A NEW APPROACH TO THE THERMAL EVOLUTION OF NEUTRON STARS

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ACKNOWLEDGMENTS

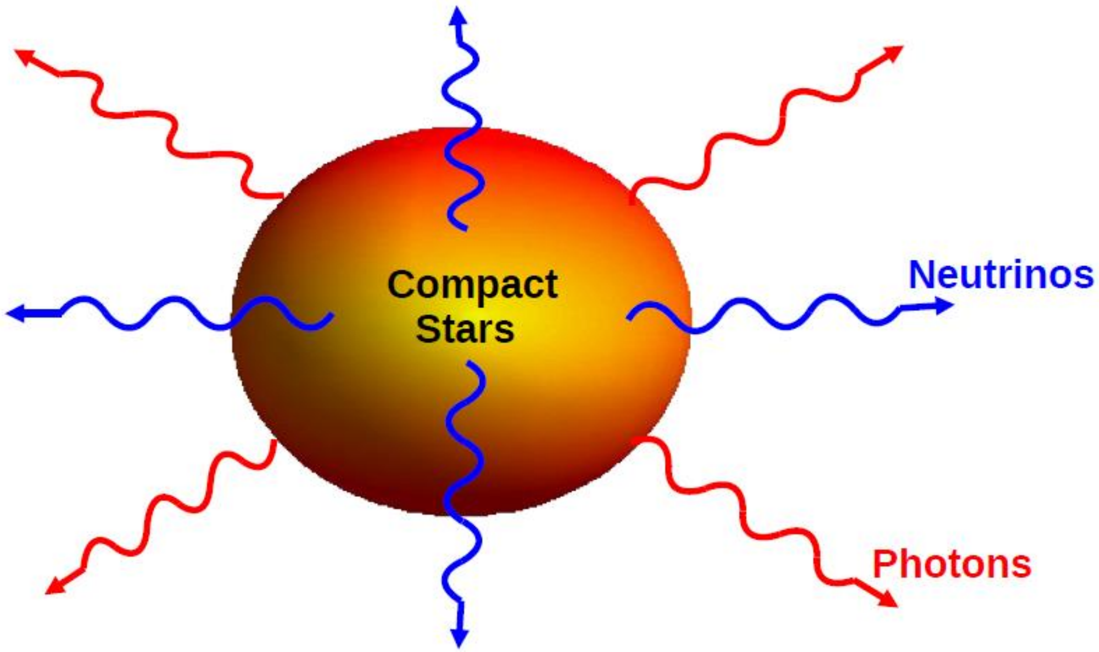
- CAPES
- CNPq
- Manuel Malheiro (!!)
- Organizes

INTRODUCTION

- Thermal evolution is driven by neutrino emissions from the core, and photon emission from the surface.

- Neutrino emissions strongly depend on the core composition.

- Depending on its mass, a neutron star may exhibit fast or slow cooling.

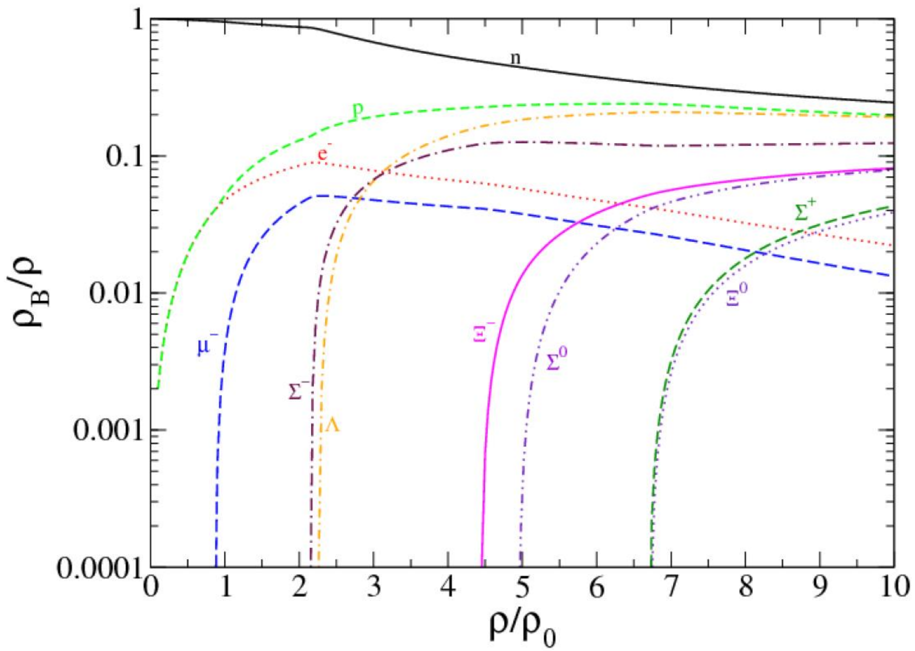


$T \approx 10^{10} K$

$$P = P(\rho, T = 0, \Omega = 0)$$

$$M = M(\rho, T = 0, \Omega = 0)$$

$$R = R(\rho, T = 0, \Omega = 0)$$



$$\varepsilon = \varepsilon(\rho, T)$$

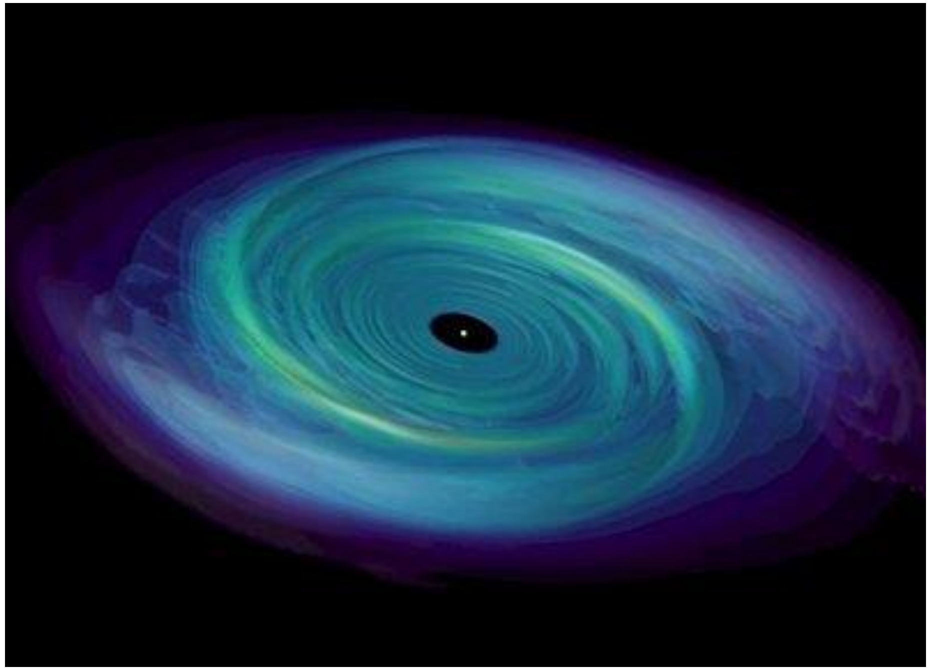
$$K = K(\rho, T)$$

$$c_v = c_v(\rho, T)$$

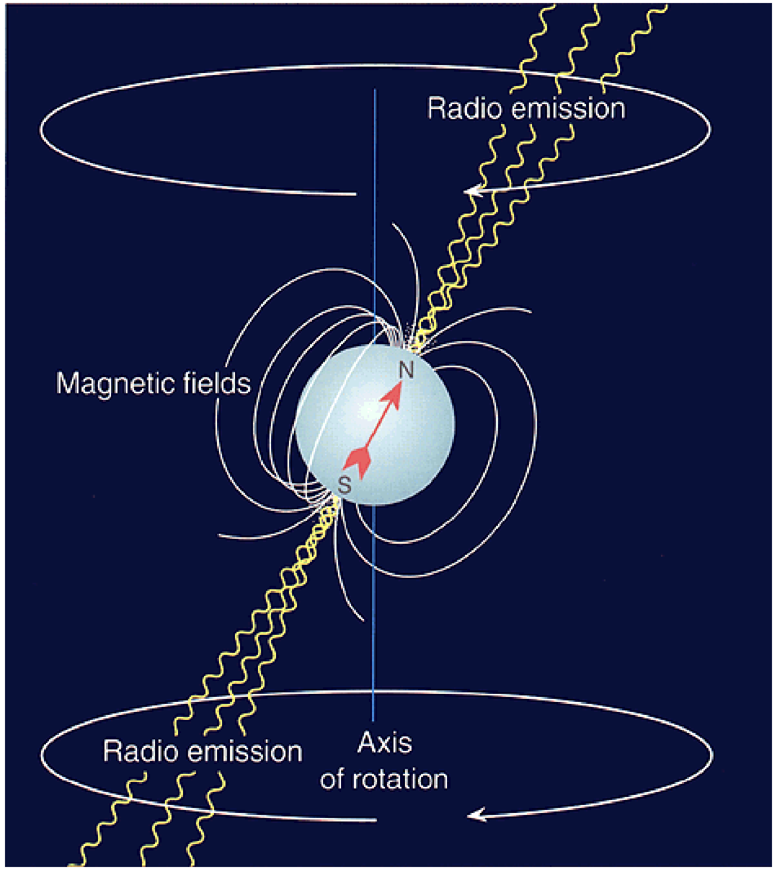
TRADITIONAL PICTURE

- Structure and composition frozen in time - "Frozen In"
- Thermal properties only change due to temperature evolution
- Dynamic => TEMPERATURE (ONLY !!)

STRUCTURE/COMPOSITION MAY NOT BE STATIC



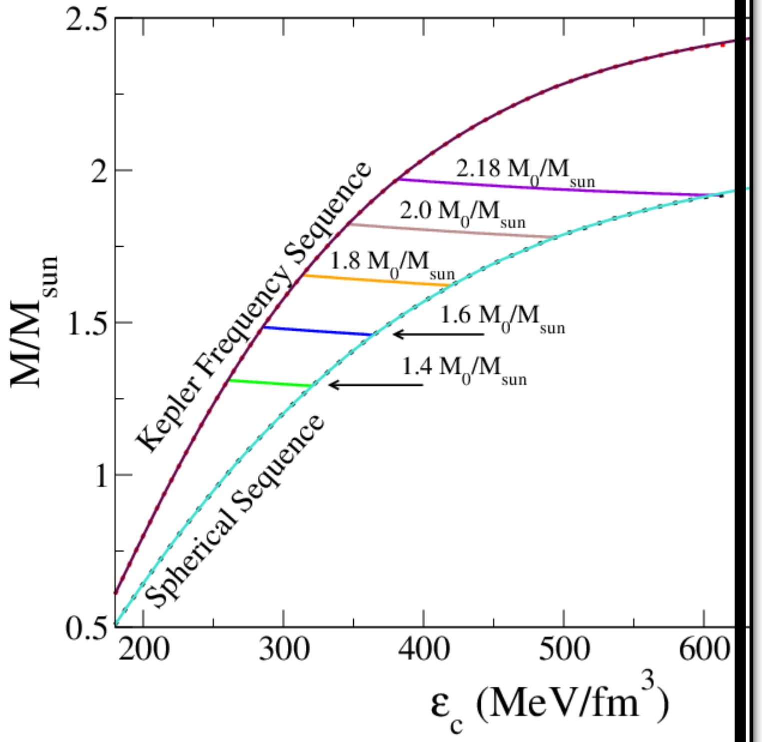
Accretion

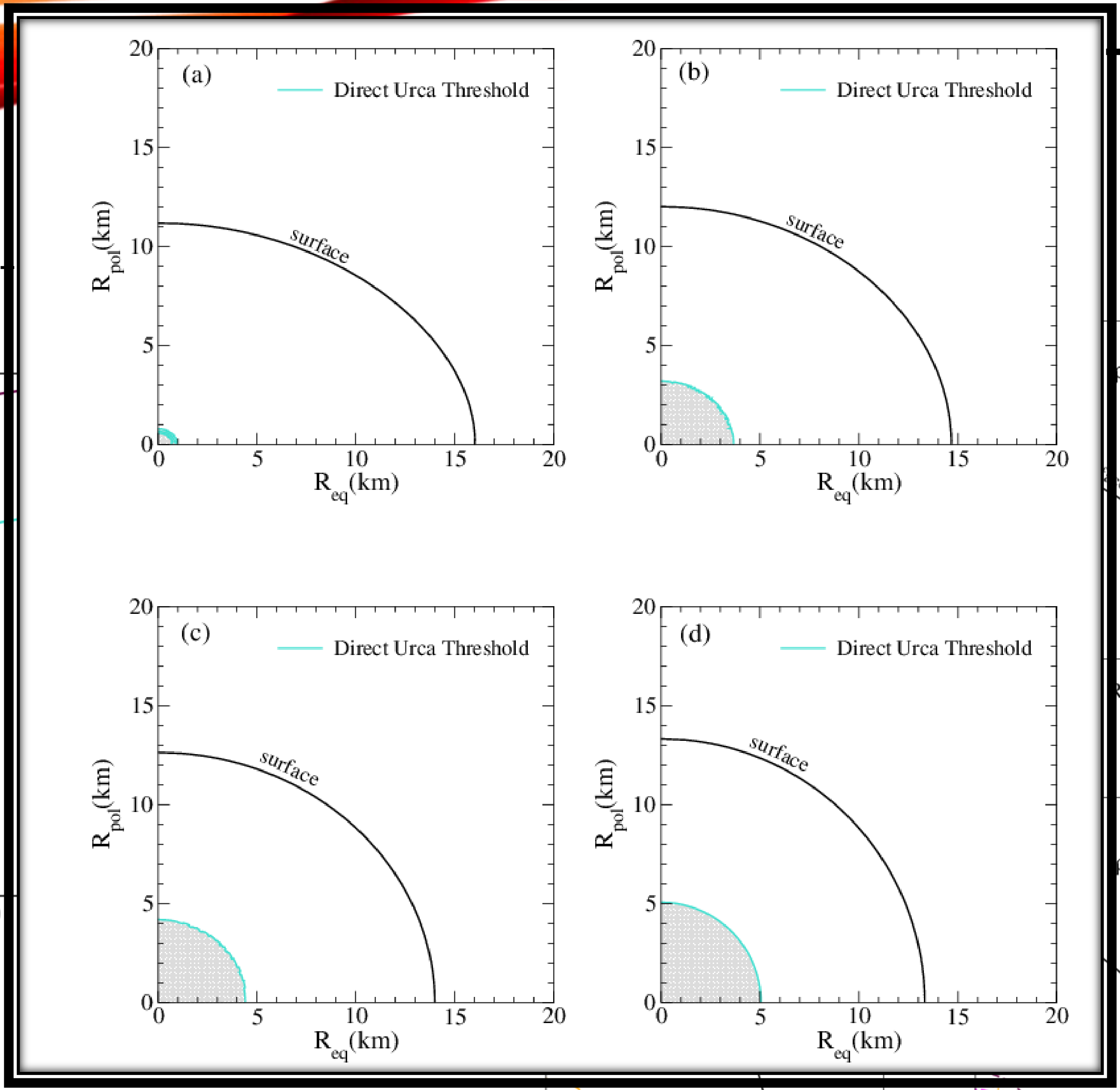


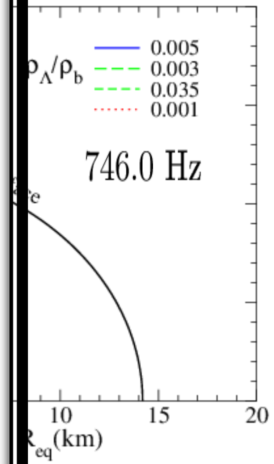
Magnetic/Spin evolution

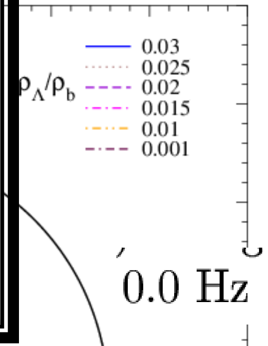
TUDIES

- Structure and Composi





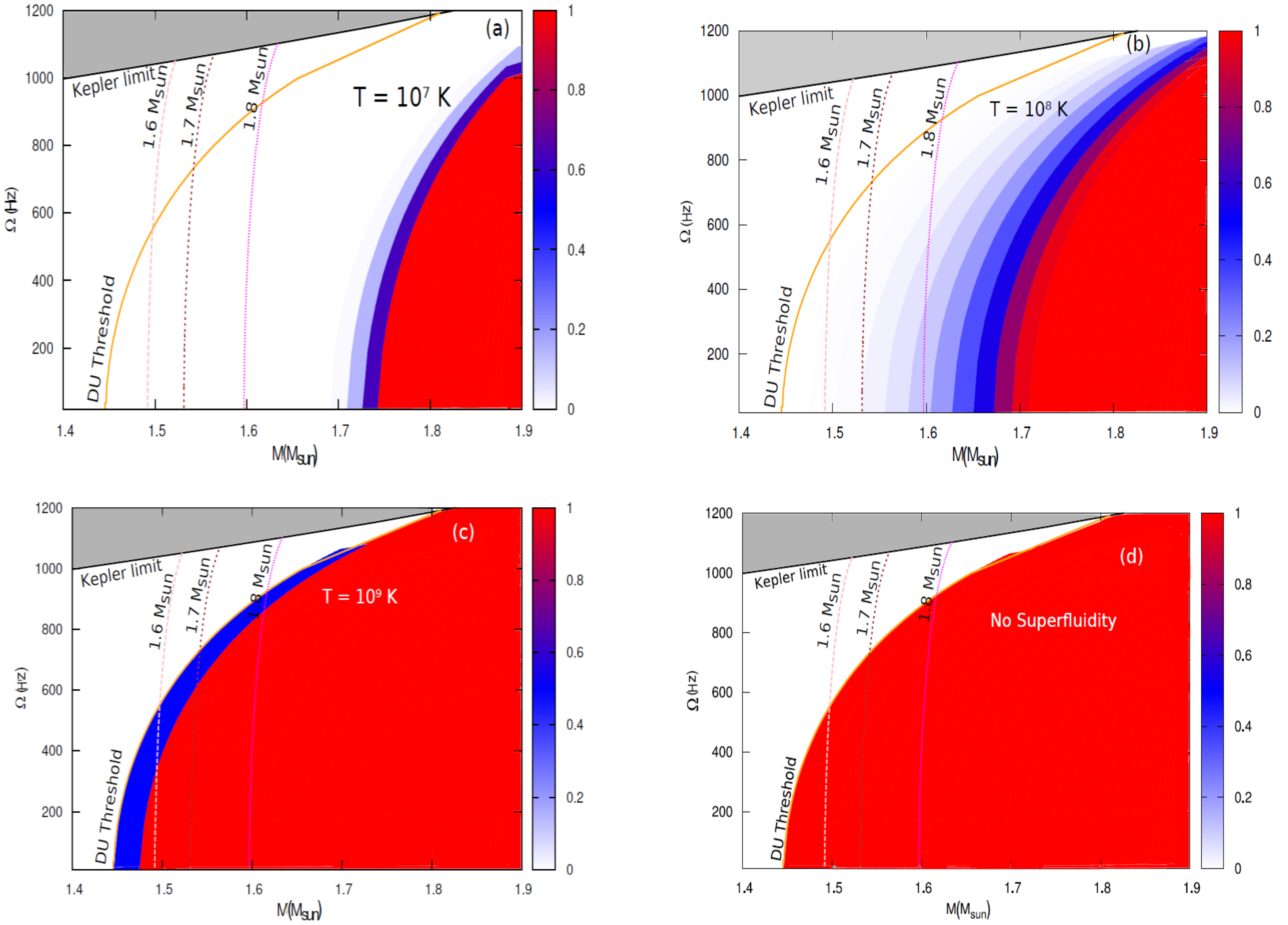




Modeling Hybrid Stars with an SU(3) non-linear sigma model
Rodrigo Negreiros (Frankfurt U.), V.A. Dexheimer (Gettysburg Coll.), S. Schramm (Frankfurt U., FIAS). Jun 2010.
Published in **Phys.Rev. C82 (2010) 035803**

PREVIOUS STUDIES

- Direct Urca and superfluidity

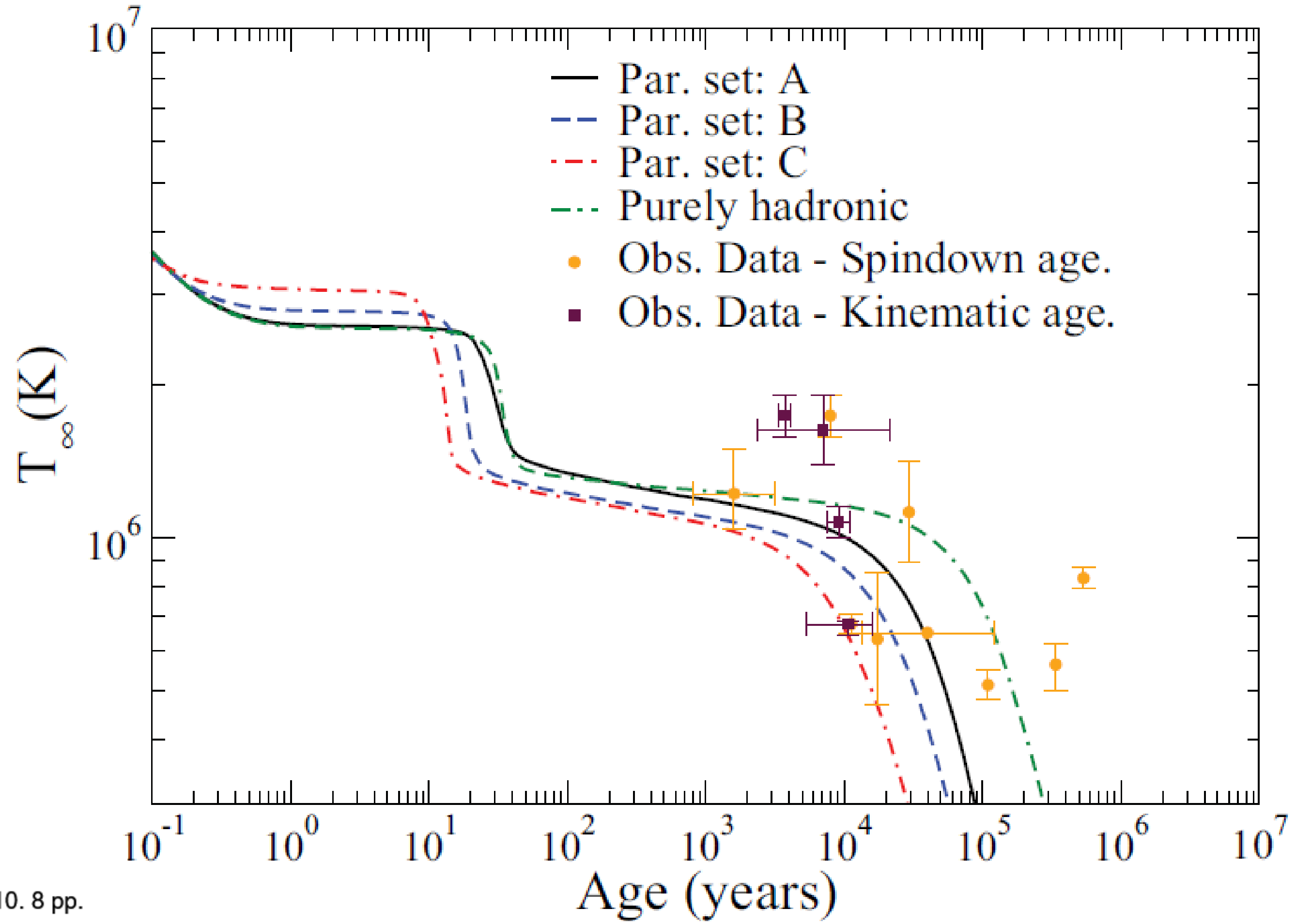


Impact of Rotation-Driven Particle Repopulation on the Thermal Evolution of Pulsars
Rodrigo Negreiros, Stefan Schramm, Fridolin Weber. Mar 2011. 4 pp.
Published in Phys.Lett. B718 (2013) 1176-1180

PREVIOUS STUDIES

- Quark core impact

Parameter set	M_q/M	R_q (km)	R (km)	M ($M_\odot$)
A	0.48	8.28	13.26	1.33
	0.60	9.14	13.15	1.55
B	0.62	8.21	12.20	1.33
	0.74	8.86	11.82	1.55
C	0.82	8.21	10.89	1.33
	0.89	8.29	10.03	1.55



Quark core impact on hybrid star cooling
Rodrigo Negreiros (Frankfurt U.), V.A. Dexheimer (Gettysburg Coll.), S. Schramm (Frankfurt U.). Nov 2010. 8 pp.
Published in **Phys.Rev. C85 (2012) 035805**

A NEW APPROACH

- Consider a dynamic structure and composition.

- Go beyond spherically symmetric stars.

$$P = P(\rho, T = 0, \Omega = 0)$$

$$M = M(\rho, T = 0, \Omega = 0)$$

$$R = R(\rho, T = 0, \Omega = 0)$$

$$\varepsilon = \varepsilon(\rho, T)$$

$$K = K(\rho, T)$$

$$c_v = c_v(\rho, T)$$

→

$$P = P(\rho, T = 0, \Omega(t), B(t))$$

$$M = M(\rho, T = 0, \Omega(t), B(t))$$

$$R = R(\rho, T = 0, \Omega(t), B(t))$$

$$\varepsilon = \varepsilon(\rho, T, \Omega(t), B(t))$$

$$K = K(\rho, T, \Omega(t), B(t))$$

$$c_v = c_v(\rho, T, \Omega(t), B(t))$$

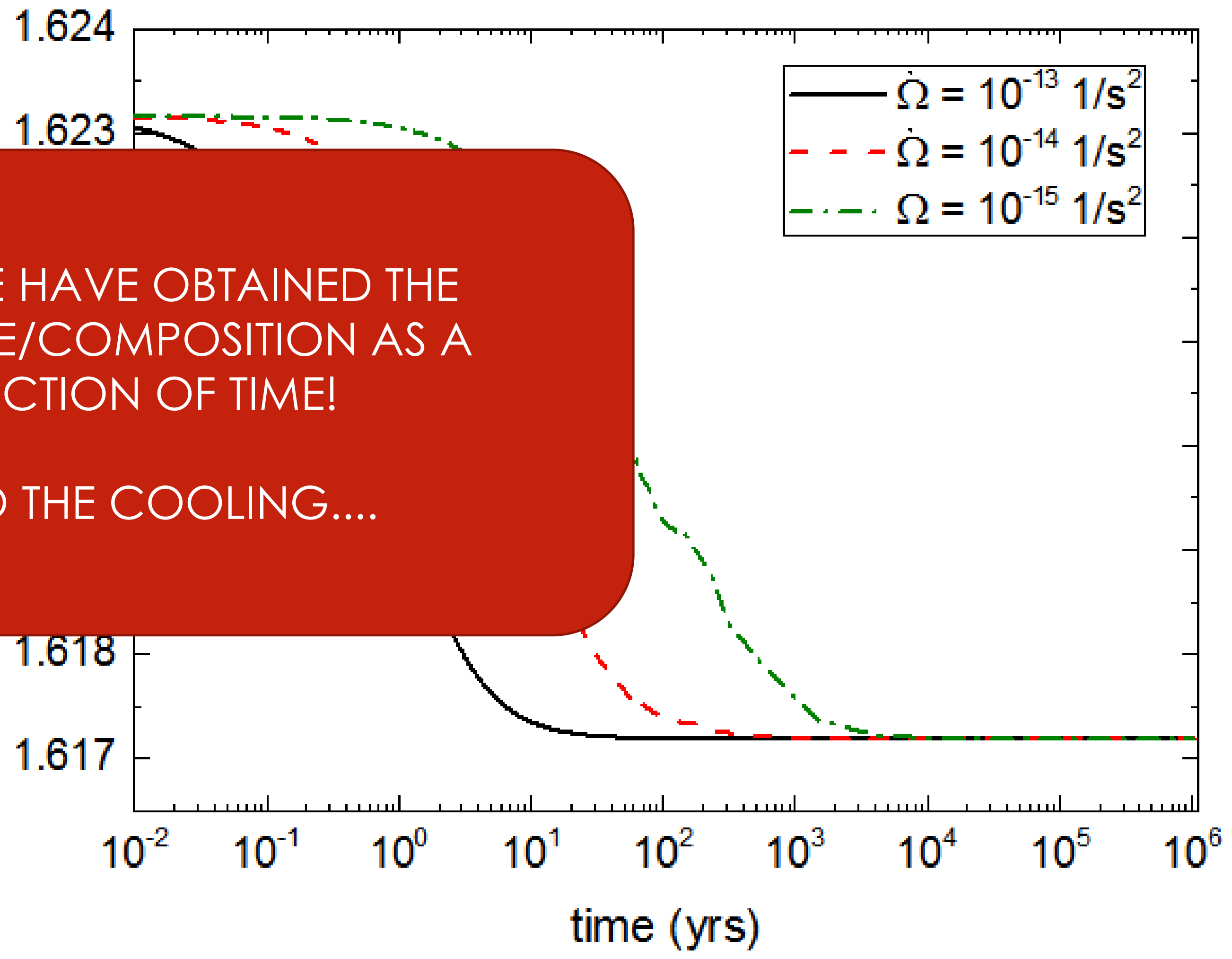
PROOF OF CONCEPT:
- STRUCTURE OF ROTATING NEUTRON STARS

- Metric $$ds^2 = -e^{\gamma+\rho}dt^2 + e^{2\alpha}(dr^2 + r^2 d\theta^2) + e^{\gamma-\rho} r^2 \sin^2\theta (d\phi - \omega dt)^2$$
- Sources $$T^{\mu\nu} = (\epsilon + p)u^\mu u^\nu + p g^{\mu\nu}$$ + magnetic terms
- Einstein's Equation $$G^{\mu\nu} = R^{\mu\nu} - \frac{1}{2} g^{\mu\nu} R = 8\pi T^{\mu\nu}$$
- Hydrostatic Equilibrium $$dp - (\epsilon + p)[d \ln u^t + u^t u_\phi d\Omega] = 0$$ + magnetic terms

PROOF OF CONCEPT: - STRUCTURE OF ROTATING NEUTRON

- Magnetic Braking model

$$\dot{\Omega} = -\, K \; \Omega^n$$



NOW, WE HAVE OBTAINED THE STRUCTURE/COMPOSITION AS A FUNCTION OF TIME!

ONTO THE COOLING....

THERMAL EVOLUTION OF AXIS-SYMMETRIC NEUTRON STARS

$$P = P(\rho, T = 0, \Omega(t), B(t))$$

$$M = M(\rho, T = 0, \Omega(t), B(t))$$

$$R = R(\rho, T = 0, \Omega(t), B(t))$$

$$\varepsilon = \varepsilon(\rho, T, \Omega(t), B(t))$$

$$K = K(\rho, T, \Omega(t), B(t))$$

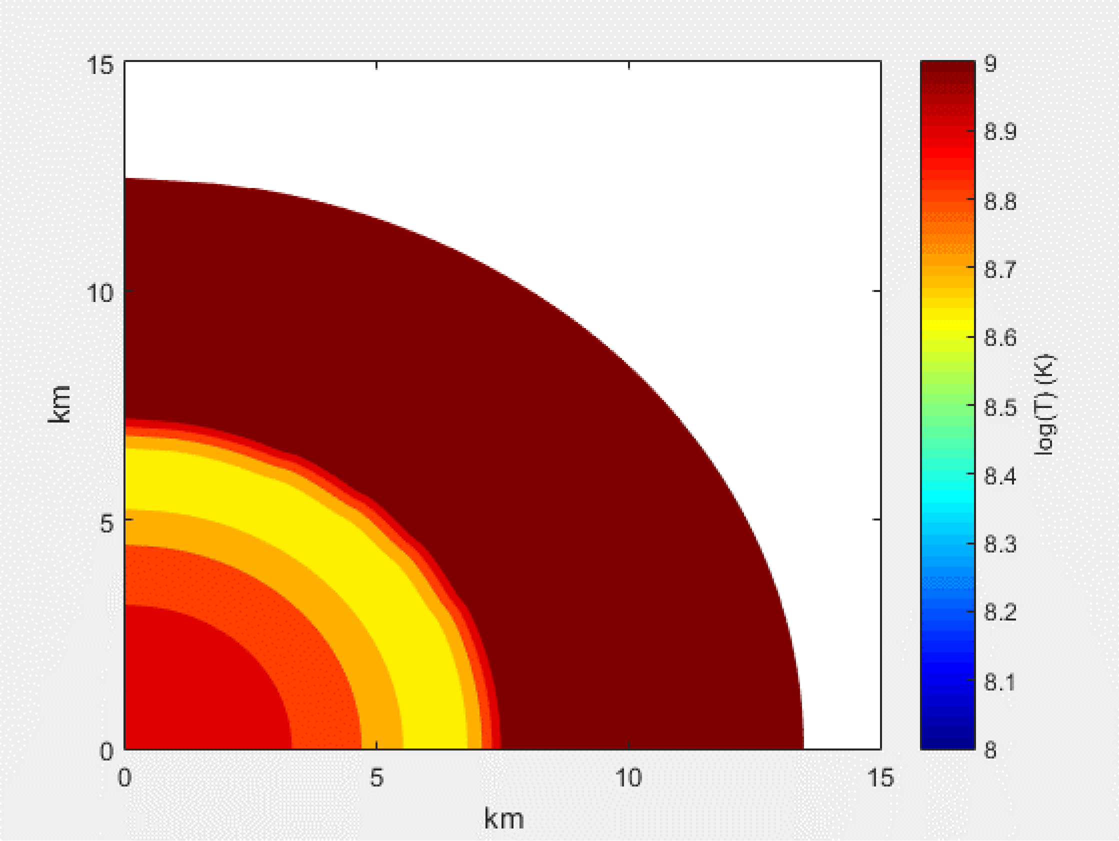
$$c_v = c_v(\rho, T, \Omega(t), B(t))$$

$$\begin{aligned}
\partial_r \tilde{H}_{\bar{r}} + \frac{1}{r}\partial_\theta \tilde{H}_{\bar{\theta}} &= -r\, e^{\phi+2\omega}\left(\frac{1}{\Gamma}e^{2\nu}\epsilon + \Gamma C_V \partial_t \tilde{T}\right) \\
&\quad -r\,\Gamma U e^{\nu+2\phi+\omega}\left(\partial_r \Omega + \frac{1}{r}\partial_\theta \Omega\right), \\
\partial_r \tilde{T} &= -\frac{1}{r\kappa}e^{\nu-\phi}\tilde{H}_{\bar{r}} - \Gamma^2 U e^{-\nu+\phi}\,\tilde{T}\partial_r \Omega, \\
\frac{1}{r}\partial_\theta \tilde{T} &= -\frac{1}{r\kappa}e^{-\nu-\phi}\tilde{H}_{\bar{\theta}} - \Gamma^2 U e^{-\nu+\phi}\,\tilde{T}\frac{1}{r}\partial_\theta \Omega \\
\Gamma U \partial_t \tilde{T} &= -\frac{1}{r\kappa}e^{-\omega-\phi}\tilde{H}_{\bar{\varphi}},
\end{aligned}$$

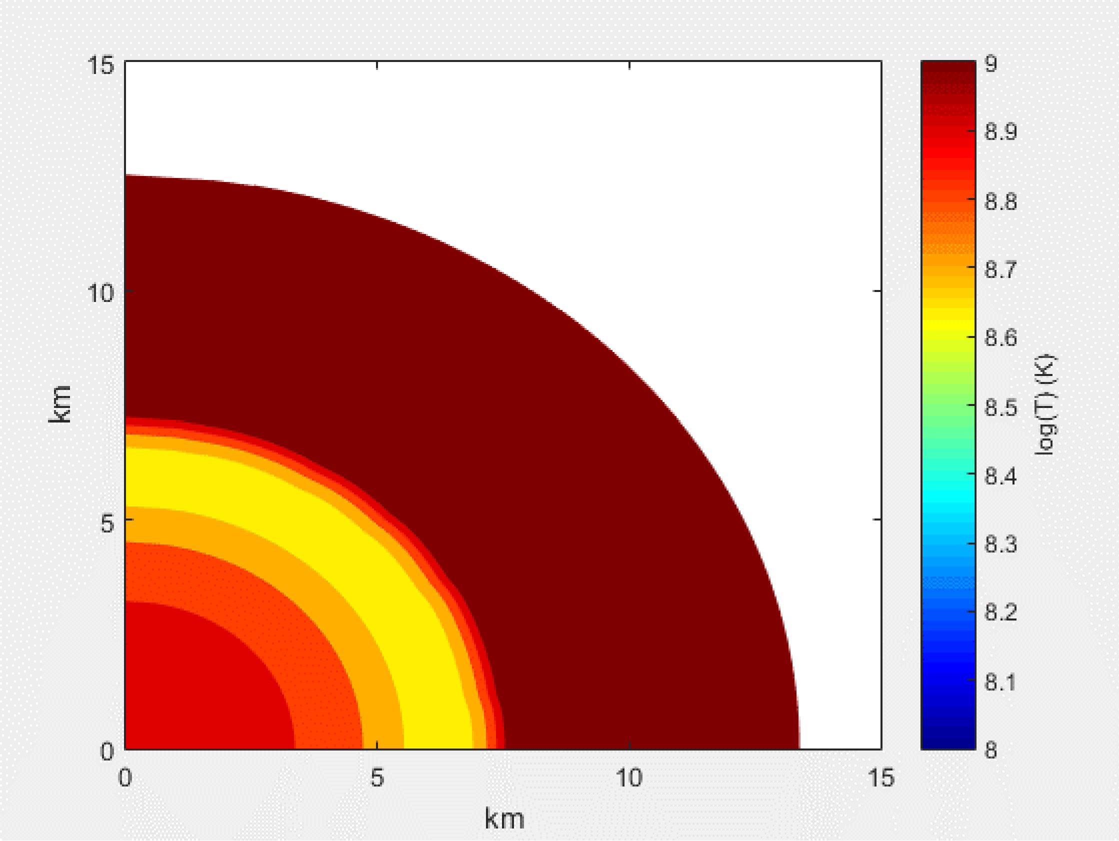
Negreiros, Schramm and Weber, Phys.Rev. D85 (2012) 104019

THERMAL EVOLUTION OF AXIS-SYMMETRIC NEUTRON STARS

- $M_0 = 1.8\ M_{sun}$, $\Omega_0 = 500$ Hz



$\dot{\Omega} = 10^{-15} s^{-2}$

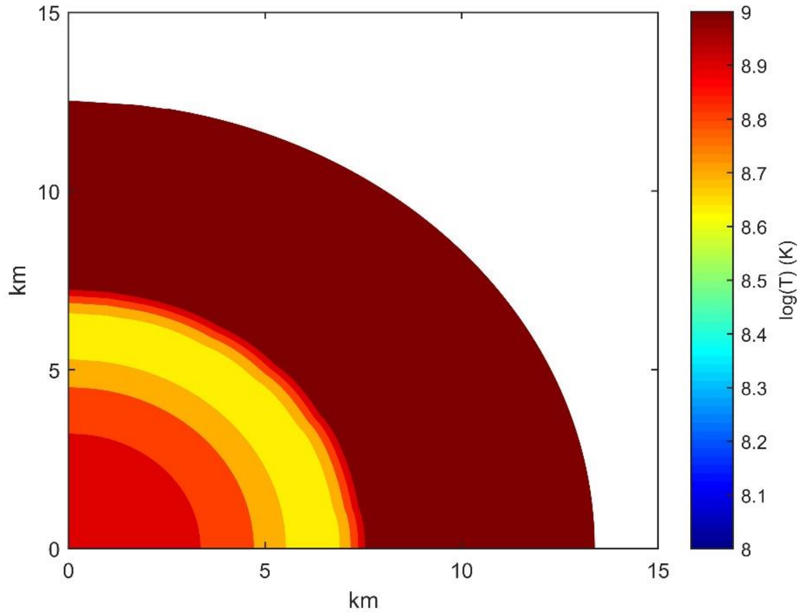


$\dot{\Omega} = 10^{-13} s^{-2}$

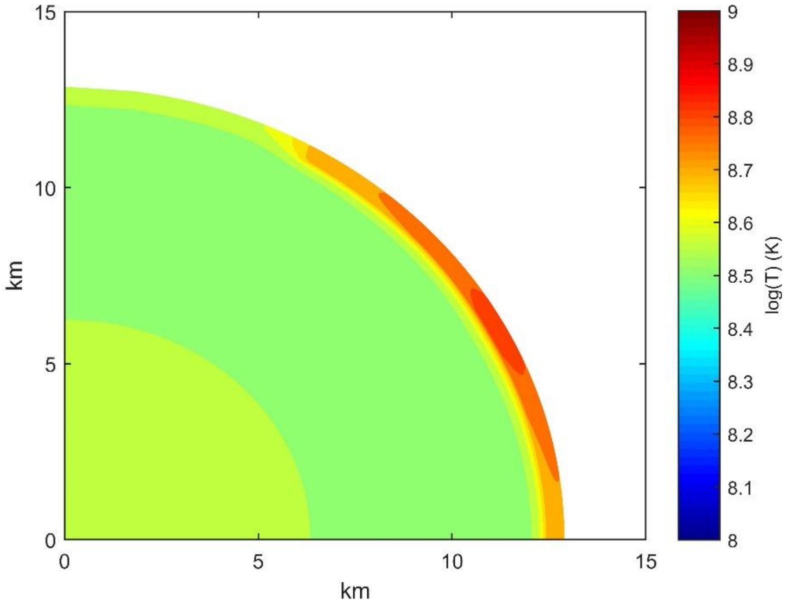
THERMAL EVOLUTION OF AXIS-SYMMETRIC NEUTRON STARS

- M_0 = 1.8 M_{sun}, Ω_0 = 500 Hz

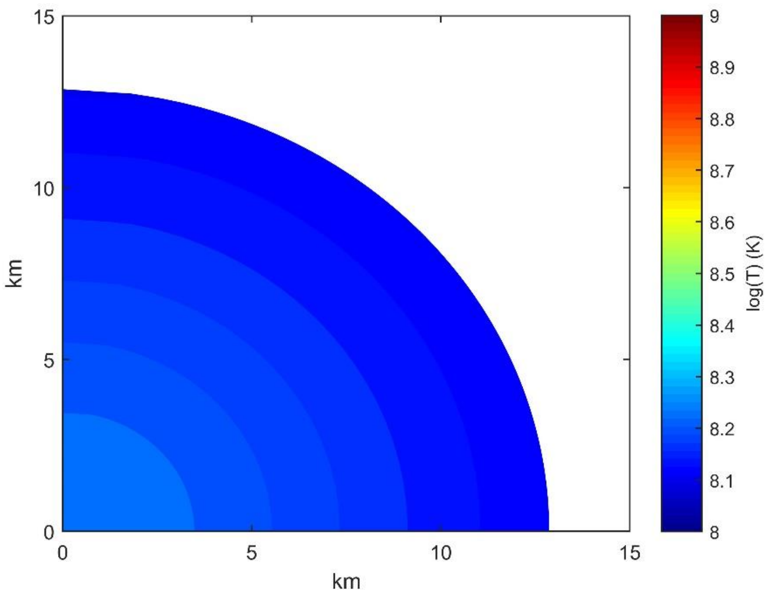
$$\dot{\Omega} = 10^{-13} s^{-2}$$



0.10 years



36 years

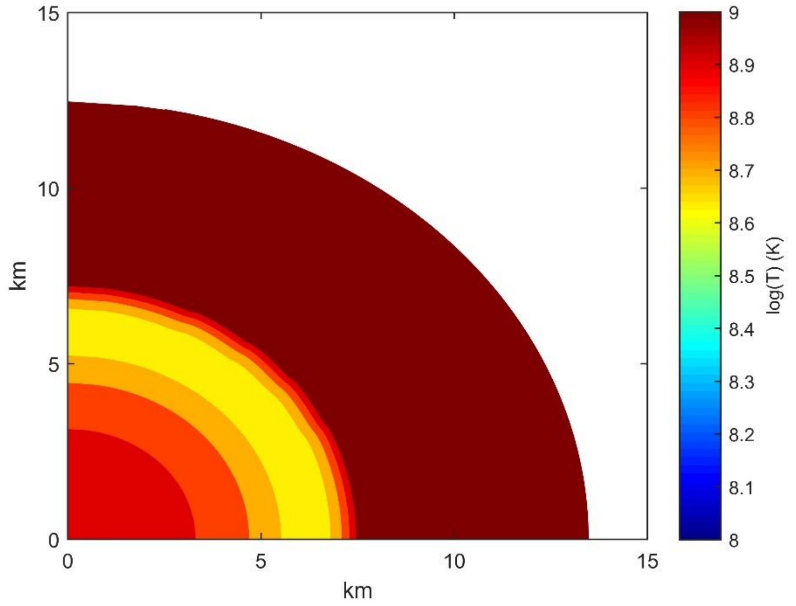


8.0E5 years

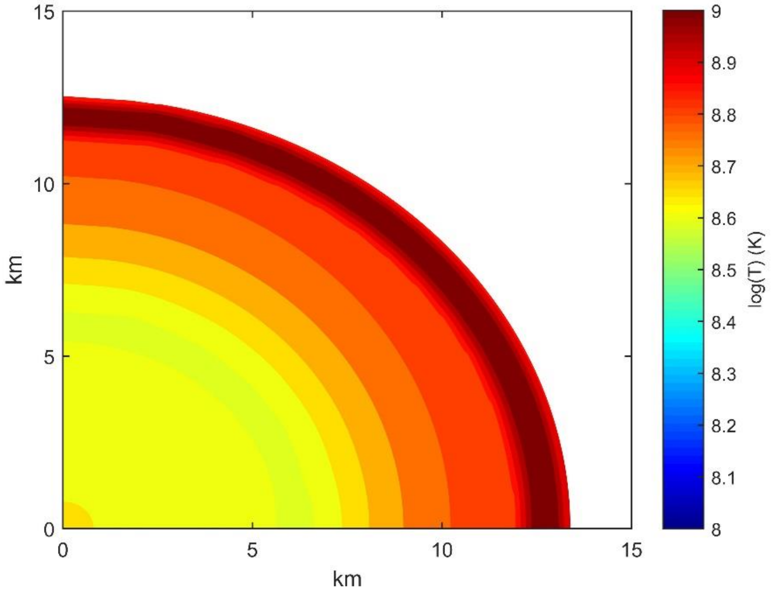
THERMAL EVOLUTION OF AXIS-SYMMETRIC NEUTRON STARS

- $M_0 = 1.8\ M_{sun}$, $\Omega_0 = 500$ Hz

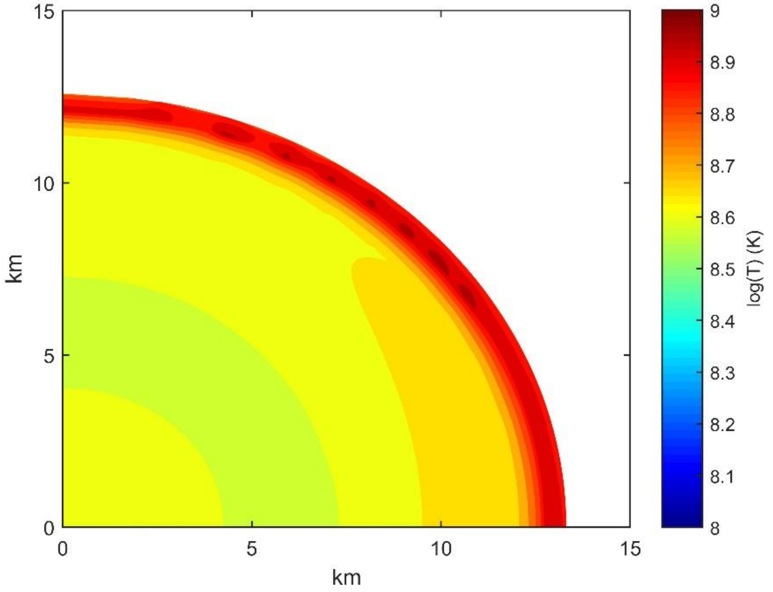
$\dot{\Omega} = 10^{-15} s^{-2}$



0.10 years



10.05 years

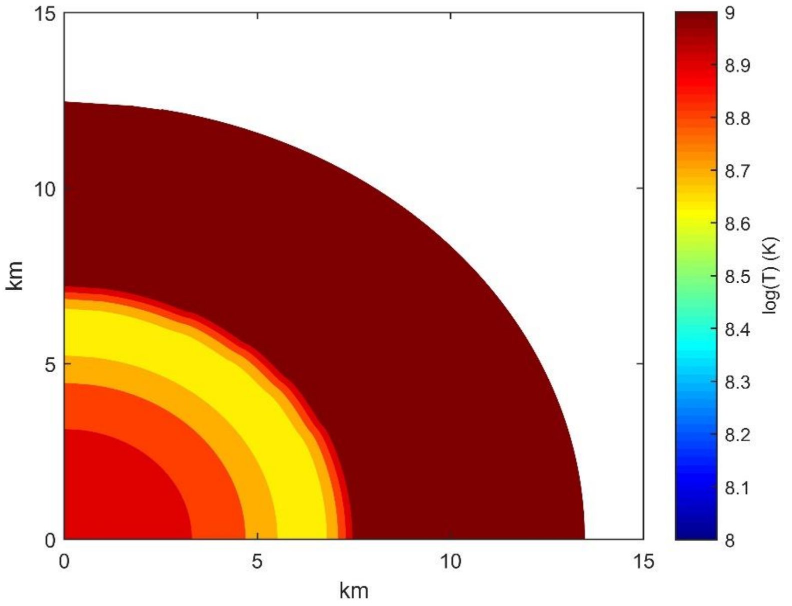


22.45 years

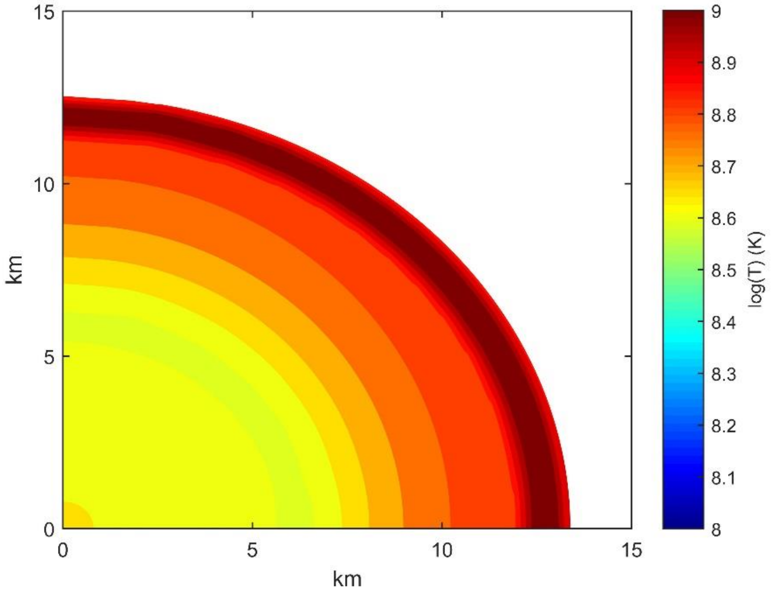
THERMAL EVOLUTION OF AXIS-SYMMETRIC NEUTRON STARS

- $M_0 = 1.8\ M_{sun}$, $\Omega_0 = 500$ Hz

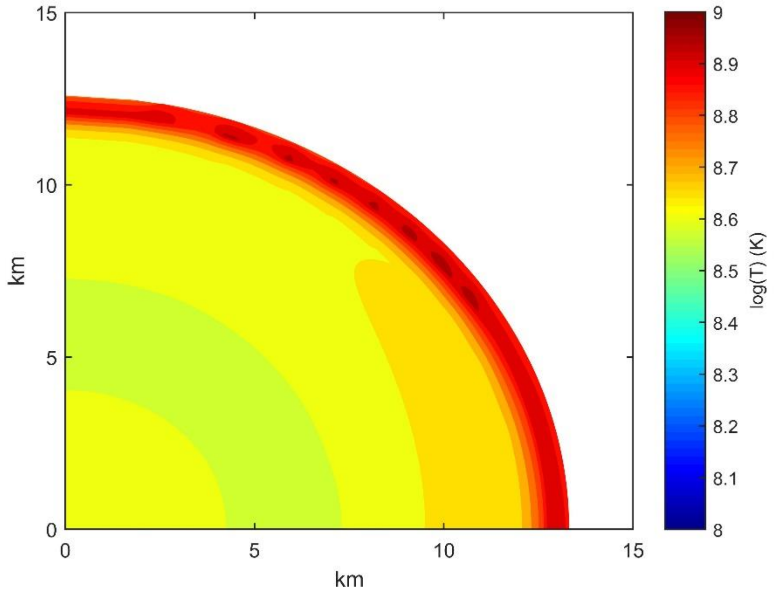
$$\dot{\Omega} = 10^{-13} s^{-2}$$



0.10 years



10.05 years

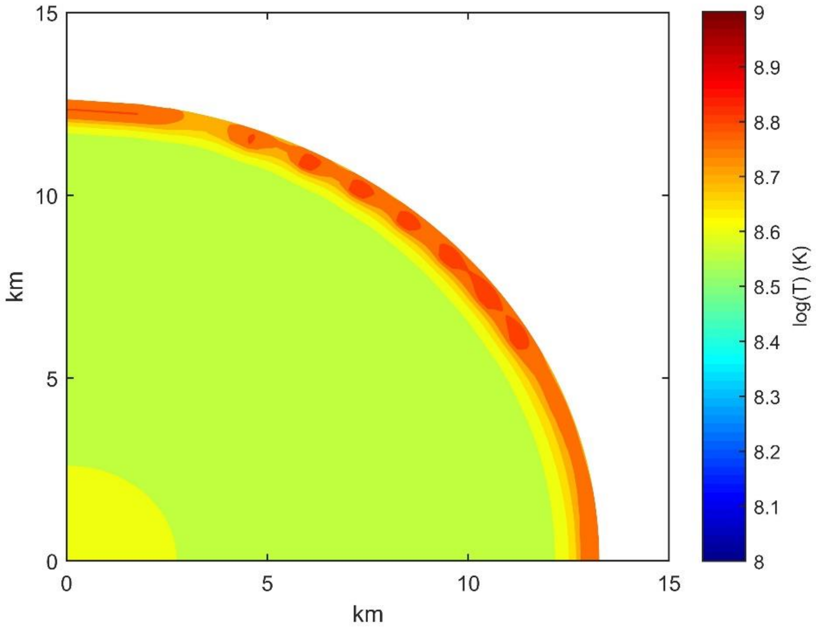


22.45 years

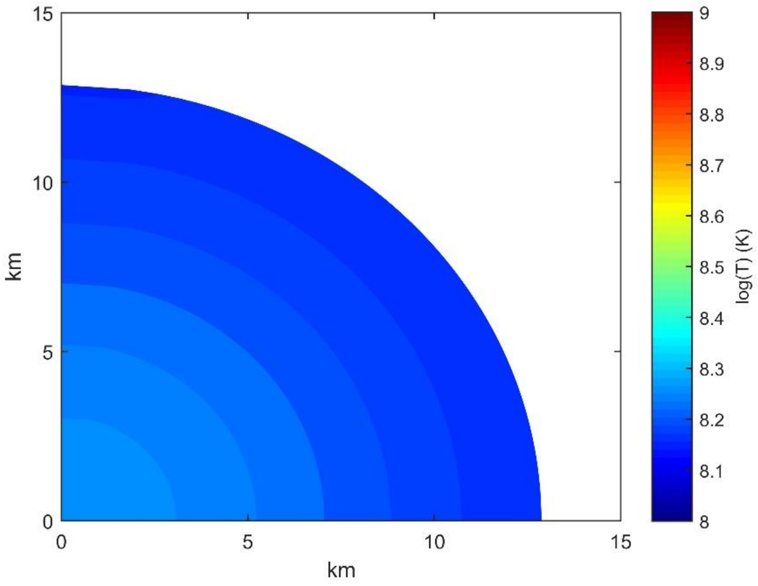
THERMAL EVOLUTION OF AXIS-SYMMETRIC NEUTRON STARS

- M_0 = 1.8 M_{sun}, Ω_0 = 500 Hz

$\dot{\Omega} = 10^{-15} s^{-2}$



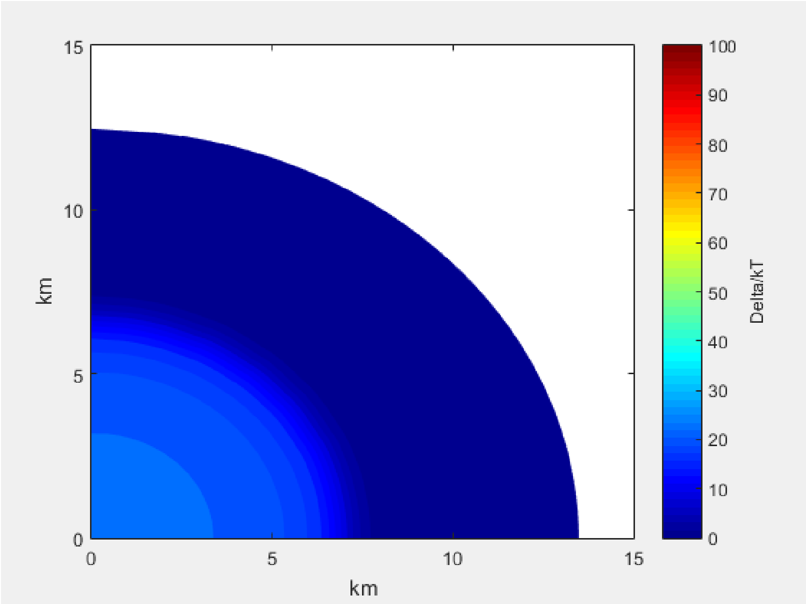
31.67 years



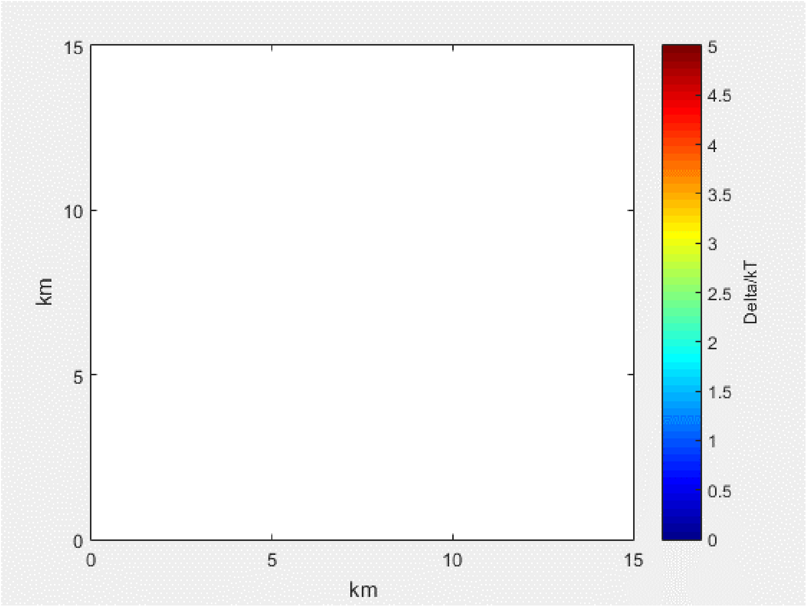
5.0E5 years

THERMAL EVOLUTION OF AXIS-SYMMETRIC NEUTRON STARS

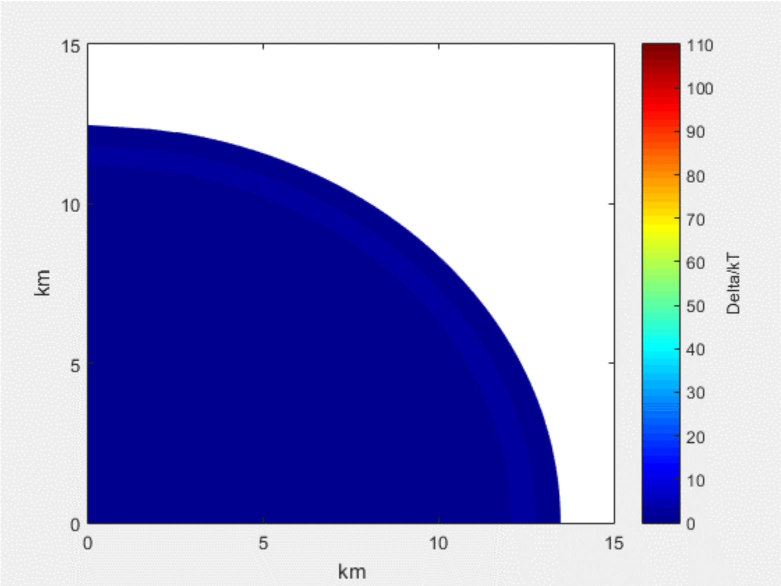
- $M_0 = 1.8\ M_{sun}$, $\Omega_0 = 500$ Hz -> MICROSCOPIC PROPERTIES



Proton Singlet GAP

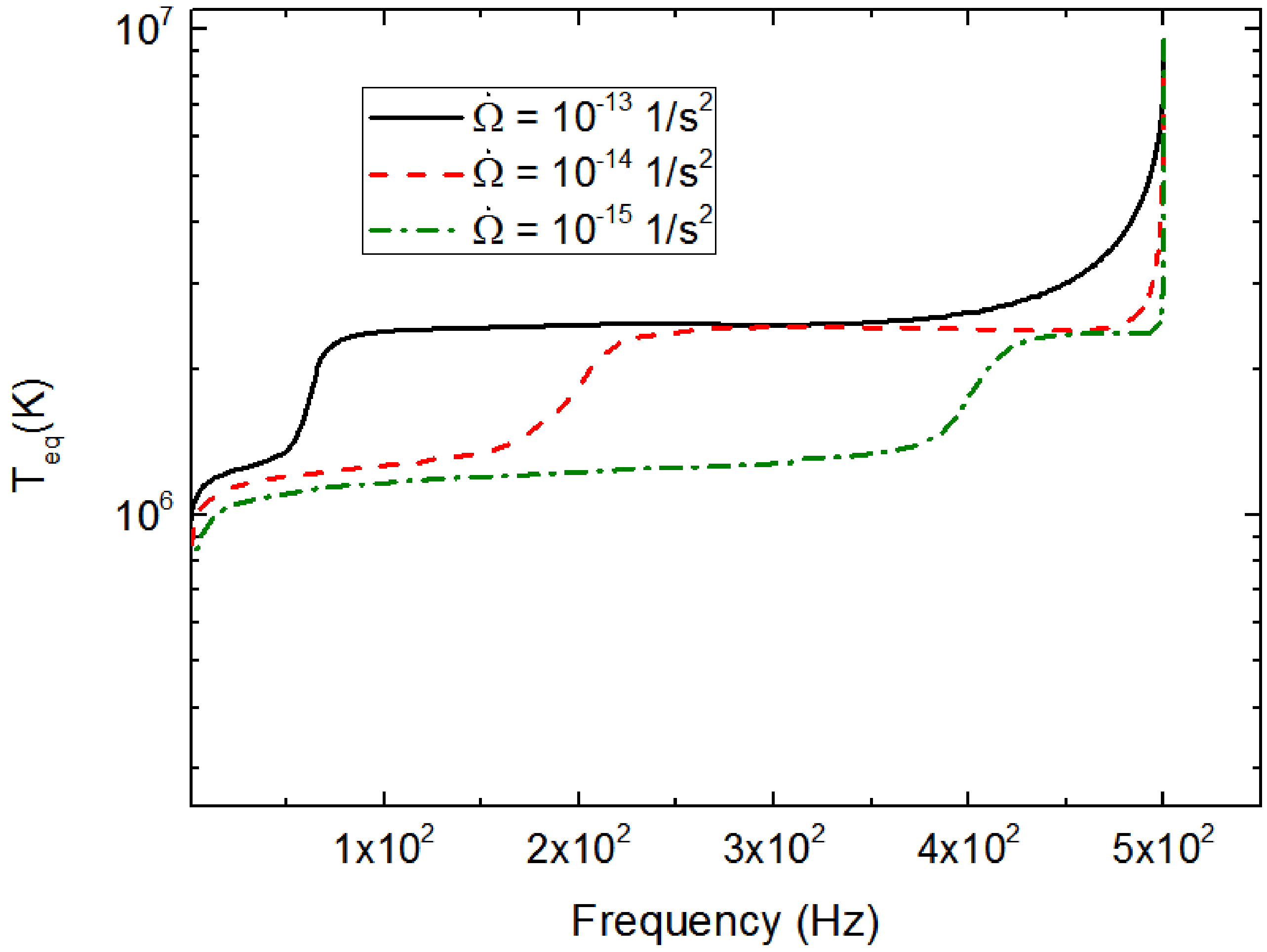


Neutron Triplet GAP



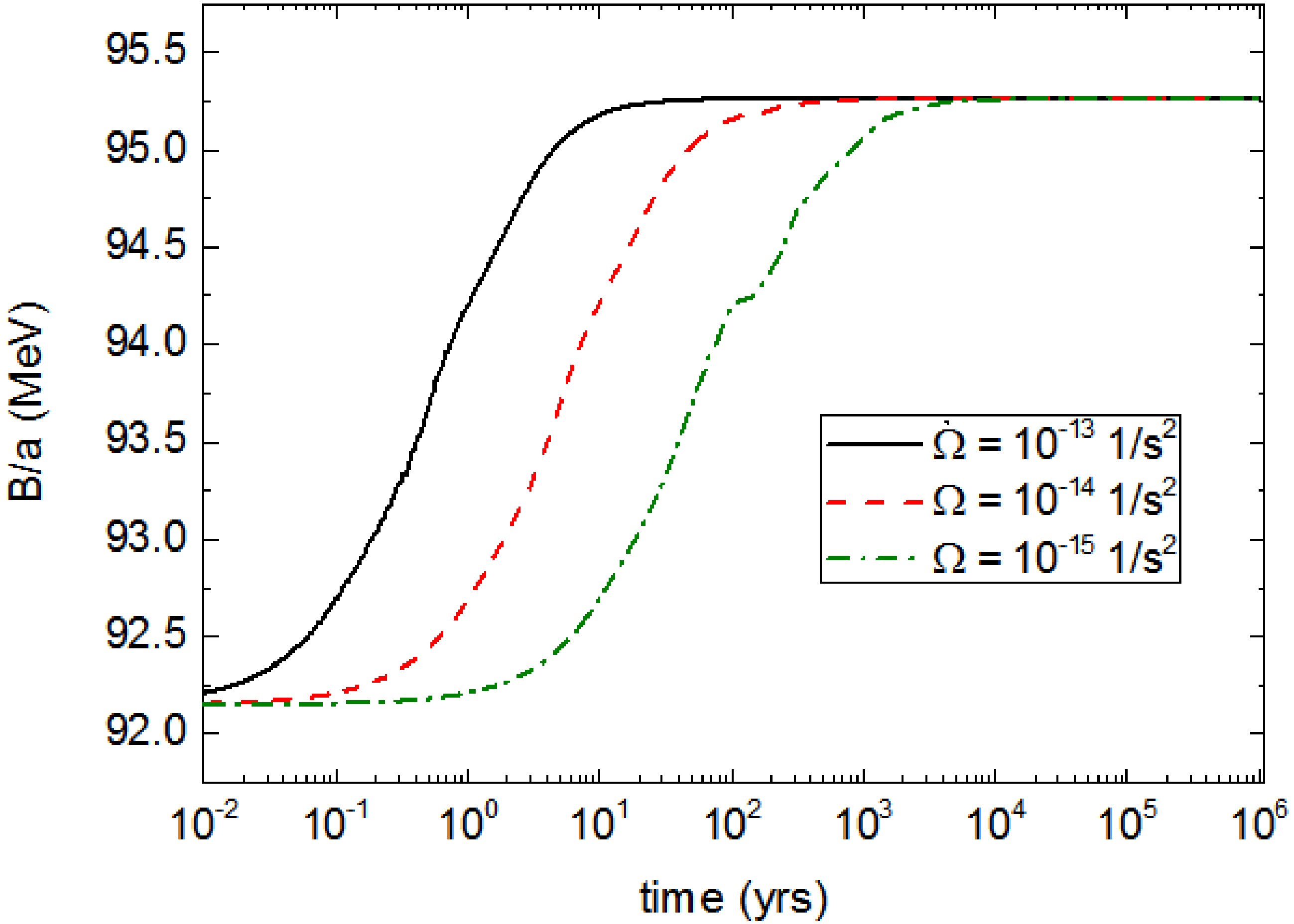
Neutron Singlet GAP

THERMAL-ROTATIONAL EVOLUTION



HEATING(?)

- Possibly
- Not for the magnetic breaking model…



PERSPECTIVES

- We are now in a position to deal fully with axis-symmetric neutron stars thermal evolution.

- We can also consider a dynamic structure/composition.

- Investigate different neutron stars evolution:

- Magnetic
- Spin-Up/accreting