Vortex Creep Heating vs. Dark Matter Heating in Neutron Stars

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DSU 2024
Corfu, Greece
Sep. 8—14, 2024

Collaboration

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Outline

- Neutron star standard cooling
- Dark matter heating
- Vortex creep heating
- Vortex creep heating vs dark matter heating

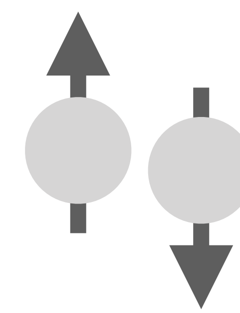
Standard Cooling of NS

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)

Form Cooper pairs



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

Equation for temperature evolution

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

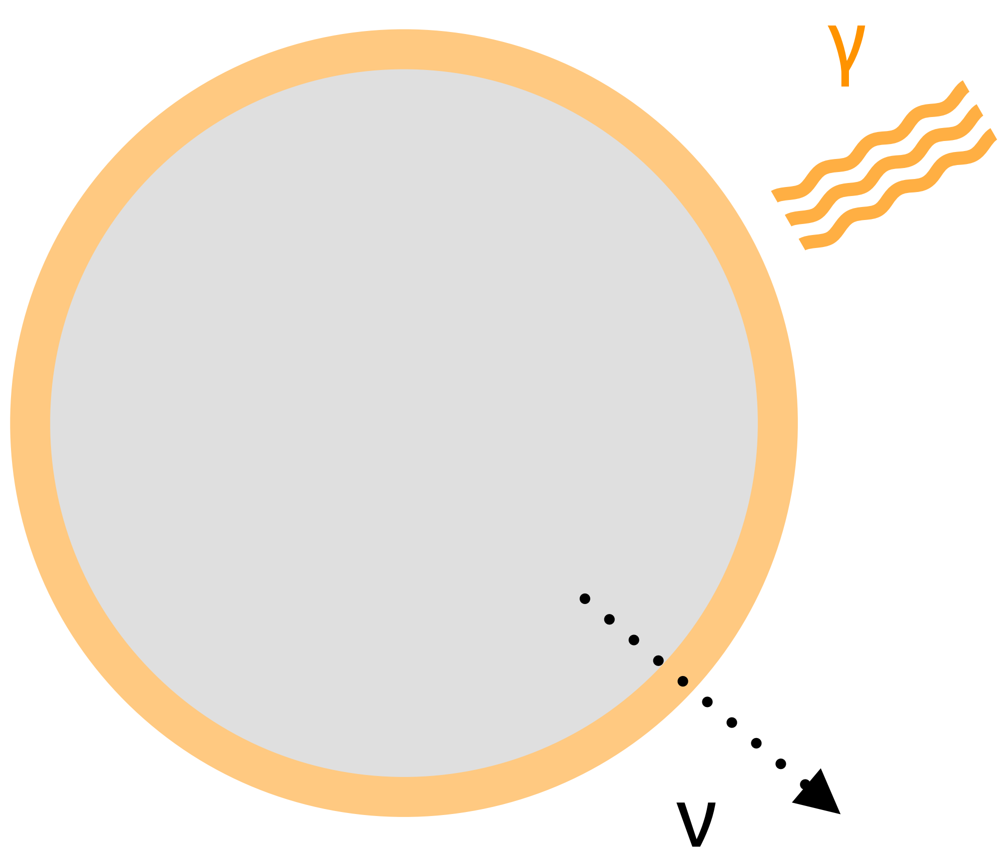
C(T): Stellar heat capacity

L_ν: Luminosity of neutrino emission

L_γ: Luminosity of photon emission

Cooling sources

Two cooling sources:



- Photon emission (from surface)

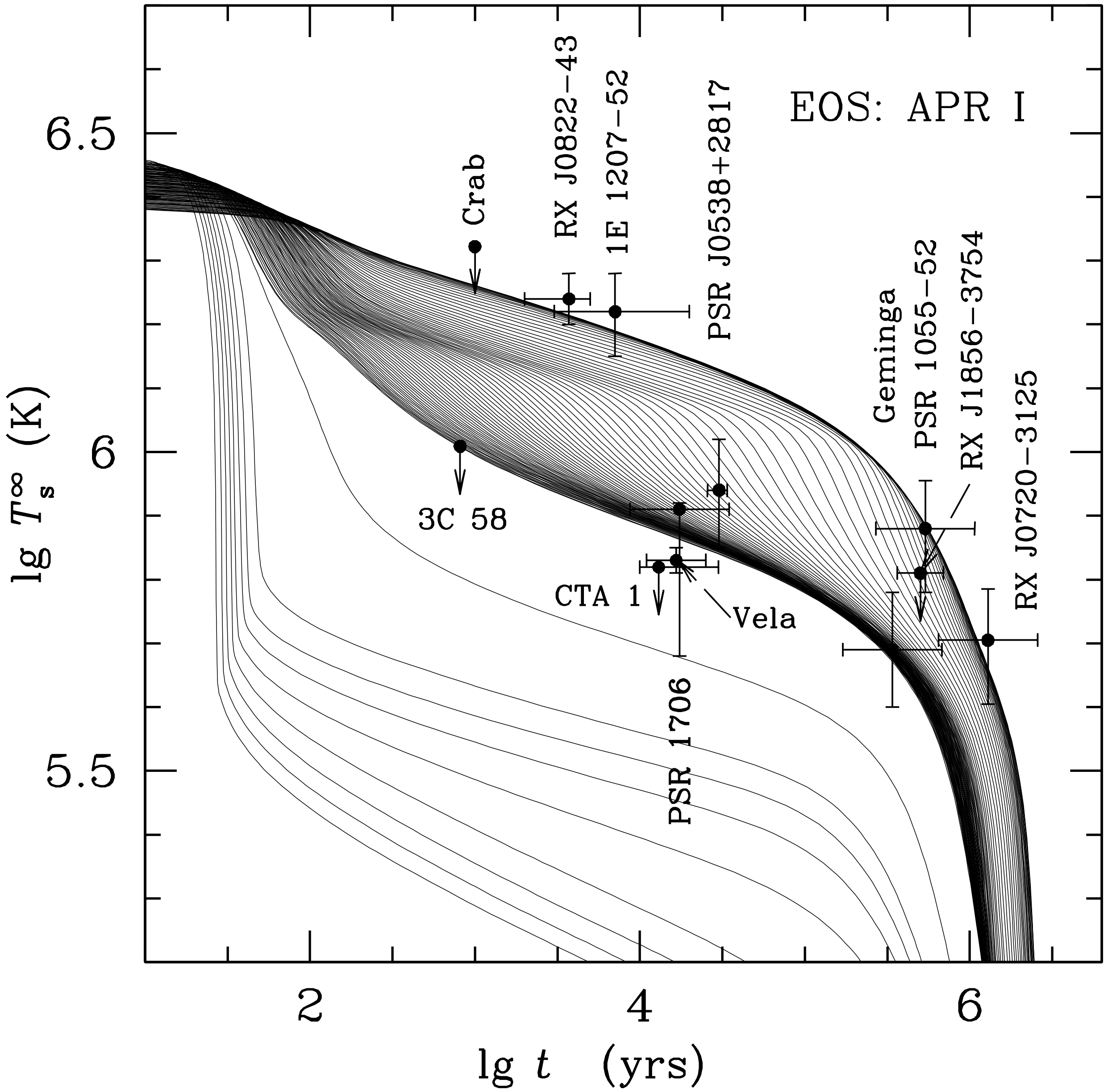
$$L_\gamma = 4\pi R^2 \sigma_{\rm SB} T_s^4$$

Dominant for $t \gtrsim 10^5$ years

- Neutrino emission (from core)

Dominant for $t \lesssim 10^5$ years

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).

- Temperature gets very low for $t \gtrsim 10^6$ years.
- Consistent with the observations for $t < 10^6$ years.

~ 50 NSs listed.

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

Dark matter heating in neutron stars

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

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

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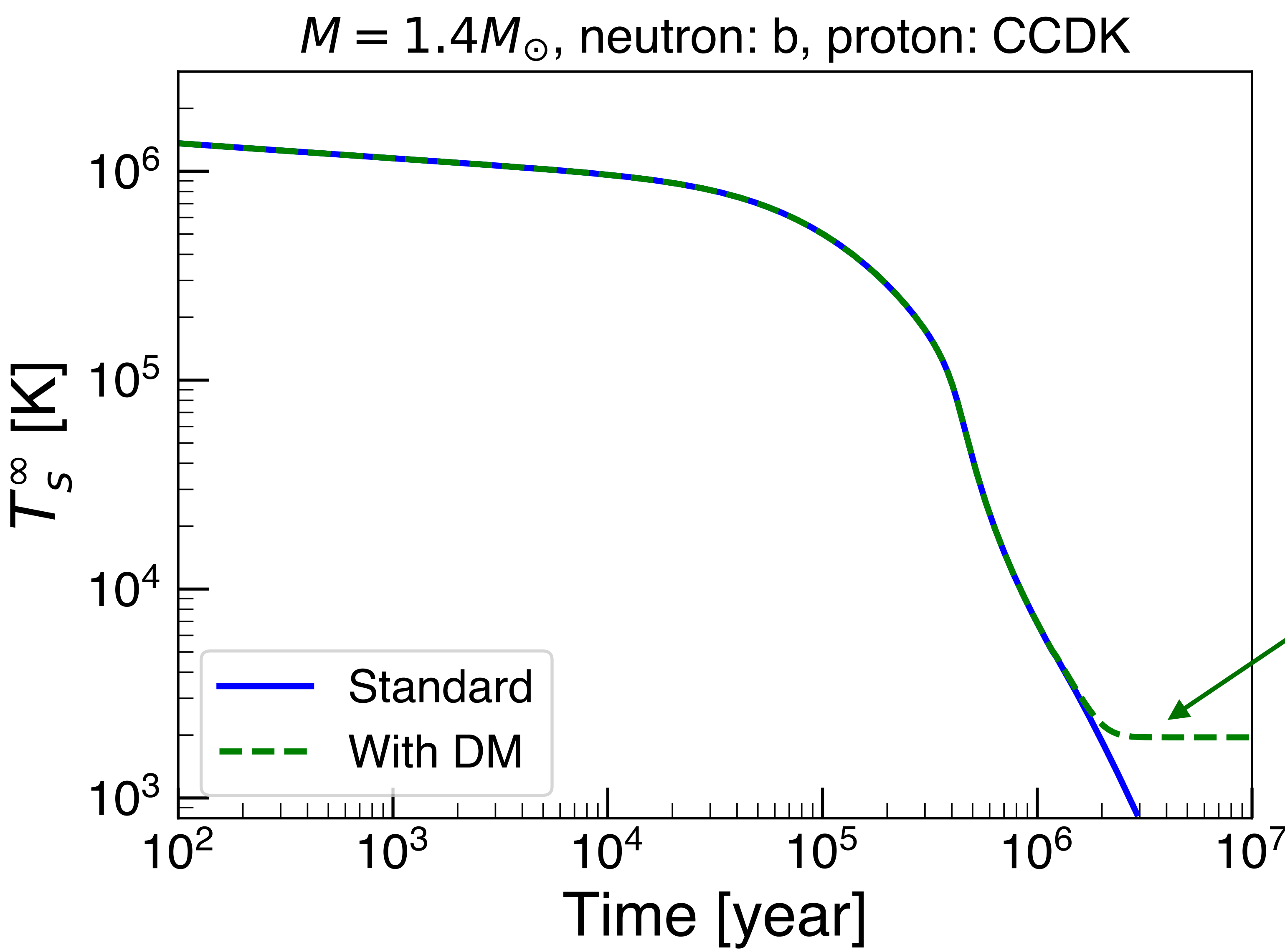
Mechanism

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

WIMP dark matter heating in NS

Dark matter heating effect may be observed in old NSs.



$\sigma_{\chi N} \gtrsim 10^{-45}\ \mathrm{cm}^2$

- 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.

Other heating sources?

If there are other heating sources in NSs, DM heating effect may be concealed.

- There is no heating source in Standard NS cooling theory.
- Is it possible to have extra heating sources?

Or, even motivated?

Old warm neutron stars?

Recently, “old but warm neutron stars” have been observed.

Milli-second pulsars

- J0437-4715: $t_{\rm sd} = (6.7 \pm 0.2) \times 10^9$ 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: $t_{\rm sd} = 11^{+6}_{-3} \times 10^9$ 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: $t_{\rm sd} = 2.0 \times 10^8$ 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: $t_{\rm sd} = 1.75 \times 10^7$ 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.

Heating mechanism?

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

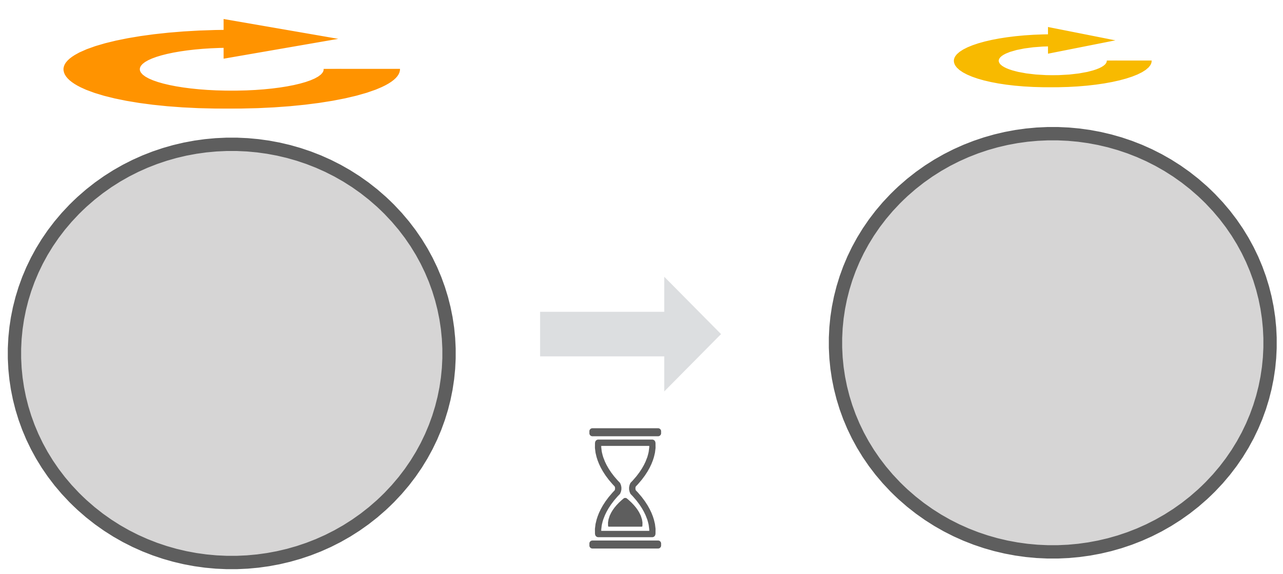
- Non-equilibrium beta processes

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.



Vortex Creep Heating

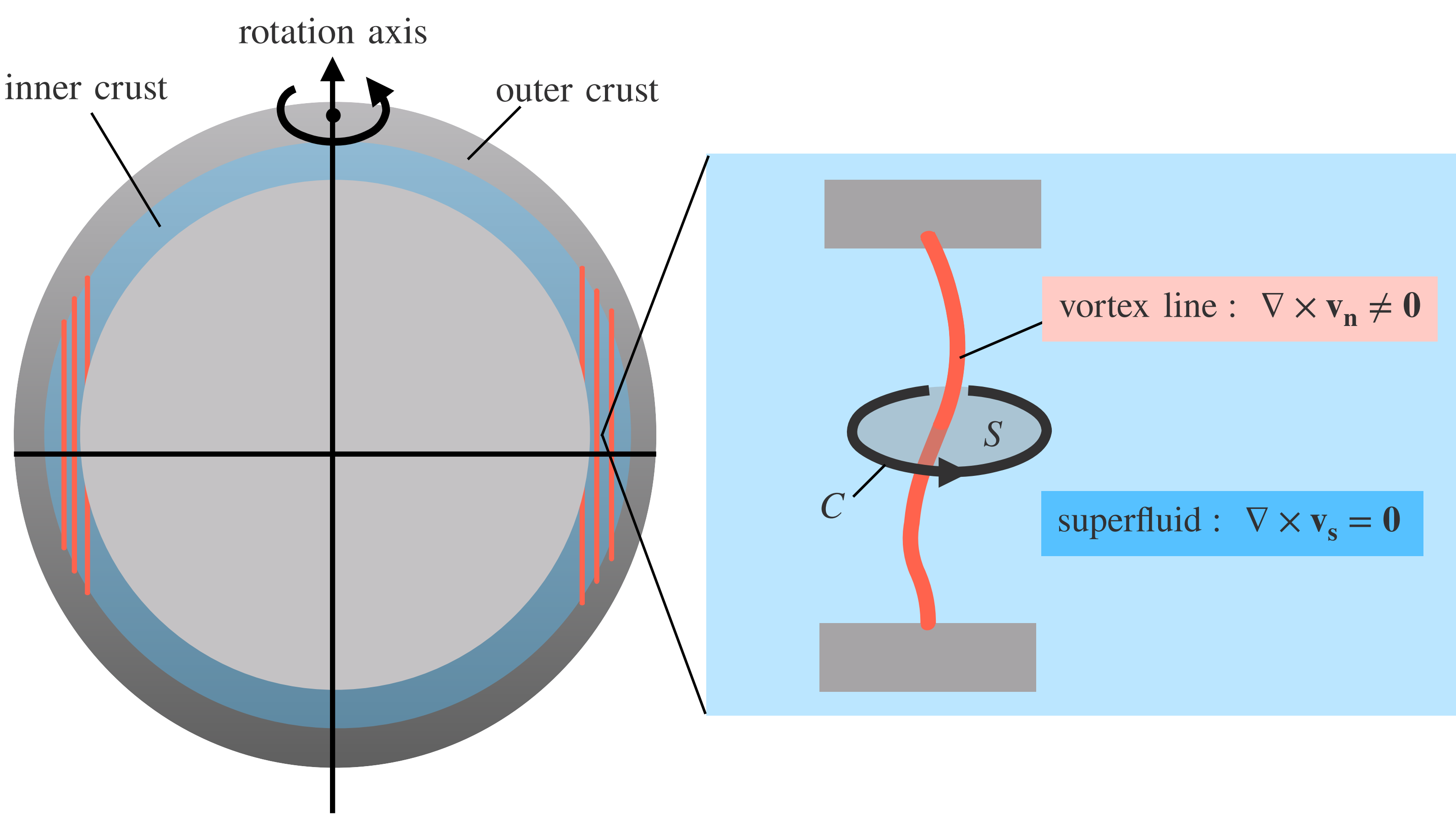
Neutron superfluid vortex lines

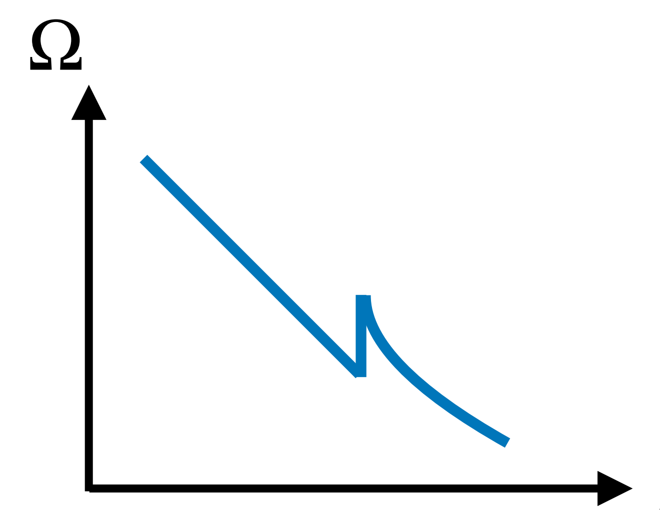
Neutrons form Cooper pairs in NSs. → Neutron superfluidity

In a rotating NS, superfluid vortex lines are formed.

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

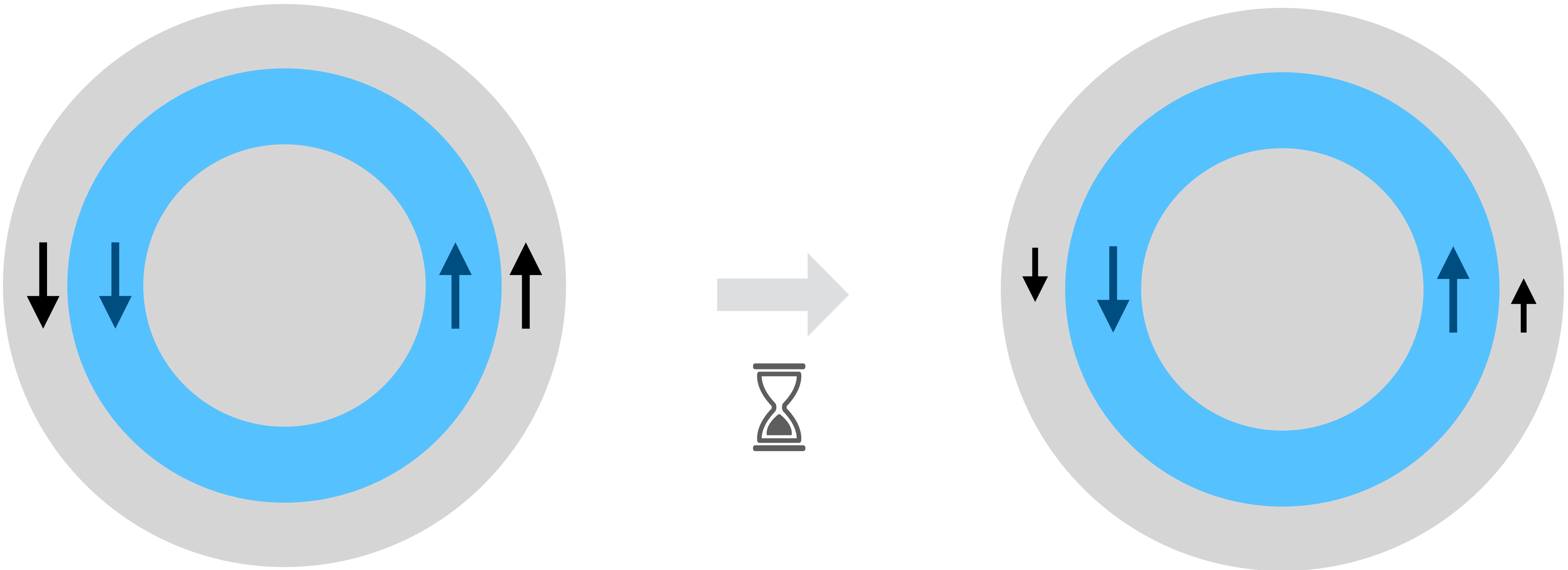
P. W. Anderson and N. Itoh, Nature **256**, 25 (1975).





Vortex lines may be relevant for pulsar glitches.

Pulsar slowdown



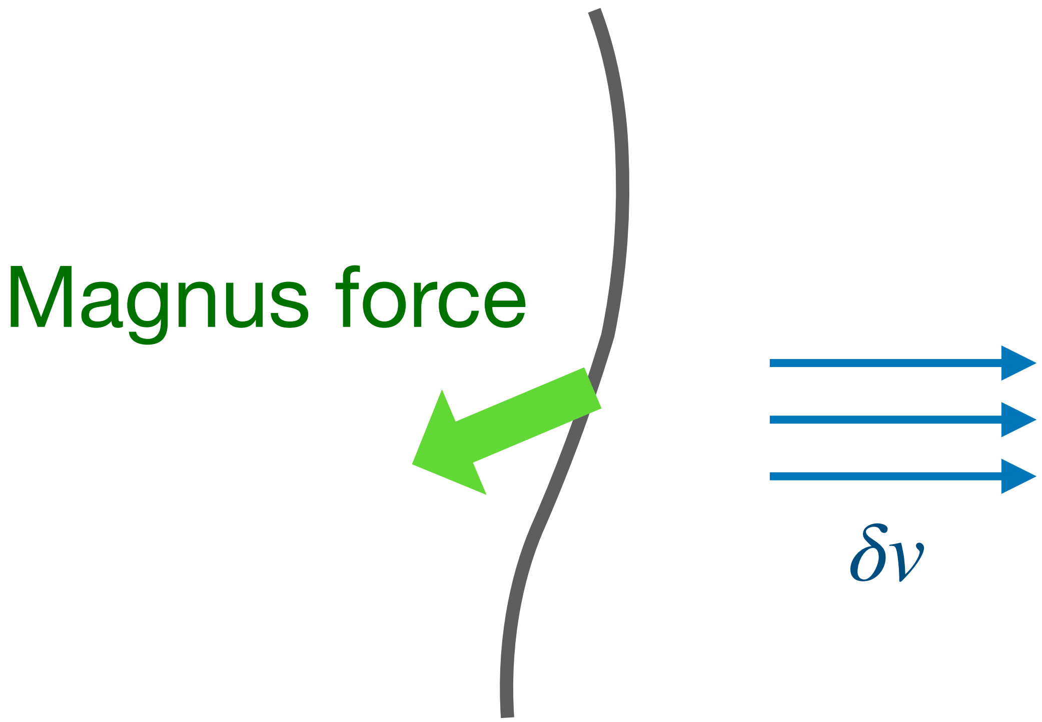
Rotation of the rigid component of NS slows down.

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.

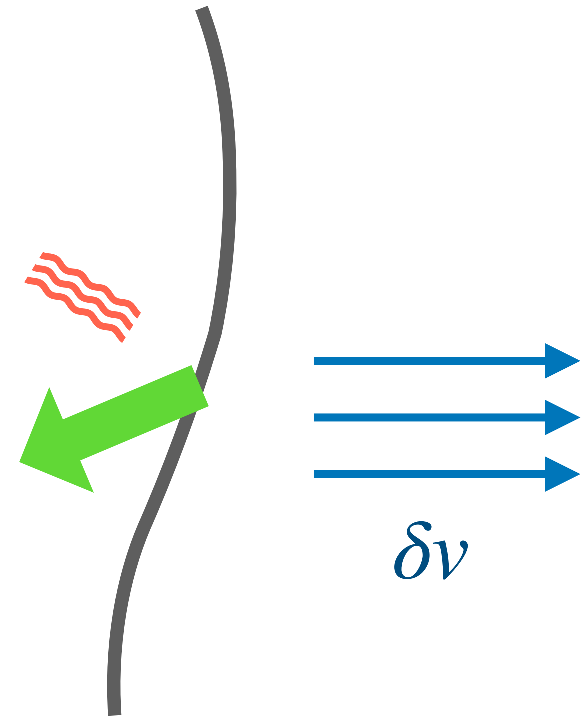
As δv increases, Magnus force increases.

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

$$\Omega_{\mathrm{SF}} - \Omega_{\mathrm{crust}} = \mathrm{const.}$$

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:

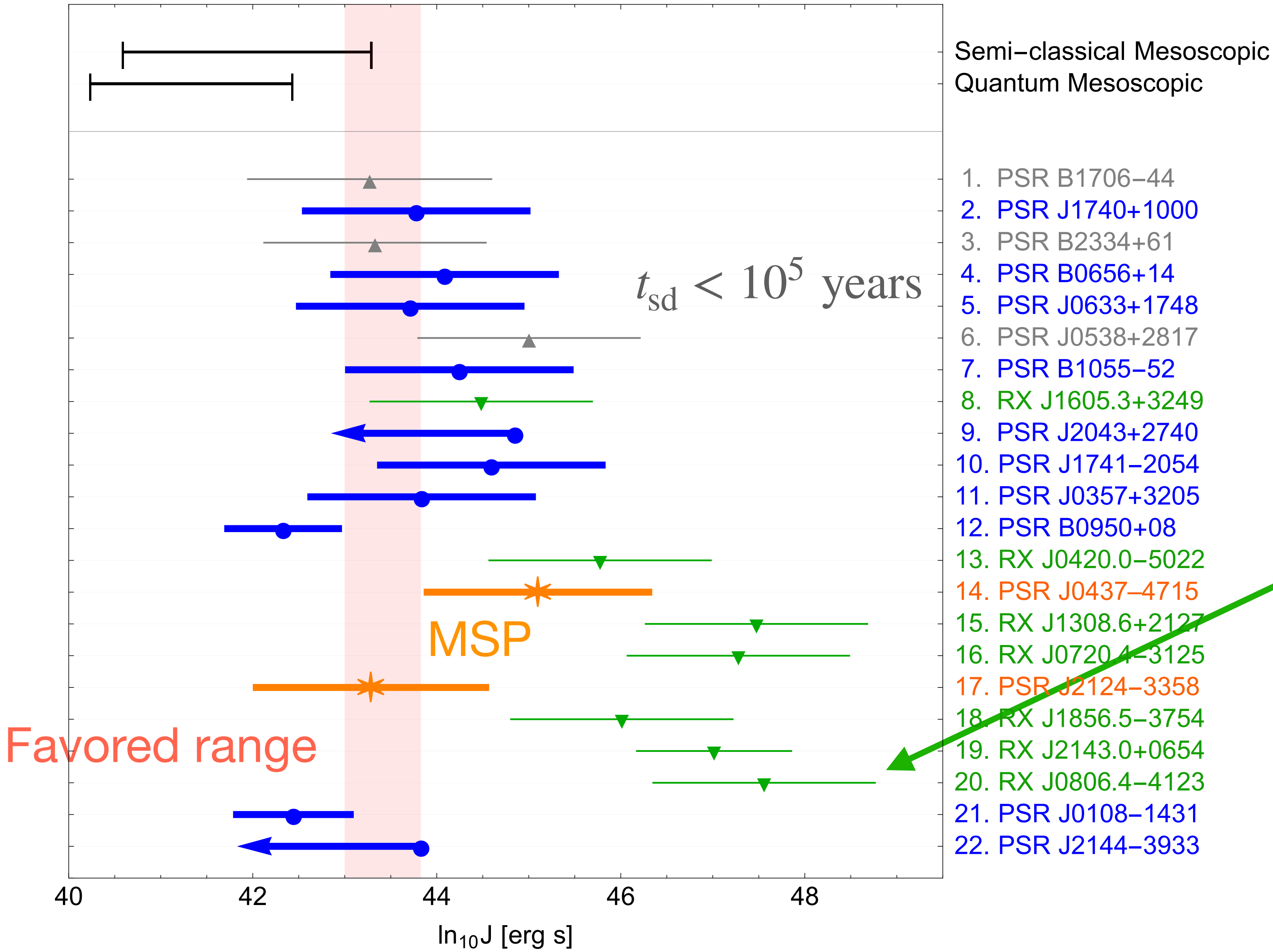
$$L_{\rm H} = L_\gamma = 4\pi R^2 \sigma_{\rm SB} T_s^4$$

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

Can be determined by observation.

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

Vortex creep heating vs observations



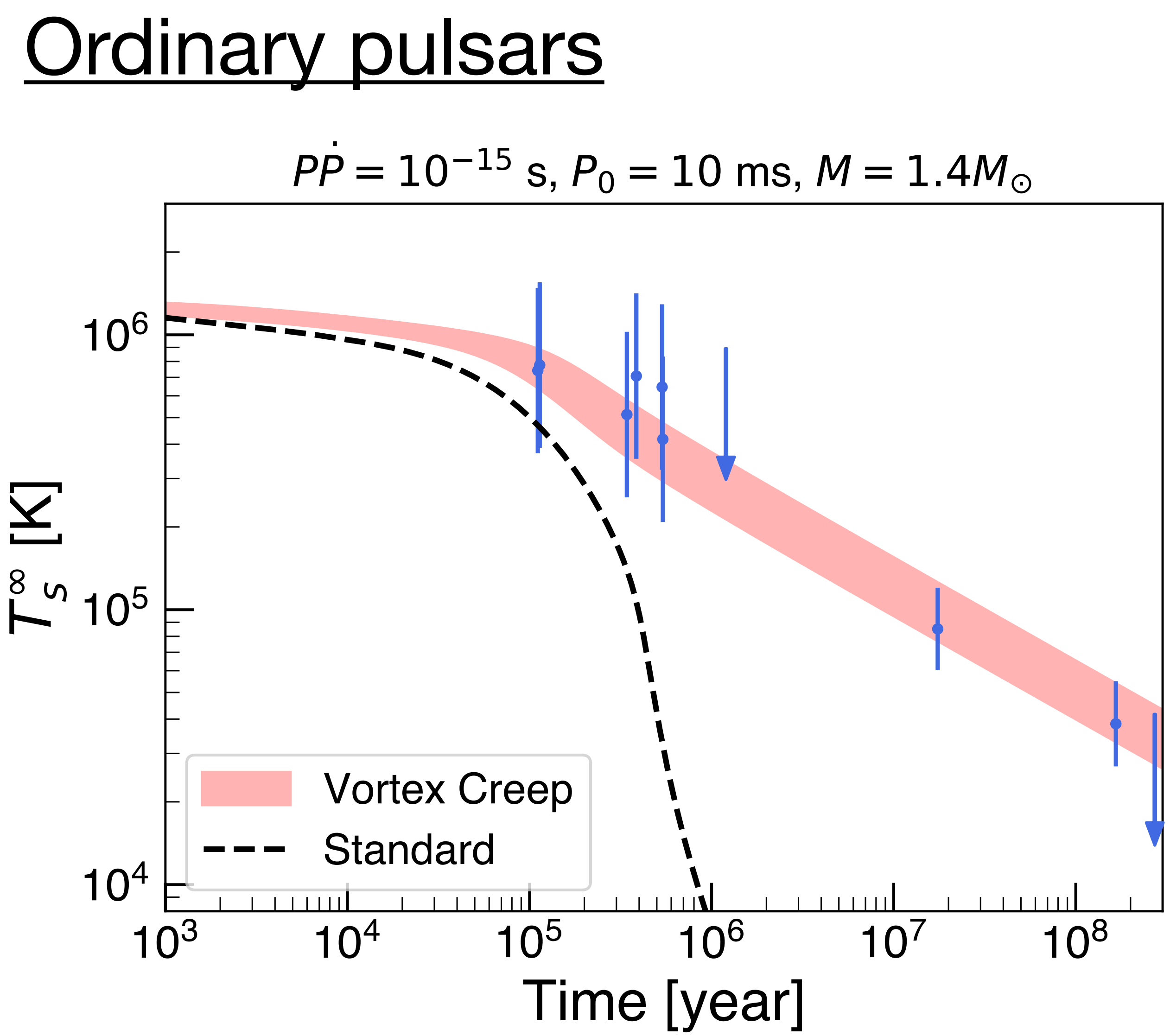
Theoretical estimations.

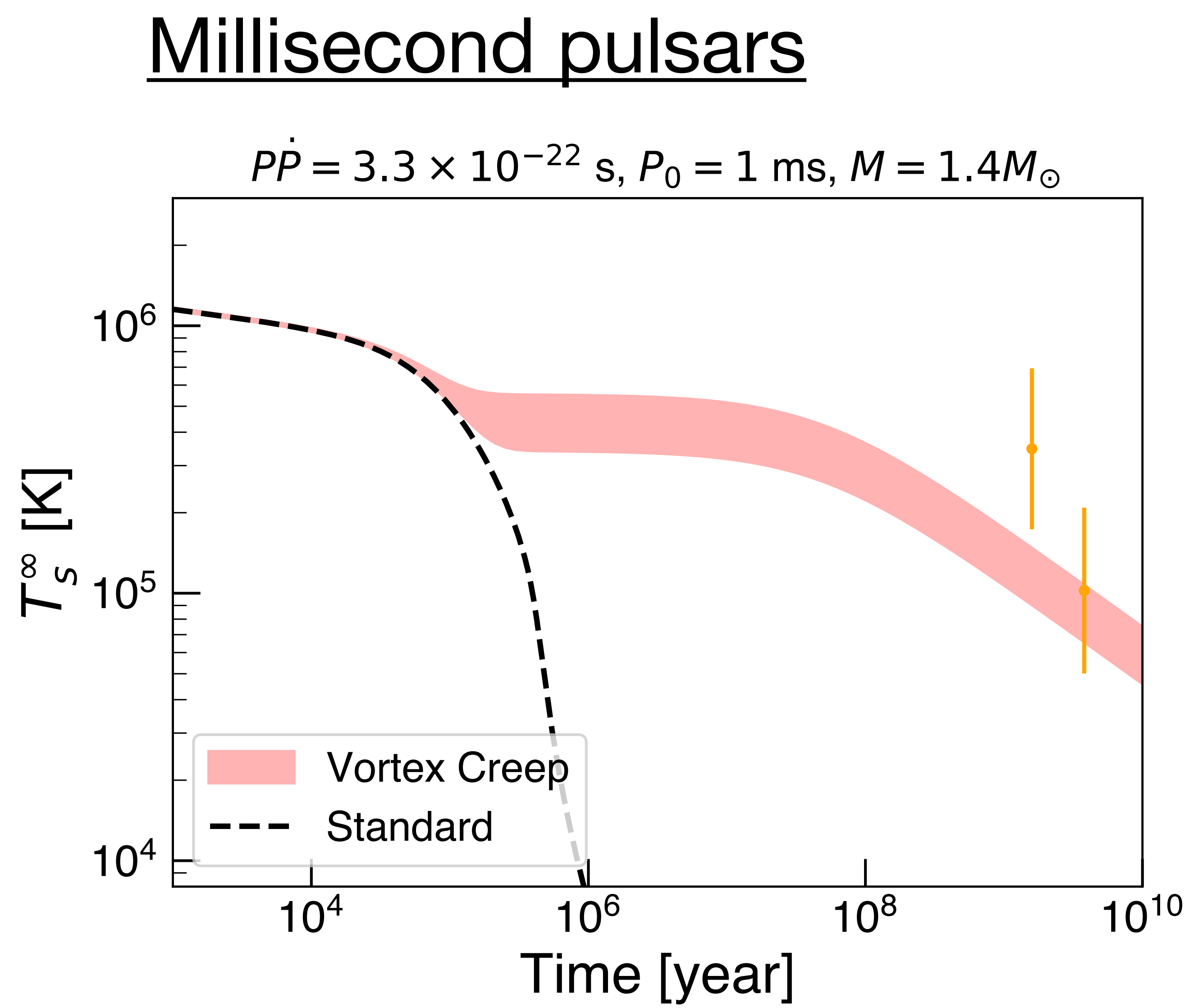
Magnetic heating suspected

- 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





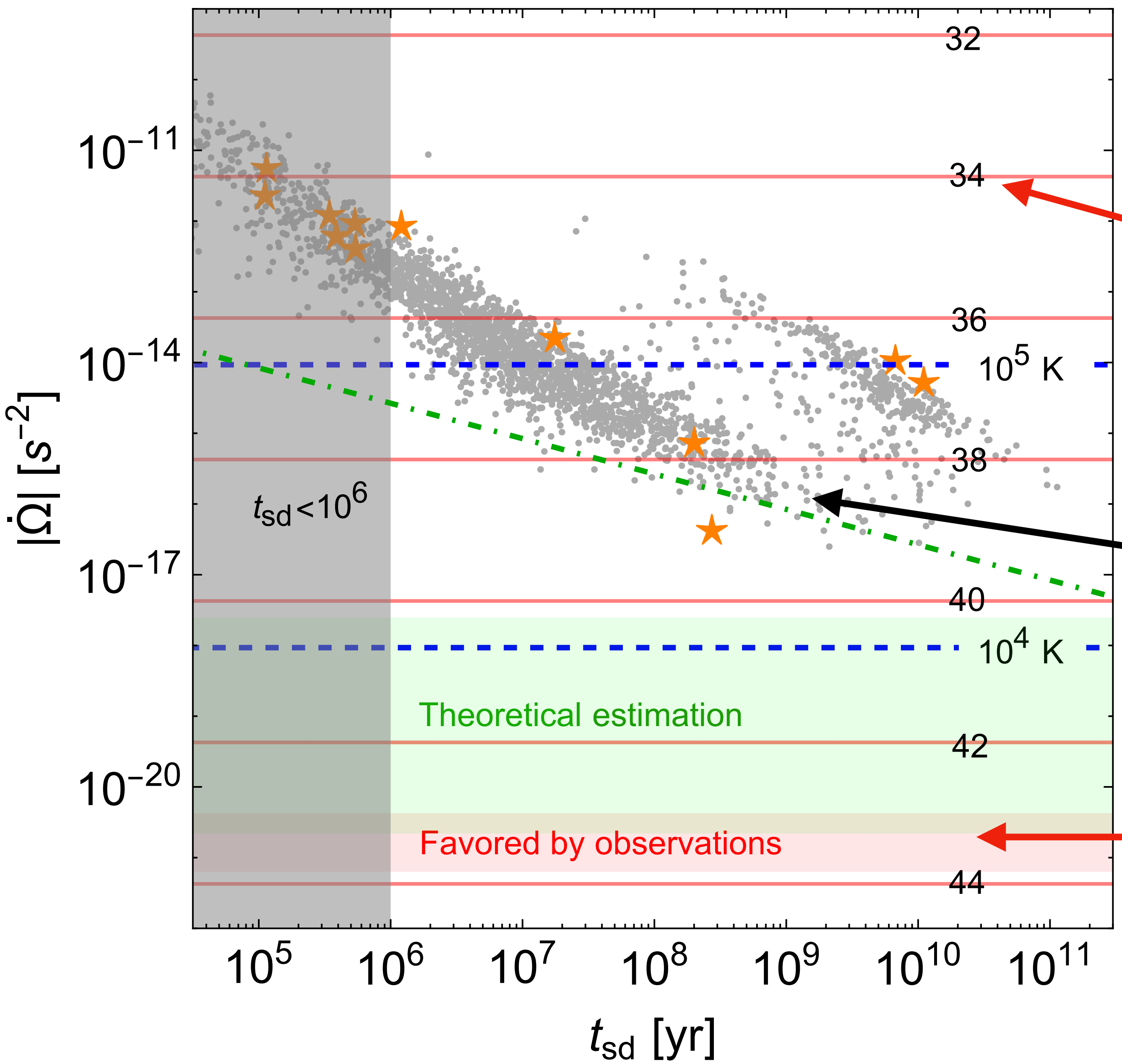
- Temperature evolution deviates at $t \gtrsim 10^5$ years.
- Even for very old NSs, $T_s \gtrsim 10^4$ K.

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

Vortex Creep Heating vs DM Heating

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])

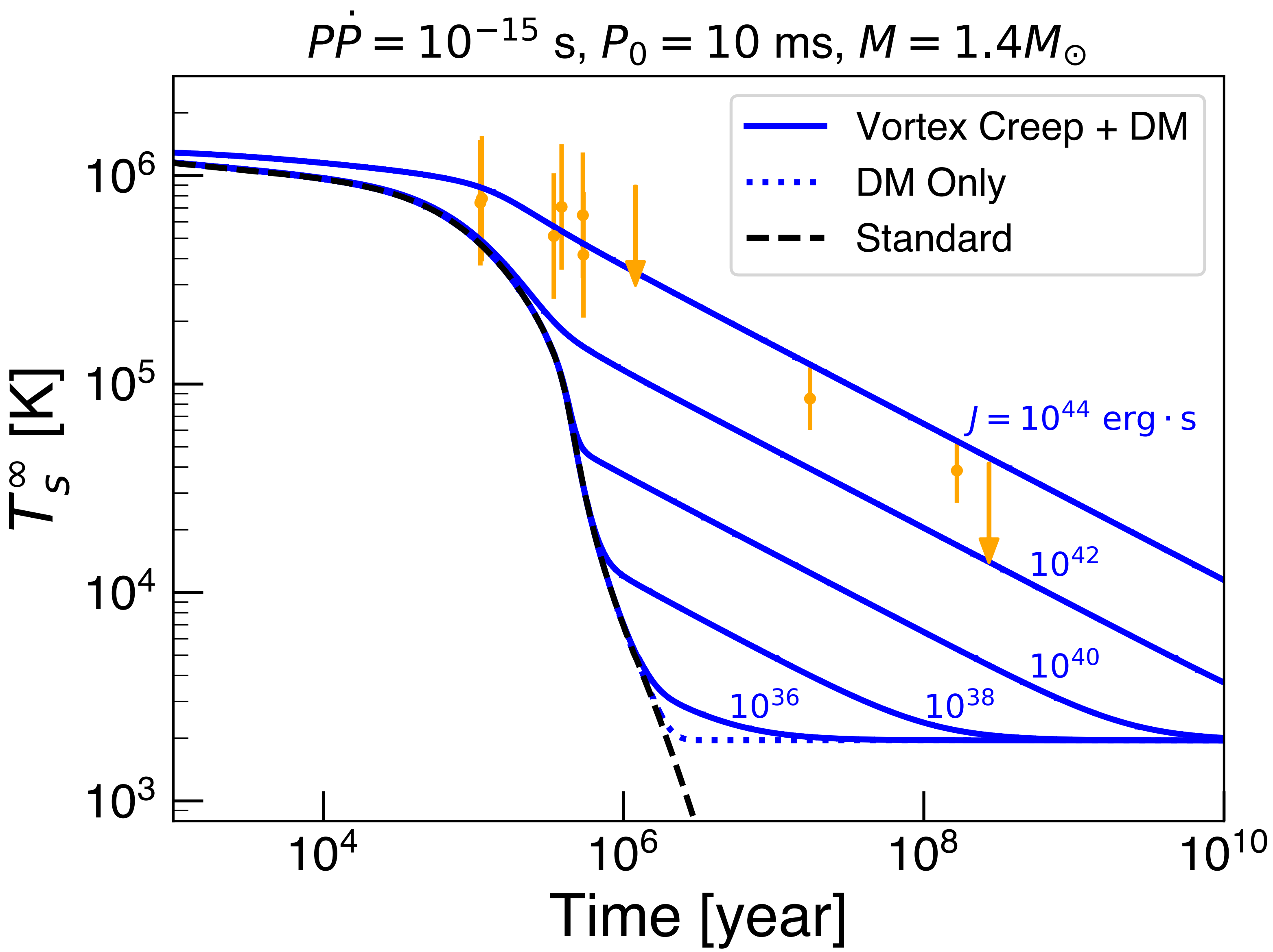
Distribution of known pulsars

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).

Vortex creep heating vs DM heating



The DM heating is buried under the vortex creep heating unless

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

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).

Conclusion

Conclusion

- Recent observations indicate the presence of old but warm NSs.

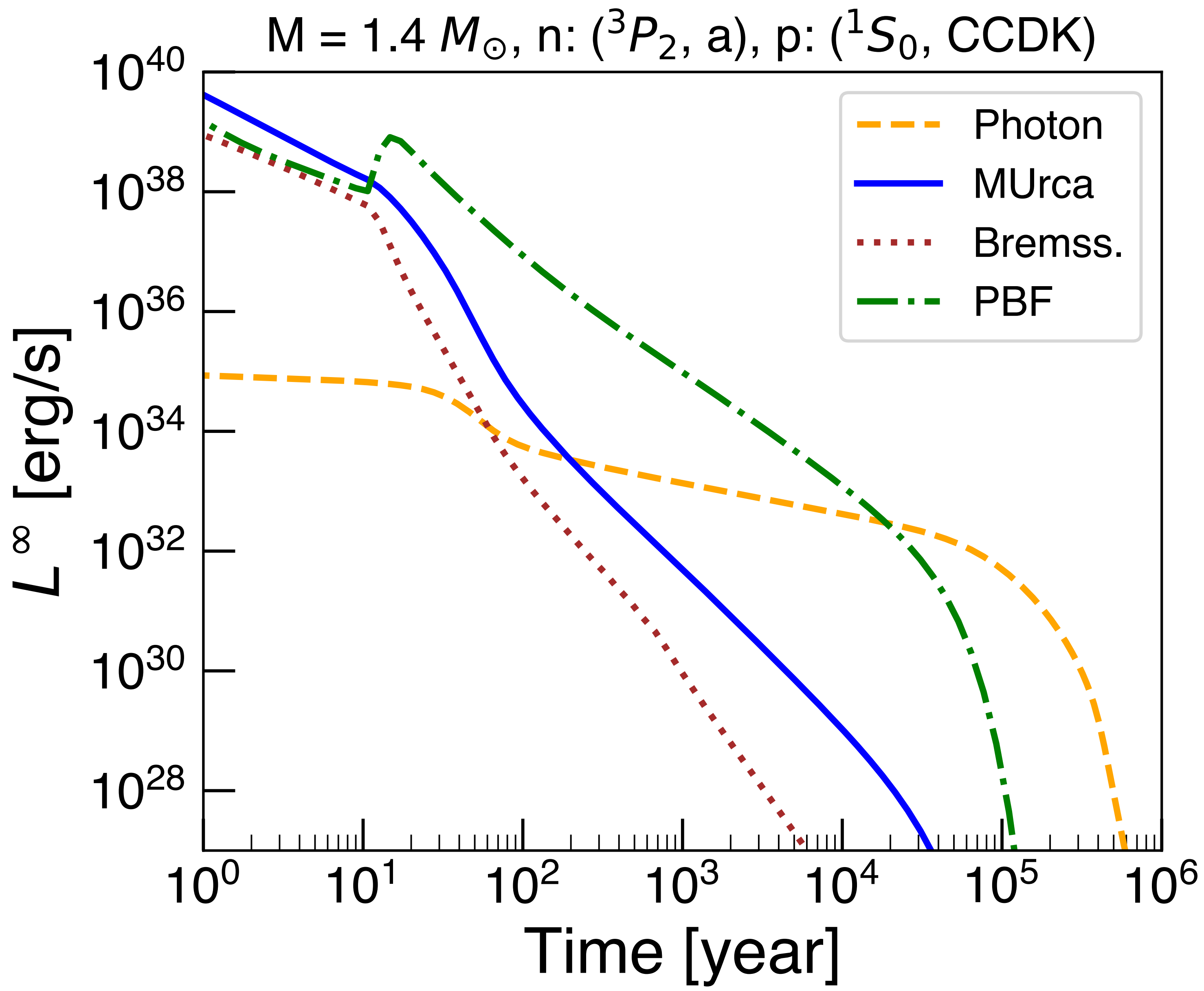
- Vortex creep heating can explain these data.

- If this is the case, the DM heating effect will most likely be concealed by the vortex creep heating.

We need to first test the vortex creep heating mechanism with future observations.

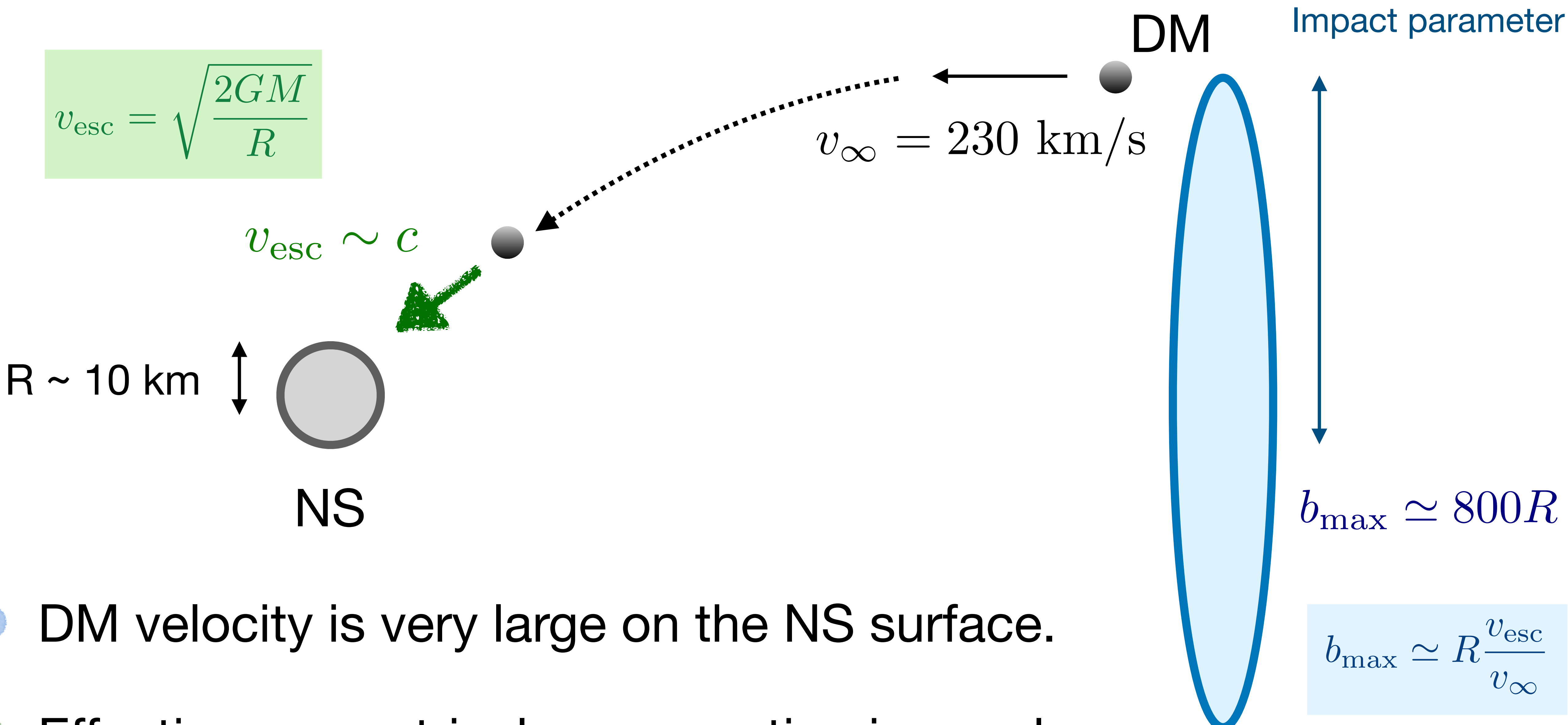
Backup

Luminosity



- Photon emission becomes dominant after ~10^5 years.
- Neutrino emission is extremely suppressed at later times.

Dark matter accretion in NS



- DM velocity is very large on the NS surface.
- Effective geometrical cross section is very large.

DM accretion rate is

$$\dot{N} \simeq \pi b_{\max}^2 v_\infty \cdot \frac{\rho_{\rm DM}}{m_{\rm DM}}$$

DM number density

Dark matter accretion in NS

It is found that

- One scattering is enough for WIMPs to be captured.

  Energy transfer ~ 100 MeV — 1 GeV.

- At least one scattering occurs if $\sigma_N \gtrsim 10^{-45}\ \mathrm{cm}^2$.

For old NSs, we have

Accretion rate = Annihilation rate

equilibrium

$$\Rightarrow \quad L_H \simeq m_{\rm DM} \dot{N} \simeq 2\pi G M R \rho_{\rm DM} / v_\infty$$

Independent of DM mass.

Recoil energy

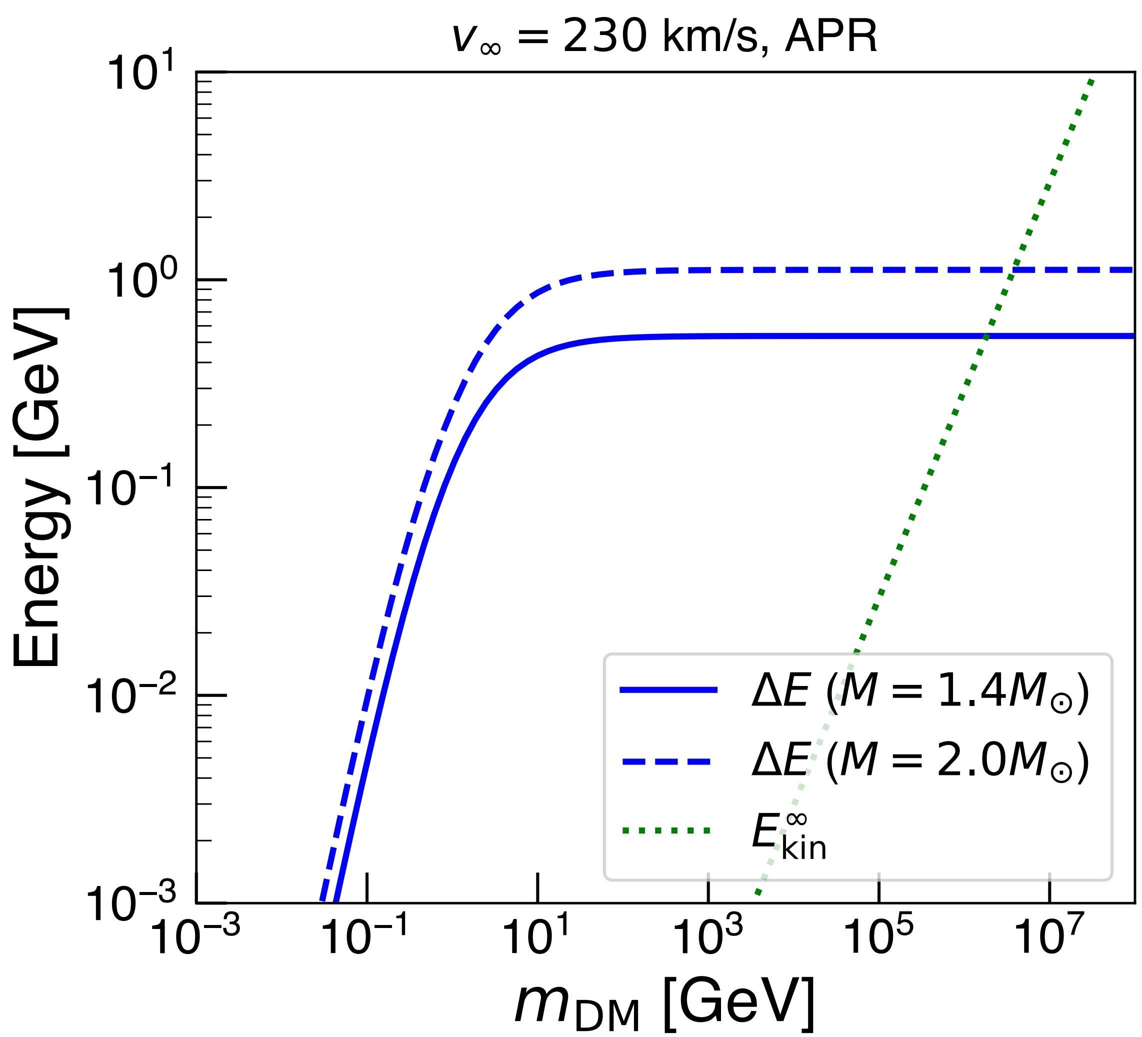
For each DM-nucleon scattering, WIMPs lose energy by

$$\Delta E = \frac{m_N m_{\rm DM}^2 \gamma_{\rm esc}^2 v_{\rm esc}^2}{m_N^2 + m_{\rm DM}^2 + 2\gamma_{\rm esc} m_{\rm DM} m_N}(1 - \cos\theta_c)$$

θ_c : scattering angle in the CM frame.

$\gamma_{\rm esc} \equiv (1 - v_{\rm esc}^2)^{-1/2}$

Let us compare this with the initial kinetic energy: $E_{\rm kin}^{\infty} = m_{\rm DM} v_{\infty}^2/2$



- One scattering is sufficient for WIMPs to lose the initial kinetic energy.
- Energy transfer can be as large as O(100) MeV.

One scattering in NS

WIMP-nucleon scattering occurs at least once if

$$\text{Mean Free Path} \sim (\sigma_N n)^{-1} \sim \frac{m_N R^3}{M \sigma_N} \lesssim R \quad \Rightarrow \quad \sigma_N \gtrsim 10^{-45}\ \text{cm}^2$$

σ_N : DM-nucleon scattering cross section

If this is satisfied, then all of the accreted WIMPs are captured.

If not, capture rate is suppressed by $\sigma_N / \sigma_{\text{th}}$.

Captured WIMPs eventually annihilate inside the NS core.

For old NSs, we have

Accretion rate = Annihilation rate

equilibrium

NS temperature with DM heating

At later times, the DM heating balances with the cooling by photon emission.

$$L_H = L_\gamma$$

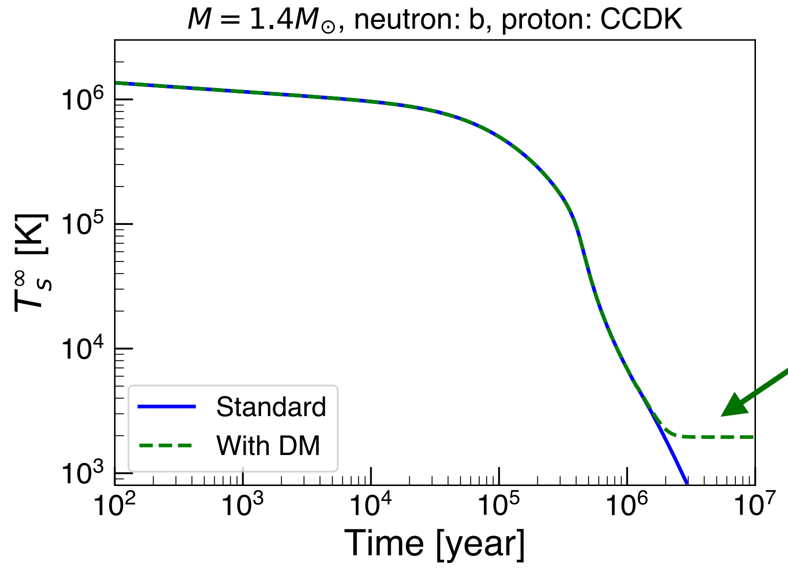
$$L_H \simeq m_{\rm DM}\dot{N} \simeq 2\pi G M R \rho_{\rm DM}/v_\infty$$

Independent of DM mass.

$$2\pi G M R \rho_{\rm DM}/v_\infty \simeq 4\pi R^2 \sigma_{\rm SB} T_s^4$$

(for $\sigma > \sigma_{\rm th}$)

$$T_s \simeq 2500 \text{ K}$$



Robust, smoking-gun prediction of DM heating.

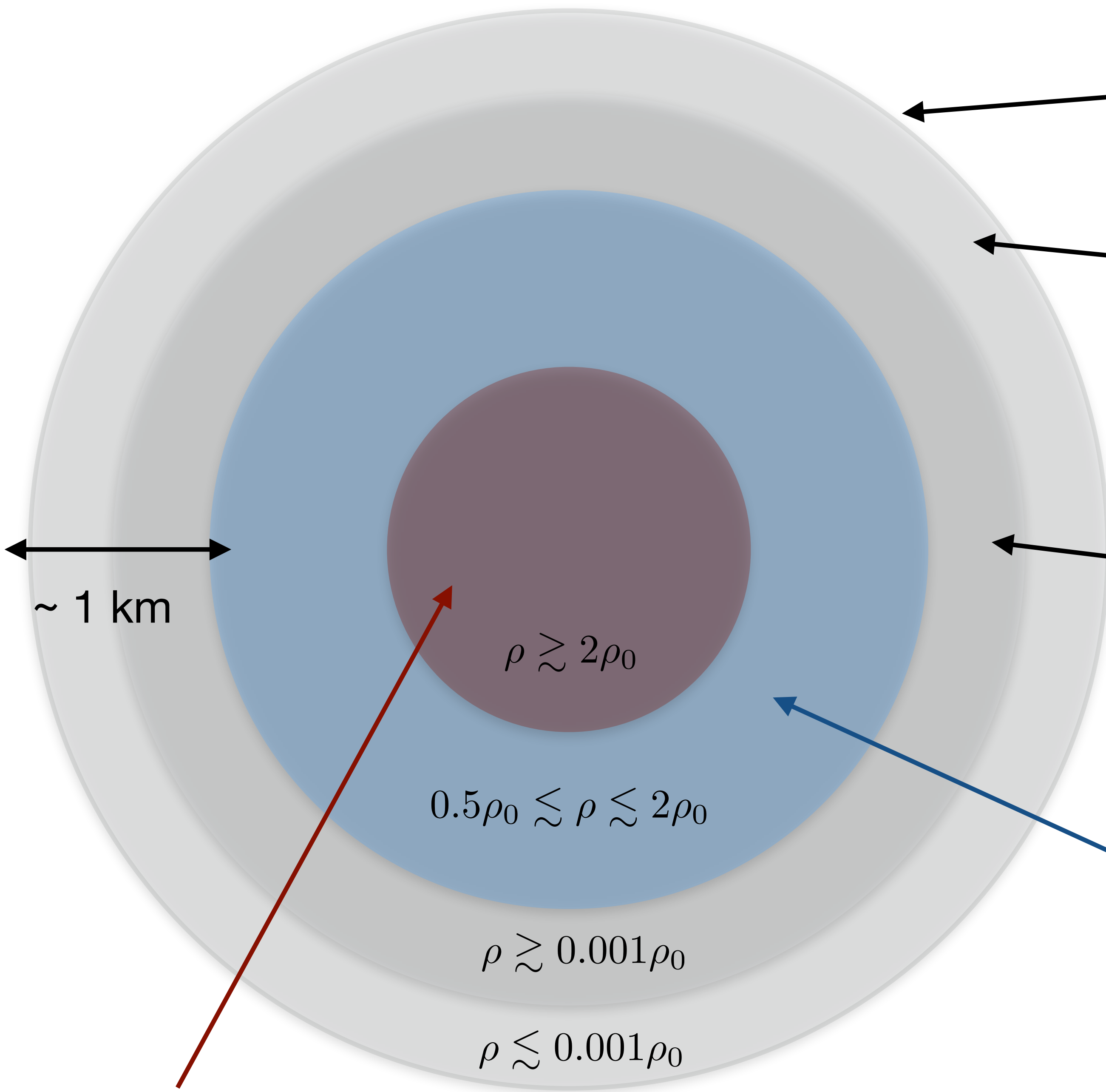
Can we observe this??

Advantage of DM heating in NSs

Bound from NS temperature may surpass those from DM direct searches in the following cases:

- Inelastic scattering occurs for $\Delta M \lesssim \mathcal{O}(100)$ MeV.
- DM interacts only with leptons.
- DM-nucleon scattering is velocity-suppressed.
- Spin-dependent scattering
- Heavy/light dark matter

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: $^1S_0$

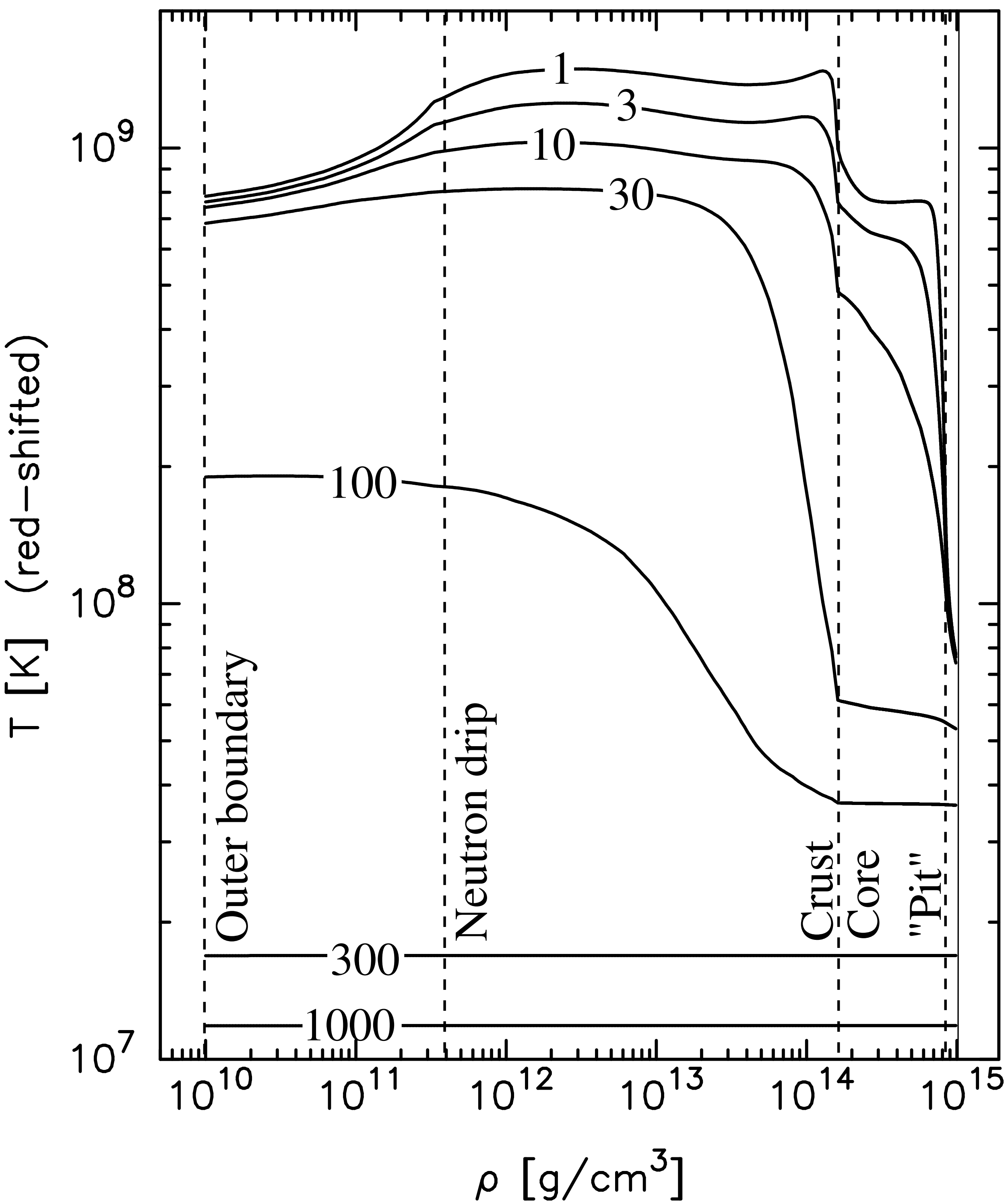
Inner core

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

Neutron superfluid: $^3P_2$

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

Temperature distribution

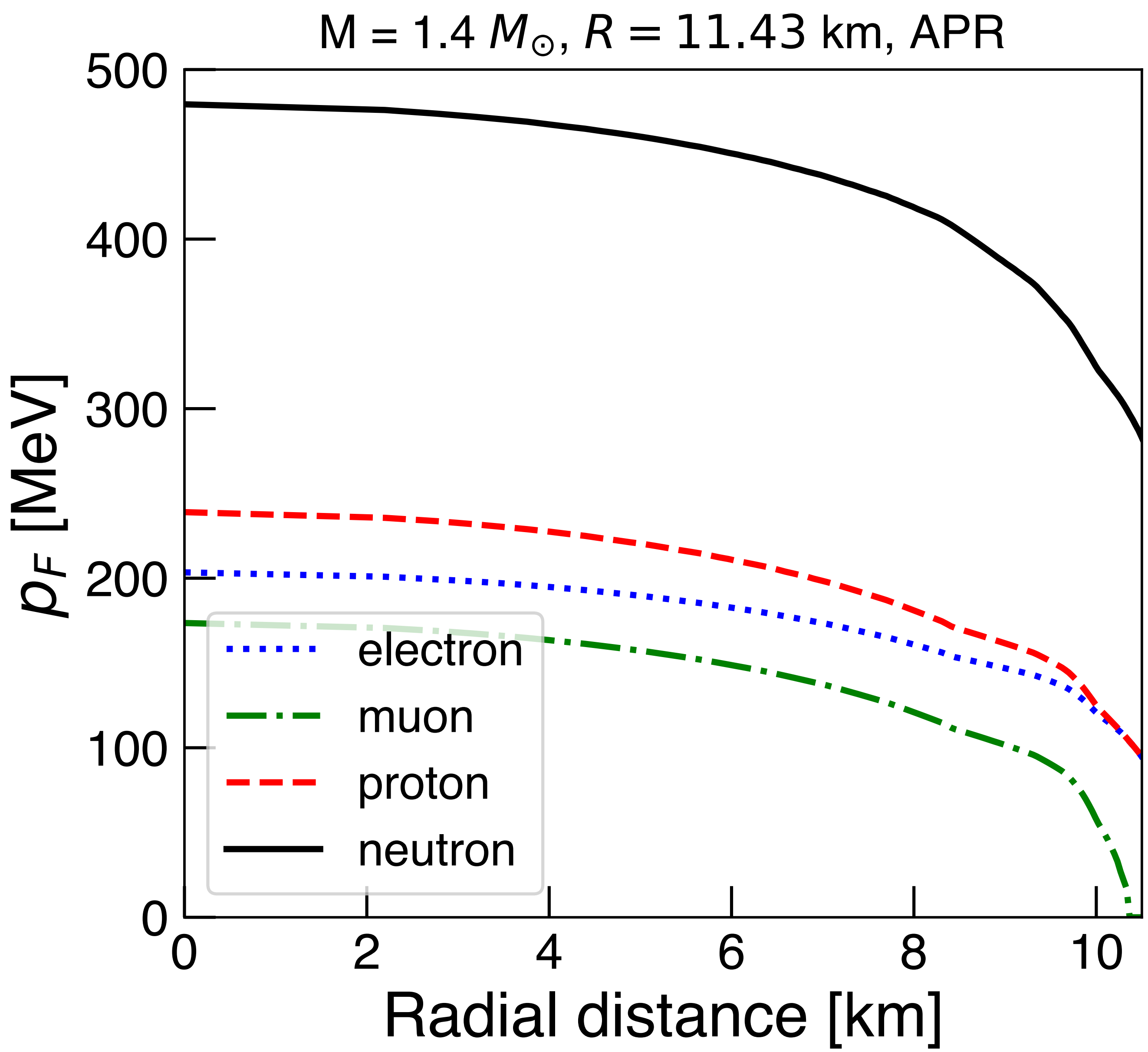


Relaxation in the Core done in ~ 100 years.

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

Fermi momenta

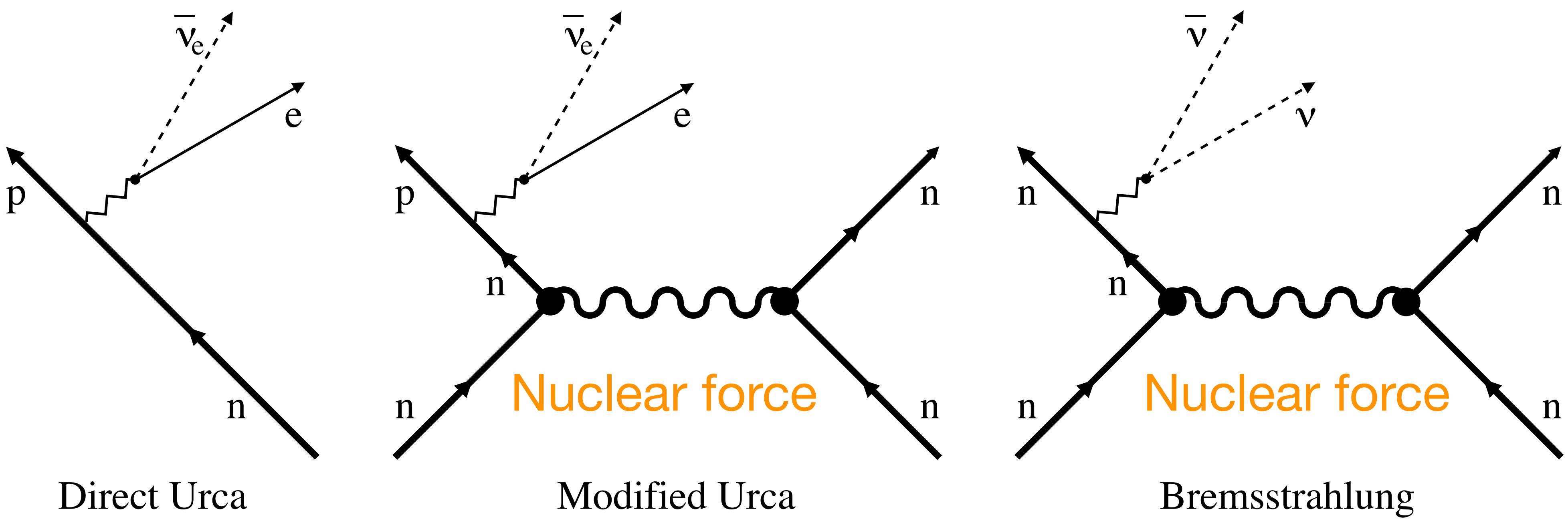
Fermi momenta in neutron star



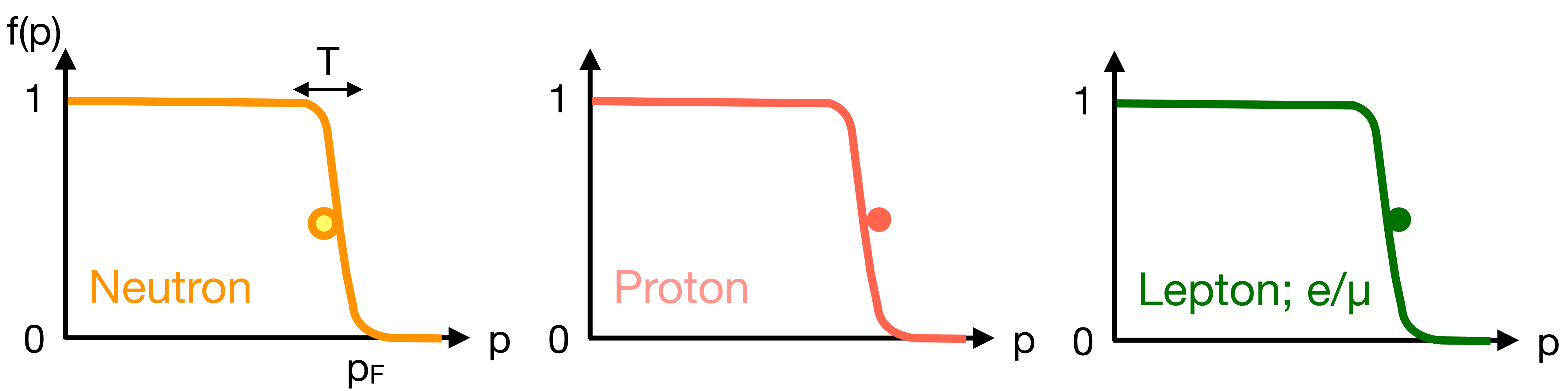
- Fermi momentum of neutron is large: 300—500 MeV
- Muons also appear in the region where $\mu_e > m_\mu$.

Neutrino emission

First we consider the processes that occur without superfluidity.



These processes occur only near the Fermi surface.



β equilibrium

Inside neutron stars, β equilibrium is achieved via the direct/modified Urca reactions

Chemical equilibrium

$$\mu_e + \mu_p = \mu_n$$

Chemical potential of neutrino is zero since it can escape from neutron star.

Charge neutrality

$$n_p = n_e$$

Muons also appear in the region where $\mu_e > m_\mu$.

Chemical equilibrium

$$\mu_e = \mu_\mu \quad (\mu_\mu + \mu_p = \mu_n)$$

Charge neutrality

$$n_p = n_e + n_\mu$$

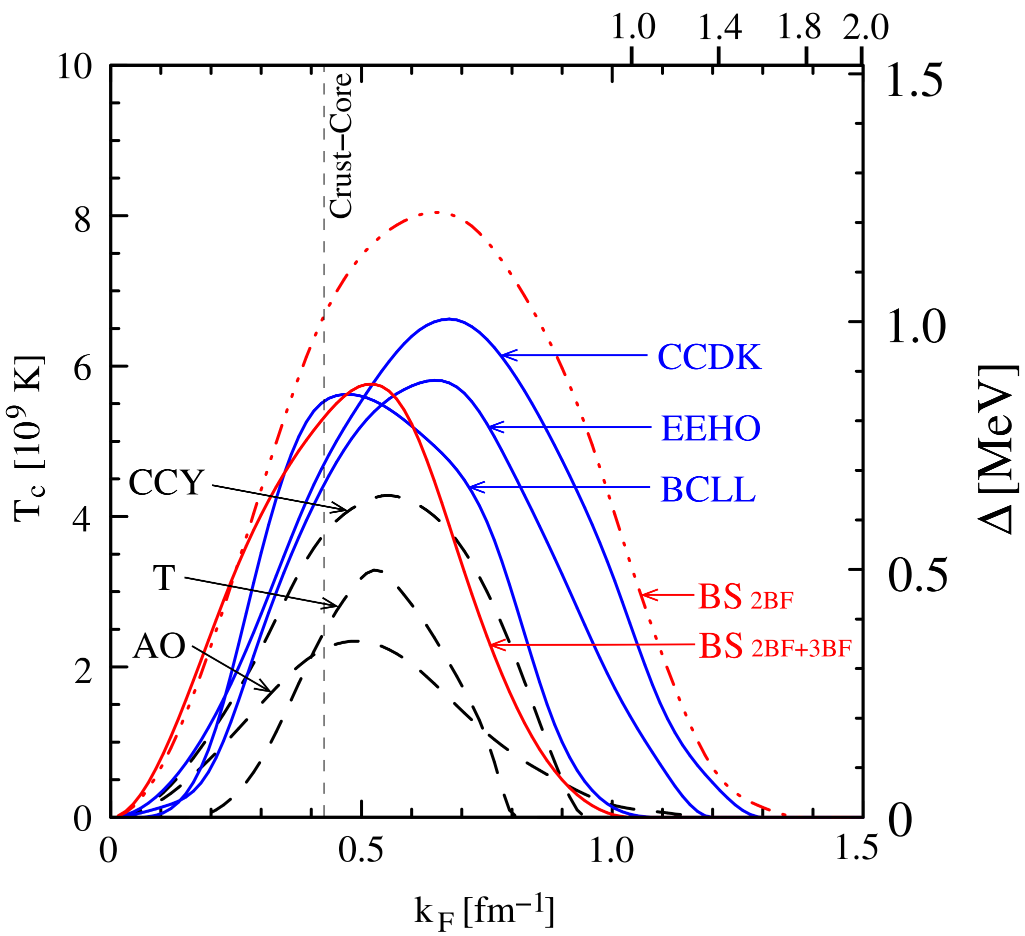
Nucleon pairing

Nucleons in a NS form pairings below their critical temperatures:

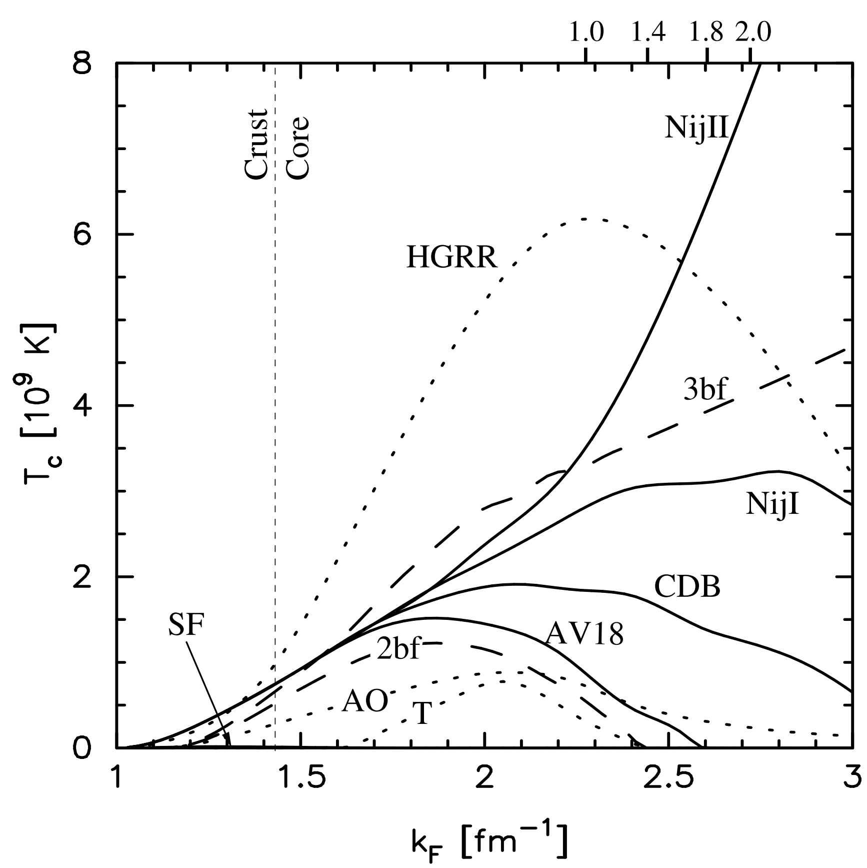
- Neutron singlet $^1S_0$ ⟵ Only in the crust. Less important.
- Proton singlet $^1S_0$
- Neutron triplet $^3P_2$

(Proton singlet and neutron triplet) ⟵ Form in the core. Important.

Proton singlet pairing gap



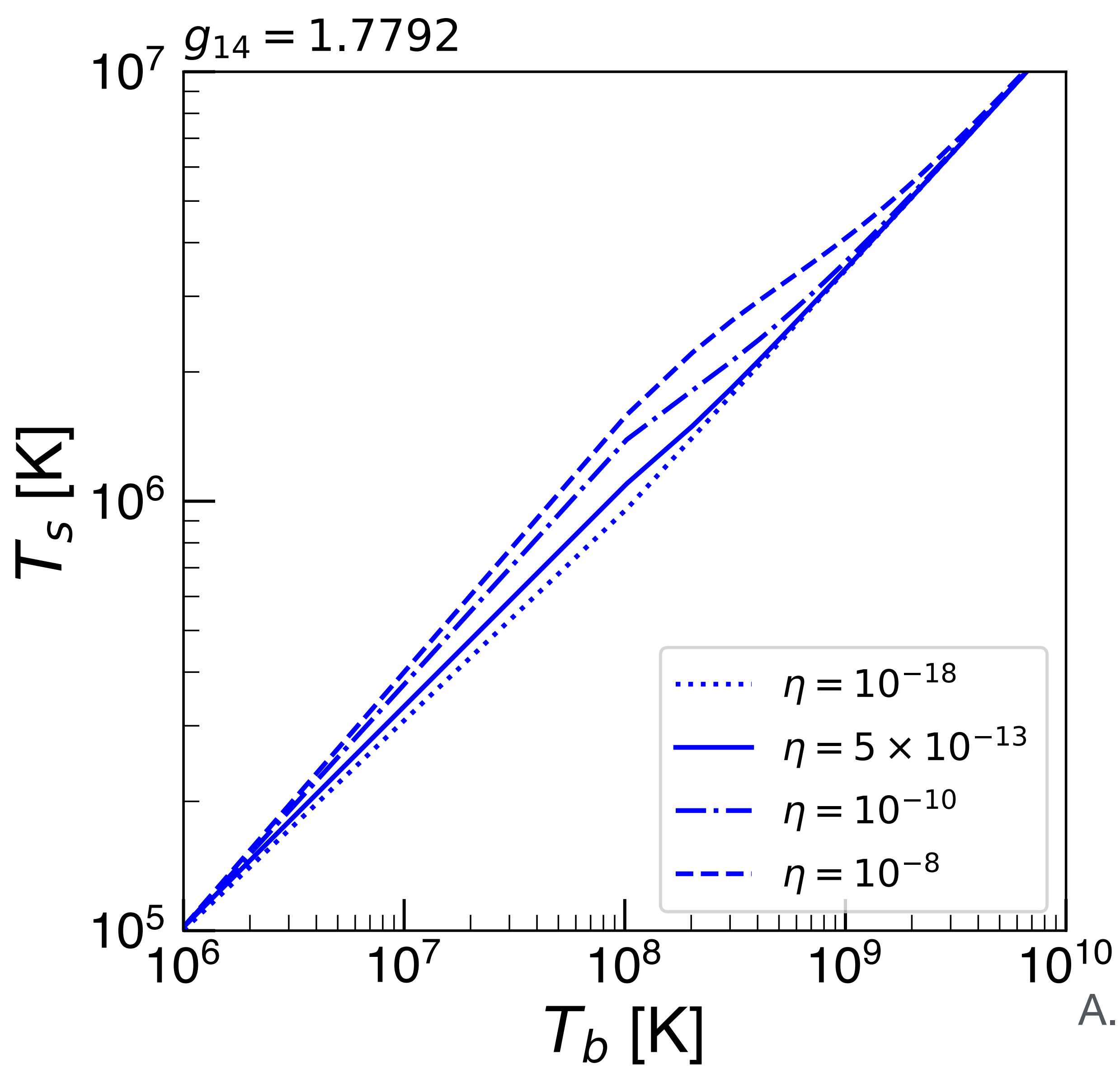
Neutron triplet pairing gap



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

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.

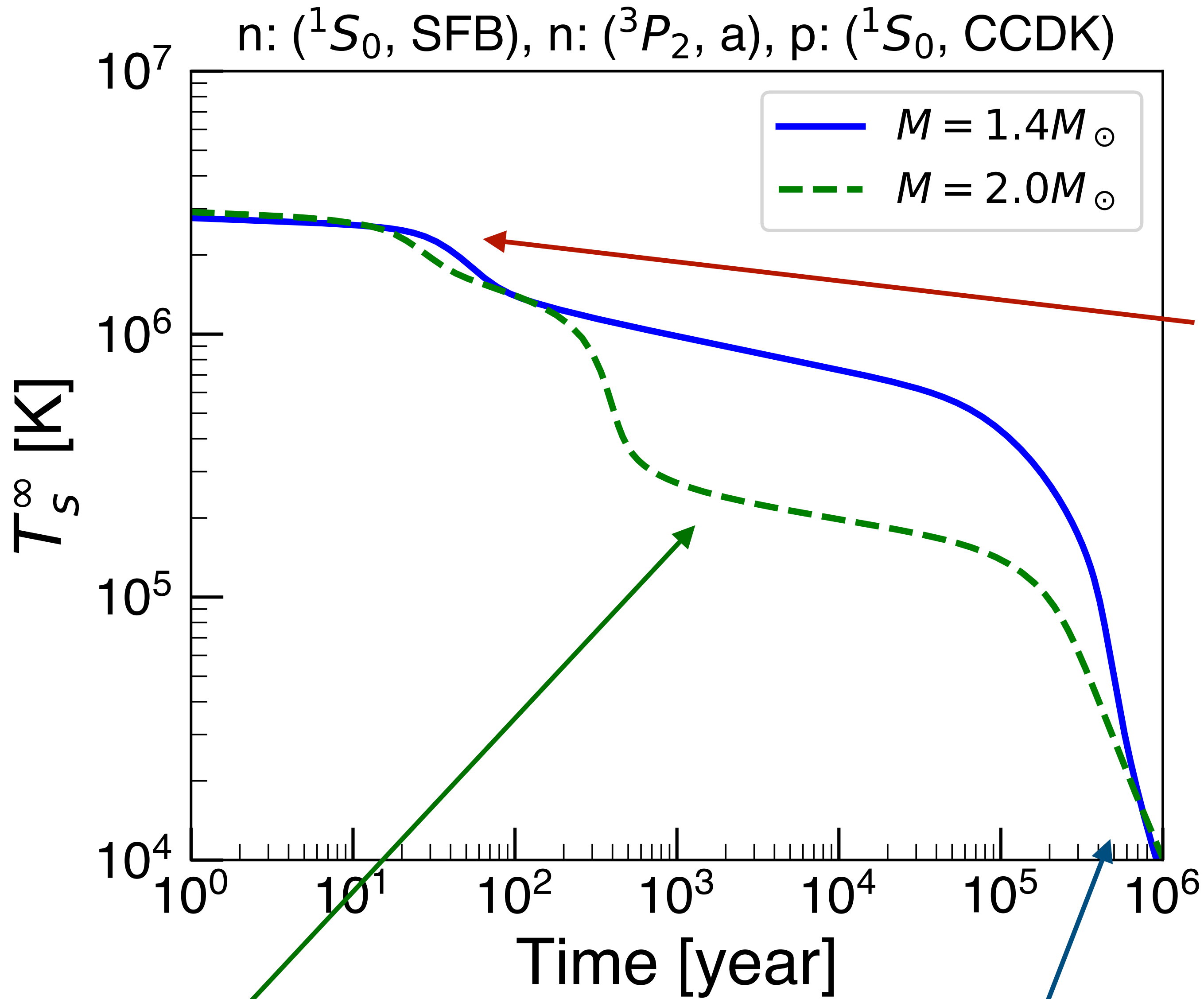
A. Y. Potekhin, G. Chabrier, and D. G. Yakovlev, A&A **323,** 415 (1997).

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

Light elements have large thermal conductivities.

Temperature evolution

We can now solve the equation for temperature evolution:

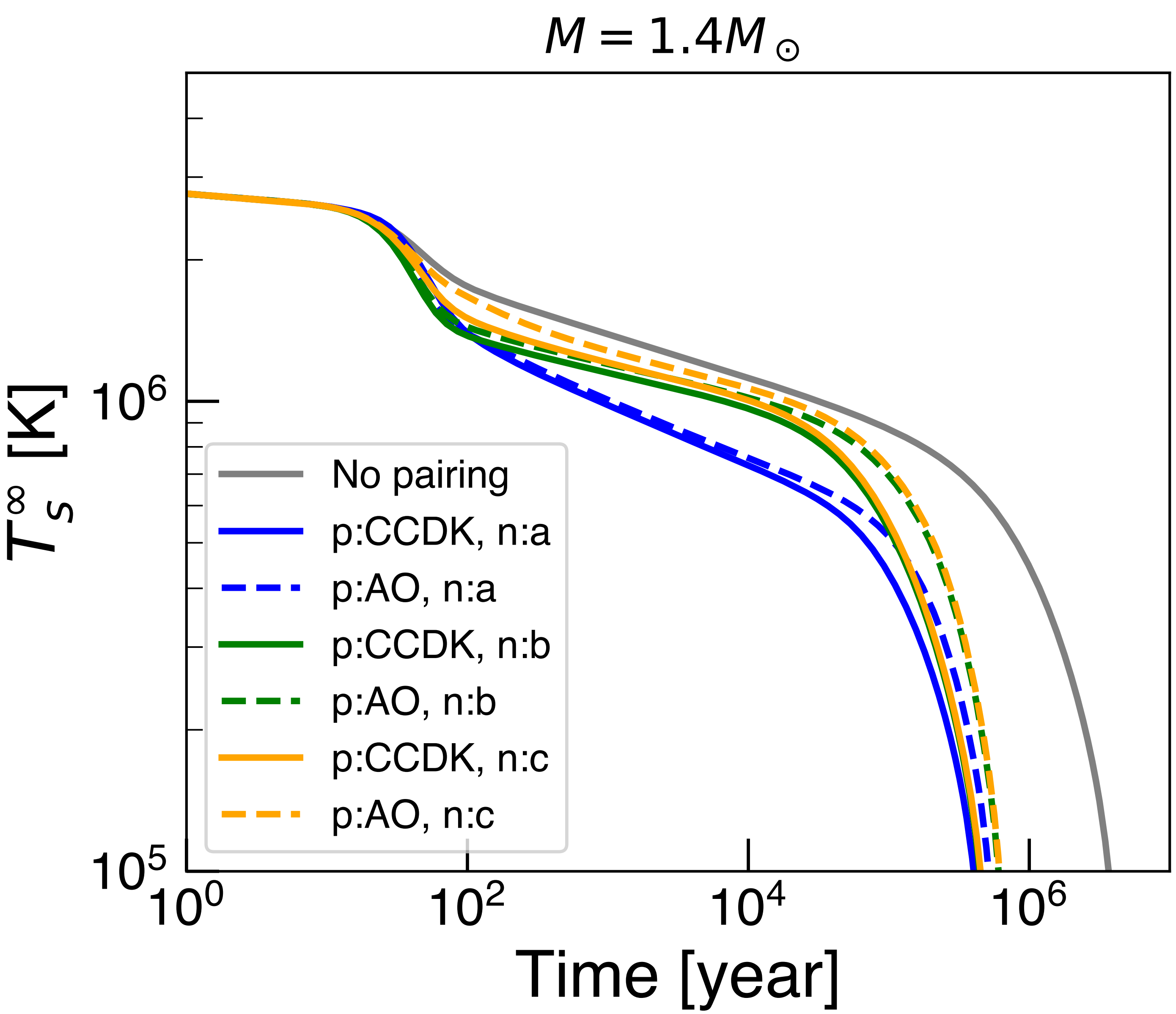


Before the thermal relaxation completed, the surface temperature does not follow the internal temperature.

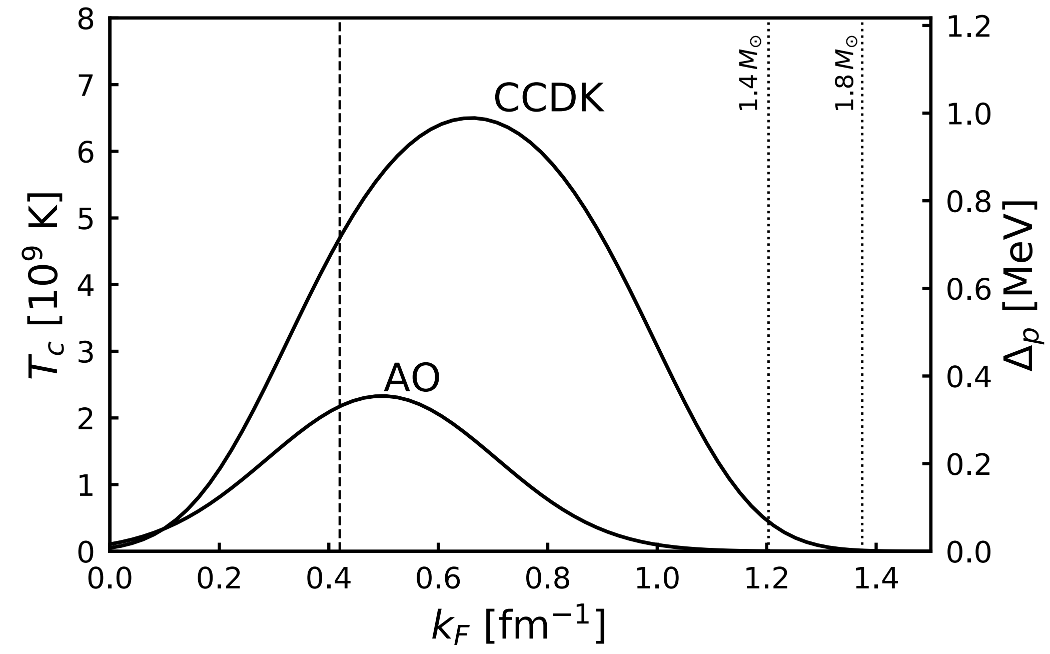
If Direct Urca occurs, the neutron star cools down rapidly.

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

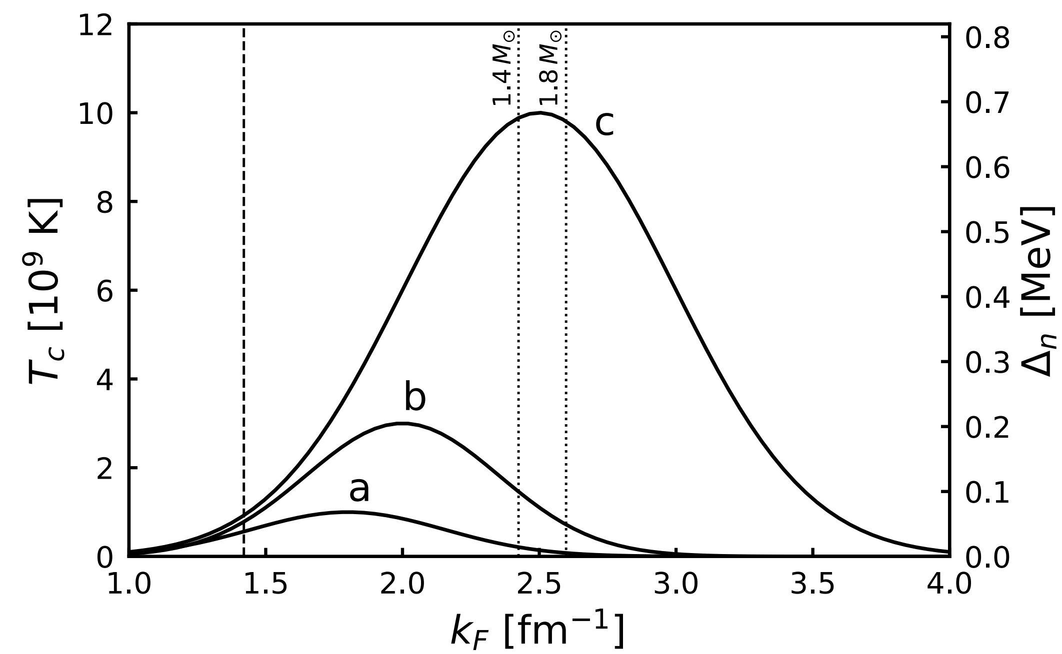
Temperature evolution (gap dependence)



Proton singlet gap



Neutron triplet gap



Uncertainty in nucleon gap models lead to the theoretical errors in the cooling calculation.

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

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

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

Agrees within ~ 30%.