Axion limit from the Cooling Neutron Star in Cassiopeia A

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

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Outline

Minimal cooling model of Neutron Star

Cooling of Cas A NS

Axion limit from cooling of the Cas A NS

Minimal Cooling Scenario

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

$L_\nu \gg L_\gamma$ for $t < 10^5$ yr

Neutrino emission L_ν in a hot NS:

- Direct URCA:

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

  $\sim T^6$,
  Highly suppressed if $M < 2M_\odot$

- Modified URCA:

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

  $\sim T^8$

- ...

Review c.f. Page et. al, 2004; Yakovlev et. al, 2004;

Pairing effect

Nucleons form cooper-pairs at low temperature

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

- Pair-breaking-formation process(PBF)
  $N + N' \to [NN'] + \nu + \bar{\nu}$ $\sim T^7$
  Rapid cooling during phase transition
- Suppression of emissions by energy gap: $\sim \exp(-\Delta(T)/T)$

Pairing in NS:

- $n-n\ {}^3P_2$ pairing (core) *Theoretically Highly Uncertain*
- $p-p\ {}^1S_0$ pairing (core)
- $n-n\ {}^1S_0$ pairing (crust) *Only relevent to relaxation*

Envelope model

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

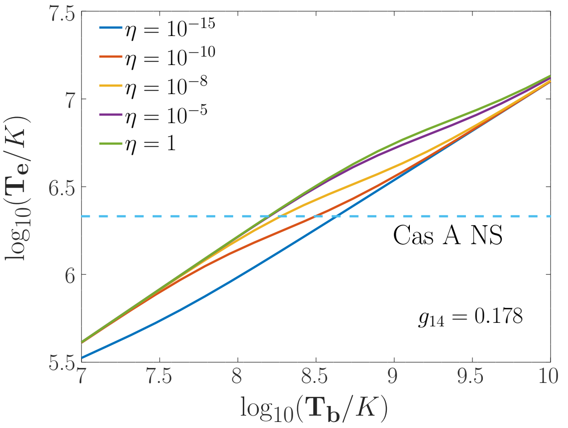
T_e: effective temperature

T_b: Interior T below envelope.

$\eta \sim \Delta M/M$

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

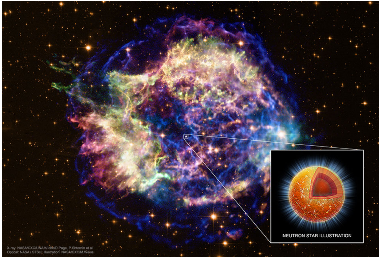
T_e-T_b relation from Potekhin, Yakovlev, 2001



Cas A NS

- NS x-ray found by Chandra at in 1999
- SN exploded in 1681 ± 19, estimated from remnant expansion

Image from apod 2017.5.1



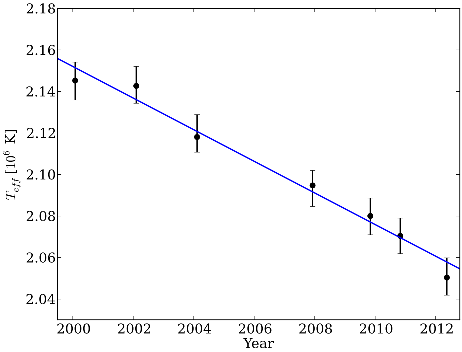


Figure from Astrophys.J. 777 (2013) 22

Heinke & Ho, 2010:

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

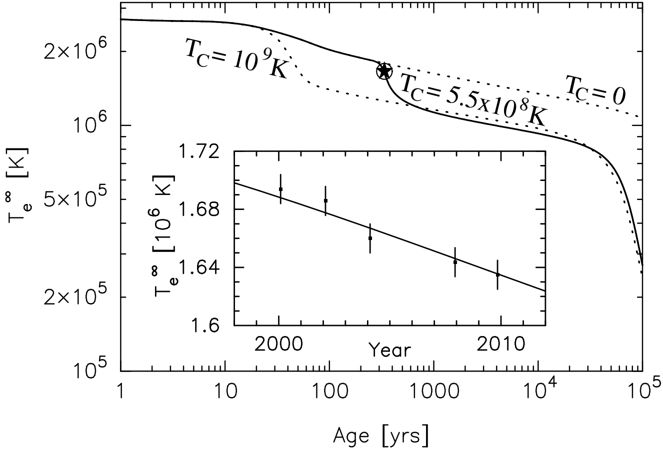
$M = 1.4 \pm 0.3\, M_\odot$

For comparison,
$(dT/dt)_{\rm MURCA} \sim 0.3\%/10$ yrs

Rapid cooling needed. (pbf?)

Minimal cooling model vs Cas A NS

Page, Prakash, Lattimer, Steiner, 2011



- Suppress MURCA by early proton-pairing
- n^3P_2 pairing triggered recently(tuned) for rapid cooling

Axion emission in NS

Axion nucleon coupling:

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

KSVZ axion (This talk)

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

DFSZ axion

$$C_p = -0.182(25) - 0.435 \sin^2\beta,$$
$$C_n = -0.160(25) + 0.414 \sin^2\beta$$

Emission processes

- PBF $N + N' \to [NN'] + a \quad \sim T^5$ Sedrakian, 2015
- Bremsstrahlung $N + N \to N + N + a \quad \sim T^6$ Iwamoto, 1984

Some technical detail

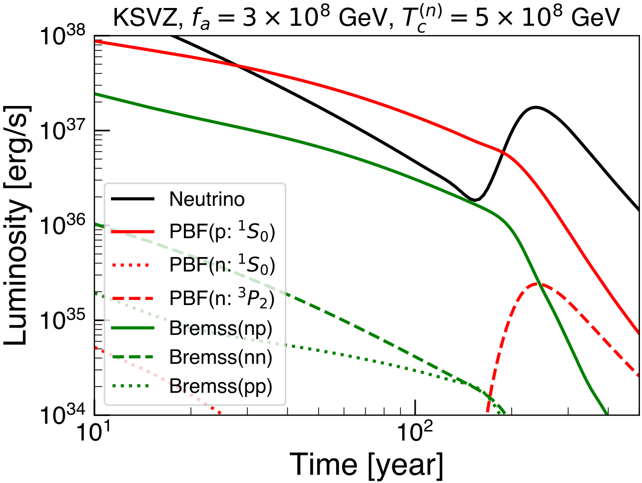
We modified public code *NSCool* to implement axion cooling in addition to minimal cooling model

To be conservative on axion limit:
n^3P_2 energy gap function is taken as free parameters

p^1S_0 energy gap is chosen from theoretical models with highest T_c(CCDK), for maximal suppression of axion emission from proton

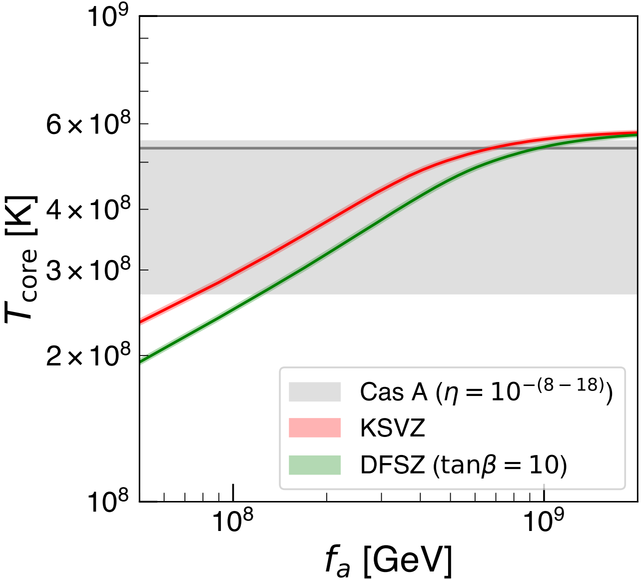
The result is not sensitive to the following choices:
APR EOS, $M = 1.4M_\odot$, SFB n^1S_0 gap.

Axion luminosity in KSVZ model

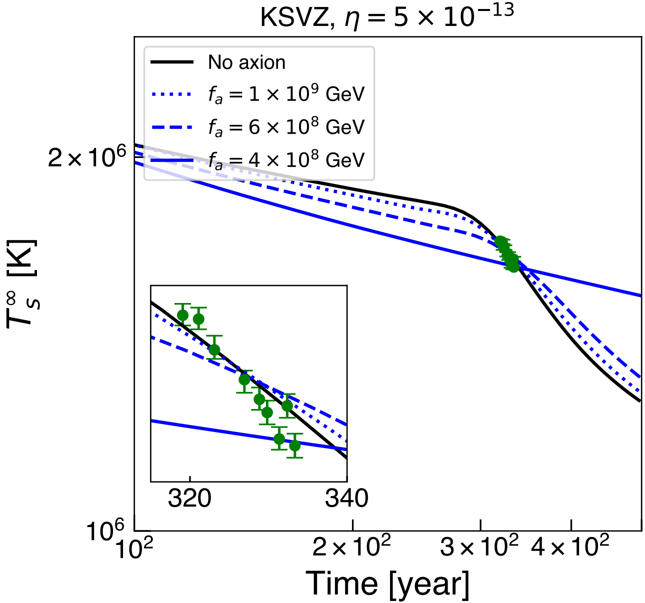


Proton pbf emission dominates L_a.

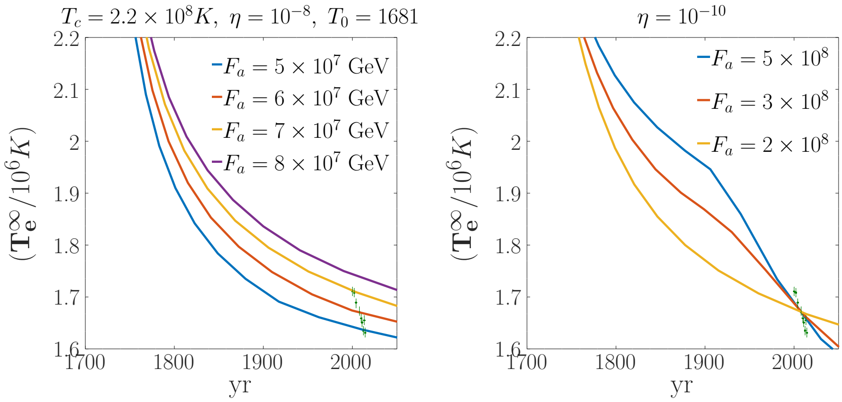
$T_{\rm core}$ from cooling model at $t_{\rm obs} = 2001$ vs F_a, without n$^3P_2$ pairing.



Fit of Cas A NS cooling data with axion emission included



For KSVZ, $C_n \sim 0$, neutron $^3P_2$ pbf mainly emits ν



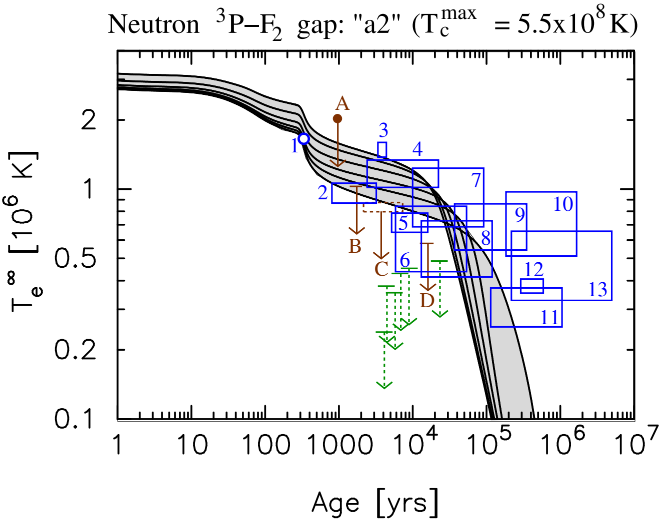
Large $\eta \rightarrow$ smaller T_b^7 ν pbf emission $\rightarrow$ Cannot fit the slope!

However, the constraint on DFSZ at high η is much weaker because of axion n^3P_2 pbf emission

Summarizing the limit

- Tight constraint for KSVZ model: $\eta \gtrsim 10^{-10}$, $F_a \gtrsim 5 \times 10^8$ GeV
- Large uncertainty set by η for DFSZ case. When $\tan\beta = 10$, for minimal η, $F_a \gtrsim 6 \times 10^8$; For maximal η, $F_a \gtrsim 1.1 \times 10^8$
- Similar things can be done with other light dark matter scenario.

Backup



From Page et. al, arXiv:1302.6626