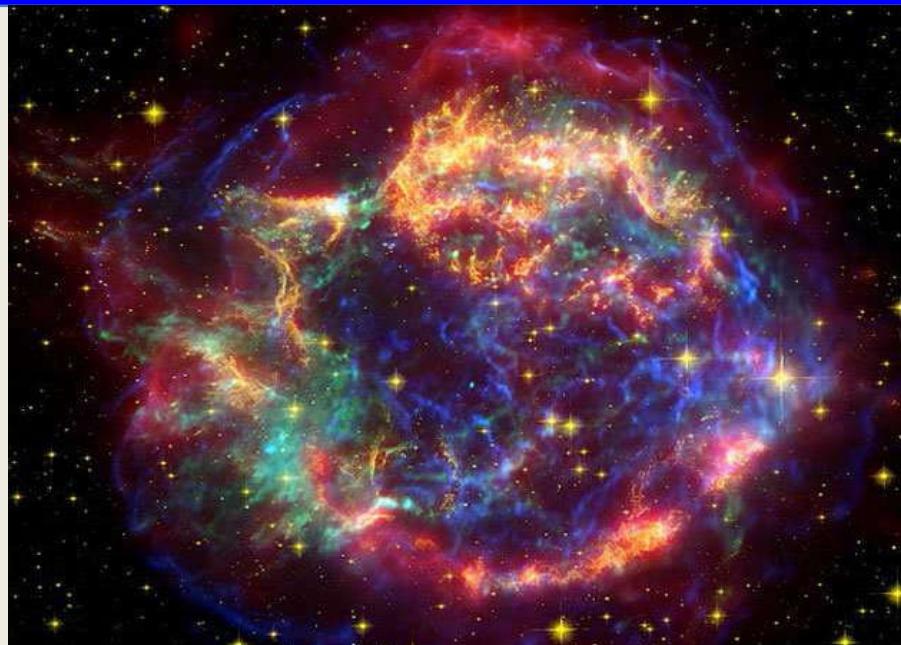


Neutron Star cooling with stiff stellar matter



Hovik Grigorian:
JINR – Dubna
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CPOD 2016
Wroclaw May 31

my co-authors: Blaschke D, Voskresensky D.

Cooling Of Neutron Stars

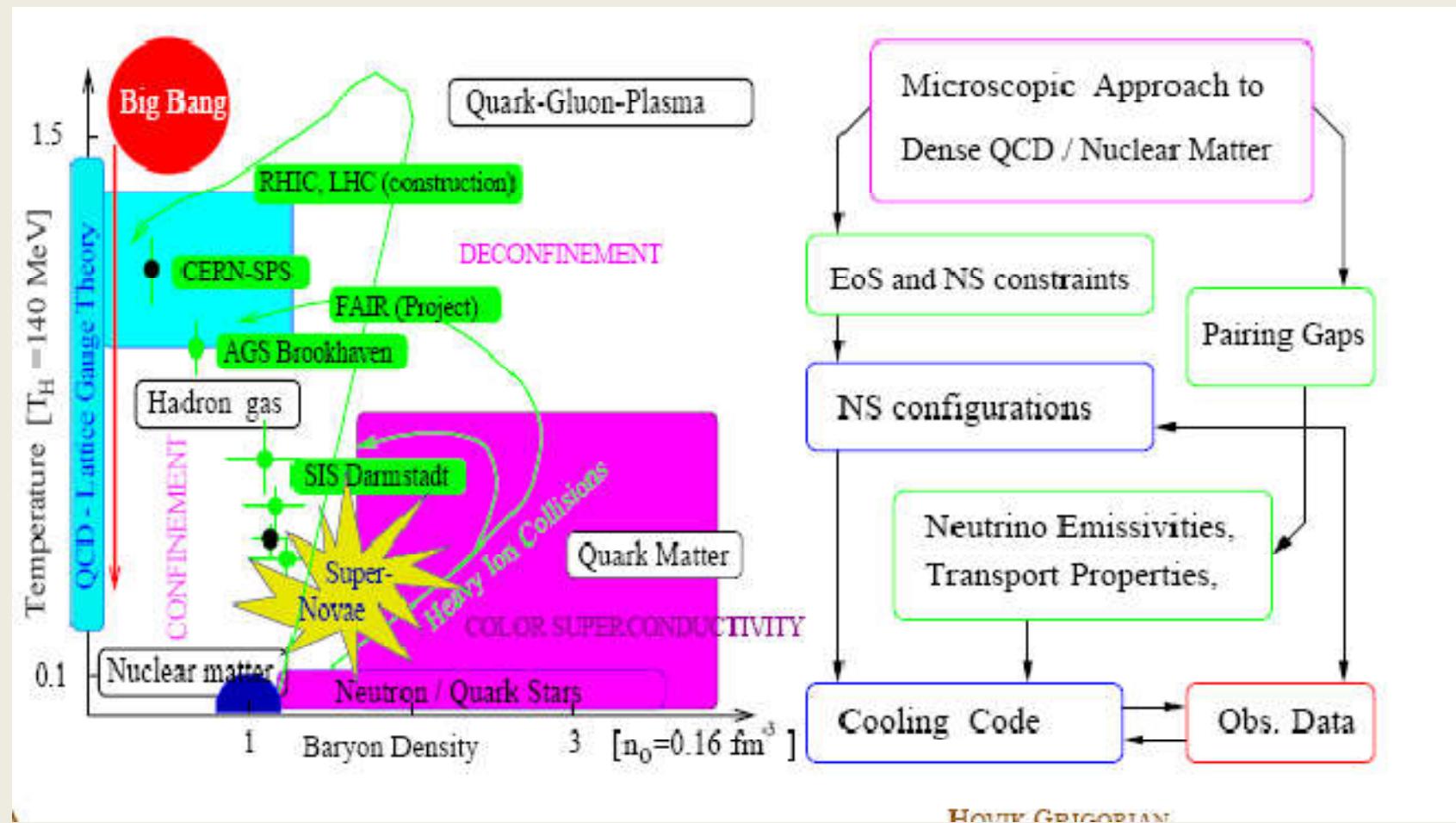
- Introduction to Cooling Simulation
- Cooling regulators
- Time Evolution of Temperature
- *Superconductivity & in-medium effects*
- *Results for NS cooling*

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

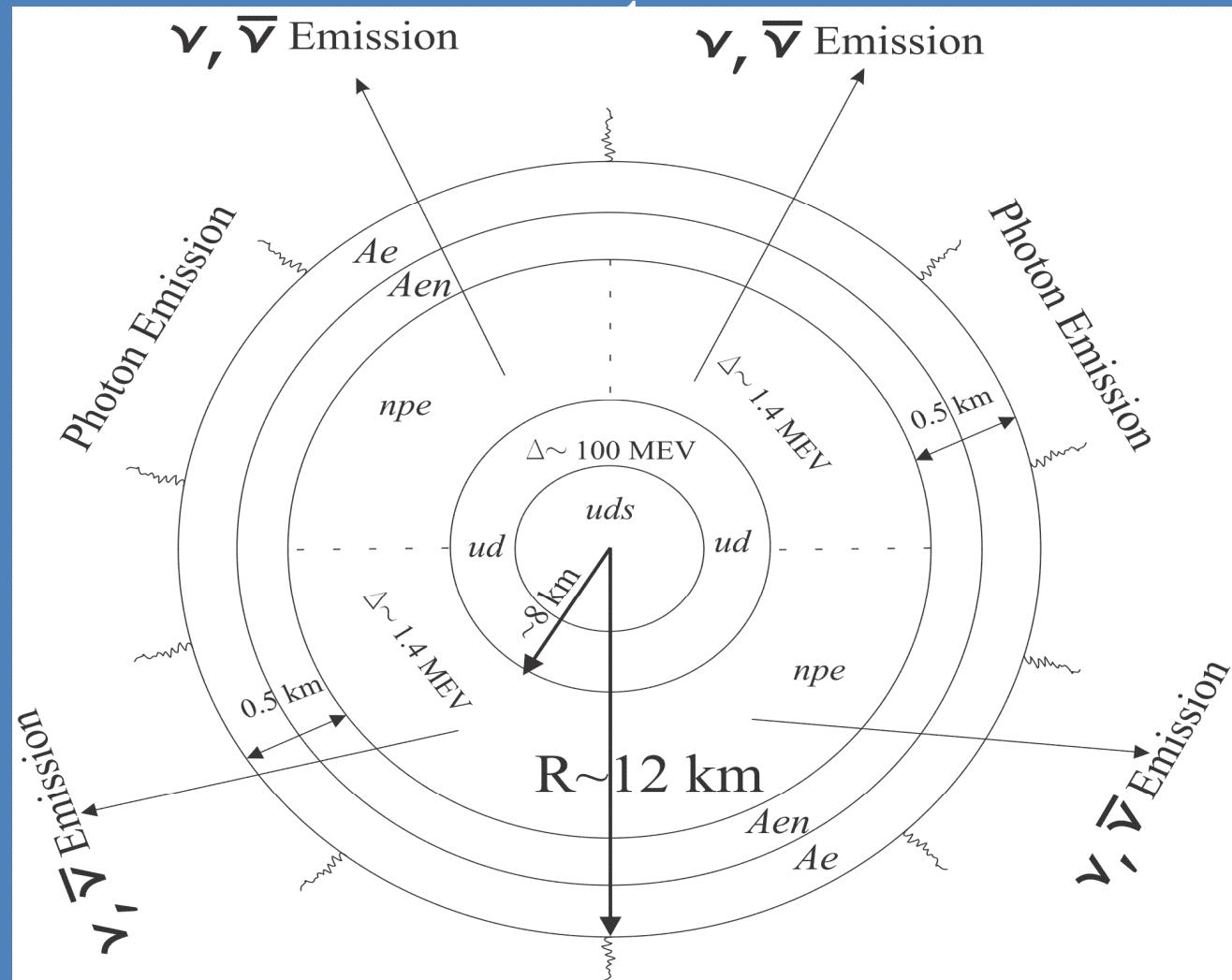
Phase Diagramm & Cooling Simulation

- ✓ 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

Phase Diagramm & Cooling Simulation



Structure Of Hybrid Star



Modification of HHJ 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:

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

where $u = n/n_0$, $e_B \simeq -15.8$ MeV is the nuclear binding energy per nucleon, $a_{\text{sym}} \simeq 32$ 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 + $\delta\nu$ + UIX*)

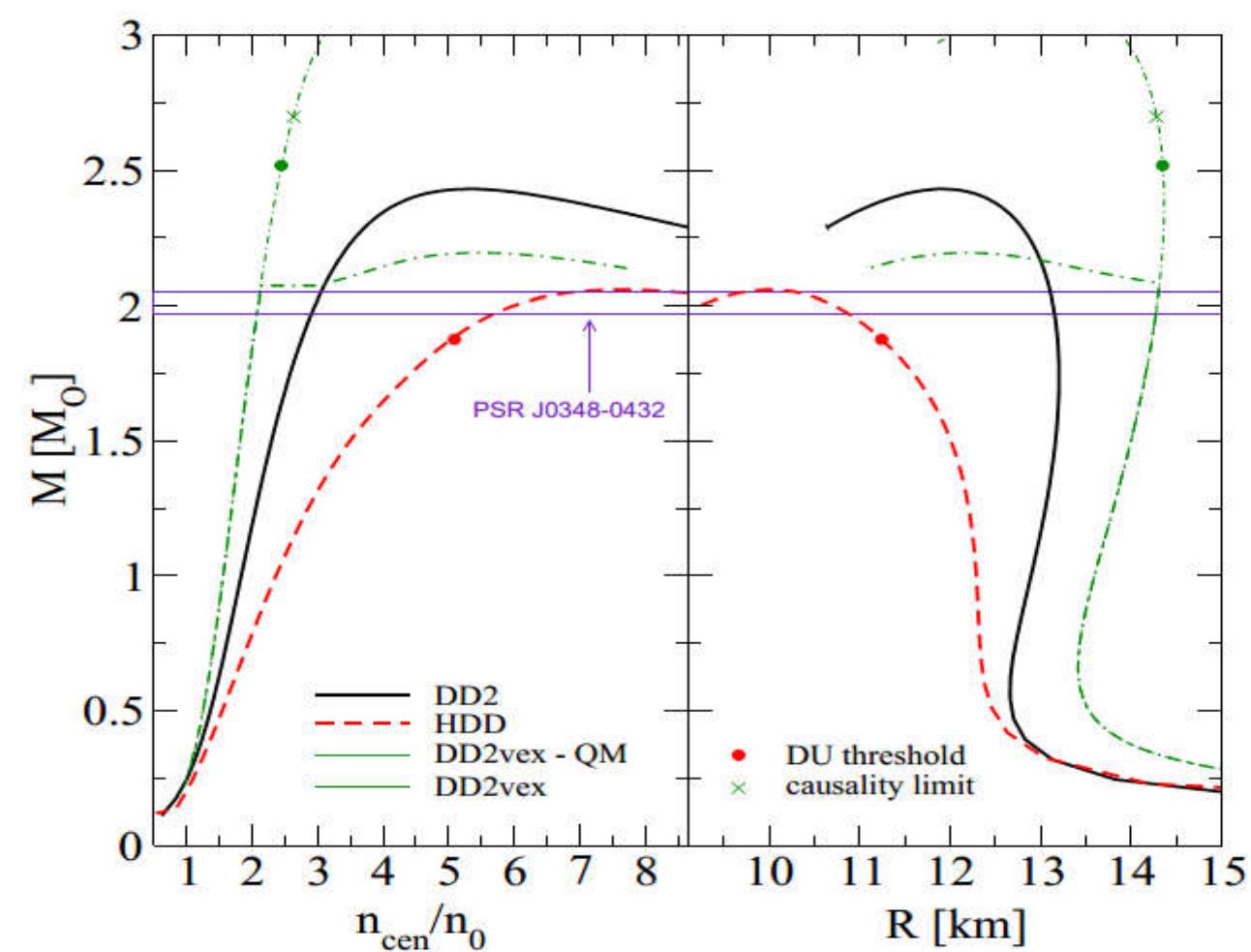
Introduction of the excluded volume

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

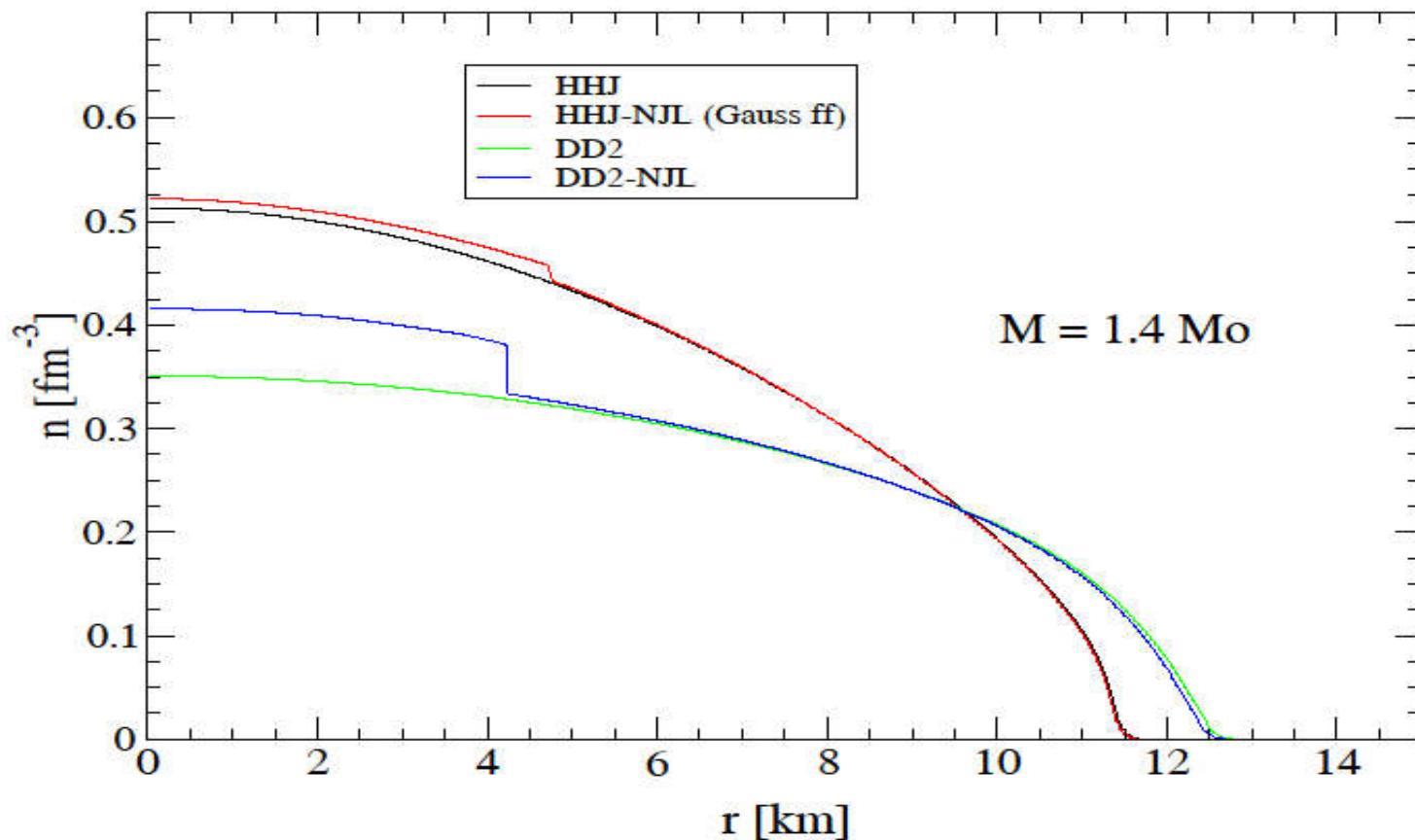
$$u \rightarrow \frac{u}{1 - \alpha u e^{-(\beta/u)^\rho}}$$

Stability of stars

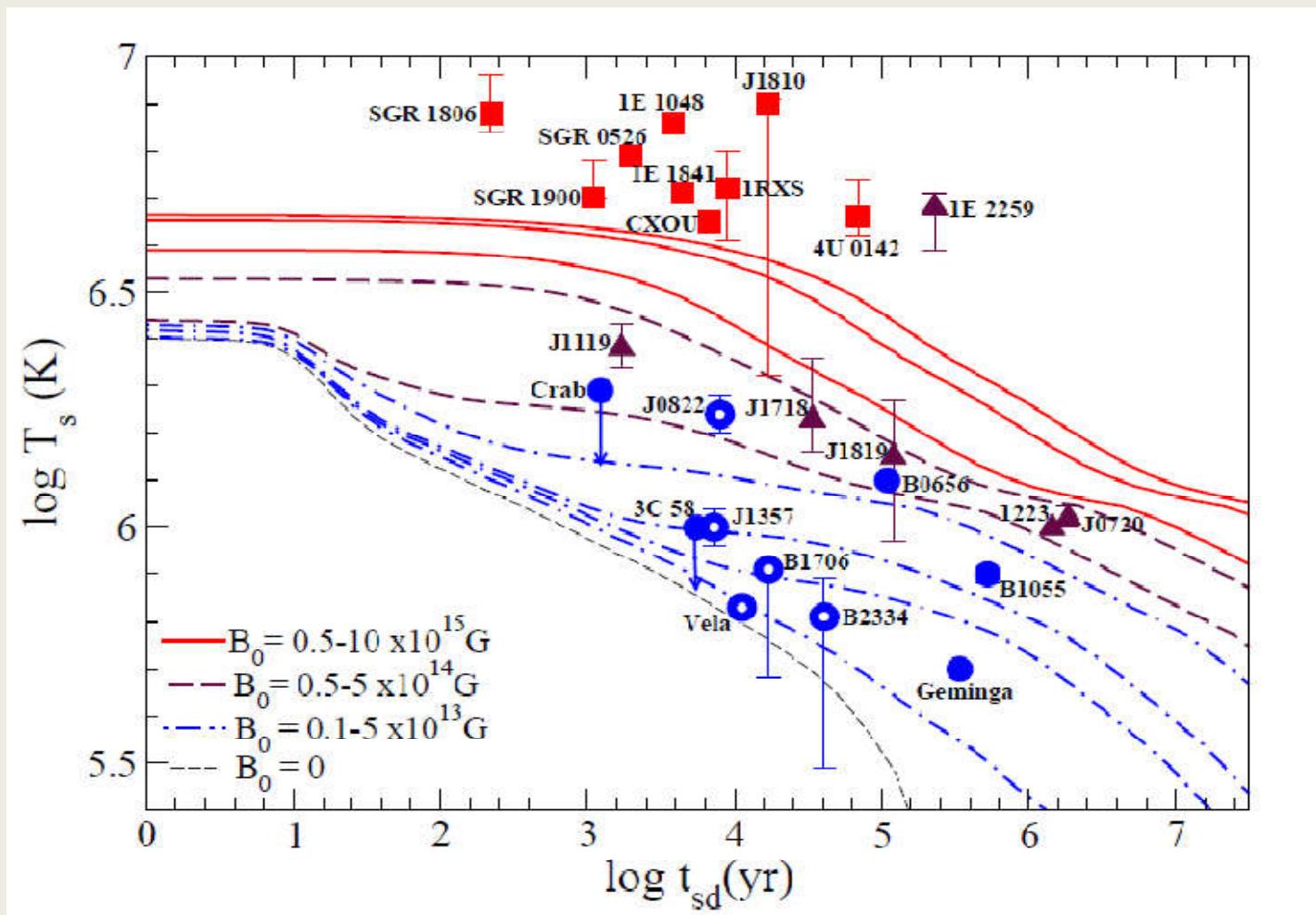
HDD, DD2 & DDvex-NJL EoS model



Different EoS model Configurations for the same mass NS



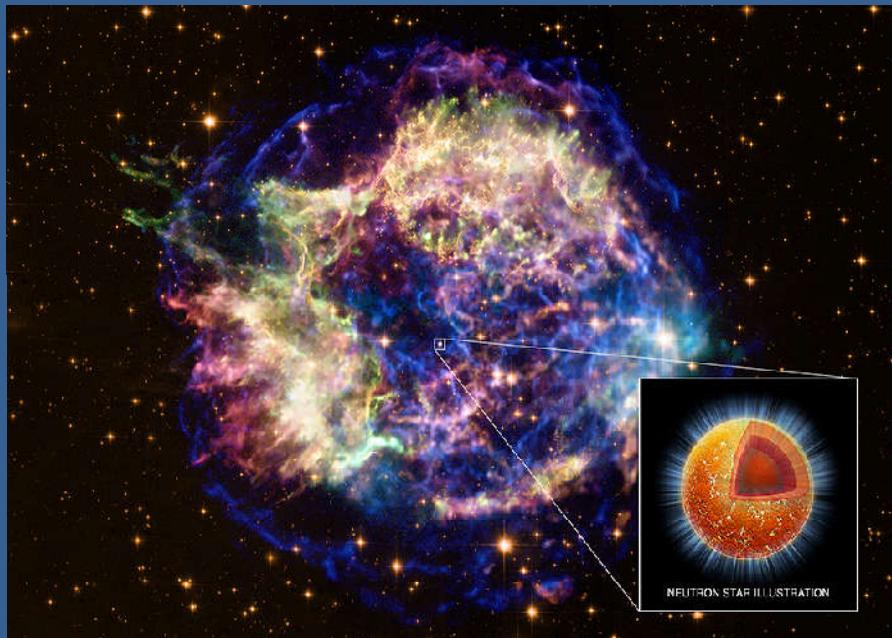
Data of NS on Magnetic Field



- Magnetars (AXPs, SGRs)**
 $B = 10^{14} - 10^{15} \text{ G}$
- Radio-quiet NSs**
 $B = 10^{13} \text{ G}$
- Radio-pulsar NSs**
 $B = 10^{12} \text{ G}$
- Radio-pulsar NSs (H-spectrum)**
 $B = 10^{12} \text{ G}$

Neutron Star in Cassiopeia A

- 16.08.1680 John Flamsteed, 6m star 3 Cas
 - 1947 re-discovery in radio
 - 1950 optical counterpart
 - $T \sim 30$ MK
 - $V_{\text{exp}} \sim 4000 - 6000$ 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]

Cooling Mechanism

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

Cooling Processes

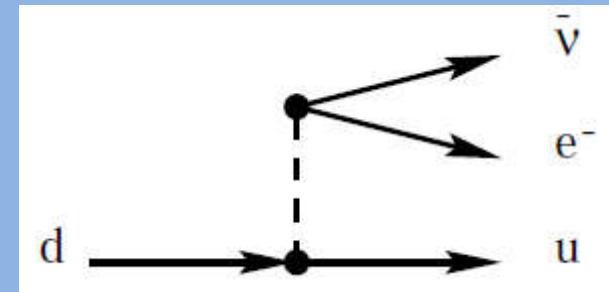
- Direct Urca: $n \rightarrow p + e + \bar{\nu}_e$
- Modified Urca: $n + n \rightarrow n + p + e + \bar{\nu}_e$
- Photons: $\rightarrow \gamma$
- Bremsstrahlung: $n + n \rightarrow n + n + \nu + \bar{\nu}$

Neutrino emissivities in quark matter:

- Quark direct Urca (QDU) the most efficient processes

$$d \rightarrow u + e + \bar{\nu} \text{ and } u + e \rightarrow d + \nu$$
$$\epsilon_{\nu}^{\text{QDU}} \simeq 9.4 \times 10^{26} \alpha_s u Y_e^{1/3} \zeta_{\text{QDU}} T_9^6 \text{ erg cm}^{-3} \text{ s}^{-1},$$

Compression n/no $\simeq 2$, strong coupling $\alpha_s \approx 1$



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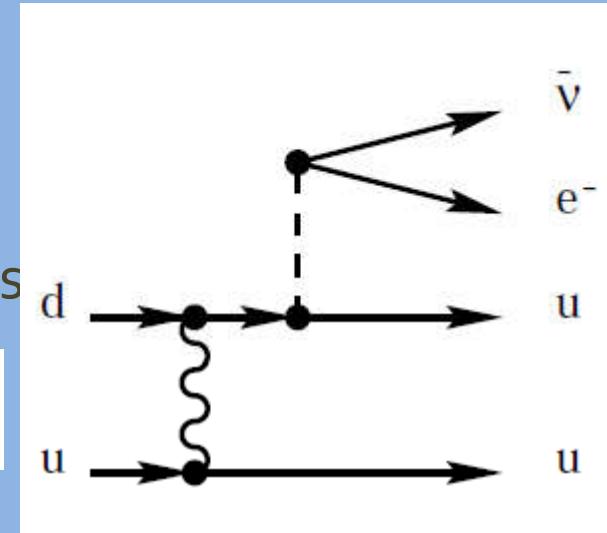
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- Quark Modified Urca (QMU) and Quark Brems

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

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



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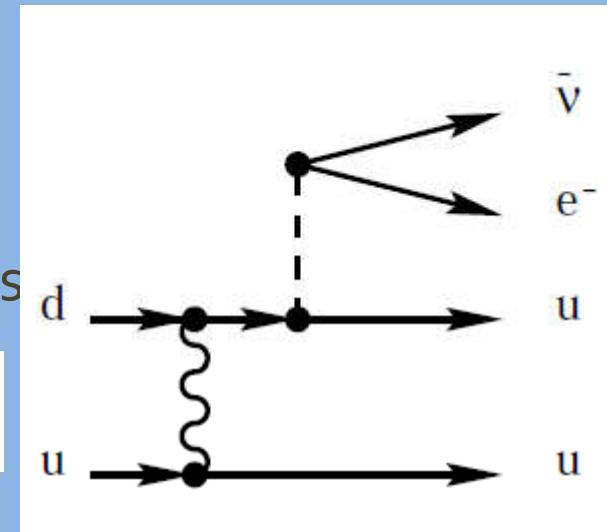
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- Suppression due to the pairing

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

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



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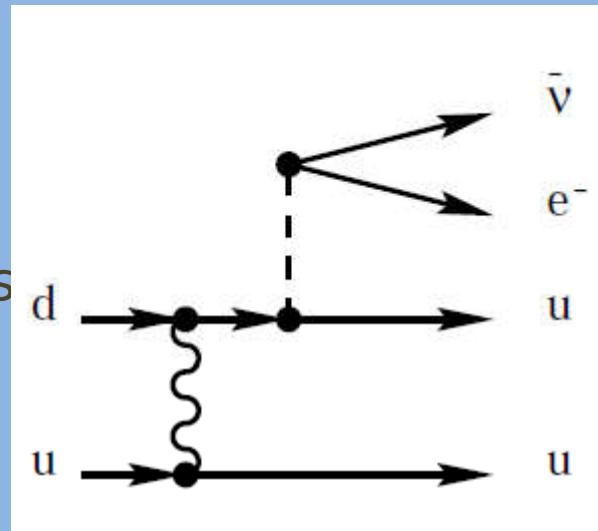
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- Enhanced cooling due to the pairing

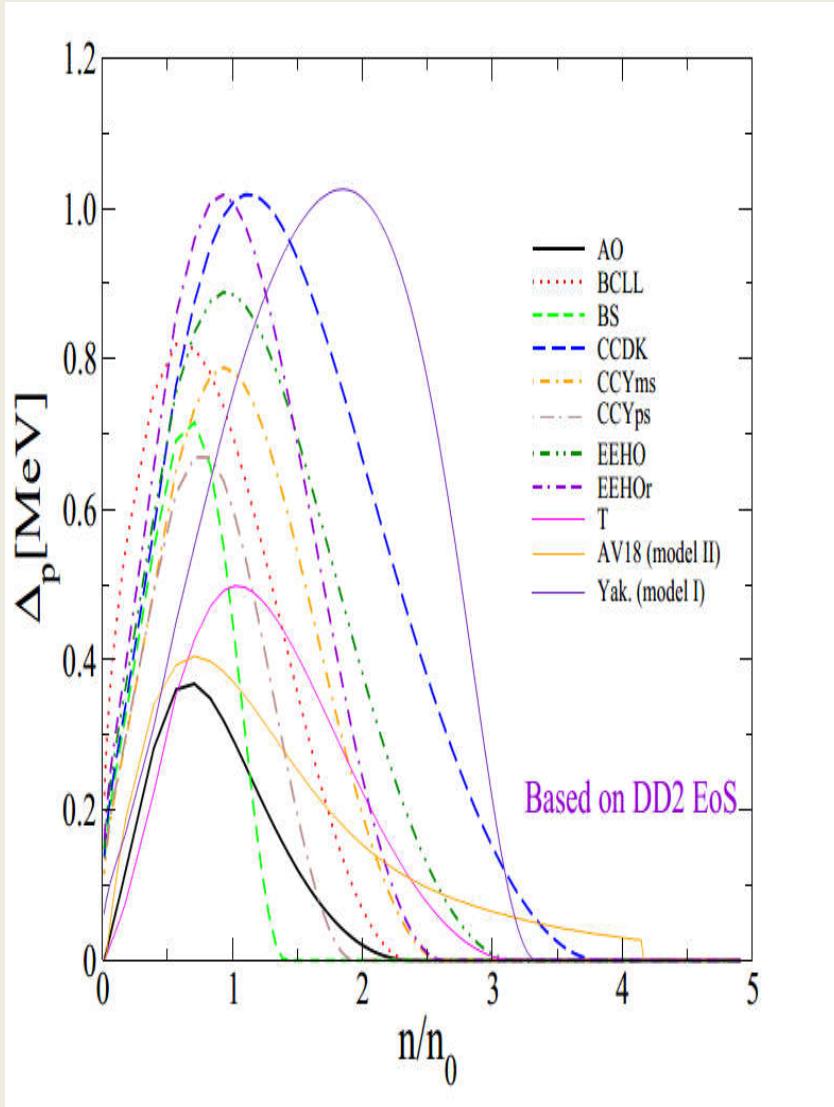
- $e+e \rightarrow e+e+\nu+\bar{\nu}$ (becomes important for $\Delta_q/T \gg 1$)

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

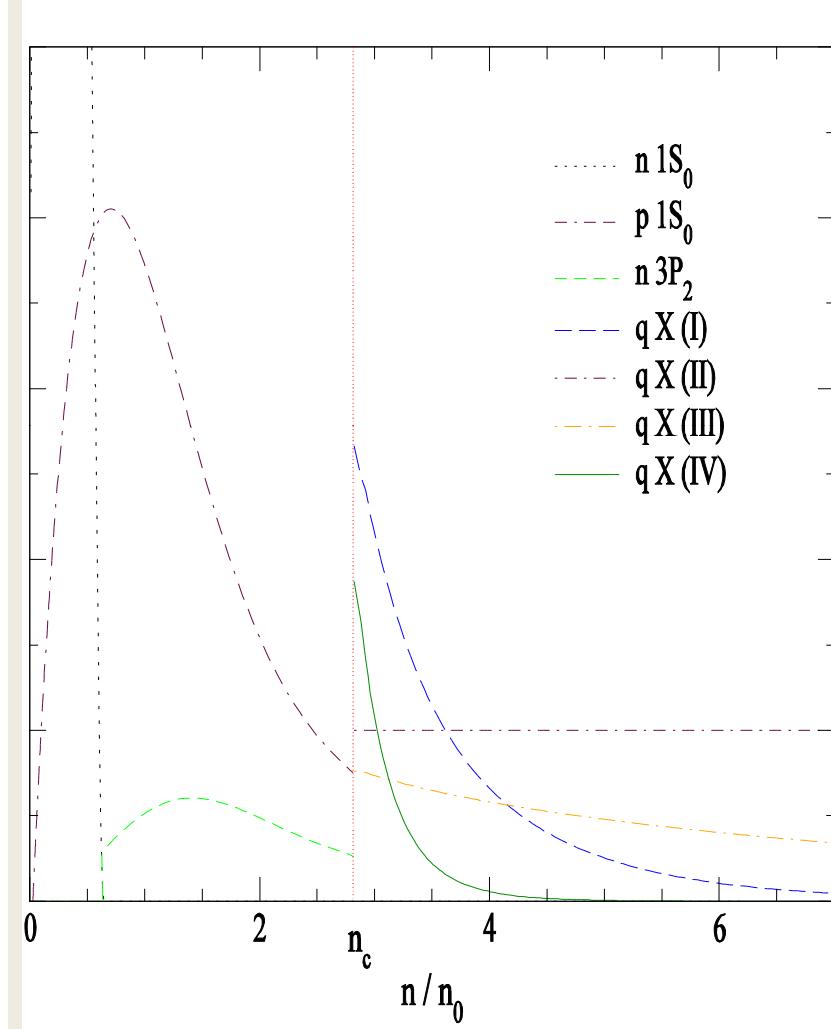
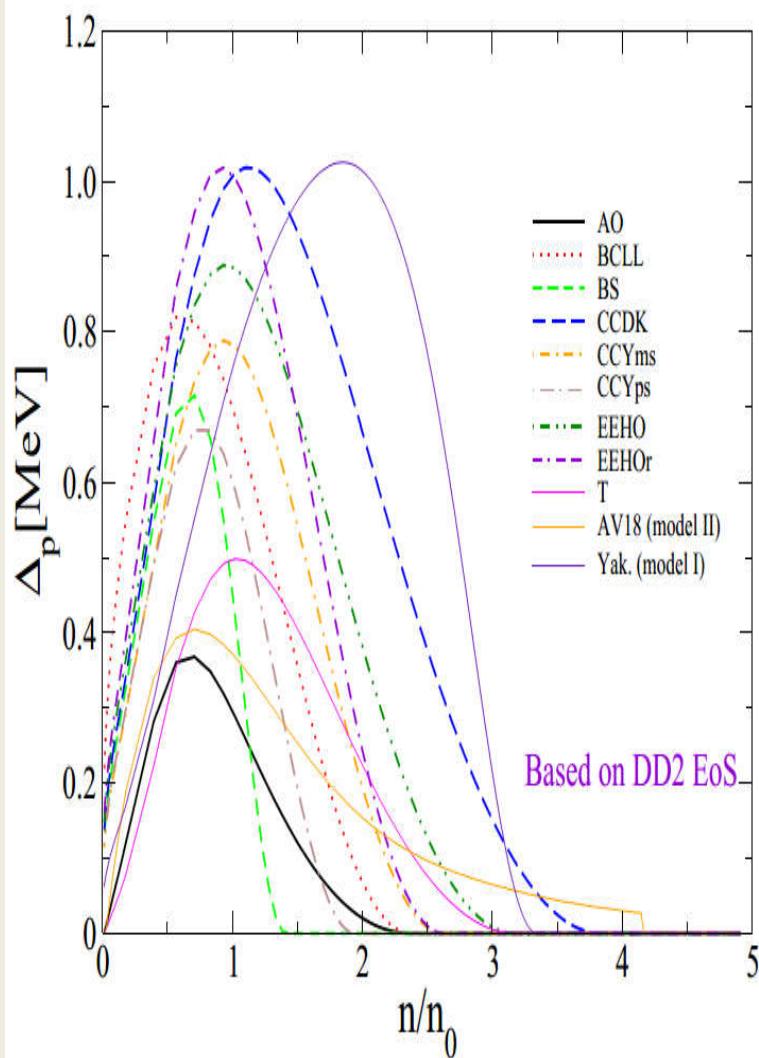


Quark PBF

SC Pairing Gaps



SC Pairing Gaps



Cooling Evolution

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

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

F.Weber: Pulsars as Astro. Labs ... (1999);

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

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

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

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

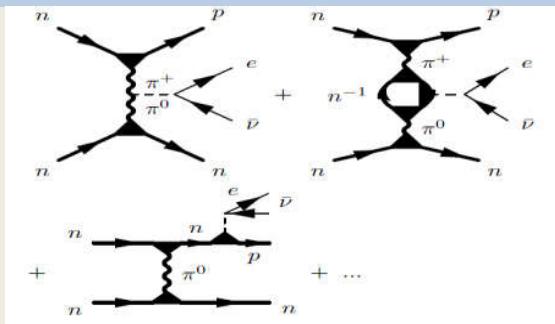
$$\frac{\partial N_B}{\partial r} = 4\pi r^2 n \left(1 - \frac{2M}{r}\right)^{-1/2}$$

F.Weber: Pulsars as Astro. Labs ... (1999);

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

Medium Effects In Cooling Of Neutron Stars

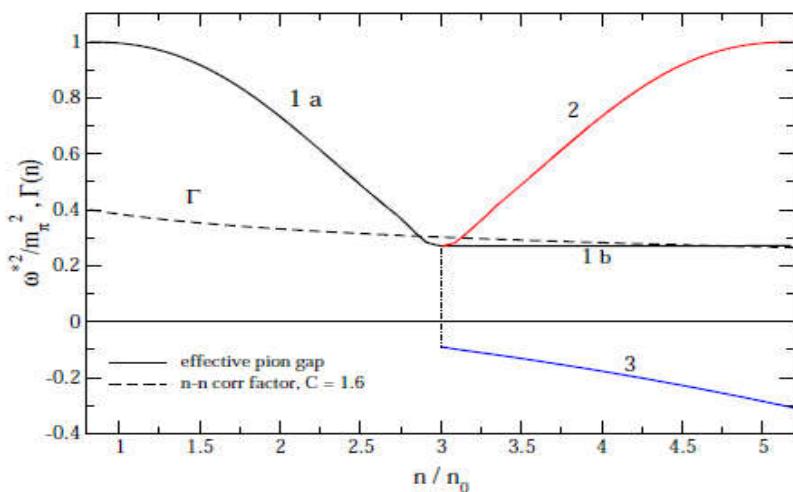
- Based on Fermi liquid theory (Landau (1956), Migdal (1967), Migdal et al. (1990))
- MMU – instead of MU



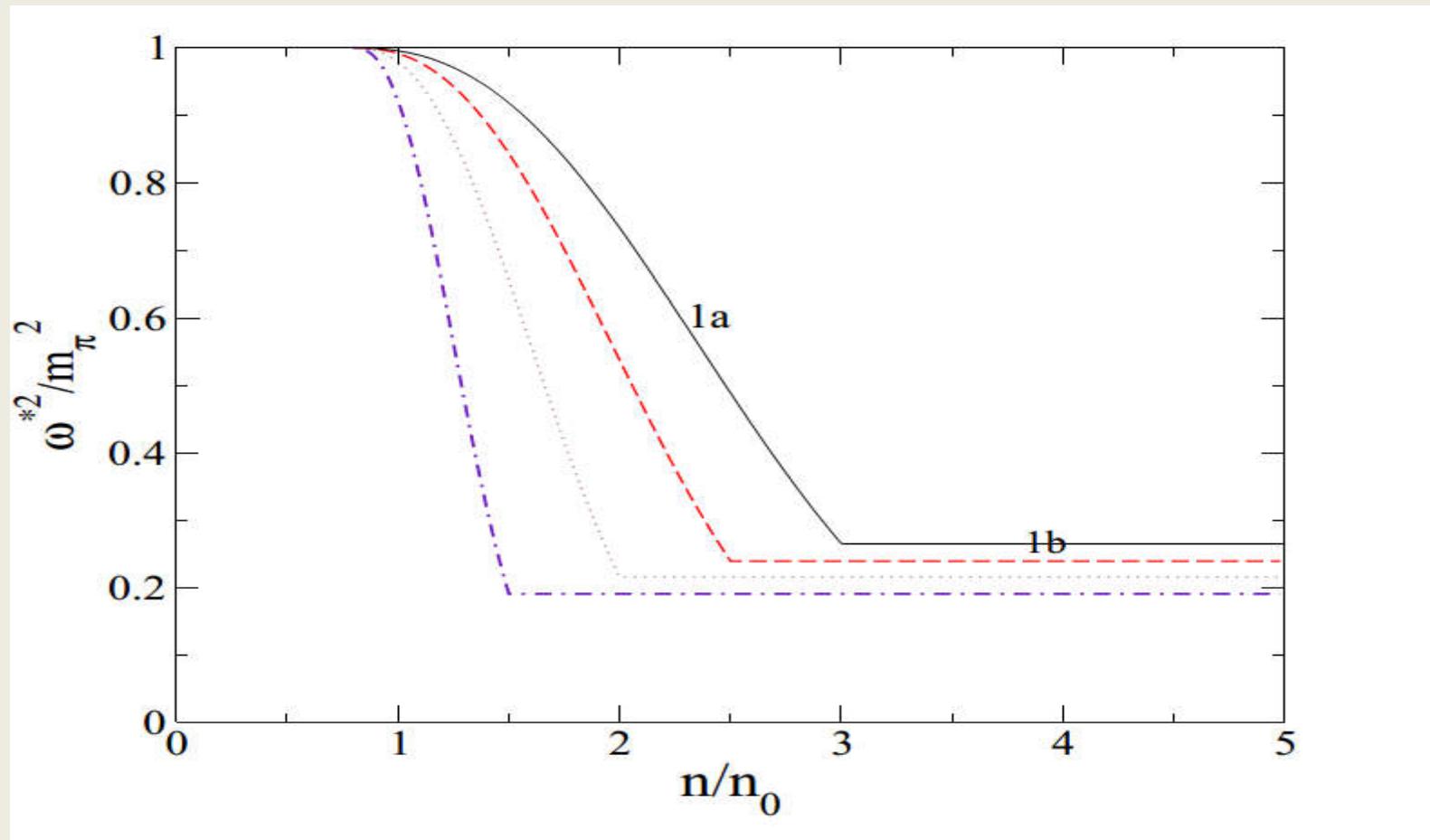
$$\frac{\varepsilon_\nu[\text{MMU}]}{\varepsilon_\nu[\text{MU}]} \sim 10^3 (n/n_0)^{10/3} \frac{\Gamma^6(n)}{[\omega^*(n)/m_\pi]^8},$$

- Main regulator in Minimal Cooling

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



Medium Effects In Cooling Of Neutron Stars



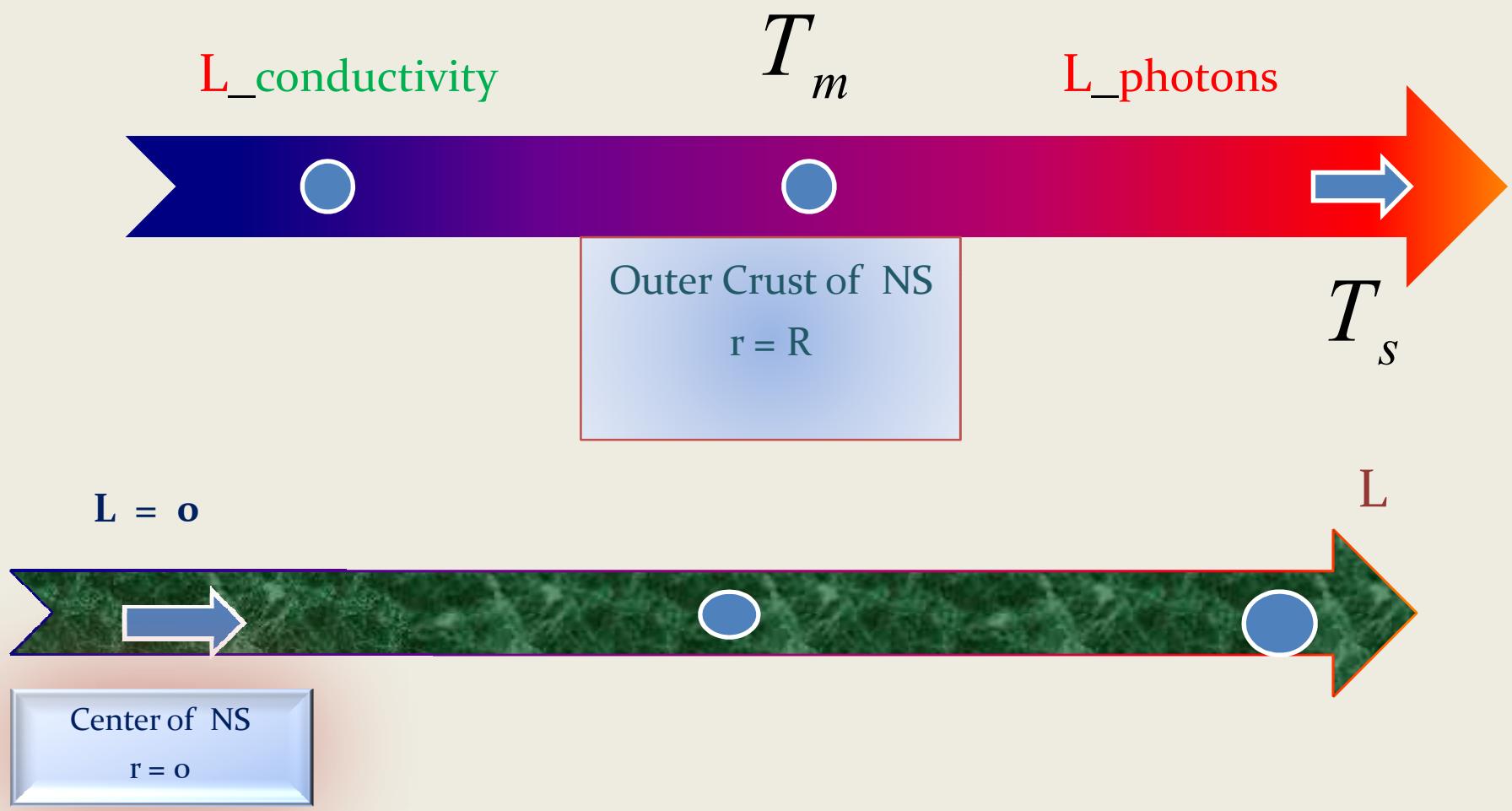
Equations for Cooling Evolution

$$\begin{cases} \frac{\partial \textcolor{red}{z}(\tau, a)}{\partial \tau} = \textcolor{blue}{A}(z, a) \frac{\partial \textcolor{red}{L}(\tau, a)}{\partial a} + \textcolor{blue}{B}(z, a) \\ \textcolor{red}{L}(\tau, a) = \textcolor{blue}{C}(z, a) \frac{\partial \textcolor{red}{z}(\tau, a)}{\partial a} \end{cases} \quad \textcolor{red}{z}(\tau, a) = \log \textcolor{red}{T}(\tau, a)$$

$$\textcolor{red}{L}_{i\pm 1/2} = \pm \frac{\textcolor{blue}{C}_i + \textcolor{blue}{C}_{i\pm 1}}{2} \frac{\textcolor{red}{z}_{i\pm 1} - \textcolor{red}{z}_i}{\Delta a_{i-1/2(1\mp 1)}}$$

$$\frac{\partial \textcolor{red}{L}_i}{\partial a} = 2 \frac{\textcolor{red}{L}_{i+1/2} - \textcolor{red}{L}_{i-1/2}}{\Delta a_i + \Delta a_{i-1}}$$

Boundary conditions



Crust Model

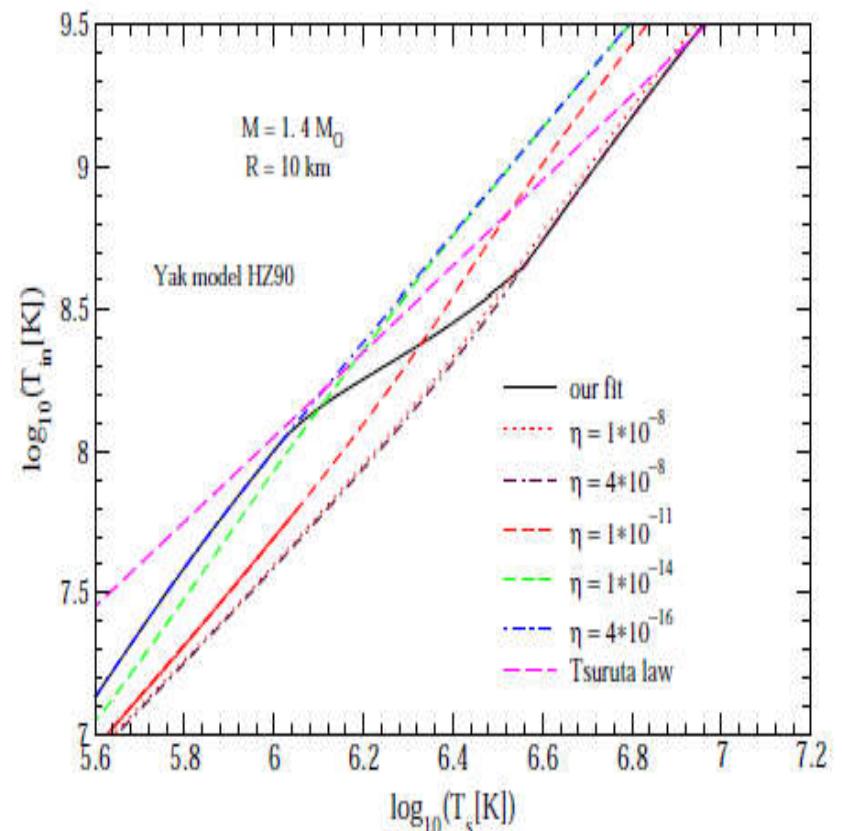
Time dependence of the light element contents in the crust

$$\Delta M_L(t) = e^{-t/\tau} \Delta M_L(0)$$

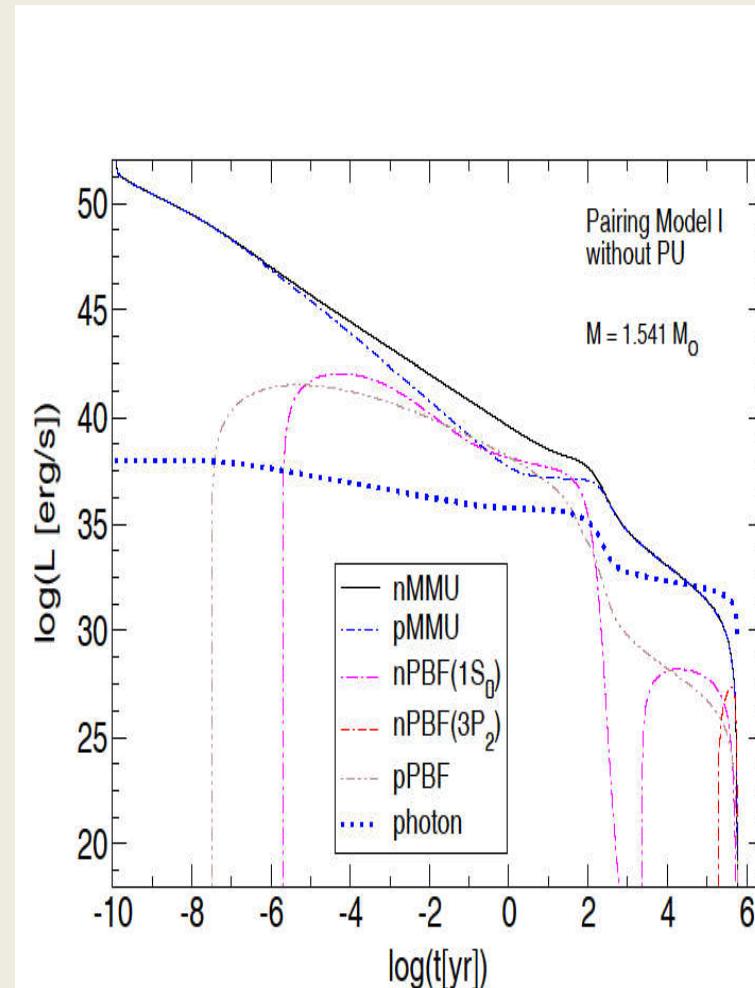
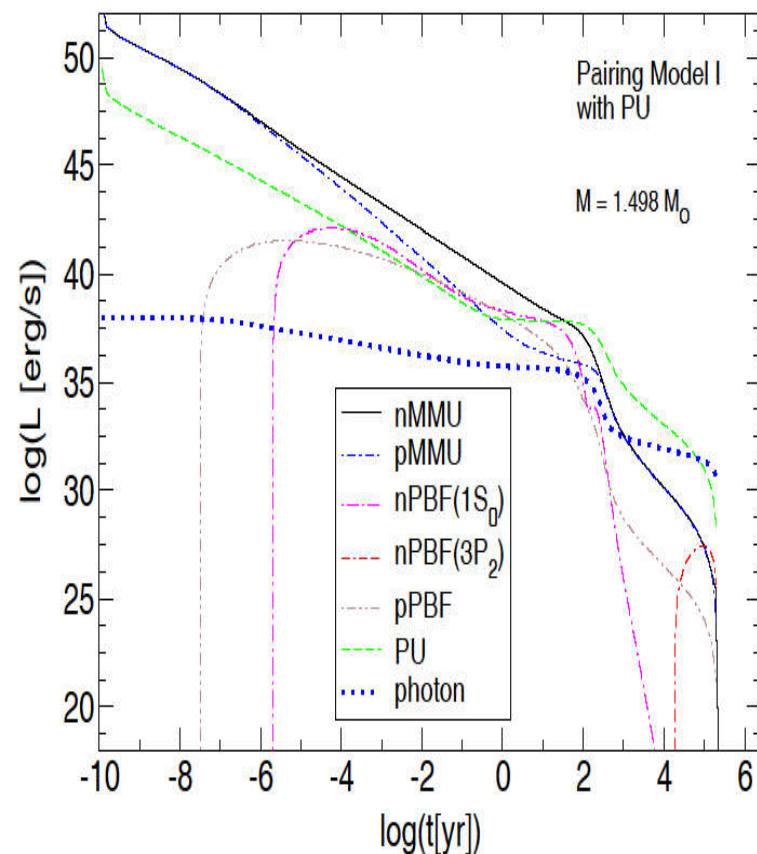
Blaschke, Grigorian, Voskresensky,
A&A 368 (2001) 561.

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

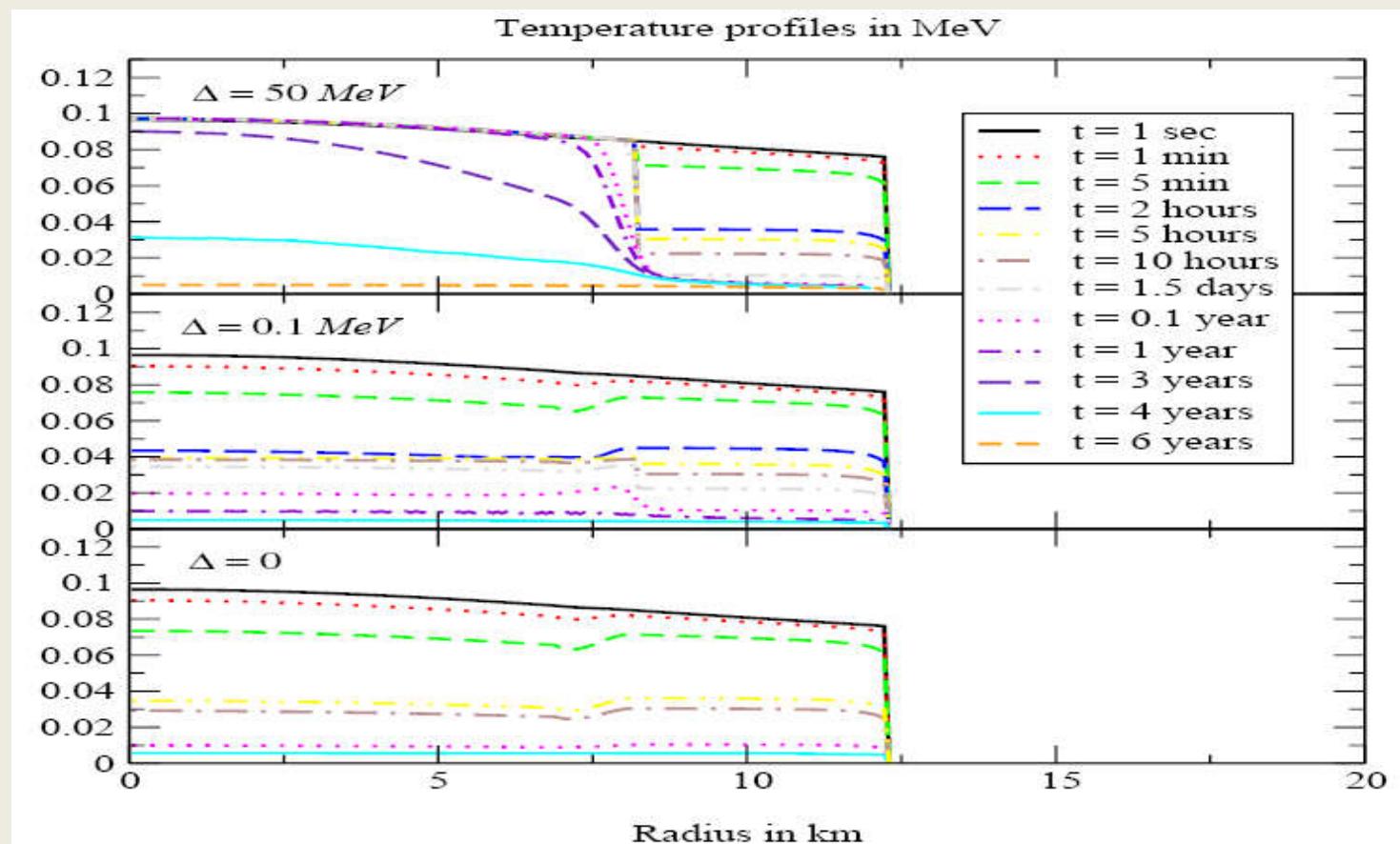
Yakovlev, Levenfish, Potekhin,
Gnedin & Chabrier, Astron. Astrophys
, 417, 169 (2004)



Contributions To Luminosities

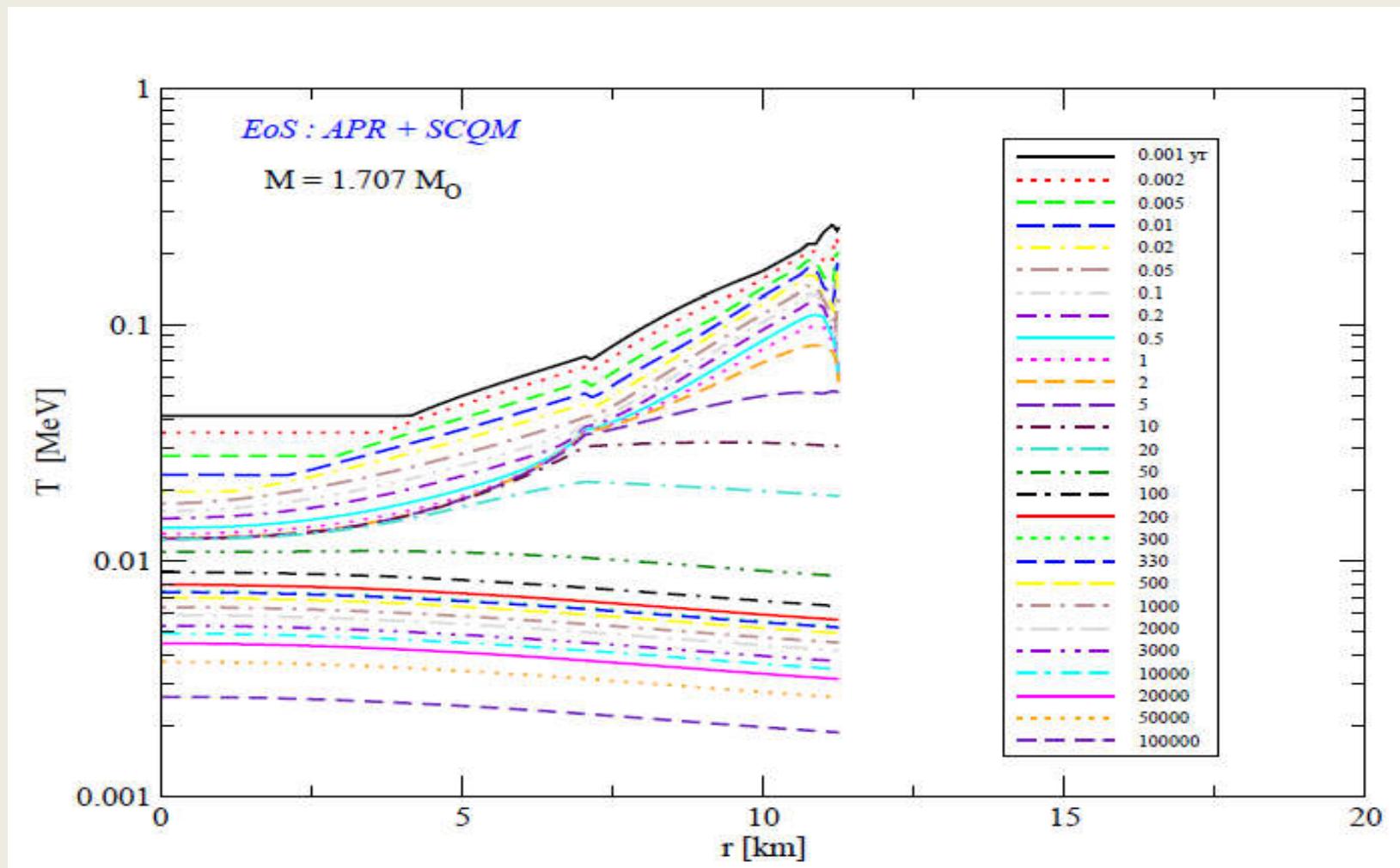


Temperature In The Hybrid Star Interior

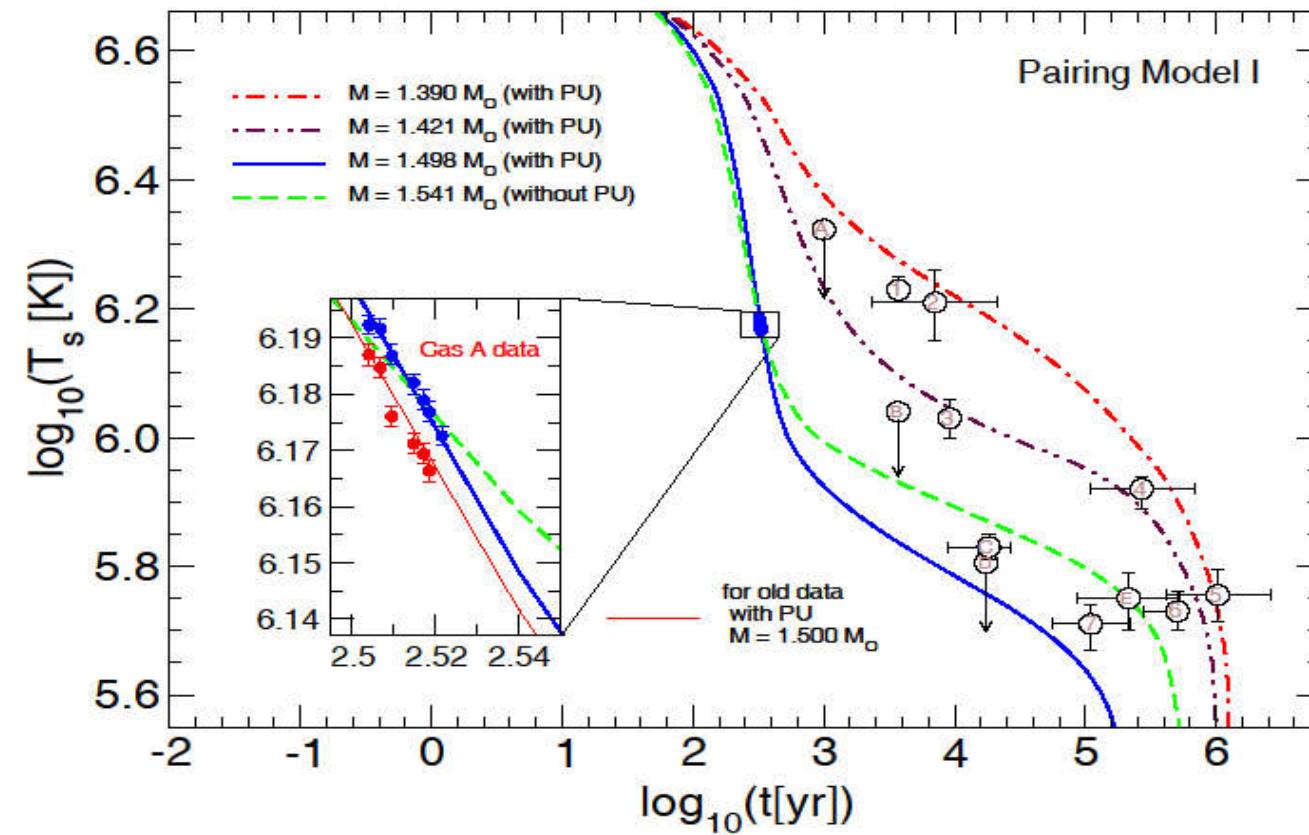


Blaschke, Grigorian, Voskresensky, A&A 368 (2001) 561

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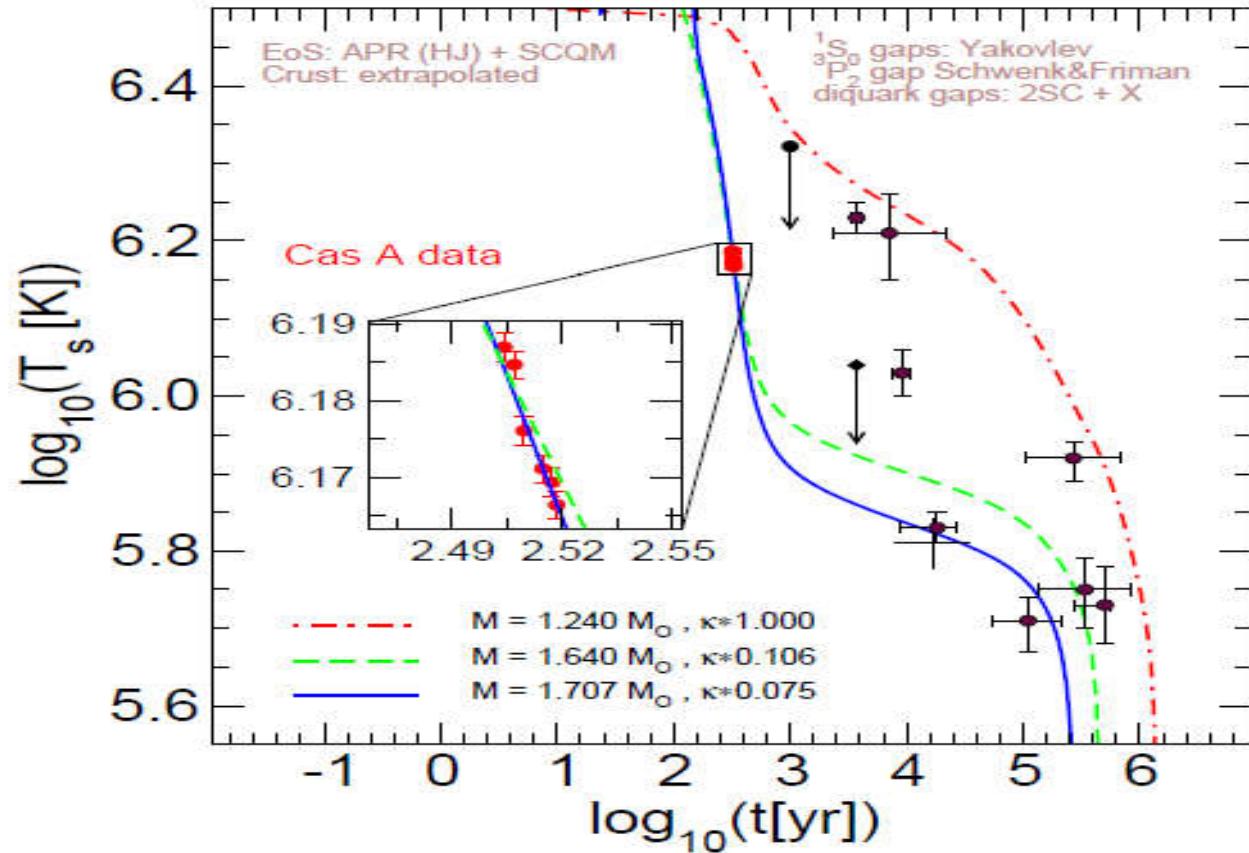


Cas A as an Hadronic Star

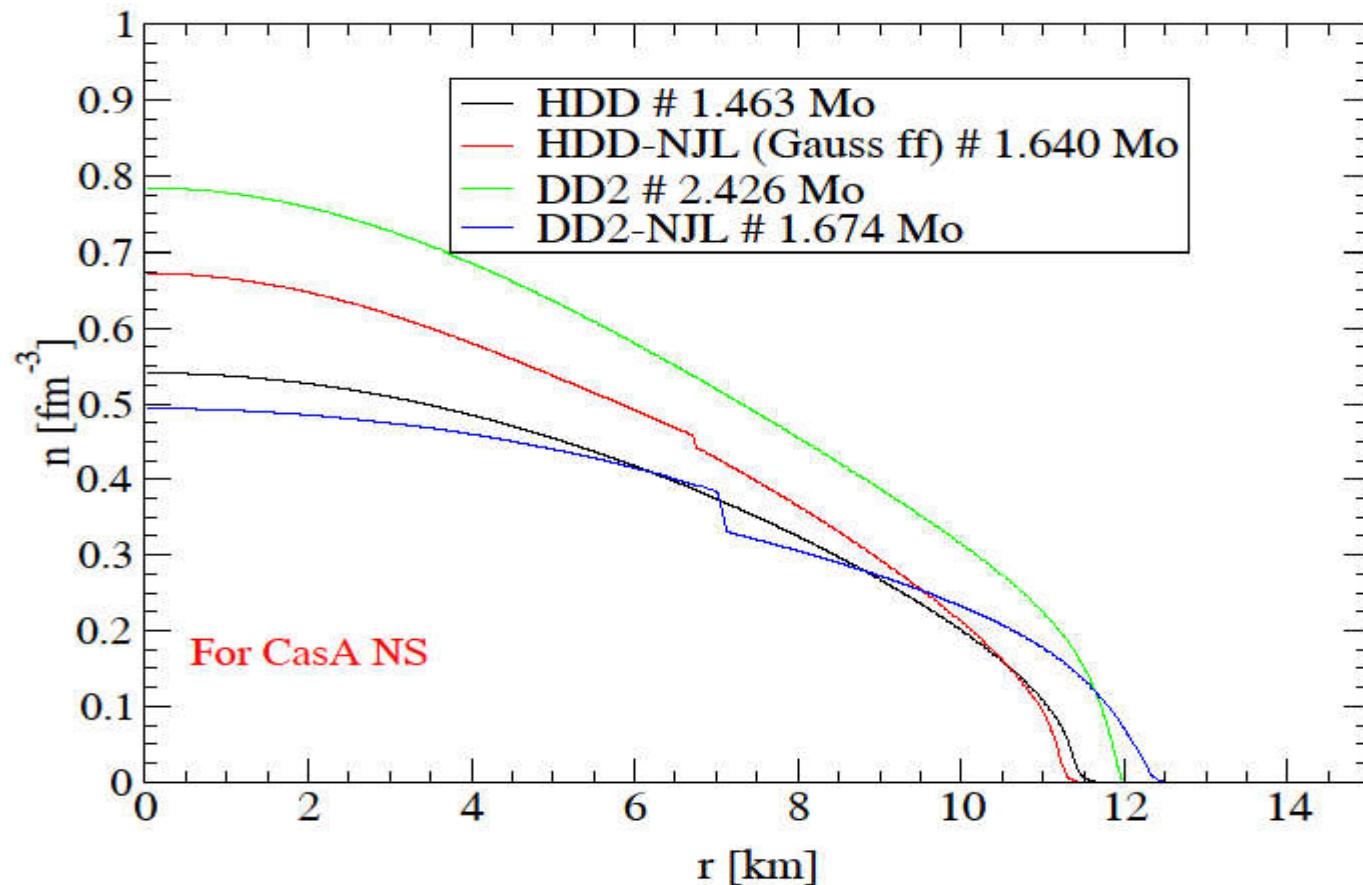


Cas A As An Hybrid Star

H. Grigorian, D. Blaschke, D.N. Voskresensky, Phys. Rev. C 71, 045801 (2005)

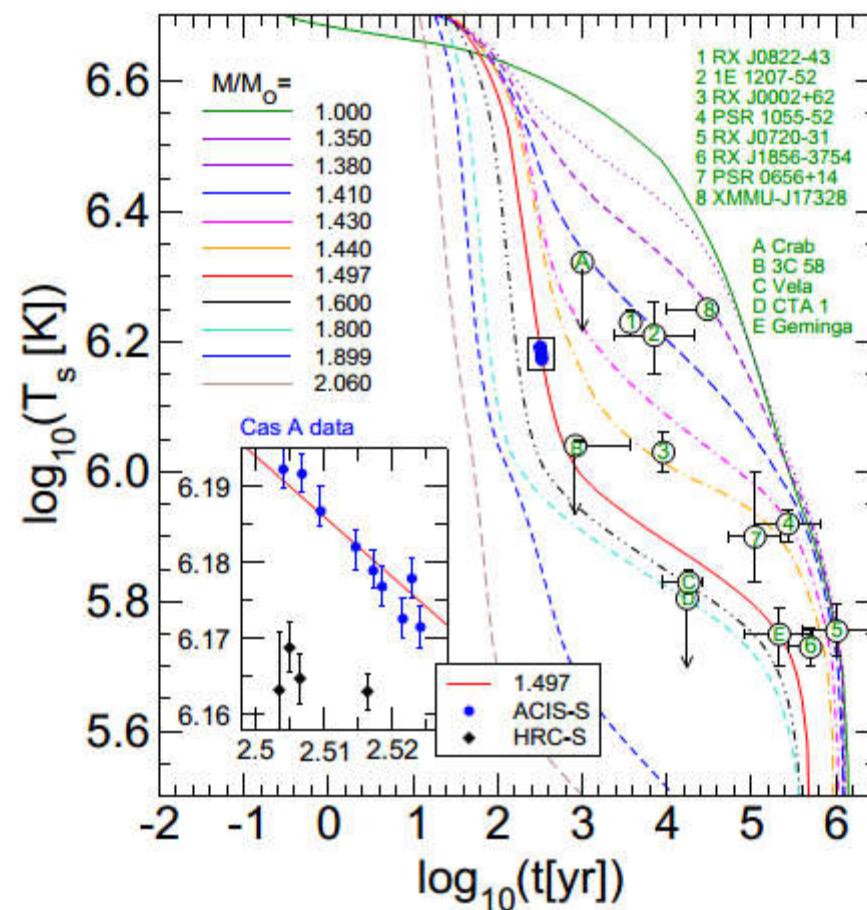
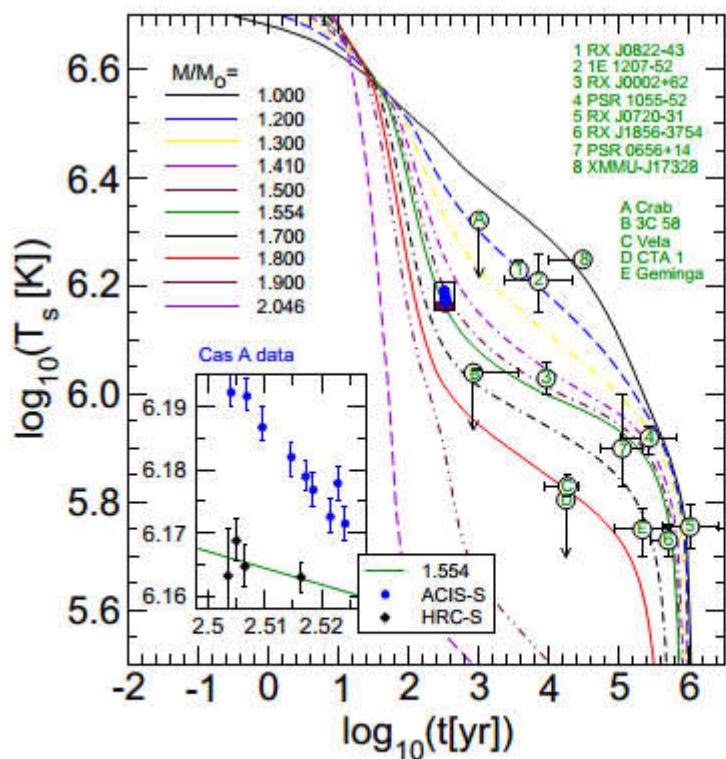


Possible internal structure of CasA



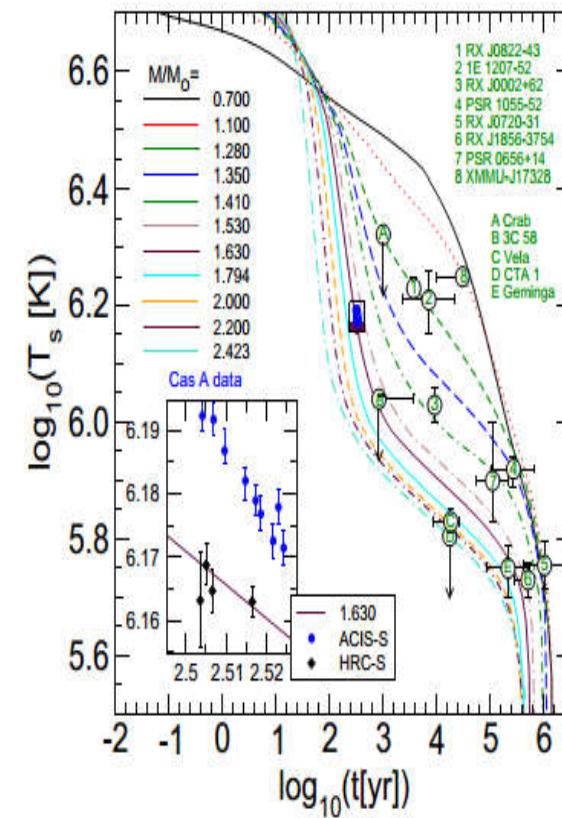
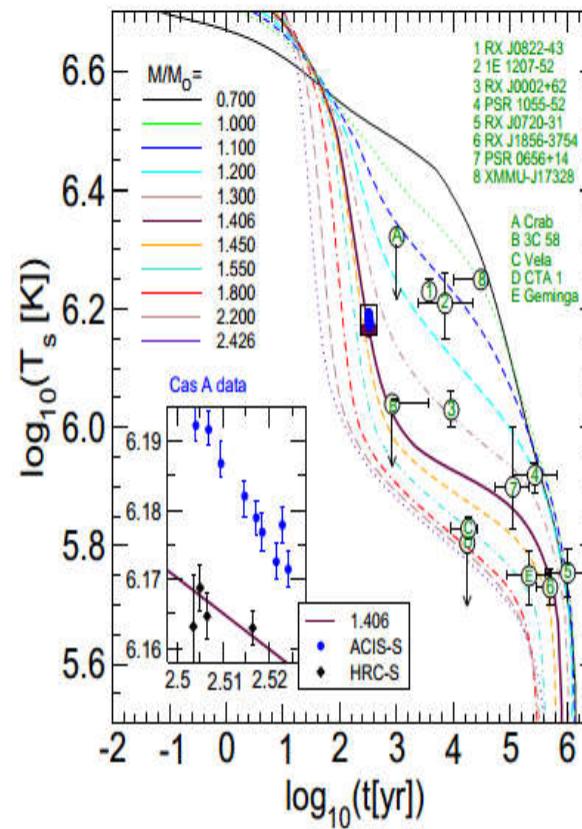
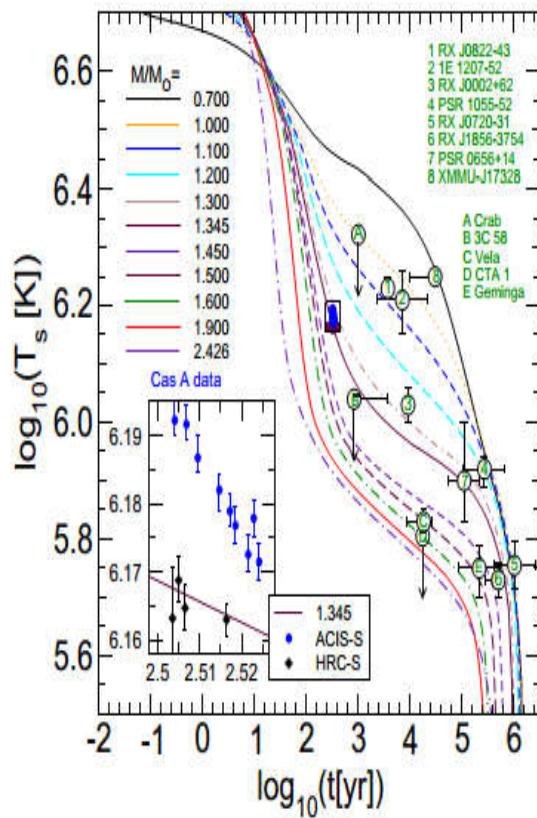
HDD - AV18 , Yak.

ME nc = 3 n0



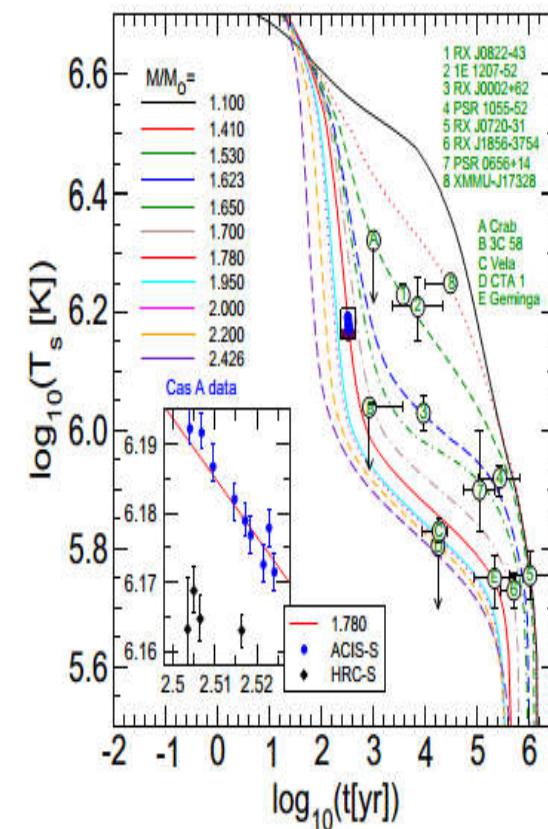
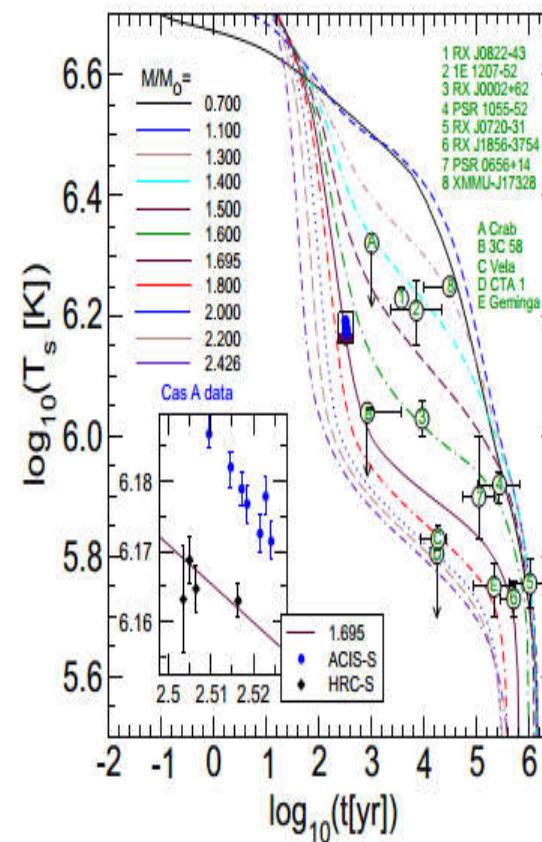
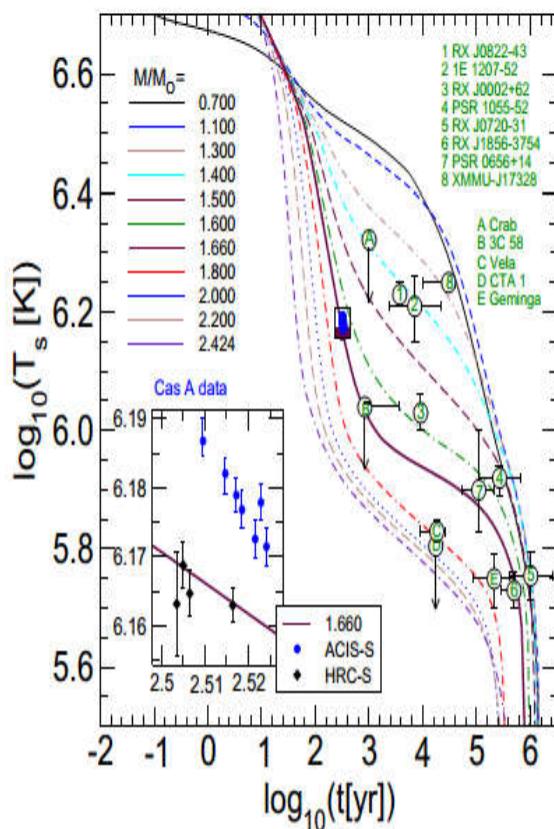
DD2 – BCLL

ME-nc =1.5,2.0,2.5n0



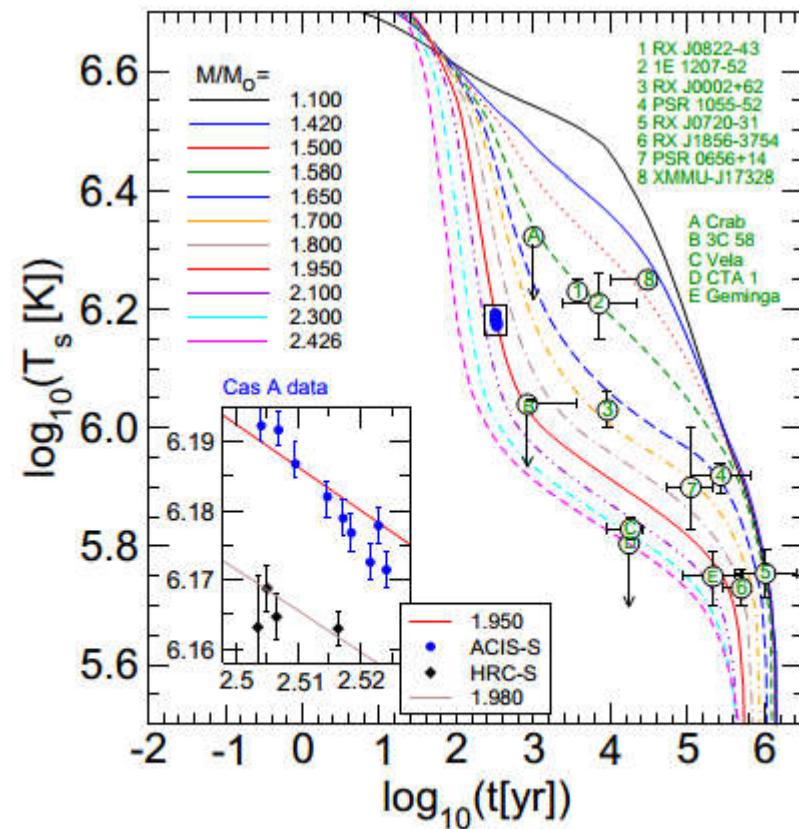
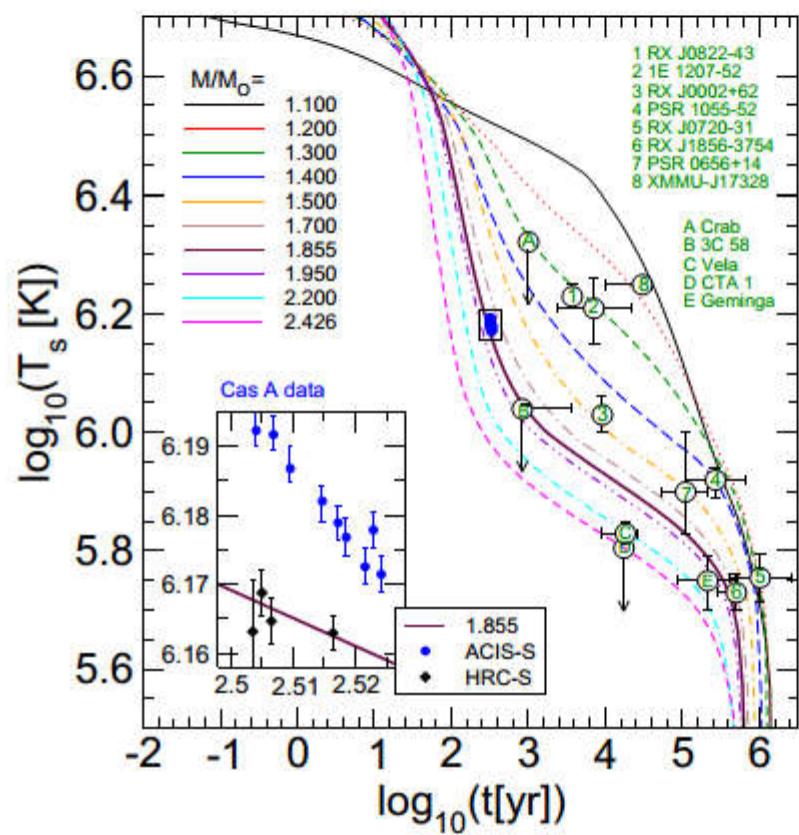
DD2 - EEHOr

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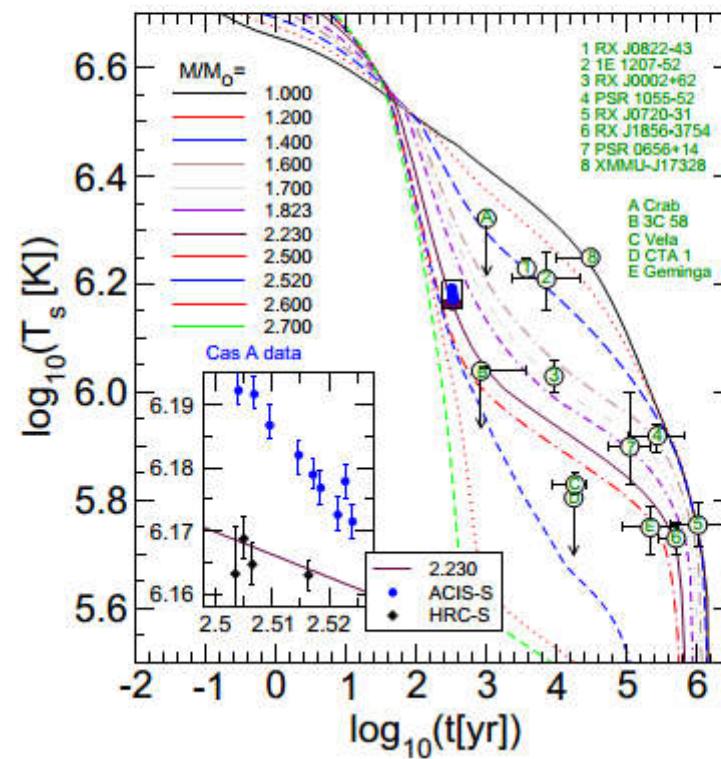
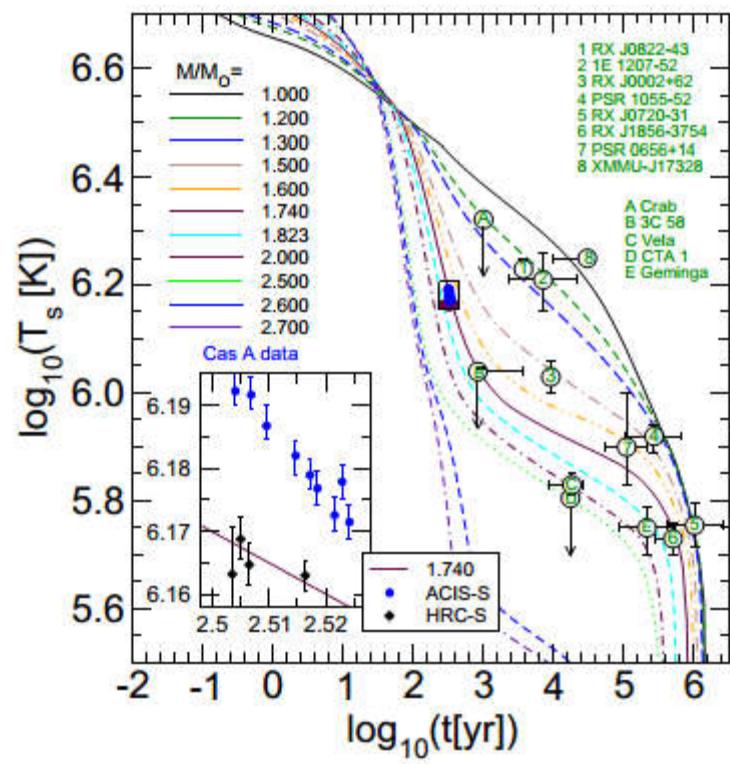


DD2- ME-nc = 3 n0

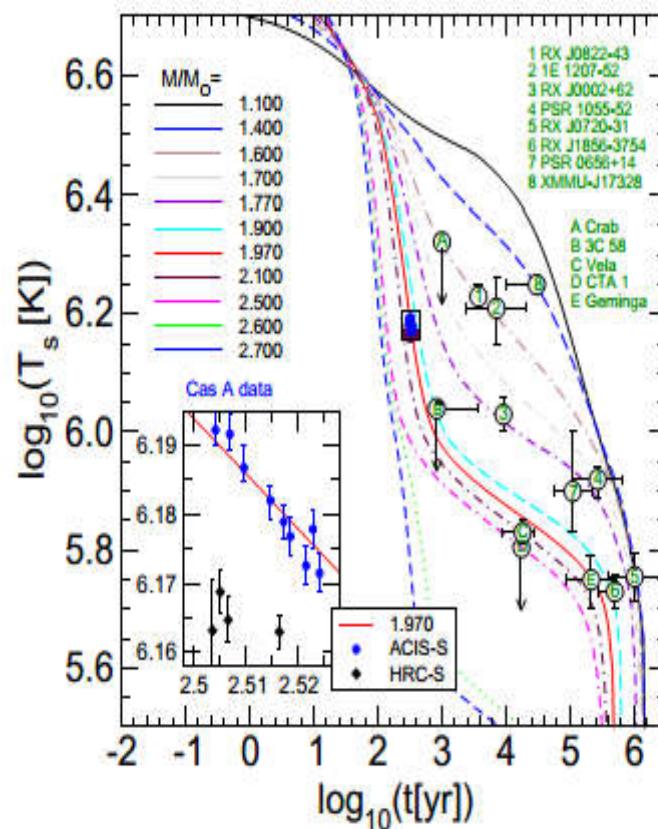
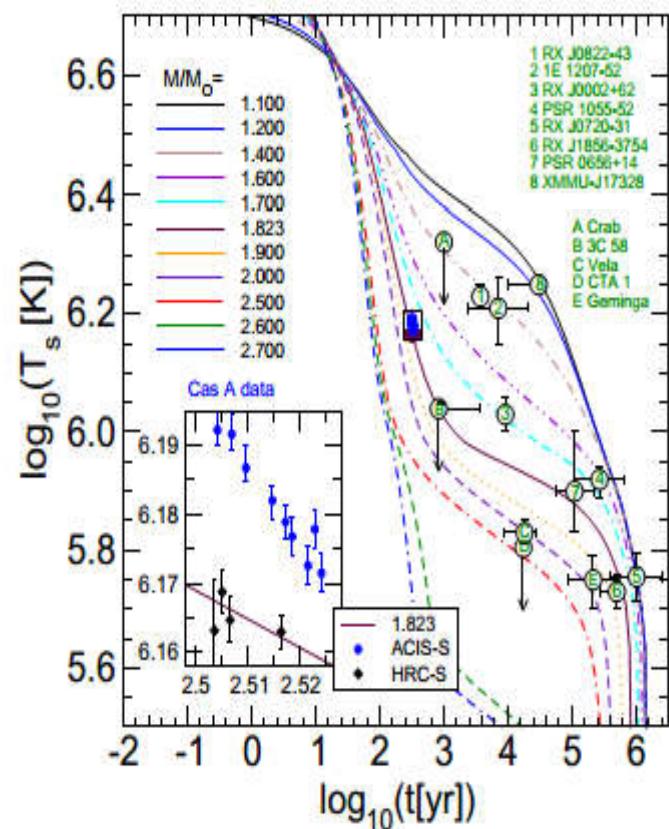
BCLL, EEHOr



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



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



Conclusions

- All known cooling data including the Cas A rapid cooling consistently described by the medium-modified superfluid cooling model
- Both alternatives for the inner structure, hadronic and hybrid star, are viable (as well for Cas A; a higher star mass favors the hybrid model)
- Influence of stiffness on EoS and cooling can be balanced by the choice of corresponding gap model.

Thank YOU! ! ! !