Dark Matter Heating vs. Rotochemical Heating in Old Neutron Stars

Keisuke Yanagi (University of Tokyo)

Based on Koichi Hamaguchi, Natsumi Nagata, KY [arXiv: 1904.04667, 1905.02991]

June 5th, 2019 @ Kyoto Univ.

Introduction/Motivation

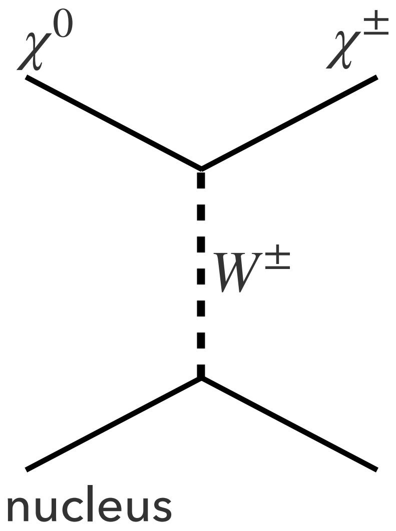
Dark matter search

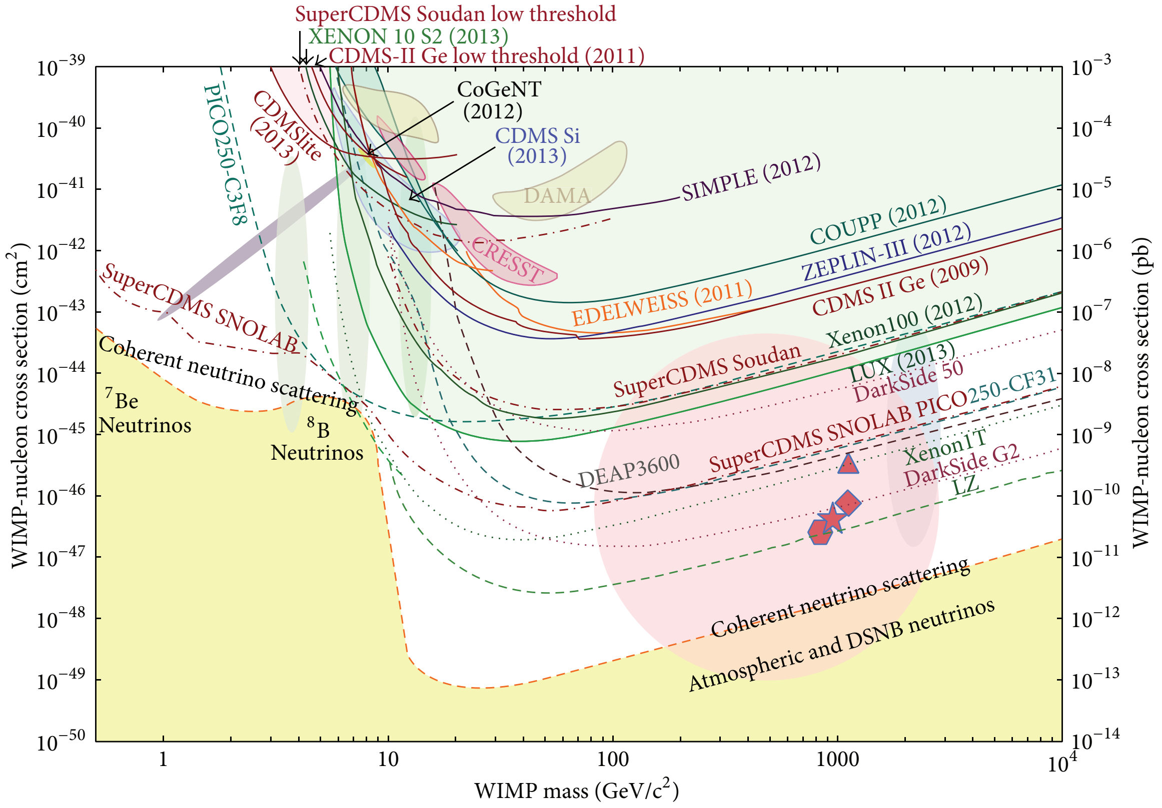
Weakly Interacting Massive Particle (WIMP)

- DM candidate which has standard model weak interaction
- Typical mass range: m ~ 100 GeV - 1 TeV

Direct detection

- DM + nucleus → DM + nucleus
- **Neutrino floor limits ultimate sensitivity**
- **Insensitive to Inelastic scattering (ΔM < 100 keV)**





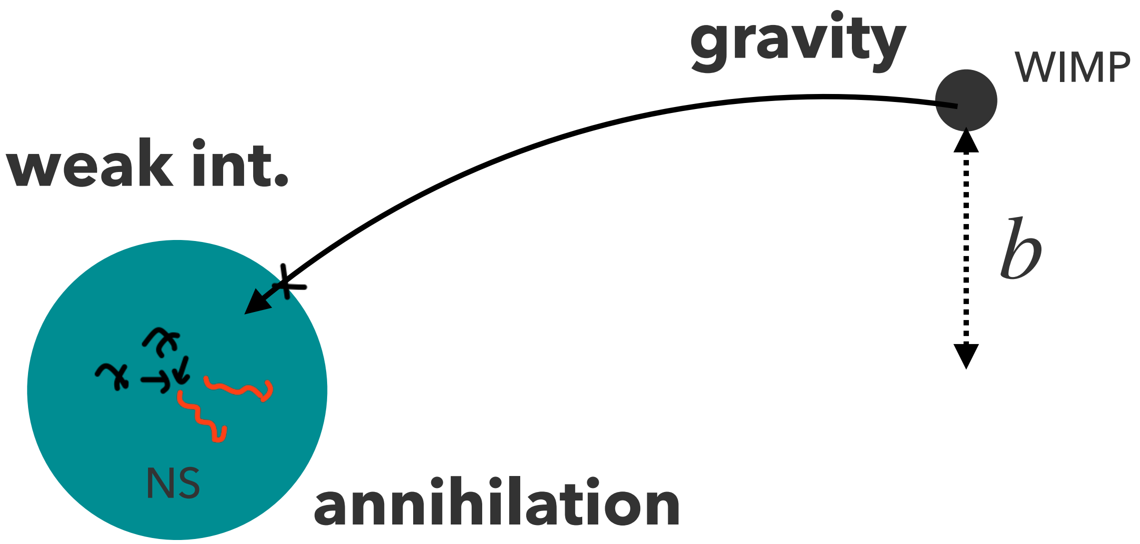
pure Higgsino/Wino DM:

$$\Delta M \sim O(100)\,\mathrm{MeV}$$

Dark matters accrete in neutron stars

- Consider weakly interacting massive particles (WIMPs)
- WIMPs scatter with nucleons and lose their kinetic energy
- Then they are trapped by a NS, and annihilate to SM particles

[Kouvaris, 0708.2362]



Energy injection

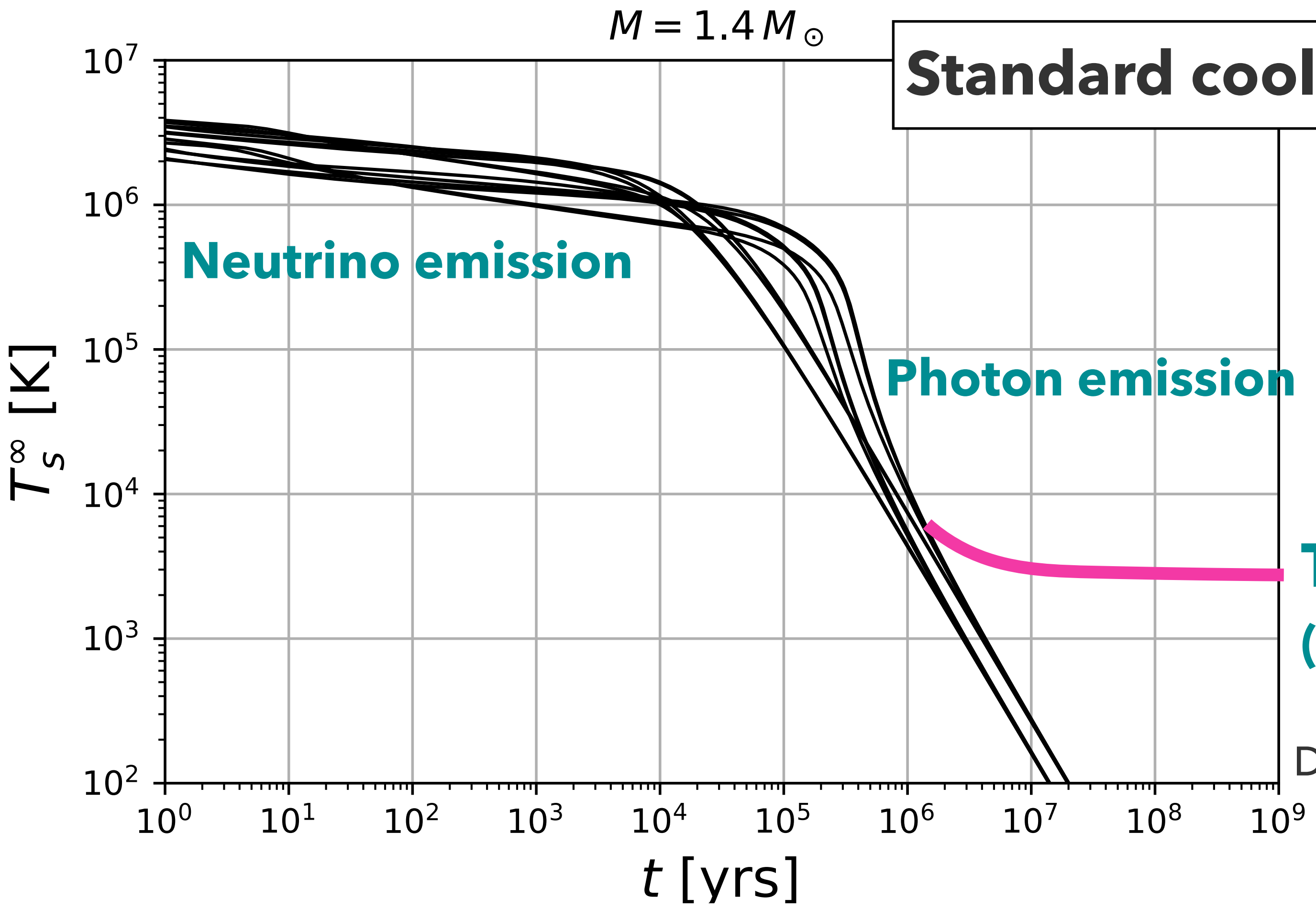
$$L_{\mathrm{WIMP}} = \text{(Energy flux)} \quad \text{x} \quad \text{(Capture probability)}$$

$$\sim \rho_{\mathrm{DM}} v_{\mathrm{DM}} \pi b_{\max}^2 \qquad \sim 1 \text{ for } \sigma_n \gtrsim 10^{-45}\,\mathrm{cm}^2$$

Dark matter kinetic/mass energy heats NS

DM scattering/annihilation deposits energy in NS

⟶ Late time heating!



Standard cooling scanario vs. DM heating

T_s ~ 3000 K by DM heating

(balance btw. photon cooling and DM heating)

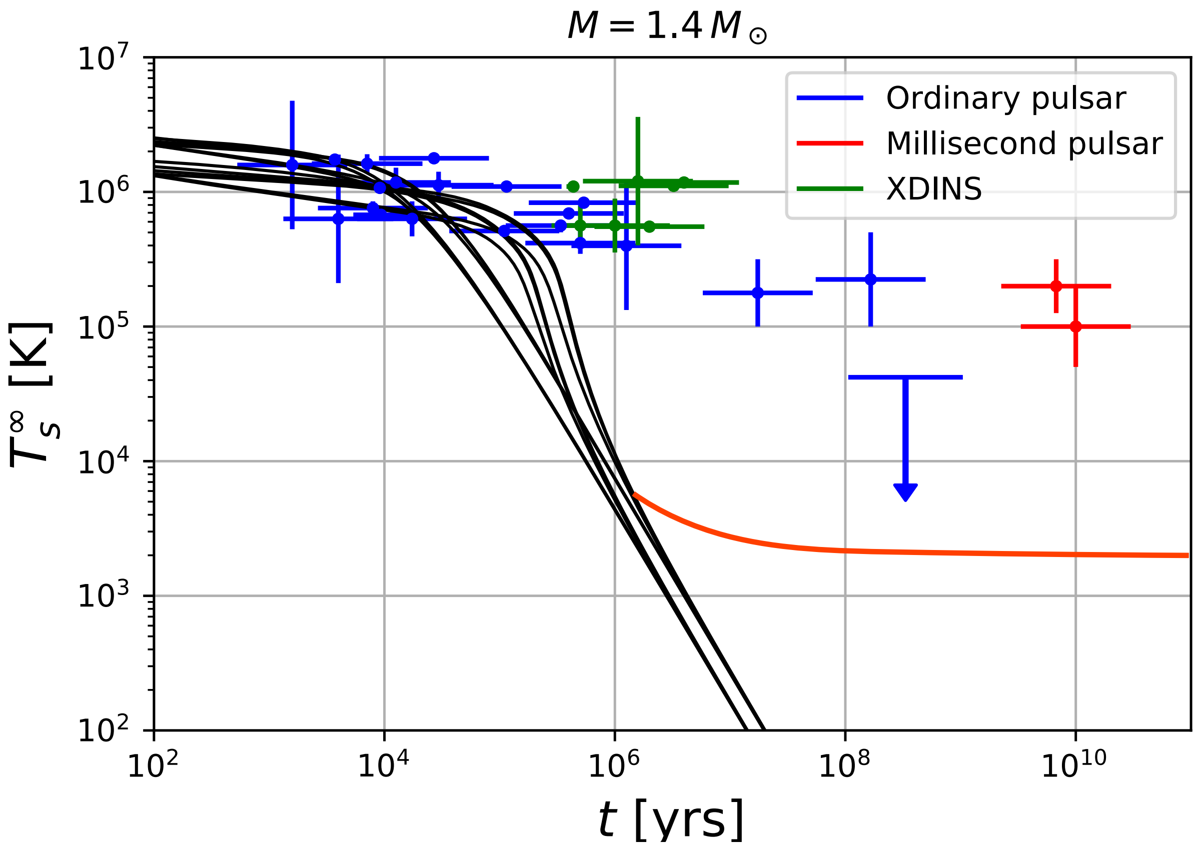
Different lines correspond to different NS models

- w/o WIMP : $T_s < 1000$ K @ t > 10 Myr
- w/ WIMP : **T_s ~ 3000 K** @ t > 10 Myr
- Sensitive to $\Delta M \lesssim 1\,\mathrm{GeV}$

[Kouvaris, 0708.2362 ;Baryakhtar+, 1704.01577]

Can we really see DM heating?

The observation suggests presence of **other heating mechanisms**



- Old NSs can be hotter than the cooling prediction or DM heating prediction
  - Several old (t > 10 Myr) pulsars have T_s ~ 10^5 K
  - WIMP cannot heat up a NS to T_s ~ 10^5 K
- An old NS is **not always warm**; it sometimes remains cold
  - PSR2144-3933: $T_s < 4\times10^4$ K @ t ~ 100 Myr

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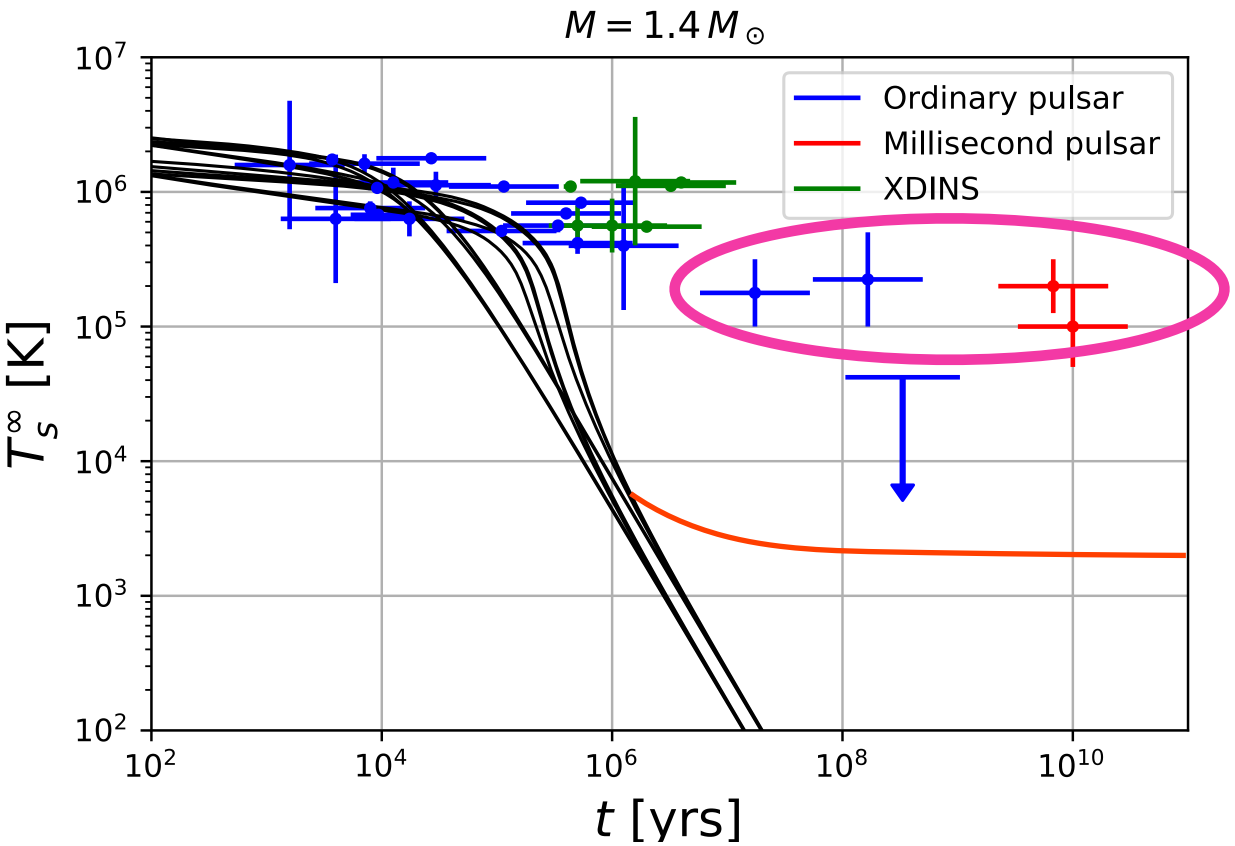

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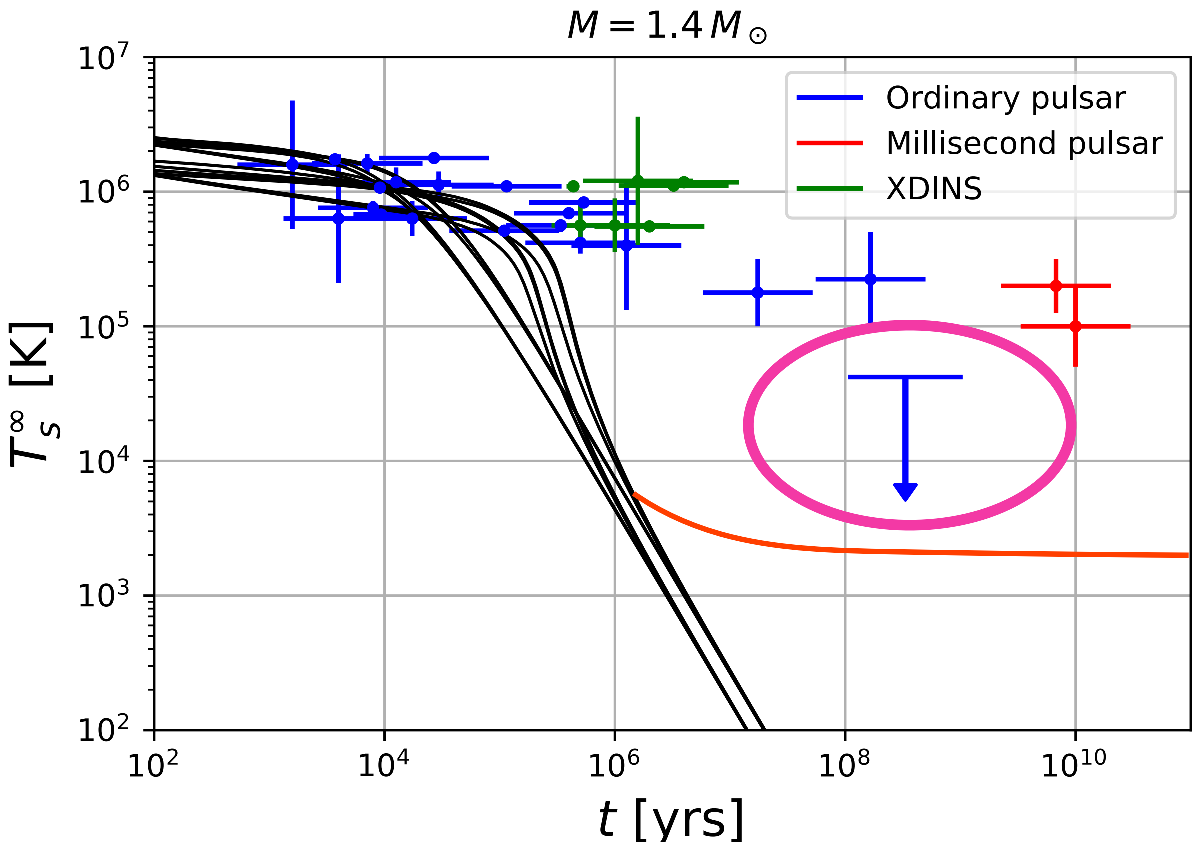

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Can we really see DM heating?

Theoretically, several heating mechanisms are suggested

[Gonzalez & Reisenegger, 1005.5699]

- **Non-equilibrium beta process (rotochemical heating)**

  ← Inevitable for pulsars

- Superfluid vortex heating
- Decay of magnetic field
- e.t.c…

Maybe responsible, but theoretically less clear…

If these mechanisms keep NS at $T_s \sim 10^5$ K, DM heating may be hidden…

Can we really see the DM heating? If so, we want to clarify the condition!

Outline

- Minimal cooling theory
- Rotochemical heating
- Results
  - We compare theory and observation including rotochemical heating [KY, Koichi Hamaguchi, Natsumi Nagata, arXiv: 1904.04667]
  - We discuss the possibility to search DM under the rotochemical heating [Koichi Hamaguchi, Natsumi Nagata, KY, arXiv: 1905.02991]

Minimal cooling of a neutron star

Basics of NS

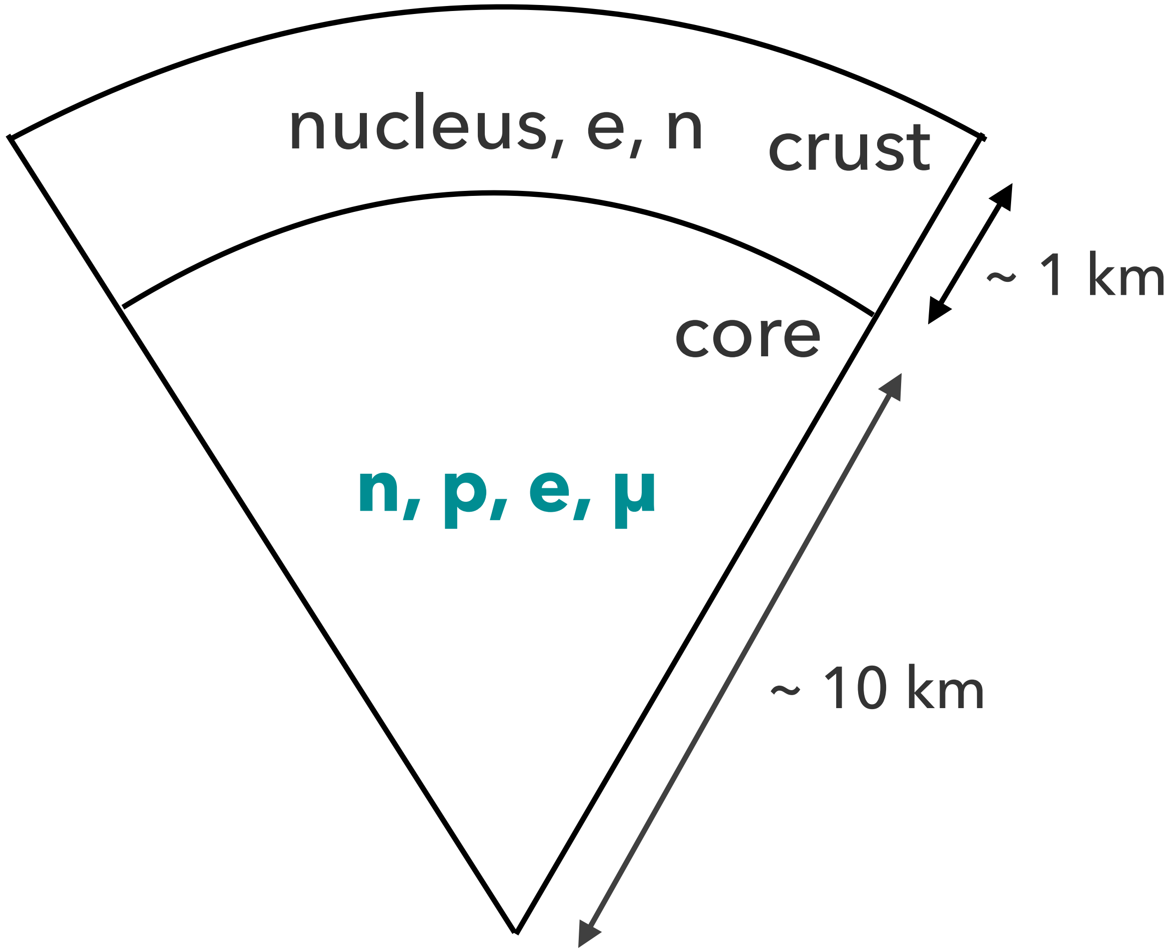
- NS core consists of n, p, e, μ
- They are Fermi-degenerate

$$p_{F,n} \sim O(100)\,\mathrm{MeV}$$

$$p_{F,e,p,\mu} \sim O(10)\,\mathrm{MeV}$$

- Birth temperature ~ 10^{11} K, and

  quickly cools to T < 10^{10} K
- **NS is cold system**



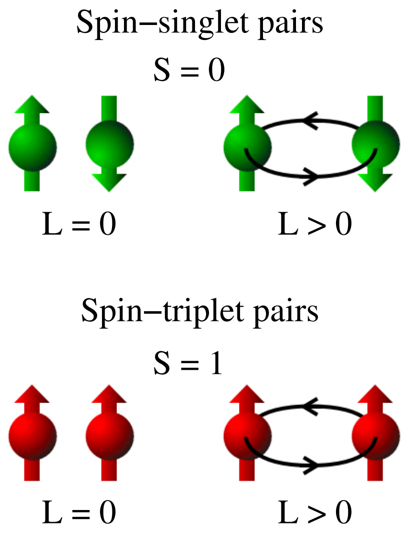
Nucleon superfluidity in NS

Cooper pairing occurs due to the attractive nuclear force

At $T < T_c^{(N)} \sim 10^{8-9}\,\mathrm{K}$

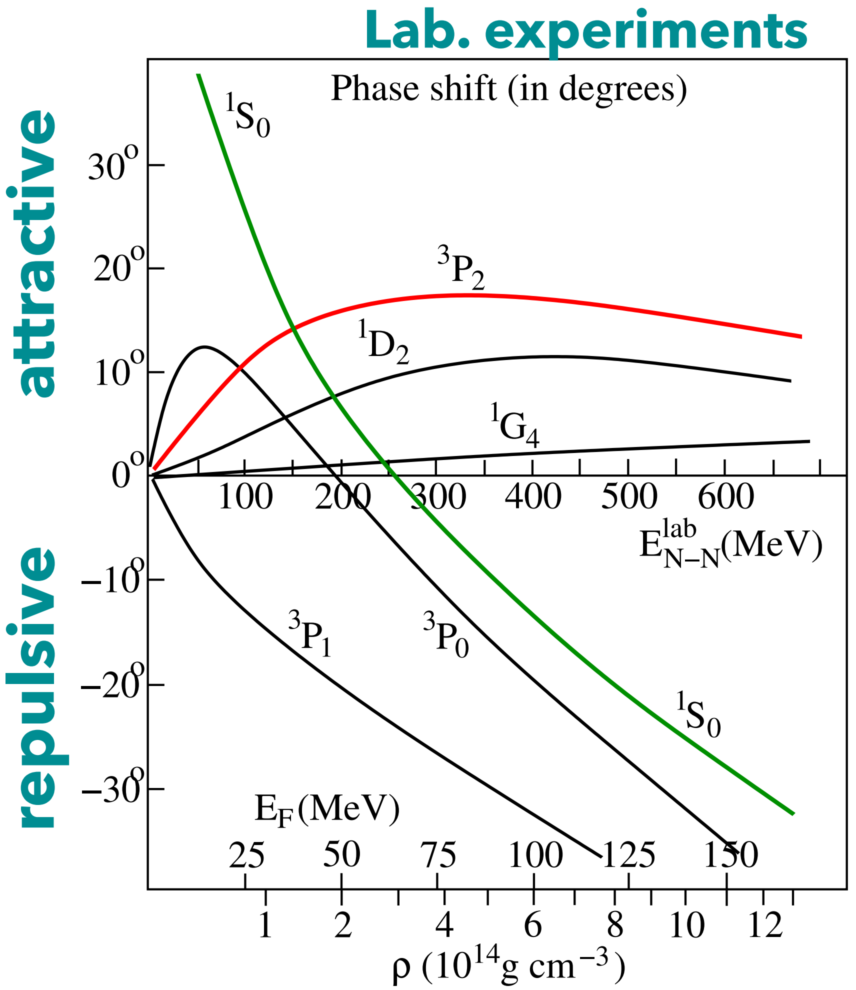
In NS core

- Proton singlet pairing ($^1S_0$)
- Neutron triplet pairing ($^3P_2$)



In NS crust (not important for thermal evolution)

- Neutron singlet pairing ($^1S_0$)

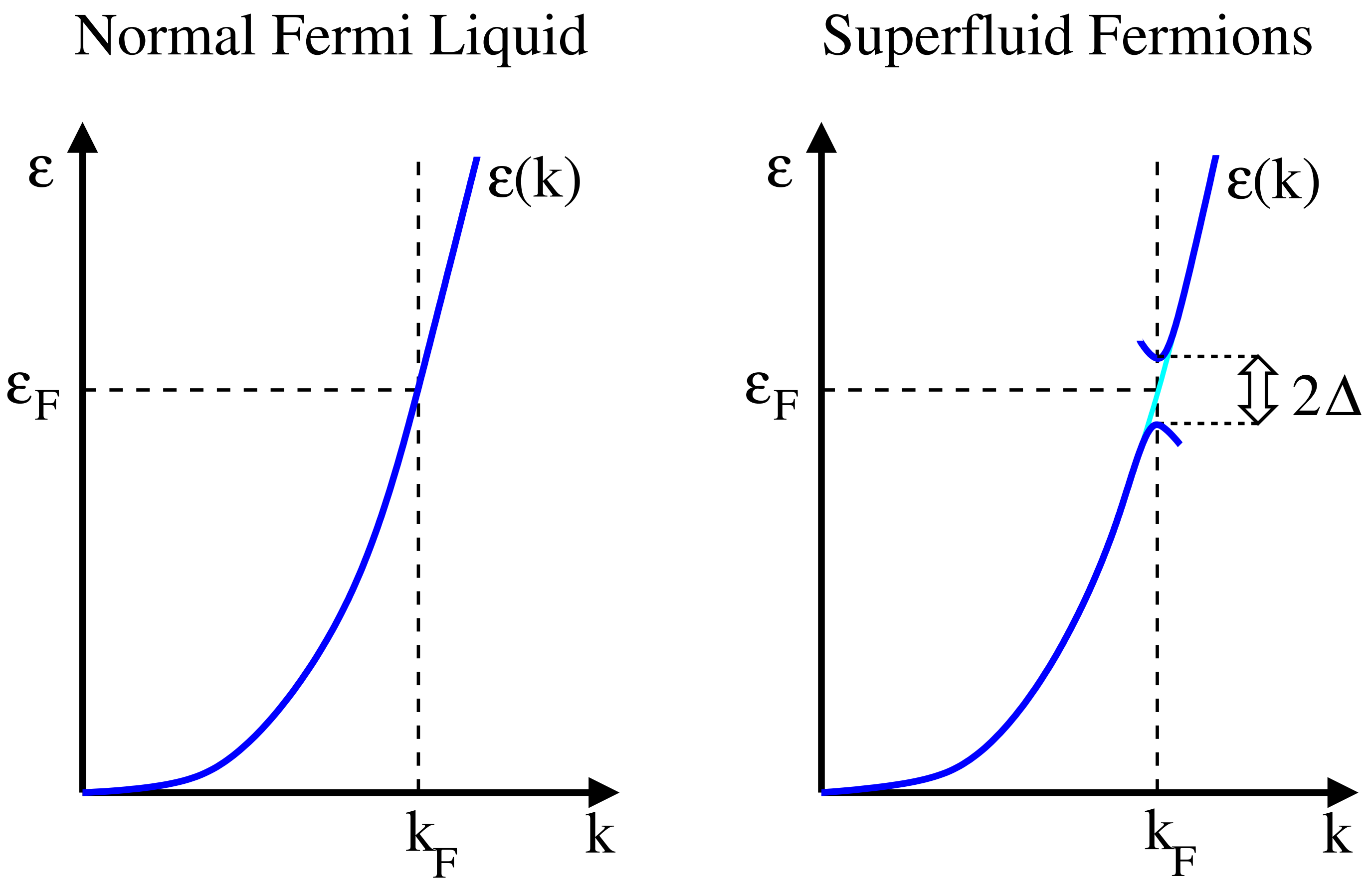


[Figures from Page et al. (2013)]

Nucleon pairing significantly affects NS thermal evolution!

Energy gap

Once Cooper paring occurs, the **energy gap** appears in the spectrum



No particle excitation

$$f(\mathbf{k}) = \frac{1}{e^{(\epsilon(\mathbf{k})-\mu)/T} + 1}$$

[Figures from Page et al. (2013)]

Near Fermi surface

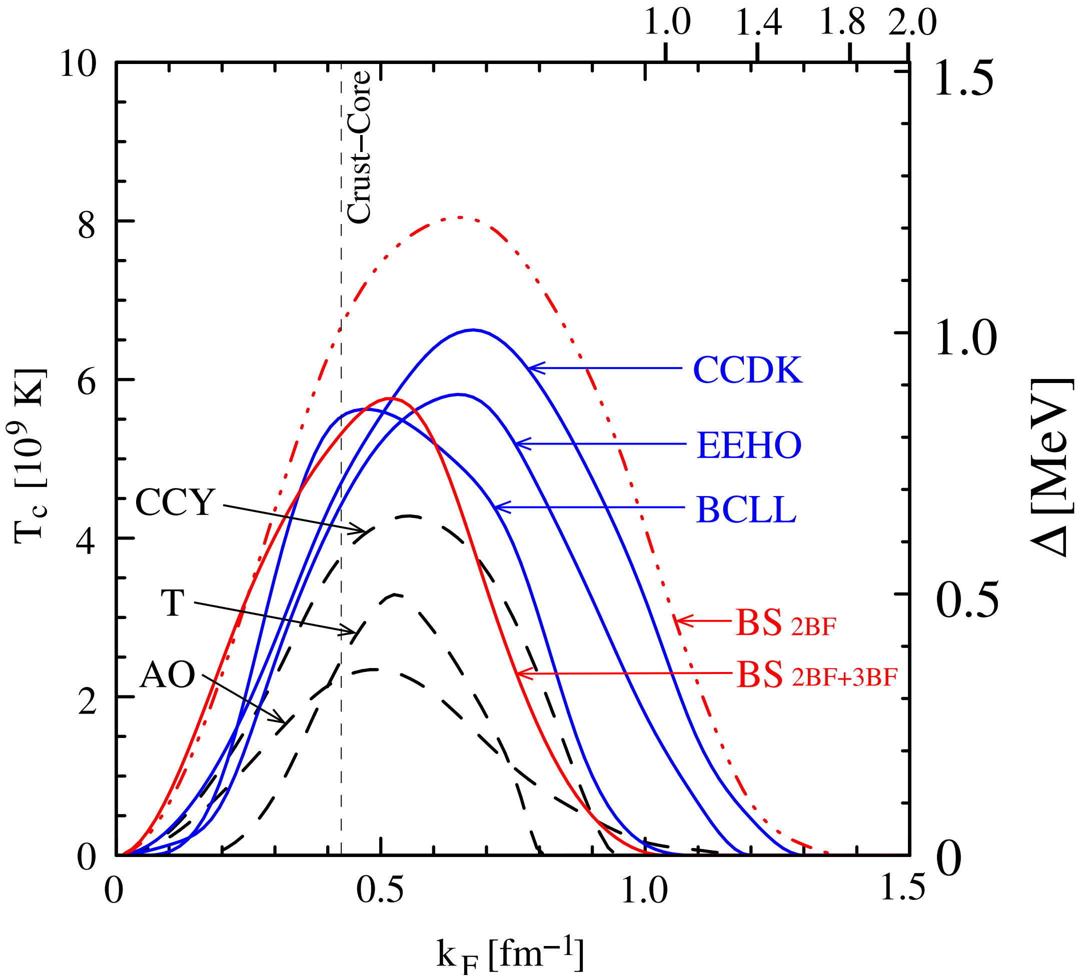
$$\epsilon_N(\mathbf{p}) \simeq \mu_N + \mathrm{sign}(p - p_{F,N})\sqrt{\Delta_N^2 + v_{F,N}^2(p - p_{F,N})^2}$$

Pairing gap models

The effects of superfluidity depends on momentum dependence of gap

$\Delta_N = \Delta_N(\mathbf{k}_F, T = 0)$

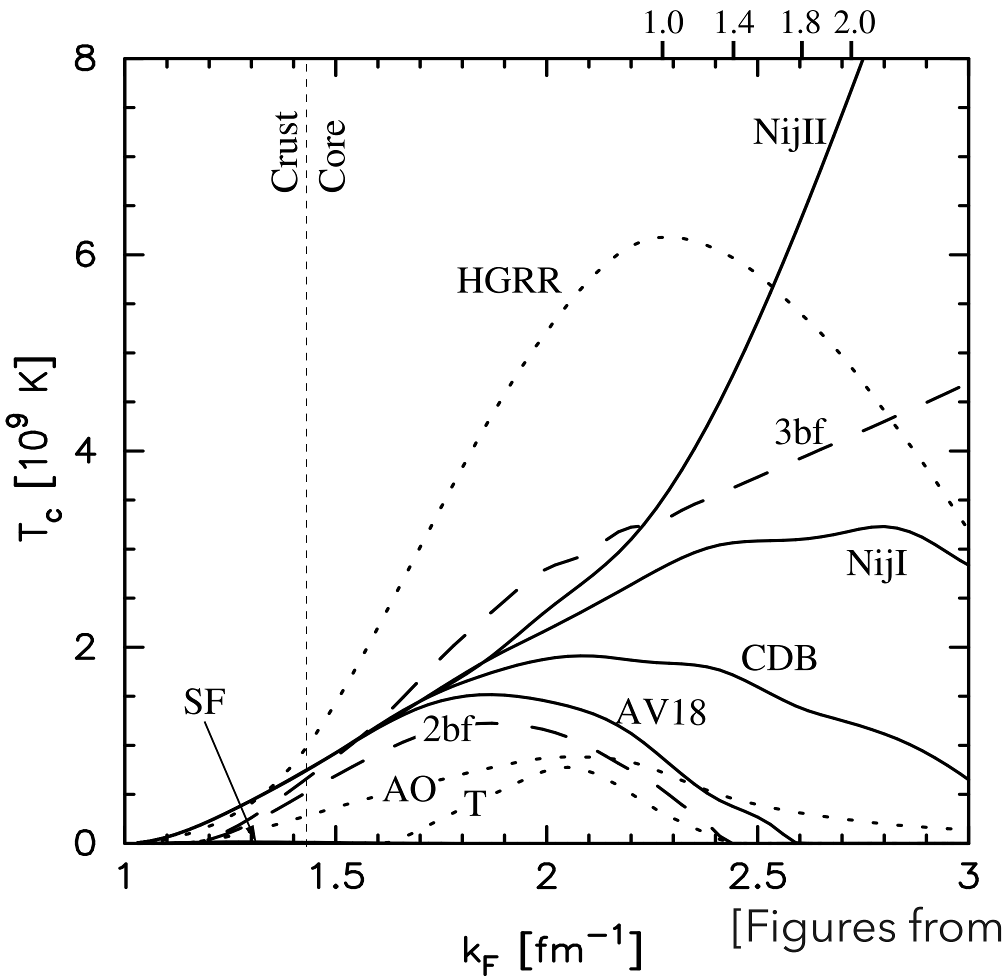
Proton ${}^1S_0$ pairing models



$$T_c^{(p)} = O(1) \times 10^9\,\mathrm{K}$$

$$\Delta_N(k_F, T = 0) \simeq 1.764\, k_B T_c^{(N)}$$

Neutron ${}^3P_2$ pairing models



[Figures from Page et al. (2013)]

$$T_c^{(n)} \sim 10^8 - 10^9\,\mathrm{K}$$

$$\Delta_N(k_F, \cos\theta = 0, T = 0) \simeq 1.188\, k_B T_c^{(N)}$$

Thermal evolution

Thermal evolution is governed by the energy conservation law

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

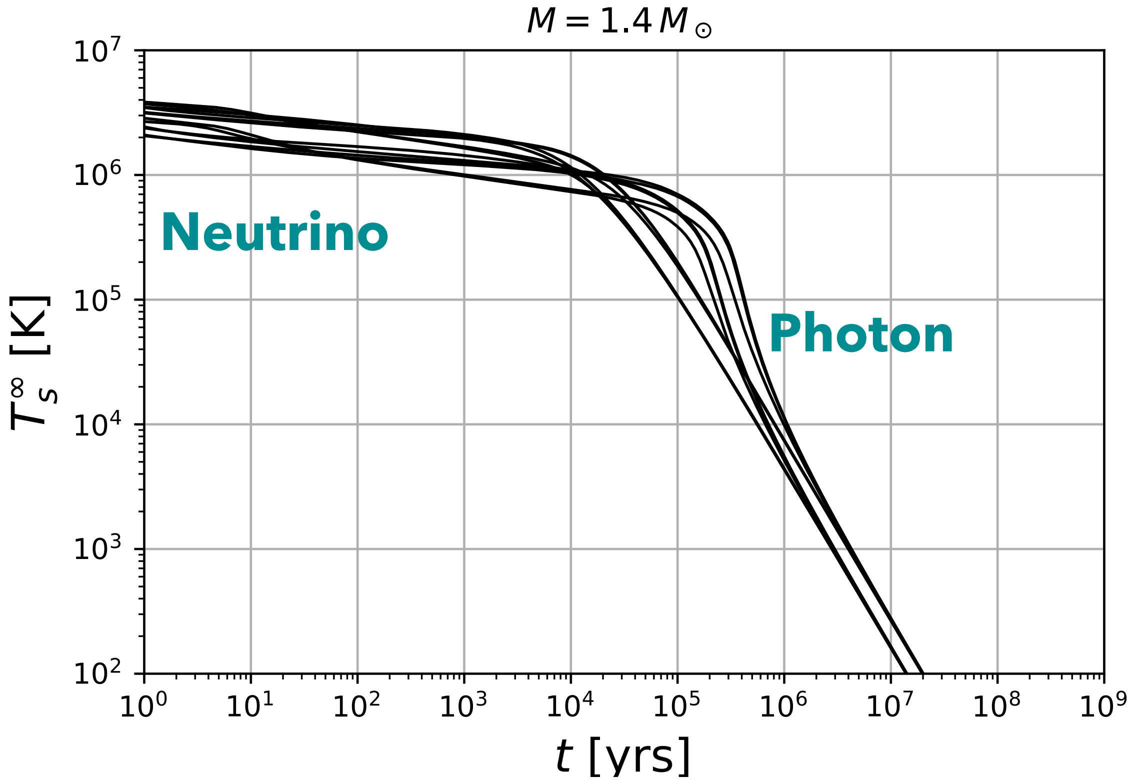
Heat capacity (n, p, e, μ)

Neutrino luminosity

Photon luminosity:

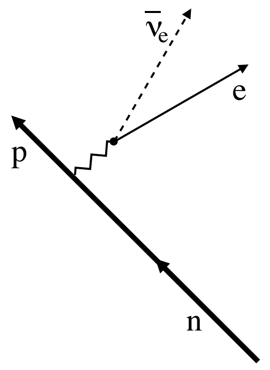
$$L_\gamma = 4\pi R^2 \sigma_B T_s^4$$

- t < 10^5 yr: **neutrino emission** from the core dominates
- t > 10^5 yr: **photon emission** from the surface dominates



Direct Urca process

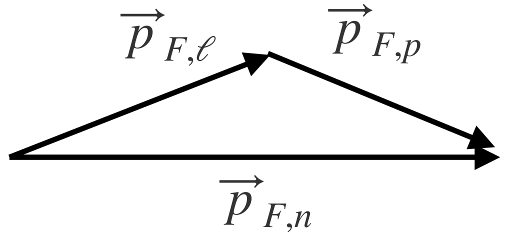
Neutrino emission from beta decay and its inverse **on Fermi surface**



$$n \to p + \ell + \bar{\nu}_\ell \qquad p + \ell \to n + \nu_\ell \qquad \ell = e, \mu$$

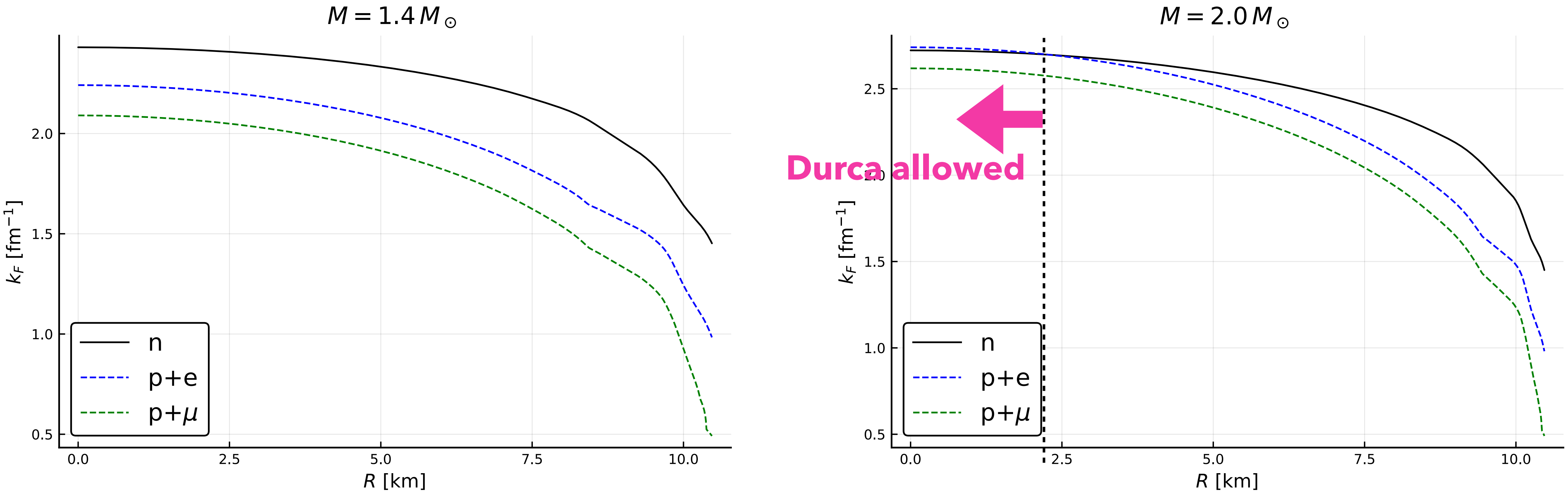
Direct Urca does not operate unless the NS is very heavy

- Nucleons and leptons are strongly degenerate; $p_\nu \sim T \ll p_{F,n,p,\ell}$
- Momentum conservation requires



$$p_{F,p} + p_{F,\ell} > p_{F,n}$$

- Since $p_F^3 \propto n$, direct Urca requires **high p, e, μ density** $(M \gtrsim 2\,M_\odot$ for APR EOS)



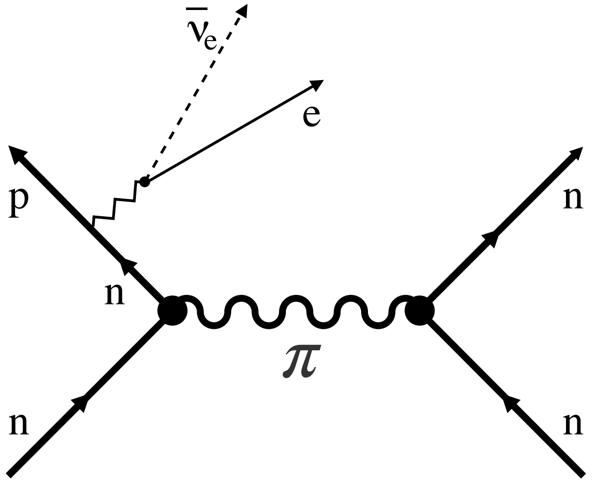
Durca allowed

Modified Urca process

Threshold of direct Urca is relaxed by spectator nucleon

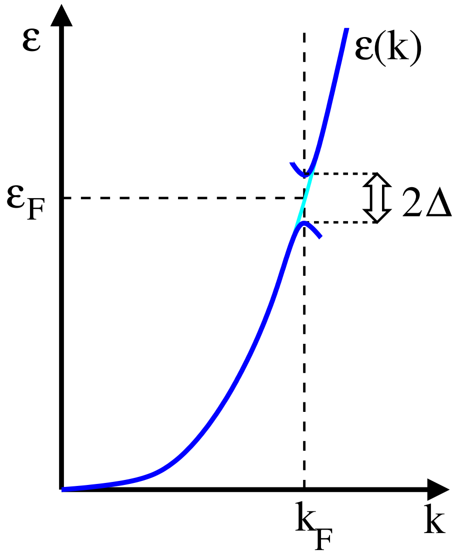
$$n + N \to p + N + \ell + \bar{\nu}_\ell$$

$$p + N + \ell \to n + N + \nu_\ell$$



$N = n$ or p

- **Beta equilibrium** is usually assumed: $\mu_n = \mu_p + \mu_\ell$
- Before Cooper pairing: Luminosity = $L_\nu^{\mathrm{MU}} \propto T^8$
- After Cooper pairing: modified Urca is highly suppressed



$\longrightarrow$ $f \sim e^{-\Delta_N/T}$ for

$$Q_{M,N\ell} = \int \left[\prod_{j=1}^{4} \frac{d^3 p_j}{(2\pi)^3} \right] \frac{d^3 p_\ell}{(2\pi)^3} \frac{d^3 p_\nu}{(2\pi)^3} (2\pi)^4 \delta^4(P_f - P_i) \cdot \epsilon_\nu \cdot \frac{1}{2} \sum_{\mathrm{spin}} |\mathcal{M}_{M,N\ell}|^2$$
$$\times \left[f_1 f_2 (1 - f_3)(1 - f_4)(1 - f_\ell) + (1 - f_1)(1 - f_2) f_3 f_4 f_\ell \right] ,$$

Cooper pair-breaking and formation (PBF)

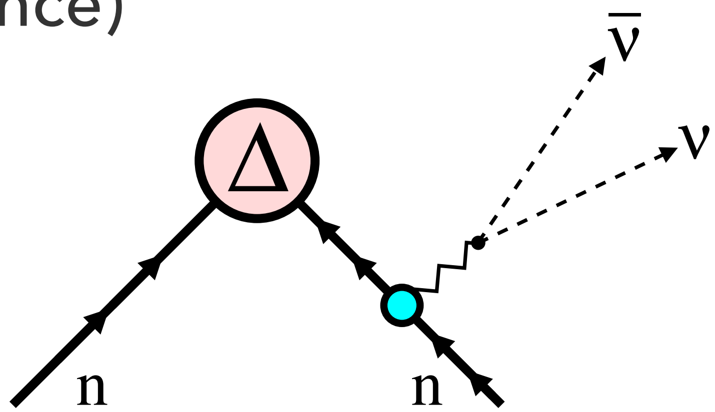
The Cooper pairing triggers rapid neutrino emission (called PBF)

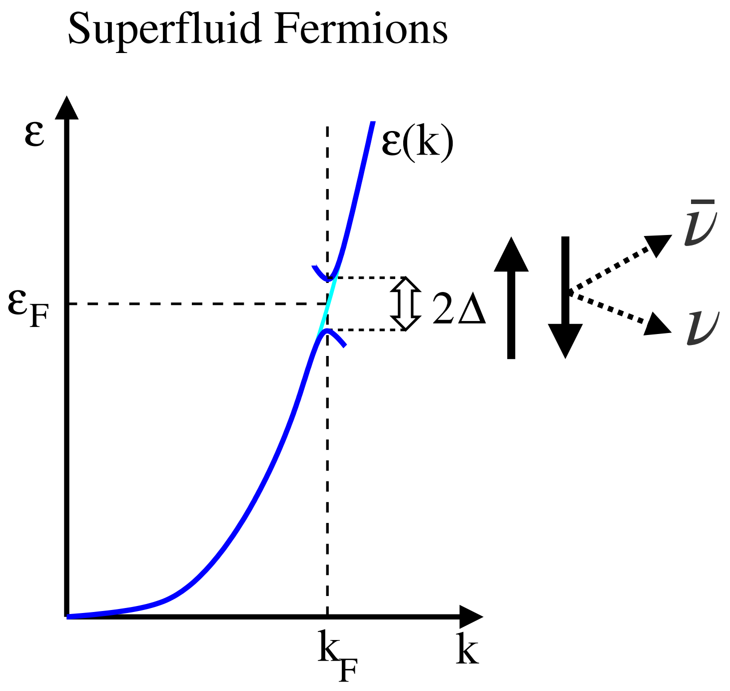
[Flowers et al. (1976)]

- **Pair-breaking** $[\tilde{N}\tilde{N}] \to \tilde{N} + \tilde{N}$ (thermal disturbance)

Cooper pair **Single (quasi-)nucleon**

- **Pair-formation** $\tilde{N} + \tilde{N} \to [\tilde{N}\tilde{N}] + \nu + \bar{\nu}$




Superfluid Fermions

Pair breaking occurs by thermal disturbance

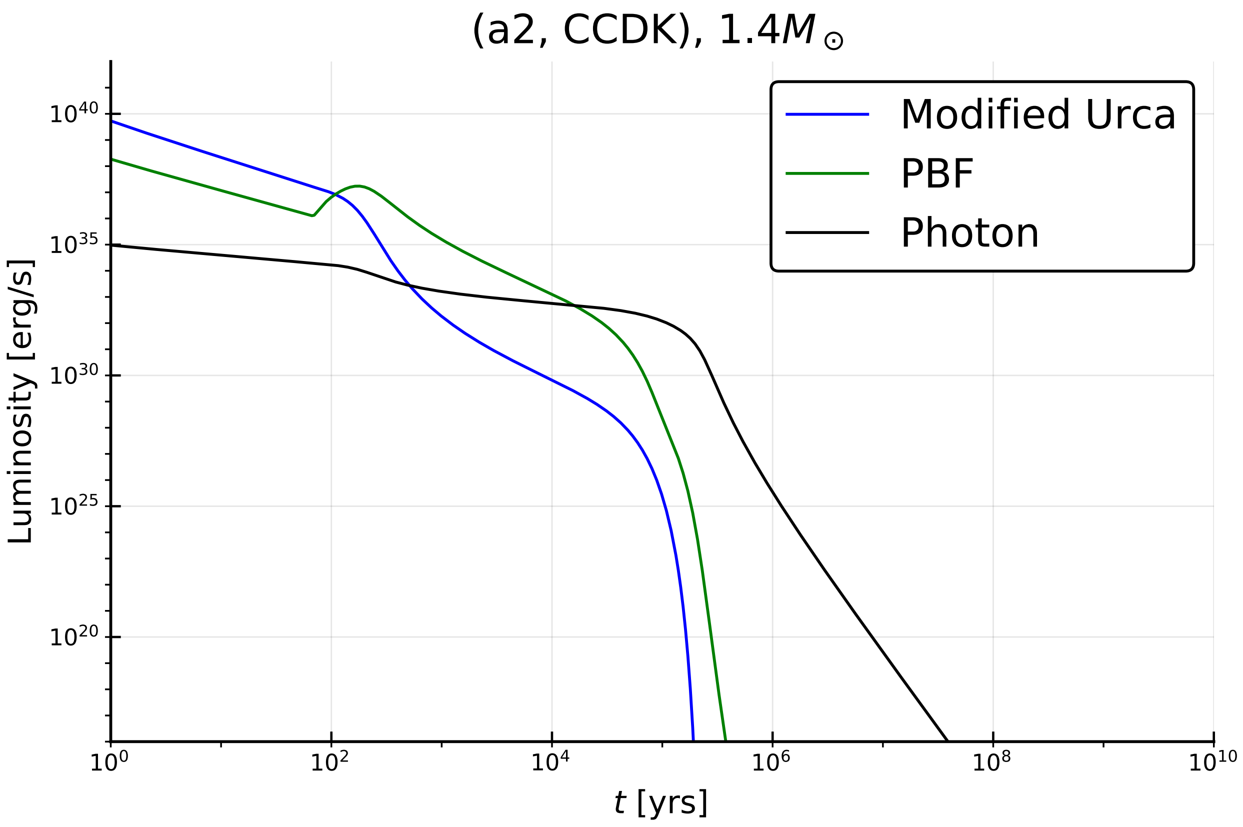
→ efficient while T ~ Δ

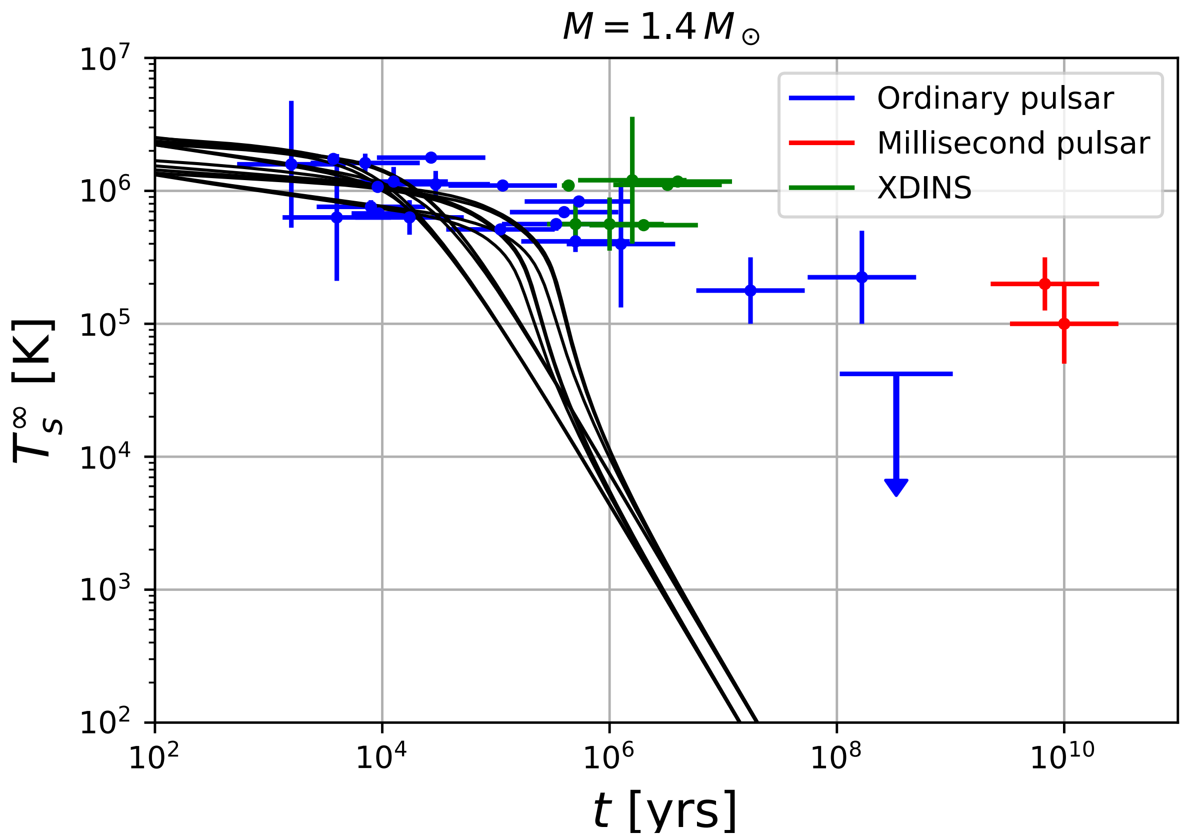
PBF dominates L_ν for $T < T_c$

Minimal cooling

Minimal cooling paradigm explains many NSs surface temperatures

[Page et al., astro-ph/0403657; Gusakov et al., astro-ph/0404002; Page et al., 0906.1621]





Different lines = Different gap/envelope model

- Direct Urca is not included
- t < 10 - 100 yr: Equilibrium modified urca $n + N \leftrightarrow p + N + \ell \pm \bar{\nu}_\ell$
- 10 - 100 yr < t < 10^5 yr: PBF $[\tilde{N}\tilde{N}] \to \tilde{N}\tilde{N} \quad \tilde{N}\tilde{N} \to [\tilde{N}\tilde{N}] + \nu\bar{\nu}$
- t > 10^5 yr : Photon emission $L_\gamma = 4\pi R^2 \sigma_B T_s^4$

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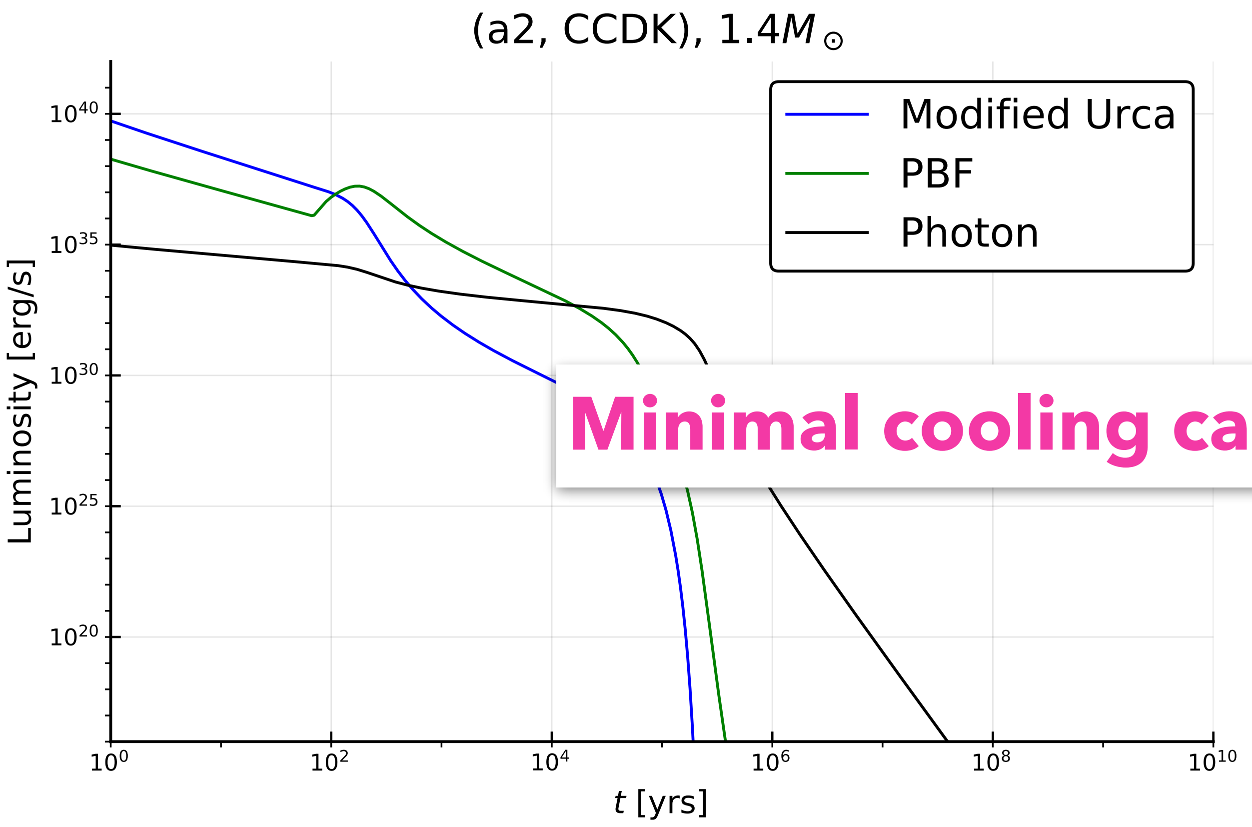

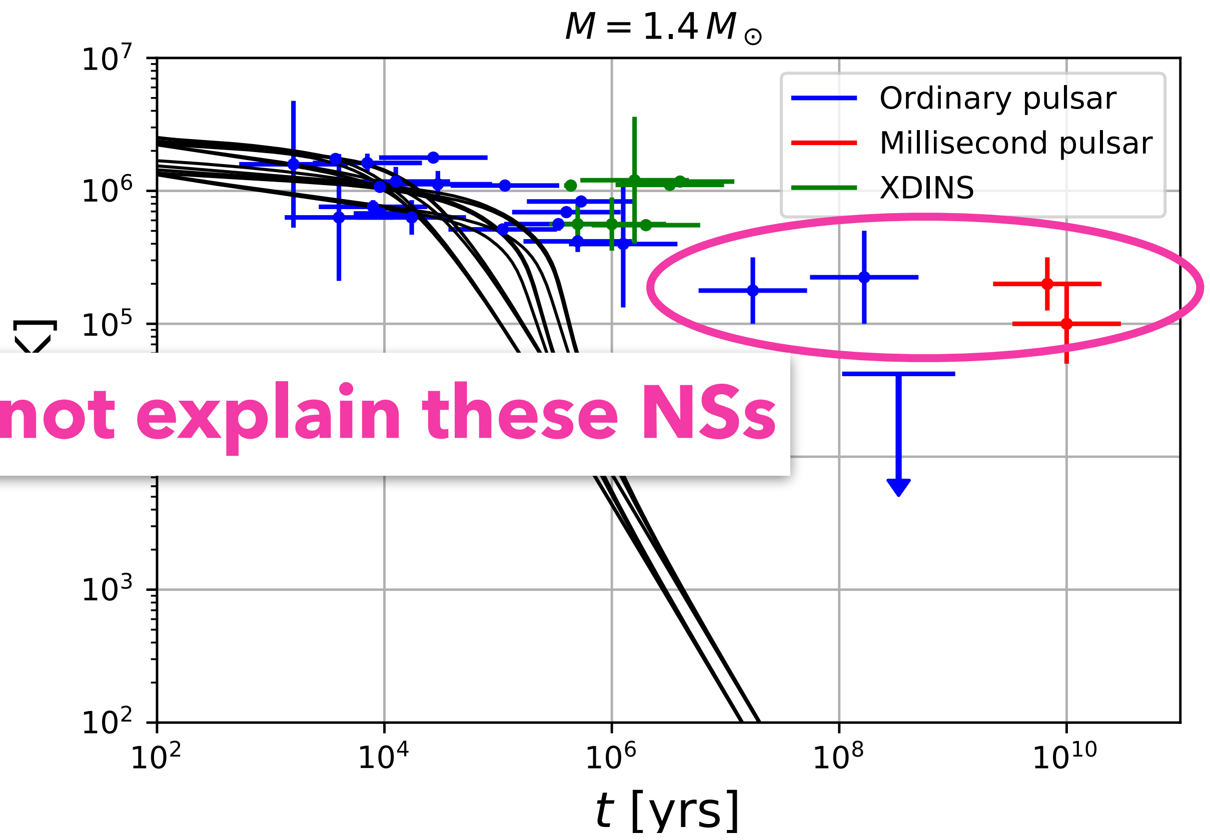

Minimal cooling cannot explain these NSs

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Rotochemical heating

Pulsar spin-down

Spin-down: NS is rotating, and its rotation is gradually slowing down

- Period and its derivative are measured

$$P \sim 10^{-3} - 1\,\mathrm{s} \qquad \dot{P} \sim 10^{-20} - 10^{-13}$$

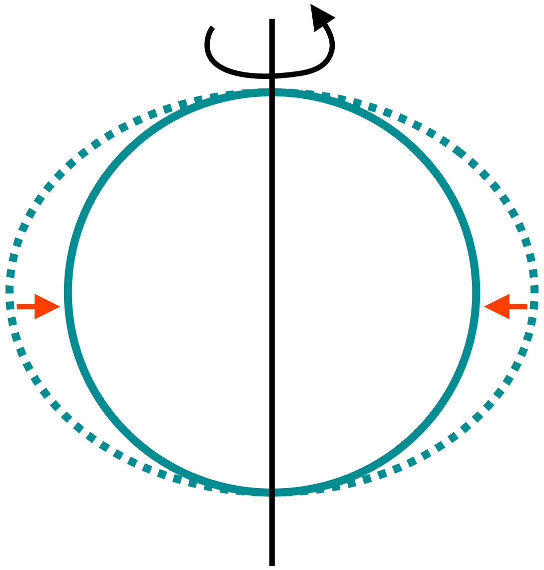
- Spin-down is caused by the **magnetic dipole radiation**

$$\frac{d\Omega}{dt} = -k\Omega^3 \qquad \longrightarrow \qquad \Omega(t) = \frac{2\pi}{\sqrt{P_0^2 + 2P\dot{P}t}}$$

$$k \propto B^2 \propto P\dot{P}$$

$$B \sim 3.2 \times 10^{19} (P\dot{P}/s)^{1/2}\,\mathrm{G}$$

- Centrifugal force is decreasing, NS is more compressed, becoming more spherical



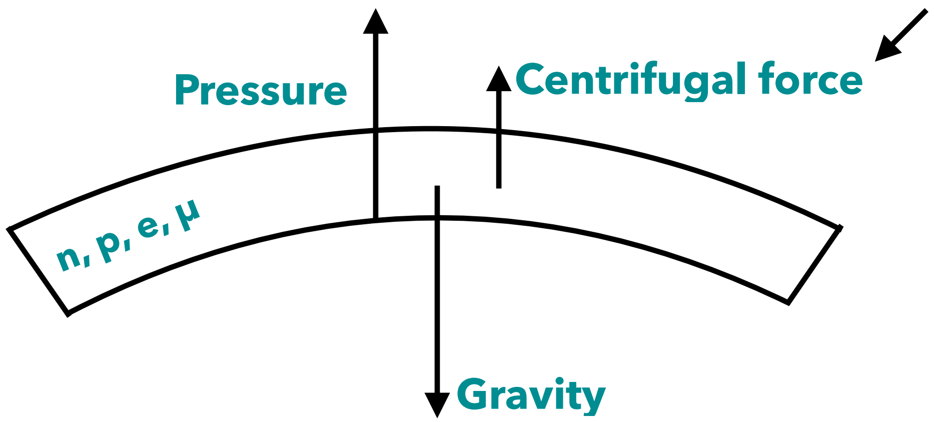
Beta equilibrium is not maintained in pulsars

Pulsar spin-down changes equilibrium particle density every moment

[Reisenegger (1995)]

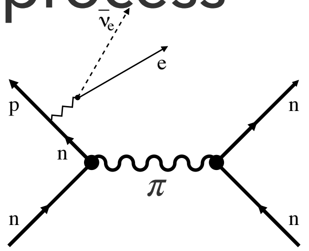
- Decrease of centrifugal force → increase of pressure

$$\Omega(t) = \frac{2\pi}{\sqrt{P_0^2 + 2P\dot{P}t}}$$



$$\rightarrow \quad n_i^{\mathrm{eq}} = n_i^{\mathrm{eq}}(t)$$

- Can the NS arrive at $n_i(t) = n_i^{\mathrm{eq}}(t)$?
- Particle number density is rearranged by **non-equilibrium** modified Urca process



For neutron

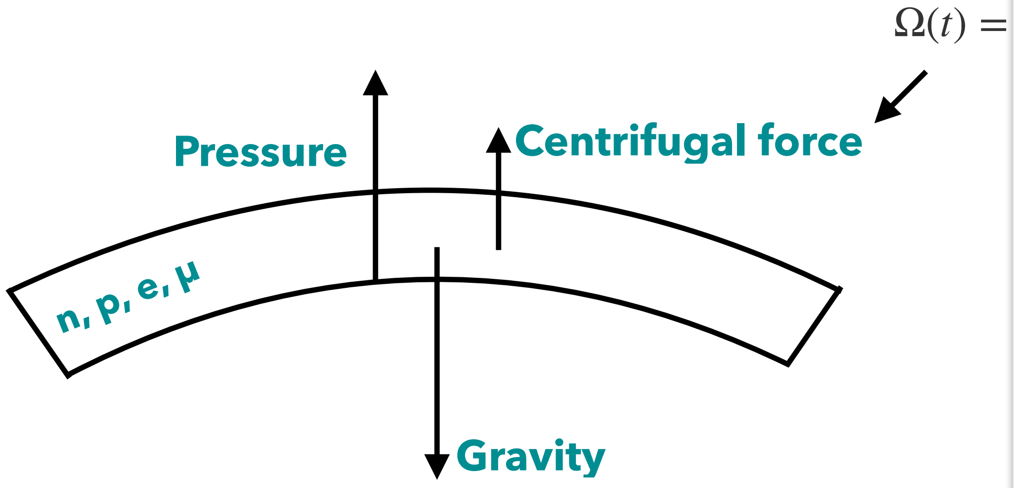
$$-\frac{dn_n}{d\tau} = \Gamma_{n\to pe} - \Gamma_{pe\to n} + \Gamma_{n\to p\mu} - \Gamma_{p\mu\to n} = \Delta\Gamma_e + \Delta\Gamma_\mu$$

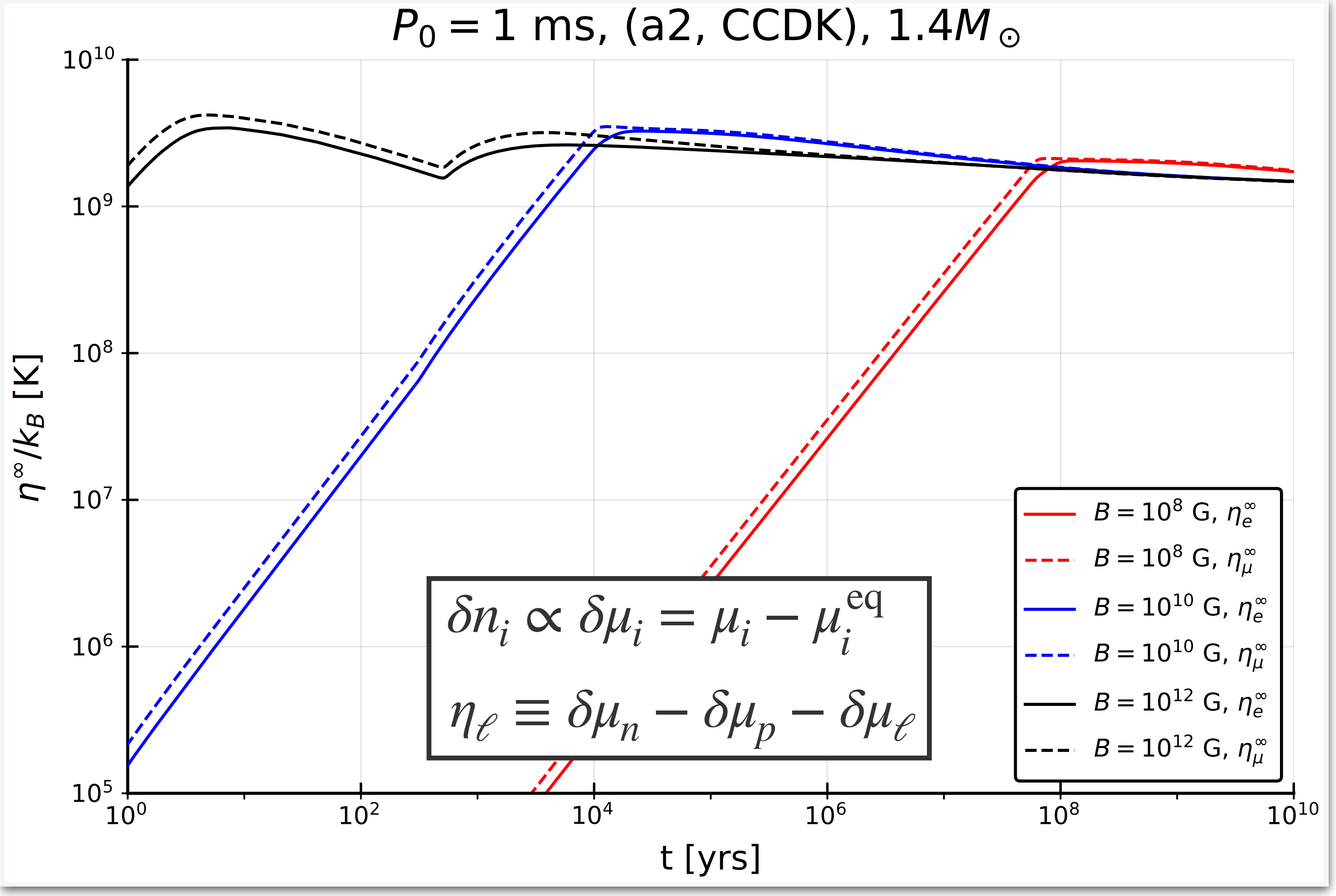
$$n_i = n_i^{\mathrm{eq}}(t) + \delta n_i \quad \rightarrow \quad \frac{d}{d\tau}\delta n_n = -\Delta\Gamma_e - \Delta\Gamma_\mu - \frac{d}{d\tau}n_n^{\mathrm{eq}}$$

Beta equilibrium is not maintained in pulsars

Pulsar spin-down changes equilib

- Decrease of centrifugal force → incr





$$\delta n_i \propto \delta\mu_i = \mu_i - \mu_i^{\mathrm{eq}}$$

$$\eta_\ell \equiv \delta\mu_n - \delta\mu_p - \delta\mu_\ell$$

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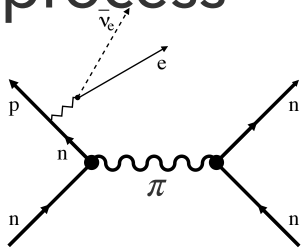


For neutron $$-\frac{dn_n}{d\tau} = \Gamma_{n\to pe} - \Gamma_{pe\to n} + \Gamma_{n\to p\mu} - \Gamma_{p\mu\to n} = \Delta\Gamma_e + \Delta\Gamma_\mu$$

$$n_i = n_i^{\mathrm{eq}}(t) + \delta n_i \quad \Rightarrow \quad \frac{d}{d\tau}\delta n_n = -\Delta\Gamma_e - \Delta\Gamma_\mu - \frac{d}{d\tau}n_n^{\mathrm{eq}}$$

The assumption of beta equilibrium is not correct!

Heating rate

The out of beta-equilibrium process generates entropy

- Suppose thermodynamic but non-chemical equilibrium NS
- Under rapid spin-down, the system goes to new equilibrium with

$$dE^\infty = T^\infty dS + \sum_{i=n,p,e,\mu} \underbrace{\mu_i^\infty dN_i}_{\text{0 if in chemical equilibrium}} = -(L_\nu^\infty + L_\gamma^\infty)dt$$

- Particle number changes by modified Urca: e.g., $-\frac{dn_n}{d\tau} = \Gamma_{n\to pe} - \Gamma_{pe\to n} + \Gamma_{n\to p\mu} - \Gamma_{p\mu\to n}$
- Using $C = T^\infty dS/dT^\infty$

$$C\frac{dT^\infty}{dt} = -L_\nu^\infty - L_\gamma^\infty + L_H^\infty \quad \text{w/} \quad L_H^\infty = \sum_{\ell=e,\mu}\sum_{N=n,p}\int dV\,\eta_\ell \cdot \Delta\Gamma_{M,N\ell}e^{2\Phi(r)}$$

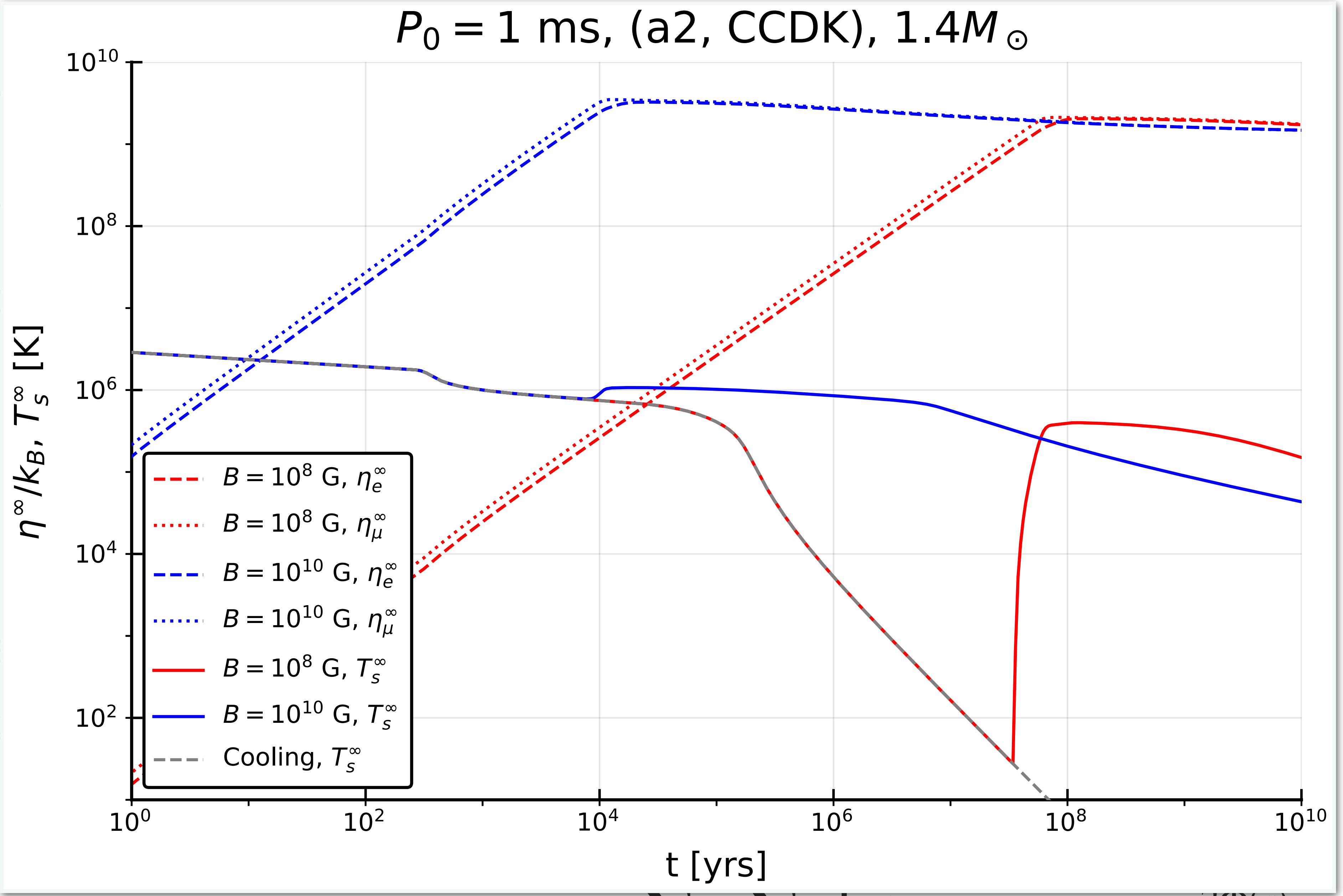
Heat production without exotic physics!

Heating rate

The out of beta-equ

- Suppose thermody
- Under rapid spin-d

dE^∞



- Particle number cha
- Using $C = T^\infty dS/d$

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Heat production without exotic physics!

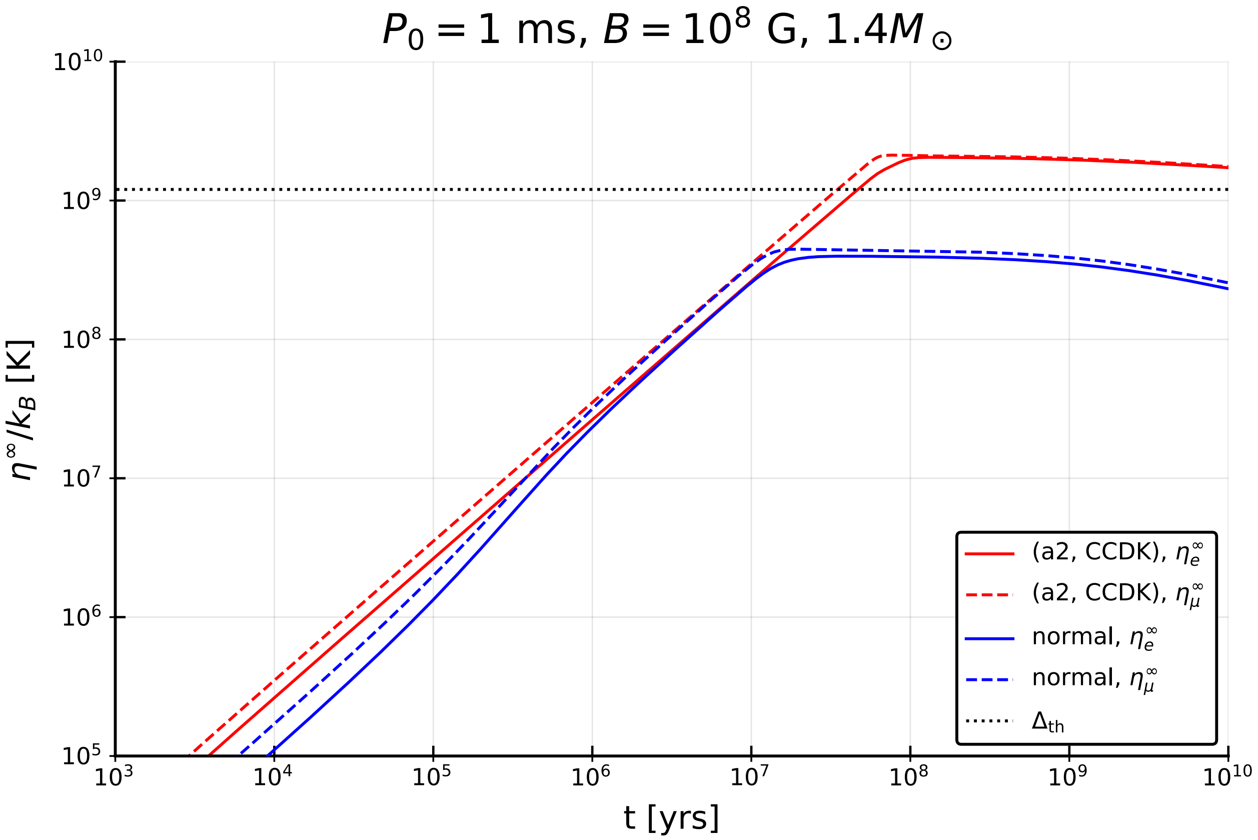
Effect of superfluidity

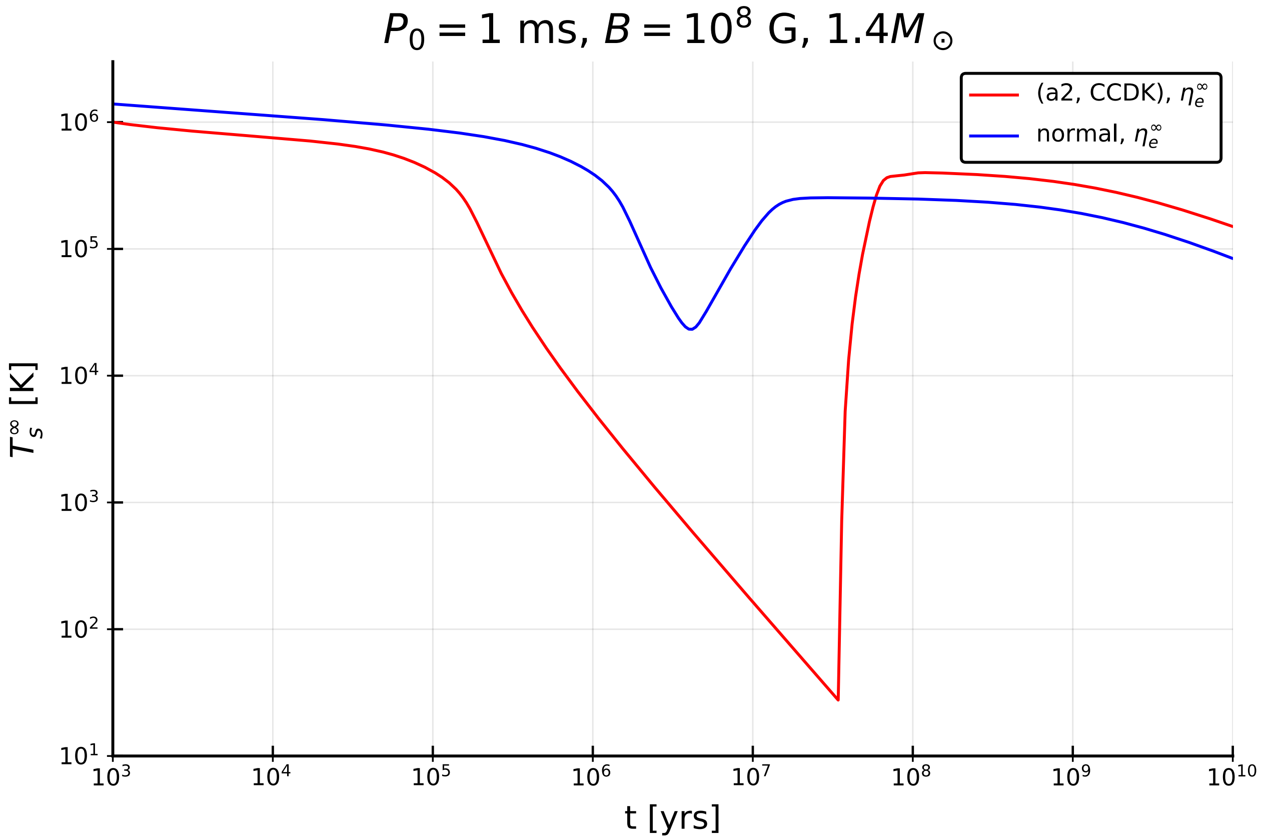
Nucleon superfluidity generates threshold [Petrovich & Reisenegger, 0912.2564]

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

$\eta_\ell > \Delta_{\rm th}$: heating begins

Larger Δ ~ larger η → hotter NS





Previous work incorporates only neutron triplet pairing [González-Jiménez et al, 1411.6500]

We include both neutron and proton pairing

Rotochemical heating vs. observation

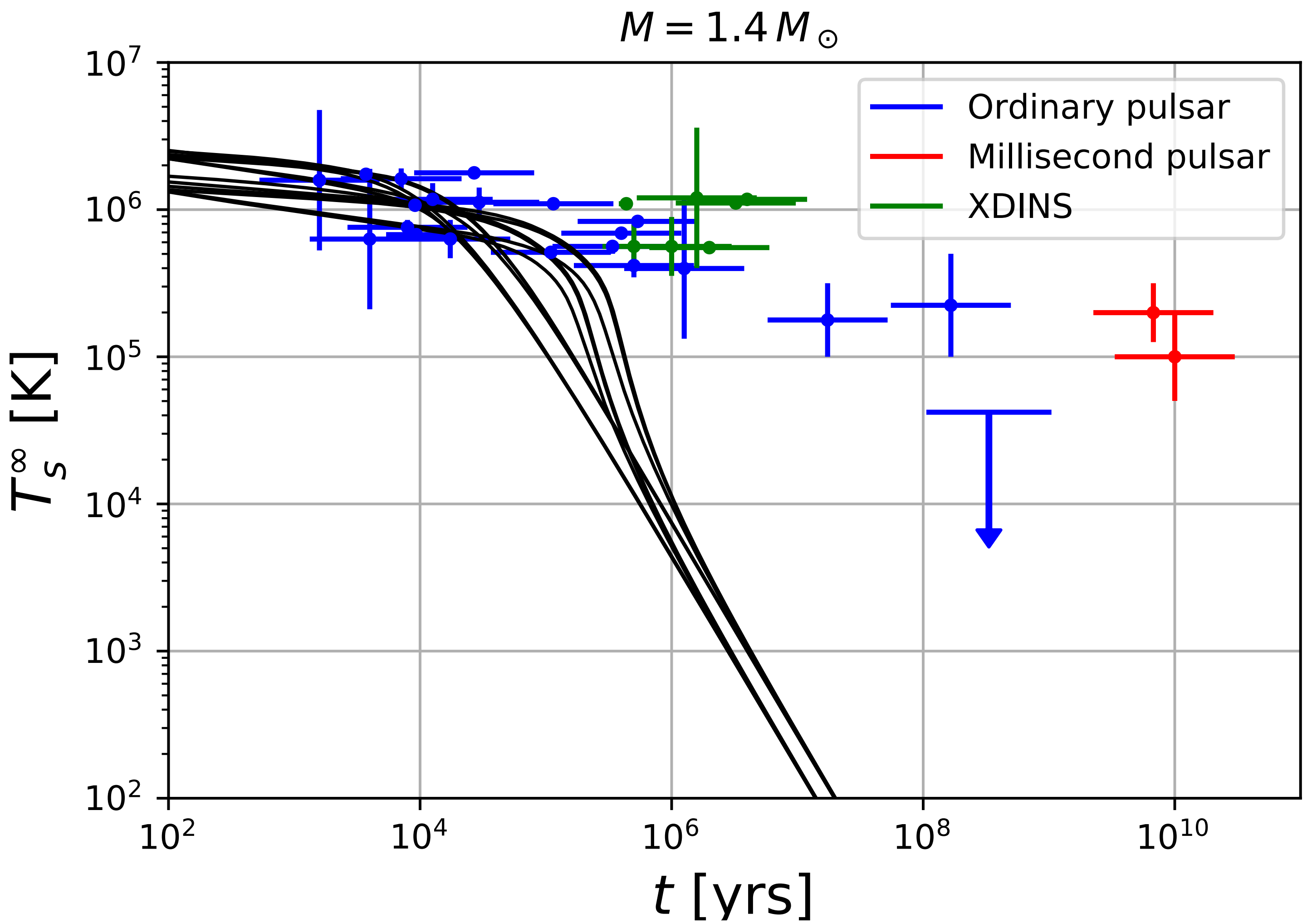
Two categories of observed pulsars

Ordinary pulsars and XDINSs $P \sim 1 - 10\,\mathrm{s}\,, \dot{P} \sim 10^{-(15-13)}$

- Ordinary pulsars : most NSs belong to this class
- XDINSs (X-ray dim Isolated Neutrons Stars) : large magnetic field, thought to be remnants of magneter

Millisecond pulsars $P \sim 1\,\mathrm{ms}\,, \dot{P} \sim 10^{-20}$

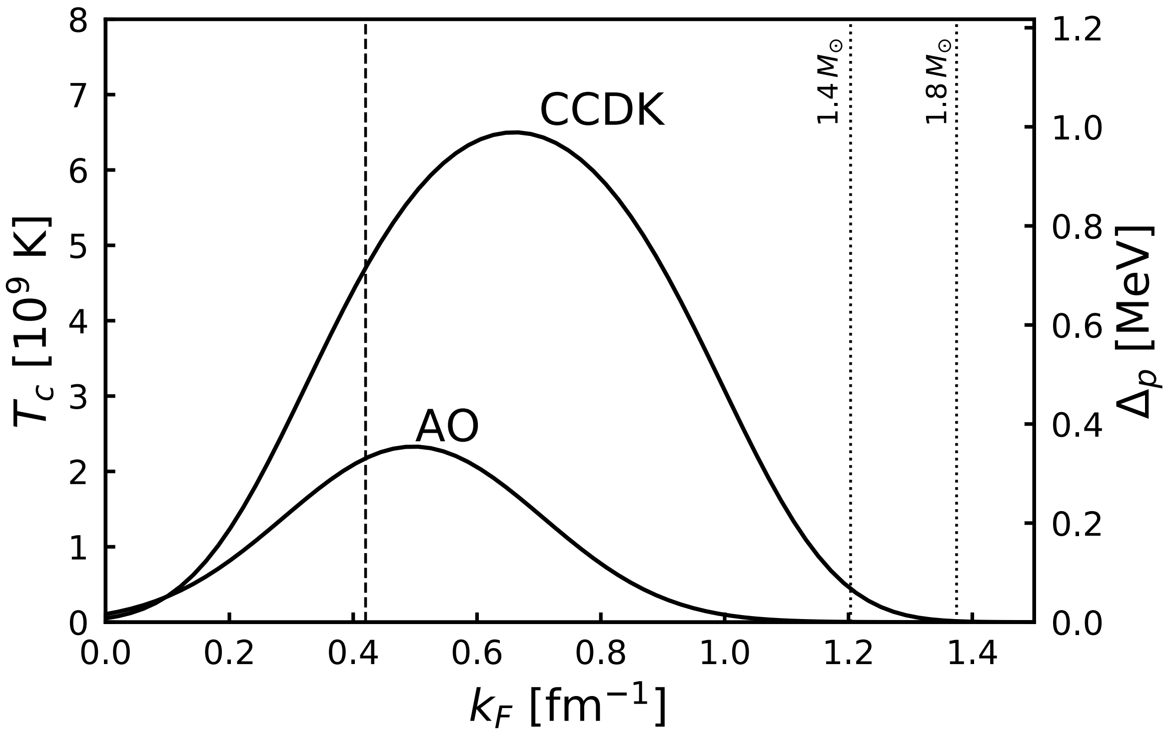
- Millisecond pulsars : small rotational period and its derivative, formed by recycle of a binary system

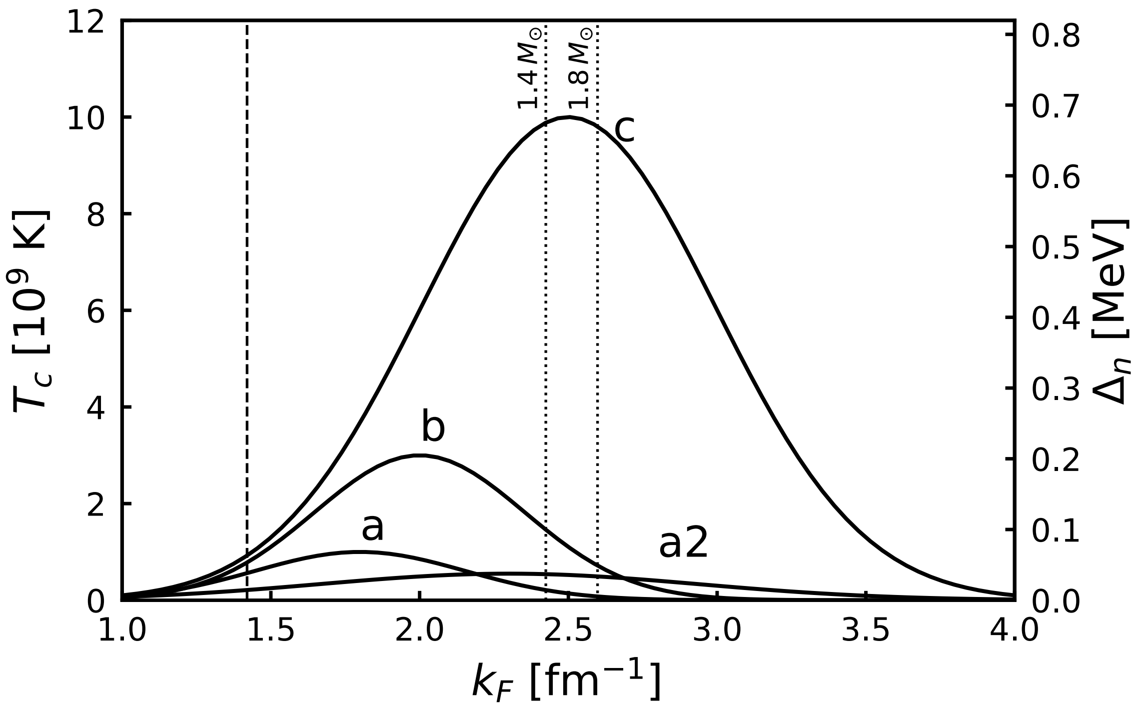


$$B \sim 3.2 \times 10^{19} \left(\frac{P\dot{P}}{s} \right)^{1/2} \mathrm{G}$$

Gap models we use

The profile of pairing gap is one major source of uncertainty



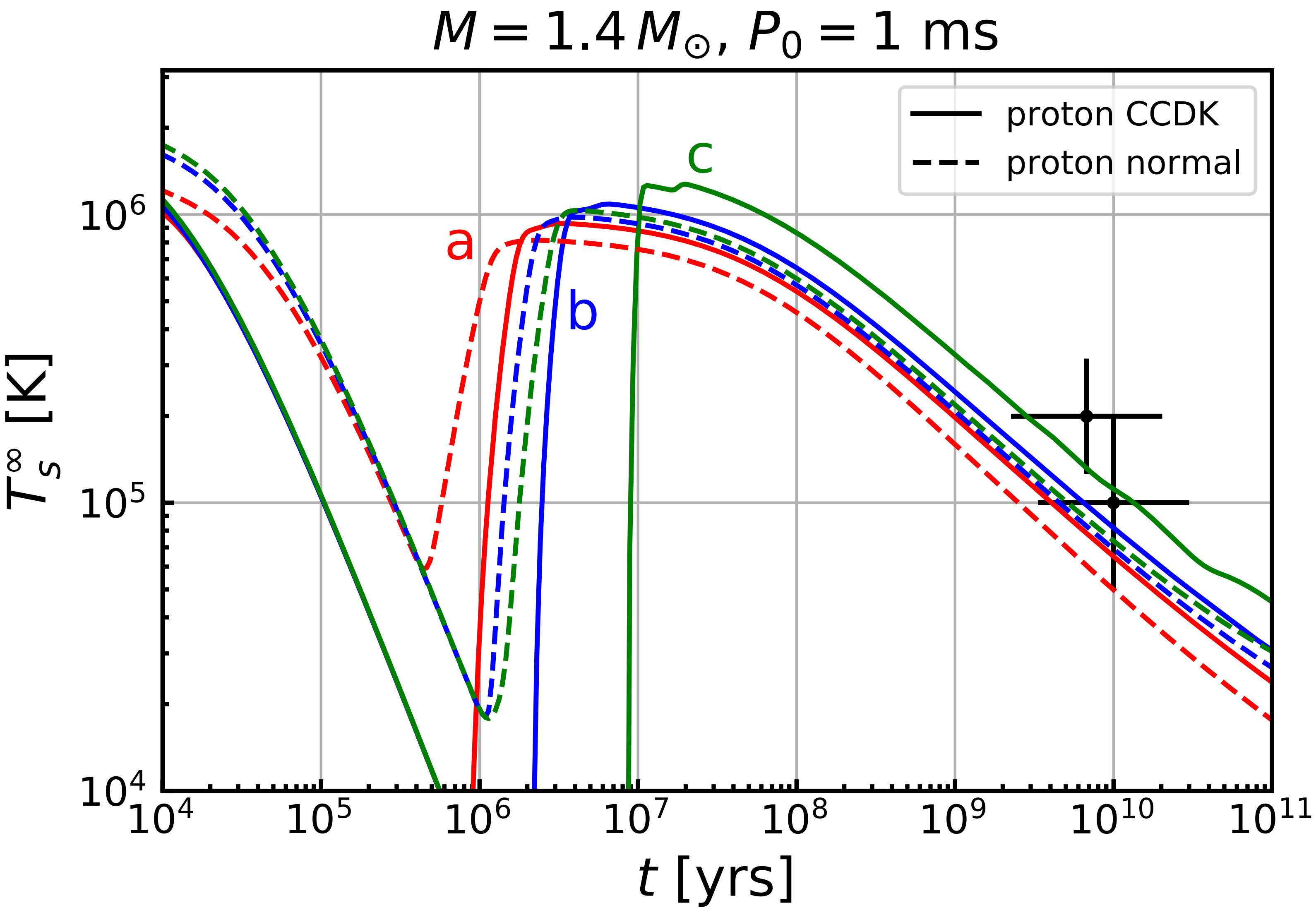


$$\Delta_{\rm th} = \min\{3\Delta_n + \Delta_p, \Delta_n + 3\Delta_p\}$$

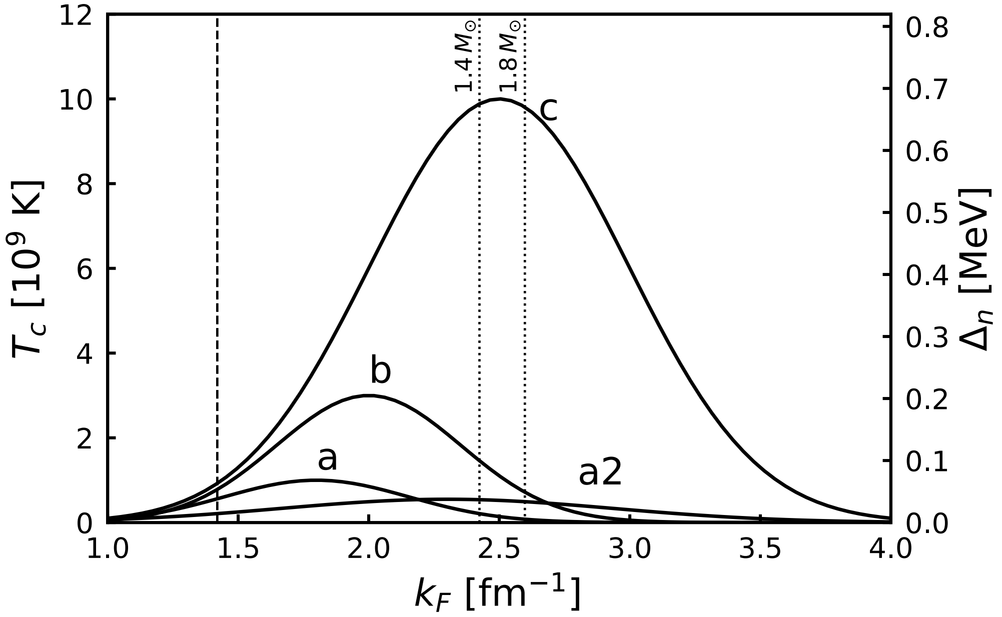
- Large gap delays the beginning of rotochemical heating
- Heating power is stronger for larger gap

Millisecond pulsars

Can we explian hot MSPs?



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



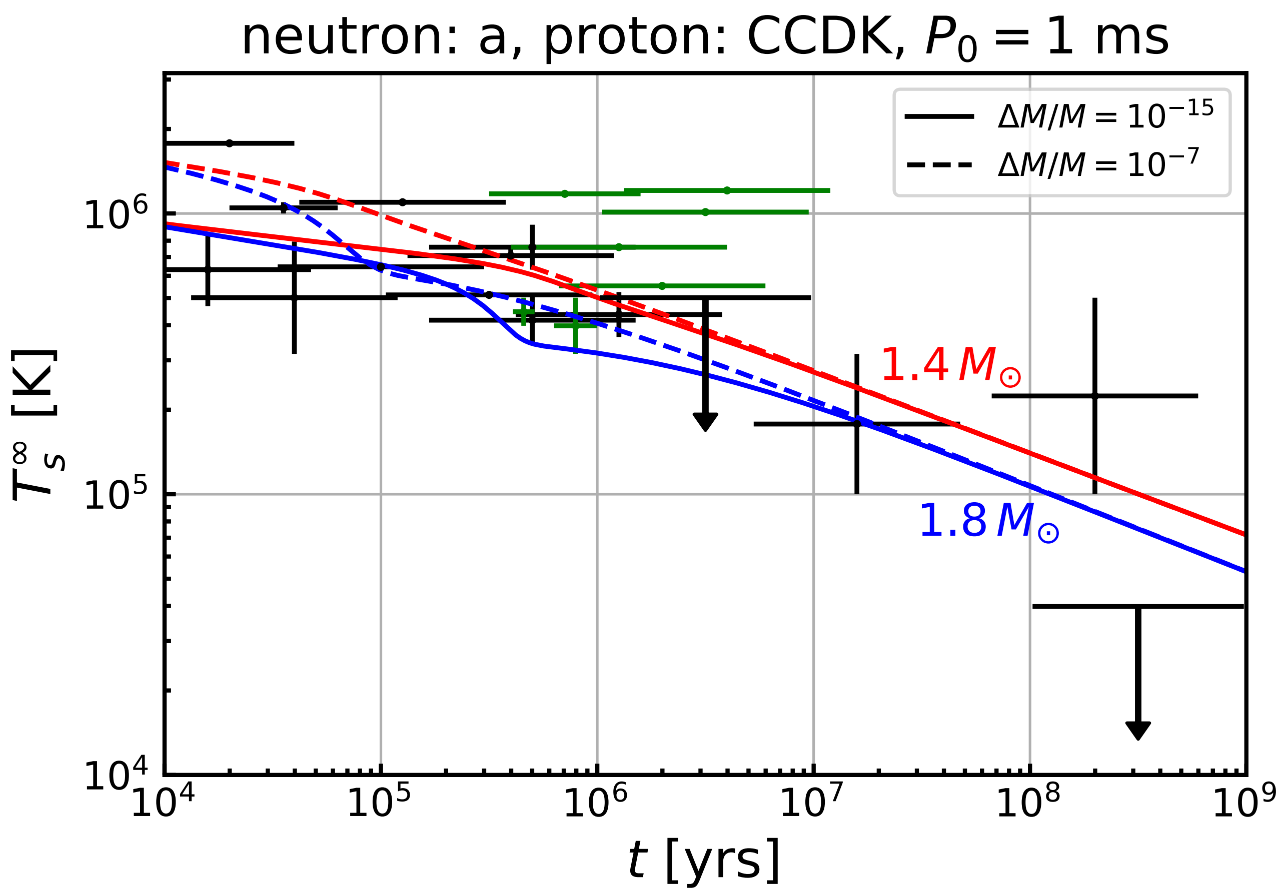
- Two old hot MSPs are explained for various choice of gap models
- **Including both proton and neutron gap enhances heating**

[KY, Koichi Hamaguchi, Natsumi Nagata, arXiv: 1904.04667]

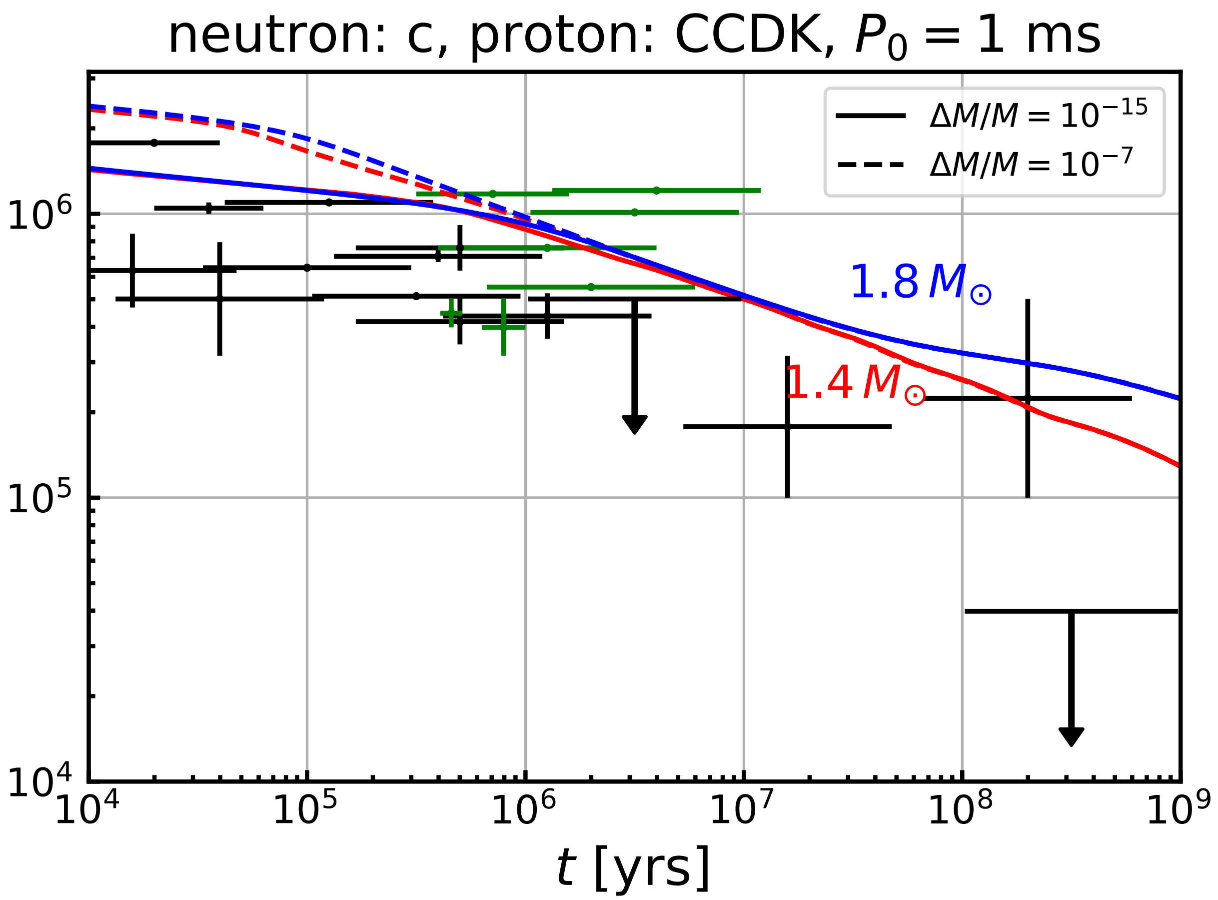
Ordinary pulsars and XDINSs

Can the same setup explain other NS temperatures?

- $P = 1\,\mathrm{s}$.
- $\dot{P} = 1 \times 10^{-15}$.



neutron: a, proton: CCDK, $P_0 = 1$ ms



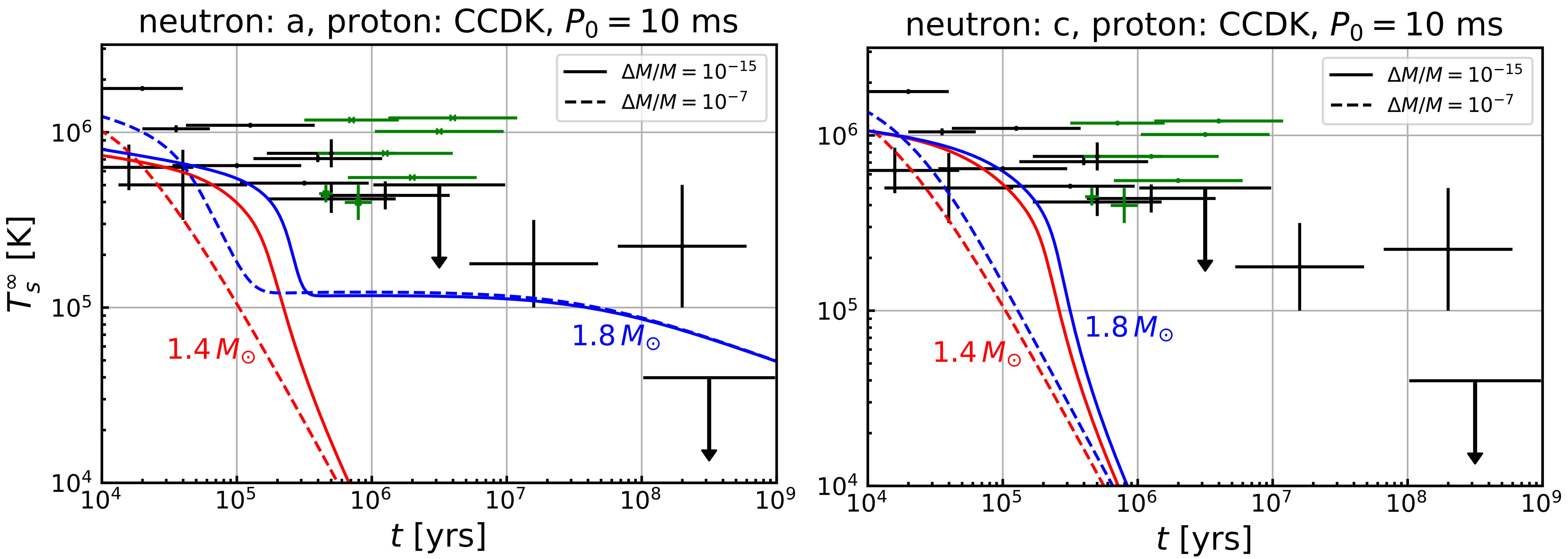
neutron: c, proton: CCDK, $P_0 = 1$ ms

- Many ordinary pulsars and XDINSs are also explained
- XDINSs are warmer, but may be explained by systematic uncertainties or heating caused by strong magnetic field

[KY, Koichi Hamaguchi, Natsumi Nagata, arXiv: 1904.04667]

Initial spin period is a key parameter

$P_0 = 10\,\mathrm{ms}$



[KY, Koichi Hamaguchi, Natsumi Nagata, arXiv: 1904.04667]

- Heating is weakened for longer initial period
- Old and cold NS is explained by assuming they had long initial period

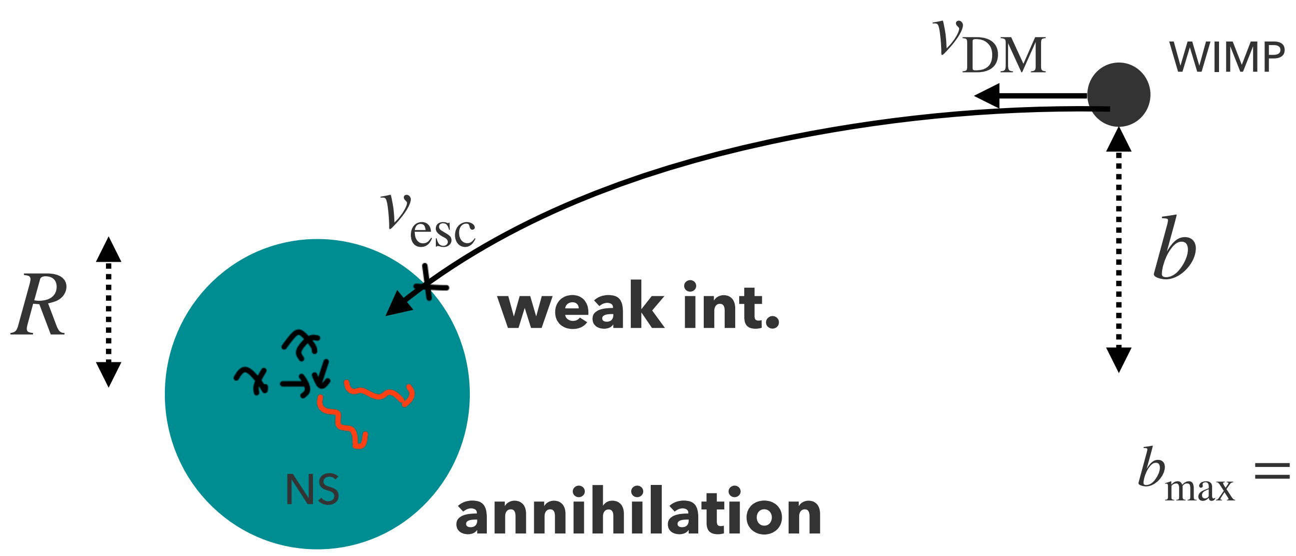
Summary of rotochemical heating vs. observation

- Old hot pulsars are explained by rotochemical heating w/ $P_0 = 1\,\mathrm{ms}$
- Middle-aged ordinary pulsars are also explained by rotochemical heating if neutron gap is small
- For large neutron gap, $P_0 > 10\,\mathrm{ms}$ is necessary to explain young pulsars
- The old cold pulsar is consistent if it has the initial period $P_0 > 10\,\mathrm{ms}$

DM heating vs. rotochemical heating

DM heating rate

DM accretion



$$b_{\rm max} = R(v_{\rm esc}/v_{\rm DM})e^{-\Phi(R)} \gg R$$

$$v_{\rm esc} = \sqrt{2GM/R} \sim O(0.1) \gg v_{\rm DM}$$

Rate of DM hitting the NS

$$\dot{N} \simeq \pi b_{\rm max}^2 v_{\rm DM}(\rho_{\rm DM}/m_{\rm DM})$$

Heating luminosity

$$L_H^\infty = e^{2\Phi(R)}\dot{N}m_{\rm DM}[\chi + (\gamma - 1)]$$

gravitational redshift factor

fraction of ann. energy into heat

$$\frac{1}{\sqrt{1-v_{\rm esc}^2}}$$

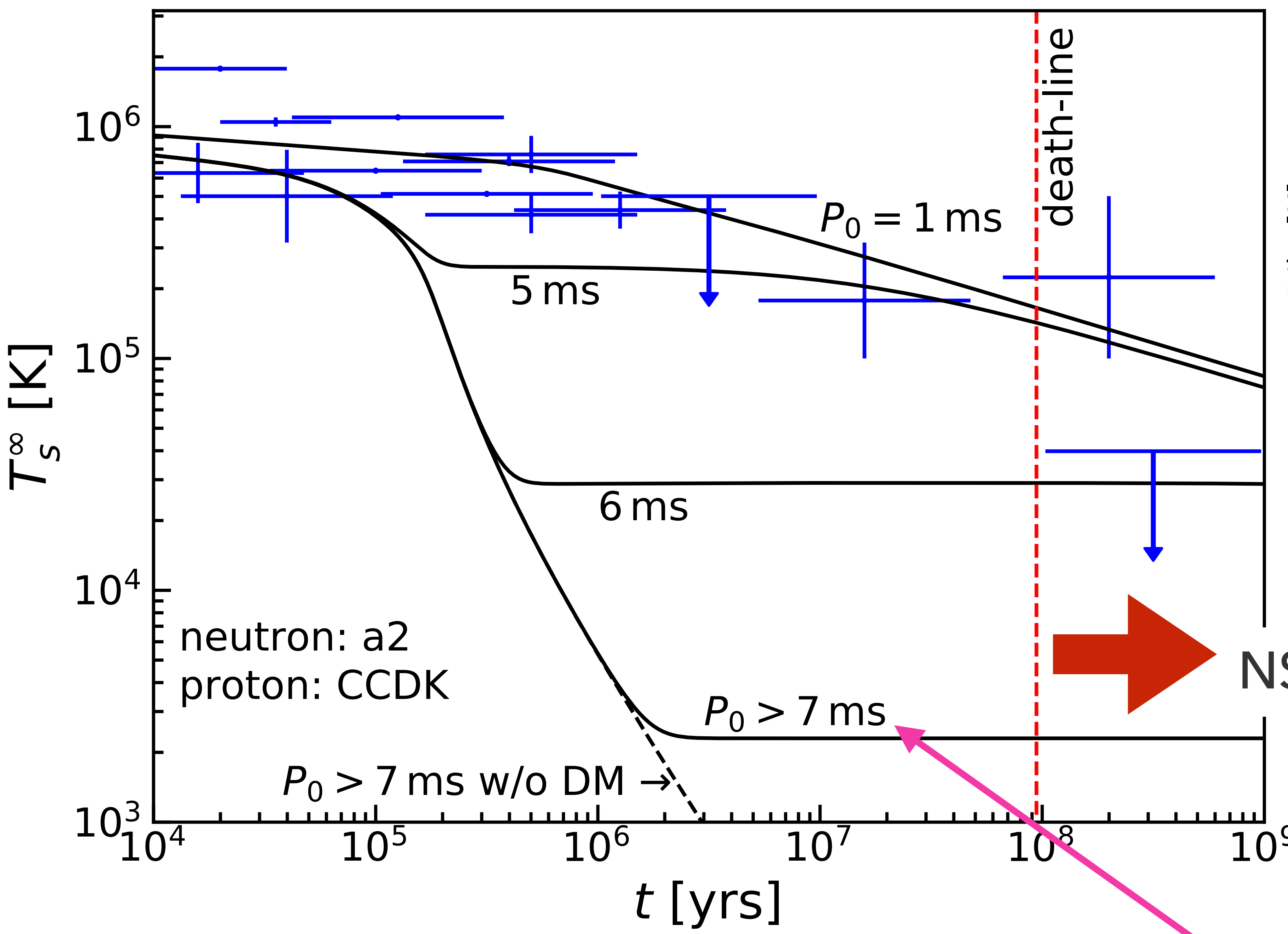
= 1 for all annihilation into heat

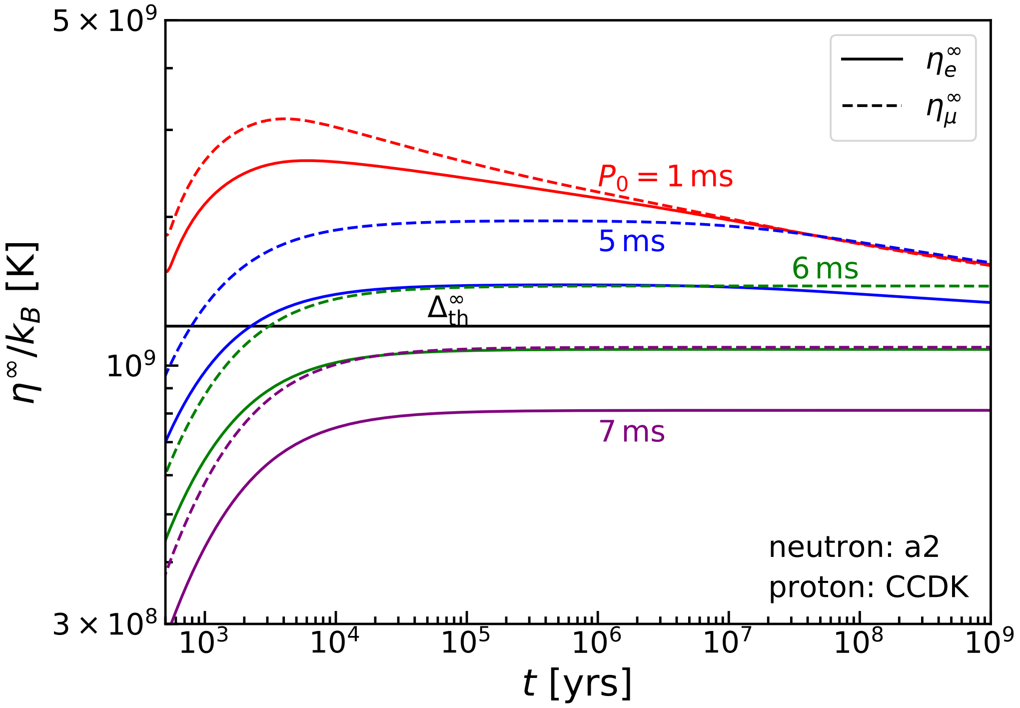
= 0 for no annihilation or all DM ann. into (e.g.) neutrinos

DM heating vs. rotochemical heating

DM heating effect is visible if the initial period is sufficiently large!

Ordinary pulsar: $P = 1\,\mathrm{s}$ $\dot{P} = 10^{-15}$





NS pulsation stops

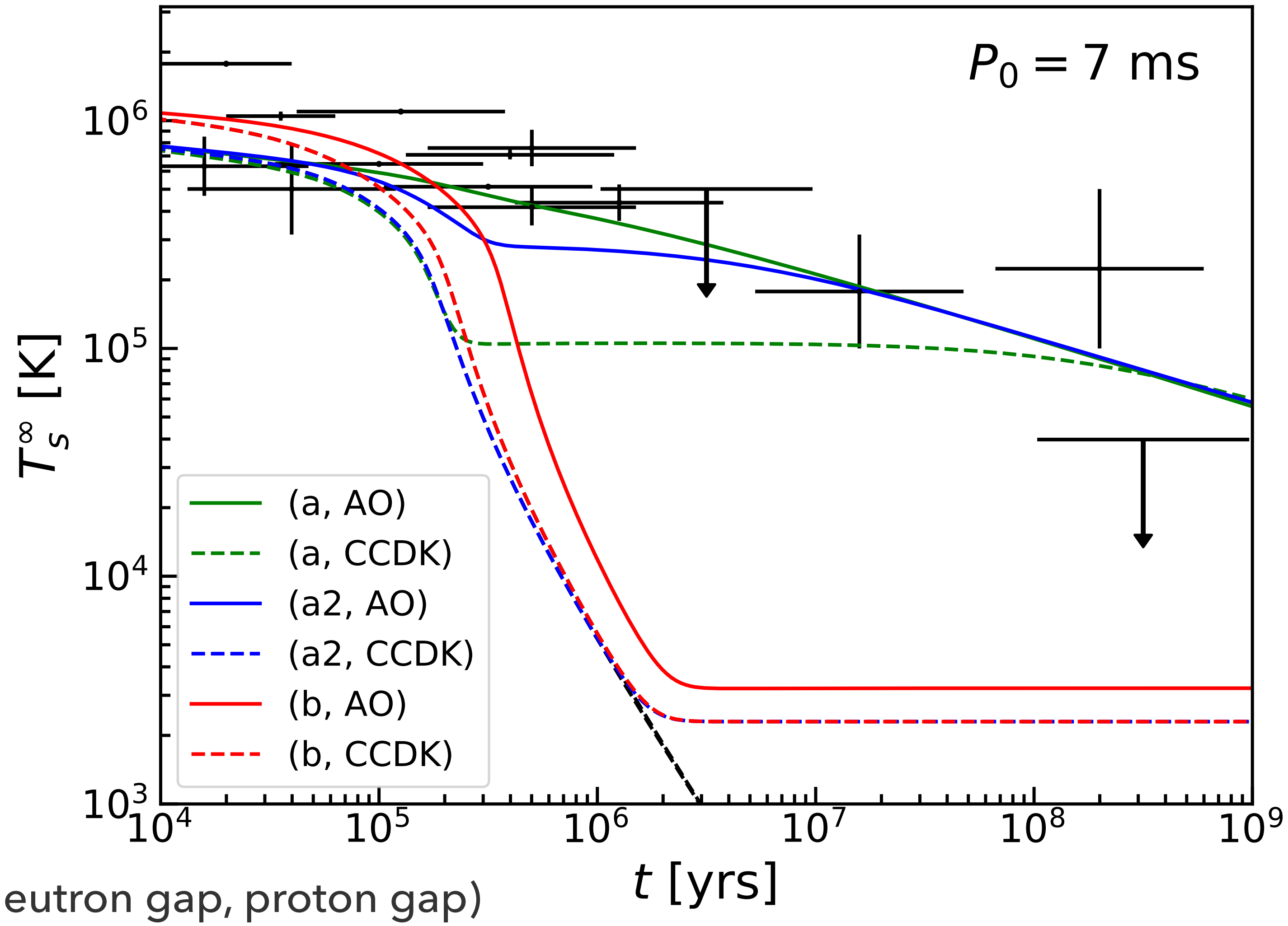
We can see the DM effect!

$P_0 \lesssim 7\,\mathrm{ms}$: DM heating < rotochemical haeting

Uncertainty from superfluid gap models

- Critical P_0 depends on the choice of gap models
- **(DM heating) >> (rotochemical heating) for $P_0 \gtrsim 100\,\mathrm{ms}$ indep. of gap models**
- Recent studies of NS birth period suggest $P_0 = O(100)\,\mathrm{ms}$

[Popov & Turolla, 1204.0632; Noutsos et.al., 1301.1265; Igoshev & Popov, 1303.5258;
Faucher-Giguere & Kaspi, astro-ph/0512585; Popov et al., 0910.2190;
Gullo´n et al., 1406.6794, 1507.05452; Mu¨ller et al., 1811.05483]



(neutron gap, proton gap)

Summary

Summary

- It is known that DM heating can heat up a old NS
- We point out that DM heating may be hidden by other NS heating mechanisms
- Among proposed heating mechanisms, rotochemical heating is inevitable for any pulsar
- We compare the prediction of rotochemical heating to observations including both neutron and proton pairing gaps
- We then find that if the initial spin period is long enough, DM heating is stronger than rotochemical heating

Backup

Direct Urca threshold

$$n \to p + \ell + \bar{\nu}_\ell \qquad p + \ell \to n + \nu_\ell$$

$\mu = \sqrt{m^2 + p_F^2}$

$p_{F,n} \sim 400\,\mathrm{MeV}$

$p_{F,p} \simeq p_{F,e} \sim 10 - 100\,\mathrm{MeV}$

- Suppose beta equilibrium

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

- Energy conservation

$$\epsilon_n = \epsilon_p + \epsilon_e \pm \epsilon_\nu$$

⟶ reaction on Fermi surface, small neutrino momentum $p_\nu \sim T \ll p_{F,n,p,e}$

- Momentum conservation

$$\mathbf{p}_n \simeq \mathbf{p}_p + \mathbf{p}_e \quad \text{with } |\mathbf{p}_i| = p_{F,i}$$

⟶ Triangle condition $p_{F,p} + p_{F,e} > p_{F,n}$

- If we neglect muon, charge neutrality requires $p_{F,p} = p_{F,e}$

$$\longrightarrow \quad n_p > n_n/8$$

Gap profile

$$\epsilon_N(\mathbf{k}) = \mu_{F,N} + \mathrm{sign}(k - k_{F,N})\sqrt{\Delta_N^2 + (k - k_{F,N})^2}$$

Gap Δ generically depends on temperature and momentum

$\Delta_N = \Delta_N(\mathbf{k}_F, T)$ where $\Delta_N(\mathbf{k}_F, T \geq T_c^{(N)}) = 0$

- $^1S_0$ pairing is isotropic $\Delta_N(\mathbf{k}_F, T) = \Delta_N(k_F, T)$
- $^3P_2$ pairing is anisotropic $\Delta_N(\mathbf{k}_F, T) \propto \sqrt{1 + 3\cos^2\theta}$ for $m_J = 0$

T=0 gap and critical temperature are related

- $^1S_0$ pairing: $\Delta_N(k_F, T = 0) \simeq 1.764\, k_B T_c^{(N)}$
- $^3P_2$ pairing: $\Delta_N(k_F, \cos\theta = 0, T = 0) \simeq 1.188\, k_B T_c^{(N)}$

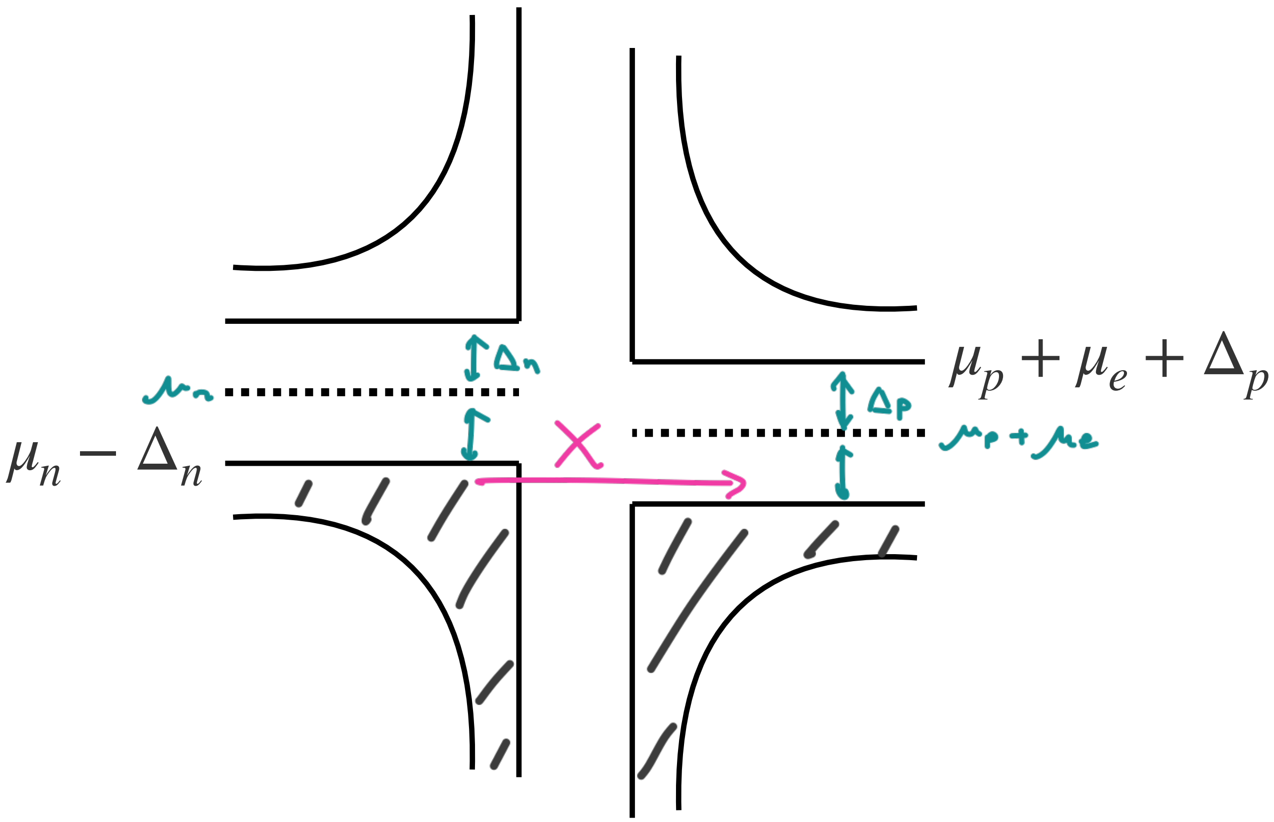
$T_c^{(N)}$ is calculated theoretically

Threshold of heating

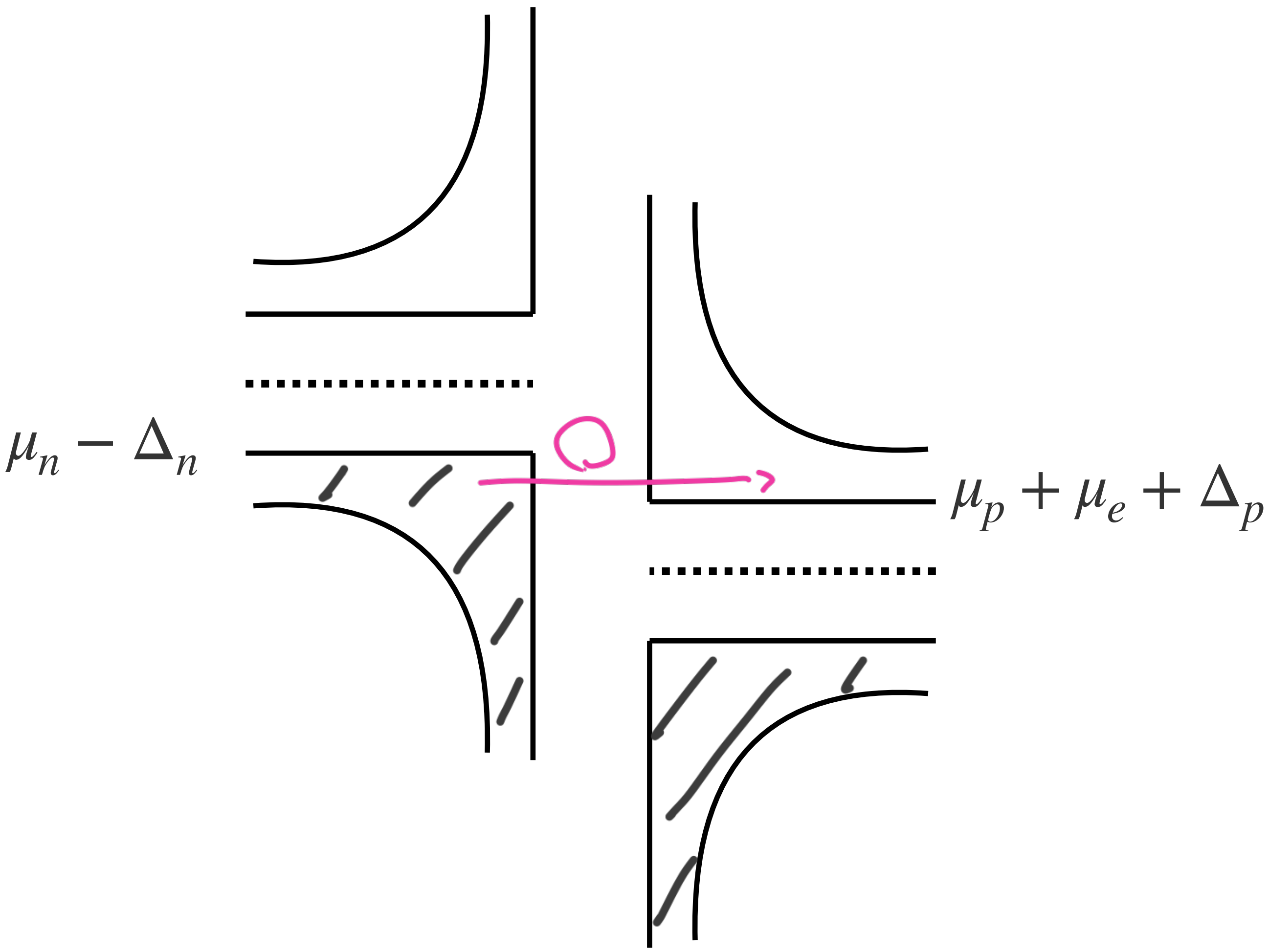
Superfluidity makes threshold for rotochemical heating

For simplicity, consider direct Urca: $n \to p + e + \bar{\nu}_e \qquad p + e \to n + \nu_e$

$$\eta_e < \Delta_n + \Delta_p$$



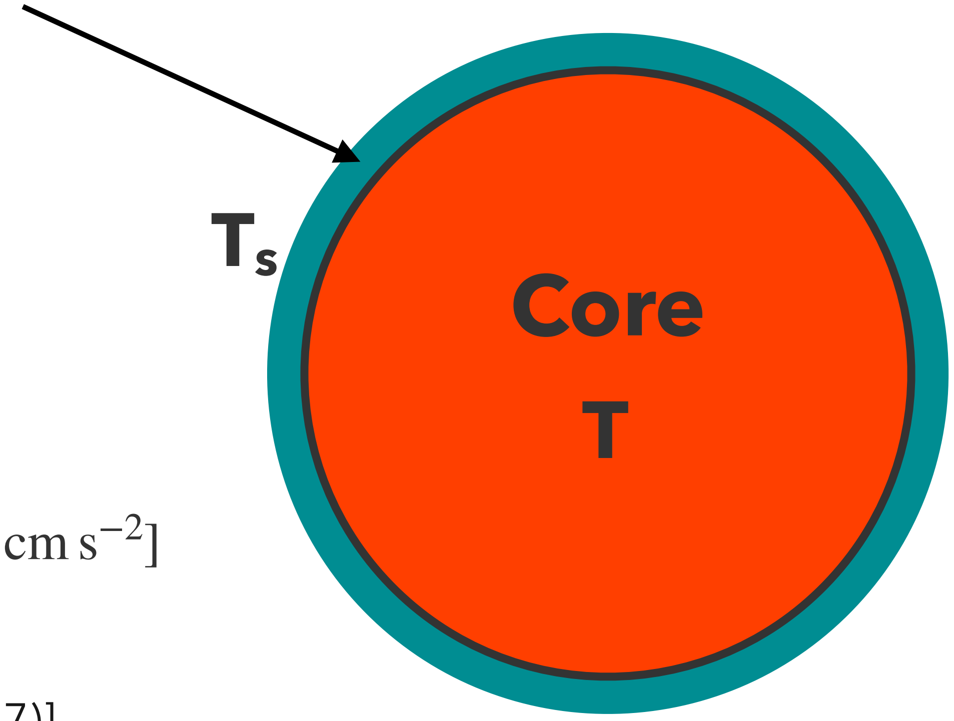
$$\eta_e > \Delta_n + \Delta_p$$



For modified Urca $\Delta_{\mathrm{th}} = \min\{3\Delta_n + \Delta_p, \Delta_n + 3\Delta_p\}$

Neutron star envelope

Envelope: composed of light elements (H, He, C,…) and heavy elements (Fe)



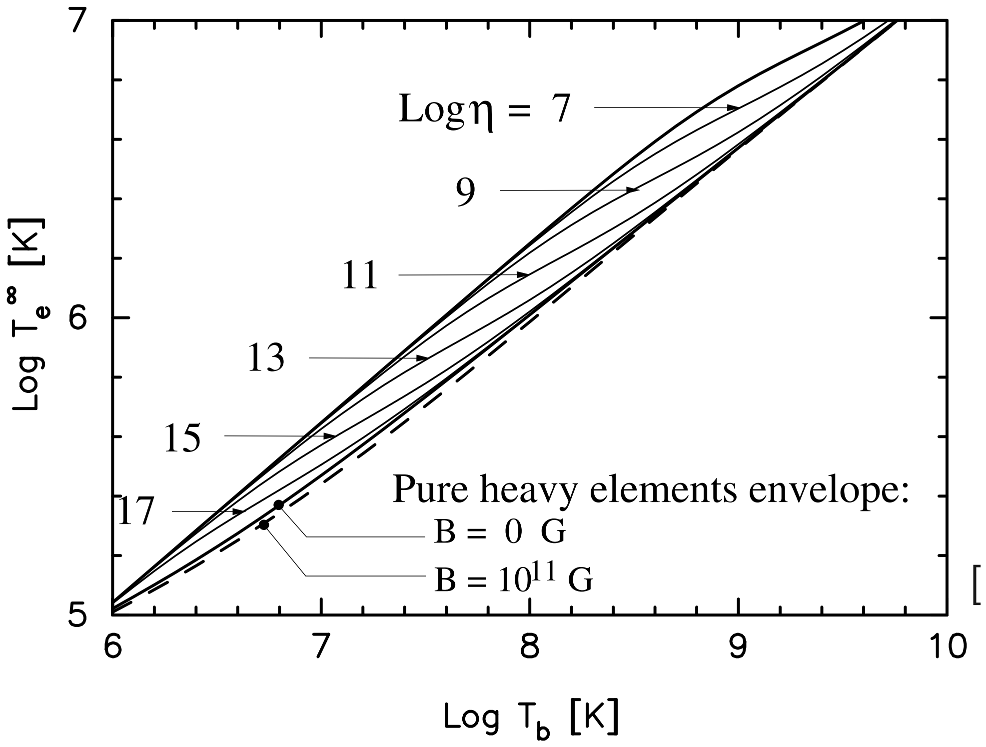
Large temperature gradient exists

$$\frac{T}{10^9\,\mathrm{K}} \sim 0.1288 \times \left(\frac{(T_s/10^6\,\mathrm{K})^4}{\underline{g_{14}}}\right)^{0.455}$$

[Gudmundsson et al. (1983)]

surface gravity $[10^{14}\,\mathrm{cm\,s^{-2}}]$

More accurate relation is available [Potekhin et al. (1997)]



[Figure from Page et al. (2004)]

Characterized by

$$\eta = g_{14}^2 \underline{\Delta M}/M$$

mass of light elements