Limit on axion decay constant from the cooling neutron star in Cassiopeia A

Keisuke Yanagi

University of Tokyo

Based on Hamaguchi, Nagata, KY, Zheng, Phys. Rev. D98 (2018) 103015

Berkeley week @ IPMU
Jan. 17, 2020

Overview

“Limit on axion decay constant from the cooling neutron star in Cassiopeia A”

Overview

"Limit on axion decay constant from the cooling neutron star in Cassiopeia A"

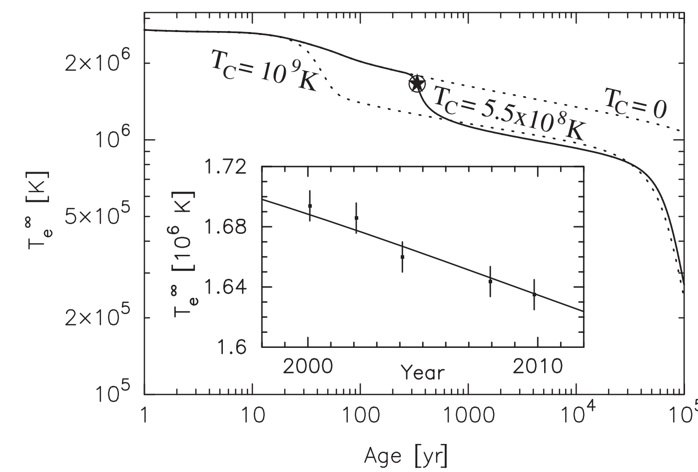
Well-motivated candidate of a new particle

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

[Pecci and Quinn (1977); Weinberg (1978); Wilczek (1978)]

NS cooling is observed

[Page et al. (2011)]



Overview

"Limit on axion decay constant from the cooling neutron star in Cassiopeia A"

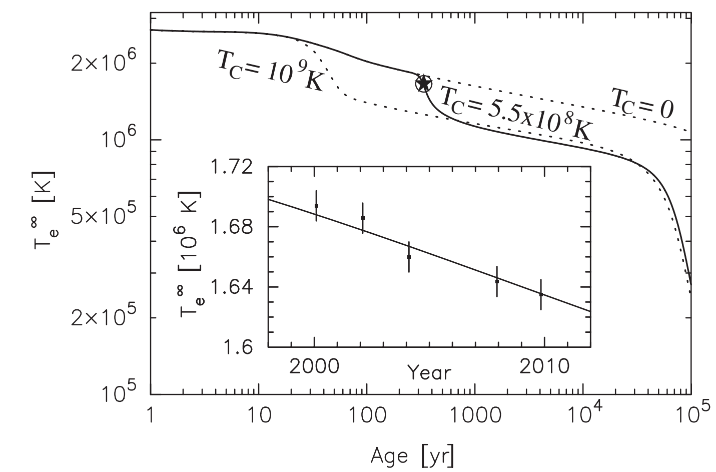
Well-motivated candidate of a new particle

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

[Pecci and Quinn (1977); Weinberg (1978); Wilczek (1978)]

NS cooling is observed

[Page et al. (2011)]



- SM: Cooling of Cas A NS can be explained by standard cooling theory [Page et al. (2011); Shternin (2011)]

Overview

"Limit on axion decay constant from the cooling neutron star in Cassiopeia A"

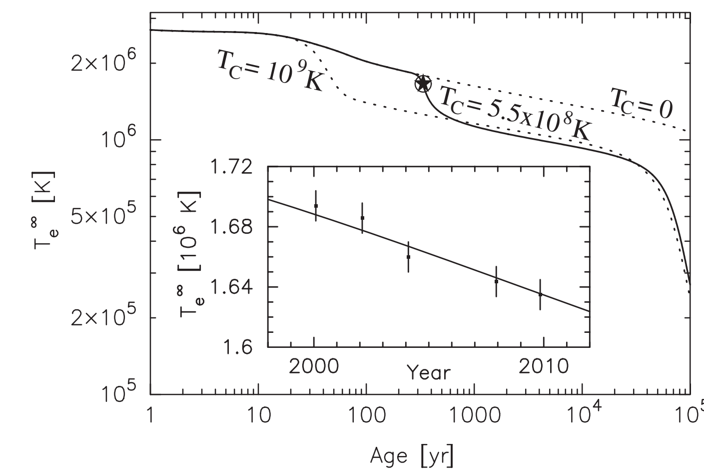
Well-motivated candidate of a new particle

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

[Pecci and Quinn (1977); Weinberg (1978); Wilczek (1978)]

NS cooling is observed

[Page et al. (2011)]

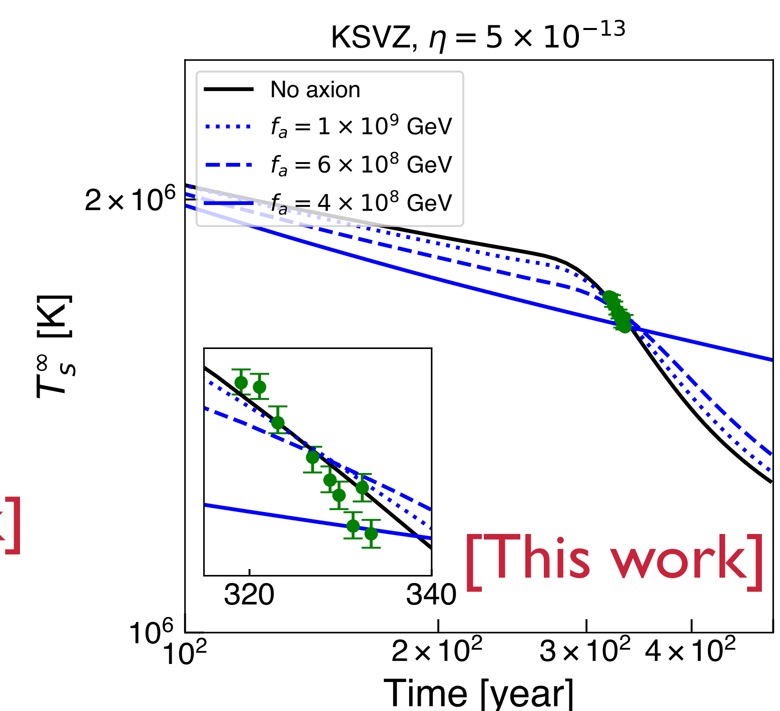


- SM: Cooling of Cas A NS can be explained by standard cooling theory [Page et al. (2011); Shternin (2011)]

- SM + Axion: if axion-nucleon coupling is too large, theory cannot explain the data

$f_a \gtrsim (5-7)\times 10^8\,\mathrm{GeV}$ [This work]

comparable to the SN1987A limit



[This work]

Overview

“Limit on axion decay constant from the cooling neutron star in Cassiopeia A”

Well-m

$\mathscr{L} =$

[Pec

- SM: C stand
- SM + theo

Cited by PDG 2019!

112. Axions and Other Similar Particles

⋮

There is another hint for excessive stellar energy losses from the neutron star (NS) in the supernova remnant Cassiopeia A (Cas A): its surface temperature measured over 10 years reveals an unusually fast cooling rate. This rapid cooling of the Cas A NS may be explained by NS minimal cooling with neutron superfluidity and proton superconductivity [93, 94]. The rapid cooling may also arise from a phase transition of the neutron condensate into a multicomponent state [95]. Recently, Ref. [96] analyzed Cas A NS cooling in the presence of axion emission and obtained

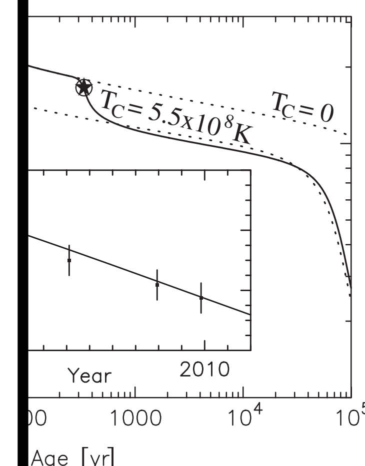
our work

$$g_{App}^2 + 1.6 g_{Ann}^2 < 1 \times 10^{-18}, \quad (112.17)$$

which is comparable to the SN 1987A bound. Refs. [97] put a more conservative bound without an

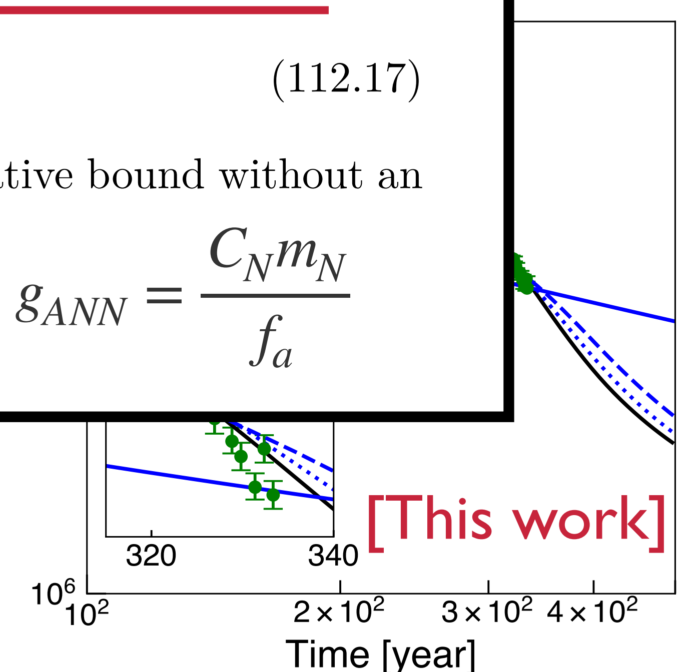
$$g_{ANN} = \frac{C_N m_N}{f_a}$$

[Page et al. (2011)]



$$f_a \gtrsim (5-7) \times 10^8\ \mathrm{GeV}$$ [This work]

comparable to the SN1987A limit



[This work]

Overview

"Limit on axion decay constant from the cooling neutron star in Cassiopeia A"

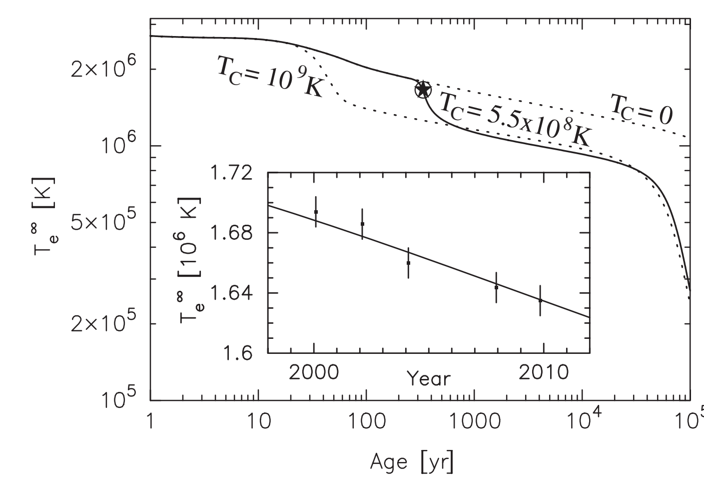
(review)

Well-motivated candidate of a new particle

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

[Pecci and Quinn (1977); Weinberg (1978); Wilczek (1978)]

NS cooling is observed [Page et al. (2011)]

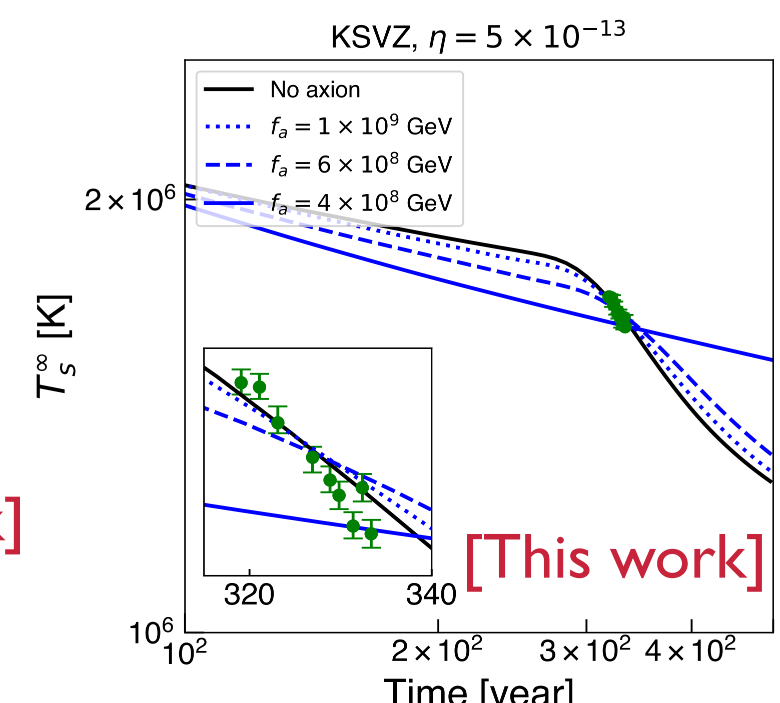


- SM: Cooling of Cas A NS can be explained by standard cooling theory [Page et al. (2011); Shternin (2011)]

- SM + Axion: if axion-nucleon coupling is too large, theory cannot explain the data

$$\Rightarrow \quad f_a \gtrsim (5-7)\times 10^8\,\mathrm{GeV}$$ [This work]

comparable to the SN1987A limit



Strong CP problem and axion

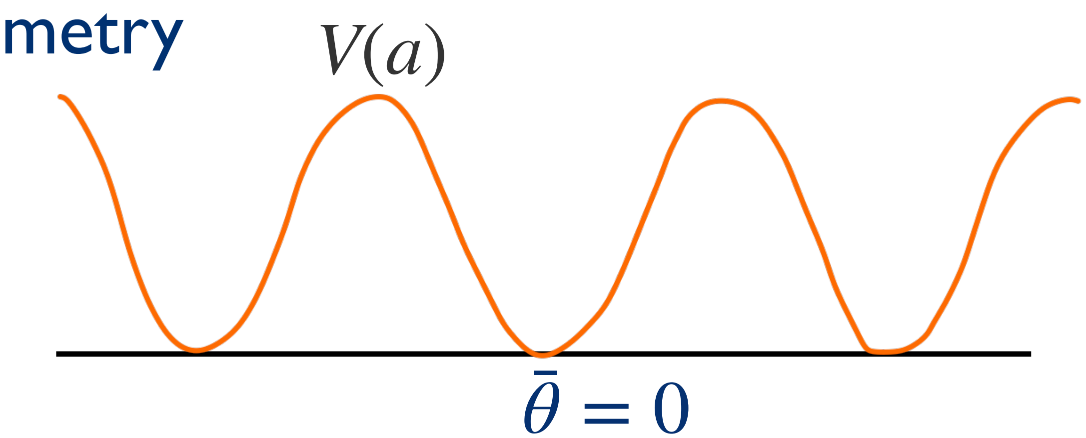
- Strong CP problem: why CP violation in strong interaction is so small?

$$\mathscr{L}_\theta = \theta \frac{\alpha_S}{8\pi} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

$$\bar{\theta} = \theta + \mathrm{arg}\det M_q \rightarrow \bar{\theta} \lesssim 10^{-10}$$ from neutron EDM [Baker et al. (2006)]

- Axion: pseudo-NG boson of $\mathrm{U}(1)_{\mathrm{PQ}}$ symmetry

$$\mathscr{L}_a = \left(\frac{a}{f_a} + \theta\right) \frac{\alpha_S}{8\pi} G_{\mu\nu}\tilde{G}^{\mu\nu}$$



CP conserving minimum is dynamically chosen

[Pecci and Quinn (1977); Weinberg (1978); Wilczek (1978)]

Axion models

- Axion couples to nucleons

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

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

- Coupling constant depends on models

  - KSVZ axion model [Kim (1979); Shifman, Vainshtein, Zakharov ((1980)]

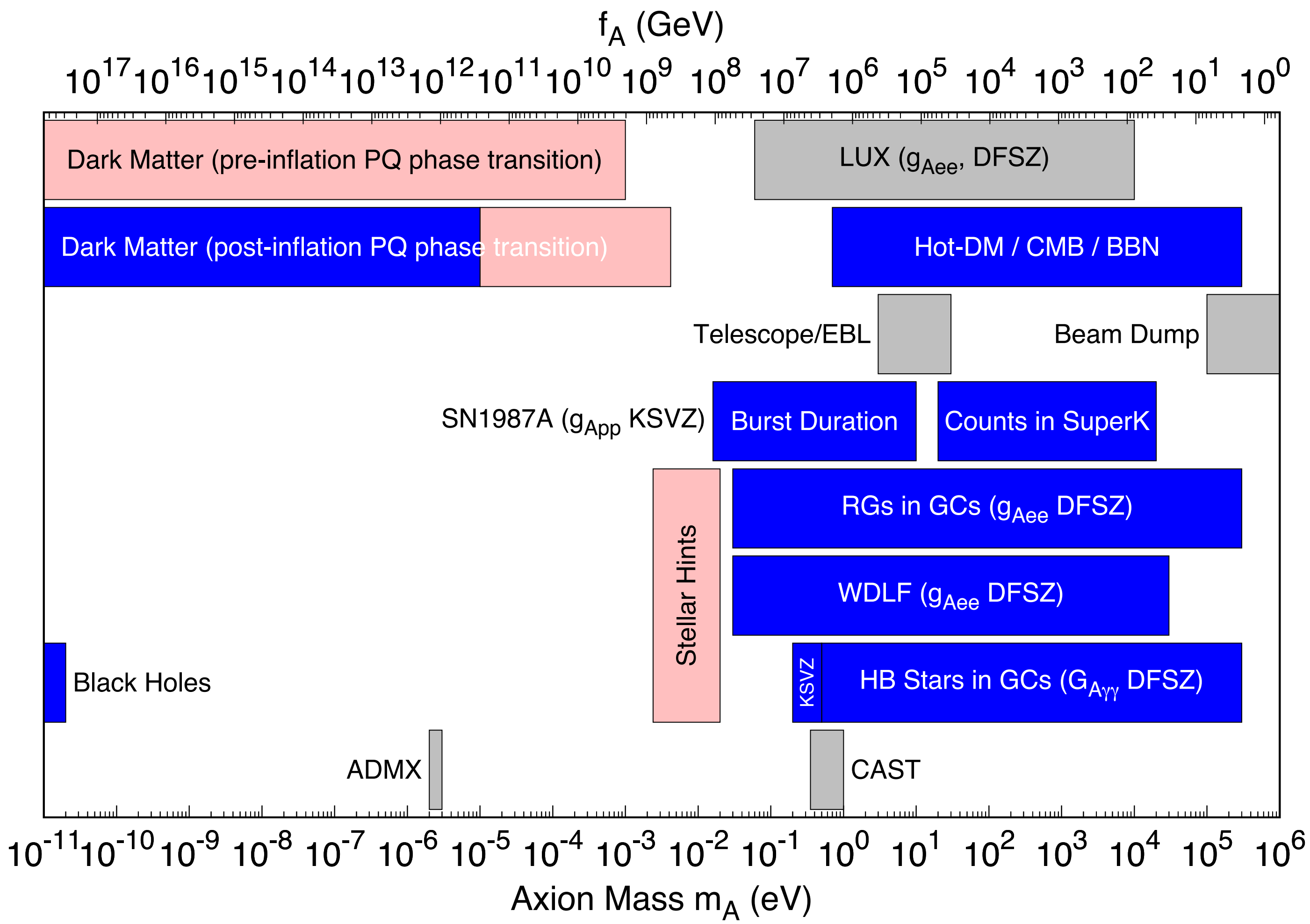
$$C_p = -0.47(3)\,, C_n = -0.02(3) \quad (C_q = 0)$$

  - DFSZ axion model [Zhitnitsky (1980); Dine, Fischler, Srednicki (1981)]

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

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

Previous constraints on axion



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

[PDG 2018]

$$m_a = \mathcal{O}(m_\pi f_\pi / f_a)$$

SN1987A: $f_a \gtrsim 10^8\,\mathrm{GeV}$

Overview

"Limit on axion decay constant from the cooling neutron star in Cassiopeia A"

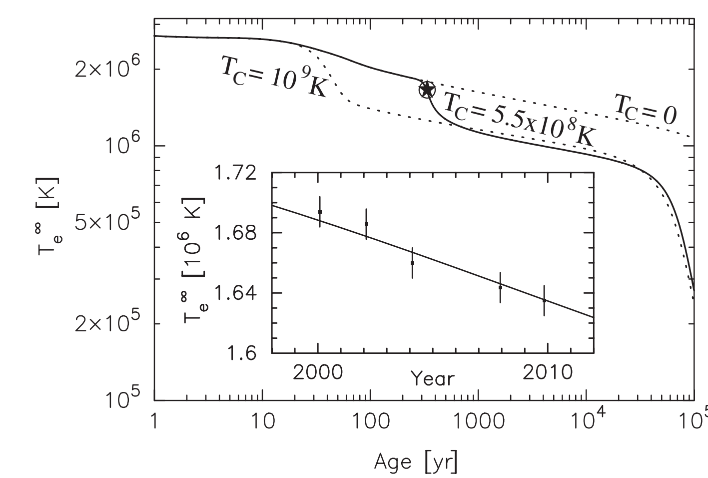
(review)

Well-motivated candidate of a new particle

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

[Pecci and Quinn (1977); Weinberg (1978); Wilczek (1978)]

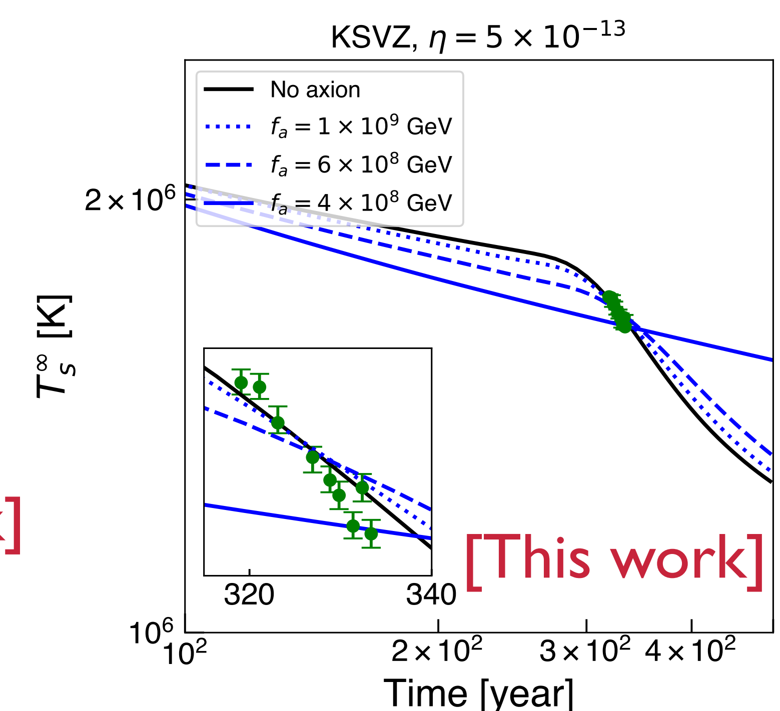
NS cooling is observed [Page et al. (2011)]



- SM: Cooling of Cas A NS can be explained by standard cooling theory [Page et al. (2011); Shternin (2011)]
- SM + Axion: if axion-nucleon coupling is too large, theory cannot explain the data

$$f_a \gtrsim (5-7)\times 10^8\,\mathrm{GeV}$$ [This work]

comparable to the SN1987A limit



Overview

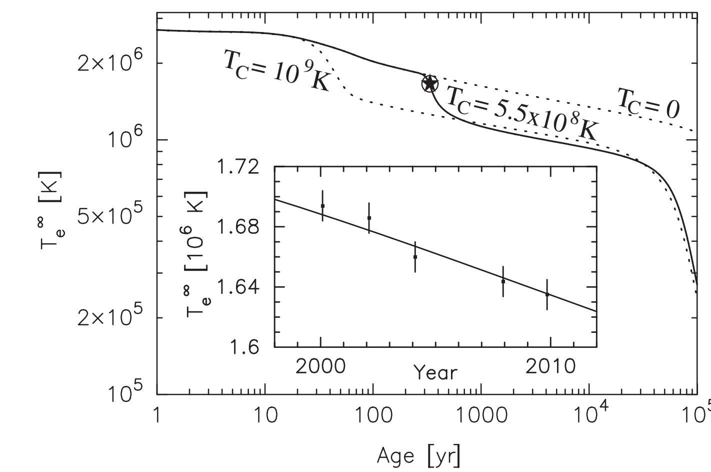
"Limit on axion decay constant from the cooling neutron star in Cassiopeia A"

Well-motivated candidate of a new particle

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

[Pecci and Quinn (1977); Weinberg (1978); Wilczek (1978)]

NS cooling is observed [Page et al. (2011)]



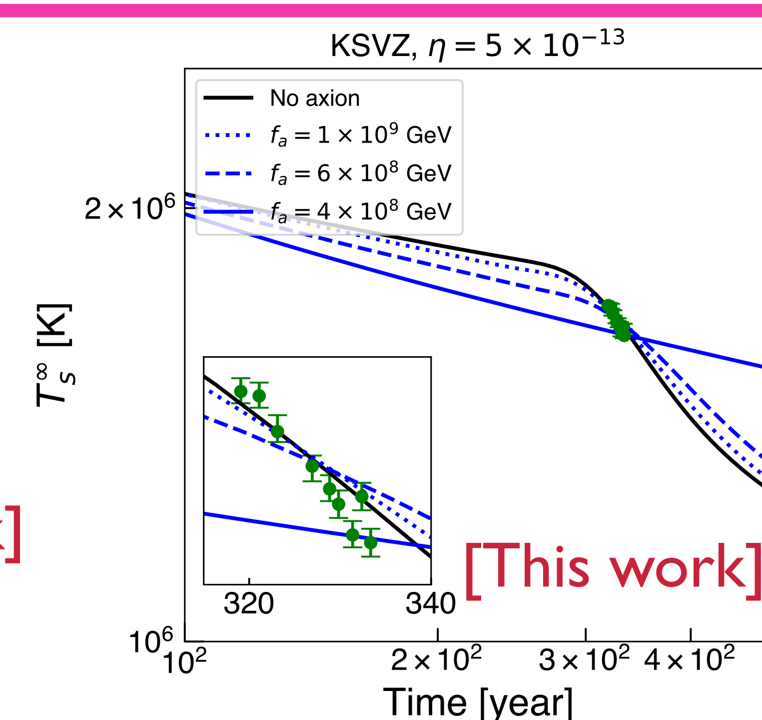
(review)

- SM: Cooling of Cas A NS can be explained by standard cooling theory [Page et al. (2011); Shternin (2011)]

- SM + Axion: if axion-nucleon coupling is too large, theory cannot explain the data

$f_a \gtrsim (5-7)\times 10^8\,\mathrm{GeV}$ [This work]

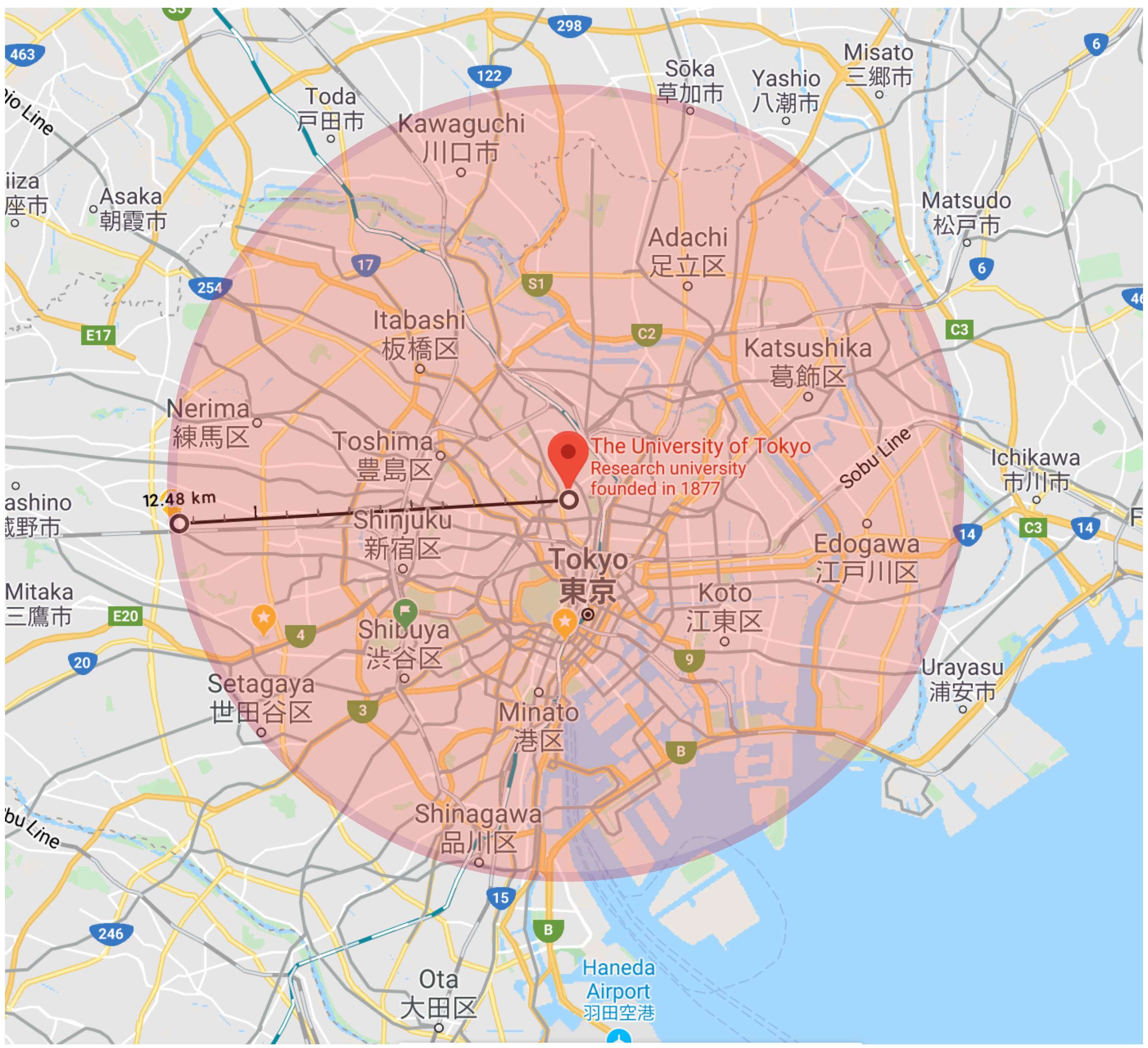
comparable to the SN1987A limit



[This work]

Neutron star

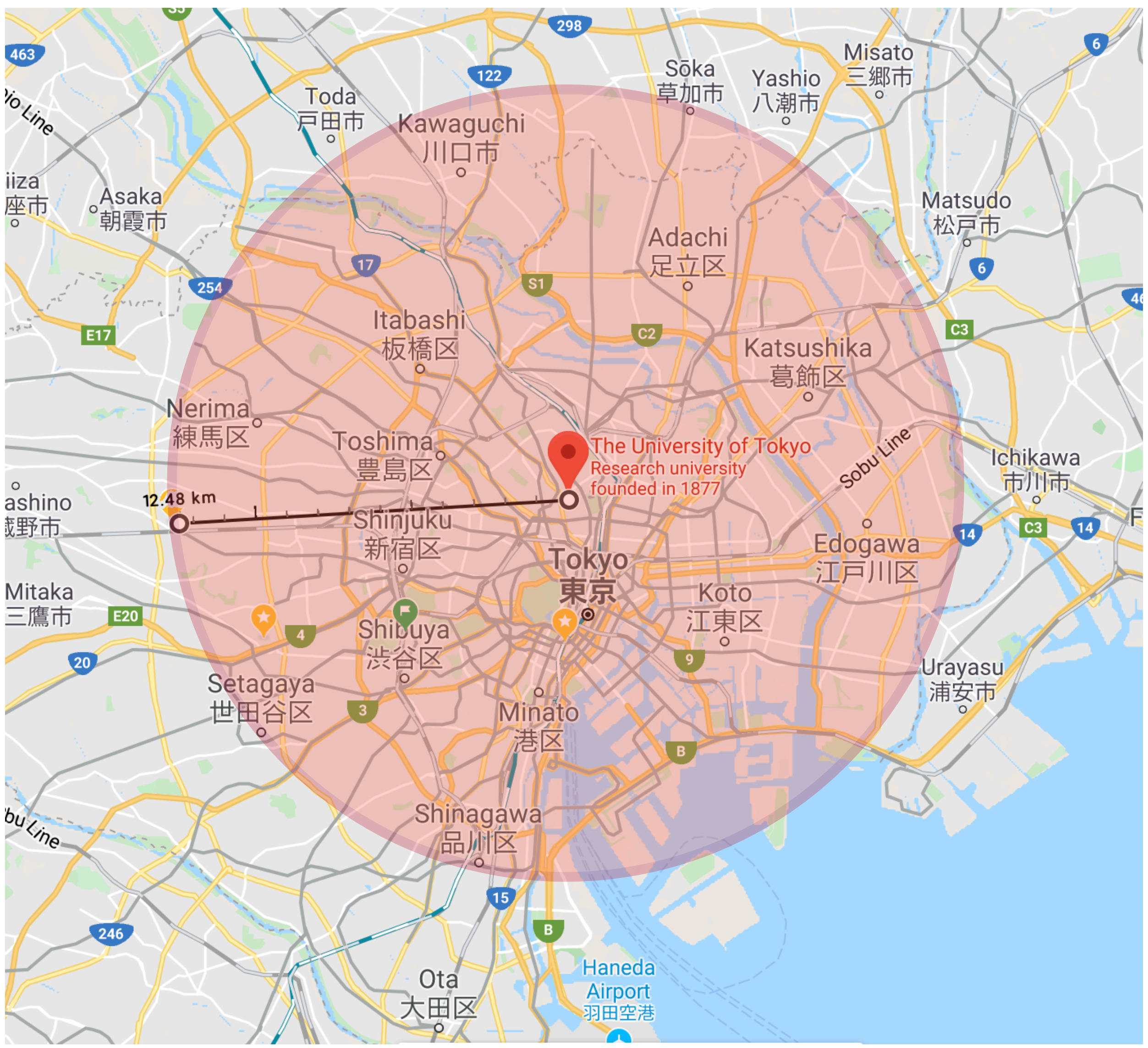
Compact astrophysical object: $M \sim 1.4 M_{\odot}$ in $R \sim 10\,\mathrm{km}$



Tokyo area

Neutron star

Compact astrophysical object: $M \sim 1.4 M_{\odot}$ in $R \sim 10\,\mathrm{km}$



Tokyo area

- Mostly consists of neutrons

$$p_{F,n} \sim O(100)\,\mathrm{MeV}$$

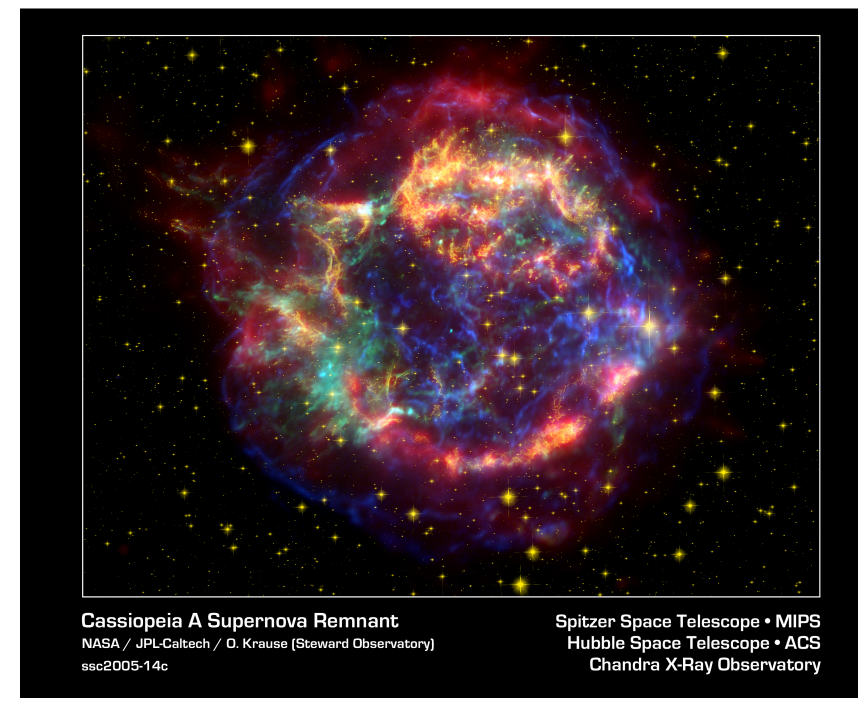
- Small amount of proton, electron, muon

$$p_{F,e,p,\mu} \sim O(10)\,\mathrm{MeV}$$

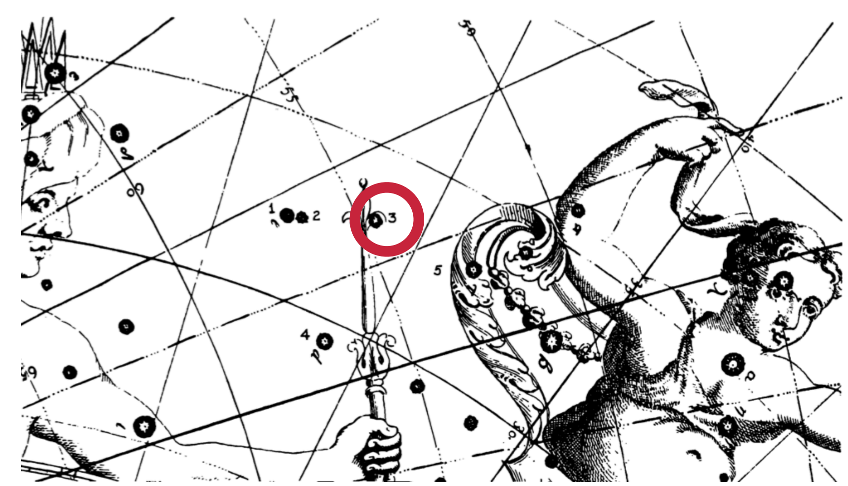
These particles are degenerate: $p_F \gg T$

NS in Cassiopeia A

- Cassiopeia A (Cas A): Supernova remnant in the Cassiopeia constellation
  - Age: ~ 340 yr
    - from remnant expansion
      [R. A. Fesen et al. (2006)]
    - Perhaps from record by J. Flamsteed at Aug. 16, 1680
      [W. B. Ashworth, Jr. (1980); K. W. Kamper (1980); D. W. Hughes (1980).]



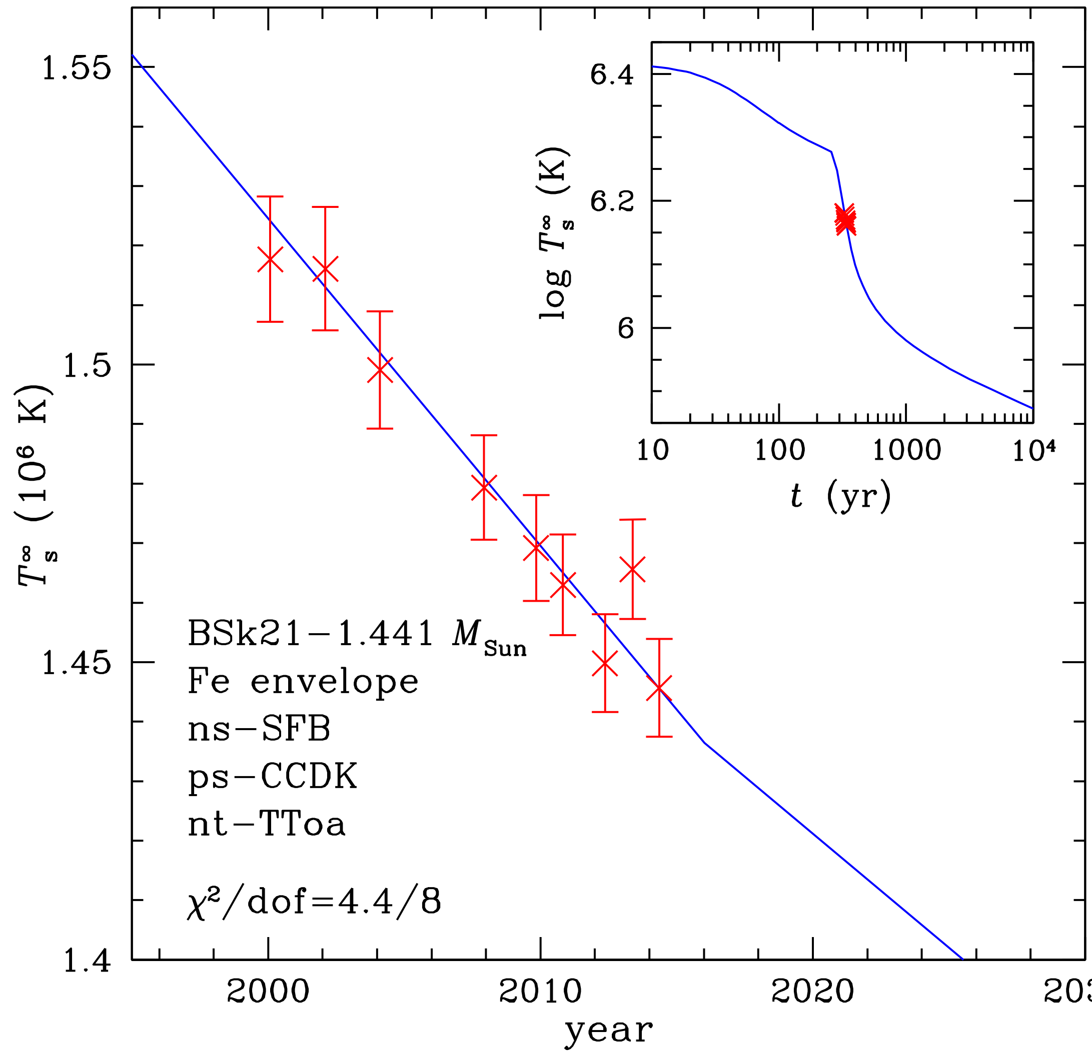
- Neutron star at the center of Cas A (Cas A NS)
  - Thermal emission is detected



[Atlas Coelestis (1729)]

Cooling of Cas A NS

Temperature is decreasing for ~ 10 years

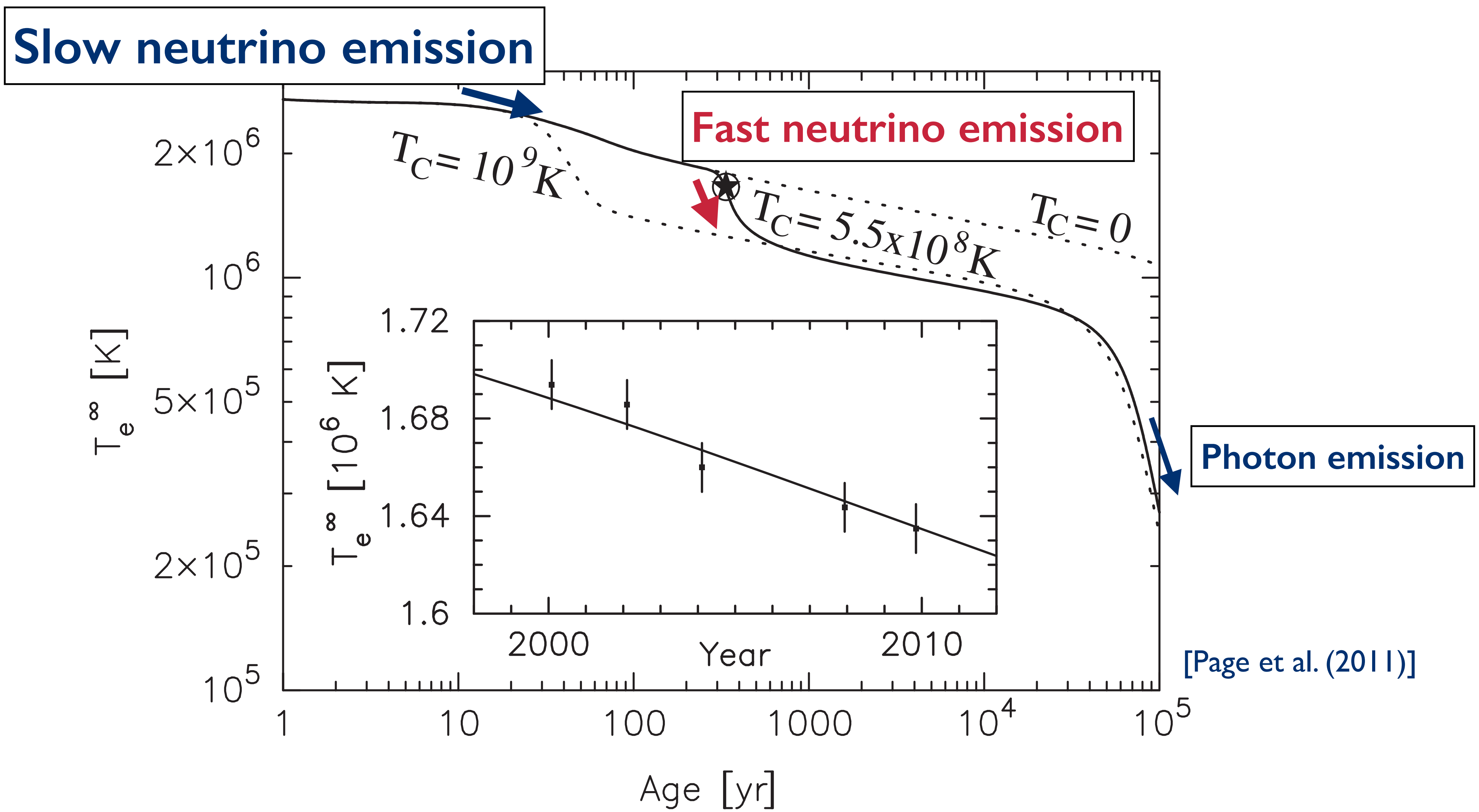


[Ho et al. (2015)]

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

Standard cooling explains temperature decline

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

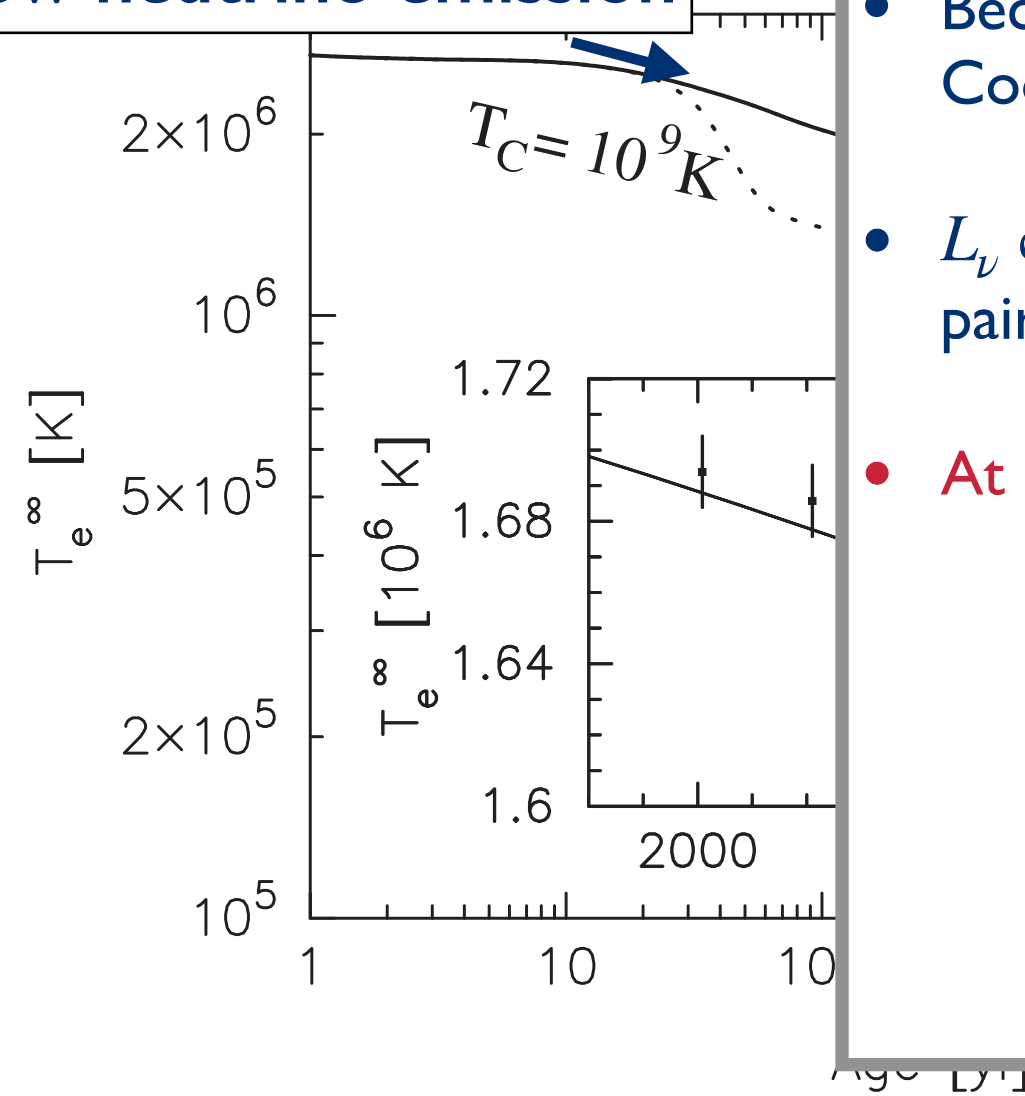


[Page et al. (2011)]

Standard cooling explains temperature decline

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

Slow neutrino emission



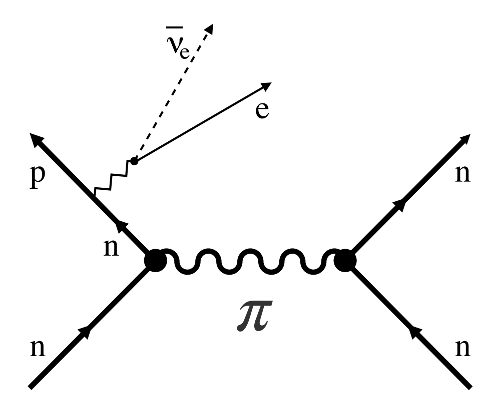
Modified Urca process

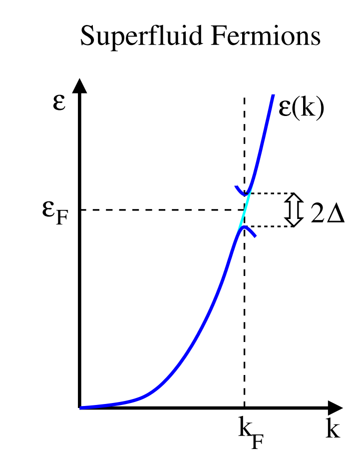
$$n + N \to p + N + e + \bar{\nu}_e$$

$$p + N + e \to n + N + \nu_e$$

$$N = n, p$$

- Because of attractive nuclear force, nucleon Cooper pairing occurs
- $L_\nu \propto T^8$ × (suppression by nucleon Cooper pairing)
- At $t \lesssim 100\,\mathrm{yr}$, only proton forms pair





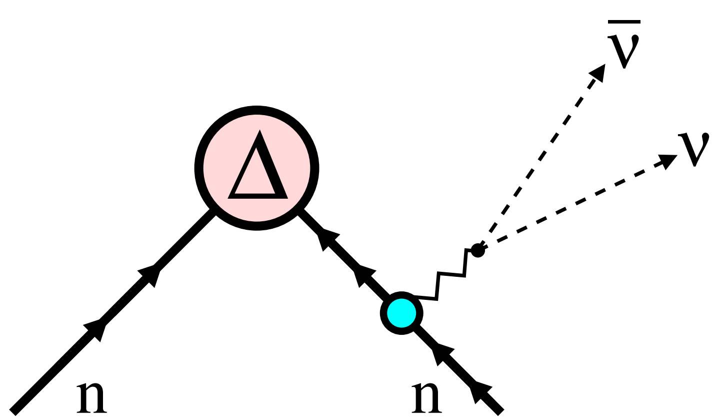
Standard cooling explains temperature decline

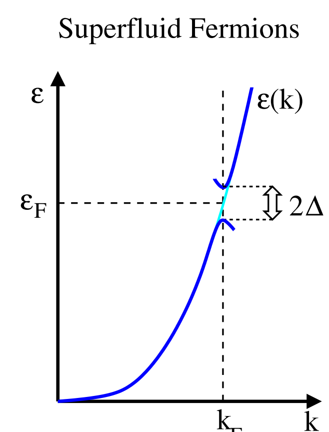
Cooper pair-breking and formation (PBF)

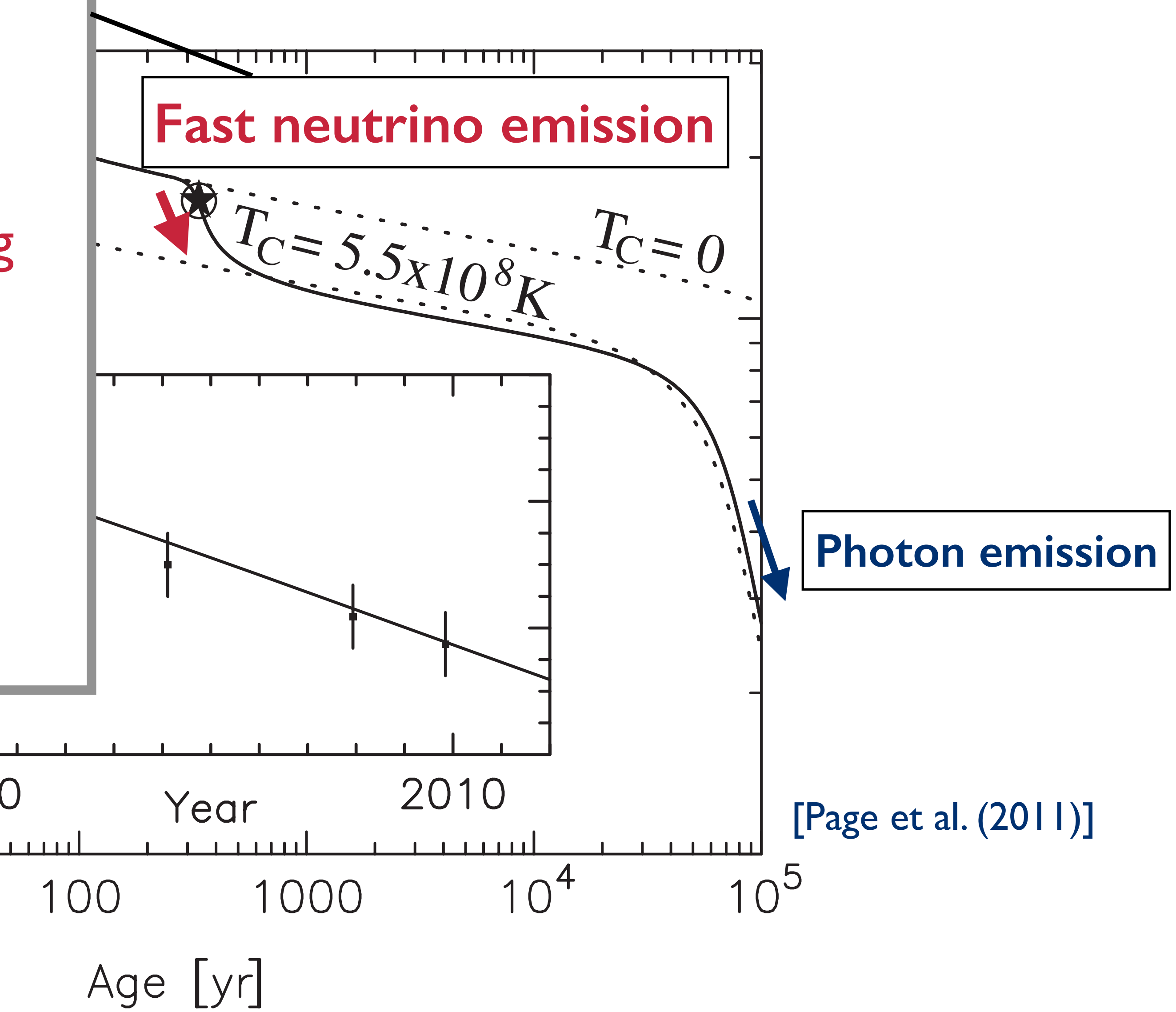
Pair-breaking: $[\tilde{N}\tilde{N}] \rightarrow \tilde{N} + \tilde{N}$

Pair-formation: $\tilde{N} + \tilde{N} \rightarrow [\tilde{N}\tilde{N}] + \nu + \bar{\nu}$

- If neutron triplet pairing occurs at $t \sim 320\,\mathrm{yr}$, PBF explains Cas A NS cooling





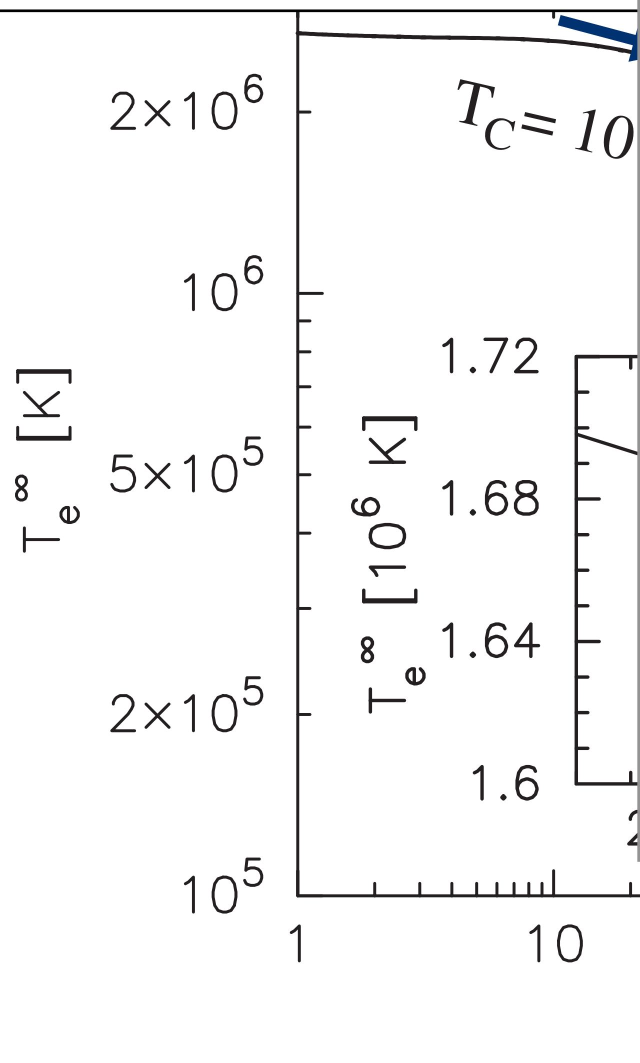


[Page et al. (2011)]

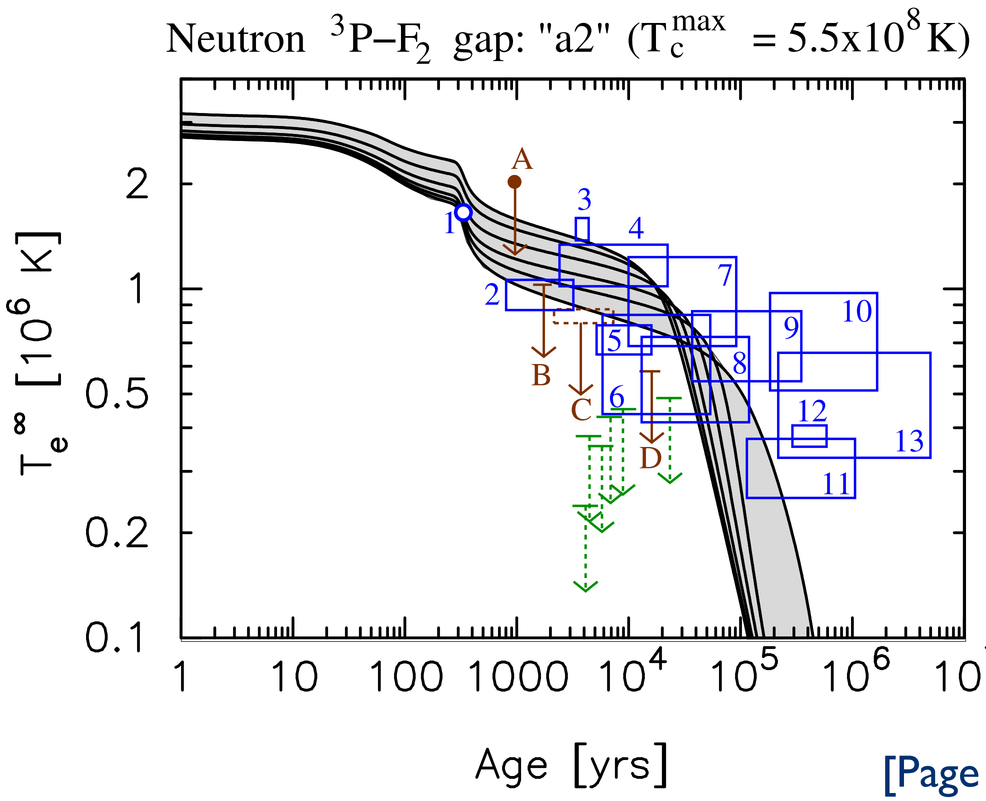
Standard cooling ex

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

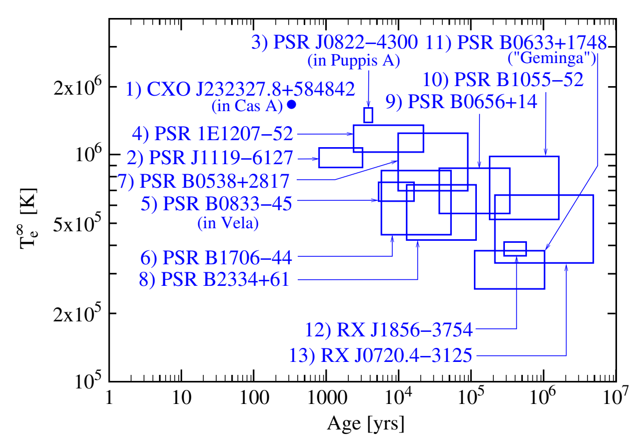
Slow neutrino emissio

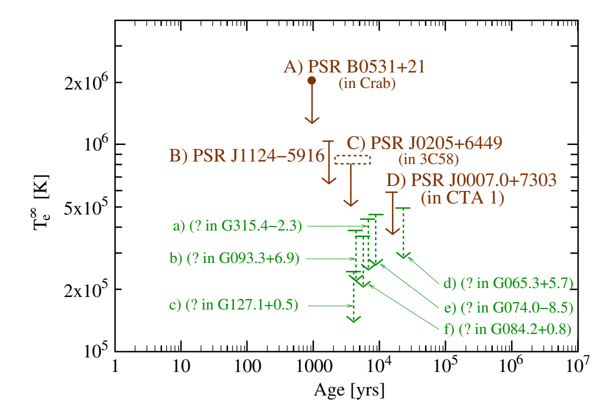


Standard cooling explains other NS temperature data



[Page et al. (2013)]





Overview

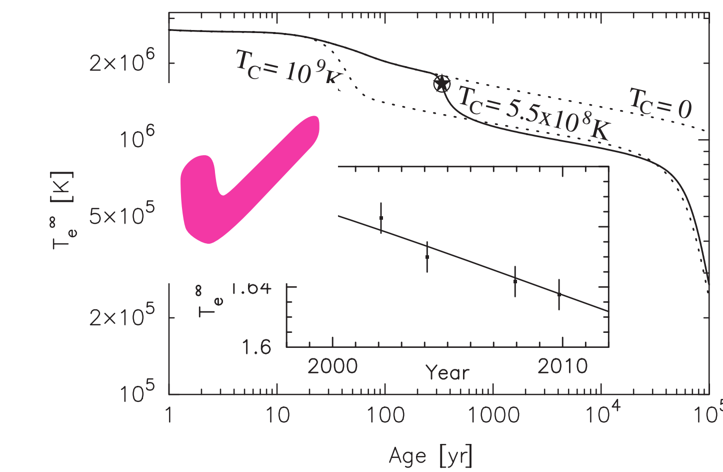
"Limit on axion decay constant from the cooling neutron star in Cassiopeia A"

Well-motivated candidate of a new particle

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

[Pecci and Quinn (1977); Weinberg (1978); Wilczek (1978)]

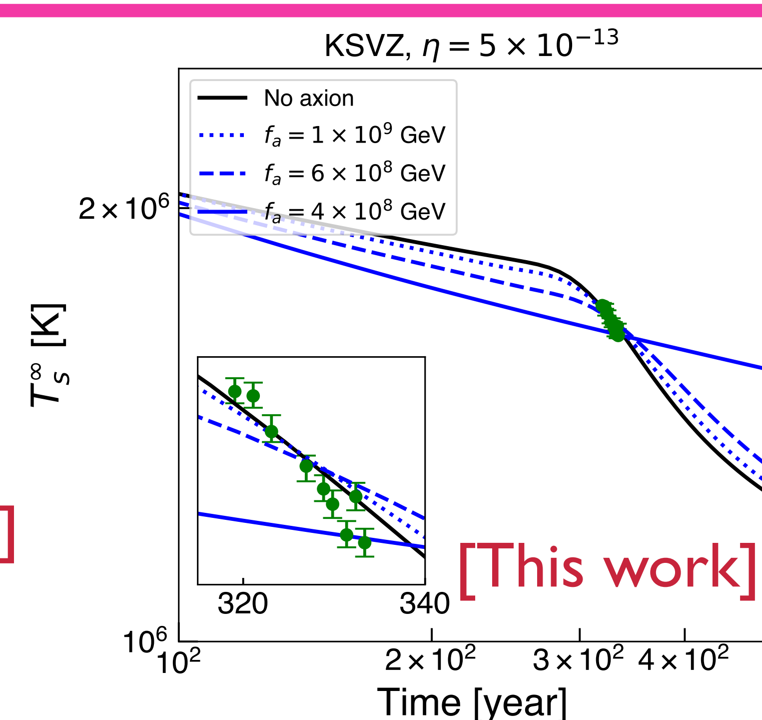
NS cooling is observed [Page et al. (2011)]



(review)

- SM: Cooling of Ca S can be explained by standard cooling t [Page et al. (2011); Shternin (2011)]

- SM + Axion: if axion-nucleon coupling is too large, theory cannot explain the data



$f_a \gtrsim (5-7)\times 10^8\,\mathrm{GeV}$ [This work]

[This work]

comparable to the SN1987A limit

Overview

“Limit on axion decay constant from the cooling neutron star in Cassiopeia A”

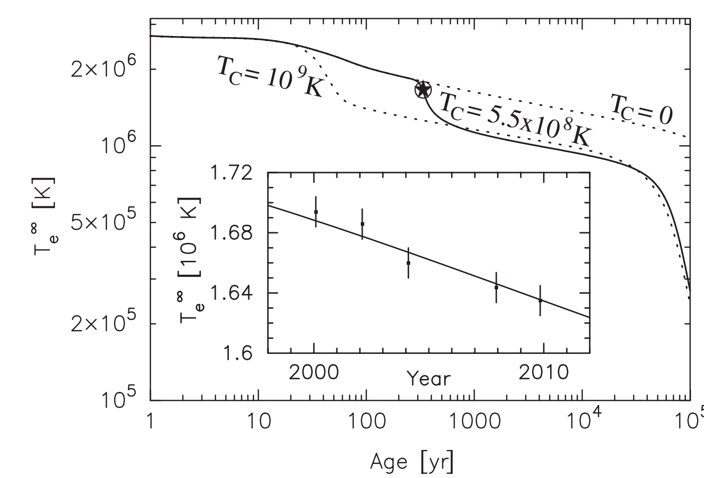
Well-motivated candidate of a new particle

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

[Pecci and Quinn (1977); Weinberg (1978); Wilczek (1978)]

NS cooling is observed

[Page et al. (2011)]



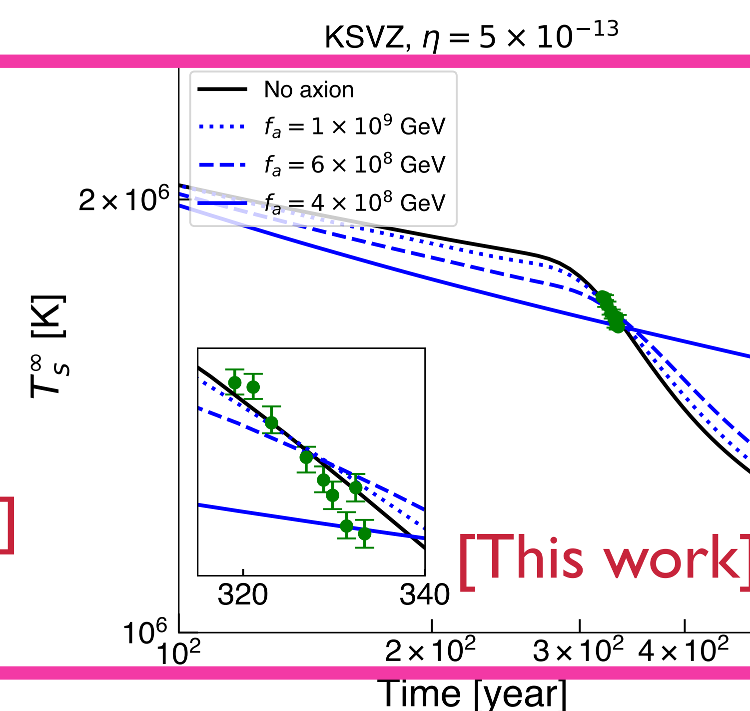
- SM: Cooling of Cas A NS can be explained by standard cooling theory [Page et al. (2011); Shternin (2011)]

(This work)

- SM + Axion: if axion-nucleon coupling is too large, theory cannot explain the data

$\Rightarrow$ $f_a \gtrsim (5-7)\times 10^8\,\mathrm{GeV}$ [This work]

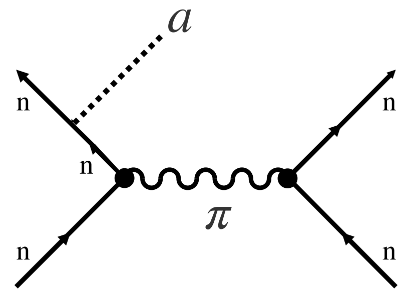
comparable to the SN1987A limit



Axion emission processes

- Axion Bremsstrahlung

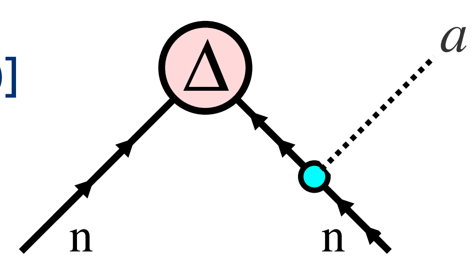
  [Iwamoto (1984, 2001); Nakagawa et al. (1987, 1988)]

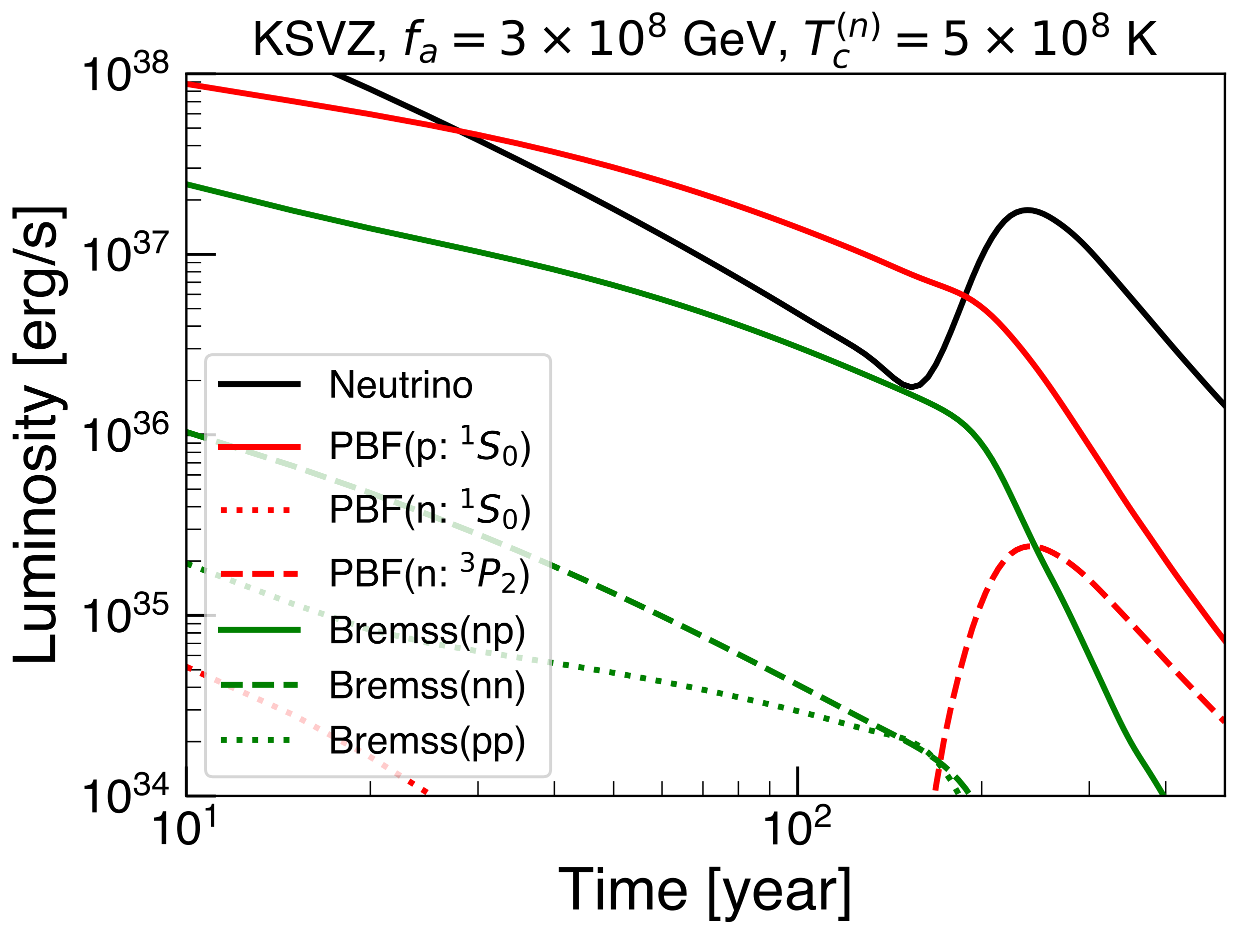


- Axion PBF

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

  [Leinson (2014); Sedrakian (2016)]





[Hamaguchi, Nagata, KY, Zheng (2018)]

- Even if $C_n \sim 0$ (KSVZ), axion emission is sizable due to the proton contribution

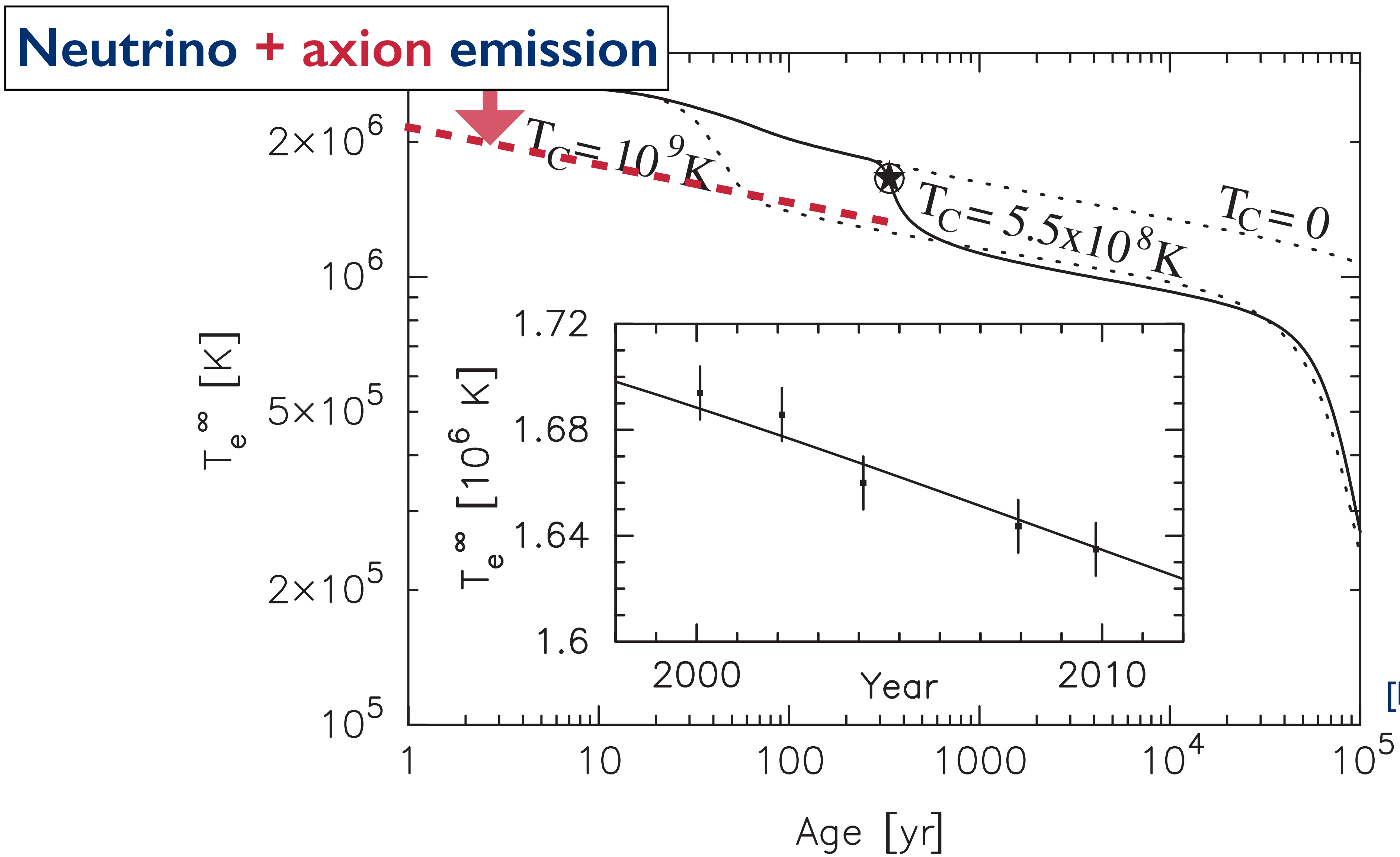
KSVZ: $C_p = -0.47(3)\,, C_n = -0.02(3)$ $\quad \mathscr{L} = \sum_{N=n,p} \frac{C_N}{2f_a} \bar{N}\gamma^\mu\gamma_5 N \partial_\mu a$

Axion emission enhances cooling

If f_a is too small, the Cas A NS would be overcooled

⟶ Constraint on f_a

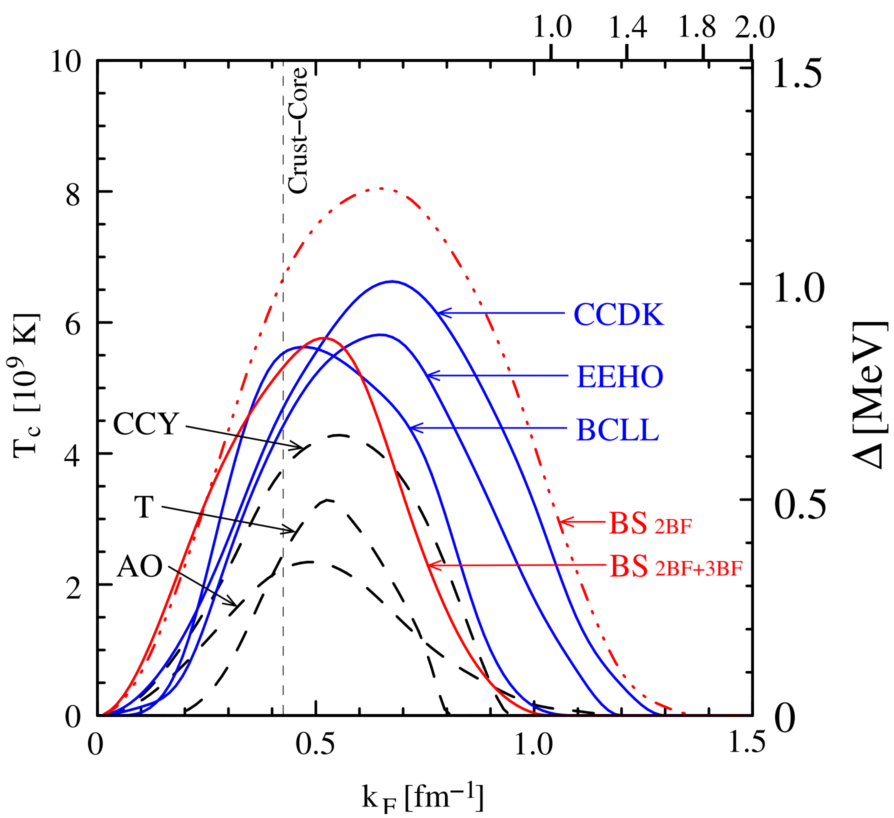
coupling $\sim \dfrac{C_N}{f_a}$



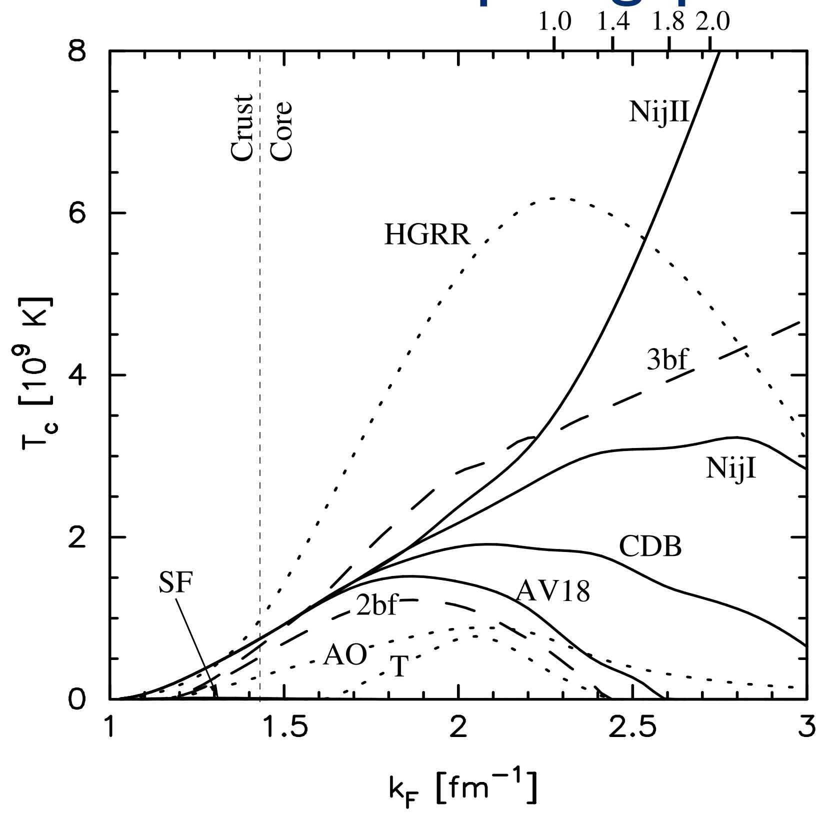
[Page et al. (2011)]

Detail 1: Gap models

proton singlet gap



neutron triplet gap



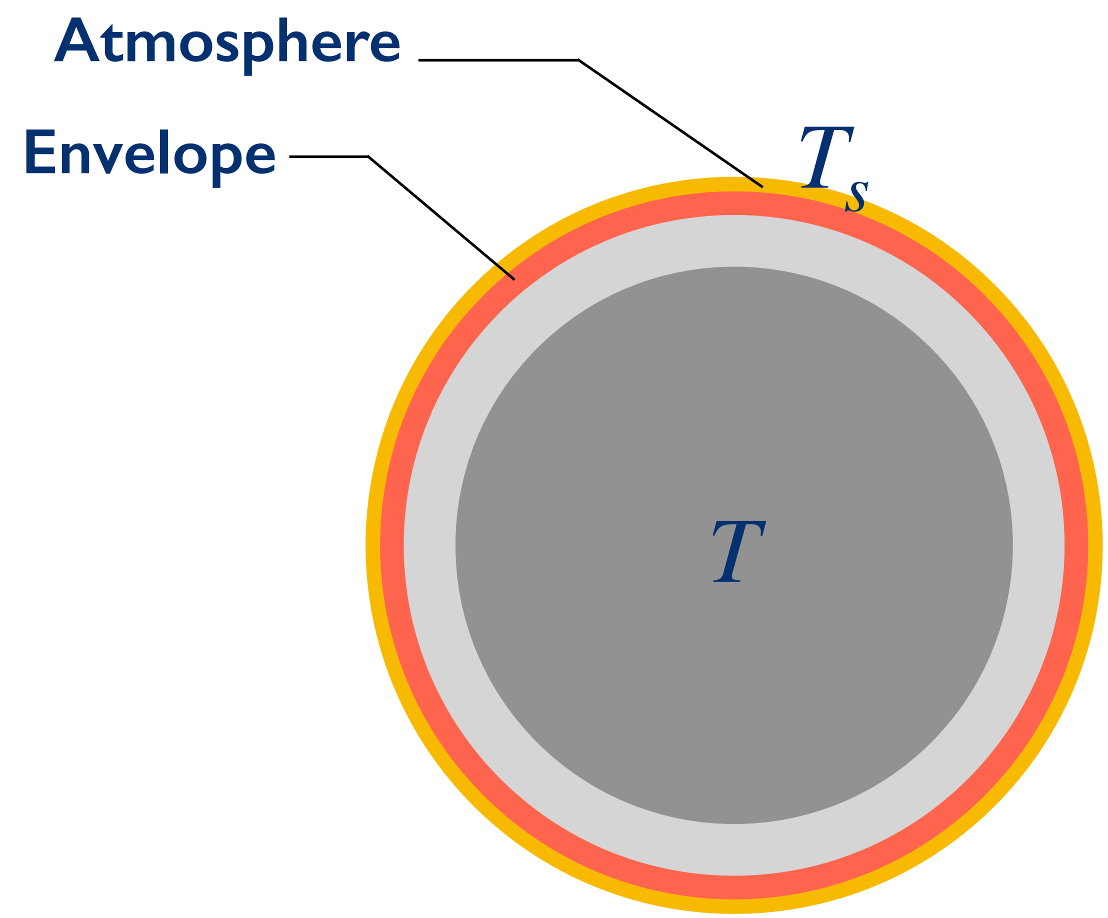
[Figures from Page et al. (2013)]

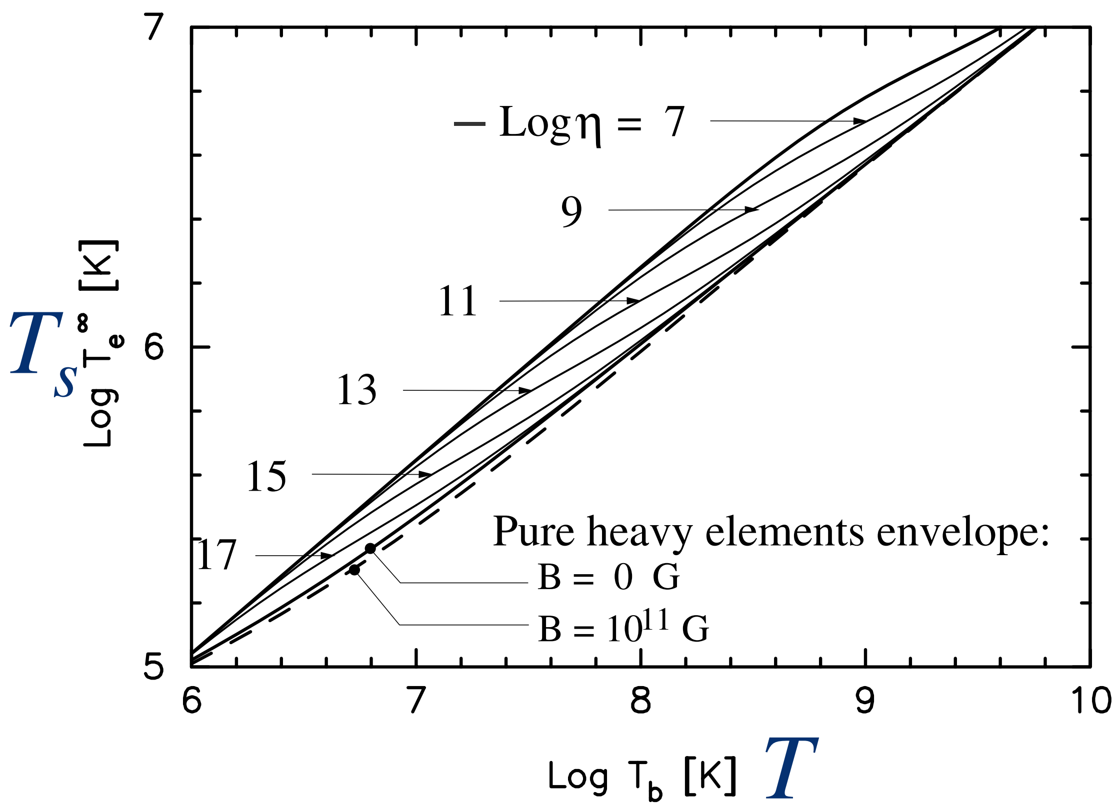
$$\epsilon_N(\mathbf{p}) \simeq \mu_N + \mathrm{sign}(p - p_{F,N})\sqrt{\Delta_N^2 + v_{F,N}^2(p - p_{F,N})^2}$$

- Gap amplitude has uncertainties due to nuclear potential modeling
- We use CCDK model for proton gap to suppress early time modified Urca
- We take neutron triplet gap as a free parameter to fit Cas A NS cooling

Details 2: Envelope

- Envelope shields atmosphere from core and crust
- Surface T and internal T are different
- $T - T_s$ relation depends on amount of light element in envelope [Potekhin et al. (1997)]

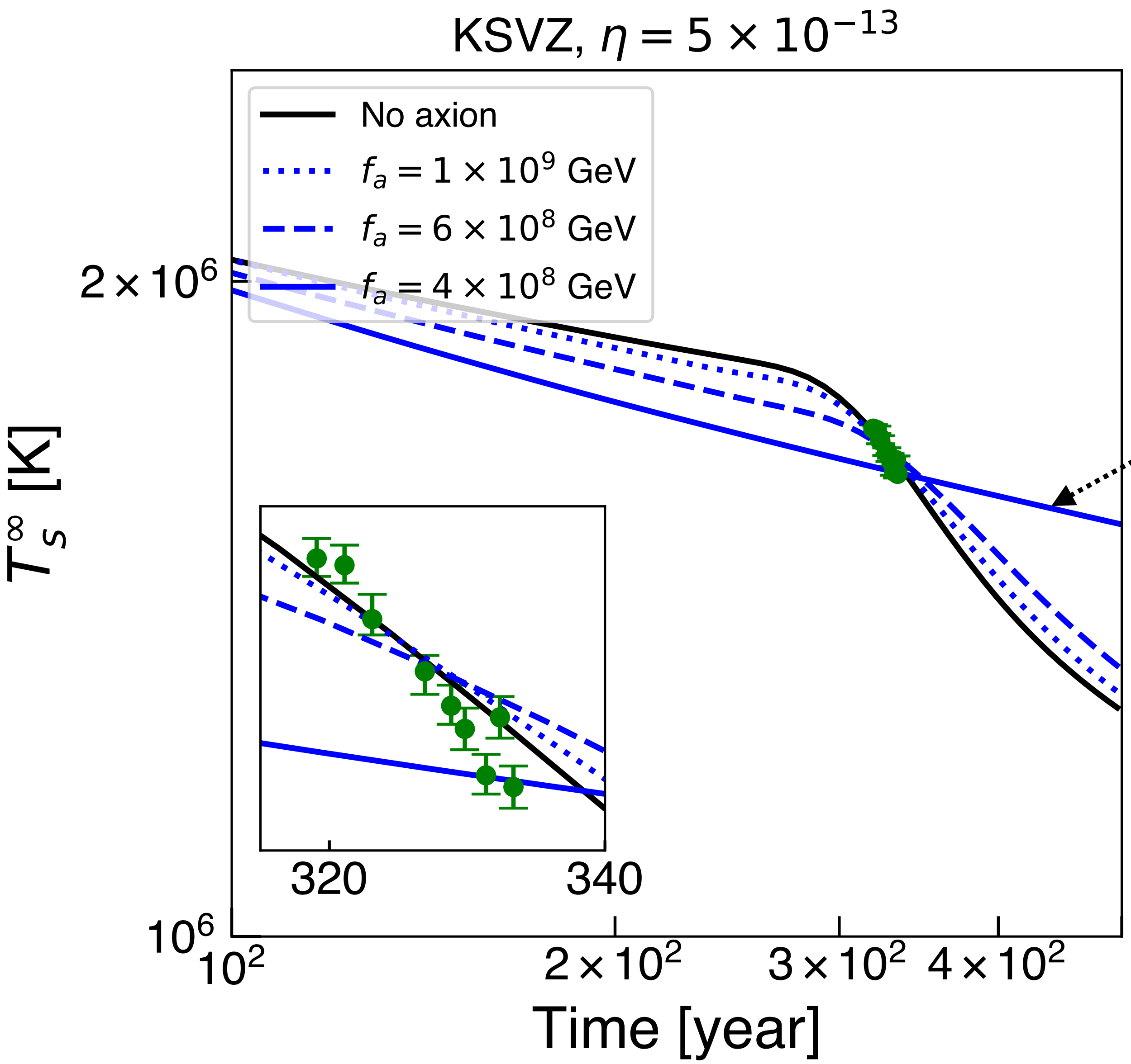




Parametrized by $\eta = g_{14}^2 \Delta M / M$

(surface gravity)/(10^{14} cm/s^2) mass of light elements

Result



We vary neutron triplet gap to fit the Cas NS cooling data

$f_a = 4 \times 10^8\,\mathrm{GeV}$
Fit fails for any neutron gap profile
NS is overcooled before neutron triplet pairing

[Hamaguchi, Nagata, KY, Zheng (2018)]

Limit on f_a of KSVZ (DFSZ, $\tan\beta = 10$) model: $f_a \gtrsim 5\,(7) \times 10^8\,\mathrm{GeV}$

comparable to the limit from SN1987A: $f_a \gtrsim 10^8\,\mathrm{GeV}$

O(1) uncertainty from the choice of η

Summary

"Limit on axion decay constant from the cooling neutron star in Cassiopeia A"

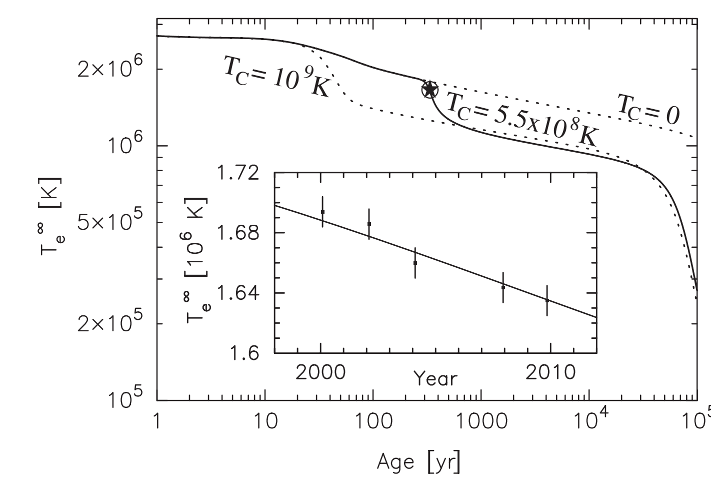
Well-motivated candidate of a new particle

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

[Pecci and Quinn (1977); Weinberg (1978); Wilczek (1978)]

NS cooling is observed

[Page et al. (2011)]



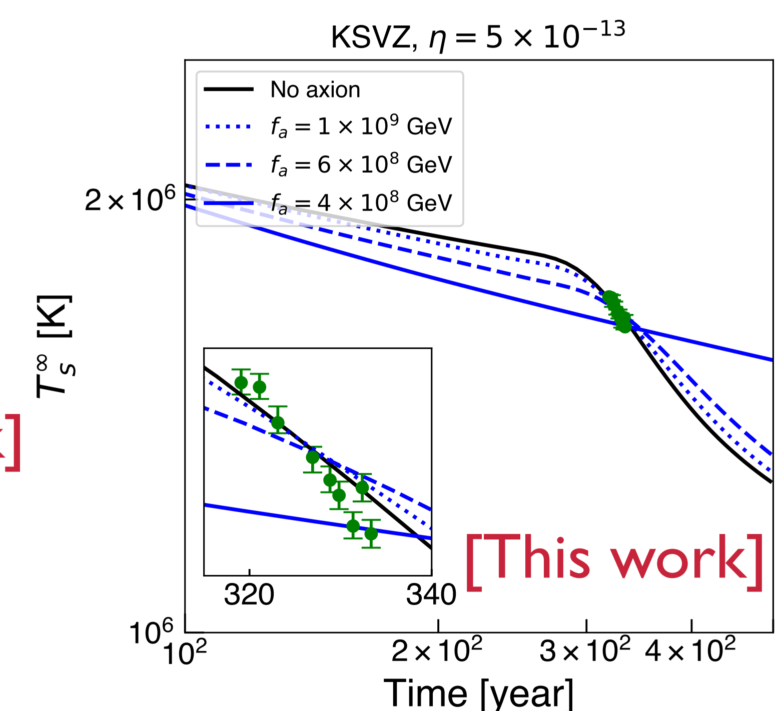
- SM: Cooling of Cas A NS can be explained by standard cooling theory [Page et al. (2011); Shternin (2011)]

- SM + Axion: if axion-nucleon coupling is too large, theory cannot explain the data

$$f_a \gtrsim (5-7)\times 10^8\,\mathrm{GeV}$$ [This work]

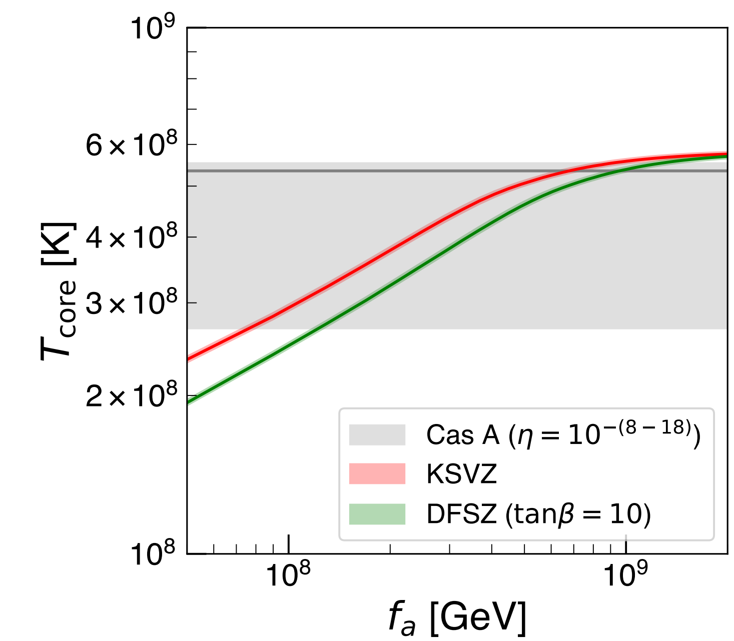
O(1) uncertainty from envelope

comparable to the SN1987A limit



Backup

More on uncertainty from light element in envelope



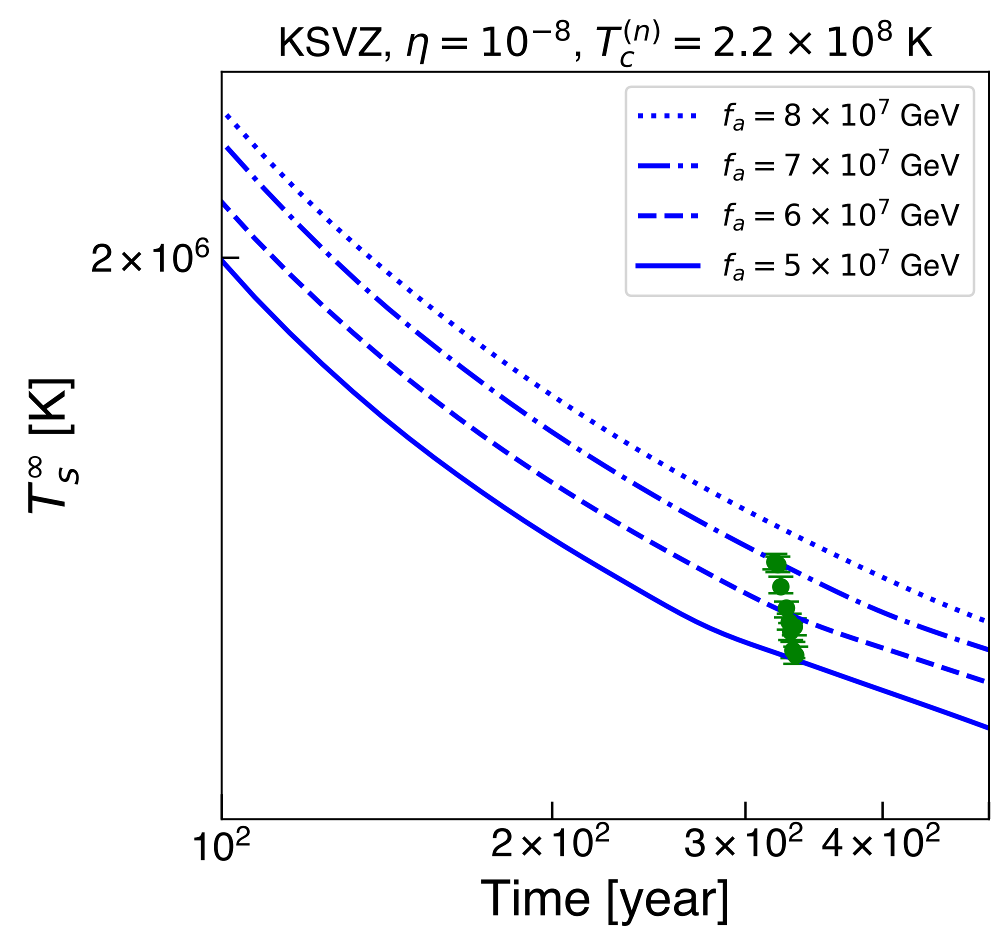
Envelope parameter η can be varied

Large η can weaken the limit

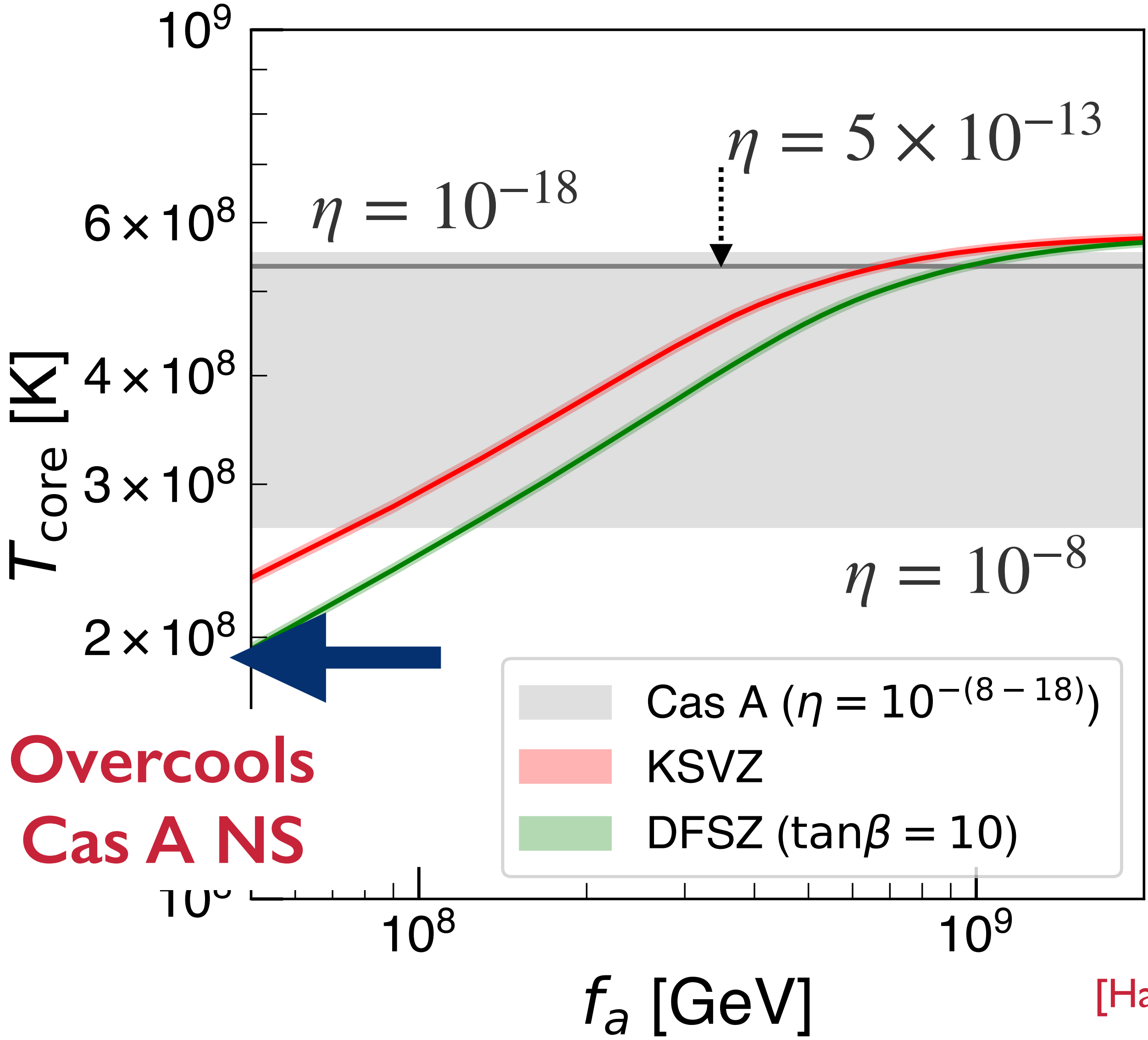
- KSVZ: For large $\eta \sim 10^{-8}$, internal T is too low to explain cooling rate

  → $f_a \gtrsim 4 \times 10^8\,\mathrm{GeV}$ is rather stringent

- DFSZ: For large η, axion emission from neutron PBF may help explain the curve



Uncertainty from envelope



Internal temperature can be different depending on light element in envelope

$T_{\rm core}$ of Cas A NS at $t = 300 - 338\,{\rm yr}$ w/o neutron triplet pairing

[Hamaguchi, Nagata, KY, Zheng (2018)]

- More conservative limit: $f_a \gtrsim 10^8\,{\rm GeV}$
- This limit does not rely on the temperature decline

Details 3: procedure to limit axion

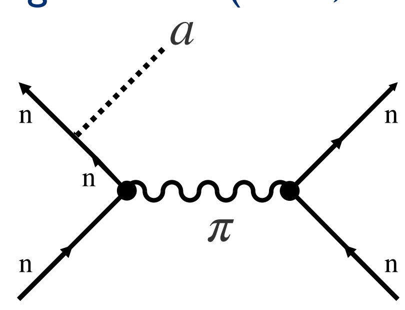
$$C\frac{dT}{dt} = -L_\nu - L_\gamma - L_a$$

- Fix axion model (KSVZ/DFSZ and f_a)
- Try to fit the Cas A NS cooling rate varying neutron triplet gap profile
  - neutron triplet gap is modeled by Gaussian shape w/ 3 free parameters
- If the fit fails, such an axion model is disfavored
- For other NS parameters, we use
  - CCDK model for proton singlet gap (insensitive to this choice if the gap is sufficiently large)
  - APR EOS
  - $M = 1.4\,M_\odot$
  - SFB model for neutron singlet pairing in crust

DFSZ axion model

- Axion Bremsstrahlung

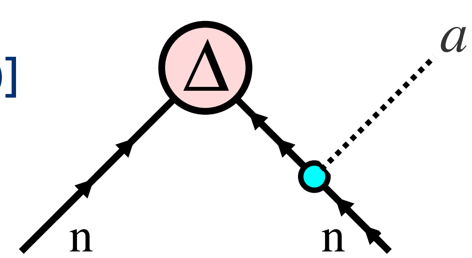
[Iwamoto (1984, 2001); Nakagawa et al. (1987, 1988)]

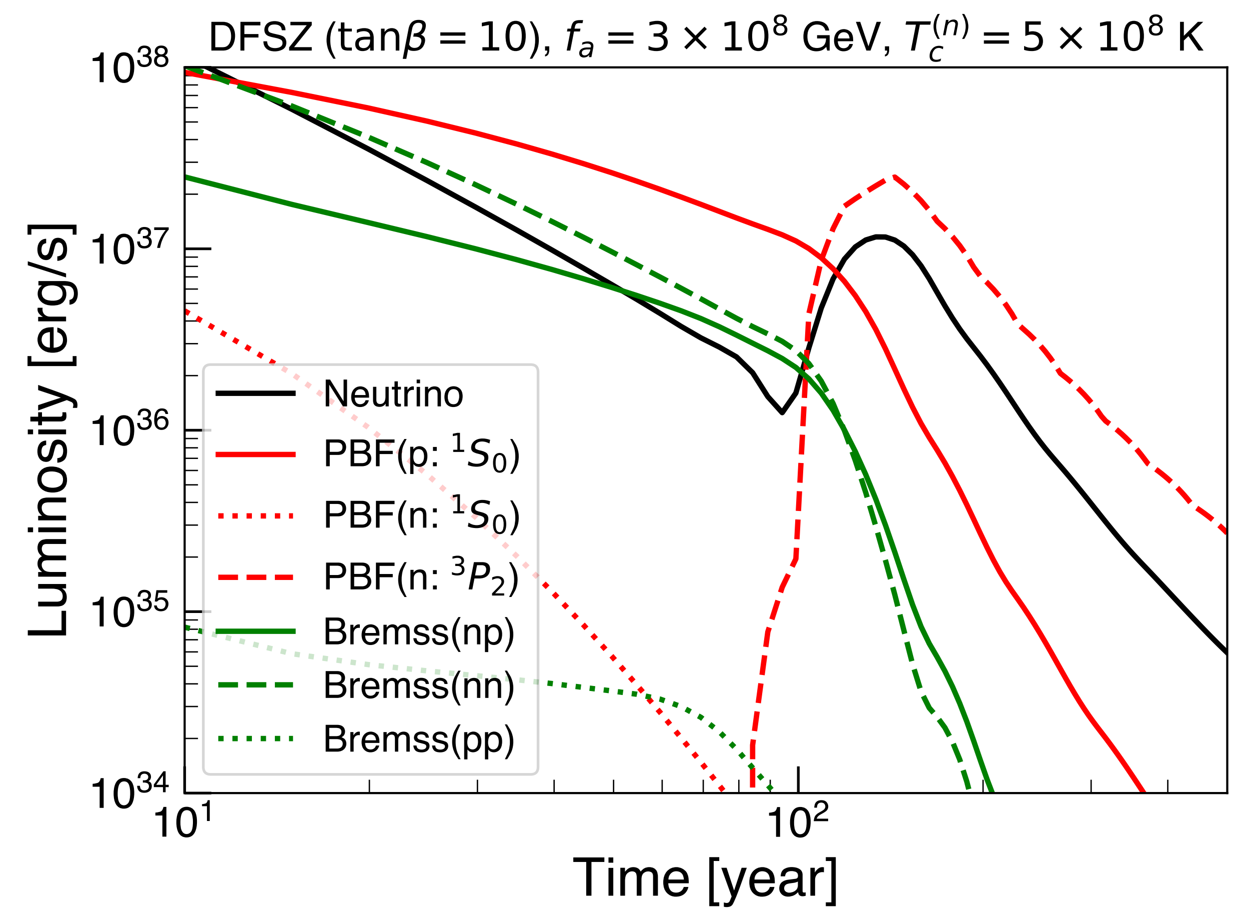


- Axion PBF

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

[Leinson (2014); Sedrakian (2016)]





[Hamaguchi, Nagata, KY, Zheng (2018)]

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

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

Axion mean free path

- If f_a is too small, axion cannot escape from the NS (R = 10 km)
- In both KSVZ and DFSZ model, axion decays by $a \to \tilde{p} + \tilde{p}$ with

$$\Gamma \sim \frac{m_p^* p_F v_F^2 T}{3\pi f_a^2} \left(\frac{c_p}{2}\right)^2$$

[Keller and Sedrakian (2012)]

- For $p_F \sim 100\,\mathrm{MeV}, m_p^* \sim 1\,\mathrm{GeV}, T \sim \Delta_p \sim 1\mathrm{MeV}$, we need

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

Related works

[Sedrakian (2016)]

- Cas A NS + PSR B0656+14, Geminga, PSR B1055-52

- Temperature decline is not used

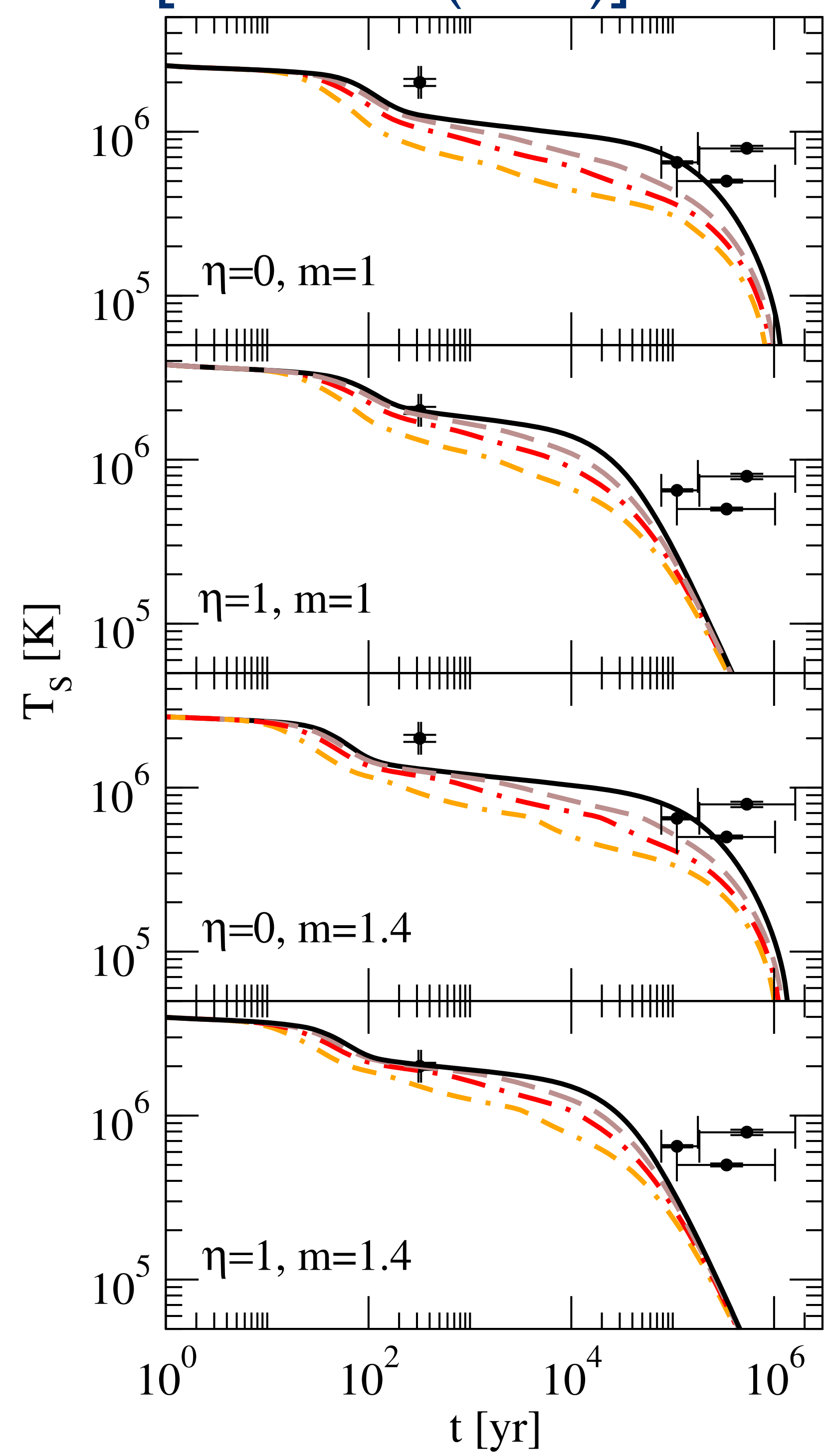
- $f_a > (5-10) \times 10^7\,\mathrm{GeV}$

[Leinson (2014)]

- Only axion-neutron PBF is considered

- Evolution of $t \lesssim 300\,\mathrm{yr}$ is not considered

[Sedrakian (2016)]



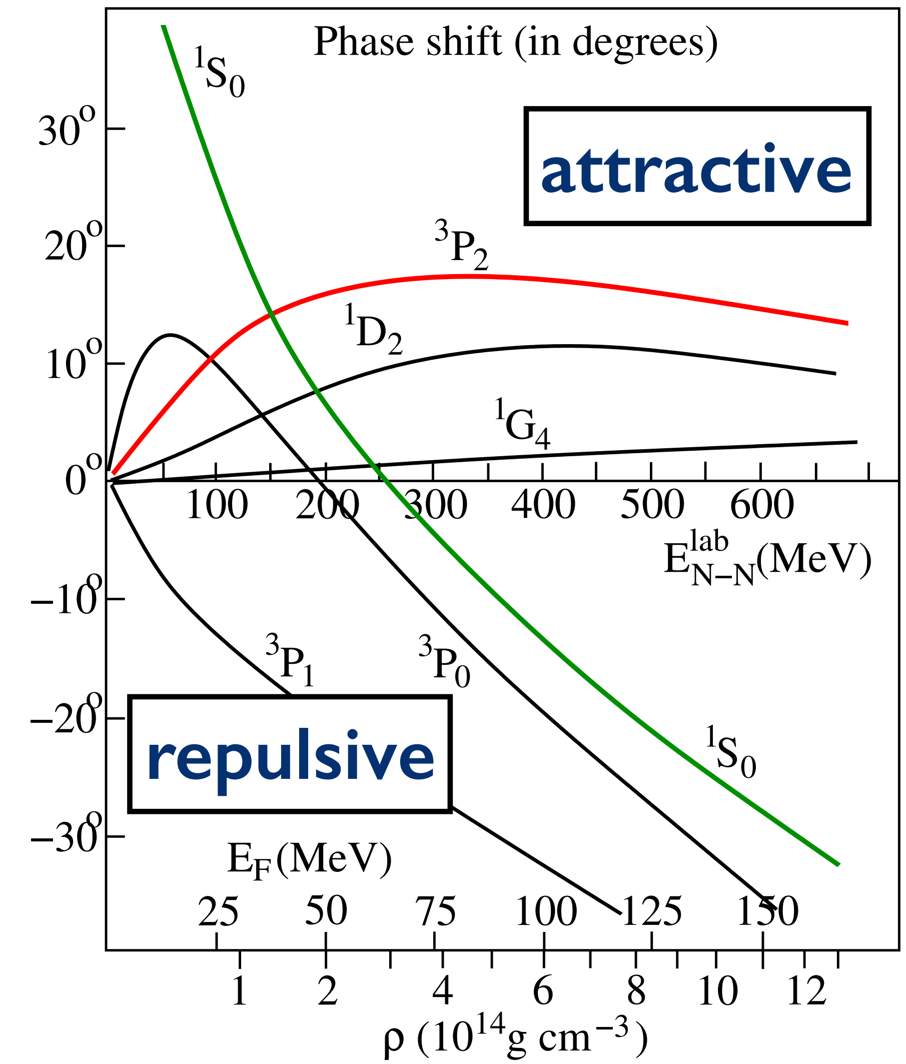
Nucleon Cooper pairing

- Attractive nuclear force induces the Cooper pairing of n-n and/or p-p

- **In the core**
  - n: spin-triplet ($^3P_2$) pairing
  - p: spin-singlet ($^1S_0$) pairing

    this difference is due to the difference of Fermi energy

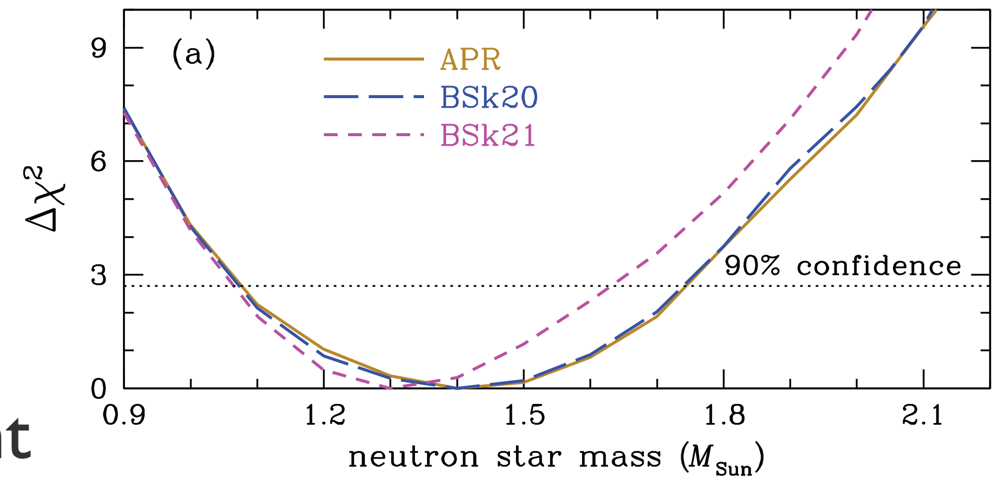
- In the crust:
  - n: spin-singlet ($^1S_0$) pairing



[Calculation by Tamagaki (1970), figure from Page et al. (2013)]

Neutron star in Cas A

- In 1999, Chandra detected hot point-like source at the center of Cas A [Tananbaum (1999)]



[Ho et al. (2015)]

- No pulsation is detected

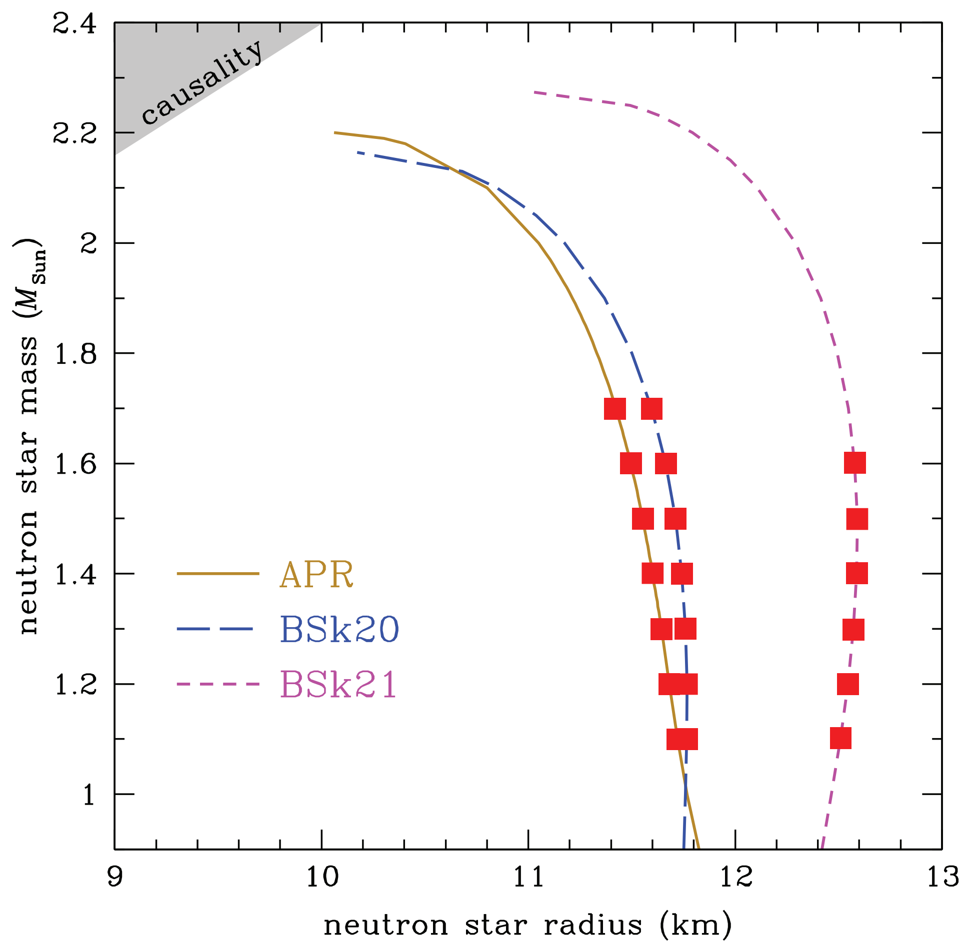
- The observed thermal spectrum is consistent with NS carbon atmosphere model [Ho and Heinke (2009)]

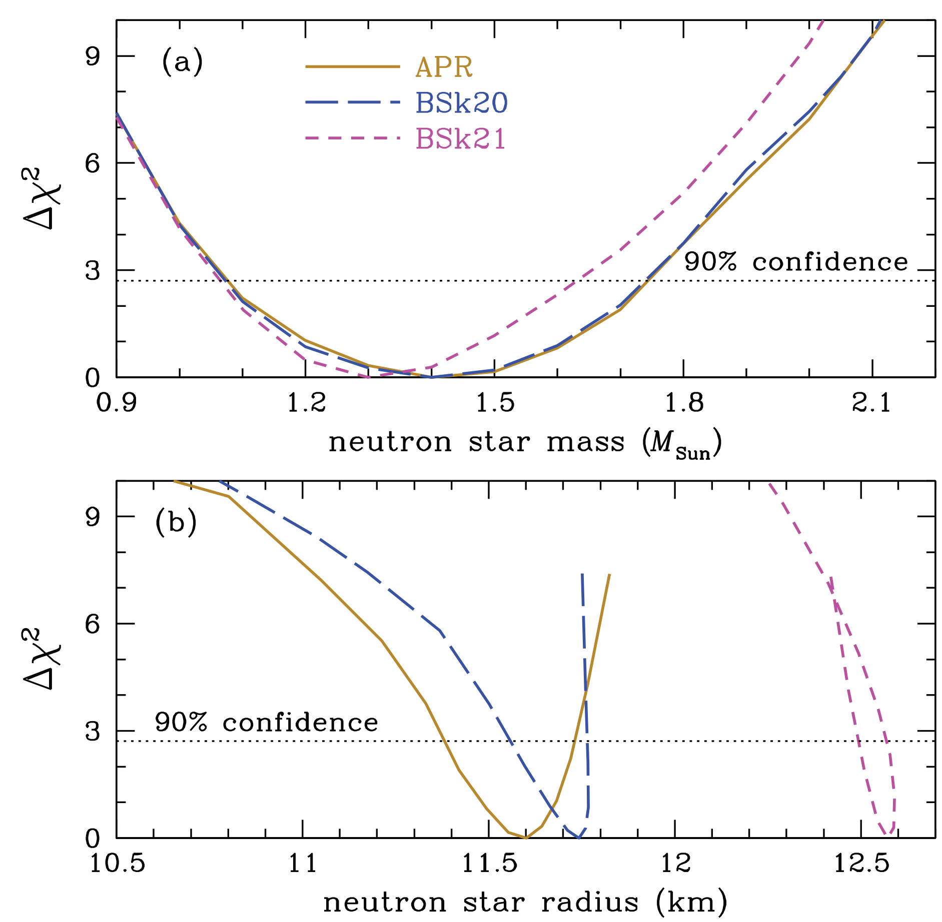
- The spectrum is fitted with

$$M = (1.4 \pm 0.3)\, M_\odot \quad R = (11 - 13)\,\mathrm{km}$$

[Ho et al. (2015)]

EOS dependence of M and R



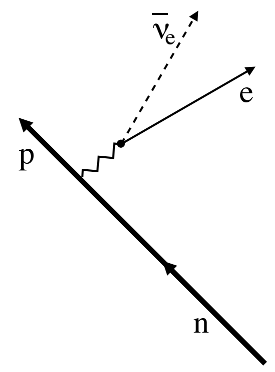


[Ho et al. (2015)]

Direct Urca process

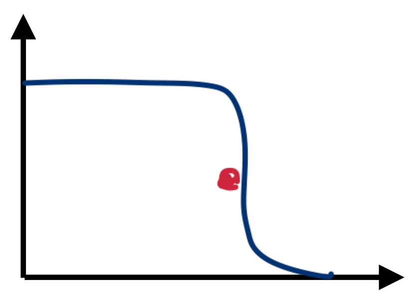
$$n \to p + \ell + \bar{\nu}_\ell \qquad p + \ell \to n + \nu_\ell$$

$\ell = e, \mu$



- Beta decay and its inverse

- Occurs around Fermi surface



- Direct Urca process does not operate unless NS is very heavy

[e.g., Lattimer et al. (1991)]

  - due to the energy and momentum conservations around Fermi surface
  - E.g., for APR EOS, $M \gtrsim 1.97\,M_\odot$ is required
  - We can neglect direct Urca in Cas A NS ($M \simeq 1.4\,M_\odot$)

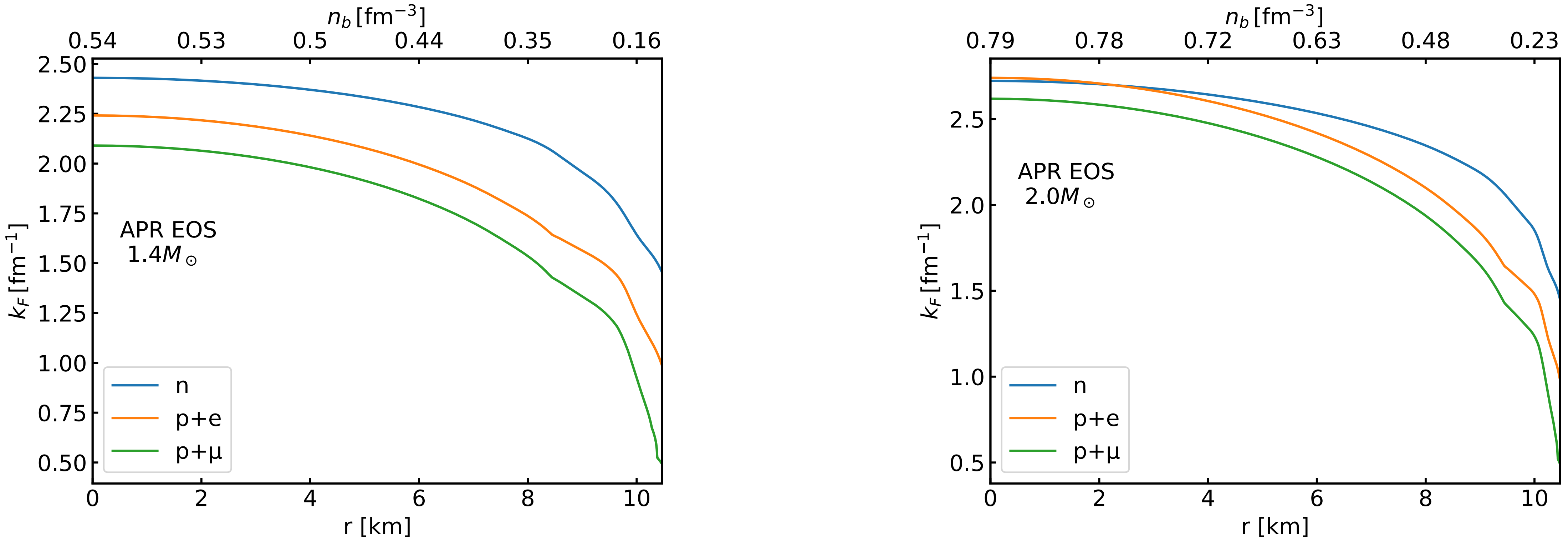
Threshold of direct Urca

- Energy conservation $\varepsilon_n = \varepsilon_p + \varepsilon_\ell \pm \varepsilon_\nu$ and beta equilibrium $\mu_{F,n} = \mu_{F,p} + \mu_{F,\ell}$

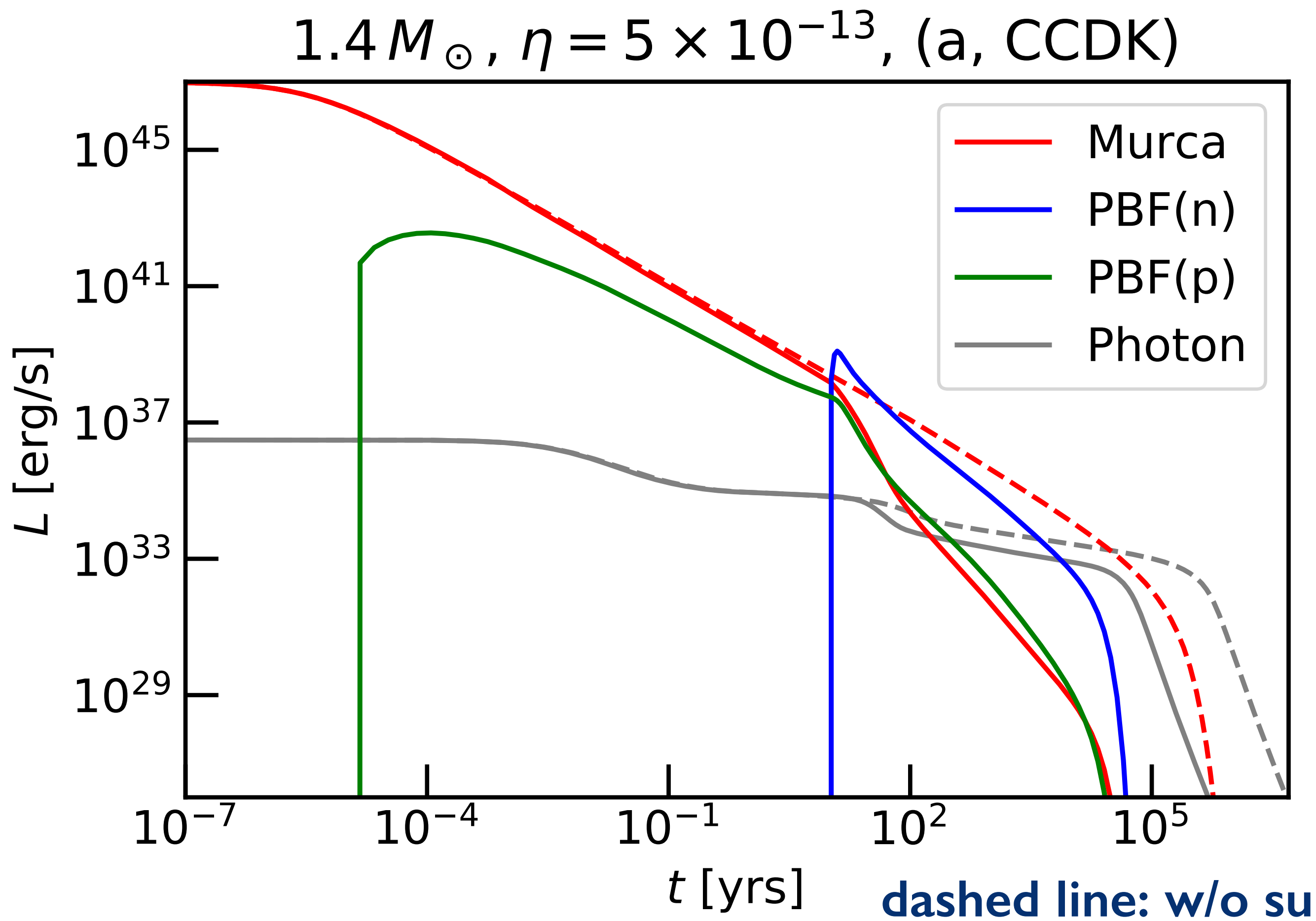
  → Emitted neutrino momentum: $p_\nu \sim T \ll p_F$

- Momentum conservation: $\overrightarrow{p}_n \simeq \overrightarrow{p}_p + \overrightarrow{p}_\ell$

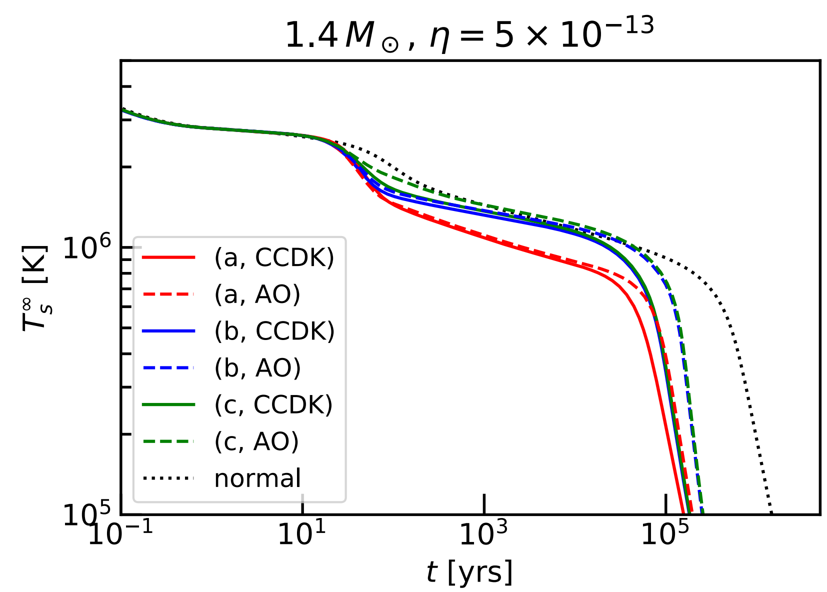
  → $p_{F,n} < p_{F,p} + p_{F,\ell}$, hence large proton fraction, is necessary



Luminosity evolution



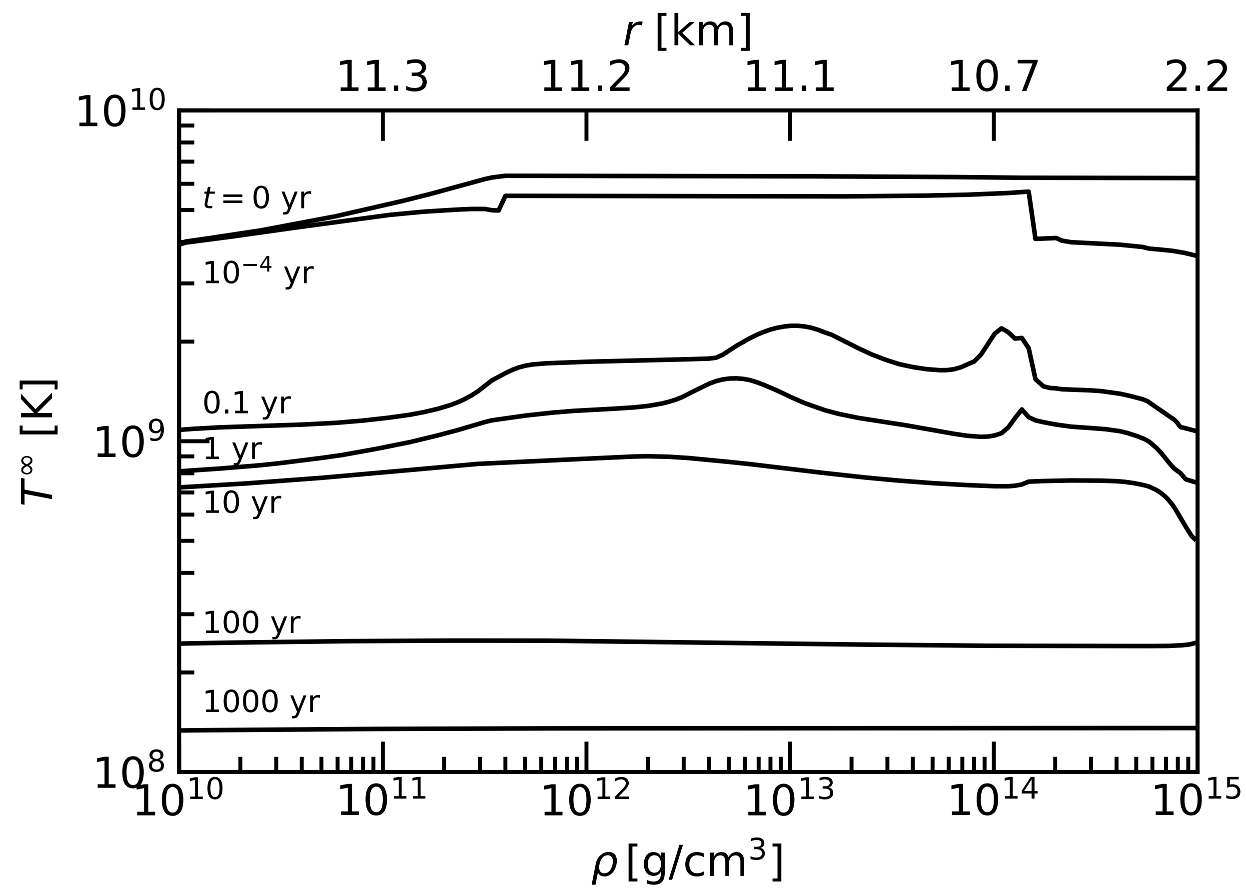
Calculated by NSCool



dashed line: w/o superfluidity

- Before neutron pairing: Modified Urca process dominates
- After neutron pairing : neutron PBF dominates
- Modified Urca process is suppressed by nucleon pairing

Thermal relaxation



(a, CCDK) gap

- Relaxation time scale is $t \sim 10 - 100\,\mathrm{yr}$

Neutron singlet gap

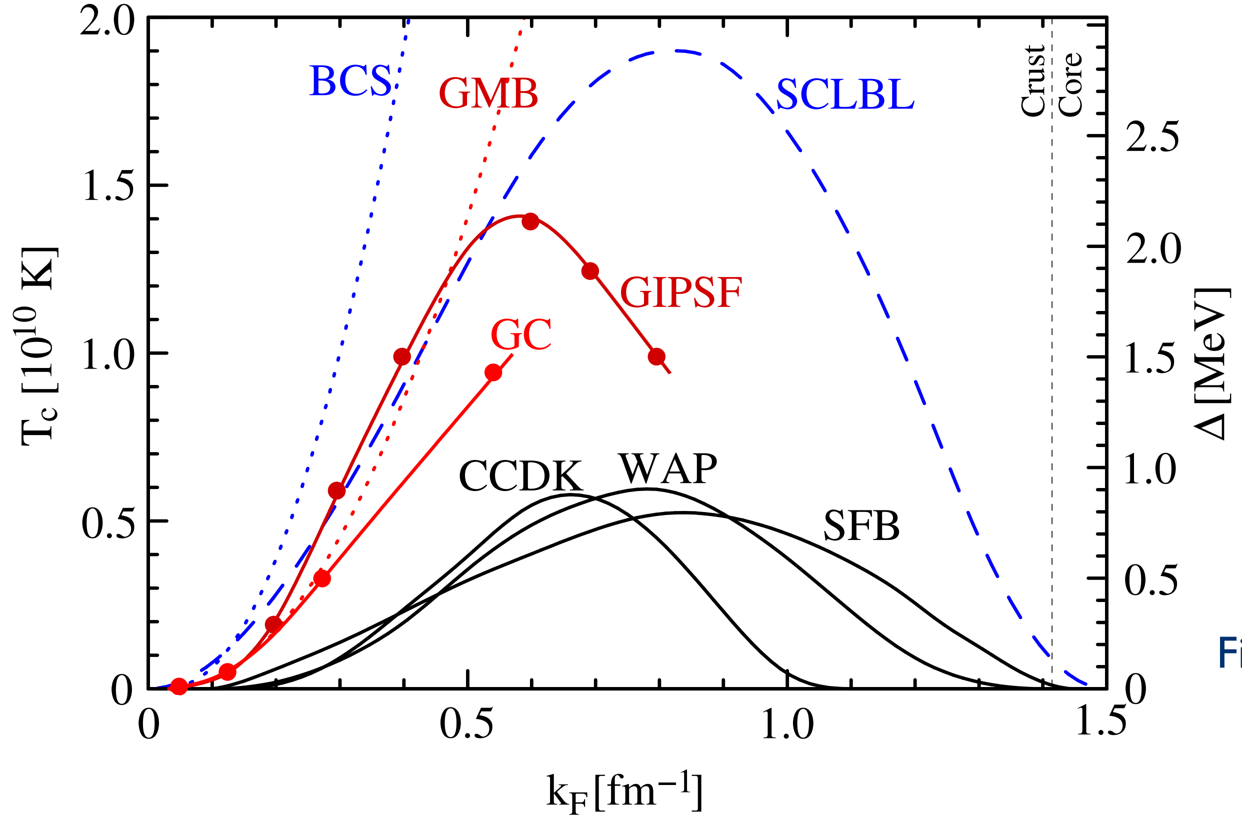
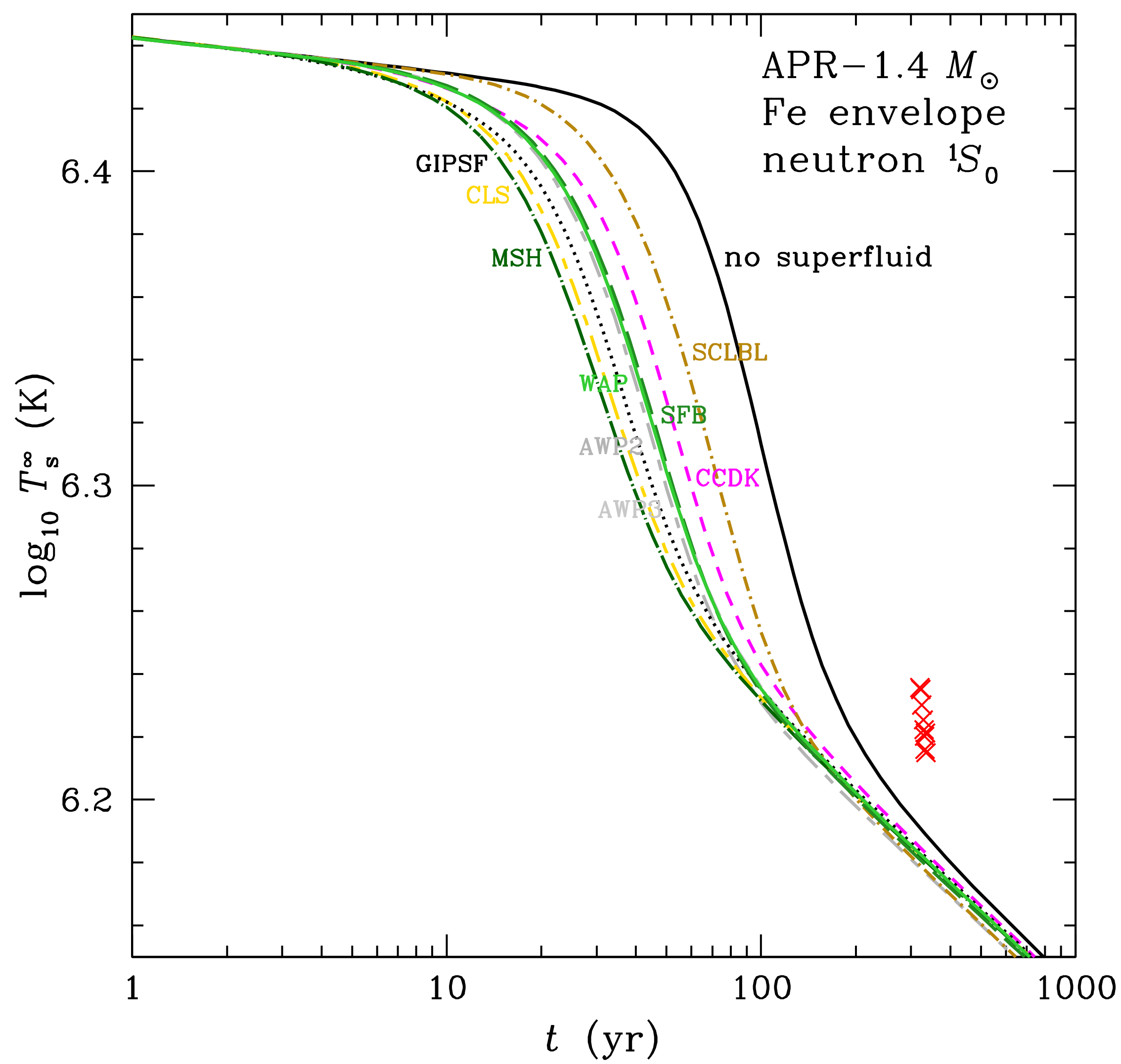
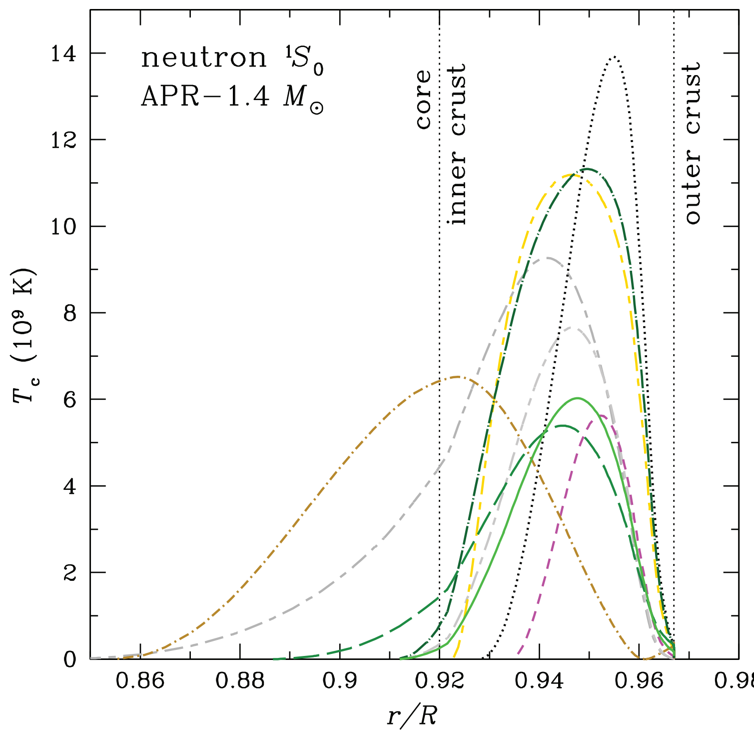


Figure from Page et al. (2013)]

- $T_c \sim (0.5 - 2) \times 10^{10}\,\mathrm{K}$
- Singlet pairing occurs only in the crust

Neutron singlet pairing for Cas A NS cooling

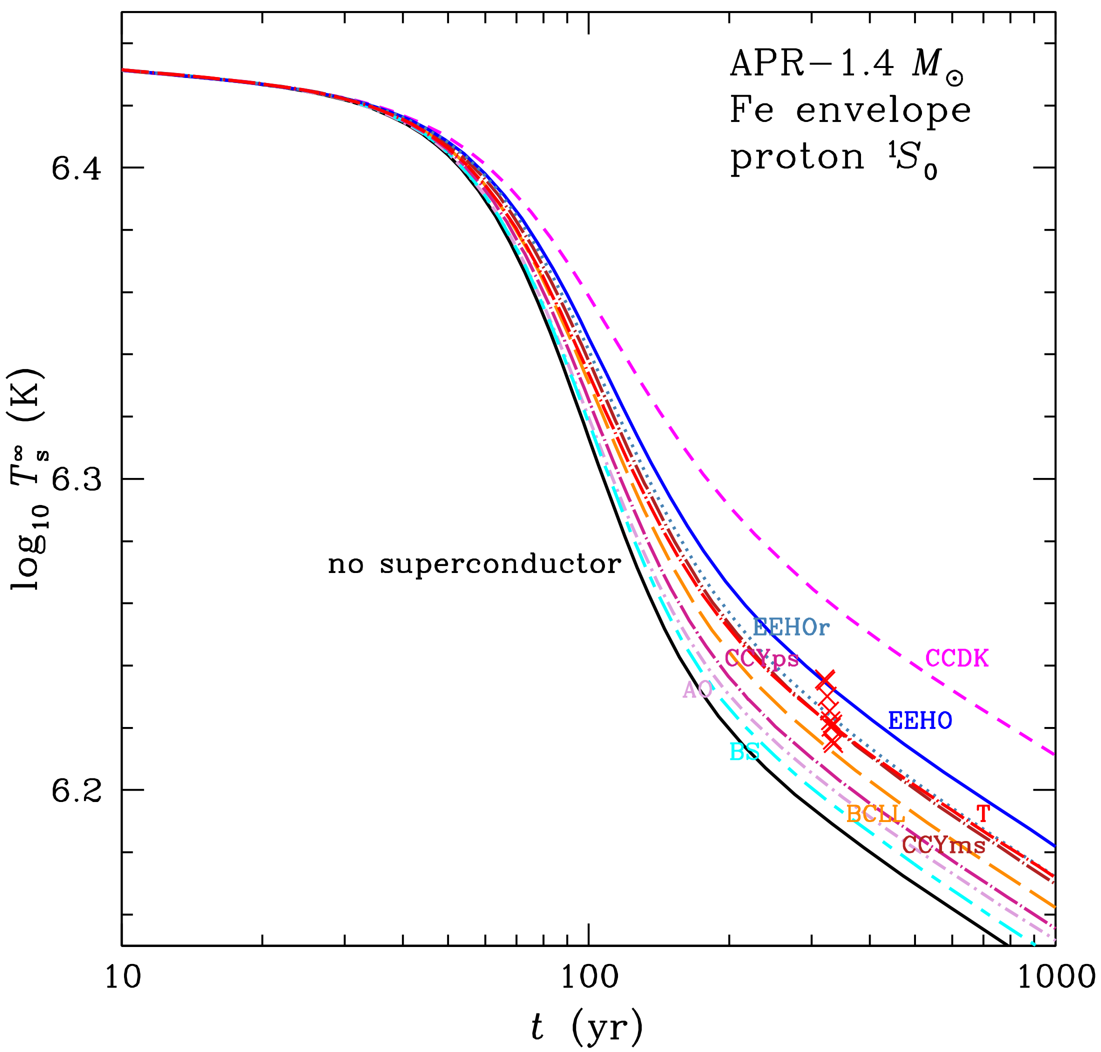


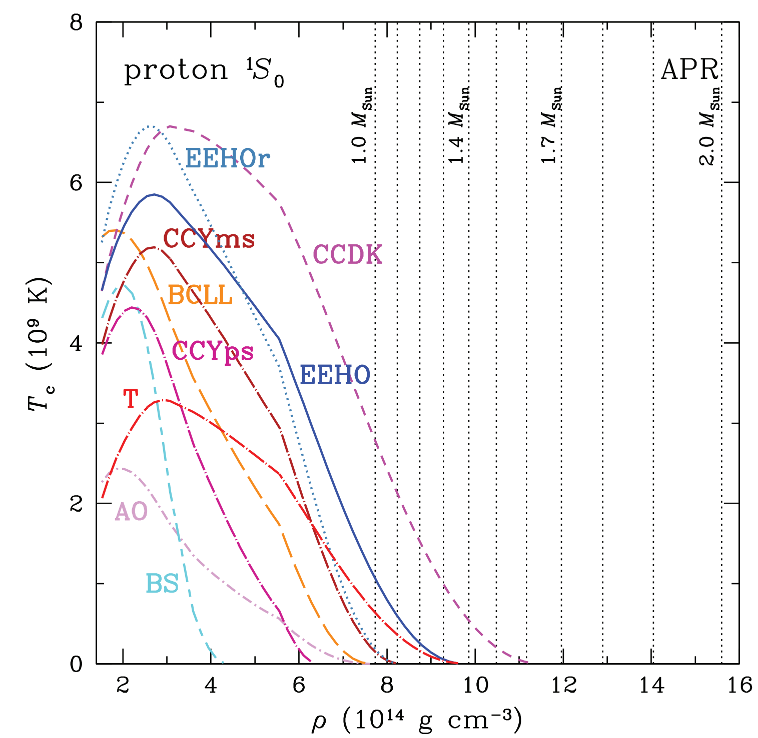


[Ho et al. (2015)]

- Only singlet neutron pairing is included
- It affects earlier time evolution

Proton singlet pairing for Cas A NS cooling

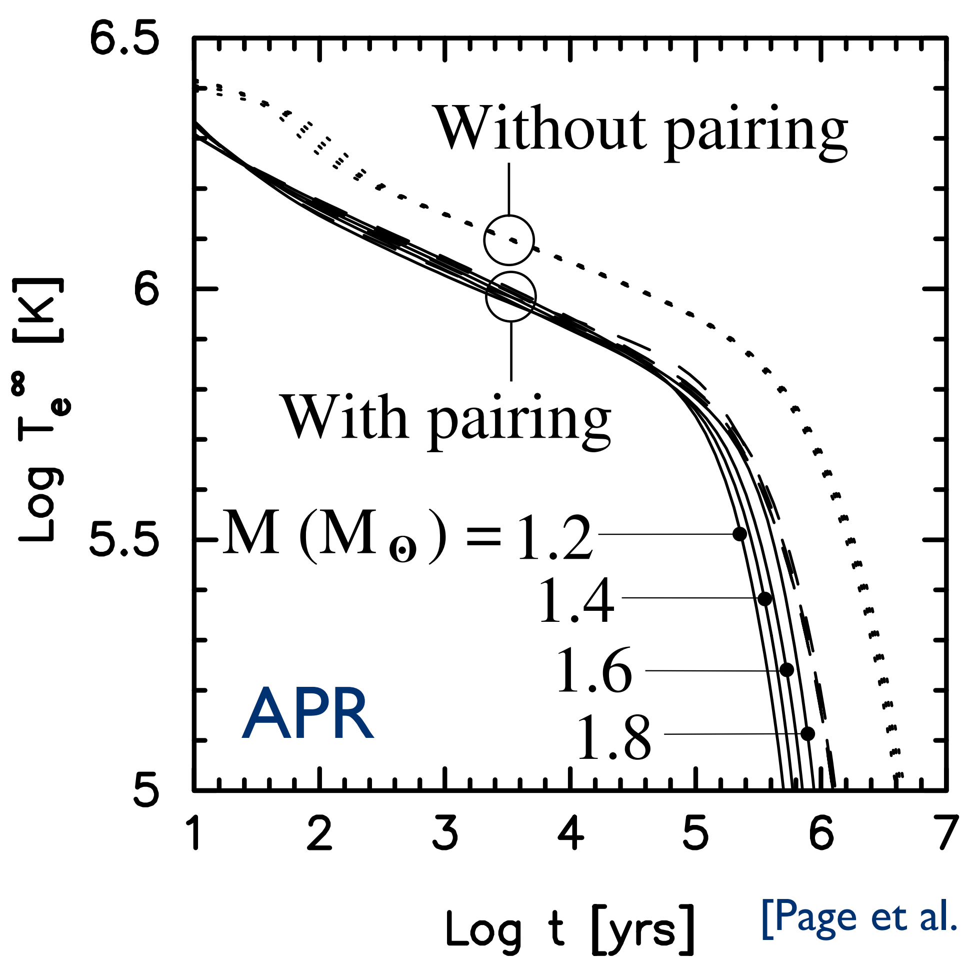




[Ho et al. (2015)]

- Only singlet proton pairing is included
- Small proton gap is not favored by Cas A temperature

Mass for thermal evolution

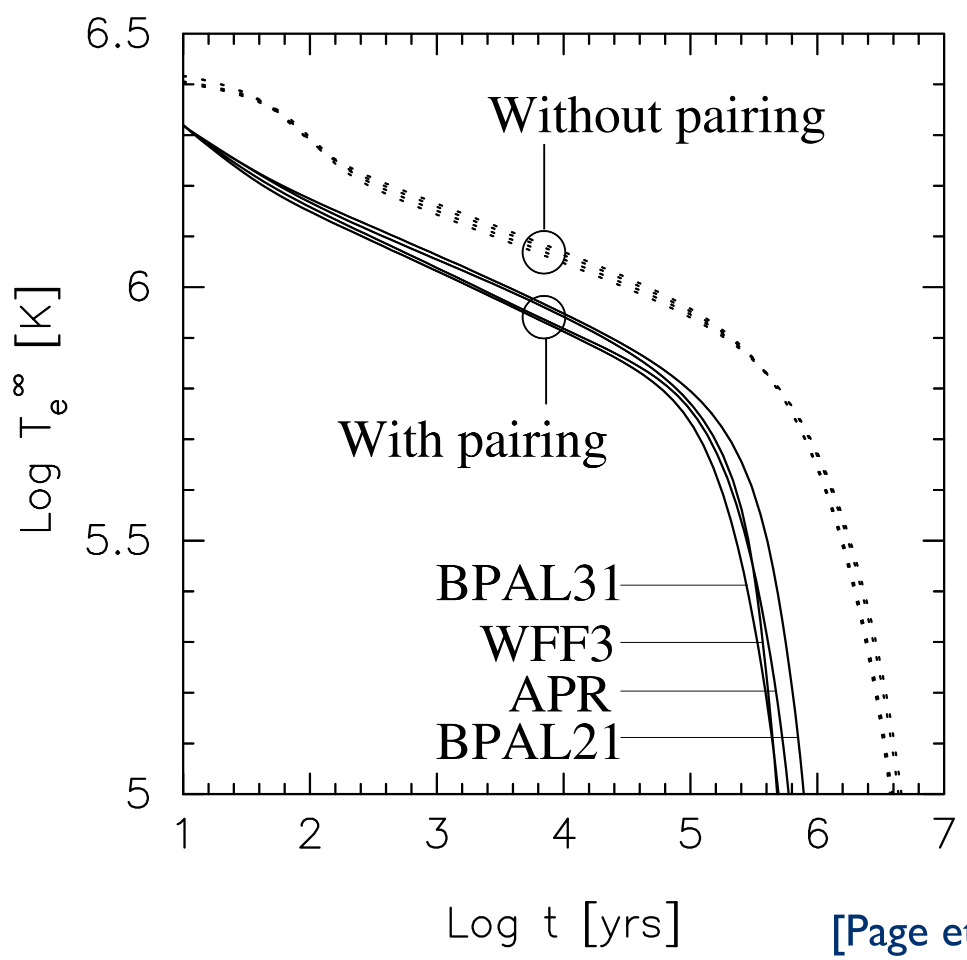


- Dashed: no proton singlet pairing
- Heavy element envelope
- (a, AO) gap

[Page et al. (2004)]

- Difference is due to the density dependence of pairing gap
- Heat capacity and neutrino luminosity slightly change

EOS for thermal evolution



- Heavy element envelope
- (a, AO) gap
- APR and WFF3 use different potential
- BPAL is phenomenological

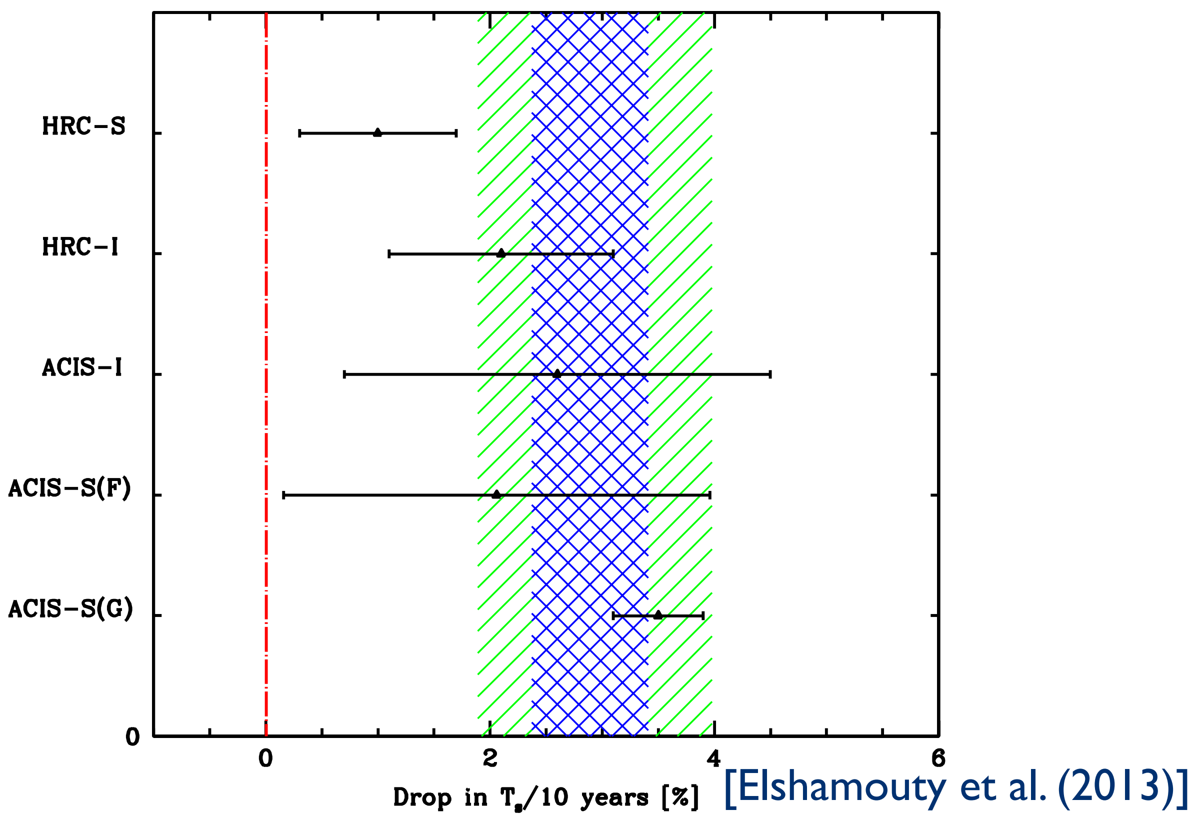
[Page et al. (2004)]

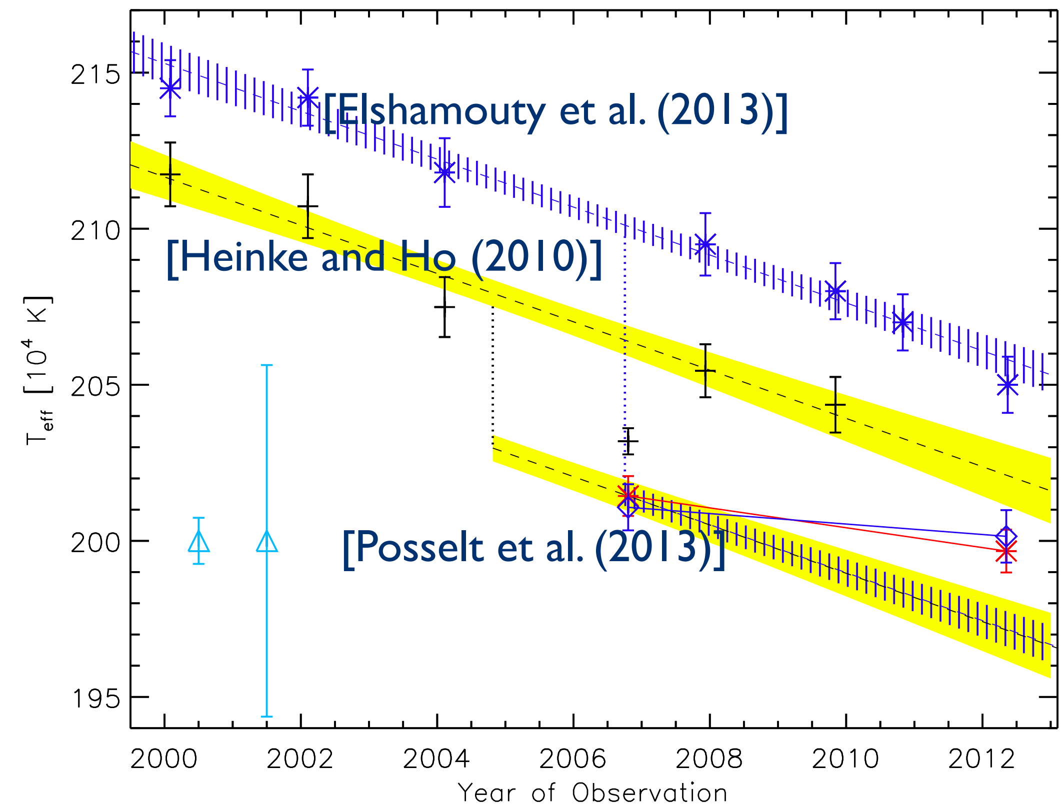
- Difference is also due to the density dependence of pairing gap

Other explanation of Cas A NS cooling

- Delayed thermal relaxation [Blaschke et al. (2012, 2013); Grigorian et al. (2016)]
- Rotation-driven direct Urca [Negreiros et al. (2013)]
- Recovery from r-mode heating [Yang et al. (2011)]
- Color superconductivity in quark phase [Noda et al. (2013); Sedrakian (2013)]
- Joule heating [Bonanno et al. (2014)]

Uncertainty of observation





- Lower cooling rate is reported
- Since modified Urca predicts $\Delta T/T \sim 0.3\,\%\,/10\,\mathrm{year}$, even $1\,\%$ decline requires fast cooling
- Even if there is no decline, our conservative limit $f_a \gtrsim 10^8\,\mathrm{GeV}$ holds