Towards model-independent analysis of cooling neutron stars

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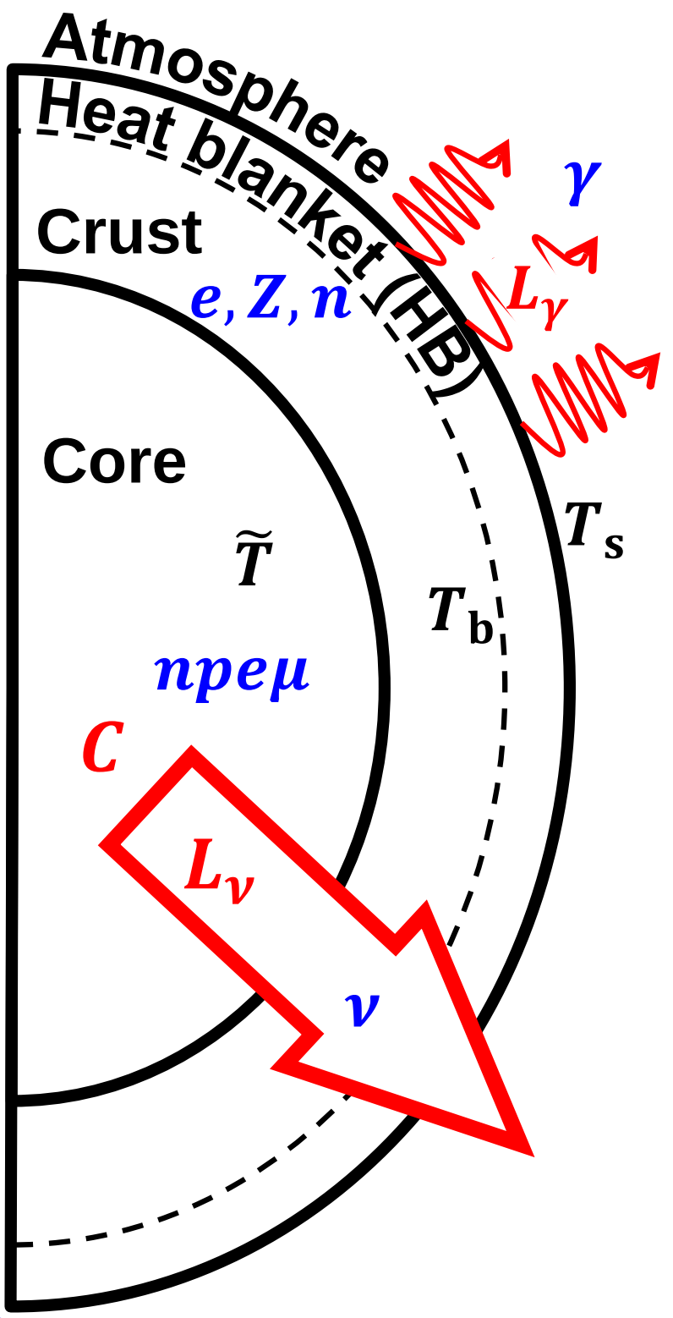
Abstract

We have elaborated a method for analysing cooling neutron stars (NSs) with nucleon cores. The method is almost independent of baryon pairing model and a model equation of state in neutron star cores. It is based on nearly universal approximations of the neutrino luminosity L_ν and the heat capacity C of the star (e.g. Ofengeim et al. 2016, 2017a) by analytic functions of stellar mass M, radius R and redshifted internal temperature $\widetilde{T}$, for some selected basic cooling scenarios. This allows us to analyse neutron stars at the neutrino cooling stage ($t \lesssim 10^5$ yr). In particular, we have considered the neutron star XMMU J173203.3−34418 (Ofengeim et al. 2015) and the Vela pulsar (Zyuzin et al., in preparation). For neutron stars of ages $10^5 - 10^6$ yr that transit from the neutrino to the photon cooling stage, we have found a simple temperature – age relation valid for both, the neutrino and photon cooling stages. Using these results, we analyse the cooling neutron star RX J1856.5−3754 (Ofengeim et al. 2017b). This model-independent analysis allows one to investigate the composition of heat-blanketing envelopes of neutron stars as well as nucleon superfluidity in neutron stars cores.

1. Neutron Star Cooling



$$\widetilde{T} = T\sqrt{g_{00}} = T_b\sqrt{1-\frac{2GM}{Rc^2}} \qquad T_s^\infty = T_s\sqrt{1-\frac{2GM}{Rc^2}}$$

$$L_\gamma^\infty = 4\pi\sigma R^2 T_s^4\left(1-\frac{2GM}{Rc^2}\right)$$

$$L_\nu^\infty = \int Q_\nu(\rho,T)\,g_{00}\,\mathrm{d}V \qquad C = \int c(\rho,T)\,\mathrm{d}V$$

$$C\frac{\mathrm{d}\widetilde{T}}{\mathrm{d}t} = -L_\nu^\infty - L_\gamma^\infty$$

Aim: to build a method for analysing cooling of NSs with *npeμ* cores applicable to many EOS and baryon superfluidity models.

- NS layers: atmosphere, crust (up to $\rho \approx 1.4 \times 10^{14}$g/cm³) and core ($\rho > 1.4 \times 10^{14}$ g/cm³).
- After first 100 yr the interior is relaxed ($\tilde{T} = const$).
- Relation between internal (T_b) and surface (T_s) temperatures is given by heat blanket (HB) theory (Potekhin et al. 2003, Yakovlev et al. 2011, Beznogov & Yakovlev 2016).
- Cooling agents: neutrinos ν and photons γ.
- Photon luminosity L_γ^∞ is determined by T_s.
- Neutrino luminosity L_ν^∞ and heat capacity C are given by emissivity Q_ν and specific heat c integrated over the core volume (Yakovlev et al. 2001).
- Q_ν and c depend on equation of state (EOS) models and baryon superfluidity in the core.

2. EOS model independent approximations for L_ν^∞ and C

Neutrino processes

nn bremsstrahlung: $n + n \to n + n + \nu + \tilde{\nu}$

modified Urca (MU): $n + n \to n + p + e + \tilde{\nu}$, $n + p + e \to n + n + \nu$
$p + n \to p + p + e + \tilde{\nu}$, $p + p + e \to n + n + \nu$

direct Urca (DU): $n \to p + e + \tilde{\nu}$, $p + e \to n + \nu$

- Yakovlev et al. (2001)
- for DU: threshold is off but only $M > 1.5\mathrm{M}_\odot$ NS models are considered.

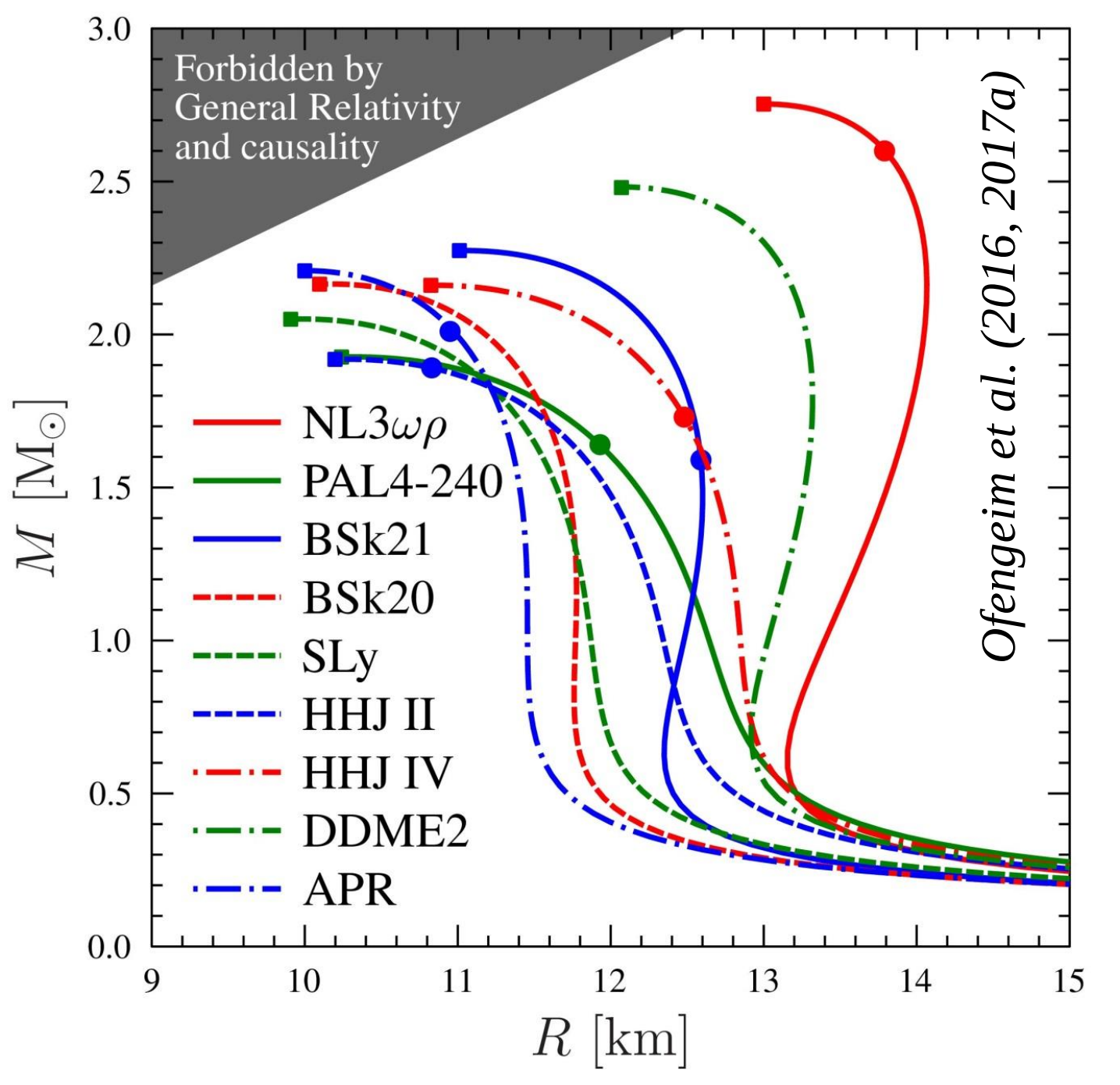
Approximations

$$L_{\nu i}^\infty = \Lambda_j(M,R)\widetilde{T}^n, \qquad C_j = \Sigma_j(M,R)\widetilde{T},$$

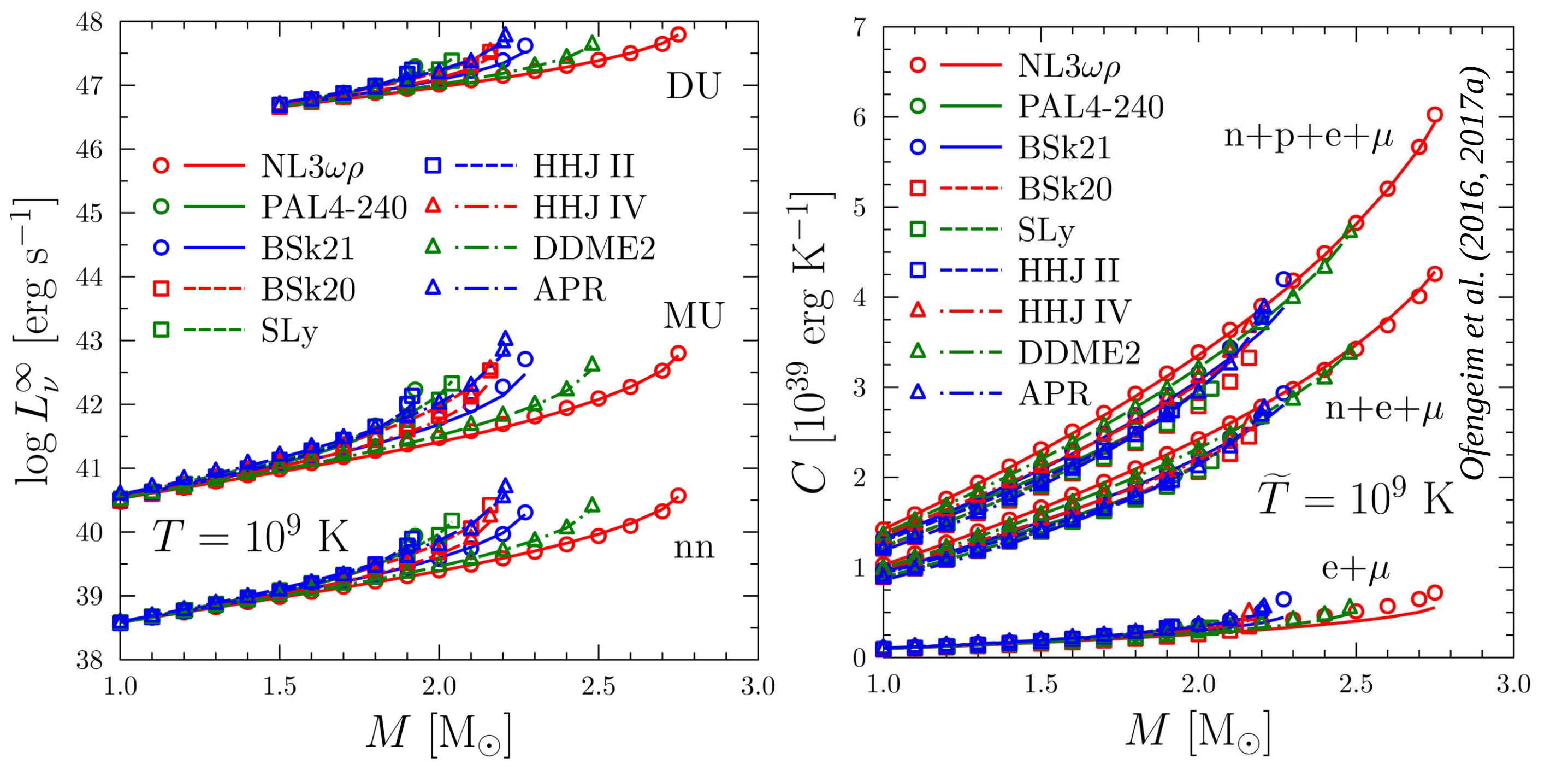
i = nn ($n = 8$), MU ($n = 8$), DU ($n = 6$)

j = *n*+*p*+*e*+*μ* (normal baryons), *n*+*e*+*μ* (superfluid protons), *e*+*μ* (all baryons are superfluid)

- Λ_i and Σ_j are analytic functions of M and R.
- For each process i or heat capacity case j, Λ_i and Σ_j are the same for all considered EOS models. EOS dependence is encapsulated in M and R values.



Mass-radius relations for EOS models taken to calibrate the approximations. Circles mark DU thresholds in the center of a star.



Approximations vs. numerically calculated $L_{\nu i}^\infty$ and C_j. Symbols for exact calculations, lines for approximations. *Left:* neutrino luminosities for nn-bremsstrahlung (nn), MU and DU processes. *Right:* heat capacities for normal baryons (*n*+*p*+*e*+*μ*), superfluid protons (*n*+*e*+*μ*), and fully superfluid baryons (*e*+*μ*).

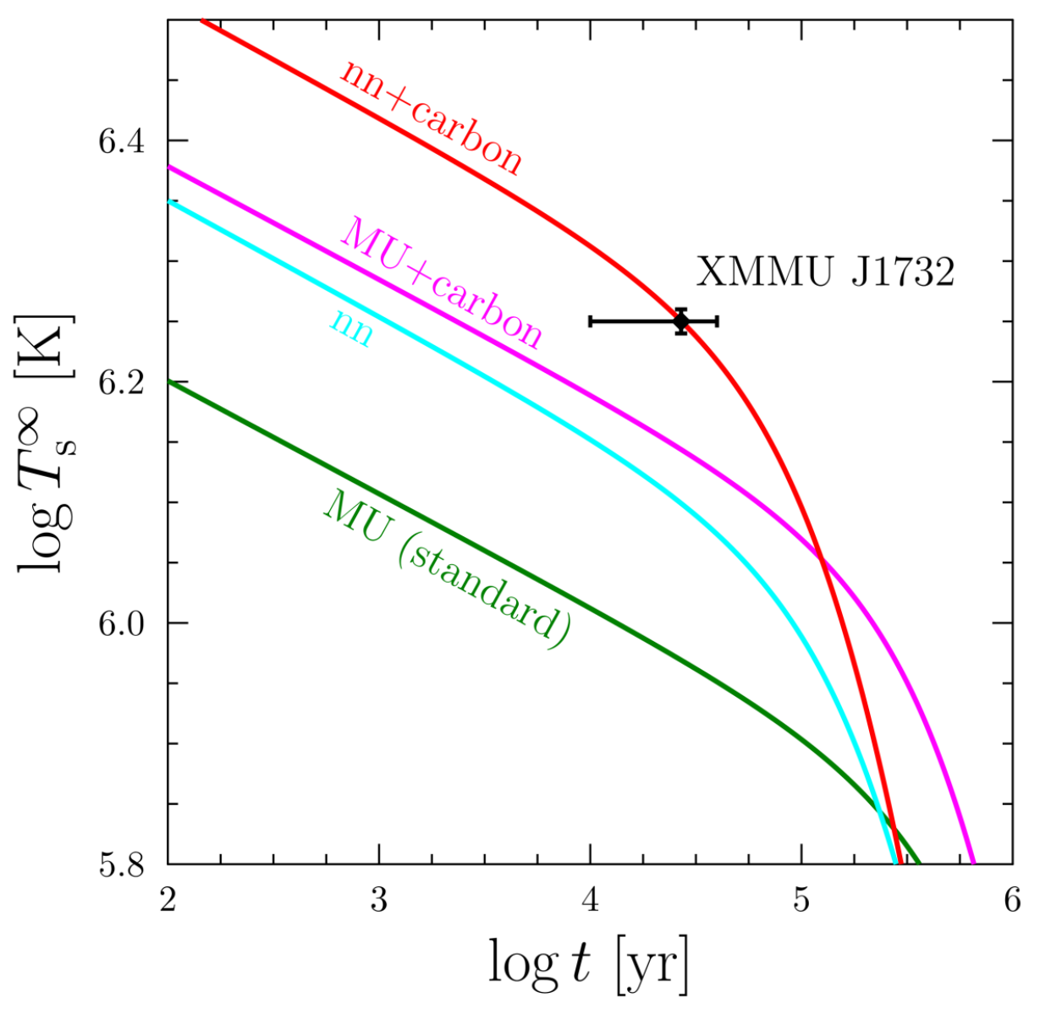
3. Analysis of ν-cooling Neutron Stars $\left(t < 10^5\ \mathrm{yr}\right)$

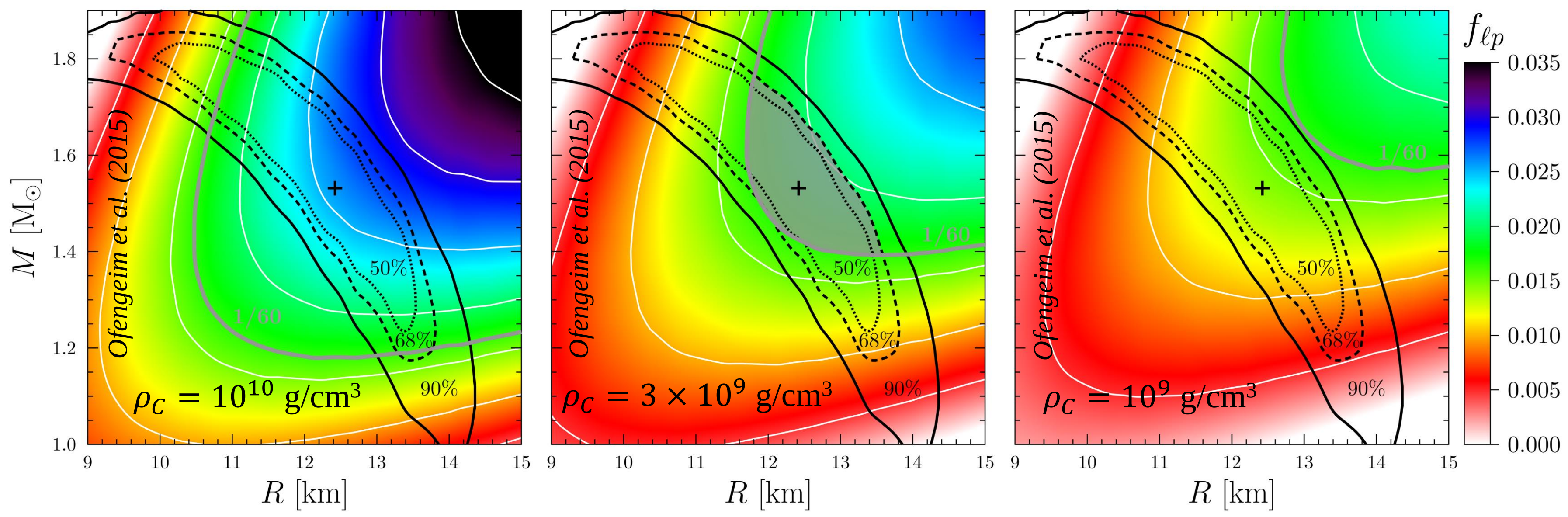
$$L_\nu^\infty \gg L_\gamma^\infty \Rightarrow \frac{\mathrm{d}\widetilde{T}}{\mathrm{d}t} \approx -q\widetilde{T}^{n-1},\ \frac{L_\nu^\infty}{C} = q(M,R)\widetilde{T}^{n-1} \Rightarrow \widetilde{T} \approx \left((n-2)qt\right)^{-\frac{1}{n-2}}$$

(e.g. Yakovlev et al 2011)

XMMU J173203.3—344518

- $t \approx 27$ kyr, $d \approx 3.2$ kpc.
- Isolated middle-aged NS with weak magnetic field.
- Klochkov et al. (2015): carbon atmosphere, $M = 1.55^{+0.28}_{-0.24}\,\mathrm{M}_\odot$, $R = 12.4^{+0.9}_{-2.2}$ km.
- too hot for standard cooling (MU + iron HB) ⇒ accreted carbon HB + superconducting protons (main ν reaction is nn brems.), i.e. $\boldsymbol{q = f_{\ell p} q_{\mathrm{stand}} + q_{\mathrm{nn}},\ f_{\ell p} \approx const}$
- Carbon extends to $\boldsymbol{\rho < \rho_C}$; HB model form Yakovlev et al. (2011).
- Each M, R: one obtains T_s^∞ form spectral analysis, then calculates $\tilde{T}$ from a HB model with fixed ρ_C, then finds $f_{\ell p}$.
- carbon burns at $\rho \sim 10^{10}$ g/cm³, proton superfluidity vanishes at high densities ⇒ one should have $\max\rho_C < 10^{10}$ g/cm³ and $\min f_{\ell p} > 0$, ⇒ restrictions on M, R plane.
- E.g., realistic values $\max\rho_C = 3 \times 10^9$ g/cm³ and $\min f_{\ell p} = 1/60$ significantly constrain M and R.

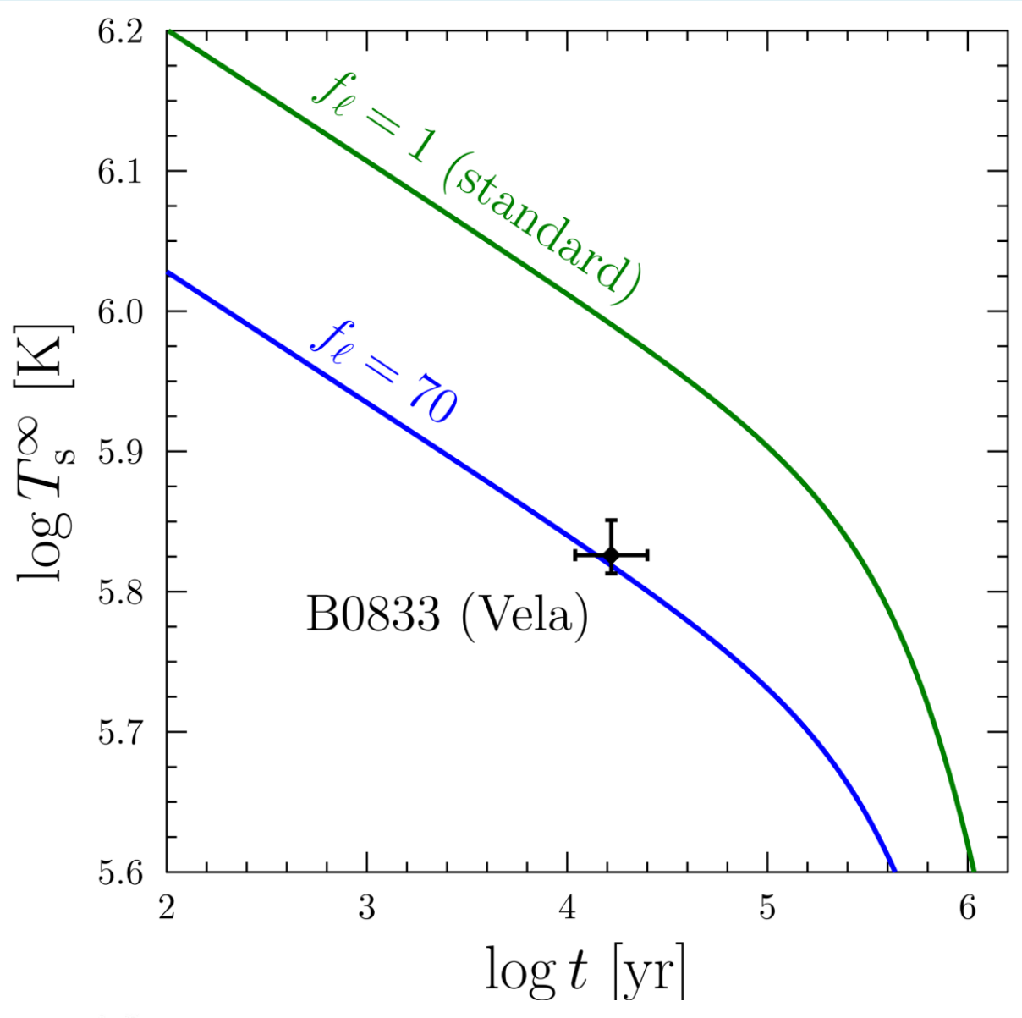


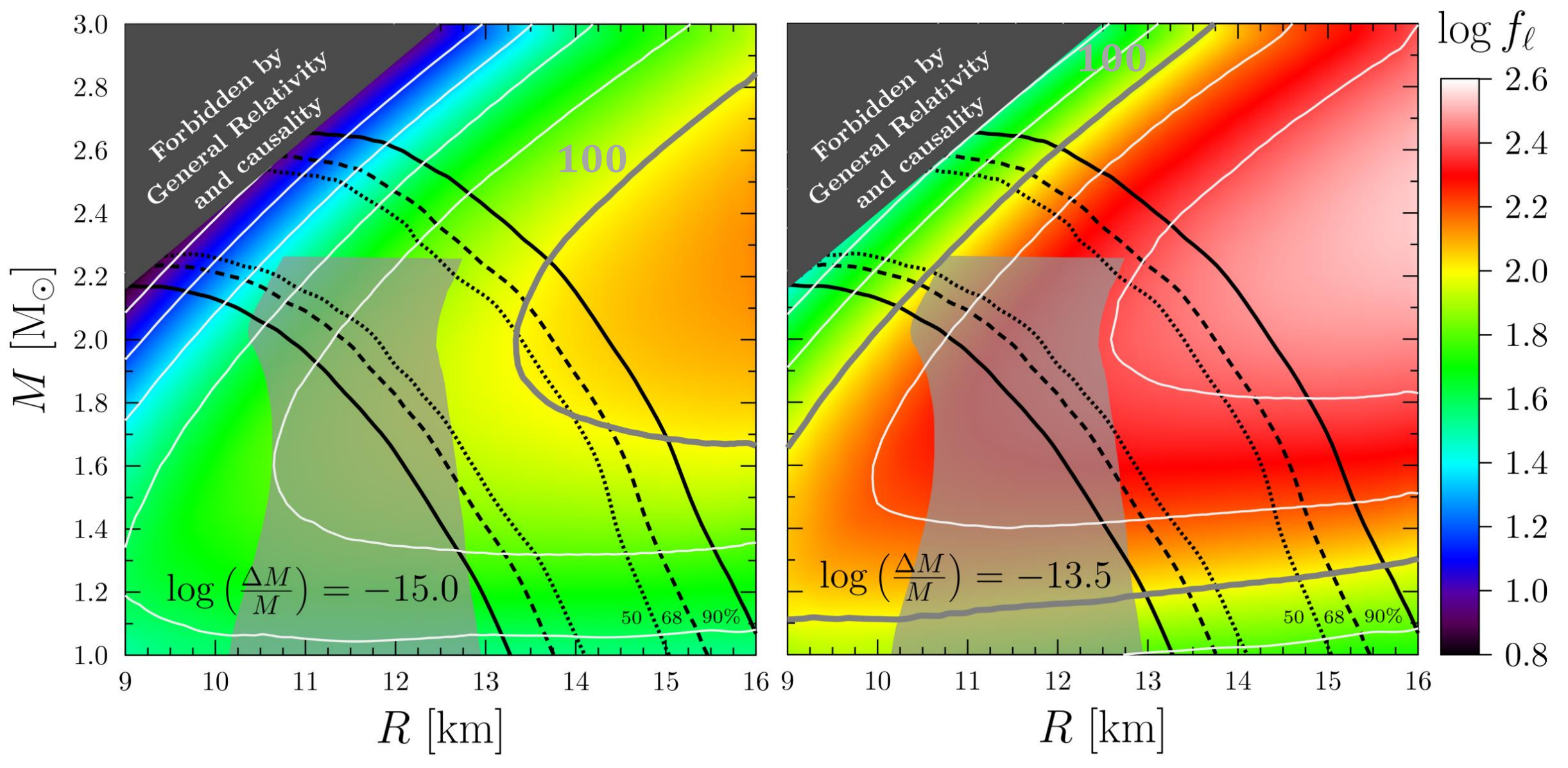


$M - R$ confidence levels (black lines) inferred from spectral analysis (Klochkov et al. 2015) vs. constraints from cooling theory. It is assumed that $\min f_{\ell p} = 1/60$ (gray line). Thin white lines mark $f_{\ell p} = 0.005, 0.010, \dots, 0.035$. Right panel shows that $\rho_C \lesssim 10^9$ g/cm³ is not allowed.

B0833-45 (Vela pulsar)

- $t \approx 11$ kyr, $d \approx 290$ pc (Dodson et al. 2003).
- Pavlov et al. (2001):
  - hydrogen magnetic atmosphere + power law
  - $M = 1.4\mathrm{M}_\odot$, $R = 10$ km
  - $T_s^\infty = (6.8 \pm 0.3) \times 10^5$ K
- Zyuzin et al. (in preparation):
  - hydrogen magnetic atmosphere + power law
  - $M - R$ confidence levels
  - $T_s^\infty = 6.7^{+0.4}_{-0.2} \times 10^5$ K
- Too cold for standard MU cooling.
- Minimal cooling (Page et al. 2004): enhancement of L_ν^∞ by ν emission from triplet Cooper pairing of neutrons.
- Yakovlev et al. (2011): $\boldsymbol{q = f_\ell q_{\mathrm{stand}},\ f_\ell \approx const}$ accounts Cooper pairing ν emission independently of a pairing model.
- accreted magnetic HB model by Potekhin et al. (2003).
- mass of accreted matter: ΔM
- Each M, R: one obtains T_s^∞ form spectral analysis, then calculates $\tilde{T}$ using at HB model with fixed $\Delta M/M$, then calculates f_ℓ.
- $f_\ell \lesssim 100$ (e.g. Page et al. 2015) + confidence levels from spectral analysis + constraints on EOS models from Nättilä et al. (2016) ⇒ $\Delta M \lesssim 10^{-13}\ \mathrm{M}_\odot$.





$M - R$ confidence levels (black lines) from spectral analysis (Zyuzin et al., in preparation) and f_ℓ colormap for different $\Delta M/M$. A gray shaded region is the EOS constraint from Nättilä et al. (2016), a gray line mark max possible $f_\ell \sim 100$, white lines are for $\log f_\ell = 1.0, 1.2, \dots 2.4$.

4. Analysis of Neutron Stars at photon cooling stage $\left(t \gtrsim 10^5\ \mathrm{yr}\right)$

$L_\nu^\infty \lesssim L_\gamma^\infty$

$$\frac{L_\nu^\infty}{C} = q(M,R)\widetilde{T}^{n-1}$$

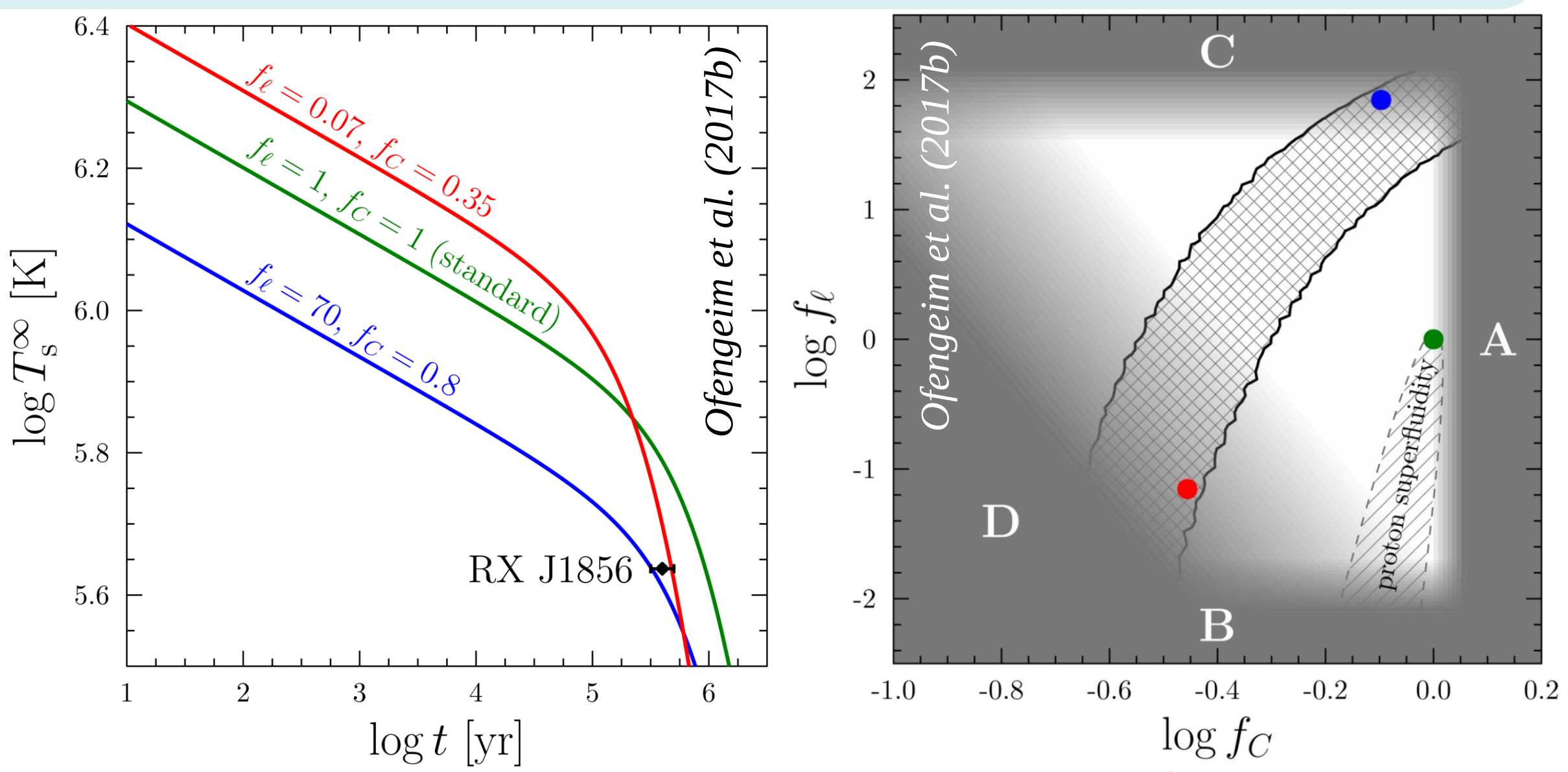
simple fit for Potekhin et al. (1997); valid for iron HB only

$$\longrightarrow \frac{L_\gamma^\infty}{C} \approx s(M,R)\widetilde{T}^{\alpha-1}$$

$$\frac{\mathrm{d}\widetilde{T}}{\mathrm{d}t} = -q\widetilde{T}^{n-1} - s\widetilde{T}^{\alpha-1} \Rightarrow \widetilde{T} \approx (s/q)^{\frac{1}{n-\alpha}}\left[\left((\alpha-2)s^{\frac{n-2}{n-\alpha}}q^{\frac{2-\alpha}{n-\alpha}}t + 1\right)^{\frac{n-2}{\alpha-2}} - 1\right]^{-\frac{1}{n-2}}$$

RX J1856-3754

- $\log t[\mathrm{yr}] = 5.5 - 5.7$ (Vigano et al. 2013), $d \approx 120$ pc (Walter et al. 2010).
- Ho et al. (2007), Potekhin (2014):
  - thin hydrogen magnetic atmosphere on a condensed iron surface
  - $M = 1.48^{+0.16}_{-0.19}\,\mathrm{M}_\odot$, $R = 12.1^{+1.3}_{-1.6}$ km, $T_s^\infty = (4.34 \pm 0.03) \times 10^5$ K
- Too cold for the standard cooling scenario.
- iron HB (below iron surface)
- pairing ⇒ $\boldsymbol{q = f_\ell q_{\mathrm{stand}}}$, $\boldsymbol{C = f_C C_{\mathrm{stand}}}$.
- Left panel: standard cooling curve and two scenarios with pairing that explain RX J1856 ($M = 1.48\mathrm{M}_\odot$, $R = 12.1$km).
- Right panel: doubly hatched strip for f_ℓ, f_C pairs that explains RX J1856, single-hatched area for partly paired p and non-paired n, gray shaded regions should be forbidden because



(A) pairing hardly enhances C
(B) proton pairing can make $f_\ell > L_{\nu\mathrm{nn}}^\infty / L_{\nu\mathrm{MU}}^\infty$ only
(C) n pairing hardly makes $f_\ell > 100$
(D) strong L_ν enhancement leads to strong C suppression; it requires strong n pairing.

Conclusions

The method for neutron star cooling analysis that is independent of EOS and baryon superfluidity models is presented. It allows one to obtain valuable information about physics of inner regions of cooling neutron stars.

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