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Cooling neutron star in the Cassiopeia A supernova remnant:
Evidence for superfluidity in the core

Physics of Neutron Stars – 2011
Saint-Petersburg, July 13

Credits

Co-authors
MNRAS 412, L108 (2011)

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Parallel paper
PRL 106, 081101 (2011)

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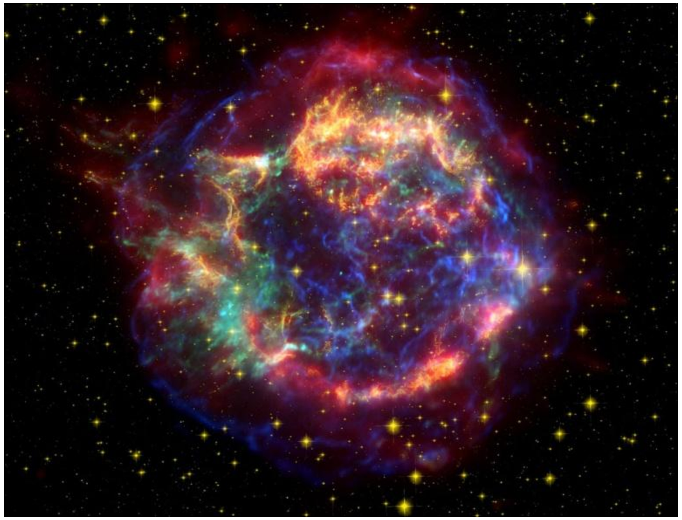


CHANDRA X-ray Observatory image of the supernova remnant Cassiopeia A.
Credit: NASA/CXC

Outline

- Introduction. “Carbon” NS in Cas A and its thermal emission
- Superfluidity in neutron stars and cooling of the Cas A NS
- Constraints on superfluidity from Cas A data
- Cas A NS and other isolated neutron stars
- Conclusions

Cassiopeia A supernova remnant

Brightest radio source

HST image

Faint in optics

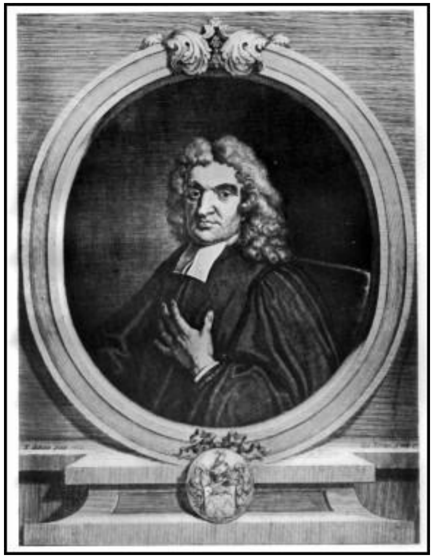
distance $d = 3.4^{+0.3}_{-0.1}$ kpc

size ~ 3.1 pc

age (from analysis of the remnant expansion)

330 ± 20 **yr**

Historical records:



No records on progenitor

British Royal astronomer John Flamsteed recorded 6th magnitude star 3 Cassiopeiae at August 16, 1680

Central object

Various predictions prior to discovery

Was discovered in first-light CHANDRA observations (1999)

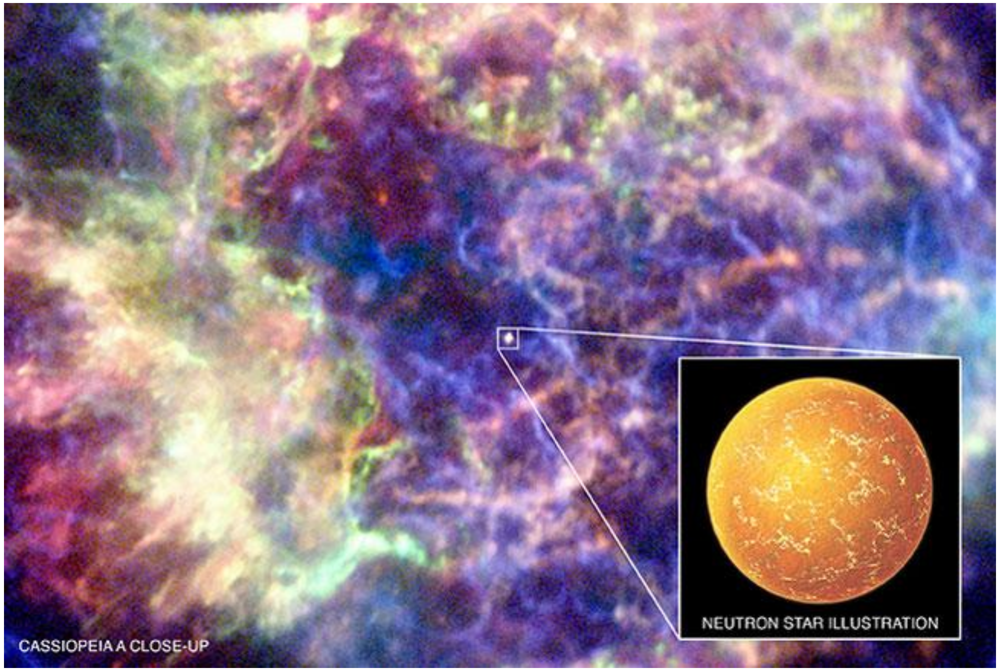
Later found in archives of ROSAT and Einstein

Many observations (2000—2009)

The main problem:

1. *Too small radius of emission area (<5 km) when fitting with H, He, Fe atmospheric models*
2. *But: no pulsations detected*

Conclusion: thermal X-ray emission of unknown origin – not from the entire stellar surface



Central part of the Cas A SNR and an artist impression of the neutron star (picture from the NASA website)

«Carbon» neutron star

Ho and Heinke (2009) Nature 462, 671

Observations are well fitted with

carbon atmospheric model

The emission – from entire star surface !

Conclusion:

Central compact object in supernovae remnant Cas A – neutron star with a carbon atmosphere

NS parameters
(from spectral analysis)

$$M \approx 1.5 - 2.4 M_\odot$$

$$R \approx 8 - 18 \text{ km}$$

$$T_s \sim 2 \times 10^6 \text{ K}$$

$$B \lesssim 10^{11} \text{ G}$$

Observations data:

16 sets of Chandra observations in 2000, 2002, 2004, 2006, 2007, 2009

totalling: 1 megasecond

+ new observation (November 2010)

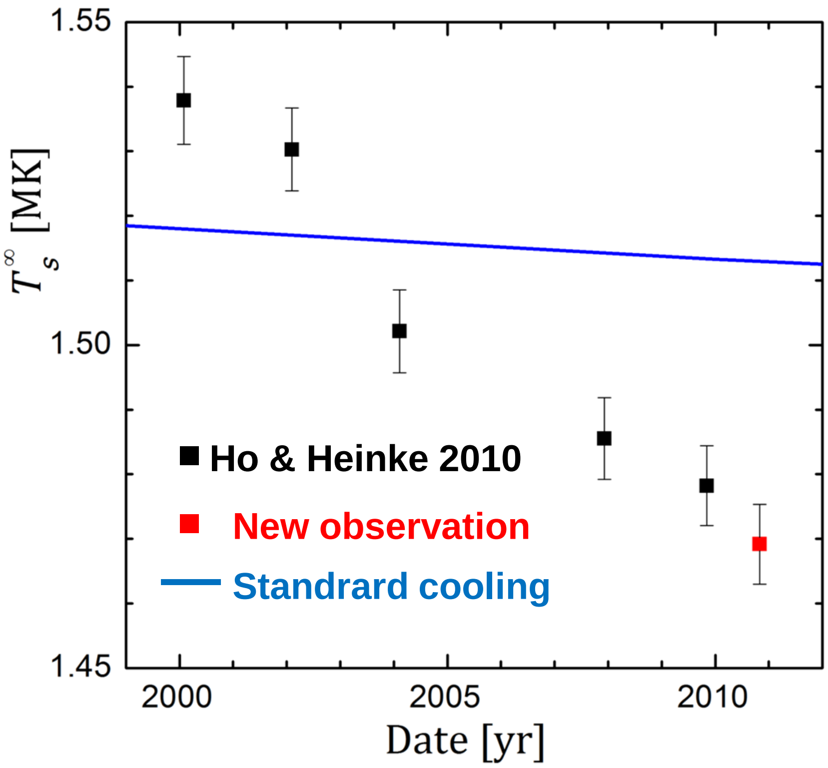
1. *Rather hot star*
2. *Low magnetic field*
3. *No stringent constraints on mass and radius*

Cas A – the youngest NS with measured surface temperature

Cooling (!) neutron star in Cas A

Heinke & Ho, ApJL (2010): Real-time cooling of the star

Surface temperature decline by 4% over 10 years (thermal flux – by 21%)



Fixed M, R, d, N_H

"Standard" cooling
Disagree with observations

Slope $$\frac{d\ln T}{d\ln t} \approx -1.3$$

Direct cooling of the isolated neutron star is observed for the first time

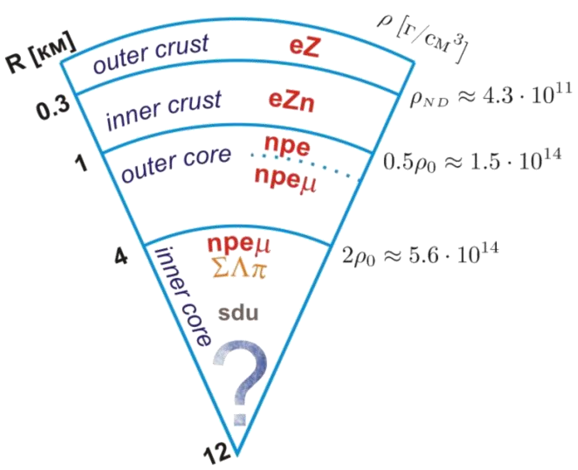
November 2010 observation : cooling continues at the same rate

Neutron star in Cas A

1. Rather hot
2. Cools too fast

See talk by Craig Heinke

Non-superfluid young NS cooling



After relaxation

$$C(\tilde{T})\frac{\mathrm{d}\tilde{T}}{\mathrm{d}t} = -L_\nu^\infty(\tilde{T}) - L_s^\infty(T_s)$$

$$C(\tilde{T}) \propto \tilde{T}$$

Neutrino reactions (*npeμ*)

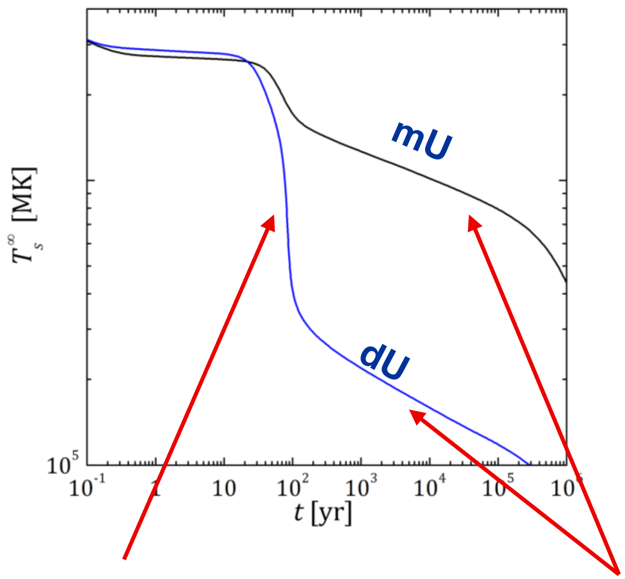
«Fast»: processes (dUrca, pion or kaon condensate)

$$L^\infty_{\text{Fast}} \propto \tilde{T}_8^6 \ \text{erg/s}$$

«Slow»: processes (mURca, NN bremmstrahlung)

$$L^\infty_{\text{Slow}} \propto \tilde{T}_8^8 \ \text{erg/s}$$

Surface temperature



relaxation

$$t_r \sim 30 - 250 \text{ yr}$$

neutrino stage

$$t > t_r$$

$$L_\nu^\infty \propto \tilde{T}^n \Rightarrow \tilde{T} \propto t^{-1/(n-2)}$$

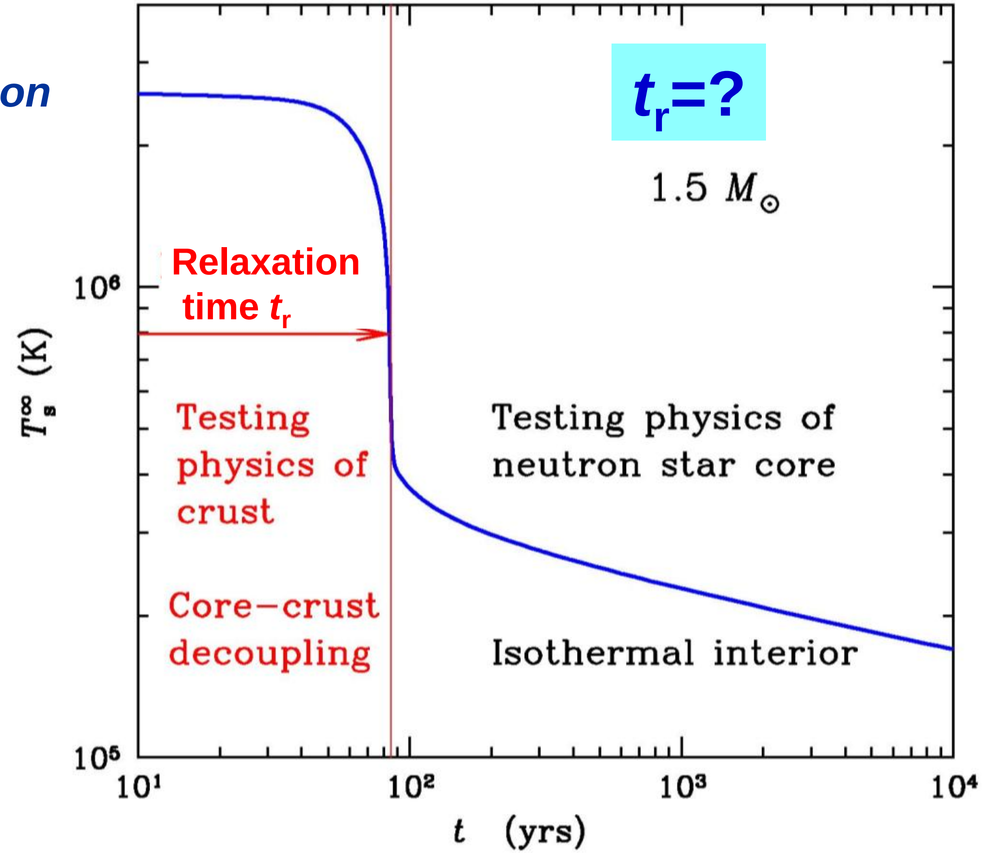
$$T_s^\infty \propto \tilde{T}^{0.4\div0.6} \Rightarrow T_s^\infty \propto t^{-(0.07\div0.15)}$$

Cas A: $T_s^\infty \propto t^{-1.3}$

Possible solutions. Relaxation time

Cas A observations:

- **Steep decline looks like a *thermal relaxation***
- ***Theory gives t_r<200 yr***



~~Case I: Delayed relaxation~~

Possible but unlikely from theory and observations (X-ray transients)

Case 2: One need to arrange the second «relaxation»

SUPERFLUIDITY

Neutrino emission from Cooper pair formation process can accelerate cooling

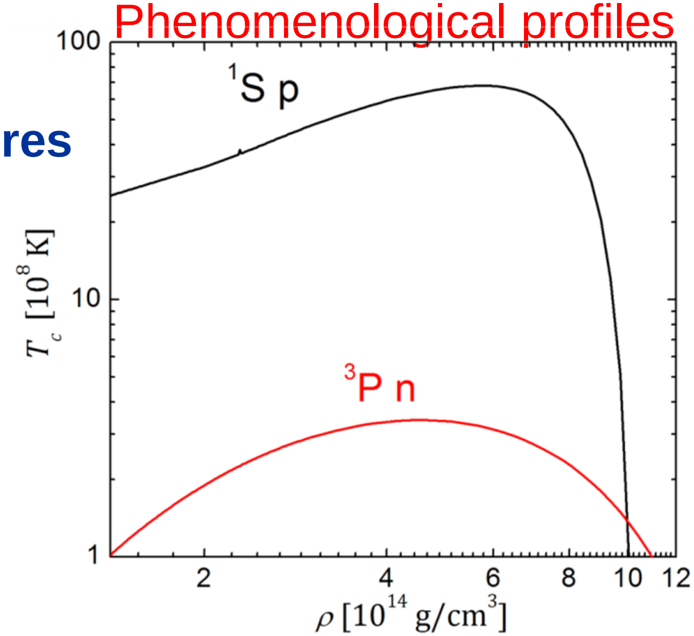
Superfluidity and cooling

Simplest case of **nuclear matter** in neutron star cores

Two types of superfluid:
  (1) $^3P_2$ neutron pairing ($T_{cn} = 10^8 – 10^{10}$ K)
  (2) $^1S_0$ proton pairing ($T_{cp} = 10^9 – 10^{10}$ K)

Two CPF emissions: (1) neutron; (2) proton

Phenomenological profiles



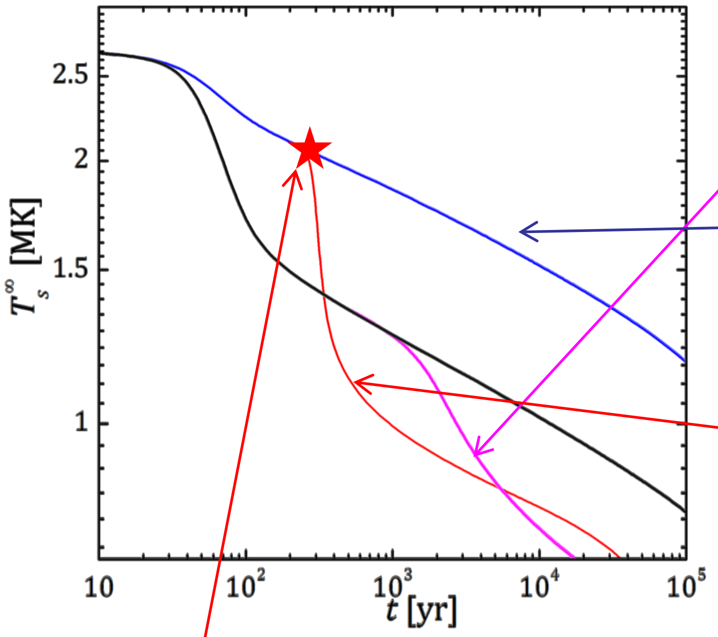
Proton CPF emission is strongly suppressed by numerical constants, it is unimportant for cooling

Divisions of responsibility:

(1) **Proton** superfluidity can strongly **suppress** standard neutrino reactions involving protons: mUrca and dUrca processes, n+p and p+p bremmstrahlung

(2) **Neutron** superfluidity can strongly **enhance** neutrino emission rate in comparison with mUrca level

Nucleon superfluidity and cooling



Neutron superfluidity:

accelerate cooling with CPF

Proton superfluidity:

decelerate cooling
CPF is unimportant

Together:

Sharp increase of the cooling rate

<u>Both SFs are important for CAS A</u>

Cooling regulators

$T_{\rm cn}^{\rm max}$ **and cooling rate at** $T < T_{\rm cn}^{\rm max}$ **– turn on point**

CPF luminosity

Critical temperature profile

– cooling rate (slope)

Model of the star

Neutron CPF emission. Collective effects

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

$$\int Q^{(\mathrm{CP})} \mathrm{d}V \propto T^8, \quad T \ll T_\mathrm{cn}$$

Collective effects

$$Q^{(\mathrm{CP})} = q\, Q_0^{(\mathrm{CP})}$$

q = suppression factor

Leinson (2001)

Leinson & Pérez (2006)

Sedrakian, Müther & Schuck (2007)

Kolomeitsev & Voskresensky (2008)

Steiner & Reddy (2009)

Leinson (2010)

^{1}S$_0$ $Q_s^{(CP)} \propto \left(\frac{4}{81}\left(\frac{v_\mathrm{F}}{c}\right)^4 C_\mathrm{V}^2 + \frac{6}{7}\left(\frac{v_\mathrm{F}}{c}\right)^2 C_\mathrm{A}^2\right) \quad q_s \ll 1$

e.g., Kolomeitsev & Voskresensky (2010)

^{3}P$_2$ $Q_t^{(\mathrm{CP})} \propto (C_\mathrm{V}^2 + 2C_\mathrm{A}^2) \quad q_t = 0.76$

Leinson (2010): $q_t = 0.19$

$$C_\mathrm{V} = 1, \quad C_\mathrm{A} = 1.26$$

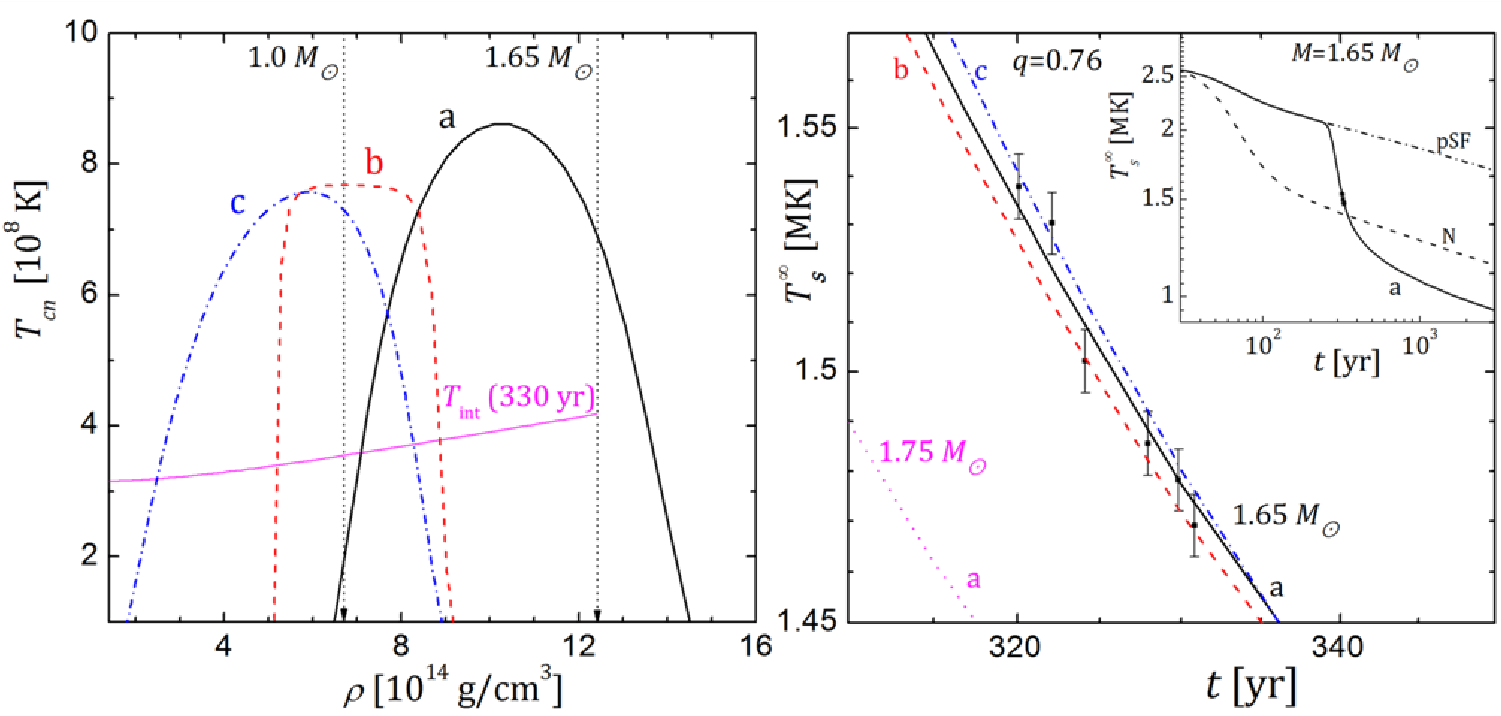
We treat q as phenomenological parameter

Results. Cas A NS cooling via CPF

mUrca cooling is suppressed by strong proton superfluidity

Model: APR EOS, M=1.65 Msun (best-fit of the spectral models)

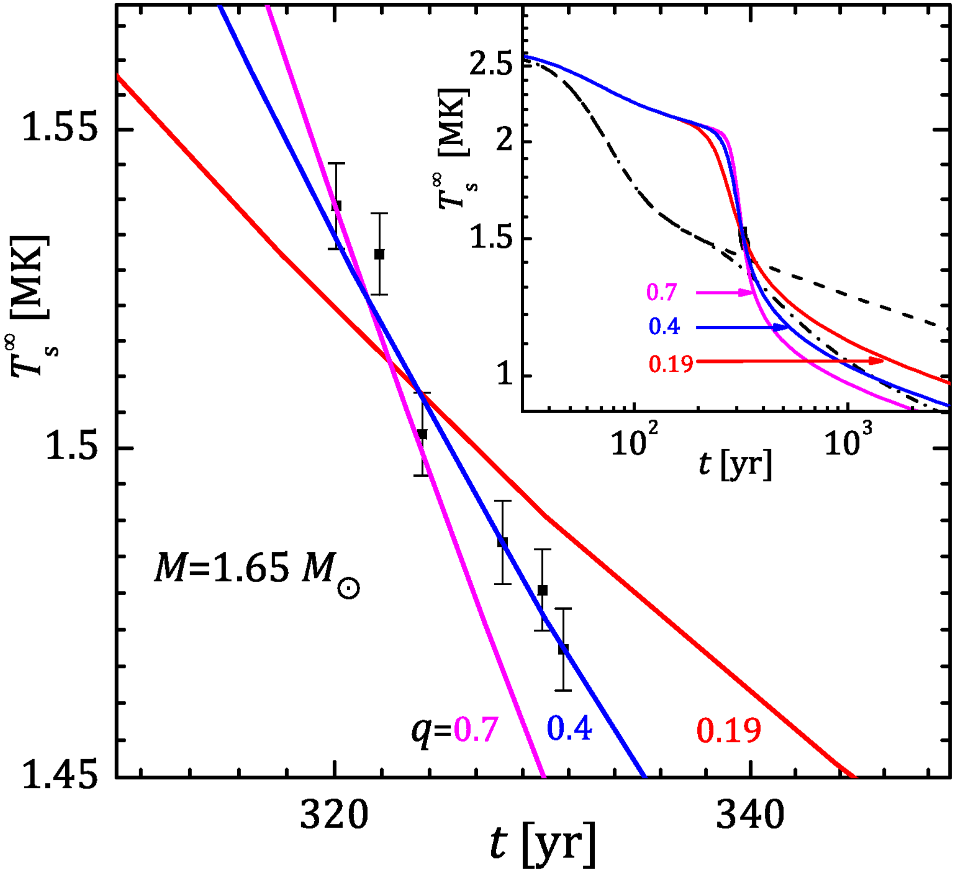
q=0.76



Superfluidity naturally explains observations

P.S. Shternin, D.G. Yakovlev, C.O. Heinke, W.C.G. Ho, D.J. Patnaude, MNRAS Lett., (2011)
D. Page, M. Prakash, J.M. Lattimer, A.W. Steiner, PRL, (2011)

Results. Parameter *q*



Constant ***T_{cn}*** **profile to maximize CPF emission**

$$q \gtrsim 0.4$$

More realistic (narrower profiles) require higher q

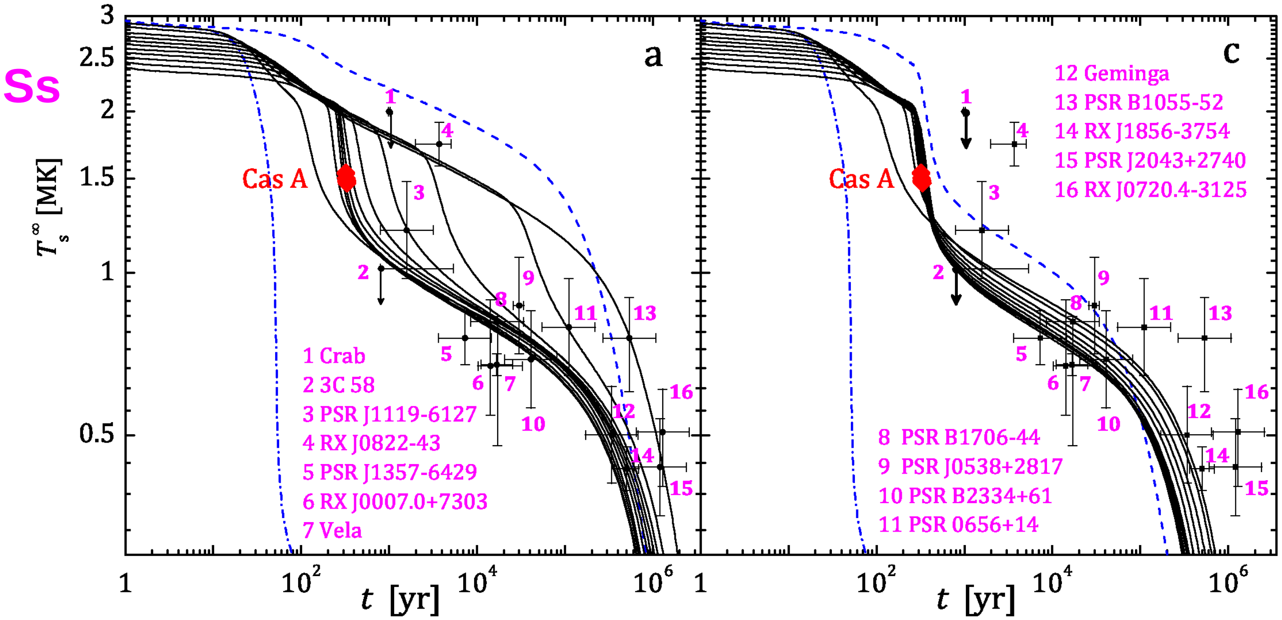
Same for weaker proton superfluidity

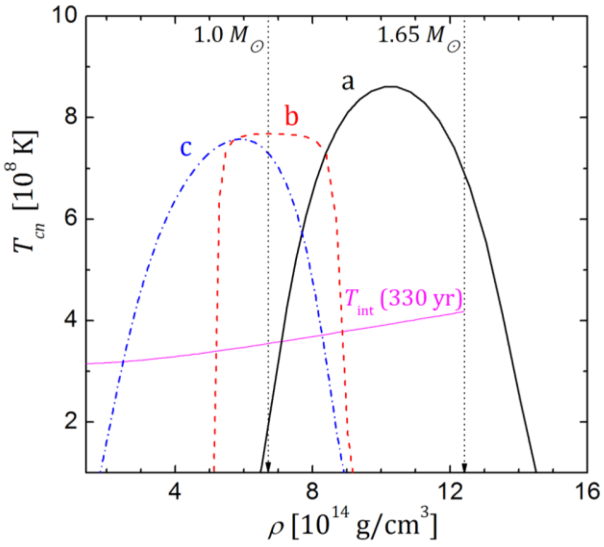
We can constrain $T_{cn}^{\max}, q,$ proton SF

Cas A NS and other isolated neutron stars

One model for all NSs

$$M = 1.0\,M_{\odot} - M_{\max}$$





Only T_{cn} profile (a) agrees with all observations

Gusakov et al. (2004)

Alternatively: broad T_{cn} profile
but $q = q(\rho)$ increasing with density

Conclusions

- **The November 2010 observations confirms the rapid cooling of the Cas A neutron star**

- **The cooling is naturally explained with aid of CPF emission of superfluid neutrons with** $T_{\rm cn}^{\rm max} \approx (5-9) \times 10^8$ K

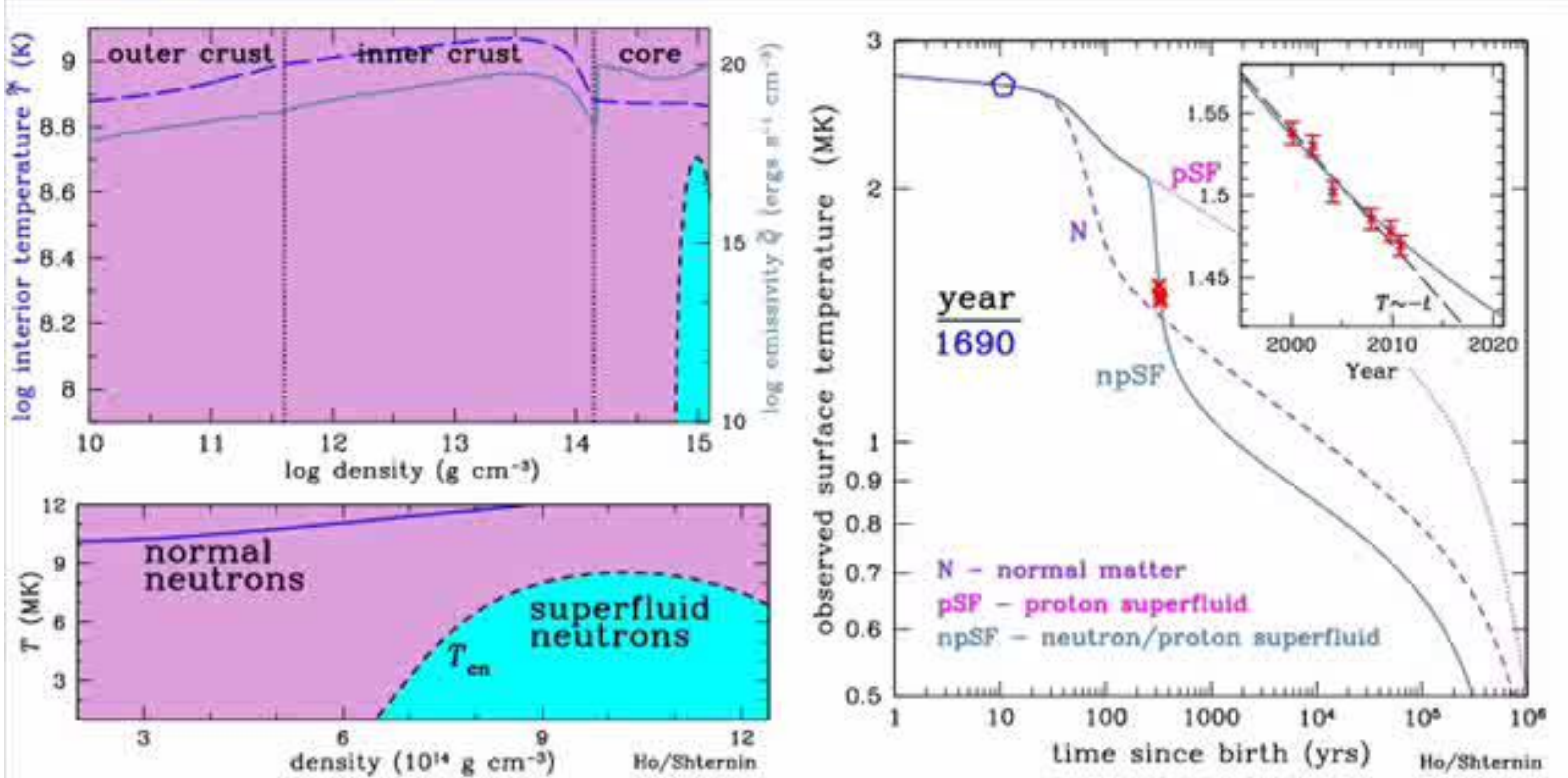
- **Critical temperature profile should not be to narrow and CPF emission should not be strongly supressed (*q*>0.4)**

- **Neutrino emission prior to onset of CPF should be 20-100 times weaker then the standard mUrca cooling rate**

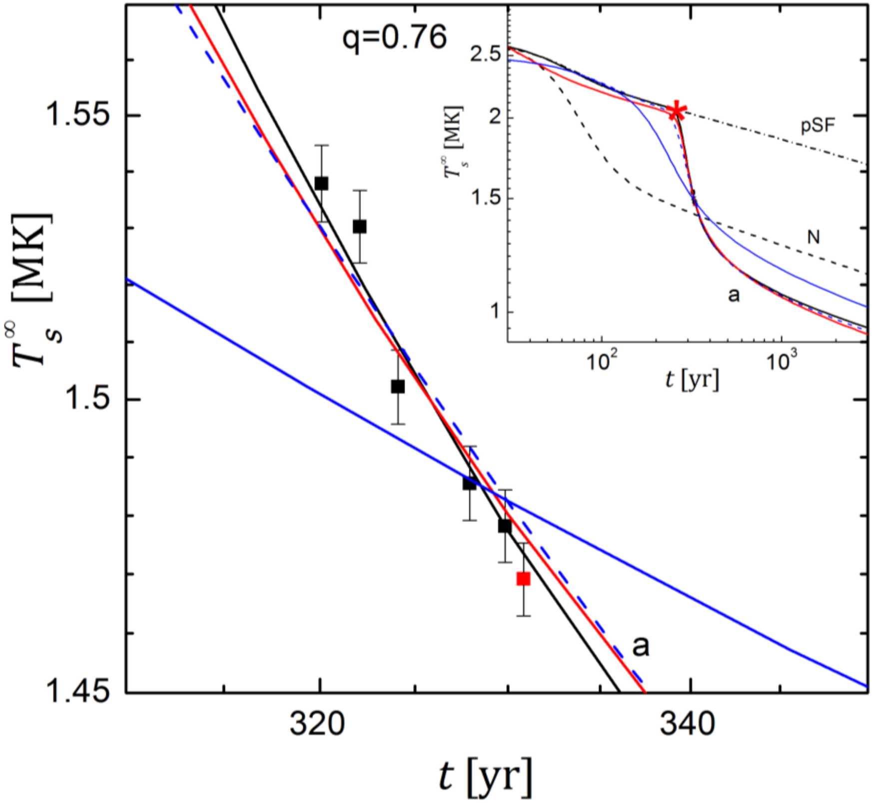
- **In order to explain the data on all INS with one model, $T_{\rm cn}$ profile should be shifted to higher densities**

- ***The Cas A NS cooling probably gives evidence of the presence of superfluidity in neutron star cores***

Movie (Wynn Ho)



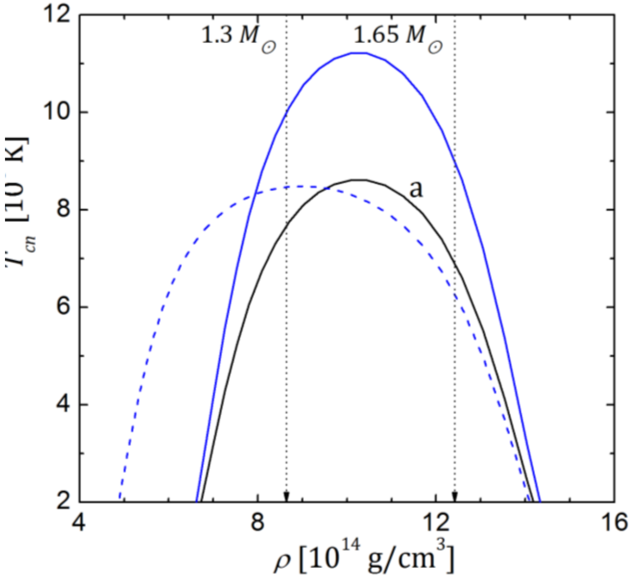
Results. Constraints of NS masses?



APR model with different masses Profile(a)

$$M = 1.65\ M_\odot \qquad T_{\rm cn8}^{\rm max} = 8.6$$
$$M = 1.9\ M_\odot \qquad T_{\rm cn8}^{\rm max} = 8.3$$
$$M = 1.3\ M_\odot \qquad T_{\rm cn8}^{\rm max} = 11.3$$

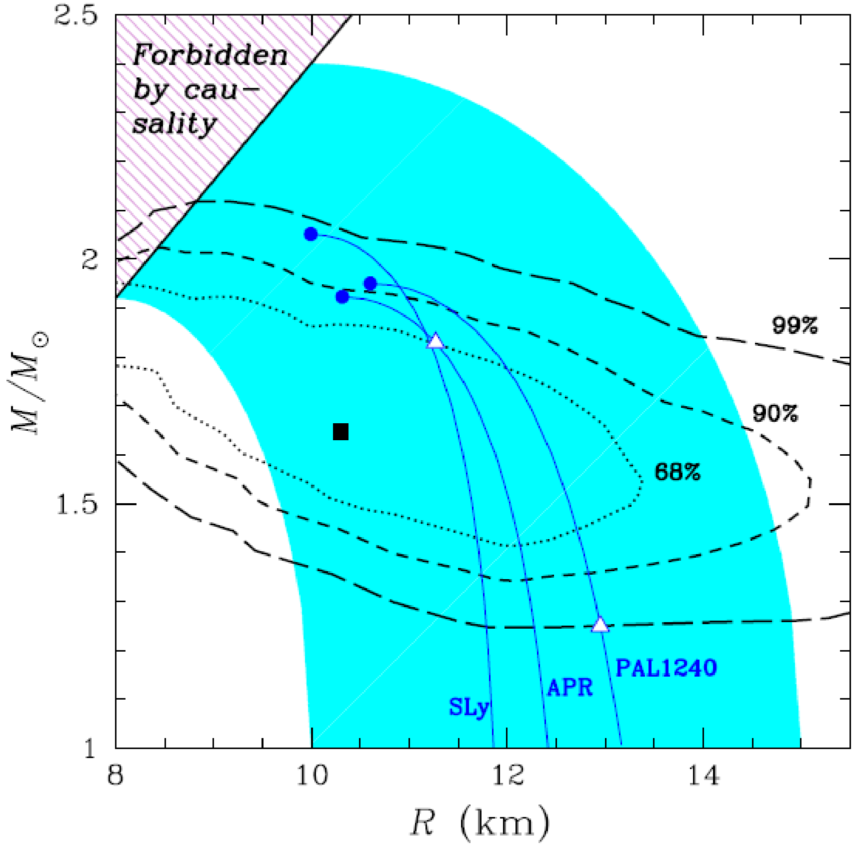
M=1.3 is bad? Shift the profile



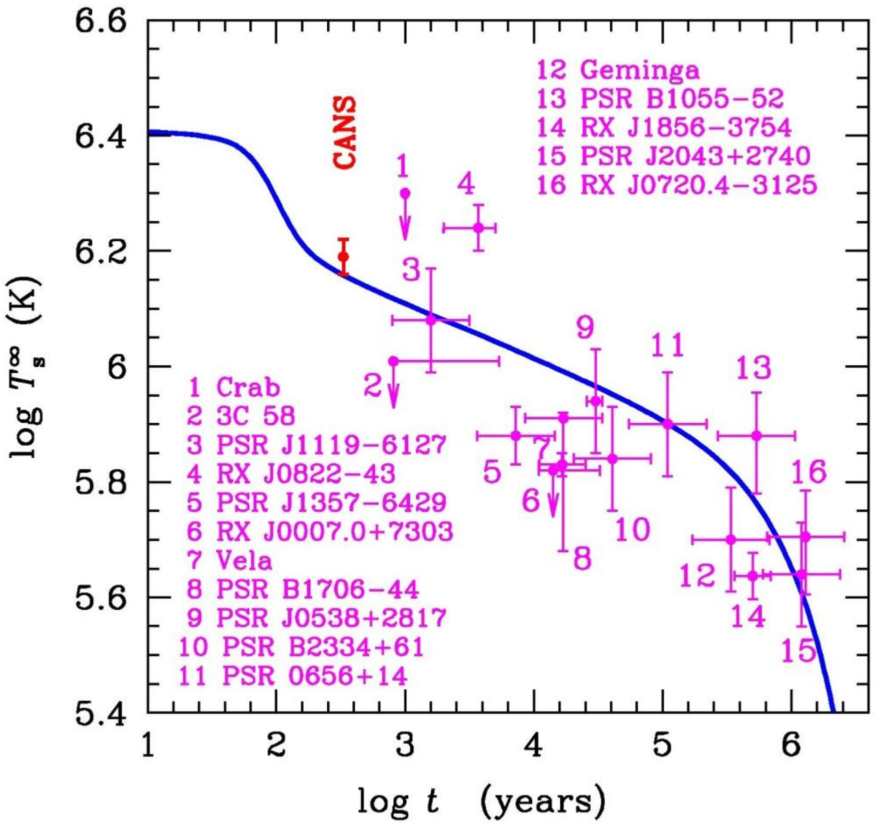
For any mass from 1.3 to 1.9 $M_{\rm sun}$ we can explain the data by modifying $T_{\rm cn}$ profile

Thermal state of the Cas A NS

Yakovlev, Ho, Shternin, Heinke, Potekhin, MNRAS (2011)



M and R confidence bands from Cas A spectral fitting

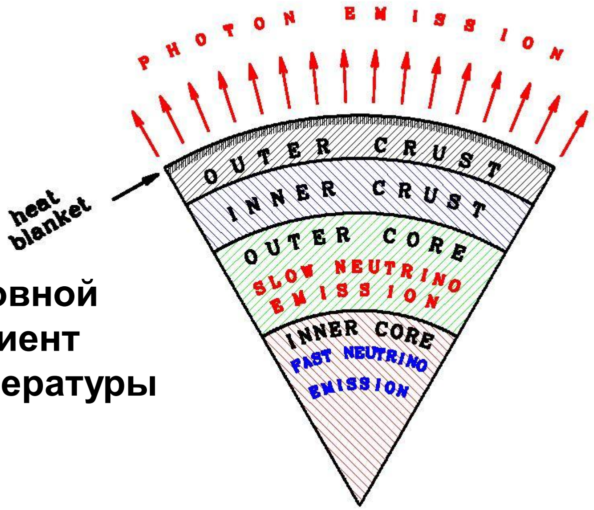


Observed temperature agrees with «standard» cooling theory (nonsuperfluid star which cools via modified Urca process)

No stringent constraints on neutron star parameters and internal structure

Теория остывания нейтронных звёзд

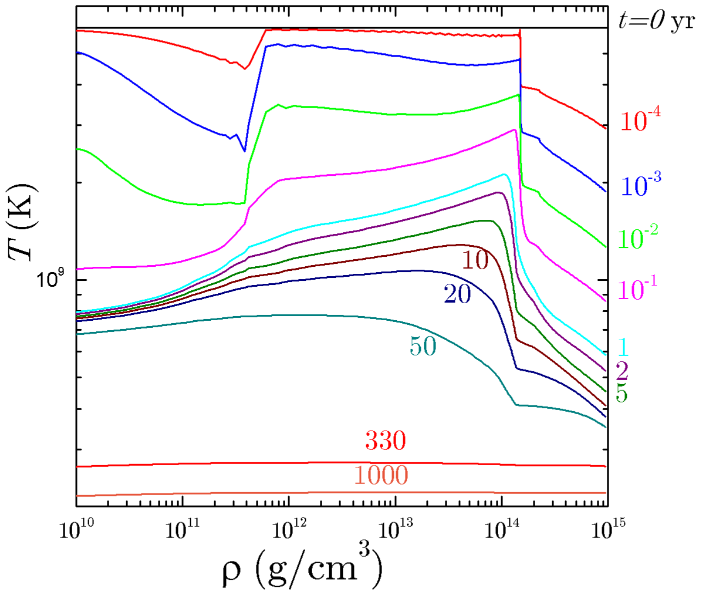
Молодые звёзды остывают за счёт нейтринного излучения

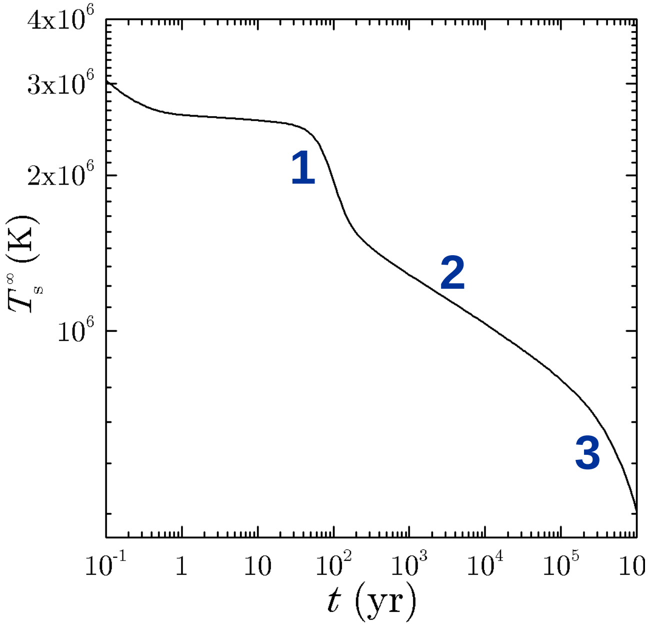


Основной градиент температуры

Три стадии остывания

Стадия	Длительность	Физика
Релаксация	**10—100 лет**	**Коры**
Нейтринная	**10—100 тыс. лет**	**Ядра, поверхности**
Фотонная	**навсегда**	**Поверхности, ядра**





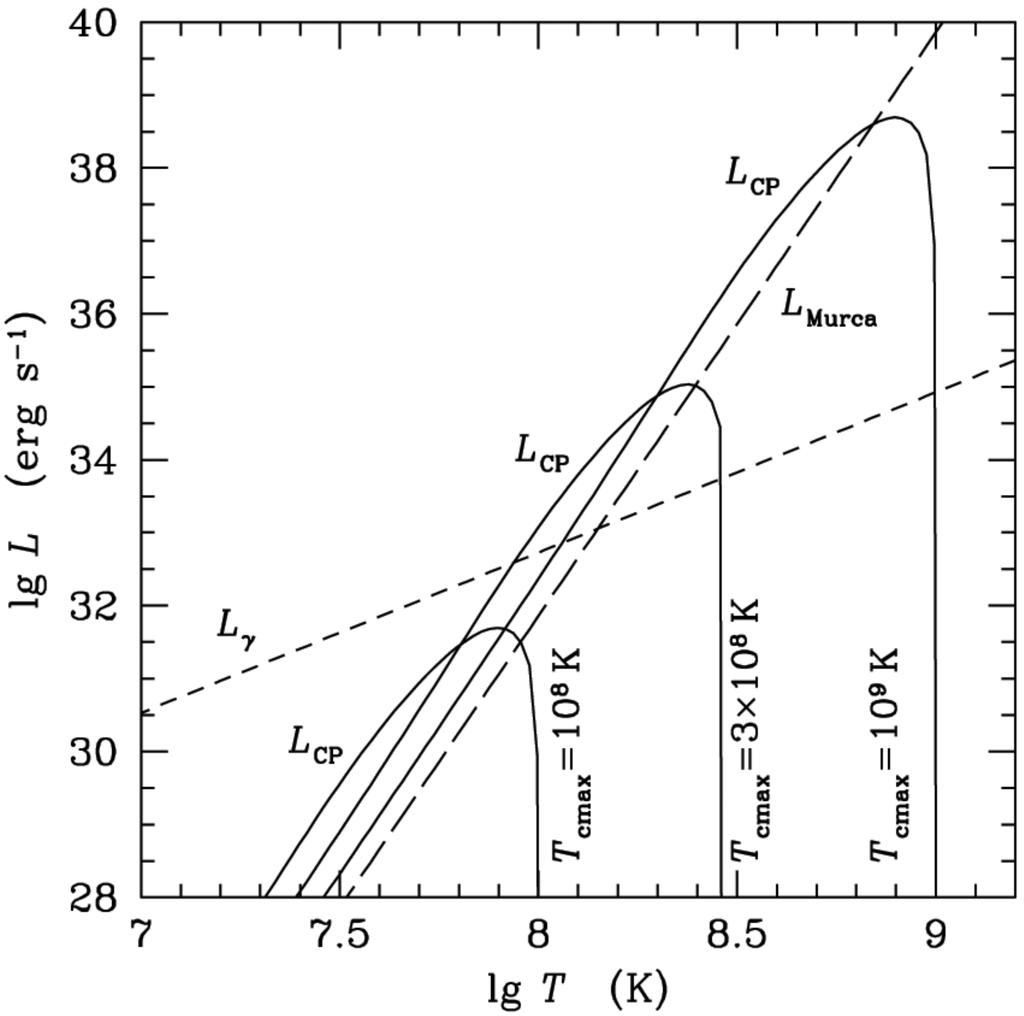
Эффективность нейтринного излучение

Излучение нейтроино при куперовском спаривании

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

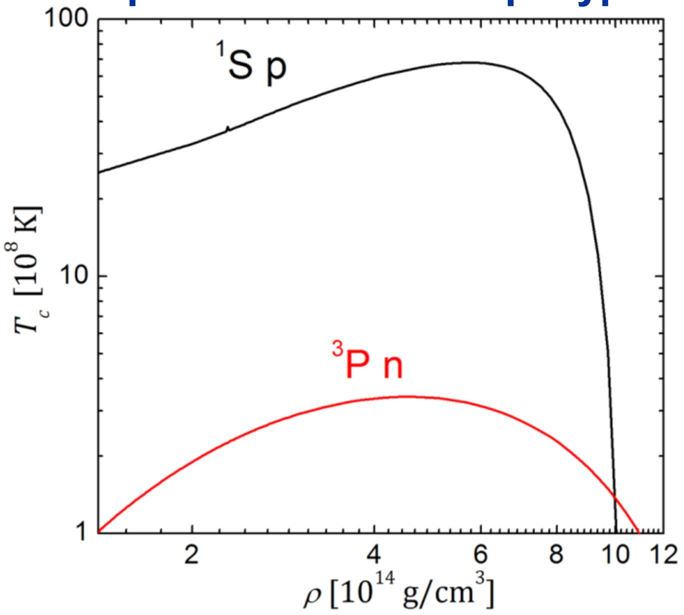
Нейтринное излучение при куперовском спаривании нейтронов может быть в 10—100 раз сильнее чем при модифицированном Урка-процессе в несверхтекучих звёздах

Моделирование:
Page et al. (2004)
Gusakov et al. (2004)



Superfluidity in neutron star

Критические температуры



Подавление «традиционных» нейтринных реакций

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

Изменение теплоемкости

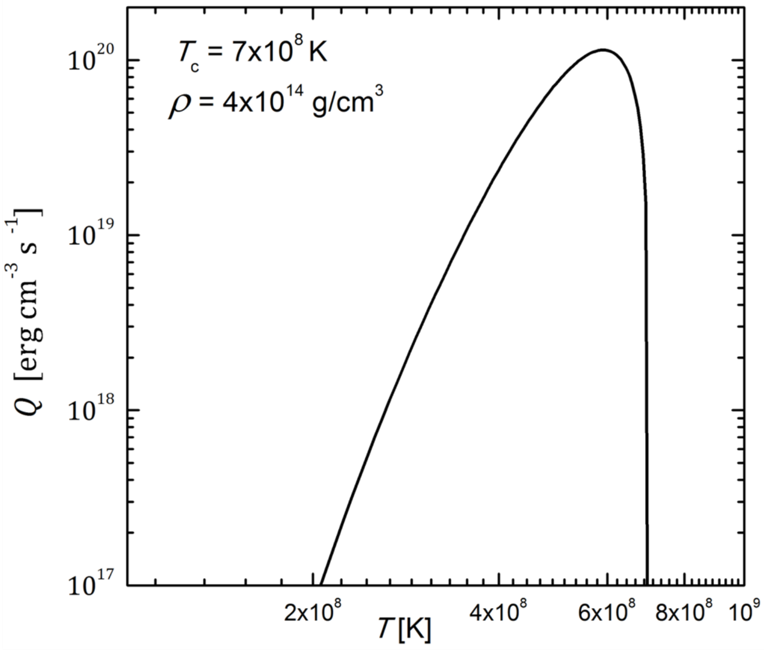
Излучение при куперовском спаривании (CPF)

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

Flowers, Ruderman & Sutherland (1976)

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

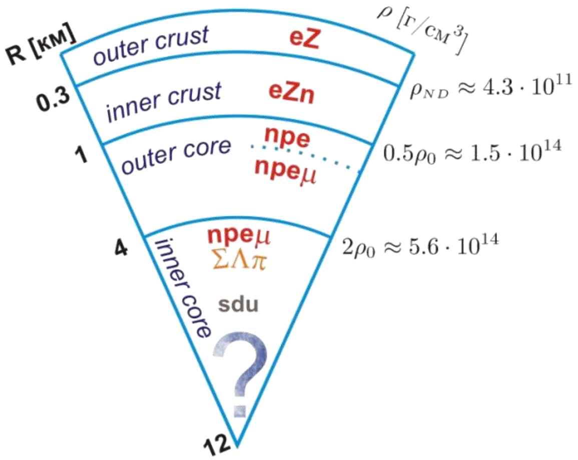
Levenfish, Kaminker & Yakovlev (1998)



Эффективно, при $T \ll T_{cnmax}$

$$\int Q \mathrm{dV} \propto T^8$$ **(как мУрка)**

Non-superfluid young NS cooling (remind talk by D.G. Yakovlev)



After relaxation

$$C(\tilde{T})\frac{\mathrm{d}\tilde{T}}{\mathrm{d}t} = -L_\nu^\infty(\tilde{T}) - L_s^\infty(T_s)$$

$$C(\tilde{T}) \propto \tilde{T}$$

Neutrino reactions (*npeμ*)

«Fast»: *Urca* processes

$$n \to p + e + \tilde{\nu}$$
$$p + e \to n + \nu$$

$$L_{\mathrm{dU}}^\infty \sim 10^{39}\, \tilde{T}_8^6 \ \mathrm{erg/s}$$

«Slow»: *mUrca* processes

$$n + N \to p + e + N + \tilde{\nu}$$
$$p + N + e \to n + N + \nu$$

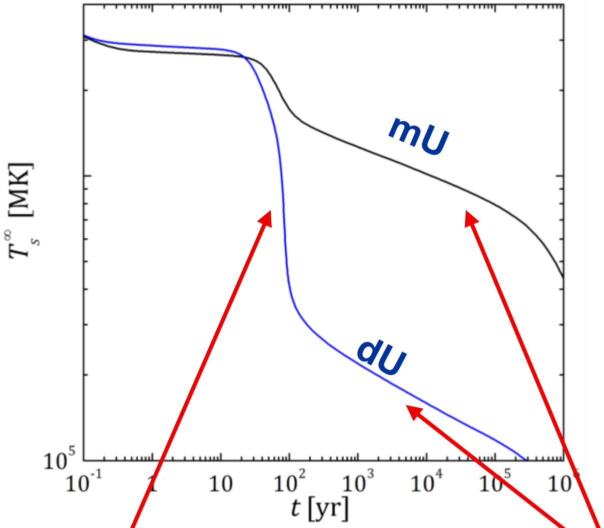
$$L_{\mathrm{mU}}^\infty \sim 10^{30}\, \tilde{T}_8^8 \ \mathrm{erg/s}$$

NN bremsstrahlung

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

$$L_{\mathrm{BS}}^\infty \sim 10^{28}\, \tilde{T}_8^8 \ \mathrm{erg/s}$$

Surface temperature



relaxation

$$t_r \sim 30 - 250 \ \mathrm{yr}$$

neutrino stage

$$t > t_r$$

$$L_\nu^\infty \propto \tilde{T}^n \Rightarrow \tilde{T} \propto t^{-1/(n-2)}$$

$$T_s^\infty \propto \tilde{T}^{0.4\div0.6} \Rightarrow T_s^\infty \propto t^{-(0.07\div0.15)}$$

Cas A: $T_s^\infty \propto t^{-1.3}$

Nucleon superfluidity

We use two phenomenological functions and one phenomenological parameter to be constrained from observations

$T_{cn}(\rho)$ – neutron critical temperature profile

***q* – CPF suppression factor**

To enhance cooling

$T_{cp}(\rho)$ – proton critical temperature profile

To suppress cooling