DM heating vs. rotochemical heating in old neutron stars

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Based on KY, Nagata Hamaguchi, MNRAS 492, 5508–5523

Hamaguchi, Nagata, KY, Phys.Lett. B795 (2019) 484-489

Nuclear theory group at UTokyo

Mar. 2, 2020

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Overview

We compare two heating mechanism in neutron stars

- DM heating
  - DM accretion heats up old NS
  - NS surface temperature measurement can probe DM

- Rotochemical heating
  - it occurs w/o any new or exotic physics (induced by NS rotation)
  - it explains observed warm NSs

- (DM heating) > (rotochemical heating)?
  - Pulsar initial rotation period is key parameter
  - old ordinary pulsar is suitable target

Outline

1. DM heating of NS
2. Standard cooling of NS
3. Rotochemical heating
4. DM heating vs. Rotochemical heating

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Dark matter

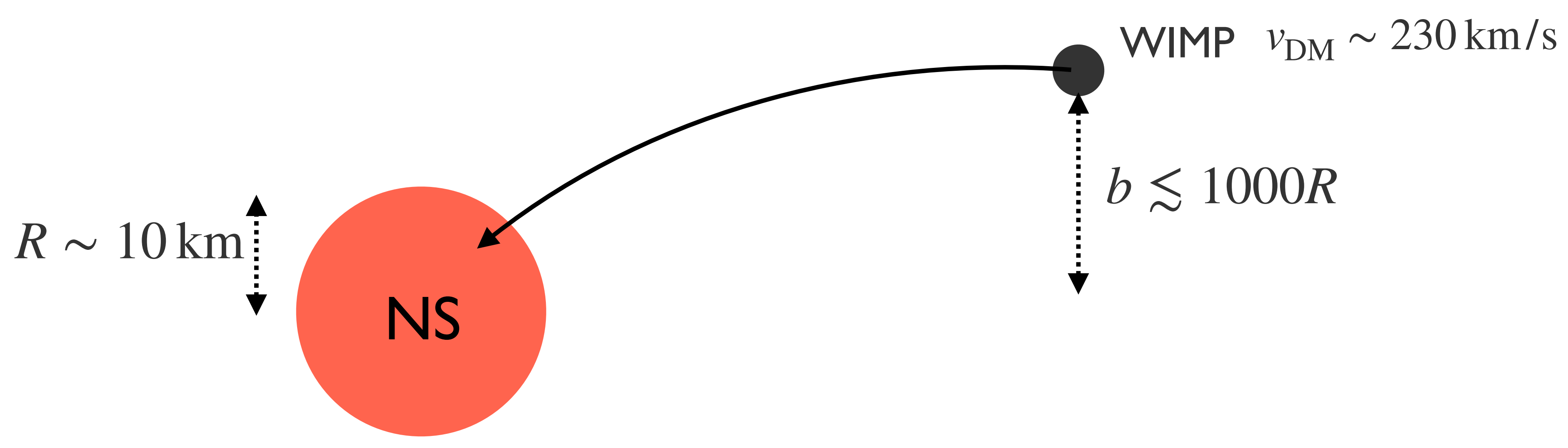
- Dark matter: 25 % of the energy density of the universe
- Particle DM candidate
  - WIMP (weakly interacting massive particle)
  - SIMP
  - FIMP
  - Axion
  - …
- WIMP
  - Weak interaction w/ SM particles
  - m ~ 100 GeV - 1 TeV gives correct abundance

Dark matters accrete in neutron stars

We can probe the DM signature in neutron stars [Kouvaris (2007)]

- DMs accrete in NS by gravity
- If $\sigma_n \gtrsim 10^{-45}\,\mathrm{cm}^2$, (DM mean free path) < (NS radius)

  → DM loses initial kinetic energy, trapped in NS gravitational potential



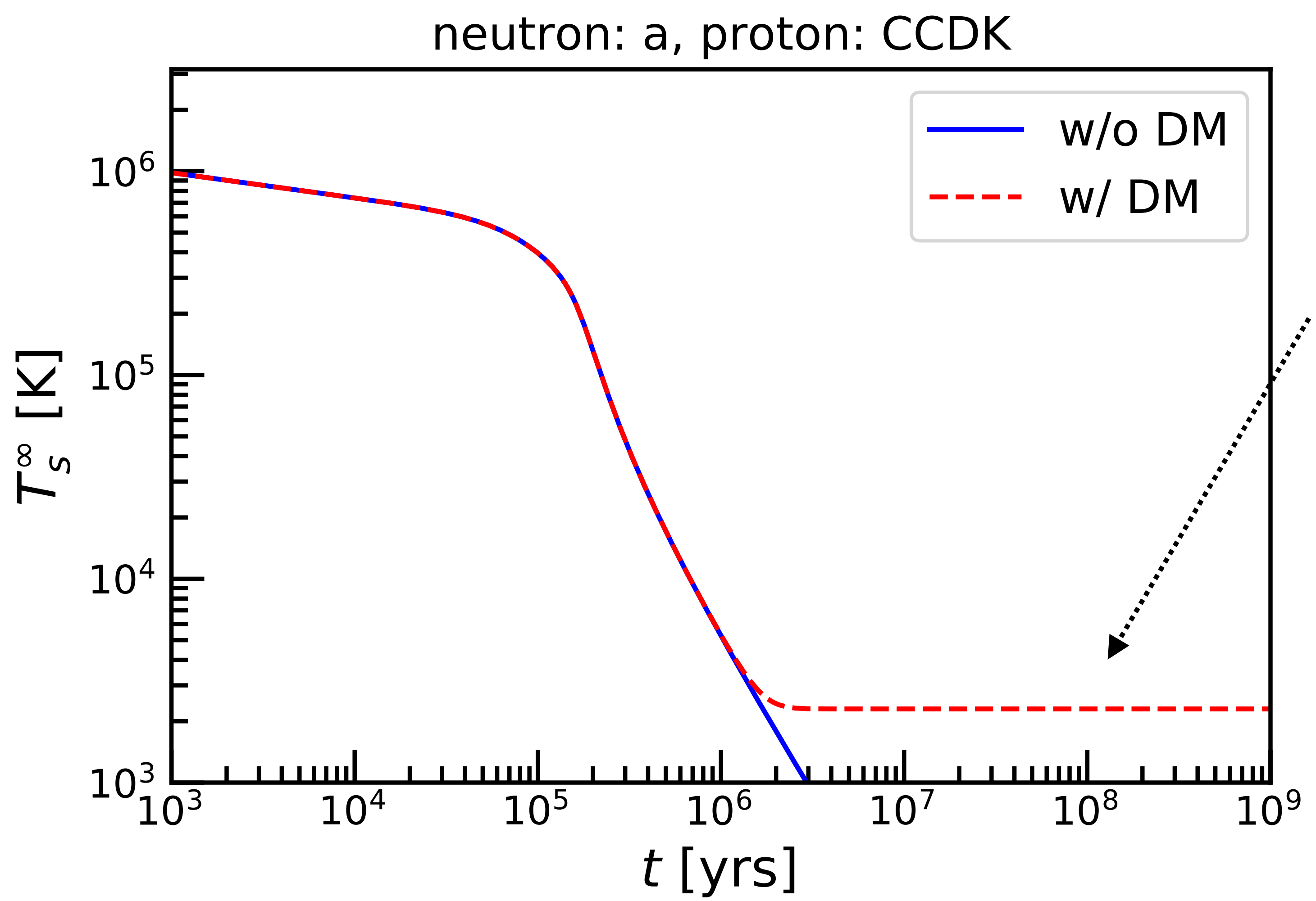
DM kinetic/mass energy → **Heat in a NS**

Heating rate: $L_{\mathrm{DM}} \sim \rho_{\mathrm{DM}} v_{\mathrm{DM}} \pi b_{\mathrm{max}}^2$ w/ $b_{\mathrm{max}} \sim \sqrt{2GMR/v_{\mathrm{DM}}^2}$

Prediction of dark matter heating

$T_s^\infty \sim 3000\,\mathrm{K}$ at $t \gtrsim 10\,\mathrm{Myr}$ is a signal of DM!

[Kouvaris (2007); Baryakhtar et al. (2017)]



Balance between photon emission and DM heating

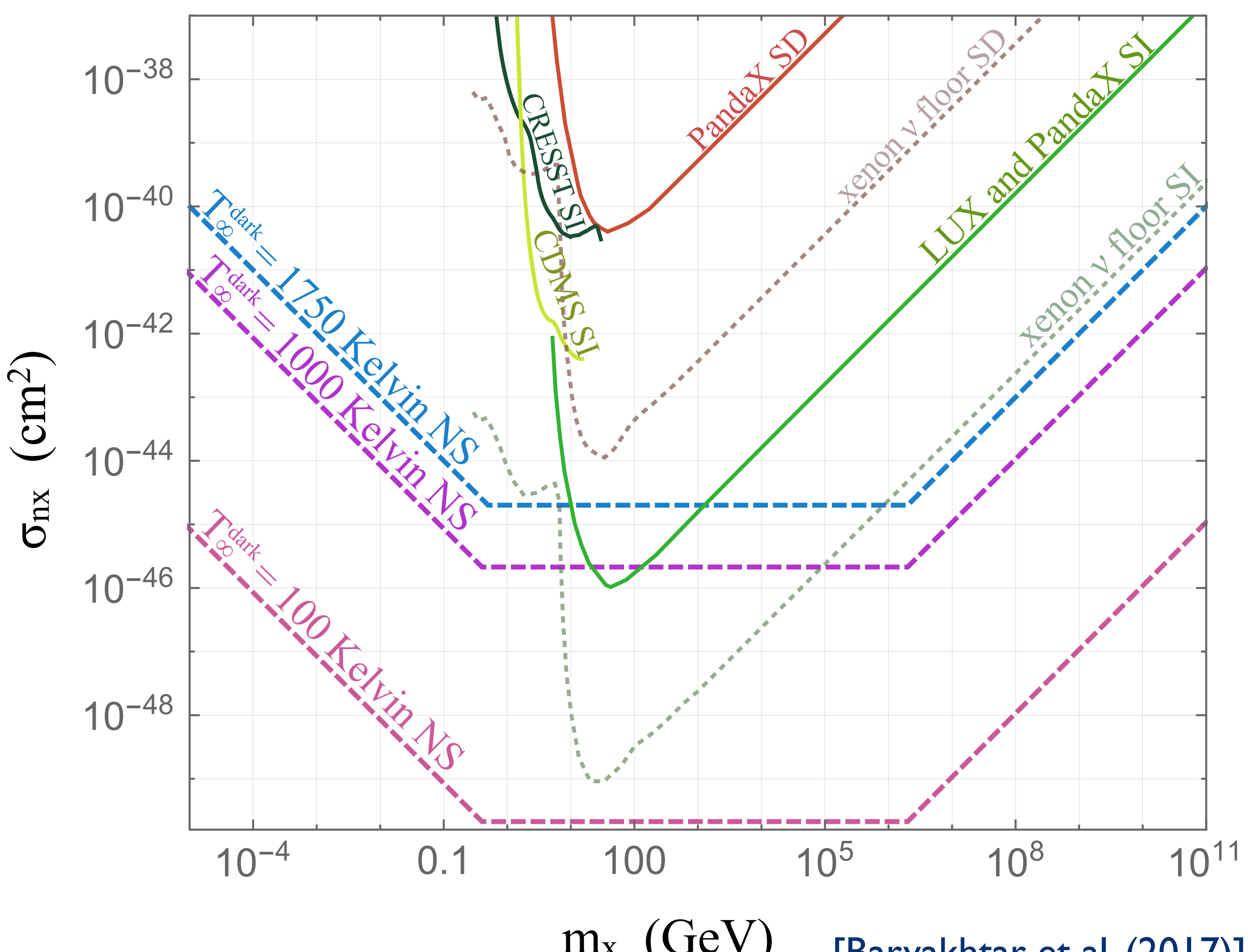
$$\Rightarrow \quad 4\pi R^2 \sigma_B T_s^4 = 2\pi G M R \rho_{\mathrm{DM}} / v_{\mathrm{DM}}$$

Surface temperature of old NSs can probe/constrain DM models!

Prospects

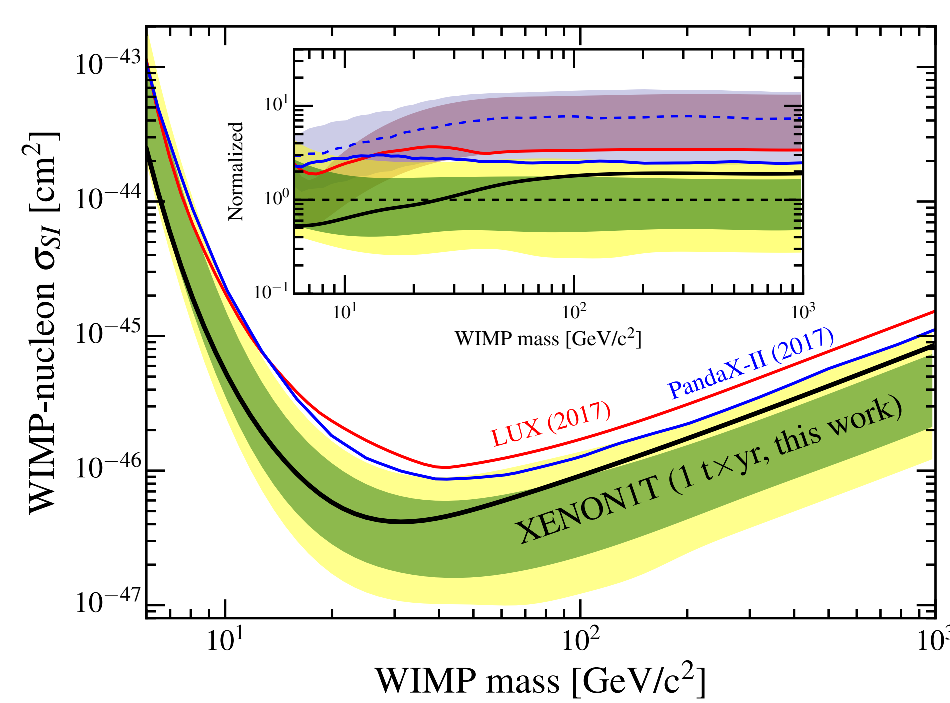
Constraints on DM-neutron cross section

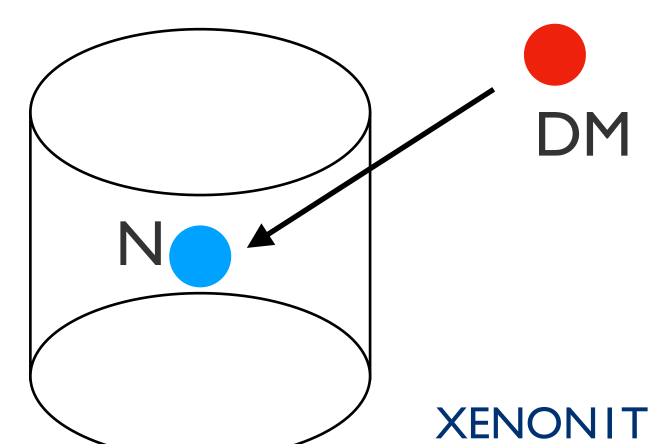
Particularly sensitive to m = 1 GeV - 1 PeV



[Baryakhtar et al. (2017)]

Direct detection experiment on the earth



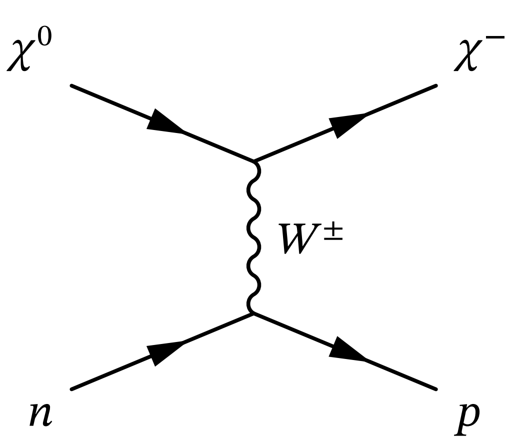


XENON1T [1805.12562]

DM heating can probe inelastic scattering of electroweak DM

- DM originally in electroweak multiplet; e.g., Wino = (χ^+, χ^0, χ^-)
- Mass splitting after EW symmetry breaking

$$\Delta M = m_{\chi^+} - m_{\chi^0} = \mathcal{O}(100)\,\text{MeV}$$



- Inelastic scattering cross section is large
  - $\sigma \sim 10^{-39}\,\text{cm}^2$
  - Recoil energy must be larger than ΔM

$$\Delta E = \frac{m_T m_\chi^2 \gamma^2}{m_T^2 + m_\chi^2 + 2\gamma m_T m_\chi} v^2 (1 - \cos\theta_{\text{CM}})$$

T: target material

  - Around earth: $\Delta E \sim 100\,\text{keV} \ll \Delta M$ $(v \sim 10^{-3})$
  - On NS: $\Delta E = \mathcal{O}(1)\,\text{GeV} \gtrsim \Delta M$

$$v_{\text{esc}} = \sqrt{\frac{2GM}{R}} \sim 0.6c$$

Advantages over the terrestrial experiments

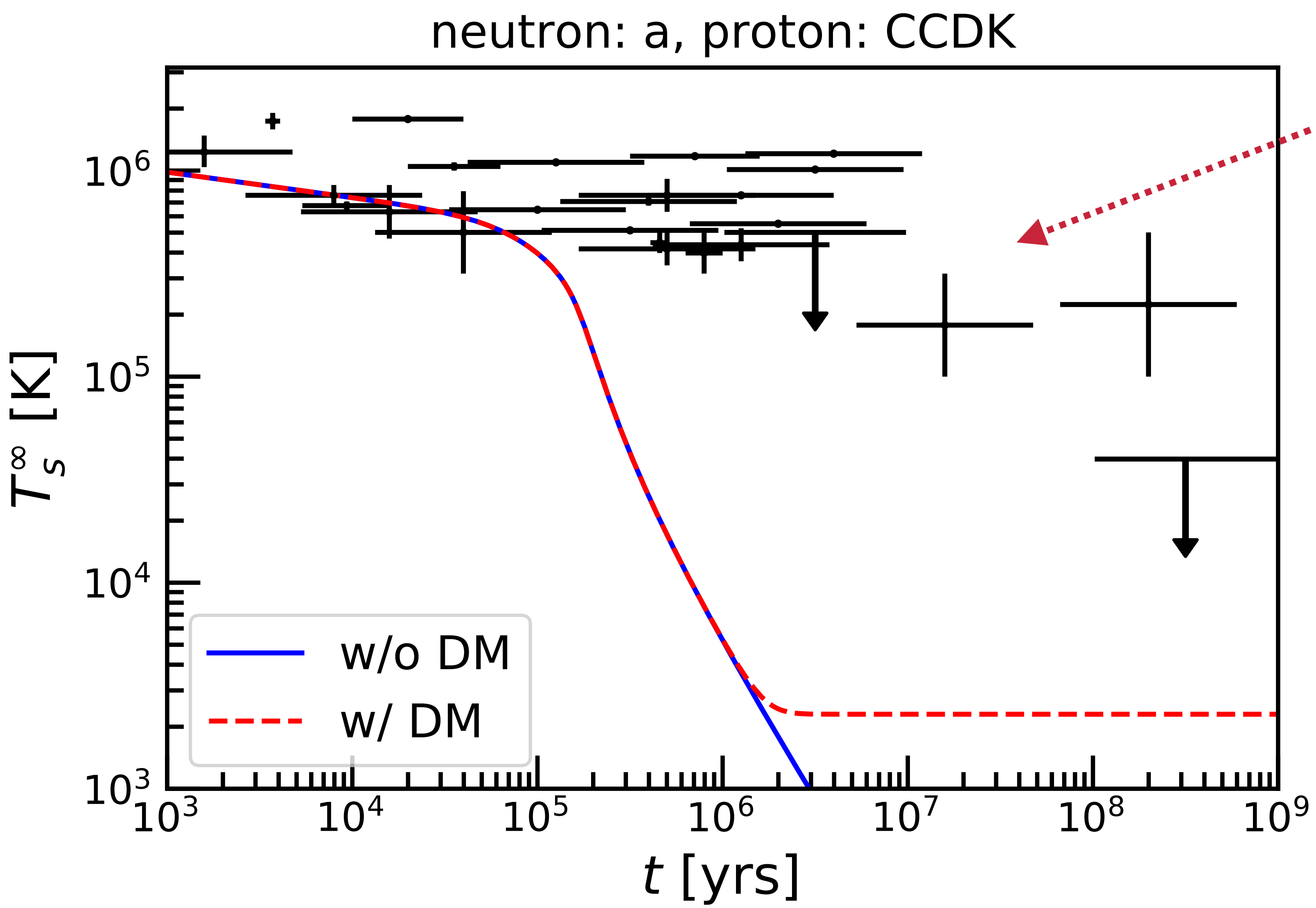
- Large DM velocity on NS surface (c.f. $v \sim 10^{-3}$ near the earth)
  - Inelastic scattering of electroweak DM ($\tilde{H}, \tilde{W}, \ldots$)
    [Baryakhtar et al. (2017); Bell et al. (2018)]
  - Velocity suppressed scattering
    [Raj et al. (2018)]
  - Spin-dependent scattering

$$v_{\rm esc} = \sqrt{\frac{2GM}{R}} \sim 0.6c$$

- No detector threshold for light DM
- No limitation from neutrino floor

Can we really observe DM heating?

The observation suggests presence of other heating mechanisms



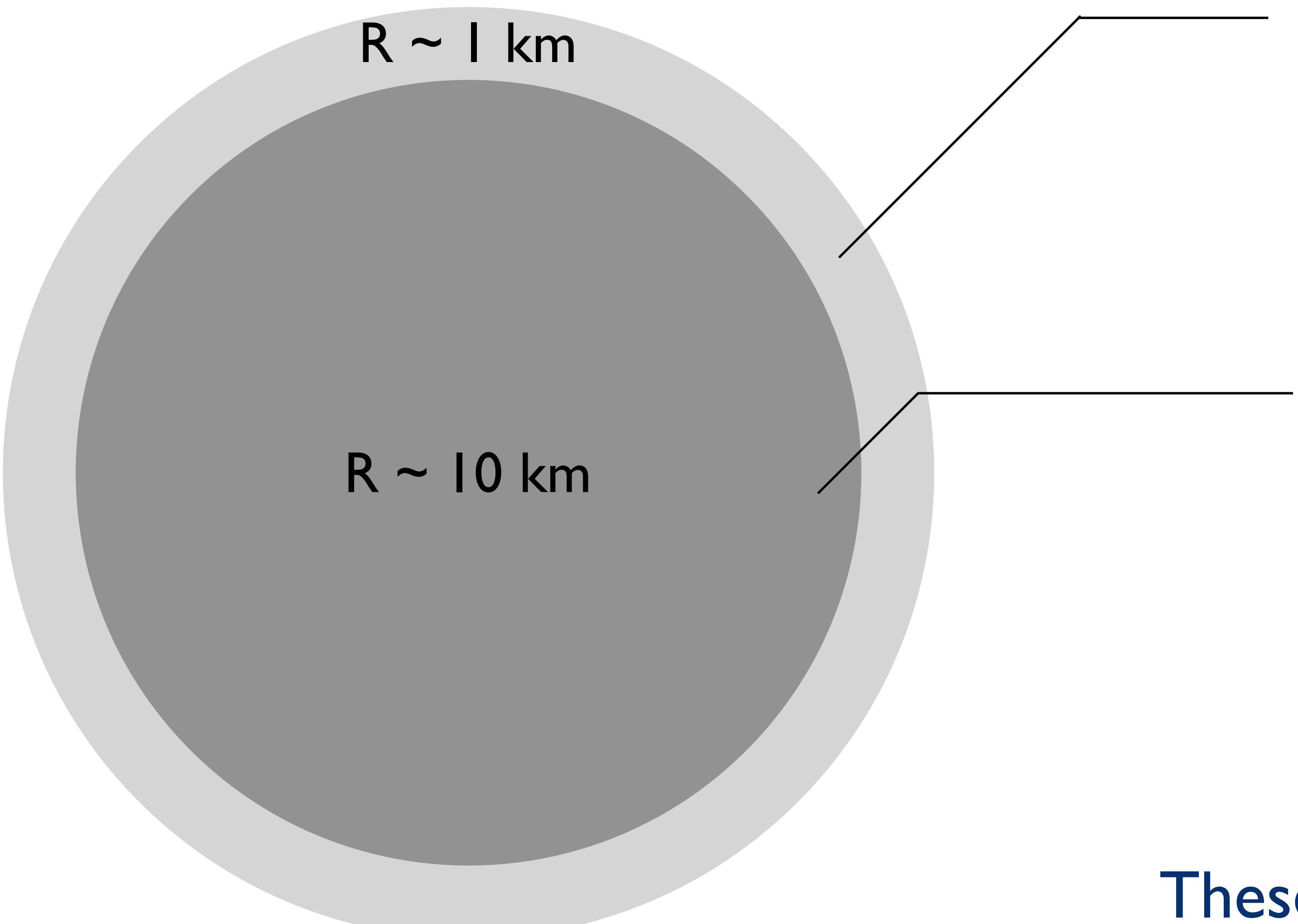
Hotter than theory prediction even if DM is included

Question: (DM heating) > (other heating) really occurs?

Outline

1. DM heating of NS
2. Standard cooling of NS
3. Rotochemical heating
4. DM heating vs. Rotochemical heating

NS basics



Crust

Nuclei, electrons, dripped neutrons

Core

Neutrons, protons, electrons, muons

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

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

These particles are degenerate: $p_F \gg T$

Standard theory of NS cooling

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

Heat capacity (n, p, e, μ)

Surface photon luminosity:

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

- L_ν: Neutrino emission luminosity
  - (Direct Urca process)
  - Modified Urca process
  - Cooper pair breaking and formation
  - + minor processes

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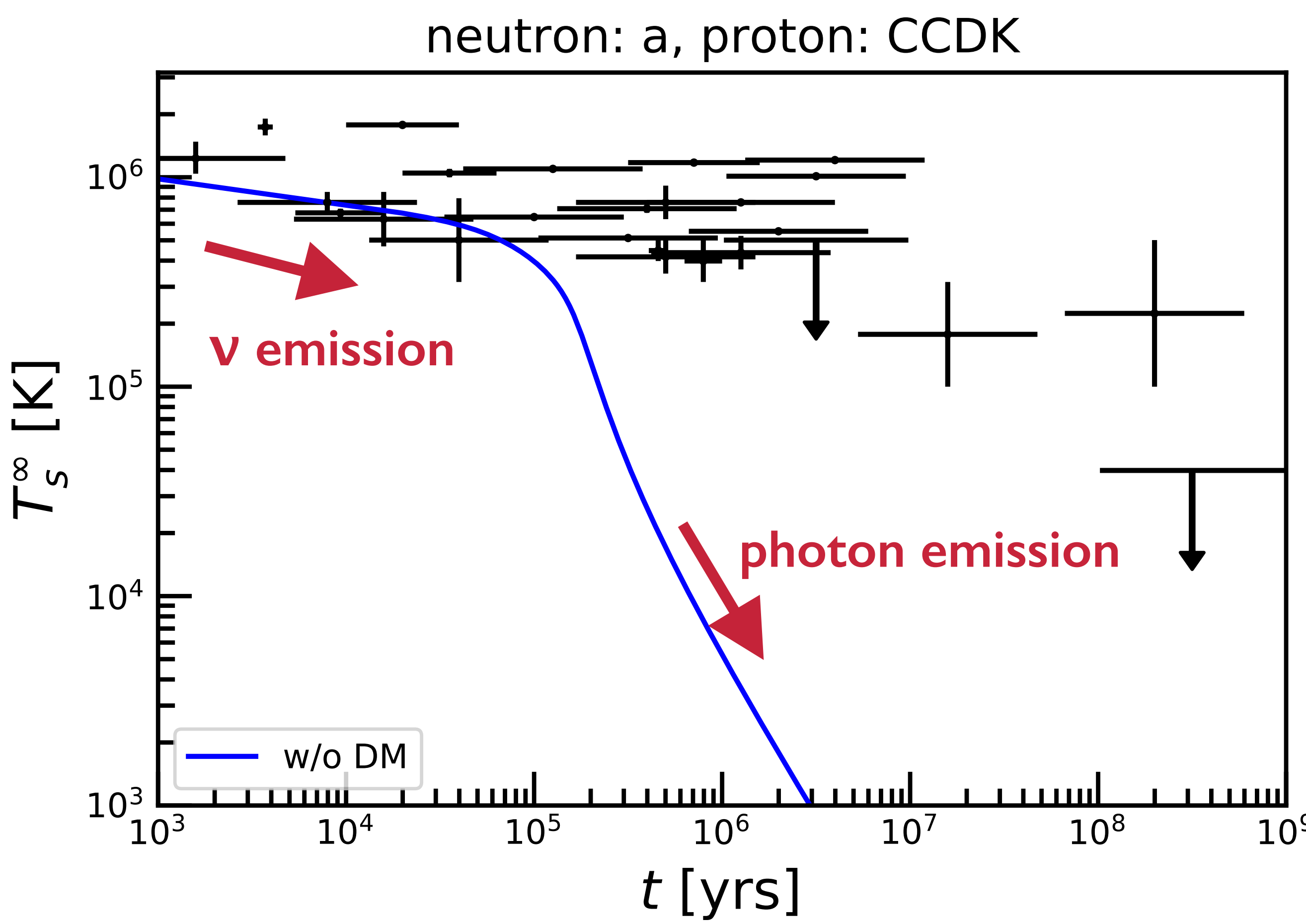

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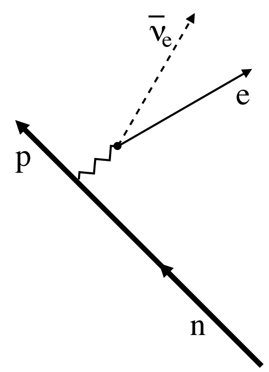
Beta decay and its inverse

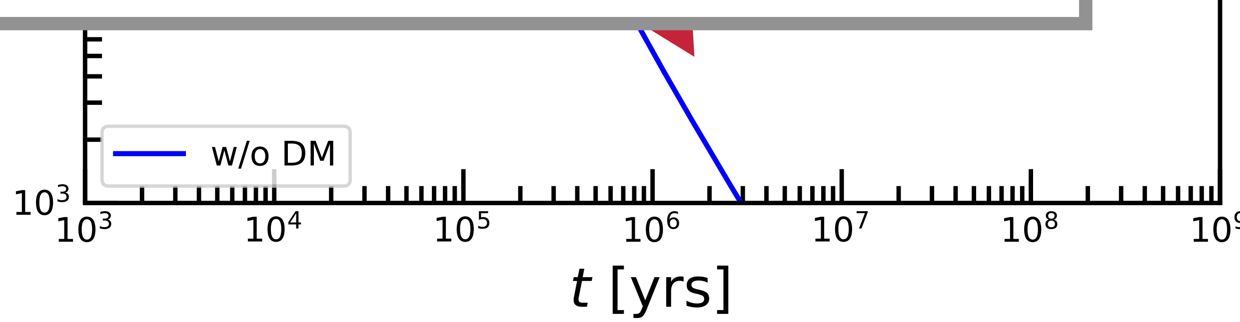
$$n \to p + e + \bar{\nu}_e$$

$$p + e \to n + \nu_e$$



- Occurs only when in a very heavy NS

e.g. $M \gtrsim 1.97\, M_\odot$ for APR EOS



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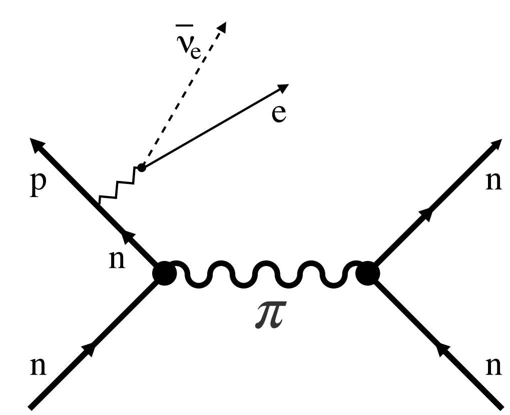
Modified Urca process

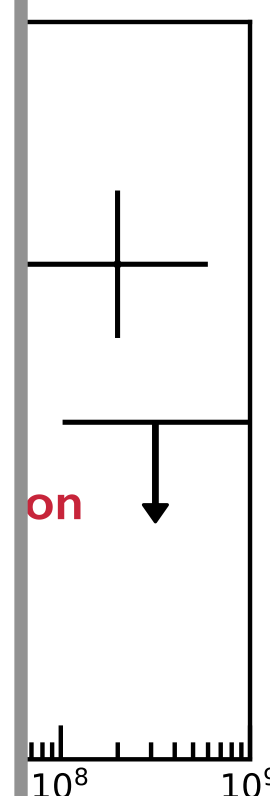
$$n + N \to p + N + e + \bar{\nu}_e$$

$$p + N + e \to n + N + \nu_e$$

$N = n, p$



- Dominant process (before Cooper pairing)
- $L_\nu \propto T^8$



Standard theory of NS cooling

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

Heat capacity (n, p, e, μ)

Surface photon luminosity:

Suppression by
$\sim e^{-\Delta/T}$

- L_ν: Neutrino emission luminosity
  - (Direct Urca process)
  - Modified Urca process
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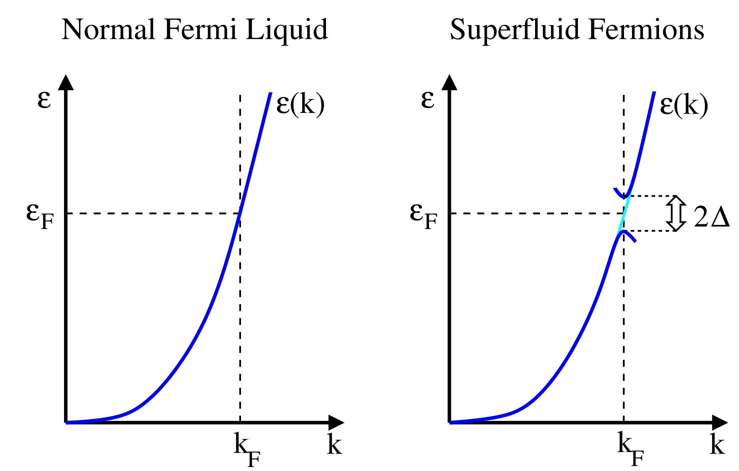
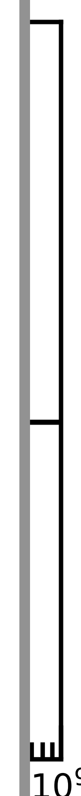
Nucleon Cooper pairing ($T < T_c$)

- Attractive nuclear force induces n-n and p-p pairing
- Energy gap Δ appears in the spectrum



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

- Suppresses heat capacity and Urca process



Standard theory of NS cooling

$$C\frac{dT}{dt} = -L$$

Heat capacity (n, p, e, μ)

- L_ν: Neutrino emission luminosity
  - (Direct Urca process)
  - Modified Urca process
  - Cooper pair breaking and formation
  - + minor processes

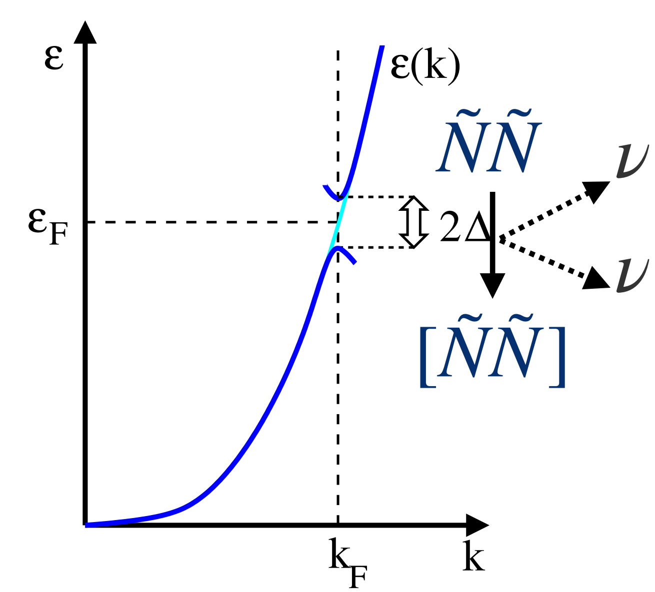
Cooper pairing triggers pair-breking and formation (PBF) process

Pair-breaking: $[\tilde{N}\tilde{N}] \rightarrow \tilde{N} + \tilde{N}$

Pair-formation: $\tilde{N} + \tilde{N} \rightarrow [\tilde{N}\tilde{N}] + \nu + \bar{\nu}$

[Flowers et al. (1976)]

Superfluid Fermions

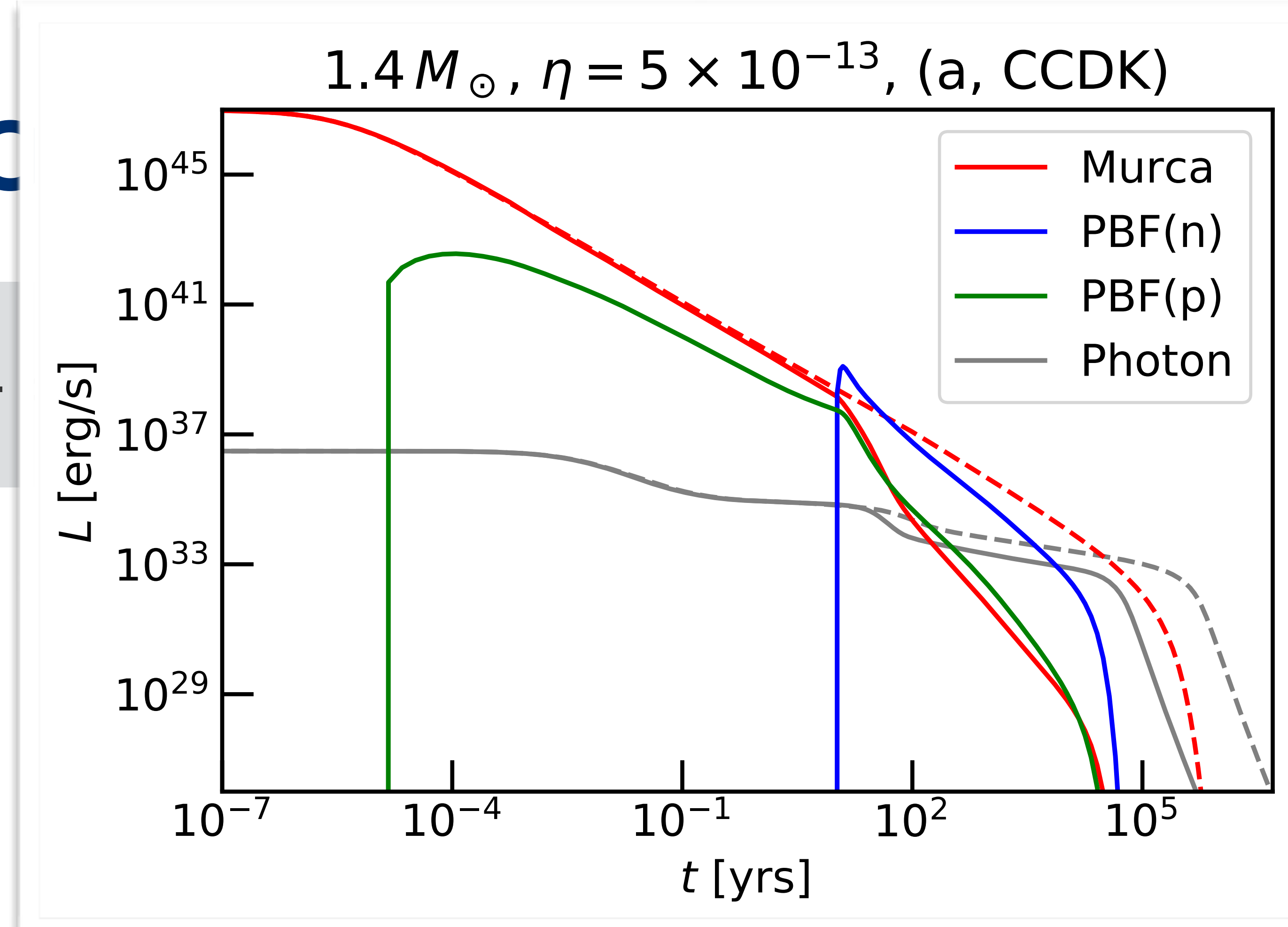


- Efficiently occurs for $T \lesssim T_c$
- Dominant neutrino emission process after pairing

Standard theo

$$C\frac{dT}{dt}$$

Heat capacity (n, p, e, μ)



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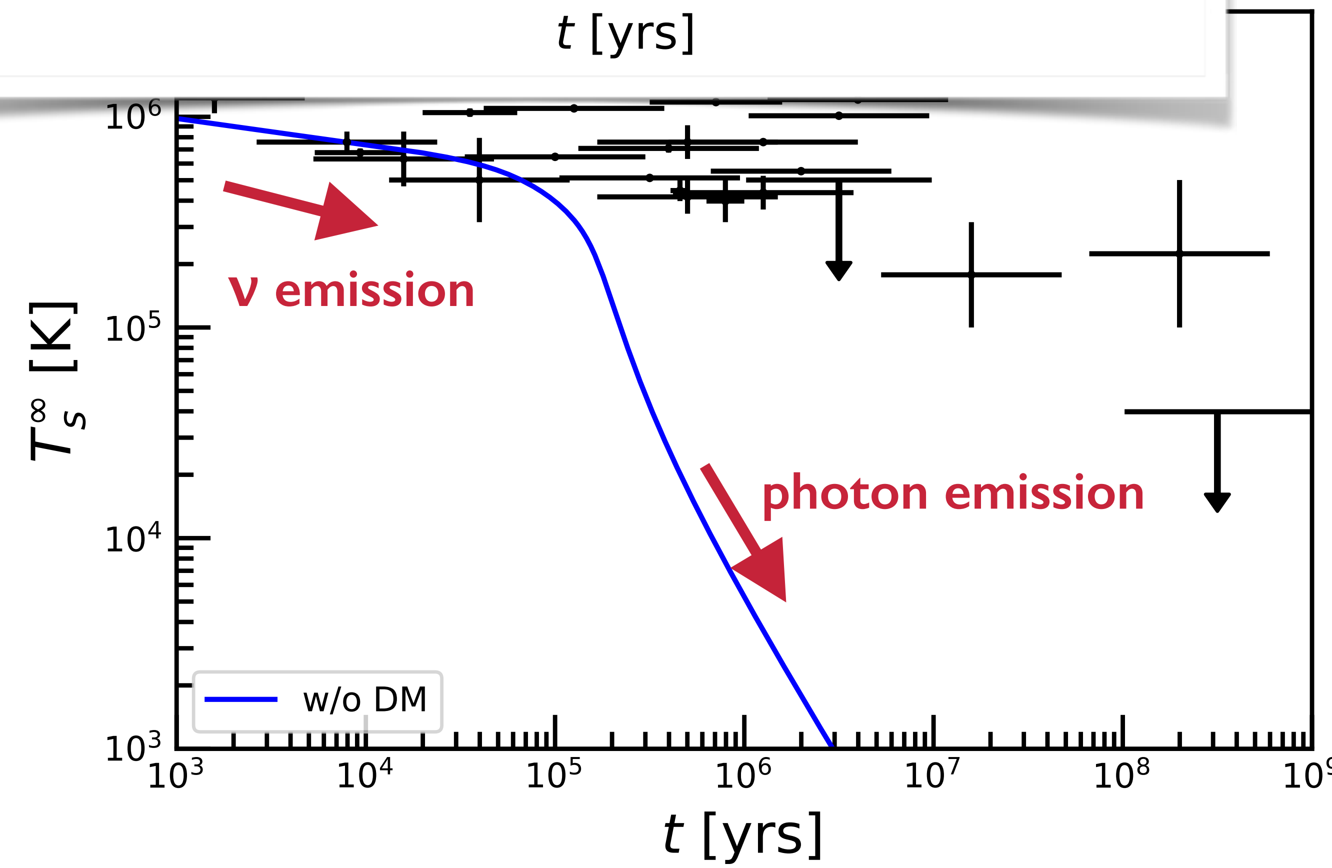
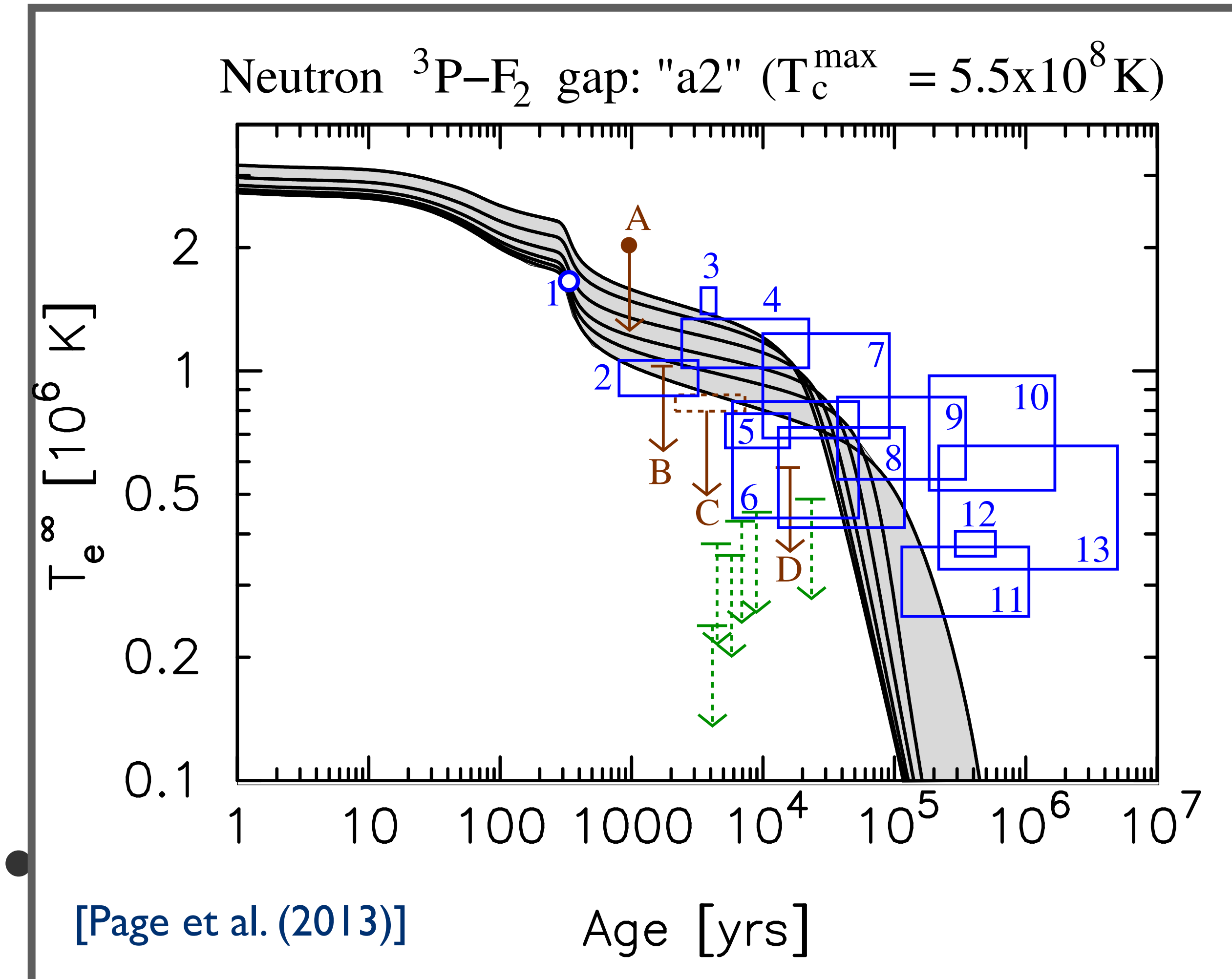


# of NS cooling



[Page et al. (2013)]

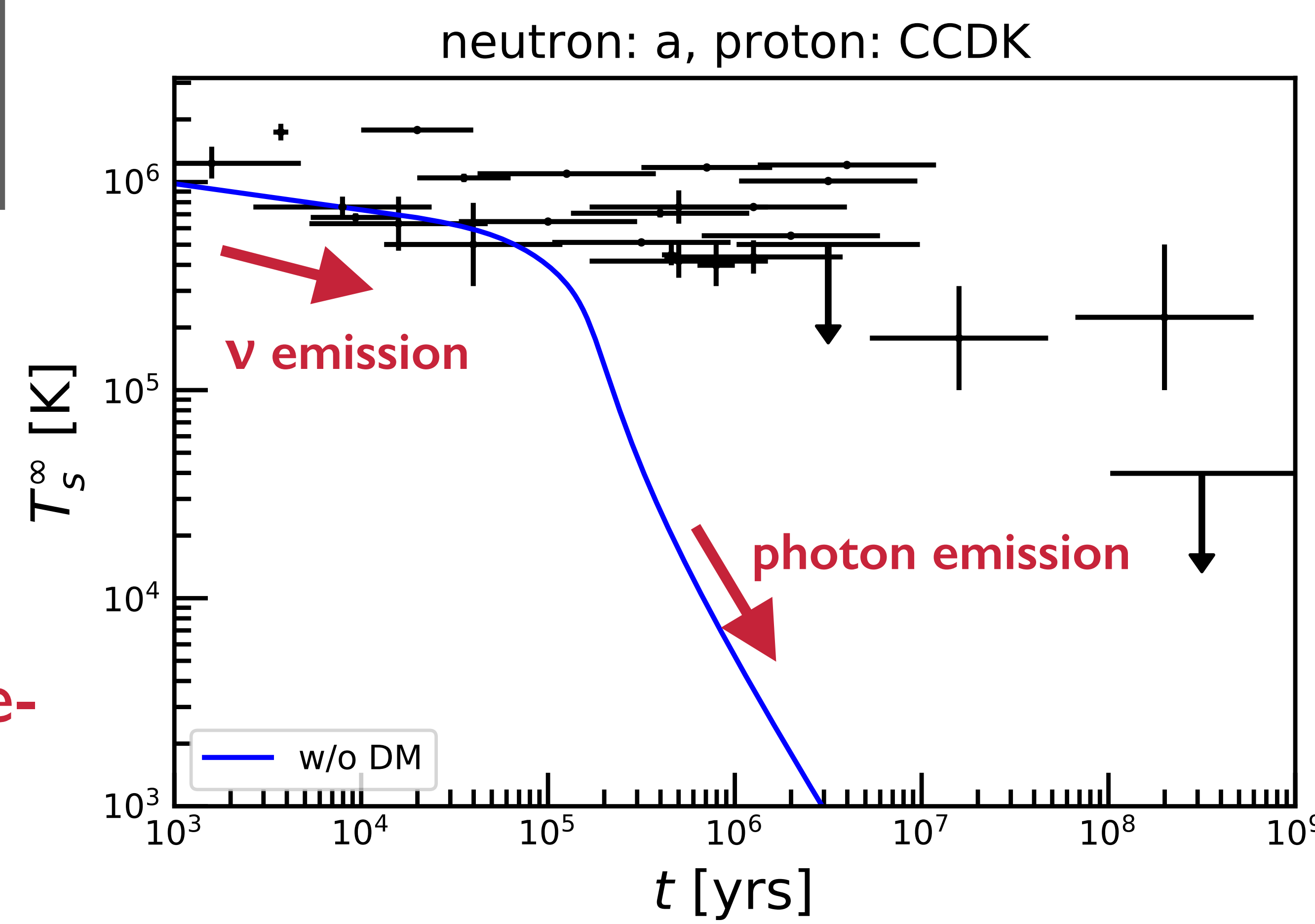
$L_\nu - L_\gamma$

Surface photon luminosity:

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

- Modified Urca process
- Cooper pair breaking and formation
- \+ minor processes

- Standard cooling explains young/middle-aged NSs



Standard theory of NS cooling

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

Heat capacity (n, p, e, μ)

Surface photon luminosity:

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

- L_ν: Neutrino emission luminosity
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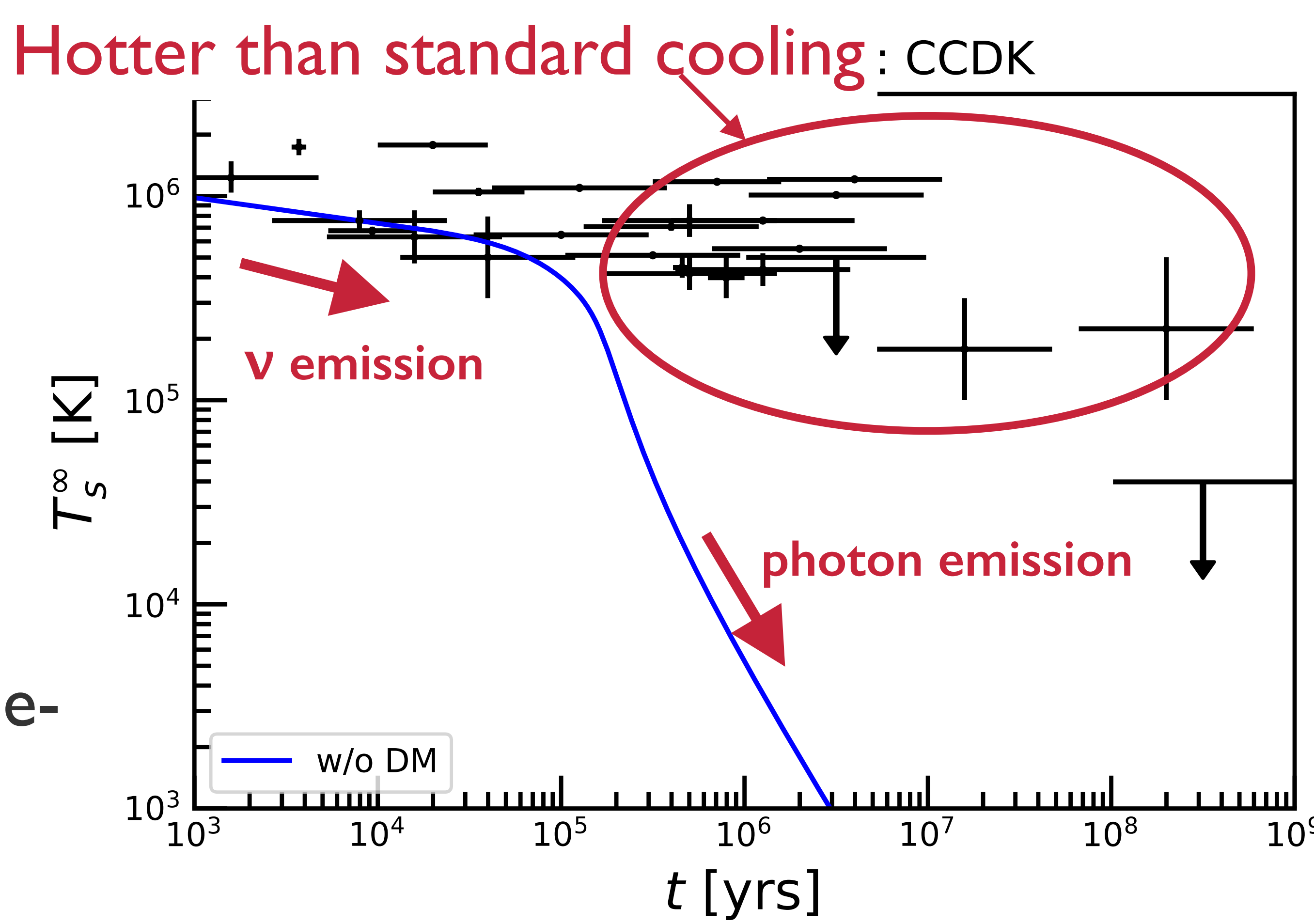

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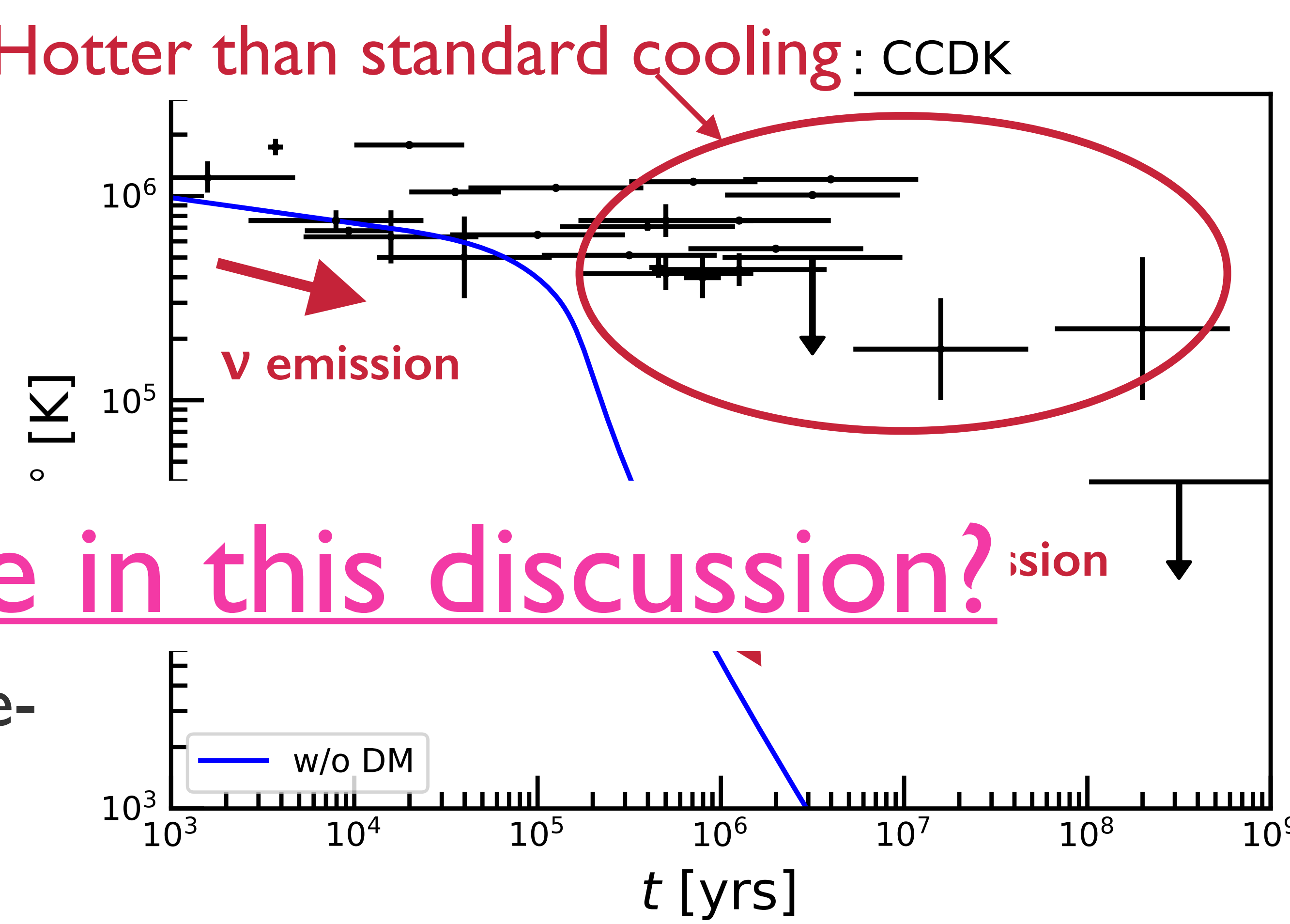
  -



Is there any loophole in this discussion?

- Standard cooling explains young/middle-aged NSs

Outline

1. DM heating of NS
2. Standard cooling of NS
3. Rotochemical heating
4. DM heating vs. Rotochemical heating

Assumption of β-equilibrium

Conventional assumption: matters are in β-equilibrium by Urca processes

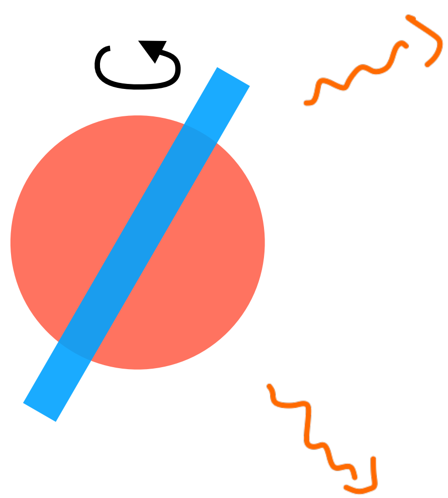
$$\Gamma_{n\to p+e} = \Gamma_{p+e\to n} \quad \mu_n = \mu_p + \mu_e$$

Assumption of β-equilibrium

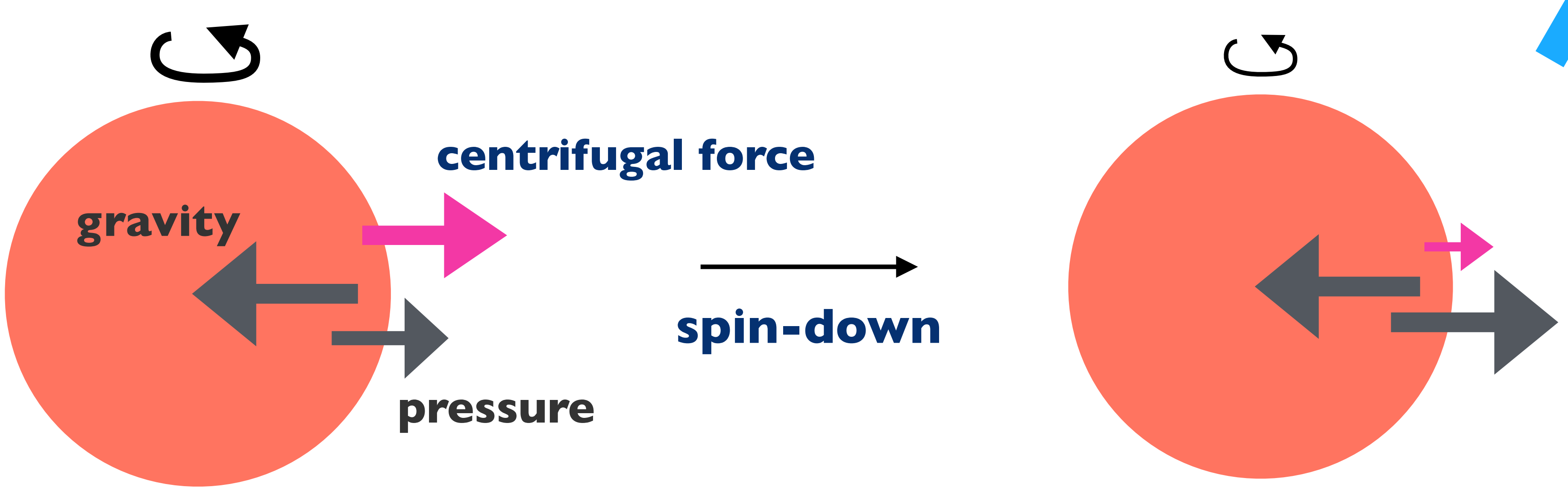
Conventional assumption: matters are in β-equilibrium by Urca processes

$$\Gamma_{n\to p+e} = \Gamma_{p+e\to n} \quad \mu_n = \mu_p + \mu_e$$

Spin-down of NS violates β-equilibrium [Reisenegger (1994)]



- NS rotation is slowing down by magnetic dipole radiation



- Continuous change of equilibrium condition (local pressure)

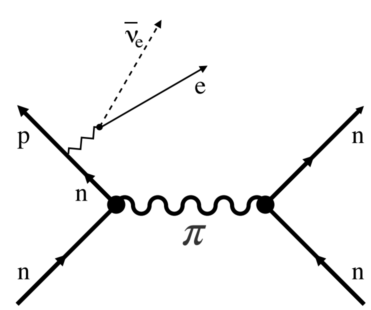
  → Urca processes is not fast enough to catch up this change

Evolution of chemical imbalance

Evolution of imbalance $\eta_e = \mu_n - \mu_p - \mu_e$

[Fernández and Reisenegger (2005)]

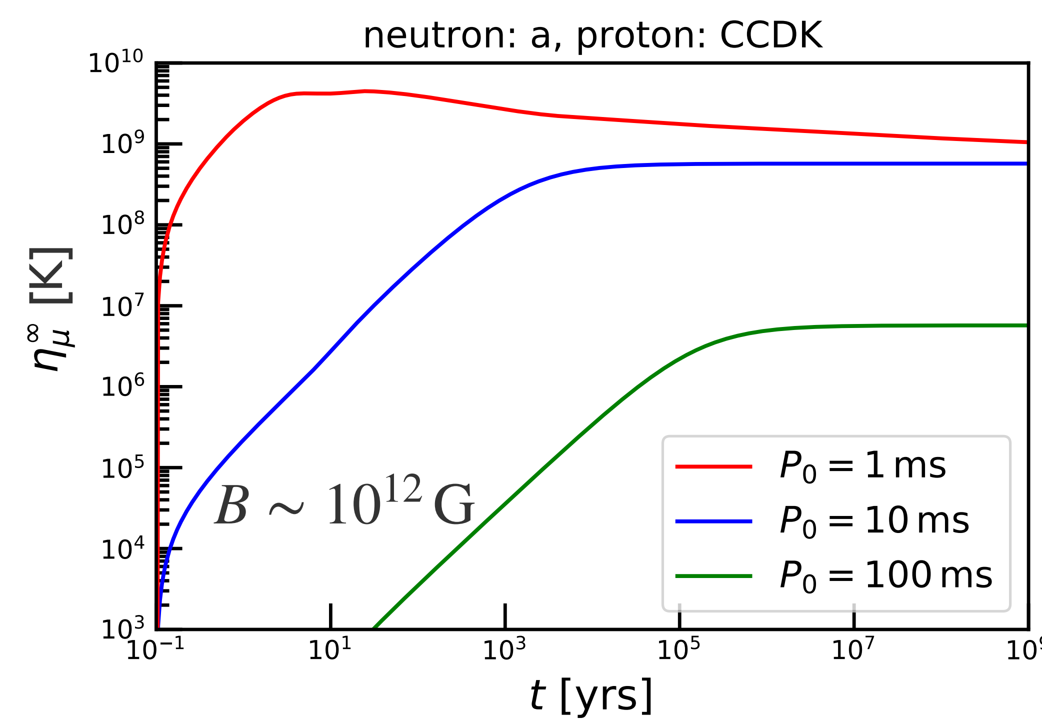
$$\frac{d\eta_e^\infty}{dt} = -\sum_{N=n,p} \int dV \underbrace{\left(Z_{npe}\Delta\Gamma_{M,Ne} + Z_{np}\Delta\Gamma_{M,N\mu}\right)}_{\text{equilibration by modified Urca}} e^{\Phi(r)} + \underbrace{2W_{npe}\Omega\dot{\Omega}}_{\text{spin-down drives NS out of equilibrium}}$$



(Z>0 and W<0 are constants which depends on NS structure)

- If modified Urca is slow, chemical imbalance grows

$$\dot{\Omega} = -k\Omega^3 \qquad k = \frac{2B_s^2 R^6 \sin^2\alpha}{3I}$$



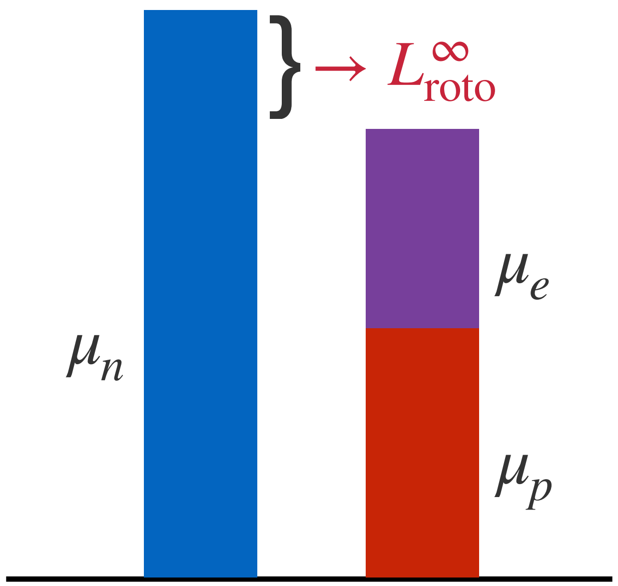
Rotochemical heating

In non-equilibrium Urca process, imbalance between chemical potentials is converted to heat [Reisenegger (1994)]

$$C\frac{dT^\infty}{dt} = -L_\nu^\infty - L_\gamma^\infty + L_{\rm roto}^\infty$$

$$L_{\rm roto}^\infty = \sum_{\ell=e,\mu}\sum_{N=n,p}\int dV\, e^{2\Phi(r)}\,(\mu_n - \mu_p - \mu_\ell)\cdot(\Gamma_{n\to p+\ell} - \Gamma_{p+\ell\to n})$$

[Fernández and Reisenegger (2005)]

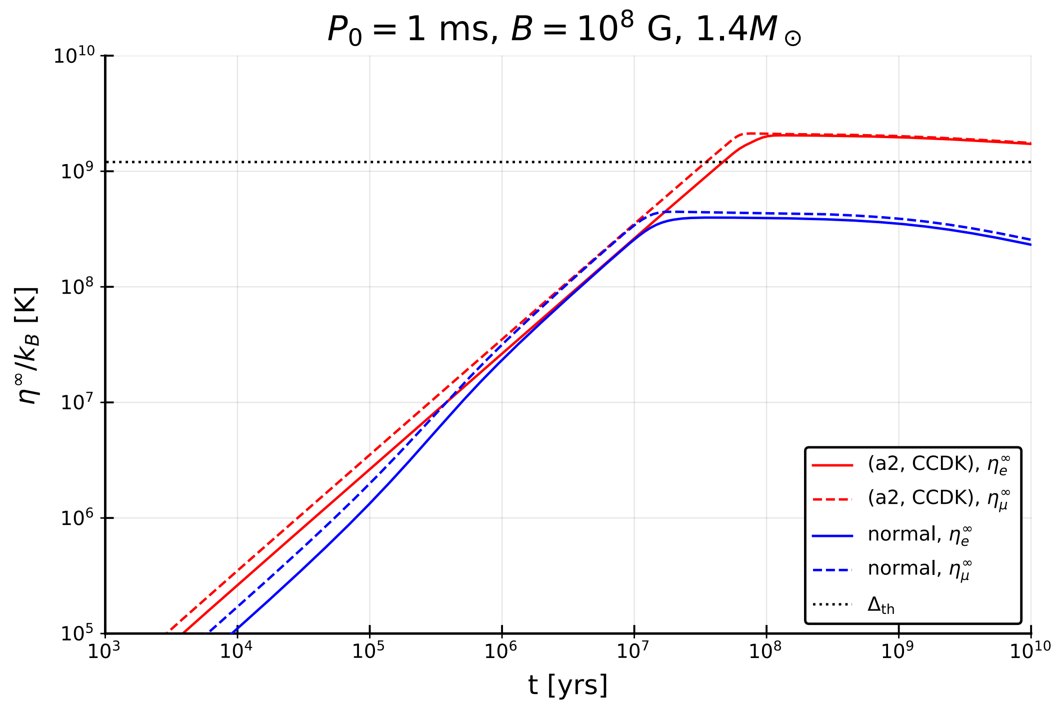


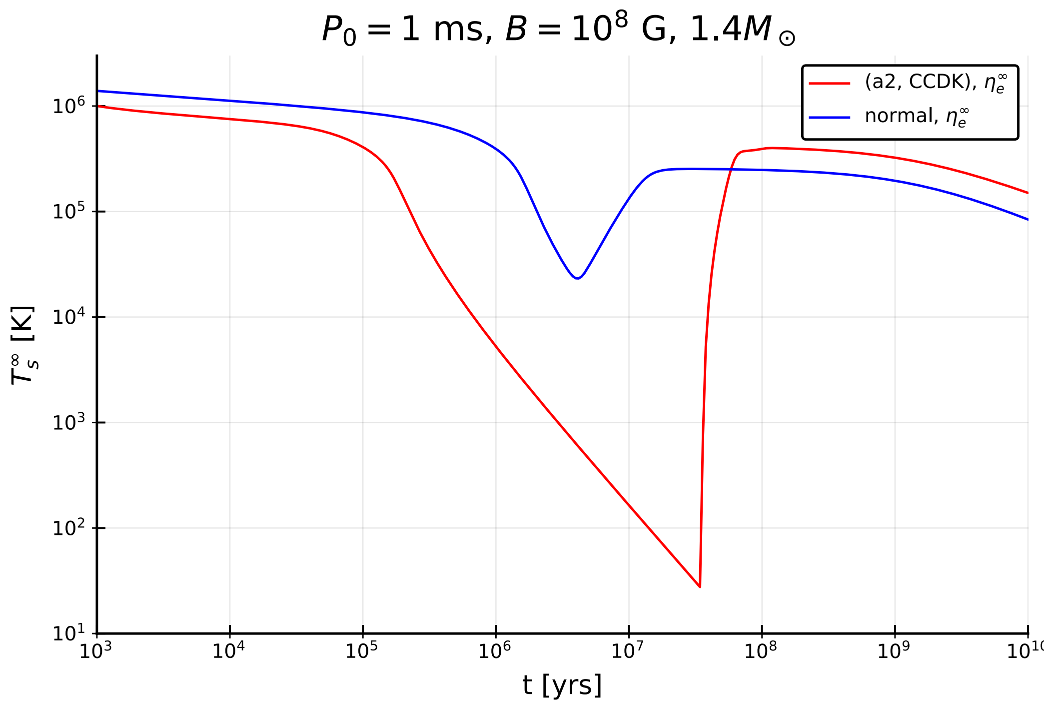
Heating occurs w/o any exotic physics

Details: Effect of Cooper pairing

- Nucleon superfluidity generates threshold $\Delta_{\rm th} = \min\{3\Delta_n + \Delta_p, \Delta_n + 3\Delta_p\}$
- Once η_ℓ exceeds $\Delta_{\rm th}$, rotochemical heating begins
- Larger gap → larger η_ℓ → hotter NS

[Petrovich & Reisenegger (2009)]





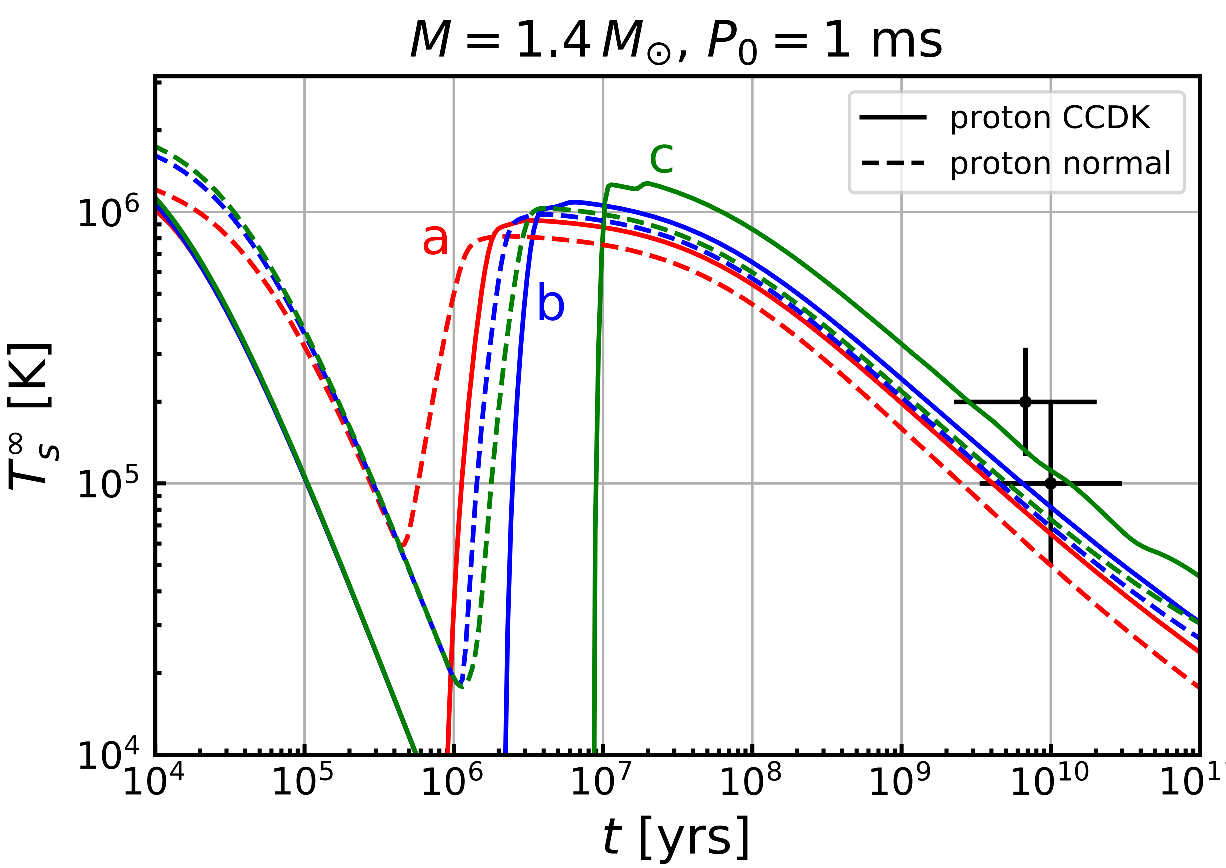
We improve previous works (e.g. González-Jiménez et al. (2014)) by including both neutron and proton pairing in numerical calculation

[KY, Nagata, Hamaguchi (2019)]

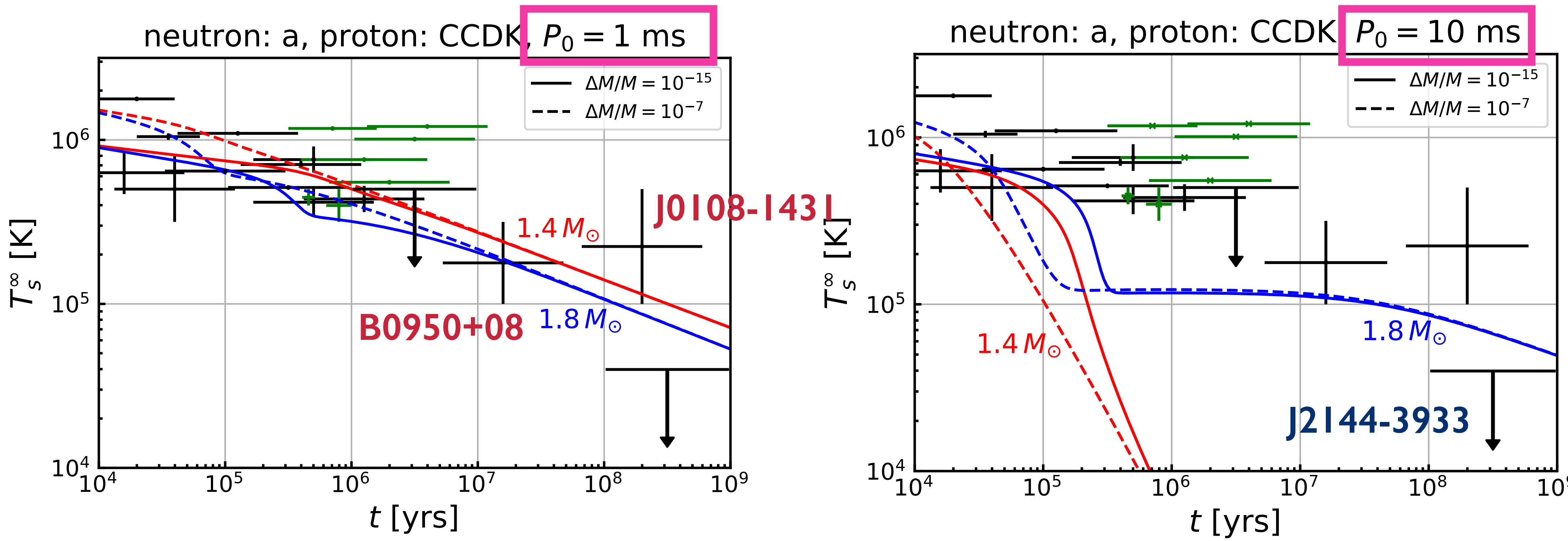
Result: Millisecond pulsars

- Millisecond pulsars (MSPs): short period (P~1ms) and small magnetic field (B~10^8 G)
- Two very old MSPs (PSR J2124-3358 & PSR J0437-4715) are much hotter than standard cooling prediction
- These are explained by rotochemical heating
- Including both neutron and proton pairing is advantageous for the explanation

[KY, Nagata, Hamaguchi (2019)]



Result: Ordinary pulsars and XDINSs



- Ordinary pulsars : P~1s and B~10^{12} G; XDINSs: larger magnetic field
- Old hot NSs (PSR J0108-1431& PSR B0950+08): P_0 = 1ms is necessary
- Old cold NS (PSR J2144-3933): P_0 > 10 ms is necessary
- Some XDINSs are even hotter. Maybe due to the magnetic field decay

[KY, Nagata, Hamaguchi (2019)]

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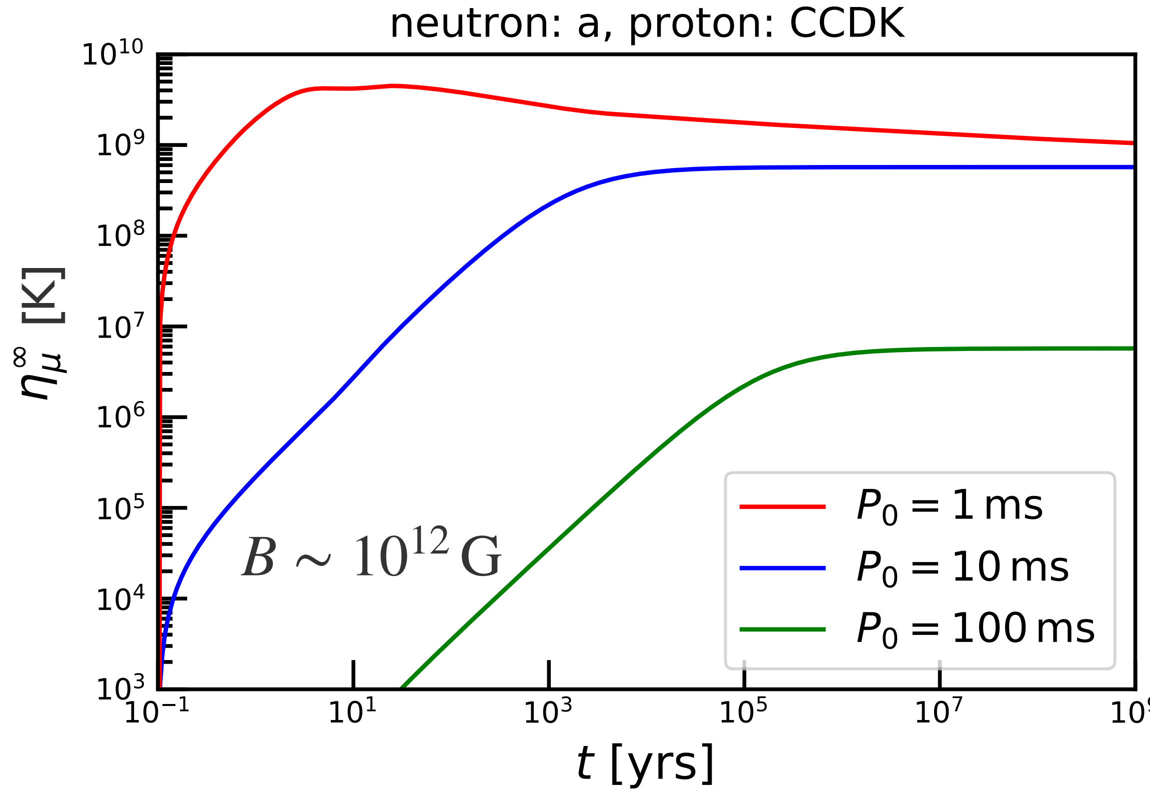
DM heating vs. rotochemical heating

- DM heating
  - $T_s \sim 3000\,\mathrm{K}$
  - For nearby NSs, this prediction cannot change by order

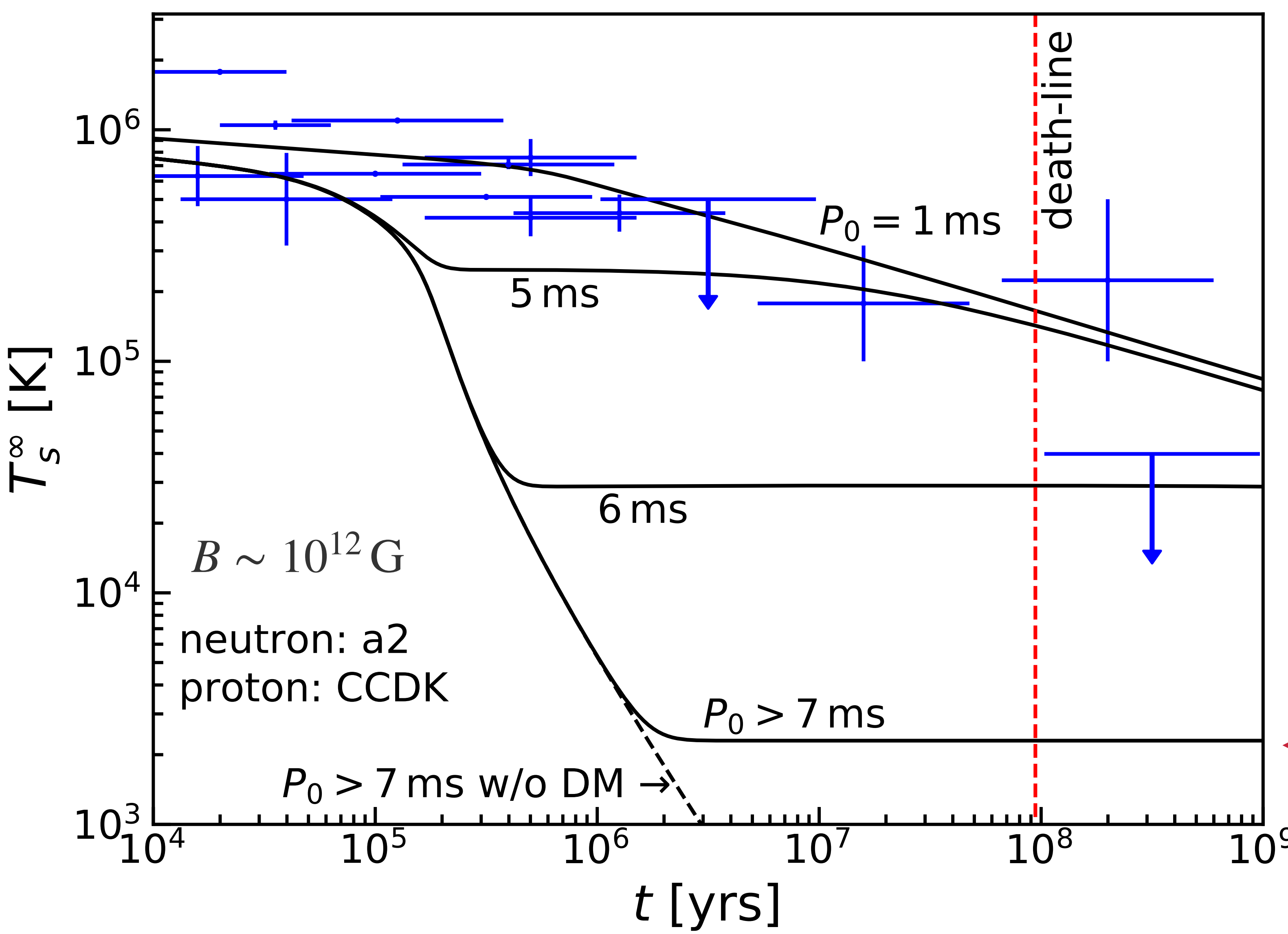
- Rotochemical heating
  - If it operates, typically $T_s \sim 10^{5-6}\,\mathrm{K}$
  - Heating rate is strongly dependent on the initial rotation period P_0
  - Heating is more efficient for smaller P_0

$$\eta_\ell = \mu_n - \mu_p - \mu_\ell$$



DM heating vs. rotochemical heating

$$C\frac{dT^\infty}{dt} = -L_\nu^\infty - L_\gamma^\infty + L_{\rm roto}^\infty + L_{\rm DM}^\infty$$



$L_{\rm DM} < L_{\rm roto}$

$L_{\rm DM} > L_{\rm roto}$ for $P_0 \gtrsim 7$ ms

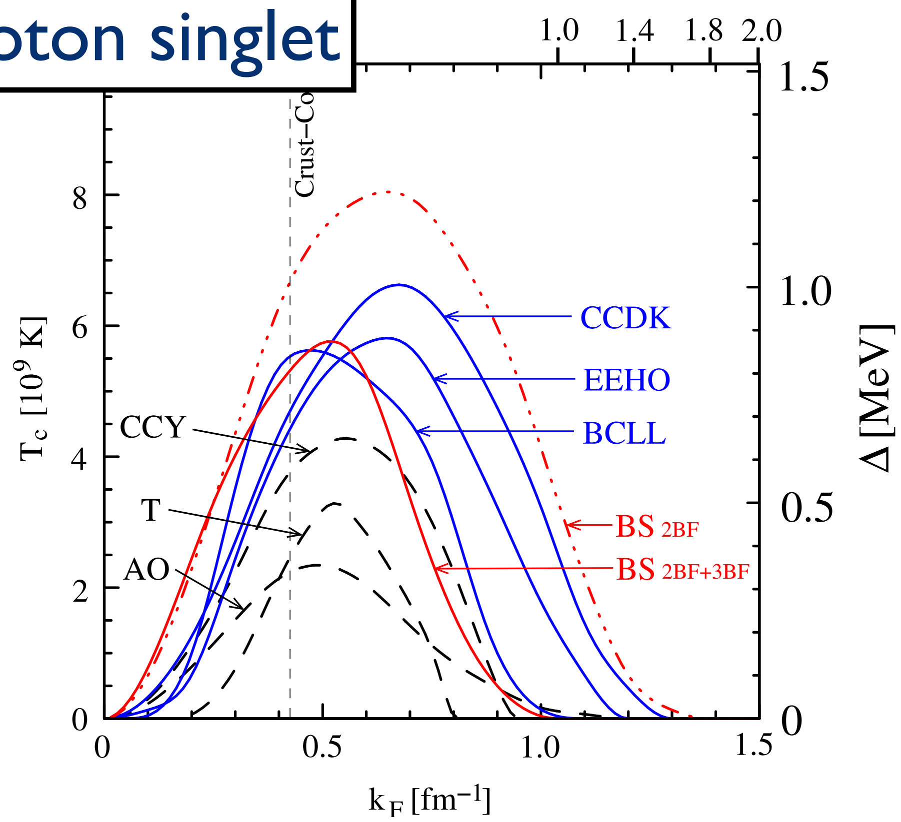
[Hamaguchi, Nagata, KY (2019)]

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

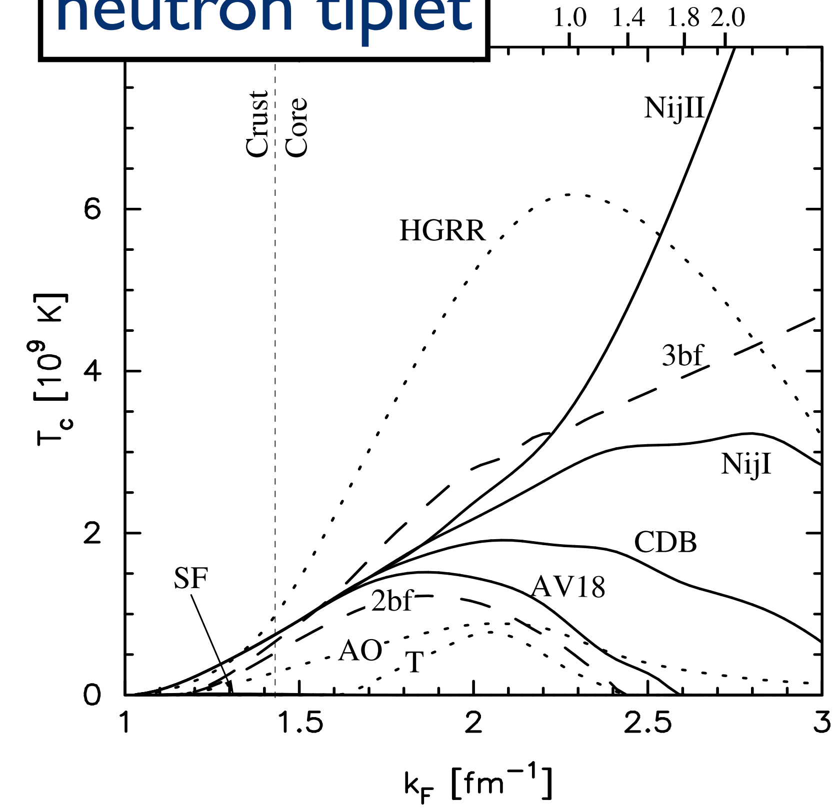
Uncertainty from pairing gap

- So far we have fixed Cooper pairing gap model
- But the gap amplitude has uncertainties due to nuclear force modeling

proton singlet



neutron tiplet



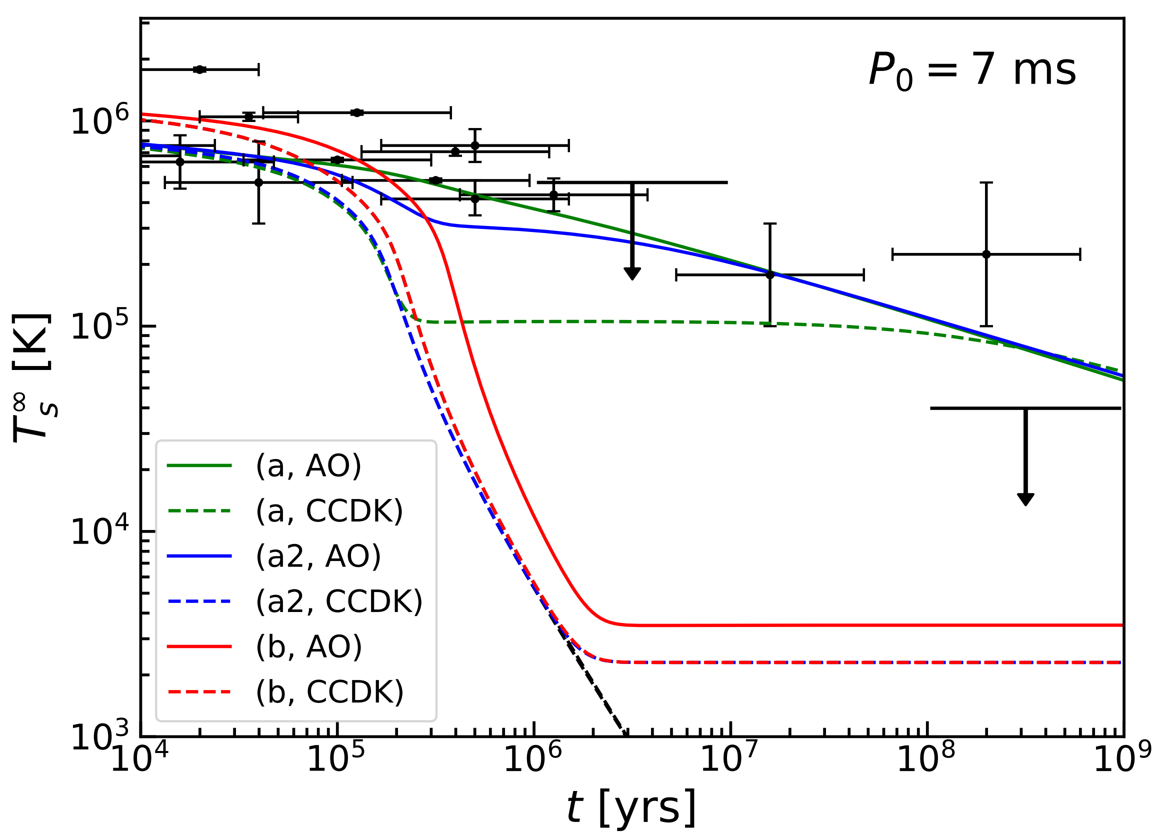
$$\epsilon_N(\mathbf{p}) \simeq \mu_N + \mathrm{sign}(p - p_{F,N})\sqrt{\Delta_N^2 + v_{F,N}^2(p - p_{F,N})^2}$$

- Proton singlet gap is rather well constrained
- Neutron triplet gap is highly uncertain. It is often taken as a free parameter

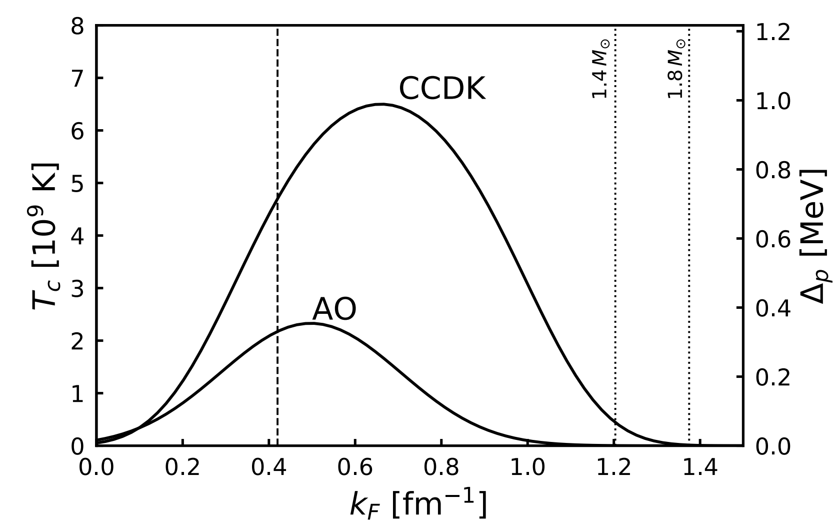
[Figures from Page et al. (2013)]

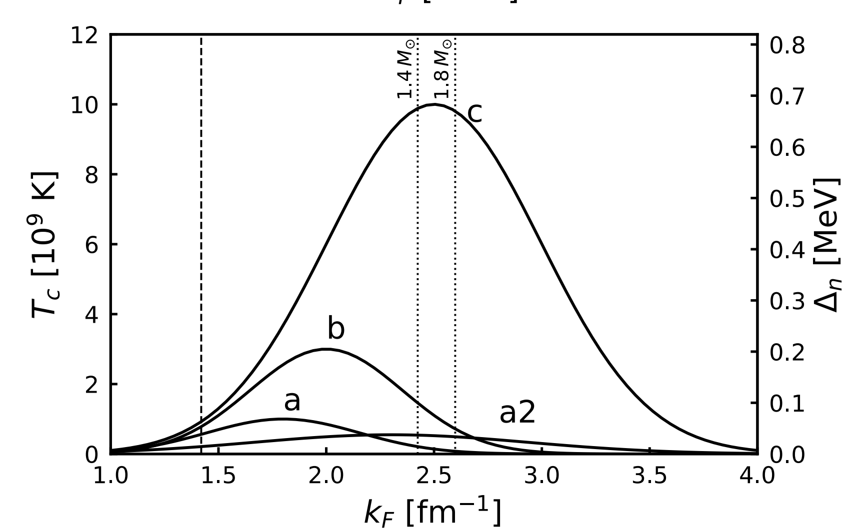
Uncertainty from pairing gap

- Strength of rotochemical heating depends on gap amplitude
- Critical P_0 depends on the choice of gap models
- If $P_0 \gtrsim 100\,\mathrm{ms}$, (DM heating) >> (rotochemical heating)



(neutron gap, proton gap)





Initial period

Several studies suggest the typical initial period of $P_0 \sim \mathcal{O}(100)\,\mathrm{ms}$

- Observed kinematic age
  [Popov & Turolla, 1204.0632; Noutsos et.al., 1301.1265; Igoshev & Popov, 1303.5258]

- Population synthesis
  [Faucher-Giguere & Kaspi, astro-ph/0512585; Popov et al., 0910.2190, Gullo´n et al., 1406.6794, 1507.05452]

- Supernova simulation for proto-NSs
  [Mu¨ller et al., 1811.05483]

Thus we expect

- For many NSs, DM heating > Rotochemical heating
- Some NSs accidentally have $P_0 \sim 1\mathrm{ms}$ → observed high $T_s \sim 10^{5-6}\,\mathrm{K}$

Summary

- DM heating
  - DM accretion heats up old NS
  - NS surface temperature measurement can probe DM
- Rotochemical heating
  - it occurs w/o any new or exotic physics (induced by NS rotation)
  - it explains observed warm NSs
- (DM heating) > (rotochemical heating)?
  - $P_0 \lesssim 10 - 100\,\mathrm{ms}$: (DM heating) < (rotochemical heating)
  - $P_0 \gtrsim 10 - 100\,\mathrm{ms}$: (DM heating) > (rotochemical heating)
  - old ordinary pulsar is suitable target

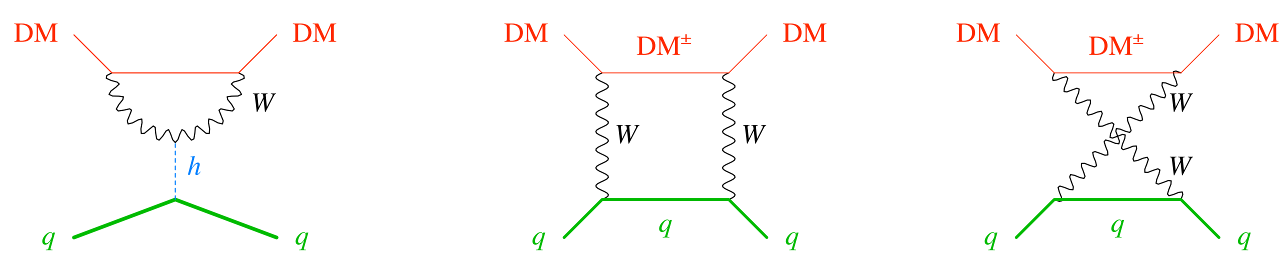
Backup

Electroweak DM

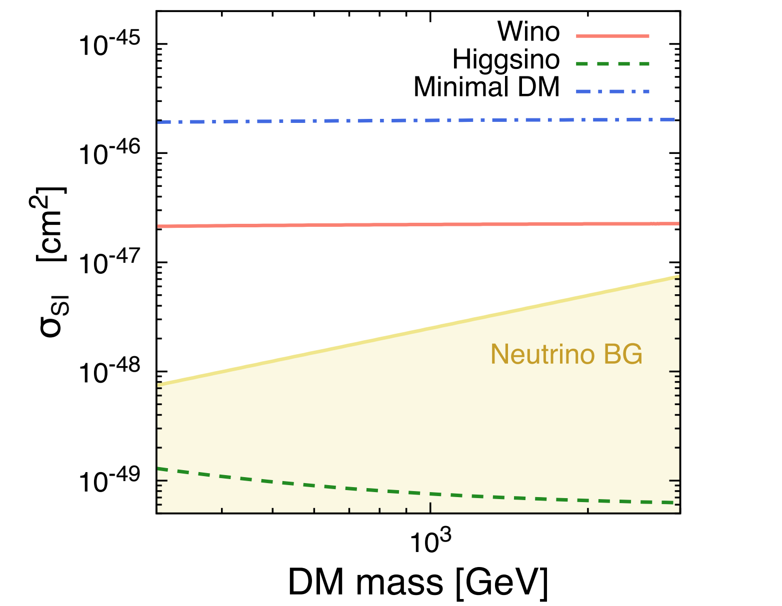
- DM originally in electroweak multiplet (e.g., Wino, Higgsino, minimal DM…)
- Mass splitting after EW symmetry breaking

$$\Delta M = m_{\chi^+} - m_{\chi^0} = \mathcal{O}(100)\,\mathrm{MeV}$$

- Elastic scattering is generally loop-suppressed

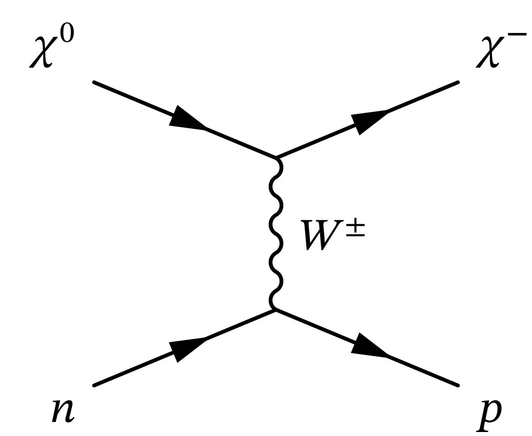


[Cirelli and Strumia (2009)]



[Hisano et al. (2015)]

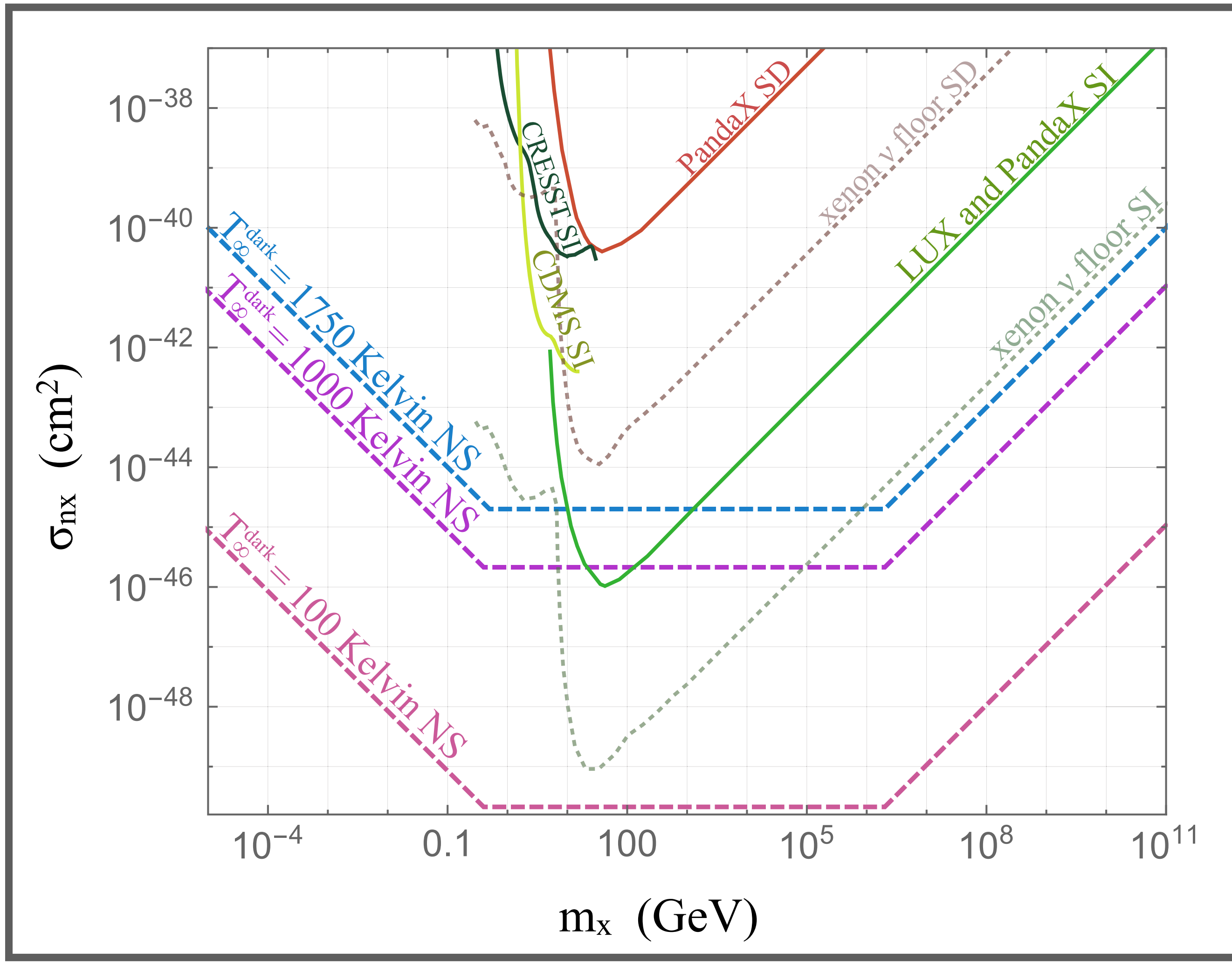
- Inelastic scattering cross section is tree-level
  - $\sigma \sim 10^{-39}\,\mathrm{cm}^2$
  - Highly suppressed on earth by kinematics

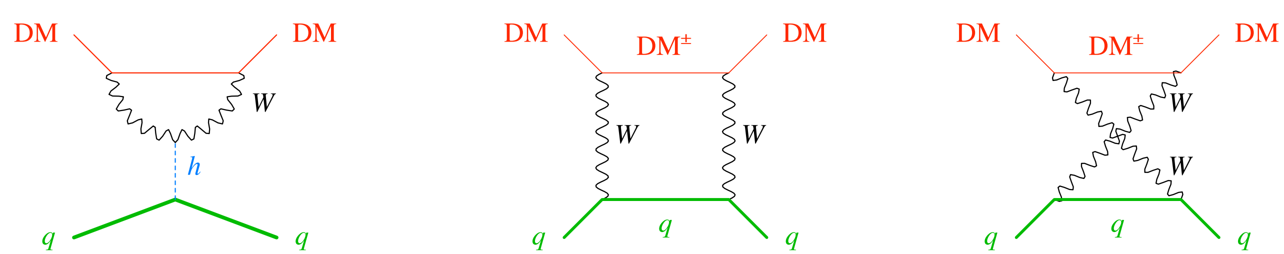


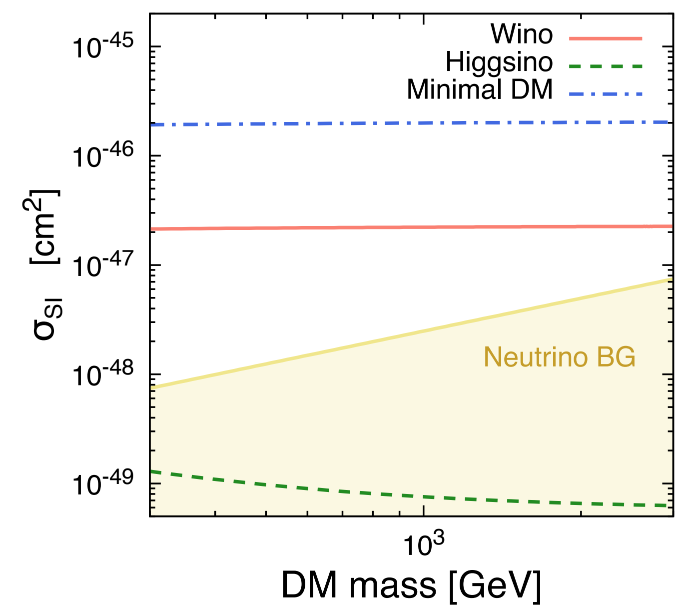
ak DM

no, Higgsino, minimal DM…)

00) MeV







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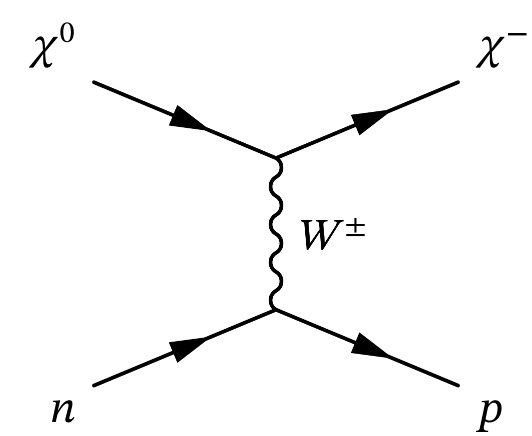
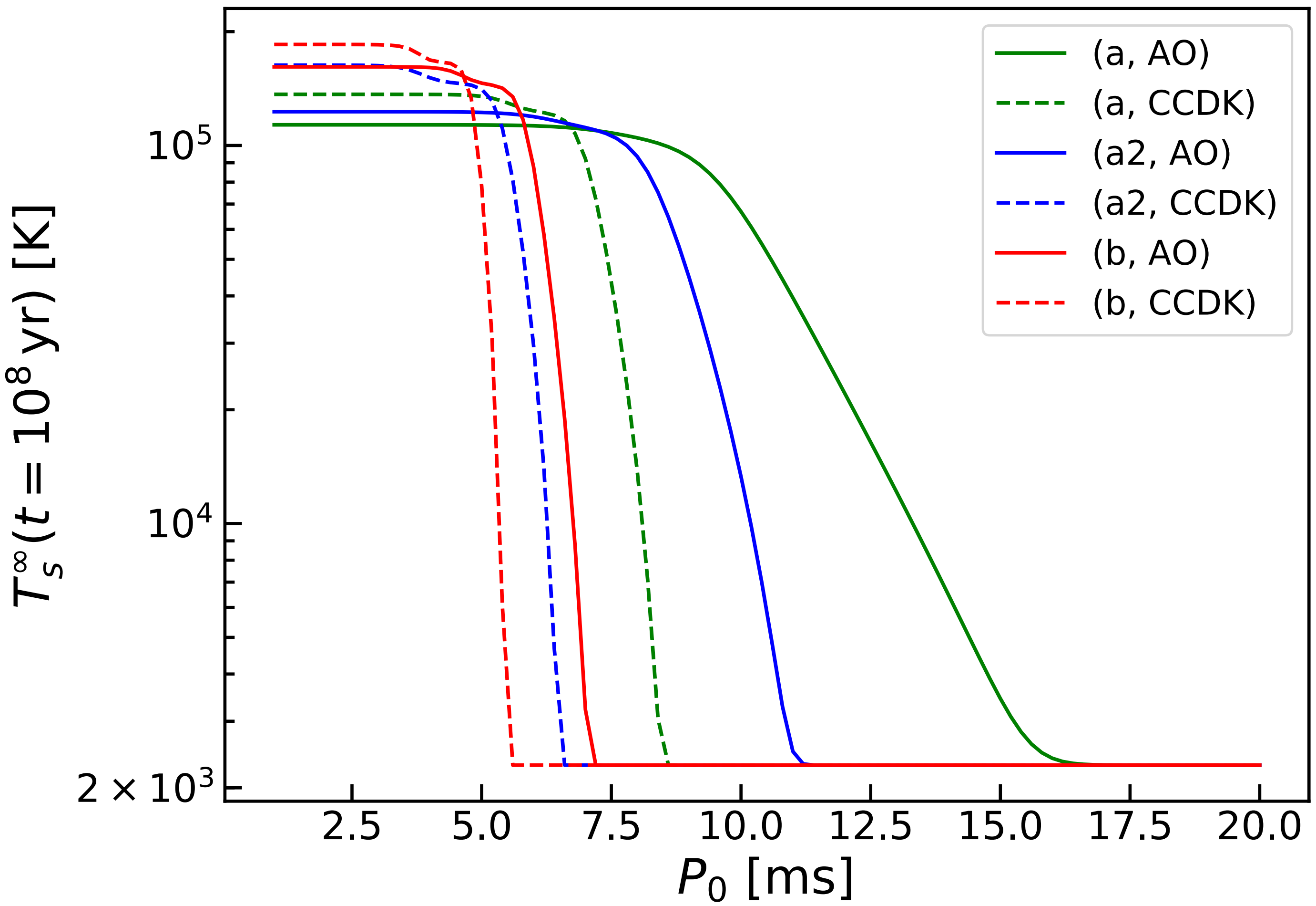


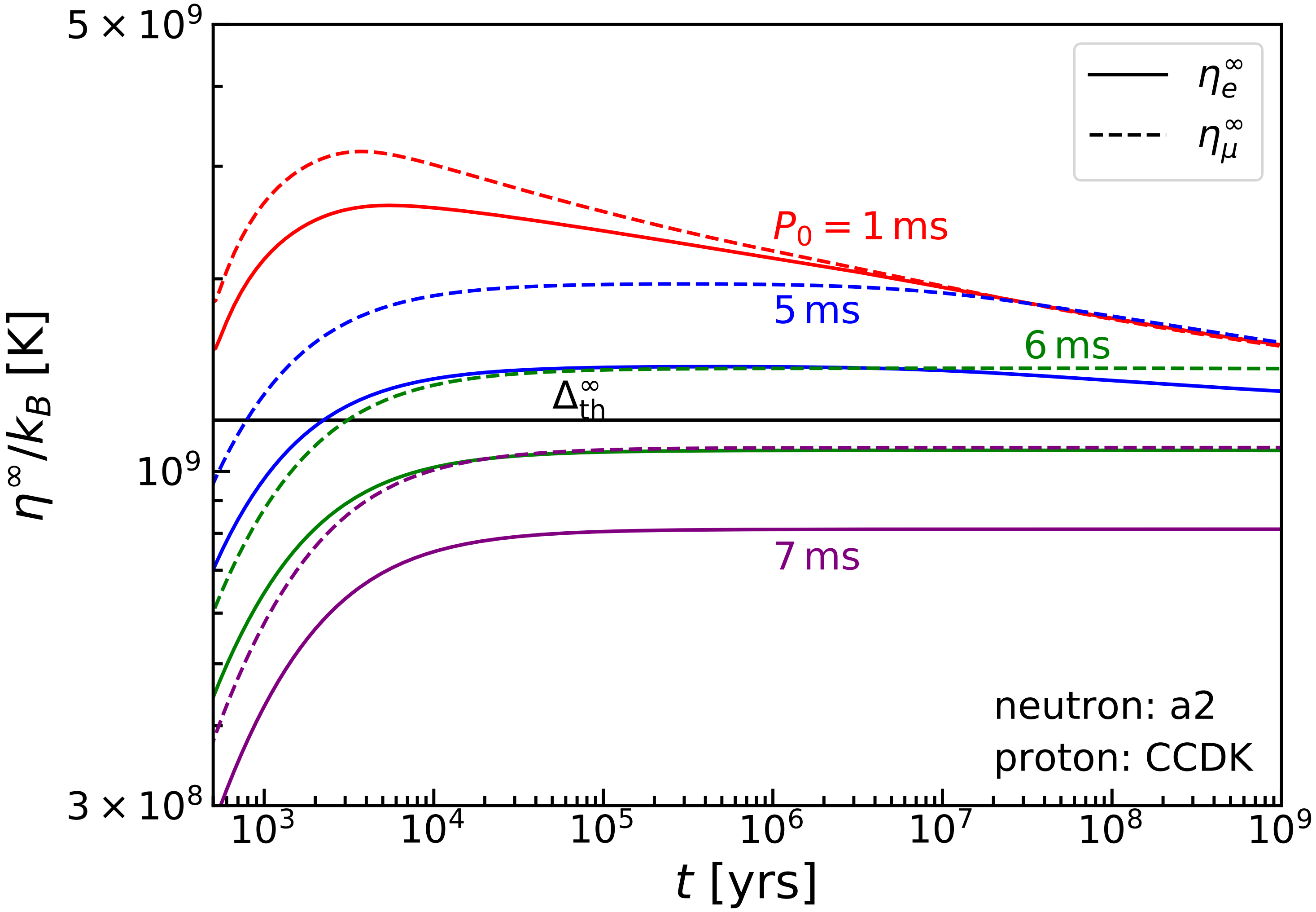
Uncertainty from pairing gap

- Strength of rotochemical heating depends on gap amplitude
- Critical P_0 depends on the choice of gap models
- $P_0 \gtrsim 100\,\mathrm{ms}$ is enough

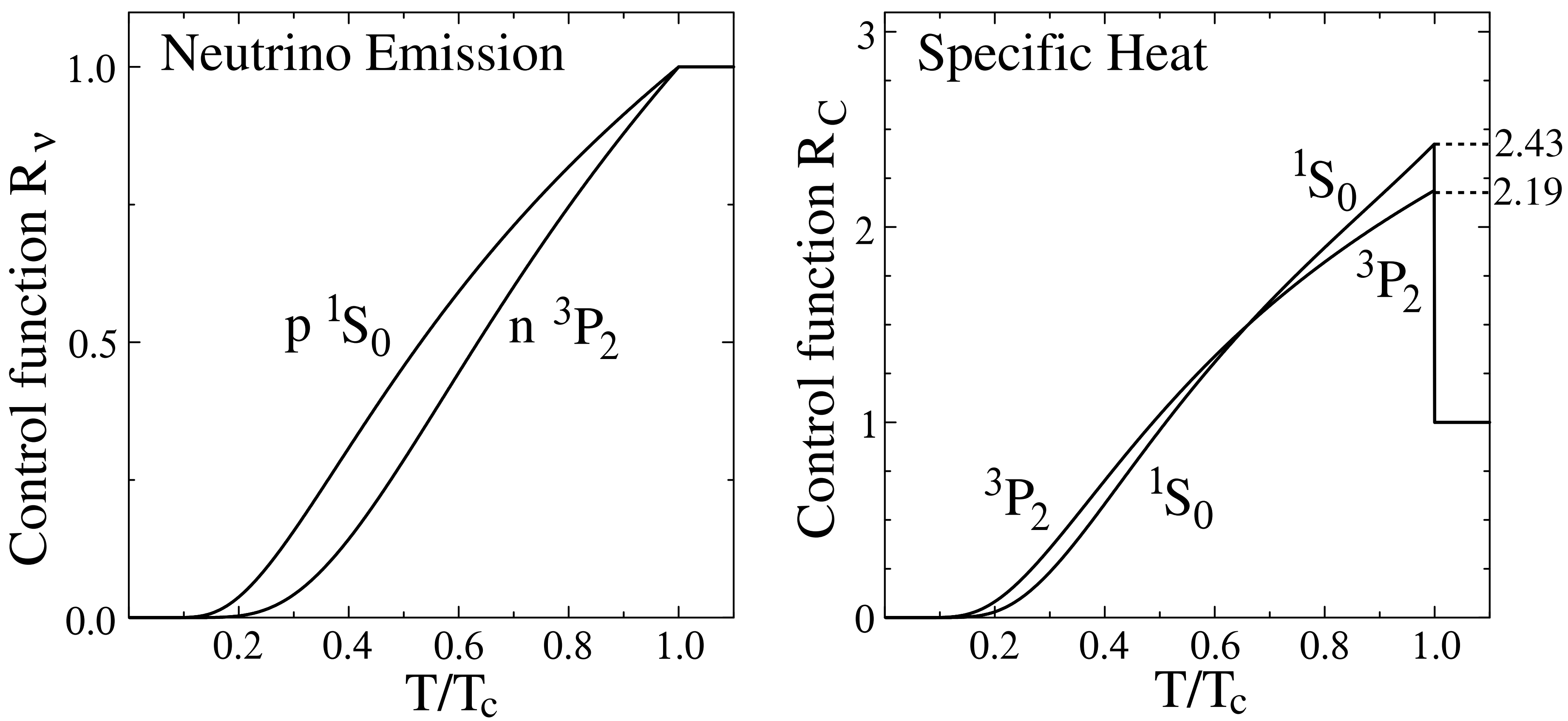


(neutron gap, proton gap)

Imbalance evolution



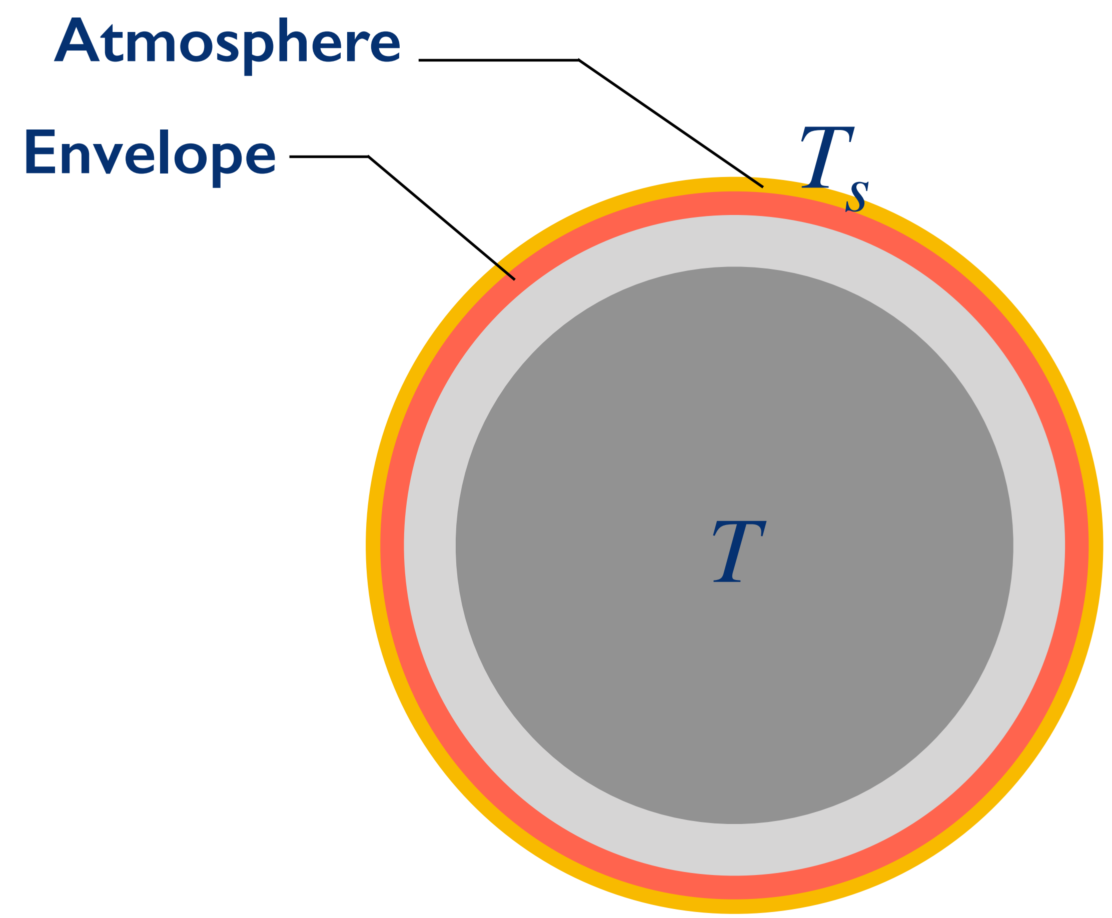
Superfluid suppression

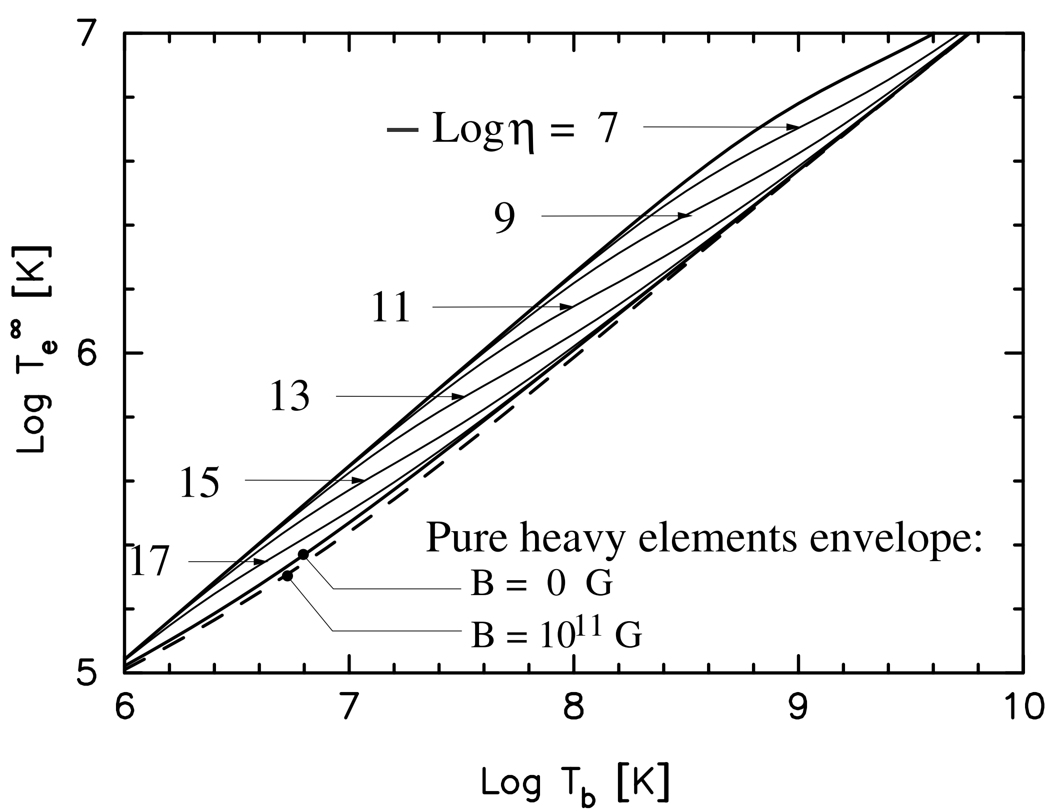


[Page et al. (2013)]

Details 2: Envelope

- Envelope shields atmosphere from core and crust
- Surface T and internal T are different
- $T - T_s$ relation depends on amount of light element in envelope [Potekhin et al. (1997)]





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

(surface gravity)/(10^{14} cm/s^2) mass of light elements

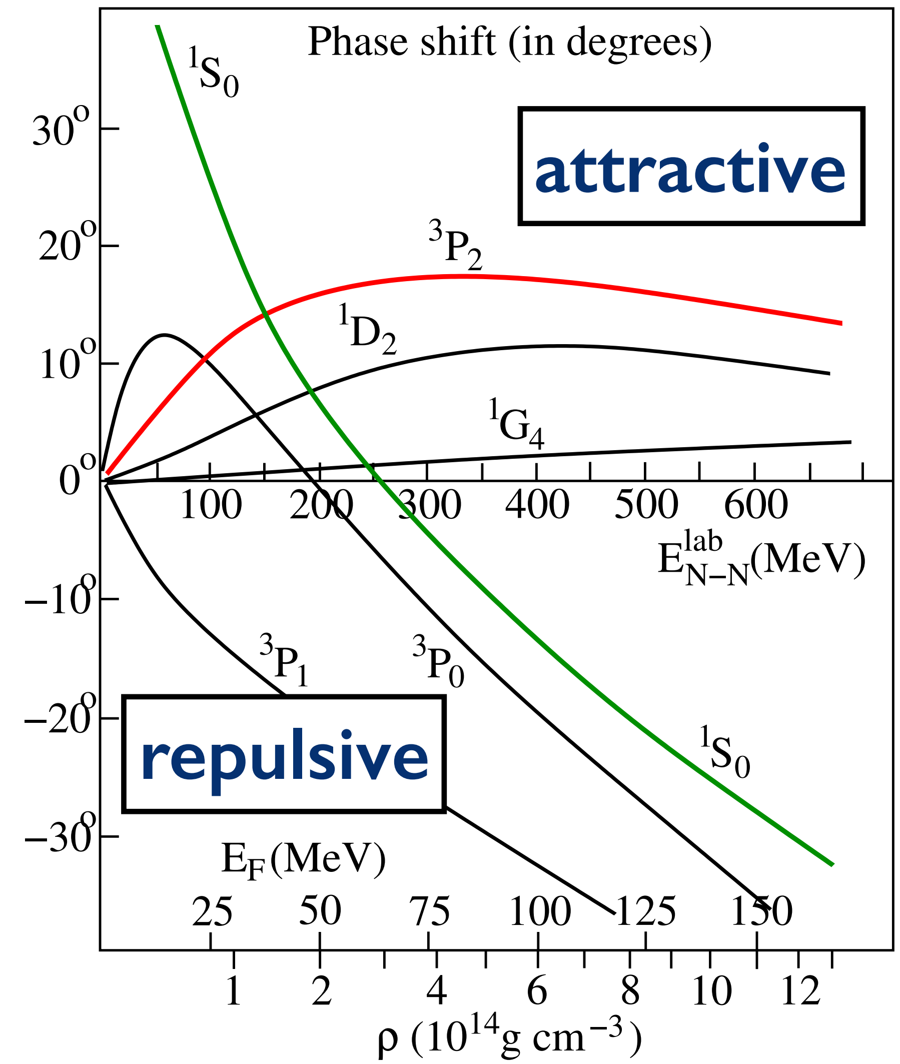
Nucleon Cooper pairing

- Attractive nuclear force induces the Cooper pairing of n-n and/or p-p

- **In the core**
  - n: spin-triplet ($^3P_2$) pairing
  - p: spin-singlet ($^1S_0$) pairing

    this difference is due to the difference of Fermi energy

- In the crust:
  - n: spin-singlet ($^1S_0$) pairing

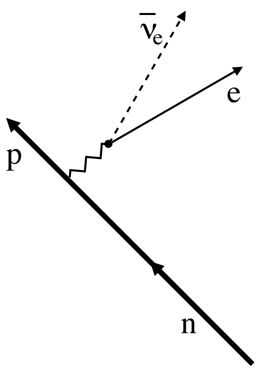


[Calculation by Tamagaki (1970), figure from Page et al. (2013)]

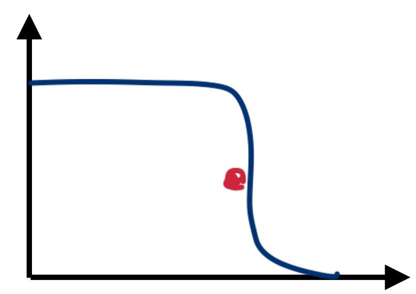
Direct Urca process

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

$\ell = e, \mu$



- Beta decay and its inverse



- Occurs around Fermi surface

- Direct Urca process does not operate unless NS is very heavy

[e.g., Lattimer et al. (1991)]

  - due to the energy and momentum conservations around Fermi surface
  - E.g., for APR EOS, $M \gtrsim 1.97\, M_\odot$ is required
  - We can neglect direct Urca in Cas A NS ($M \simeq 1.4\, M_\odot$)

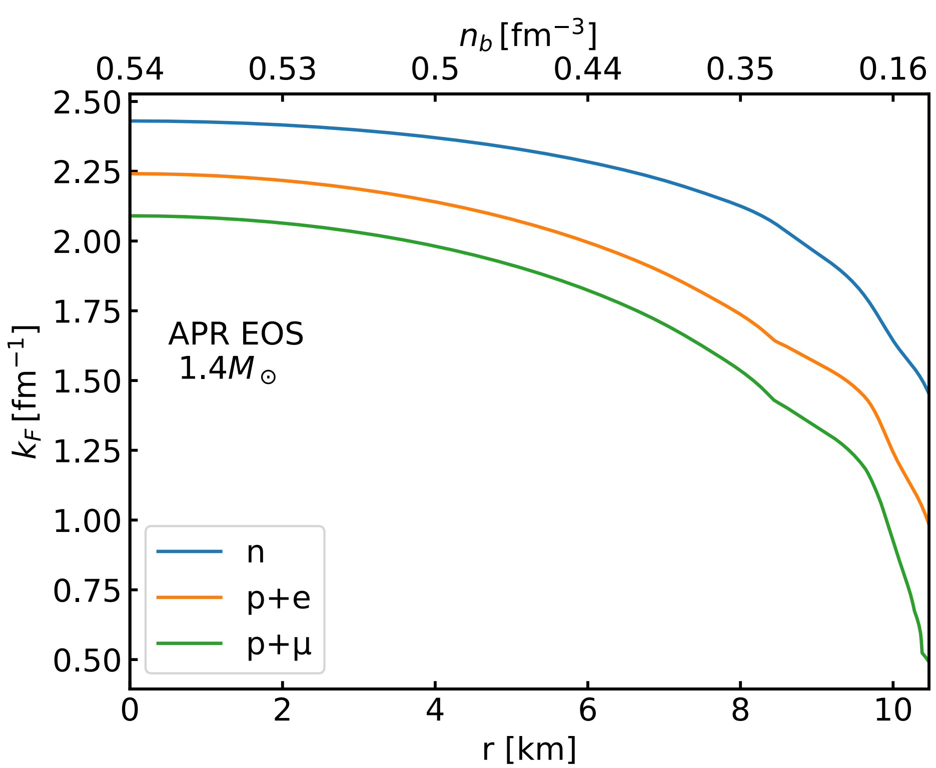
Threshold of direct Urca

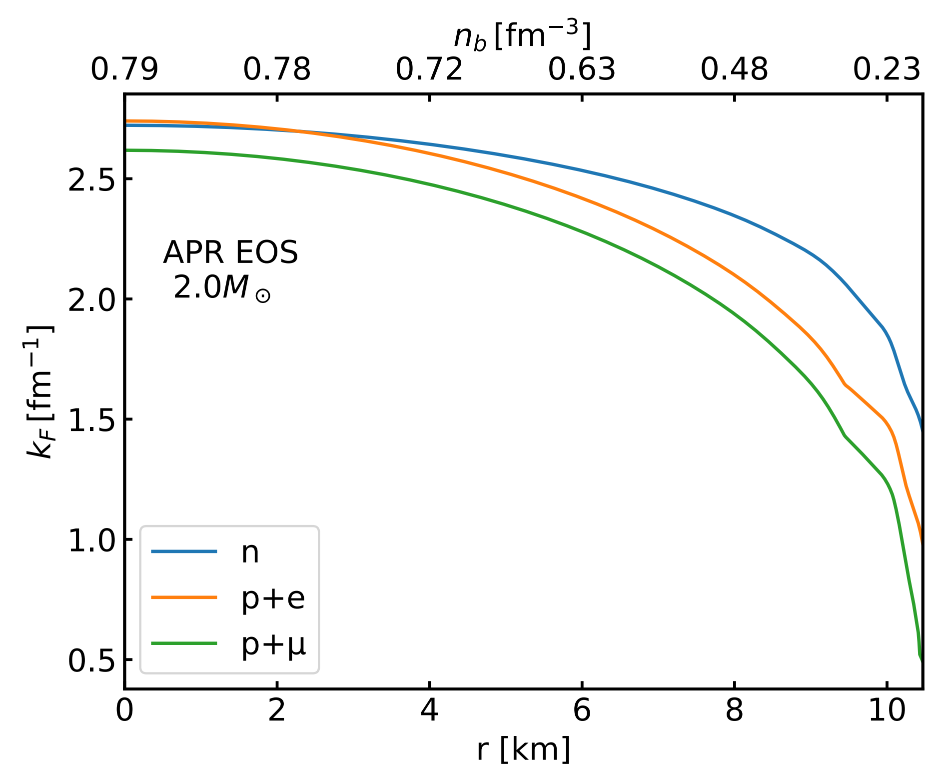
- Energy conservation $\varepsilon_n = \varepsilon_p + \varepsilon_\ell \pm \varepsilon_\nu$ and beta equilibrium $\mu_{F,n} = \mu_{F,p} + \mu_{F,\ell}$

  → Emitted neutrino momentum: $p_\nu \sim T \ll p_F$

- Momentum conservation: $\overrightarrow{p}_n \simeq \overrightarrow{p}_p + \overrightarrow{p}_\ell$

  → $p_{F,n} < p_{F,p} + p_{F,\ell}$, hence large proton fraction, is necessary

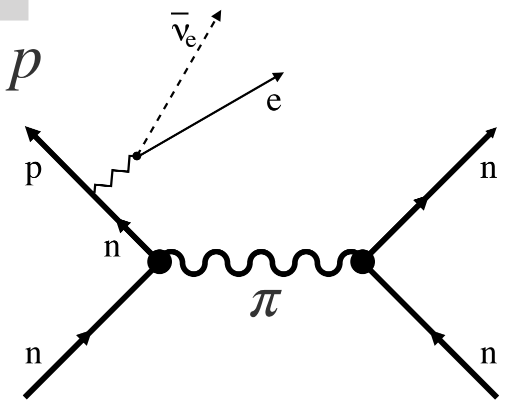




Modified Urca process

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

$N = n \text{ or } p$



- Threshold is relaxed
- Emissivity

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

- Before pairing: $L_\nu \propto T^8$
- After pairing: exponentially suppressed by the gap: $f \sim \exp(-\Delta/T) \ll 1$

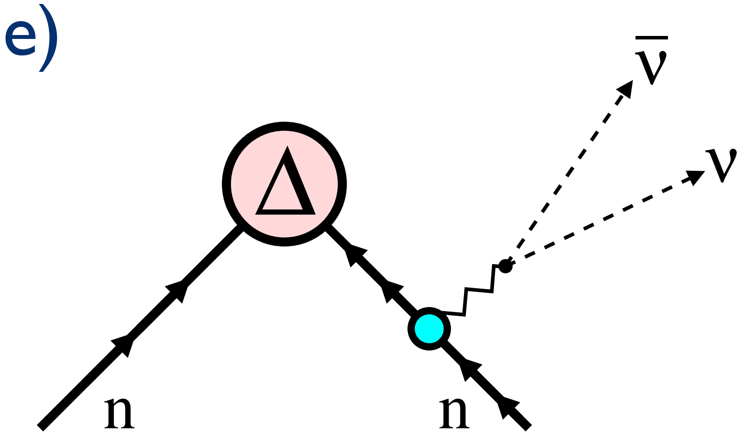
Cooper pair breaking and formation (PBF)

- Cooper pairing triggers another neutrino emission [Flowers et al. (1976)]

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

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

  - Pair-formation: $\tilde{N} + \tilde{N} \rightarrow [\tilde{N}\tilde{N}] + \nu + \bar{\nu}$

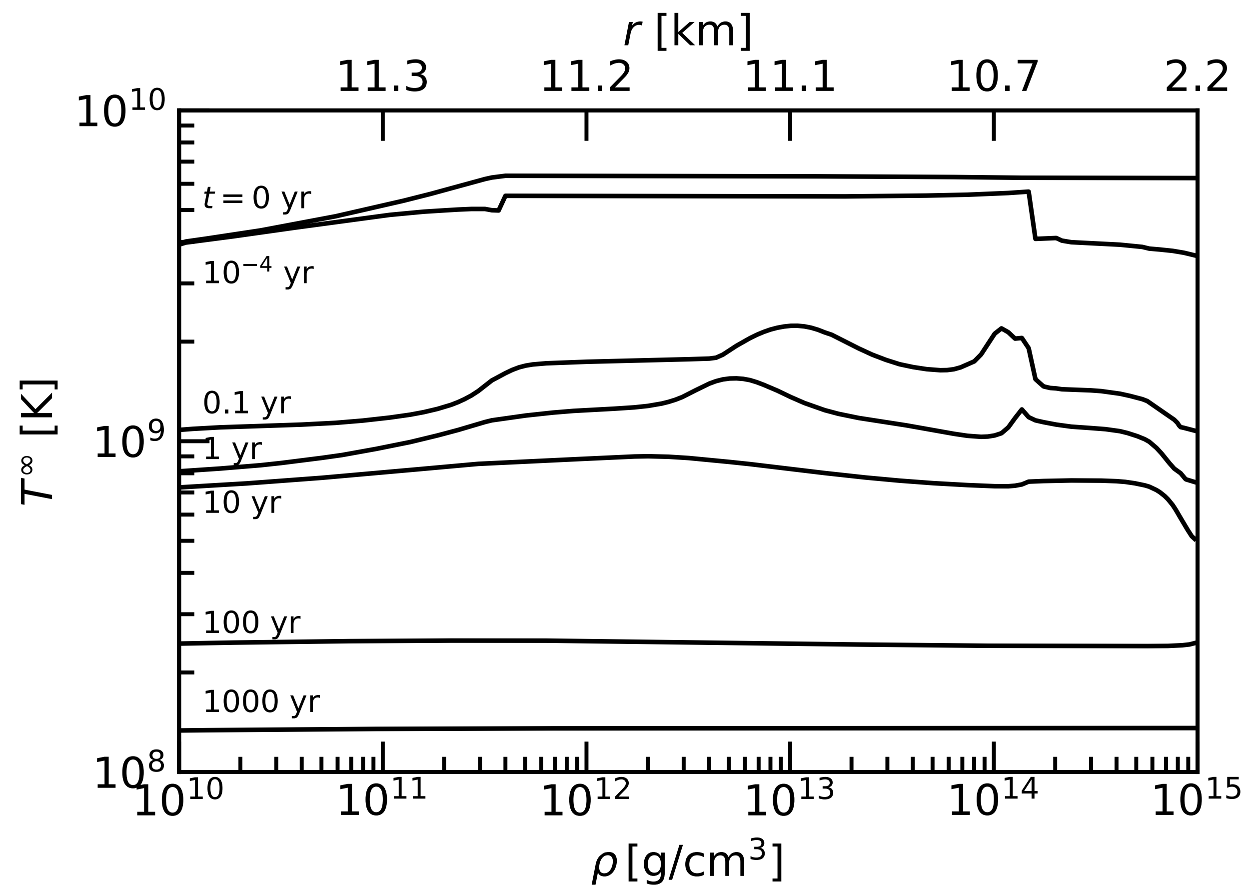


- Does not occur for $T > T_c$

- Efficiently occurs for $T \lesssim T_c$

- Suppressed for $T \ll T_c$ because excitation of quasi-nucleon is suppressed

Thermal relaxation



(a, CCDK) gap

- Relaxation time scale is $t \sim 10 - 100\,\mathrm{yr}$

Neutron singlet gap

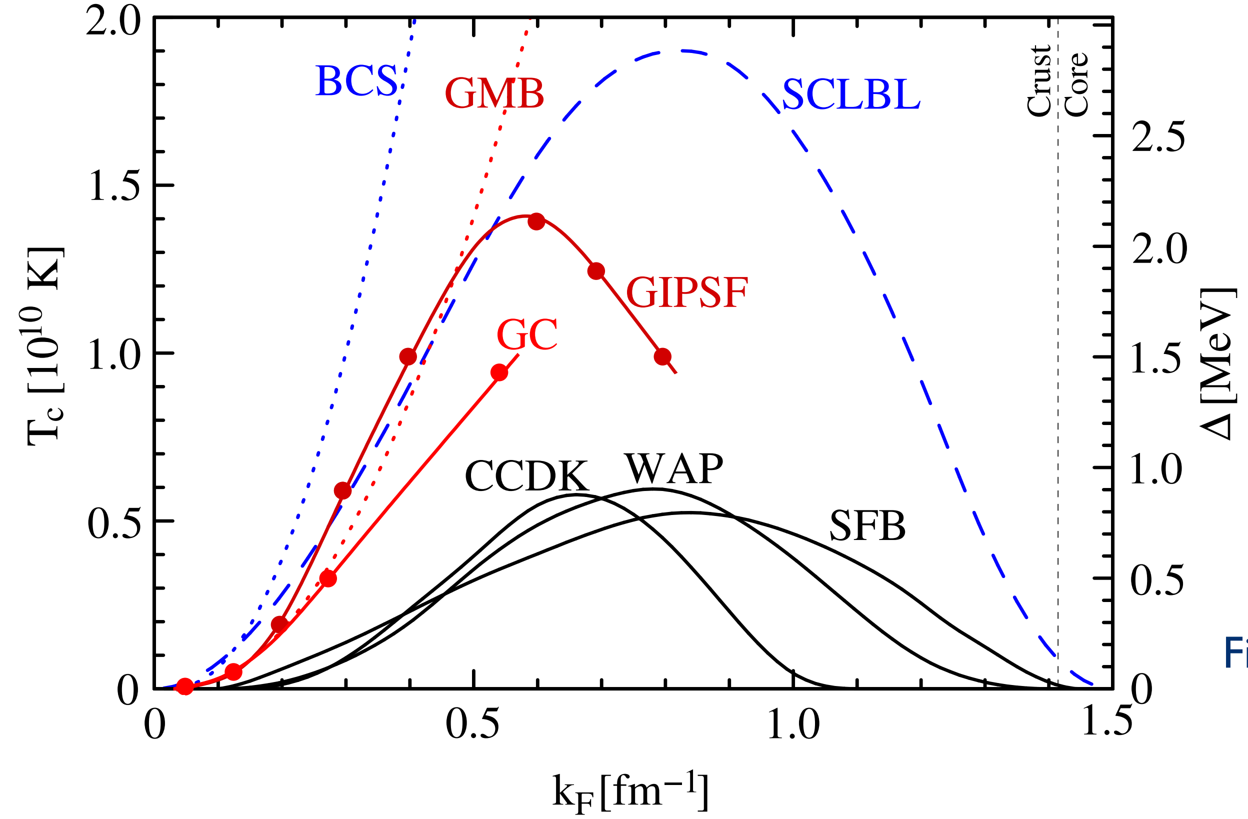
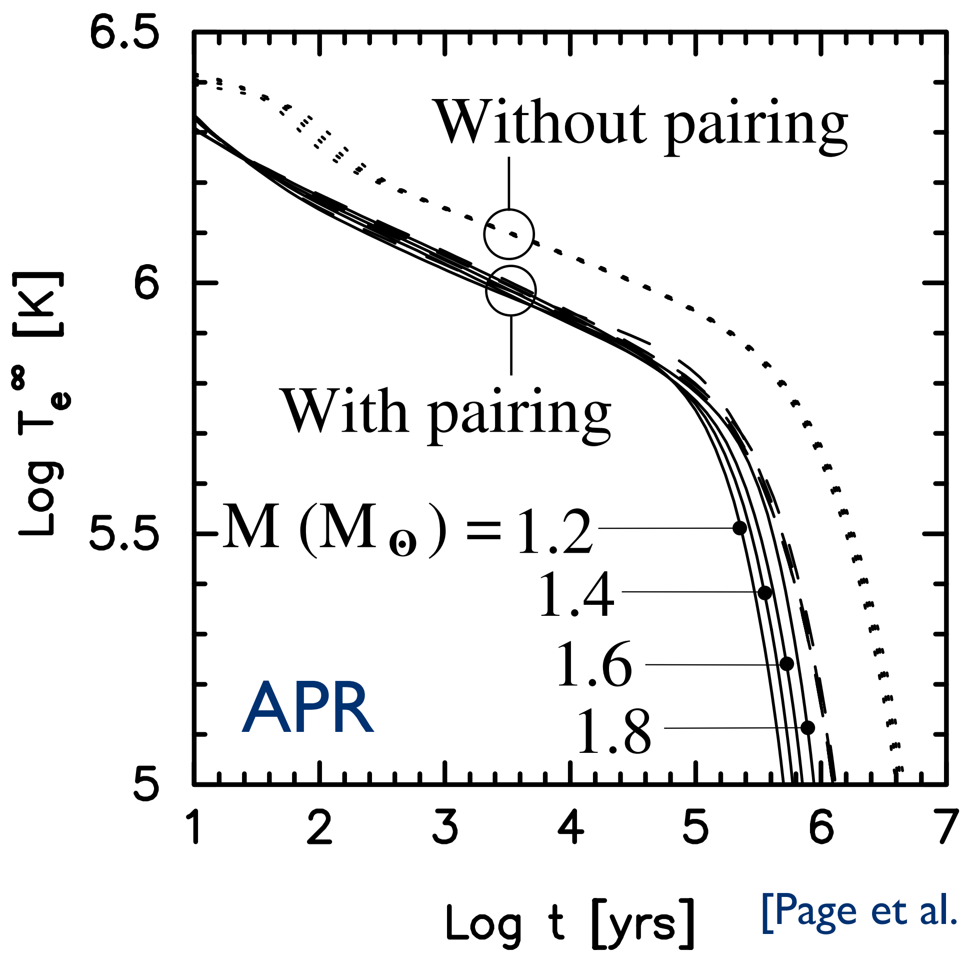


Figure from Page et al. (2013)]

- $T_c \sim (0.5 - 2) \times 10^{10}\,\mathrm{K}$
- Singlet pairing occurs only in the crust

Mass for thermal evolution

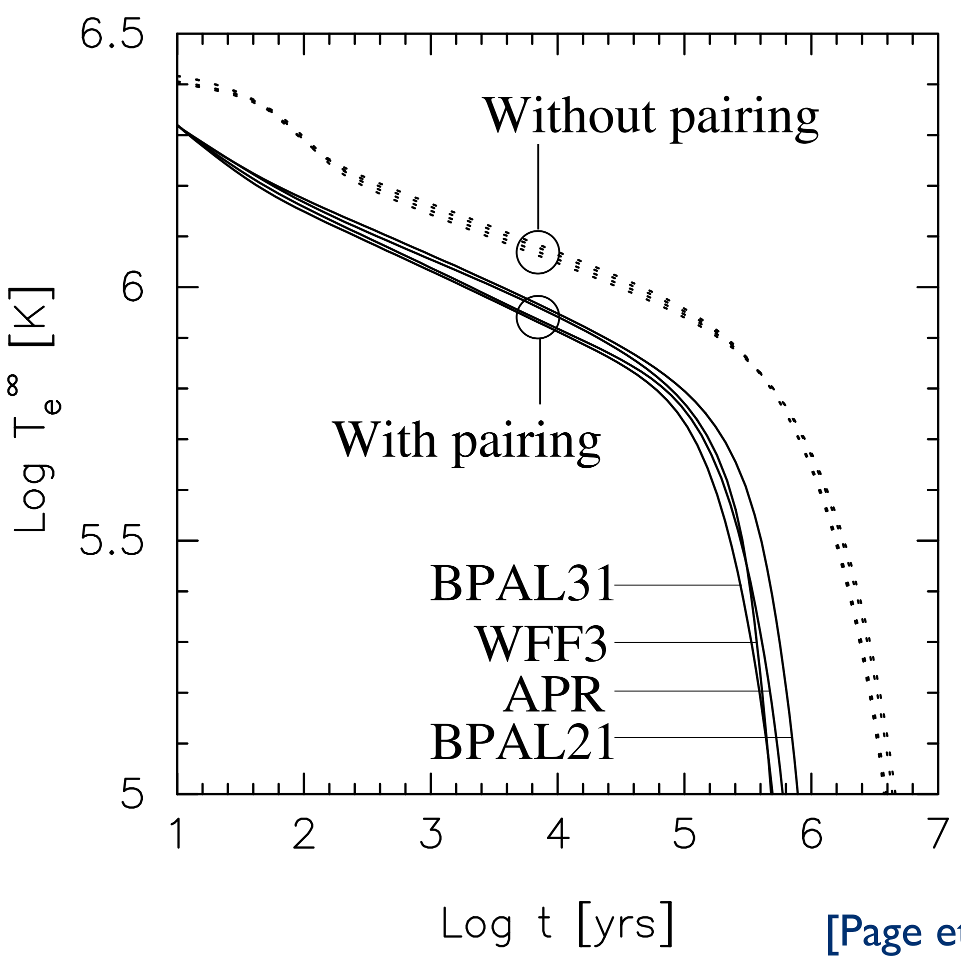


[Page et al. (2004)]

- Dashed: no proton singlet pairing
- Heavy element envelope
- (a, AO) gap

- Difference is due to the density dependence of pairing gap
- Heat capacity and neutrino luminosity slightly change

EOS for thermal evolution



[Page et al. (2004)]

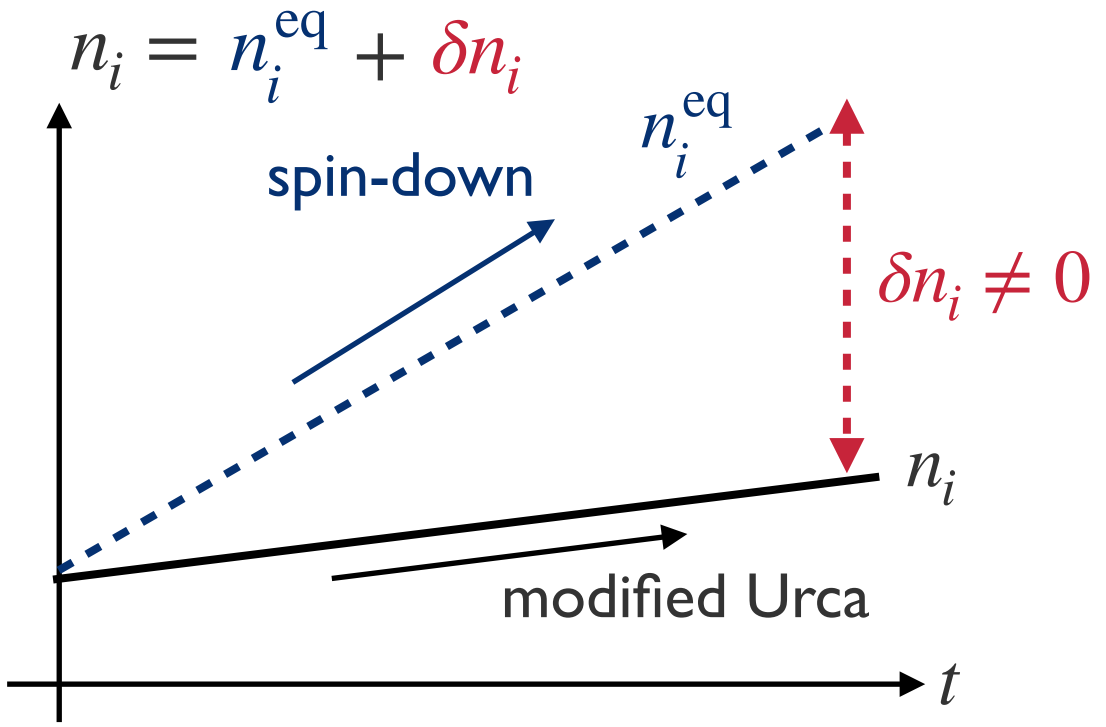
- Heavy element envelope
- (a, AO) gap
- APR and WFF3 use different potential
- BPAL is phenomenological

- Difference is also due to the density dependence of pairing gap

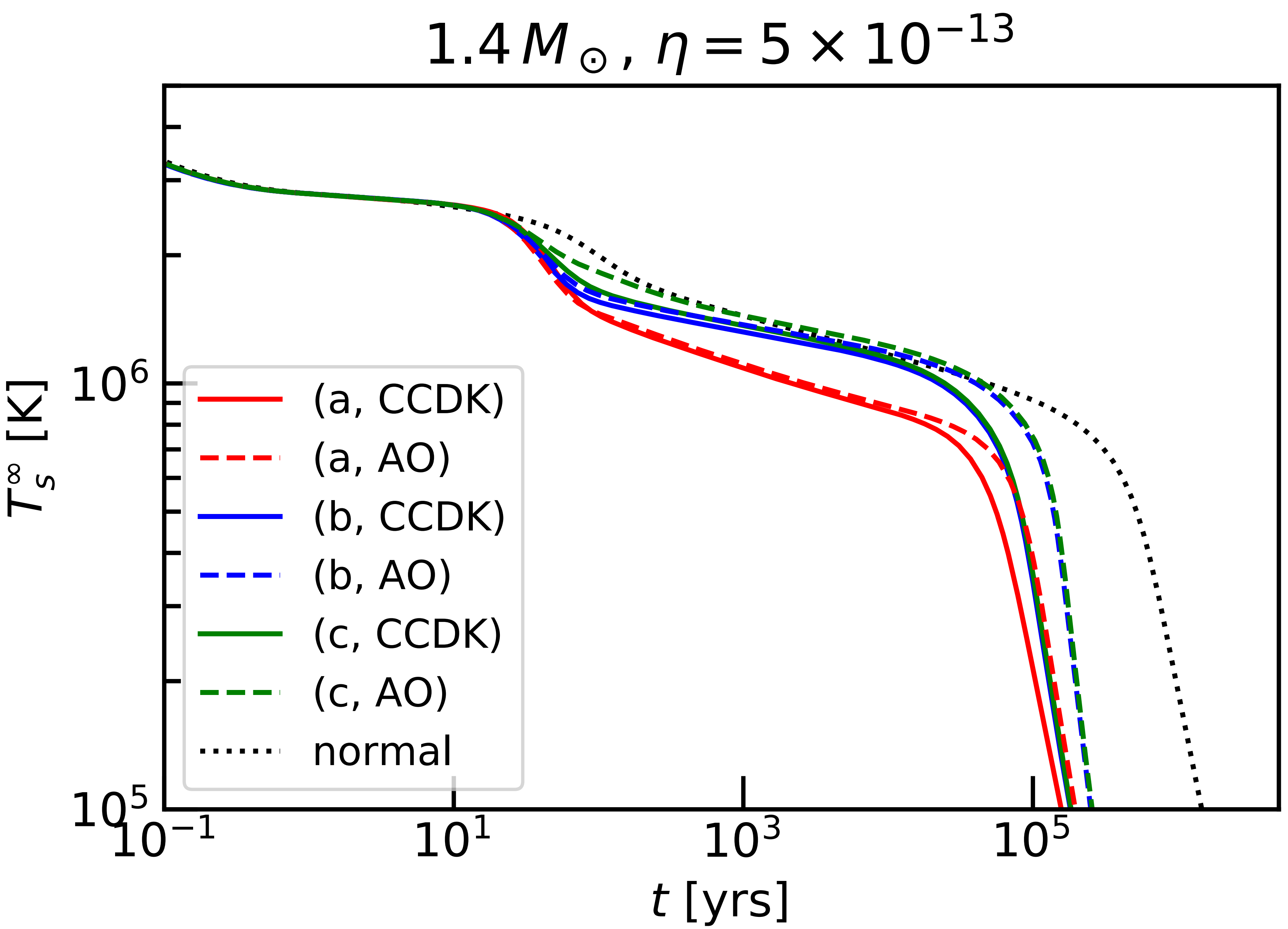
Pulsar spin-down violates β-equilibrium

- Each particle goes to new equilibrium $n_i^{\mathrm{eq}}(t)$ by modified Urca process
- If (modified) Urca is too slow, it cannot catch up with change of $n_i^{\mathrm{eq}}(t)$

(Schematic picture)



Gap dependence of cooling



Neutron star age

- Spin-down age
  - Assume rotational energy loss purely from magnetic dipole radiation

$$\dot{\Omega} = -k\Omega^3 \qquad k = \frac{2B_s^2 R^6 \sin^2\alpha}{3I}$$

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

if $P_{\rm now} \gg P_0$

$$\Rightarrow \boxed{t_{\rm sd} = \frac{P}{2\dot{P}}}$$

- Kinematic age
  - Estimate age from associated supernova remnant velocity