A Limit on Axion from the Cooling Neutron Star in Cassiopeia A

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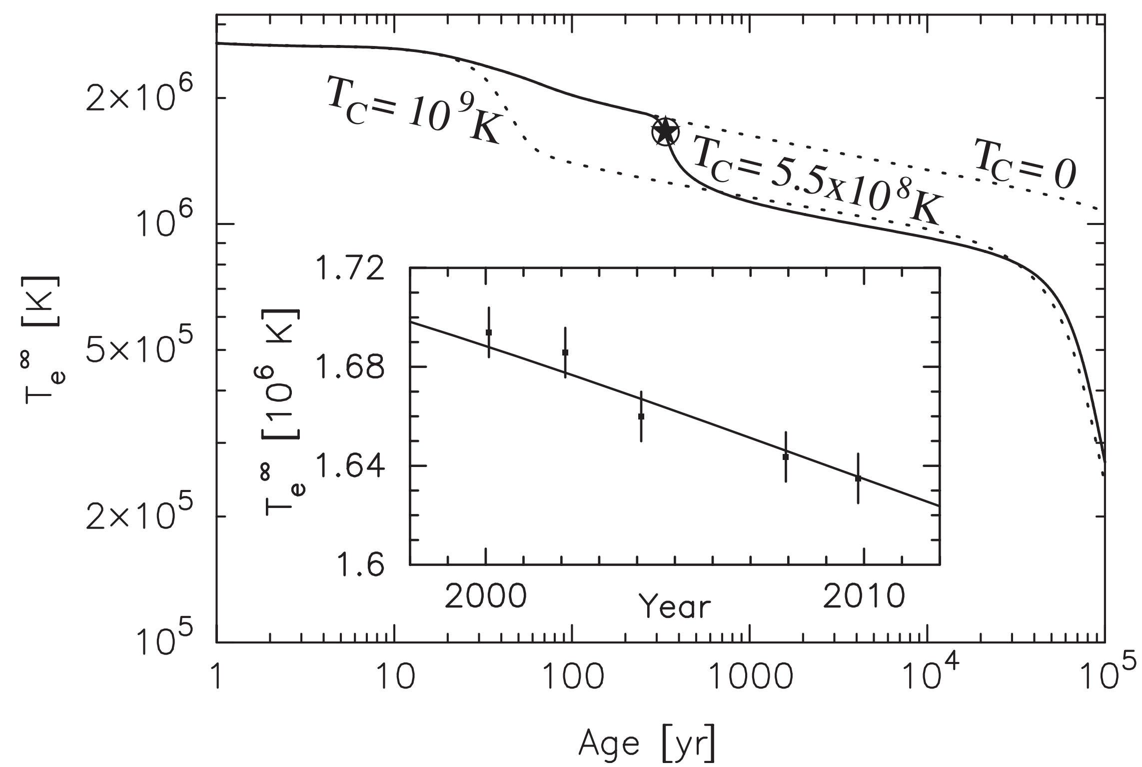
Nov. 8 Seminar @ CTPU

Based on K. Hamaguchi, N. Nagata, K.Y., J. Zheng [1806.07151]

Short summary

[Page et al. (2011)]



Within the Standard Model

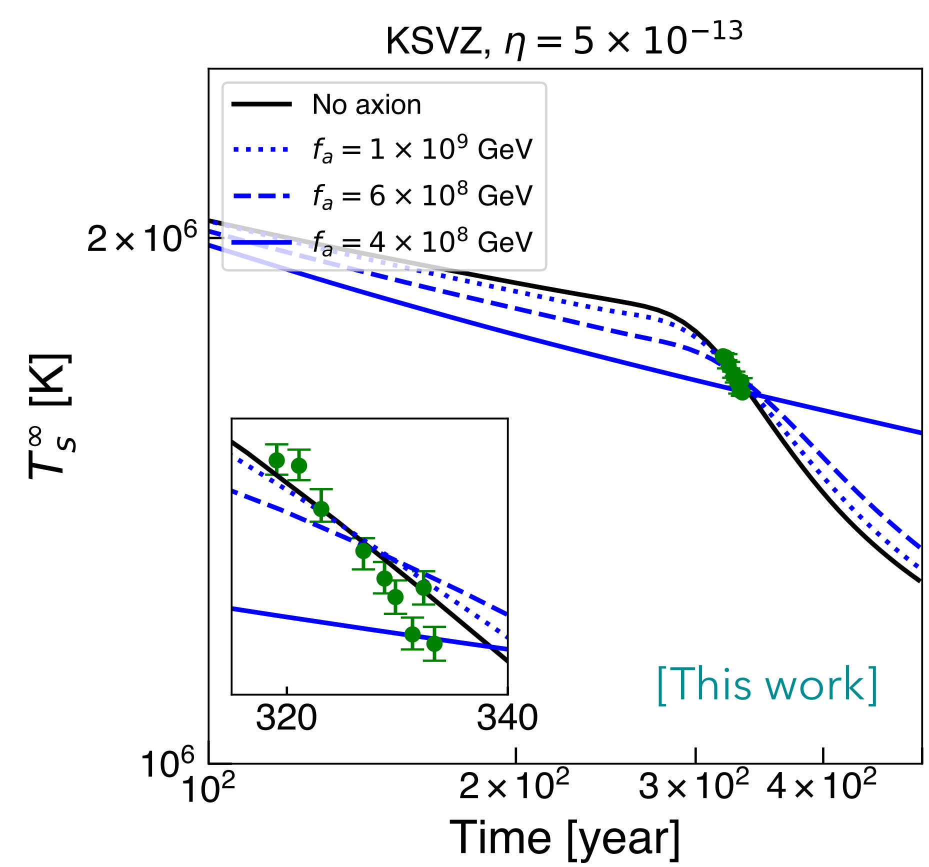
Cooling theory can fit the observed surface temperature of Cas A neutron star (NS)

SM + Axion

If the axion couplings to nucleons are too large, cooling is enhanced and cannot fit Cas A NS

$$f_a > O(10^8)\,\mathrm{GeV}$$

comparable to the SN1987A limit



Outline

- The neutron star in the Cassiopeia A
- The standard theory of NS cooling
- Cooling theory vs. Cas A NS observation
- Axion emission from neutron star

The Neutron Star in the Cassiopeia A

The Cassiopeia A (Cas A)

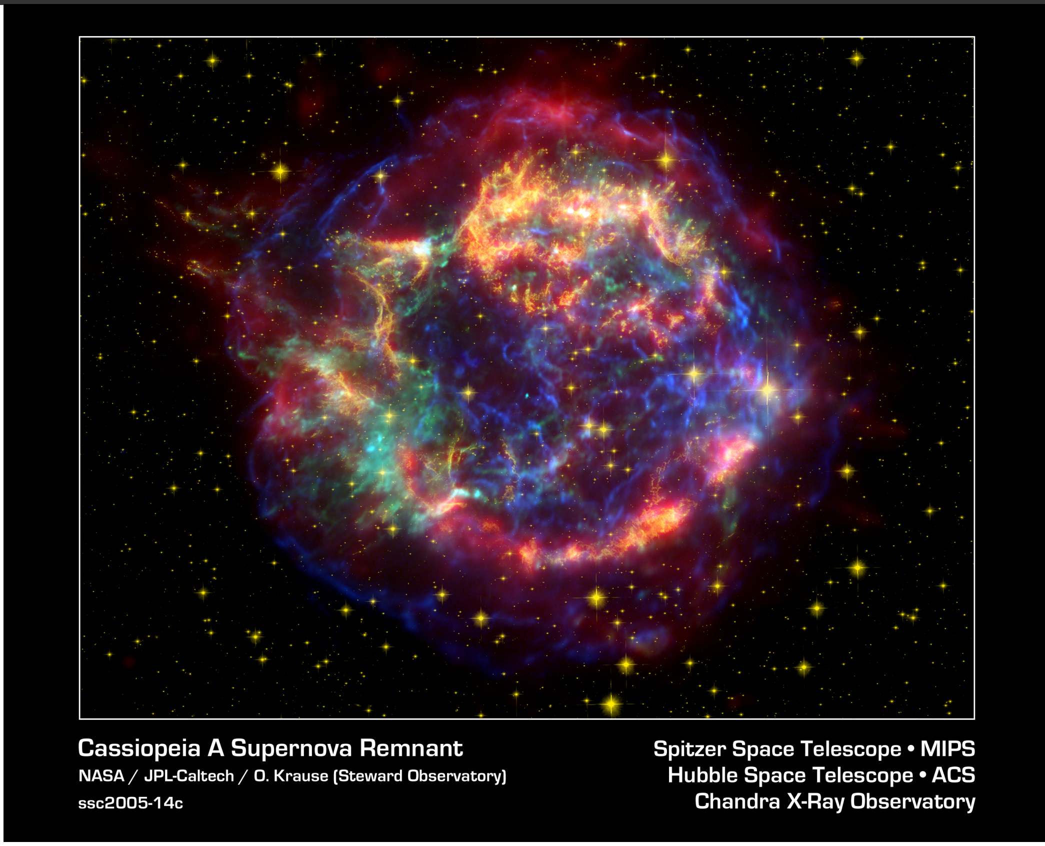
Supernova remnant in the Cassiopeia constellation

- Birth date

$$1681 \pm 19 \text{ yr}$$

from remnant expansion

[R. A. Fesen et al. (2006)]

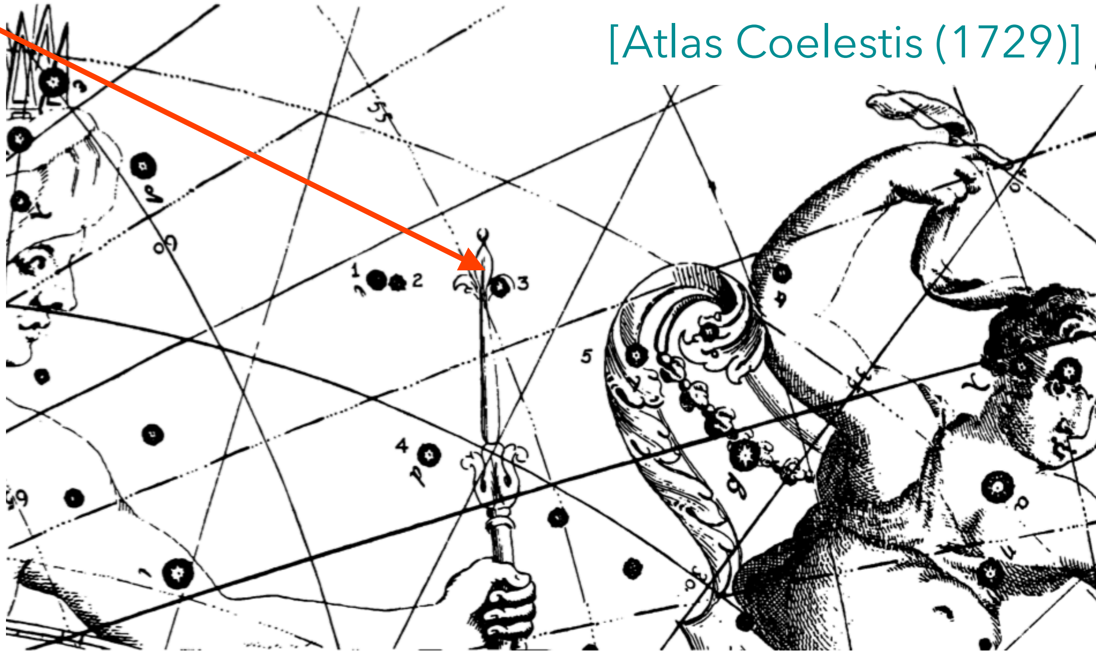


[Wikipedia]

Perhaps identical to the *3 Cassiopeiae* recorded by J. Flamsteed on August 16, 1680

[W. B. Ashworth, Jr. (1980); K. W. Kamper (1980); D. W. Hughes (1980).]

[Atlas Coelestis (1729)]



- Distance

$$d = 3.4^{0.3}_{-0.1} \text{ kpc} \qquad 1 \text{ pc} \sim 3 \text{ light year}$$

[J. E. Reed et al. (1995)]

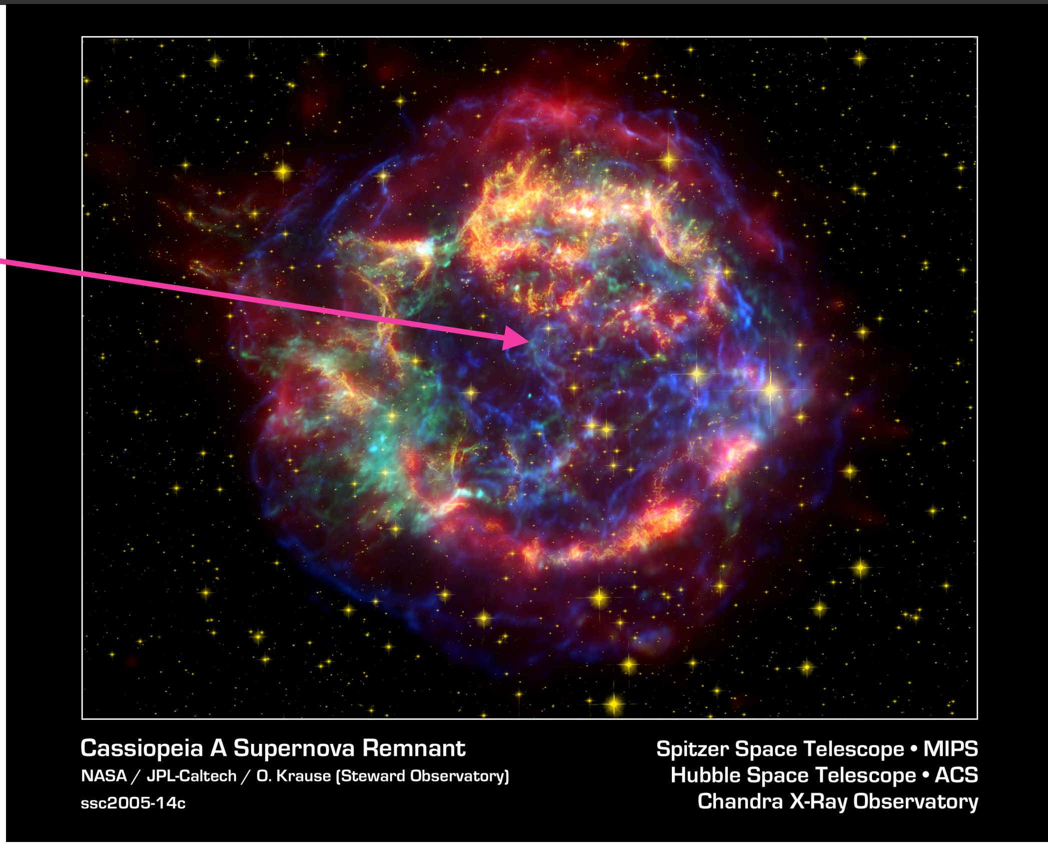
The neutron star in Cas A

- In 1999, the *Chandra* detected hot point-like source at the center of Cas A

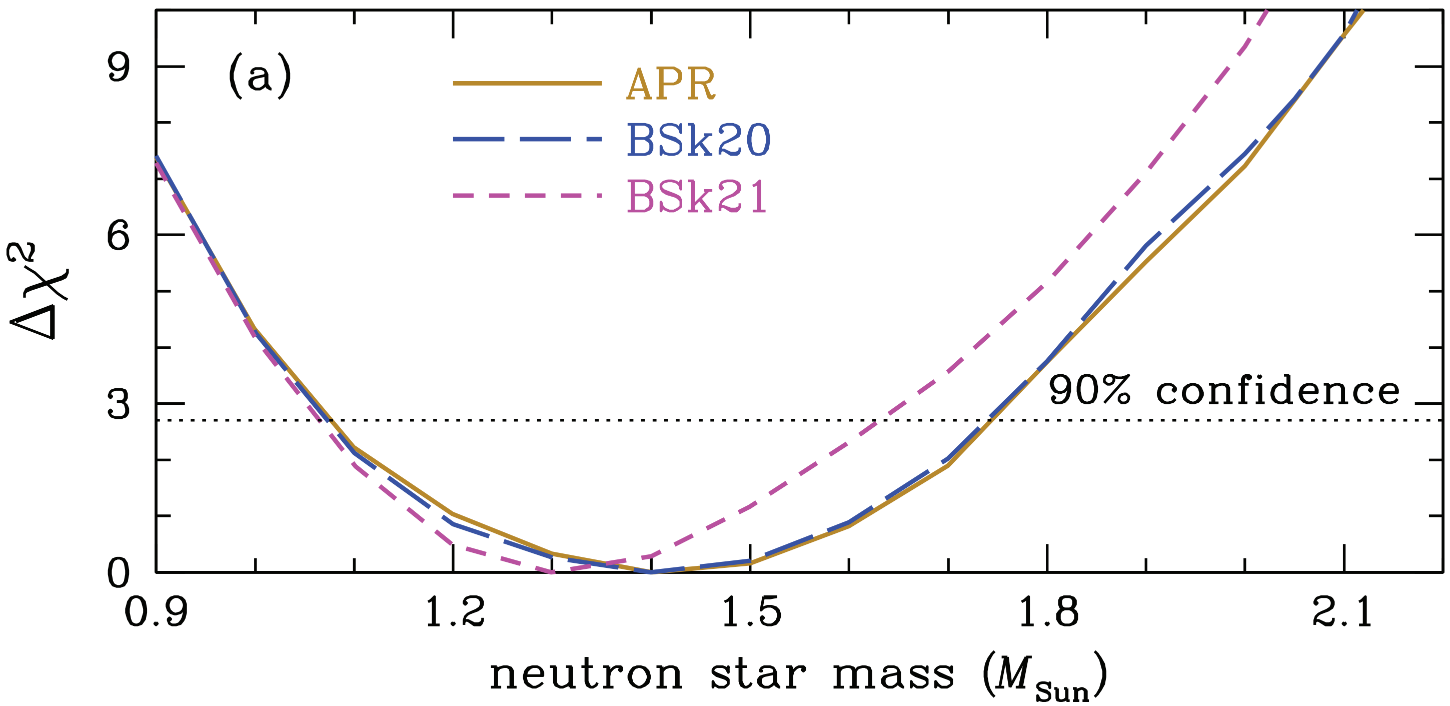
[Tananbaum (1999)]

- NS carbon atmosphere model is consistent with the observed thermal spectrum

[W. C. G. Ho and C. O. Heinke, Nature 462, 71 (2009)]



No pulsation detected



[Ho et al. (2015)]

$$M = (1.4 \pm 0.3)\, M_\odot$$

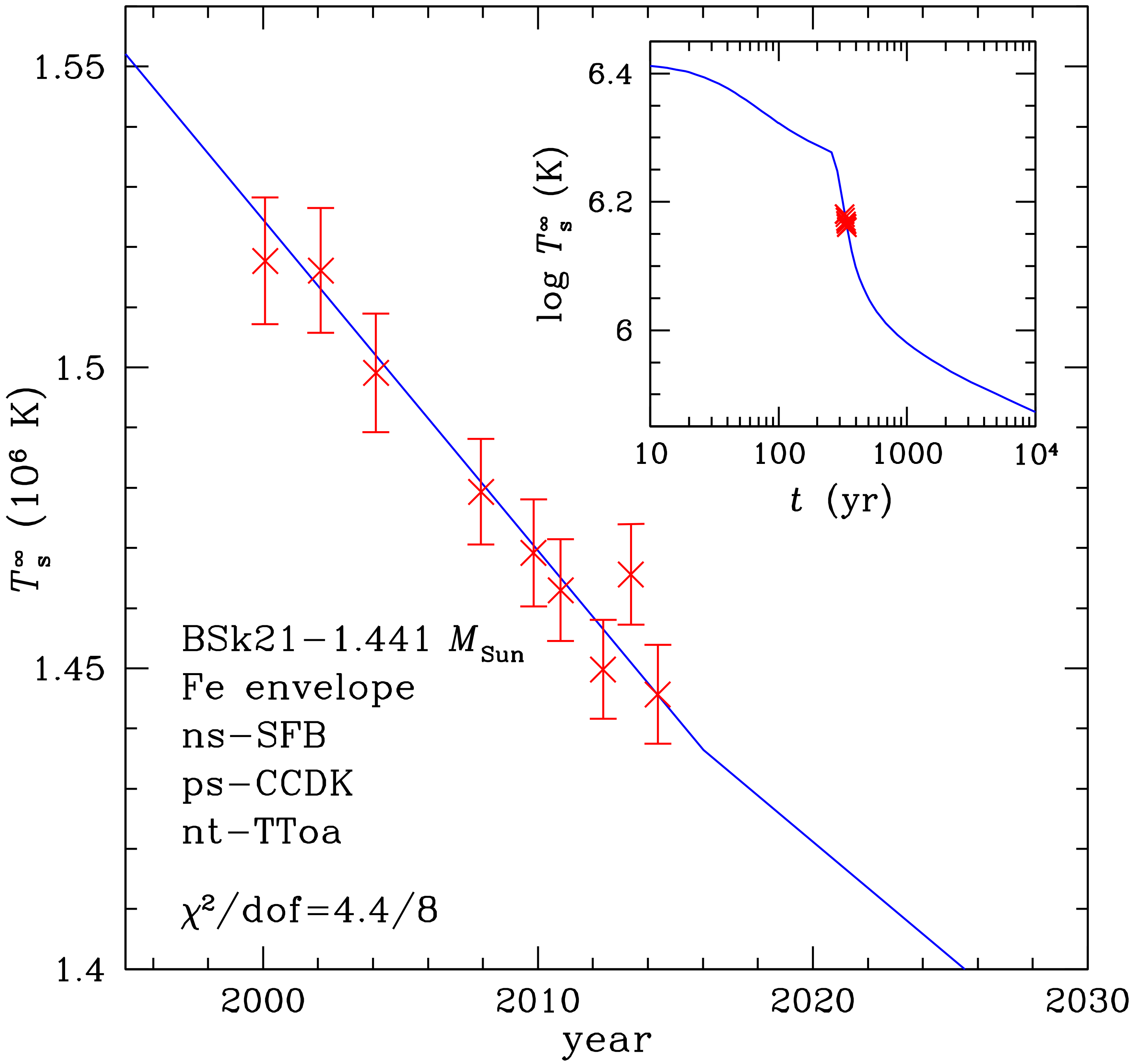
$$R = (11 - 13)\,\mathrm{km}$$

depending on Equation of State (EOS)

Cooling of Cas A NS

Surface temperature detected for 14 years

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



[Ho et al. (2015)]

- First direct observation of NS cooling
- Temperature decrease:

$$\left(\frac{\Delta T_s^\infty}{T_s^\infty}\right)_{\rm CasA} = 3 - 4\,\%/10\,\text{year}$$

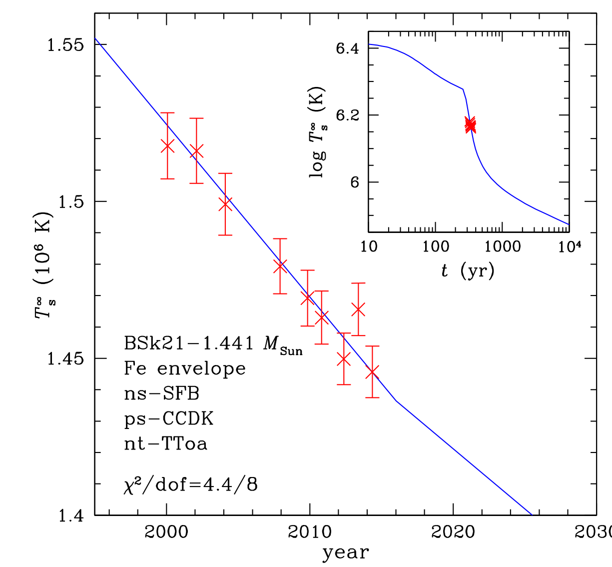
Can we explain this decrease?

⟶ **Yes!**

Why Cas A NS is special?

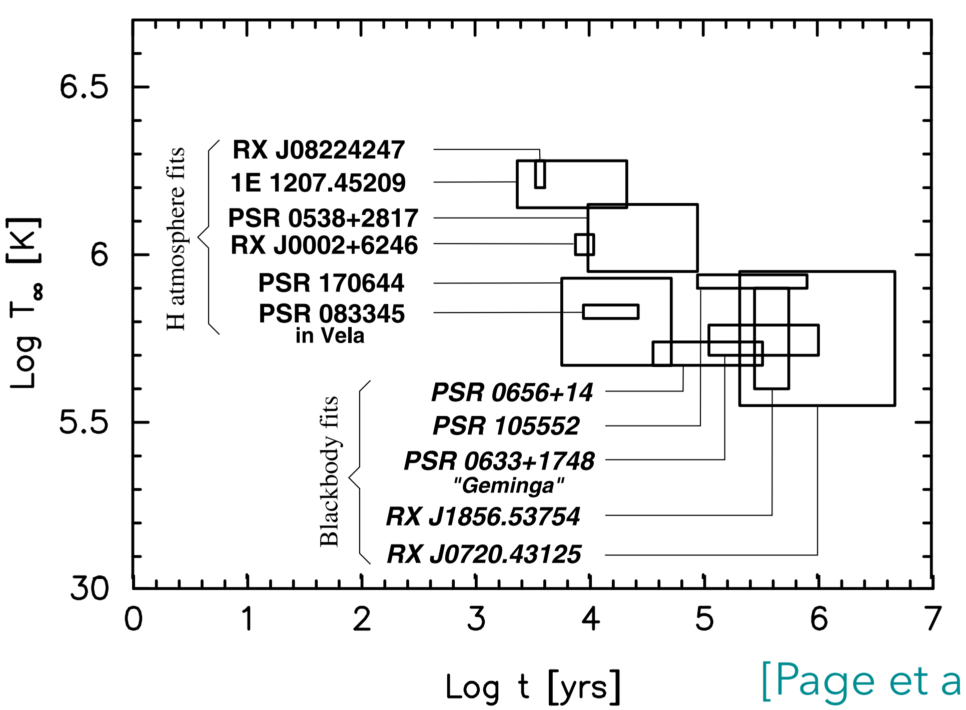
In Cas A NS, temperature decline rate is available
More powerful to constrain cooling theory

Cas A NS: 14 years data $\{(t_0, T^\infty_{s,0}), (t_1, T^\infty_{s,1}), \ldots\}$

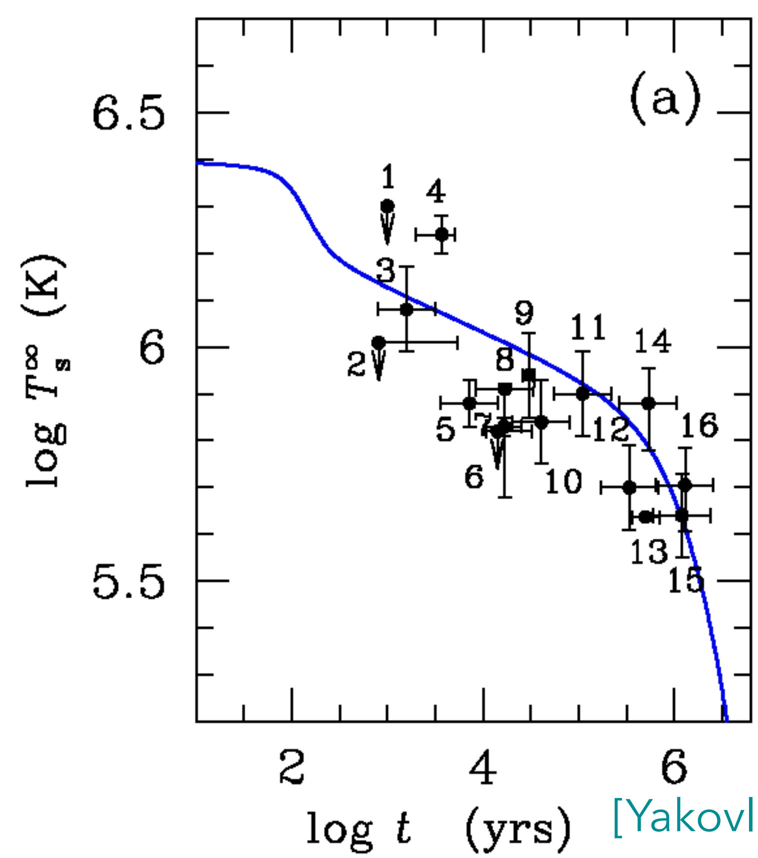


Other NS:

- About 30 observations of surface temperature
- Single measurement of (t, T^∞_s) for each NS



[Page et al. (2004)]



[Yakovlev et al. (2008)]

The standard theory of NS cooling

Overview of the cooling theory

Thermal balance equation

Internal temperature

Neutrino luminosity

$$C\frac{dT}{dt} = -L_\nu - \cancel{L_\gamma}$$

Heat capacity (n, p, e, μ)

$C \propto T$

Photon luminosity: $L_\gamma = 4\pi R^2 \sigma_B T_s^2$

negligible at Cas A age ~ 340 yr

Technical comments

- At early stage t < O(100) yr, NS is not isothermal; $T = T(r)$
- We follow the heat conduction equation

Neutrino emission

Neutrino emission is the dominant cooling source of Cas A NS

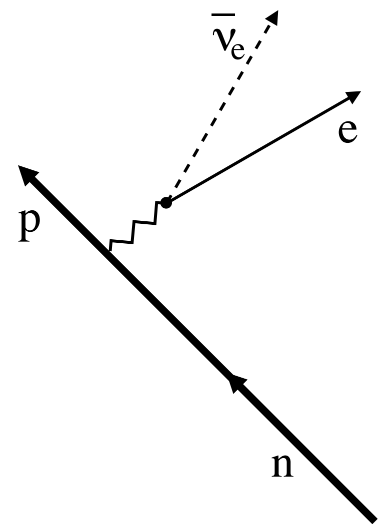
- Direct Urca process
- Modified Urca process
- Bremsstrahlung
- Cooper pair-breaking and formation

Basics of NS core structure

- neutron, proton, electron, muon
- **Fermi degeneracy:** $p_{F,n} \sim 400\,\mathrm{MeV} \quad p_{F,p} \simeq p_{F,e} \sim 10 - 100\,\mathrm{MeV}$
- **Low-T:** $T \lesssim 10^{11}\,\mathrm{K} \ll p_F$

Direct Urca process

Beta decay and its inverse **on Fermi surface**



$$n \to p + \ell + \bar{\nu}_\ell$$

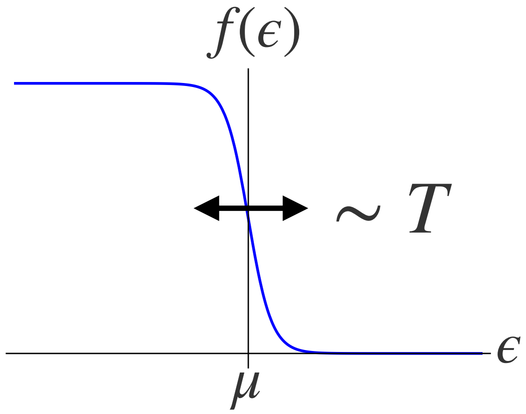
$$p + \ell \to n + \nu_\ell$$

$\ell = e, \mu$

Direct Urca is powerful, but **forbidden** in Cas A NS

- Nucleons and leptons are strongly degenerate; $\epsilon_\nu \sim T \ll p_{F,n,p,\ell}$ **10 - 100 MeV**
- Momentum conservation requires

$$p_{F,p} + p_{F,e} > p_{F,n}$$



- Since $p_F^3 \propto n$, direct Urca requires large p, e, μ density

Direct Urca occurs only for $M \gtrsim 2\,M_\odot$, not likely in Cas A NS

$M \simeq 1.4\,M_\odot$

Modified Urca process and Bremsstrahlung

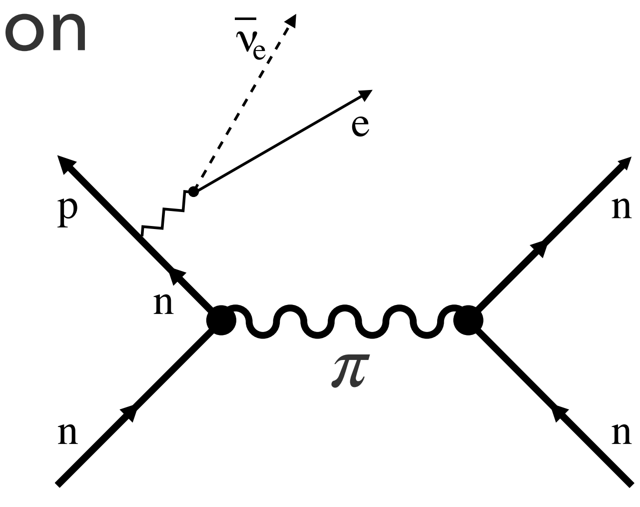
Modified Urca process

- Threshold of direct Urca is relaxed by spectator nucleon

$$n + N \to p + N + \ell + \bar{\nu}_\ell$$

$$p + N + \ell \to n + N + \nu_\ell$$

$N = n \text{ or } p$

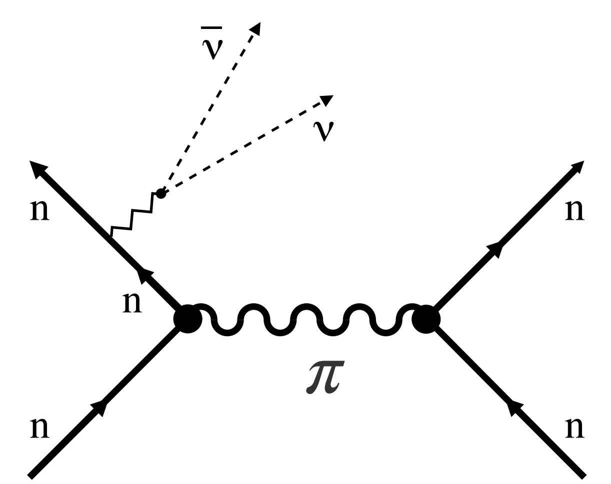


- Luminosity: $L_\nu^{\mathrm{MU}} \propto T^8$ before the Cooper pairing

$$L_\nu^{\mathrm{MU}} \sim \underbrace{\int d^3p_n}_{T} \underbrace{\int d^3p_N}_{T} \cdot \underbrace{\int d^3p_p}_{T} \underbrace{\int d^3p_N}_{T} \underbrace{\int d^3p_e}_{T} \cdot \underbrace{\int d^3p_\nu \delta^4(p_i - p_f) E_\nu}_{T^3}$$

Bremsstrahlung

- $L_\nu^{\mathrm{Brems}} \propto T^8$
- But subdominant $L_\nu^{\mathrm{Brems}} \sim O(0.01) L_\nu^{\mathrm{MU}}$



Nucleon superfluidity in NS

BCS theory: attractive interaction destabilize the Fermi surface

[Cooper (1956)]

⟶ **Cooper pairing**

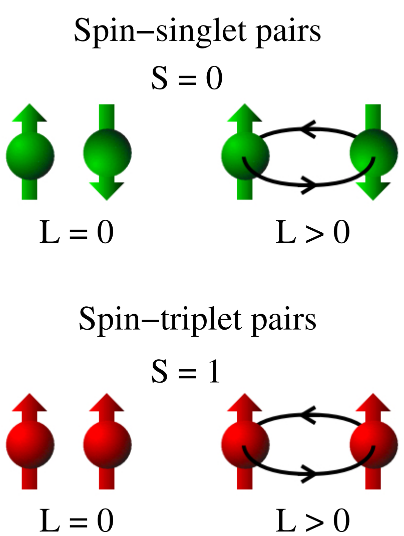
Nuclear force becomes attractive for certain density and angular momentum

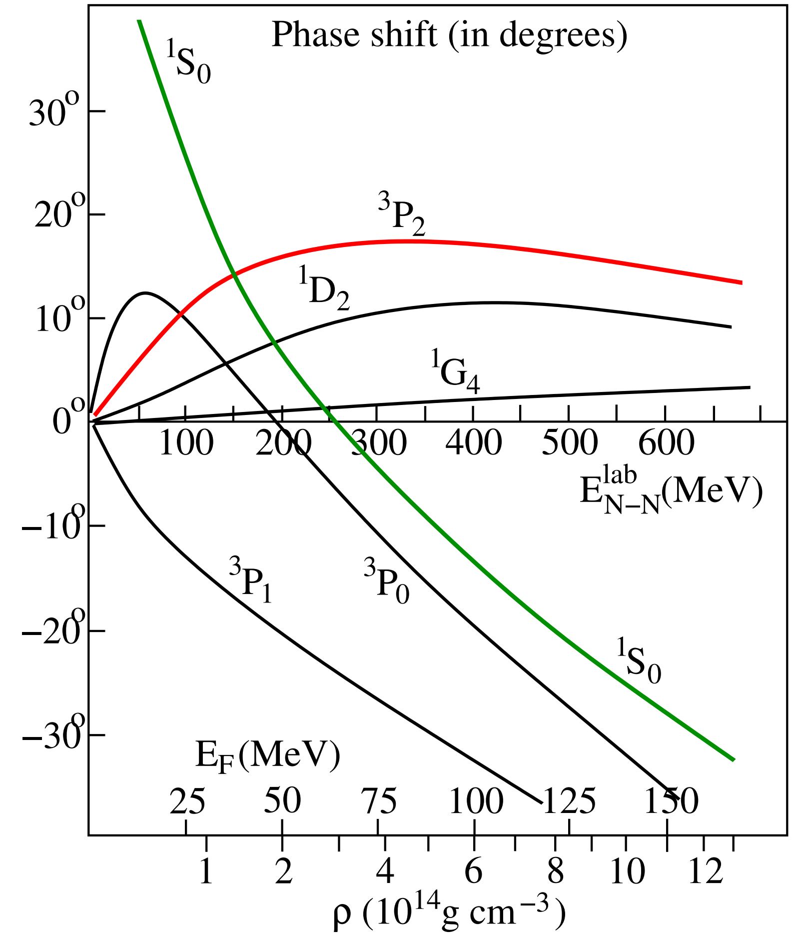
(at least Lab. experiments)

$T < T_c^{(N)}$

In NS core

- Proton singlet pairing ($^1S_0$)
- Neutron triplet pairing ($^3P_2$)





[Page et al. (2013)]

In NS crust (not important for thermal evolution)

- Neutron singlet pairing ($^1S_0$)

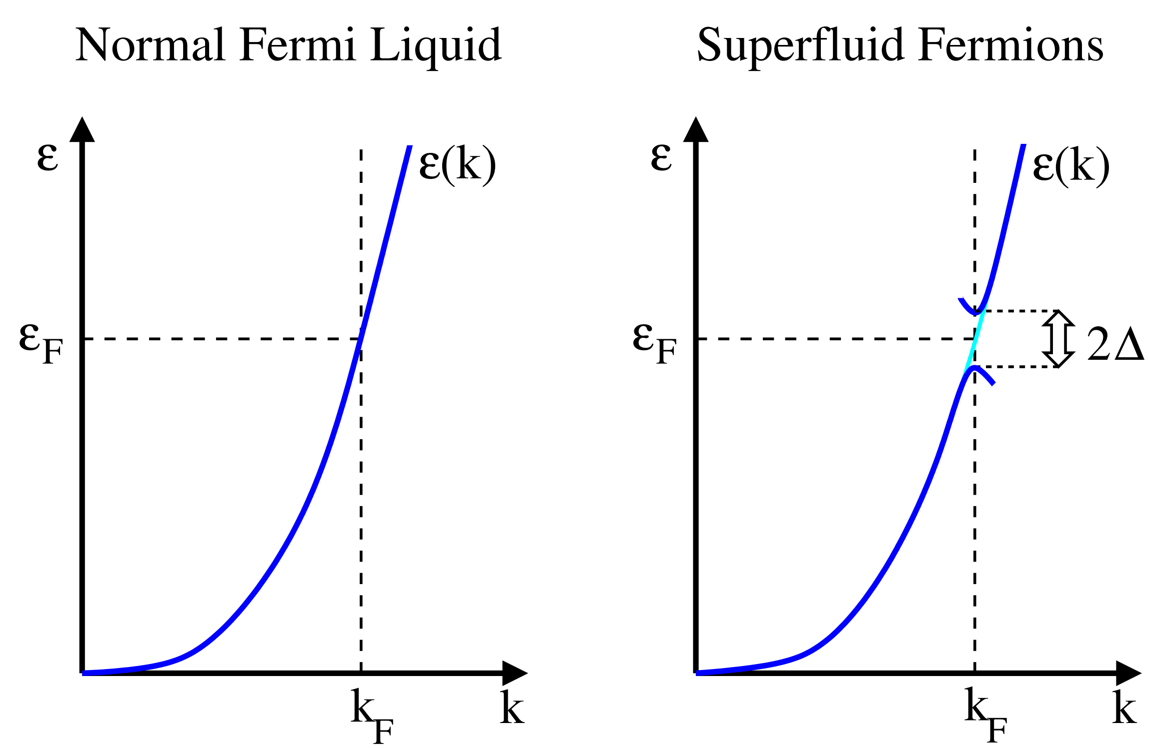
Suppression by the nucleon superfluidity

Cooper pairing of protons and neutrons suppresses the Urca and Brems.

Energy gap appears below critical temperature

$$\epsilon_N(\mathbf{k}) = \mu_{F,N} + \mathrm{sign}(k - k_{F,N})\sqrt{\underline{\Delta_N^2} + (k - k_{F,N})^2} \qquad T < T_c^{(N)}$$

Gap, O(0.1 - 1) MeV ~ O($10^{9\text{-}10}$) K



Phase space suppression by

$$f \sim e^{-\Delta_N/T}$$

[Page et al. (2013)]

Modified Urca and Bremsstrahlung is negligible for $T < T_c^{(N)}$

Cooper pair-breaking and formation (PBF)

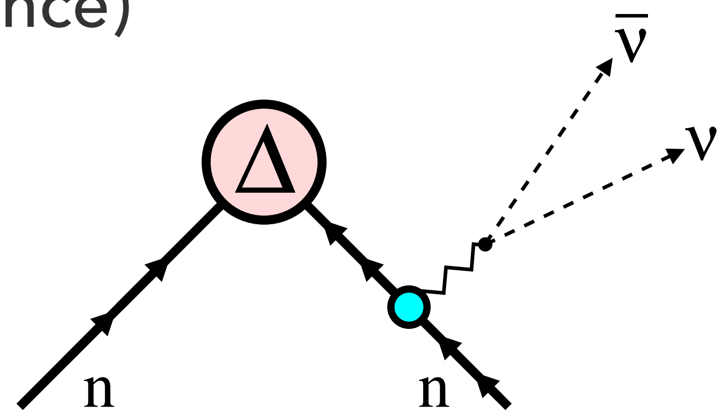
The Cooper pairing triggers rapid neutrino emission (called PBF)

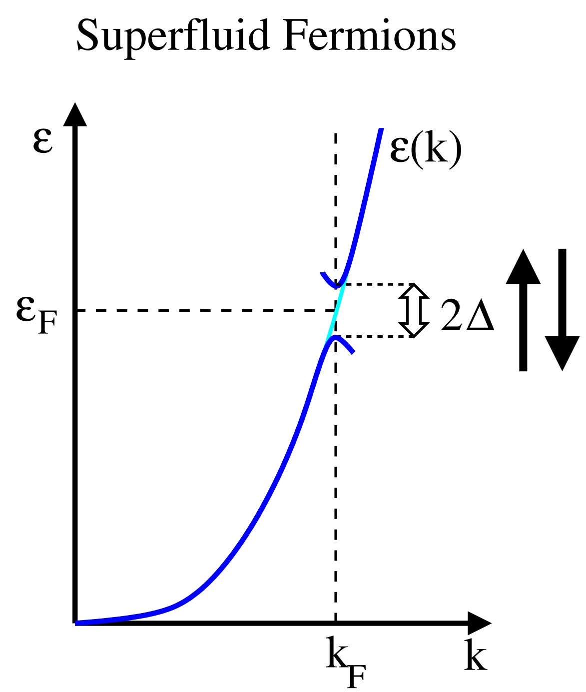
[Flowers et al. (1976)]

- **Pair-breaking** $[\tilde{N}\tilde{N}] \to \tilde{N} + \tilde{N}$ (thermal disturbance)

Cooper pair Single (quasi-)nucleon

- **Pair-formation** $\tilde{N} + \tilde{N} \to [\tilde{N}\tilde{N}] + \nu + \bar{\nu}$





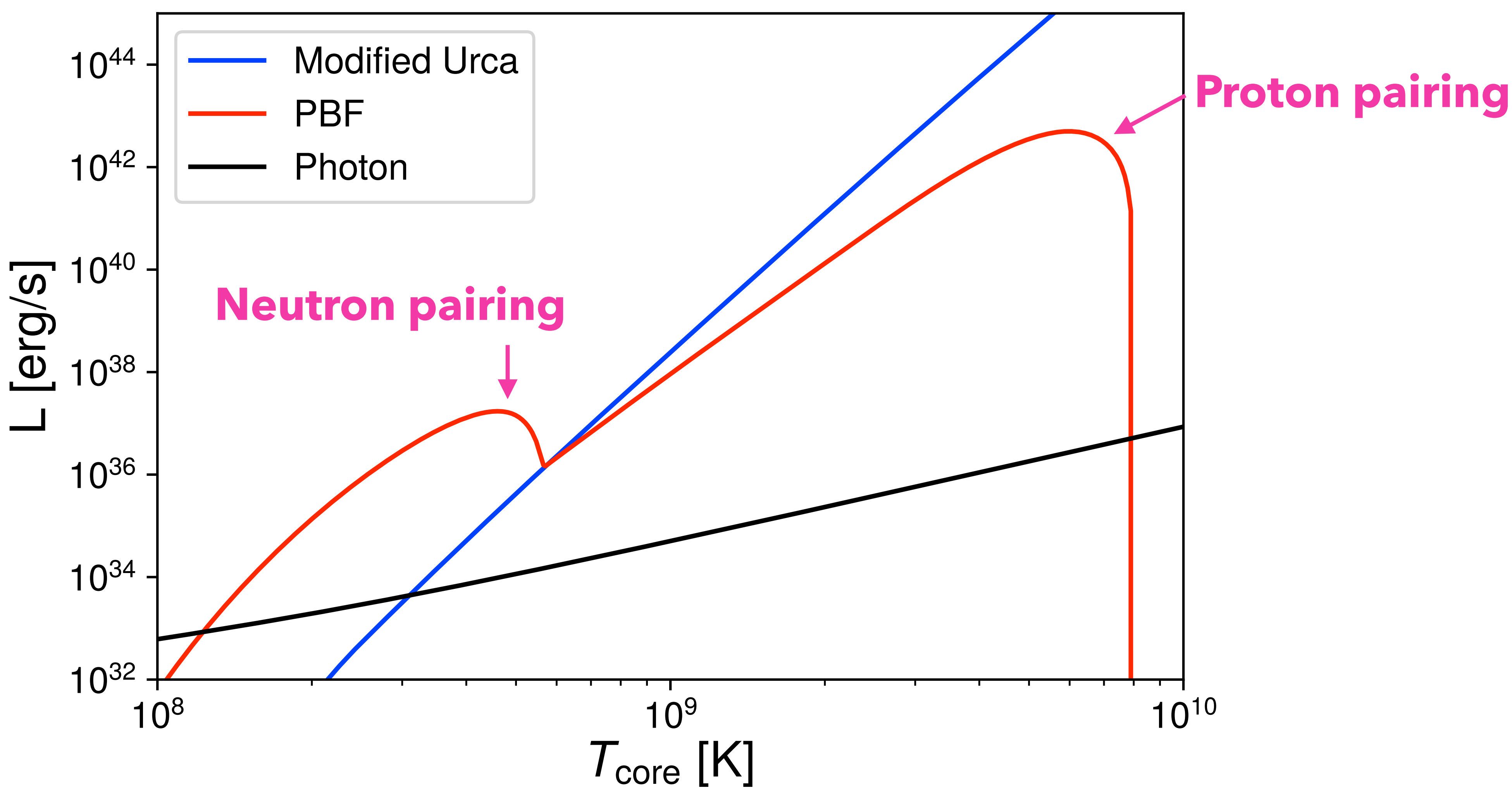
Pair breaking occurs by thermal disturbance

$\longrightarrow$ efficient while T ~ Δ

PBF dominates L_ν for $T < T_c$

Summary of neutrino emission

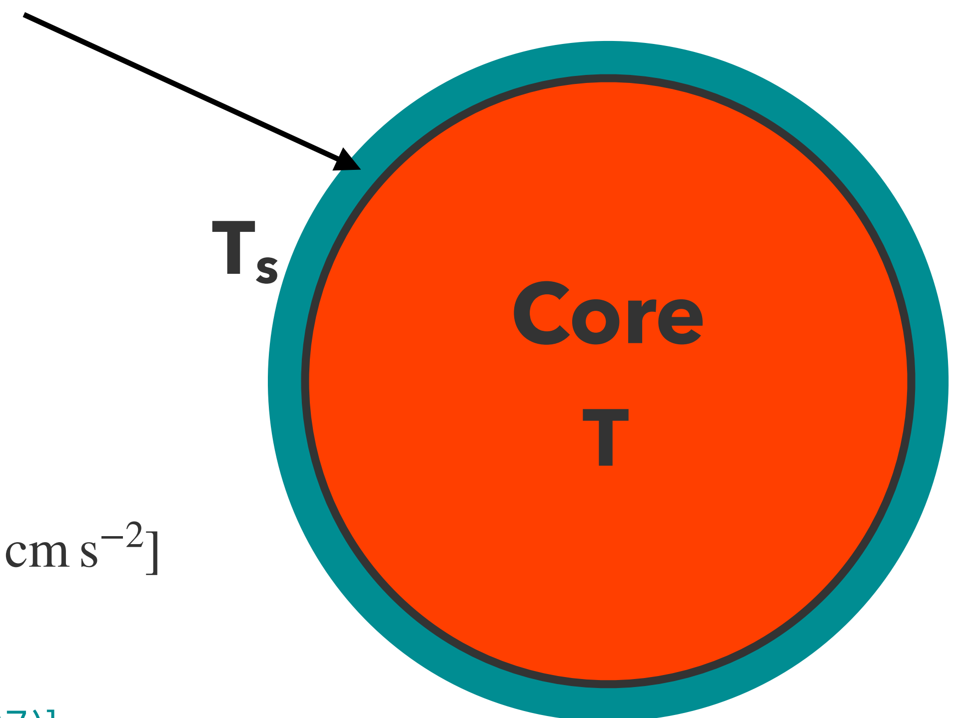
- Direct Urca process is powerful, but forbidden in Cas A NS
- Weaker Modified Urca dominates before Cooper pairing
- After pairing, the PBF process dominates the cooling



Cooling theory vs. Cas A NS observation

Neutron star envelope

Envelope: composed of light elements (H, He, C,…) and heavy elements (Fe)



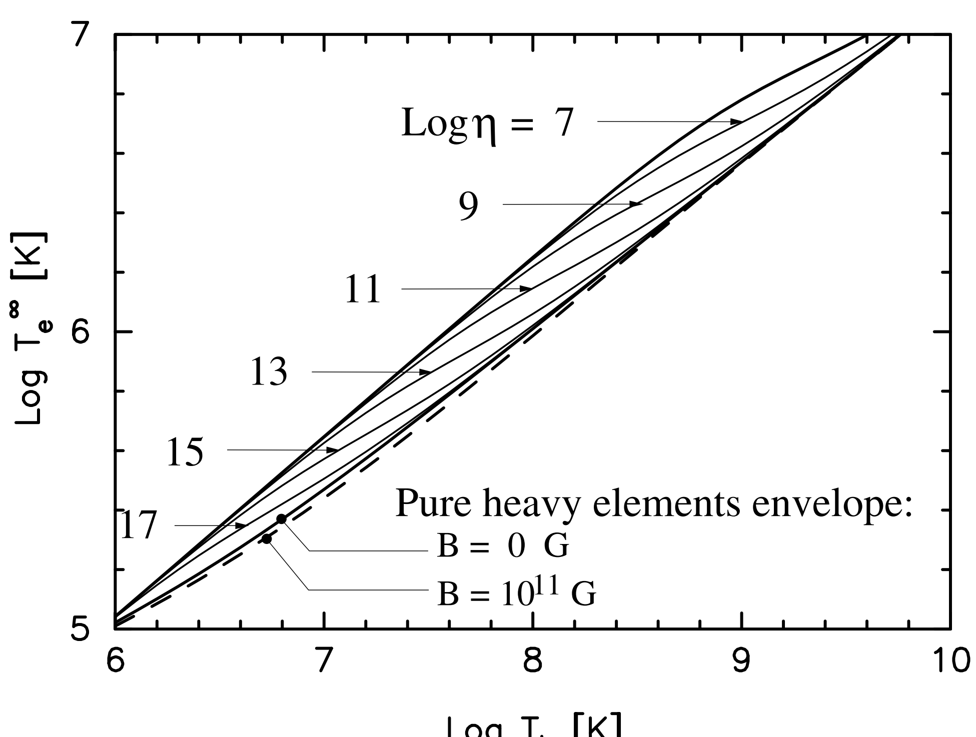
Large temperature gradient exists

$$\frac{T}{10^9\,\mathrm{K}} \sim 0.1288 \times \left(\frac{(T_s/10^6\,\mathrm{K})^4}{\underline{g_{14}}} \right)^{0.455}$$

[Gudmundsson et al. (1983)]

surface gravity $[10^{14}\,\mathrm{cm\,s^{-2}}]$

More accurate relation is available [Potekhin et al. (1997)]



[Figure from Page et al. (2004)]

Characterized by

$$\eta = g_{14}^2 \underline{\Delta M} / M$$

mass of light elements

Without superfluidity

Let's compare theory to Cas A observation, ignoring superfluidity

$$C\frac{dT}{dt} = -L_\nu \quad \Rightarrow \quad T \propto t^{-1/6}$$

$C \propto T$ $\qquad$ $L_\nu \propto T^8$

Using $t \simeq 330\,\mathrm{yr}$ $\;\Delta t \simeq 10\,\mathrm{yr}$ $\;T_s \propto T^{0.55}$

$$\frac{\Delta T}{T} = \frac{1}{6}\frac{\Delta t}{t} \sim 0.5\,\%\,/10\,\mathrm{year} \qquad \left(\frac{\Delta T_s^\infty}{T_s^\infty}\right)_{\mathrm{theory}} \sim 0.3\,\%\,/10\,\mathrm{year}$$

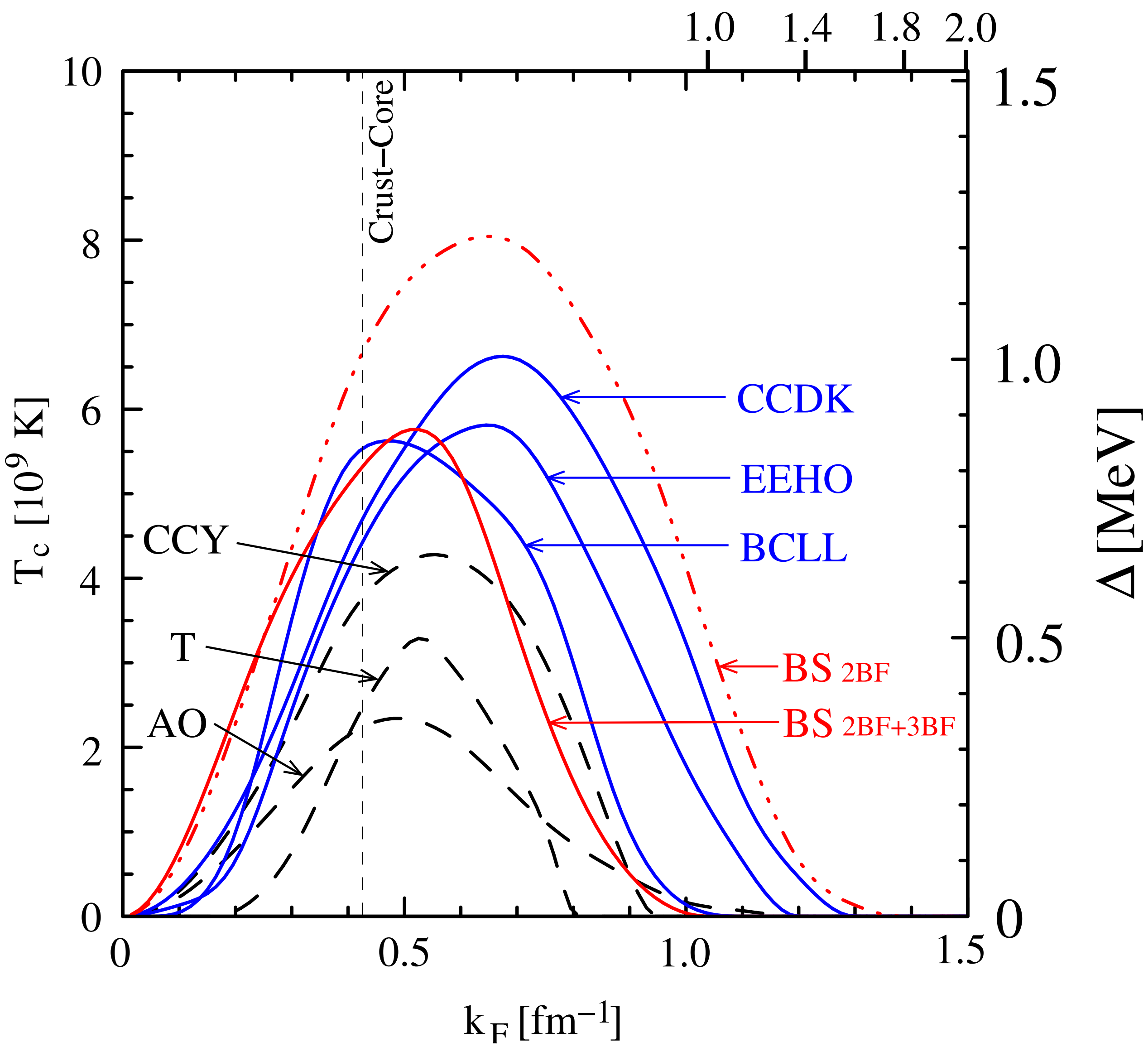
Theory **without superfluidity** cannot explain Cas A NS

$$\left(\frac{\Delta T_s^\infty}{T_s^\infty}\right)_{\mathrm{CasA}} = 3 - 4\,\%$$

Pairing gap models

The effects of superfluidity depends on the **gap profile** $\Delta_N = \Delta_N(\mathbf{k}_F, T=0)$

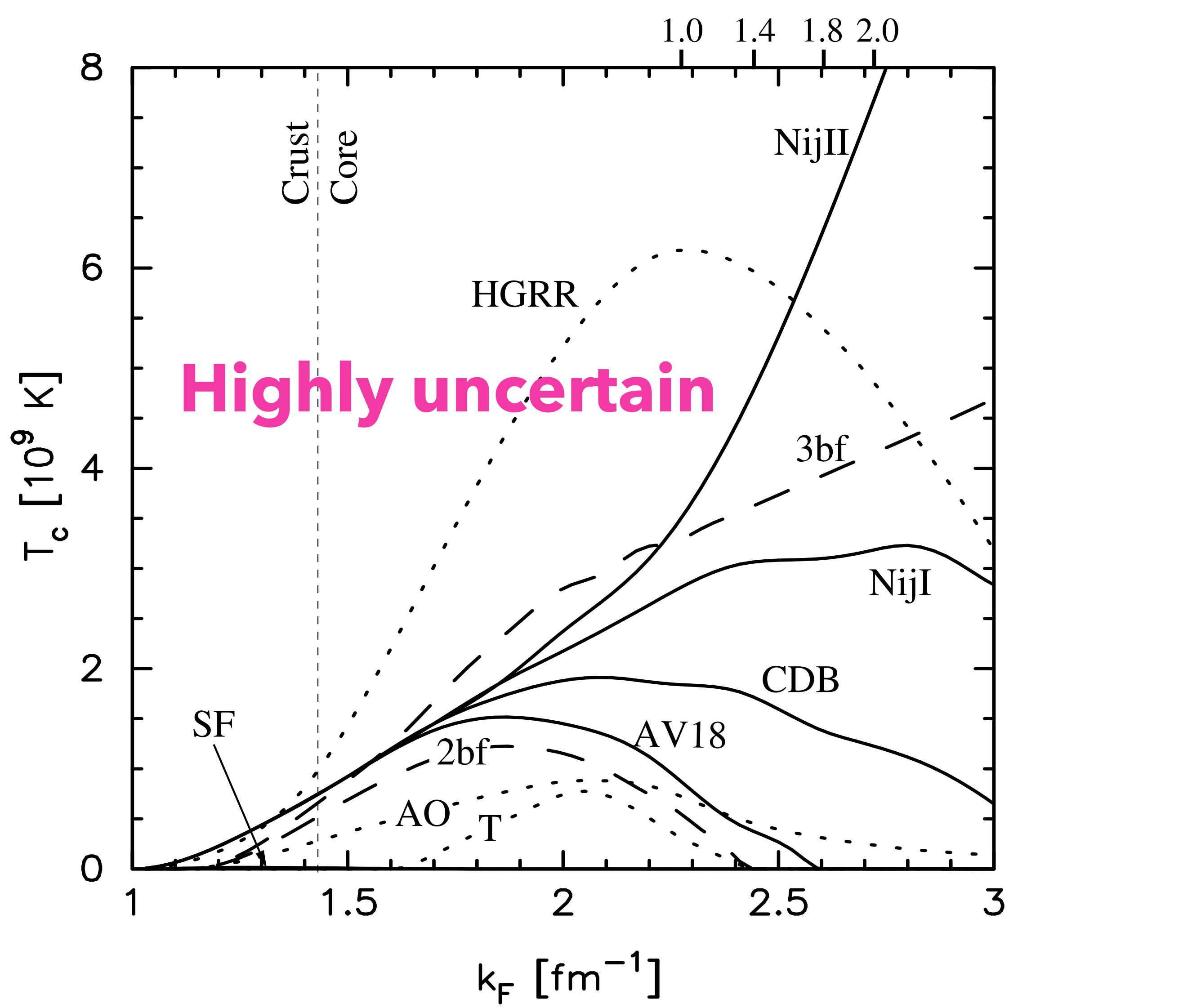
Proton $^1S_0$ pairing models



$T_c^{(p)} = O(1) \times 10^9\,\mathrm{K}$

$\Delta_N(k_F, T=0) \simeq 1.764\, k_B T_c^{(N)}$

Neutron $^3P_2$ pairing models



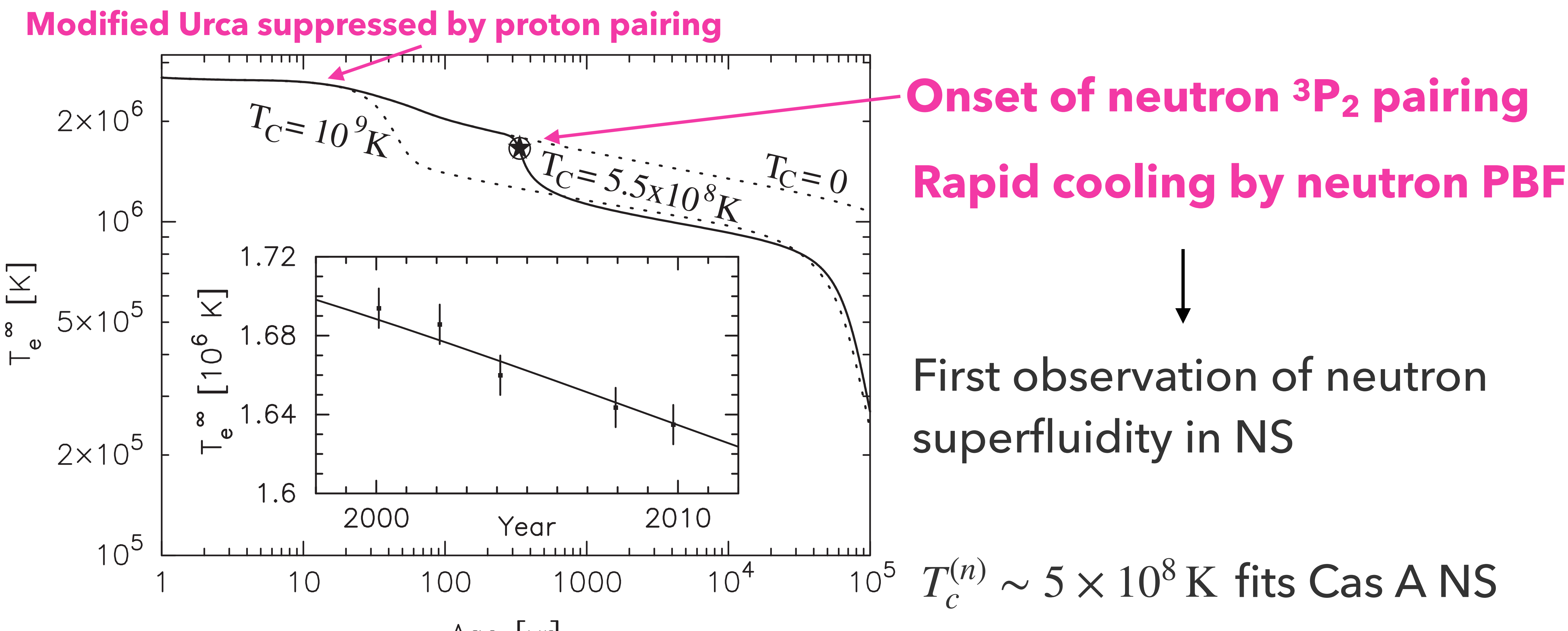
[Figures from Page et al. (2013)]

$T_c^{(n)} \sim 10^8 - 10^9\,\mathrm{K}$

$\Delta_N(k_F, \cos\theta = 0, T=0) \simeq 1.188\, k_B T_c^{(N)}$

Neutrino triplet pairing is necessary

Neutron triplet pairing explains the rapid cooling of Cas A NS!



[Page et al. (2011)]

First observation of neutron superfluidity in NS

$T_c^{(n)} \sim 5\times10^8\,\mathrm{K}$ fits Cas A NS

Proton $^1S_0$ pairing

- Large T_c is necessary to avoid overcool by modified Urca before t ~ 330 yr

$$T_c^{(p)} \gtrsim 10^9\,\mathrm{K}$$

Axion emission from neutron star

Axion couplings to nucleons

Next, we consider **SM + Axion**

- Axion: a Nambu-Goldstone boson associated with Peccei-Quinn symmetry [Pecci and Quinn (1977); Weinberg (1978); Wilczek (1978)]

$$\mathscr{L} = \frac{1}{2}\left(\partial_\mu a\right)^2 + \frac{1}{f_a}\frac{\alpha_S}{8\pi}G_{\mu\nu}\tilde{G}^{\mu\nu} + \sum_q \frac{C_q}{2f_a}\bar{q}\gamma^\mu\gamma_5 q\partial_\mu a + \cdots$$

- Axion couplings to nucleons

$$\mathscr{L} = \sum_{N=n,p} \frac{C_N}{2f_a}\bar{N}\gamma^\mu\gamma_5 N\partial_\mu a + \cdots$$

- Model dependence

can be 0

KSVZ model: $C_p = -0.47(3)\,,\, C_n = -0.02(3)$ $(C_q = 0)$

[Kim (1979); Shifman, Vainshtein, Zakharov ((1980)]

DFSZ model: $C_p = -0.182(25) - 0.435\sin\beta^2$

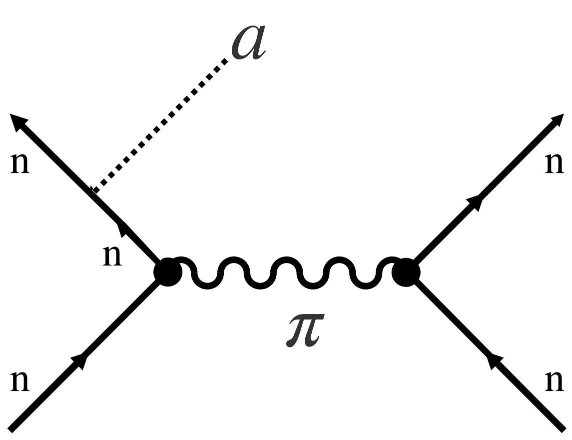
$$C_n = -0.160(25) + 0.414\sin\beta^2 \quad (C_{u,c,t} = \frac{1}{3}\cos\beta\,,\, C_{d,s,b} = \frac{1}{3}\sin\beta^2)$$

[Zhitnitsky (1980); Dine, Fischler, Srednicki (1981)]

Axion emission from neutron star

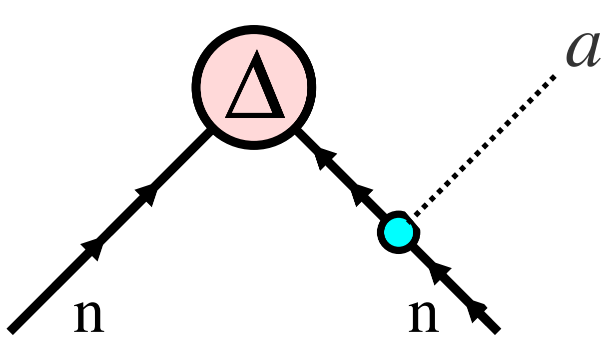
Extra cooling by axion $$C\frac{dT}{dt} = -L_\nu - \underline{L_a}$$

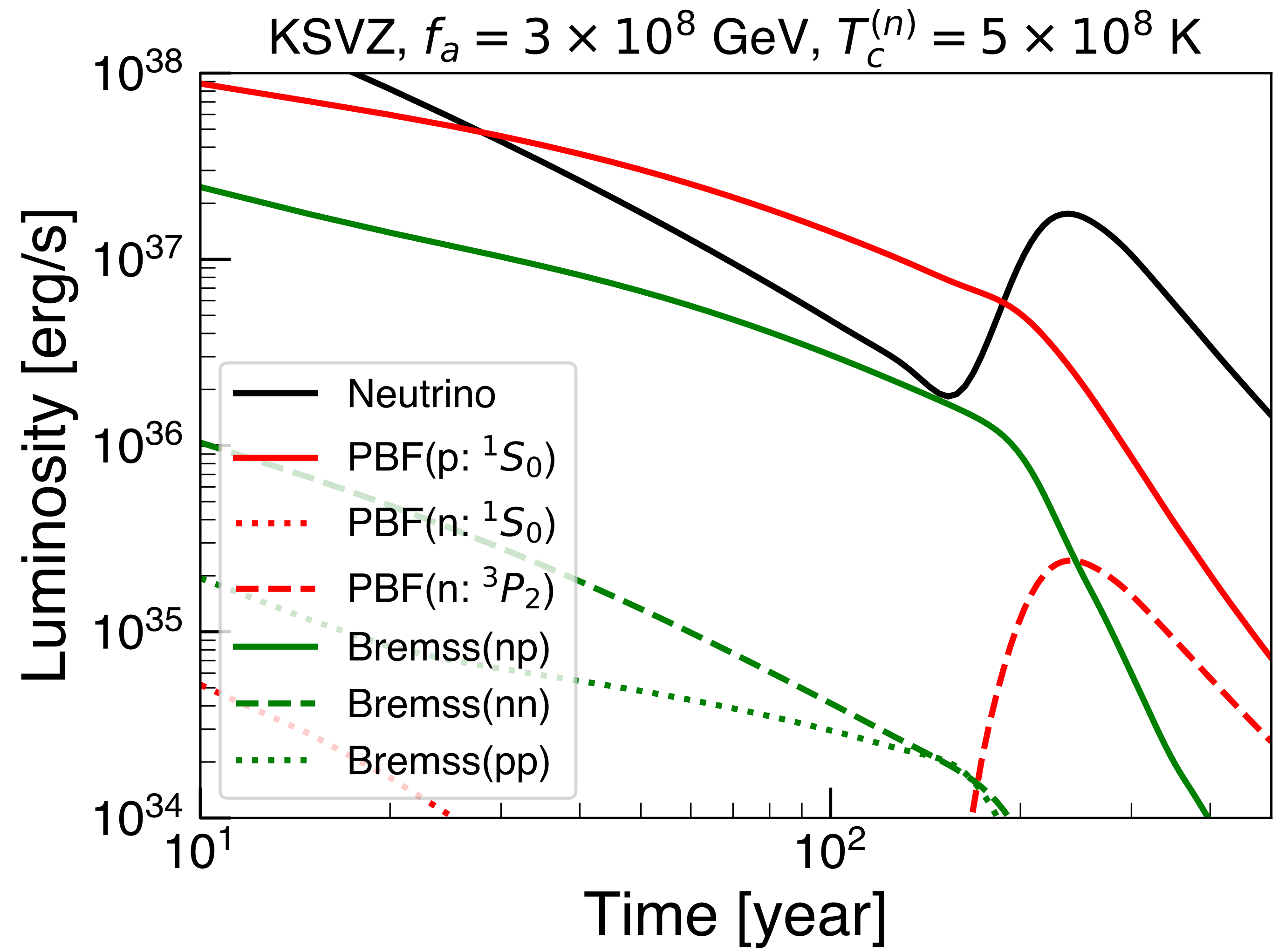
- Axion Bremsstrahlung



- Axion PBF

$$\tilde{N} + \tilde{N} \rightarrow [\tilde{N}\tilde{N}] + a$$





Even if C_n ~ 0, axion emission is sizable due to the proton contribution!

How to constrain the axion model?

If SM + axion cannot fit the Cas A NS, the model is excluded

constraint on f_a

$$\mathscr{L} = \sum_{N=n,p} \frac{C_N}{2f_a} \bar{N}\gamma^\mu \gamma_5 N \partial_\mu a + \cdots$$

Cooling model parameters

- Neutron $^3P_2$ gap model $\longrightarrow$ **vary to fit Cas A NS (3 parameter Gaussian model)**
- Proton $^1S_0$ gap model $\longrightarrow$ **does not matter as long as large enough**

(we use CCDK model)
[Chen et al. (1993)]

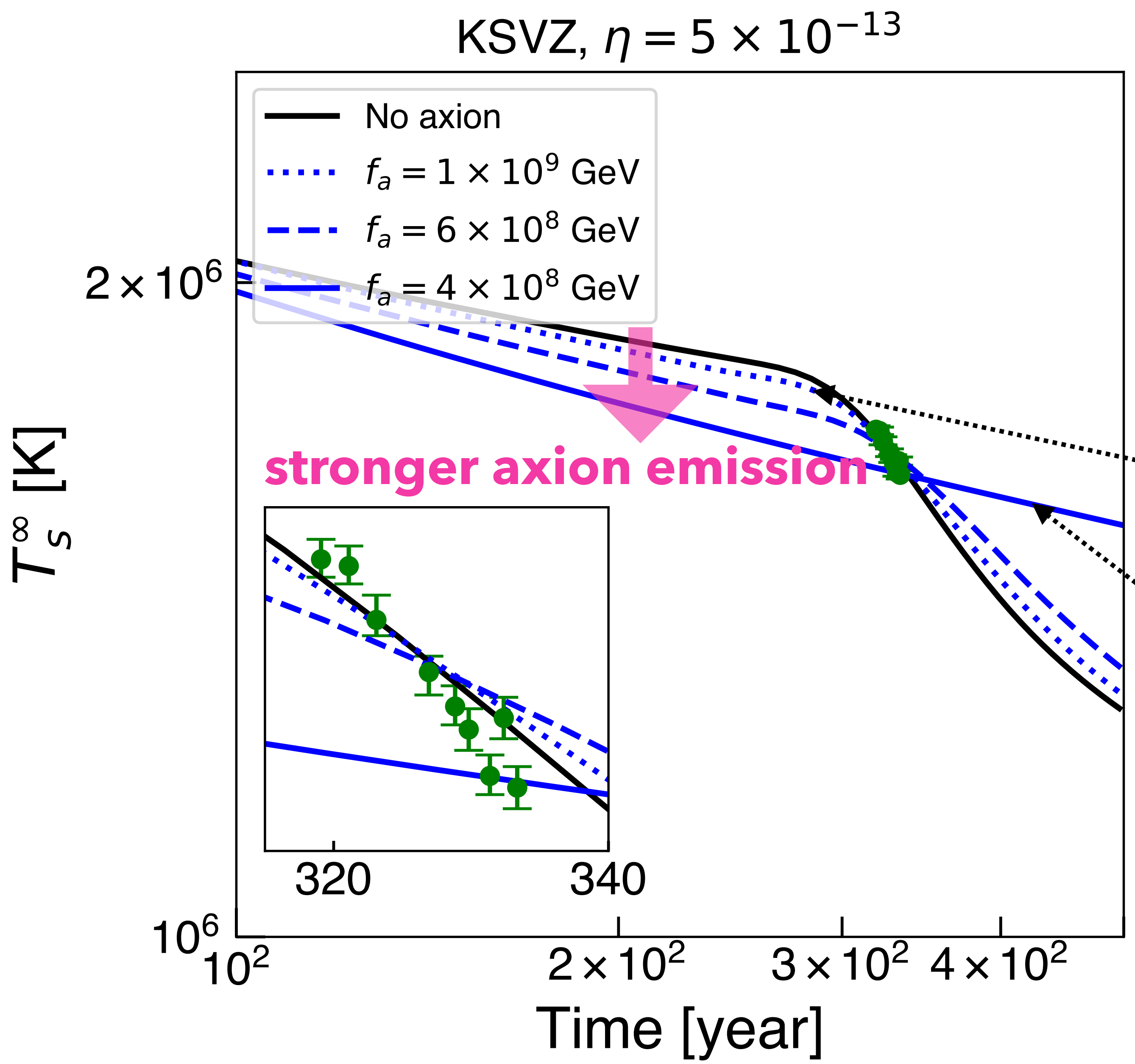
- Neutron $^1S_0$ gap model $\longrightarrow$ SFB model
- Equation of state $\longrightarrow$ APR
- NS mass $\longrightarrow$ $M = 1.4\, M_\odot$

$\Bigg\}$ not so sensitive to these choices

Limit on axion decay constant

For fixed f_a, we vary the neutron gap profile to fit the Cas A NS temperature

If the fit fails for any gap parameter, we exclude that axion model



Limit on f_a of KSVZ (DFSZ) model

$$f_a \gtrsim 5\,(7) \times 10^8\,\mathrm{GeV}$$

$f_a = 1 \times 10^9\,\mathrm{GeV}$:a certain neutron gap fit the data

$f_a = 4 \times 10^8\,\mathrm{GeV}$

the fit fails for any gap profile

NS is **overcooled** before neutron Cooper pairing

comparable to the limit from SN1987A

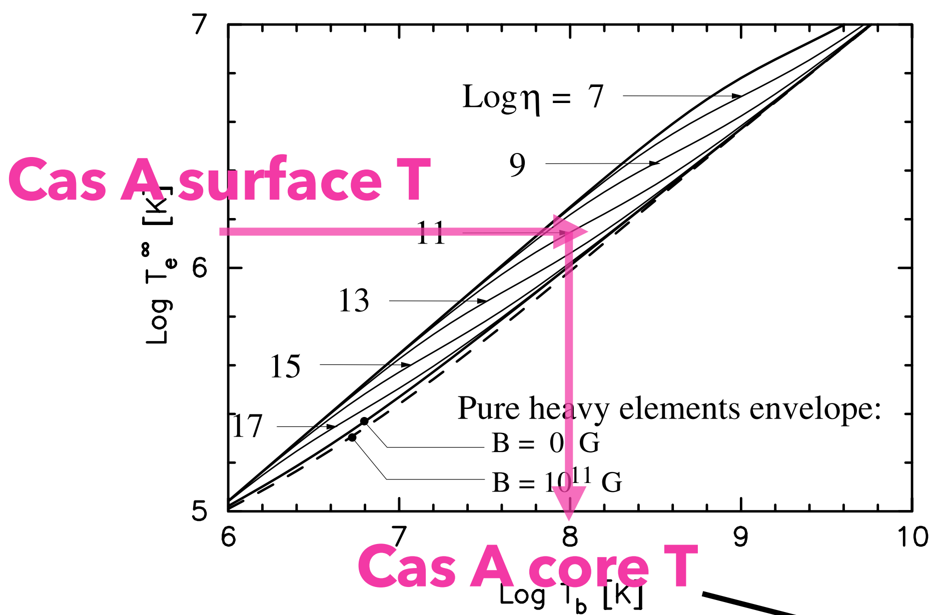
$$f_a \gtrsim 4 \times 10^8\,\mathrm{GeV}$$

Uncertainty from envelope

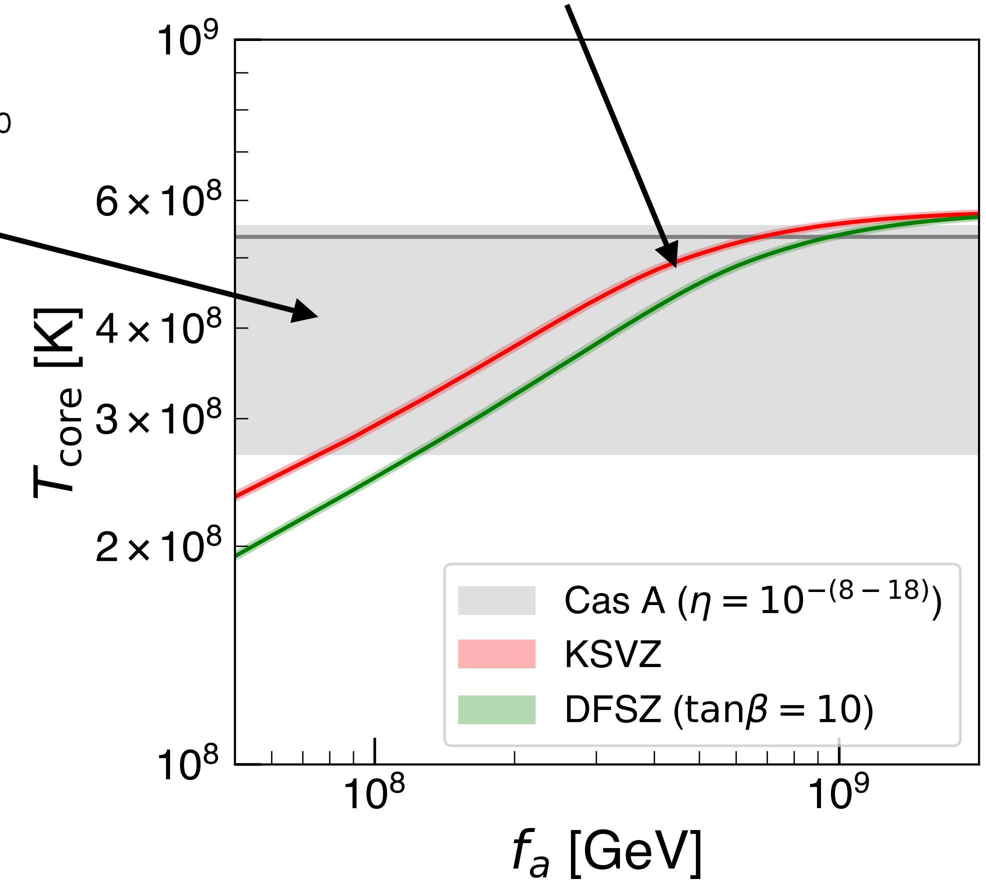
O(1) uncertainty on the limit coming from envelope profile

We do not know $\eta = g_{14}^2 \Delta M/M$

$T_s - T$ relation



$T_{\rm core}$ at Cas A age from theory



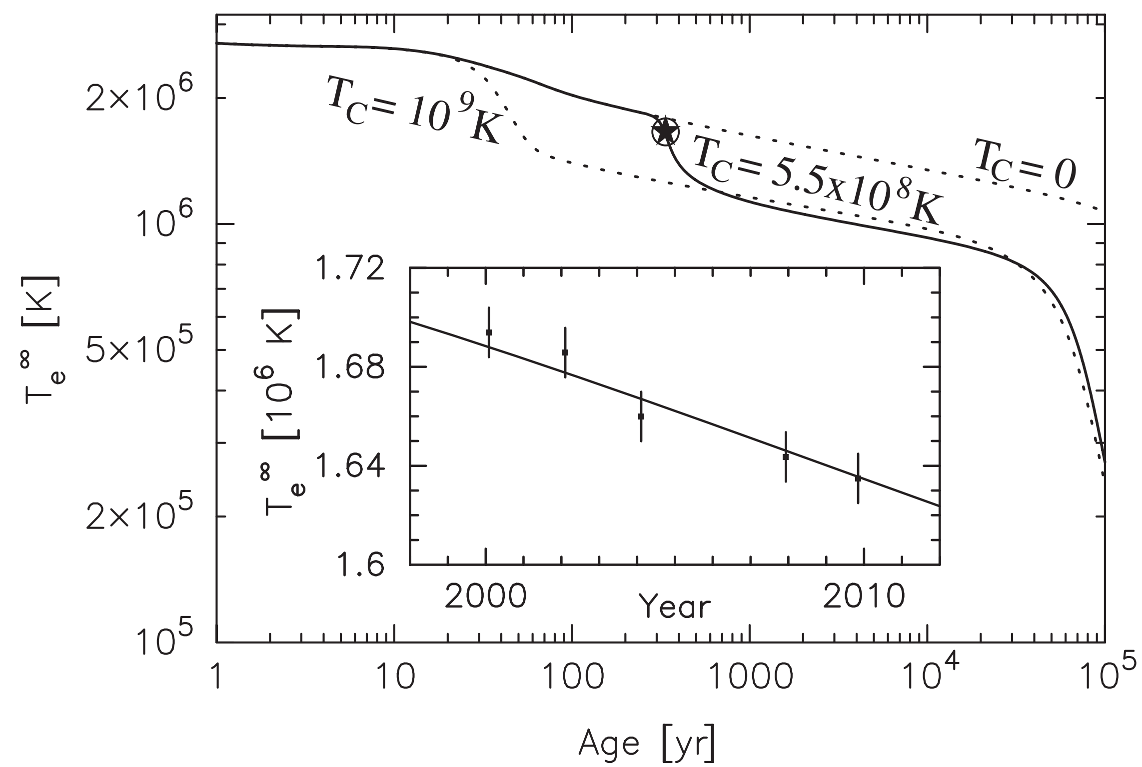
We evaluate the uncertainty from envelope

$$f_a > O(10^8)\,\mathrm{GeV}$$

Summary

Summary

[Page et al., Phys. Rev. Lett. 106, 081101 (2011)]



Within the Standard Model

Cooling theory can fit the observed surface temperature of Cas A neutron star (NS)

Neutron triplet pairing is important

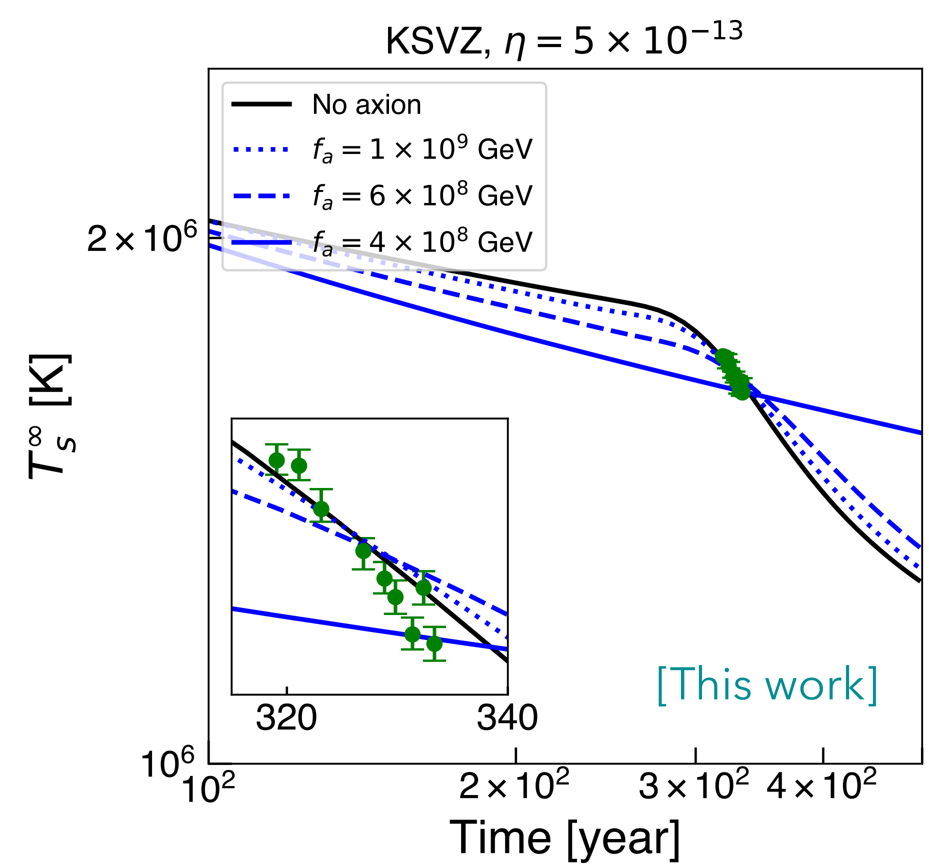
SM + Axion

If the axion couplings to nucleons are too large, cooling is enhanced and cannot fit Cas A NS

$$f_a > O(10^8)\,\mathrm{GeV}$$

comparable to the SN1987A limit

O(1) uncertainty from envelope profile



Backup

Direct Urca threshold

$$n \to p + \ell + \bar{\nu}_\ell \qquad p + \ell \to n + \nu_\ell$$

$\mu = \sqrt{m^2 + p_F^2}$

$p_{F,n} \sim 400\,\mathrm{MeV}$

$p_{F,p} \simeq p_{F,e} \sim 10 - 100\,\mathrm{MeV}$

- Suppose beta equilibrium

$$\mu_n = \mu_p + \mu_e$$

- Energy conservation

$$\epsilon_n = \epsilon_p + \epsilon_e \pm \epsilon_\nu$$

$\longrightarrow$ reaction on Fermi surface, small neutrino momentum $p_\nu \sim T \ll p_{F,n,p,e}$

- Momentum conservation

$$\mathbf{p}_n \simeq \mathbf{p}_p + \mathbf{p}_e \quad \text{with } |\mathbf{p}_i| = p_{F,i}$$

$\longrightarrow$ Triangle condition $\quad p_{F,p} + p_{F,e} > p_{F,n}$

- If we neglect muon, charge neutrality requires $p_{F,p} = p_{F,e}$

$$\longrightarrow \quad n_p > n_n/8$$

Gap profile

$$\epsilon_N(\mathbf{k}) = \mu_{F,N} + \mathrm{sign}(k - k_{F,N})\sqrt{\Delta_N^2 + (k - k_{F,N})^2}$$

Gap Δ is generically depends on temperature and momentum

$$\Delta_N = \Delta_N(\mathbf{k}_F, T) \qquad \text{where } \Delta_N(\mathbf{k}_F, T \geq T_c^{(N)}) = 0$$

- $^1S_0$ pairing is isotropic $\quad \Delta_N(\mathbf{k}_F, T) = \Delta_N(k_F, T)$
- $^3P_2$ pairing is anisotropic $\quad \Delta_N(\mathbf{k}_F, T) \propto \sqrt{1 + 3\cos^2\theta}$ for $m_J = 0$

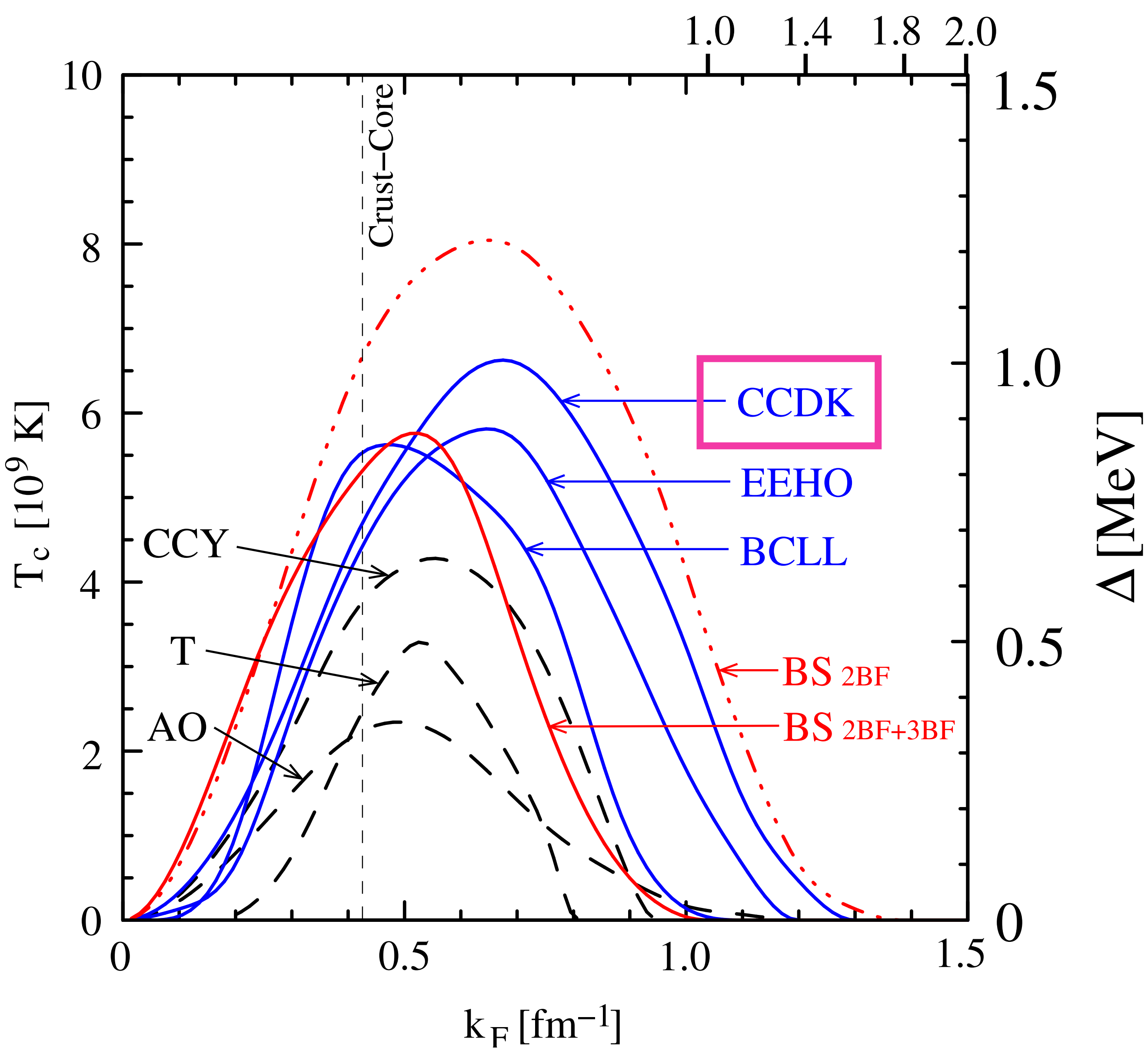
T=0 gap and critical temperature are related

- $^1S_0$ pairing: $\Delta_N(k_F, T = 0) \simeq 1.764\, k_B T_c^{(N)}$
- $^3P_2$ pairing: $\Delta_N(k_F, \cos\theta = 0, T = 0) \simeq 1.188\, k_B T_c^{(N)}$

$T_c^{(N)}$ is calculated theoretically

Proton singlet gap model

Theoretical calculations are relatively certain



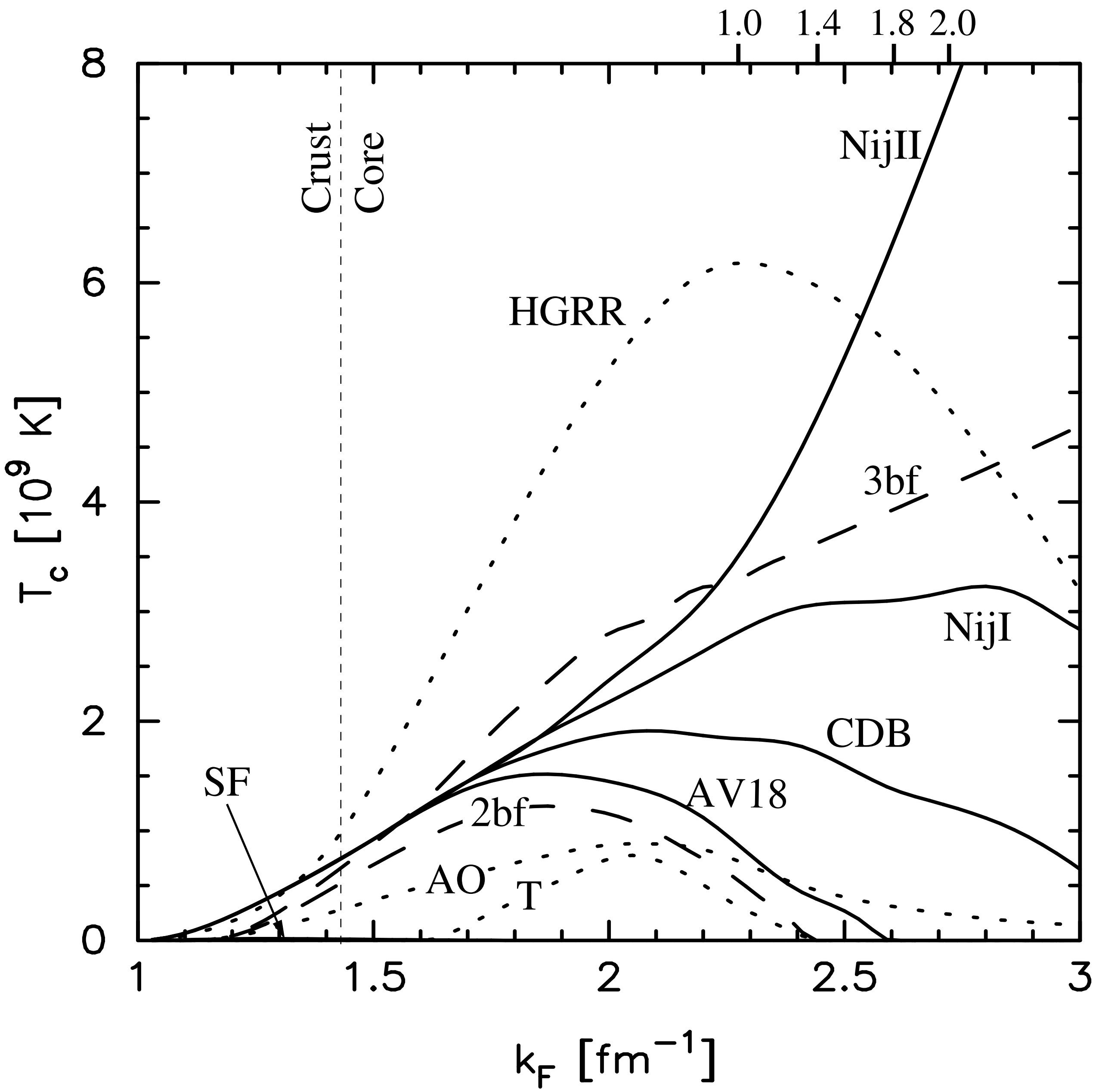
We use CCDK model because

- Large proton gap is more favorable for Cas A
- Axion emission from proton is suppressed

⟶ derived bound on f_a is **conservative**

Neutron triplet gap model

Theoretical calculations are highly uncertain



We model the gap by the Gaussian

3 parameters

- Height $\longrightarrow T_c^{(n)}$
- Width
- Center

Large η

Large η may weaken the limit on f_a

- How large?

  $\eta \lesssim 10^{-8}$ (Maximally carbon-rich)

  to avoid pycnonuclear fusion

- Large η $\longleftrightarrow$ low T_{core}

  $\longrightarrow$ **Low neutrino PBF luminosity**

KSVZ: $\eta = 10^{-8}$ cannot fit Cas A NS

- neutrino emission alone is insufficient
- axion emission cannot help

$\longrightarrow$ $f_a \gtrsim 5 \times 10^8\,\mathrm{GeV}$

DFSZ: $\eta = 10^{-8}$ can fit because C_n is sizable

$\longrightarrow$ weaker constraint