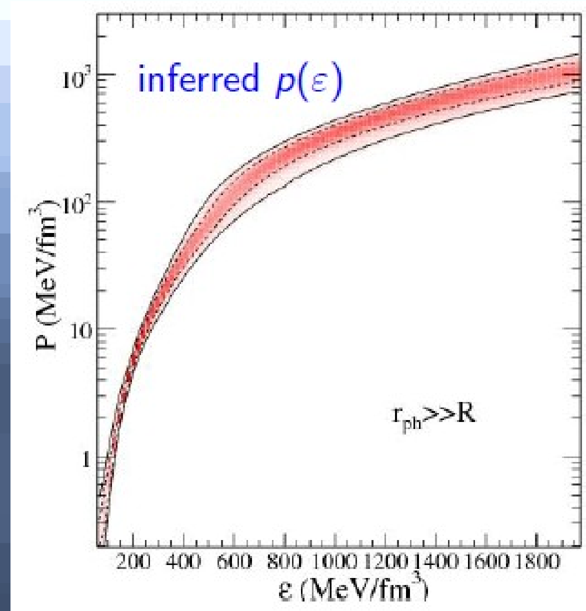

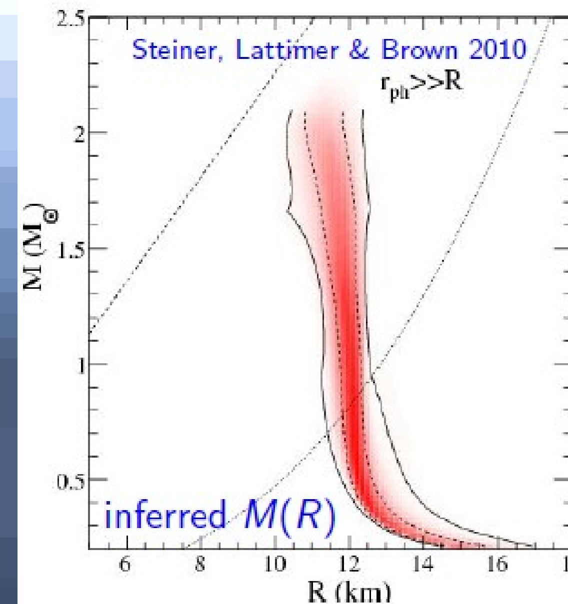

Bayesian TOV inversion [Steiner, Lattimer, Brown (2010)]

- $\varepsilon < 0.5\varepsilon_0$: Known crustal EOS
- $0.5\varepsilon_0 < \varepsilon < \varepsilon_1$: EOS parametrized by K, K', S_v, γ
- $\varepsilon_1 < \varepsilon < \varepsilon_2$: n_1; $\varepsilon > \varepsilon_2$: Polytropic EOS with n_2
- EOS parameters $(K, K', S_v, \gamma, \varepsilon_1, n_1, \varepsilon_2, n_2)$ uniformly distributed
- M and R probability distributions for 8 neutron stars treated equally.

$$\varepsilon = n_B \left\{ m_B + B + \frac{K}{18}(u-1)^2 + \frac{K'}{162}(u-1)^3 + (1-2x)^2[S_k u^{2/3} + S_p u^\gamma] + \frac{3}{4}\hbar c x (3\pi^2 n_b x)^{1/3} \right\}$$

QCD Phase Diagram

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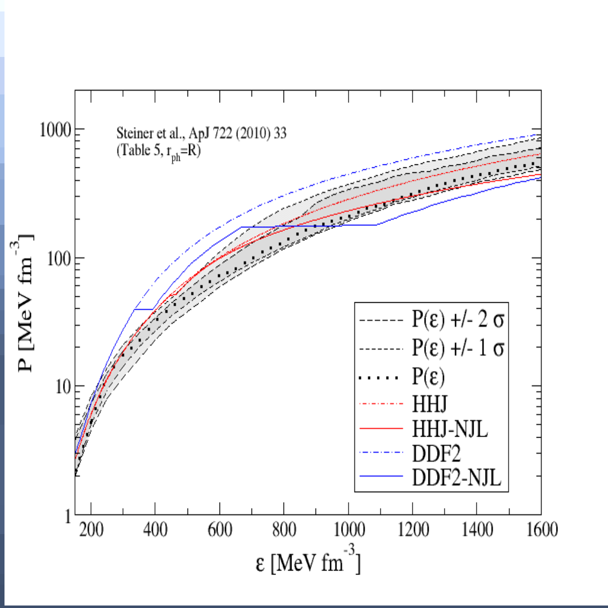

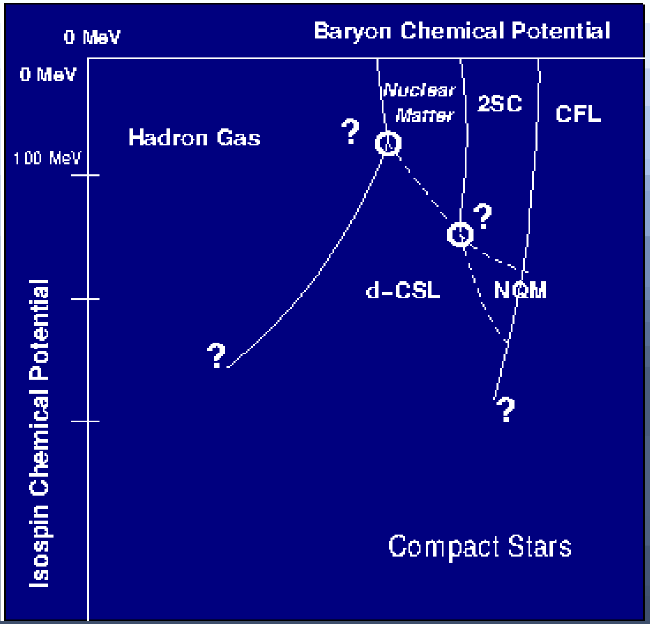

Comparison with recent hadronic and hybrid EoS:

- Analysis depends on the template for P(epsilon)
- Systematic investigations of EoS classes possible
- Much more and sufficiently precise data needed!

QCD Phase Diagram

Heavy-Ion Collisions

Chemical freeze-out
(Hadron Resonances)

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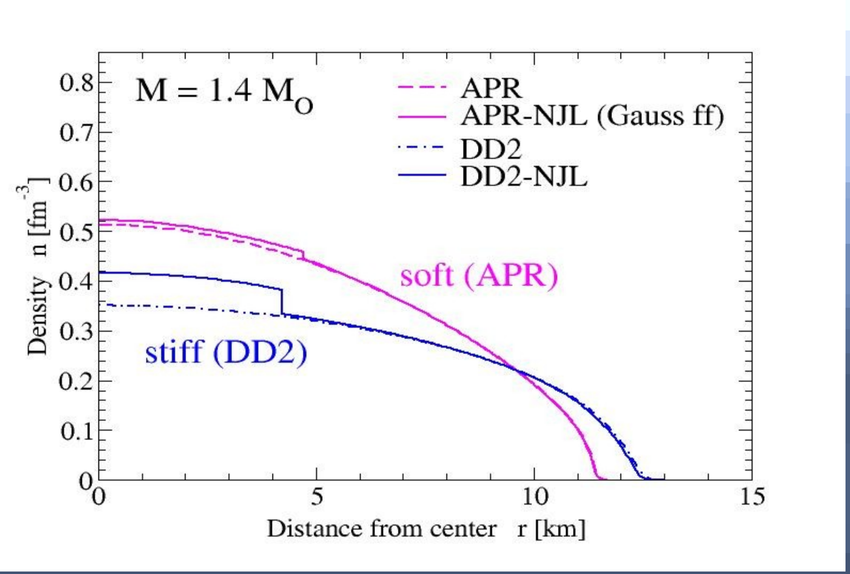
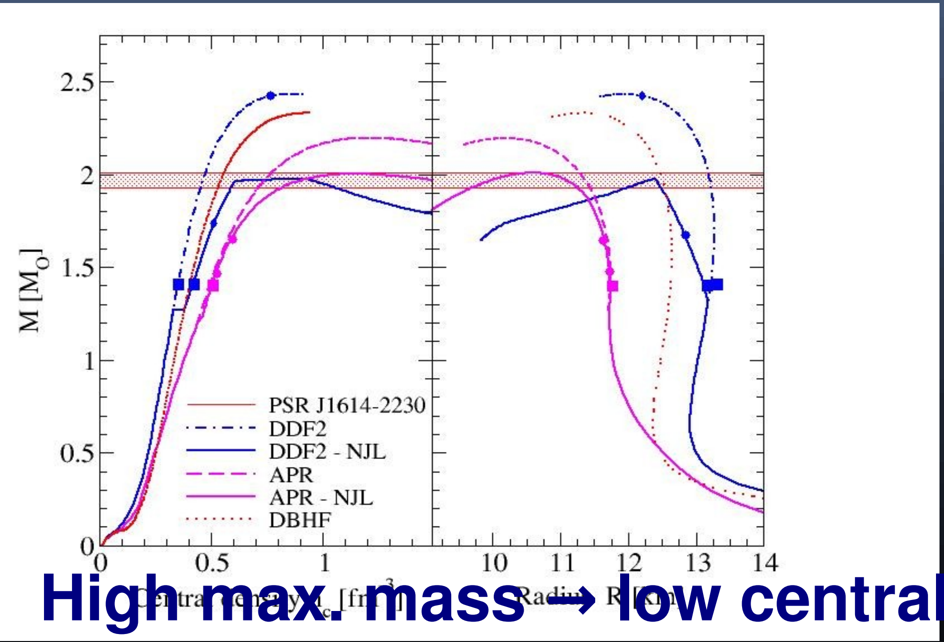
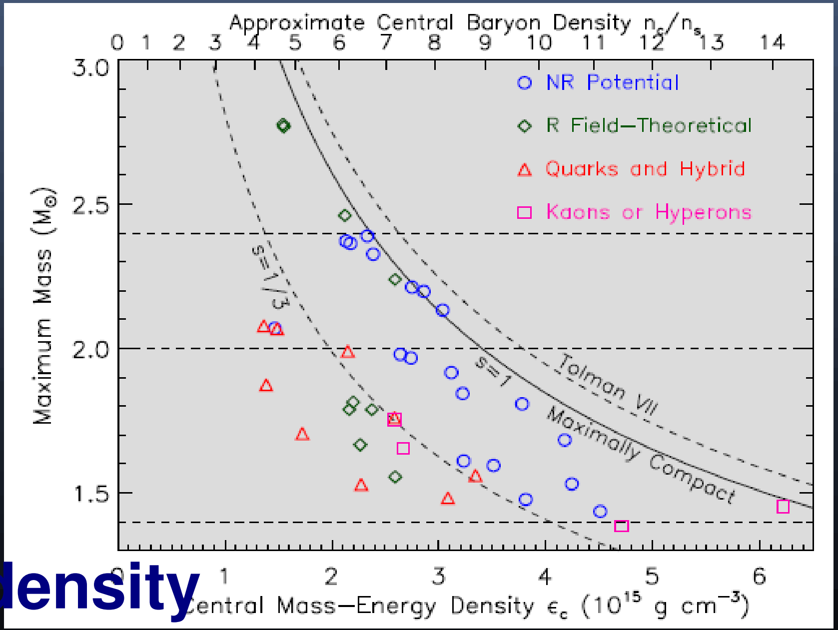
Compact Stars

M(R) ↔ P(epsilon)
PSR J1614-2230

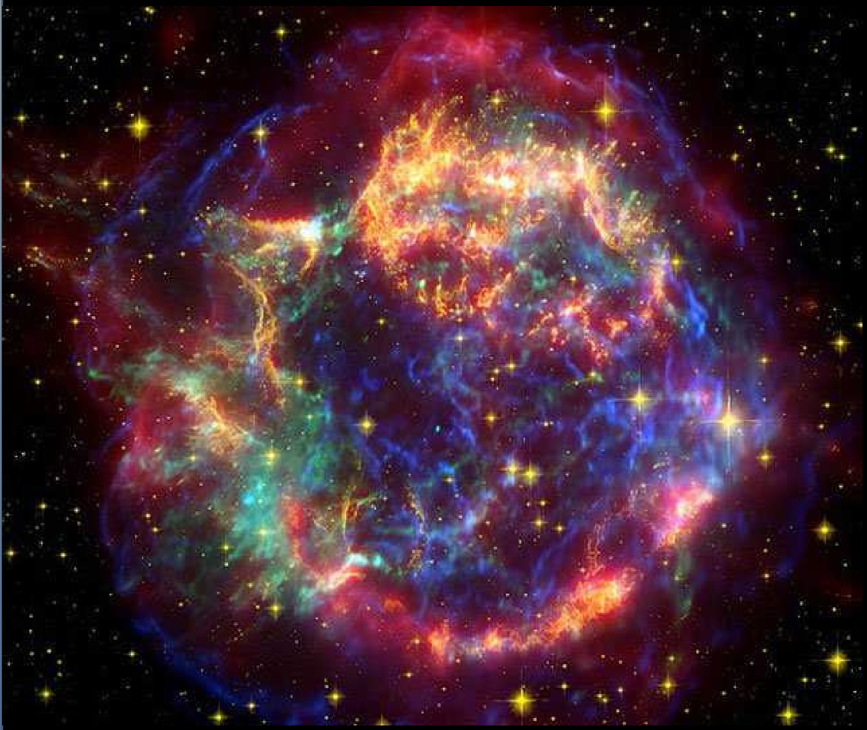






High max. mass → low central density

Neutron Star in Cassiopeia A (Cas A)

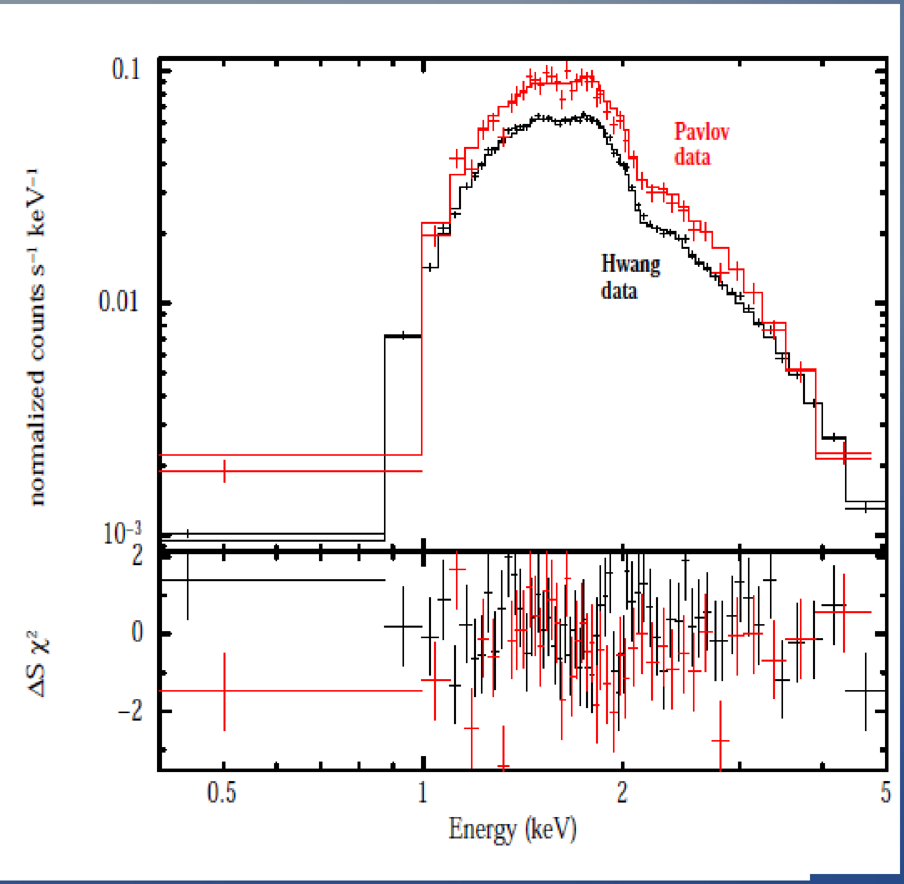


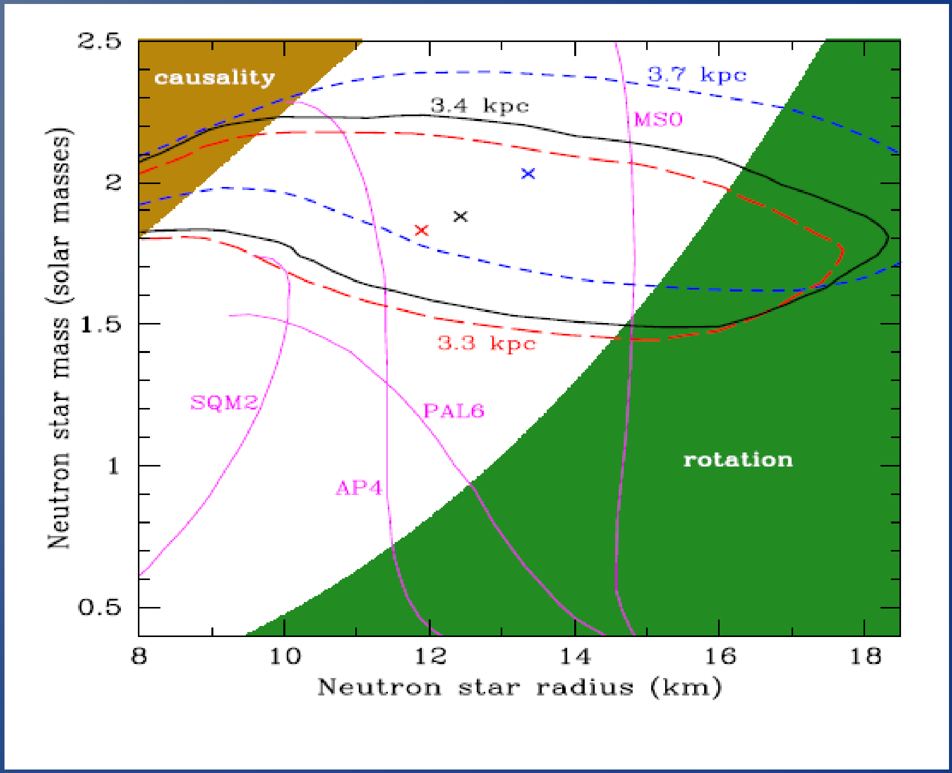
- 16.08.1680 John Flamsteed
- 6m star 3 Cas
- 1947 re-discovery in radio
- 1950 optical counterpart
- T ~ 30 MK
- V exp ~ 4000 – 6000 km/s
- distance 11.000 ly = 3.4 kpc

picture: spitzer space telescope

Cas A Cooling Observations

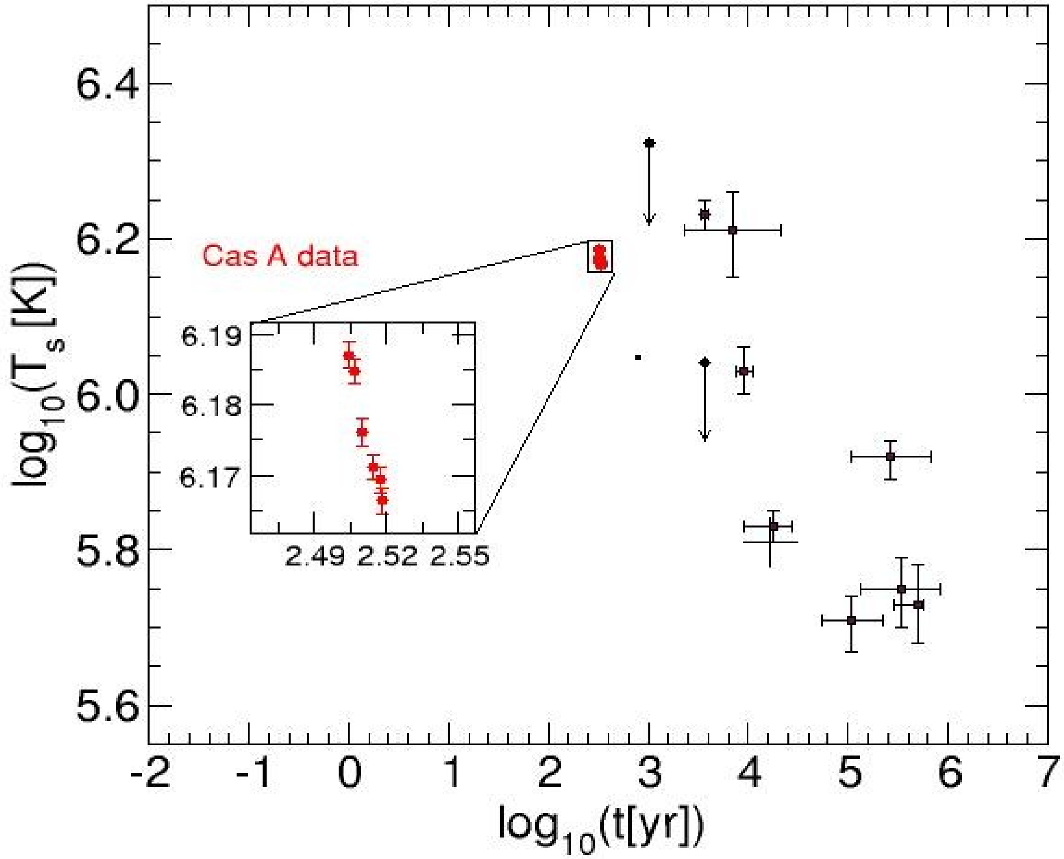
Cas A is a rapidly cooling star – Temperature drop ~4% in 10 years





- **W.C.G. Ho, C.O. Heinke, Nature 462, 71 (2009)**

Cas A Cooling Observations



Cooling Evolution

The energy flux per unit time l(r) through a spherical slice at distance r from the center is:

$$l(r) = -4\pi r^2 k(r) \frac{\partial (T e^{\Phi})}{\partial r} e^{-\Phi} \sqrt{1 - \frac{2M}{r}}.$$

The equations for energy balance and thermal energy transport are:

$$\frac{\partial}{\partial N_B}(l e^{2\Phi}) = -\frac{1}{n}(\epsilon_\nu e^{2\Phi} + c_V \frac{\partial}{\partial t}(T e^{\Phi}))$$

$$\frac{\partial}{\partial N_B}(T e^{\Phi}) = -\frac{1}{k} \frac{l e^{\Phi}}{16\pi^2 r^4 n}$$

where n = n(r) is the baryon number density, NB = NB(r) is the total baryon number in the sphere with radius r

$$\frac{\partial N_B}{\partial r} = 4\pi r^2 n (1 - \frac{2M}{r})^{-1/2}$$

F.Weber: Pulsars as Astro. Labs ... (1999);
D. Blaschke Grigorian, Voskresensky, A& A 368 (2001)561.

Crust Model

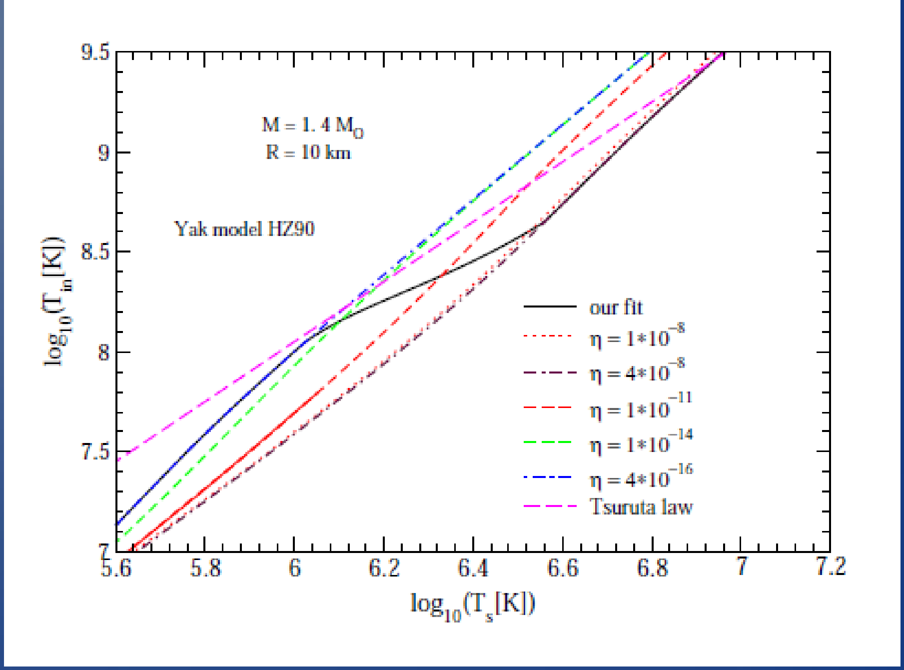
Time dependence of the light element contents in the crust

$$\Delta M_{\rm L}(t) = e^{-t/\tau}\,\Delta M_{\rm L}(0)$$

Page,Lattimer,Prakash & Steiner, Astrophys. J. 155, 623 (2004)

Yakovlev, Levenfish, Potekhin, Gnedin & Chabrier , Astron. Astrophys , 417, 169 (2004)

Blaschke, Grigorian, Voskresensky, A& A 424 (2004) 979

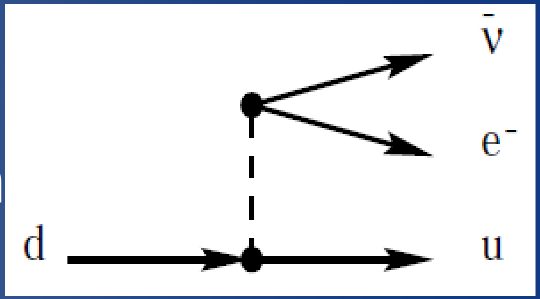


Neutrino Emissivities in Quark Matter

Quark direct Urca (QDU) the most efficient process

$d \to u + e + \bar{\nu}$ and $u + e \to d + \nu$

$$\epsilon_\nu^{\rm QDU} \simeq 9.4 \times 10^{26} \alpha_s u Y_e^{1/3} \zeta_{\rm QDU}\, T_9^6 \ {\rm erg\ cm^{-3}\ s^{-1}},$$

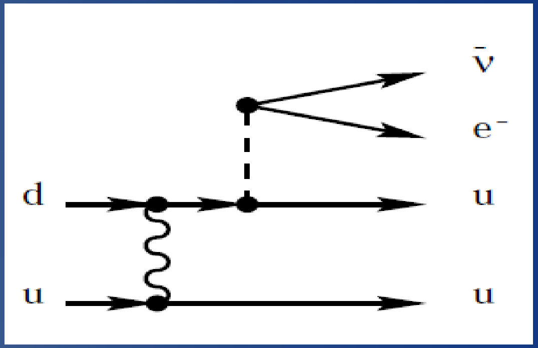


Compression n/n0 ≃ 2, strong couplin

Quark Modified Urca (QMU) and
Quark Bremsstrahlung

$d + q \to u + q + e + \bar{\nu}$ and $q_1 + q_2 \to q_1 + q_2 + \nu + \bar{\nu}$

$$\epsilon_\nu^{\rm QMU} \sim \epsilon_\nu^{\rm QB} \simeq 9.0 \times 10^{19} \zeta_{\rm QMU}\, T_9^8 \ {\rm erg\ cm^{-3}\ s^{-1}}.$$



Suppression due to the pairing

QDU : $\zeta_{\rm QDU} \sim \exp(-\Delta_q/T)$

QMU and **QB** : $\zeta_{\rm QMU} \sim \exp(-2\Delta_q/T)$ for $T < T_{{\rm crit},q} \simeq 0.57\, \Delta_q$

Enhanced cooling due to the pairing: Quark PBF

- $e + e \to e + e + \nu + \bar{\nu}$ (becomes important for $\Delta_q/T >> 1$)

$$\epsilon_\nu^{ee} = 2.8 \times 10^{12} Y_e^{1/3} u^{1/3} T_9^8 \ {\rm erg\ cm^{-3}\ s^{-1}},$$

Quark PBF

SC pairing gaps – hybrid stars

2SC phase: 1 color (blue) is unpaired (mixed superconductivity)

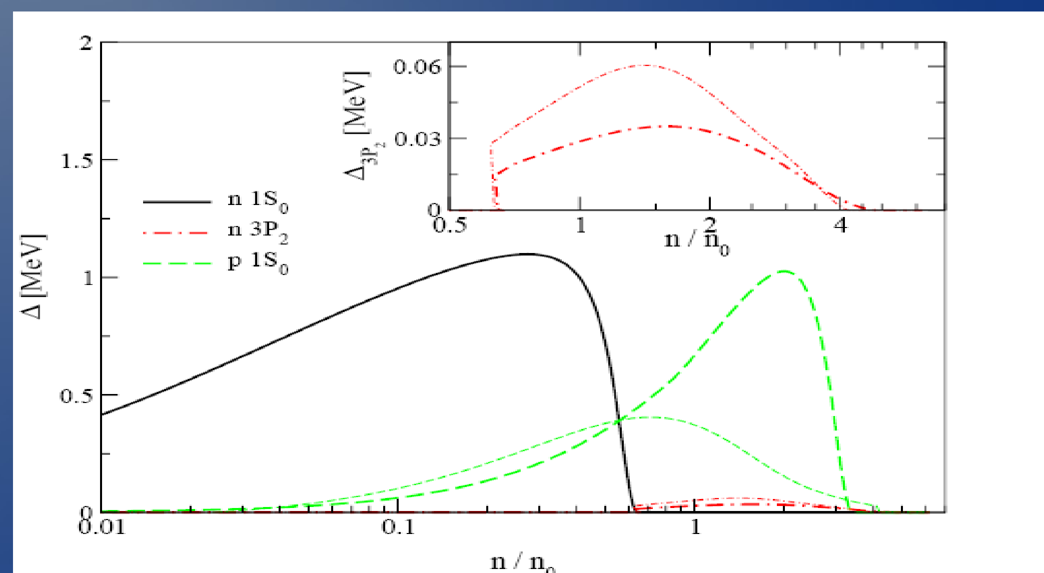
Ansatz 2SC + X phase:

$$\Delta_0^X = \Delta_0 \exp -\alpha \left(\frac{\mu - \mu_c}{\mu_c} \right)$$

Model	Δ_0 [MeV]	α	BC	T – t	Log N – Log S	$M_{typ} \leq 1.5\, M_\odot$	All tests
I	1	10	+	+	○	-	-
II	0.1	0	+	-	+	-	-
III	0.1	2	+	○	+	-	-
IV	5	25	+	+	+	+	+

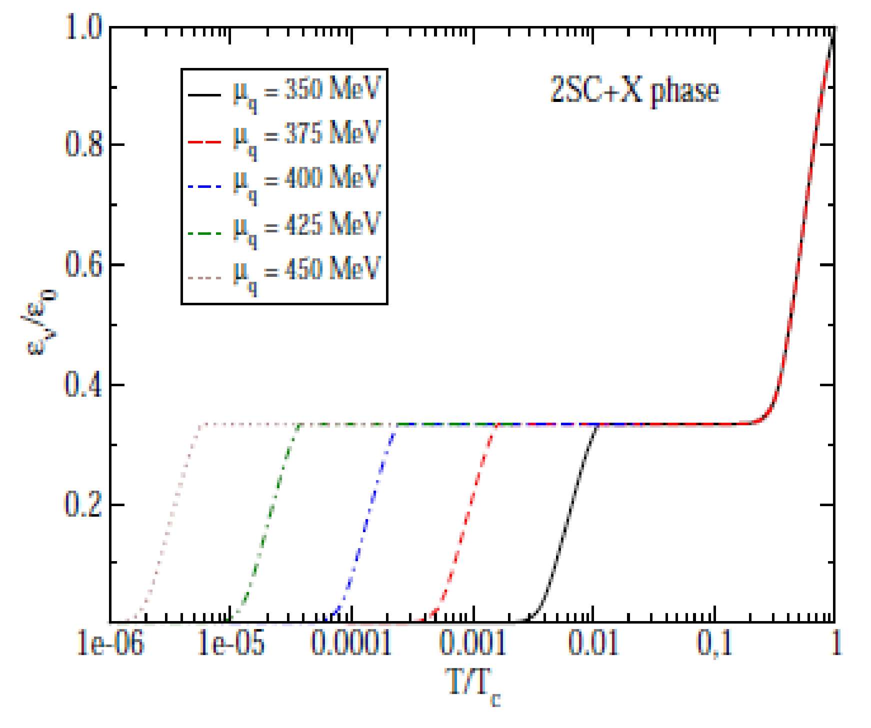
Grigorian, DB, Voskresensky , PRC 71 (2005) 045801

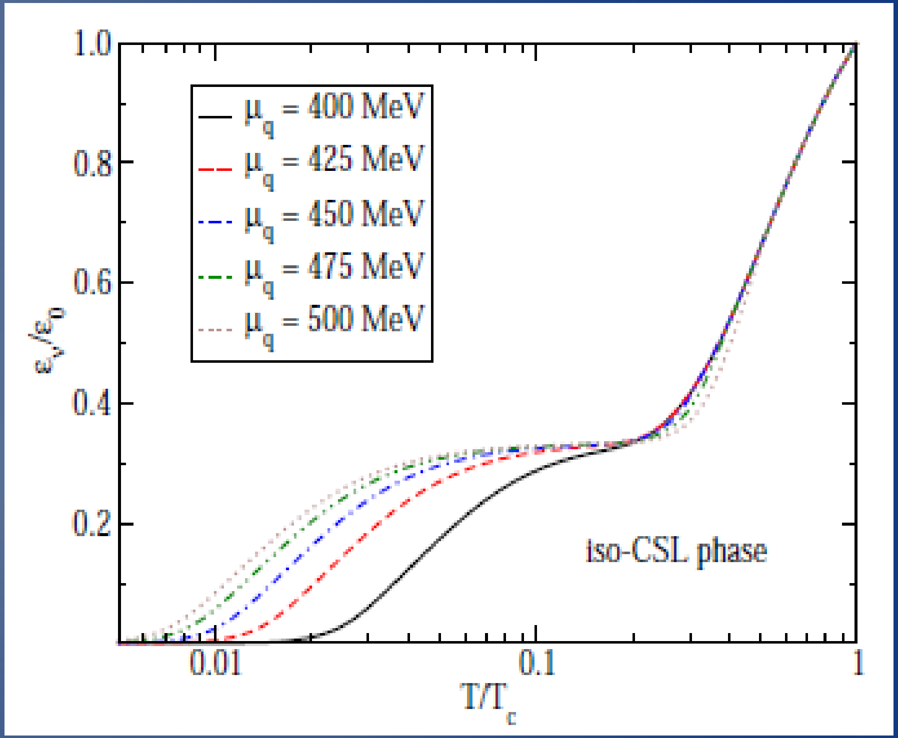
Pairing gaps for hadronic phase
(AV18 - Takatsuka et al. (2004)
Yakovlev et al. (1999))



Blaschke, Grigorian, Voskresensky , A&A 424 (2004) 979

SC pairing gaps – consistent picture?



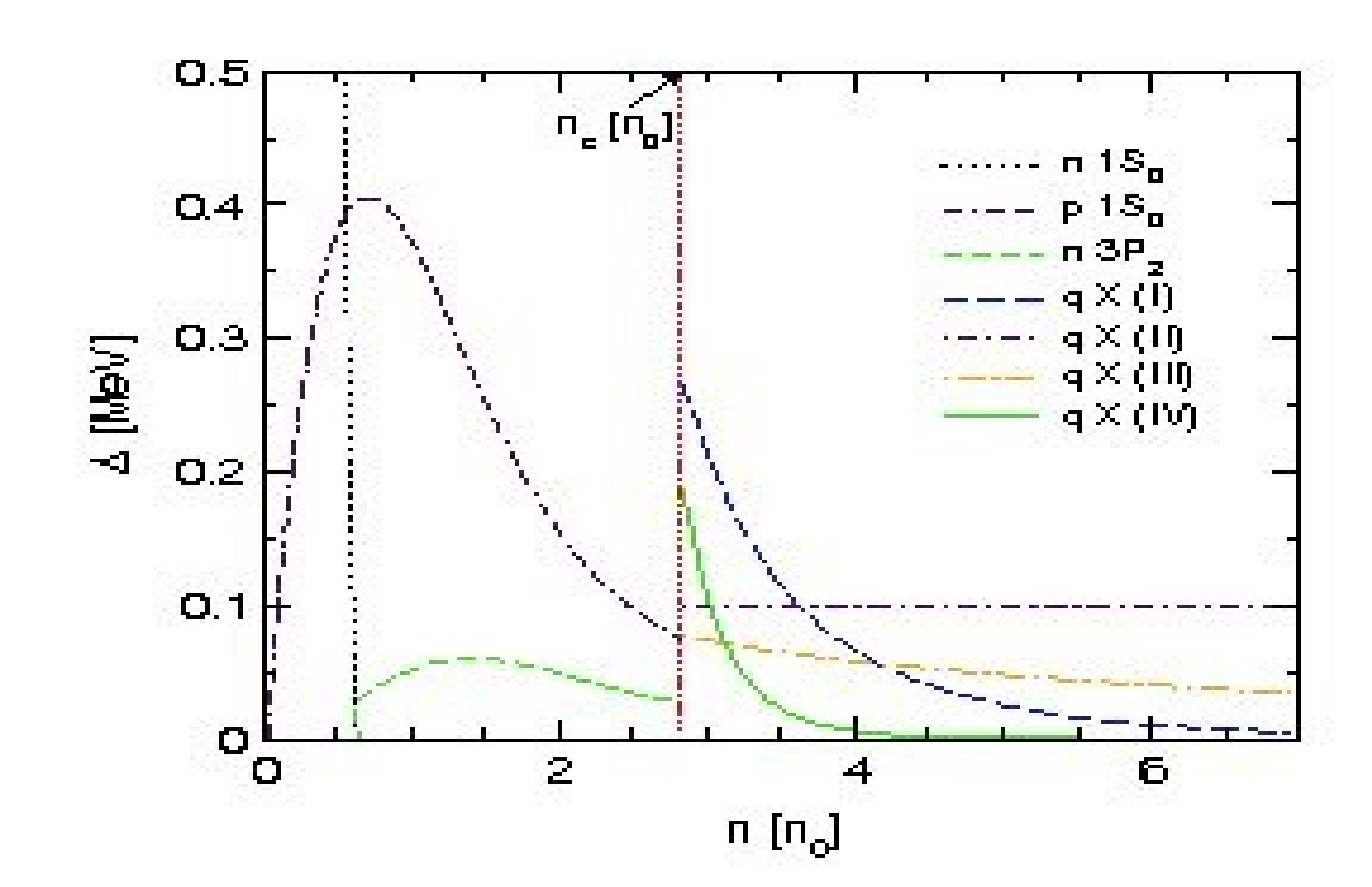


2SC + X phase (blue quarks)

Isotropic CSL phase for d-quarks

D.B., J. Berdermann, AIP Conf.Proc. 964 (2007) 290

SC pairing gaps – hybrid stars

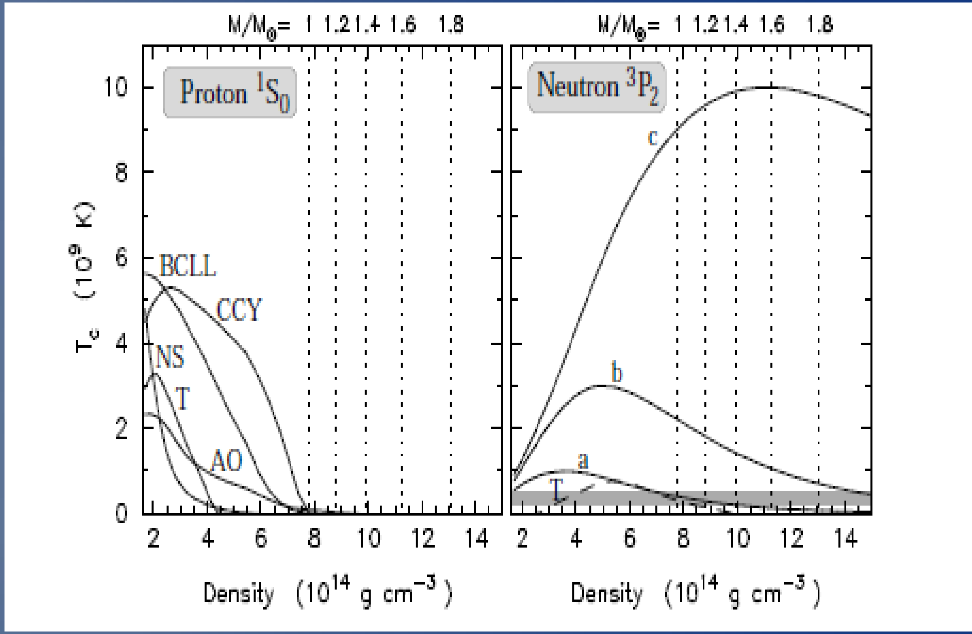


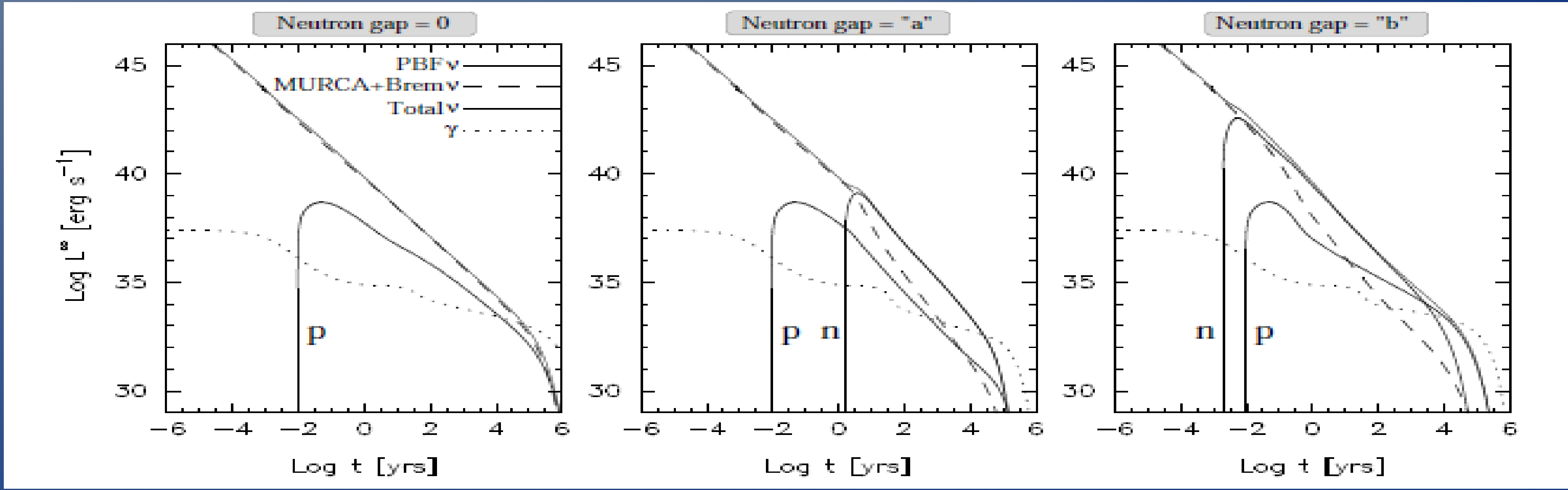
Popov, Grigorian, Blaschke, PRC 74 (2006)

Influence of SC on luminosity

Critical temperature T_c, for the proton $^1S_0$ and neutron $^3P_2$ gaps, used in

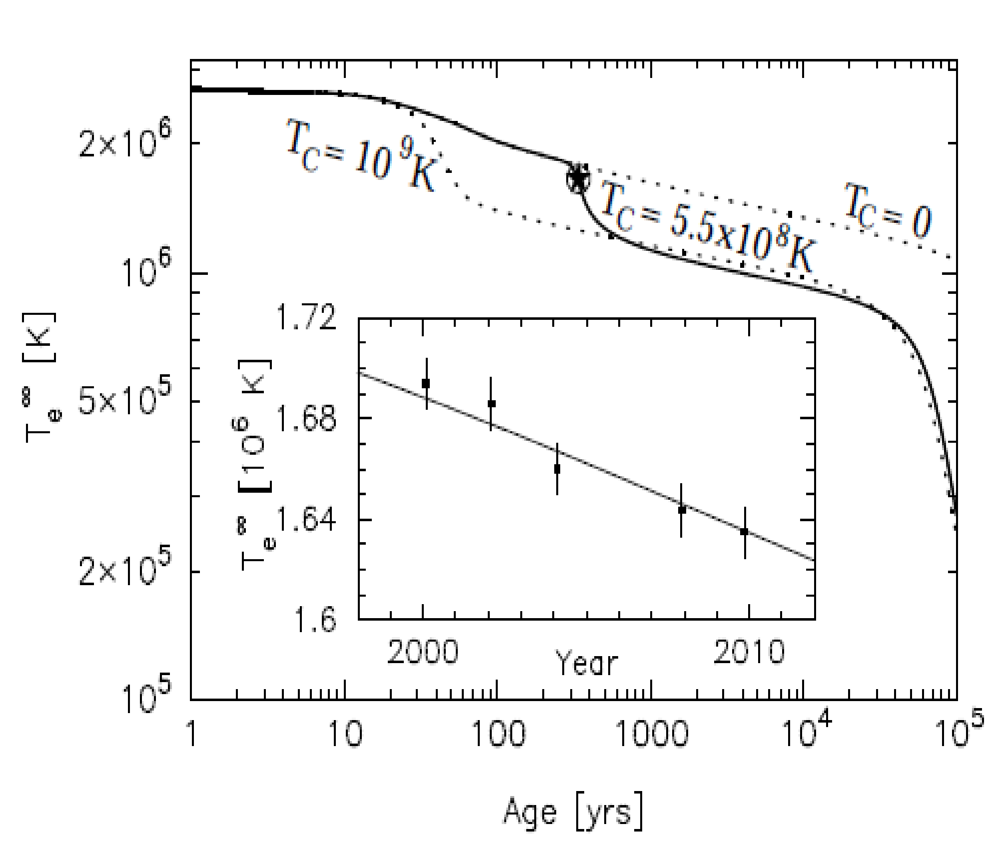
Page, Lattimer, Prakash & Steiner,
Astrophys. J. 707 (2009) 1131

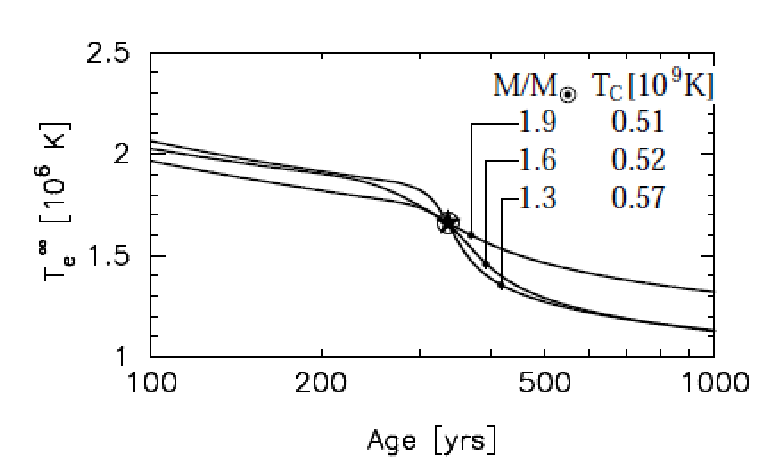




T_c ‘measurement’ from Cas A

- 1.4 M⊙ star built from the APR EoS
- Rapid cooling at ages ~30-100 yrs due to the thermal relaxation of the crust
- Mass dependence





Page, Lattimer, Prakash & Steiner,
Phys. Rev. Lett. 106 (2011) 081101

Medium effects in cooling of neutron stars

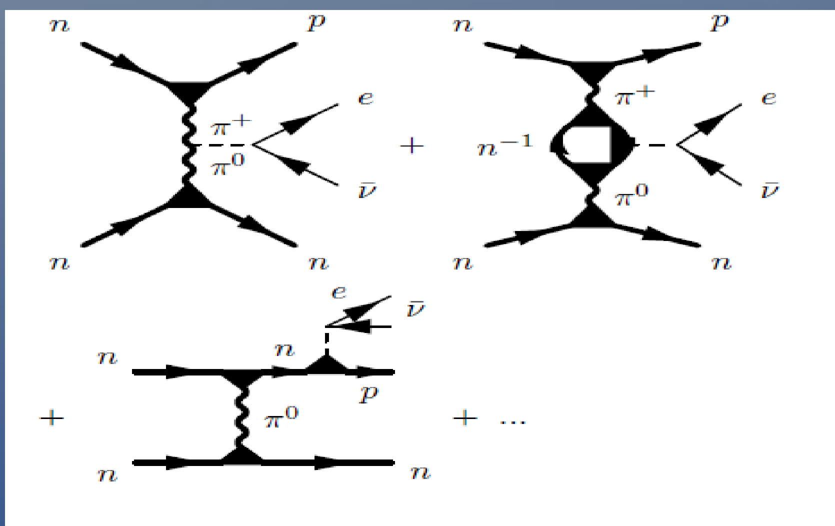
Based on Fermi liquid theory: Landau (1956), Migdal (1967), Migdal et al. (1990):

MMU – medium-modified modified Urca process

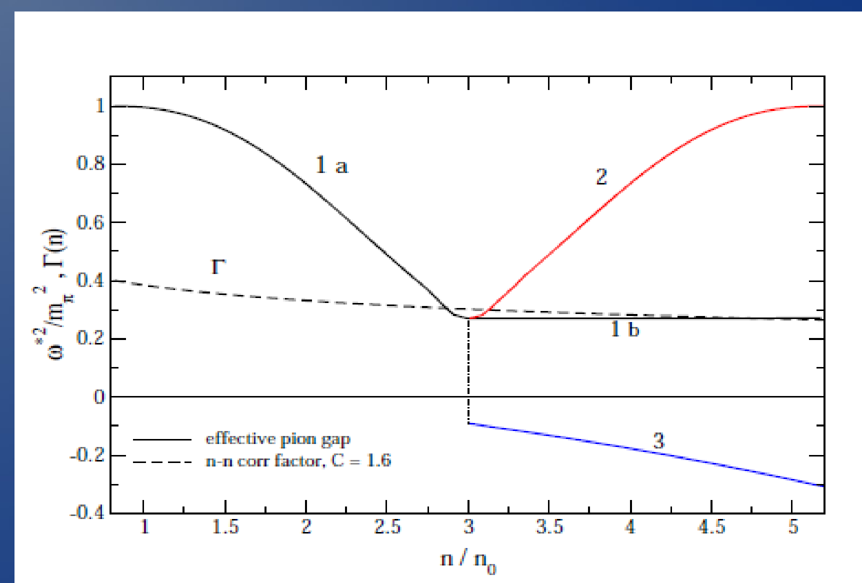
Main regulator in Minimal Cooling:

PBF – pair breaking/formation

$$\varepsilon_\nu[\mathrm{MpPBF}] \sim 10^{29}\,\frac{m_N^*}{m_N}\left[\frac{p_{Fp}}{p_{Fn}(n_0)}\right]\left[\frac{\Delta_{pp}}{\mathrm{MeV}}\right]^7 \times \left[\frac{T}{\Delta_{pp}}\right]^{1/2}\xi_{pp}^2\ \frac{\mathrm{erg}}{\mathrm{cm^3\ sec}}\,,\quad T < T_{cp}.$$

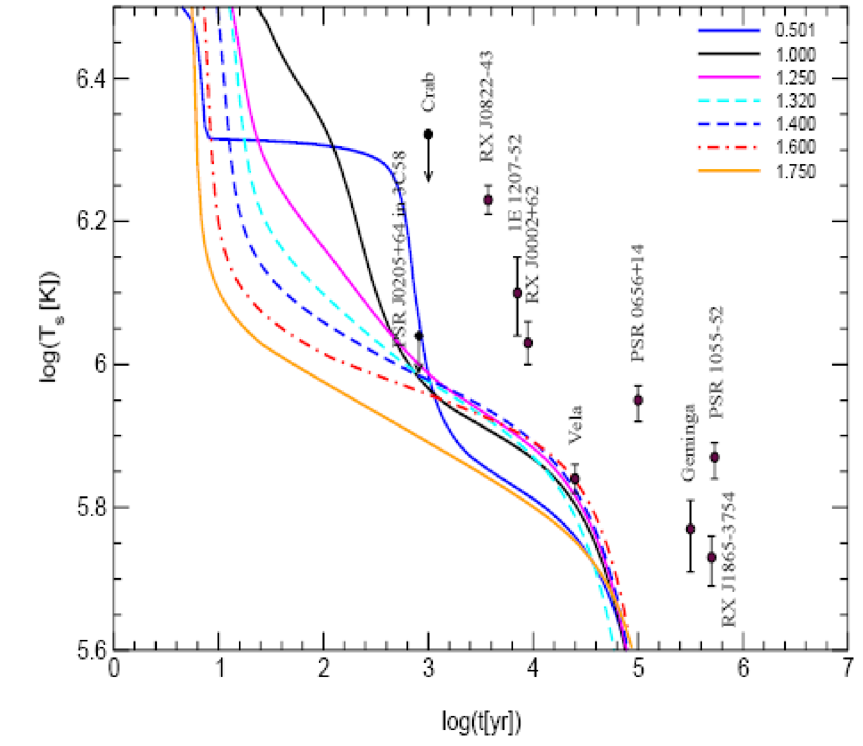


$$\frac{\epsilon_\nu[\mathrm{MMU}]}{\epsilon_\nu[\mathrm{MU}]} \sim 3\left(\frac{n}{n_0}\right)^{10/3}\frac{[\Gamma(n)/\Gamma(n_0)]^6}{[\omega^*(n)/m_\pi]^8}$$

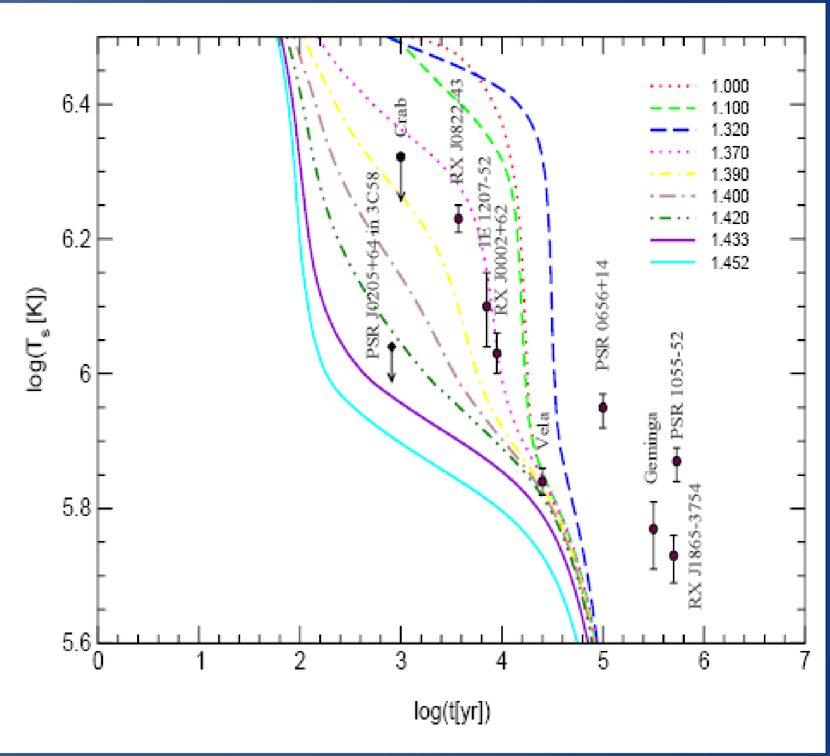


Anomalies because of PBF proccess

AV18 gaps, pion condensate, without suppression of 3P2 neutron pairing - Enhanced PBF process



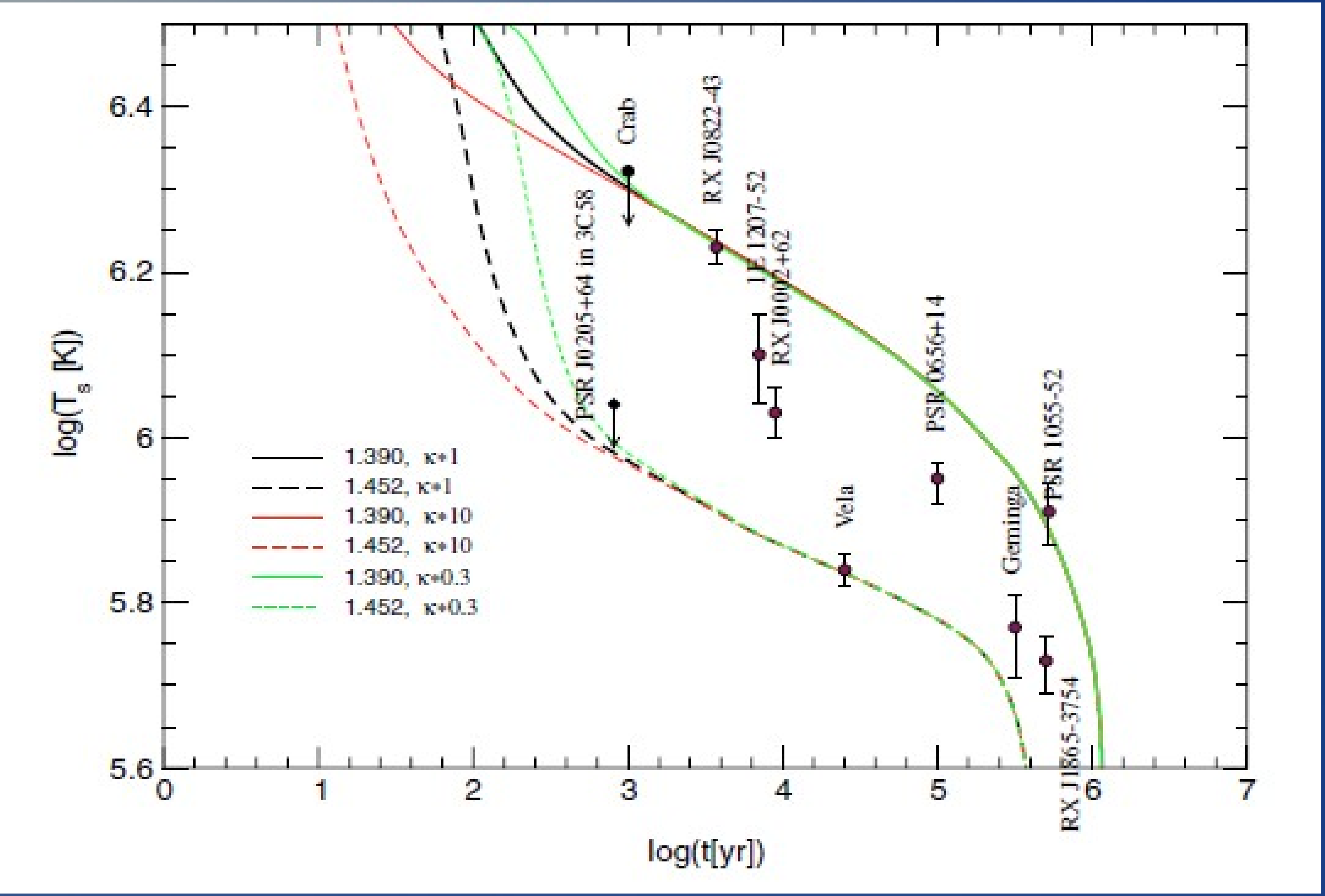
Gaps taken from Yakovlev at al. (2003)



n 3P2 gap **strongly suppressed:** Friman&Schwenk, PRL (2004)

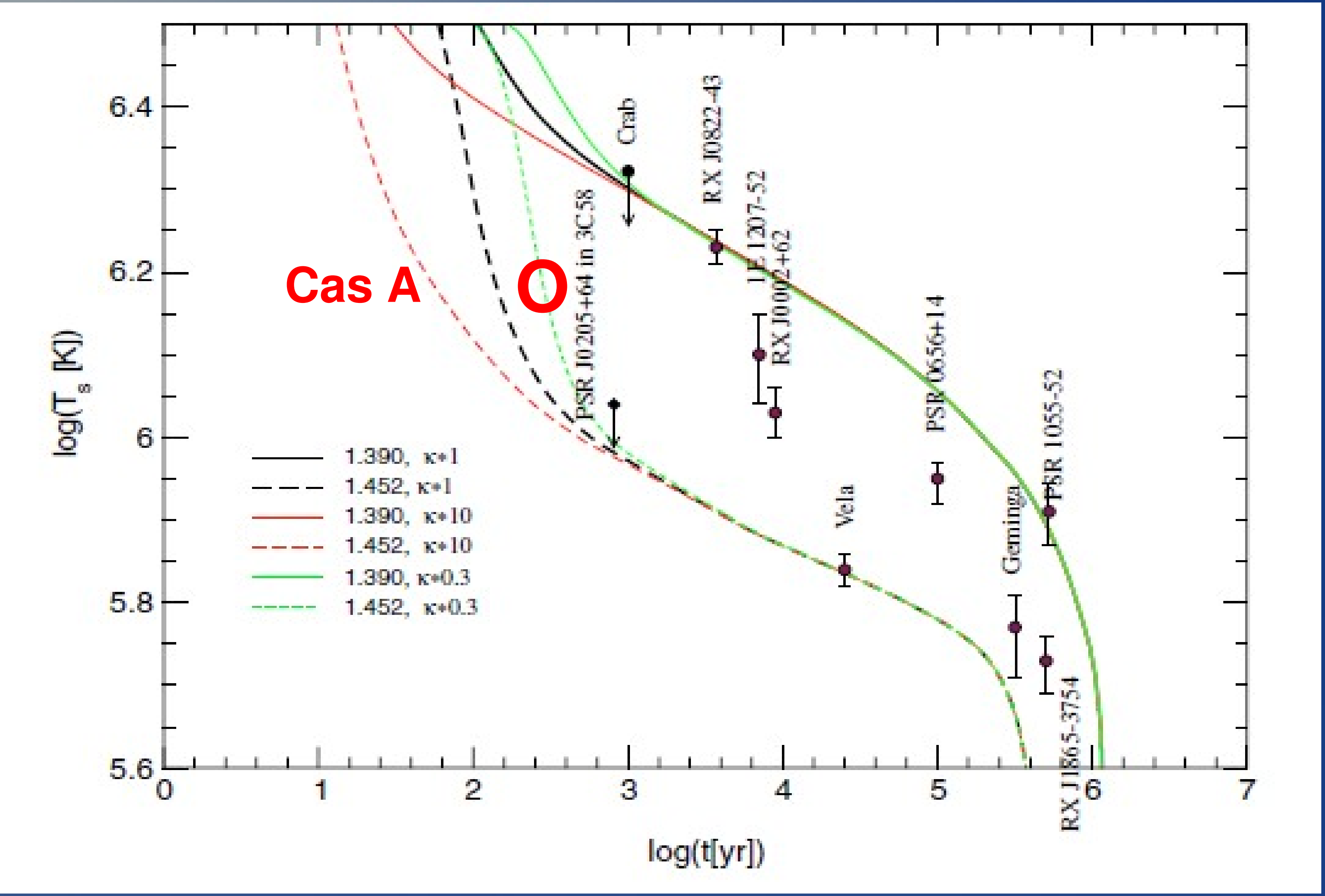
Grigorian, Voskresensky, Astron.Astrophys. 444 (2005)

The influence of the (core) heat conductivity



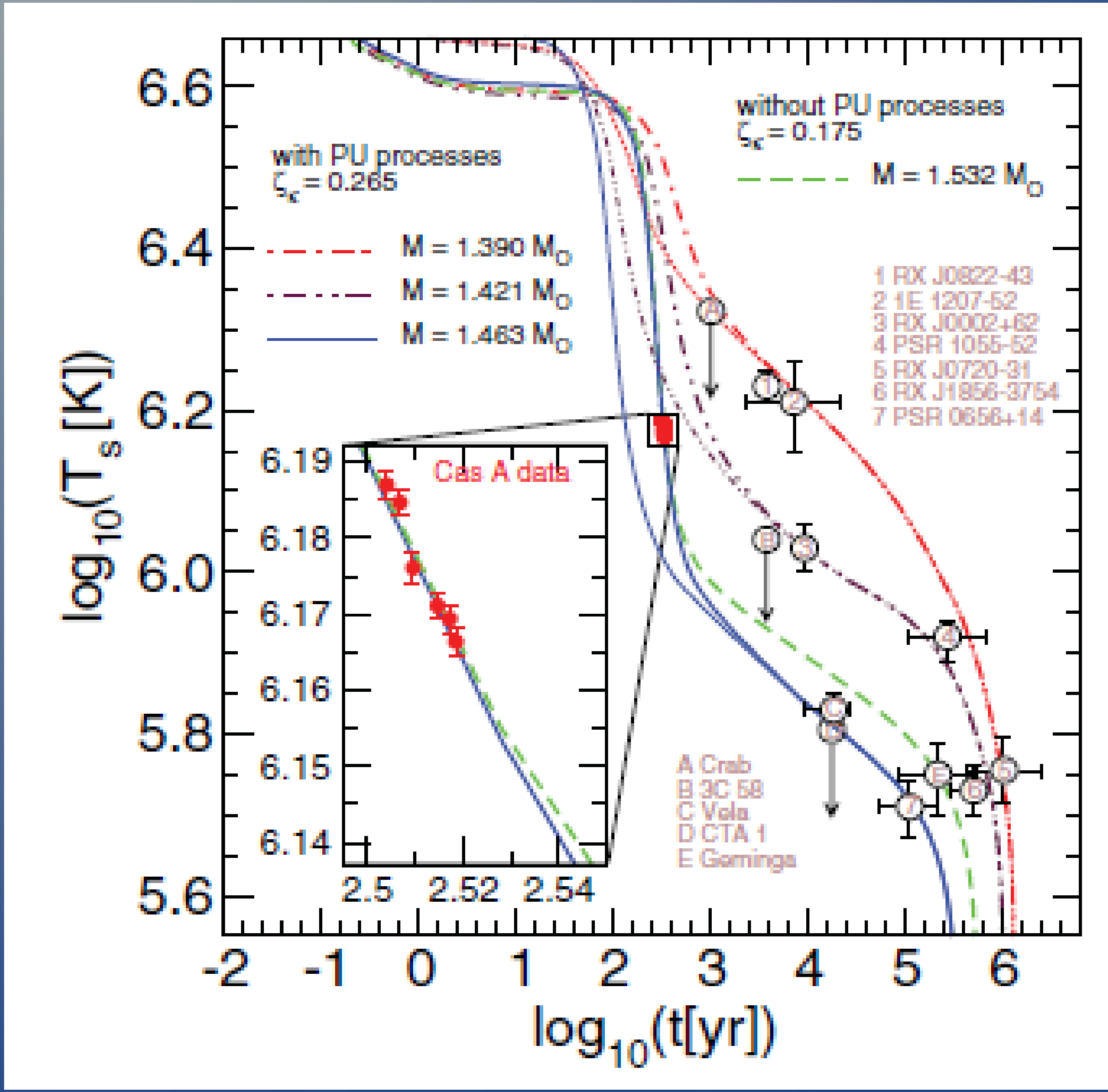
Blaschke, Grigorian, Voskresensky, A&A 424, 979 (2004)

The influence of the (core) heat conductivity



Blaschke, Grigorian, Voskresensky, A&A 424, 979 (2004)

Cas A as a Hadronic Star

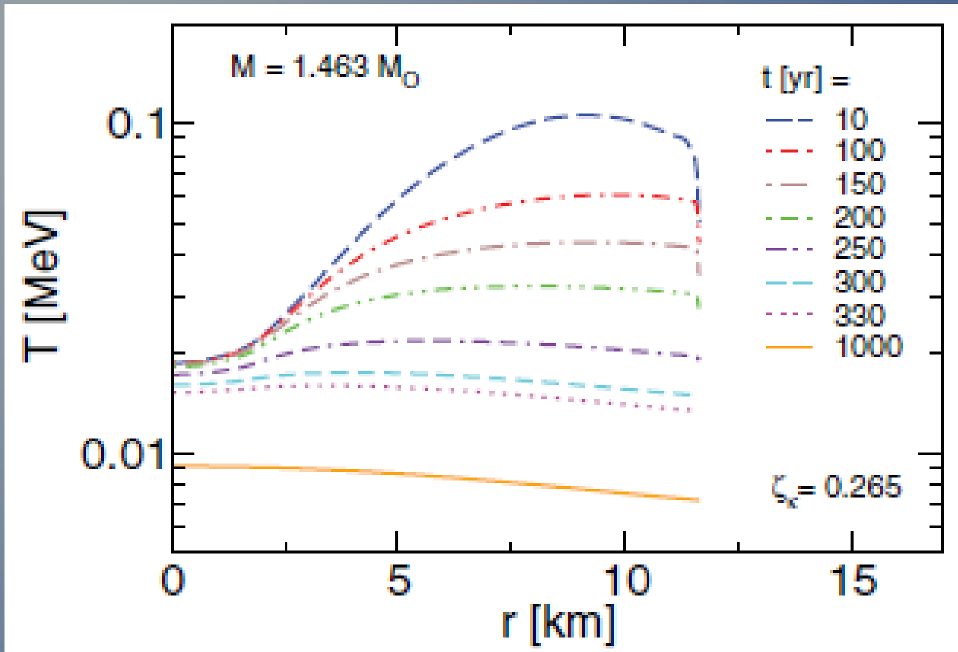


Soft hadronic EoS (APR)

D.B., H. Grigorian, D.N. Voskresensky, F. Weber, PRC 85, 022802 (2012)

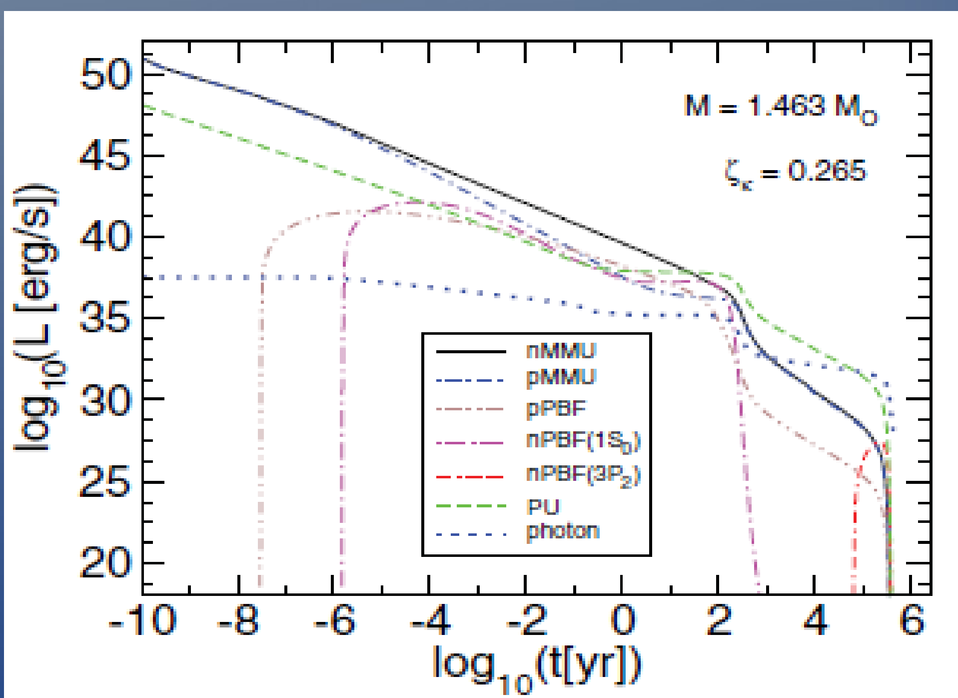
D.B., H. Grigorian, D.N. Voskresensky, A&A 424, 979 (2004)

Cas A as Hadronic Star



T-profile evolution:

Thermal equilibration after
~ 300 yrs

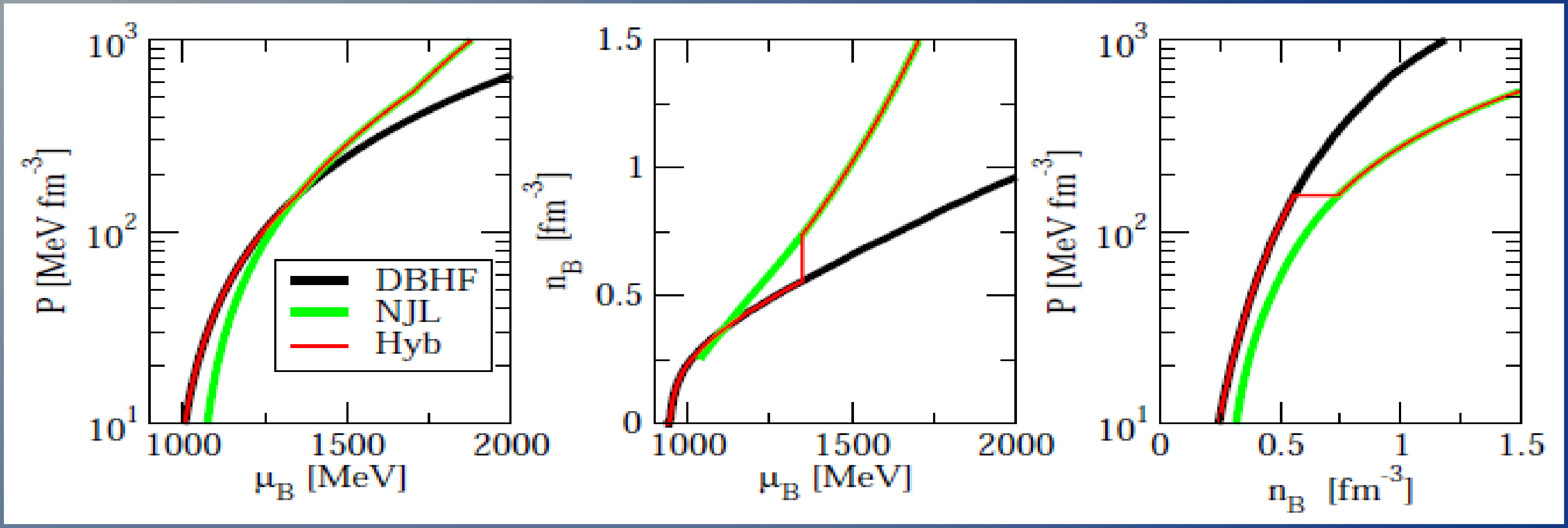


Individual contributions to total luminosity:

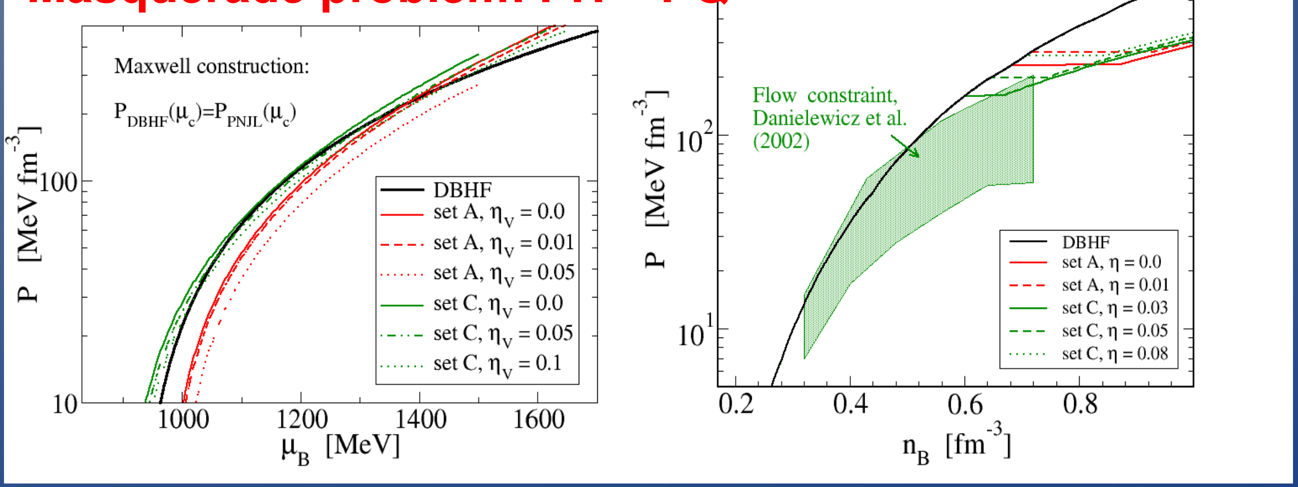
MMU: medium modified mod. Urca
PBF: pair breaking and formation
PU: pion condensate Urca

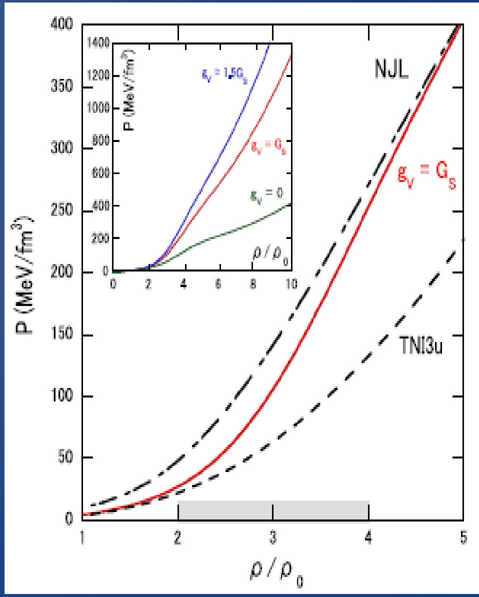
ζ_K :
suppresses thermal conductivity

Phase transition: Maxwell construction



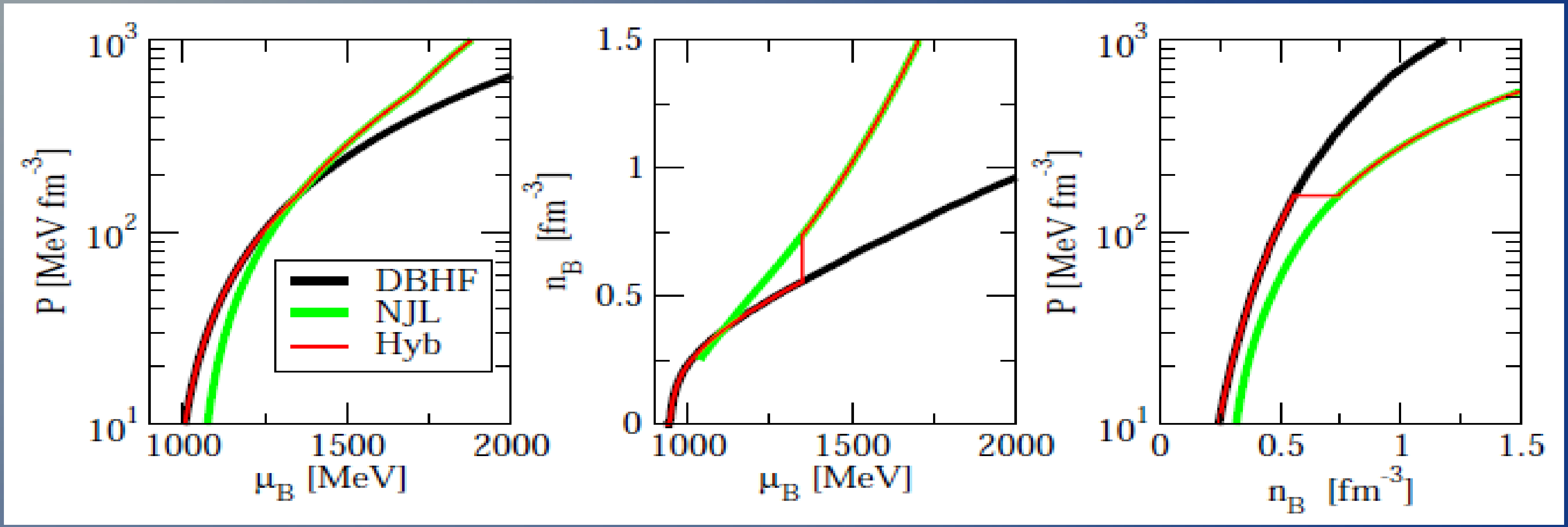
Masquerade problem: PH ~ PQ



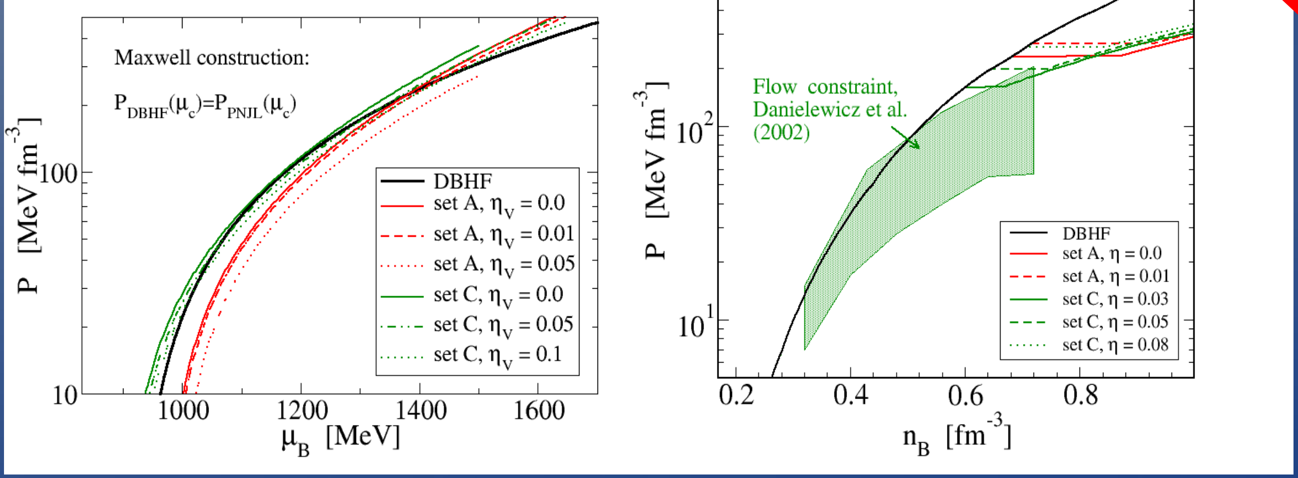


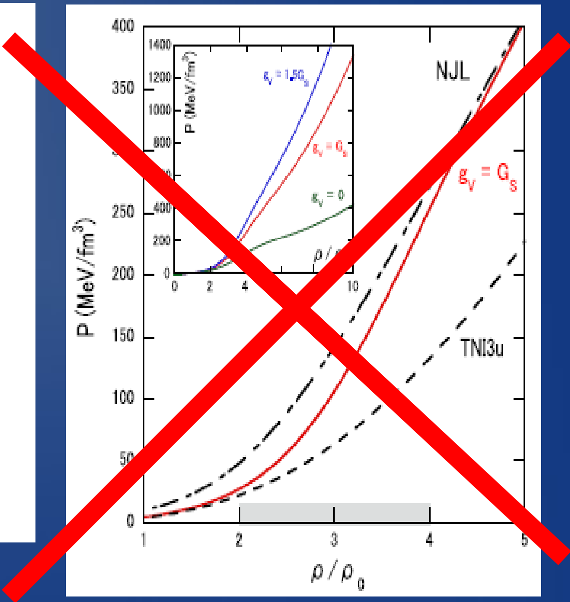
D.B., Benic, Contrera; Klahn, Lastowiecki (2012)

Phase transition: Maxwell construction



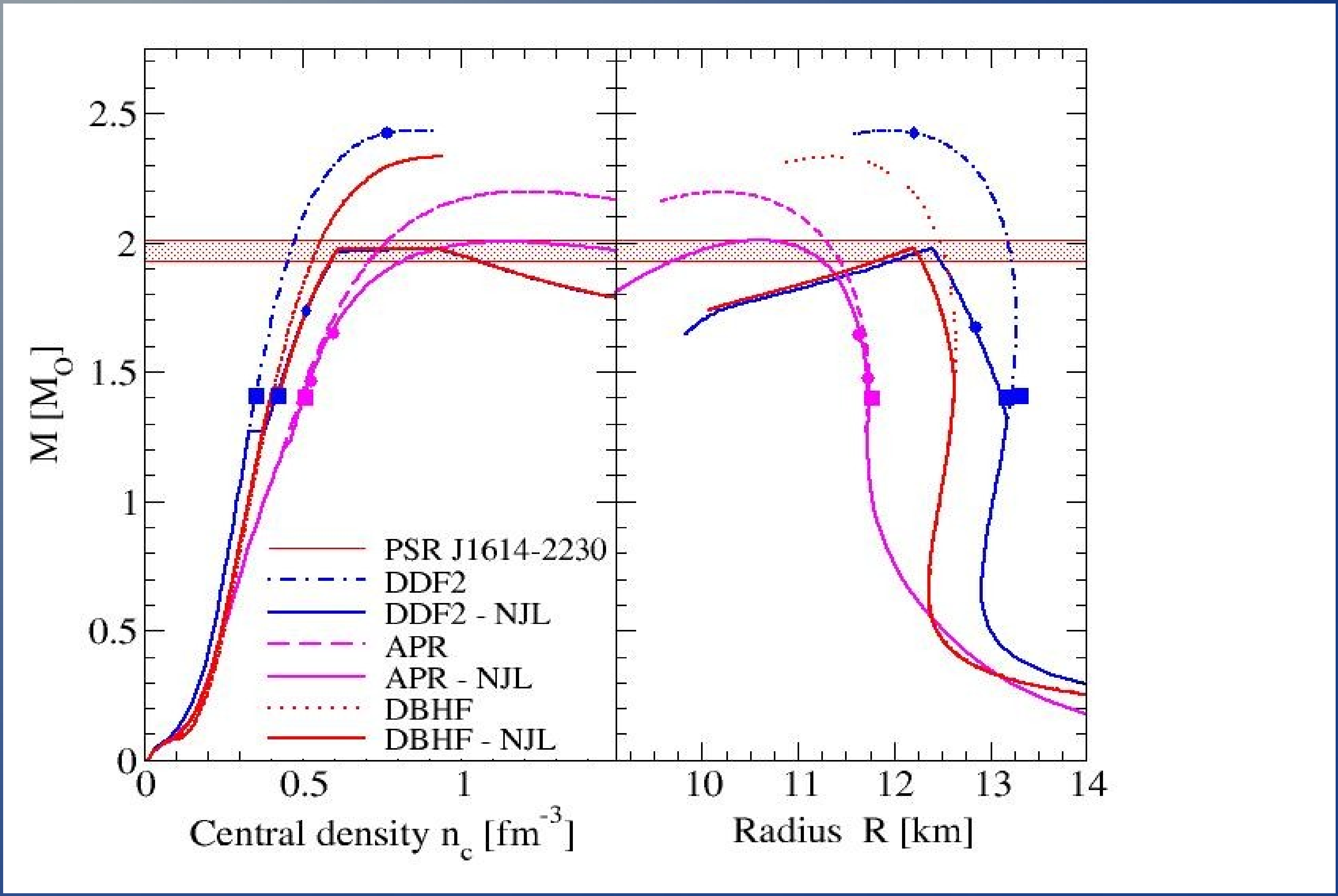
Always softens the EoS !



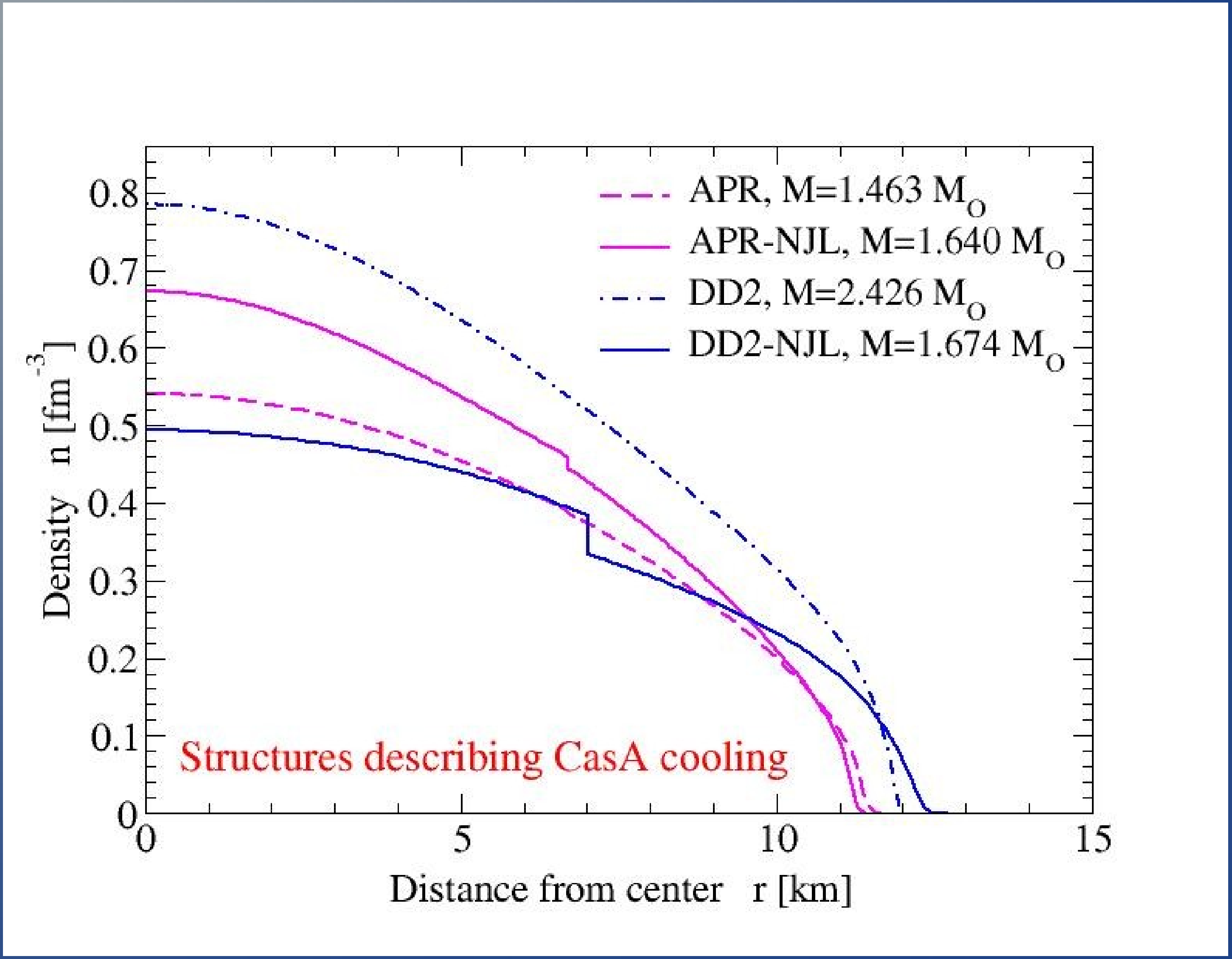


D.B., S. Benic, G. Contrera et al., in preparation (2012)

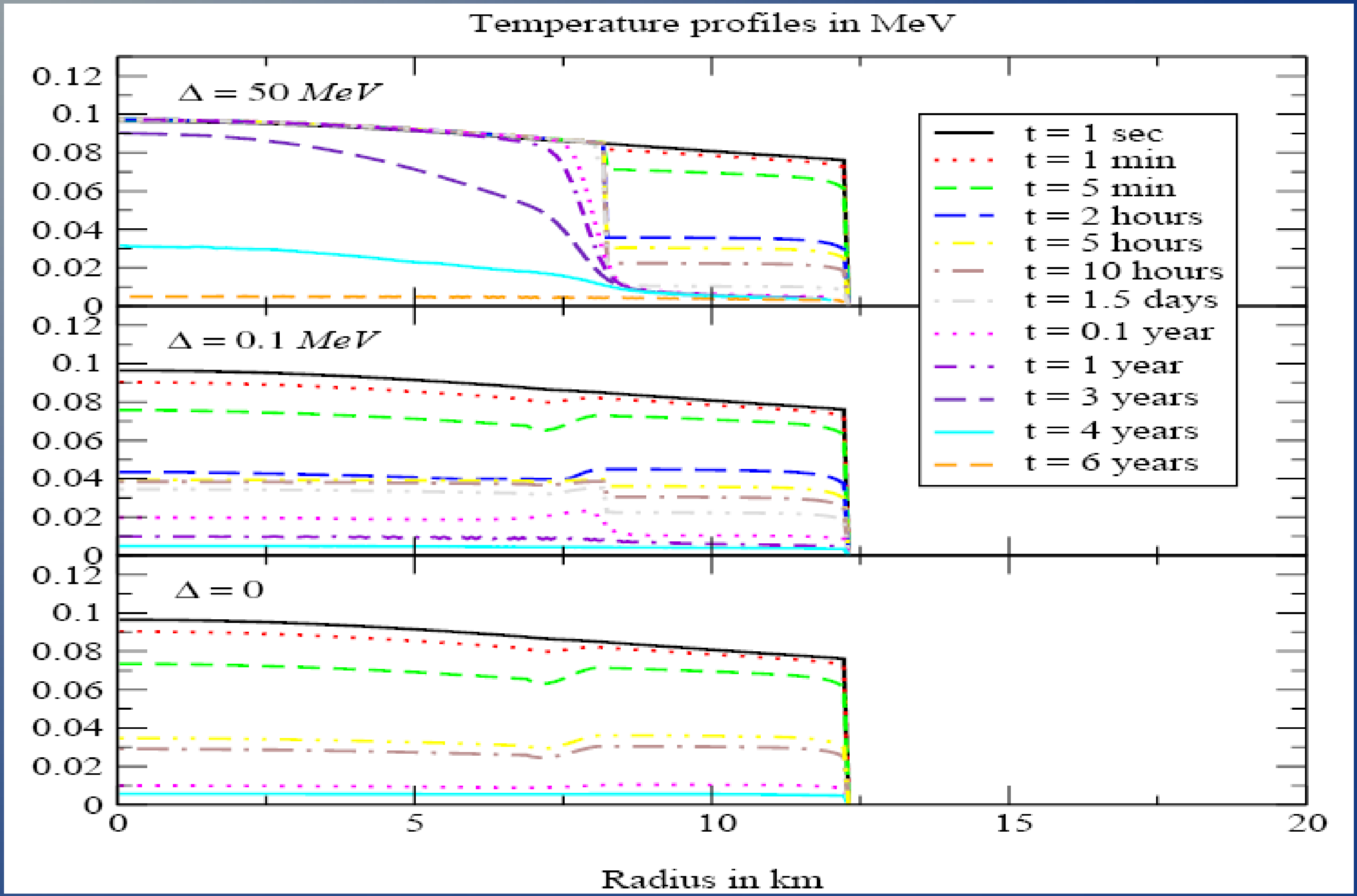
Hybrid star configuration sequences



Hybrid Star Structure & Cas A

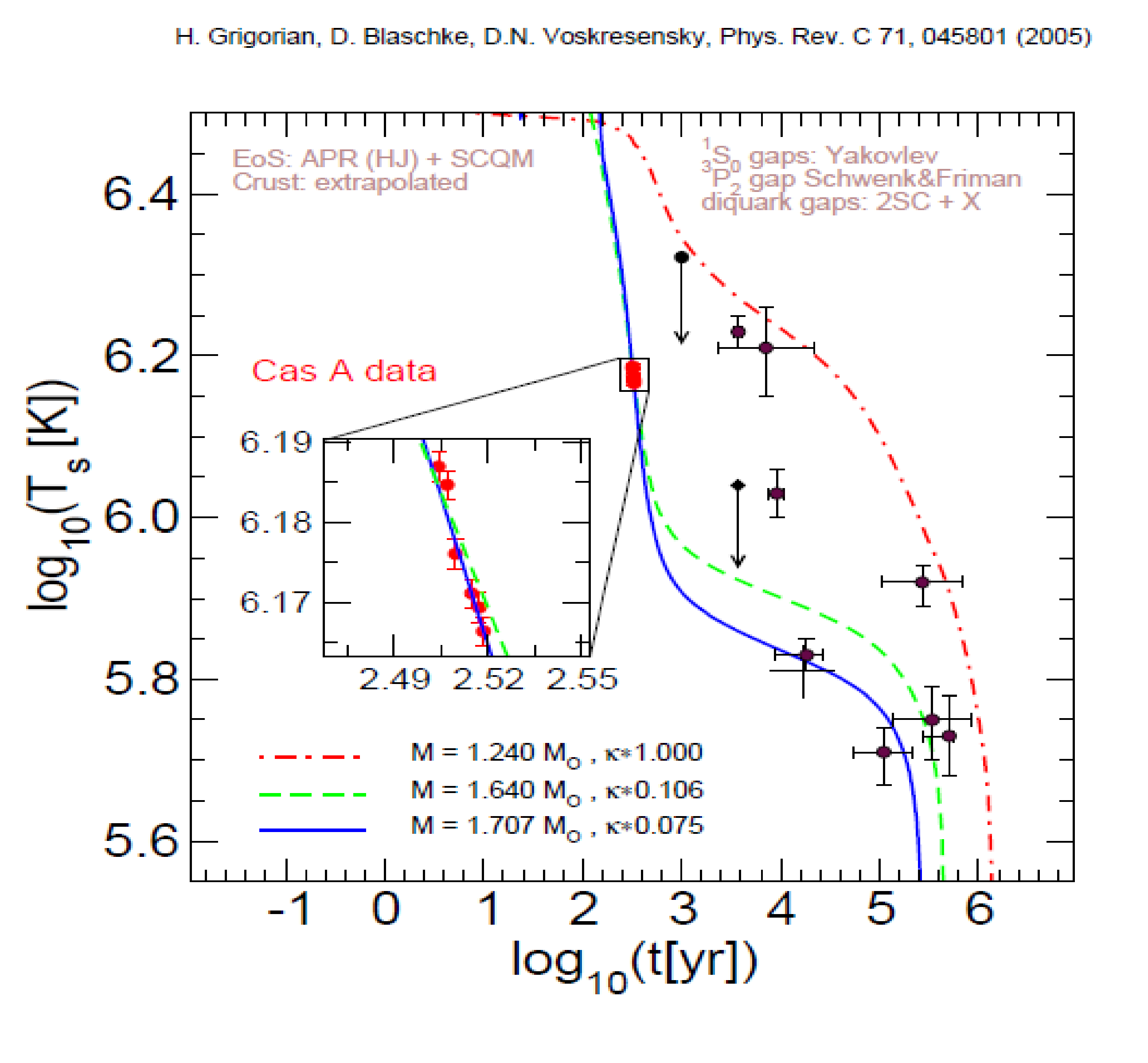


Temperature in the Hybrid Star Interior



- **Blaschke, Grigorian, Voskresensky, A& A 368 (2001) 561**

Cas A as a Hybrid Star

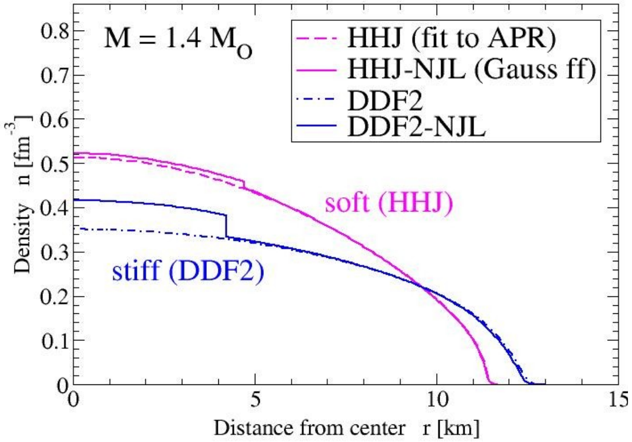


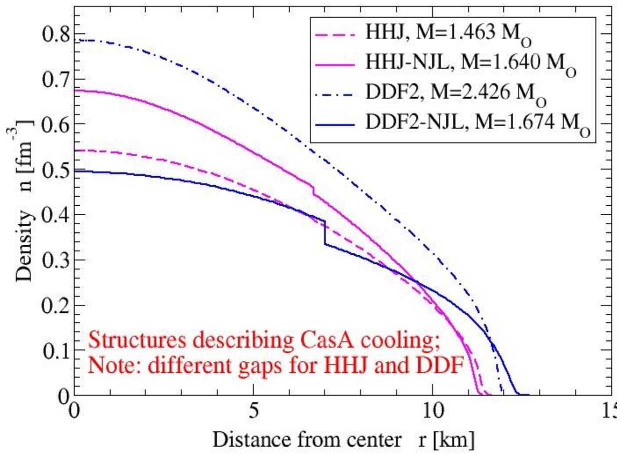
Soft hadronic EoS (APR)

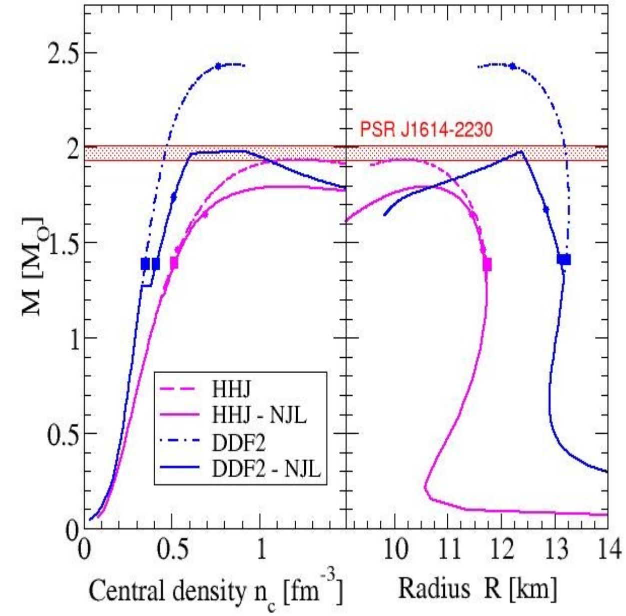
What PSR J1614-2230 (Demorest) & Cas A imply for compact star structure & cooling

D. Blaschke @ Confinement X

Stiff nuclear EoS (DDF2) → low central density → slow cooling

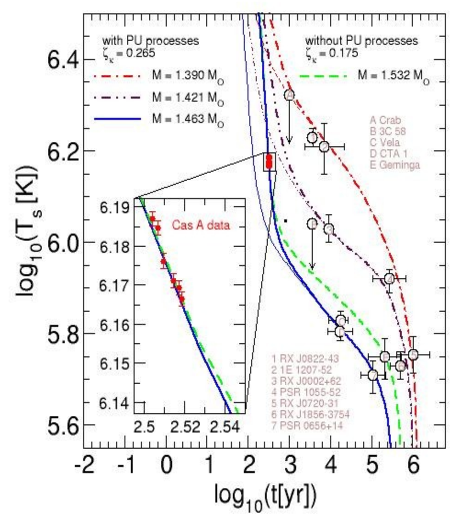


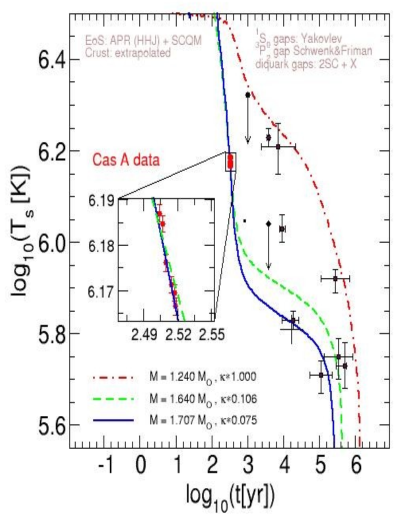




HHJ and HHJ-NJL EoS too soft for Demorest, but CasA cooling OK [DB et al., PRC (2012)]

MCasA = 1.463 MO MCasA = 1.640 MO

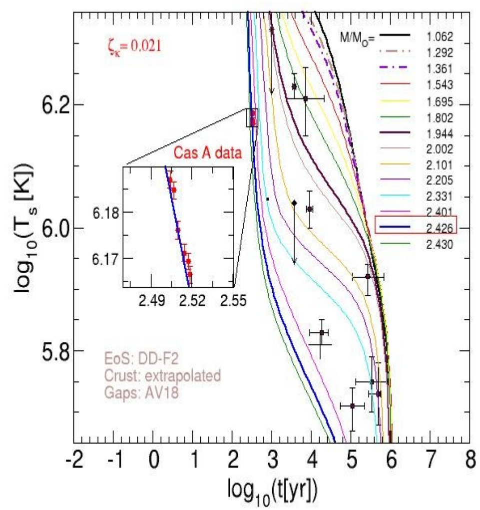


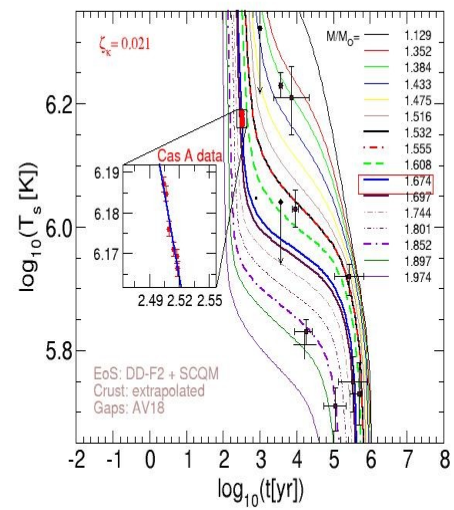


DDF2 and DDF2-NJL support 2 MO

Hadronic cooling too slow, but hybrid OK

MCasA = 2.426 MO MCasA = 1.674 MO





Conclusions

- Cas A rapid cooling is consistently described by the nuclear medium cooling (NMC) model as a “first drop” delayed by low thermal conductivity
- Both alternatives for the inner structure, hadronic and hybrid star, are viable for Cas A if hadronic matter is just stiff enough (e.g., APR); for a too stiff hadronic EoS (e.g., DD2) the hadronic scenario requires a modification of pairing gaps while the hybrid model is OK
- In contrast to the minimal cooling scenario, the NMC model is sensitive to the star mass and the thermal conductivity of the superfluid star core
- Discriminating test? Log N – Log S !! (?)

- **Research ...**
- **... is gong on!**

- Thanks for Your attention!

It's cool to be a CompStar member!