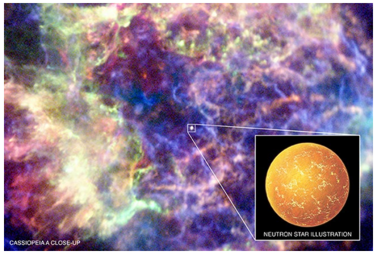
Ioffe Institute

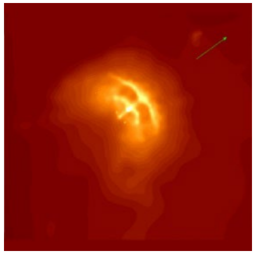
Department of Theoretical Astrophysics

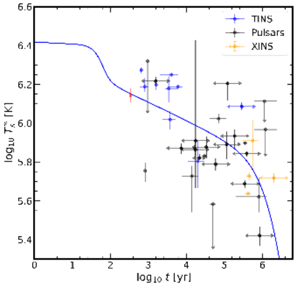
Peter Shternin

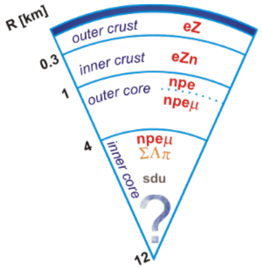
Neutron star cooling

Can we learn something about superfluidity?

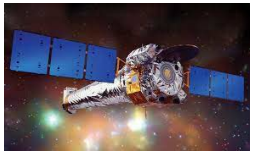


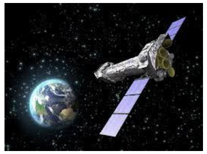


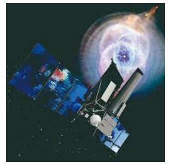


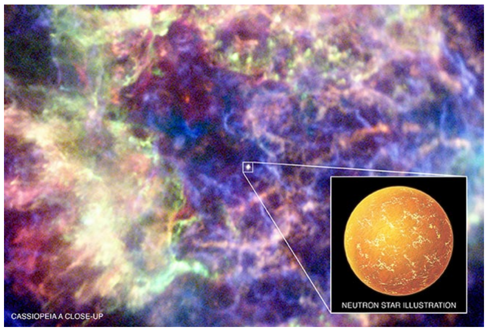


Concept of the NS cooling

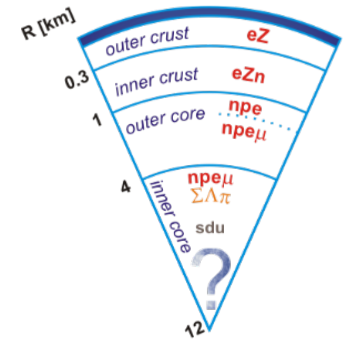


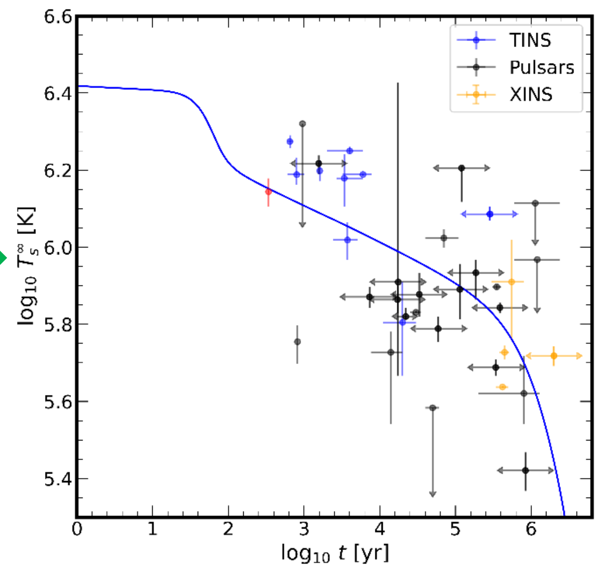


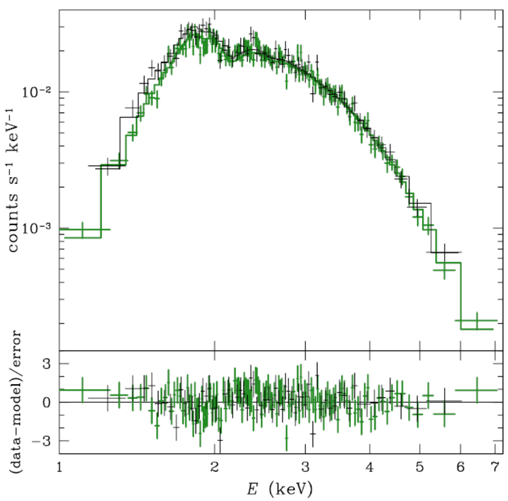




What information on NS parameters and properties of dense matter can be extracted from observations of thermal radiation emergent from NS surface?





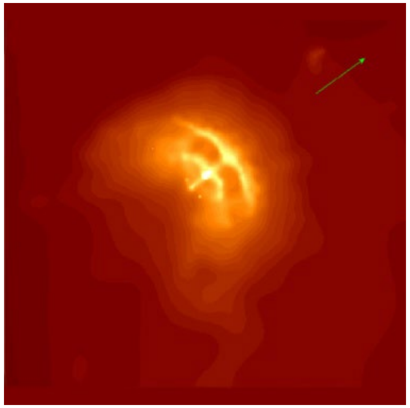


Measure thermal state of a neutron star

Model thermal state of a neutron star

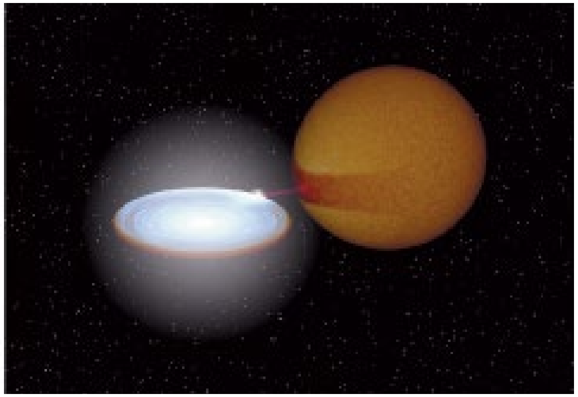
Objects

Isolated NSs



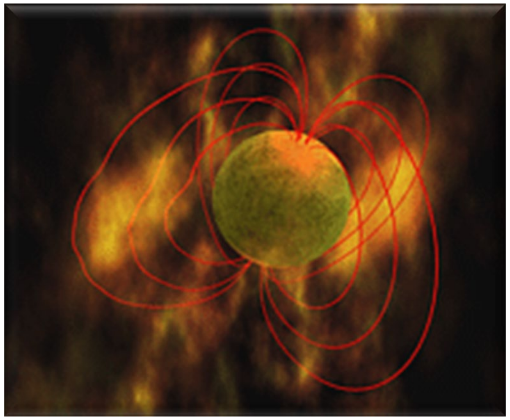
Cooling of initially hot neutron star due to neutrino and photon emission

X-ray transients



Transient heating due to accretion (deep crustal heating). Thermal states in quiescence and cooling to quiescent state

Magnetars

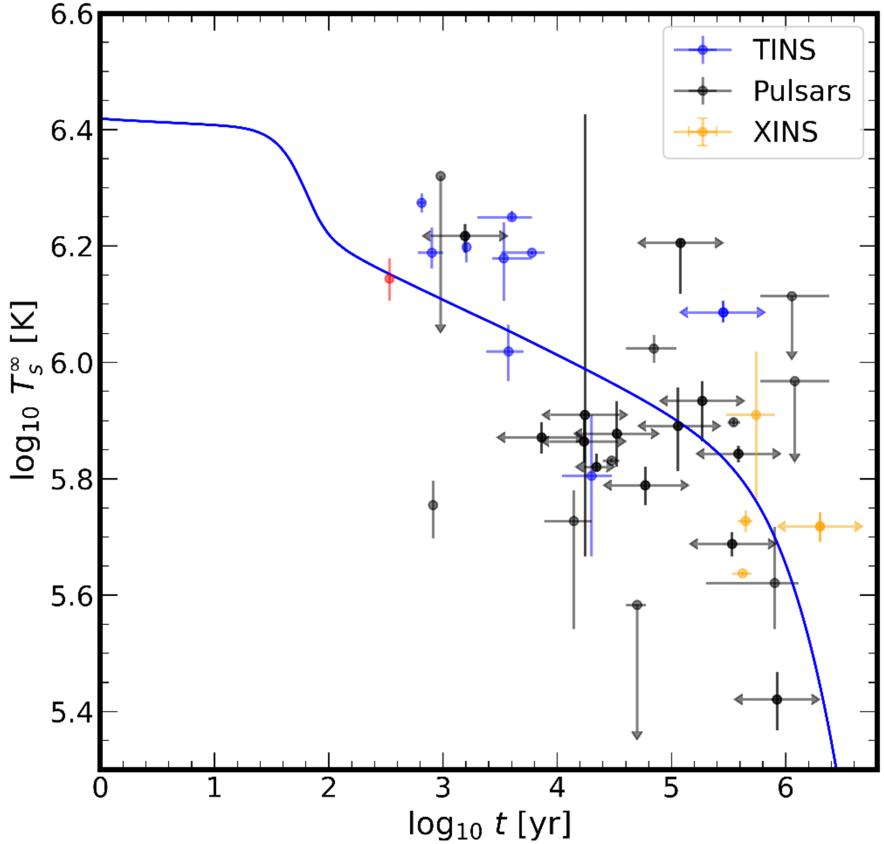


Highly-magnetized stars. Believed to stay hot due to magnetic field dissipation

Observational data

Isolated NSs: Born hot and cool down

Subset of the data from *Potekhin et al.* 2020
http://www.ioffe.ru/astro/NSG/thermal/cooldat.html



$$T_s^\infty = T_s\sqrt{1 - R_g/R}$$ **– as seen by distant observer**

Spectrum contains emission from the whole (a large part of) surface

Surface temperatures

atmosphere models
distances

ages

historical
remnant
kinematical

characteristic $\tau_c = \dfrac{P}{2\dot{P}}$

Plan

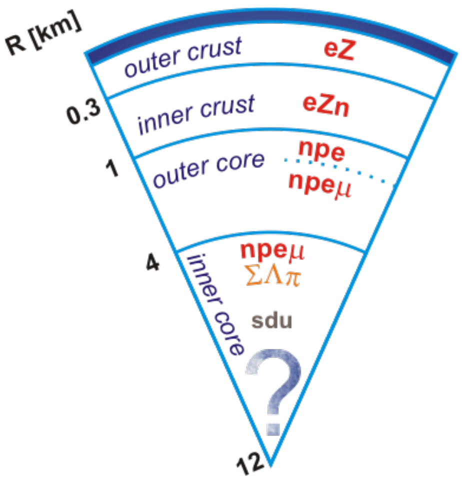
Cooling of non-superfluid NSs. Basics

Neutrino emission processes.
Fast and slow cooling

Heat blanketing envelopes

Impact of superfluidity on NS cooling

Neutron star in Cassiopeia A SNR



Only nucleon NS cores will be discussed.

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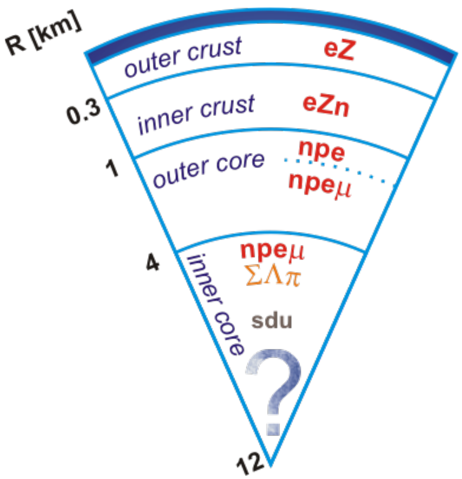
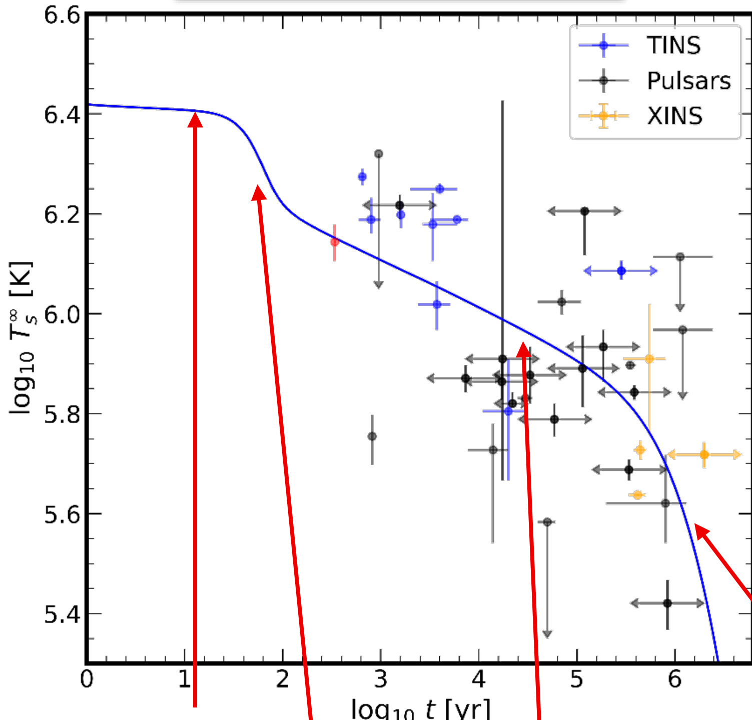


Only nucleon NS cores will be discussed.

Basics. Cooling stages

NS cools down due to neutrino emission from the bulk and and photon emission from the surface

Typical cooling curve



Crustal cooling

Neutrino stage

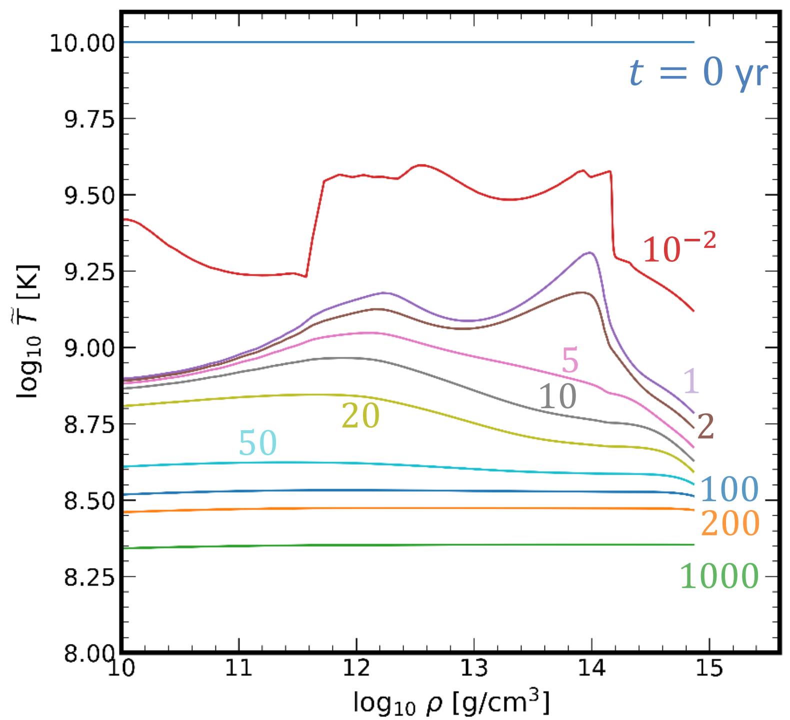
Relaxation

$$t_r \sim 30 - 300 \text{ yr}$$

Photon stage

internal temperature

$$\widetilde{T}(r) \equiv T_{\rm int}(r) e^{\Phi(r)}$$



Isothermal interiors

$$C(\widetilde{T})\frac{d\widetilde{T}}{dt} = -L_\nu^\infty(\widetilde{T}) - L_\gamma^\infty(T_s) + L_{\rm Heat}^\infty$$

Basics. Heat Blanket

The main temperature gradient is located in the outermost part of the star

No. 1, 1983 NEUTRON STAR ENVELOPES 295

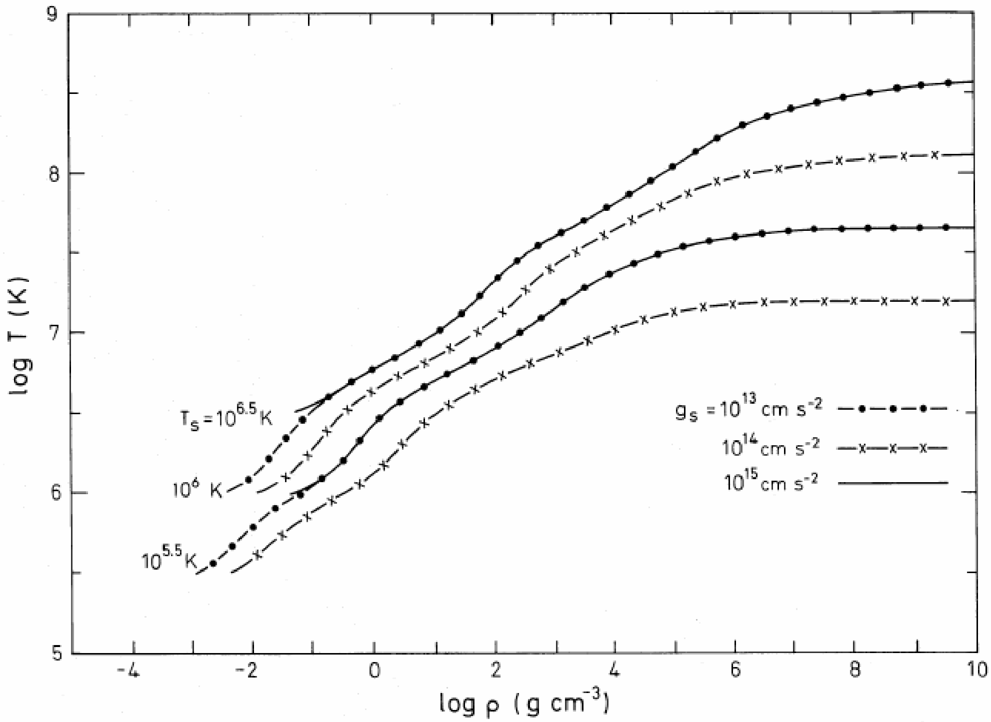


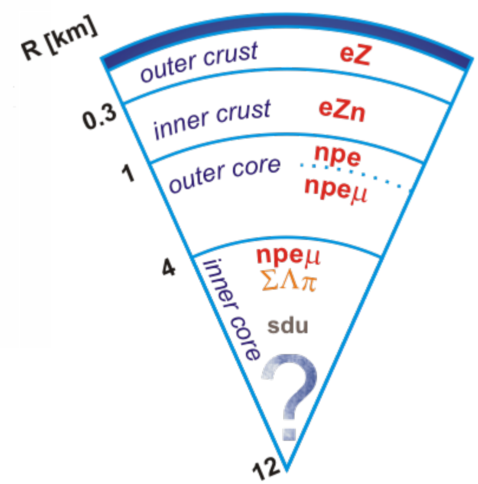
FIG. 5.—Temperature-density profiles for various values of surface temperatures and surface gravities

Gudmundsson, Pethick & Epstein, 1983

Separate stationary calculations

For $\rho_b = 10^{10}$ g/cm^3 $t_{\rm th} \lesssim 1$ yr

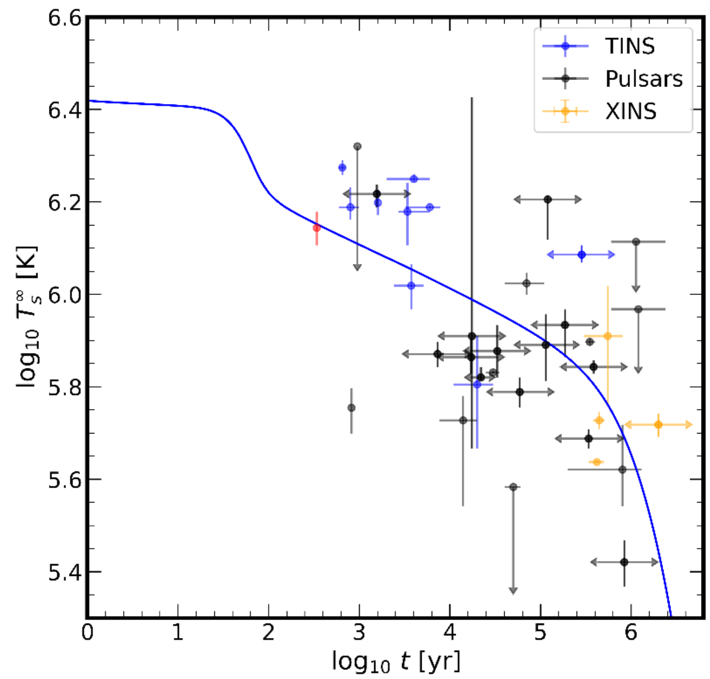
$$T_{s6} = 0.87 g_{14}^{0.25} T_{b8}^{0.55}$$



$$L_\gamma^\infty(T_s) = 4\pi\sigma R_\infty^2 \left(T_s^\infty\right)^4$$

$$T_s = T_s(\tilde{T}) \sim \sqrt{\tilde{T}}$$

NS cooling. Neutrino stage



Isothermal interiors

$$t \gtrsim 10 - 100 \text{ yr}$$

$$\widetilde{T}(r) \equiv T_{\text{int}}(r) \mathrm{e}^{\Phi(r)} = const$$

Global thermal balance equation

$$C(\widetilde{T}) \frac{\mathrm{d}\widetilde{T}}{\mathrm{d}t} = -L_\nu^\infty(\widetilde{T}) - \cancel{L_\gamma^\infty(T_s)} + \cancel{L_{\text{Heat}}^\infty}$$

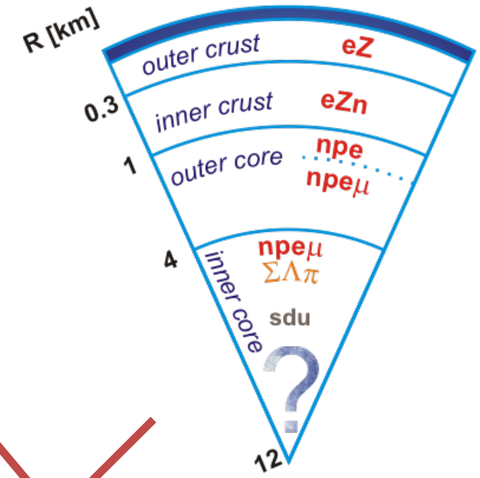
$L_\gamma^\infty(T_s) = 4\pi\sigma R_\infty^2 \left(T_s^\infty\right)^4$ ***= redshifted thermal photon luminosity of NS***

$T_s = T_s(\tilde{T}) \sim \sqrt{\tilde{T}}$ ***= solution for heat blanket***

$$R_\infty = R\sqrt{1 - 2GM / Rc^2}$$

$$T_s^\infty = T_s\sqrt{1 - 2GM / Rc^2}$$

Basics. Cooling regulators



Main cooling regulators

Neutrino emission mechanisms

Composition and EOS

Heat capacity

Superfluidity

$$C(\widetilde{T})\frac{\mathrm{d}\widetilde{T}}{\mathrm{d}t} = -L_\nu^\infty(\widetilde{T}) - \cancel{L_\gamma^\infty(T_s)} + \cancel{L_{\mathrm{Heat}}^\infty}$$

Observed emission

Heat blanketing envelope $T_s(\widetilde{T}_{\mathrm{int}})$

Atmosphere models $F_\nu(T_s)$

Cooling regulators. Neutrino emission. Urca family

Urca processes (β-transformations)

$$B_1 \to B_2 + l + \overline{\nu_l}, \quad B_2 + l \to \nu_l$$

Gamov&Schoenberg, 1941

$B_{1,2}$ - baryons; l - lepton

$\overline{\nu_l}\nu_l$ escape the star, thieving energy

Nucleon Direct Urca process

$$B_1 = n; \; B_2 = p; \; l = e, \mu$$

The strongest neutrino emission
Fastest cooling

$$Q \sim 10^{27} T_9^6 \text{ erg cm}^{-3} \text{ s}^{-1}$$
$$L_\nu \sim 10^{46} T_9^6 \text{ erg s}^{-1}$$

DUrca is a threshold process:

$$p_{Fn} \leqslant p_{Fp} + p_{Fe}$$

Should be enough protons

$$x_p \gtrsim 11\% \Rightarrow \rho \gtrsim \rho_{DU}$$

Operates in the inner core depending on the EOS

Cooling regulators. Neutrino emission. Urca family

Urca processes (β-transformations)

$$B_1 \to B_2 + l + \overline{\nu_l}, \quad B_2 + l \to \nu_l$$

Gamov&Schoenberg, 1941

$B_{1,2}$ - baryons; l - lepton

$\overline{\nu_l}\nu_l$ escape the star, thieving energy

Nucleon Modified Urca process

$$N + n \to N + p + e + \overline{\nu_e}, \quad N + p + l \to N + n + \nu_e$$

Operates always

Additional fermions add

$$\left(\frac{k_B T}{\epsilon_F}\right)^2 \ll 1$$

Slow cooling

$$Q \sim 10^{20} - 10^{21} T_9^8 \text{ erg cm}^{-3} \text{ s}^{-1}$$

$$L_\nu \sim 10^{39} T_9^8 \text{ erg s}^{-1}$$

Neutrino emission. Bremsstrahlung

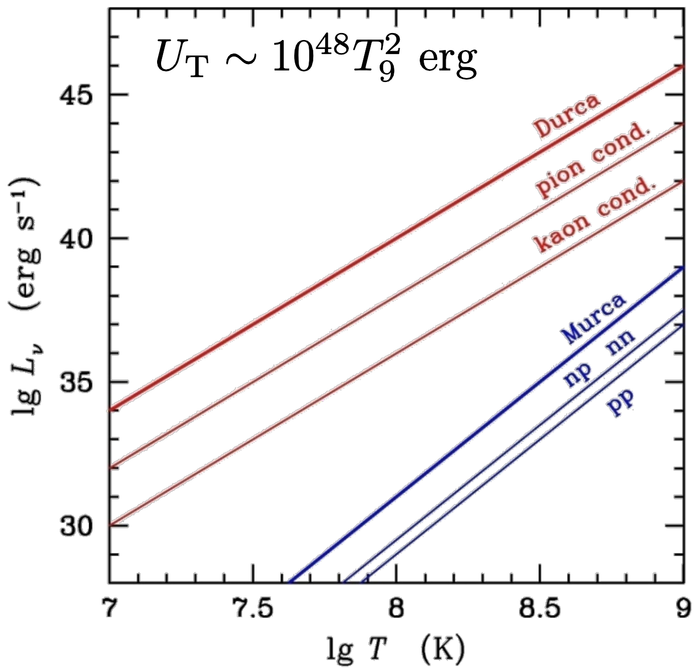
Always present
Gives slowest cooling

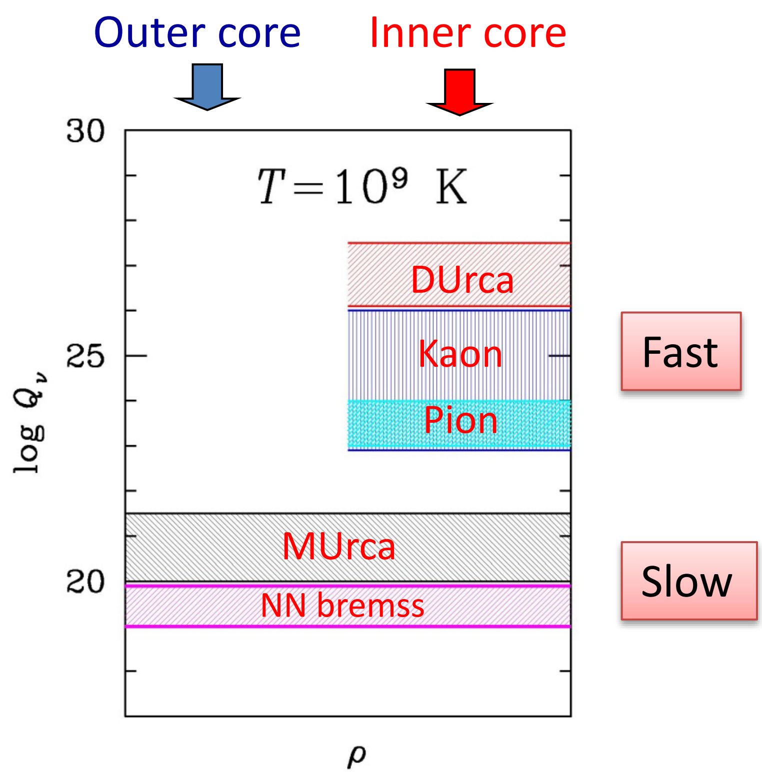
$$N + N \to N + N + \nu + \overline{\nu}$$

$$Q \sim 10^{19} T_9^6 \text{ erg cm}^{-3} \text{ s}^{-1}$$

$$L_\nu \sim 10^{38} T_9^6 \text{ erg s}^{-1}$$

Basic neutrino emission levels





Non-superfluid NS cooling. Neutrino stage.

Isothermal interiors $t \gtrsim 10-100\ \mathrm{yr}$

$$\widetilde{T}(r) \equiv T_{\mathrm{int}}(r)\exp(\Phi(r)) = const$$

Global thermal balance equation:

$$\frac{\mathrm{d}\widetilde{T}}{\mathrm{d}t} = -\ell(\widetilde{T}), \ \ell(\widetilde{T}) \equiv \frac{L_\nu^\infty(\widetilde{T})}{C(\widetilde{T})}$$

Only one cooling function $\ell(T)$

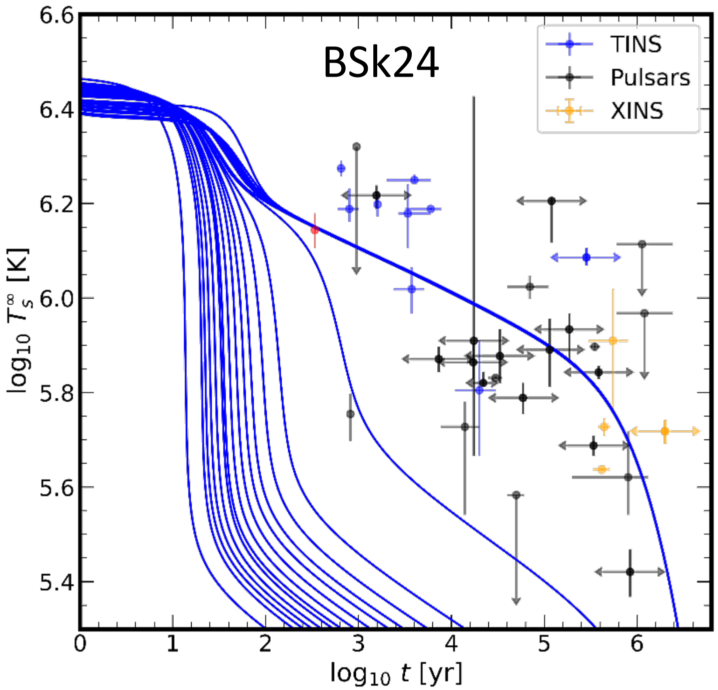
$$\ell(\widetilde{T}) \propto \widetilde{T}^n \Rightarrow \widetilde{T}(t) \propto t^{-1/(n-1)}$$

Slow cooling n=7
Fast cooling n=5

There are warmer and cooler stars than the `standard cooling candle'

Cooling curves

$M = 1M_\odot \ldots 2.27M_\odot$ per $0.05M_\odot$



Direct Urca gap

$$M_{\mathrm{DU}} = 1.596M_\odot$$

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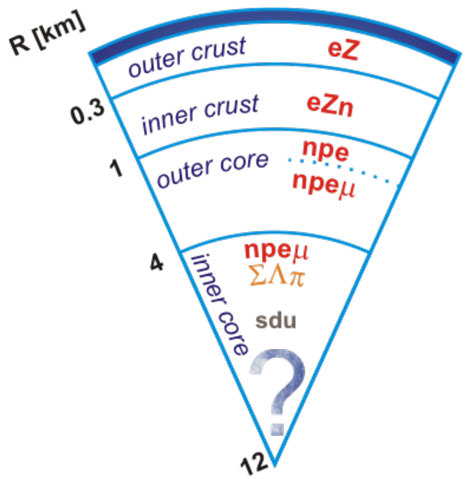


Only nucleon NS cores will be discussed.

Curse of Heat Blanket

Partially accrected envelopes

Dipole magnetic field

$$T_s(\tilde{T}_{\text{int}})$$

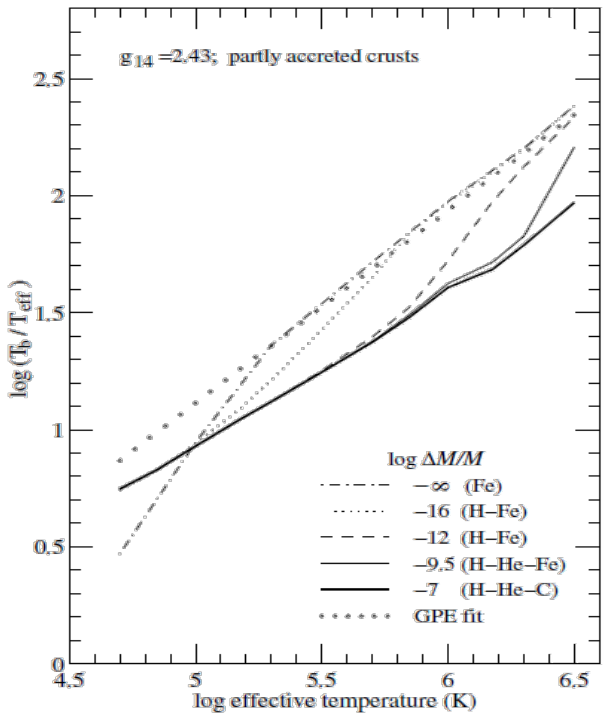


Fig. 8. Temperature increase through partly accreted NS crusts.

Potekhin, Chabrier & Yakovlev, 1997

Accreted stars look hotter

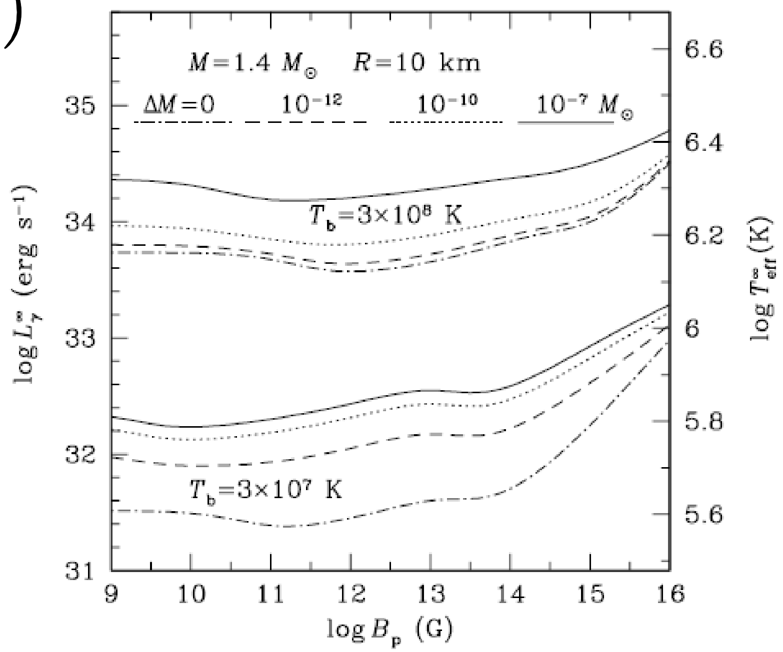


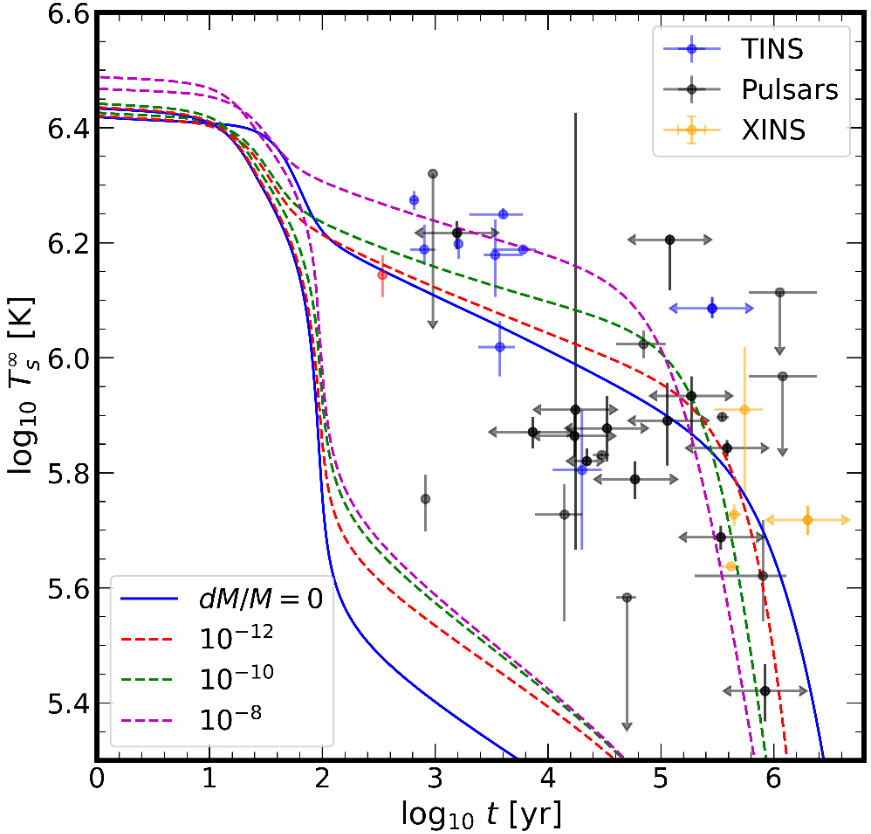
FIG. 8.—Photon surface luminosity (redshifted as detected by a distant observer: *left-hand axis*; redshifted effective surface temperature: *right-hand axis*) of a canonical NS with a dipole magnetic field, for two values of T_b and four models of the heat-blanketing envelope (accreted mass $\Delta M = 0$, 10^{-12}, 10^{-10}, or 10^{-7} $M_\odot$) vs. magnetic field strength at the magnetic pole.

Potekhin, Yakovlev, Chabrier & Gnedin 2003

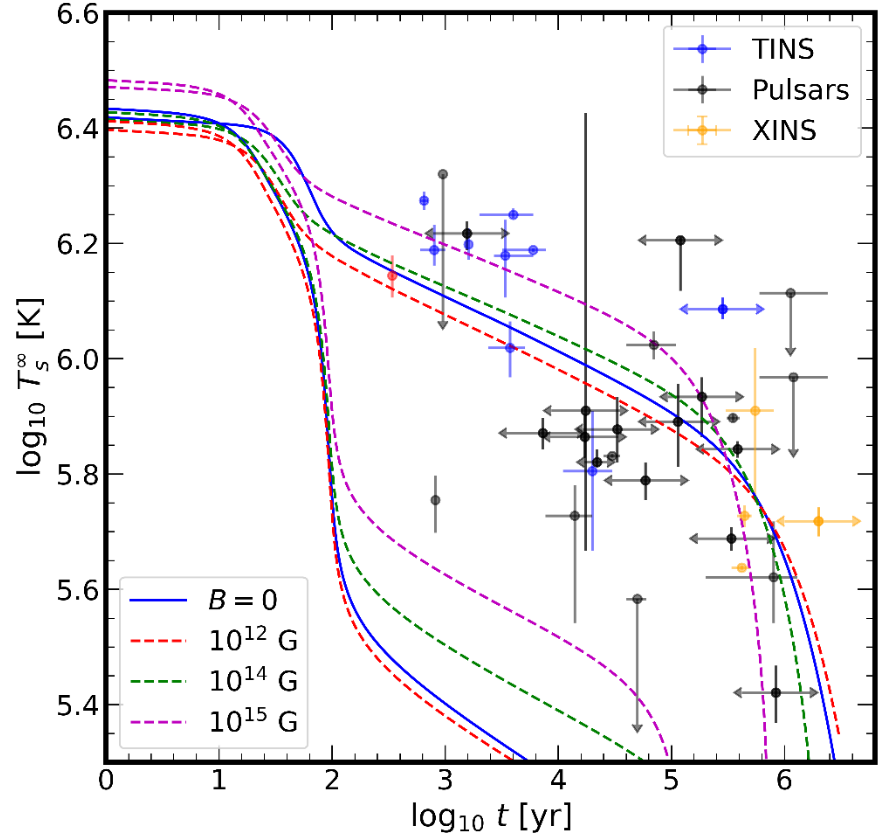
Stars look same from inside but look different from outside

Curse of Heat Blanket

Accreted envelopes (ΔM/M)



Magnetic field



Notice: NSs with accreted envelopes cool faster at the photon cooling stage

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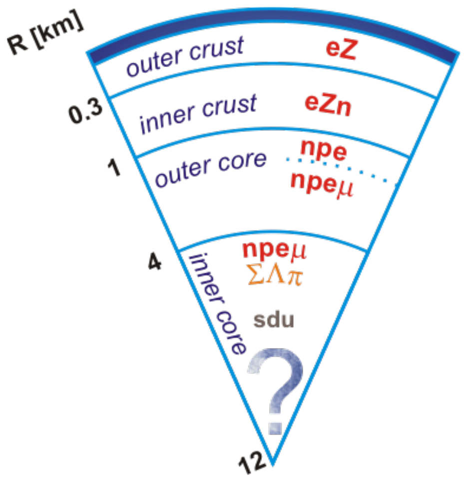


Only nucleon superfluidity in the core will be discussed.
Singlet proton
Triplet neutron

Superfluidity In NS cores. Zoo of the SF models

Singlet proton pairing

$$T_C \sim 5 \times 10^9 \text{ K}$$

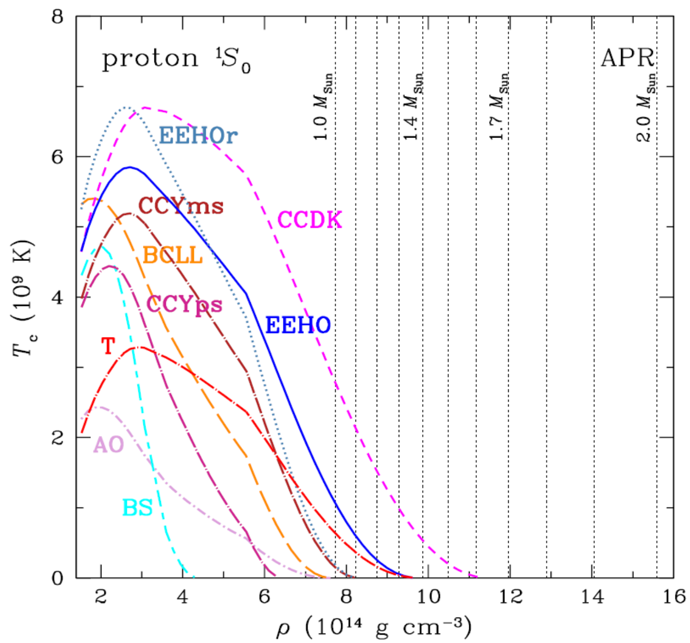


FIG. 7. (Color online) Critical temperature T_c for proton superfluidity as a function of mass density of a NS constructed using the APR EOS. Different curves correspond to different proton singlet gap models that are shown in Fig. 1. Vertical dotted lines denote the core density of NSs of different mass.

Figures from *Ho et al.* 2015, PRC **91,** 015806

Triplet neutron pairing

$$T_C \sim 0.5 \times 10^9 \text{ K}$$

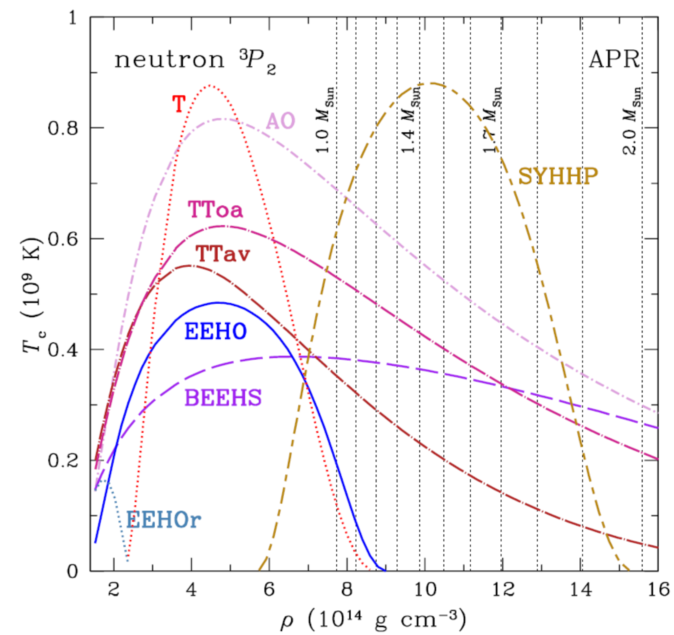


FIG. 10. (Color online) Critical temperature T_c for neutron
triplet s ... NS
construc ... nd
to differ ... cal
dotted l ... ss.

Microscopic calculations result in pairing profiles peaked at low densities

Heat Capacity

$$C_v = R_c(T/T_c)\, C_v^0$$

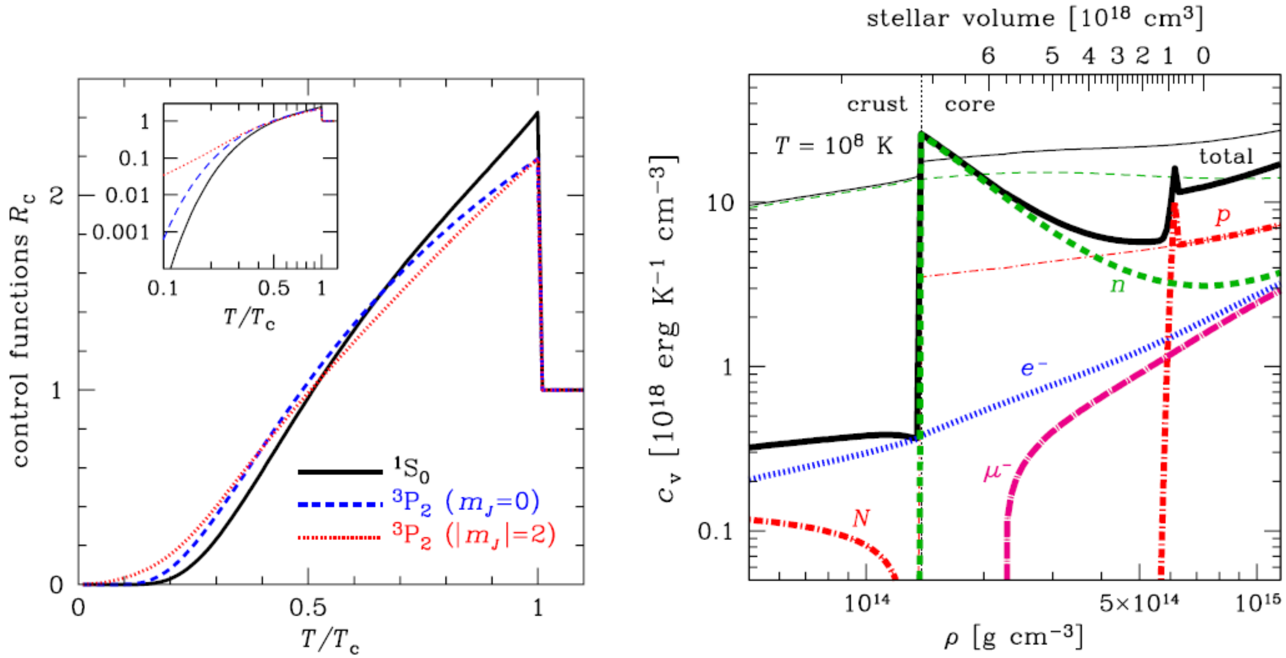


Fig. 6 Left panel: Specific heat control functions for the $^1S_0$, $^3P_2$ ($m_J = 0$), and $^3P_2$ ($|m_J| = 2$) types of pairing listed in Sect. 3.1. The inset displays the same functions on a logarithmic scale. Right panel: Total and partial specific heats near the bottom of the crust and in the core of a neutron star at $T = 10^8$ K as functions of density. The solid lines show the total c_V, and the other lines show the contributions of electrons (e^-), neutrons (n), nuclei (N, in the crust), muons and protons (μ^- and p, in the core). Thin lines show results of a calculation with nucleons assumed to be unpaired, and thick lines take pairing into account. The top axis shows the volume contained inside a sphere with given ρ for a $1.4\, M_\odot$ neutron star. The stellar structure and composition are adopted from the BSk21 model.

Figures from *Potekhin, Pons & Page* 2015, SSRv **191,** 239

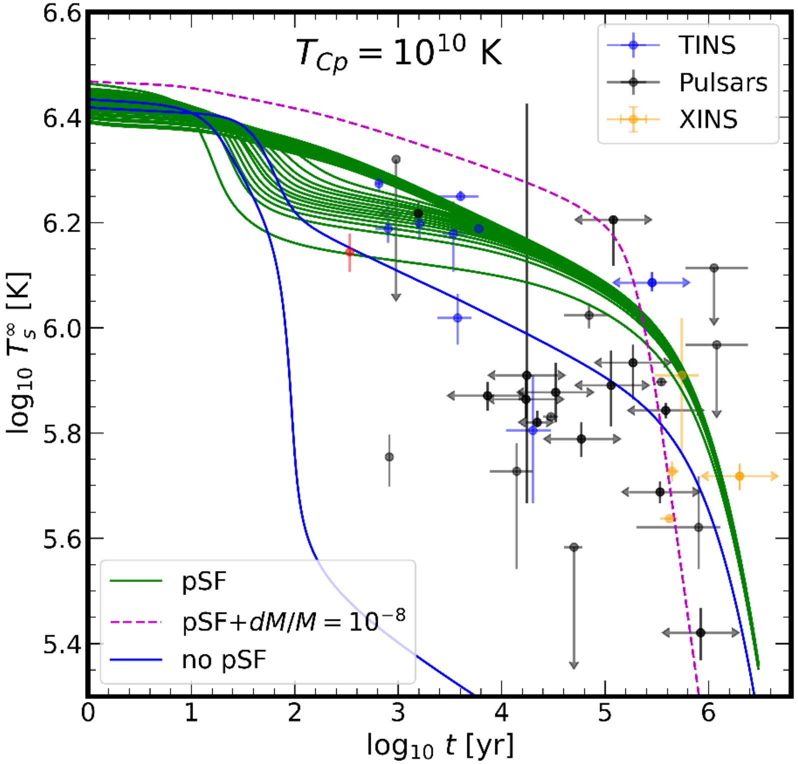
Superfluidity. Effects on neutrino emission.

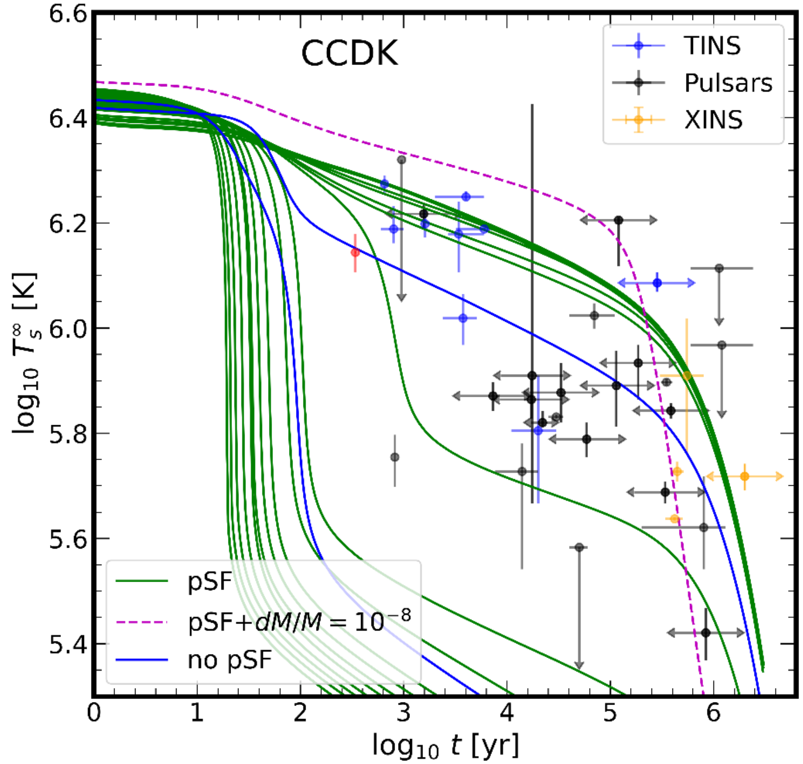
Two main effects

I. Damping of the traditional neutrino processes

$$L_\nu \to L_\nu \times \exp\left(-\alpha T_c/T\right), \quad T \ll T_c$$

Proton superfluidity only (for a moment)



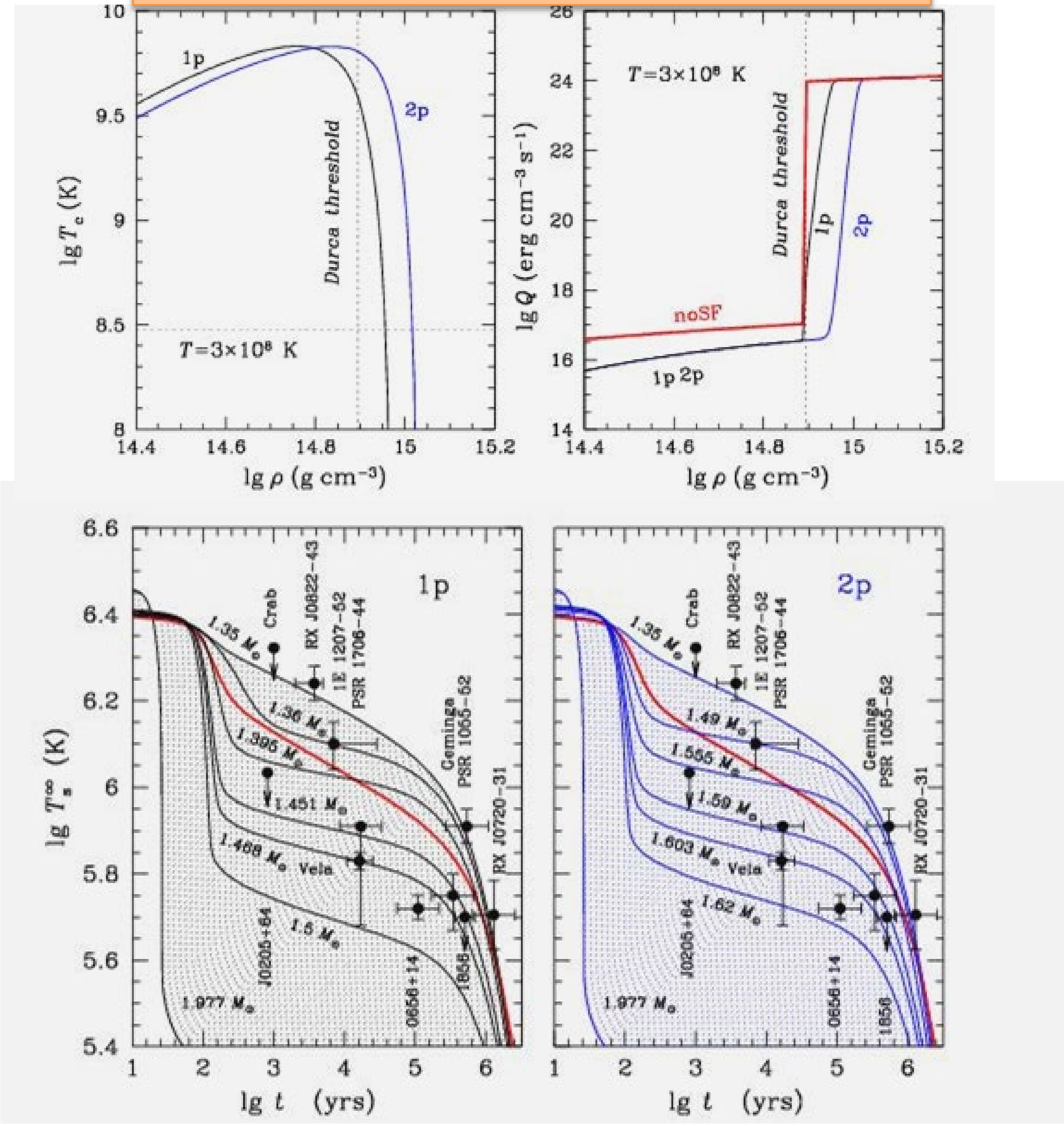


Cooling due to nn bremsstrahlung

Superfluidity. Filling the dUrca gap

Figures from Yakovlev & Pethick 2004, *ARA&A* **42,** 169

Smooth transition to fast cooling.
Smearing of dUrca threshold



Cooper pairing formation emission

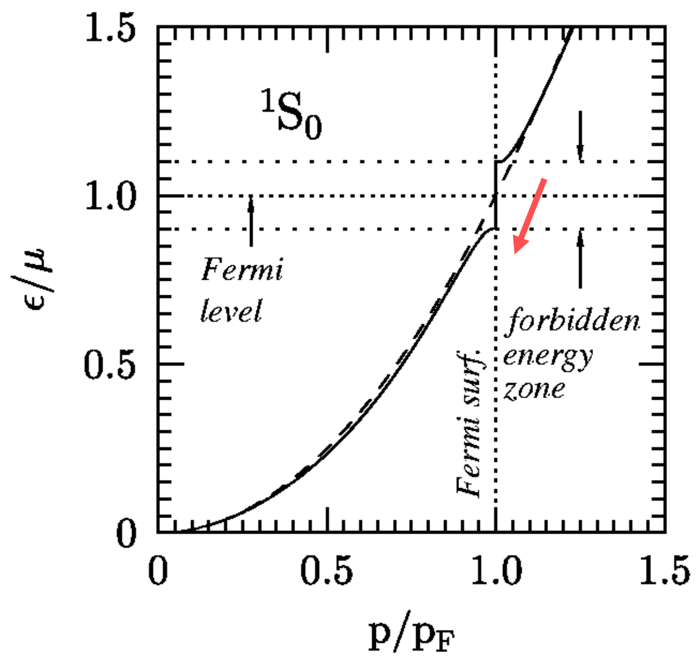
Two main effects

II. New channel of neutrino emission due to Cooper pairing

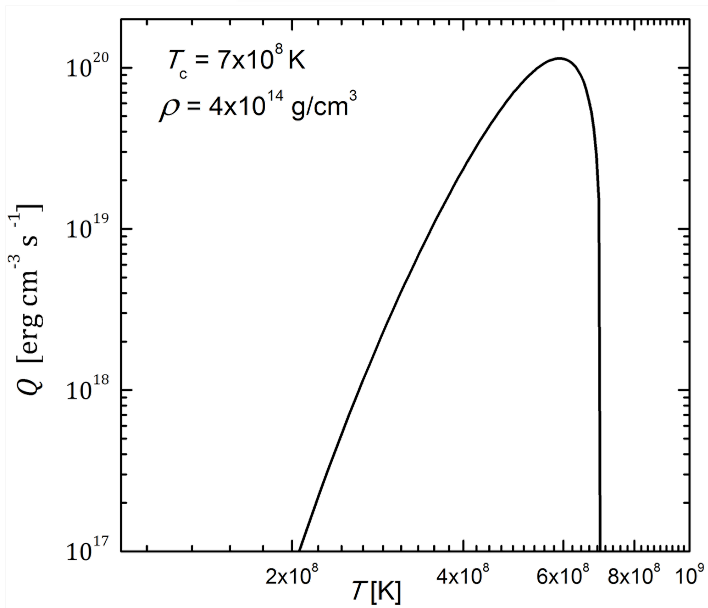
Flowers, Ruderman and Sutherland (1976)

$$\tilde{N} + \tilde{N} \to \nu + \bar{\nu}$$

$$Q_0^{(\mathrm{CP})} = 1.17 \times 10^{21} \frac{m_\mathrm{n}^*}{m_\mathrm{n}} \frac{p_{\mathrm{Fn}}}{m_\mathrm{n} c} T_9^7 \mathcal{N}_\nu R\left(\frac{\Delta}{T}\right) \frac{\mathrm{erg}}{\mathrm{cm}^3\ \mathrm{s}}$$



CPF emissivity



Maximal at $T \sim 0.7 T_c$

CPF emission. Collective effects

Cooper pair condensate response

$$Q_{\rm CP0} \to q Q_{\rm CP0}$$

Kundu,& Reddy 2004, Leinson & Perez 2006, Kolomeitsev & Voskresensky 2010, Steiner & Reddy 2009, Leinson 2009, Sedrakian 2012, ..

Singlet pairing

$$Q_{\rm CP0} \propto g_V^2 \to \left(\frac{4}{81} \left(\frac{v_{Fn}}{c} \right)^4 g_V^2 + \frac{6}{7} \left(\frac{v_{Fn}}{c} \right)^2 g_A^2 \right) \qquad q_s \ll 1$$

Triplet pairing

$$Q_{\rm CP0} \propto (g_V^2 + 2g_A^2) \to 2g_A^2$$

(phen) Page et al. 2009 $\quad q = 0.76$

$$Q_{\rm CP0} \propto (g_V^2 + 2g_A^2) \to \frac{1}{2} g_A^2$$

(micro) Leinson 2010 $\quad q = 0.19$

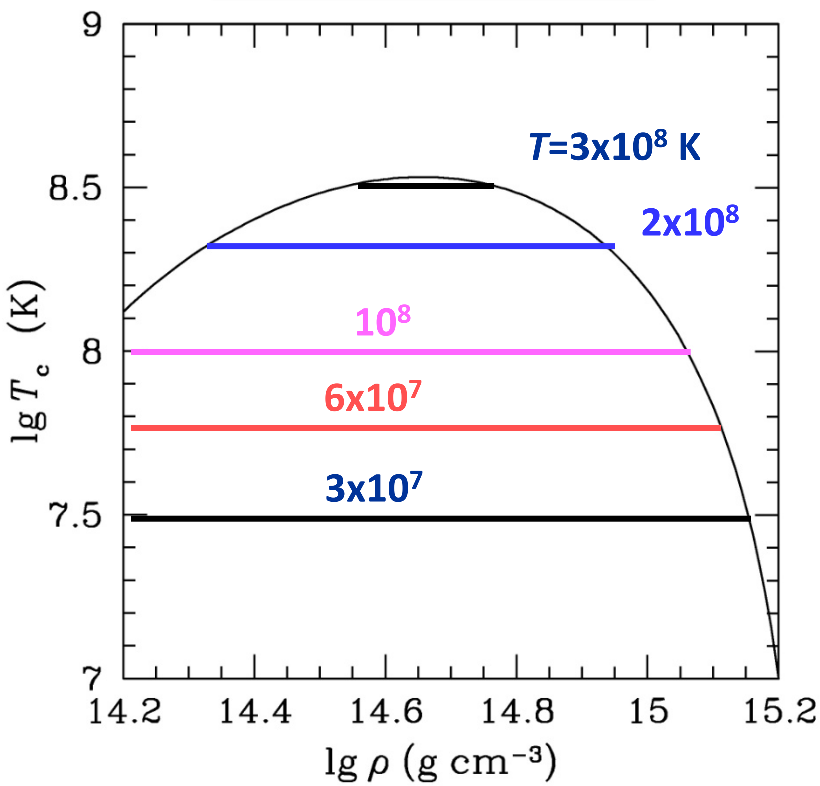
In this talk q – phenomenological parameter of the CPF strength
Can be density-dependent

CPF emission of triplet neutron pairing

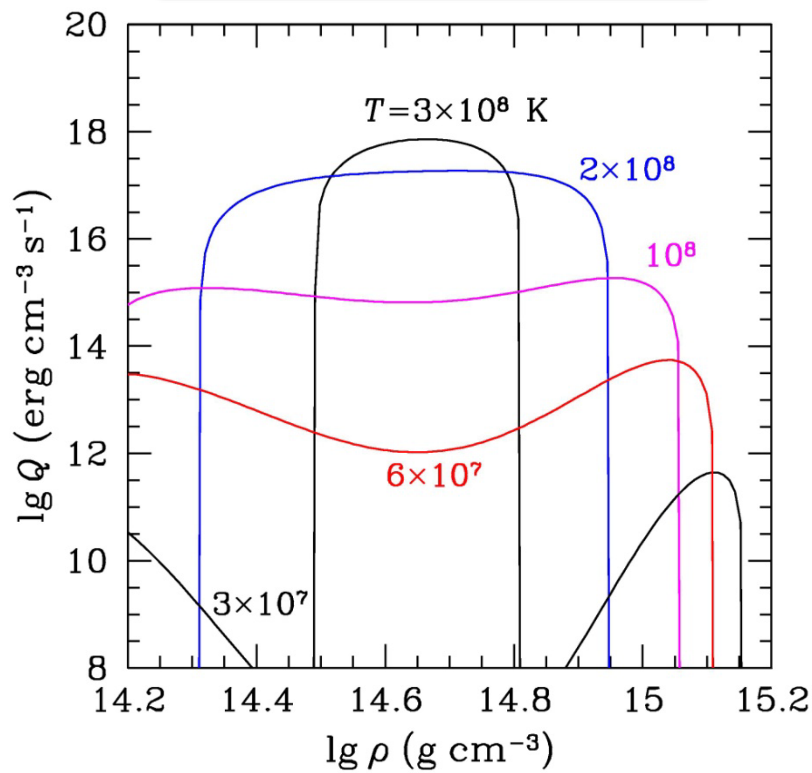
mimics slow cooling

$$L_{\rm CP} = \int Q_{\rm CP}\, {\rm d}V \propto T^7 \cdot T$$

Bell-shaped profile



Distribution over the core

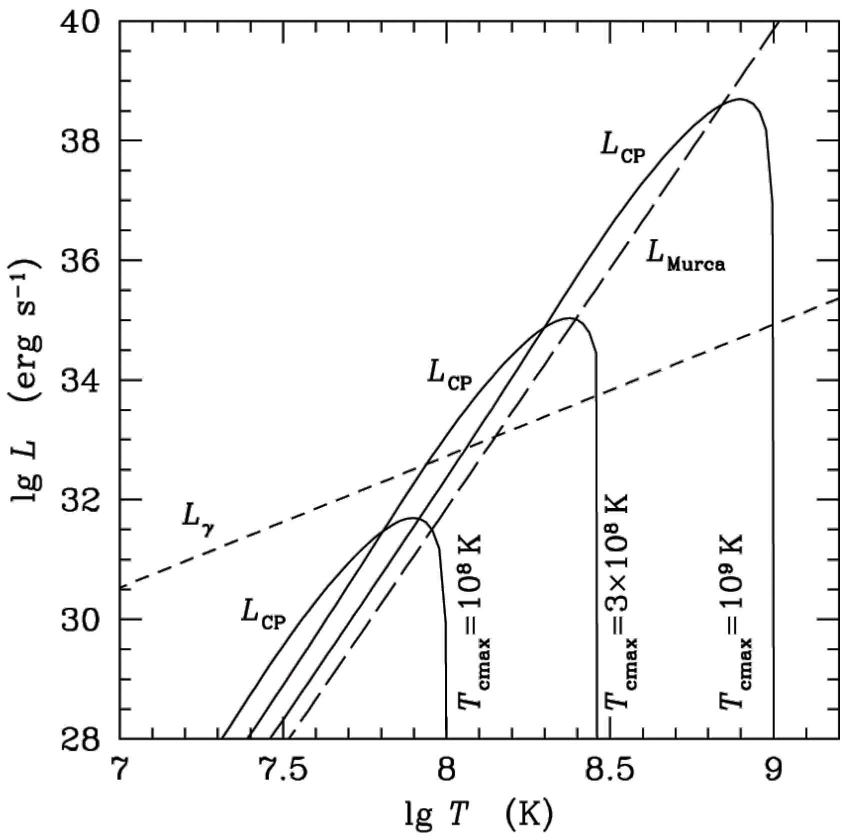


CPF neutrino emission of triplet neutron pairing

$$L_\nu^{Cooper} \sim (10-100)\ L_\nu^{Murca} \propto T^8$$

Neutrino emission due to Cooper pairing of neutrons can be 10—100 times stronger than Murca in non-superfluid NSs

This statement, however, strongly depends on the model parameters, namely $T_{cn}(\rho)$ and q

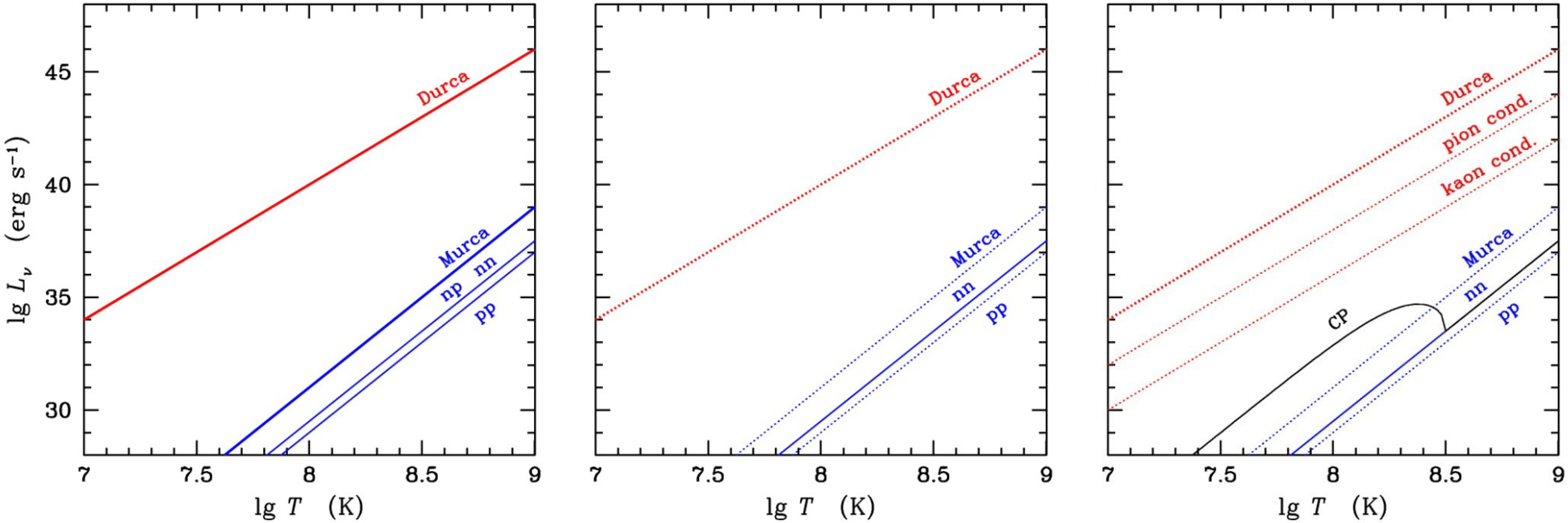


Neutrino luminosities in superfluid neutron stars

Nonsuperfluid star
with nucleon core
Durca or Murca cooling

Star with strong
proton superfluidity
Very slow cooling

Star with strong proton
and moderate neutron
superfluidity



Divisions of responsibility

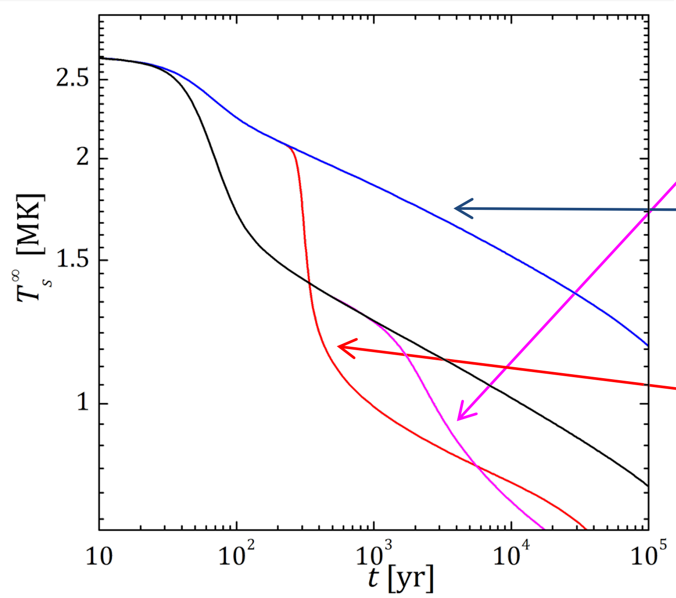
$^1S_0$ proton superfluidity

effectively damp standard neutrino reactions which involve protons: MUrca, Durca, pp and np bremsstrahlung

$^3P_J/^3F_J$ neutron superfluidity

moderately enhance neutrino emission with respect to MUrca

Nucleon superfluidity and cooling. Second temperature drop



Neutron superfluidity:

accelerate cooling with CPF

Proton superfluidity:

decelerate cooling
CPF is unimportant

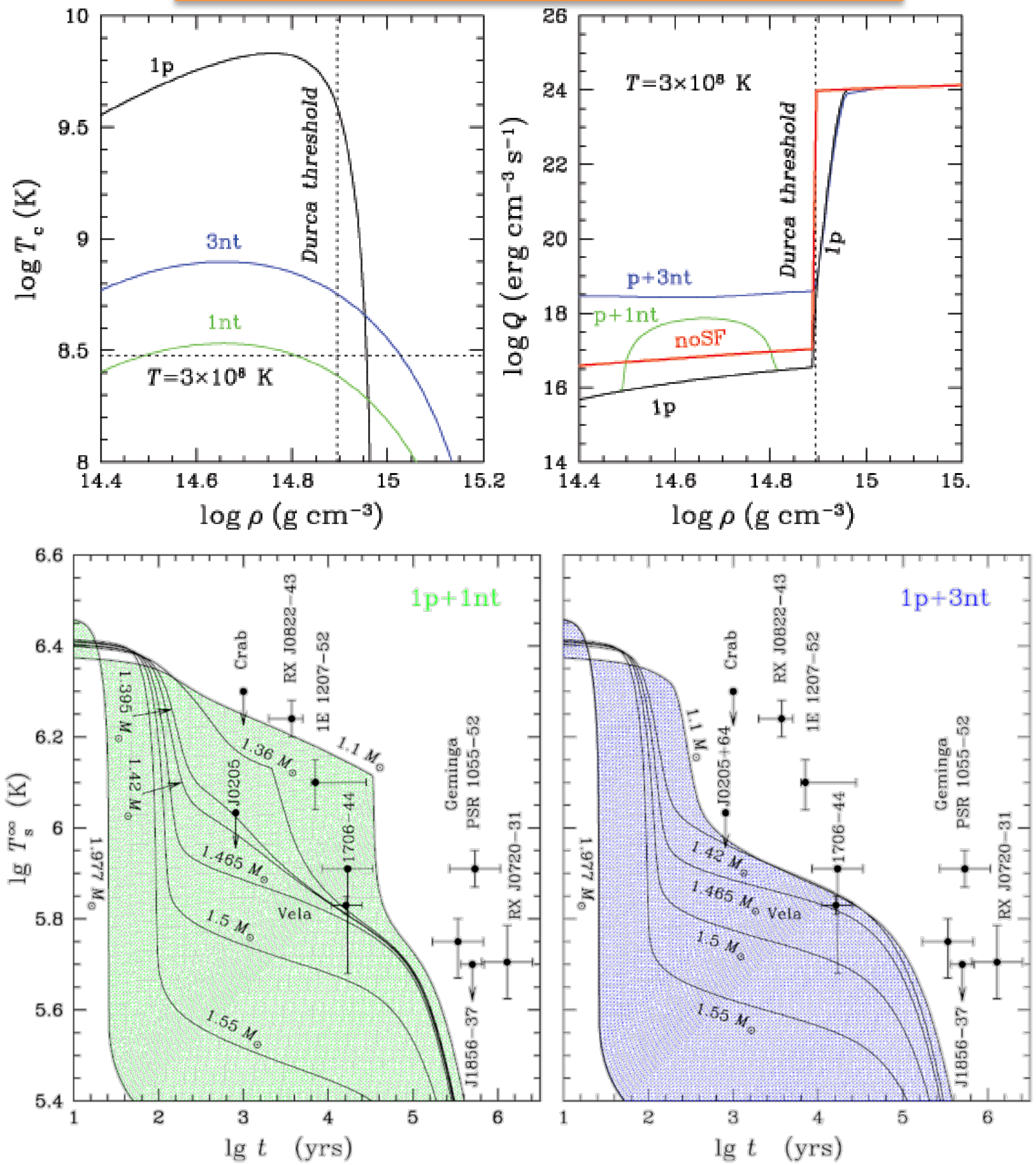
Together:

Sharp increase of the cooling rate

Positions and sizes of "second temperature drop" strongly depend on NS mass, superfluid/superconducting volume of the star, strength of CPF emission (parameter q), etc.

Mild neutron superfluidity

Figures from Yakovlev & Pethick 2004, *ARA&A* **42,** 169

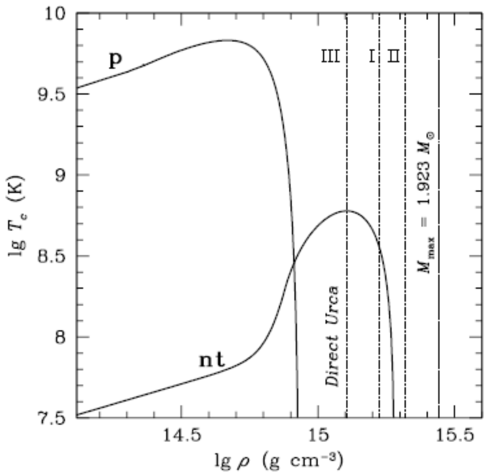


Well-developed neutron superfluidity in low-mass stars (or large q) contradicts observations of hot NSs

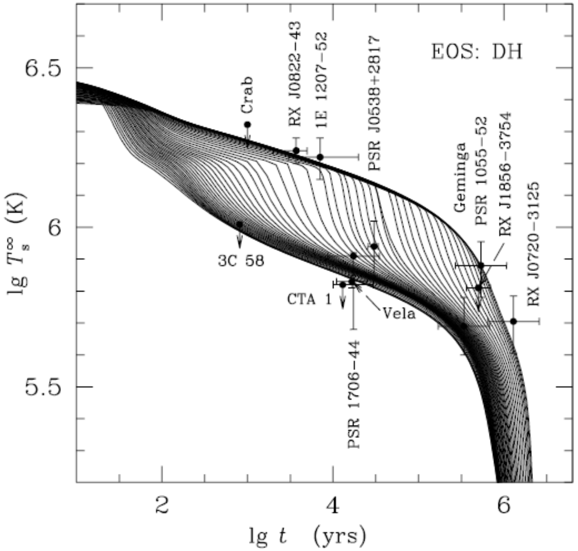
Need low neutron critical temperatures at low densities – in low-mass stars
Equivalently – damp $q(\rho)$ at low densities

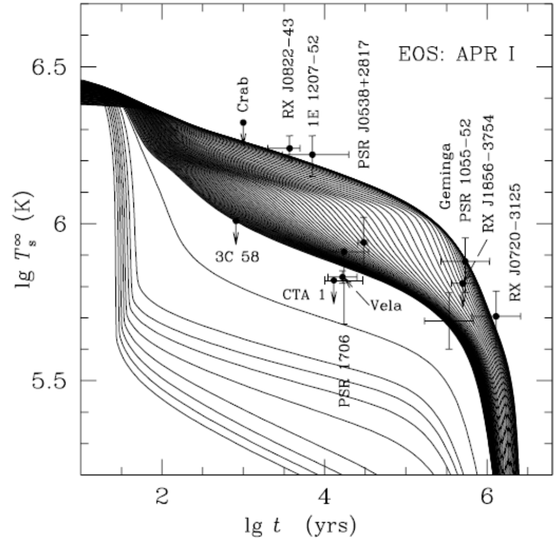
Mild neutron superfluidity

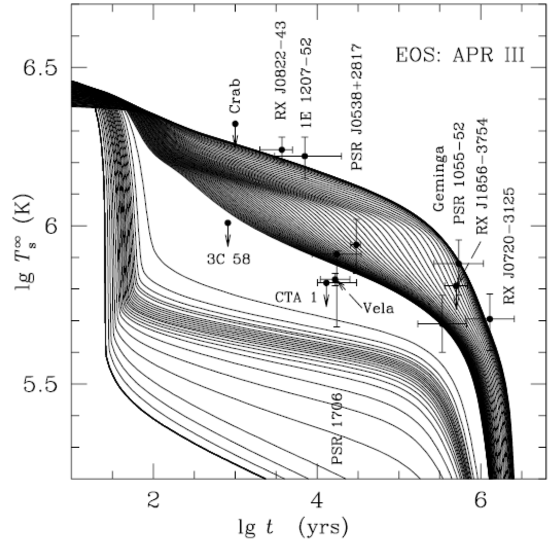
Shifted neutron superfluidity to high densities



Figures from *Gusakov et al.* 2005, MNRAS **363,** 555





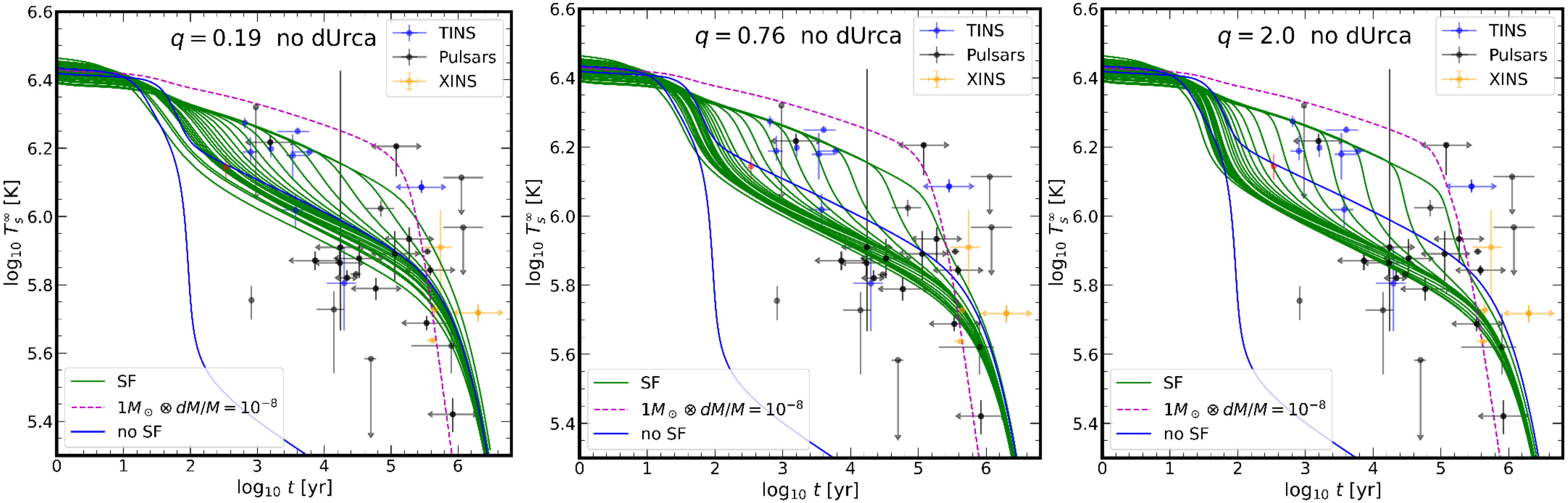


Minimal cooling paradigm

Explain thermal states of all isolated neutron stars without fast cooling

Page et al. 2004,2009, Gusakov et al. 2004

Strong proton, moderate neutron superfluidity (but damped at low densities – `knee' stars)



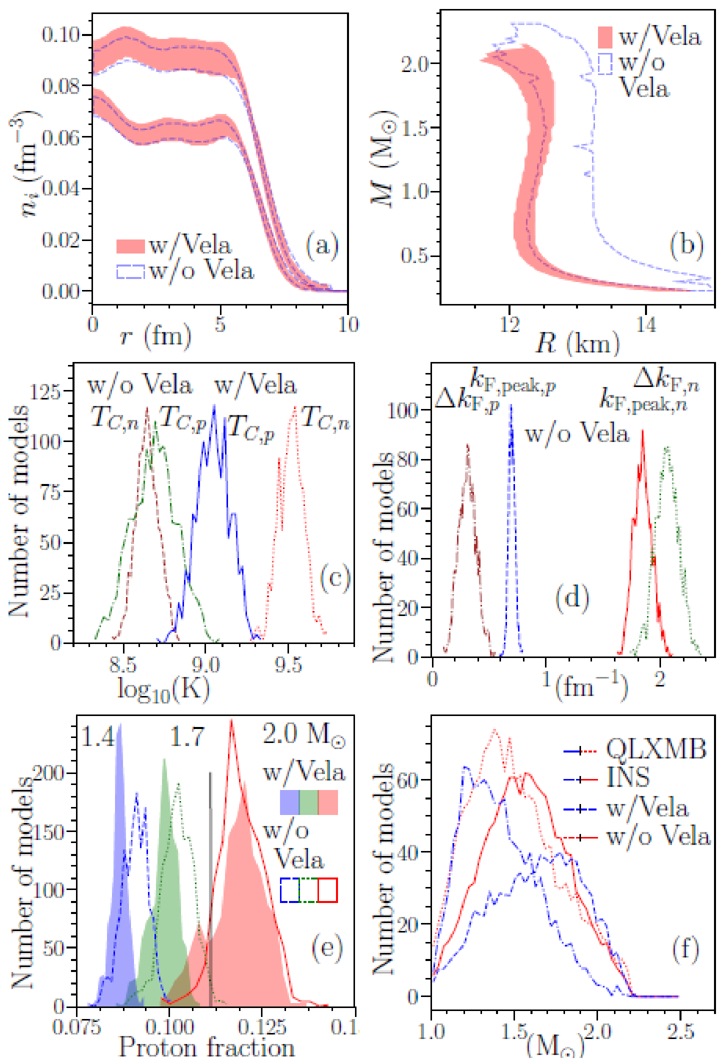
Explanation of coolest stars is problematic

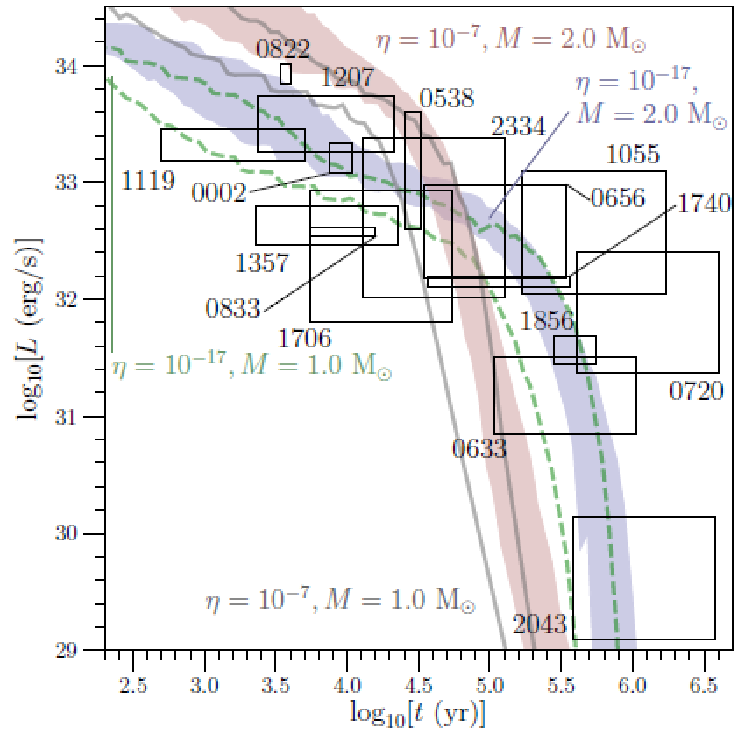
Faster cooling mechanisms seems to be necessary

Here Direct Urca switched off by hand

Minimal cooling. Bayesian analysis

Beloin et al. 2018, 2019





Explanation of coolest stars (Vela and colder) is problematic

Figures from *Beloin et al.* 2019, PRC **100,** 055801

Plan

Cooling of non-superfluid NSs. Basics

Neutrino emission processes.
Fast and slow cooling

Heat blanketing envelopes

Impact of superfluidity on NS cooling

Neutron star in Cassiopeia A SNR

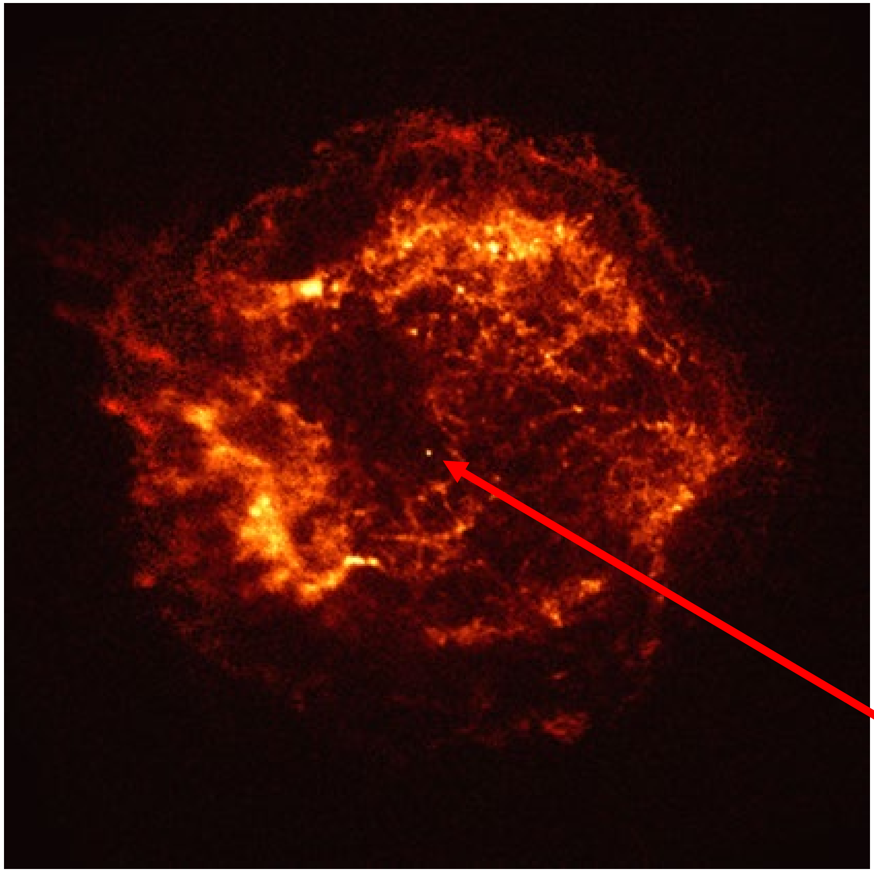
What we learned by now:

Warm stars :
- possible indication of proton superfluidity
- Suppressed CPF at low densities

Cold stars:
- Enhanced cooling (SF ceases at high densities)
- CPF is likely not enough
- dUrca smearing by SF?

CCO in Cas A supernova remnant

Chandra First Light

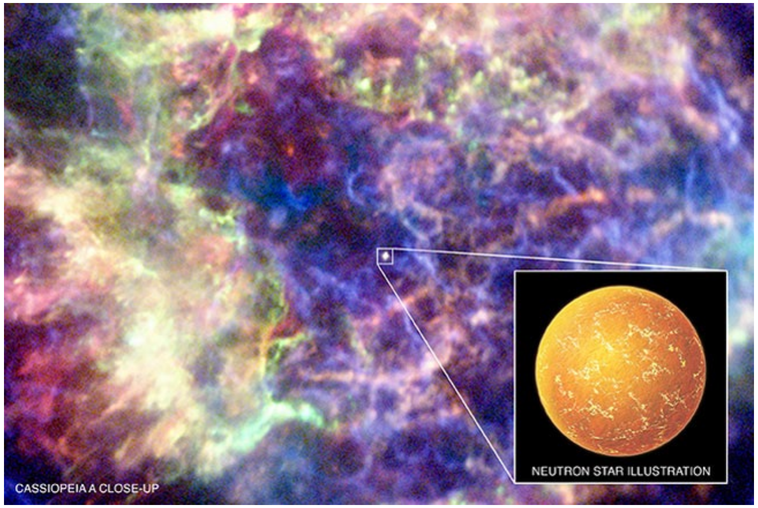


Credit: NASA/CXC/SAO

SNR Cassiopeia A
Age 340 yr (Flamsteed: 1680?)
Distance $3.4^{+0.3}_{-0.1}$ kpc

Central compact object (CCO) with purely thermal X-ray spectrum – a NS – was discovered

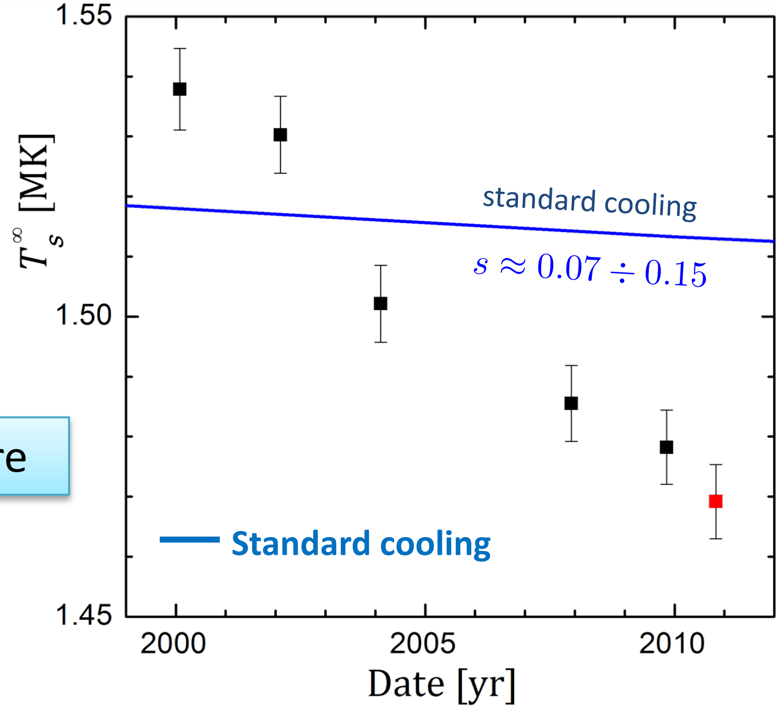
CCO in Cas A supernova remnant



Heinke & Ho, ApJL 2010

Real-time cooling of the NS

4% in 10 yrs



Ho & Heinke , Nature 2009

NS spectra can be described by a carbon atmosphere

Age 340 yr (1680)
Distance $3.4^{+0.3}_{-0.1}$ kpc
Surface temperature ≈ 2 MK
Several other CCO whose spectra are consistent with carbon atmosphere model are known now

Cooling curve slope

$$s \equiv -\frac{\mathrm{d}\ \ln T_s^\infty}{\mathrm{d}\ \ln t} \approx 1.3$$

CCO in Cas A supernova remnant: Evidence for superfluidity

Page et al., 2011; Shternin et al., 2011

Model: Observed cooling is due to CPF emission

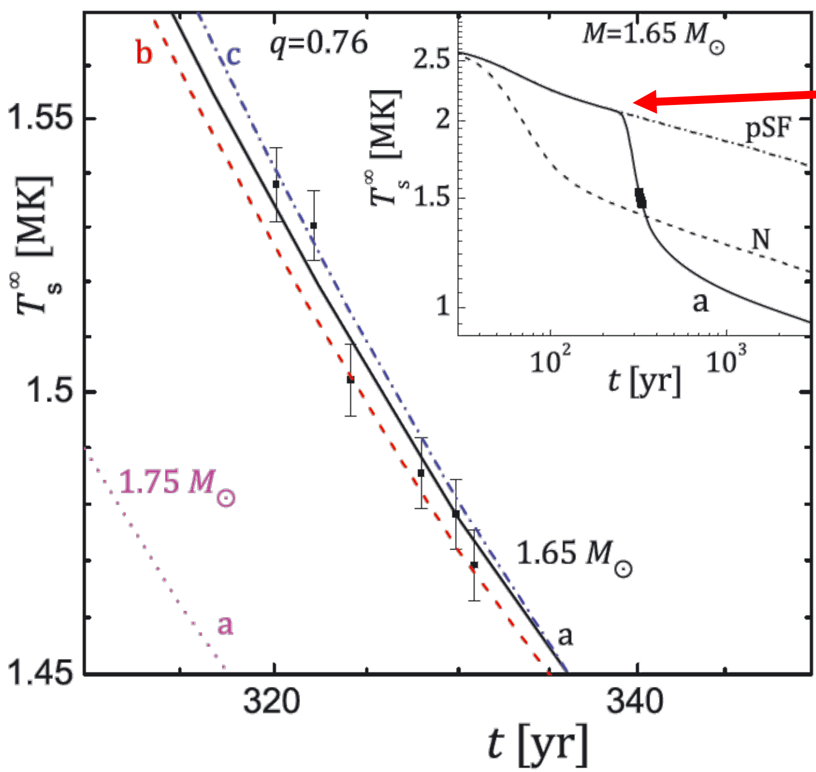


Figure from Shternin et al. 2011, *MNRAS* **412,** L108

Recent onset of the neutron superfluidity (~100 yr ago)
Unique opportunity to constrain the properties of superfluidity in dense matter

Other models exist:
Blaschke+12,13, Bonanno +14
Negreiros+13, Taranto+16, Yang+11,
Noga+13, Sedrakian+13,
Hamaguchi+18

Cooling of the Cas A neutron star. Current status

Chandra/ACIS observations

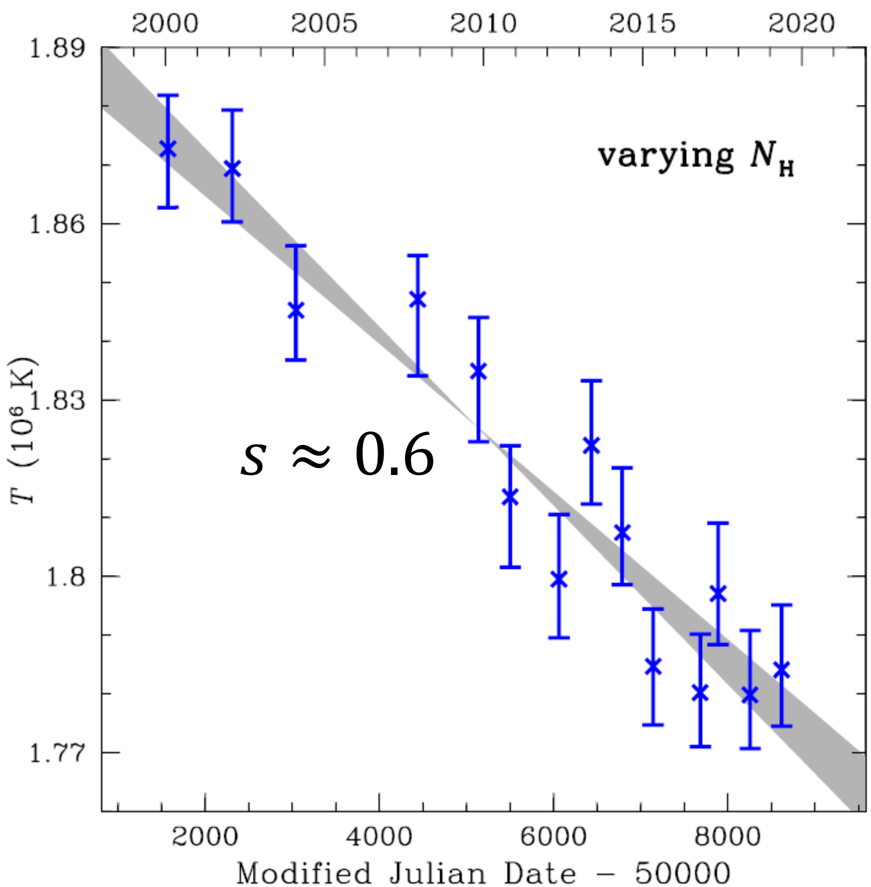


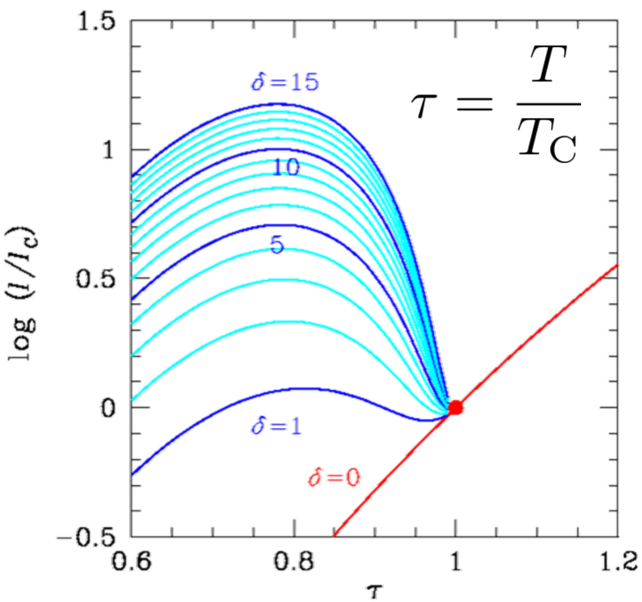
Figure from *Ho et al.* 2021, *MNRAS* **506,** 5015

14 observation epochs
(Jan 2000 – May 2019)
Heinke&Ho 11, PS+11, Elshamouty+13, Ho+15, Wijngaarden+19, Ho+21

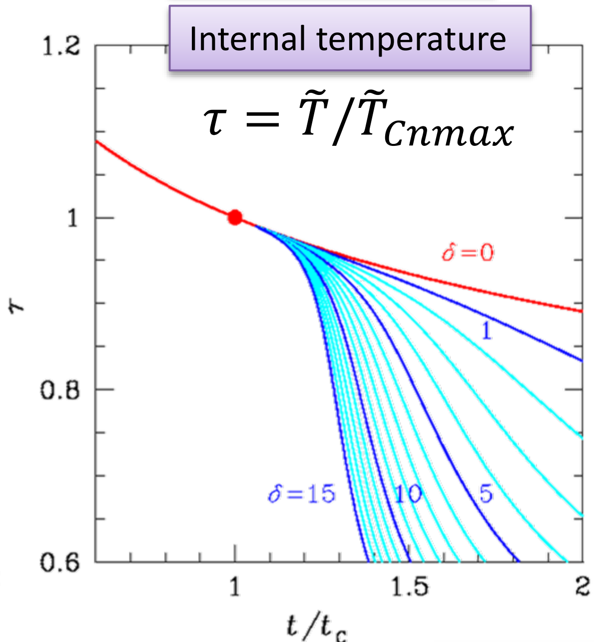
Discussion: cooling is slower/statistically insignificant
Posselt et al., 2013;
Posselt&Pavlov 2018

Dimensionless self-similar solutions

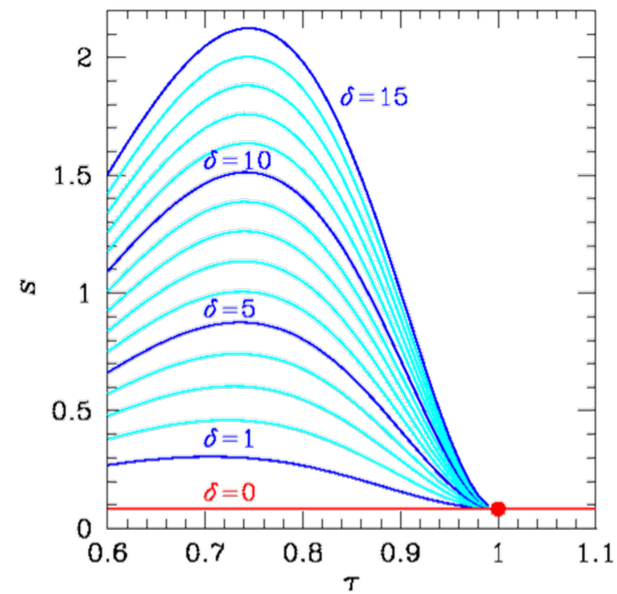
Neutrino luminosity



Cooling curves



Cooling slope



Figures from *Shternin & Yakovlev* 2015, MNRAS **446,** 3621

Universal neutrino cooling function

$$\ell_{\mathrm{CP}} = 117.6\delta\ell_0\tau^7(1-\tau)^2 \quad \tau \gtrsim 0.6$$

$$\frac{\mathrm{d}\widetilde{T}}{\mathrm{d}t} = -\ell_0\tau^7(1+117.6\delta(1-\tau)^2)$$

δ parameter encapsulates q, $T_{cn}(\rho)$, initial neutrino cooling

CCO in Cas A supernova remnant: Evidence for superfluidity

Page et al., 2011; Shternin et al., 2011

Model: Observed cooling is due to CPF emission

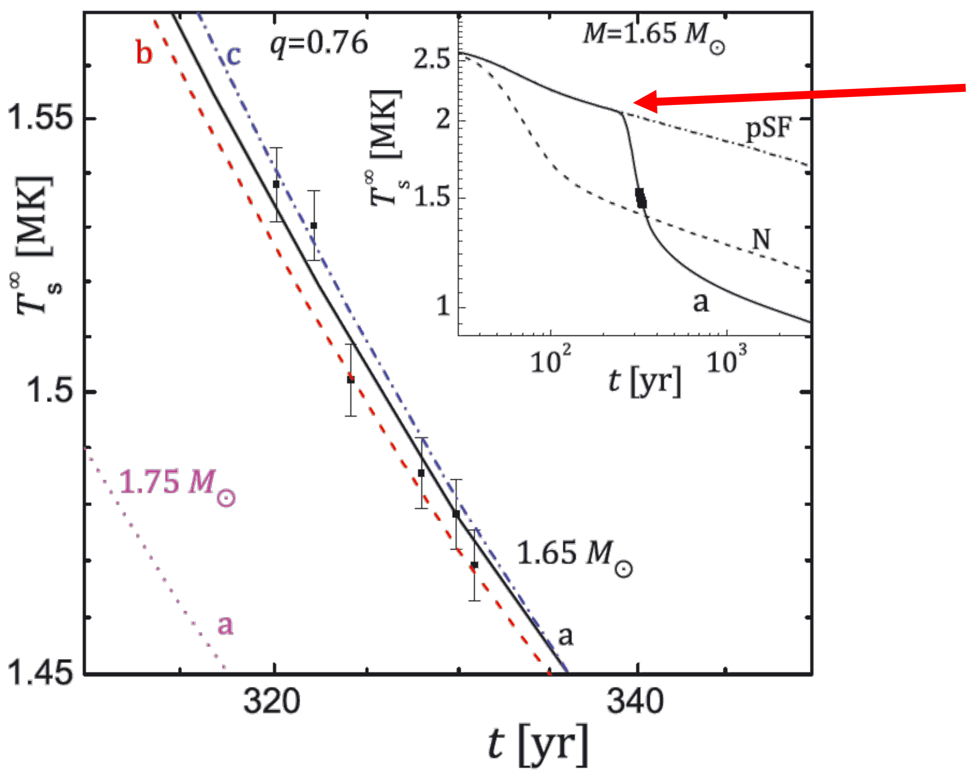


Figure from Shternin et al. 2011, *MNRAS* **412,** L108

Recent onset of the neutron superfluidity (~100 yr ago)
Unique opportunity to constrain the properties of superfluidity in dense matter

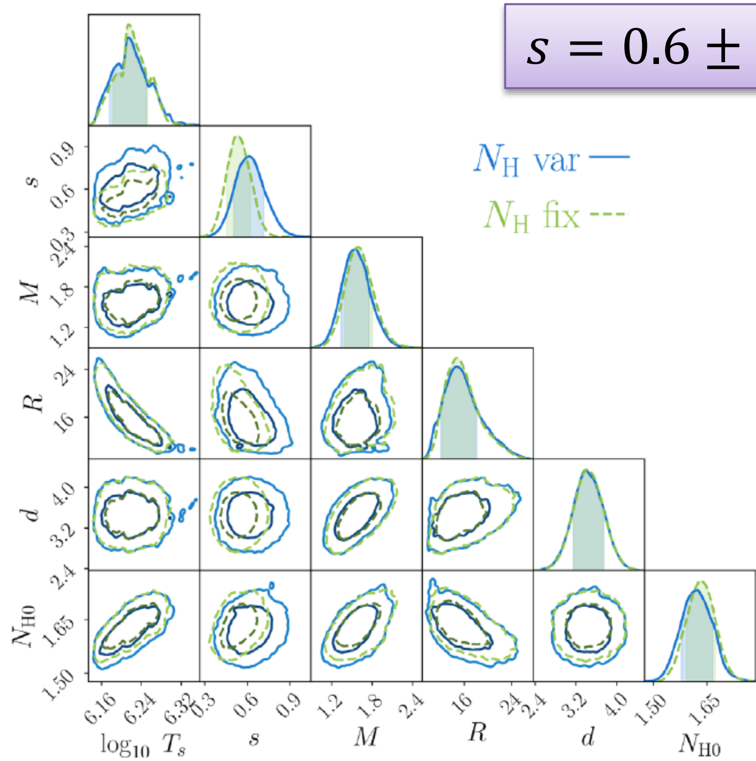
Idea: Simultaneous analysis of spectral data and cooling scenario. Analytical solutions and robust constraints.
=> Conservative inferences of the superfluidity parameters.

Cas A NS spectral analysis

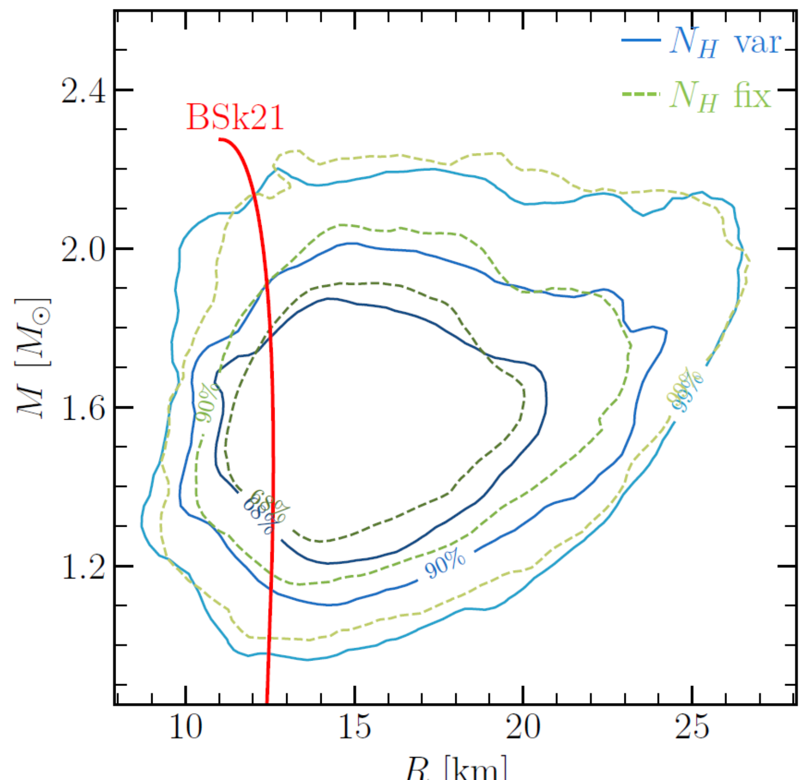
pyXSpec+emcee

$$PILEUP(\alpha(t))\otimes[TBABS(N_H(t)) * SPEXPCUT * NSX(M,R,T_s(t),d)]$$

Model	$N_{\rm H}$	EOS	$\log_{10}T_{s0}/(1\ \rm K)$	s	M ($\rm M_\odot$)	R (km)	d (kpc)	$N_{\rm H0}$ (10^{22} cm^{-2})	$\sigma_{N_{\rm H}}$ (10^{20} cm^{-2})	χ^2/d.o.f.
1	Var	–	$6.216^{+0.034}_{-0.040}$	$0.61^{+0.10}_{-0.11}$	$1.55^{+0.21}_{-0.21}$	$14.8^{+3.4}_{-2.7}$	$3.40^{+0.35}_{-0.26}$	$1.621^{+0.045}_{-0.042}$	$3.6^{+1.8}_{-1.4}$	1613.3/1618
2	Fix	–	$6.215^{+0.038}_{-0.031}$	$0.54^{+0.08}_{-0.09}$	$1.59^{+0.21}_{-0.20}$	$14.8^{+3.0}_{-2.5}$	$3.43^{+0.32}_{-0.27}$	$1.634^{+0.040}_{-0.039}$	–	1640.2/1633
3	Var	BSk21	$6.262^{+0.013}_{-0.027}$	$0.66^{+0.10}_{-0.09}$	$1.57^{+0.16}_{-0.24}$	12.6	$3.35^{+0.24}_{-0.30}$	$1.643^{+0.039}_{-0.034}$	$3.6^{+1.6}_{-1.4}$	1614.5/1619
4	Fix	BSk21	$6.264^{+0.013}_{-0.026}$	$0.58^{+0.08}_{-0.08}$	$1.61^{+0.15}_{-0.24}$	12.6	$3.40^{+0.18}_{-0.35}$	$1.658^{+0.030}_{-0.035}$	–	1640.4/1634



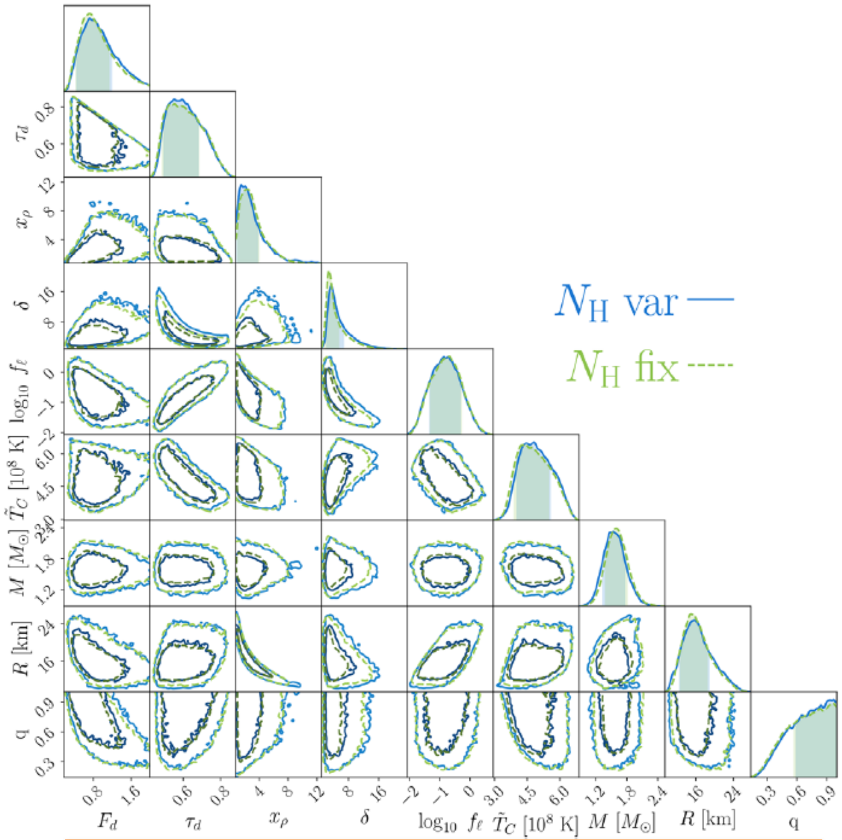
$s = 0.6 \pm 0.1$



Shternin et al. 2021, *MNRAS* **506,** 709-726

“Model-independent” Cas A analysis. Superfluidity parameters

Model	F_d	τ_d	x_ρ	δ	$\log_{10} f_{\ell 0}$	$\tilde{T}_{Cn\max}$ (10^8 K)	M ($M_\odot$)	R (km)	q
1	$0.77^{+0.42}_{-0.31}$	$0.57^{+0.12}_{-0.07}$	$1.5^{+2.2}_{-0.7}$	$3.4^{+3.2}_{-1.4}$	$-0.64^{+0.34}_{-0.68}$	$4.5^{+1.1}_{-0.5}$	$1.56^{+0.20}_{-0.22}$	$15.6^{+3.3}_{-3.0}$	>0.61 (0.42)
2	$0.69^{+0.45}_{-0.26}$	$0.57^{+0.12}_{-0.08}$	$2.3^{+1.6}_{-1.4}$	$2.8^{+2.7}_{-1.1}$	$-0.70^{+0.42}_{-0.61}$	$4.4^{+1.1}_{-0.5}$	$1.60^{+0.20}_{-0.22}$	$14.8^{+3.6}_{-2.2}$	>0.59 (0.40)
3	$1.00^{+0.41}_{-0.24}$	$0.53^{+0.11}_{-0.05}$	$5.6^{+0.6}_{-0.9}$	$4.1^{+4.8}_{-1.5}$	$-1.17^{+0.34}_{-0.47}$	$4.3^{+0.9}_{-0.5}$	$1.57^{+0.16}_{-0.25}$	12.6	>0.67 (0.52)
4	$0.93^{+0.40}_{-0.23}$	$0.55^{+0.10}_{-0.08}$	$5.6^{+0.6}_{-0.8}$	$3.5^{+4.1}_{-1.3}$	$-1.19^{+0.46}_{-0.40}$	$4.4^{+0.7}_{-0.6}$	$1.64^{+0.12}_{-0.27}$	12.6	>0.65 (0.49)



$$\tilde{T}_{Cn\max} = (4-6)\times 10^8\ K$$

$$T_{Cn\max} = (5-10)\times 10^8\ K$$

$$q > 0.4\ (90\%)$$

Inference of T_C only weakly correlates with s and q

Shternin et al. 2021, *MNRAS* **506,** 709-726

Summary

NS cooling theory: one basic phenomenological concept, but many theoretical realizations. Observations are leading with respect to theory.

There are warm (slow cooling?) and cold (fast cooling) sources

Inference on internal neutrino emission is disguised by unknown composition of heat blanket

Constraints on superfluidity

Warmest stars – possible proton pairing; need suppressed CPF at low densities

Cooling of CasA NS:

$T_{Cnmax} = (5-10) \times 10^8\ K$

$q > 0.4$

Cold stars – enhanced cooling – pairing should cease at large densities

Alternative scenarios:
- Internal heating
- Magnetic fields (including buried)
- In-medium effects
- Exotic cooling scenarios / different NS families
- etc.

Do not expect from the cooling theory more than it can give © Dima Yakovlev