

Statistical Analysis of Neutron Star Cooling: Implications for the Nuclear Equation of State and Nucleon Pairing

Afonso Ávila, Ricardo Z. Ferreira and Violetta Sagun

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PhD in Physics

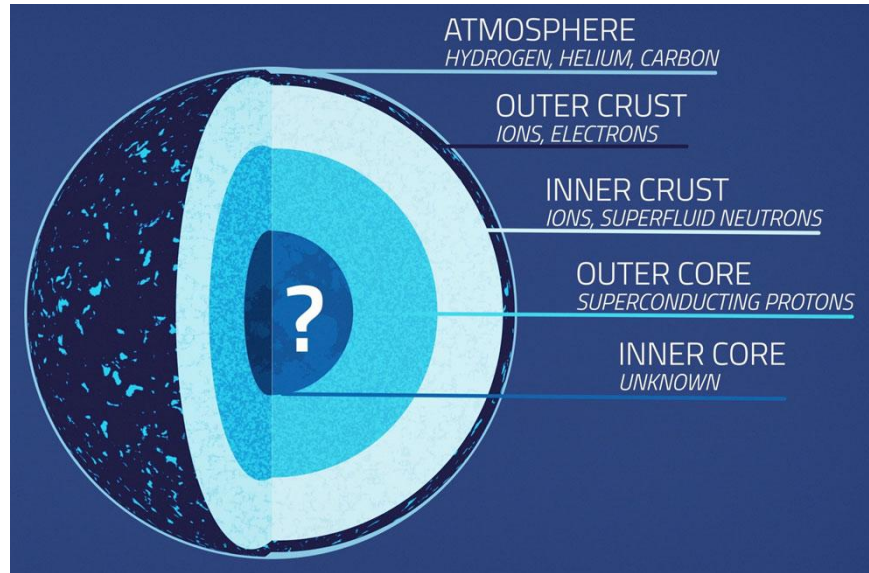
SCALES 1st General Meeting - Superfluid Condensates in Astrophysics and Laboratory Experiments

June 2026



Neutron Stars (NSs)

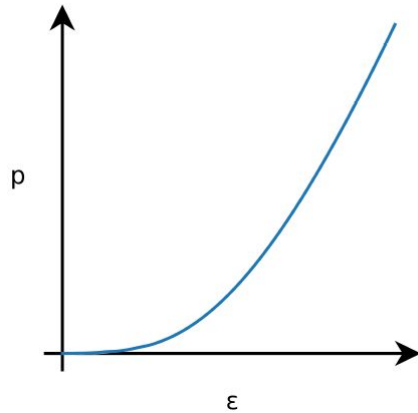
Neutron stars (NSs) are the final stage in the evolution of ordinary stars, they are formed when a star ceases its nuclear fuel.



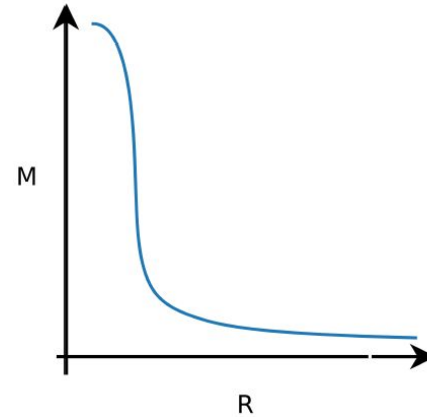
Credit: NASA's Goddard Space Flight Center / Conceptual Image Lab

How to model NSs

Equation of State (EoS)



Observable Mass-Radius



The **Tolman-Oppenheimer-Volkoff (TOV)** equation describes the structure of a spherically symmetric body made of isotropic matter which is in static gravitational equilibrium.

$$\frac{dp}{dr} = -\frac{(\epsilon + p)(M + 4\pi r^3 p)}{r^2 (1 - 2M/r)}$$

$$M(r) = 4\pi \int_0^r \epsilon(r') r'^2 dr'$$

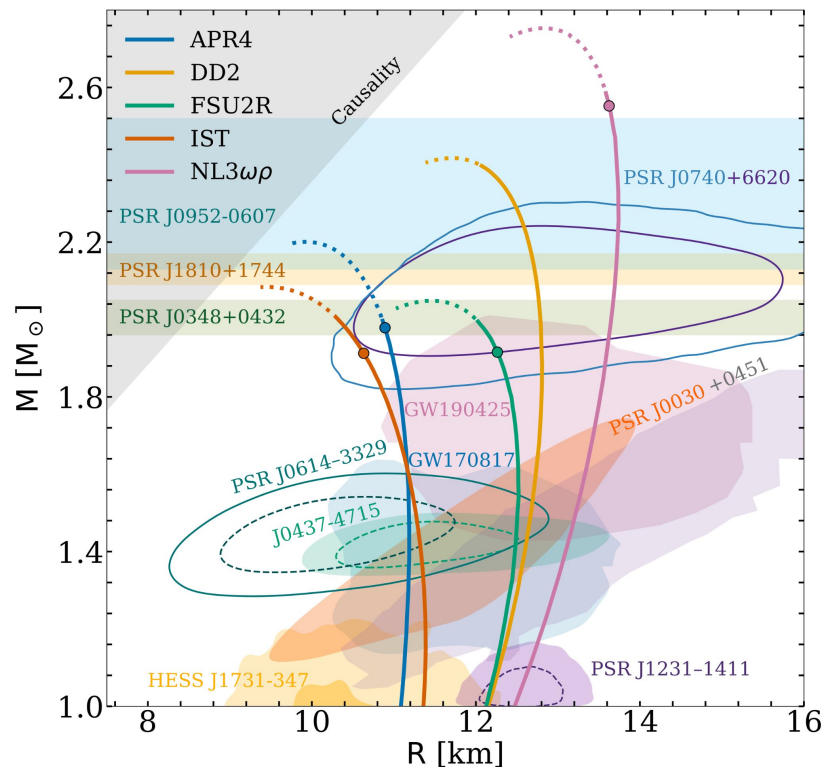
Motivation

Mass-radius observations constrain the EoS.
Present-day constraints leave the radius at
 $\sim 10 - 14$ km and the mass up to $2.5 M_{\odot}$

Complementary Probe:

NSs thermal evolution is sensitive to the
**interior composition and the nucleon
pairing gaps** Δ

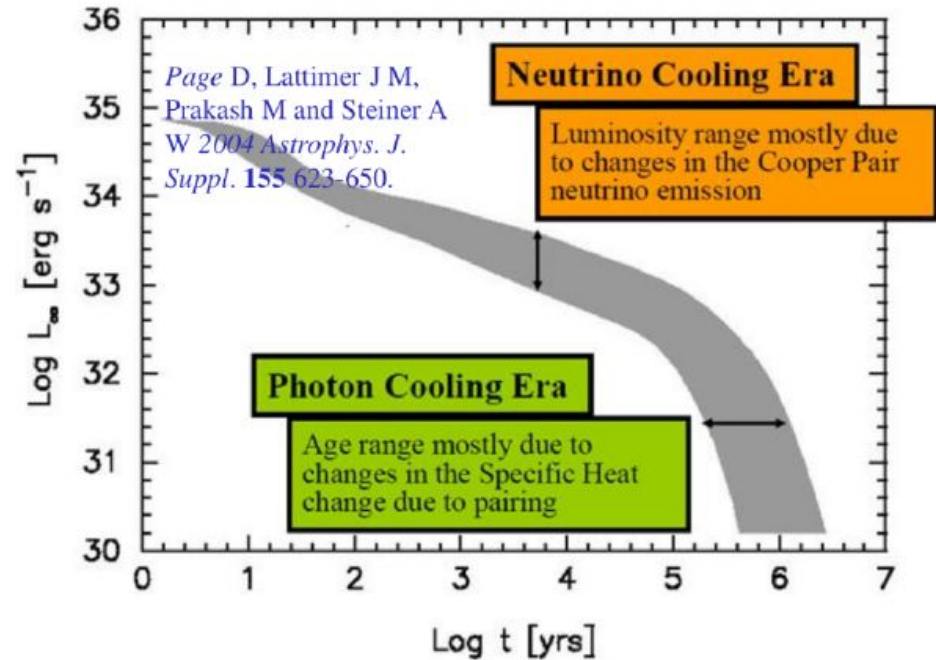
[Ávila, Ferreira & Sagun, 2026 (in prep.)]



NSs thermal evolution

The thermal evolution of NS can be divided into **three** stages:

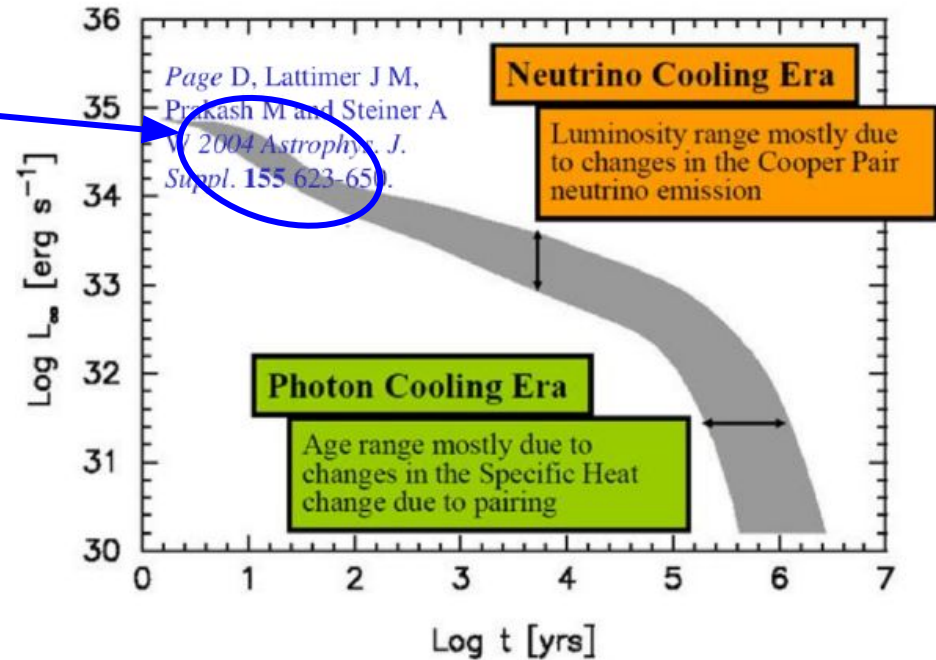
1. Newly born NS with the thermally decoupled core and crust
 $\lesssim 100$ yr [Sales et al., 2020]
2. **Neutrino emission** dominant stage
 $100 - 10^5$ yr
3. **Photon emission** dominant stage
 $\gtrsim 10^5$ yr [Page et al., 2004]



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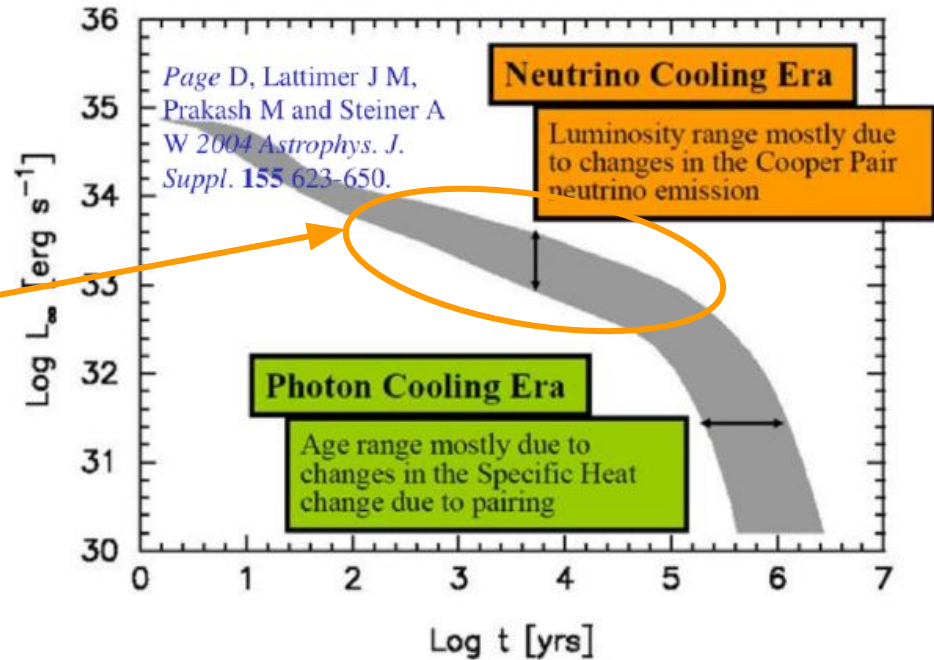
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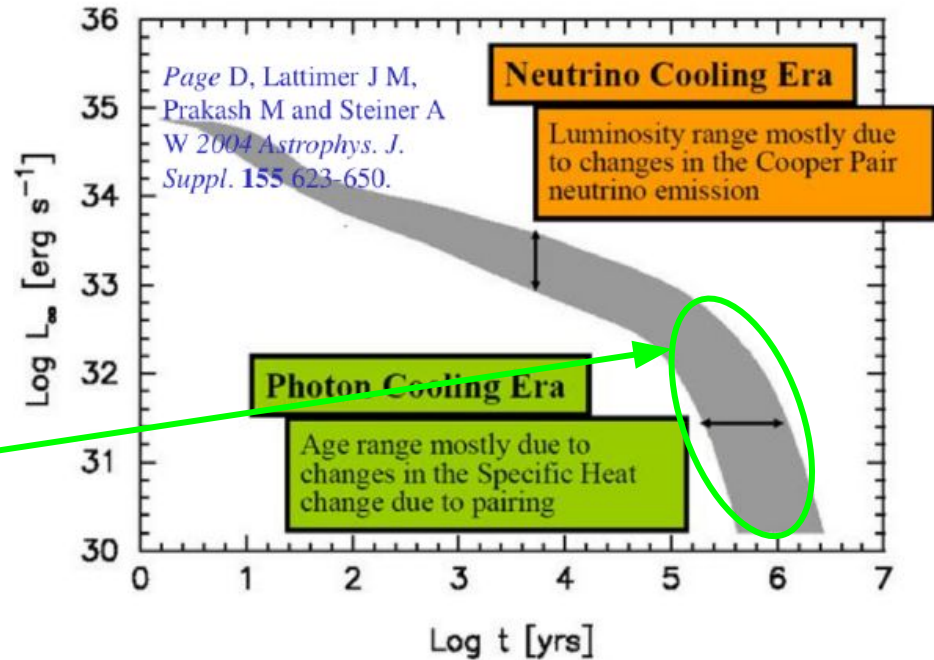
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NSs thermal evolution

The evolution of NSs is governed by the thermal balance equation

$$C_v \frac{dT^\infty}{dt} = -L_\nu^\infty - L_\gamma^\infty \pm H^\infty$$

[Page et al., 2006]

Name	Process ^c	Emissivity ^d (erg cm ⁻³ s ⁻¹)	
Modified Urca cycle (neutron branch)	$n + n \rightarrow n + p + e^- + \bar{\nu}_e$ $n + p + e^- \rightarrow n + n + \nu_e$	$\sim 2 \times 10^{21} R T_9^8$	Slow
Modified Urca cycle (proton branch)	$p + n \rightarrow p + p + e^- + \bar{\nu}_e$ $p + p + e^- \rightarrow p + n + \nu_e$	$\sim 10^{21} R T_9^8$	Slow
Bremsstrahlung	$n + n \rightarrow n + n + \nu + \bar{\nu}$ $n + p \rightarrow n + p + \nu + \bar{\nu}$ $p + p \rightarrow p + p + \nu + \bar{\nu}$	$\sim 10^{19} R T_9^8$	Slow
Cooper pair formations	$n + n \rightarrow [nn] + \nu + \bar{\nu}$ $p + p \rightarrow [pp] + \nu + \bar{\nu}$	$\sim 5 \times 10^{21} R T_9^7$ $\sim 5 \times 10^{19} R T_9^7$	Slow
Direct Urca cycle	$n \rightarrow p + e^- + \bar{\nu}_e$ $p + e^- \rightarrow n + \nu_e$	$\sim 10^{27} R T_9^6$	Fast

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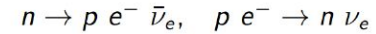
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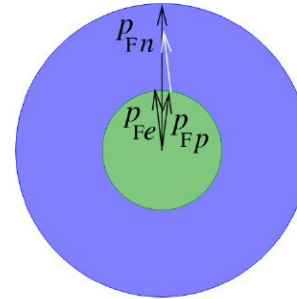
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When can direct Urca happen?

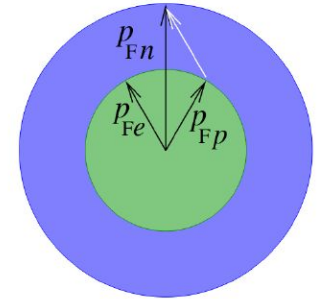


Low density
Low proton fraction
Direct Urca closed



$\vec{p}_n = \vec{p}_p + \vec{p}_e$ is impossible
because $p_{Fn} > p_{Fp} + p_{Fe}$

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High proton fraction
Direct Urca open



$\vec{p}_n = \vec{p}_p + \vec{p}_e$ is possible
because $p_{Fn} < p_{Fp} + p_{Fe}$

Credit: Mark Alford

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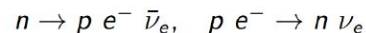
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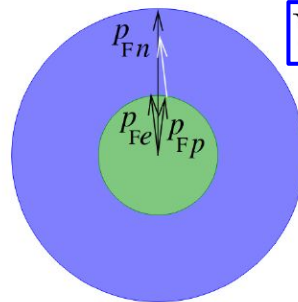
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[Lattimer et al., 1999]

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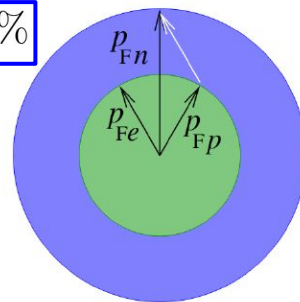


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Low proton fraction
Direct Urca closed



$$Y_p \gtrsim 11\%$$

High density
High proton fraction
Direct Urca open



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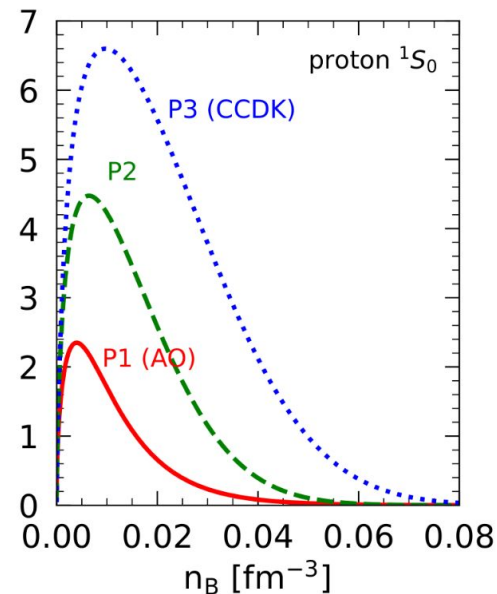
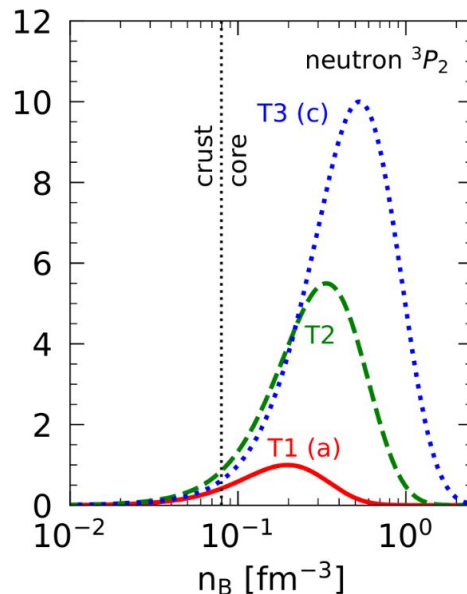
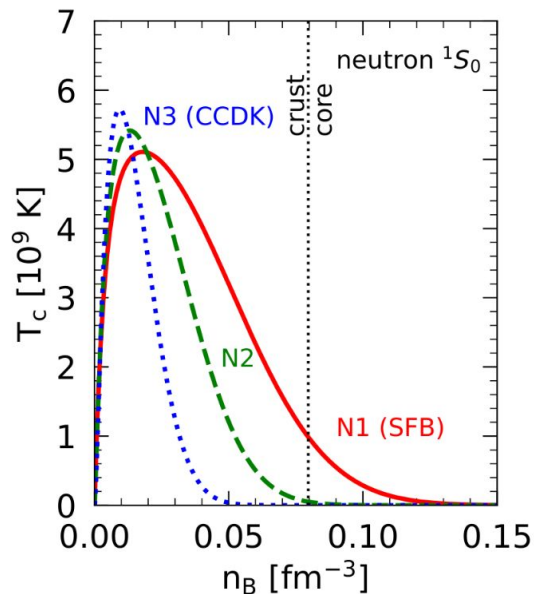
Credit: Mark Alford

Nuclear superfluidity and superconductivity

$$e^{-\Delta/k_B T}$$

$$T_c(k_F) = T_{c,\max} \exp \left[- \left(\frac{k_F - k_{F,0}}{\delta k_F} \right)^2 - r \left(\frac{k_F - k_{F,0}}{\delta k_F} \right)^4 \right]$$

[Yanagi, 2019]



[Ávila, Ferreira & Sagun, 2026 (in prep.)]

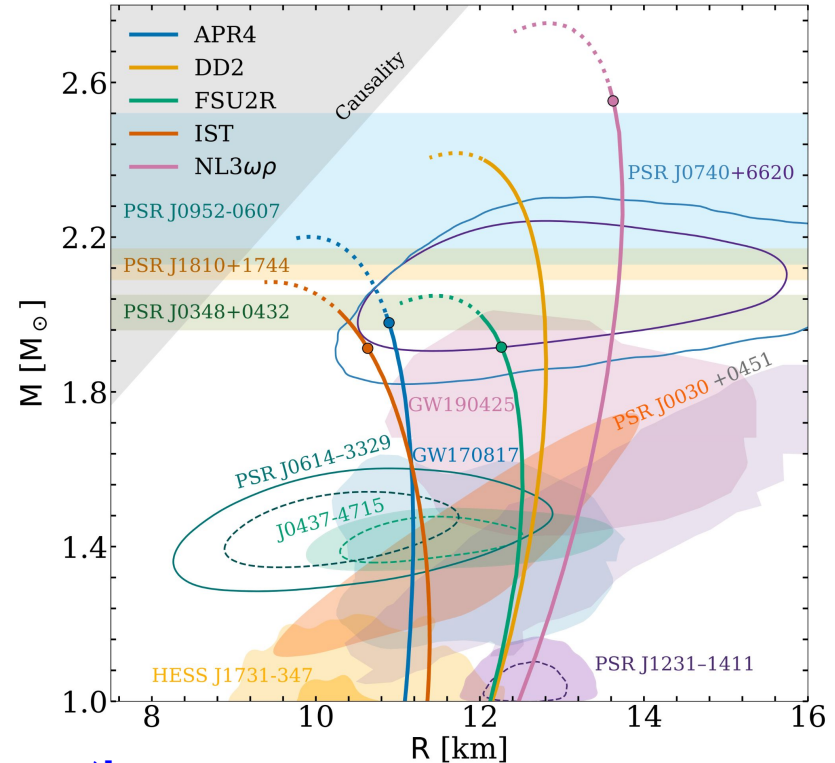
$$n = \frac{k_F^3}{3\pi^2}$$

Equations of state (EoSs)

To account for the different baryonic matter uncertainties, we use **five** different EoSs:

- APR4
- FSU2R
- DD2
- IST
- NL3 $\omega\rho$

EoS	M_{\max} [M_{\odot}]	$R_{1.4}$ [km]	M_{DU} [M_{\odot}]	n_{DU} [fm^{-3}]
APR4	2.17	11.33	1.98	0.78
DD2	2.42	13.20	N/A	N/A
FSU2R	2.05	12.80	1.92	0.61
IST	2.08	11.40	1.91	0.87
NL3 $\omega\rho$	2.75	13.82	2.55	0.50



[Ávila, Ferreira & Sagun, 2026 (in prep.)]

Observational Data

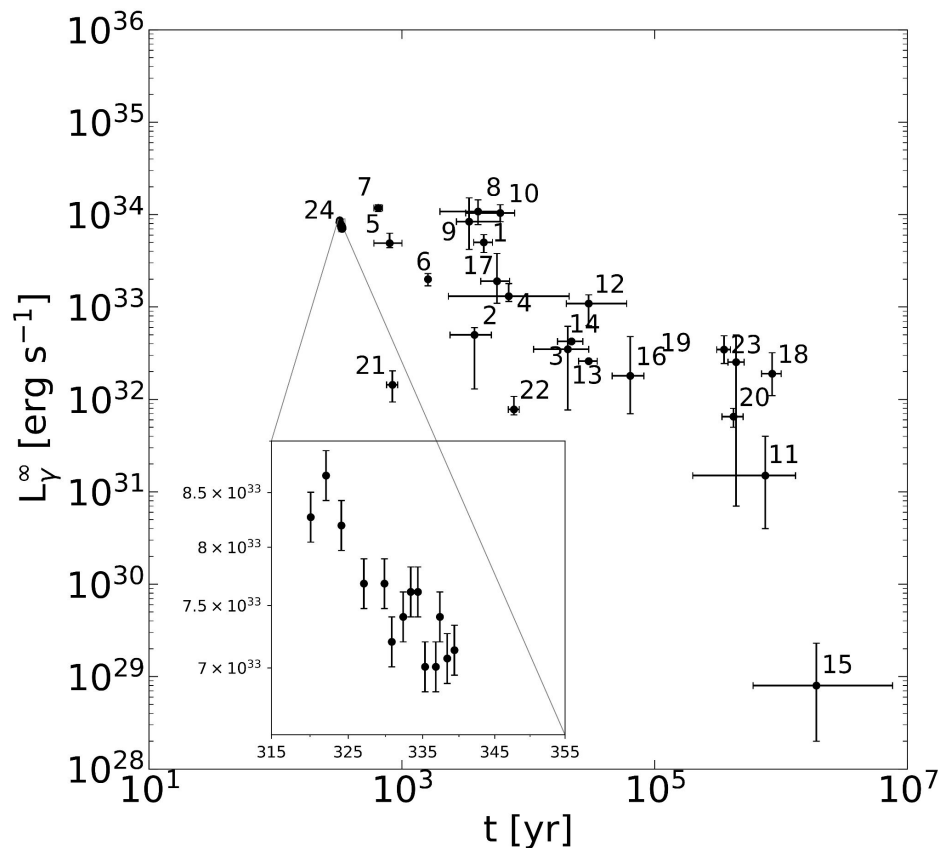
24 sources from X-ray observations

[Potekhin et al., 2020 & 2023]

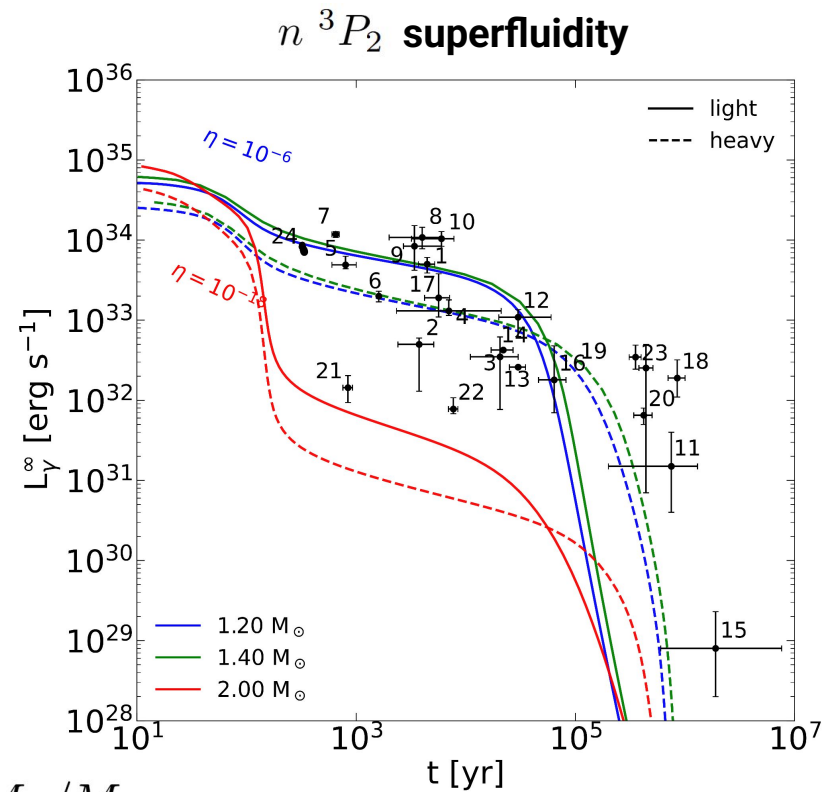
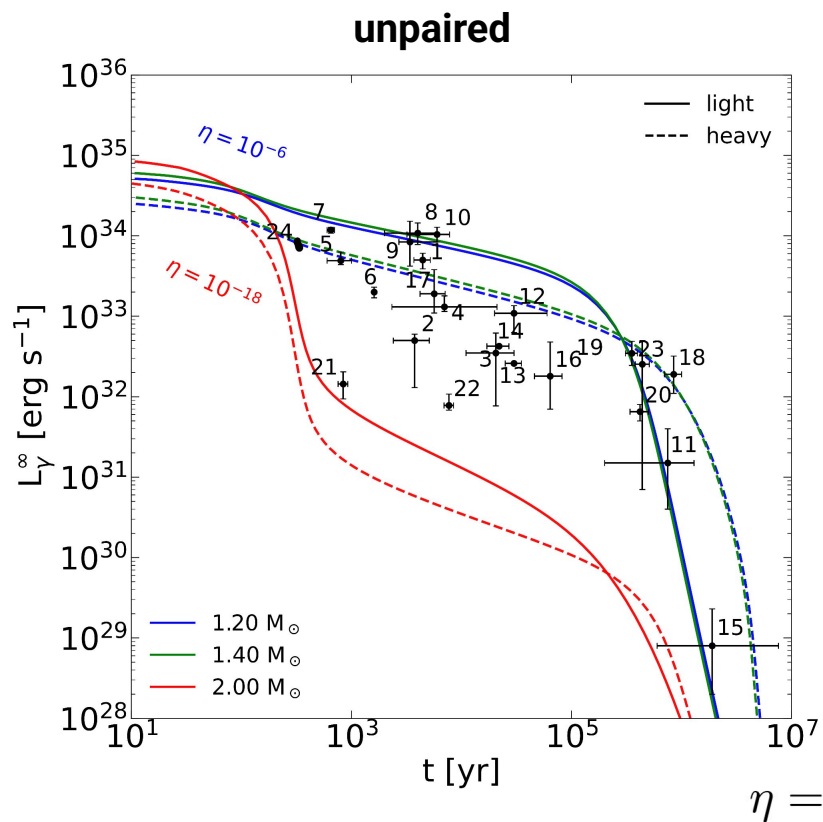
Cas A (24) data from Chandra telescope

[Shternin et al., 2022]

[Ávila, Ferreira & Sagun, 2026 (in prep.)]



Effects of Mass, Envelope and Pairing in NS Cooling

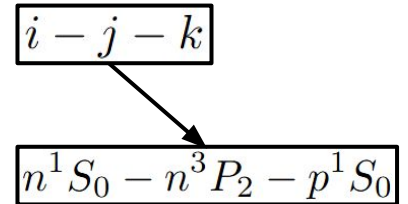


Statistical Approach

Our statistical analysis follows the frequentist framework adopted in [\[Tanabashi et al., 2018\]](#)

For each NS, the predicted luminosity depends on:

- EoS,
- Superconductivity/superfluidity model, models are labeled
- Nuisance parameters, $\theta^i = \{M_{\text{NS}}^i, \Delta M^i\}$.



Likelihood (evaluated at the central observed age)

$$\mathcal{L}_i \propto \mathcal{N}(L(\text{EoS}, \theta^i) - L_0^i, \sigma_L^i) \quad | \quad \mathcal{L} = \prod_{i=1}^{24} \mathcal{L}_i,$$

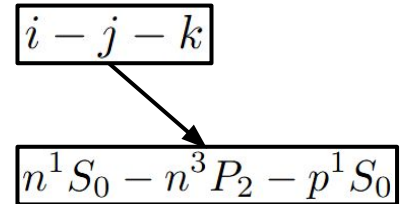
where L_0^i and σ_L^i are the observed luminosity and its uncertainty.

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**15 pairings
sets x 5 EoSs**

where L_0^i and σ_L^i are the observed luminosity and its uncertainty.

Goodness-of-fit

$$\chi^2 = \frac{(L(\text{EoS}, \boldsymbol{\theta}) - L_0)^2}{\sigma_L^2}$$

$$\chi_{\text{red}}^2 = \chi^2 / (N - M)$$

I - Individual Fits

For each NS, we vary the gravitational mass, envelope composition and pairing and minimize the individual likelihood.

II - Global Fit

We impose a single pairing configuration for all NSs and compute the reduced global minimum χ^2

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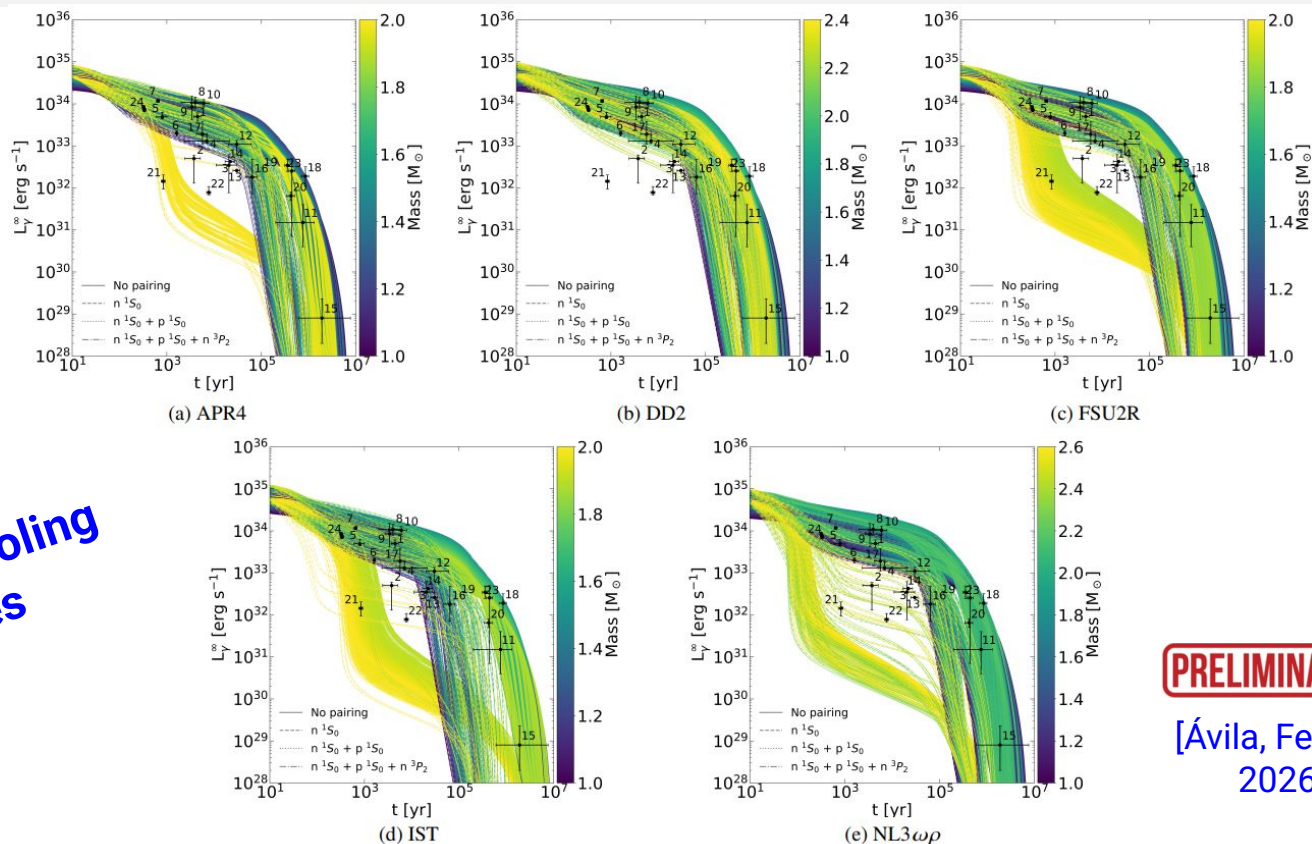
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Parameters that simultaneously reproduce the full cooling dataset

Thermal Evolution

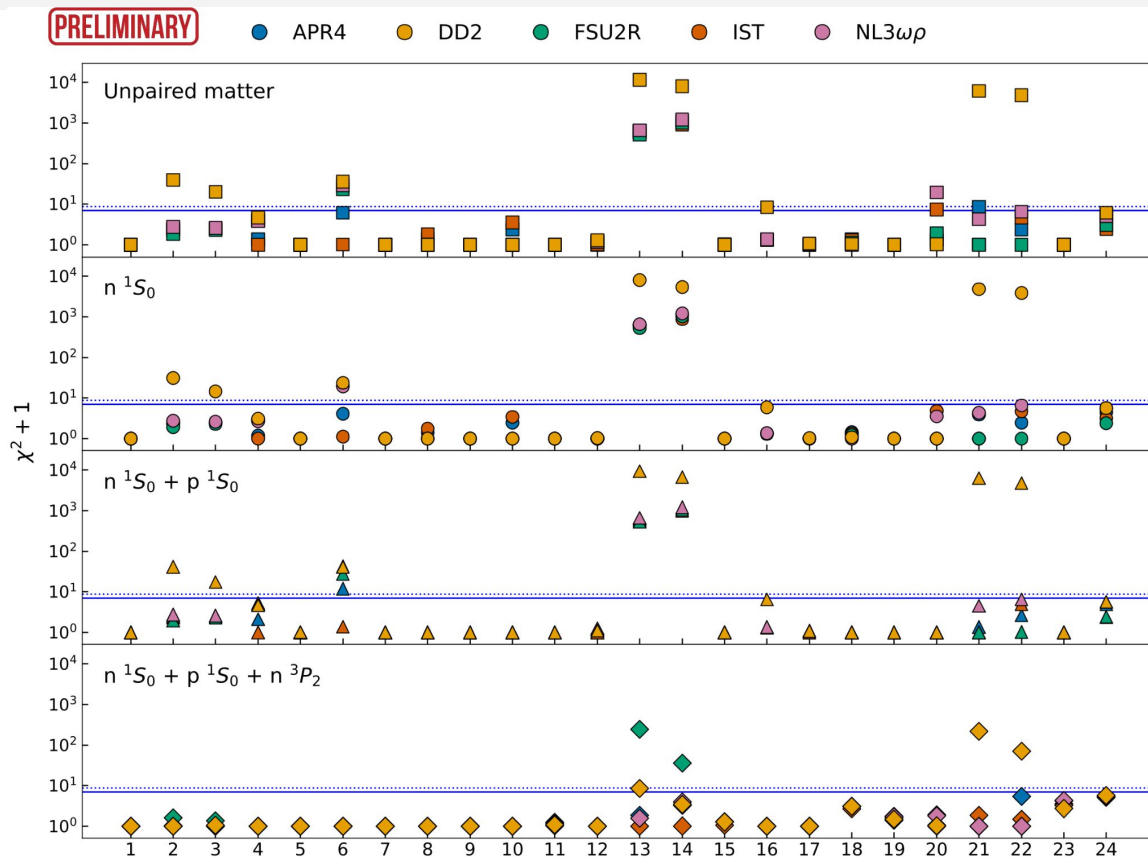


90000+ cooling curves

PRELIMINARY

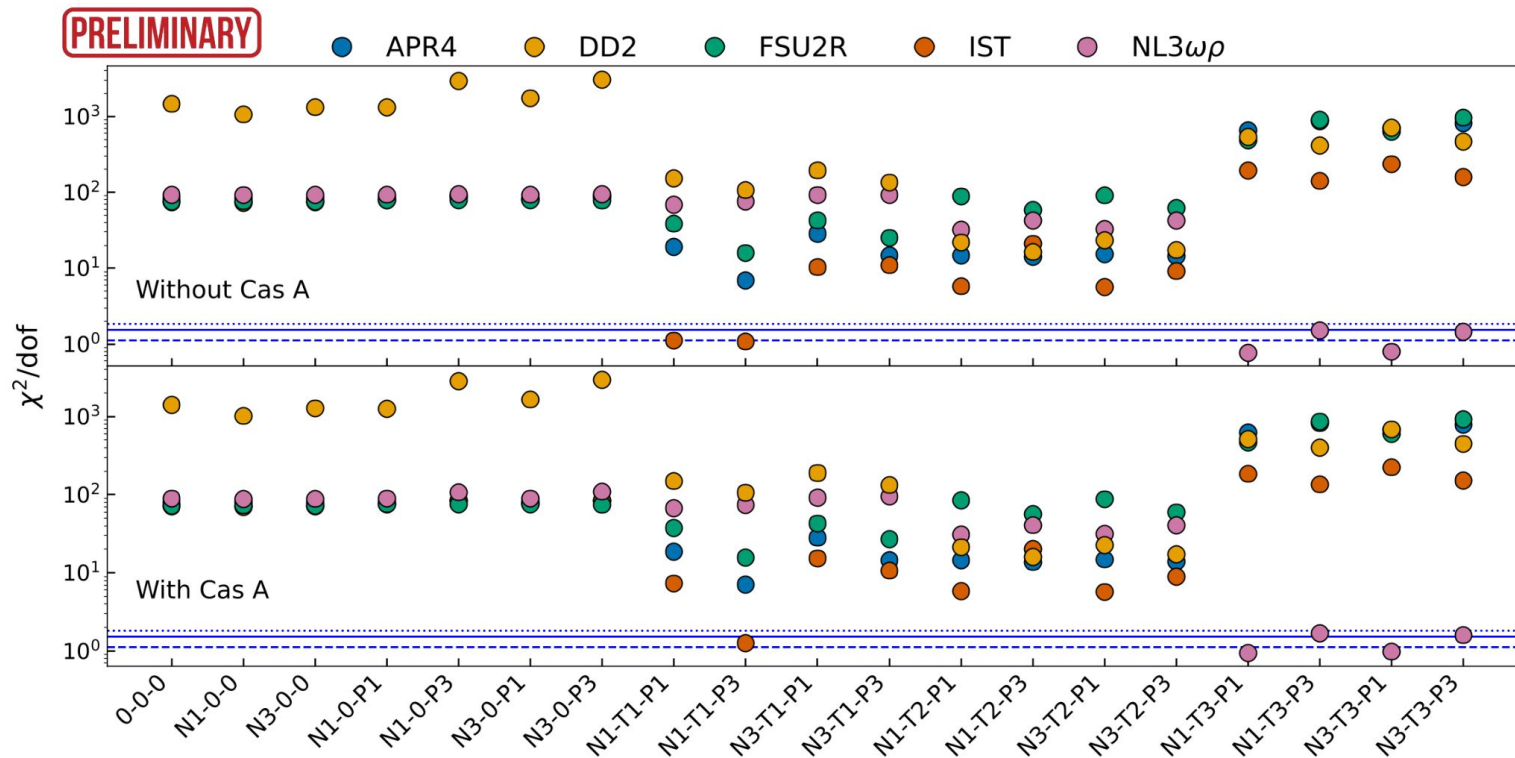
[Ávila, Ferreira & Sagun, 2026 (in prep.)]

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[Ávila, Ferreira & Sagun,
2026 (in prep.)]

II - Global Fit



[Ávila, Ferreira & Sagun, 2026 (in prep.)]

Conclusions

- Models with unpaired matter fail to reproduce the observational data, while **including triplet pairing significantly improves** the agreement
- Only the **NL3 $\omega\rho$** and partially the **IST** EoSs **reproduce the full cooling** dataset
- **Cas A** does not significantly alter the global fit, but **acts as a strong discriminator** for **specific** pairing configurations

Backup Slides

Observational Data

No.	Object name	t [kyr]	L_{γ}^{∞} [10^{33} erg s $^{-1}$]	Refs.
1	RX J0822.0-4300 (Puppis A)	$4.45^{+0.75}_{-0.75}$	$5^{+1.1}_{-1.1}$	(Becker et al. 2012; De Luca et al. 2012)
2	CXOU J085201.4-461753 (Vela Jr.)	$3.075^{+2.025}_{-0.675}$	$0.5^{+0.1}_{-0.37}$	(Allen et al. 2015; Ho et al. 2026; Marino et al. 2024)
3	2XMM J104608.7-594306 (Homunculus)	$20.5^{+9.5}_{-9.5}$	$0.348^{+0.272}_{-0.271}$	(Pires et al. 2015)
4	1E 1207.4-5209 (G296.5+10.0)	$7^{+14}_{-4.667}$	$1.31^{+0.49}_{-0.16}$	(Roger et al. 1988; Mereghetti et al. 2002)
5	CXOU J160103.1-513353 (G330.2+1.0)	$0.8^{+0.2}_{-0.2}$	$4.9^{+1.4}_{-0.5}$	(Borkowski et al. 2018; Ho et al. 2021)
6	1WGA J1713.4-3949 (G347.3-0.5)	$1.6085^{+0.0005}_{-0.0005}$	$2^{+0.3}_{-0.3}$	(Ho et al. 2021; Cassam-Chenai et al. 2004)
7	XMMU J172054.5-372652 (G350.1-0.3)	$0.65^{+0.05}_{-0.05}$	11.8^{+1}_{-1}	(Mayer & Becker 2021; Ho et al. 2021)
8	XMMU J173203.3-344518 (HESS J1731-347)	4^{+2}_{-2}	$10.8^{+3.7}_{-3}$	(Maxted et al. 2018; Doroshenko et al. 2022)
9	CXOU J181852.0-150213 (G015.9+00.2)	$3.4^{+2.6}_{-0.7}$	$8.4^{+6.8}_{-4.2}$	(Sasaki et al. 2018; Klochkov et al. 2016)
10	CXOU J185238.6+004020 (Kes 79)	$6^{+1.8}_{-2.8}$	$10.4^{+2.4}_{-2}$	(Sun et al. 2004; Bogdanov 2014)
11	PSR J0357+3205 (Morla)	750^{+550}_{-550}	$0.015^{+0.025}_{-0.011}$	(Kirichenko et al. 2014)
12	PSR J0538+2817 (Sim 147)	30^{+30}_{-10}	$1.09^{+0.27}_{-0.46}$	(Ng et al. 2006; Kramer et al. 2003)
13	CXOU J061705.3+222127 (IC 443)	30^{+5}_{-5}	$0.26^{+0.01}_{-0.01}$	(Chevalier 1999; Swartz et al. 2015)
14	PSR B0833-45 (Vela)	22^{+5}_{-5}	$0.424^{+0.012}_{-0.012}$	(Aschenbach 2002; Ofengeim & Zyuzin 2018)
15	PSR B0950+08	1900^{+5700}_{-1300}	$0.00008^{+0.00015}_{-0.00006}$	(Igoshev 2019; Abramkin et al. 2022)
16	PSR B1951+32 (CTB 80)	64^{+18}_{-18}	$0.18^{+0.3}_{-0.11}$	(Migliazzo et al. 2002; Li et al. 2005)
17	PSR J1119-6127 (G292.2-00.5)	$5.65^{+1.45}_{-1.45}$	$1.9^{+1.9}_{-0.8}$	(Kumar et al. 2012; Ng et al. 2012)
18	RX J0720.4-3125	850^{+150}_{-150}	$0.19^{+0.13}_{-0.08}$	(Tetzlaff et al. 2011; Hambaryan et al. 2017)
19	RX J1605.3+3249	440^{+70}_{-60}	$0.253^{+0.246}_{-0.246}$	(Tetzlaff et al. 2012; Malacaria et al. 2019; Pires et al. 2019)
20	RX J1856.5-3754 (Upper Scorpius)	420^{+80}_{-80}	$0.065^{+0.015}_{-0.015}$	(Mignani et al. 2013; Yoneyama et al. 2017)
21	PSR J0205+6449 (3C 58)	$0.841^{+0.084}_{-0.084}$	$0.144^{+0.06}_{-0.05}$	(Kotthes 2013; Potekhin et al. 2020; Marino et al. 2024)
22	PSR B2334+61	$7.7^{+0.77}_{-0.77}$	$0.078^{+0.03}_{-0.01}$	(Marino et al. 2024)
23	PSR B0656+14 (Monogem Ring)	$353.18^{+43.65}_{-43.65}$	$0.347^{+0.143}_{-0.101}$	(Suzuki et al. 2021; Zharikov et al. 2021)

Table A1. Observational dataset used in this work, taken from (Potekhin et al. 2020) (see also Potekhin, A. Y. (2023)). Stellar age, t , is presented in kyr and luminosities, L_{γ}^{∞} , are given in units of 10^{33} erg s $^{-1}$.

[Ávila, Ferreira & Sagun, 2026 (in prep.)]

Observational Data - Cas A

No.	Object name	t [yr]	L_{γ}^{∞} [10^{33} erg s $^{-1}$]	Refs.
		320.08	$8.272^{+0.232}_{-0.225}$	
		322.10	$8.662^{+0.243}_{-0.236}$	
		324.10	$8.197^{+0.230}_{-0.223}$	
		327.09	$7.685^{+0.215}_{-0.209}$	
		329.84	$7.685^{+0.215}_{-0.209}$	
		330.83	$7.205^{+0.202}_{-0.196}$	
24	Cas A (GRADED N_{H} var)	332.37	$7.407^{+0.208}_{-0.202}$	(Shternin et al. 2022)
		333.39	$7.614^{+0.213}_{-0.208}$	
		334.36	$7.614^{+0.213}_{-0.208}$	
		335.33	$7.009^{+0.196}_{-0.191}$	
		336.80	$7.009^{+0.196}_{-0.191}$	
		337.38	$7.407^{+0.208}_{-0.202}$	
		338.37	$7.073^{+0.198}_{-0.193}$	
		339.37	$7.139^{+0.199}_{-0.195}$	

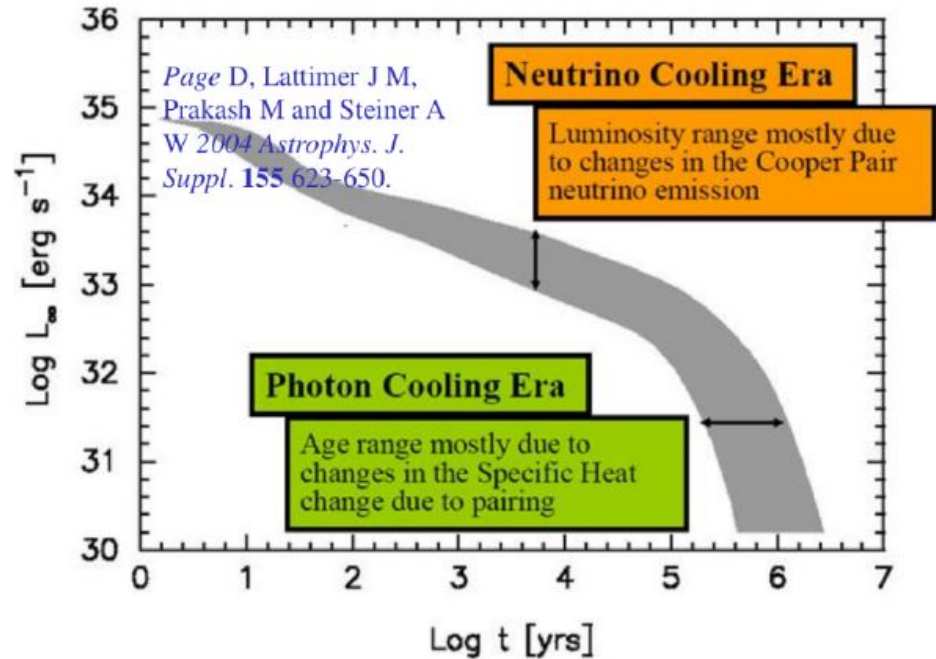
[Ávila, Ferreira & Sagun, 2026 (in prep.)]

Table A2. Measurements obtained for Cas A with *Chandra* ACIS in GRADED mode, whereas the hydrogen column density, N_{H} , is variable. Time is given in years, and luminosities are expressed in units of 10^{33} erg s $^{-1}$.

NS Cooling Era and Processes

[Page et al., 2006]

Name	Process ^c	Emissivity ^d (erg cm ⁻³ s ⁻¹)	
Modified Urca cycle (neutron branch)	$n + n \rightarrow n + p + e^- + \bar{\nu}_e$ $n + p + e^- \rightarrow n + n + \nu_e$	$\sim 2 \times 10^{21} R T_9^8$	Slow
Modified Urca cycle (proton branch)	$p + n \rightarrow p + p + e^- + \bar{\nu}_e$ $p + p + e^- \rightarrow p + n + \nu_e$	$\sim 10^{21} R T_9^8$	Slow
Bremsstrahlung	$n + n \rightarrow n + n + \nu + \bar{\nu}$ $n + p \rightarrow n + p + \nu + \bar{\nu}$ $p + p \rightarrow p + p + \nu + \bar{\nu}$	$\sim 10^{19} R T_9^8$	Slow
Cooper pair formations	$n + n \rightarrow [nn] + \nu + \bar{\nu}$ $p + p \rightarrow [pp] + \nu + \bar{\nu}$	$\sim 5 \times 10^{21} R T_9^7$ $\sim 5 \times 10^{19} R T_9^7$	Slow
Direct Urca cycle	$n \rightarrow p + e^- + \bar{\nu}_e$ $p + e^- \rightarrow n + \nu_e$	$\sim 10^{27} R T_9^6$	Fast



Pairing in NSs

$$2S+1 L_J$$

S = total spin quantum number
2S+1 = multiplicity (singlet, doublet, triplet, etc.)
L = total orbital quantum number
J = total angular momentum quantum number

L	0	1	2	3	4
symbol	S	P	D	F	G

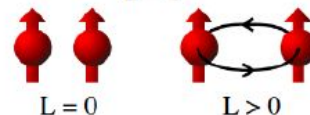
Spin-singlet pairs

$$S = 0$$



Spin-triplet pairs

$$S = 1$$



Example:

$s_1, s_2, \dots \rightarrow S$
 $l_1, l_2, \dots \rightarrow L$
 $S, L \rightarrow J$

\Rightarrow

$s_1 = +1/2 \quad s_2 = -1/2 \Rightarrow S = 0$ - singlet state

$s_1 = +1/2 \quad s_2 = +1/2 \Rightarrow S = 1$ - triplet state

$$2^{*0+1} S_0 = {}^1 S_0 \qquad 2^{*1+1} P_2 = {}^3 P_2$$

Neutrino Processes: Nucleonic and Hyperonic DU

TABLE 1
WEAK PROCESSES FOR NUCLEONS AND HYPERONS

Transition	R
$n \rightarrow p \ell \bar{\nu}_\ell$	1
$\Lambda \rightarrow p \ell \bar{\nu}_\ell$	0.0394
$\Sigma^- \rightarrow n \ell \bar{\nu}_\ell$	0.0125
$\Sigma^- \rightarrow \Lambda \ell \bar{\nu}_\ell$	0.2055
$\Sigma^- \rightarrow \Sigma^0 \ell \bar{\nu}_\ell$	0.6052
$\Xi^- \rightarrow \Lambda \ell \bar{\nu}_\ell$	0.0175
$\Xi^- \rightarrow \Sigma^0 \ell \bar{\nu}_\ell$	0.0282
$\Xi^0 \rightarrow \Sigma^+ \ell \bar{\nu}_\ell$	0.0564
$\Xi^- \rightarrow \Xi^0 \ell \bar{\nu}_\ell$	0.2218

Muons presence
=

Higher Grav. Masses

[Page et al., 2004]

**Only IST is formulated in
npe matter!**

Neutron β -decay and its inverse process, known as the nucleonic DU process (**np**)

$$\begin{cases} n \rightarrow p + \ell + \bar{\nu}_\ell \\ p + \ell \rightarrow n + \nu_\ell \end{cases} \implies \ell = e^- \text{ or } \mu$$

The minimal proton fraction for the nucleonic DU to become **active**

$$Y_p = \frac{1}{1 + (1 + x_e^{1/3})^3}, \text{ where } x_e = \frac{n_e}{n_e + n_\mu} \quad (9)$$

Triangle inequality or **DU threshold** (for npe matter):

$$\text{proton fraction } (Y_p) \text{ above 11\%} \implies \boxed{p_{Fp} + p_{Fe} \geq p_{Fn}} \quad (10)$$

[Lattimer et al. (1991)]

Cooper Pairs

- Formation of Cooper Pairs \implies particle excitations are gapped

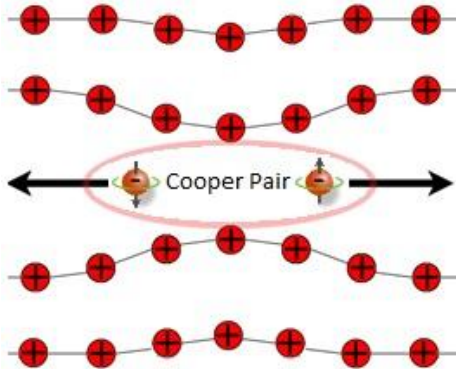
Temperature falls below the critical value (temperature at which pairing occurs) for **neutron superfluidity** and **proton superconductivity**,
 $T \ll T_c$



ν -emission suppressed by $e^{-\Delta/k_B T}$

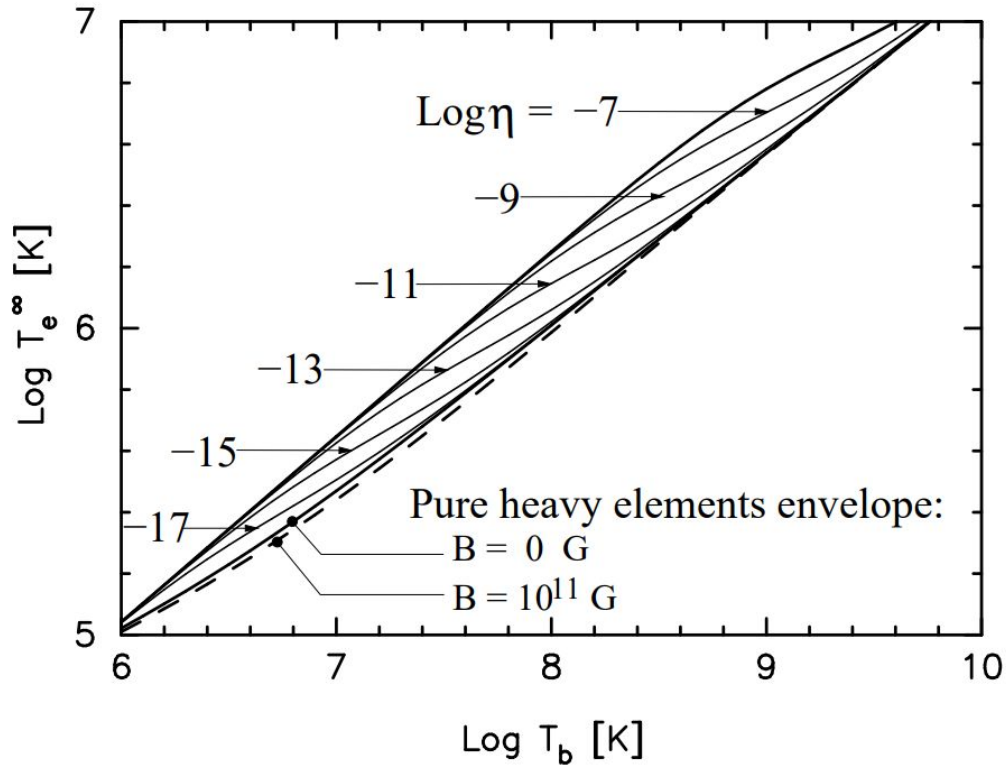
Where Δ corresponds to the energy gap.

Once reached this T_c the effect of the PBF mechanism² leads to a neutrino emissivity of the order of $\epsilon_\nu \sim T^7 (\nu-\bar{\nu})$ [Page et al. (2006)]



²formation and breaking of Copper pairs

Envelope in NS Cooling



$$T_e \propto T_b^{0.5+\alpha} \quad (\alpha \ll 1)$$

$$T_b^\infty = e^\Phi T_e = T_s^\infty$$

[Page et al., 2004]

Cassiopea A (Cas A)

- It's a NS of about 356 years old
- Shows an unusually rapid cooling behaviour: **surface temperature drop** is 1.4 - 2.5% over 20 years of observations
- Mass of $M = 1.55 \pm 0.25 M_{\odot}$

We know that Cas A is a rapid cooling object...

