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Cooling of rapidly rotating neutron stars in 2D

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Cooling of rapidly rotating NSs

Introduction

Main part

- Models of rotating NSs & Mechanical structure
- Cooling of rotating NSs

Conclusions

Introduction

"Mystery" of dense matter equation of state (EOS)

P vs ρ dependence

Chemical composition

Mechanical structure of a NS

Transport & thermal & emission properties of a NS

- Mass & Radius measure-ments of NSs
- GW observations of binary NS mergers

Thermal evolution of NSs:

- **Cooling of isolated NSs**
- Heating of NSs in LMXBS

Most of such cooling calculations are done for spherically symmetric (1D) systems. However, NSs do rotate and they can rotate very fast. Thus, a question arises of how rotation affects thermal evolution.

There are much less papers dedicated to this question and most of them focus on surface temperature distribution (which is logical as only surface temperature can be observed).

Thus, we had two main goals:

- Investigate how the temperature distribution on the surface and throughout the whole volume of the star is affected by rotation;
- Study the effects of the core and crust EOSs on the cooling of a rotating NS.

Models of rotating NSs

We employ *LORENE* library to solve the coupled system of mechanical structure and Einstein field equations for a rotating NS.

To compute the mechanical structure we need to specify EOSs. We have employed three core EOSs:

Model	$M_{G,\mathrm{max}}$, $\mathrm{M}_\odot$	$R_{1.4}$, km	M_{DU}, $\mathrm{M}_\odot$
APR	2.17	11.33	2.00
IUF	1.95	12.64	1.77
NL3-$\omega\rho$	2.75	13.82	2.55

We have also considered two EOSs of the crust, but both the mechanical structure and cooling were almost identical, so I will present the results with only one EOS of the crust.

Mechanical structure

We assume uniform (rigid) rotation with constant frequency (no spin-down) and compare NSs with equal baryonic masses as it is a conserved quantity in the absences of accretion and mass loss.

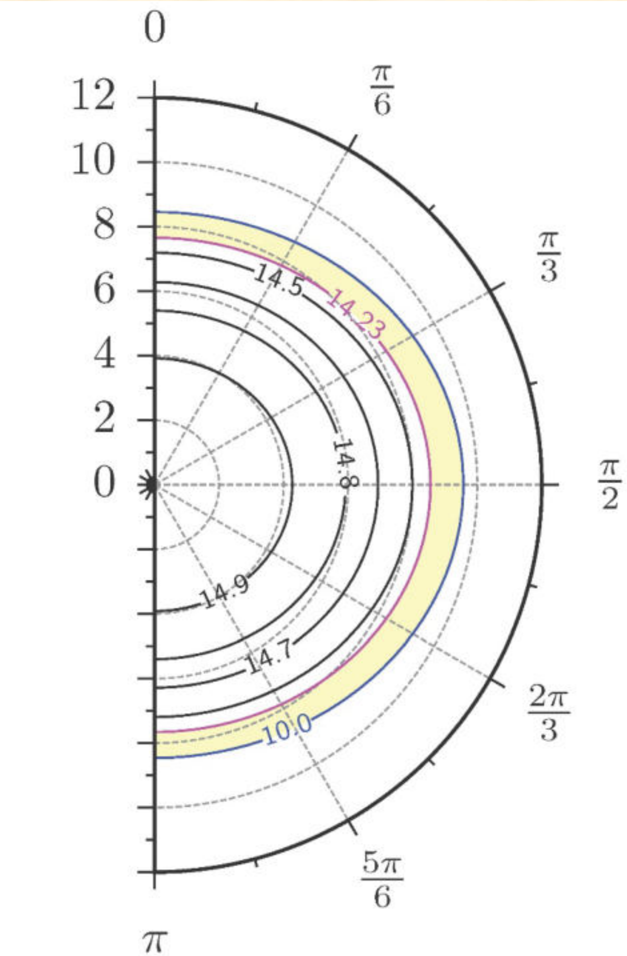
The value of choice for the baryonic mass is $M_{\mathrm{B}} = 1.6\,\mathrm{M}_{\odot}$, which results in gravitational masses close to the canonical value of $1.4\,\mathrm{M}_{\odot}$.

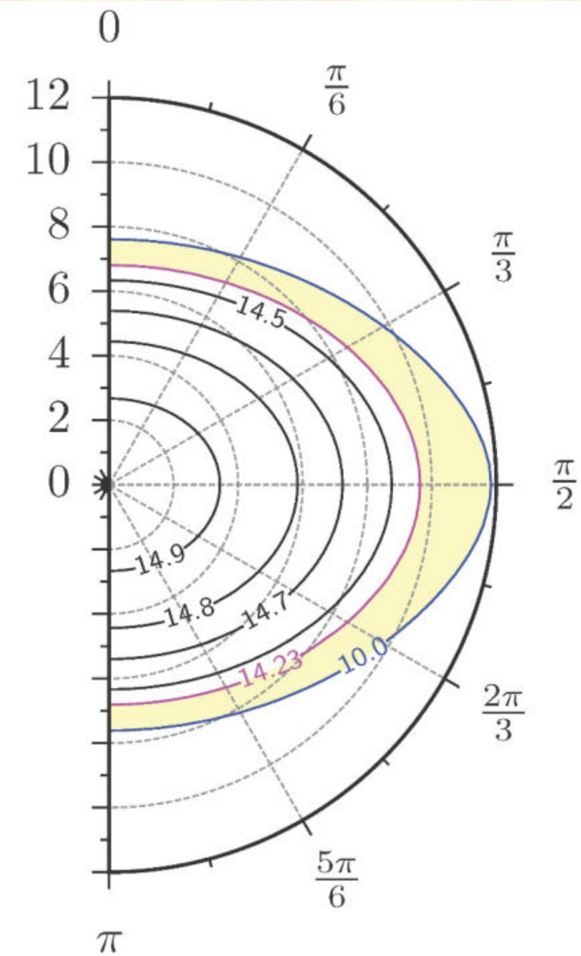
For the rotation frequency we have considered two values.

The first one, 716 Hz, corresponds to the fastest know millisecond pulsar (PSR J1748–2446ad).

The second one corresponds to 99% of the Kepler frequency and is EOS dependent.

Mechanical structure. APR EOS. 716 Hz (left) and 1096 Hz (right)

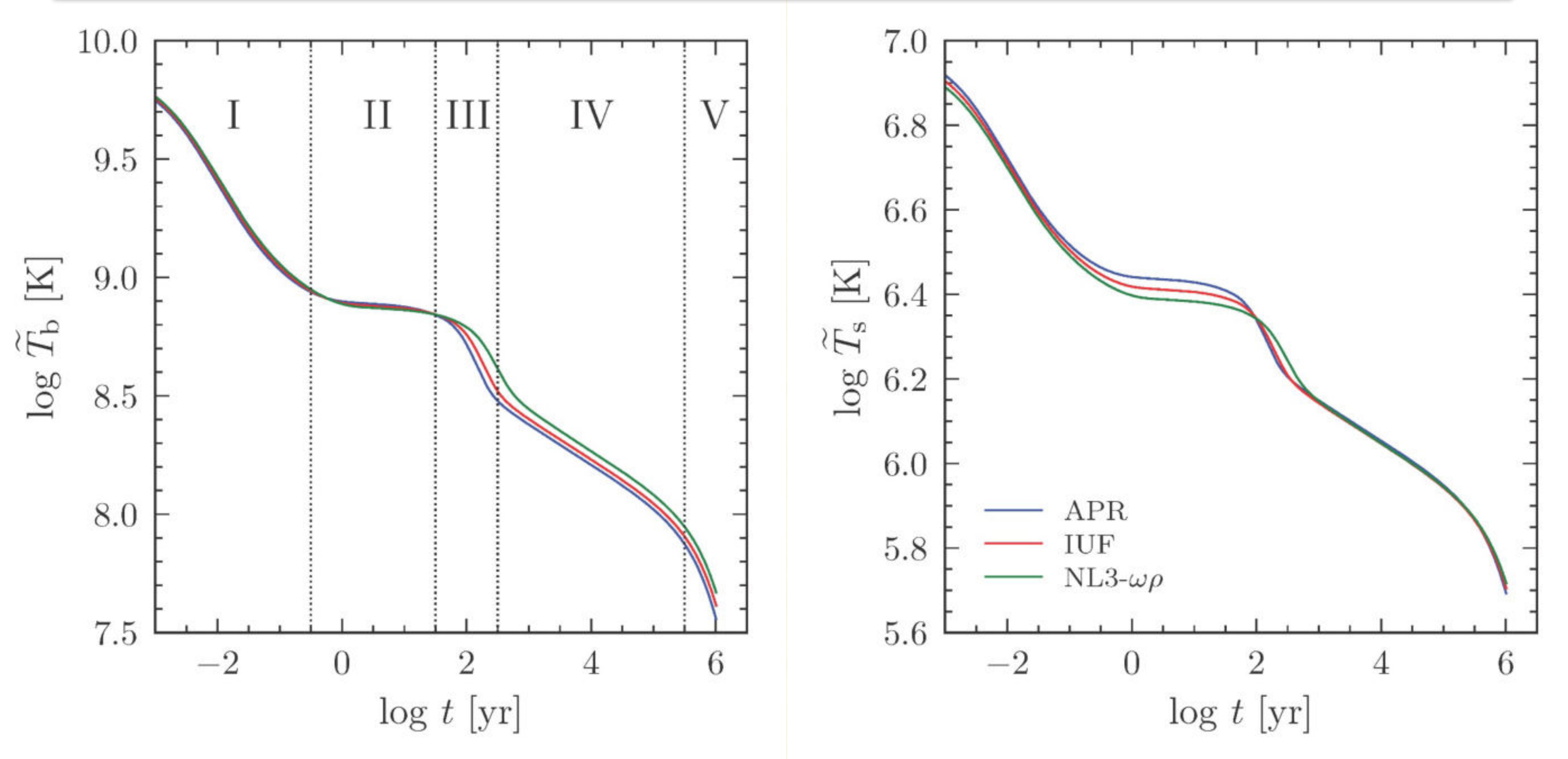




Cooling of rotating NSs

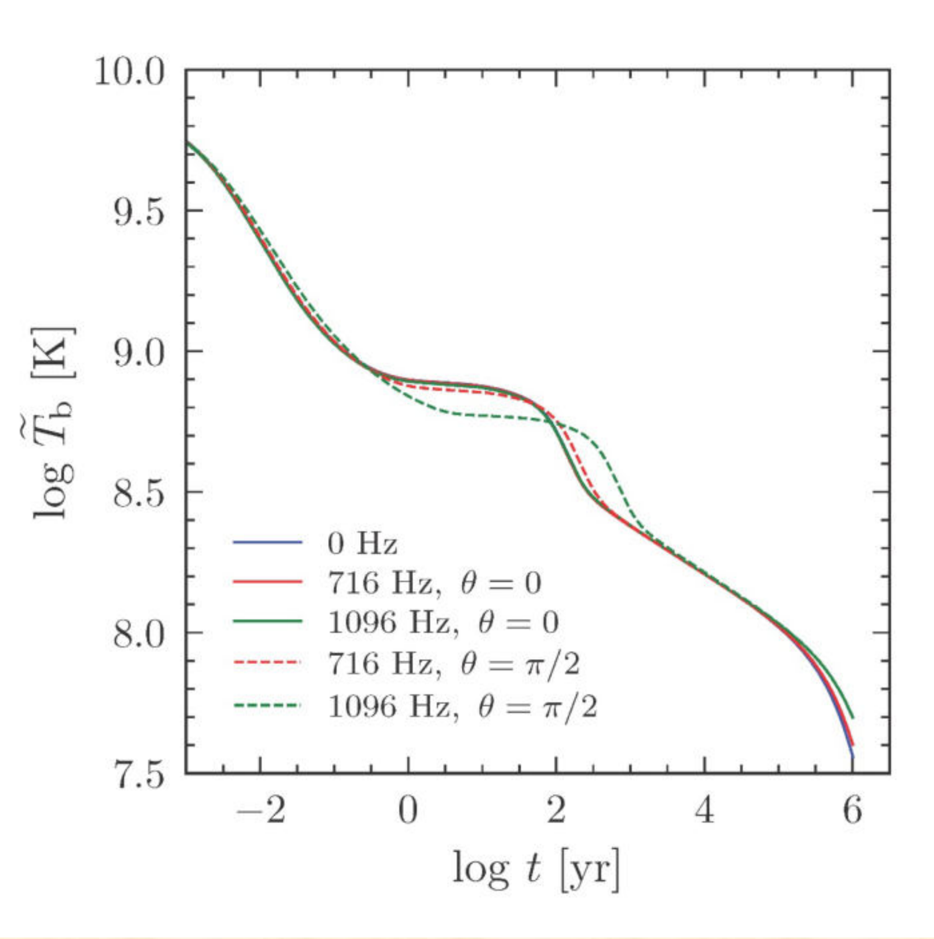
We consider standard long-term cooling. No superfluidity/superconductivity, no enhanced neutrino emission mechanisms, no magnetic fields.

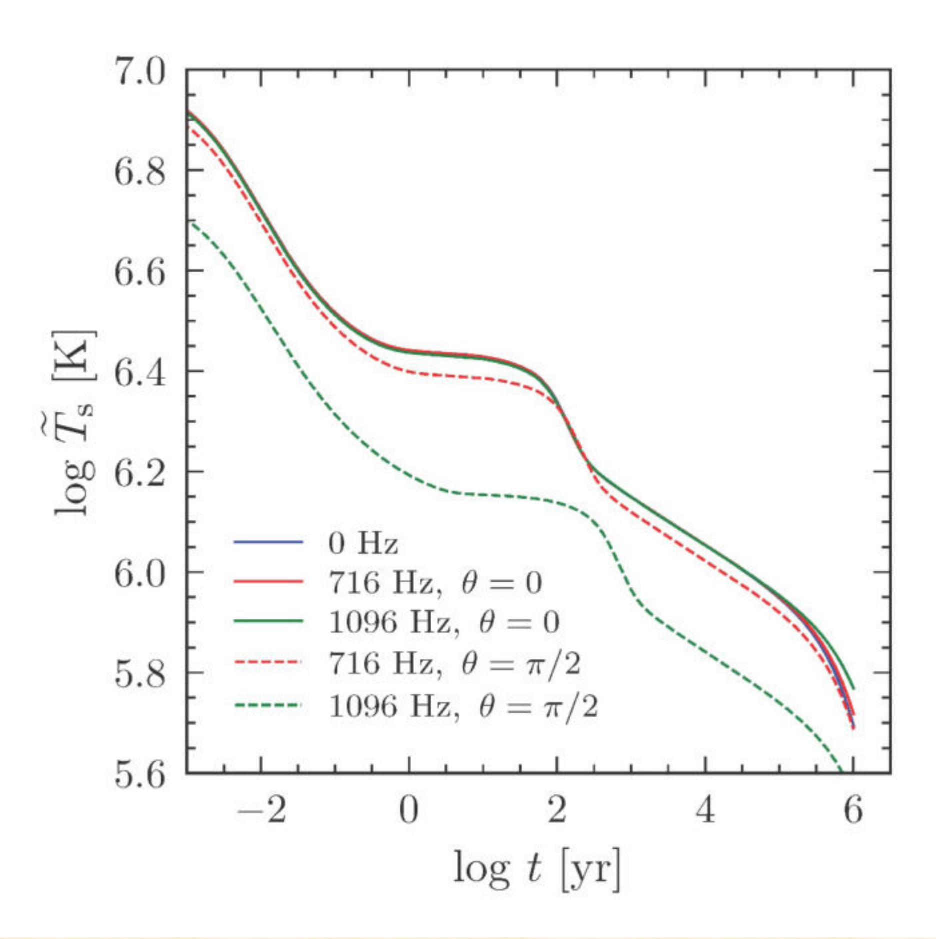
Let us start with non-rotating NSs as a limiting case. Redshifted temperatures at the bottom of the envelope (left) and on the surface (right) are shown as functions of time (cooling curves).



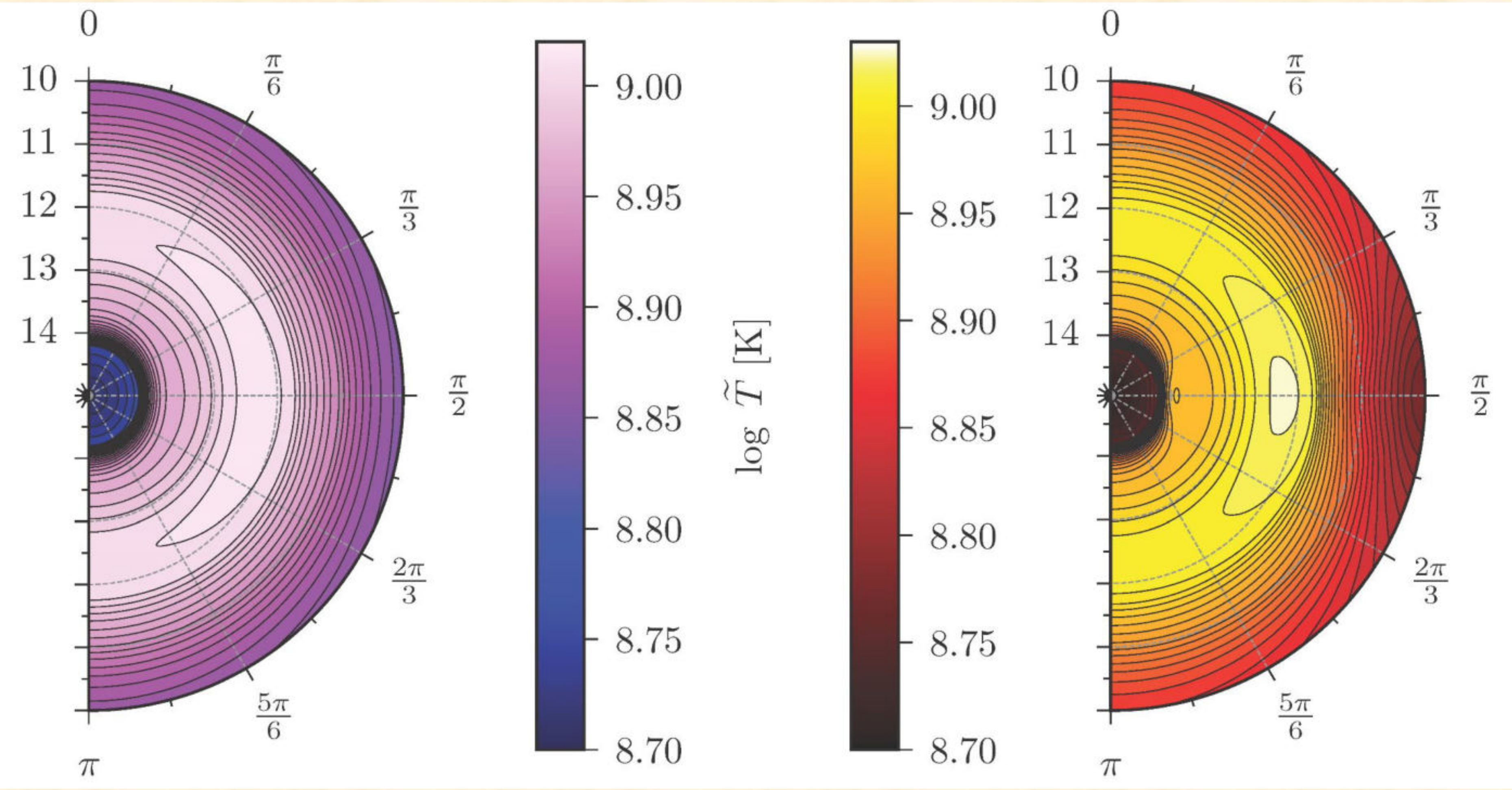
Cooling of rotating NSs

Cooling curves for the bottom of the envelope (left) and for the surface (right). APR EOS.

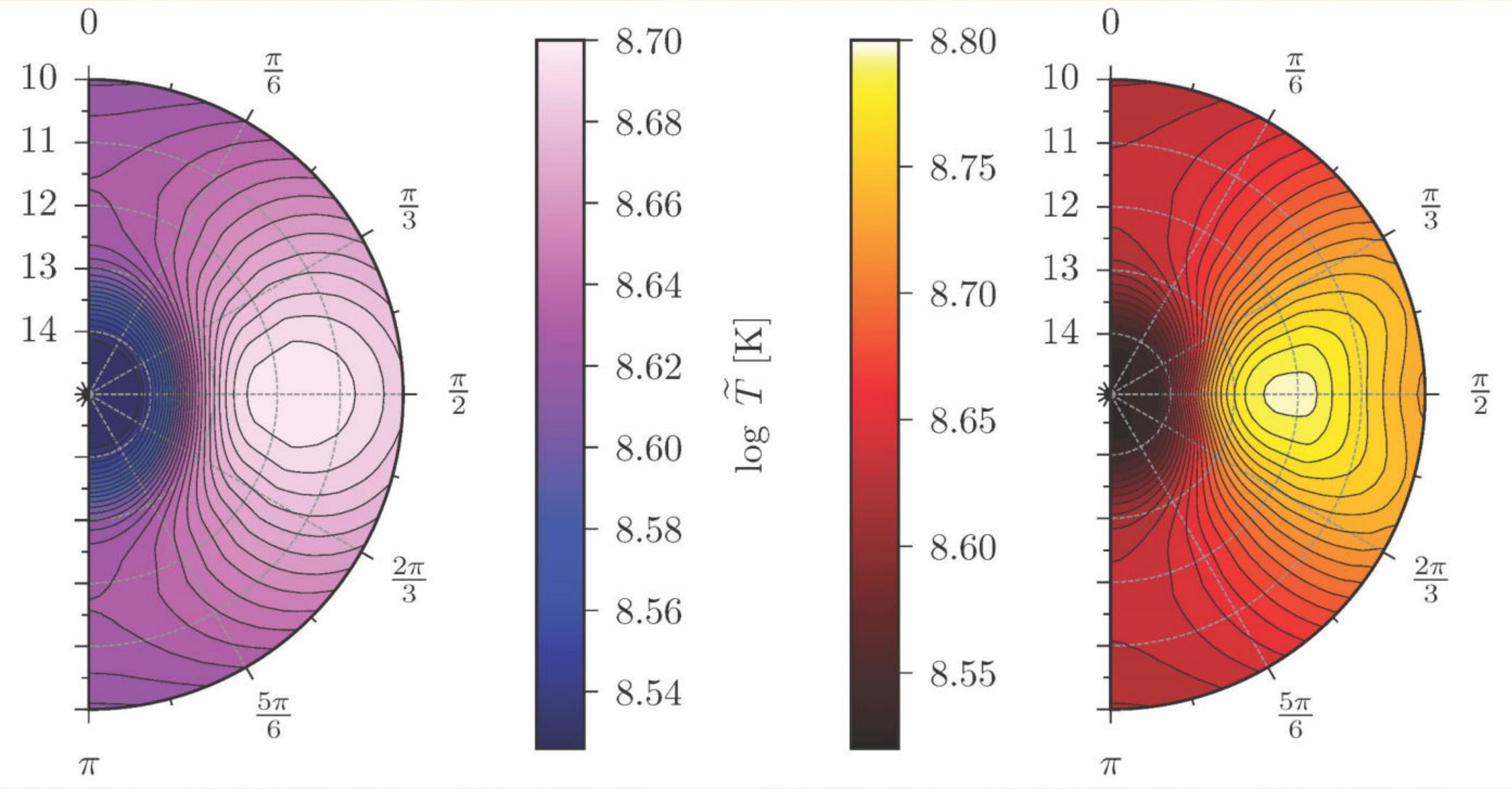




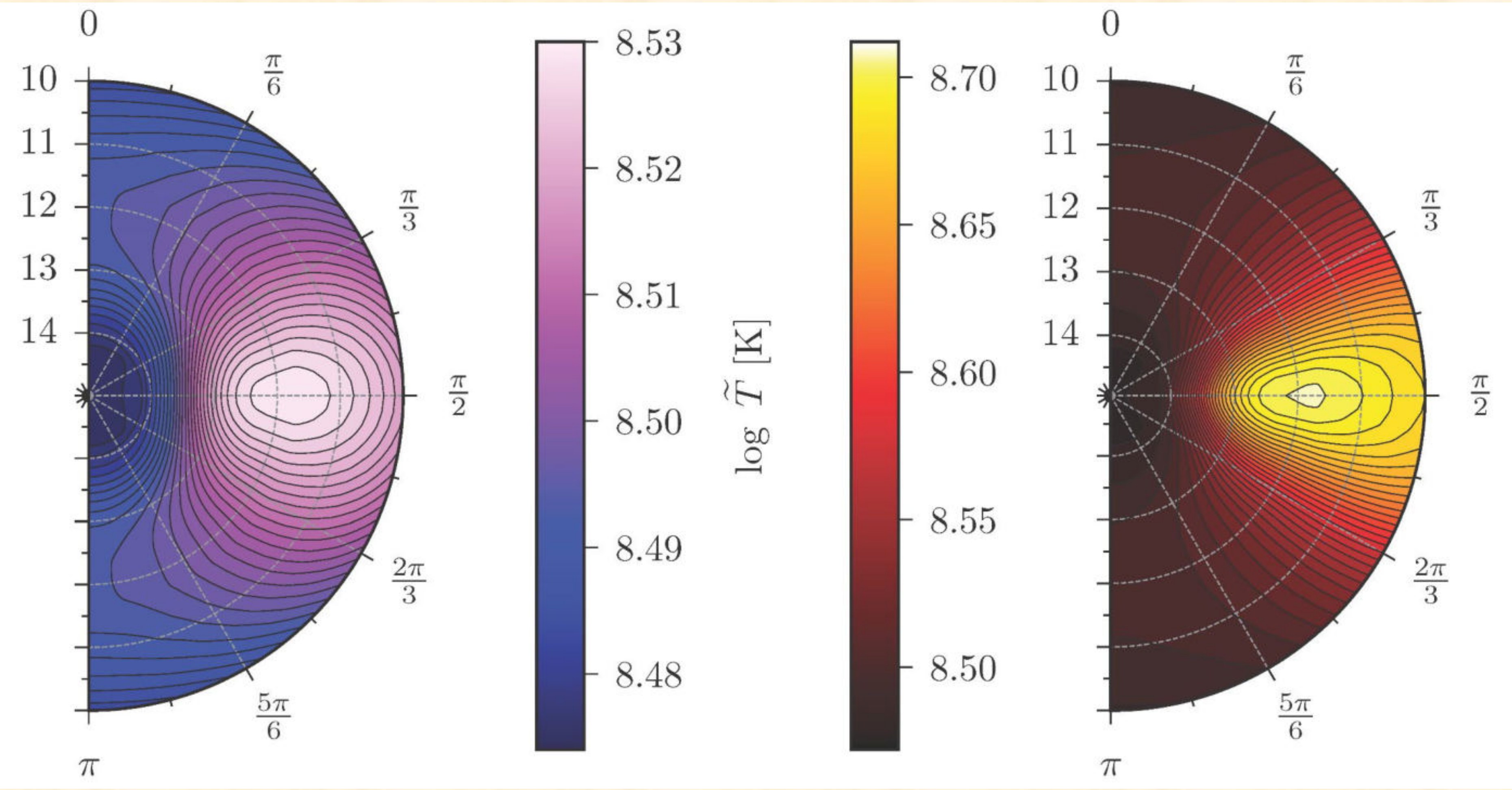
Internal redshifted temperature distribution. APR EOS. 716 Hz (left) and 1096 Hz (right). Age $t = 10$ years.



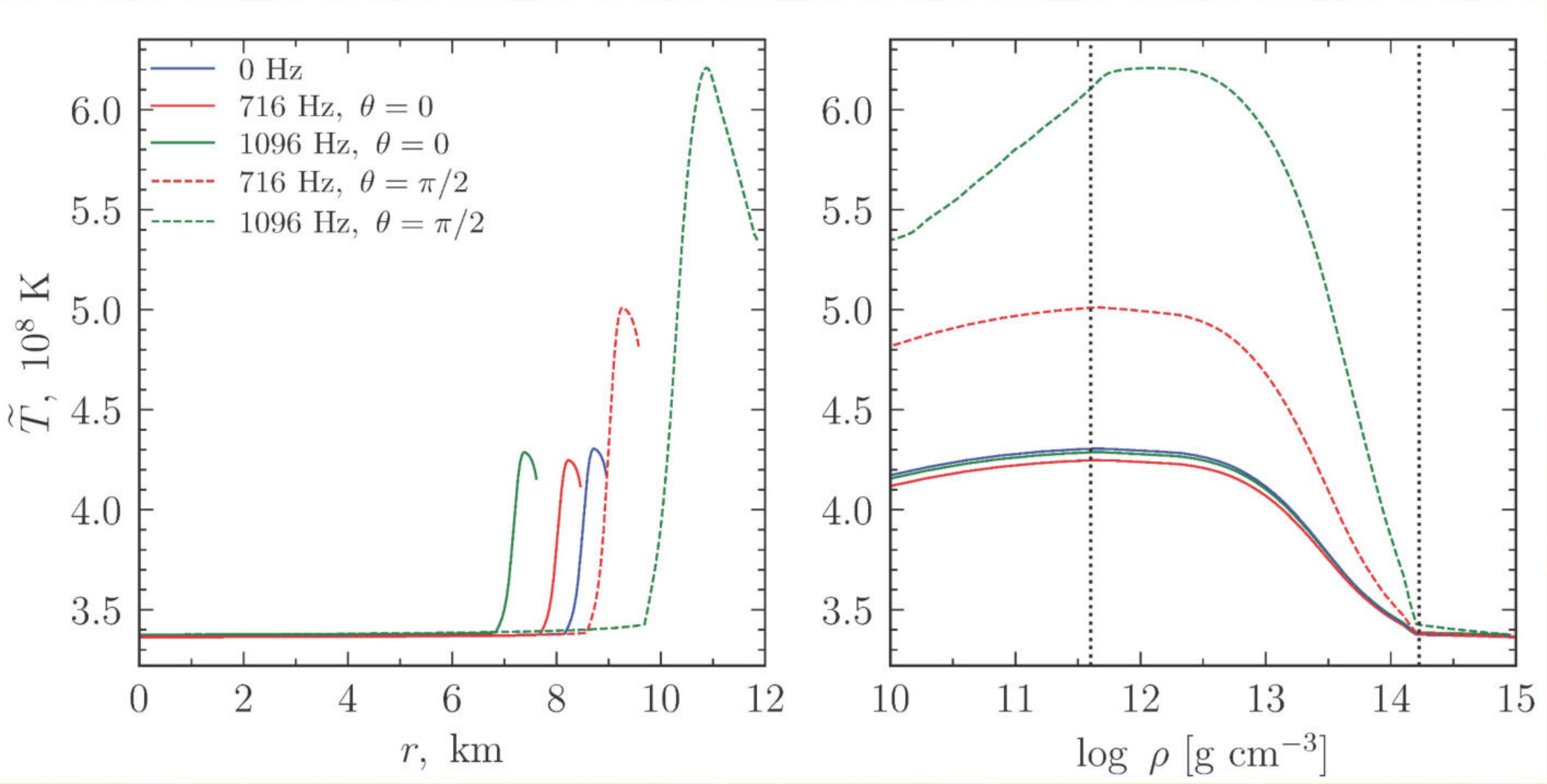
Internal redshifted temperature distribution. APR EOS. 716 Hz (left) and 1096 Hz (right). Age $t = 150$ years.



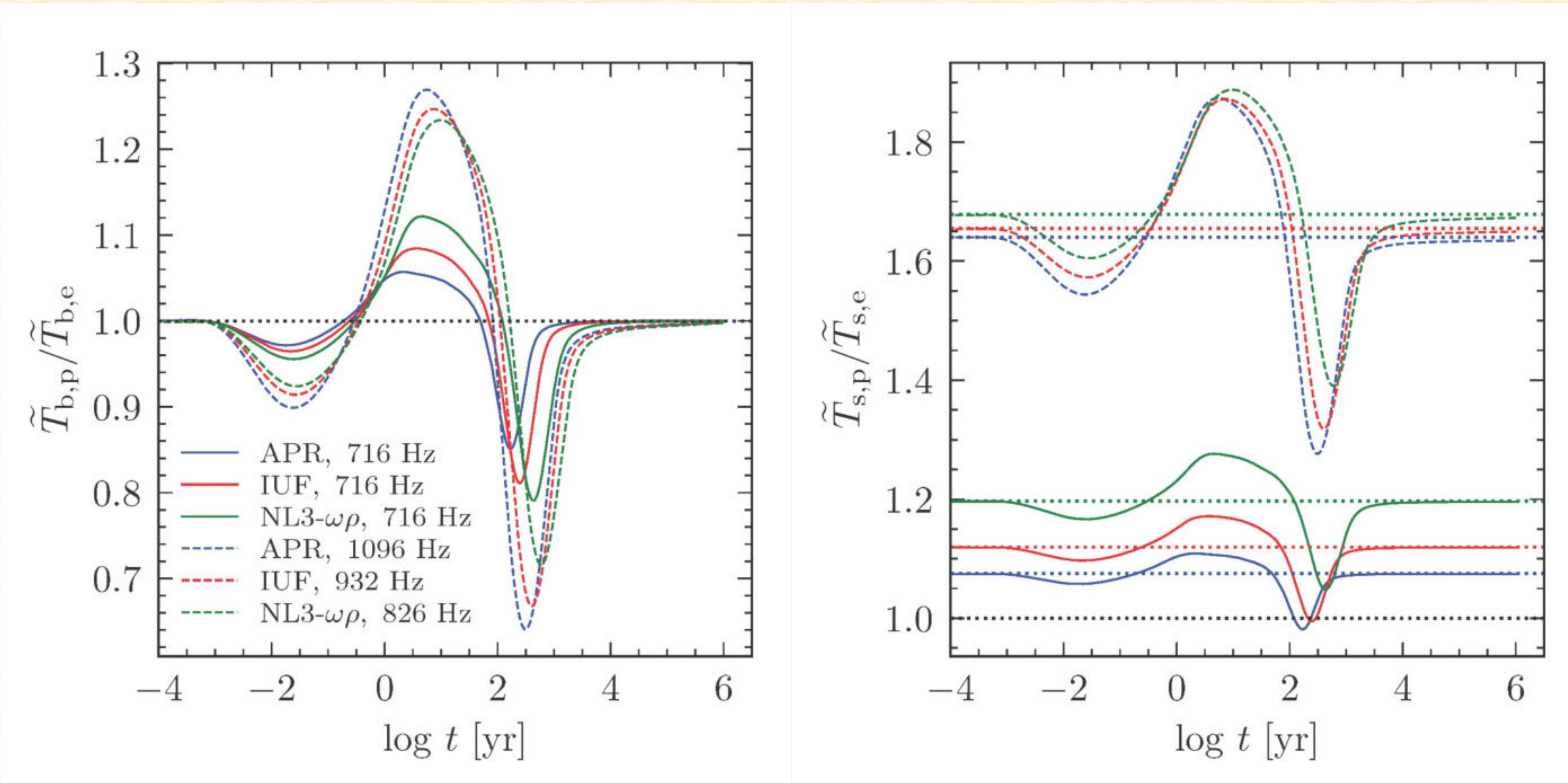
Internal redshifted temperature distribution. APR EOS. 716 Hz (left) and 1096 Hz (right). Age $t = 300$ years.



Profiles of redshifted temperature as a function of radial coordinate (left) and logarithm of density (right). APR EOS. $t = 150$ years.



Ratio of polar to equatorial temperature as functions of time. Bottom temperature (left) and surface temperature (right).



Conclusions

- We have investigated the standard cooling of isolated nucleonic NSs uniformly rotating with frequencies up to the mass shedding limit.
- The results indicate complex time-dependent evolution of temperature distribution throughout the whole volume of the star and, in particular, in the crust.
- We show that most of that complexity can be attributed to the formation of a "heat blob" in the crust and to the latitude dependence of the heat diffusion timescale through the crust.
- The "heat blob" itself forms in the equatorial plane due to rotation-induced deformation of the crust and persists over $1 \lesssim \log t \lesssim 3$.

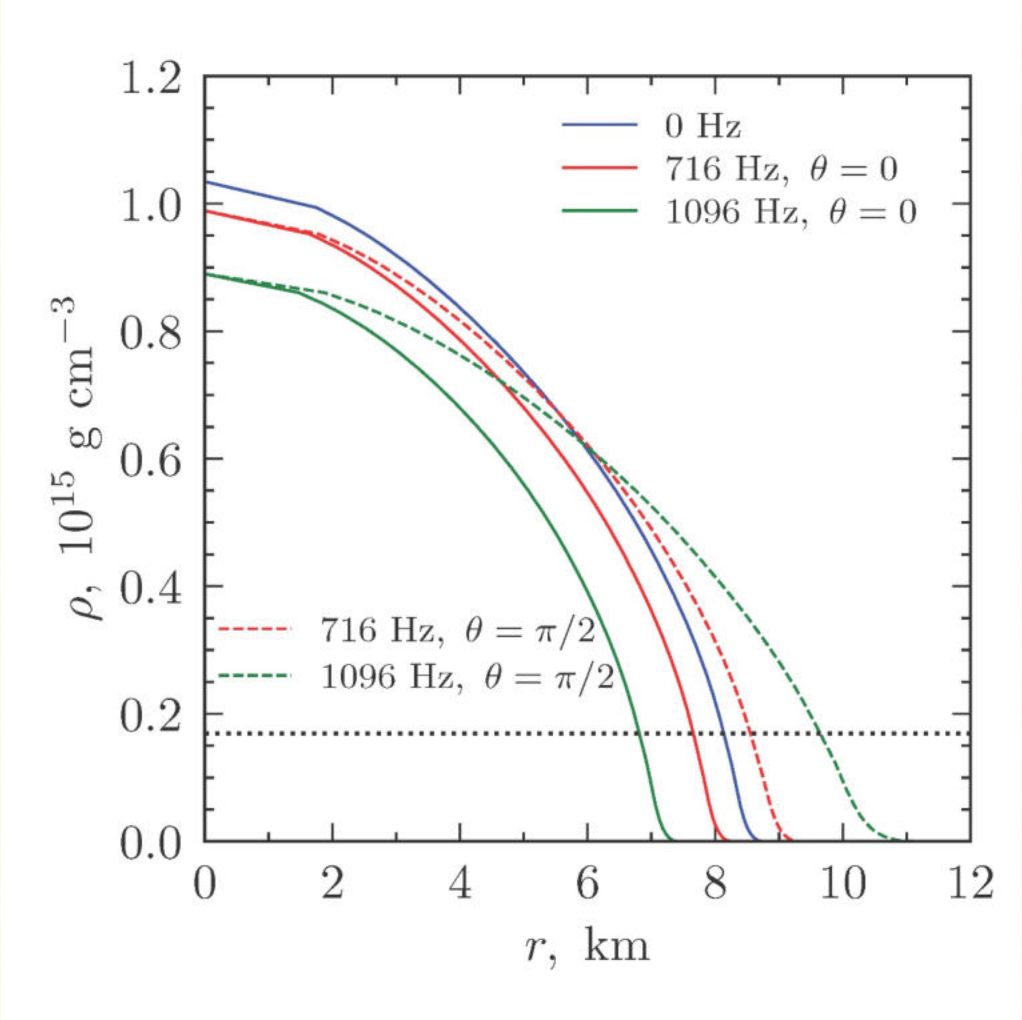
Conclusions

- In contrast with the crust, the core is little affected by rotation. Even for near-Kepler models polar to equatorial temperature differences do not exceed few percent.
- The angular distribution of the surface temperature is strongly affected by the dependence of the “$T_\mathrm{s} - T_\mathrm{b}$” relation on the surface gravity acceleration.

All figures presented here are taken from our paper, ApJ, **942**, 72 (2023)

Thank you!

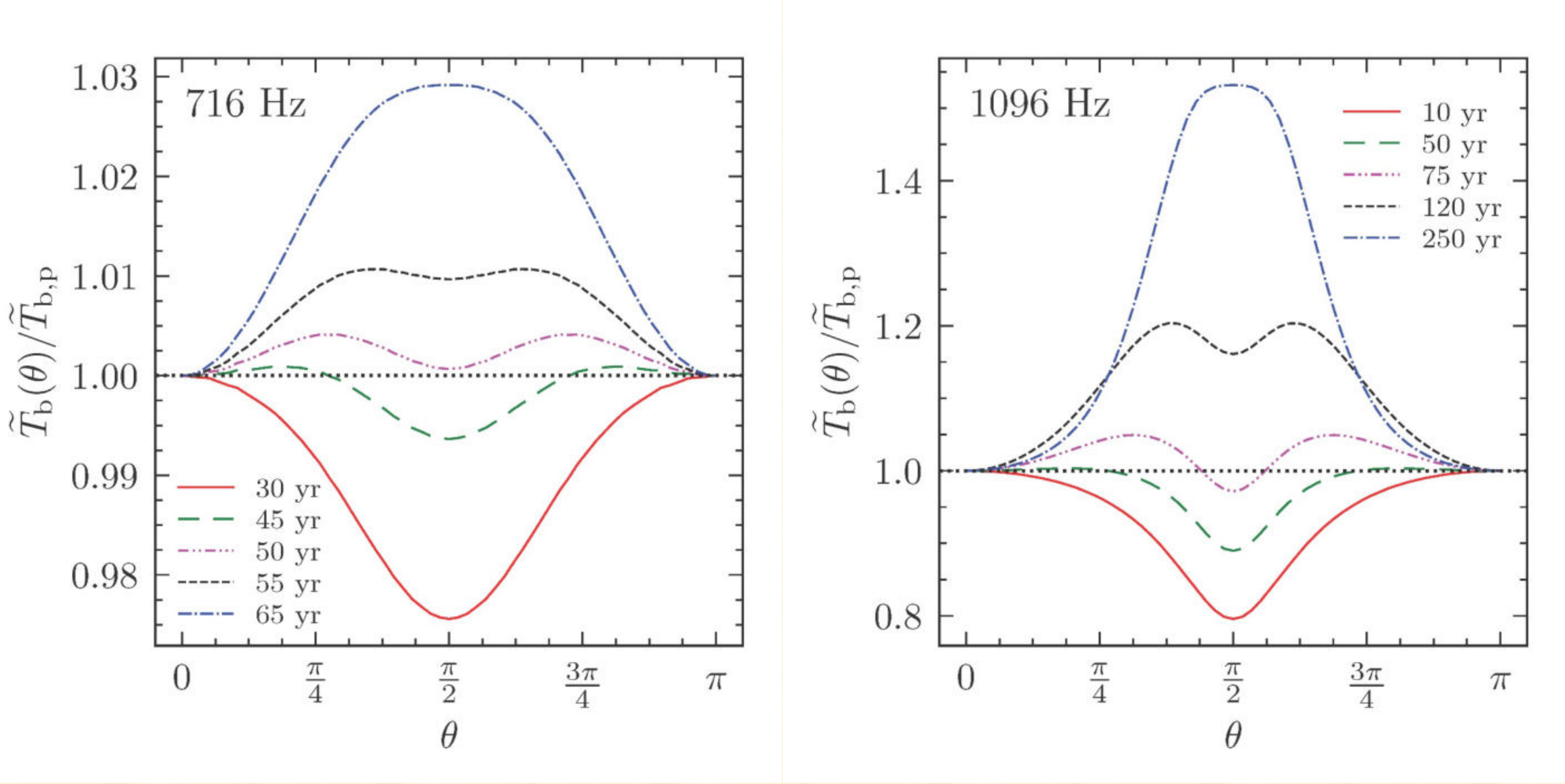
Mechanical structure. APR EOS. Radial density profiles



A quick reminder of a standard approach to long-term cooling of NSs

- Within a few hours to a day after the birth of a NS its temperature drops well below 10^{10} K.
- At such temperatures thermal effects on NS composition and mechanical structure become negligible everywhere except for the heat blanketing envelope.
- The chemical composition and equilibrium configurations may be assessed by employing a barotropic EOS of cold matter in β-equilibrium.
- The barotropic EOS allows one to decouple mechanical structure and thermal evolution equations. The former has then to be calculated only once while the latter are solved repeatedly as time progresses.

Normalized temperature at the bottom of the envelope as a function of θ for different moments in time. APR EOS.



Ratio of polar to equatorial temperature as functions of time for different densities inside the star. APR EOS. 1096 Hz.