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”

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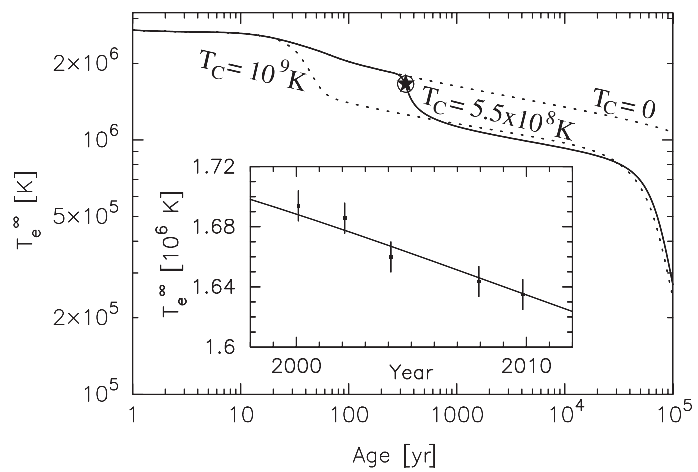
[Pecci and Quinn (1977); Weinberg (1978); Wilczek (1978)]

NS cooling is observed

[Page et al. (2011)]



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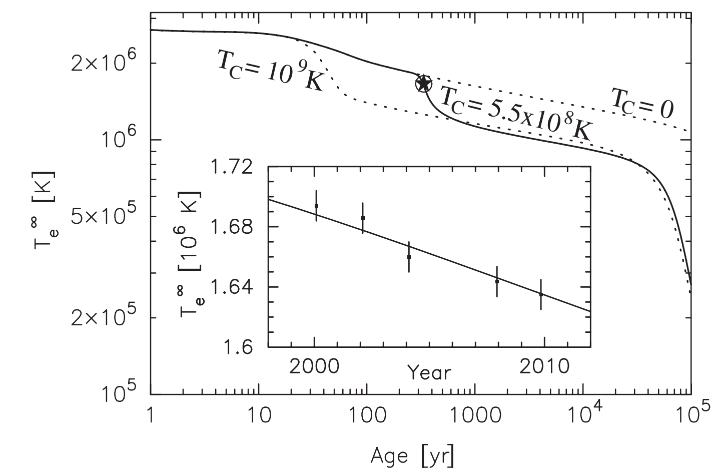

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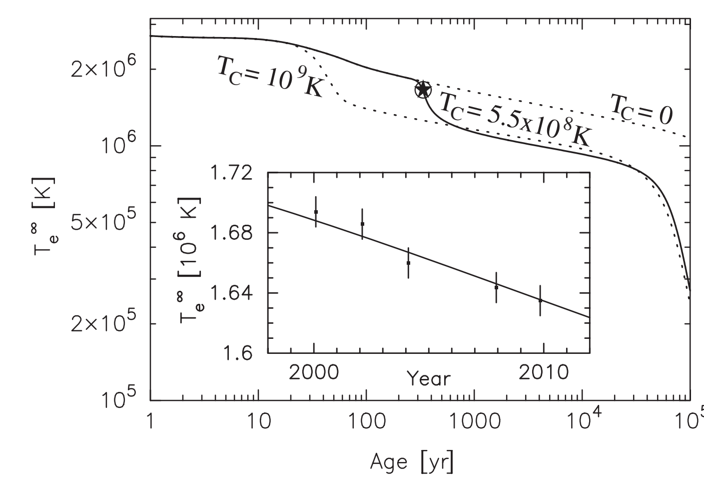

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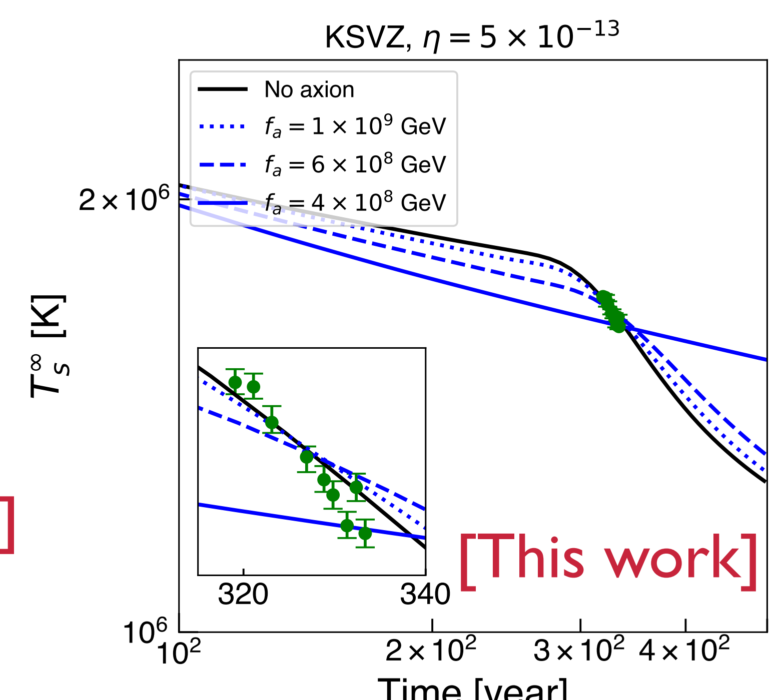

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Cited by PDG 2019!

112. Axions and Other Similar Particles

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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

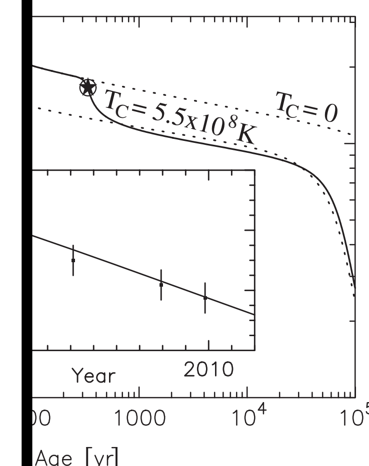
our work

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

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)]



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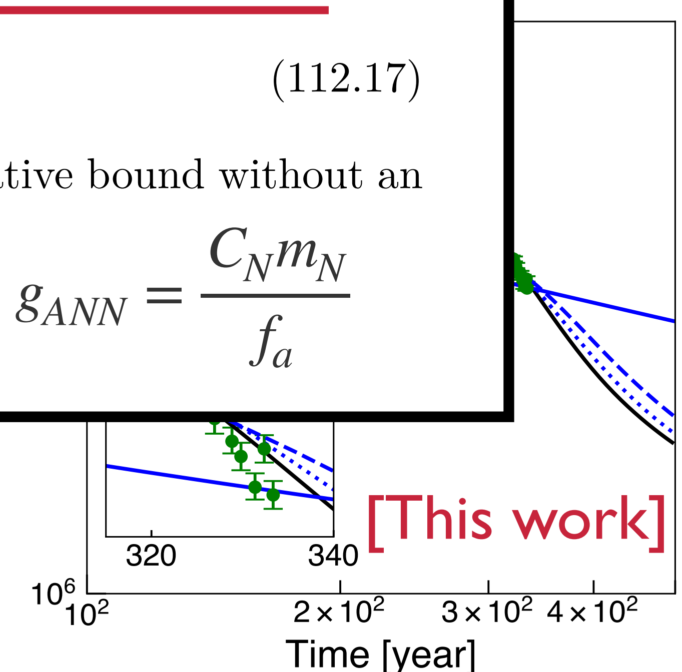

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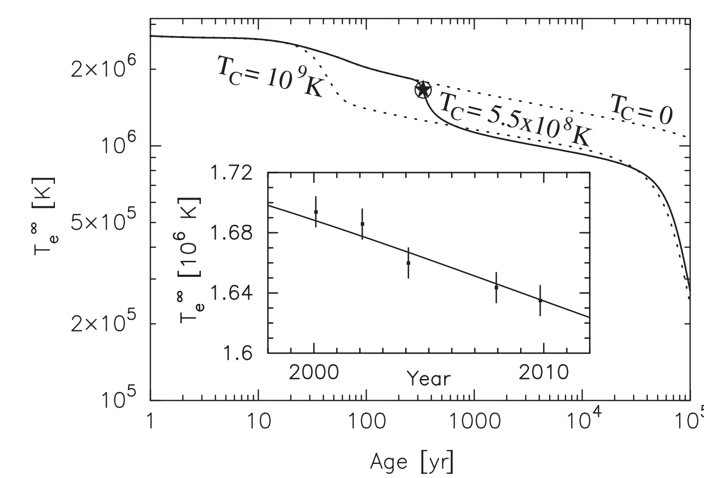

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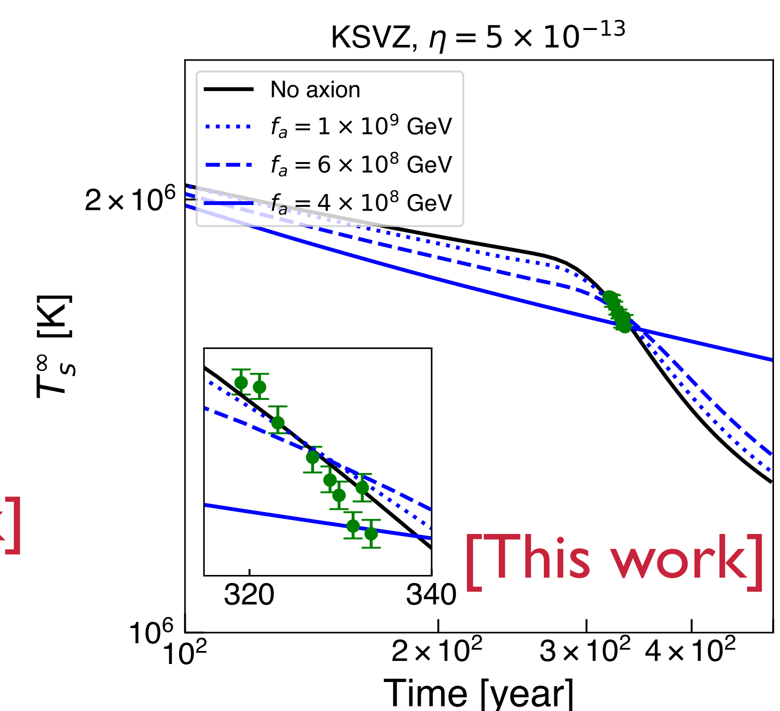


[This work]

Strong CP problem and axion

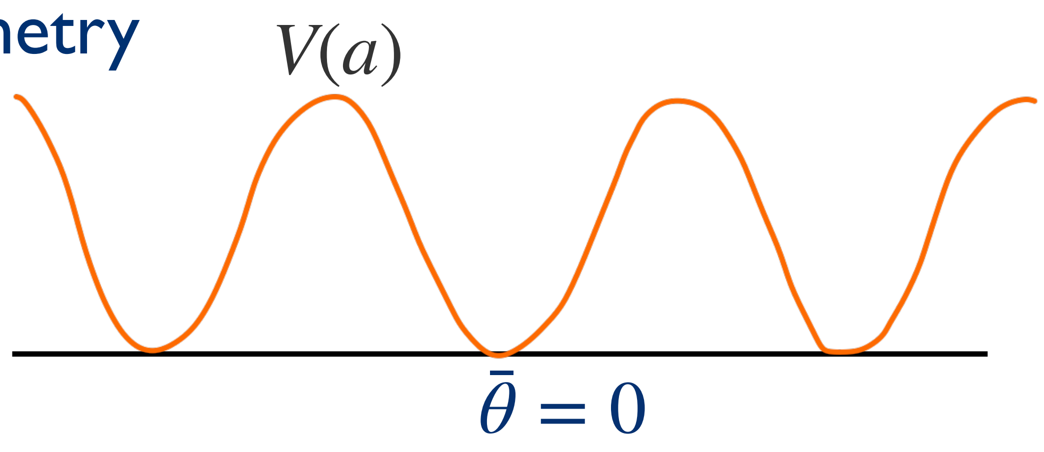
- Strong CP problem: why CP violation in strong interaction is so small?

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

$$\bar{\theta} = \theta + \arg\det M_q \to \bar{\theta} \lesssim 10^{-10}$$ 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)]

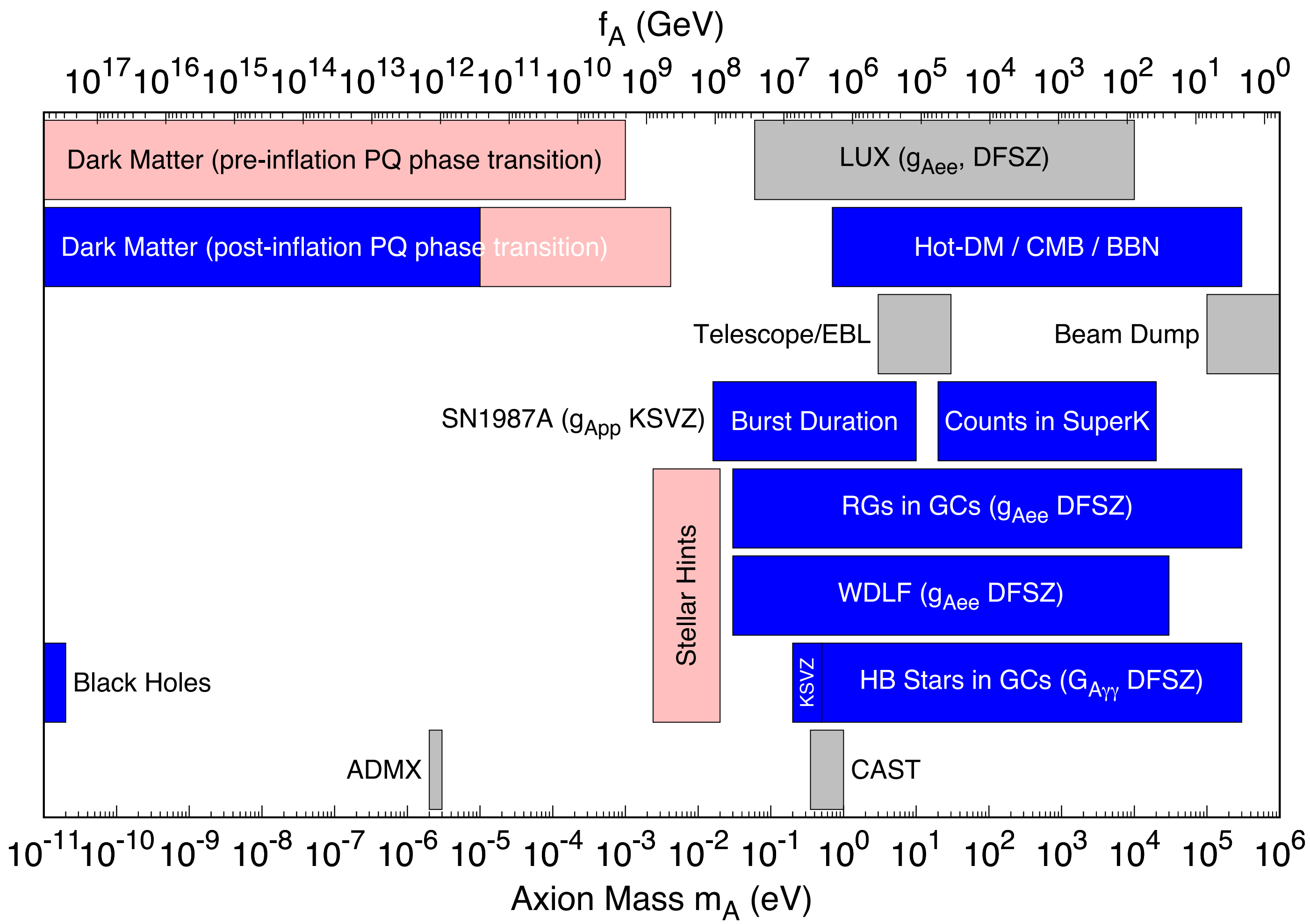
$$C_p = -0.47(3)\,,\, C_n = -0.02(3) \quad (C_q = 0)$$

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

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

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

Previous constraints on axion



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[PDG 2018]

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

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

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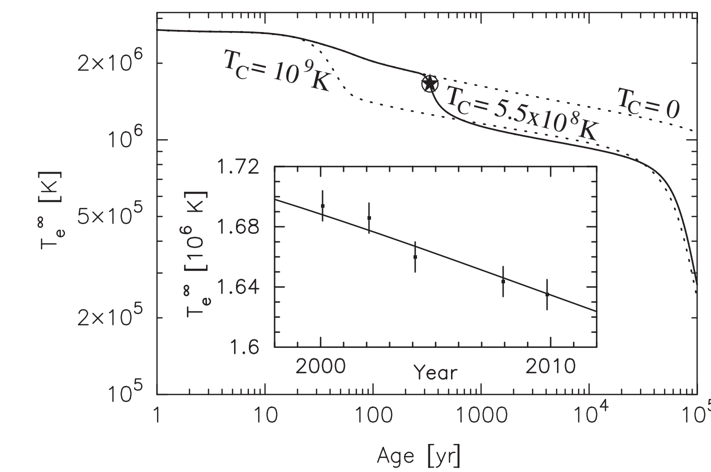

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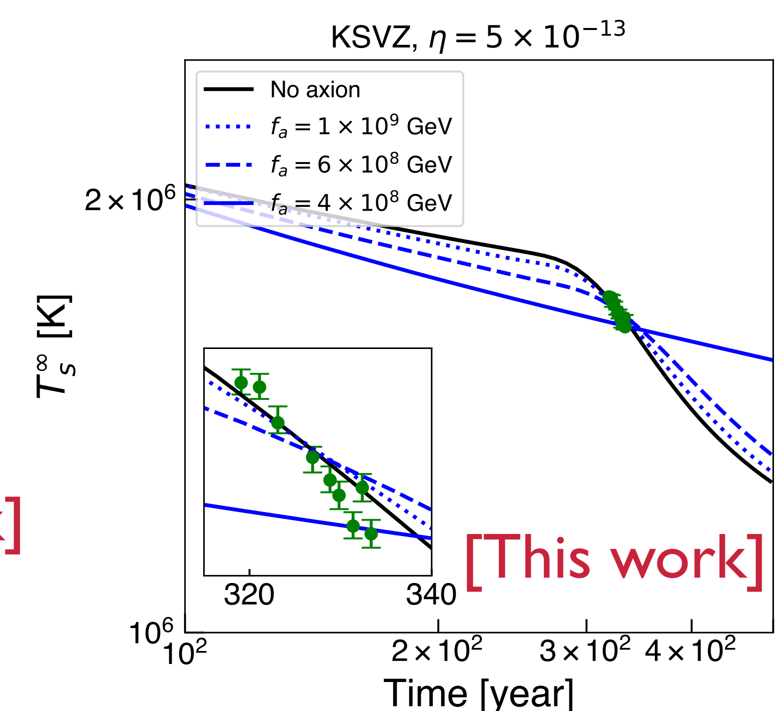

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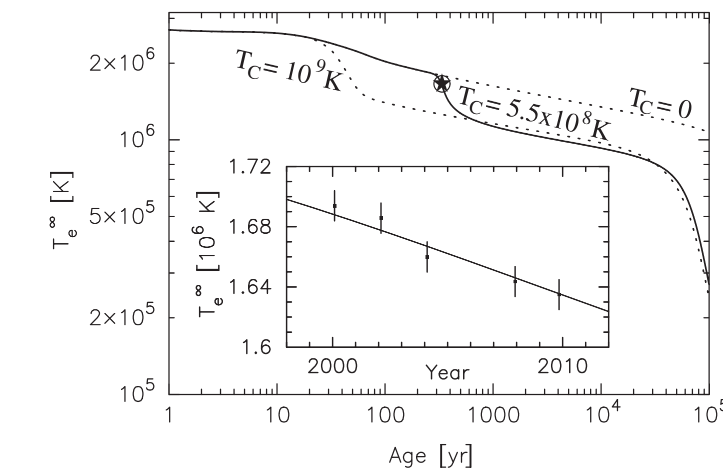

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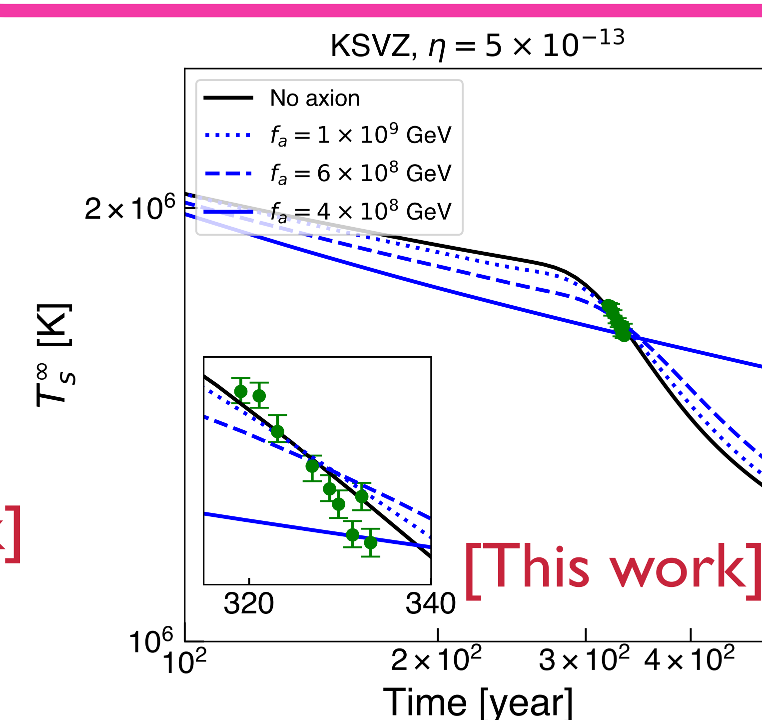
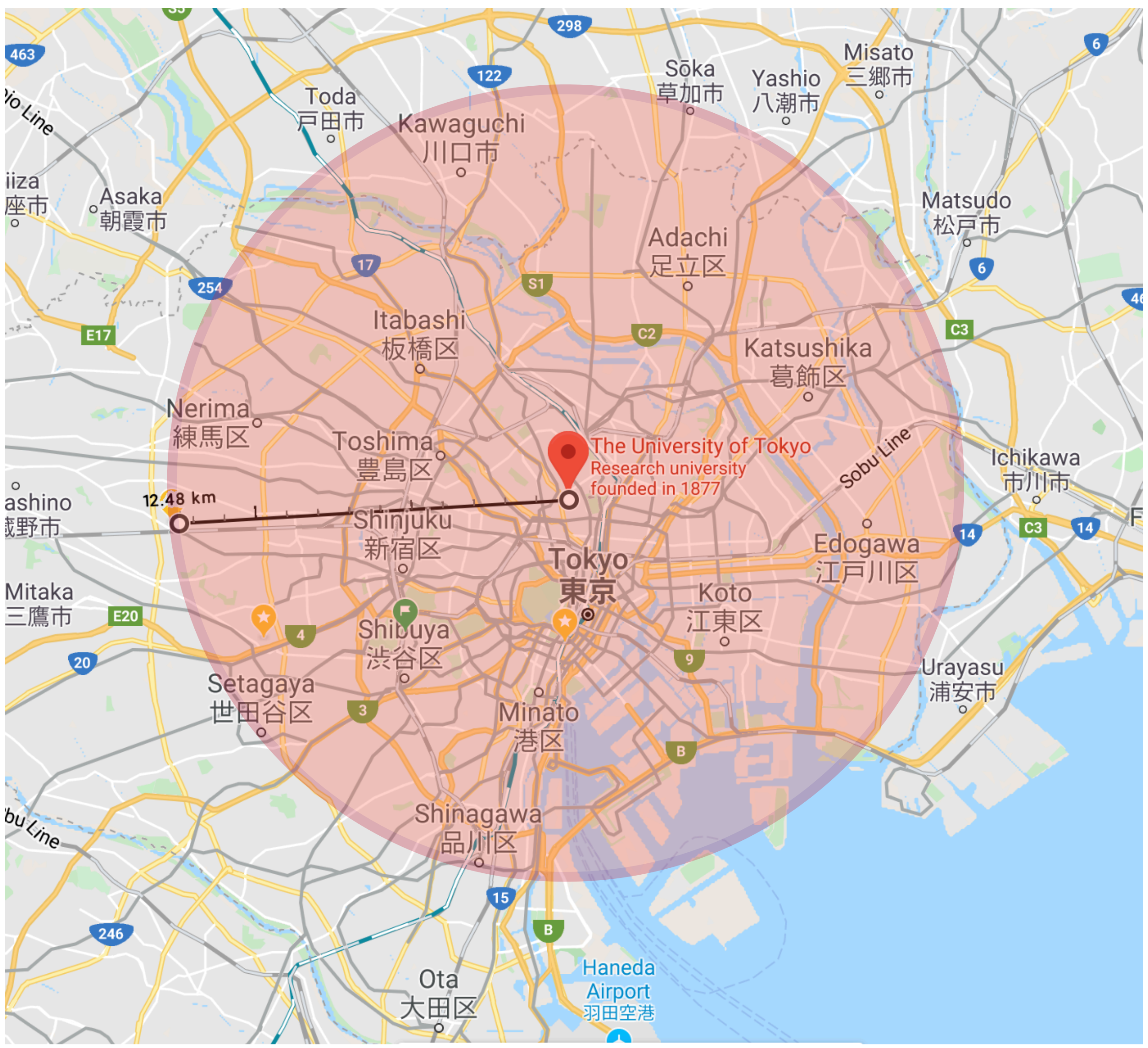


Neutron star

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



Tokyo area

Neutron star

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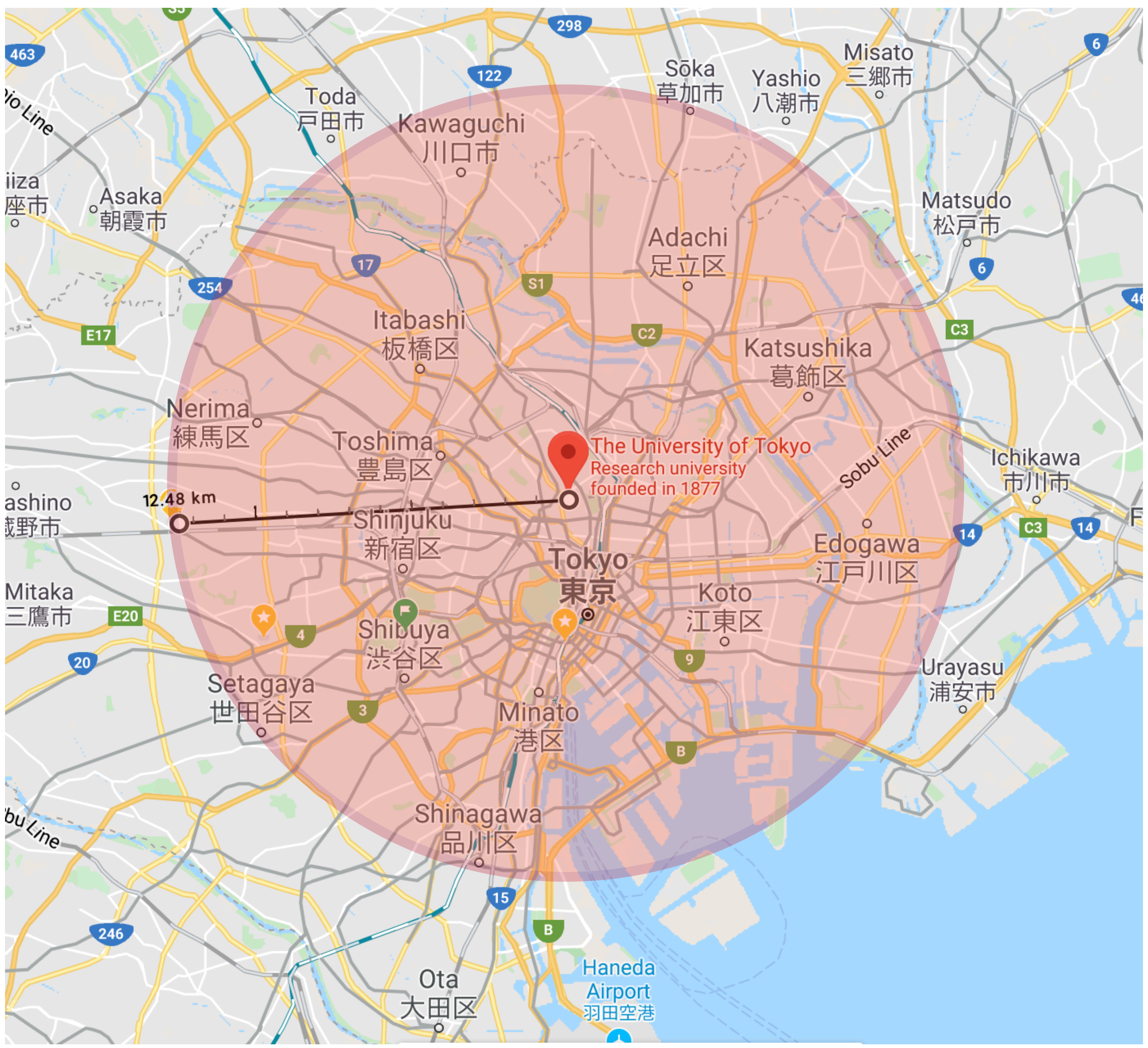


Tokyo area

- Mostly consists of neutrons

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

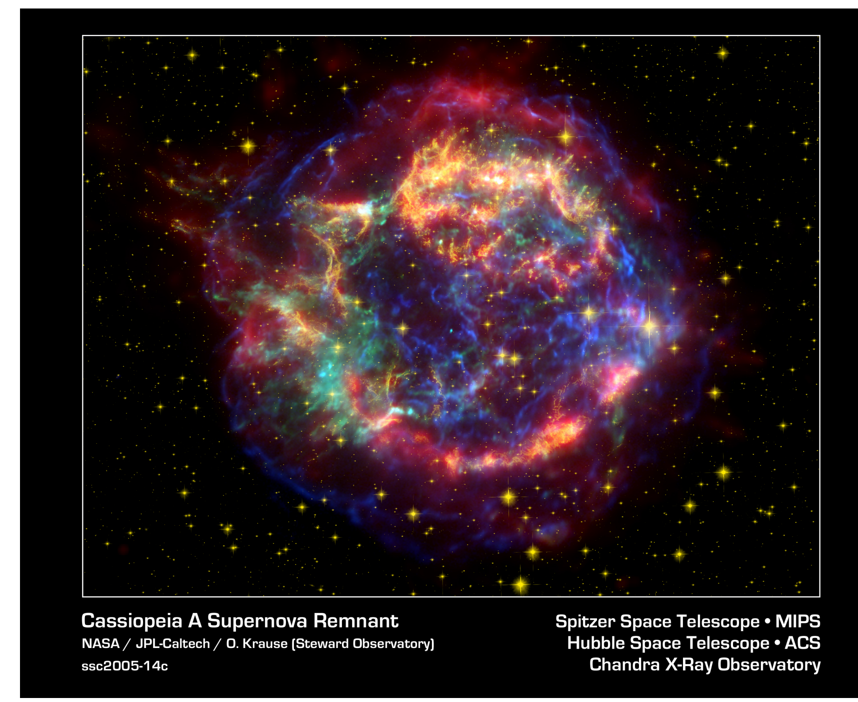
- Small amount of proton, electron, muon

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

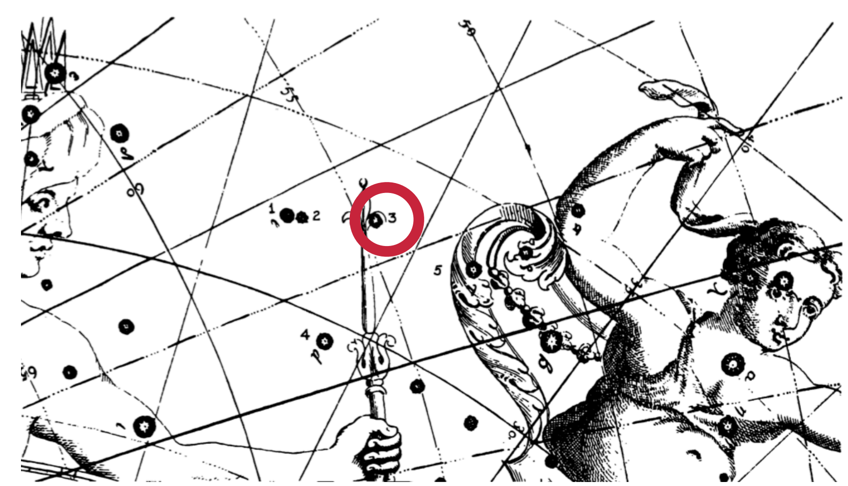
These particles are degenerate: $p_F \gg T$

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).]



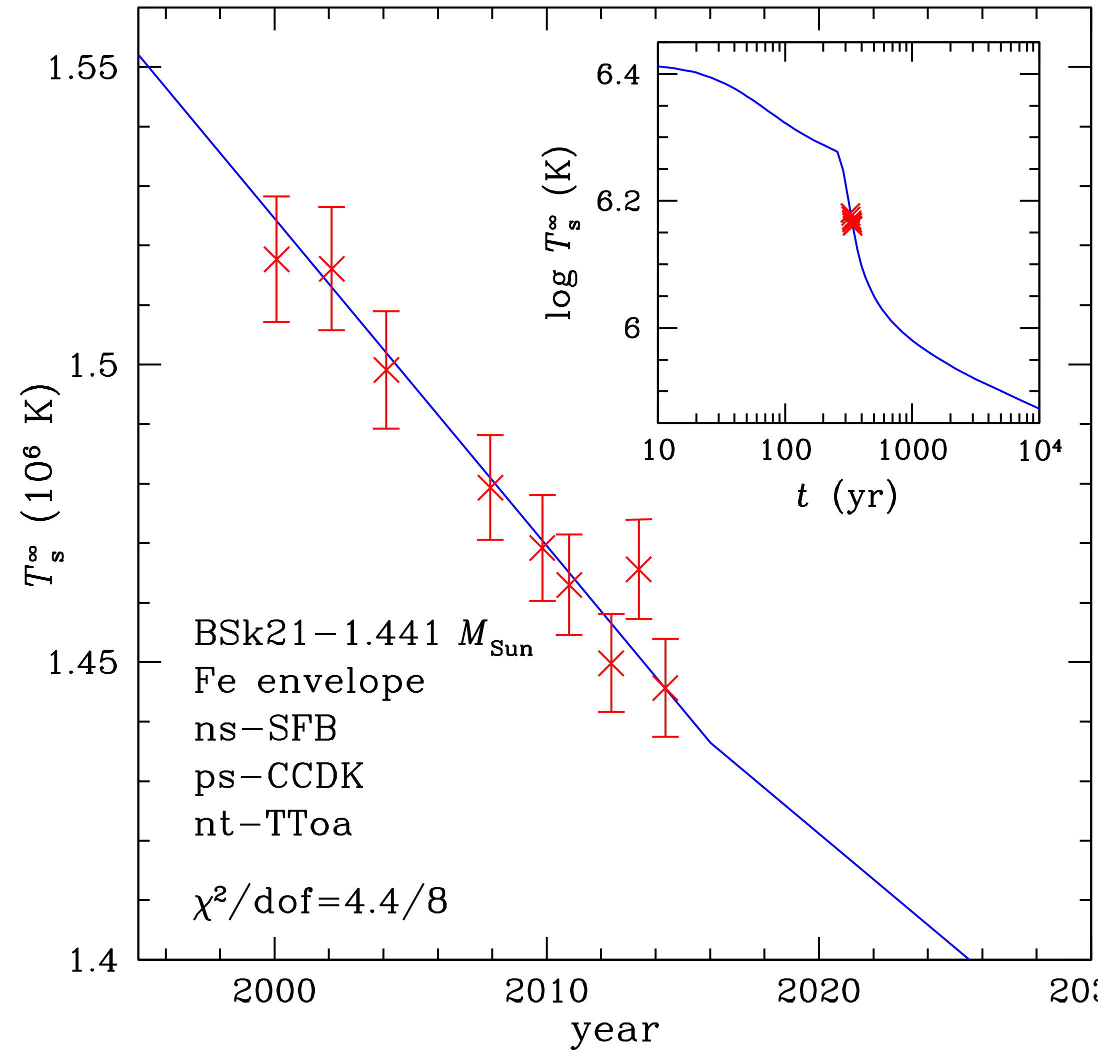
- Neutron star at the center of Cas A (Cas A NS)
  - Thermal emission is detected



[Atlas Coelestis (1729)]

Cooling of Cas A NS

Temperature is decreasing for ~ 10 years

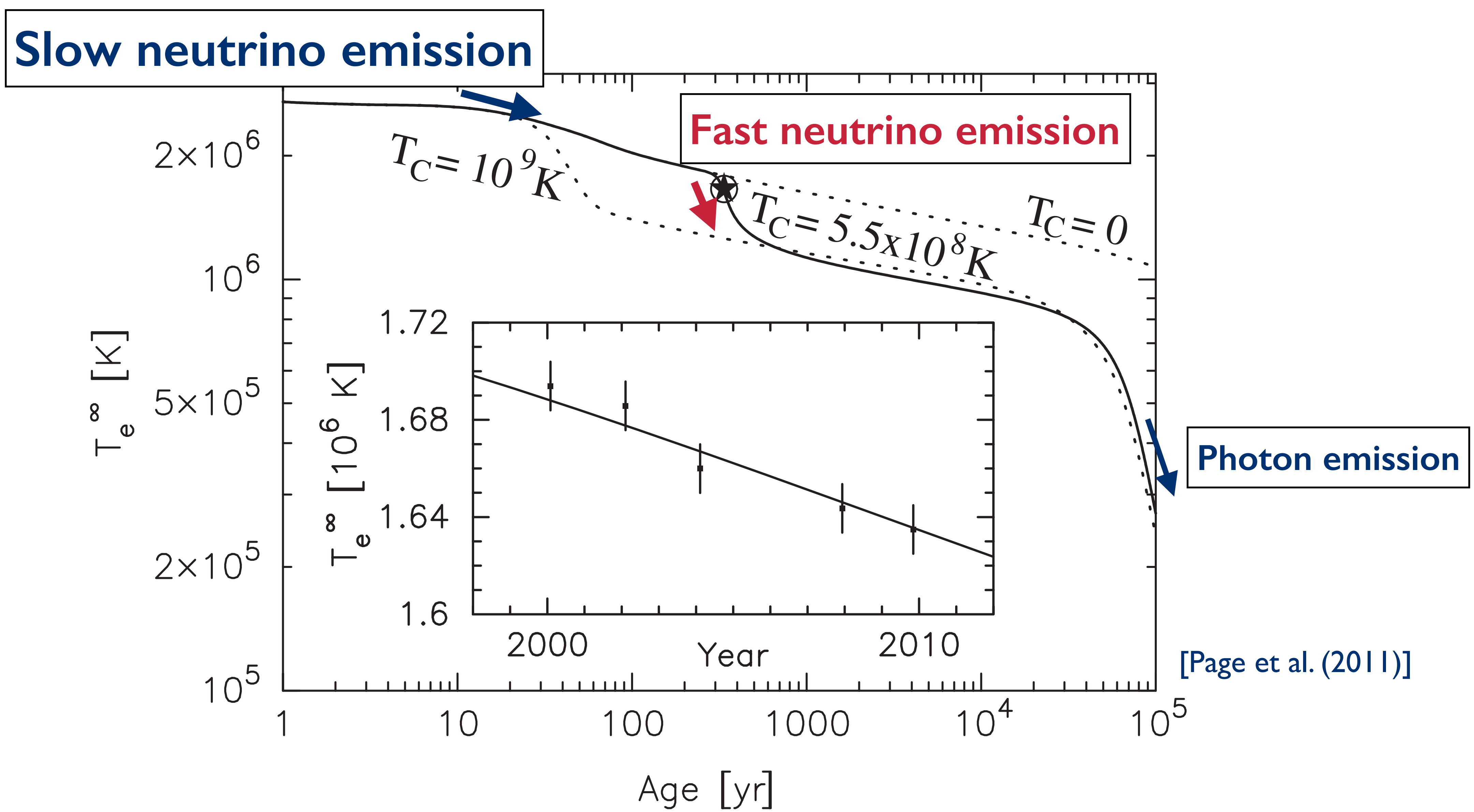


[Ho et al. (2015)]

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

Standard cooling explains temperature decline

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



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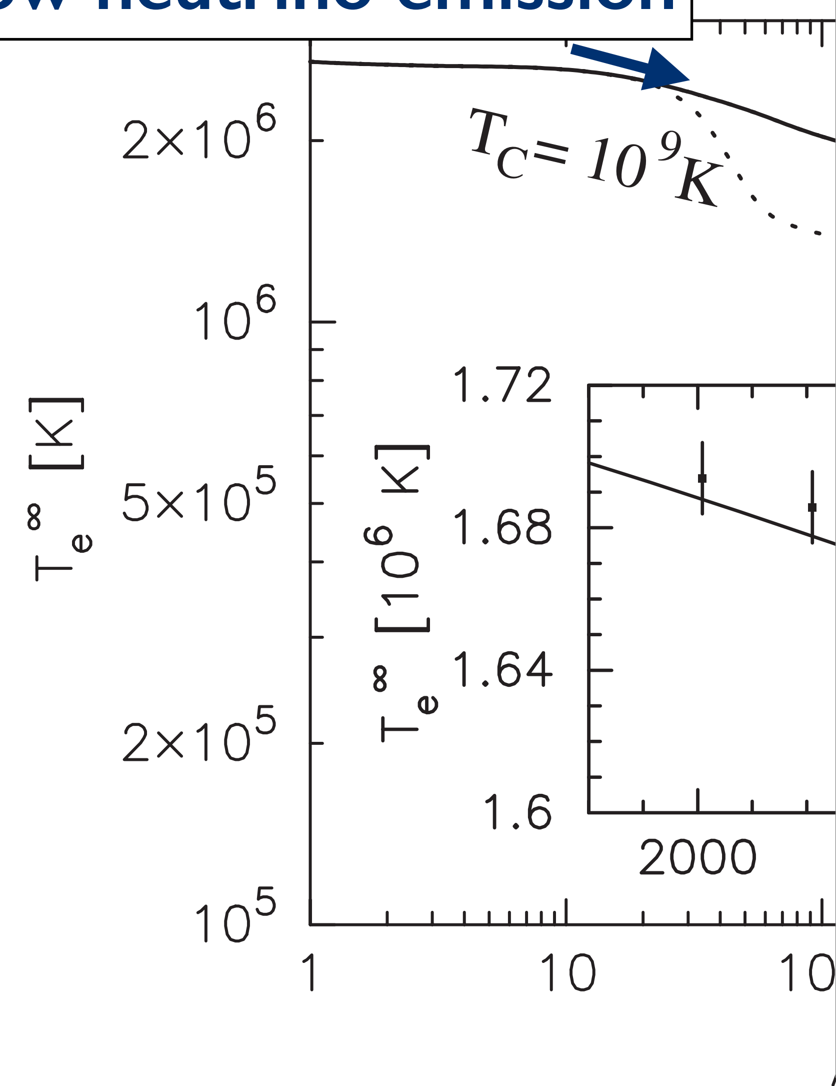
Slow neutrino emission



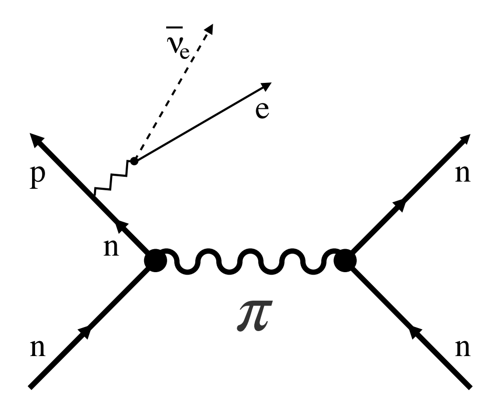
Modified Urca process

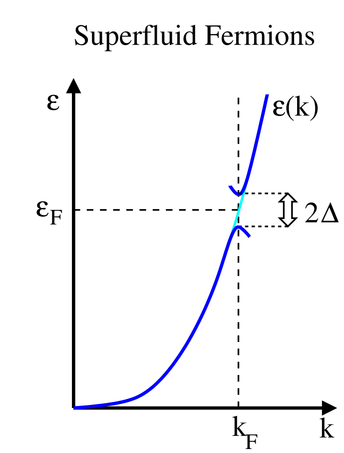
$$n + N \to p + N + e + \bar{\nu}_e$$

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

$$N = n, p$$

- 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





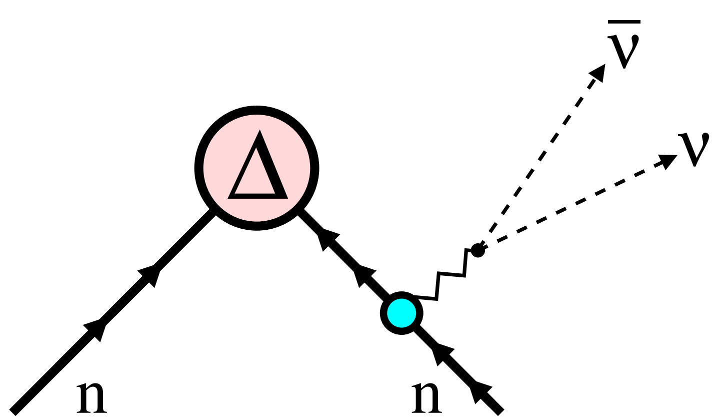
Standard cooling explains temperature decline

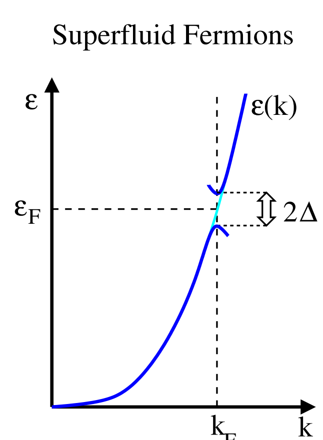
Cooper pair-breking and formation (PBF)

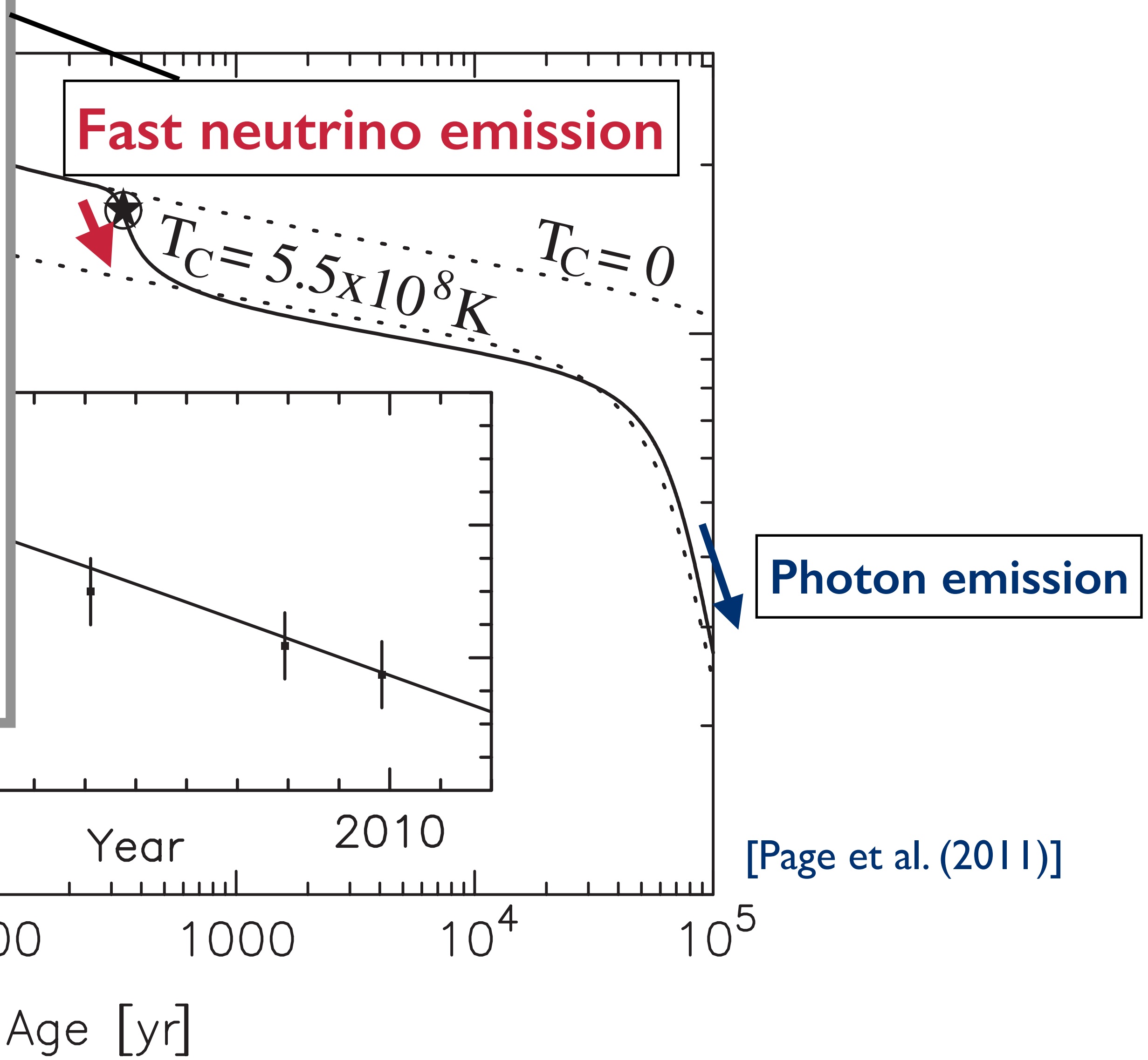
Pair-breaking: $[\tilde{N}\tilde{N}] \to \tilde{N} + \tilde{N}$

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

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







[Page et al. (2011)]

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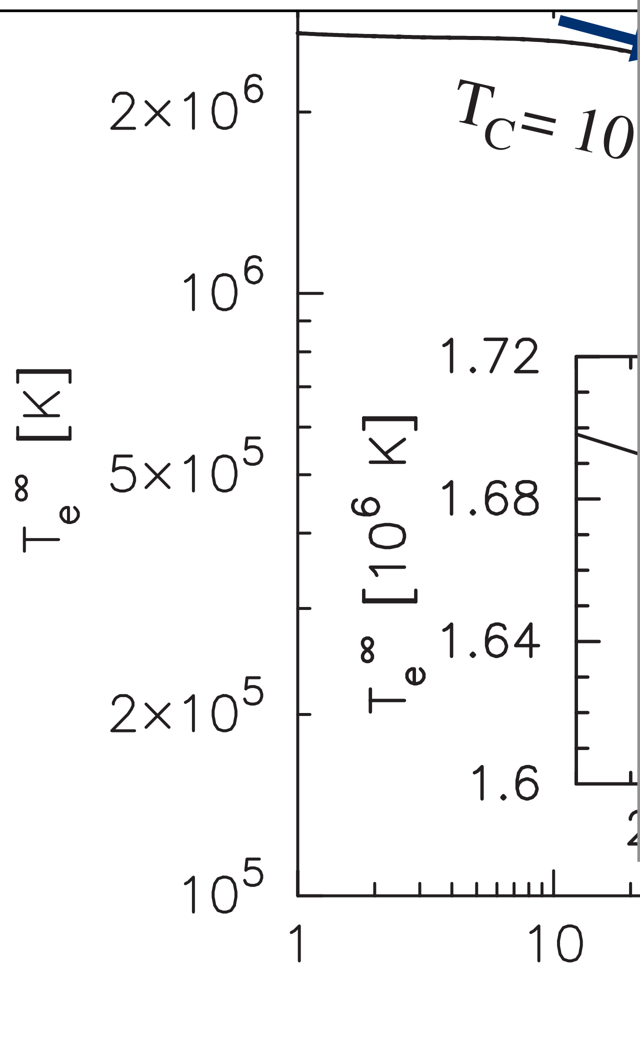

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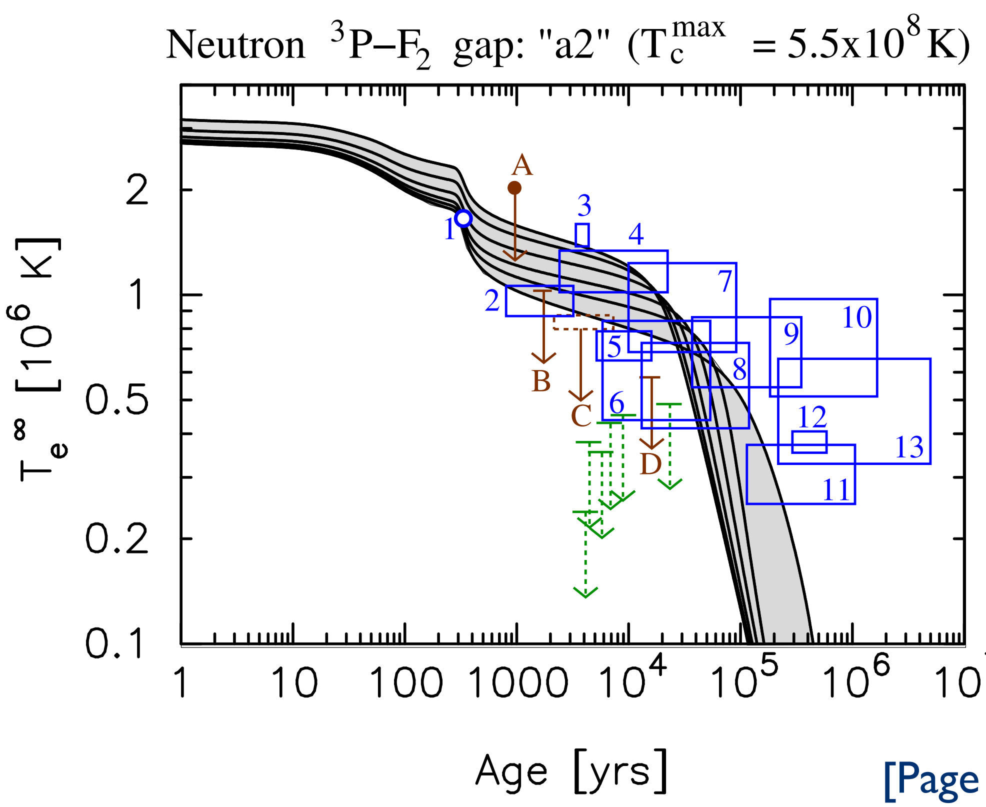
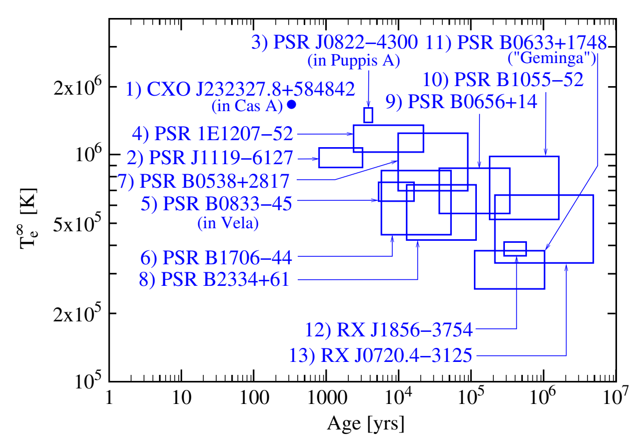
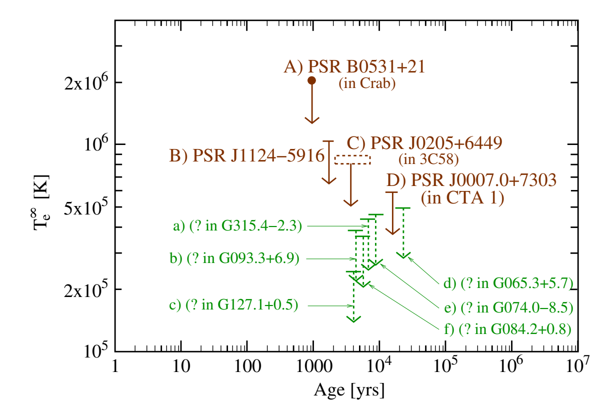
Standard cooling explains other NS temperature data



[Page et al. (2013)]





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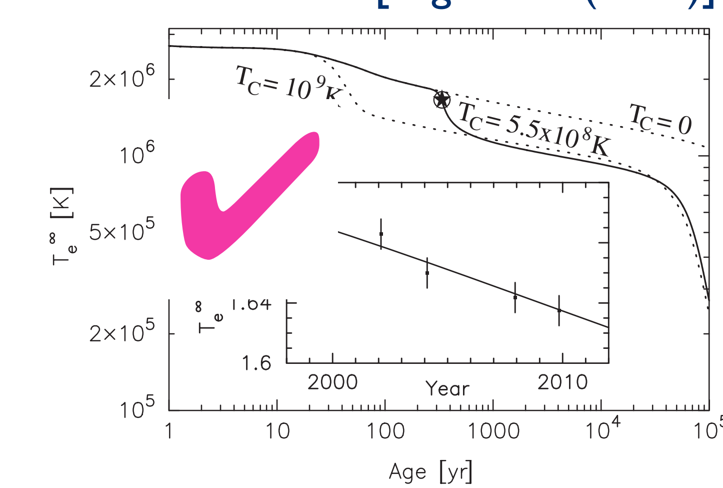

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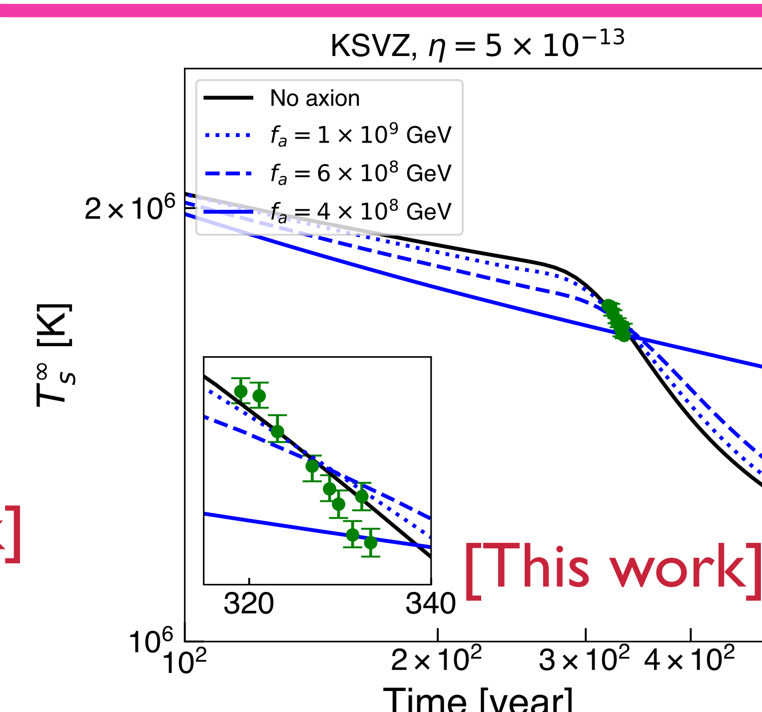

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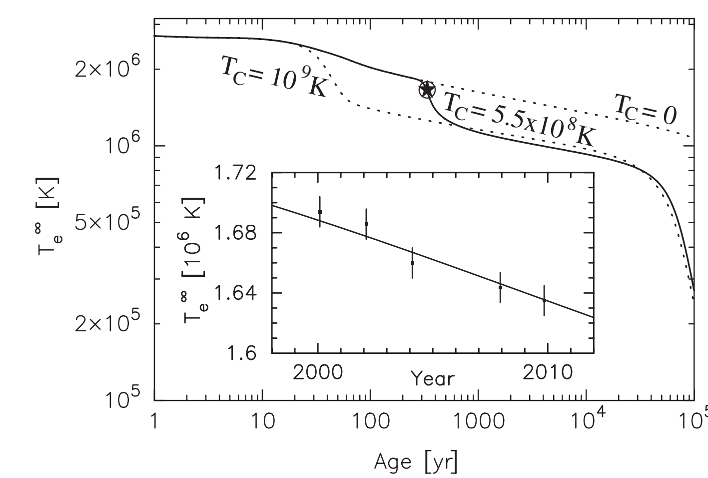

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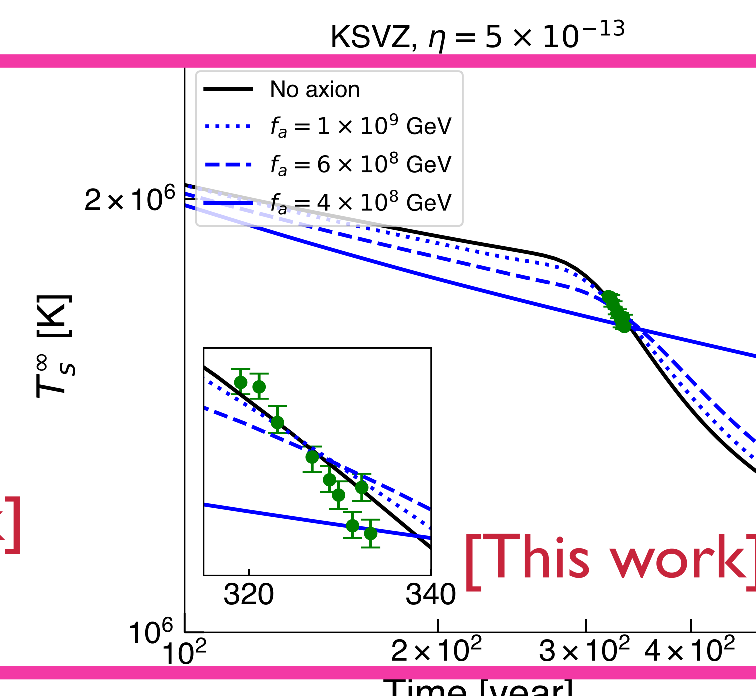
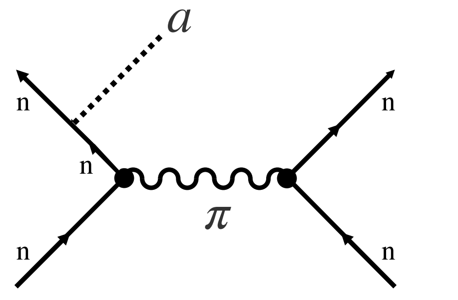


[This work]

Axion emission processes

- Axion Bremsstrahlung

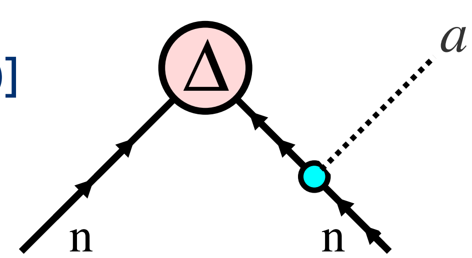
[Iwamoto (1984, 2001); Nakagawa et al. (1987, 1988)]

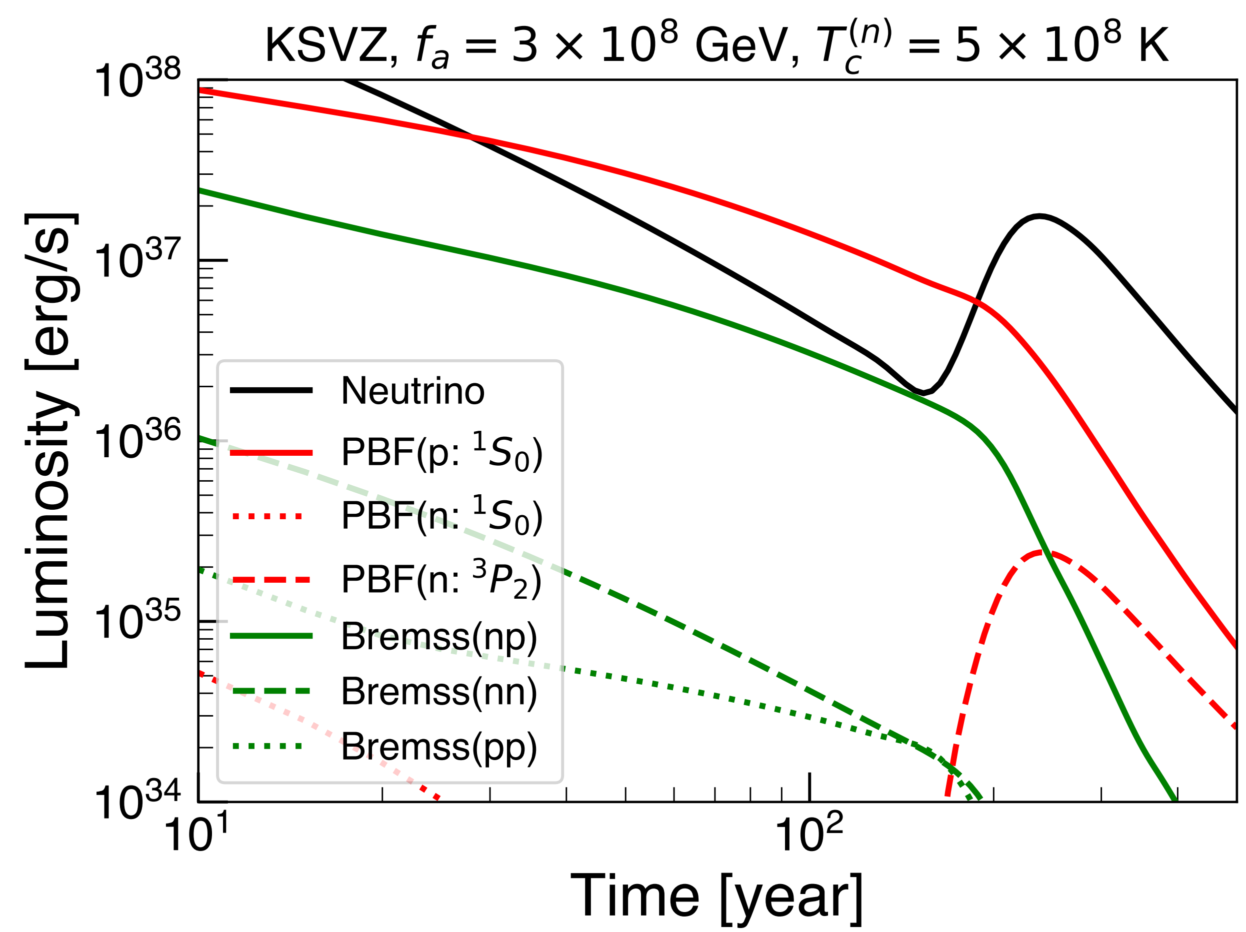


- Axion PBF

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

[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

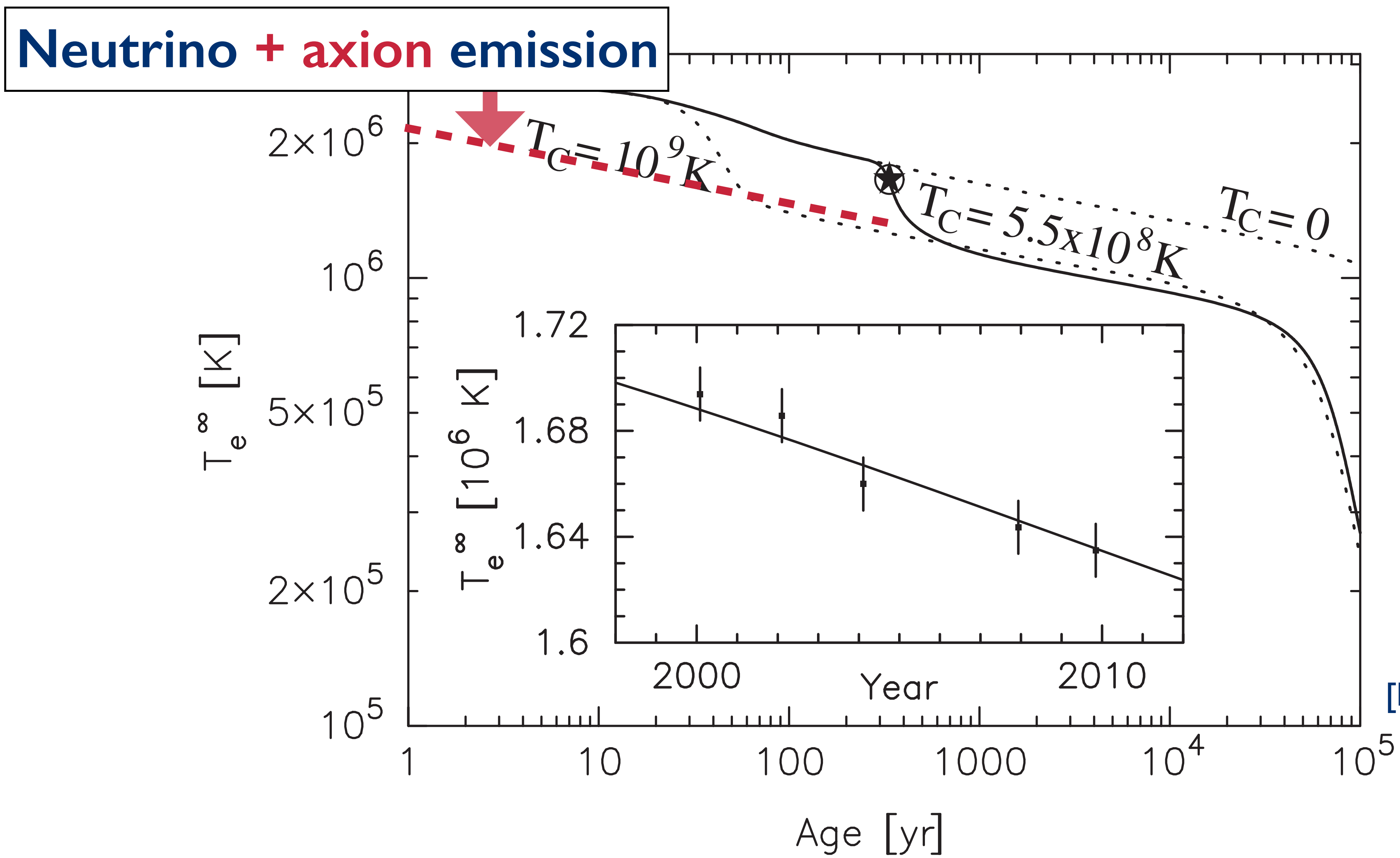
KSVZ: $C_p = -0.47(3)\,, C_n = -0.02(3)$ $\quad \mathscr{L} = \sum_{N=n,p} \frac{C_N}{2f_a} \bar{N}\gamma^\mu\gamma_5 N \partial_\mu a$

Axion emission enhances cooling

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

⟶ Constraint on f_a

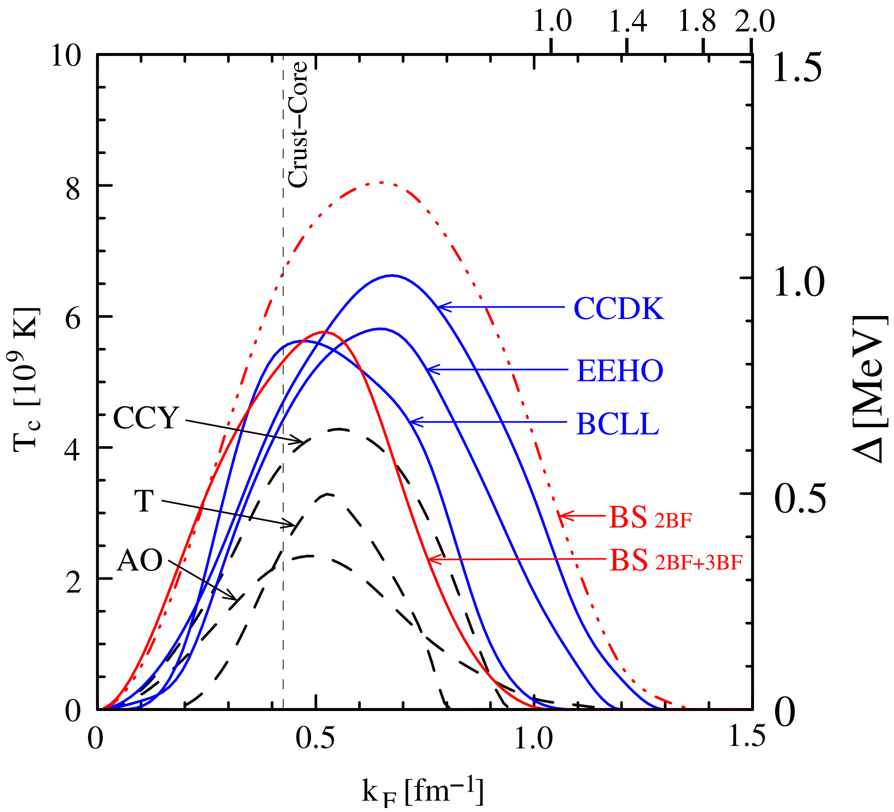
coupling $\sim \dfrac{C_N}{f_a}$



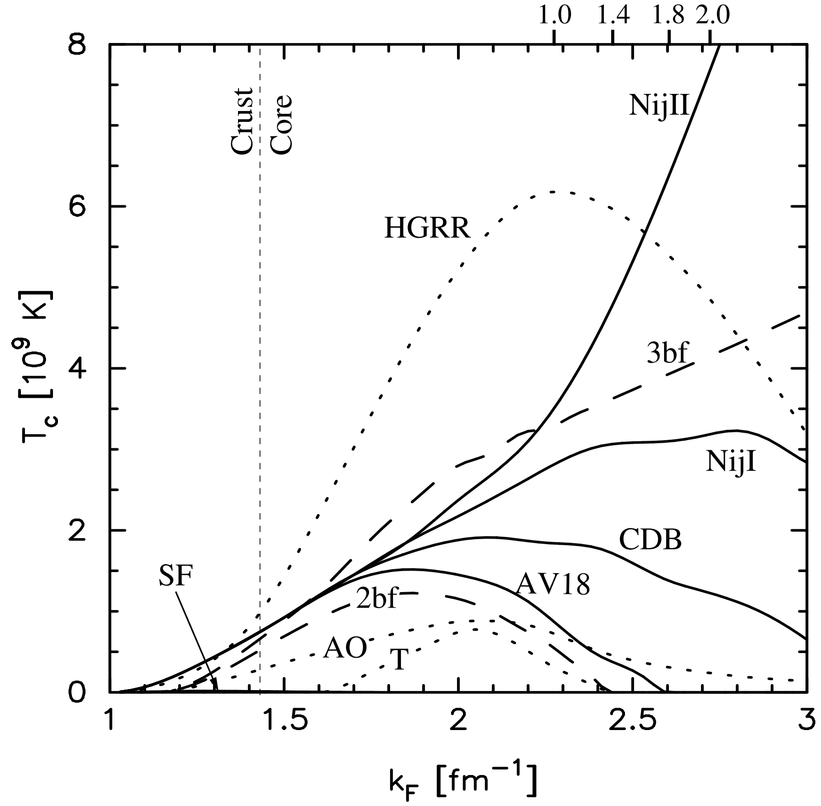
[Page et al. (2011)]

Detail 1: Gap models

proton singlet gap



neutron triplet gap



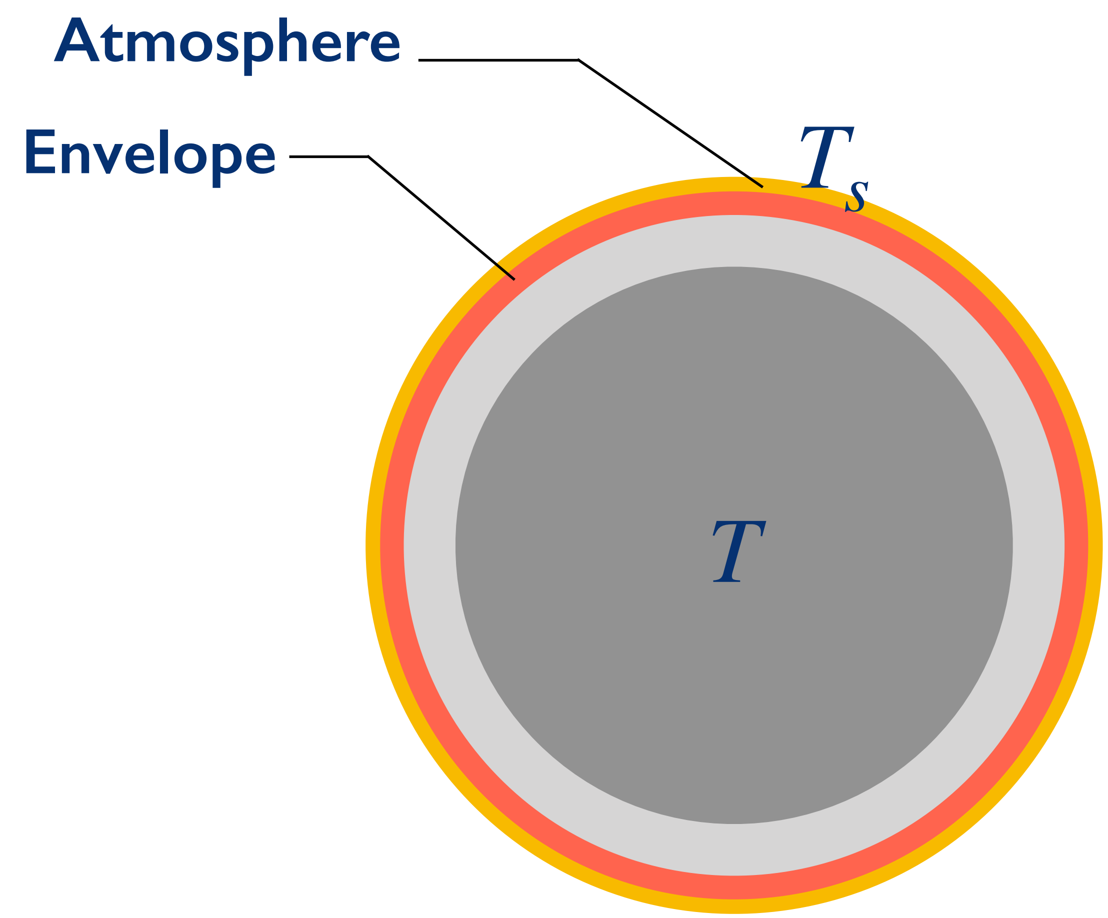
[Figures from Page et al. (2013)]

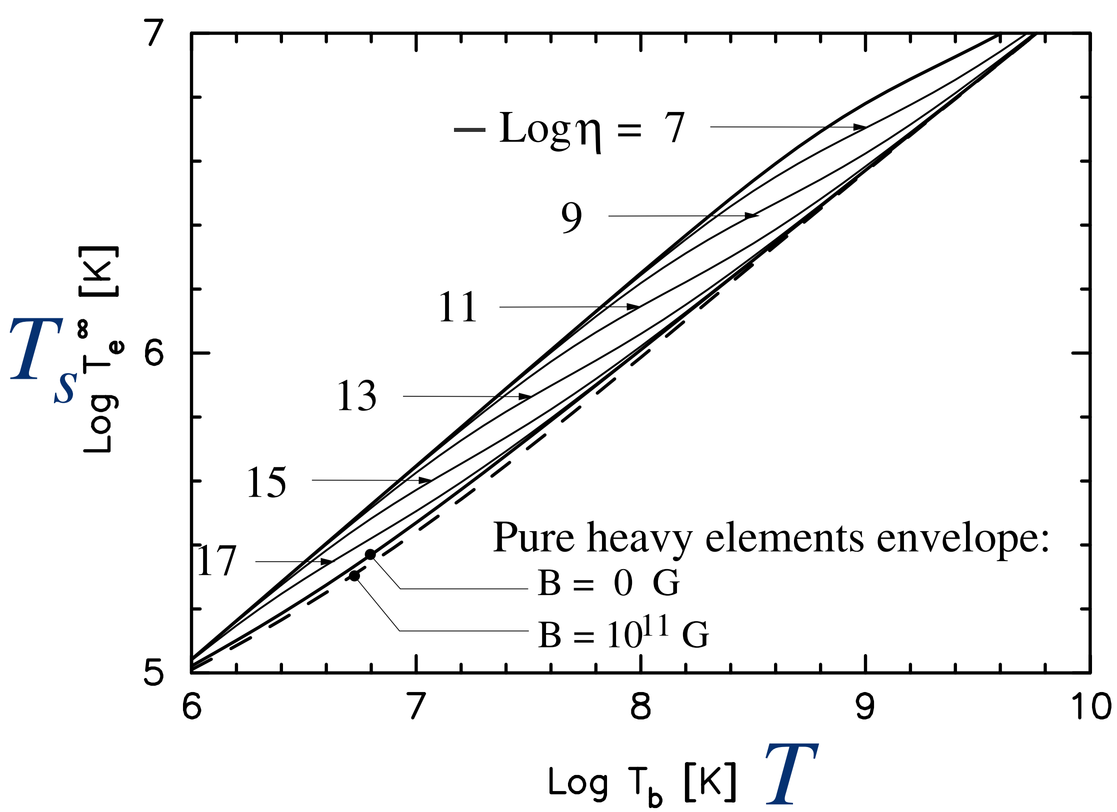
$$\epsilon_N(\mathbf{p}) \simeq \mu_N + \mathrm{sign}(p - p_{F,N})\sqrt{\Delta_N^2 + v_{F,N}^2(p - p_{F,N})^2}$$

- 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)]

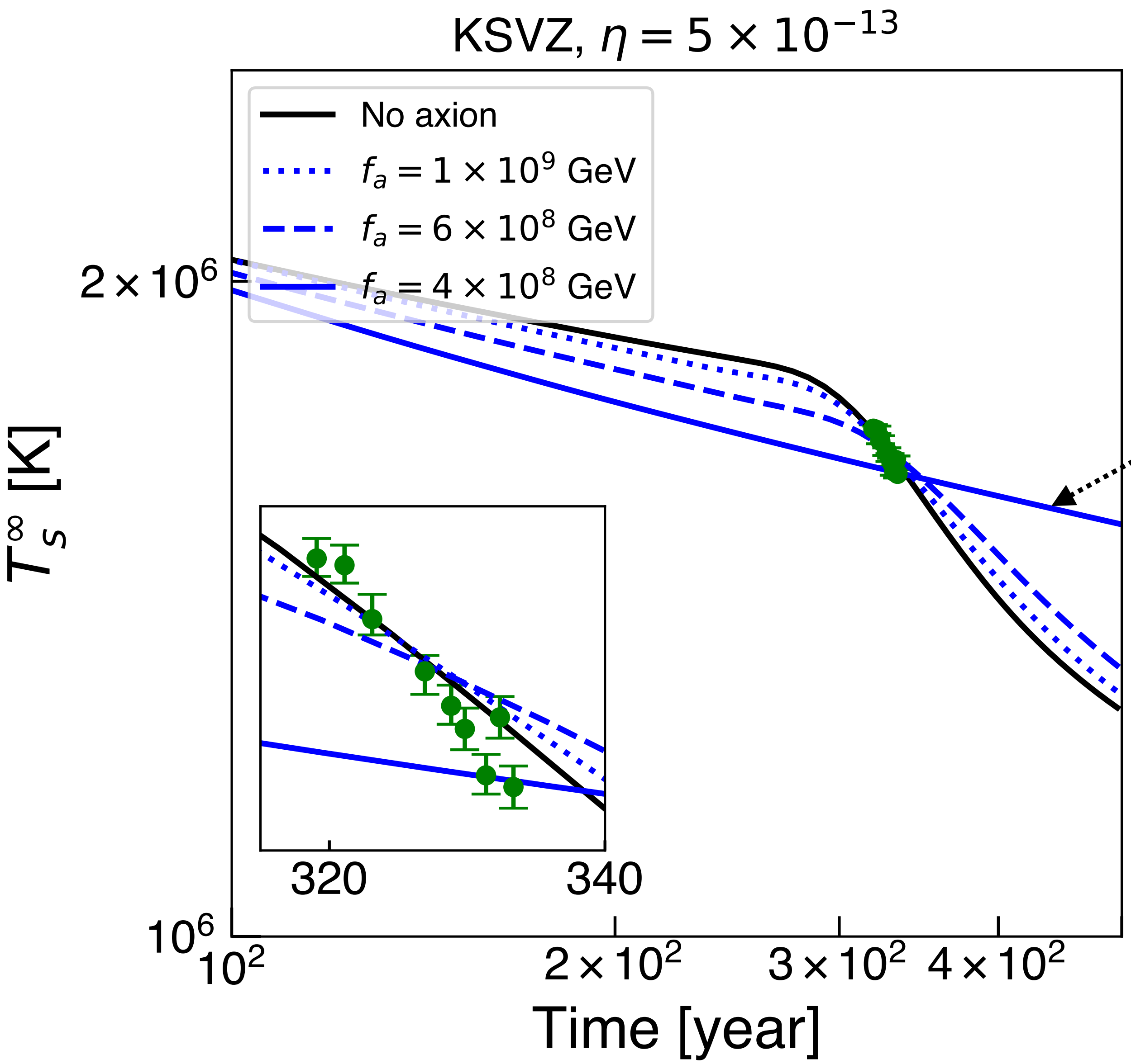




Parametrized by $\eta = g_{14}^2 \Delta M / M$

(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"

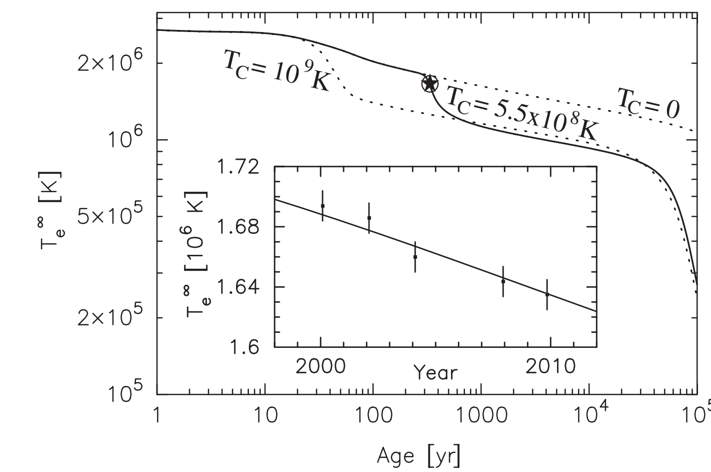
Well-motivated candidate of a new particle

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

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

NS cooling is observed

[Page et al. (2011)]



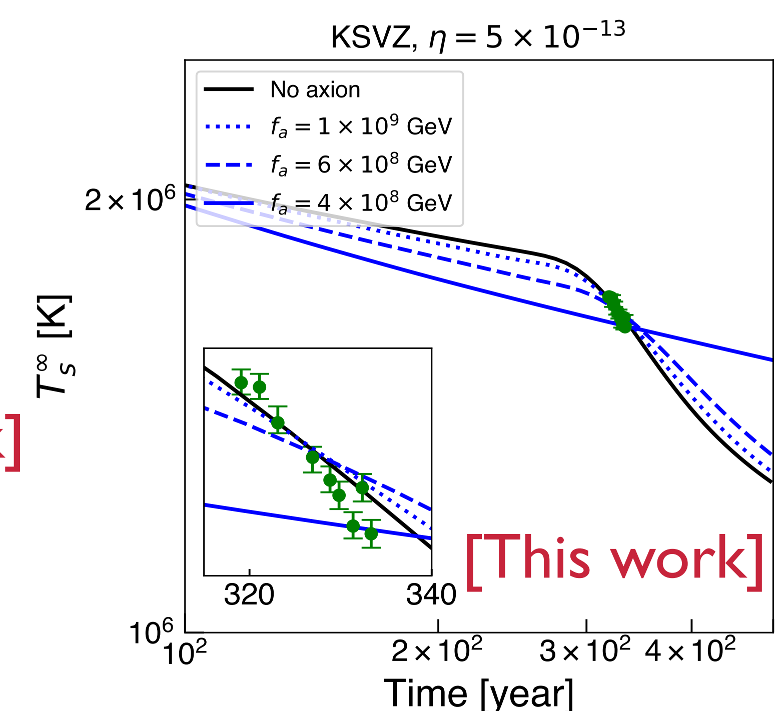
- SM: Cooling of Cas A NS can be explained by standard cooling theory [Page et al. (2011); Shternin (2011)]

- 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]

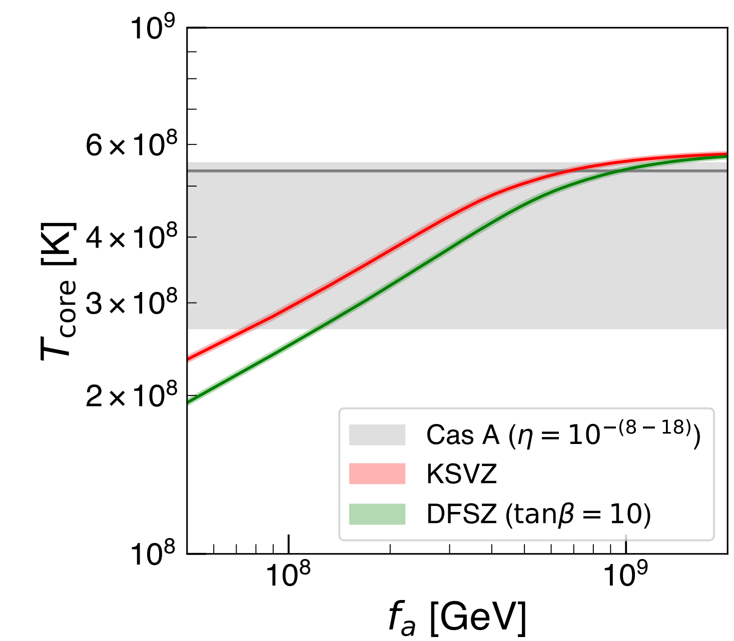
O(1) uncertainty from envelope

comparable to the SN1987A limit



Backup

More on uncertainty from light element in envelope



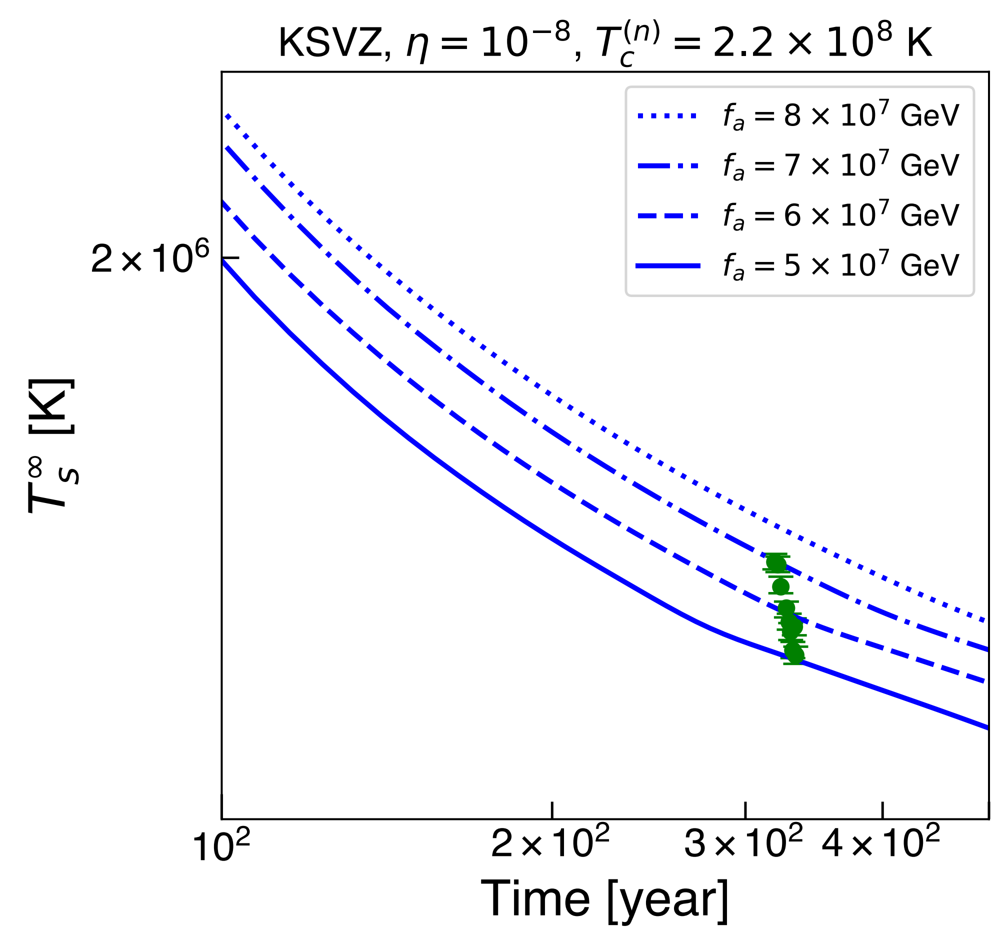
Envelope parameter η can be varied

Large η can weaken the limit

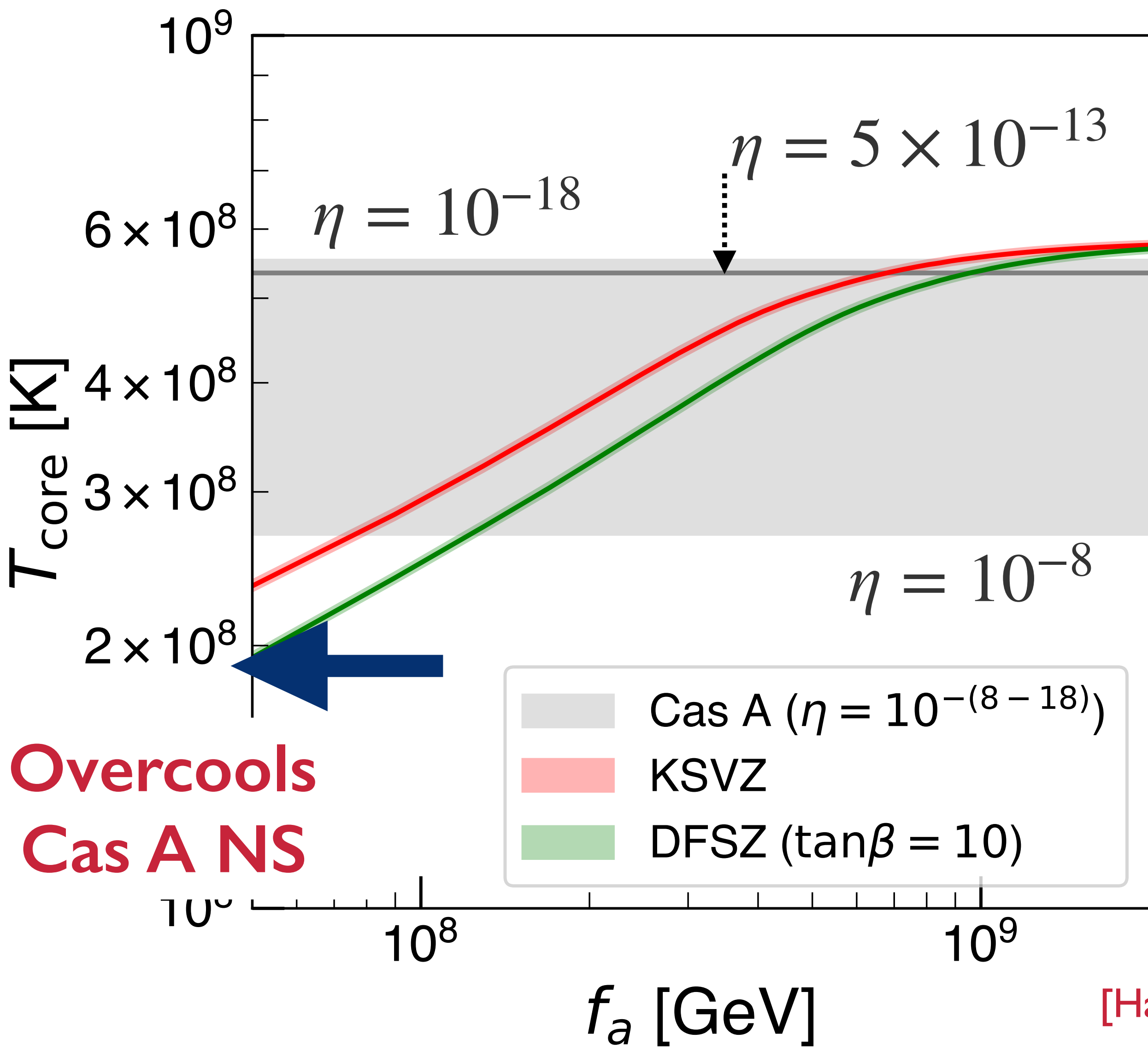
- KSVZ: For large $\eta \sim 10^{-8}$, internal T is too low to explain cooling rate

  → $f_a \gtrsim 4 \times 10^8\,\mathrm{GeV}$ 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 $t = 300 - 338\,\mathrm{yr}$
w/o neutron triplet pairing

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

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

Details 3: procedure to limit axion

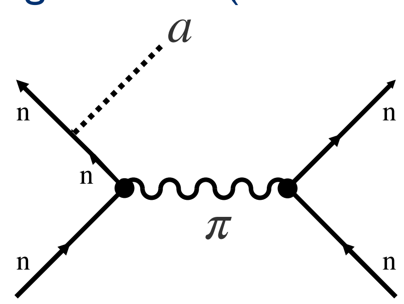
$$C\frac{dT}{dt} = -L_\nu - L_\gamma - L_a$$

- 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

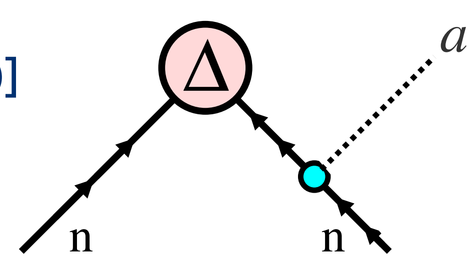
[Iwamoto (1984, 2001); Nakagawa et al. (1987, 1988)]

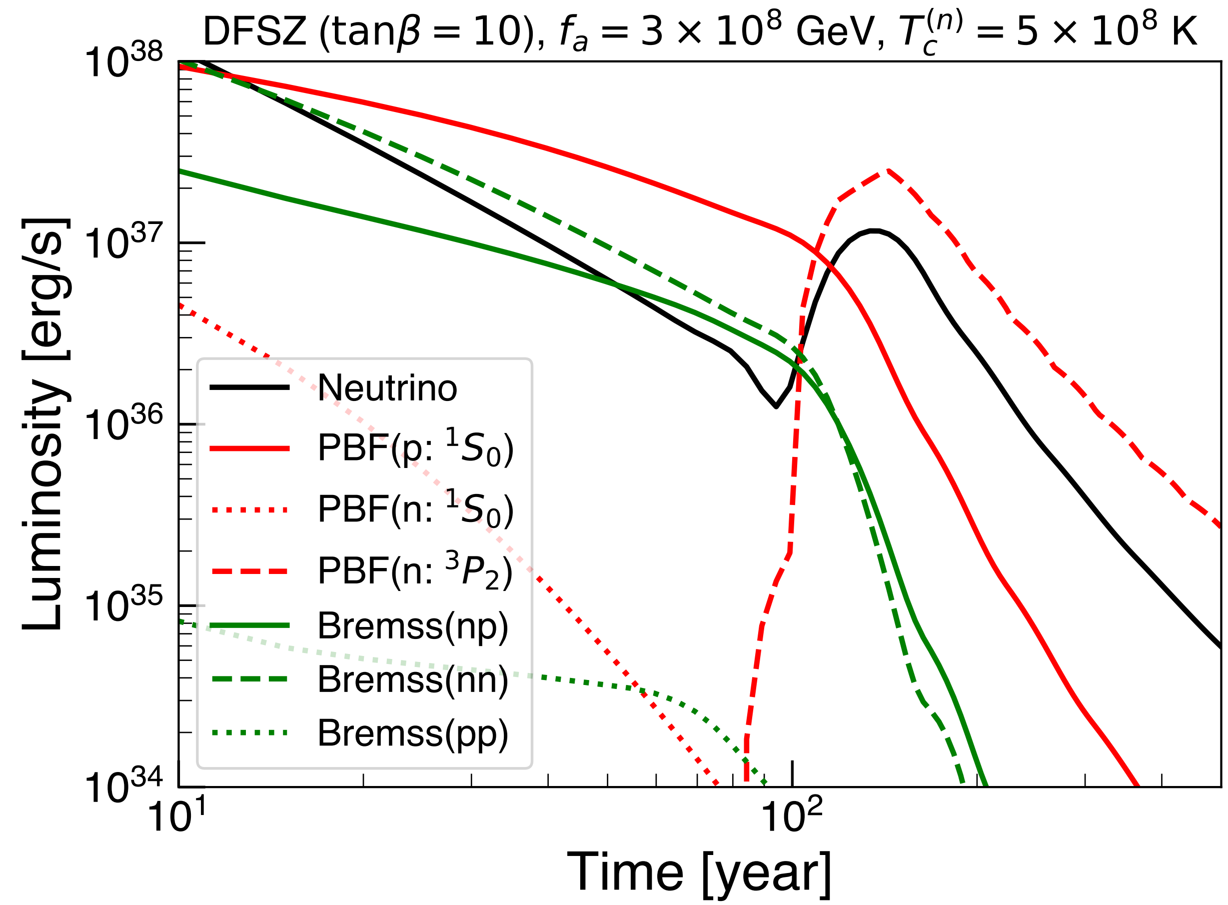


- Axion PBF

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

[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

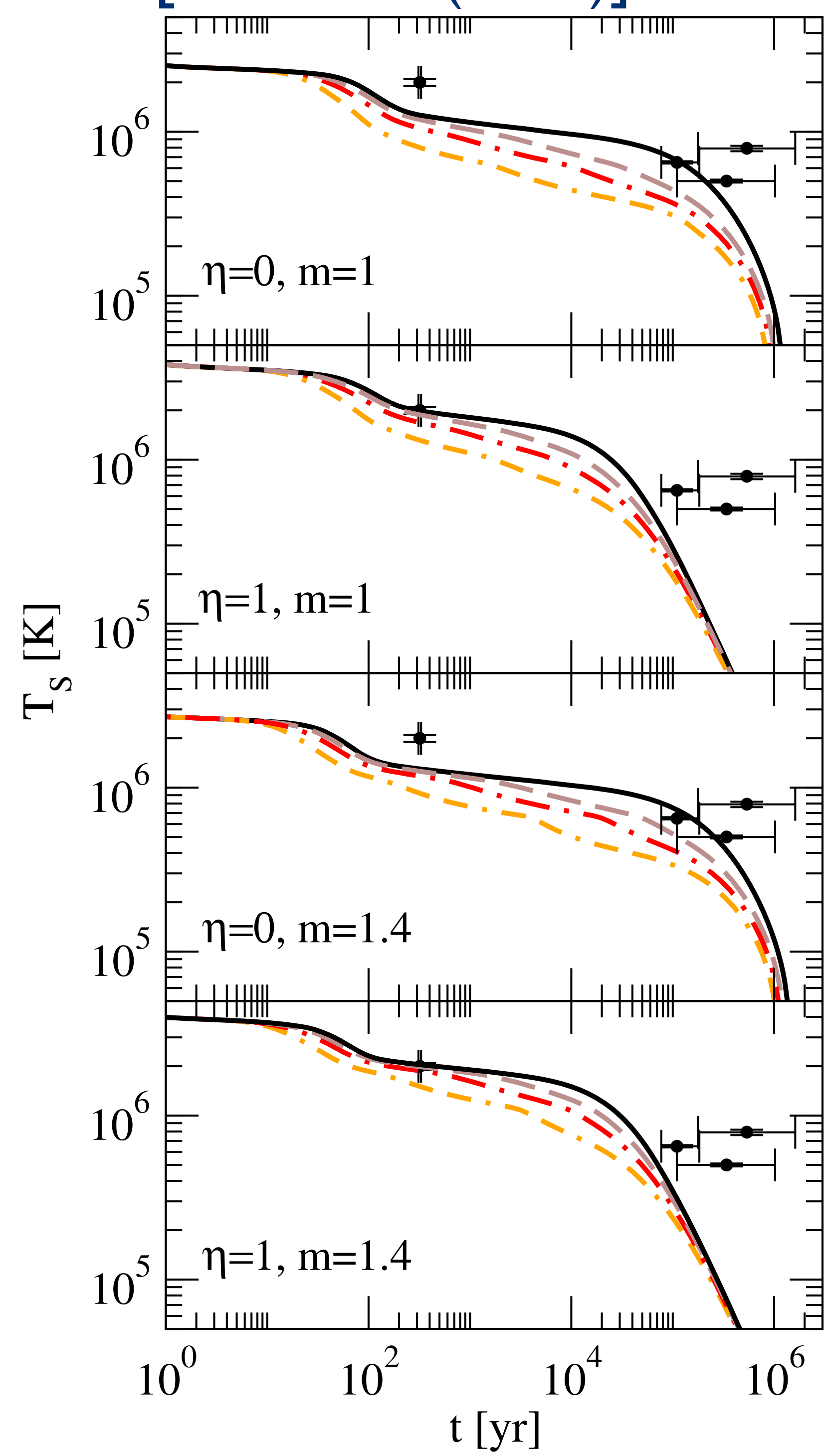
[Sedrakian (2016)]

- 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)]



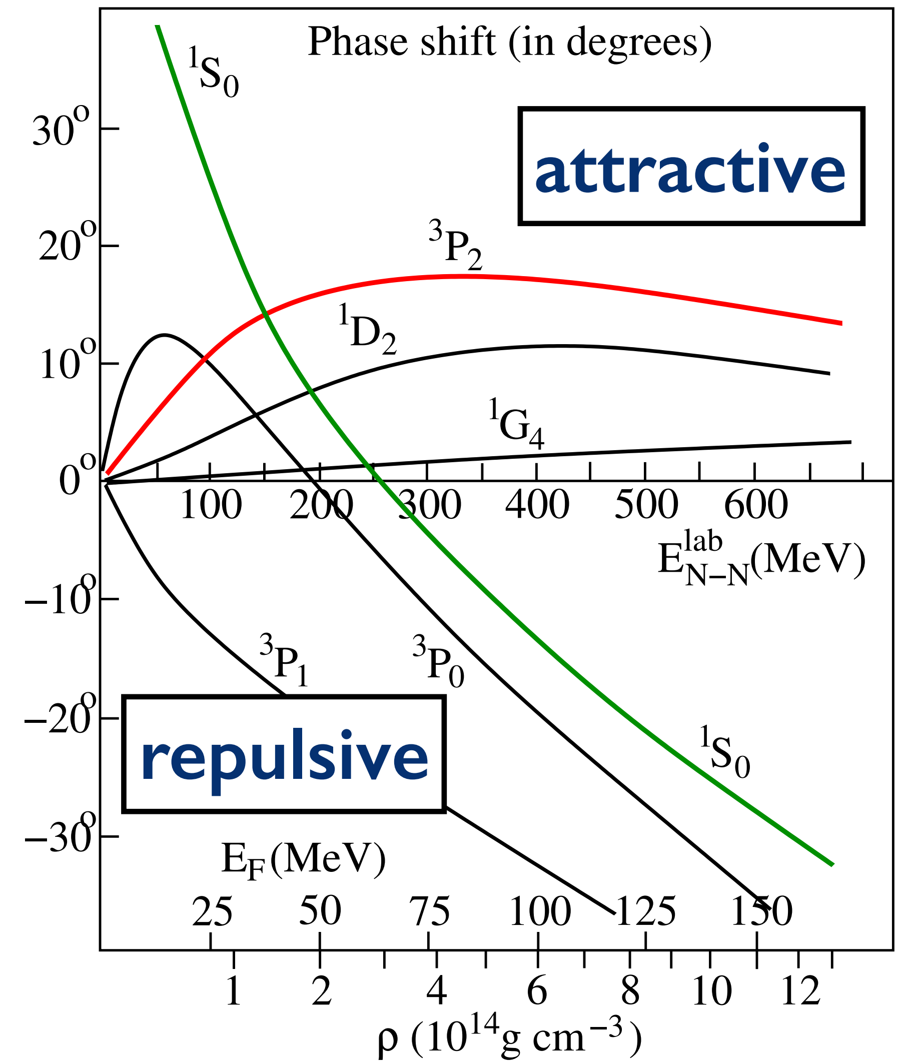
Nucleon Cooper pairing

- 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

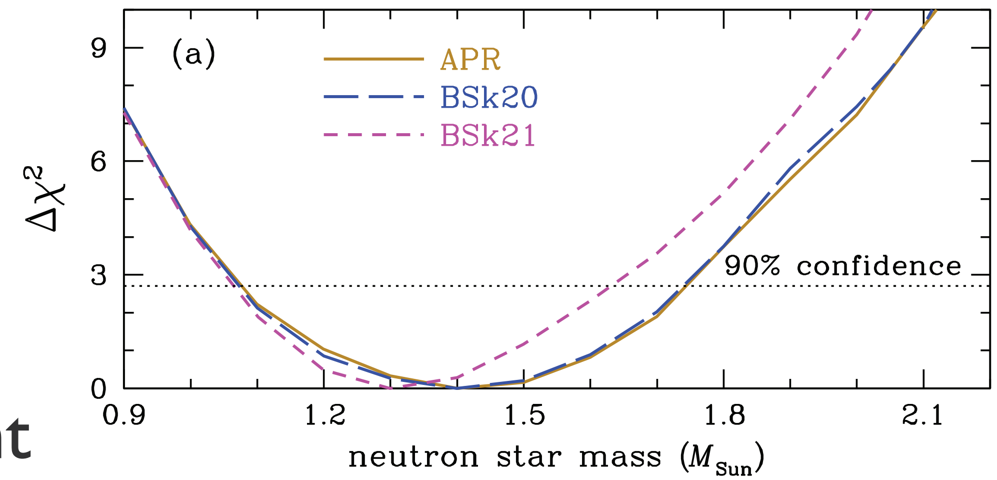
- In the crust:
  - n: spin-singlet ($^1S_0$) pairing



[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

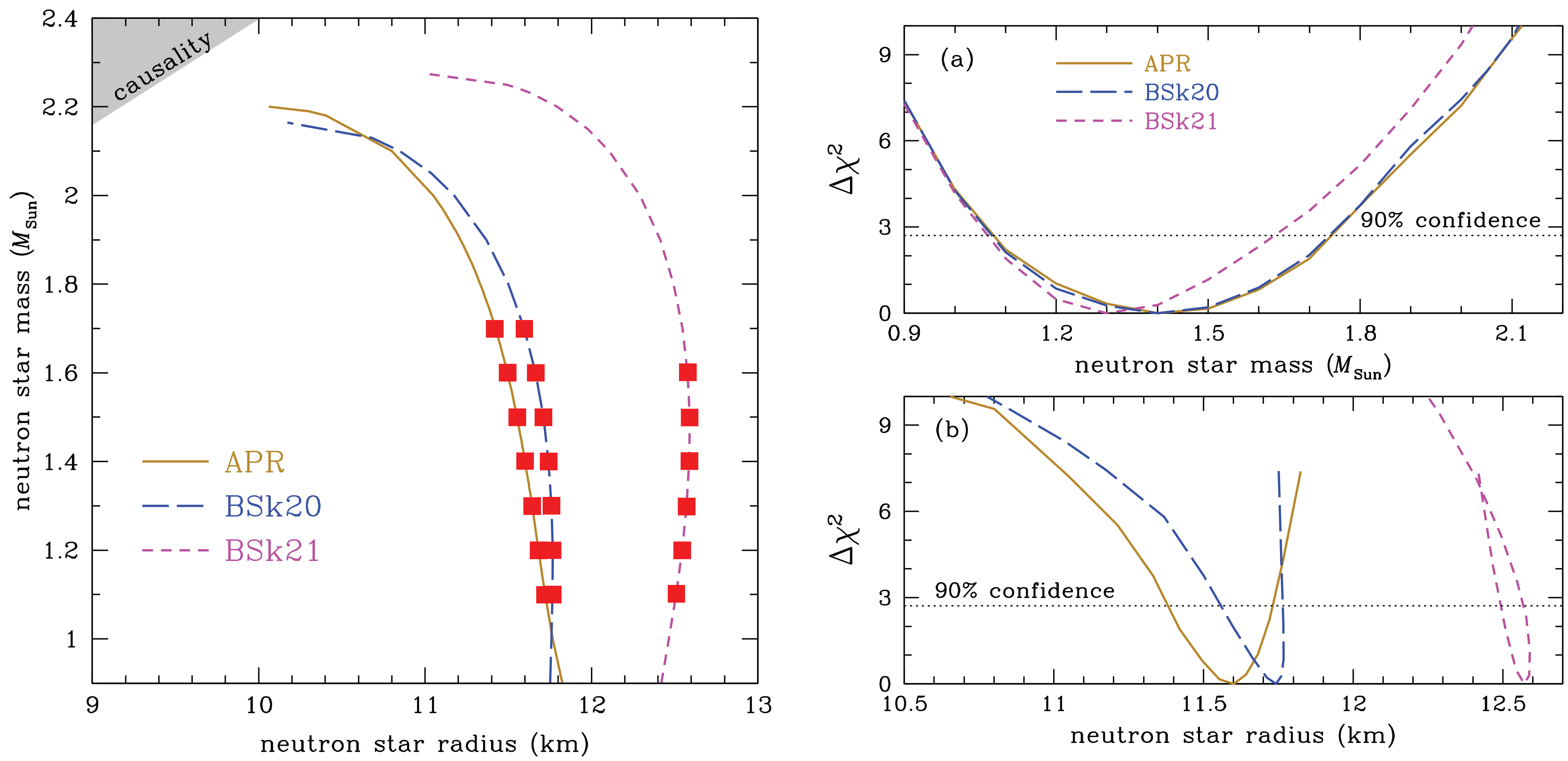
[Ho and Heinke (2009)]

- 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

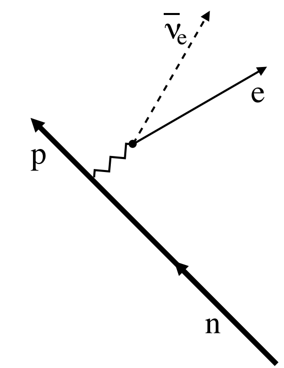


[Ho et al. (2015)]

Direct Urca process

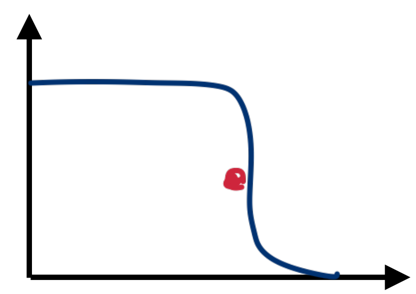
$$n \to p + \ell + \bar{\nu}_\ell \qquad p + \ell \to n + \nu_\ell$$

$\ell = e, \mu$



- 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 ($M \simeq 1.4\, M_\odot$)

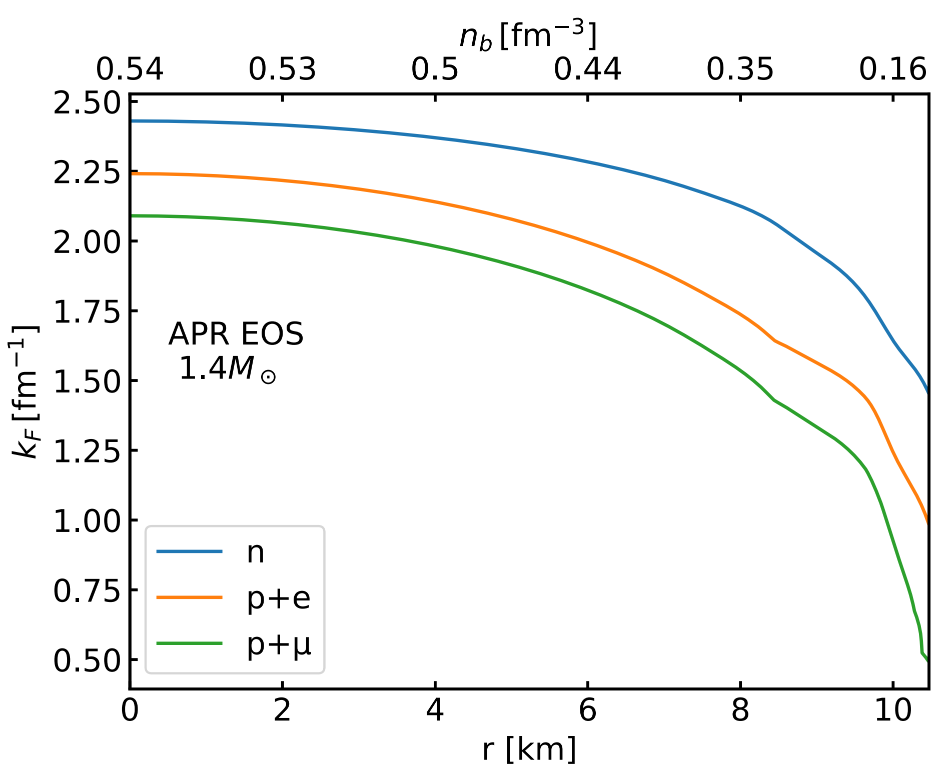
Threshold of direct Urca

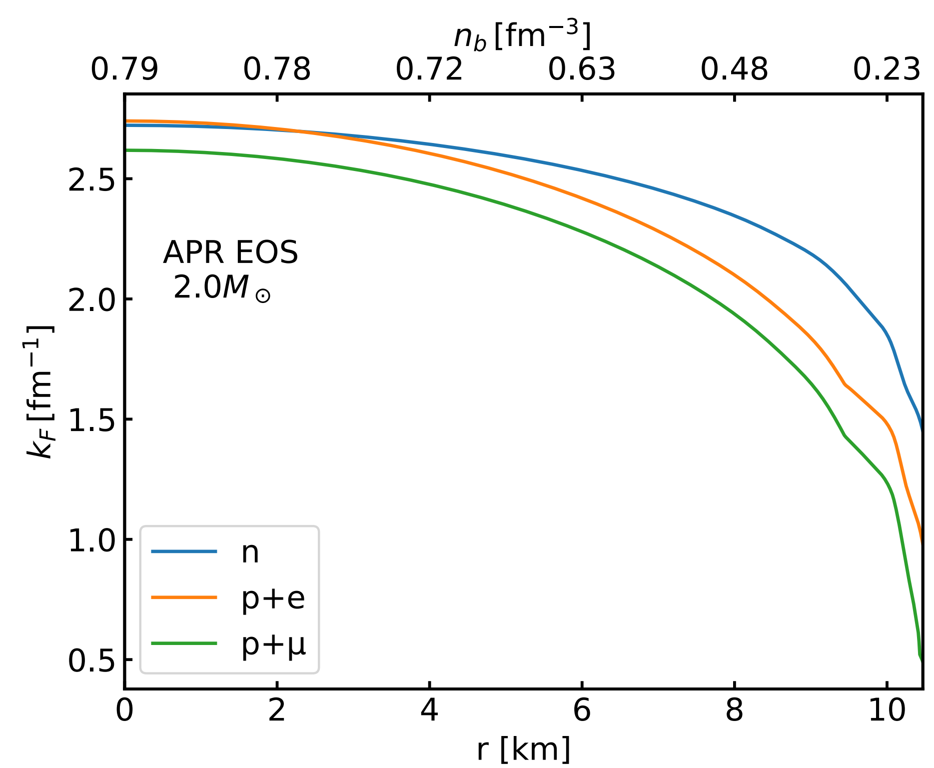
- Energy conservation $\varepsilon_n = \varepsilon_p + \varepsilon_\ell \pm \varepsilon_\nu$ and beta equilibrium $\mu_{F,n} = \mu_{F,p} + \mu_{F,\ell}$

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

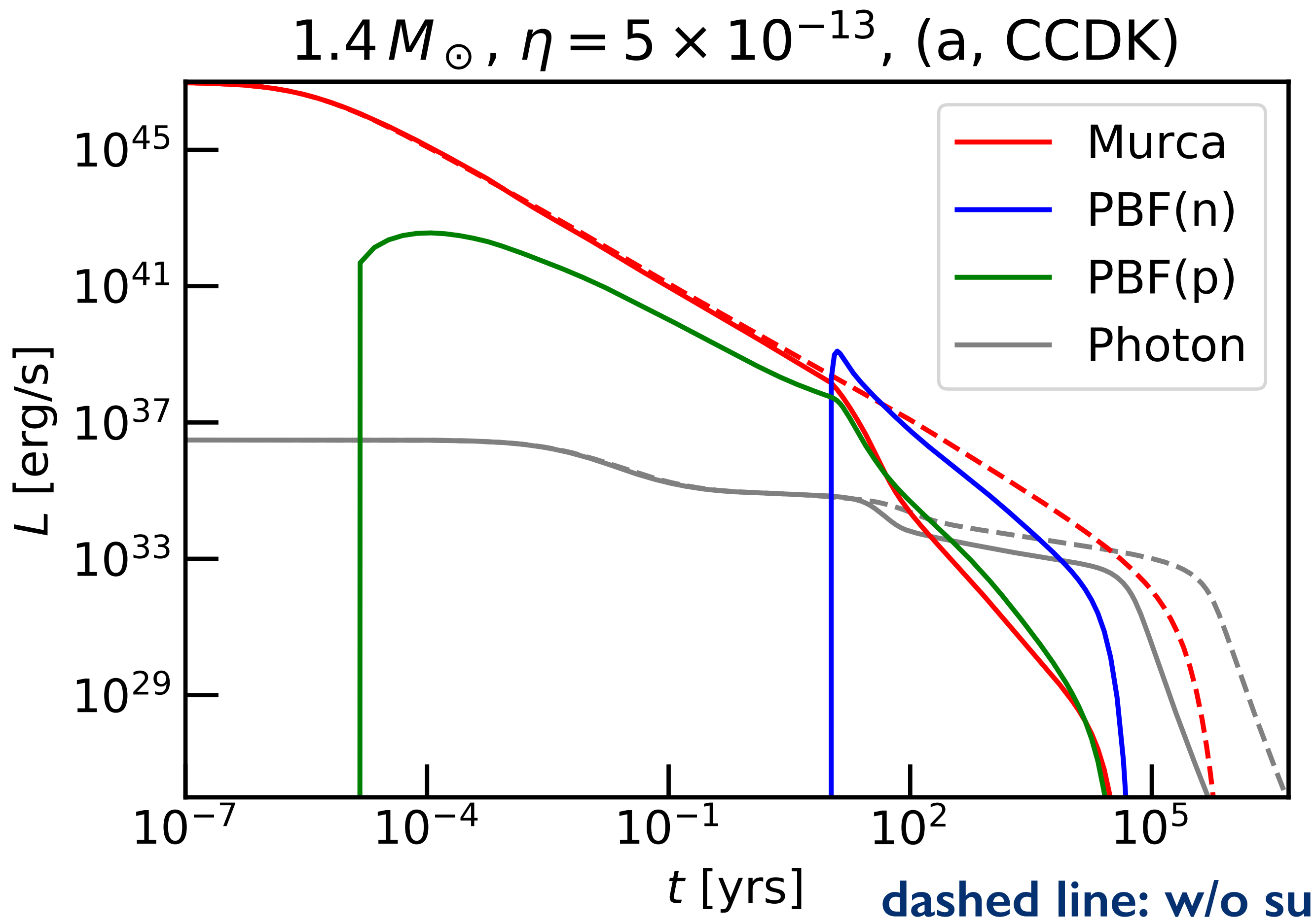
- Momentum conservation: $\overrightarrow{p}_n \simeq \overrightarrow{p}_p + \overrightarrow{p}_\ell$

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

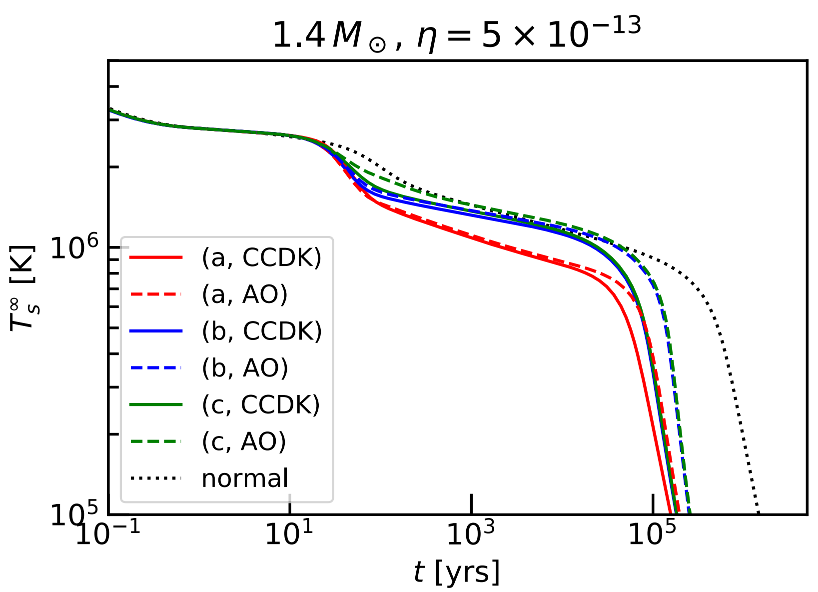




Luminosity evolution



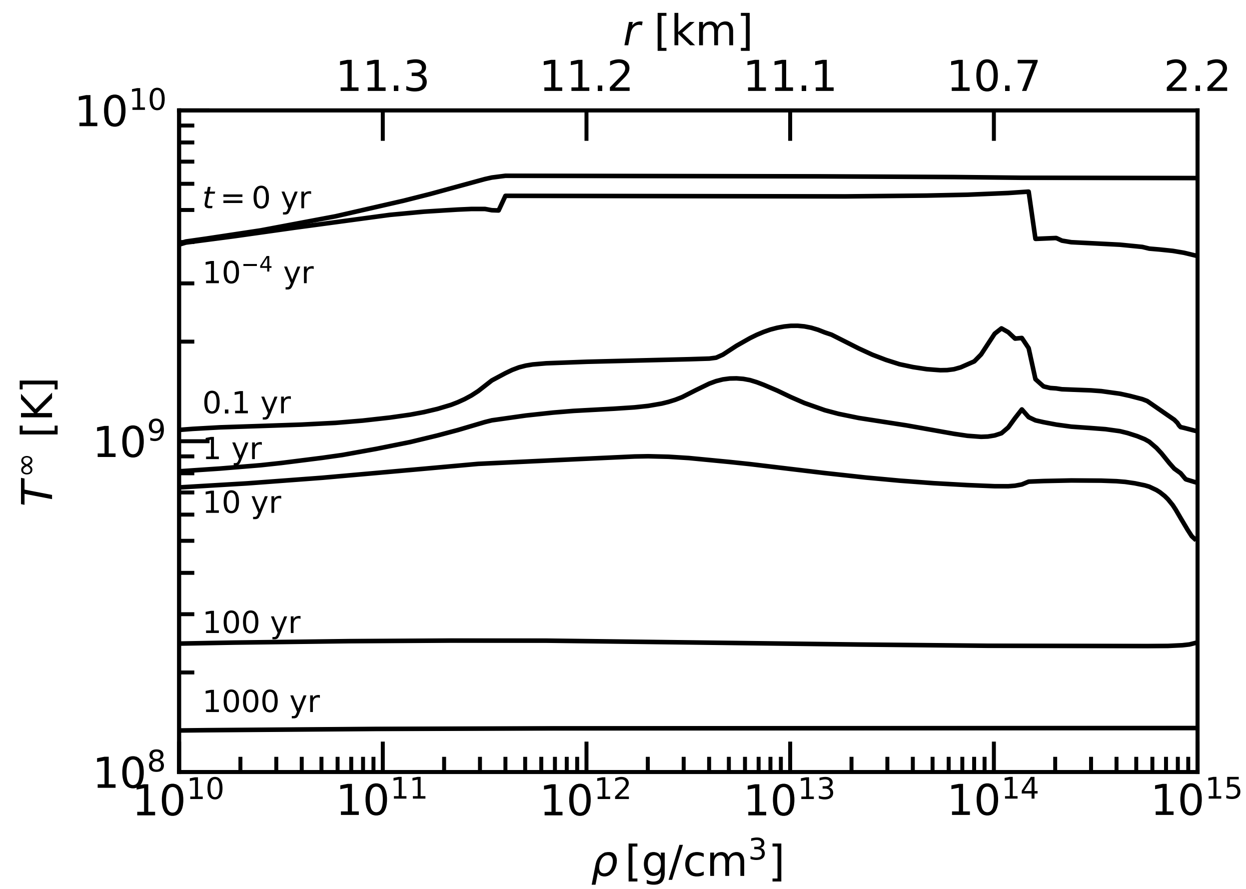
Calculated by NSCool



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

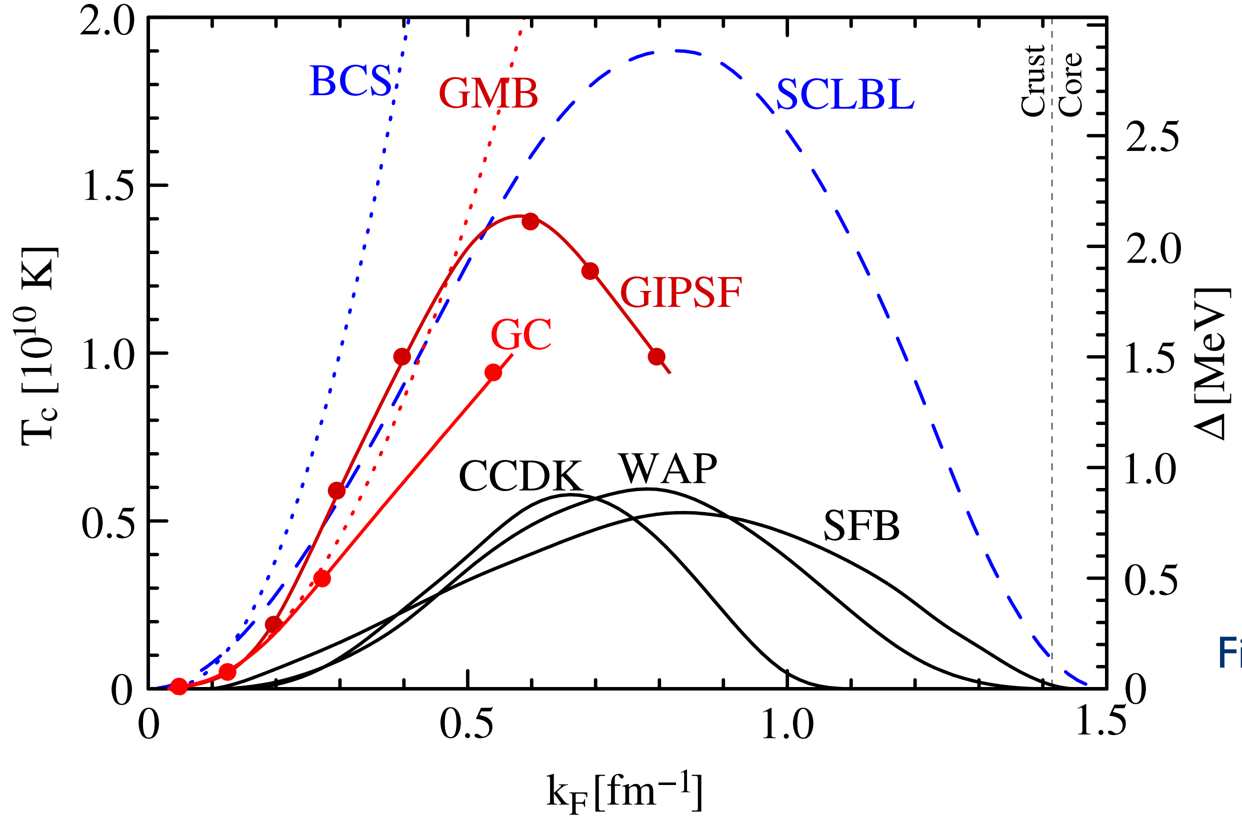
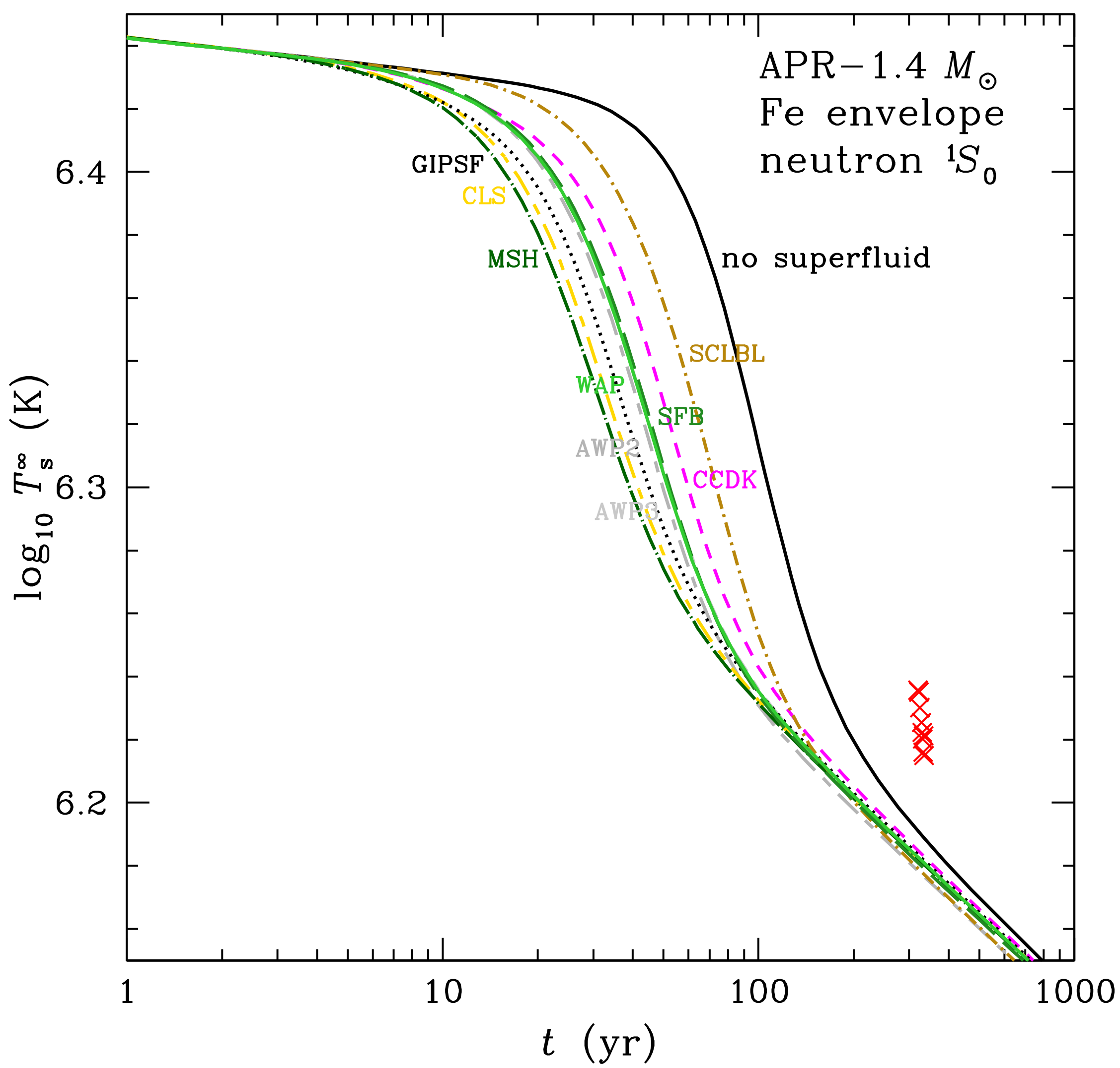
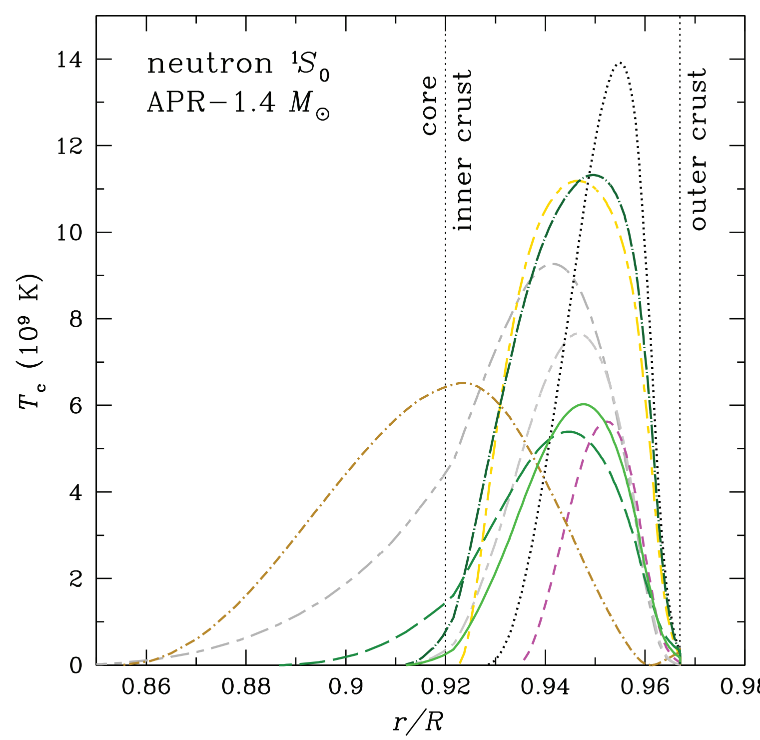


Figure from Page et al. (2013)]

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

Neutron singlet pairing for Cas A NS cooling

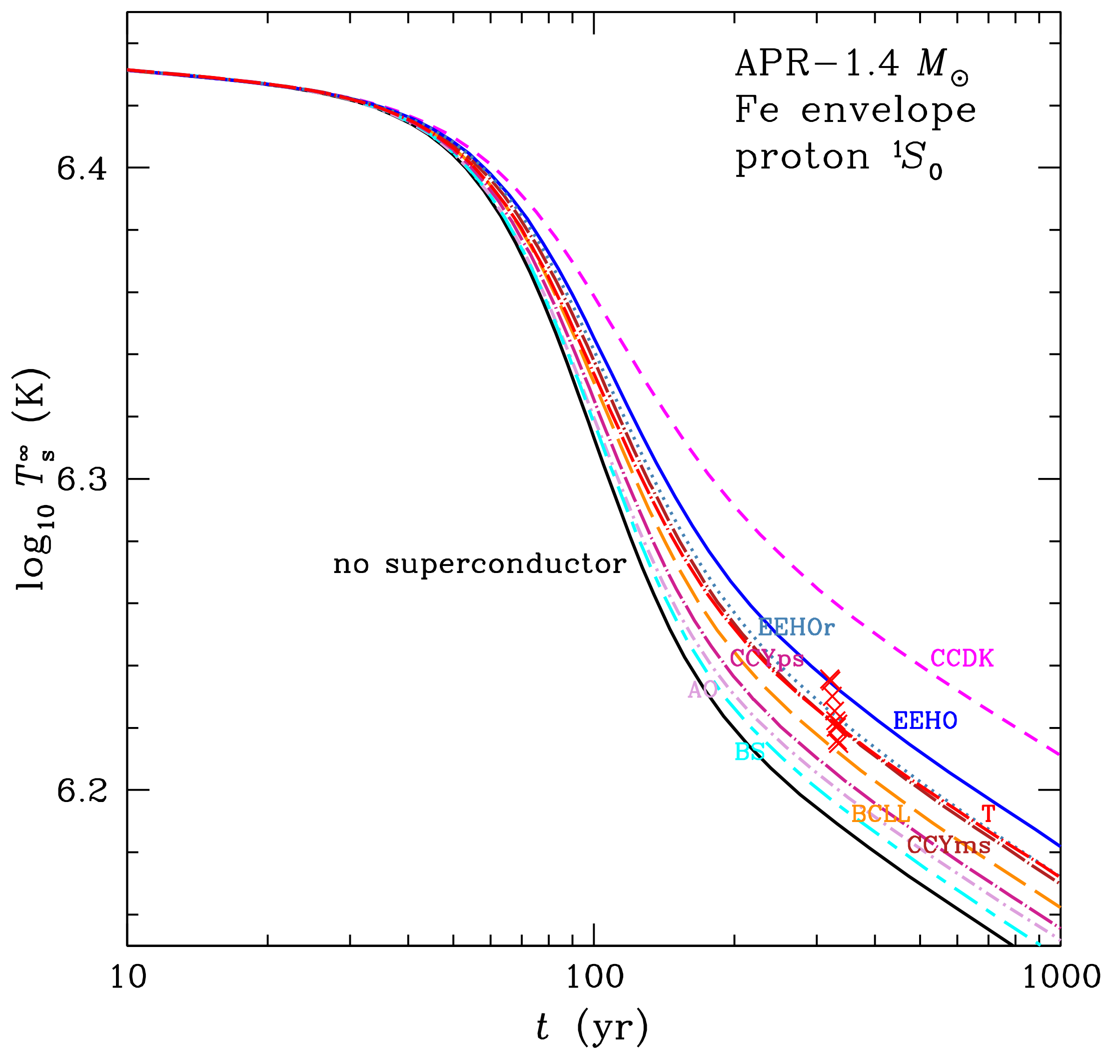


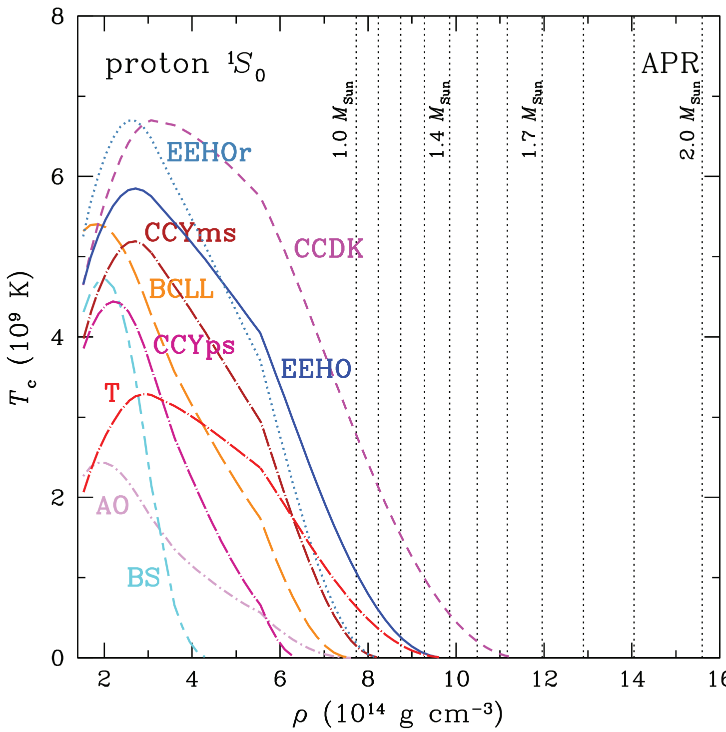


[Ho et al. (2015)]

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

Proton singlet pairing for Cas A NS cooling

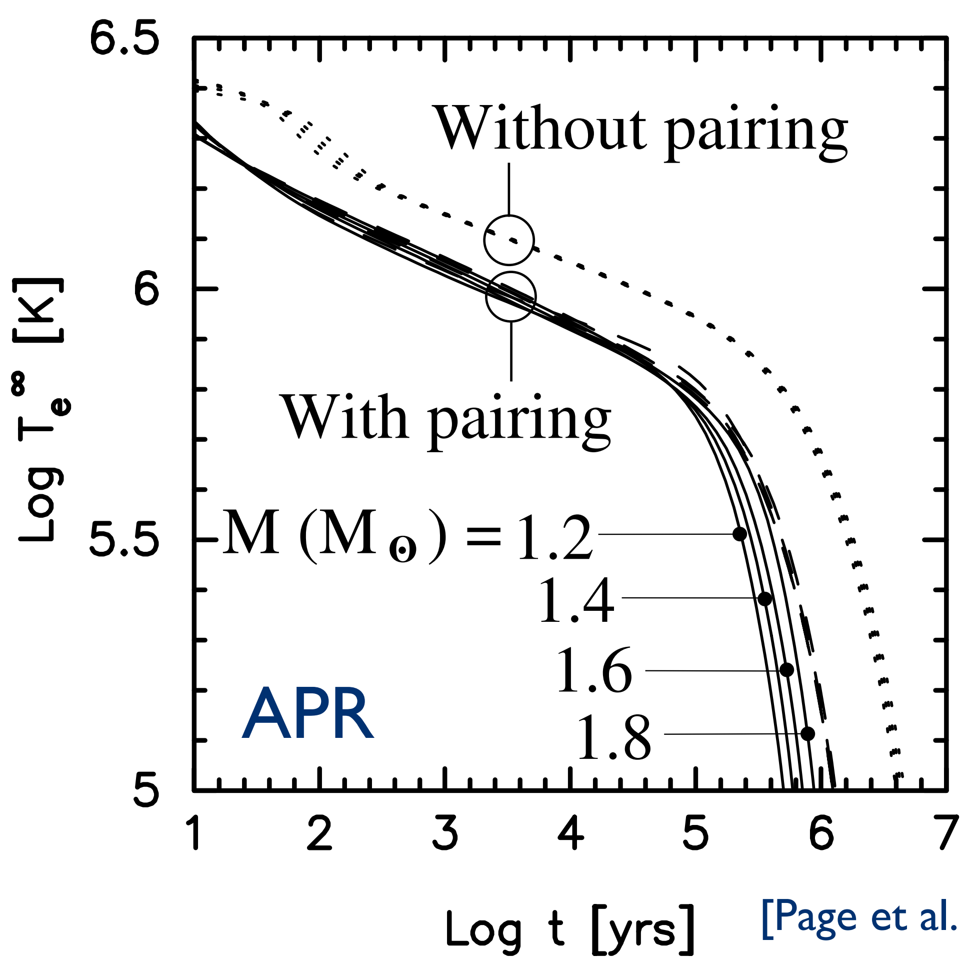




[Ho et al. (2015)]

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

Mass for thermal evolution

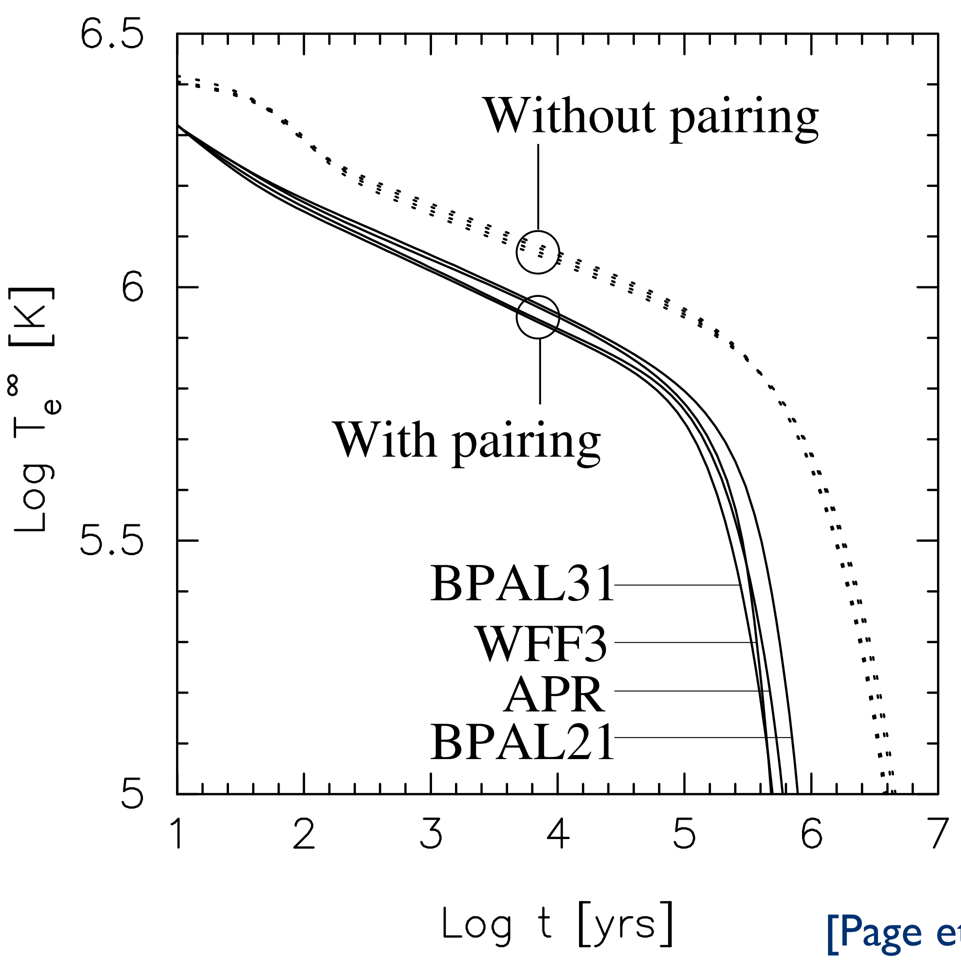


[Page et al. (2004)]

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

- 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

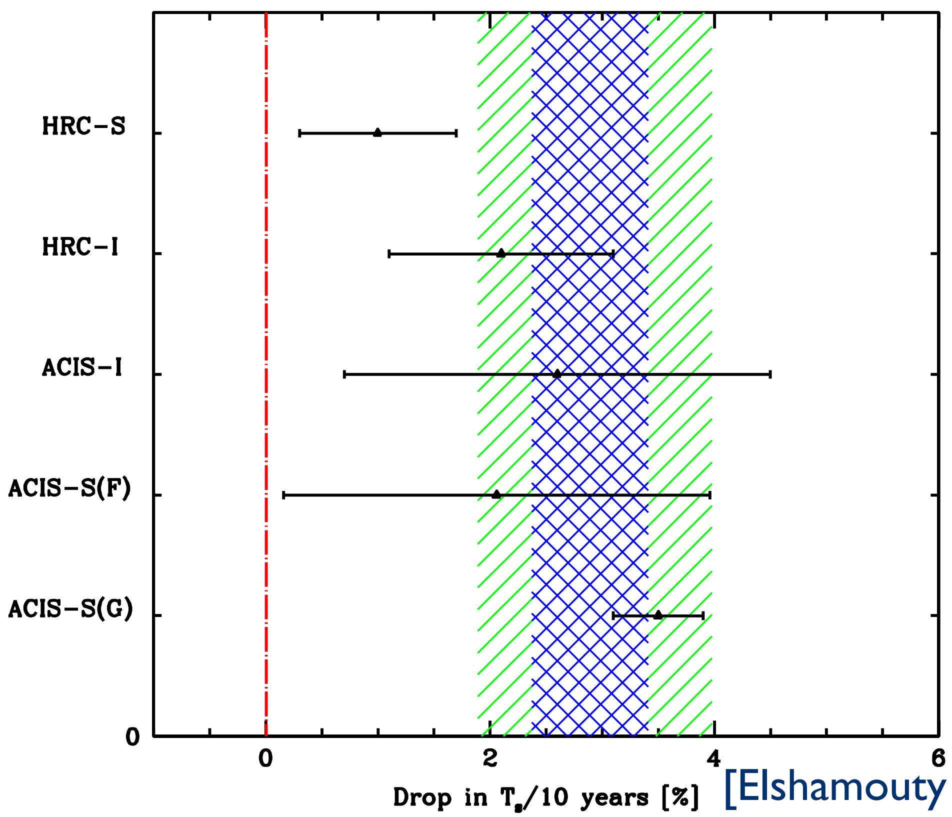
[Page et al. (2004)]

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

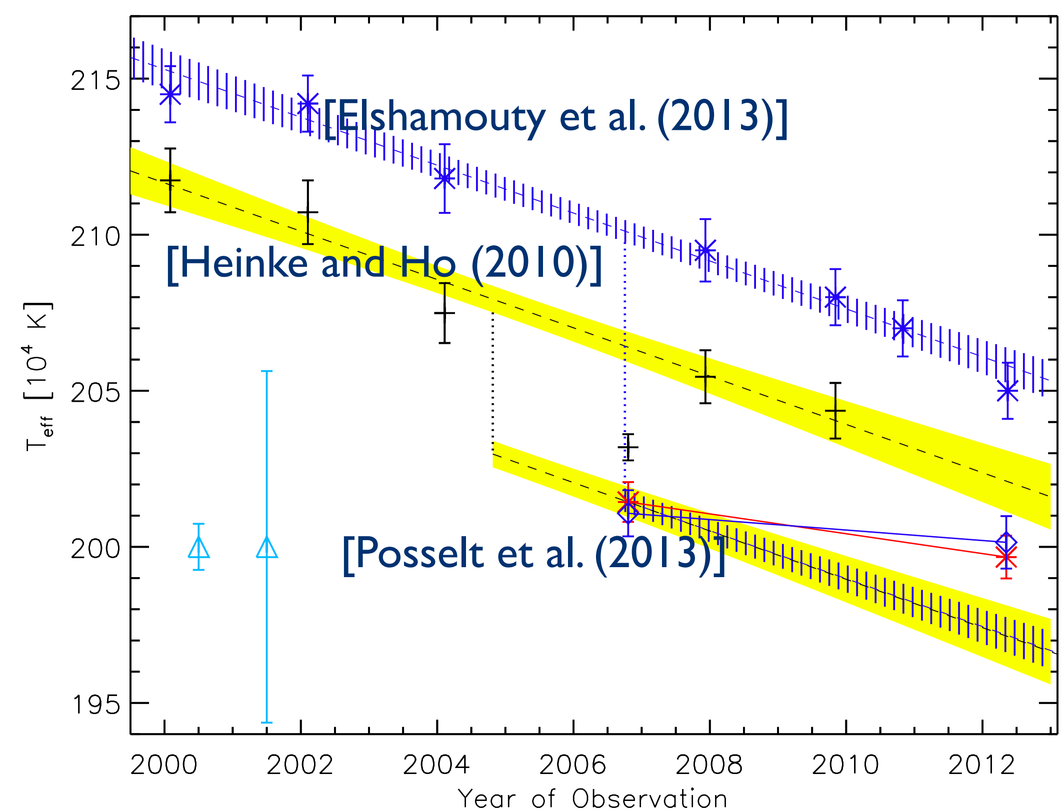
Other explanation of Cas A NS cooling

- 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



[Elshamouty et al. (2013)]



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