Evolution of Neutron Stars and Observational Constraints

J.M. Lattimer

Department of Physics & Astronomy
Stony Brook University

18 November 2011

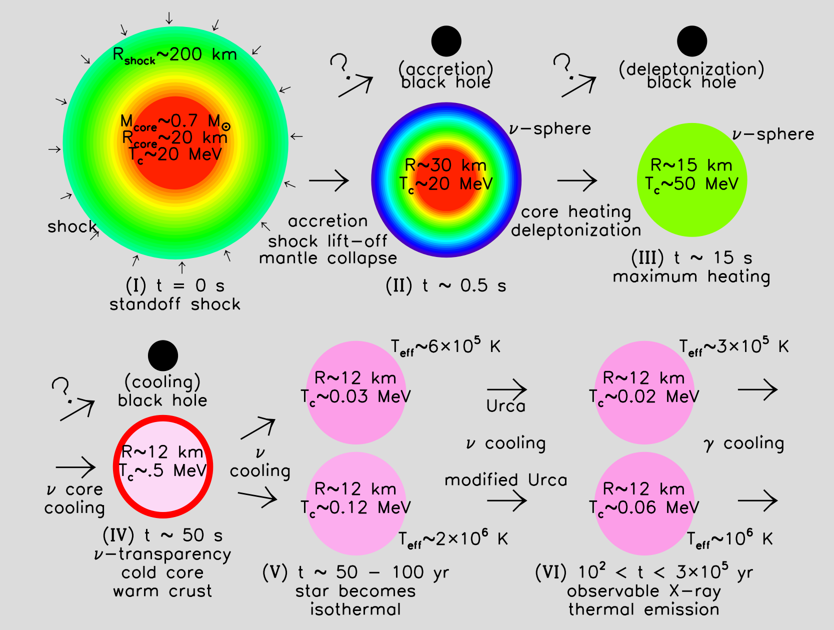
Collaborators: D. Page (UNAM), M. Prakash (Ohio U.), A. Steiner (INT)

5th Meeting of OMEG Institute
NAOJ, Mitaka, Japan

Outline

- Formation of Neutron Stars and Proto-Neutron Stars
- Neutrino Cooling Processes
    - Direct Urca Process
    - Modified Urca Process
    - Cooper Pair Formation and Breaking
- Observations of Cooling Neutron Stars
- Cas A: A Direct Detection of Core Superfluidity?

Proto-Neutron Stars



$R_{shock}\sim 200$ km

$M_{core}\sim 0.7\ M_\odot$
$R_{core}\sim 20$ km
$T_c\sim 20$ MeV

shock

accretion
shock lift−off
mantle collapse

(I) t = 0 s
standoff shock

(accretion)
black hole

$\nu-$sphere

$R\sim 30$ km
$T_c\sim 20$ MeV

core heating
deleptonization

(II) t ∼ 0.5 s

(deleptonization)
black hole

$\nu-$sphere

$R\sim 15$ km
$T_c\sim 50$ MeV

(III) t ∼ 15 s
maximum heating

(cooling)
black hole

$R\sim 12$ km
$T_c\sim .5$ MeV

ν core
cooling

(IV) t ∼ 50 s
$\nu-$transparency
cold core
warm crust

ν
cooling

$T_{eff}\sim 6\times 10^5$ K

$R\sim 12$ km
$T_c\sim 0.03$ MeV

Urca

ν cooling

modified Urca

$R\sim 12$ km
$T_c\sim 0.12$ MeV

$T_{eff}\sim 2\times 10^6$ K

(V) t ∼ 50 − 100 yr
star becomes
isothermal

$T_{eff}\sim 3\times 10^5$ K

$R\sim 12$ km
$T_c\sim 0.02$ MeV

γ cooling

$R\sim 12$ km
$T_c\sim 0.06$ MeV

$T_{eff}\sim 10^6$ K

(VI) $10^2 < t < 3\times 10^5$ yr
observable X−ray
thermal emission

The Urca Processes

Gamow & Schönberg proposed the direct Urca process: nucleons at the top of the Fermi sea beta decay.

$n \rightarrow p + e^- + \nu_e$,
$p \rightarrow n + e^+ + \bar{\nu}_e$

Energy conservation guaranteed by beta equilibrium
$\mu_n - \mu_p = \mu_e$

Momentum conservation requires $|k_{Fn}| \leq |k_{Fp}| + |k_{Fe}|$.

Charge neutrality requires $k_{Fp} = k_{Fe}$, therefore $|k_{Fp}| \geq 2|k_{Fn}|$.

Degeneracy implies $n_i \propto k_{Fi}^3$, thus $x \geq x_{DU} = 1/9$.

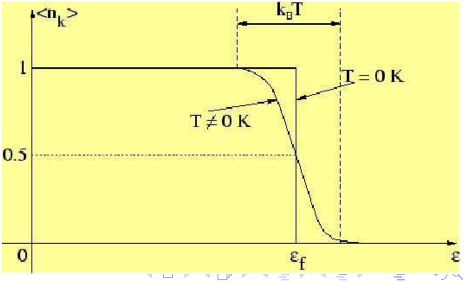
With muons $(n > 2n_s), x_{DU} = \frac{2}{2+(1+2^{1/3})^3} \simeq 0.148$

If $x < x_{DU}$, bystander nucleons needed: modified Urca process.
$(n,p) + n \rightarrow (n,p) + p + e^- + \nu_e$,
$(n,p) + p \rightarrow (n,p) + n + e^+ + \bar{\nu}_e$

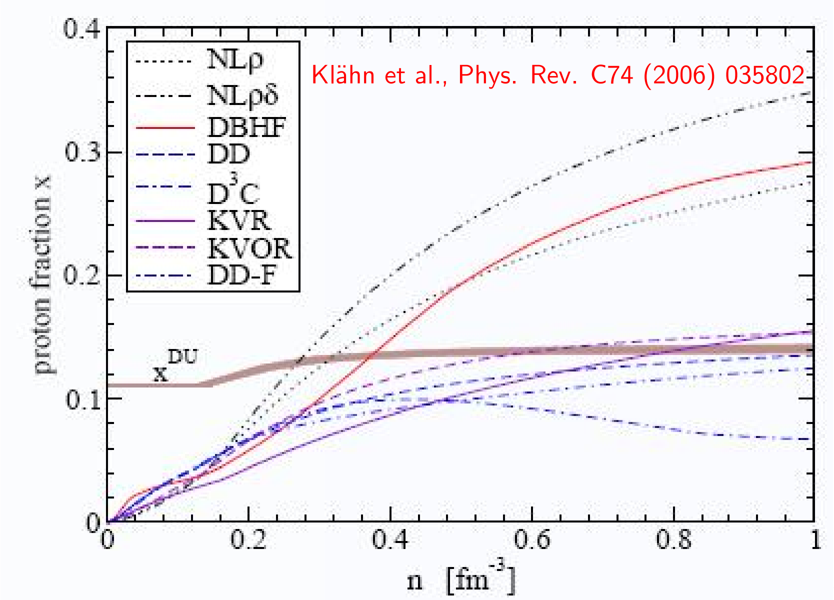
Neutrino emissivities:
$\dot{\epsilon}_{MU} \simeq (T/\mu_n)^2 \, \dot{\epsilon}_{DU} \sim 10^{-6} \dot{\epsilon}_{DU}$.

Beta equilibrium composition:

$$x_\beta \simeq (3\pi^2 n)^{-1} \left(4E_{sym}/\hbar c\right)^3 \simeq 0.04 \left(n/n_s\right)^{0.5-2} .$$

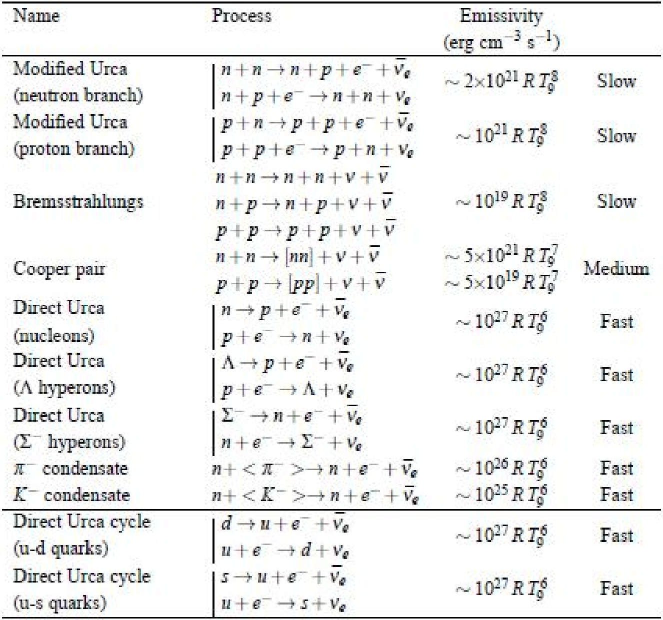


Direct Urca Threshold



Klähn et al., Phys. Rev. C74 (2006) 035802

Neutrino Emissivities



Name	Process	Emissivity (erg cm^{-3} s^{-1})	
Modified Urca (neutron branch)	$n+n\to n+p+e^-+\bar{\nu}_e$ $n+p+e^-\to n+n+\nu_e$	$\sim 2\times10^{21}\,R\,T_9^8$	Slow
Modified Urca (proton branch)	$p+n\to p+p+e^-+\bar{\nu}_e$ $p+p+e^-\to p+n+\nu_e$	$\sim 10^{21}\,R\,T_9^8$	Slow
Bremsstrahlungs	$n+n\to n+n+\nu+\bar{\nu}$ $n+p\to n+p+\nu+\bar{\nu}$ $p+p\to p+p+\nu+\bar{\nu}$	$\sim 10^{19}\,R\,T_9^8$	Slow
Cooper pair	$n+n\to[nn]+\nu+\bar{\nu}$ $p+p\to[pp]+\nu+\bar{\nu}$	$\sim 5\times10^{21}\,R\,T_9^7$ $\sim 5\times10^{19}\,R\,T_9^7$	Medium
Direct Urca (nucleons)	$n\to p+e^-+\bar{\nu}_e$ $p+e^-\to n+\nu_e$	$\sim 10^{27}\,R\,T_9^6$	Fast
Direct Urca (Λ hyperons)	$\Lambda\to p+e^-+\bar{\nu}_e$ $p+e^-\to\Lambda+\nu_e$	$\sim 10^{27}\,R\,T_9^6$	Fast
Direct Urca (Σ^- hyperons)	$\Sigma^-\to n+e^-+\bar{\nu}_e$ $n+e^-\to\Sigma^-+\nu_e$	$\sim 10^{27}\,R\,T_9^6$	Fast
π^- condensate	$n+<\pi^->\to n+e^-+\bar{\nu}_e$	$\sim 10^{26}\,R\,T_9^6$	Fast
K^- condensate	$n+<K^->\to n+e^-+\bar{\nu}_e$	$\sim 10^{25}\,R\,T_9^6$	Fast
Direct Urca cycle (u-d quarks)	$d\to u+e^-+\bar{\nu}_e$ $u+e^-\to d+\nu_e$	$\sim 10^{27}\,R\,T_9^6$	Fast
Direct Urca cycle (u-s quarks)	$s\to u+e^-+\bar{\nu}_e$ $u+e^-\to s+\nu_e$	$\sim 10^{27}\,R\,T_9^6$	Fast

Neutron Star Cooling Basics

$$\frac{dE_{th}}{dt} = C_v \frac{dT}{dt} = -L_\nu - L_\gamma + H$$

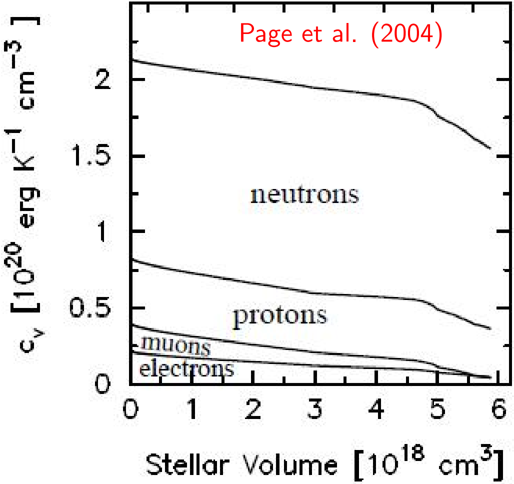
$C_V = \sum_i \int c_{V,i} dV$.
For normal (unpaired)
degenerate matter

$$c_{V,i} = \frac{m_i^* p_{Fi}}{3\hbar^3} k_B^2 T.$$

$$L_\gamma = 4\pi R^2 \sigma T_e^4$$

$$T_e \simeq 10^6 \left(\frac{T_{int}}{10^8 \text{ K}}\right)^{0.5+\alpha}$$

$\alpha << 1$.



Schematic Cooling Model

$$C_V = C_9 T_9$$

$$C_9 \simeq 10^{39}\ \mathrm{erg/K}$$

$$L_\nu = N_9 T_9^8$$

$$N_9 \simeq 10^{40} \mathrm{erg/s}$$

$$L_\gamma = S_9 T_9^{2+4\alpha}$$

$$S_9 \simeq 10^{33} \mathrm{erg/s}$$

Neutrino cooling ($t < 10^4$ yr)

$$T_9 \simeq \left(\frac{\tau_{MU}}{t}\right)^{1/6}$$

$$\tau_{MU} \simeq 10^9 \left(\frac{C_9}{6N_9}\right)\ \mathrm{s} \sim 1\ \mathrm{yr}$$

Photon cooling

$$T_9 \simeq \left(\frac{\tau_\gamma}{t}\right)^{1/4\alpha}$$

$$\tau_\gamma \simeq 10^9 \left(\frac{C_9}{4\alpha S_9}\right)\ \mathrm{s} \sim 10^8\ \mathrm{yr}$$

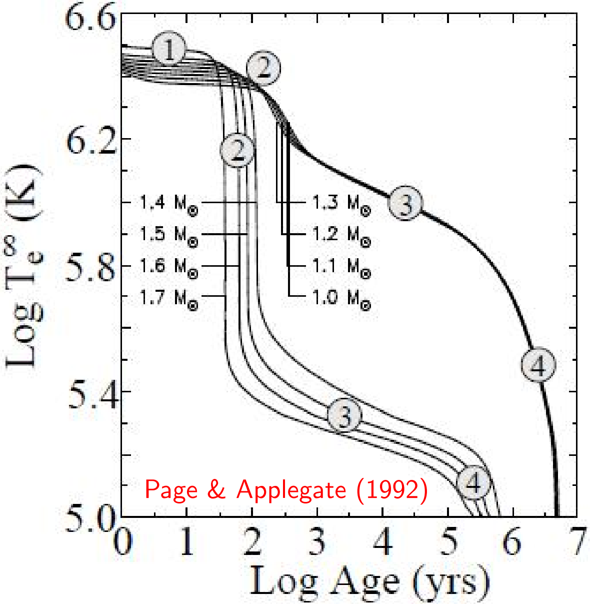
Slow Vs. Fast Cooling

1. $t < 30 - 50$ yr, crust retains initial heat
2. $t > 30 - 50$ yr, star becomes isothermal
3. In ν cooling era,

   $$\frac{d \ln T}{d \ln t} \sim -\frac{1}{12}$$

4. In γ cooling era,

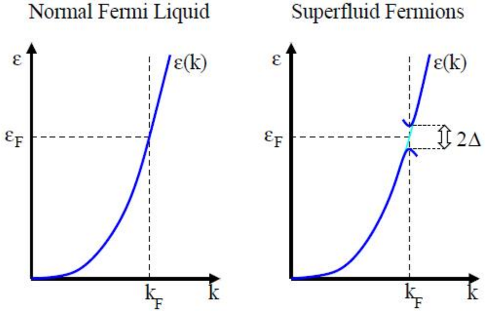
   $$\frac{d \ln T}{d \ln t} \sim -\frac{1}{8\alpha}$$

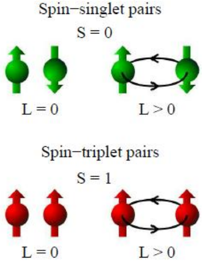


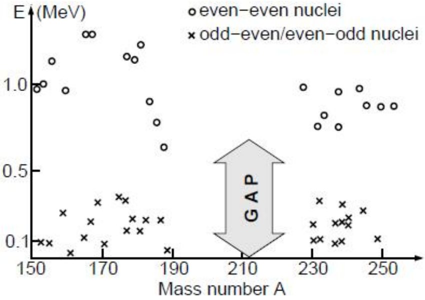
Page & Applegate (1992)

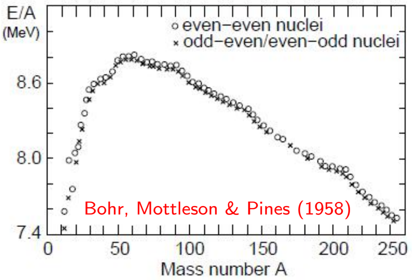
Pairing

Comparison of quasi-particle spectra for normal and superfluid matter.



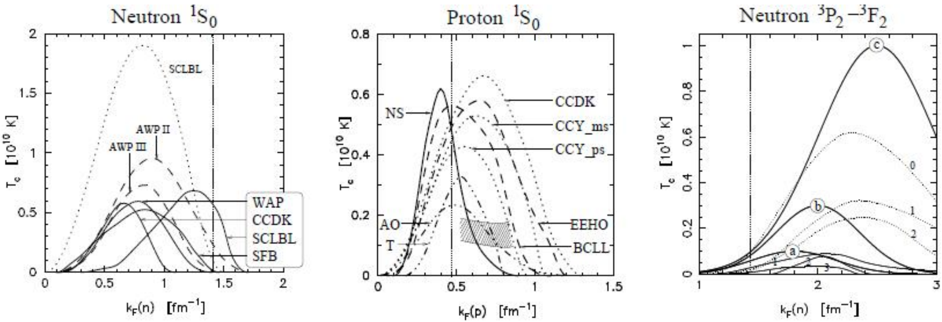






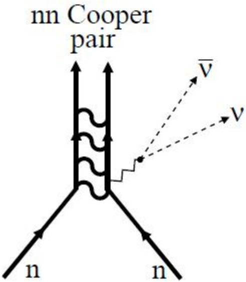
Bohr, Mottleson & Pines (1958)

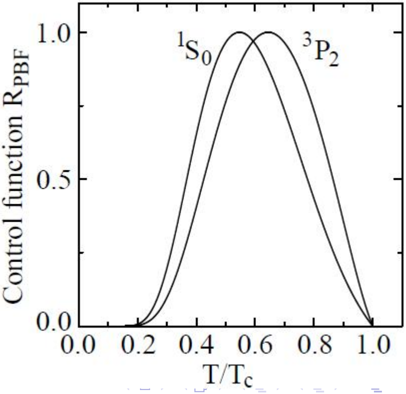
Superfluid Gaps



Cooper Pair PBF Process

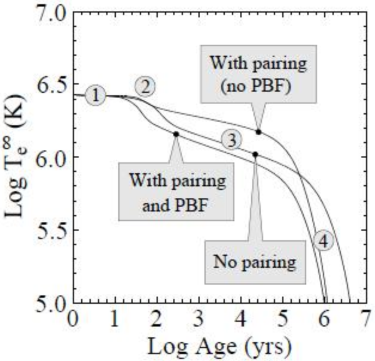
- Formation of fermionic pair condensate triggers the pair breaking and formation (PBF) process.
- Phase transition (second order) begins when $T = T_c$ and pairs begin to form.
- Thermal agitation breaks pairs so there is a continuous breaking and formation of pairs with ν emission.
- Discovered by Flowers, Ruderman & Sutherland (1976).

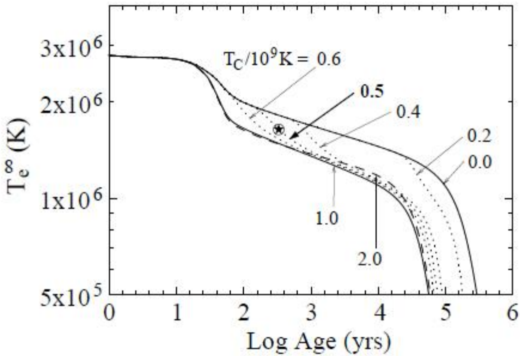




The Impact of the PBF Process

- Modifications made to both ν emissivities and specific heat.
- Modified URCA and bremmstrahlung are suppressed when $T < T_c$, leading to faster cooling in γ era.
- Suppression of specific heat not as significant.
- PBF leads to significant cooling during ν era.
- $^1S_0$ n pairing in crust reduces thermal relaxation time due to C_V reduction.





Transitory Episode of Rapid Cooling

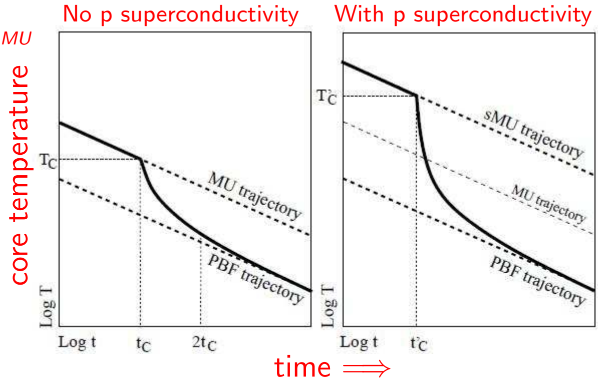
MU emissivity: $\dot{\varepsilon}_{MU} \propto T^8$

PBF emissivity ($f \sim 10$):
$\dot{\varepsilon}_{PBF} \propto F(T)\ T^7 \propto T^8 \simeq f\dot{\varepsilon}_{MU}$

Specific heat: $C_V \propto T$

Neutrino dominated cooling:
$C_V dT/dt = -L_\nu$

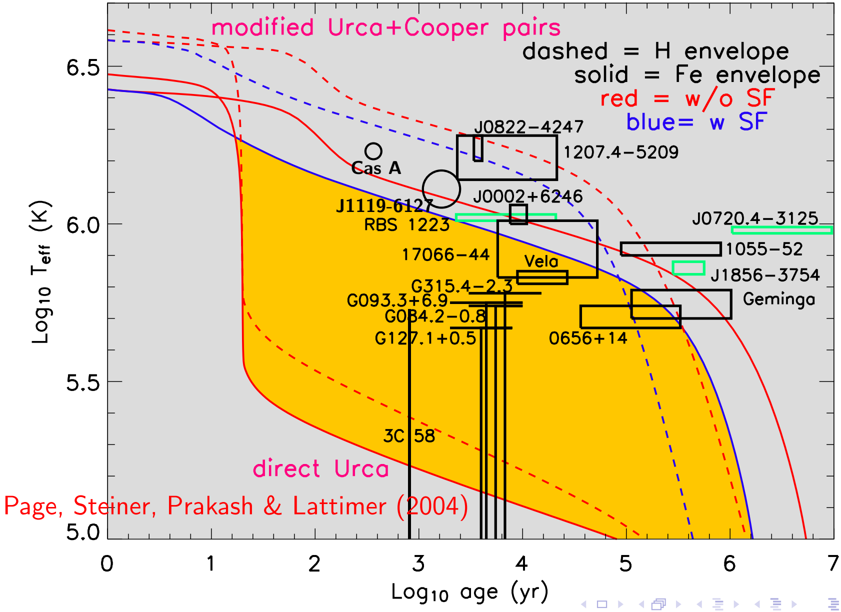
$\implies T \propto (t/\tau)^{-1/6}$
$\tau_{PBF} = \tau_{MU}/f$



Slope: $(d \ln T/d \ln t)_{transitory}$
$\simeq (1-10)(d \ln T/d \ln t)_{MU}$
$\simeq (1-25)(d \ln T/d \ln t)_{MU}$ in the case of proton superconductivity

Slope sensitive to n $^3P_2$ critical temperature (T_C) and existence of $^1S_0$ proton superconductivity

Neutron Star Cooling – Models Versus Observations



Cas A

Remnant of Type IIb (gravitational collapse, no H envelope) SN in 1680 (Flamsteed).

3.4 kpc distance

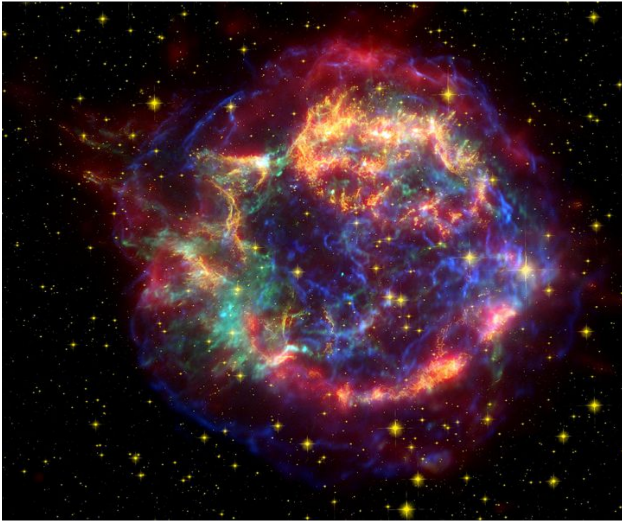
3.1 pc diameter

Strongest radio source outside solar system, discovered in 1947.

X-ray source detected (Aerobee flight, 1965)

X-ray point source detected (Chandra, 1999)

1 of 2 known CO-rich SNR (massive progenitor and neutron star?)



Spitzer, Hubble, Chandra

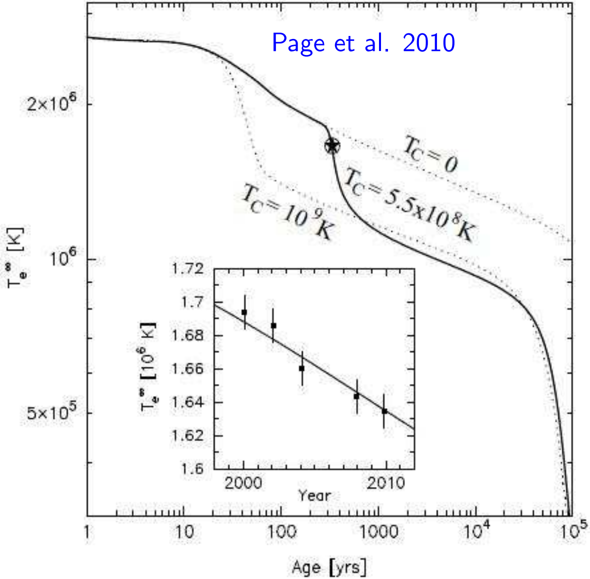
Cas A Superfluidity

X-ray spectrum indicates thin C atmosphere, $T_e \sim 1.7 \times 10^8$ K (Ho & Heinke 2009)

10 years of X-ray data show cooling at the rate $\frac{d \ln T_e}{d \ln t} = -1.23 \pm 0.14$ (Heinke & Ho 2010)

Modified Urca: $\left(\frac{d \ln T_e}{d \ln t}\right)_{MU} \simeq -0.08$

We infer that
$T_C \simeq 5 \pm 1 \times 10^8$ K
$T_C \propto (t_C L / C_V)^{-1/6}$



Conclusions

- Cas A provides the first direct evidence of superfluuidity and superconductivity in a neutron star's core
- The n $^3P_2$ critical temperature is 5×10^8 K to within 20%.
- The p $^1S_0$ critical temperature is larger than 10^9 K
- These results are consistent with the Minimal Cooling Paradigm (Page et al. 2004)
- Possible caveats:
  - Chandra sensitivity might be degrading with time (Rutledge, INT, 2011)
  - Thermal conductivity of neutron star matter might be grossly overestimated (Blatschke et al. 2011)