The Peculiar Thermal Relaxation of Neutron Stars

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Collaborator: Ang Li and Rodrigo Negreiros

FB23 IHEP, Beijing, China; Sept 26, 2024

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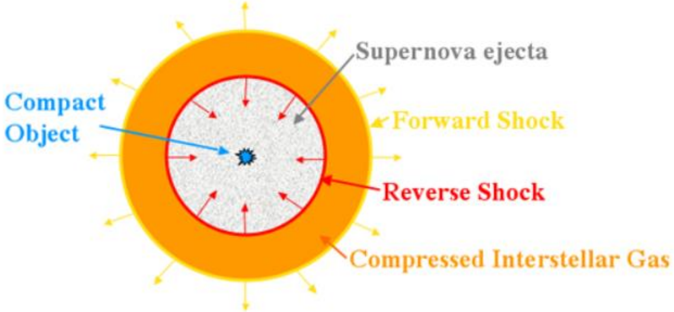
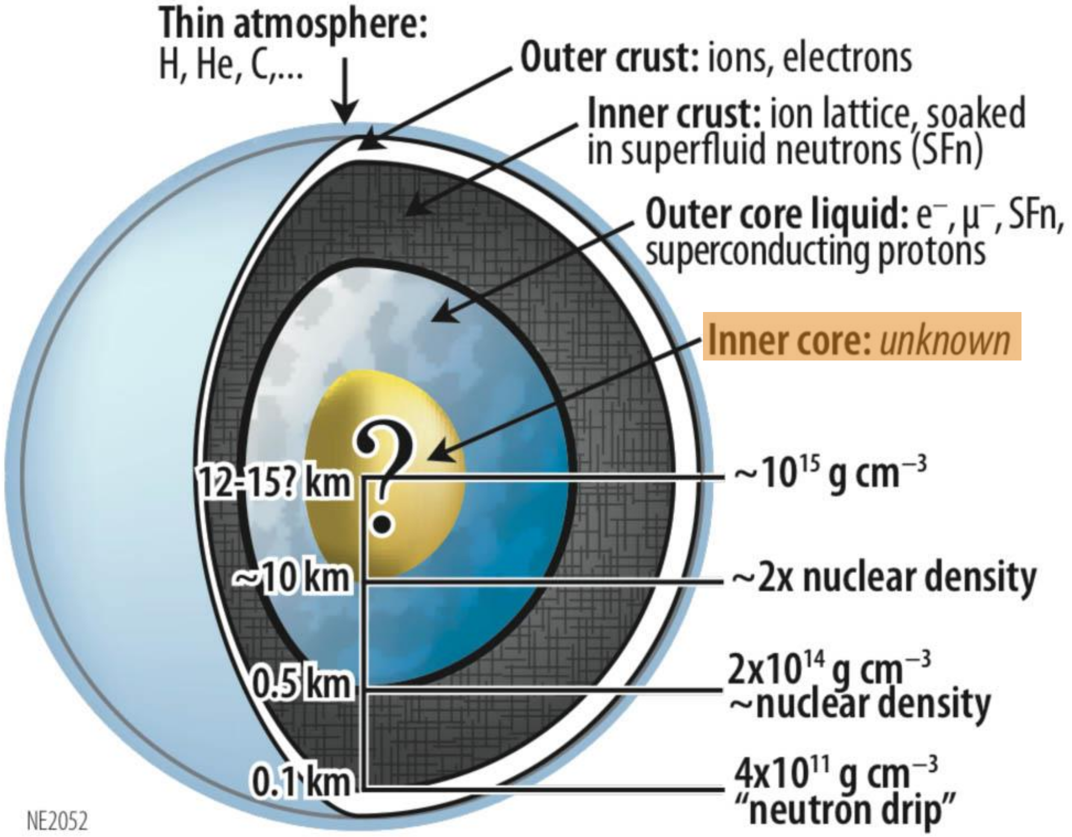
Neutron Stars

Walter Baade

Fritz Zwicky

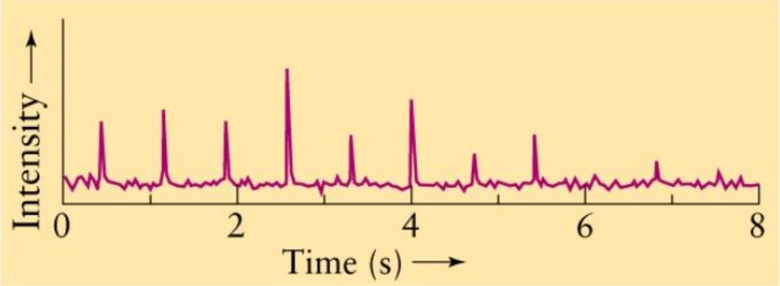


1930’s， the possible existence of neutron stars



Index of /Images/nicer (nasa.gov)

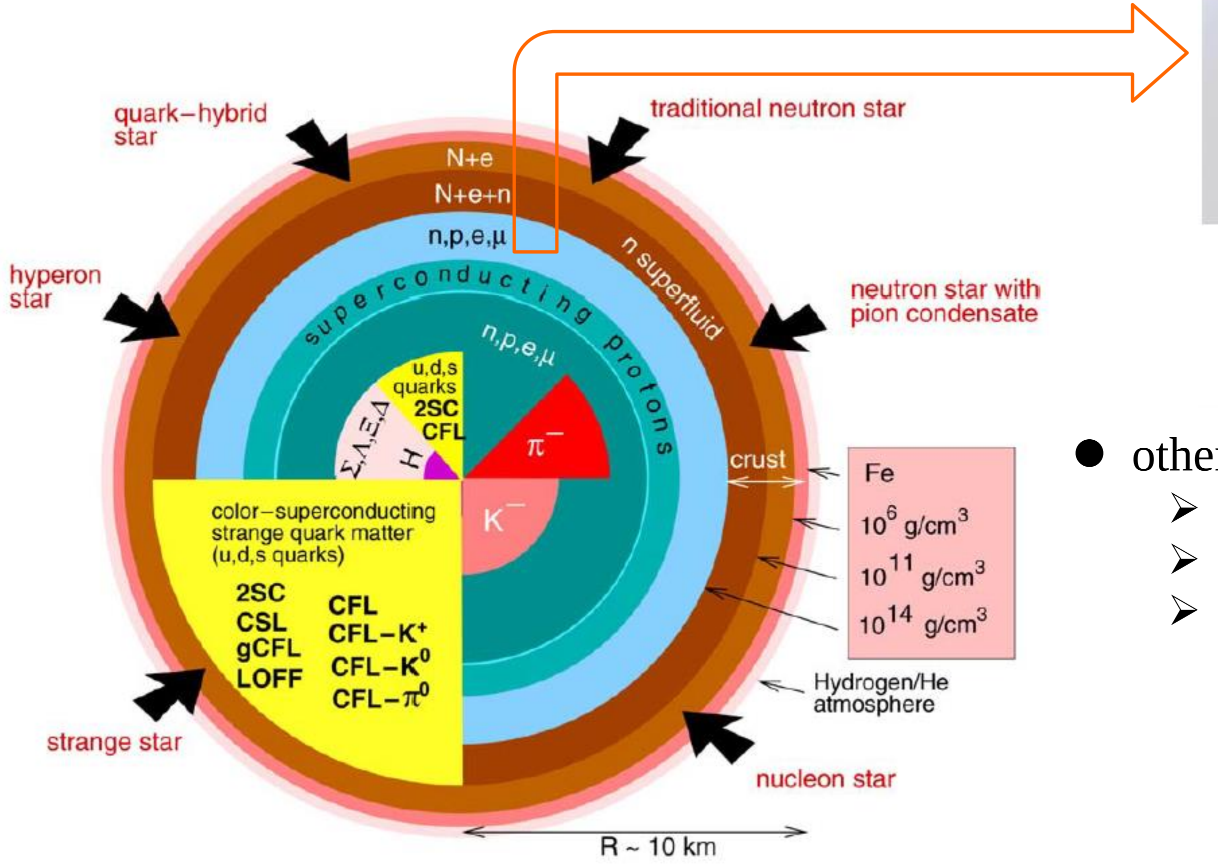
Jocelyn Bell



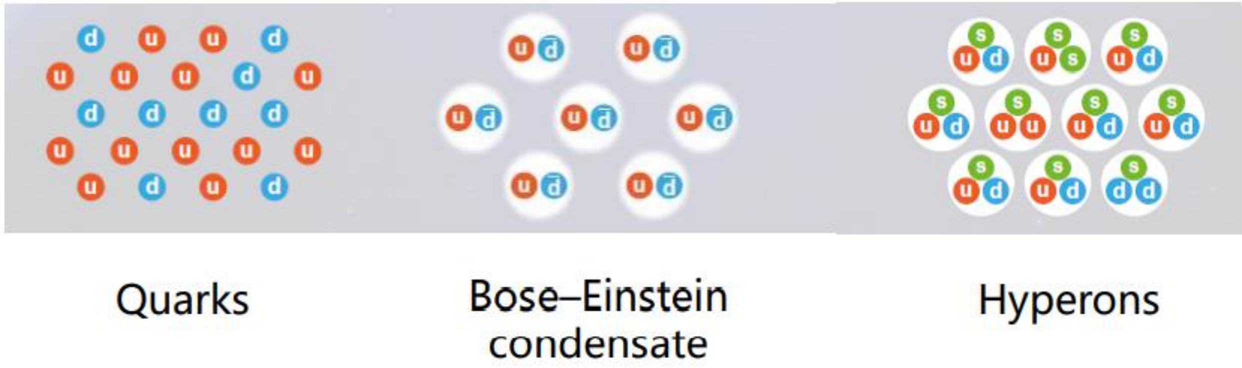
Lecture 19: Neutron Stars (ualberta.ca)

1967， the first observation of pulsar

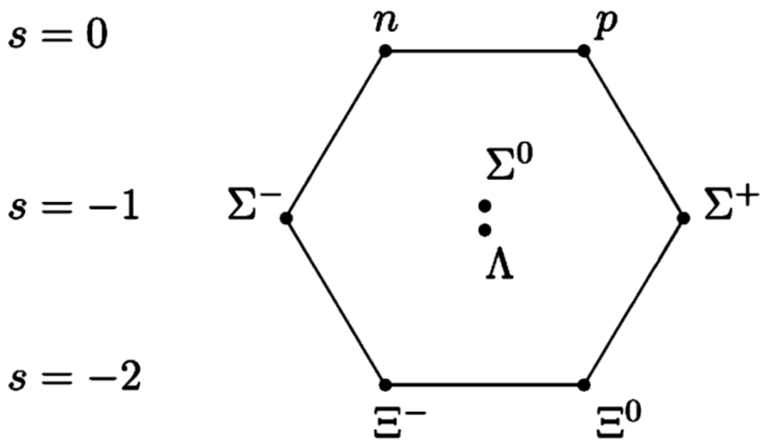
Neutron Star Inner Core



Weber2005_PPNP54-193

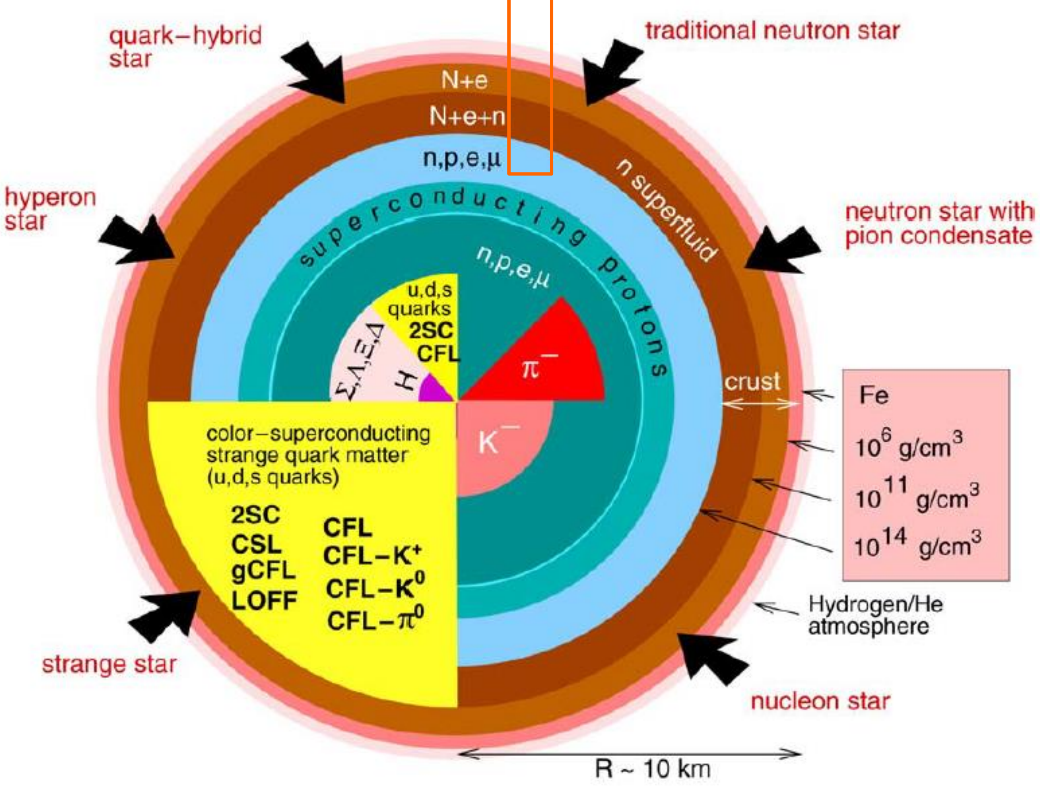


- other possible compositions:
  - excited nucleon Δ
  - dark matter
  - ……

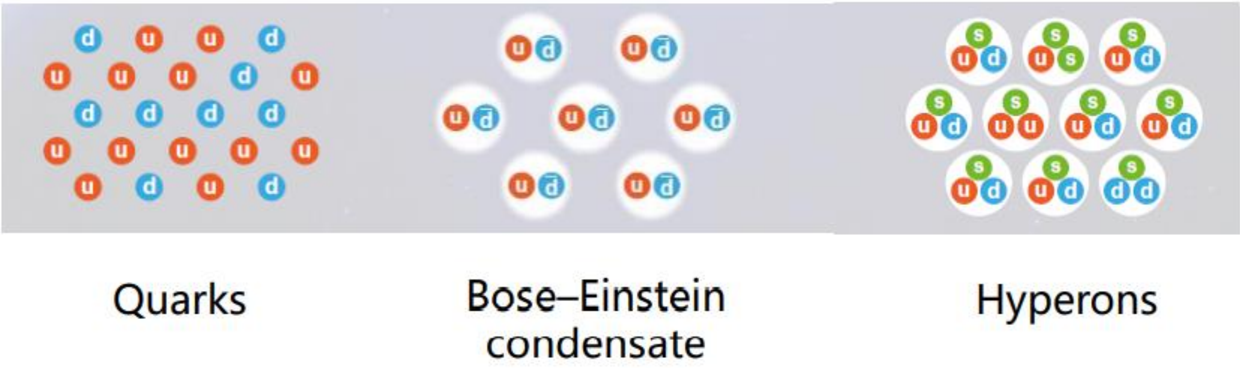


Alexandrou2009_PRD80-114503

Neutron Star Inner Core



Weber2005_PPNP54-193



- other possible compositions:
  - excited nucleon Δ
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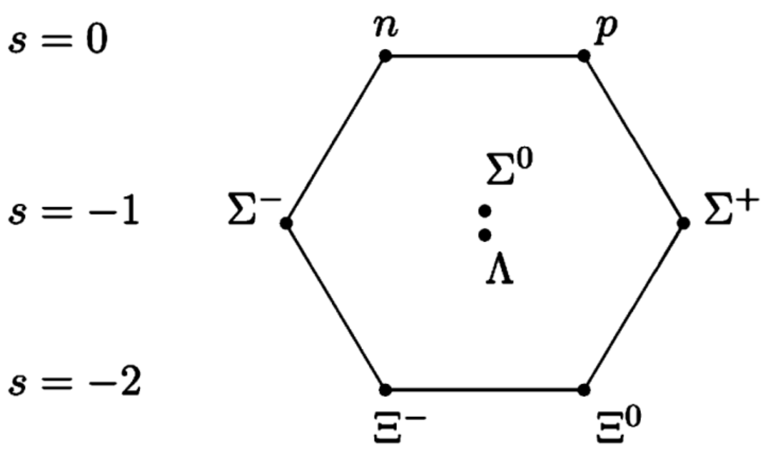
  - ……
- classification of neutron stars
  - nucleon star
  - hyperon star
  - quark star
  - hybrid star
  - dark matter mixed star
  - ……

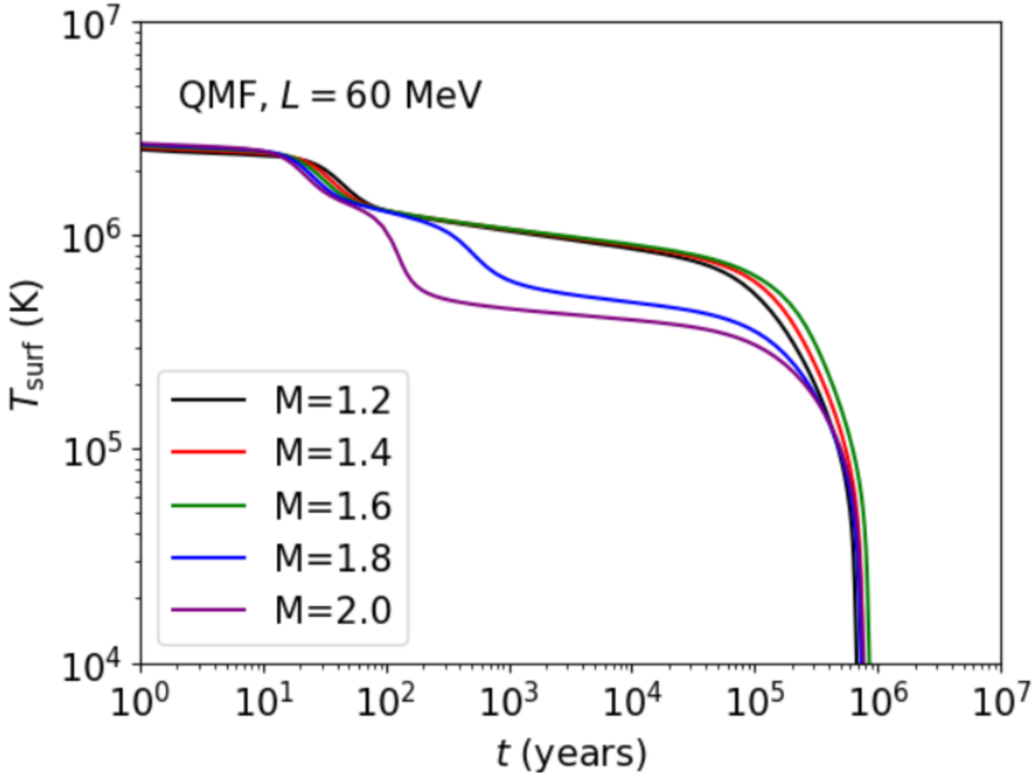


Alexandrou2009_PRD80-114503

Neutron Star Long-term Cooling

$$\frac{\partial(le^{2\Phi})}{\partial m} = -\frac{1}{\varepsilon\sqrt{1-2m/r}}\left(\epsilon_\nu e^{2\Phi} + c_v\frac{\partial(Te^{\Phi})}{\partial t}\right),$$

$$\frac{\partial(Te^{\Phi})}{\partial m} = -\frac{(le^{\Phi})}{16\pi^2 r^4 \kappa\varepsilon\sqrt{1-2m/r}}.$$



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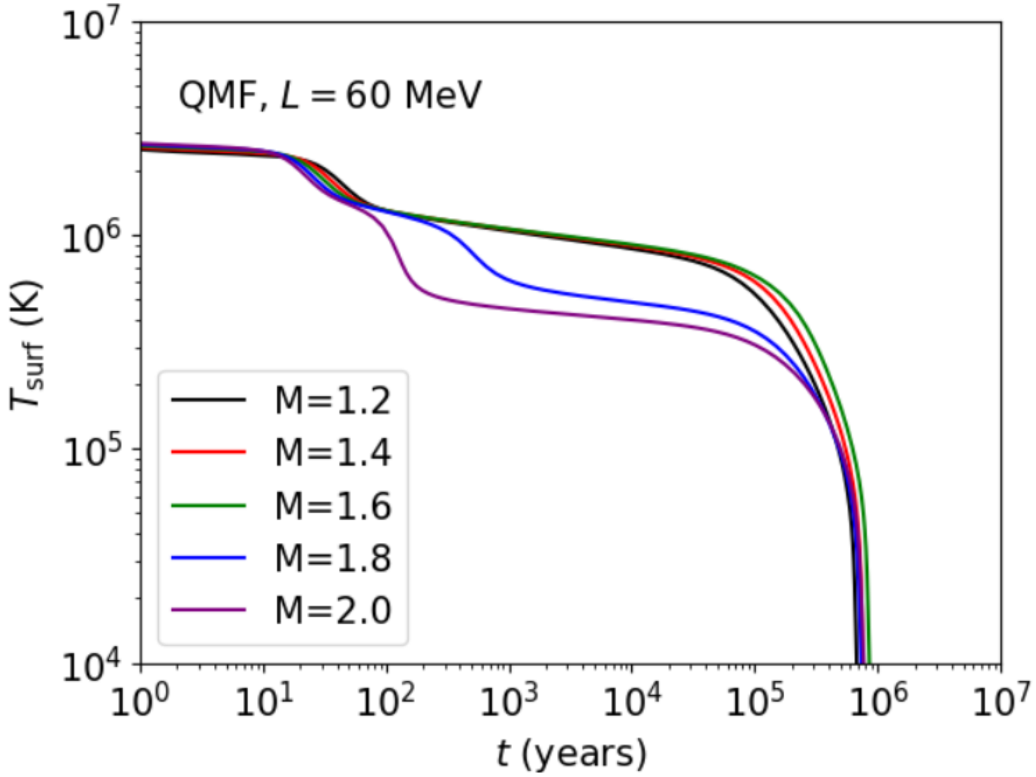
MICRO

- neutrino emissivity ϵ
- specific heat c_v
- thermal conductivity κ



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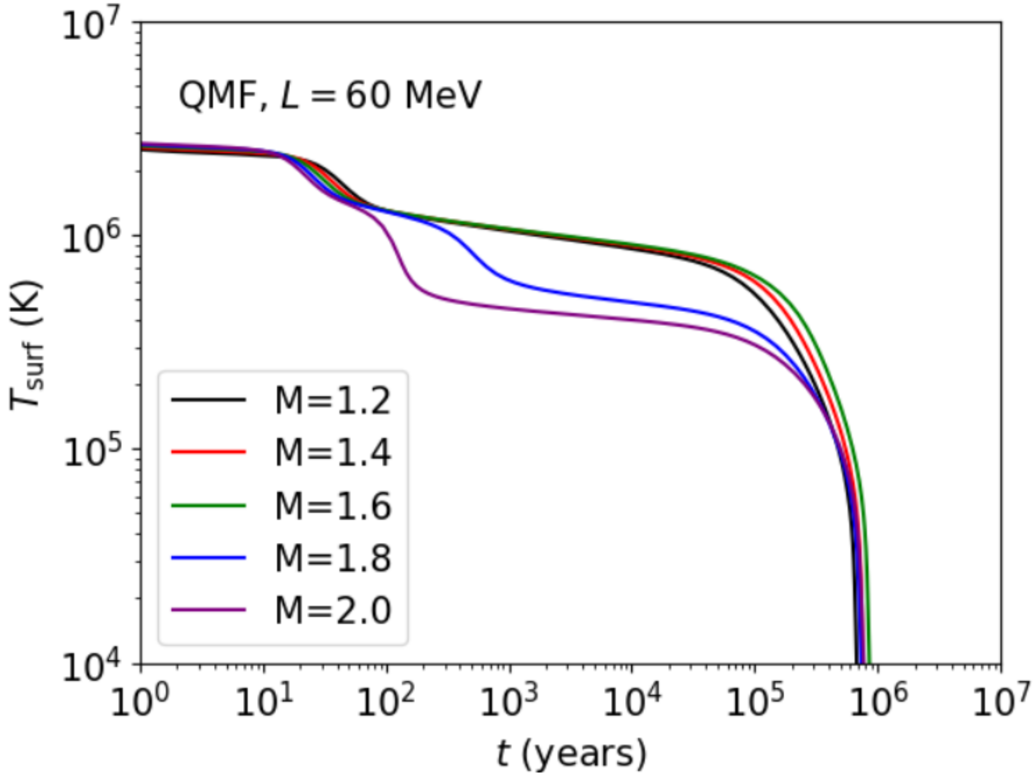
MACRO

- mass and radius profile $m(r)$
- curvature profile $\phi(r)$



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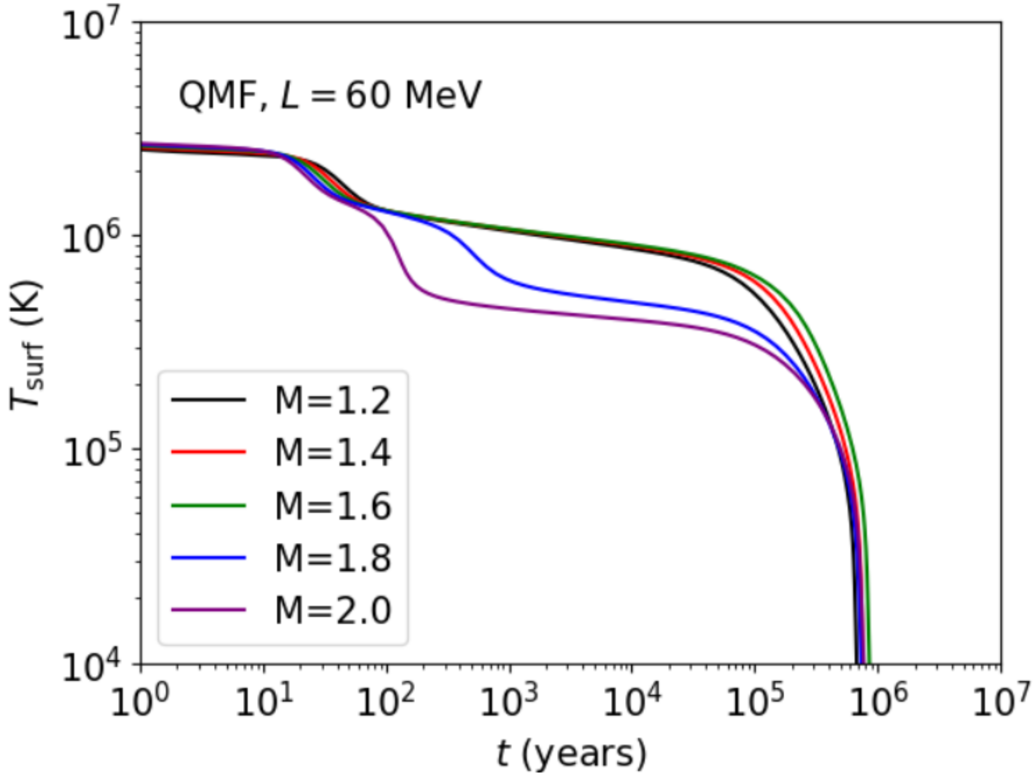
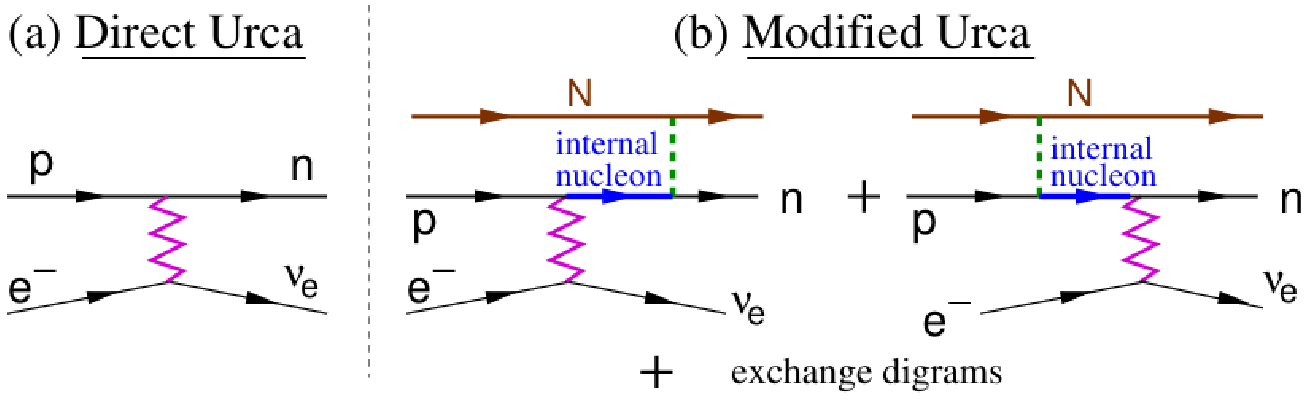


- ✓ **Equation of State (EoS)**
- ✓ **Superfluidity (SF)**
- ✓ Composition: hyperon? quark? Δ? ...
- ✓ Mass
- ✓ Magnetic field, envelopes …

Neutrino Emissivity

- **dUrca vs. mUrca** Alford2024_arXiv2406.13717



$$n \to p + e^- + \bar{\nu}_e, \quad p + e^- \to n + \nu_e$$

$$(n,p) + p + e^- \to (n,p) + n + \nu_e$$
$$(n,p) + n \to (n,p) + p + e^- + \bar{\nu}_e$$

spectator nucleon

$$\epsilon_{\mathrm{dUrca}}/\epsilon_{\mathrm{mUrca}} = 5 \times 10^5 T_9^{-2}$$

	threshold
np dUrca	$Y_p > 1/9$
mUrca	×
hyperon dUrca	nearly the onset density of hyperon

- **Cooper pair breaking and formation (PBF)**

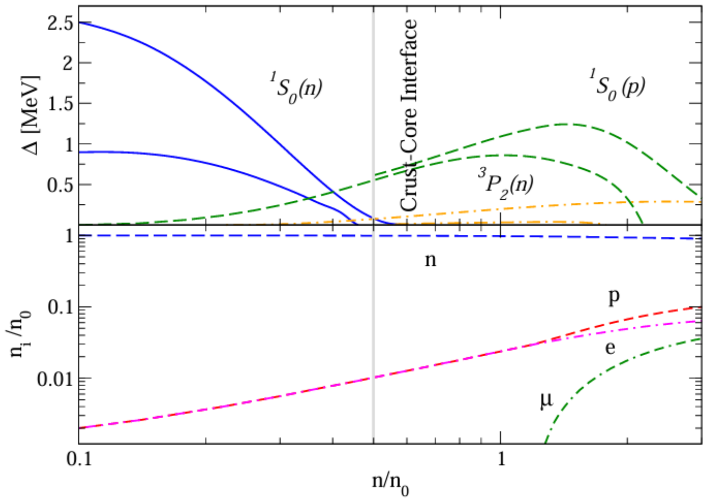
Raduta2017_MNRAS475-4347

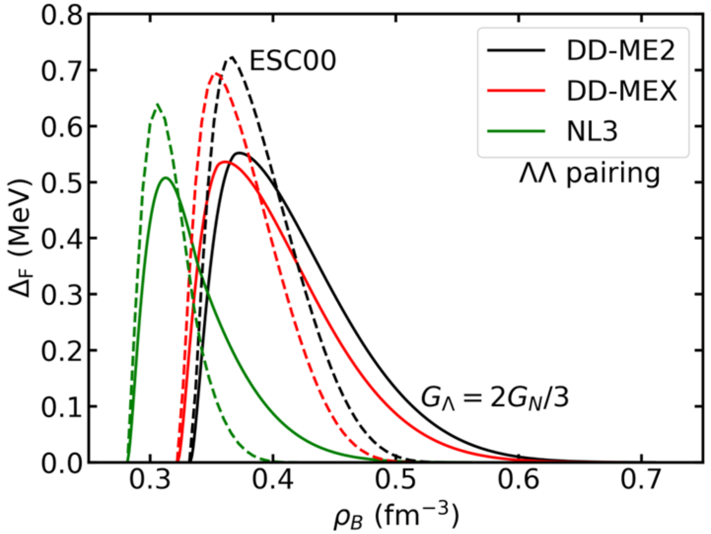
$$\{YY\} \to Y + Y + \nu + \bar{\nu}, \quad Y + Y \to \{YY\} + \nu + \bar{\nu}.$$

$$\epsilon_{\mathrm{PBF}}/\epsilon_{\mathrm{mUrca}} \sim 10$$

PBF process is triggered when internal temperature decreases to the critical temperature

Superfluidity and Neutron Star Cooling

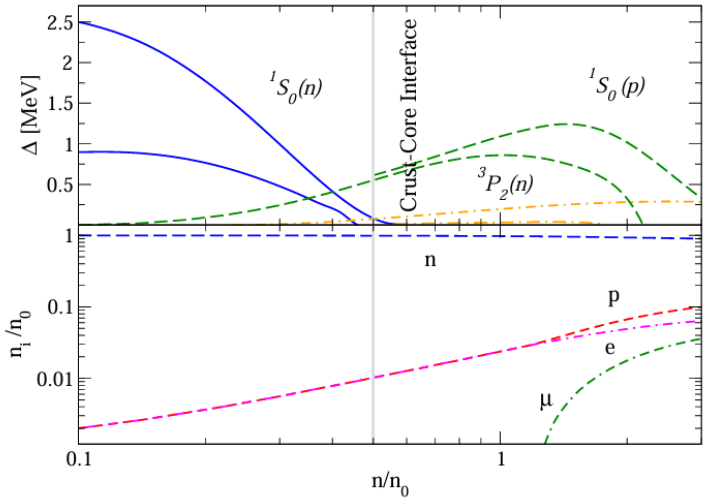


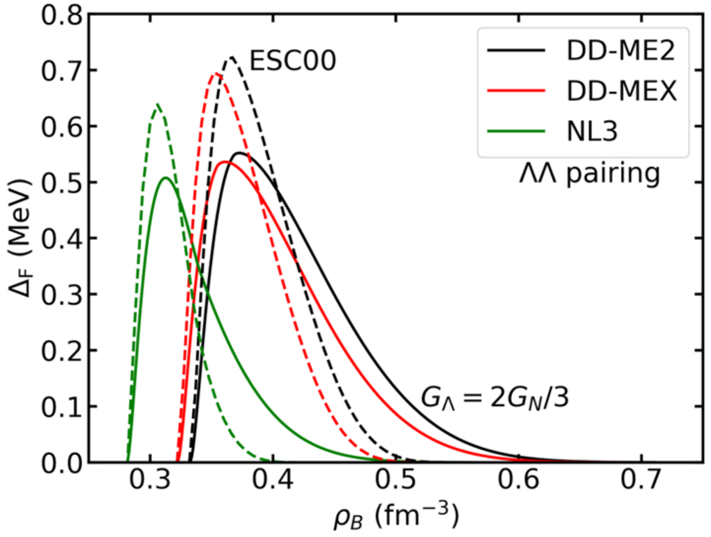


<u>Baryon superfluidity is widely present within neutron stars.</u>

Sedrakian2024_arXiv2407.13686
Tu2022_PRC106-025806

Superfluidity and Neutron Star Cooling





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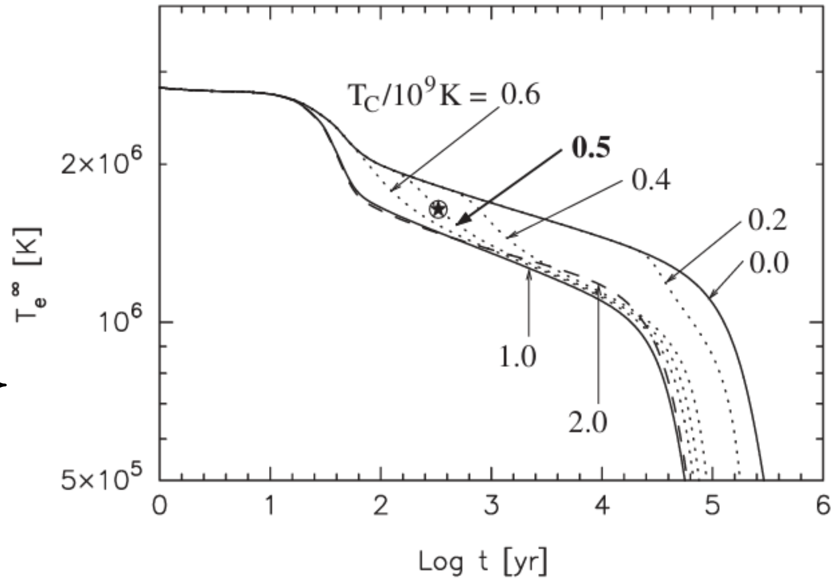
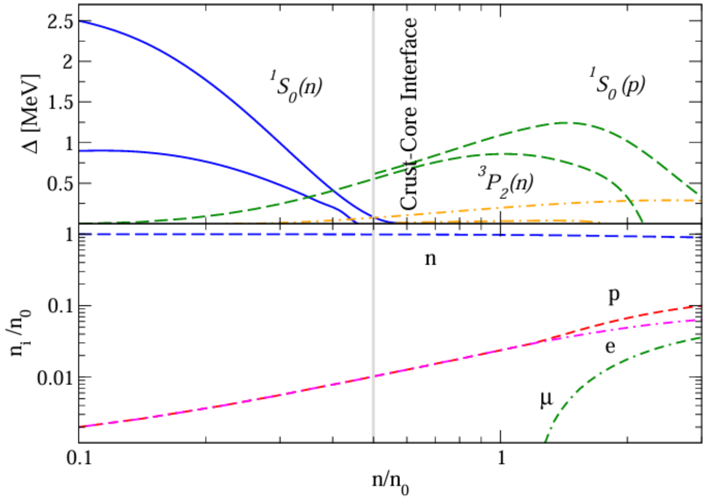
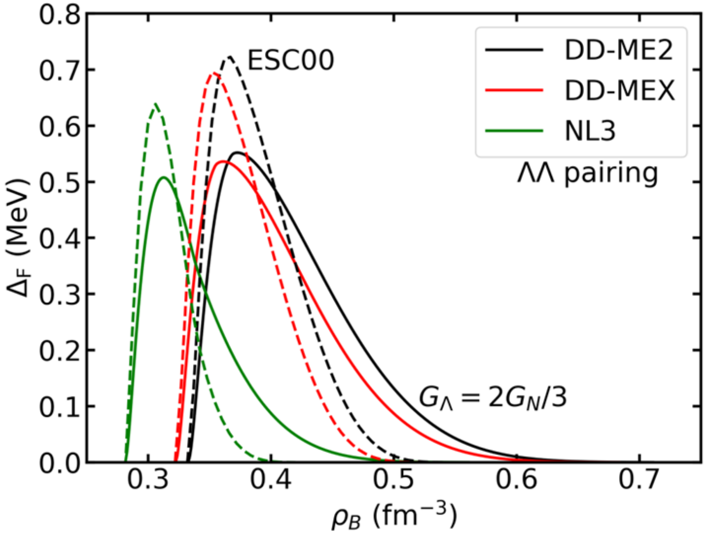
PBF, accelerate cooling



Sedrakian2024_arXiv2407.13686
Tu2022_PRC106-025806
Page2011_PRL106-081101

Superfluidity and Neutron Star Cooling





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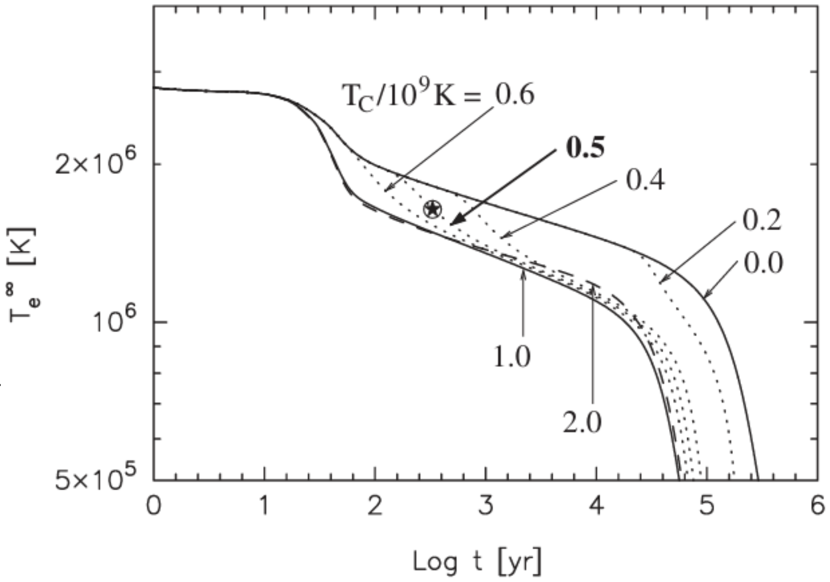
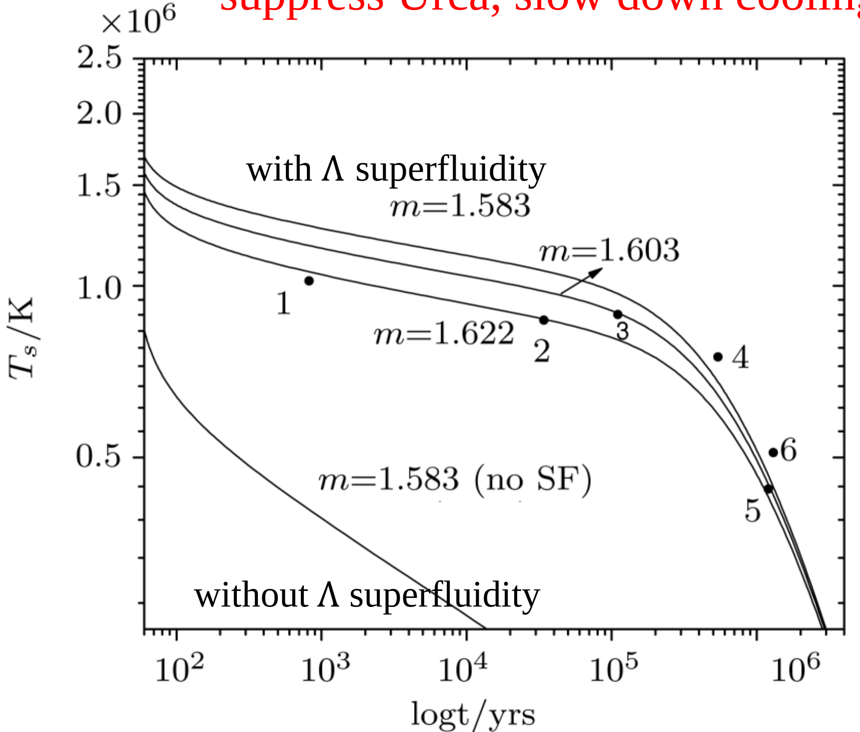


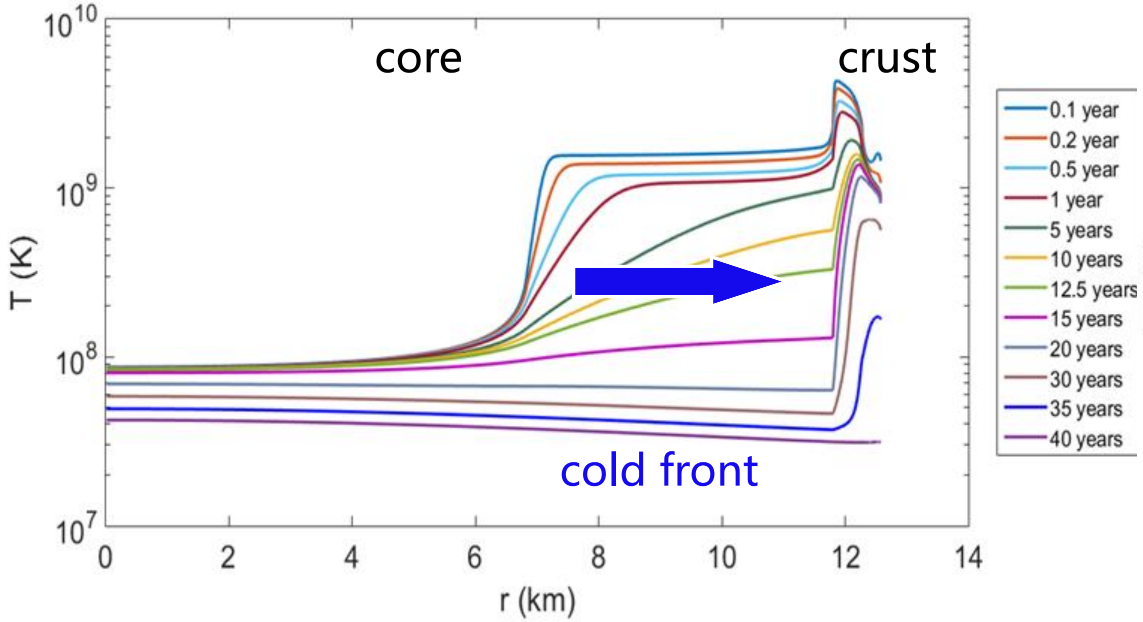
suppress Urca, slow down cooling

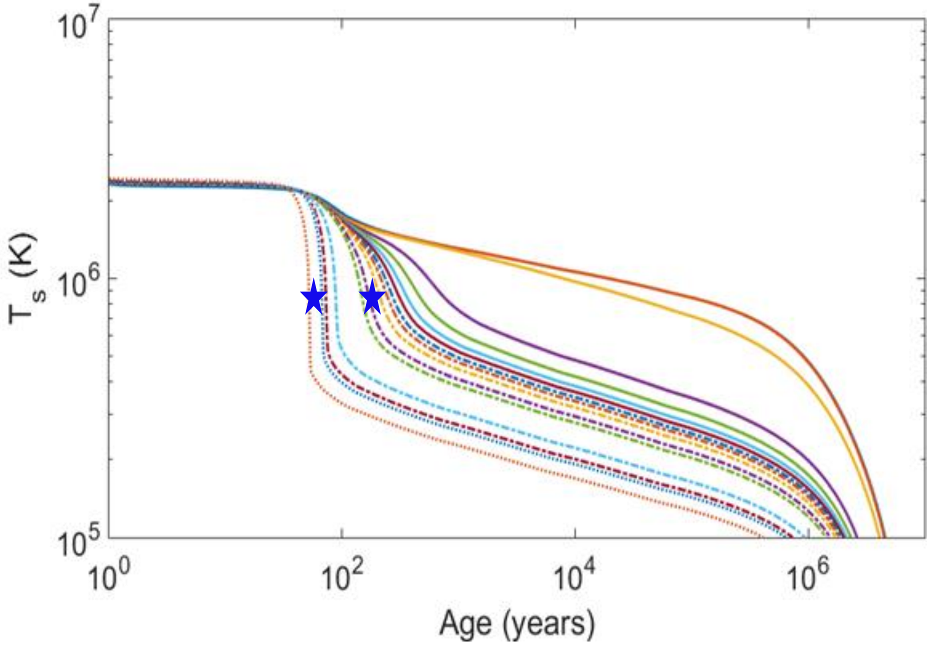


Sedrakian2024_arXiv2407.13686
Tu2022_PRC106-025806
Page2011_PRL106-081101
Xu2011_CTP56-521

Superfluidity is essential to the neutron star cooling

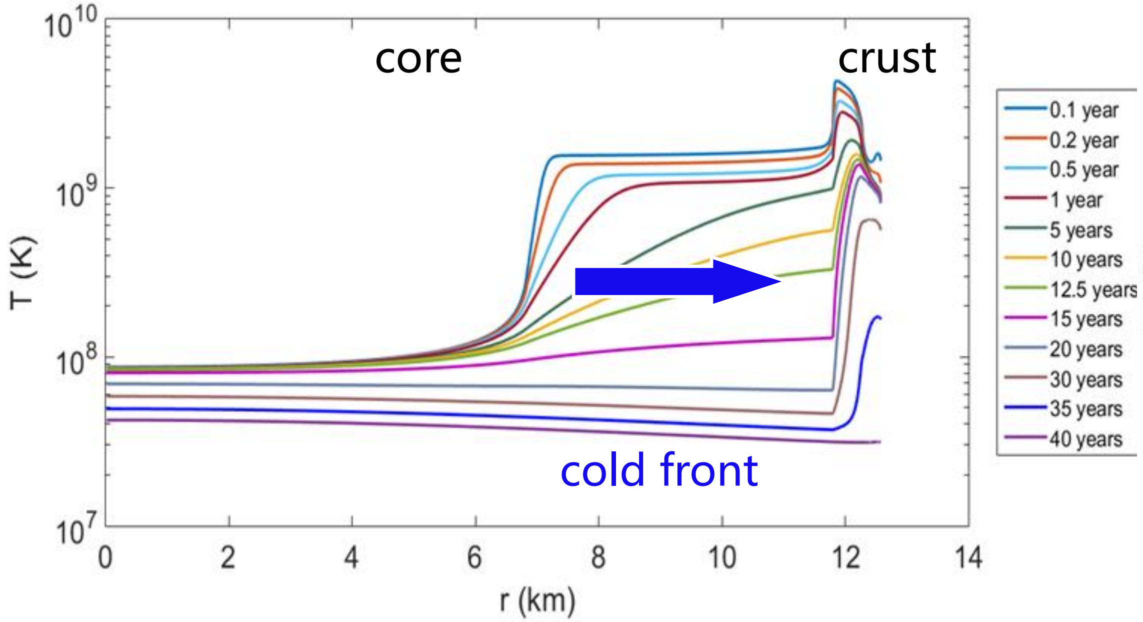
Thermal Relaxation of Neutron Star

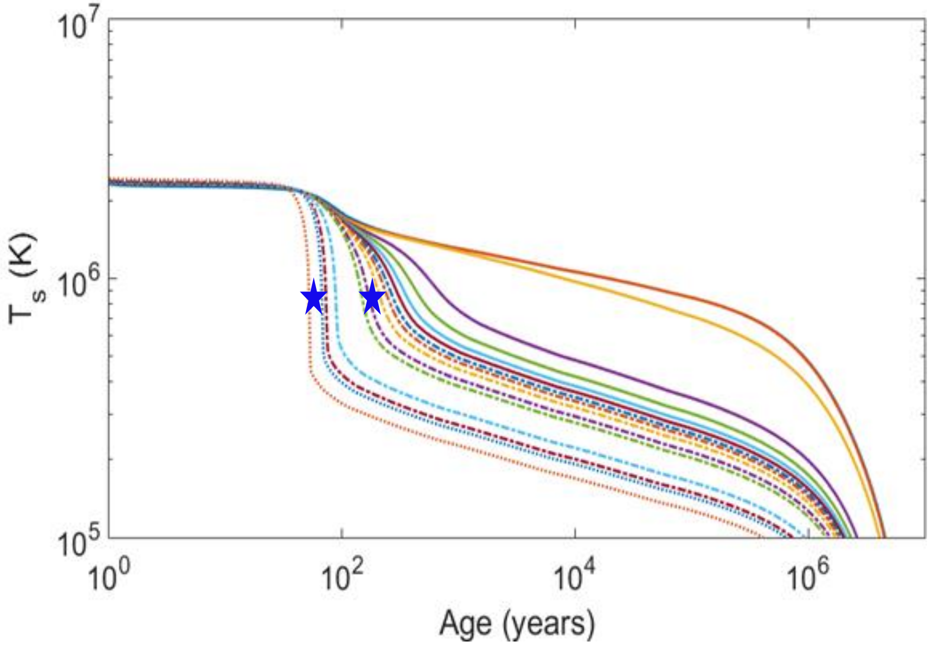




Sales2020_A&A642-A42
Gnedin2001_MNRAS324-725
Lattimer1994_ApJ425-802

Thermal Relaxation of Neutron Star





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Thermal relaxation: the **thermal coupling** between the core and crust

$$t_w = t \text{ for } \max\left|\frac{\mathrm{d}\ln(T_s)}{\mathrm{d}(\ln(t))}\right| \qquad t_w \sim 10\text{–}100 \text{ years}$$

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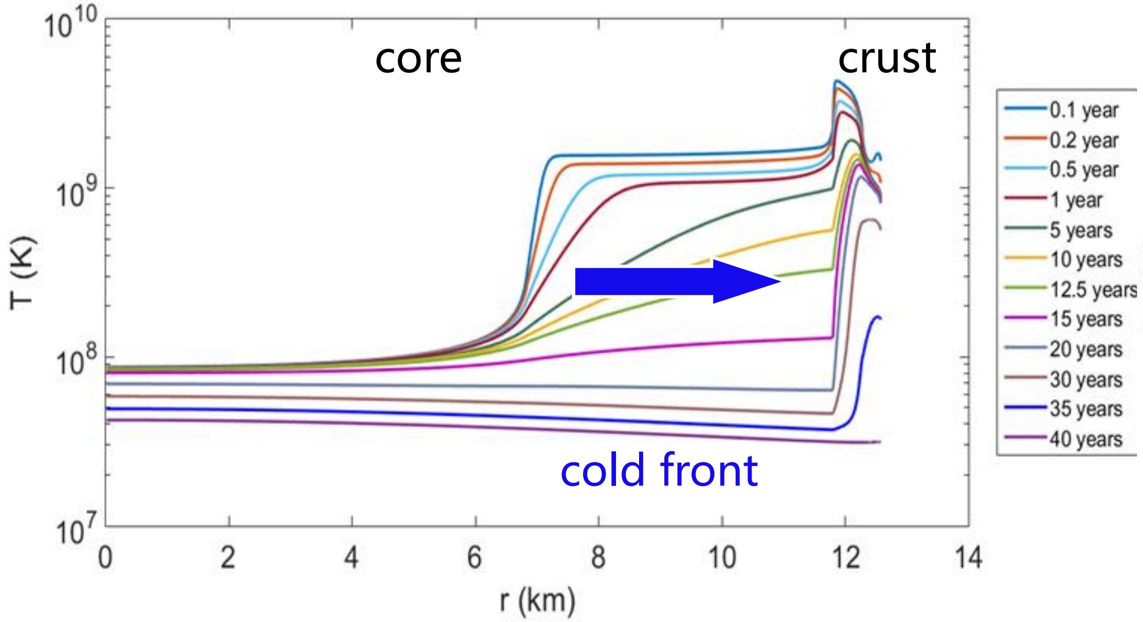

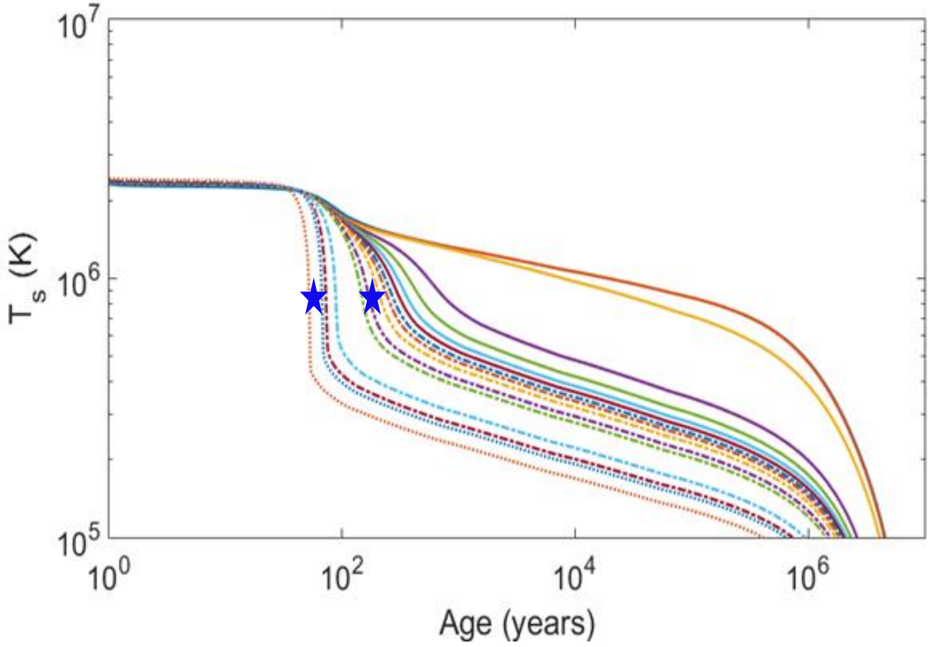

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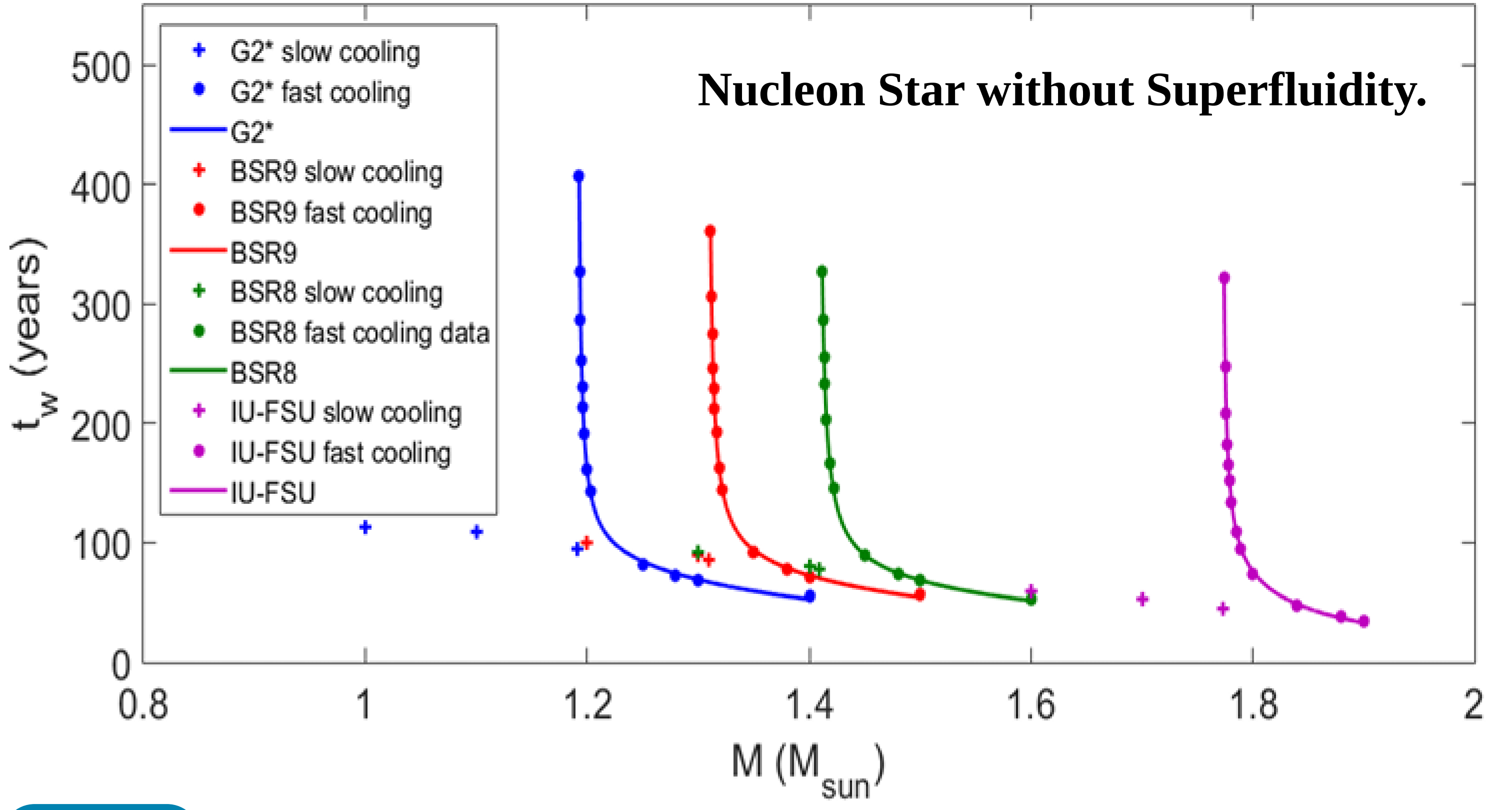
Fitting: $t_w \approx \alpha t_1$

$$\alpha = \left(\frac{\Delta R_{\text{crust}}}{1\text{ km}}\right)^2 (1 - 2M/R)^{-3/2}$$

Linear!

Thermal Relaxation of Neutron Star



Sales2020_A&A642-A42

Abnormally long relaxation time above the dURca allowed mass!

?

1. How does the ***superfluidity*** affect the thermal relaxation?
2. Can we observe the peculiar thermal relaxation in other type neutron star, e.g., ***hyperon star***?

Contents

Thermal Relaxation of Neutron Star

Lalazissis2005_PRC71-024312
A. Bouyssy *et al.*, PLB 64 (1976) 276
Page2004_ApJSupp155-623

- EoS: $n + p + \Lambda + (\sigma\omega\rho\sigma^*\phi)$

$$
\begin{aligned}
\mathcal{L} = & \sum_B \bar{\psi}_B \left[\gamma^\mu \left(i\partial_\mu - g_{\omega B}\omega_\mu - g_{\rho B}\boldsymbol{\rho}_\mu \boldsymbol{\tau}_B - g_{\phi B}\phi_\mu\right)\right. \\
& \left. - \left(M_B - g_{\sigma B}\sigma - g_{\delta B}\boldsymbol{\delta} - g_{\sigma^* B}\sigma^*\right)\right] \psi_B \\
& + \frac{1}{2}(\partial^\mu \sigma \partial_\mu \sigma - m_\sigma^2 \sigma^2) + \frac{1}{2}(\partial^\mu \sigma^* \partial_\mu \sigma^* - m_{\sigma^*}^2 \sigma^{*2}) + \frac{1}{2}(\partial^\mu \boldsymbol{\delta} \partial_\mu \boldsymbol{\delta} - m_\delta^2 \boldsymbol{\delta}^2) \\
& - \frac{1}{4} W^{\mu\nu} W_{\mu\nu} + \frac{1}{2} m_\omega^2 \omega^\mu \omega_\mu - \frac{1}{4} \boldsymbol{R}^{\mu\nu} \boldsymbol{R}_{\mu\nu} + \frac{1}{2} m_\rho^2 \boldsymbol{\rho}^\mu \boldsymbol{\rho}_\mu - \frac{1}{4} \Phi^{\mu\nu} \Phi_{\mu\nu} + \frac{1}{2} m_\phi^2 \phi^\mu \phi_\mu \\
& + \sum_l \bar{\psi}_l (i\gamma_\mu \partial^\mu - m_l) \psi_l,
\end{aligned}
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RMF model

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RMF model

NN interaction	DD-ME2
ρ_{sat} (fm^{-3})	0.152
E/A (MeV)	−16.14
K_0 (MeV)	250.89
m^*	0.572
a_4 (MeV)	32.3

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_NY_ and _YY_ interactions

$U_\Lambda^{(N)} \simeq -30$ MeV

$2U_\Lambda^{(\Lambda)} \simeq -10$ MeV

No *np* dUrca， *Λp* dUrca

$M_c^{\mathrm{DU}} = 1.3184 M_\odot$

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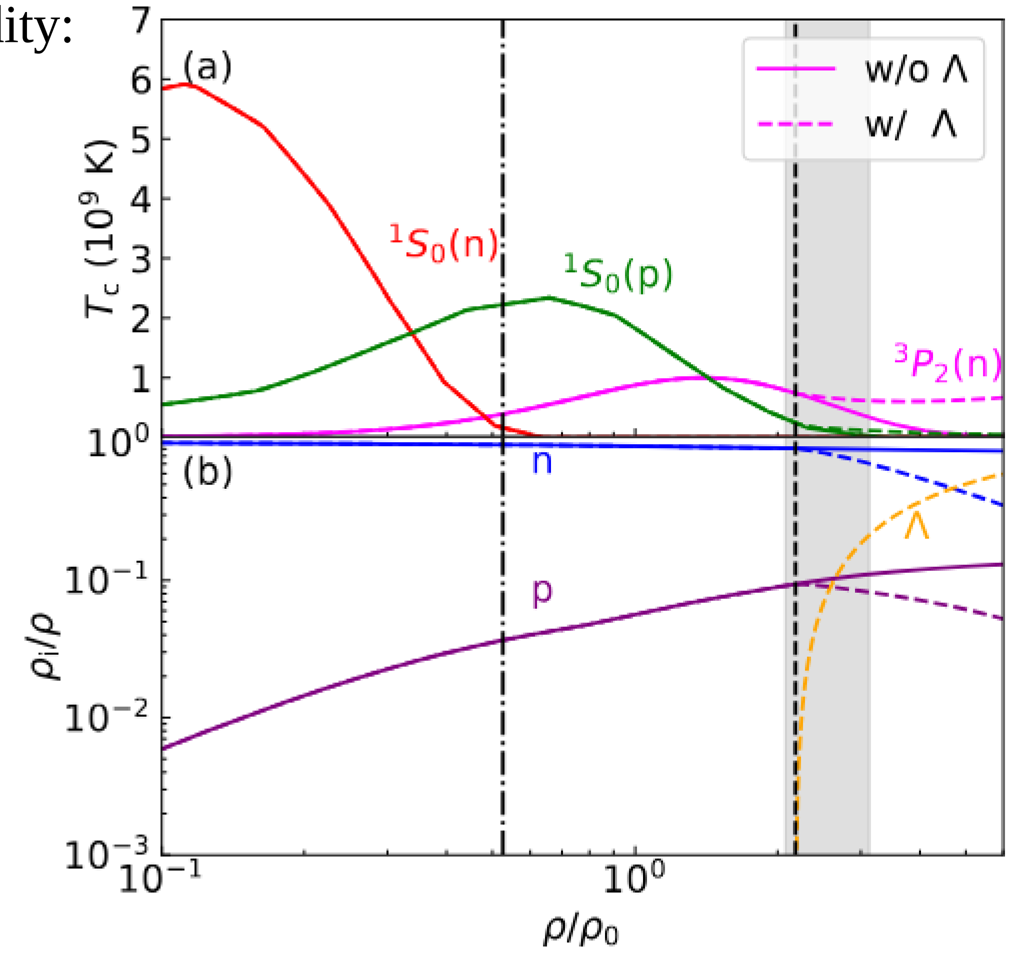
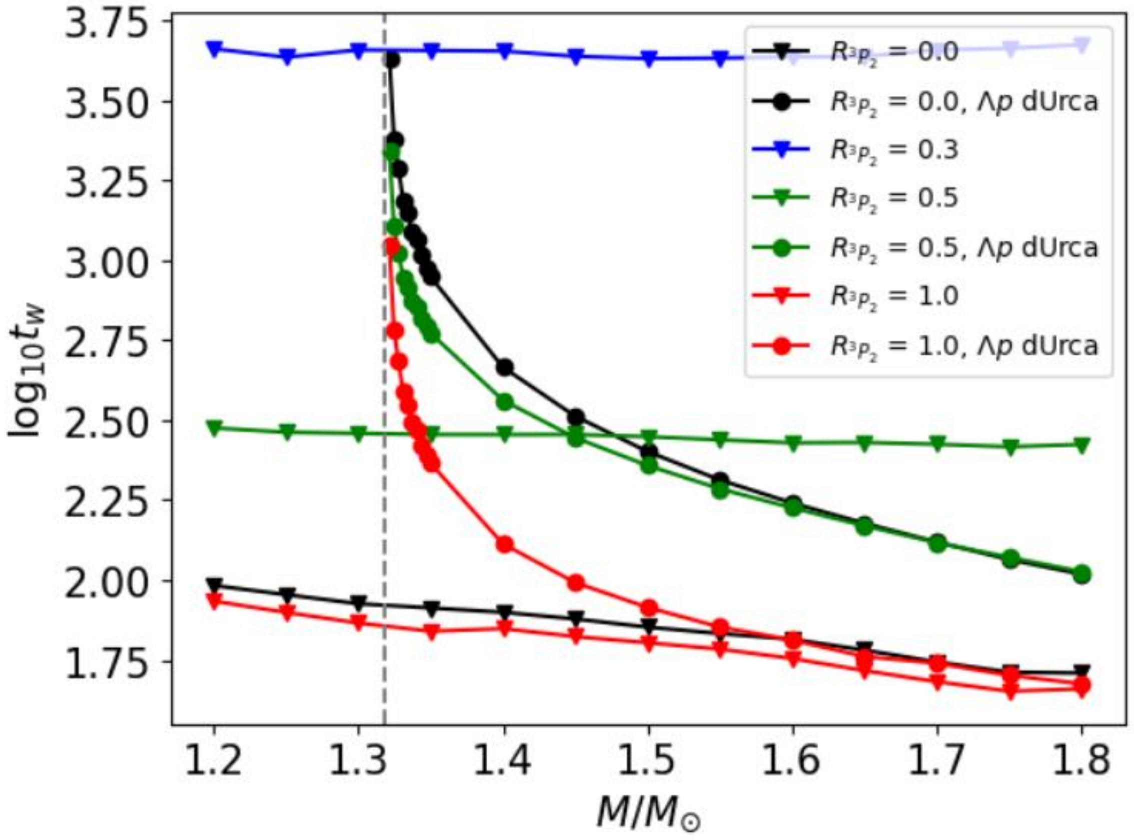
- Superfluidity:



$$T_{cn} = R_{^3P_2} T_{max}$$

Thermal Relaxation of Neutron Star



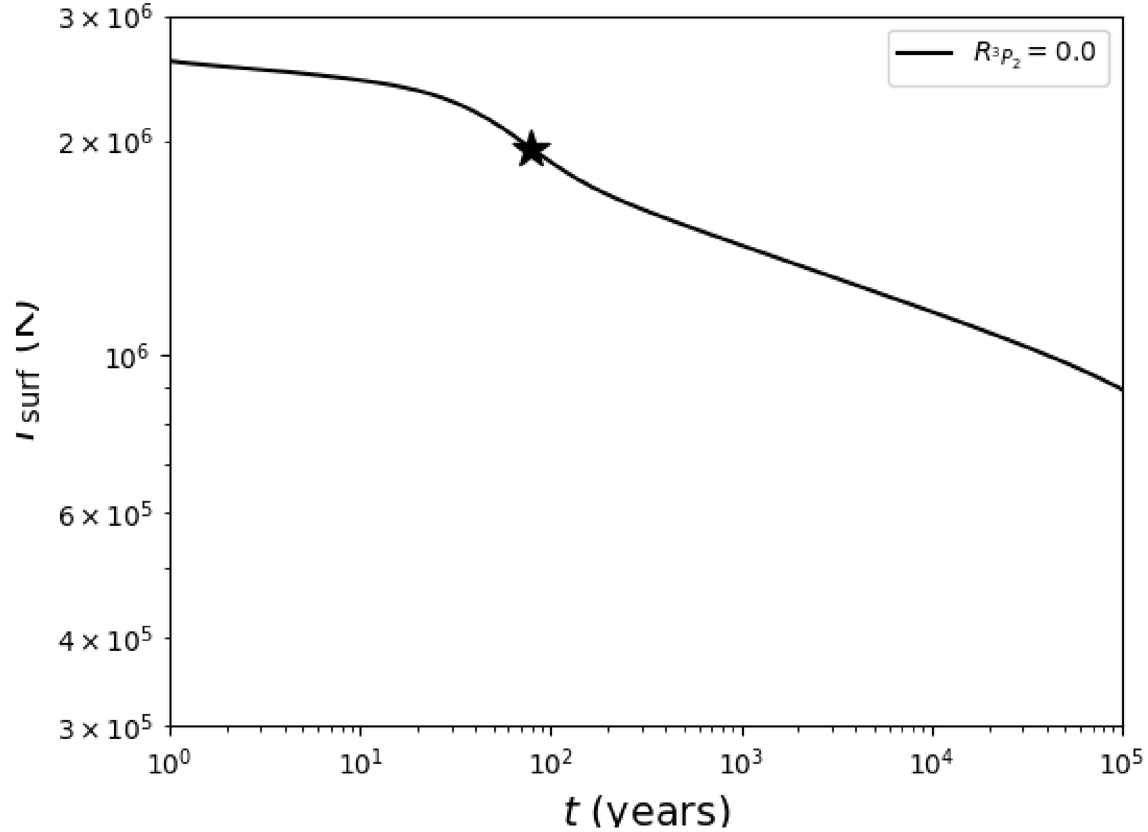
$$T_{\rm cn} = R_{^3P_2} T_{\rm max}$$

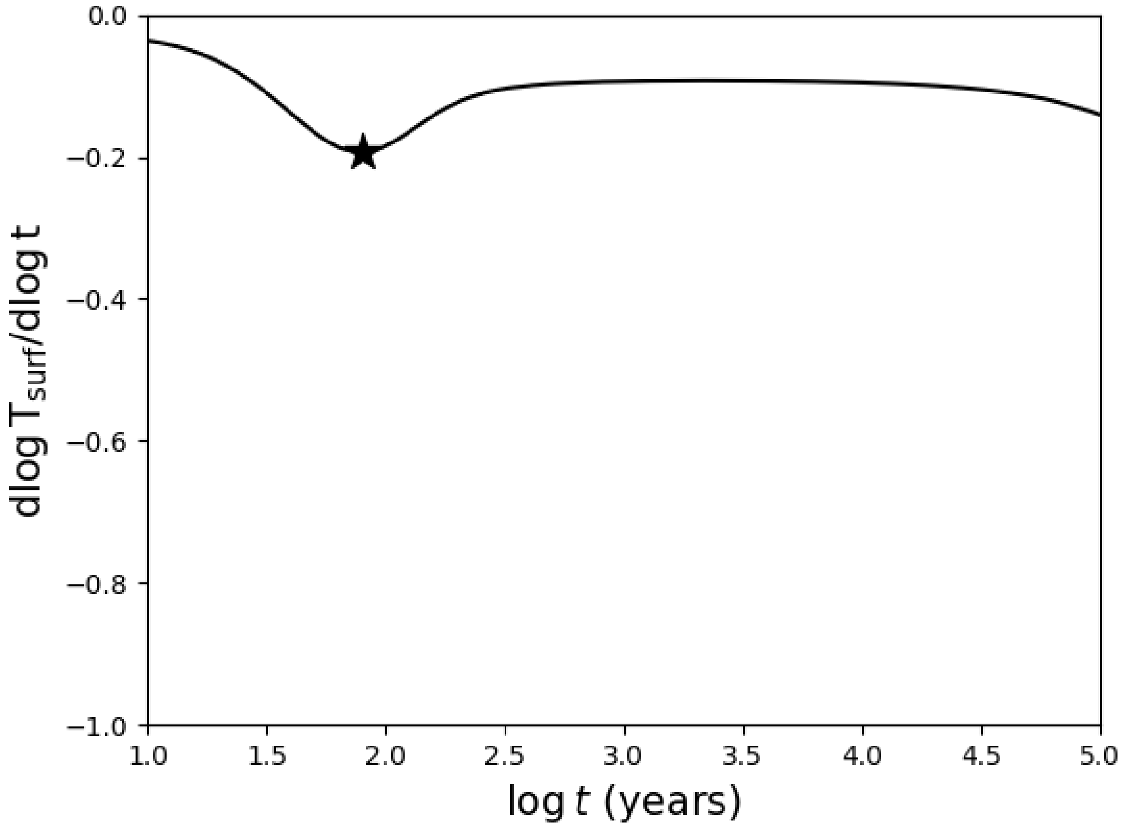
- Closing the dUrca, the dependence of t_w on mass is linear, while its dependence on the critical temperature is nonlinear;

- Above the mass that dUrca sets in, the dependences of t_w on both mass and critical temperature are nonlinear.

Contents

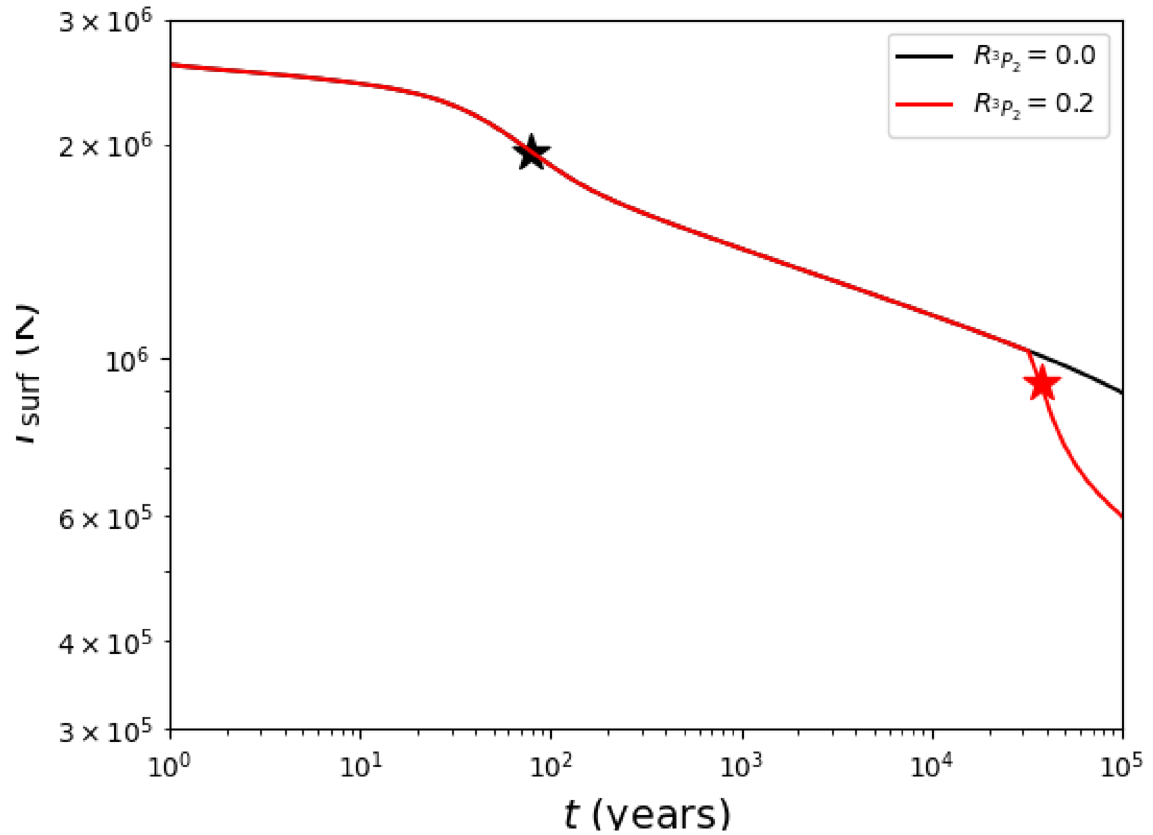
Peculiar Thermal Relaxation from Superfluidity

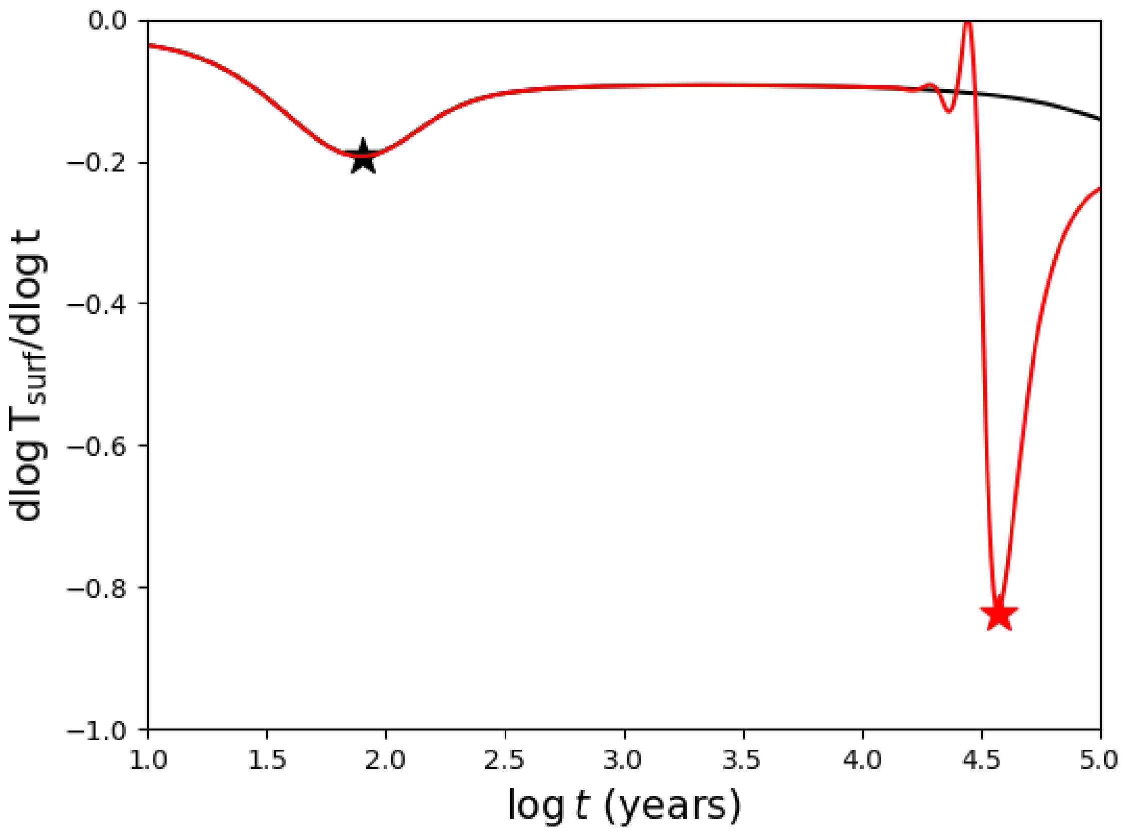




$$M = 1.4\ M_\odot$$

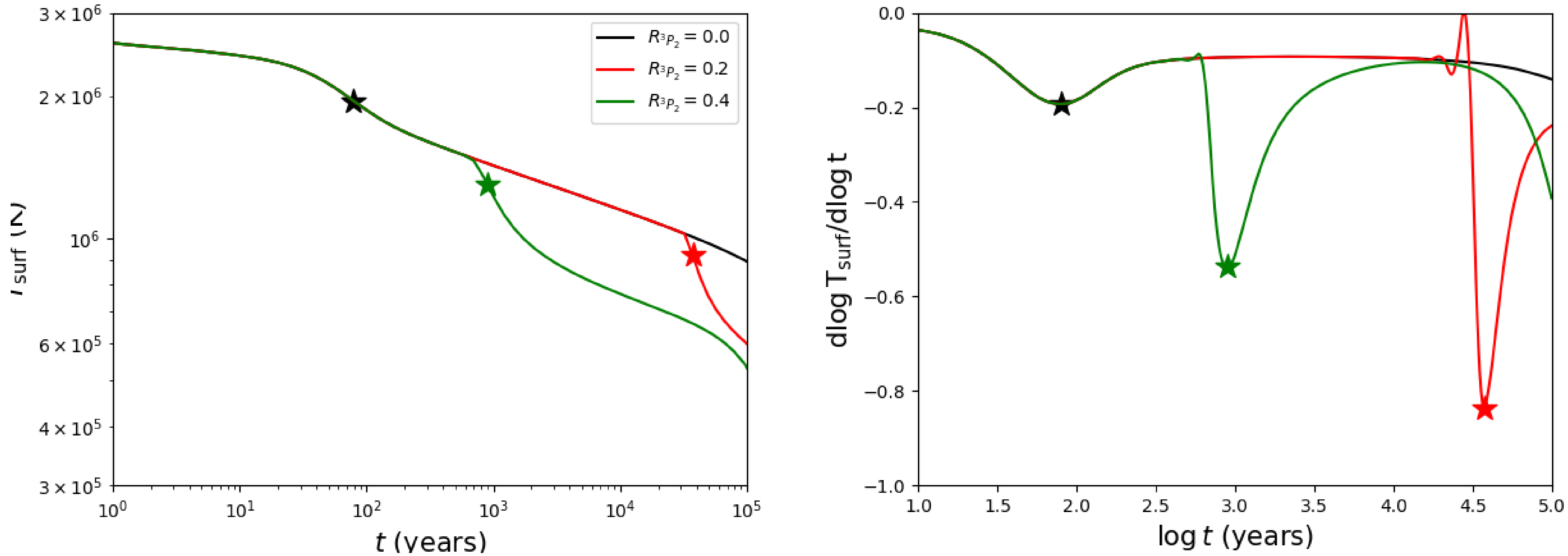
Peculiar Thermal Relaxation from Superfluidity





$M = 1.4\ M_\odot$

Peculiar Thermal Relaxation from Superfluidity



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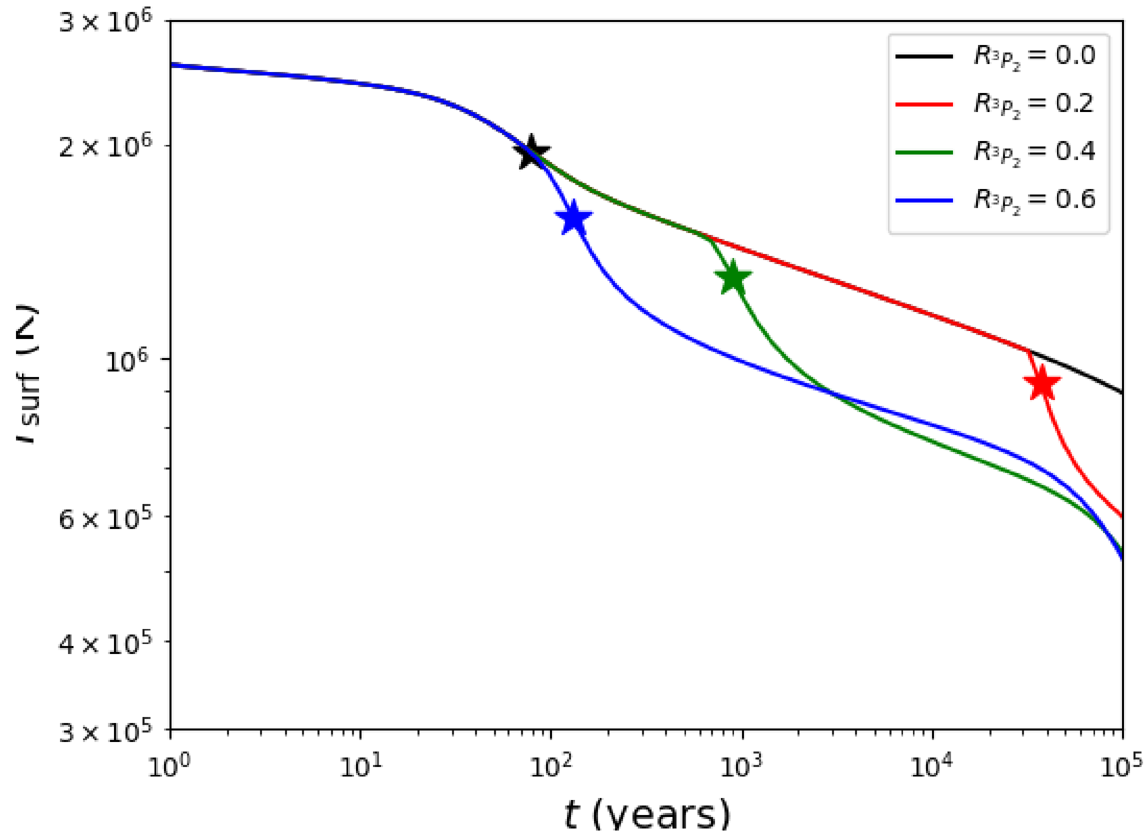

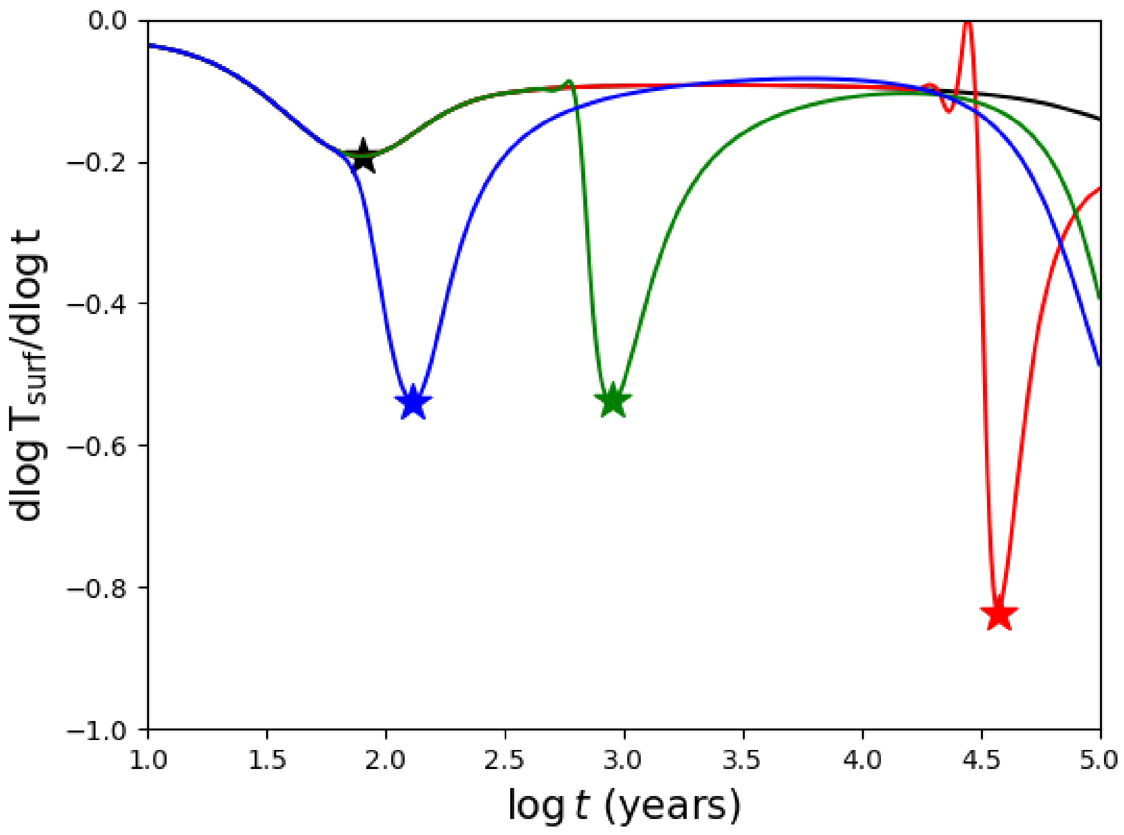

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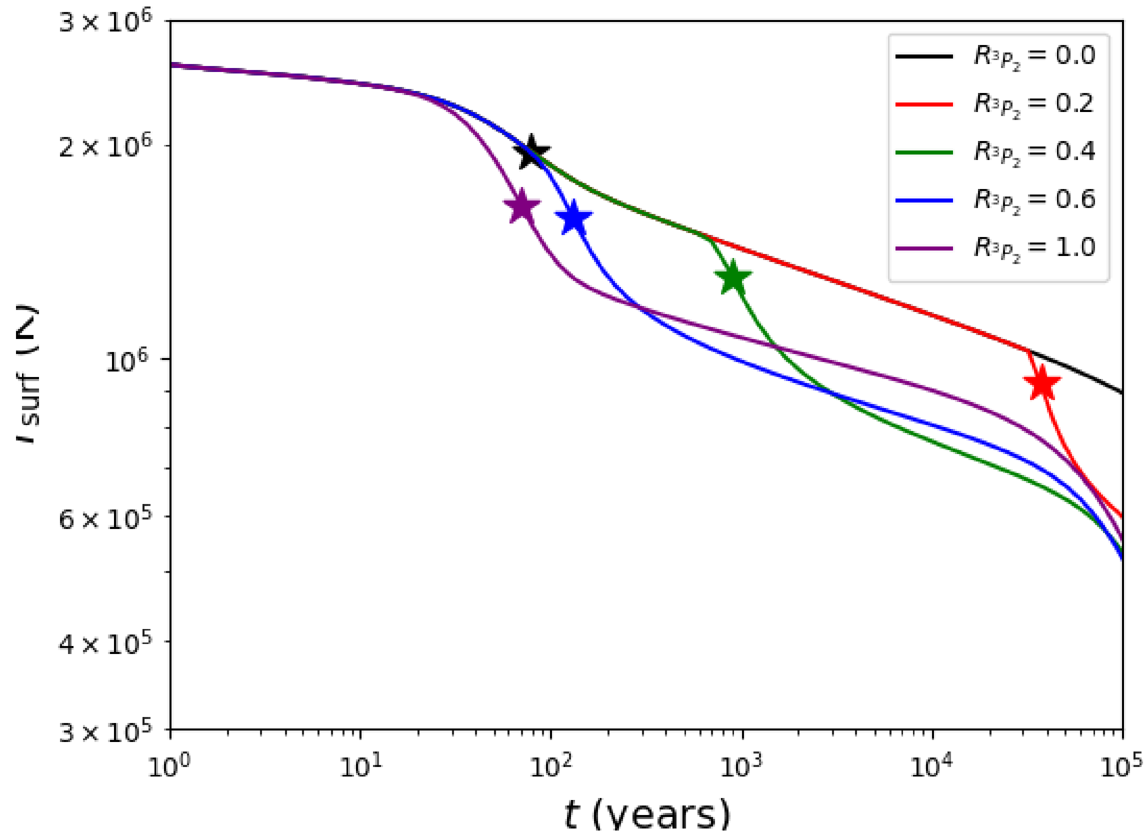

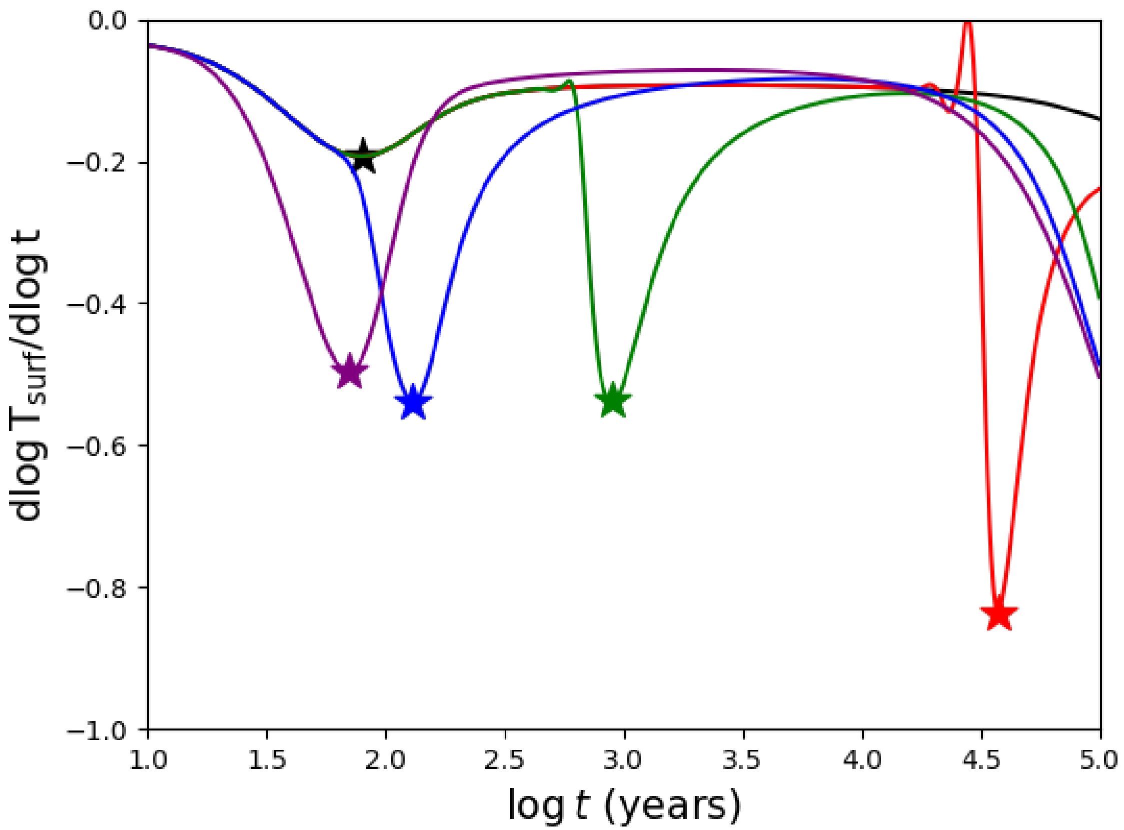

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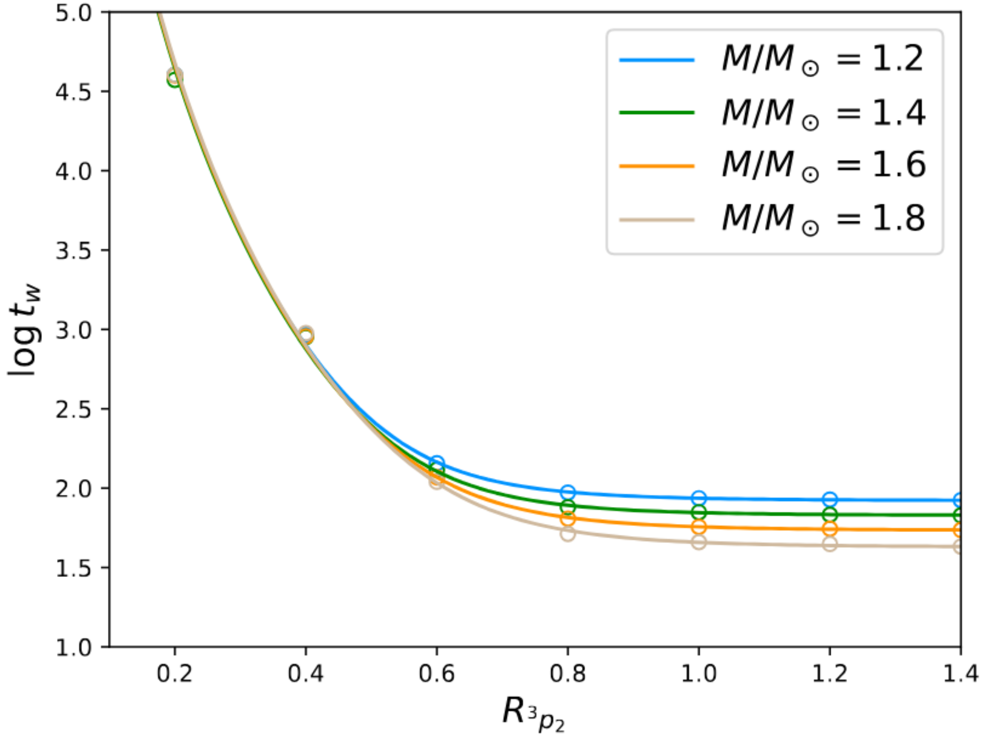

The smaller critical temperature T_{cn}, the longer relaxation time

The late trigger of PBF process: waiting time $t_{\rm wait}$

global energy balance: $$C_V \frac{dT}{dt} = -R_{\rm eff} L_\nu^{\rm mu}$$

$$C_V = C_9 T_9 \text{ with } C_9 \approx 10^{39} \text{ erg/K} \qquad C_V = \int c_v \mathrm{d}V$$

$$L_\nu^{\rm mu} = L_9 T_9^8 \text{ with } L_9 \approx 10^{40} \text{ erg/s} \qquad L_\nu = \int \epsilon \mathrm{d}V$$

$$T_9 = T/10^9 \text{ K}$$

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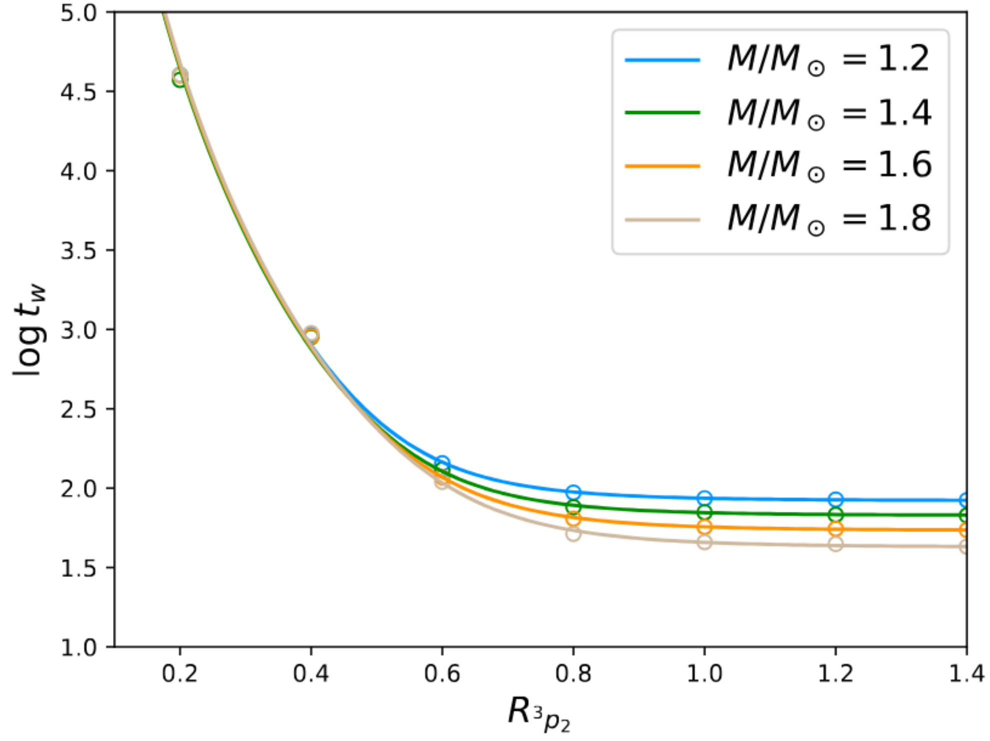
Peculiar Thermal Relaxation from Superfluidity



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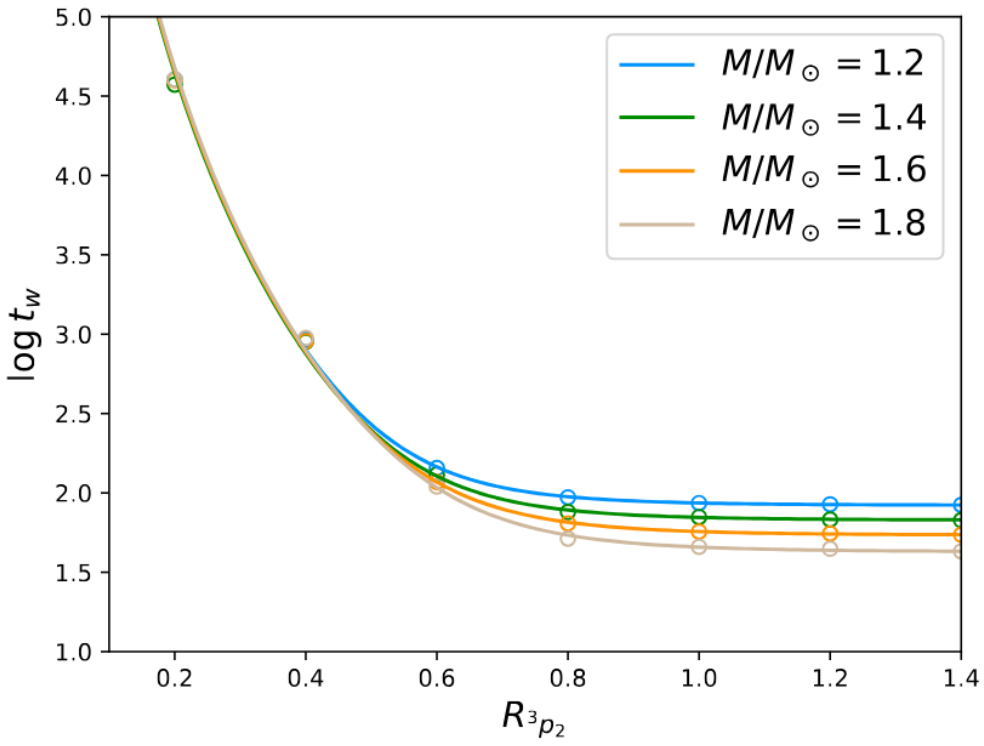
$$t(T) = \tau_{\rm mu}^{\rm eff} \left(\frac{1}{T_9^6} - \frac{1}{T_{0,9}^6} \right) \longrightarrow t_{\rm wait} = t(T_{\rm cn})$$

$$\tau_{\rm mu}^{\rm eff} = \tau_{\rm mu}/R_{\rm eff} \qquad \tau_{\rm mu} = 10^9 C_9/6L_9 \approx 1.0 \text{ year}$$

$\tau_{\rm mu}$: time-scale of mUrca dominated cooling
$R_{\rm eff}$: SF effective suppression factor

Peculiar Thermal Relaxation from Superfluidity



The smaller critical temperature T_{cn}, the longer relaxation time

The late trigger of PBF process: waiting time t_{wait}

$$t_{\mathrm{w}} \approx t_{\mathrm{wait}} + t_{\mathrm{w}}^{\mathrm{PBF}}$$

$$t_{\mathrm{w}} \approx \tau_{\mathrm{mu}}^{\mathrm{eff}} \left(\frac{1}{T_{\mathrm{cn},9}^6} - \frac{1}{T_{0,9}^6} \right) + \alpha t_1$$

re-coupling of core and crust

waiting for the trigger of PBF; nonlinear

Fitting:

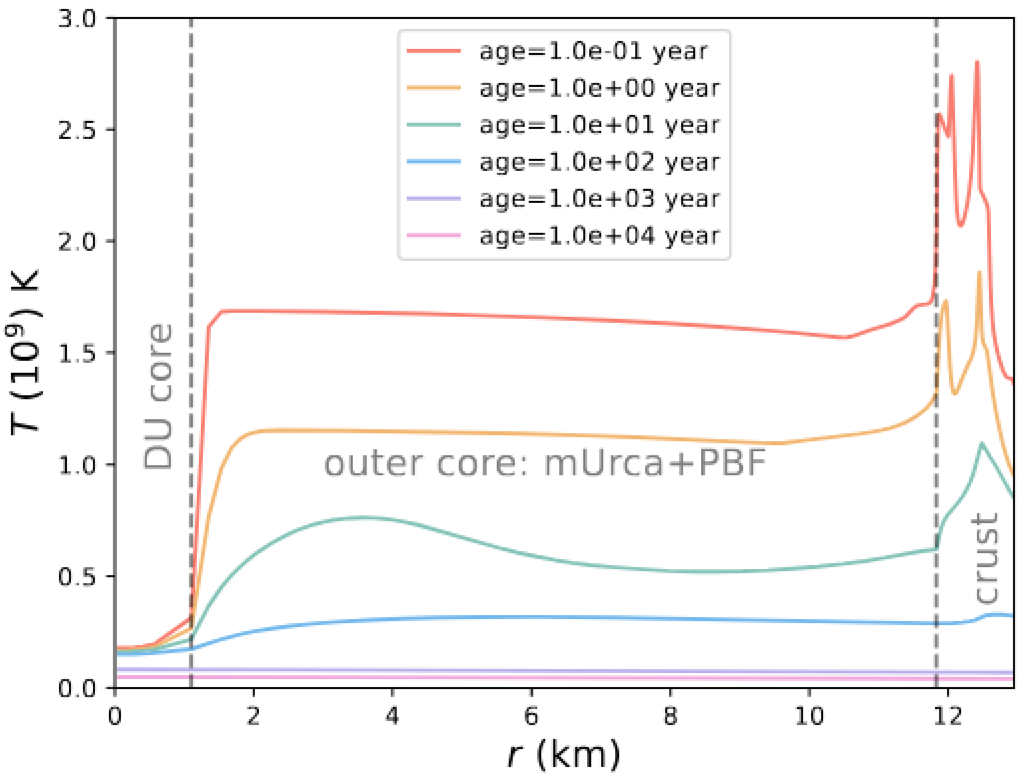
$\tau_{\mathrm{mu}}^{\mathrm{eff}}$ =2.8–3.0 years

t_1=30–37 years

Other interactions (NL3 and PKDD) give the similar results: **Model-independent.**

Contents

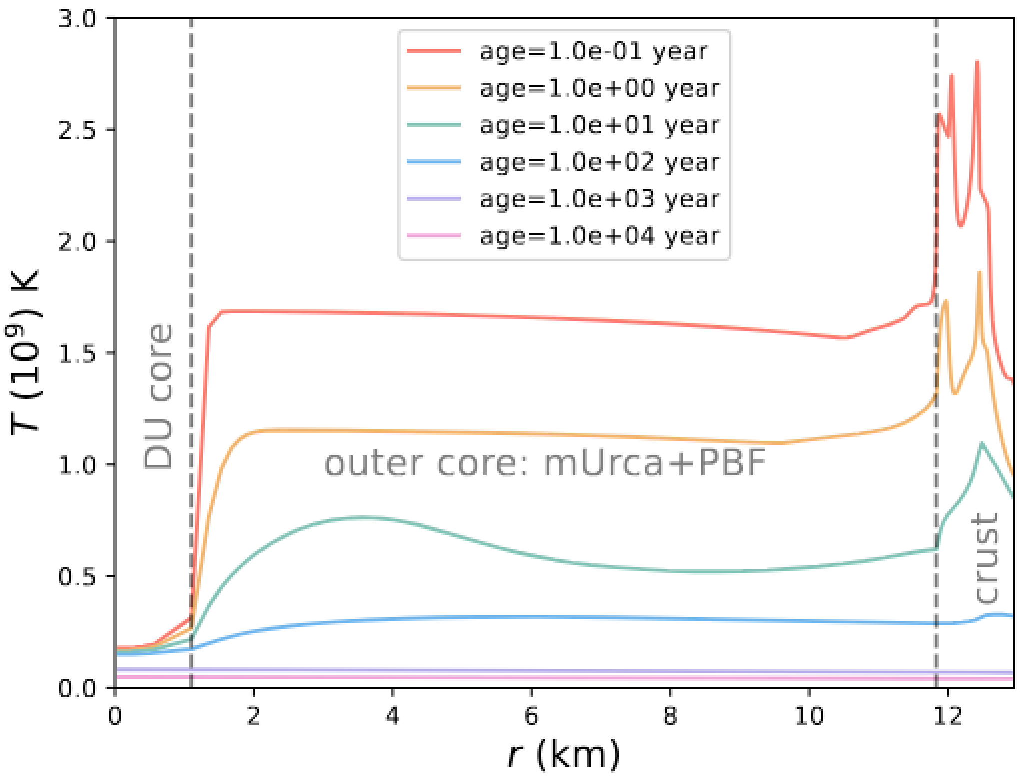
Peculiar Thermal Relaxation of Hyperon Star



Neutron star with $M = 1.3310 M_{\odot}$ and a ***very small*** DU core

- DU core:
  - dUrca process, **Low temperature**;
- outer core:
  - mUrca + PBF process;

Peculiar Thermal Relaxation of Hyperon Star



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- DU core:
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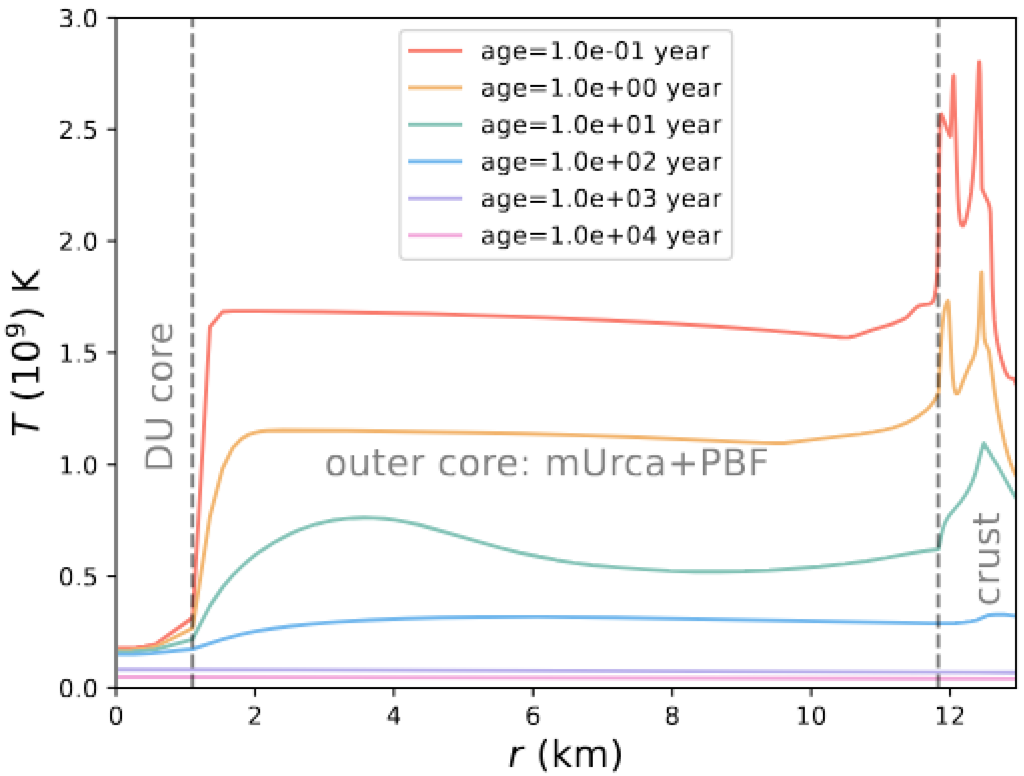
  - Thermal compensation to the DU core.

Peculiar Thermal Relaxation of Hyperon Star

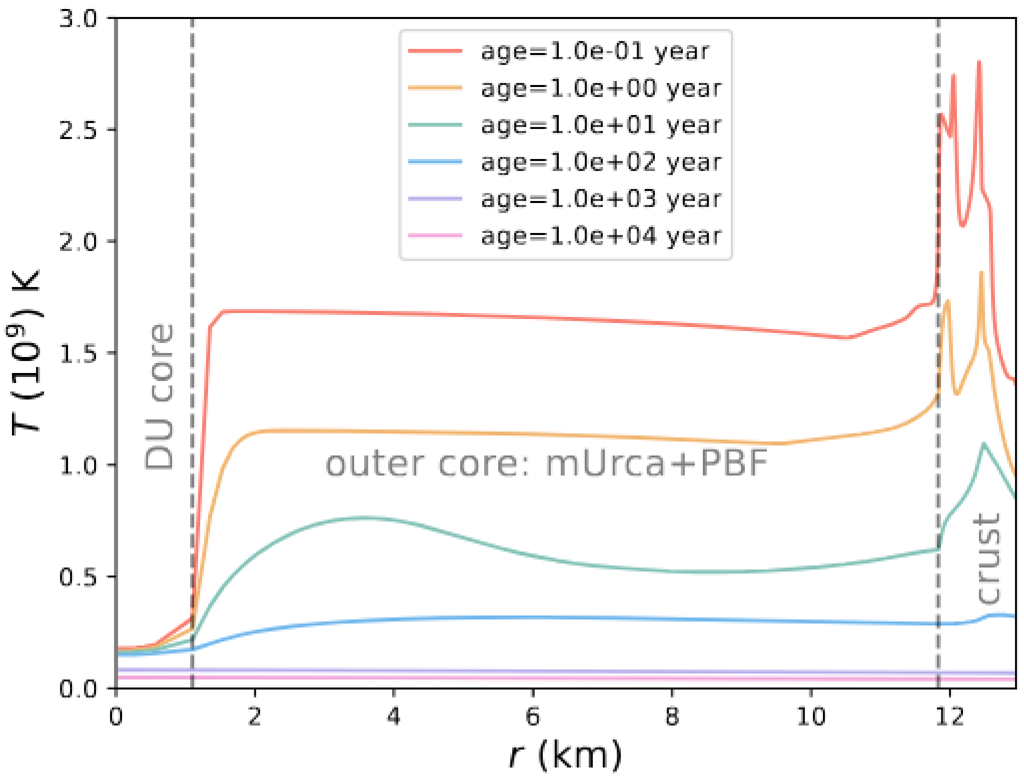


Neutron star with $M = 1.3310 M_{\odot}$ and a ***very small*** DU core

- DU core:
  - dUrca process, **Low temperature;**
  - the temperature is nearly ***constant*** if the DU core is very small.
- outer core:
  - mUrca + PBF process;
  - Thermal compensation to the DU core.

→ thermal coupling between DU core and outer core

Peculiar Thermal Relaxation of Hyperon Star



Neutron star with $M = 1.3310 M_\odot$ and a ***very small*** DU core

The thermal coupling between DU core and outer core:

Outer core energy balance

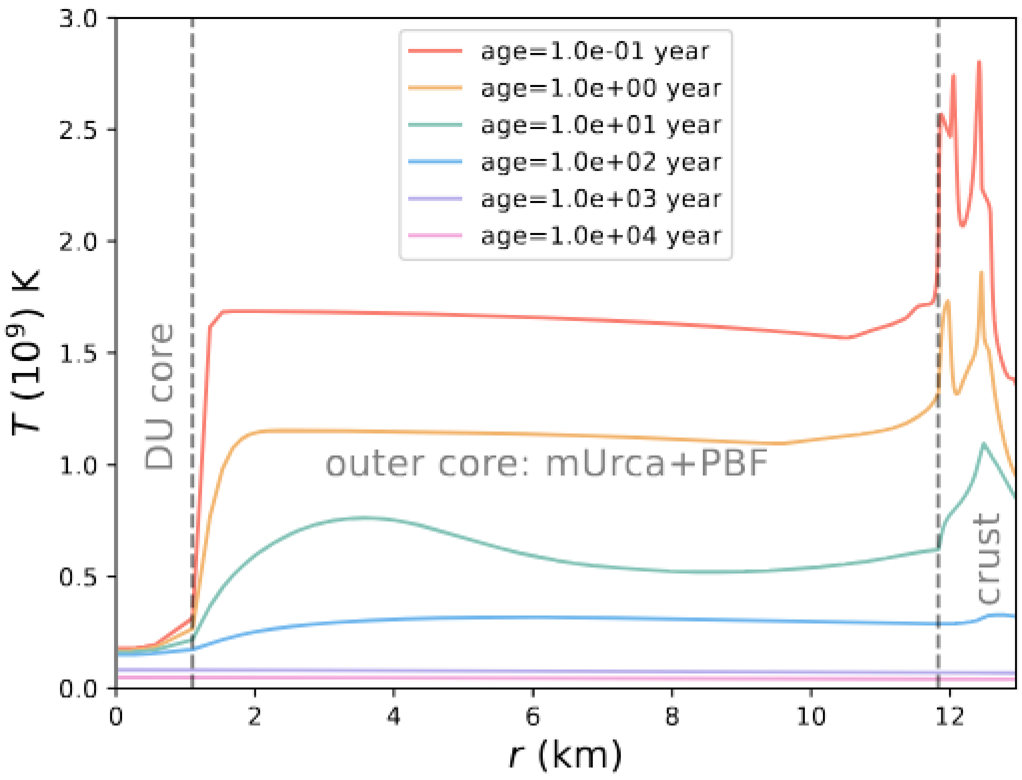
$$C_V \frac{dT}{dt} = -R_{\rm eff} L_\nu^{\rm mu} \theta(T - T_{\rm cn}) \quad \text{mUrca}$$

$$- f_{\rm PBF} L_\nu^{\rm mu} \theta(T_{\rm cn} - T) \quad \text{mUrca+PBF}$$

$$- R f_{\rm DU} L_\nu^{\rm mu} T_{\rm DU}^8 / f_V \quad \text{DU core energy loss}$$

$T_{\rm DU}$: DU core temperature before reaching relaxation
$f_{\rm DU}$: ratio of neutrino emissivity of dUrca to mUrca
f_V: ratio of the outer core volume to DU core
R: ratio of neutrino emissivity of Λp to np dUrca, ~ 0.04

Peculiar Thermal Relaxation of Hyperon Star

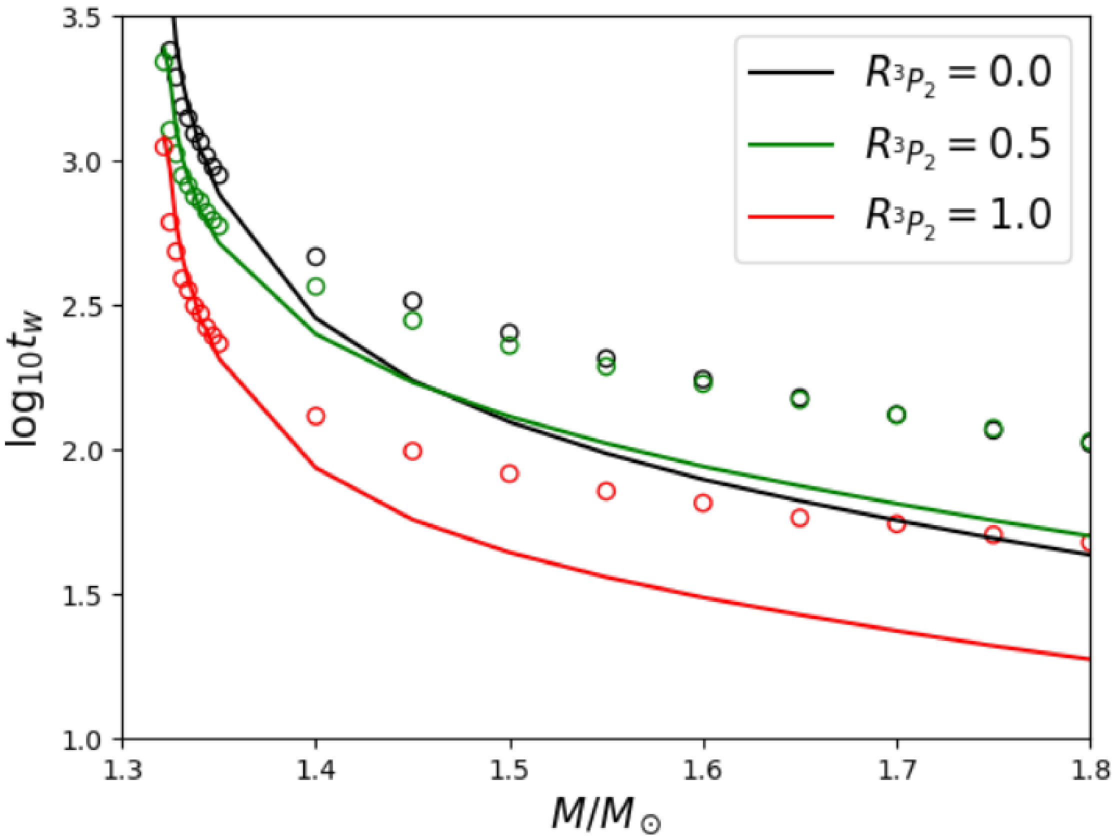


The thermal coupling between DU core and outer core:

DU core energy balance

$$C_V \frac{dT}{dt} = 0$$

Peculiar Thermal Relaxation of Hyperon Star



The thermal coupling between DU core and outer core:

$$t_w \approx -\frac{6\tau_{\rm mu}}{R_{\rm eff}} \int_{T_0}^{T_{\rm cn}} \frac{T_9}{T_9^8 + a_1} dT_9 - \frac{6\tau_{\rm mu}}{f_{\rm PBF}} \int_{T_{\rm cn}}^{T_{\rm t}} \frac{T_9}{T_9^8 + a_2} dT_9 + \alpha t_2$$

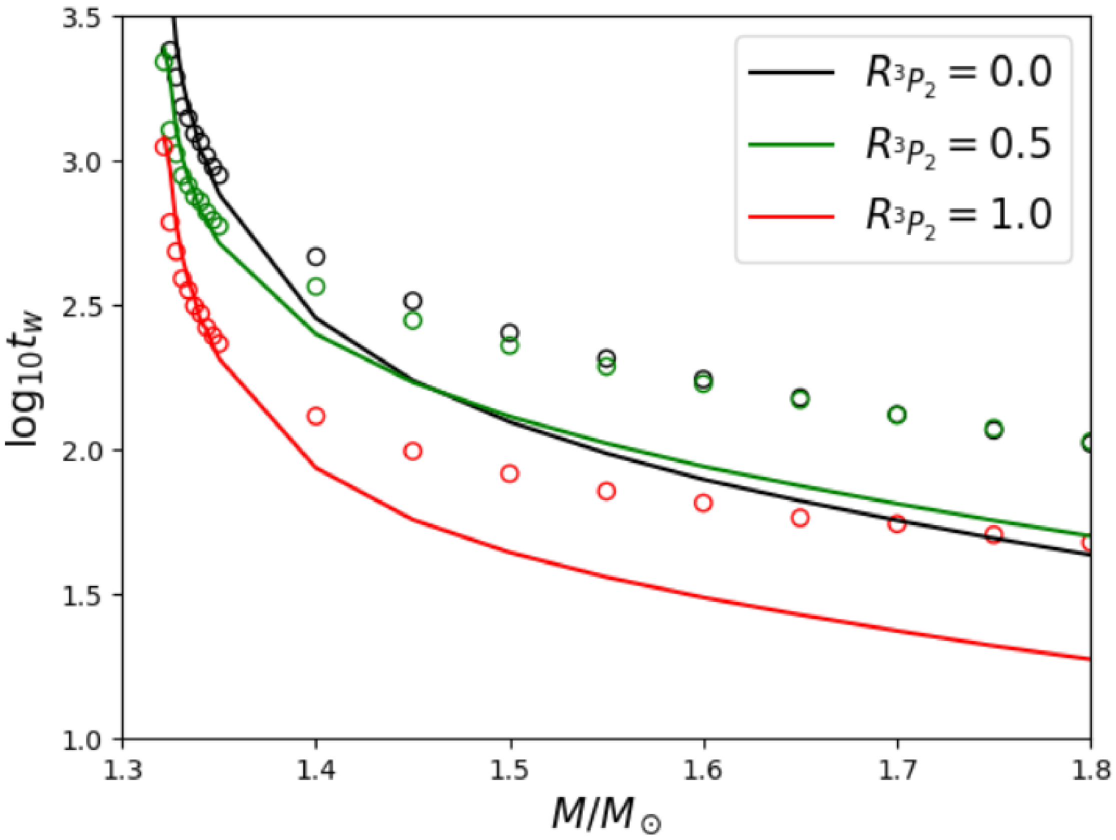
coupling of DU core and outer core (first two terms)

coupling of entire core and crust ($+\alpha t_2$)

$T_{\rm t}$: the outer core temperature that reaching relaxation

$T_{\rm t} \approx T_{\rm DU}$ for a neutron star with a very small DU core

Peculiar Thermal Relaxation of Hyperon Star



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coupling of DU core and outer core

coupling of entire core and crust

$$a_1 = \frac{R f_{\rm DU} T_{\rm DU,9}^6 / R_{\rm eff}}{[(R_{\rm core}/R_{\rm DU})^3 - 1]}, \quad a_2 = \frac{R f_{\rm DU} T_{\rm DU,9}^6 / f_{\rm PBF}}{[(R_{\rm core}/R_{\rm DU})^3 - 1]}$$

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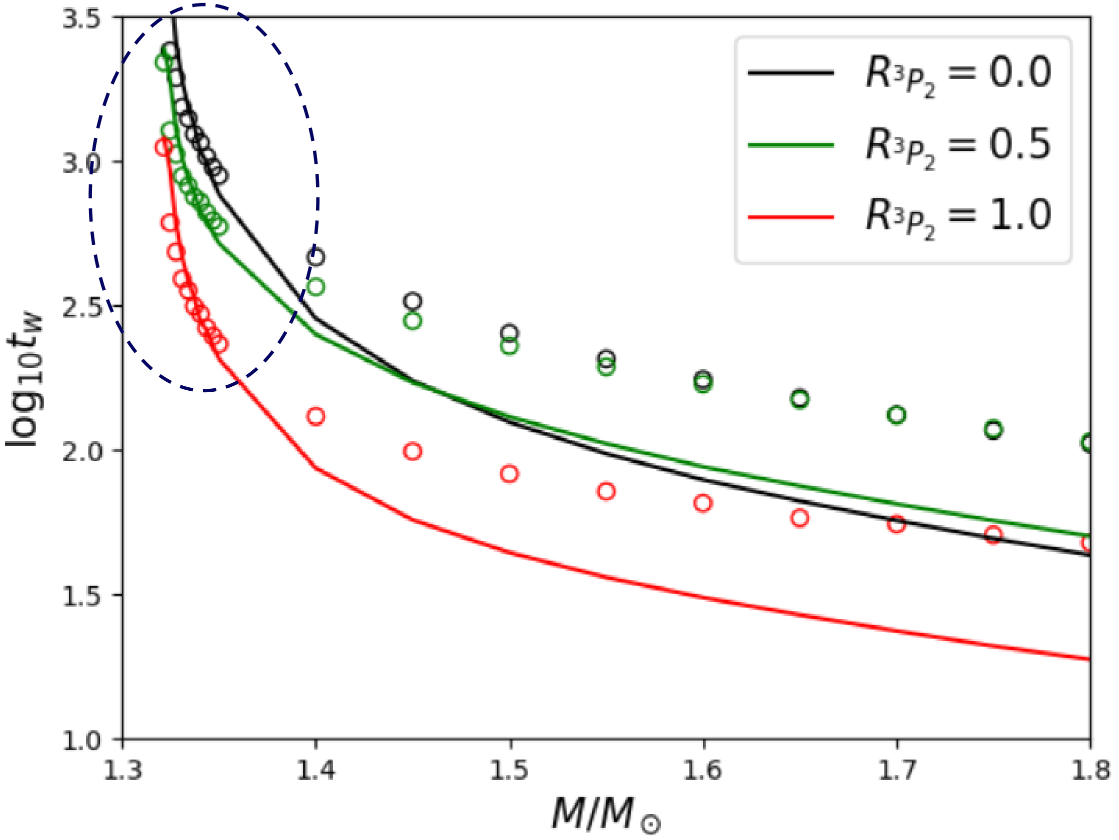

- Suitable for a neutron star with a small DU core

The thermal coupling between DU core and outer core:

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Contents

Summary and Perspective

- **Summary:**
  - PBF and dUrca processes change the thermodynamic structure of neutron stars, leading to the re-coupling of the crust and core and peculiar relaxation times.
  - A possible way to probe the superfluidity and internal thermal properties of neutron stars.

- **Perspective:**
  - More precise microscopic physical inputs for neutron stars are needed.
  - Suitable observation targets are required.

Thanks for your attention!