The Frontier of Particle Physics: Exploring Muons, Quantum Science and the Cosmos

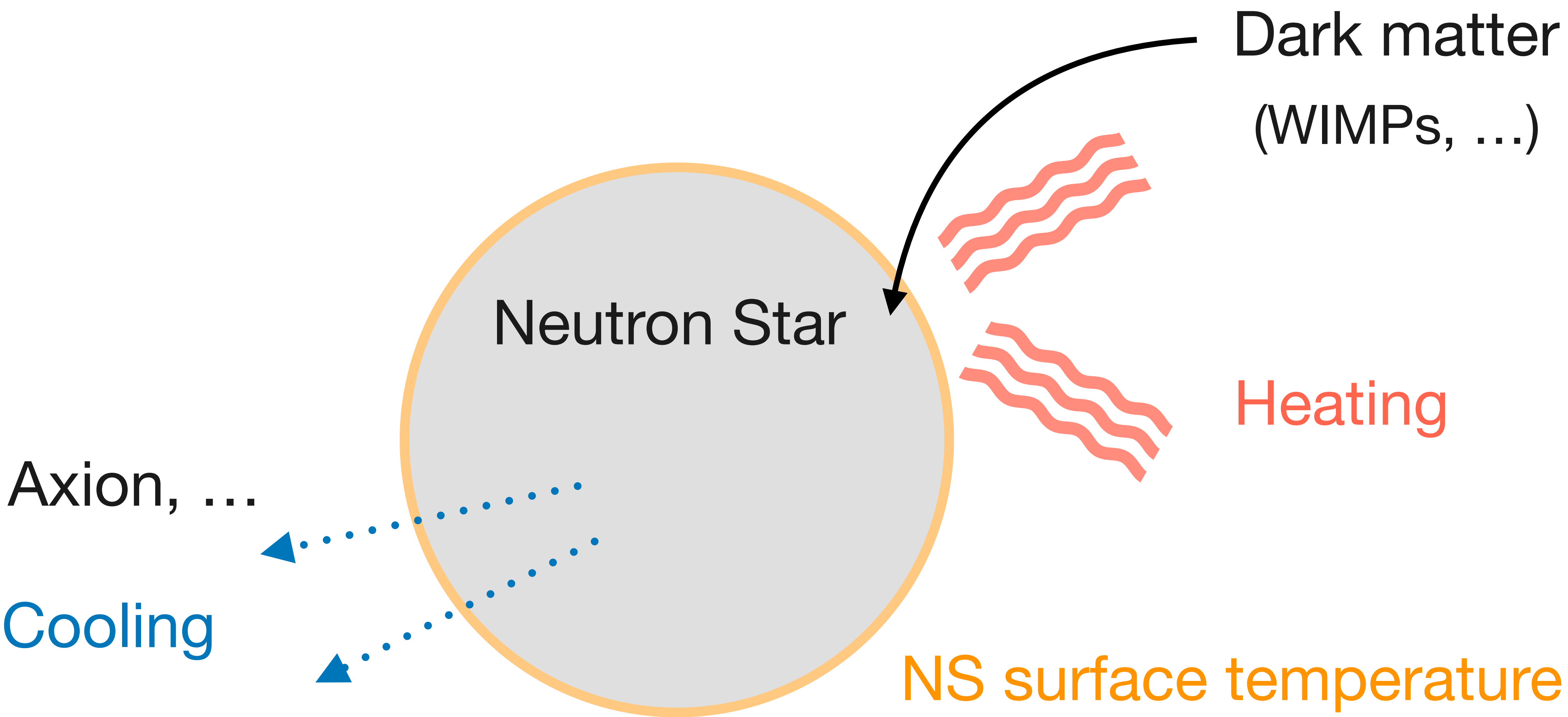
Exploring Physics Beyond the Standard Model via Temperature Observations of Neutron Stars

Natsumi Nagata (U. of Tokyo)

Jun 19, 2025
YITP, Kyoto

Today’s topic

Search for new physics via temperature observations of neutron stars (NSs).



Explore the effects of new physics by searching for deviations from standard NS cooling.

Outline

- Standard NS cooling
- Heating

  WIMPs, … ⇒ May be hidden by NS internal heating
- Cooling

  Axion, … ⇒ Limit from Cassiopeia A NS

Standard NS cooling theory

Standard NS cooling

D. Page, 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)

- Supposed to be in the β equilibrium.
- In Fermi degenerate states.

Equation for temperature evolution

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

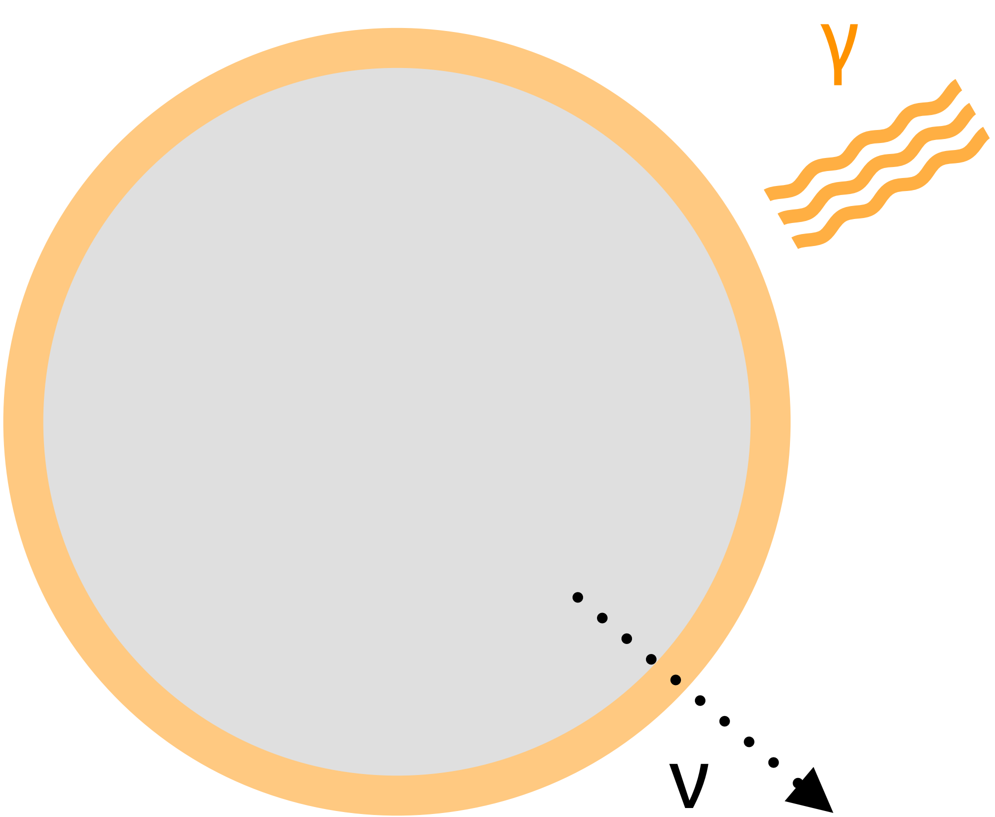
$C(T)$: Stellar heat capacity

L_ν: Luminosity of neutrino emission

L_γ: Luminosity of photon emission

Cooling sources

Two cooling sources:



- Photon emission (from surface)

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

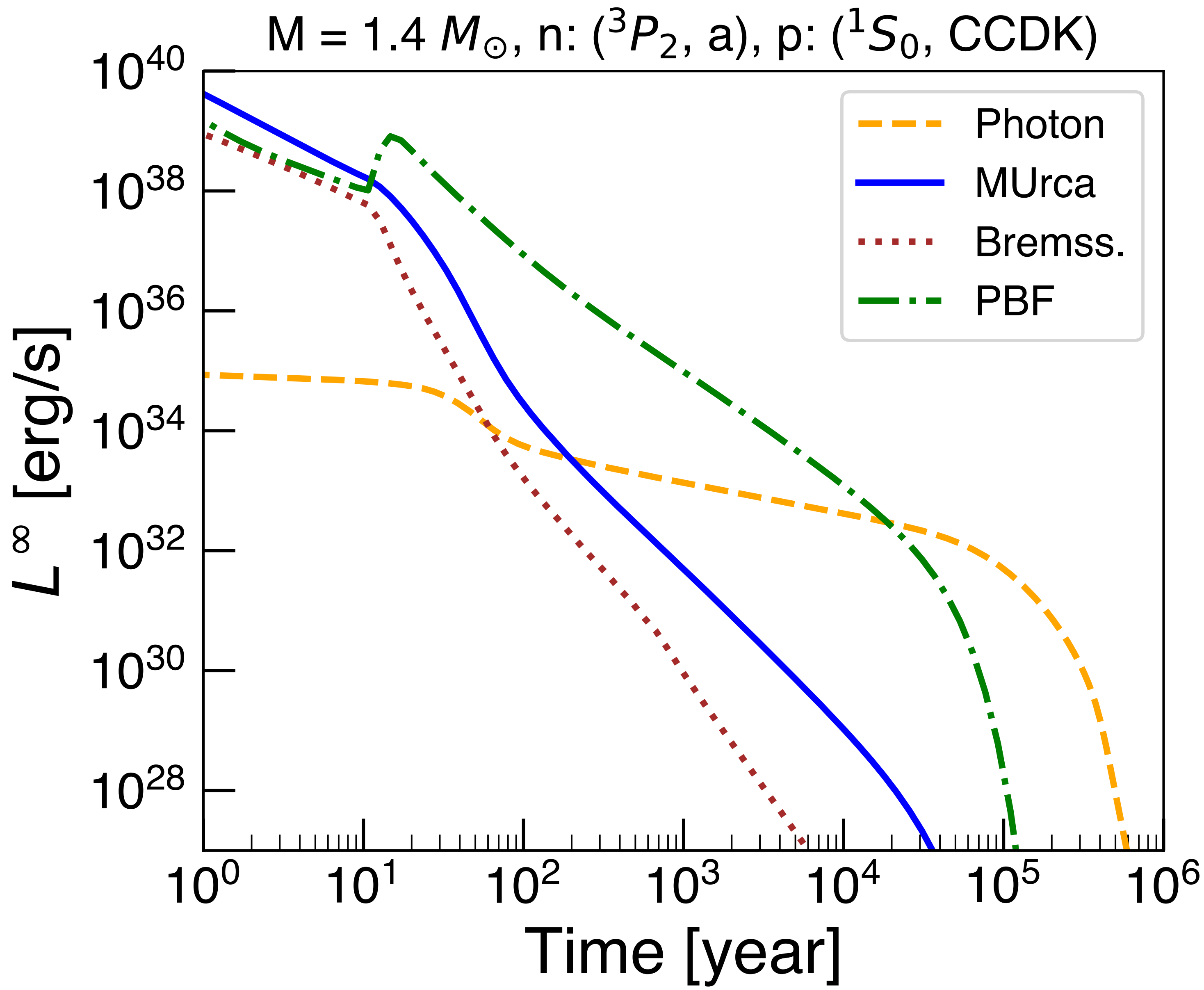
Dominant for $t \gtrsim 10^5$ years

- Neutrino emission (from core)

Dominant for $t \lesssim 10^5$ years

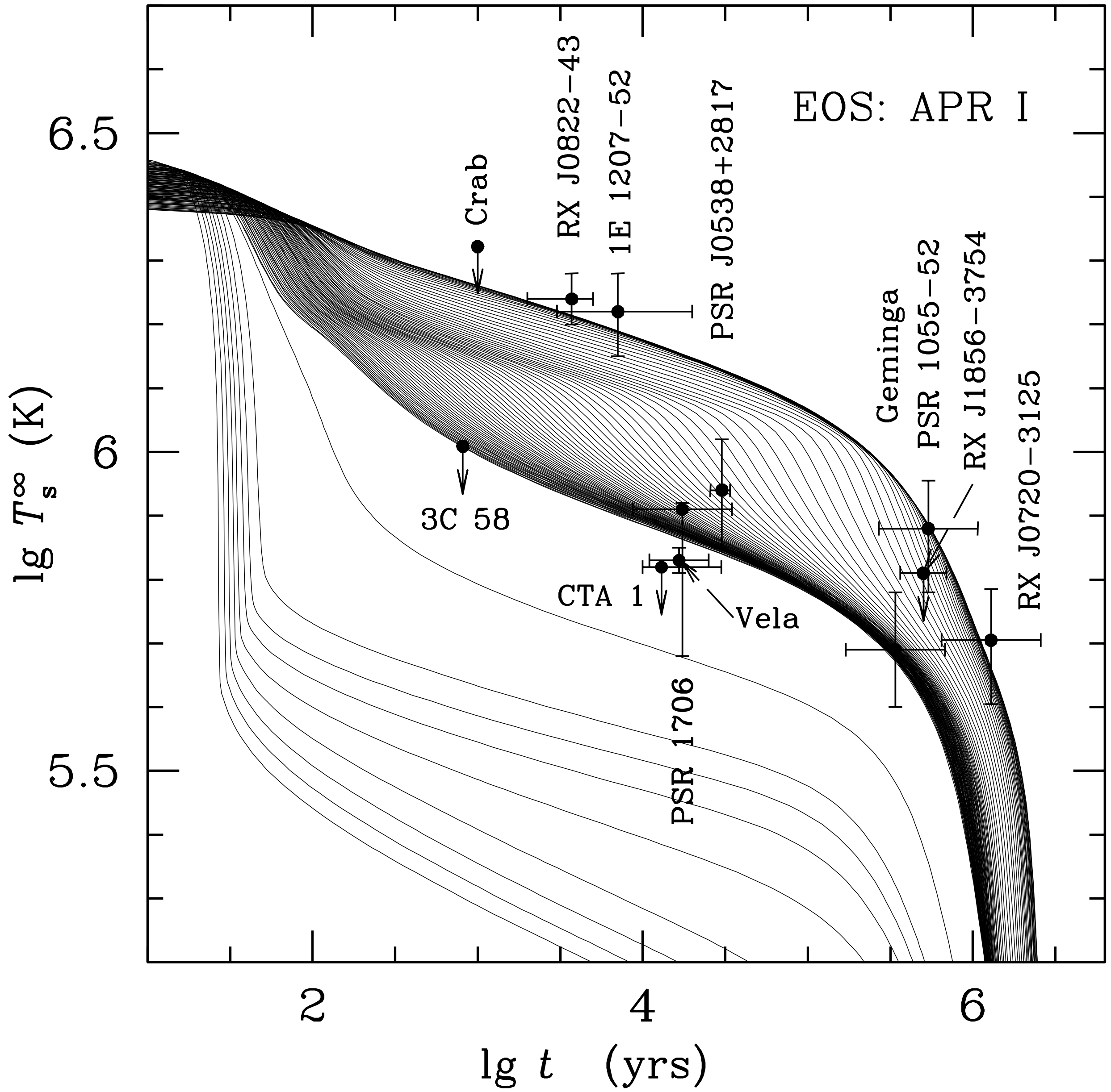
  - Direct Urca process (DUrca)
  - Modified Urca process (MUrca)
  - Bremsstrahlung
  - PBF process

Luminosity



- Neutrino emission is dominant for young NSs.
- Photon emission is dominant for old NSs.

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).

Consistent with the observations for $t < 10^6$ years.

For the latest data, see http://www.ioffe.ru/astro/NSG/thermal/cooldat.html

~ 50 NSs listed.

DM heating vs NS internal heating

Dark matter heating in NSs

It has been discussed that the signature of dark matter (DM) may be detected via the NS temperature observations.

C. Kouvaris, Phys. Rev. **D77**, 023006 (2008).

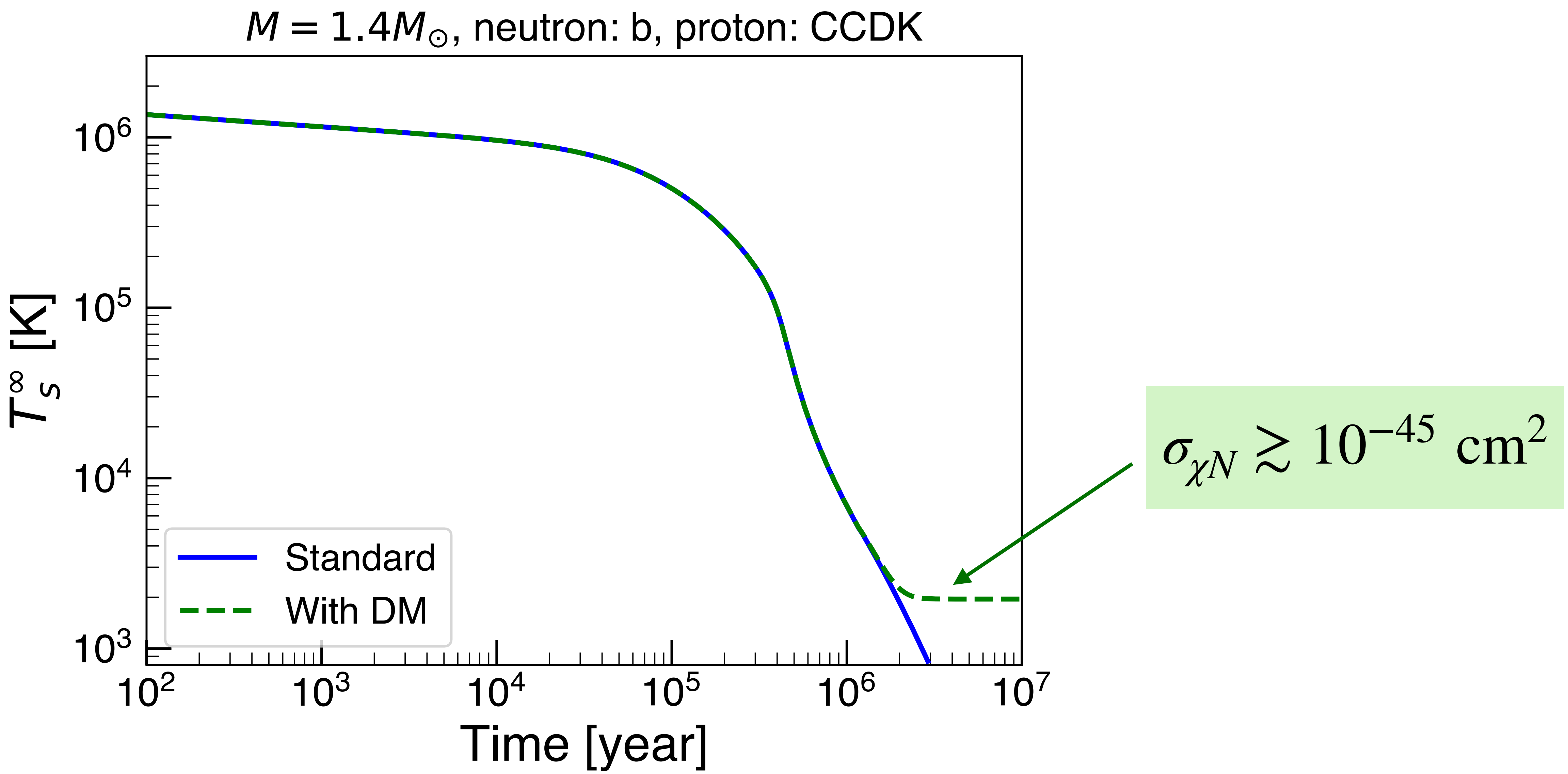
Generated by ChatGPT 4o

Mechanism

DM accretes on a NS. → Deposit its energy inside the NS. → Heat the NS!

Dark matter heating in NSs

Dark matter heating effect may be observed in old NSs.



- In the standard cooling scenario, temperature becomes very low for $t > 10^7$ years.
- With DM heating effect, $T_s^\infty \to \sim 2 \times 10^3\ \mathrm{K}$ at later times.

Old warm neutron stars?

Recently, "old but warm neutron stars" have been observed.

Milli-second pulsars

- J0437-4715: $t_{\mathrm{sd}} = (6.7 \pm 0.2) \times 10^9$ years, $T_s^\infty = (1.25 - 3.5) \times 10^5$ K

O. Kargaltsev, G. G. Pavlov, and R. W. Romani, Astrophys. J. **602**, 327 (2004);
M. Durant, *et al.*, Astrophys. J. **746**, 6 (2012).

- J2124-3358: $t_{\mathrm{sd}} = 11^{+6}_{-3} \times 10^9$ years, $T_s^\infty = (0.5 - 2.1) \times 10^5$ K

B. Rangelov, *et al.*, Astrophys. J. **835**, 264 (2017).

Ordinary pulsars

- J0108-1431: $t_{\mathrm{sd}} = 2.0 \times 10^8$ years, $T_s^\infty = (2.7 - 5.5) \times 10^4$ K

V. Abramkin, Y. Shibanov, R. P. Mignani, and G. G. Pavlov, Astrophys. J. **911**, 1 (2021).

- B0950+08: $t_{\mathrm{sd}} = 1.75 \times 10^7$ years, $T_s^\infty = (6 - 12) \times 10^4$ K

V. Abramkin, G. G. Pavlov, Y. Shibanov, and O. Kargaltsev, Astrophys. J. **924**, 128 (2022).

These observations cannot be explained in the standard cooling.

Internal heating

In actual NSs, the following internal heating mechanisms due to the slowdown of NS rotation may operate:

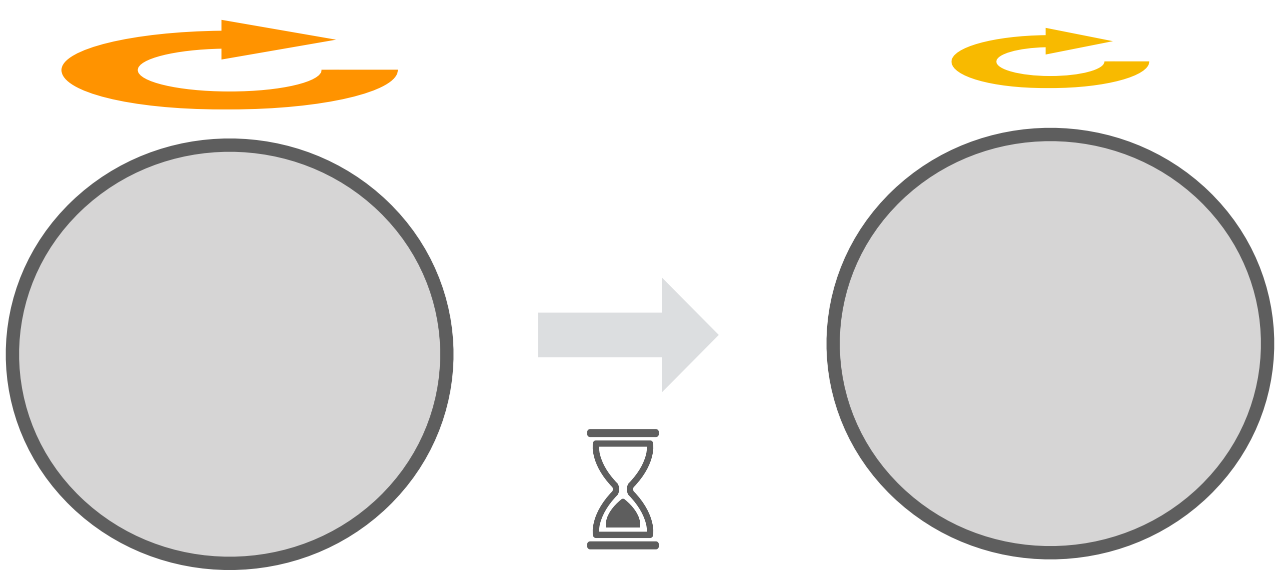
- Non-equilibrium beta processes

See K. Hamaguchi, N. Nagata, K. Yanagi, Phys. Lett. **B795**, 484 (2019);
K. Hamaguchi, N. Nagata, K. Yanagi, MNRS **492**, 5508 (2020).

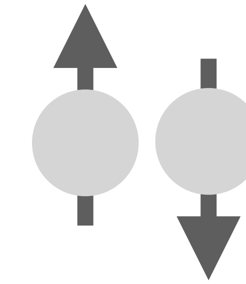
DM heating effect can be observed in ordinary pulsars.

- Friction caused by vortex creep

We discuss this today.



Neutron superfluid vortex line

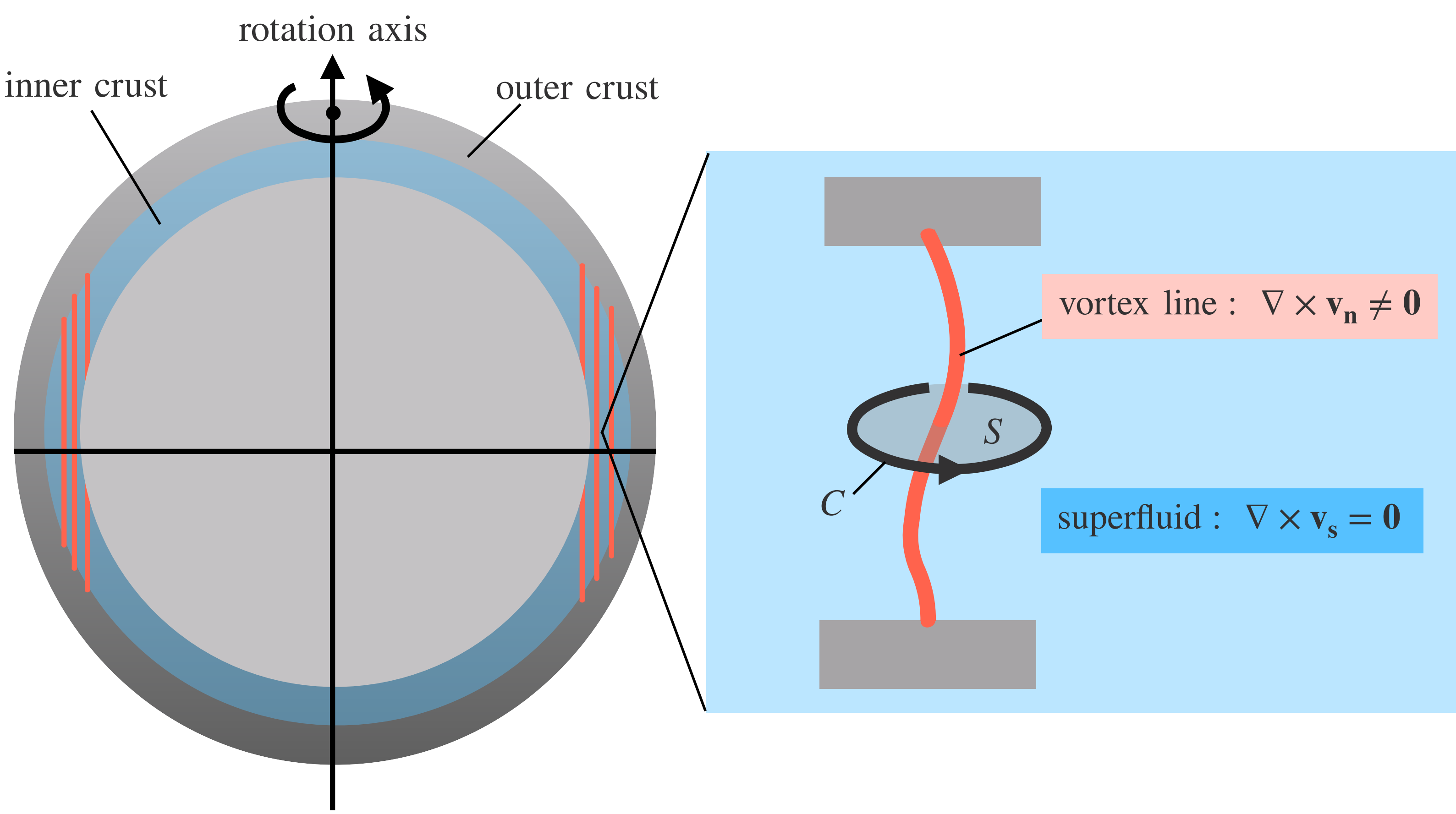


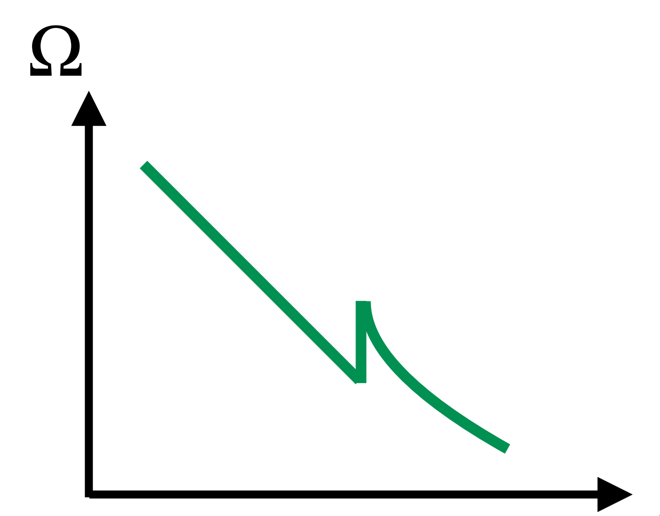
Neutrons form Cooper pairs in NSs. → Neutron superfluidity

In a rotating NS, superfluid vortex lines are formed.

The vortex lines are fixed to the crust by nuclear interactions.

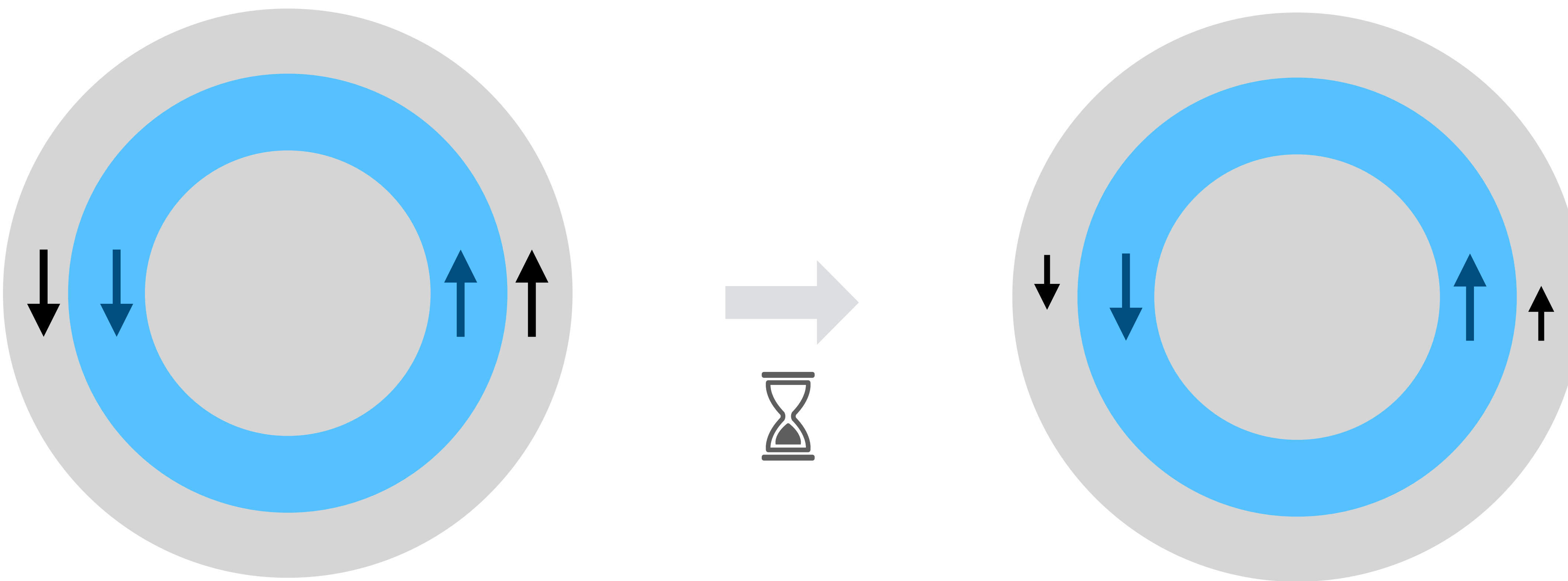
P. W. Anderson and N. Itoh, Nature **256**, 25 (1975).





Vortex lines may be relevant for pulsar glitches.

Pulsar slowdown



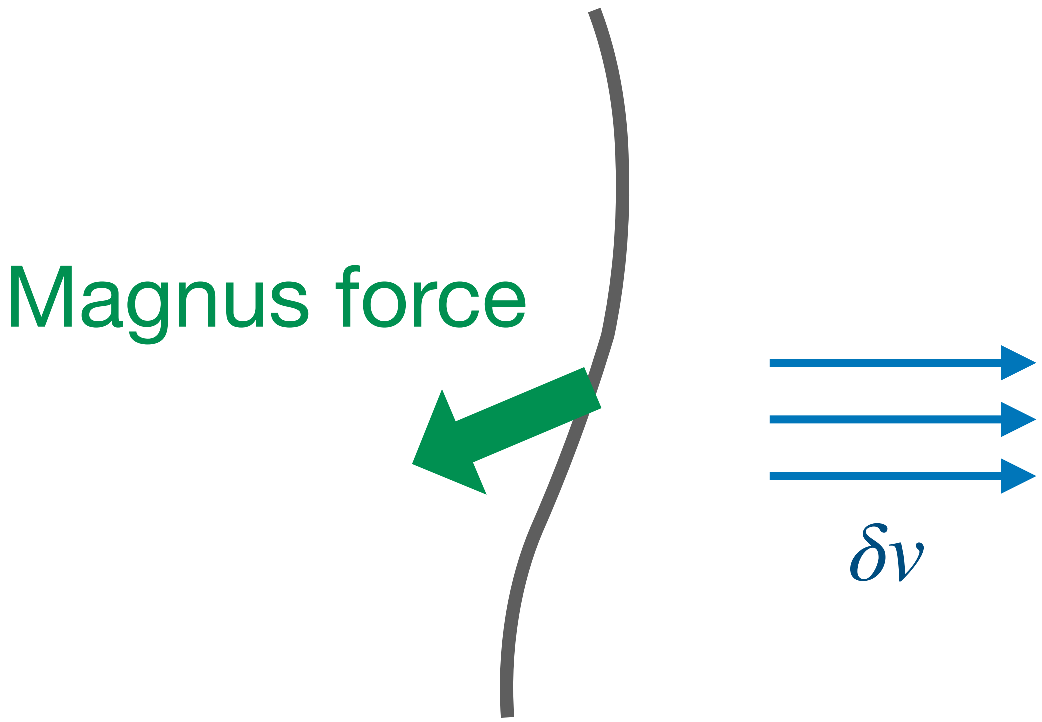
Rotation of the rigid component of NS slows down.

But the superfluid component does not.

→ The rotational speed difference δv develops.

Magnus force

Vortex lines are pinned to the crust, feeling a superfluid flow.



Magnus force acts on vortex lines.

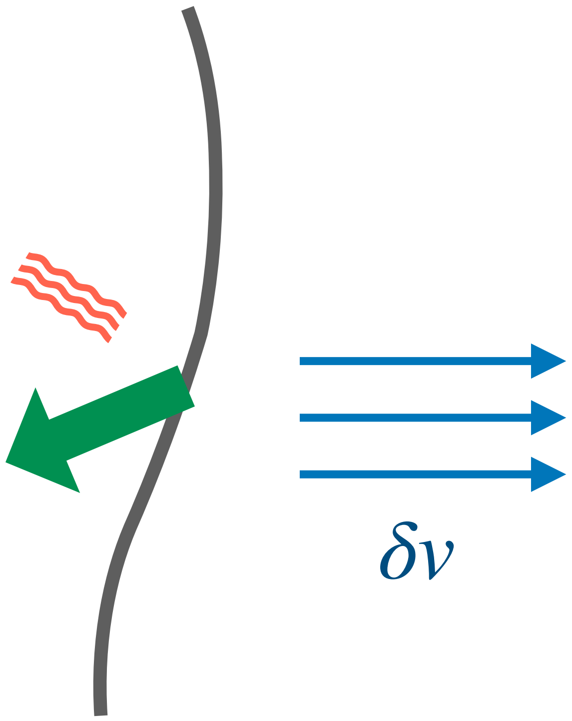
As δv increases, Magnus force increases.

When it gets large enough, vortex lines start to move outwards.

Vortex creep → δv decreases → Vortex lines pinned

Start over

Vortex creep



Vortex creep results in

$$\Omega_{\rm SF} - \Omega_{\rm crust} = \text{const.}$$

This difference is determined by the pinning force.

During this process, the rotational energy stored in the superfluid component is dissipated as frictional heat:

➡ Vortex creep heating

M. A. Alpar, et.al., Astrophys. J. **276**, 325 (1984);
M. Shibazaki and F. K. Lamb, Astrophys. J. **346**, 808 (1989).

Vortex creep heating

M. A. Alpar, et.al., Astrophys. J. **276**, 325 (1984);
M. Shibazaki and F. K. Lamb, Astrophys. J. **346**, 808 (1989).

Heating luminosity is given by

$$L_{\rm H} = \int dI_{\rm crust} (\Omega_{\rm SF} - \Omega_{\rm crust}) |\dot{\Omega}| \equiv J |\dot{\Omega}|$$

Moment of inertia

Determined by the pinning force.

All NSs have similar values of J.

In old NSs, this heating balances with the photon cooling:

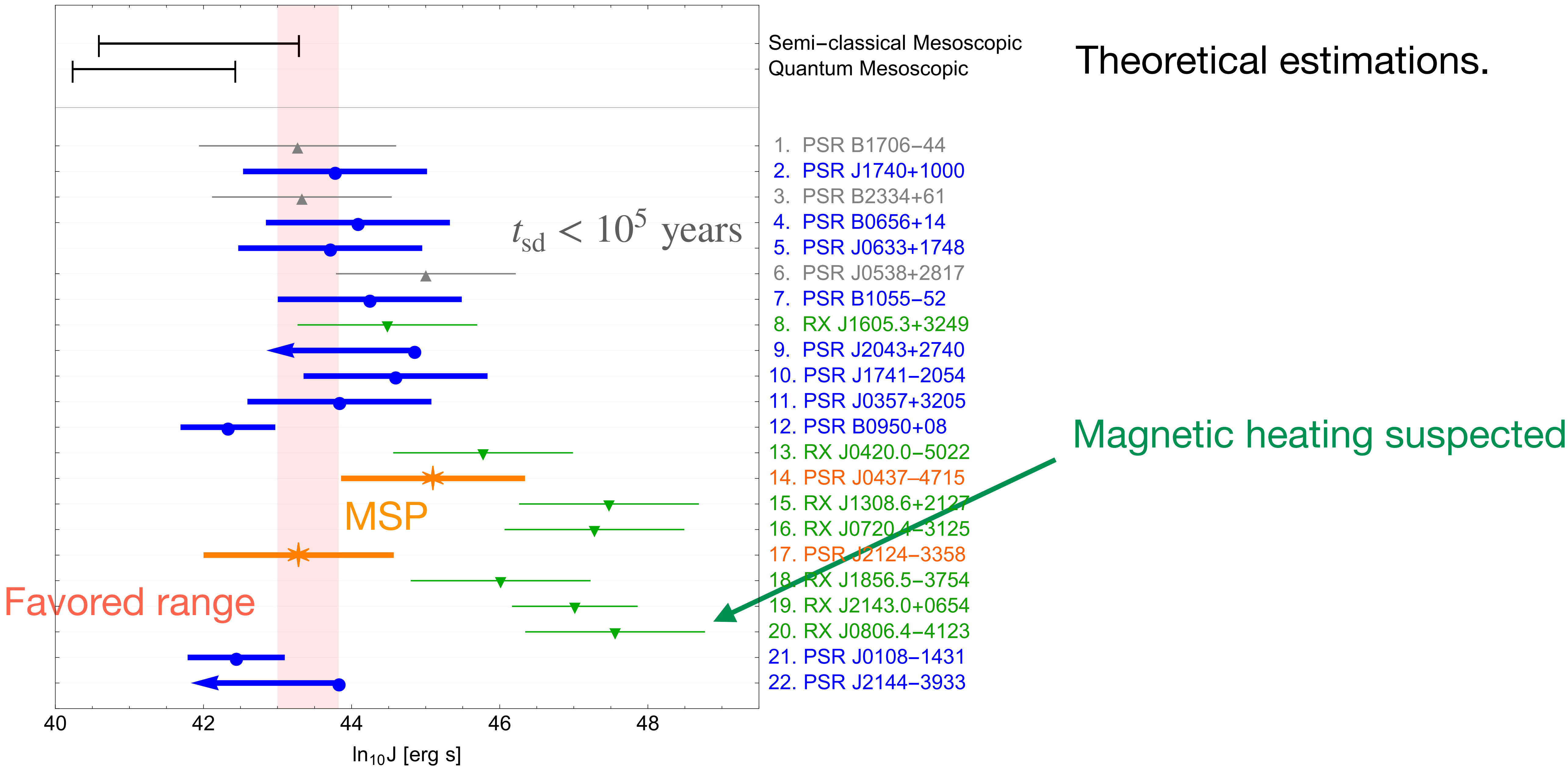
$$L_{\rm H} = L_\gamma = 4\pi R^2 \sigma_{\rm SB} T_s^4$$

$$J_{\rm obs} = 4\pi R^2 \sigma_{\rm SB} T_s^4 / |\dot{\Omega}|$$

Can be determined by observation.

The vortex heating mechanism predicts $J_{\rm obs}$ to be almost universal.

Vortex creep heating vs observations

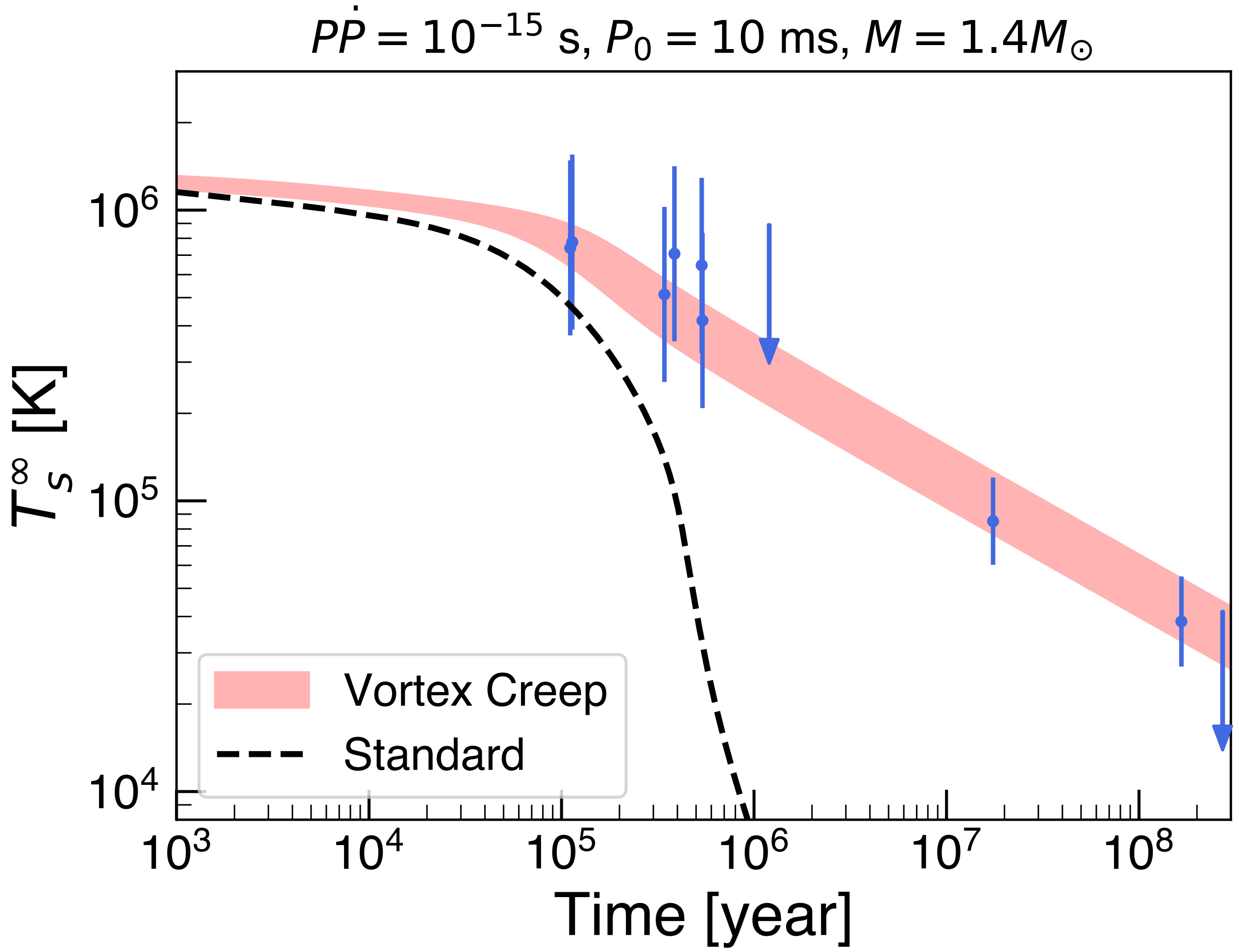


- Observations find similar values of J.
- Theoretical calculations are in the same ballpark.

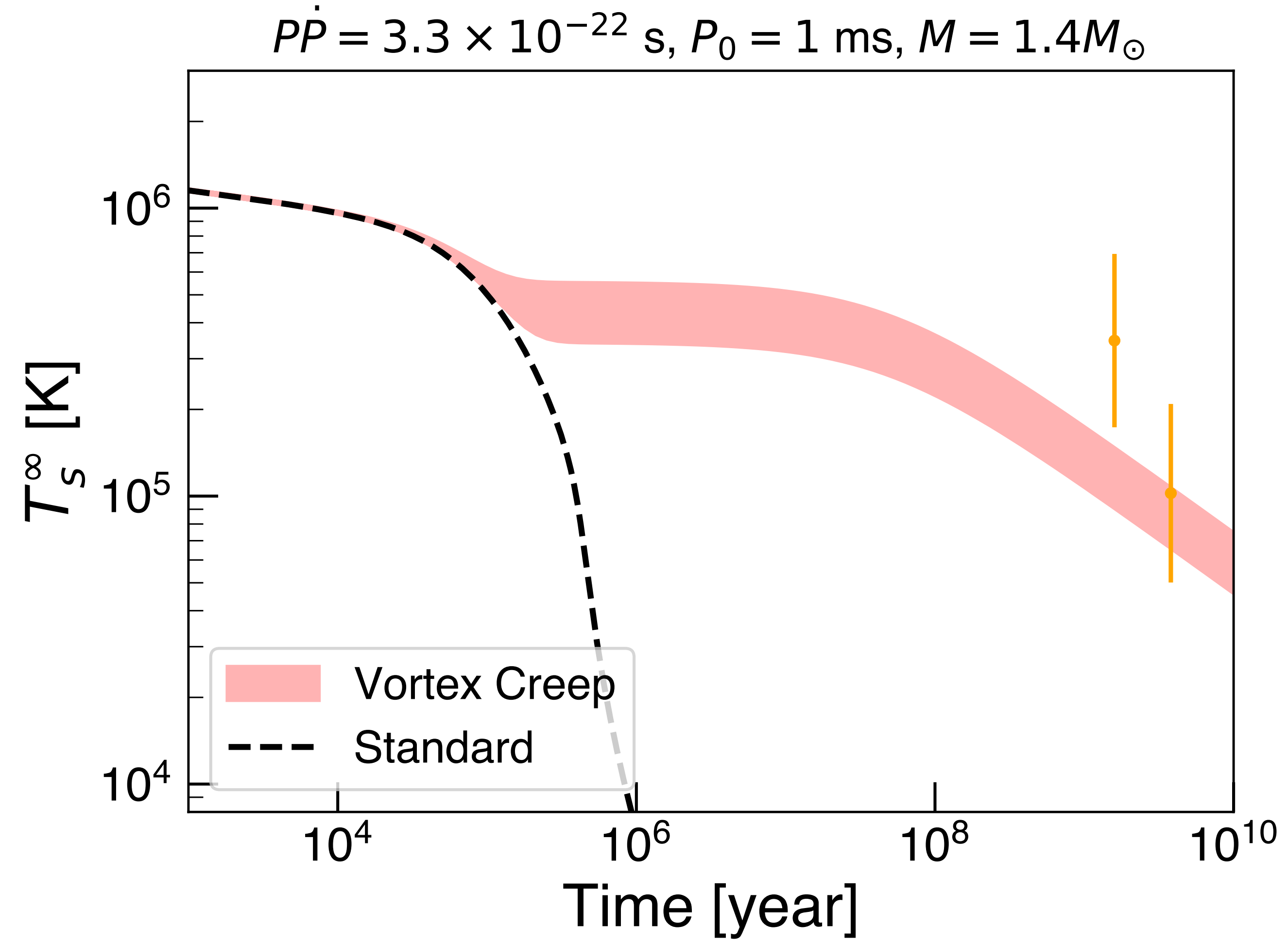
M. Fujiwara, K. Hamaguchi, N. Nagata, M. E. Ramirez-Quezada, JCAP **03**, 051 (2024).

Vortex creep heating vs observations

Ordinary pulsars



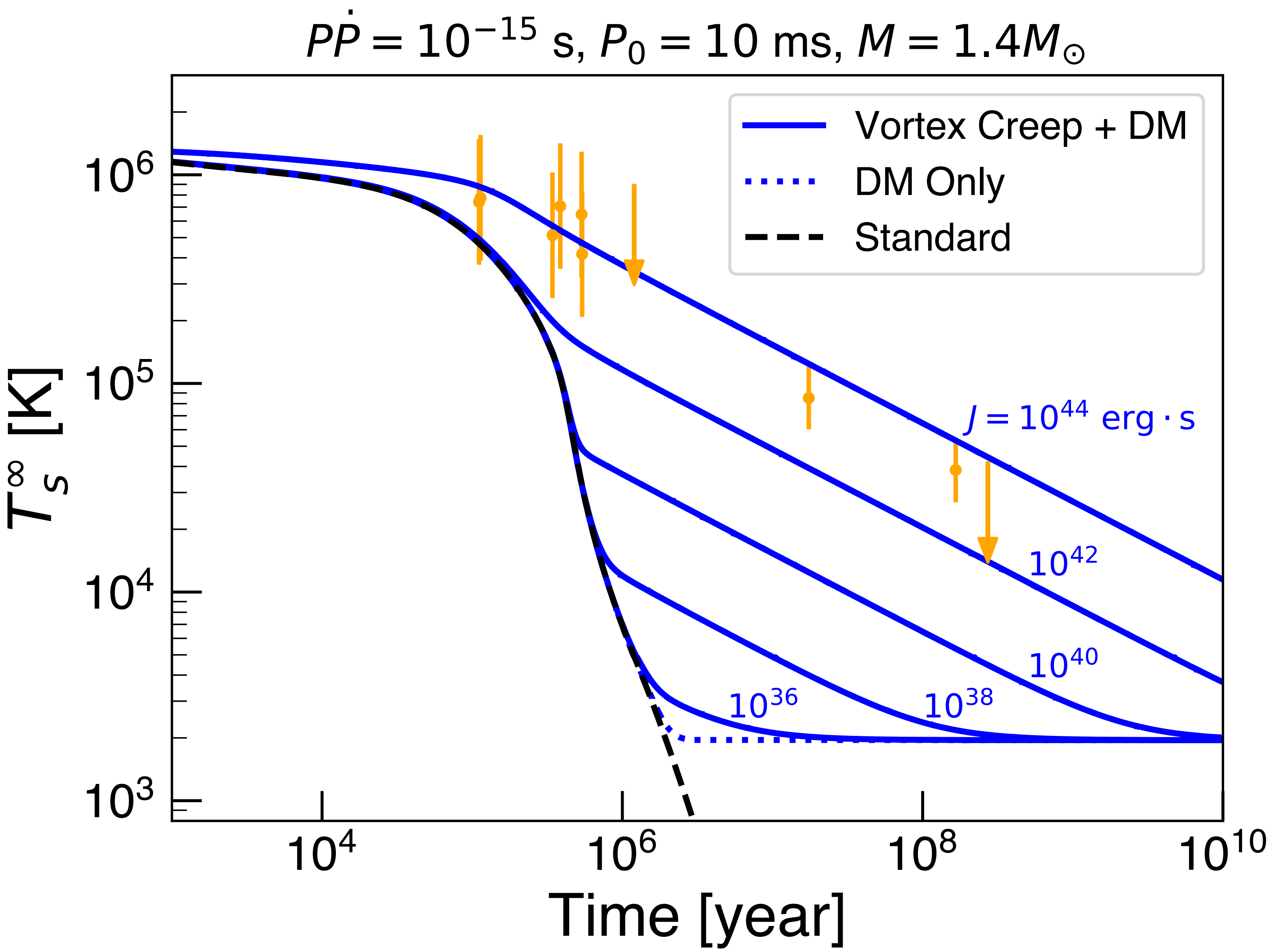
Millisecond pulsars



- Temperature evolution deviates at $t \gtrsim 10^5$ years.
- Even for very old NSs, $T_s \gtrsim 10^4$ K.

M. Fujiwara, K. Hamaguchi, N. Nagata, M. E. Ramirez-Quezada, JCAP **03**, 051 (2024).

Vortex creep heating vs DM heating



The DM heating is buried under the vortex creep heating unless

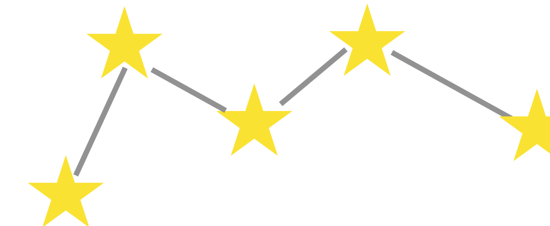
$$J \lesssim 10^{38} \text{ erg} \cdot \text{s}$$

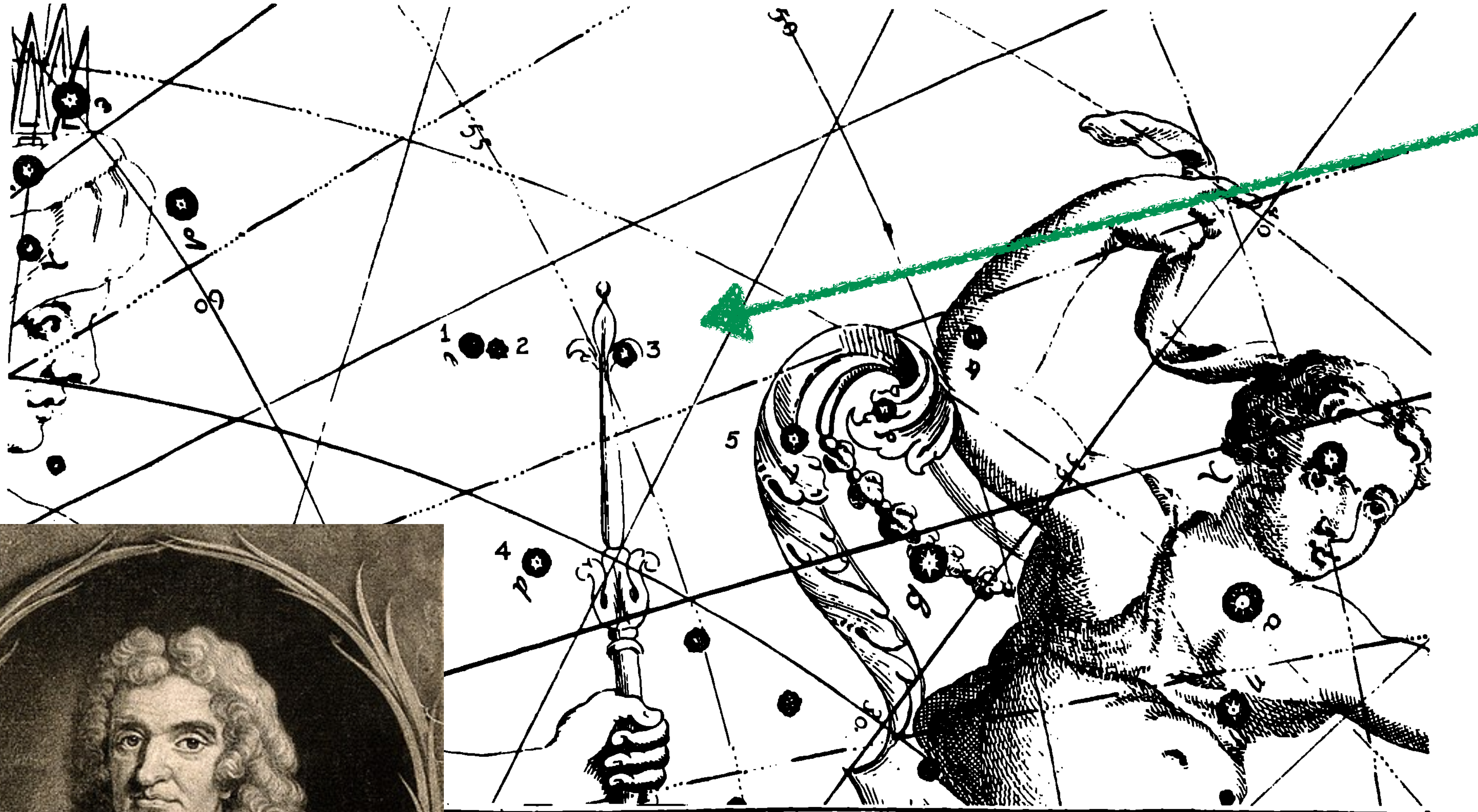
Much smaller than the values favored by obs. and theor.

M. Fujiwara, K. Hamaguchi, N. Nagata, M. E. Ramirez-Quezada, Phys. Lett. **B848**, 138341 (2024).

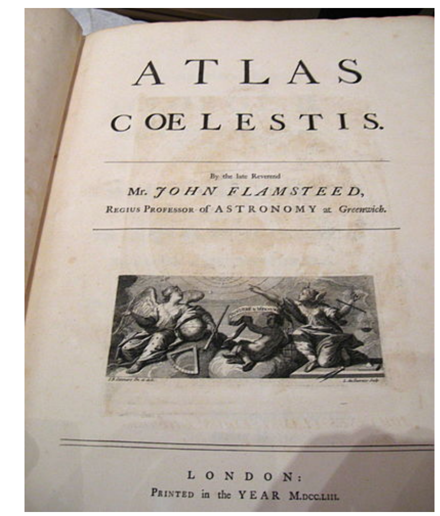
Cas A NS axion limit

3 Cassiopeiae

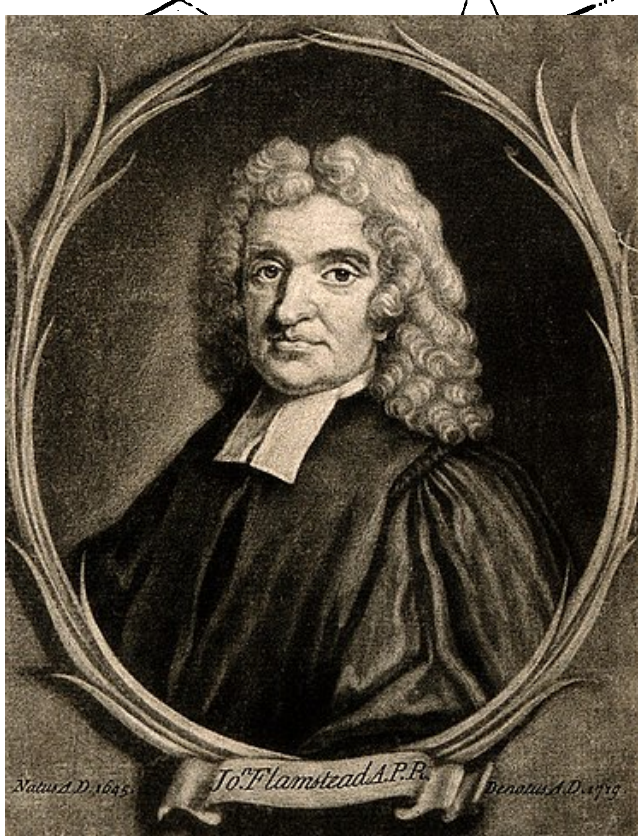




3 Cassiopeiae



Atlas Coelestis (1729)



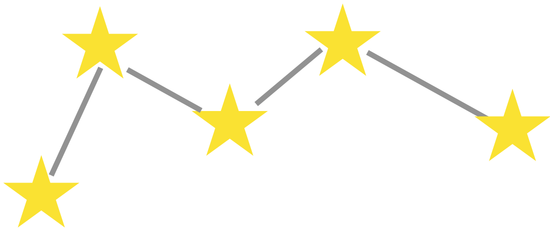
John Flamsteed

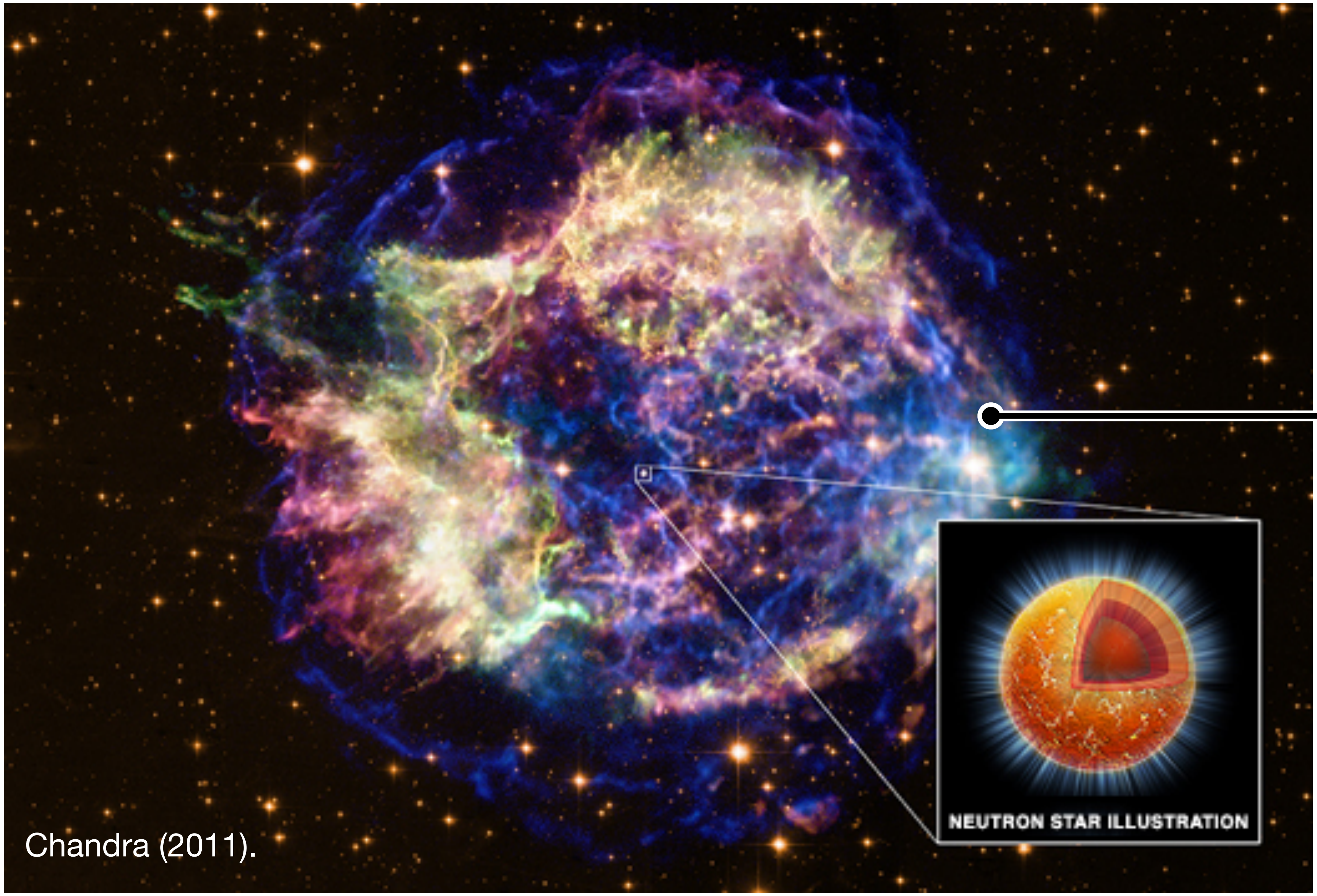
First Astronomer Royal

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

Neutron star (NS) was found in the center.

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

Cas A NS cooling

Chandra

The Astrophysical Journal Letters, 719:L167–L171, 2010 August 20 doi:10.1088/2041-8205/719/2/L167

DIRECT OBSERVATION OF THE COOLING OF THE CASSIOPEIA A NEUTRON STAR

Craig O. Heinke[1] and Wynn C. G. Ho[2]
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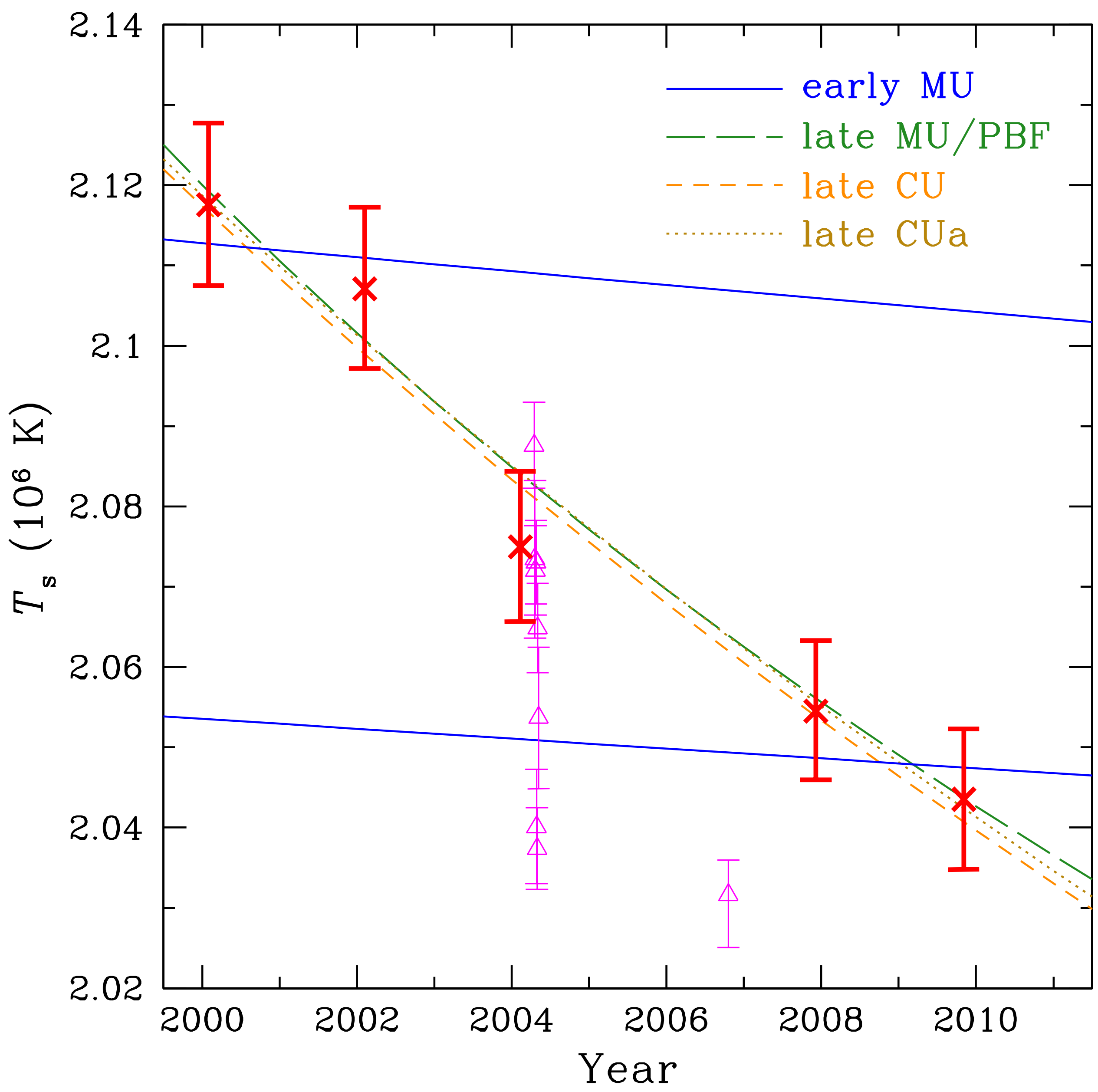
[2] School of Mathematics, University of Southampton, Southampton SO17 1BJ, UK; wynnho@slac.stanford.edu
Received 2010 April 14; accepted 2010 July 8; published 2010 August 2

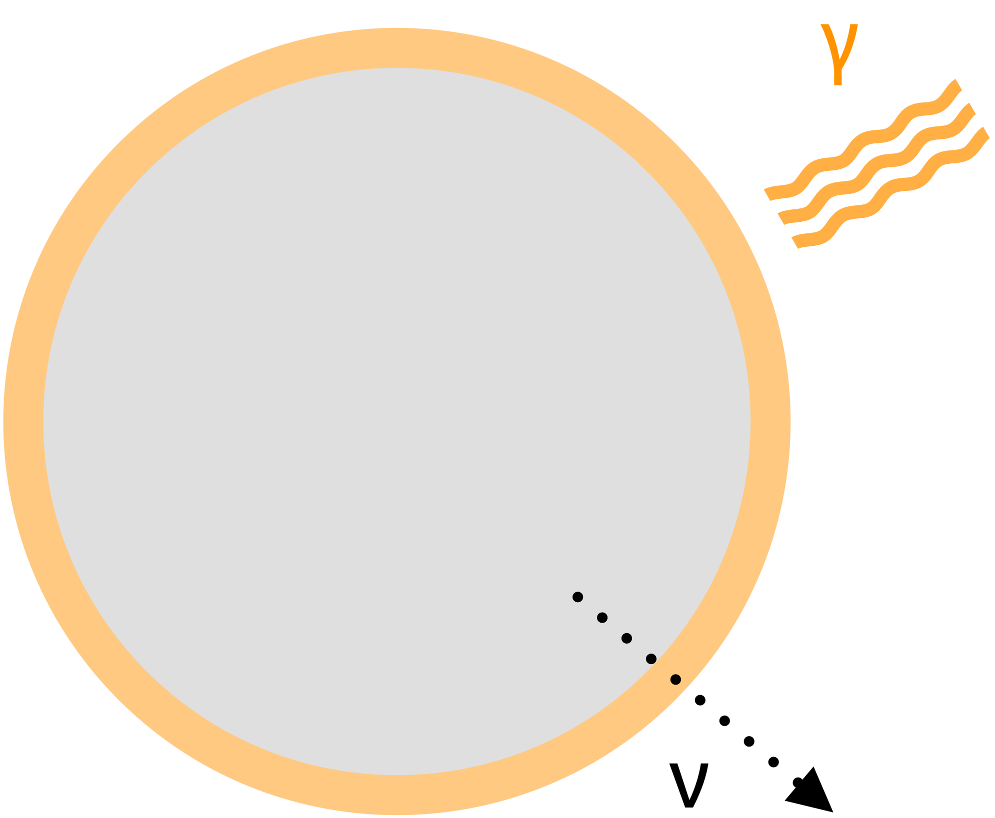


Cooling of Cas A NS is observed directly.

3—4% decrease in ten years.

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)

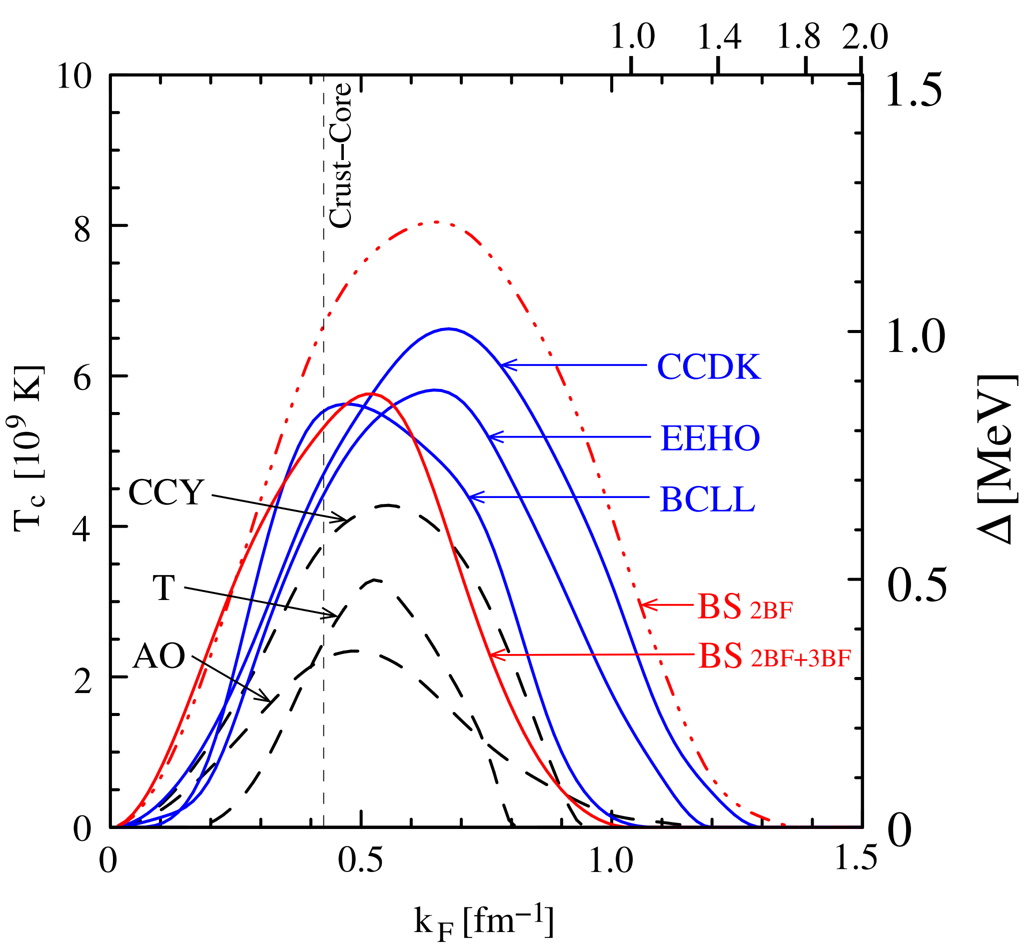
Dominant for $t \lesssim 10^5$ years

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

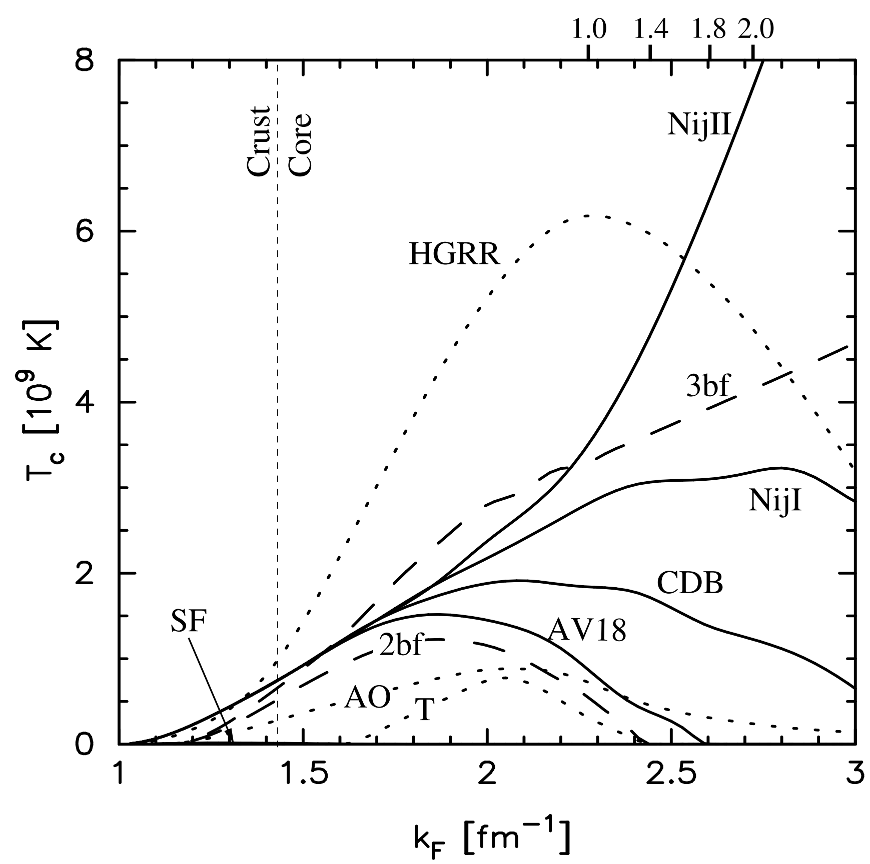
Pair-breaking and formation (PBF)

- Neutrinos are emitted when Cooper pairs are formed.
- This process enhances the neutrino emission when $T \simeq T_C$.

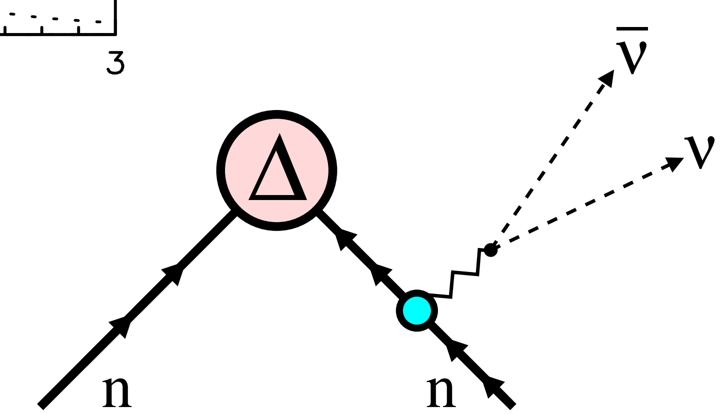
Proton singlet pairing gap



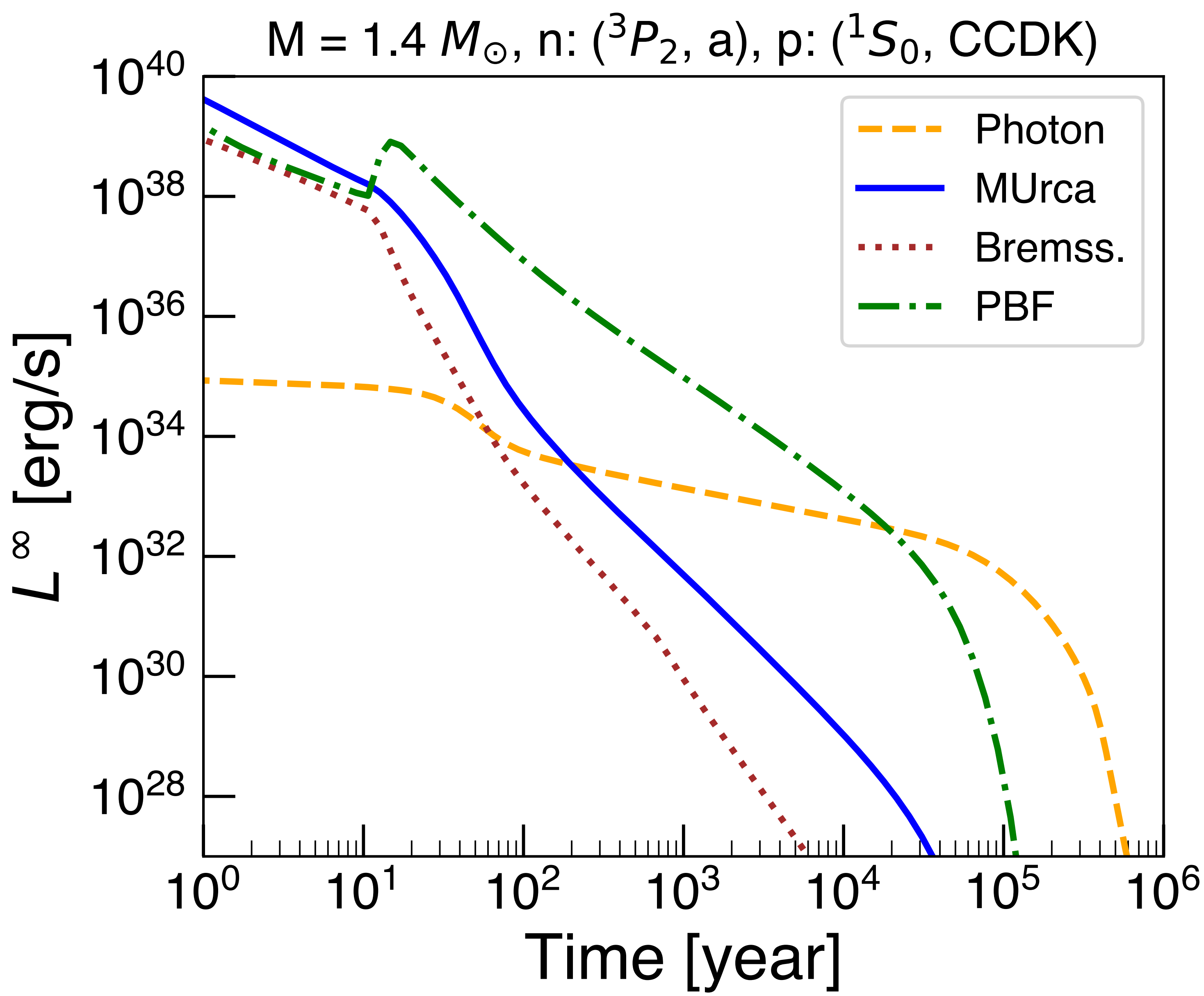
Neutron triplet pairing gap



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

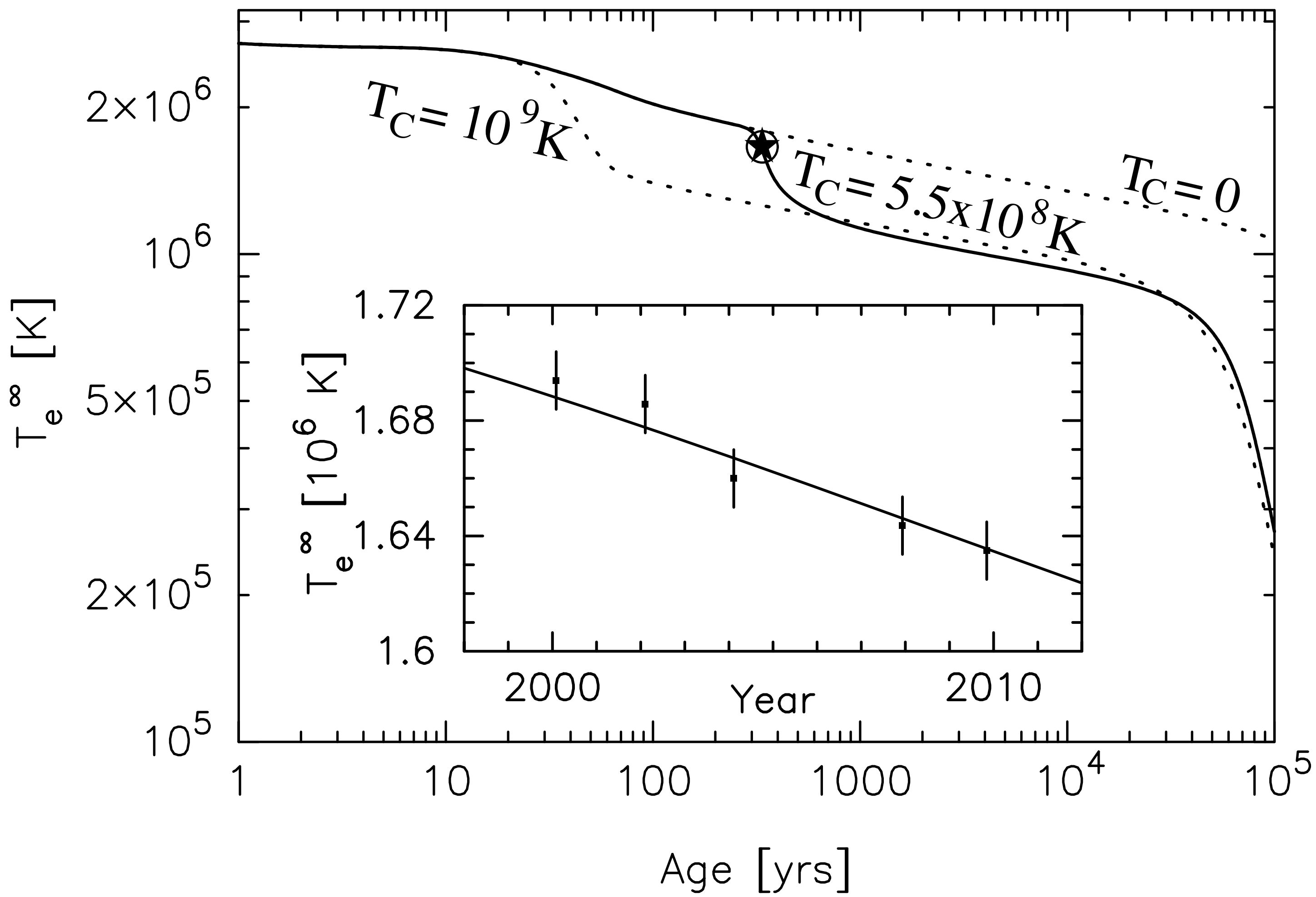


Luminosity



- PBF emission suddenly increases when neutrons in the core form triplet Cooper pairs.
- Neutrino emissions are suppressed at low temperatures. $\propto e^{-\frac{\Delta_N}{T}}$

Explanation of Cas A NS cooling



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

If the critical temperature of neutrino triplet pairing is

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

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.

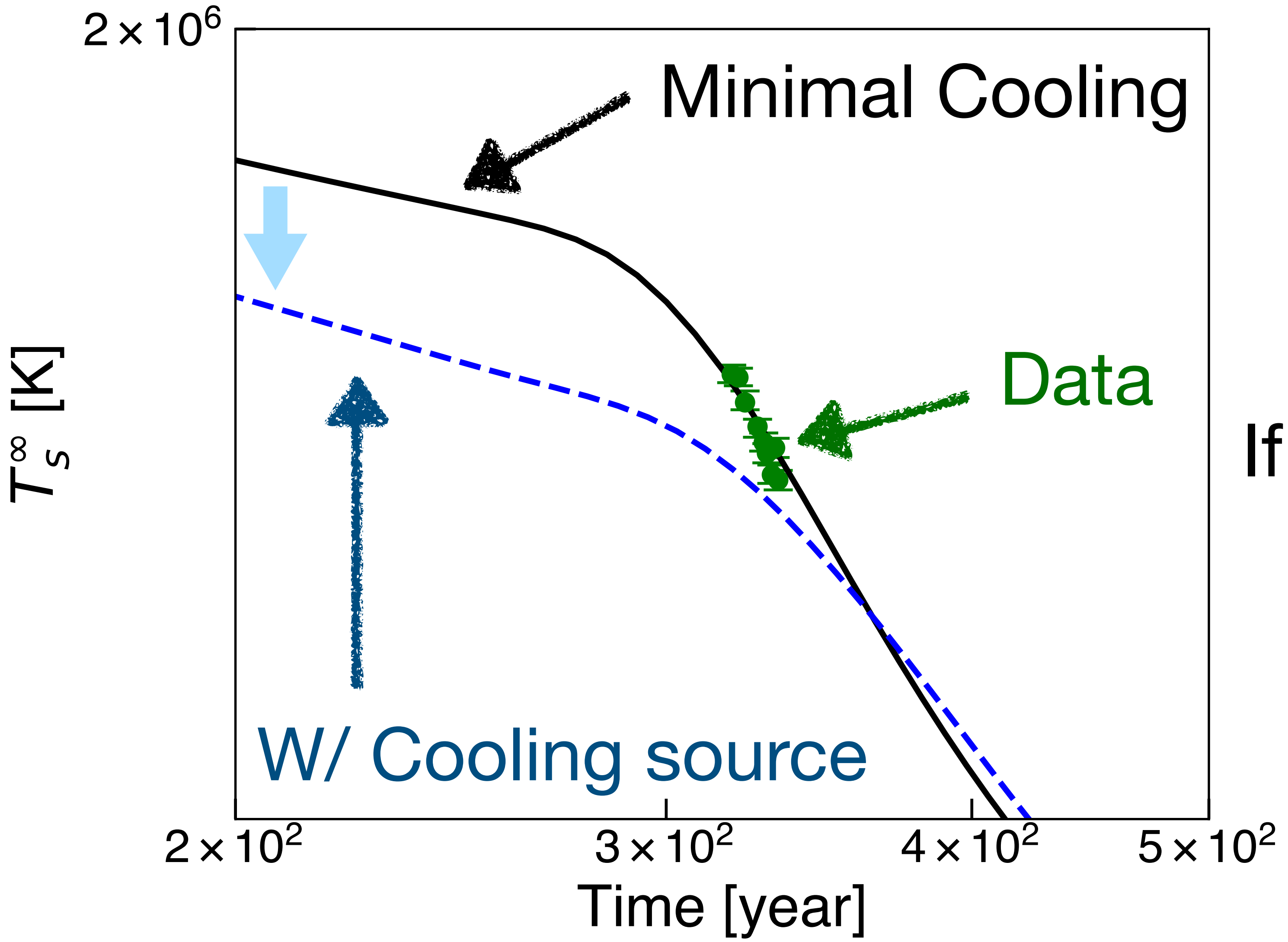
Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY LETTERS
Mon. Not. R. Astron. Soc. **412,** L108–L112 (2011) doi:10.1111/j.1745-3933.2011.01015.x

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.

Extra cooling source



If there is a cooling source,

- Temperature
- Cooling rate

decrease.

Cas A NS cooling data cannot be explained.

→ Limit on the cooling source.

We consider axion as a cooling source.

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 model: no direct coupling to quarks

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

C_n is very small

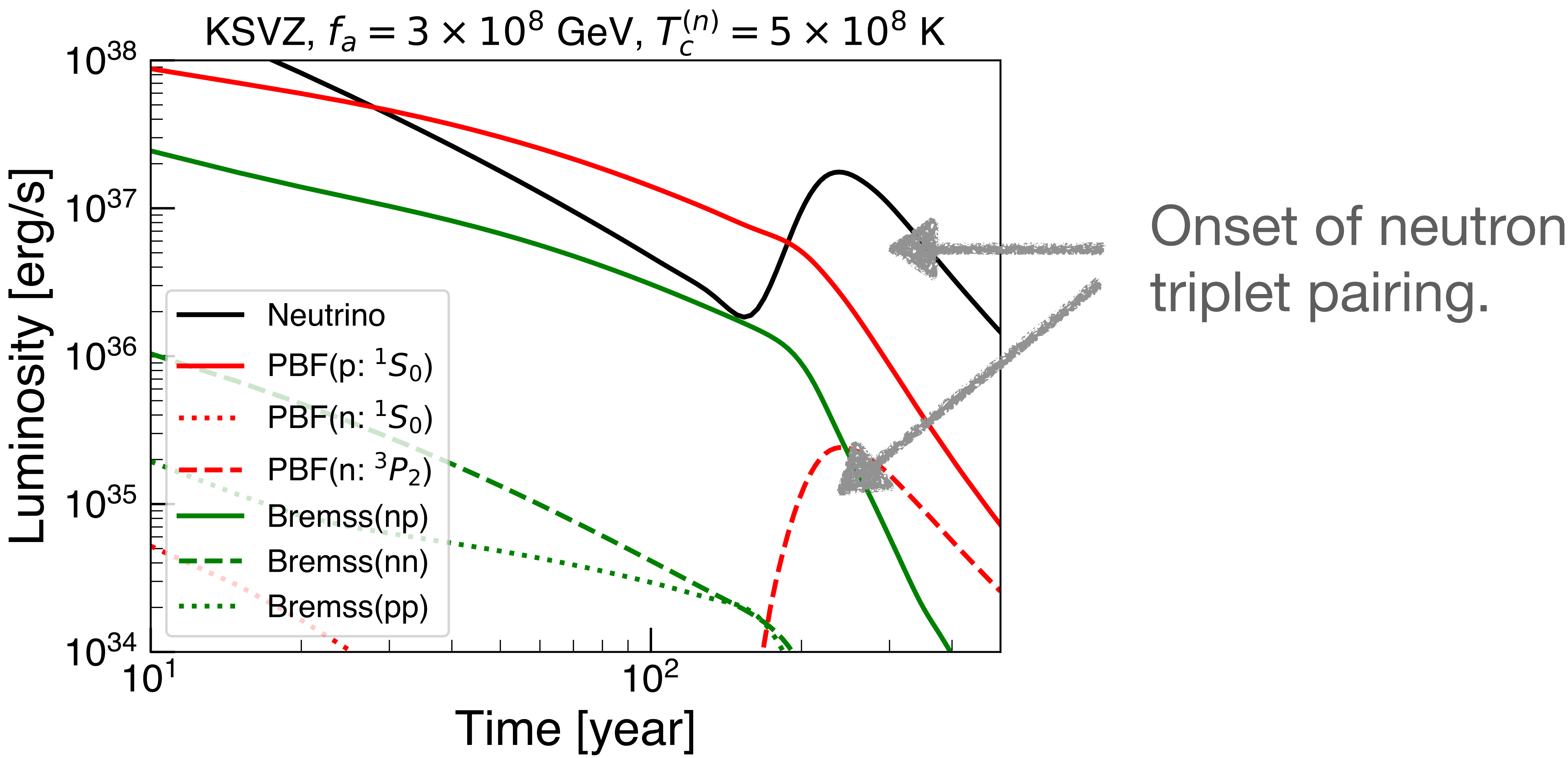
- DFSZ model: axion couples to quarks directly

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

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

Both can be sizable.

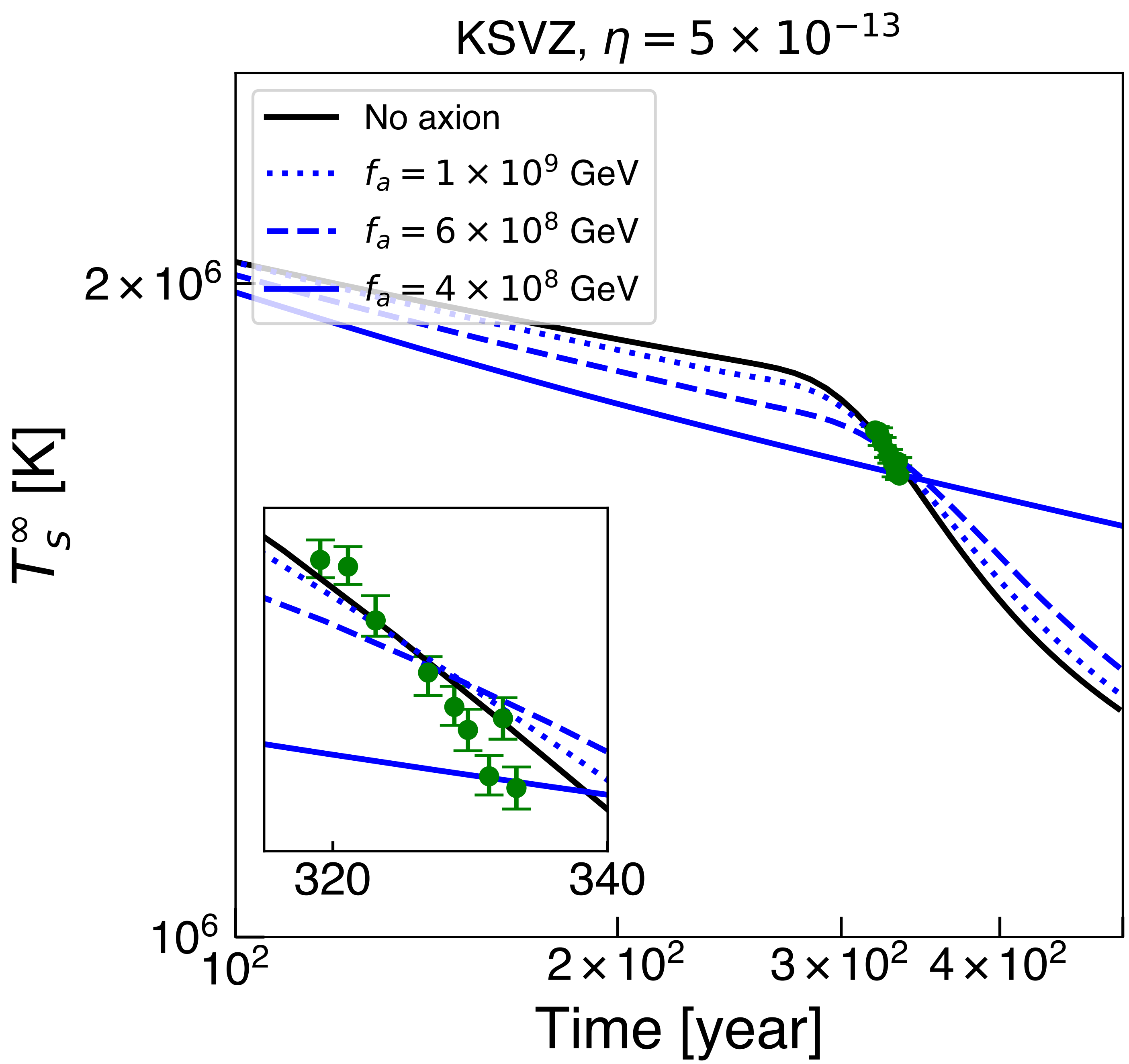
Luminosity of axion emission (KSVZ)



- 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).

Cooling curves vs data



Our limit

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

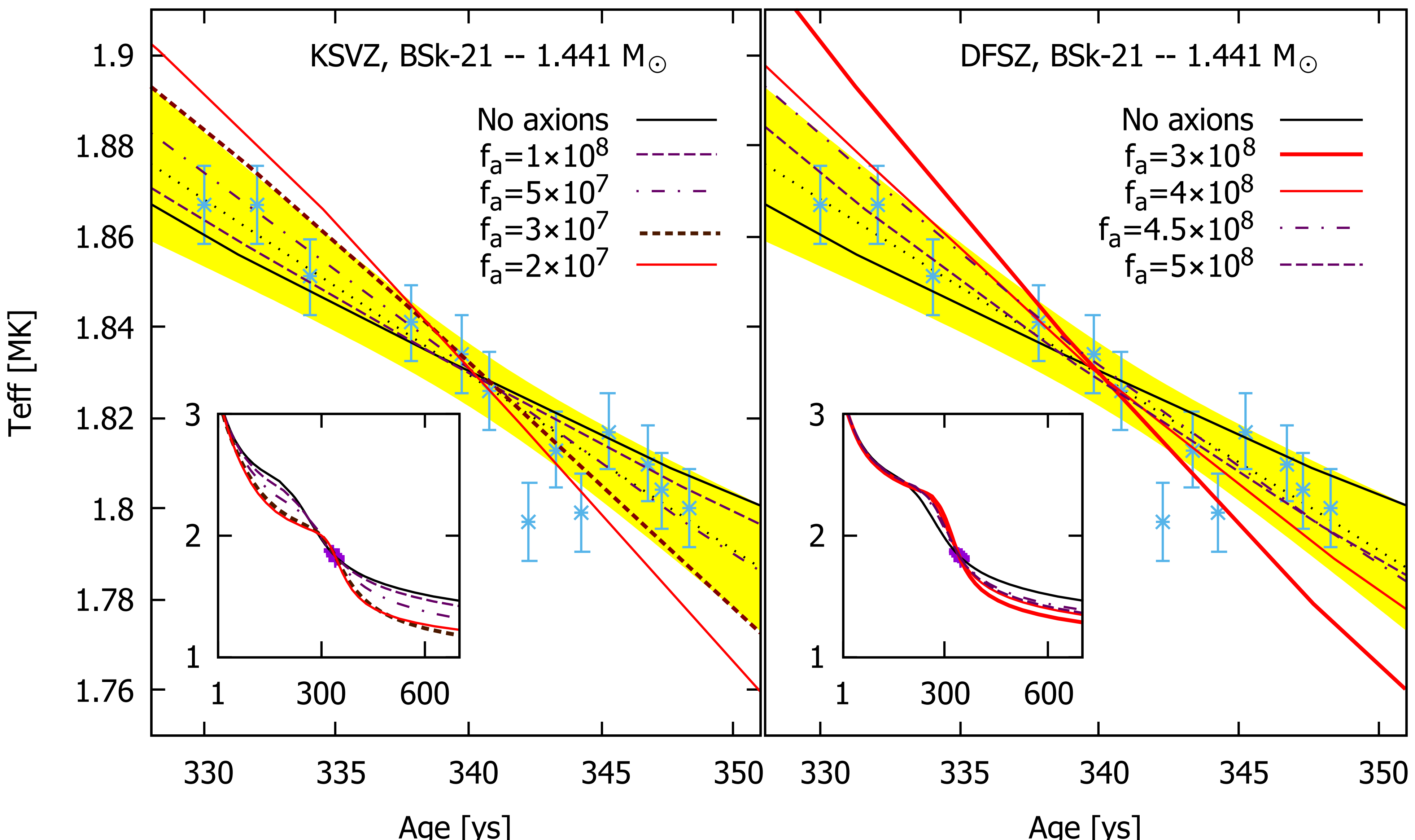
KSVZ (DFSZ, tanβ = 10)

Cf.) SN1987A

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

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

Later work

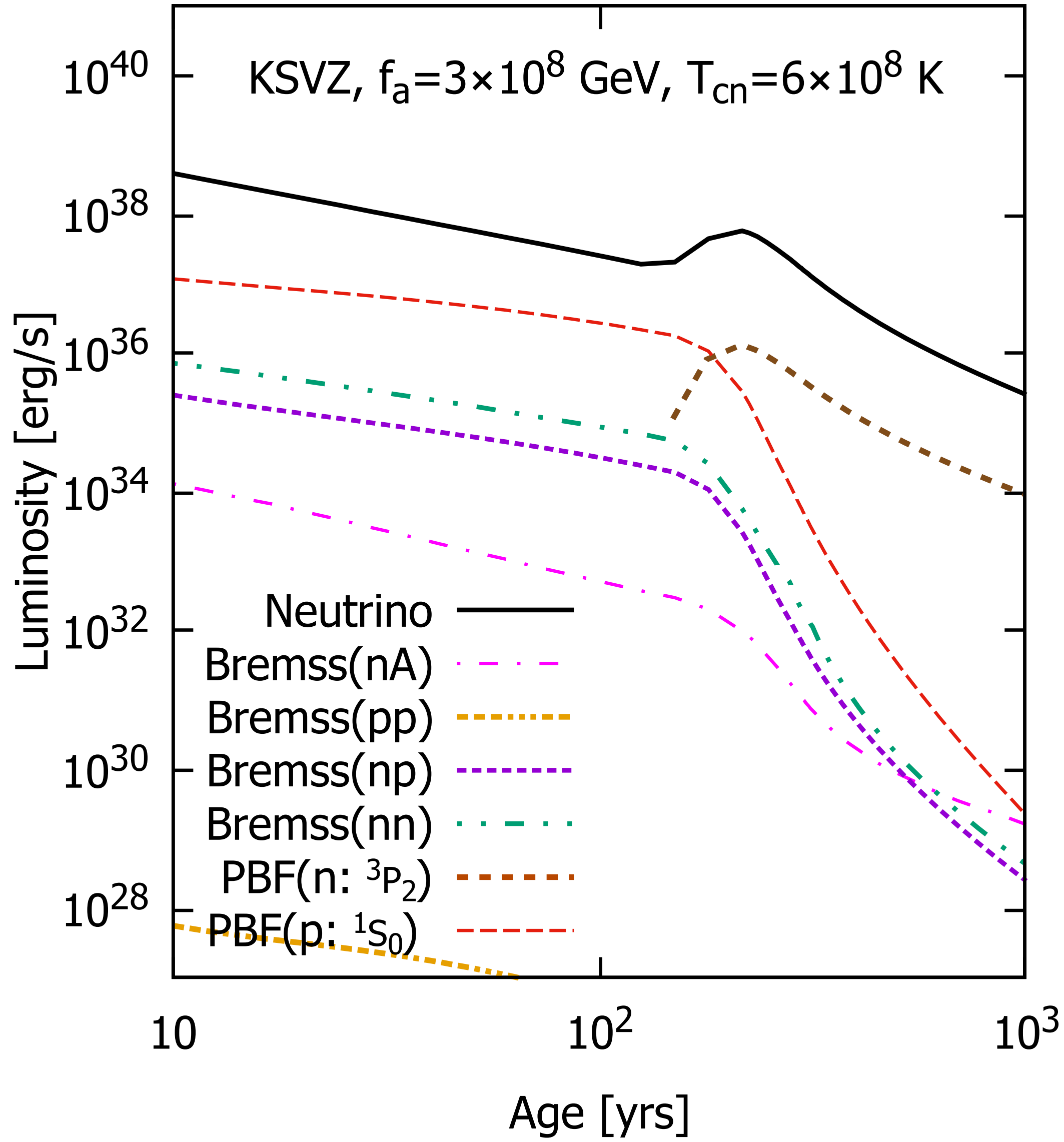


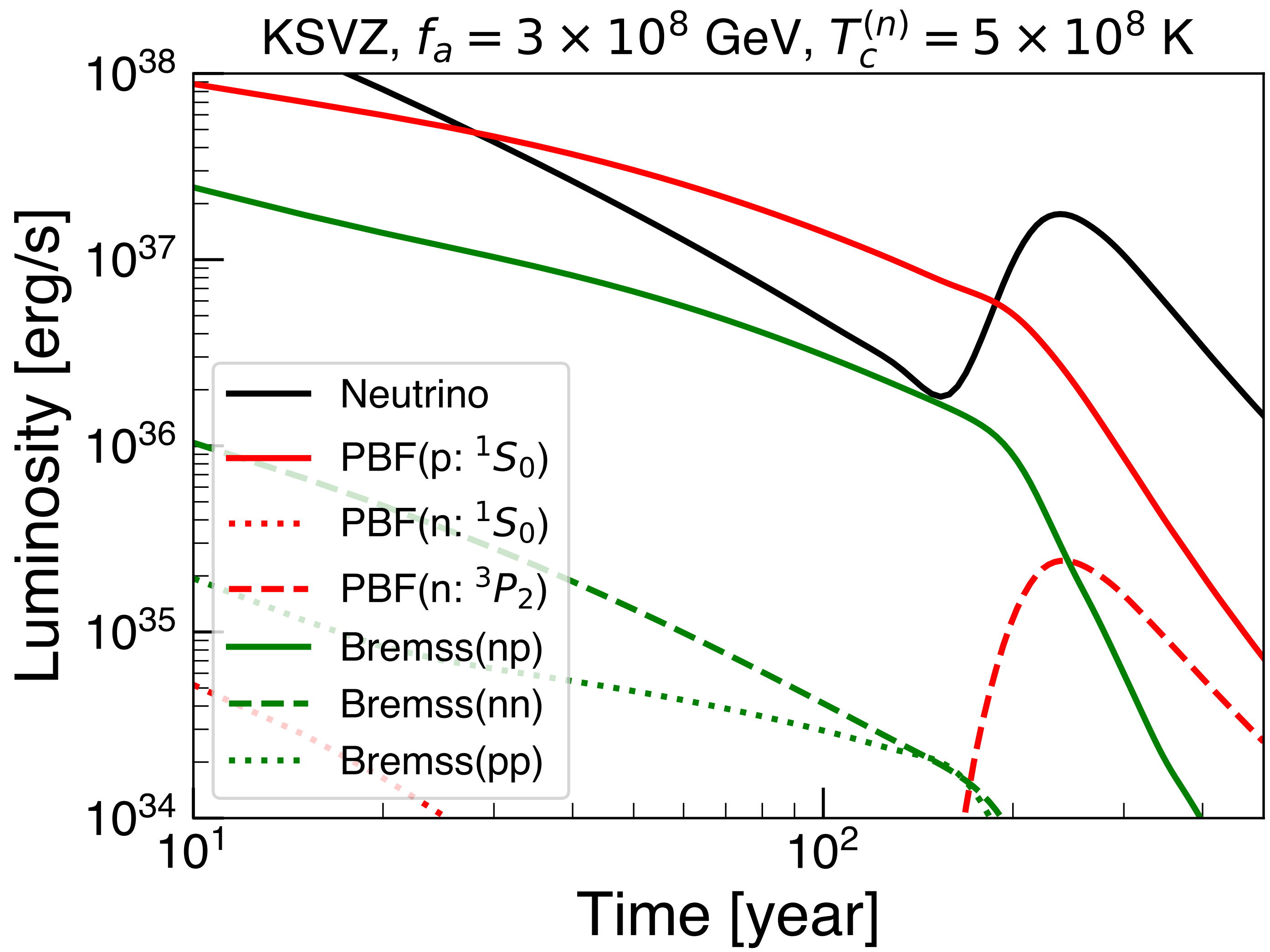
L. B. Leinson, JCAP **09**, 001 (2021).

- $f_a > 3 \times 10^7$ GeV : KSVZ
- $f_a > 4.5 \times 10^8$ GeV : DFSZ

Much weaker limit for KSVZ.

Later work





It seems that the deviation originates from proton PBF.

- Ours: J. Keller, A. Sedrakian, Nucl. Phys. **A897**, 62 (2013); A. Sedrakian, Phys. Rev. **D93**, 065044 (2016).
- Leinson: his own calculation

Axion PBF emission

We revisit the calculation of the axion emissivity from singlet proton Cooper pairs by using the method of Bogolyubov transformations.

Previous calculation

J. Keller, A. Sedrakian, Nucl. Phys. **A897**, 62 (2013); A. Sedrakian, Phys. Rev. **D93**, 065044 (2016).

- Transport equation
- Correlation functions of nucleon axial currents

Our result agrees with the previous calculation.

K. Hamaguchi, N. Nagata, and J. Zheng, arXiv:2502.18931.

Source of discrepancy

Derivation of the axion emissivity was not given in Leinson's paper.

Instead, semi-analytic formula was given.

$$Q_{pa}^{\rm PBF} = 1.55 \times 10^{40} g_{app}^2 \left(\frac{m_p^*}{m_p}\right)^2 \left(\frac{T}{10^9\ \rm K}\right)^5 \left(\frac{p_{F,p}}{m_p c}\right)^3 \frac{6}{7} F_2\left(\frac{T}{T_{cp}}\right) \frac{\rm erg}{\rm cm^3 \cdot s}$$ JCAP

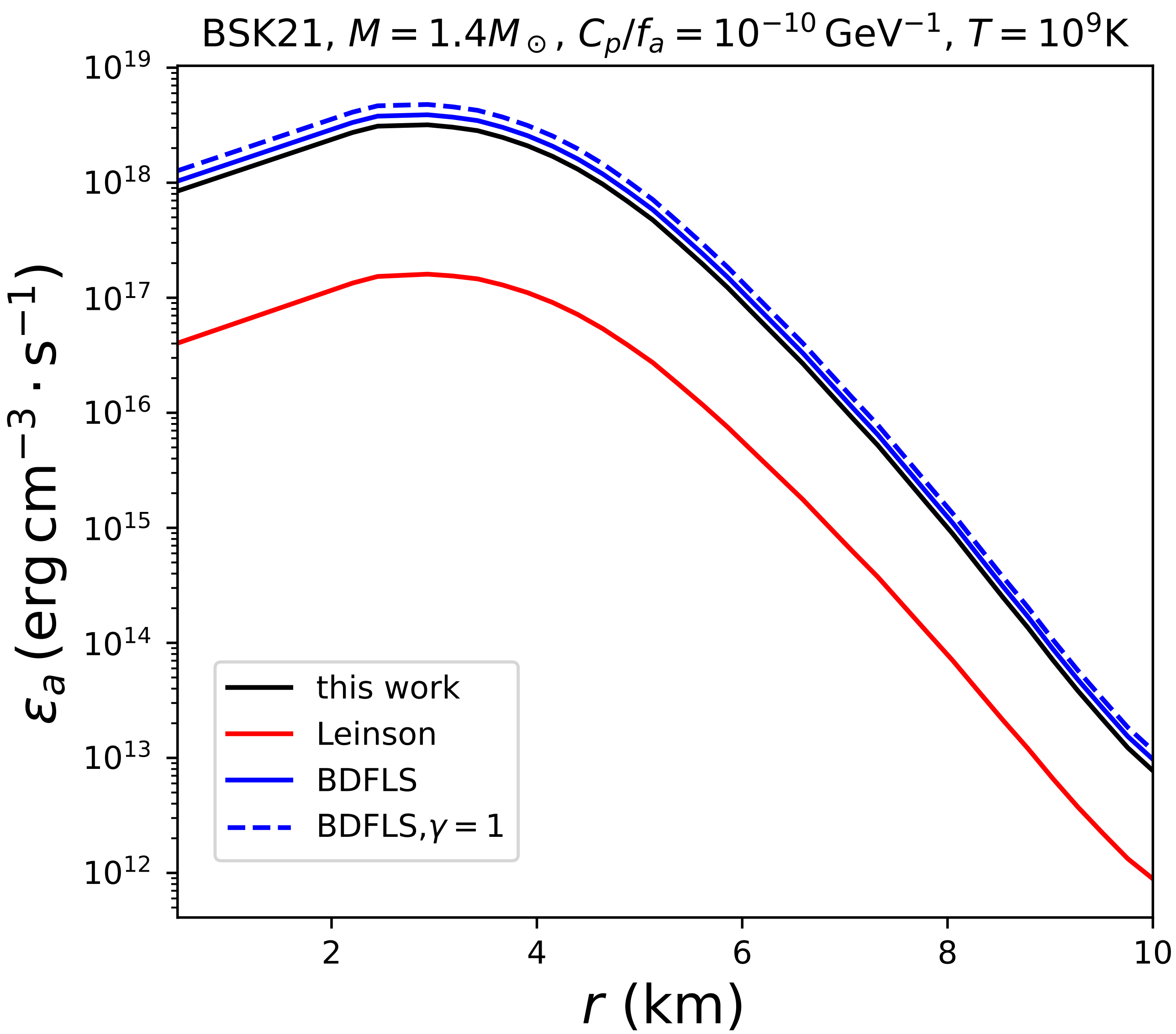
$$Q_{pa}^{\rm PBF} = 1.55 \times 10^{40} g_{app}^2 \frac{p_{F,p}}{m_p^*} \left(\frac{m_p^*}{m_p}\right)^2 \left(\frac{T}{10^9\ \rm K}\right)^5 \left(\frac{p_{F,p}}{m_p c}\right)^2 \left[\left(\frac{m_p^*}{m_p}\right)^2 + \frac{11}{42}\right] F_2\left(\frac{T}{T_{cp}}\right) \frac{\rm erg}{\rm cm^3 \cdot s}$$ arXiv, v1

$$Q_{pa}^{\rm PBF} = 1.55 \times 10^{40} g_{app}^2 \frac{p_{F,p}}{m_p^*} \left(\frac{m_p^*}{m_p}\right)^2 \left(\frac{T}{10^9\ \rm K}\right)^5 \left(\frac{p_{F,p}}{m_p c}\right)^2 \frac{6}{7} F_2\left(\frac{T}{T_{cp}}\right) \frac{\rm erg}{\rm cm^3 \cdot s}$$ arXiv, v2

We find that these expressions show a different dependence on the effective mass compared to ours.

- Leinson: $\propto (m_p^*)^2 p_{F,p}^3$
- Ours: $\propto p_{F,p}^3 / m_p^*$

Axion emissivity



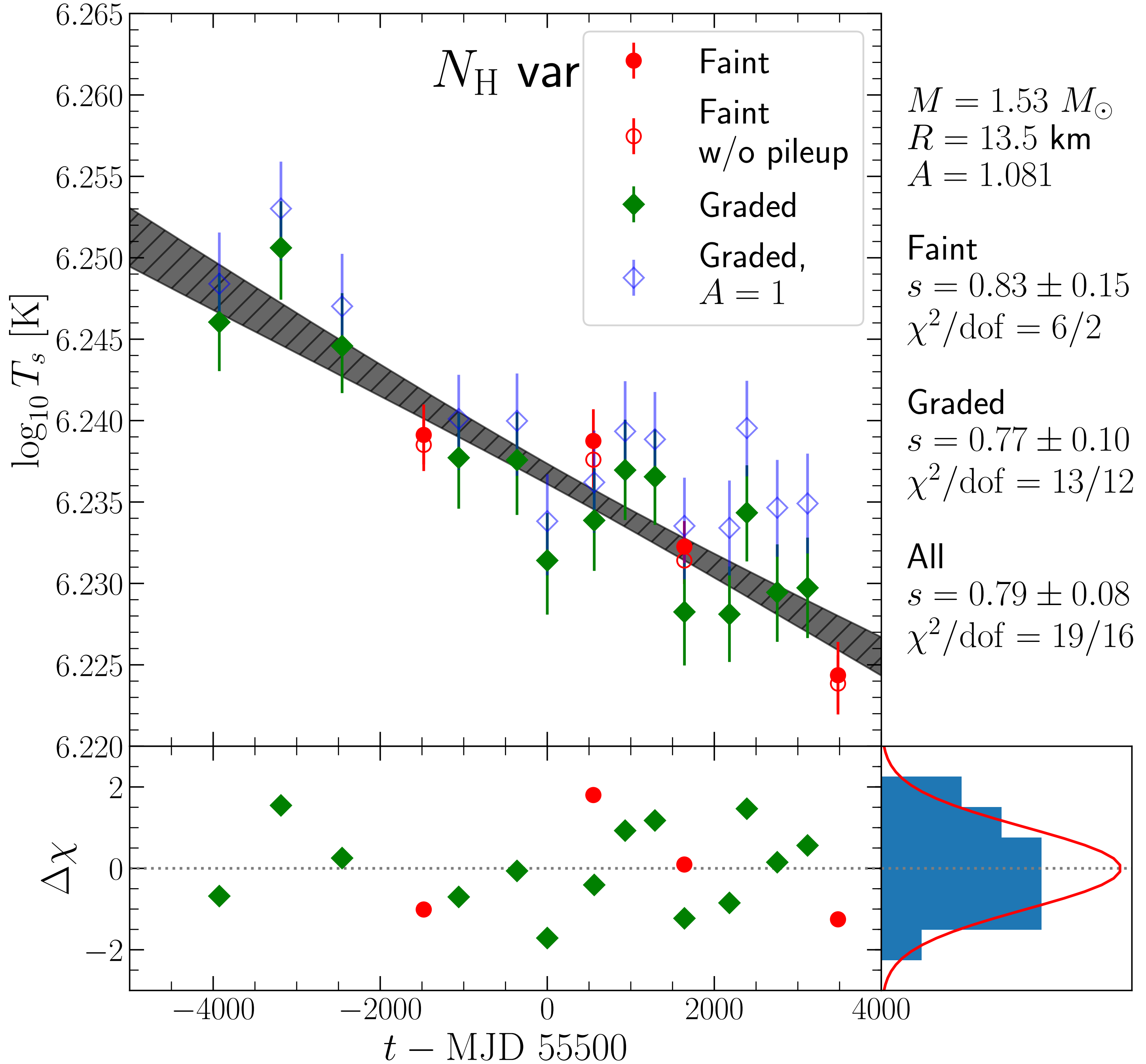
M. Buschmann, et.al.,
Phys. Rev. Lett. **128**, 091102 (2022).

L. B. Leinson, JCAP **09**, 001 (2021).

- Our result agrees well with M. Buschmann, et. al.
- Leinson's result is significantly lower than the others.

K. Hamaguchi, N. Nagata, and J. Zheng, arXiv:2502.18931.

Observation update



P. S. Shternin, MNRAS **518**, 2775 (2022).

Updated Cas A NS limit on axion is coming (hopefully) soon.

Summary

Today's topic

Search for new physics via temperature observations of neutron stars (NSs).

- Heating

  WIMPs, … ➡ Vortex creep heating may conceal the DM heating.

- Cooling

  Axion, … ➡ Limit from Cassiopeia A NS

Our limit

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

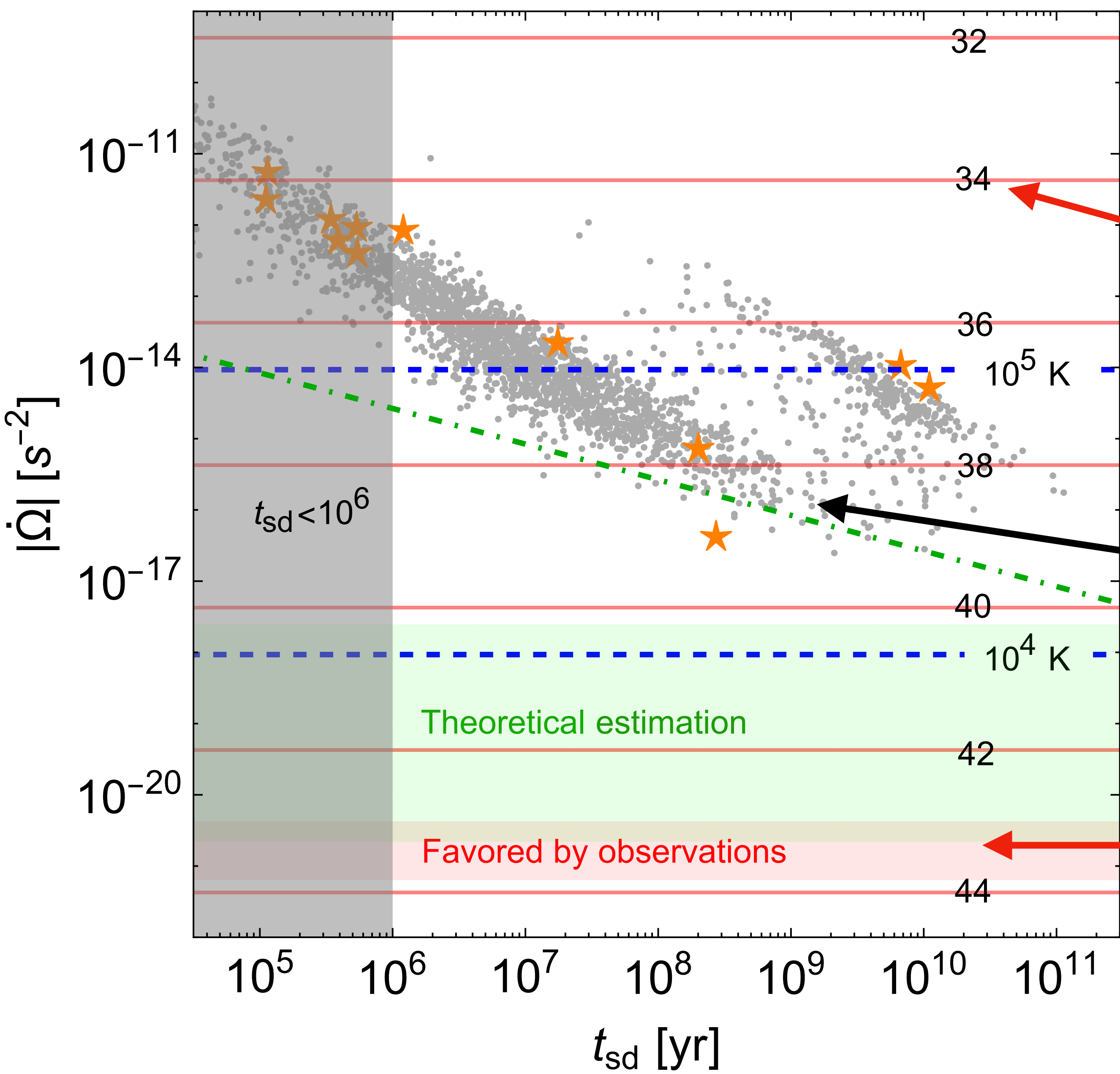
KSVZ (DFSZ, tanβ = 10)

Update results coming soon.

Backup

Vortex creep heating vs DM heating

To see the DM heating effect, we want $L_{\rm vortex} < L_{\rm DM}$.



➡ Upper limit on $J|\dot{\Omega}|$

Limit on J (log J [erg s])

Distribution of known pulsars

For observationally favored value of J, we need this size of $|\dot{\Omega}|$

J must be much smaller than the values favored by obs. and theor.

M. Fujiwara, K. Hamaguchi, N. Nagata, M. E. Ramirez-Quezada, Phys. Lett. **B848**, 138341 (2024).

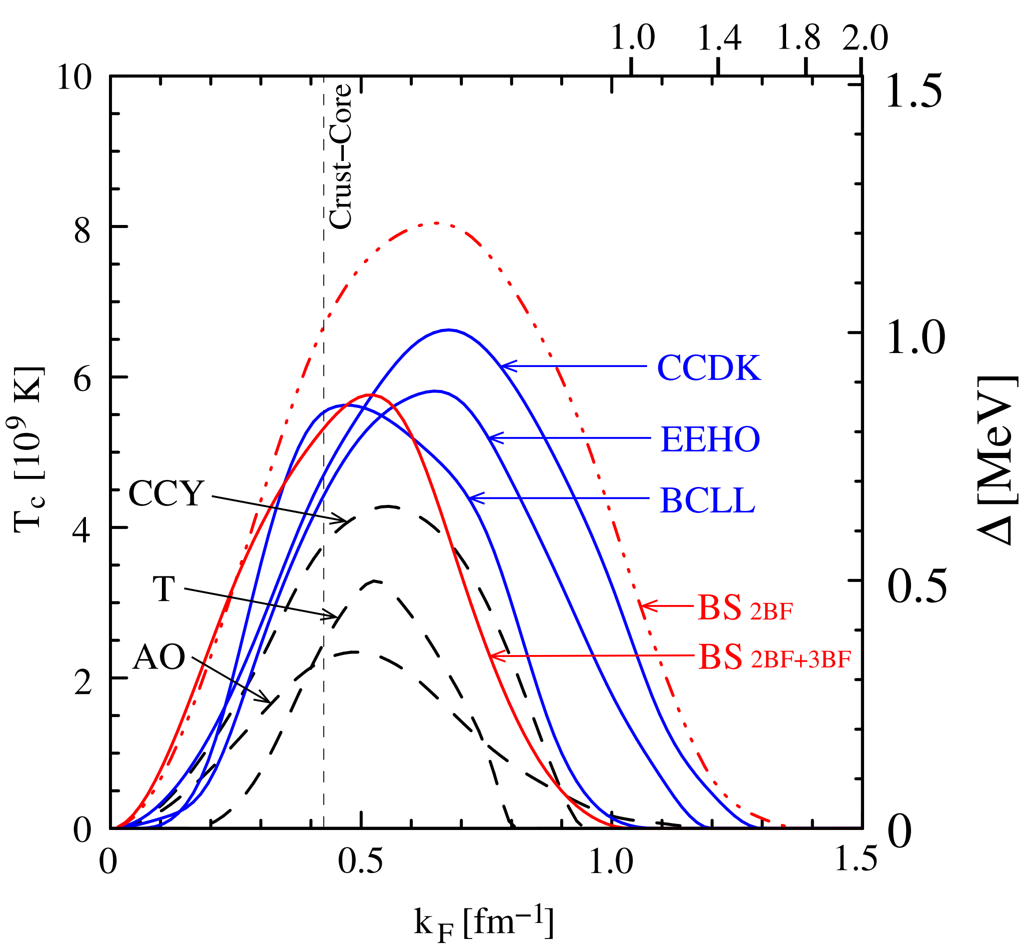
Nucleon Cooper pairs

Nucleons in a NS form pairings below their critical temperatures:

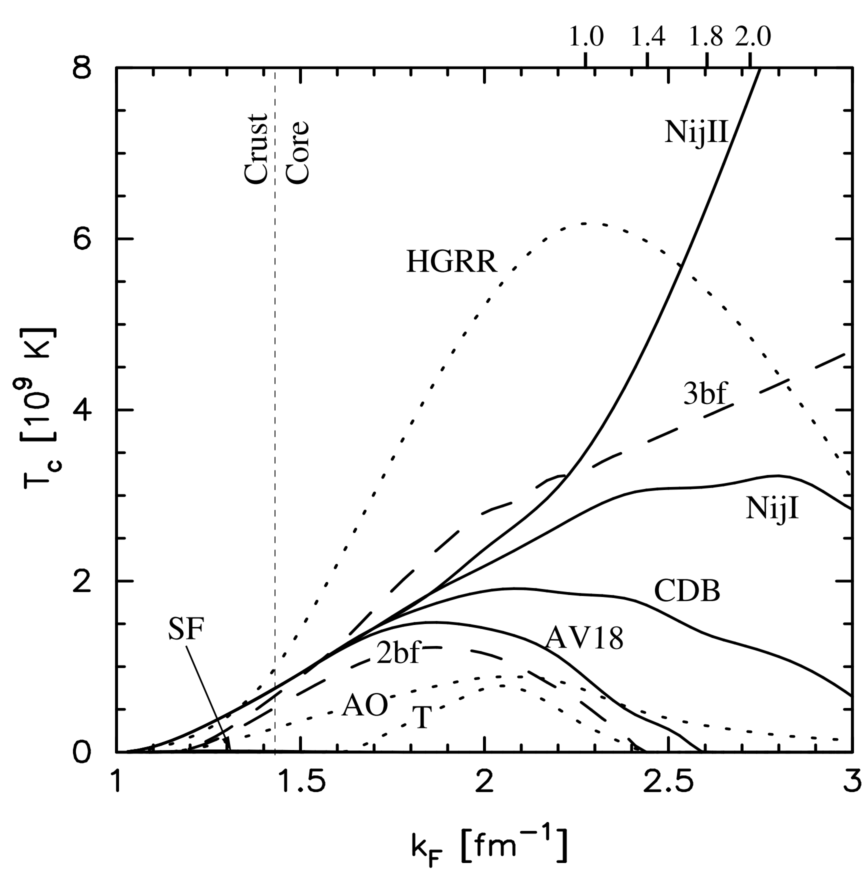
- Neutron singlet $^1S_0$ ← Only in the crust. Less important.
- Proton singlet $^1S_0$
- Neutron triplet $^3P_2$

} ← Form in the core. Important.

Proton singlet pairing gap

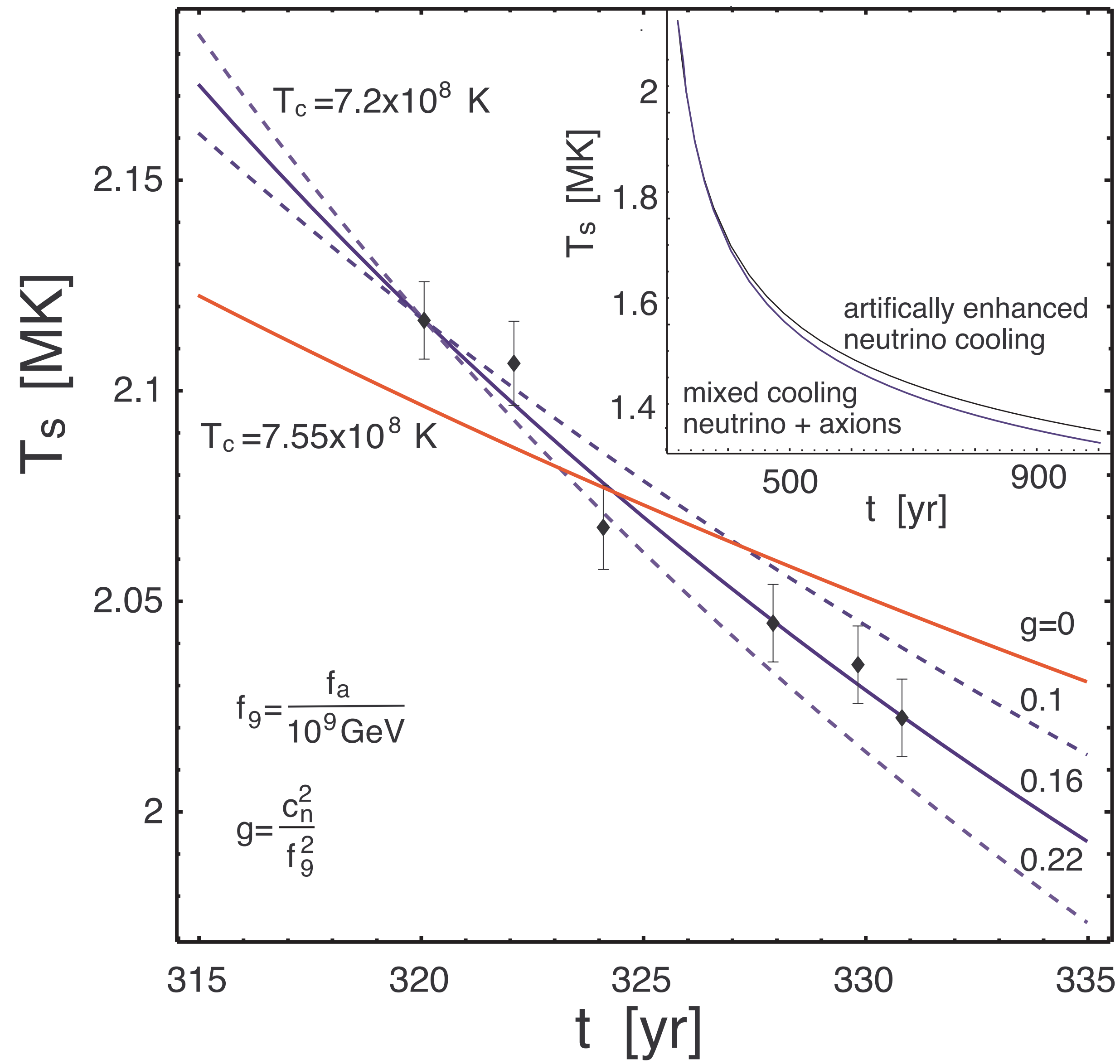


Neutron triplet pairing gap



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

Previous work

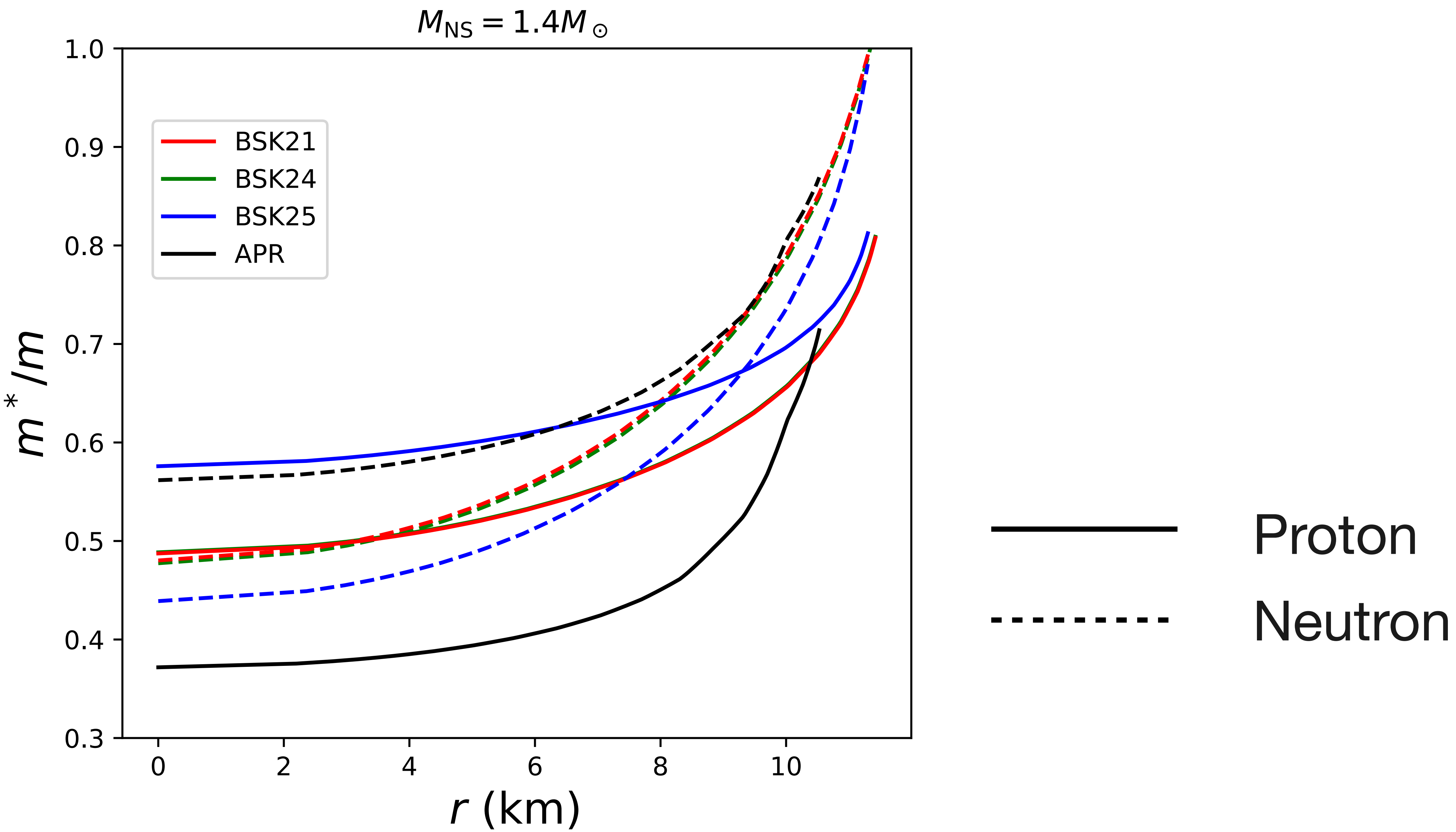


$$\frac{C_n^2}{f_a^2} \simeq 1.6 \times 10^{-19}\ \mathrm{GeV}^{-2}$$

L. Leinson, JCAP **1408**, 031 (2014).

- It was argued that the Cas A NS cooling data favors the presence of an extra cooling source.
- Axion-proton coupling was neglected.

Effective mass



The factor of $(m_p^*)^3$ leads to almost an order-of-magnitude difference in emissivity.

K. Hamaguchi, N. Nagata, and J. Zheng, arXiv:2502.18931.

Observation update

For a long time, the cooling trend was primarily observed in data taken in the GRADED mode of the ACIS detectors.

→ Instrumental effect?

B. Posselt, et.al., Astrophys. J. **779**, 186 (2013).

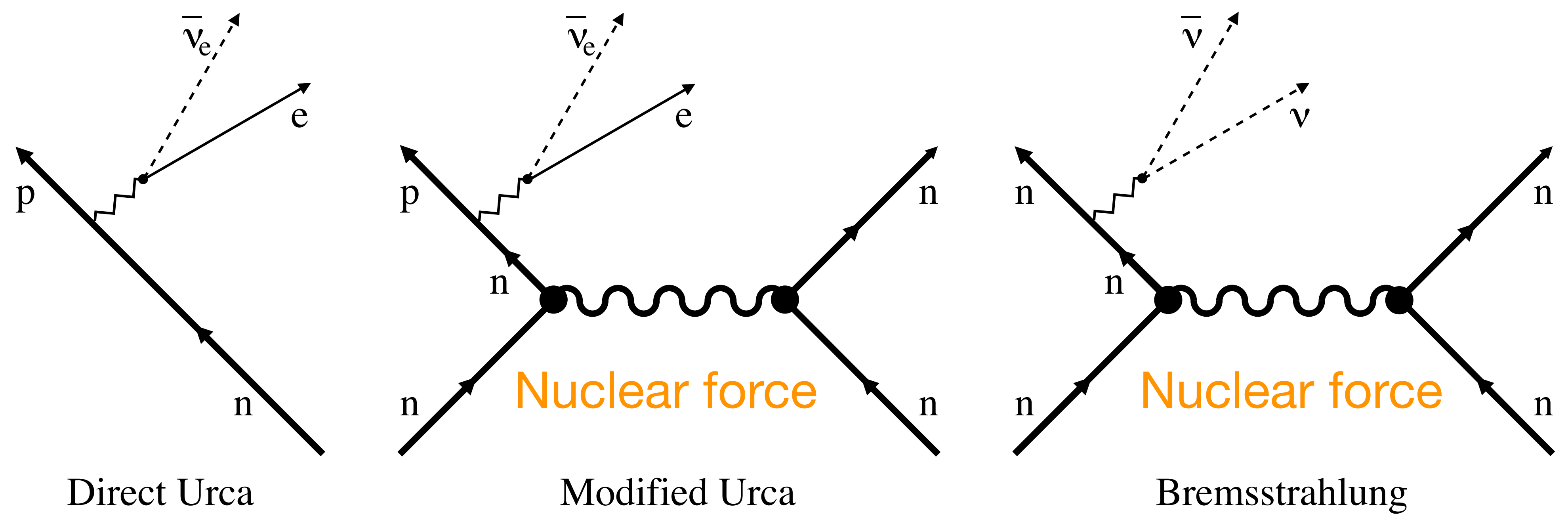
More recently, observations in the FAINT mode have accumulated sufficient temporal coverage to confirm the rapid cooling.

B. Posselt and G. G. Pavlov, Astrophys. J. **932**, 83 (2022).

→ $2.2 \pm 0.3\,\%$ in ten years

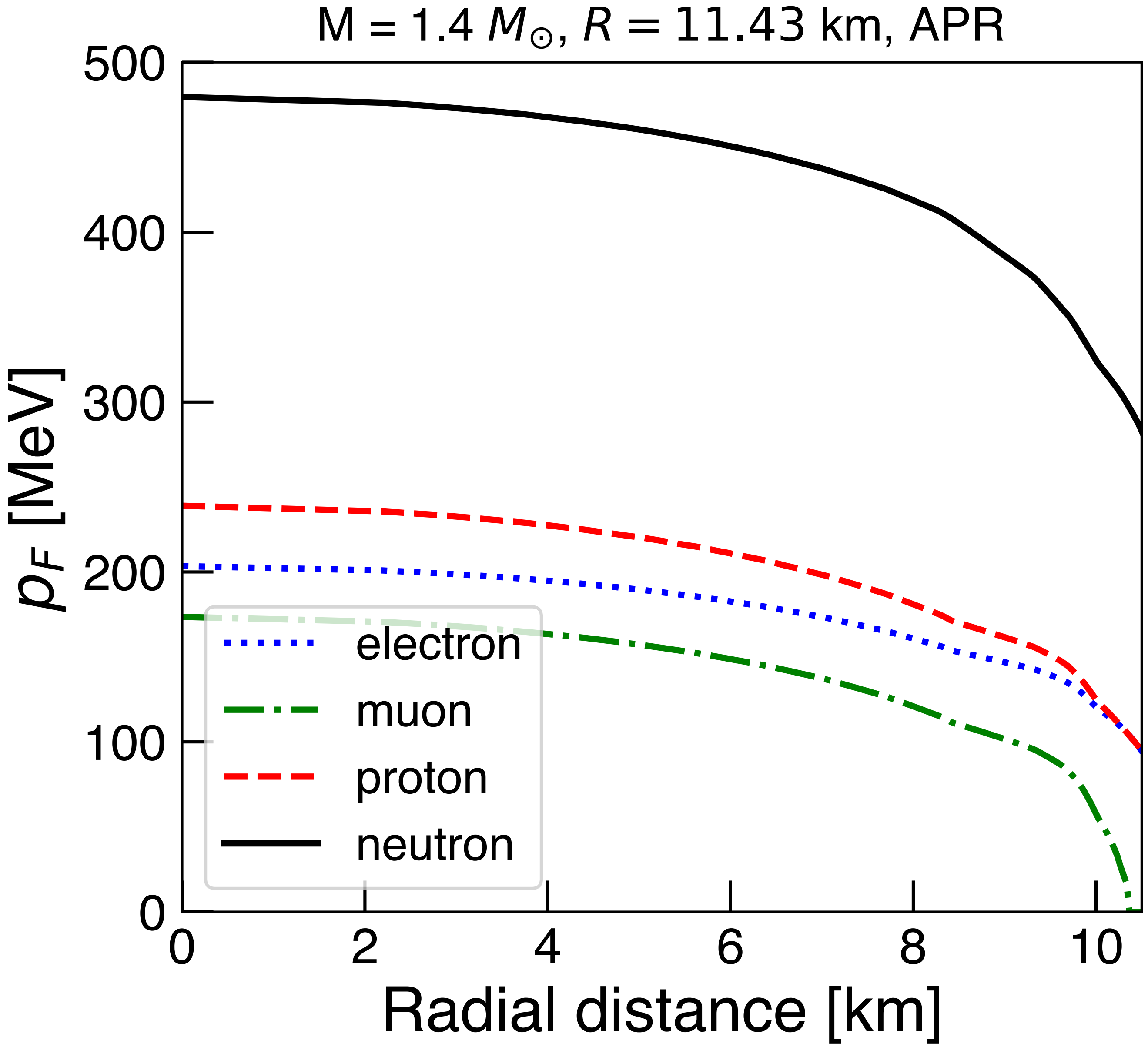
P. S. Shternin, MNRAS **518**, 2775 (2022).

Neutrino emission processes



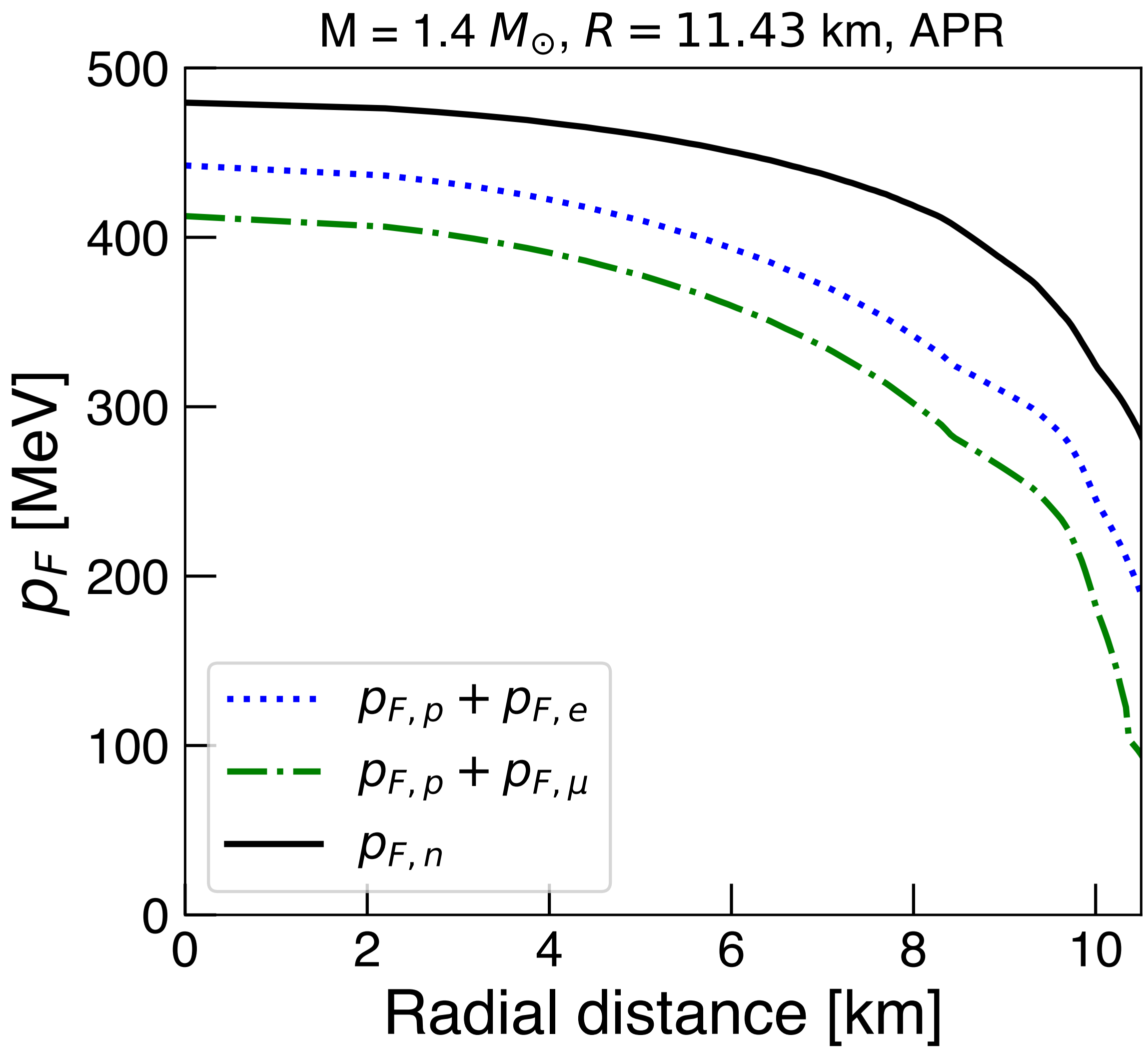
- These processes can occur without superfluidity.
- Direct Urca can occur only in heavy stars.

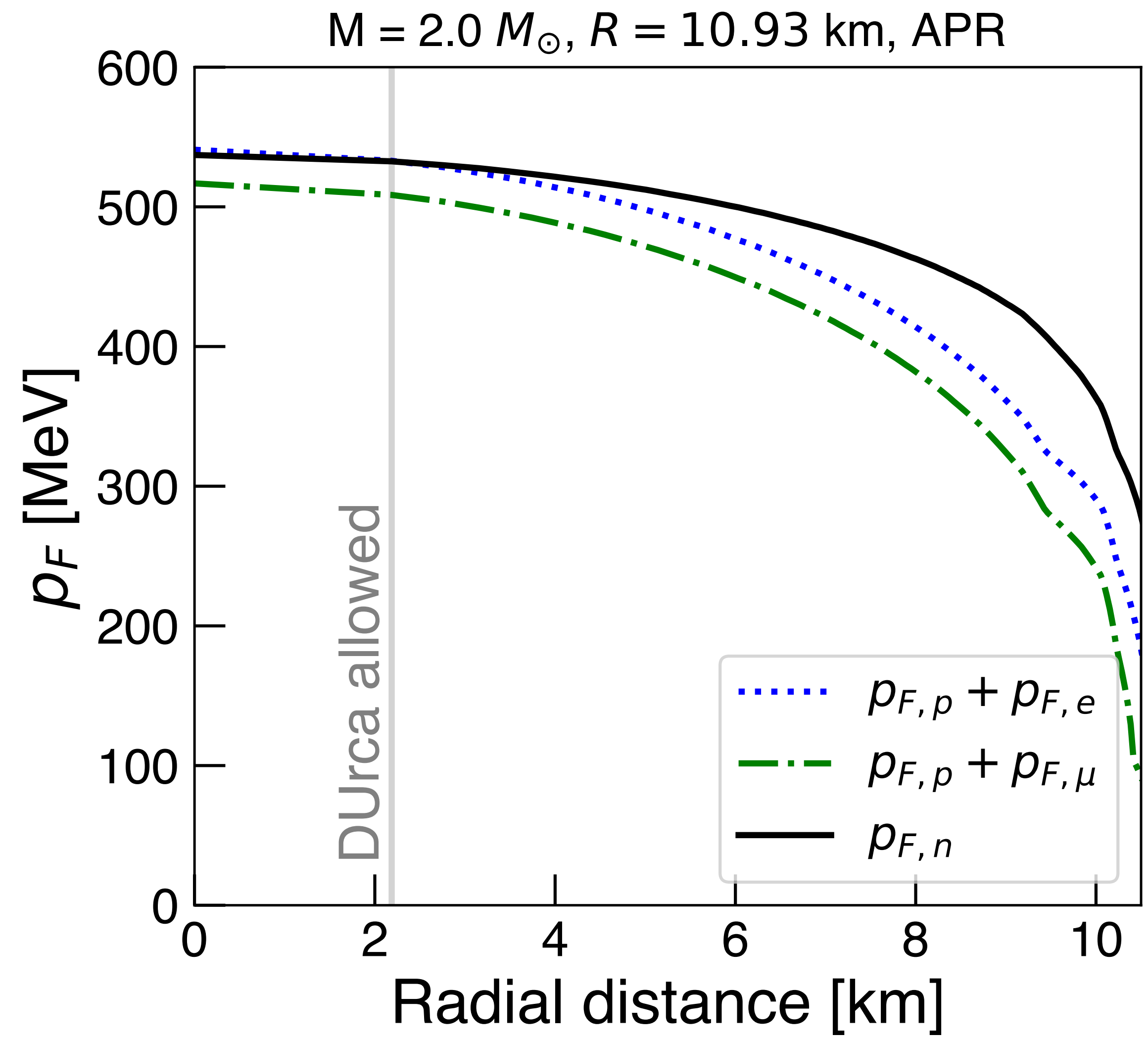
Fermio momenta



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

Direct Urca condition



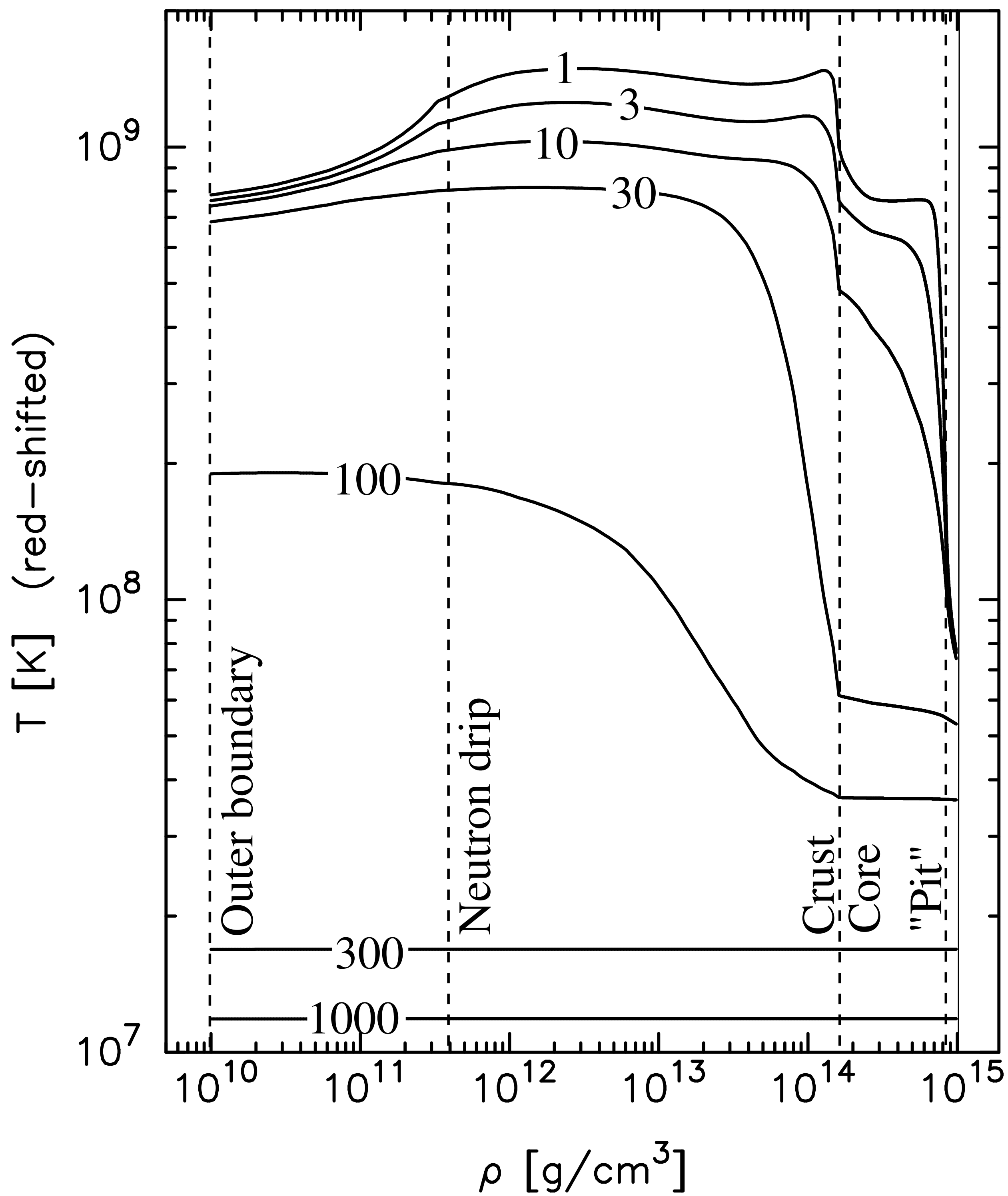


- Direct Urca can occur only in the high density region in a heavy star.

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

- Other processes become important if Direct Urca is forbidden.

Temperature distribution

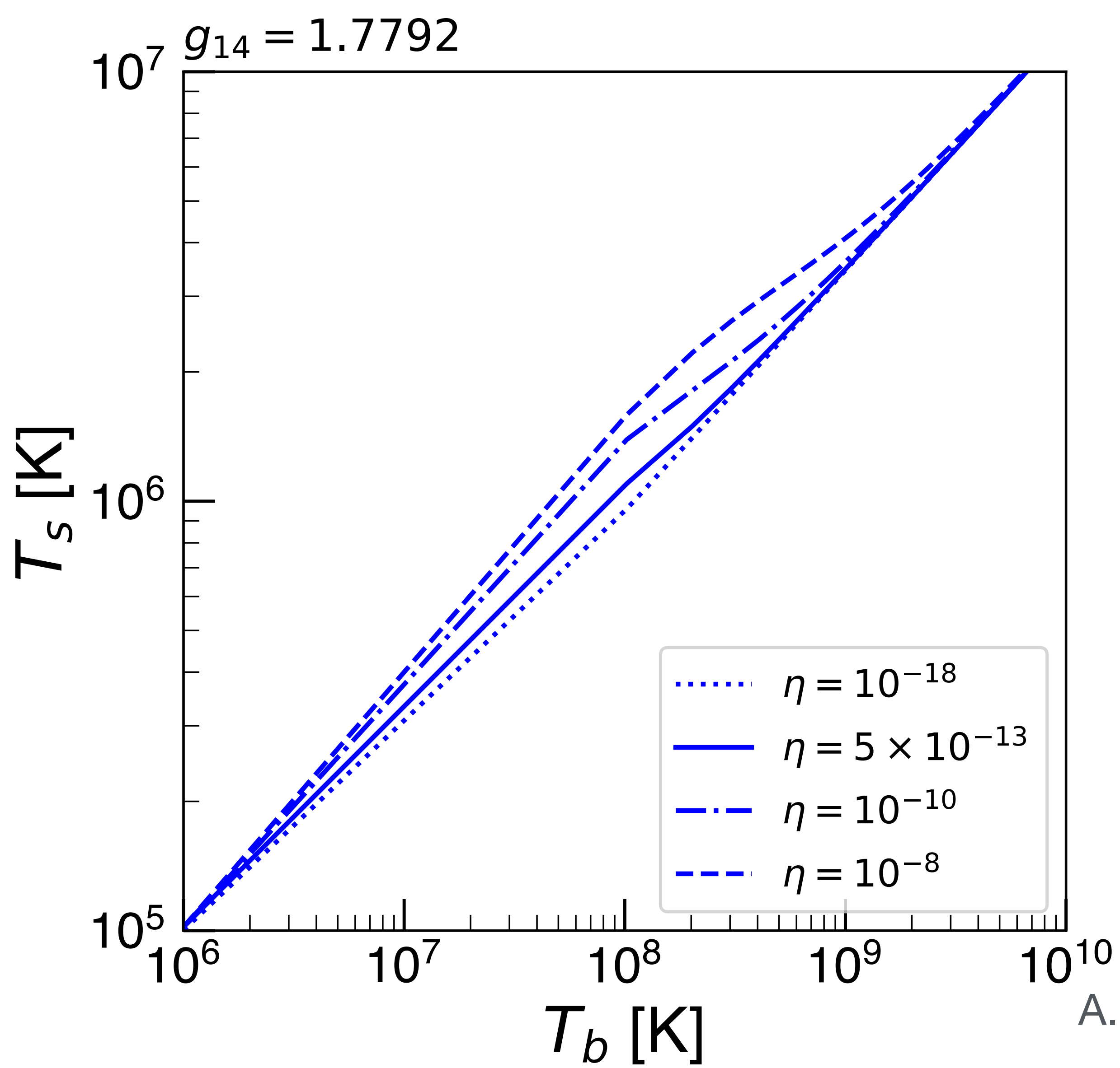


Relaxation in the Core completes in ~ 100 years.

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

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}.

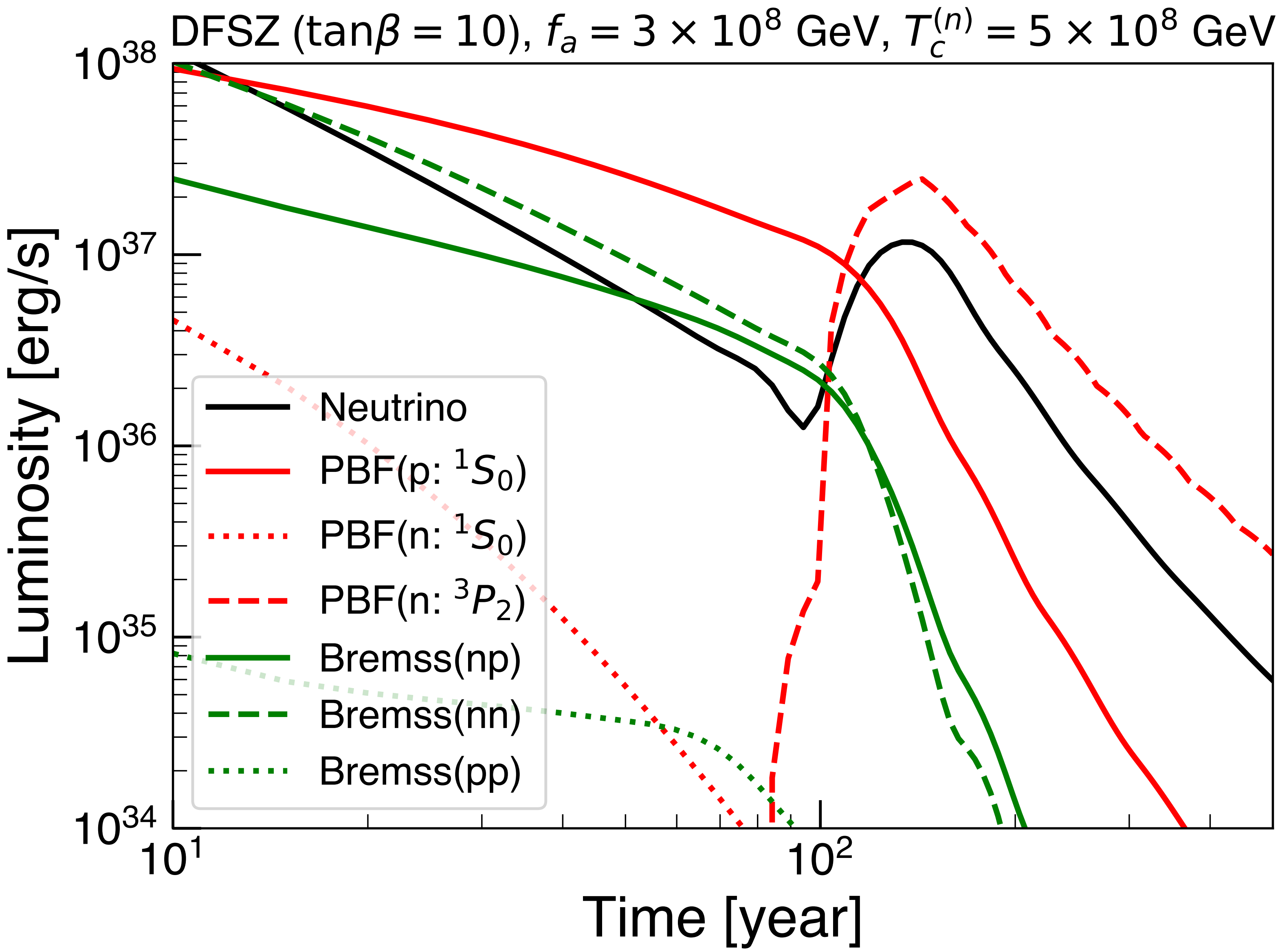
ΔM: mass of light elements.

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.

Luminosity of axion emission (DFSZ)



Axion emission is stronger than the KSVZ case.

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

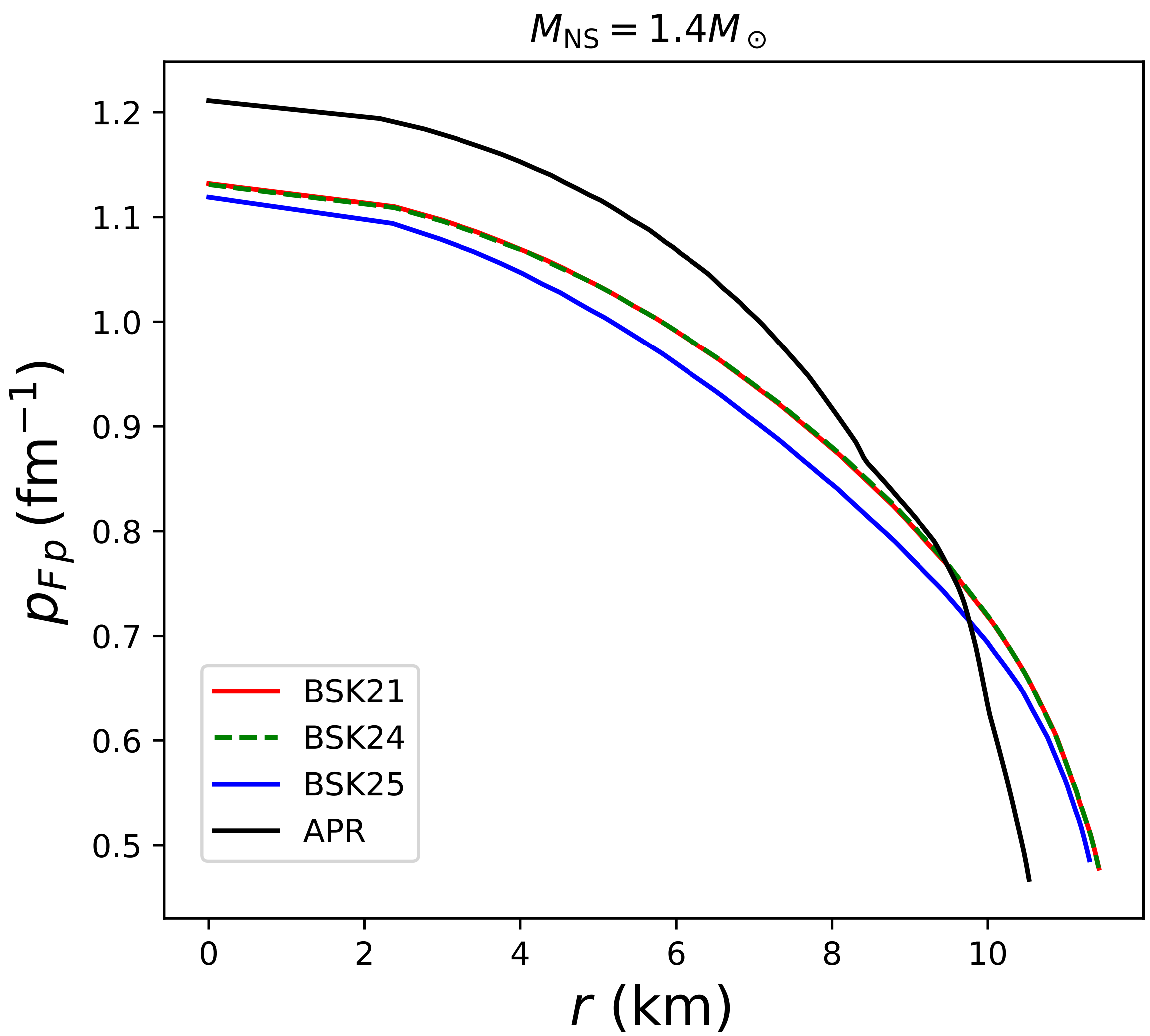
Technical details

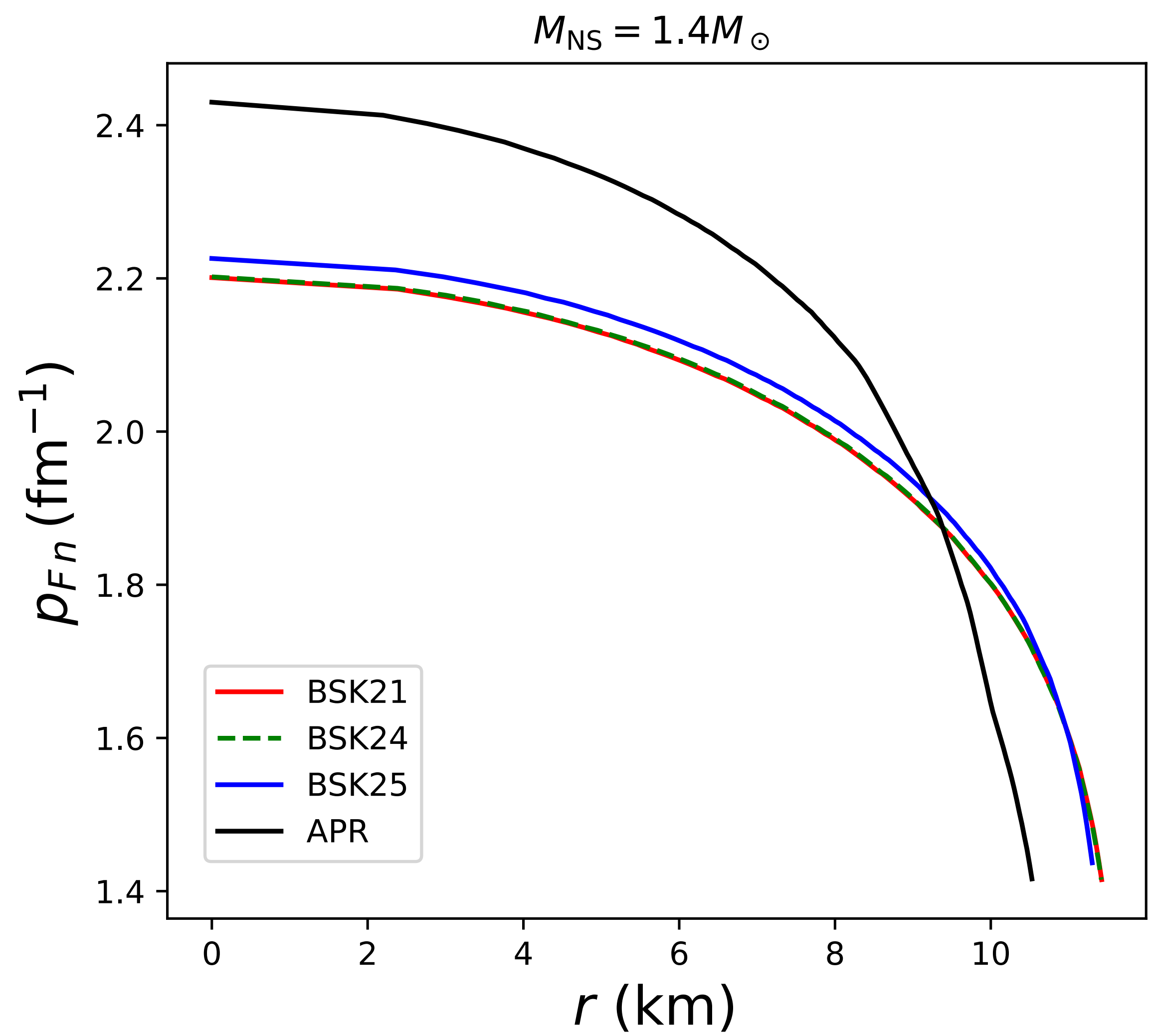
- APR equation of state
- NS mass: $M = 1.4M_\odot$
- Neutron $^1S_0$ gap: SFB model Not so relevant.
- Proton $^1S_0$ gap: CCDK model

  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.

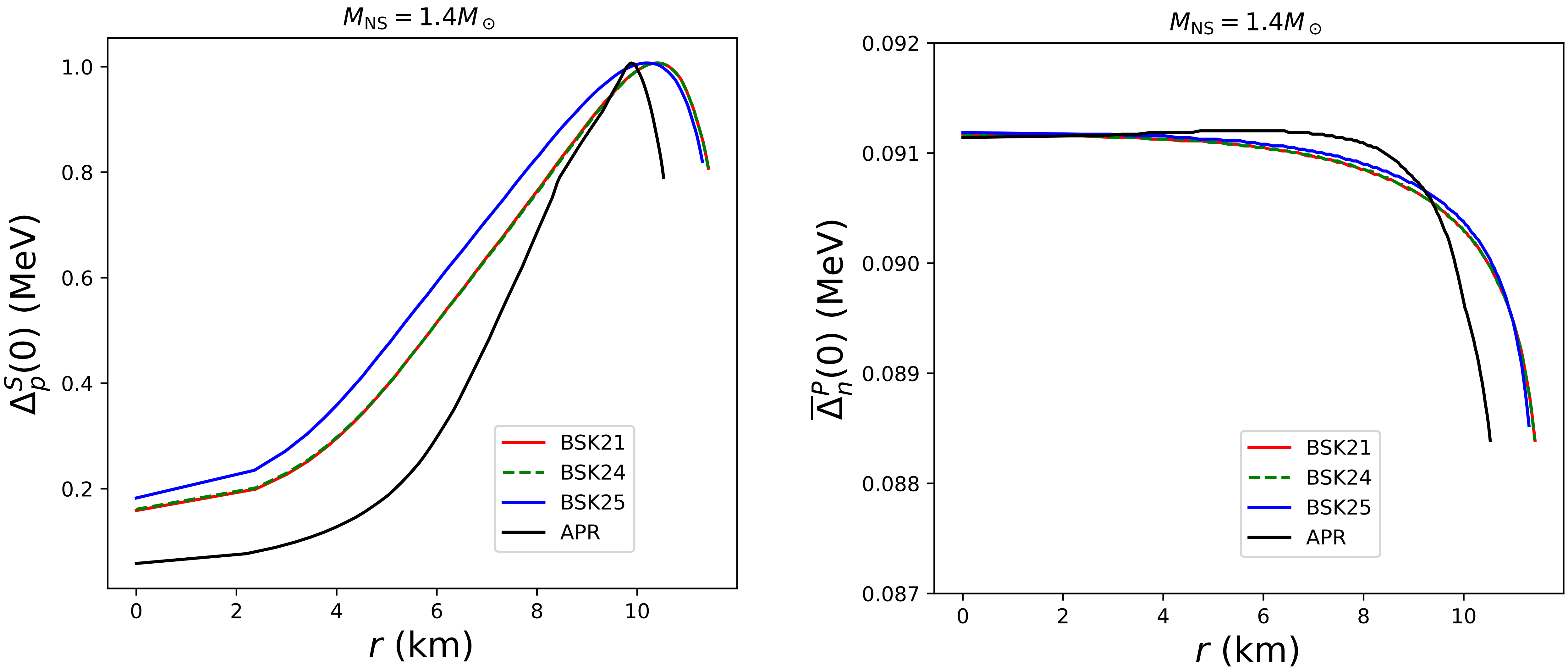
EOS dependence: Fermi momentum





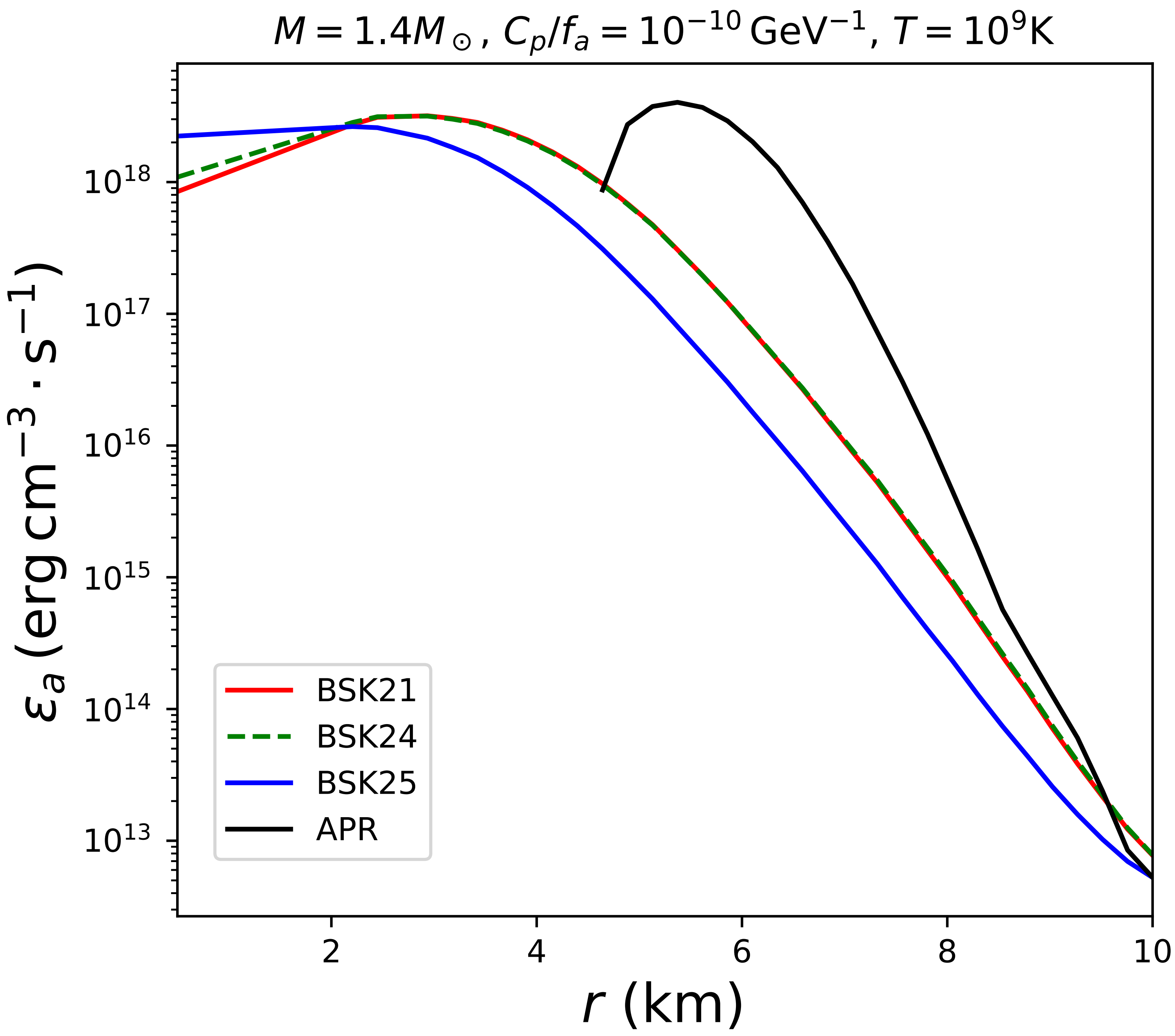
K. Hamaguchi, N. Nagata, and J. Zheng, arXiv:2502.18931.

EOS dependence: pairing gaps



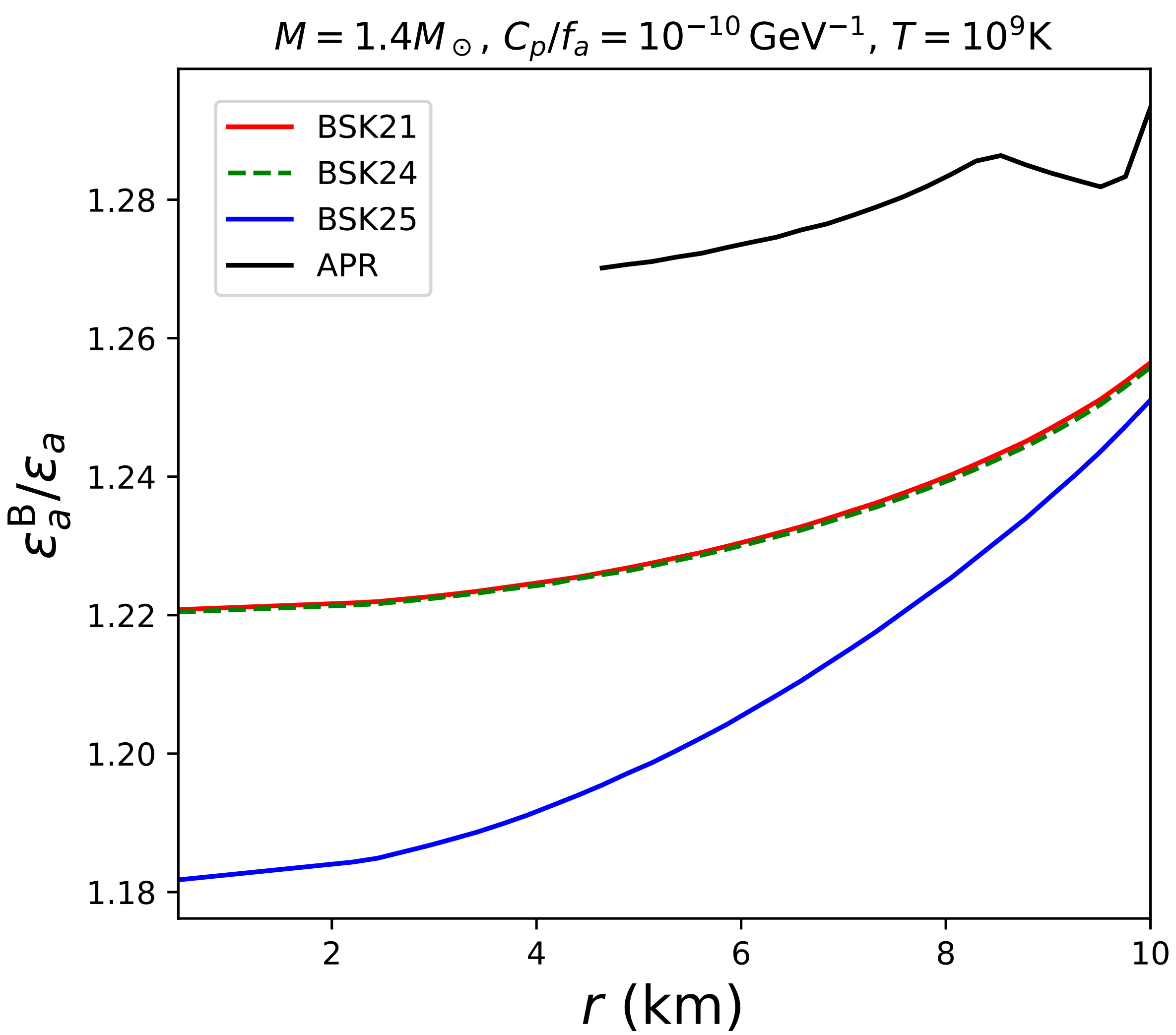
K. Hamaguchi, N. Nagata, and J. Zheng, arXiv:2502.18931.

EOS dependence: axion emissivity

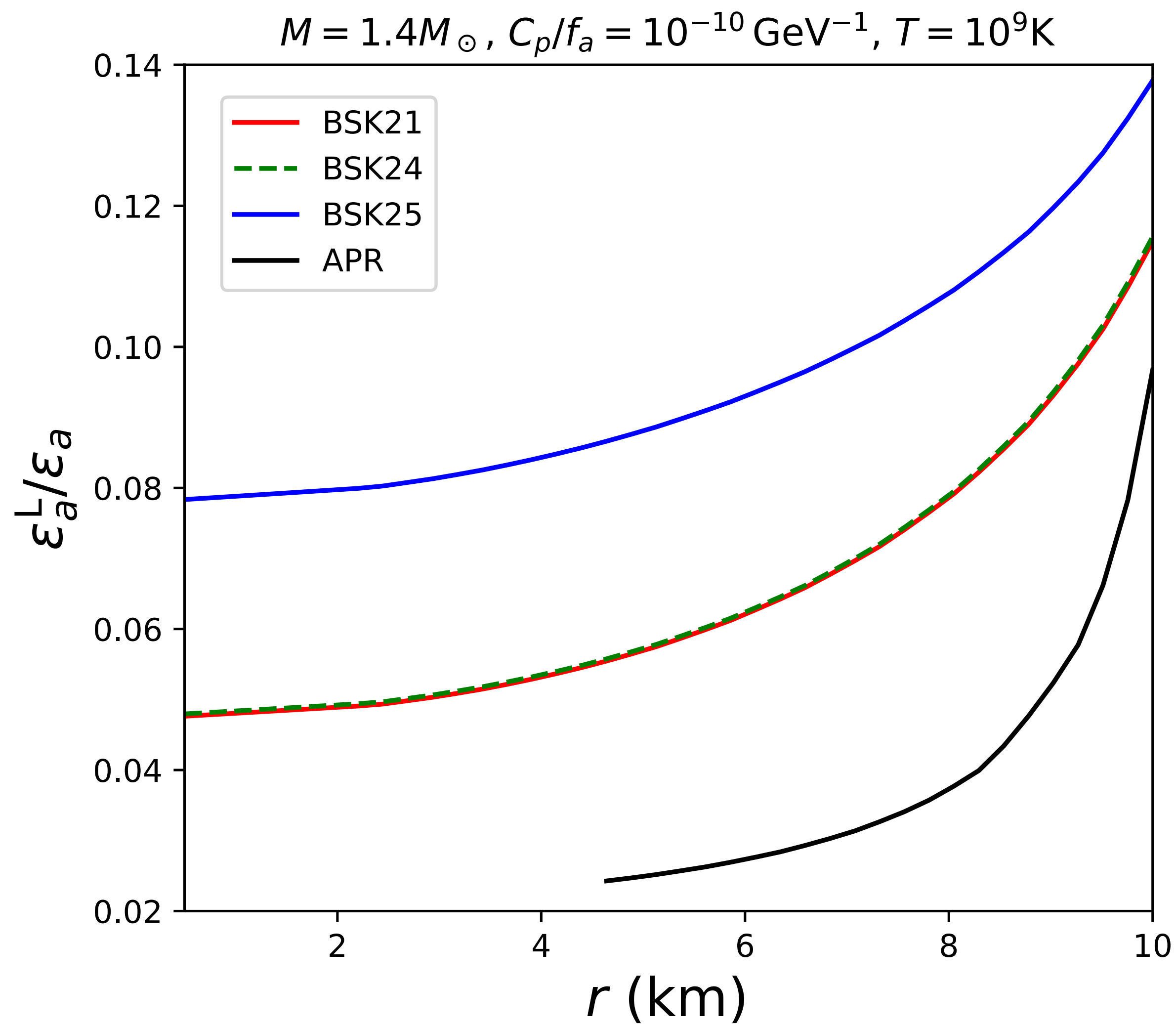


K. Hamaguchi, N. Nagata, and J. Zheng, arXiv:2502.18931.

EOS dependence: differences



M. Buschmann, et.al.,
Phys. Rev. Lett. **128**, 091102 (2022).

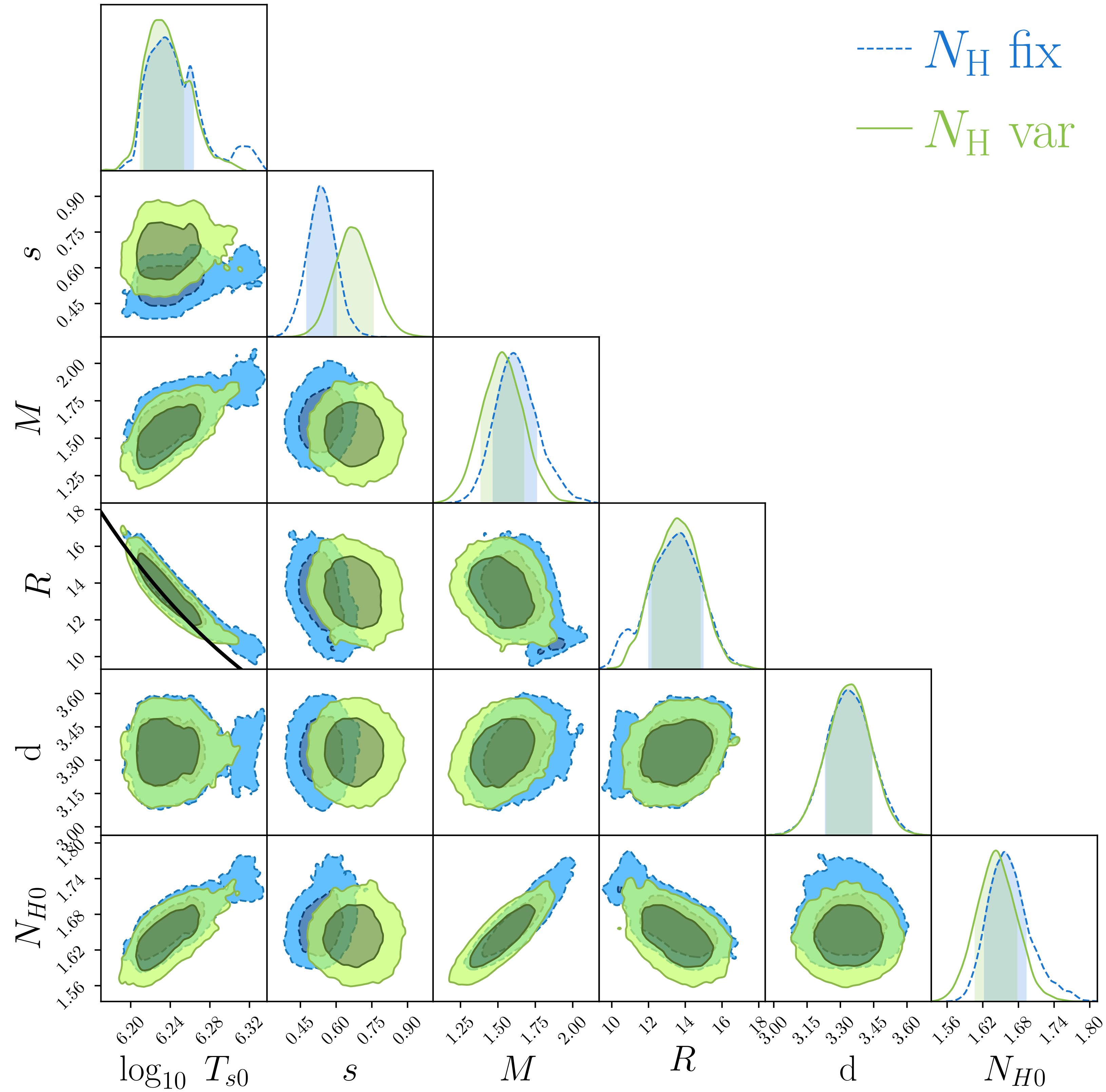


L. B. Leinson, JCAP **09**, 001 (2021).

K. Hamaguchi, N. Nagata, and J. Zheng, arXiv:2502.18931.

Spectral parameters

P. S. Shternin, MNRAS **518**, 2775 (2022).



Spin-down age

For magnetic dipole radiation,

$$\dot{\Omega} = -k\Omega^3 \qquad k = \frac{2B_s^2 \sin^2\alpha\, R^6}{3c^3 I} = -\frac{\dot{\Omega}_{\rm now}}{\Omega_{\rm now}^3} = \frac{P_{\rm now}\dot{P}_{\rm now}}{4\pi^2}$$

By solving this, we have

$$P(t) = \sqrt{P_0^2 + 2P_{\rm now}\dot{P}_{\rm now} t}$$

(P_0: initial period)

In particular, for $P_0 \ll P_{\rm now}$, we can estimate the neutron star age

$$t_{\rm sd} = \frac{P_{\rm now}}{2\dot{P}_{\rm now}}$$

t_{sd} is called spin-down age or characteristic age.

Pulsar age

Let us compare the spin-down age with the actual age in the case of the Crab pulsar.

Actual age

It was born in 1054, so its age is 967 years old.

Spin-down age

$$P = 0.033392 \text{ s}, \quad \dot{P} = 4.21 \times 10^{-13}$$

$$t_{\rm sd} = \frac{P}{2\dot{P}} = 1.26 \times 10^3 \text{ yrs}$$

Agrees within ~ 30%.