Constraining Superfluidity in Dense Matter from the Cooling of Isolated Neutron Stars

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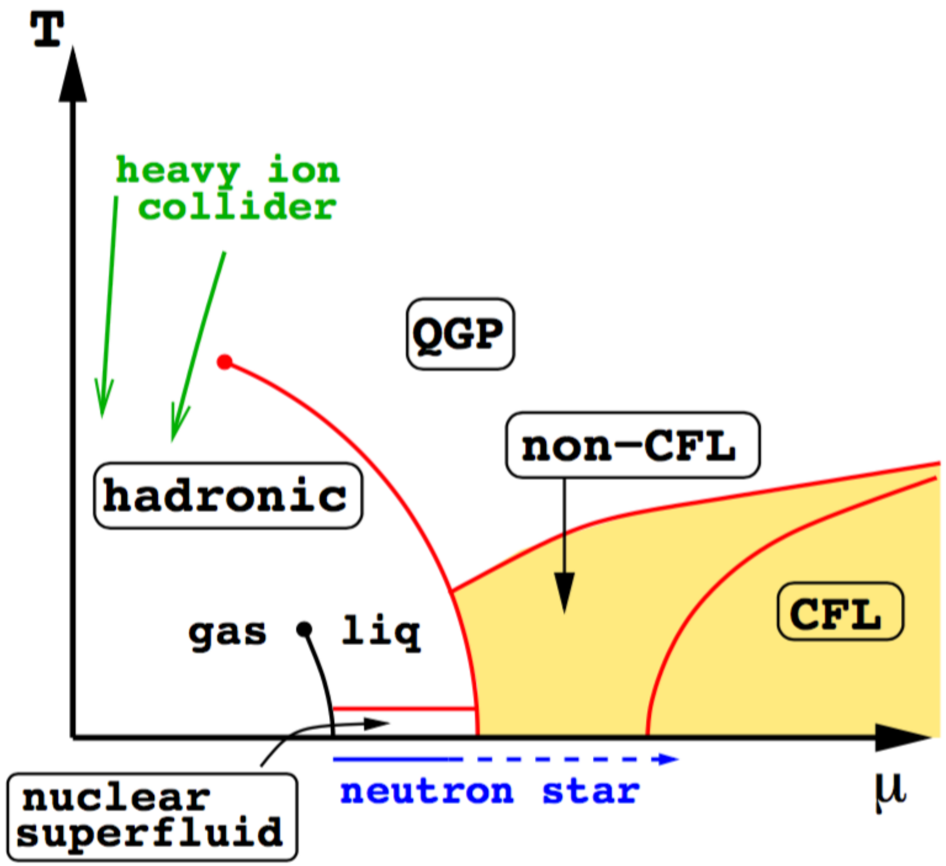
Isolated Neutron Stars

- Neutron stars (NS) which have no binary companion are considered “isolated”
- These isolated NSs offer an excellent chance to study the rate at which dense matter cools without the confounding effects of accretion
- In isolated NSs the temperature decreases monotonically at a rate determined by the nature of dense matter

- Our model assumes the Minimal Cooling Paradigm

Neutron Stars are “Cold” QCD matter



Alford, Rajagopal, Schafer and Schmitt
arXiv:0709.4635

Minimal Cooling

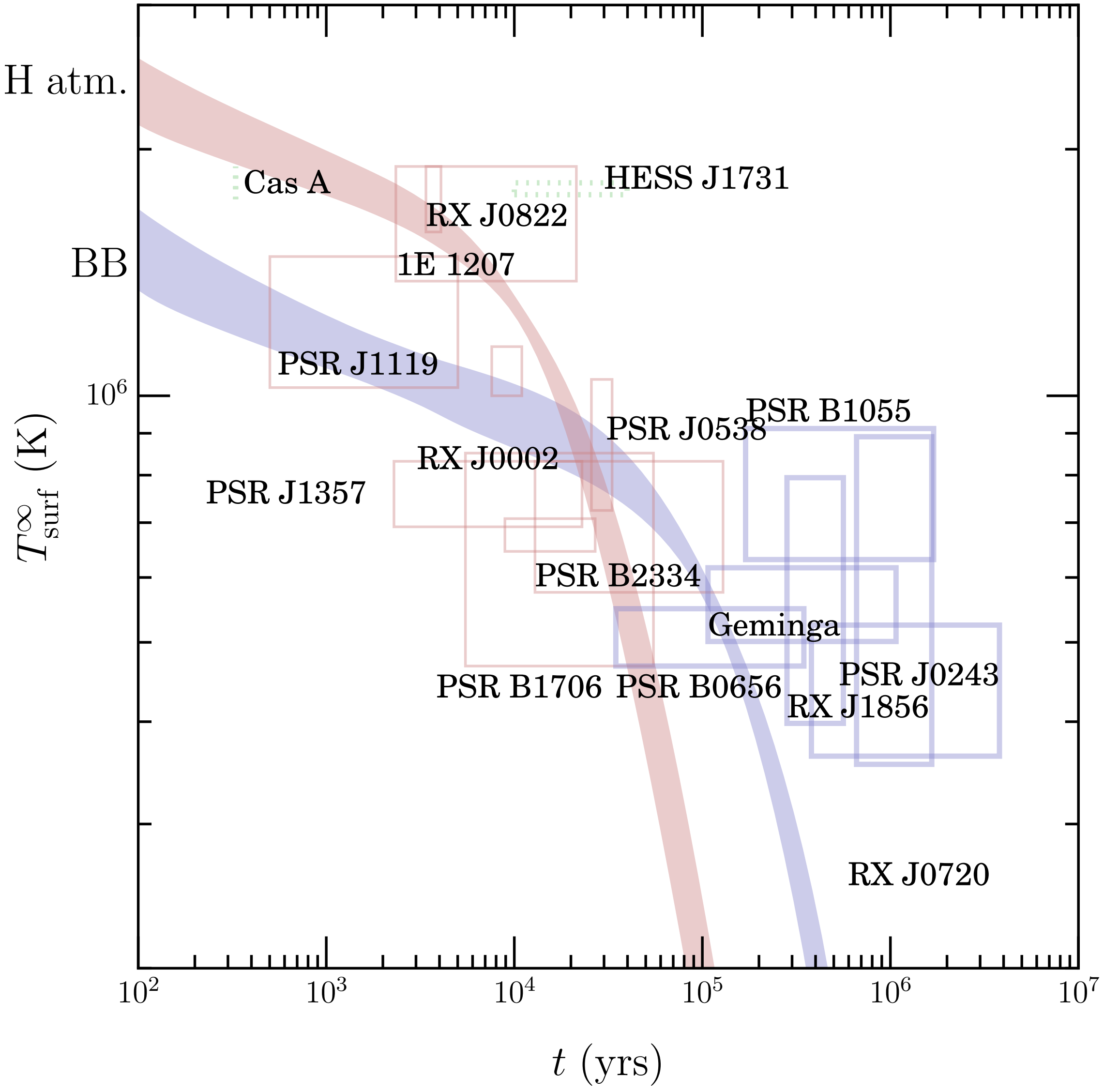
- Includes: nucleons, leptons, modified direct Urca and neutrino emission via Cooper pair breaking and formation
- Excludes: hyperons, bose condensates, deconfined quarks and direct Urca process
- Minimal Cooling contains parameters for equations of state for dense matter, NS envelope composition, and mass of NS but for this research we are primarily concerned with superfluid properties of dense matter

Selected NS data samples

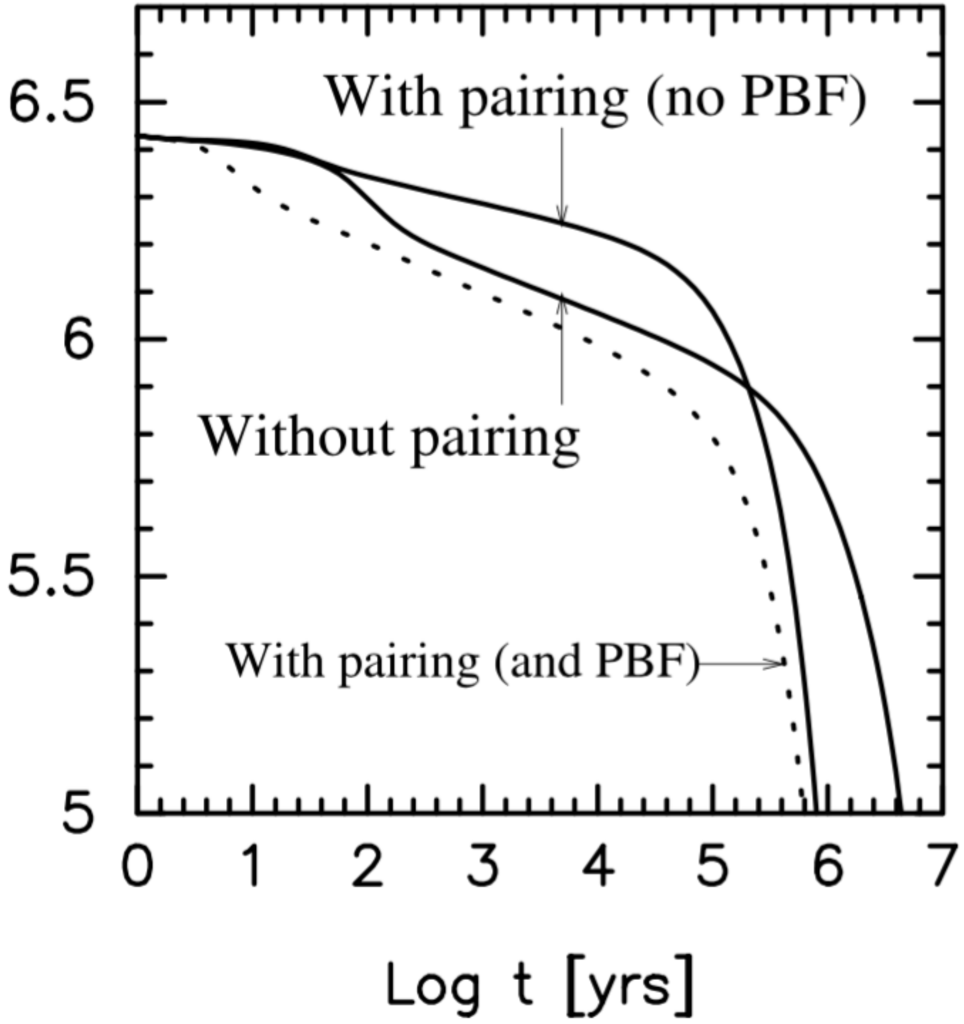
Star	$\log_{10}(t_{sd}/yr)$ or $\log_{10}(t_{kin}/yr)$	B (G)	$\log_{10}(T/K)$	atmosphere model	mass	radius
Cas A NS	2.518 (observed)	8×10^{10}	$6.26^{+0.02}_{-0.02}$	C	1.4 $M_\odot^*$	12-15 km
			$6.447^{+0.012}_{-0.012}$	H	1.4 $M_\odot^*$	4 km
			$6.653^{+0.008}_{-0.008}$	BB	1.4 $M_\odot^*$	1±1 km
PSR J1119−6127	3.20 (sd)	4.1×10^{13}	$6.18^{+0.08**}_{-0.08}$	HA	1.4 $M_\odot^*$	10 km*
			$6.38^{+0.02}_{-0.02}$	BB	1.4 $M_\odot^*$	2.7±0.7 km
RX J0822−4247	$3.57^{+0.04}_{-0.04}$ (kin)	$\sim 10^{12}$G	$6.24^{+0.04}_{-0.04}$	HA	1.4 $M_\odot^*$	10 km*
			$6.65^{+0.04}_{-0.04}$	BB	1.4 $M_\odot^*$	2 km (approx)
1E 1207.4−5209++	$3.85^{+0.48}_{-0.48}$ (kin)	3×10^{12} G	$6.21^{+0.07}_{-0.07}$	HA	1.4 $M_\odot^*$	10 km*
			$6.48^{+0.01}_{-0.01}$	BB	1.4 $M_\odot^*$	<1.5 km
PSR J1357−6429	3.86 (sd)	8×10^{12}G	$5.88^{+0.04}_{-0.04}$	HA	1.5 − 1.6 $M_\odot$	10 km*
			$6.23^{+0.05}_{-0.05}$	BB	1.5 − 1.6 $M_\odot$	2.5±0.5 km
RX J0002+6246†	$3.96^{+0.08}_{-0.08}$ (kin)		$6.03^{+0.03}_{-0.03}$	HA		
			$6.15^{+0.11}_{-0.11}$	BB		
PSR B0833−45	$4.26^{+0.17}_{-0.31}$ (kin)	3×10^{12}G	$5.83^{+0.02}_{-0.02}$	HA	1.4 $M_\odot^*$	13 km
			$6.18^{+0.02}_{-0.02}$	BB	1.4 $M_\odot^*$	2.1±0.2 km
PSR B1706−44	4.24 (sd)	3×10^{12}G	$5.80^{+0.13}_{-0.13}$	HA	1.45 − 1.59 $M_\odot$	13 km
			$6.22^{+0.04}_{-0.04}$	BB	1.4 $M_\odot^*$	< 6 km
Hess J1731−347	$4.43^{+0.17}_{-0.43}$ (kin; [17])	$\sim 10^{10-11}$G	$6.25^{+0.01}_{-0.0045}$	C		
PSR J0538+2817‖	$4.47^{+0.05}_{-0.06}$ (sd; [19])	$\sim 10^{12}$G	$6.04^{+0.1}_{-0.1}$	HA	1.4 $M_\odot^*$	10.5 km
			$6.327^{+0.007}_{-0.007}$	BB	1.4 $M_\odot^*$	<2 km
PSR B2334+61	4.61 (sd)	10^{10-12}G	$5.84^{+0.08}_{-0.08}$	HA		10 km*
PSR B0656+14	5.04 (sd)	5×10^{12}G [23]	$5.71^{+0.03}_{-0.04}$	BB		12-17 km
PSR B0633+1748	5.53 (sd)		$5.75^{+0.04}_{-0.05}$	BB		10 km*
RX J1856.4−3754‡	$5.70^{+0.05}_{-0.25}$ (kin)	4×10^{12}G	$5.75^{+0.15}_{-0.15}$	BB		14 km
PSR B1055−52§	5.73 (sd)	4×10^{12}G	$5.88^{+0.08}_{-0.08}$	BB	1.4 $M_\odot^*$	13 km
PSR J0243+2740¶	6.08 (sd)	10^{14}G	$5.64^{+0.08}_{-0.08}$	HA		10 km*
PSR J0720.4-3125	6.11 (sd)	10^{13}G [29]	$5.75^{+0.20}_{-0.20}$	BB	1.4 $M_\odot^*$	11-13 km

Superfluidity

- Cooper pairs of nucleons form in NS, analogous to terrestrial pairing of electrons in low-temperature metals
- The PBF (pair breaking and formation) process can contribute greatly to the overall neutrino emissivity of isolated NS
- The critical temperature for the formation of these pairs (and a minimum critical temperature for pair breaking thermal excitations) are not well established
- The neutron singlet gap $^1S_0$ is well studied, while the proton $^1S_0$ and neutron triplet $^3P_2$ have greater uncertainties



Beloin et al (preliminary)



Page et al. 2004

Monte Carlo

- We treated $^1S_0$ and $^3P_2$ pairing gaps as a series of six free parameters.

- Assume a gaussian distribution

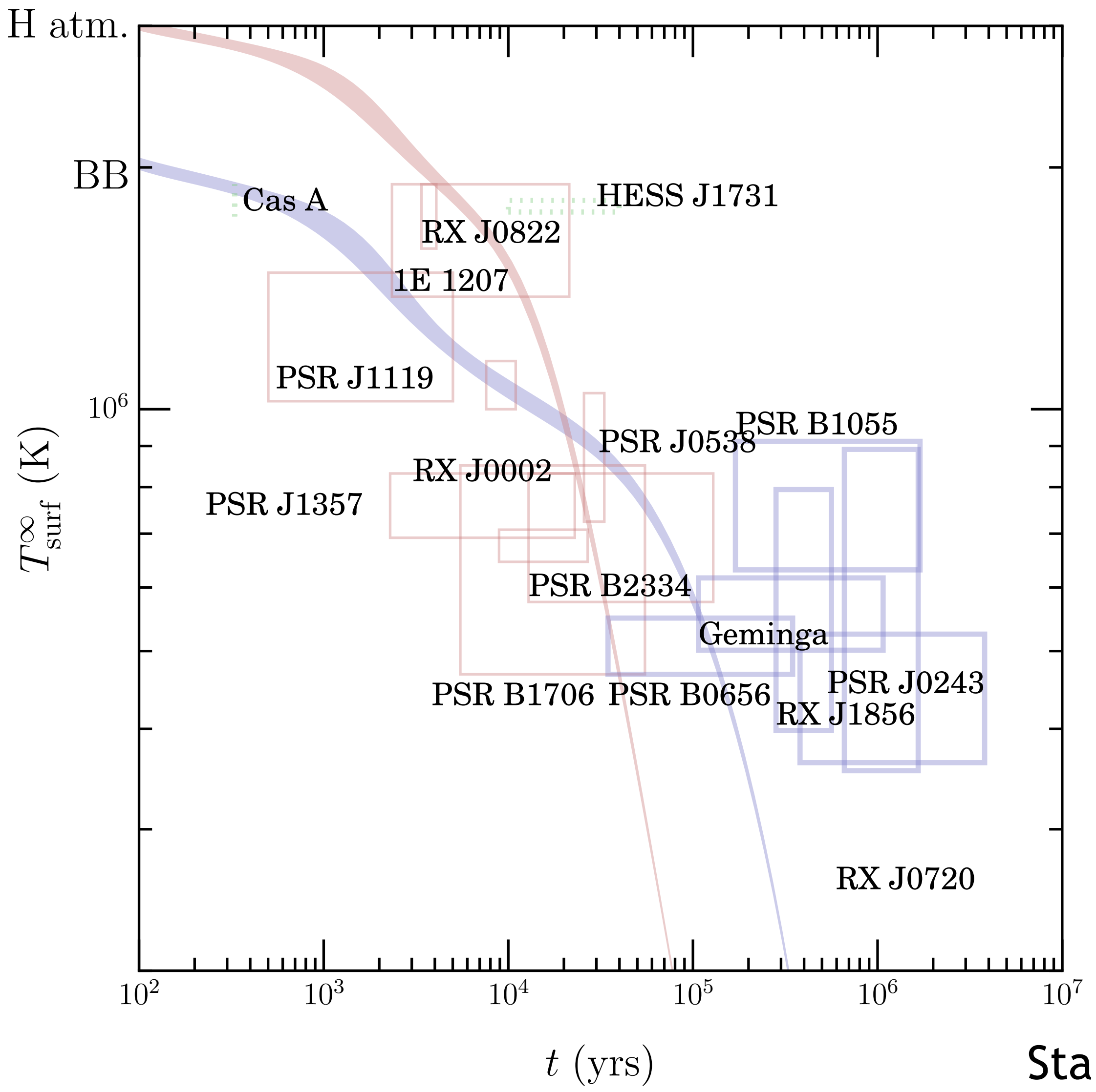
$$T_C = T_{C,peak}\ \exp[\frac{(k-k_{f,peak})^2}{2\Delta k}]$$

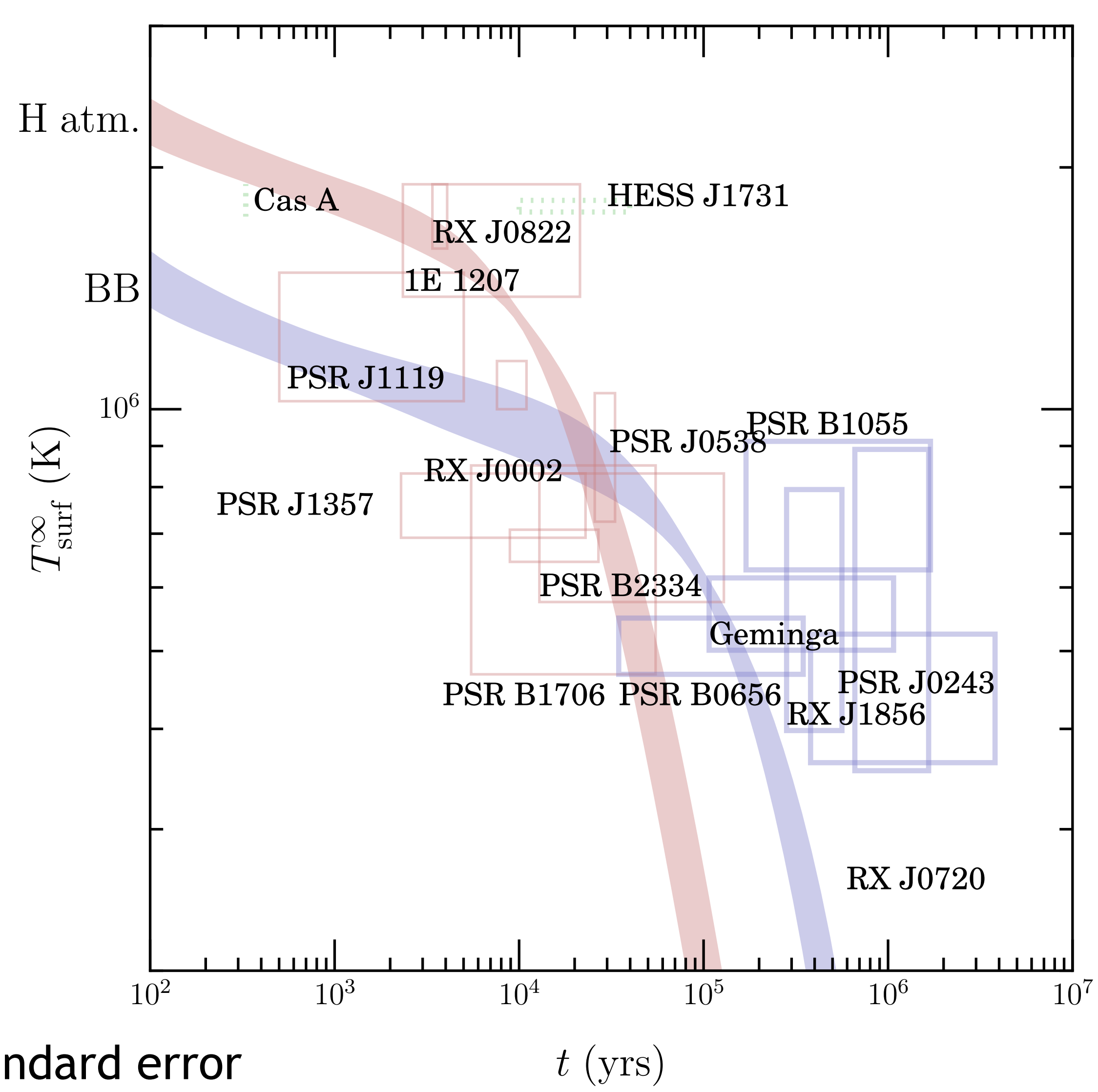
$$k_f = (3\pi^2 n)^{1/3}$$

- Hence the six parameters are T_{cn} , $k_{max\,n}$, Δk_n for neutrons and T_{cp} , $k_{max\,p}$, Δk_p for protons

$$\mathcal{L} \propto \prod_j \sum_k \sqrt{\left(\frac{dT}{dt}\right)^2_k + 1}\ e^{\frac{-(t_k - t_j)^2}{2\delta t_j{}^2}}\, e^{\frac{-(T_k - T_j)^2}{2\delta T_j{}^2}}$$

Fitting with/without Carbon-envelope stars



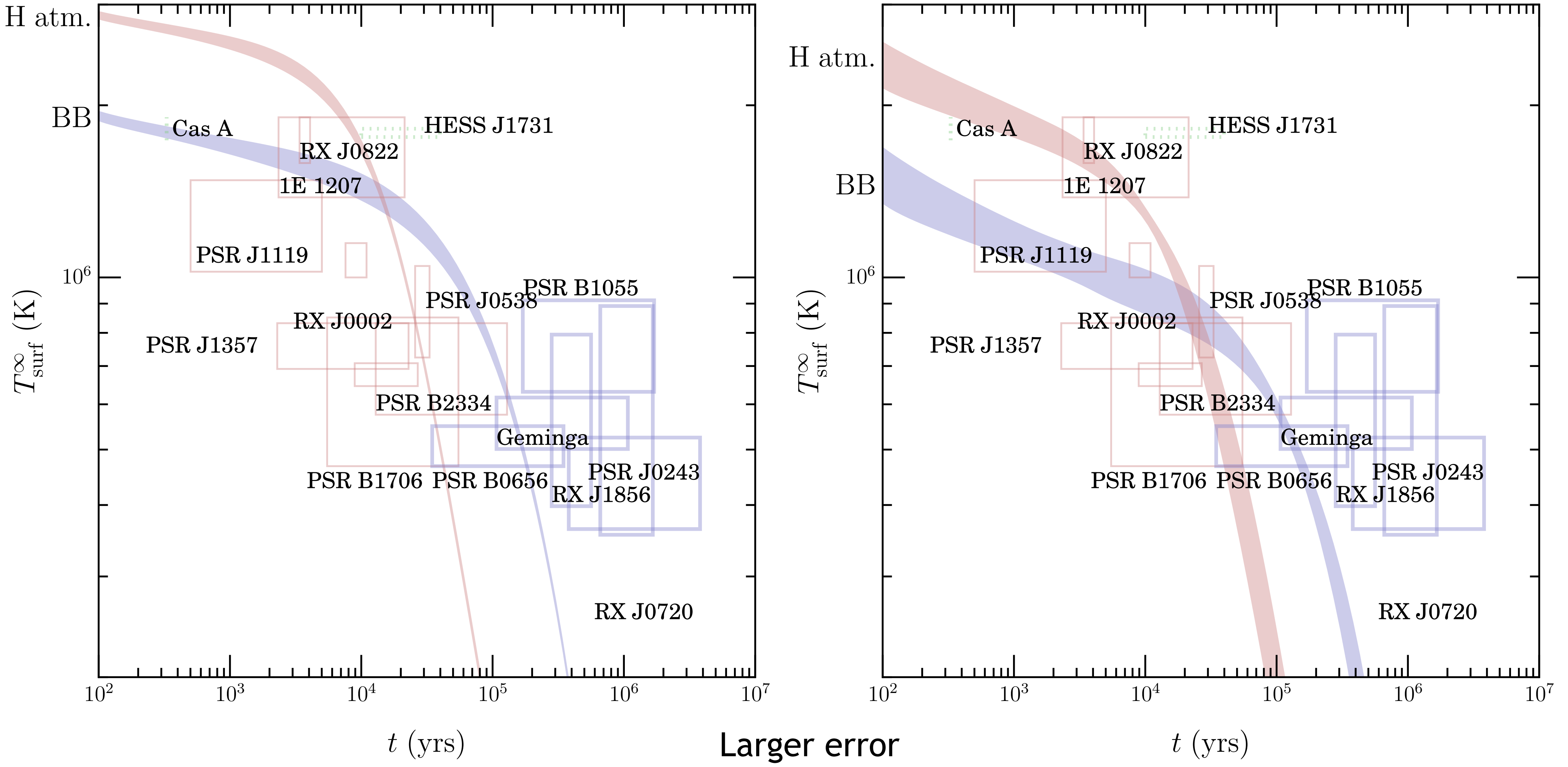


Standard error

Carbon-envelope stars included

Carbon-envelope stars excluded

Enhanced error fitting



Larger error

Carbon-envelope stars included

Carbon-envelope stars excluded

Quantity	Value and 1−σ uncertainty
$T_{c,\mathrm{peak},n}$	$(4.09 \pm 0.23) \times 10^9$ K
$k_{F,\mathrm{peak},n}$	(1.87 ± 0.16) fm^{-1}
$\Delta k_{F,n}$	(1.48 ± 0.35) fm^{-1}
$T_{c,\mathrm{peak},p}$	$(6.7 \pm 2.1) \times 10^8$ K
$k_{F,\mathrm{peak},p}$	(0.89 ± 0.12) fm^{-1}
$\Delta k_{F,p}$	(0.94 ± 0.16) fm^{-1}

with Carbon stars; standard error

Quantity	Value and 1−σ uncertainty
$T_{c,\mathrm{peak},n}$	$(1.25 \pm 0.48) \times 10^9$ K
$k_{F,\mathrm{peak},n}$	(1.860 ± 0.087) fm^{-1}
$\Delta k_{F,n}$	(1.18 ± 0.42) fm^{-1}
$T_{c,\mathrm{peak},p}$	$(5.2 \pm 2.5) \times 10^9$ K
$k_{F,\mathrm{peak},p}$	(0.895 ± 0.088) fm^{-1}
$\Delta k_{F,p}$	(0.50 ± 0.27) fm^{-1}

without Carbon stars; standard error

Quantity	Value and 1−σ uncertainty
$T_{c,\mathrm{peak},n}$	$(4.09 \pm 0.39) \times 10^9$ K
$k_{F,\mathrm{peak},n}$	(1.88 ± 0.052) fm^{-1}
$\Delta k_{F,n}$	(1.50 ± 0.20) fm^{-1}
$T_{c,\mathrm{peak},p}$	$(5.2 \pm 1.8) \times 10^9$ K
$k_{F,\mathrm{peak},p}$	(0.918 ± 0.055) fm^{-1}
$\Delta k_{F,p}$	(0.76 ± 0.12) fm^{-1}

with Carbon stars; larger error (2.2)

Quantity	Value and 1−σ uncertainty
$T_{c,\mathrm{peak},n}$	$(1.19 \pm 0.52) \times 10^9$ K
$k_{F,\mathrm{peak},n}$	(1.878 ± 0.061) fm^{-1}
$\Delta k_{F,n}$	(1.16 ± 0.37) fm^{-1}
$T_{c,\mathrm{peak},p}$	$(4.9 \pm 2.3) \times 10^9$ K
$k_{F,\mathrm{peak},p}$	(0.889 ± 0.067) fm^{-1}
$\Delta k_{F,p}$	(0.59 ± 0.20) fm^{-1}

without Carbon stars; larger error (1.7)

Conclusions

- The preliminary results disagree the findings of the Minimal Cooling Paradigm
- The current calculated likelihood values are anomalously small, strong tension arrises when fitting RX J0002 and Hess J1731 simultaneously. Increasing uncertainties in cooling curves can provide a higher likelihood
- One possible explanation is the existence of enhanced cooling in fact occurs for certain NS mass and radii combinations. This enhanced cooling would manifest itself as exotic matter (e.g. hyperons) or perhaps enhanced cooling processes such as direct Urca