Magnetic Field in (Hybrid,Quark) Neutron Stars

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In collaboration with:
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Igor Mishustin (FIAS), Manuel Malheiro (ITA),
Marcelo Chiaparrini (UERJ), Eduardo Lenho (UERJ).

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CAPES

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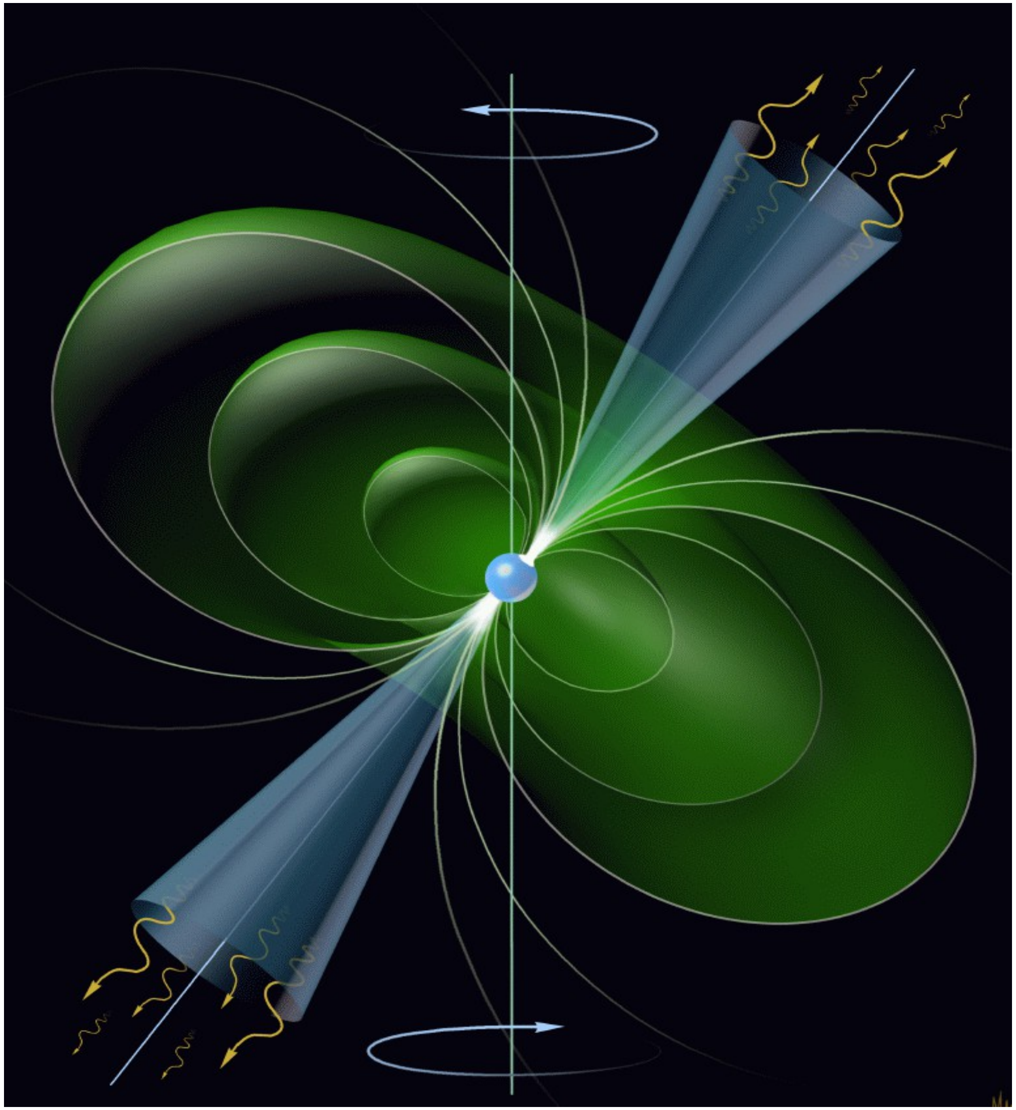
Neutron Stars – Magnetic Fields

Might affect neutron stars in different ways:



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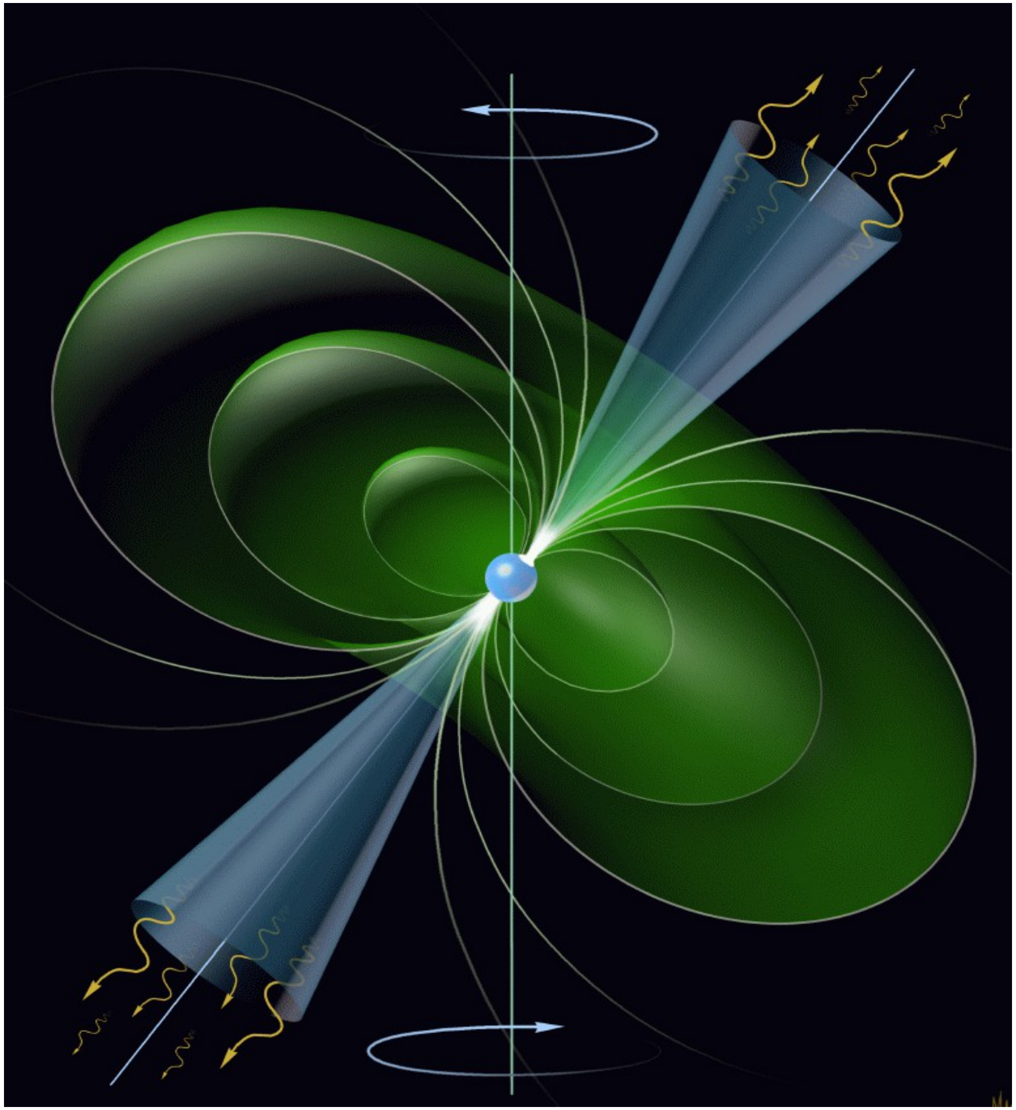

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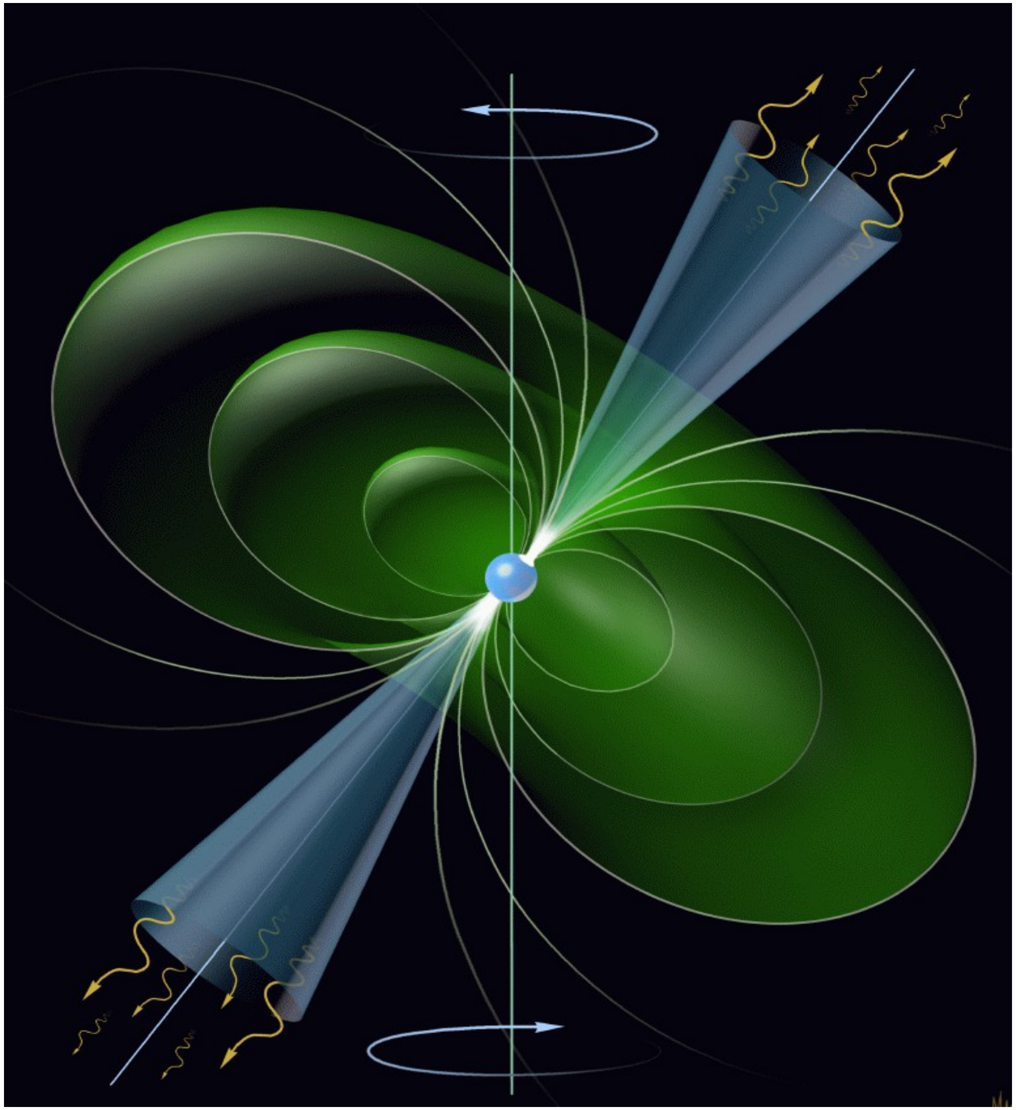

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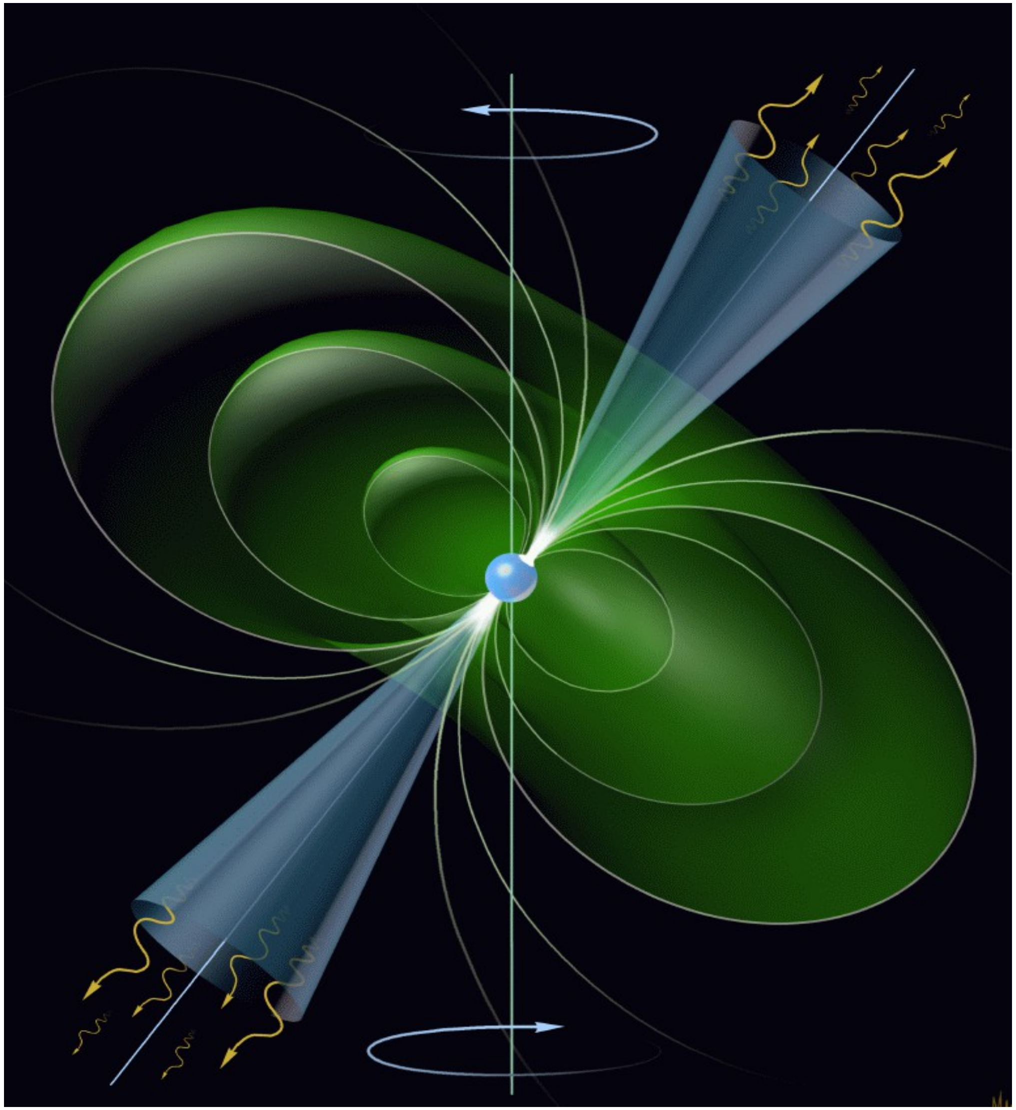

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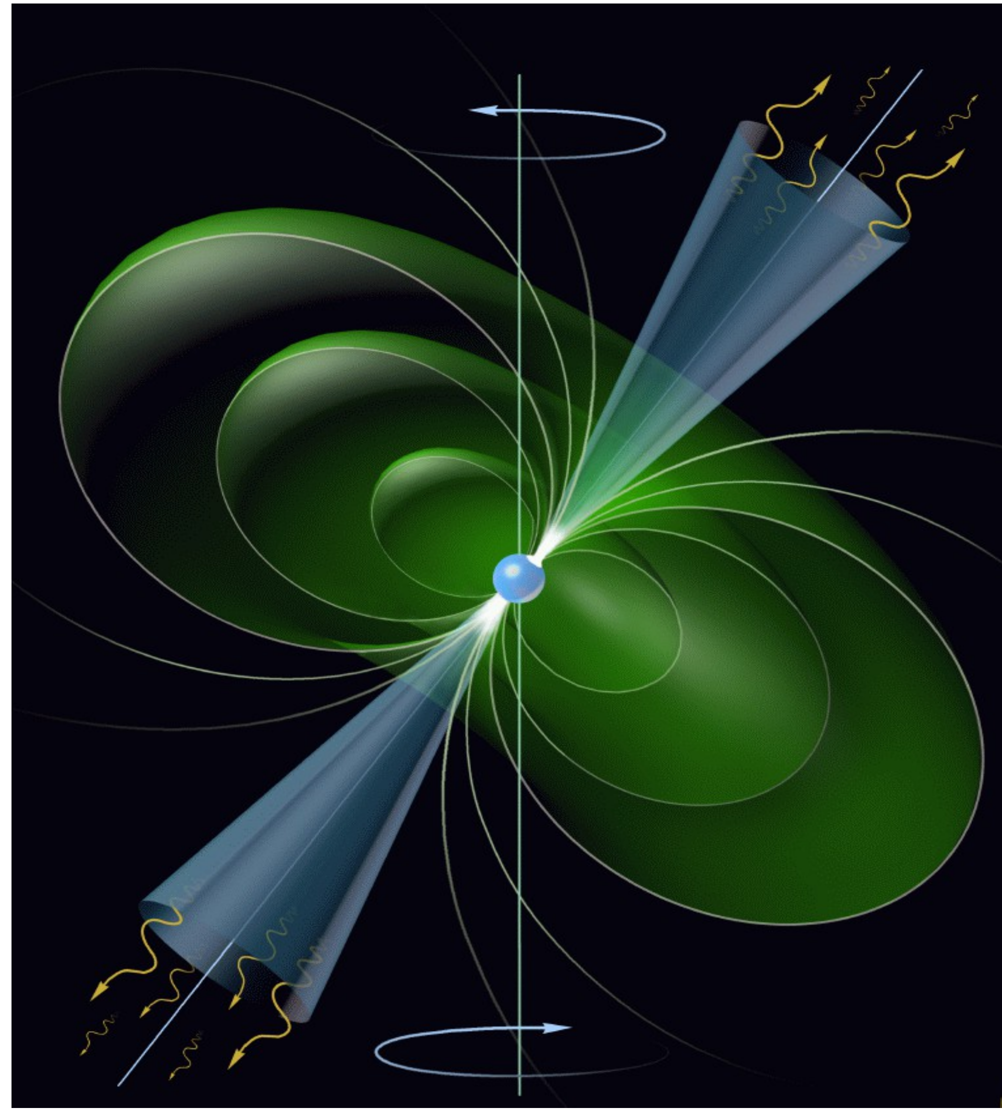

If the magnetic field is high enough it might affect the microscopic composition of the neutron star

- A magnetic field in the z-direction forces the eigenstates in the x and y directions of the charged particles to be quantized into Landau levels v

$$E^*_{i_{\nu s}} = \sqrt{k^2_{z_i} + \left(\sqrt{m_i^{*2} + 2\nu|q_i|B^*} - s_i\kappa_i B^*\right)^2}$$

Neutron Stars – Magnetic Fields – Microscopic Effects

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Protons

$$B \sim 10^{18-20}\mathrm{G}$$

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Protons → $$B \sim 10^{18-20}\mathrm{G}$$

electrons → $$B \sim 10^{13}\mathrm{G}$$

Magnetic Field:

$$B^*(\mu_B) = B_{surf} + B_c \left[1 - e^{b\frac{(\mu_B - 938)^a}{938}}\right]$$

V. Dexheimer, R. Negreiros, S. Schramm, Eur.Phys.J. A48 (2012) 189

Neutron Stars – Magnetic Fields – Microscopic Effects

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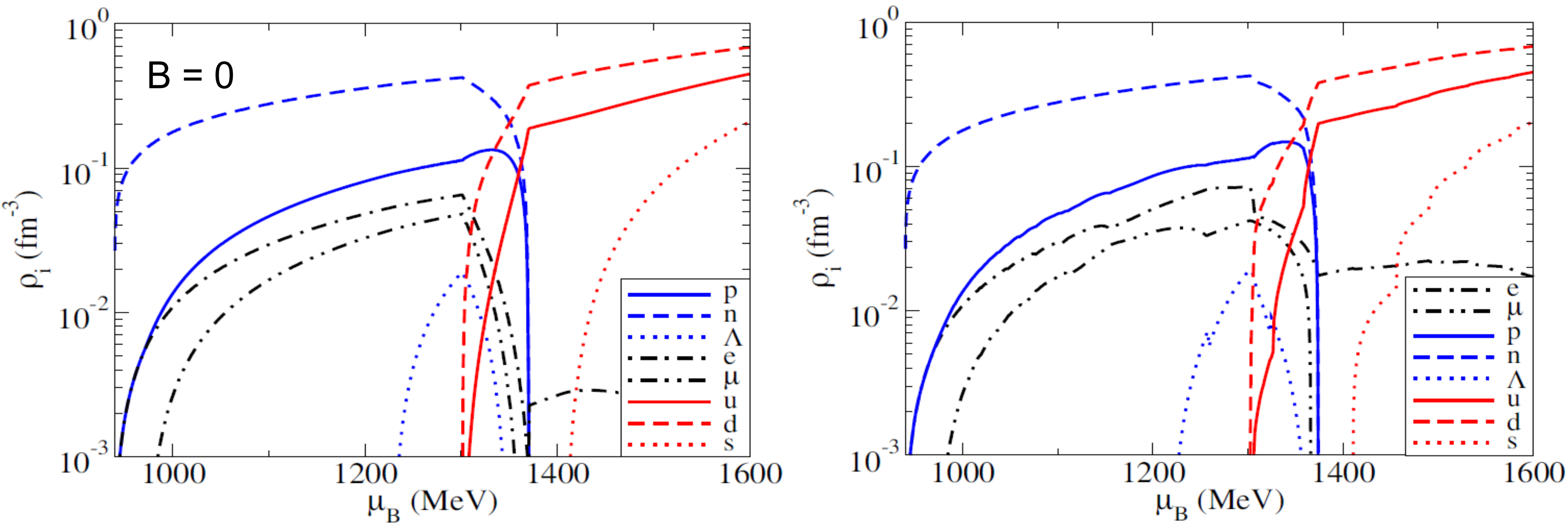
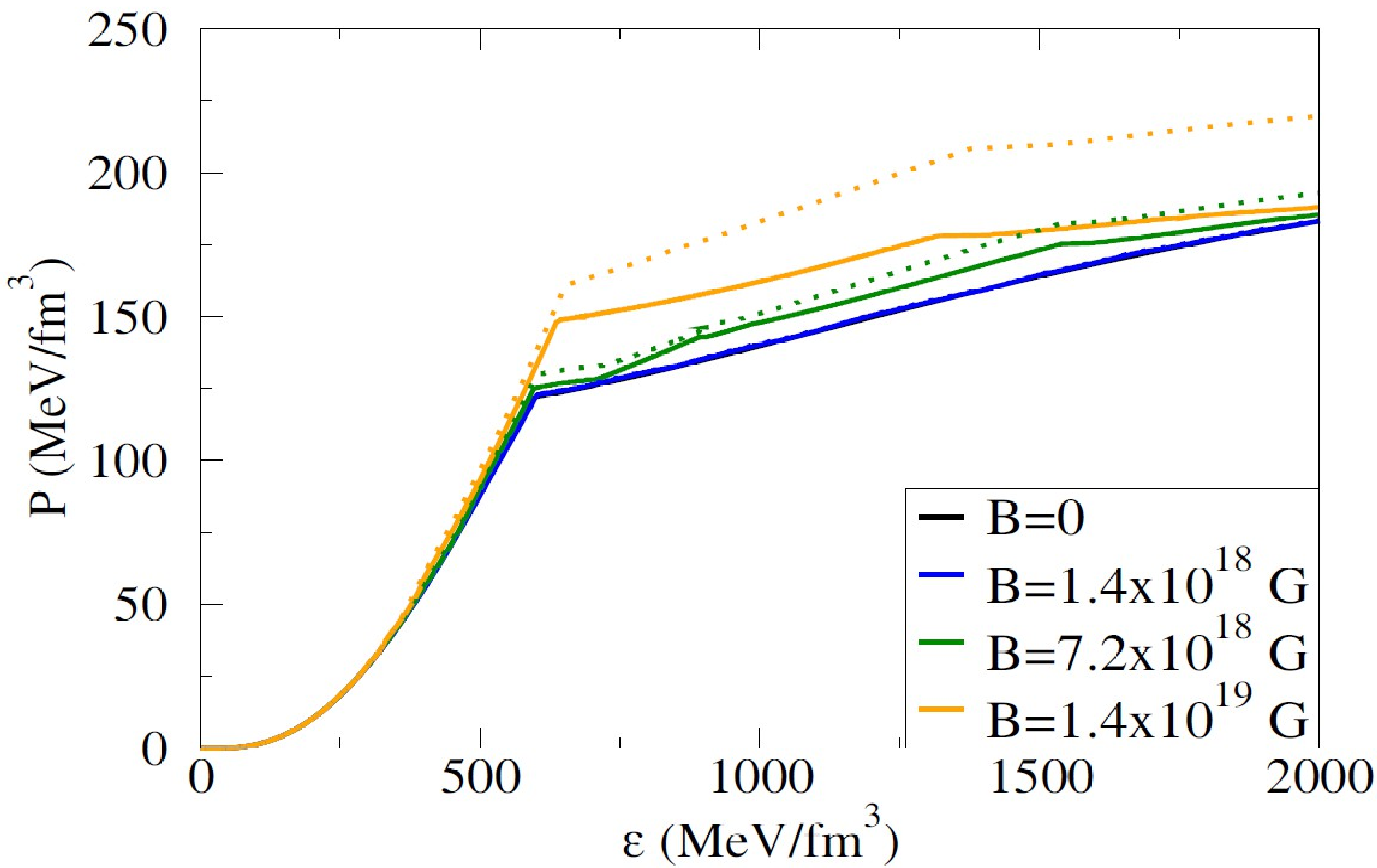
Composition



V. Dexheimer, R. Negreiros, S. Schramm, Eur.Phys.J. A48 (2012) 189

Equation of State



V. Dexheimer, R. Negreiros, S. Schramm, Eur.Phys.J. A48 (2012) 189

Make sure you check Eduardo Lenho's talk!!

Neutron Stars – Magnetic Fields

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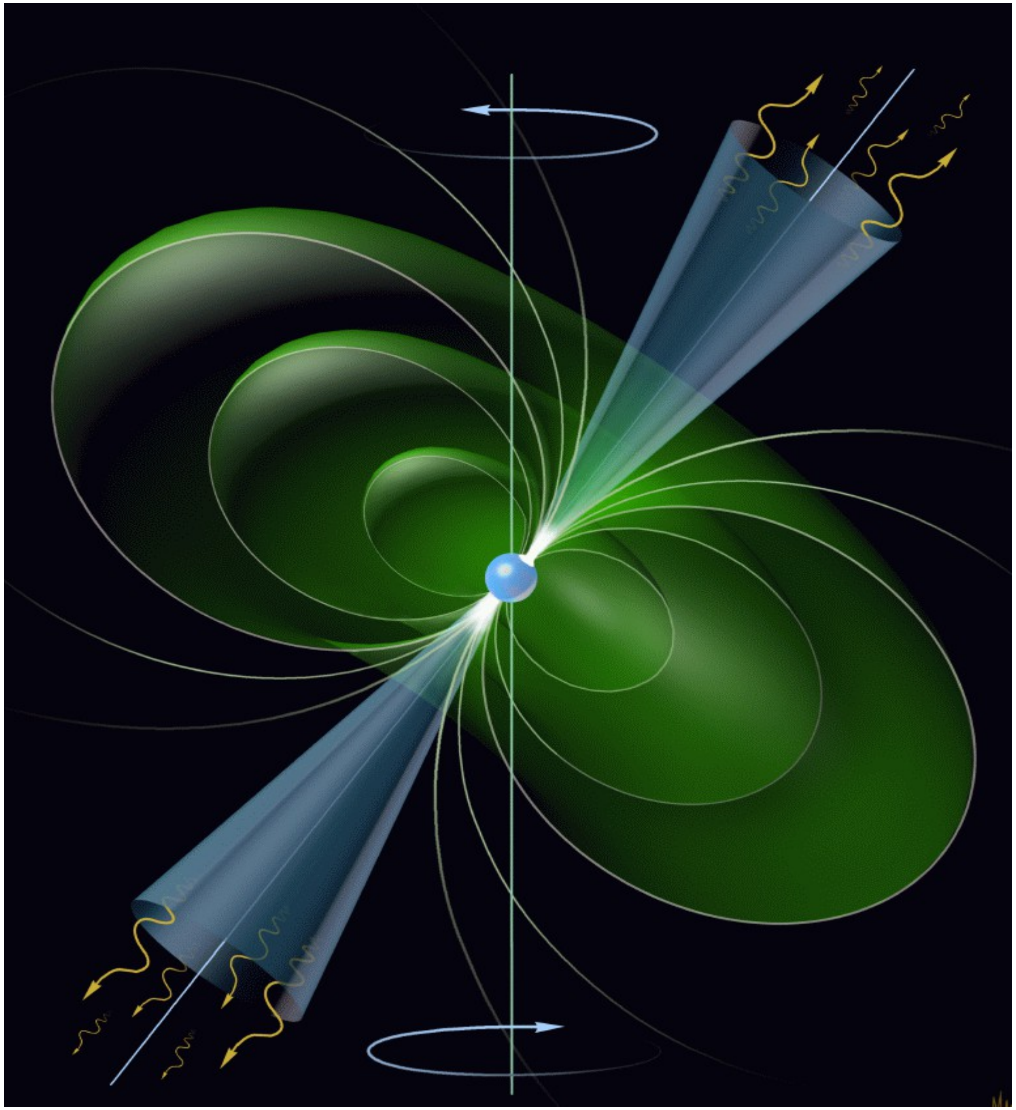

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Neutron Stars – Magnetic Fields – Macroscopic Effects

- **Evidently the microscopic effects introduced by the magnetic field will lead to modifications of the structure of the object.**

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Magnetic Field energy density → $B = 10^{19}\,\mathrm{G} \rightarrow \epsilon_B \sim 10^3 \ \mathrm{MeV/fm^3}$

Neutron Stars – Magnetic Fields – Macroscopic Effects

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- **Further curvature the objec**

Anisotropic energy-momentum tensor

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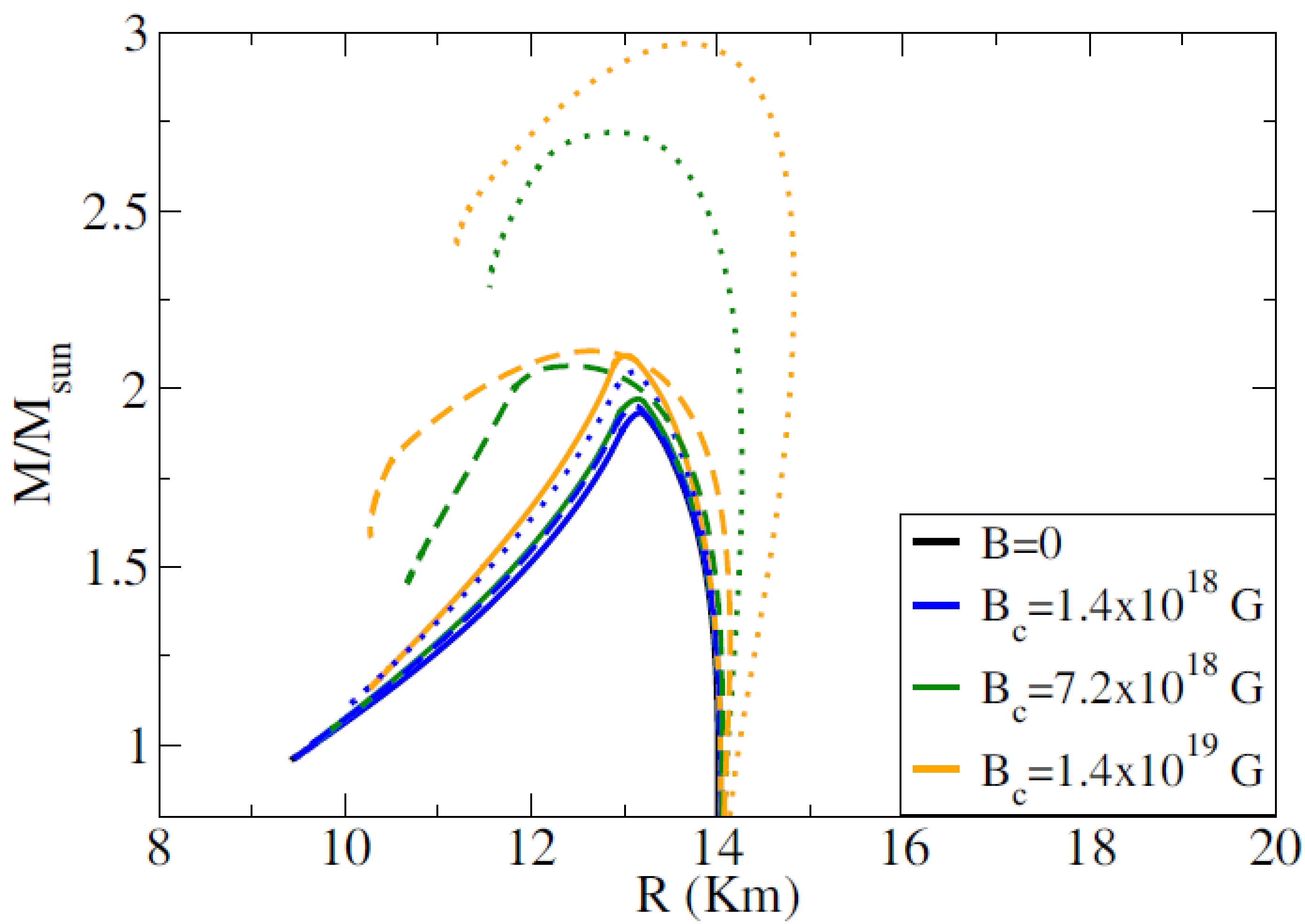
Neutron Stars – Magnetic Fields – Macroscopic Effects

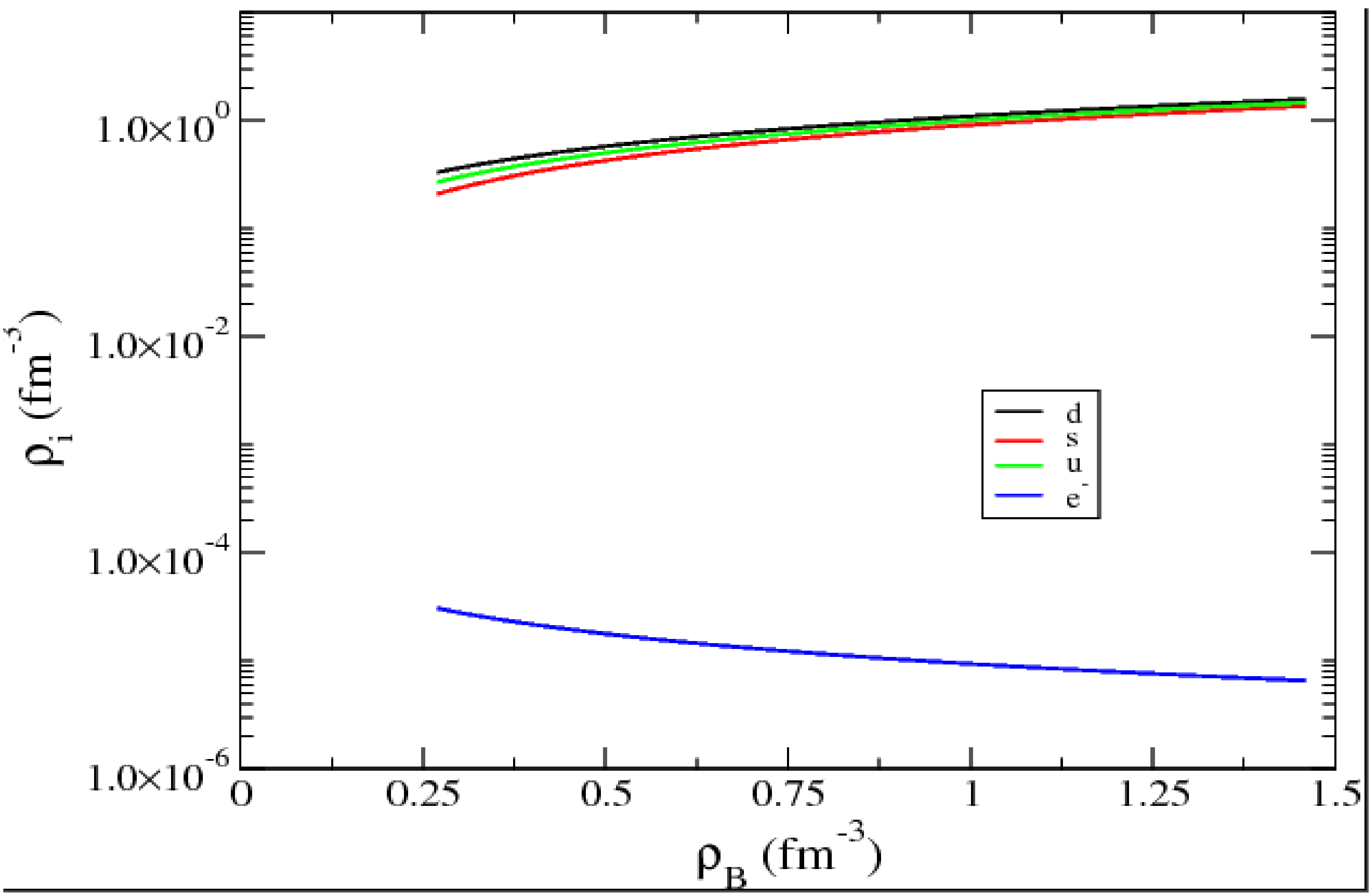


V. Dexheimer, R. Negreiros, S. Schramm, Eur.Phys.J. A48 (2012) 189

Quark Stars

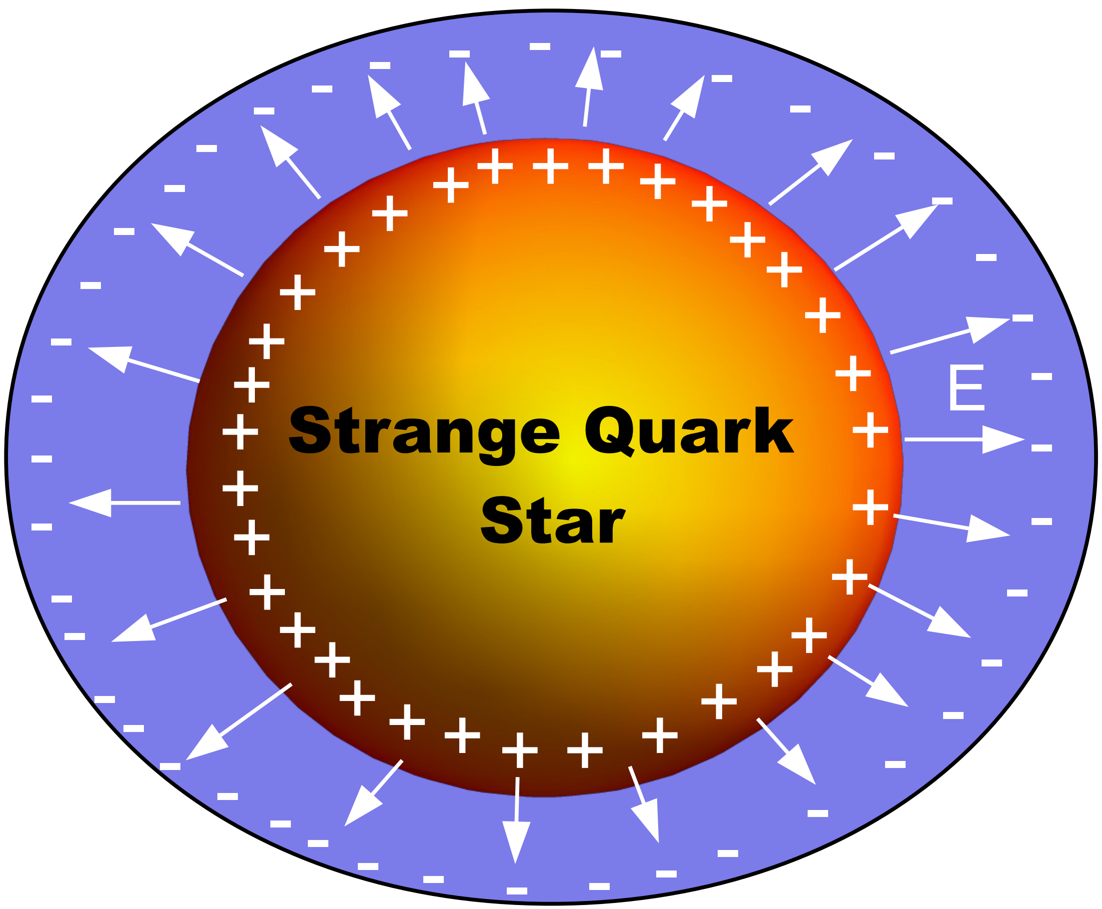
- Crustless compact stars composed of absolutely stable quark matter.
- Consists of roughly the same number of up, down and strange quarks.
- Relatively small number of electrons are needed for charge neutrality.
- Possibly in a color superconductor state.
- Higher concentration of electrons in the low density regions (surface) due to massive strange quarks suppression.
- Ultra high electric fields (10^{16-18} V/cm) on the surface.

Quark Stars - Composition



Quark Stars – Surface Electric Field

- Suppression of strange quarks near the surface increases the quantity of electrons.
- Electrons, are allowed to move to the outside of the star, establishing an electric field.



Alcock, C., Farhi, E., Olinto, A. *ApJ* 310, 261 (1986)
Usov, V. *PRD* 70, 14 (2004)

Quark Stars – Surface Electric Field

- Given by the solution of the following Poisson equation

$$\nabla^2 \mu_e = 4\pi e^2 (n_q - \mu_e^3 / 3\pi^2)$$

↓

$E = 10^{16\text{-}18}$ V/cm

Alcock, C., Farhi, E., Olinto, A. *ApJ* 310, 261 (1986)
Usov, V. *PRD* 70, 14 (2004)

Quark Stars – Structure

- Solution of Einstein's equation of general relativity

$$T_\nu{}^\mu = (p+\epsilon)u_\nu u^\mu + p\,\delta_\nu{}^\mu + \frac{1}{4\pi}\left(F^{\mu l}F_{\nu l} + \frac{1}{4\pi}\delta_\nu{}^\mu F_{kl}F^{kl}\right)$$

→ Energy-Momentum Tensor (EOS)

$$\frac{dP}{dr} = -\frac{2G\left(m + \frac{4\pi r^3}{c^2}\left(p - \frac{Q^2}{4\pi r^4 c^2}\right)\right)}{c^2 r^2\left(1 - \frac{2Gm}{c^2 r} + \frac{GQ^2}{r^2 c^4}\right)}(p+\epsilon) + \frac{Q}{4\pi r^4}\frac{dQ}{dr}$$

→ TOV equation (General Relativistic Hydrostatic equilibrium)

$$\frac{dm}{dr} = \frac{4\pi r^2}{c^2}\epsilon + \frac{Q}{c^2 r}\frac{dQ}{dr}$$

→ Stellar mass

$$\frac{dQ}{dr} = \frac{r^2\sigma\,\exp\left(-((r-r_g)/b)^2\right)\exp(\Lambda/2)}{2(\sqrt{\pi}b^3/4 + r_g b^2 + \sqrt{\pi}r_g^2 b/2)}$$

→ Maxwell's Eq.

Quark Stars – Structure

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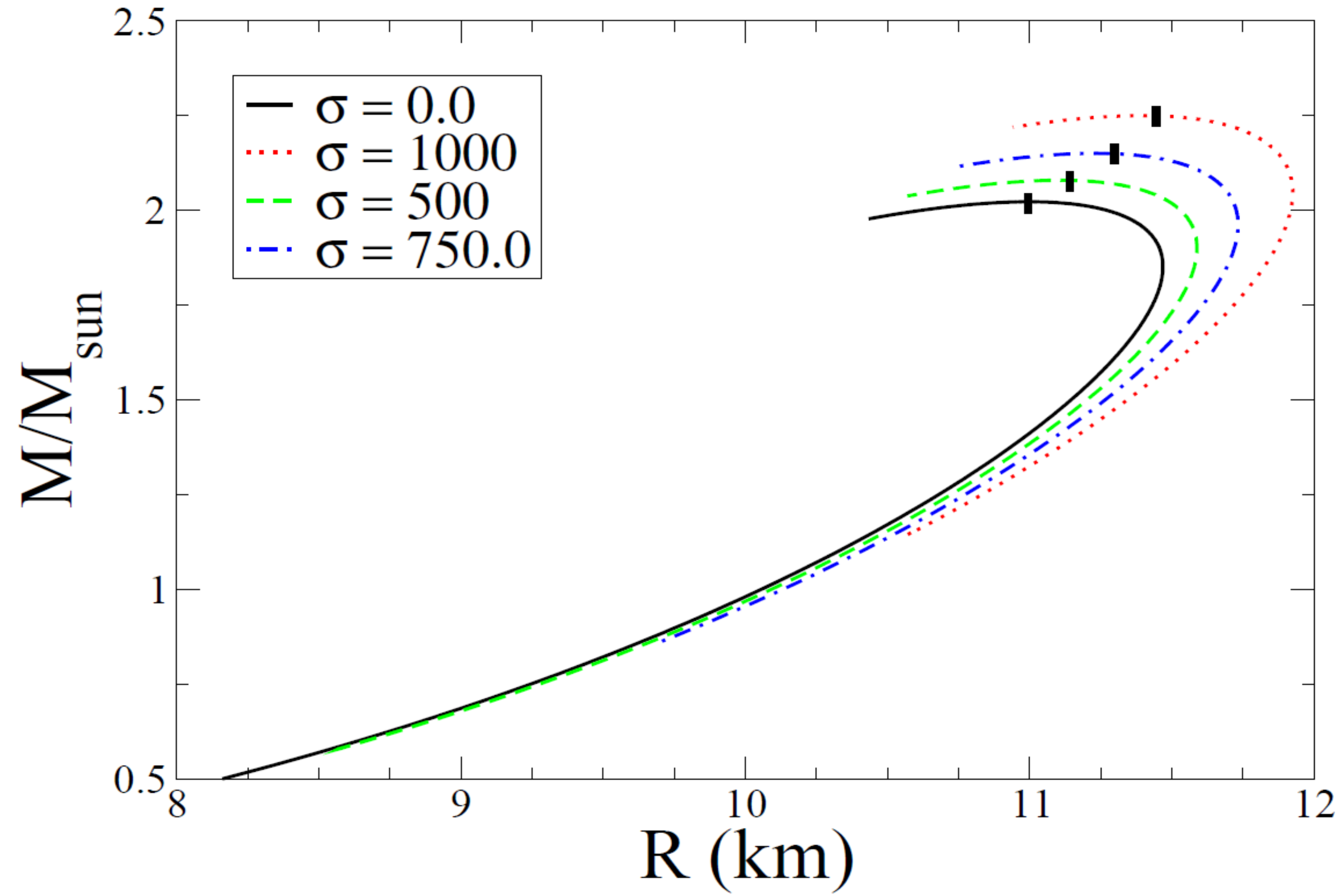
Quark Stars – Structure

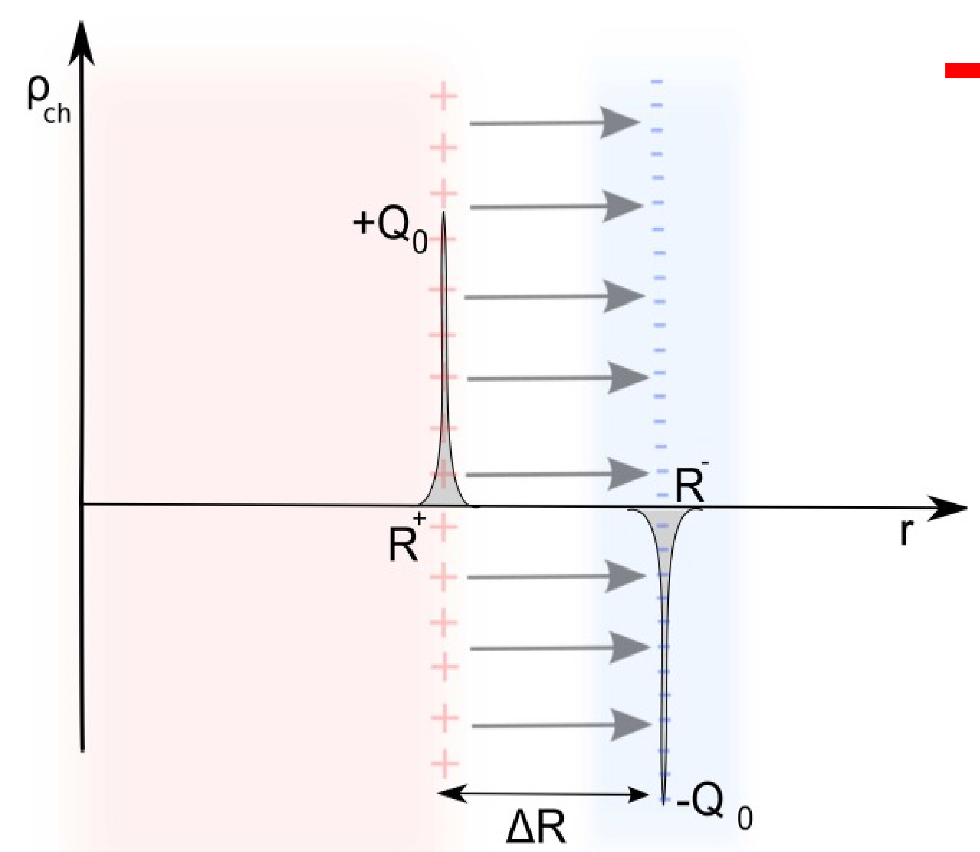
- Stellar mass for positively charged quark star's core



Negreiros R., Weber F., Malheiro M., Usov V., *PRD* 80, 083006 (2009)

Quark Stars – Structure

- Stellar mass of GLOBALY neutral quark stars



$$\rho_{\rm ch} = +K \frac{\delta(r - R^{+})}{4\pi r^2} - K \frac{\delta(r - R^{-})}{4\pi r^2}$$

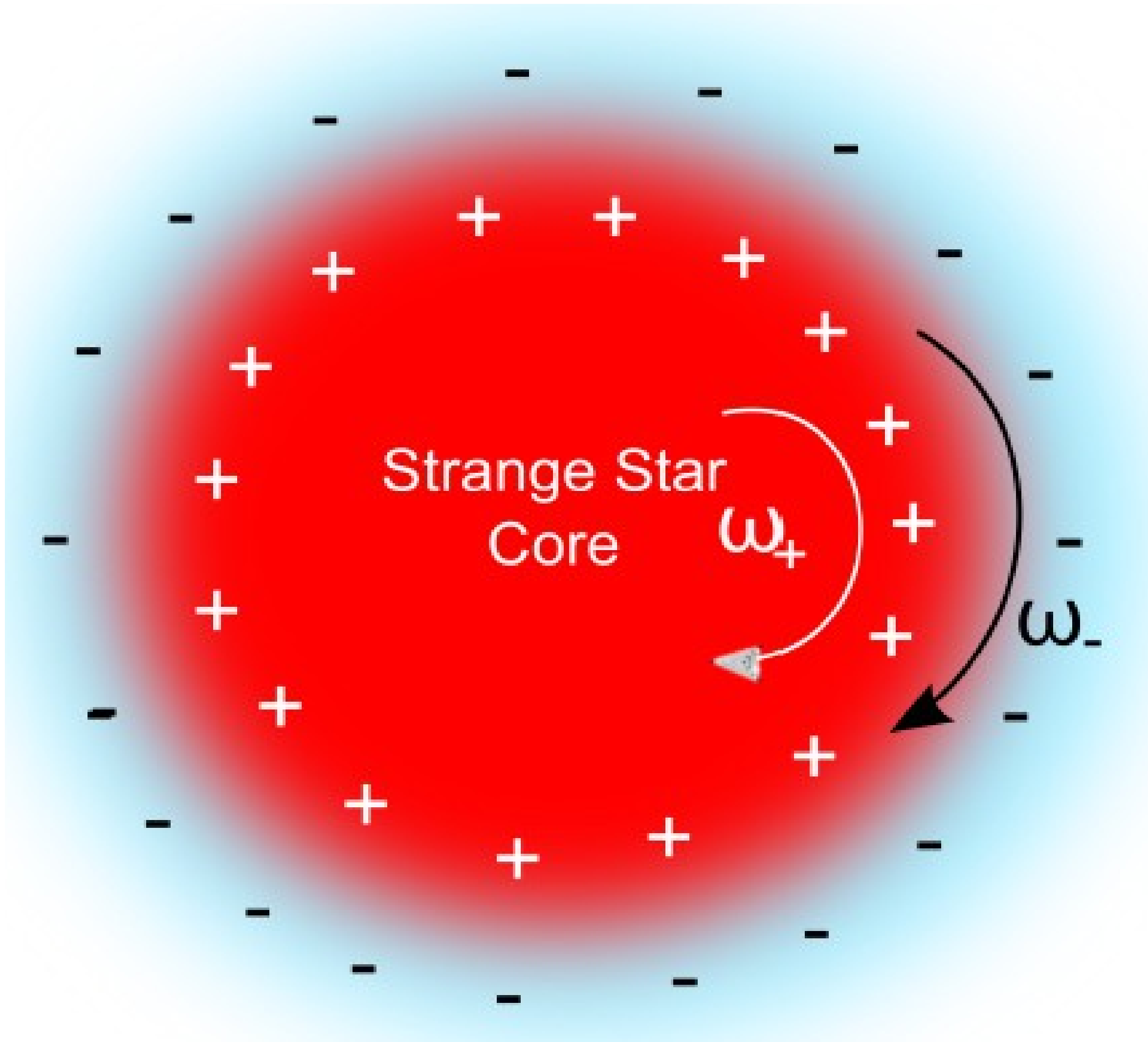
$$m_{\mathcal{E}} = \int_0^r \frac{Q(r')^2}{2r'^2} dr' + \frac{Q(r)^2}{2r}$$

$$\frac{M_{\mathcal{E}}}{M_\odot} = 3.12^{-61} \; R_s^4 \; E^2 \; \frac{\Delta R}{R^+ \; R^-}$$

Electromagnetic Mass

Negreiros R., Mishustin I., Schramm S., Weber F.,
Phys.Rev. D82 (2010) 103010

Quark Stars – Rotation



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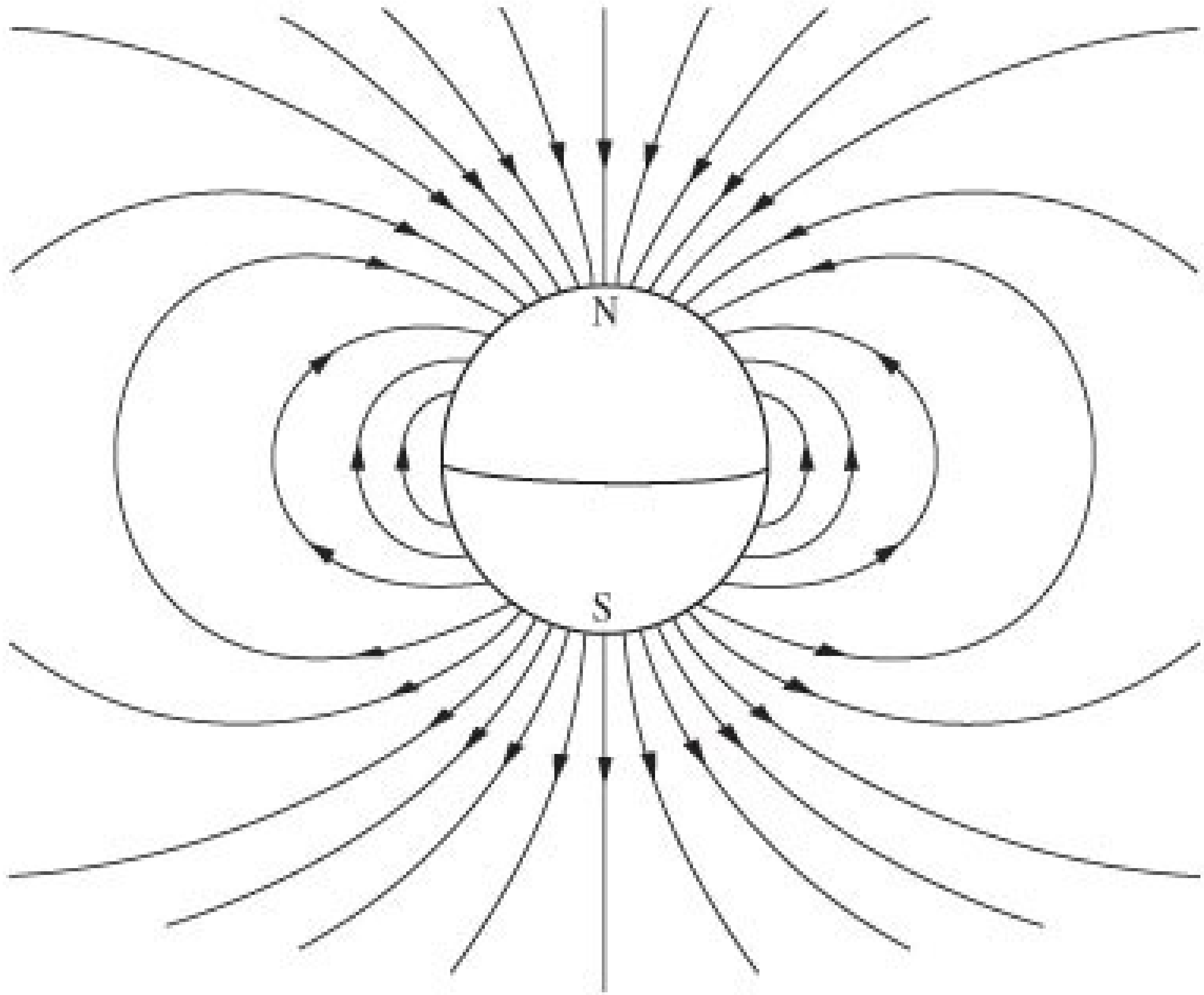

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Quark Stars – Rotation

Surface Current →

$$I = \sigma\,(\omega_+ - \omega_-)$$

Dipole Field →

$$\vec{B} = \frac{1}{3}\mu_0\,\sigma\,(\omega_+ - \omega_-)\frac{R^4}{r^3}(2\cos\theta\,\hat{r} + \sin\theta\,\hat{\theta})$$

↓

$$B_{\rm p} = E(\omega_+ - \omega_-)R \times 7.4104 \times 10^{-9}\ \mathrm{G}$$

$$B_{\rm eq} = E(\omega_+ - \omega_-)R \times 3.7052 \times 10^{-9}\ \mathrm{G}$$

Negreiros R., Mishustin I., Schramm S., Weber F.,
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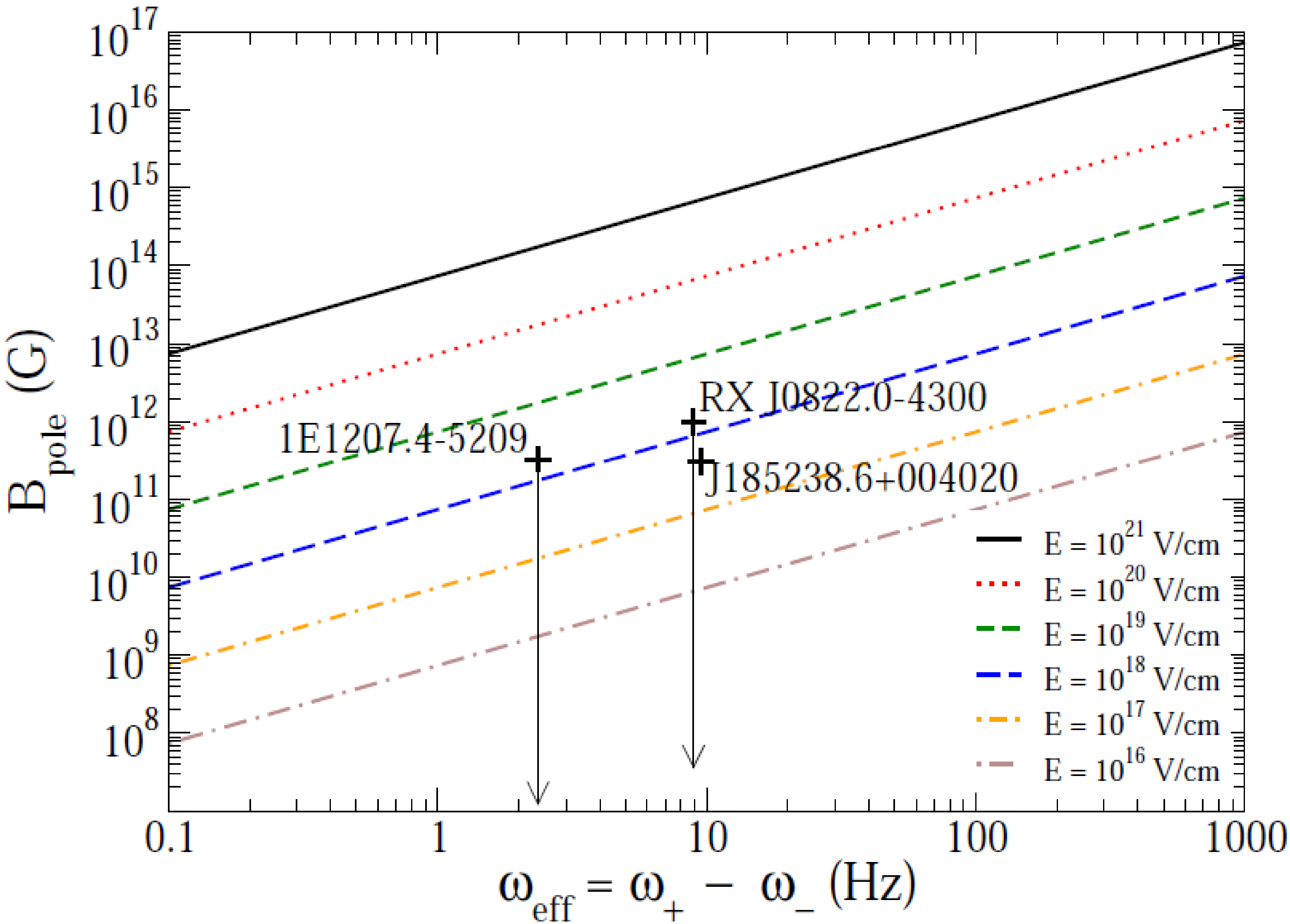

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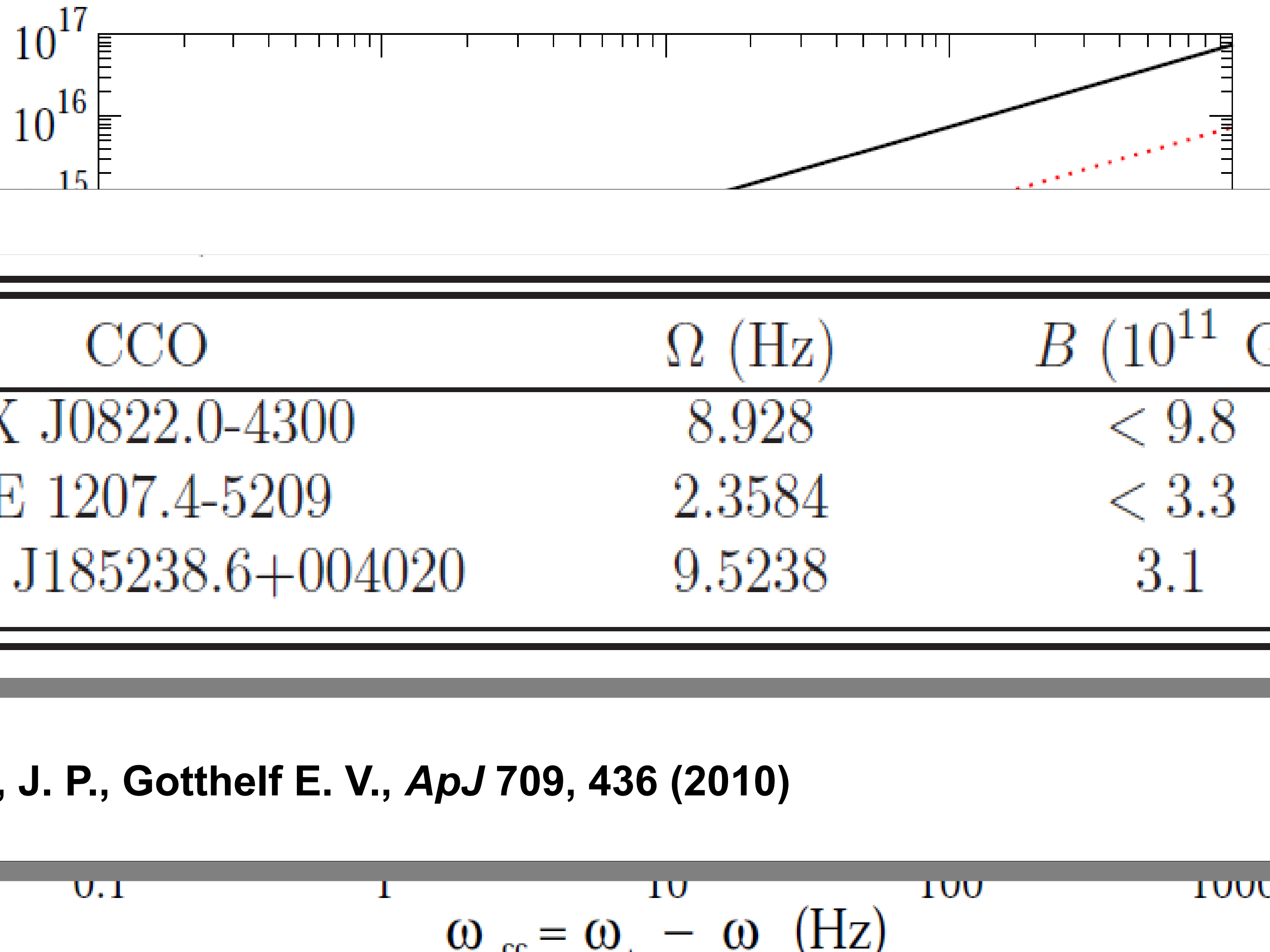

CCO	Ω (Hz)	B (10^{11} G)
RX J0822.0-4300	8.928	< 9.8
1E 1207.4-5209	2.3584	< 3.3
CXOU J185238.6+004020	9.5238	3.1

Halpern, J. P., Gotthelf E. V., *ApJ* 709, 436 (2010)

Negreiros R., Mishustin I., Schramm S., Weber F.,
Phys.Rev. D82 (2010) 103010

Neutron Stars – Magnetic Fields

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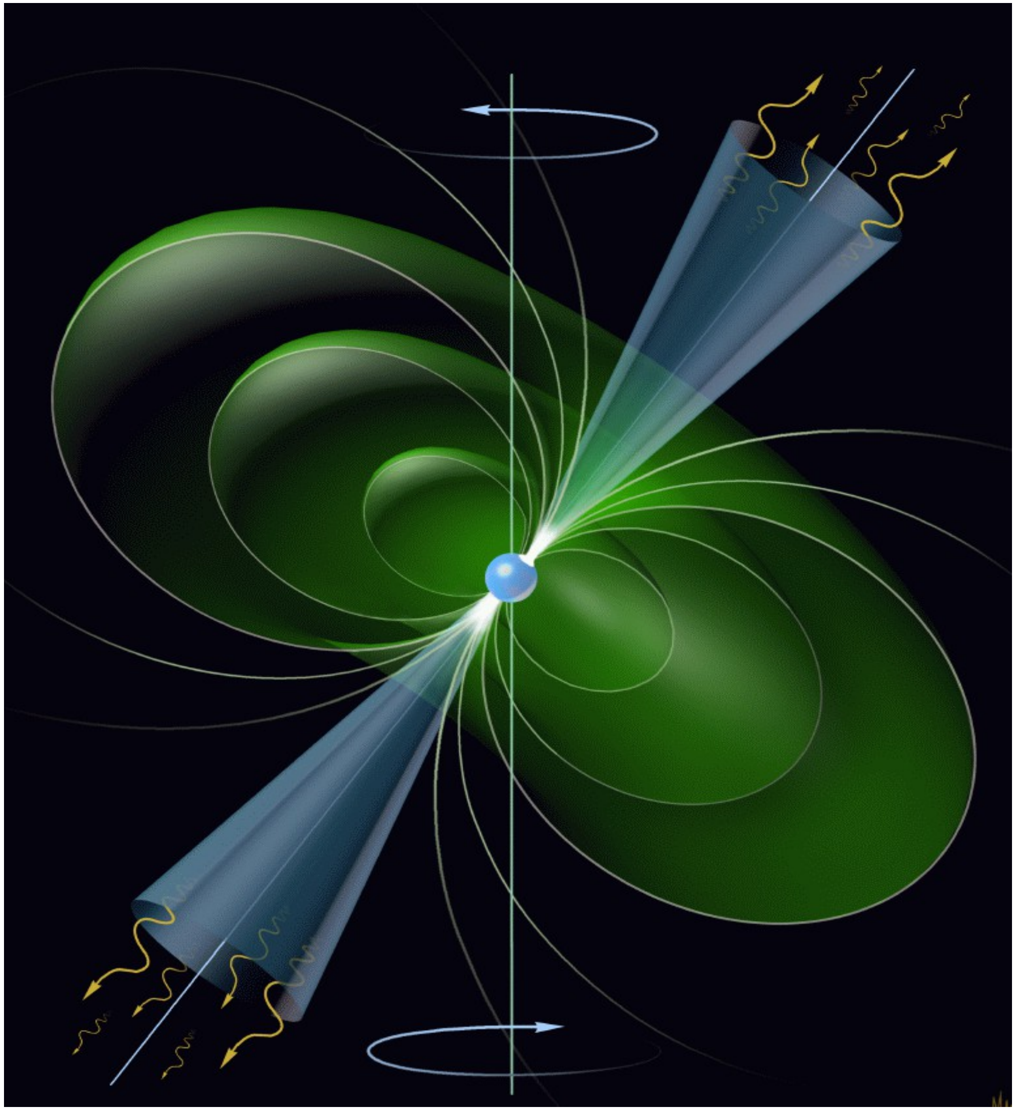

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- **Magnetic fields inside the object might lead to anisotropic heat transport.**

- **Magnetic fields may also influence the Direct Urca process emissivity in neutron stars.**

Direct Urca Effect under the influence of magnetic field

Direct Urca Process

$$n \rightarrow p + e + \bar{\nu}$$
$$p + e \rightarrow n + \nu$$

Neutron Stars – Magnetic Fields - Cooling

Direct Urca Effect under the influence of magnetic field

Direct Urca Process

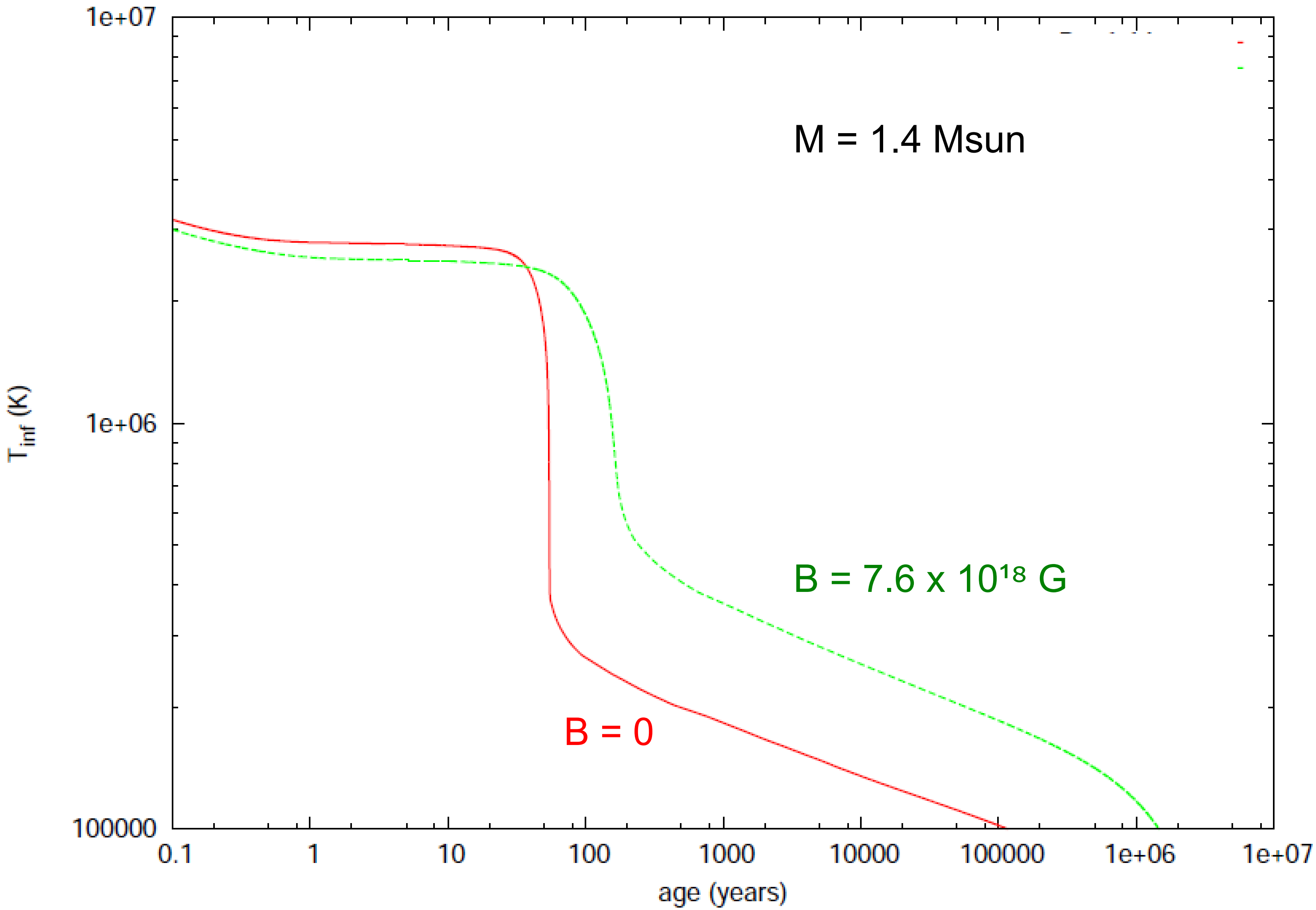
$$n \rightarrow p + e + \bar{\nu}$$
$$p + e \rightarrow n + \nu$$

Direct Urca Process under the influence of B

$$\varepsilon^{\mathrm{NM}}_{\mathrm{Urca}}(B_m) = \frac{457\pi}{5040} G_F^2 \cos^2\theta_c \,(qB_m)\left[(g_V + g_A)^2\left(1 - \frac{p_{F_p}}{\mu_p^*}\right) + (g_V - g_A)^2\left(1 - \frac{p_{F_n}}{\mu_n^*}\cos\theta_{14}\right)\right.$$
$$\left. - (g_V^2 - g_A^2)\frac{m^{*2}}{\mu_n^* \mu_p^*}\right] \times \exp\left[\frac{(p_{F_p} + p_{F_e})^2 - p_{F_n}^2}{2qB_m}\right]\frac{\mu_n^* \mu_p^* \mu_e}{p_{F_p} p_{F_e}} T^6 \Theta$$

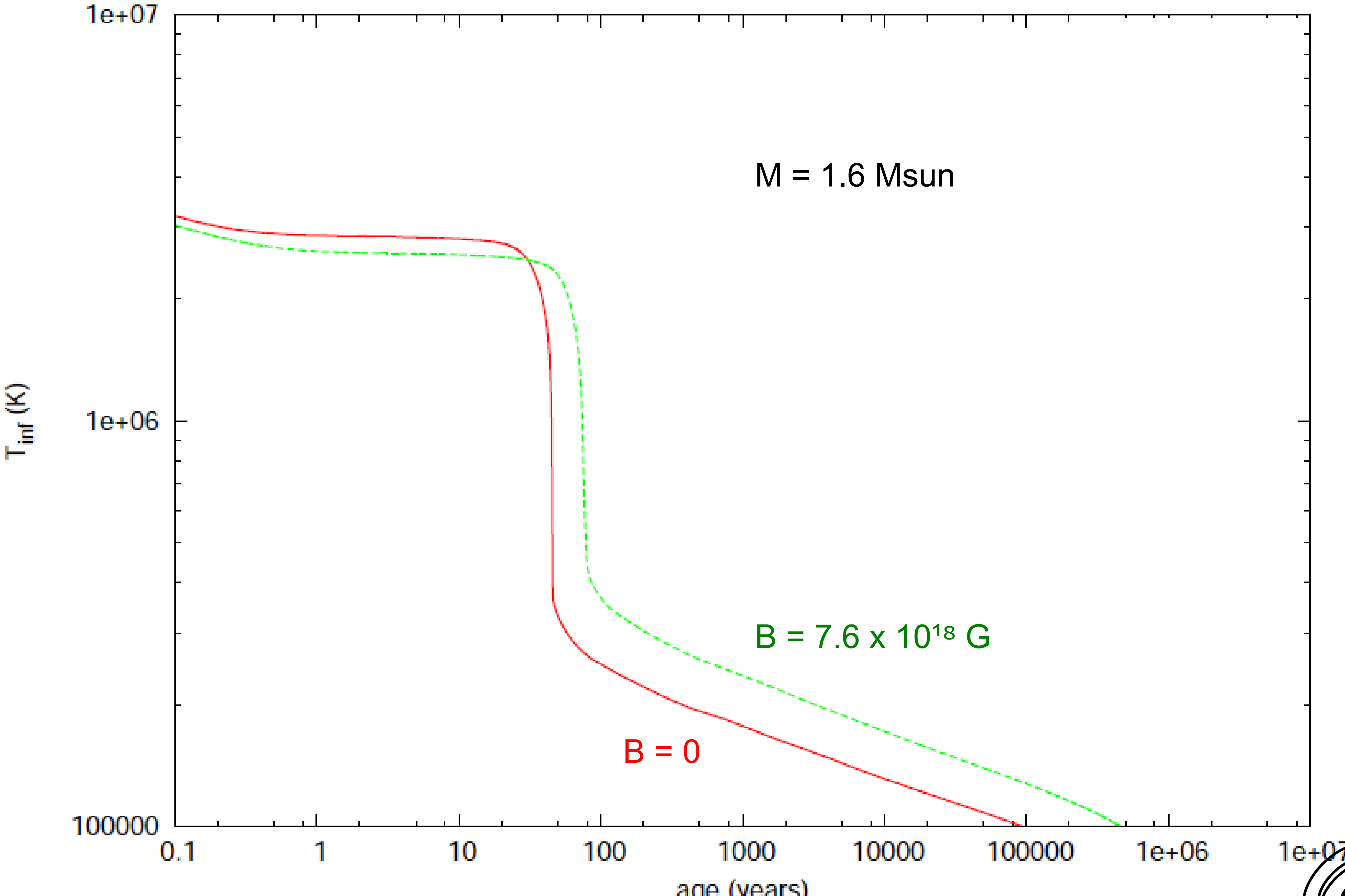
Bandyopadhyay, D., Chakrabarty, S., Dey, P., & Pal, S. (1998). Physical Review D, 58(12), 12130

Neutron Stars – Magnetic Fields - Cooling



Lenho, E., Negreiros, R., Chiapparini, M. - In progress

Neutron Stars – Magnetic Fields - Cooling



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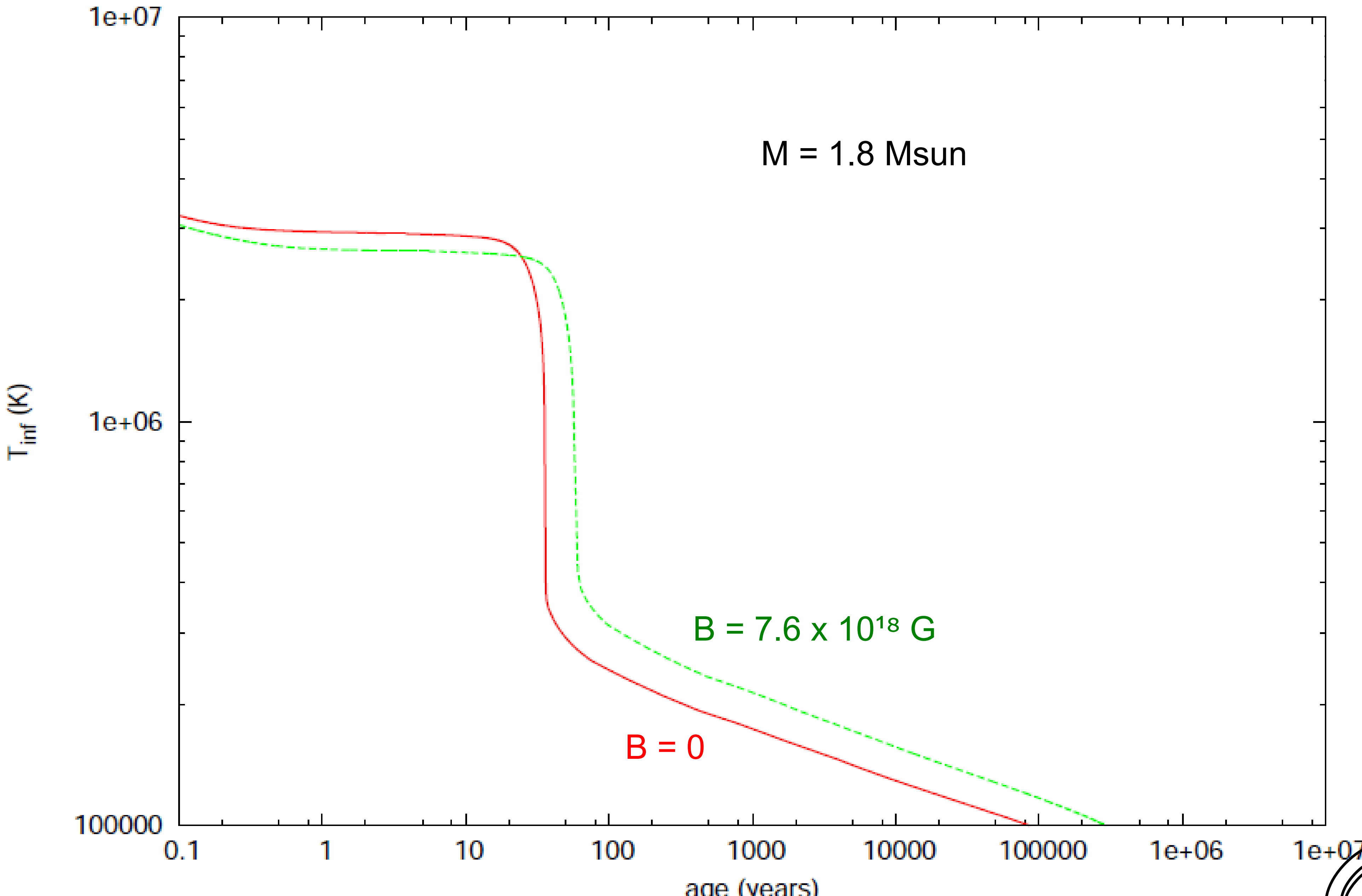

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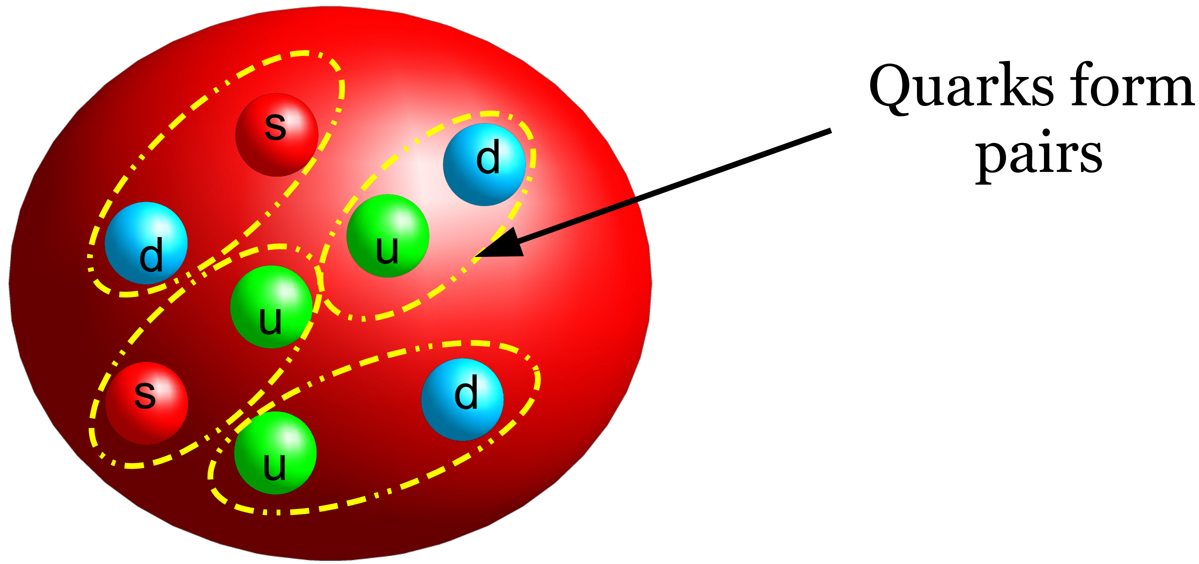
Vortex Expulsion in Quark Stars



… exhibits suppression of neutrino emissivities and a reduction of specific heat

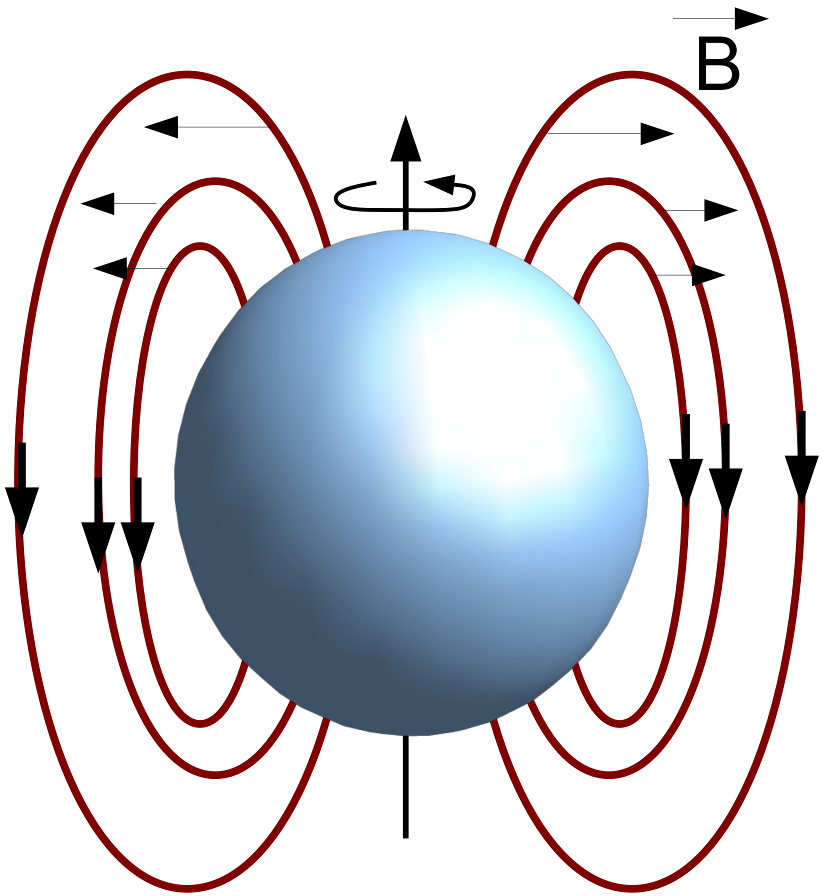
Neutrino emissivities:

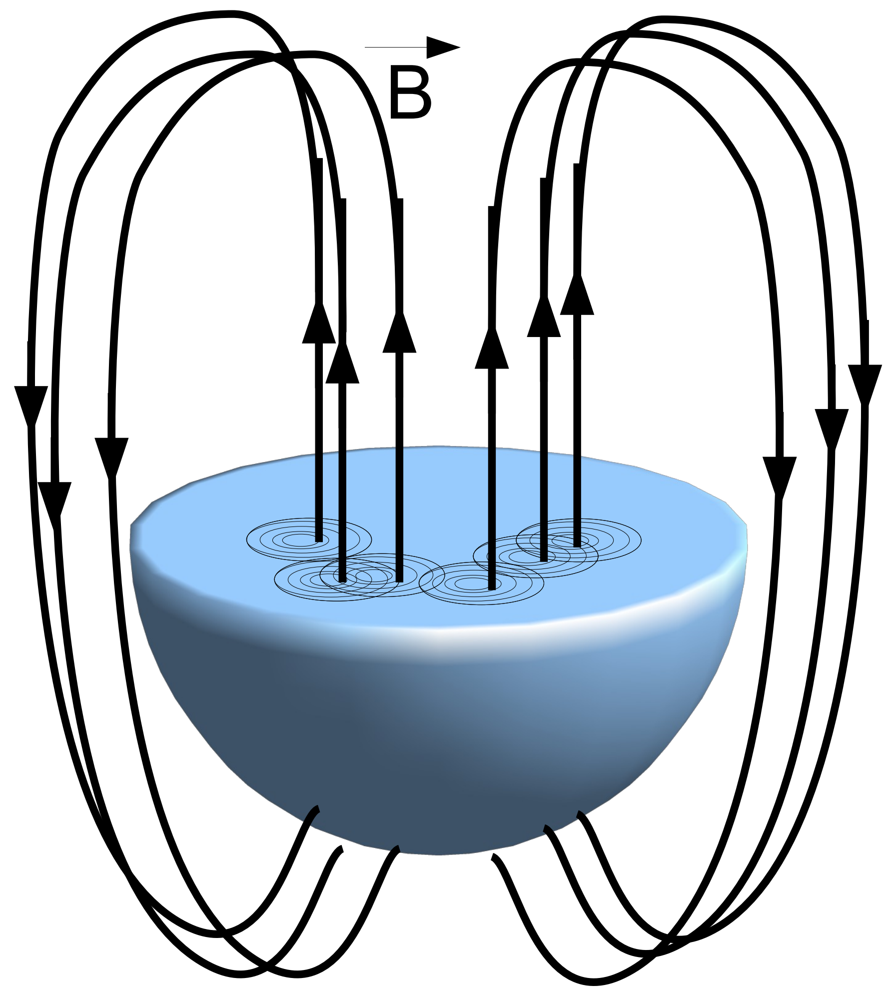
$$\epsilon_\nu \longrightarrow \epsilon_\nu \, e^{-(\Delta/kT)}$$

Specific heat:

$$C_{v,\mathrm{CFL,Q}} = 3.2 C_Q \left(\frac{T_c}{T}\right) \times \left[2.5 - 1.7\left(\frac{T}{T_c}\right) + 3.6\left(\frac{T}{T_c}\right)^2\right] e^{-\Delta/(\kappa_B T)}$$

Neutron Stars – Magnetic Fields - Cooling





Niebergal, B., Ouyed, R., Negreiros, R., Weber, F. ;Phys.Rev.D81:043005,2010

Neutron Stars – Magnetic Fields - Cooling

Label	Name (K)	$T \times 10^6$ (10^3 years)	Age
A	SGR 1806-20	$7.56^{+0.8}_{-0.7}$	0.15
B	1E 1048.1-5937	$7.22^{+0.13}_{-0.07}$	2.5
C	CXO J164710.2-455216	7.07	0.5
D	SGR 0526-66	$6.16^{+0.07}_{-0.07}$	1.3
E	1RXS J170849.0-400910	$5.3^{+0.98}_{-1.23}$	6.0
F	1E 1841-045	$5.14^{+0.02}_{-0.02}$	3.0
G	SGR 1900+14	$5.06^{+0.93}_{-0.06}$	0.73
H	CXOU J010043.1-721134	$4.44^{+0.02}_{-0.02}$	4.5
I	XTE J1810-197	$7.92^{+0.22}_{-5.83}$	11.3
J	RX J0720.4-3125	$1.05^{+0.06}_{-0.06}$	1266
L	RBS 1223	$1.00^{+0.0}_{-0.0}$	974

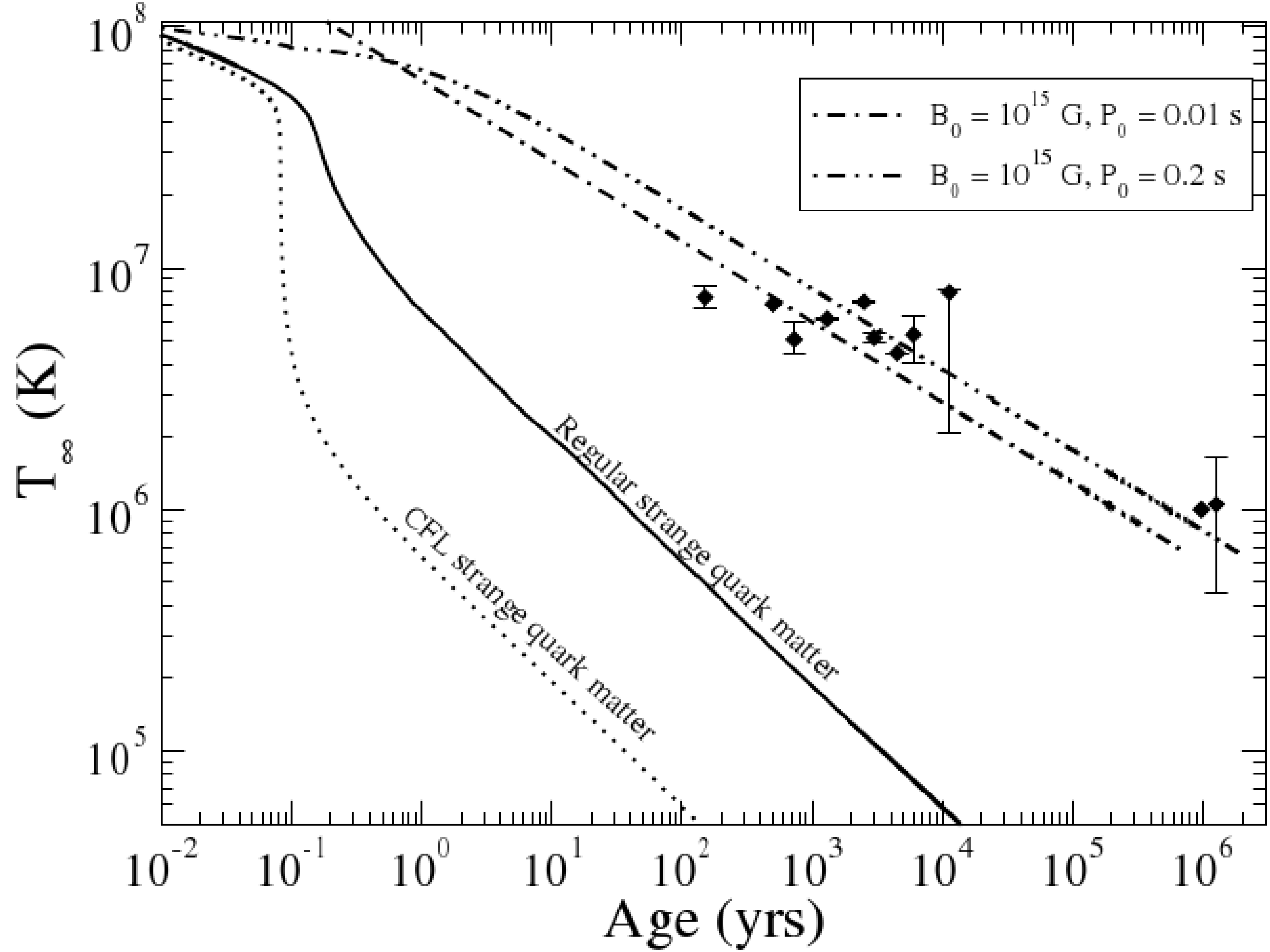
Soft Gamma-Ray Repeaters and Anomalous X-ray pulsars

- Emission of irregular bursts of ultra energetic X-ray and Gamma radiation.

- Very high observed temperatures.

Niebergal, B., Ouyed, R., Negreiros, R., Weber, F. ;Phys.Rev.D81:043005,2010

Neutron Stars – Magnetic Fields - Cooling



Niebergal, B., Ouyed, R., Negreiros, R., Weber, F. ;Phys.Rev.D81:043005,2010

2D COOLING

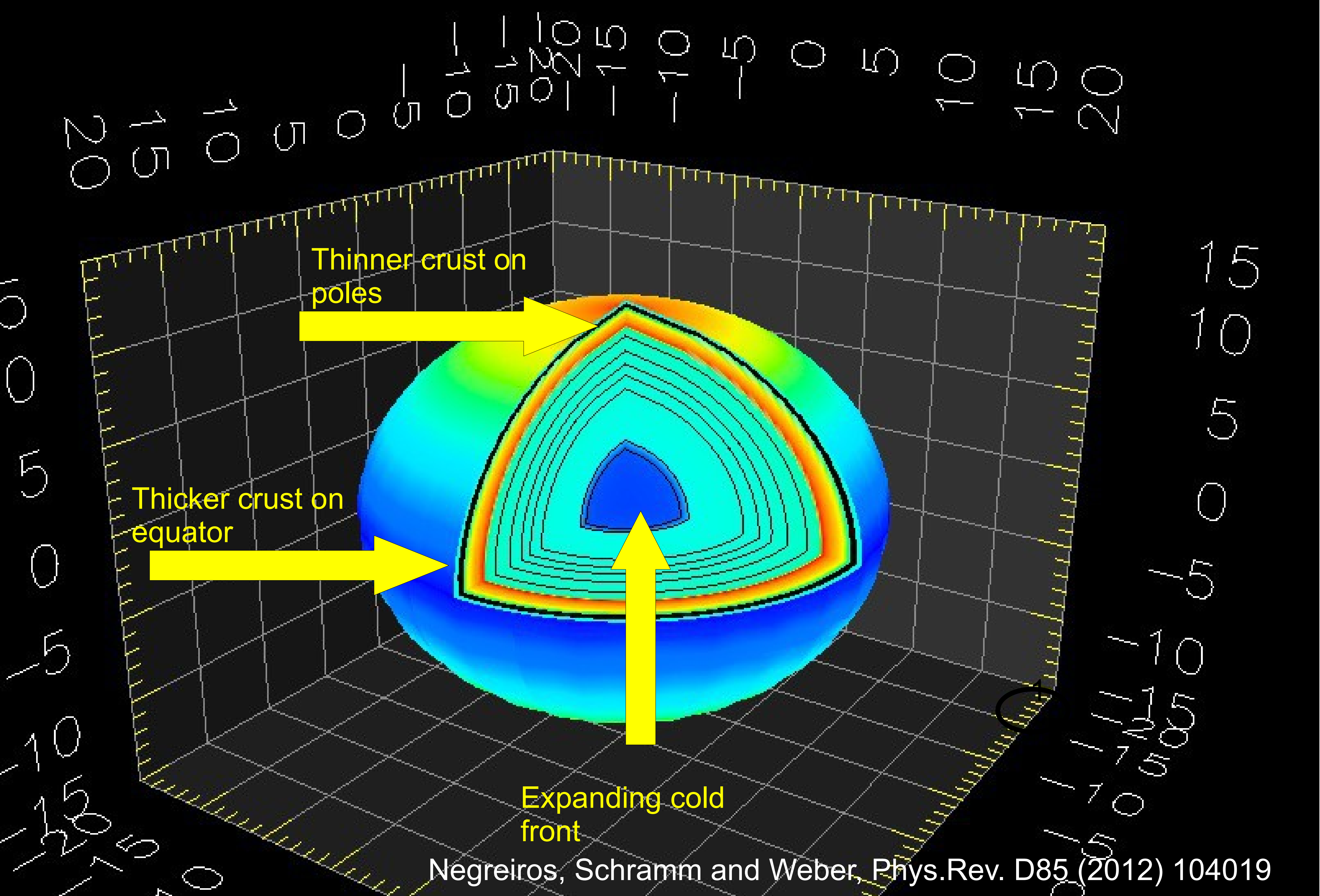
$$\partial_t\tilde{T} = -\frac{1}{\Gamma^2}e^{2\nu}\frac{\epsilon}{C_V} - r\sin\theta\,U e^{\nu+\gamma-\xi}\frac{1}{C_V}\left(\partial_r\Omega + \frac{1}{r}\partial_\theta\Omega\right)$$

$$+\frac{1}{r^2\sin\theta}\frac{1}{\Gamma}e^{3\nu-\gamma-2\xi}\frac{1}{C_V}\left(\partial_r\left(r^2\kappa\sin\theta\,e^{\gamma}\left(\partial_r\tilde{T}+\Gamma^2 U e^{-2\nu+\gamma}\tilde{T}\partial_r\Omega\right)\right)\right.$$

$$\left.+\frac{1}{r^2}\partial_\theta\left(r^2\kappa\sin\theta\,e^{\gamma}\left(\partial_\theta\tilde{T}+\Gamma^2 U e^{-2\nu+\gamma}\tilde{T}\partial_\theta\Omega\right)\right)\right)$$

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

2D Calculations – break down



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

Neutron Stars – Magnetic Fields - Conclusions

- One needs extremely high magnetic field (~ 10^{18} G) for it to have any appreciable effect in the microscopic composition.

- For leptons, however, a magnetic field of (~ 10^{14} G) is already high enough to lead to appreciable effects.

- The modifications of a high magnetic field on the composition will lead to substantial modifications of the macroscopic structure.

- A self-consistent treatment of neutron stars with high-magnetic fields need the inclusion of the magnetic field as a source of curvature in Einstein's equation.

- The combined microscopic and macroscopic effects leads to potential modification of the cooling properties of the star.

- Once more, a self-consistent treatment of the thermal evolution of high magnetic field neutron stars need to take into account anisotropic heat-transport, breaking of spherical symmetry, and curvature effects due to the ultra-high magnetic field.

- Thermal evolution studies may potentially allow us to probe the inner configuration of the magnetic field in neutron stars.

- **ACKNOWLEDGMENTS!**

Acknowledgments

- R. N. acknowledges financial support of CAPES.

- S. S. acknowledge access to the computer facilities of the CSC Frankfurt.

- F.W. is supported by the National Science Foundation (USA) under Grant No. PHY-0854699.

Compact Stars

Objects that are born after supernova explosions...

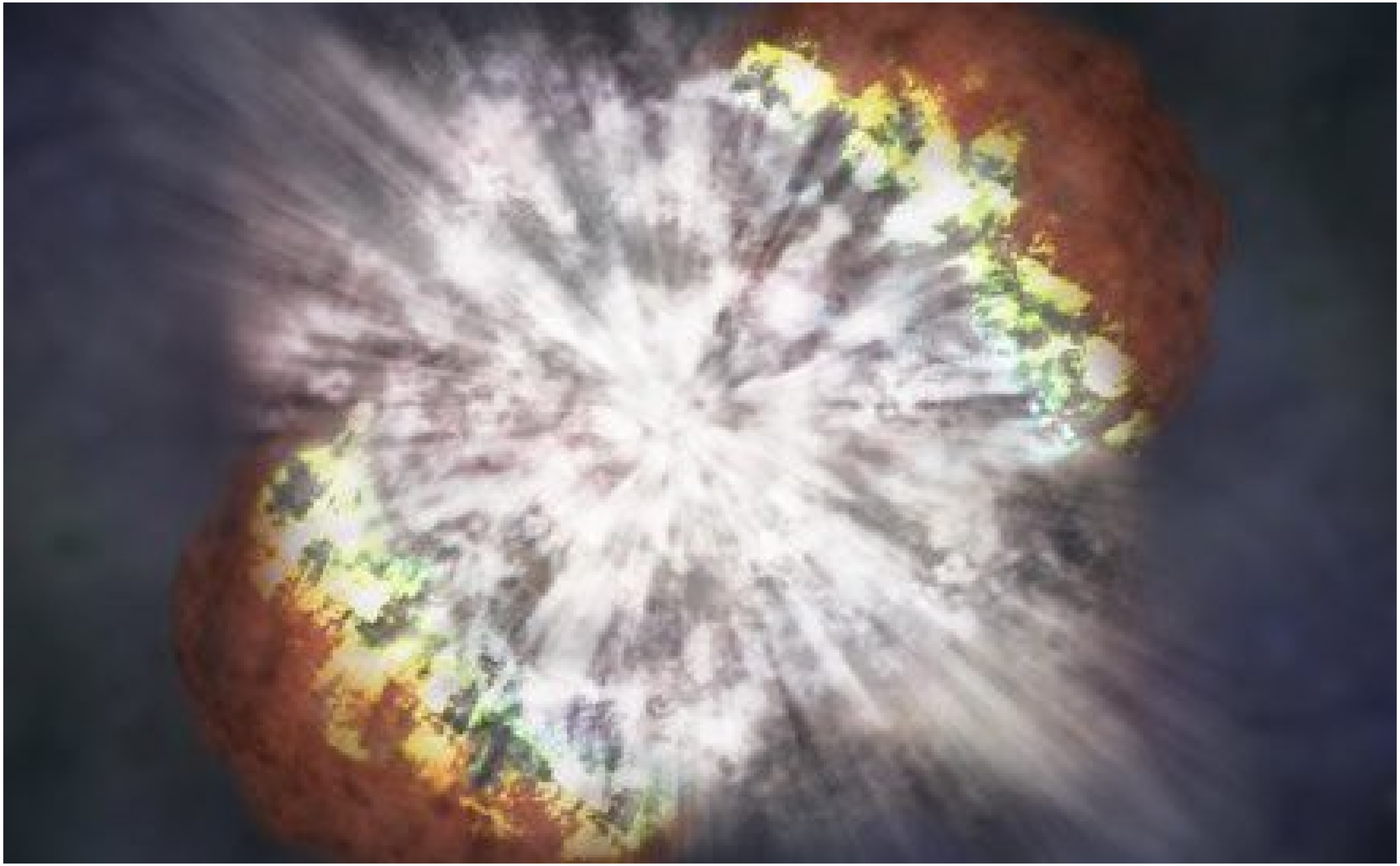


Image credit: Illustration: NASA/CXC/M.Weiss; X-ray: NASA/CXC/UC Berkeley/N.Smith et al.; IR: Lick/UC Berkeley/J.Bloom & C.Hansen

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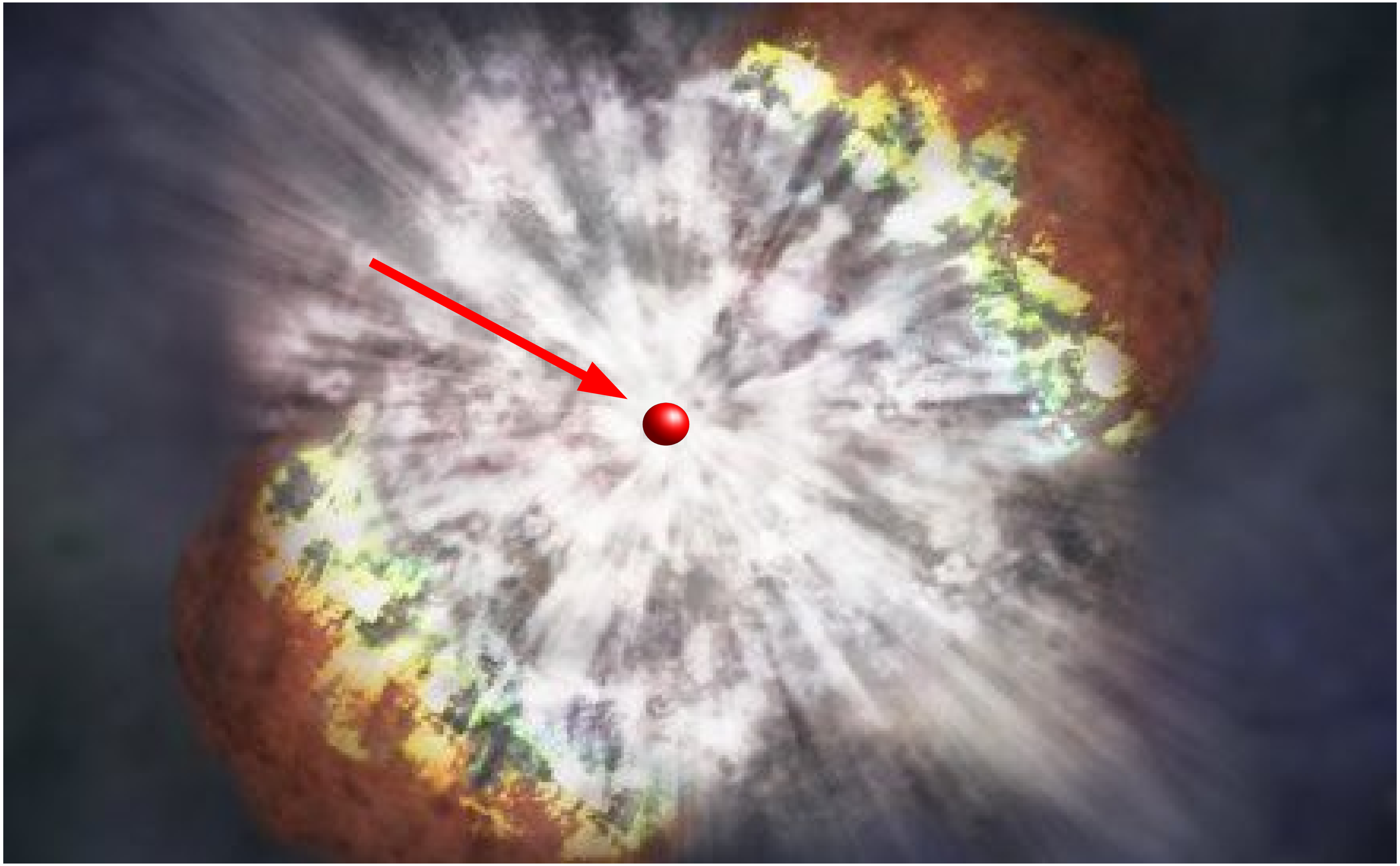


Image credit: Illustration: NASA/CXC/M.Weiss; X-ray: NASA/CXC/UC Berkeley/N.Smith et al.; IR: Lick/UC Berkeley/J.Bloom & C.Hansen

Many models for the microscopic composition

$N \sim 10^{57}$ baryons

$M \sim 1-2\ M_{sun}$

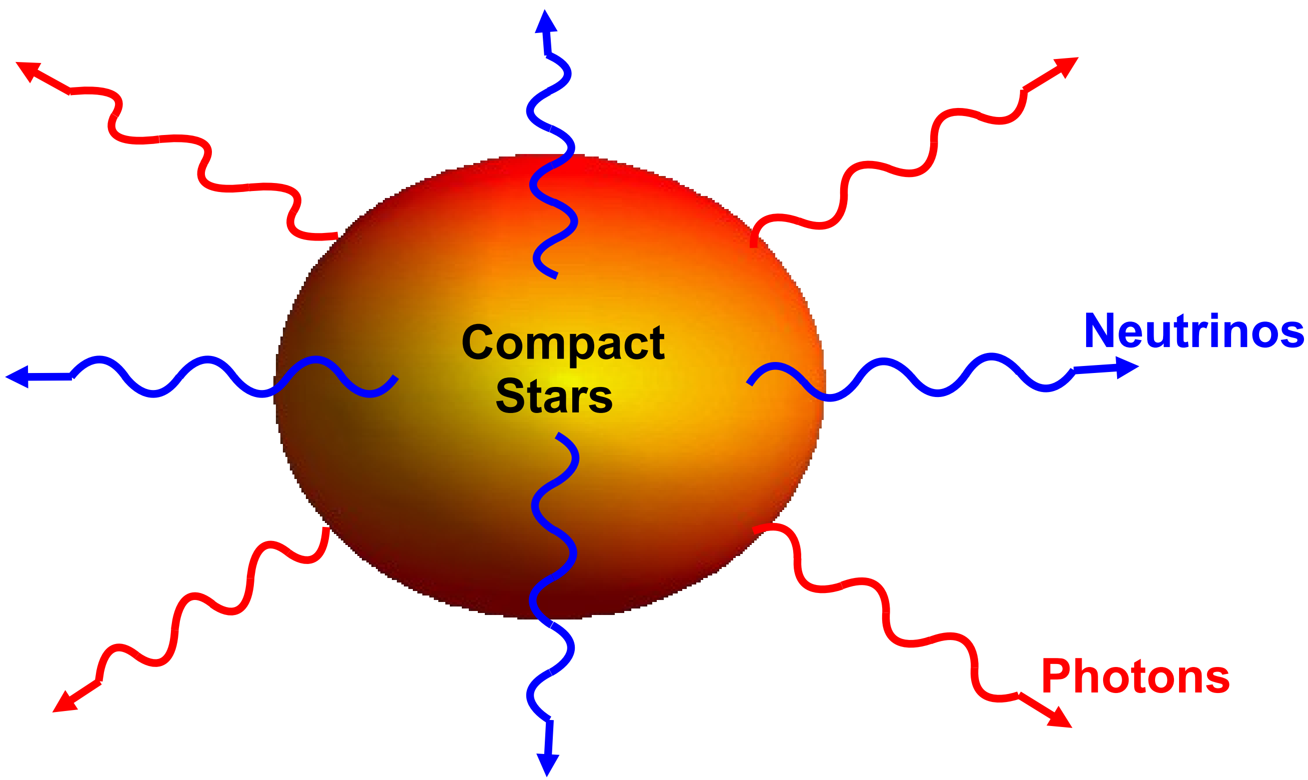
$R \sim$ 10-15 km

$T \sim 10^{6\ \ldots\ 11}$ K

Weber, Hamil, Mimura and Negreiros (2011)

Thermal Evolution

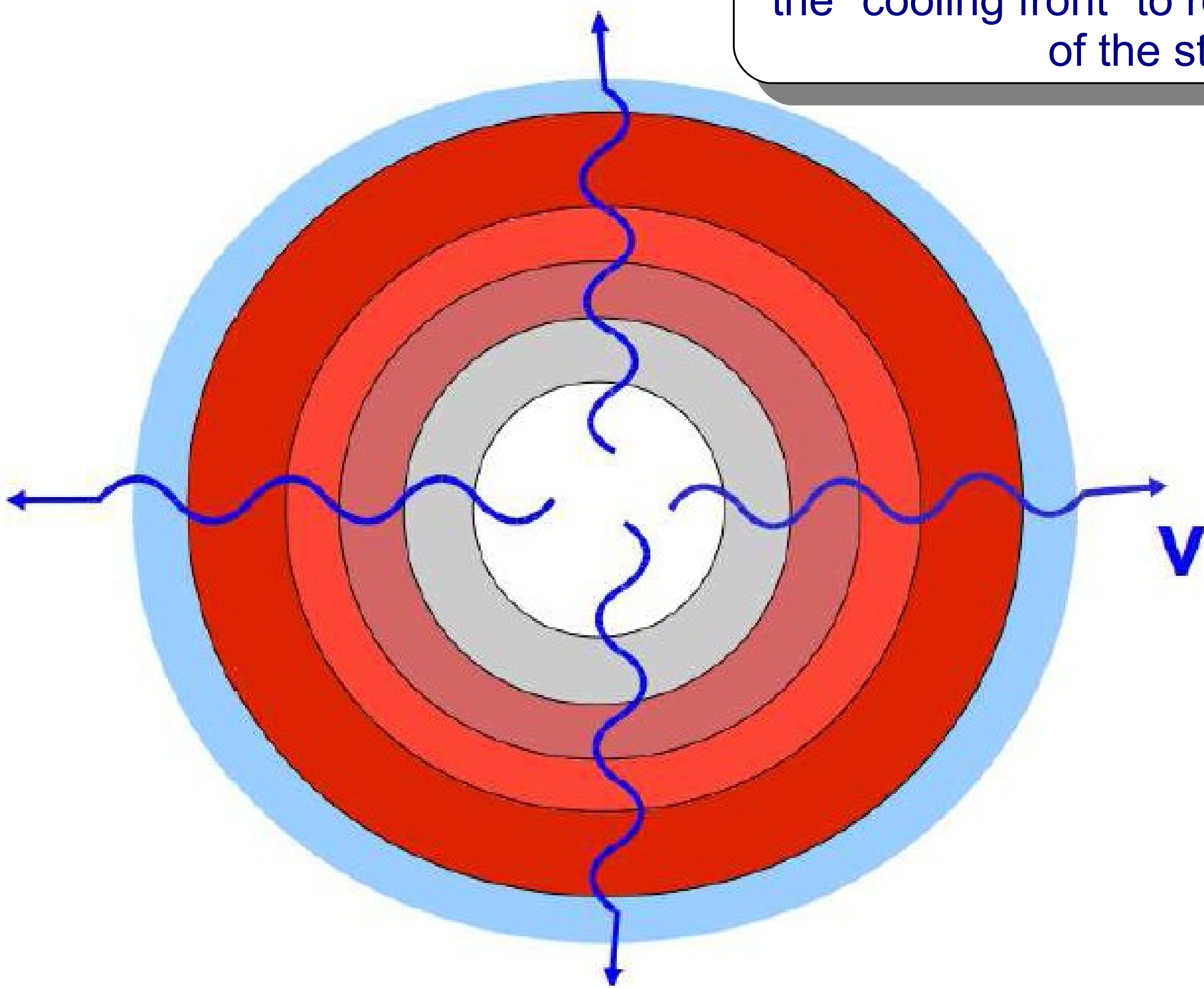
- Thermal evolution is driven by neutrino emissions from core, and photon emission from the surface.
- Neutrino emissions strongly depend on the core composition.
- Depending on its mass, a neutron star may exhibit fast or slow cooling.



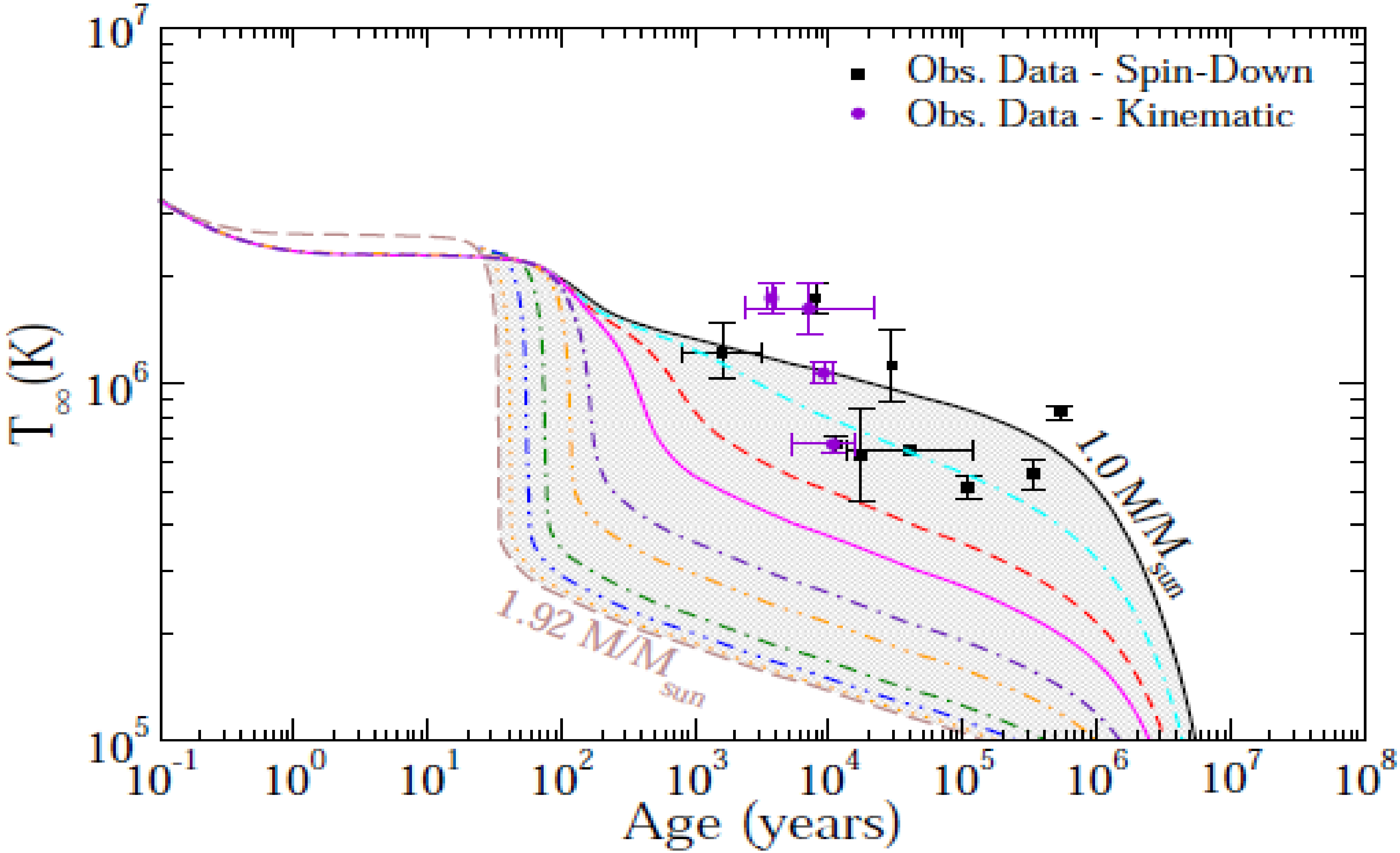
Thermal relaxation time

Neutron stars cool inside out ...

Due to stronger neutrino emissions on the core, it takes ~ 100 years for the "cooling front" to reach the surface of the star.



Cooling Curves



R. Negreiros, V.A. Dexheimer, S. Schramm, Phys.Rev. C 82, 035803 (2010)

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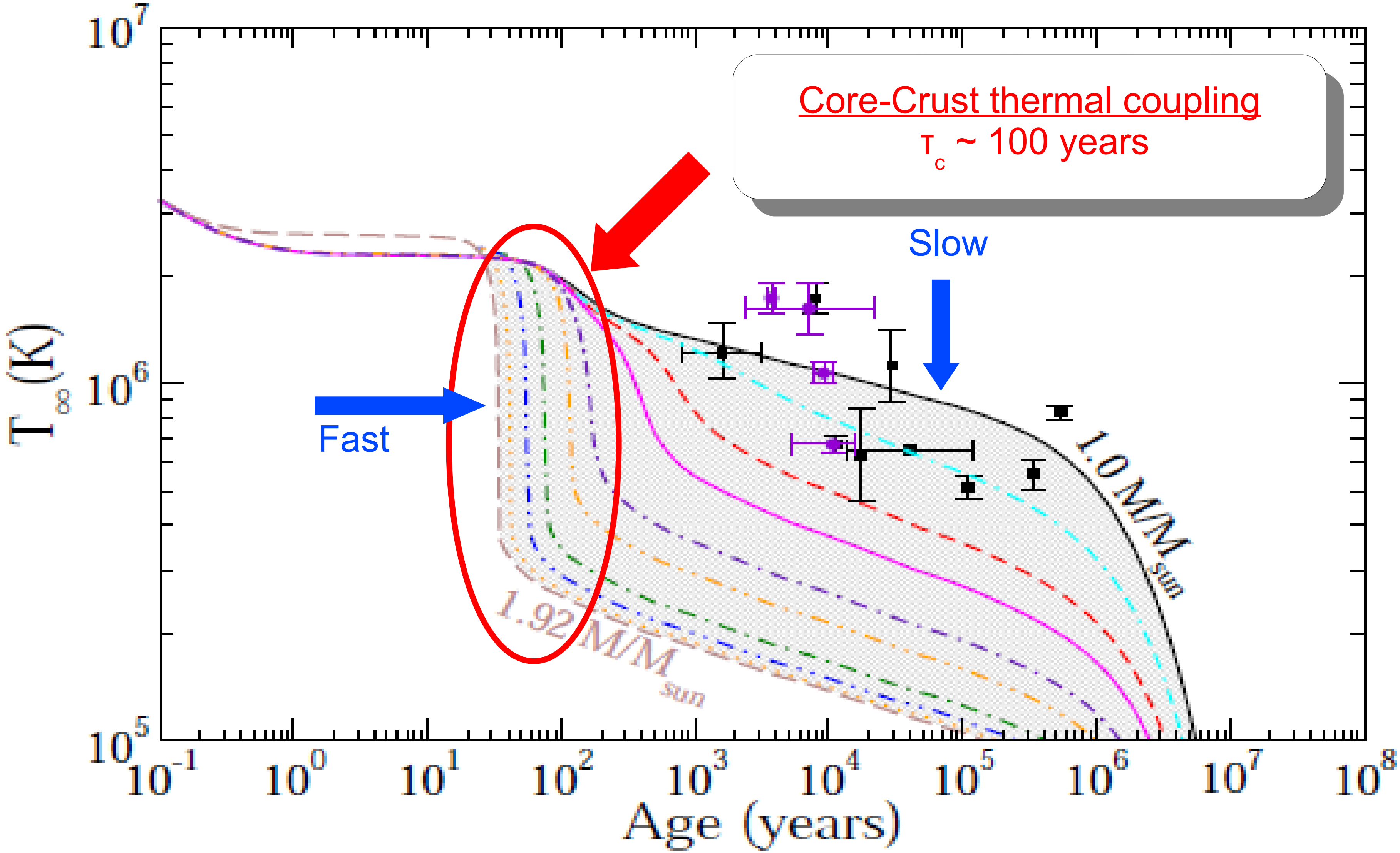
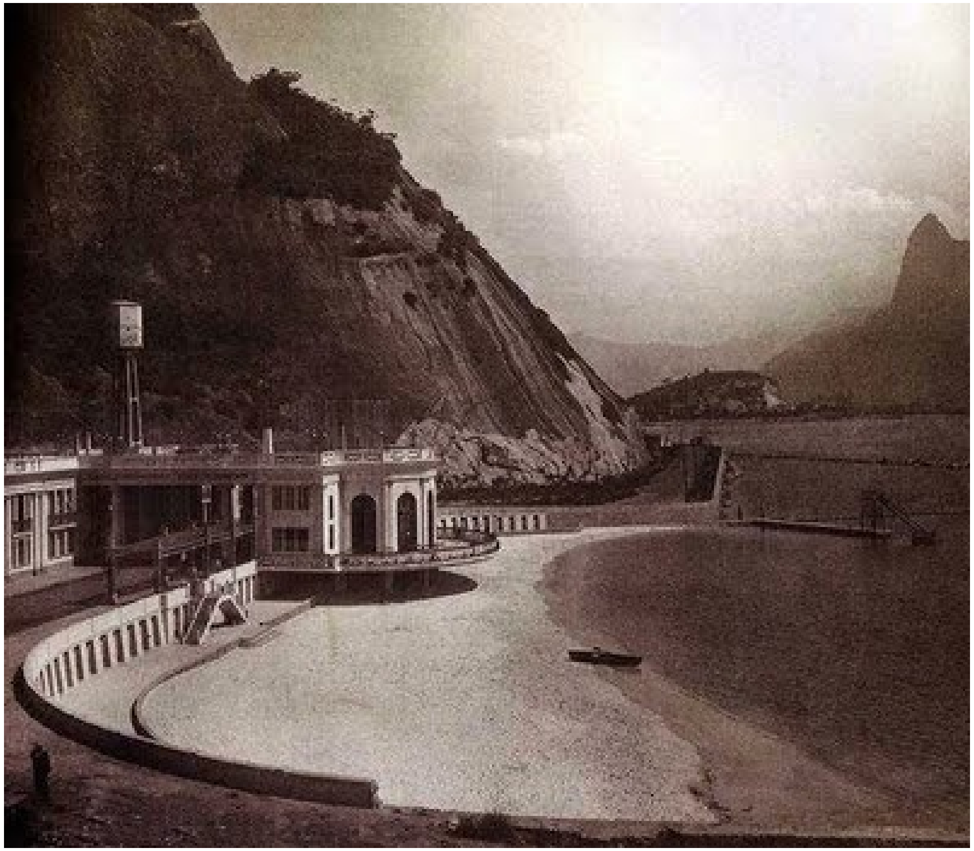


R. Negreiros, V.A. Dexheimer, S. Schramm, Phys.Rev.C 82, 035803 (2010)

Direct Urca Process

The direct Urca process induces fast cooling



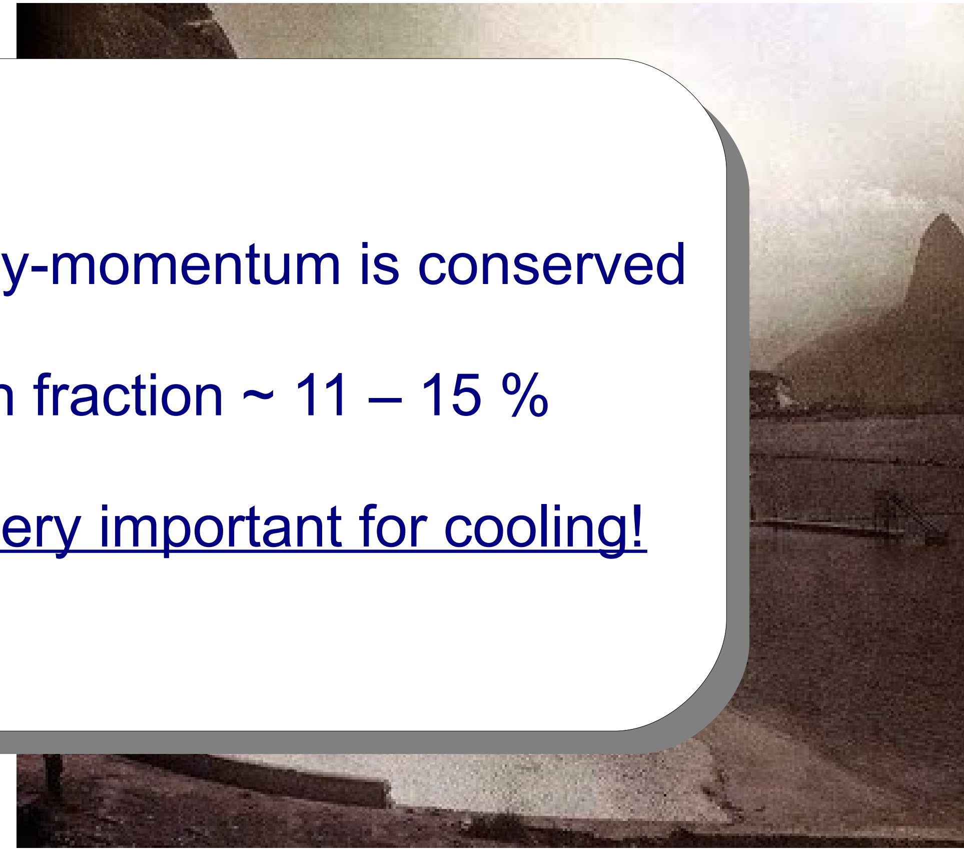
$$n \rightarrow p + e + \bar{\nu}$$

$$p + e \rightarrow n + \nu$$

$$\epsilon_{\nu,\mathrm{DU}} = 4.0 \times 10^{27} \left(\frac{Y_e \rho}{\rho_s}\right)^{1/3} \frac{m^*_{B1} m^*_{B2}}{m_n^2} \, R \, T_9^6 \, \Theta \quad \mathrm{ergs\ cm^{-3} s^{-1}}$$

Direct Urca Process

The direc
fast coo



n –
p +

Can only take place if energy-momentum is conserved

Usual threshold: proton fraction ~ 11 – 15 %

Microscopic composition very important for cooling!

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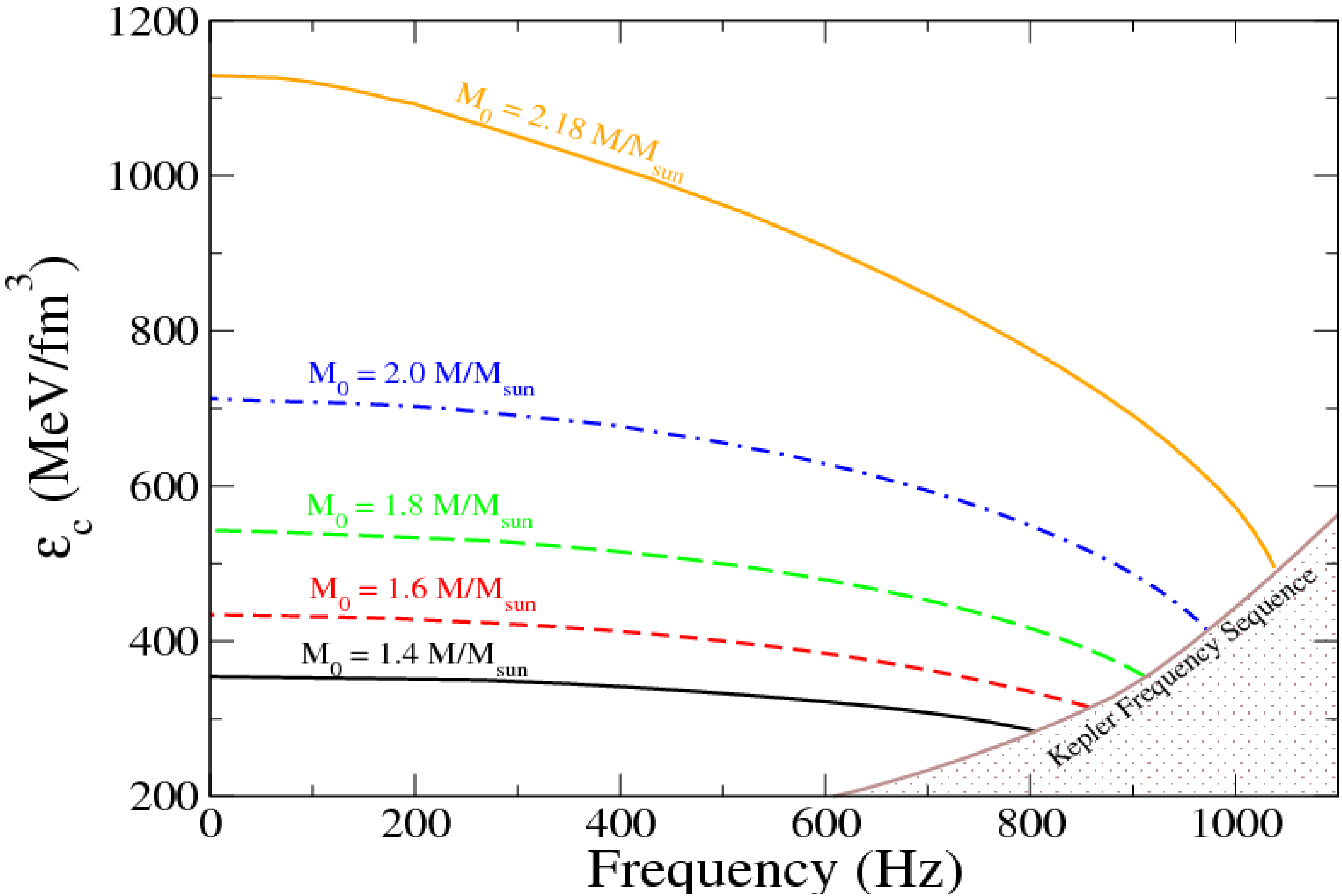
- Rotation may strongly affect the structure of NS.



Introducing rotation

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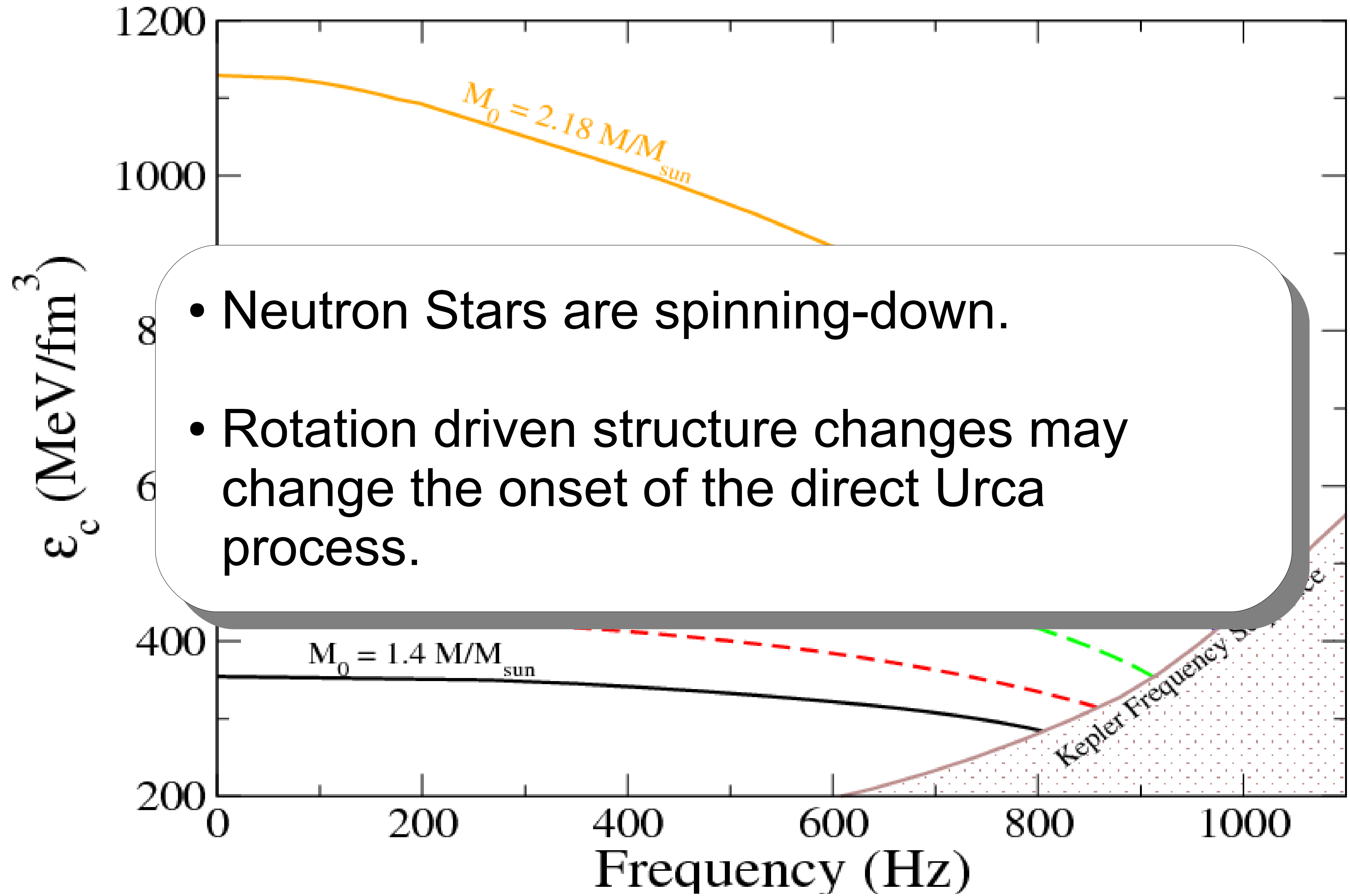
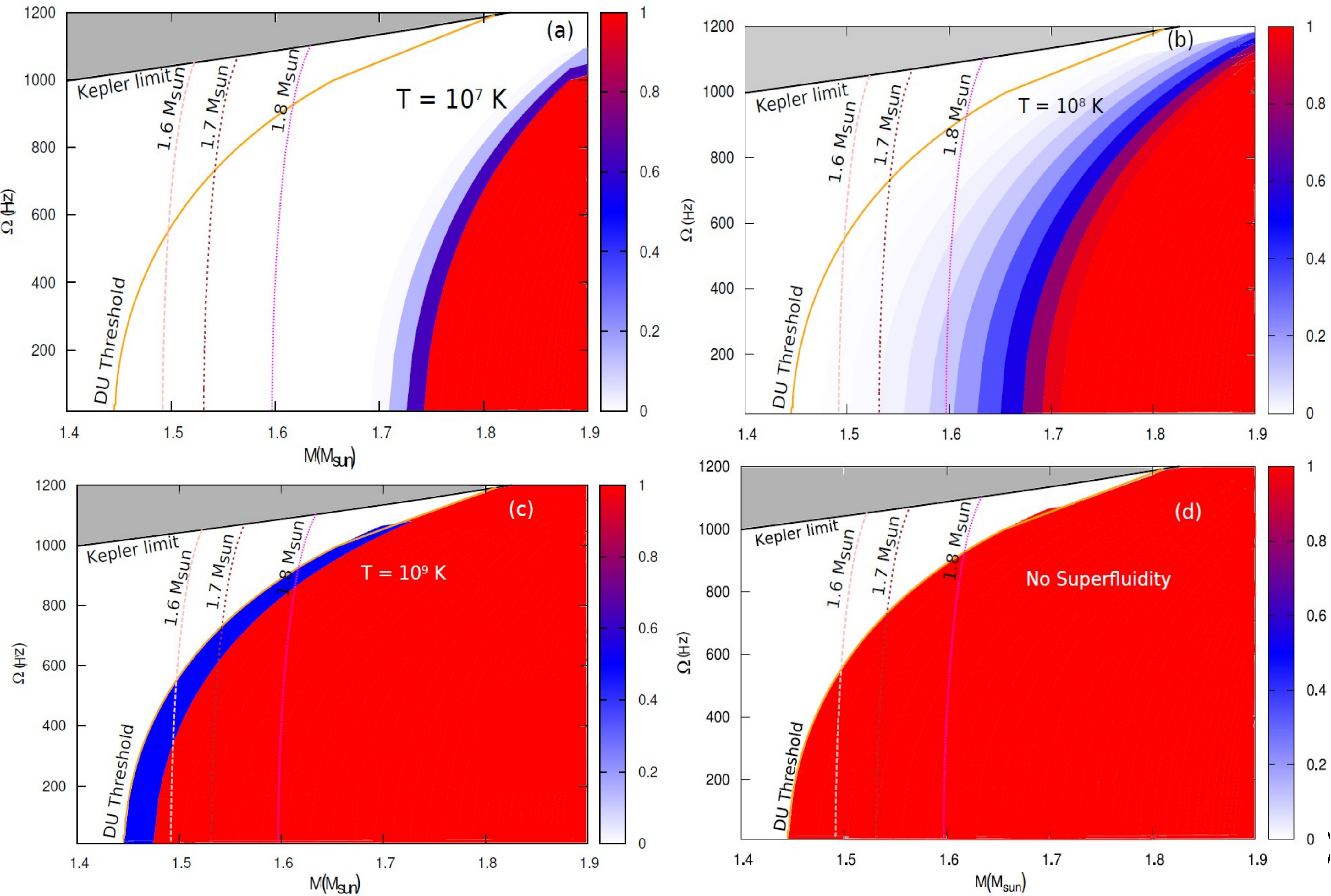
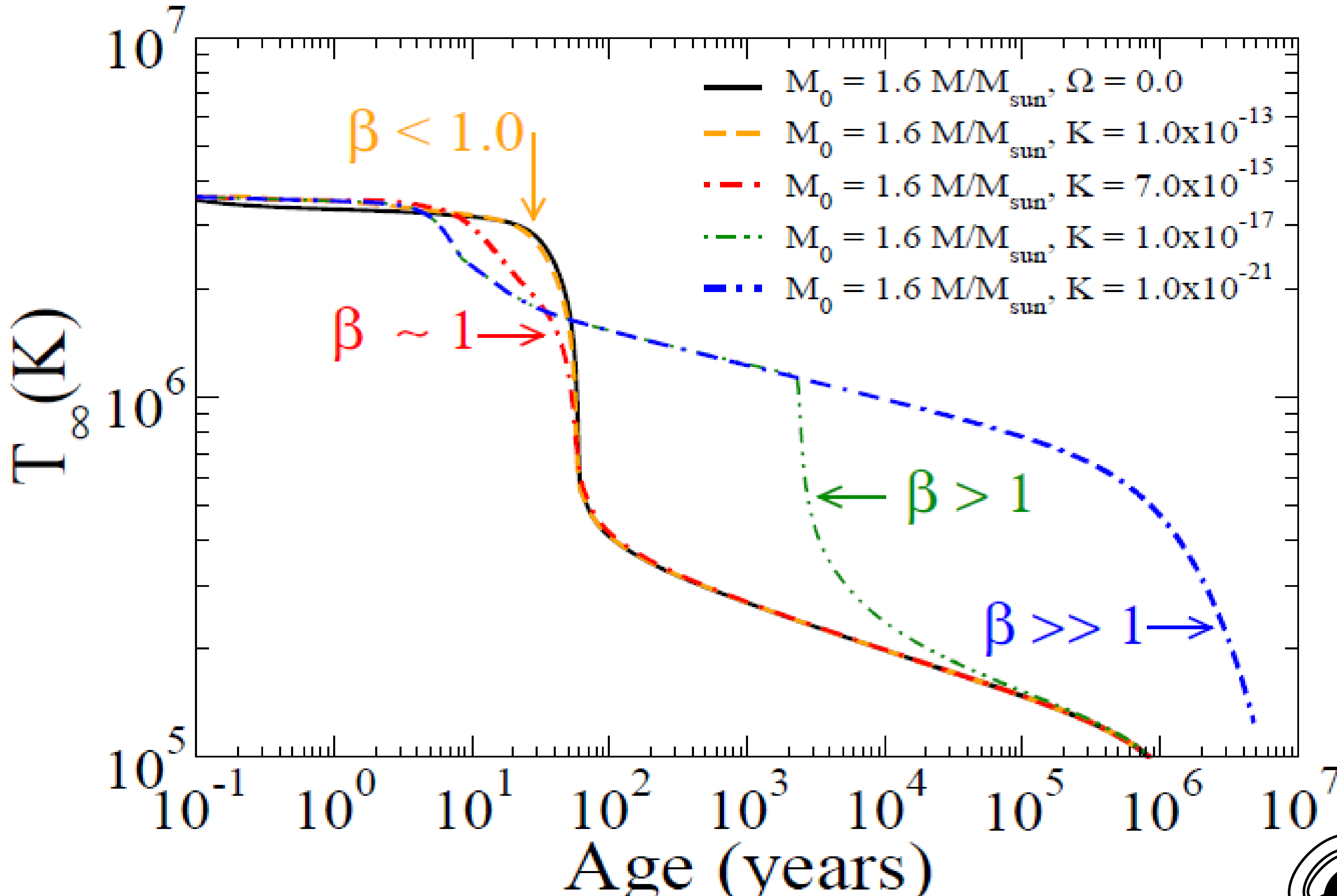


- Neutron Stars are spinning-down.
- Rotation driven structure changes may change the onset of the direct Urca process.

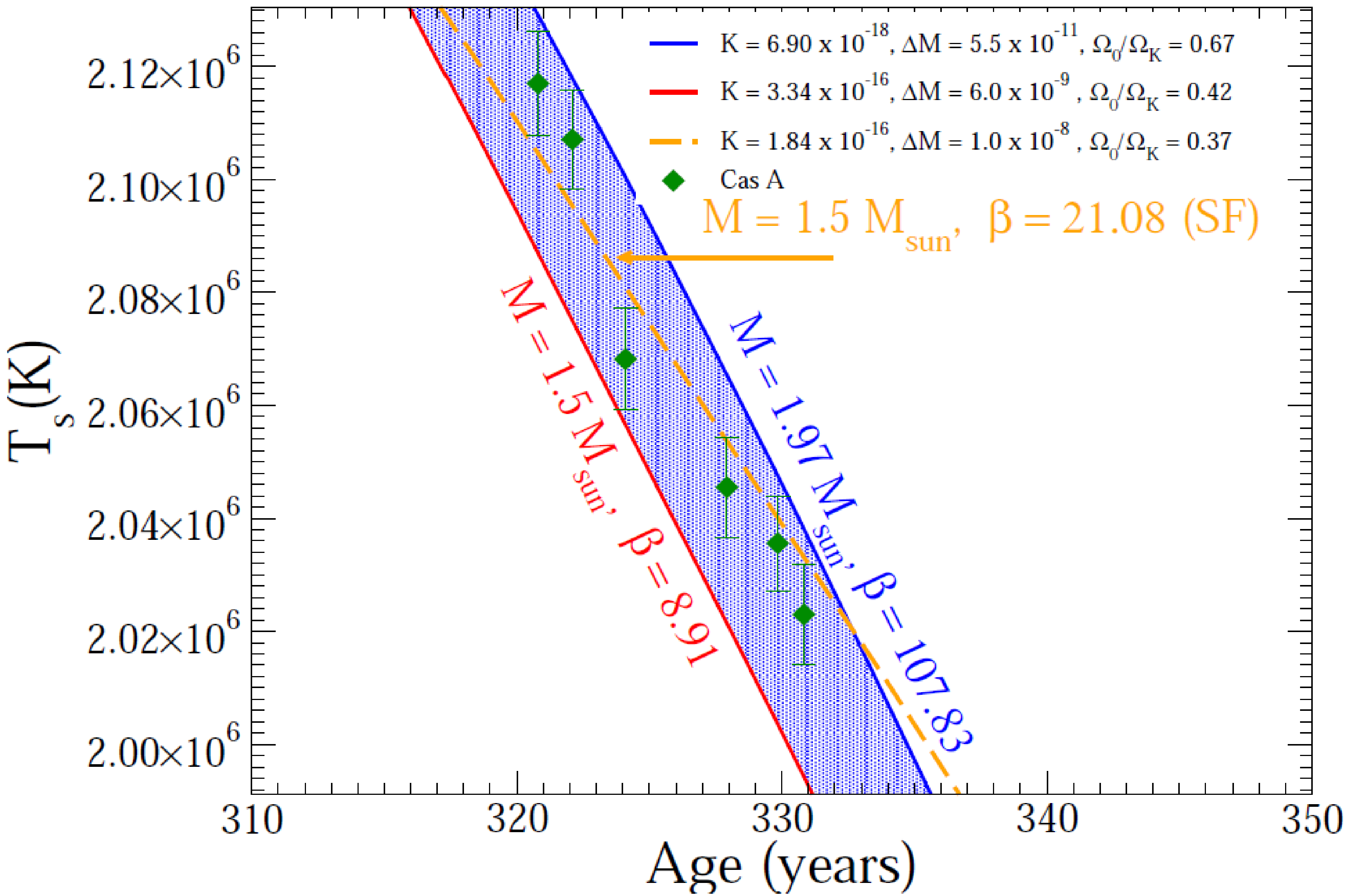
Introducing rotation



Cooling of spinning-down neutron stars



Applying to Cas A



2D simulations

- Neutron star thermal evolution:

➔ Spherically symmetric
➔ "Frozen in" composition

- We have introduced a dynamic composition.

- A self-consistent calculation required 2D calculations.

2D Calculations

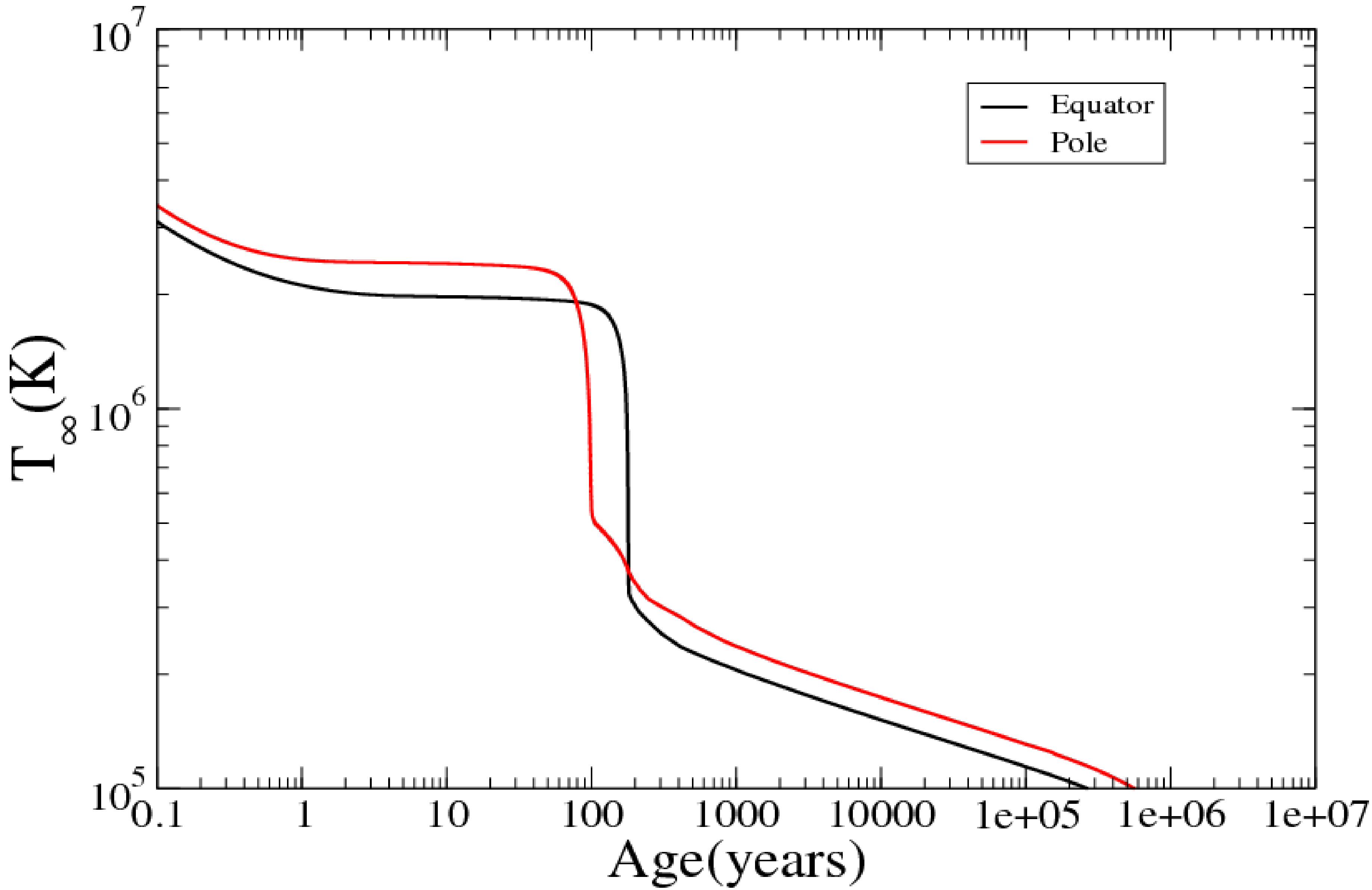
2D calculations are needed for a consistent description of the thermal evolution of spinning down(up) compact stars.

$$
\begin{aligned}
\partial_t \tilde{T} \;=\; & -\frac{1}{\Gamma^2} e^{2\nu} \frac{\epsilon}{C_V} - r \sin\theta \, U e^{\nu+\gamma-\xi} \frac{1}{C_V} \left(\partial_r \Omega + \frac{1}{r} \partial_\theta \Omega \right) \\
& + \frac{1}{r^2 \sin\theta} \frac{1}{\Gamma} e^{3\nu-\gamma-2\xi} \frac{1}{C_V} \Bigg(\partial_r \Big(r^2 \kappa \sin\theta \, e^\gamma \Big(\partial_r \tilde{T} + \Gamma^2 U e^{-2\nu+\gamma} \tilde{T} \partial_r \Omega \Big) \Big) \\
& + \frac{1}{r^2} \partial_\theta \Big(r^2 \kappa \sin\theta \, e^\gamma \Big(\partial_\theta \tilde{T} + \Gamma^2 U e^{-2\nu+\gamma} \tilde{T} \partial_\theta \Omega \Big) \Big) \Bigg)
\end{aligned}
$$

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

2D Calculations

Mg = 1.48, ec = 350 MeV/fm³, freq = 750 Hz



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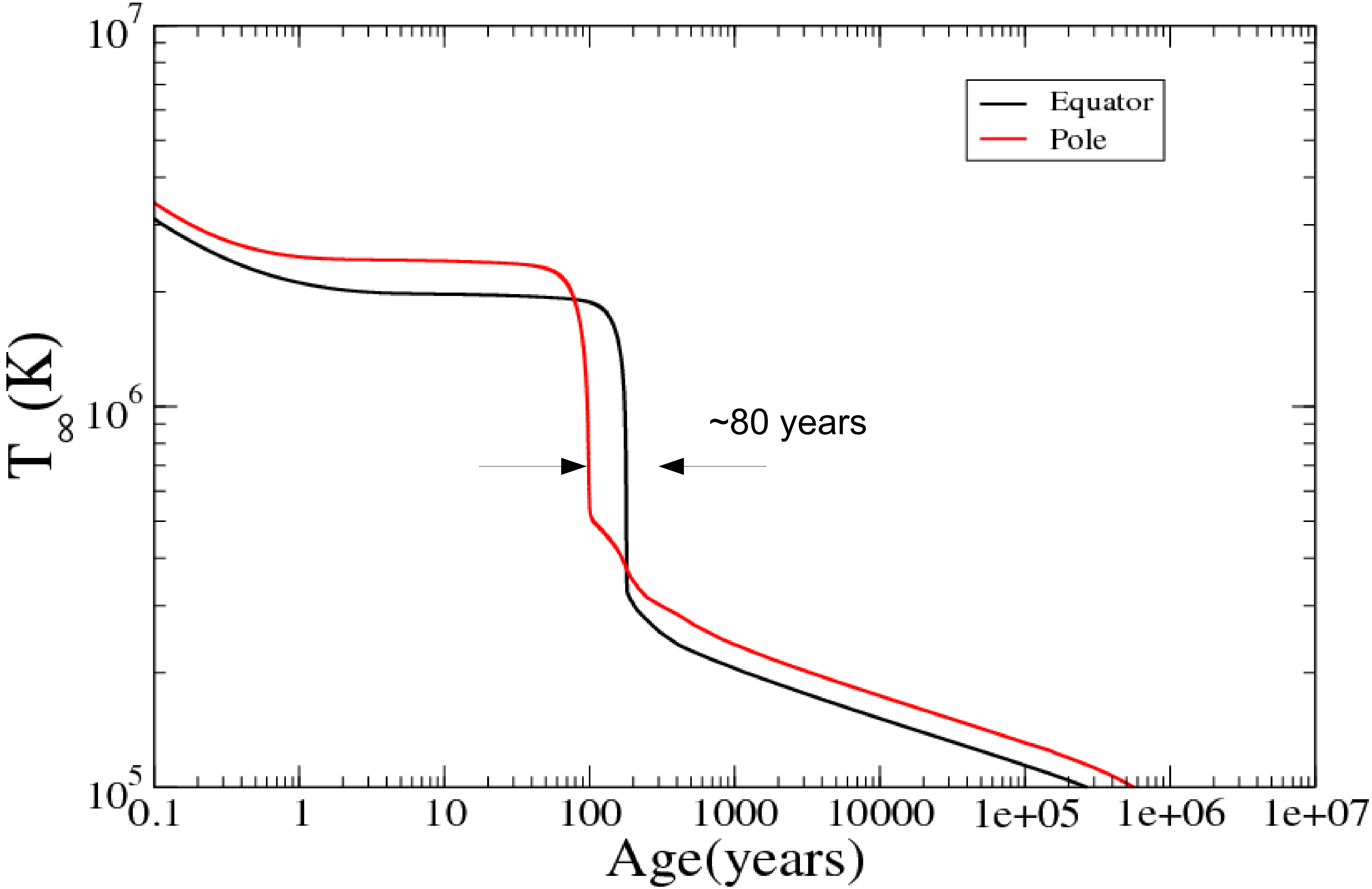

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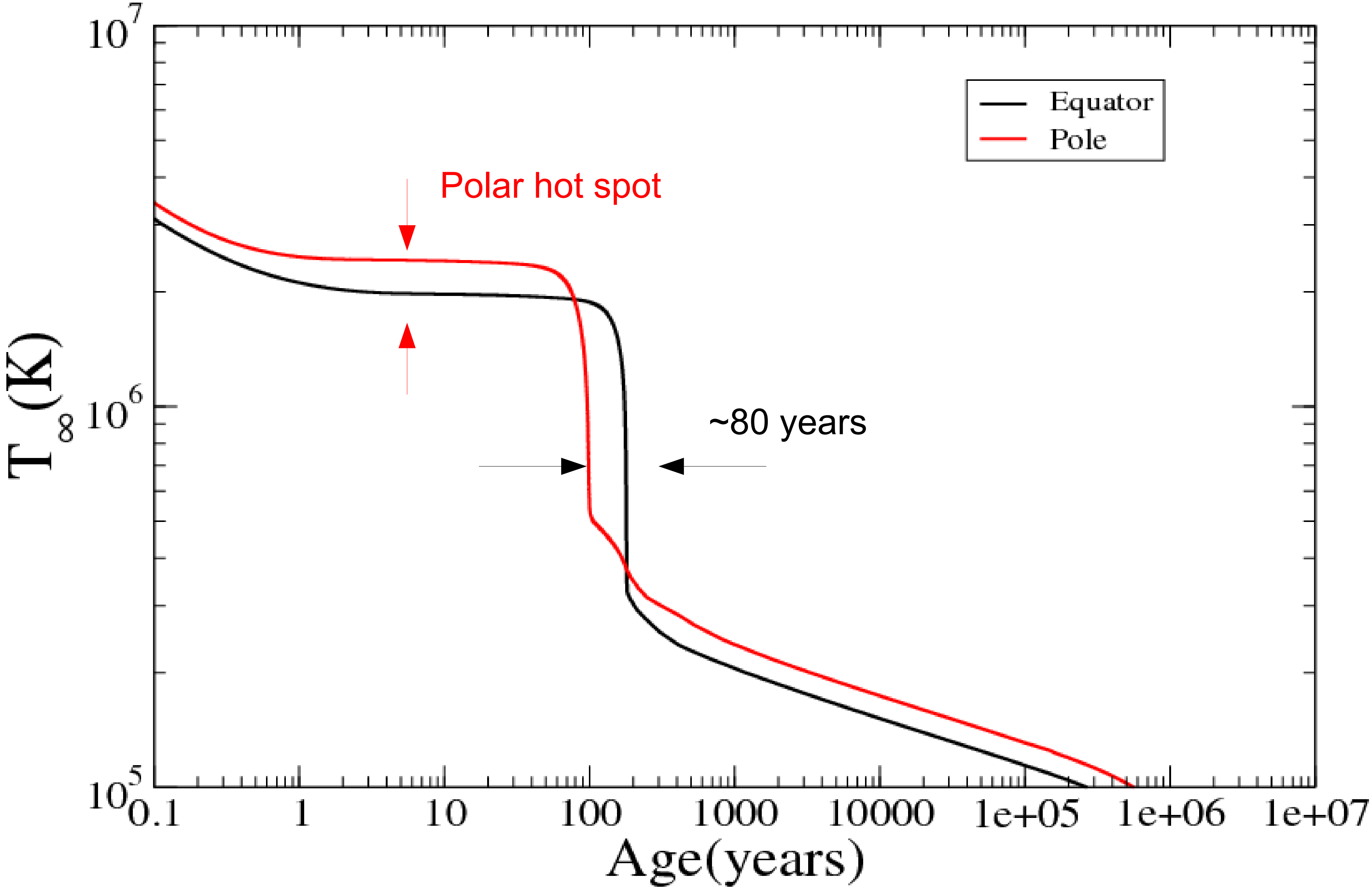

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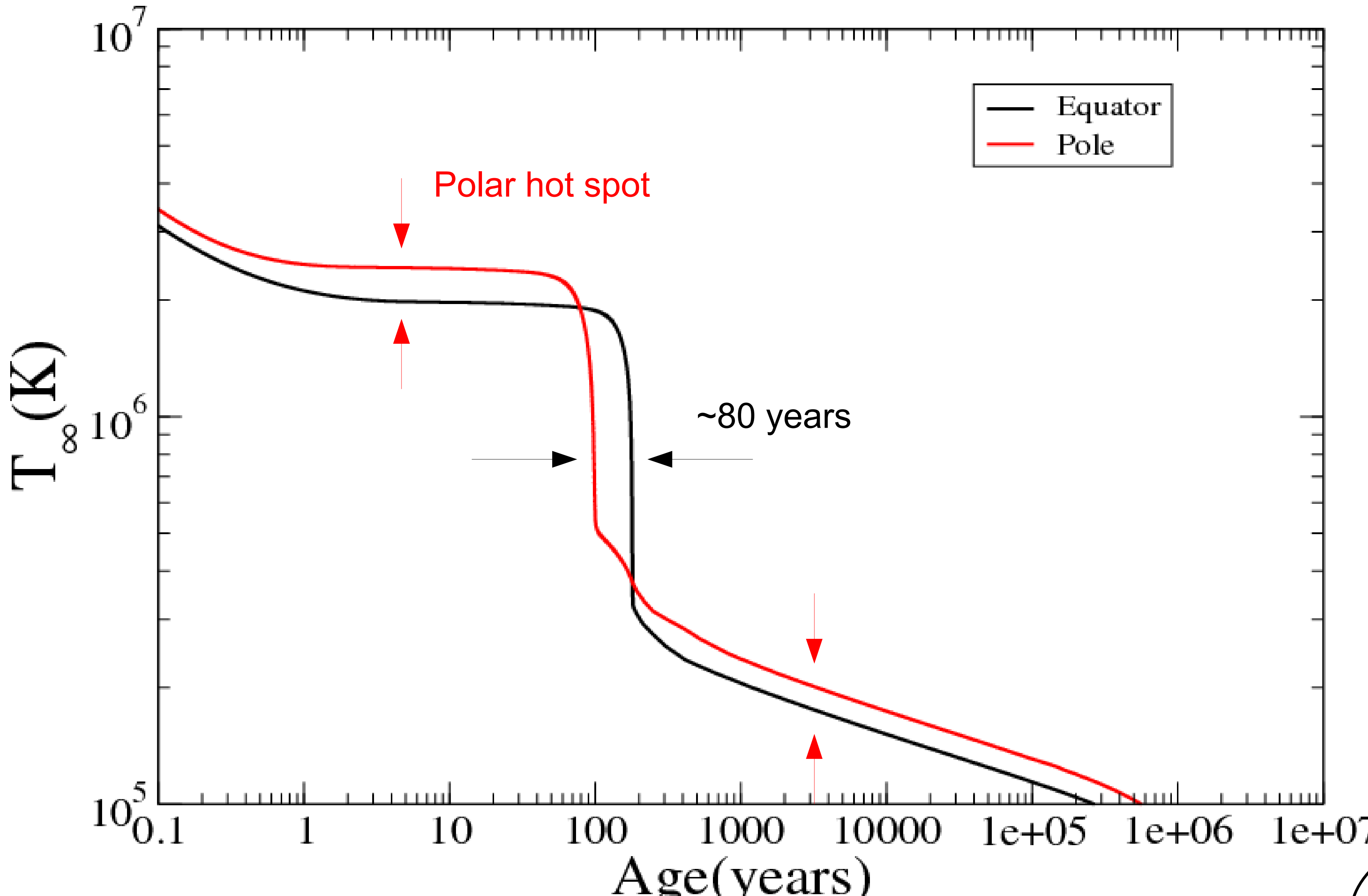

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2D Calculations – break down

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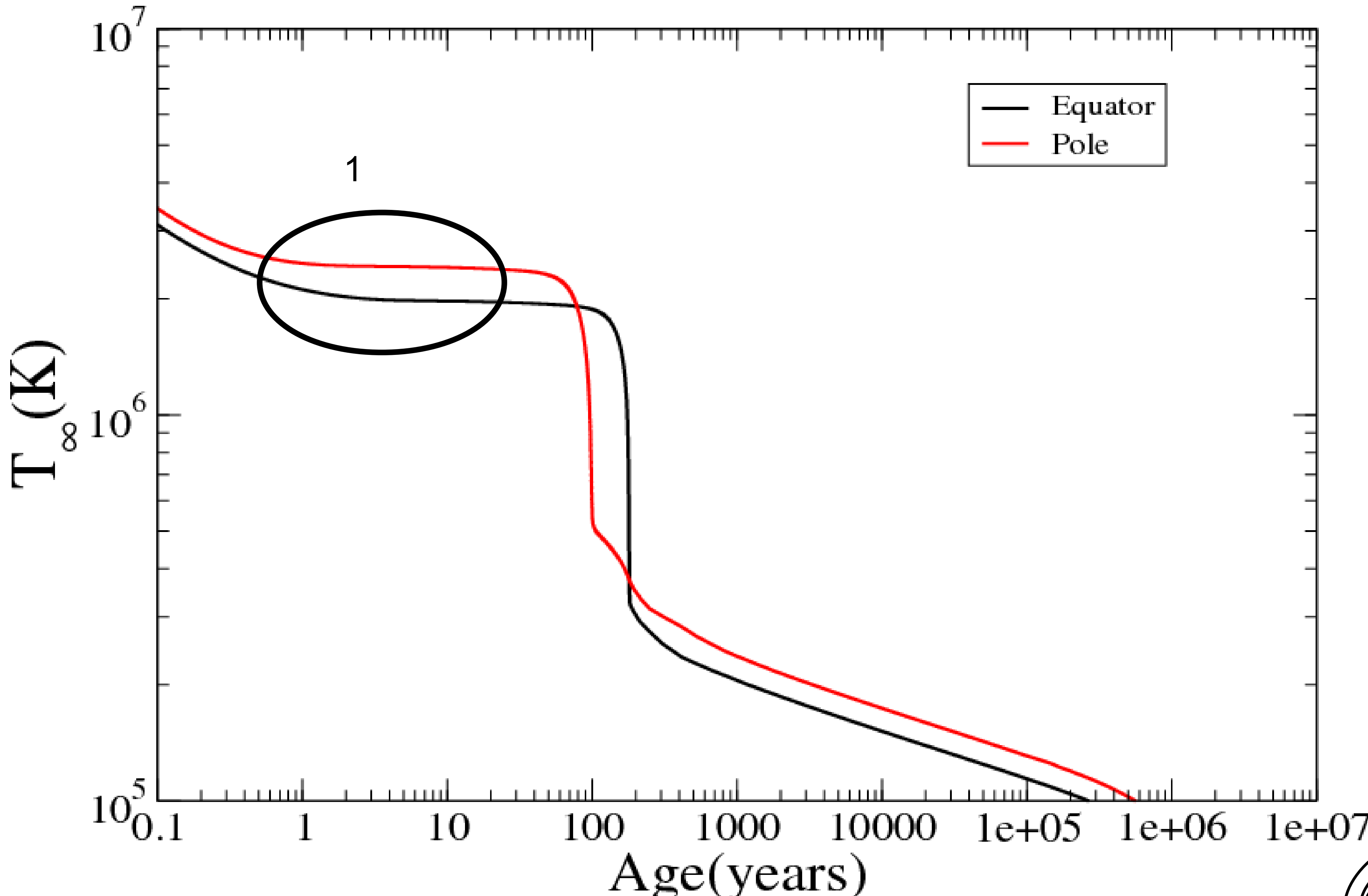

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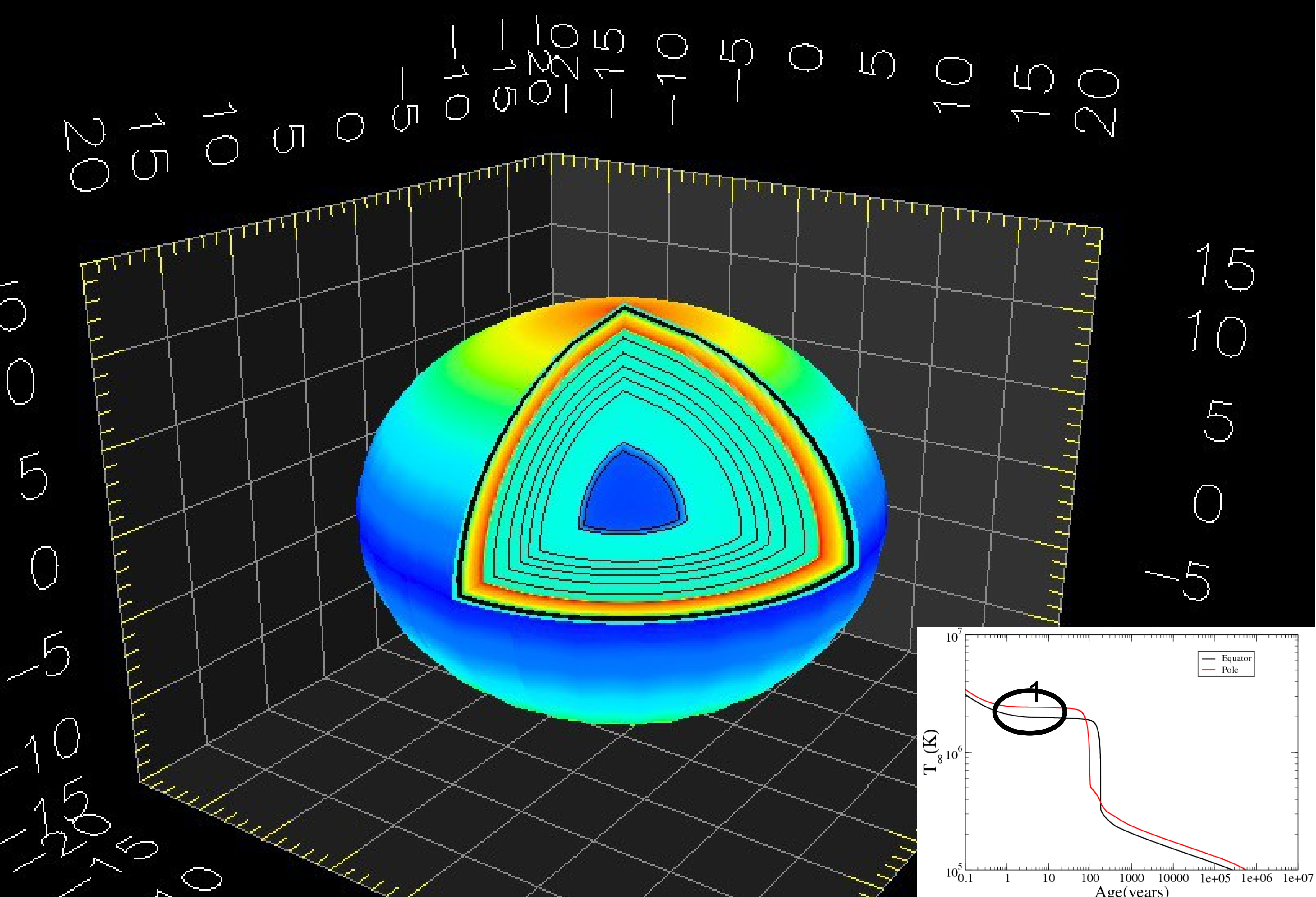

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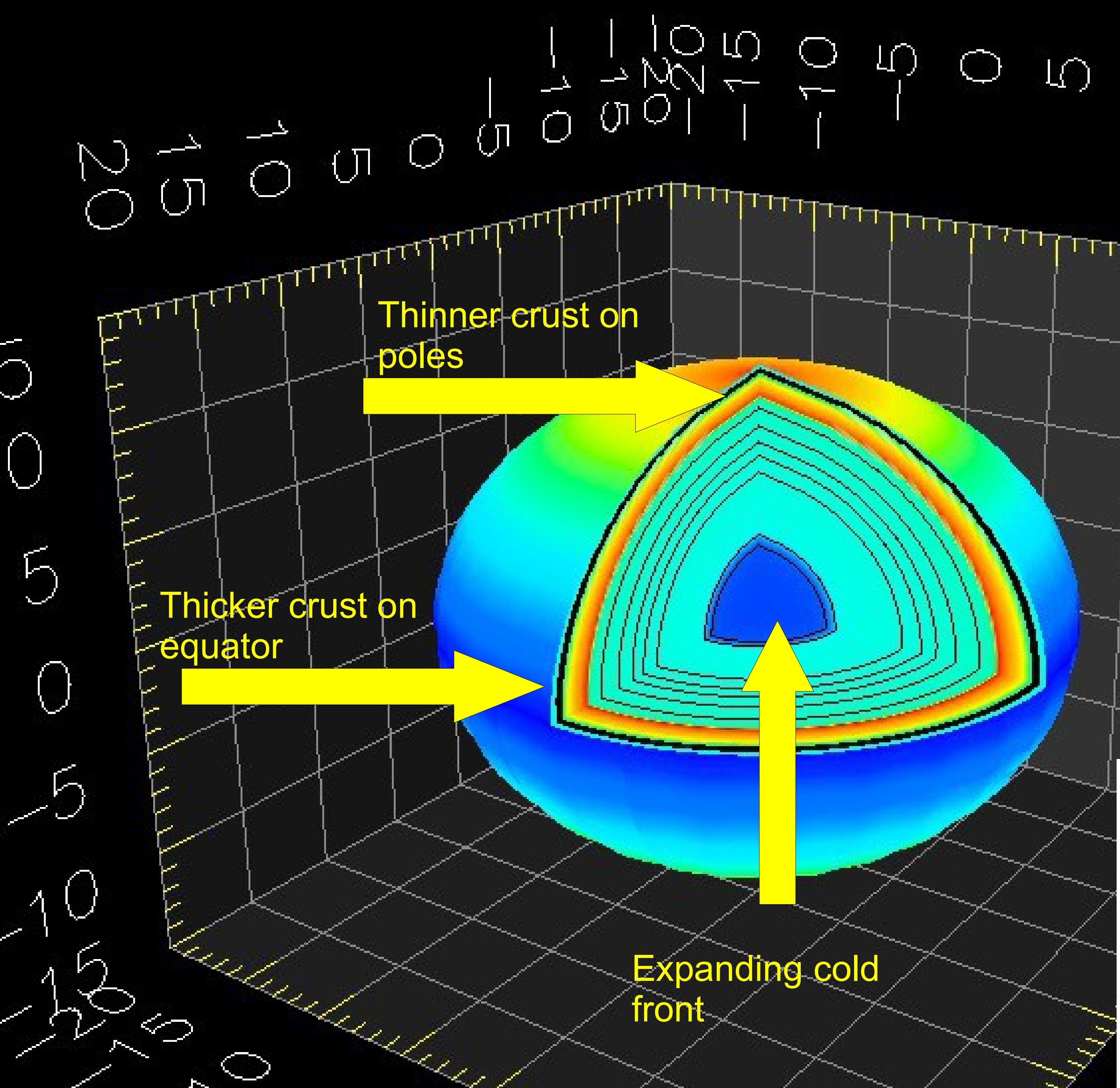

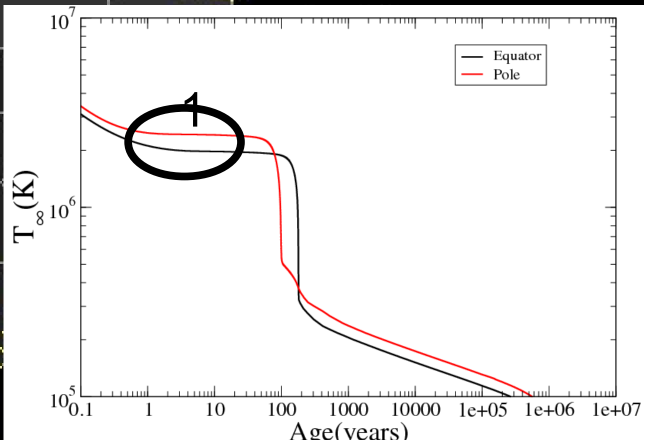

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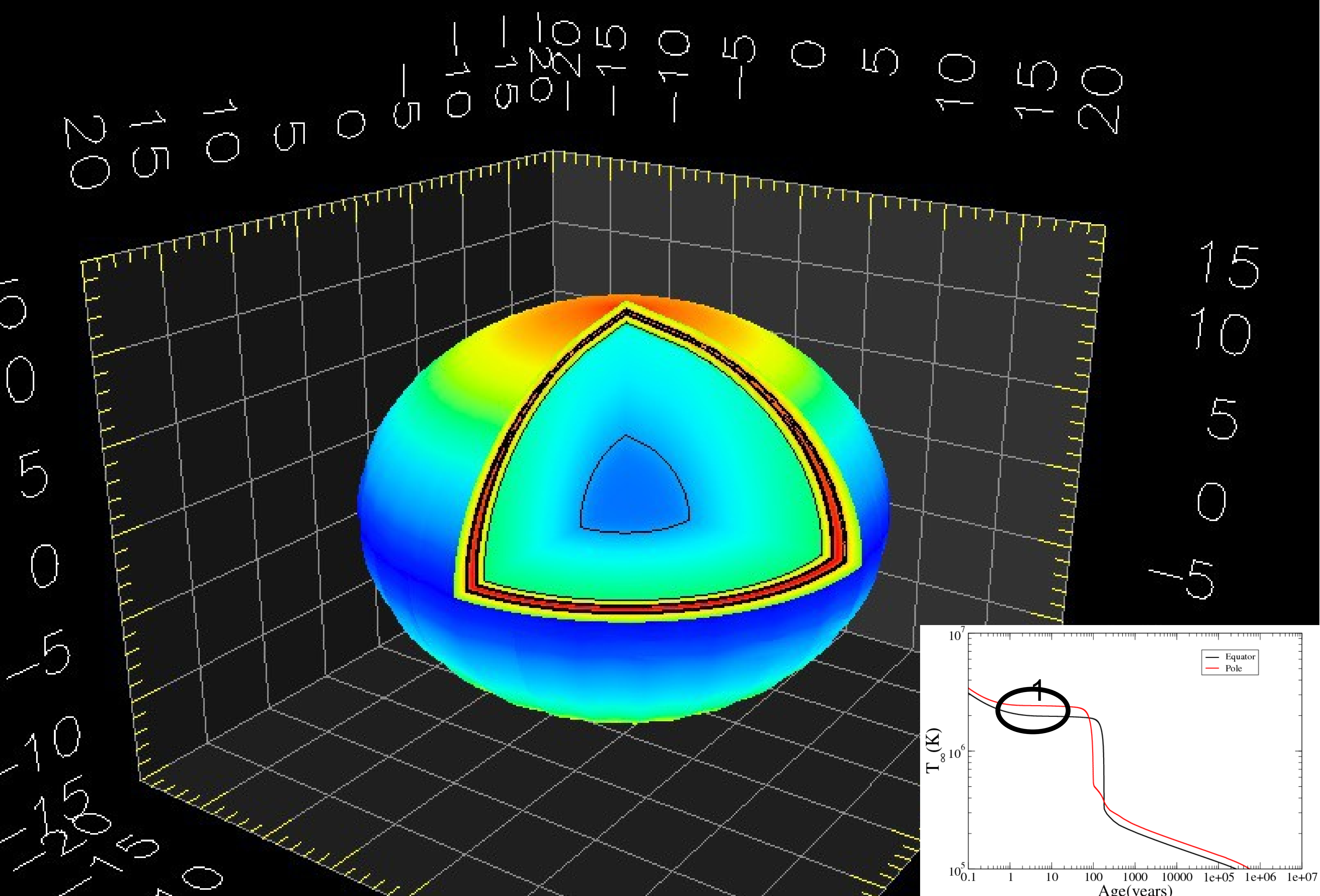

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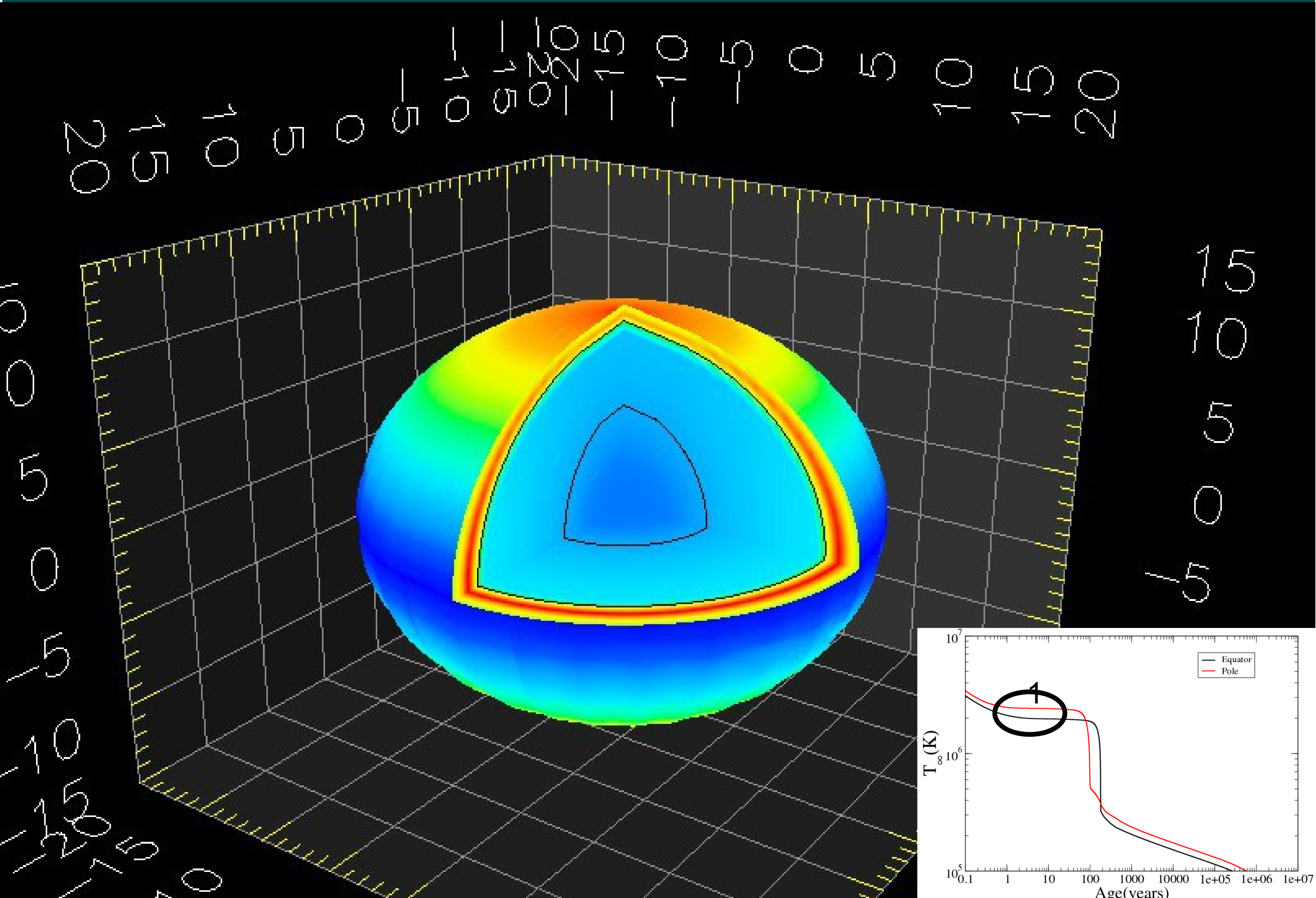

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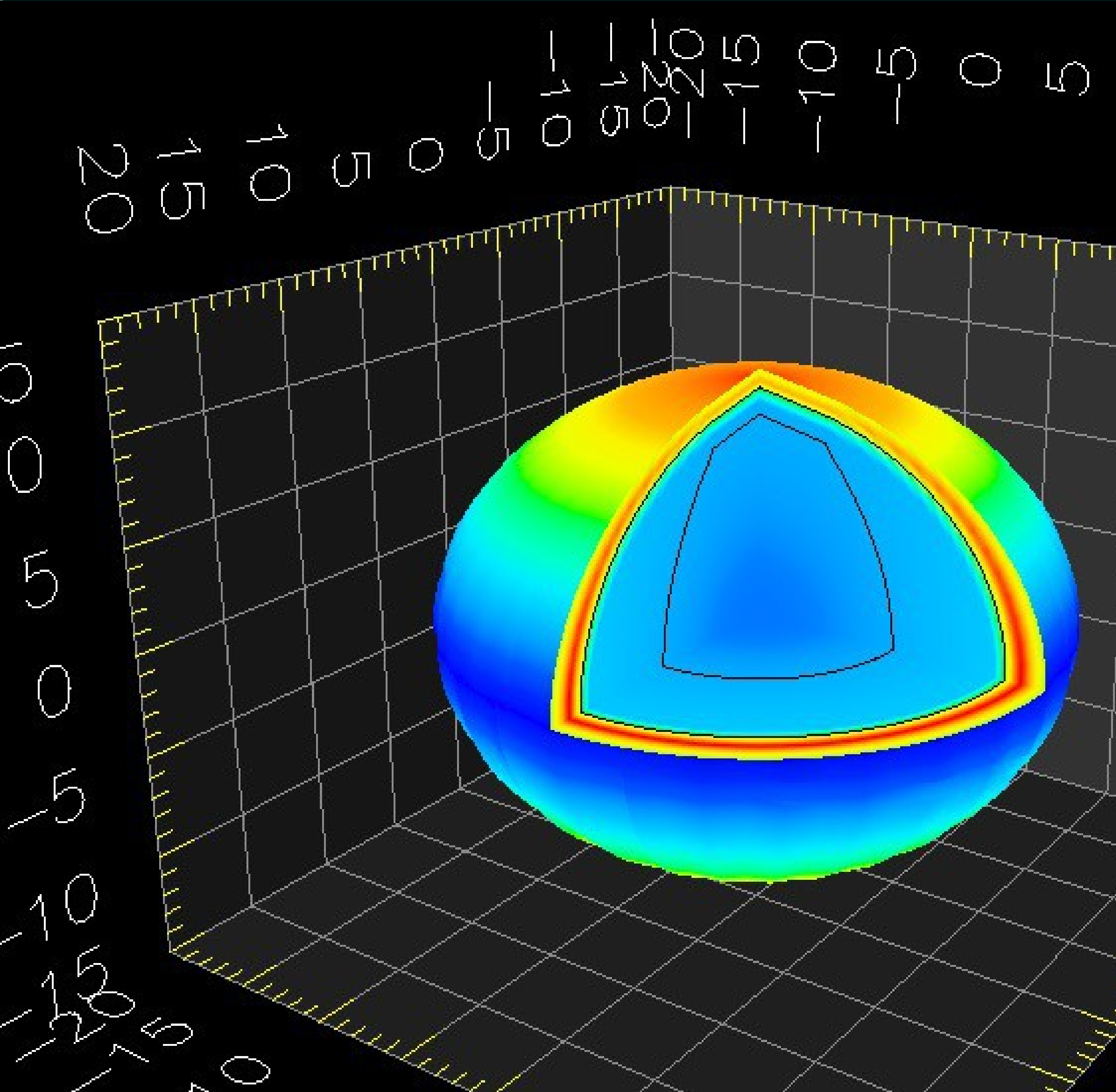

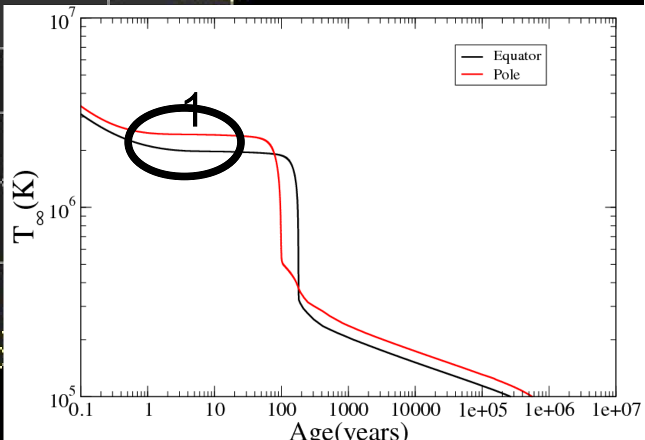

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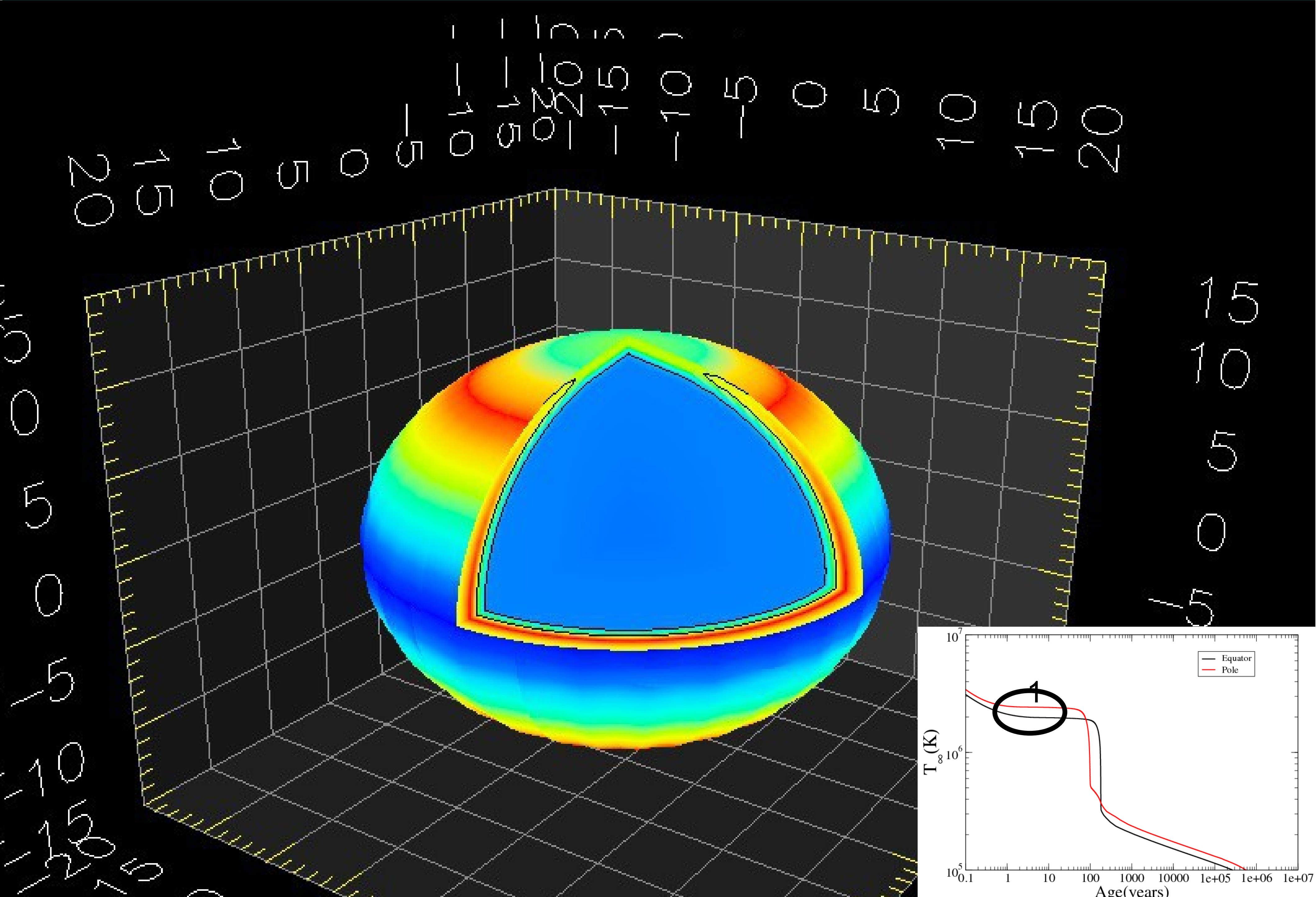

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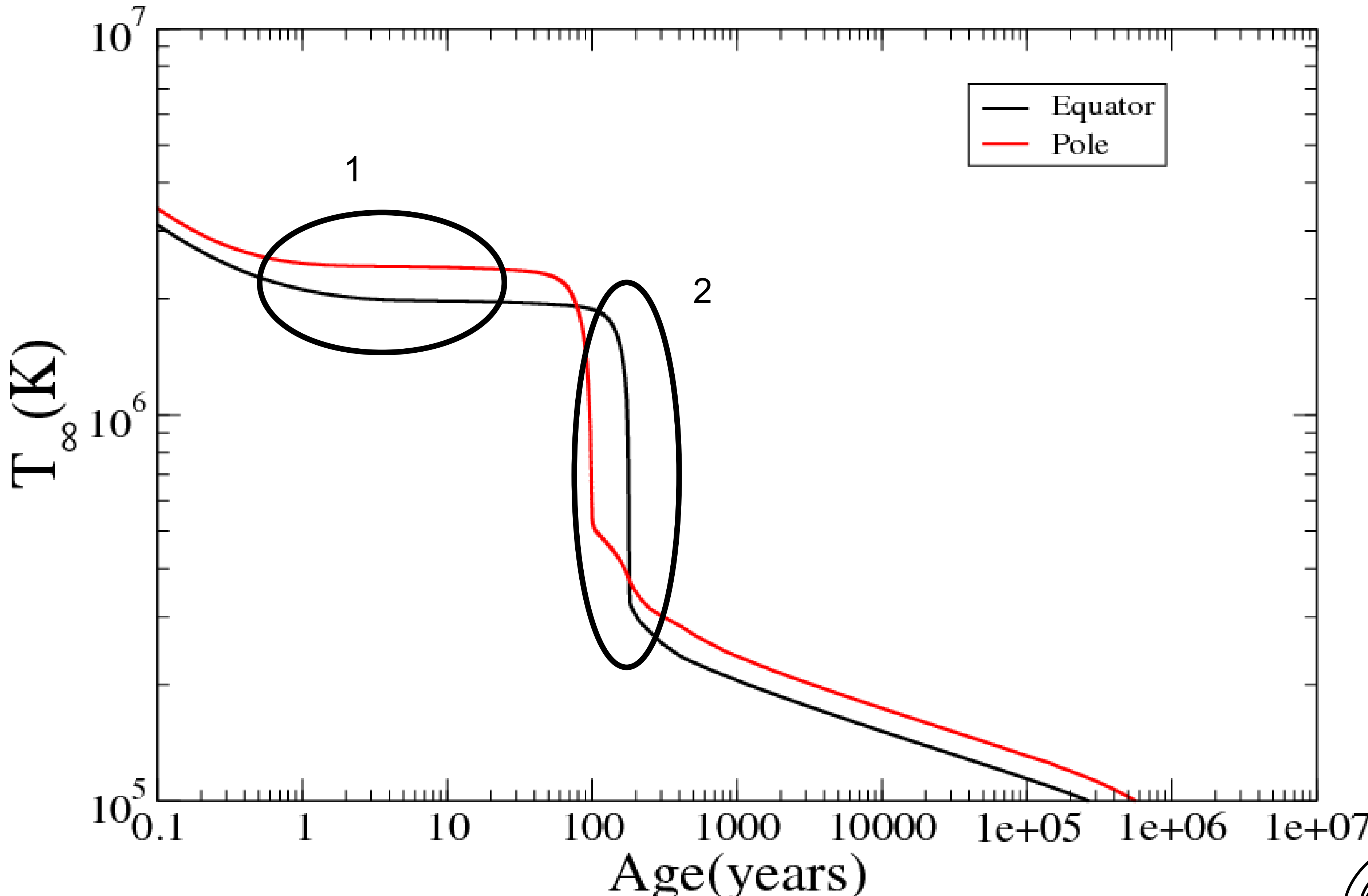

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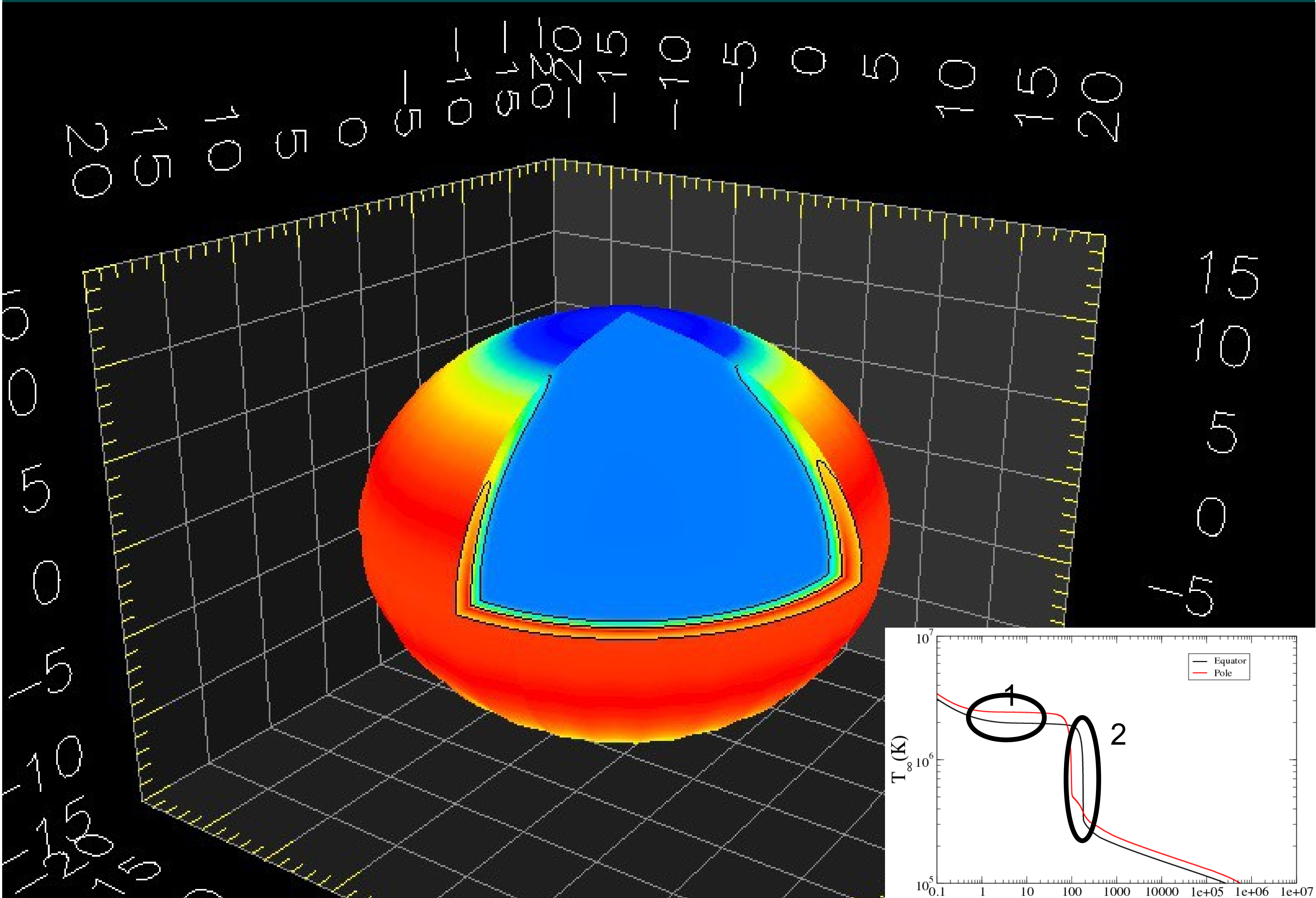

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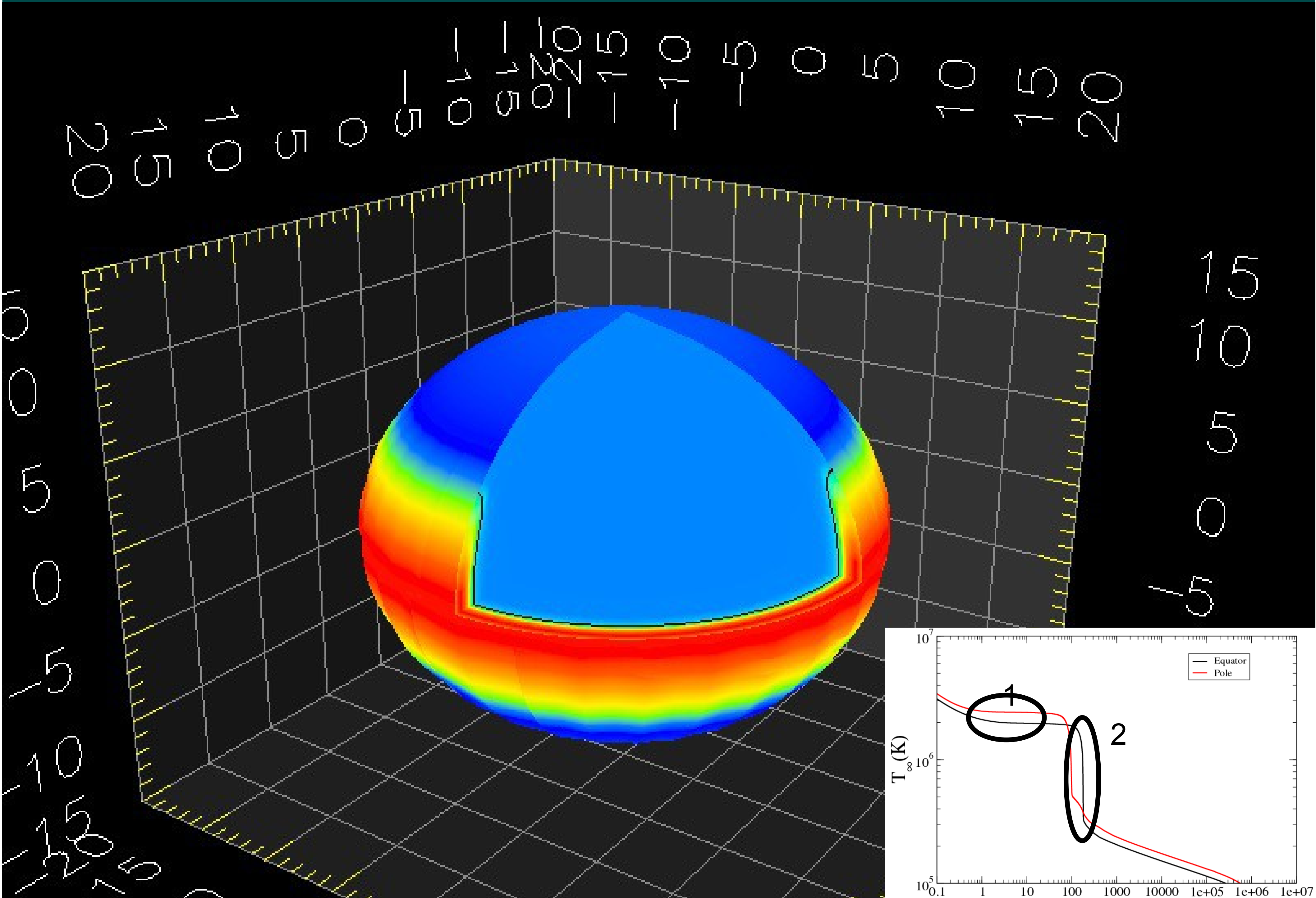

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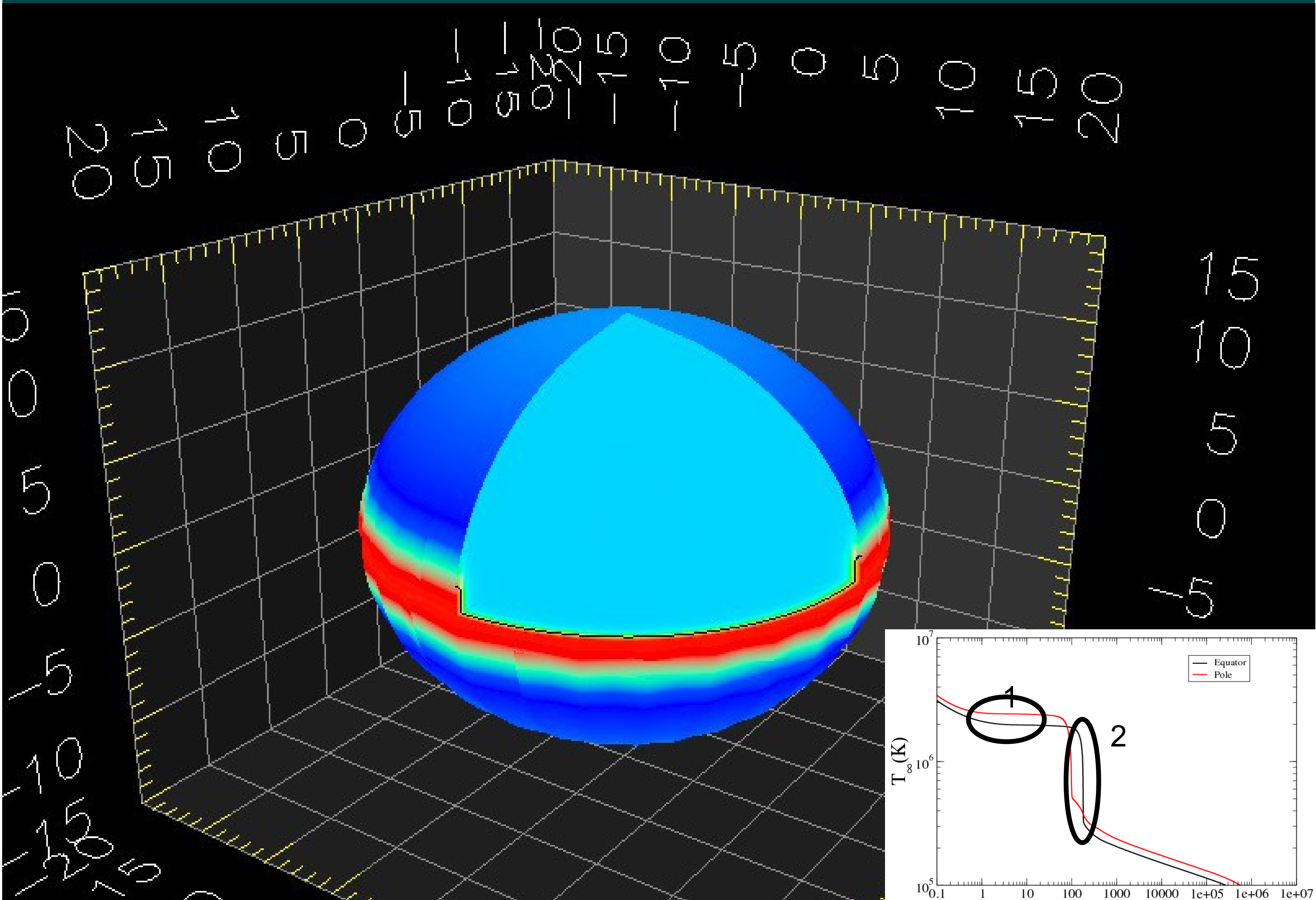

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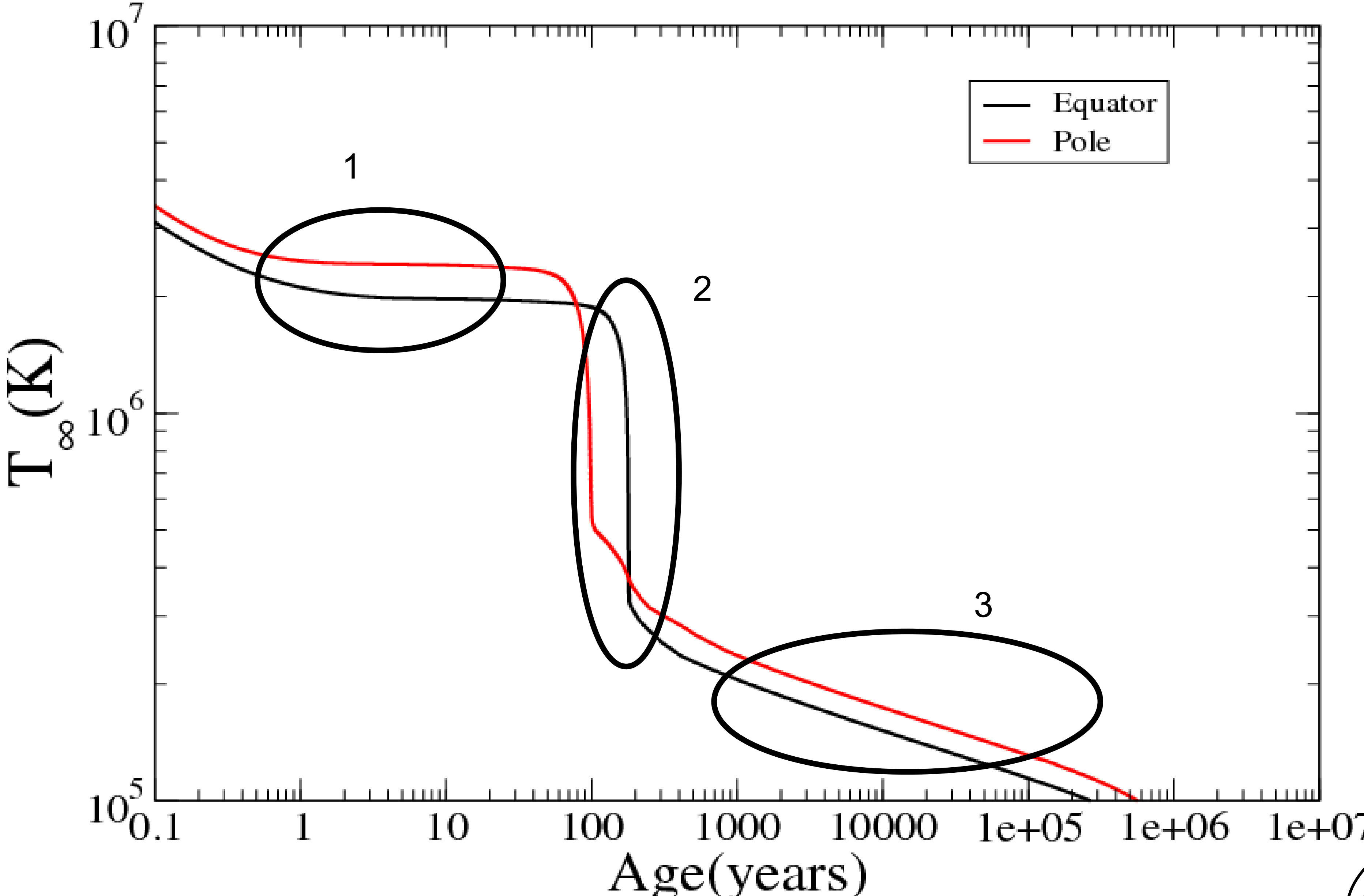

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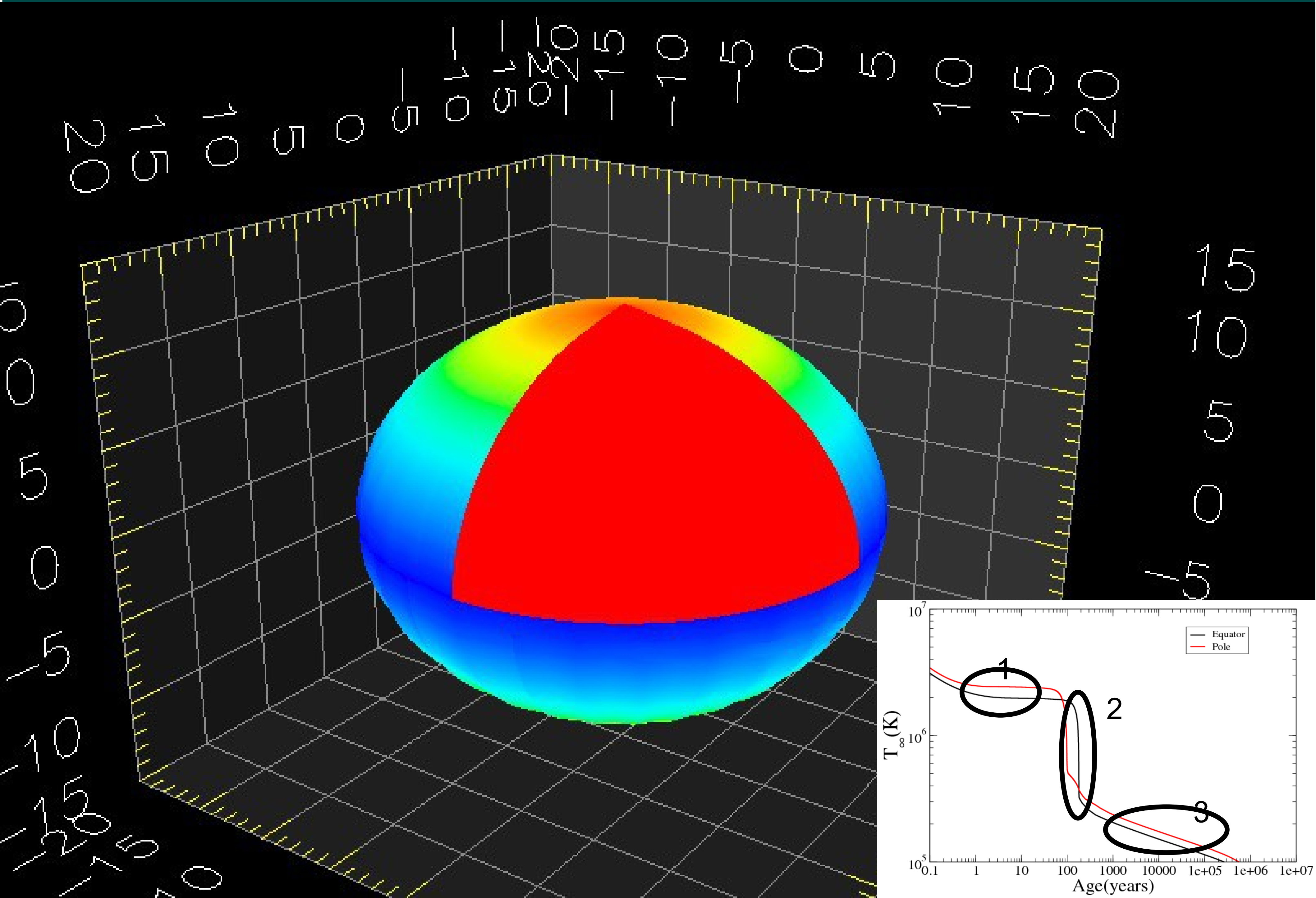


Summary....

- Coupling the spin-evolution to the thermal evolution might help in explaining the slow cooling exhibited by a few objects.
- We showed that the spin-evolution might have far-reaching implications for the cooling of neutron stars and should not be neglected.
- Agrees with the cooling of the object in Cas A.
- We want to expand the model by including quark matter.

Thank you!

Conclusions and Outlook

- Rotation is important!

- 2D thermal evolution simulations are needed, if one wants to consistently calculate the cooling of neutron stars.

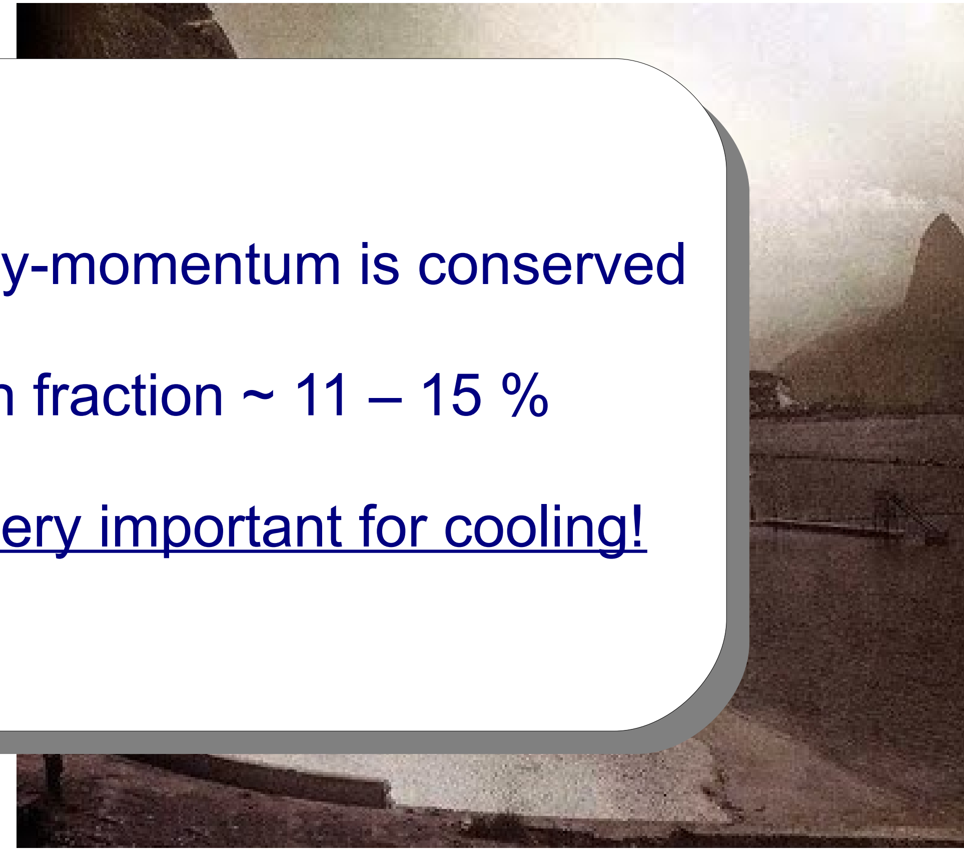
- Coupling the spin-evolution to the thermal evolution seems to be a natural explanation for the slow cooling observed for neutron stars.

- We showed that the spin-evolution might have far-reaching implications for the cooling of neutron stars and should not be neglected.

- Agrees very well with the cooling of the object in Cas A.

Direct Urca Process

The direc
fast coo



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Why 2D simulations??

- Neutron stars are rotating.

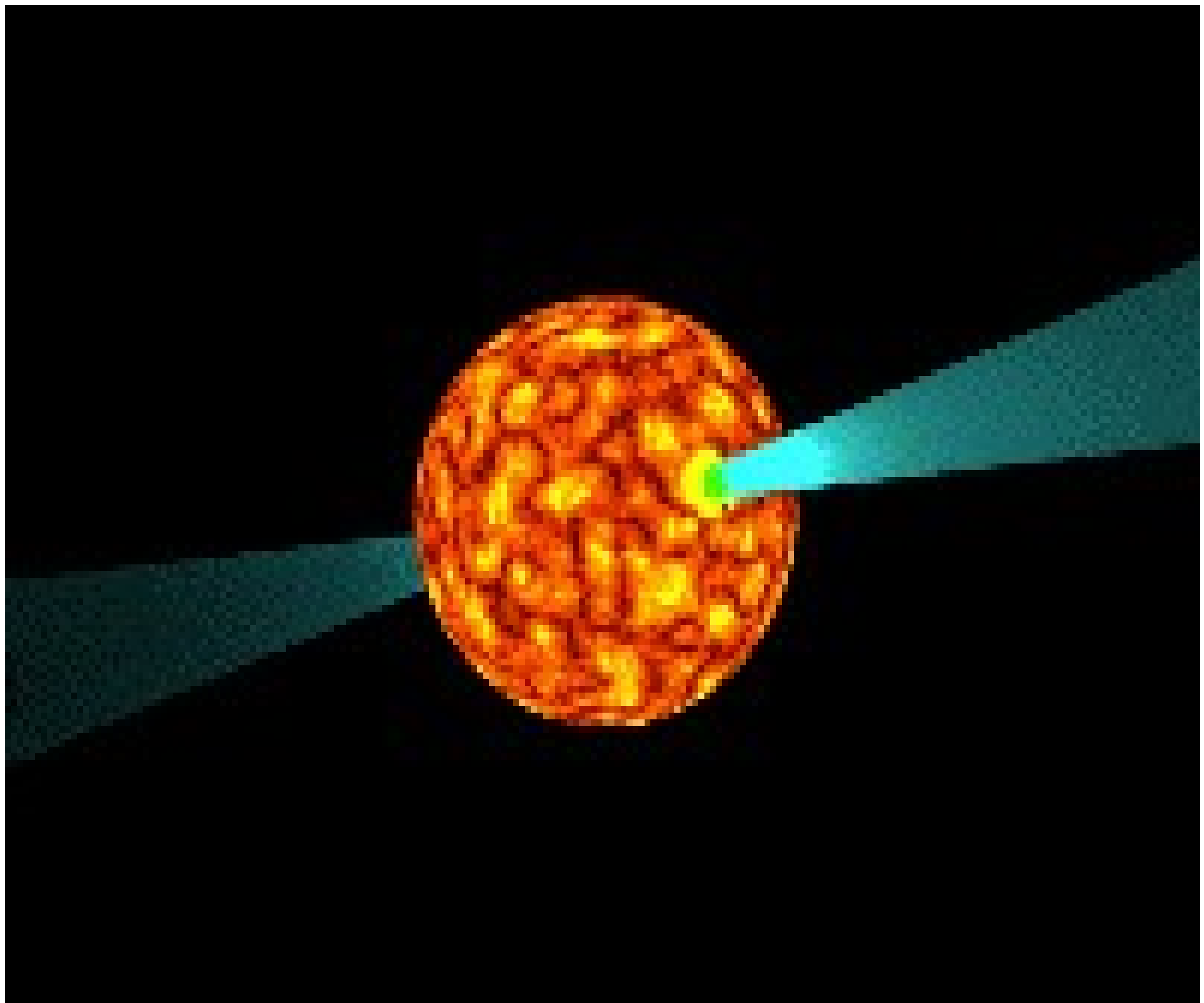


Image credit: cambridgephysics.org

Why 2D simulations??

- Neutron stars have magnetic field

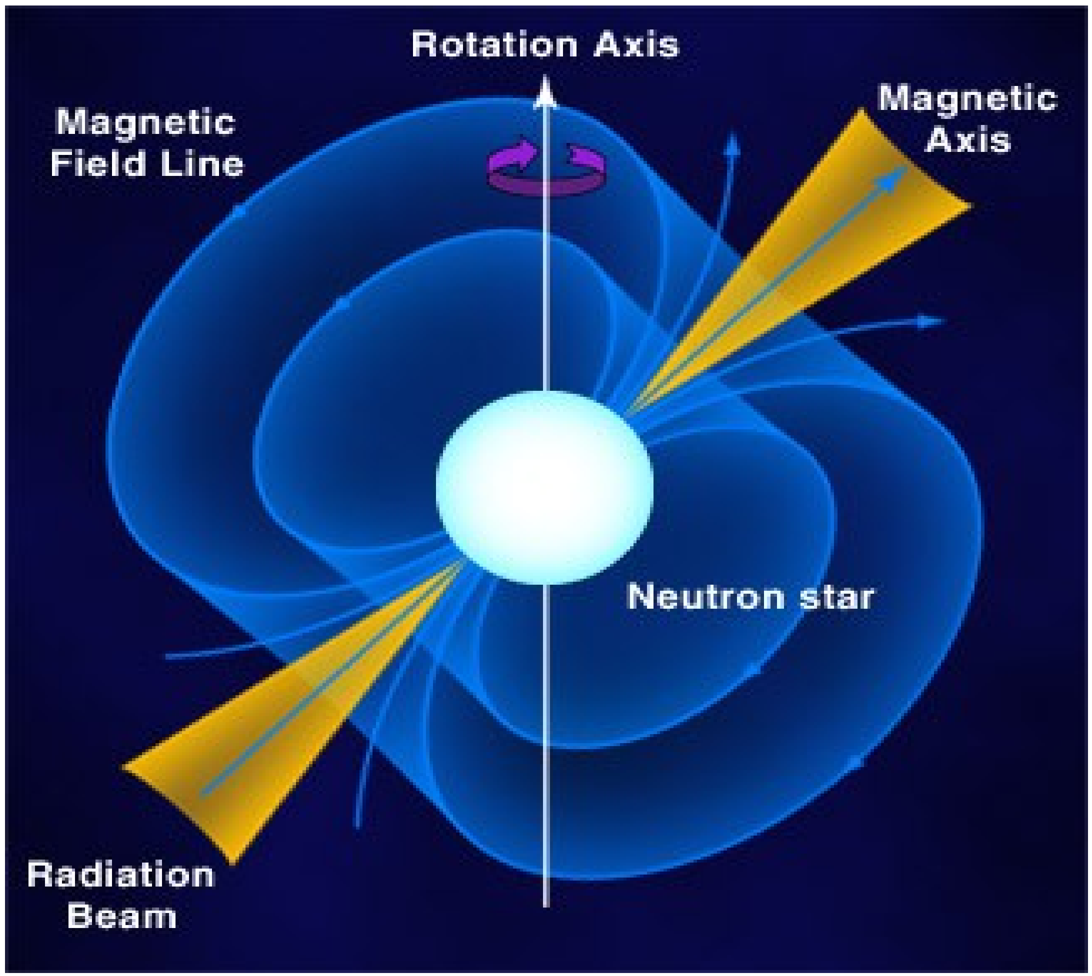
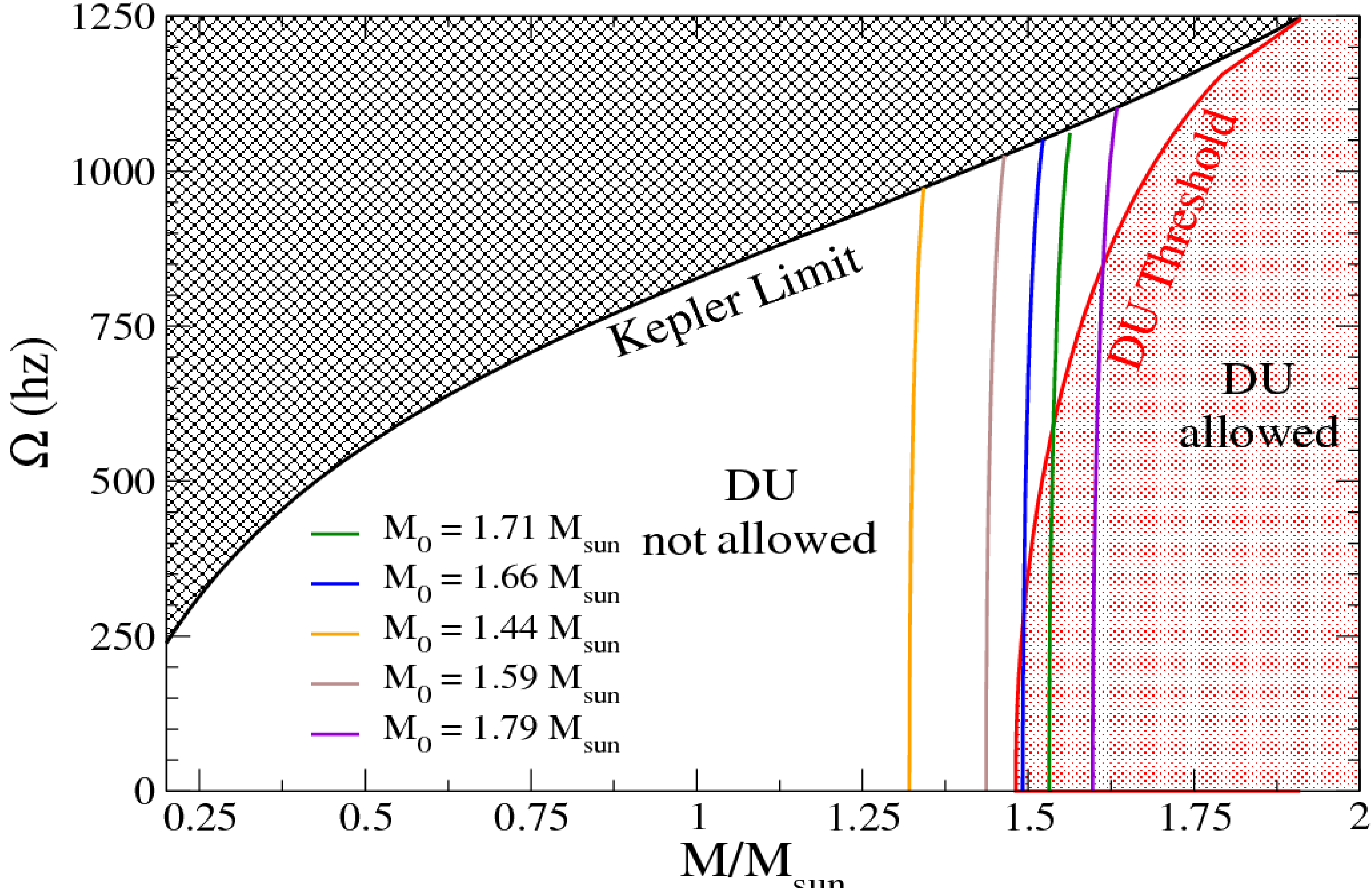


Image credit: http://www.physics.hku.hk/~nature/CD/regular_e/lectures/chap16.html

Why 2D simulations??

- We have shown that spin-down may play an important role for the thermal evolution



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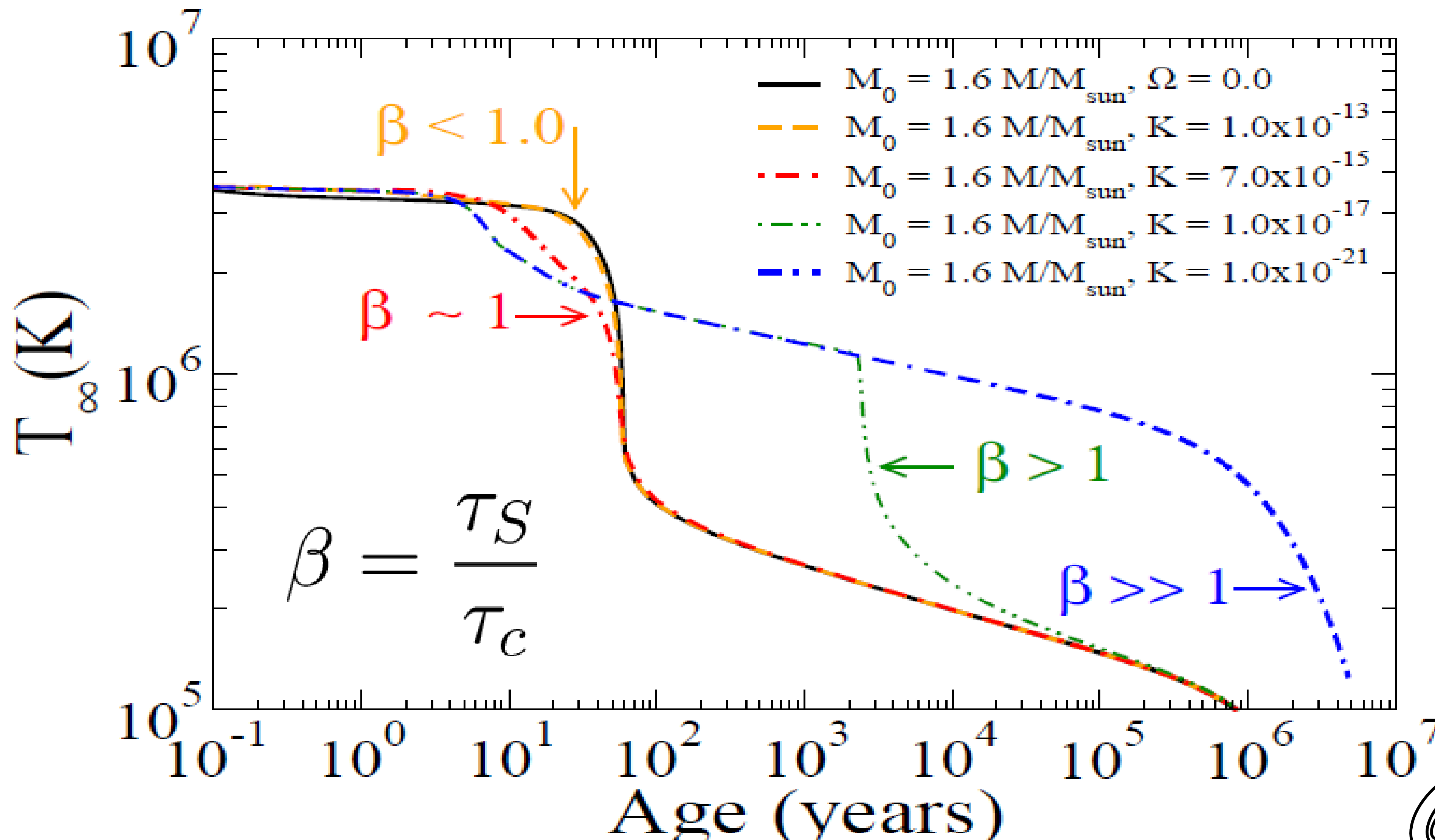
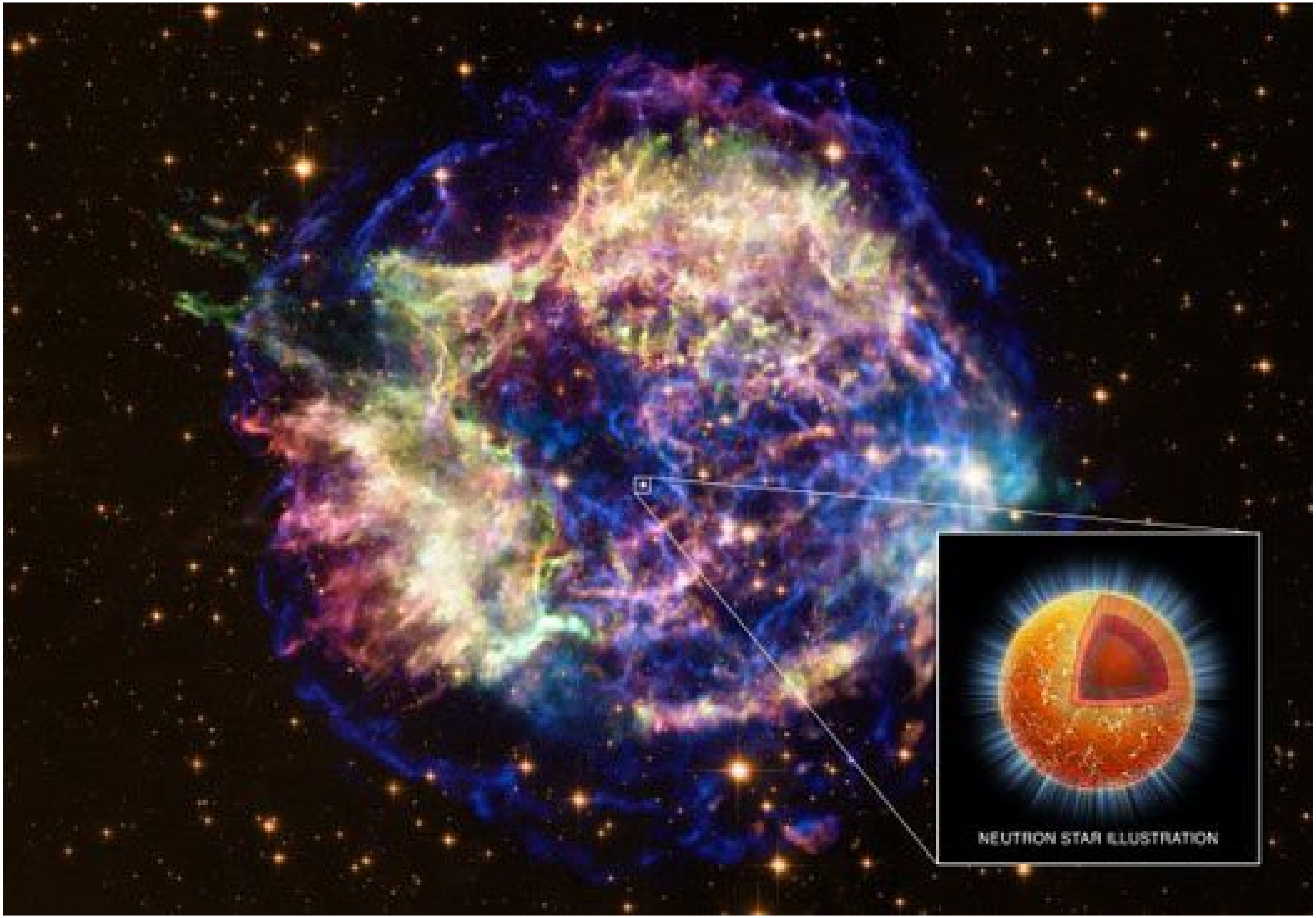
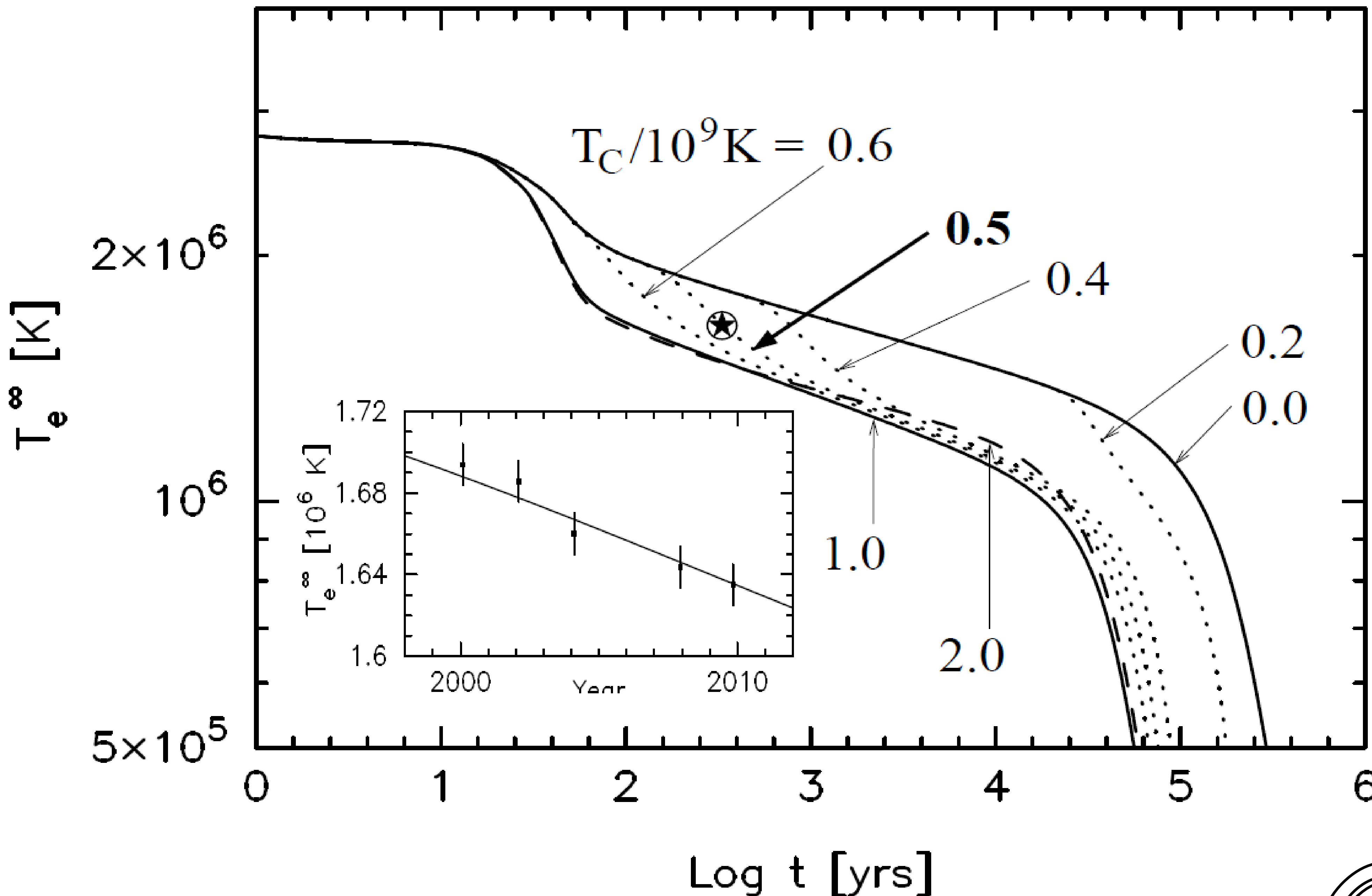


Cas A



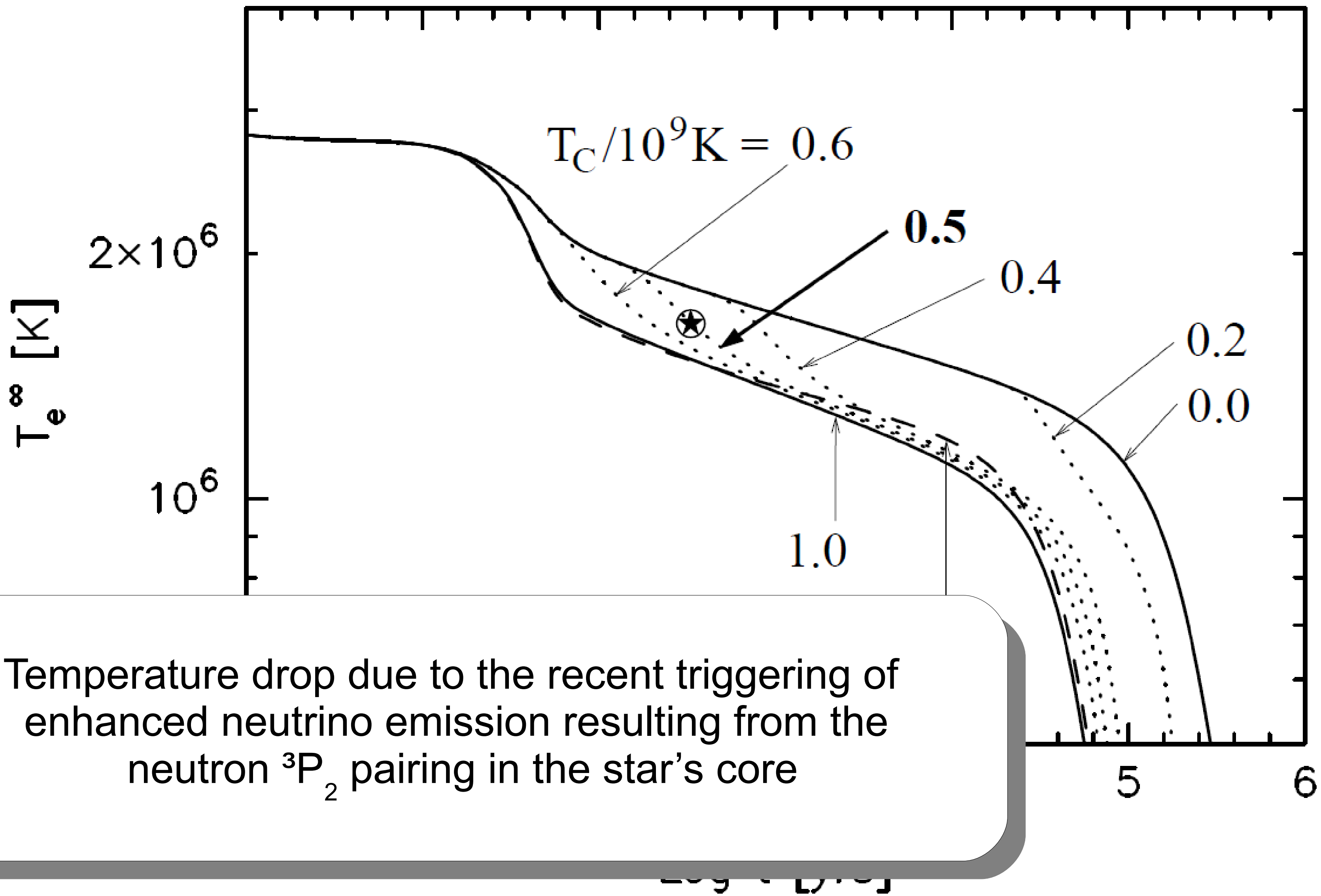
From NASA website

Connection with Cas A



From: Dany Page, Madappa Prakash, James M Lattimer, and Andrew W Steiner, PRL (2010).

Connection with Cas A

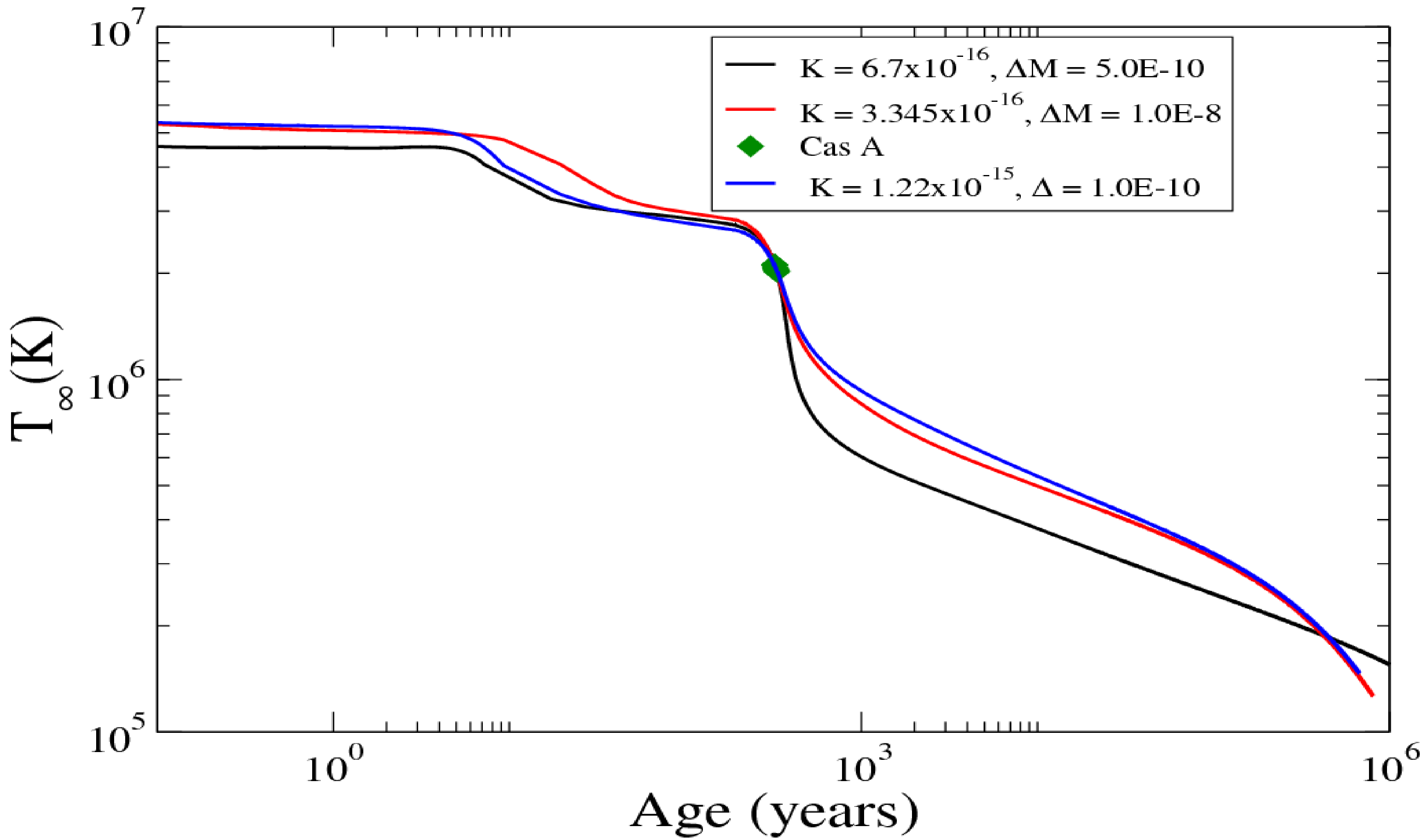


Temperature drop due to the recent triggering of enhanced neutrino emission resulting from the neutron $^3P_2$ pairing in the star's core

From: Dany Page, Madappa Prakash, James M Lattimer, and Andrew W Steiner, 8-11 (2010).

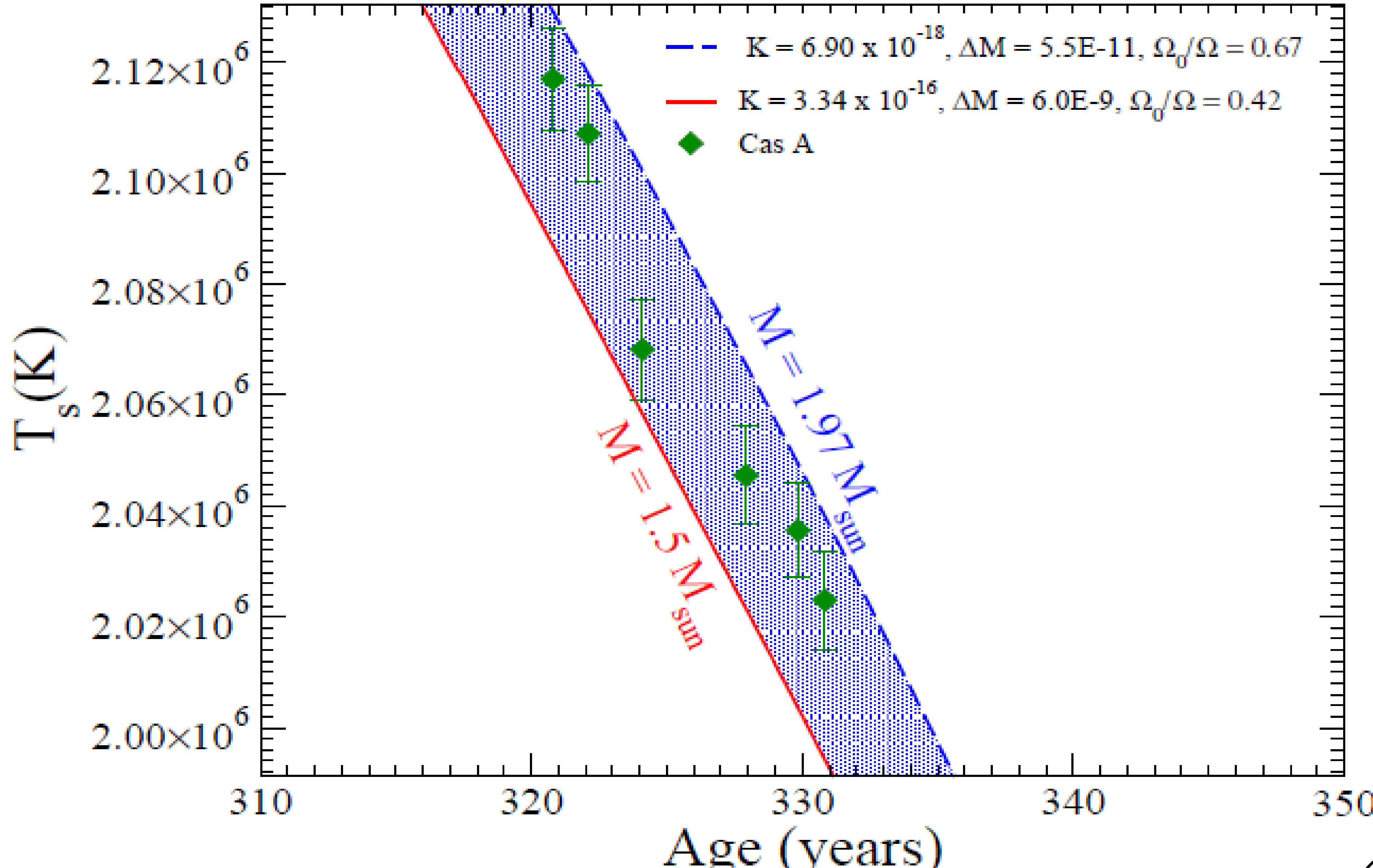
Connection with Cas A

- We propose a different explanation for the behavior of Cas A
- We believe that the delayed temperature drop might be explained by the late onset of the DU process, due to spin-down.



Negreiros, Schramm and Weber (2011)

Connection with Cas A



Negreiros, Schramm and Weber (2011)

2D Calculations

2D calculations are needed for a consistent description of the thermal evolution of spinning down(up) compact stars.

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

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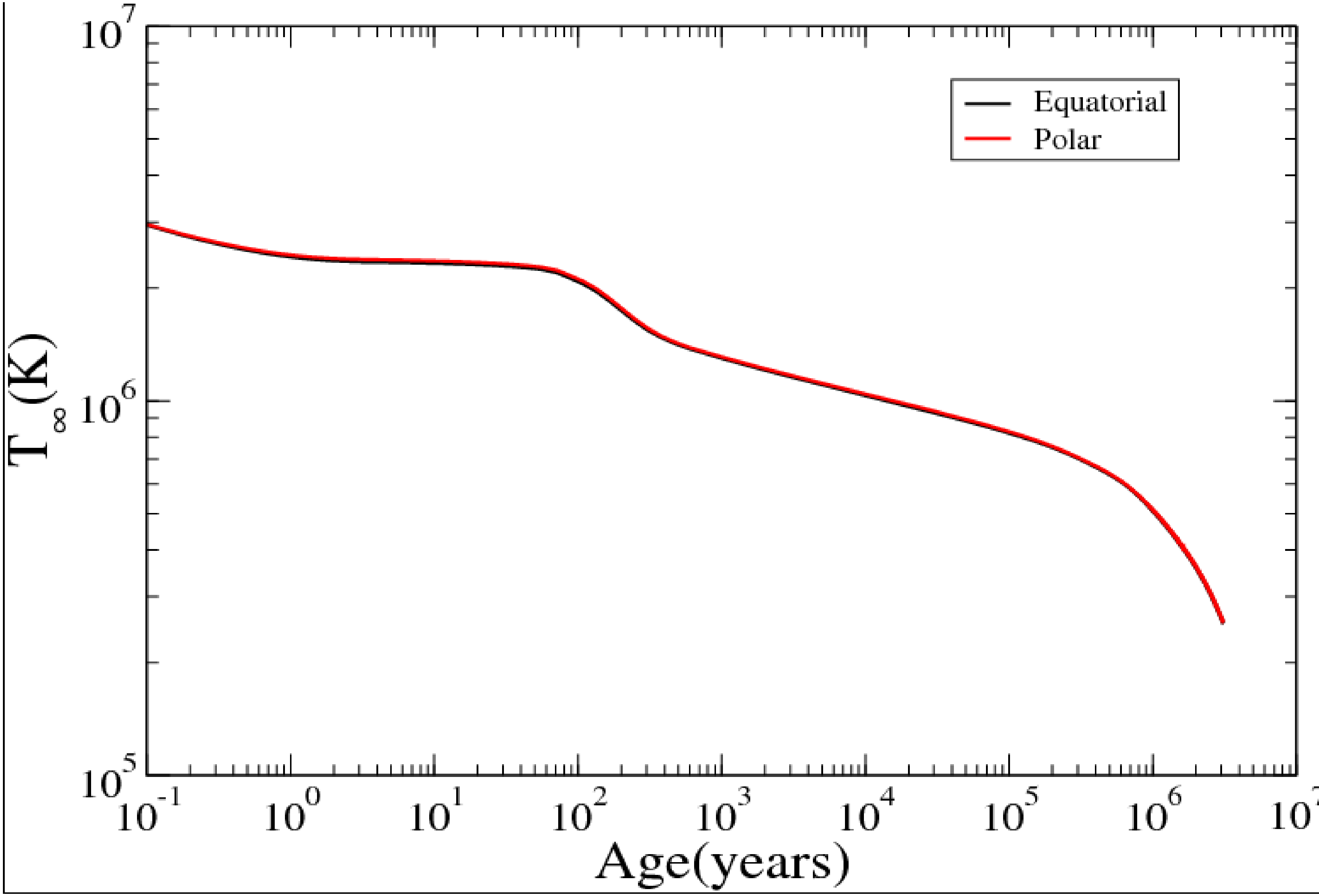
\end{aligned}
$$

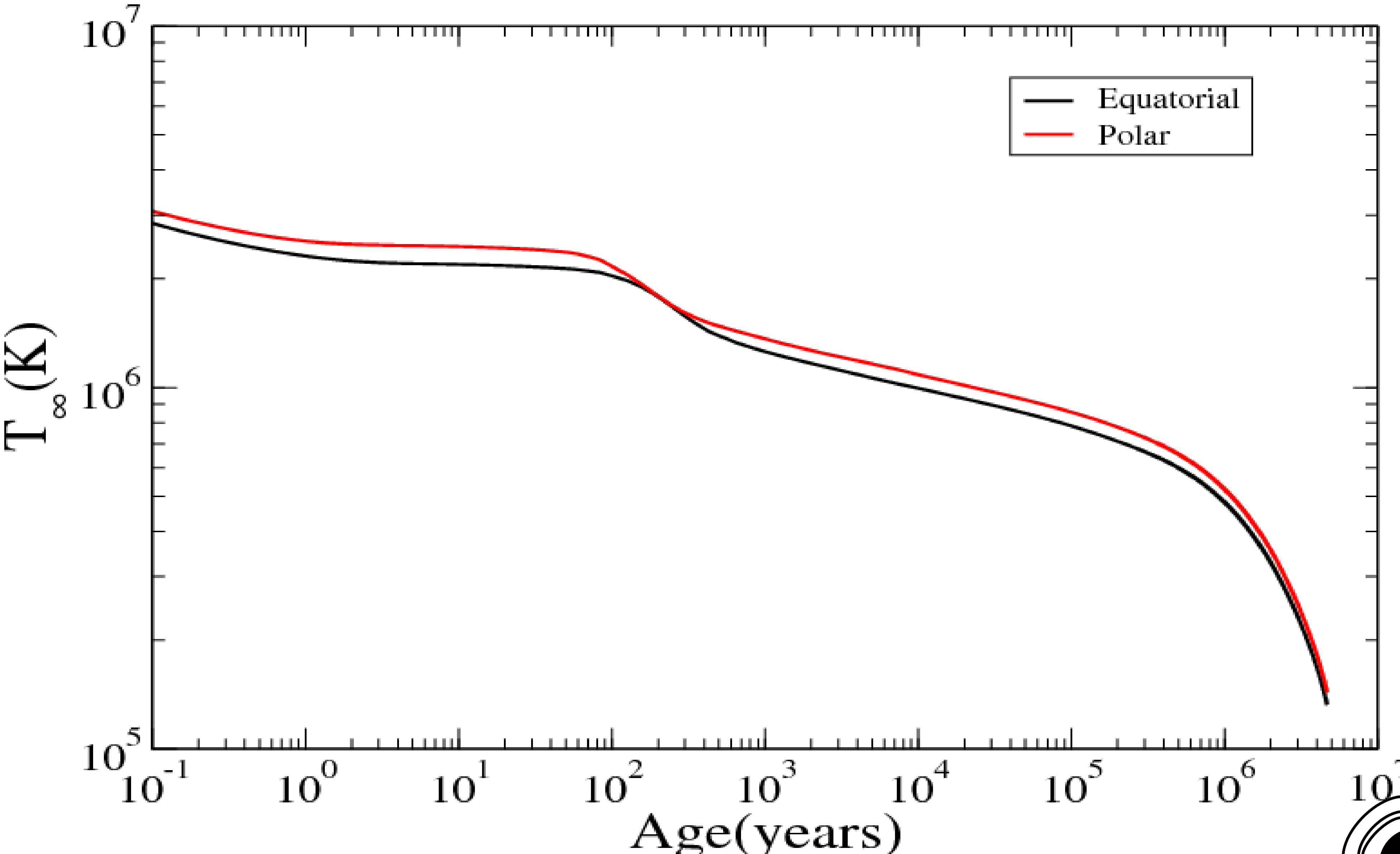
2D Calculations

Mg = 1.10, Freq = 138 hz



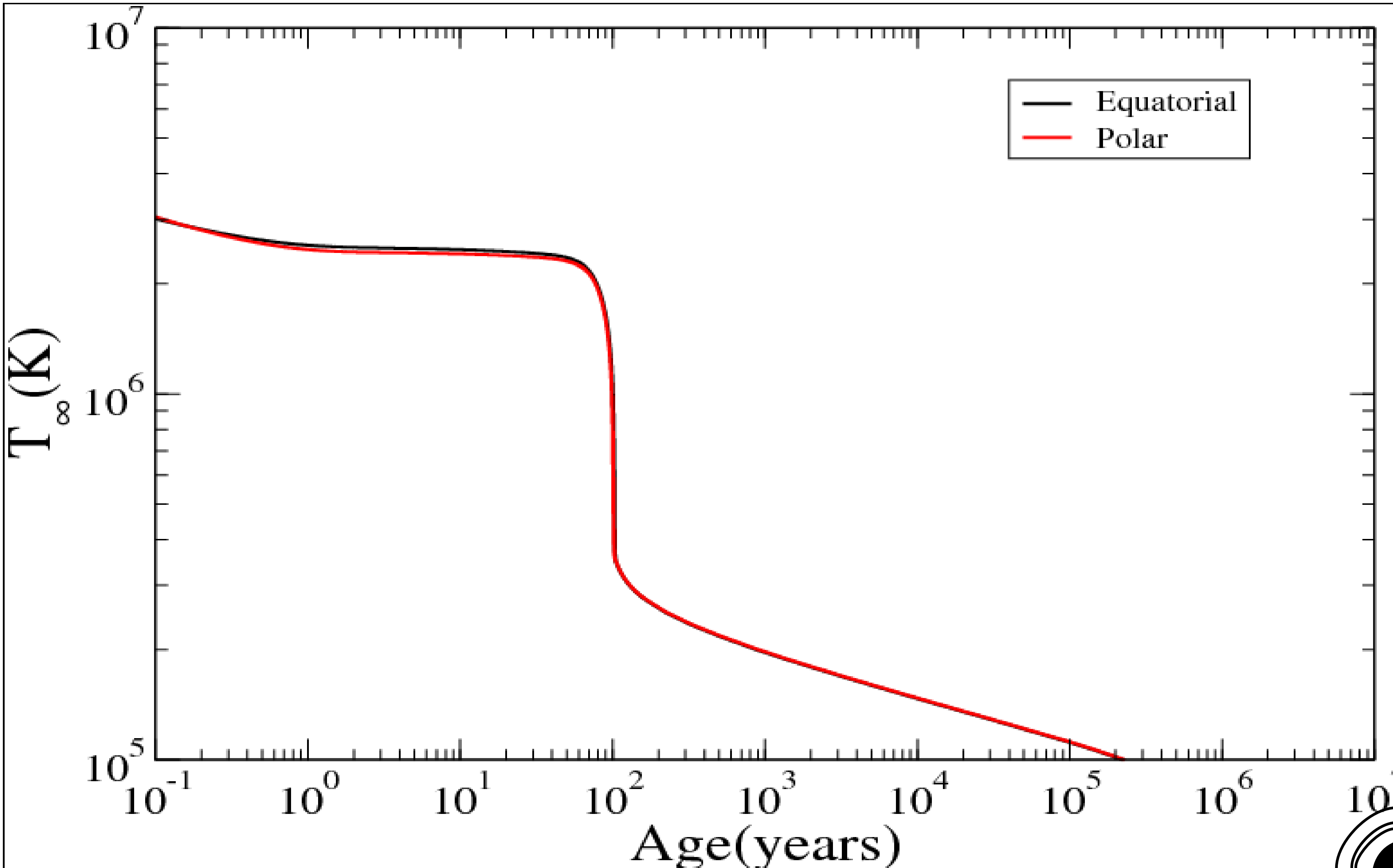
2D Calculations

Mg = 1.10, Freq = 588 hz



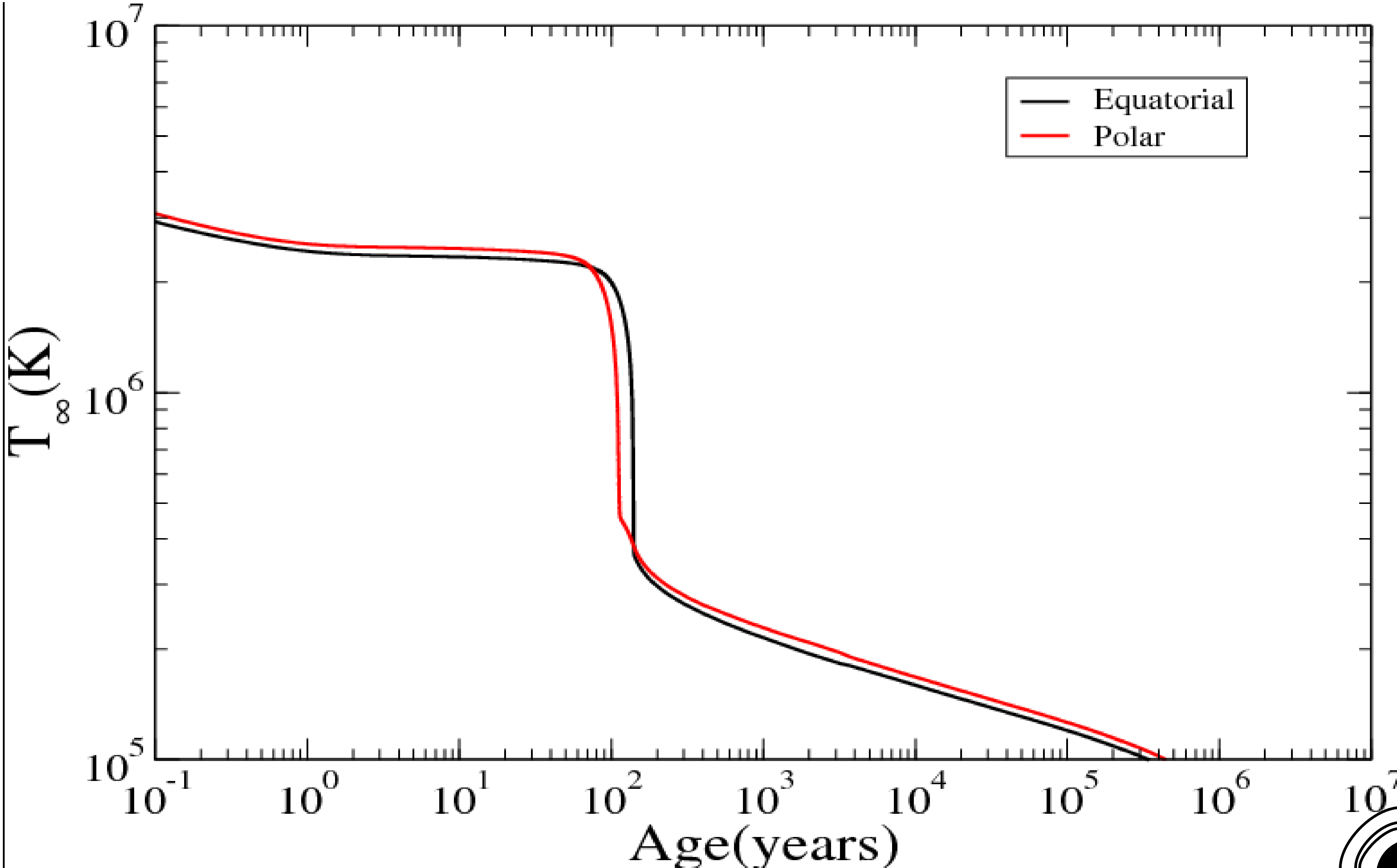
2D Calculations

Mg = 1.40, Freq = 154 hz



2D Calculations

Mg = 1.34, Freq = 489 hz



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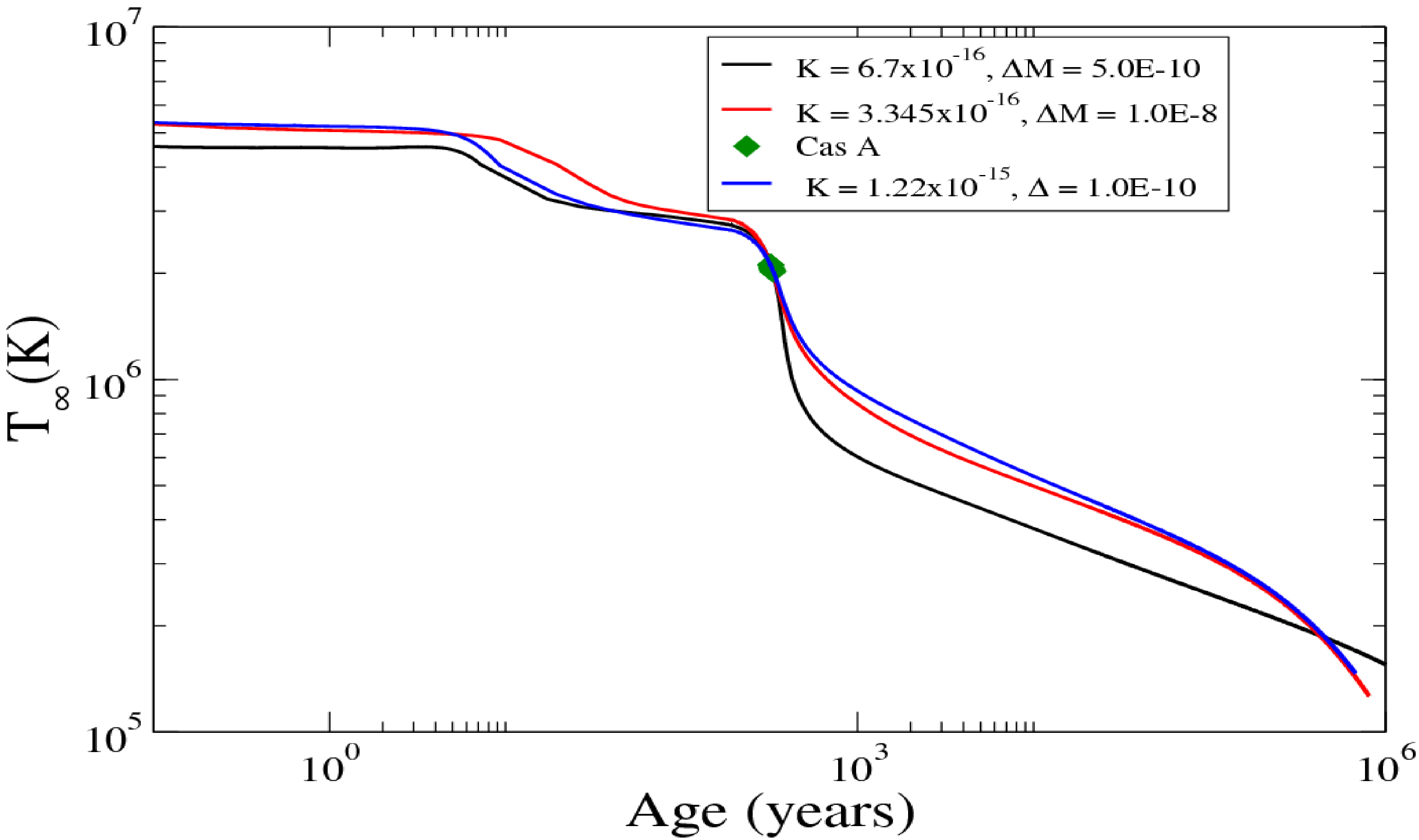

Negreiros, Schramm and Weber (astro-ph:1103.3870)