Dark Matter Heating vs. Rotochemical Heating in Old Neutron Stars

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Based on Koichi Hamaguchi, Natsumi Nagata, KY
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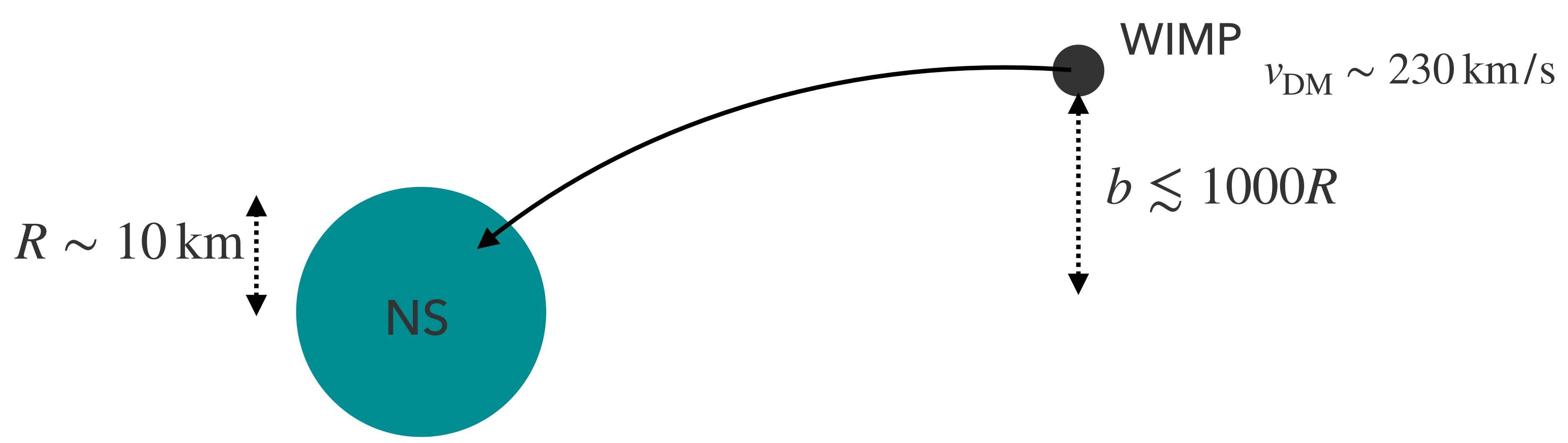
Introduction

Dark matters accrete in neutron stars

We can probe the WIMP DM signature in Neutron stars [Kouvaris, 0708.2362]

- WIMPs accrete in NS by gravity
- If $\sigma_n \gtrsim 10^{-45}\,\mathrm{cm}^2$, they lose kinetic energy by scattering with nucleons, and trapped by the NS



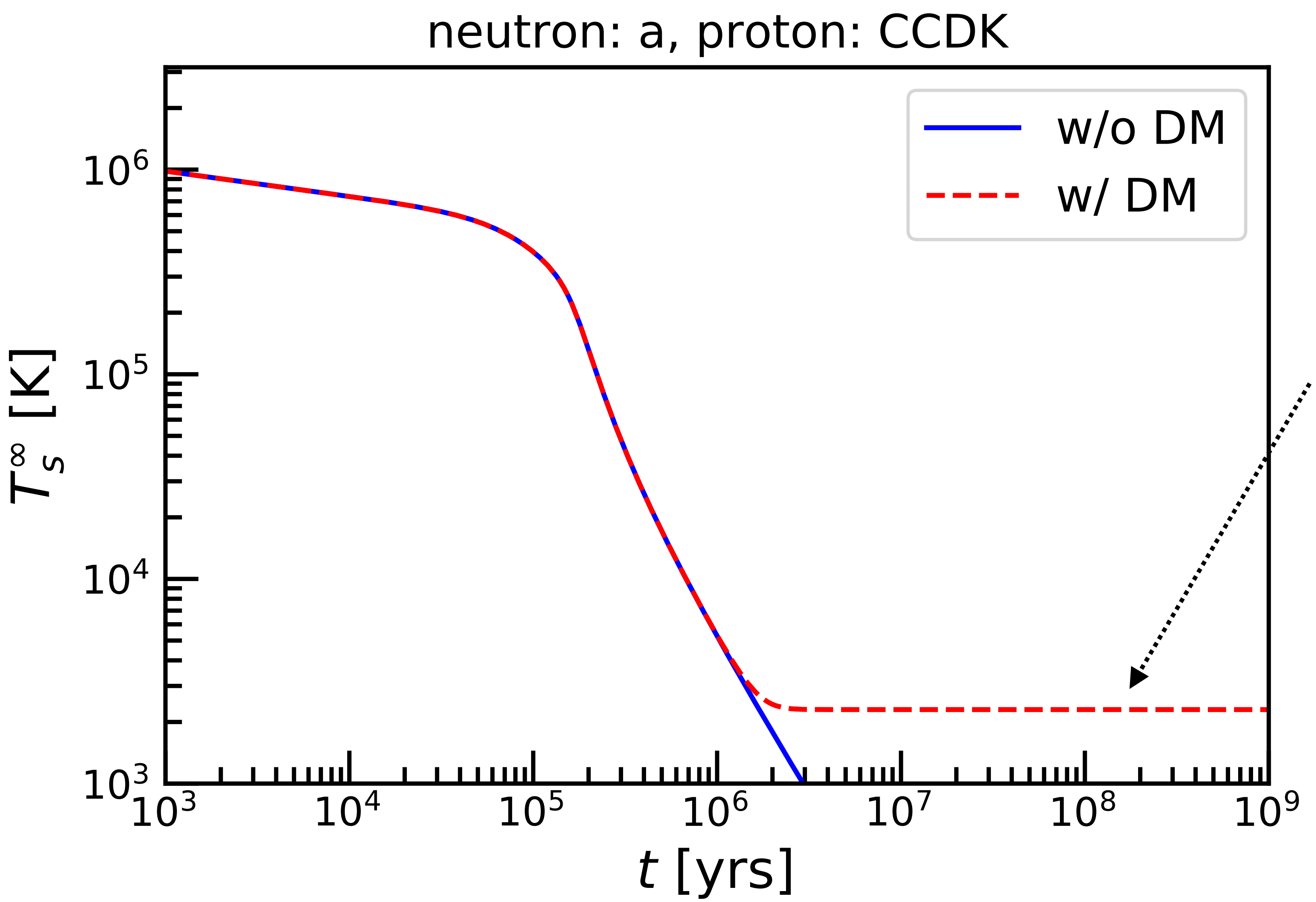
DM kinetic/mass energy → **Heat in a NS**

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

Prediction of dark matter heating

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

[Kouvaris, 0708.2362 ;Baryakhtar+, 1704.01577]



Balance between photon emission and DM heating

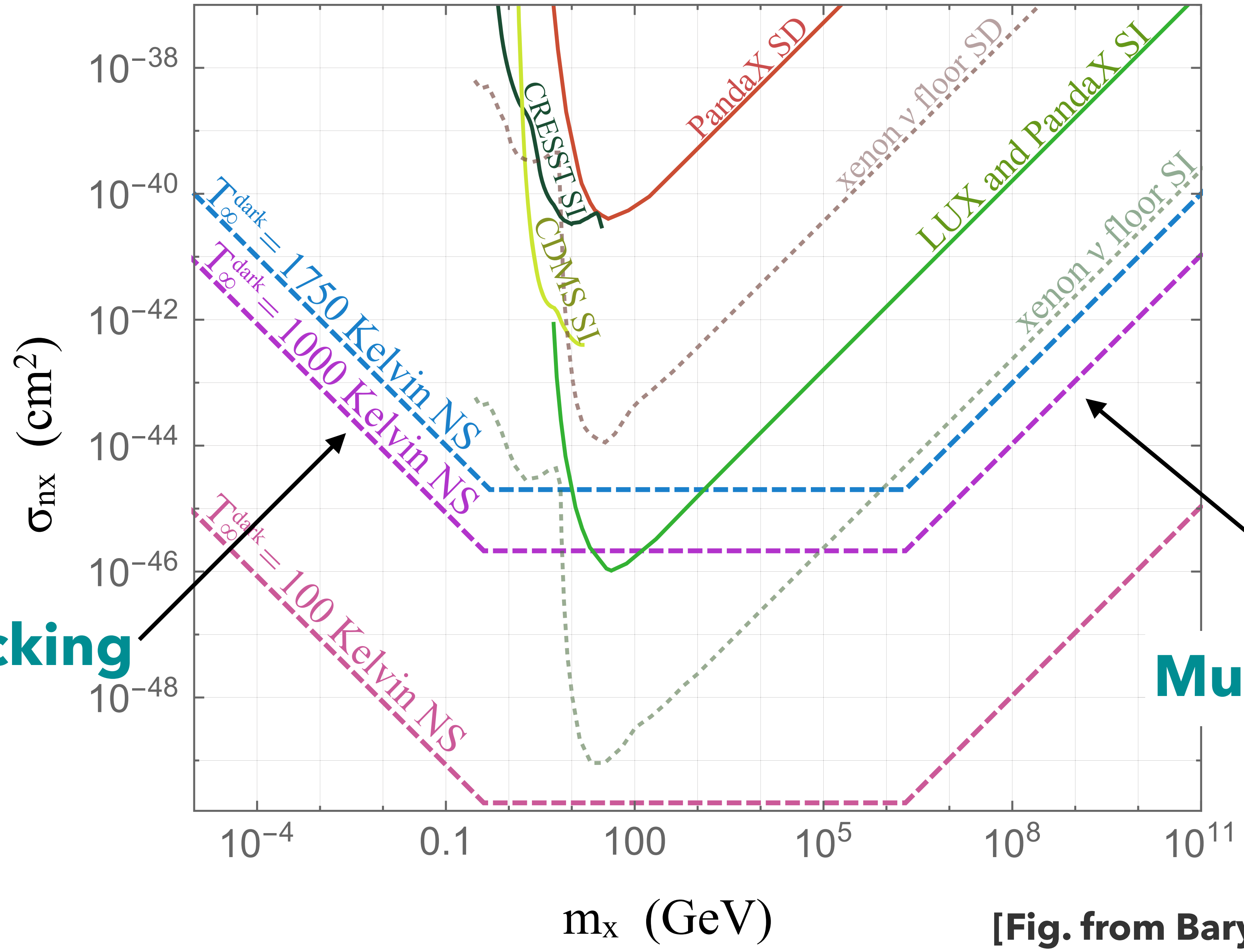
$$\Rightarrow 4\pi R^2 \sigma_B T_s^4 = 2\pi G M R \rho_{\mathrm{DM}} / v_{\mathrm{DM}}$$

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

Prospects

Constraints on DM-neutron cross section

Particularly sensitive to 1 GeV - 1 PeV



Pauli blocking

Multiple scattering

[Fig. from Baryakhtar+, 1704.01577]

Advantages over the terrestrial experiments

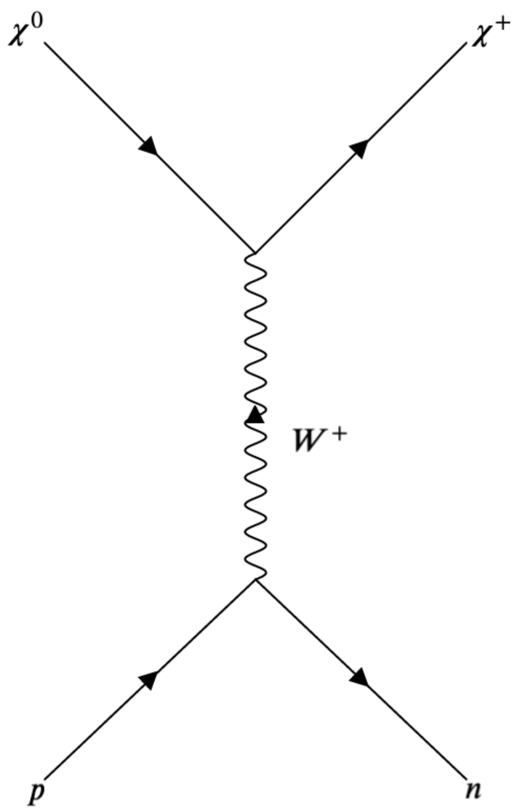
- Velocity on the surface of a typical NS ($M = 1.4\,M_\odot$ and $R = 10\,\mathrm{km}$)

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

- **Inelastic scattering** of electroweak DM (pure $\tilde{H}$, $\tilde{W}$, ...)

$$\Delta E = \frac{m_n m_\chi^2 \gamma^2}{m_n^2 + m_\chi^2 + 2\gamma m_n m_\chi} v_{\rm esc}^2 (1 - \cos\theta_{\rm CM}) \sim \mathcal{O}(1)\,\mathrm{GeV}$$

c.f. $\Delta E \sim 100\,\mathrm{keV}$ on the earth



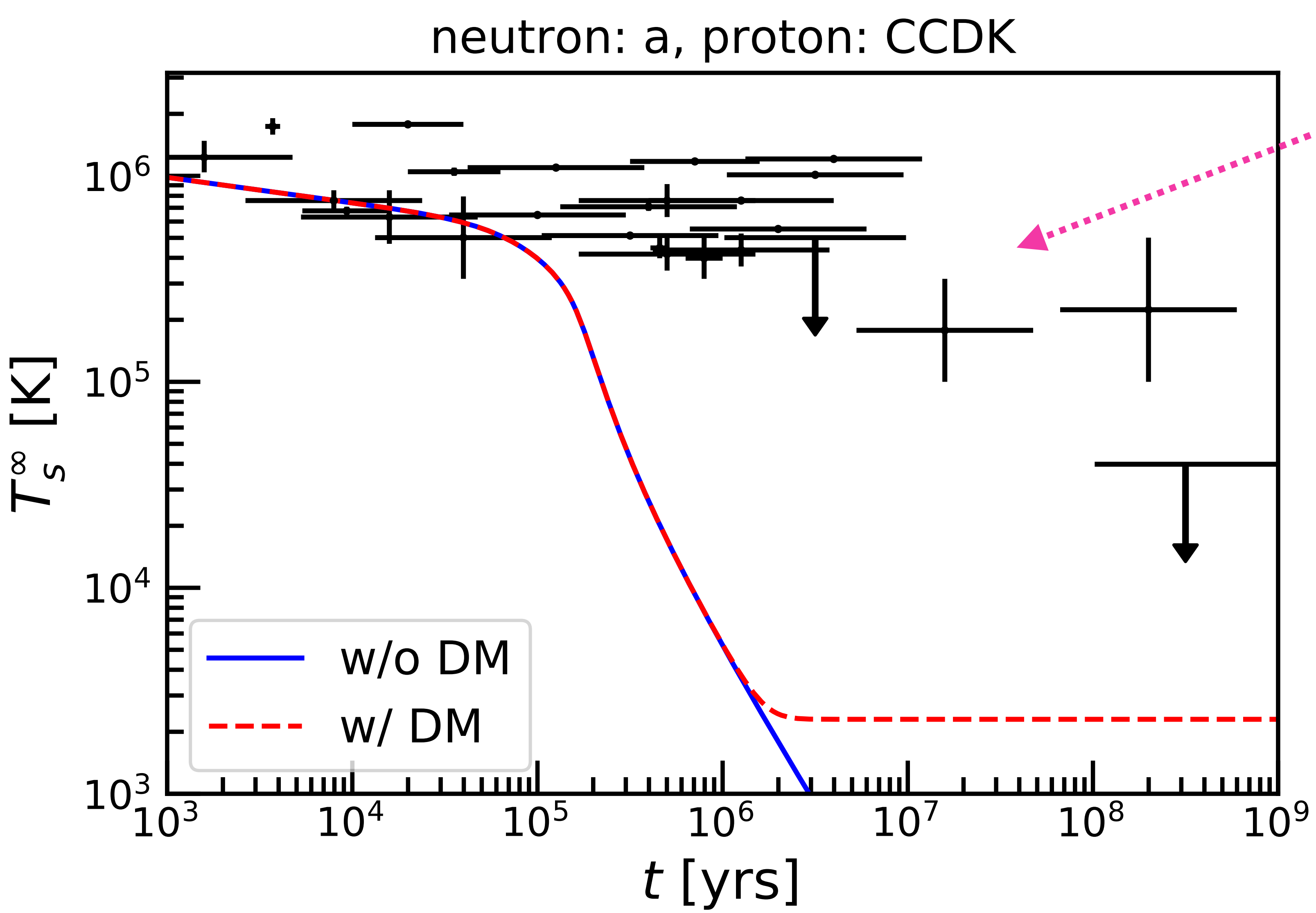
- Velocity suppressed scattering
- Spin-dependent scattering

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

Can we really see DM heating?

The observation suggests presence of other heating mechanisms

These effects are overlooked in the previous studies of DM heating



Hotter than theory prediction even if DM is included

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

Theory of NS cooling/heating

Standard theory of NS cooling

Thermal evolution equation

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

Heat capacity (n, p, e, μ)

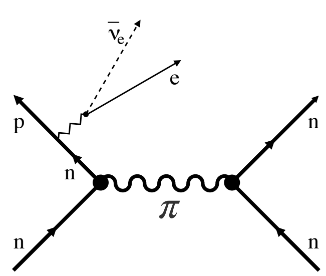
Surface photon luminosity: $L_\gamma = 4\pi R^2 \sigma_B T_s^4$

Neutrino luminosity L_ν

- Modified Urca process

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

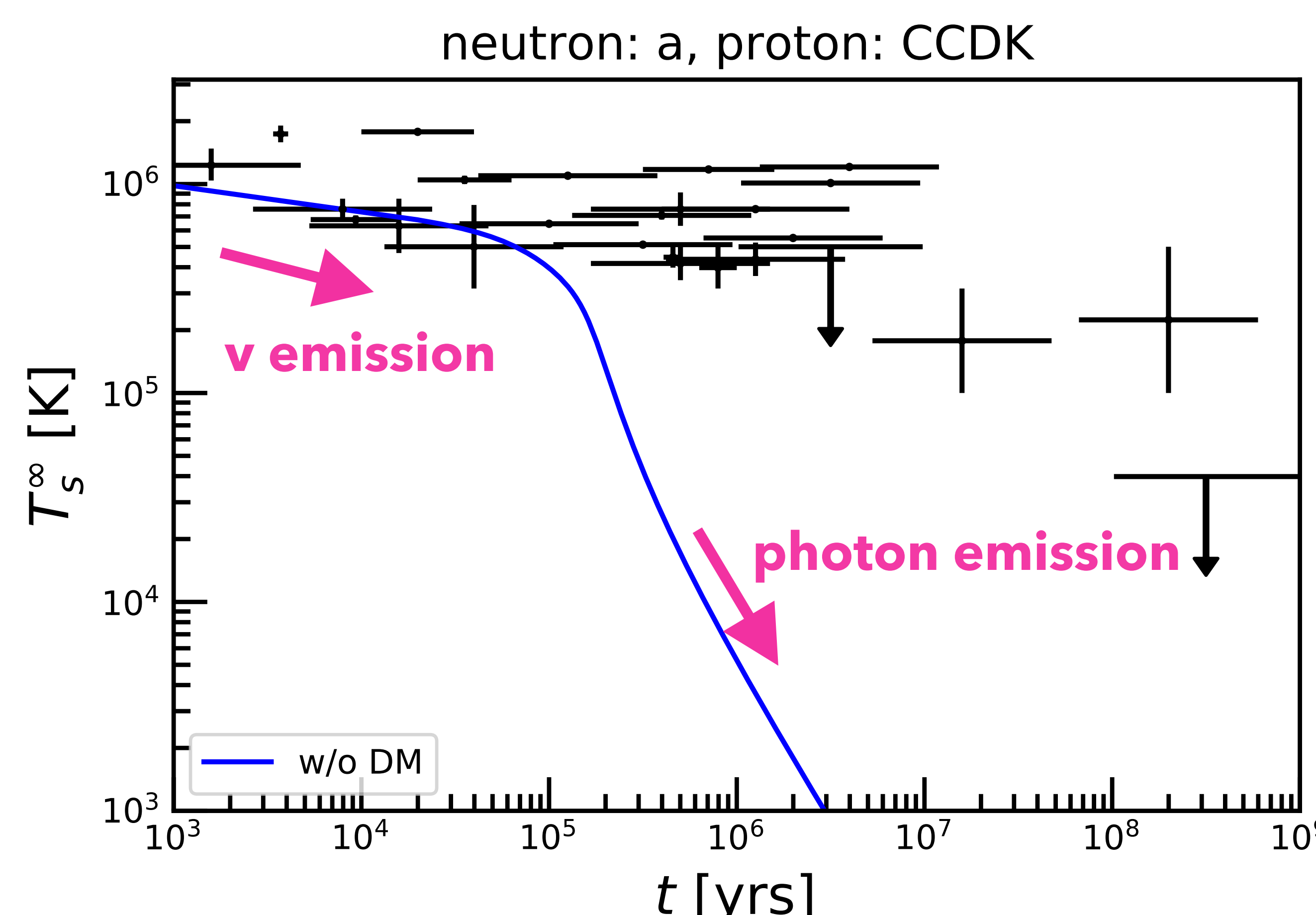
$N = n, p\,;\ell = e, \mu$



- Cooper pair breaking and formation

$[\tilde{N}\tilde{N}] \to \tilde{N}\tilde{N} \quad \tilde{N}\tilde{N} \to [\tilde{N}\tilde{N}] + \nu\bar{\nu}$

+ minor processes…



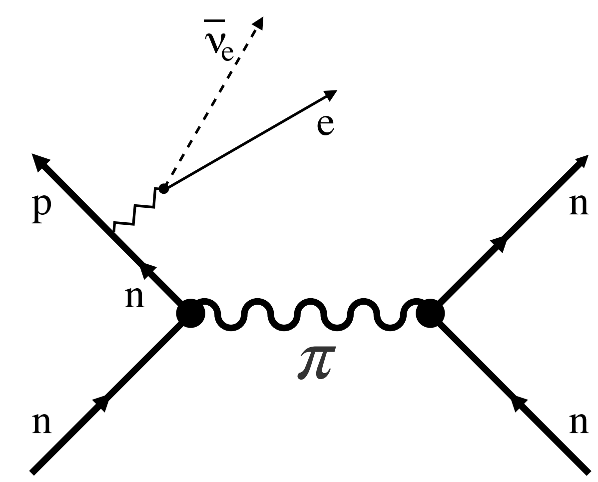
Any loophole?

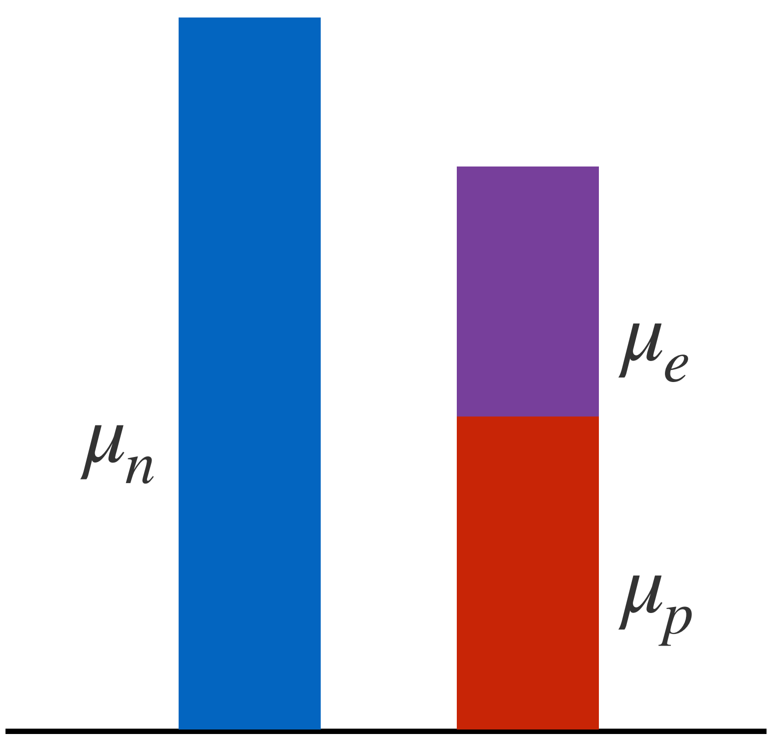
Assumption of β-equilibrium

Conventional assumption: matters are in **β-equilibrium** by weak interaction

$$\Gamma_{n\to p+\ell} = \Gamma_{p+\ell\to n}$$

Modified Urca process tries to maintain β-equilibrium

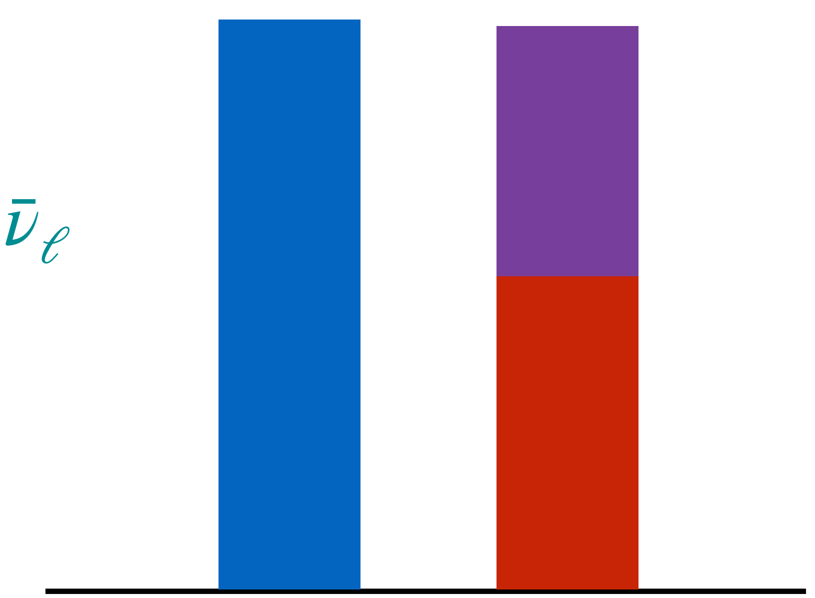




$$\mu_n \neq \mu_p + \mu_e$$

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

equilibration



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

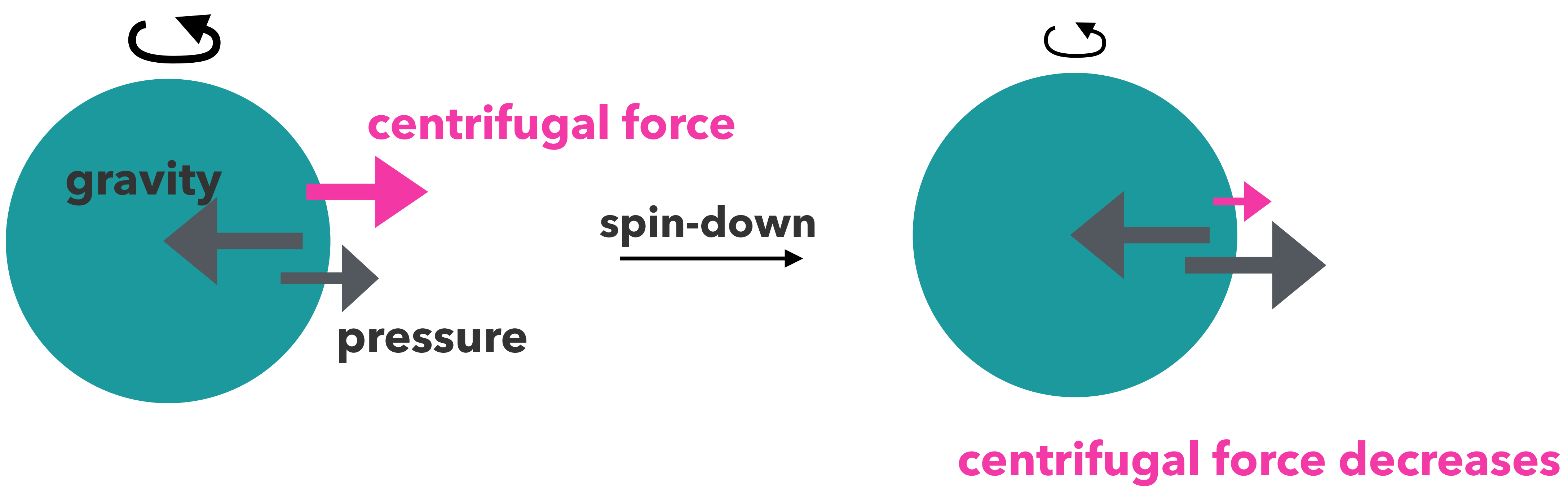
Pulsar spin-down

NS spin-down violates β-equilibrium assumption

The rotation of actual pulsar is slowing down (spin-down)

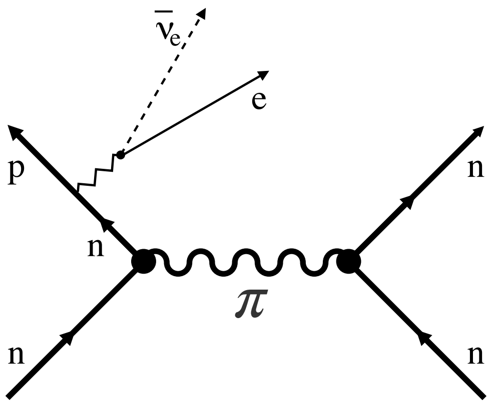
- Continuous decrease of centrifugal force
  → change of equilibrium condition
  → **β-equilibrium is broken**

$$\Gamma_{n\to p+\ell} \neq \Gamma_{p+\ell\to n}$$



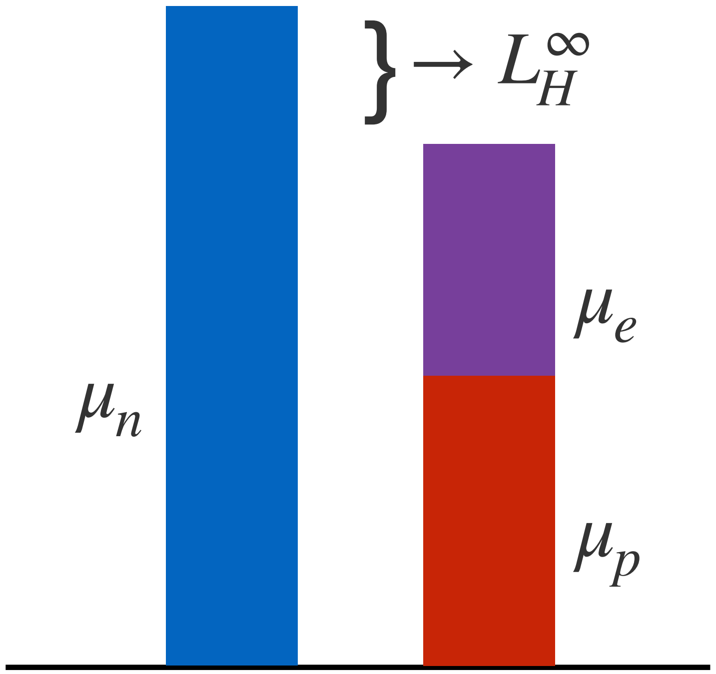
Rotochemical heating

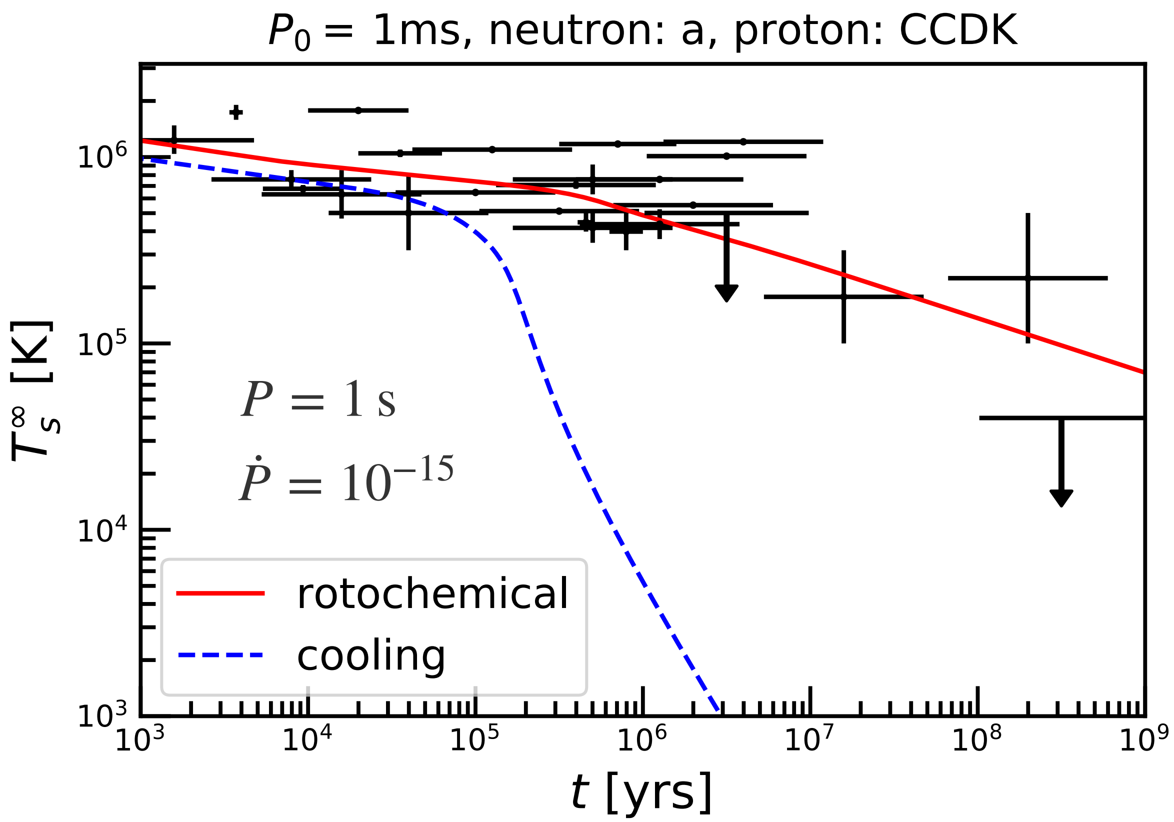
In **non-equilibrium** modified Urca process, imbalance between chemical potentials is converted to heat [Reisenegger, astro-ph/9410035]



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

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





Consistent with the observations w/o any exotic physics

DM heating vs. rotochemical heating

DM heating vs. rotochemical heating

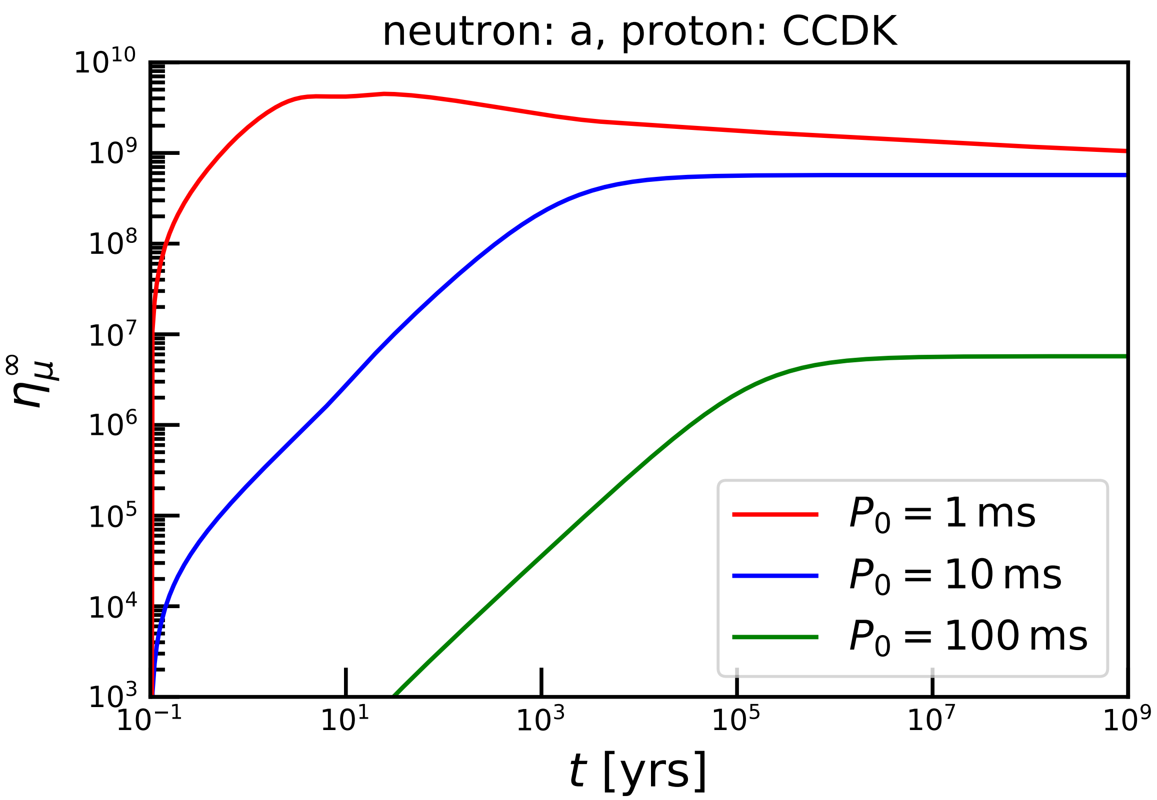
DM heating

- $T_s \sim 3000\,\mathrm{K}$
- 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

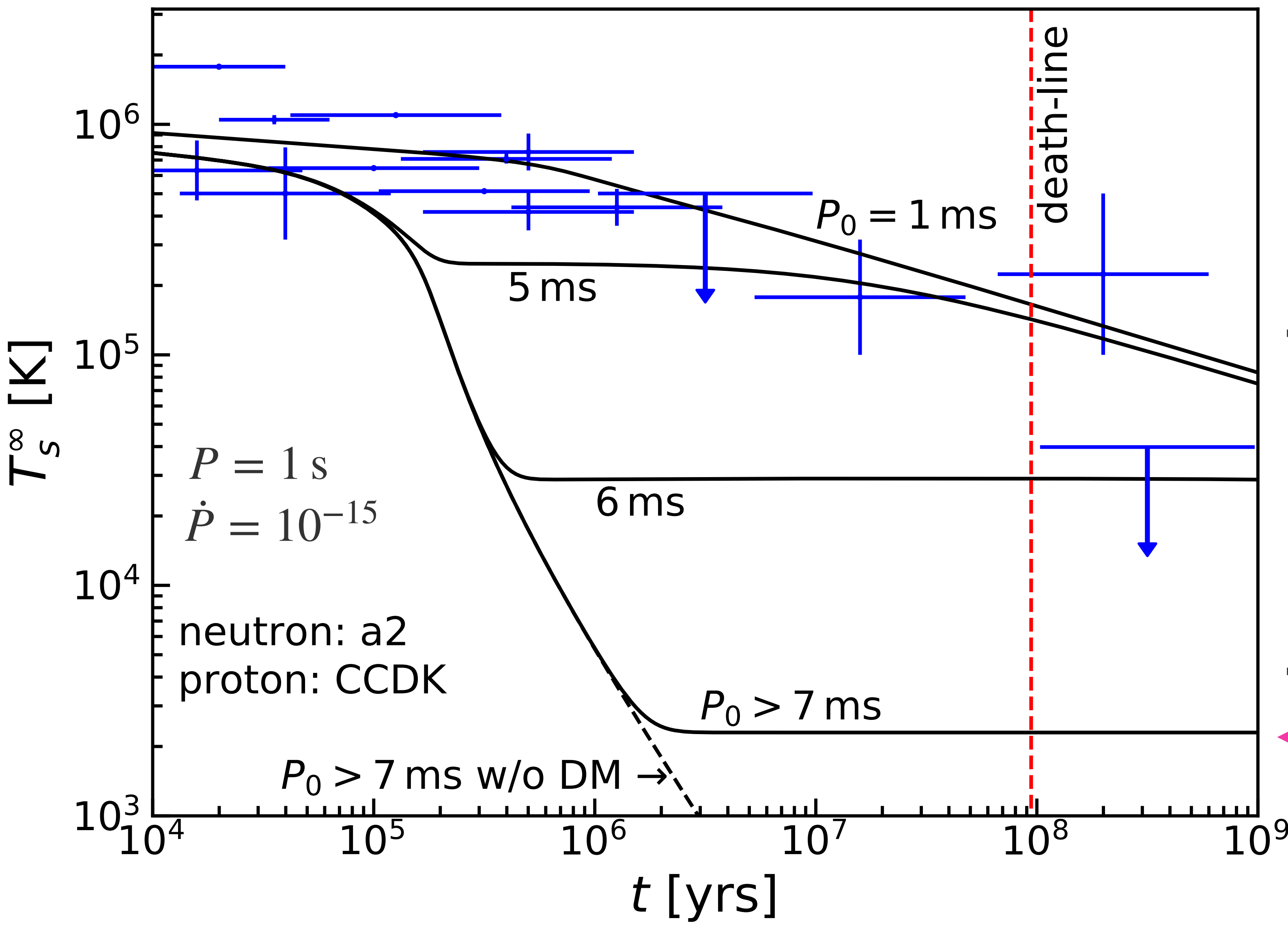
$$\eta_\ell = \mu_n - \mu_p - \mu_\ell$$



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

DM heating vs. rotochemical heating

Numerical simulation including both DM and 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

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

Initial period

Several studies suggest that typically, $P_0 \sim \mathcal{O}(10 - 100)\,\mathrm{ms}$

- 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

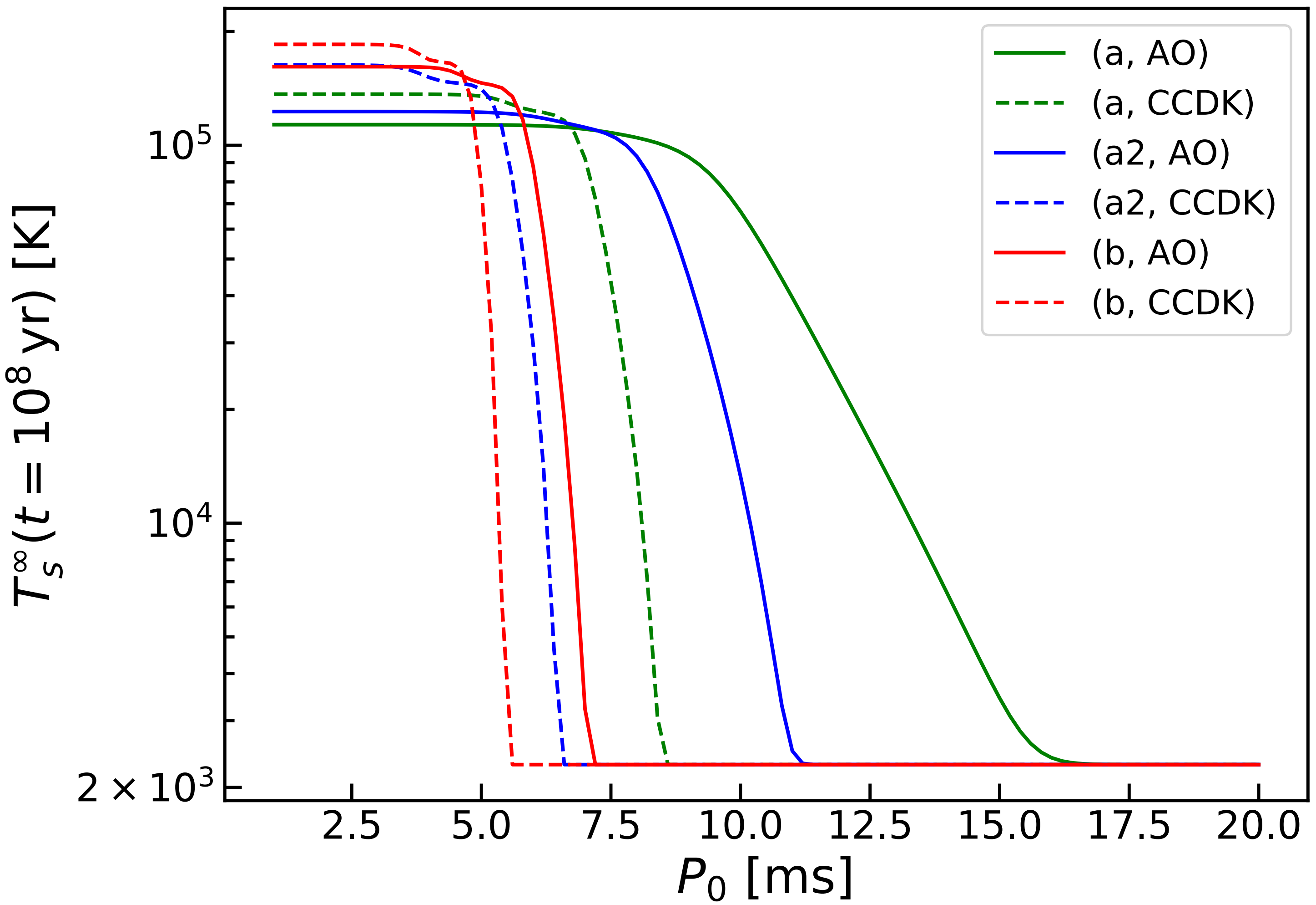
- DM heating predicts $T_s \sim 3000\,\mathrm{K}$ for old NSs
- It can constrain WIMP models which are difficult to probe on the earth
- However, rotochemical heating, inherent in pulsars, can be much stronger than DM heating
- We show that DM heating is theoretically visible even if rotochemical heating operates

Backup

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)