中性子星温度観測を通じたWIMP暗黒物質探索

Probing WIMP dark matter via the temperature observations of neutron stars

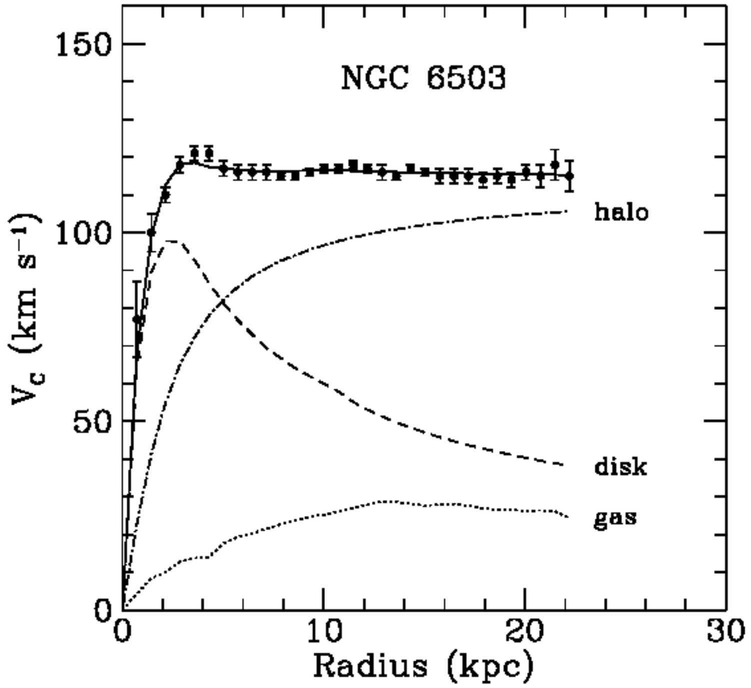
永田夏海 (Natsumi Nagata)

東京大学 (University of Tokyo)

〜中性子星の観測と理論〜研究活性化ワークショップ 2023
京都大学理学研究科セミナーハウス
2022年9月6—8日

Evidence for dark matter (DM)

Rotational curves

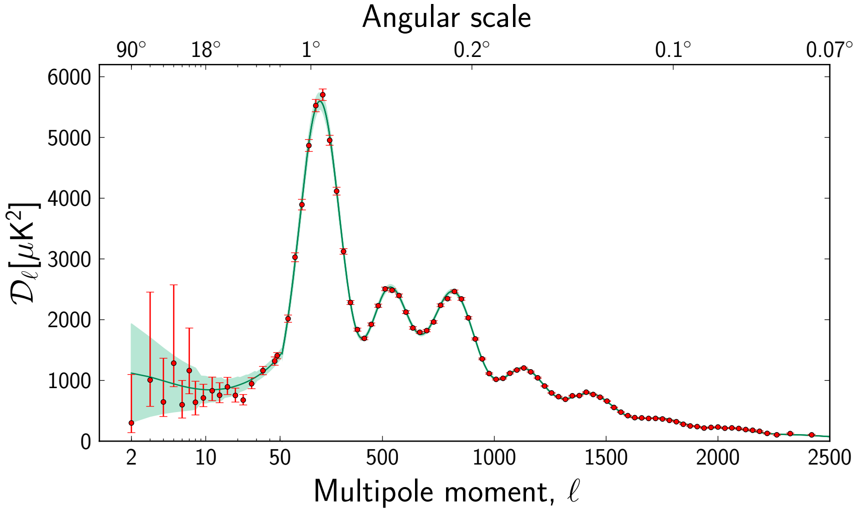


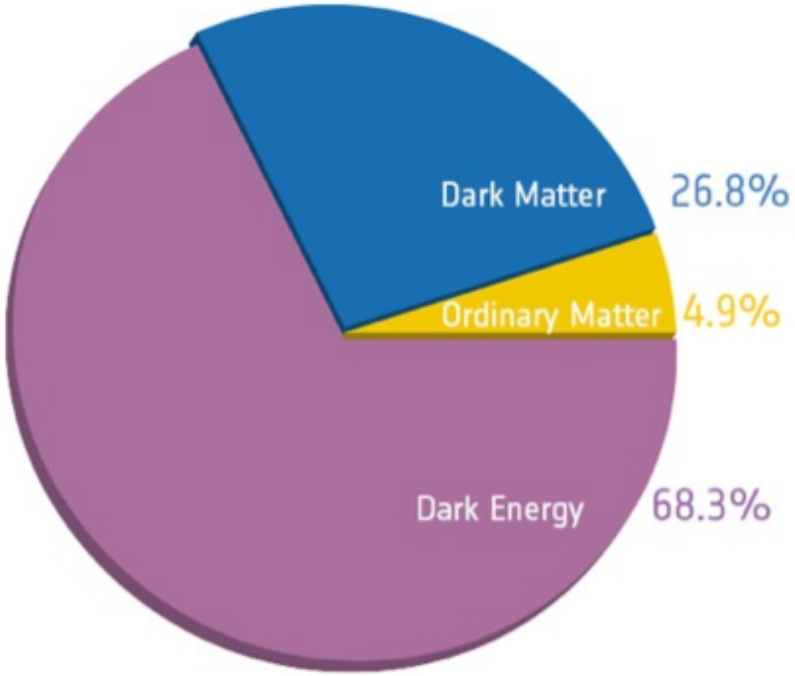
Begeman et. al. (1991)

Bullet cluster

Clowe et. al. (2006)

Cosmic microwave background





Planck (2013)

Dark matter (DM) exists.

But its nature is unknown…

WIMP

Weakly-Interacting Massive Particles (WIMPs)

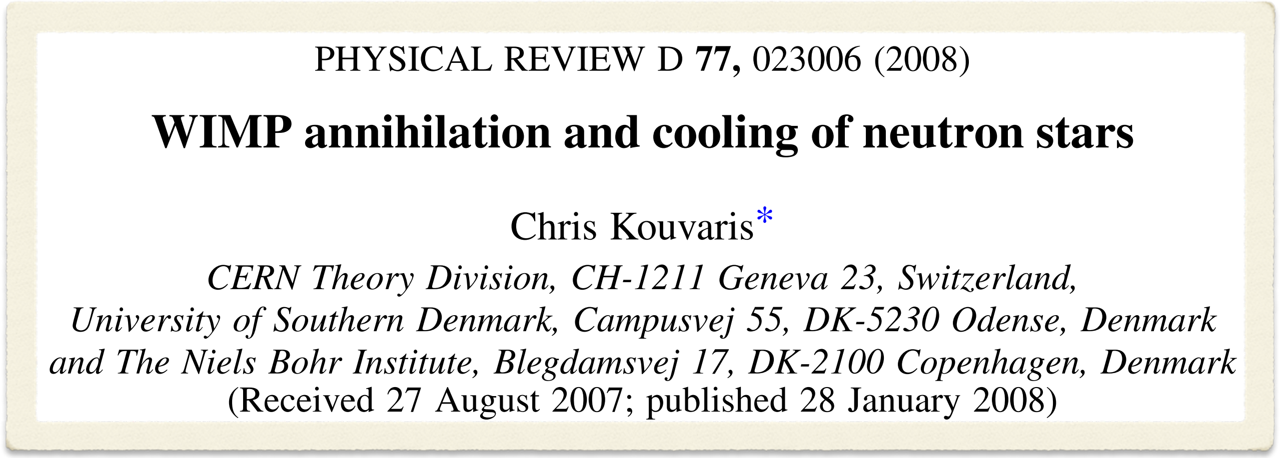
- Electrically neutral and colorless particles.
- Stable.
- Masses of O(100—1000) GeV.
- Have interactions comparable to EW interactions.

→ Observed Dark Matter (DM) density can be explained by their thermal relic.

Many new physics models predict such a particle.

WIMP dark matter heating in NS

It has been discussed that the signature of WIMP DM may be detected via the neutron star temperature observations.



PHYSICAL REVIEW D **77,** 023006 (2008)

WIMP annihilation and cooling of neutron stars

Chris Kouvaris*

CERN Theory Division, CH-1211 Geneva 23, Switzerland,
University of Southern Denmark, Campusvej 55, DK-5230 Odense, Denmark
and The Niels Bohr Institute, Blegdamsvej 17, DK-2100 Copenhagen, Denmark
(Received 27 August 2007; published 28 January 2008)

PHYSICAL REVIEW D **81,** 123521 (2010)

Neutron stars as dark matter probes

Arnaud de Lavallaz* and Malcolm Fairbairn†

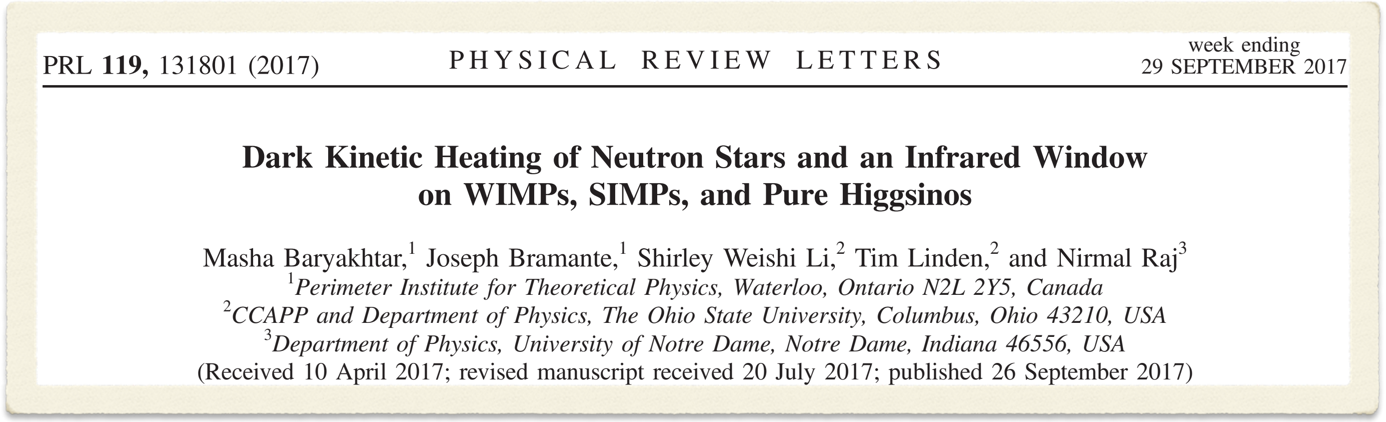
Physics, King's College London, Strand, London WC2R 2LS, United Kingdom
(Received 6 April 2010; published 18 June 2010)

PHYSICAL REVIEW D **82,** 063531 (2010)

Can neutron stars constrain dark matter?

Chris Kouvaris* and Peter Tinyakov†

Service de Physique Théorique, Université Libre de Bruxelles, 1050 Brussels, Belgium
(Received 29 May 2010; published 28 September 2010)



PRL **119,** 131801 (2017) PHYSICAL REVIEW LETTERS week ending 29 SEPTEMBER 2017

Dark Kinetic Heating of Neutron Stars and an Infrared Window on WIMPs, SIMPs, and Pure Higgsinos

Masha Baryakhtar,[1] Joseph Bramante,[1] Shirley Weishi Li,[2] Tim Linden,[2] and Nirmal Raj[3]
[1]*Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada*
[2]*CCAPP and Department of Physics, The Ohio State University, Columbus, Ohio 43210, USA*
[3]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
(Received 10 April 2017; revised manuscript received 20 July 2017; published 26 September 2017)

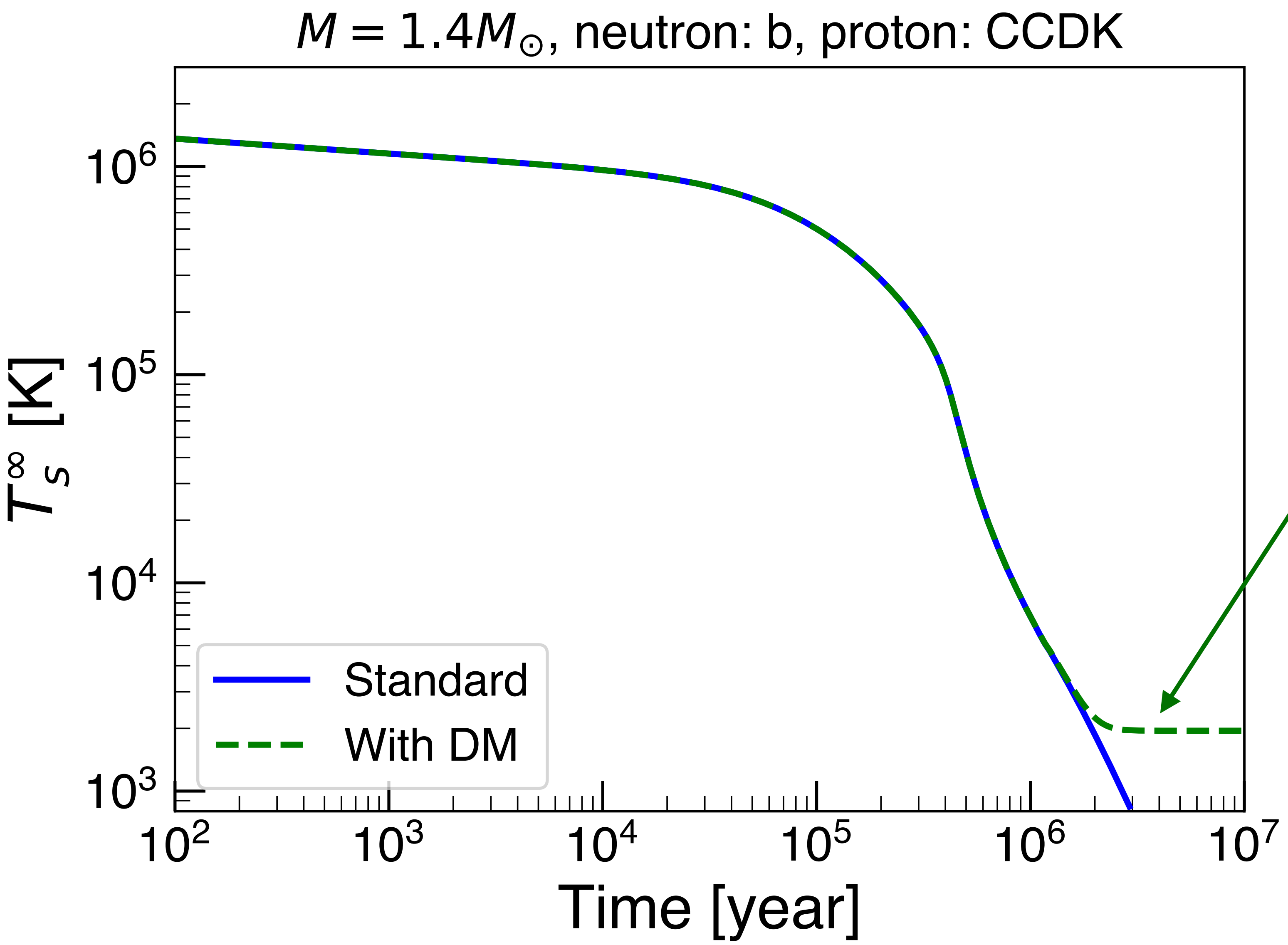
Idea

WIMP DM accretes on a neutron star (NS).

Annihilation of WIMPs in the NS core causes heating effect.

WIMP dark matter heating in NS

Dark matter heating effect may be observed in old NSs.



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

Condition for capture

$L_\gamma \simeq L_{\rm DM}$

- 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.

Questions

Is this strategy promising?

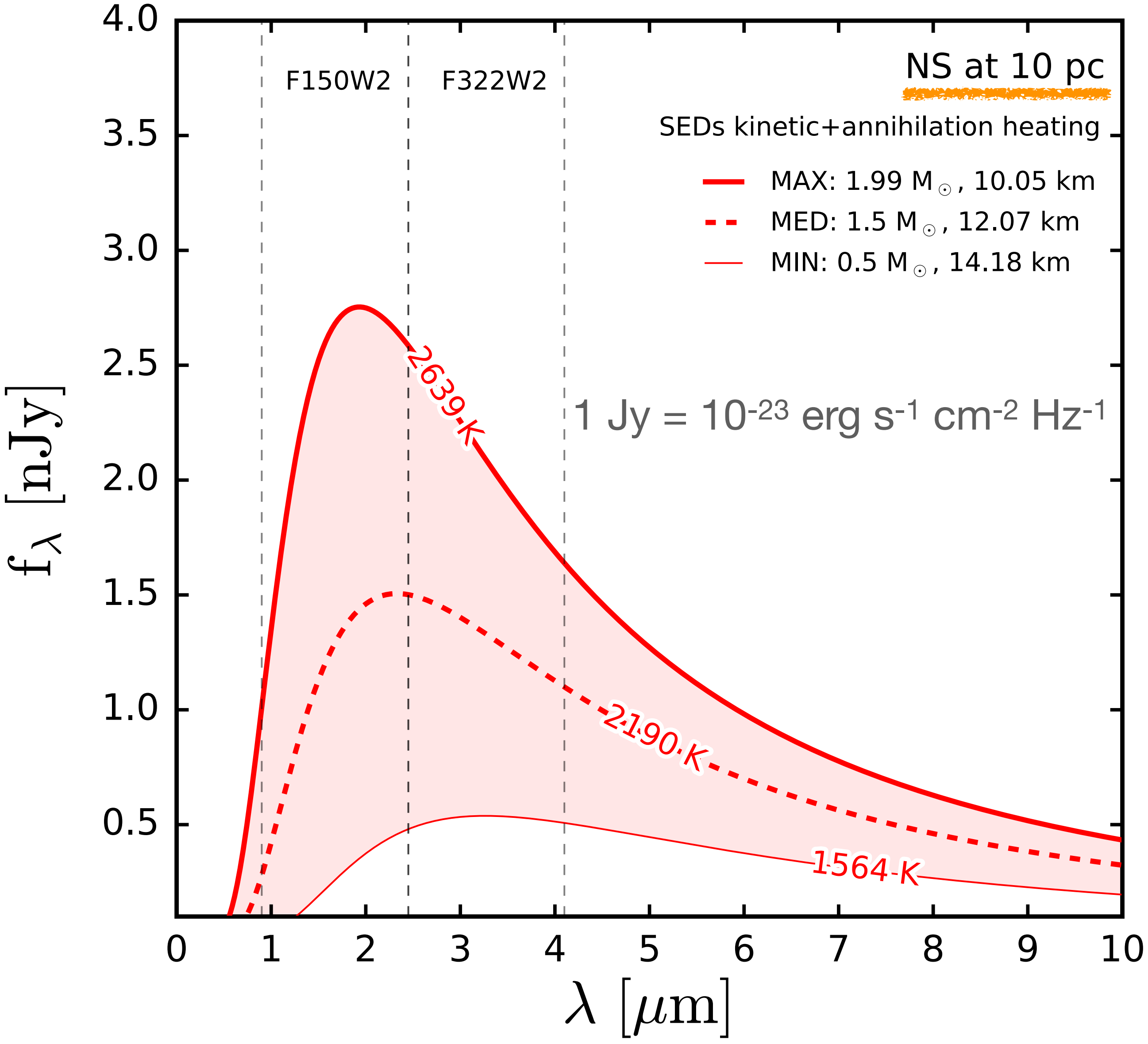
- Observation
  - Nearby old NSs
  - IR telescopes
- Theory

  Validity of the standard cooling in old NSs?

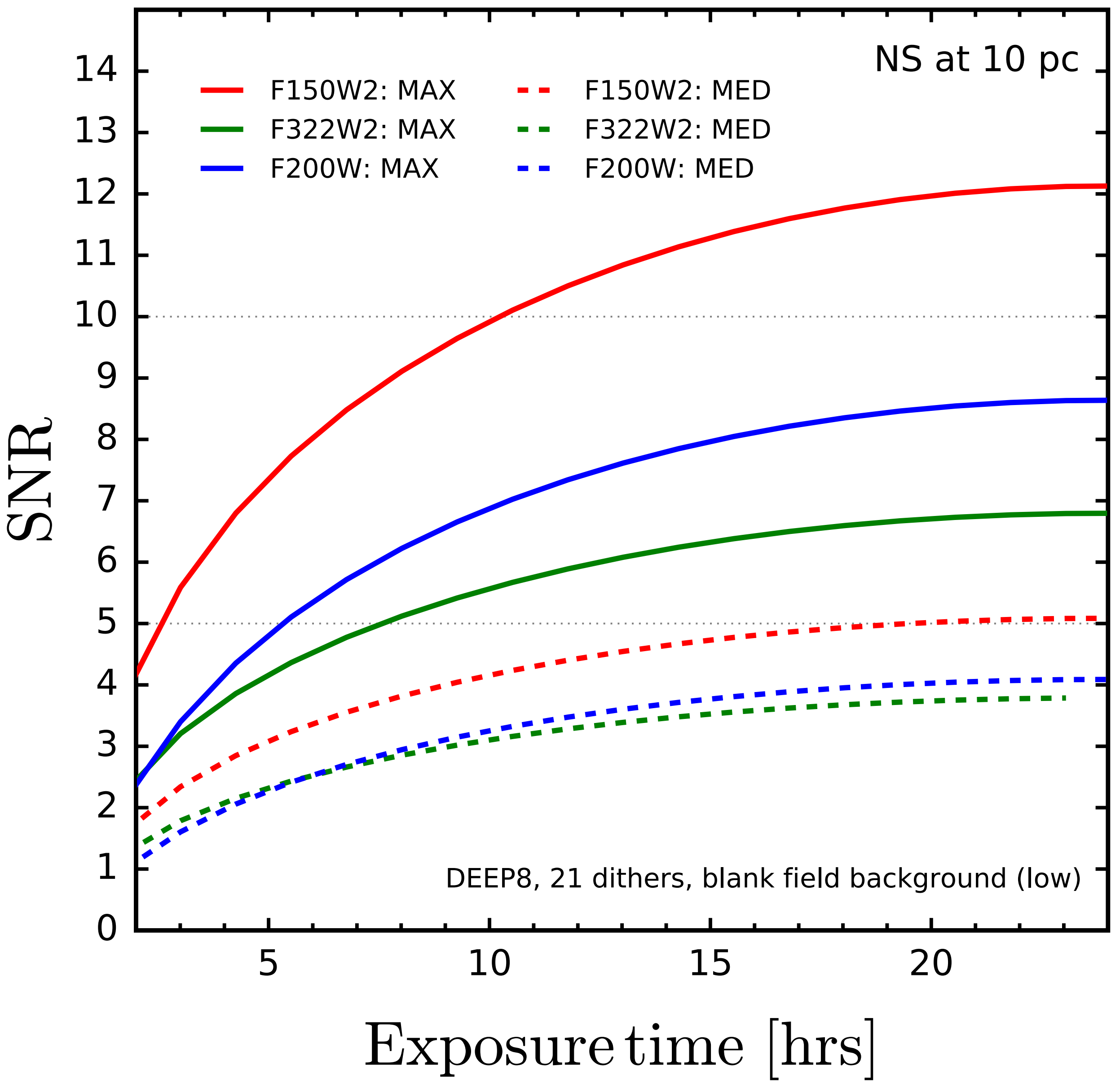
JWST study

S. Chatterjee, et.al., Phys. Rev. D **108**, 2 (2023).

Spectral distributions



Signal-to-noise ratio



- $\lambda \sim 2\ \mu m$ ➡ Near-Infrared Camera (NIRCam) on JWST
- With the F150W2 filter, SNR $\gtrsim 5$ is obtained for 24 hours.

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.

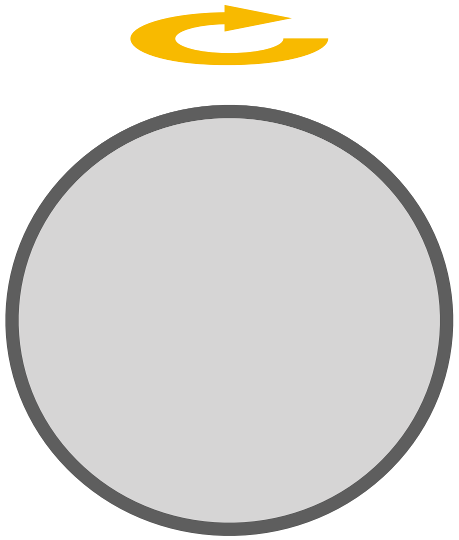
Candidates for heating sources

Heating mechanisms discussed in the literature:

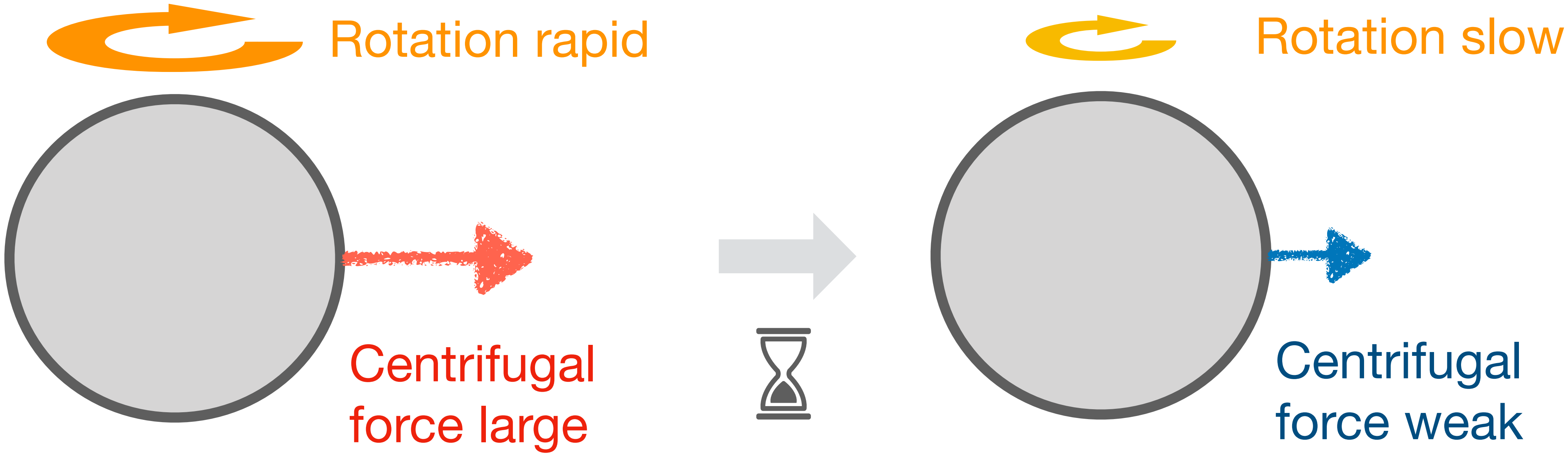
- Non-equilibrium beta processes
- Friction caused by vortex creep

Heat originates from the slowdown of pulsar rotation.

- Consistency with current observation?
- Implications for DM heating?



Rotochemical heating



Rotation rapid

Centrifugal force large

Rotation slow

Centrifugal force weak

Local pressure changes. Chemical equilibrium condition changes.

The beta processes are highly suppressed at later times.

⇒ Deviation from β equilibrium

A. Reisenegger, Astrophys. J. **442**, 749 (1995).

The imbalance in chemical potentials is dissipated as heat.

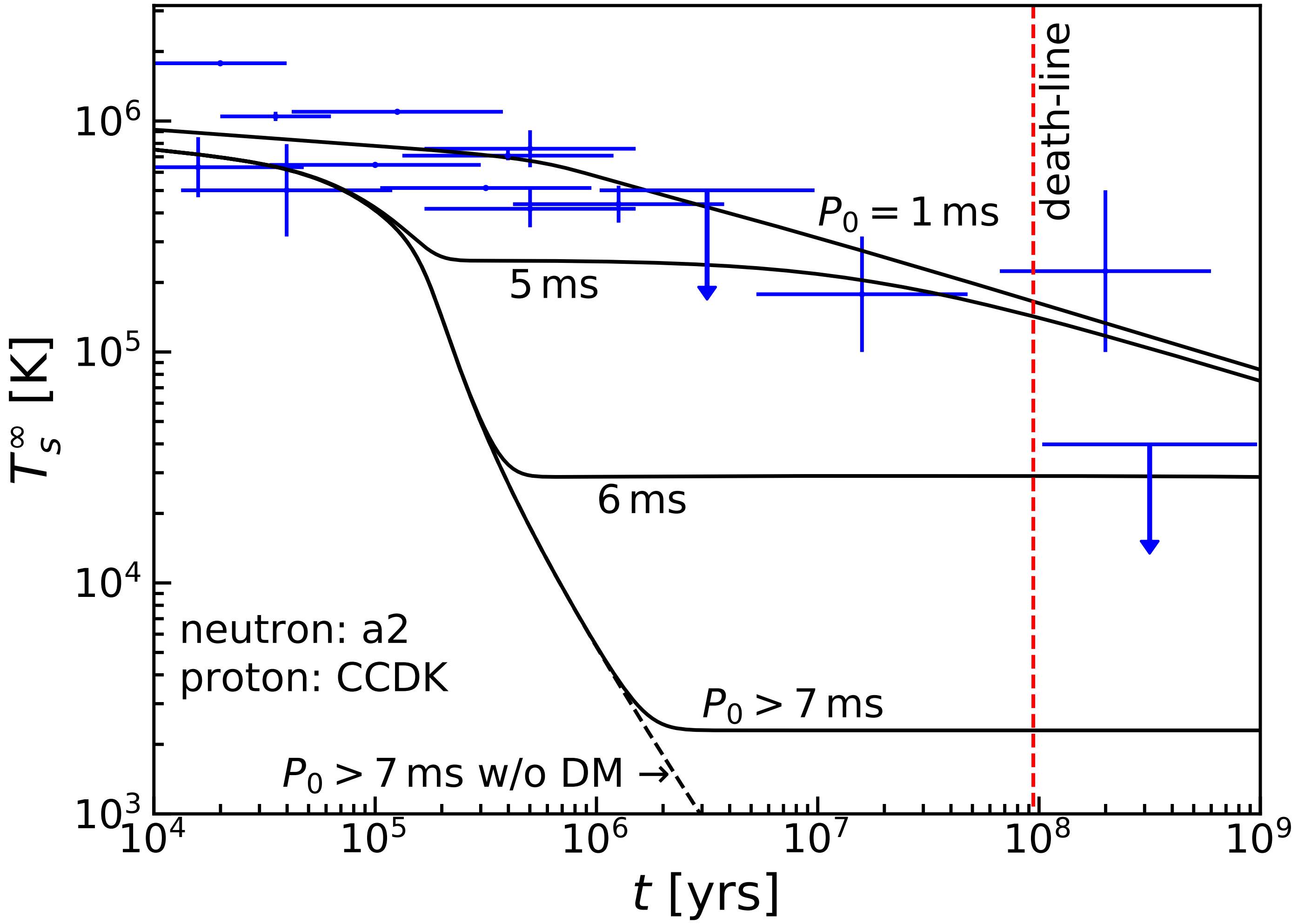
⇒ Rotochemical heating

R. Fernandez and A. Reisenegger, Astrophys. J. **625**, 291 (2005);
C. Petrovich, A. Reisenegger, Astron. Astrophys. **521**, A77 (2010).

Rotochemical heating vs DM heating

It turns out that rotochemical heating can explain the observed data.

K. Hamaguchi, N. Nagata, K. Yanagi, MNRS **492**, 5508 (2020).



- If P_0 is large enough, DM heating effect can be observed.
- It is always concealed in millisecond pulsars.

K. Hamaguchi, N. Nagata, K. Yanagi, Phys. Lett. **B795**, 484 (2019).

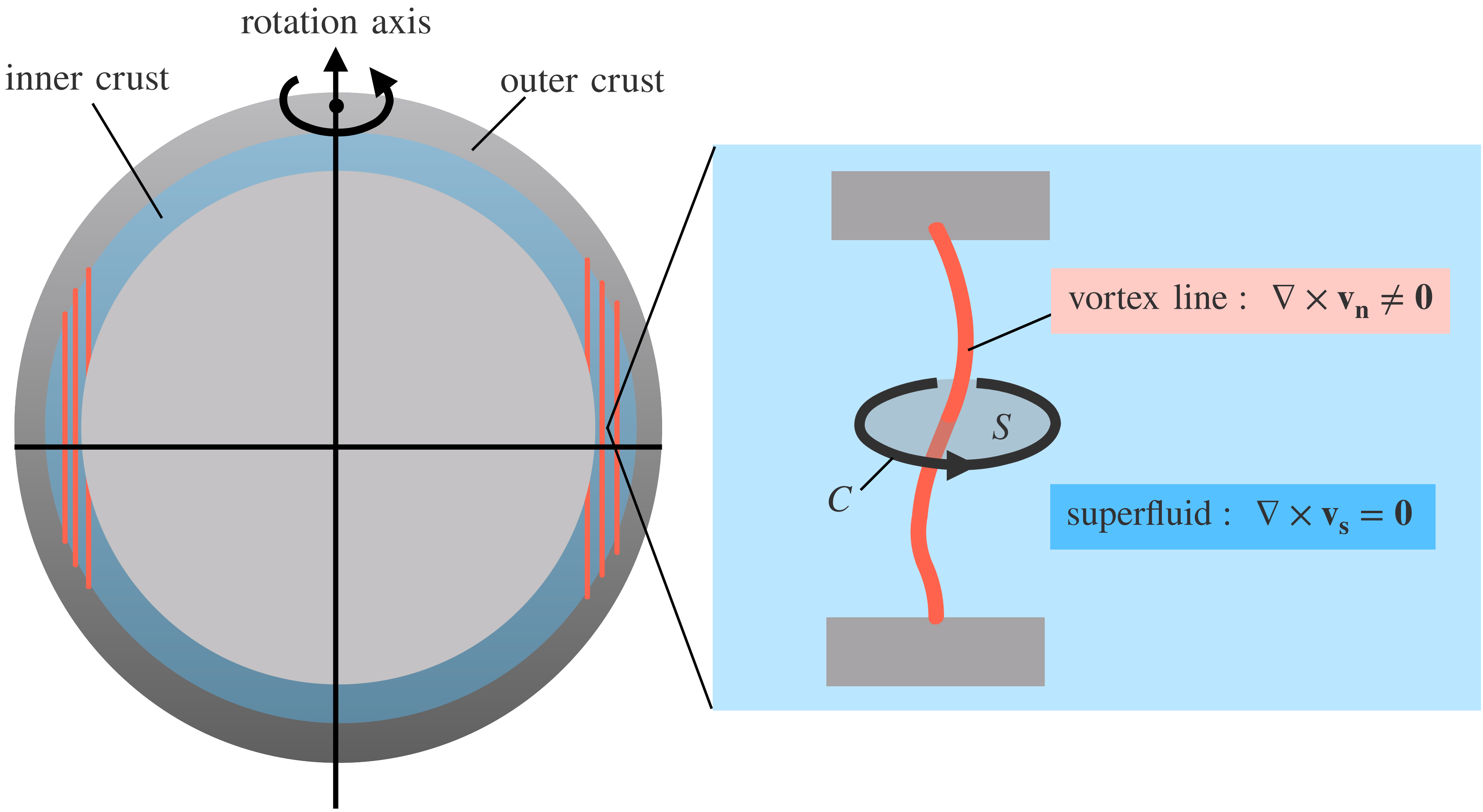
Neutron superfluid vortex lines

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).



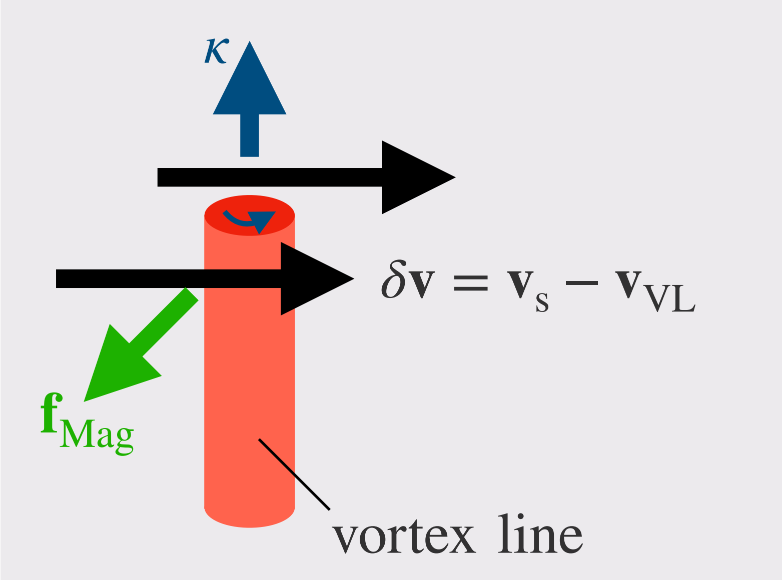
Vortex creep

Due to the pulsar radiation, the crust component slows down.

But the superfluid component does not.

⇨ The rotational speed difference developed.

This induces Magnus force.



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

Vortex creep

⇨ Speed difference decreases.

The vortex creep keeps the speed difference constant.

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

Determined by the pinning force.

Vortex creep heating

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

The rotational energy stored in the superfluid component is dissipated as heat:

$$L_{\mathrm{H}} = \int \underbrace{dI_{\mathrm{crust}}}_{\text{Moment of inertia}} \underbrace{(\Omega_{\mathrm{SF}} - \Omega_{\mathrm{crust}})}_{\text{Determined by the pinning force.}} |\dot{\Omega}| \equiv J|\dot{\Omega}|$$

All NSs have similar values of J.

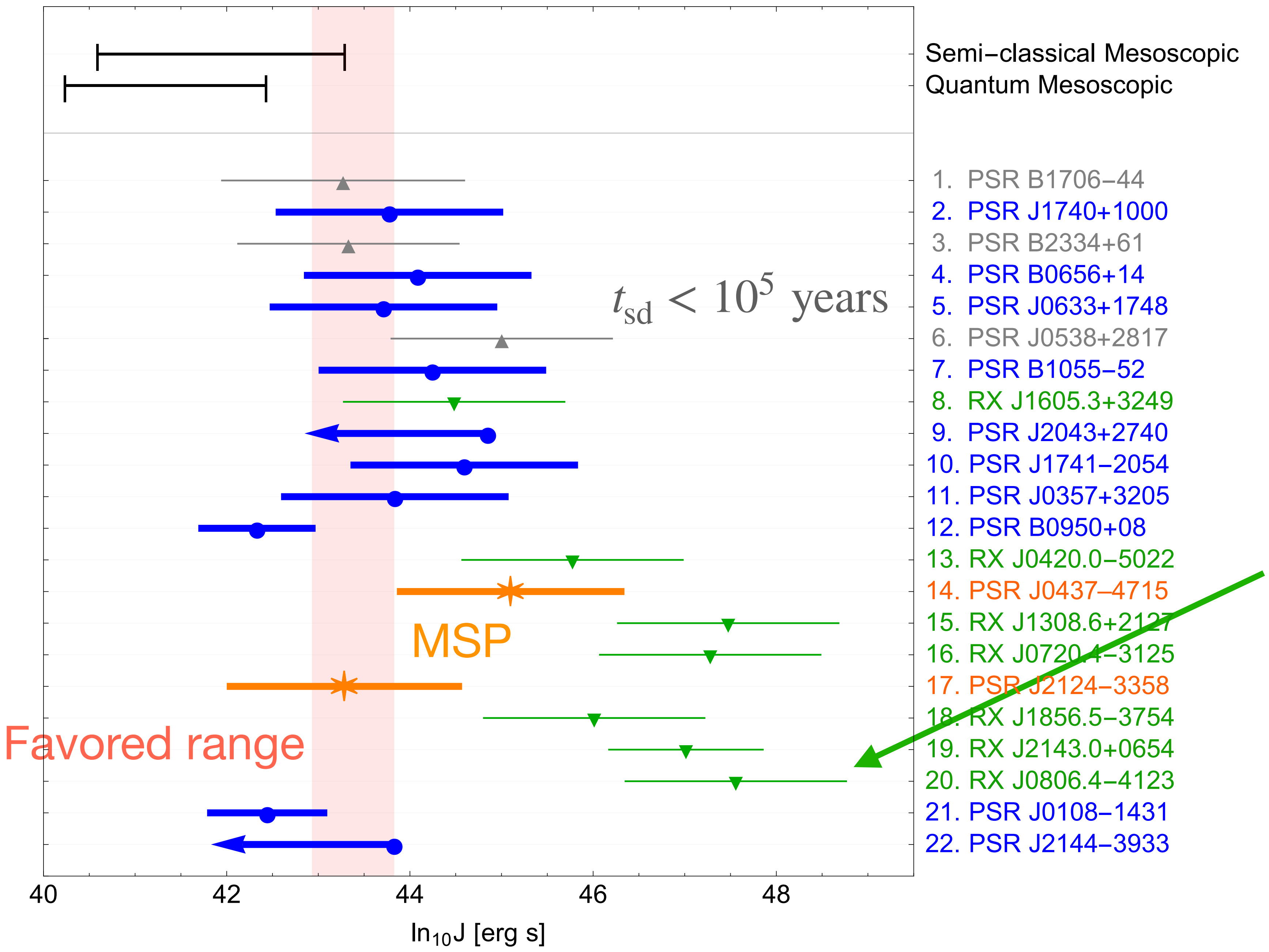
In old NSs, this heating balances with the photon cooling:

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

➡ $J_{\mathrm{obs}} = 4\pi R^2 \sigma_{\mathrm{SB}} T_s^4 / |\dot{\Omega}|$ Can be determined by observation.

The vortex heating mechanism predicts this to be almost universal.

Vortex creep heating vs observations



Theoretical estimations.

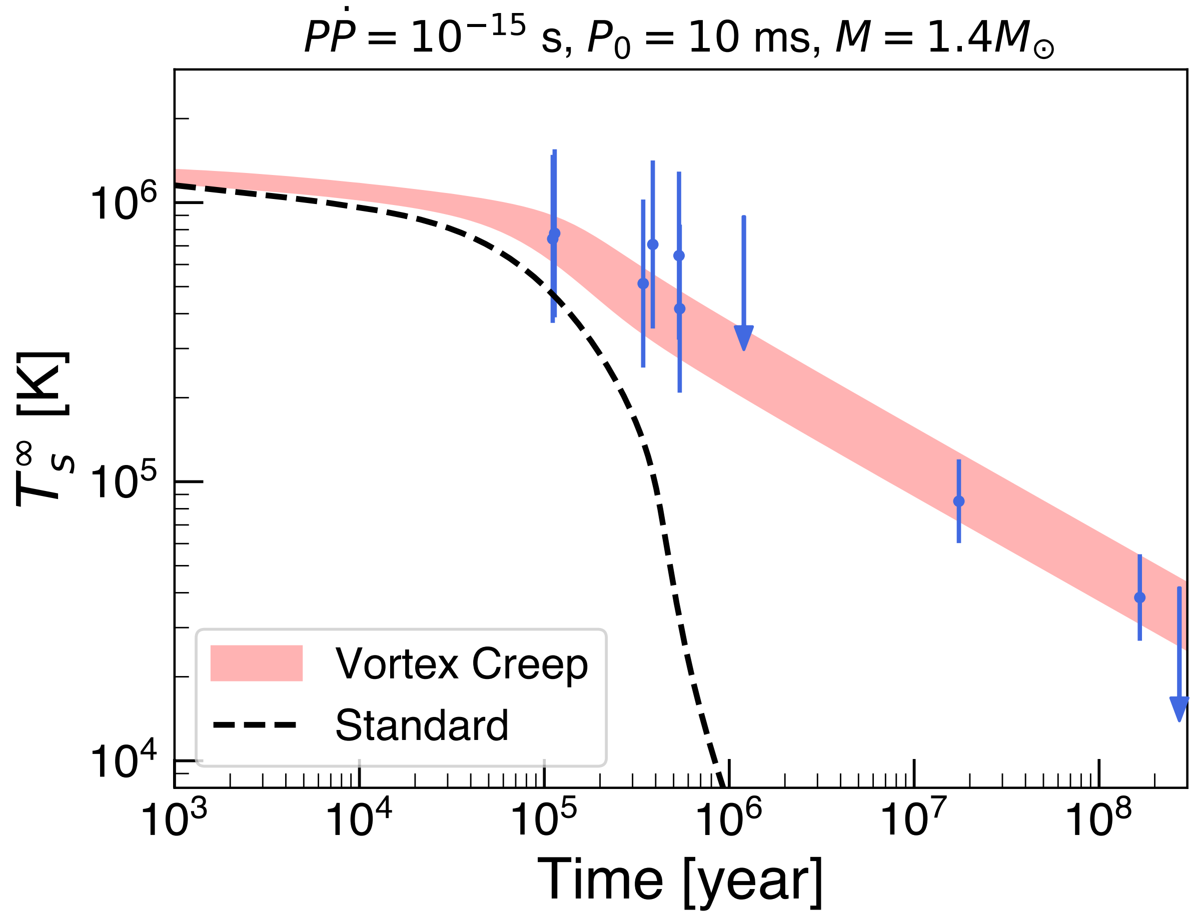
XDINSs

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

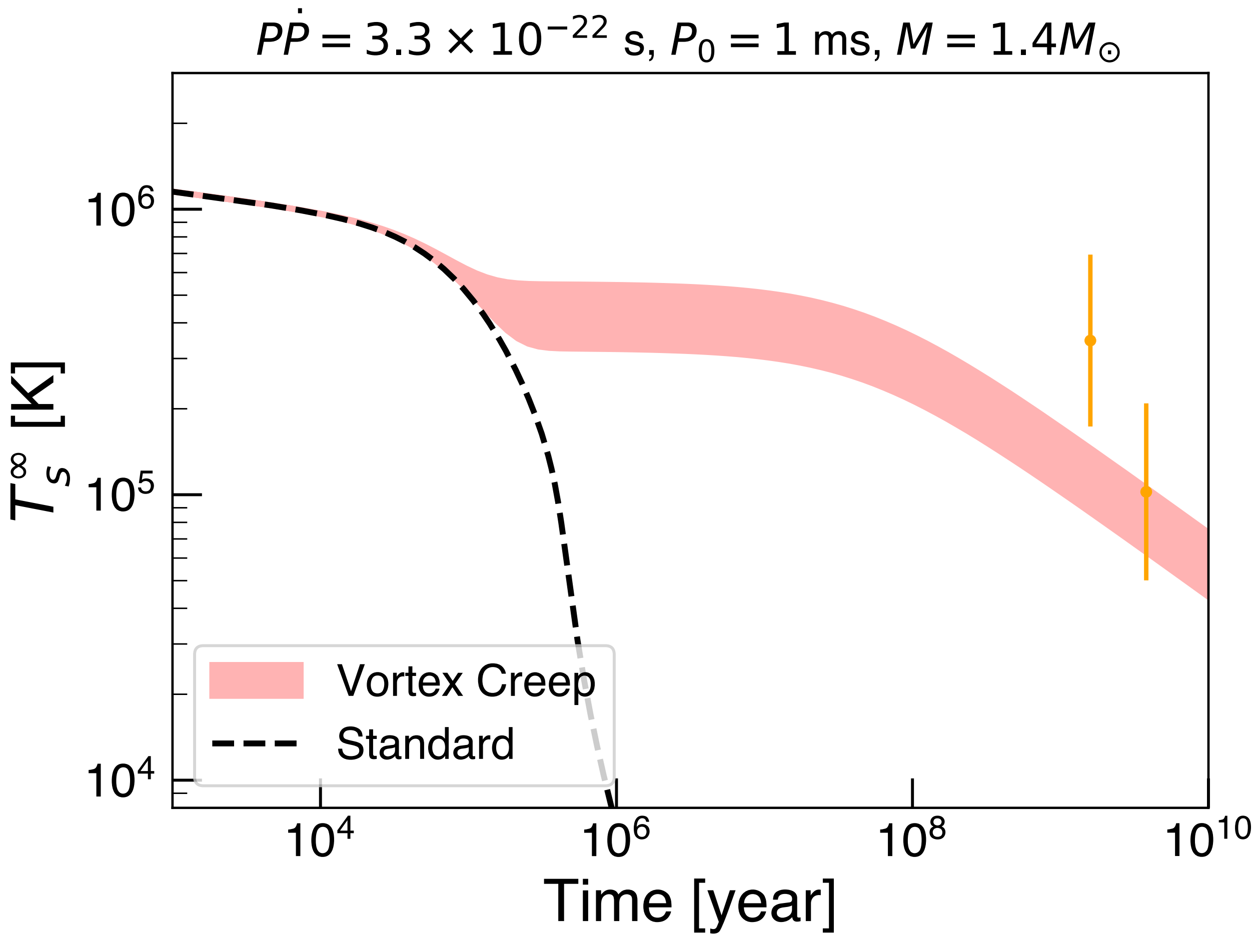
M. Fujiwara, K. Hamaguchi, N. Nagata, M. E. Ramirez-Quezada, arXiv:2308.16066.

Vortex creep heating vs observations

Ordinary pulsars



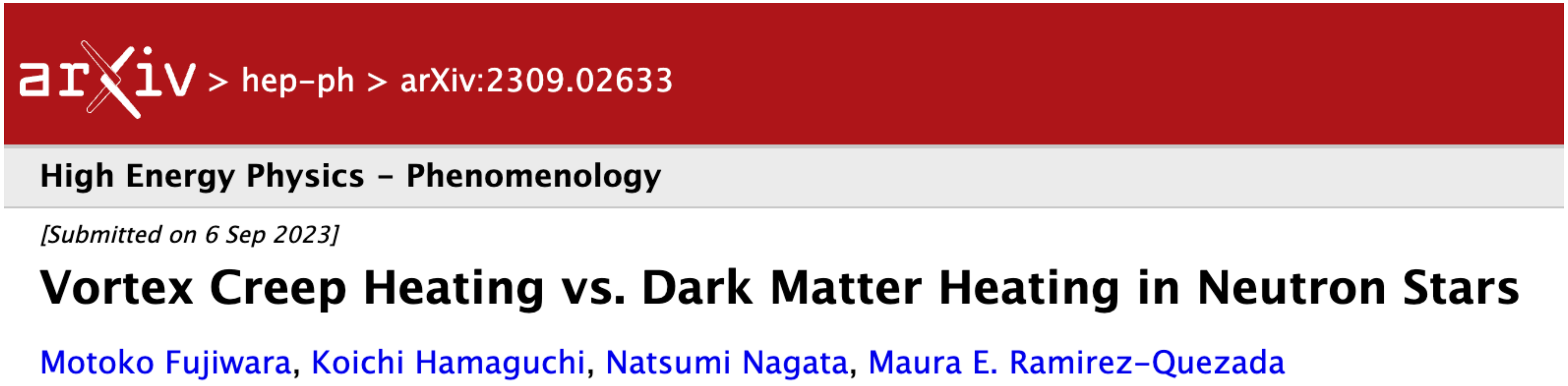
Millisecond pulsars



- 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, arXiv:2308.16066.

arXiv today



arXiv > hep-ph > arXiv:2309.02633

High Energy Physics – Phenomenology

[Submitted on 6 Sep 2023]

Vortex Creep Heating vs. Dark Matter Heating in Neutron Stars

Motoko Fujiwara, Koichi Hamaguchi, Natsumi Nagata, Maura E. Ramirez-Quezada

Motoko Fujiwara (TUM)

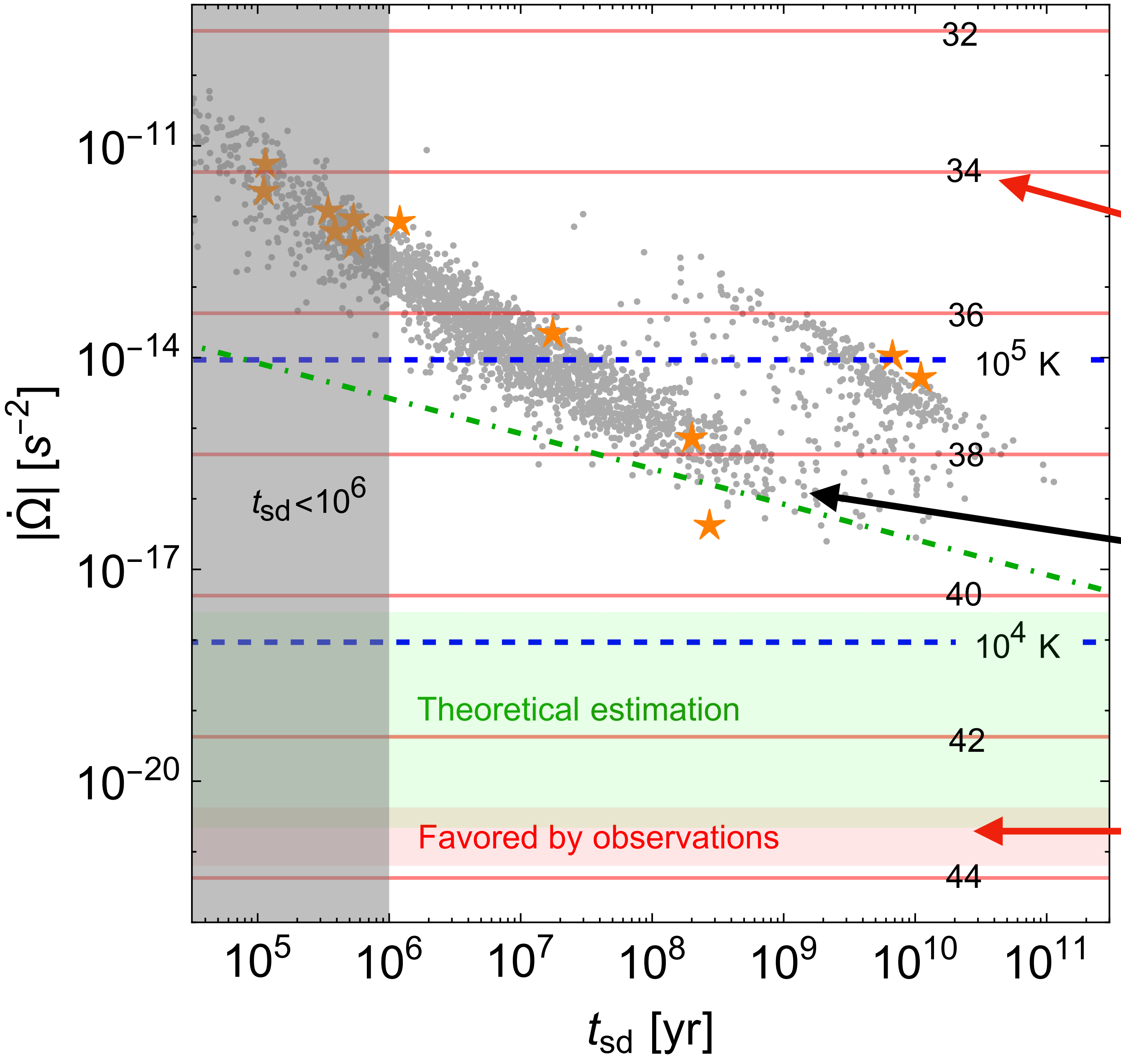
Koichi Hamaguchi (U. Tokyo)

Maura Ramirez-Quezada (U. Tokyo → Mainz)

Vortex creep heating vs DM heating

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

➡ Upper limit on $J|\dot{\Omega}|$



Limit on J (log J [erg s])

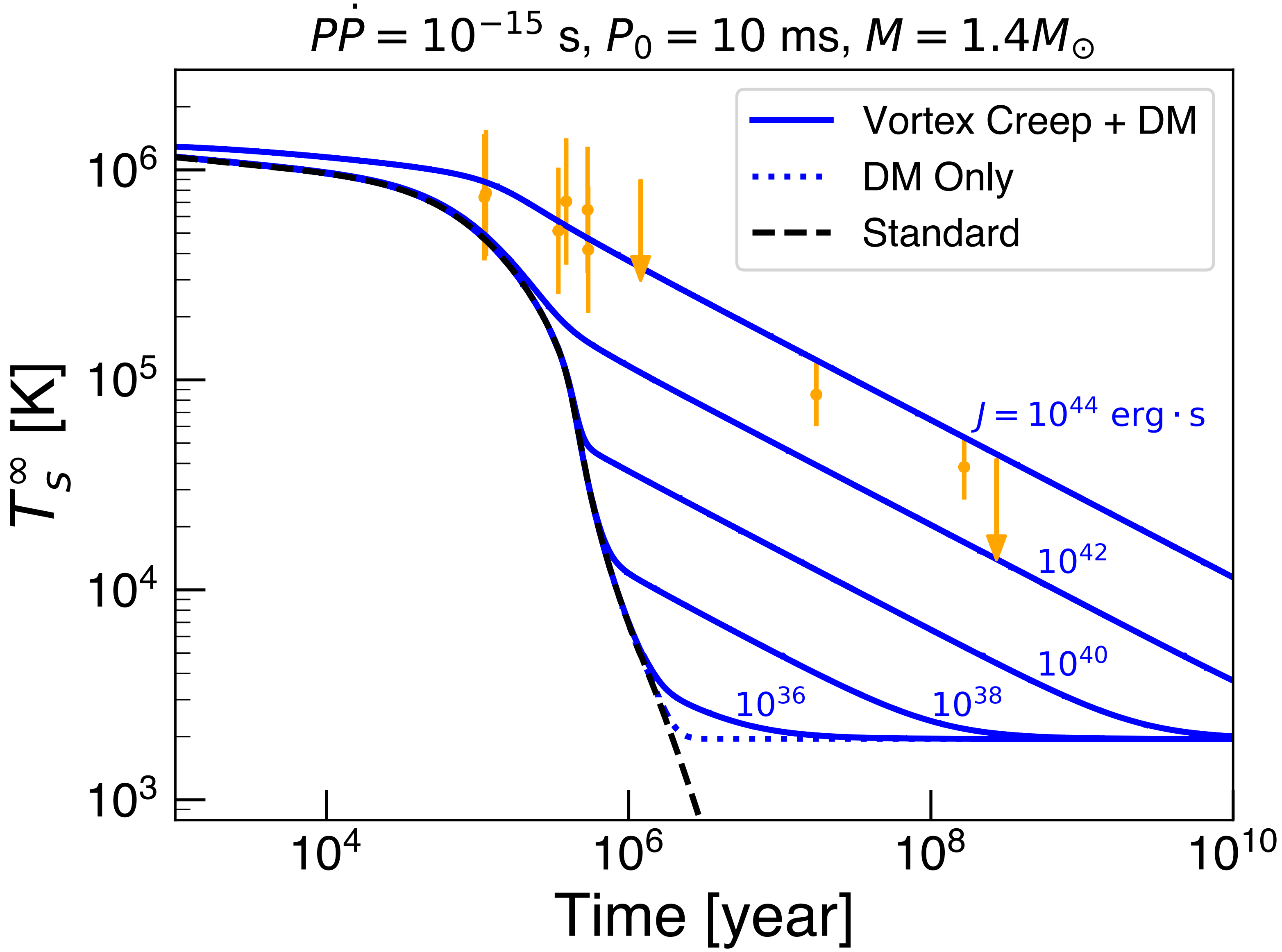
Distribution of known pulsars

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, arXiv:2309.02633.

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, arXiv:2309.02633.

Conclusion

- We discussed the feasibility of the WIMP DM search via the NS temperature observation.

Potenital obstacles

- Non-equilibrium β processes.
    - For ordinary pulsars, DM heating effect can be observed if their initial period is relatively large.
    - For millisecond pulsars, DM heating effect is always hidden by the rotochemical heating.
- Vortex creep heating

  This heating effect seems to dominate the DM heating…

Backup

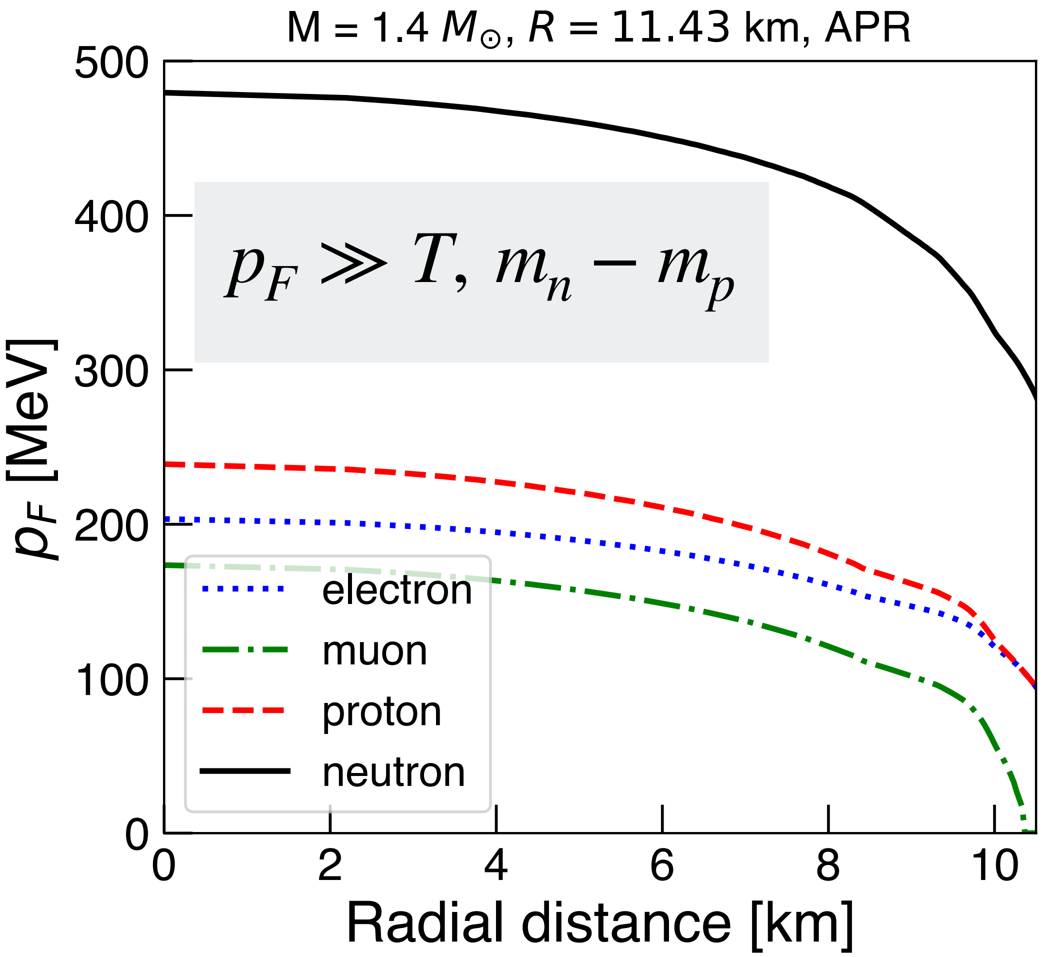
Standard Cooling of NS

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)

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



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

Equation for temperature evolution

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

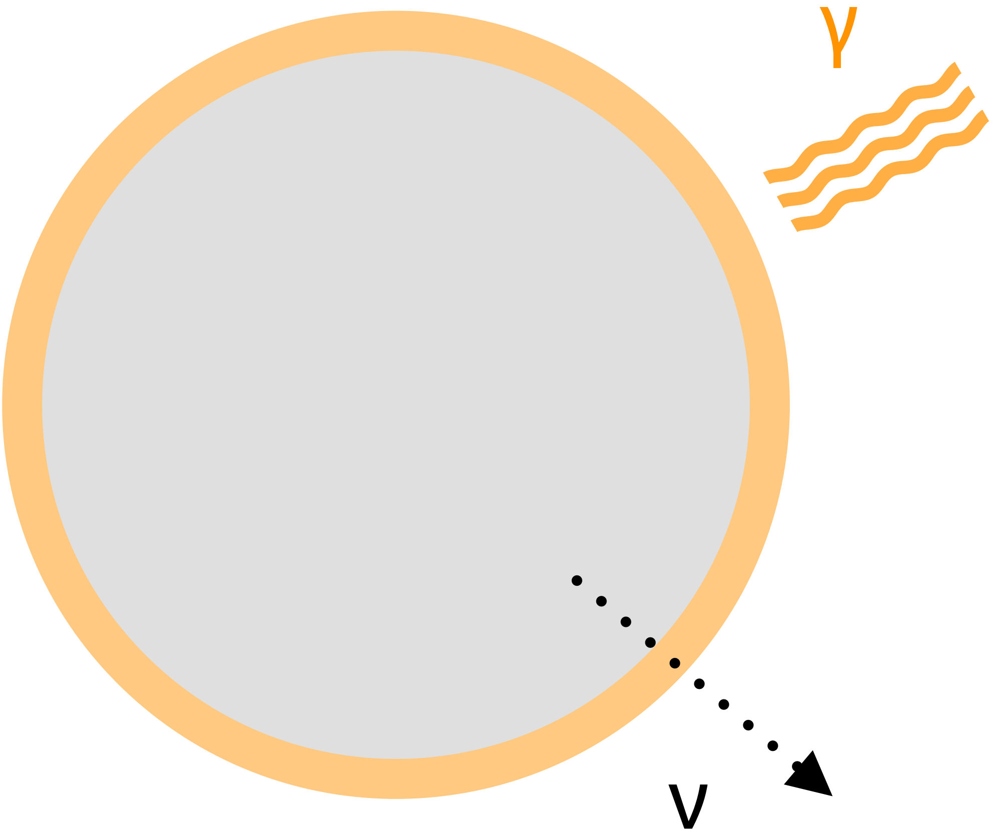
C(T): Stellar heat capacity

L_ν: Luminosity of neutrino emission

L_γ: Luminosity of photon emission

Cooling sources

Two cooling sources:



Dominant for $t \lesssim 10^5$ years

Photon emission (from surface)

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

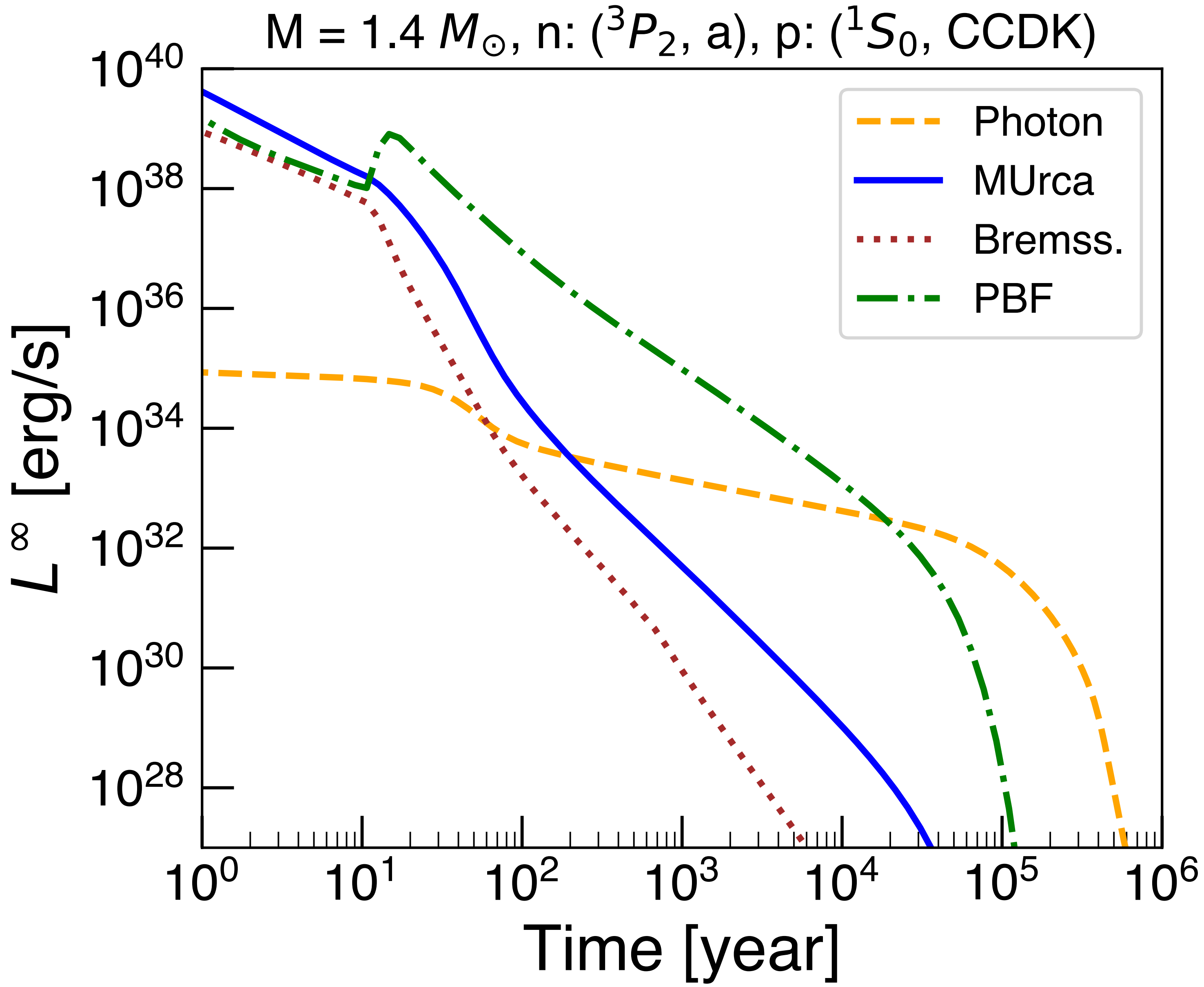
Dominant for $t \gtrsim 10^5$ years

Neutrino emission (from core)

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

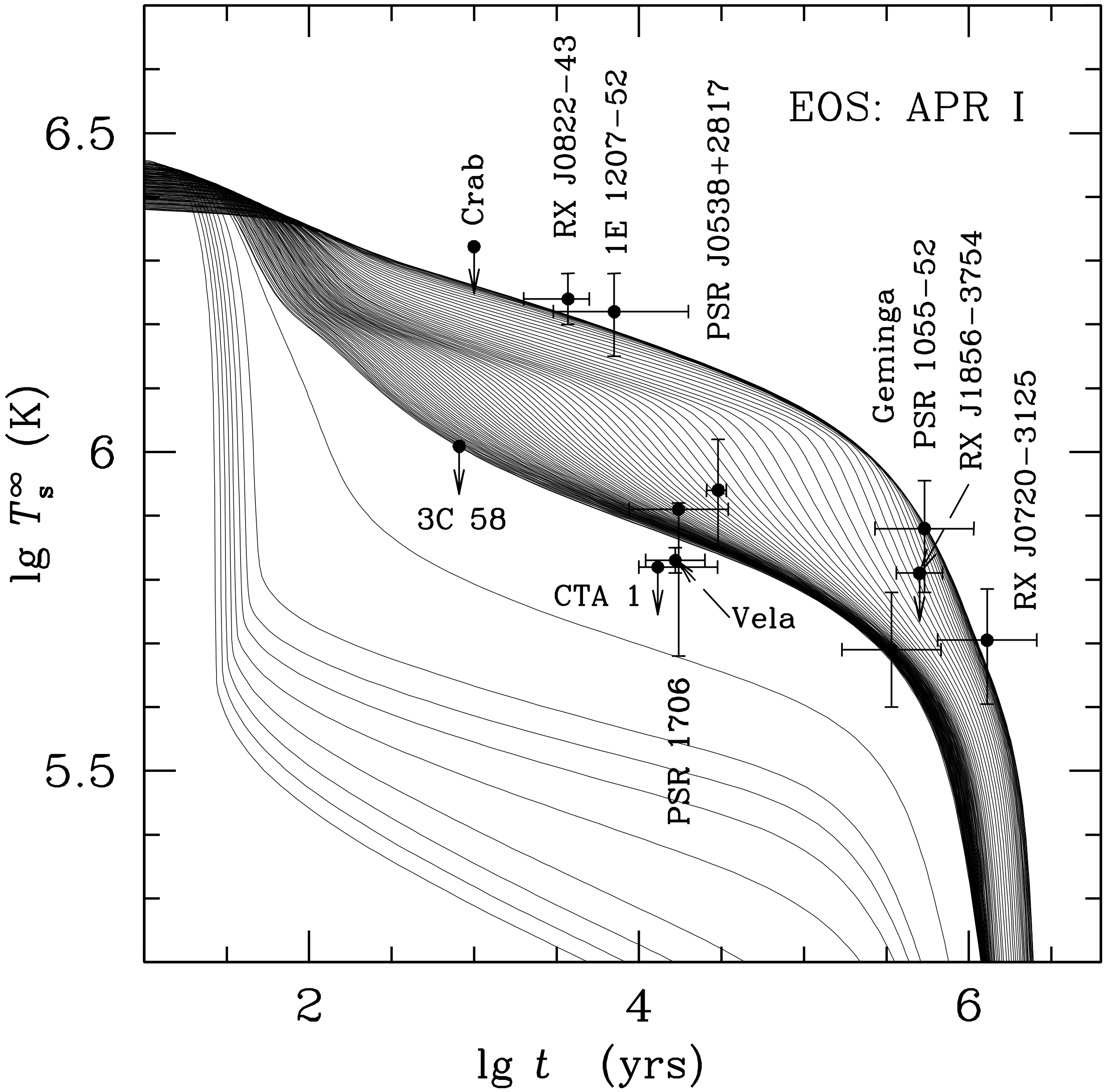
Occurs when nucleon pairings
are formed.

Luminosity



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

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).

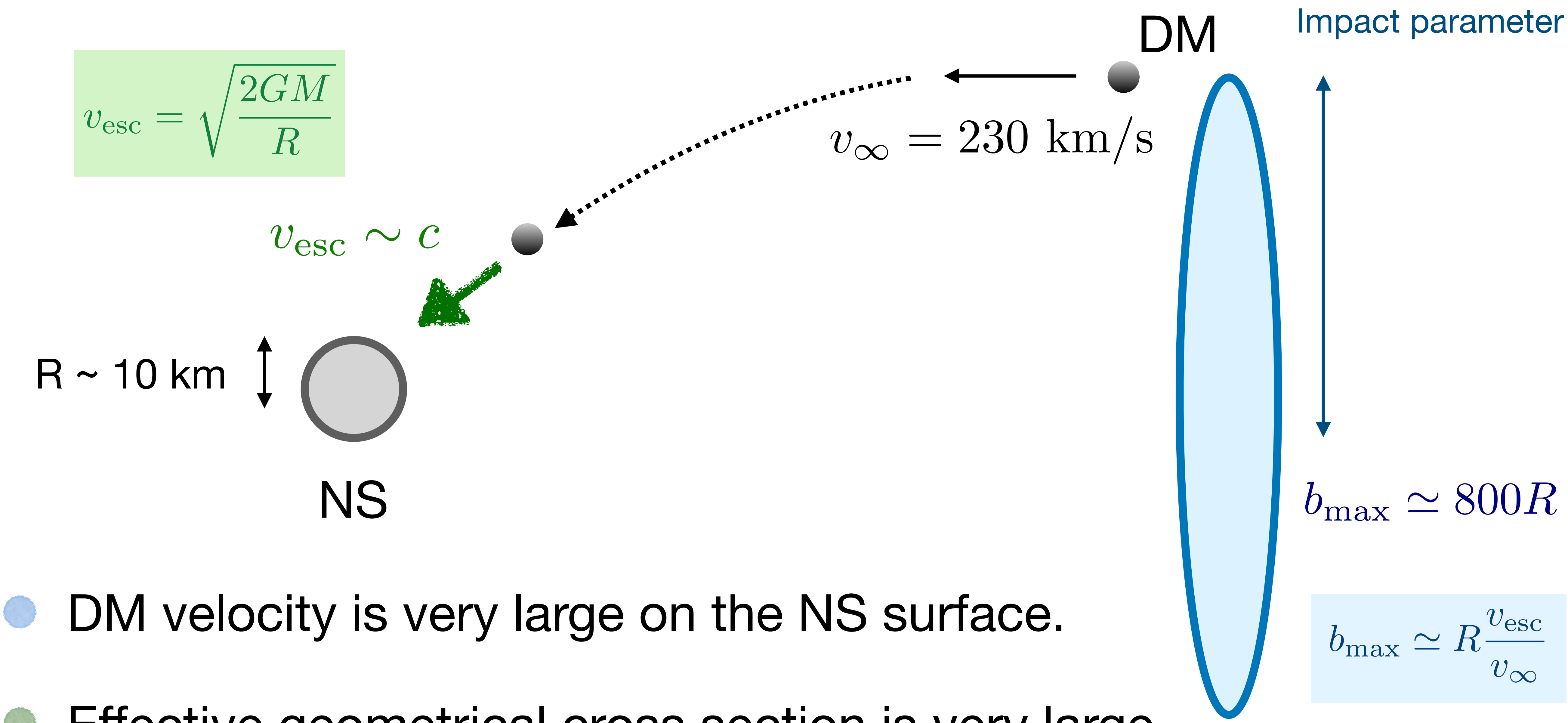
- Temperature gets very low for $t \gtrsim 10^6$ years.
- Consistent with the observations for $t < 10^6$ years.

~ 50 NSs listed.

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

Dark matter accretion in NS

$$v_{\rm esc} = \sqrt{\frac{2GM}{R}}$$



$$b_{\rm max} \simeq R\frac{v_{\rm esc}}{v_\infty}$$

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

DM accretion rate is

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

DM number density

Recoil energy

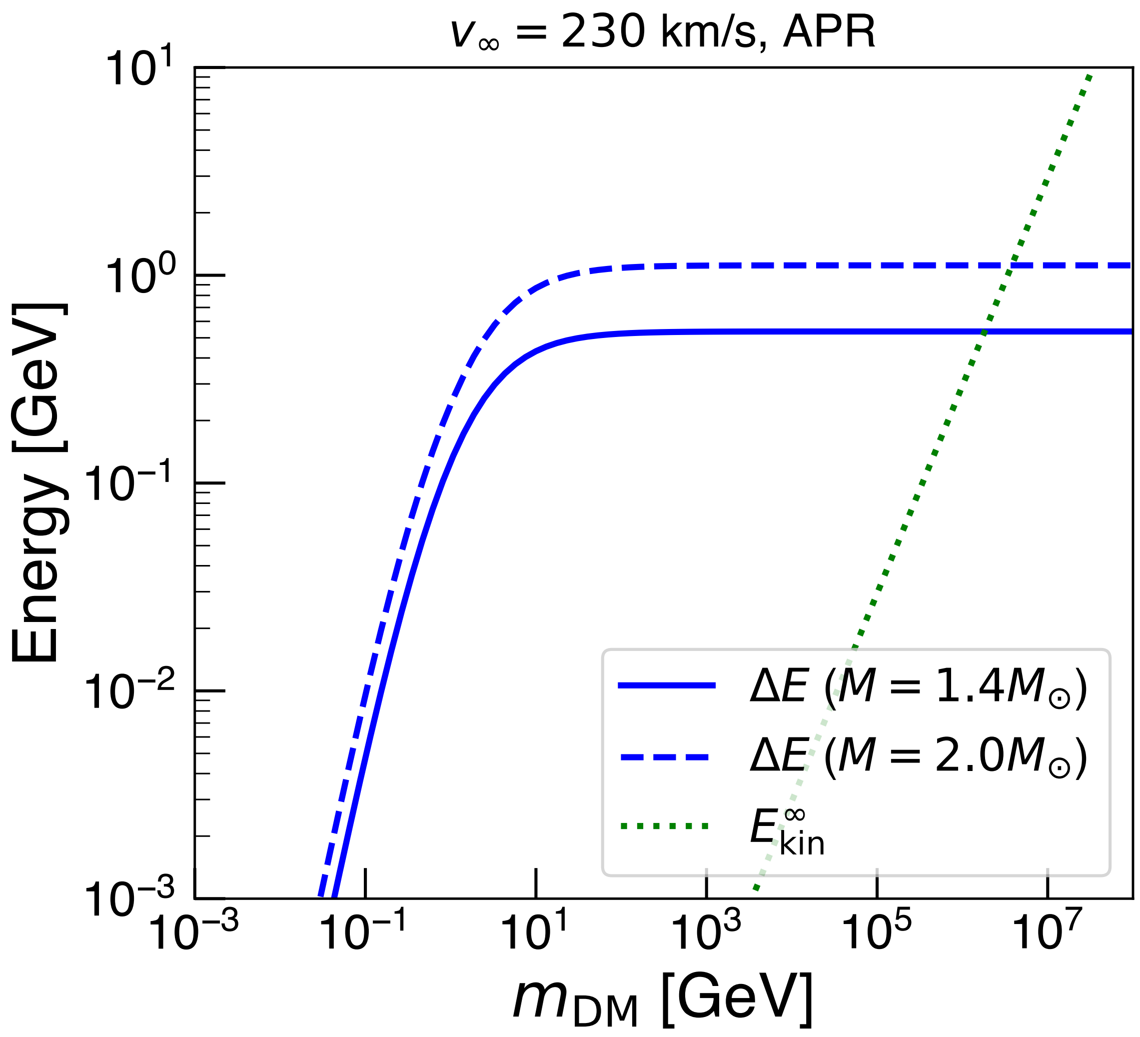
For each DM-nucleon scattering, WIMPs lose energy by

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

θ_c : scattering angle in the CM frame.

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

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



- 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

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

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 $\sigma_N / \sigma_{\mathrm{th}}$.

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.

$$L_H = L_\gamma$$

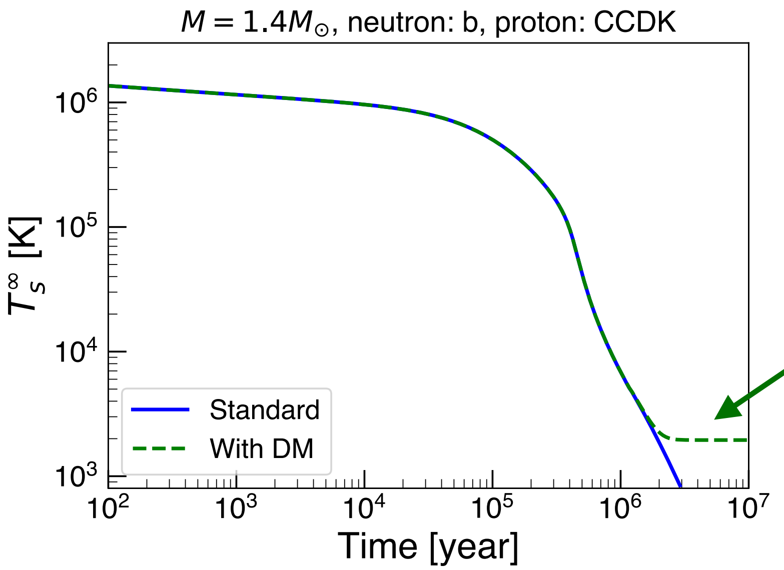
$$L_H \simeq m_{\rm DM}\dot{N} \simeq 2\pi G M R \rho_{\rm DM}/v_\infty$$

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

$$T_s \simeq 2500~{\rm K}$$



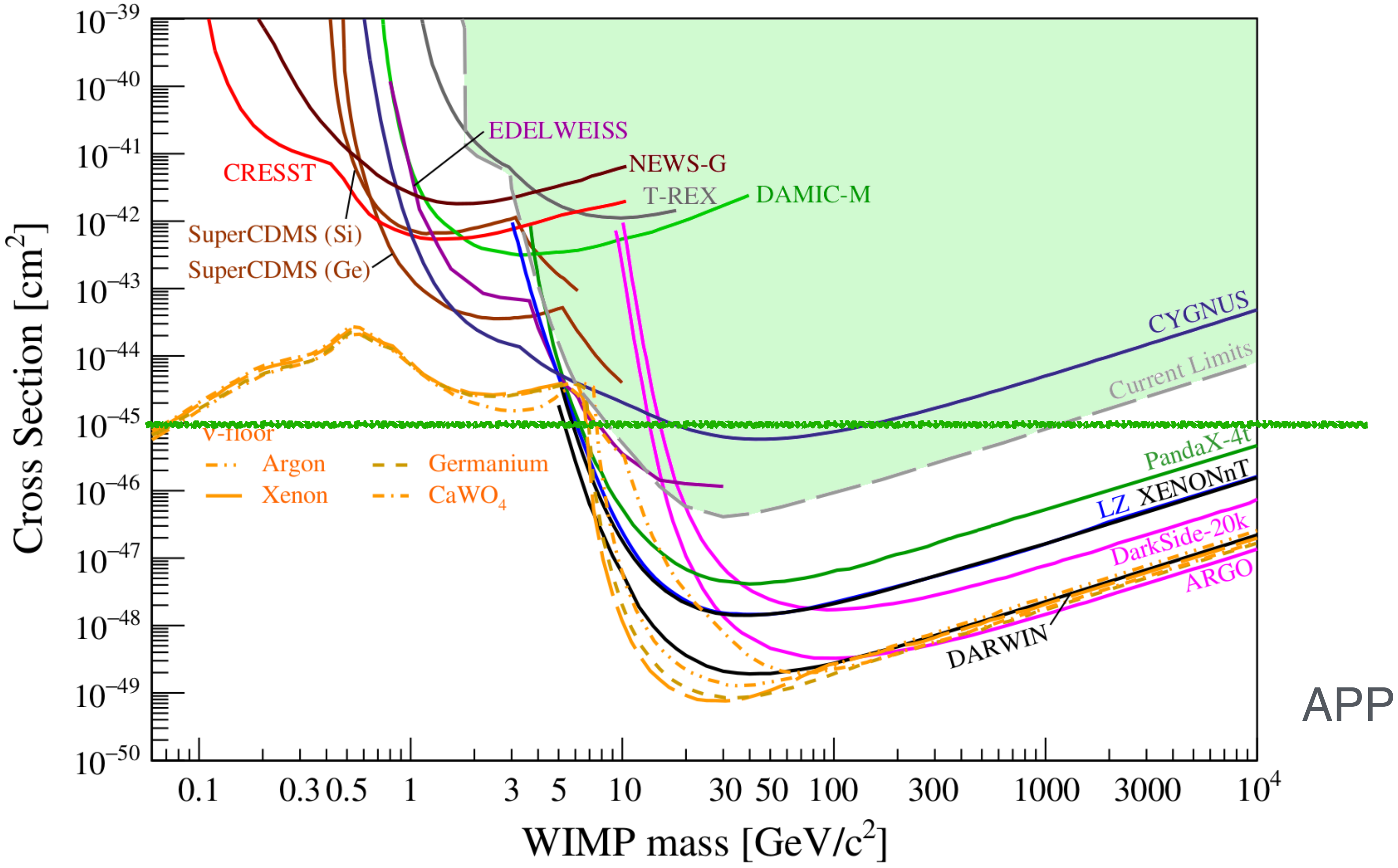
Robust, smoking-gun prediction of DM heating.

Can we observe this??

DM heating vs direct detection

In any case, an observation of a NS with $T_s \lesssim 2 \times 10^3\ \mathrm{K}$ disfavors WIMPs which have $\sigma_N \gtrsim 10^{-45}\ \mathrm{cm}^2$.

Prospects for direct detection experiments



$\sigma_N = 10^{-45}\ \mathrm{cm}^2$

APPEC Committee Report, arXiv:2104.07634.

Such a large scattering cross section can be probed in direct detection experiments. Why we should care about DM heating??

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

Spin-down age

For magnetic dipole radiation,

$$\dot{\Omega} = -k\Omega^3$$

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

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

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

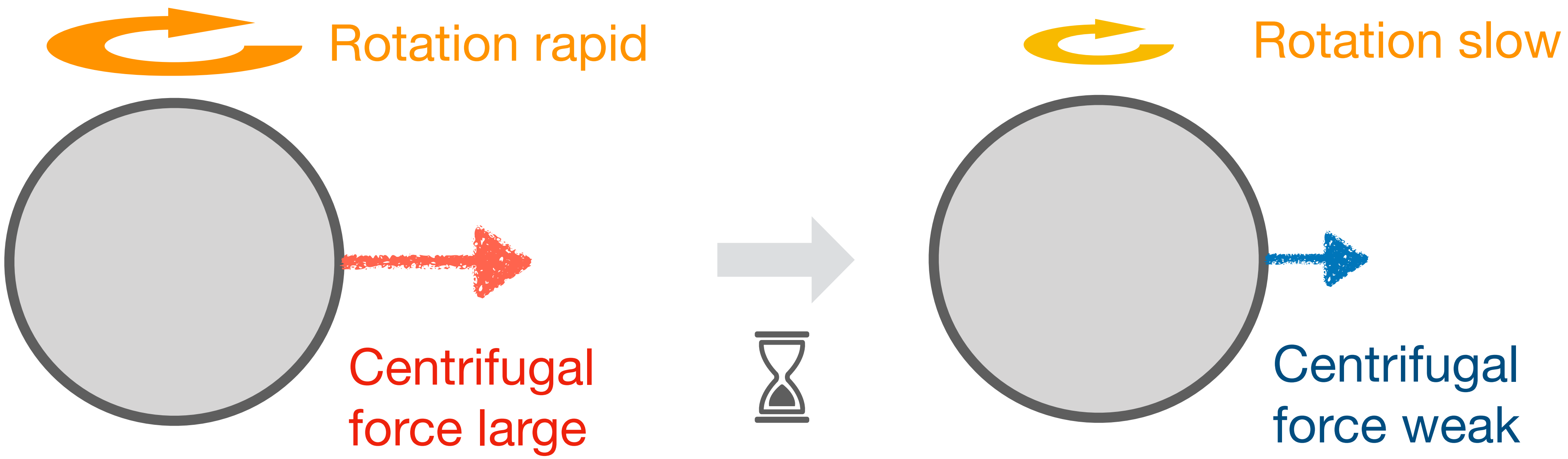
$t_{\rm sd}$ is called spin-down age or characteristic age.

Non-equilibrium β processes

Loop hole in standard cooling

In the standard cooling, β equilibrium is assumed.

In a real pulsar

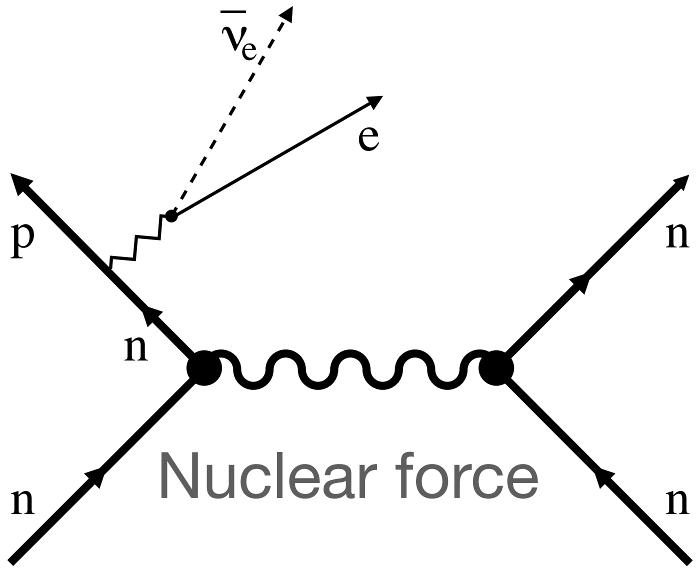


Local pressure changes. Chemical equilibrium condition changes.

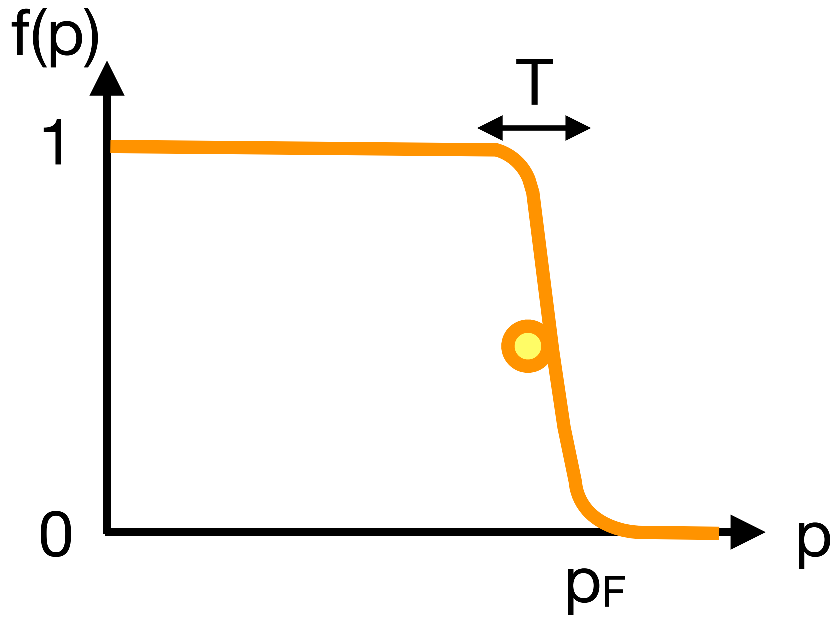
If the beta processes are rapid enough, the system can follow the change in the equilibrium condition. But…

Neutrino emission

The beta processes are highly suppressed at later times, i.e., for low temperatures.



Modified Urca



Only the particles near the Fermi surface can participate in the processes.

➡ Deviation from β equilibrium

A. Reisenegger, Astrophys. J. **442**, 749 (1995).

The imbalance in chemical potentials is dissipated as heat.

➡ Rotochemical heating

R. Fernandez and A. Reisenegger, Astrophys. J. **625**, 291 (2005);
C. Petrovich, A. Reisenegger, Astron. Astrophys. **521**, A77 (2010).

Out of β equilibrium

Deviation from β equilibrium is quantified by

$$\boxed{\eta_\ell \equiv \mu_n - \mu_p - \mu_\ell} \quad (\ell = e, \mu)$$

At early times

Urca processes are rapid.

➡ NS can follow the change in the equilibrium condition.

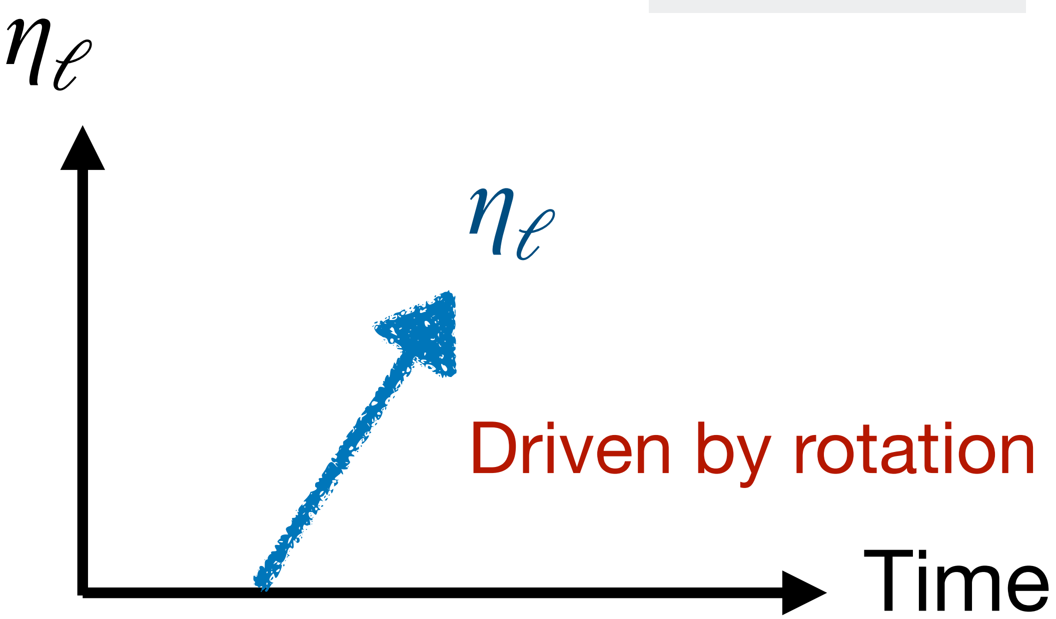
$$\boxed{\eta_\ell = 0}$$

At later times

Urca processes are too slow.

➡ Deviation from β equilibrium

➡ η_ℓ increases!

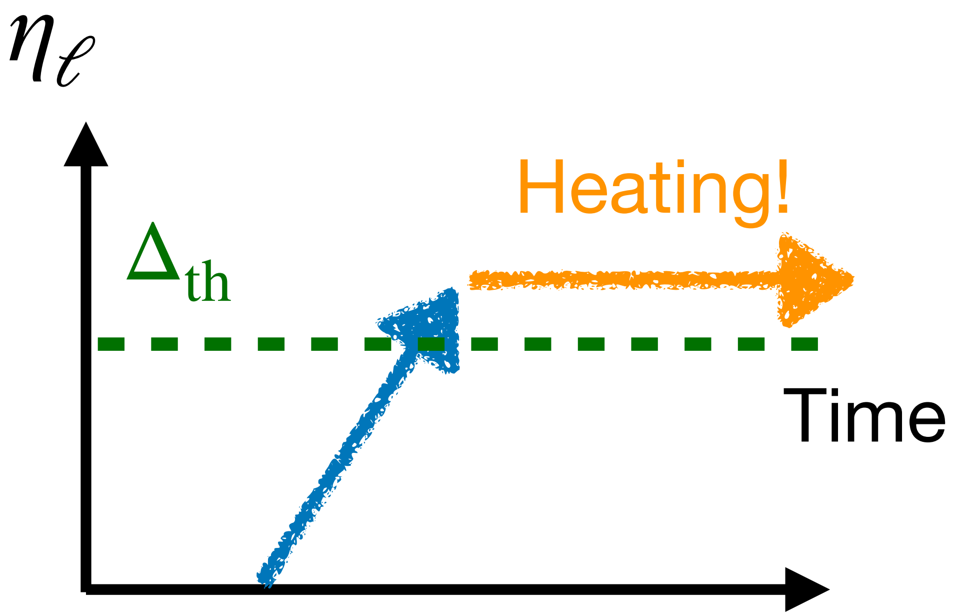


Rotochemical heating

R. Fernandez and A. Reisenegger, Astrophys. J. **625**, 291 (2005);
C. Petrovich, A. Reisenegger, Astron. Astrophys. **521**, A77 (2010).

Once η_ℓ exceeds a threshold $\Delta_{\rm th}$ determined by nucleon gaps,

$$\Delta_{\rm th} = \min\{3\Delta_n + \Delta_p, \Delta_n + 3\Delta_p\}$$



- Urca processes are enhanced.
- Generation of heat

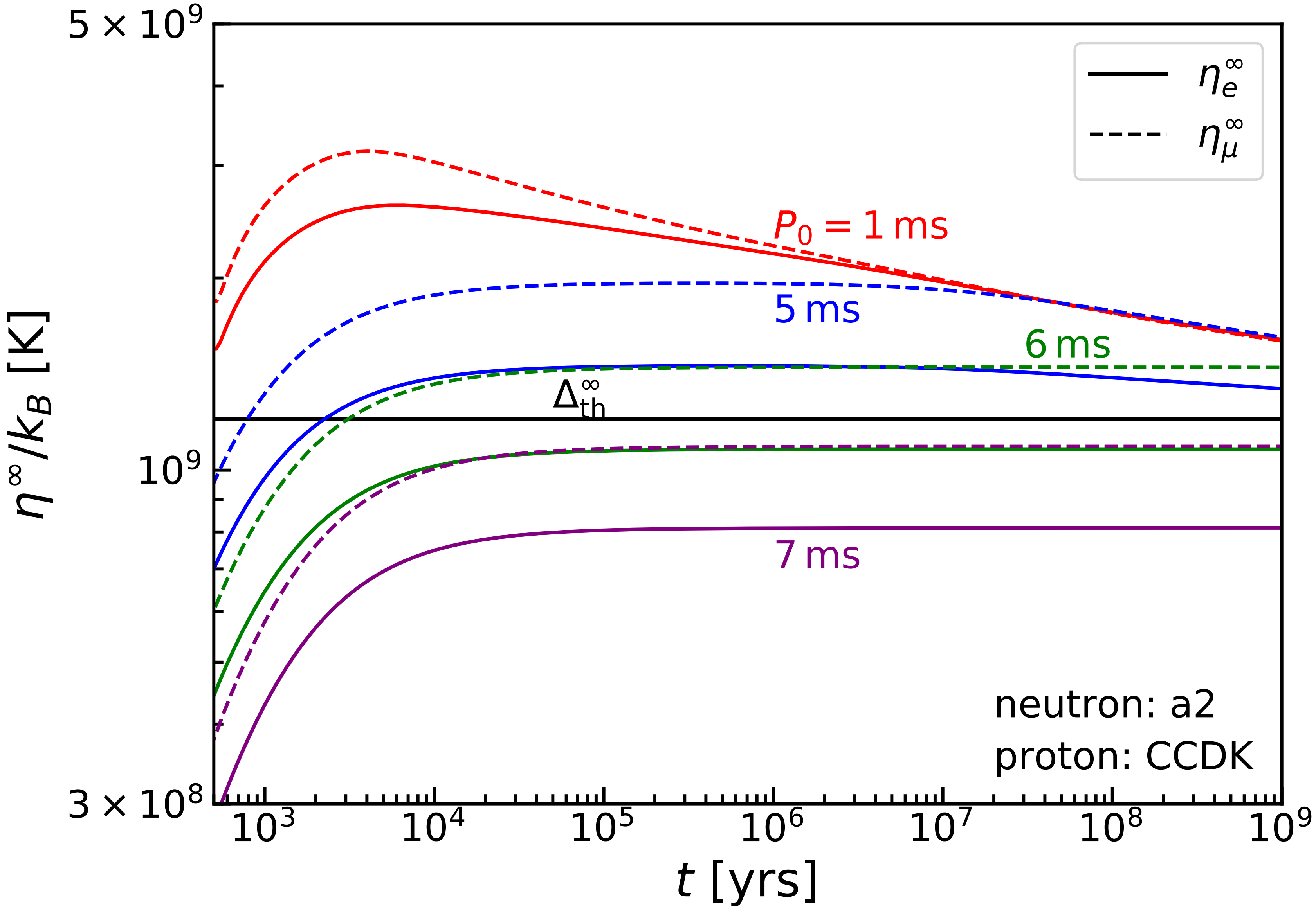
Called the rotochemical heating.

It occurs in the same setup as the standard cooling.

- No exotic physics needed.
- This effect should have been included from the beginning…

Evolution of chemical imbalance

Since the deviation from equilibrium is driven by rotation, it strongly depends on the value of period.



$$M = 1.4 M_\odot$$

$$P = 1\ \mathrm{s}$$

$$\dot{P} = 10^{-15}$$

Magnetic dipole radiation

$$\dot{\Omega} = -k\Omega^3$$

Rotochemical heating occurs if the initial period P_0 is small enough.

K. Hamaguchi, N. Nagata, K. Yanagi, Phys. Lett. **B795**, 484 (2019).

Non-equilibrium β processes

- When Urca processes are rapid enough, the system can follow the new equilibrium conditions.

- At low temperatures, Urca processes get very slow.

  ➡ Deviation from β equilibrium

  A. Reisenegger, Astrophys. J. **442**, 749 (1995).

  ➡ Energy excess in chemical potentials

This energy excess is dissipated by

- ▶ Increase in neutrino emission
- ▶ Generation of heating.

Rotochemical heating

A. Reisenegger, Astrophys. J. **442**, 749 (1995);
R. Fernandez and A. Reisenegger, Astrophys. J. **625**, 291 (2005).

Out of β equilibrium

The excess of energy is dissipated by

- Increase of neutrino emission
- Generation of heat

P. Haensel, Astron. Astrophys. **262**, 131 (1992);
A. Reisenegger, Astrophys. J. **442**, 749 (1995).

Deviation from β equilibrium is quantified by

$$\boxed{\eta_\ell \equiv \mu_n - \mu_p - \mu_\ell} \quad (\ell = e, \mu)$$

Heating luminosity

$$L_H = \sum_{\ell=e,\mu} \sum_{N=n,p} \int dV\, \eta_\ell \cdot \Delta\Gamma_{M,N\ell}$$

where

$$\Delta\Gamma_{M,N\ell} \equiv \Gamma(n + N \to p + N + \ell + \bar{\nu}_\ell) - \Gamma(p + N + \ell \to n + N + \nu_\ell)$$

Evolution of chemical imbalance

The time evolution off η_ℓ is determined by

$$\frac{d\eta_e}{dt} = -\sum_{N=n,p}\int dV\,\left(Z_{npe}\Delta\Gamma_{M,Ne} + Z_{np}\Delta\Gamma_{M,N\mu}\right) + 2W_{npe}\Omega\dot{\Omega}$$

Bring the system back to equilibrium.

Drive the system out of equilibrium.

W < 0, Z > 0: coefficients which depend on NS structure.

R. Fernandez and A. Reisenegger, Astrophys. J. **625**, 291 (2005).

Once the second term wins, the imbalance increases.

Magnetic dipole radiation

$$\dot{\Omega} = -k\Omega^3 \quad \Rightarrow \quad \Omega\dot{\Omega} = -\frac{4\pi^2 P_{\rm now}\dot{P}_{\rm now}}{(P_0^2 + 2P_{\rm now}\dot{P}_{\rm now}t)^2}$$

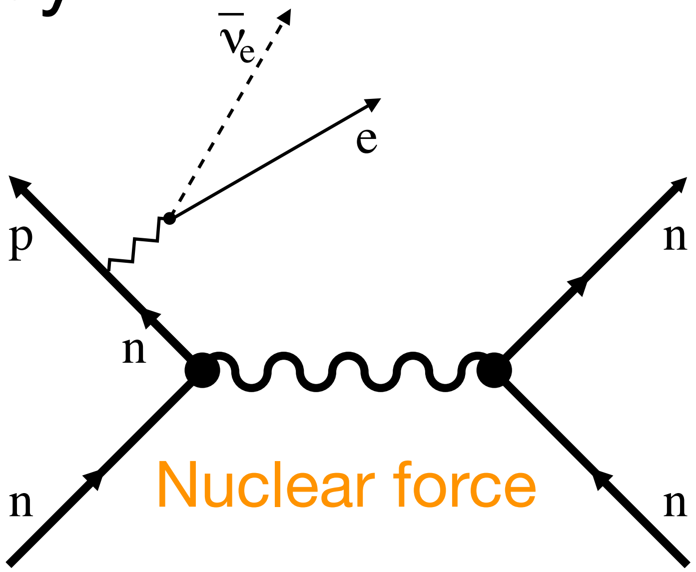
(P_0: initial period)

Rotochemical heating

If the imbalance overcomes the threshold given by

$$\Delta_{\rm th} = \min\left\{3\Delta_n + \Delta_p, \Delta_n + 3\Delta_p\right\}$$

Pauli blocking is overcame by the chemical imbalance.



Modified Urca

➡ Heating becomes effective.

This mechanism is called the rotochemical heating.

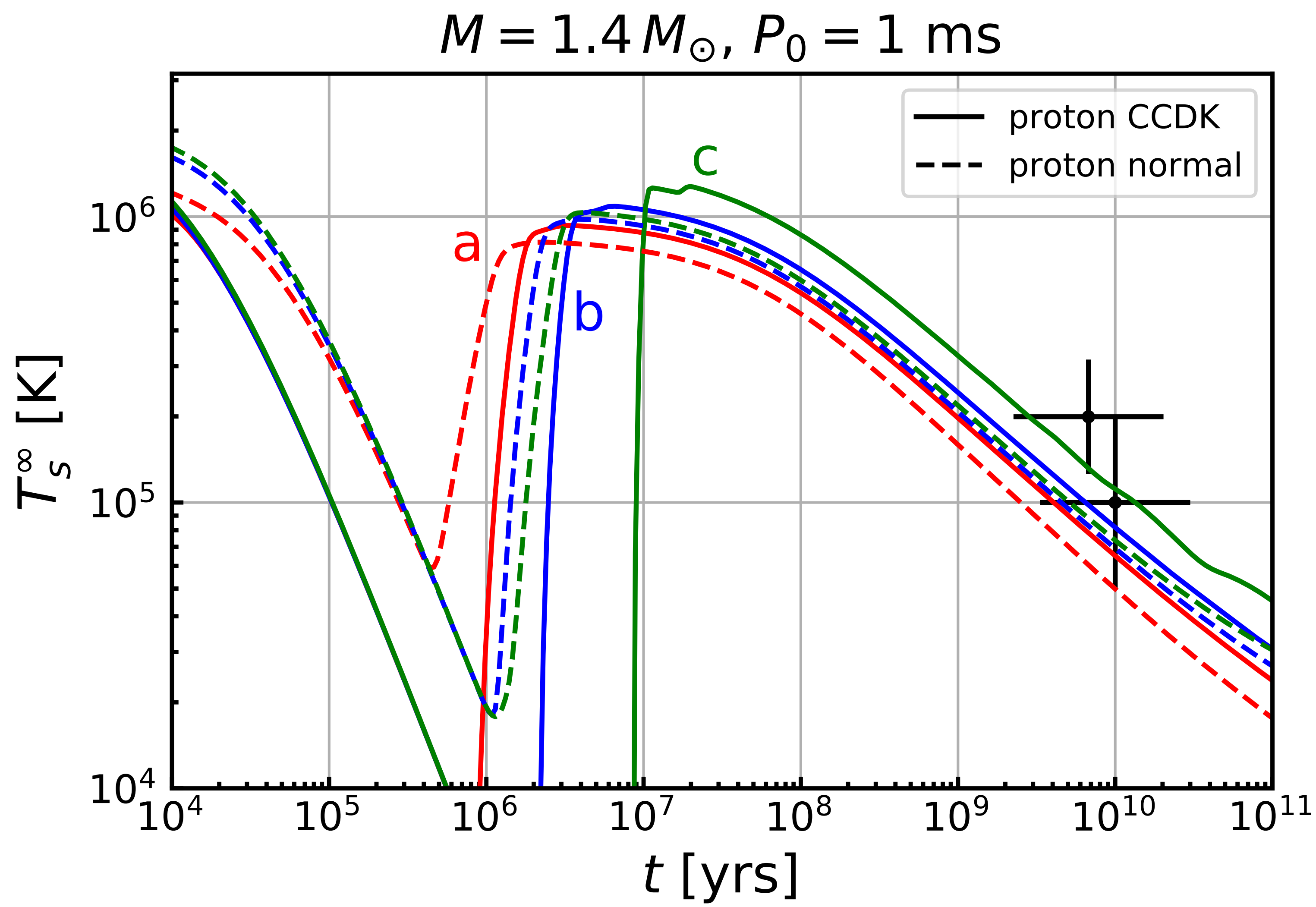
A. Reisenegger, Astrophys. J. **442**, 749 (1995);
R. Fernandez and A. Reisenegger, Astrophys. J. **625**, 291 (2005).

It occurs in the same setup as the standard cooling.

No exotic effects are needed.

Millisecond pulsars

We take account of the effect of non-equilibrium β processes.



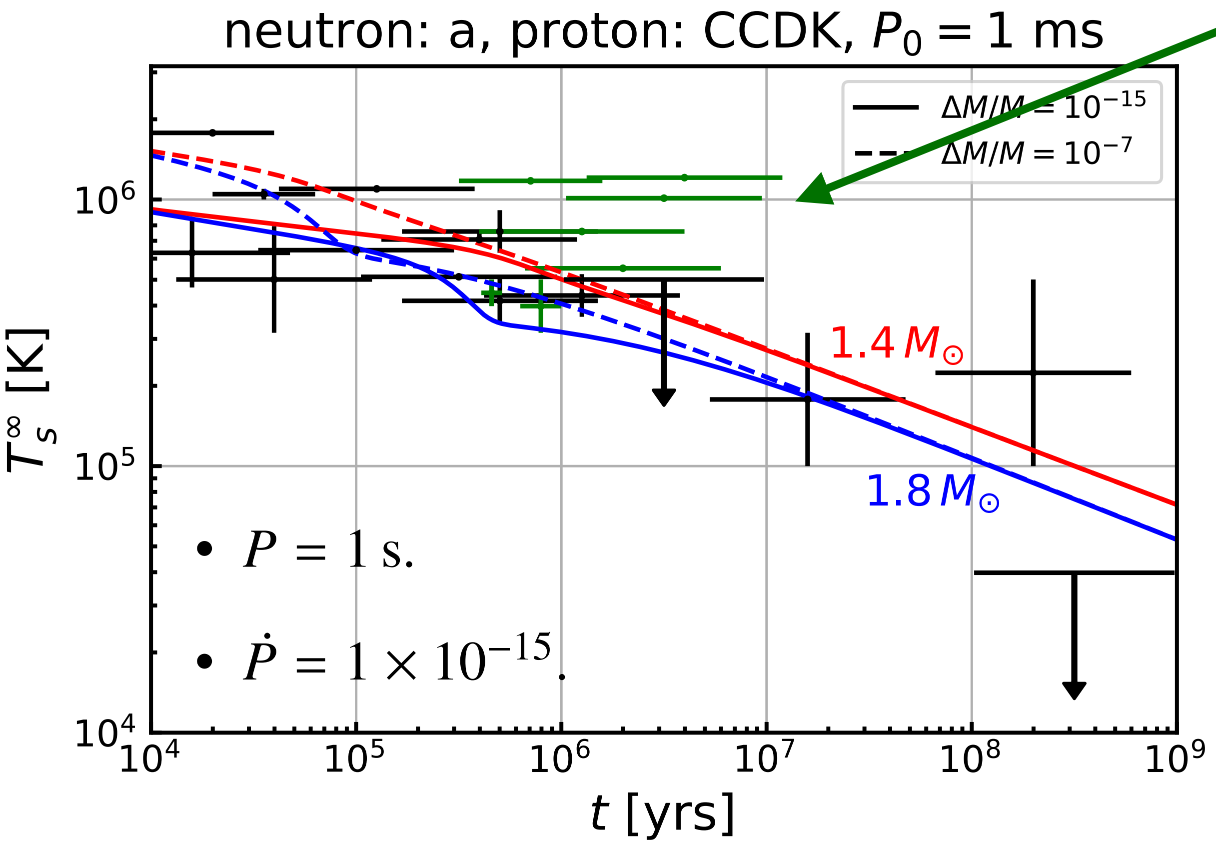
- $M = 1.4\,M_\odot$.
- $P = 5.8\,\mathrm{ms}$.
- $\dot{P} = 5.7 \times 10^{-20}$.

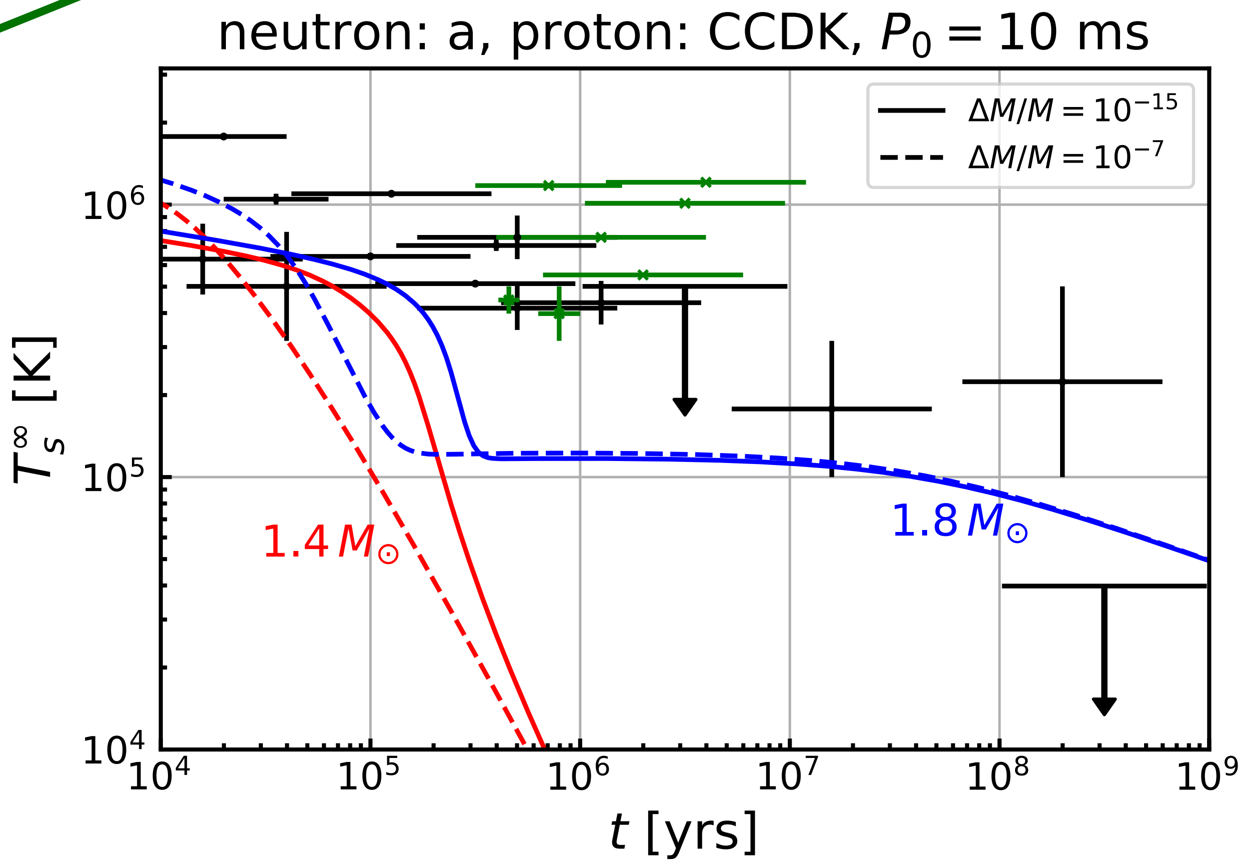
- Rotochemical heating always occurs in MSPs.
- We can explain the observations.

K. Hamaguchi, N. Nagata, K. Yanagi, MNRS **492**, 5508 (2020).

Ordinary pulsars

Heating due to magnetic field decay may occur.





- The temperature evolution highly depends on the initial period P_0 of pulsars.
- We can explain all of the observations.
  - Cool star: large initial period → no rotochemical heating.
  - Warm star: small initial period → rotochemical heating effective.

K. Hamaguchi, N. Nagata, K. Yanagi, MNRS **492**, 5508 (2020).