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

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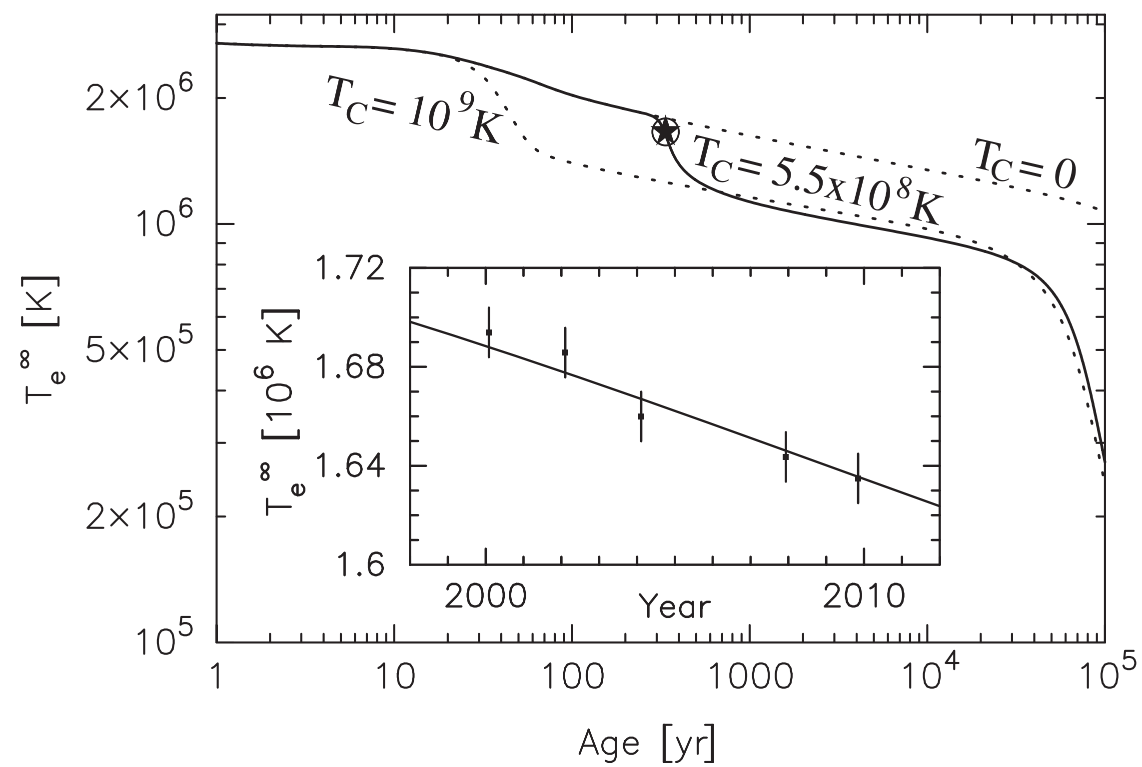
Oct. 30 2018

The 8th KIAS workshop on particle physics and cosmology

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

Short summary

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



Within the Standard Model

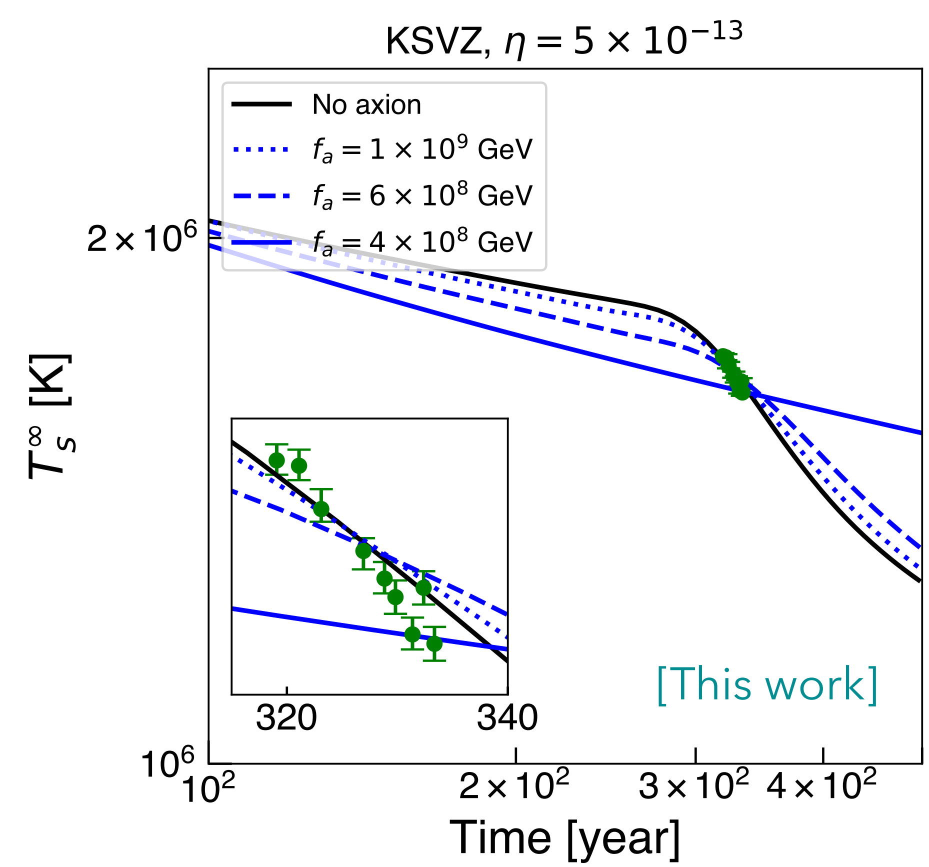
Cooling theory can fit the observed surface temperature of Cas A neutron star (NS)

SM + Axion

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

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

comparable to the SN1987A limit



Outline

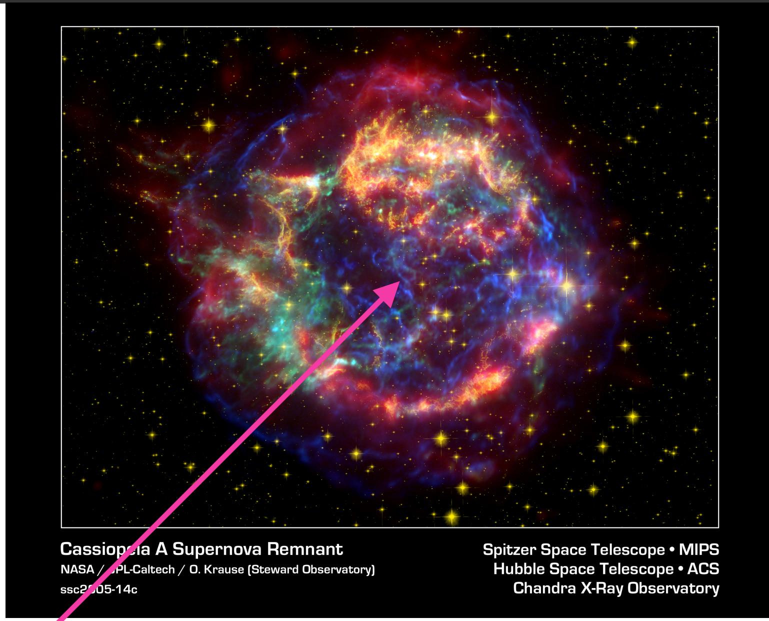
- Observation of neutron star in Cassiopeia A

- Cooling theory of a neutron star

- Axion emission from neutron star

Observation of neutron star in Cassiopeia A

Neutron star in the Cassiopeia A



[Wikipedia]

Cassiopeia A

- Supernova remnant in the Cassiopeia constellation
- Distance: $d = 3.4^{0.3}_{-0.1}$ kpc [Reed et al., Astrophys. J. 440, 706 (1995).]
- Birth date from remnant expansion: 1681 ± 19

[Fesen et al., Astrophys. J. 645, 283 (2006)]

Age: $t \simeq 340\,\mathrm{yr}$

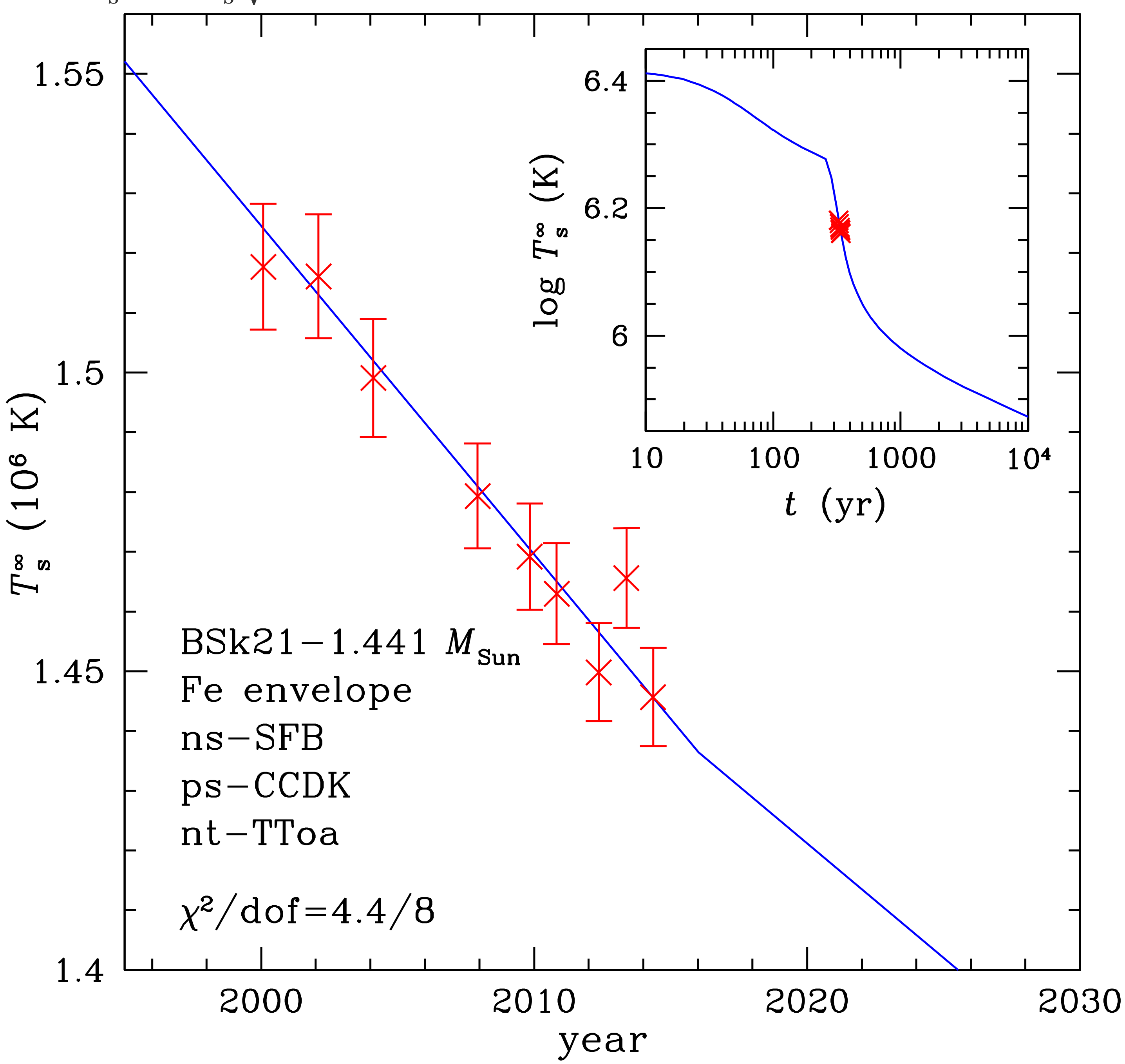
Neutron star in Cas A (Cas A NS)

- Point source in the center of Cas A
- Thermal X-ray spectrum detected by the *Chandra* [Tananbaum (1999)]
- Carbon atmosphere fit: $M = (1.4 \pm 0.3)\,M_\odot$

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!** (blue line: theory)

Cooling theory of neutron star

Cooling theory of NS without Cooper pairing

Thermal balance equation

Internal temperature

Neutrino luminosity

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

Heat capacity (n, p, e, μ)

$C \propto T$

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

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negligible at Cas A age ~ 340 yr

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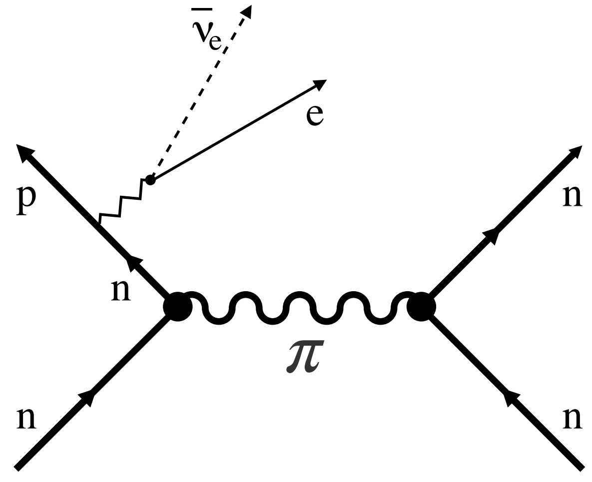
Neutrino emission

- Direct Urca process

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

- Modified Urca process

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



Cooling theory of NS without Cooper pairing

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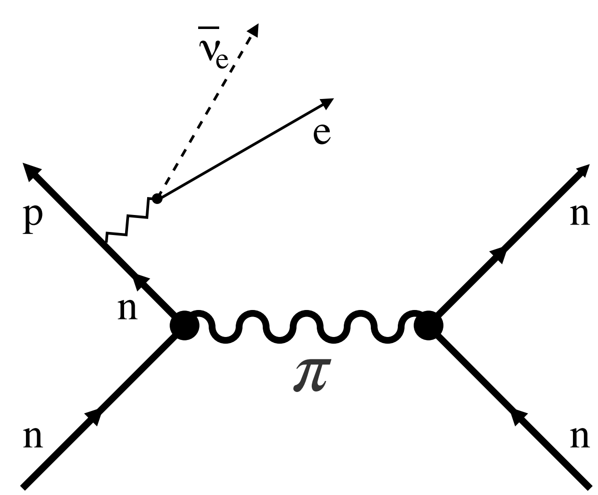
Neutrino emission

- Direct Urca process $L_\nu^{\mathrm{DU}} \propto T^6$

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

- Modified Urca process $L_\nu^{\mathrm{MU}} \propto T^8$

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



Cooling theory of NS without Cooper pairing

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

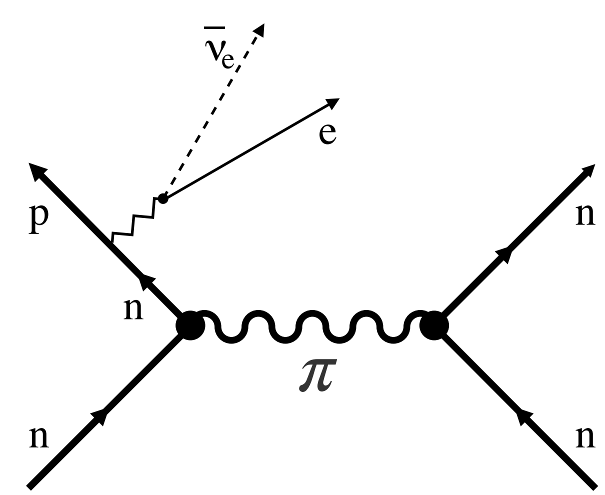
Neutrino emission

- Direct Urca process $\cancel{L_\nu^{\mathrm{DU}} \propto} T^6$ **forbidden for** $M \lesssim 2\,M_\odot$

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

- Modified Urca process $L_\nu^{\mathrm{MU}} \propto T^8$

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

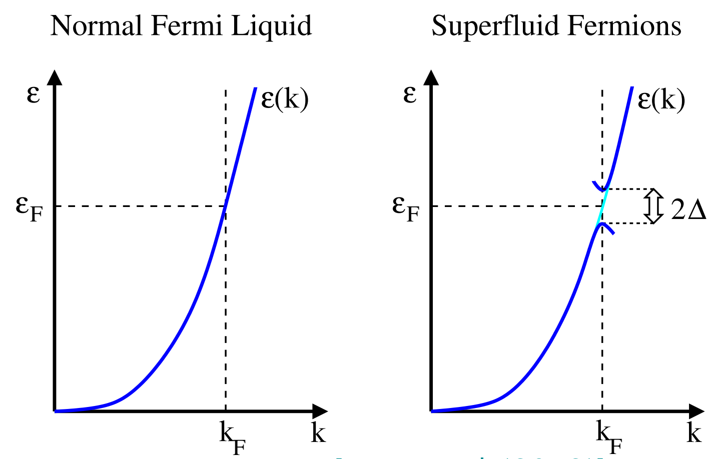


Cooling theory of NS with Cooper pairing

Thermal balance equatio

T < T$_c$, neutrons and protons form Cooper pairs

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



[Page et al. (2013)]

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

In NS core

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

Neutrino emission

- Direct Urca process $\cancel{L_\nu^{\mathrm{DU}} \propto T^6}$

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

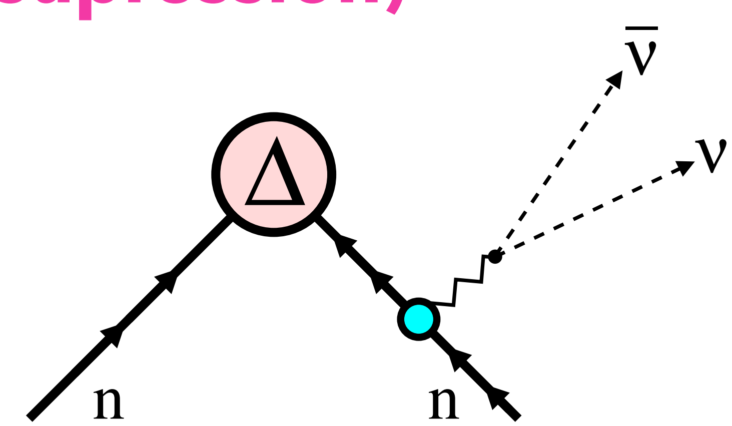
- Modified Urca process $L_\nu^{\mathrm{MU}} \propto T^8$ **× (exponential supression)**

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

- **Pair-breaking and formation (PBF)**

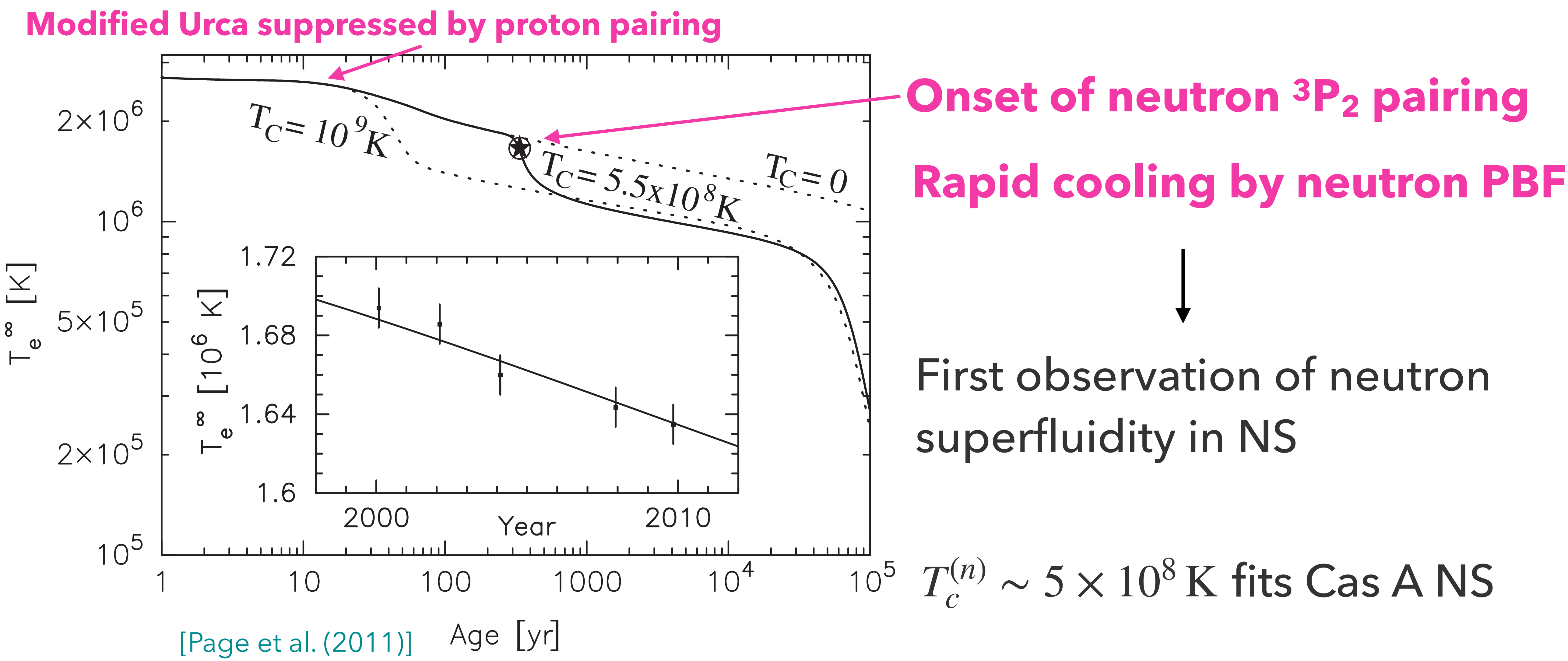
$$\tilde{N} + \tilde{N} \to [\tilde{N}\tilde{N}] + \nu + \bar{\nu}$$

dominant for T < T$_c$



Cooling theory vs. Cas A observation

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



[Page et al. (2011)]

First observation of neutron superfluidity in NS

$T_c^{(n)} \sim 5 \times 10^8\,\mathrm{K}$ 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: $C_p = -0.47(3)\,,\, C_n = -0.02(3) \quad (C_q = 0)$

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

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

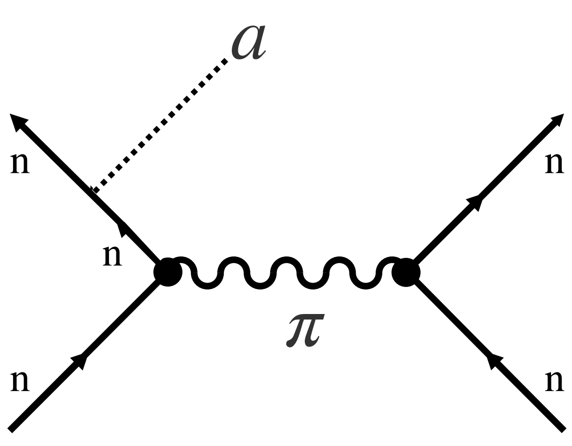
$$C_n = -0.160(25) + 0.414\sin\beta^2 \quad \left(C_{u,c,t} = \frac{1}{3}\cos\beta\,,\, C_{d,s,b} = \frac{1}{3}\sin\beta^2\right)$$

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

Axion emission from neutron star

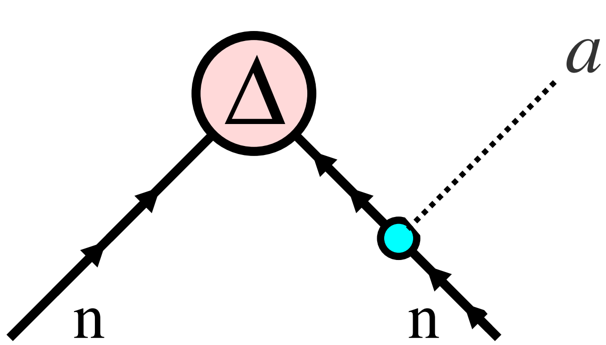
Extra cooling by axion $$C\frac{dT}{dt} = -L_\nu - \underline{L_a}$$

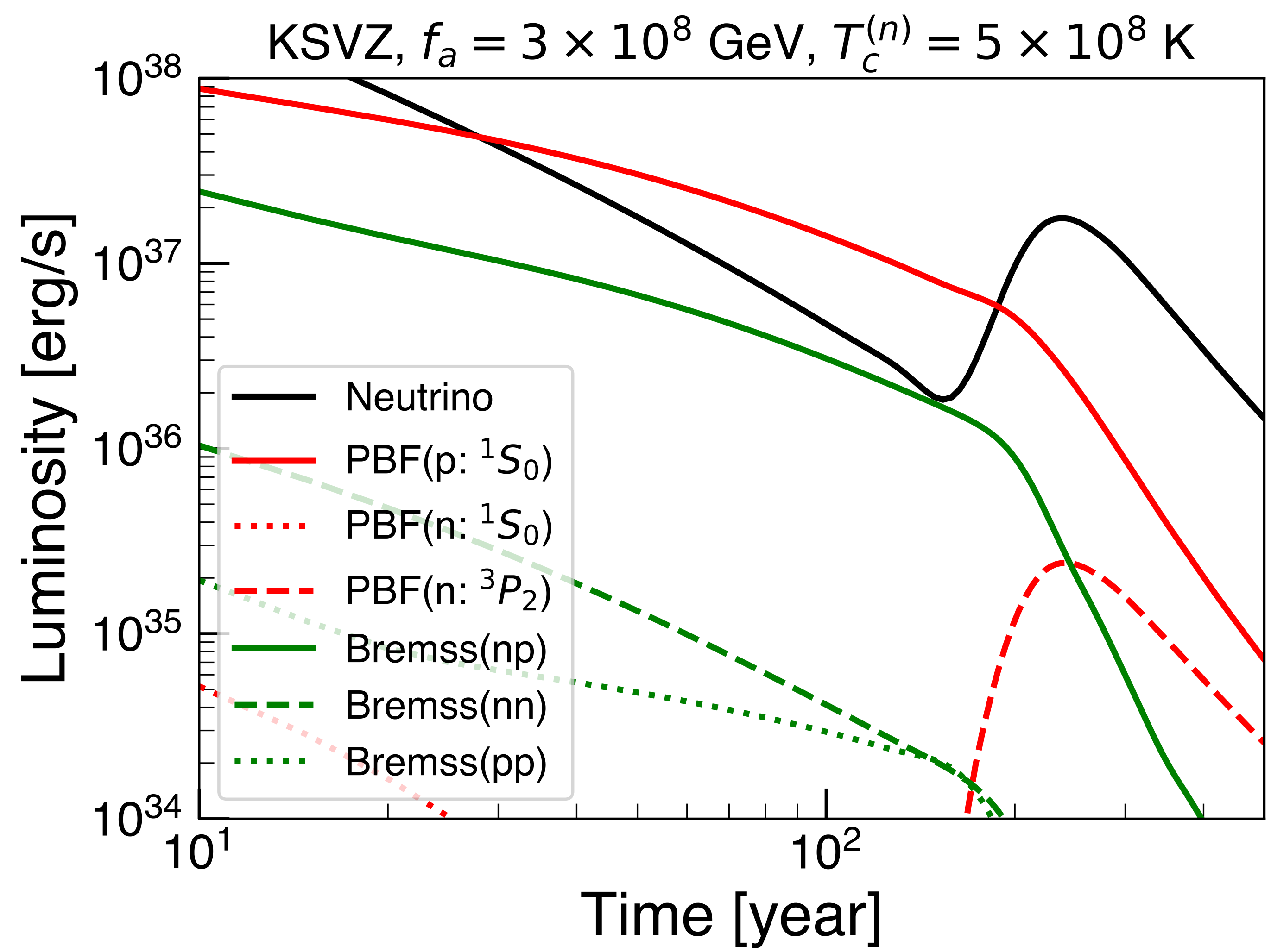
- Axion Bremsstrahlung



- Axion PBF

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



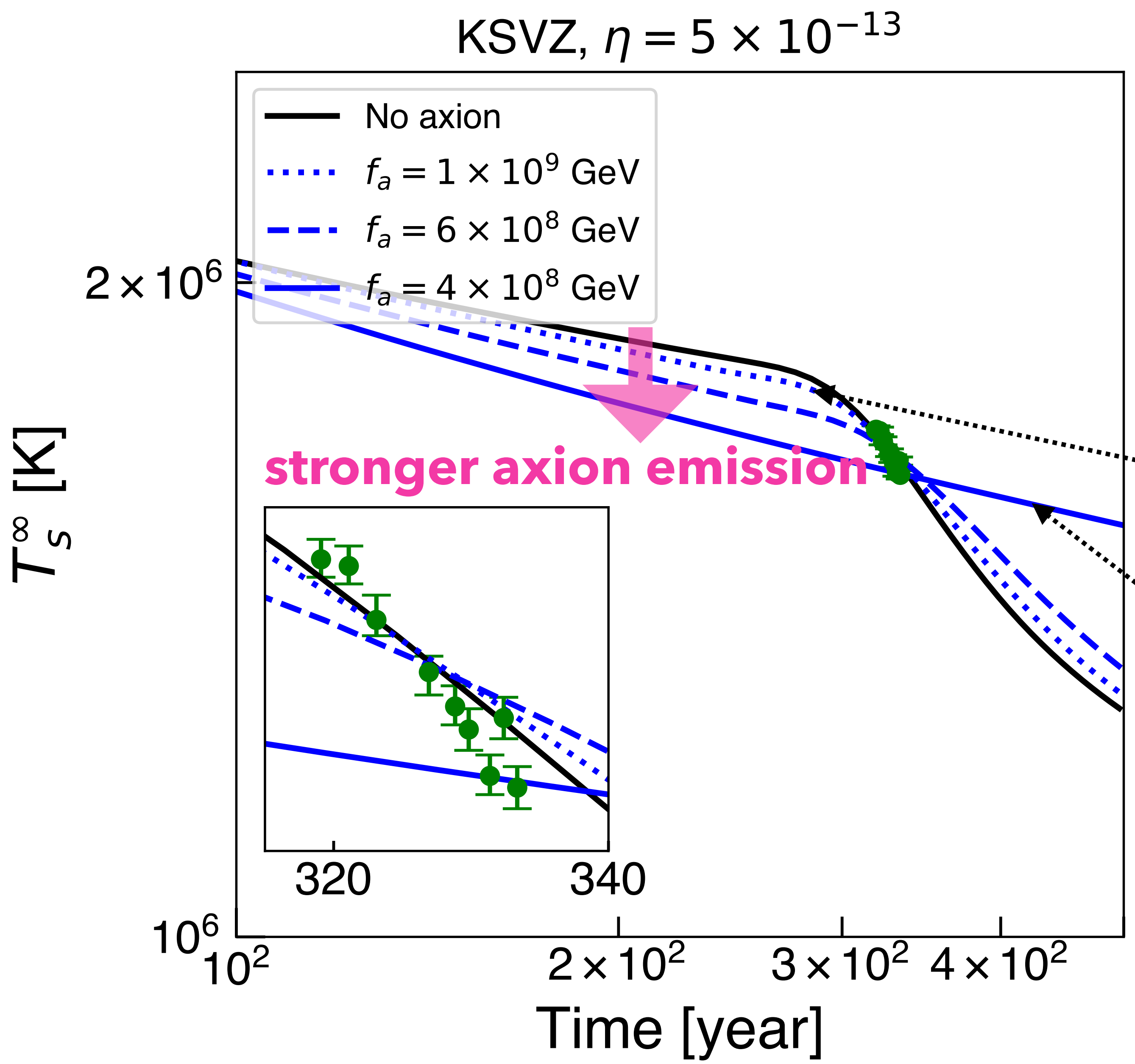


Even if $C_n \sim 0$, axion emission is sizable due to the proton contribution!

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

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

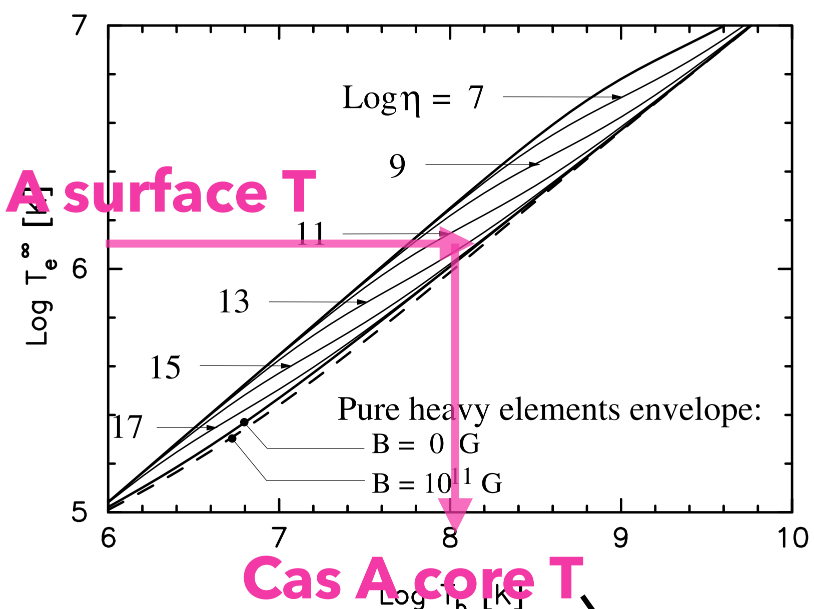
Characterized by

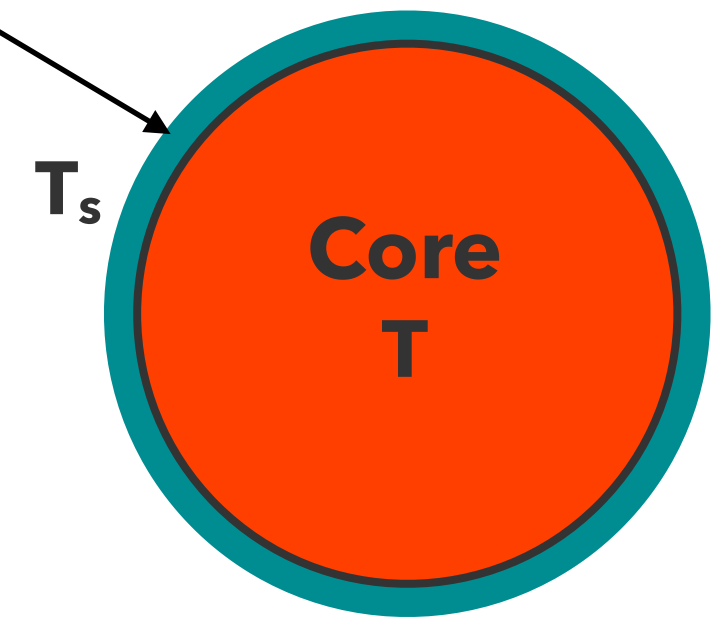
$$\eta = g_{14}^2 \Delta M/M$$

mass of light elements

We do not know η

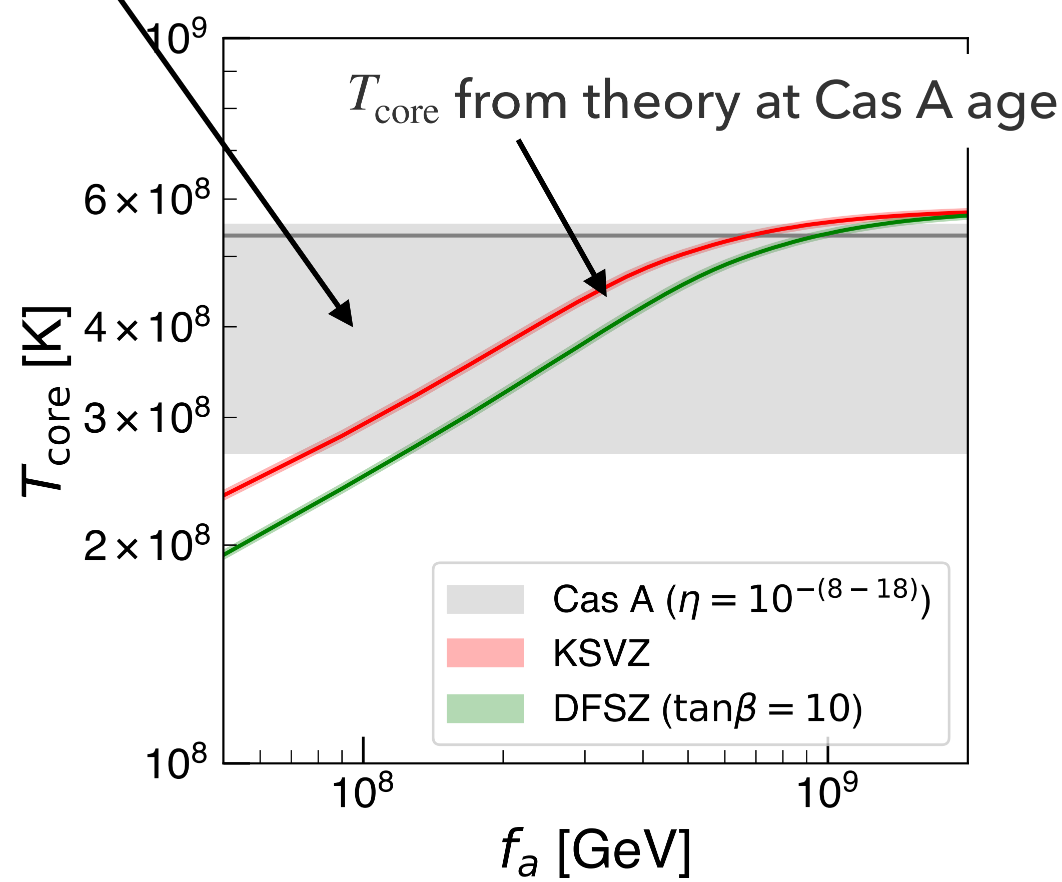
$T_s - T$ relation





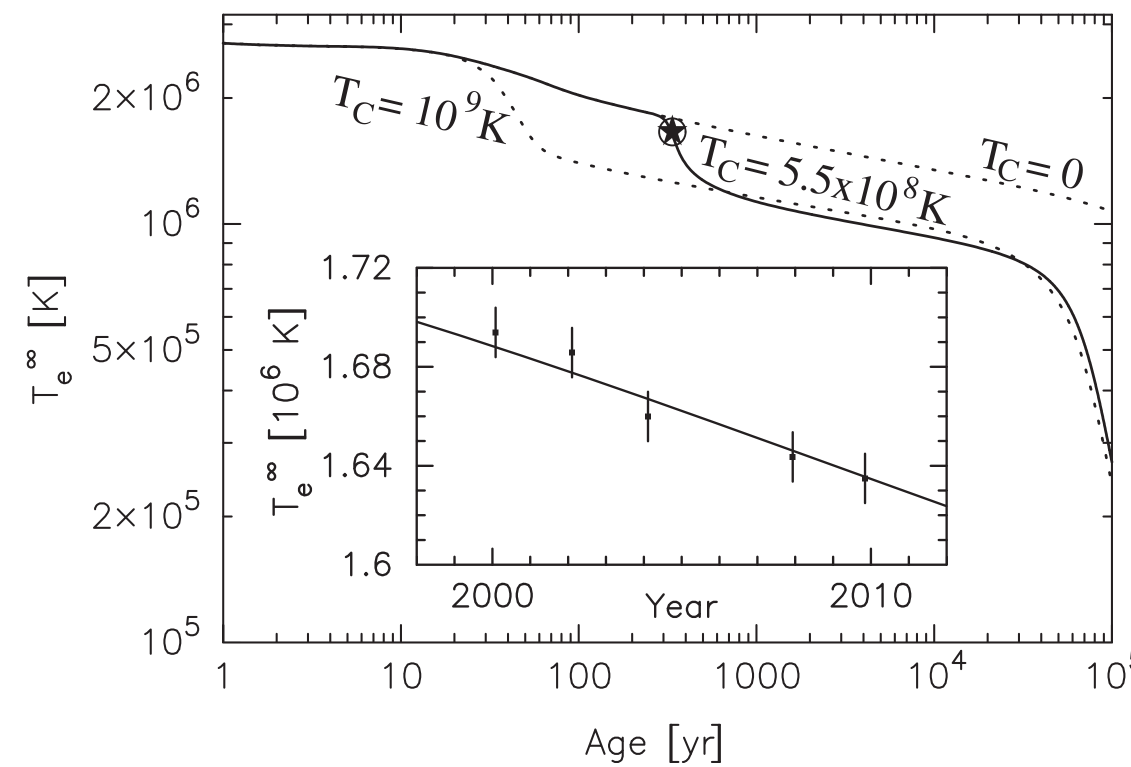
We evaluate the uncertainty from envelope

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



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

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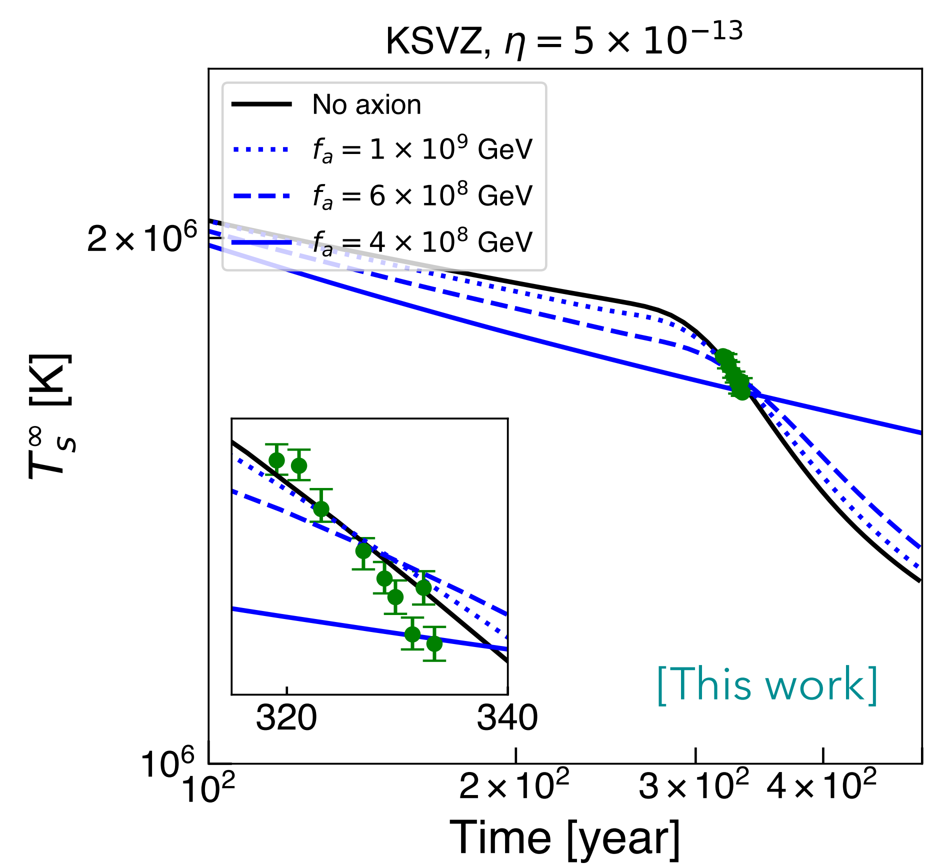
If the axion couplings to nucleons are too large, cooling is enhanced and cannot fit Cas A NS

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

comparable to the SN1987A limit

O(1) uncertainty from envelope profile

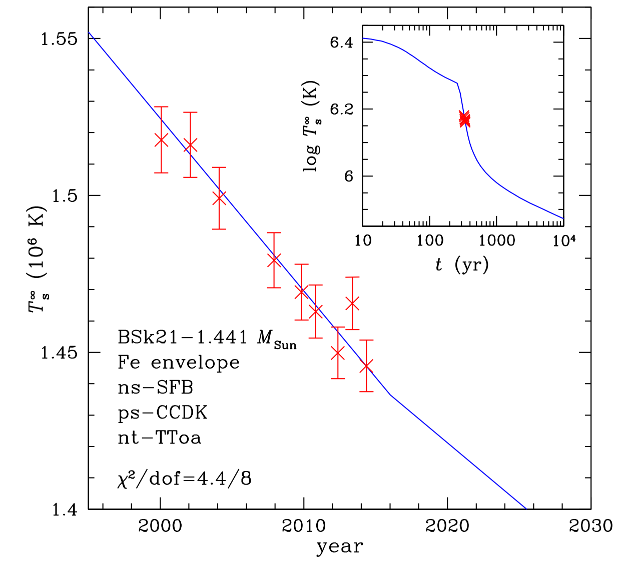


Backup

Why Cas A NS is special?

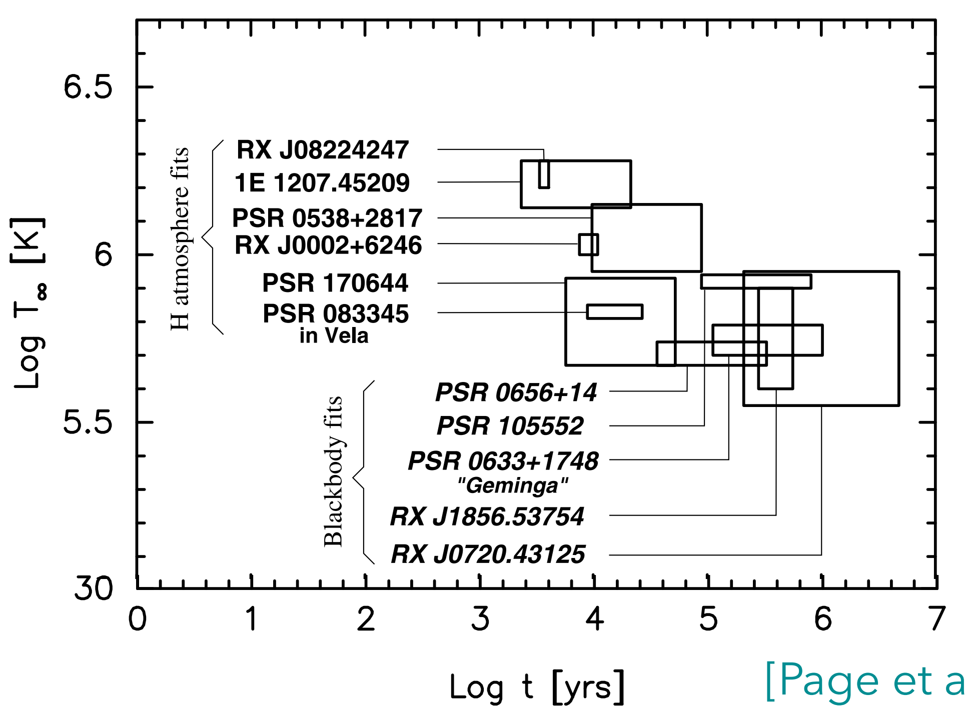
In Cas A NS, temperature decline rate is available
More powerful to constrain cooling theory

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

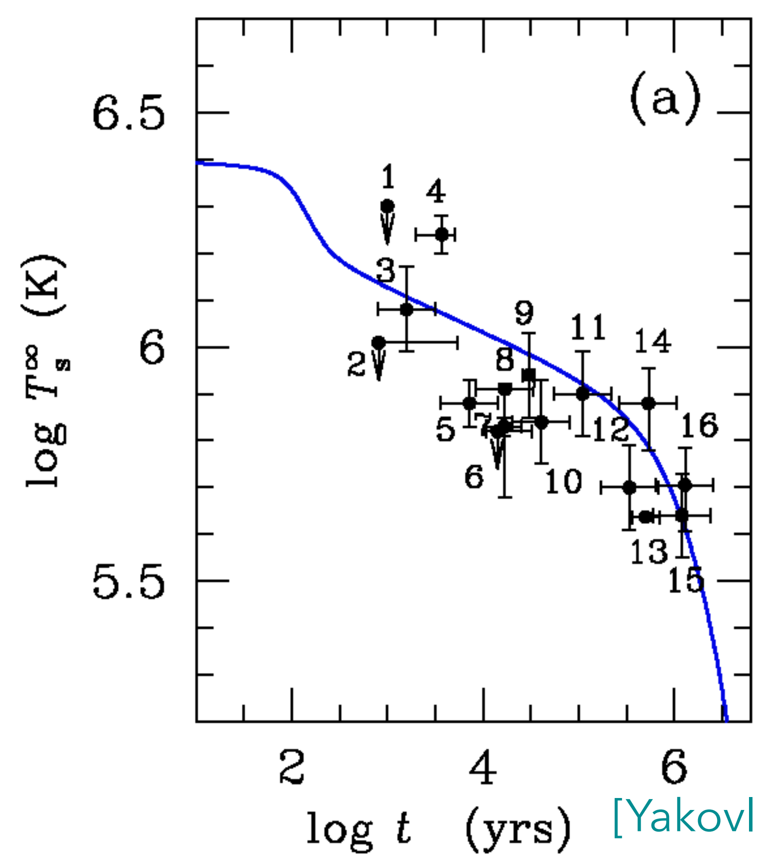


Other NS:

- About 30 observations of surface temperature
- Single measurement of (t, T^{∞}_{s}) for each NS



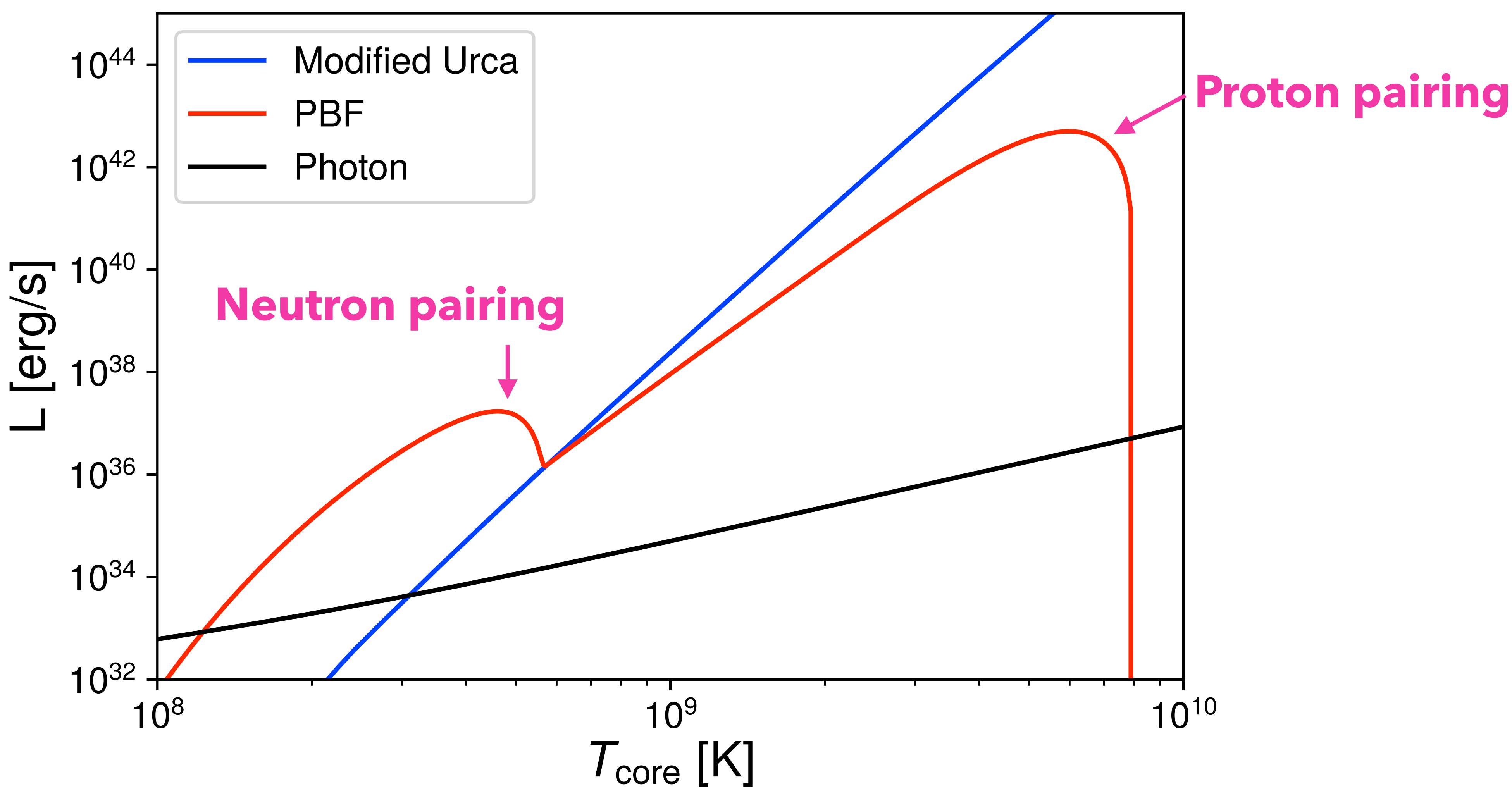
[Page et al. (2004)]



[Yakovlev et al. (2008)]

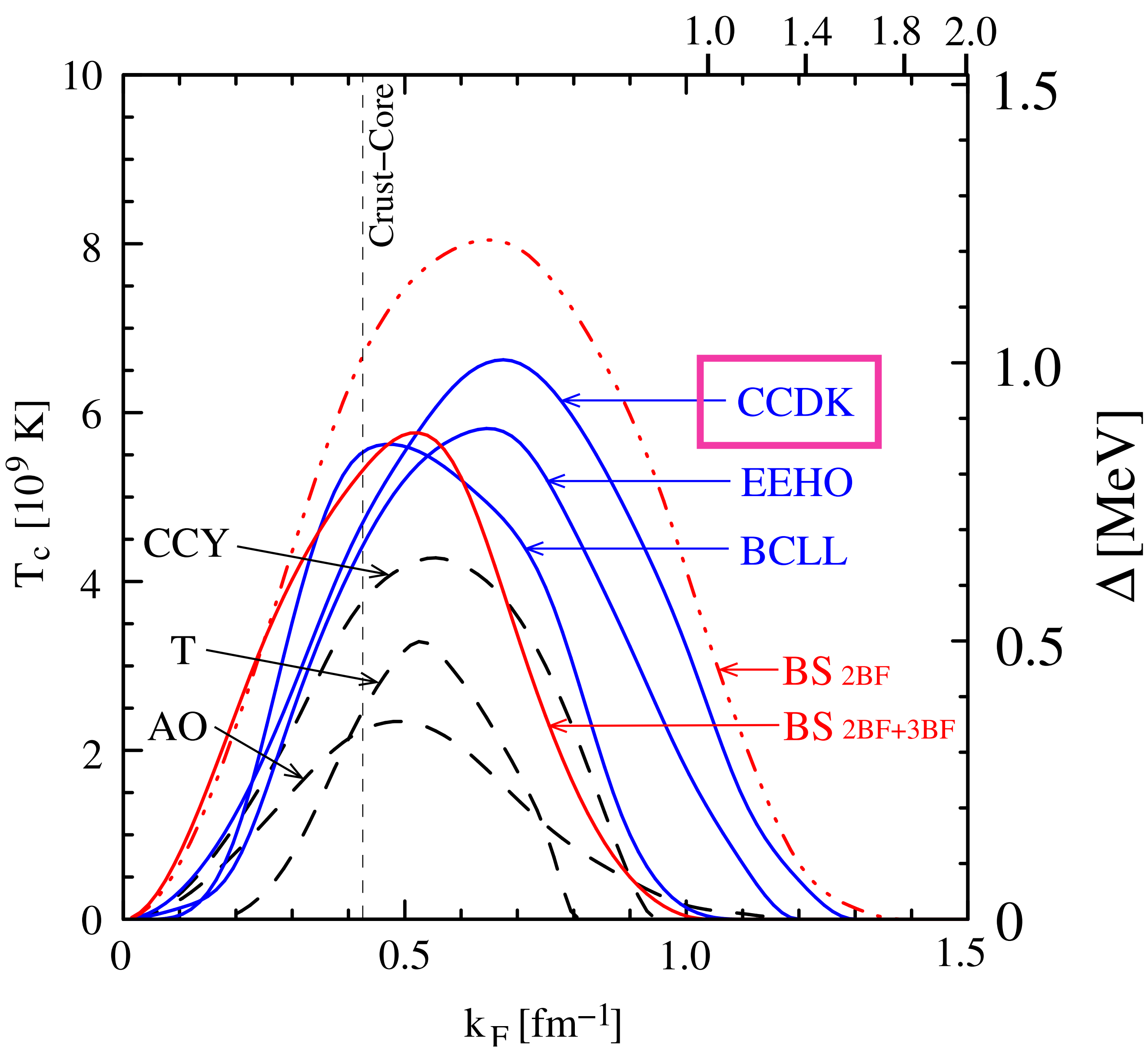
Summary of neutrino emission

- 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



Proton singlet gap model

Theoretical calculations are relatively certain



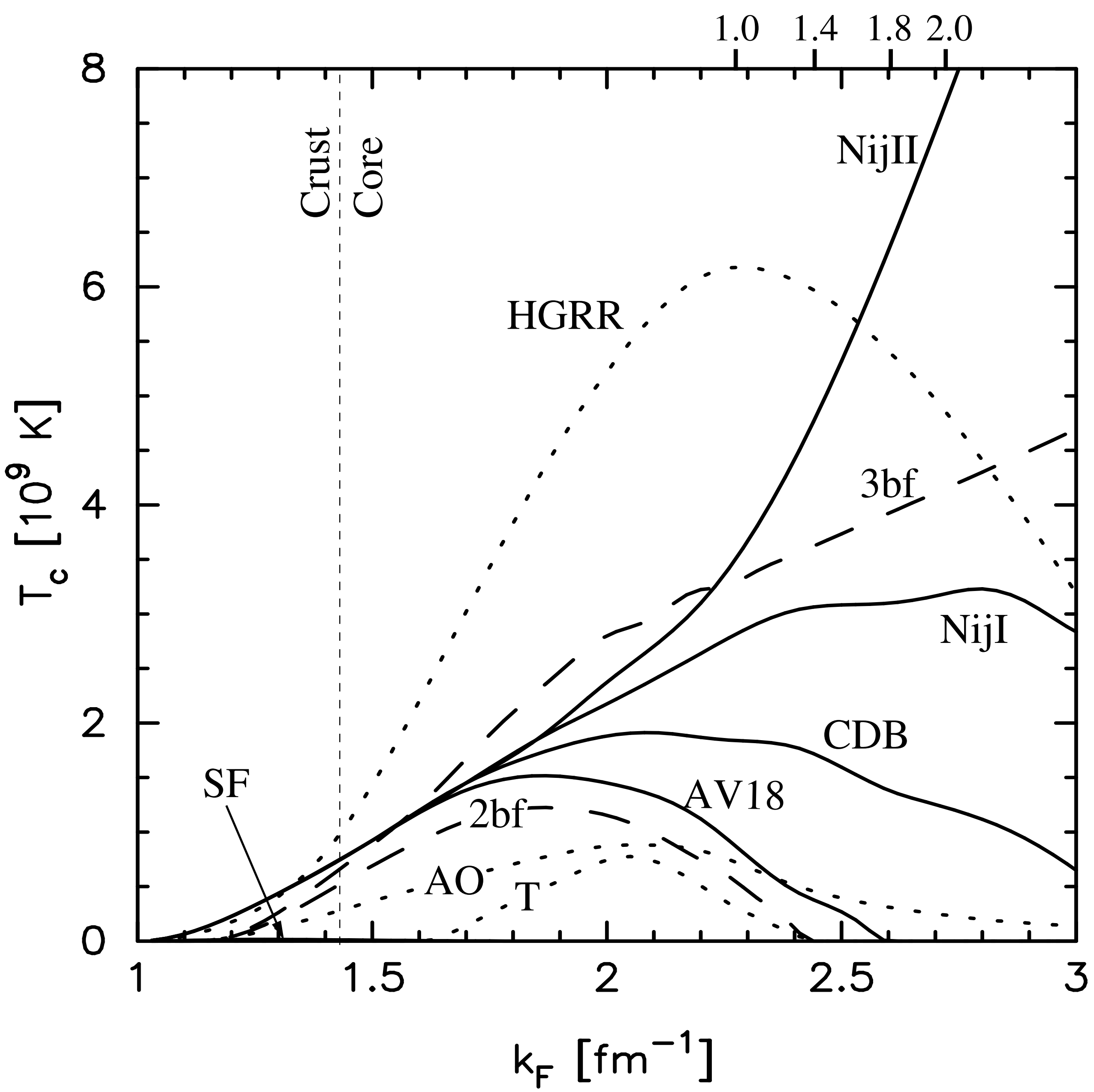
We use CCDK model because

- 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

How to constrain the axion model?

If SM + axion cannot fit the Cas 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 ⟶ **vary to fit Cas A NS (3 parameter Gaussian model)**
- Proton $^1S_0$ gap model ⟶ **does not matter as long as large enough**

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

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

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