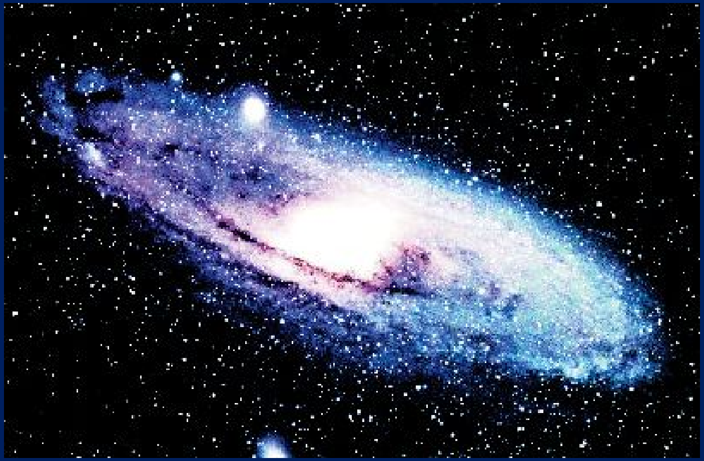
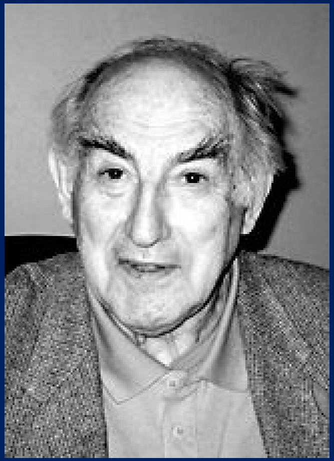

COOLING NEUTRON STARS AND SUPERFLUIDITY OF DENSE MATTER

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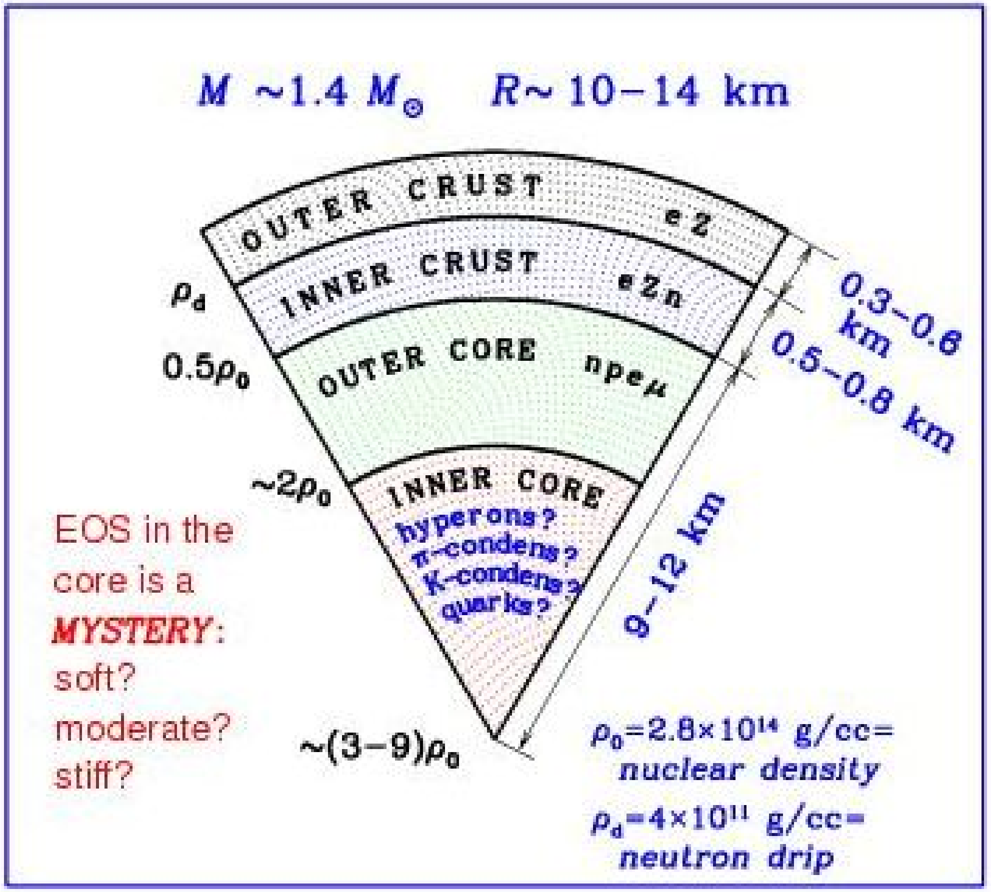
- *Introduction*
- *Cooling of non-superfluid neutron stars*
- *Neutron Star in Cassiopeia A*
- *Cooling of superfluid neutron stars*
- *Conclusions*

V. Ginzburg Conference, May 28, 2012

Neutron star structure



Mystery:
EOS of superdense matter in the core

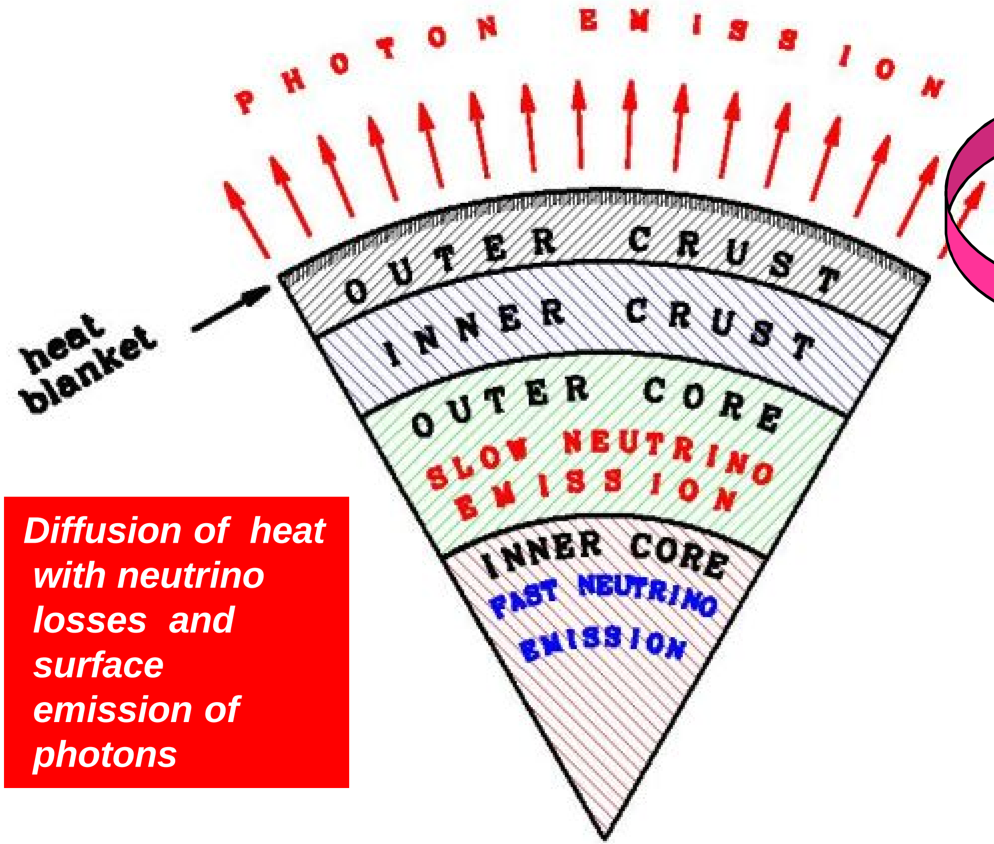
For simplicity, consider nucleon core:

- ***neutrons***
- ***protons***
- ***electrons***
- ***muons***

EOS=?

Superlfuidity=?

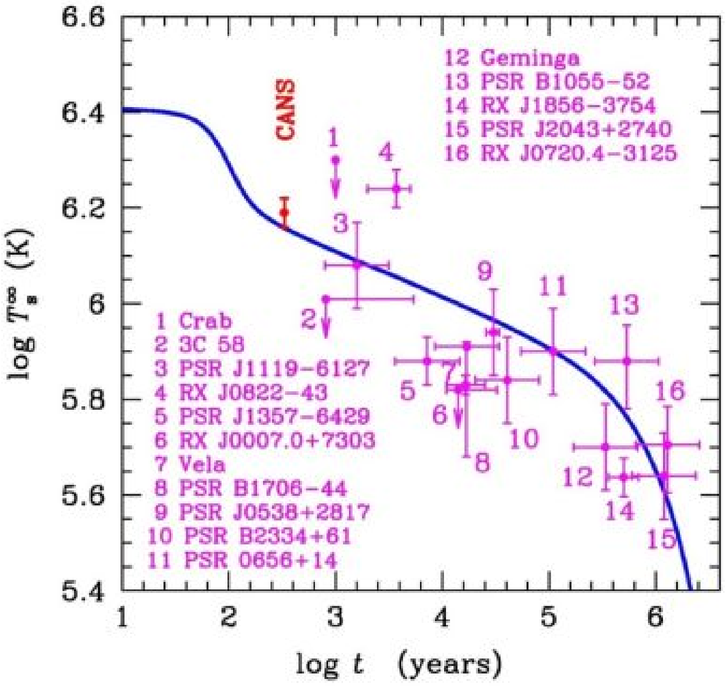
Cooling of neutron stars



Diffusion of heat with neutrino losses and surface emission of photons

Cooling regulators:

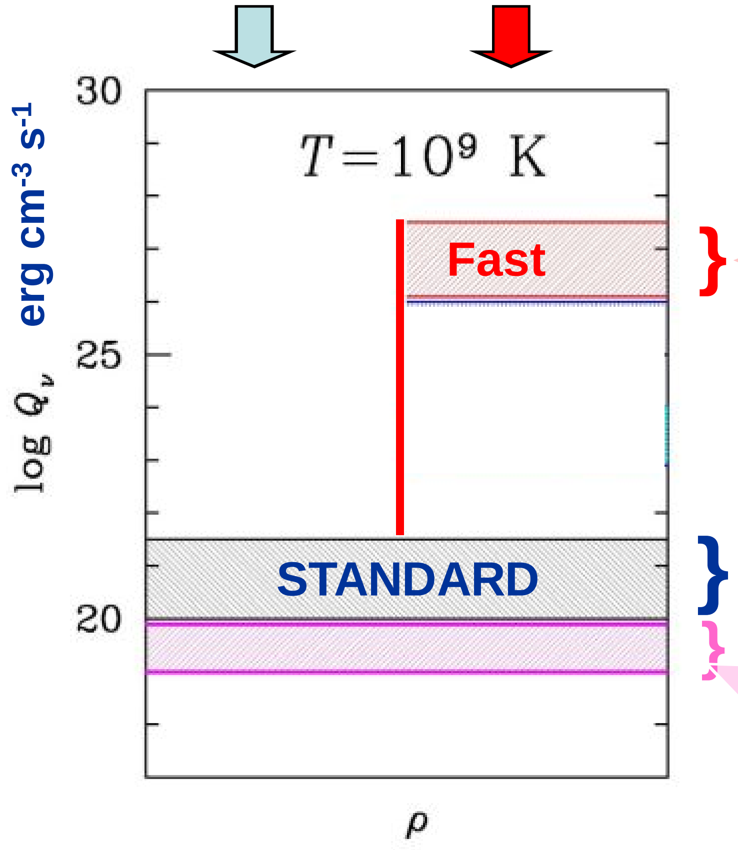
- *EOS*
- *Neutrino emission*
- *Heat capacity*
- *Thermal conductivity*
- *Superfluidity*



Neutrino emission from cores of non-superfluid NSs

Outer core
Slow emission

Inner core
Fast emission



NS with nucleon core:
N=n, p

Direct Urca

$$n \rightarrow p + e + \bar{\nu}_e \qquad p + e \rightarrow n + \nu_e$$

Modified Urca

$$nN \rightarrow pNe\bar{\nu} \qquad pNe \rightarrow nN\nu$$

NN bremsstrahlung

$$N + N \rightarrow N + N + \nu + \bar{\nu}$$

$$\left\{ \begin{matrix} n+n \\ n+p \\ p+p \end{matrix} \right.$$

Enhanced emission in inner cores of massive neutron stars:

$$Q_{\mathrm{FAST}} = Q_{0\mathrm{F}} T^6 \qquad L_{\mathrm{FAST}} = L_{0\mathrm{F}} T^6$$

Everywhere in neutron star cores:

$$Q_{\mathrm{SLOW}} = Q_{0\mathrm{S}} T^8 \qquad L_{\mathrm{SLOW}} = L_{0\mathrm{S}} T^8$$

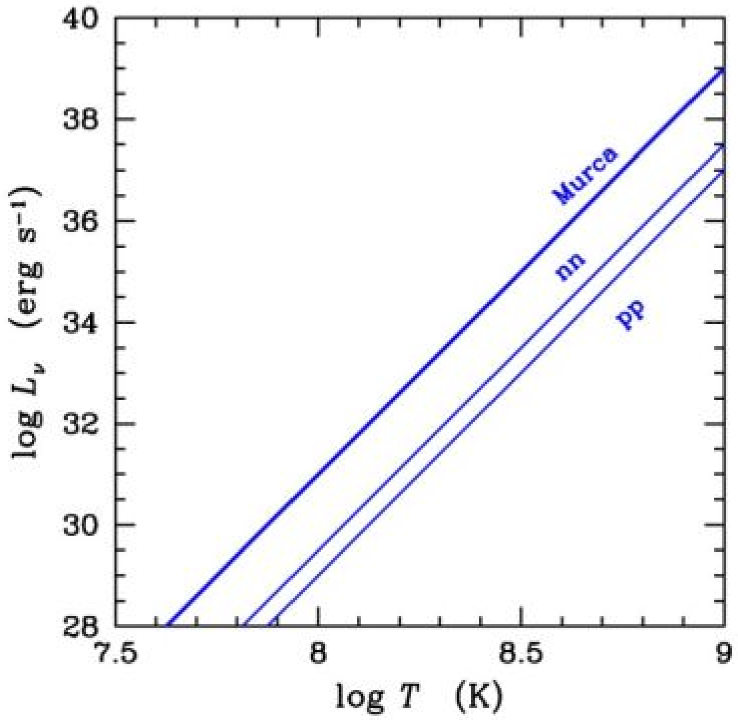
Neutrino emission of non-superfluid Neutron star: Murca cooling

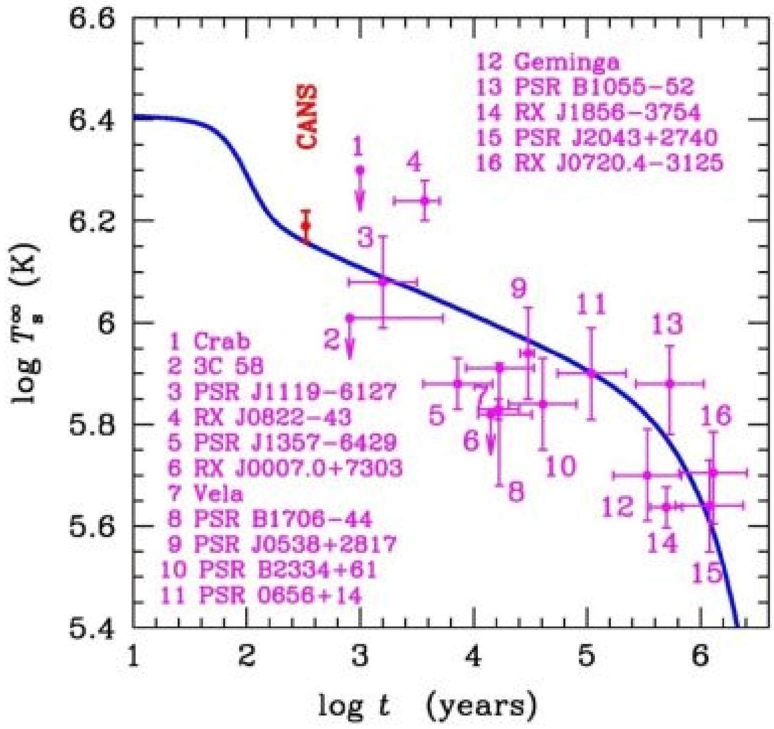
Casino da Urca – Urca – Durca – Murca – Kurca

K.P. Levenfish

G.A. Gamow

Hereafter: assume direct Urca is forbidden





1. $nN \to pNe\bar{\nu}$ $\quad pNe \to nN\nu$

2. $nn \to nn\nu\bar{\nu}$ $\quad$ 3. $np \to np\nu\bar{\nu}$ $\quad$ 4. $pp \to pp\nu\bar{\nu}$

$$s = -\frac{d \ln T_s}{d \ln t} \approx 0.1$$

Cassiopeia A supernova remnant

Very bright radio source
Weak in optics due to interstellar absoprtion

Distance: $3.4^{+0.3}_{-0.1}$ **kpc** *(Reed et al. 1995)*

Diameter: **3.1 pc**

No historical data on progenitor

Asymmetric envelope expansion
Age 330 ± 20 **yrs => 1680**
from observations of expanding envelope
(Fesen et al. 2006)

Cassiopeia A observed by
the Hubble Space Telescope

MYSTERIOUS COMPACT CENTRAL OBJECT IN Cas A SNR

Various theoretical predictions:
e.g., a black hole (Shklovsky 1979)

Discovery:** Tananbaum **(1999)
*first-light **Chandra** X-ray observations*
Later found** in **ROSAT** and **Einstein
archives

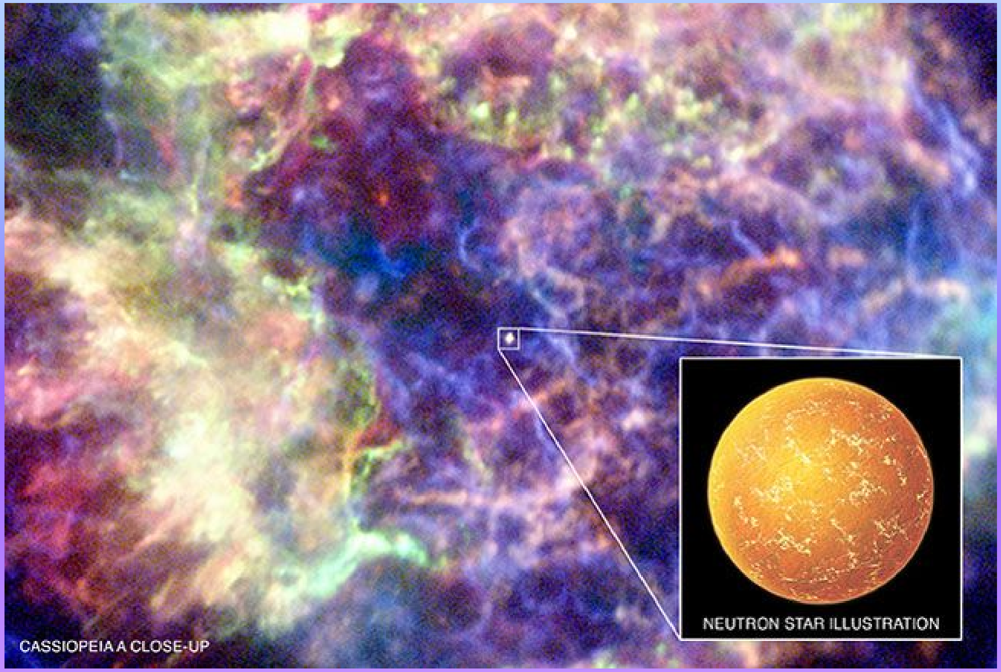
Later studies (2000-2009):

Pavlov et al. (2000)
Chakrabarty et al. (2001)
Pavlov and Luna (2009)

Main features:

1. *No evidence of pulsations*
2. *Spectral fits using black-body model or He, H, Fe atmosphere models give too small radius R<5 km*

***Conclusion:** MYSTERY –*
Not a thermal X-ray radiation emitted from the entire surface of neutron star



A Chandra X-ray Observatory image of the supernova remnant Cassiopeia A.
Credit: Chandra image:
NASA/CXC/Southampton/W.Ho;
illustration: NASA/CXC/M.Weiss

COOLING NEUTRON STAR IN Cas A SNR

Ho and Heinke (2009) Nature 462, 671

Fitting the observed spectrum with carbon atmosphere model gives the emission from the entire neutron star surface

Conclusion:

Cas A SNR contains cooling neutron star with carbon surface

It is the youngest cooling NS whose thermal radiation is observed

Neutron star parameters

$M \approx 1.5 - 2.4 M_\odot$ $\quad R \approx 8 - 18$ km

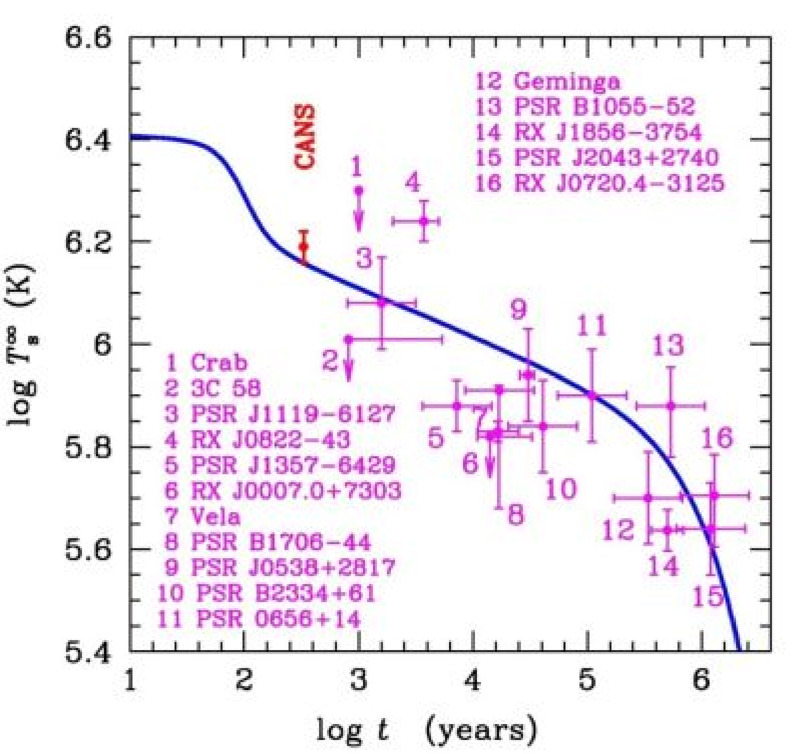
$T_s \sim 2 \times 10^6$ K $\quad B \lesssim 10^{11}$ G

Main features:

1. *Rather warm neutron star*
2. *Consistent with standard cooling*
3. *Not interesting for cooling theory!!! (Yakovlev et al. 2011)*

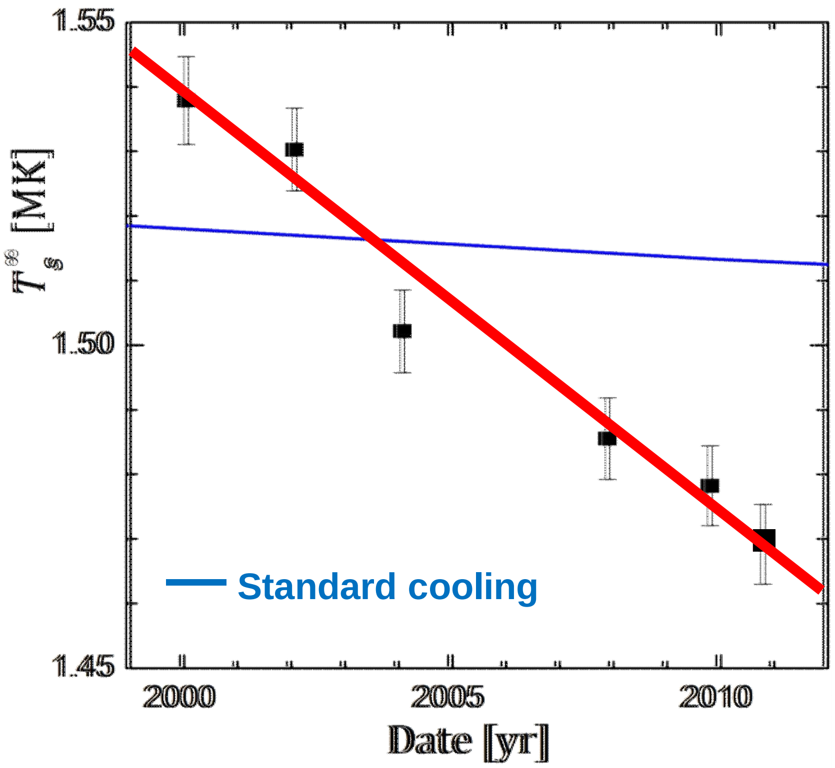
OBSERVATIONS available for Ho and Heinke (2009) Heinke and Ho (2010):

16 sets of Chandra observations in 2000, 2002, 2004, 2006, 2007, 2009 totaling 1 megasecond (two weeks)



REVOLUTION: Cooling Dynamics of Cas A NS!

Heinke & Ho, ApJL (2010): **Surface temperature decline by 4% over 10 years**



M, R, d, N_H are fixed

"Standard cooling" cannot explain these observations

Observed cooling curve slope

$$s = -\frac{d\ln T_s}{d\ln t} \approx 1.35 \pm 0.15\ (2\sigma)$$

Standard cooling curve slope

$$s = -\frac{d\ln T_s}{d\ln t} \approx 0.1$$

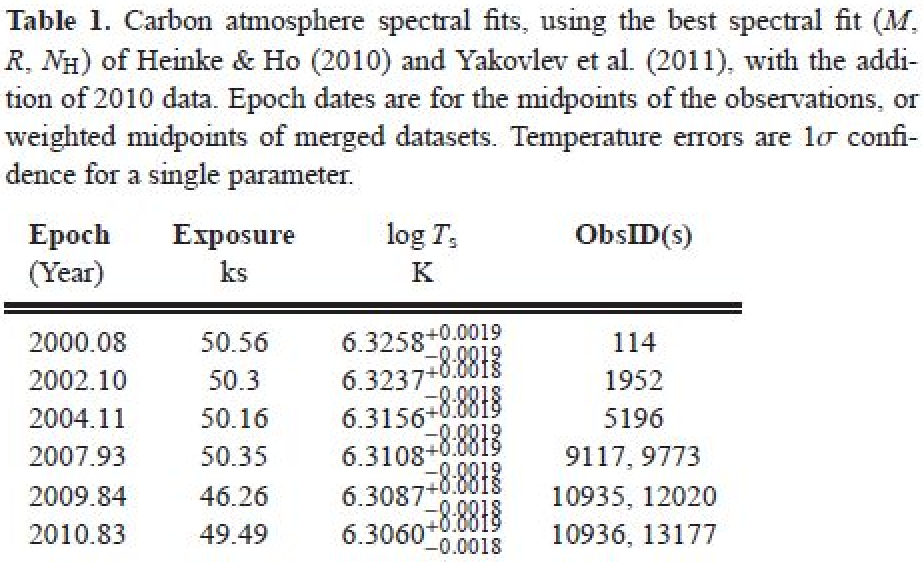


Table 1. Carbon atmosphere spectral fits, using the best spectral fit (M, R, $N_{\rm H}$) of Heinke & Ho (2010) and Yakovlev et al. (2011), with the addition of 2010 data. Epoch dates are for the midpoints of the observations, or weighted midpoints of merged datasets. Temperature errors are 1σ confidence for a single parameter.

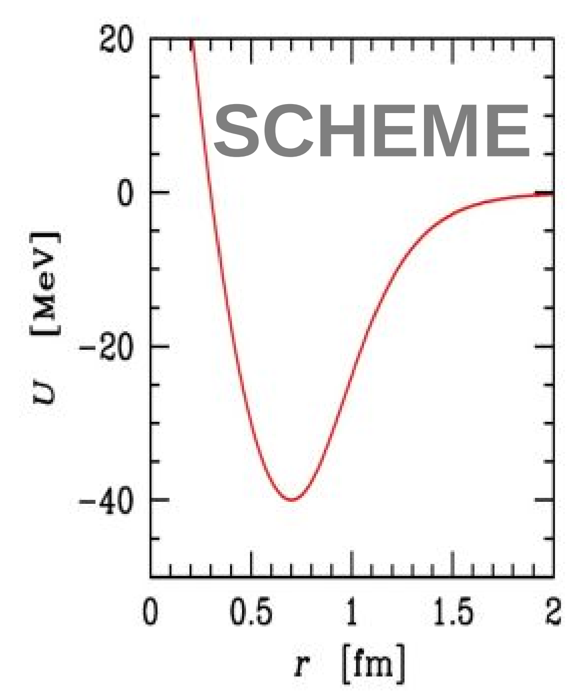
Epoch (Year)	Exposure ks	$\log T_s$ K	ObsID(s)
2000.08	50.56	$6.3258^{+0.0019}_{-0.0019}$	114
2002.10	50.3	$6.3237^{+0.0018}_{-0.0018}$	1952
2004.11	50.16	$6.3156^{+0.0019}_{-0.0019}$	5196
2007.93	50.35	$6.3108^{+0.0019}_{-0.0019}$	9117, 9773
2009.84	46.26	$6.3087^{+0.0018}_{-0.0018}$	10935, 12020
2010.83	49.49	$6.3060^{+0.0019}_{-0.0018}$	10936, 13177

Cas A neutron star:

1. **Is warm as for standard cooling**
2. **Cools much faster than for standard cooling**

Superfluidity – neutron stars

Mechanism of superfluidity: *Cooper pairing of degenerate neutrons and/or protons due to nuclear attraction*



Any superfluidity is defined by
critical temperature T_C*, that depends on density*

Pairing type: *singlet-state* $(^1S_0)$
or triplet state $(^3P_2)$

Inner crust of neutron star:
Singlet-state pairing of free neutrons
Singlet-state pairing of nucleons in atomic nuclei

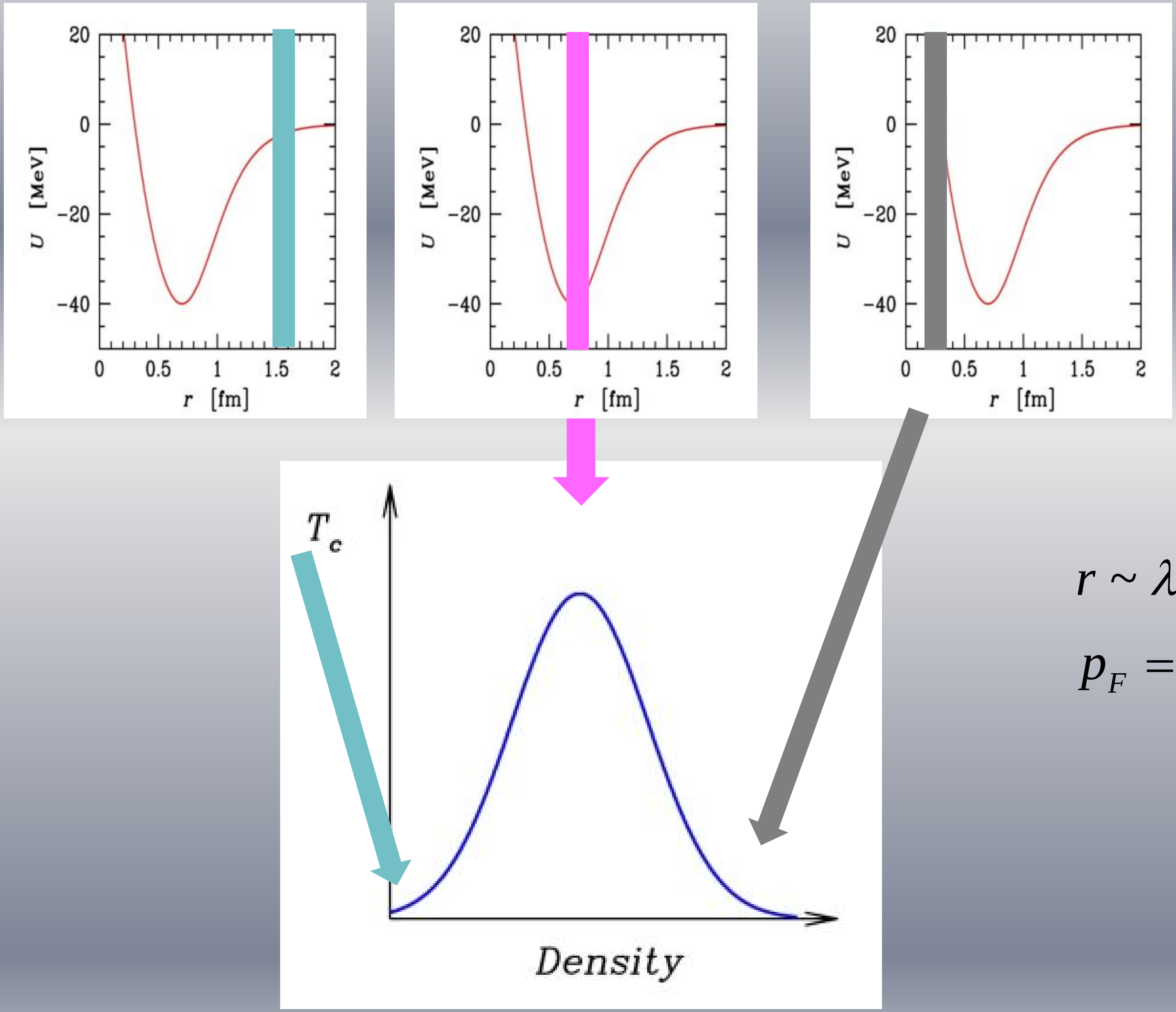
Neutron star core (typically):
Singlet-state pairing of protons
Triplet-state pairing of neutrons

Superfluidity – neutron stars

Low densities
Weak pairing

Medium densities
Strong pairing

High densities
Repulsion, no pairing



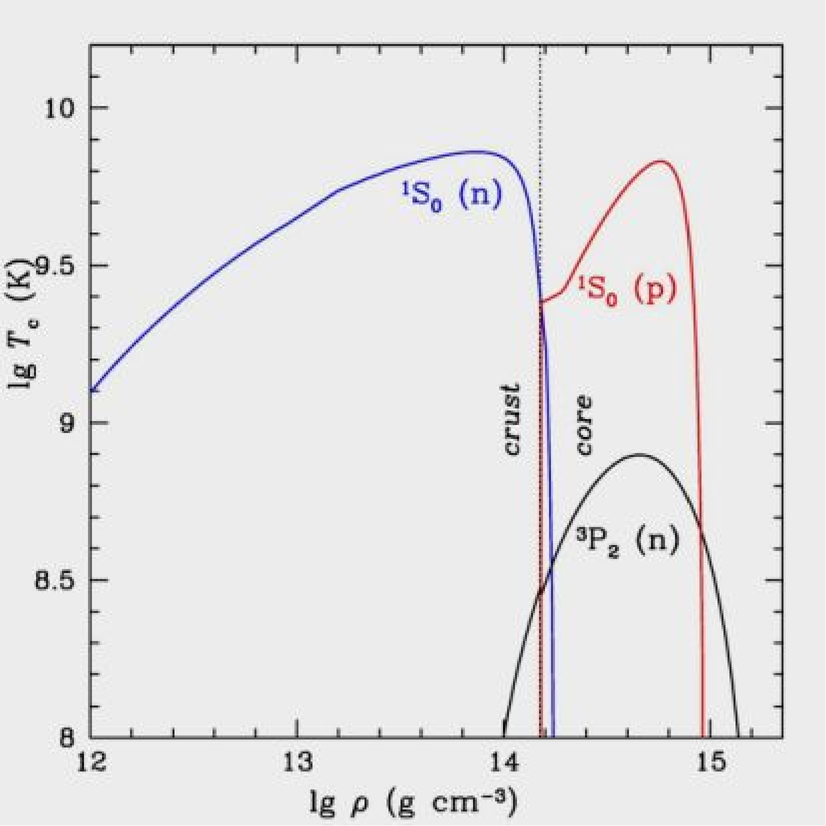
$$r \sim \lambda \sim \hbar / p_F$$

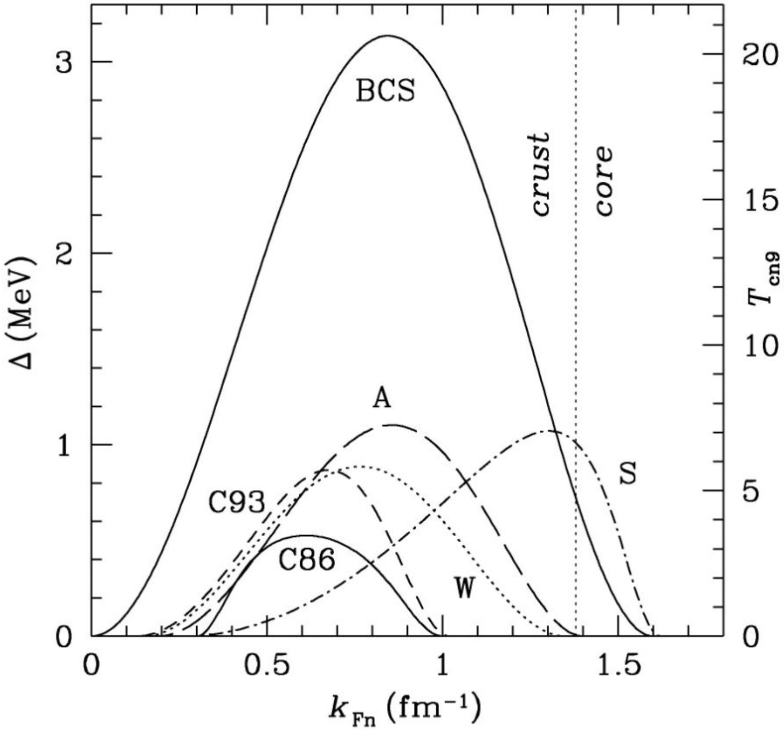
$$p_F = \hbar(3\pi^2 n)^{1/3}$$

Superfluidity – Critical temperatures

Dependence of T_c on density

$\Delta_0 \sim 1\ \text{MeV} \qquad T_c \sim 10^{10}\ \text{K} \quad \text{high}\ \ T_c\,!!!$





At high densities superfluidity disappears

After Lombardo & Schulze (2001)
A=Ainsworth, Wambach, Pines (1989)
S=Schulze et al. (1996)
W=Wambach, Ainsworth, Pines (1993)
C86=Chen et al. (1986)
C93=Chen et al. (1993)

Our task is to study $T_{cn}(\rho),\ T_{cp}(\rho)$ **in neutron star core**

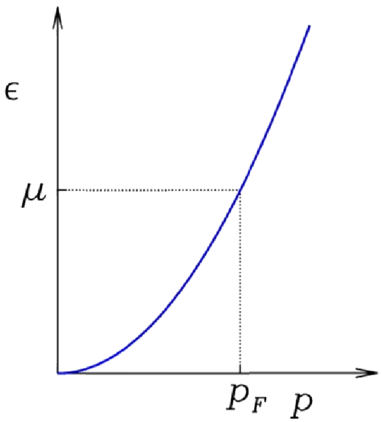
Superfluidity – microscopic manifestations

Creates gap $\Delta(\rho, T)$ ***in energy spectrum near Fermi level***

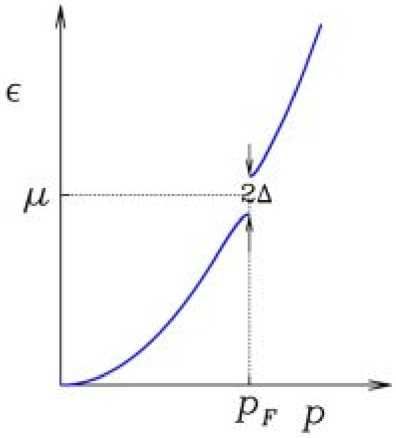
$$\varepsilon = \frac{p^2}{2m}$$

Microscopic calculations of the gap are very model dependent (nuclear interaction; many-body effects)

T=0

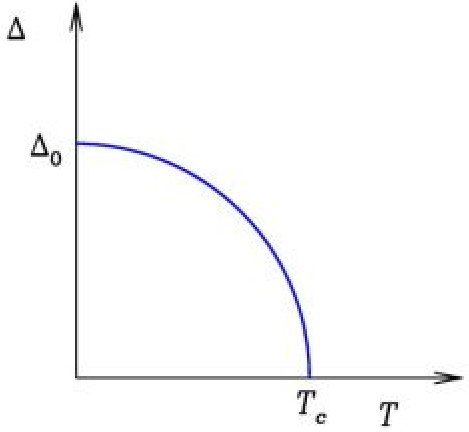


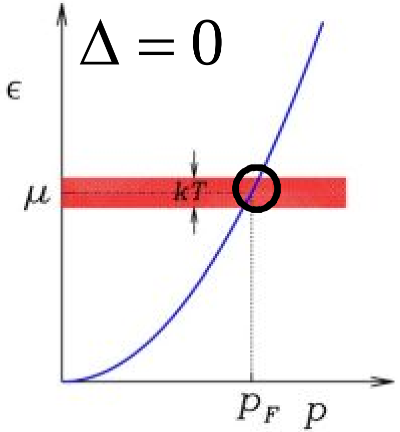
Free Fermi gas



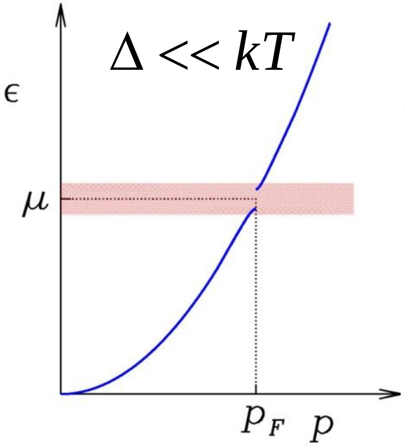
Superfluid Fermi gas

Temperature dependence

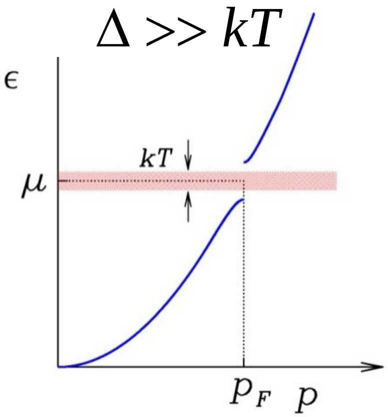




Free Fermi gas T>T_c



Superfluid Fermi gas T~T_c



Superfluid Fermi gas T<<T_c

Effects of superfluidity on properties of matter

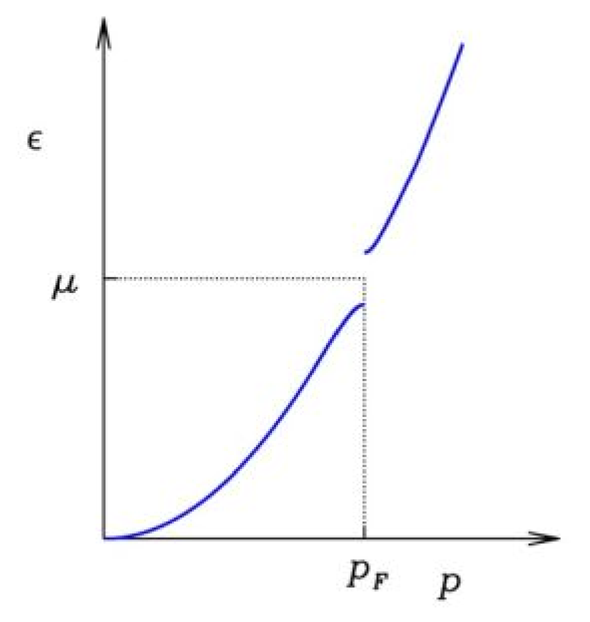
Cooper pairing at $T<T_c$

- has almost no effect of EOS and hydrostatic structure of neutron stars

- suppresses ordinary neutrino processes (especially at $T<<T_c$)

- switches on a new specific mechanism of neutrino emission

- affects heat capacity



Neutrino emission due to Cooper pairing

Flowers, Ruderman and Sutherland (1976)

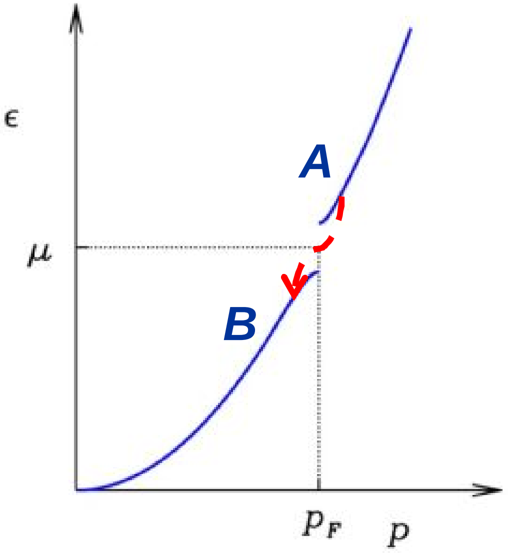
Voskresensky and Senatorov (1987)

Schaab et al. (1997)

$$\tilde{n} + \tilde{n} \rightarrow \nu + \bar{\nu}$$

Physics:

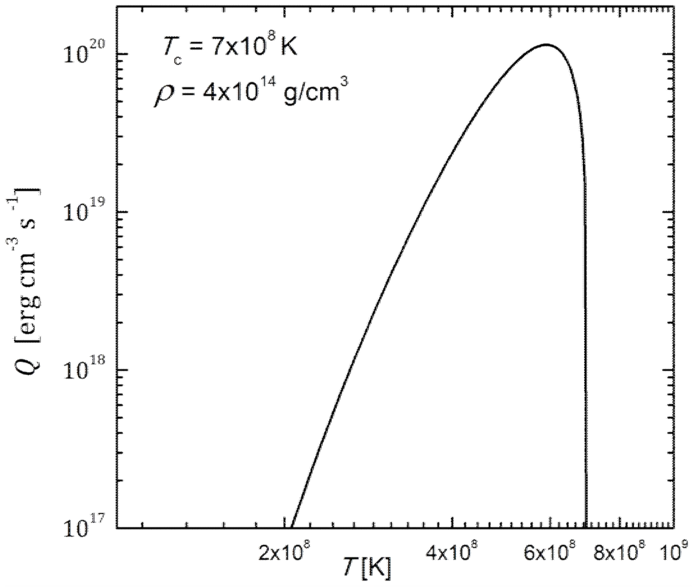
Jumping over cliff from branch A to B



Features:

- ***Efficient only for triplet-state pairing of neutrons***
- ***Non-monotonic T-dependence***
- ***Strong many-body effects***

Leinson (2001)
Leinson and Perez (2007)
Sedrakian, Muether, Schuck (2007)
Kolomeitsev, Voskresensky (2008)
Steiner, Reddy (2009)
Leinson (2010)



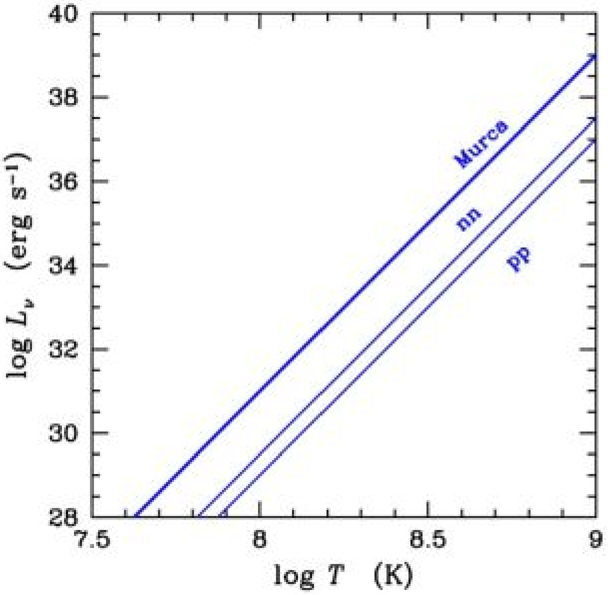
Temperature dependence of neutrino emissivity due to Cooper pairing

Neutrino luminosity of superfluid neutron star

Non-superfluid star with nucleon core

Standard Murca cooling

$$L_\nu = L_\nu^{Murca}$$



$$\boxed{nN \to pNe\bar{\nu} \qquad pNe \to nN\nu}$$

$nn \to nn\nu\bar{\nu}$

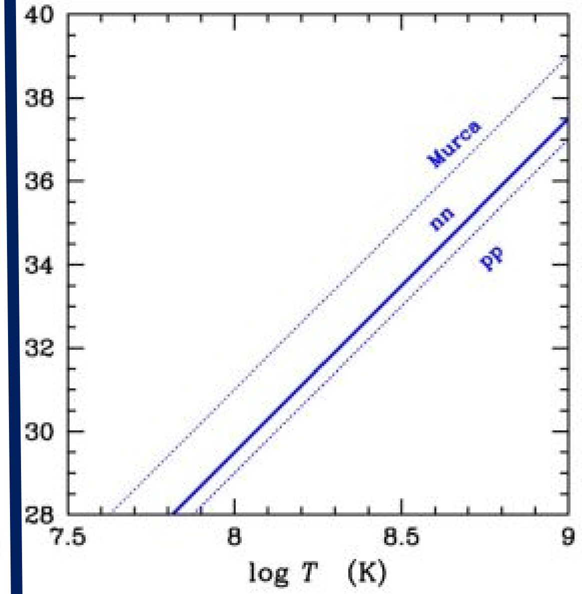
$np \to np\nu\bar{\nu}$

$pp \to pp\nu\bar{\nu}$

Add strong proton superfluidity

Very slow cooling

$$L_\nu \sim 0.01\ L_\nu^{Murca}$$



~~$nN \to pNe\bar{\nu} \qquad pNe \to nN\nu$~~

$$\boxed{nn \to nn\nu\bar{\nu}}$$

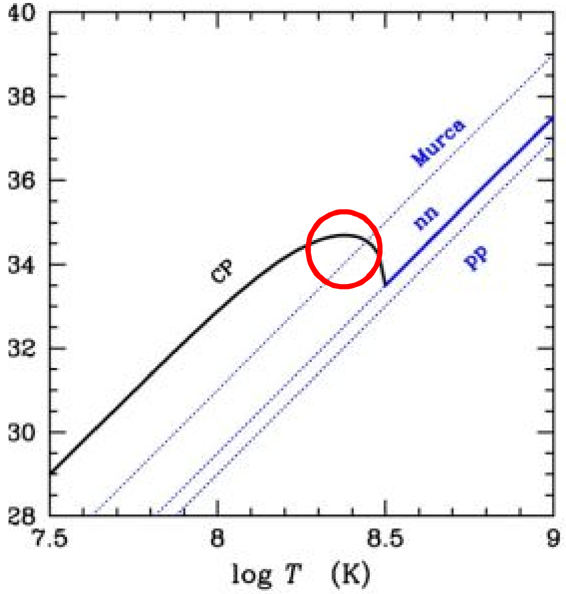
~~$np \to np\nu\bar{\nu}$~~

~~$pp \to pp\nu\bar{\nu}$~~

Add moderate neutron superfluidity:

CP neutrino splash

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



~~$nN \to pNe\bar{\nu} \qquad pNe \to nN\nu$~~

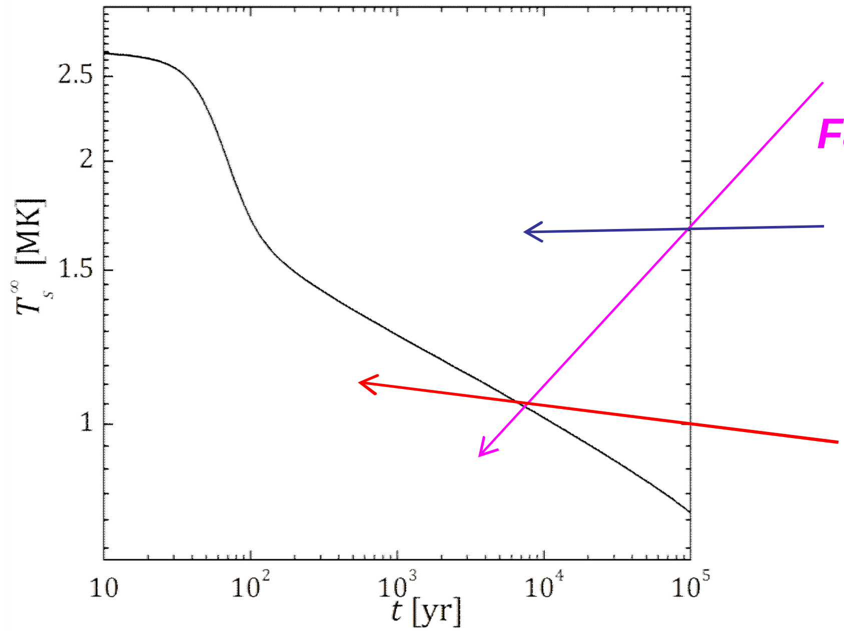
~~$nn \to nn\nu\bar{\nu}$~~

~~$np \to np\nu\bar{\nu}$~~

~~$pp \to pp\nu\bar{\nu}$~~

$$\boxed{\tilde{n}\tilde{n} \to \nu\bar{\nu}}$$

Effects of Superfluidity on Cooling



Neutron superfluidity:

Faster cooling because of CP neutrino emission

Proton superfluidity:

Slower cooling because of suppression of neutrino emission

Together:

Sharp acceleration of cooling

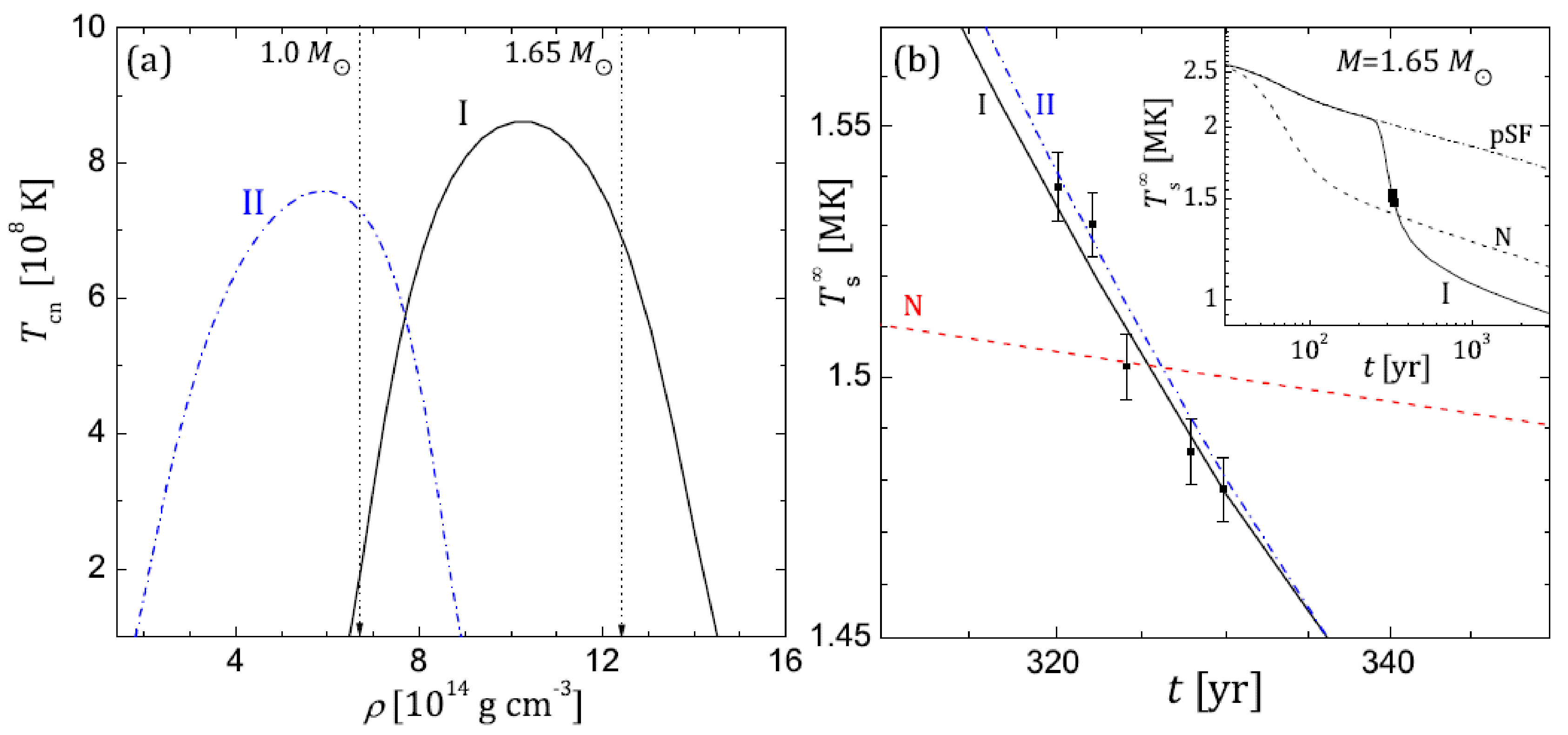
Superfluidity naturally explains observations!
Both, neutron and proton, superfluids are needed

Superfluidity	*Strong proton*	*Moderate neutron*
T_c – profile	*>$3\mathrm{x}10^9$ K, profile unimportant*	*maximum: T_{Cn}(max)~(5-9)x10^8 K and wide T_c –profile over NS core*
Appears	*Early*	*a few decays ago*
What for?	*suppresses neutrino emission before the appearance of neutron superfluidity*	*produces splash of neutrino emission*

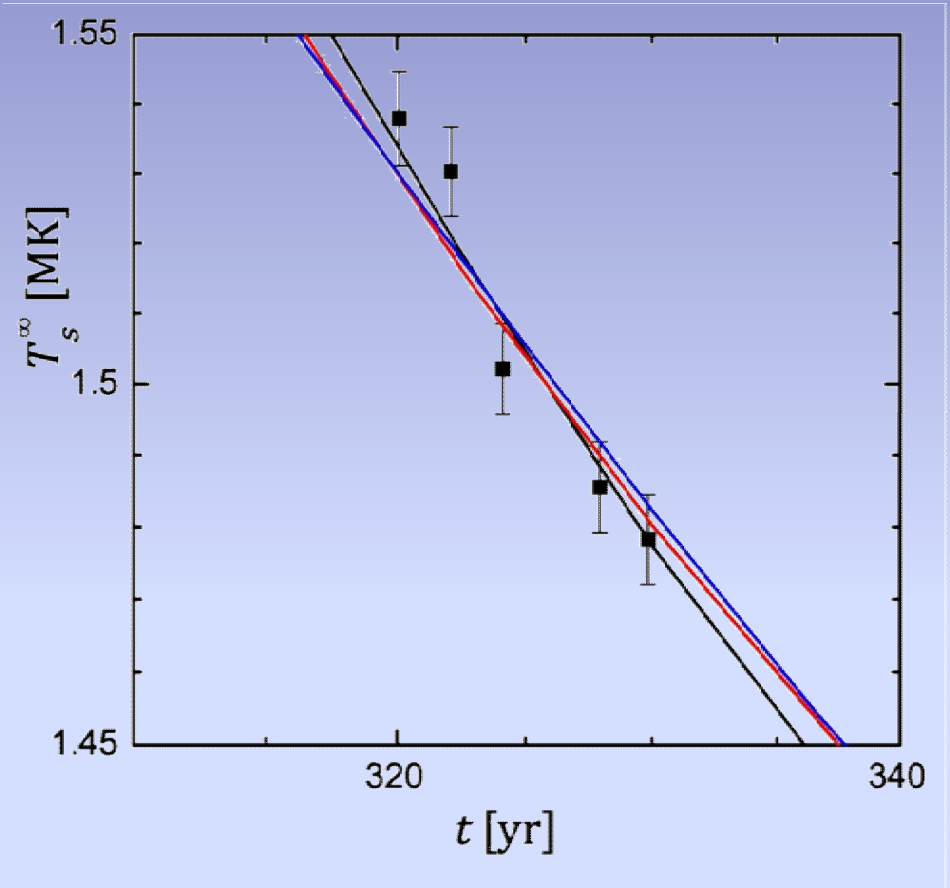
Example: Cooling of 1.65 Msun Star

APR EOS

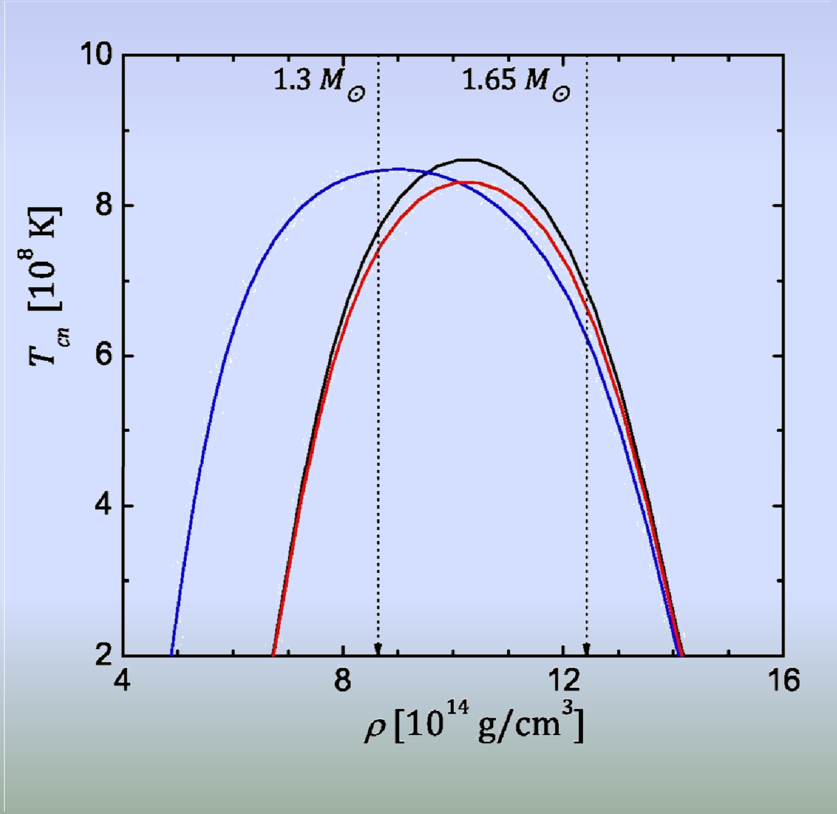
Neutrino emission peak: ~80 yrs ago

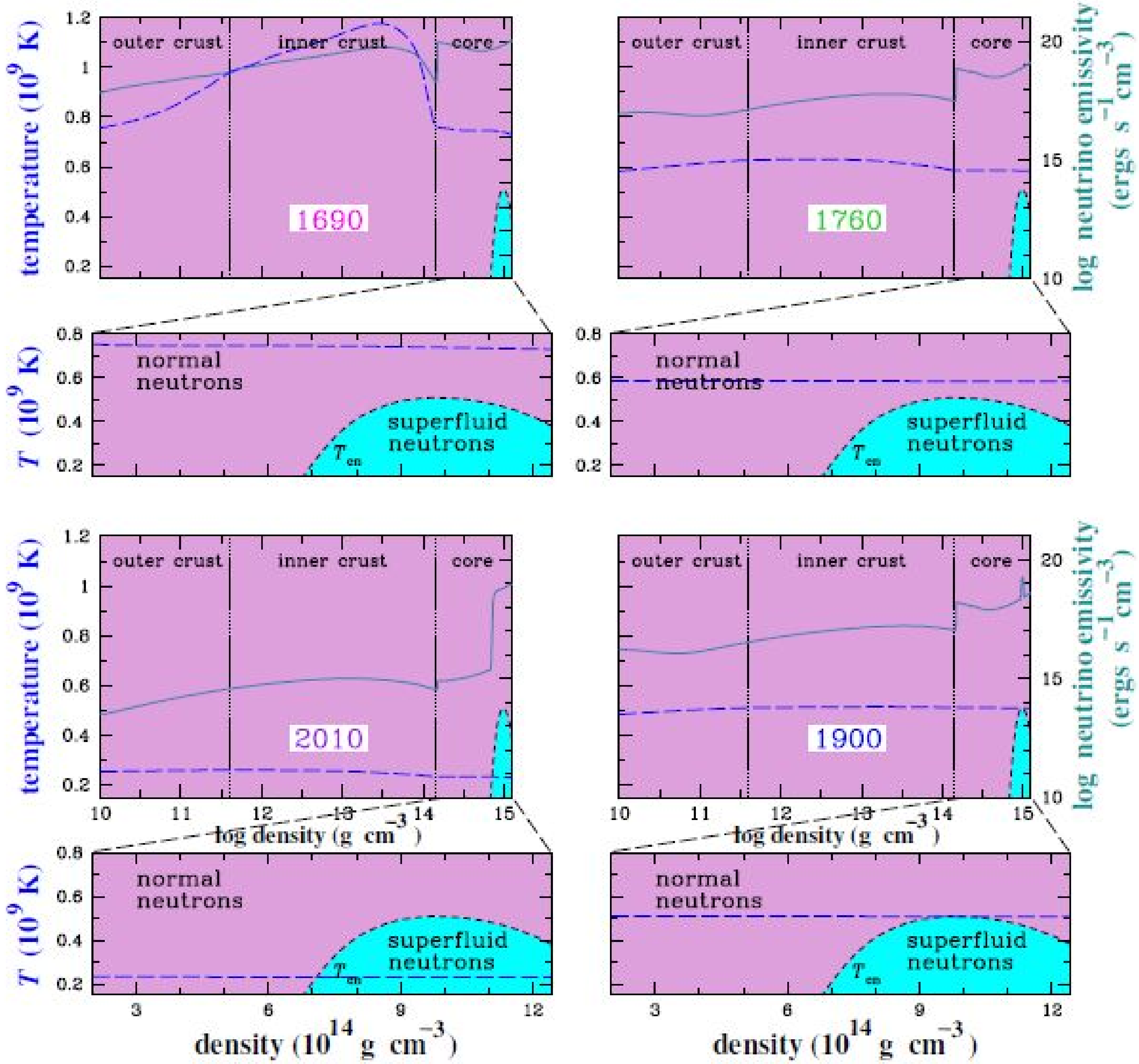


Neutron stars of different masses



$$M = 1.65\ M_\odot \qquad T_{\rm cn8}^{\rm max} = 8.6$$
$$M = 1.9\ M_\odot \qquad T_{\rm cn8}^{\rm max} = 8.3$$
$$M = 1.3\ M_\odot \qquad T_{\rm cn8}^{\rm max} = 8.5$$

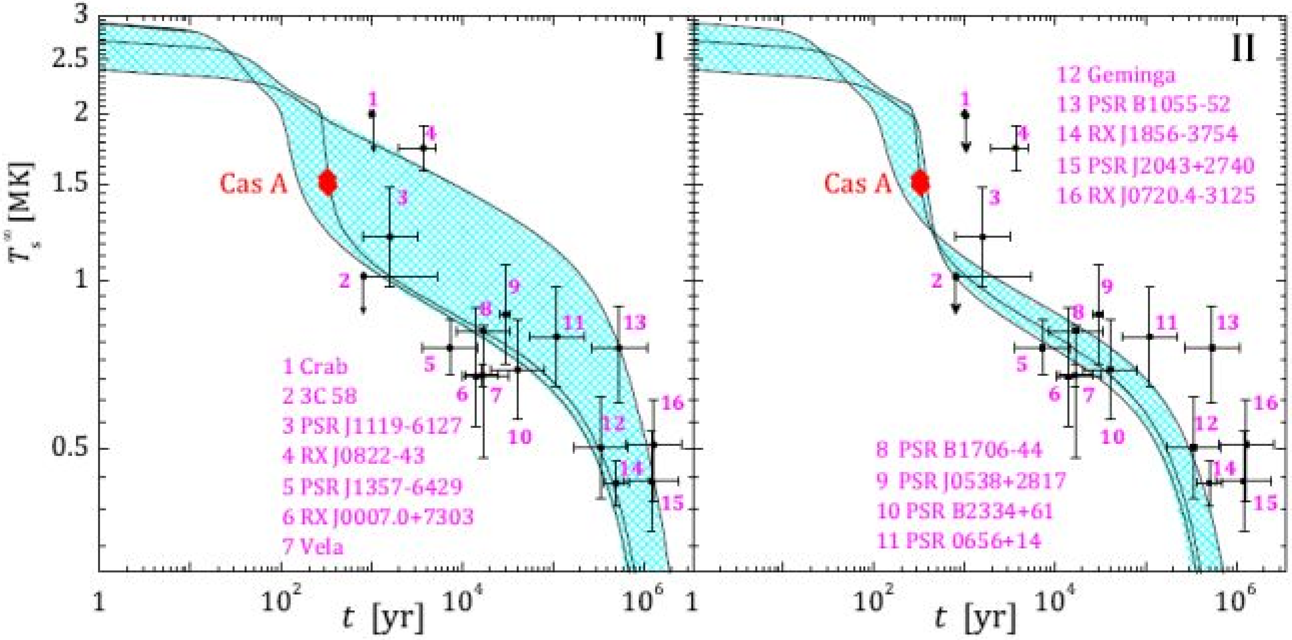


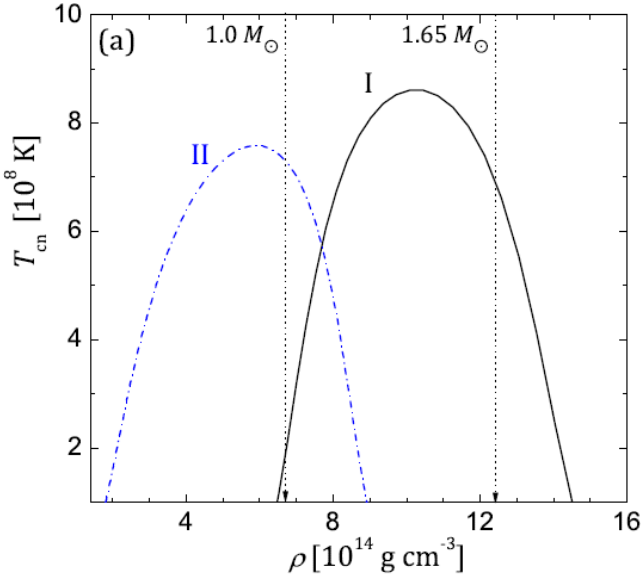

outer crust
inner crust
core
1690
1760
2010
1900
temperature (10^9 K)
log neutrino emissivity (ergs s^{-1} cm^{-3})
log density (g cm^{-3})
normal neutrons
superfluid neutrons
T_{cn}
T (10^9 K)
density (10^{14} g cm^{-3})
1.2
1
0.8
0.6
0.4
0.2
10
15
20
10
11
12
13
14
15
3
6
9
12

Cas A neutron star among other isolated neutron stars

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

One model of superfluidity for all neutron stars





Only T_{cn} superfluidity I explains all the sources

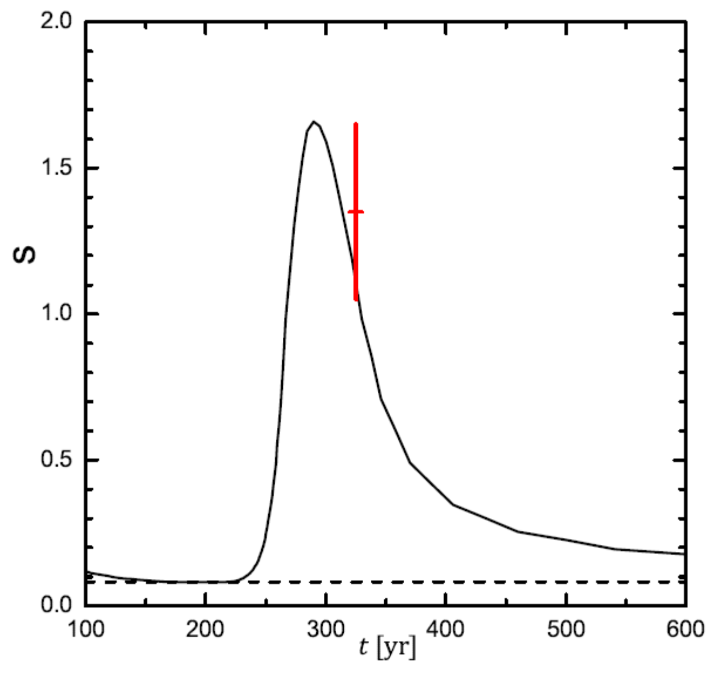
Gusakov et al. (2004)

Alternatively: wider $T_{cn}(\rho)$ profile, but the efficiency of CP neutrino emission at low densities is weak

Slope of cooling curve

Measure $T_s^\infty(t) \sim t^{-s}$ $\Rightarrow$ infer $s = -\dfrac{d\log T_s^\infty}{d\log t}$ *= slope of cooling curve*

$$\begin{cases} s \approx 1/12 & \text{= standard cooling (Murca)} \\ s \approx 1/8 & \text{= enhanced cooling (Durca)} \\ s \gg 0.1 & \text{=> something extraordinary!} \end{cases}$$



Theoretical model for Cas A NS
Shternin et al. (2011)
Now: s = 1.35 = very big number
=> unique phenomenon!
Happens very rarely!

Measurements of s in the next decade confirm or reject this interpretation

CONCLUSIONS

- **Observations of cooling Cas A NS in real time – matter of good luck!**

- **Natural explanation: onset of neutron superfluidity in NS core about 80 years ago; maximum T_{cn} in the core >~7 x 10^8 K**

- **Profile of critical temperature of neutrons over NS core should be wide**

- **Neutrino emission prior to onset of neutron superfluidity should be 20-100 times smaller than standard level ➔ strong proton superfluidity in NS core?**

- **To explain all observations of cooling NSs by one model of superfluidity, T_{cn} profile has to be shifted to higher densities**

- **Prediction: fast cooling will last for a few decades**

- Cooling of Cas A NS → direct evidence for superfluidity?

Two teams

Minimal cooling theory:

Page, Lattimer, Prakash, Steiner (2004)

Gusakov, Kaminker, Yakovlev, Gnedin (2004)

Superfluid Cas A neutron star:

D. Page, M. Prakash, J.M. Lattimer, A.W. Steiner, PRL, **vol. 106, Issue 8, id. 081101 (2011)**

P.S. Shternin, D.G. Yakovlev, C.O. Heinke, W.C.G. Ho, D.J. Patnaude, MNRAS Lett., 412, L108 (2011)

Doubts

Carbon atmosphere: *why?*

Theory: *probability to observe is small (too good to be true)*

Theory: *to explain observations of all cooling neutron stars one needs unusual* T_{cn} *– profile over neutron star core*

Observations: *data processing???*