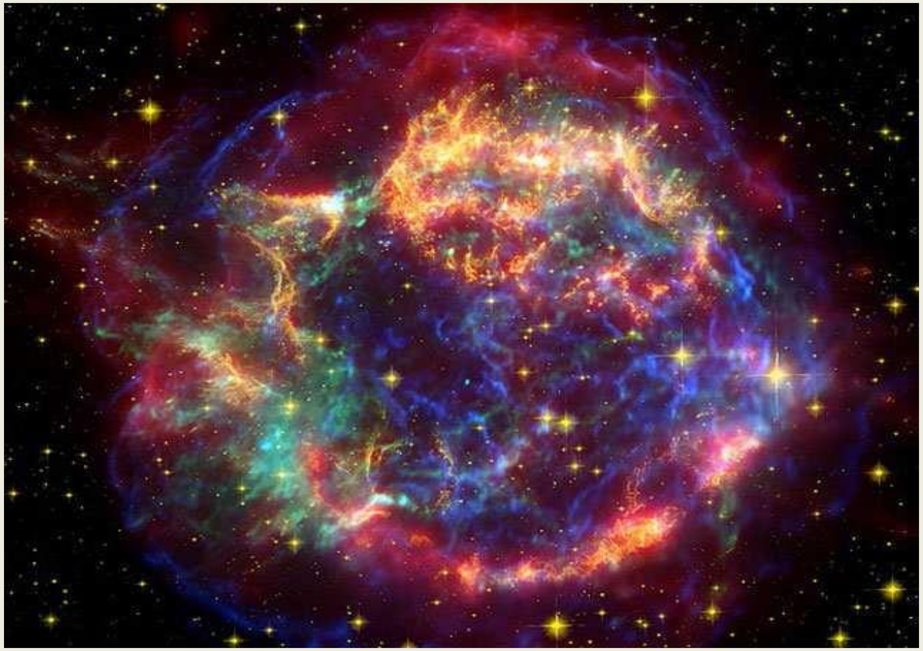
Cooling of massive neutron stars



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MPCS&RG **- 2017**
Yerevan - 21 September

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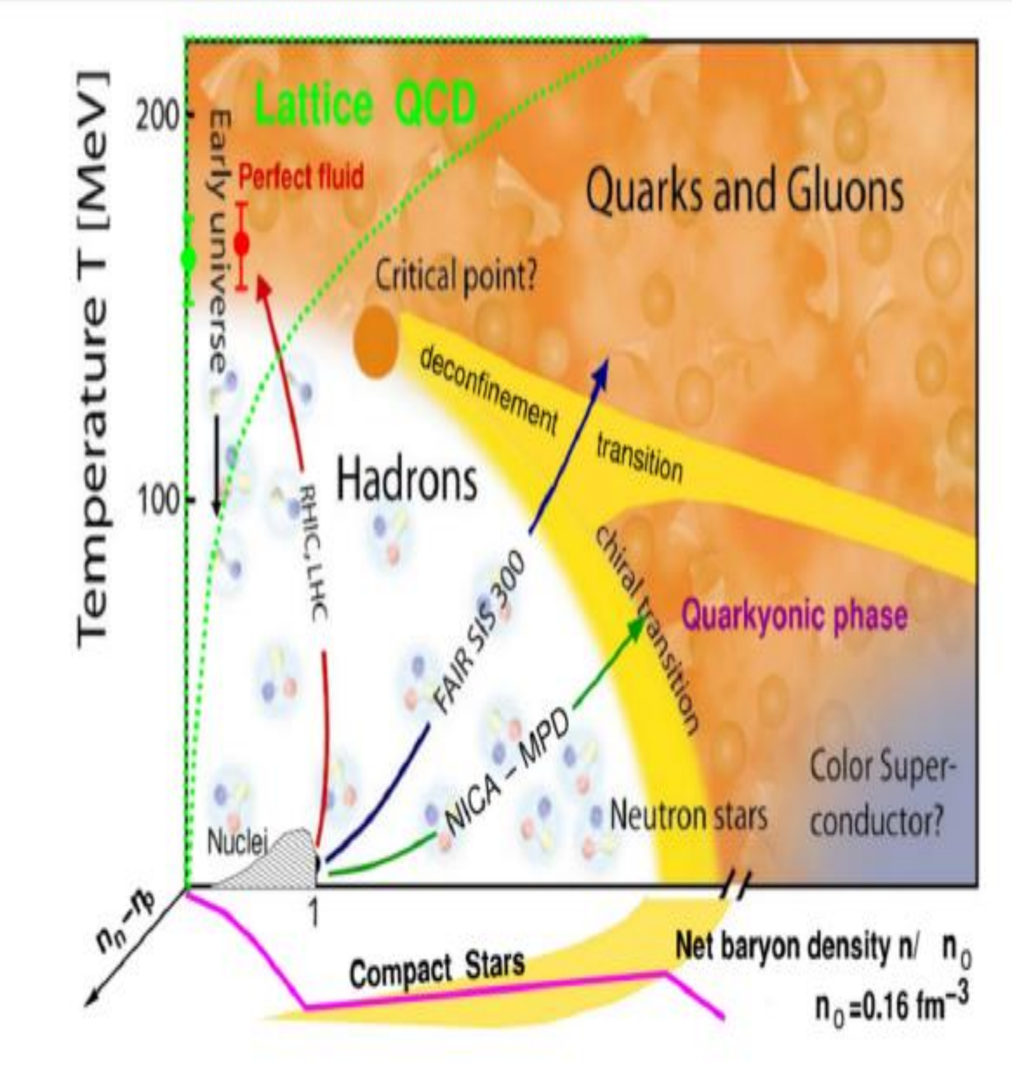
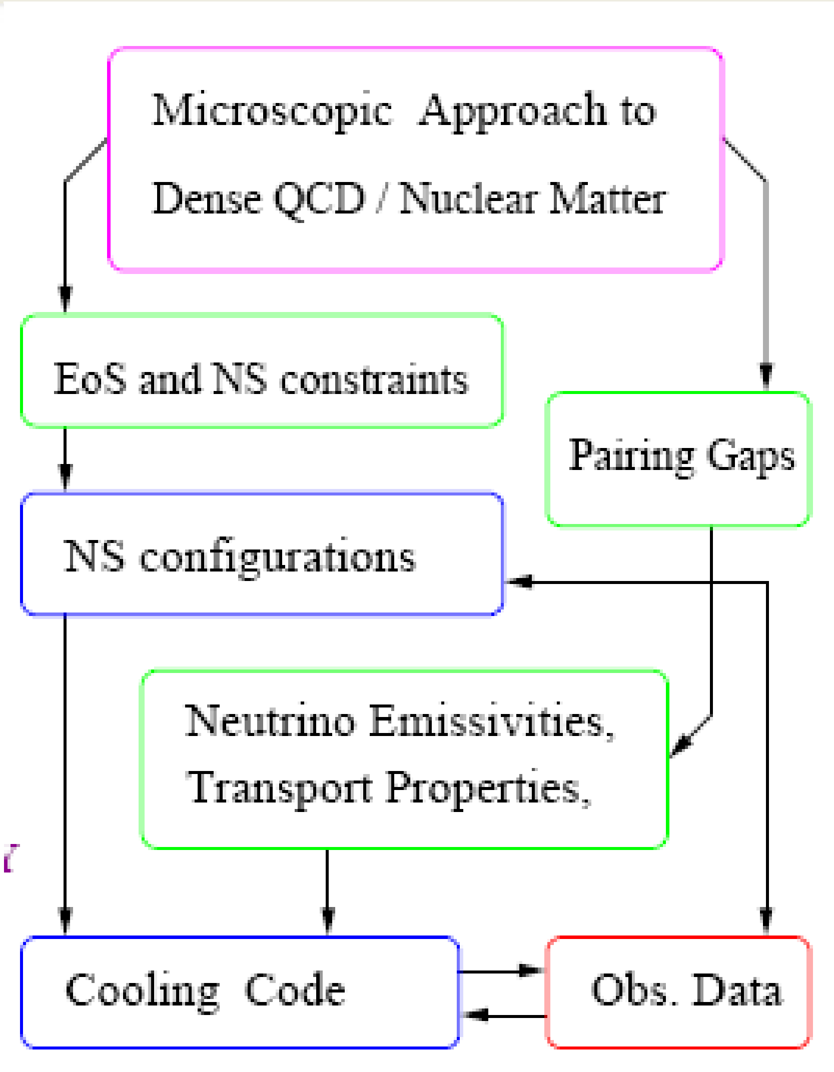
Cooling Of Neutron Stars

- Introduction to Cooling Simulation
- Cooling regulators
- Time Evolution of Temperature
- *Super conductivity & in-medium effects*
- ***Results for NS cooling***

H. Grigorian, D. N. Voskresensky and D. Blaschke
Eur. Phys. J. A **52: 67 (2016).**

Phase Diagramm & Cooling Simulation

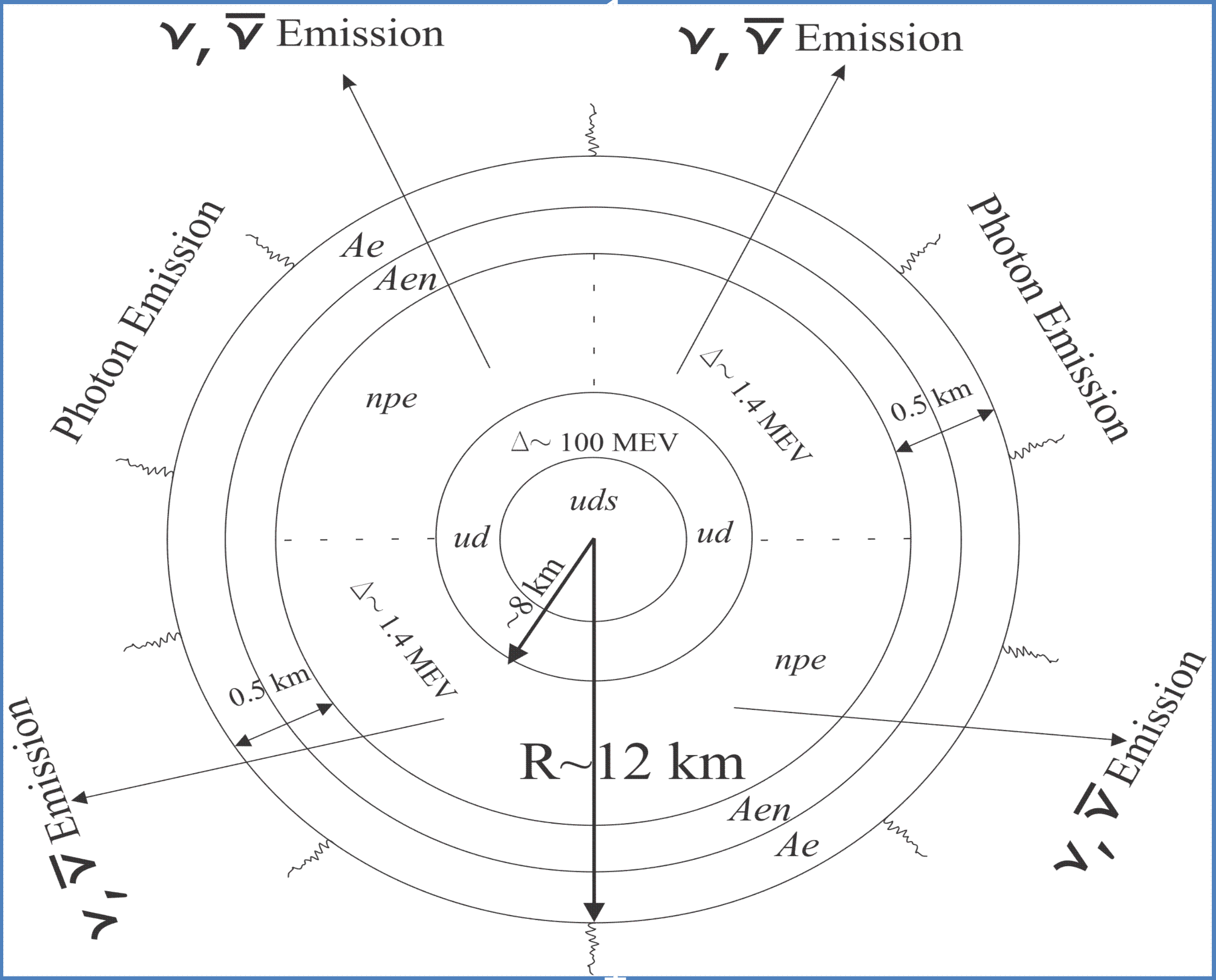




Phase Diagramm & Cooling Simulation

- ✓Description of the stellar matter - local properties (EoS of super-dense matter)
- ✓Modeling of the gravitationally self bound compact star - including the density profiles
- ✓Extrapolations of the energy loss mechanisms to higher densities and temperatures
- ✓ Consistency of the approaches
- ✓Comparison with observational data

Structure Of Hybrid Star



Static neutron star mass and radius

The structure and global properties of compact stars are obtained by solving the Tolman-Oppenheimer-Volkoff (TOV) equations[1,2]:

$$\begin{cases} \dfrac{dP(r)}{dr} = -\dfrac{GM(r)\varepsilon(r)}{r^2} \dfrac{\left(1 + \dfrac{P(r)}{\varepsilon(r)}\right)\left(1 + \dfrac{4\pi r^3 P(r)}{M(r)}\right)}{\left(1 - \dfrac{2GM(r)}{r}\right)}; \\ \dfrac{dM(r)}{dr} = 4\pi r^2 \varepsilon(r); \\ \dfrac{dN_B(r)}{dr} = 4\pi r^2 \left(1 - \dfrac{2GM(r)}{r}\right)^{-1/2} n(r). \end{cases}$$

[1] R. C. Tolman, Phys. Rev. **55**, 364 (1939).

[2] J. R. Oppenheimer and G. M. Volkoff, Phys. Rev. **55**, 374 (1939).

Modification of HHJ (HDD) parameterization of EoS

As mentioned, we adopted the HHJ ($\delta = 0.2$) EoS for the description of the nucleon contribution. The energy density of nucleons is parameterized as follows:

$$E_N = un_0\left[m_N + e_B u \frac{2+\delta-u}{1+\delta u} + a_{sym} u^{0.6}(1-2x_p)^2\right], \quad (5)$$

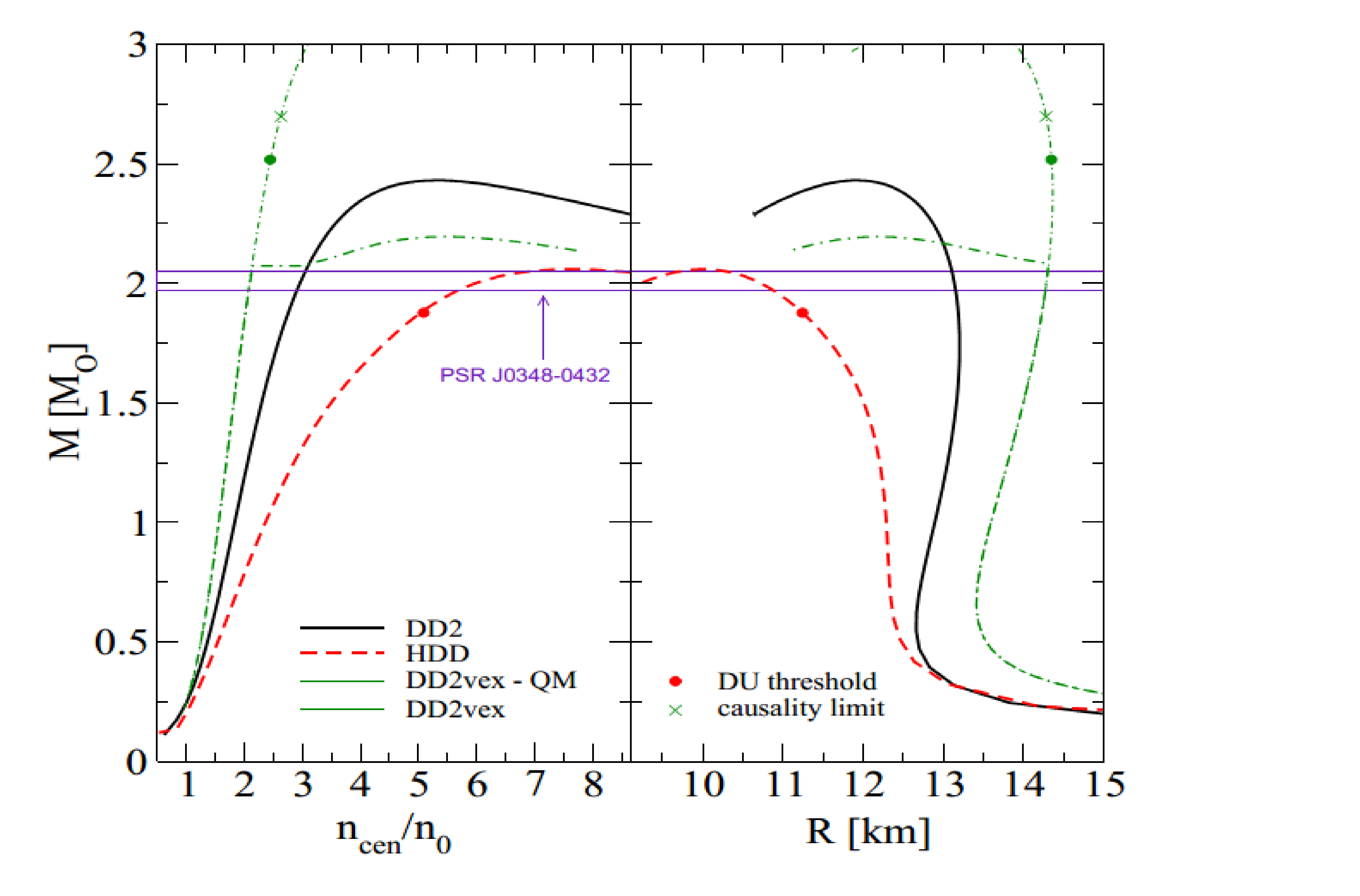
where $u = n/n_0$, $e_B \simeq -15.8$ MeV is the nuclear binding energy per nucleon, $a_{sym} \simeq 32$ MeV is the symmetry energy coefficient and we chose $\delta = 0.2$. With these values of parameters one gets the best fit of APR (A18 + δv + UIX*)

Introduction of the excluded volume

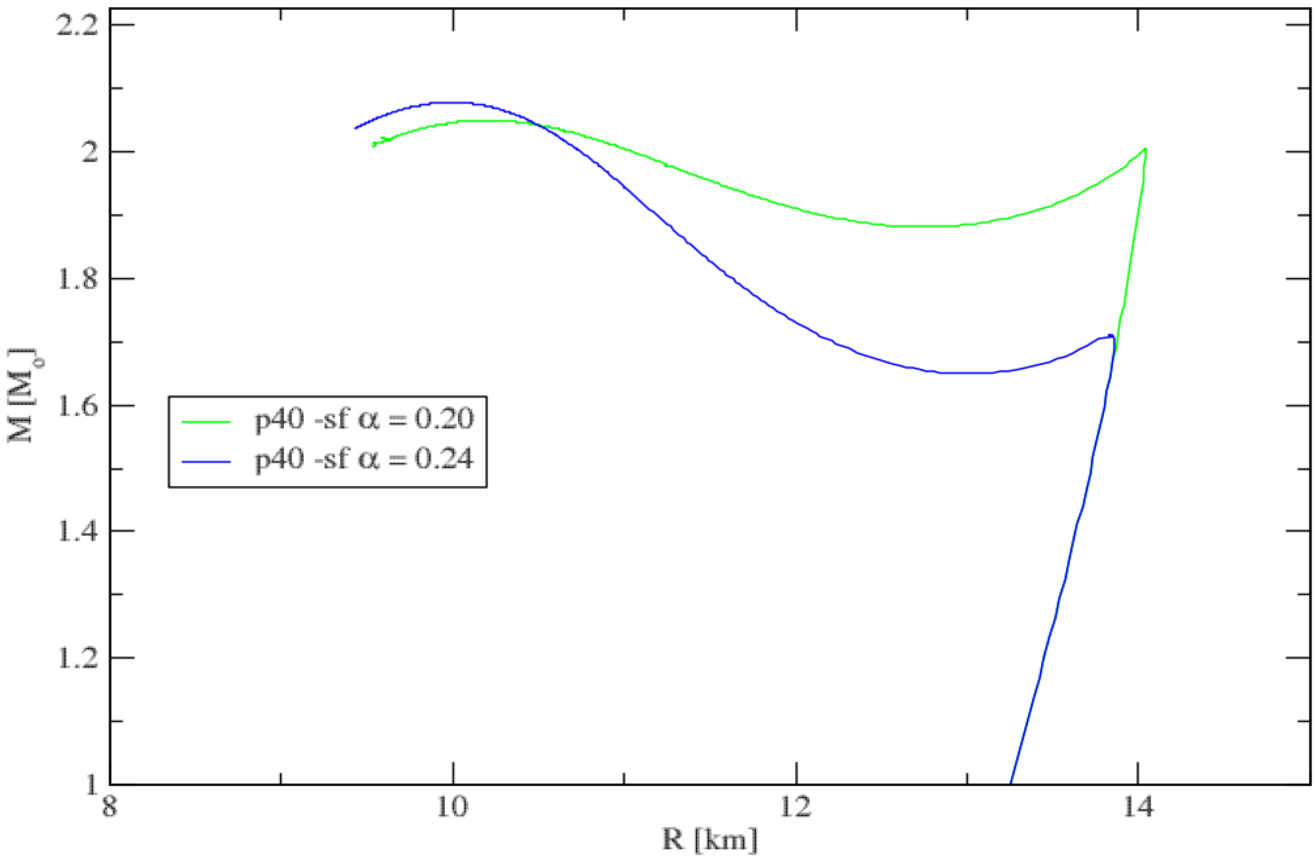
$$u \to \frac{u}{1 - \alpha u e^{-(\beta/u)^{\sigma}}}$$

H. Heiselberg and M. Hjorth-Jensen, Astrophys. J. **525**, L45 (1999).

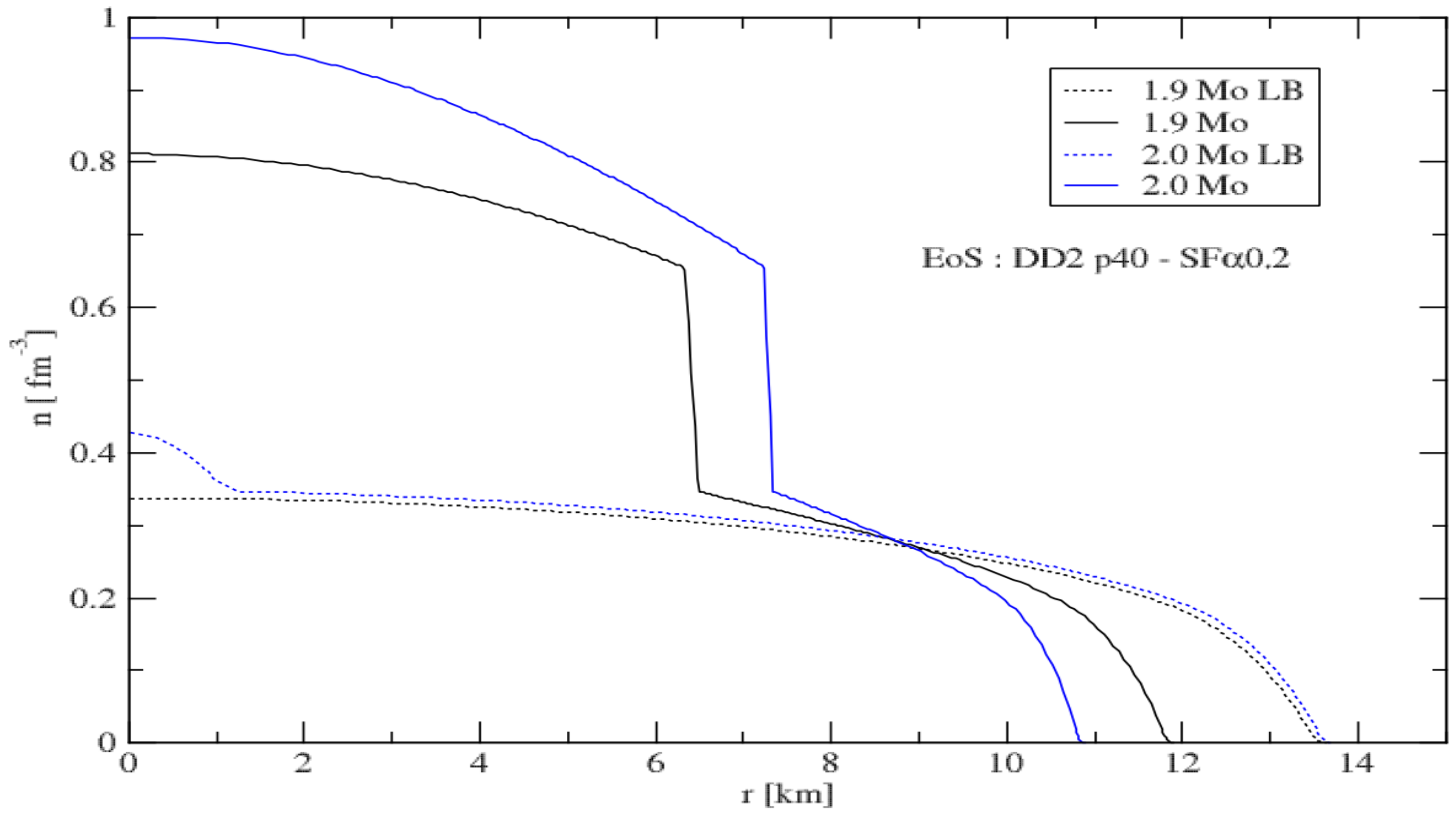
Stability of stars
HDD, DD2 & DDvex-NJL EoS model



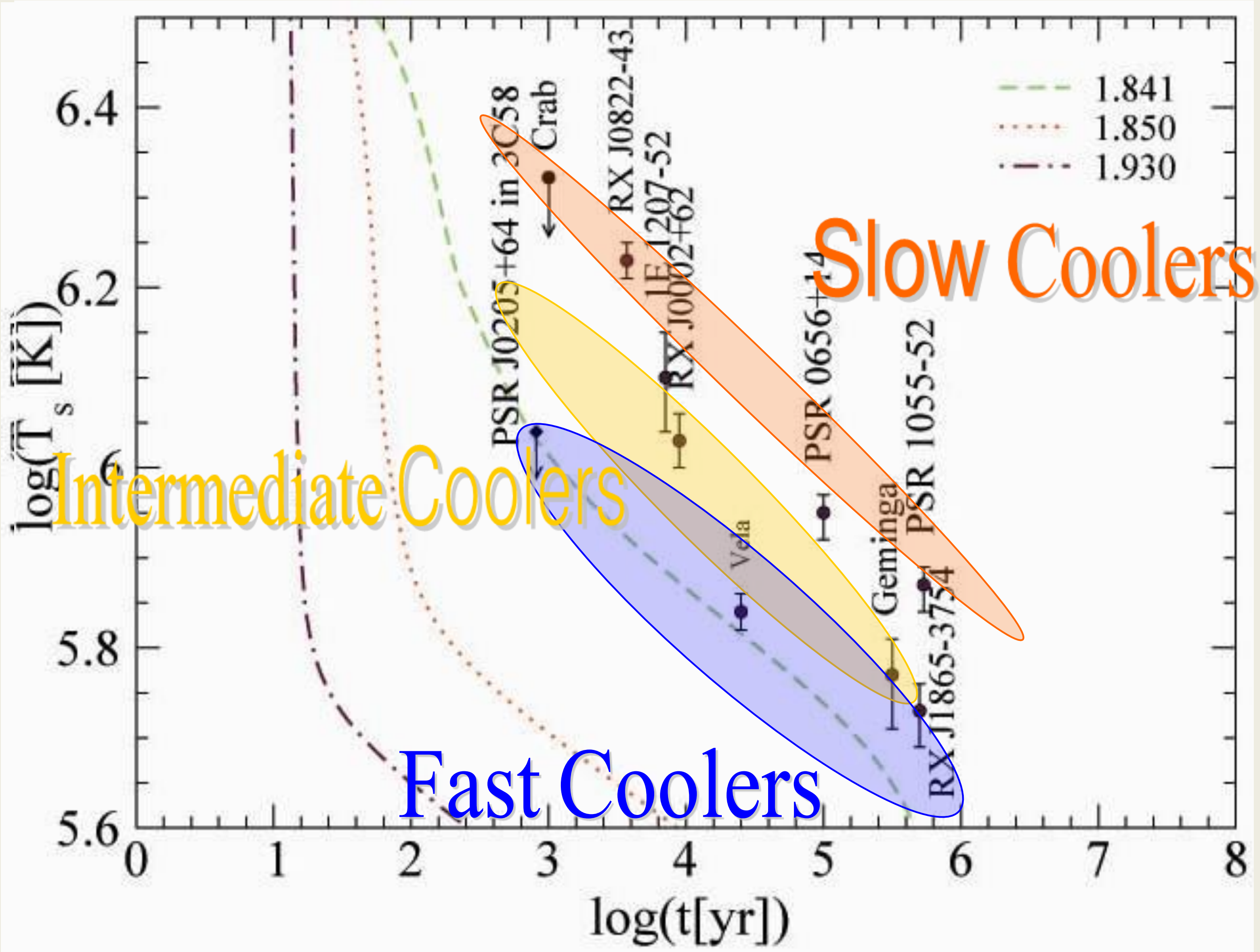
High Mass Twin CS



Different Configurations with the same NS mass



Surface Temperature & Age Data



Cooling Mechanism

$$\frac{dU}{dt} = \sum_i C_i \frac{dT}{dt} = -\varepsilon_\gamma - \sum_j \varepsilon_\nu^j$$

Cooling Processes

- Direct Urca: $n \to p + e + \bar{\nu}_e$
- Modified Urca: $n + n \to n + p + e + \bar{\nu}_e$
- Photons: $\to \gamma$
- Bremsstrahlung: $n + n \to n + n + \nu + \bar{\nu}$

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.

Neutrino emissivities in hadronic matter:

- Direct Urca (DU) the most efficient processes

$$\epsilon_{DU} = M_{DU} * (m_p^*)(m_n^*) * \Gamma_{wN}^2 * (n_e)^{1/3}(T_9)^6 * R_D;$$
$$M_{DU} = 4 \times 10^{27} \quad erg/s/cm^3$$

- Modified Urca (MU) and Bremsstrahlung

$$\epsilon_{MUp} = F_M * M_p * (m_p)^3 (m_n^*)(T_9)^8 (n_e)^{1/3} * R_{MUp}(v_n, v_p);$$
$$\epsilon_{nnBS} = P_{nnBS} * R_{BS}^{nn}(v_n) * \Gamma_w^2 \Gamma_s^4 (n_b)^{4/3} (T_9)^8 (m_n^*)^4 / (\omega)^3;$$

- Suppression due to the pairing

$$v_N = \Delta_N(T)/T = \sqrt{1-\tau_N}\left(1.456 - \frac{0.157}{\sqrt{\tau_N}} + \frac{1.766}{\tau_N}\right)$$

- Enhanced cooling due to the pairing

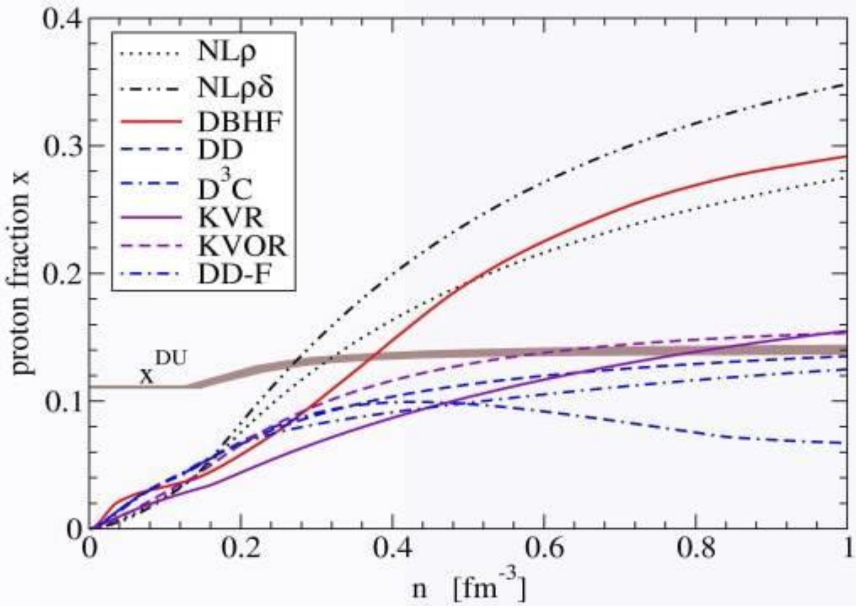
$$\epsilon_\nu^{\rm NPBF} = 6.6 \times 10^{28} (m_n^*/m_n)(\Delta_n(T)/{\rm MeV})^7 \; u^{1/3} \times \xi \; I(\Delta_n(T)/T) \; {\rm erg\ cm^{-3} s^{-1}},$$
$$\epsilon_\nu^{\rm PPBF} = 0.8 \times 10^{28} (m_p^*/m_p)(\Delta_p(T)/{\rm MeV})^7 \; u^{2/3} \times \; I(\Delta_p(T)/T) \; {\rm erg\ cm^{-3} s^{-1}},$$

DU constraint

$n \to p + e + \bar{\nu}_e$ implies $p_n \leq p_p + p_e$, charge neutrality results in

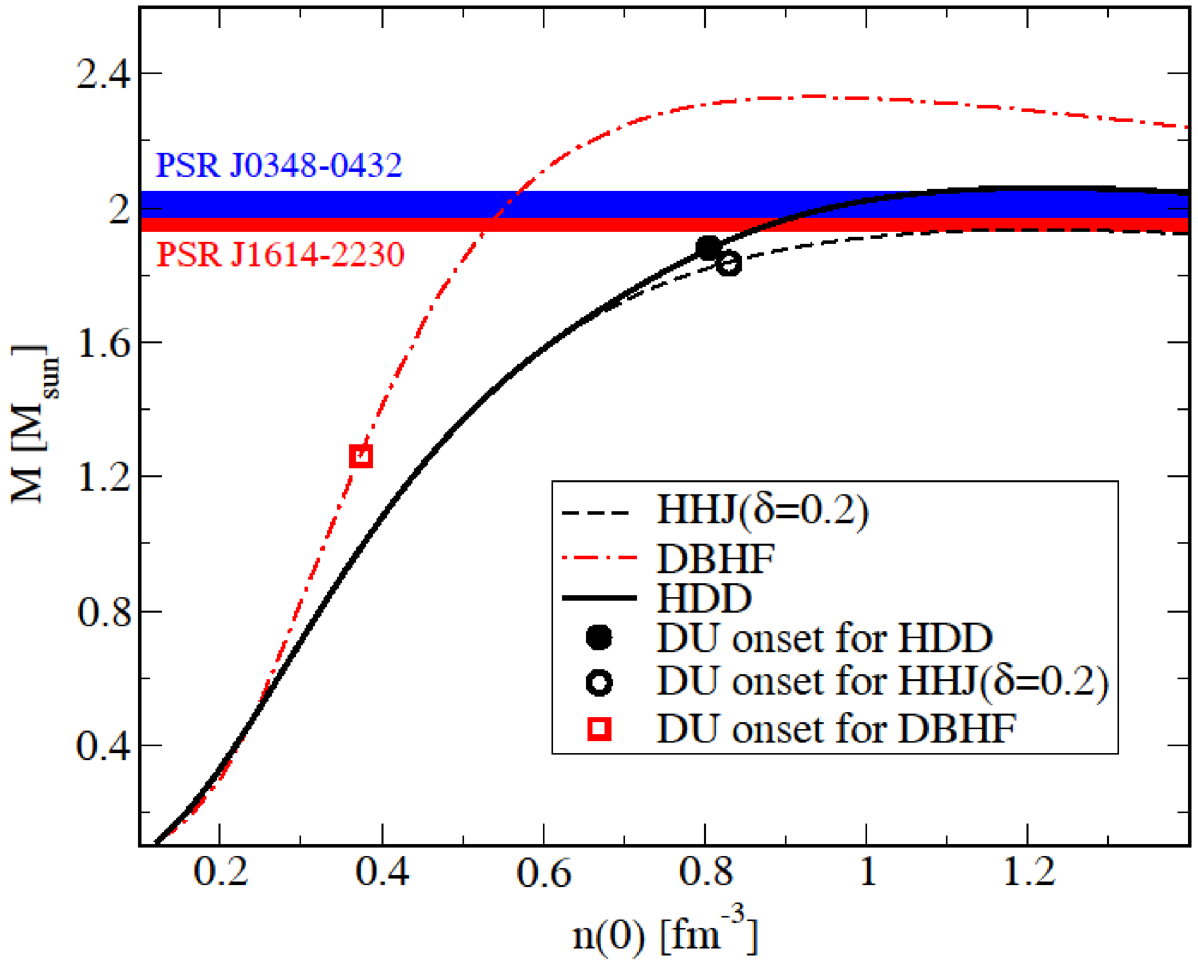
$$x_{DU}(x_e) \geq \frac{1}{1 + (1 + x_e^{1/3})^3} \qquad x_e = n_e/(n_e + n_\mu)$$

- no muons: $x_{DU} = 11.1\%$
- relativistic limit ($n_e = n_\mu$): $x_{DU} = 14.8\%$



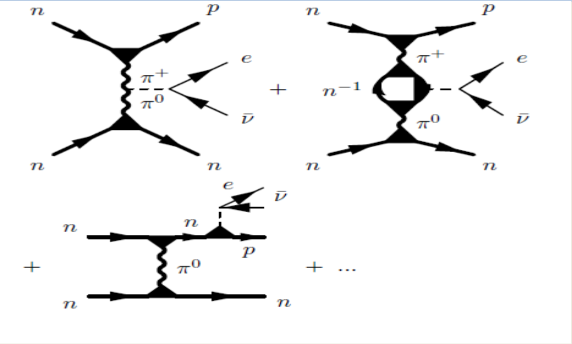
NLρ, NL$\rho\delta$, DBHF :
DU occurs below $2.5 n_0$

The Mass constraint and DU - onsets



Medium Effects In Cooling Of Neutron Stars

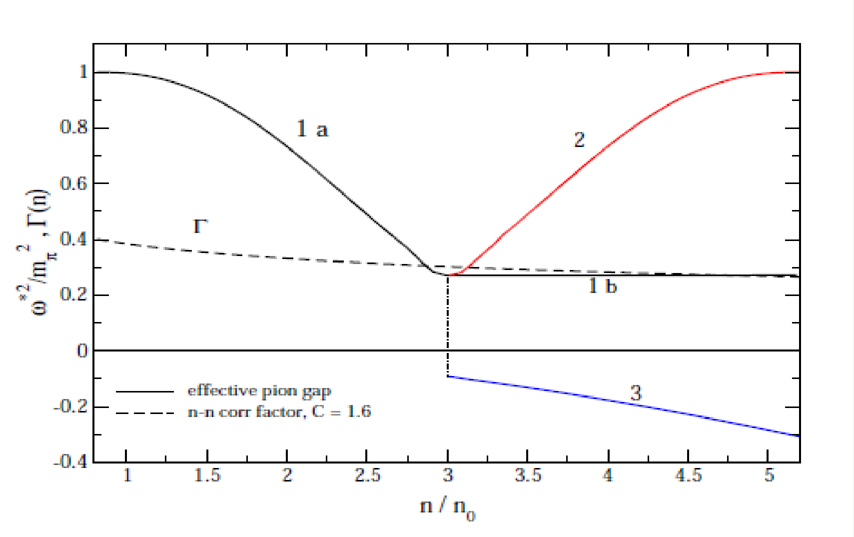
- Based on Fermi liquid theory (Landau (1956), Migdal (1967), Migdal et al. (1990))
- MMU – insted of MU



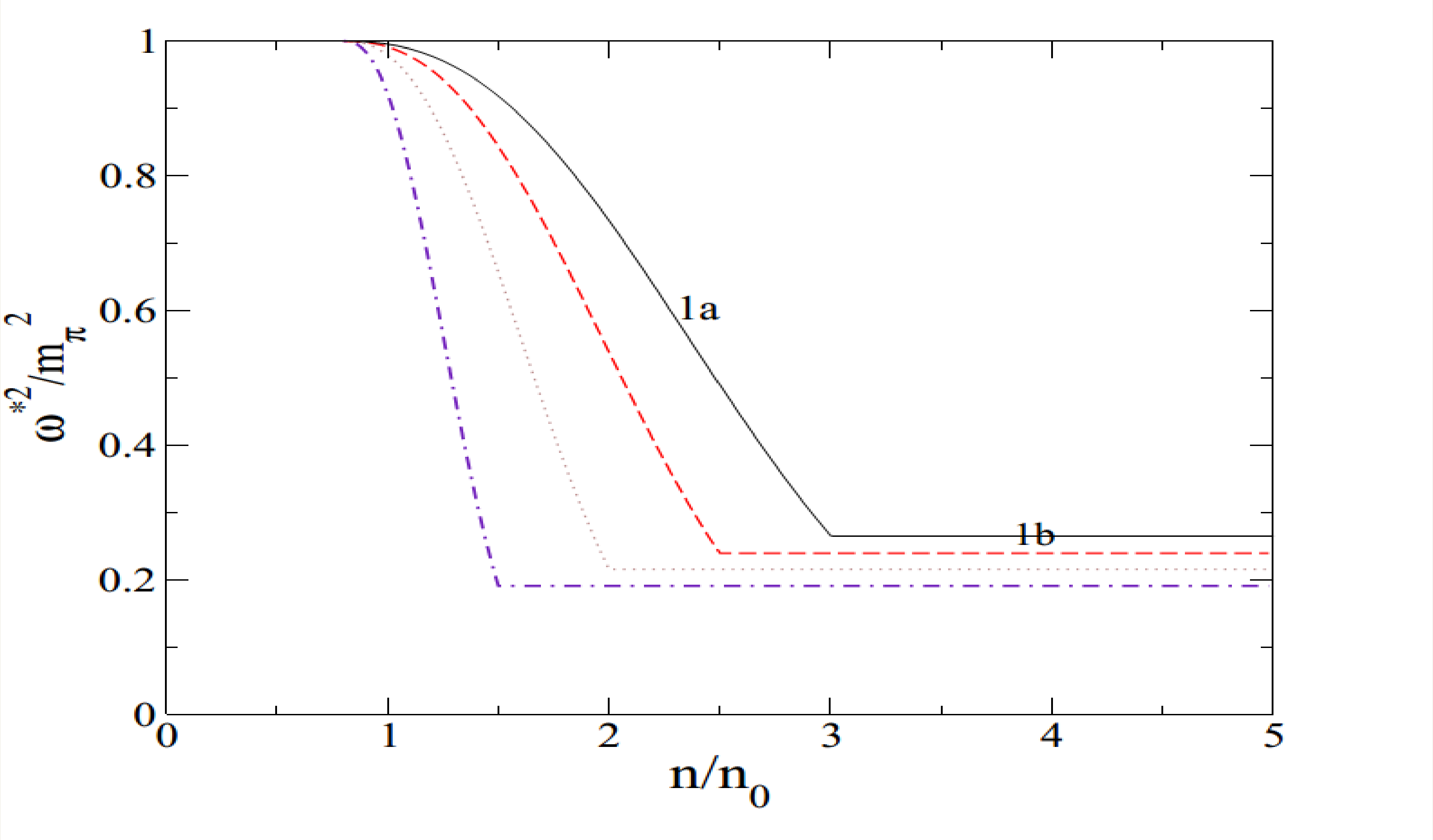
$$\frac{\varepsilon_\nu[\mathrm{MMU}]}{\varepsilon_\nu[\mathrm{MU}]} \sim 10^3\ (n/n_0)^{10/3}\frac{\Gamma^6(n)}{[\omega^*(n)/m_\pi]^8},$$

- Main regulator in Minimal Cooling

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



Medium Effects In Cooling Of Neutron Stars



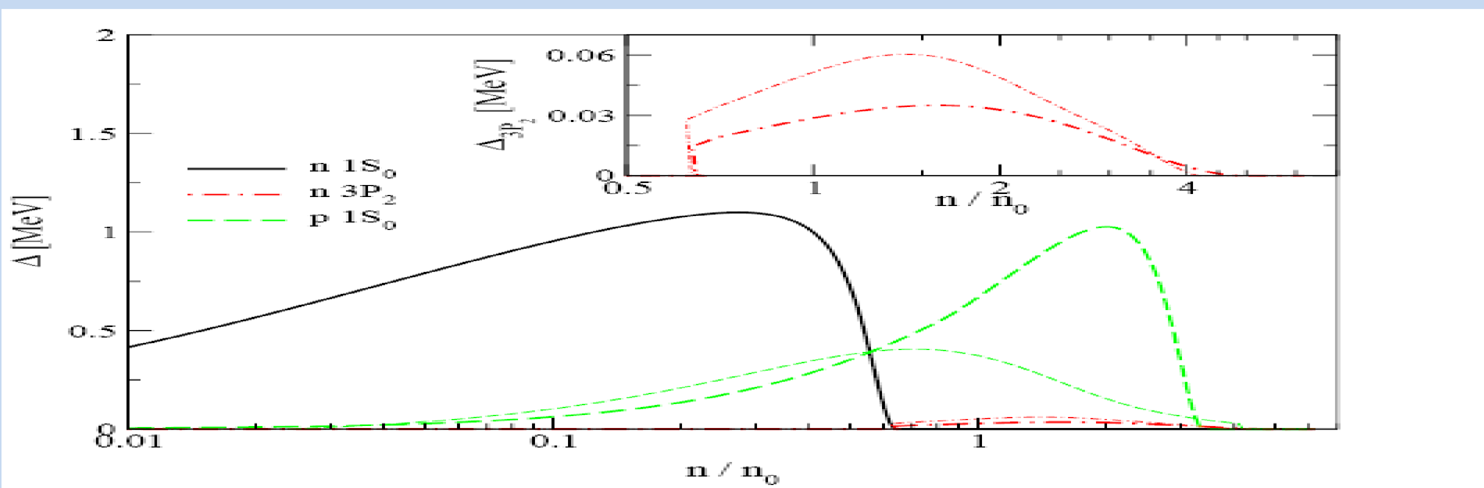
SC Pairing Gaps

•2SC phase: 1 color (blue) is unpaired (mixed superconductivity)
Ansatz   2SC + X phase:

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

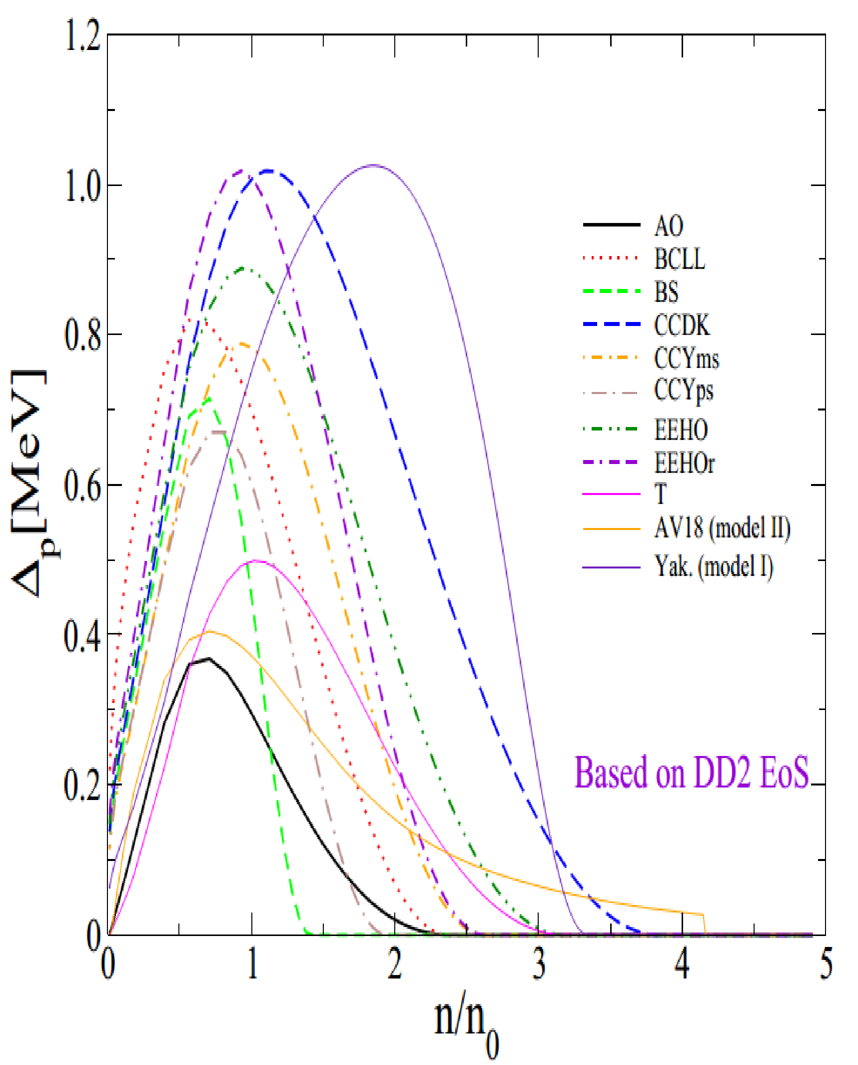
Model	Δ_0 [MeV]	α
I	1	10
II	0.1	0
III	0.1	2
IV	5	25

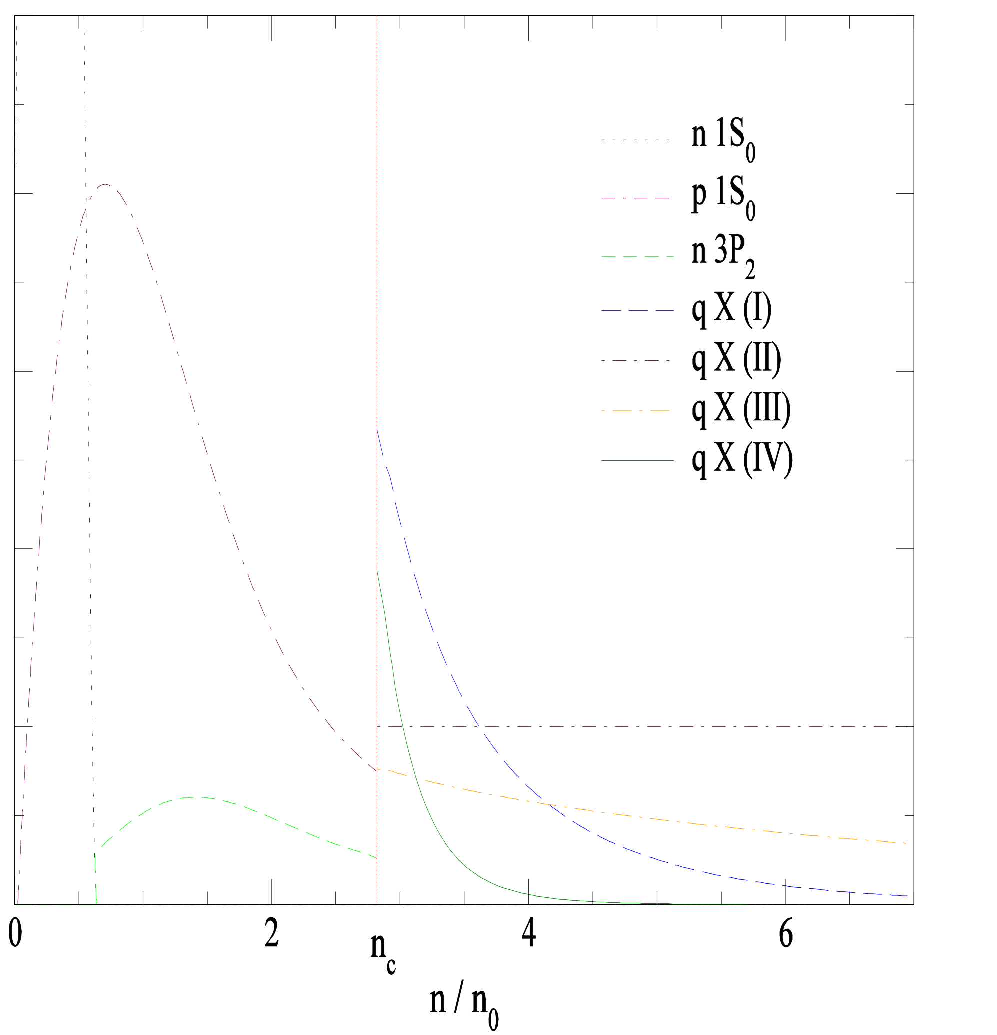
Pairing gaps for hadronic phase
(**AV18 - Takatsuka et al. (2004)**)



Po

SC Pairing Gaps

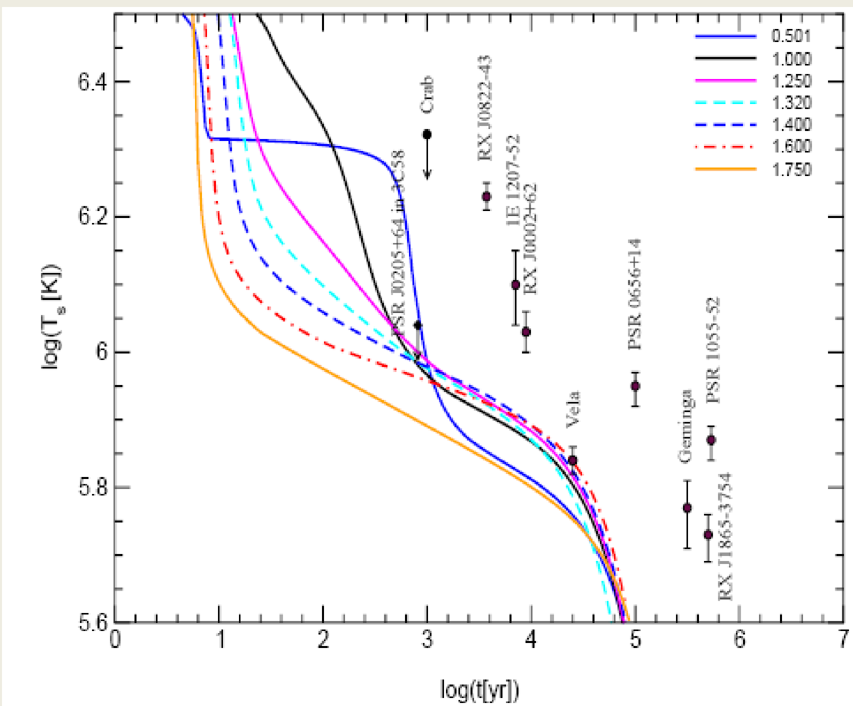


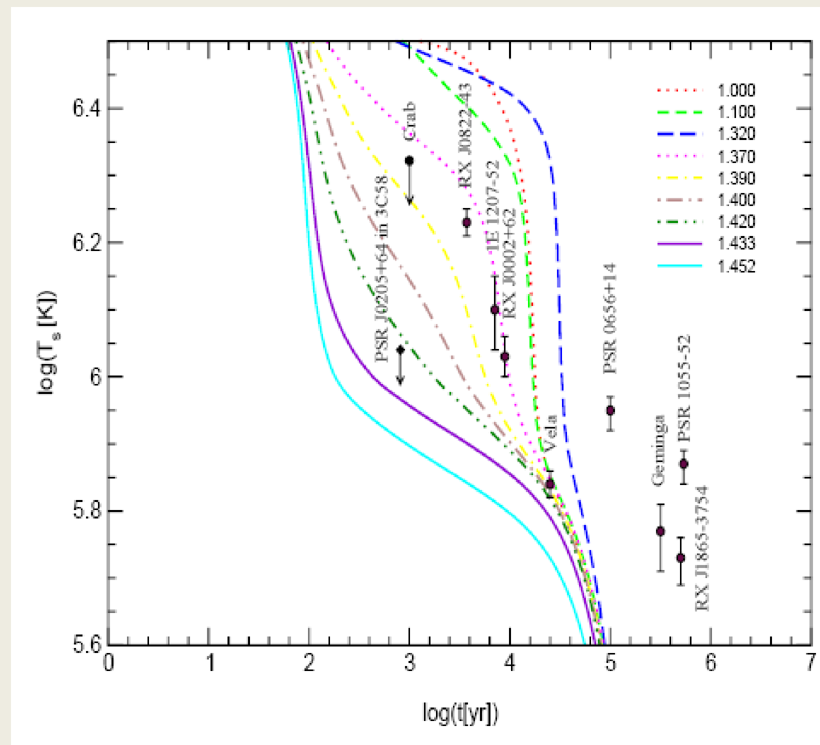


Anomalies Because Of PBF Proccess

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

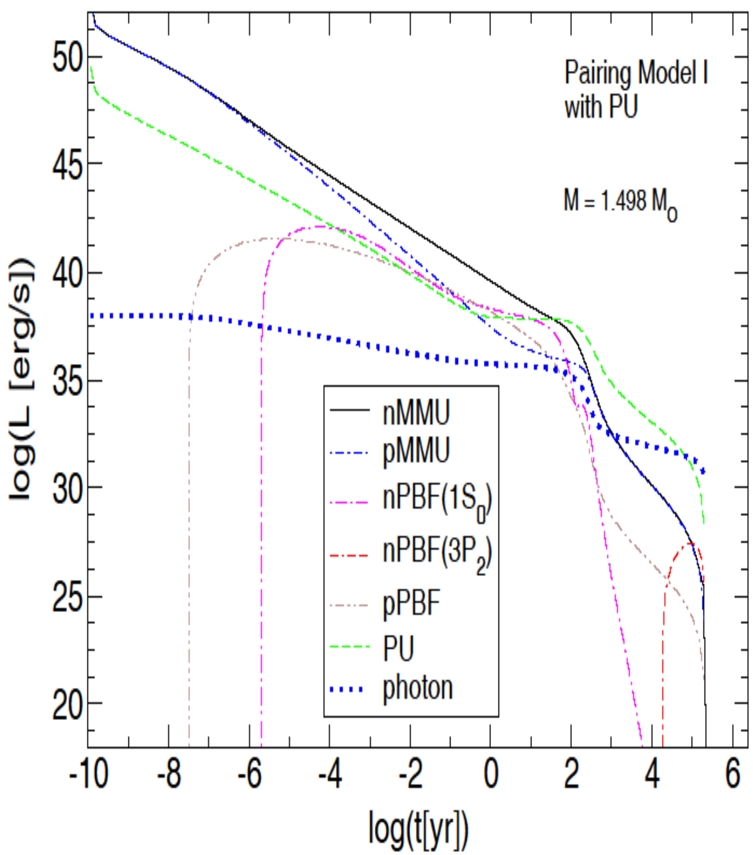
The gaps from Yakovlev at al. (2003)

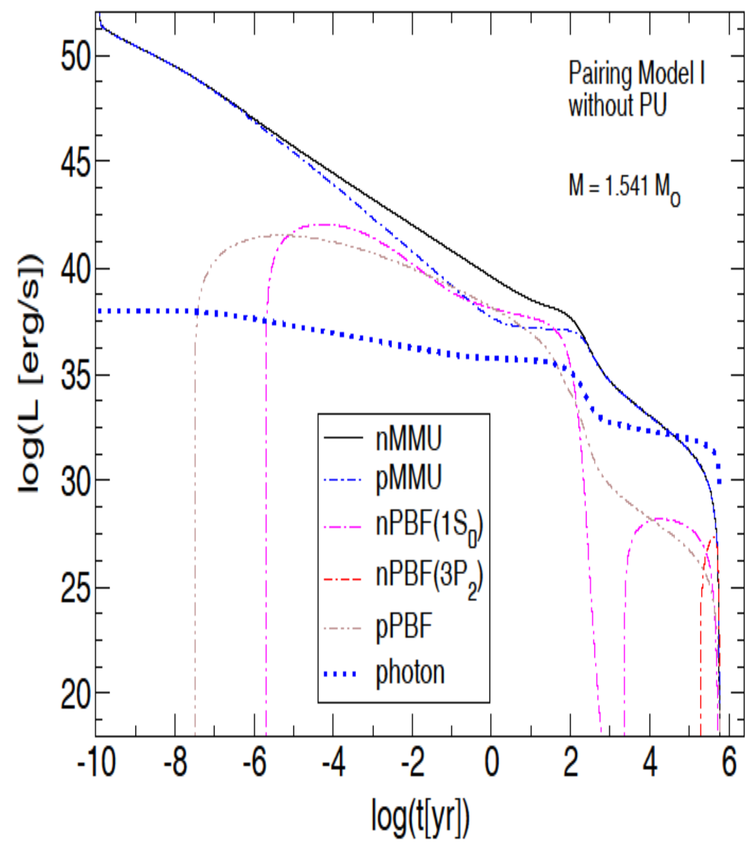




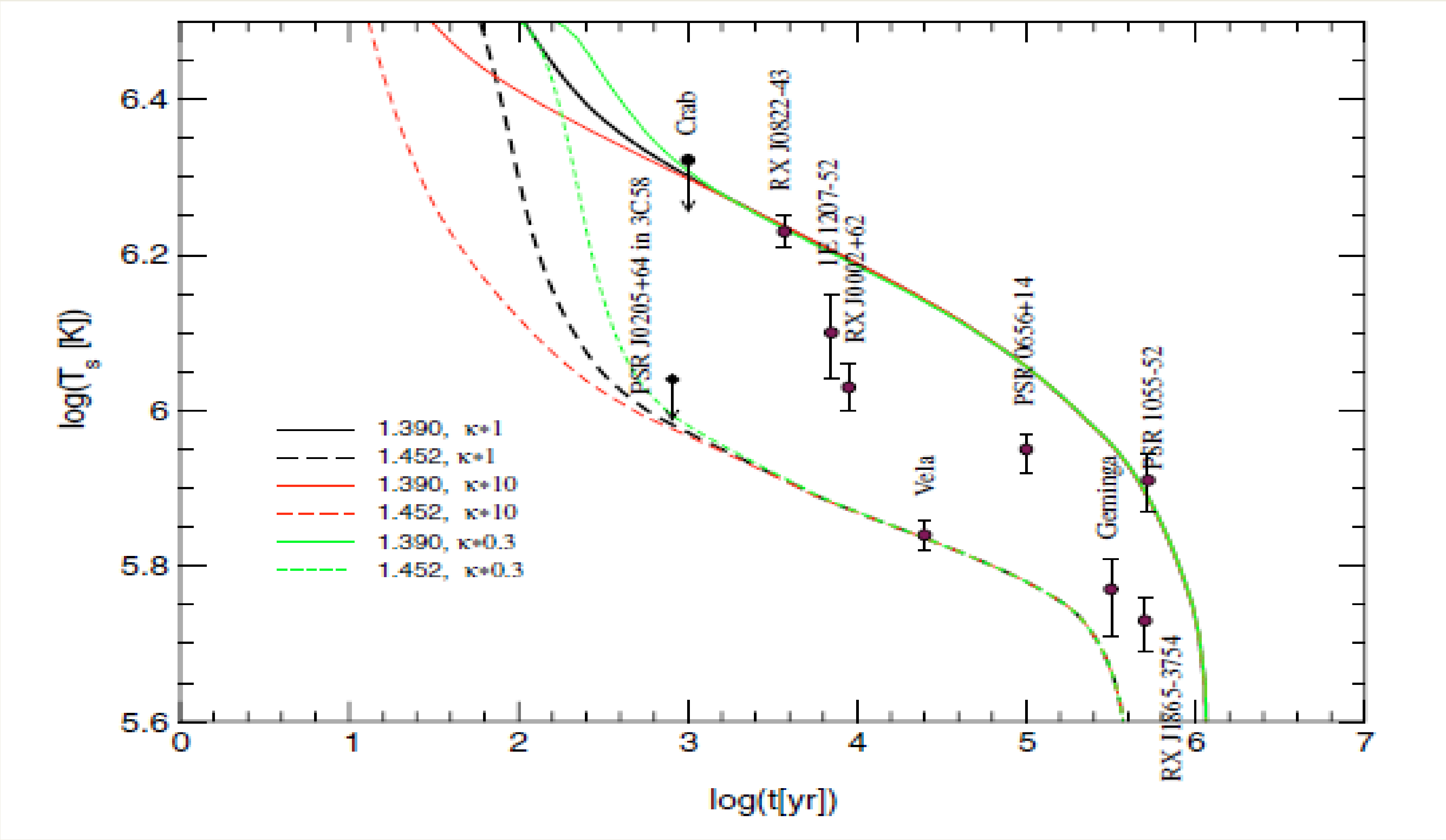
Grigorian, Voskresensky Astron.Astrophys. 444 (2005)

Contributions To Luminosities





The Influence Of A Change Of The Heat Conductivity On The Scenario



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

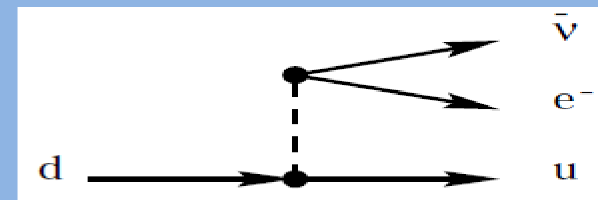
Neutrino emissivities in quark matter:

- Quark direct Urca (QDU) the most efficient processes

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

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

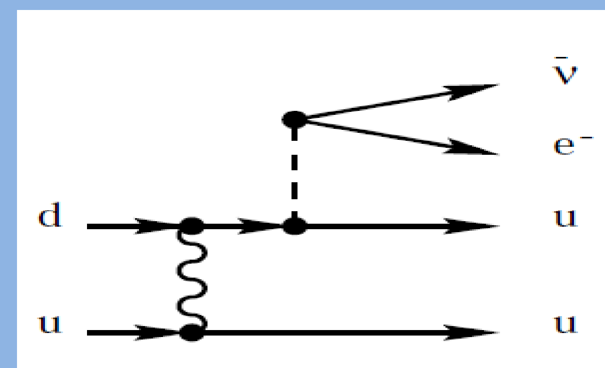
Compression n/no ≃ 2 , strong coupling αs ≈ 1



- Quark Modified Urca (QMU) and Quark Bremsstrahlung

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

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



- Suppression due to the pairing

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

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

- Enhanced cooling due to the pairing

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

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

Quark PBF

Crust Model

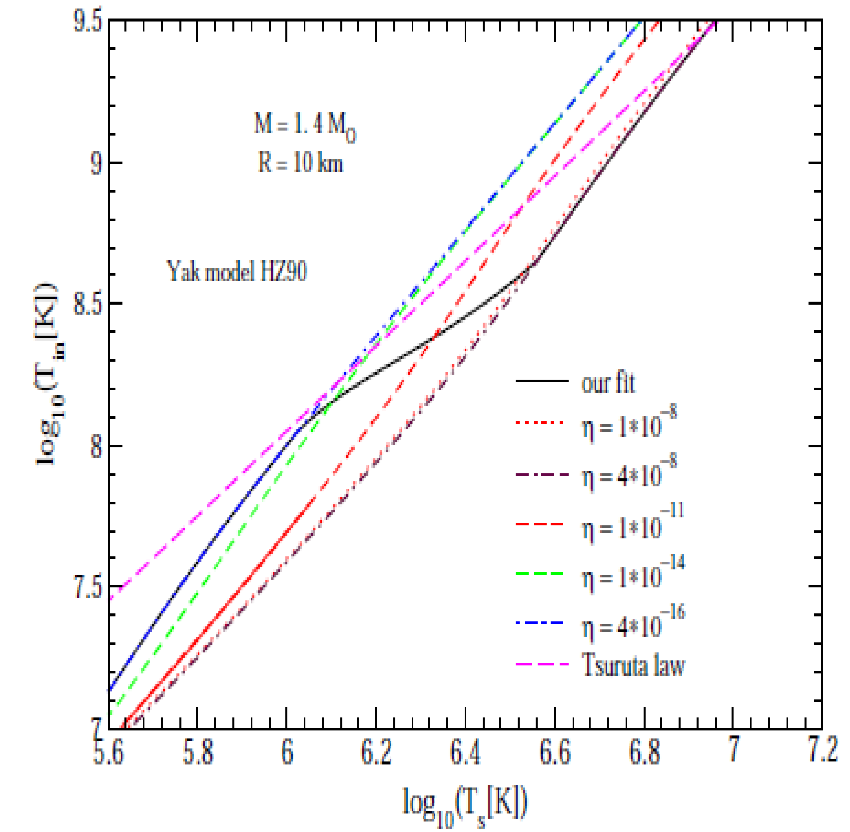
Time dependence of the light element contents in the crust

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

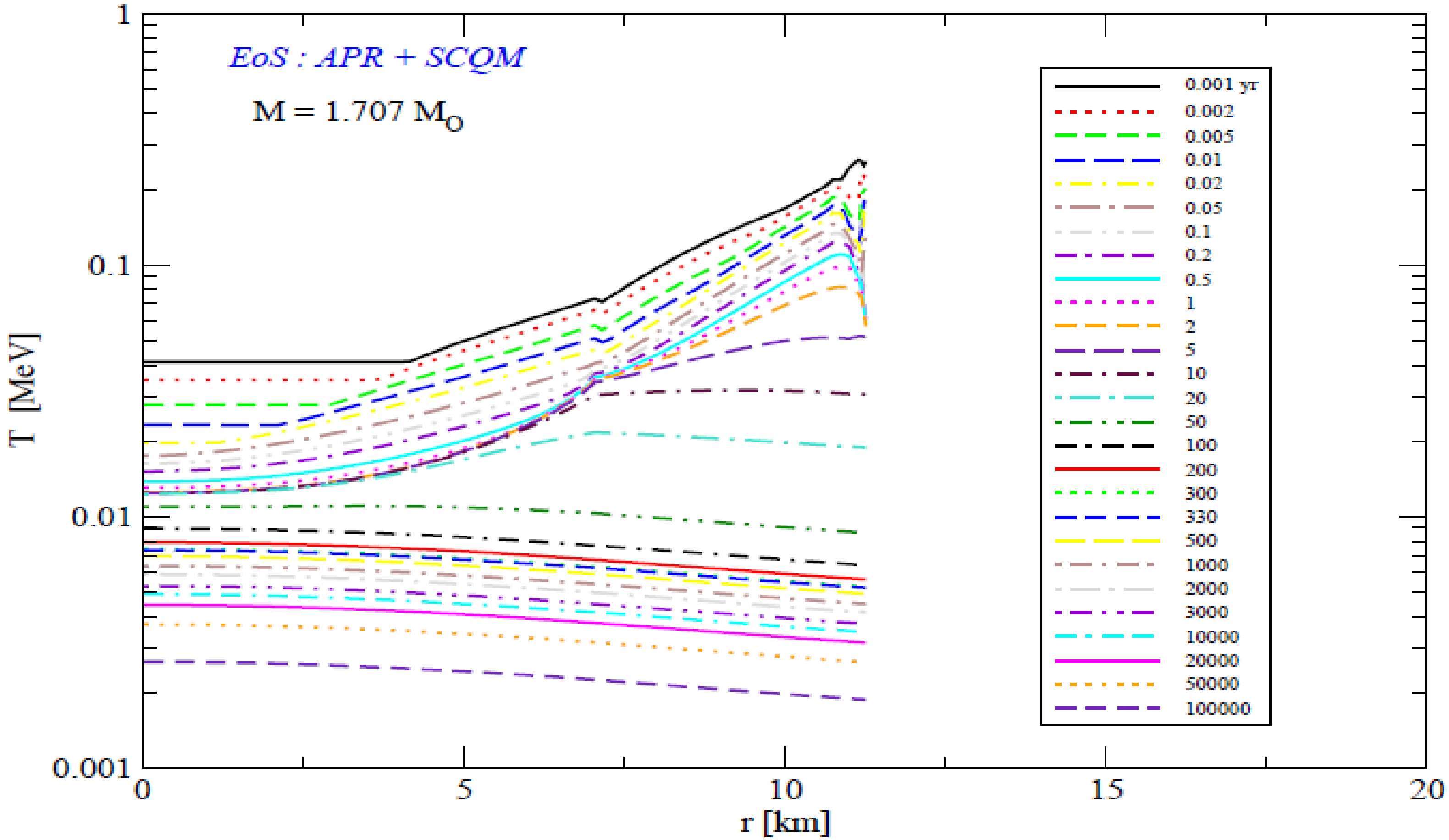
Blaschke, Grigorian, Voskresensky, A& A 368 (2001)561.

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

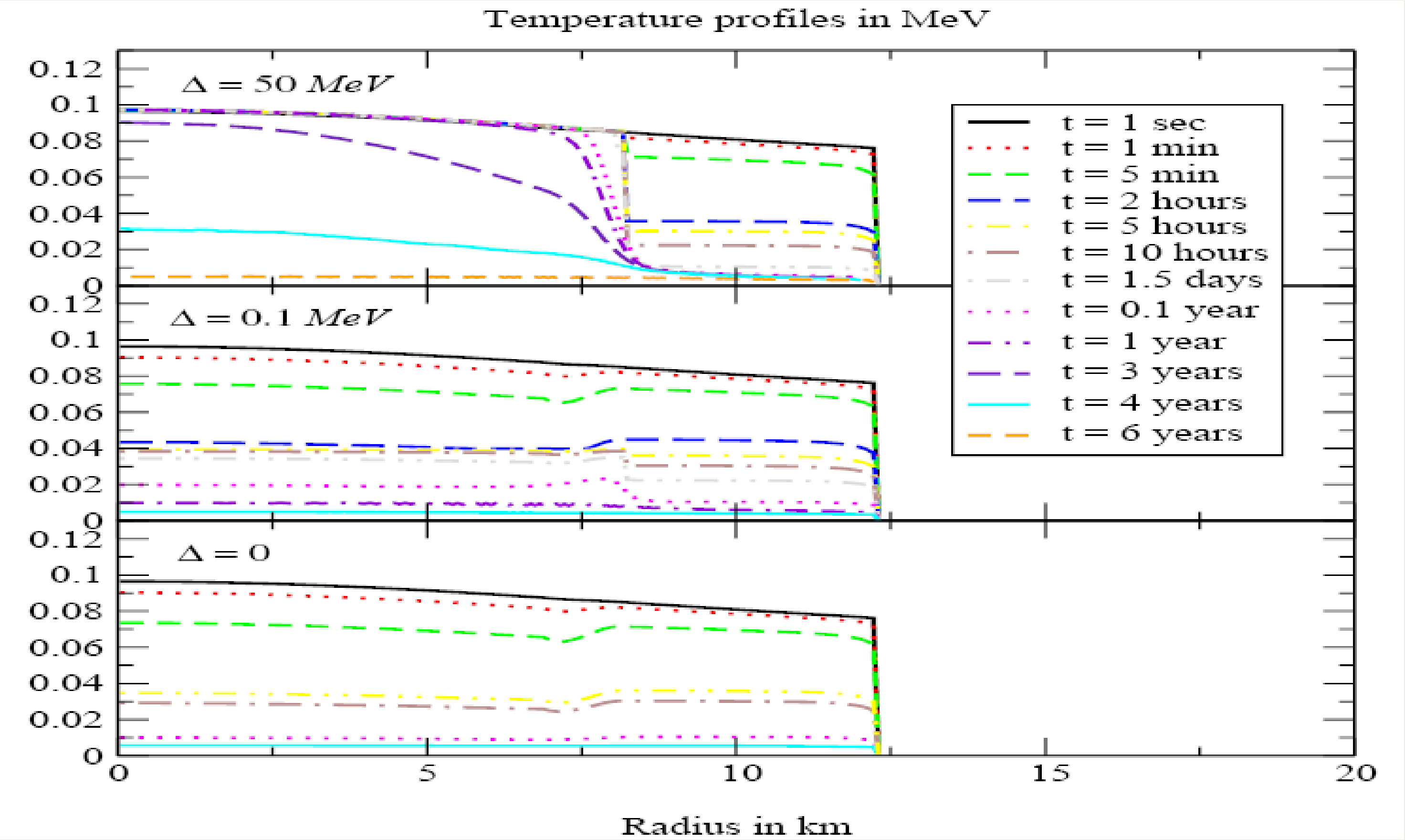
Yakovlev, Levenfish, Potekhin, Gnedin & Chabrier , Astron. Astrophys , 417, 169 (2004)



Temperature In The Hybrid Star Interior

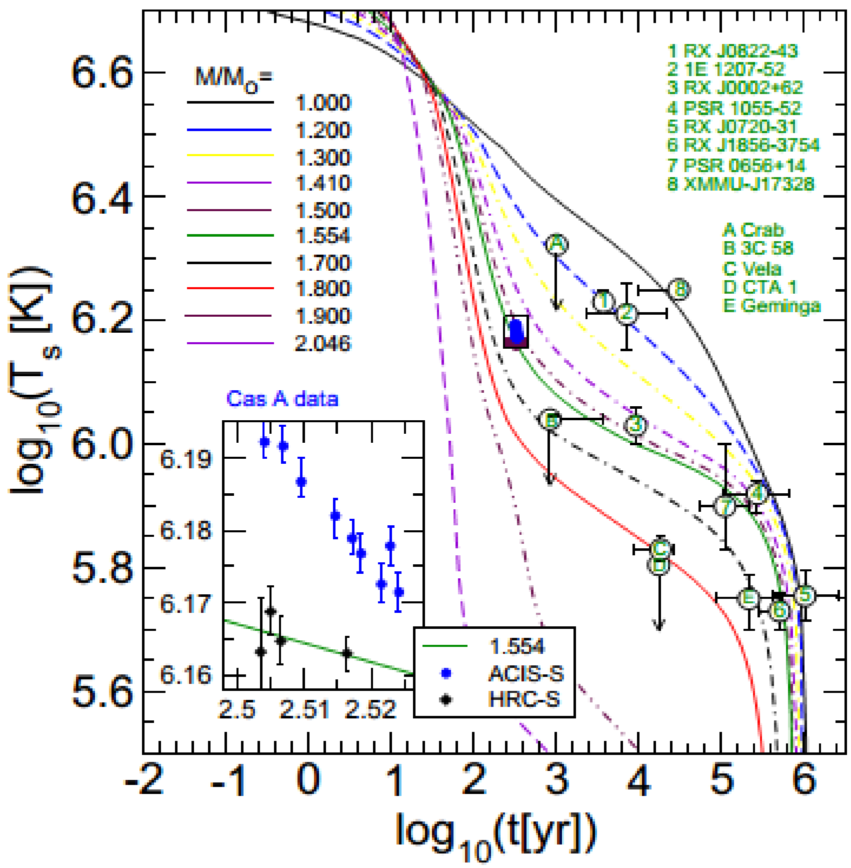


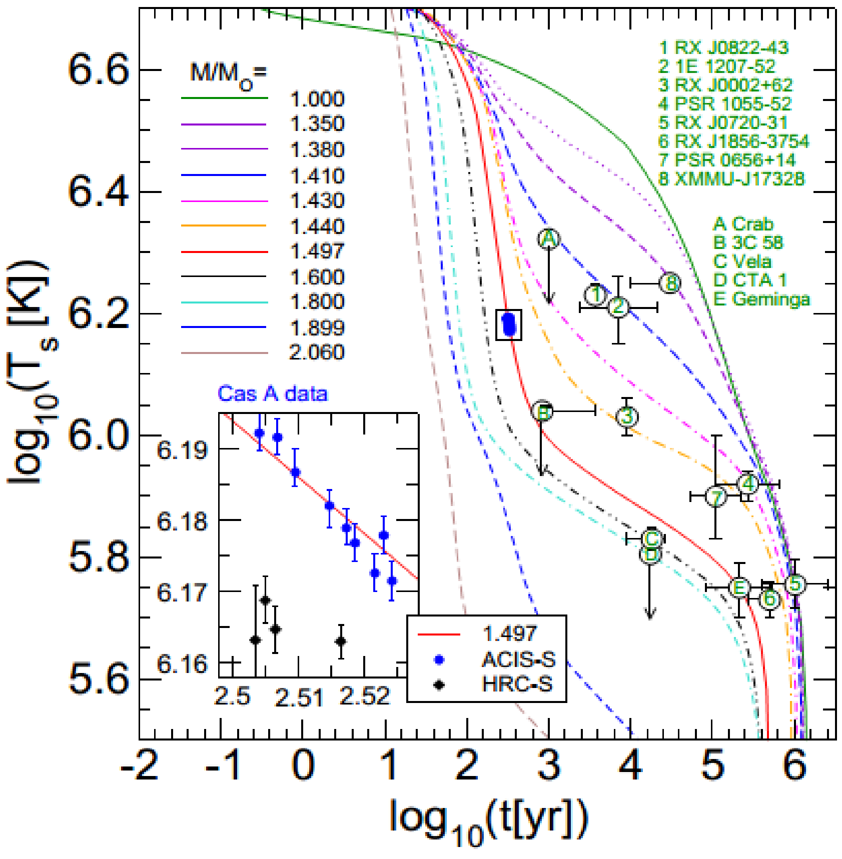
Temperature In The Hybrid Star Interior



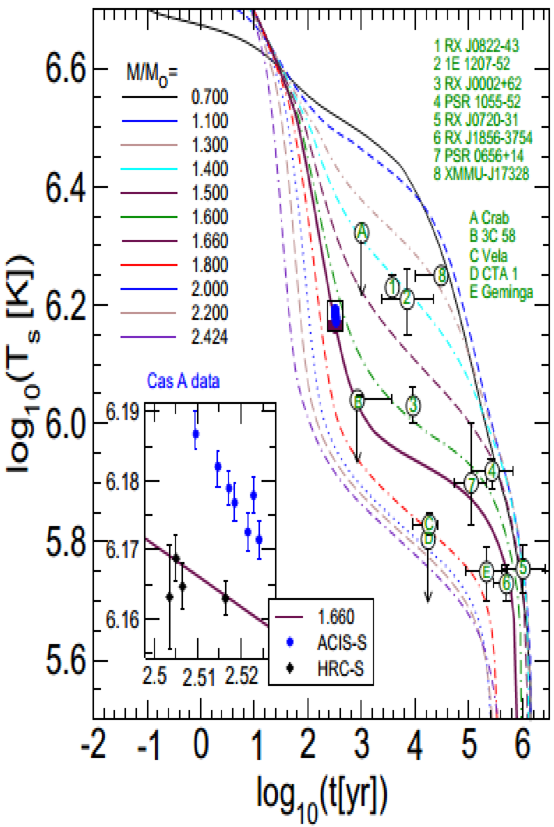
Blaschke, Grigorian, Voskresensky, A& A 368 (2001) 561

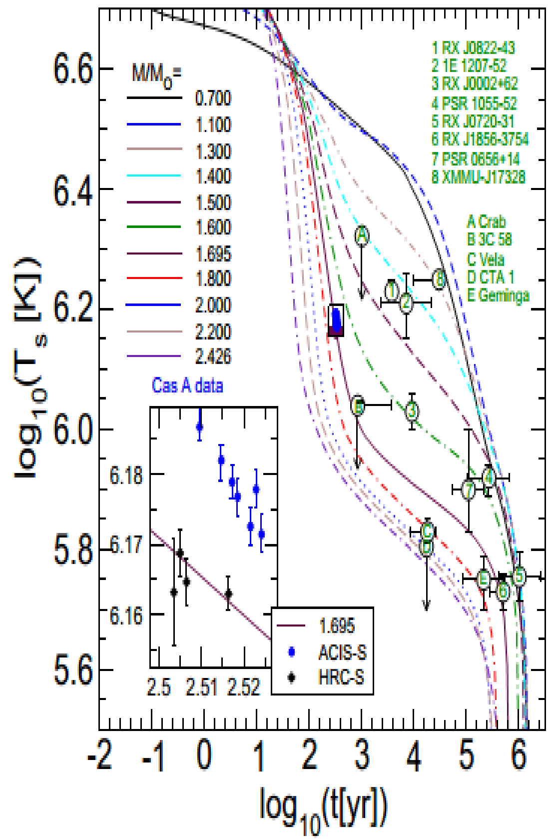
HDD – AV18 , Yak.
ME nc = 3 n0

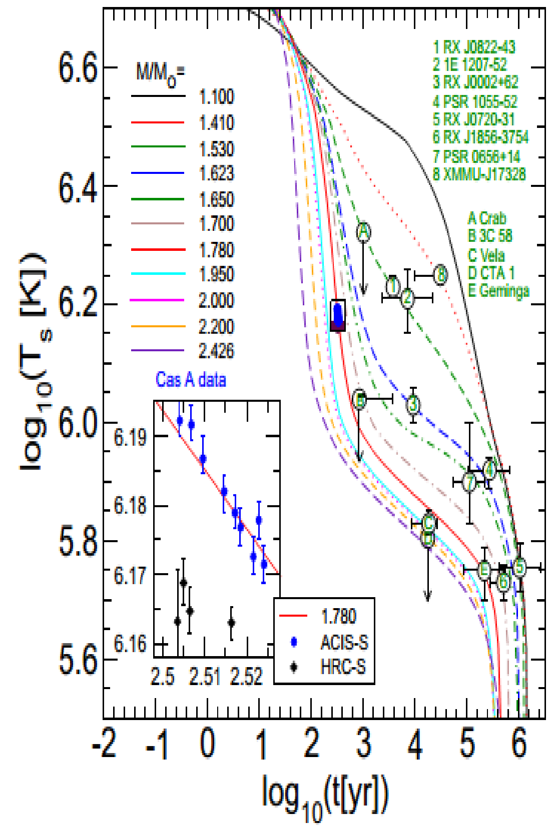




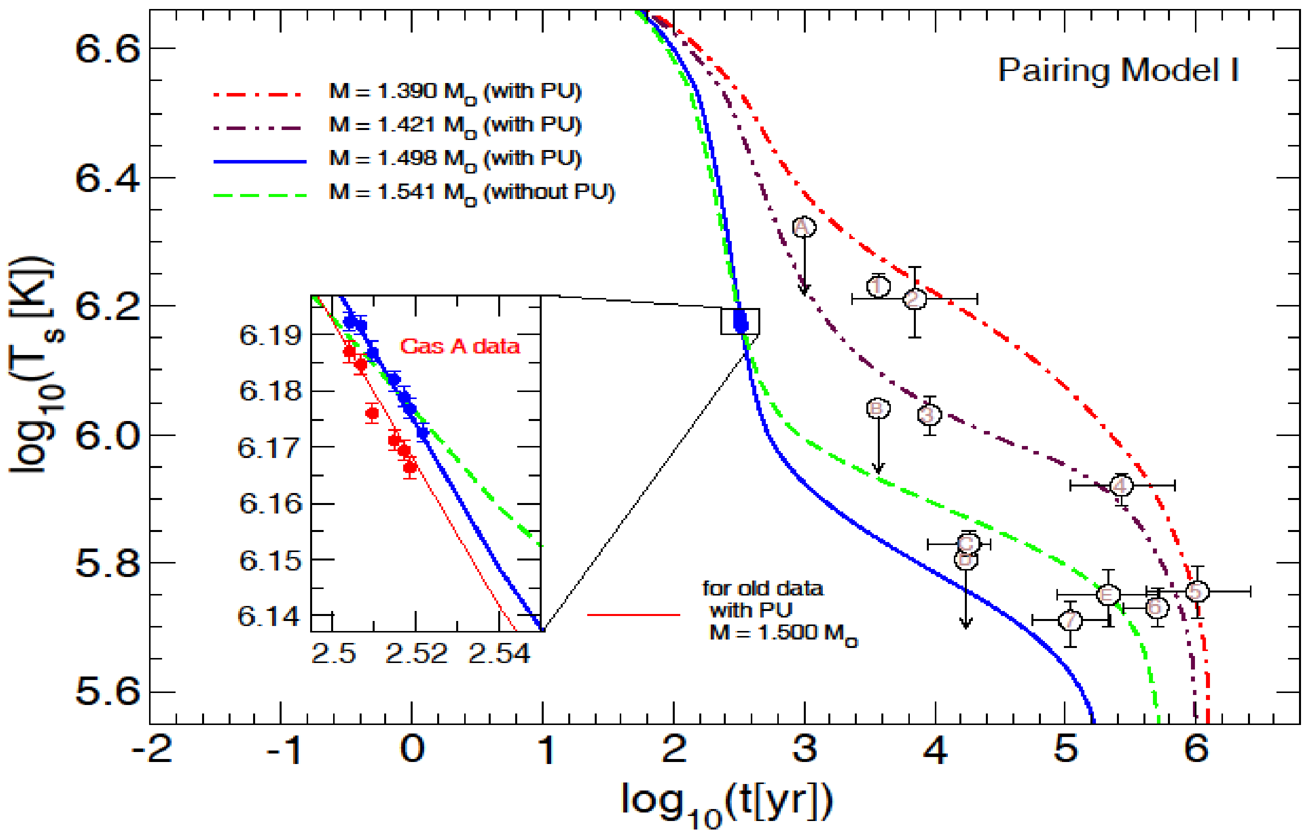
DD2 – EEHOr
ME-nc=1.5,2.0,2.5n0



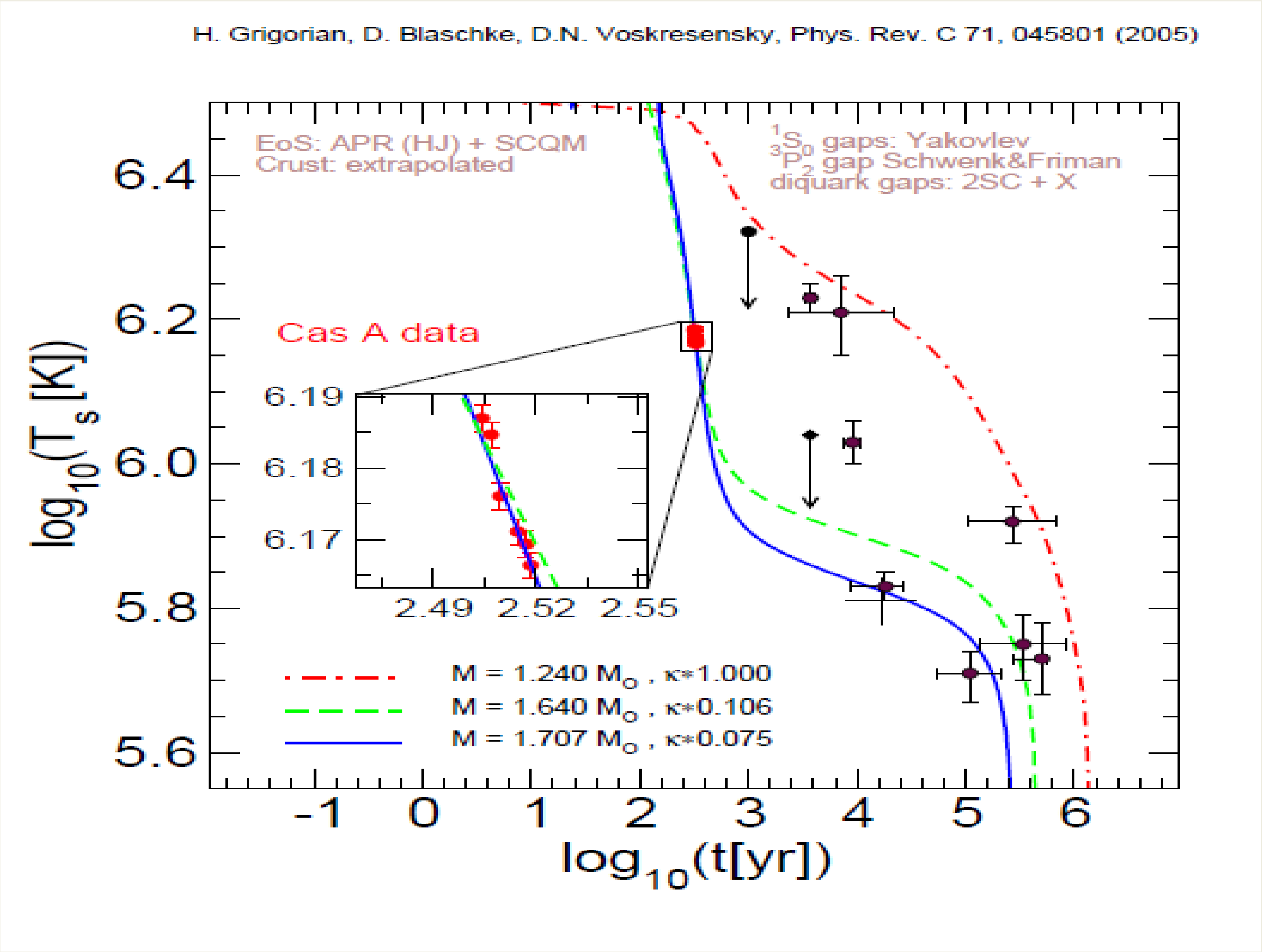




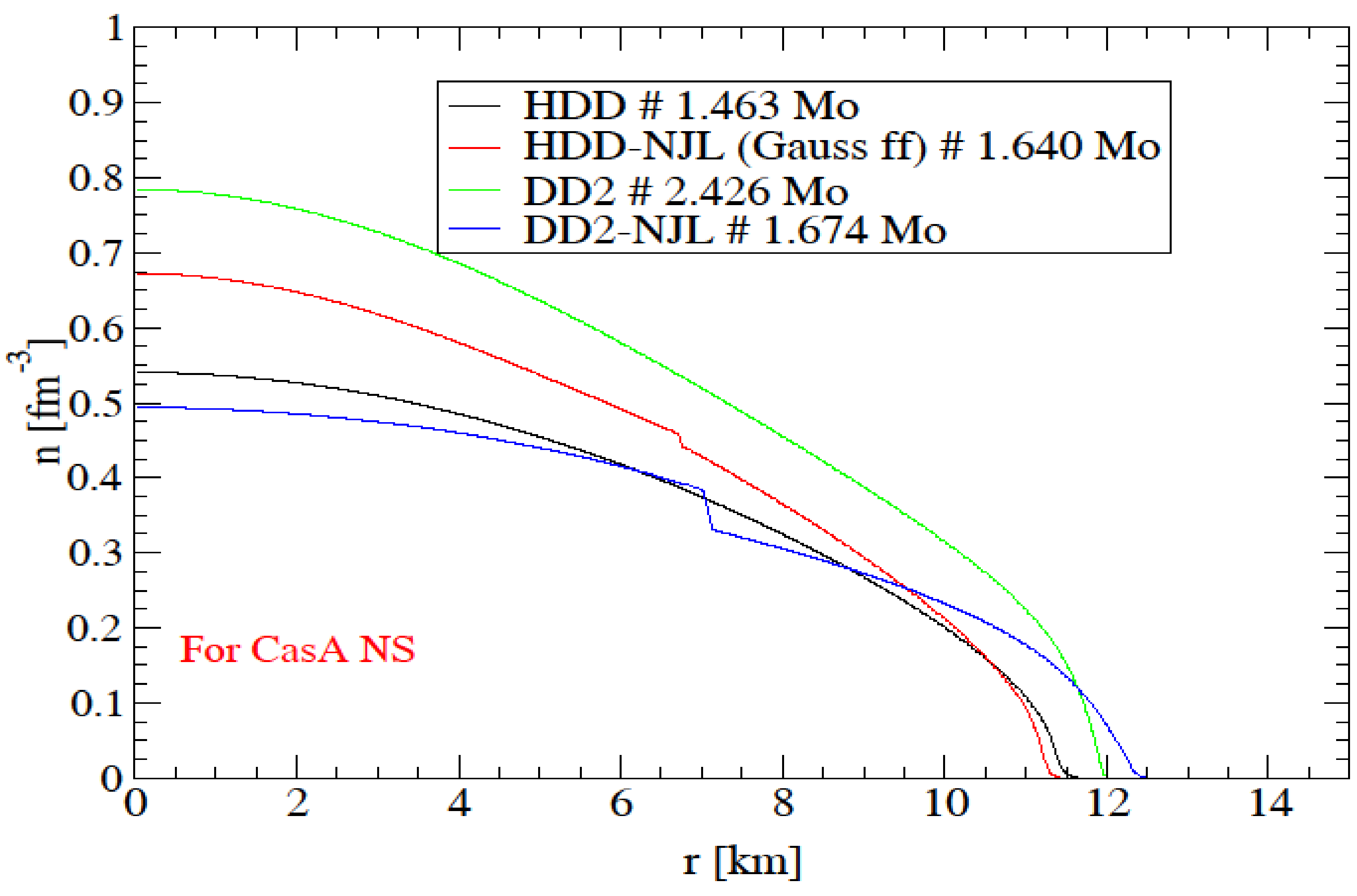
Cas A as an Hadronic Star



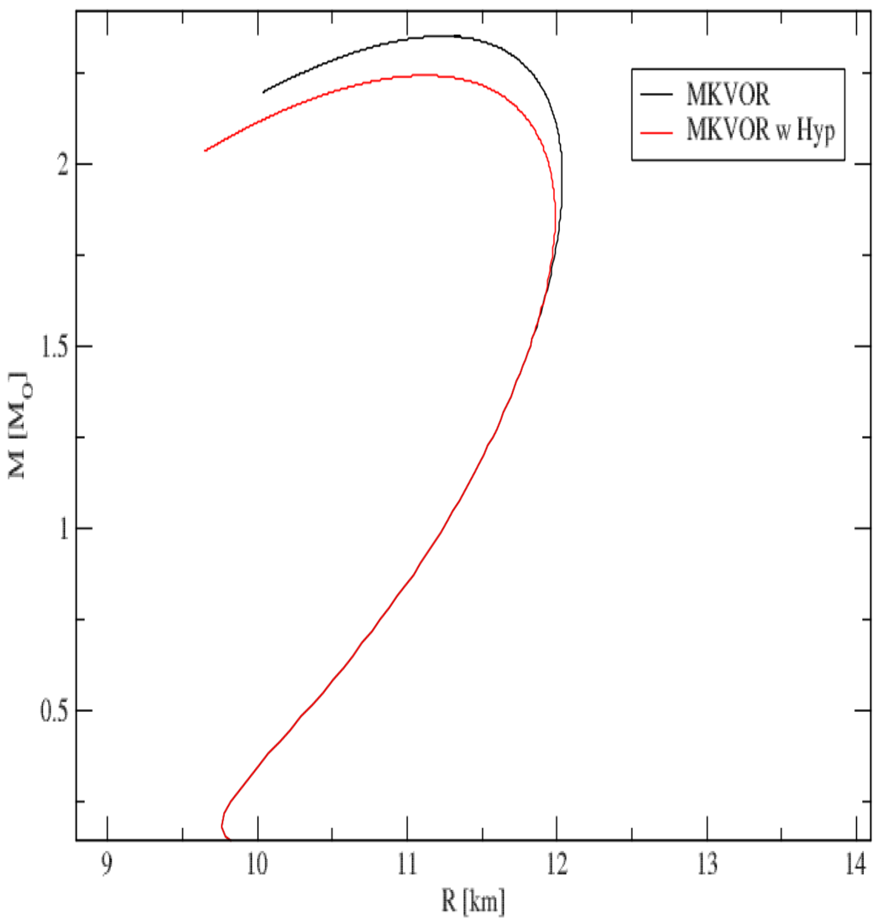
Cas A As An Hybrid Star



Possible internal structure of CasA



MKVOR – EoS model



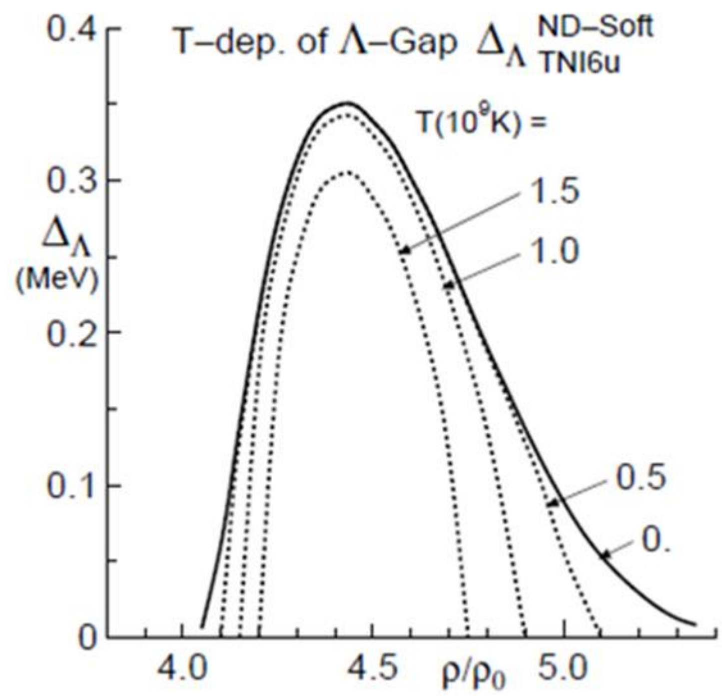
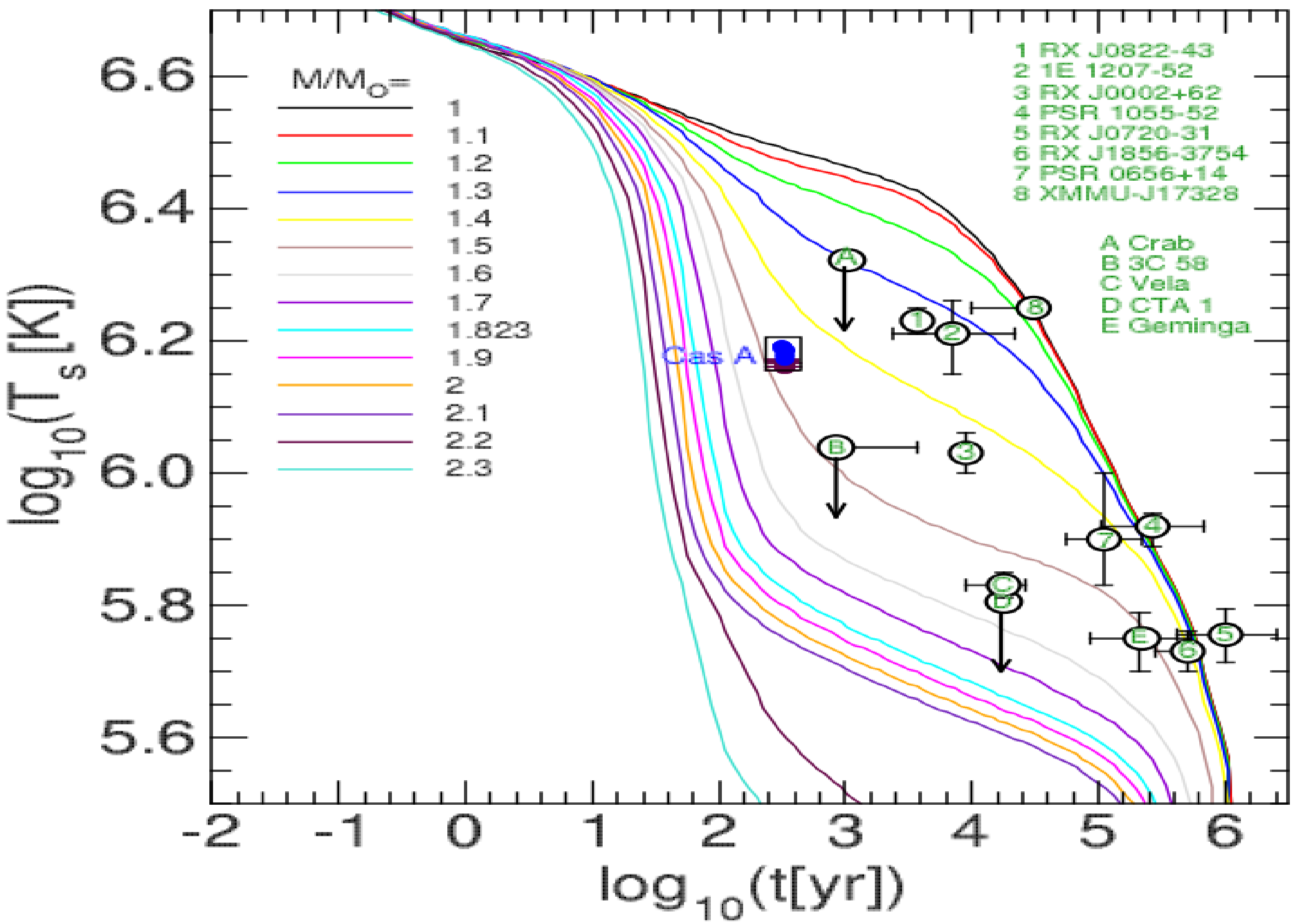
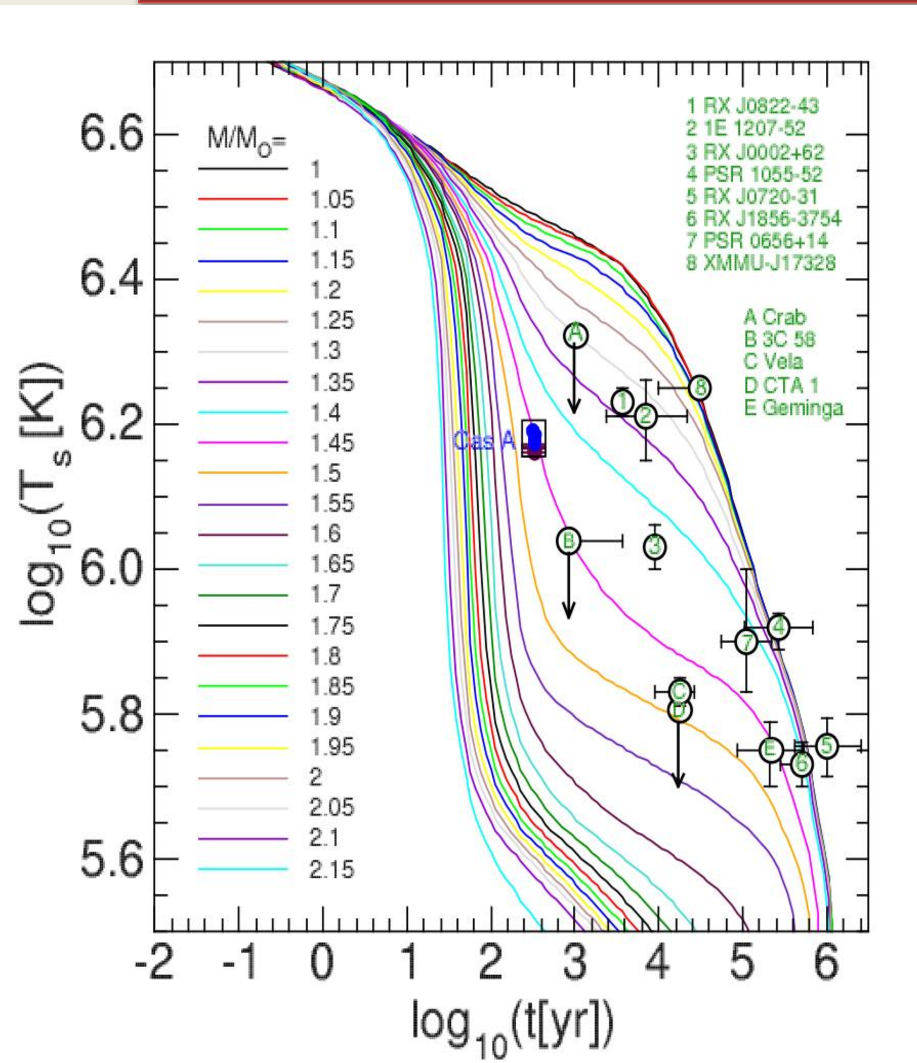


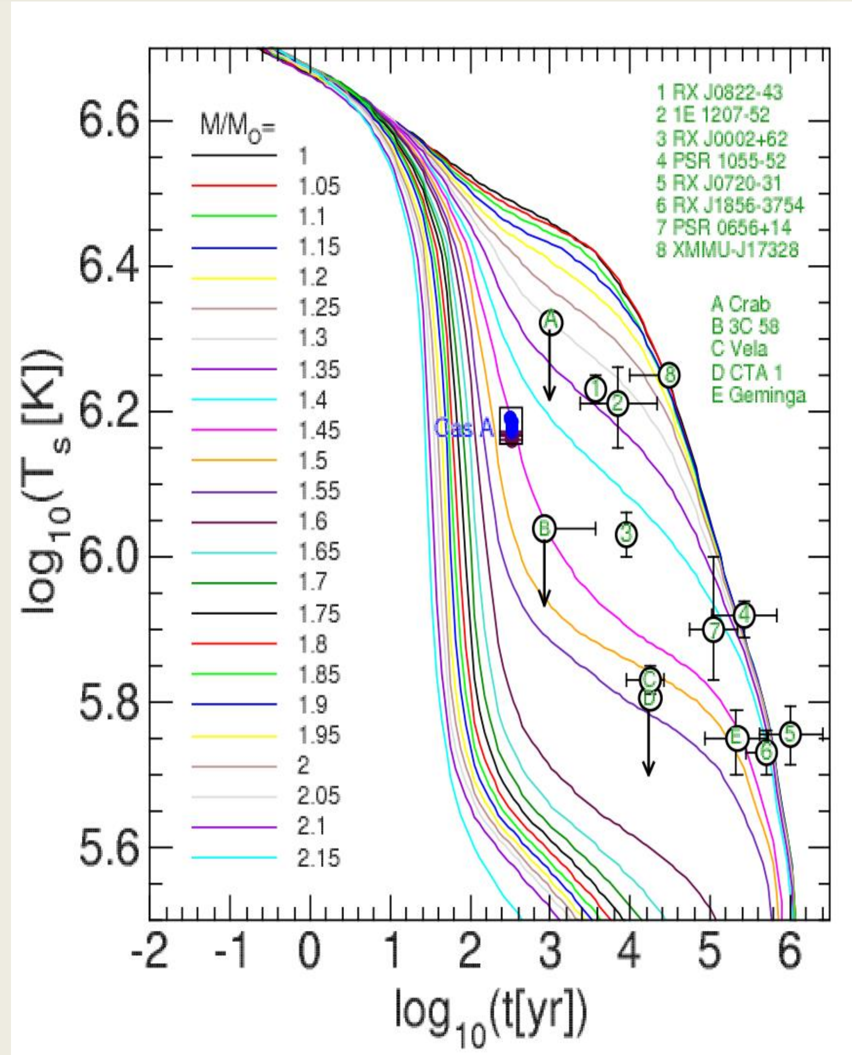
Fig. 8. Temperature(T) dependence of Λ energy gap (Δ_Λ) for the case of TNI6u EOS and ND-Soft potential, as an example.

MKVOR – EEHOr
ME-nc=3.0n0

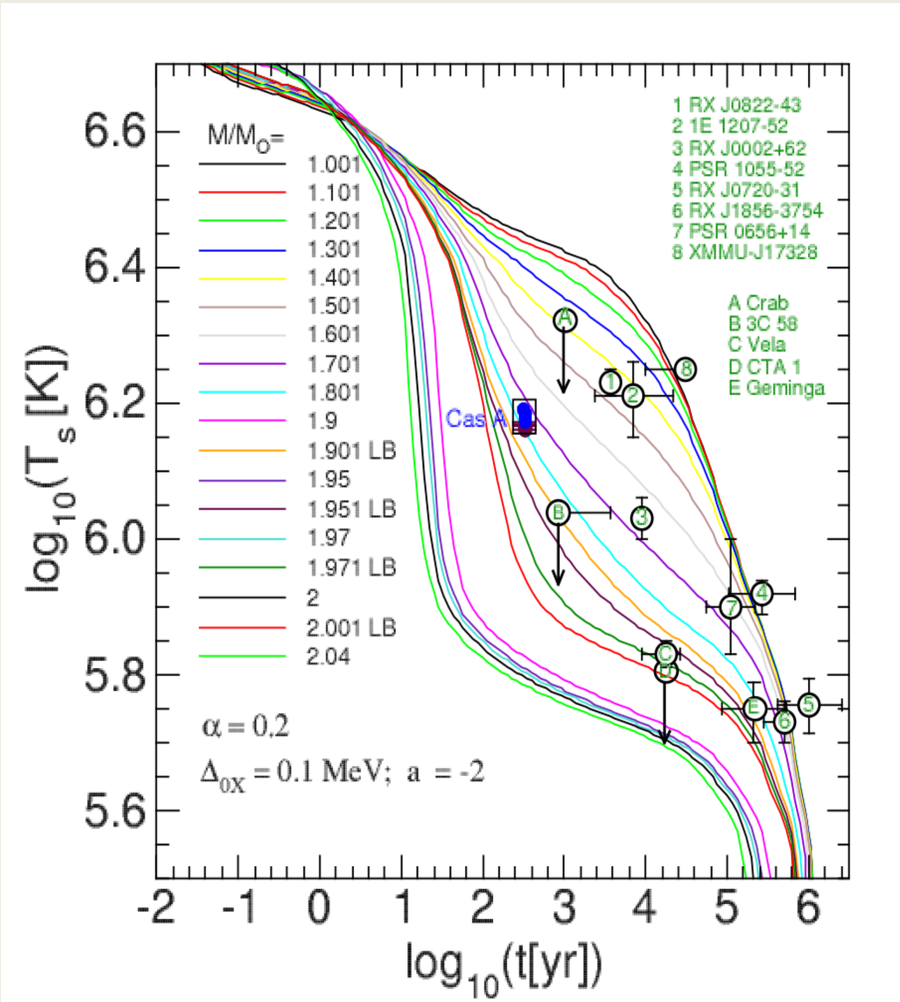


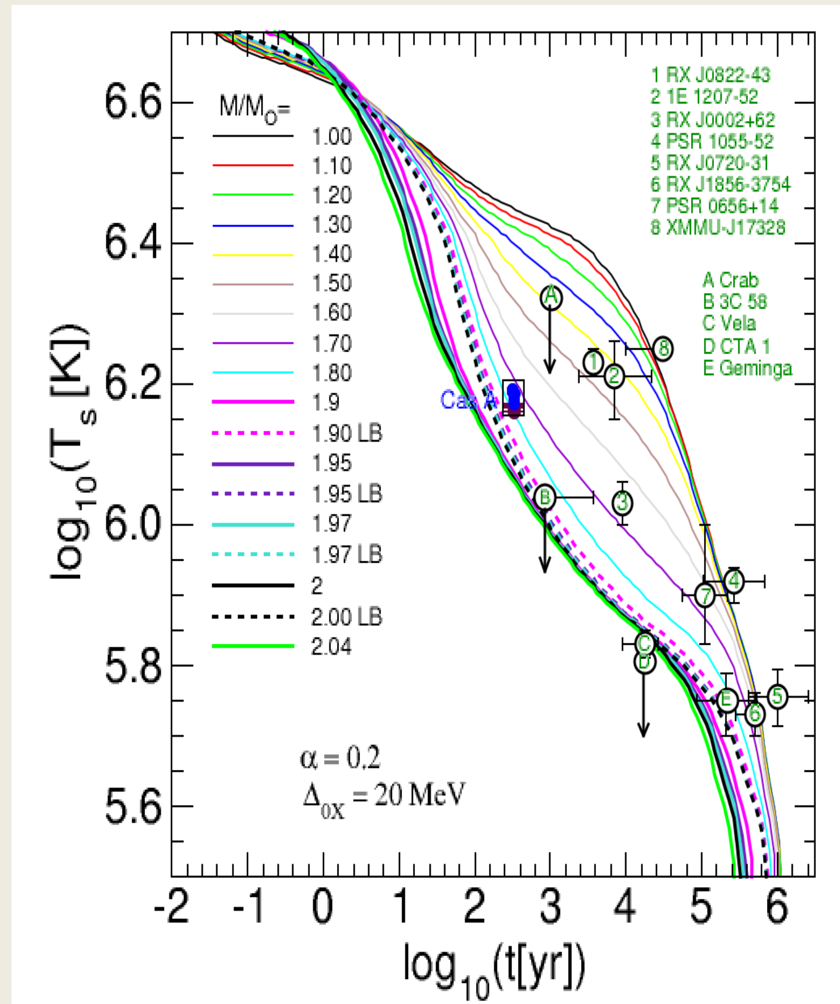
MKVOR Hyp – EEHOr ME-nc=3.0n0

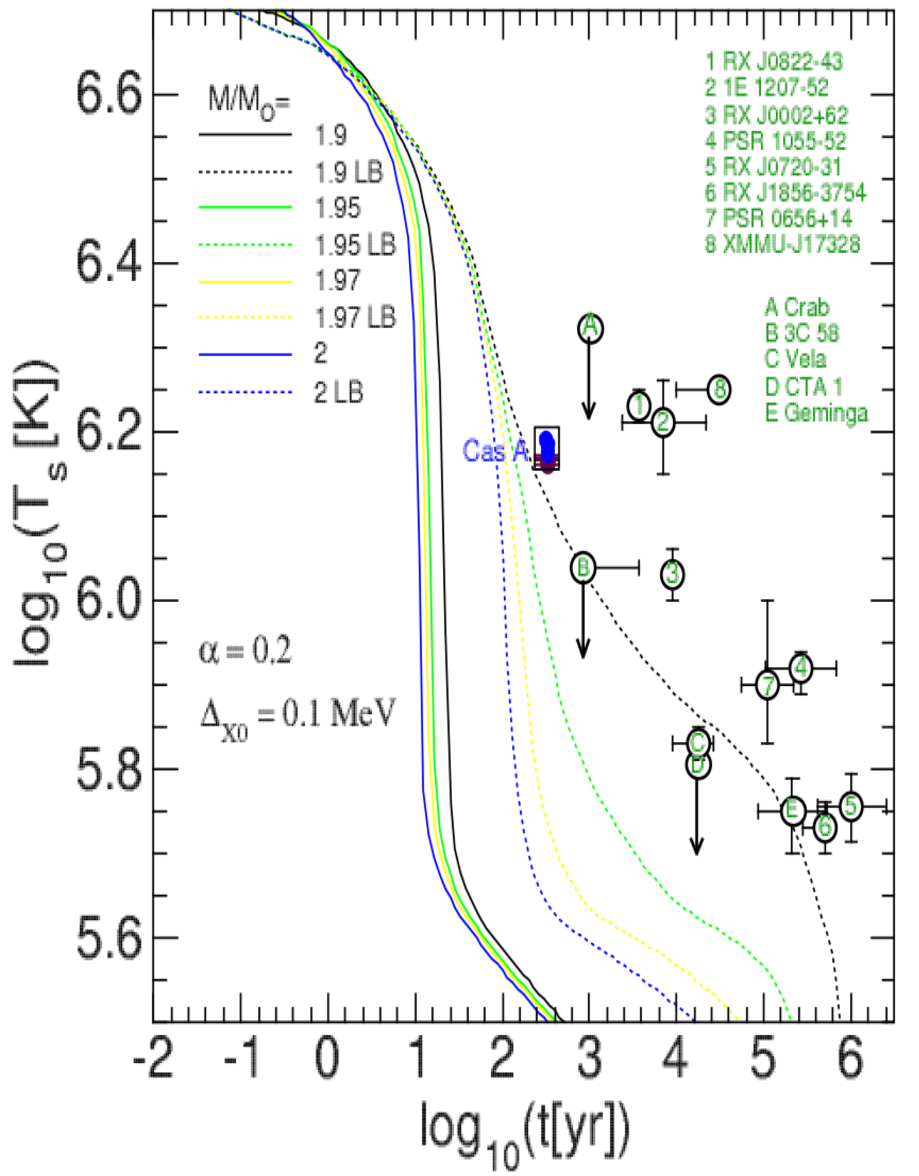




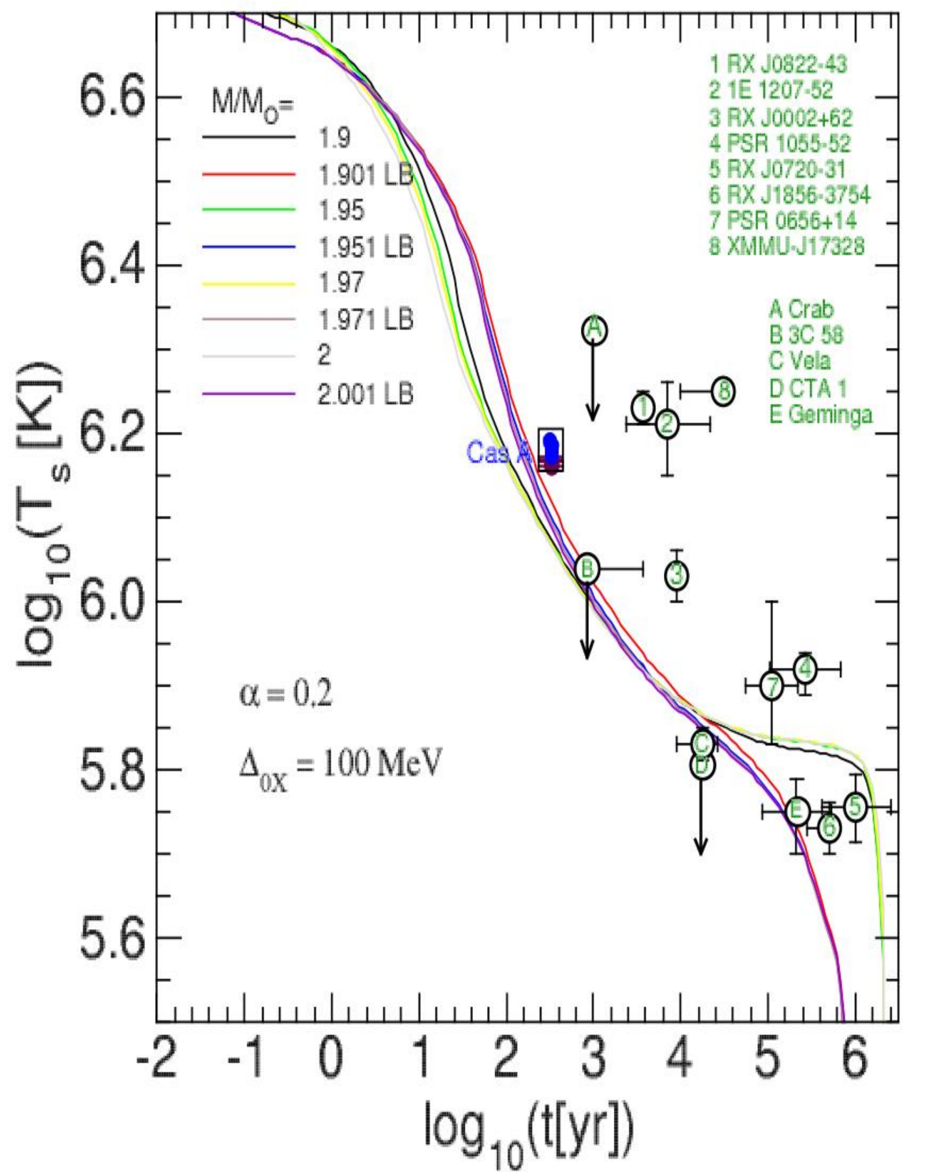
Cooling of Twin CS



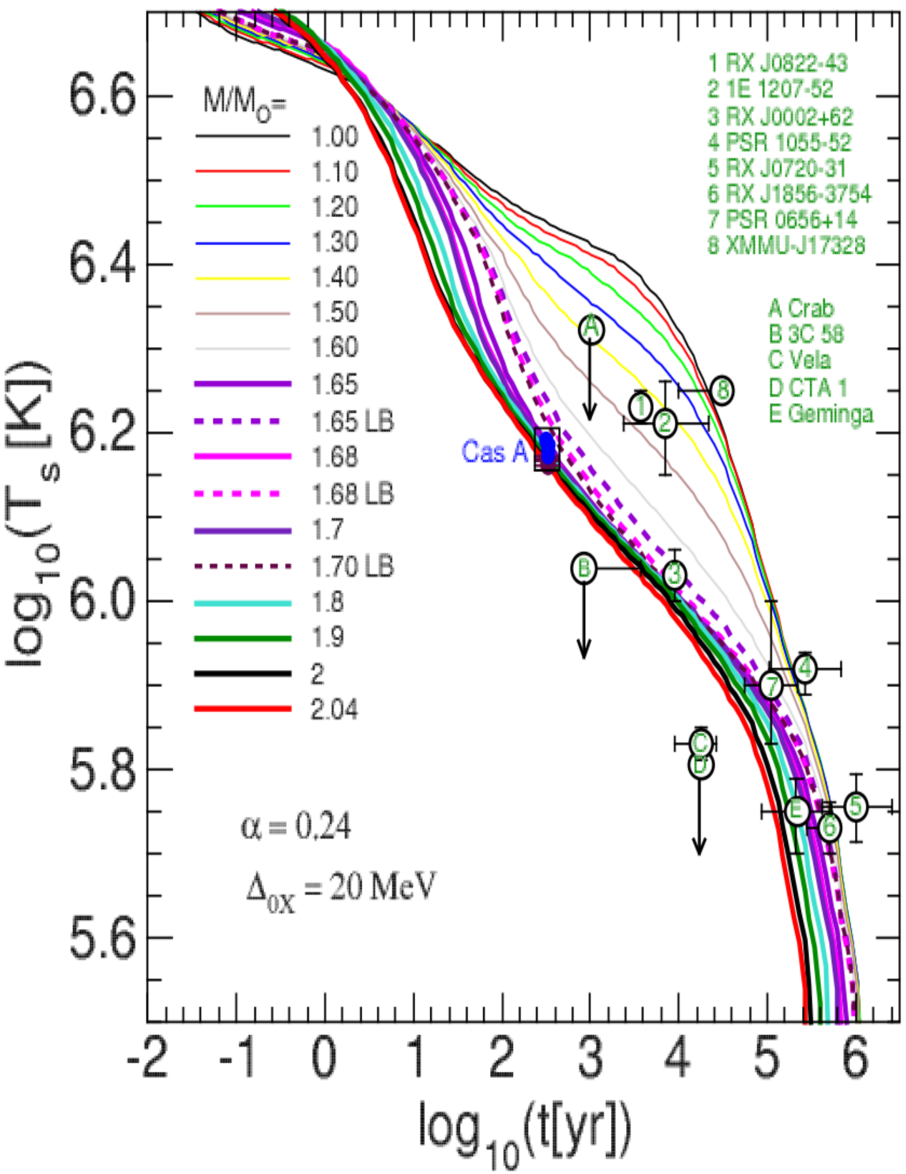




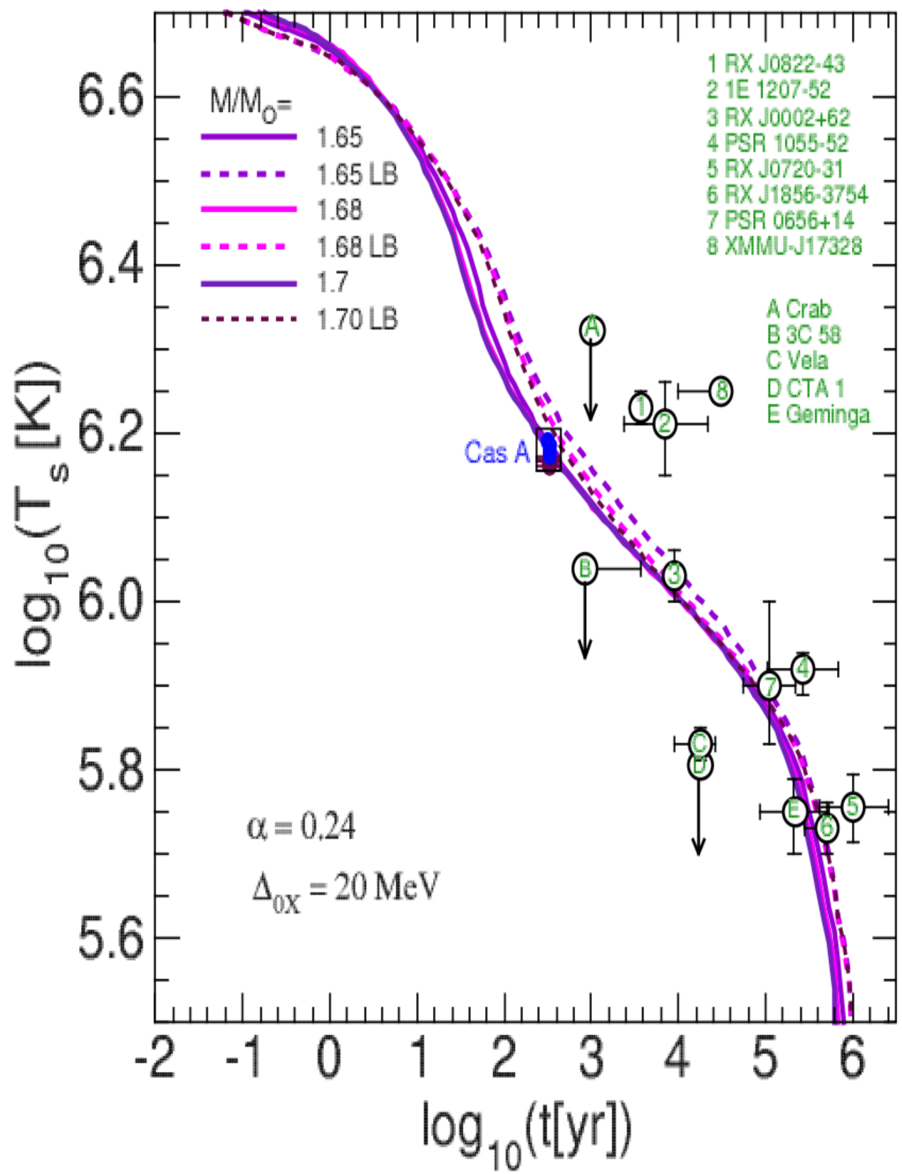
$\log_{10}(T_s\,[K])$
$\log_{10}(t[yr])$
M/M$_O$=
1.9
1.9 LB
1.95
1.95 LB
1.97
1.97 LB
2
2 LB
1 RX J0822-43
2 1E 1207-52
3 RX J0002+62
4 PSR 1055-52
5 RX J0720-31
6 RX J1856-3754
7 PSR 0656+14
8 XMMU-J17328
A Crab
B 3C 58
C Vela
D CTA 1
E Geminga
Cas A
$\alpha = 0.2$
$\Delta_{X0} = 0.1$ MeV



$\log_{10}(T_s\,[K])$
$\log_{10}(t[yr])$
M/M$_O$=
1.9
1.901 LB
1.95
1.951 LB
1.97
1.971 LB
2
2.001 LB
1 RX J0822-43
2 1E 1207-52
3 RX J0002+62
4 PSR 1055-52
5 RX J0720-31
6 RX J1856-3754
7 PSR 0656+14
8 XMMU-J17328
A Crab
B 3C 58
C Vela
D CTA 1
E Geminga
Cas A
$\alpha = 0.2$
$\Delta_{0X} = 100$ MeV



M/M_O=
1.00
1.10
1.20
1.30
1.40
1.50
1.60
1.65
1.65 LB
1.68
1.68 LB
1.7
1.70 LB
1.8
1.9
2
2.04
1 RX J0822-43
2 1E 1207-52
3 RX J0002+62
4 PSR 1055-52
5 RX J0720-31
6 RX J1856-3754
7 PSR 0656+14
8 XMMU-J17328
A Crab
B 3C 58
C Vela
D CTA 1
E Geminga
Cas A
α = 0.24
Δ0X = 20 MeV
log10(Ts [K])
log10(t[yr])



M/M_O=
1.65
1.65 LB
1.68
1.68 LB
1.7
1.70 LB
1 RX J0822-43
2 1E 1207-52
3 RX J0002+62
4 PSR 1055-52
5 RX J0720-31
6 RX J1856-3754
7 PSR 0656+14
8 XMMU-J17328
A Crab
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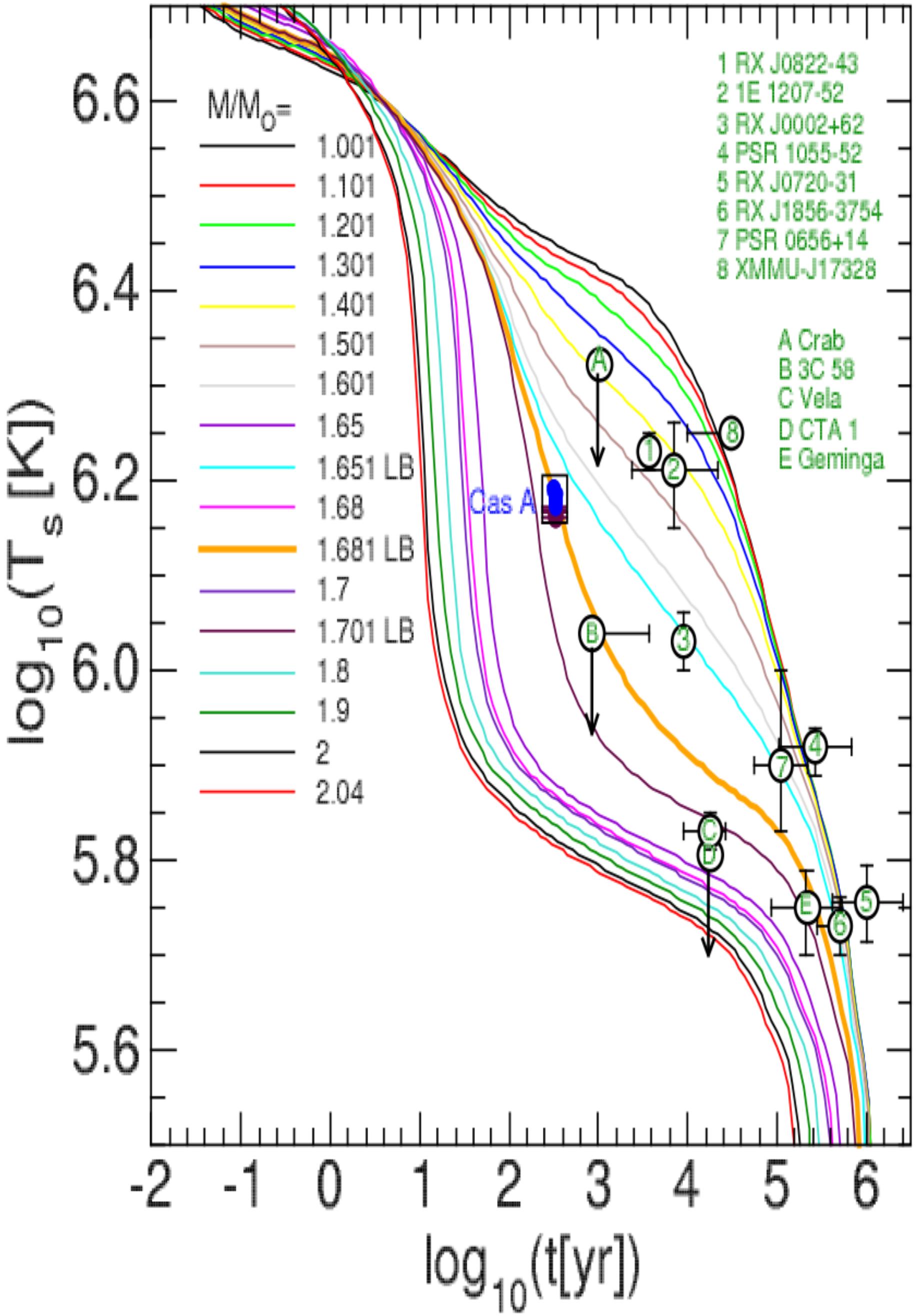
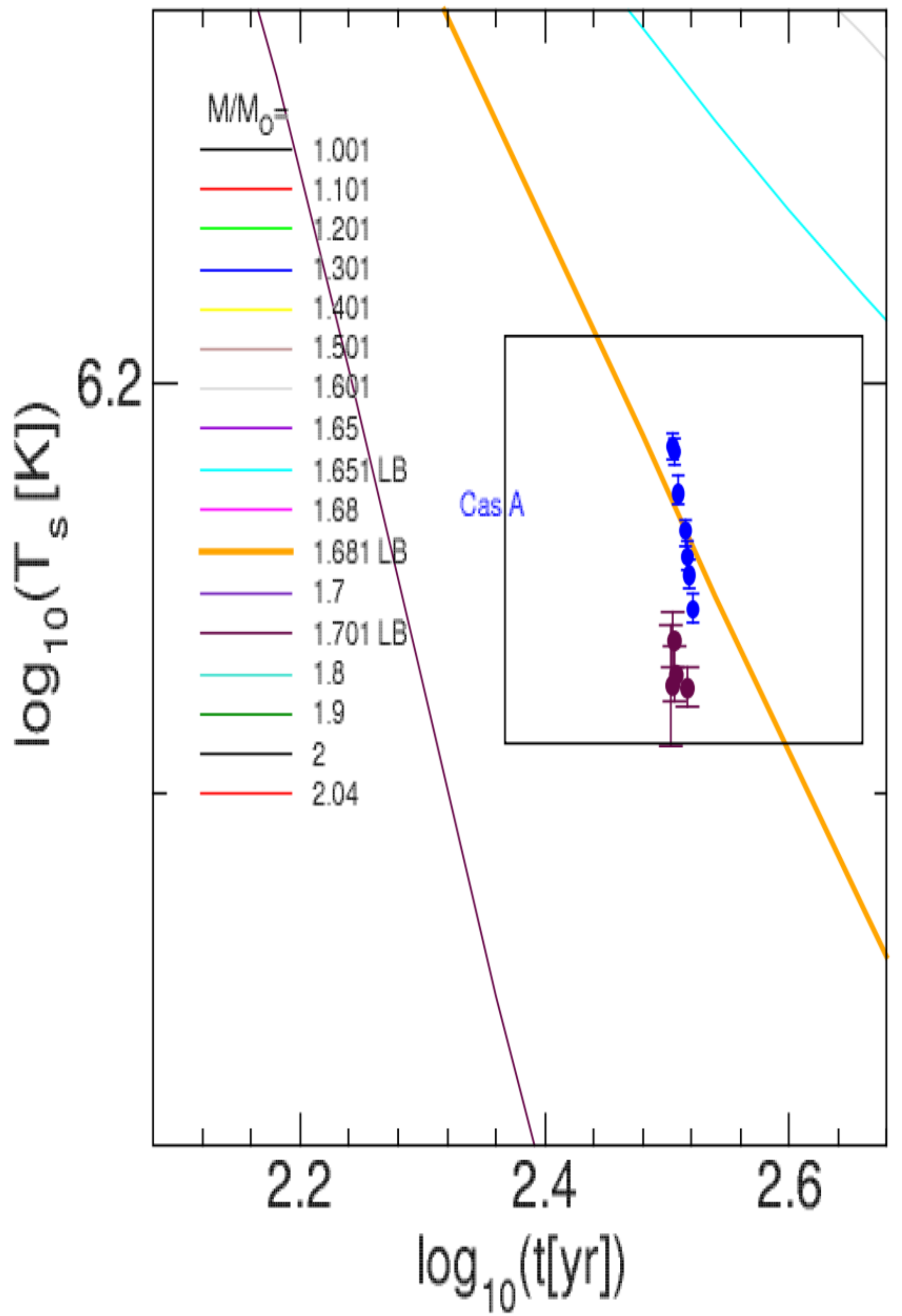
C Vela
D CTA 1
E Geminga
Cas A
α = 0.24
Δ0X = 20 MeV
log10(Ts [K])
log10(t[yr])


log10(Ts [K])
log10(t[yr])
M/Mo=
1.001
1.101
1.201
1.301
1.401
1.501
1.601
1.65
1.651 LB
1.68
1.681 LB
1.7
1.701 LB
1.8
1.9
2
2.04
1 RX J0822-43
2 1E 1207-52
3 RX J0002+62
4 PSR 1055-52
5 RX J0720-31
6 RX J1856-3754
7 PSR 0656+14
8 XMMU-J17328
A Crab
B 3C 58
C Vela
D CTA 1
E Geminga
Cas A
6.6
6.4
6.2
6.0
5.8
5.6
-2
-1
0
1
2
3
4
5
6

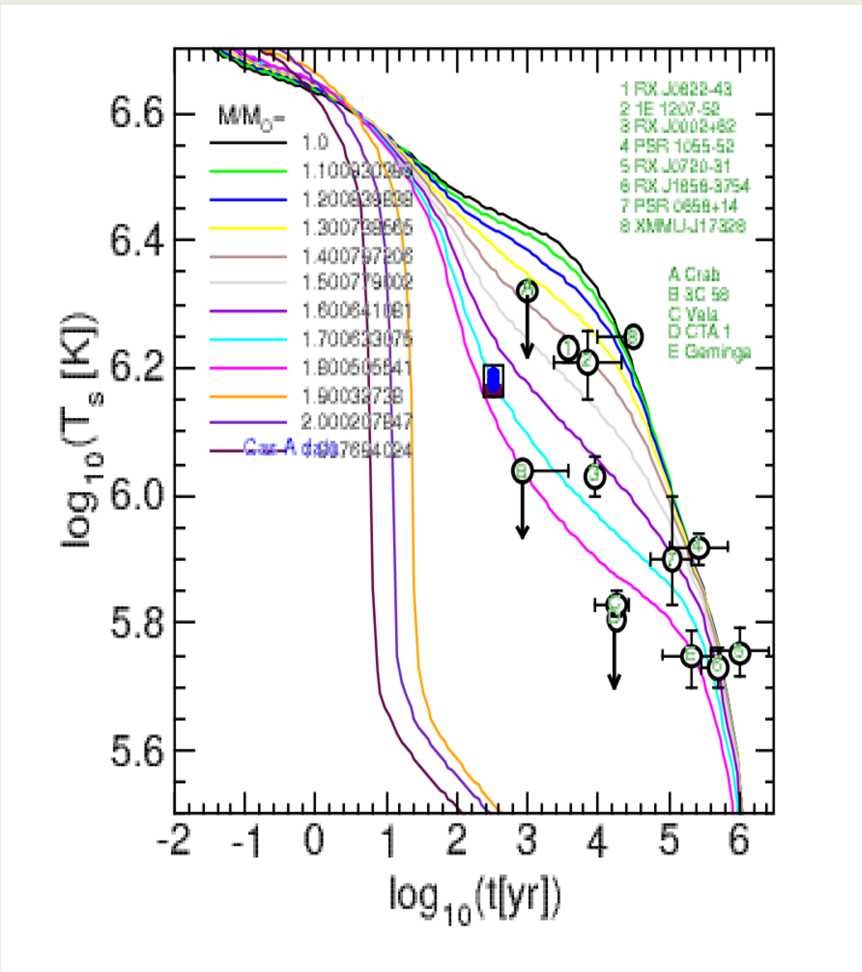

log10(Ts [K])
log10(t[yr])
M/Mo=
1.001
1.101
1.201
1.301
1.401
1.501
1.601
1.65
1.651 LB
1.68
1.681 LB
1.7
1.701 LB
1.8
1.9
2
2.04
Cas A
6.2
2.2
2.4
2.6

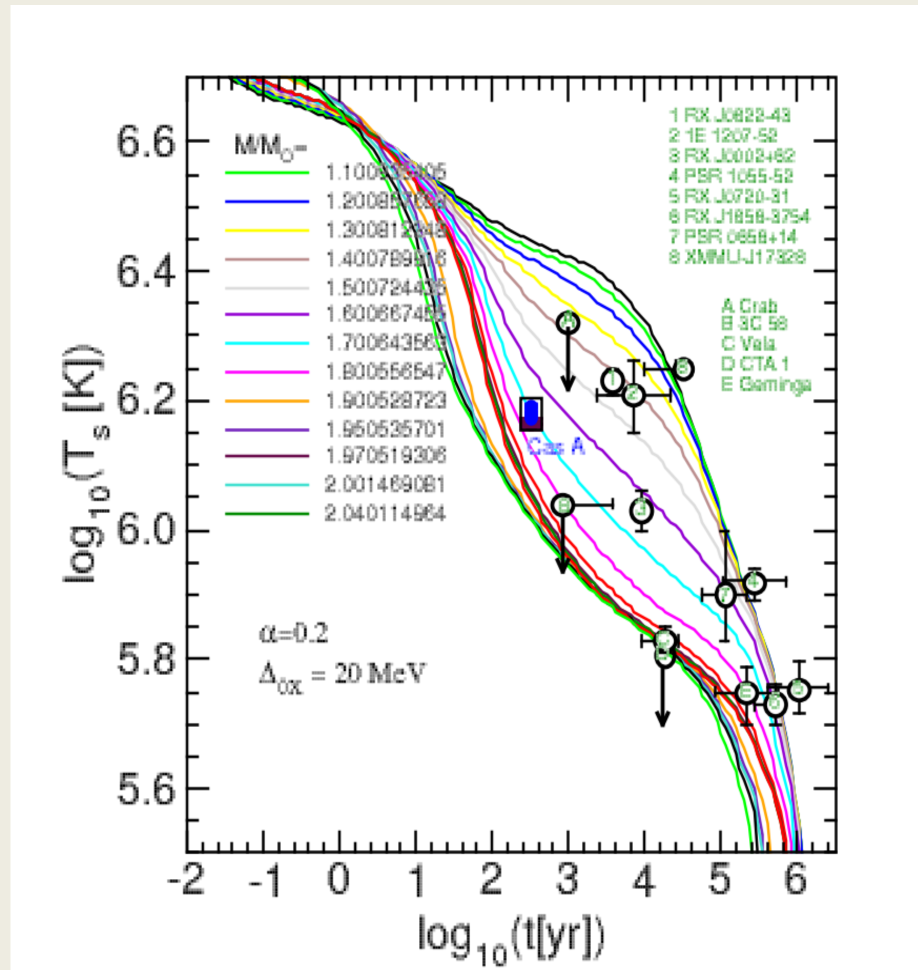
Conclusions

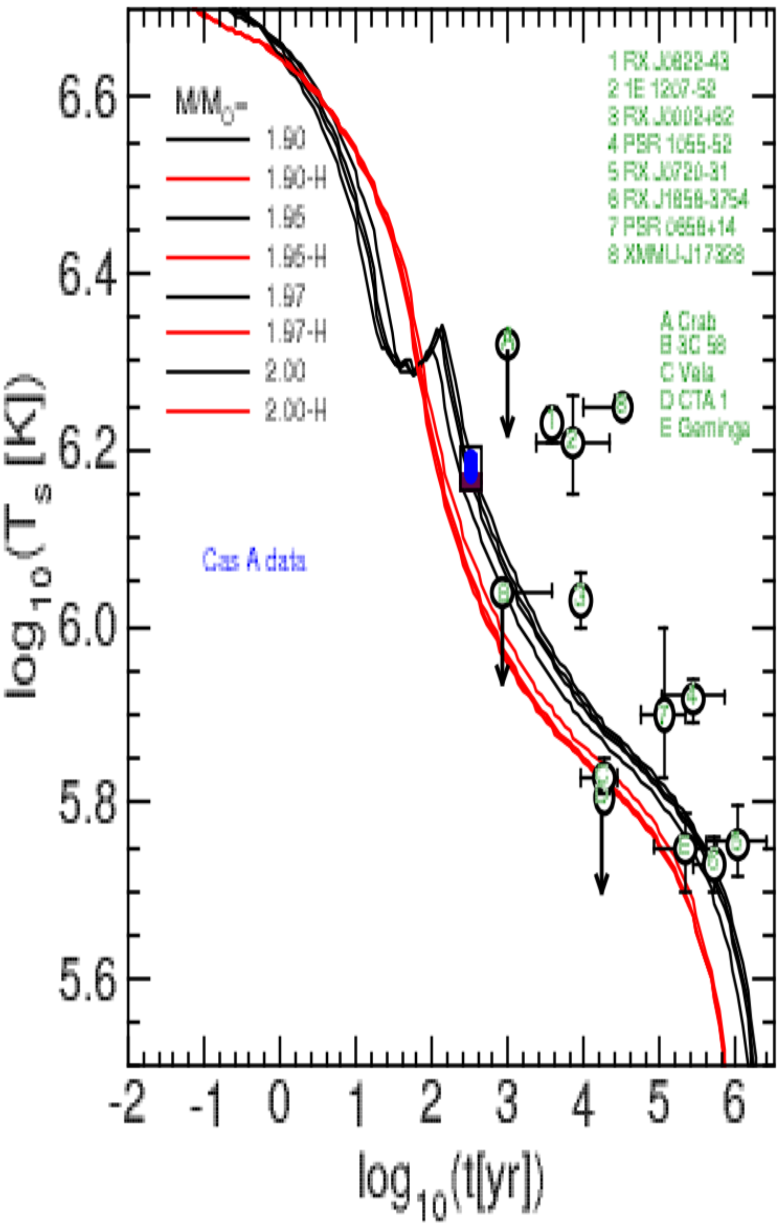
- All known cooling data including the Cas A rapid cooling consistently described by the ``nuclear medium cooling'' scenario
- Influence of stiffness on EoS and cooling can be balanced by the choice of corresponding gap model.
- In case of existence of III CSF high-mass twin stars could show different cooling behavior depending on core superconductivity

Thank YOU!!!!!

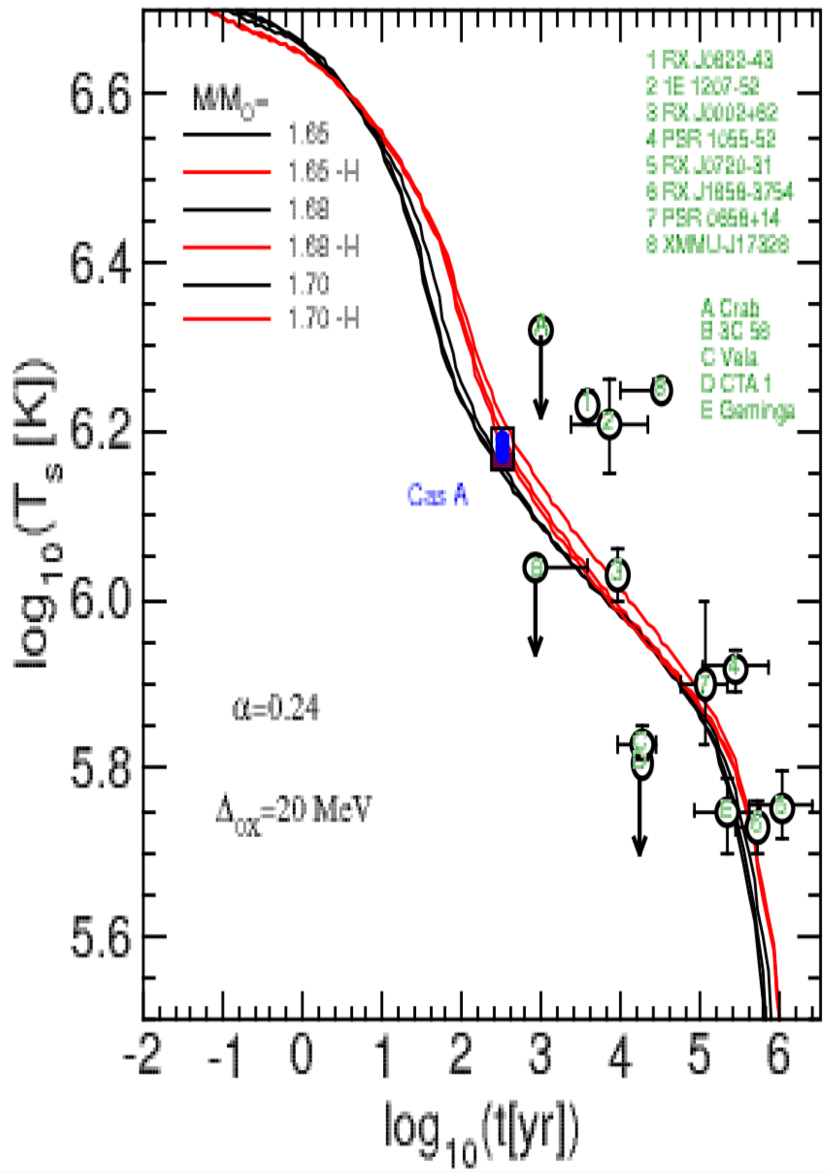
Cooling of Twin CS



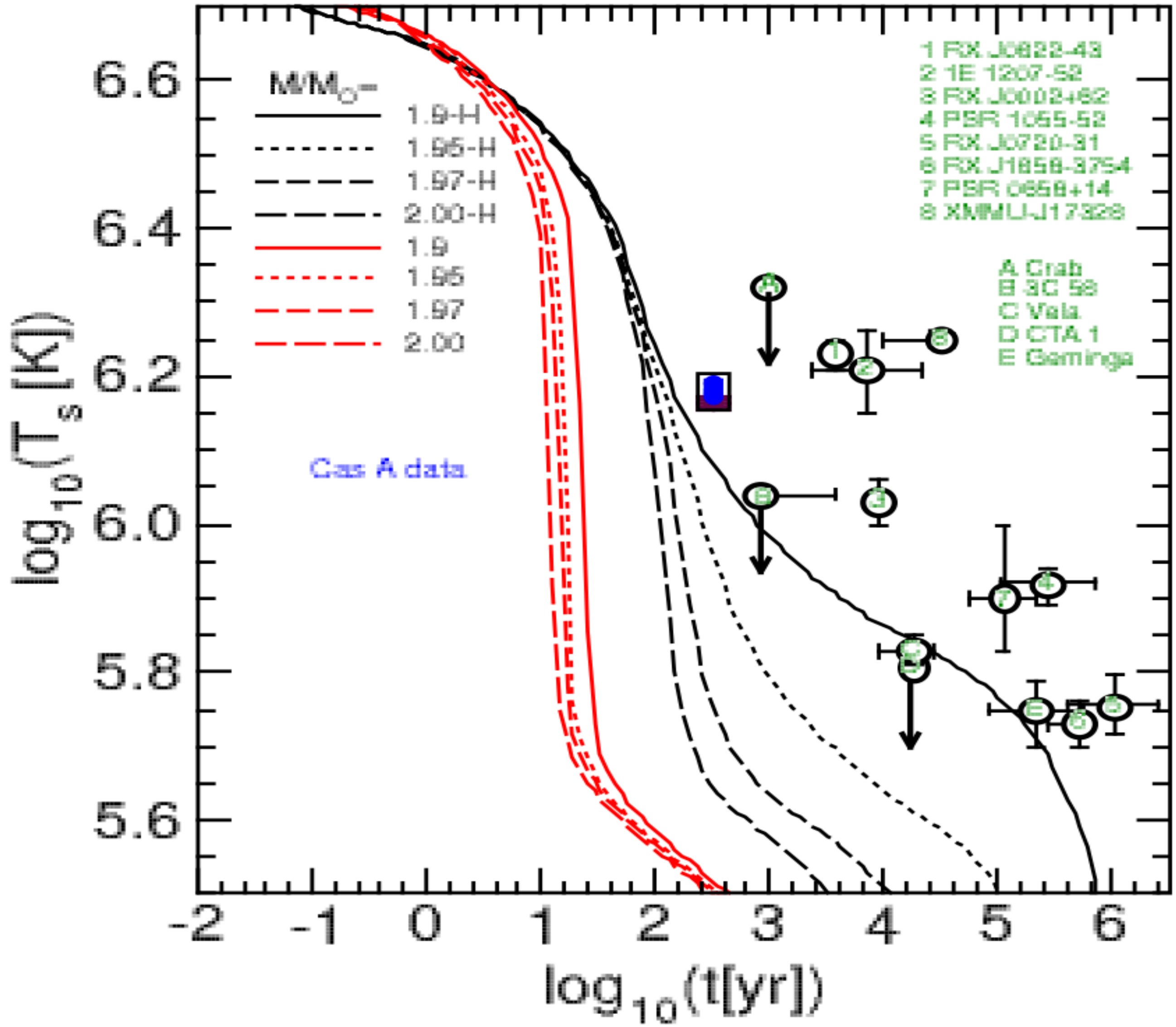




log10(Ts [K])
log10(t[yr])
M/M☉=
1.90
1.90-H
1.95
1.95-H
1.97
1.97-H
2.00
2.00-H
1 RX J0822-43
2 1E 1207-52
3 RX J0002+62
4 PSR 1055-52
5 RX J0720-31
6 RX J1856-3754
7 PSR 0656+14
8 XMMU-J17328
A Crab
B 3C 58
C Vela
D CTA 1
E Geminga
Cas A data

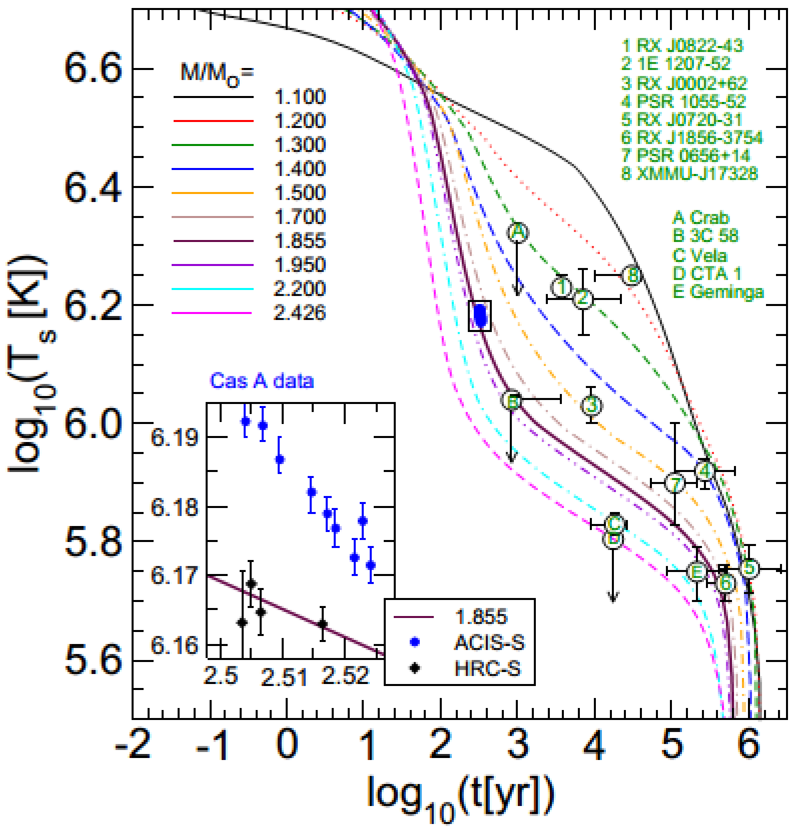


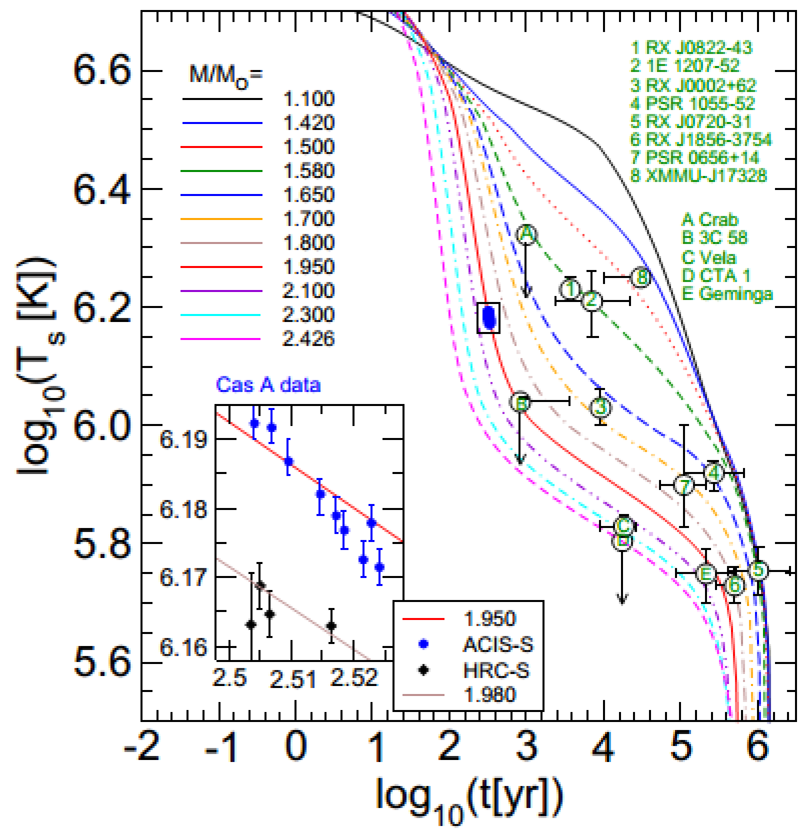
log10(Ts [K])
log10(t[yr])
M/M☉=
1.65
1.65 -H
1.68
1.68 -H
1.70
1.70 -H
1 RX J0822-43
2 1E 1207-52
3 RX J0002+62
4 PSR 1055-52
5 RX J0720-31
6 RX J1856-3754
7 PSR 0656+14
8 XMMU-J17328
A Crab
B 3C 58
C Vela
D CTA 1
E Geminga
Cas A
α=0.24
Δ0X=20 MeV



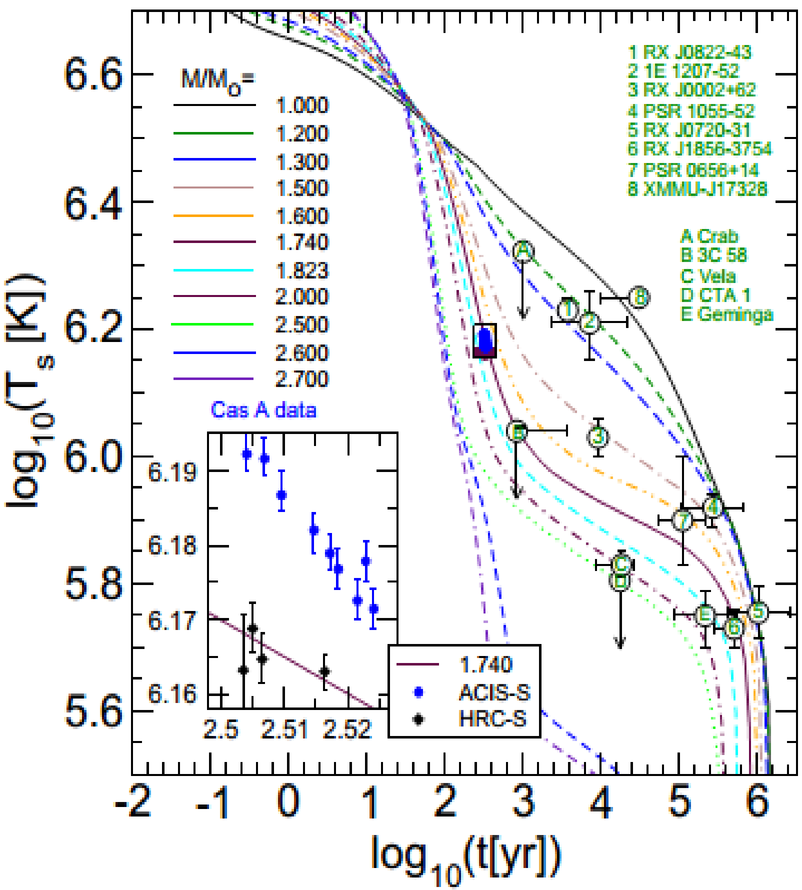
M/M☉=
1.9-H
1.95-H
1.97-H
2.00-H
1.9
1.95
1.97
2.00
Cas A data
1 RX J0822-43
2 1E 1207-52
3 RX J0002+62
4 PSR 1055-52
5 RX J0720-31
6 RX J1856-3754
7 PSR 0656+14
8 XMMU-J17328
A Crab
B 3C 58
C Vela
D CTA 1
E Geminga
$\log_{10}(T_s\,[K])$
$\log_{10}(t[yr])$

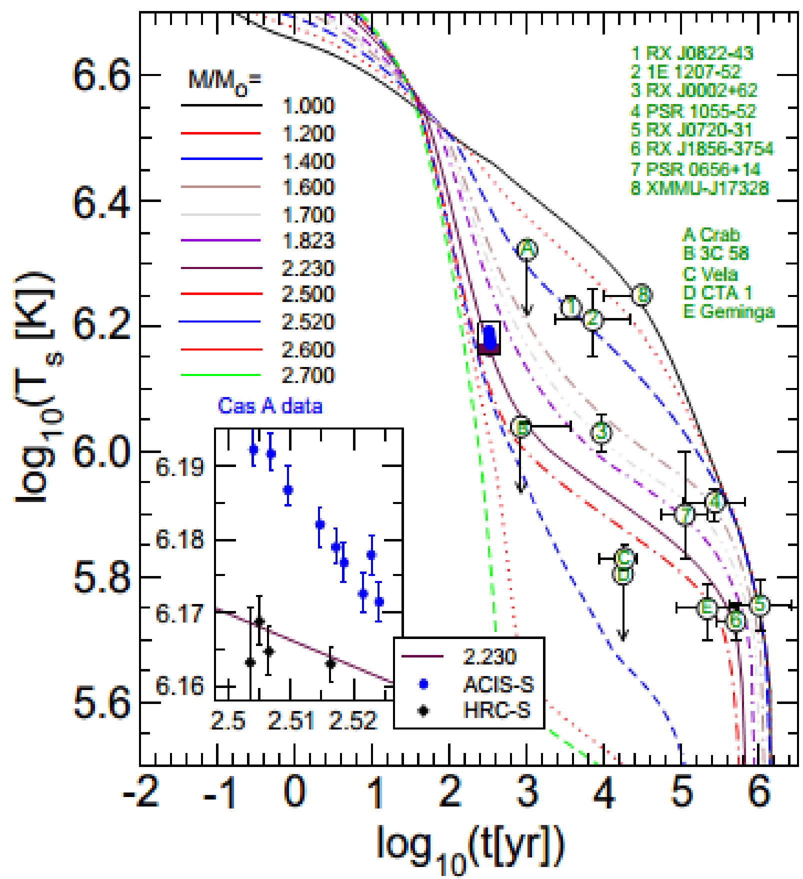
DD2- ME-nc = 3 n0
BCLL, EEHOr



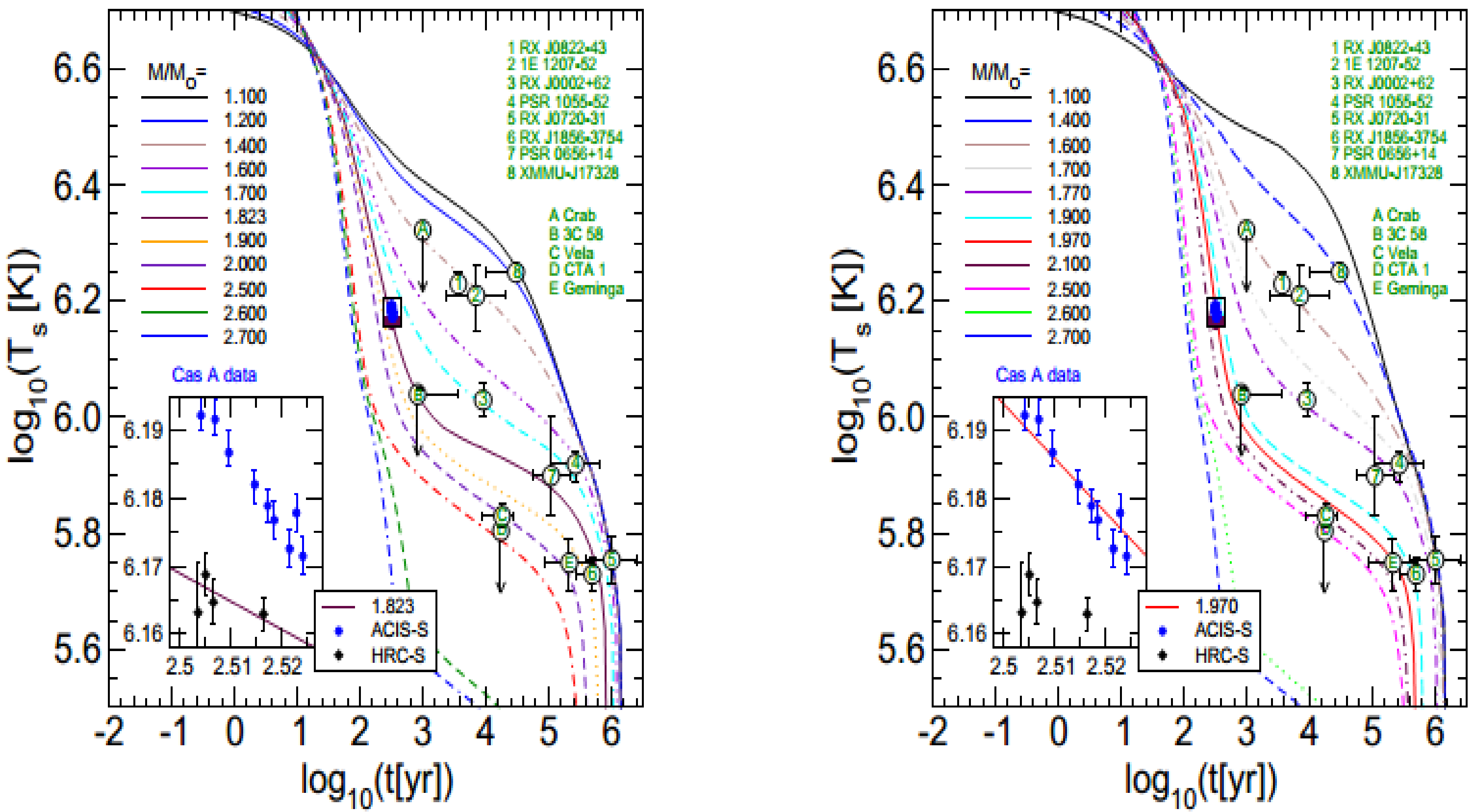


DD2 vex-p40, AO
ME-nc = 2.0,2.5 n0

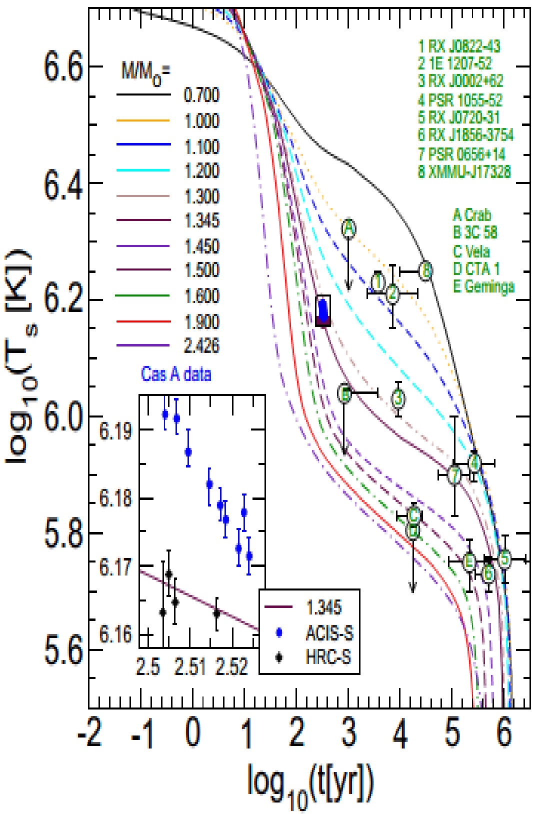


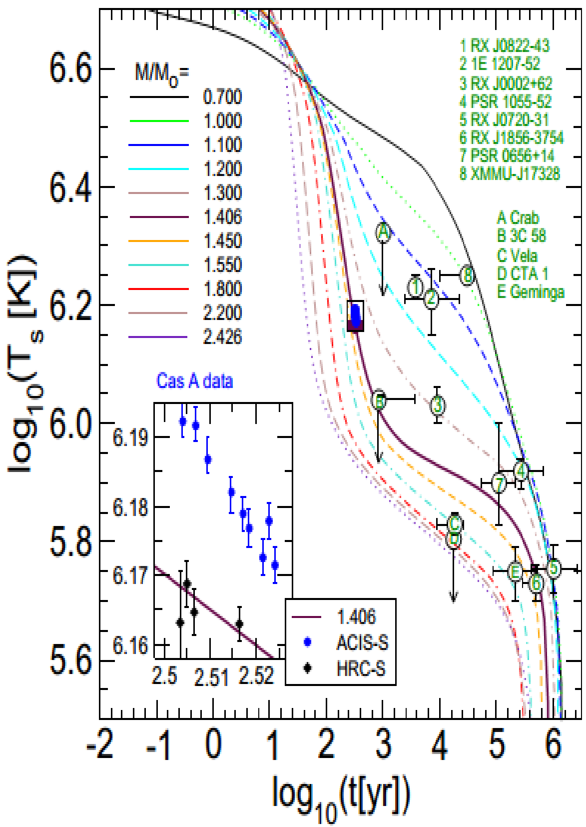


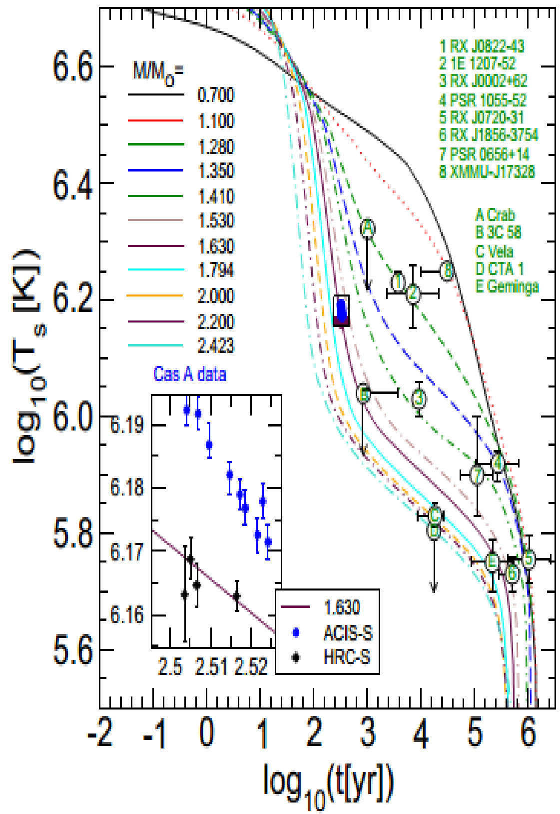
DD2 vex p40, BCLL
ME-nc = 1.5,2.0 n0



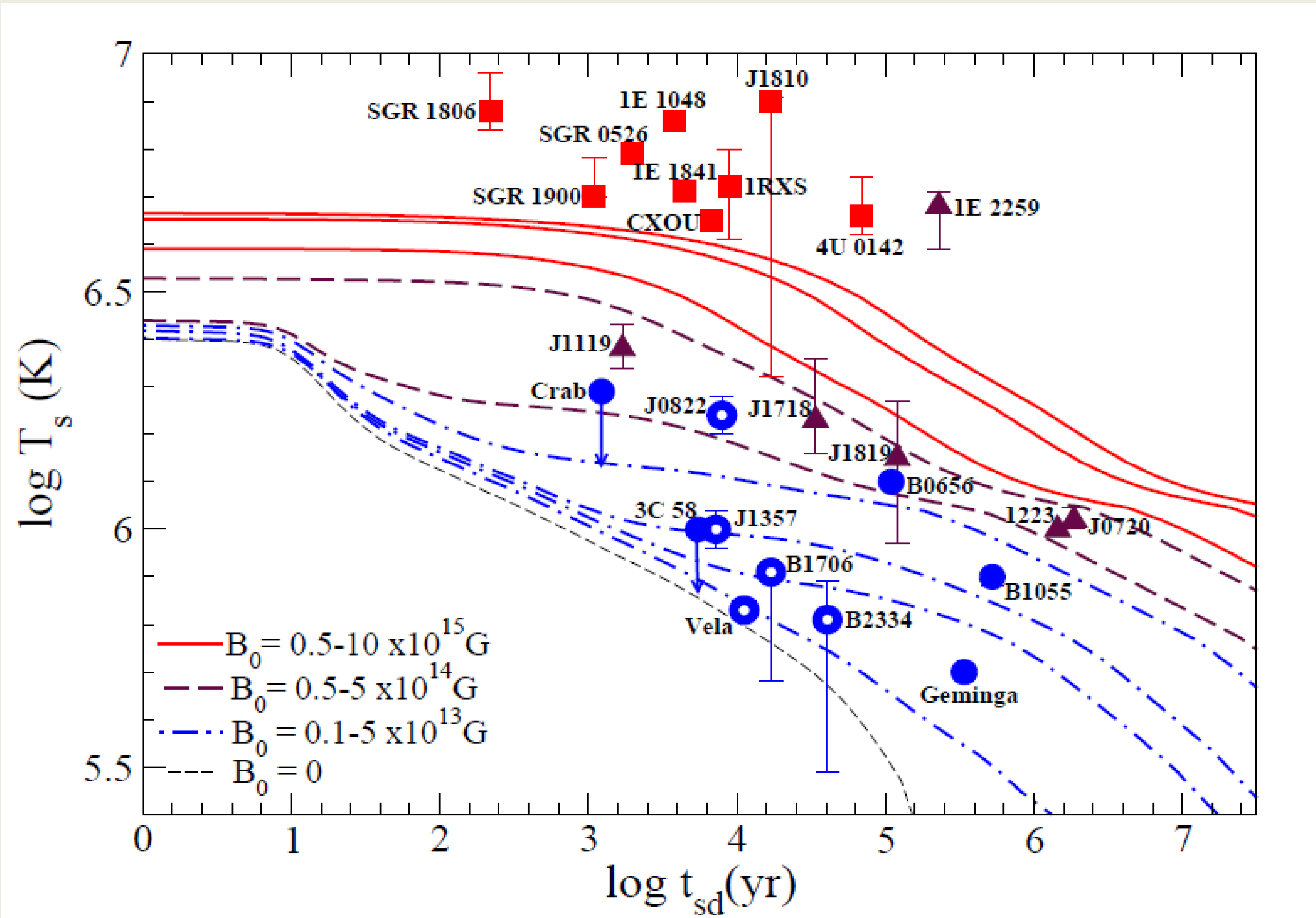
DD2 – BCLL
ME-nc =1.5,2.0,2.5n0







Data of NS on Magnetic Field



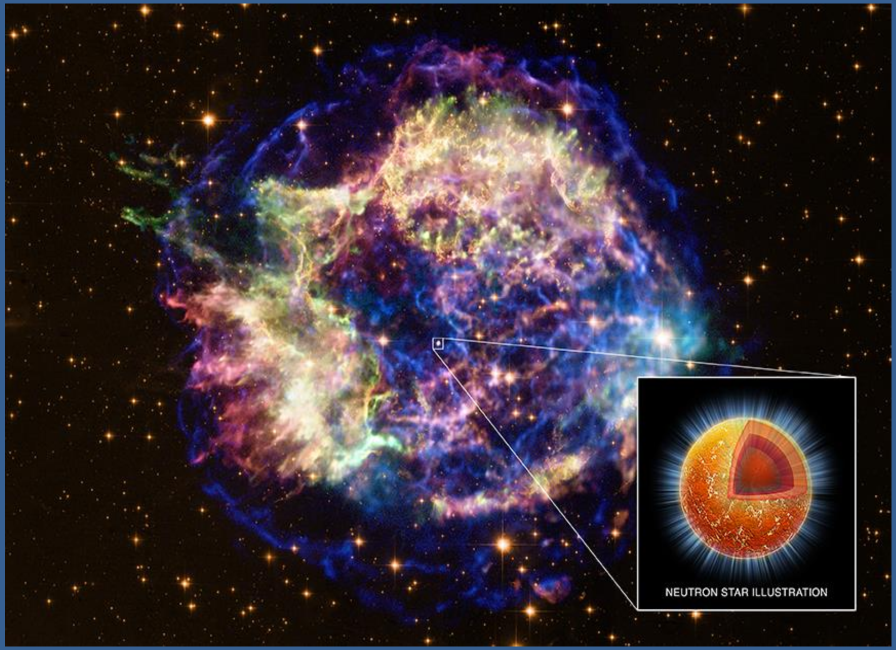
Magnetars AXPs, SGRs
B = 10^14 - 10^15 G

Radio-quiet NSs
B = 10^13 G

Radio-pulsar NSs
B = 10^12 G

Radio-pulsar NSs
B = 10^12 G
H - spectrum

Neutron Star in Cassiopeia A

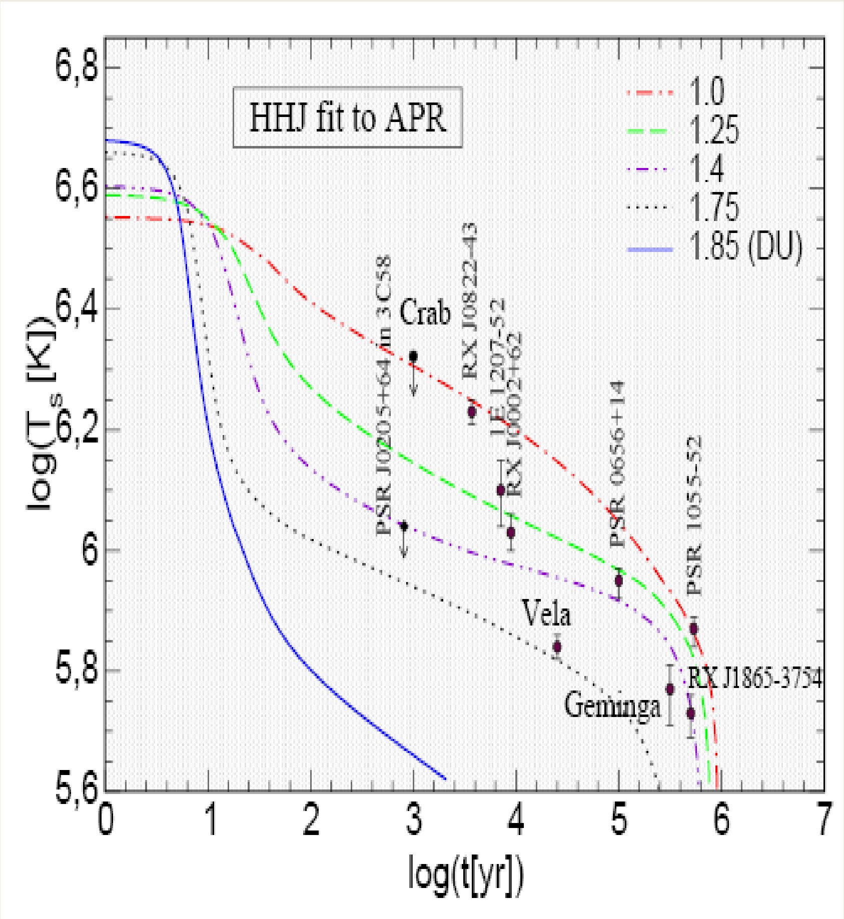


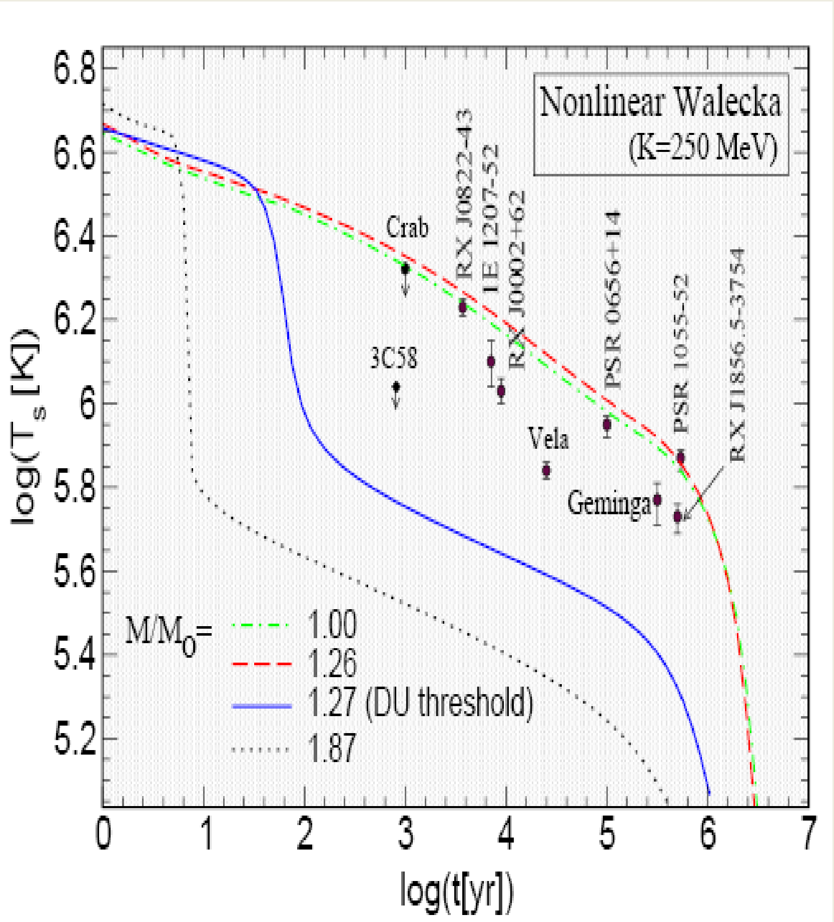
- 16.08.1680 John Flamsteed, 6m star 3 Cas
- 1947 re-discovery in radio
- 1950 optical counterpart
- T ~ 30 MK
- V exp ~ 4000 – 6000 km/s
- distance 11.000 ly = 3.4 kpc

picture: spitzer space telescope

D.Blaschke, H. Grigorian, D. Voskresensky, F. Weber,
Phys. Rev. C 85 (2012) 022802
e-Print: **arXiv:1108.4125** [nucl-th]

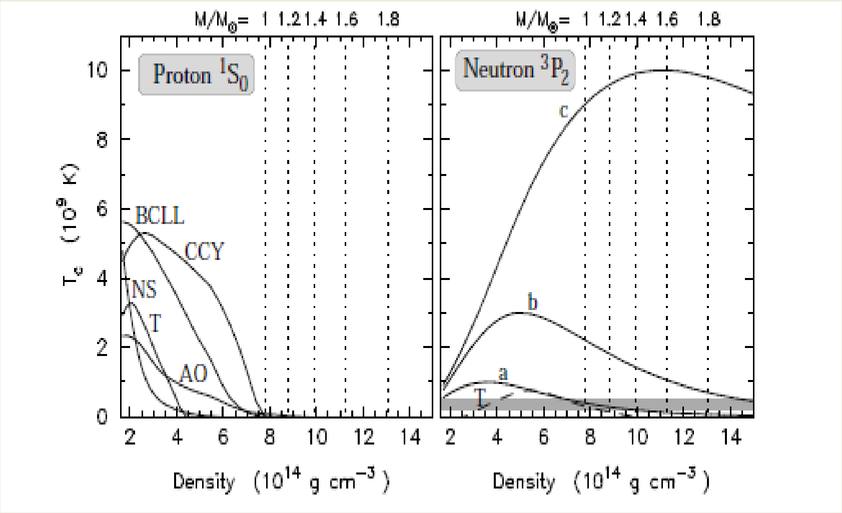
DU Problem & Constraint

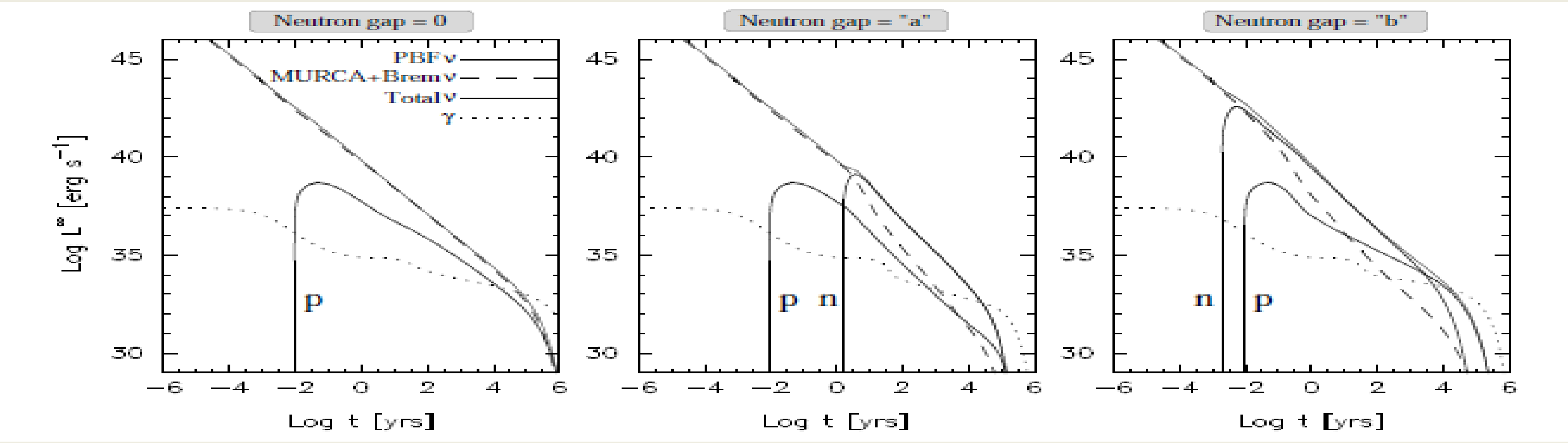




Influence Of SC On Luminosity

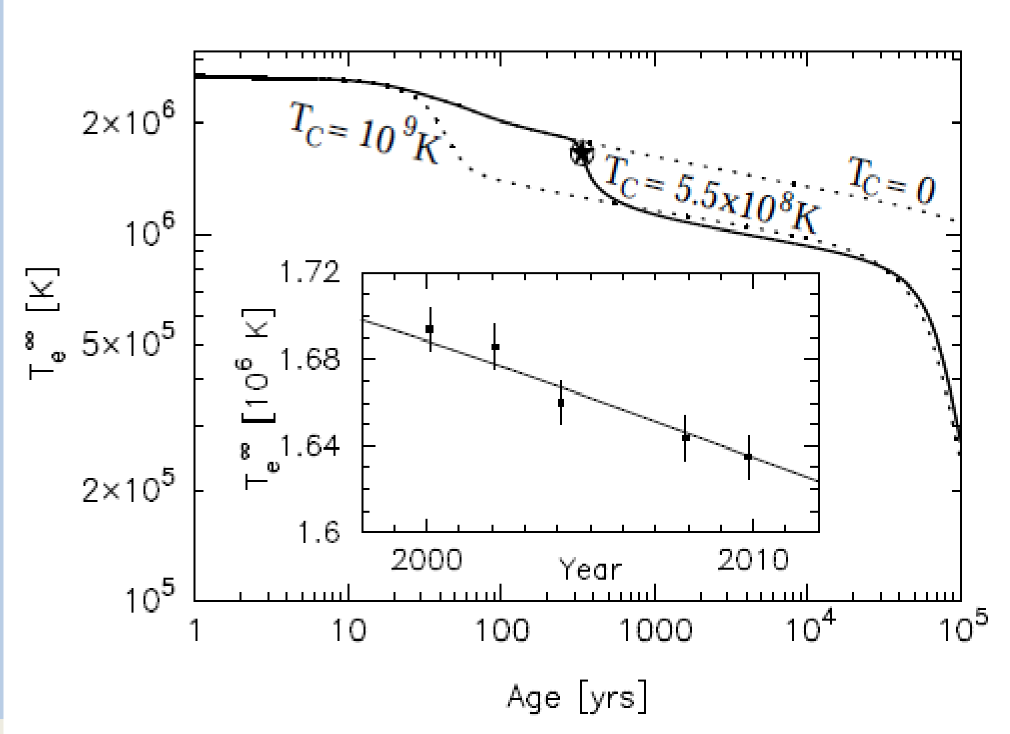
- Critical temperature, Tc, for the proton 1So and neutron 3P2 gaps, used in PAGE, LATTIMER, PRAKASH, & STEINER Astrophys.J.707:1131 (2009)

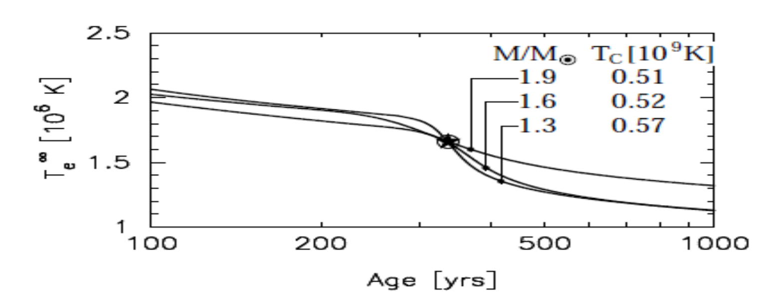




Tc ‘Measurement’ From Cas A

- Assumed to be a star with mass = 1.4 M⊙ from the APR EoS
- Rapidly cools at ages ~ 30-100 yrs due to the thermal relaxation of the crust
- Mass dependence





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

Equations for Cooling Evolution

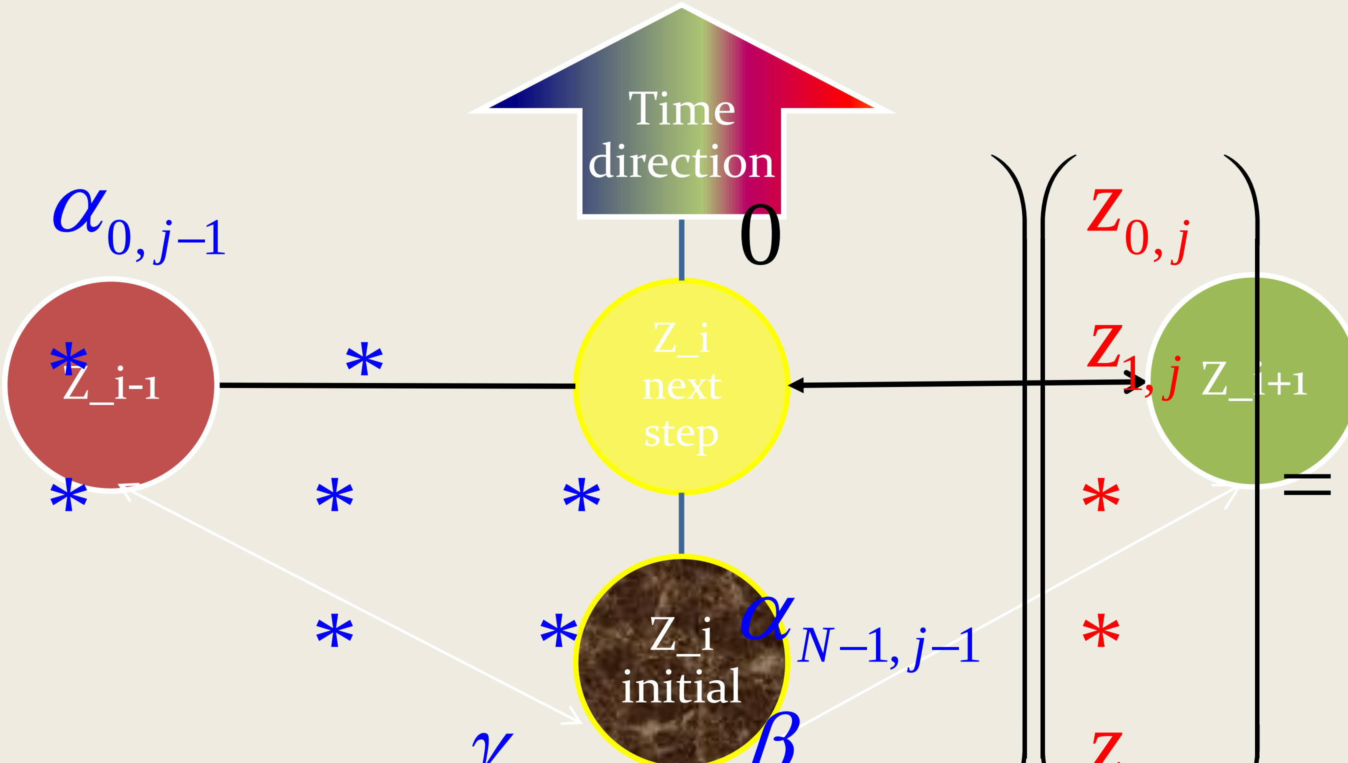
$$\begin{cases} \dfrac{\partial z(\tau,a)}{\partial \tau} = A(z,a)\dfrac{\partial L(\tau,a)}{\partial a} + B(z,a) \\ L(\tau,a) = C(z,a)\dfrac{\partial z(\tau,a)}{\partial a} \end{cases}$$

$$z(\tau,a) = \log T(\tau,a)$$

$$L_{i\pm 1/2} = \pm \frac{C_i + C_{i\pm 1}}{2} \frac{z_{i\pm 1} - z_i}{\Delta a_{i-1/2(1\mp 1)}}$$

$$\frac{\partial L_i}{\partial a} = 2\frac{L_{i+1/2} - L_{i-1/2}}{\Delta a_i + \Delta a_{i-1}}$$

Finite difference scheme



$$\begin{pmatrix} \beta_{0,j-1} & \alpha_{0,j-1} & & & 0 \\ \gamma_{1,j-1} & * & * & & \\ & * & * & * & \\ & & * & * & \alpha_{N-1,j-1} \\ 0 & & & \gamma_{N,j-1} & \beta_{N,j-1} \end{pmatrix} \begin{pmatrix} z_{0,j} \\ z_{1,j} \\ * \\ * \\ z_{N,j} \end{pmatrix} = \begin{pmatrix} \delta_{0,j-1} \\ \delta_{1,j-1} \\ * \\ * \\ \delta_{N,j-1} \end{pmatrix}$$

$$\alpha_{i,j-1} z_{i+1,j} + \beta_{i,j-1} z_{i,j} + \gamma_{i,j-1} z_{i-1,i} = \delta_{i,j-1}$$

Boundary conditions