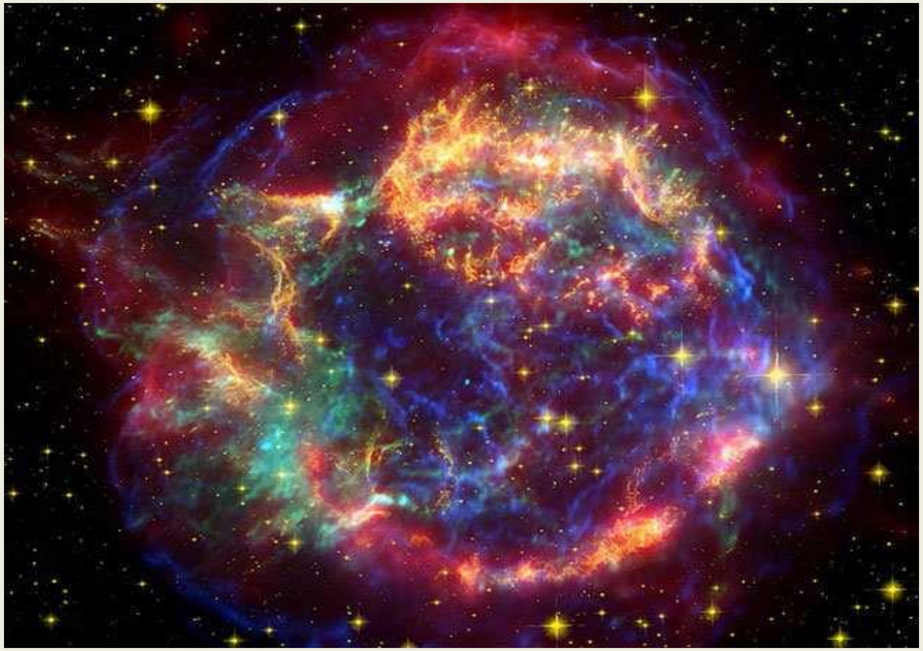
Modeling the Evolution of Cooling of Neutron Stars



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Yerevan State University,
AANL CP&IT
(Yeravan, Armenia)

Seminar LIT – 2023
16 November
JINR, Dubna

my co-authors: D.Blaschke, D.Voskresensky,
A. Ayriyan E. Kolomeitsev, K. Maslov,

Соответствие исследований тематическому плану ОИЯИ

06-6-1119-2024/2026 "Методы, алгоритмы и программное обеспечение для моделирования физических систем, математической обработки и анализа экспериментальных данных"

Проект 1: Моделирование, обработка и анализ экспериментальных данных

FTE: 0.2

Задача

Применение современных методов машинного обучения для задачи распознавания заряженных частиц, в частности для MPD и BM@N

Сотрудничество:

А.А. Апарин (ЛФВЭ)

К.В. Герценбергер (ЛФВЭ)

Проект 2: Методы вычислительной физики для исследования сложных систем

FTE: 0.8

Задача

Методы моделирования сложных процессов в плотной ядерной материи на основе уравнения состояния (СТИ и компактные звёзды)

Сотрудничество:

Д.Н. Воскресенский (ЛТФ)

Ю.Б. Иванов (ЛТФ)

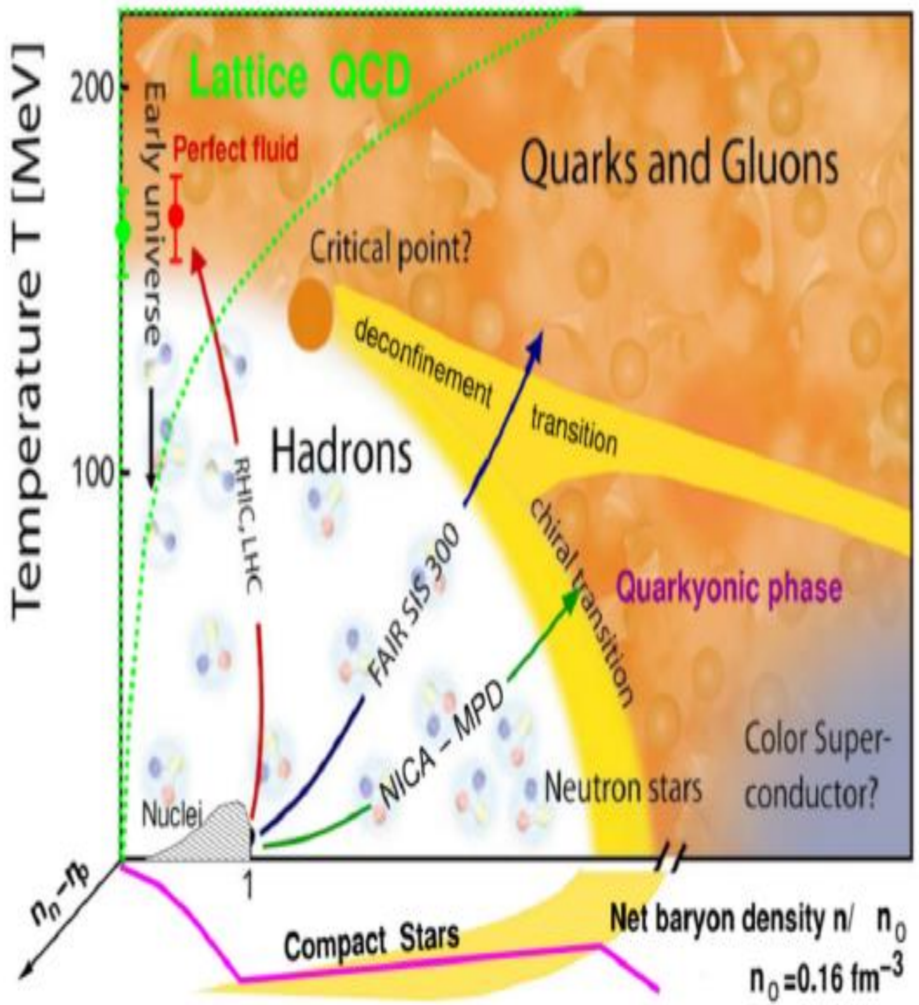
Е.Э. Коломейцев (ЛТФ)

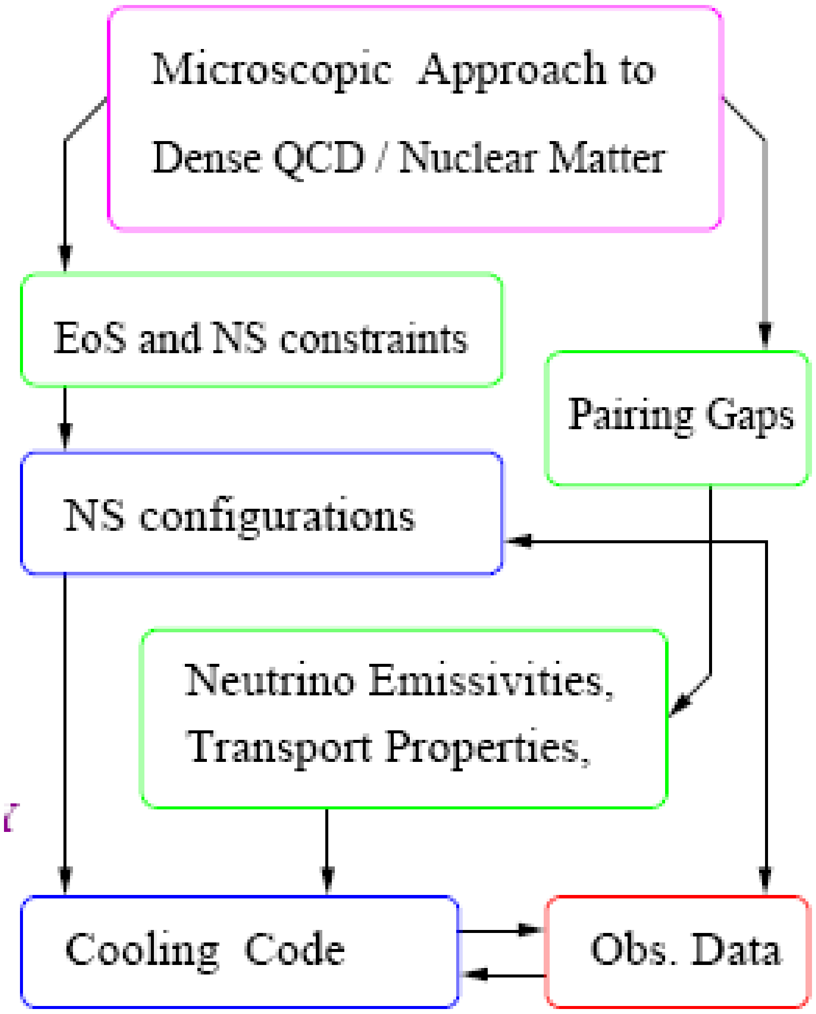
Simulation of Cooling Evolution of Neutron Stars

- Introduction
- Neutron Stars structure
- Neutron Stars cooling problem
- Simulations algorithm
- ***Results for NS cooling***

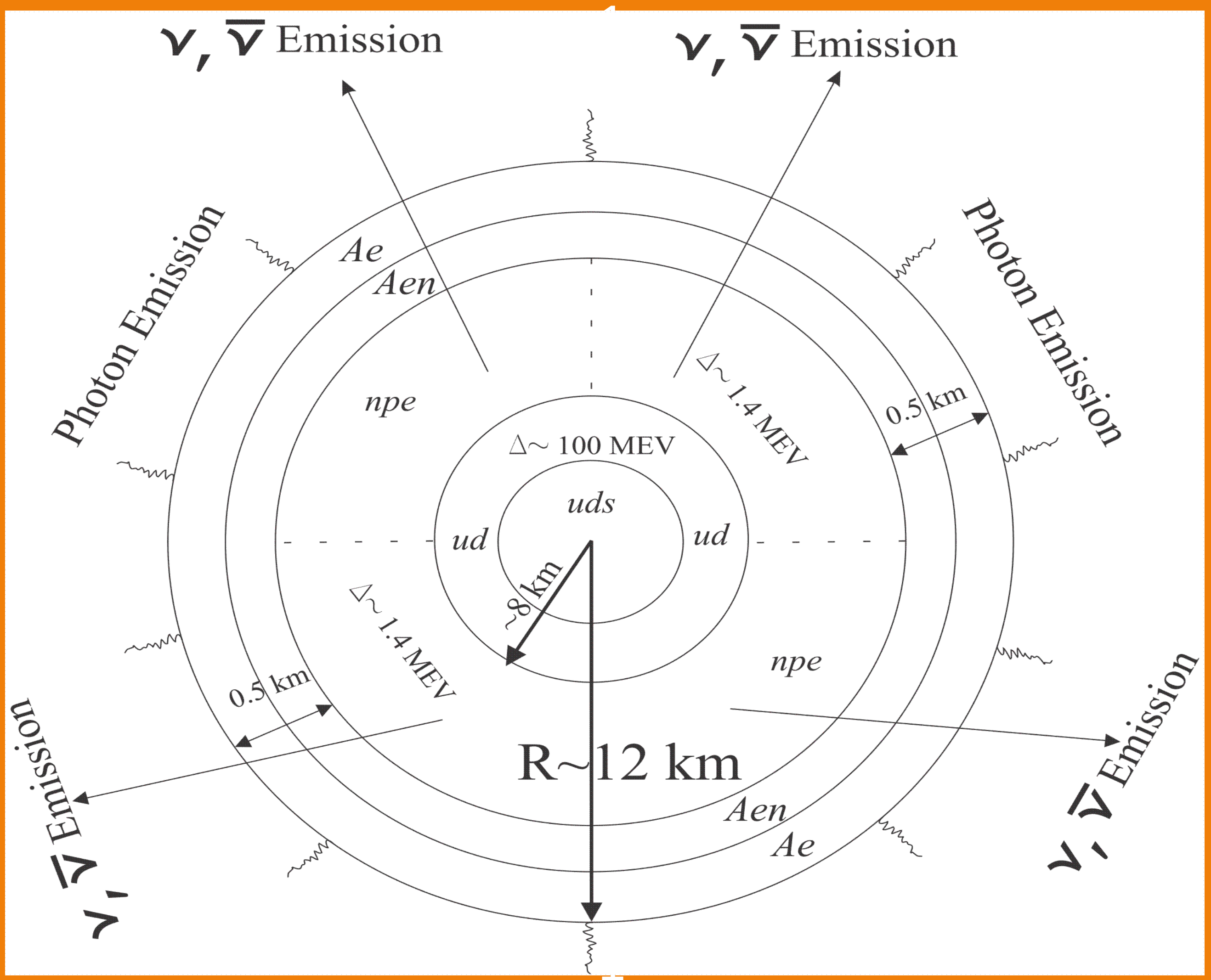
H. Grigorian, D. N. Voskresensky and D. Blaschke
Eur. Phys. J. A **52: 67 (2016).**

Phase Diagramm & Cooling Simulation





Structure Of Hybrid Star



Static neutron star mass and radius

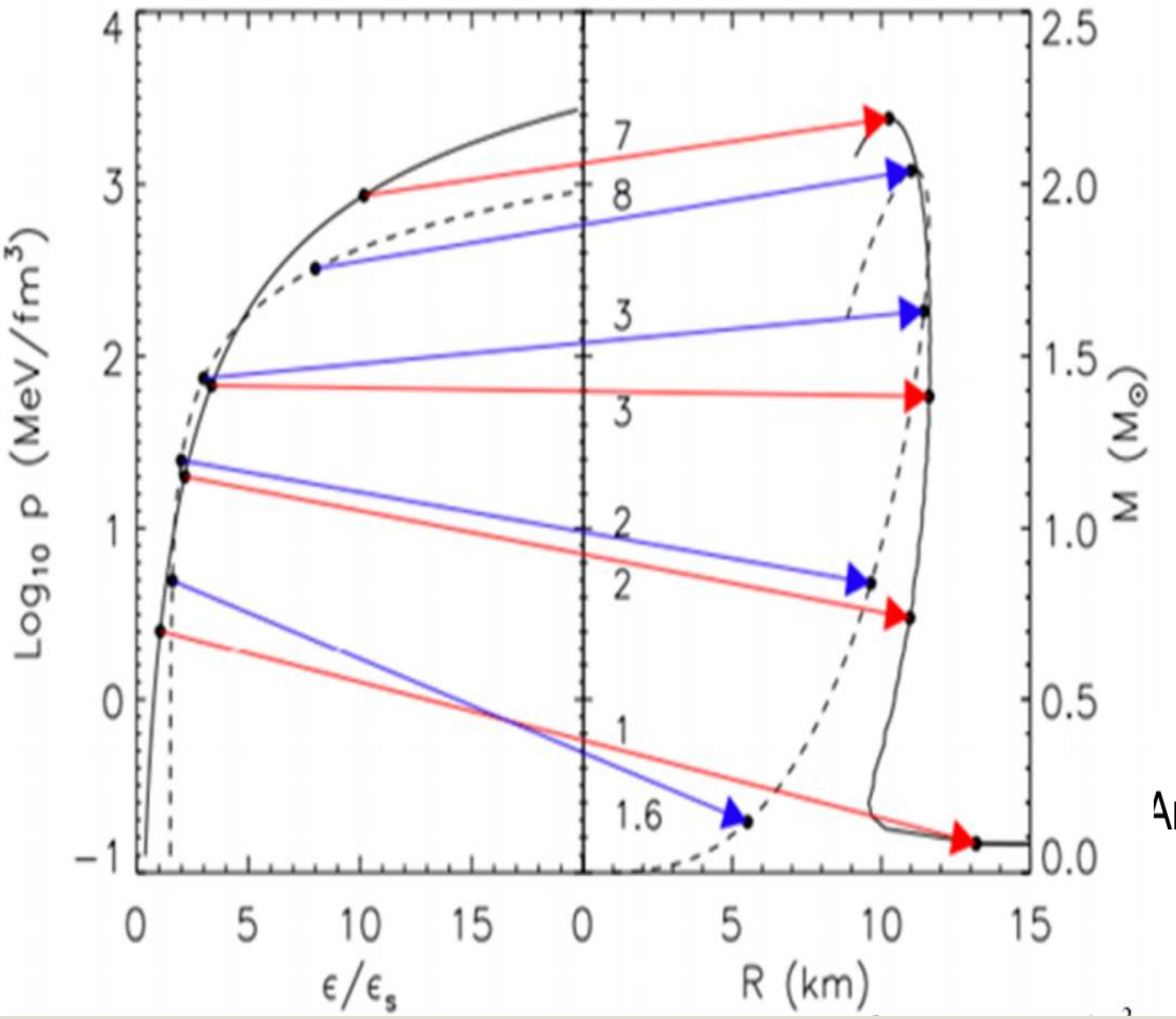
The structure and global properties of compact stars are obtained by solving the Tolman-Oppenheimer-Volkoff (TOV) equations[1,2]:

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

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

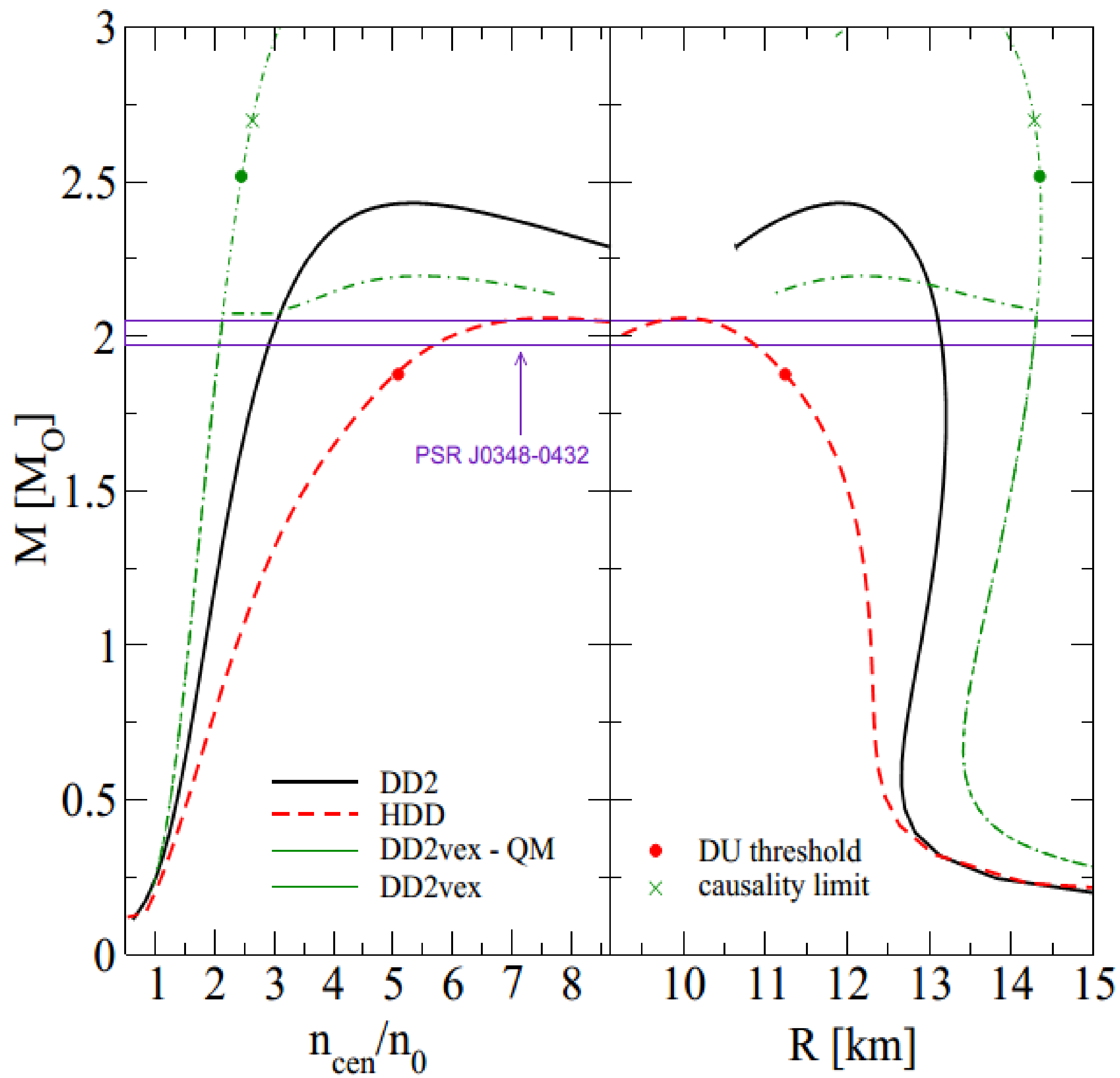
[2] J. R. Oppenheimer and G. M. Volkoff, Phys. Rev. **55**, 374 (1939).

EoS vs. Mass Radious of NS

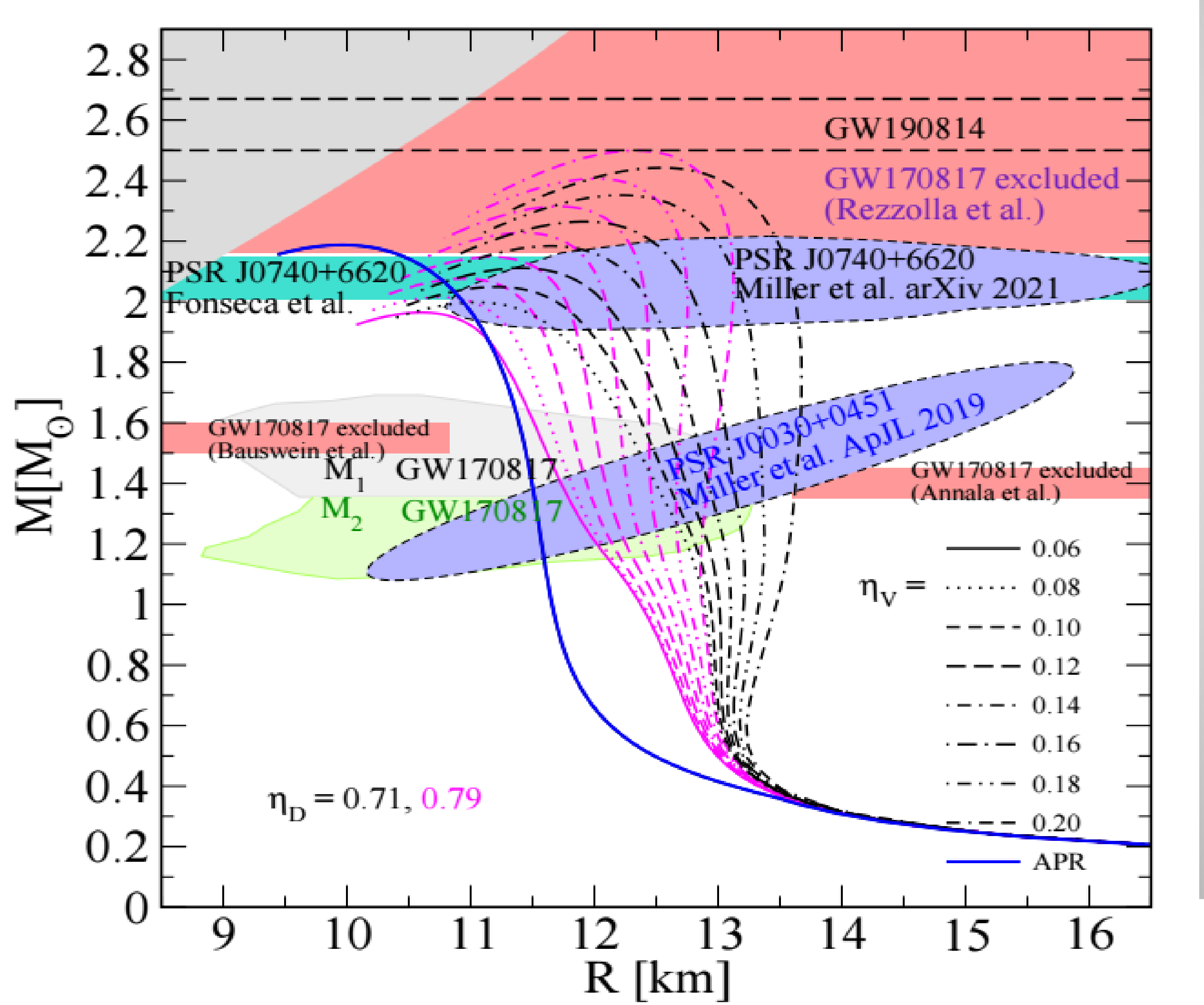


Lattimer,
Annu. Rev. Nucl. Part. Sci. 62, 485 (2012)
arXiv: 1305.3510

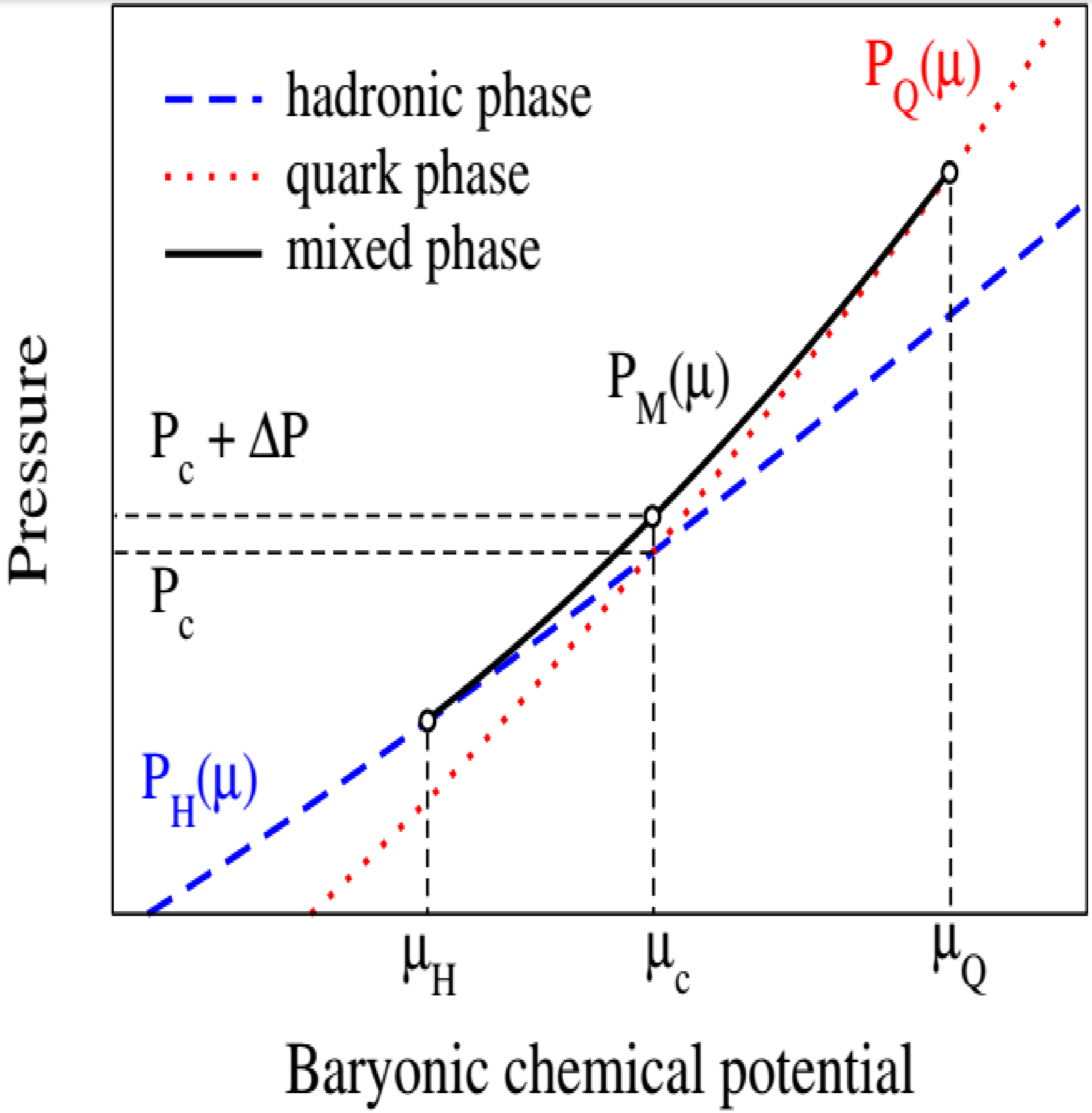
Stability of stars
HDD, DD2 & DDvex-NJL EoS models



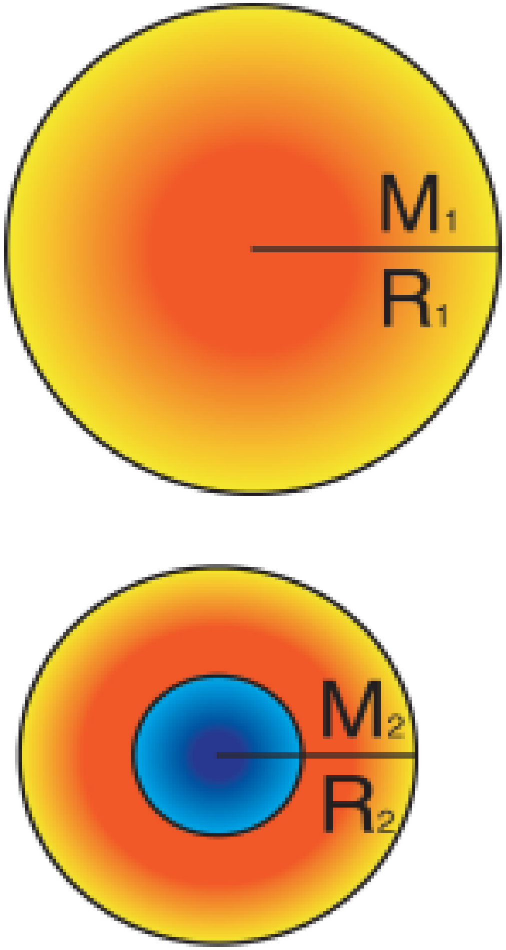
Modern MR Data and Models

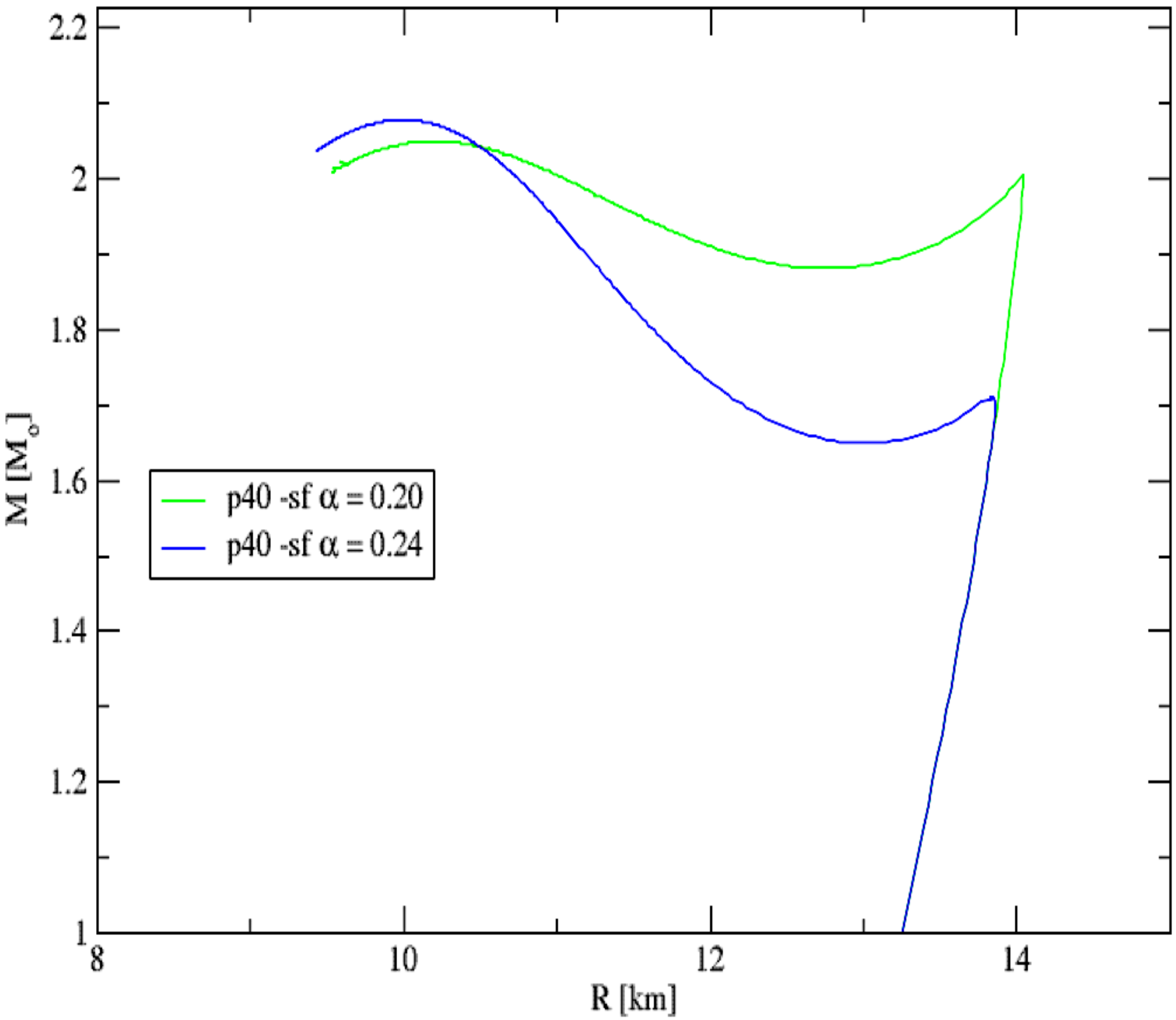


Mixed Phase in Quark-Hadron Phase Transition

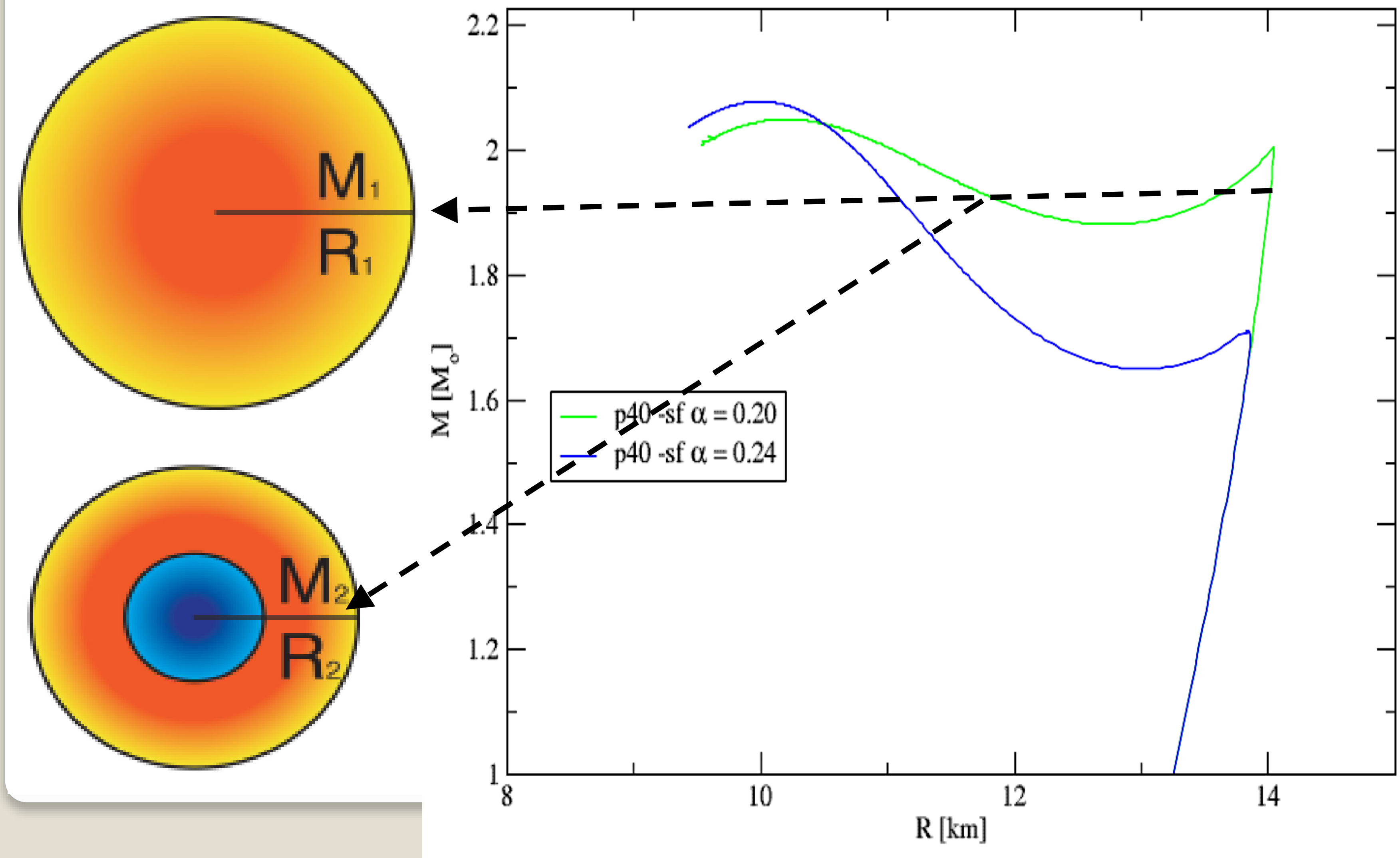


High Mass Twin CS

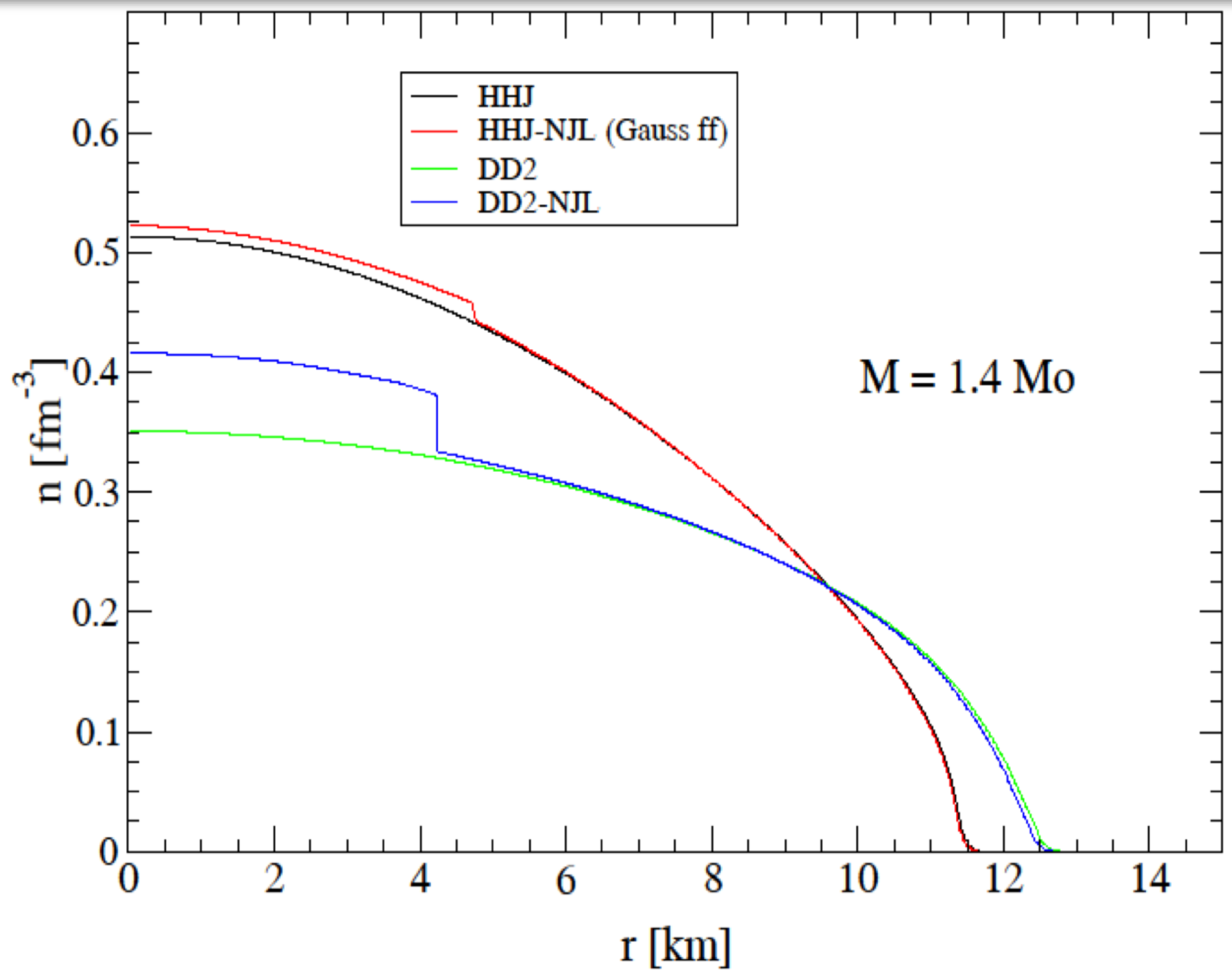




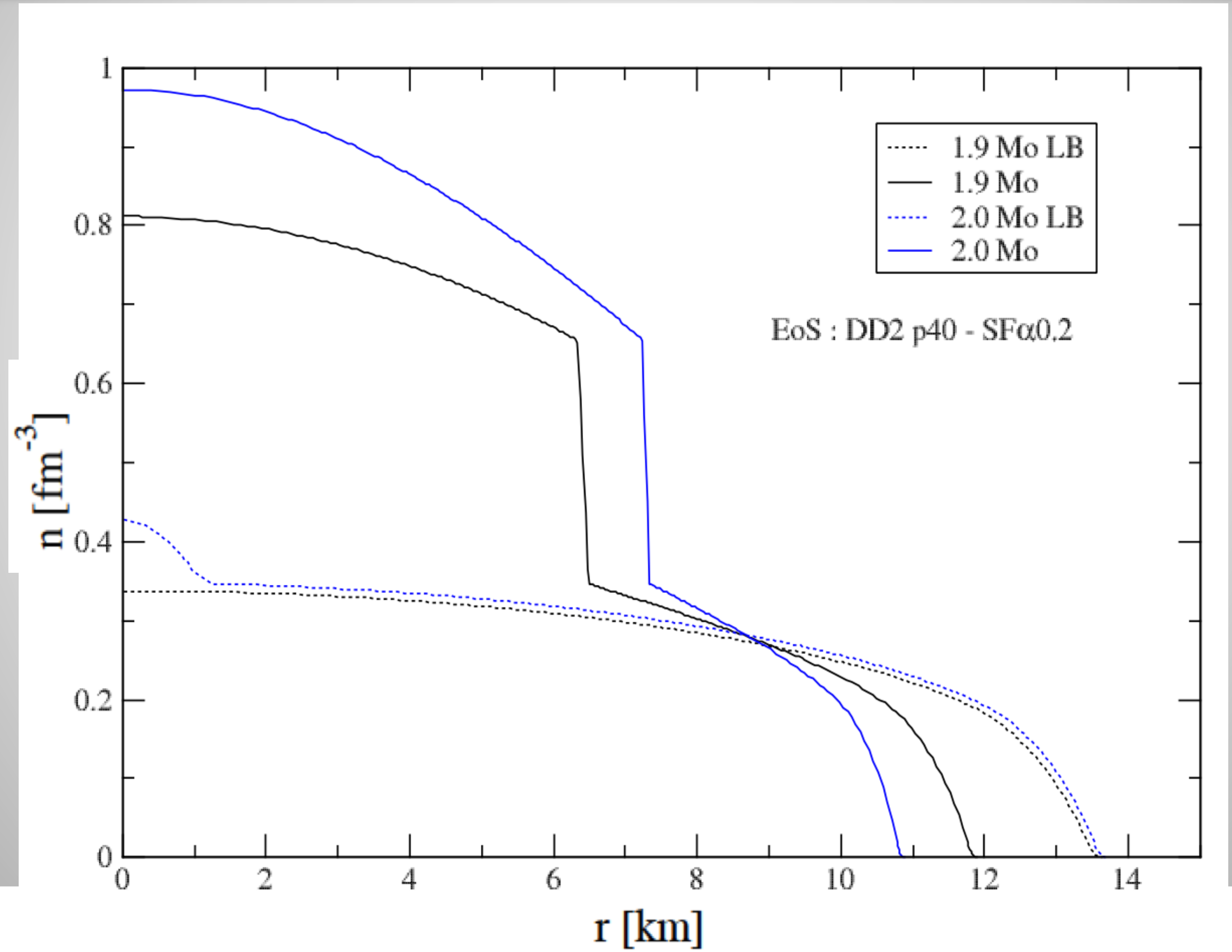
High Mass Twin CS



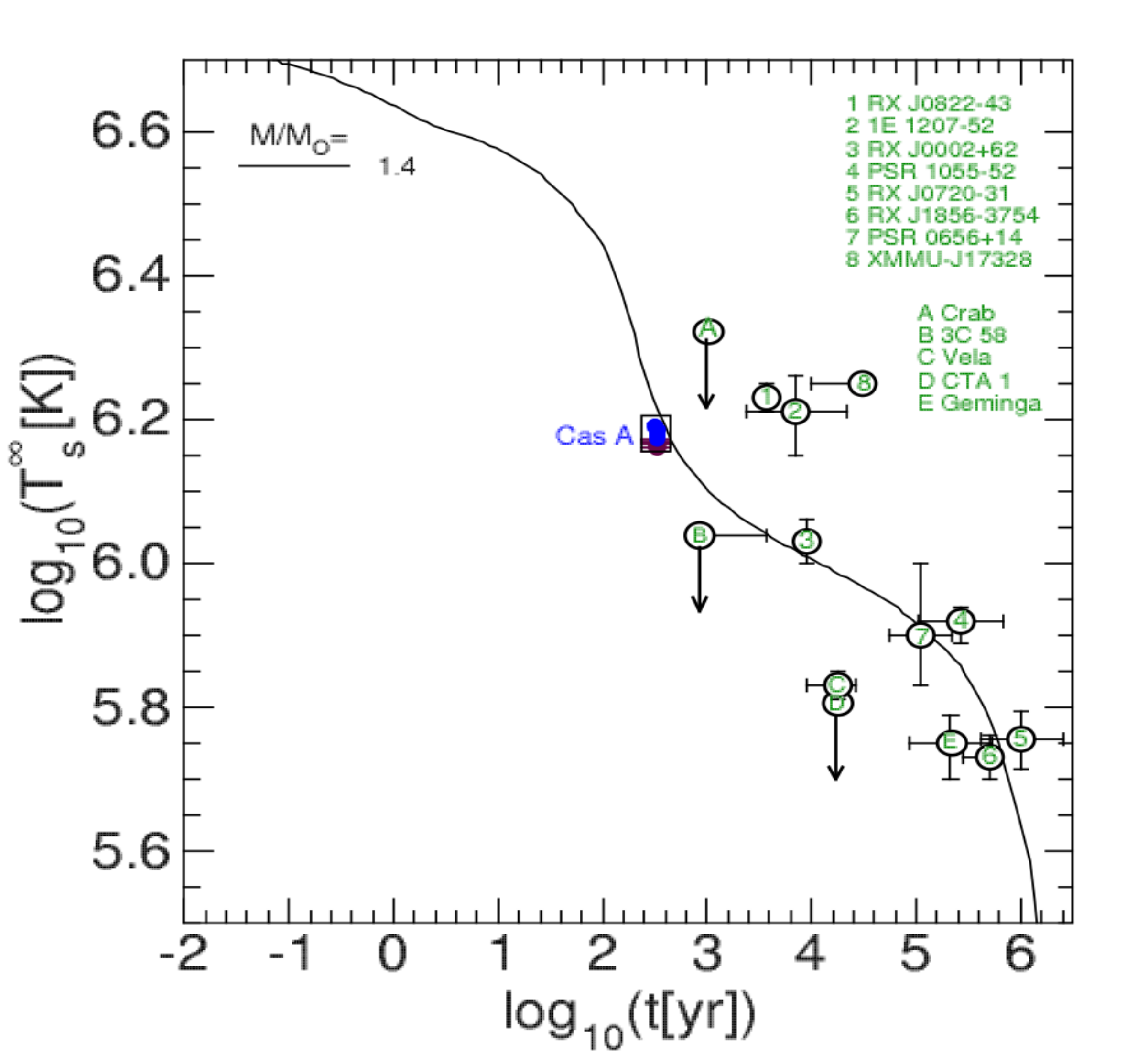
Different Configurations with the same NS mass



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

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);

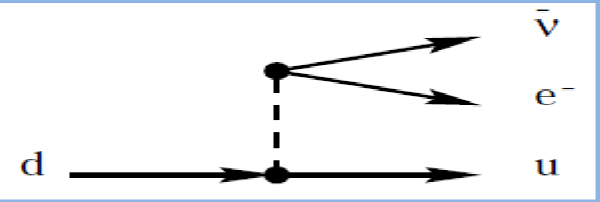
D. Blaschke Grigorian, Voskresensky, A& A 368 (2001)561.

Neutrino emissivities in quark matter:

- Quark direct Urca (QDU) the most efficient processes

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

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

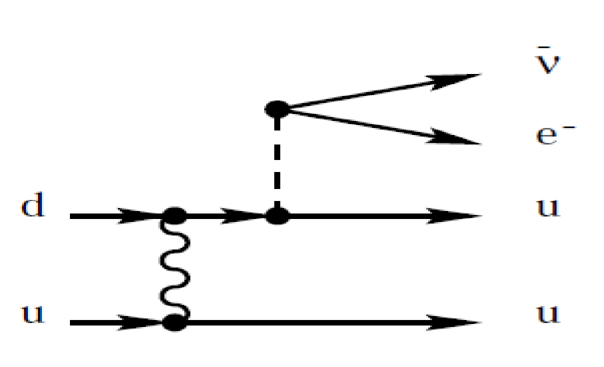


Compression n/no ≃ 2 , strong coupling αs ≈ 1

- Quark Modified Urca (QMU) and Quark Bremsstrahlung

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

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



- 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

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

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

Quark PBF

Neutrino emissivities in hadronic matter:

- Direct Urca (DU) the most efficient processes

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

- 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

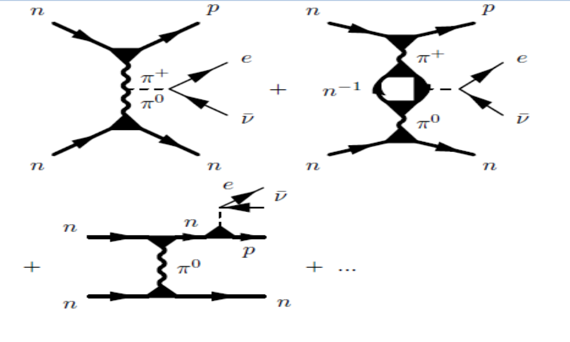
$$v_N = \Delta_N(T)/T = \sqrt{1-\tau_N}\left(1.456 - \frac{0.157}{\sqrt{\tau_N}} + \frac{1.766}{\tau_N}\right)$$

- Enhanced cooling due to the pairing

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

Medium Effects In Cooling Of Neutron Stars

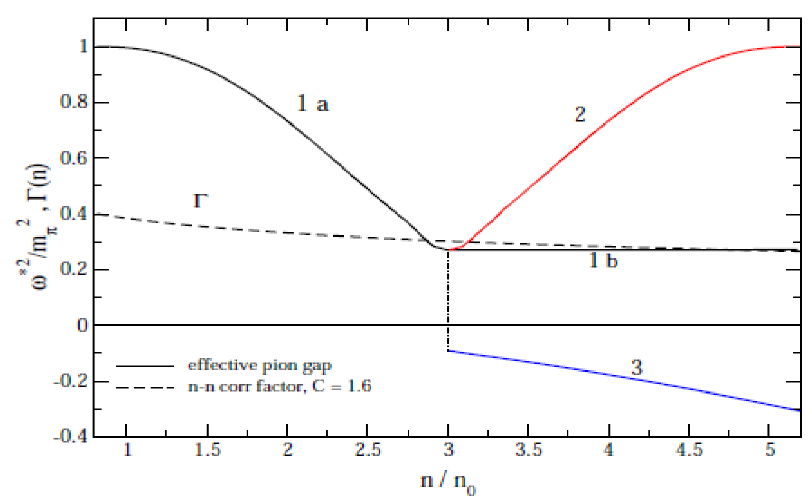
- Based on Fermi liquid theory (Landau (1956), Migdal (1967), Migdal et al. (1990))
- MMU – insted of MU



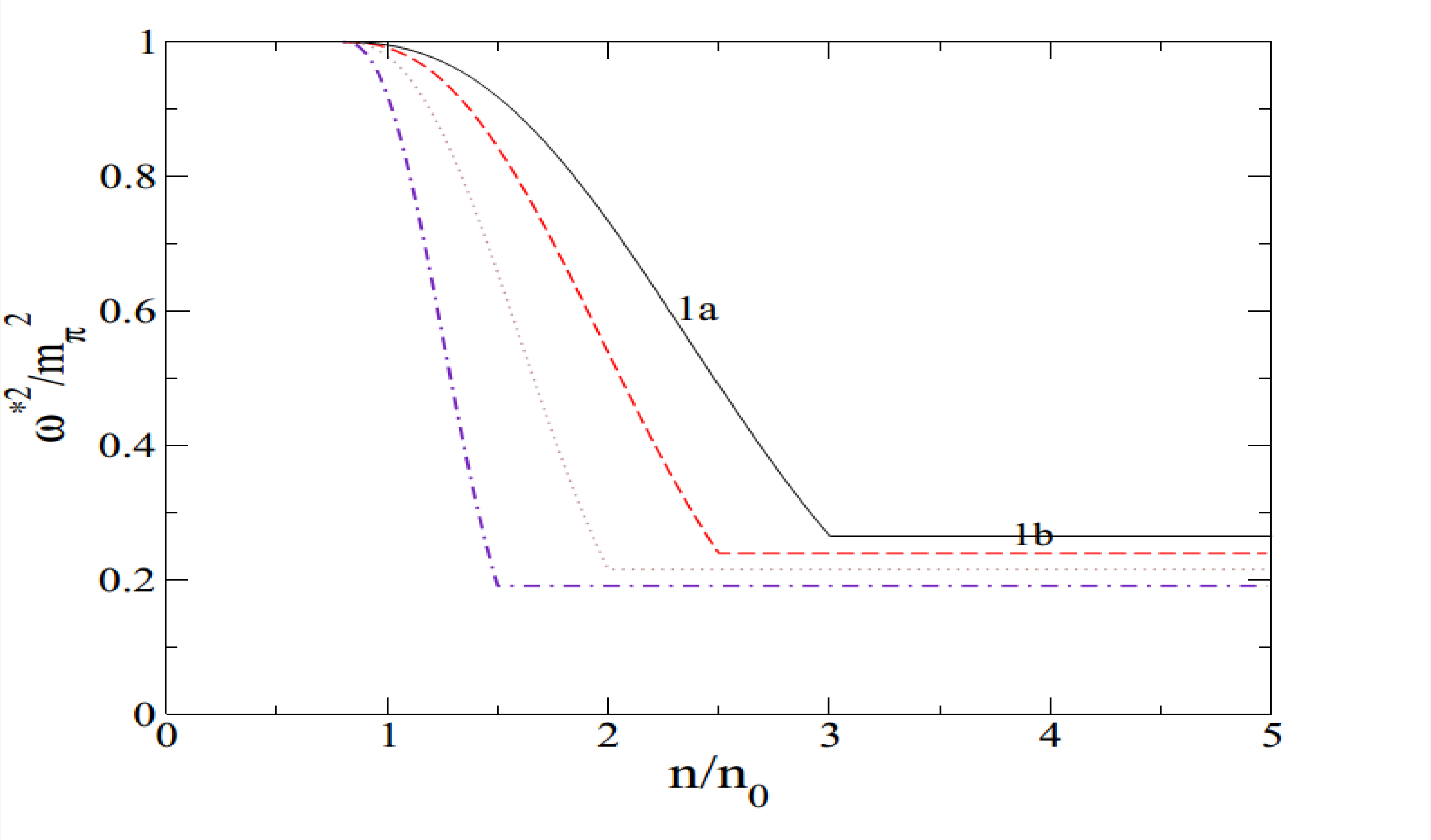
$$\frac{\varepsilon_\nu[\mathrm{MMU}]}{\varepsilon_\nu[\mathrm{MU}]} \sim 10^3 \, (n/n_0)^{10/3} \frac{\Gamma^6(n)}{[\omega^*(n)/m_\pi]^8},$$

- Main regulator in Minimal Cooling

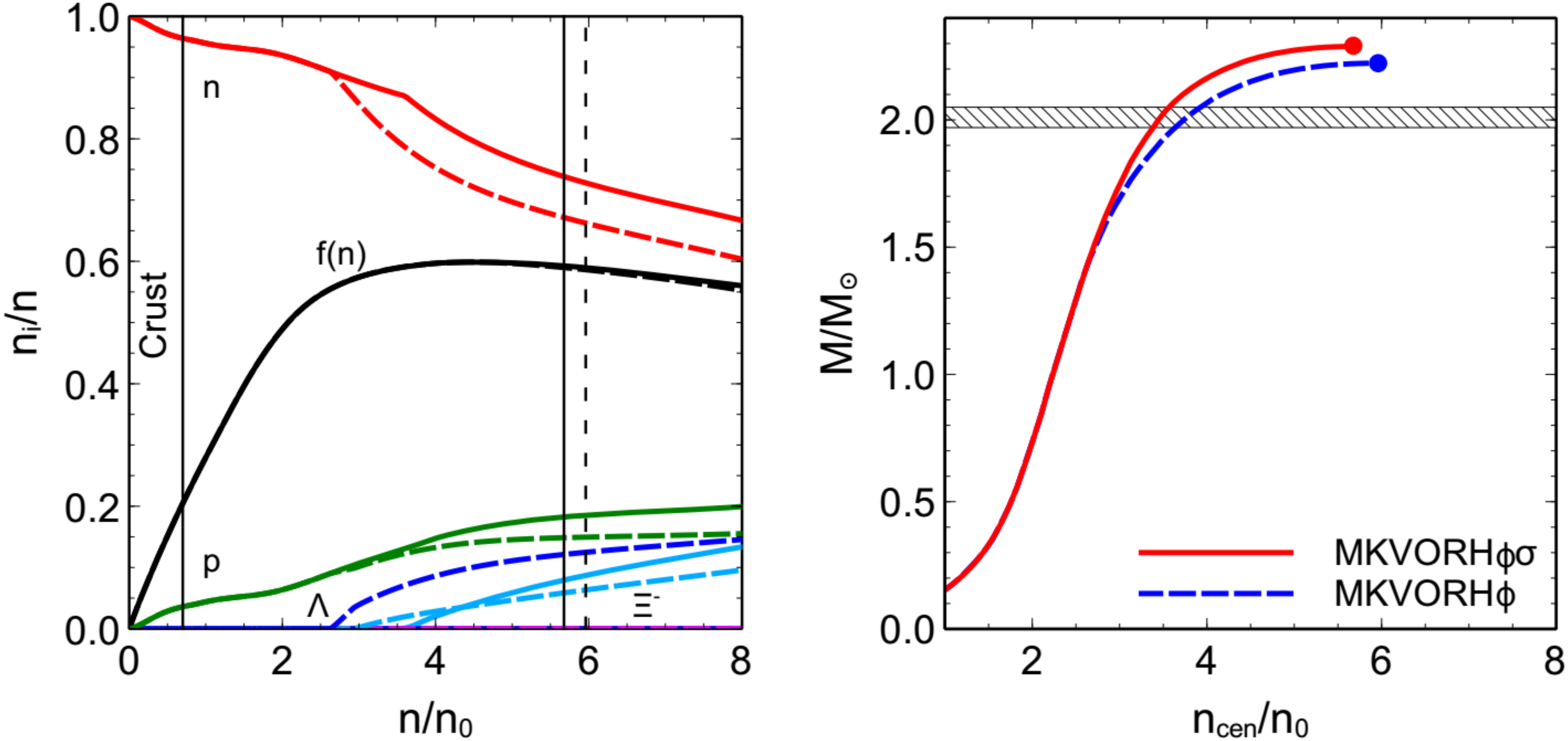
$$\varepsilon_\nu[\mathrm{MpPBF}] \sim 10^{29} \, \frac{m_N^*}{m_N} \left[\frac{p_{Fp}}{p_{Fn}(n_0)}\right] \left[\frac{\Delta_{pp}}{\mathrm{MeV}}\right]^7 \times \left[\frac{T}{\Delta_{pp}}\right]^{1/2} \xi_{pp}^2 \, \frac{\mathrm{erg}}{\mathrm{cm}^3\ \mathrm{sec}}, \quad T < T_{cp}.$$



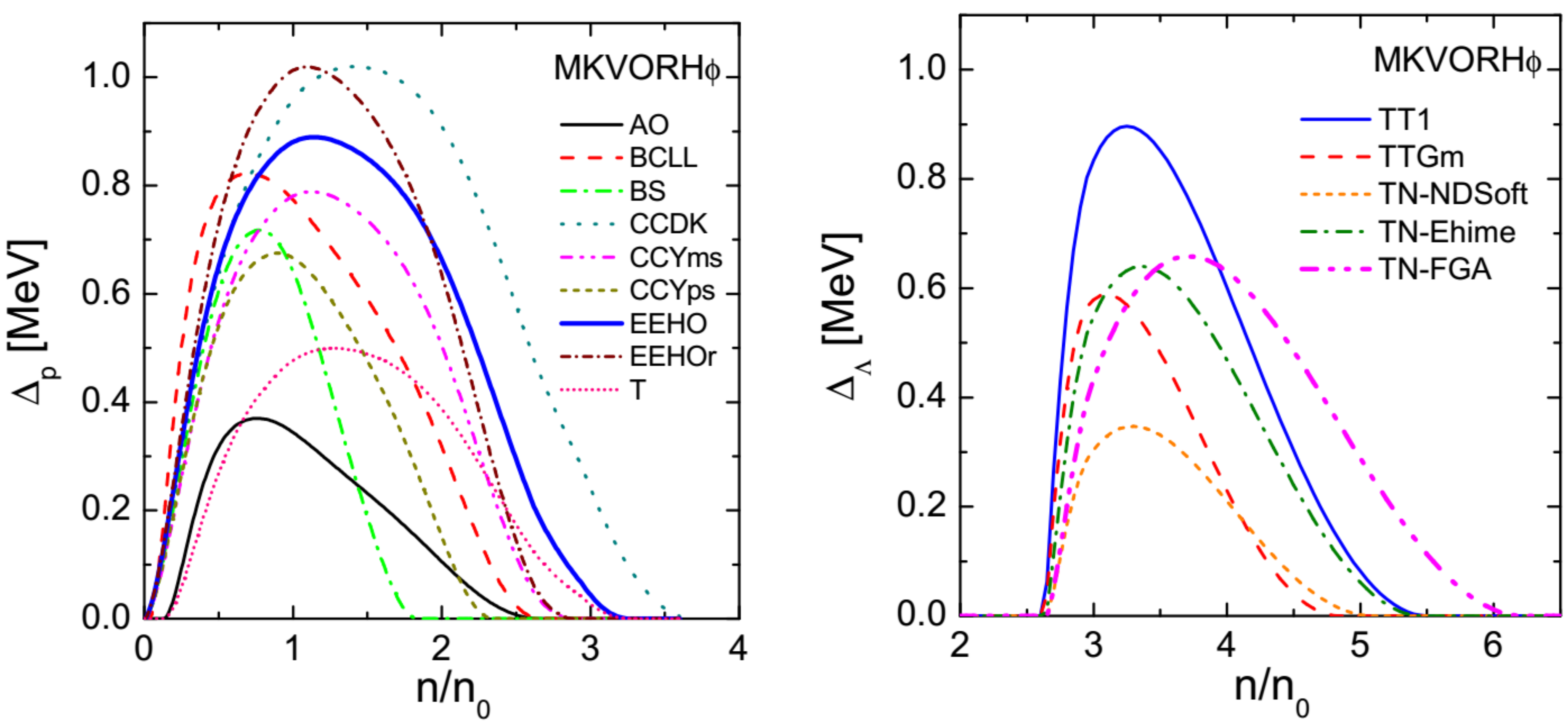
Medium Effects In Cooling Of Neutron Stars



MKVOR – EoS model



MKVORHp – Gap models



Equations for Cooling Evolution

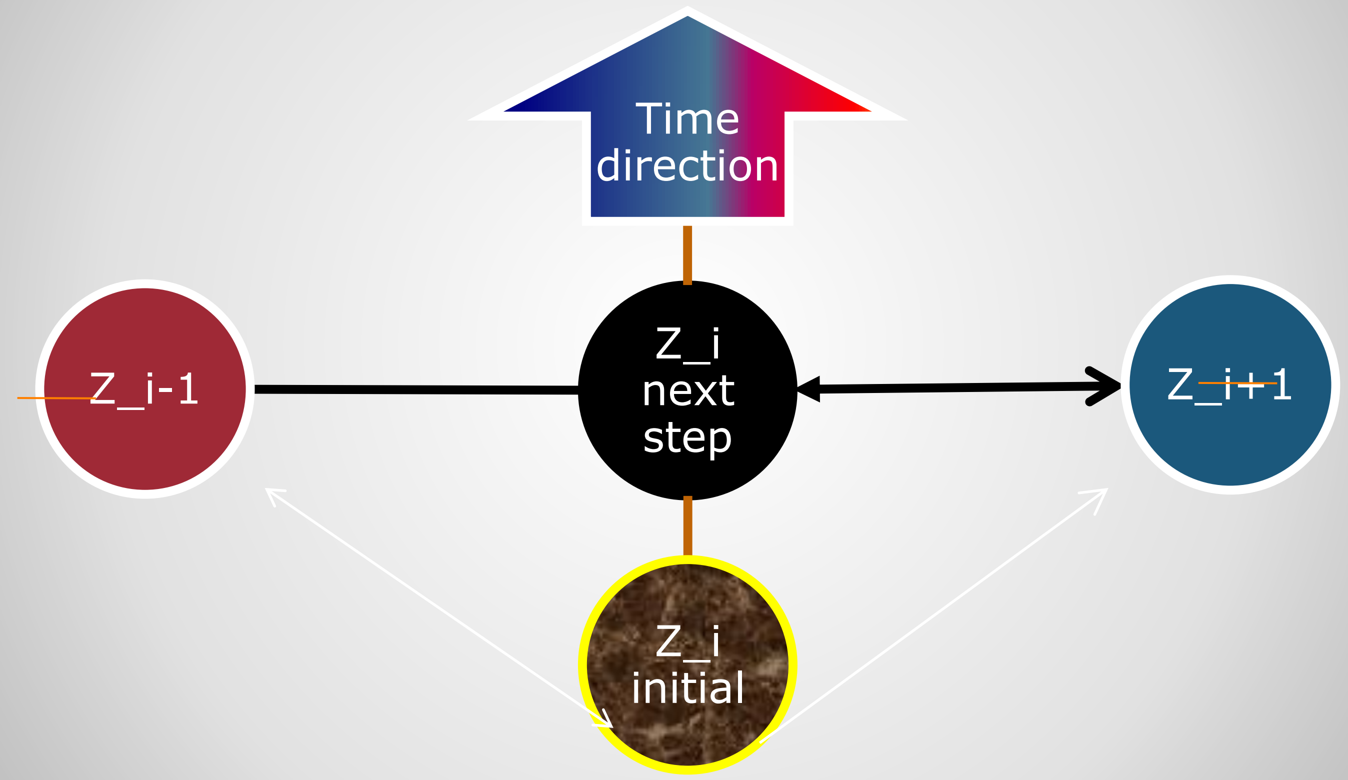
$$\begin{cases} \dfrac{\partial z(\tau,a)}{\partial \tau} = A(z,a)\dfrac{\partial L(\tau,a)}{\partial a} + B(z,a) \\ L(\tau,a) = C(z,a)\dfrac{\partial z(\tau,a)}{\partial a} \end{cases}$$

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

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

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

Finite difference scheme



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

Finite difference scheme

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

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

Crust Model

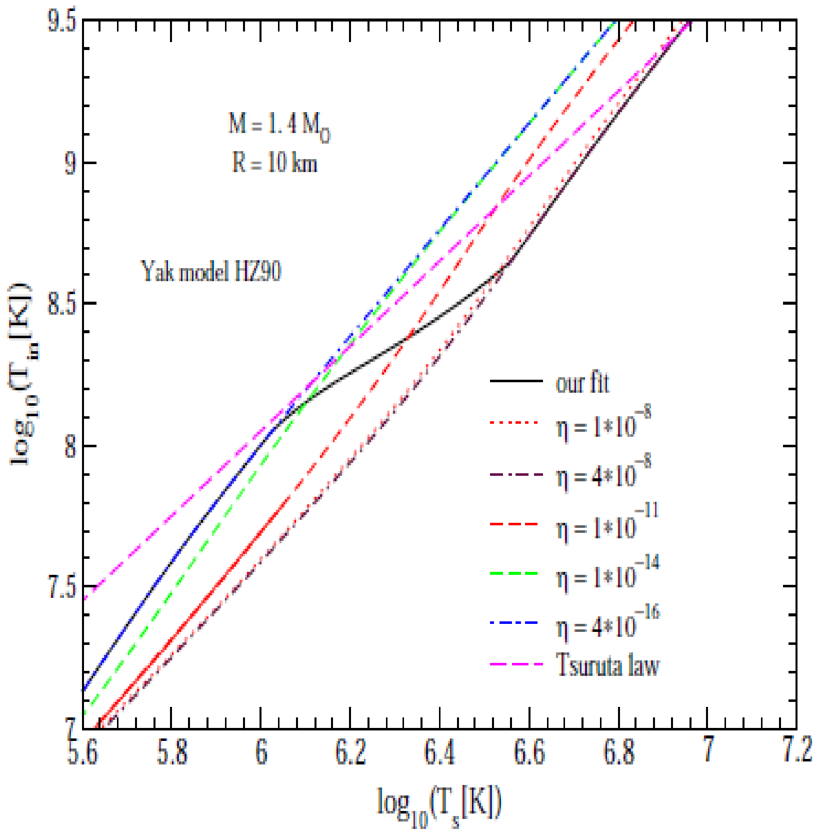
Time dependence of the light element contents in the crust

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

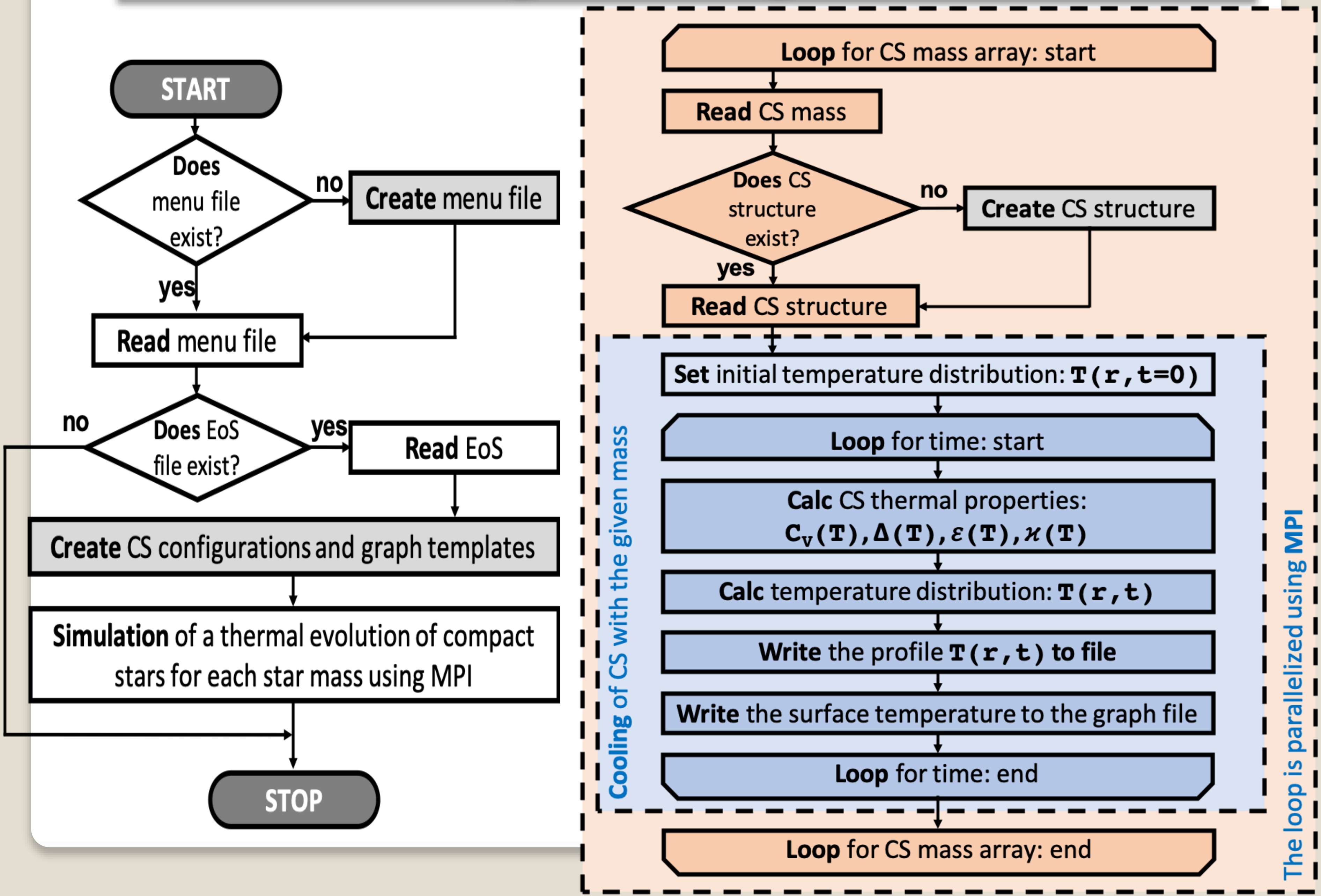
Blaschke, Grigorian, Voskresensky, A& A 368 (2001)561.

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

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



Program Algorithm

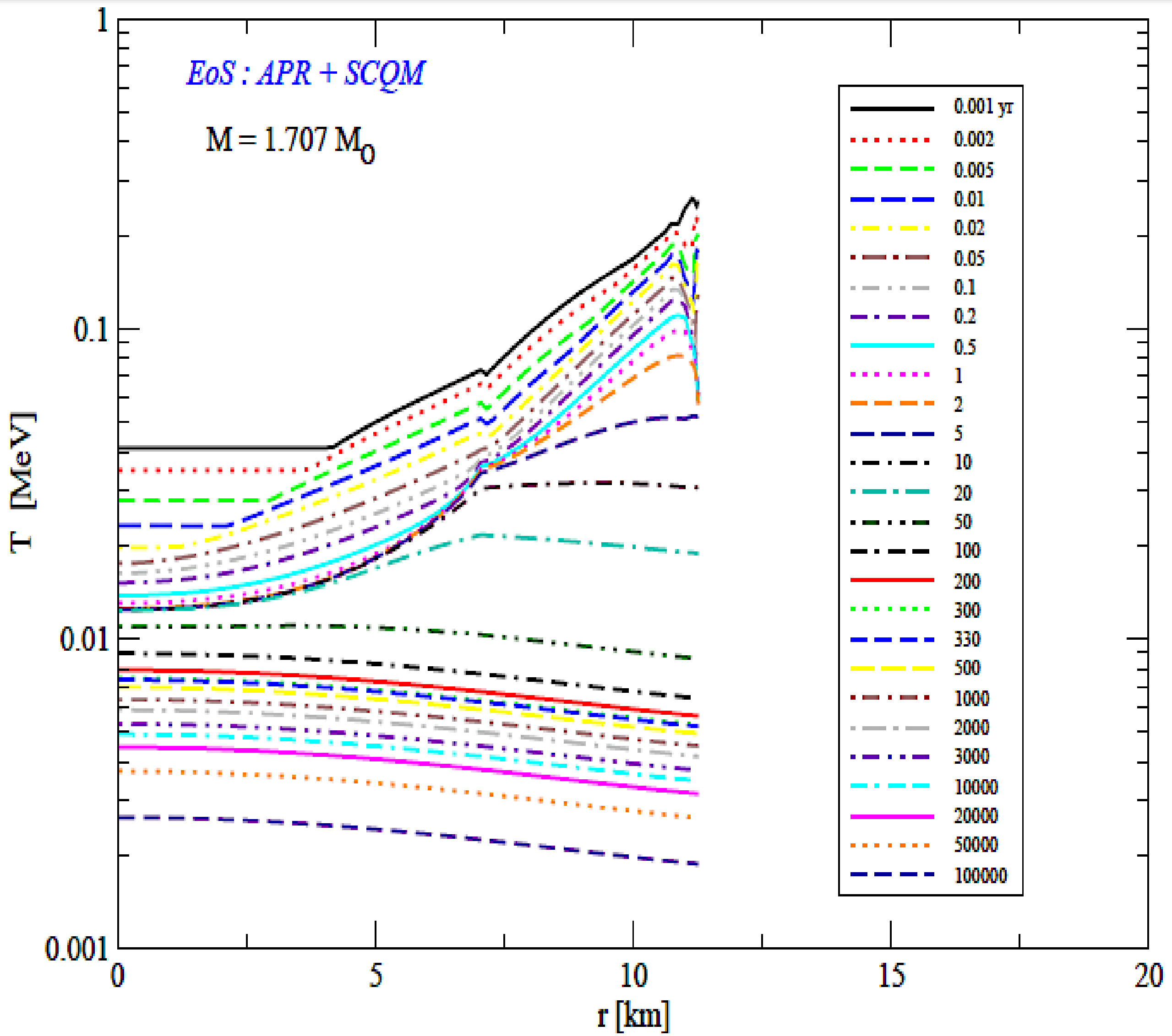


Model parameters – DD2

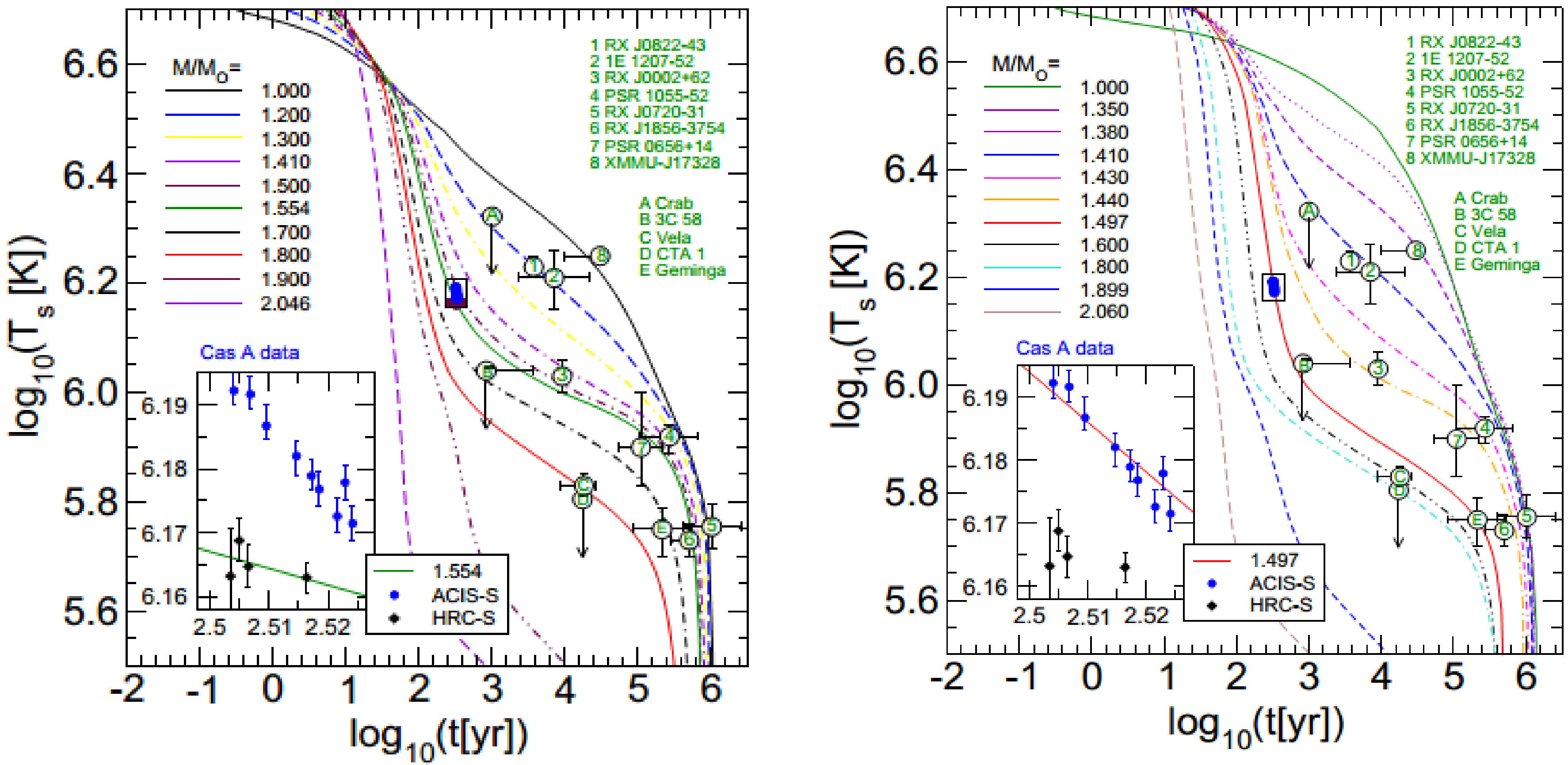
```
                               Menu_dd2_2017n.dat
Model Parametrs

The HOME directory is : .\Data\DD2\Configs-2
The EV UOTPUT directory : .\Data\DD2\17-12-2019\EV-DD2-pi-F4-o3-D
Make EoS file : 0
Make new config. file : 0
Read full EoS from a file : 1
Read from : .\EoS\DD2_HG
Hadronic EoS
LWalecka (0)  NLW (1) HDD (3) BSk20 (4): 3
Normal Shell : 0
Quark EoS SM model (1) Bag model (0) : 0
In case of SM  GF (0)  GL(1)  NJL (2) : 0
with Quark core : 1
without Mixed phase : 1
Superconducting Quark core : 1
Quark Star : 0
Medium effects : 1
Pion condensate : 1
Crust Model (Yakovlev - Y Tsuruta - T our - G)  : G
Gaps in Hadrons Model (Yakovlev - Y AV18 - A Schwenk - U Armen-fit - F)  : F
for F-fit p-Gap
1-AO
2-BCLL
3-BS
4-CCDK
5-CCYms
6-CCYps
7-EEHO
8-EEHOr
9-T
: 4
for F-fit n-Gap
2-AWP2
3 - AWP3
4 - CCDK
5 - CLS
6 - GIPSF
7 - MSH
8 - SCLBL
9 - SFB
0 - WAP : o
XGaps in 2SC QModel constant 0 - 0
 constant 0.1 MeV - 1
constant 0.05 MeV - 5
constant 0.03 MeV - 3
 rising 0.03 +  MeV - A
 incrising 0.03 - MeV - B
       constant 0.03 ++ MeV - C
 constant 0.03 -- MeV - D
 : C
```

```
                               Menu_dd2_2017n.dat
Gap factors in HM
Protons  1S0p : 1
Neutrons 1S0n : 1
Neutrons 3P2n : 0.1

End time point log10(t/yr) : 8

initial temperatur in MeV : 0.5

minimal value of log Temperature : 5.5

Print output files for LogN-LogS : 0

Print profiles for the time points : 0

Number of points : 7
0 0 0 0 0 0 0

 The Masses [Mo] of Configurations to be Cooled

Number of points : 51
1.450
0.5 0.51 0.52 0.53 0.54 0.55 0.56 0.57 0.58 0.59
0.6 0.61 0.62 0.63 0.64 0.65 0.66 0.67 0.68 0.69
0.7 0.71 0.72 0.73 0.74 0.75 0.76 0.77 0.78 0.79
0.8 0.81 0.82 0.83 0.84 0.85 0.86 0.87 0.88 0.89
0.9 0.91 0.92 0.93 0.94 0.95 0.96 0.97 0.98 0.99



1.0 1.01 1.02 1.03 1.04 1.05 1.06 1.07 1.08 1.09
1.10 1.11 1.12 1.13 1.14 1.15 1.16 1.17 1.18 1.19
1.20 1.21 1.22 1.23 1.24 1.25 1.26 1.27 1.28 1.29
1.30 1.31 1.32 1.33 1.34 1.35 1.36 1.37 1.38 1.39
1.40 1.41 1.42 1.43 1.44 1.45 1.46 1.47 1.48 1.49
1.50 1.51 1.52 1.53 1.54 1.55 1.56 1.57 1.58 1.59
1.60 1.61 1.62 1.63 1.64 1.65 1.66 1.67 1.68 1.69
1.70 1.71 1.72 1.73 1.74 1.75 1.76 1.77 1.78 1.79
1.80 1.81 1.82 1.83 1.84 1.85 1.86 1.87 1.88 1.89
1.90 1.91 1.92 1.93 1.94 1.95 1.96 1.97 1.98 1.99
2.00 2.01 2.02 2.03 2.04
2.05 2.06 2.07 2.08 2.09
2.10 2.11 2.12 2.13 2.14 2.15 2.16 2.17 2.18 2.19
2.20
2.21 2.22 2.23 2.24 2.25 2.26 2.27 2.28 2.29
2.30 2.31 2.32 2.33 2.34 2.35 2.36 2.37 2.38 2.39
2.40 2.41

1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 2.1 2.2
```

Temperature in the Hybrid Star Interior

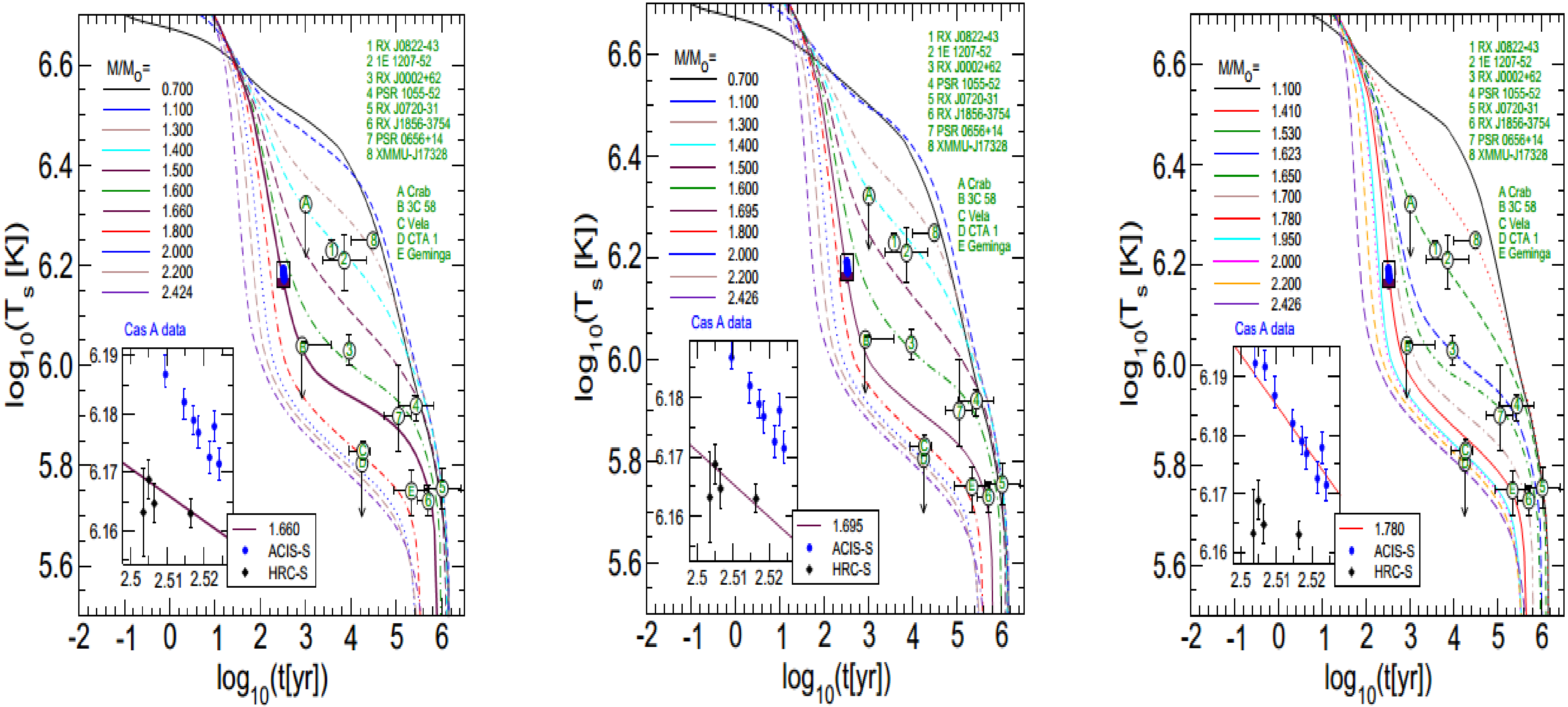


HDD – AV18 , Yak.
ME nc = 3 n0

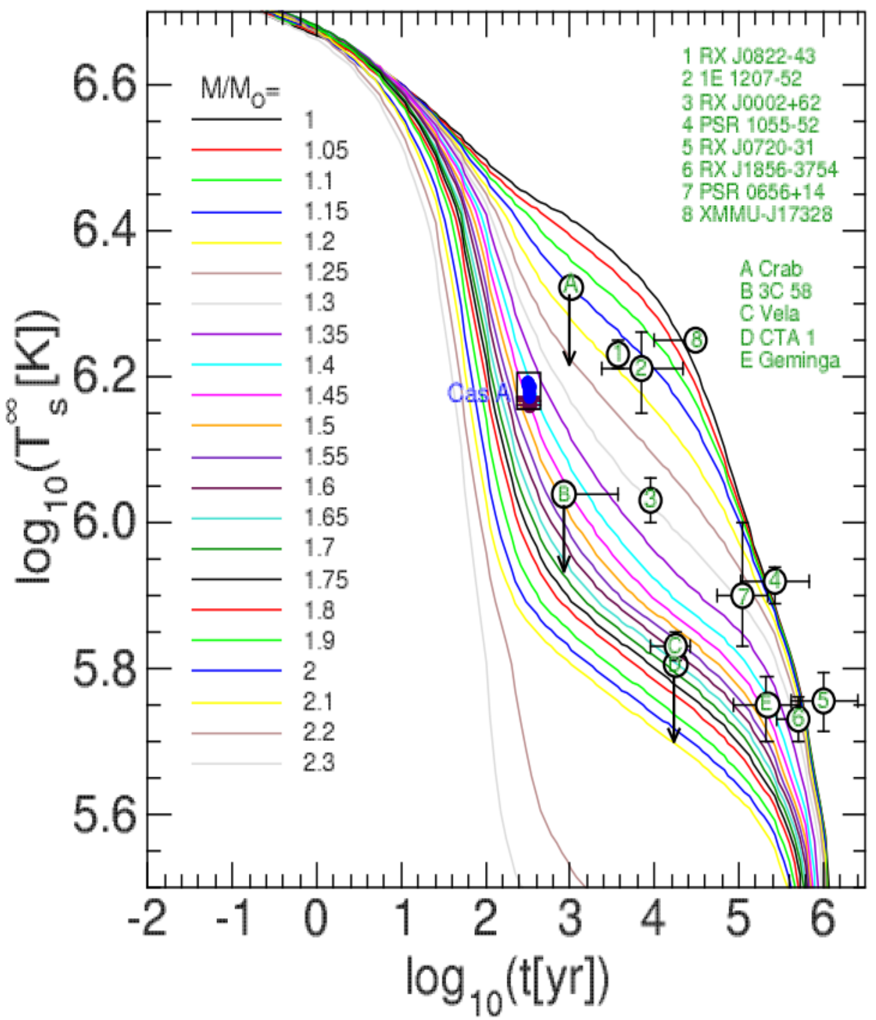


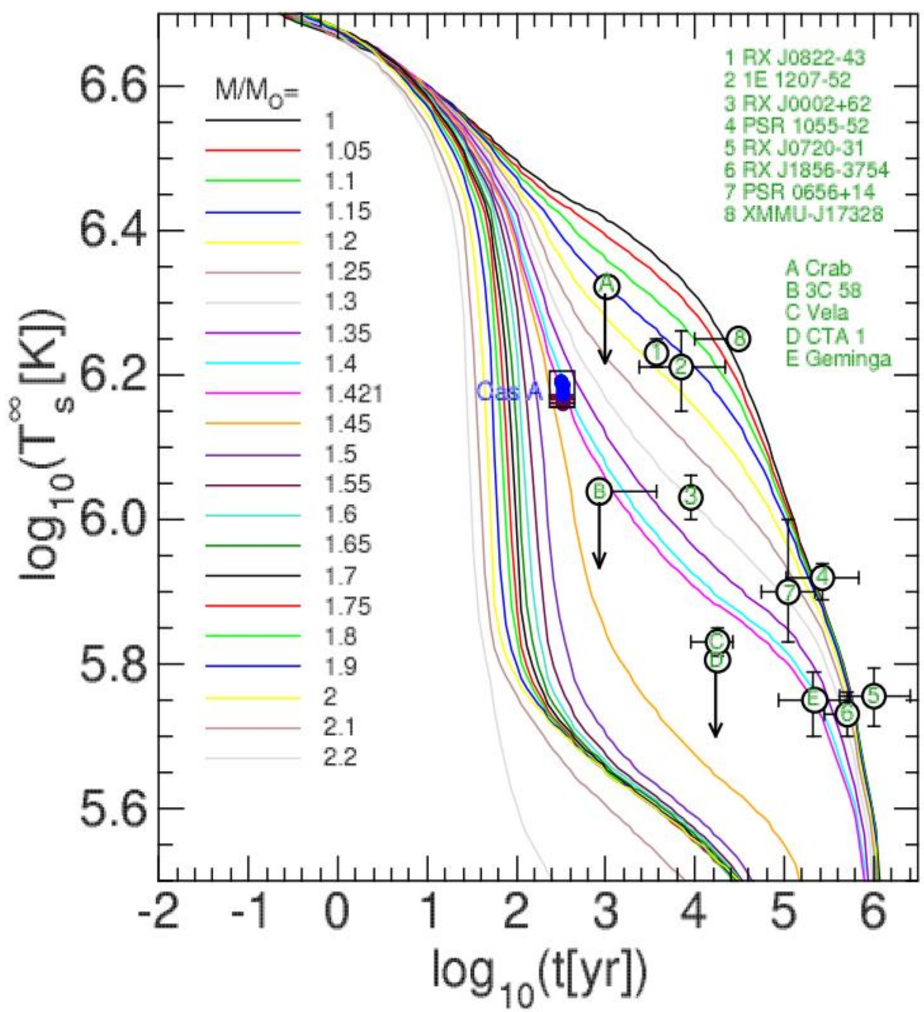
DD2 – EEHOr

ME-nc=1.5,2.0,2.5n0

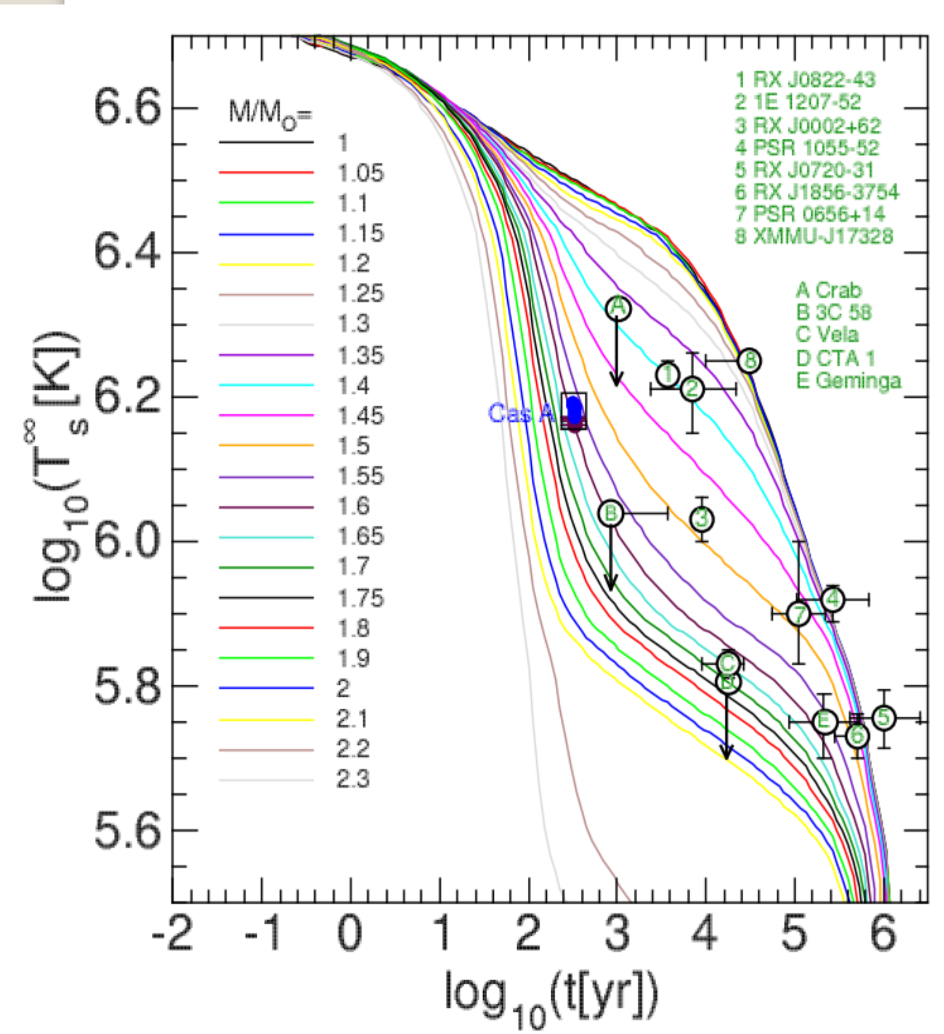


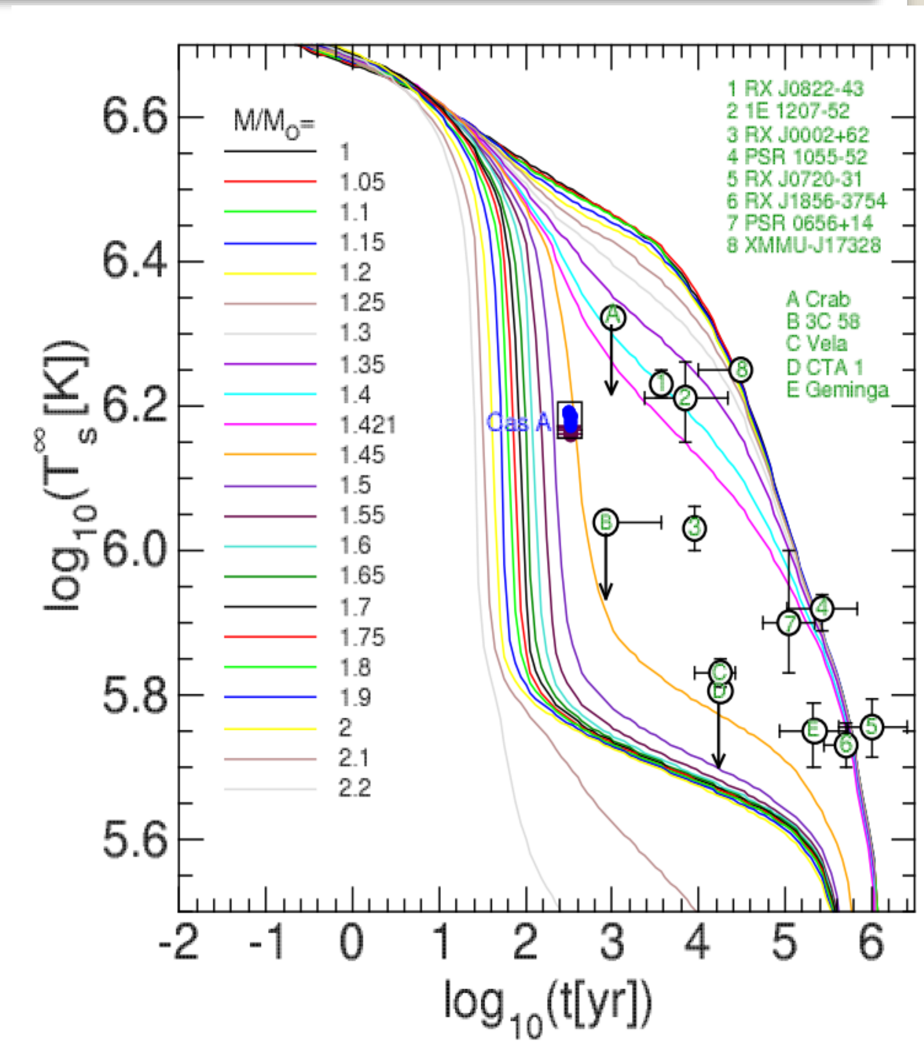
MKVOR – BCLL, TN-FGA ME-nc=3.0n0



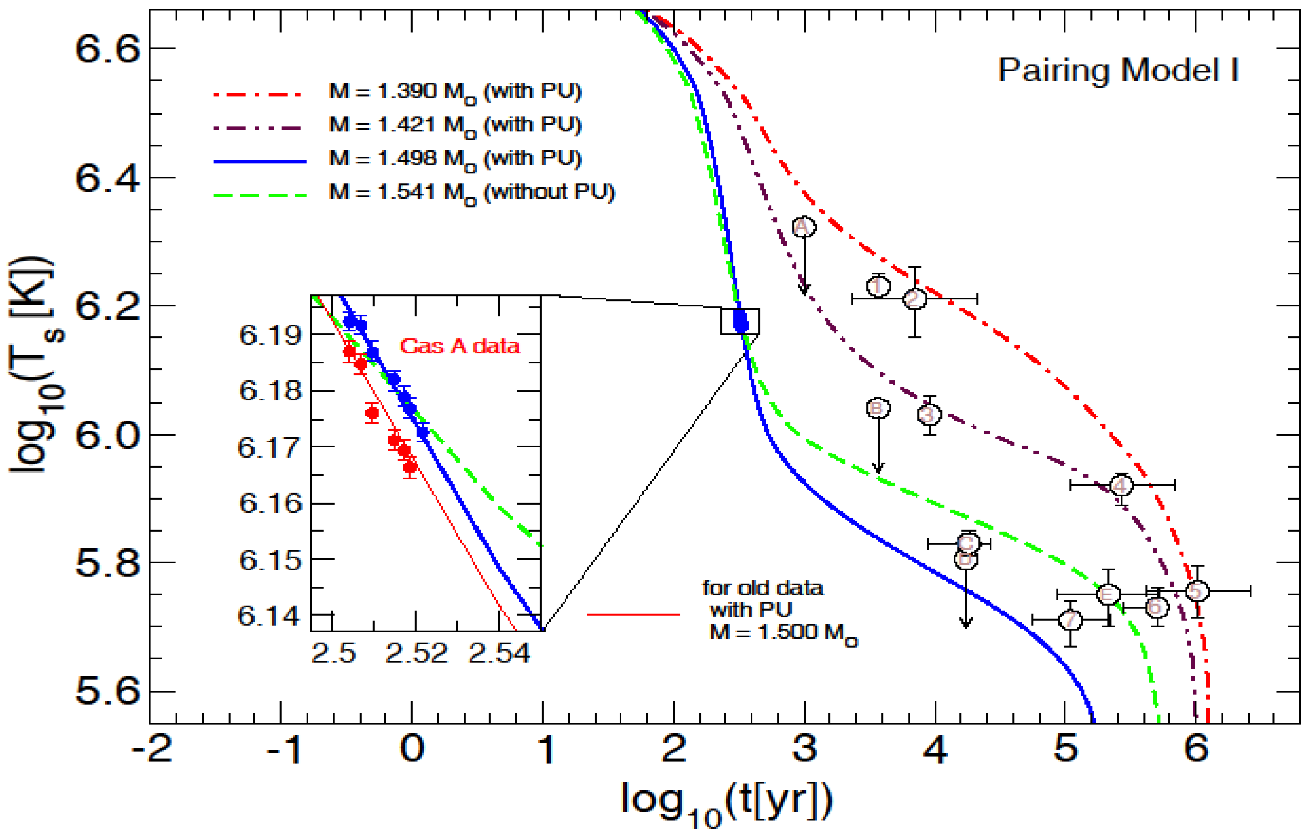


MKVOR Hyp – EEHOr, TN-FGA ME-nc=3.0n0



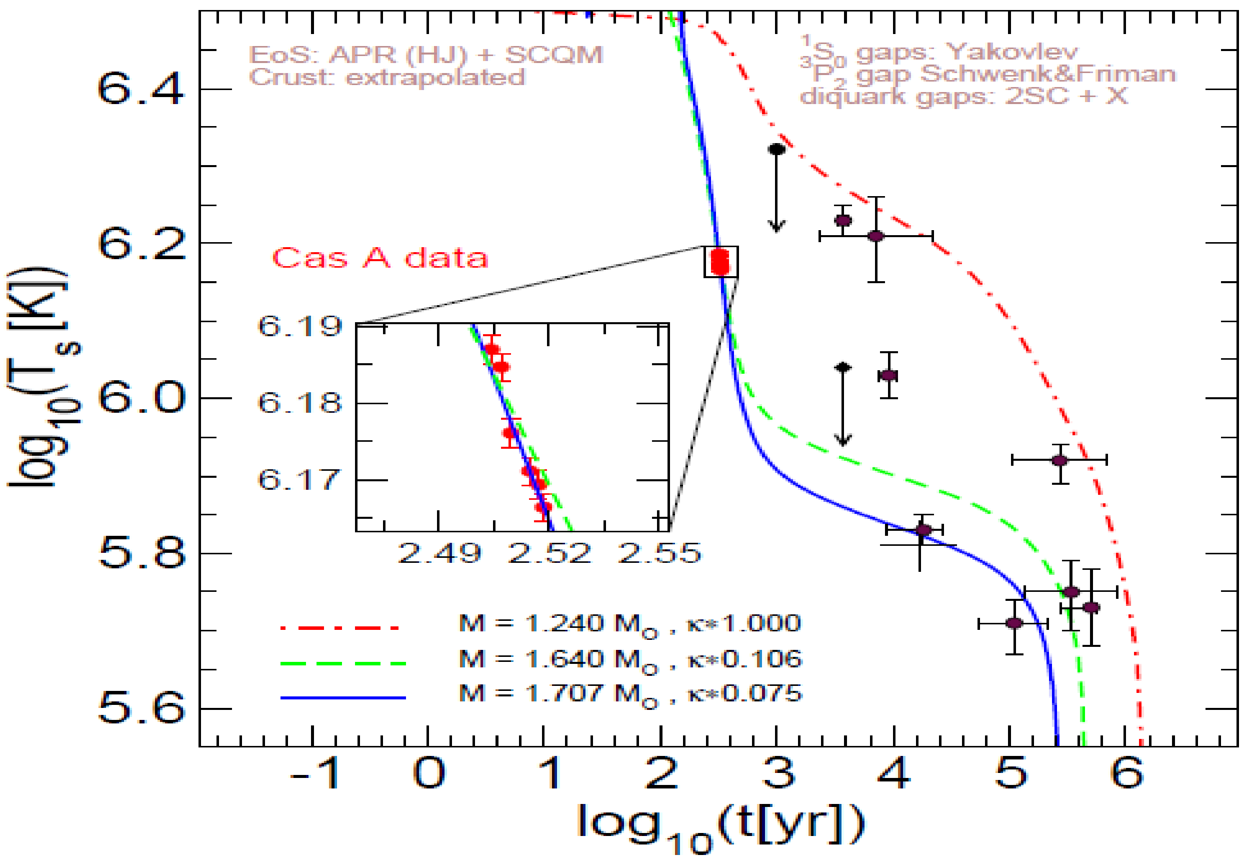


Cas A as an Hadronic Star

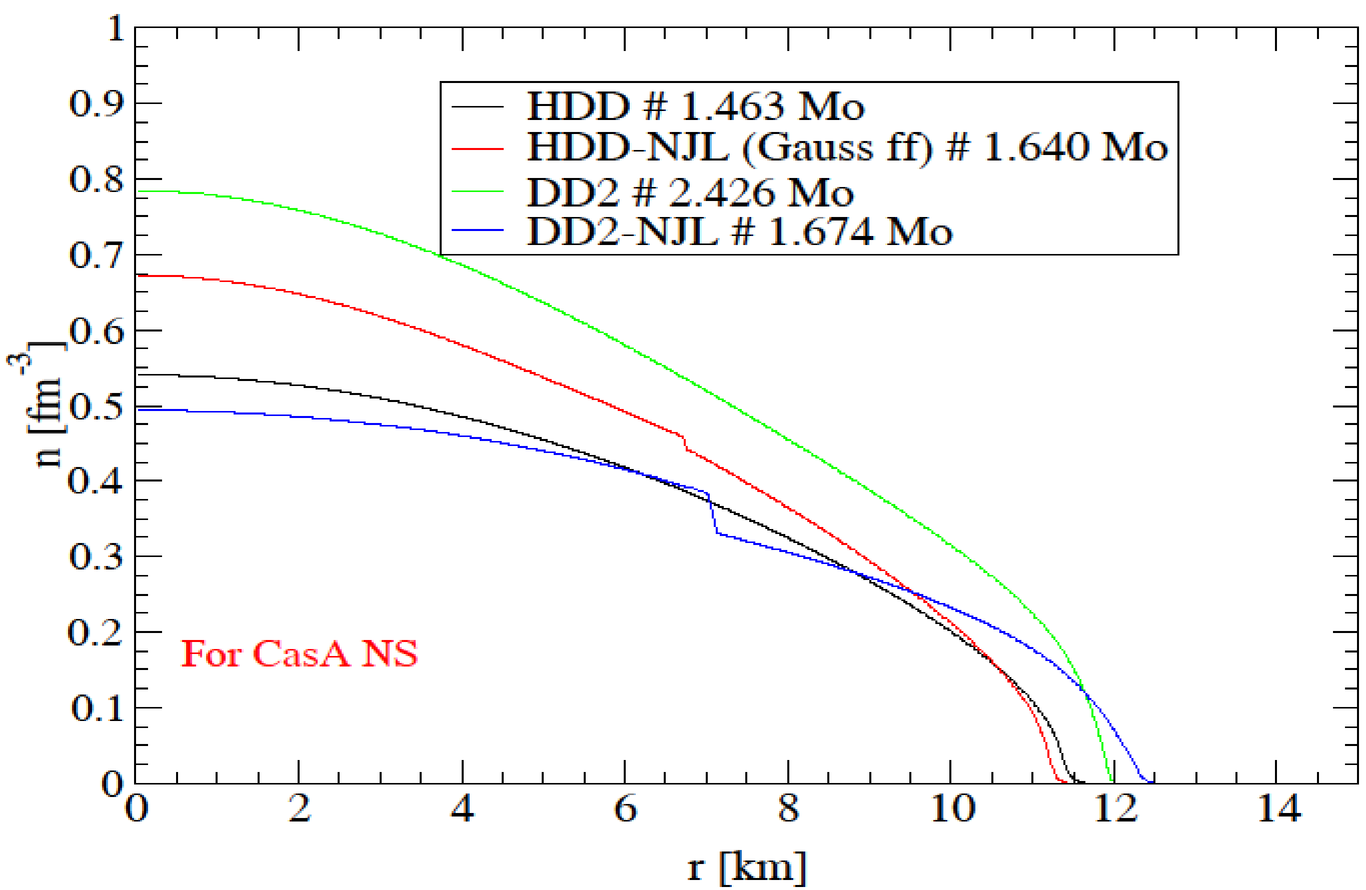


Cas A As An Hybrid Star

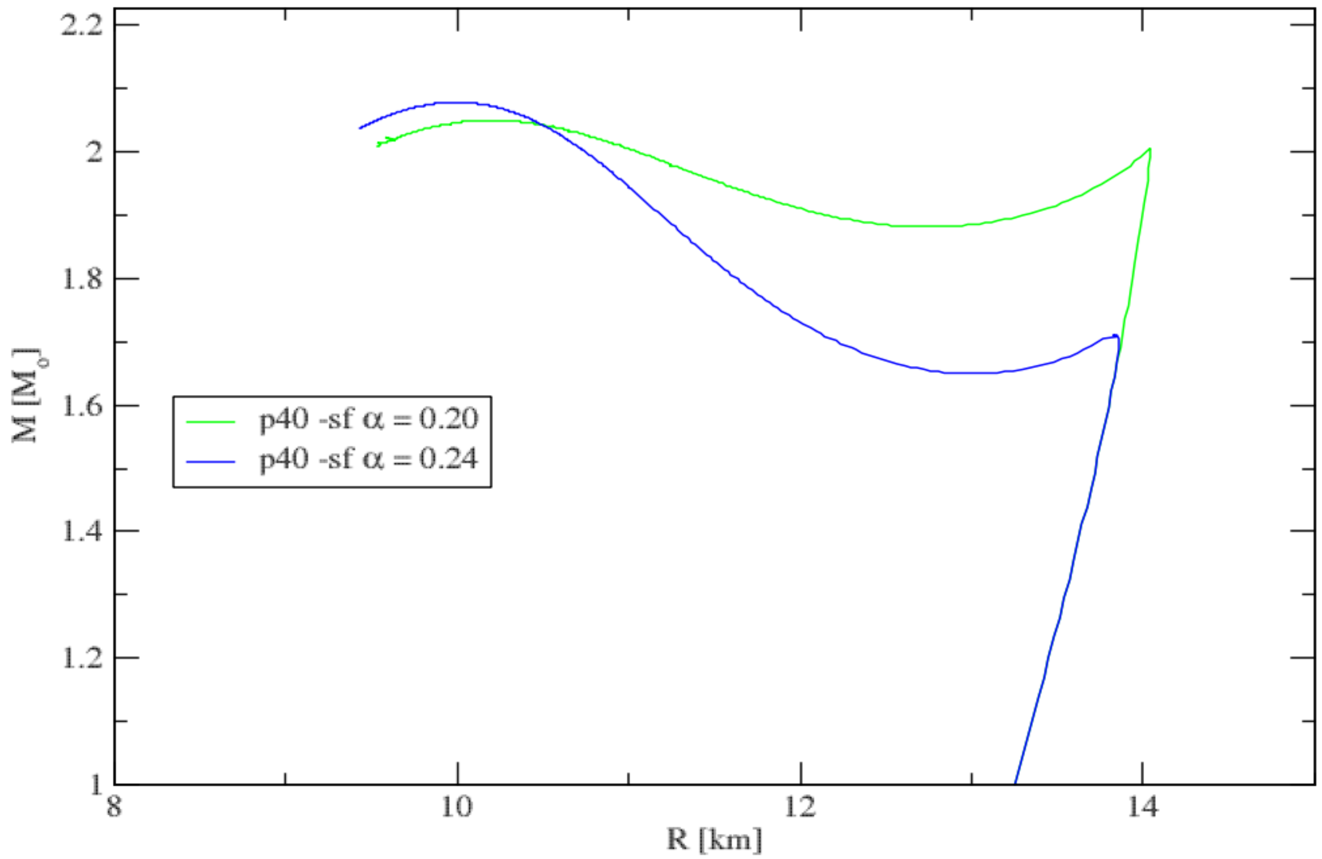
H. Grigorian, D. Blaschke, D.N. Voskresensky, Phys. Rev. C 71, 045801 (2005)



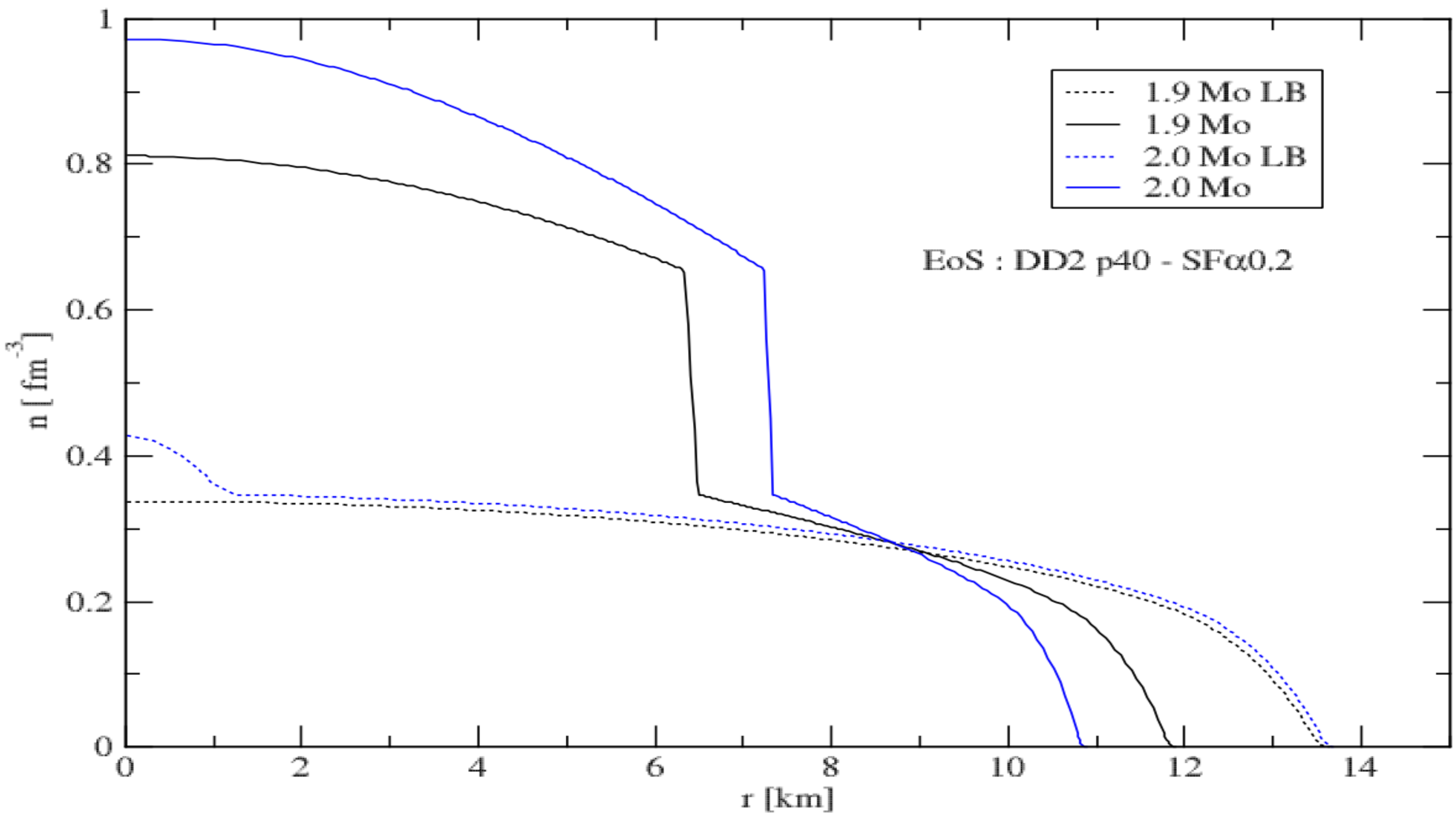
Possible internal structure of CasA



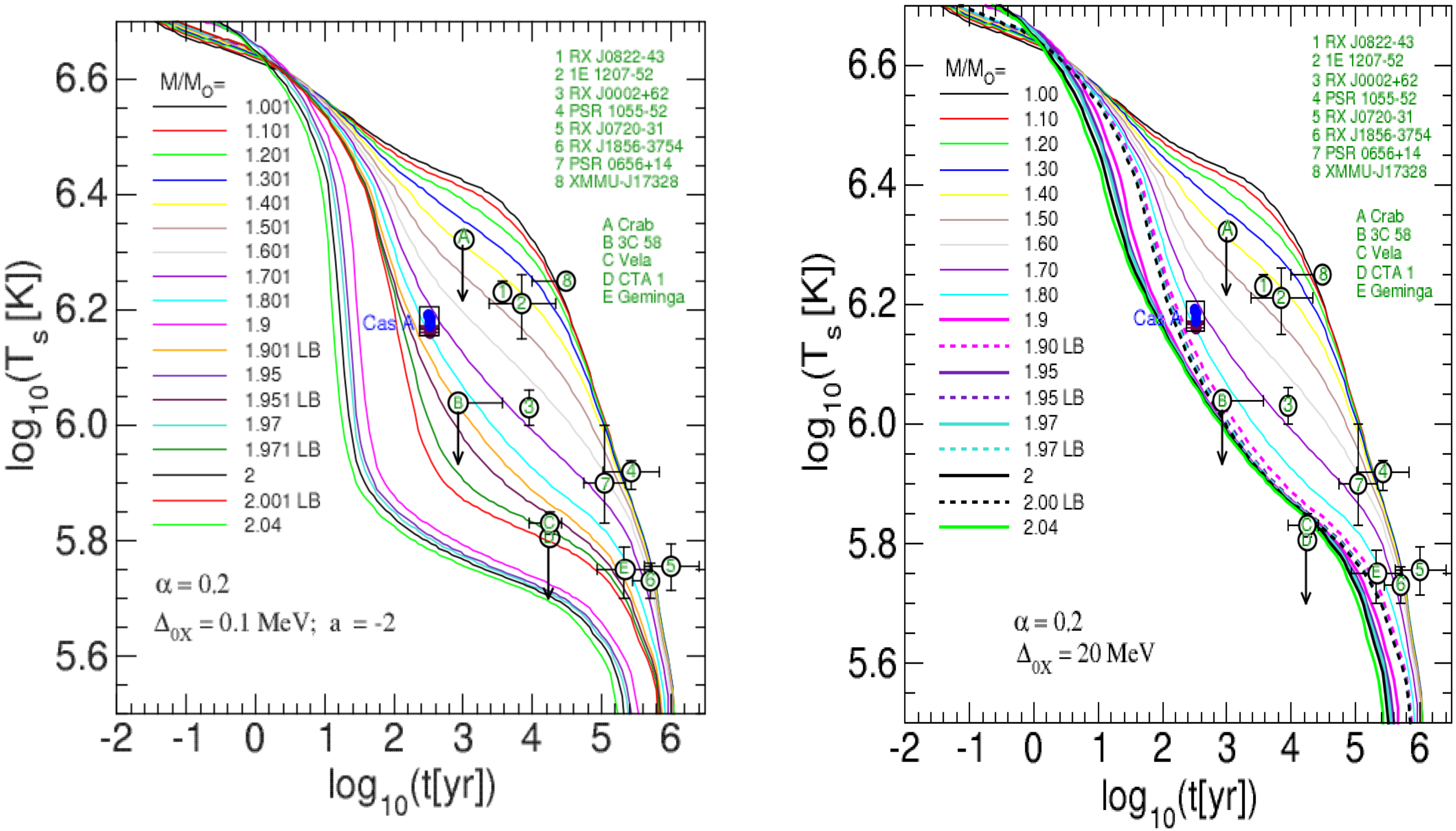
High Mass Twin CS



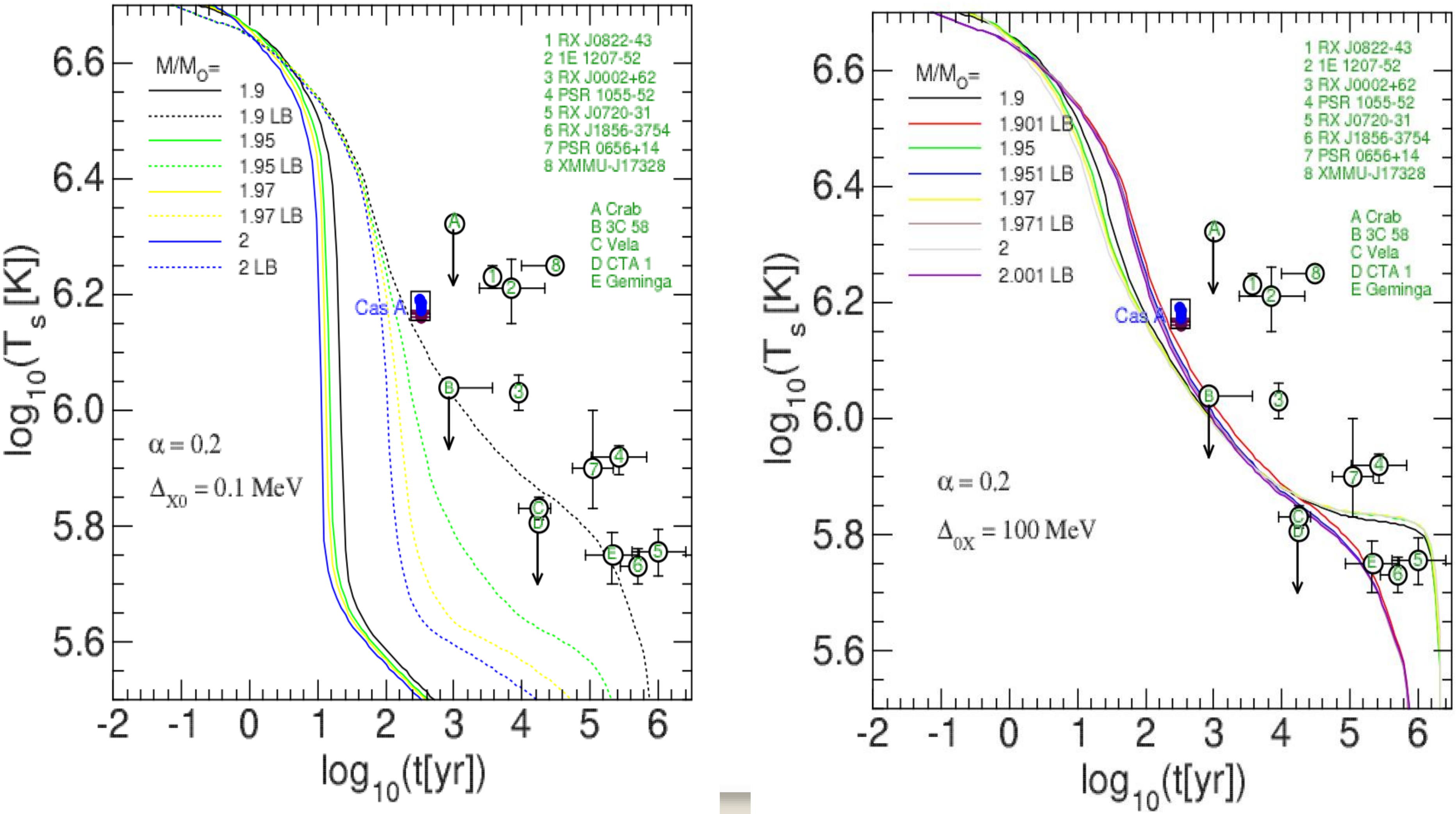
Different Configurations with the same NS mass

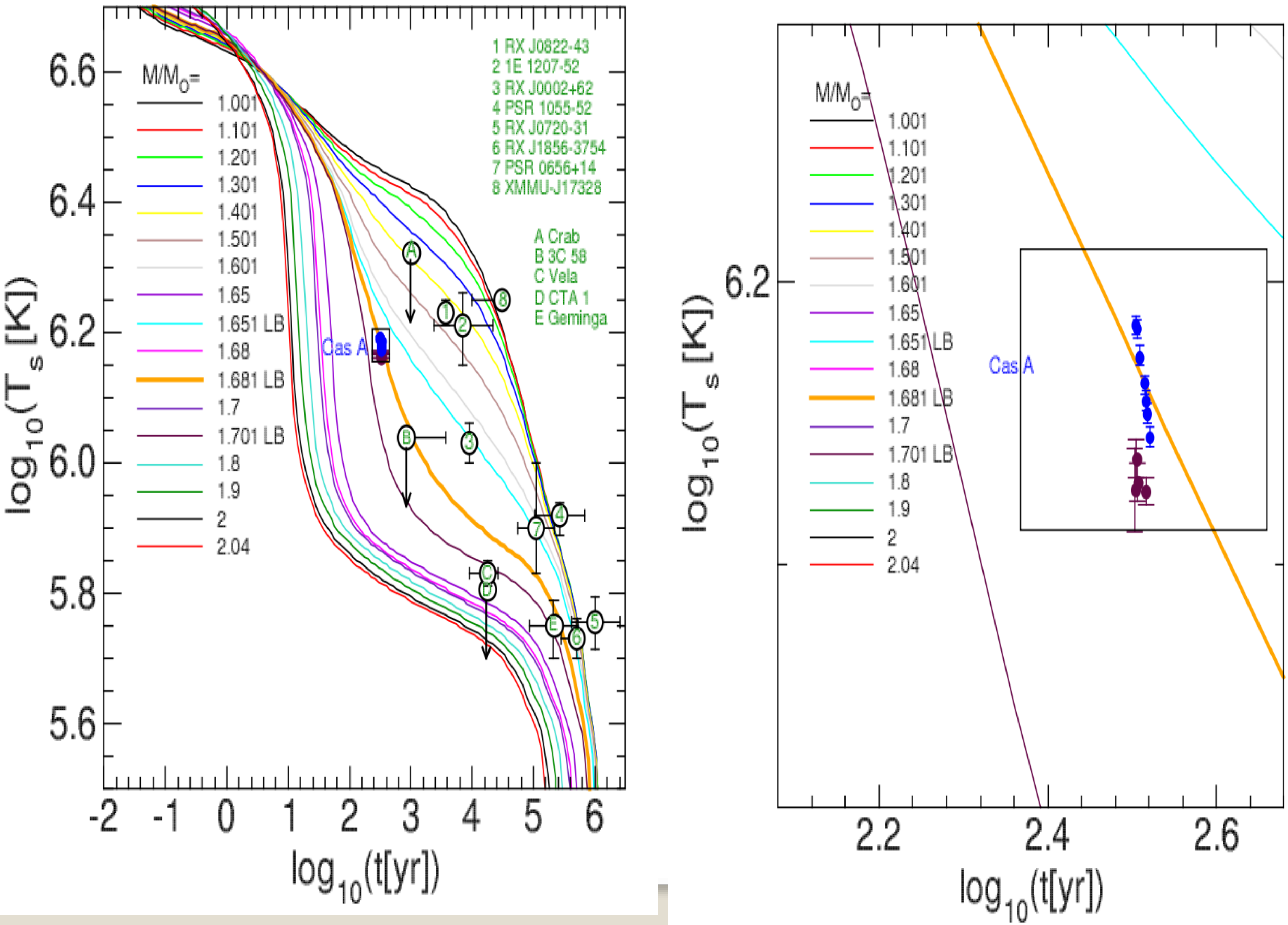


Cooling of Twin CS



Highmass Twins: QM SC Effect





M/M$_O$=
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
$\log_{10}(T_s[K])$
$\log_{10}(t[yr])$

Cooling of Neutron Stars admixed with Light Dark Matter

$$\frac{e^{-\lambda-2\Phi}}{4\pi r^2}\frac{\partial}{\partial r}\left(e^{2\Phi}L\right) = -Q + Q_h - \frac{c_V}{e^{\Phi}}\frac{\partial T}{\partial t},$$

$$\frac{L}{4\pi\kappa r^2} = e^{-\lambda-\Phi}\frac{\partial}{\partial r}\left(Te^{\Phi}\right)$$

$$N_\chi(t) \simeq N_{\chi,0} + \frac{dN_\chi}{dt}(t - t_0),$$

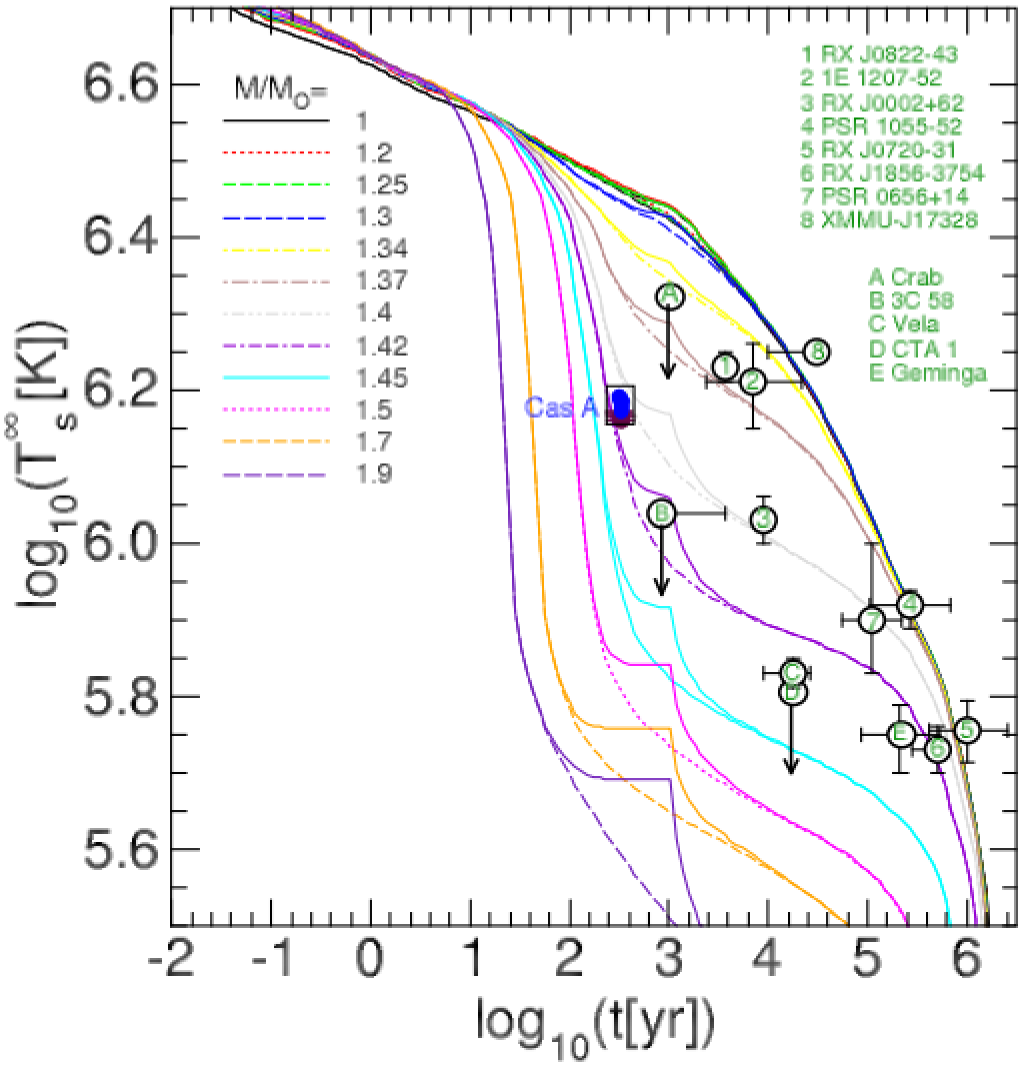
$$\frac{dN_\chi}{dt} = C_\chi - C_a N_\chi^2.$$

The DM capture rate can be approximated by

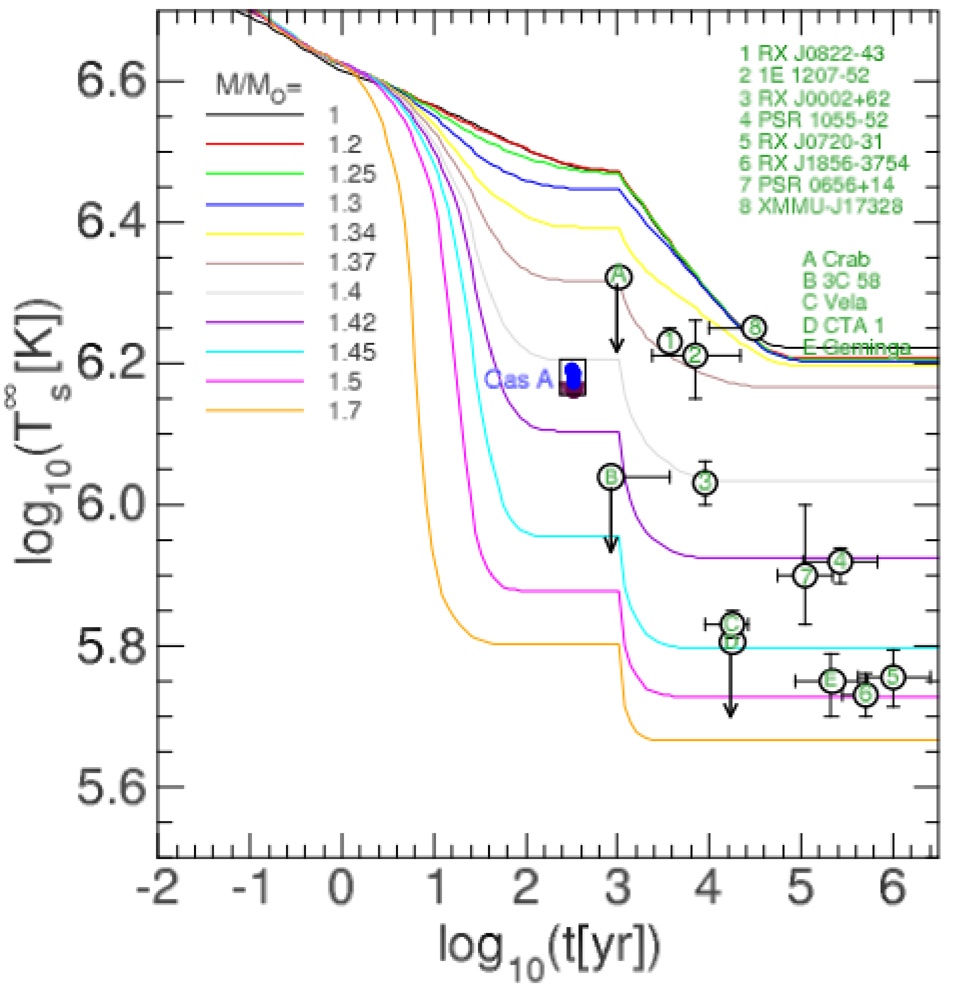
$$C_\chi \simeq 5.6\times10^{26}\left(\frac{M}{1.5M_\odot}\right)\left(\frac{R}{14\text{ km}}\right)\left(\frac{0.1\text{GeV}}{m_\chi}\right)\left(\frac{\rho_\chi}{0.4\frac{\text{GeV}}{\text{cm}^3}}\right)\text{s}^{-1}$$

the thermally-averaged self-annihilation rate $\langle\sigma v\rangle \sim 3$
$10^{-26}\,\text{cm}^3\text{s}^{-1}$,

$$C_a \simeq 2\times10^{-42}\left(\frac{0.1\text{ GeV}}{m_\chi}\frac{2\rho_0}{\rho_N}\frac{T}{0.5\,\text{MeV}}\right)^{-3/2}\text{s}^{-1}.$$



NSs with masses $M \in [1, 1.9]M_\odot$ with the effect of self-annihilating LDM ($m_\chi = 0.1$ GeV) originating a plateau or without LDM (continuous decline). Existing series of cooling



M. Ángeles Pérez-García, H. Grigorian, C. Albertus, D. Barba, J. Silk

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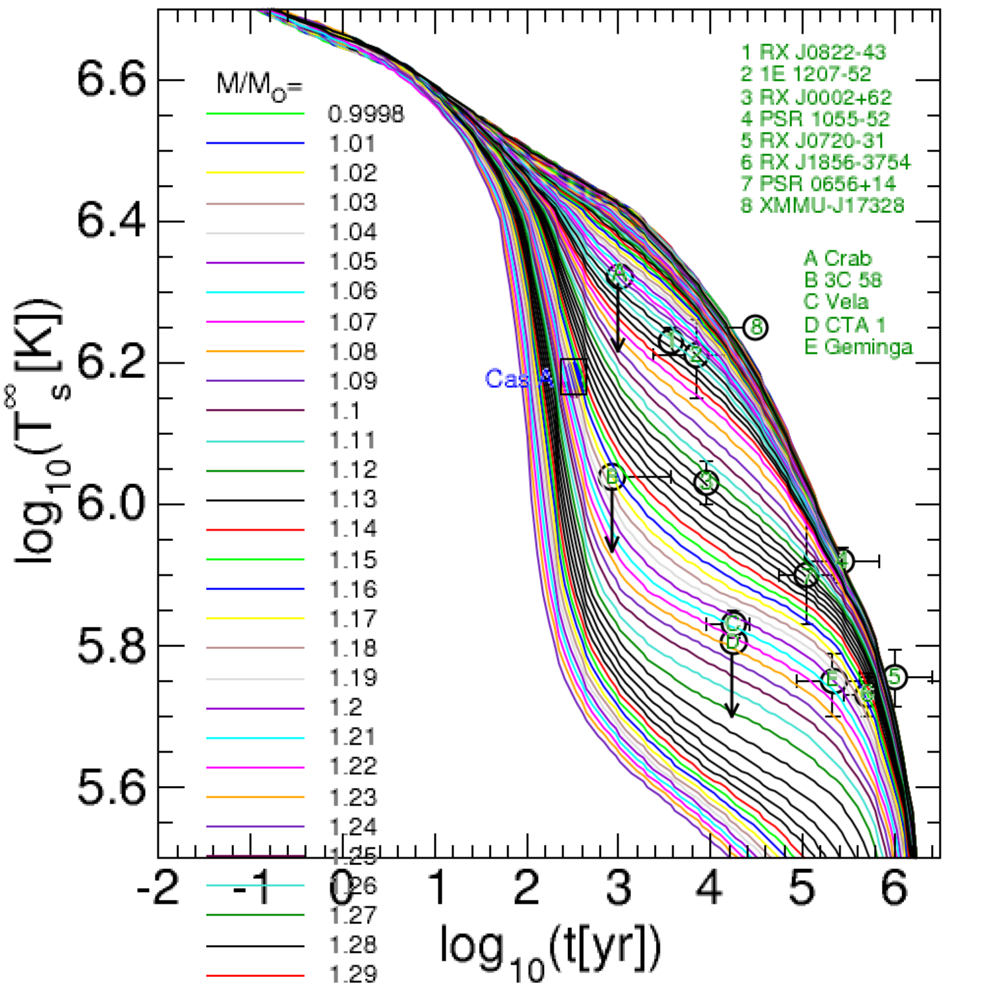
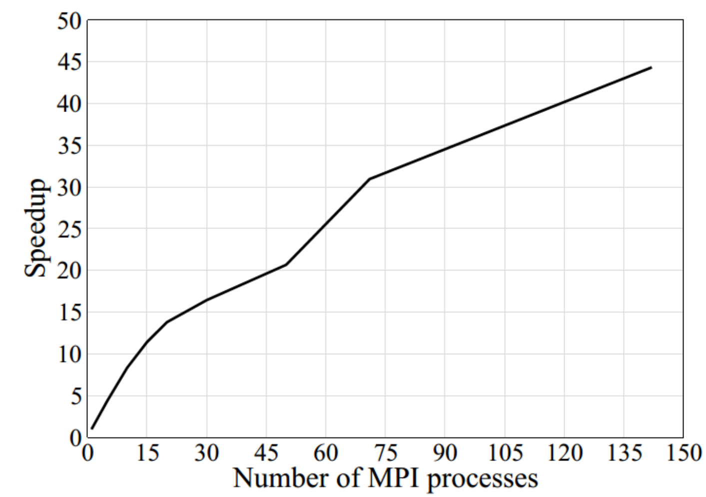
FIG. 2. Surface temperature as a function of NS age with masses $M \in [1, 1.7] M_\odot$ including self-annihilating conducting DM ($m_\chi = 0.1$ GeV). χ emissivity has been enhanced a factor 5 larger than in Figure 1. LDM enhanced processes are active up to $\tau \sim 10^3$ yr, followed by a period of decline, and again for $t \gtrsim 1.5 \times 10^3$ yr. See text for details.

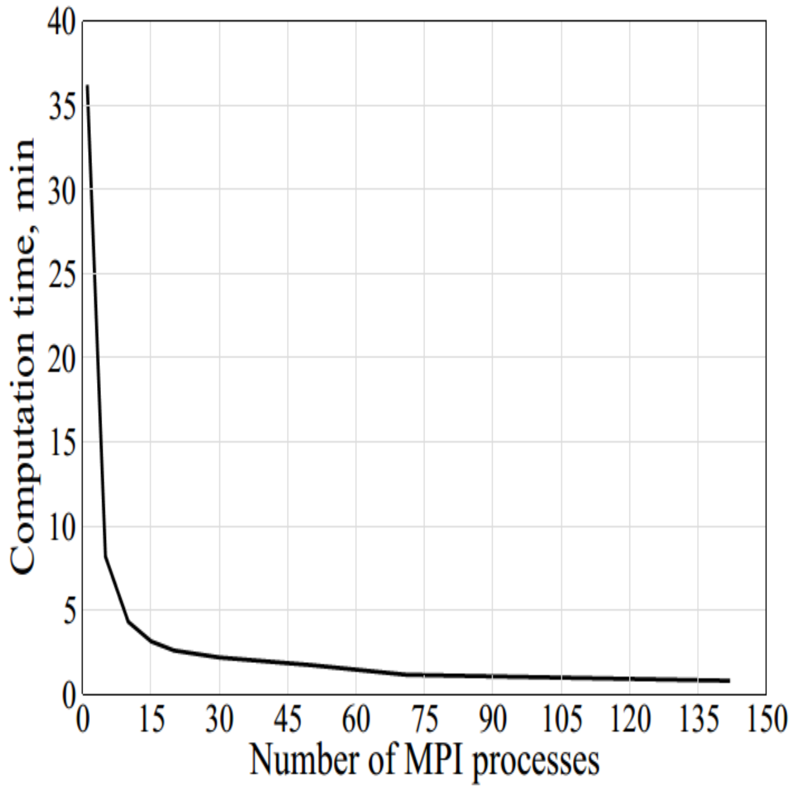
Results produced with use of MPI Technology

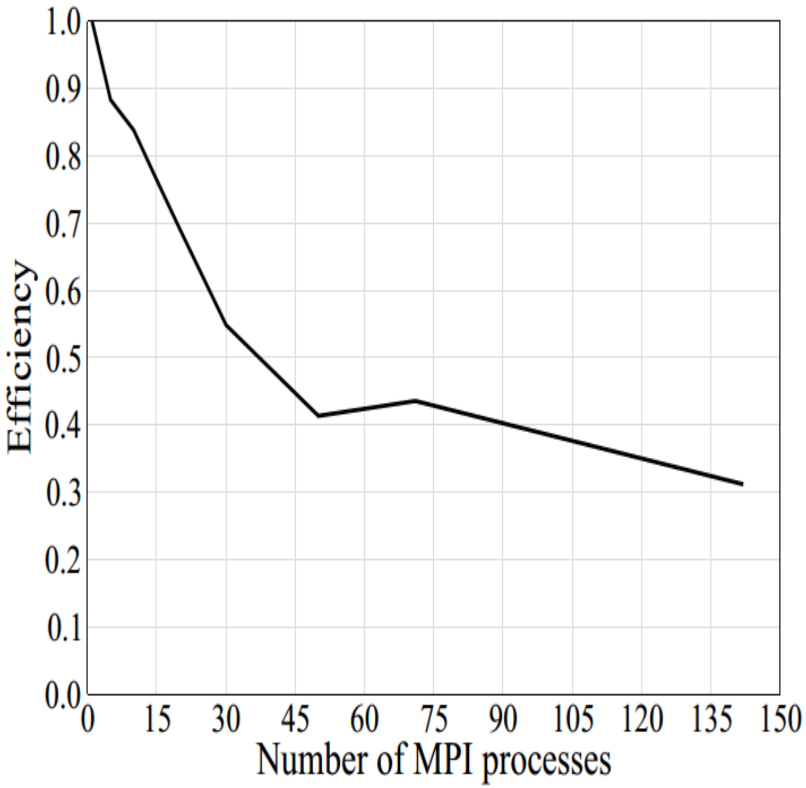


142 configurations has been calculated in 0m49s on the 142 processes.
On 1 process it takes 36m14s
– acc is ~ 44 times

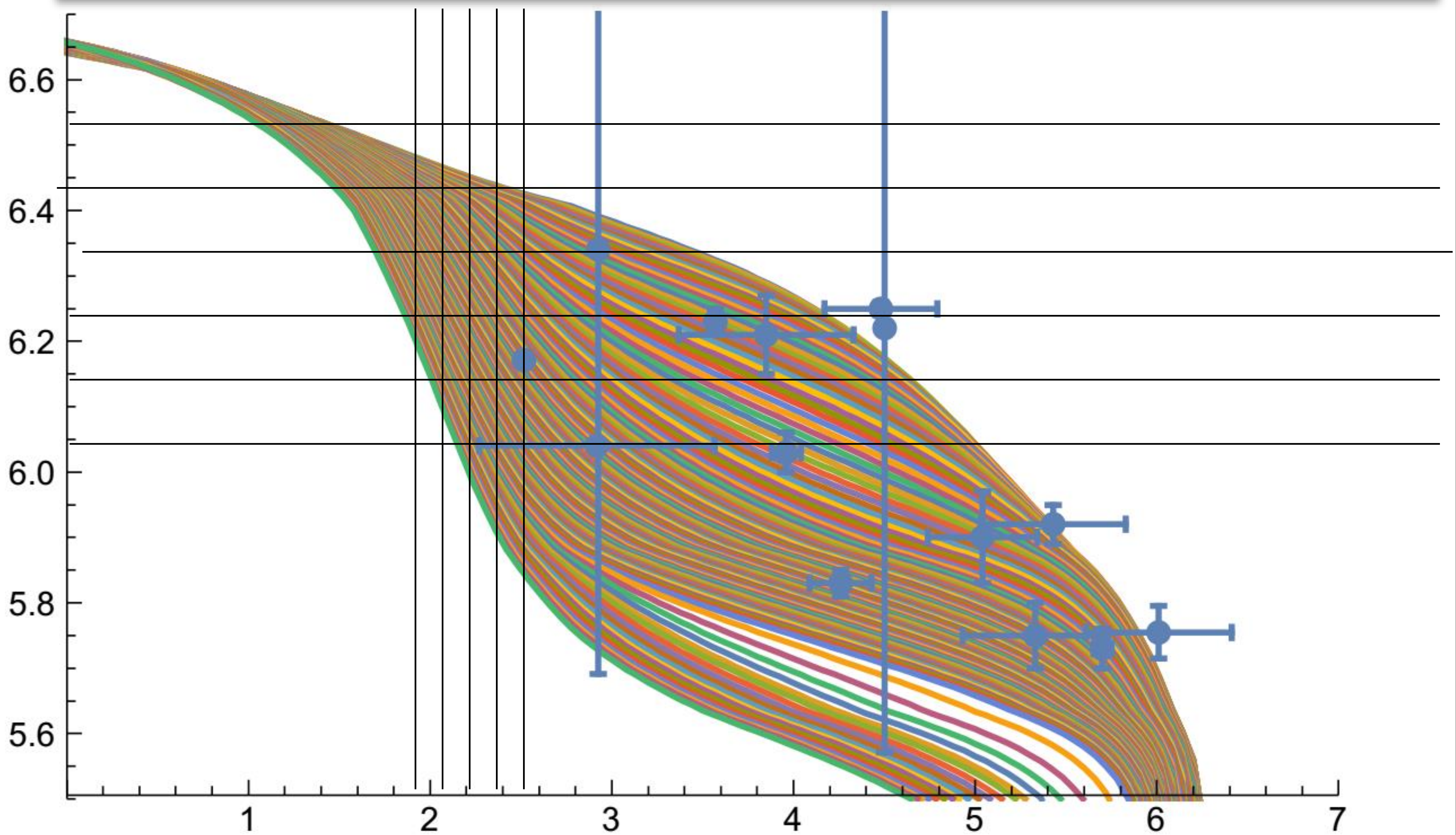


Calculation Time and efficiency

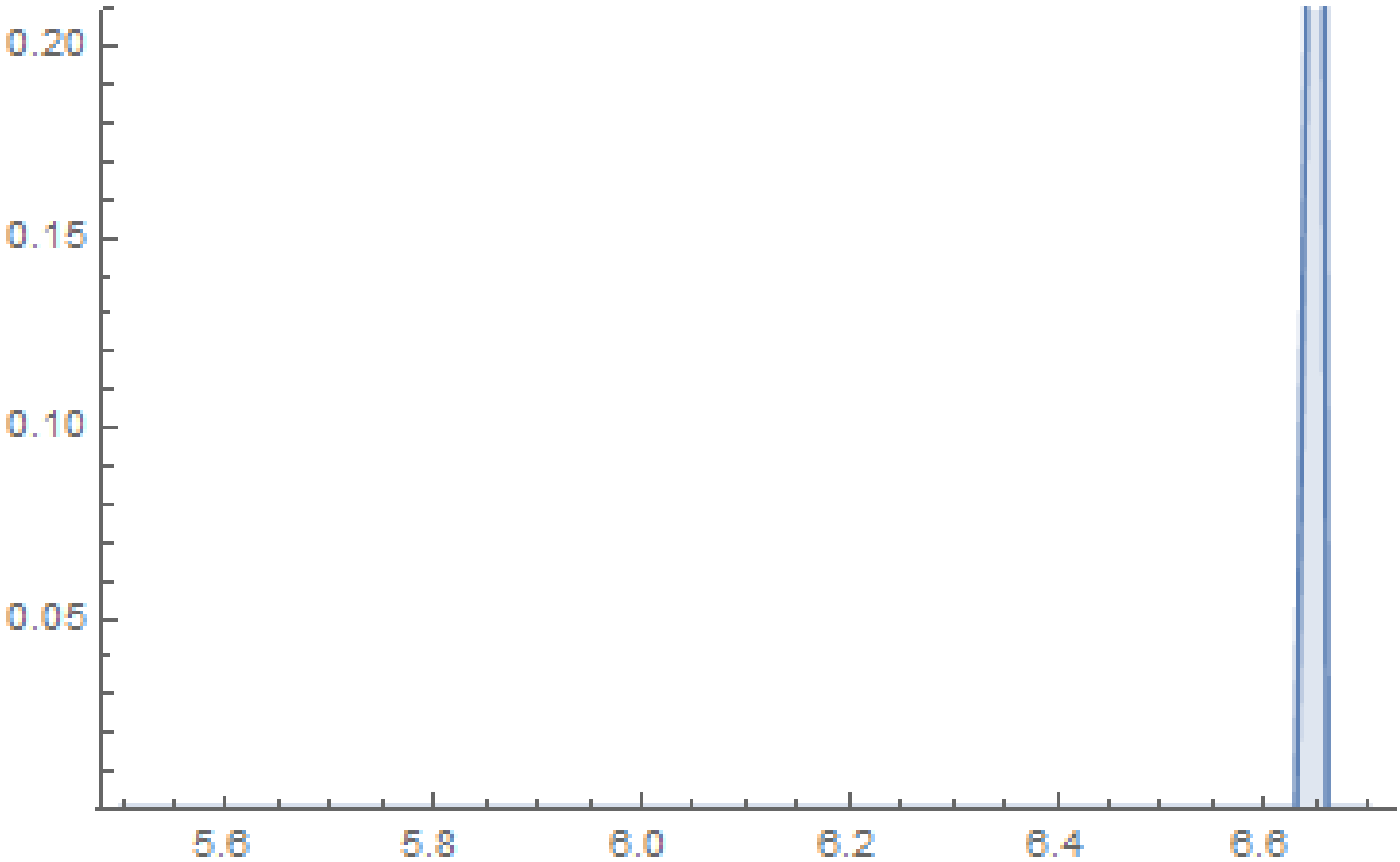




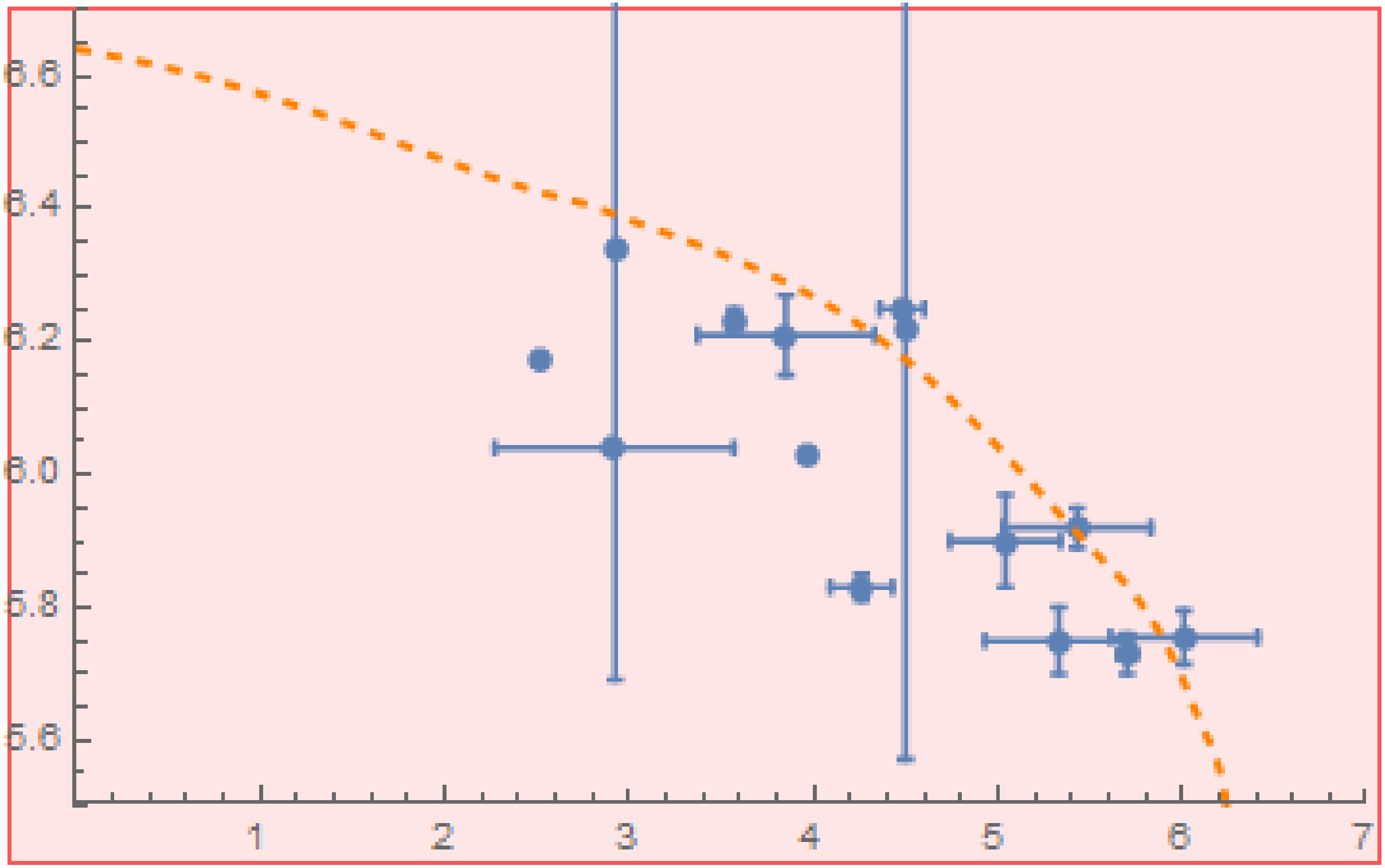
Distribution of Evolution tracks via Temperature at given Time



Distribution of Evolution tracks via Temperature at given Time

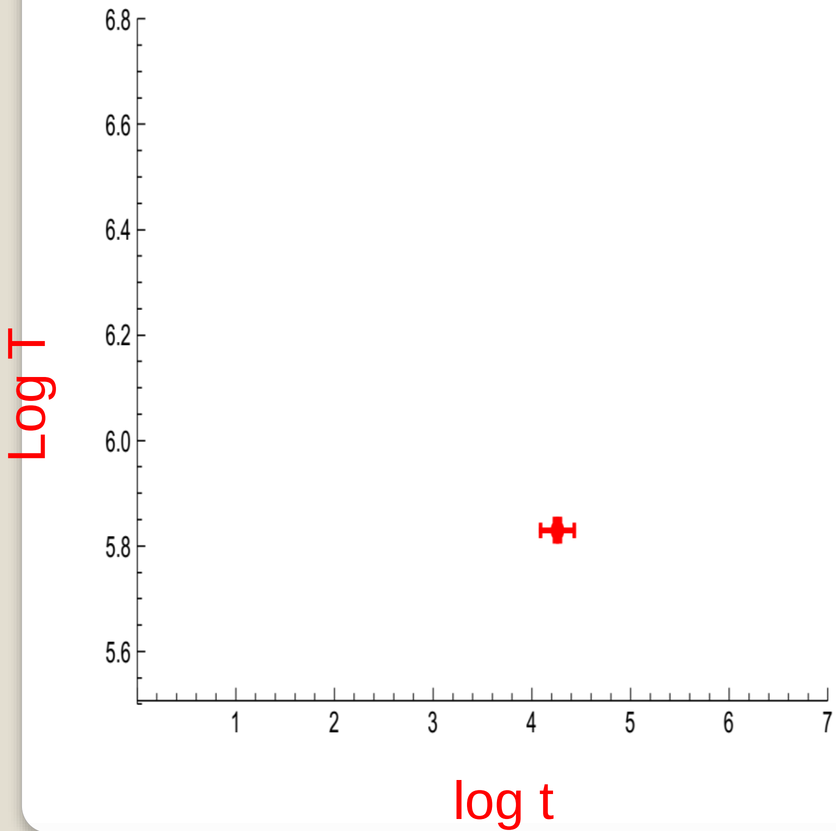


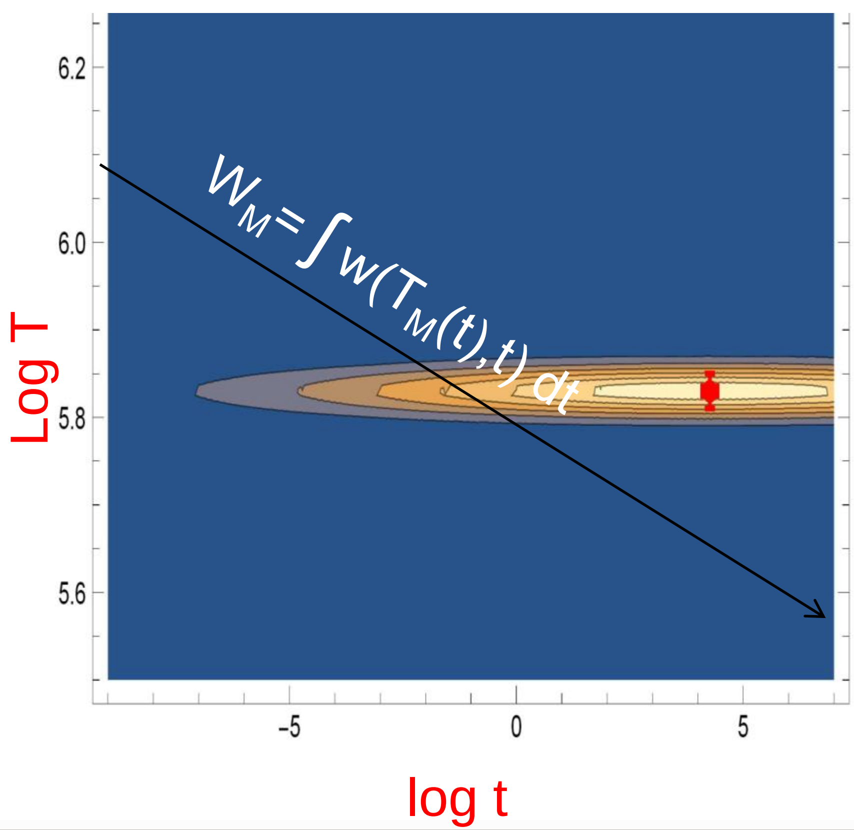
Evolution tracks for different NS Masses



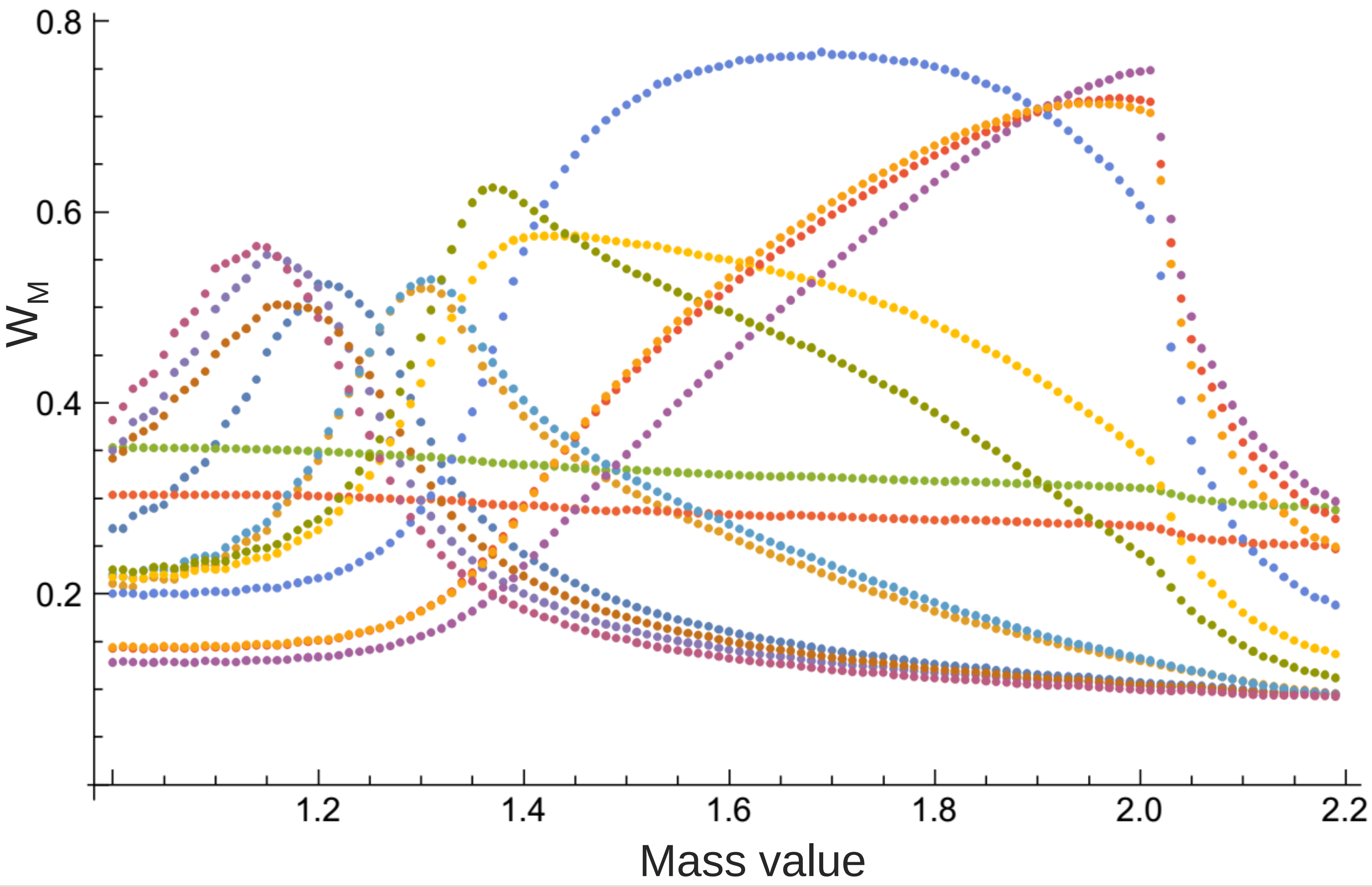
Weighting of Data point on the Temperature - Age Diagram

$$w(T,t) = \mathrm{Exp}\{(\log T - \log T_D)^2/\sigma_T + (\log t - \log t_D)^2/\sigma_t\}$$

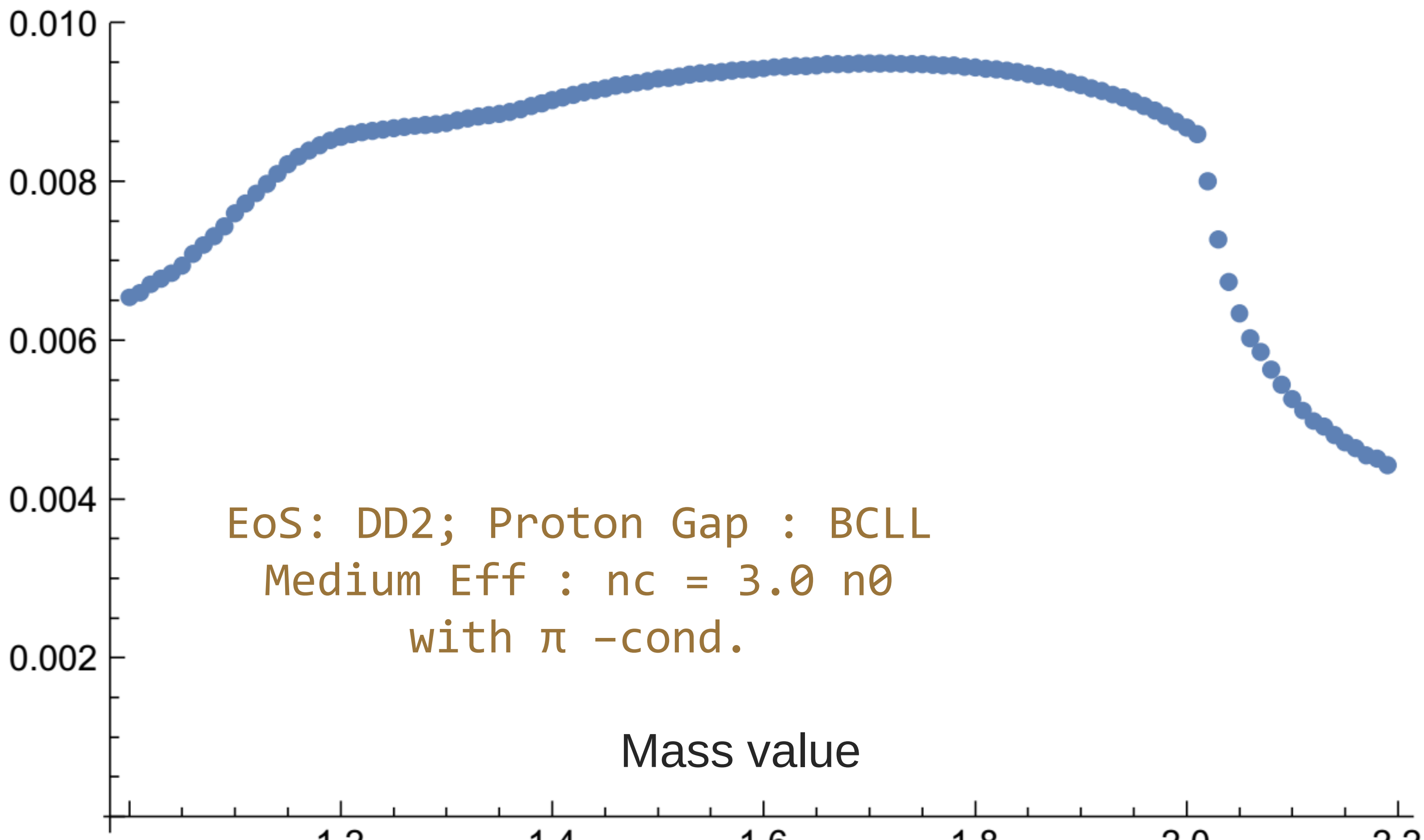




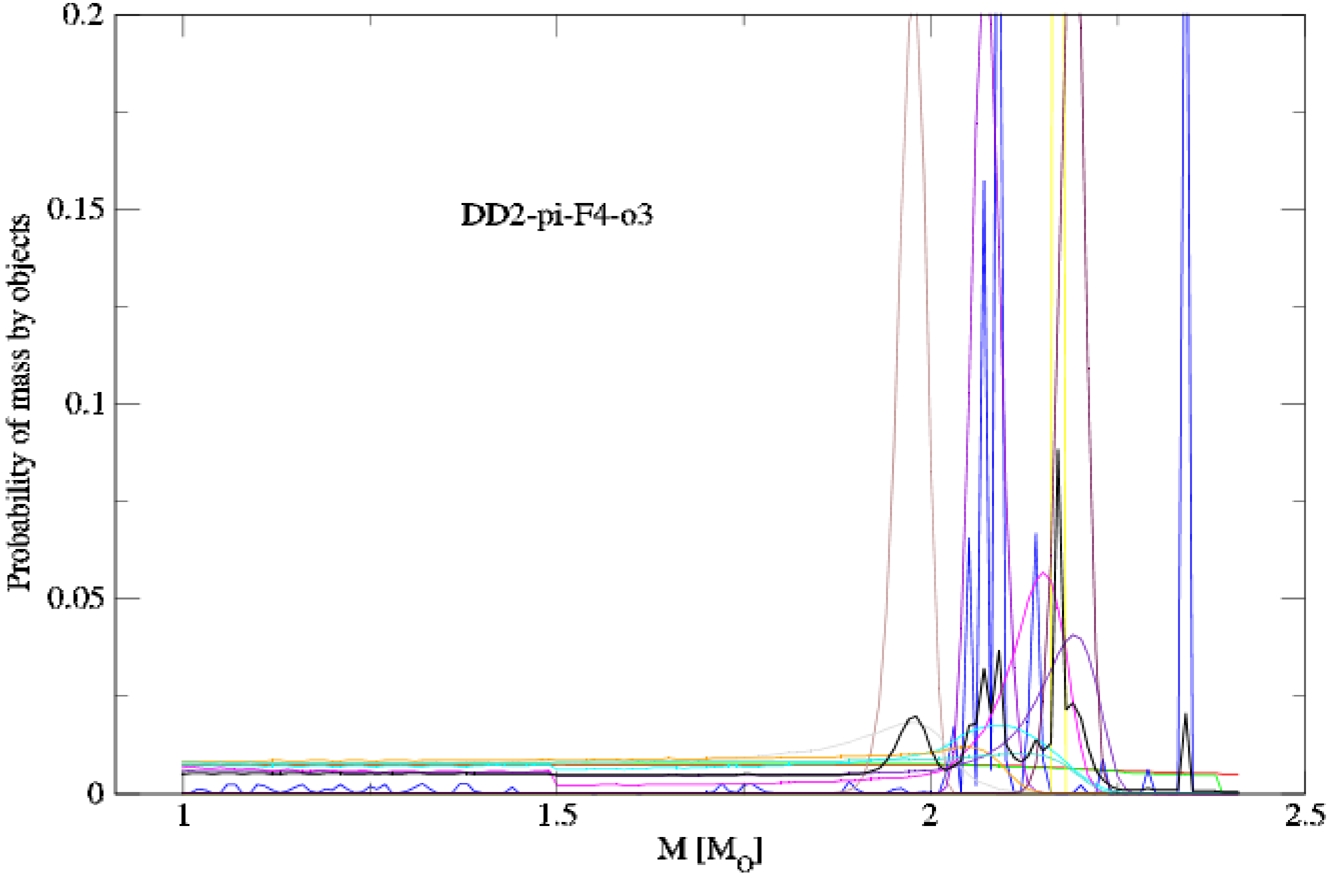
Expected Mass value for the Data points on the T - t Diagram



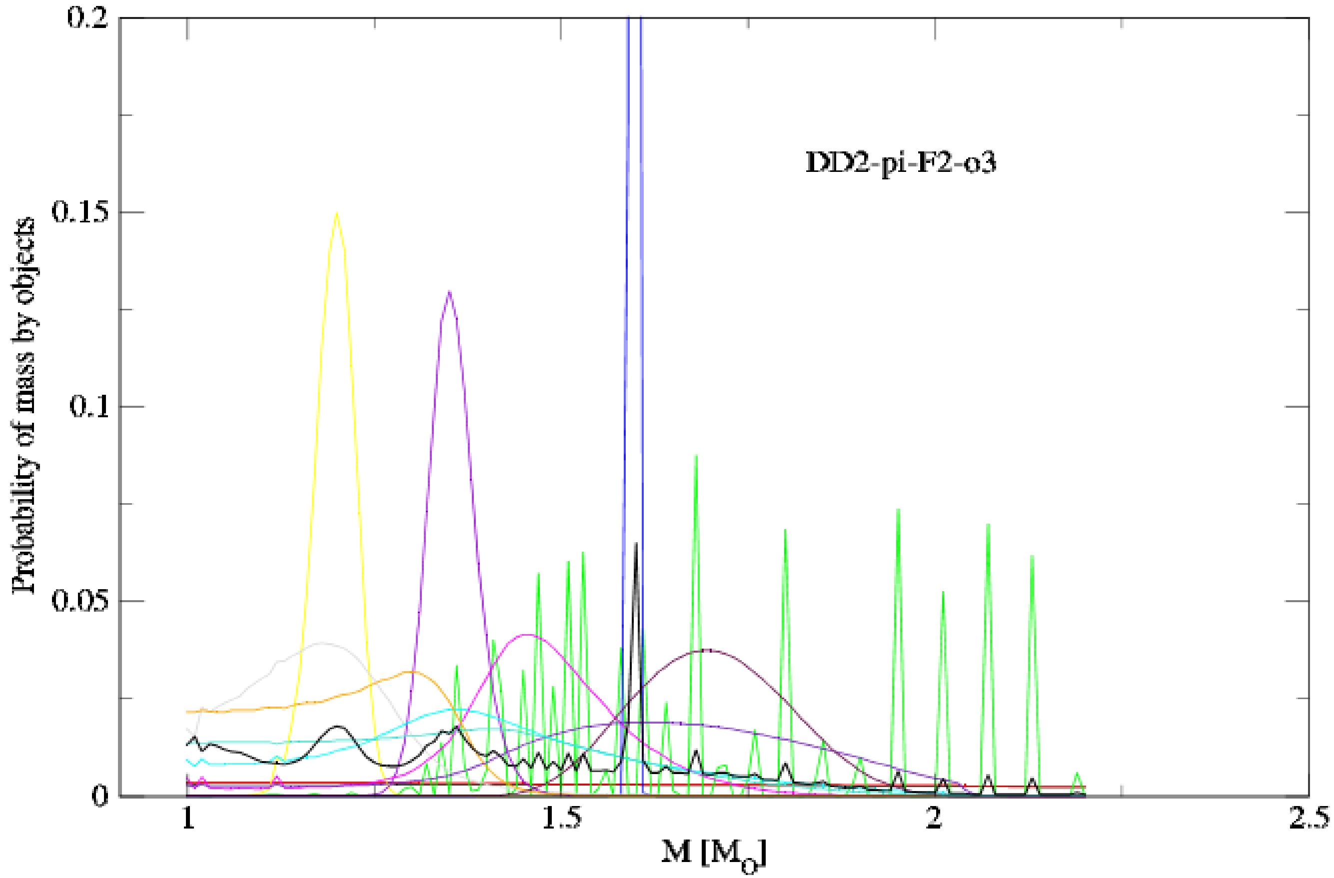
Expected Mass value for the Data points on the T - t Diagram



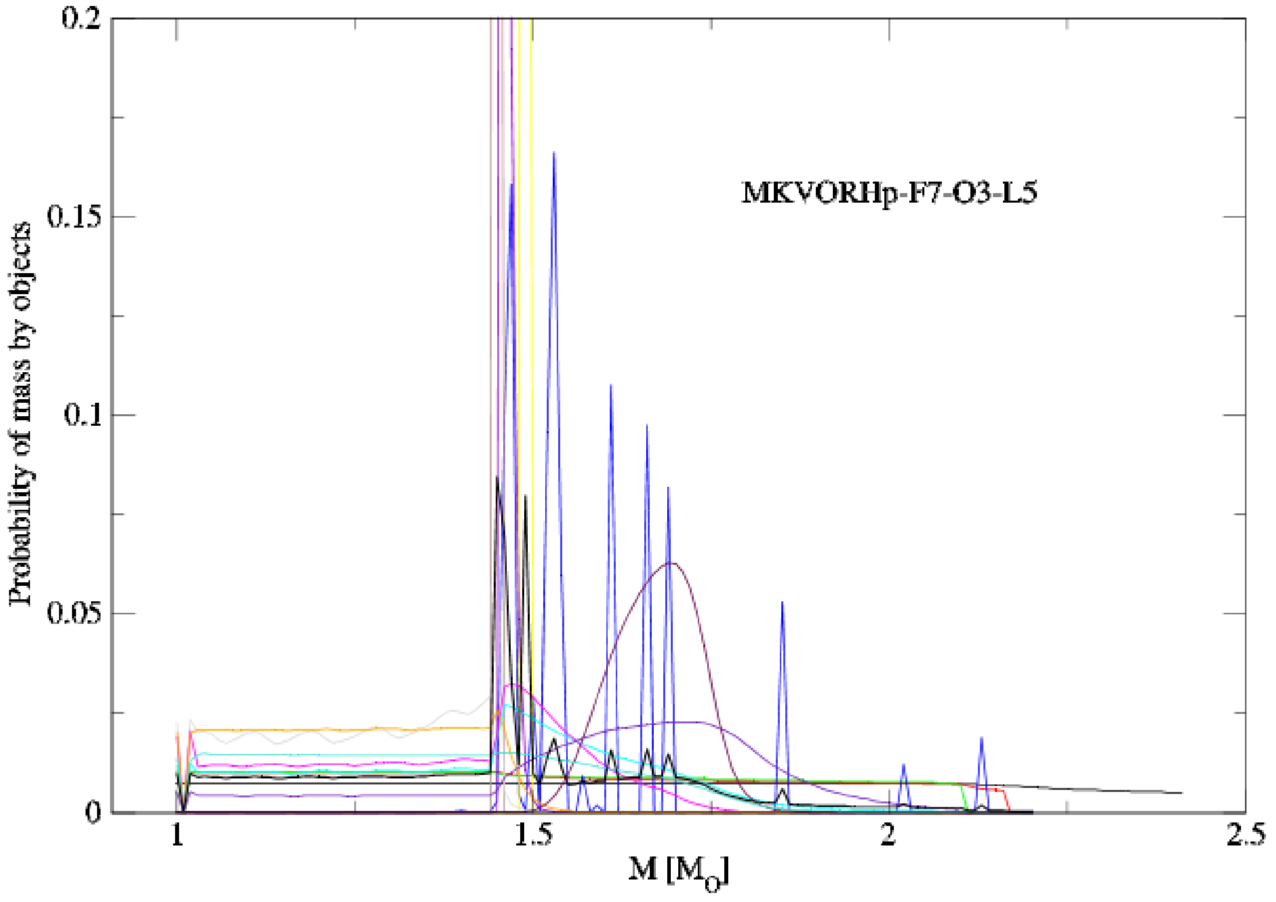
Expected Mass value for the Data points on the T - t Diagram



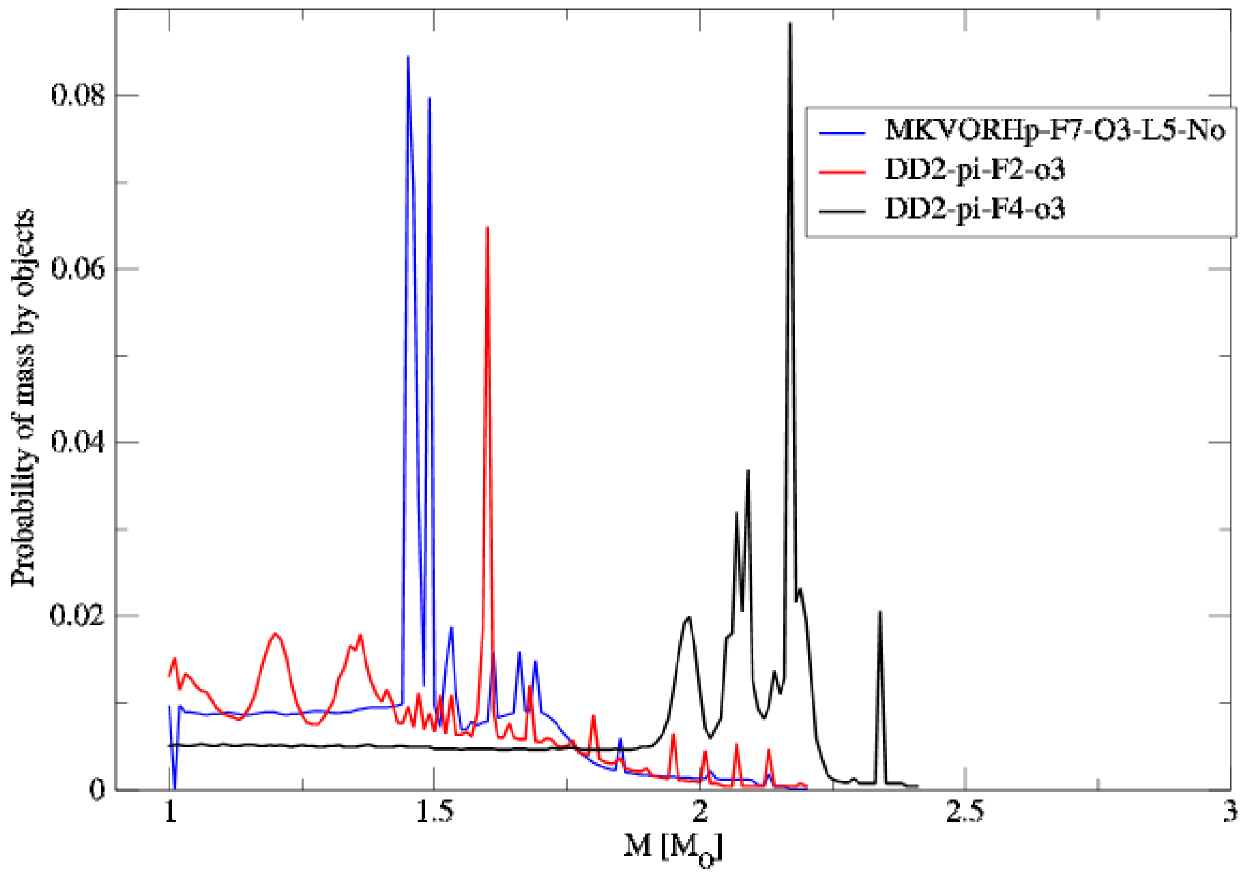
Expected Mass value for the Data points on the T - t Diagram



Expected Mass value for the Data points on the T - t Diagram



Expected Mass value for the Data points on the T - t Diagram



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 Hyperons and/or Quarks or Dark-Matter in high-mass stars could show different cooling behavior depending on core superconductivity
- Parallelization allowed to make the calculations for statistical analyses of models in reasonable time

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Thank YOU!!!!!