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

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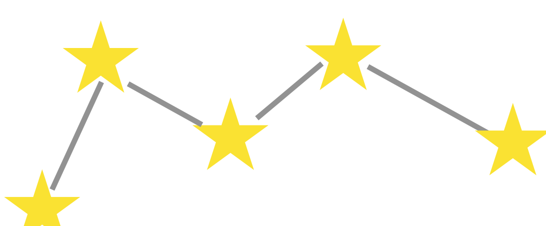


KEK-PH 2018 winter
Dec. 5, 2018

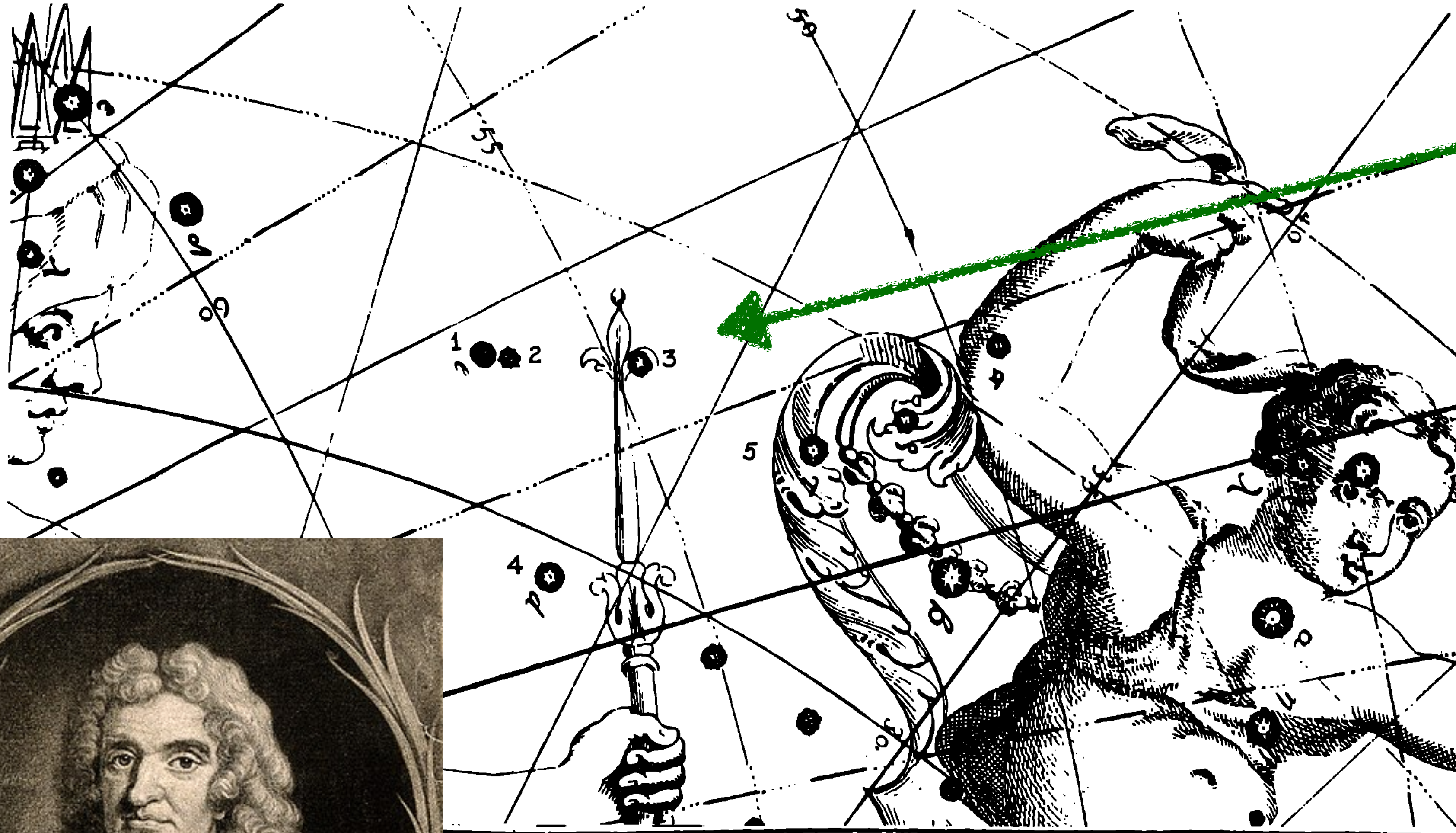
K. Hamaguchi, N. Nagata, K. Yanagi, and J. Zheng, Phys. Rev. **D98**, 103015 (2018).

Outline

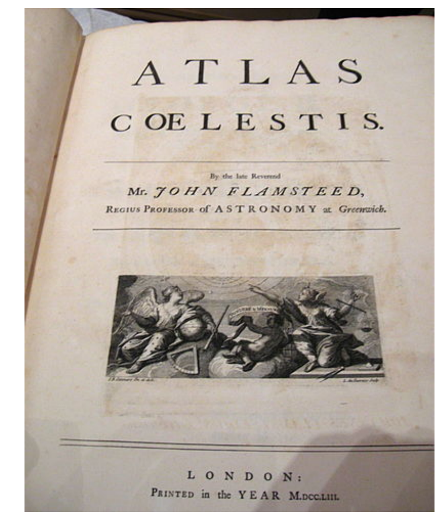
- Cassiopeia A (Cas A) Neutron Star
- Standard Neutron Star Cooling and Cas A
- Axion Emission from Neutron Star
- Conclusion

Cas A NS

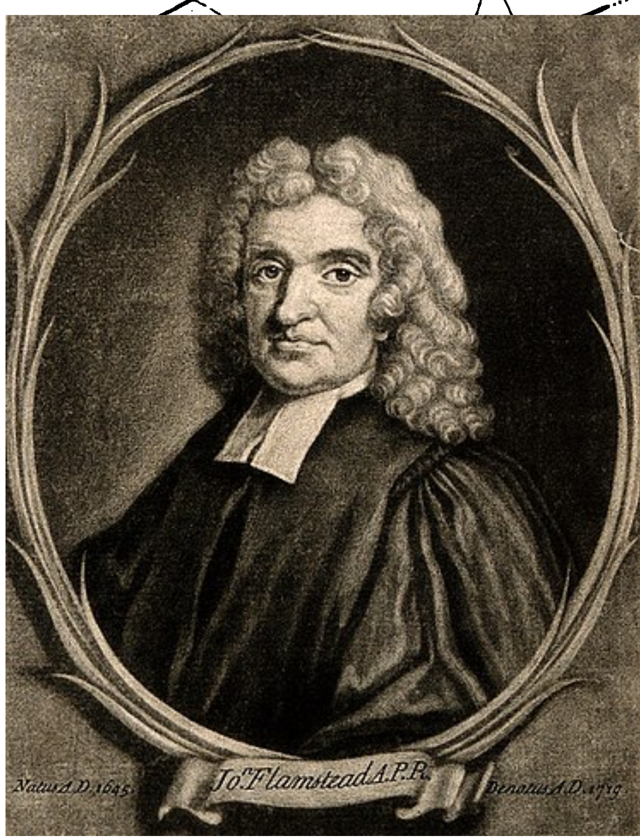
3 Cassiopeiae



3 Cassiopeiae



Atlas Coelestis (1729)



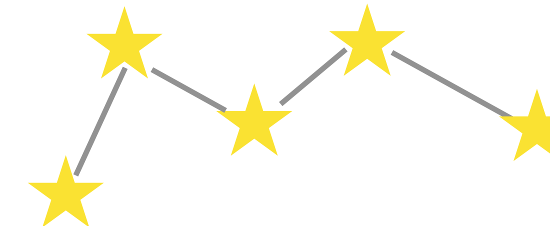
John Flamsteed

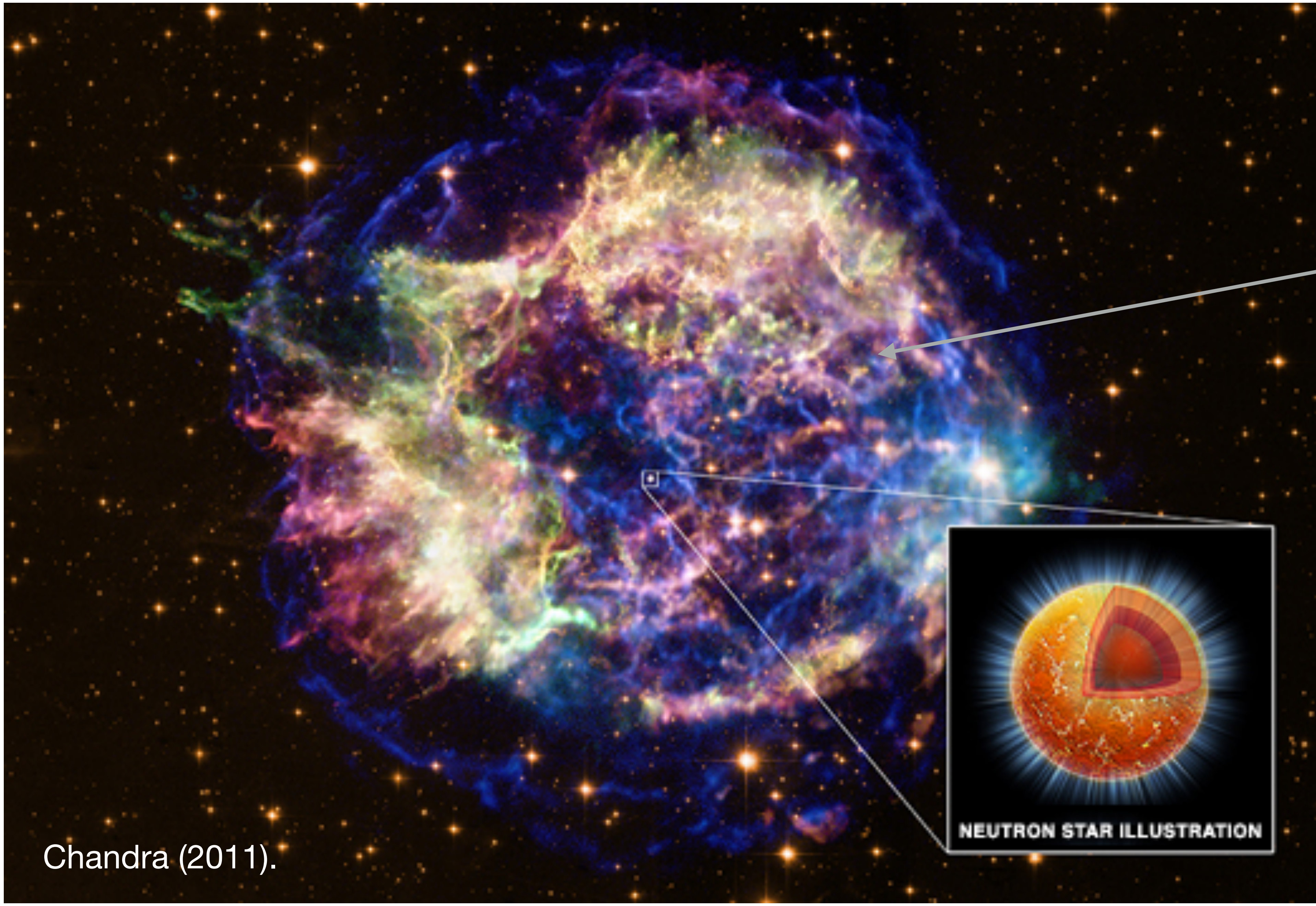
First Astronomer Royal

He recorded *3 Cassiopeiae* on August 16, 1680.

➡ Never been observed since then.

Cassiopeia A (Cas A)





$d = 3.4^{+0.3}_{-0.1}$ kpc

Explosion date estimated from the remnant expansion: 1681 ± 19.

Neutron star (NS) was found in the center.

Cas A NS Cooling

The Astrophysical Journal Letters, 719:L167–L171, 2010 August 20

DIRECT OBSERVATION OF THE COOLING OF THE CASSIOPEIA A NEUTRON STAR

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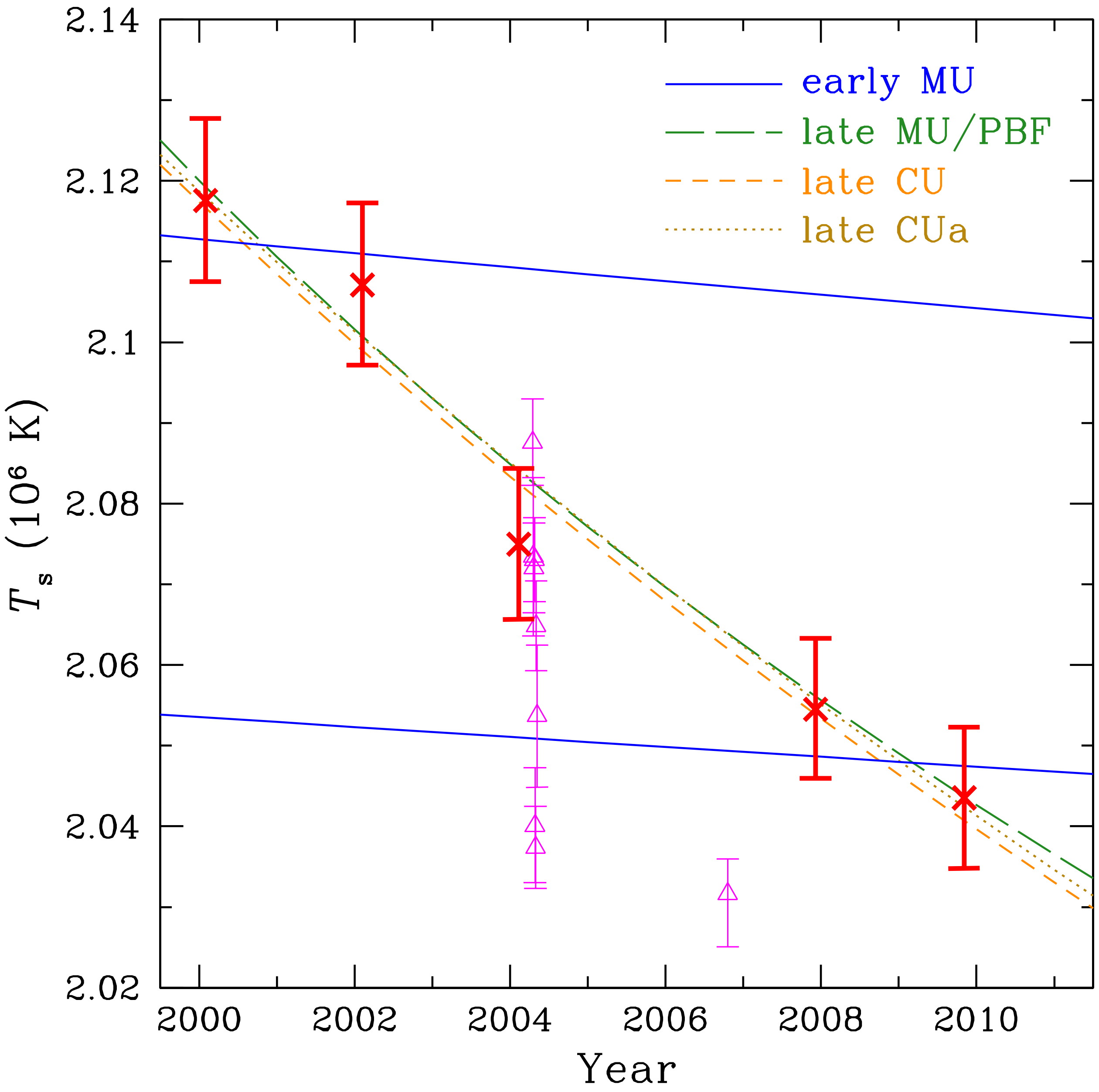
Chandra



Cooling of Cas A NS directly observed.

This was rather rapid.

Today's topic

- Observed cooling curve of the Cas A NS can be explained by the standard cooling theory.

D. Pager, M. Prakash, J. M. Lattimer, and A. W. Steiner, Phys .Rev. Lett. **106**, 081101 (2011);
See also, P. S. Shternin, D. G. Yakovlev, C. O. Heinke, W. C. G. Ho, and D. J. Patnaude, MNRS 412, L108 (2011).

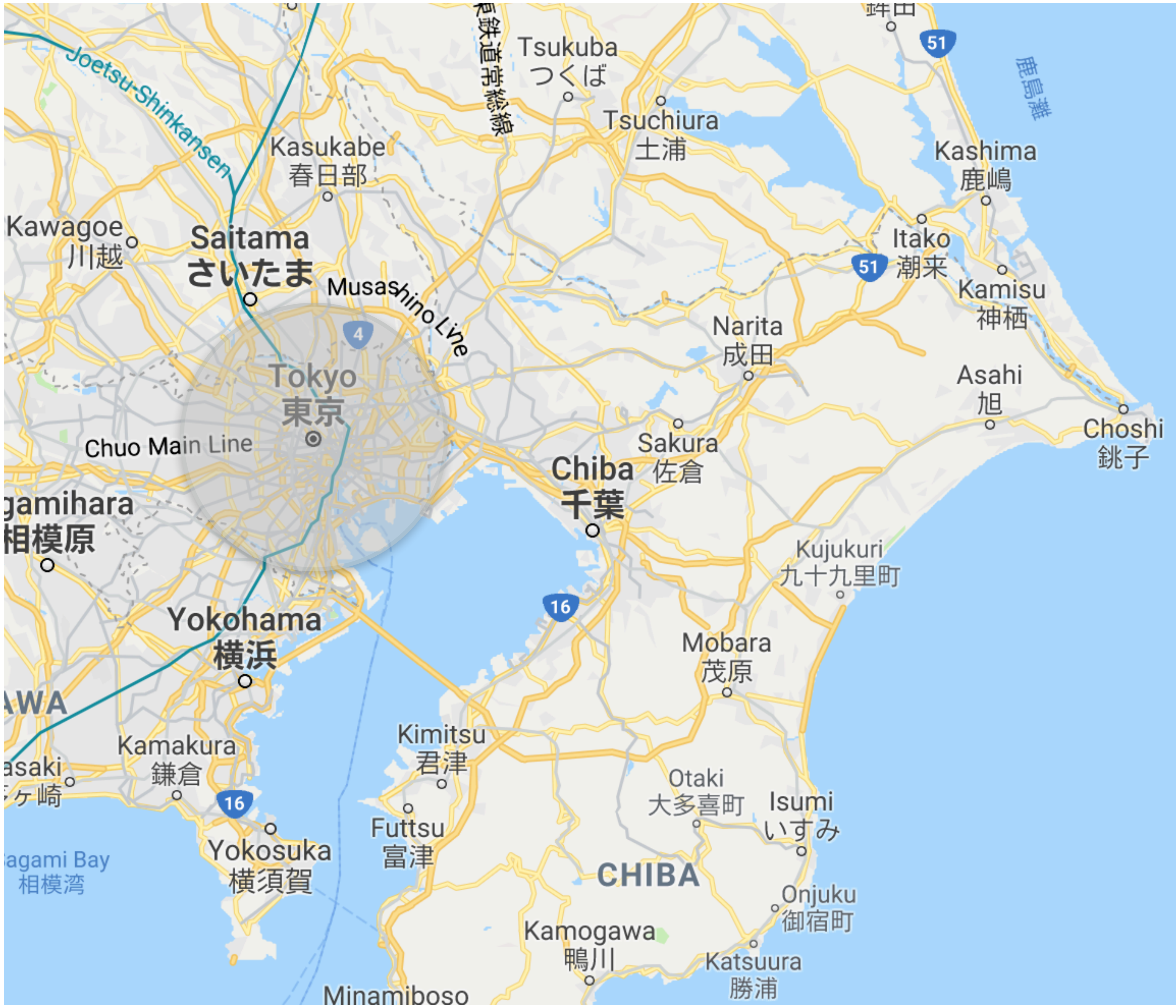
Neutron superfluidity plays an important role.

- This might be spoiled if there is an extra cooling source such as axion.

We may give a limit on such a cooling source.

Standard NS Cooling and Cas A

Size of neutron star vs Tokyo



- Radius ~10 km
- 1—2 $M_\odot$

As high as nuclear density.

- Neutrons, protons, electrons are degenerate.
- Neutrons and protons are in superfluidity and superconductivity.

Standard Cooling

Equation for temperature evolution

$$C(T)\frac{dT}{dt} = -L_\nu - L_\gamma - L_{\mathrm{cool}}$$

C(T): Stellar heat capacity

L_ν: Luminosity of neutrino emission

L_γ: Luminosity of photon emission

L_{cool}: Extra cooling source

Photon emission — Dominant for $t \gtrsim 10^5$ years

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

Neutrino emission — Dominant for $t \lesssim 10^5$ years

- Direct Urca process — β decay. Occurs only in a heavy NS.
- Modified Urca process
- Bremsstrahlung
- PBF process — Occurs just after nucleon pairs form.

Pairing effects on neutron star cooling

Nucleons in a NS are expected to form pairings:

- Neutron singlet $^1S_0$ — Only in the crust
- Proton singlet $^1S_0$
- Proton triplet $^3P_2$

Form in the core. Important.

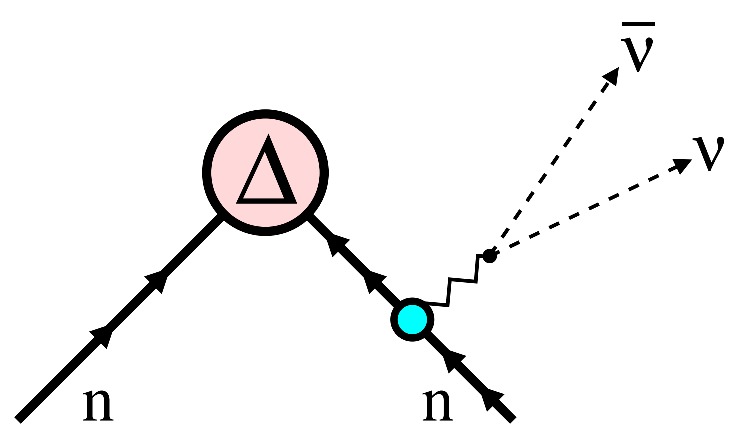
Effects of pairings

- Ordinary neutrino emission processes are suppressed.

Due to the energy gap.

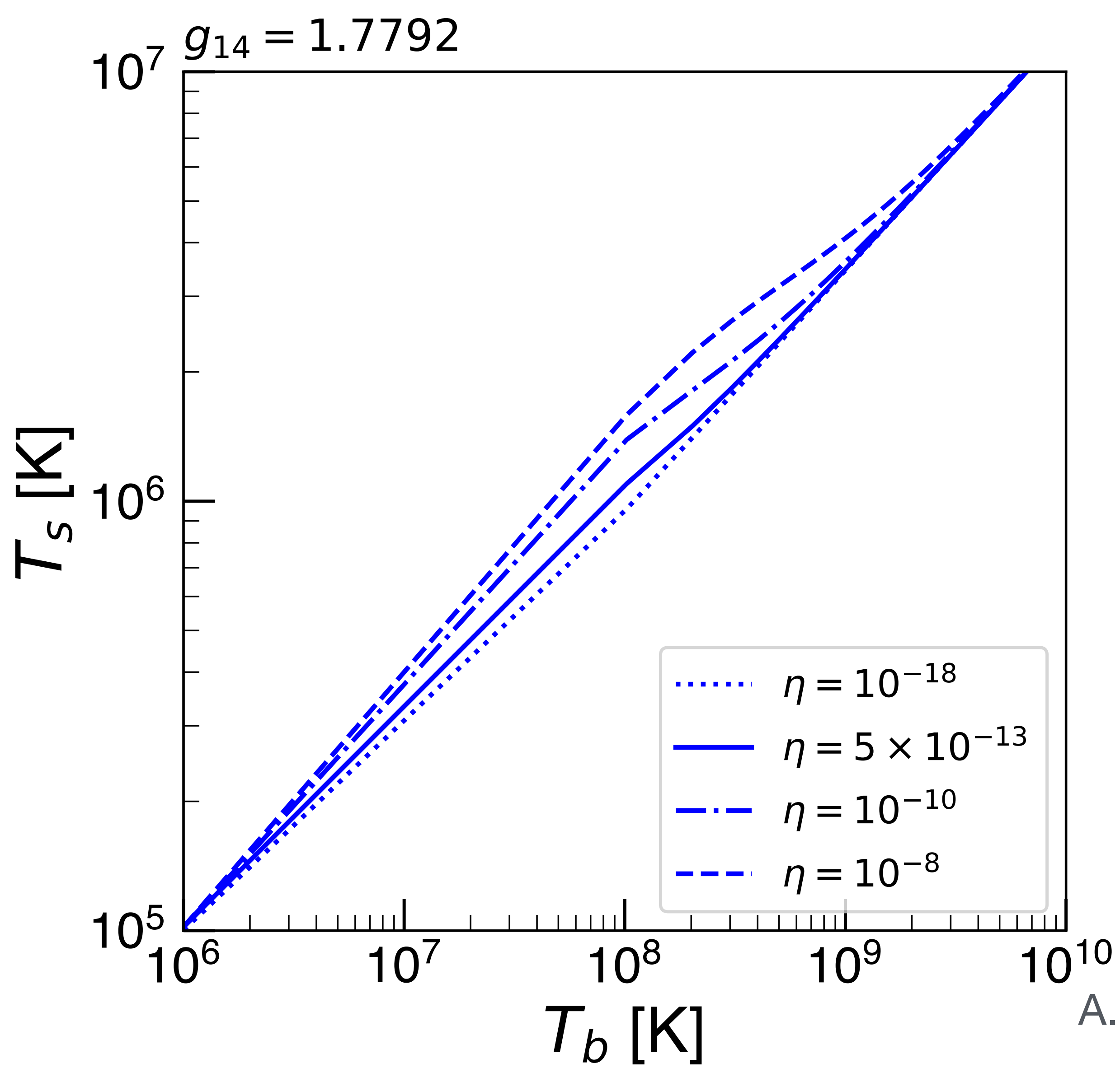
- Cooper pair breaking and formation (PBF) enhances neutrino emission.

This process significantly enhances the neutrino emission when $T \lesssim T_C$



Surface temperature

It is the surface temperature that we observe, so we need to relate it to the internal temperature.



This relation depends on the amount of light elements in the envelope.

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

g_{14}: surface gravity in units of 10^{14} cm s^{-2}.

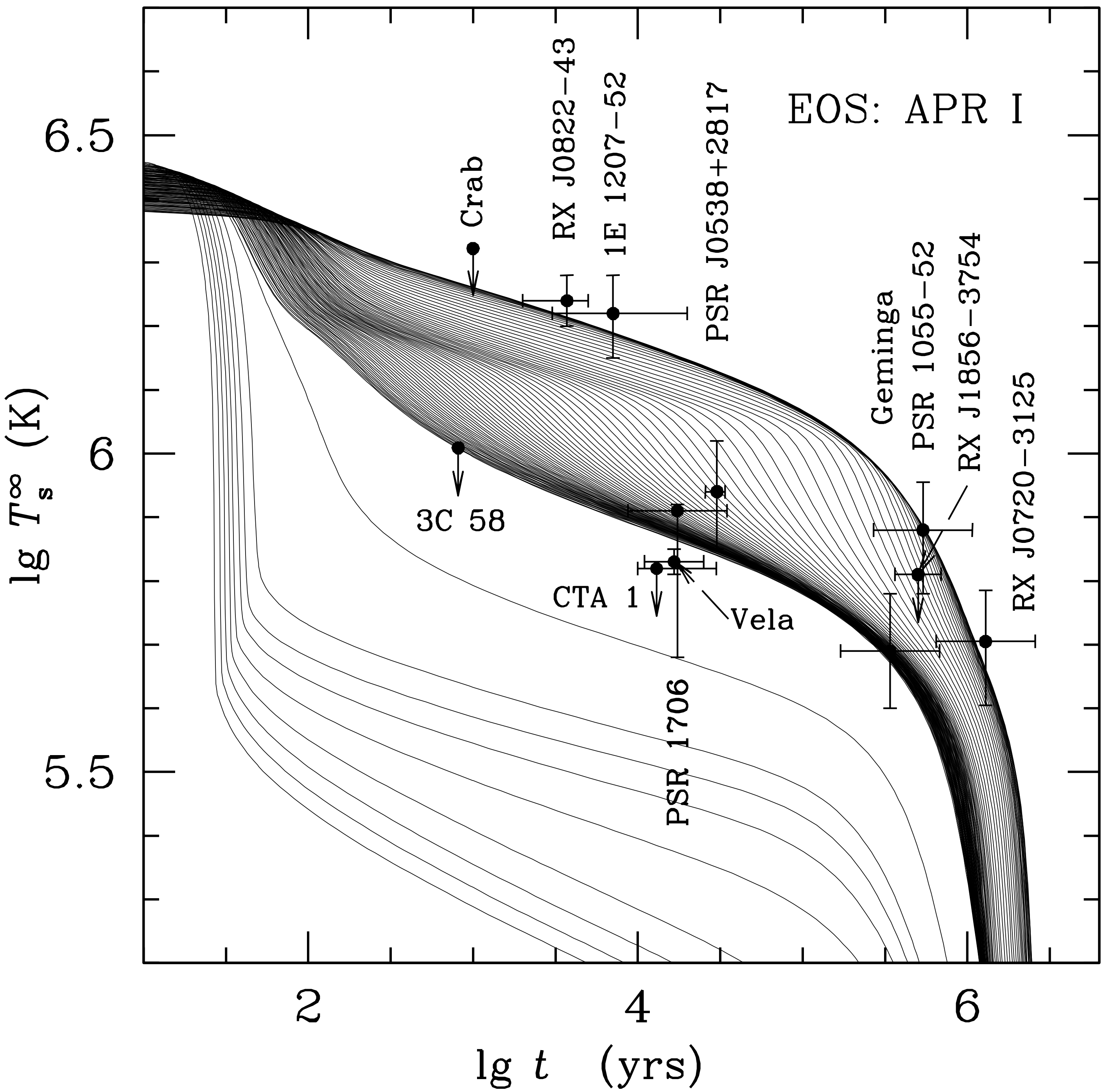
ΔM: mass of light elements.

A. Y. Potekhin, G. Chabrier, and D. G. Yakovlev, A&A **323,** 415 (1997).

As the amount of light elements gets increased, the surface temperature becomes larger.

Light elements have large thermal conductivities.

Success of Standard Cooling



$$M = (1.01 - 1.92)M_\odot$$

O. Y. Gnedin, M. Gusakov, A. Kaminker, D. G. Yakovlev, Mon. Not. Roy. Astron. Soc. **363,** 555 (2005).

Standard cooling scenario can explain most of the data.

How to explain Cas A cooling

Observation

3—4% decrease in ten years.

Modified Urca/Bremsstrahlung

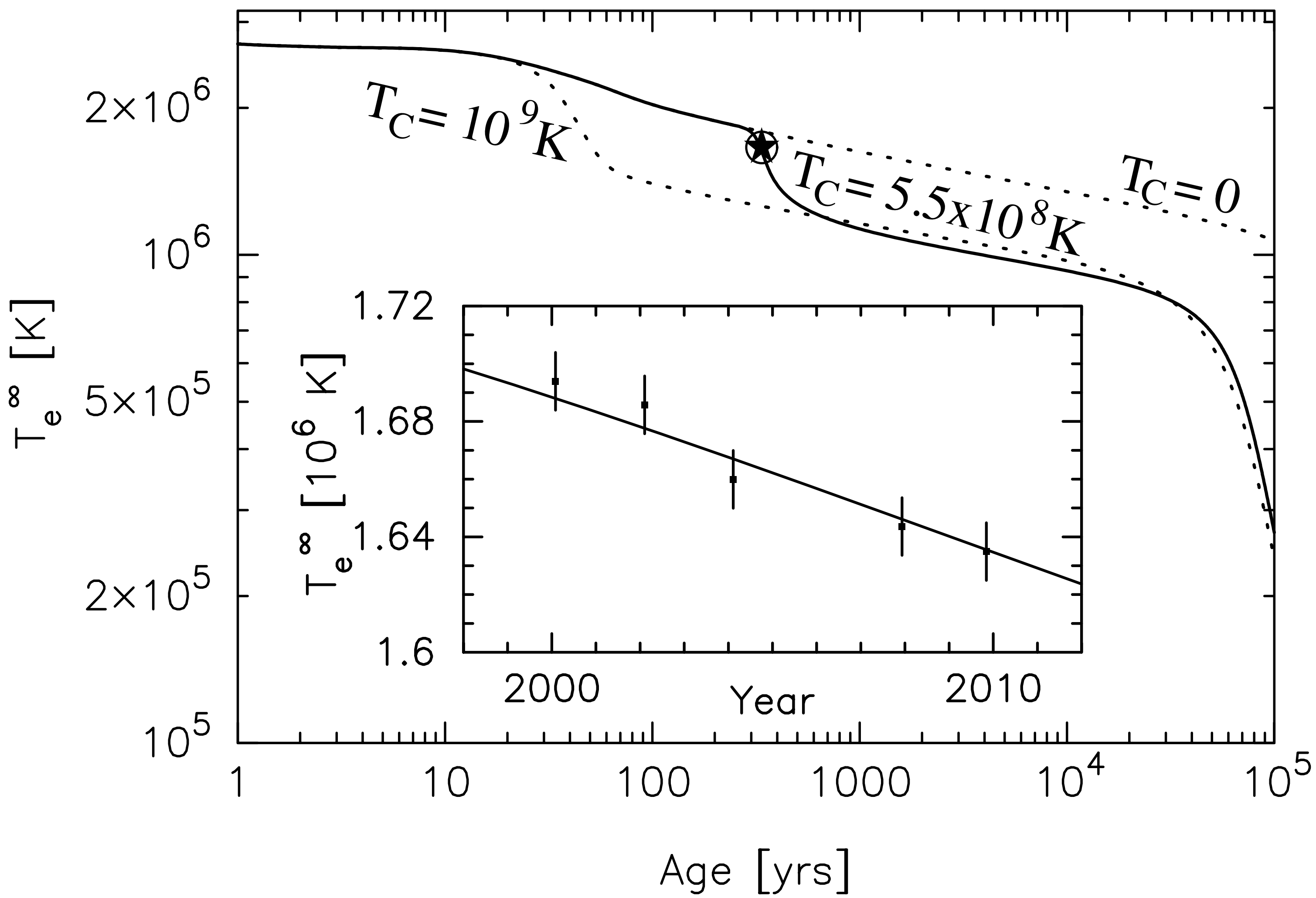
Only 0.3% decrease in T in ten years.

PBF

Rapid cooling but does not last so long.

If this process has just started recently, the Cas A NS cooling can be explained.

Fit in the minimal cooling paradigm



D. Pager, M. Prakash, J. M. Lattimer, and A. W. Steiner, Phys .Rev. Lett. **106**, 081101 (2011).

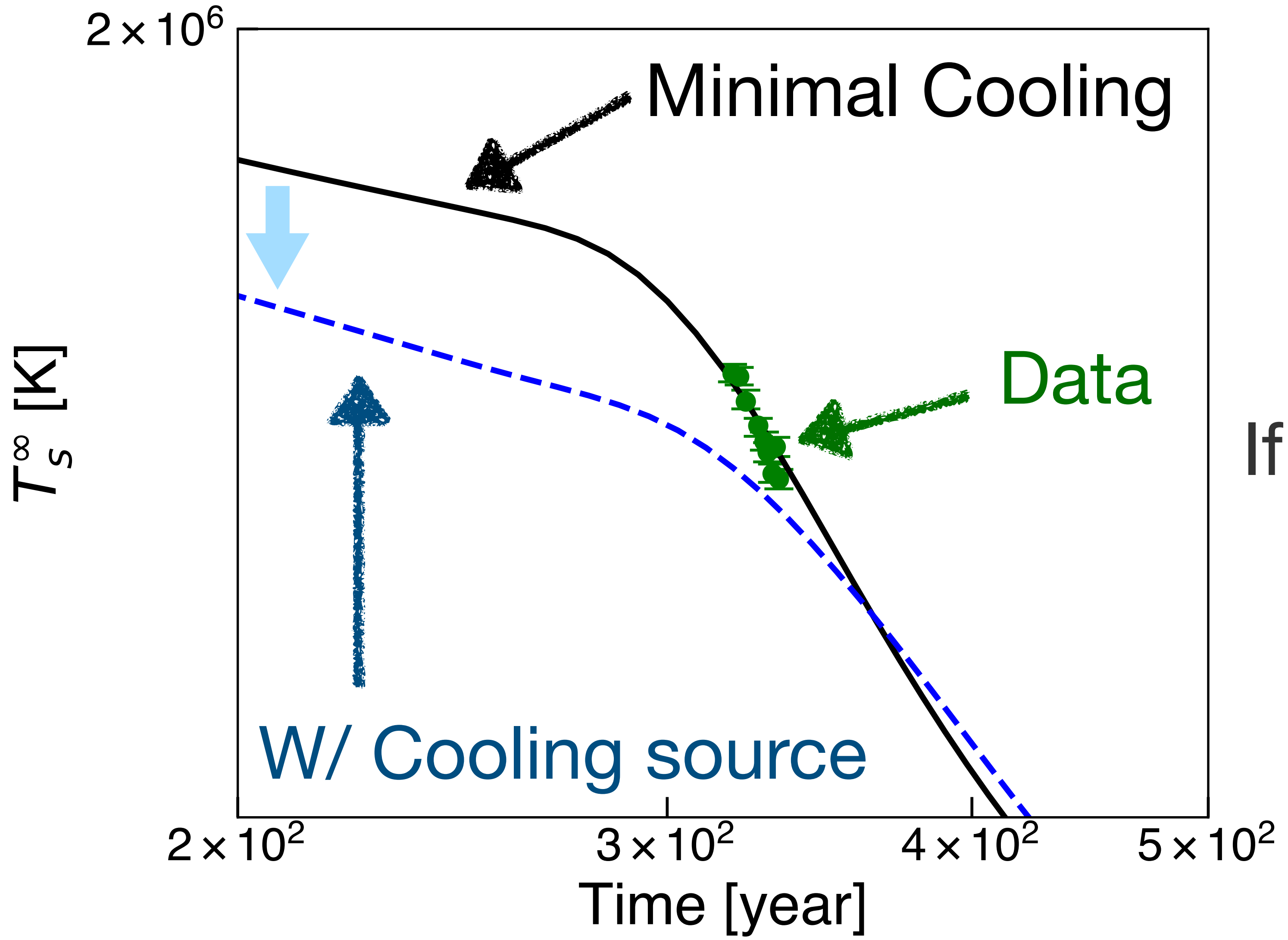
Critical temperature of neutrino triplet pairings is taken to be

$$T_C^{(n)} \sim 5 \times 10^8 \text{ K}$$

PBF has just started.

Cas A NS cooling can be explained.

Cooling source and Cas A NS



If there is a cooling source,

- Temperature
- Cooling rate

decrease.

Cas A NS data cannot be explained.

Limit on the cooling source!

We consider axion as a cooling source.

Axion emission from NS

Axion-nucleon couplings

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

KSVZ axion model J. E. Kim (1970); M. A. Shifman, A. I. Vainshtein, V. I. Zakharov (1980).

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

Note that C_n may be zero within uncertainty.

DFSZ axion model A. R. Zhitnitsky (1980); M. Dine, W. Fischler, M. Srednicki (1981).

$$C_{u,c,t} = \frac{1}{3}\cos^2\beta, \quad C_{d,s,b} = \frac{1}{3}\sin^2\beta$$

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

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

Both can be sizable.

Axion emission processes

- PBF
- Bremsstrahlung

We have modified NSCool to implement these processes.

Other details

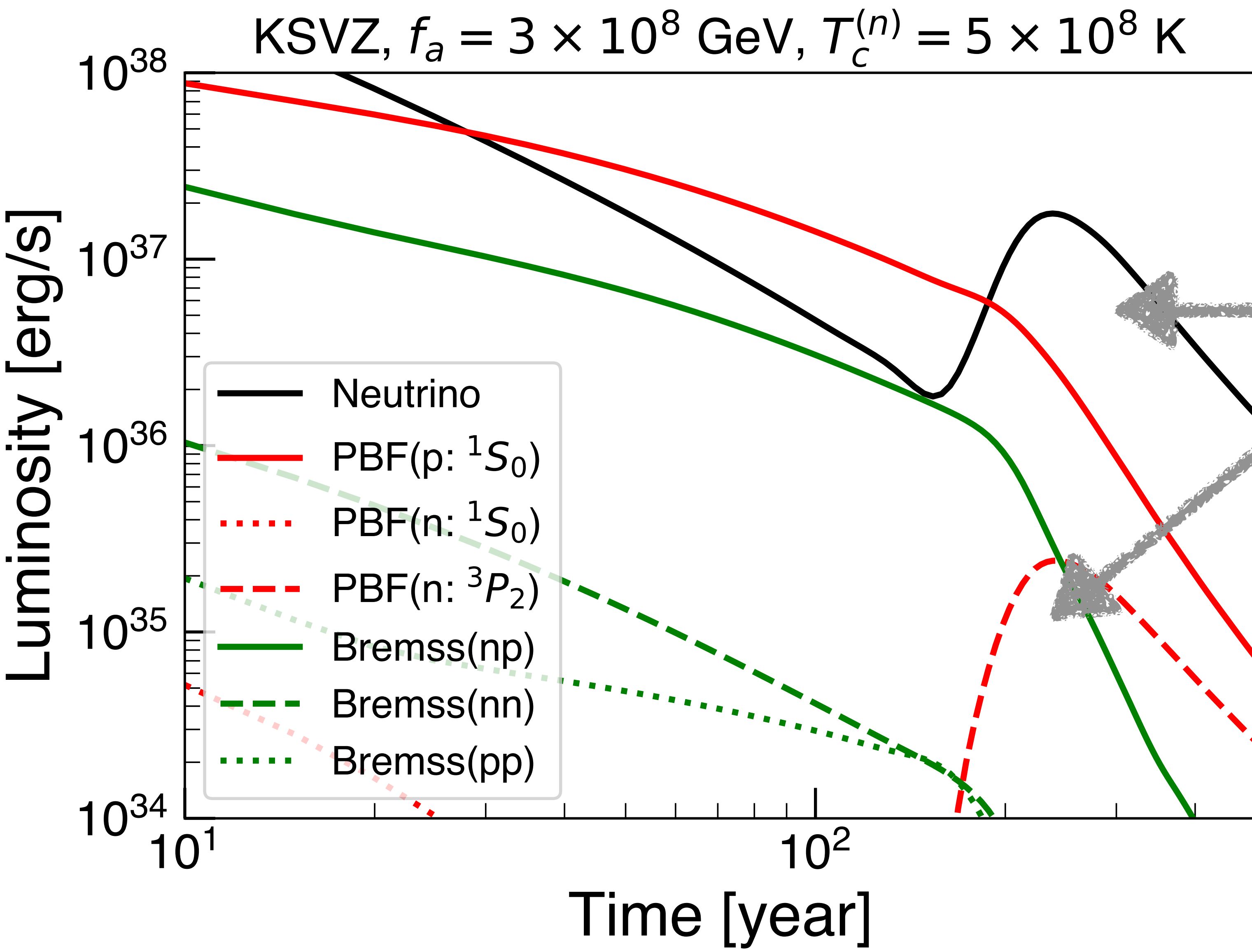
- APR equation of state
- NS mass: $M = 1.4 M_\odot$
- Neutron $^1S_0$ gap: SFB model   Not so relevant.
- Proton $^1S_0$ gap: CCDK model

Any gap models are OK as long as it is large enough.

- Neutron $^3P_2$ gap (Highly uncertain)

Regard gap height ($\propto T_C$) and width as free parameters.

Luminosity of axion emission



Onset of neutron triplet pairing.

Neutron PBF

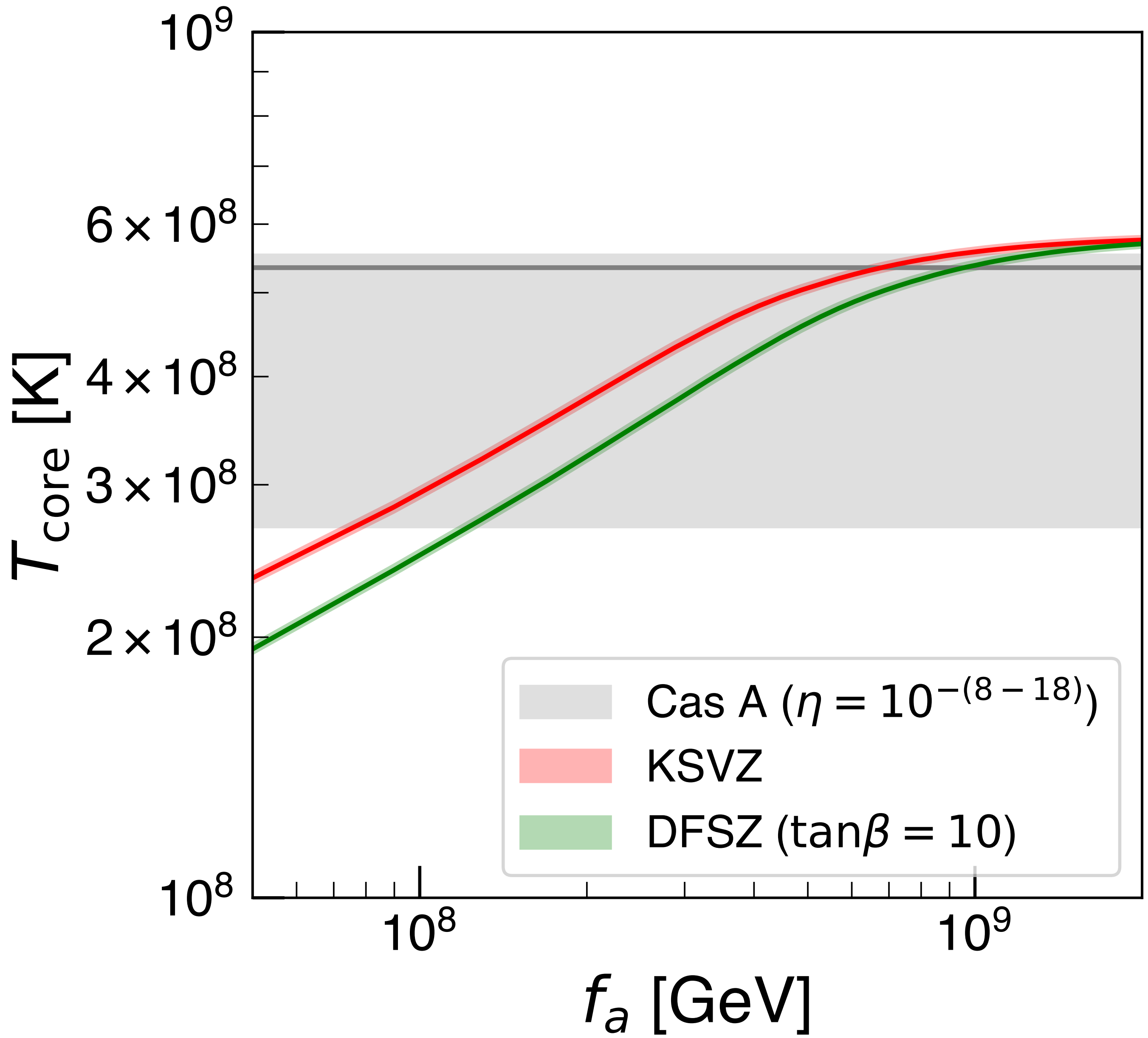
Axion emission can be as strong as neutrino emission.

Axion emission is sizable even if $C_n \simeq 0$

K. Hamaguchi, N. Nagata, K. Yanagi, and J. Zheng, Phys. Rev. **D98**, 103015 (2018).

Core temperature of Cas A NS

Inferred core temperature @ Cas A NS age (Jan. 30, 2000)



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

Band: t = 300—338 years

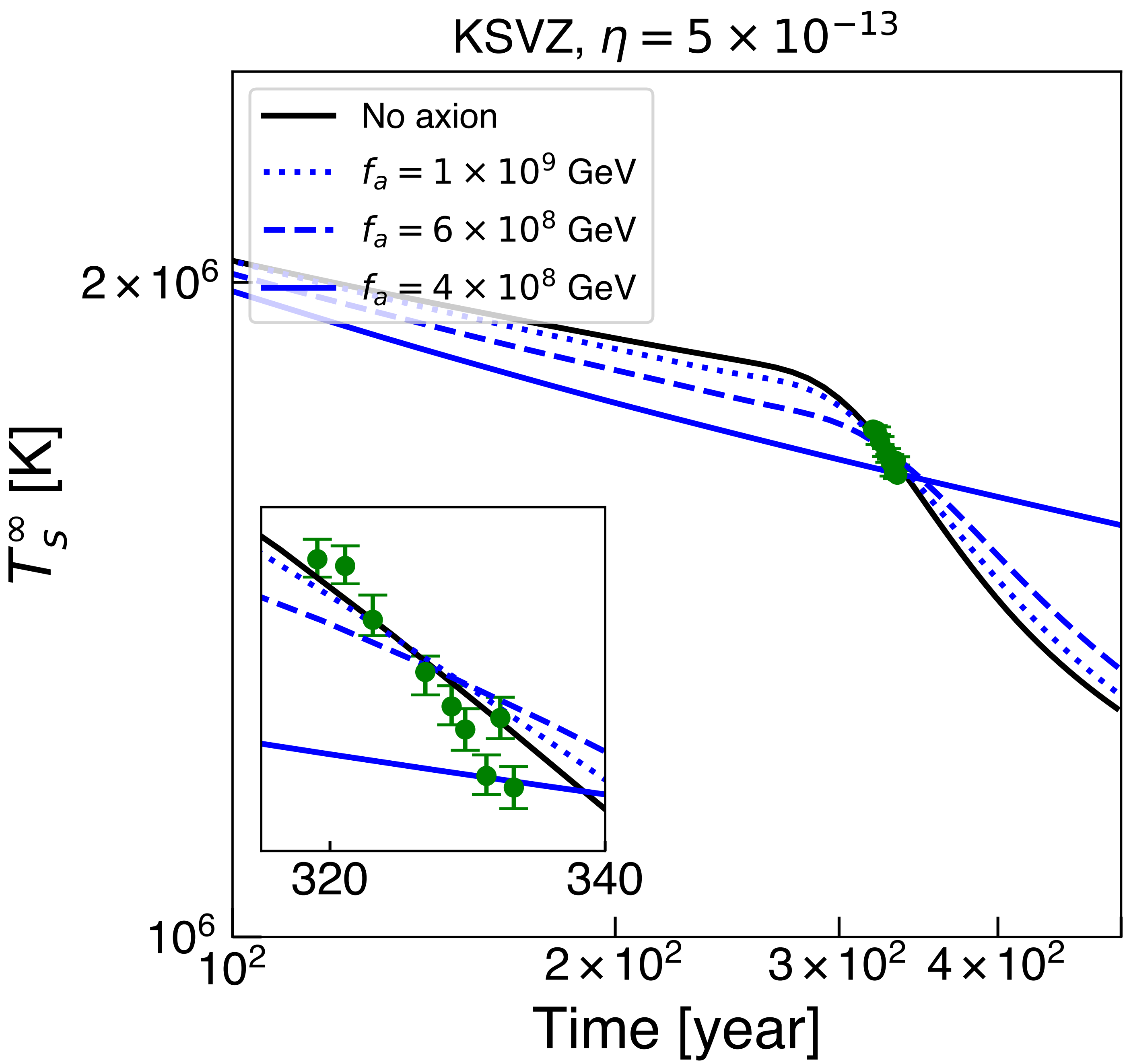
No neutron triplet superfluidity

Core temperature is too low for $f_a \lesssim$ a few $\times 10^8$ GeV

Large uncertainty due to the ignorance of the envelope properties.

K. Hamaguchi, N. Nagata, K. Yanagi, and J. Zheng, Phys. Rev. **D98**, 103015 (2018).

Cooling curves vs data



Our limit

$$f_a \gtrsim 5\ (7) \times 10^8\ \text{GeV}$$

KSVZ (DFSZ, tanβ = 10)

Cf.) SN1987A

$$f_a \gtrsim 4 \times 10^8\ \text{GeV} \quad \text{(KSVZ)}$$

We obtained a bound comparable to other astrophysical limits.

K. Hamaguchi, N. Nagata, K. Yanagi, and J. Zheng, Phys. Rev. **D98**, 103015 (2018).

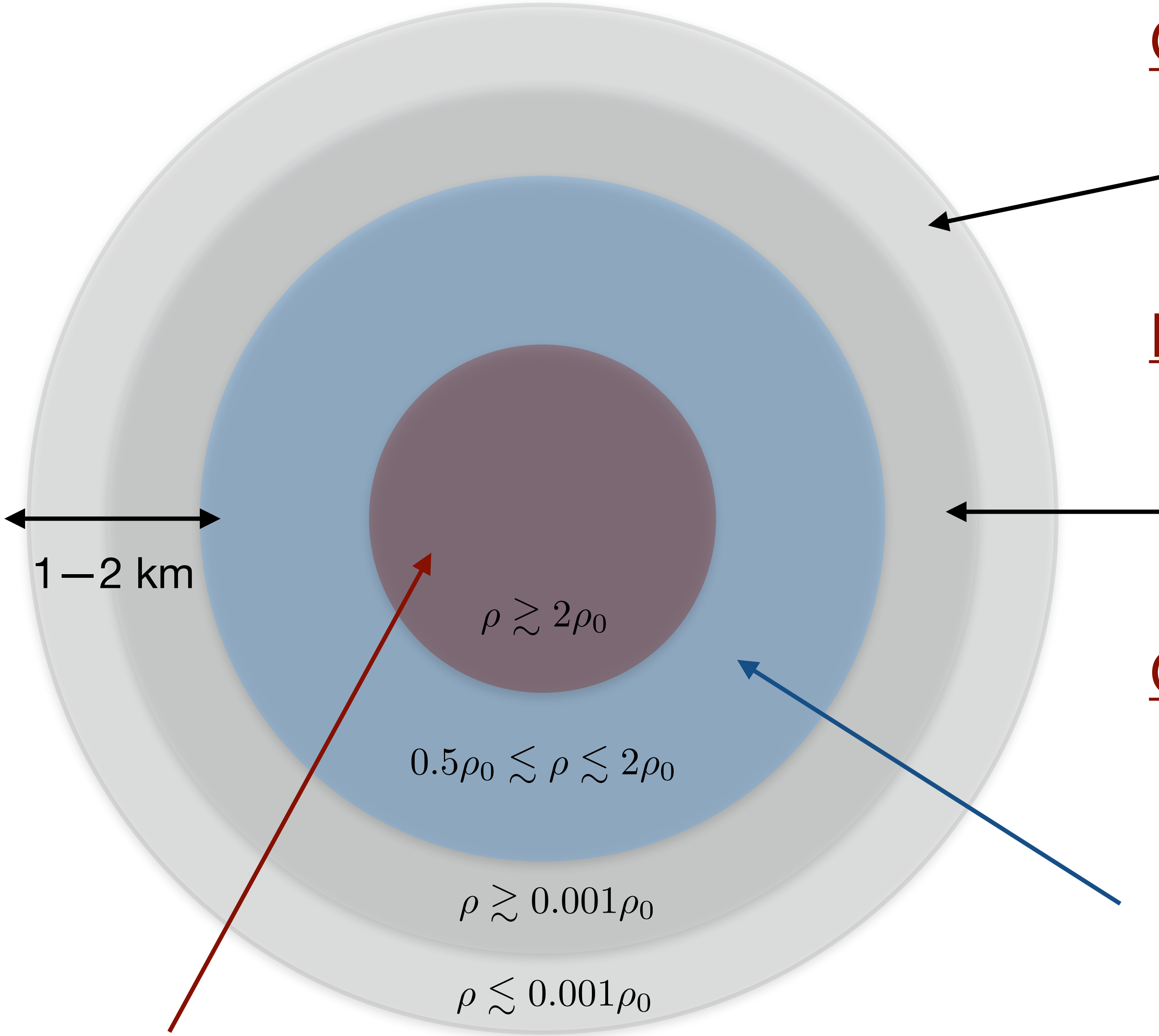
Conclusion

Conclusion

- Observed rapid cooling of Cas A NS can be explained in the minimal cooling scenario.
- Presence of additional cooling source may spoil the success, which thus restricts such possibilities.
- We obtain a lower limit on the axion decay constant, which is as strong as existing astrophysical bounds.

Backup

Neutron star structure



Outer crust

Neutron-rich nucleus (crystal)

Electron

Inner crust

Neutron-rich nucleus, electron

Neutron superfluid: $^1S_0$

Outer crust

Electron, muon

Neutron superfluid: $^3P_2$

Proton superconductor: $^1S_0$

- Fermi momentum of neutrons is so large that neutron pairs cannot form singlet.
- Proton density is not so large. Proton pairs can form singlet.

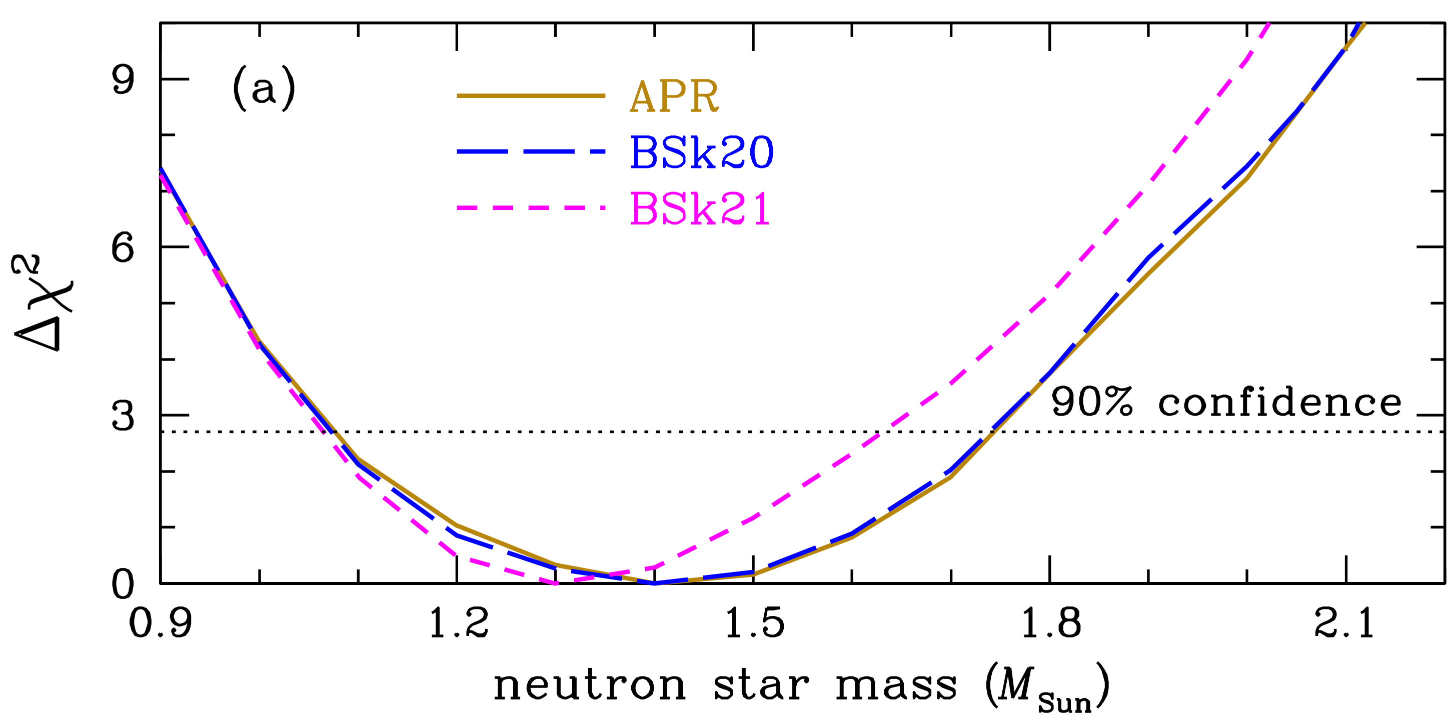
Inner crust

$$\rho_0 = 2.8 \times 10^{14}\ \mathrm{g \cdot cm^{-3}}$$

Neutron superfluid: $^3P_2$

Hyperons, π/K condensation, quarks (?)

Spectral fit of Cas A NS



K. G. Elshamouty, C. O. Heinke, W. C. Ho, A. Y. Potekhin, Phys .Rev. **C91**, 015806 (2015).

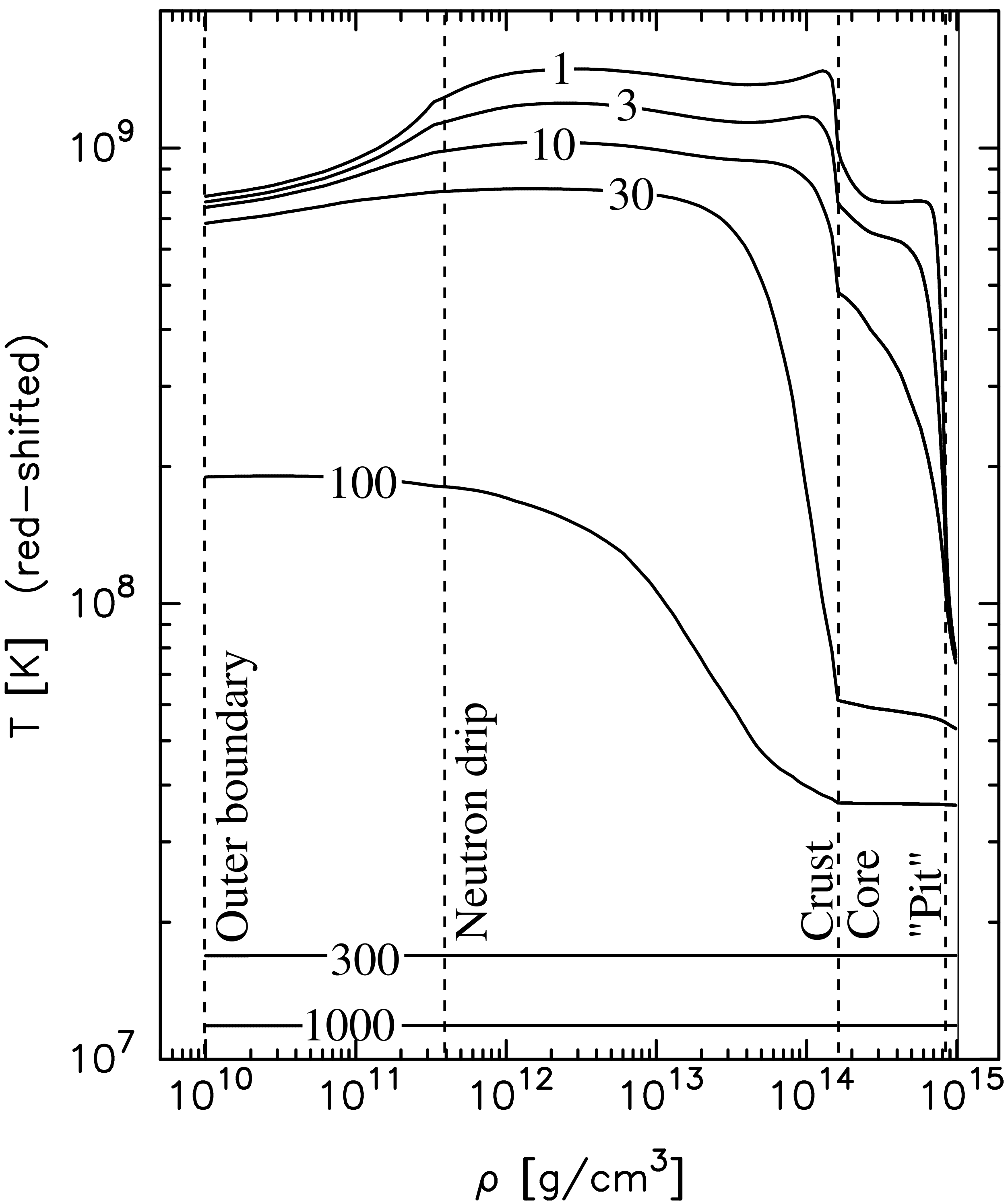
- Non-magnetic carbon atmosphere model fits the X-ray spectrum of Cas A NS quite well.

C. O. Heinke, W. C. Ho, Nature **462**, 71 (2009).

- Through the gravitational redshift, we can infer the NS mass.

$$M \simeq (1.4 \pm 0.3) M_\odot$$

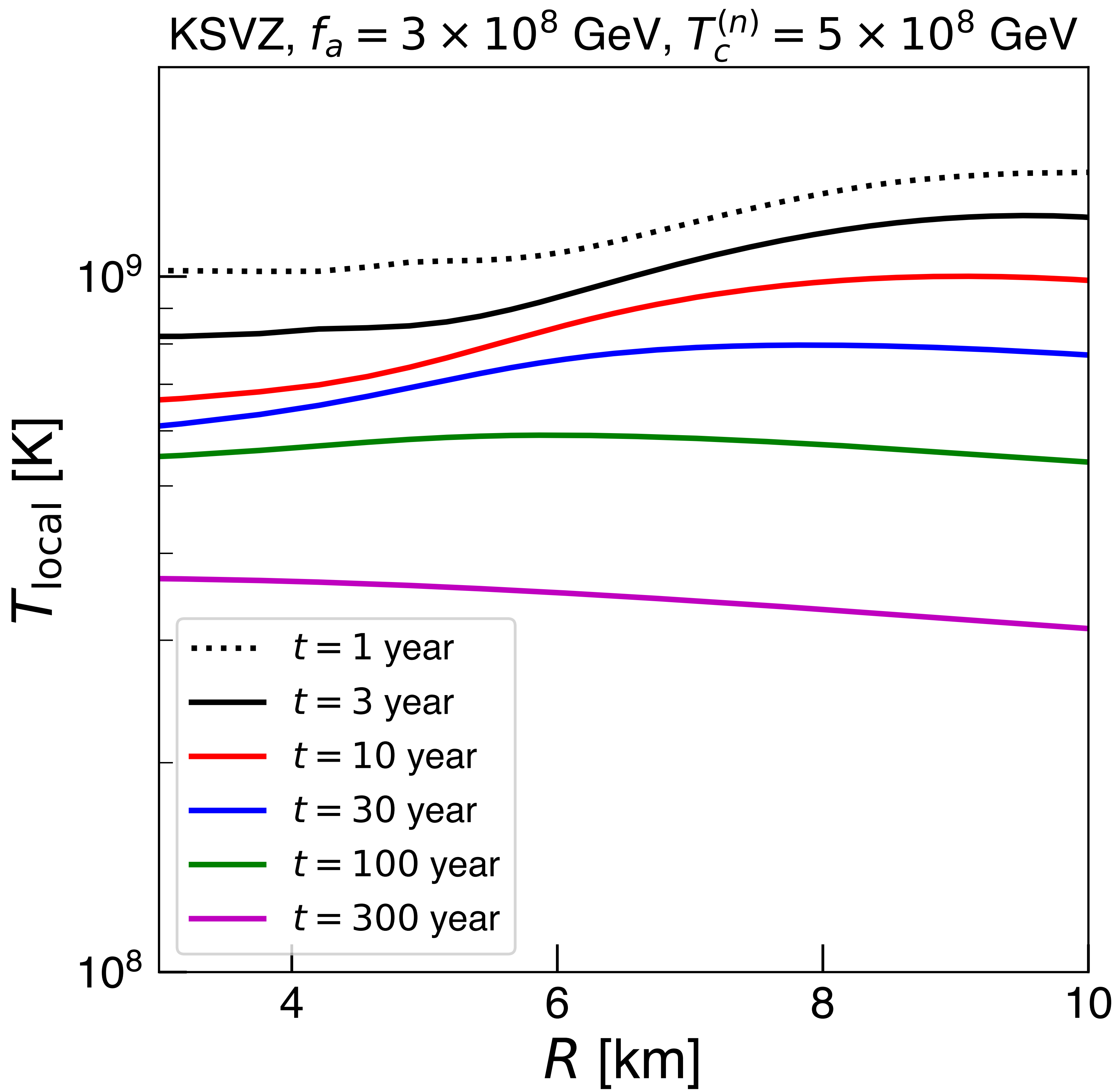
Temperature distribution



Relaxation in the Core done in ~ 100 years.

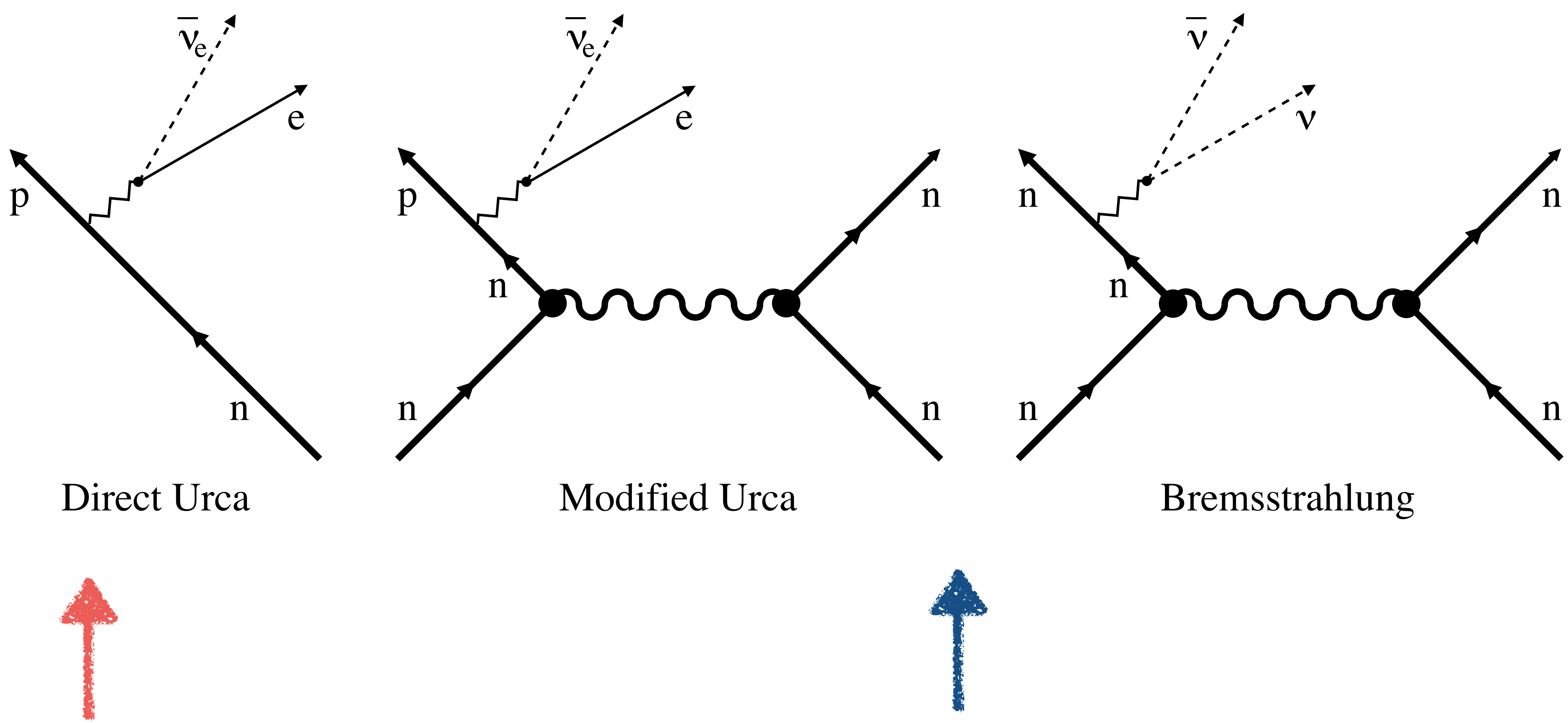
D. Page, J. M. Lattimer, M. Prakash, A. W. Steiner [arXiv: 1302.6626].

Relaxation in the presence of axion



Neutrino emission

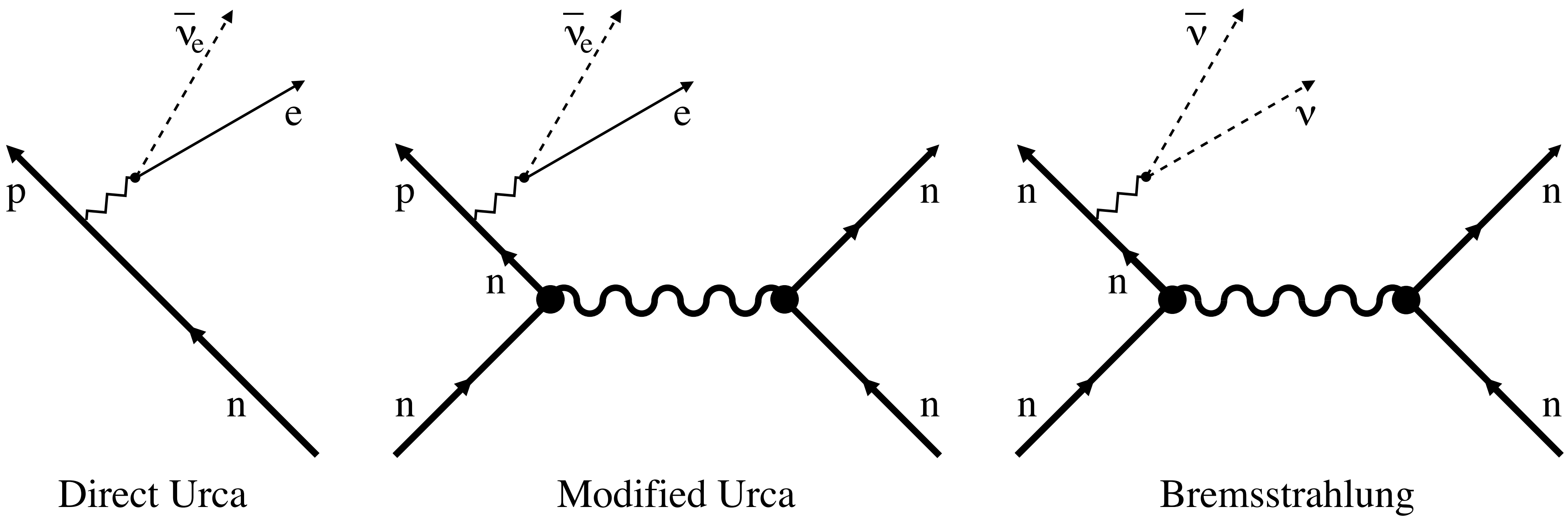
Other neutrino emission process can occur via the momentum exchange with another nucleon.



$\propto T^6$ $\propto T^8$

If the direct Urca process can occur, the neutrino emission is significantly increased.

Neutrino emission



These processes occur near the Fermi surface.

$$p_F \simeq 300 \times \left(\frac{\rho_0}{2 \times 10^{14}\ \mathrm{g/cm^3}} \right)^{\frac{1}{3}}\ \mathrm{MeV}$$

$$p_F \gg T,\ m_n - m_p$$

If the direct Urca process can occur, the neutrino emission is significantly increased.

Direct Urca process $n \to p + e^- + \nu, \quad e^- + p \to n + \nu$

Chemical equilibrium

$$\mu_e + \mu_p = \mu_n \quad \Rightarrow \quad p_{F,e} + \frac{p_{F,p}^2}{2m_p} + m_p \simeq \frac{p_{F,n}^2}{2m_n} + m_n$$

Neutrino chemical potential is zero.

Charge neutrality

$$n_p = n_e \quad \Rightarrow \quad p_{F,p} = p_{F,e} \qquad p_F = (3\pi^2\hbar^3)^{\frac{1}{3}} n^{\frac{1}{3}}$$

So, as long as the above approximation is valid, the typical size of the Fermi momenta of protons and electrons are O(10) MeV.

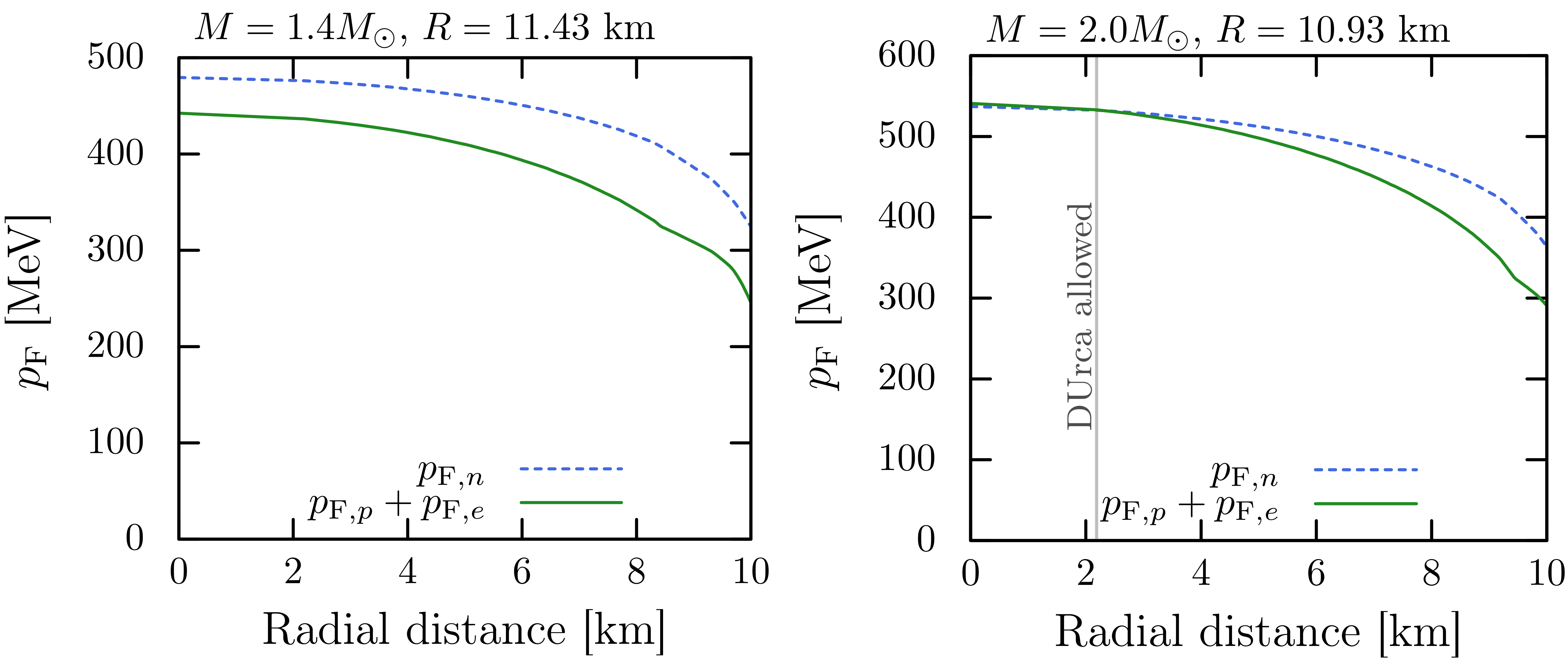
Momentum conservation

$$p_p + p_e > p_n$$

Neutrino momentum is negligible.

Therefore, the Direct Urca process can occur only where the density is huge so that the above approximation is not valid.

Direct Urca condition



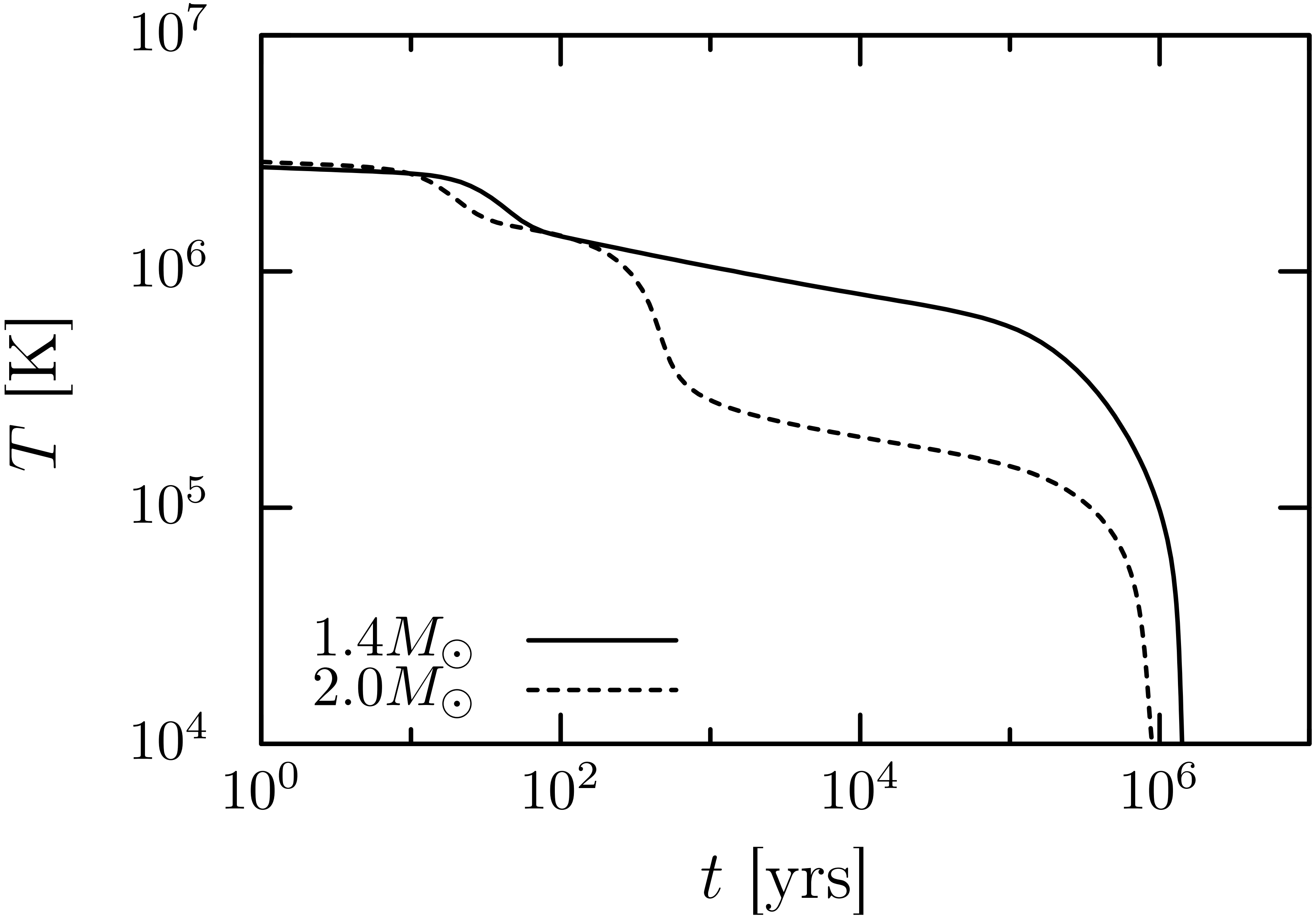
This process can occur only at high-density regions.

Only massive stars (>~ 2 solar mass) allow this process. W/ APR

We expect that Direct Urca does not occur in Cas A NS.

$$M \simeq (1.4 \pm 0.3) M_\odot$$

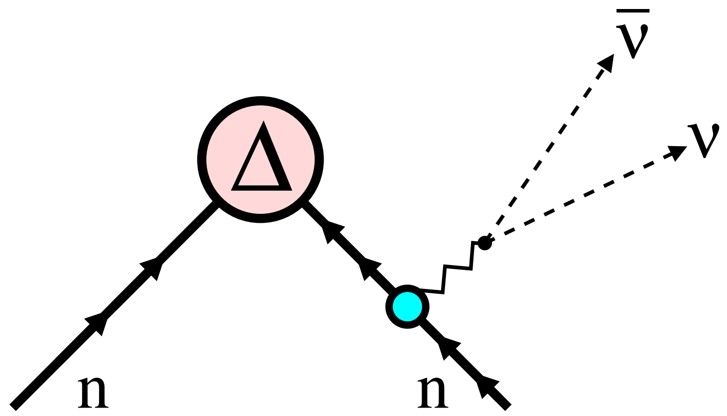
Cooling curves



The direct Urca process affects the neutron star cooling significantly.

Cooper pair neutrino process (PBF)

Thermal disturbance induces the breaking of nucleon pairs.



During the reformation of cooper pairs, the gap energy is released via neutrino emission.

This process significantly enhances the neutrino emission when $T \lesssim T_C$

- If $T > T_C$, this process does not occur.
- If $T << T_C$, pair breaking rarely occurs.

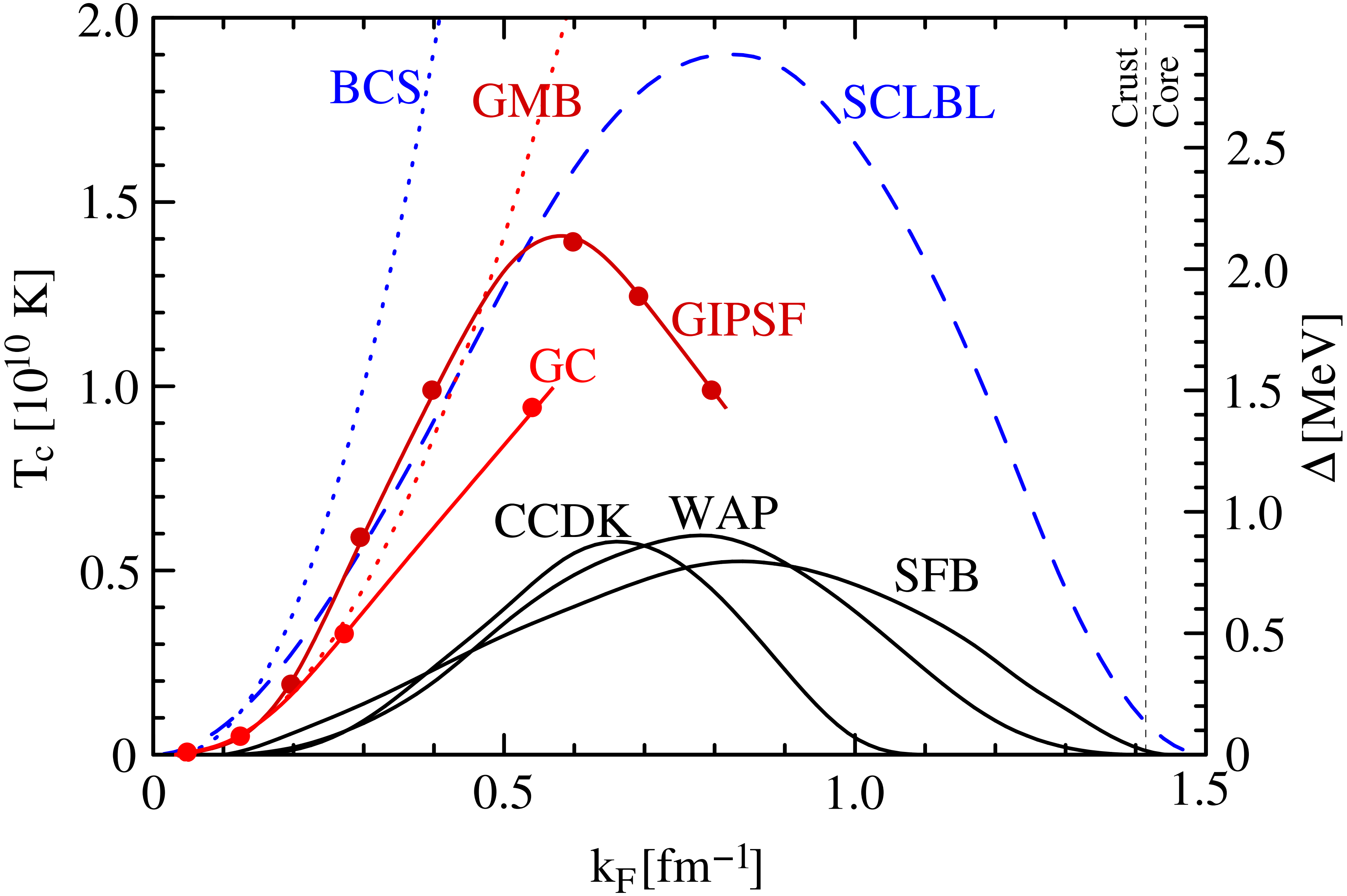
PBF associated with neutrino triplet pairings is most significant.

Summary for standard cooling

- Photon emission is unimportant for a young NS.
- Direct Urca does not occur in Cas A NS.
- Modified Urca and bremsstrahlung are suppressed after the onset of nucleon pairings.
- PBF enhances neutrino emission when the temperature is just below the critical temperature.

$^1S_0$ neutron gap

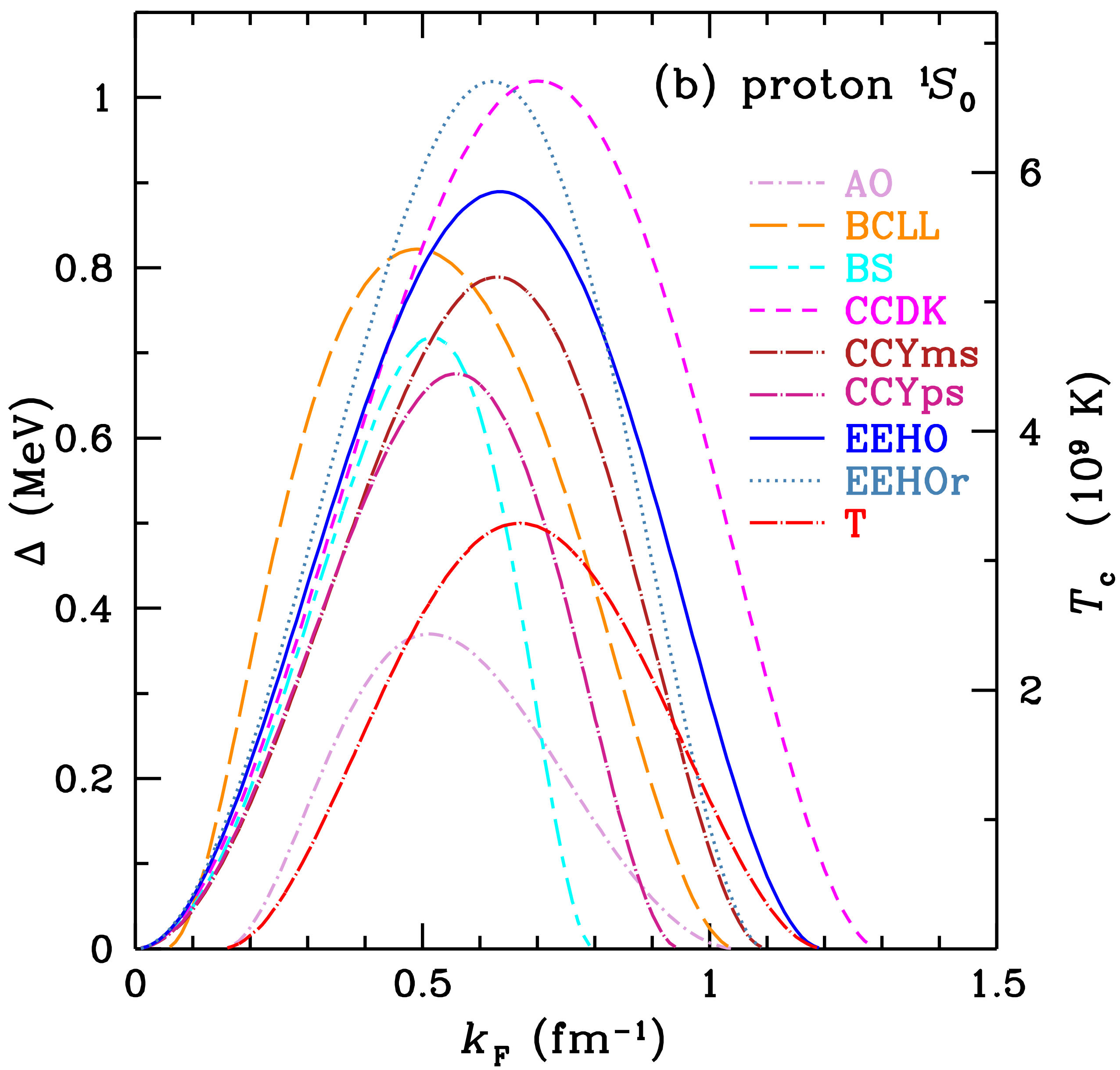
By solving the gap equation, we can obtain the pairing gap.

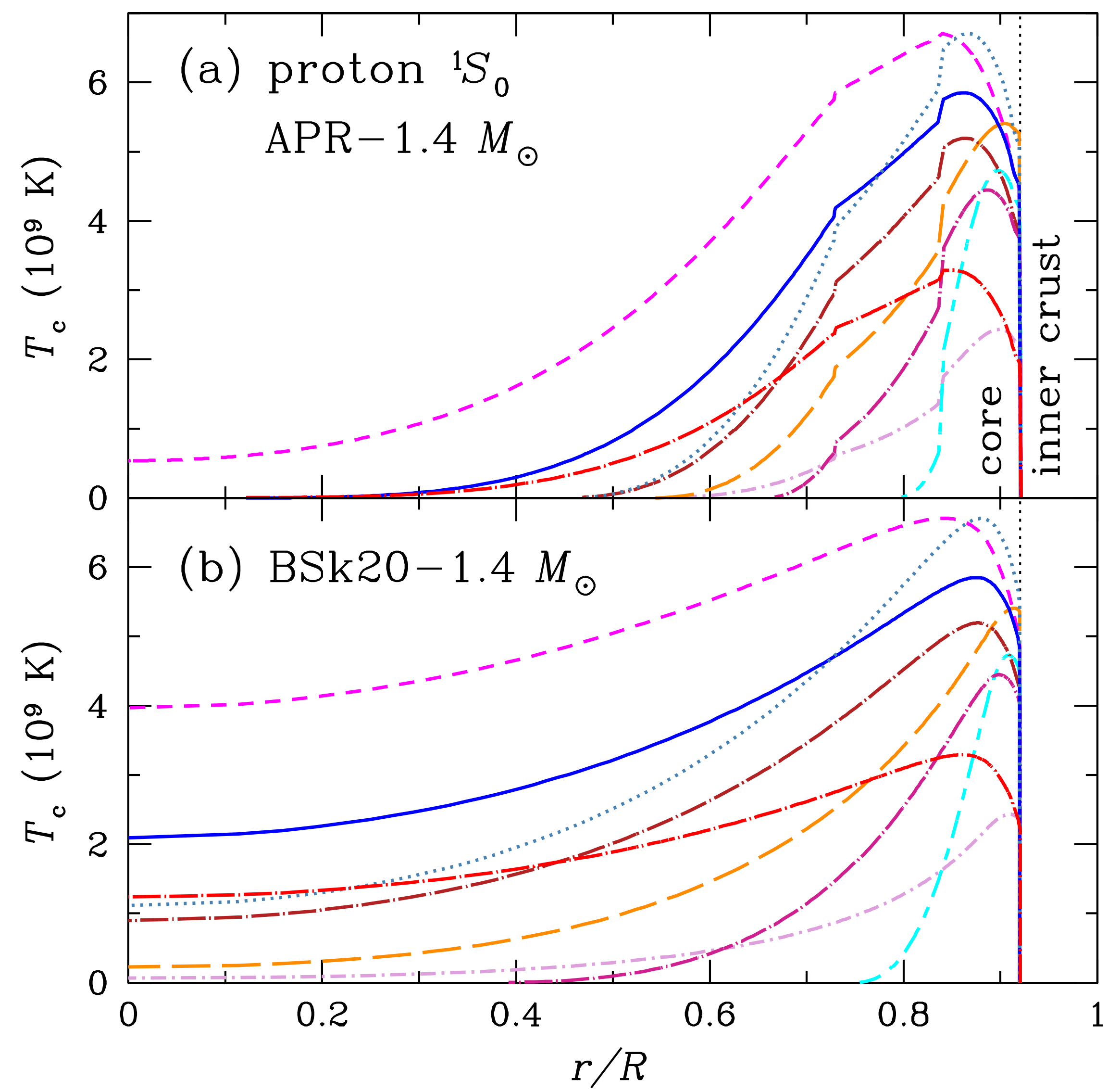


D. Page, J. M. Lattimer, M. Prakash, A. W. Steiner [arXiv: 1302.6626].

- BCS, GMB: a weak-limit approximated analytical solution without and with medium effects.
- Others: calculations using different models for nuclear potential.

$^1S_0$ proton gap



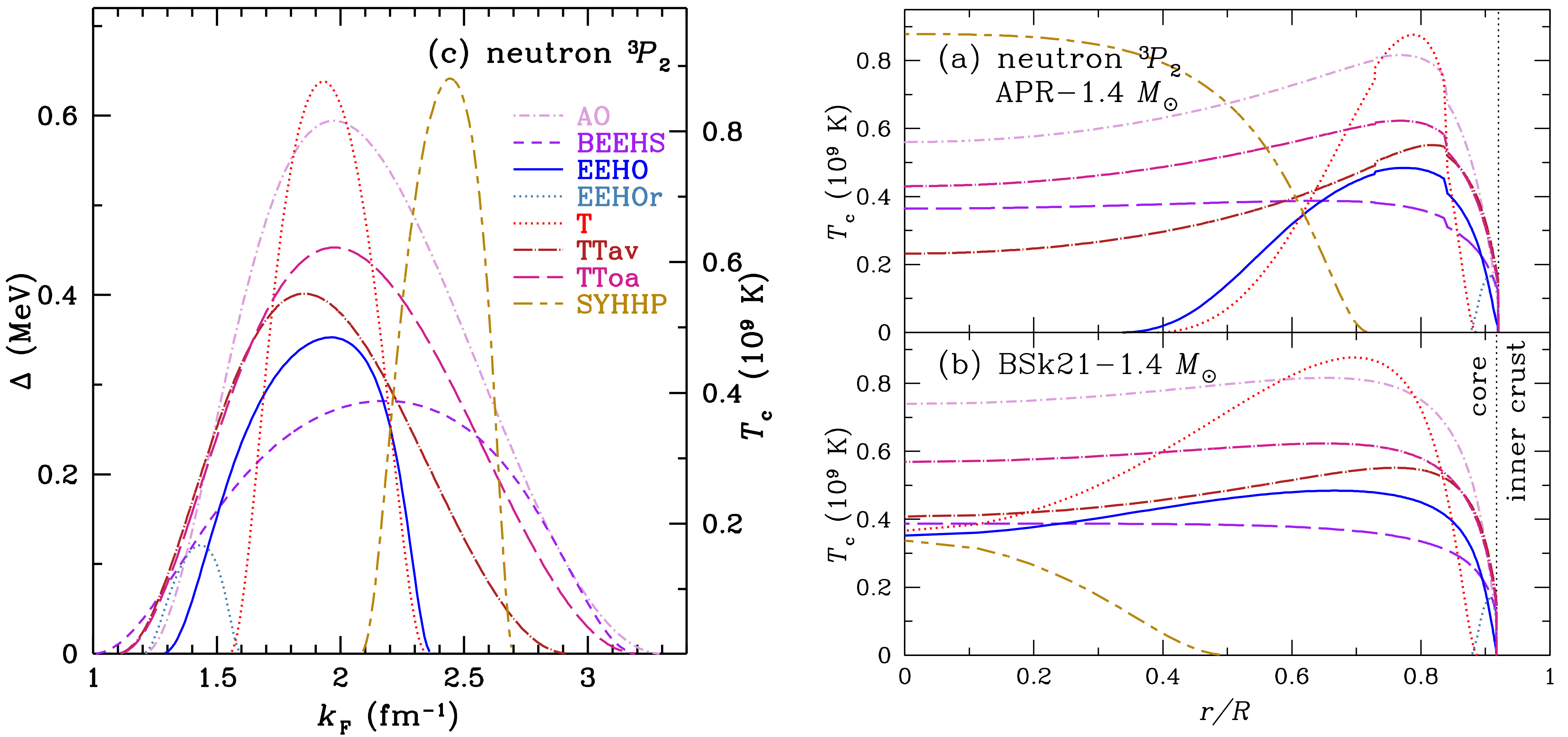


K. G. Elshamouty, C. O. Heinke, W. C. Ho, A. Y. Potekhin, Phys .Rev. **C91**, 015806 (2015).

We use the CCDK model to suppress neutron emission before the onset of neutron triplet pairing.

$^3P_2$ neutron gap

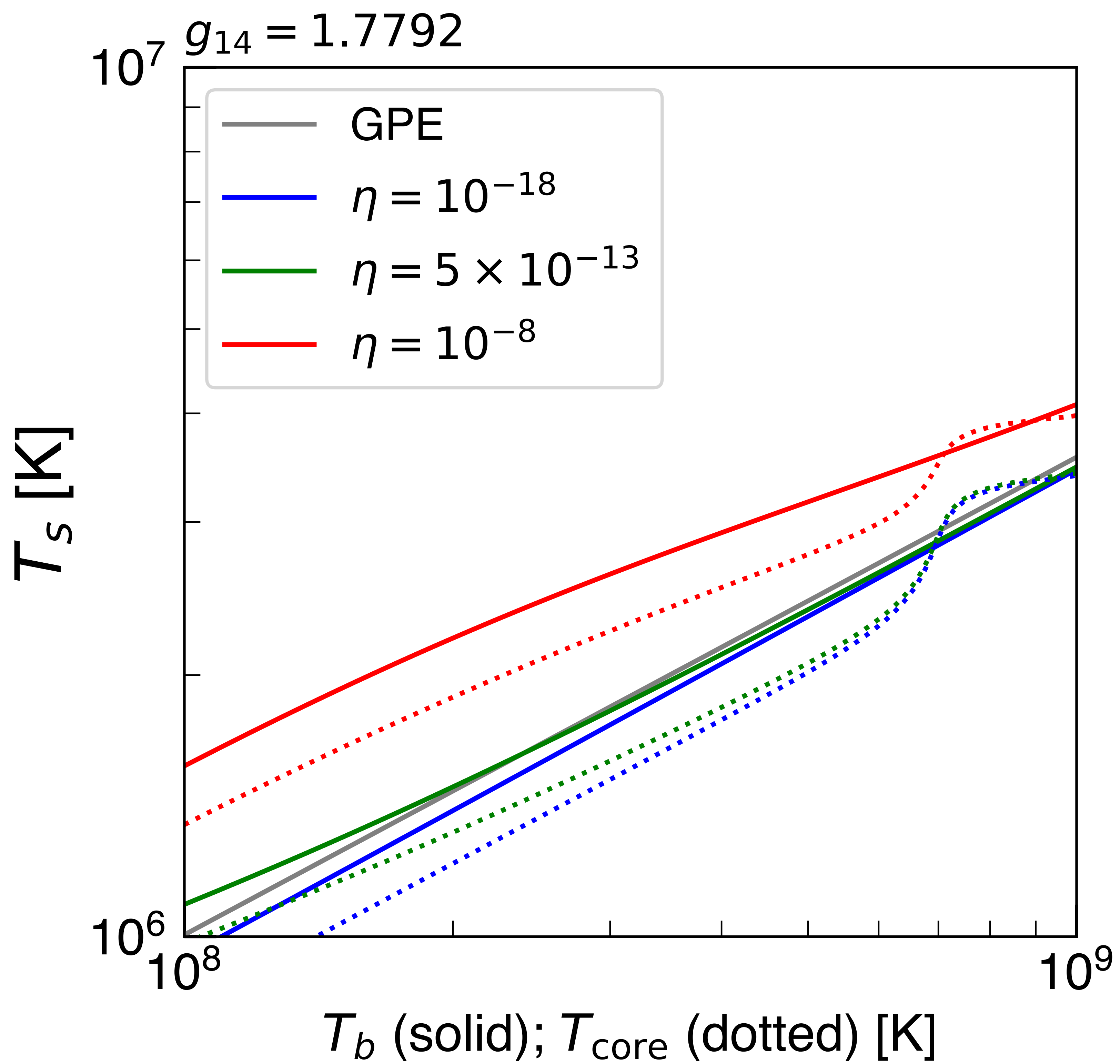
Large theoretical uncertainty



K. G. Elshamouty, C. O. Heinke, W. C. Ho, A. Y. Potekhin, Phys .Rev. **C91**, 015806 (2015).

- Model this gap with a Gaussian shape in k_F.
- Regard its height, width and position as free parameters.

Core and boundary temperature



Cas A NS cooling

Cas A NS temperature data

TABLE I. *Chandra* ACIS-S Graded mode temperatures.

ObsID	Year	$T_{\rm eff}$ [a]
114	2000.08	$2.145^{+0.009}_{-0.008}$
1952	2002.10	$2.142^{+0.009}_{-0.008}$
5196	2004.11	$2.118^{+0.011}_{-0.007}$
(9117,9773) [b]	2007.93	$2.095^{+0.007}_{-0.010}$
(10935,12020) [b]	2009.84	$2.080^{+0.009}_{-0.008}$
(10936,13177) [b]	2010.83	$2.070^{+0.009}_{-0.009}$
14229	2012.37	$2.050^{+0.009}_{-0.008}$
14480	2013.38	$2.075^{+0.009}_{-0.009}$
14481	2014.36	$2.045^{+0.009}_{-0.009}$

$[\times 10^6$ K$]$

3—4% decrease in ten years.

K. G. Elshamouty, C. O. Heinke, W. C. Ho, A. Y. Potekhin, Phys .Rev. **C91**, 015806 (2015).

Can we explain this cooling behavior with ordinary (slow) neutrino emission processes??

Slow neutrino emission

Temperature evolution

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

Heat capacity

$$C(T) = C_9 T_9, \quad C_9 \sim 10^{39}\ \text{erg}\cdot\text{K}^{-1}$$

$T_9 = T/(10^9\ \text{K})$

Modified Urca + Bremsstrahlung

$$L_\nu = L_9 T_9^8, \quad L_9 \sim 10^{40}\ \text{erg}\cdot\text{s}^{-1}$$

$$\Rightarrow \quad T_9 = \left(\frac{C_9 \cdot 10^9\ \text{K}}{6 L_9\, t}\right)^{\frac{1}{6}} \sim \left(\frac{1\ \text{year}}{t}\right)^{\frac{1}{6}}$$

Internal temperature goes as $T \propto t^{-\frac{1}{6}}$

Surface vs internal temperatures

$$T_9 \simeq 0.1288 \times \left(\frac{T_{s6}^4}{g_{14}}\right)^{0.455}$$

$T_{s6} = T_s/(10^6\ \text{K})$

E. H. Gudmundsson, C. J. Pethick, and R. I. Epstein (1983).

Slow neutrino emission and Cas A NS

From the above formulae, we finally obtain $T_s \propto t^{-0.09}$

➡ Only 0.3% decrease in T in ten years.

The slow neutrino emission cannot explain the observed rapid cooling of the Cas A NS.

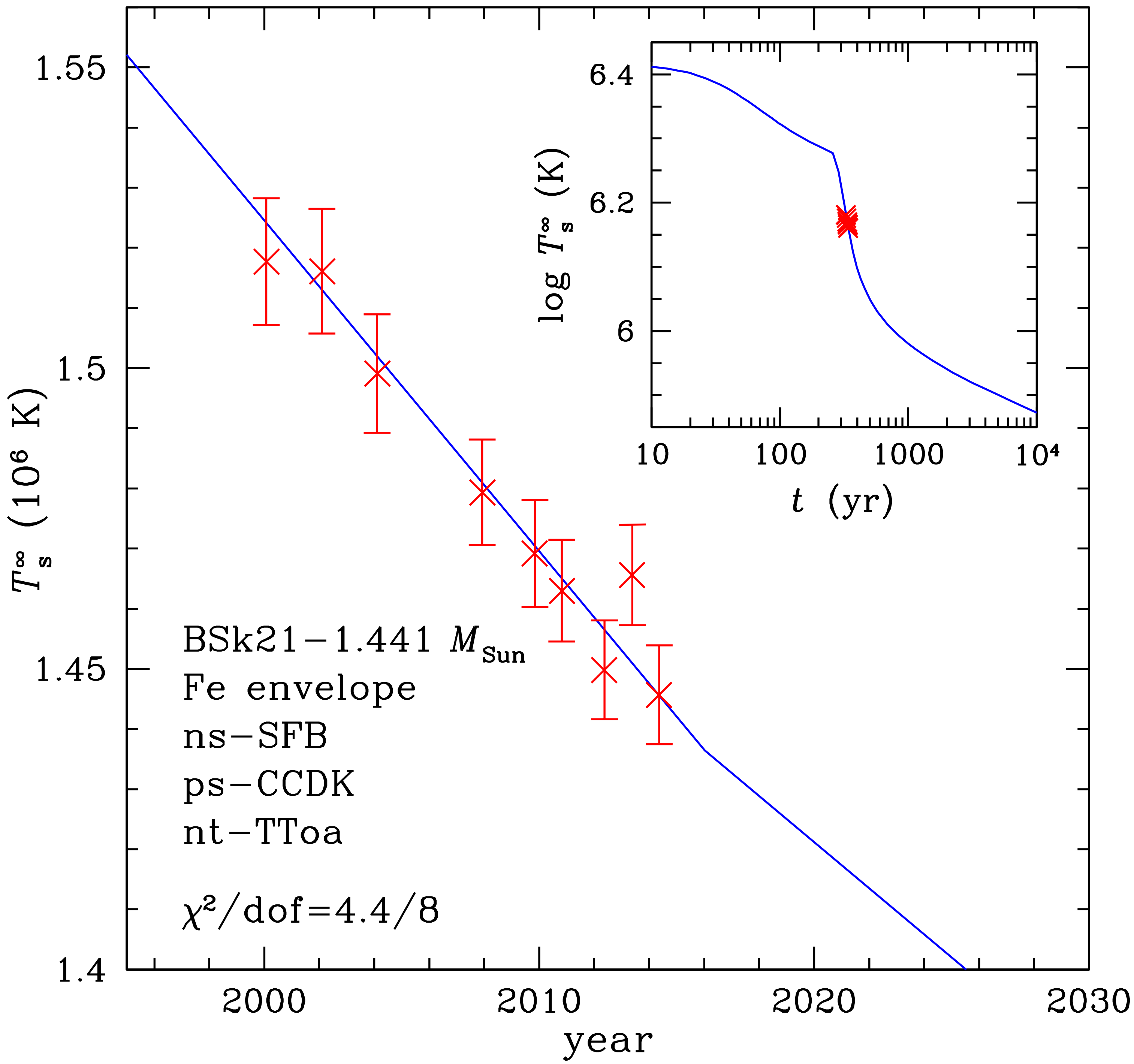
Solution in the minimal cooling paradigm

Use the PBF process to enhance the cooling rate.

This process does not last so long.

We need to take the critical temperature to be just above the internal temperature of Cas A NS (~ 5×10^8 K).

Fit with minimal cooling



K. G. Elshamouty, C. O. Heinke, W. C. Ho, A. Y. Potekhin, Phys .Rev. **C91**, 015806 (2015).

Axion

Axion is a Nambu-Goldstone boson associated with the Peccei-Quinn symmetry.

R. D Peccei and H. R. Quinn (1977); S. Weinberg (1978); F. Wilczek (1978).

Lagrangian

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a}\frac{\alpha_s}{8\pi}G_{\mu\nu}\widetilde{G}^{\mu\nu} + \sum_q \frac{C_q}{2f_a}\bar{q}\gamma^\mu\gamma_5 q\,\partial_\mu a + \ldots$$

Axion-nucleon couplings

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

$$C_N = \sum_{q=u,d,s}\left(C_q - \frac{m_*}{m_q}\right)\Delta q^{(N)}$$

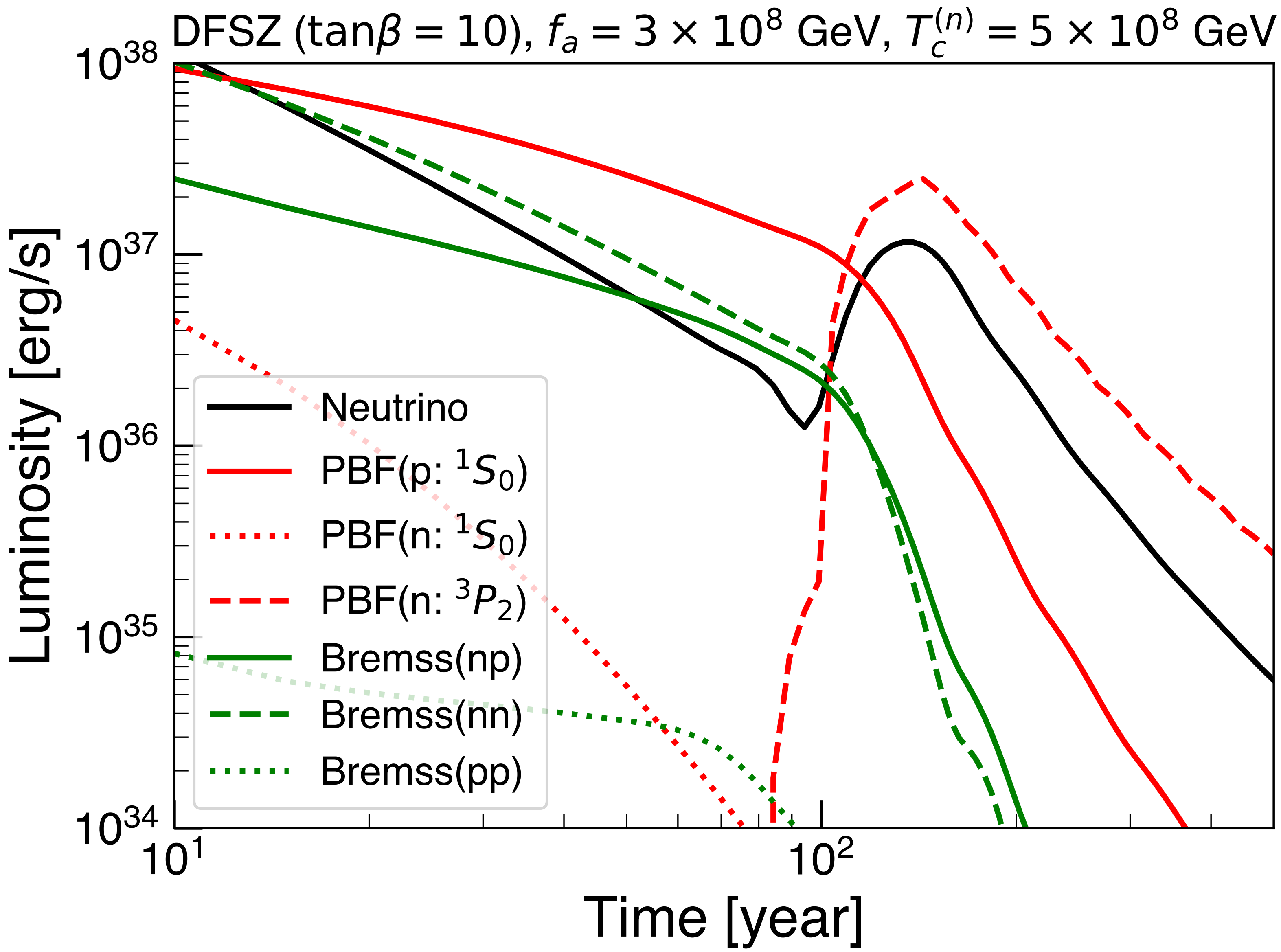
$$m_* \equiv \frac{m_u m_d m_s}{m_u m_d + m_u m_s + m_d m_s}$$

Spin fractions

$$2s_\mu^{(N)}\Delta q^{(N)} \equiv \langle N|\bar{q}\gamma_\mu\gamma_5 q|N\rangle$$

Gluon contribution can be taken into account as quark contributions through a field rotation.

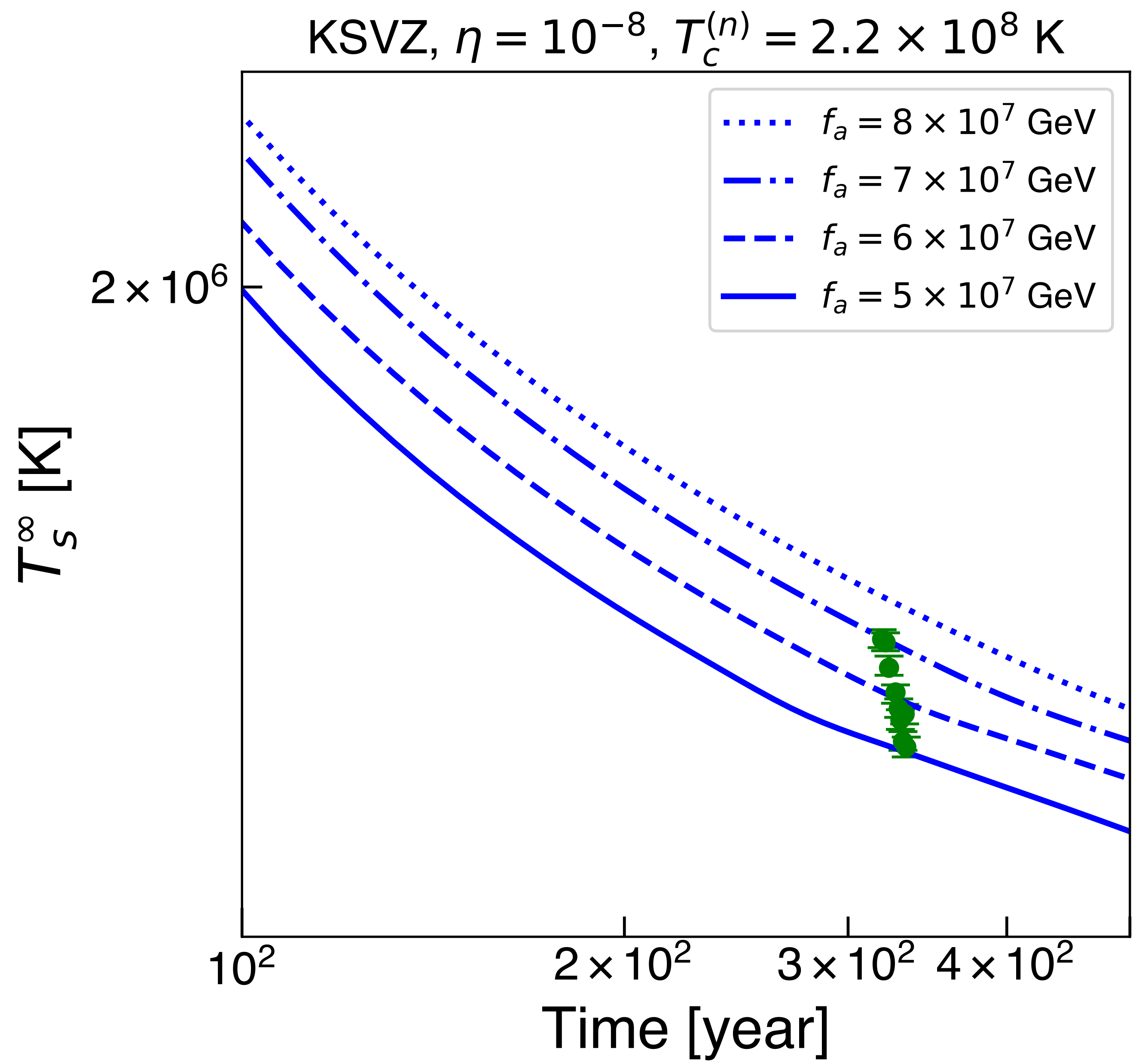
Luminosity of axion emission



Axion emission is stronger than the KSVZ case.

K. Hamaguchi, N. Nagata, K. Yanagi, and J. Zheng, Phys. Rev. **D98**, 103015 (2018).

Large η in KSVZ



For large η, the core temperature gets small.

Cannot explain the rapid cooling of Cas A.

K. Hamaguchi, N. Nagata, K. Yanagi, and J. Zheng, Phys. Rev. **D98**, 103015 (2018).