Axion Limit from the Cooling Neutron Star in Cassiopeia A

Jiaming Zheng

University of Tokyo, Hongo

Base on

K. Hamaguchi, N. Nagata, K. Yanagi, J. Zheng, 1806.07151

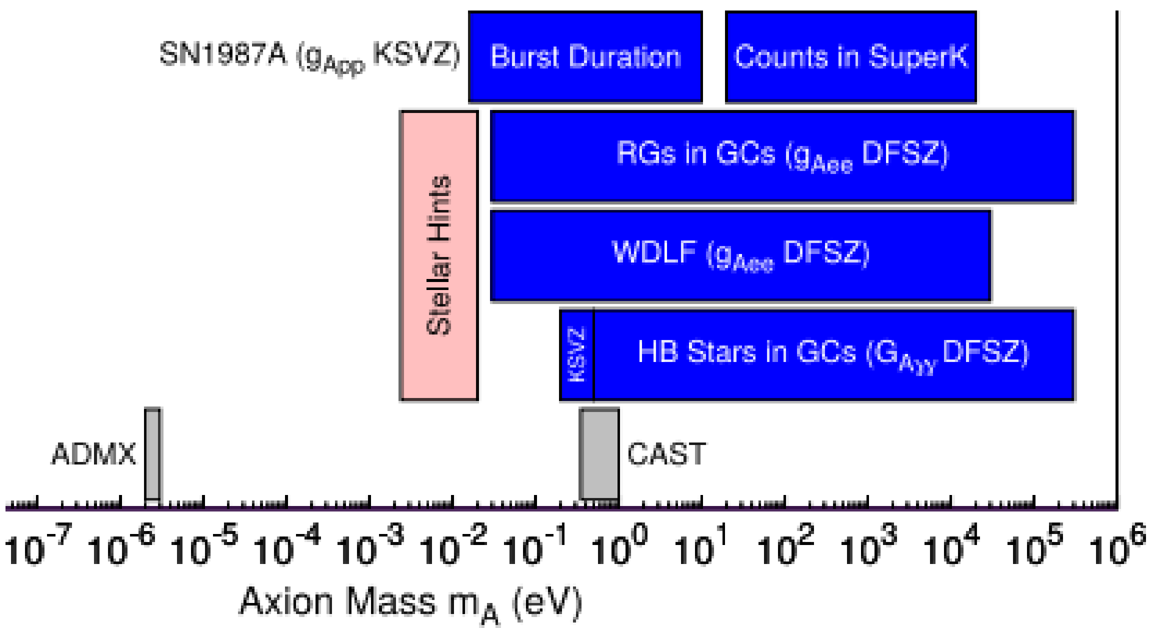
Seminar at IPMU

Feb 6, 2019

Axion

- Axion is the pseudo-Goldstone boson of PQ symmetry
- Solves strong CP problem

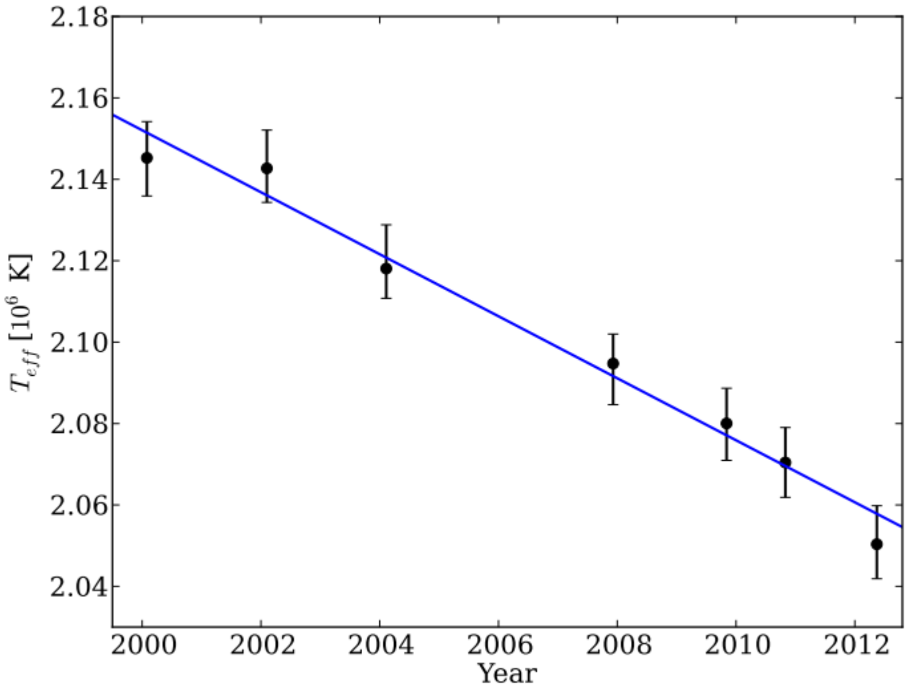
Astrophysical constraints:



PDG 2018

What about neutron star

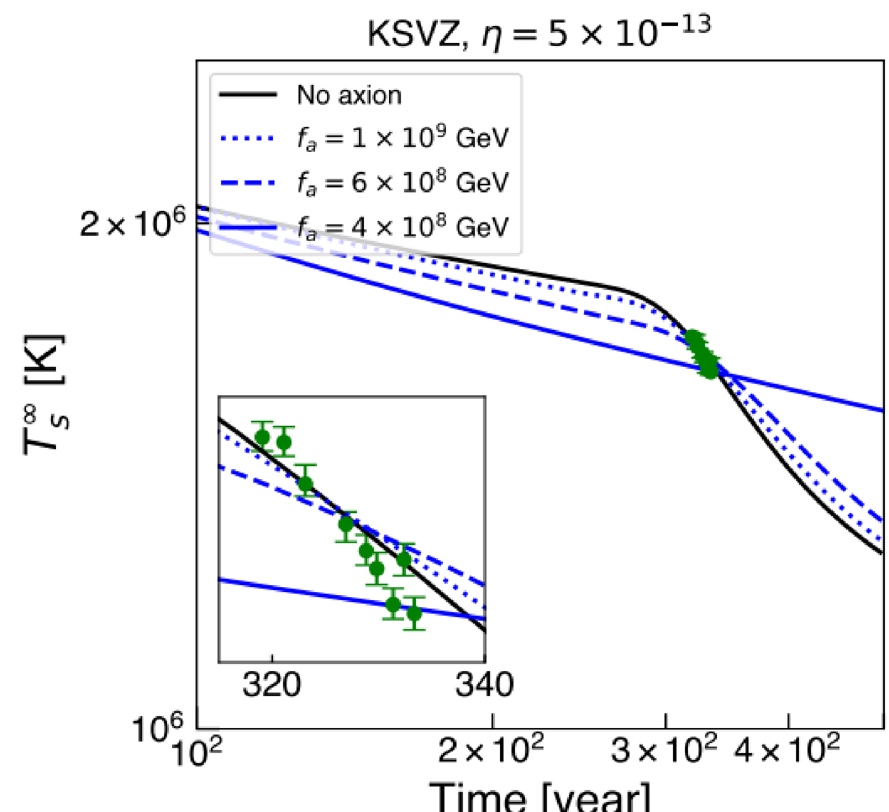
Summary



The rapid cooling of CAS A NS was observed

- The cooling can be explained in the standard cooling model

- Axion enhances the cooling and get constrained



Outline

- Neutron star cooling, theory
- CAS A NS cooling, obs. vs theory
- Axion emission from CAS A NS, constraint
- Summary

Neutron Star Cooling, theory

Neutron star interior is almost isothermal after relaxation time scale ~ 100 yr

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

Photon is emitted only from the surface:

$$L_\gamma = 4\pi R^2 \sigma_{SB} T_e^4$$

$L_\gamma \ll L_\nu$ for $t \lesssim 10^6$ yr

$t \approx 300$ yr for CAS A

Internal T is determined from T_e by envelope model

For a review, c.f. 1302.6626

Envelope model

From Potekhin, Yakovlev, 2001

$$L_\gamma = 4\pi R^2 \sigma_{SB} T_e^4$$

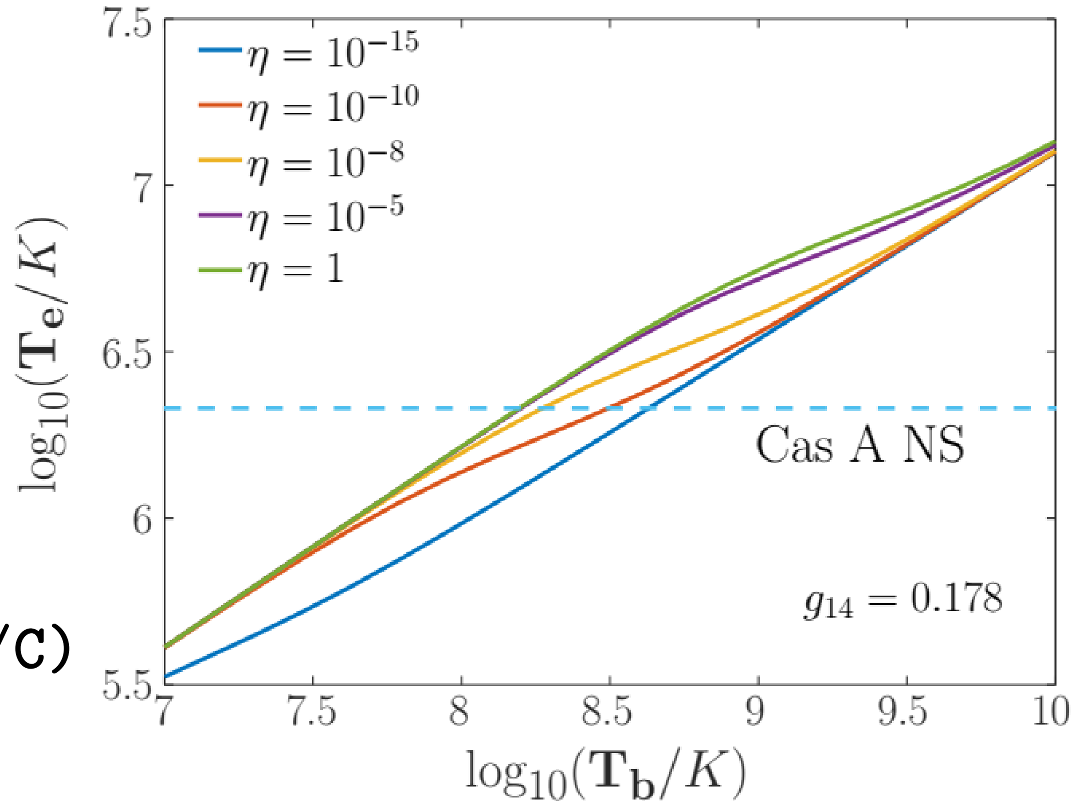
T_e Effective temperature

T_b Internal temperature below the envelope

$\eta \sim \Delta M / M_{NS}$

ΔM Mass of light element (H/He/C) in the envelope

$\eta \to 0$: Fe envelope



$$T_e \approx T_b^\alpha \quad \alpha \sim 0.5$$

Major uncertainty:

The composition of envelope, and thus η is unknown ..

Neutrino emission

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

- Direct URCA process(fast)

$$n \to p + e^- + \bar{\nu}$$
$$p + e^- \to n + \nu$$

$$\int \mathrm{d}^3 p_n \int \mathrm{d}^3 p_p \int \mathrm{d}^3 p_e \int \mathrm{d}^3 p_\nu E_\nu \delta^{(4)}$$

T T T T^3 T T^{-1}

$$L \sim T^6$$

Highly suppressed for $M \lesssim 2M_\odot$

Emission take place near Fermi surfaces:

$$p^{p,n,e} \approx p_F^{p,n,e}$$

Charge neutrality: $E_F^p = E_F^e$

Chemical equilibrium: $E_F^n = E_F^p + E_F^e$

Contradicts energy-momentum conservation

$M \gtrsim 2M_\odot$: muon is produced in higher density medium

Neutrino emission

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

- **Modified URCA process(slow)**

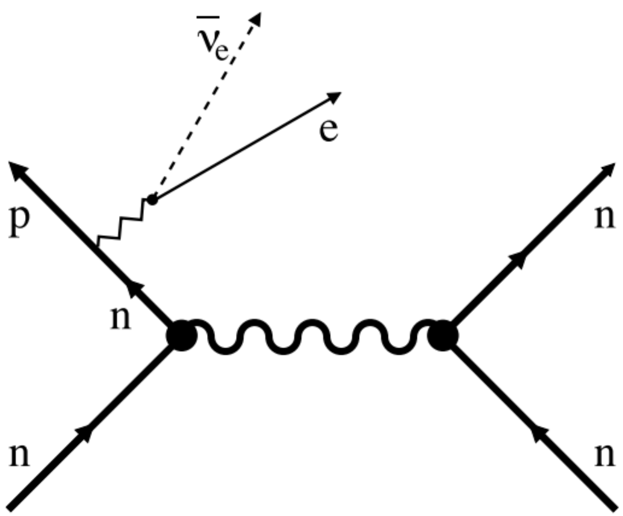
$$N + n \rightarrow N' + p + e^- + \bar{\nu}$$

$$N + p + e^- \rightarrow N' + n + \nu$$

$$N \; n \; N' \; p \; e \; \nu \; \delta \; E$$

T T T T T T^3 T^{-1} T

$$L \sim T^8$$



Modified Urca

Power law cooling:

$$L_\nu = hT^\alpha, \; C = cT$$

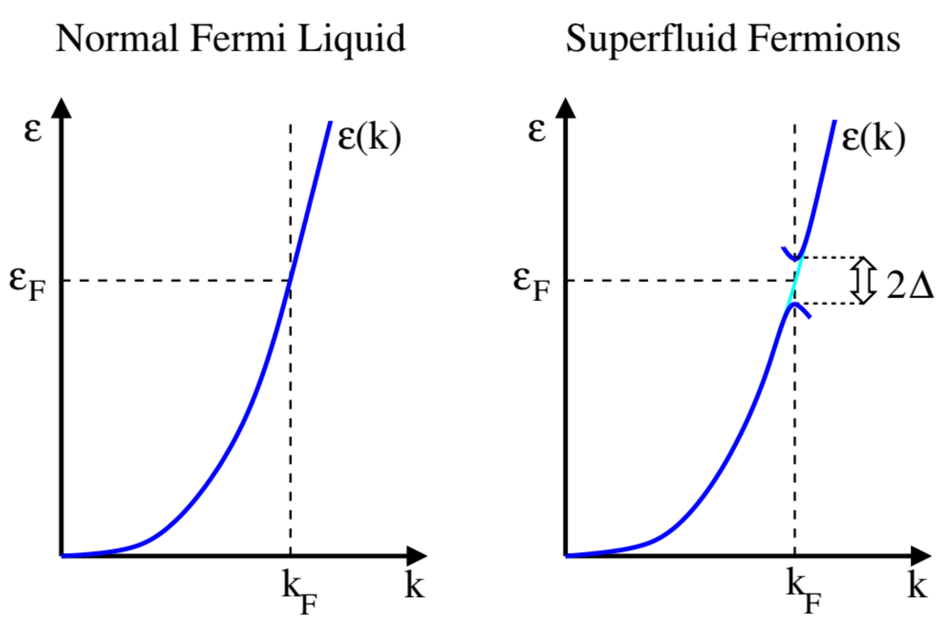
$$\frac{1}{T^{\alpha-2}} = \frac{1}{T_i^{\alpha-2}} + \frac{(\alpha-2)h\Delta t}{c}$$

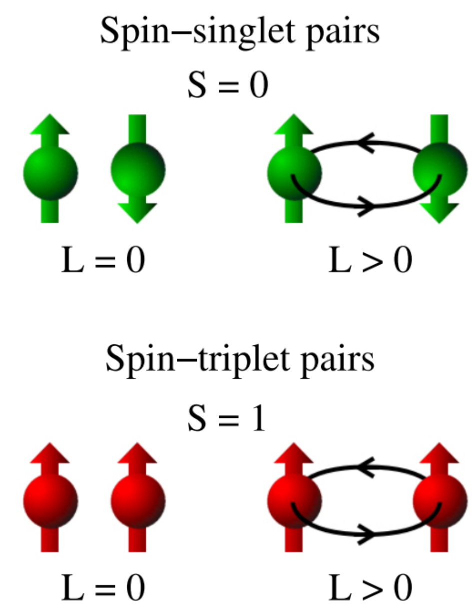
- **Larger α: slower cooling**
- **For $T \ll T_i$, T_i doesn't matter**
- $T \sim \Delta t^{-\frac{1}{\alpha-2}}, \quad T_e \sim \Delta t^{-\frac{1}{2\alpha-4}}$

Neutrino emission

- Nucleon form cooper-pairs at low T

$$T_c \sim \Delta(T=0) \sim \mathcal{O}(1\ \mathrm{MeV})$$



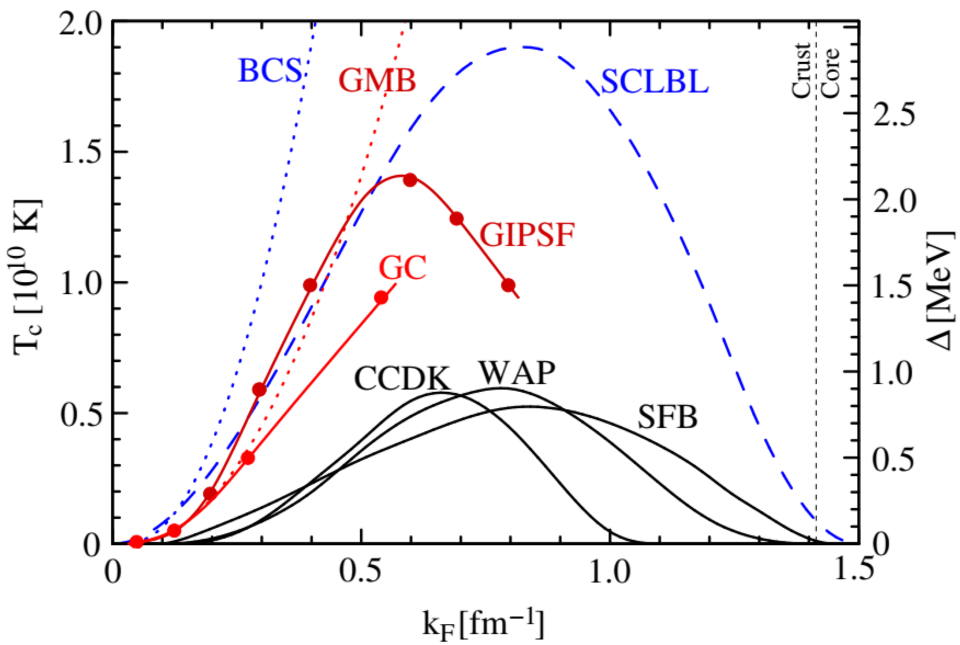


n, p

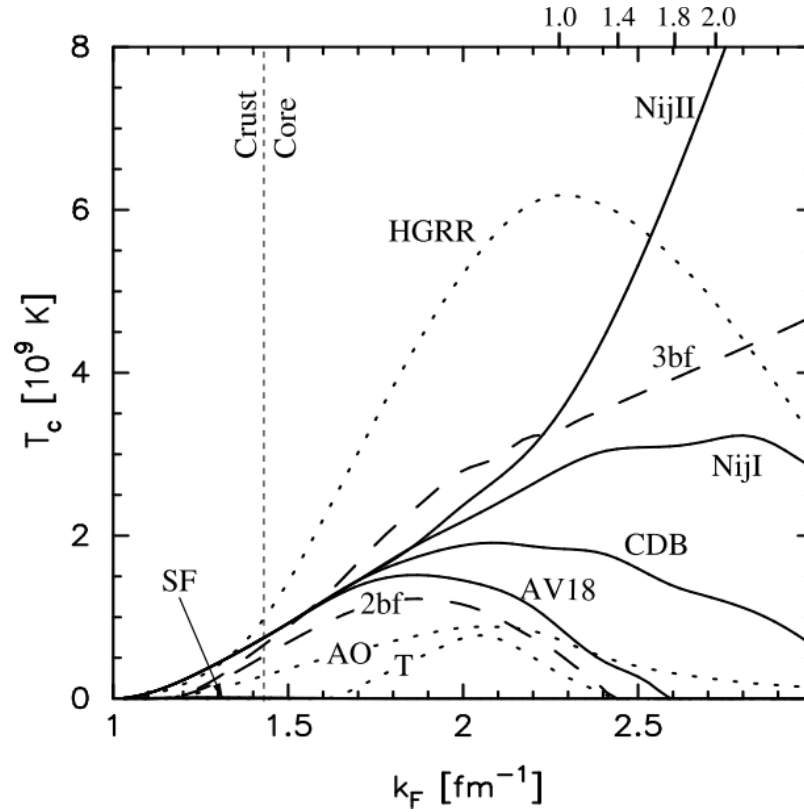
p

- Suppress emission from nucleon $\sim \exp(-\mathrm{N}\Delta/\mathrm{T})$
- Reduces specific heat for $T < T_c$

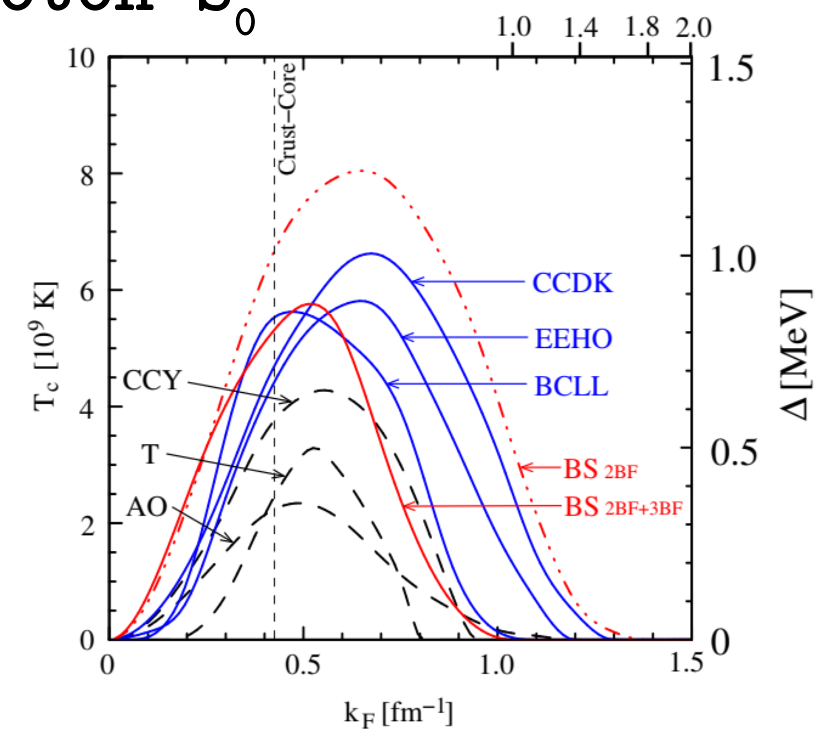
Neutron $^1S_0$



Neutron $^3P_2$



Proton $^1S_0$



$^1S_0$ is repulsive at high density:

- Neutron $^1S_0$ in crust
- Proton $^1S_0$ in core

HUGE theoretical uncertainty

Neutrino emission

- The pair-breaking-formation process (PBF)

$E > \Delta$

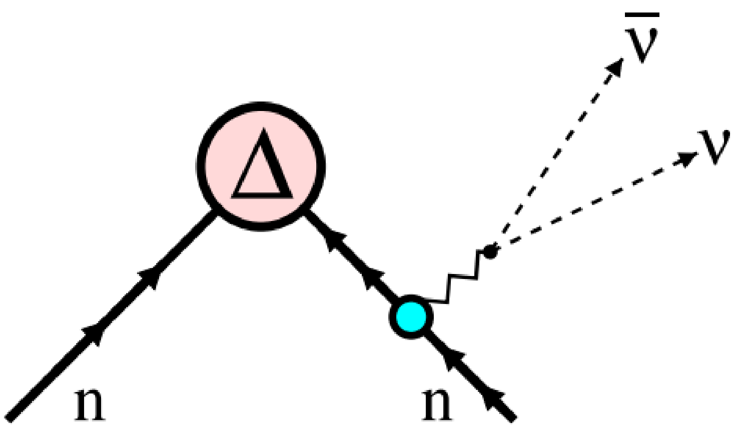
$$N + N' \to [NN'] + \nu + \bar{\nu} \qquad L \sim T^7 R \sim T^7 \, \exp(-2\mathrm{E}/\mathrm{T})$$

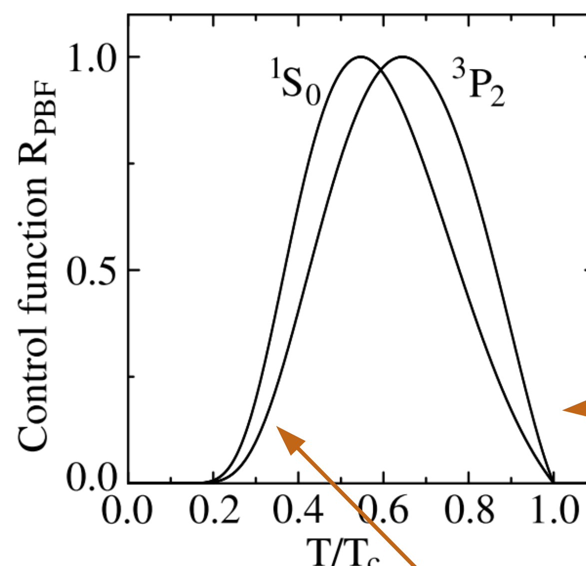
equivalently,

$$\tilde{E}_p = \sqrt{\epsilon_p^2 + \Delta_p^2}$$

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

$$\epsilon_p = v_F(p - p_F)$$

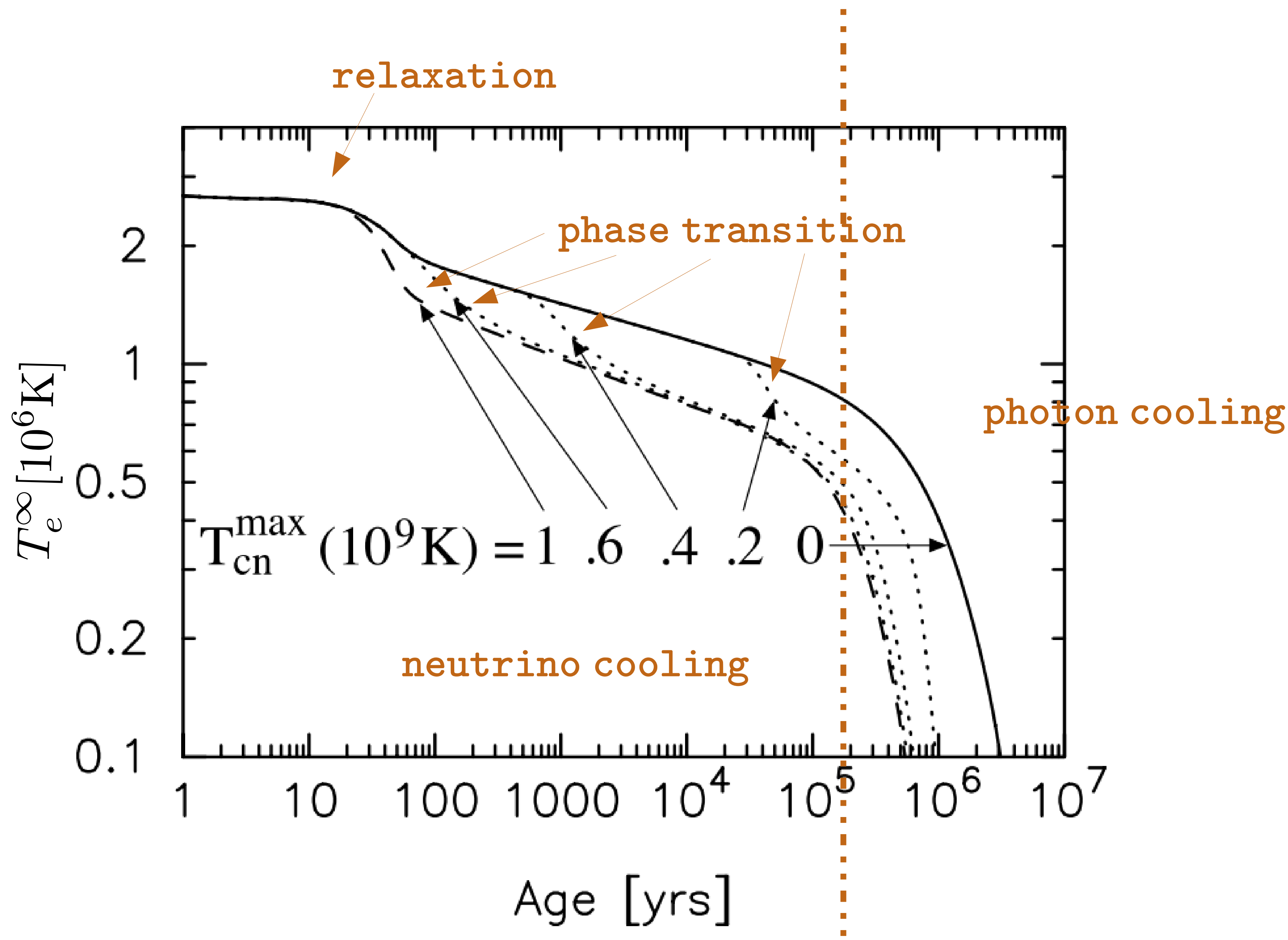




trigger after phase transition

This causes a momentary rapid cooling

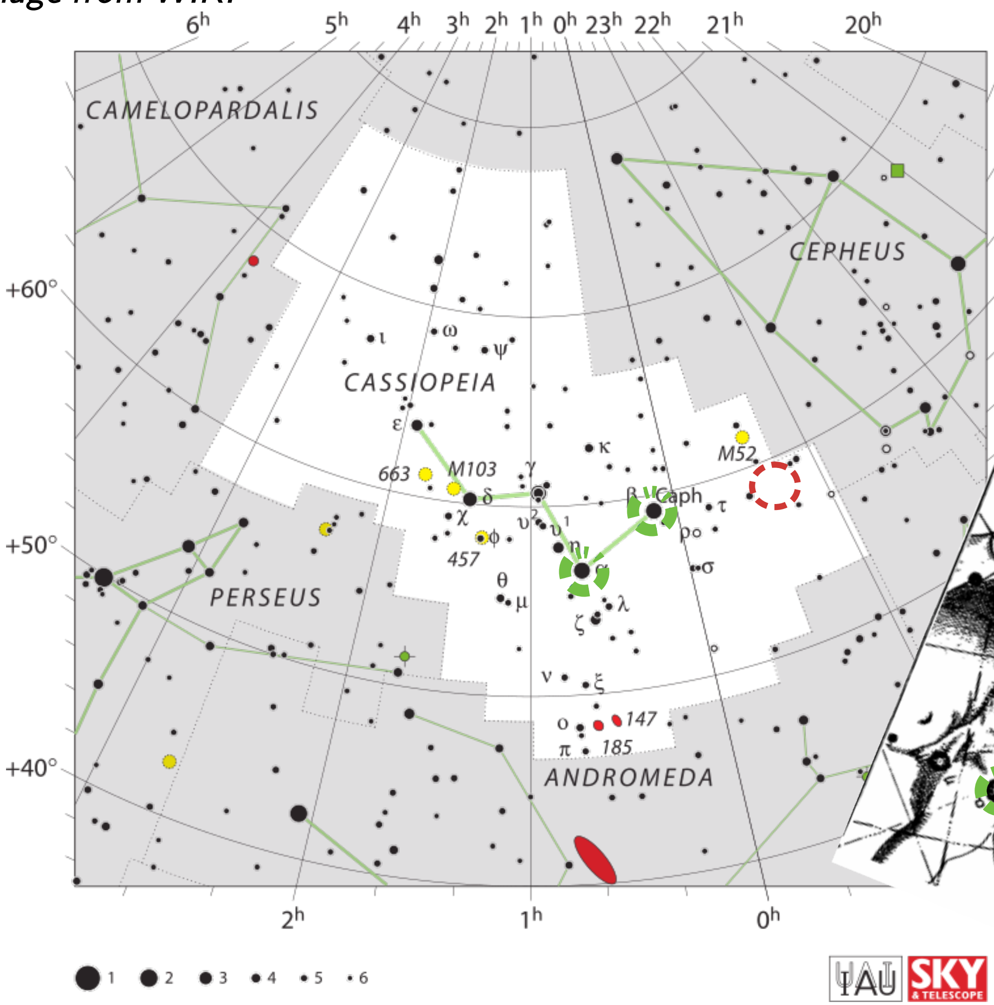
Suppress by $\exp(-2\Delta/T)$

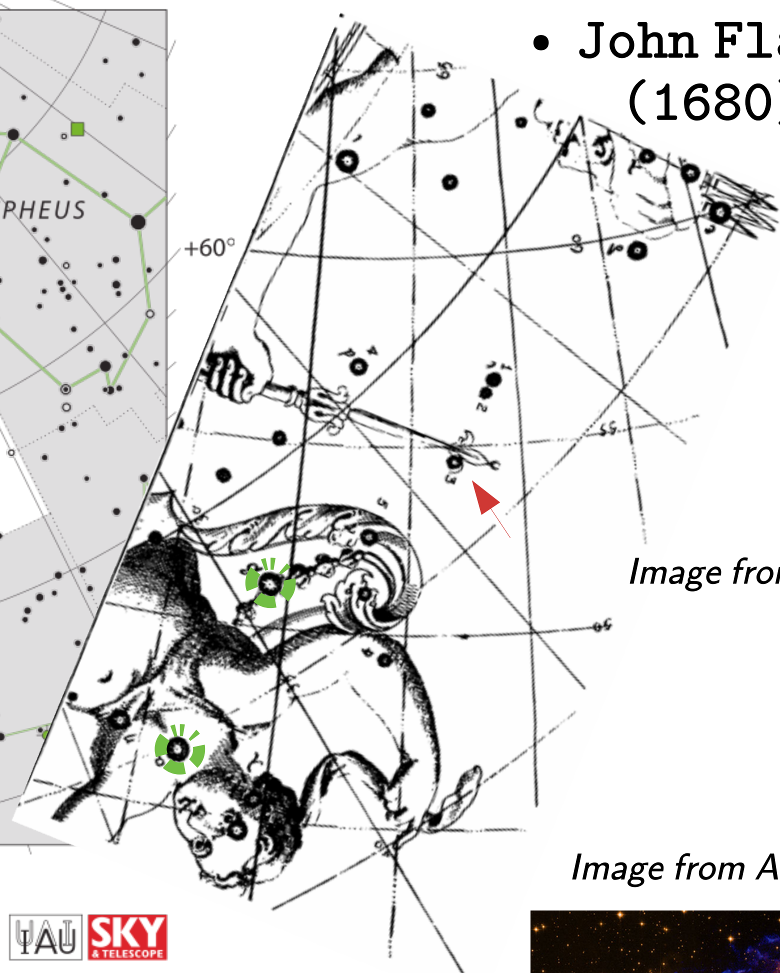


relaxation
phase transition
photon cooling
neutrino cooling
$T_{cn}^{max}(10^9K) = 1 \ .6 \ .4 \ .2 \ 0$
$T_e^\infty[10^6K]$
Age [yrs]

The CAS A NS (OBS)

Image from WIKI

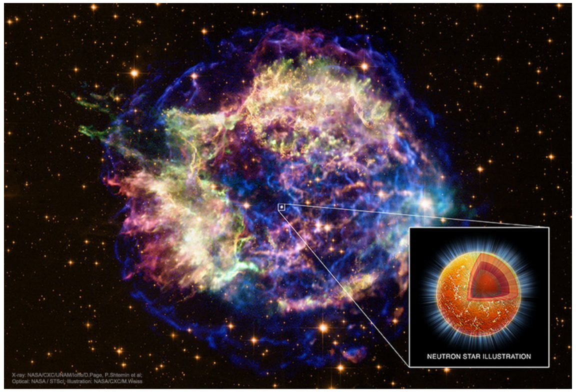




- John Flamsteed: 3 CAS ? (1680)

Image from Ashworth, 1980

Image from APOD 2017.5.1



- Remnant expansion: SN exploded in 1681 ± 19
-
- NS x-ray found by Chandra in 1999

The Cooling of CAS A NS (OBS)

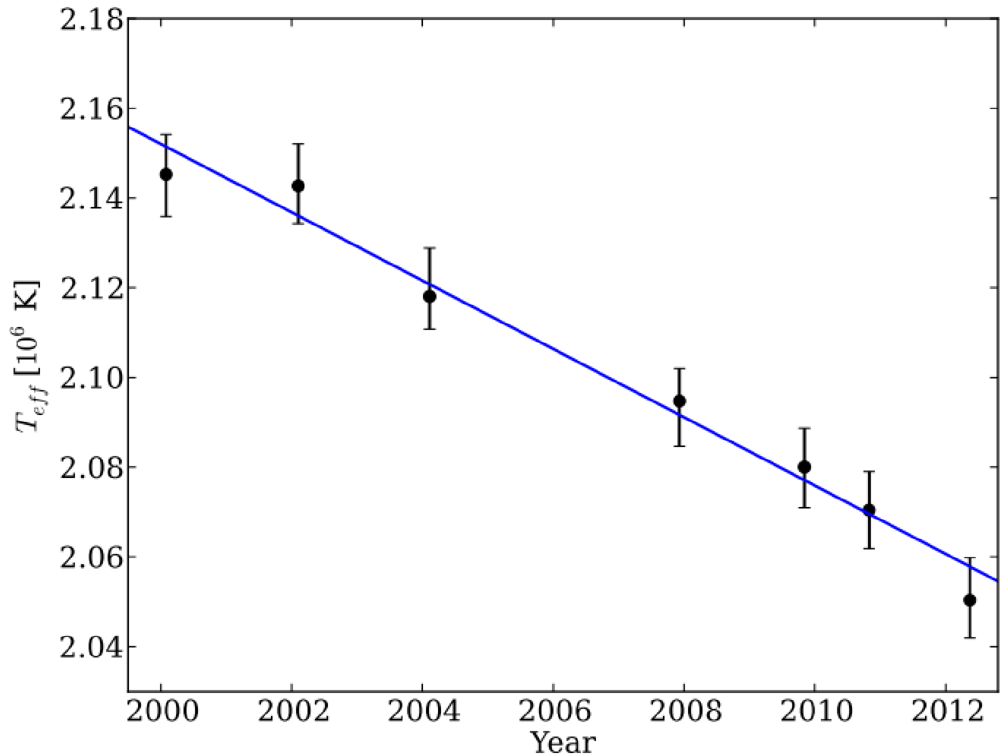


Figure from Astrophys.J. 777 (2013) 22

Heinke & Ho, *Nature* 2010:

Cooling by $2 \sim 4\%/10$ yrs

$M = 1.4 \pm 0.3 \ \ M_\odot$

Can we explain it with standard cooling?

The Cooling of CAS A NS (TH)

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

D. URCA is irrelevant: $M = 1.4 \pm 0.3 \;\; M_\odot < 2M_\odot$

Even if it is, T would be too low

M. URCA is too slow:

$$L \sim T^8, \; C \sim T \qquad \longrightarrow \qquad \left(\frac{\Delta T_e}{T_e}\right)_{10\text{yrs}} \sim \; -\frac{1}{12}\frac{\Delta t}{t} \; \sim \; 0.3\%$$

$$T_e \sim T^{\frac{1}{2}}$$

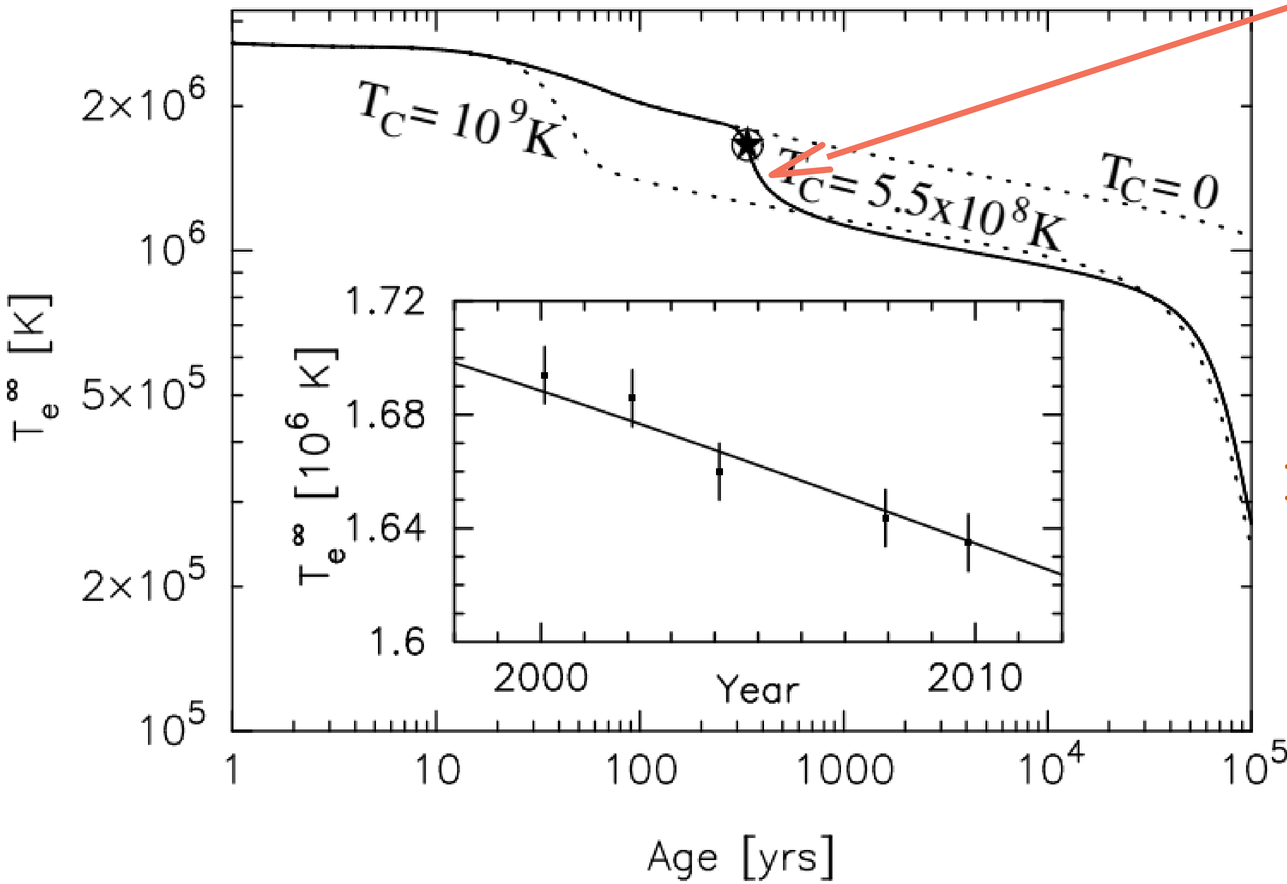
$$<< \; \boxed{(2 \sim 4)\%}_{\text{obs}}$$

A rapid process is needed to explain the fast cooling of the CAS A NS

The Cooling of CAS A NS (TH)

Page, Prakash, Lattimer, Steiner, PRL 2011
Shternin, Yakovlev, Heinke, Ho, Patnaude, 2012 MNRAS :

CAS A NS rapid cooling can be explained by PBF



$^3P_2$ pairing model tuned to fit the data (Tc in particular)

- Large model uncertainty in triplet pairing

Envelope with a thin light element layer:

$$\eta = 5 \times 10^{-13}$$

Otherwise, T is too low to fit the slope.

Viewed as direct evidence of phase transition in NS

Axion emission in NS

Axion emitted mainly by nucleon

Axion-nucleon coupling:

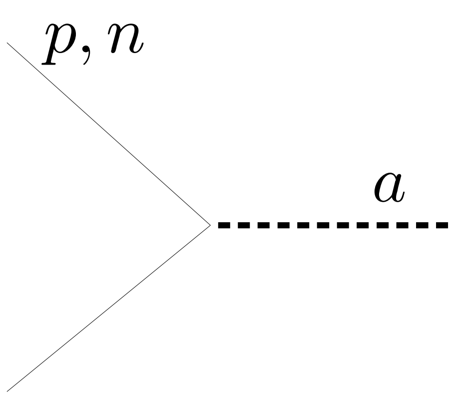
$$\mathcal{L}_{\rm int} = \sum_{N=p,n} \frac{C_N}{2f_a} \bar{N}\gamma^\mu\gamma_5 N \partial_\mu a$$

- **KSVZ:** $C_p = -0.47(3)\,,\ \ C_n = -0.02(3)$

  (This talk)

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

  $C_n = -0.160(25) + 0.414\sin^2\beta$

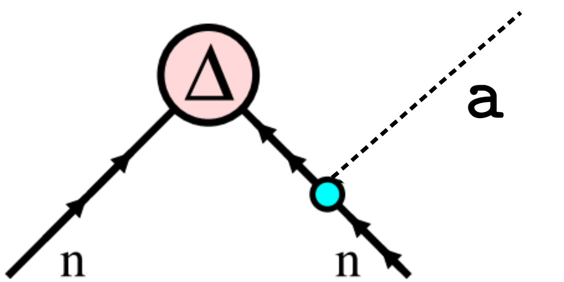


Axion emission in NS

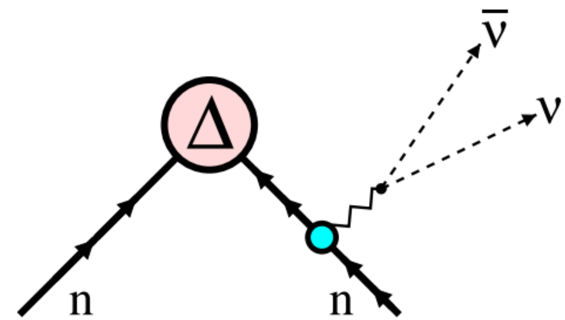
$$C\frac{dT}{dt} = -L_\nu - L_a$$

Dominant processes

PBF

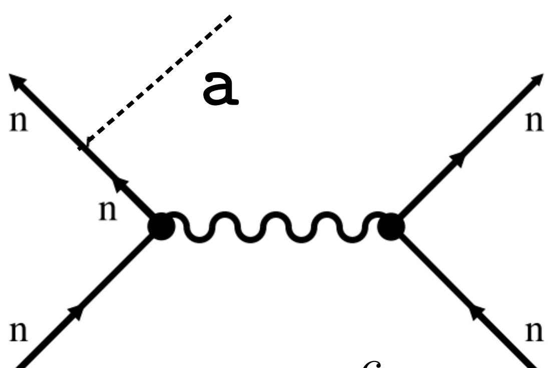


$L \sim T^5$

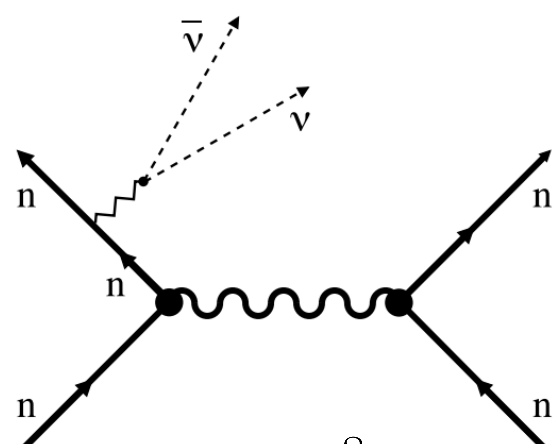


$L \sim T^7$

Bremsstrahlung



$L \sim T^6$



$L \sim T^8$

Axion emission in CAS A NS

Some technical detail:

We used the public code **NSCool** for simulation and added extra cooling by axion emission

- PBF
- Bremsstrahlung

To be conservative on axion limit:

Proton $^1S_0$: CCDK (Highest T_c)

- Suppress axion emission
- Prevent over cooling by MURCA

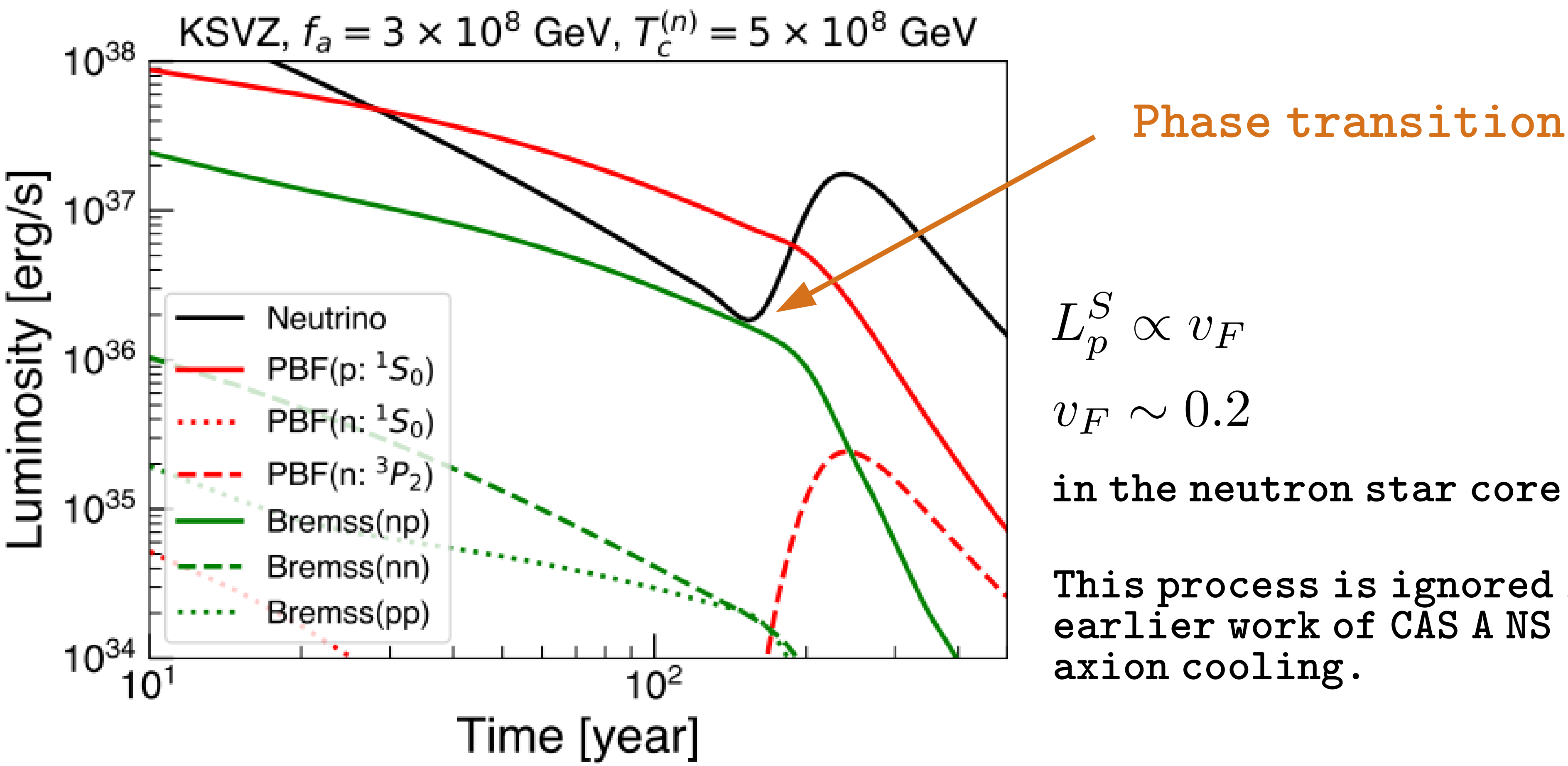
Neutron $^3P_2$: Gaussian with free parameter

Choice of convenience: (doesn't matter)

- APR EOS
- Neutron $^1S_0$: SFB (only relevant to relaxation)
- $M = 1.4 \pm M_\odot$

Axion emission in CAS A NS

Axion luminosity in KSVZ:



$$L_p^S \propto v_F$$

$$v_F \sim 0.2$$

in the neutron star core

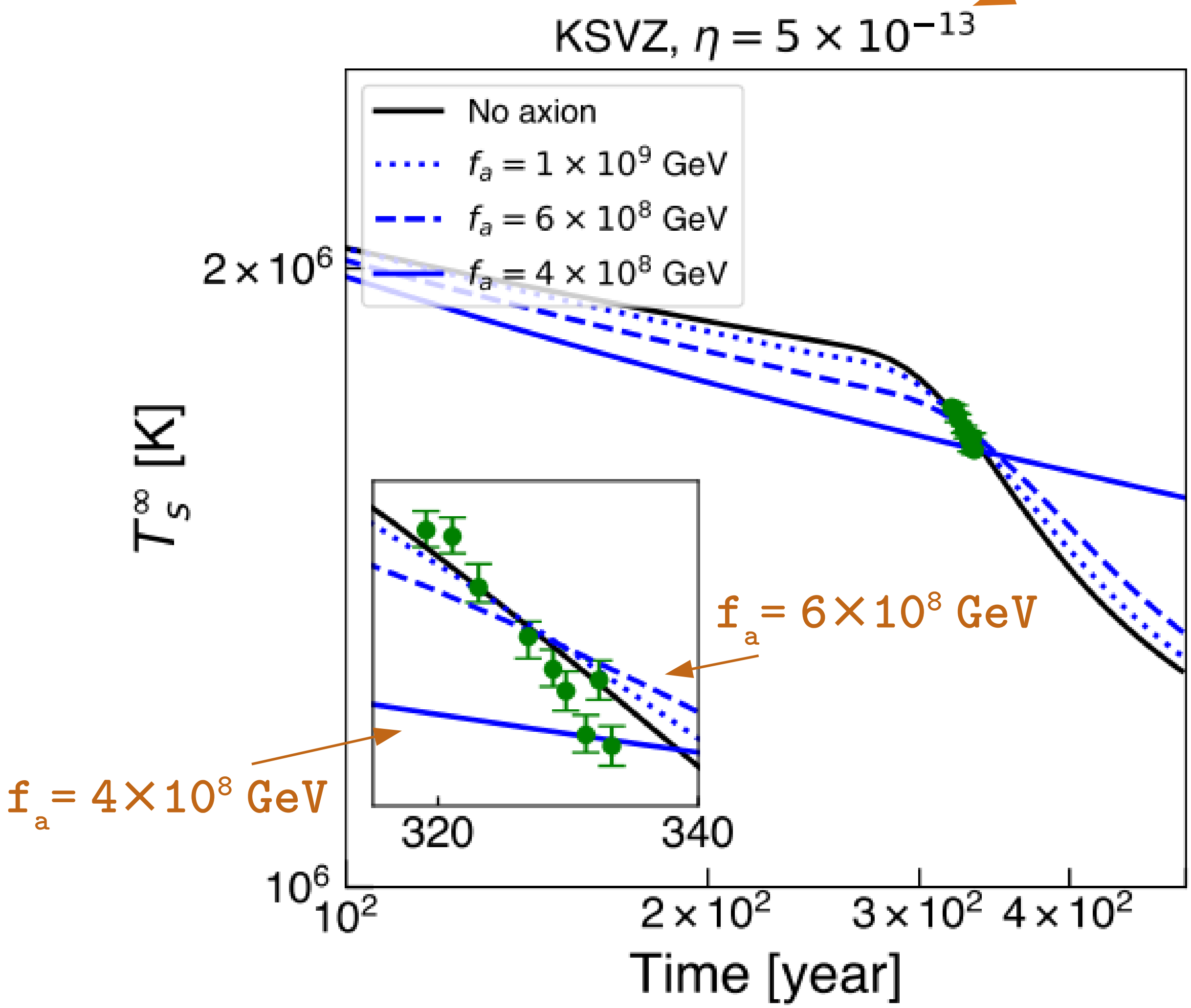
This process is ignored in earlier work of CAS A NS axion cooling.

Proton PBF emission dominates L_a

Axion emission in CAS A NS

Cooling with axion vs data

envelope with thin light element layer



$$f_a \gtrsim 5 \times 10^8 \text{ GeV}$$

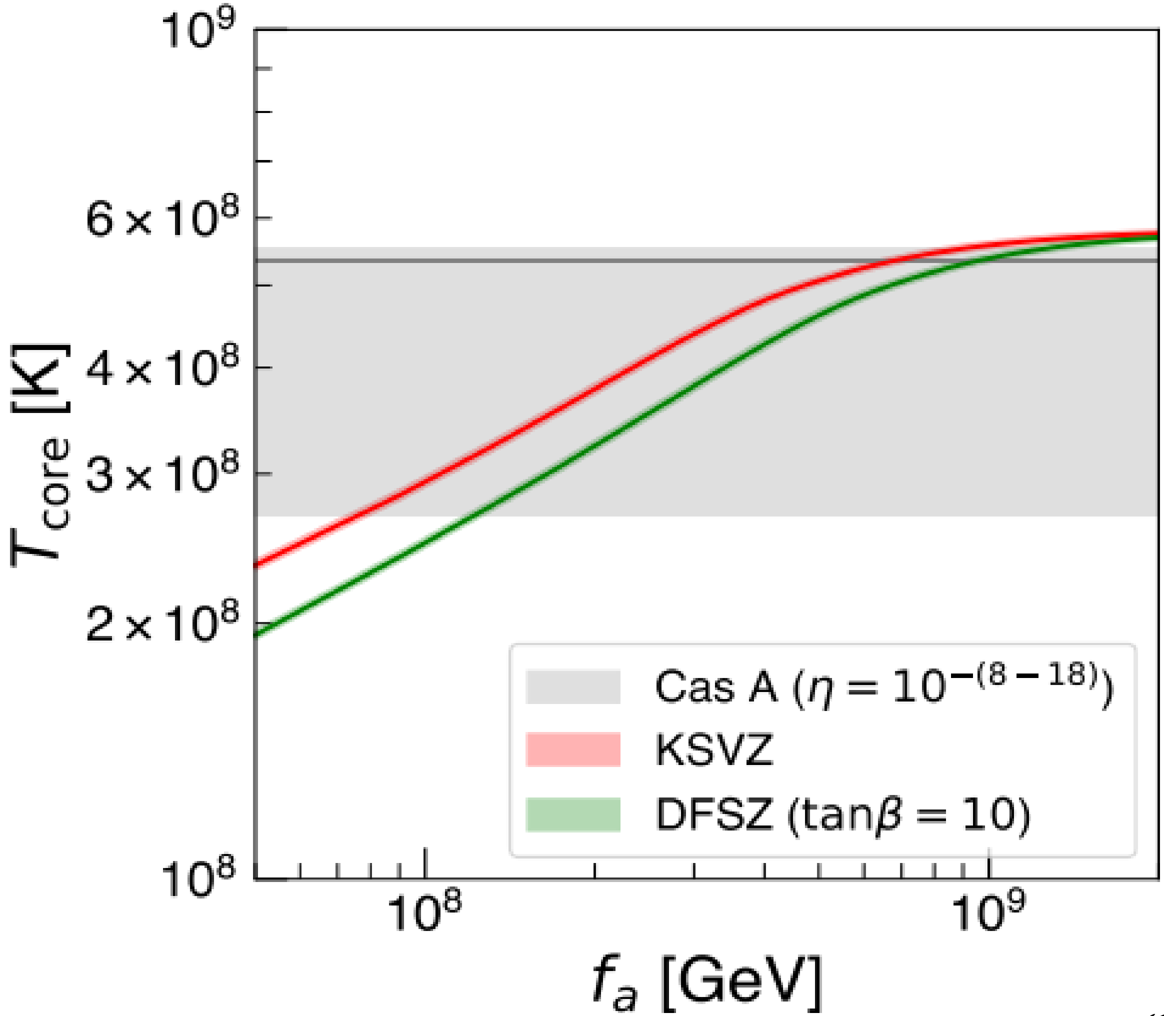
KSVZ,
assume thin carbon layer

SN1987A limit:
$$f_a \gtrsim 4 \times 10^8 \text{ GeV}$$

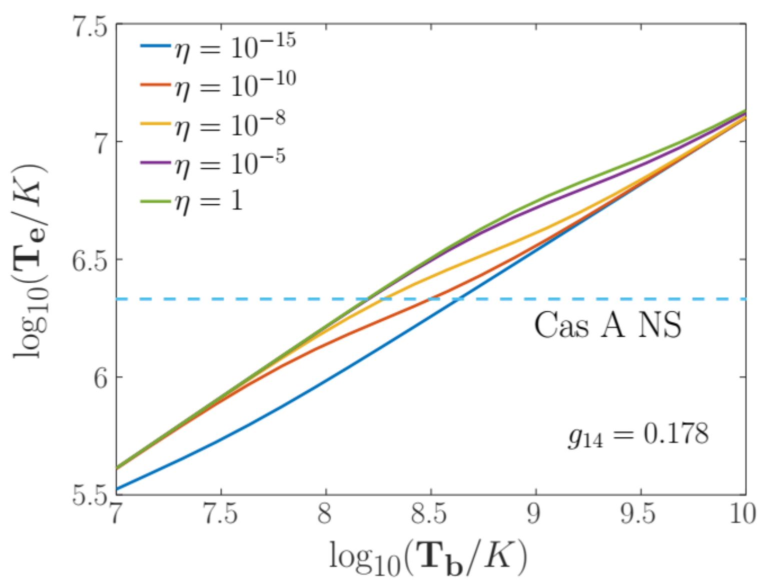
Axion emission in CAS A NS

$T_{\rm core}$ from cooling model at $t_{\rm obs} = 2001$ vs f_a

n^3P_2 pairing turned off



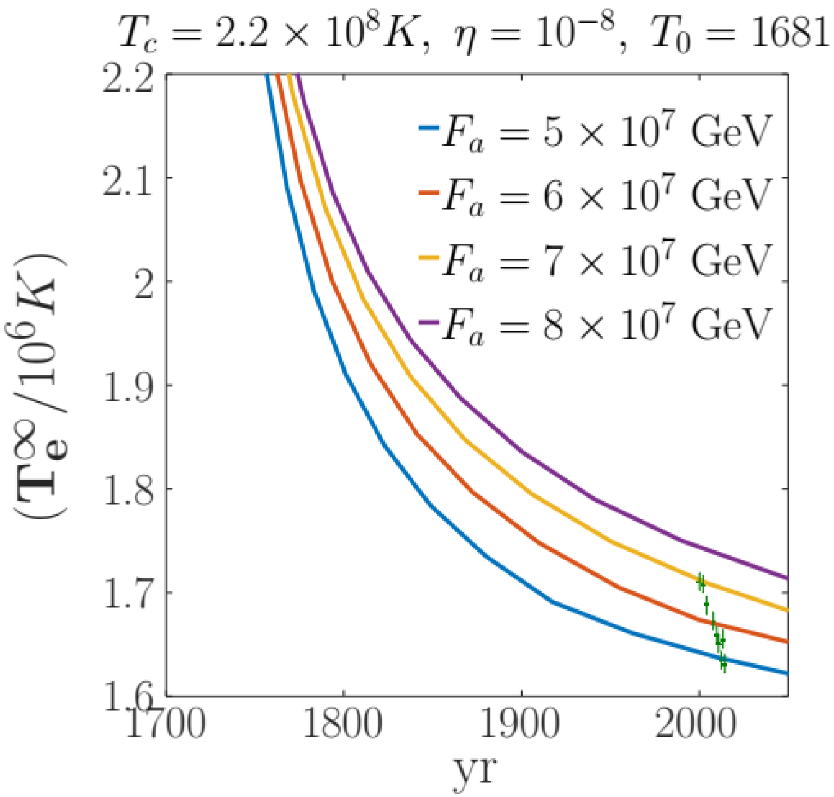
Uncertainty from envelope parameter η

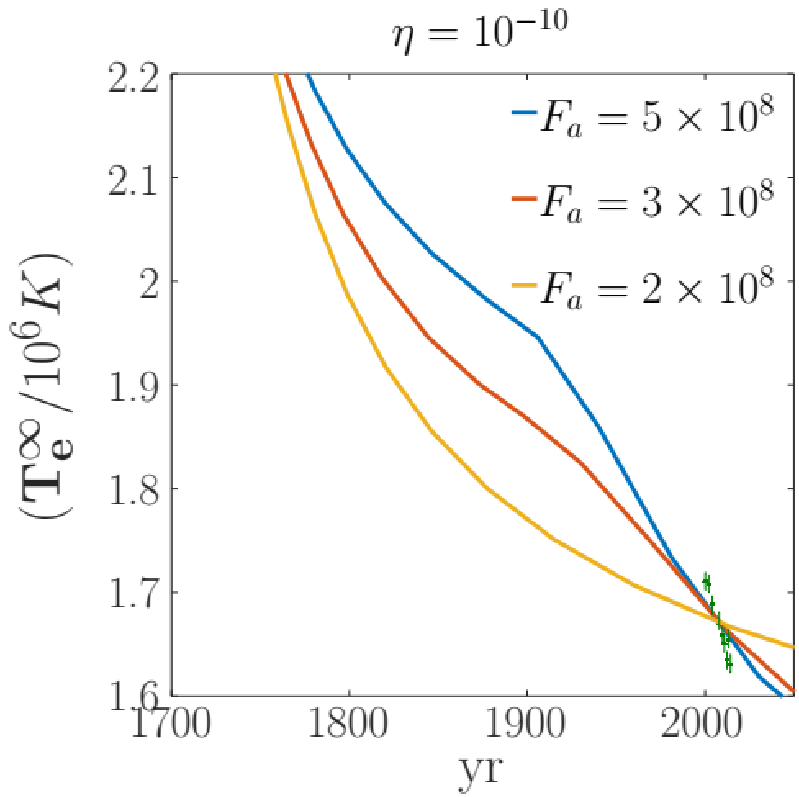


$\mathcal{O}(1) \times 10^8$GeV **uncertainty**

More on envelope uncertainty

We can do better for KSVZ! $C_n \sim 0$, n^3P_2 PBF emits ν not a





Large η ➤ low T_b ➤ low L_ν ➤ **Cannot fit the slope by neutrino alone**

Neutron PBF

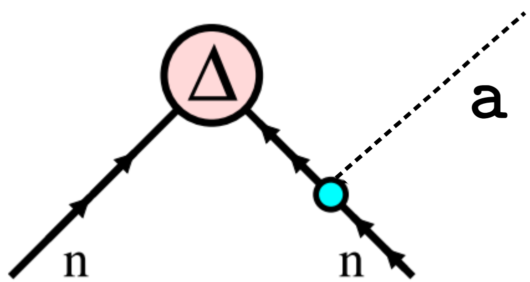
KSVZ: Neutrino only ➤ Low η ➤ $f_a \gtrsim 5 \times 10^8$ GeV

DFSZ: Neutrino + axion ➤ Any η ➤ $f_a \gtrsim 1 \times 10^8$ GeV

The axion mean free path

Determined by the inverse proton PBF:

$$\mathrm{a} \rightarrow \tilde{p} \; + \; \tilde{p}$$



$$\Gamma_{a\rightarrow\tilde{p}\tilde{p}} \sim \frac{m_p^* p_F v_F^2 T}{3\pi f_a^2} \left(\frac{C_p}{2}\right)^2$$

For simplicity, take $l_a = 1/\Gamma_{a\rightarrow\tilde{p}+\tilde{p}} \gtrsim 10\mathrm{km}$

For $p_F \sim 100$ MeV, $m_p^* \sim 1$ GeV, $T \sim \Delta_p \sim 1$ MeV,

$$f_a \gtrsim \left(\frac{C_p}{2}\right) \times 10^6 \ \mathrm{GeV}$$

otherwise, the axion is reabsorbed back to the NS

Summary

- The rapid cooling of CAS A NS is observed and explained by the standard model;
- Axion emission enhances the cooling and get constrained
- We obtained a tight bound for KSVZ, $f_a \gtrsim 5 \times 10^8$ GeV
  For DFSZ the bound is weakened, $f_a \gtrsim 1 \times 10^8$ GeV,
  due to the uncertainty of the NS envelope.
- For comparison, these are comparable to the SN1987A bound: $f_a \gtrsim 4 \times 10^8$ GeV
- Mean free path of the axion requires $f_a \gtrsim \left(\frac{C_p}{2}\right) \times 10^6$ GeV for the bound to be valid.

Uncertainty ?

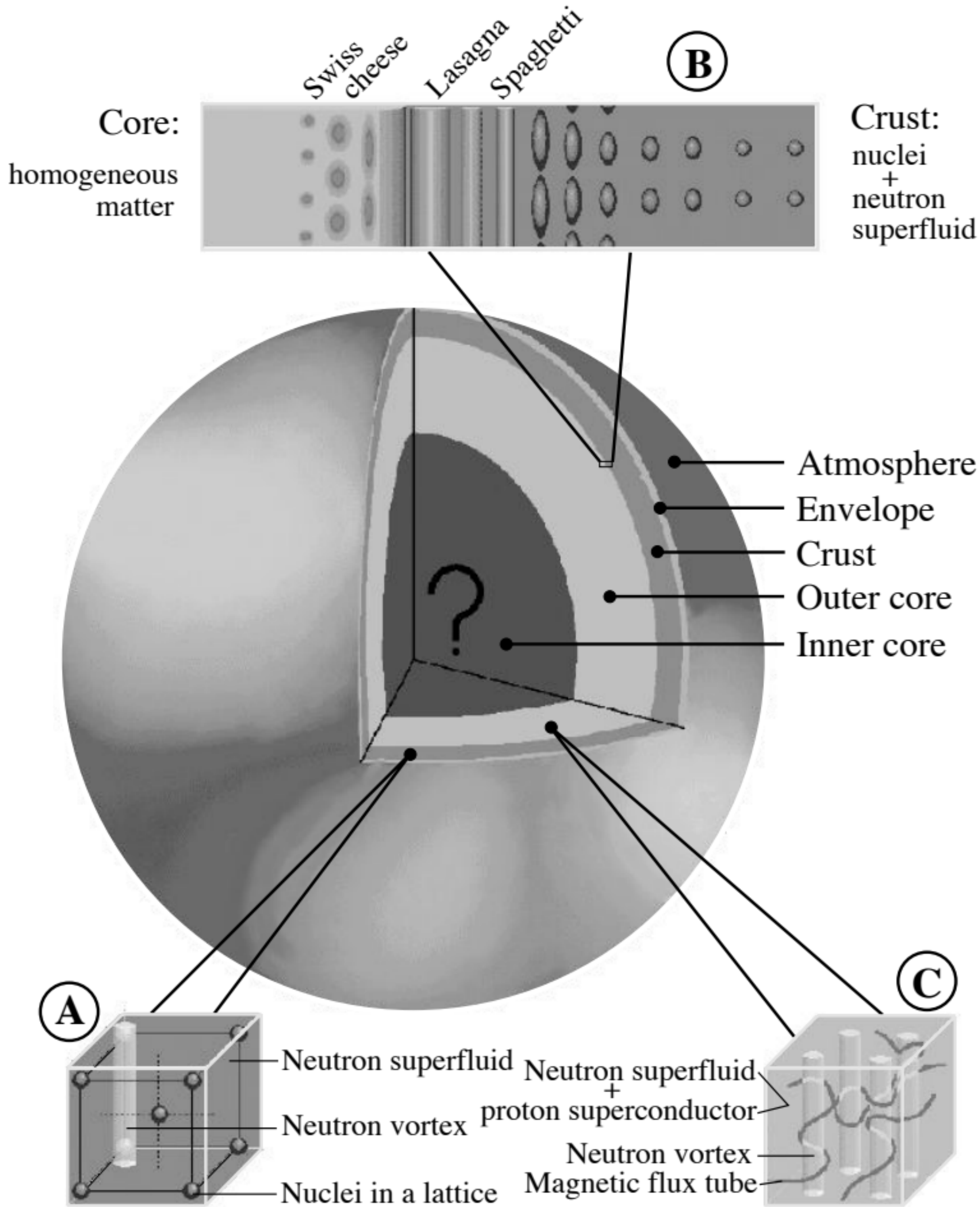
- Envelope: Major uncertainty. We estimated it.

- Data: Mostly on the cooling part by contamination of camera. We only rely on this for KSVZ. The average temperature give us a weeker bound. Future experiment?

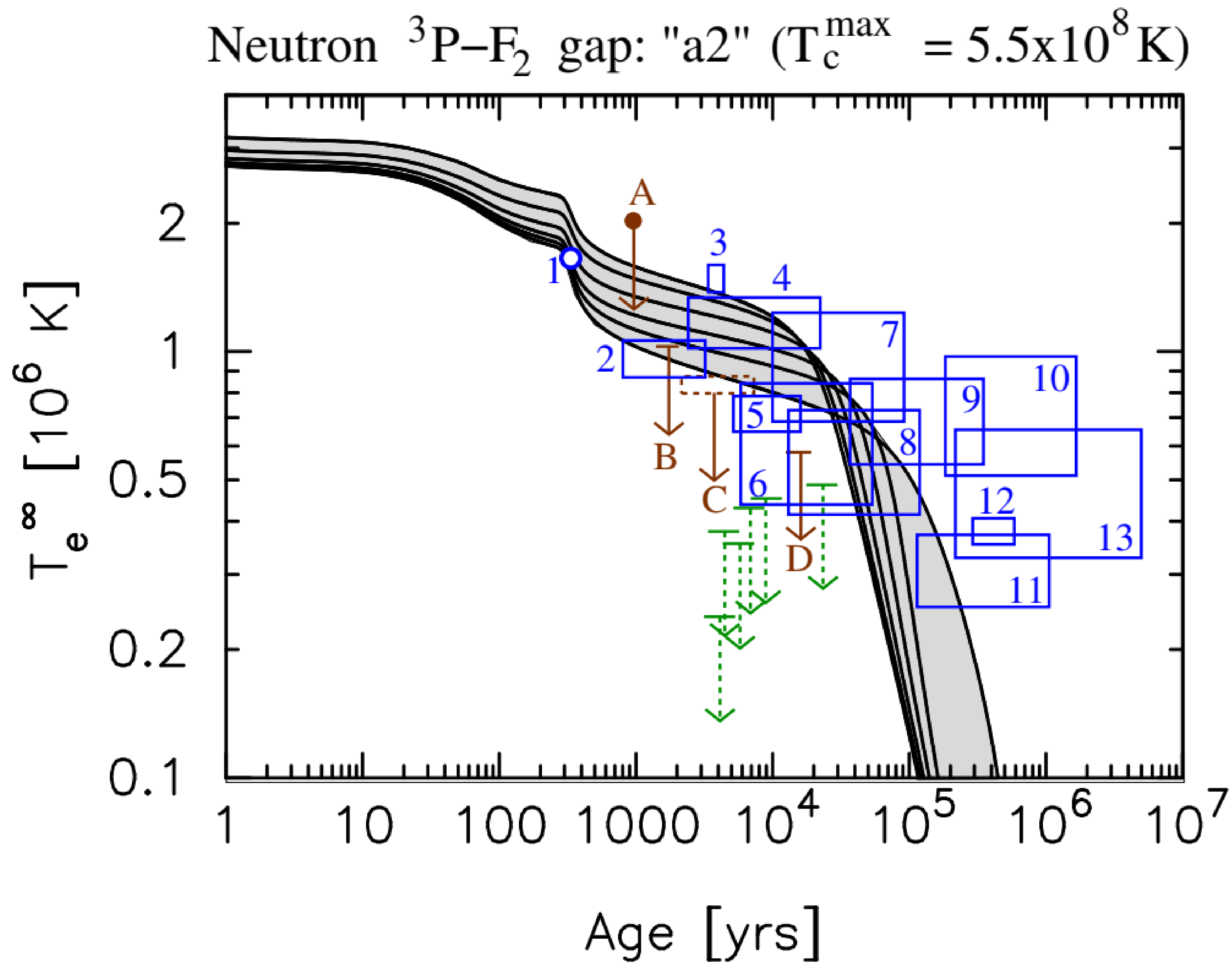
- Relaxation time scale: The relaxation is already simulated by NSCOOL. There were proposals of longer relaxation after the discovery of the rapid cooling of CAS A NS. Need better understanding or analyze an older neutron star

Thank You !

BACKUP SLIDES



Swiss cheese
Lasagna
Spaghetti
B
Core:
homogeneous matter
Crust:
nuclei + neutron superfluid
Atmosphere
Envelope
Crust
Outer core
Inner core
?
A
Neutron superfluid
Neutron vortex
Nuclei in a lattice
C
Neutron superfluid + proton superconductor
Neutron vortex
Magnetic flux tube


Neutron $^3P-F_2$ gap: "a2" (T_c^{max} = $5.5x10^8$ K)
T_e^∞ [10^6 K]
Age [yrs]
A
B
C
D
1
2
3
4
5
6
7
8
9
10
11
12
13
2
1
0.5
0.2
0.1
1
10
100
1000
10^4
10^5
10^6
10^7