Cooling of magnetized neutron stars

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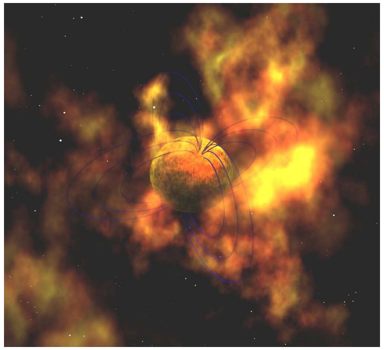
Motivation I: Observations

Most thermally emitting NS have $B \geq 10^{13} G$



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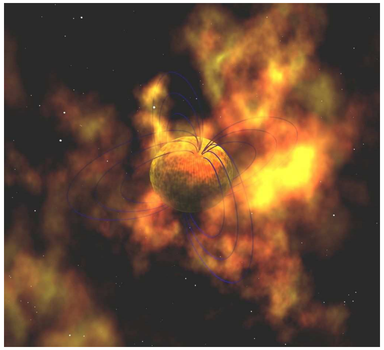

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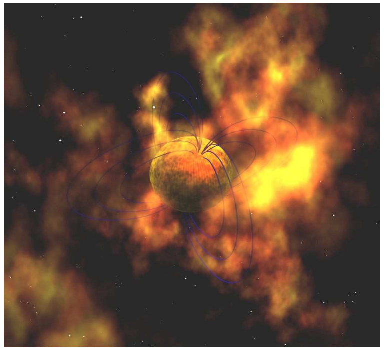

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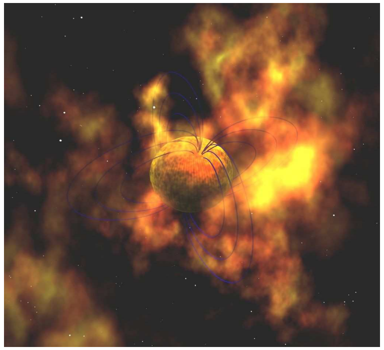

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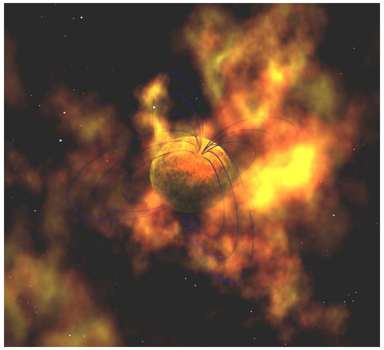

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- Magnetic field is unavoidable in NSs!

Thermal diffusion

- Diffusion equation in 2D axial symmetry

$$C_v e^{\Phi(r)} \frac{\partial T}{\partial t} + \vec{\nabla} \cdot (-\hat{\kappa} \cdot \vec{\nabla}(e^{\Phi(r)} T)) = e^{2\Phi(r)} Q$$

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- Boundary condition: magnetized envelopes [Potekhin & Yakovlev 2001]

$$T_s(B, \theta, T_b) \simeq T_s(T_b) \chi(B, \theta, T_b)$$

Magnetic field structure

- Crustal confined poloidal magnetic field that matches (continuity of $B_\perp$) with the vacuum dipolar solution at the surface

$$\vec{B} = C\left(2\frac{\cos\theta}{r}A(r), -\frac{\sin\theta}{r}\frac{\partial(rA(r))}{\partial r}, 0\right)$$

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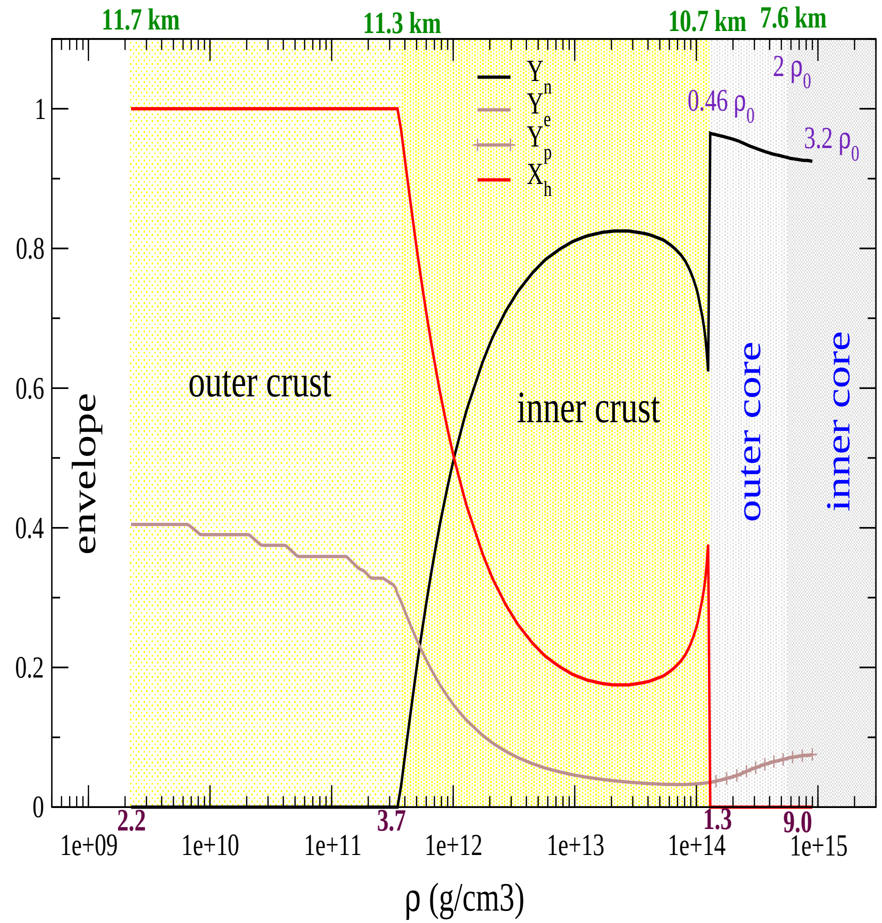
- Field evolution & Joule decay [Miralles & Urpin 1998]

$$\begin{aligned}\frac{\partial\vec{B}}{\partial t} &= -\vec{\nabla}\times\left(\frac{c^2}{4\pi\sigma_{\|}}\left(\vec{\nabla}\times\vec{B}+\frac{\omega_B\tau_0}{B}\left(\vec{\nabla}\times\vec{B}\right)\times\vec{B}\right)\right)\\ &\simeq -\frac{\vec{B}}{\tau_{\mathrm{Ohm}}}-\frac{\vec{B}}{\tau_{\mathrm{Hall}}} \quad \tau_{\mathrm{Hall}}\simeq\frac{1}{B}\end{aligned}$$

$$B_{t\ll\tau_{\mathrm{Ohm}}} \simeq (1+t/\tau_{\mathrm{Hall}})^{-1} \qquad B_{t\gg\tau_{\mathrm{Ohm}}} \simeq \exp(-t/\tau_{\mathrm{Ohm}})$$

Microphysics I: Matter composition



EoS

- Crust: A, e, n SLy

  [Douchin & Haensel 2001]

- Core : RMF $n, p, e,$

  [Glendenning 1998], $E_s = 32$ MeV, $K = 280$ MeV

NS configuration

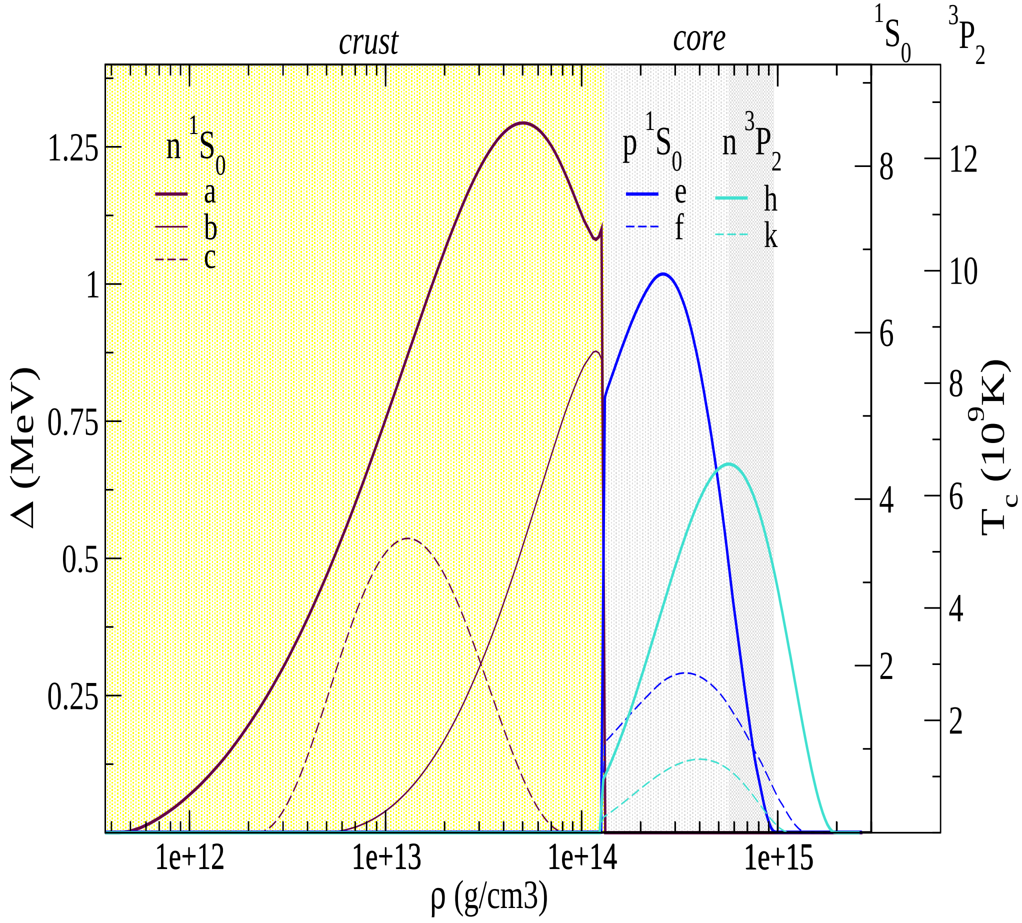
	ρ_c (g/cm^3)	M ($M_\odot$)	R_{NS}	R_c(km)
A	$8.1\,10^{14}$	1.35	12.83	1.24
B	$1.1\,10^{15}$	1.63	12.36	0.86

Microphysics I: Matter composition

- Crust: n in ${}^1S_0$
- Core: p in ${}^1S_0$
  n in ${}^3P_2$

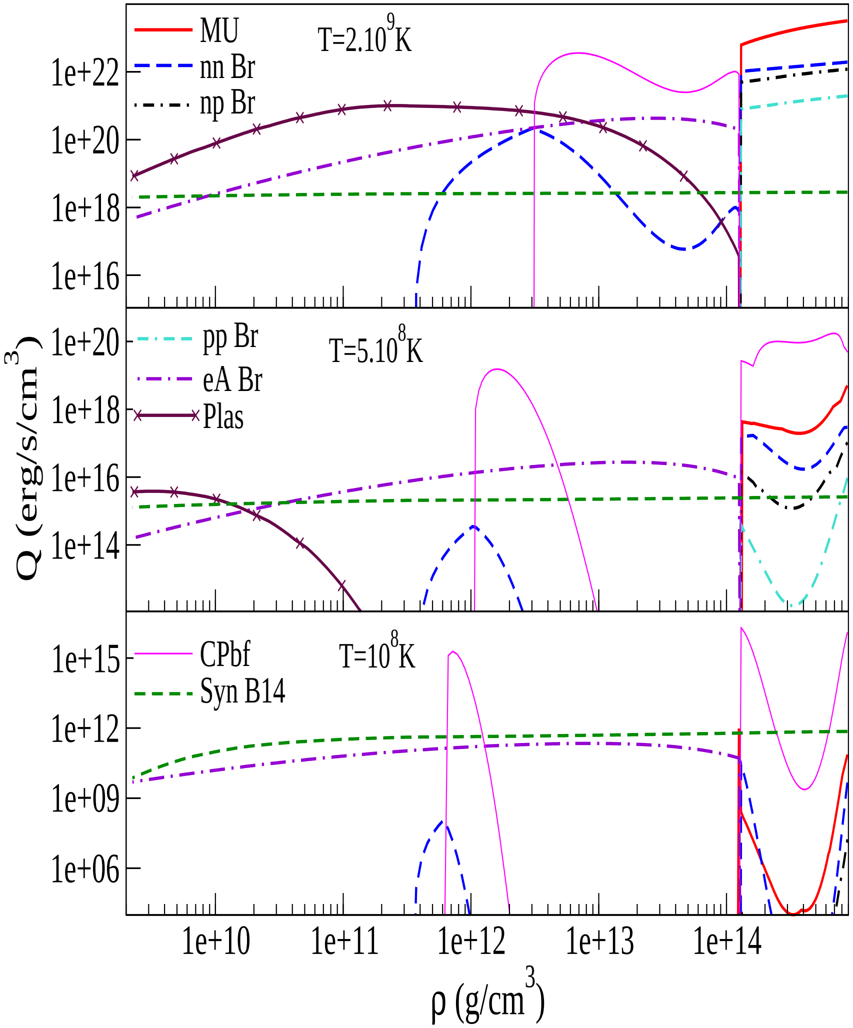
Parameterizations from [Andersson etal. 2005], [Kaminker 2001]

Calculations from [Wambach et al. 1993], [Schulze et. al 1998], [Elgaroy 1996], [Admunsen 1985], [Baldo et al. 1998]



Microphysics II

Neutrino emissivities



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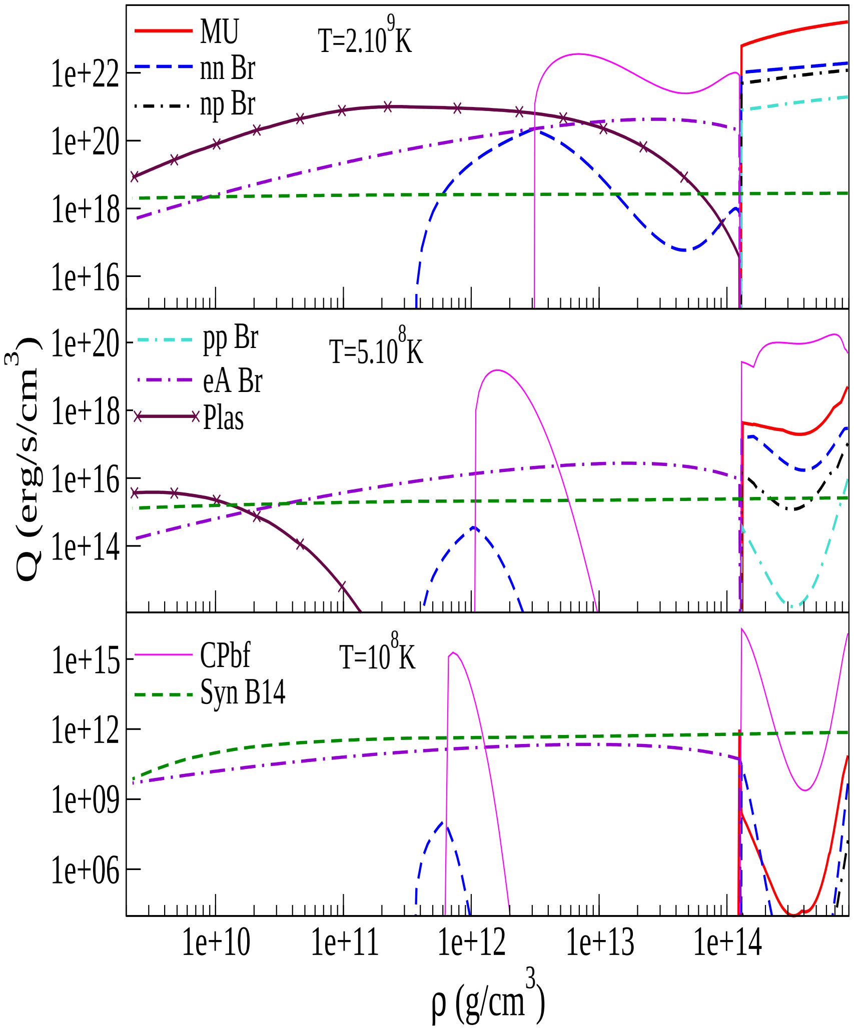

- Crust
  1. eA Bremsstrahlung
  2. Plasmon decay
  3. Pair $e-e^+$ formation
  4. nn Bremsstrahlung
  5. Cooper pairing of n
  6. Synchrotron
- Core
  1. Modified Urca
  2. nn Bremsstrahlung
  3. Direct Urca
  4. Cooper pairing of n, p

Review [Yakovlev et. al 2001]

Crust Formation & SF

- Crust solidification
  ($\Gamma > 175$)

$$\Gamma = \frac{Z^2 e^2}{a k_B T} \approx \frac{Z^2}{T^6} \left(\frac{\rho}{A}\right)^{1/3}$$

- Superfluidity (SF)
  1. $T/T_c << 1$ strong SF
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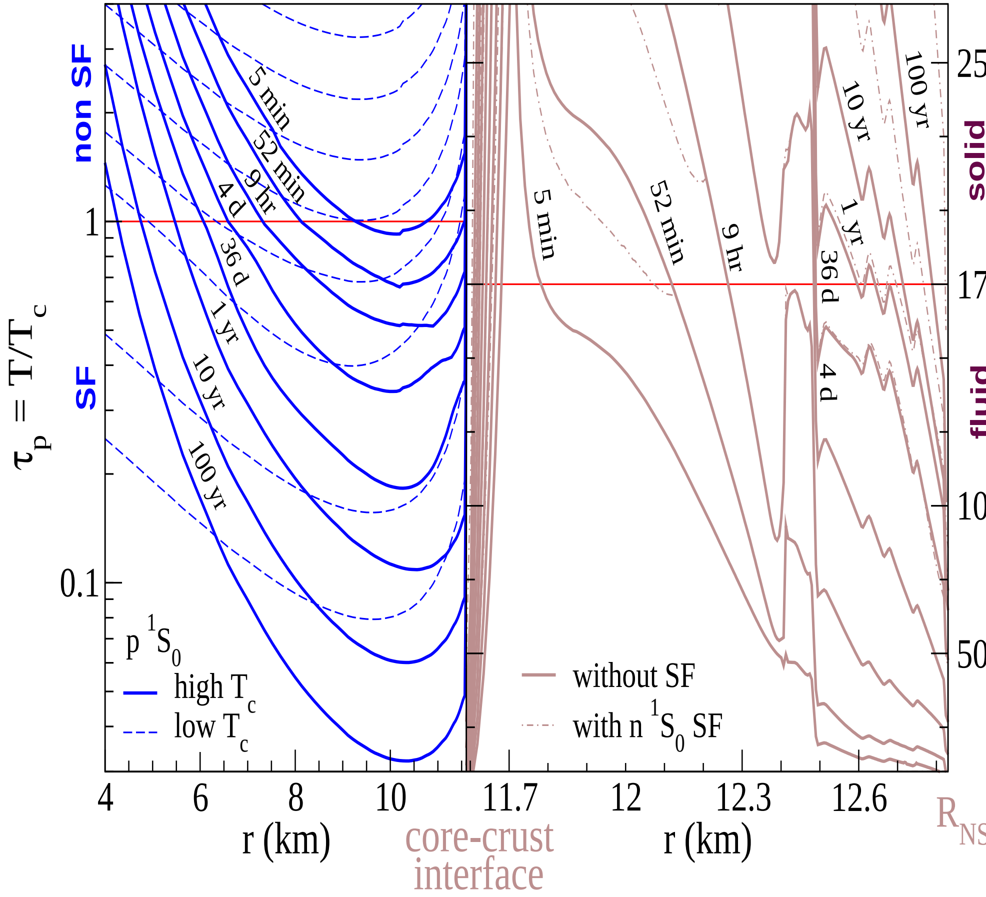
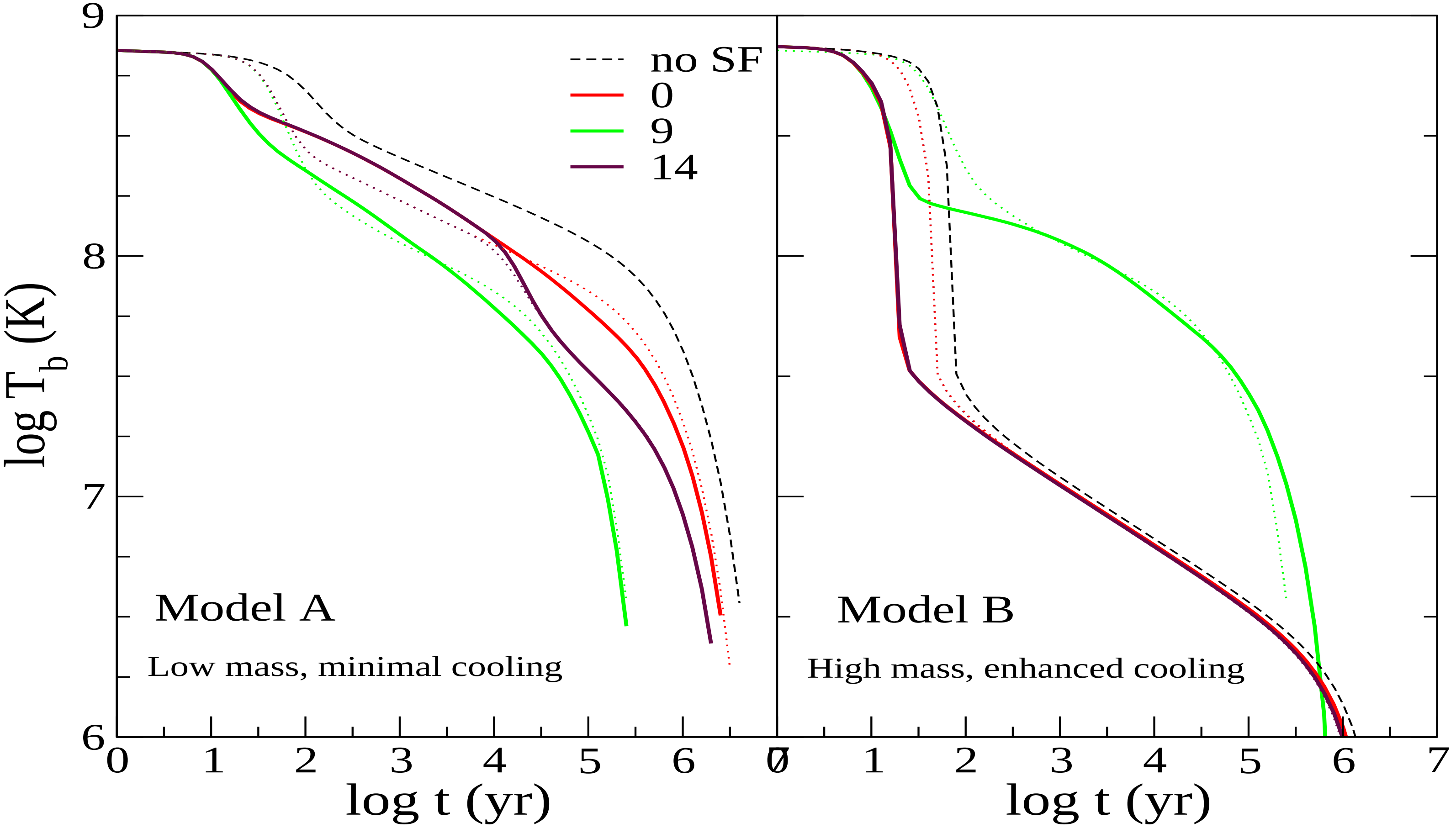


Weakly magnetized NS ($B \leq 10^{12}$ G)



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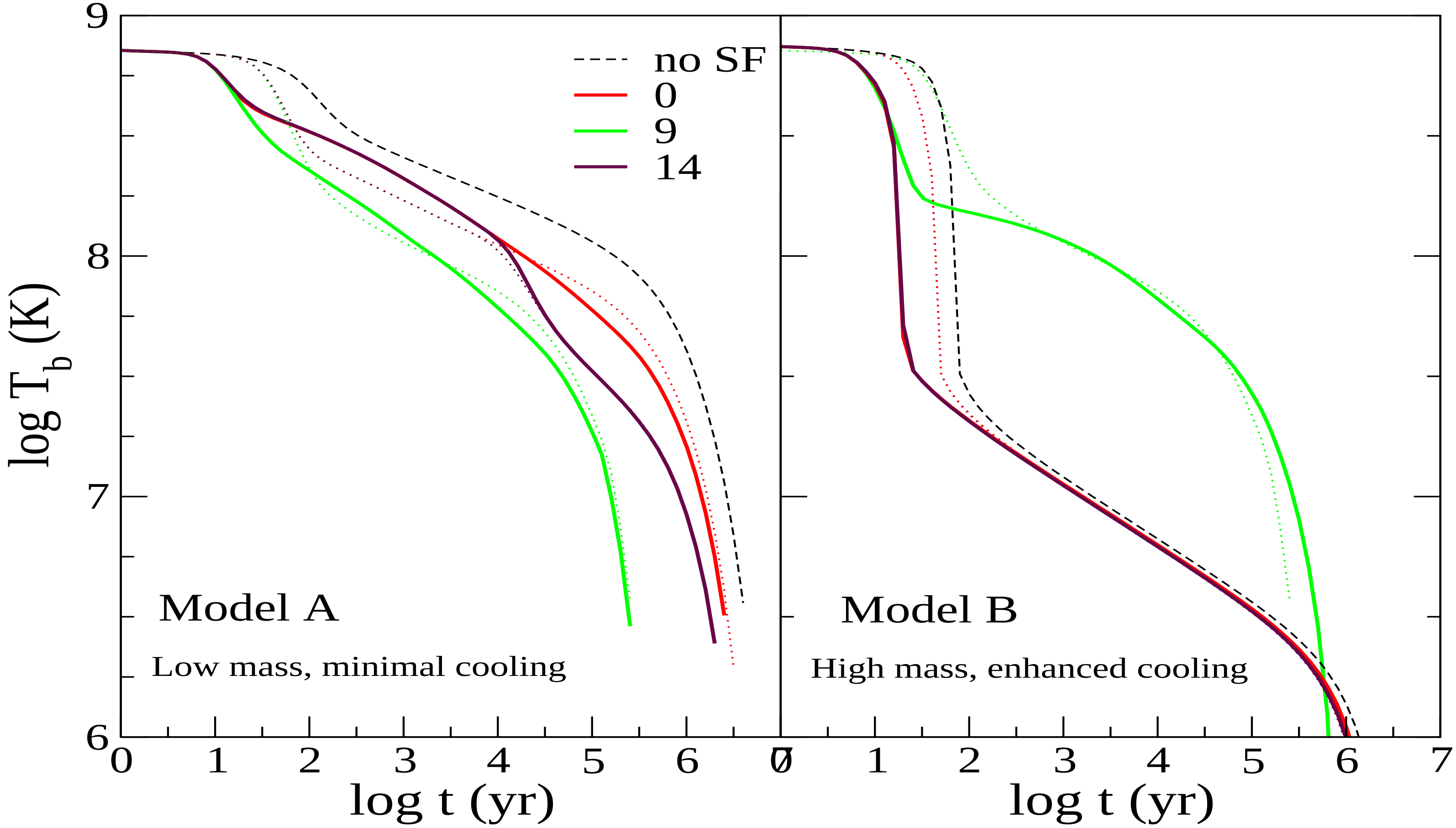

- 1D cooling & SF effects [Page et al. 2006, Yakovlev et al. 2004 reviews; Vorskresensky et al. 2004 core cooling]

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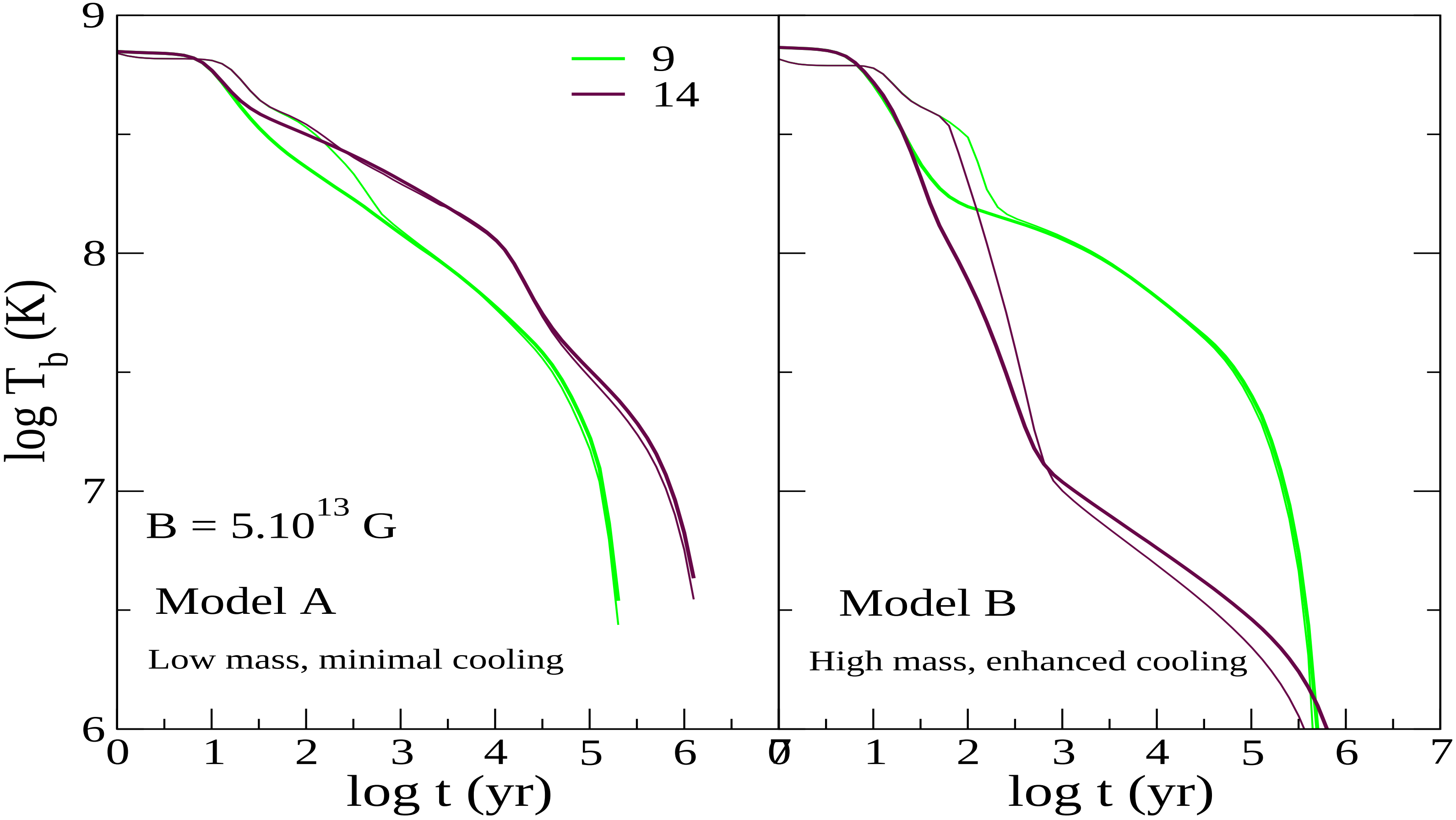

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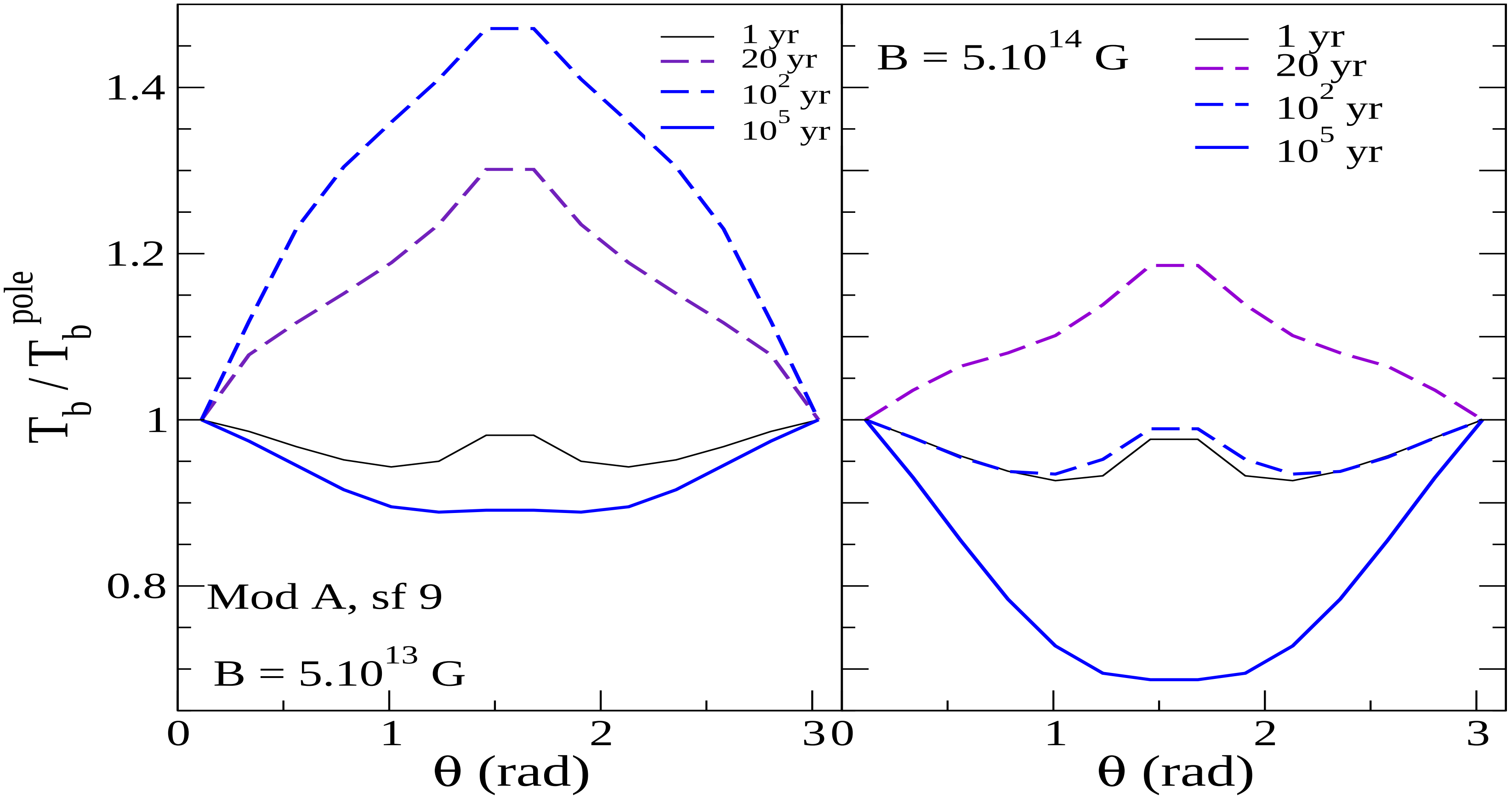

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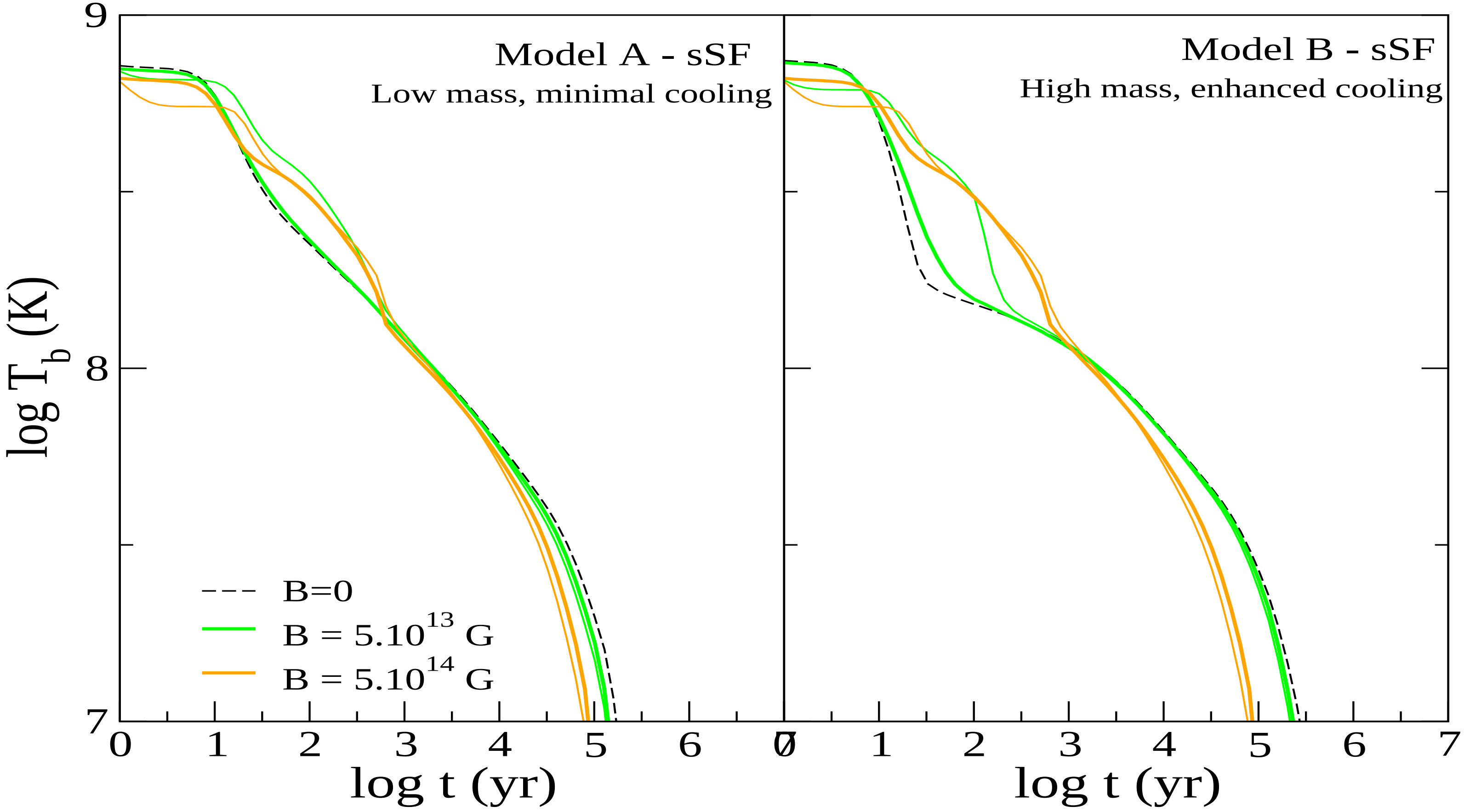

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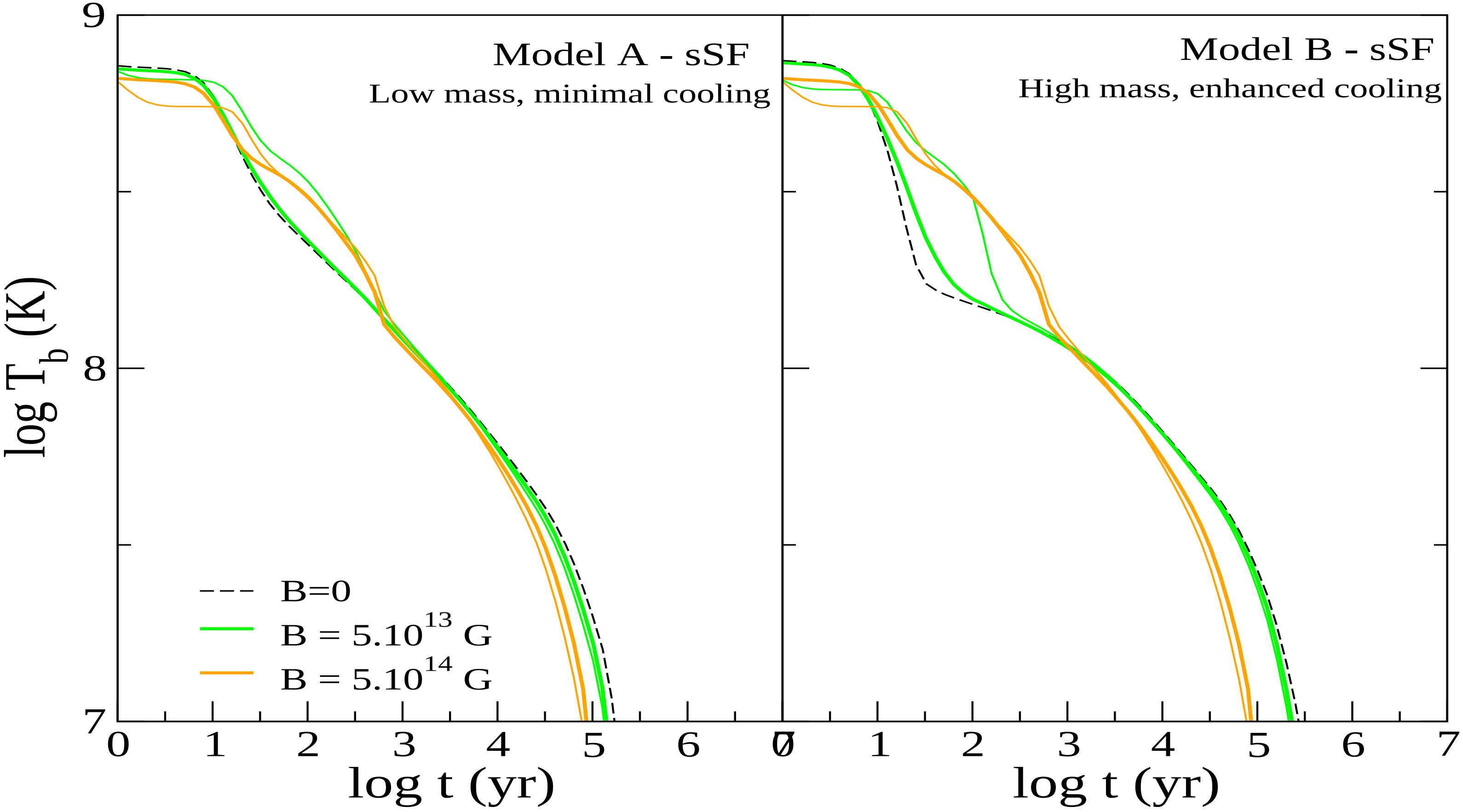
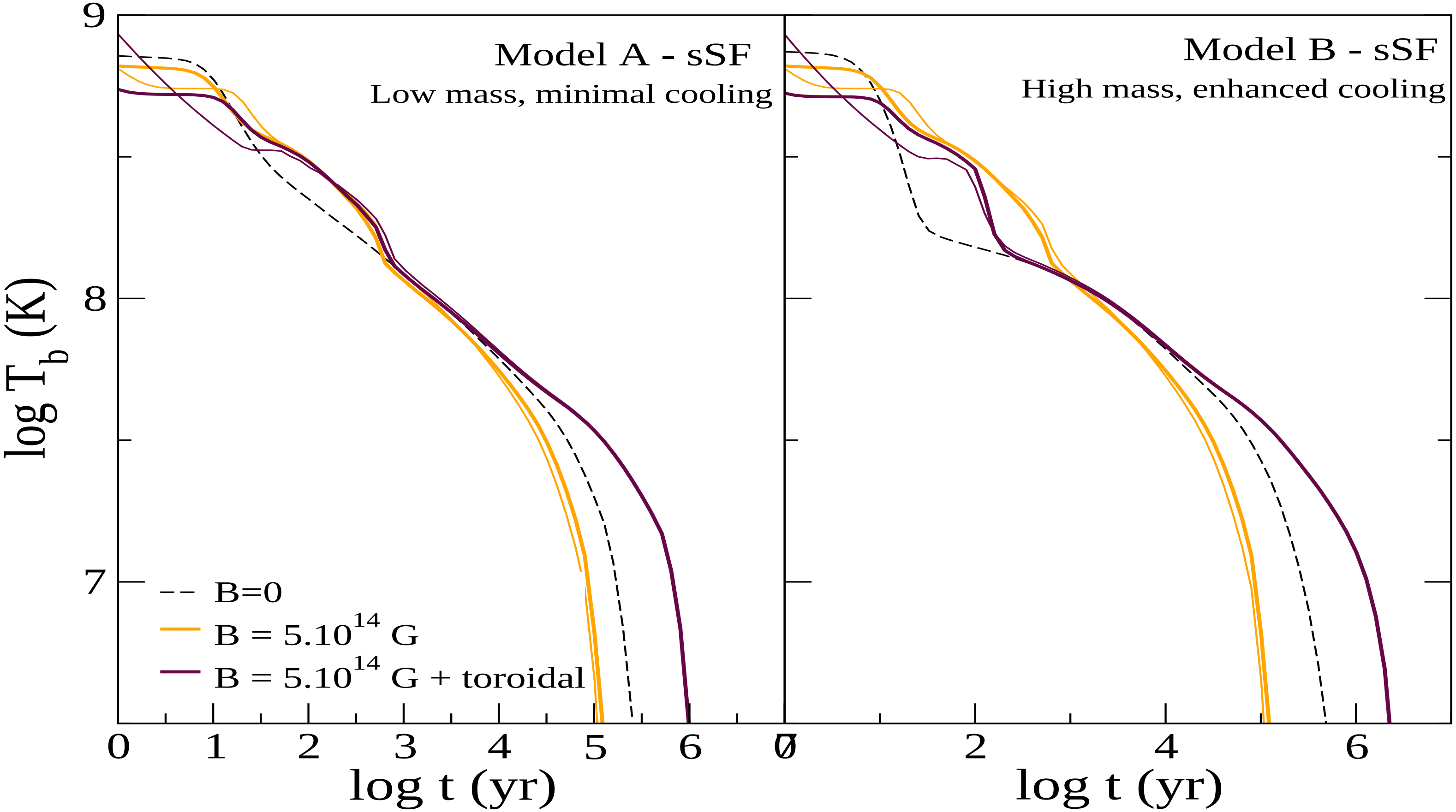
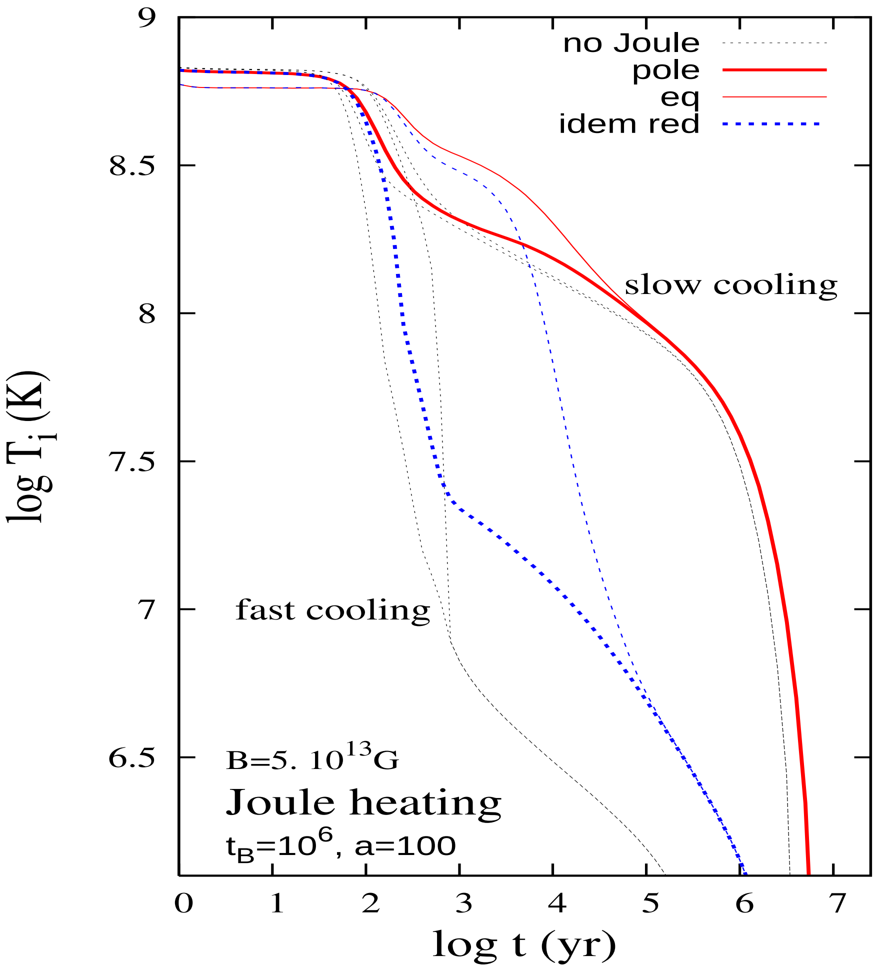


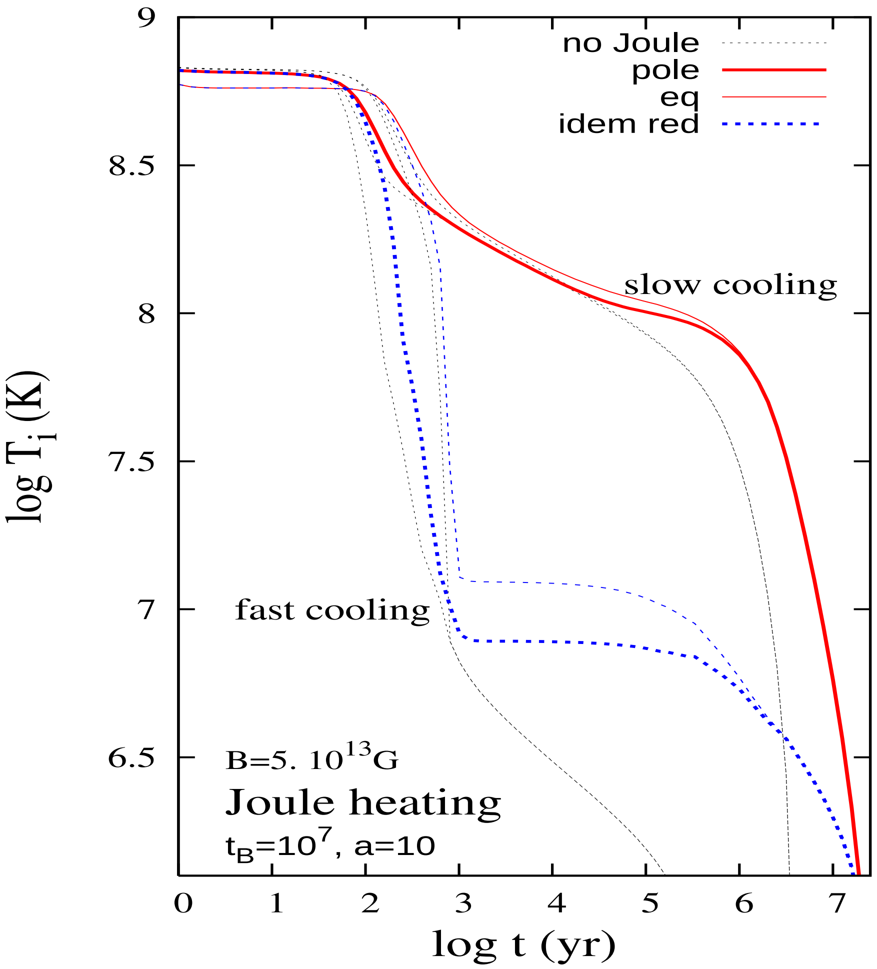
- B induces an anisotropic T-distribution → 2D-cooling

Effect of toroidal field



Large B strength: Joule heating?





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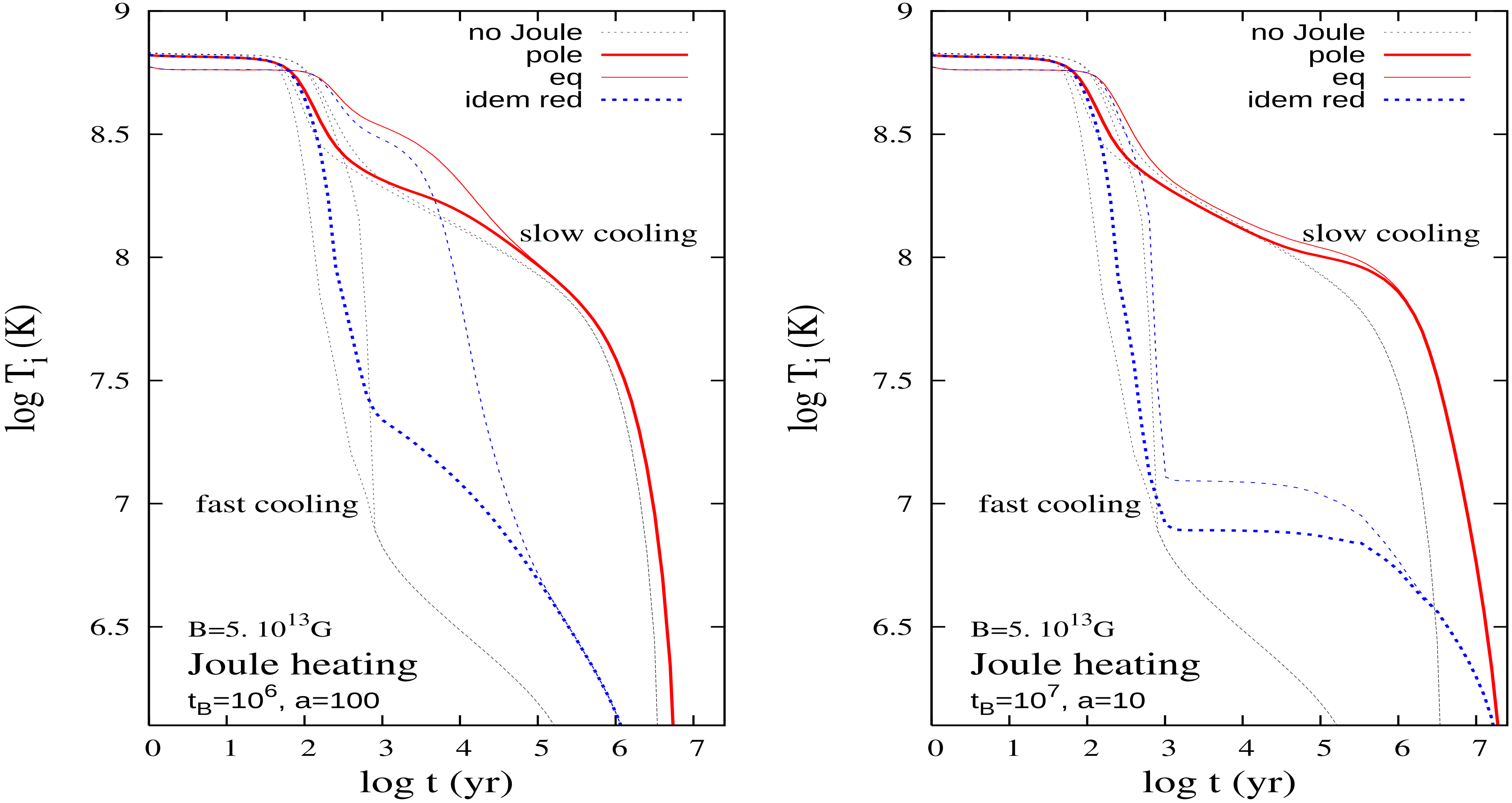
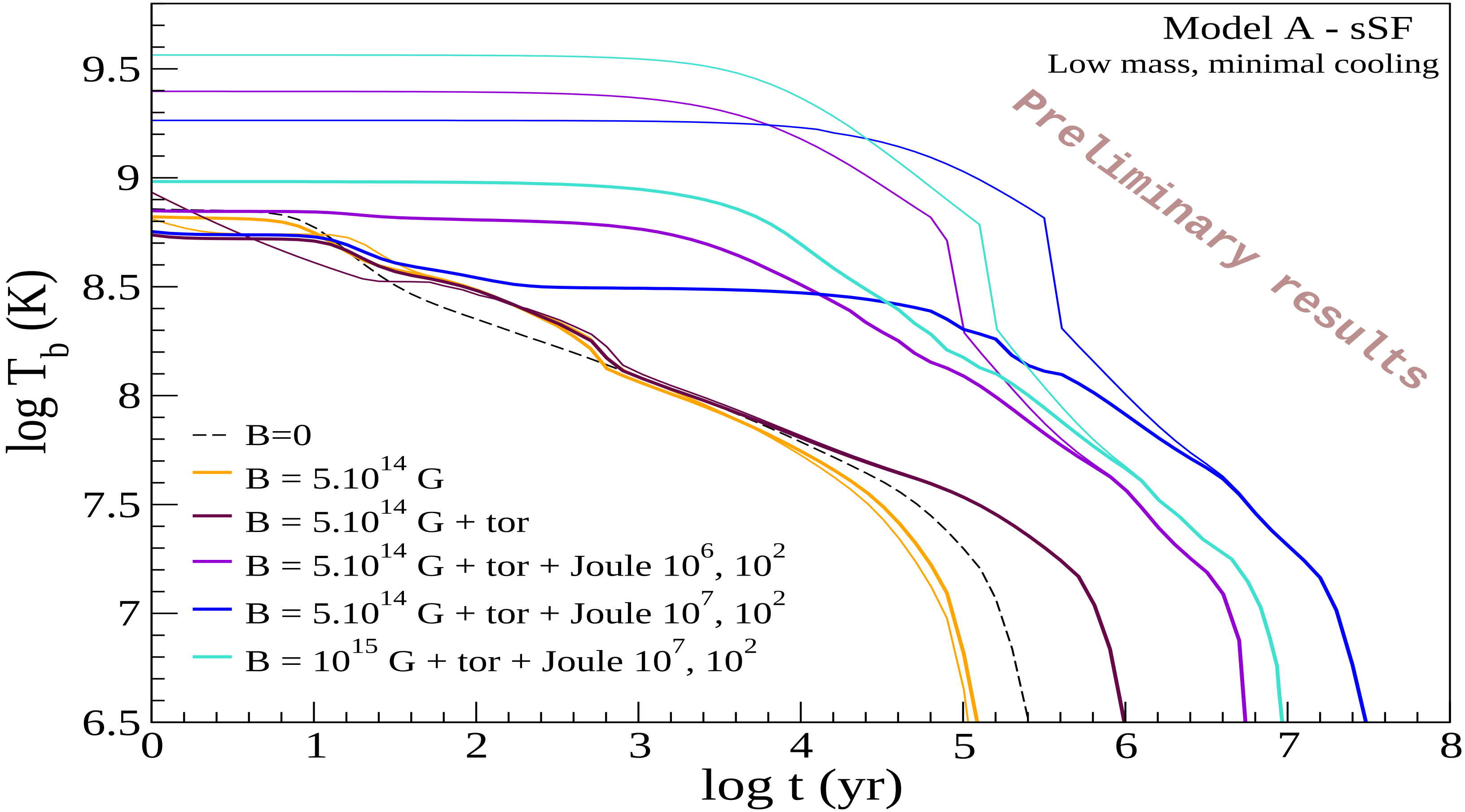


- B decay can be an efficient heating mechanism

Effect of Joule heating



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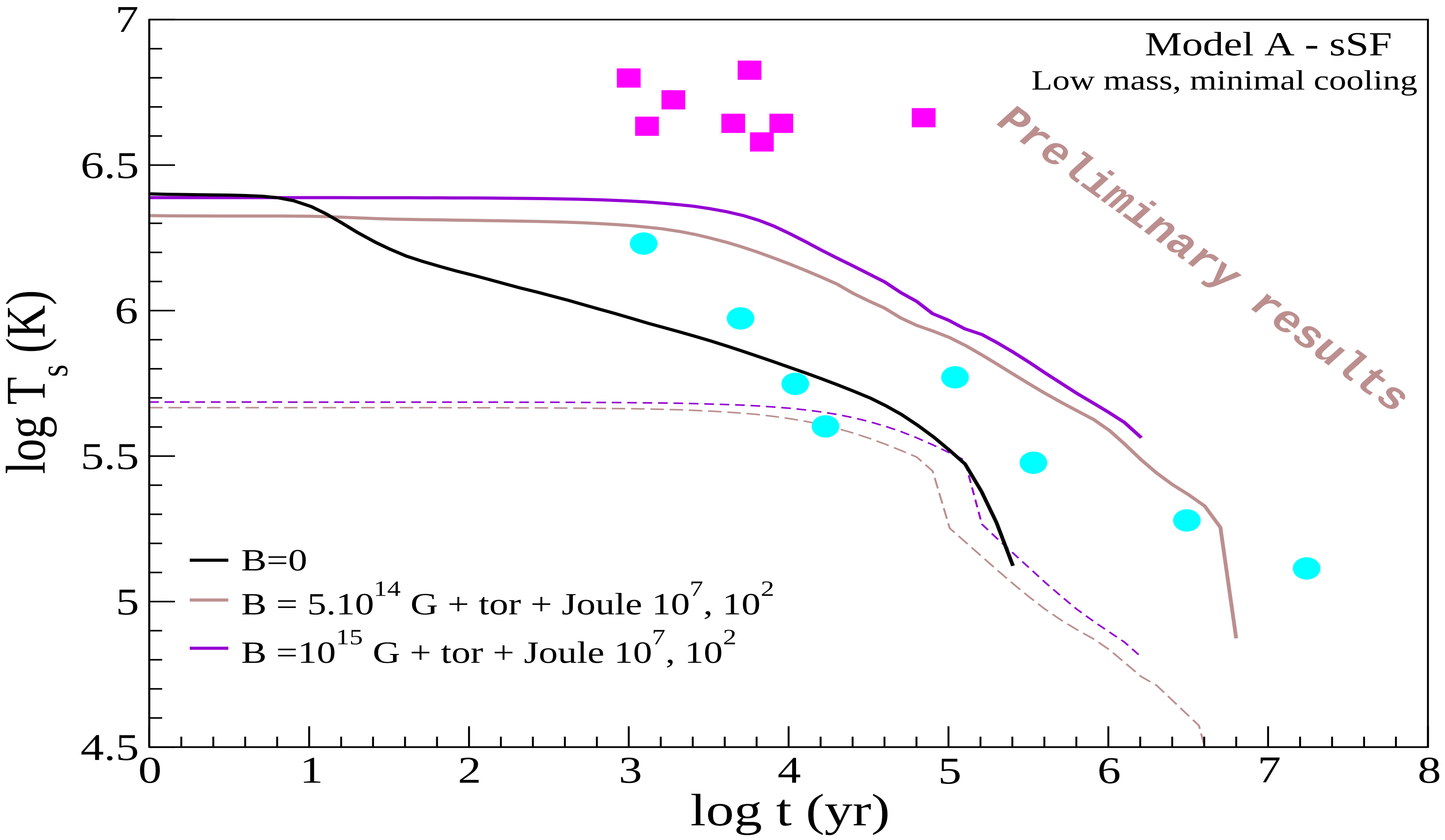

Conclusions

- Thermal evolution of magnetized NS
  2D evolution with strong magnetic field $B \simeq 10^{13-15}$ G
- Thermal crust-core coupling; next: magnetic coupling
- Magnetic and thermal evolution:
  1. fixed B induces a thermal anisotropy $T_b(\theta)$
  2. B decay affects the thermal state of the NS through Joule heating
  3. next: consistent (B, T) evolution
- Dynamic timescales for cristalization of the crust & growth of the superfluid core: *preliminary results*