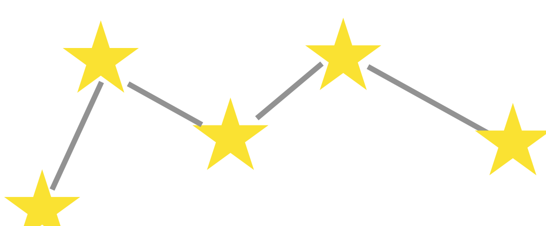
Limit on the Axion Decay Constant from the Cooling Neutron Star in Cassiopeia A

Natsumi Nagata

University of Tokyo



Seminar @ Osaka University
Apr. 16, 2019

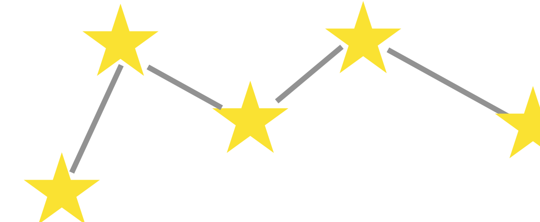
K. Hamaguchi, N. Nagata, K. Yanagi, and J. Zheng, Phys. Rev. **D98**, 103015 (2018).

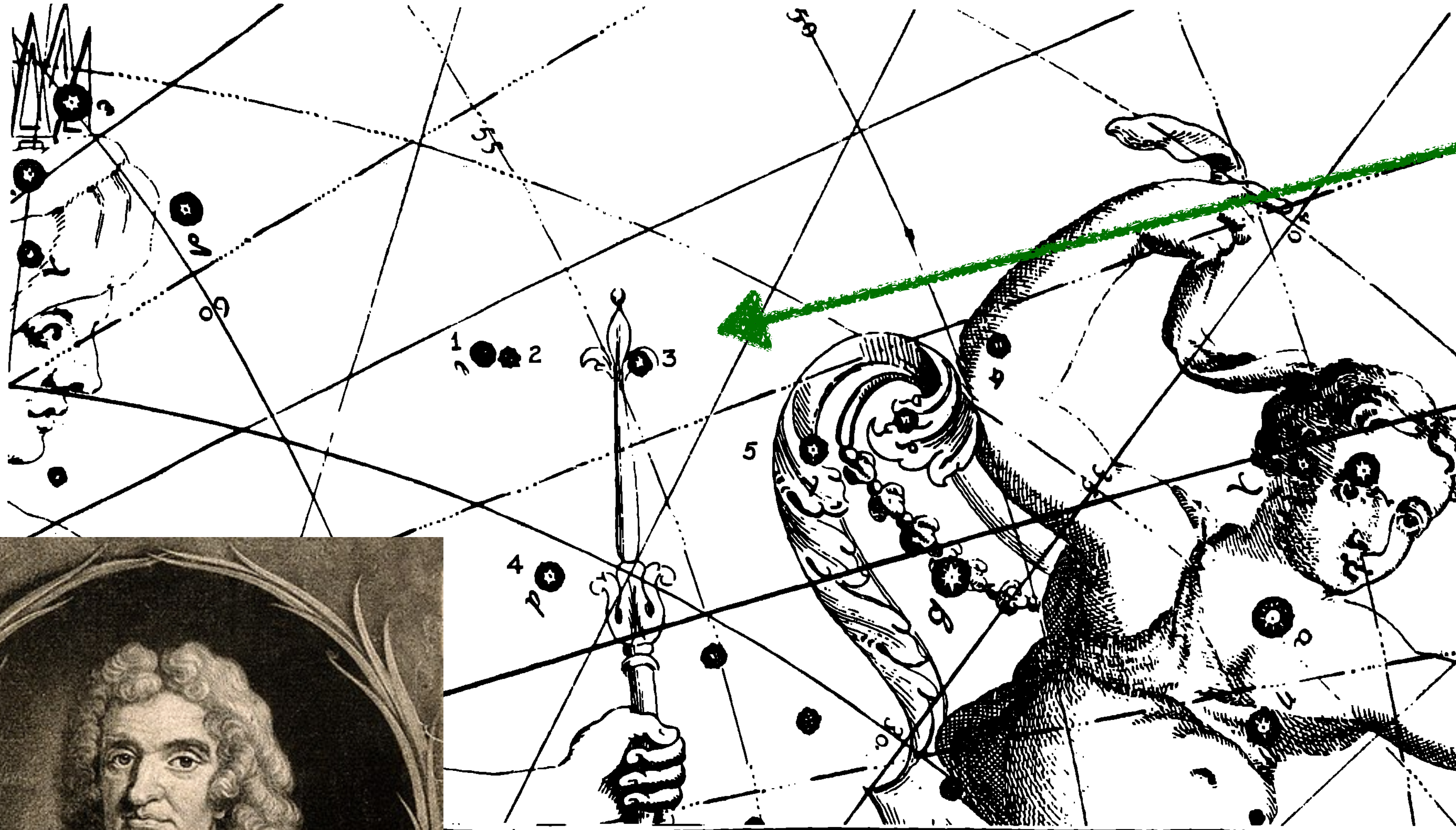
Outline

- Cassiopeia A (Cas A) Neutron Star
- Standard Neutron Star Cooling and Cas A
- Axion Emission from Neutron Star
- Limit on Axion Decay Constant
- Conclusion

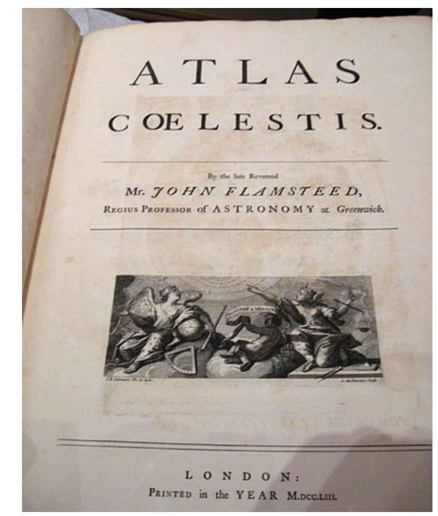
Cas A NS

3 Cassiopeiae

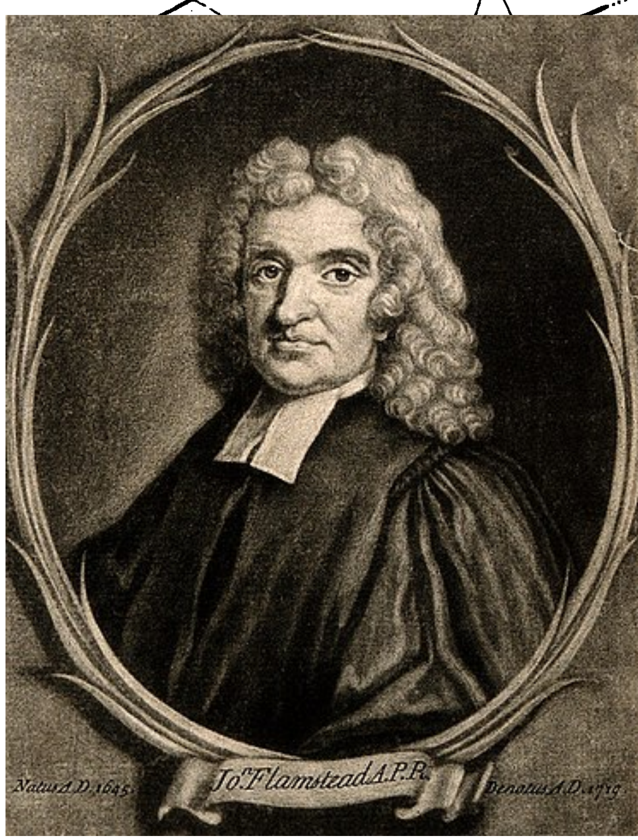




3 Cassiopeiae



Atlas Coelestis (1729)



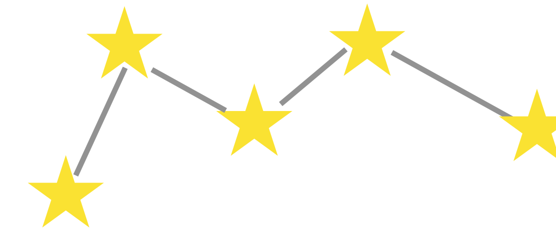
John Flamsteed

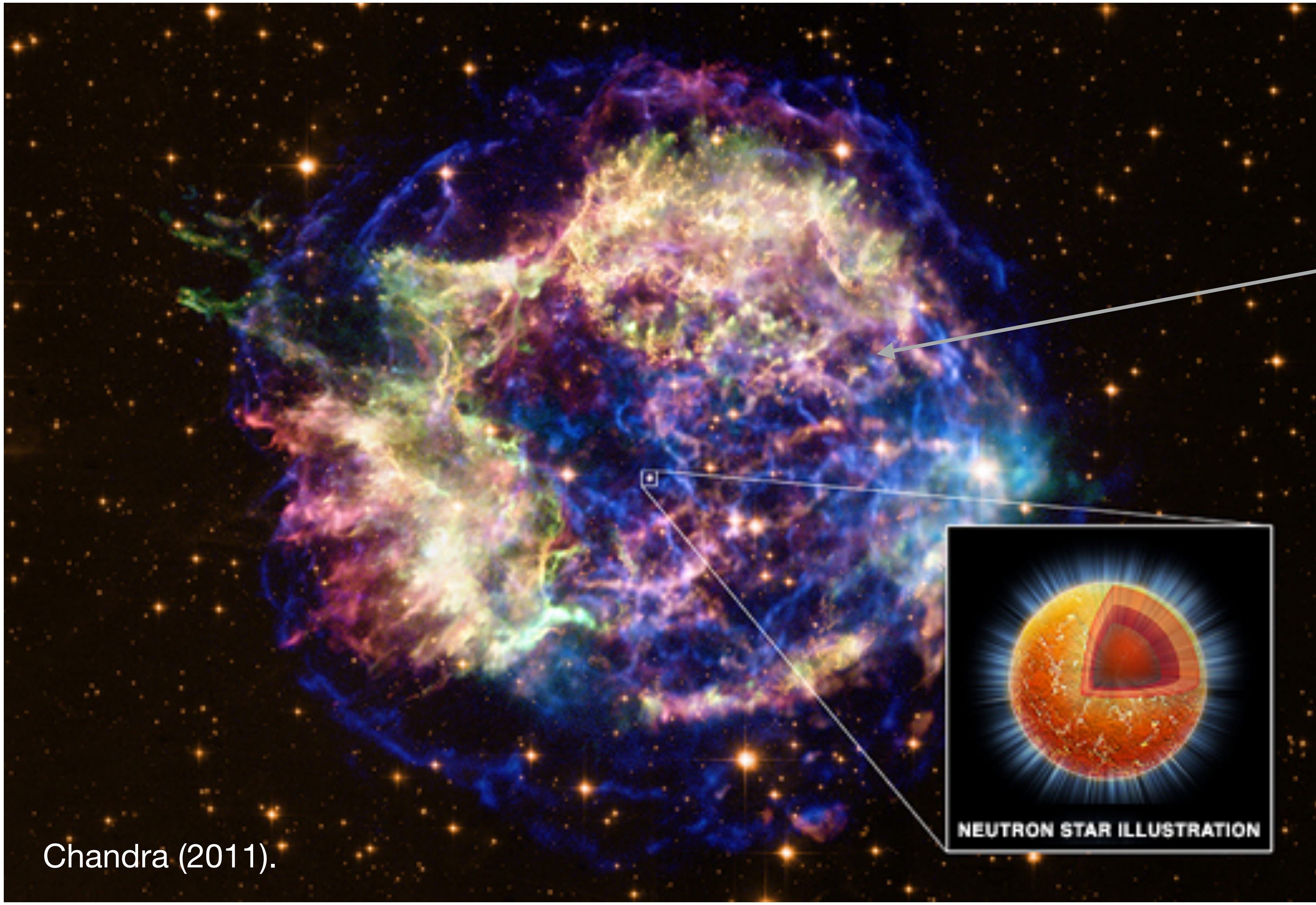
First Astronomer Royal

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

Never been observed since then.

Cassiopeia A (Cas A)





Supernova remnant

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

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

Neutron star (NS) was found in the center.

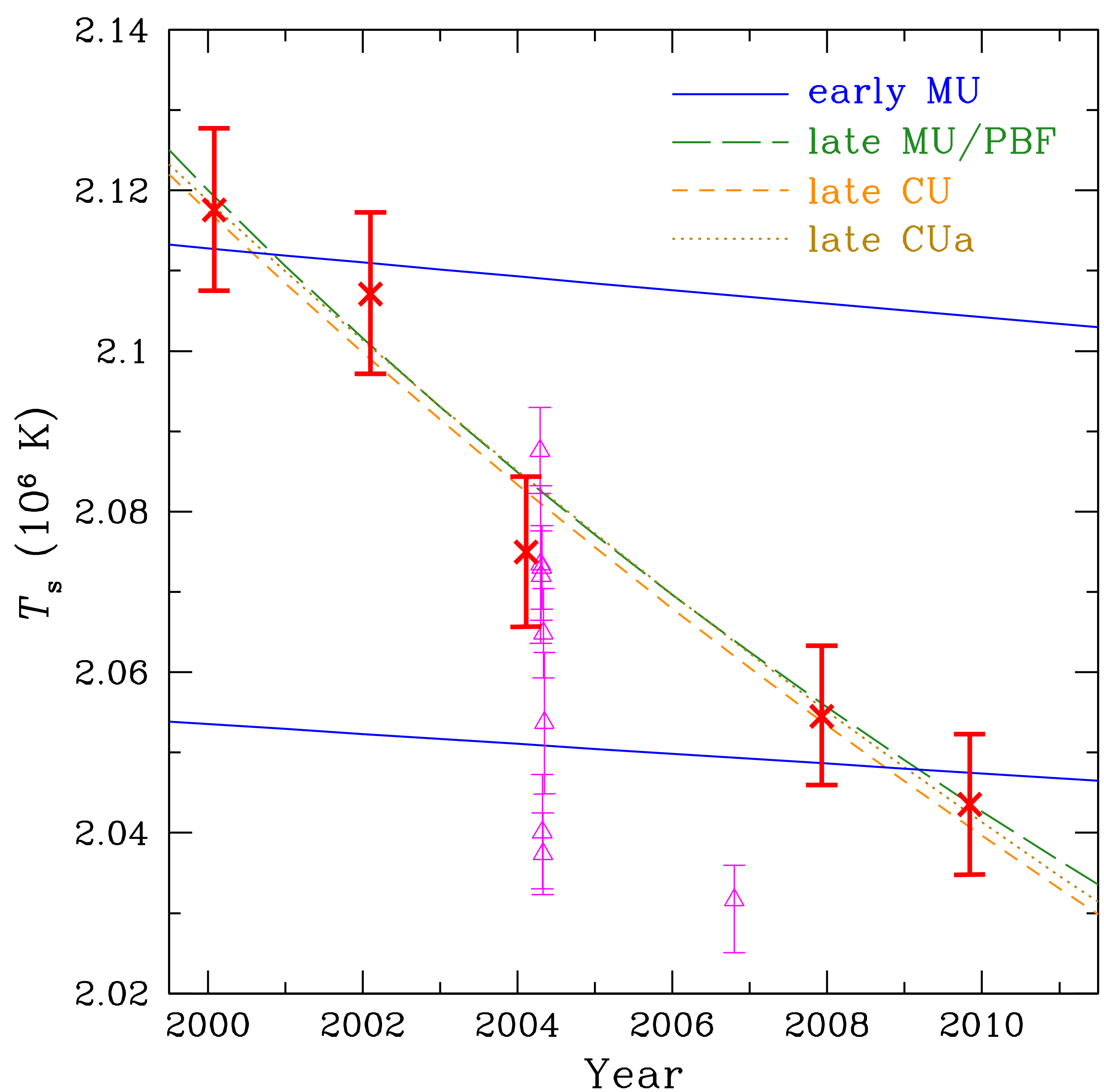
Cas A NS Cooling

THE ASTROPHYSICAL JOURNAL LETTERS, 719:L167–L171, 2010 August 20

DIRECT OBSERVATION OF THE COOLING OF THE CASSIOPEIA A NEUTRON STAR

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

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);
P. S. Shternin, D. G. Yakovlev, C. O. Heinke, W. C. G. Ho, and D. J. Patnaude, MNRS **412**, L108 (2011).

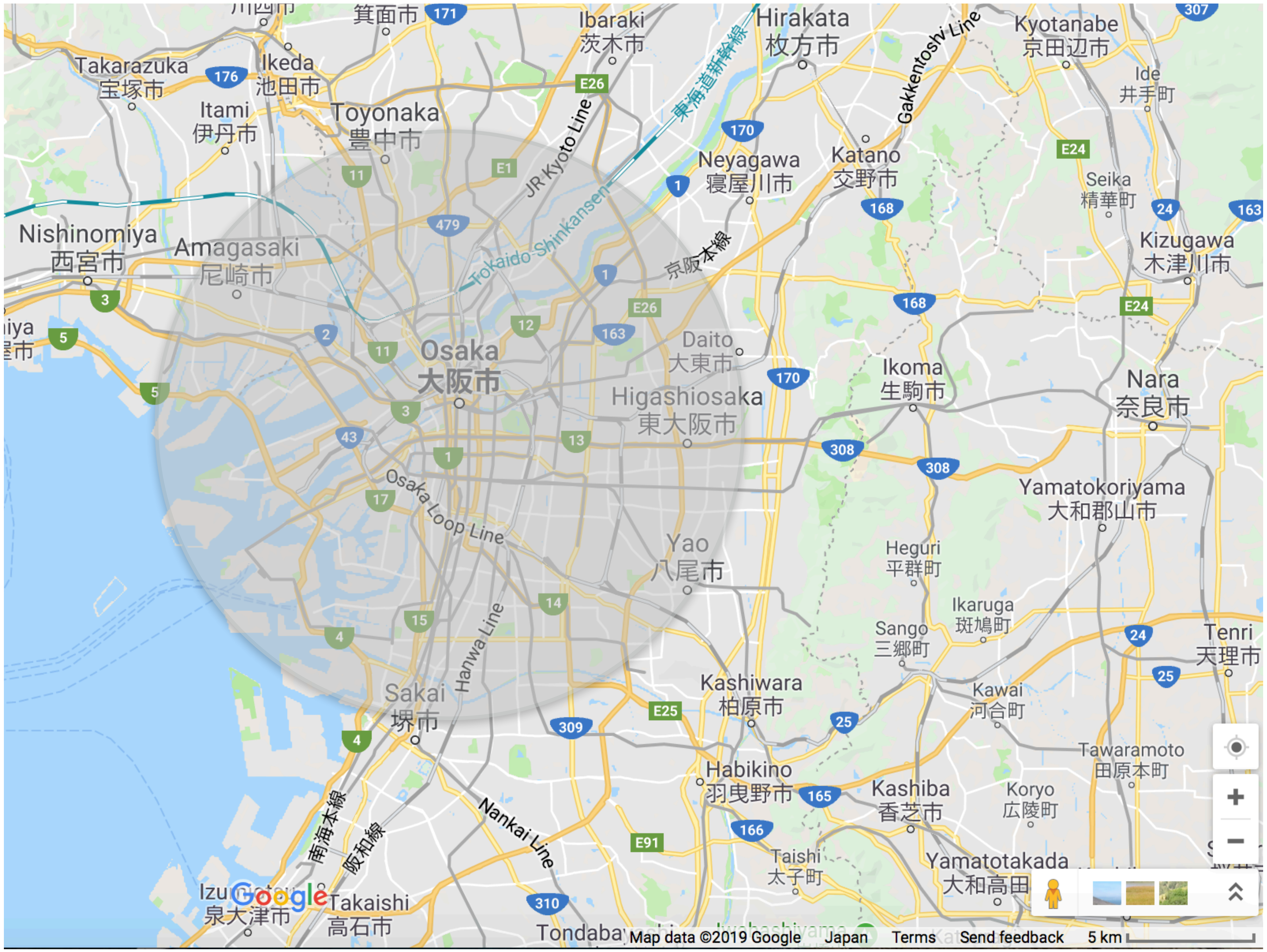
Neutron superfluidity plays an important role.

- 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 Osaka

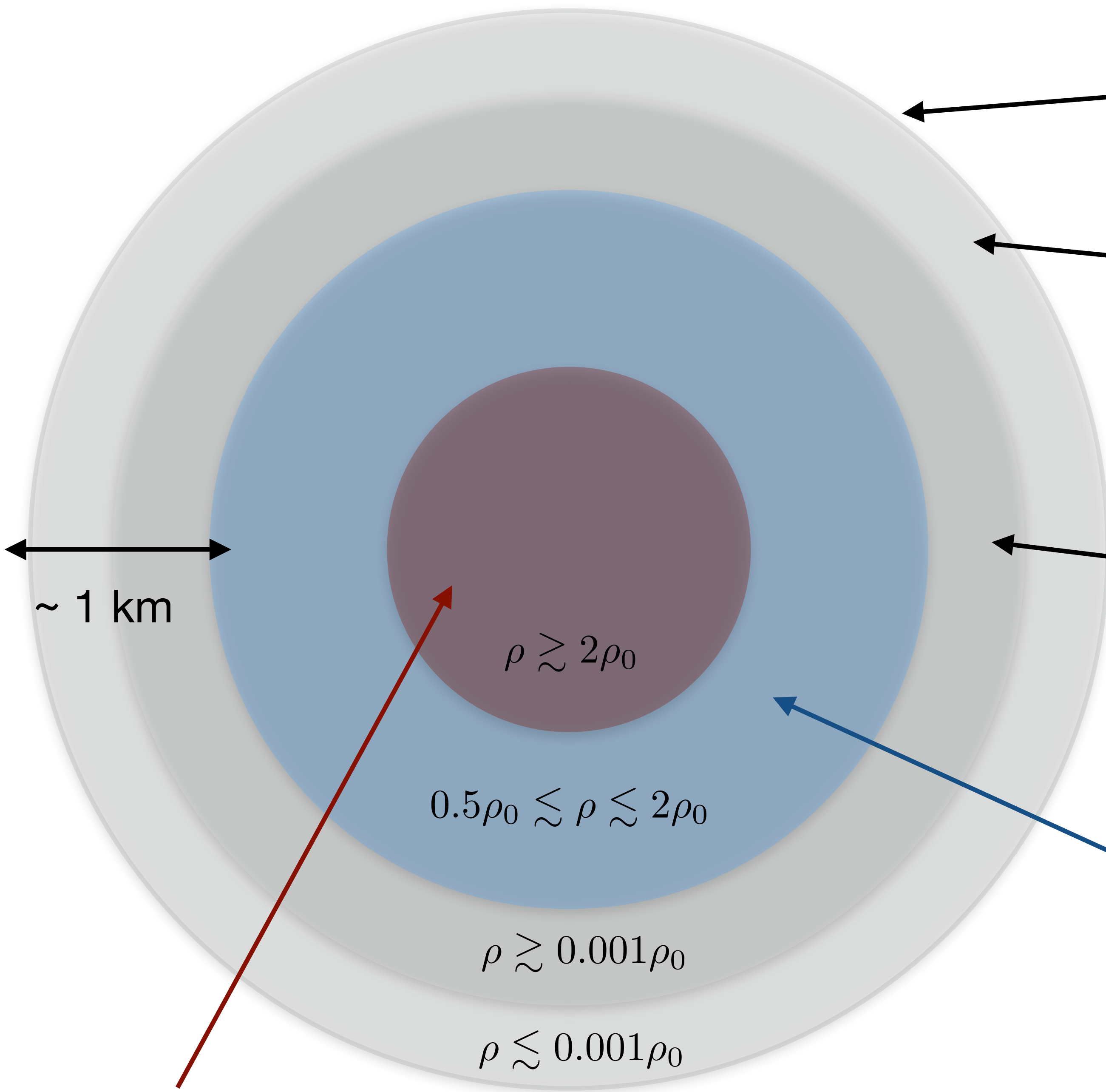


- Radius ~10 km
- $1-2\ M_{\odot}$

As high as nuclear density.

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

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.

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)

Nucleon superfluidity taken into account.

Equation for temperature evolution

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

$C(T)$: Stellar heat capacity

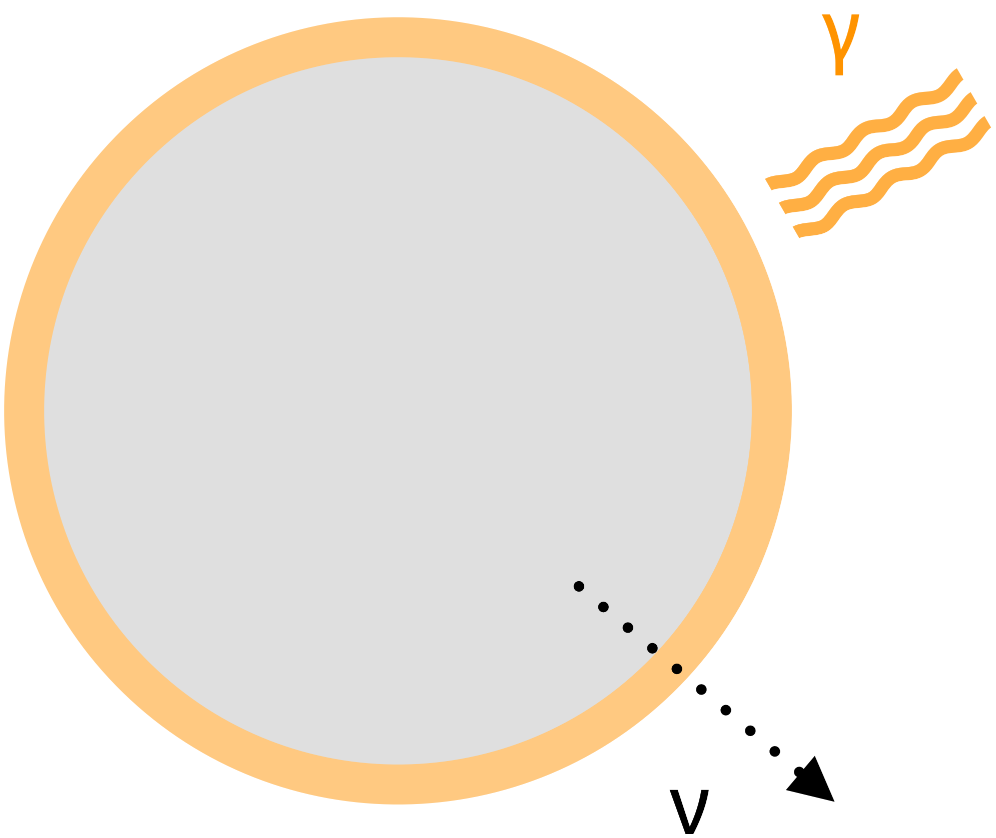
L_ν: Luminosity of neutrino emission

L_γ: Luminosity of photon emission

Thermal relaxation completed at $t \lesssim 100$ yrs

Cooling sources

Two cooling sources:



Photon emission (from surface)

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

Dominant for $t \gtrsim 10^5$ years

Neutrino emission (from core)

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

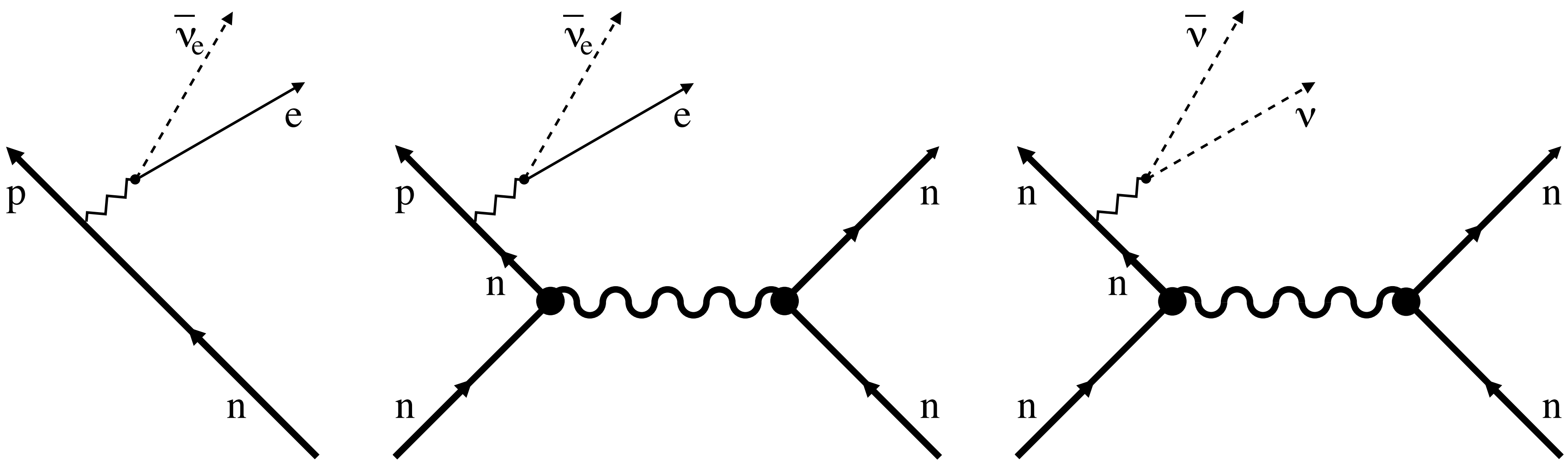
PBF process occurs only in the presence of nucleon superfluidity.

Dominant for $t \lesssim 10^5$ years

cf.) Cas A NS: ~ 338 yrs

Neutrino emission

These processes can occur in a non-superfluid NS core.

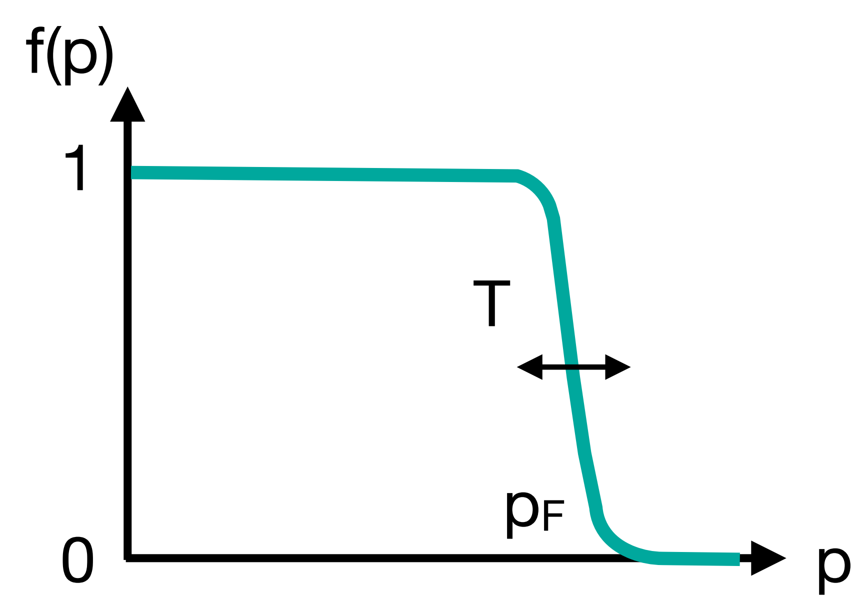


Direct Urca　　Modified Urca　　Bremsstrahlung

These processes occur only near the Fermi surface.

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

$$\boxed{p_F \gg T,\, m_n - m_p}$$



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

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

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.

Direct Urca process

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

To satisfy the momentum conservation in the DUrca process

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

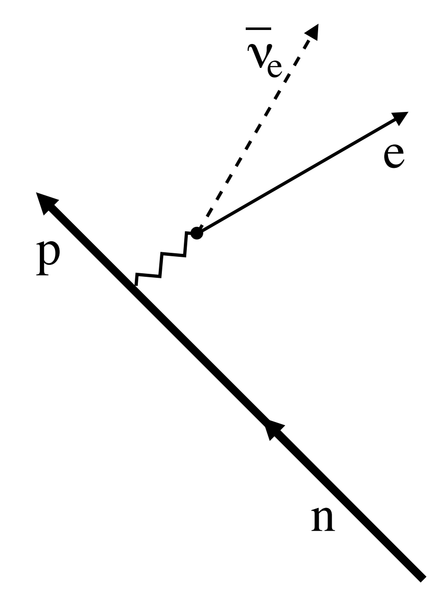
is required.

(Neutrino momentum, ~ T, is negligible.)

Emissivity (energy loss rate per unit time & volume)

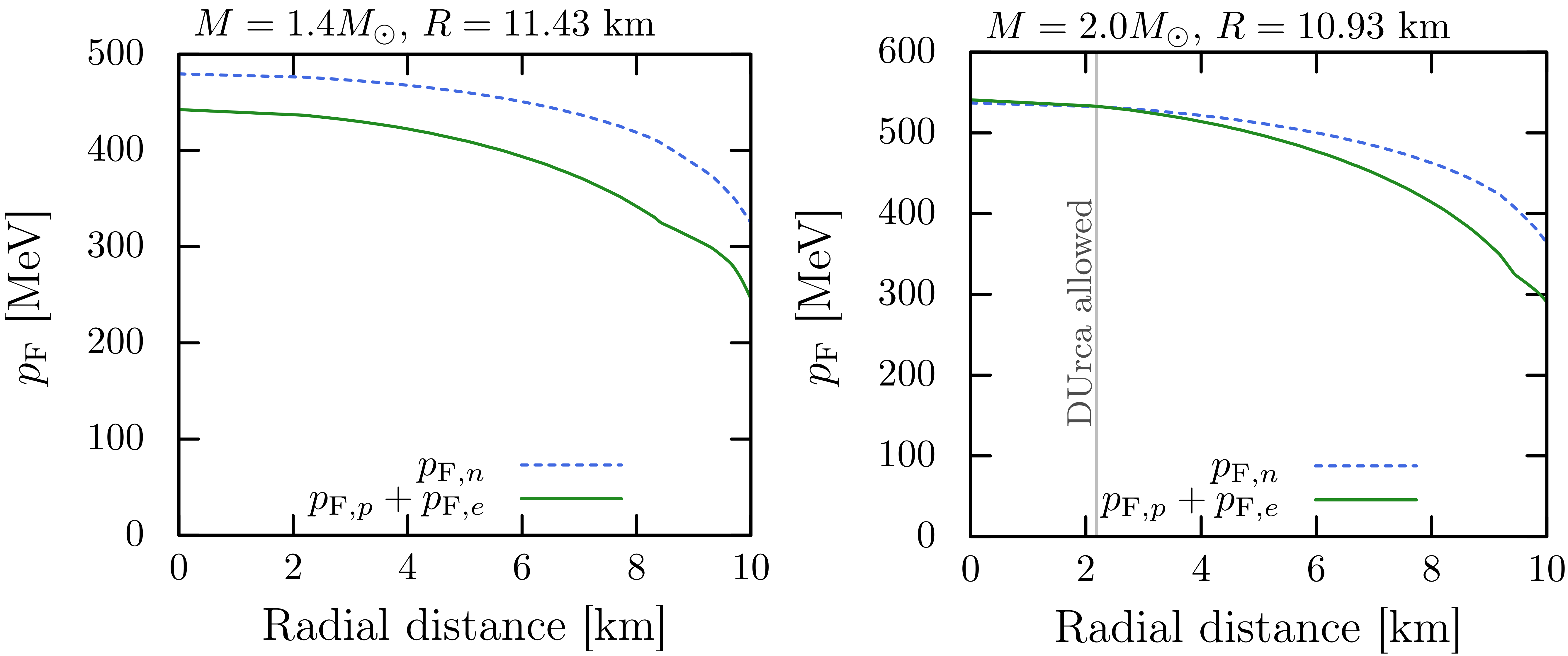
$$Q_D \simeq 4 \times 10^{27} \times \left(\frac{T}{10^9 \text{ K}}\right)^6 \Theta(p_{F,p} + p_{F,e} - p_{F,n}) \text{ erg} \cdot \text{cm}^{-3} \cdot \text{s}^{-1}$$

This dominates other processes (if occurs).



Direct Urca

Direct Urca condition



This process can occur only at high-density regions.

Only massive stars ($\gtrsim 2M_\odot$) allow this process.

W/ APR equation of state.

Direct Urca in Cas A NS

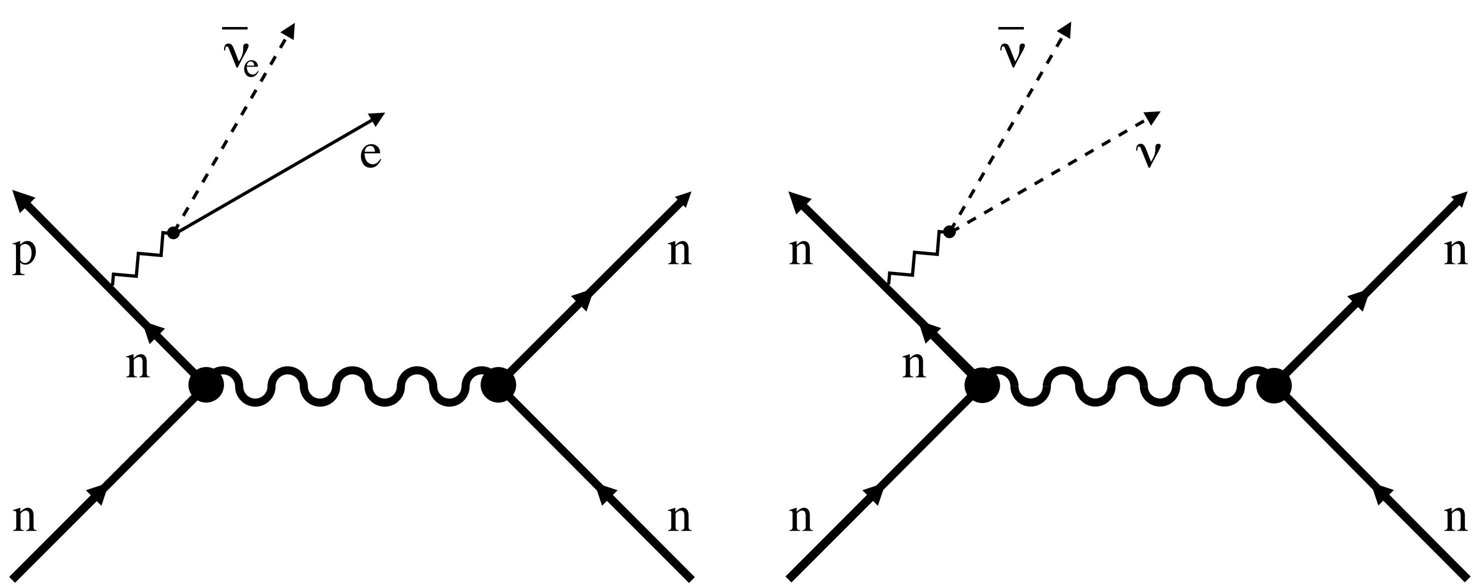
The mass of Cas A NS is estimated to be

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

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

Direct Urca does not operate in Cas A NS.

Slow neutrino emission processes



Modified Urca

Bremsstrahlung

$$\propto T^8$$

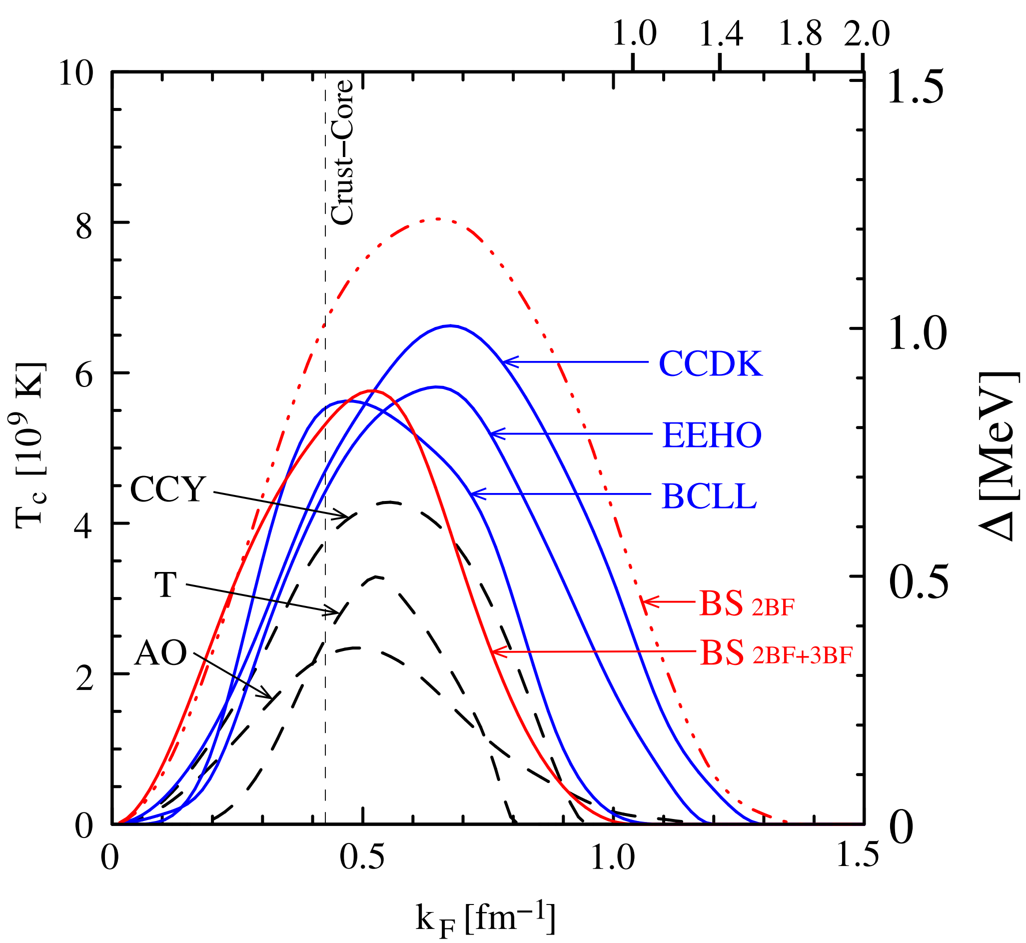
Nucleon pairing

Nucleons in a NS form pairings below their critical temperatures:

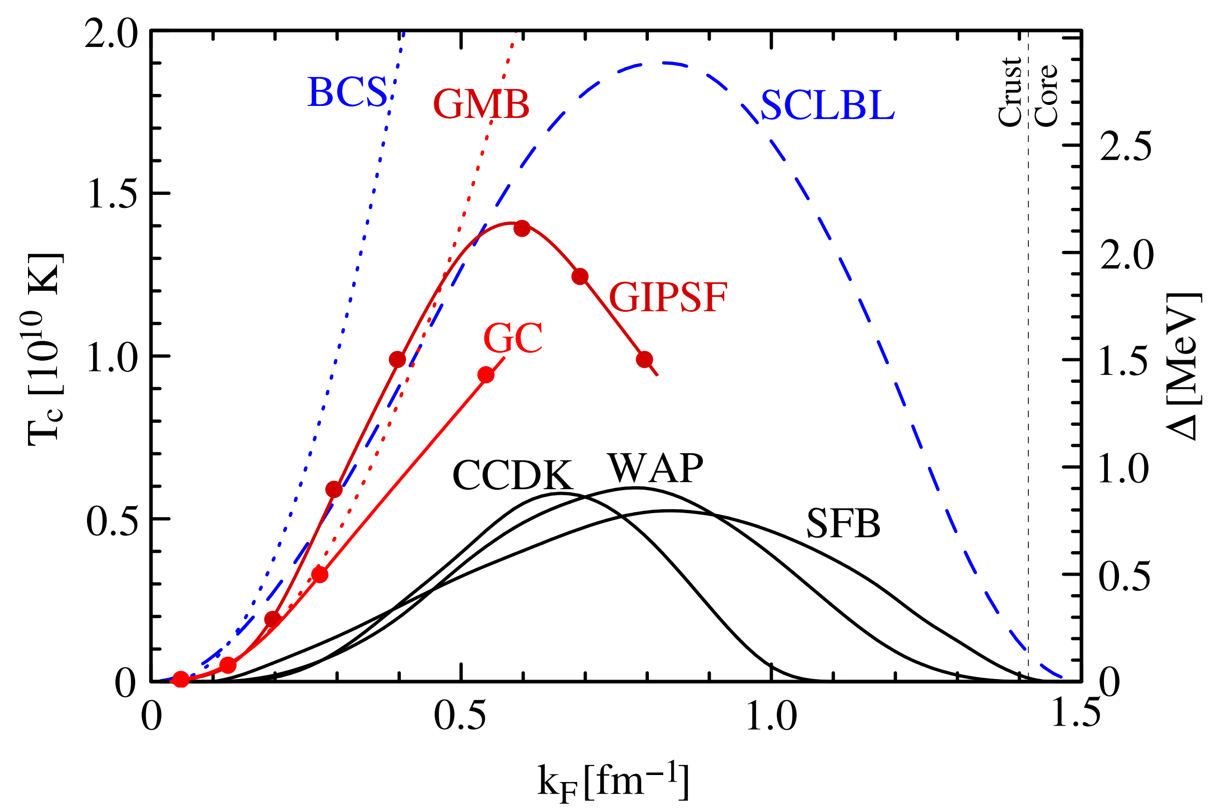
- Neutron singlet $^1S_0$ ⟵ Only in the crust. Less important.
- Proton singlet $^1S_0$
- Proton triplet $^3P_2$

} ⟵ Form in the core. Important.

Proton singlet pairing gap



Neutron singlet pairing gap



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

Effects of nucleon parings

In the presence of pairing gap, the energy of quasi-particle is

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

This gap introduces a suppression factor to

- Slow neutrino emission process
- Heat capacity

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

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

→ Pair-breaking and formation (PBF) process

PBF process

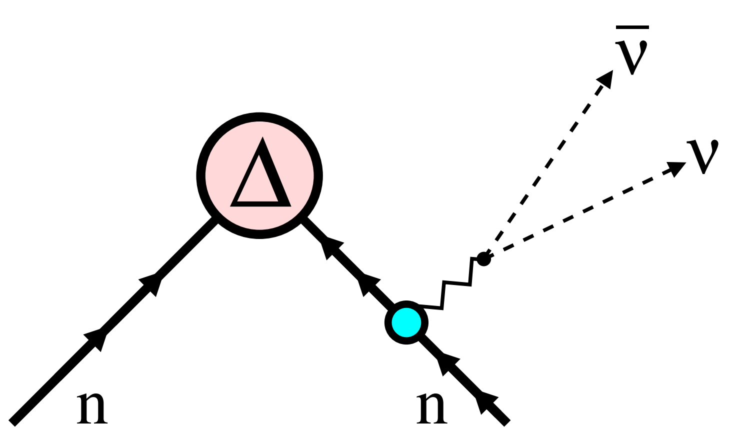
Thermal disturbance induces the breaking of nucleon pairs.

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

  Unimportant in Cas A NS.

- Direct Urca process

  Does not operate in Cas A NS.

- Modified Urca & bremsstrahlung

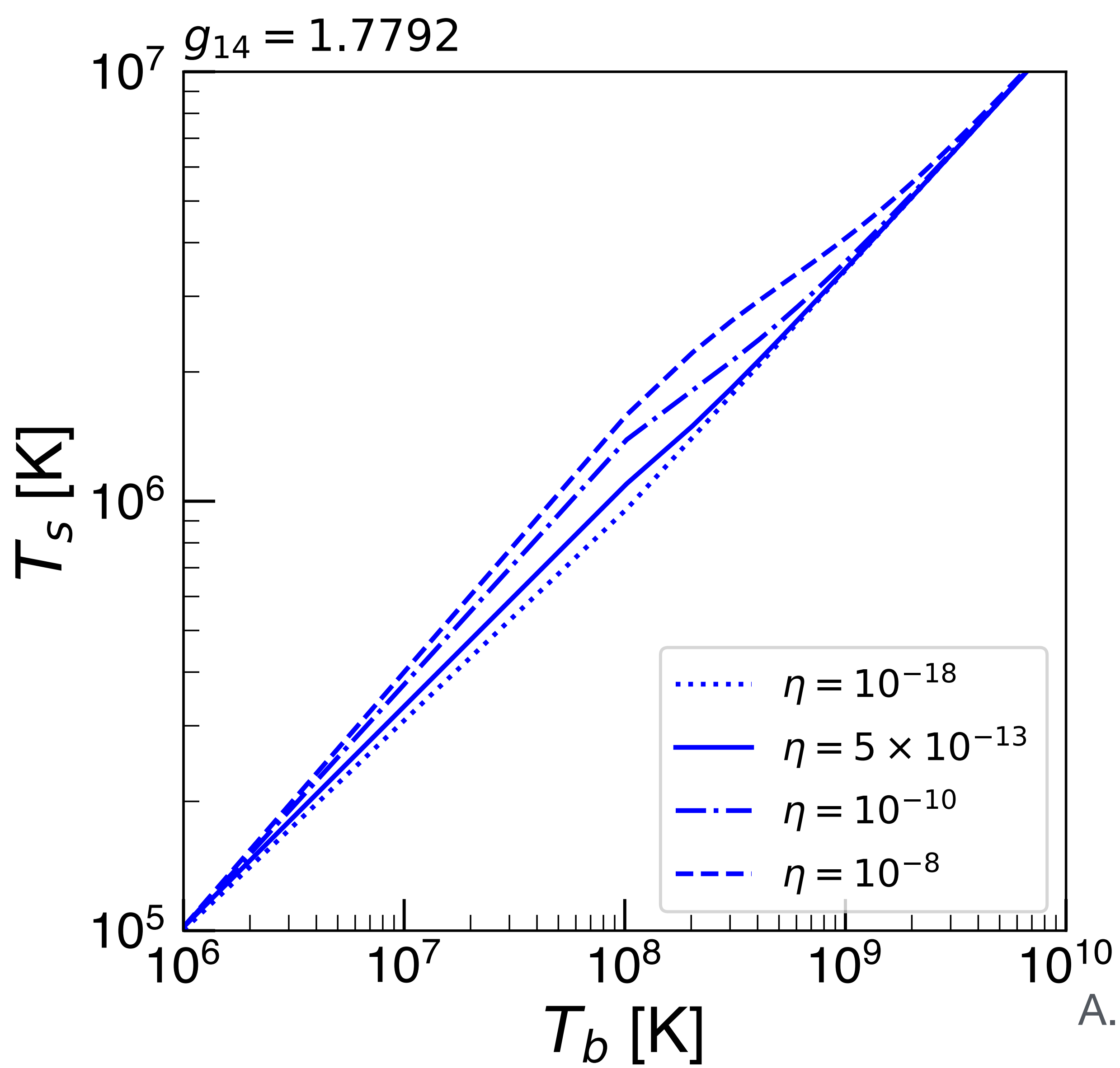
  Suppressed after the onset of nucleon superfluidity.

- PBF

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

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}.

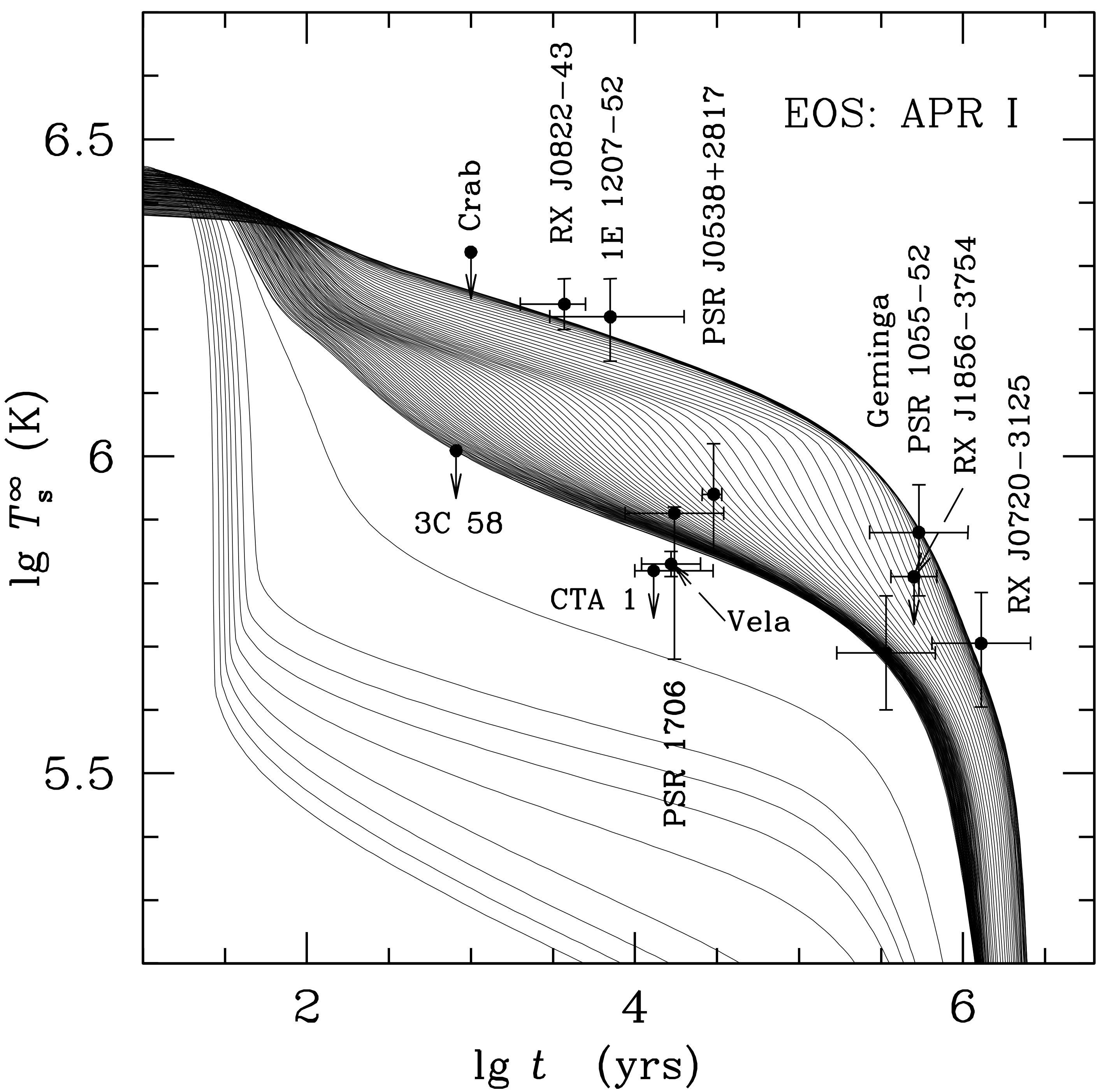
ΔM: mass of light elements.

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.

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 the standard cooling scenario??

How to explain Cas A cooling

Observation

3—4% decrease in ten years.

Modified Urca/Bremsstrahlung

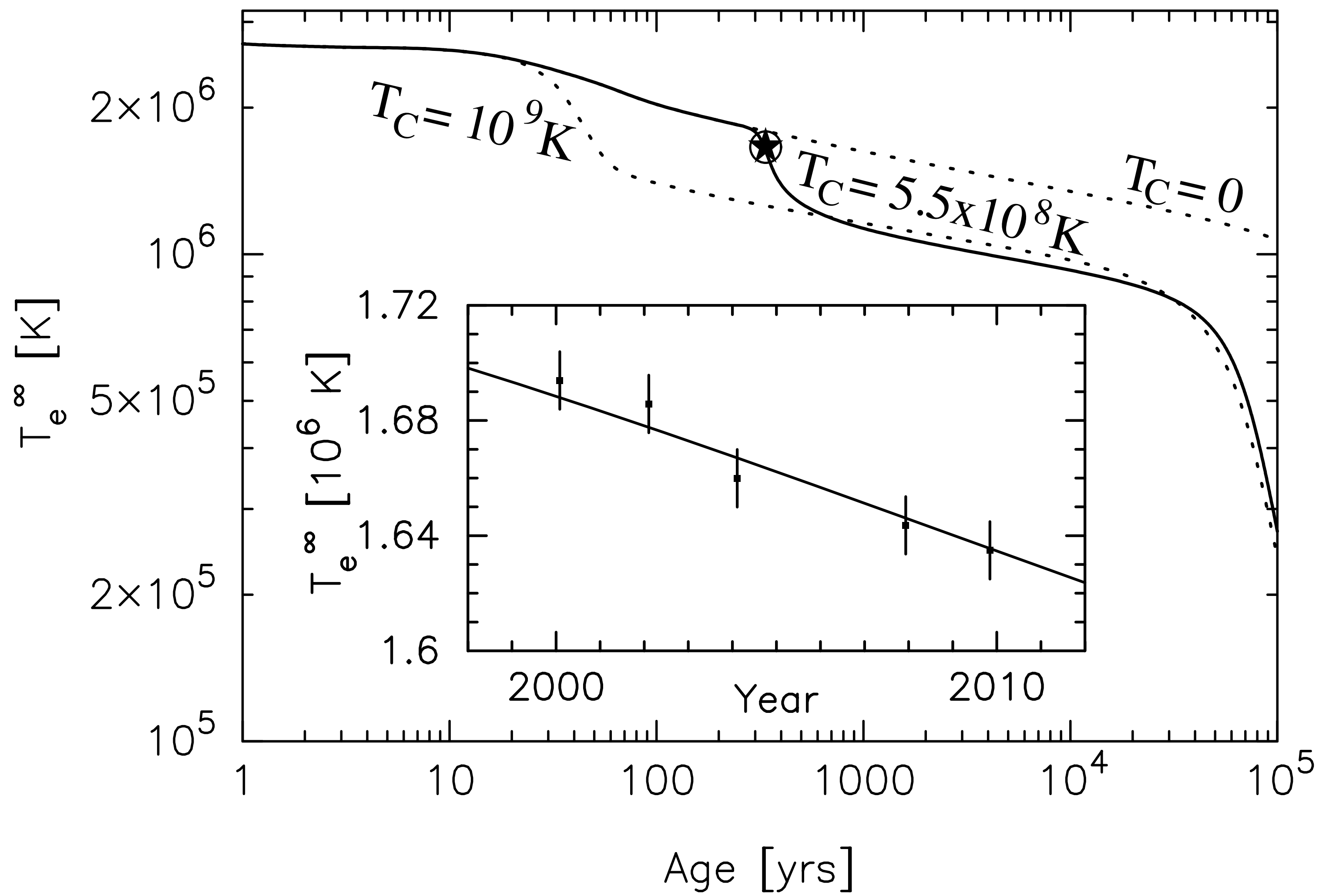
Only 0.3% decrease in T in ten years.

PBF

Rapid cooling but does not last so long.

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

Fit in the minimal cooling paradigm



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

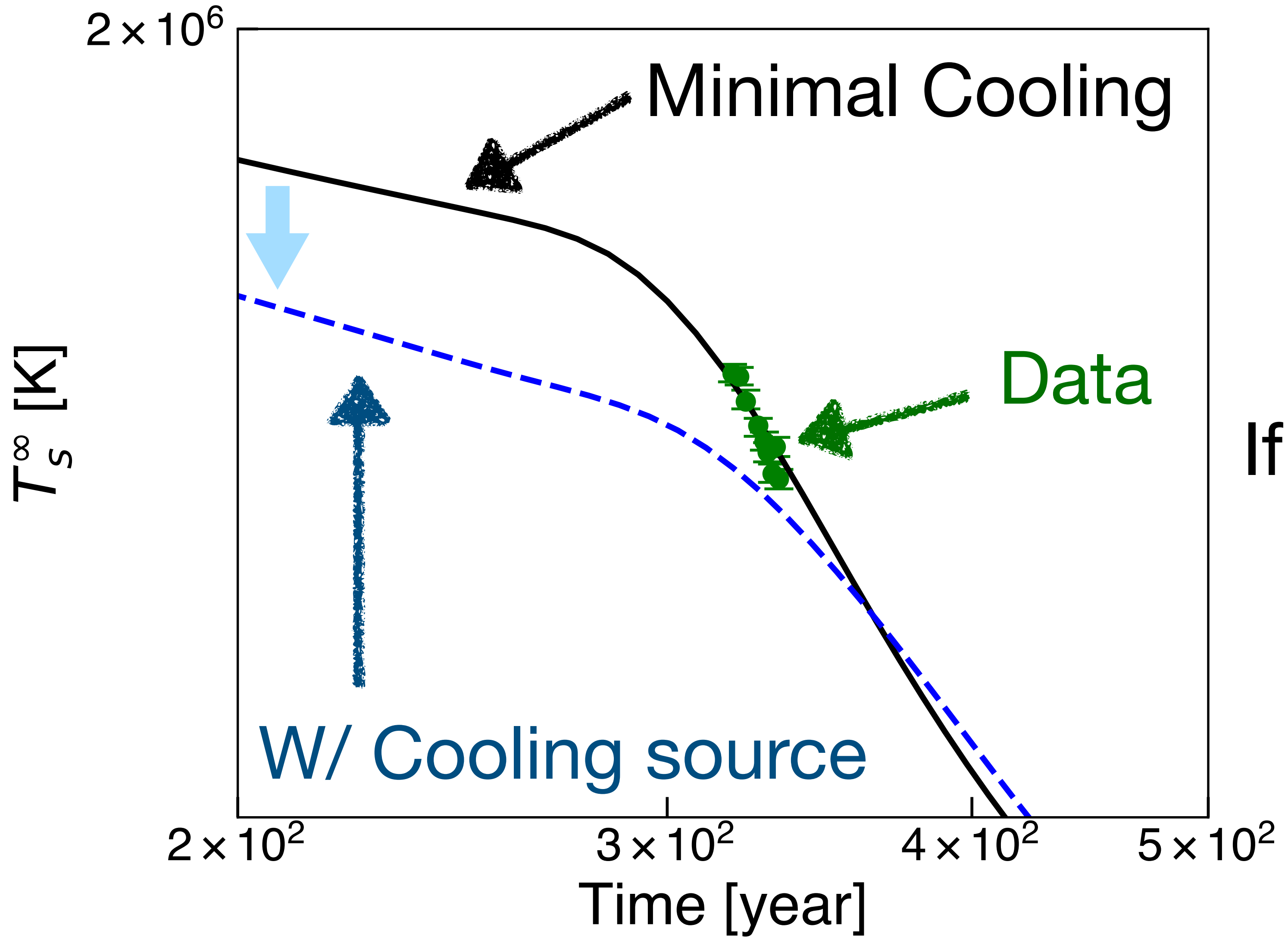
Mon. Not. R. Astron. Soc. **412,** L108–L112 (2011) doi:10.1111/j.1745-3933.2011.01015.x

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 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

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

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
- Bremsstrahlung

We have modified NSCool to implement these processes.

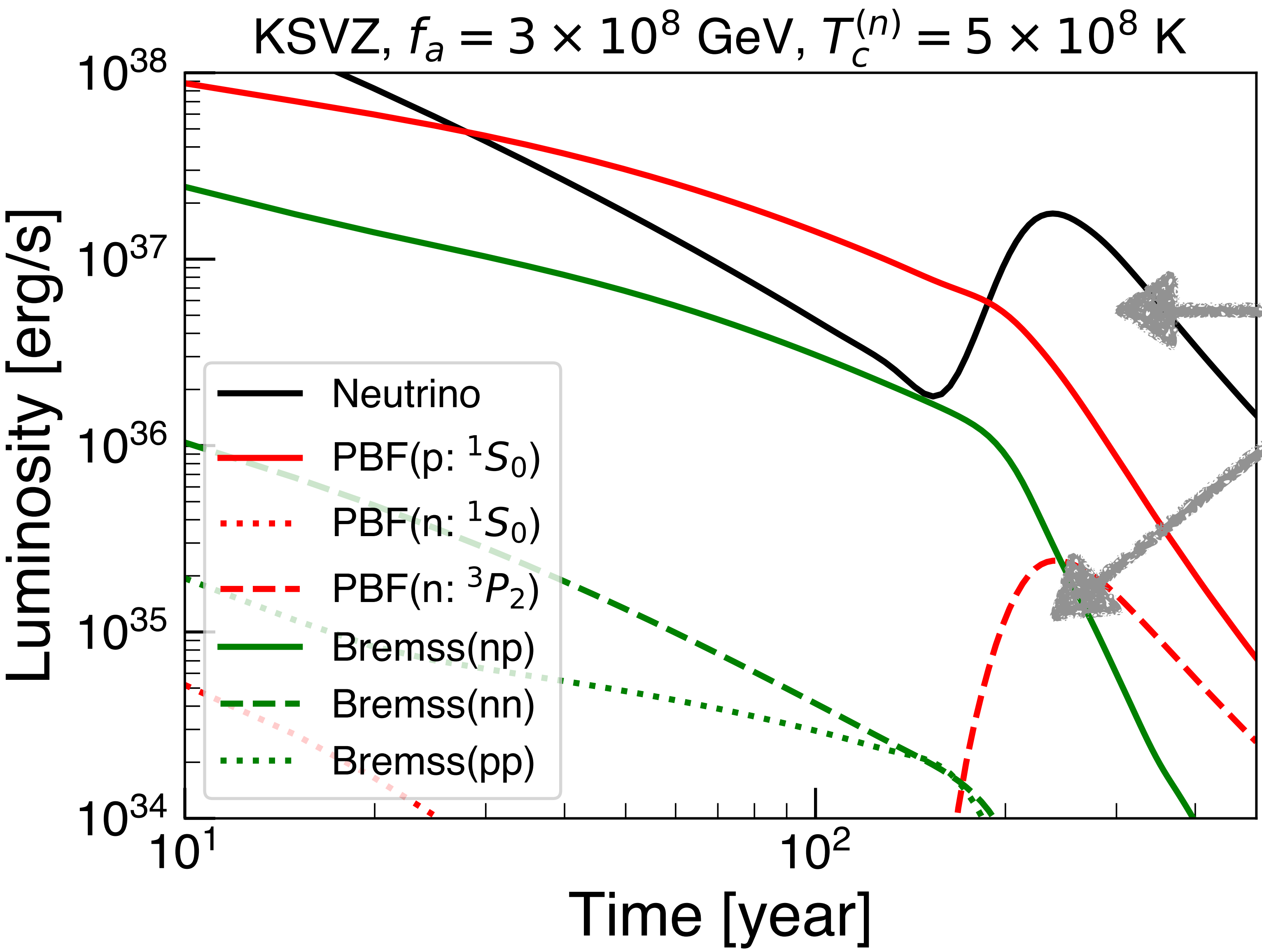
Technical details

- APR equation of state
- NS mass: $M = 1.4M_\odot$
- 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.

Luminosity of axion emission



Onset of neutron triplet pairing.

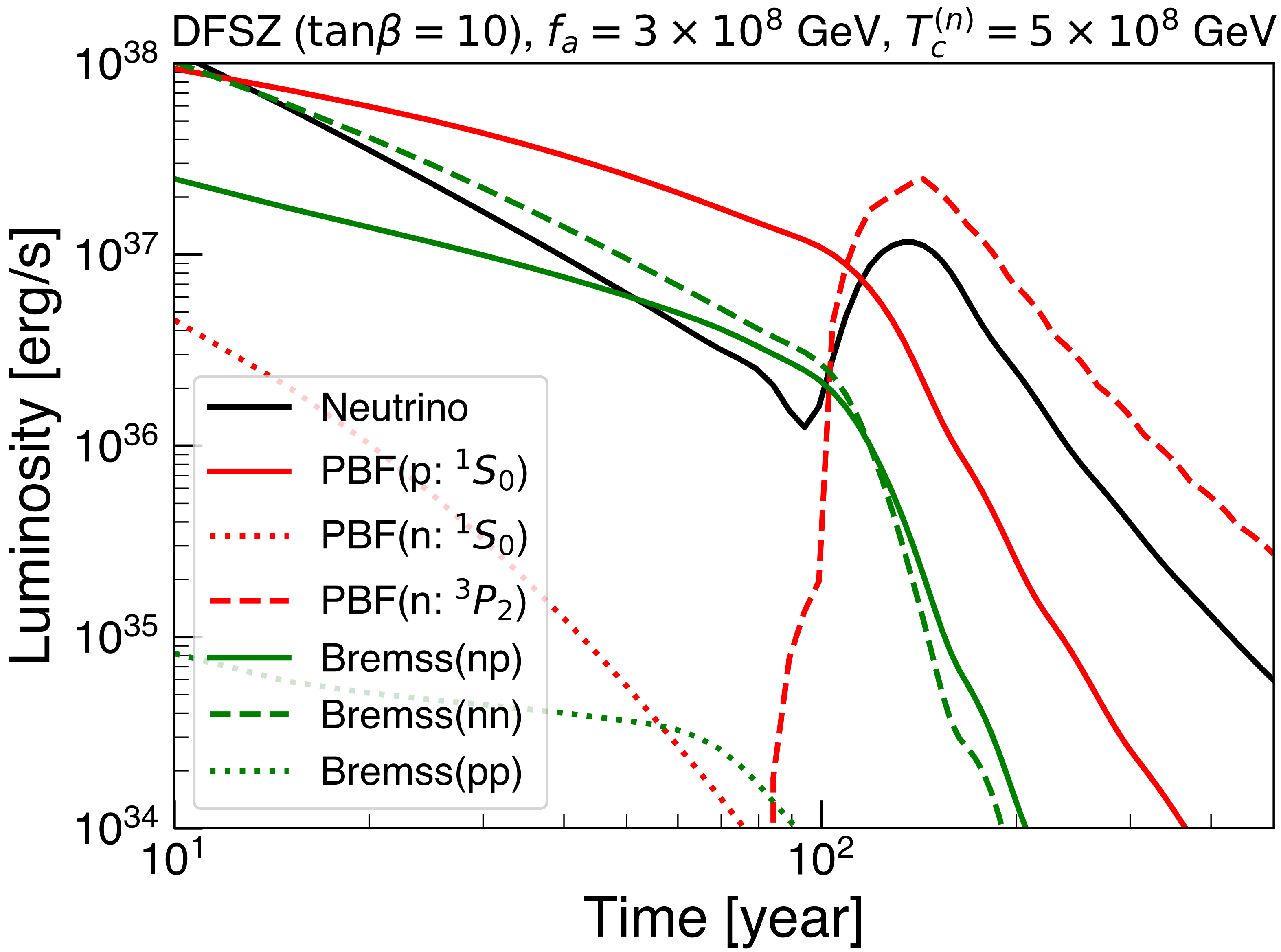
Neutron PBF

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



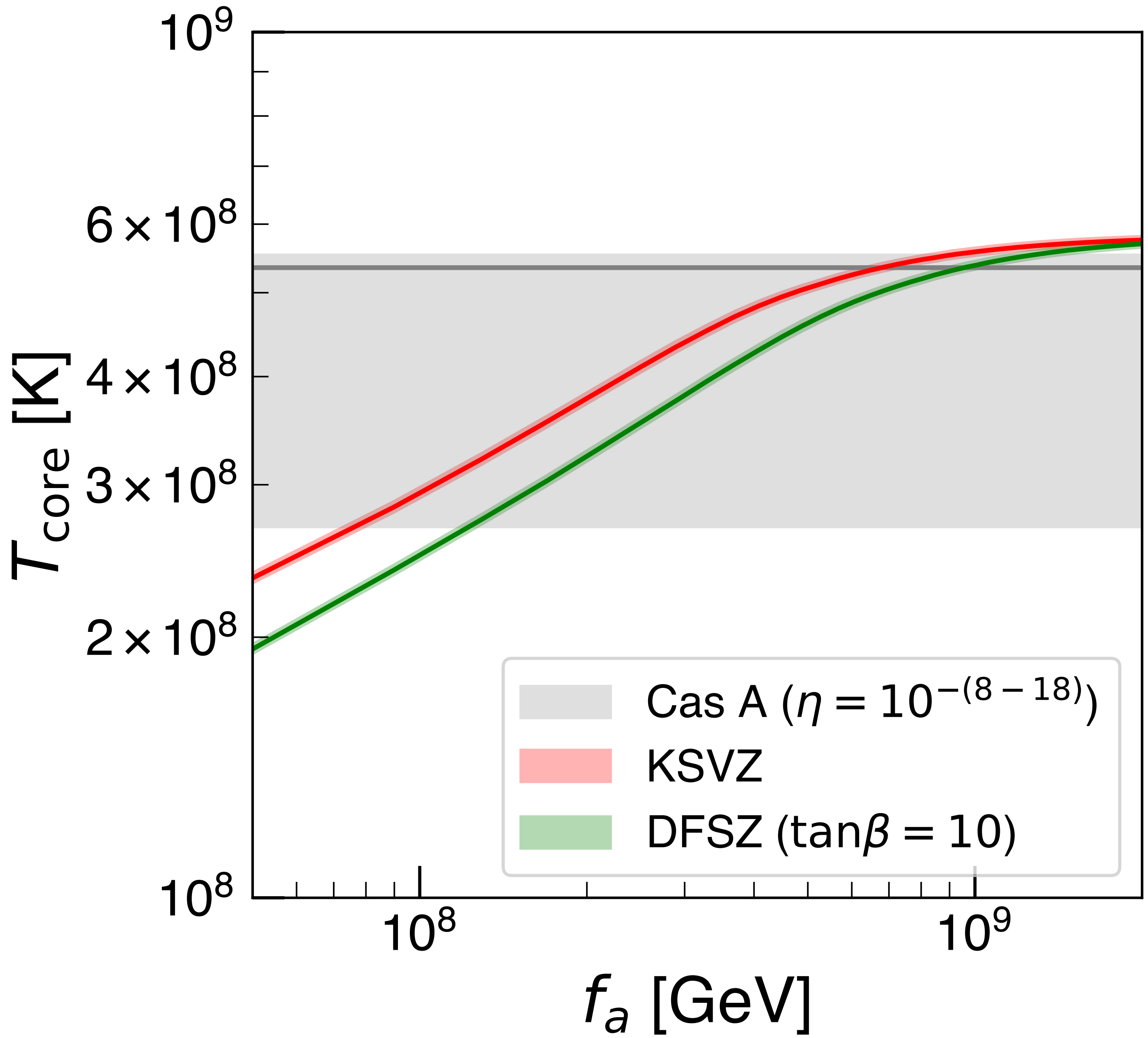
Axion emission is stronger than the KSVZ case.

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

Limit on axion decay constant

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

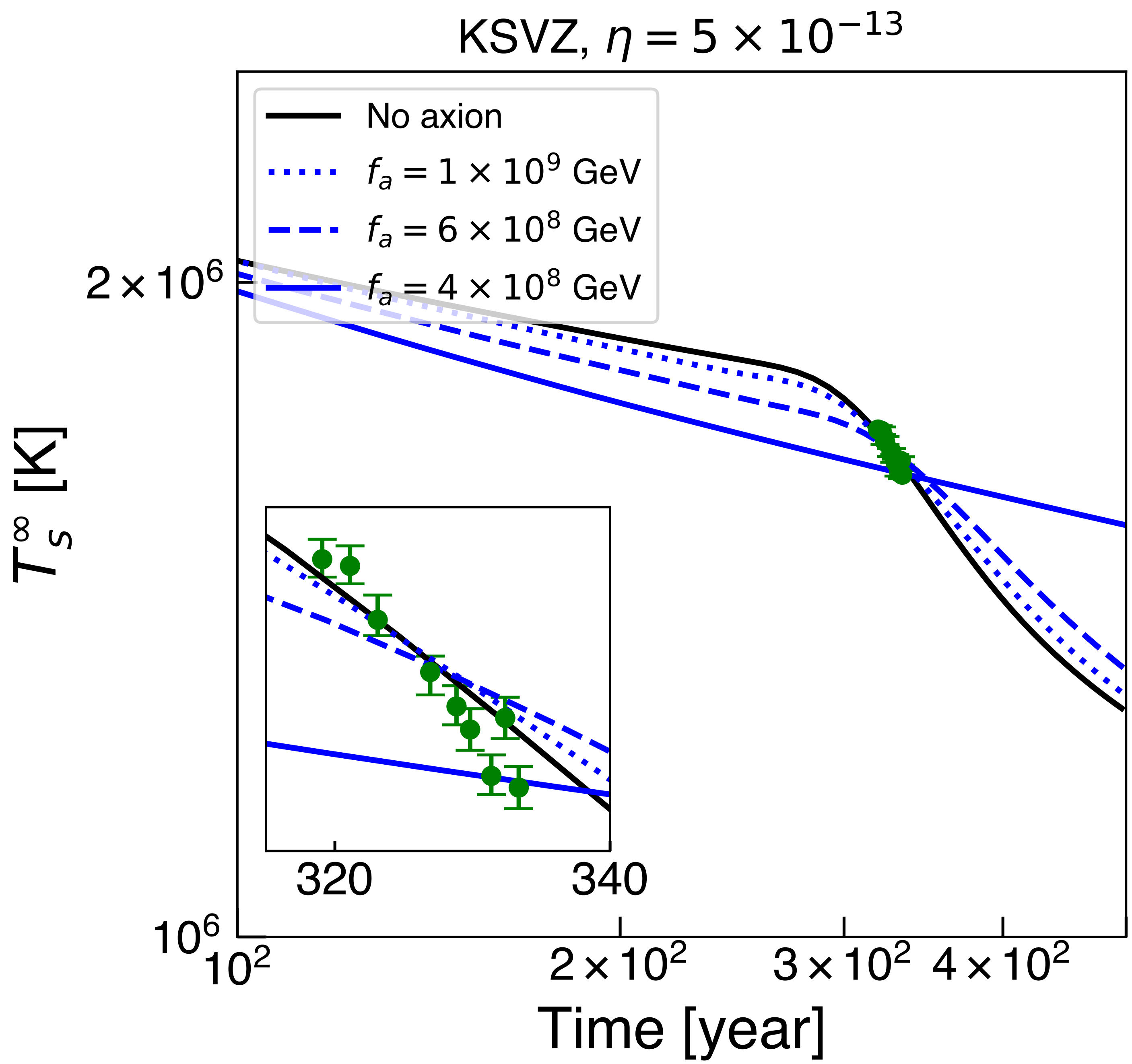
No neutron triplet superfluidity

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

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

KSVZ (DFSZ, tanβ = 10)

Cf.) SN1987A

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

We obtained a bound comparable to other astrophysical limits.

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

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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

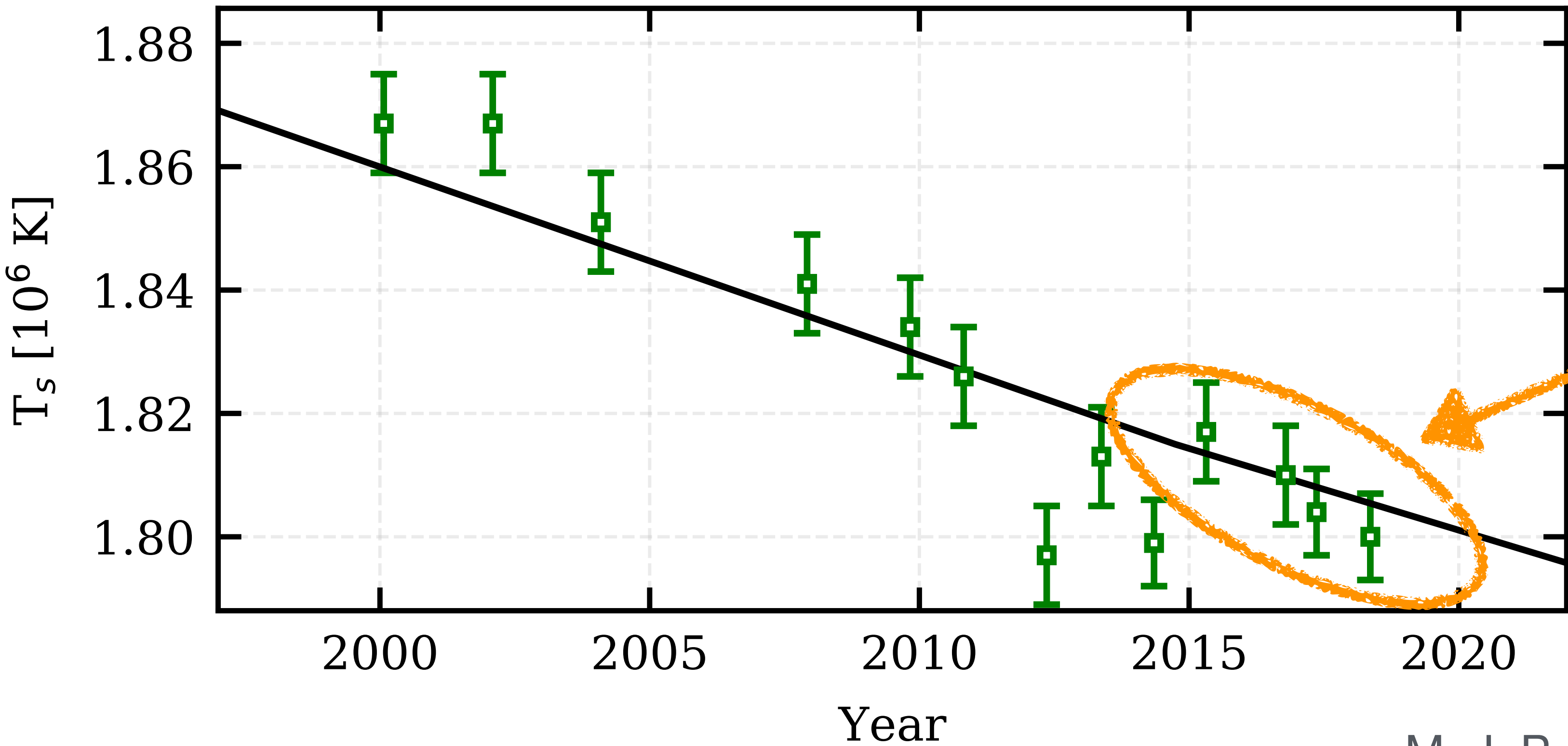
Invisible A^0 (Axion) Limits from Nucleon Coupling

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

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.

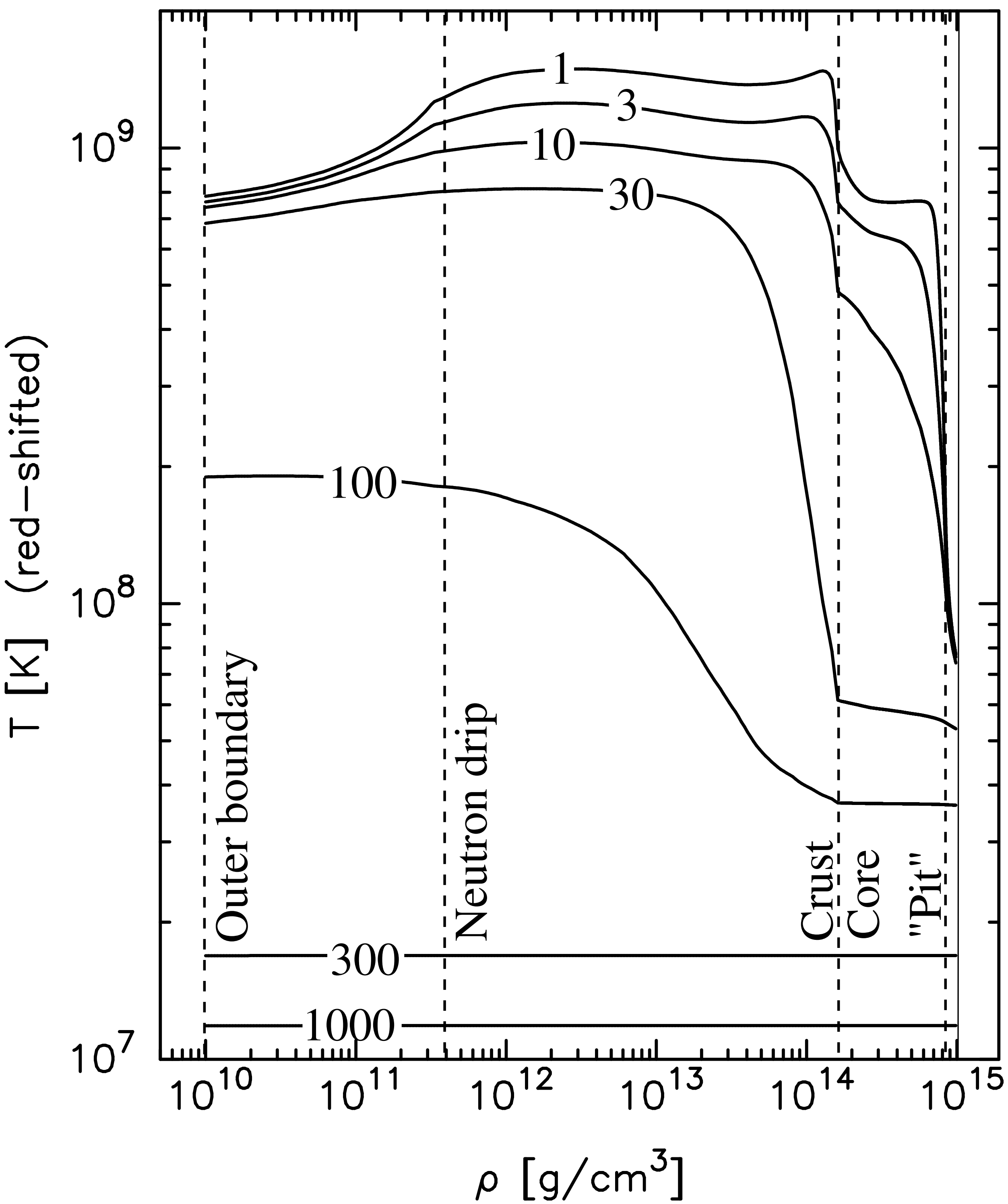
Conclusion

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

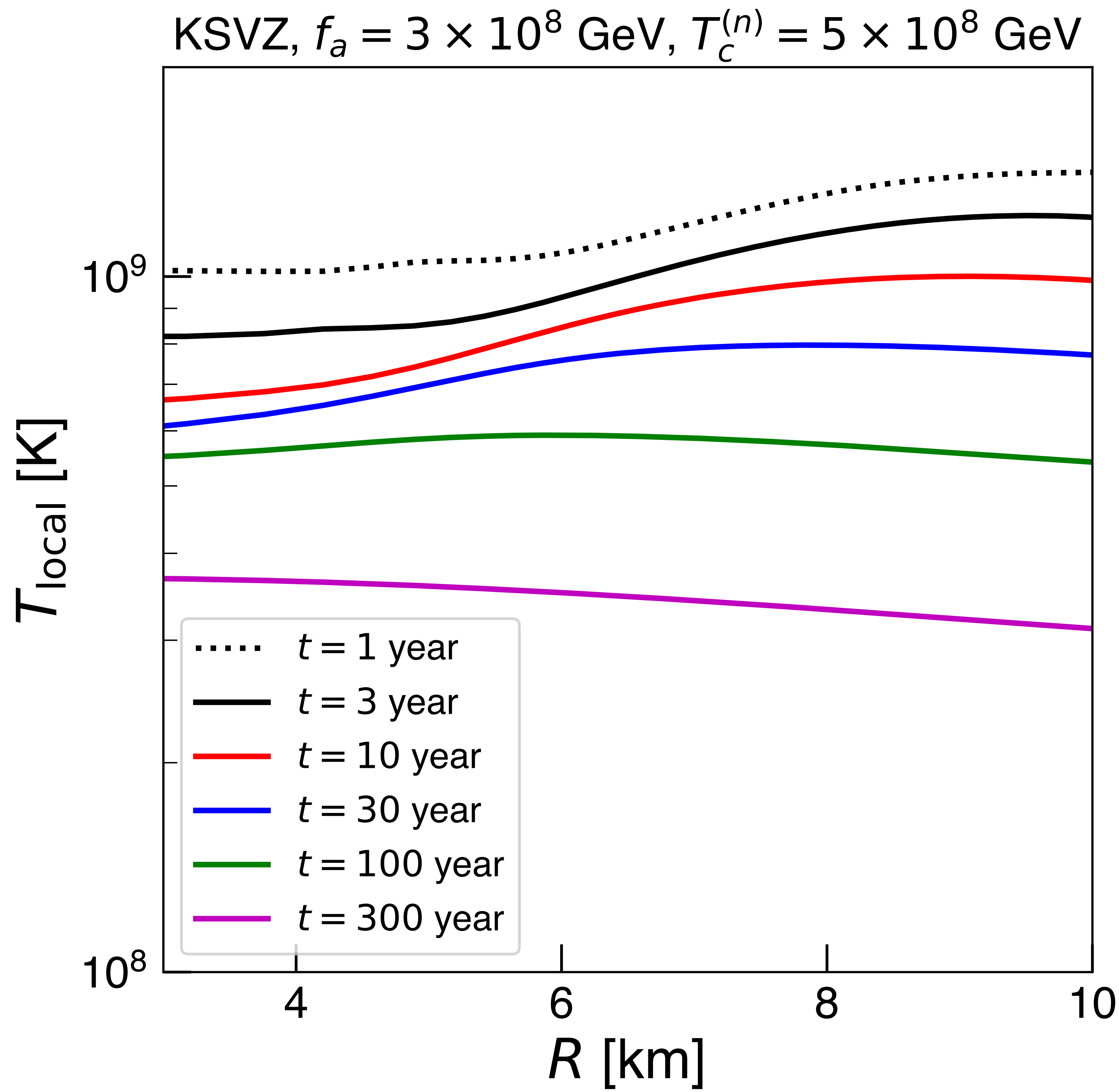
Temperature distribution



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



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.

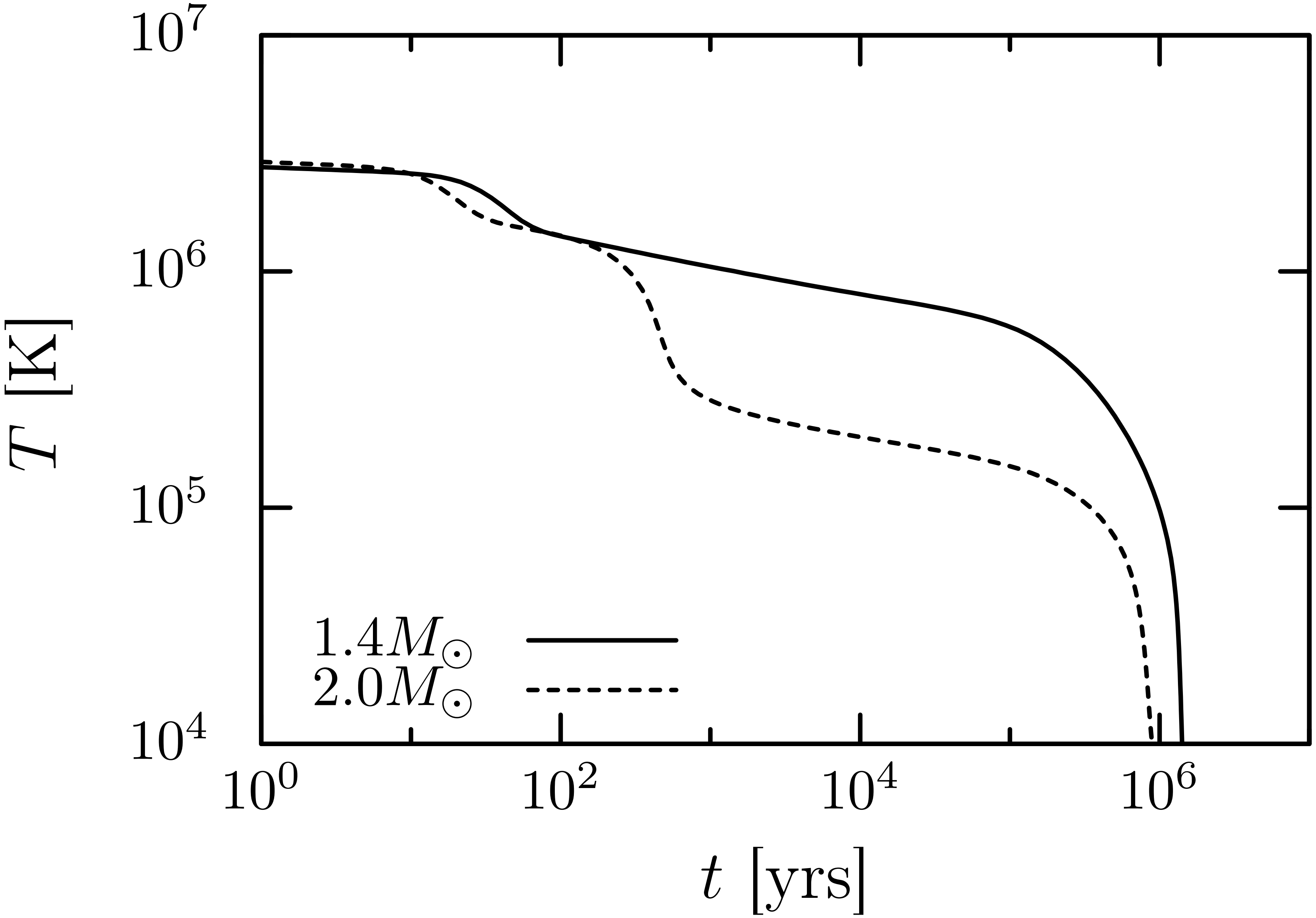
Momentum conservation

$$p_p + p_e > p_n$$

Neutrino momentum is negligible.

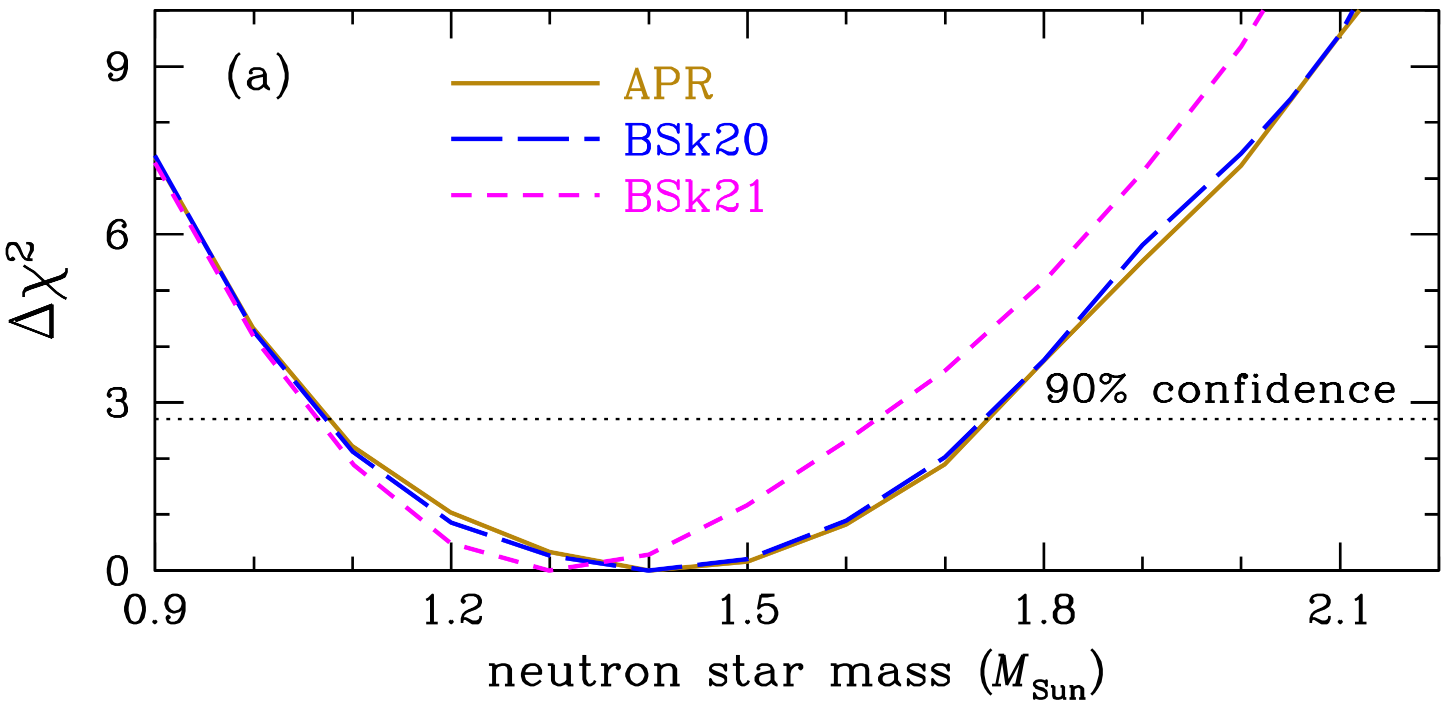
Therefore, the Direct Urca process can occur only where the density is huge so that the above approximation is not valid.

Cooling curves



The direct Urca process affects the neutron star cooling significantly.

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.

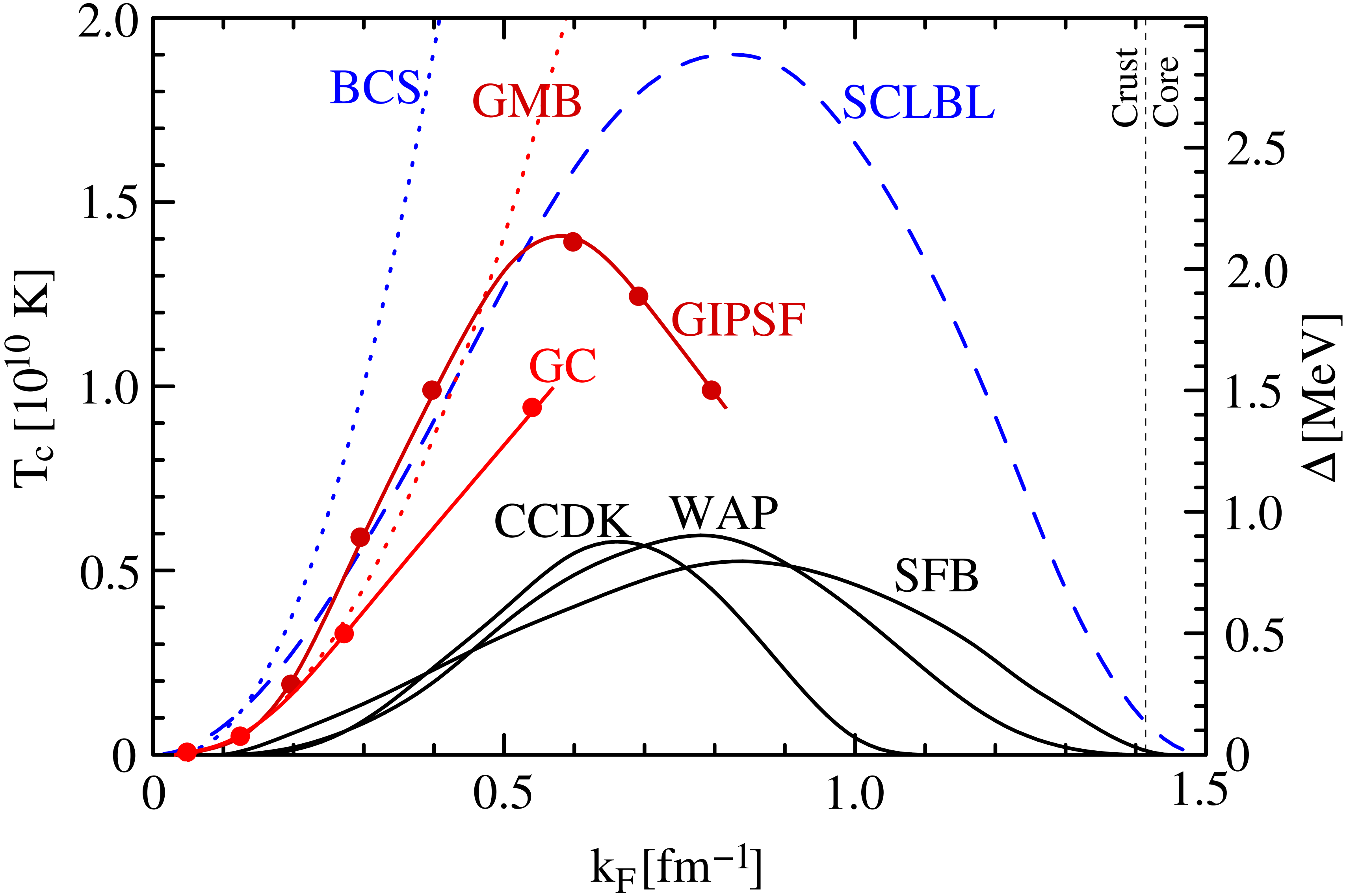
C. O. Heinke, W. C. Ho, Nature **462**, 71 (2009).

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

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

$^1S_0$ neutron gap

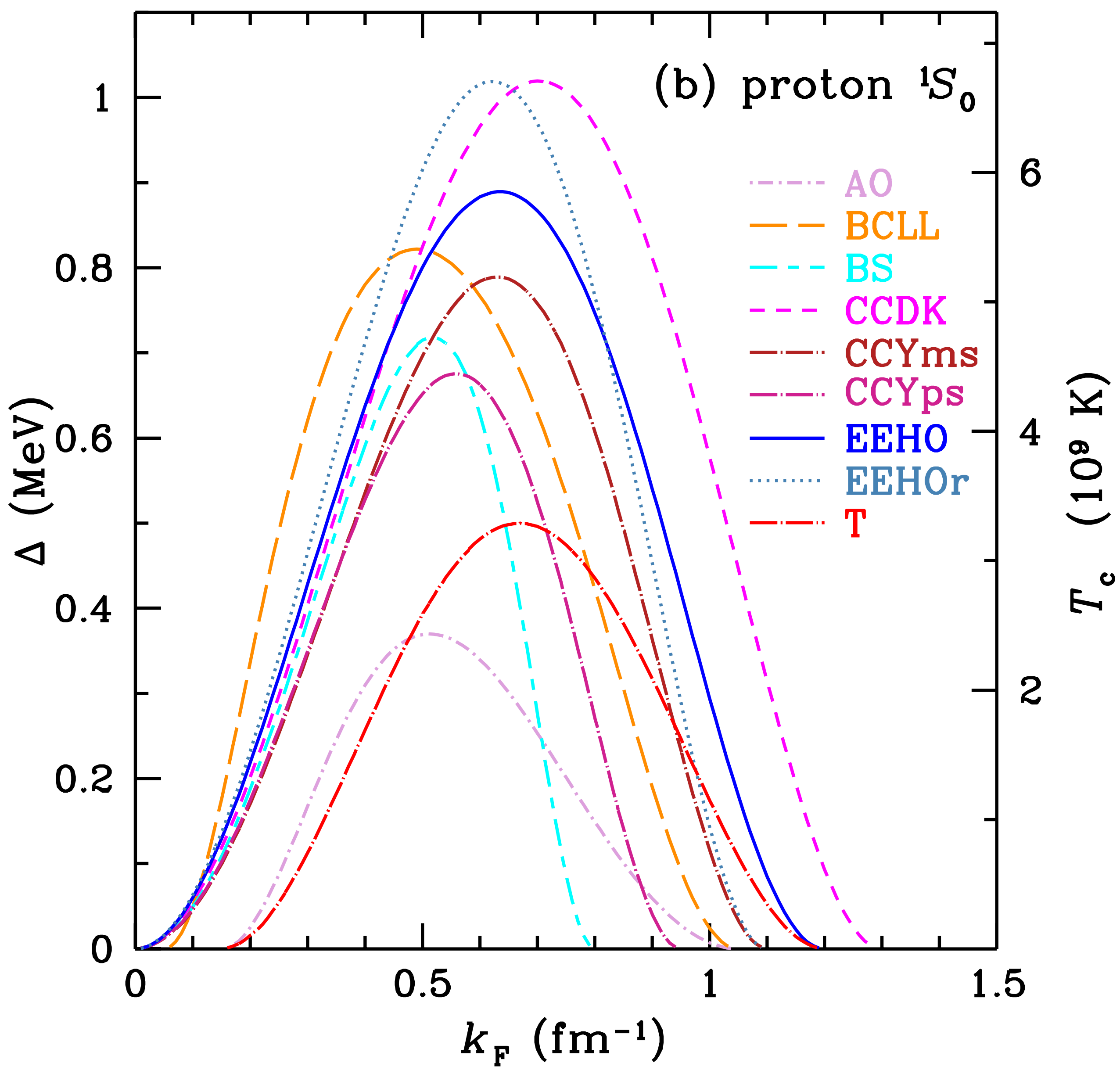
By solving the gap equation, we can obtain the pairing gap.

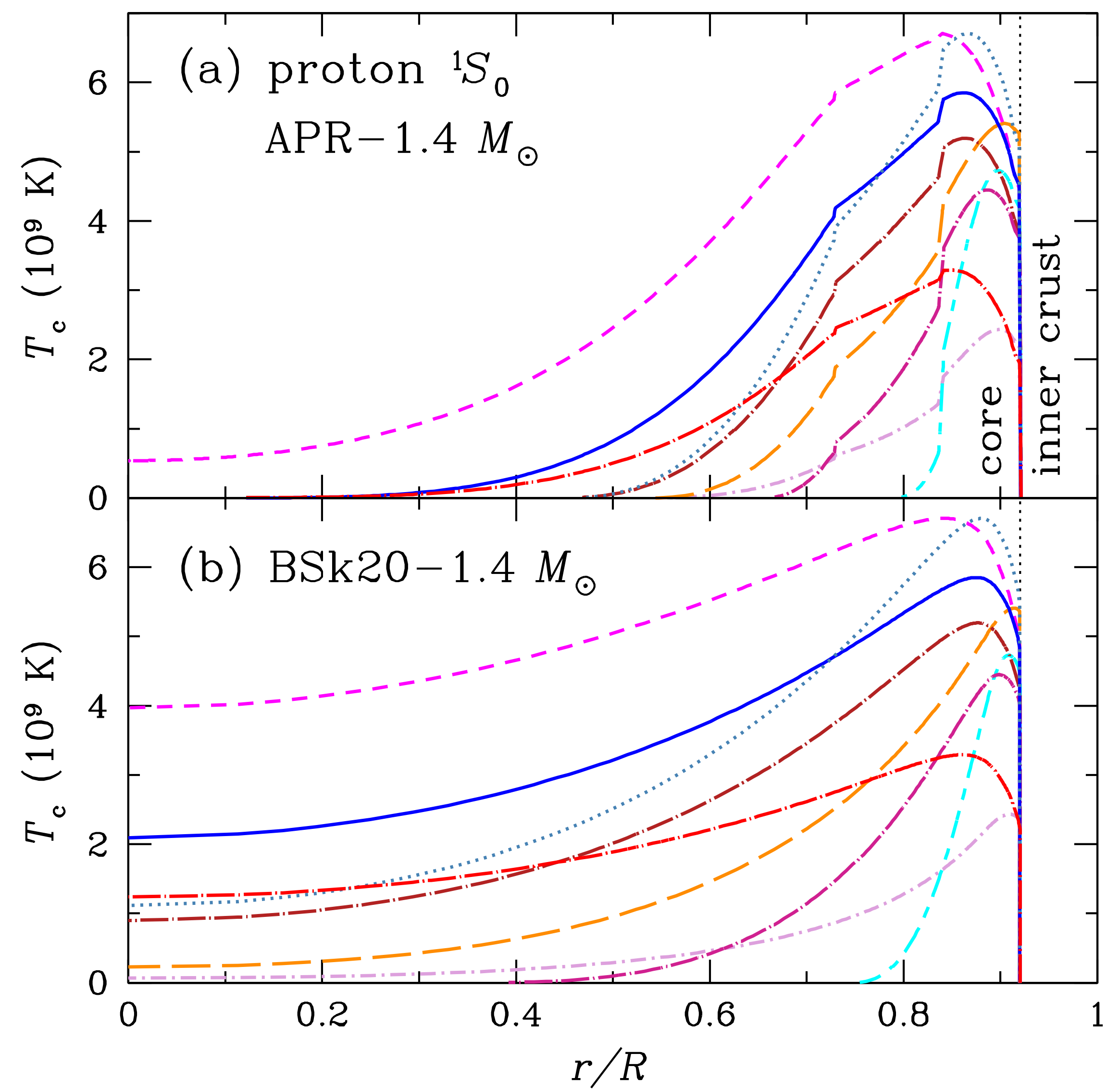


D. Page, J. M. Lattimer, M. Prakash, A. W. Steiner [arXiv: 1302.6626].

- 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

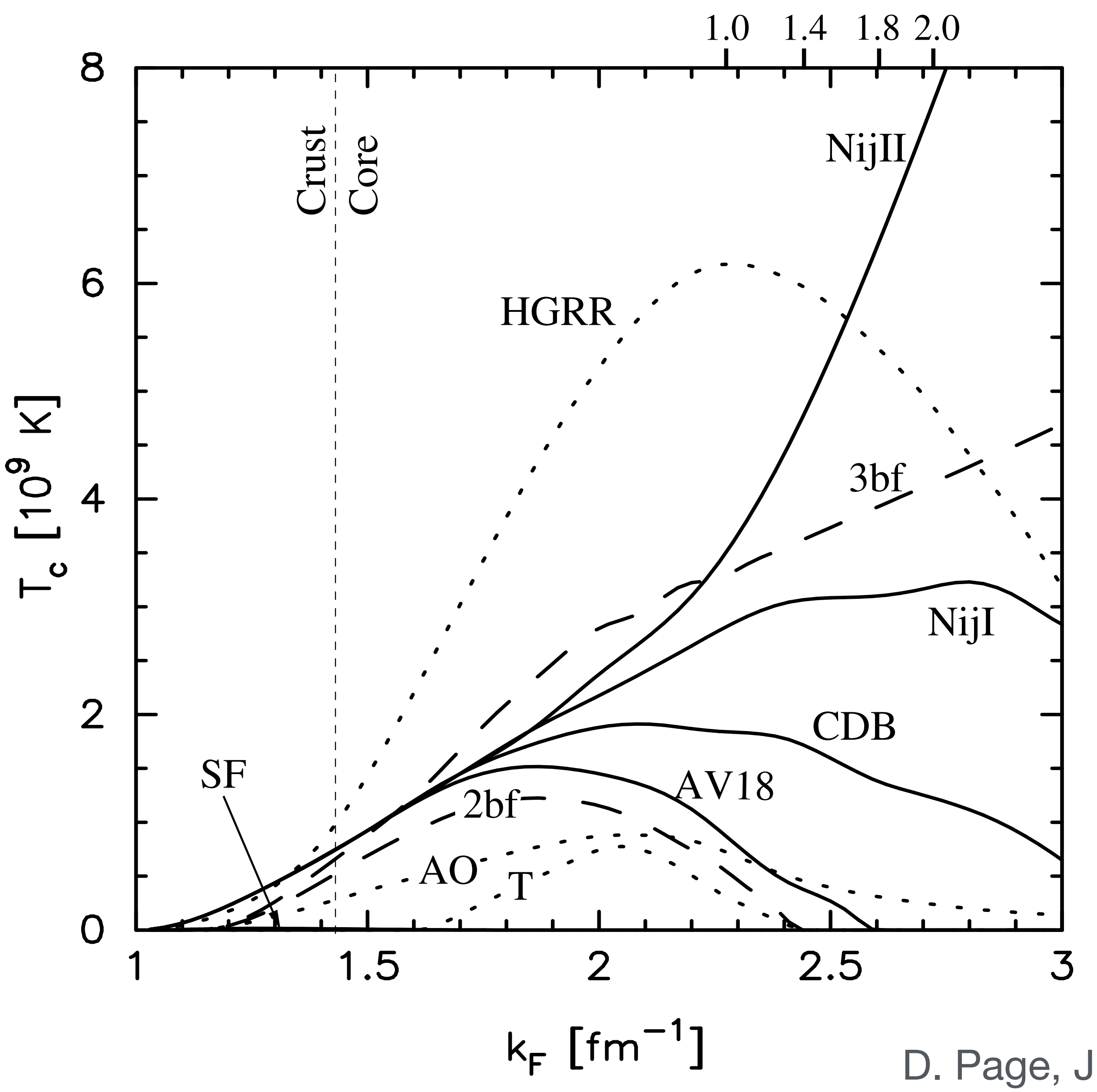




K. G. Elshamouty, C. O. Heinke, W. C. Ho, A. Y. Potekhin, Phys .Rev. **C91**, 015806 (2015).

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

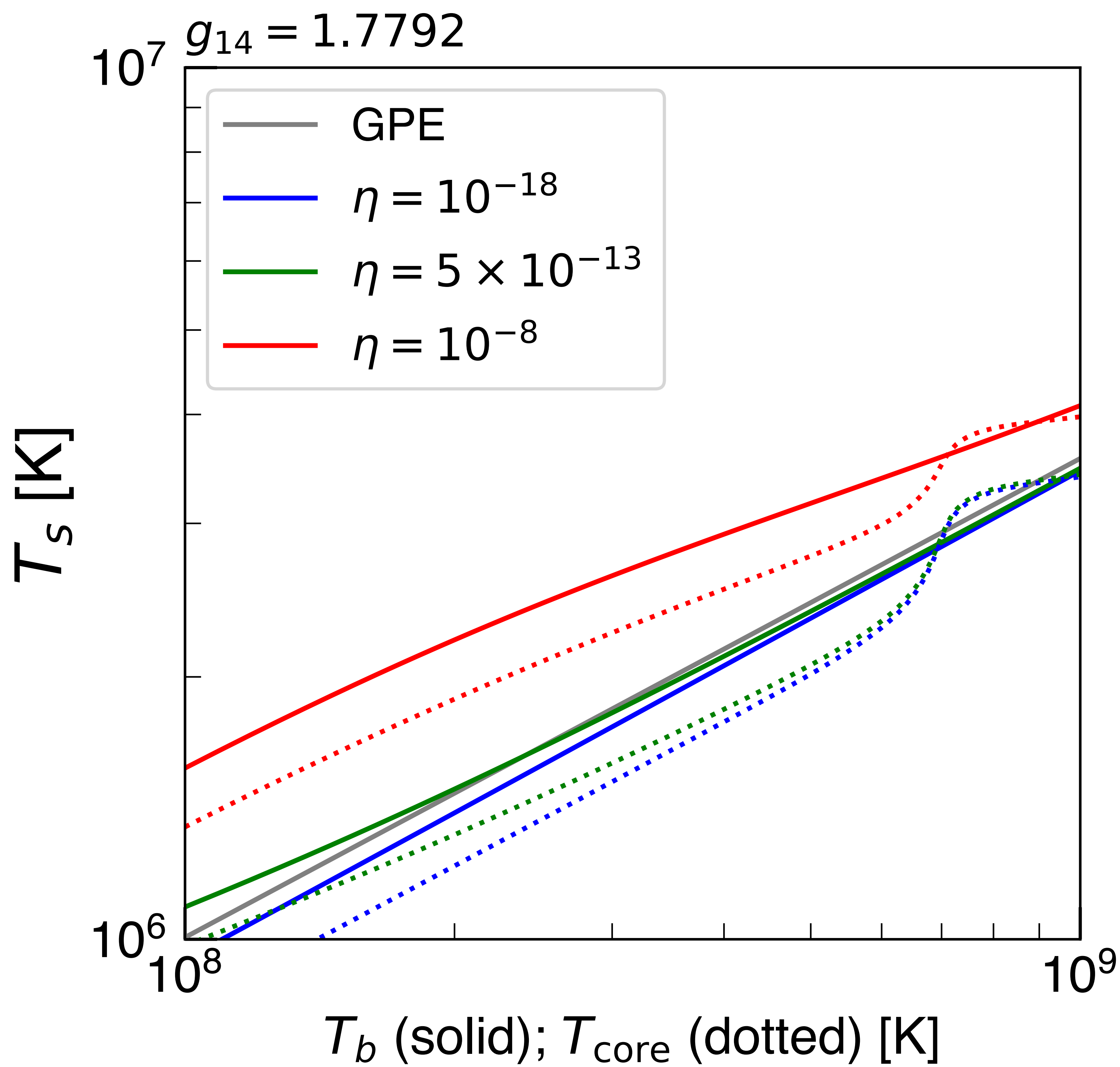
$^3P_2$ neutron gap



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

Large theoretical uncertainty

Core and boundary temperature



Slow neutrino emission

Temperature evolution

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

Heat capacity

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

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

Modified Urca + Bremsstrahlung

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

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

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

Surface vs internal temperatures

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

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

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.

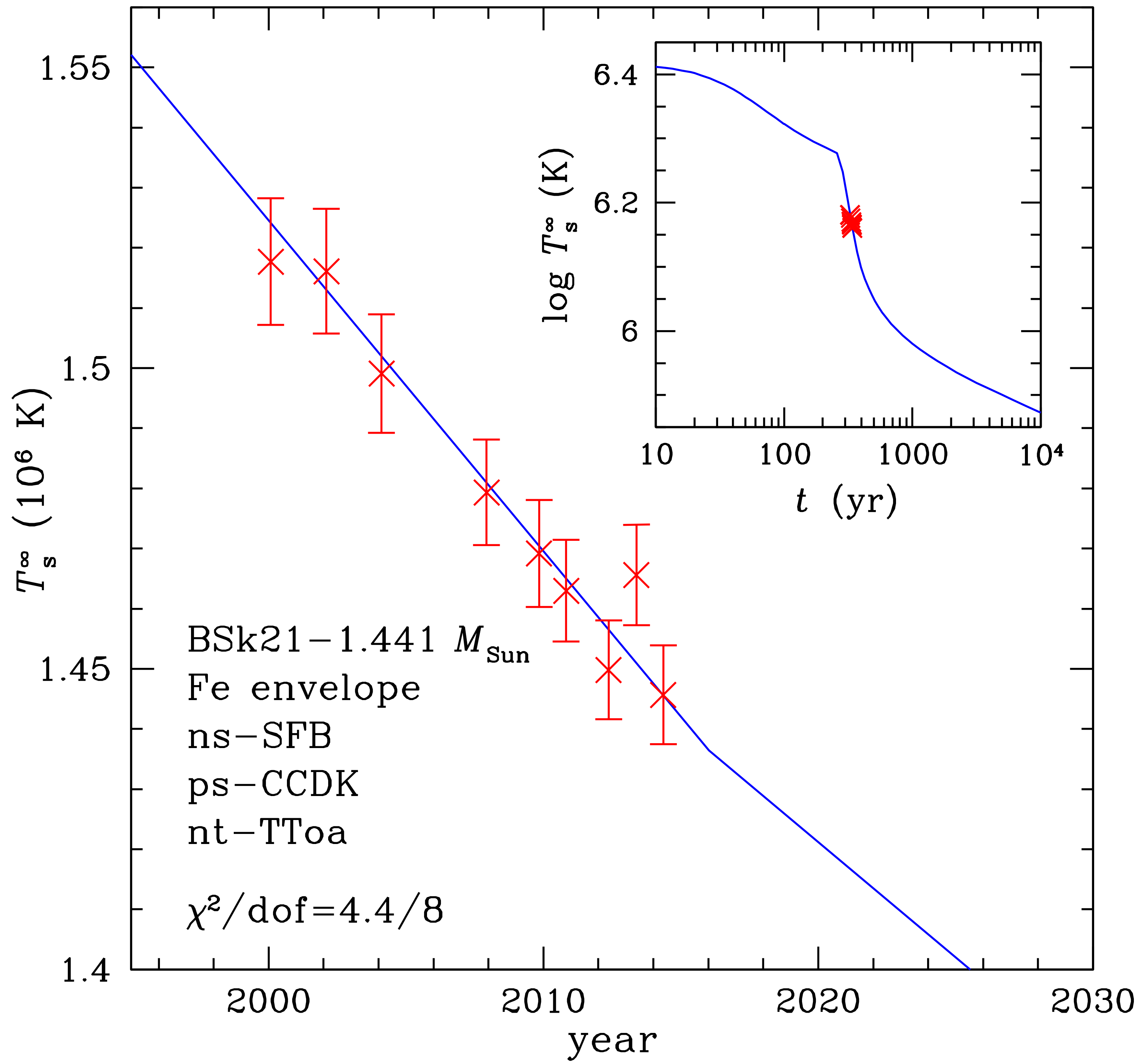
Solution in the minimal cooling paradigm

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

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

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

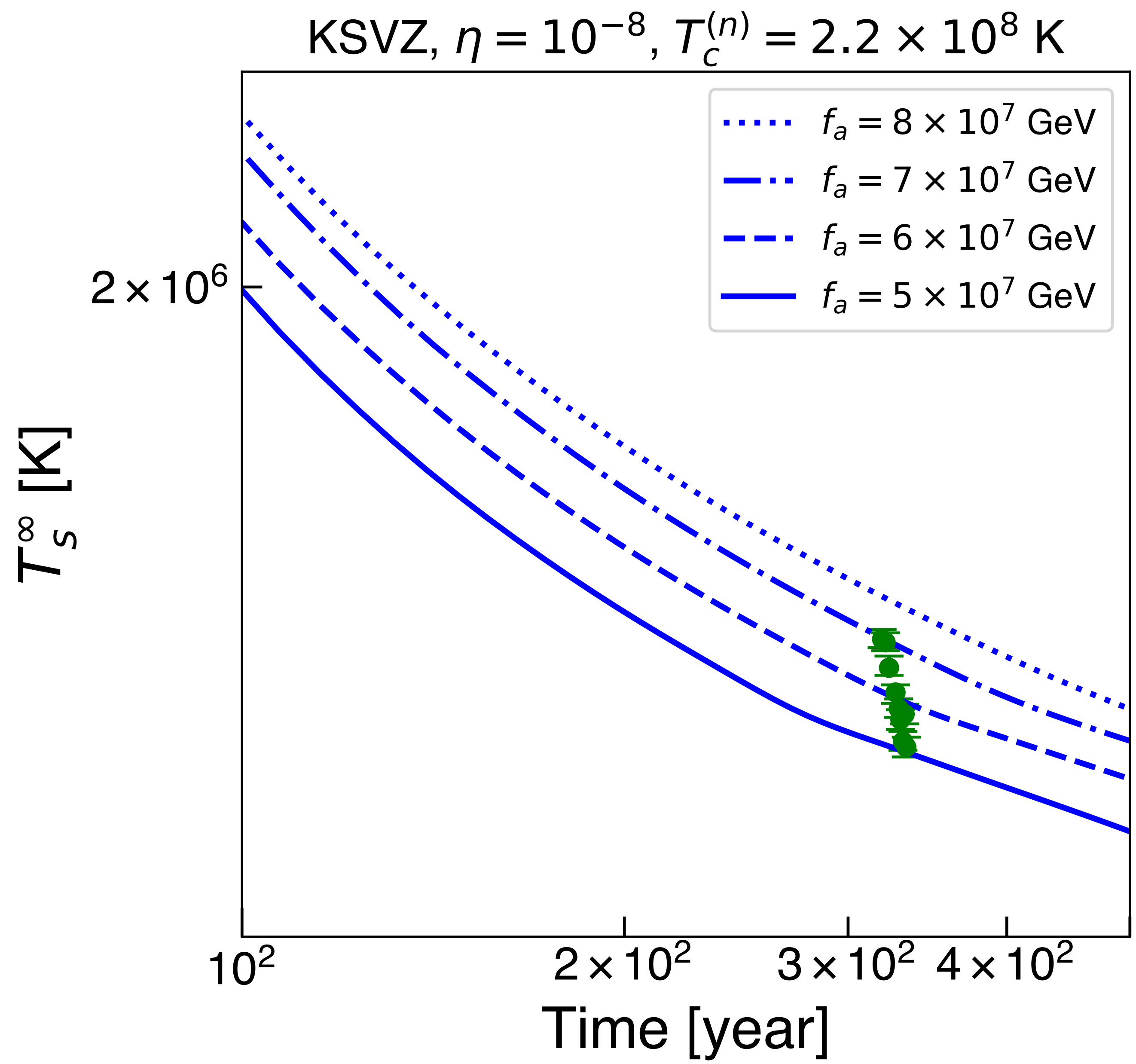
$$m_* \equiv \frac{m_u m_d m_s}{m_u m_d + m_u m_s + m_d m_s}$$

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.

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

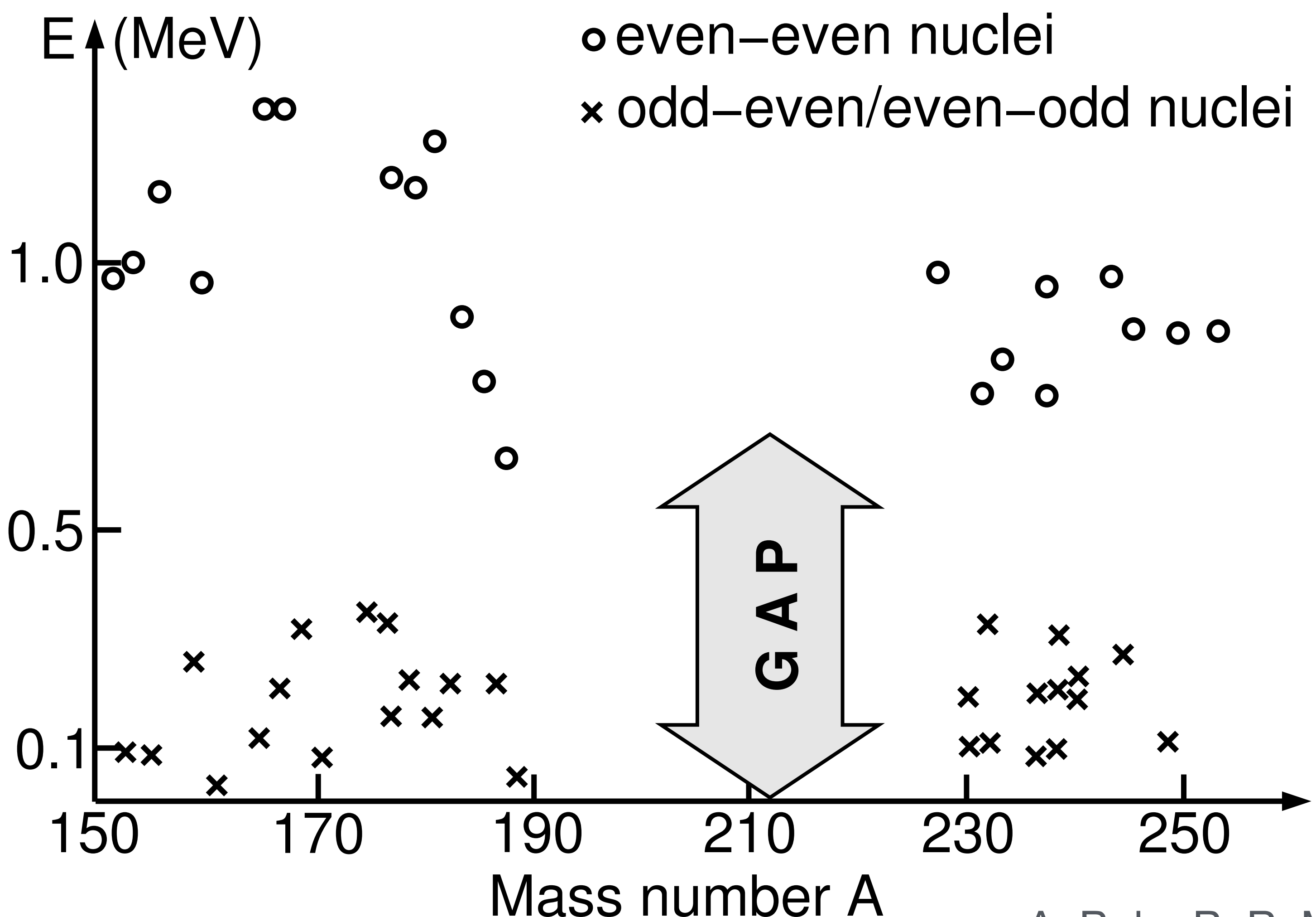
  S. H. Yang, C. M. Pi, X. P. Zheng, APJ. **735**, L29 (2011).

- Quark color superconducting

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

Pairing in Nuclei

Lowest excitation levels of nuclei



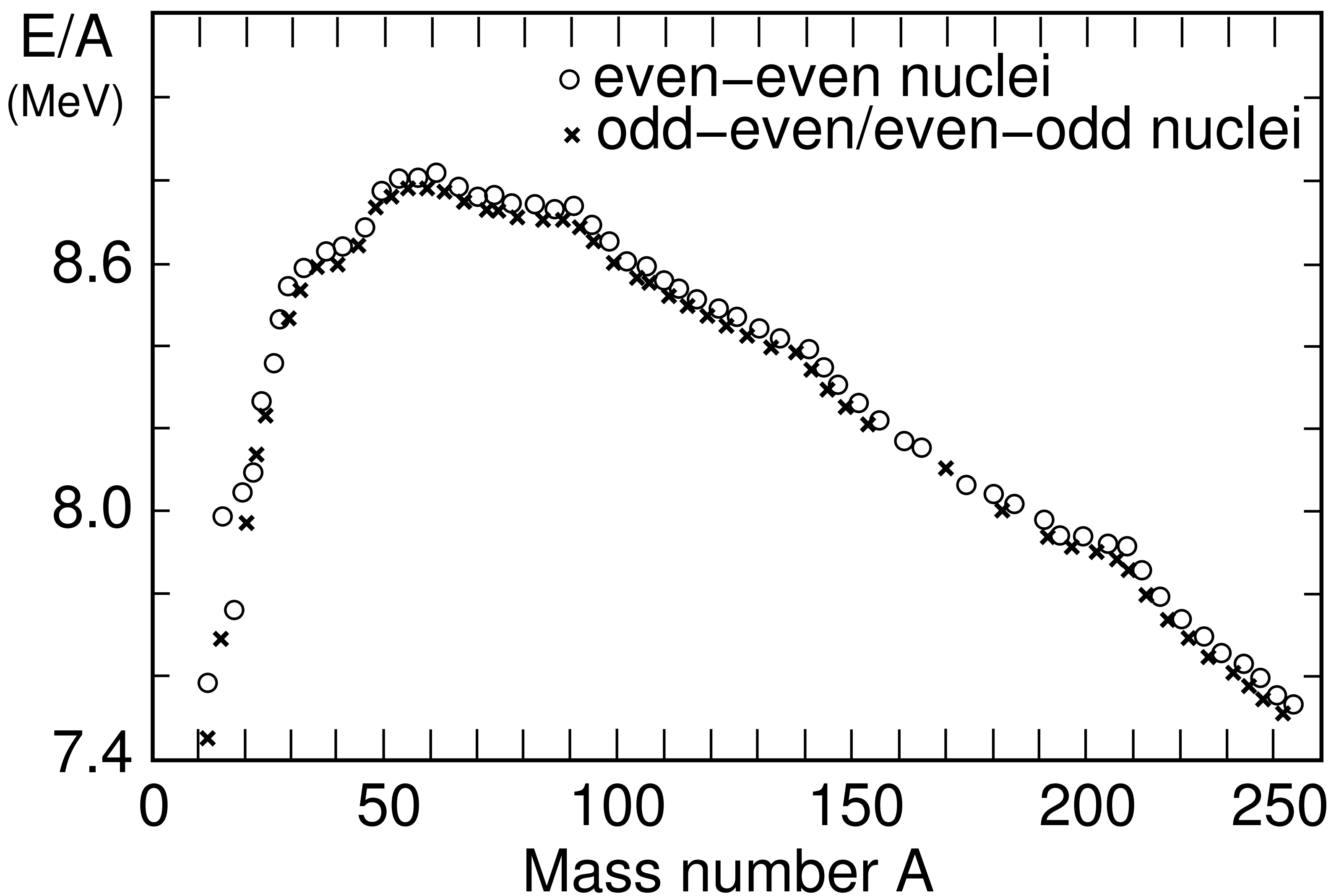
A. Bohr, B. R. Mottelson, and D. Pines, Phys. Rev. **110**, 936 (1958).

A nucleon in even-even nuclei requires a minimum energy for excitation.

Suggests the presence of a gap.

Pairing in Nuclei

Binding energy per nucleon

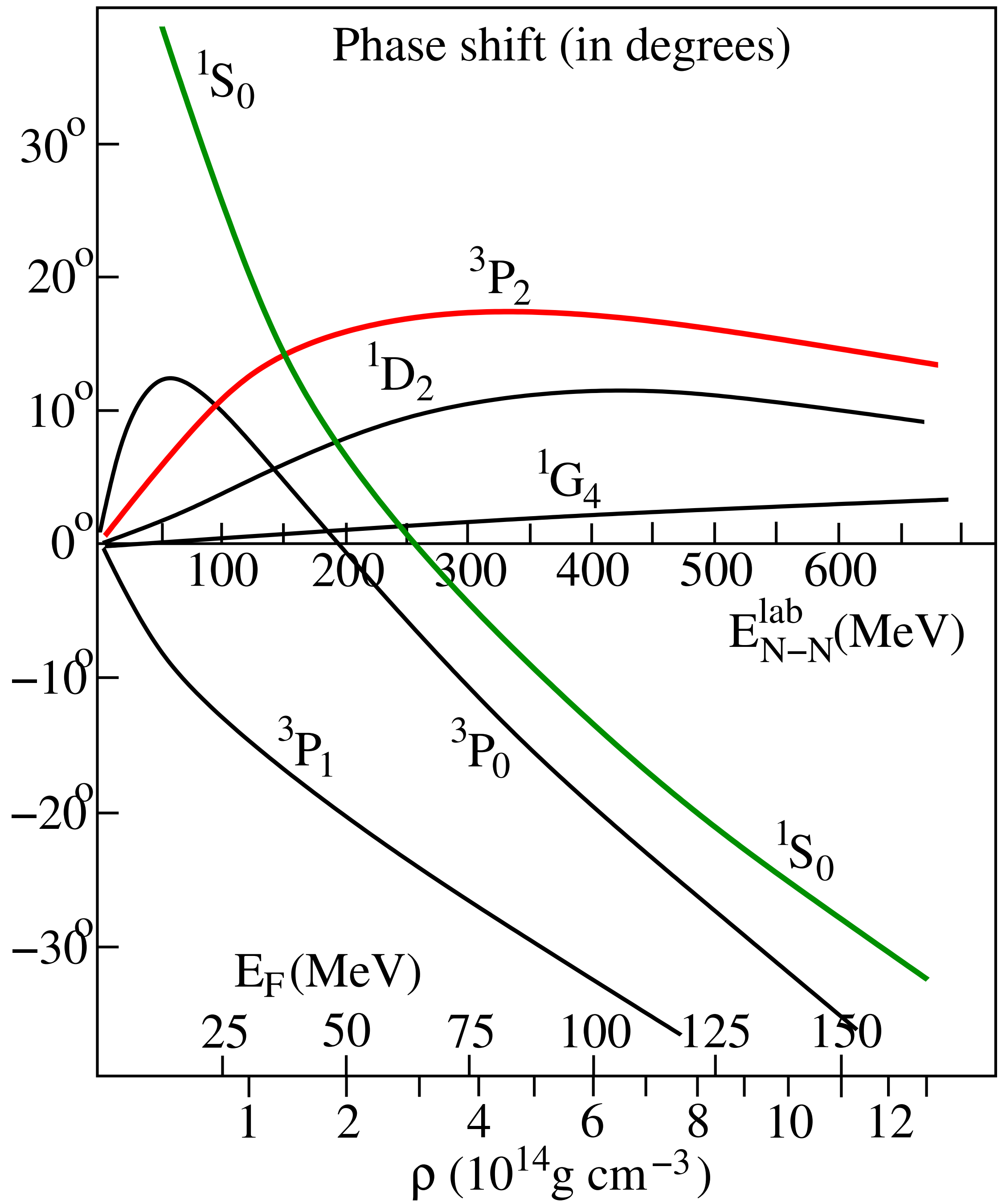


E. Segre, Nuclei and Particles.

Even-even nuclei are more bound than odd-even/odd-odd nuclei.

Pairing in Nuclei

Phase shifts for nucleon-nucleon scattering



A positive phase-shift implies an attractive interaction.

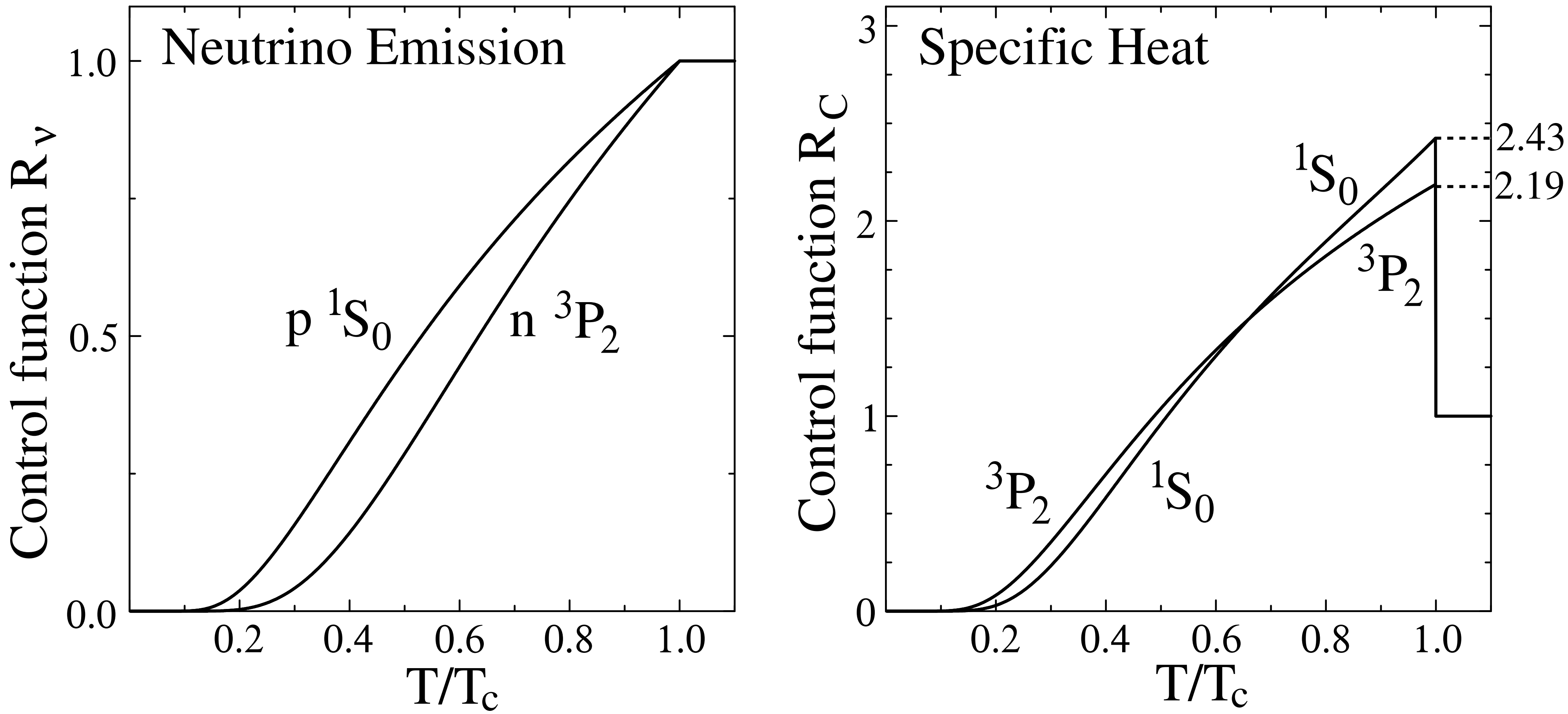
From this result, we expect

- Nucleons pair in a spin-singlet state at low densities.
- A spin-triplet pairing occurs at high densities.

Medium effects may modify the interactions.

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

Pairing effects on neutron star cooling



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

Due to the energy gap, available phase space is limited at low temperatures.

- Cooling by neutrino emission is suppressed.
- Specific heat is suppressed.
- Cooper pair breaking and formation enhance neutrino emission