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Cooling of rapidly rotating neutron stars in 2D

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Thermal and magnetic evolution of neutron stars,
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Cooling of rapidly rotating NSs

Introduction

Main part

- Spacetime metric
- Models of rotating NSs
- Cooling of rotating NSs
  - Without superfluidity
  - With crustal superfluidity

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 measurements 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.

Spacetime metric

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

The motion of the matter is assumed to be:

- Axisymmetric
- Stationary
- Purely azimuthal (i.e., no convection, no meridional currents, no mass flows induced by heat transport)

The EOS of the matter is barotropic.

Following *LORENE* we employ *quasi-isotropic* spherical coordinate system.

Note that such quasi-isotropic coordinates are different from conventional Schwarzschild coordinates.

Spacetime metric

Choosing “natural” tetrad $e_\alpha = \partial_\alpha = \partial/\partial x_\alpha$ with $x_\alpha = (ct, r, \theta, \varphi)^{\mathrm{T}}$ we obtain the following expression for the line element:

$$ds^2 = g_{\alpha\beta}\mathrm{d}x^\alpha \mathrm{d}x^\beta = -N^2 c^2 \mathrm{d}t^2 + A^2\left(\mathrm{d}r^2 + r^2\mathrm{d}\theta^2\right) + B^2 r^2 \sin^2\theta\left(\mathrm{d}\varphi - N^\varphi \mathrm{d}t\right)^2$$

where N, A, B and N^φ are four metric functions that are calculated by *LORENE* together with the mechanical structure of a rotating NS.

Models of rotating NSs

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 the 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.

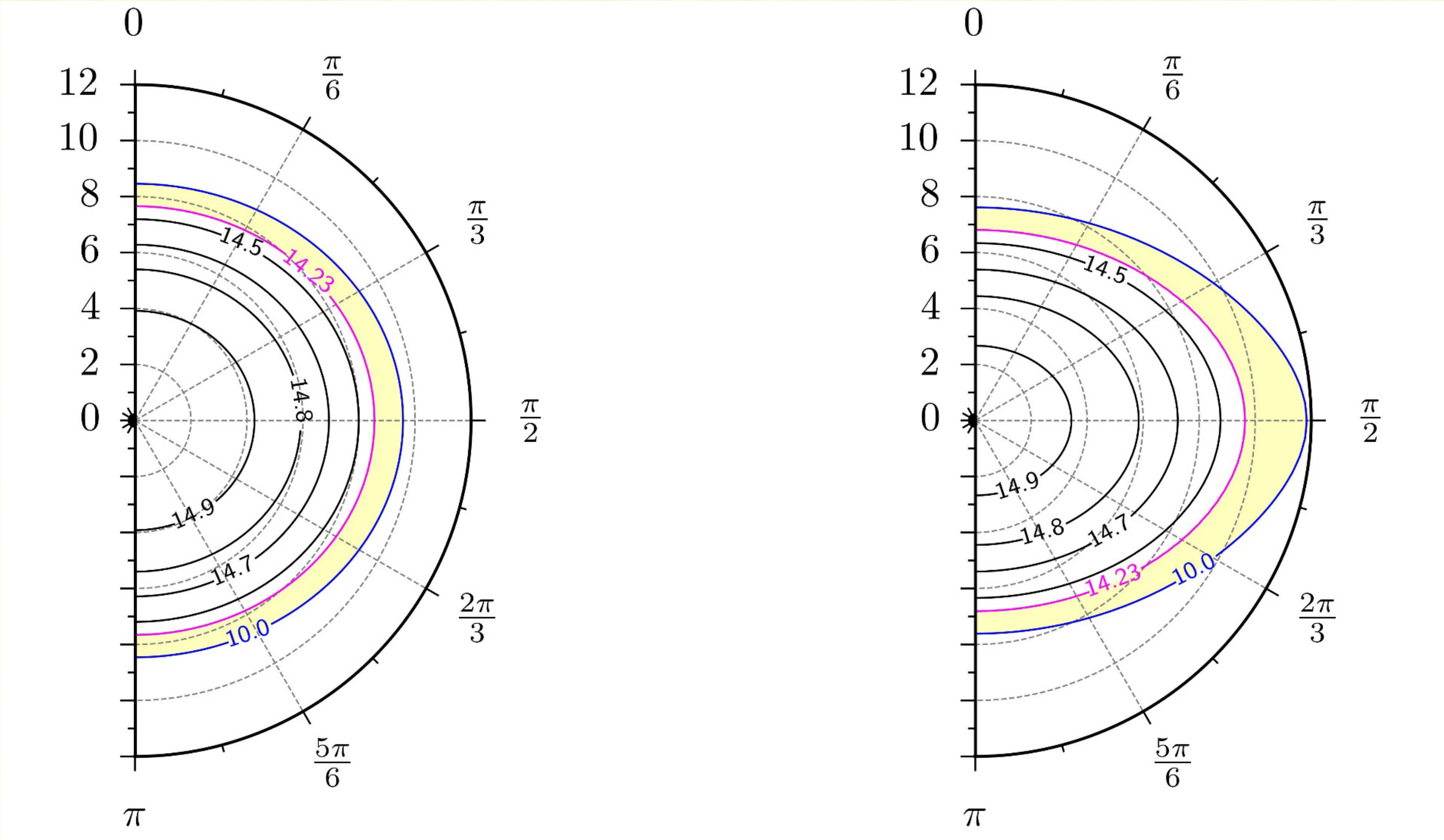
The value of choice for the baryonic mass is $M_{\mathrm{B}} = 1.6\,\mathrm{M}_{\odot}$, which results in gravitational masses close to the canonical value of $1.4\,\mathrm{M}_{\odot}$.

For the rotation frequency we have considered two values.

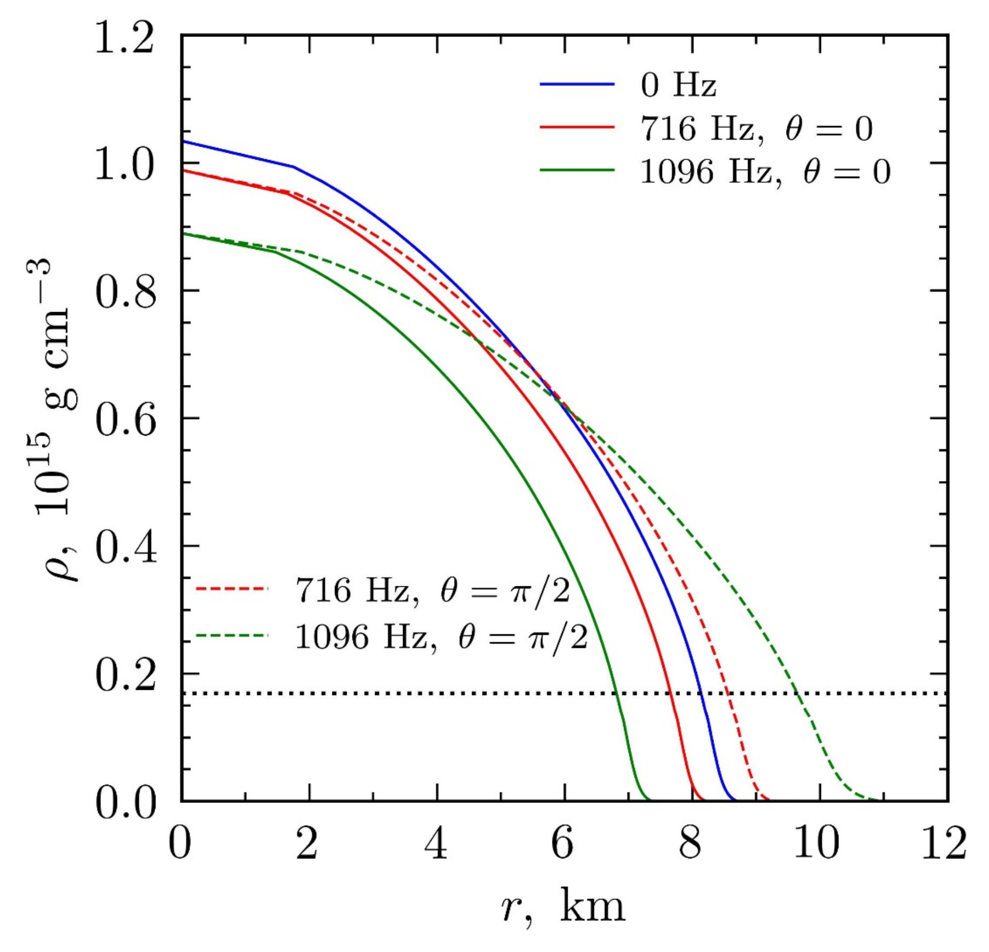
The first one, 716 Hz, corresponds to the fastest know millisecond pulsar (PSR J1748–2446ad).

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)



Mechanical structure. APR EOS. Radial density profiles

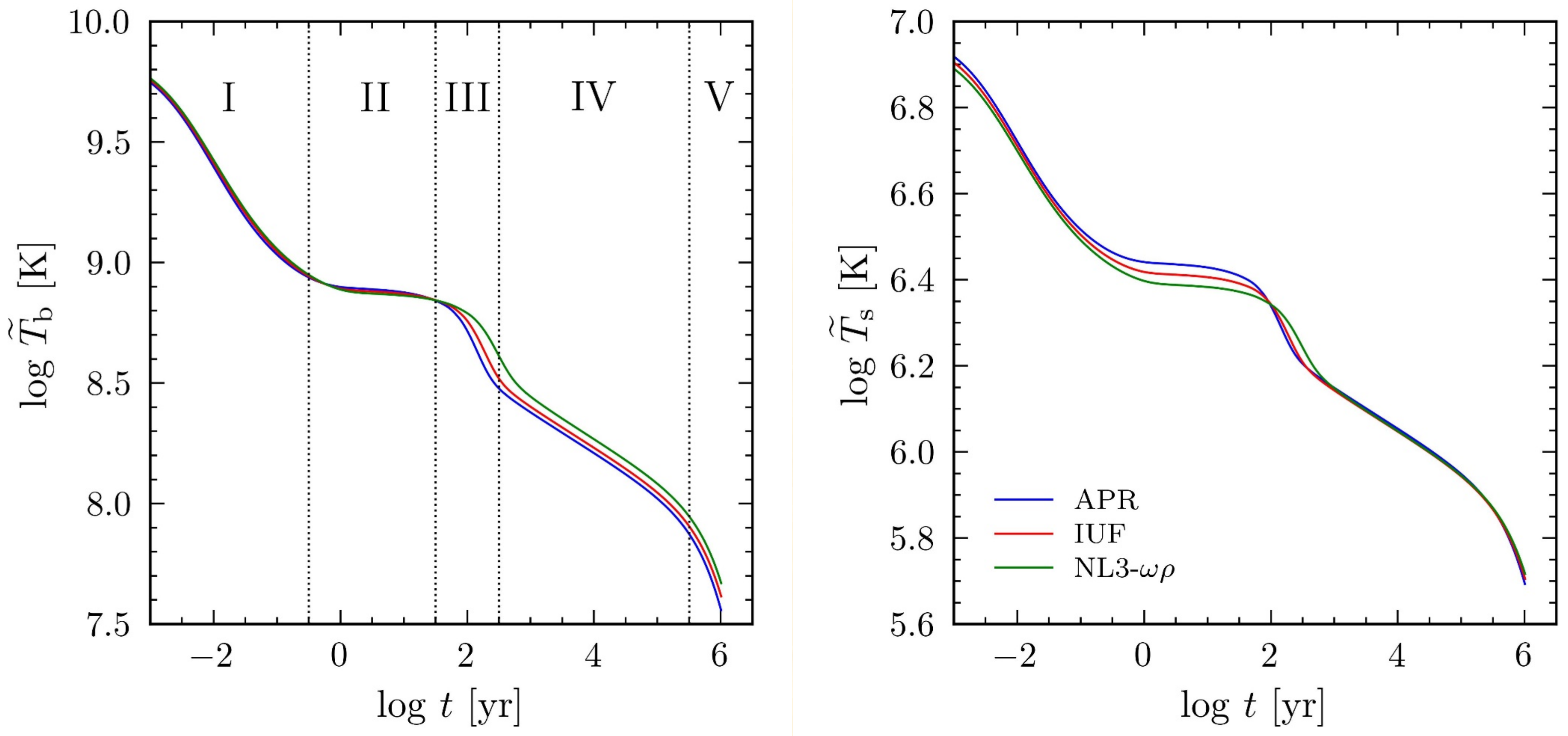


Cooling of rotating NSs

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

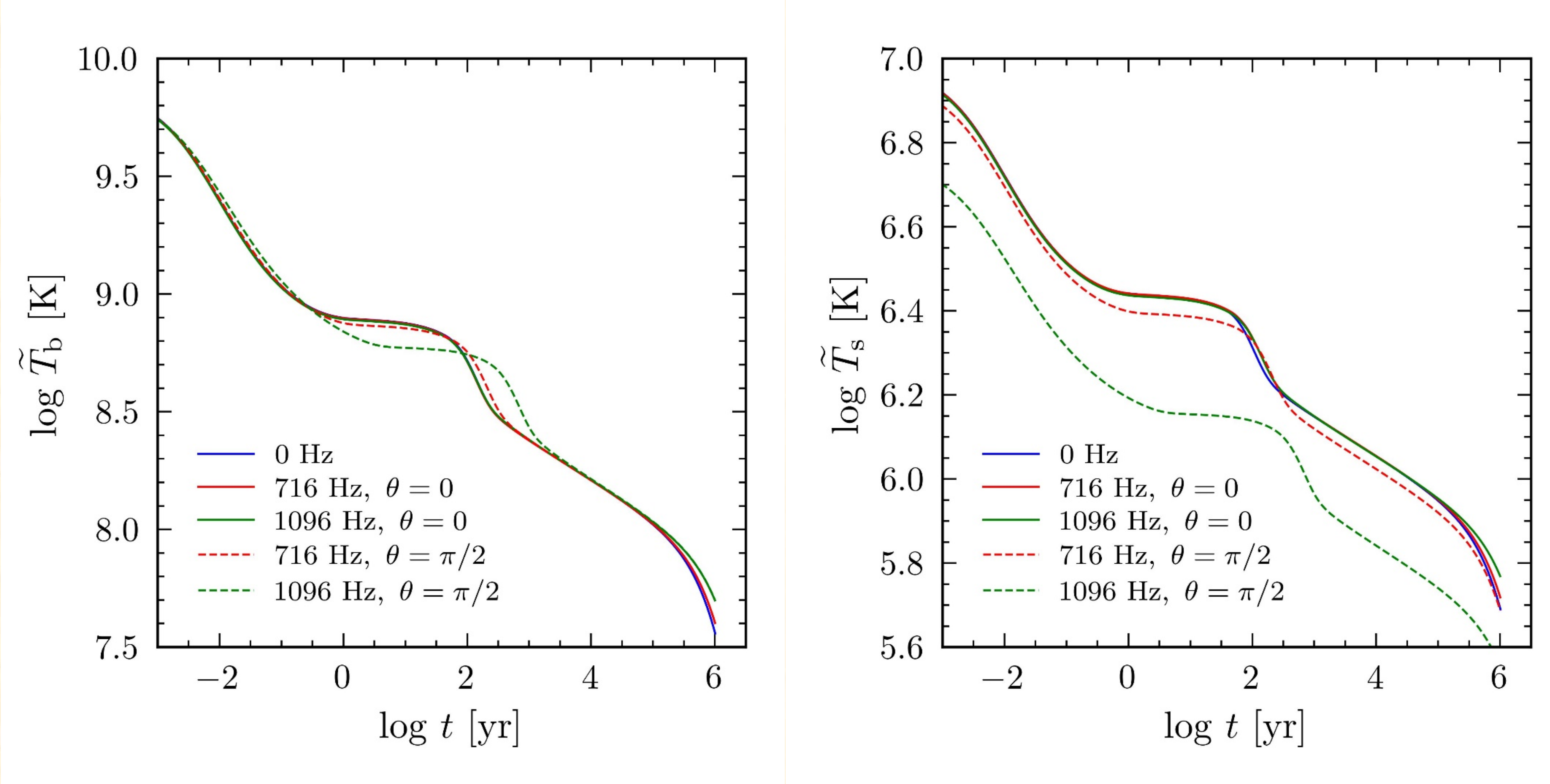
Cooling of rotating NSs

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



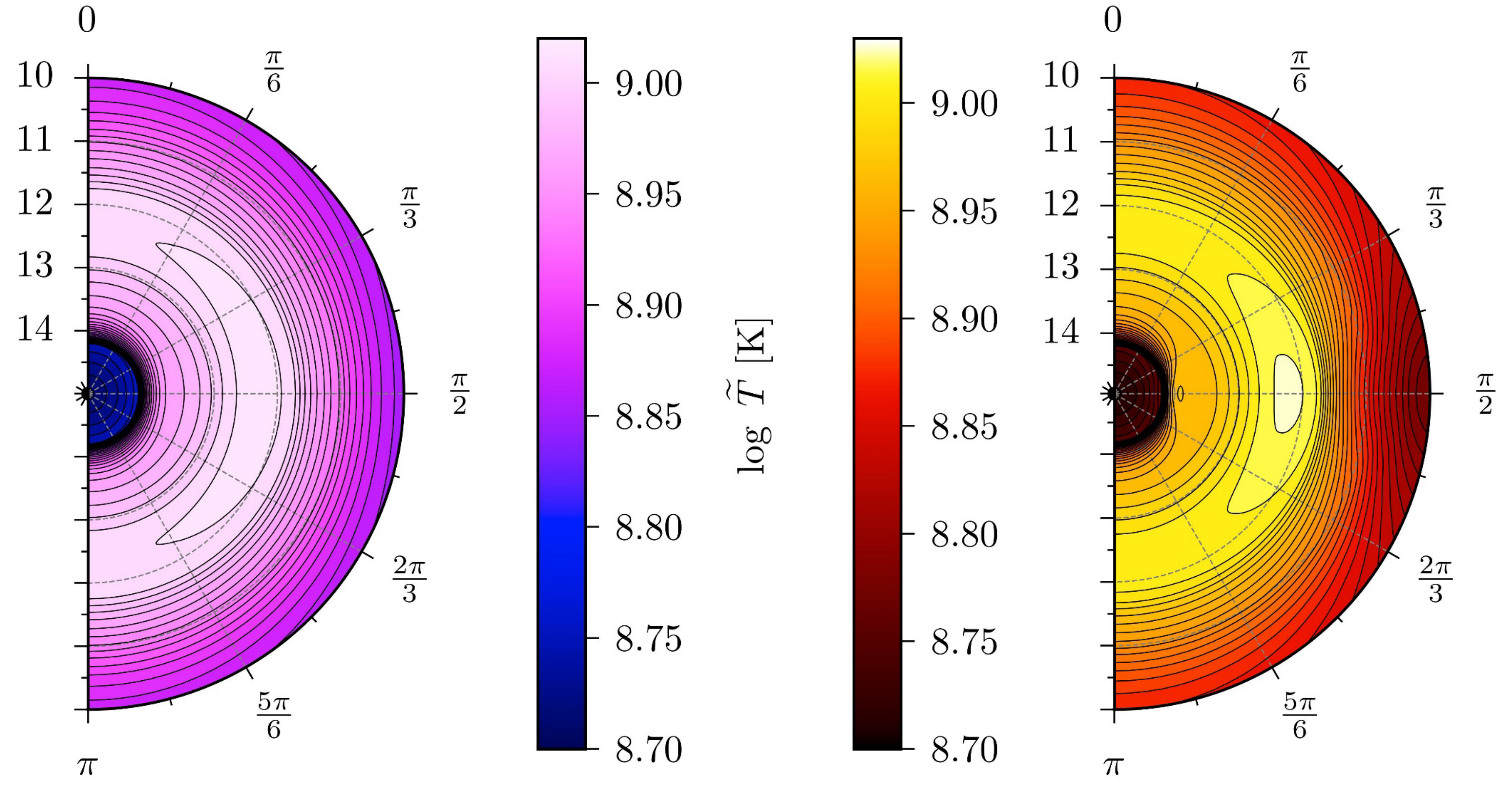
Cooling of rotating NSs

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



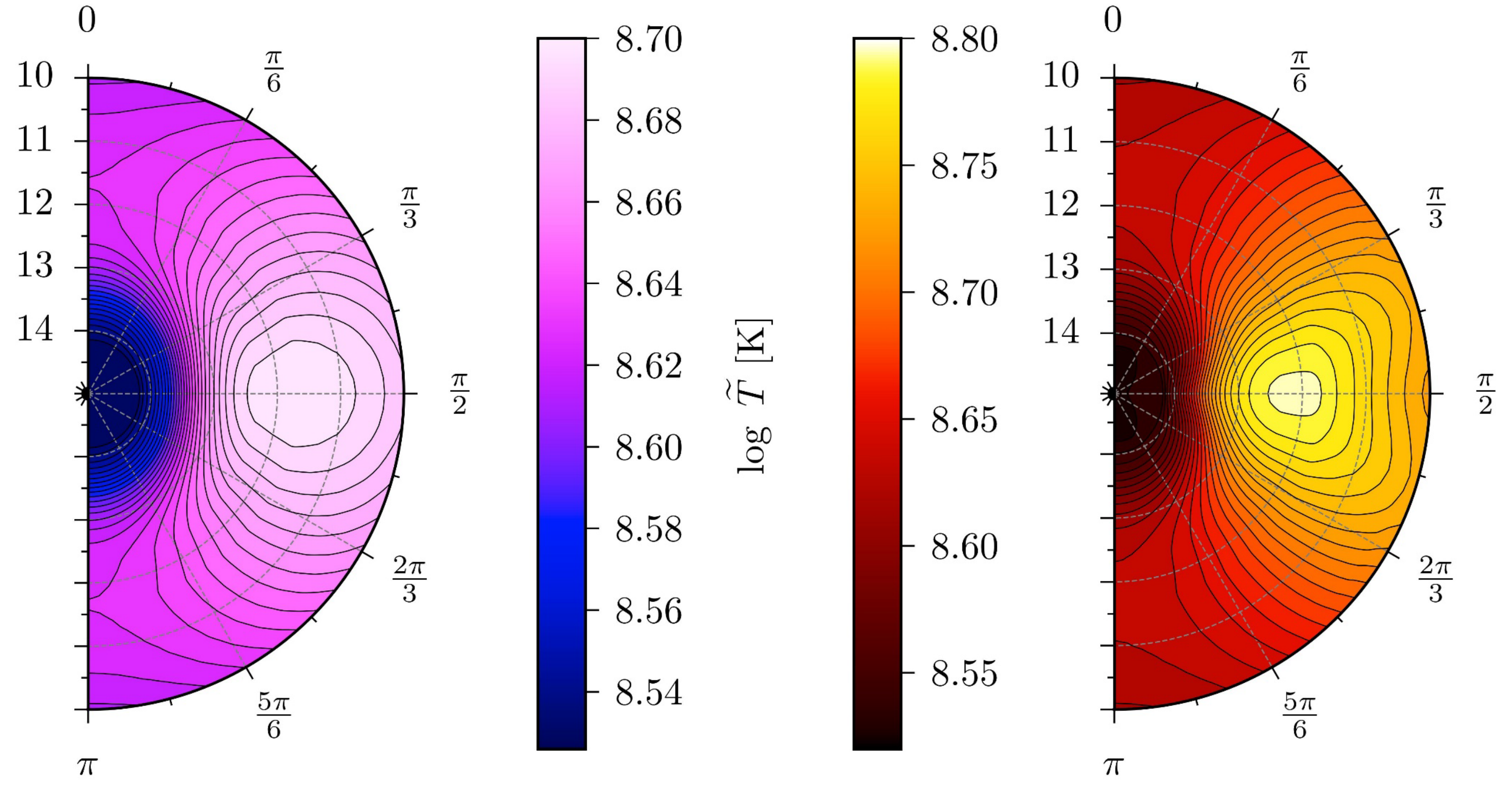
Cooling of rotating NSs

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



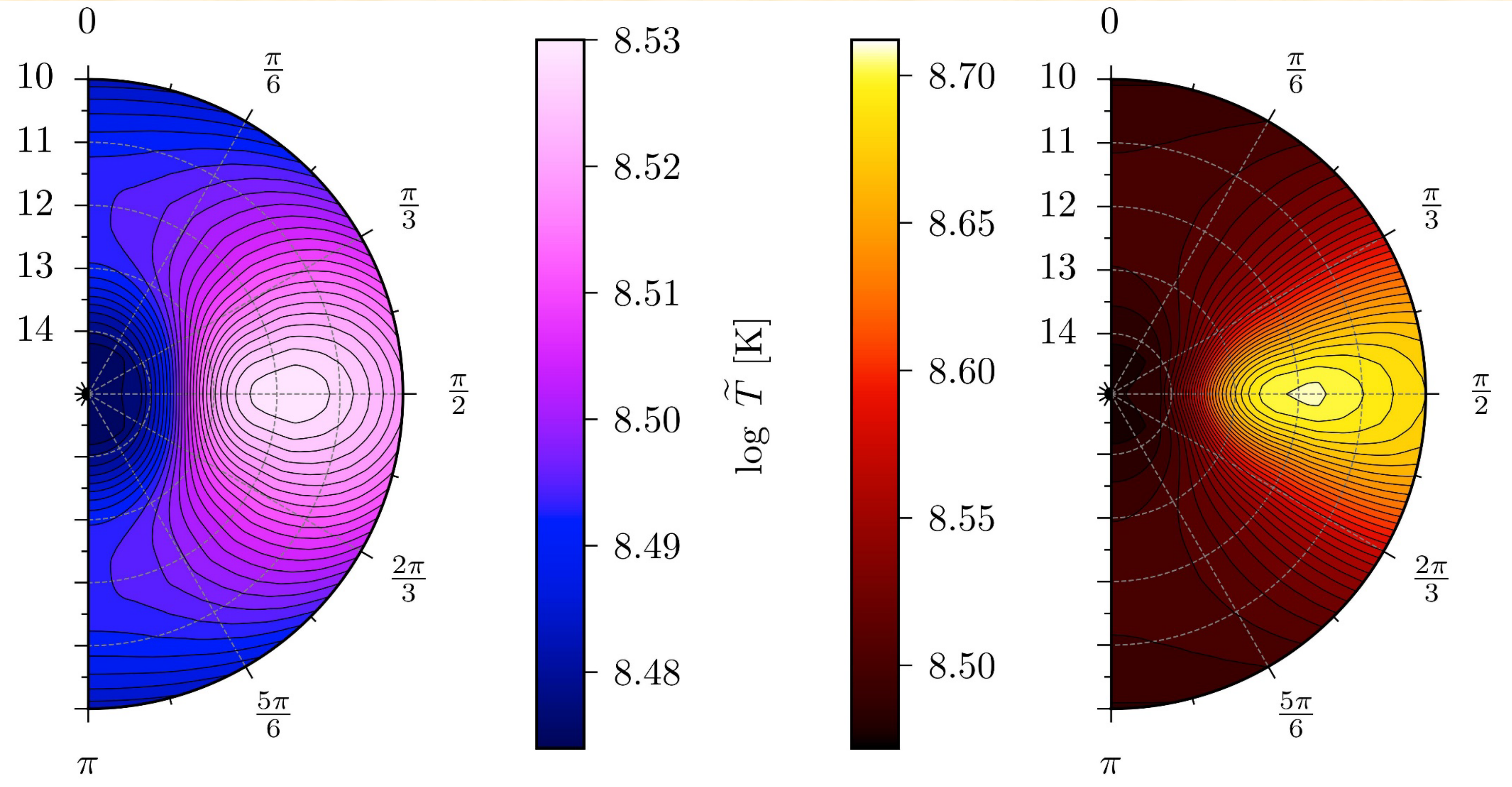
Cooling of rotating NSs

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



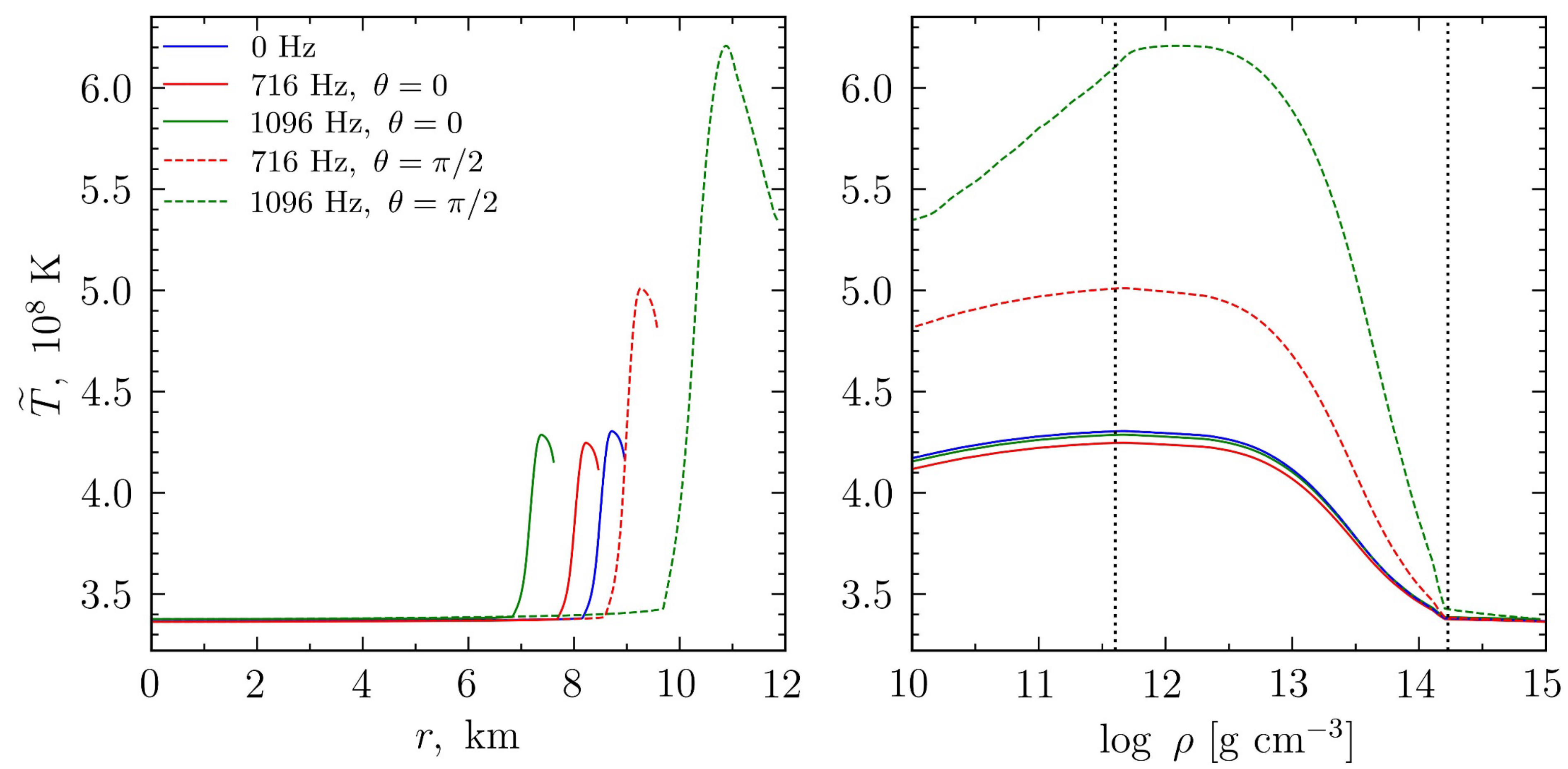
Cooling of rotating NSs

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



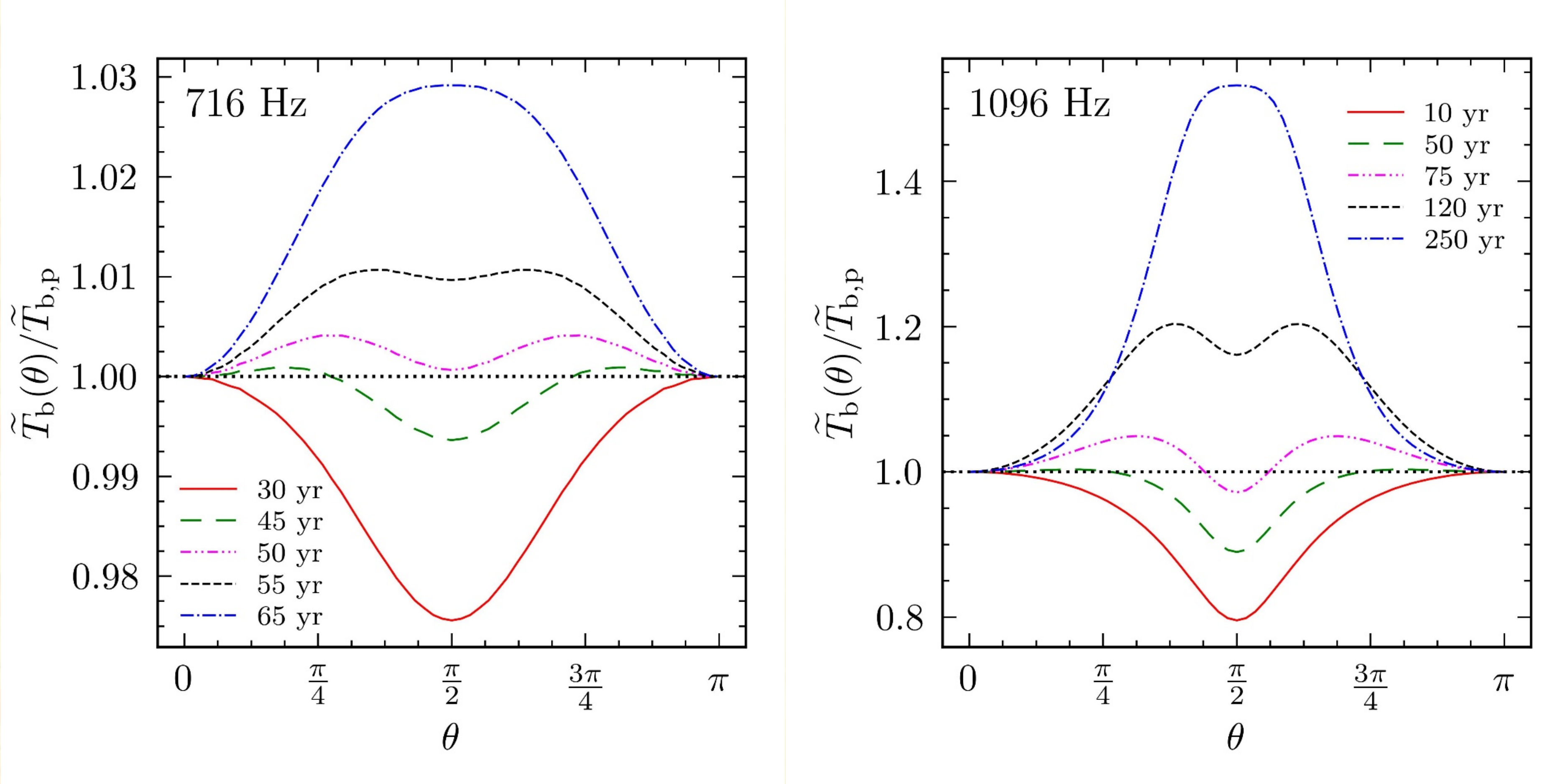
Cooling of rotating NSs

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



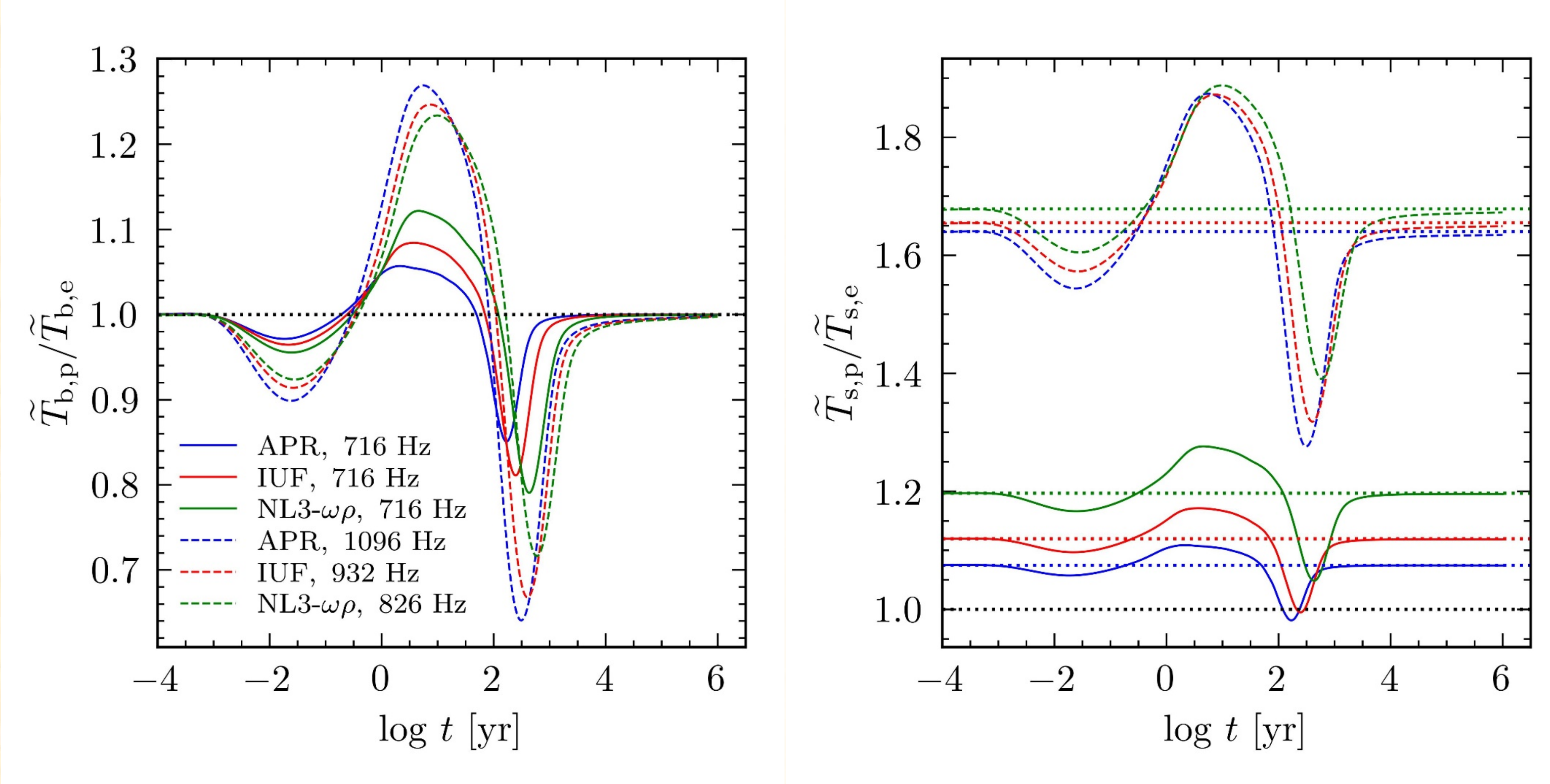
Cooling of rotating NSs

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



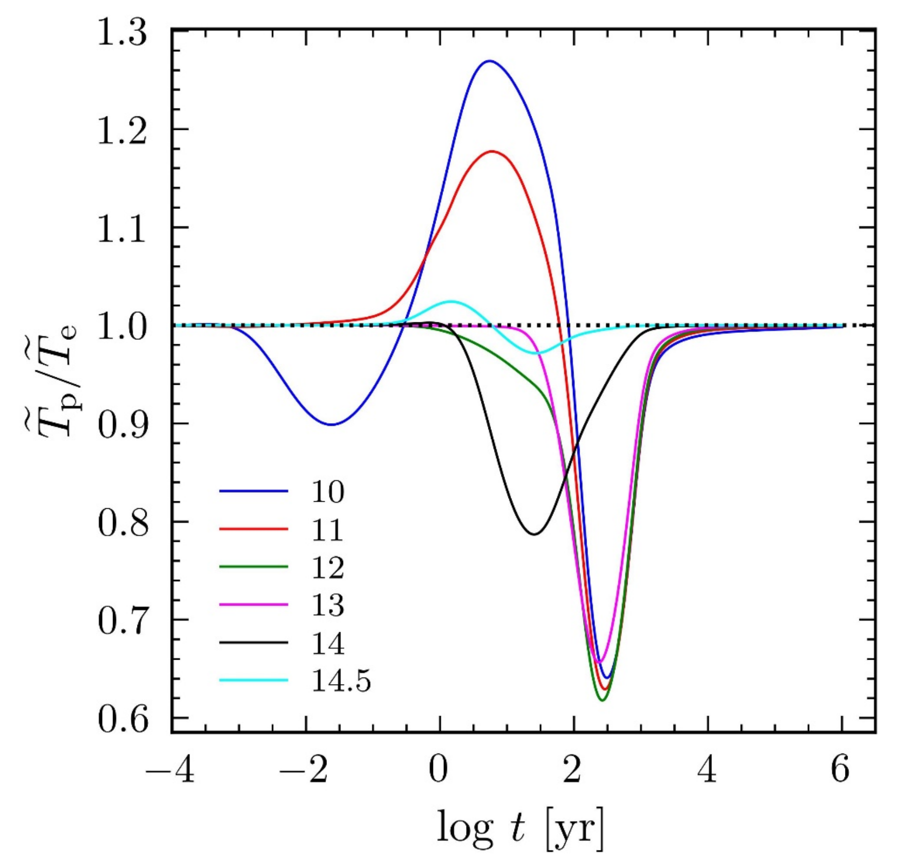
Cooling of rotating NSs

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



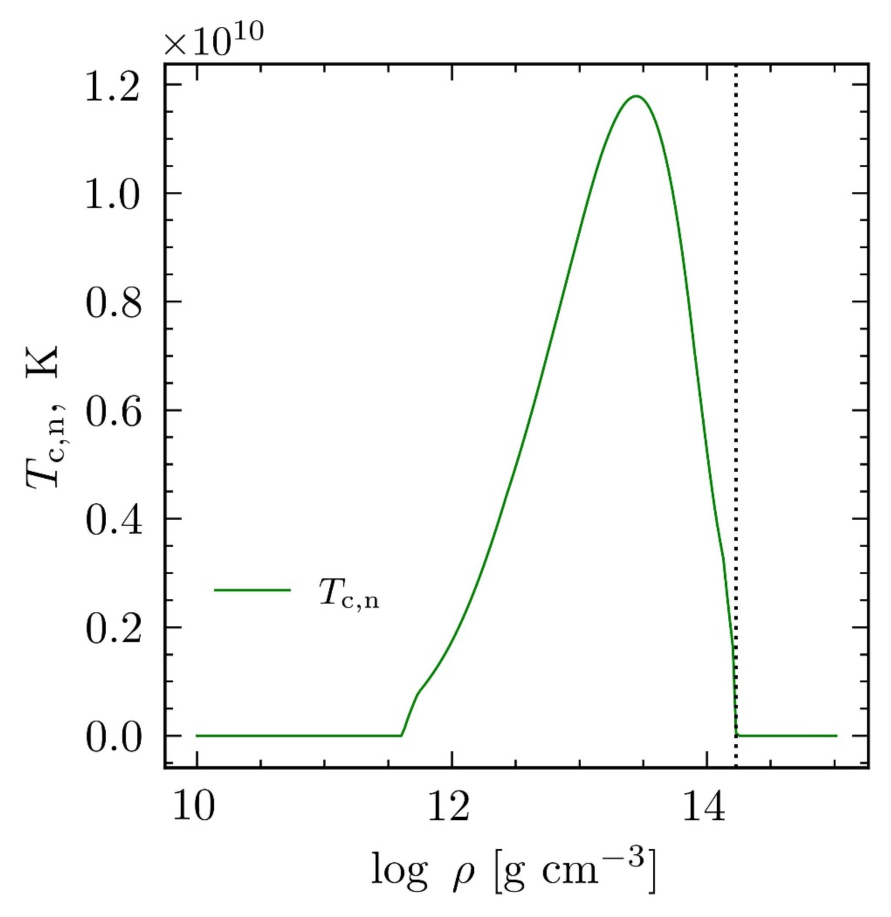
Cooling of rotating NSs

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



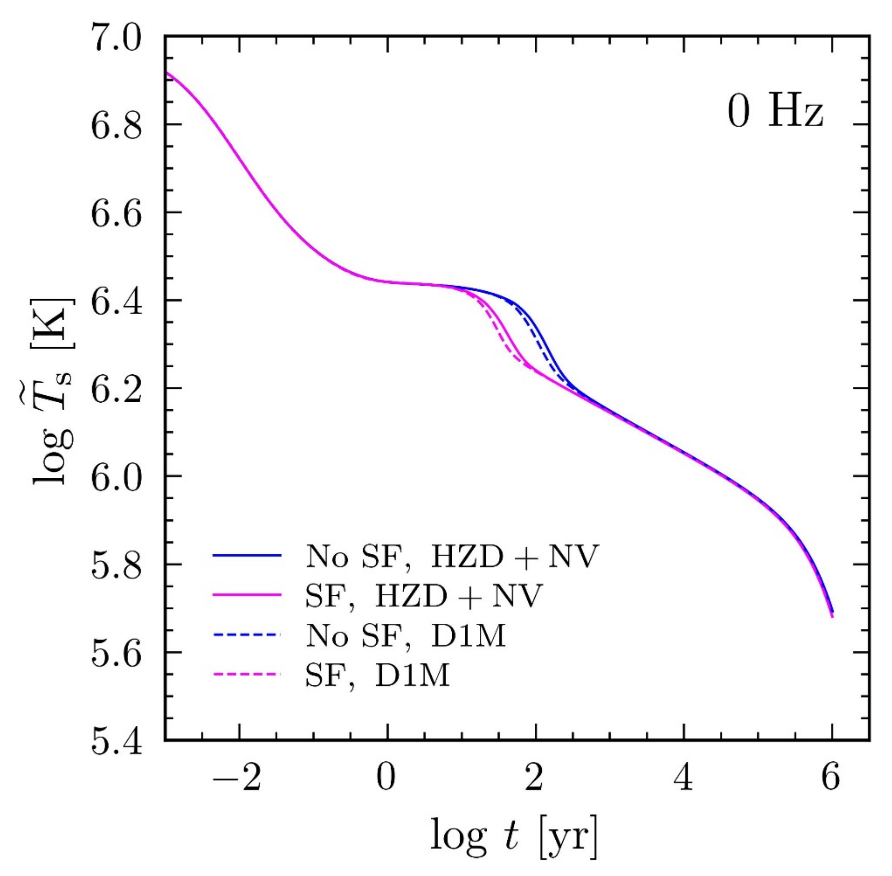
Cooling of rotating NSs

We have considered ${}^1S_0$ neutron superfluidity with the pairing gap from Ding et al., PRC 94, 025802 (2016).



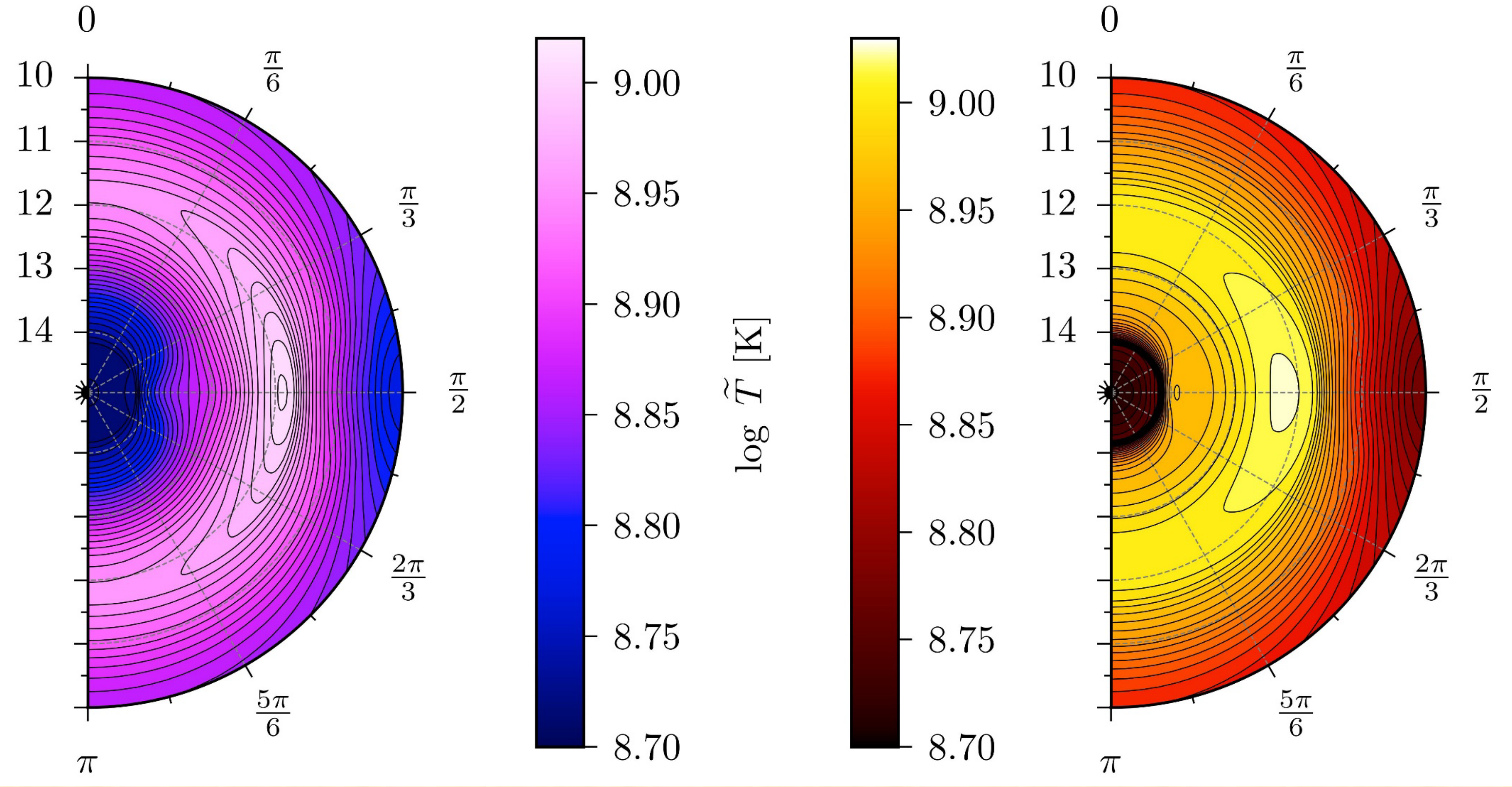
Cooling of rotating NSs

Comparison of different EOSs of the crust with and without $^1S_0$ neutron superfluidity, APR EOS of the core, non-rating NS.



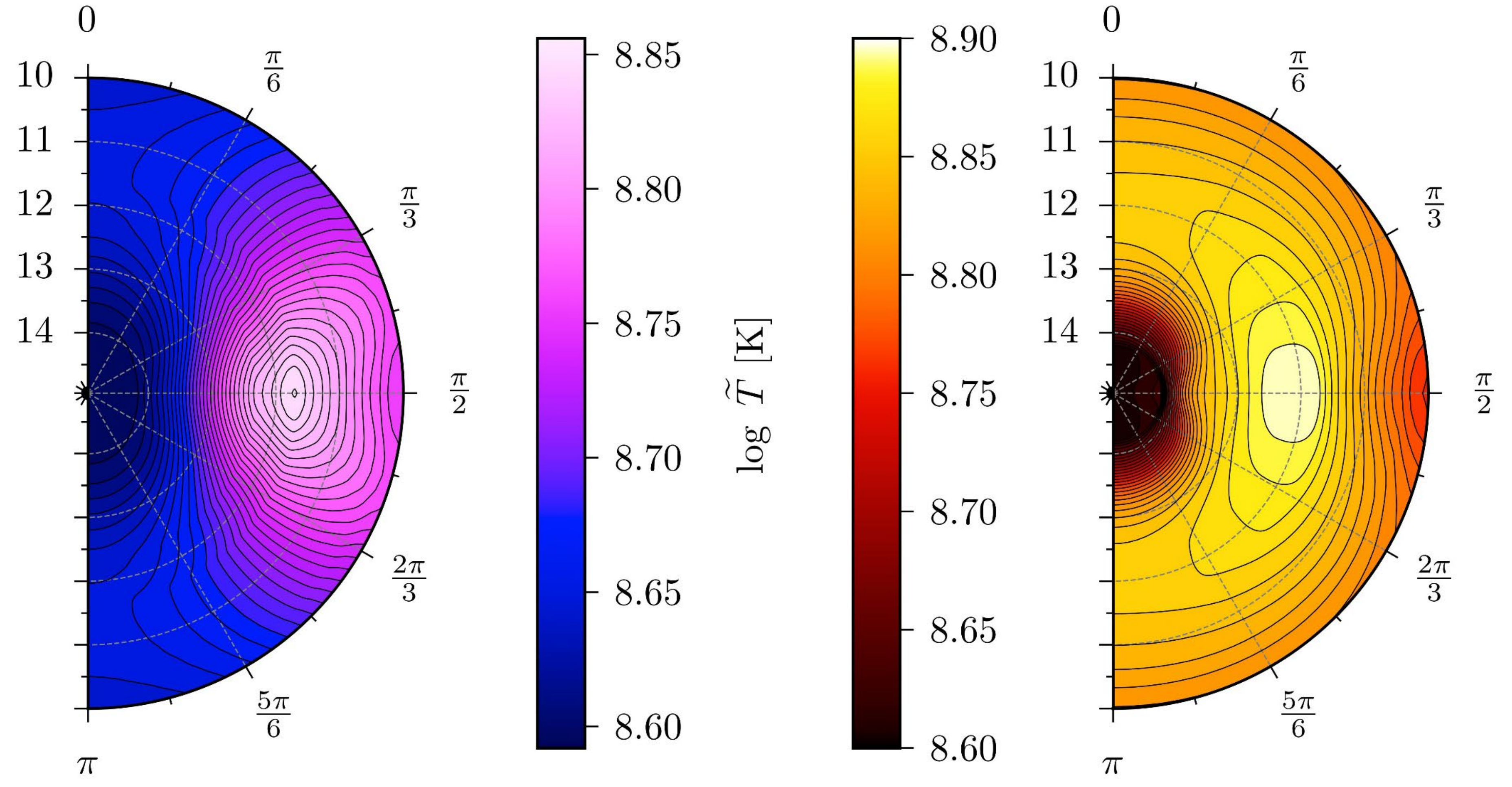
Cooling of rotating NSs

Internal redshifted temperature distribution. APR EOS. 1096 Hz. With superfluidity (left) and without it (right). Age $t = 10$ years.



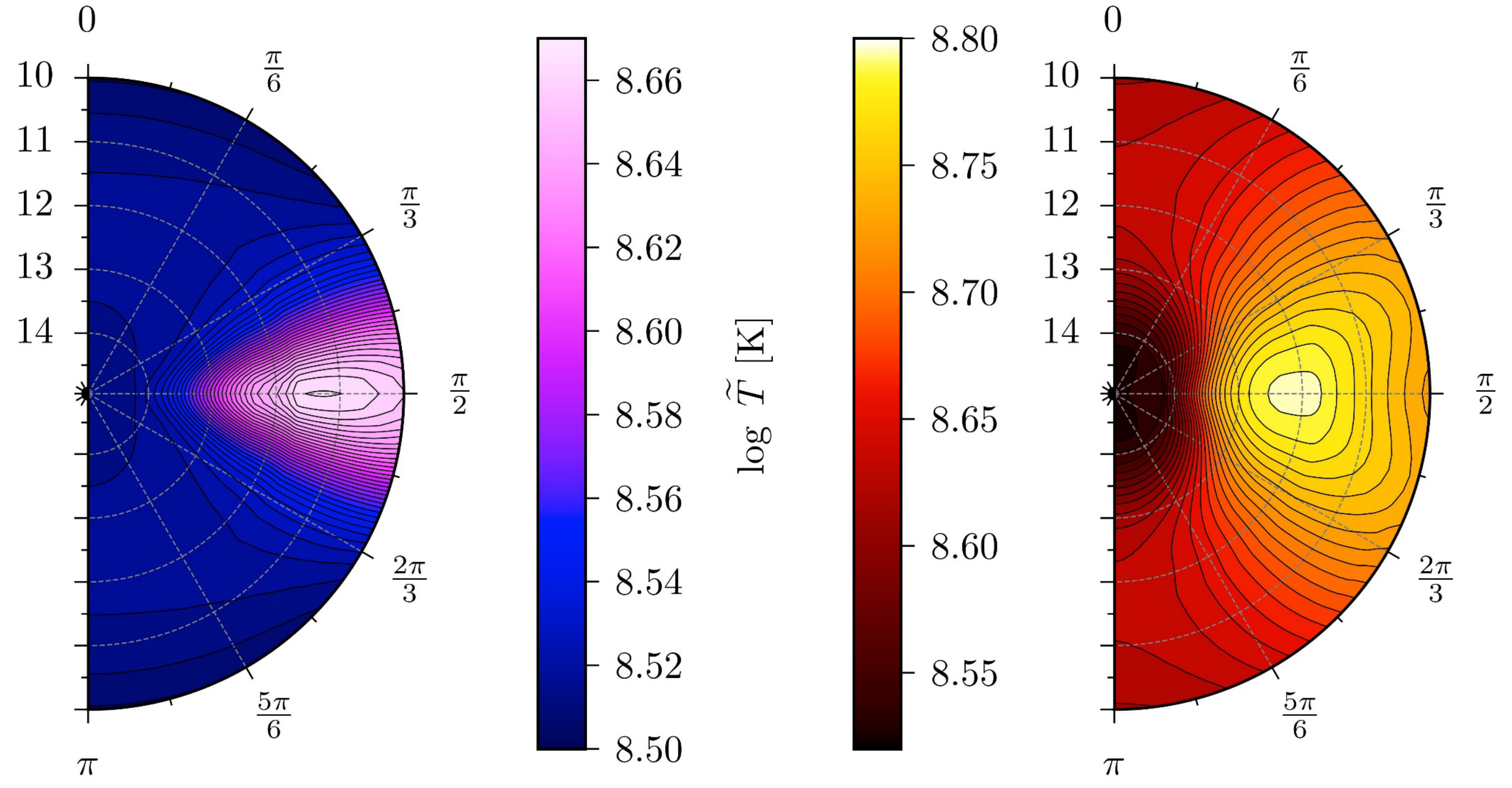
Cooling of rotating NSs

Internal redshifted temperature distribution. APR EOS. 1096 Hz. With superfluidity (left) and without it (right). Age $t = 50$ years.



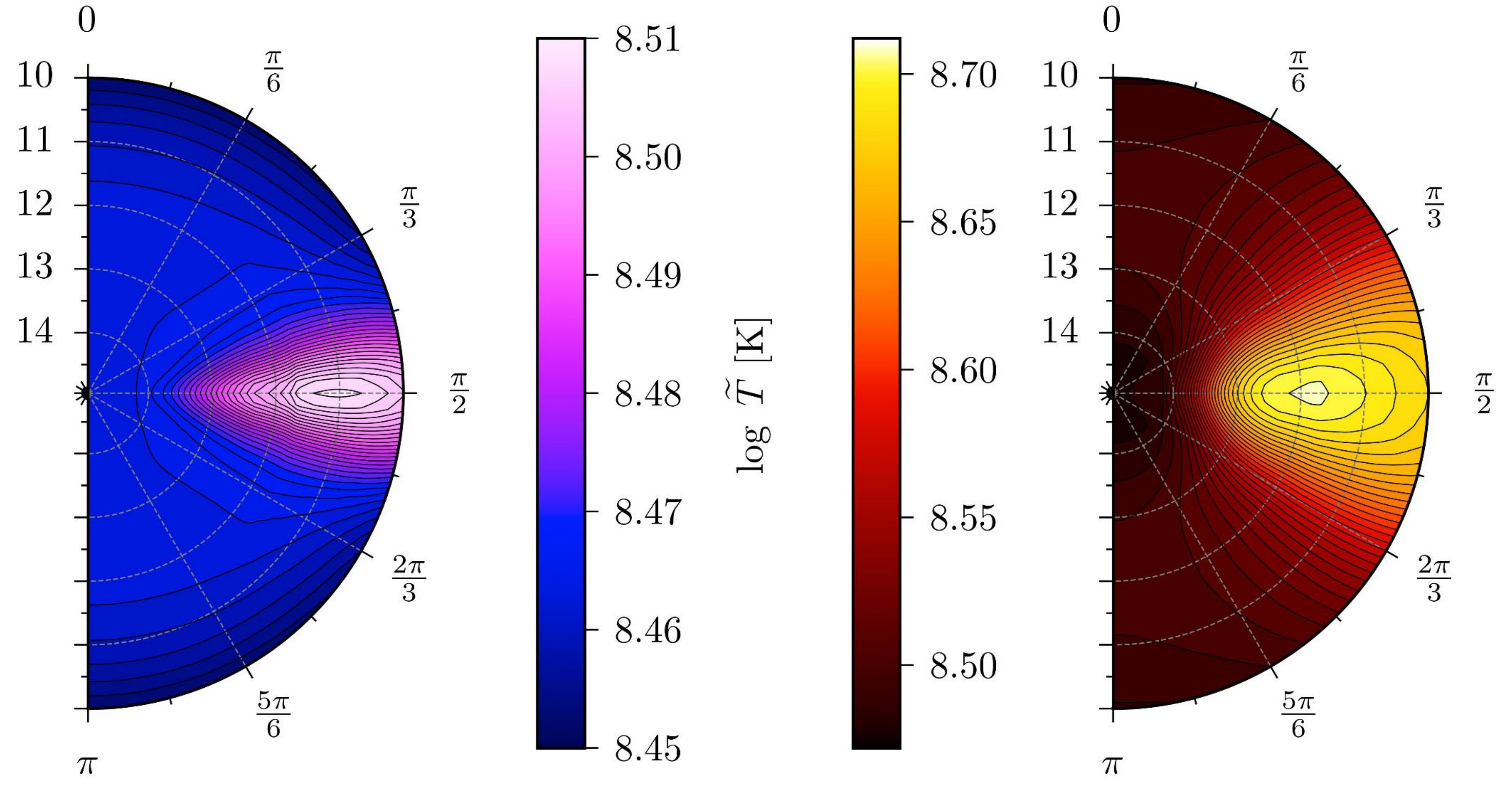
Cooling of rotating NSs

Internal redshifted temperature distribution. APR EOS. 1096 Hz. With superfluidity (left) and without it (right). Age $t = 150$ years.



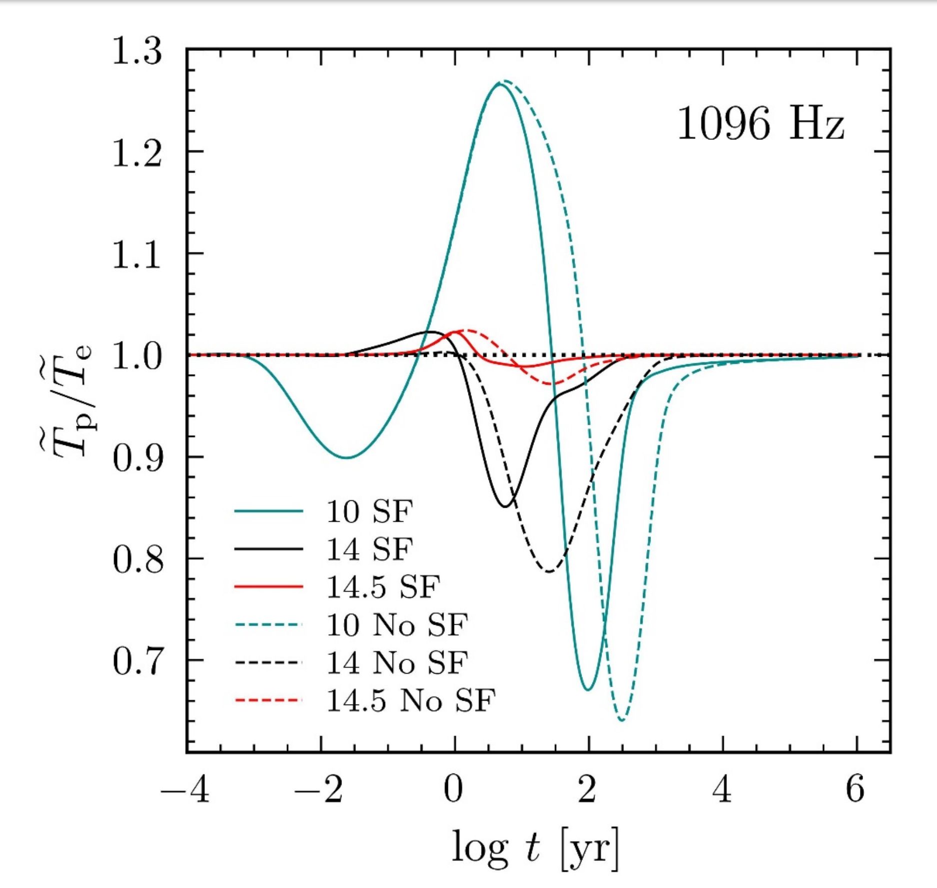
Cooling of rotating NSs

Internal redshifted temperature distribution. APR EOS. 1096 Hz. With superfluidity (left) and without it (right). Age $t = 300$ years.



Cooling of rotating NSs

Ratio of polar to equatorial temperature as functions of time for different densities inside the star. APR EOS. With and without superfluidity.



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.
- Crustal superfluidity reduce the impact of a “heat blob” and accelerates crust-core thermalization. It also has a slight impact on the temperature distribution in the outer layers of the core.

All figures presented here are either taken from our paper, ApJ, **942**, 72 (2023), or prepared specifically for this talk.

Thank you!