Axion Cooling in Neutron Stars

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Axion-Like Particles
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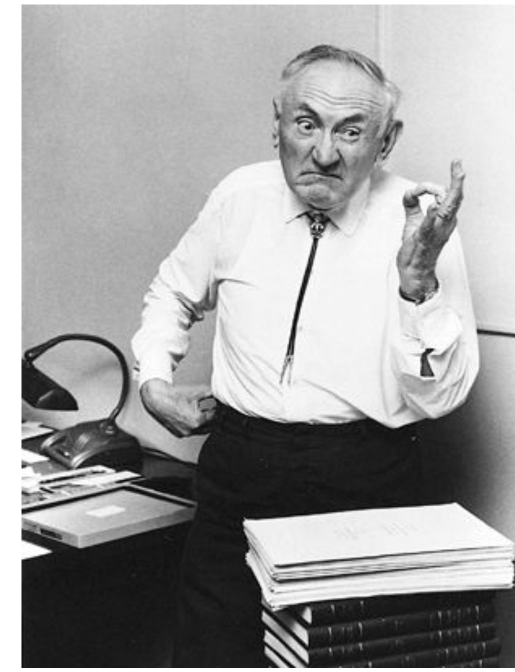
Introduction

Prediction of neutron stars

5. *The super-nova process*

We have tentatively suggested that the super-nova process represents the transition of an ordinary star into a neutron star. If neutrons are produced on the surface of an ordinary star they will "rain" down towards the center if we assume that the light pressure on neutrons is practically zero. This view explains the speed of the star's transformation into a neutron star. We are fully aware that our suggestion carries with it grave implications regarding the ordinary views about the constitution of stars and therefore will require further careful studies.

W. BAADE
F. ZWICKY



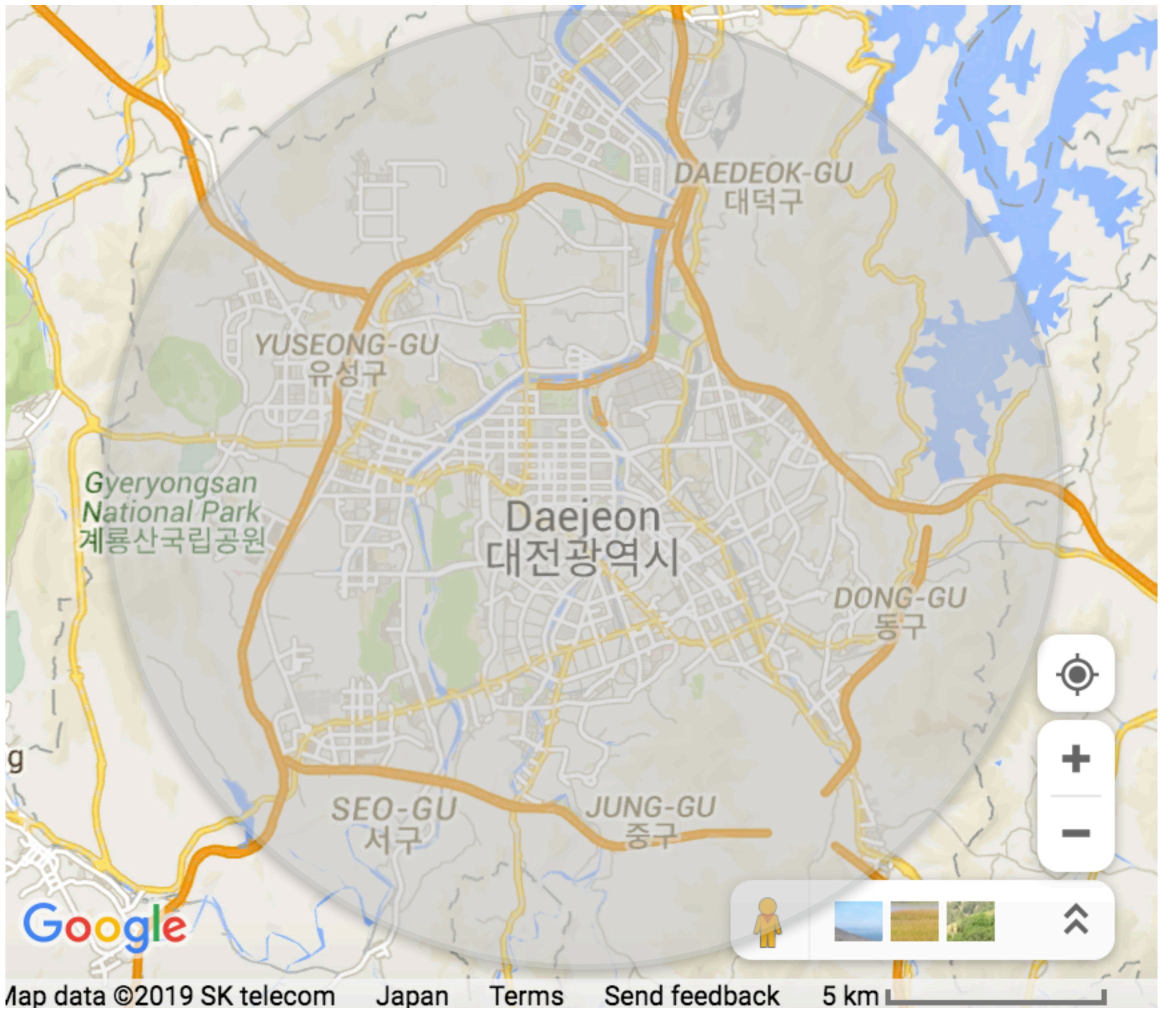
W. Baade and F. Zwicky, Phys. Rev. **45**, 138 (1934); Phys. Rev. **46**, 76 (1934).

- Neutron Star was predicted by W. Baade and F. Zwicky in 1934.

Just 2 years after the discovery of neutron.

- It was assumed to be the final stage of the supernova process.

Neutron Star (NS) in Daejeon



NS size

- Radius ~10 km
- 1—2 $M_\odot$

  As high as nuclear density.

- Neutrons, protons, electrons are Fermi degenerate.

  ➡ Degeneracy pressure balances with gravity

- These particles are in β equilibrium.

$$n \to p + \ell^- + \bar{\nu}_\ell, \ \ell^- + p \to n + \bar{\nu}_\ell$$

Axion cooling in neutron stars

- NS is born in a very high-temperature state ($T \sim 10^{11}$ K).

- Since NS is a dead star, basically there is no heating source:

  ➡ NS just cools via neutrino & photon emission.

  Standard Cooling Theory

- Axion can be an extra cooling source.

> We may probe it by searching for deviation from the prediction in the standard cooling theory.

It turns out that this method can give a limit on the axion decay constant as strong as that from SN1987A.

Outline

- Introduction
- Standard Neutron Star Cooling
- Axion Emission from Neutron Star
- Limit on Axion Decay Constant
- Conclusion

Standard NS Cooling

Standard Cooling of NS

D. Pager, J. M. Lattimer, M. Prakash, A. W. Steiner, Astrophys. J. Suppl. **155**, 623 (2004);
M. E. Gusakov, A. D. Kaminker, D. G. Yakovlev, O. Y. Gnedin, Astron. Astrophys. **423**, 1063 (2004).

Consider a NS composed of

- Neutrons
- Protons
- Leptons (e, μ)

- These particles are supposed to be in the β equilibrium.
- Nucleon superfluidity taken into account.

Equation for temperature evolution

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

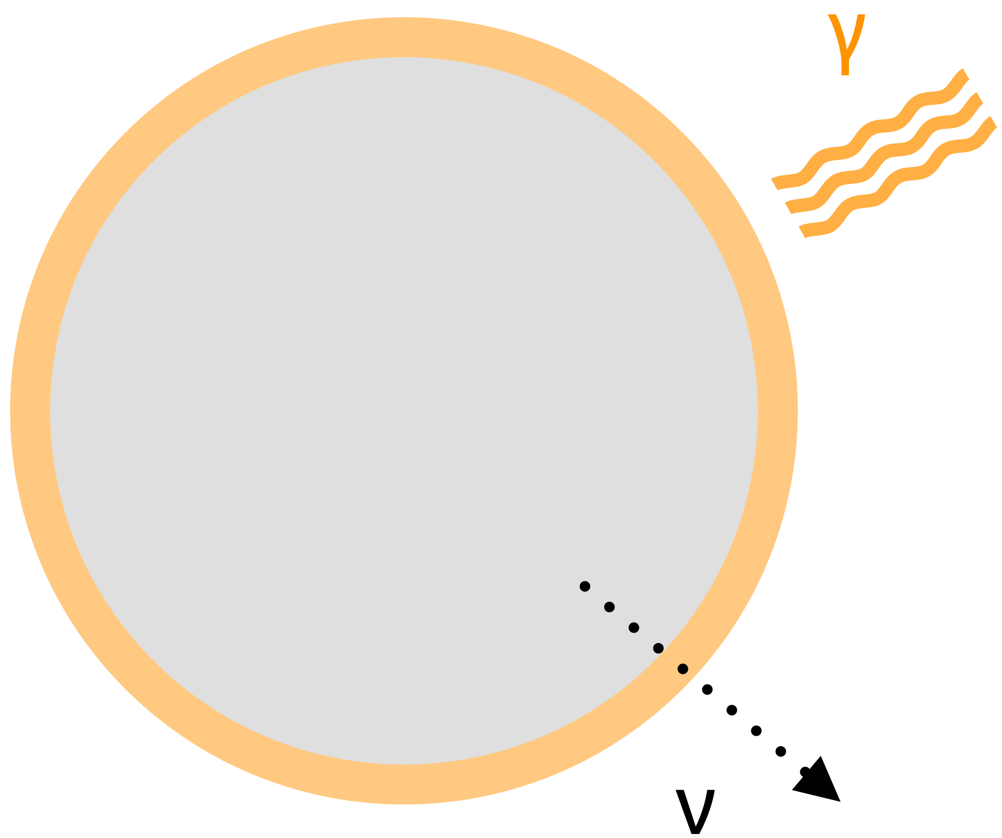
C(T): Stellar heat capacity

L_ν: Luminosity of neutrino emission

L_γ: Luminosity of photon emission

Cooling sources

Two cooling sources:



Dominant for $t \lesssim 10^5$ years

<u>Photon emission (from surface)</u>

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

Dominant for $t \gtrsim 10^5$ years

<u>Neutrino emission (from core)</u>

- Direct Urca process (DUrca)
- Modified Urca process (MUrca)
- Bremsstrahlung
- PBF process

PBF process occurs only in the presence of nucleon superfluidity.

Name: Urca

APRIL 1, 1941 PHYSICAL REVIEW VOLUME 59

Neutrino Theory of Stellar Collapse

G. Gamow, *George Washington University, Washington, D. C.*
M. Schoenberg,* *University of São Paulo, São Paulo, Brazil*

(Received February 6, 1941)

of β-particles. In fact, when the temperature and density in the interior of a contracting star reach certain values depending on the kind of nuclei involved, we should expect processes of the type

$$\begin{cases} {}_Z N^A + e^- \rightarrow {}_{Z-1}N^A + \text{antineutrino} \\ {}_{Z-1}N^A \rightarrow {}_Z N^A + e^- + \text{neutrino}, \end{cases} \quad (3)$$

which we shall call, for brevity, "urca-processes."

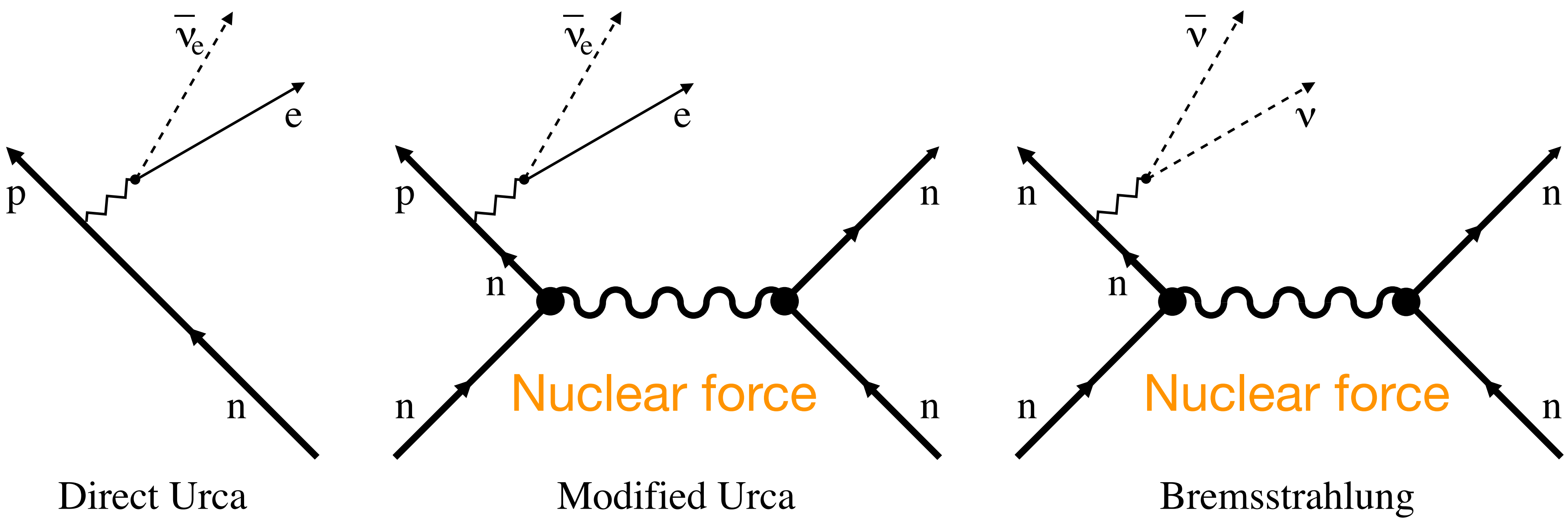
Named after a casino in Rio de Janeiro:

Cassino da Urca

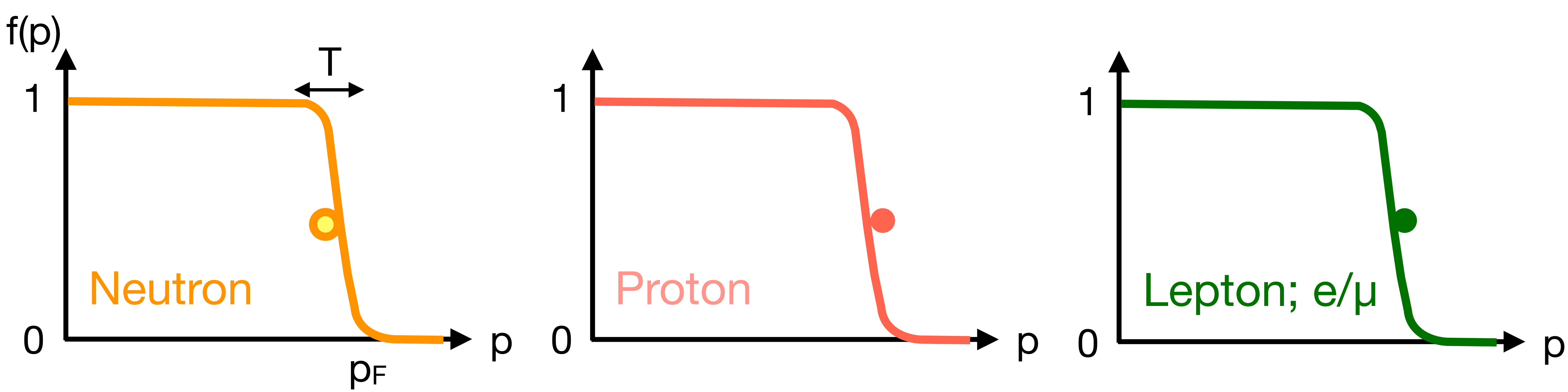
- To commemorate the casino where they first met.
- Rapid disappearance of energy (money) of a star (gambler).
- **U**n**R**ecordable **C**ooling **A**gent.
- "Urca" means "thief" in Russian.

Neutrino emission

First we consider the processes that occur without superfluidity.

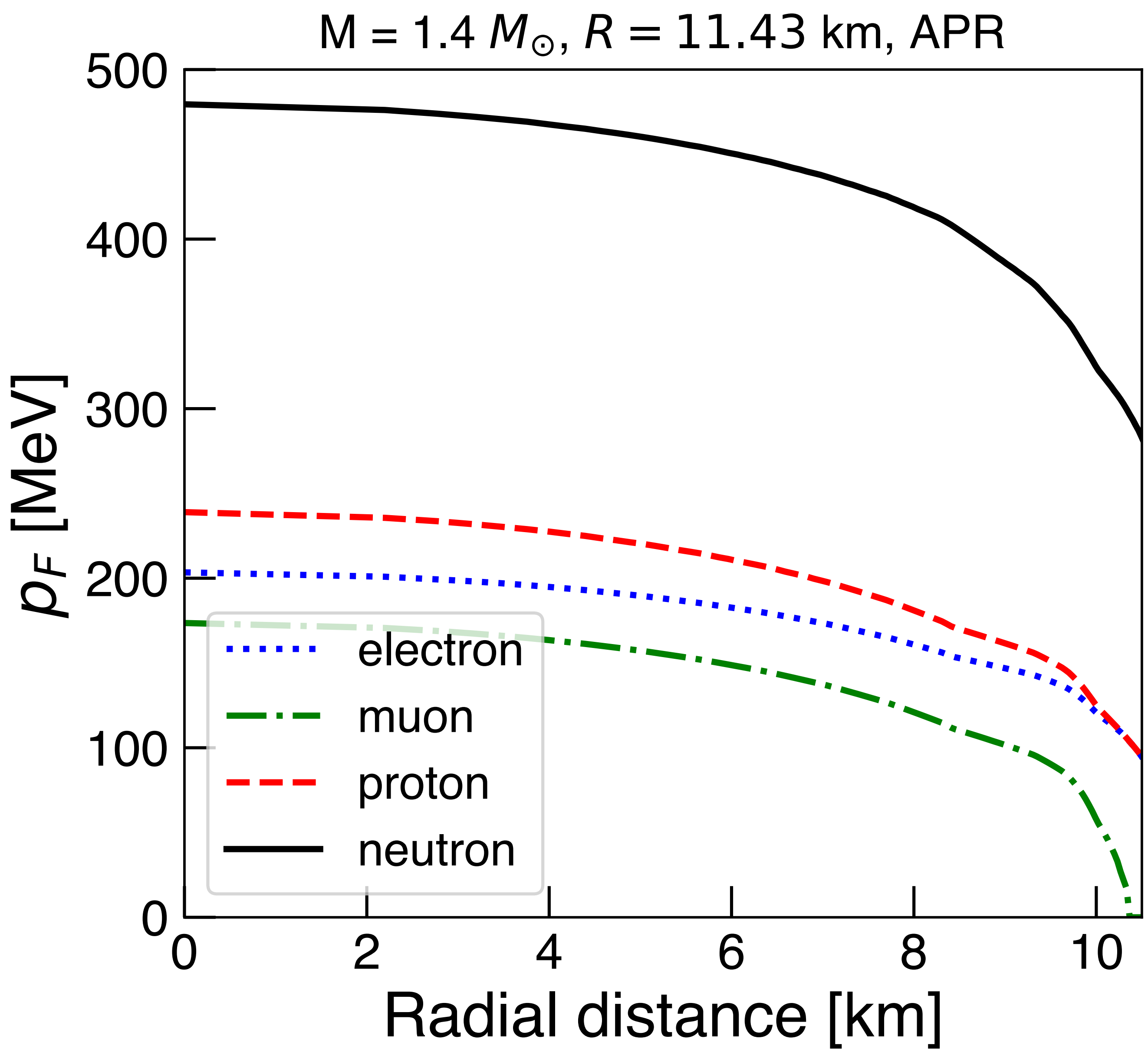


These processes occur only near the Fermi surface.



Fermi momenta

Fermi momenta in neutron star



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

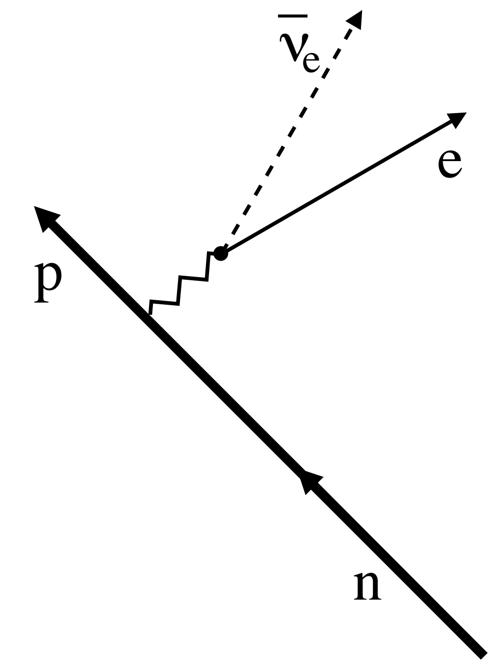
- Fermi momentum of neutron is large: 300—500 MeV
- Those for other particles are smaller by a factor of ~2.

Direct Urca process

$$n \to p + \ell^- + \bar{\nu}_\ell, \;\; \ell^- + p \to n + \bar{\nu}_\ell$$

$$(\ell = e, \mu)$$

β decay & electron capture



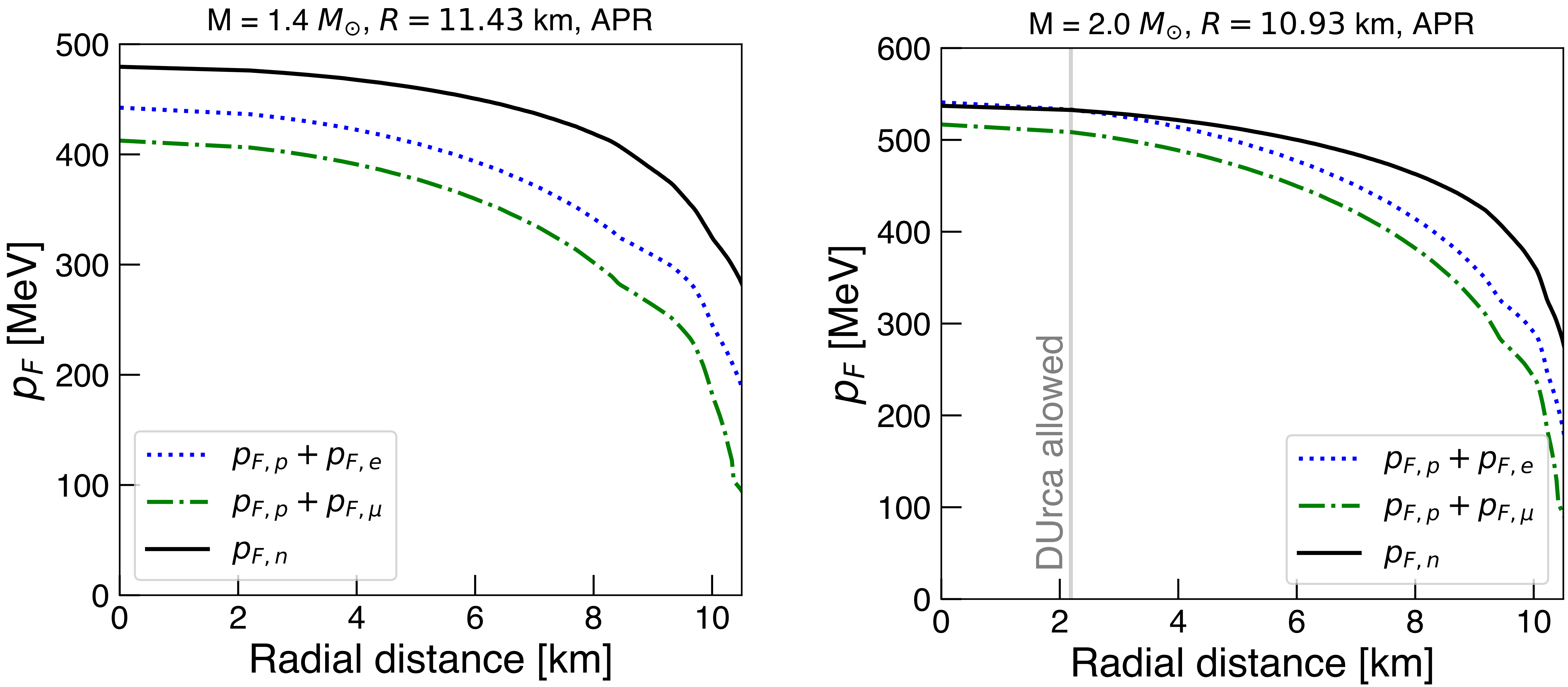
Direct Urca

- Direct Urca is the dominant process, if it occurs.
- Due to the momentum conservation, Direct Urca can occur only if

$$p_{F,p} + p_{F,e} > p_{F,n}$$

Neutrino momentum can be neglected.

Direct Urca condition



- Direct Urca can occur only in the high density region in a heavy star.

For the APR equation of state, $M \gtrsim 2M_\odot$

- Other processes become important if Direct Urca is forbidden.

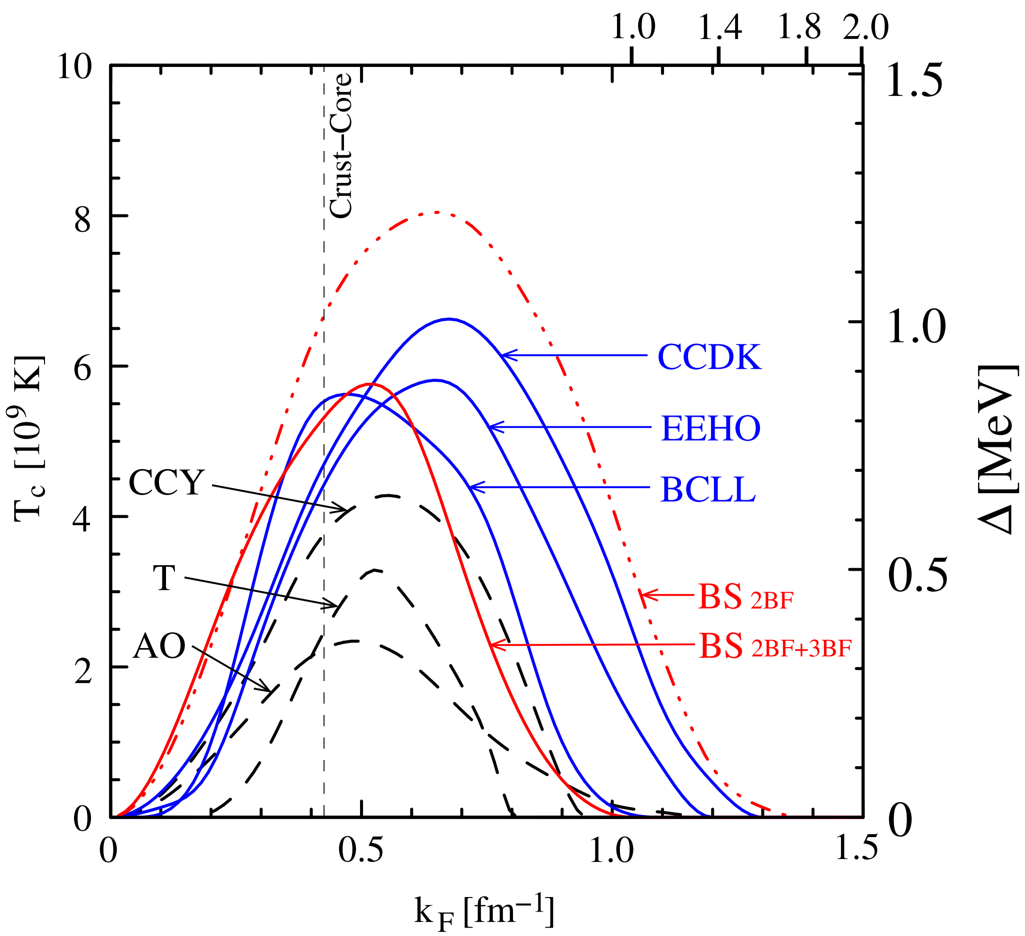
Nucleon pairing

Nucleons in a NS form pairings below their critical temperatures:

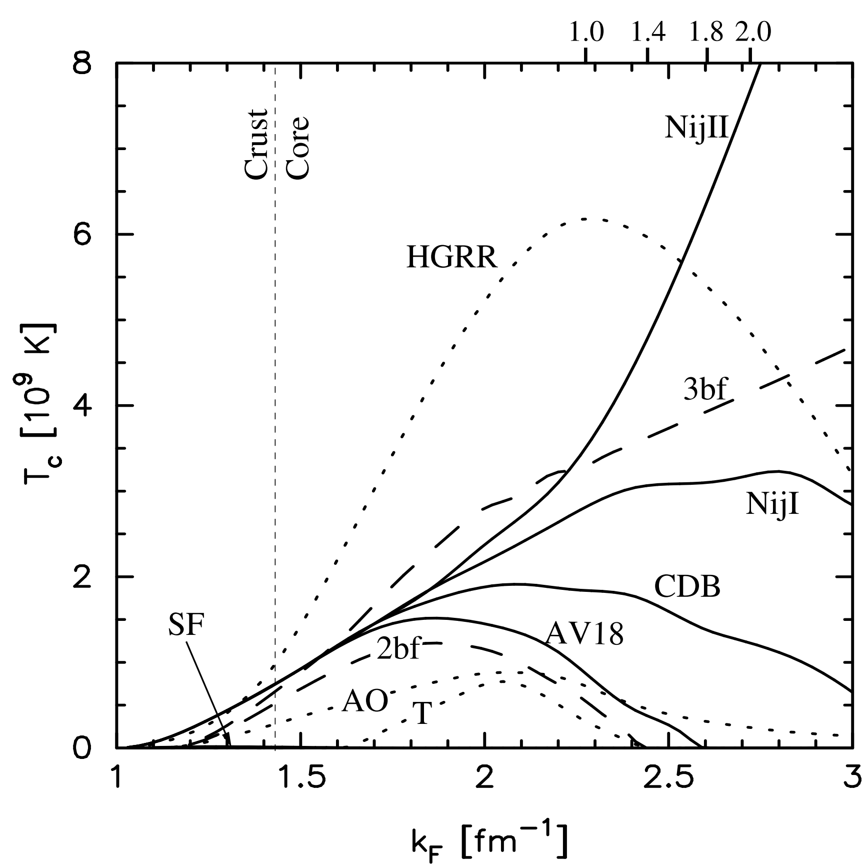
- Neutron singlet $^1S_0$ ← Only in the crust. Less important.
- Proton singlet $^1S_0$
- Neutron triplet $^3P_2$

} ← Form in the core. Important.

Proton singlet pairing gap



Neutron triplet pairing gap



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

Effects of nucleon parings

When pairings are formed, the energy of quasi-particle is given by

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

The paring gap introduces a suppression factor to

- Neutrino emission processes
- Heat capacity

$$\propto e^{-\frac{\Delta_N}{T}}$$

via the distribution functions.

In addition, a new neutrino emission process is turned on:

→ Pair-breaking and formation (PBF) process

PBF process

Thermal disturbance induces the breaking of nucleon pairs.

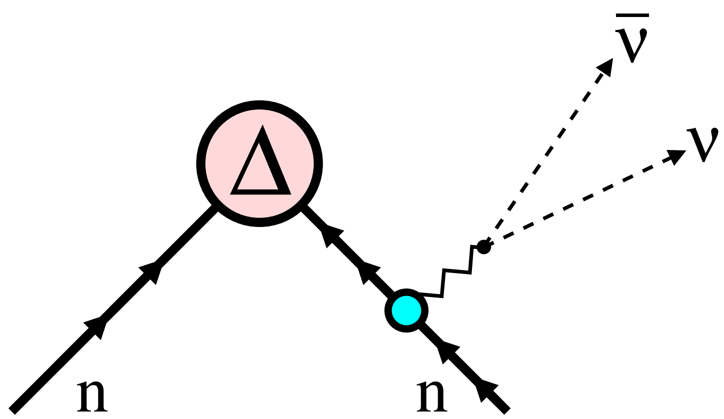
↓

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

This process significantly enhances the neutrino emission only when

$$T \lesssim T_C$$

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



Summary for standard cooling

Photon emission

Emitted from the surface. Dominant for $t \gtrsim 10^5$ years.

Direct Urca process

Occurs only in heavy stars.

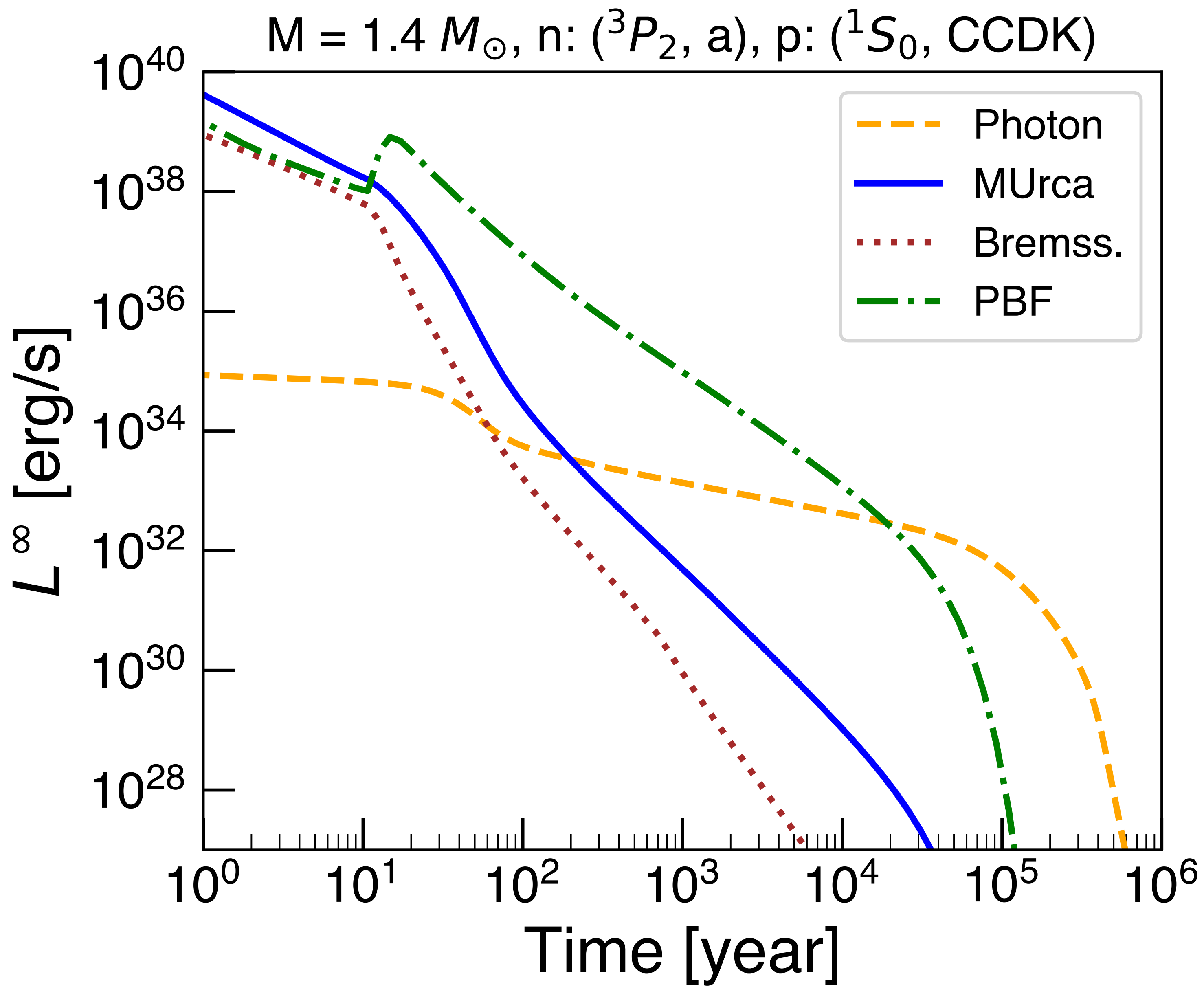
Modified Urca & bremsstrahlung

Always occur, but the emission is weaker.

PBF

Strongly enhances the neutrino emission at $T \lesssim T_C$

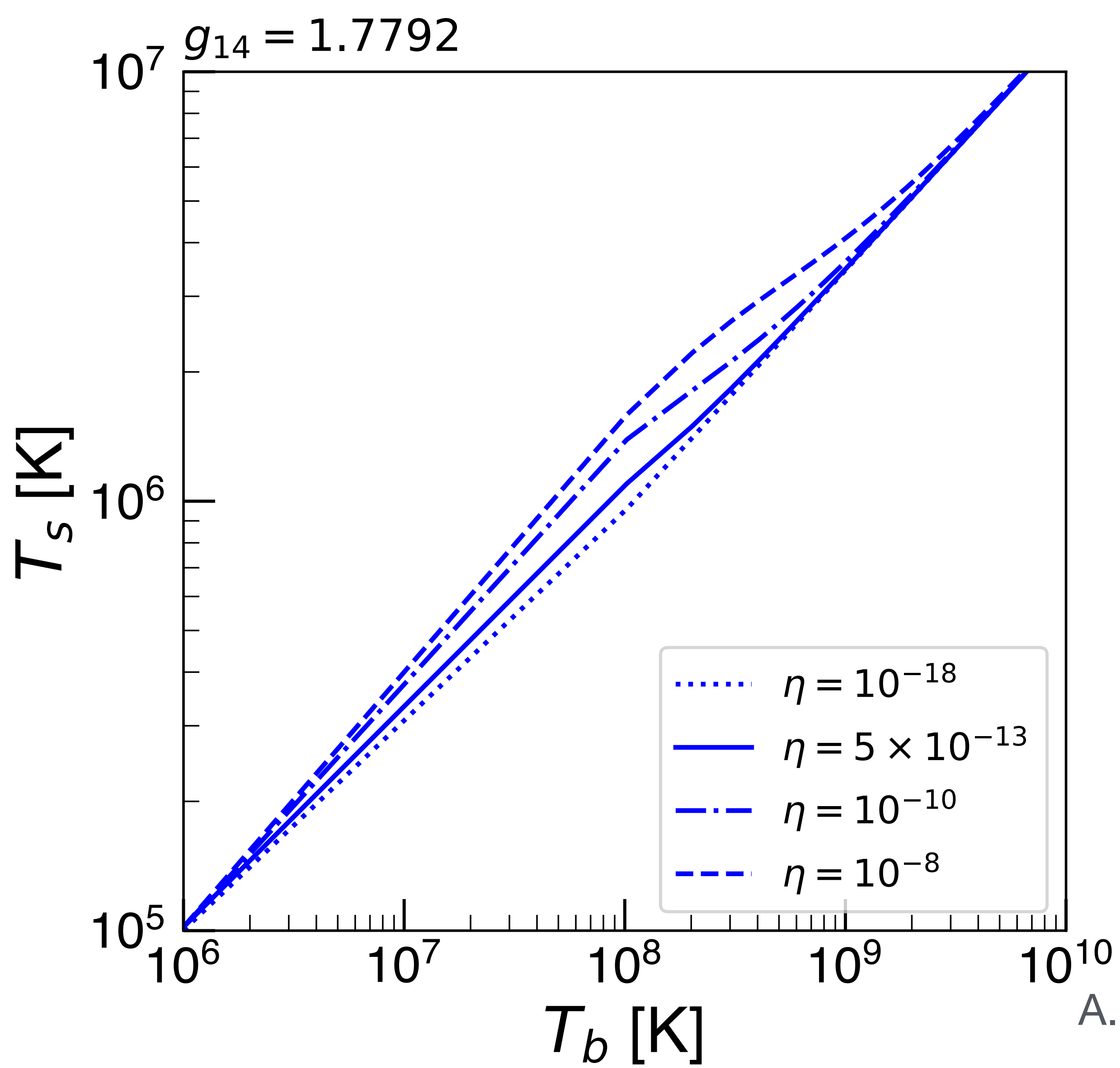
Luminosity



- PBF emission suddenly increases when neutrons in the core form triplet Cooper pairs.
- Photon emission becomes dominant after ~10^5 years.

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}.

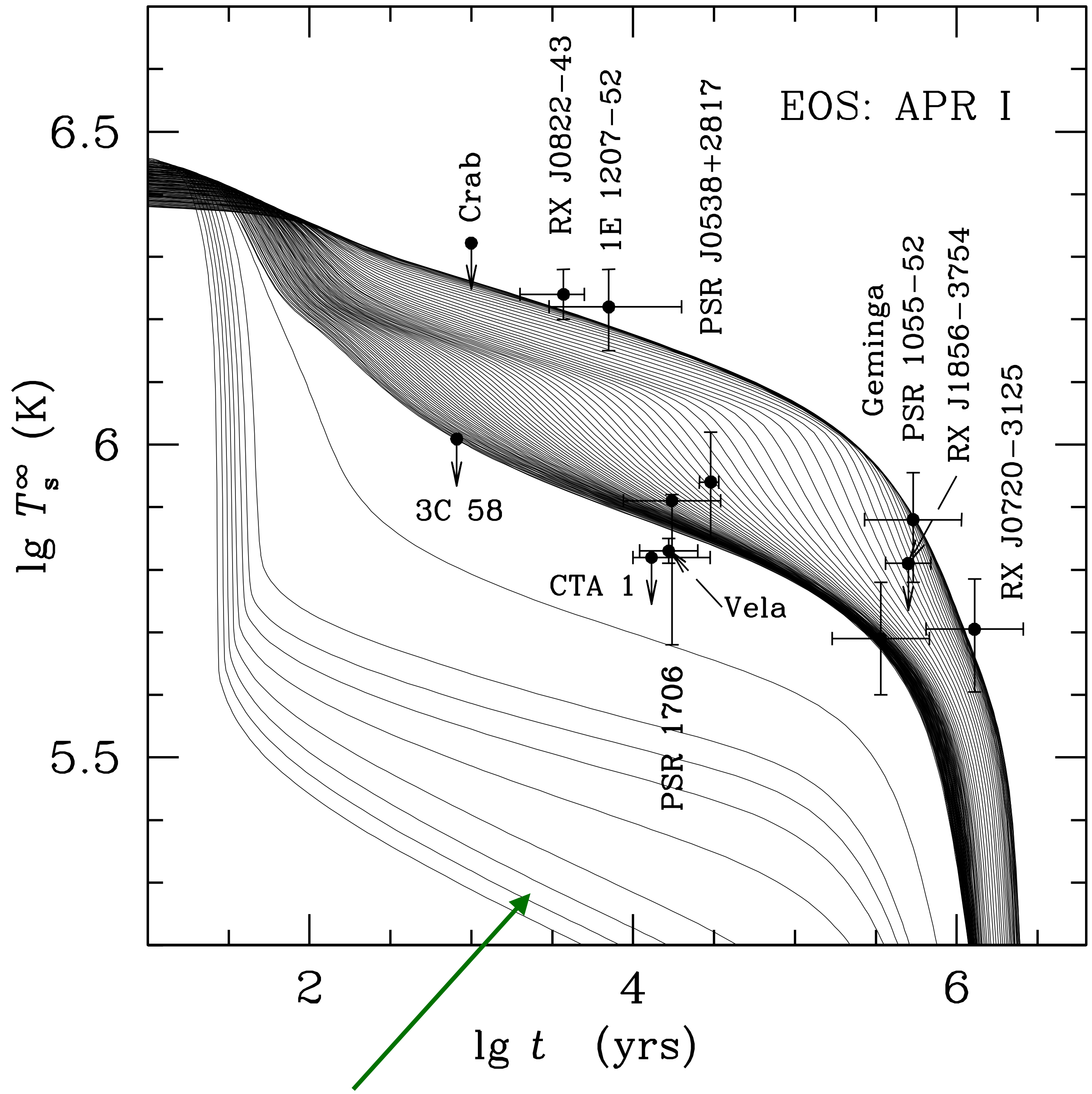
ΔM: mass of light elements.

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

Larger amount of light elements leads to higher surface temperature.

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).

- If Direct Urca occurs, the neutron star cools down rapidly.
- Standard Cooling scenario is consistent with observations.

Axion emission from NS

Axion-nucleon couplings

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

KSVZ axion 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

Equation for temperature evolution

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

Axion emission processes

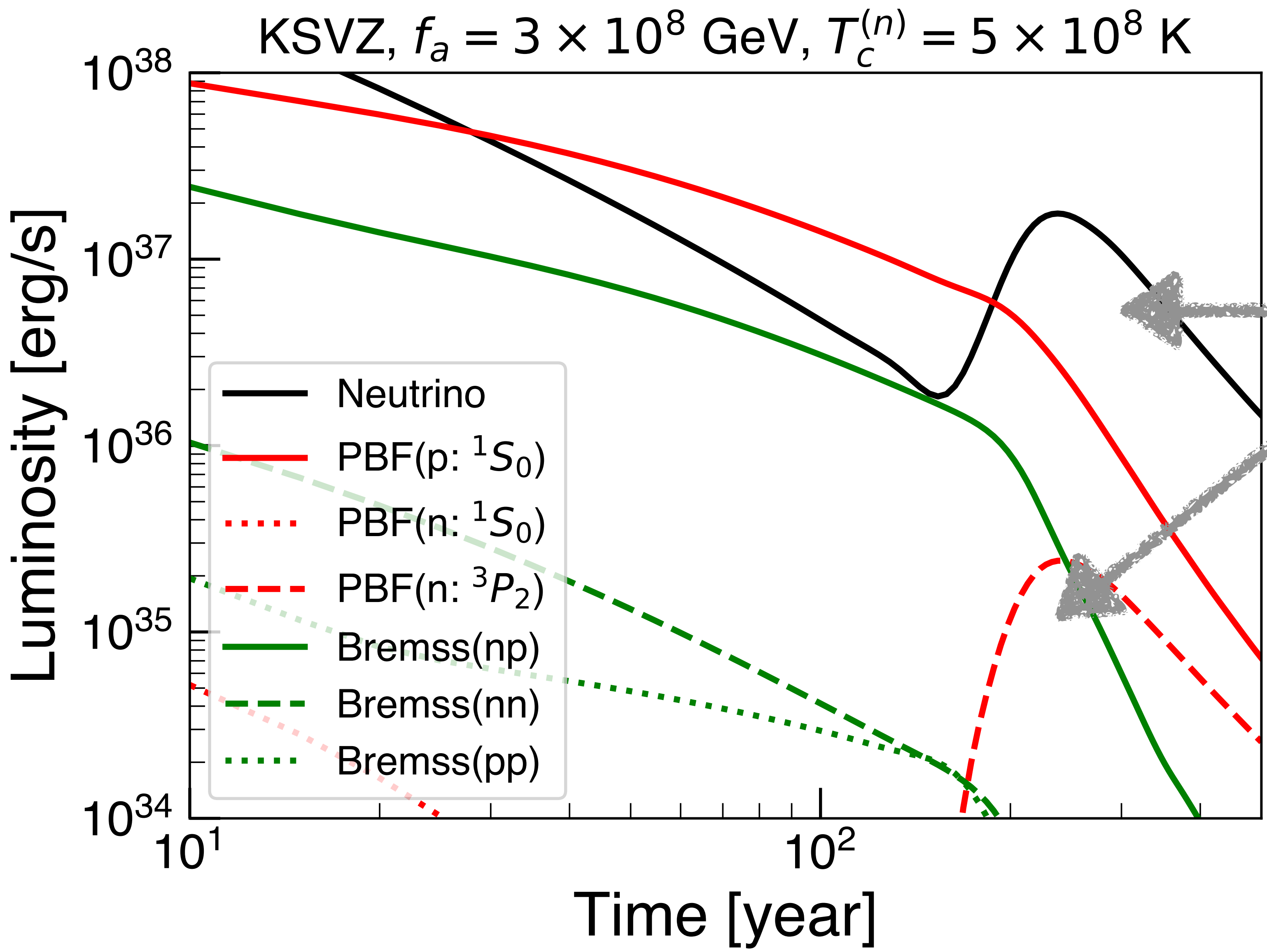
- PBF

  J. Keller, A. Sedrakian, Nucl. Phys. **A897**, 62 (2013);
  L. B. Leison, JCAP **1408**, 031 (2014);
  A. Sedrakian, Phys. Rev. **D93**, 065044 (2016).

- Bremsstrahlung

  N. Iwamoto, Phys. Rev. Lett. **53**, 1198 (1984);
  M. Nakagawa, Y. Kohyama, and N. Itoh, Astrophys. J. **322**, 291 (1987);
  M. Nakagawa, T. Adachi, K. Kohyama, and N. Itoh, Astrophys. J **326**, 241 (1988);
  N. Iwamoto, Phys. Rev. **D64**, 043002 (2001); H. Umeda, N. Iwamoto, S. Tsuruta, L. Qin, and K. Nomoto, arXiv: 9806337.

Luminosity of axion emission



Onset of neutron triplet pairing.

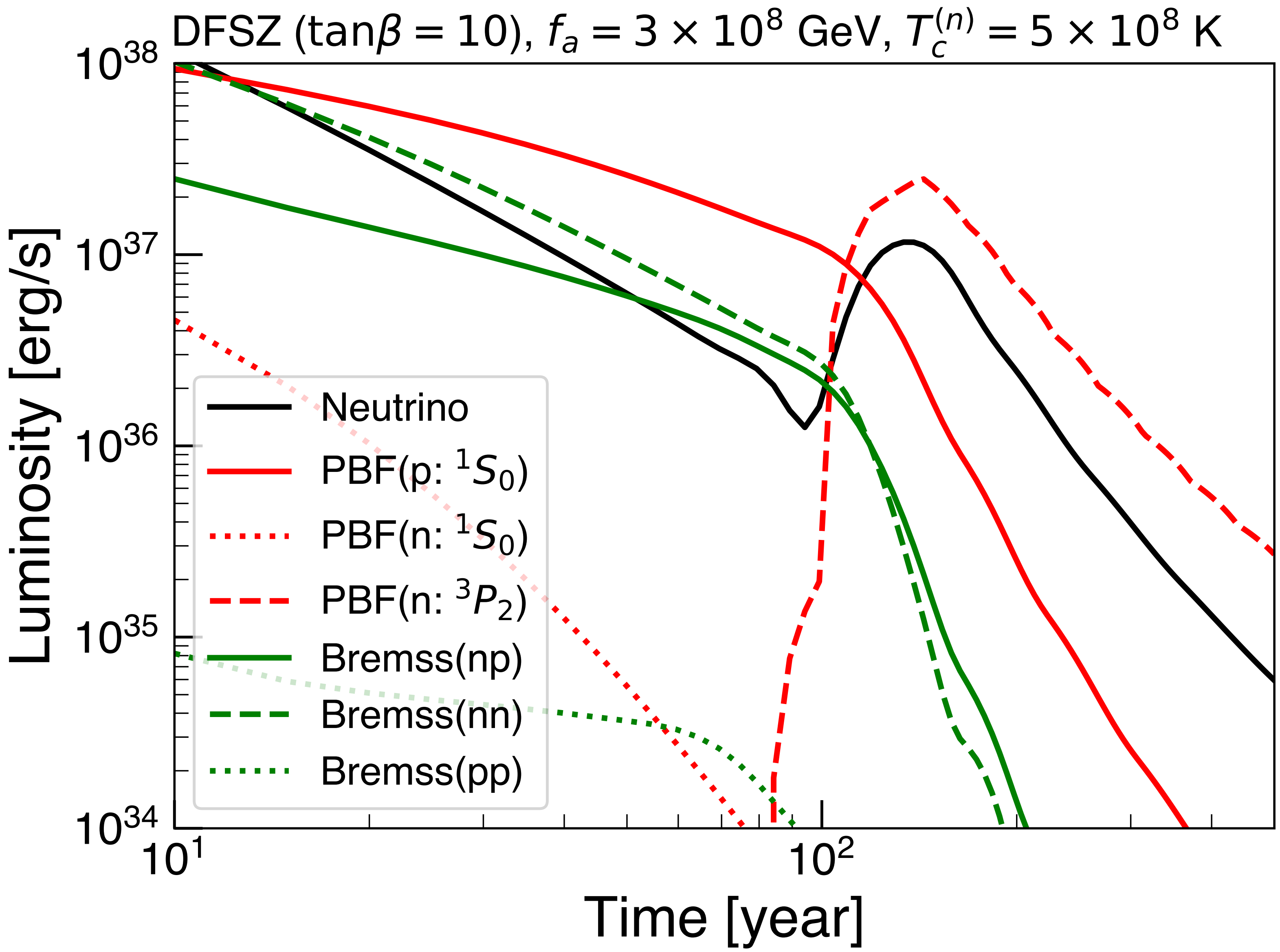
Neutron PBF

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).

Luminosity of axion emission

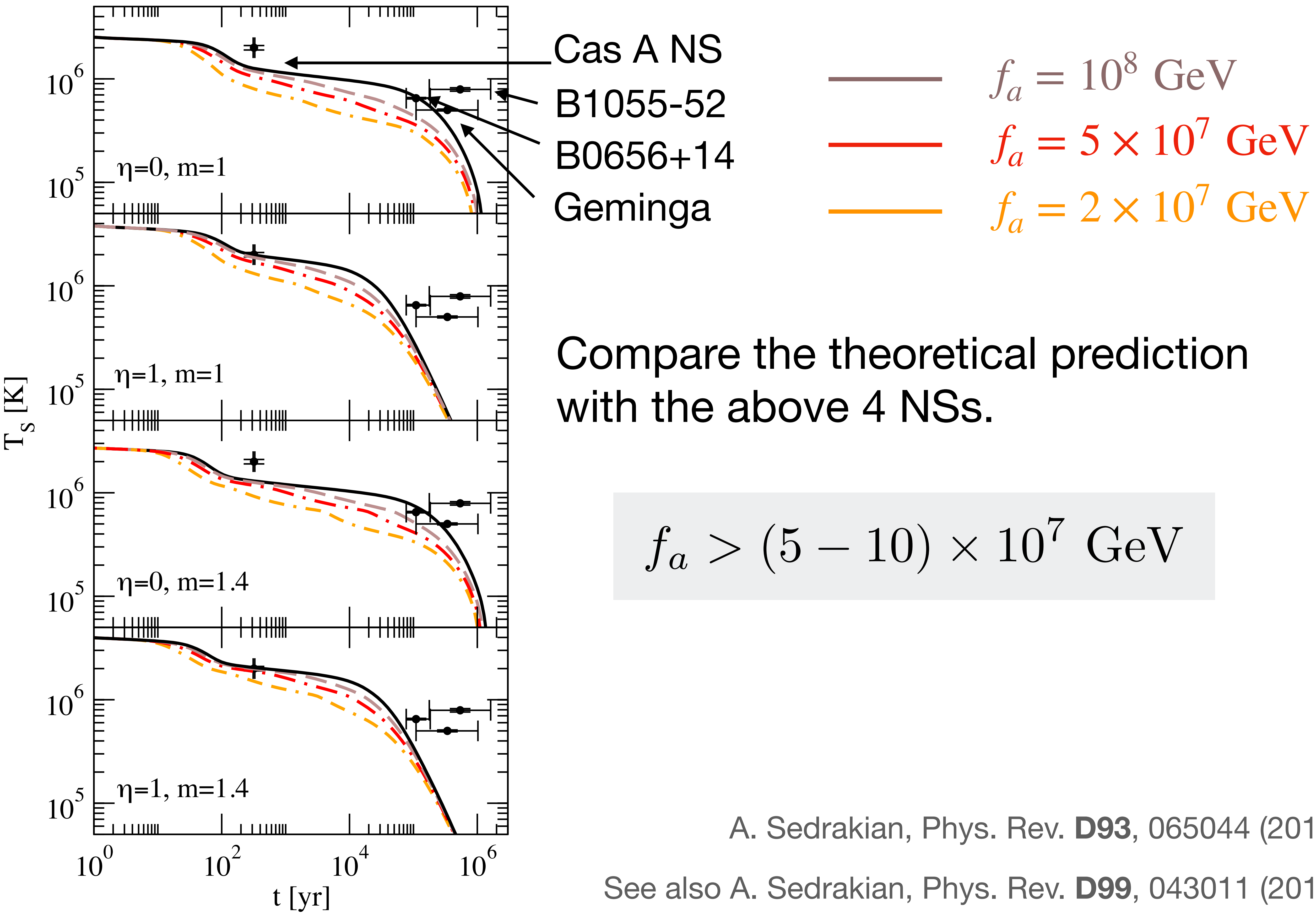


Axion emission is stronger than the KSVZ case.

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

Limit on axion decay constant

Limits on axion decay constant



Compare the theoretical prediction with the above 4 NSs.

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

A. Sedrakian, Phys. Rev. **D93**, 065044 (2016).

See also A. Sedrakian, Phys. Rev. **D99**, 043011 (2019).

Recent update

Recent new limits from NS cooling:

- Cassiopeia A Neutron Star

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

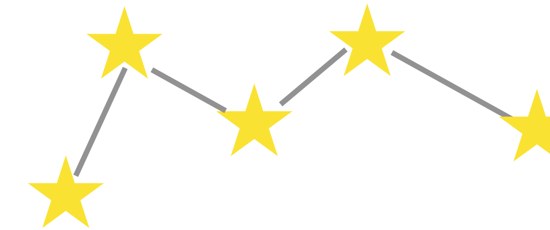
- XMMU J173203.3-344518

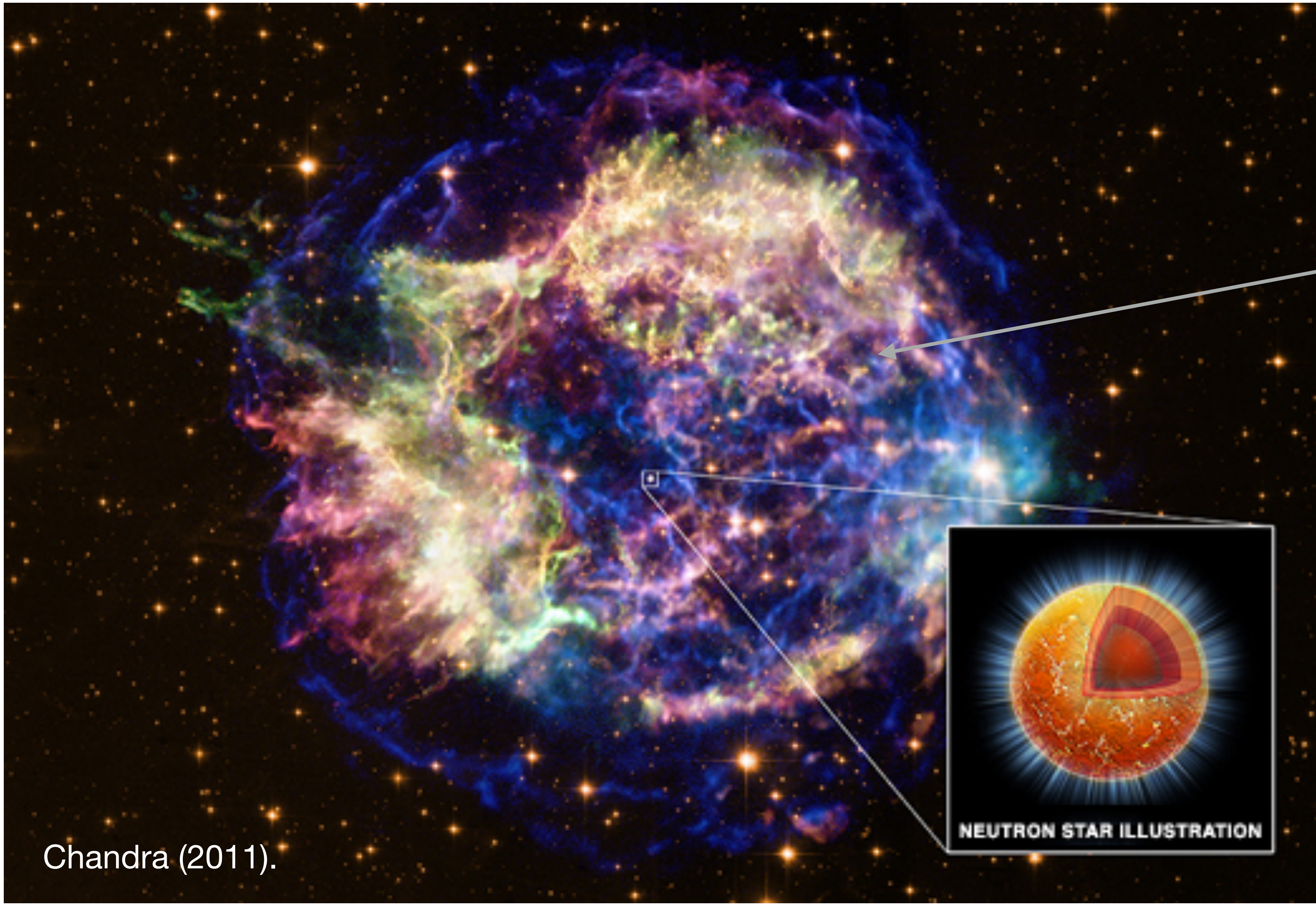
  M. V. Beznogov, et. al., Phys. Rev. C **98**, 035802 (2018).

  L. B. Leison, arXiv:1909.03941.

These limits are as strong as the SN1987A bound.

Cassiopeia A (Cas A)





Supernova remnant

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

Neutron star (NS) was found in the center.

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

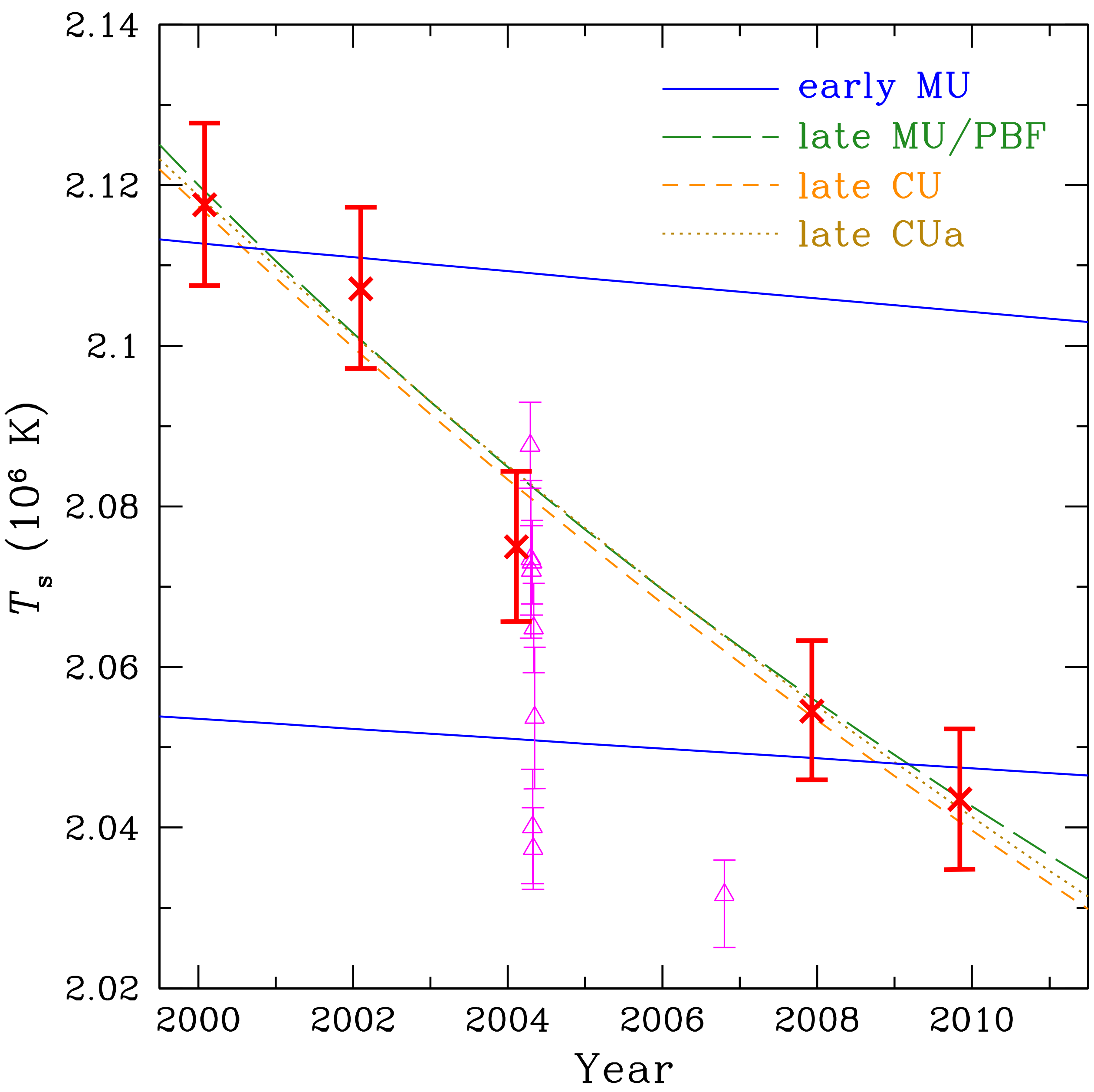
Cas A NS Cooling

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

DIRECT OBSERVATION OF THE COOLING OF THE CASSIOPEIA A NEUTRON STAR

Craig O. Heinke[1] and Wynn C. G. Ho[2]
[1] Department of Physics, University of Alberta, Room 238 CEB, Edmonton, AB T6G 2G7, Canada; heinke@ualberta.ca
[2] School of Mathematics, University of Southampton, Southampton SO17 1BJ, UK; wynnho@slac.stanford.edu
Received 2010 April 14; accepted 2010 July 8; published 2010 August 2

Chandra



Cooling of Cas A NS directly observed.

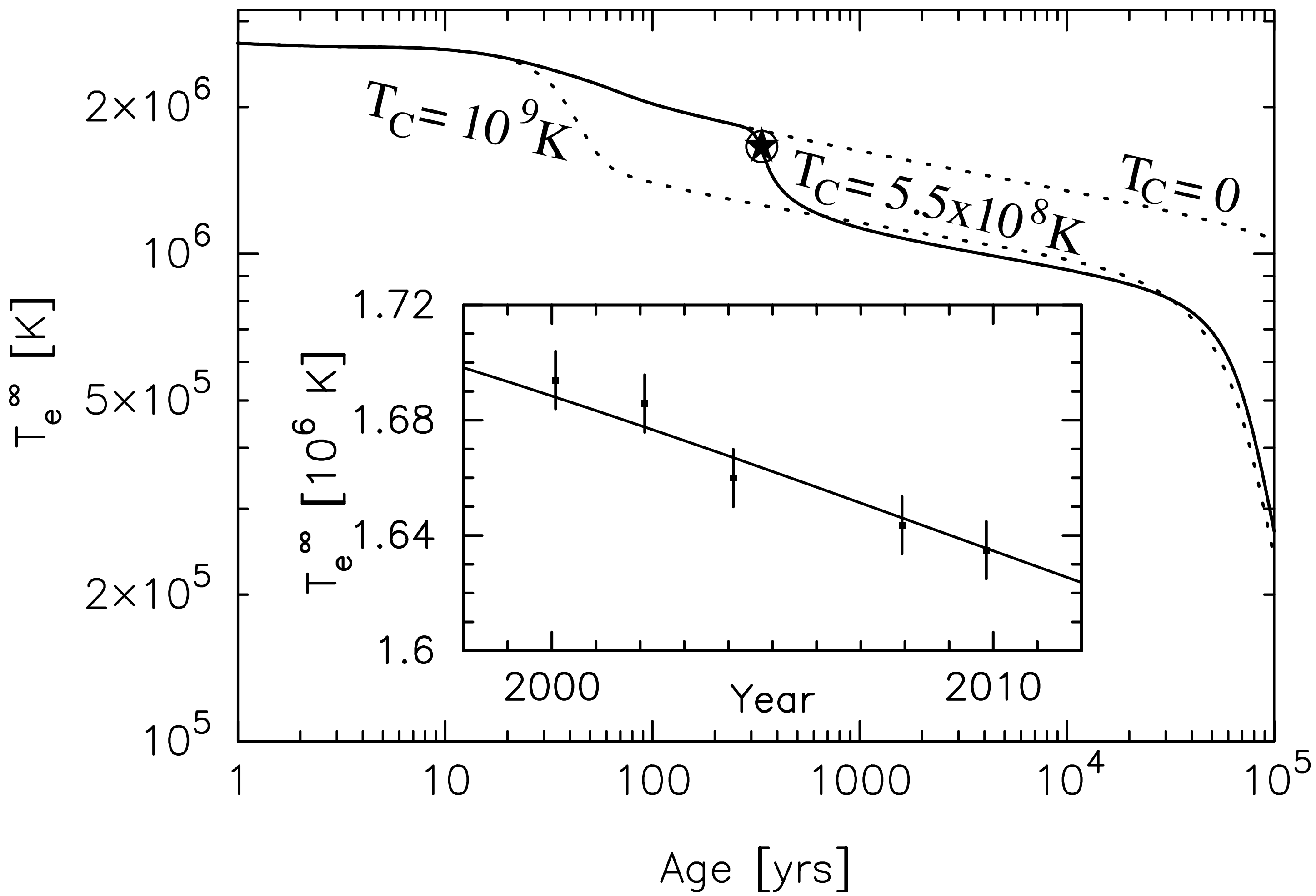
- This was rather rapid.

  3—4% decrease in ten years.

- This is the only NS whose cooling curve is observed for the moment.

Fit in the minimal cooling paradigm

We need PBF to explain the rapid cooling.



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

If the critical temperature of neutrino triplet pairing is

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

PBF has just started.

Cas A NS cooling can be explained.

Direct evidence of superfluidity in NS

Selected for a Viewpoint in *Physics*

PRL **106**, 081101 (2011) PHYSICAL REVIEW LETTERS week ending 25 FEBRUARY 2011

Rapid Cooling of the Neutron Star in Cassiopeia A Triggered by Neutron Superfluidity in Dense Matter

Dany Page,[1] Madappa Prakash,[2] James M. Lattimer,[3] and Andrew W. Steiner[4]

We propose that the observed cooling of the neutron star in Cassiopeia A is due to enhanced neutrino emission from the recent onset of the breaking and formation of neutron Cooper pairs in the $^3P_2$ channel. We find that the critical temperature for this superfluid transition is $\simeq 0.5 \times 10^9$ K. The observed rapidity of the cooling implies that protons were already in a superconducting state with a larger critical temperature. This is the first direct evidence that superfluidity and superconductivity occur at supranuclear densities within neutron stars. Our prediction that this cooling will continue for several decades at the present rate can be tested by continuous monitoring of this neutron star.

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY LETTERS

Mon. Not. R. Astron. Soc. **412,** L108–L112 (2011) doi:10.1111/j.1745-3933.2011.01015.x

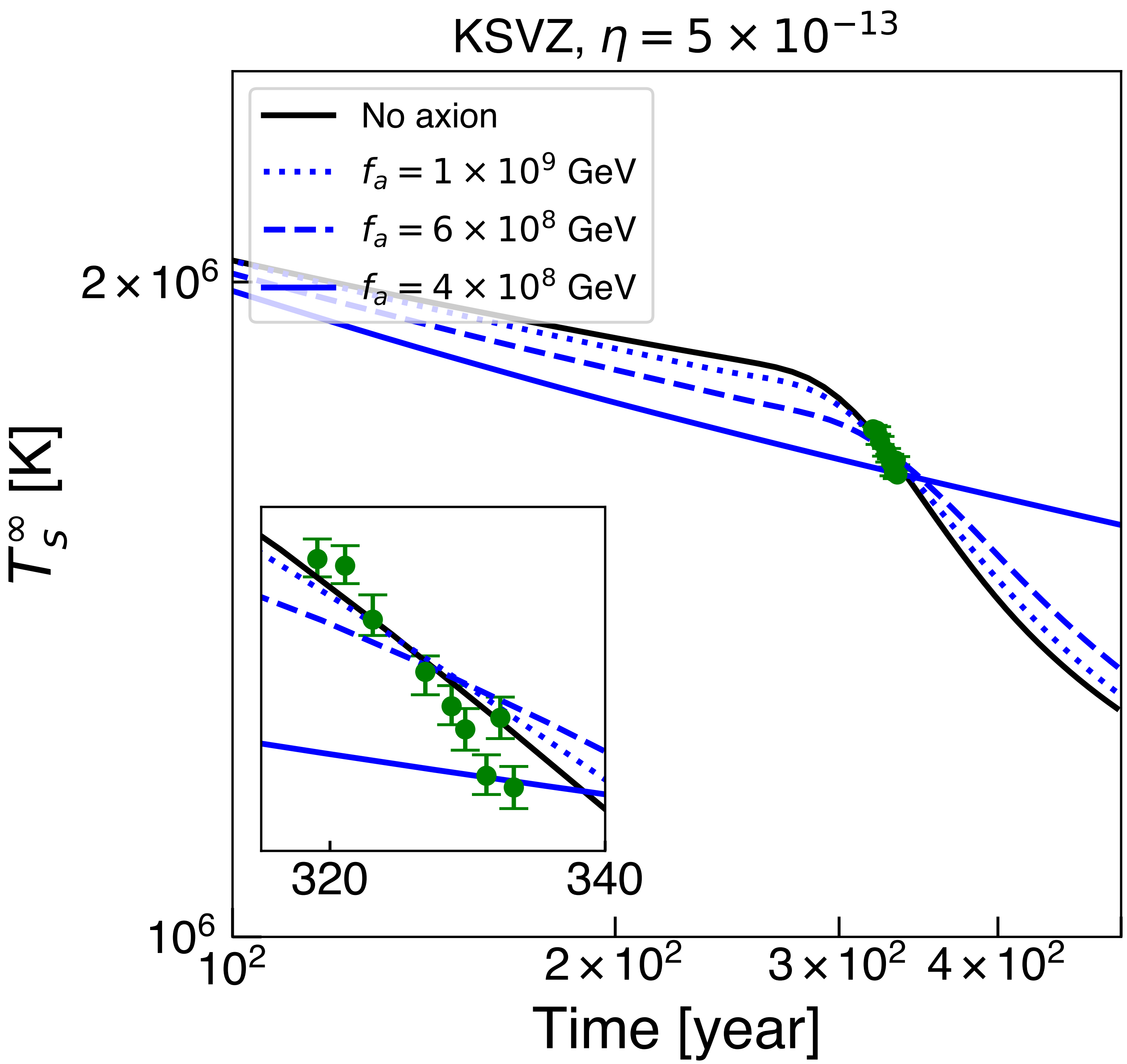
Cooling neutron star in the Cassiopeia A supernova remnant: evidence for superfluidity in the core

Peter S. Shternin,[1,2★] Dmitry G. Yakovlev,[1] Craig O. Heinke,[3] Wynn C. G. Ho[4★] and Daniel J. Patnaude[5]

than the standard modified Urca process). This is serious evidence for nucleon superfluidity in NS cores that comes from observations of cooling NSs.

Cooling curves vs data

Now that $T_c^{(n)}$ is fixed, we can obtain a more robust limit:



Our limit

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

KSVZ (DFSZ, tanβ = 10)

Cf.) SN1987A

$f_a \gtrsim 4 \times 10^8$ GeV (KSVZ)

We obtained a bound comparable to other astrophysical limits.

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

PDG 2019

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PDG particle data group 1957 2017 Live

Home | pdgLive | Summary Tables | Reviews, Tables, Plots | Particle Listings

pdgLive Home > Axions (A^0) and Other Very Light Bosons, Searches for > **Invisible A^0 (Axion) Limits from Nucleon Coupling**

2019 Review of Particle Physics.
Warning: production version with current encodings in progress

Invisible A^0 (Axion) Limits from Nucleon Coupling

INSPIRE search

Limits are for the axion mass in eV.

VALUE (eV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 65	95	1 AKHMATOV	2018	CNTR	Solar axion
< 6.6	90	2 ARMENGAUD	2018	EDE3	Solar axion
< 0.085	90	3 BEZNOGOV	2018	ASTR	Neutron star cooling
< 12.7	95	4 GAVRILYUK	2018	CNTR	Solar axion
< 0.01		5 HAMAGUCHI	2018	ASTR	Neutron star cooling
		6 ABEL	2017		Neutron EDM
< 93	90	7 ABGRALL	2017	HPGE	Solar axion
< 4	90	8 FU	2017A	PNDX	Solar axion
		9 KLIMCHITSKAYA	2017A		Casimir effect

XMMU J173203.3-344518

XMMU J173203.3-344518

- NS in the center of the supernova remnant G353.6-0.7.
- Hottest NS among those with weak magnetic fields.

$$T_s^\infty = 1.78^{+0.04}_{-0.02} \times 10^6 \text{ K}$$

D. Klochkov, et. al., Astron. Astrophys. **573**, A53 (2015).

- Approximately 27000 yrs

W. W. Tian, et. al., Astrophys. J. **679**, L85 (2008).

To explain this temperature, we need

M. V. Beznogov, et. al., Phys. Rev. C **98**, 035802 (2018).

- $f_a > 6.7 \times 10^7$ GeV : KSVZ
- $f_a > 1.7 \times 10^9$ GeV : DFSZ

See also L. B. Leison, arXiv:1909.03941.

Comments on other light DM cases

The above limits are applicable to axion-like particles (ALPs) if

$$m_a \lesssim 10^8 \text{ K} \sim 10 \text{ keV}$$

and

$$f_a \gtrsim 10^6 \text{ GeV}$$

Mean free path > NS radius

For other light DM particles,

$\frac{1}{\Lambda}|\phi|^2 \bar{N} i\gamma_5 N$ (ϕ: light scalar DM) → $\Lambda \gtrsim 1 \text{ TeV}$

$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma_5\chi\bar{N}\gamma_\mu\gamma_5 N$ (χ: light fermion DM) → $\Lambda \gtrsim 100 \text{ GeV}$

K. Hamaguchi, N. Nagata, K. Yanagi, and J. Zheng, in preparation.

FAST

Many pulsars are expected to be discovered by

Five-hundred-meter Aperture Spherical radio Telescope (FAST)

（五百米口径球面射电望远镜）

in China in the near future.

- Largest radio telescope
- Started on Sep. 25, 2016.

About 5000 (4000 new discovery) pulsars will be observed.

Various new data are coming in the near future.

Conclusion

Conclusion

- Standard NS cooling theory is consistent with the observed NS temperature data.
- Presence of additional cooling source may spoil the success, which thus restricts such possibilities.
- Recent limits on the axion decay constant from NS cooling are as strong as other astrophysical bounds.
- More data will be available in the near future.

New Directions in Cosmology

24-27 March 2020
Hongo Campus
Asia/Tokyo timezone

- Overview
- Timetable
- Registration
- Participant List
- Accommodations
- Transportation
- Information

Contact

newcosmo@hep-th.phys...

We are pleased to announce the international workshop "New Directions in Cosmology." The aim of the workshop is to bring together experts and to exchange ideas in cosmology, astroparticle physics, and related subjects in particle physics.

Dates and venue

Dates: March 24-27, 2020
Venue: Room 285/337A, Faculty of Science Bldg.1 East, Hongo Campus, The University of Tokyo.

Important dates

Abstract submission deadline: Jan. 10, 2020
Registration deadline: Jan. 31, 2020

We are going to have a workshop in University of Tokyo, Hongo campus, from Mar. 24 to Mar. 27, 2020.

Check out https://indico.ipmu.jp/event/309/

Backup

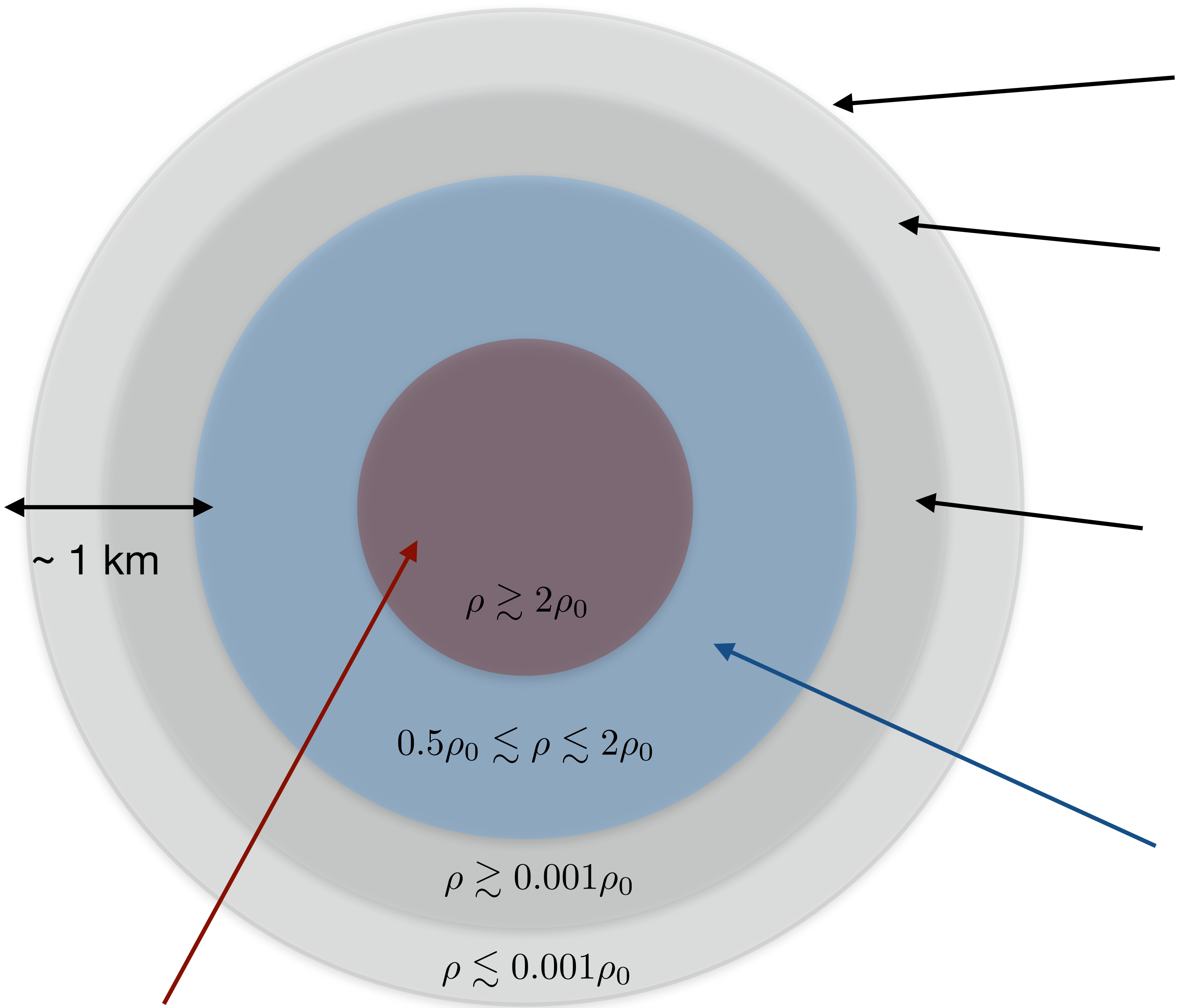
How neutron stars are born

At the end of a star life, a core-collapse supernova explosion occurs, and its remnant core can become neutron star.

Destiny of stars

Mass [$M_\odot$]	Core-collapse	Final state
— 0.08	No	Brown dwarf
0.08 — 8	No	White dwarf
8 — 30	Yes	Neutron star
30 —	Yes	Black hole

Neutron star structure



Envelope, atmosphere

Outer crust

Neutron-rich nucleus (crystal)

Electron

Inner crust

Neutron-rich nucleus, electron

Neutron superfluid: $^1S_0$

Outer core

Electron, muon

Neutron superfluid: $^3P_2$

Proton superconductor: $^1S_0$

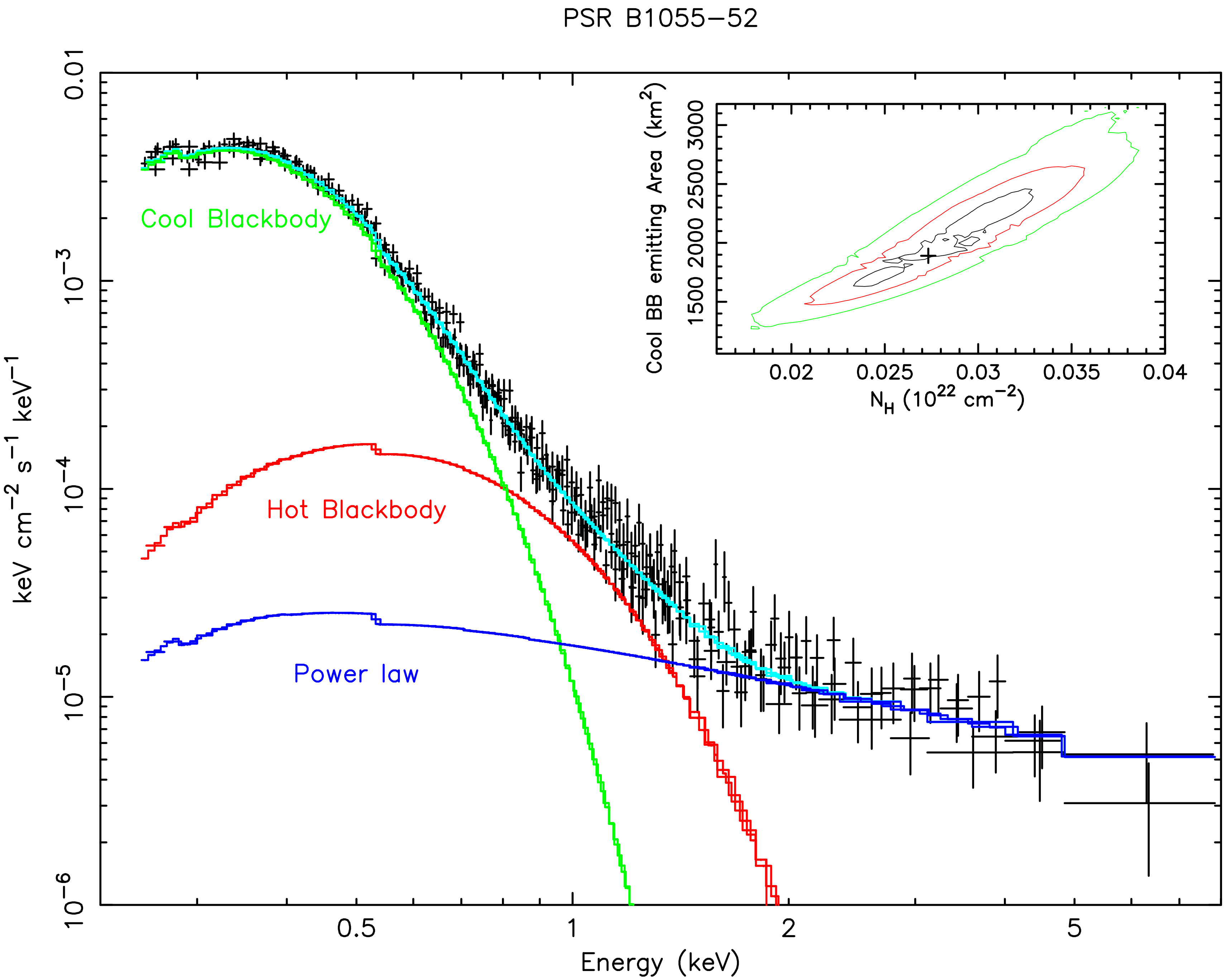
Inner core

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

Neutron superfluid: $^3P_2$

~~Hyperons, π/K condensation, quarks (?)~~ We do not consider them in this talk.

PSR B1055-52



$$T_{\text{cool}} = (7.9 \pm 0.3) \times 10^5 \text{ K}$$

$$R_{\text{cool}} = 12.3^{+1.5}_{-0.7} \text{ km}$$

$$T_{\text{hot}} = (1.79 \pm 0.06) \times 10^6 \text{ K}$$

$$R_{\text{hot}} = 460 \pm 60 \text{ m}$$

2 Black body components + power low fit

G. Bignami, P. Caraveo, A. de Luca, S. Mereghetti, M. Negroni, Astrophys. J. **623**, 1051 (2005).

Early stage of neutron star

- Right after the supernova explosion, a neutron star is in a very high-temperature state with $T \sim 10^{11}$ K.

- After ~ 20s, the temperature gets low enough for neutrinos to escape from the neutron star.

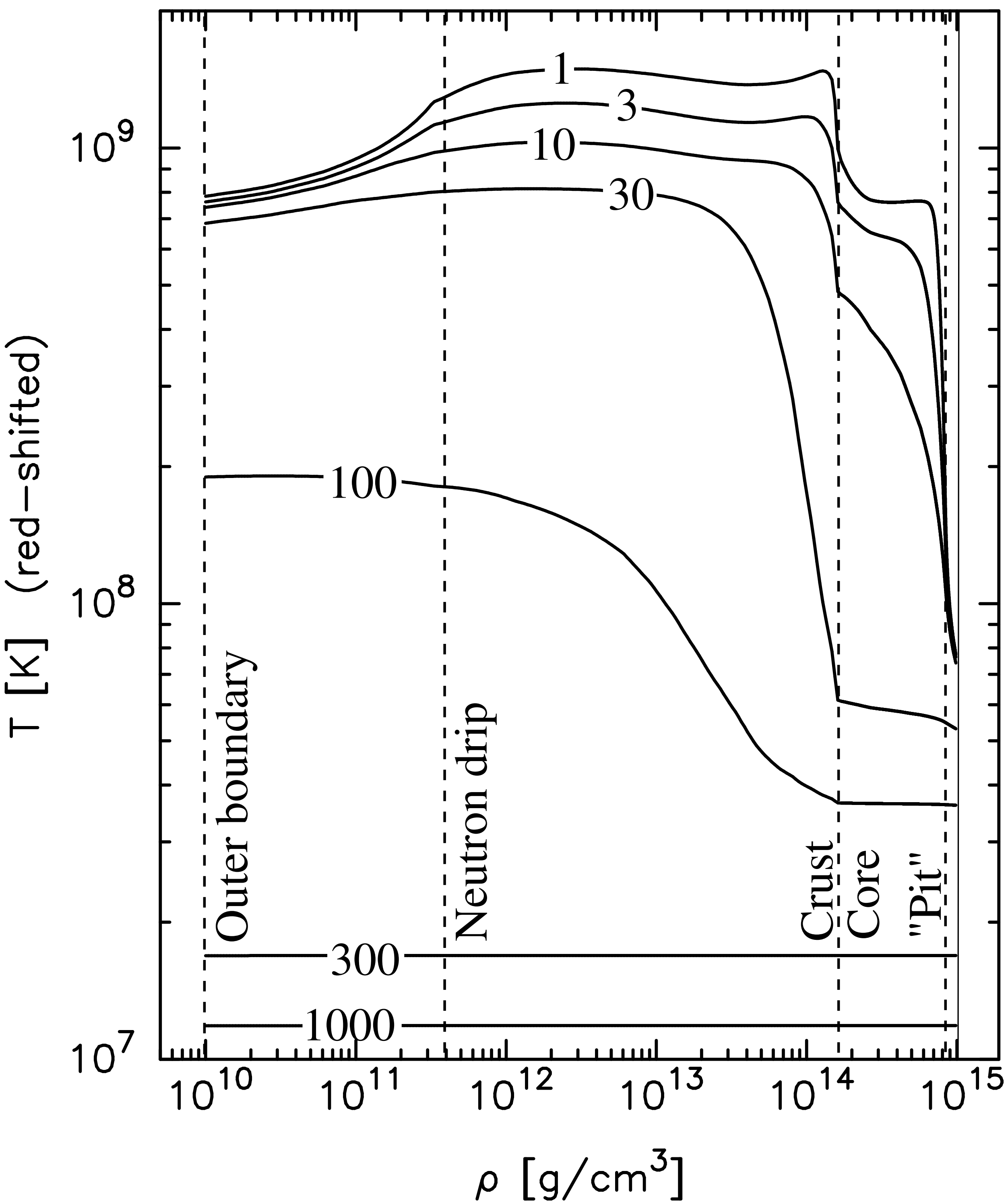
- Thermal relaxation completed after 10—100 years, and the temperature becomes constant inside the neutron star.

    - We focus on this case in what follows.

    - The following results rarely depend on the initial conditions.

Temperature decreases very rapidly in the first moments.

Temperature distribution

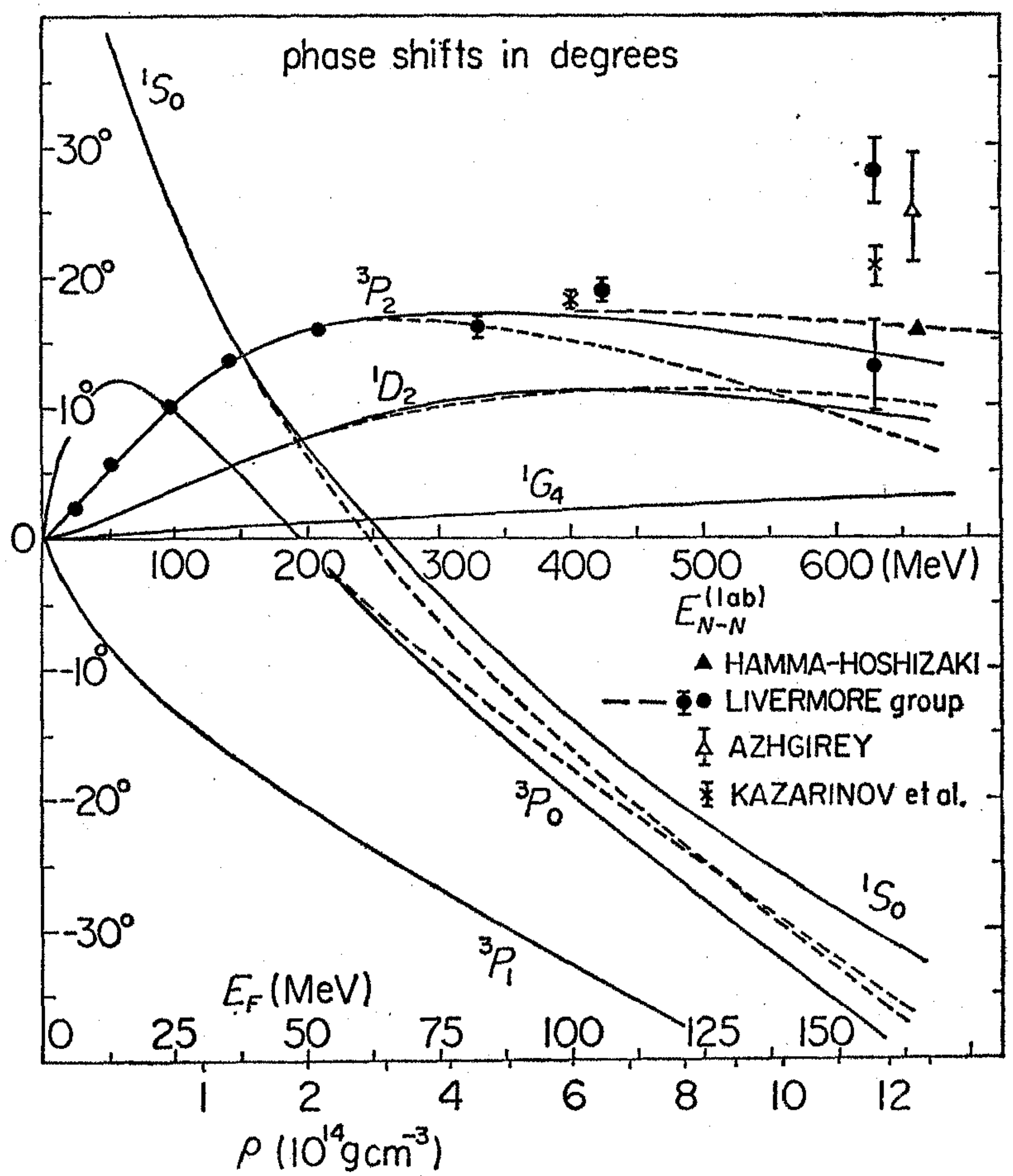


Relaxation in the Core done in ~ 100 years.

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

Pairing in Nuclei

Phase shift in nucleon-nucleon scatterings



R. Tamagaki, Prog. Theor. Phys. **44**, 905 (1970).

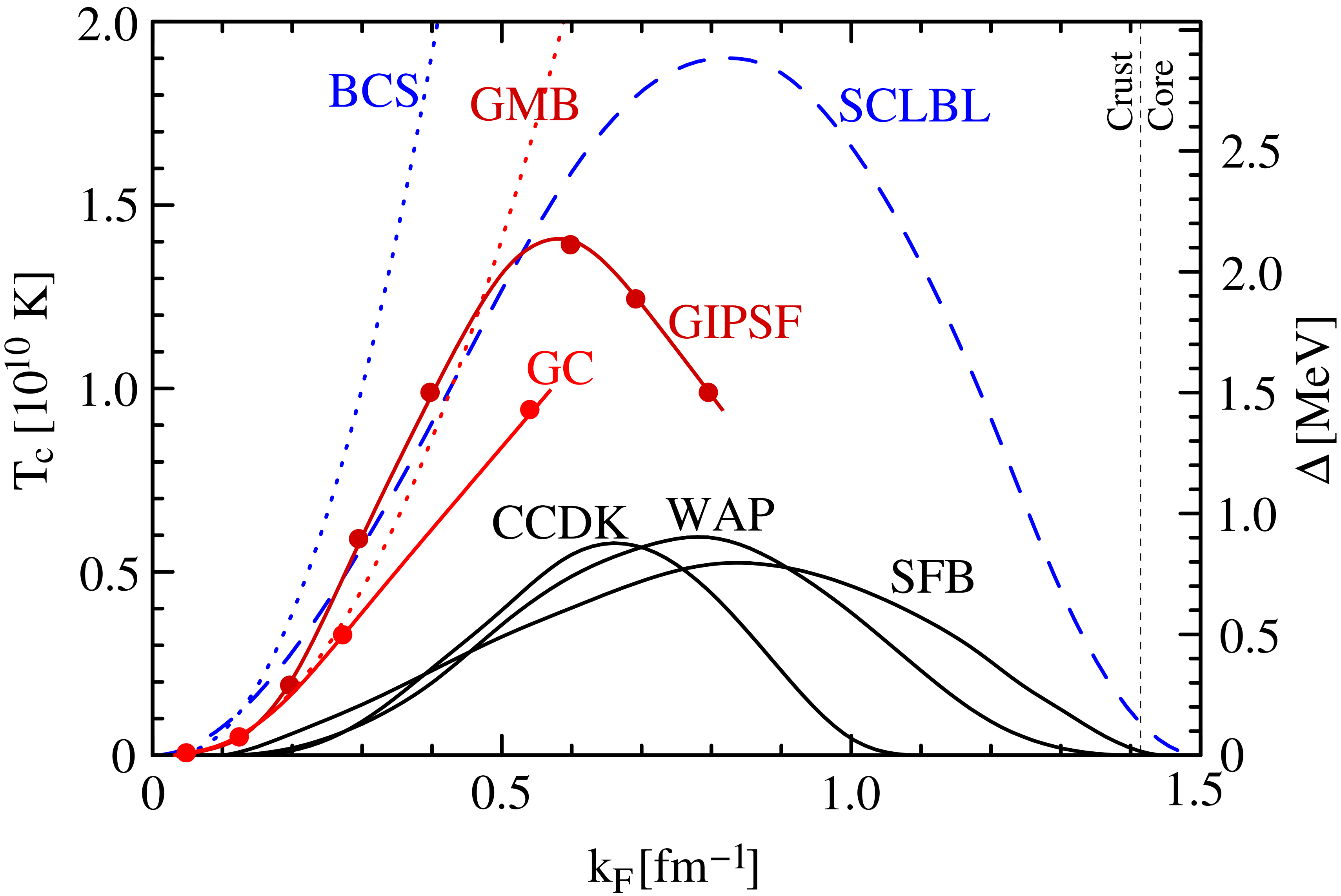
Positive phase shift corresponds to attractive force.

- Singlet paring forms at low densities.
- Triplet paring forms at high densities.

Note that interactions may be modified by medium effect in neutron stars.

$^1S_0$ neutron gap

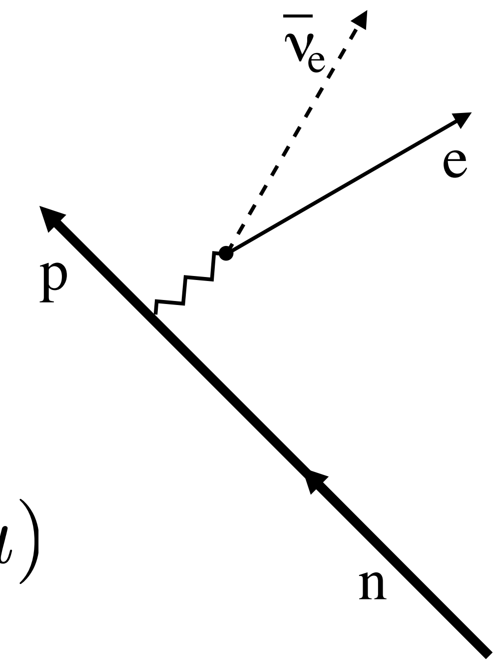
By solving the gap equation, we can obtain the pairing gap.



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.

Direct Urca process



Direct Urca

Let us consider the direct Urca process:

$$n \to p + \ell^- + \bar{\nu}_\ell,\ \ \ell^- + p \to n + \bar{\nu}_\ell \qquad (\ell = e, \mu)$$

β decay & electron capture

We calculate emissivity of this process.

Emissivity ≡ energy loss per volume per time.

$$Q^{(\mathrm{D})} = 2 \int \frac{d^3\boldsymbol{p}_n}{(2\pi)^3}\frac{d^3\boldsymbol{p}_p}{(2\pi)^3}\frac{d^3\boldsymbol{p}_e}{(2\pi)^3}\frac{d^3\boldsymbol{p}_\nu}{(2\pi)^3} \cdot p_\nu^0 \cdot f_n(1-f_p)(1-f_e)$$
$$\times (2\pi)^4 \delta^4(p_n - p_p - p_e - p_\nu) \cdot \sum_{\mathrm{spin}} |\mathcal{M}(n \to pe\bar{\nu})|^2$$

β decay + inverse

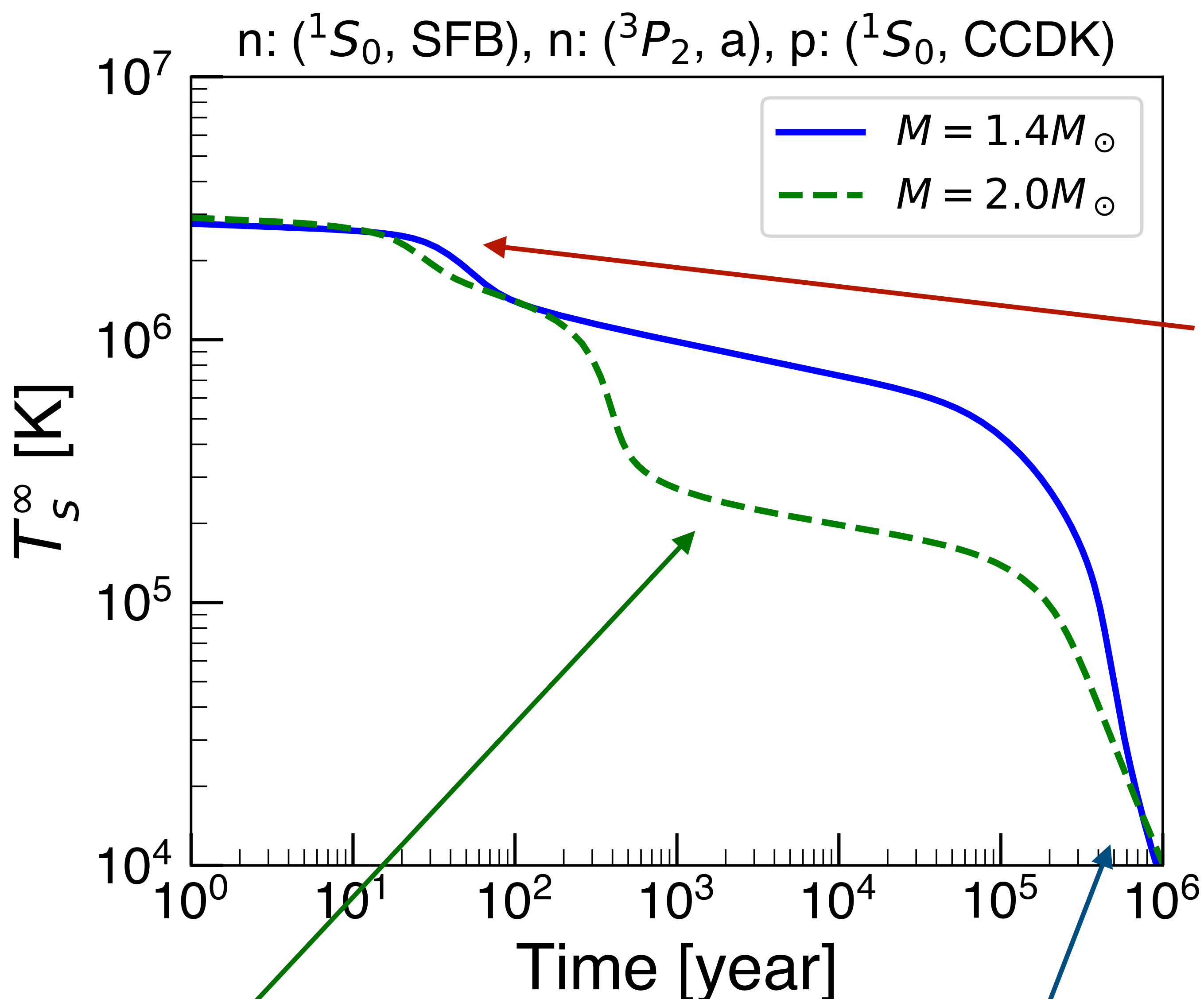
Energy loss by neutrino emission

Matrix element

f_i : Fermi distribution functions

Temperature evolution

We can now solve the equation for temperature evolution:

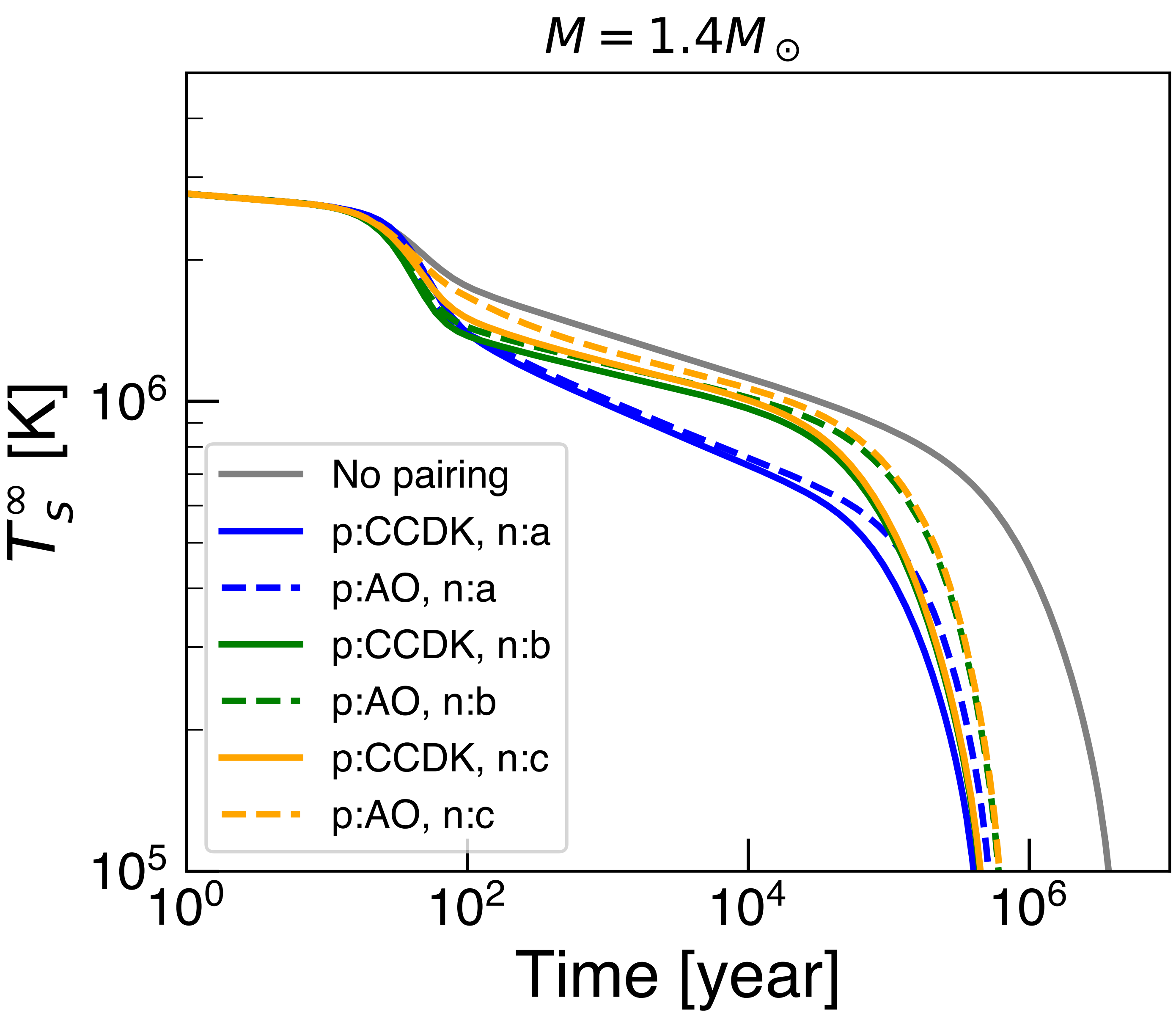


Before the thermal relaxation completed, the surface temperature does not follow the internal temperature.

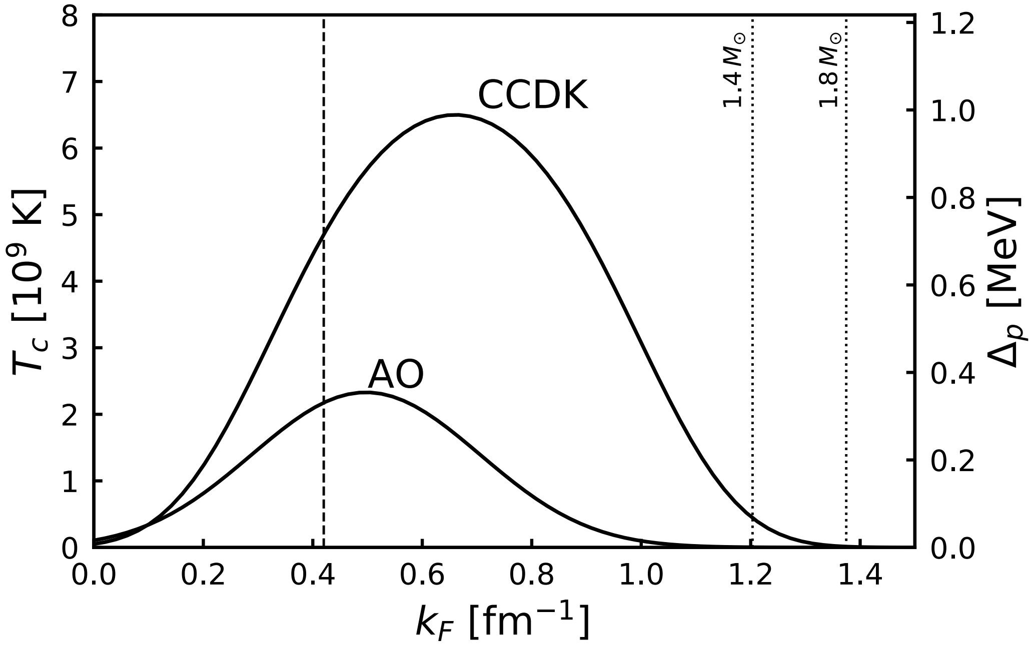
If Direct Urca occurs, the neutron star cools down rapidly.

Temperature of NSs (older than 10^6 years) is very low.

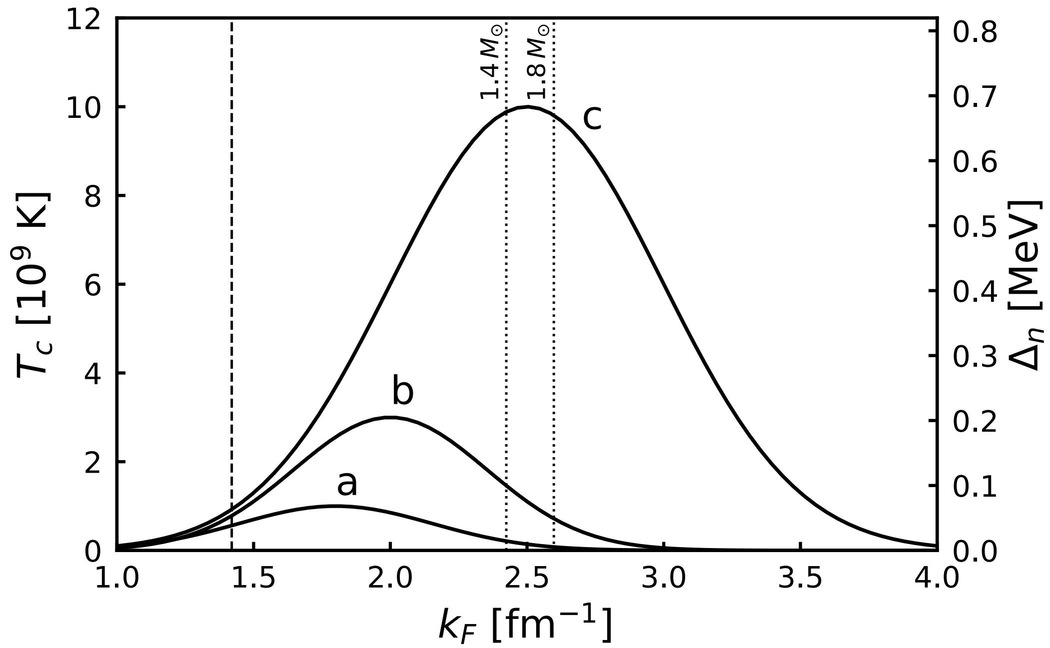
Temperature evolution (gap dependence)



Proton singlet gap

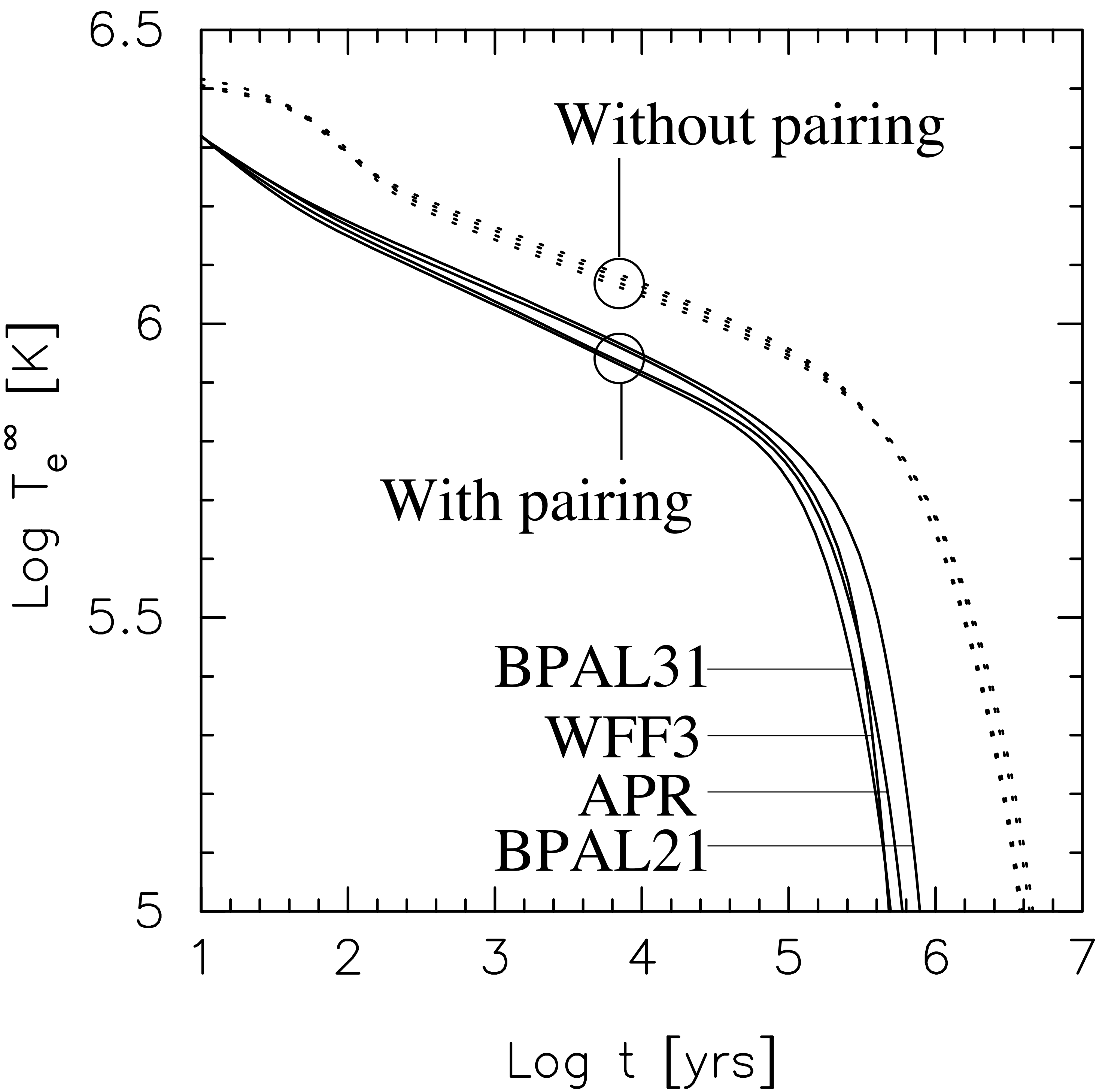


Neutron triplet gap



Cause uncertainty in the cooling calculation.

EOS dependence



J. M. Lattimer, D. Page, M. Prakash, A. W. Steiner, Astrophys. J. Suppl. **155**, 623 (2004).

NSCool

NSCool is a useful public code for the NS cooling computation.

http://www.astroscu.unam.mx/neutrones/NSCool/

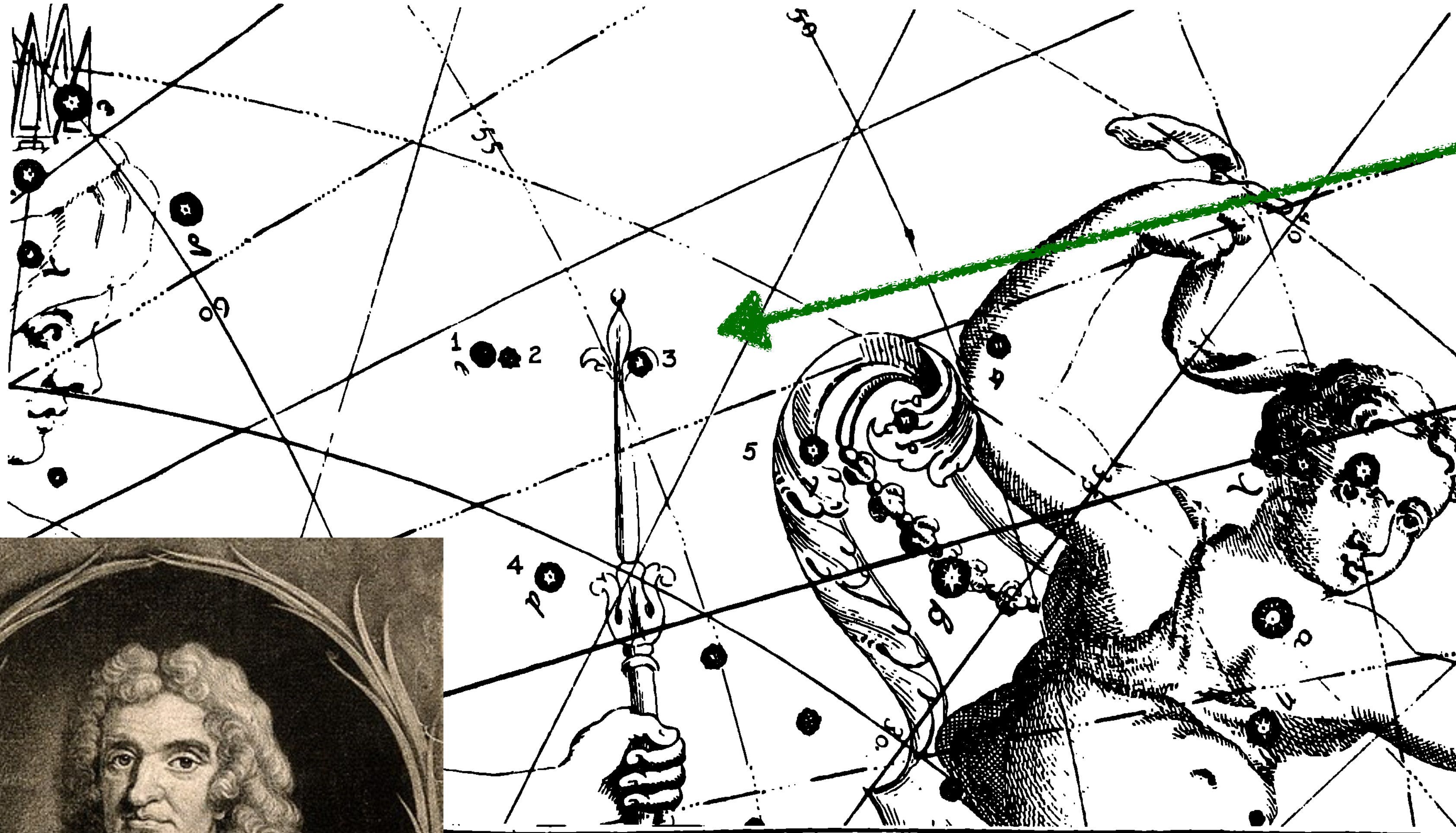
Features

- Written in fortran 77.
- Computes NS structure based on various EOSs.
- Solves the thermal transport equation.

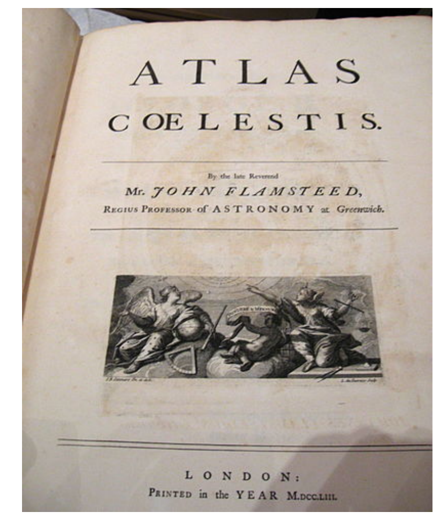
  We can follow the temperature evolution before the thermal relaxation has completed.

- Gravitational corrections included.
- Various sub-dominant processes included.

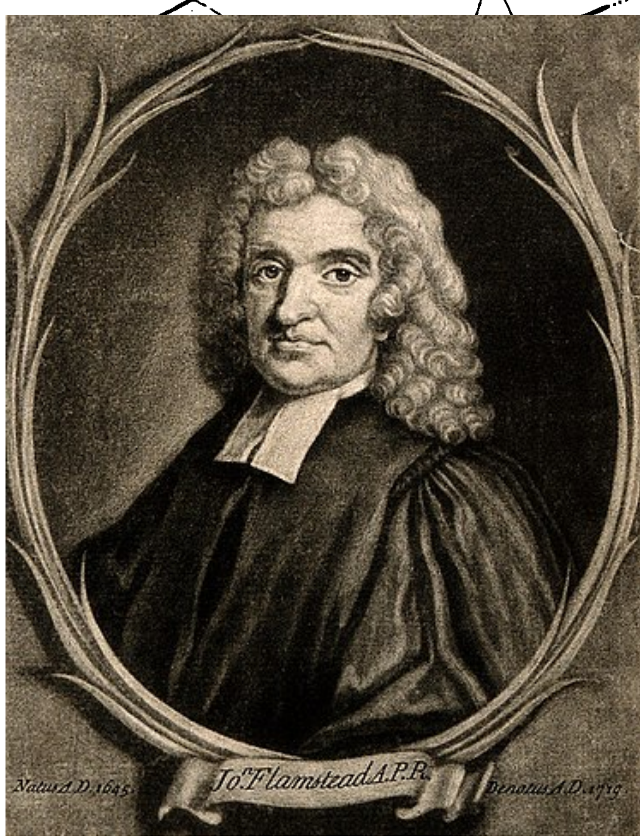
3 Cassiopeiae



3 Cassiopeiae



Atlas Coelestis (1729)



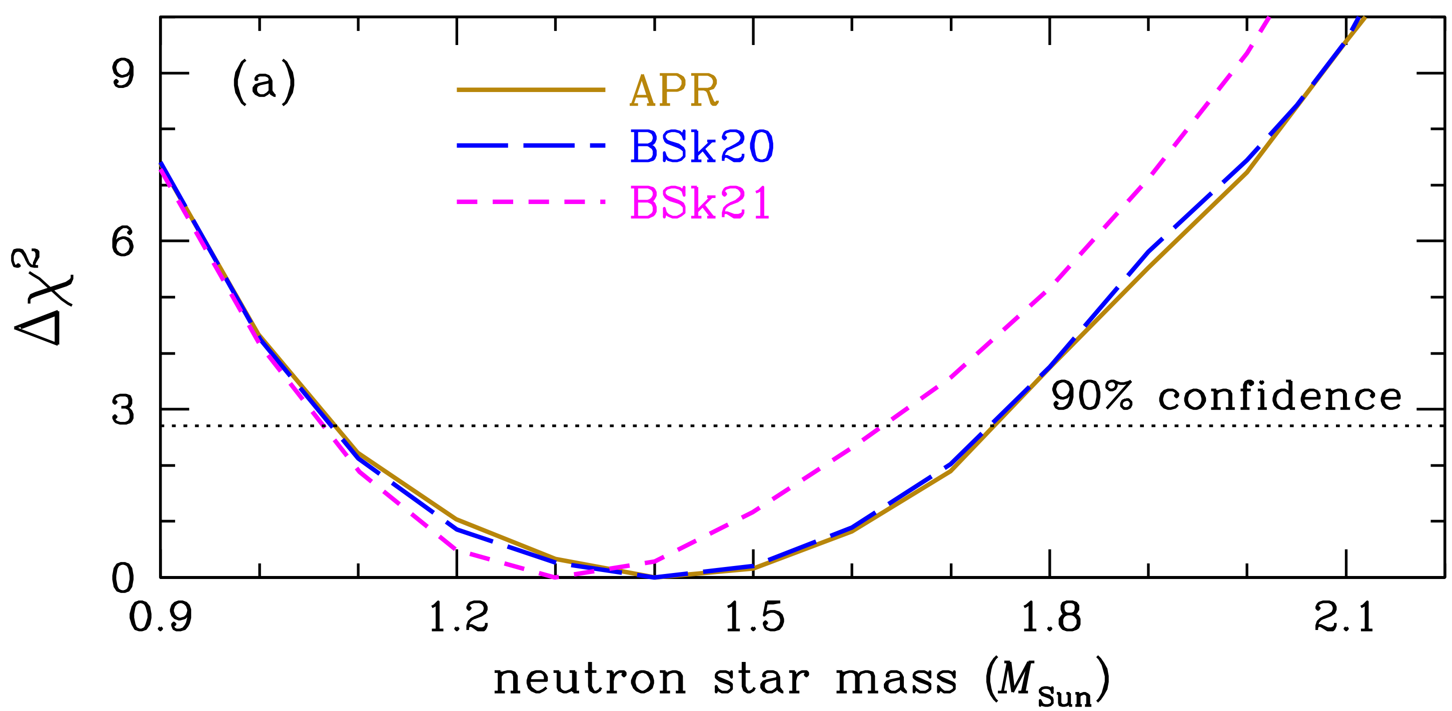
John Flamsteed

First Astronomer Royal

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

➡ Never been observed since then.

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.

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

How to explain Cas A cooling

Observation

3—4% decrease in ten years.

Modified Urca/Bremsstrahlung

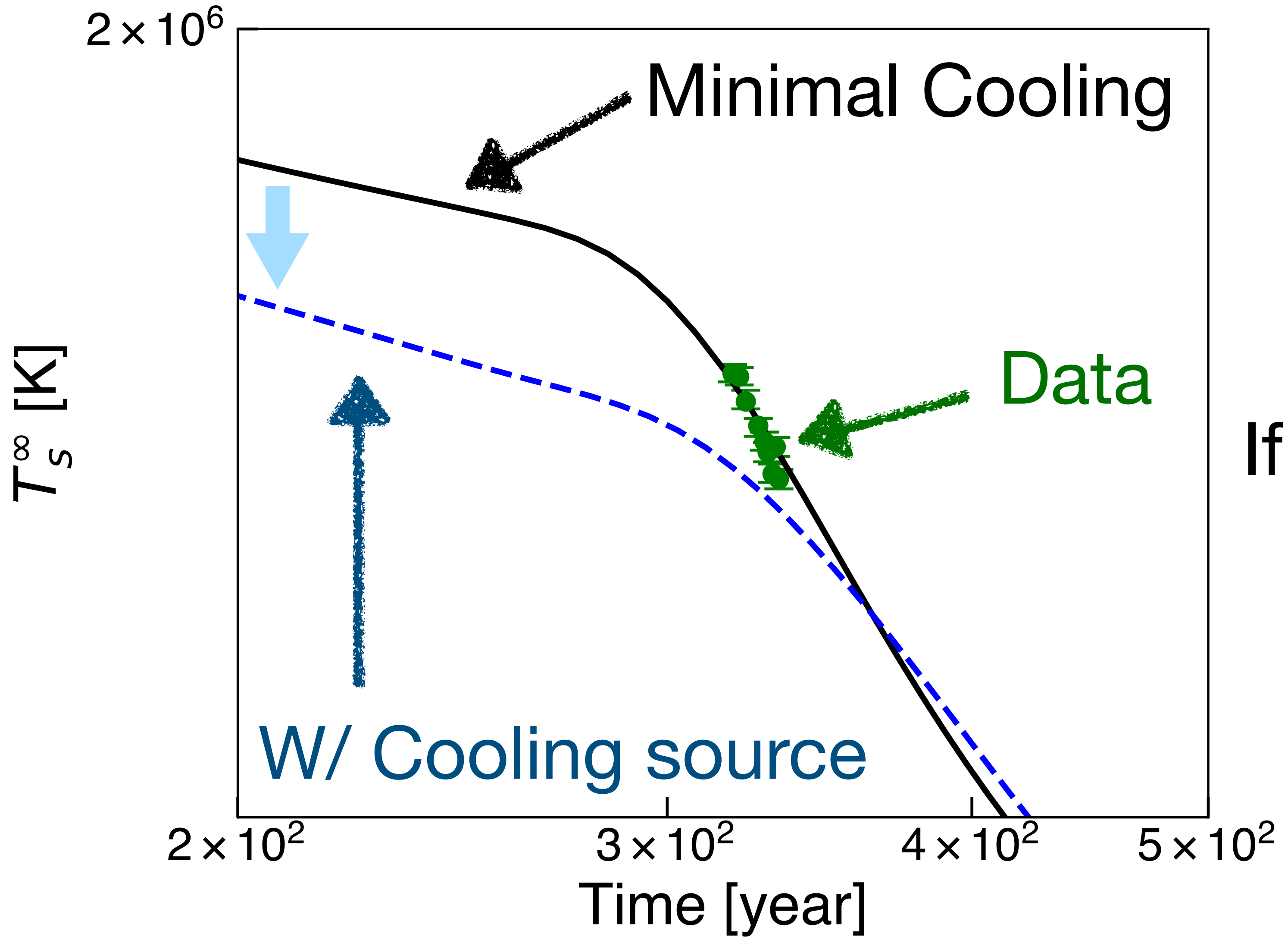
Only 0.3% decrease in T in ten years.

PBF

Rapid cooling but does not last so long.

➡ If PBF process has just started recently, the 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.

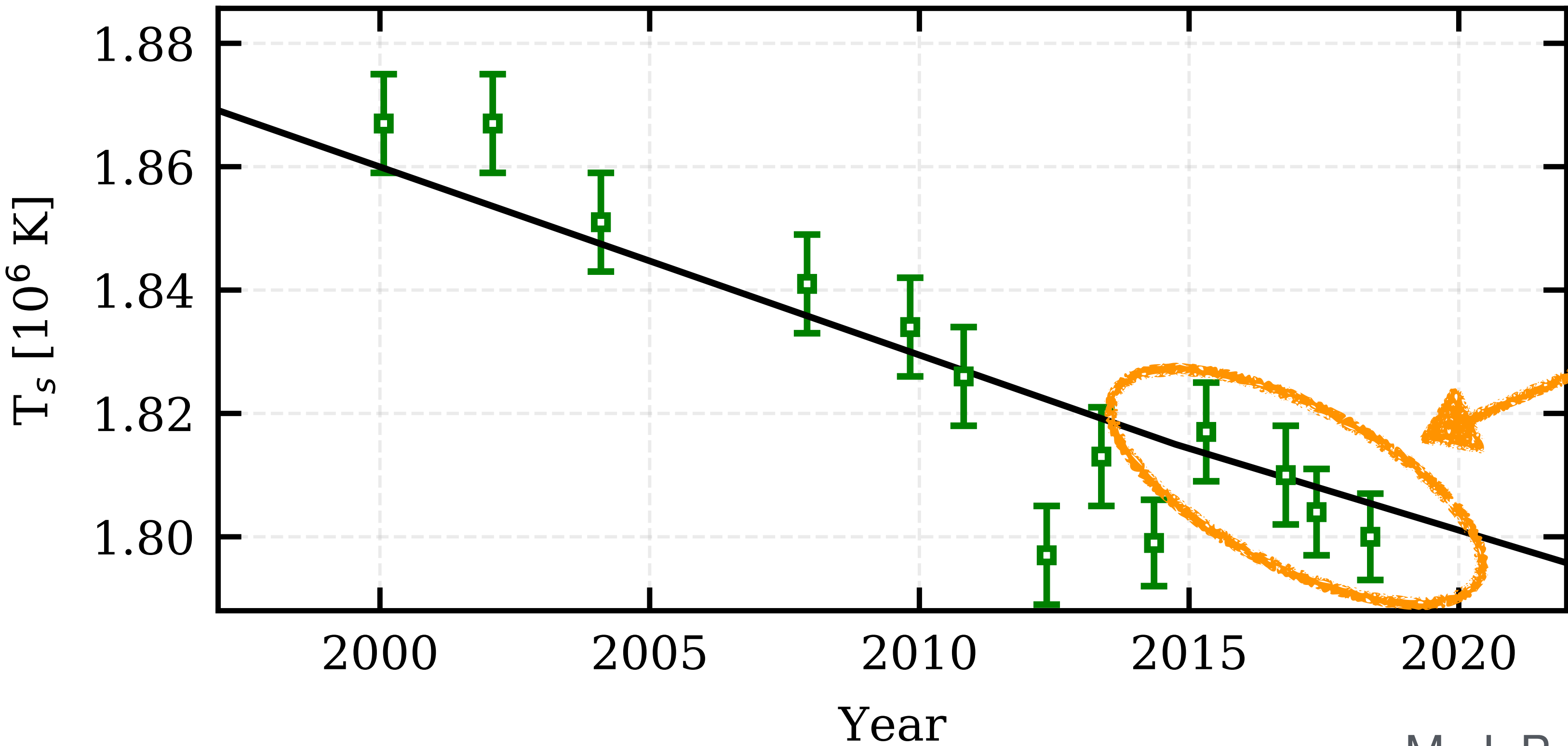
Technical details

- 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 fine as long as it is large enough.
- Neutron $^3P_2$ gap (Highly uncertain)

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

Recent update



Four new data were announced.

M. J. P. Wijingaarden, et. al., MNRAS **484**, 974 (2019).

Cas A NS temperature is still decreasing!! ~ 2% in ten yrs.

Additional data, observations of different NSs, etc., allow us to test the NS cooling theory.

We are working on more detailed analysis with this new data.

K. Hamaguchi, N. Nagata, K. Yanagi, and J. Zheng, in preparation.

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

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

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

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

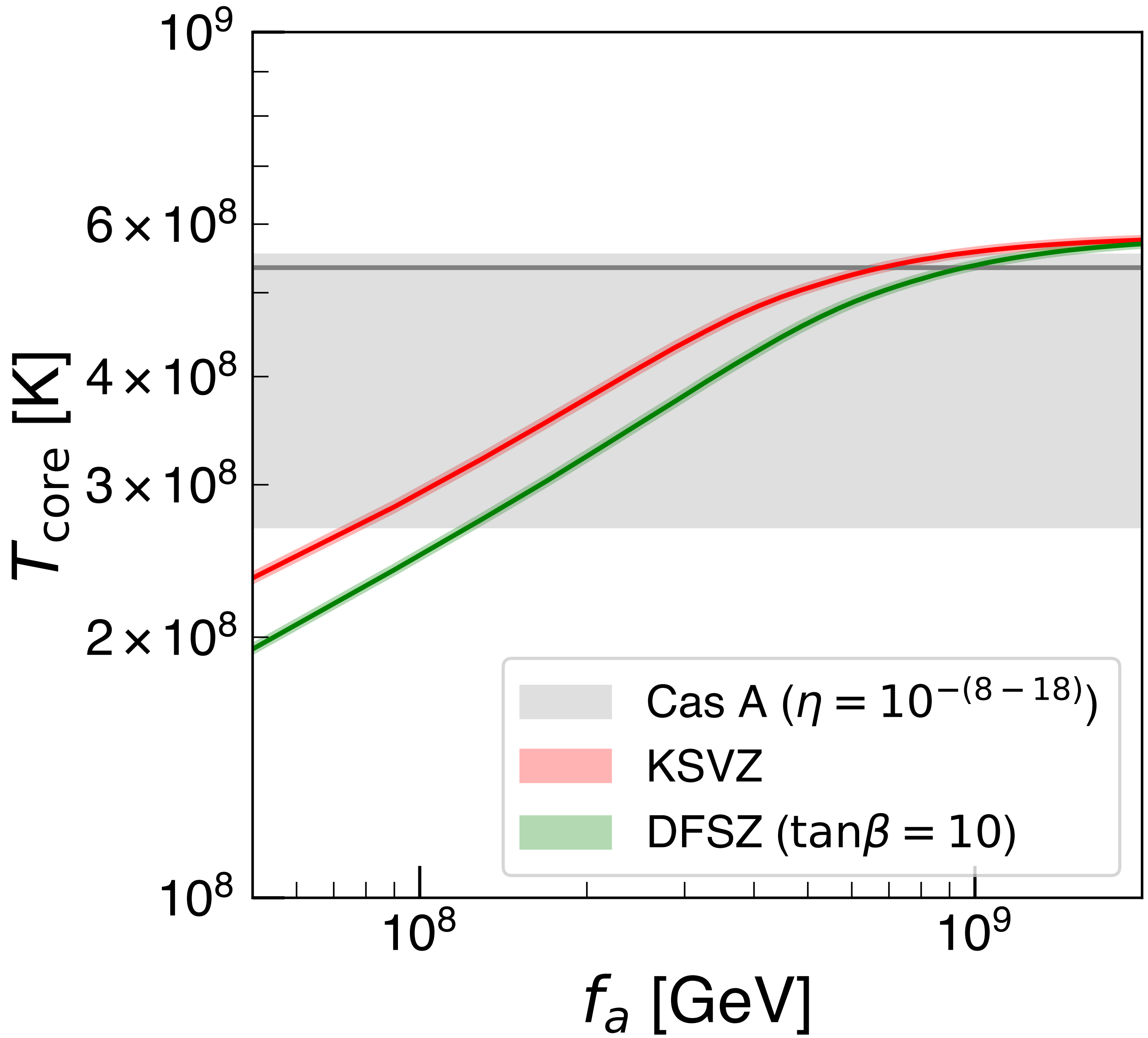
Spin fractions

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

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

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

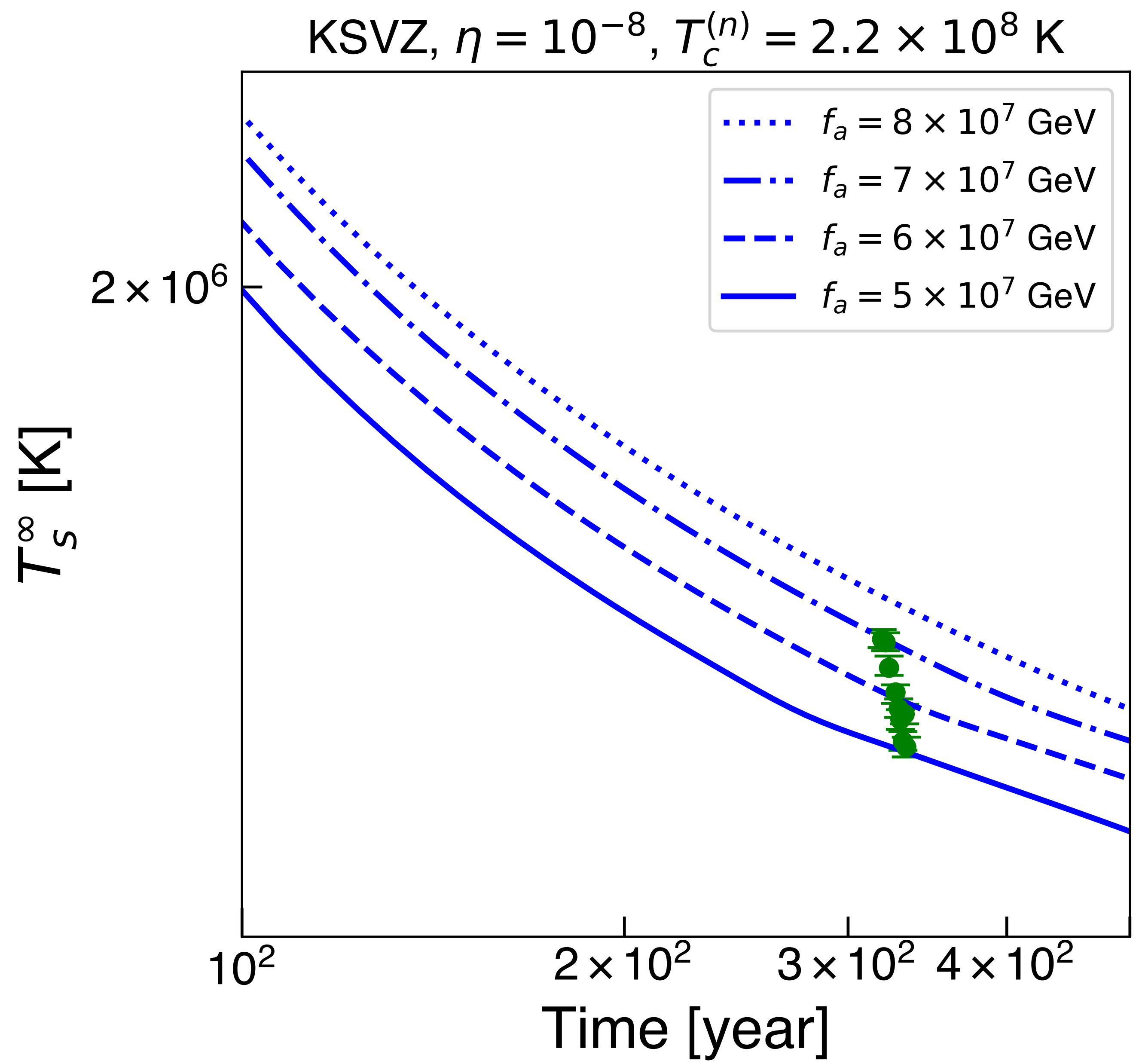
No neutron triplet superfluidity

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).

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).

Other possibilities

Other possibilities to explain the rapid cooling in Cas A NS are

- Direct Urca

  R. Nigreiros, S. Schramm, F. Weber, Phys. Lett. **718**, 1176 (2013). [rotationally induced]

  A. Bonanno, M. Baldo, G. F. Burgio, V. Urpin, A&A **561**, L5 (2014). [+ heating by magnetic field decay]

  G. Taranto, G. F. Burgio, and H. J. Schulze, MNRAS **456**, 1451 (2016).

- Slow thermal relaxation

  D. Blaschke, H. Grigorian, D. N. Voskresensky, and F. Weber, Phys. Rev. **85**, 022802 (2012).

  D. Blaschke, H. Grigorian, D. N. Voskresensky, Phys. Rev. **88**, 065805 (2013).

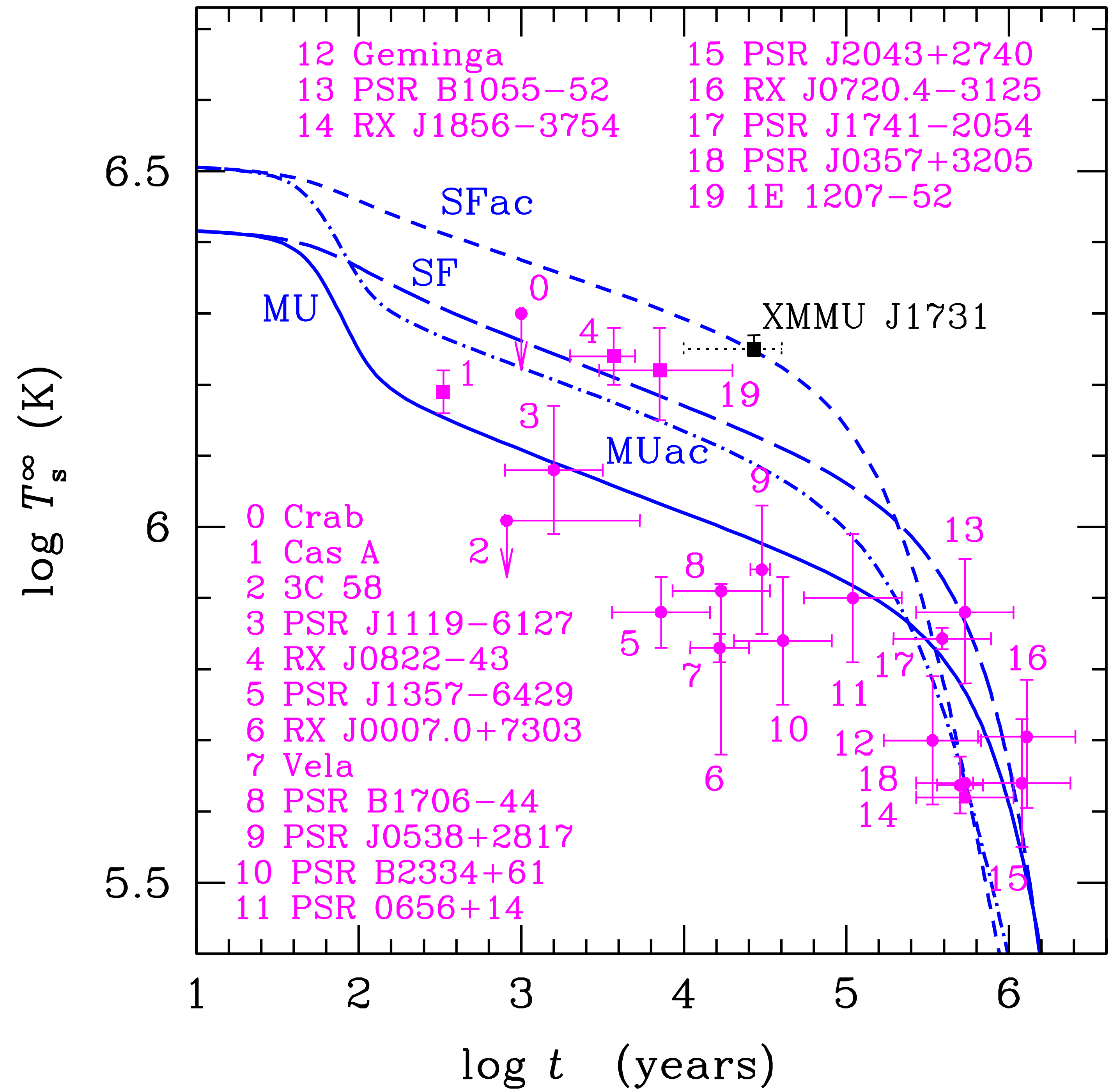
- Stellar fluid oscillations

  S. H. Yang, C. M. Pi, X. P. Zheng, APJ. **735**, L29 (2011).

- Quark color superconducting

  T. Noda, et. al., APJ. **765**, 1 (2013).

XMMU J173203.3-344518



- Large proton gap
- Large η

Can explain the observed temperature.

D. Klochkov, et. al., Astron. Astrophys. **573**, A53 (2015).