Dark Matter Heating
vs.
Rotochemical Heating
in Old Neutron Stars

Koichi Hamaguchi (University of Tokyo)

Summer Institute 2019 @SANDPINE, Gangneung, August 22, 2019

Based on

KH, N. Nagata, K. Yanagi, [arXiv:1905.02991] Phys.Lett. B795 (2019) 484

K. Yanagi, N. Nagata, KH, [arXiv:1904.04667]

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See also the **talk by Jiaming Zheng** tonight.

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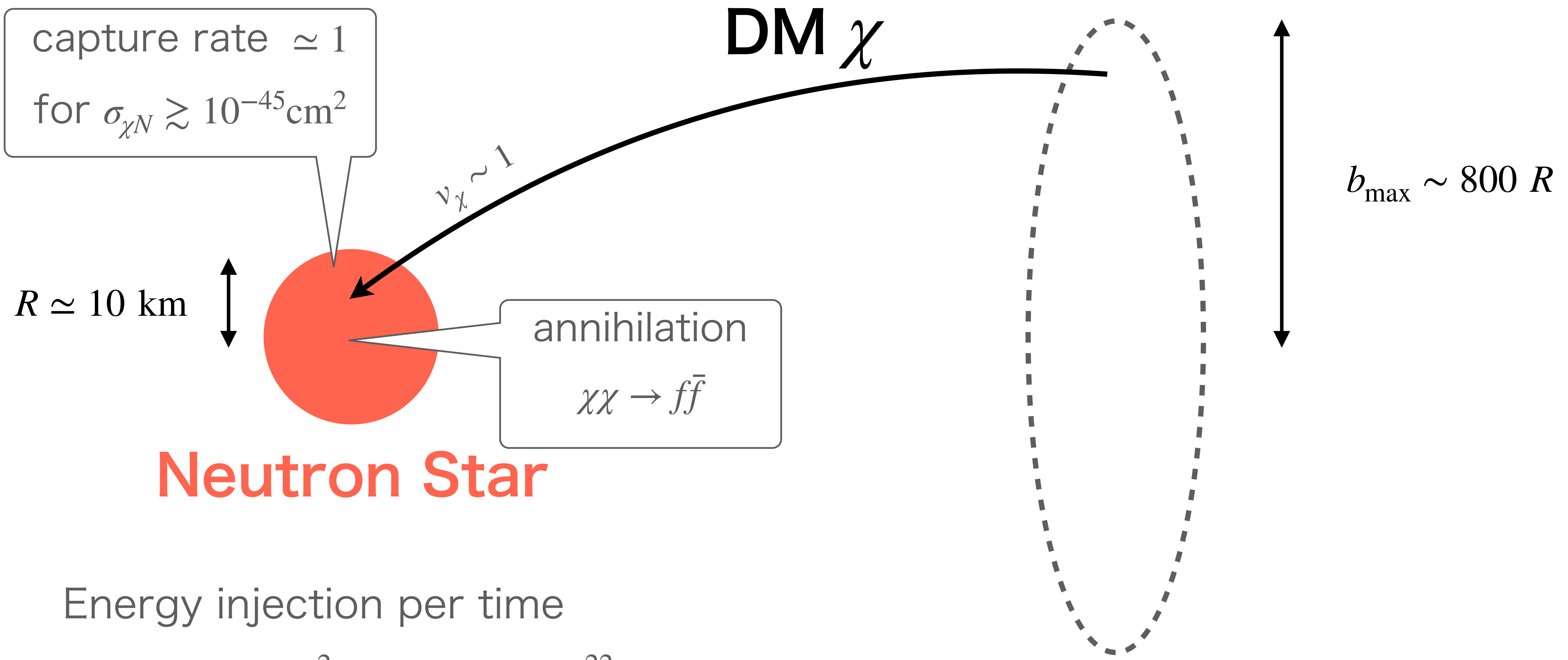
Introduction (outline)

1. WIMP DMs hit a neutron star (NS), and annihilate inside the NS.

[C. Kouvaris, 0708.2362]



DM χ

capture rate $\simeq 1$

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

$v_\chi \sim 1$

$R \simeq 10$ km

$b_{\max} \sim 800\ R$

annihilation

$\chi\chi \to f\bar{f}$

Neutron Star

Energy injection per time

$L_{\mathrm{WIMP}\to NS} \sim \pi b_{\max}^2 \rho_\chi v_\chi \simeq 3 \times 10^{22}\mathrm{erg/s}$

(independent of DM mass) → **DM heats NS !**

Introduction (outline)

1. WIMP DMs hit a neutron star (NS), and annihilate inside the NS.
2. **Old and warm ($\sim 2000K$) NS = DM signal?!**

C. Kouvaris 0708.2362,
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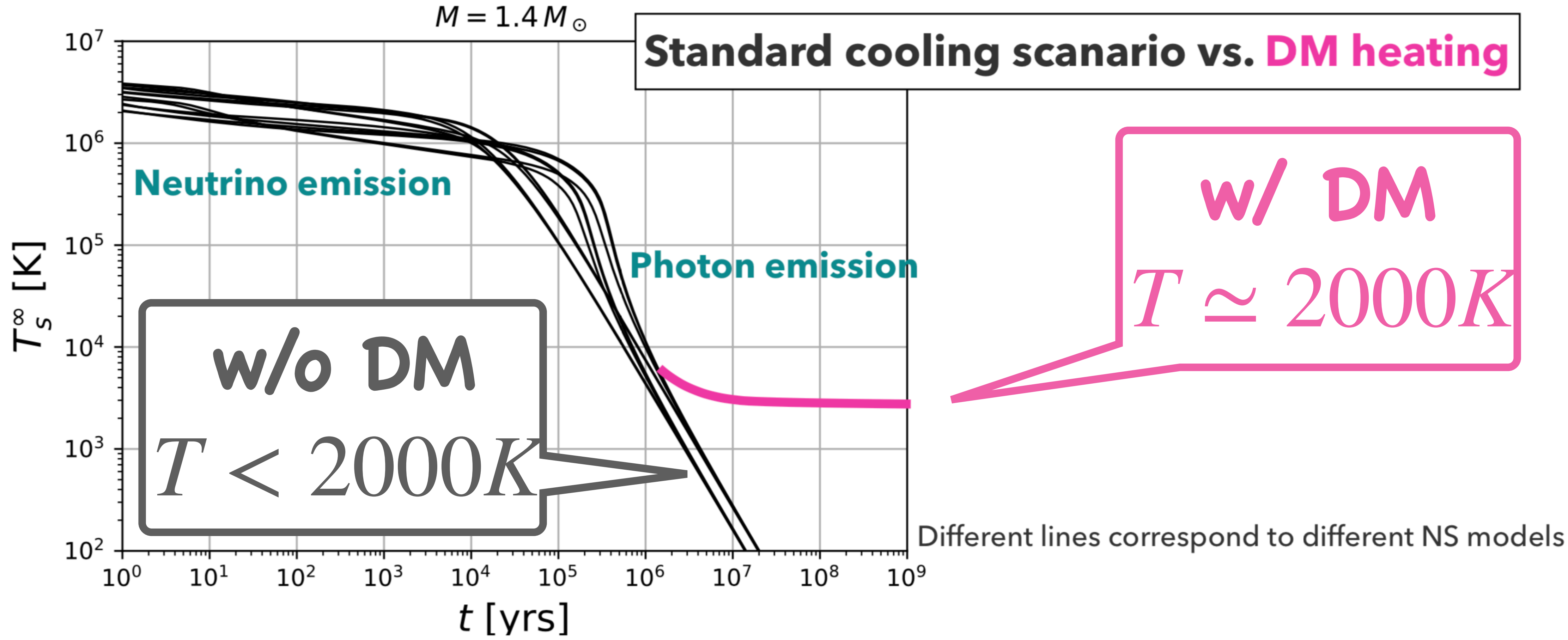
Fig. by K.Yanagi.



Standard cooling scanario vs. DM heating

Neutrino emission

Photon emission

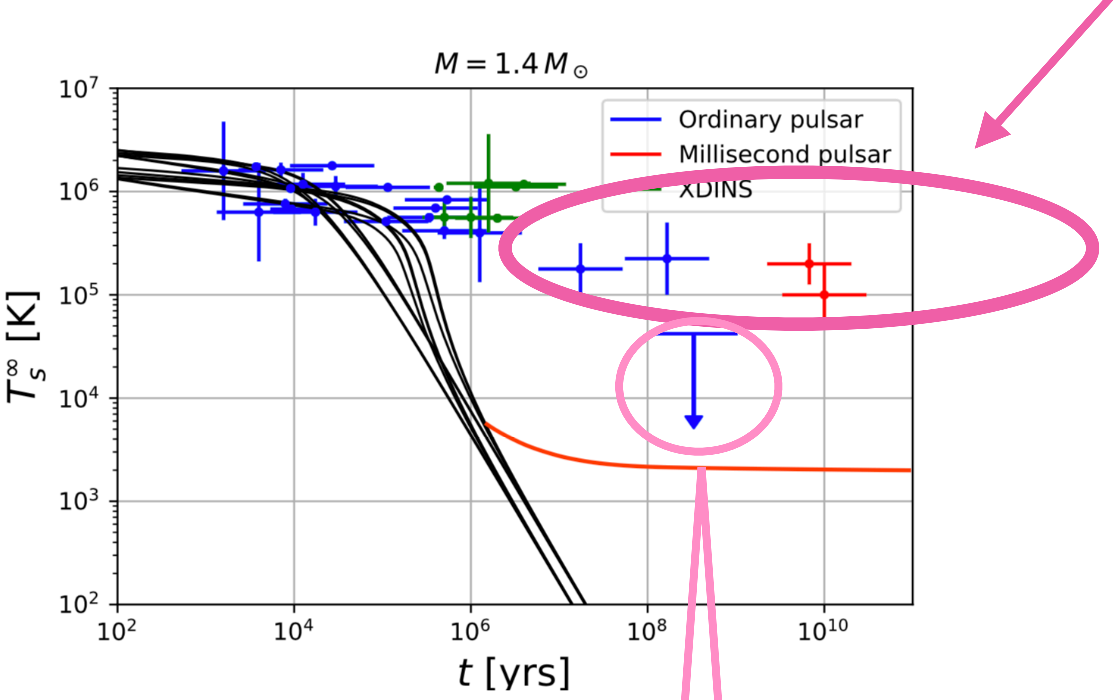
w/o DM
$T < 2000K$

w/ DM
$T \simeq 2000K$

Different lines correspond to different NS models

Introduction (outline)

1. WIMP DMs hit a neutron star (NS), and annihilate inside the NS.
2. **Old and warm** ($\sim 2000K$) **NS = DM signal?!**
3. **But…** old and warmer ($T \gg 2000K$) NSs are already observed!



There are also cooler ones.

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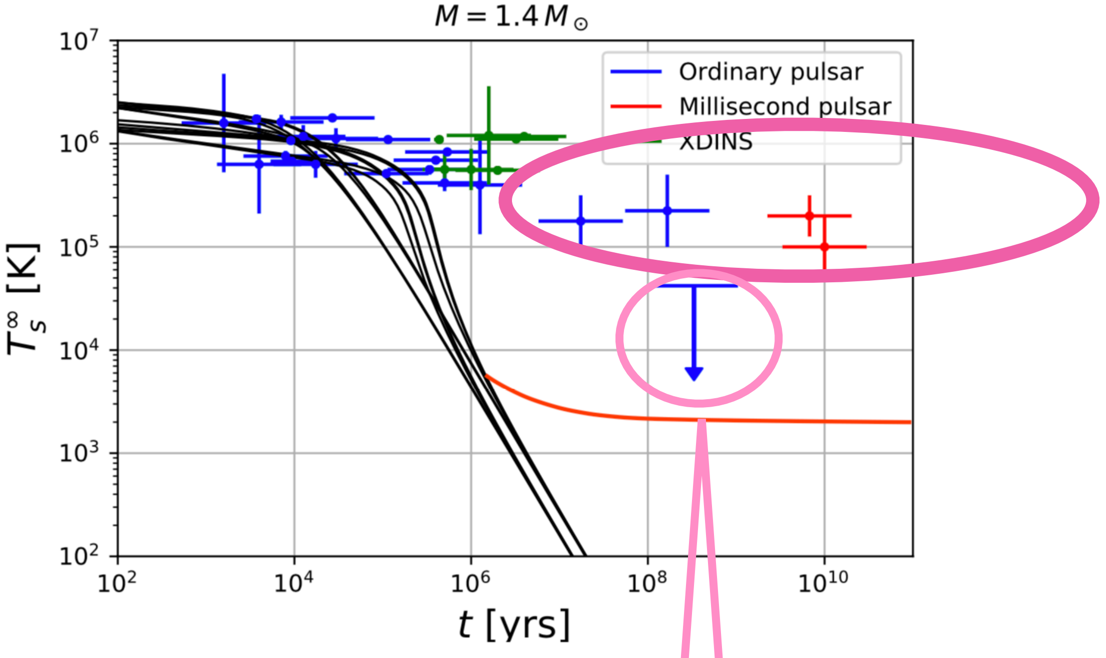
In addition, a mechanism inherent in NS (“rotochemical heating”) can explain them.



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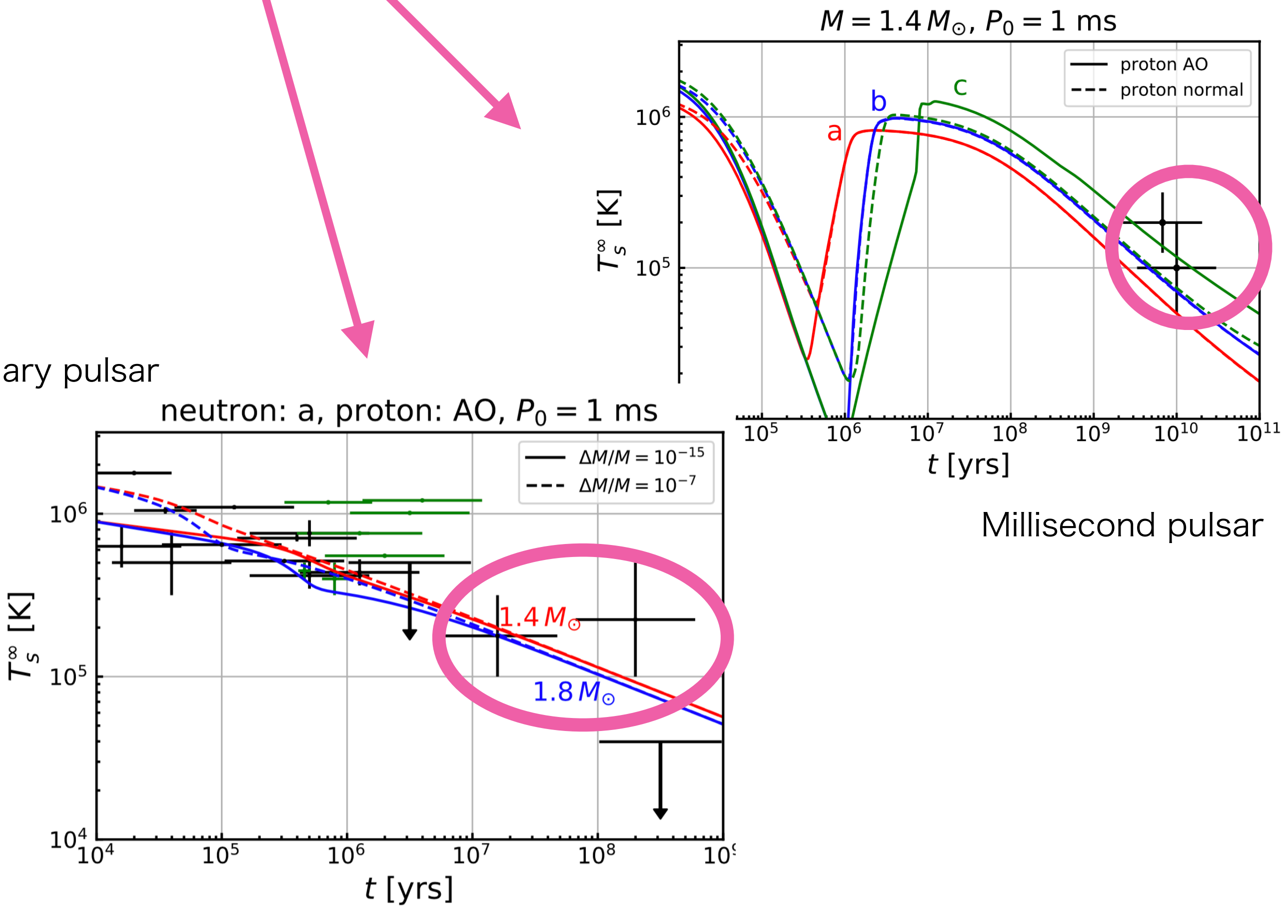

Ordinary pulsar

Millisecond pulsar

Reisengger,’94, Haensel,’92, Gourgoulhon, Haensel,’93, Fernandez, Reisenegger,’05,…… **Yanagi, Nagata, KH, 1904.04667**

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   In addition, a mechanism inherent in NS ("rotochemical heating") can explain them.

4. Question:

Can we really see the signal of the DM heating?
If so, what is the condition for that?

Plan

0. Introduction

1. $C\dfrac{dT}{dt} = -L_\nu - L_\gamma$

2. $C\dfrac{dT}{dt} = -L_\nu - L_\gamma + L_{\text{DM}}^{\text{heat}}$

3. $C\dfrac{dT}{dt} = -L_\nu - L_\gamma + L_{\text{rotochemical}}^{\text{heat}}$

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5. Summary

Plan

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1. $C\frac{dT}{dt} = -L_\nu - L_\gamma$ **NS Cooling**

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Our works

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1. NS Cooling

For reviews, e.g., D.G.Yakovlev+, astro-ph/0402143,
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LHS = Temperature Evolution.

$C = \frac{dE_{thermal}}{dT}$ (heat capacity)

$C = C_n + C_p + C_e + C_\mu$

RHS = Cooling Luminosity.

$-L = \frac{dE_{thermal}}{dt}$

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

dominant process at late time

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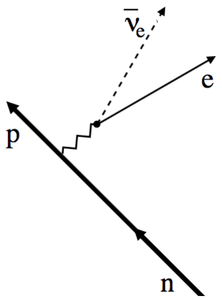
Neutrino emission

- Direct Urca



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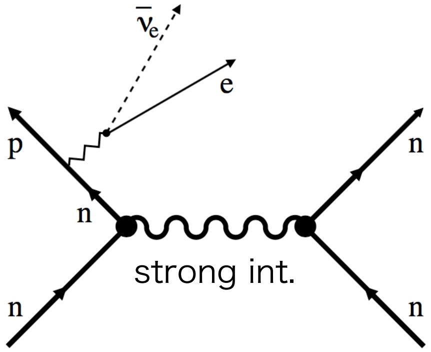
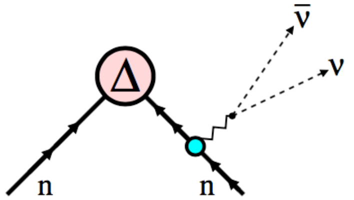


- PBF



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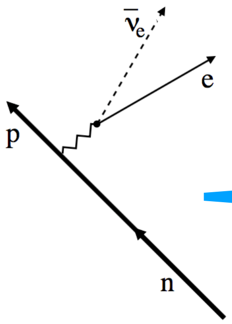

β decay and its inverse: $\begin{cases} n \to p + e^- + \bar{\nu}_e \\ p + e^- \to n + \nu_e \end{cases}$

It does **NOT** work in typical NS because $p_p + p_e < p_n$.

Discarded in "minimal cooling" scenario.
D.Page+, astro-ph/0403657,
M.E.Gusakov+, astro-ph/0404002,
D.Page+, 0906.1621

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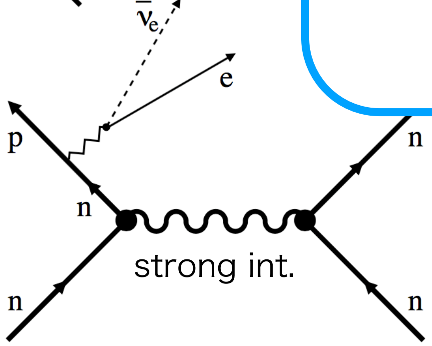

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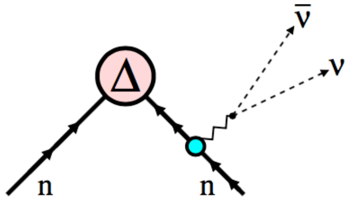
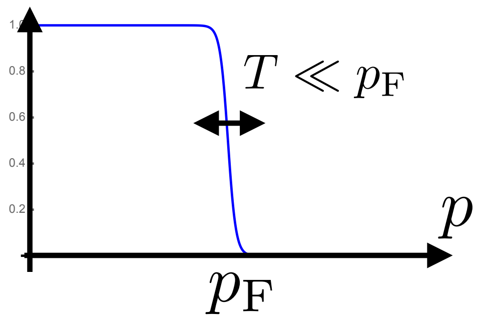


※ Neutron, proton, electron
are all **Fermi degenerate.**



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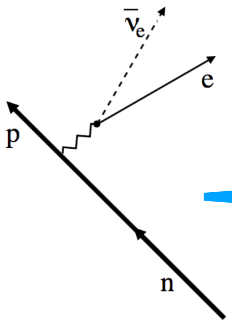

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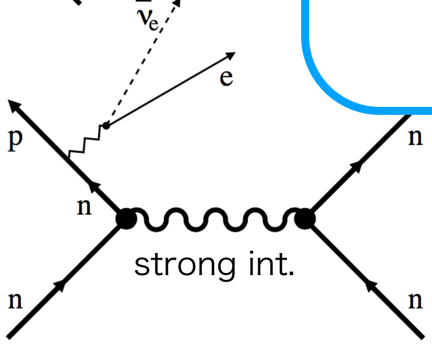

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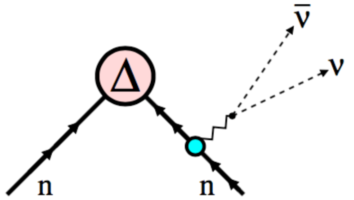

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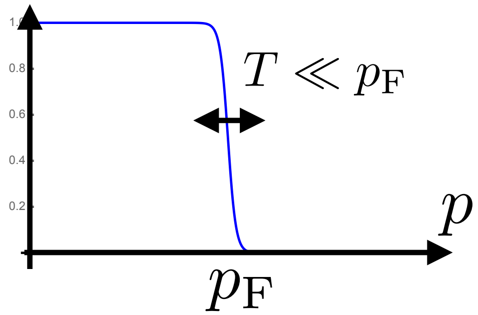

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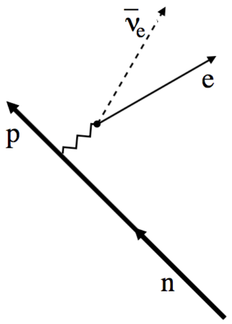

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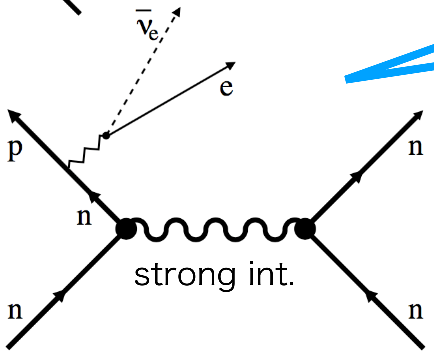

$$\begin{cases} n + N \to p + e^- + N + \bar{\nu}_e \\ p + N + e^- \to n + N + \nu_e \end{cases} \quad (N = p \ or \ n)$$

dominant process for $T > T_c$

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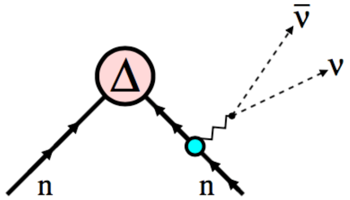

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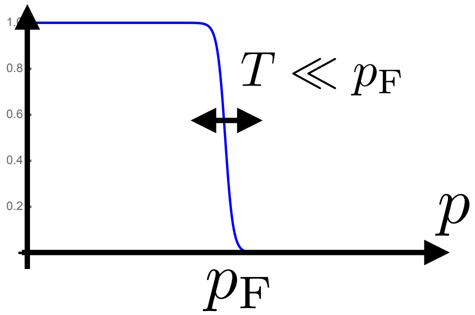

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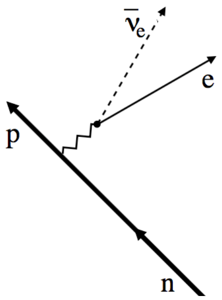

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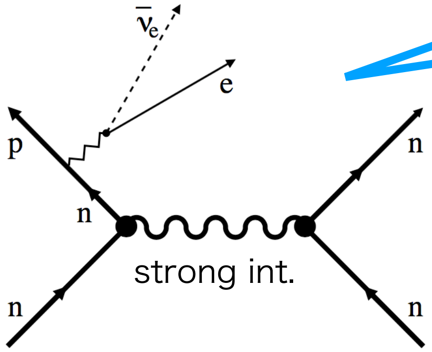

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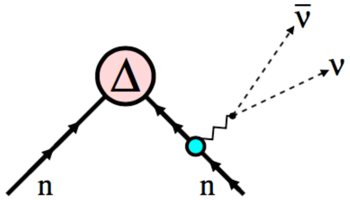

PBF (Cooper-pair breaking and formation)

$$\begin{cases} [\tilde{N}\tilde{N}] \to \tilde{N} + \tilde{N} \\ \tilde{N} + \tilde{N} \to [\tilde{N}\tilde{N}] + \nu + \bar{\nu} \end{cases} \quad (\tilde{N} : \text{quasi-paticle}, [\tilde{N}\tilde{N}] : \text{Cooper-pair})$$

Important for $T < T_c$.

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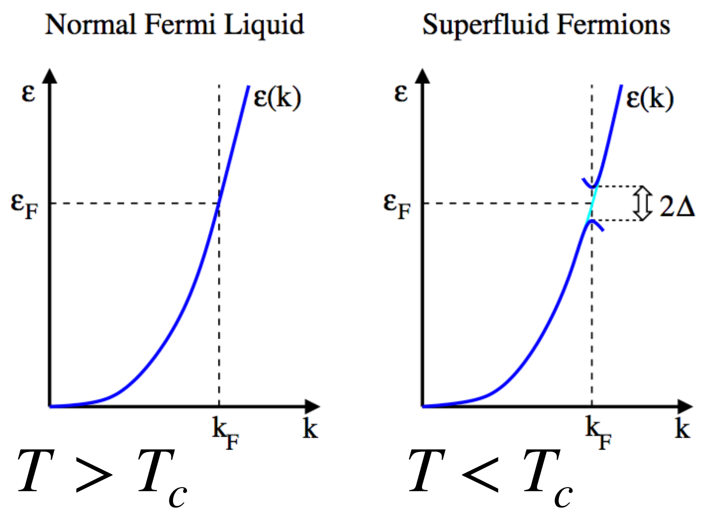
dominant process at late time

Neutrino emission

Superfuidity (pairing) plays important roles.

At $T < T_c$ **, Cooper pairing** (p-p and n-n) **occurs.**

- Heat capacity C is suppressed.
- M.Urca luminosity $L_{\nu,MU}$ is suppressed.
- PBF occurs at $T < T_c$.
- It is also important for the "rotochecmical heating" (see below).



$T > T_c$ $T < T_c$

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The minimal cooling scenario can explain many NS temperature observations.

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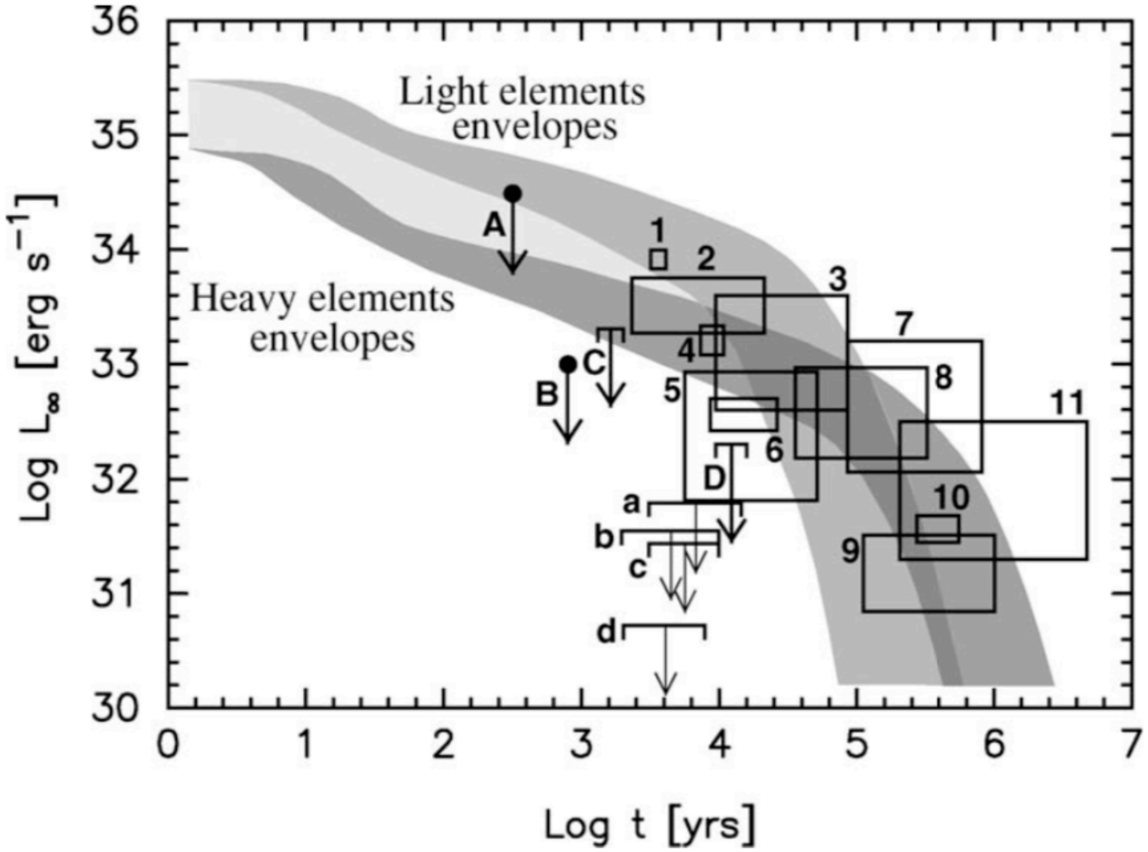
D. Page et al. / Nuclear Physics A 777 (2006) 497–530



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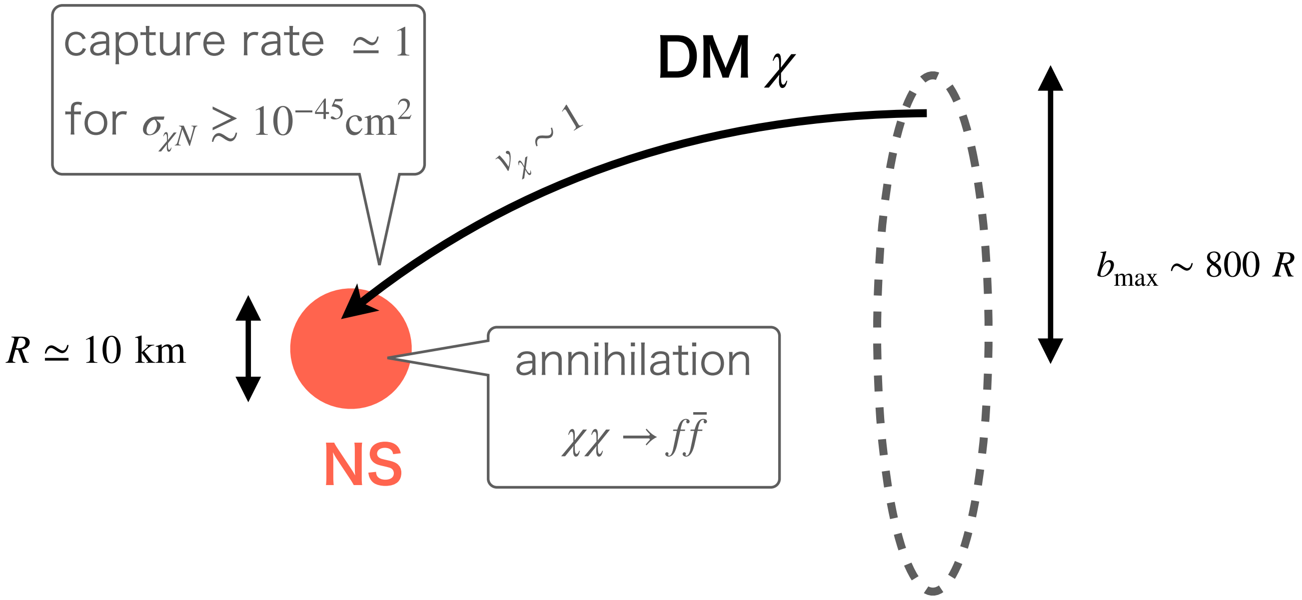

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DM χ

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$b_{\mathrm{max}} \sim 800\ R$

$R \simeq 10$ km

NS

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$\chi\chi \to f\bar{f}$

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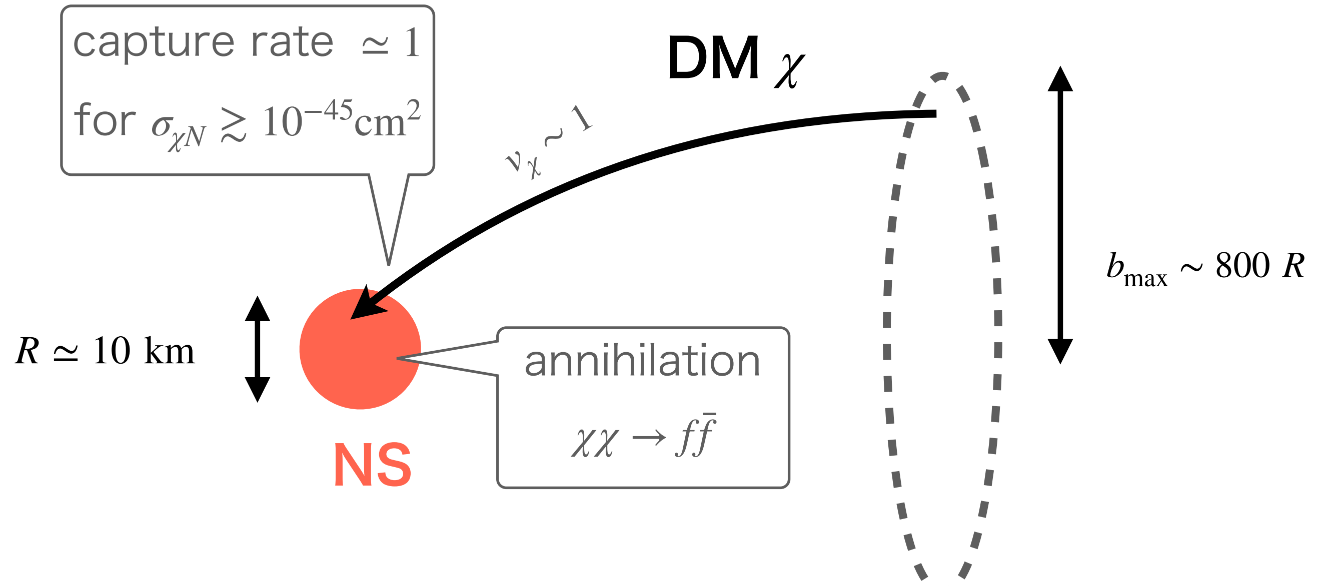

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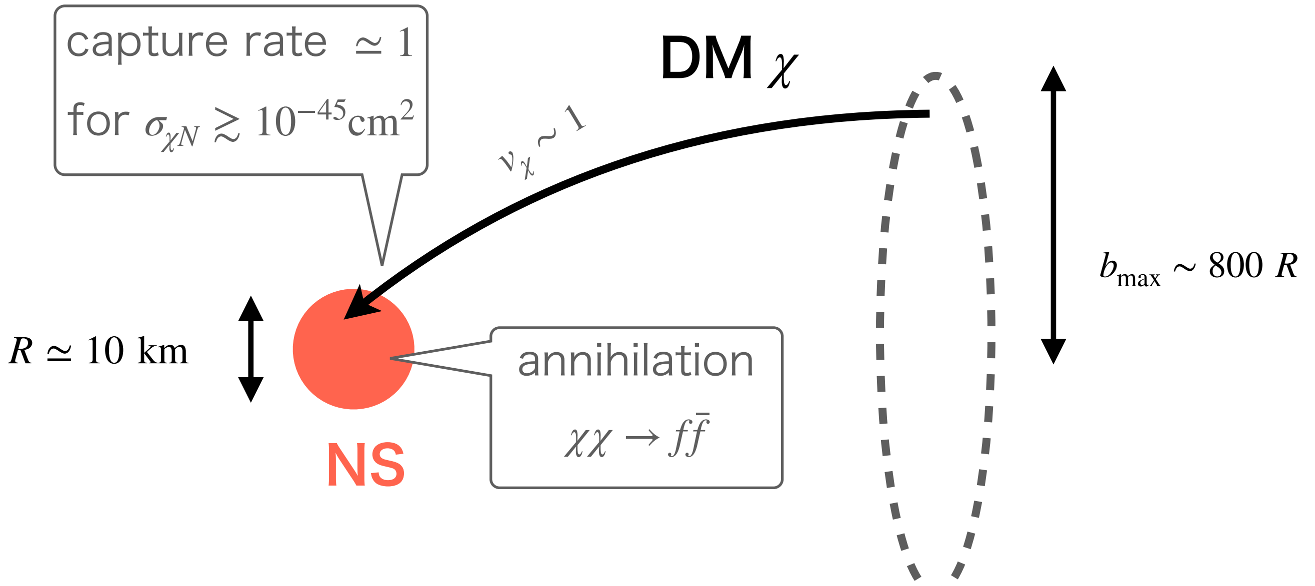
R. Garani+ 1906.10145



capture rate $\simeq 1$
for $\sigma_{\chi N} \gtrsim 10^{-45}\mathrm{cm}^2$

DM χ

$v_\chi \sim 1$

$b_{\max} \sim 800\ R$

$R \simeq 10$ km

NS

annihilation
$\chi\chi \to f\bar{f}$

$$\boxed{C\frac{dT}{dt} = -L_\nu - L_\gamma + L_{\mathrm{DM}}^{\mathrm{heat}}}$$

Photon emission

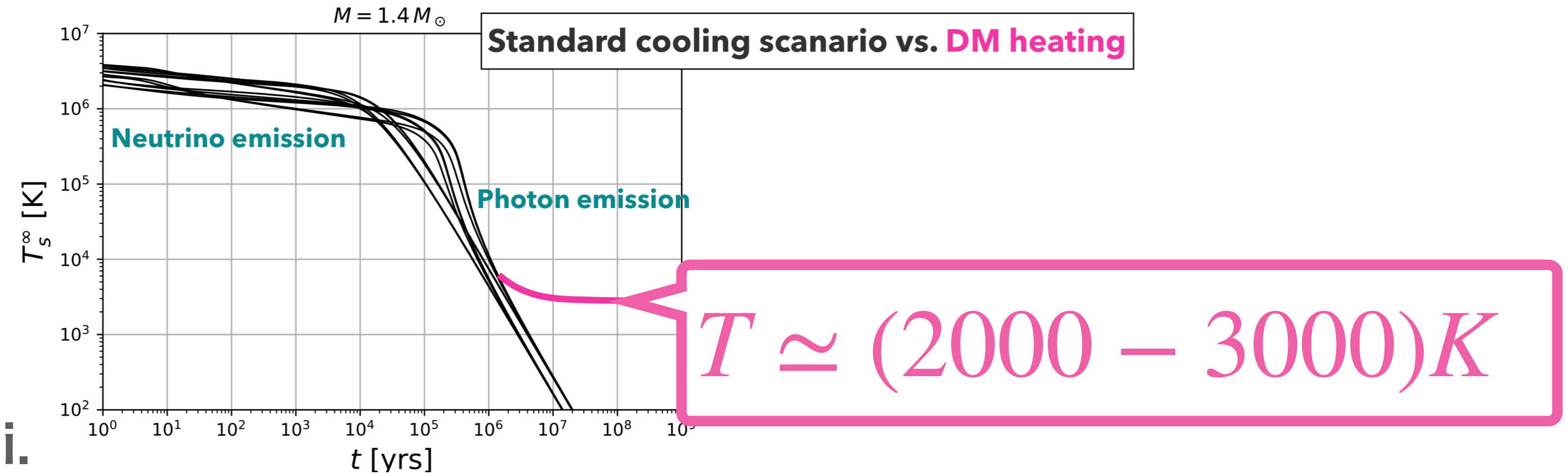
$$L_\gamma = 4\pi R^2 \sigma_{SB} T_s^4$$

dominant process at late time

DM heating

$$L_{\mathrm{DM}}^{\mathrm{heat}} \sim \pi b_{\max}^2 \rho_\chi v_\chi \simeq 3 \times 10^{22} \mathrm{erg/s}$$

independent of the DM mass



$$T \simeq (2000 - 3000)K$$

Fig. by K.Yanagi.

2. NS Heating by DM

C. Kouvaris 0708.2362,
G. Bertone+ 0709.1485,
C. Kouvaris+ 1004.0586,
A. de Lavallaz+ 1004.0629
+ many recent works:
e.g., J. Bramante+ 1703.04043
M. Baryakhtar+ 1704.01577
N. Raj+ 1707.09442
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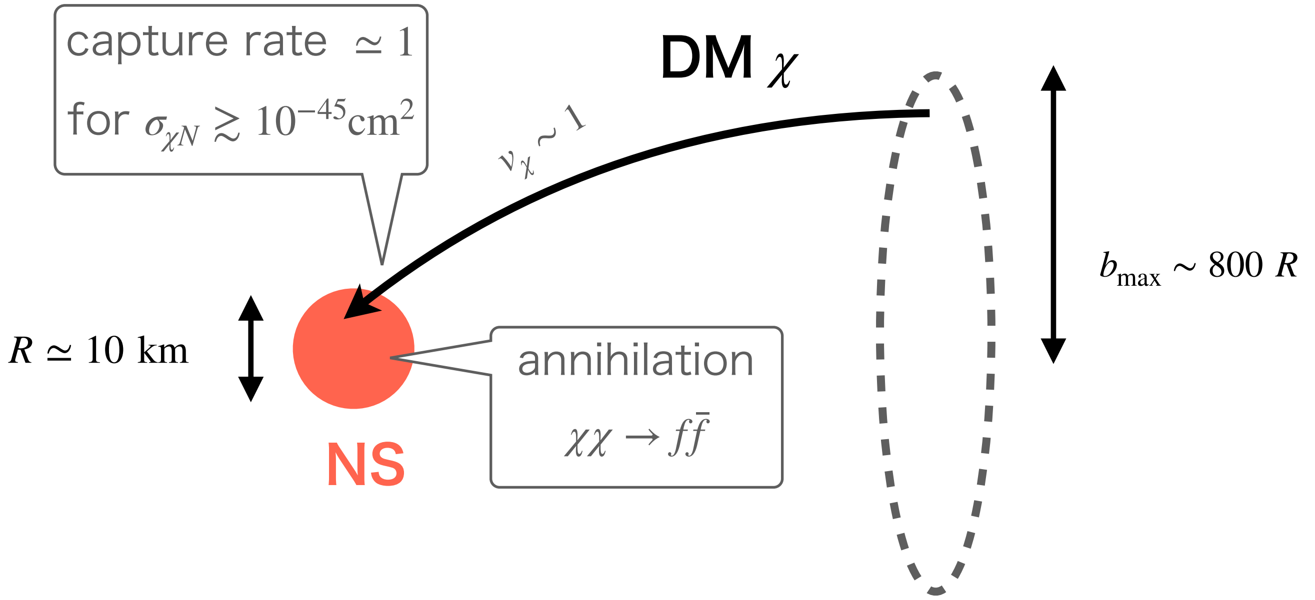


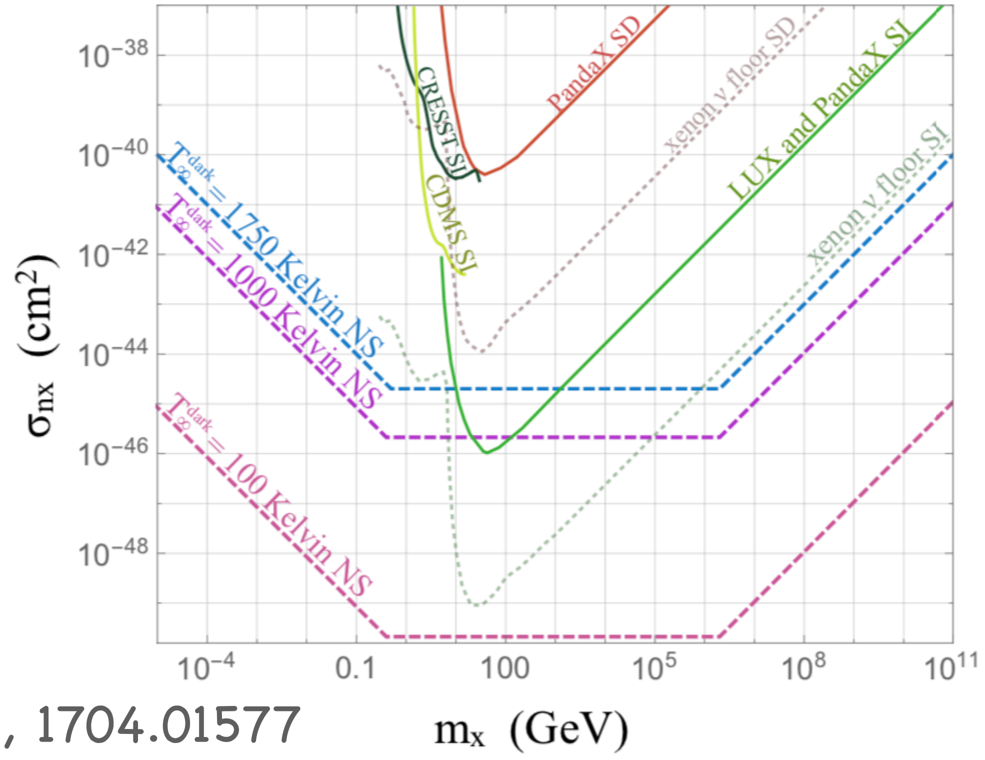
capture rate $\simeq 1$
for $\sigma_{\chi N} \gtrsim 10^{-45}{\rm cm}^2$

annihilation
$\chi\chi \to f\bar{f}$

☑ $v_\chi \sim 1$ at NS surface
-> It is also sensitive to inelastic scattering (e.g., pure-Wino: $\chi^0 + N \to \chi^- + N'$)
or other velocity-suppressed scatterings.

☑ It can also probe light DM (<< 1 GeV).
-> cf. Talk by Tongyan Lin.

☑ In principle, it can go beyond the neutrino floor.



Baryakhtar+, 1704.01577

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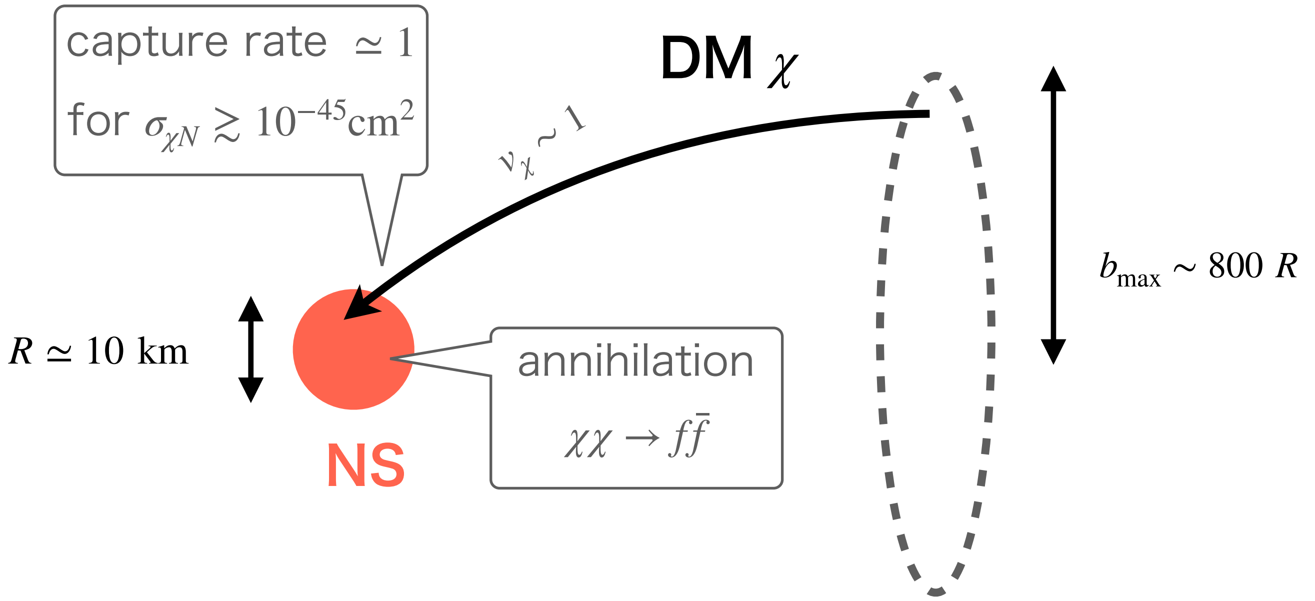

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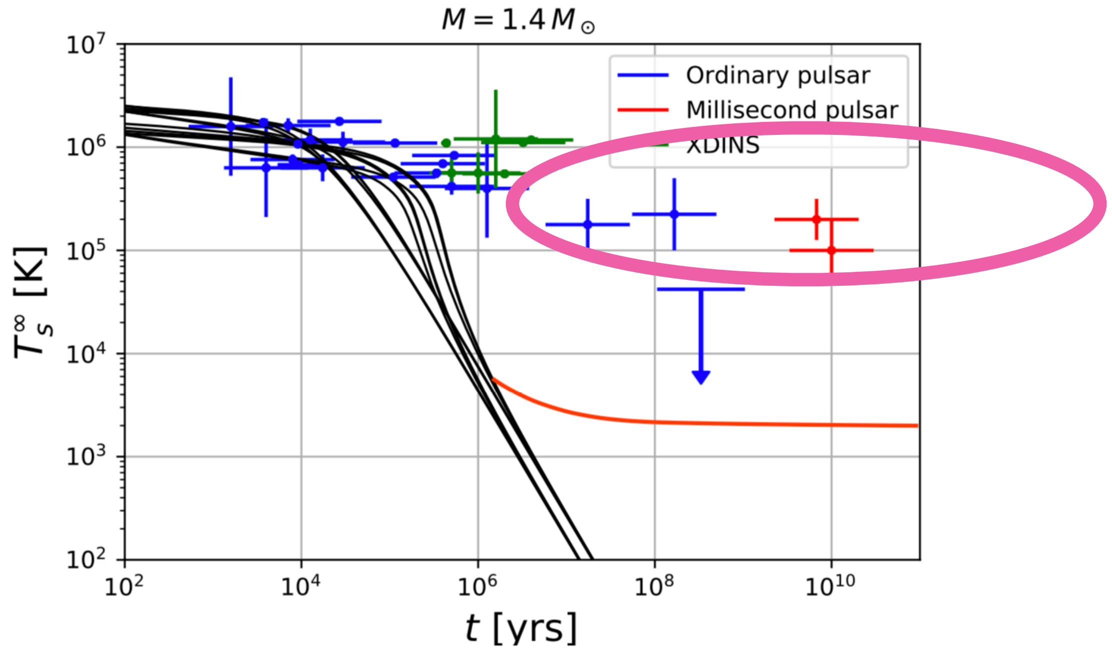
But,...



Plan

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

2. $C\frac{dT}{dt} = -L_\nu - L_\gamma + L_{\text{DM}}^{\text{heat}}$

done

3. $\boxed{C\frac{dT}{dt} = -L_\nu - L_\gamma + L_{\text{rotochemical}}^{\text{heat}}}$

4. $C\frac{dT}{dt} = -L_\nu - L_\gamma + L_{\text{rotochemical}}^{\text{heat}} + L_{\text{DM}}^{\text{heat}}$

Previous works

Our works

K. Yanagi, N. Nagata, KH, [1904.04667]

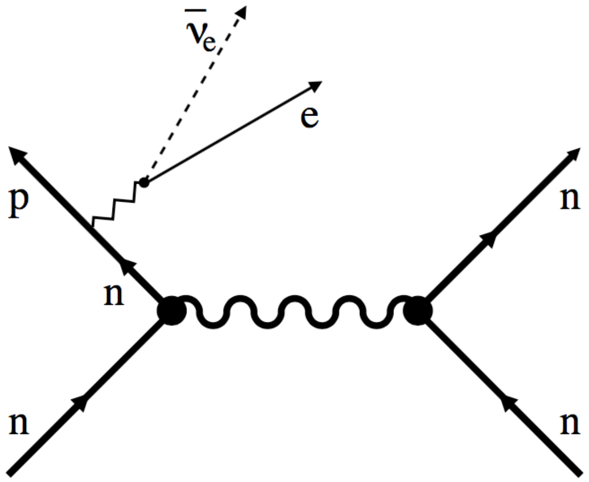
KH, N. Nagata, K. Yanagi, [1905.02991]

5. Summary

3. Rotochemical Heating $C\frac{dT}{dt} = -L_\nu - L_\gamma + L^{\text{heat}}_{\text{rotochemical}}$

- Modified Urca (dominant process at $T > T_c$)

$$\begin{cases} n + N \to p + e^- + N + \bar{\nu}_e \\ p + N + e^- \to n + N + \nu_e \end{cases} \quad (N = p \ or \ n)$$



- In the minimal cooling, β-equilibrium is assumed.

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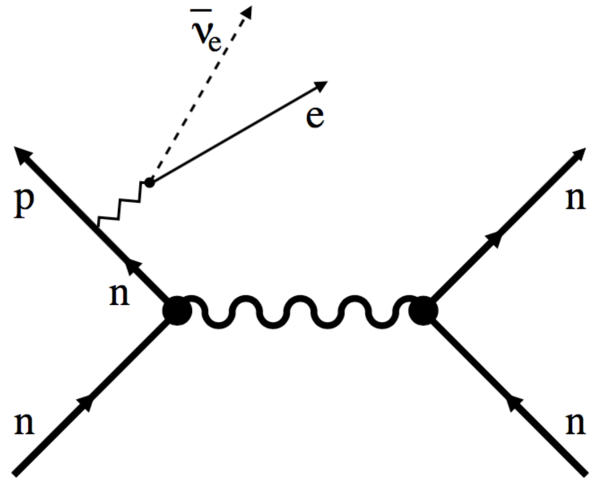

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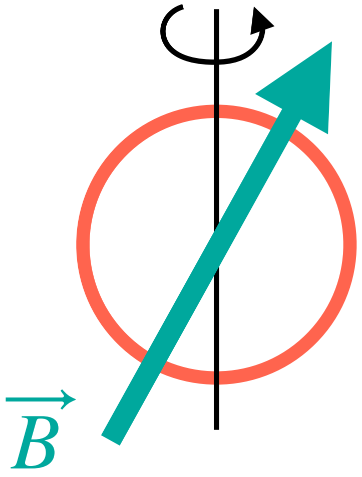
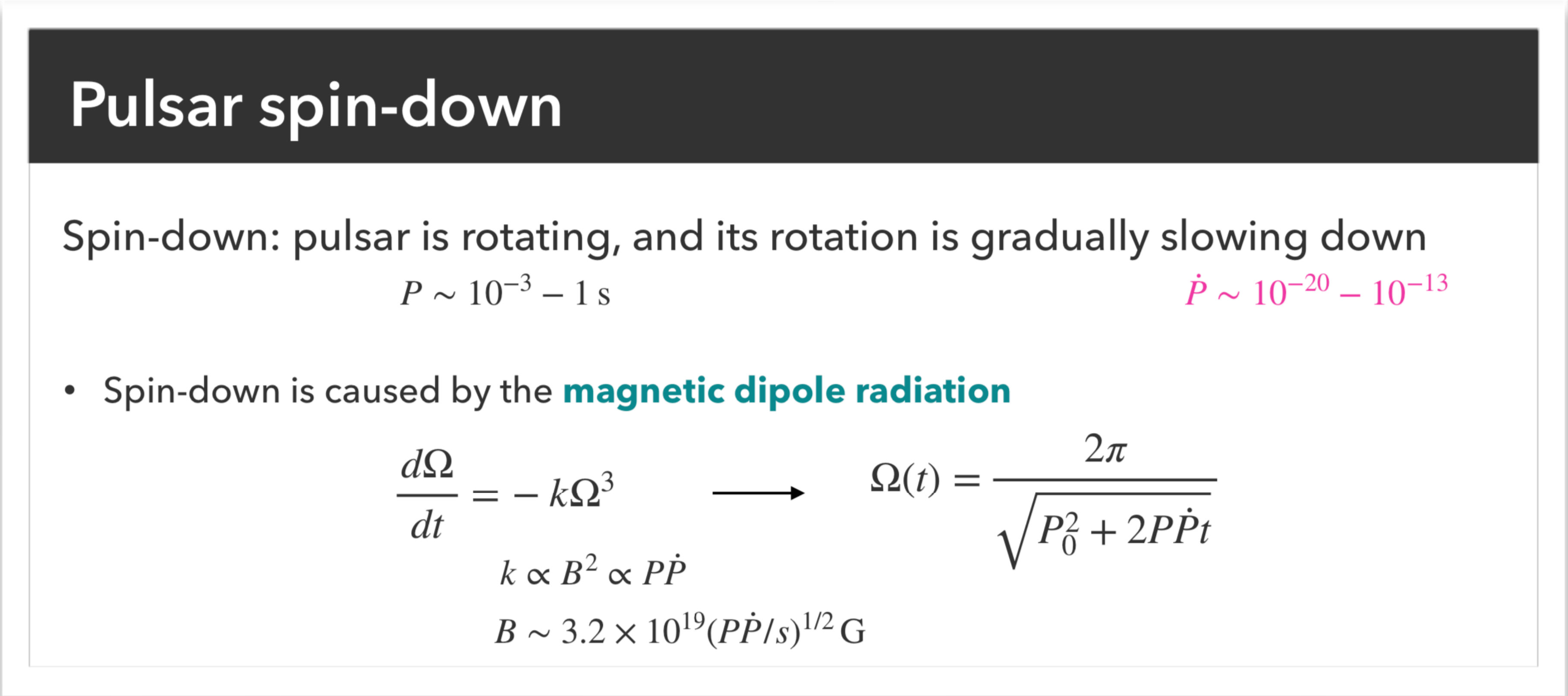
$$\Gamma_{n\to p+e} = \Gamma_{p+e\to n}, \qquad \mu_n = \mu_p + \mu_e\ .$$

- However, β-equilibrium is NOT maintained in rotating pulsars!

A.Reisenegger [astro-ph/9410035]

Key: Spin-down of pulsar rotation





Pulsar spin-down

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

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

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

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

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

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

slide thanks to K.Yanagi.

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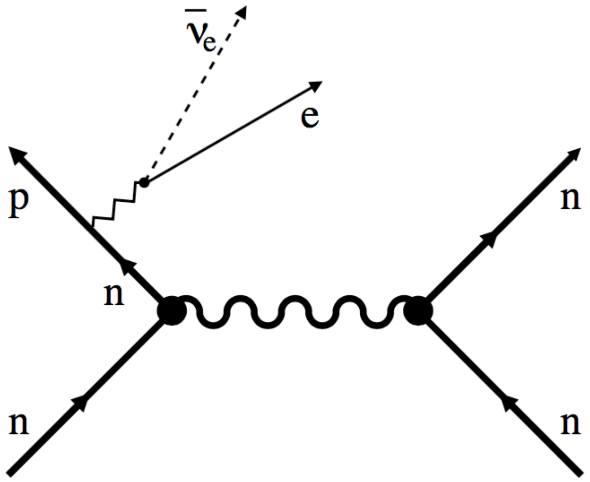

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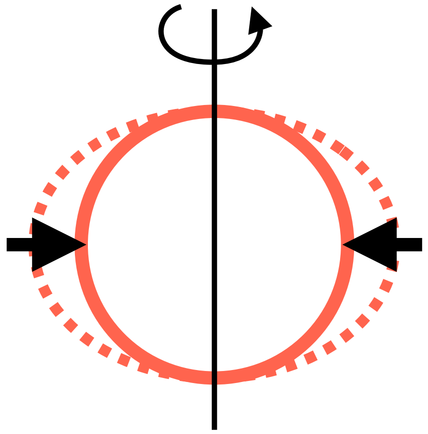
A.Reisenegger [astro-ph/9410035]



Key: Spin-down of pulsar rotation

-> change of would-be equilibrium number-density

(determined by the balance among gravity, pressure, centrifugal forces)

-> change of chemical potential

-> $\mu_n > \mu_p + \mu_e$. (M.Urca is too slow to catch up.)

- The deviation from β-equilibrium **heats the NS**.

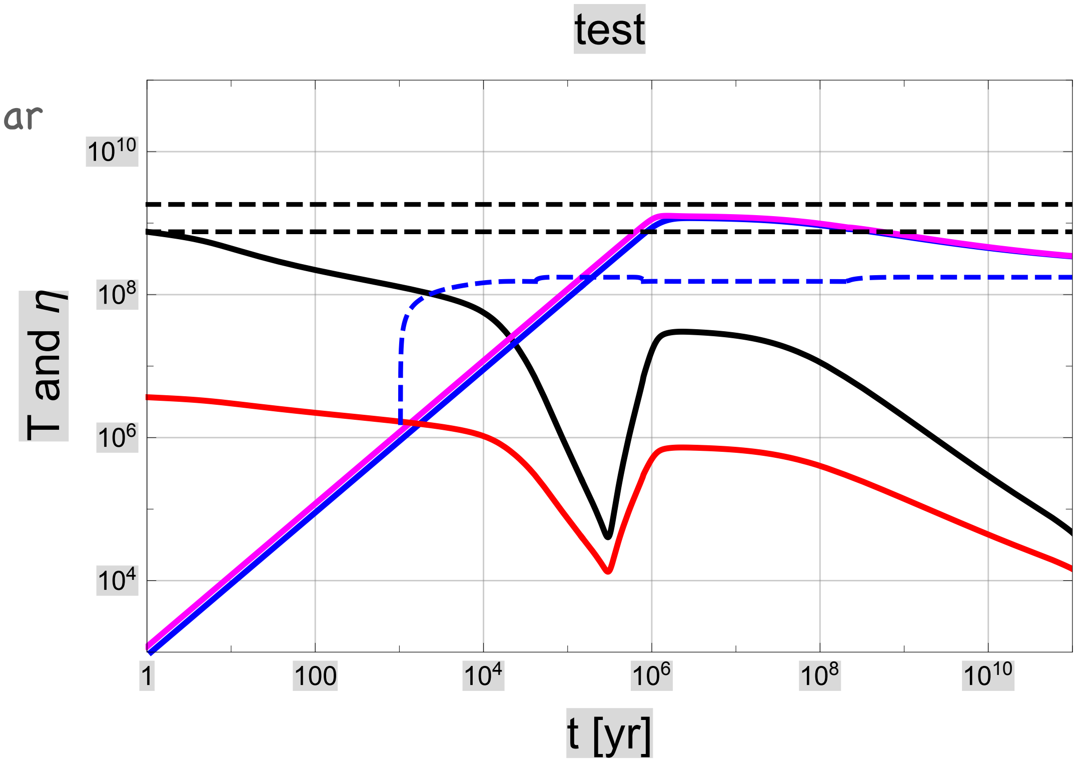
$$L^{\text{heat}}_{\text{rotochemical}} = \int dV \left(\mu_n - \mu_p - \mu_e\right)\left(\Gamma_{n\to p+e} - \Gamma_{p+e\to n}\right) > 0.$$

"Rotochemical heating" (nothing special, just normal physics!)

3. Rotochemical Heating $C\frac{dT}{dt} = -L_\nu - L_\gamma + L^{\text{heat}}_{\text{rotochemical}}$

- Again, the **superfluidity (pairing gap)** plays an important role.

Example for millisecond pulsar
neutron gap: "a"
proton gap: AO
$M = 1.4M_\odot$
$P_0 = 1\text{ms}$
$P\dot{P} = 3.3 \times 10^{-22}\text{s}$



deviation from β-eq.

$\eta_\ell = \mu_n - \mu_p - \mu_\ell \ (\ell = e, \mu)$

pairing gap Δ

internal temperature T

surface temperature T_s

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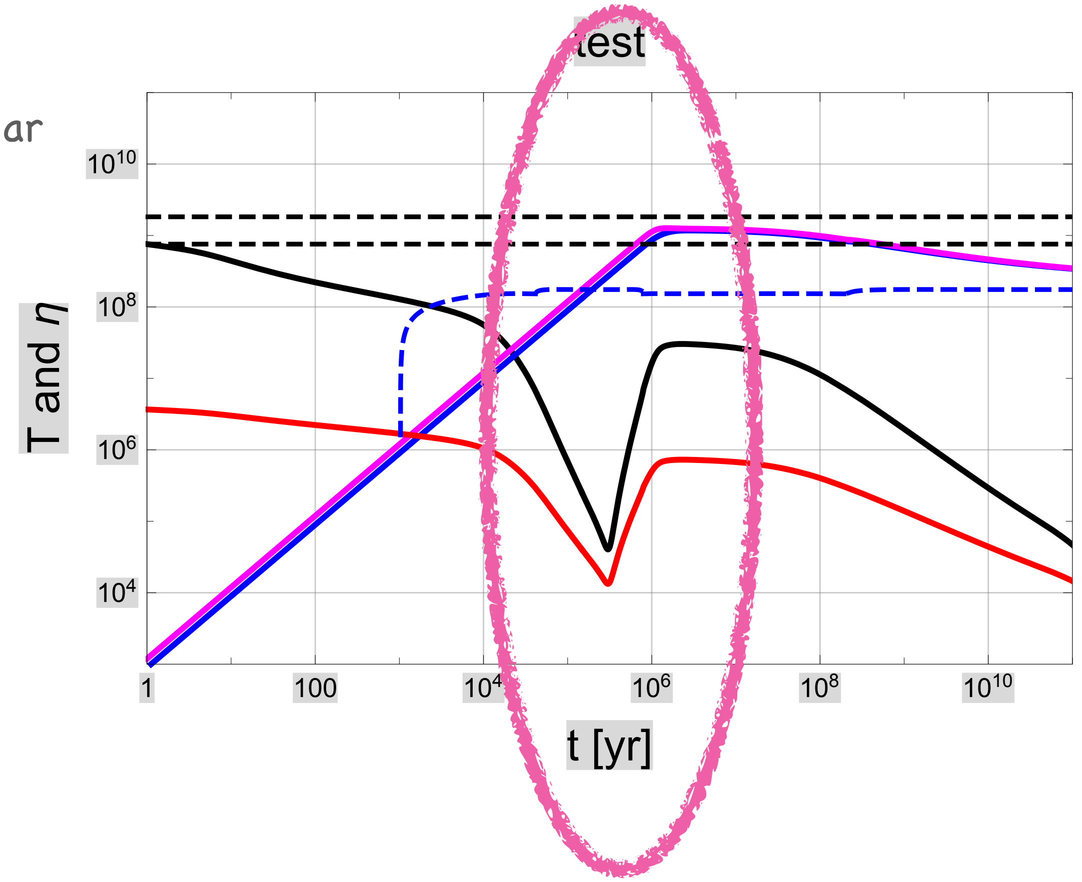

deviation from β-eq.

$\eta_\ell = \mu_n - \mu_p - \mu_\ell \ (\ell = e, \mu)$

pairing gap Δ

internal temperature T

surface temperature T_s

Rotochemical heating begins when $\eta_\ell > \Delta$. [Petrovich & Reisenegger, 0912.2564]

3. Rotochemical Heating $C\frac{dT}{dt} = -L_\nu - L_\gamma + L^{\text{heat}}_{\text{rotochemical}}$

- Recently, we have updated the calculation, including for the first time

  ☑ both neutron superfulidity and proton superconductivity
  ☑ with radius dependence
  ☑ with temperature dependence
  ☑ with angular dependence (for neutron triplet pairing)

simultaneously. (**K. Yanagi, N. Nagata, KH, [arXiv:1904.04667]**)

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  simultaneously. **(K. Yanagi, N. Nagata, KH, [arXiv:1904.04667])**

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

$$L^\infty_{\nu,M} = \sum_{\ell=e,\mu}\sum_{N=n,p}\int dV\, Q_{M,N\ell}\, e^{2\Phi(r)}$$

$$Q_{M,N\ell} = Q^{(0)}_{M,N\ell}\, I^N_{M,\epsilon}$$

$$L^\infty_H = \sum_{\ell=e,\mu}\sum_{N=n,p}\int dV\, \eta_\ell \cdot \Delta\Gamma_{M,N\ell}\, e^{2\Phi(r)}$$

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

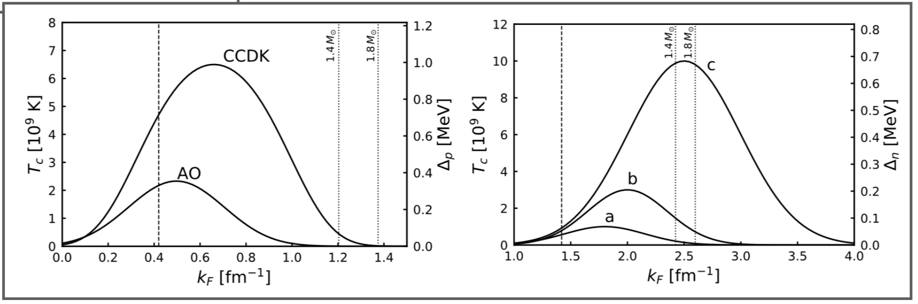
$$\frac{d\eta_\mu^\infty}{dt} = -\sum_{N=n,p}\int dV\,(Z_{np}\Delta\Gamma_{M,Ne} + Z_{np\mu}\Delta\Gamma_{M,N\mu})\, e^{\Phi(r)} + 2W_{np\mu}\Omega\dot{\Omega}$$

$$\Delta\Gamma_{M,N\ell} = \frac{Q^{(0)}_{M,N\ell}}{T(r)}\, I^N_{M,\Gamma}$$

$$I^N_{M,\epsilon} = \frac{60480}{11513\pi^8}\frac{1}{A^N_0}\int\prod_{j=1}^{5}\frac{d\Omega_j}{4\pi}\int_0^\infty dx_\nu\int_{-\infty}^{\infty}dx_n dx_p dx_{N_1} dx_{N_2}\, x_\nu^3 \cdot f(z_n)f(z_p)f(z_{N_1})f(z_{N_2})$$
$$\times\left[f(x_\nu - \xi_\ell - z_n - z_p - z_{N_1} - z_{N_2}) + f(x_\nu + \xi_\ell - z_n - z_p - z_{N_1} - z_{N_2})\right]\delta^3\left(\sum_{j=1}^{5}\boldsymbol{p}_j\right), \quad (18)$$

$$I^N_{M,\Gamma} = \frac{60480}{11513\pi^8}\frac{1}{A^N_0}\int\prod_{j=1}^{5}\frac{d\Omega_j}{4\pi}\int_0^\infty dx_\nu\int_{-\infty}^{\infty}dx_n dx_p dx_{N_1} dx_{N_2}\, x_\nu^2 \cdot f(z_n)f(z_p)f(z_{N_1})f(z_{N_2})$$
$$\times\left[f(x_\nu - \xi_\ell - z_n - z_p - z_{N_1} - z_{N_2}) - f(x_\nu + \xi_\ell - z_n - z_p - z_{N_1} - z_{N_2})\right]\delta^3\left(\sum_{j=1}^{5}\boldsymbol{p}_j\right), \quad (19)$$

$$\tilde{N}\tilde{N} \to [NN] + \nu_\ell + \bar{\nu}_\ell$$



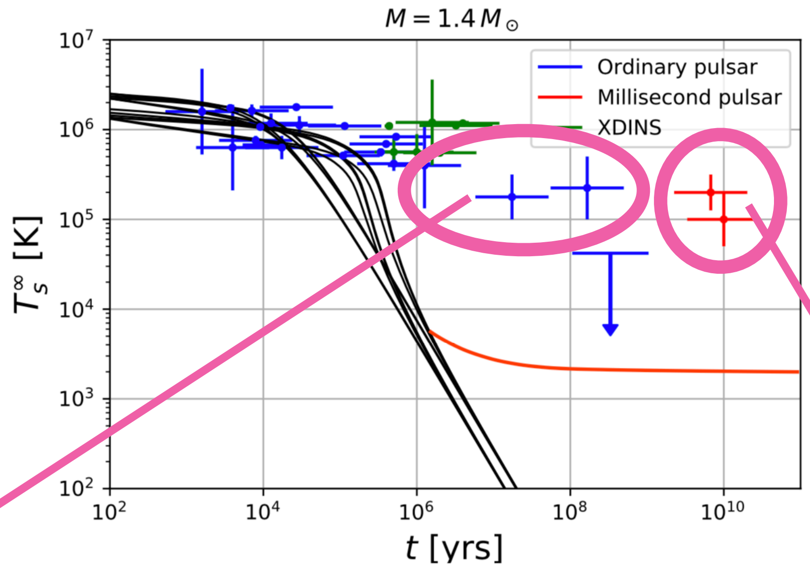
non-equilibrium

$$n + N_1 \to p + N_2 + \ell + \bar{\nu}_\ell$$
$$p + N_2 + \ell \to n + N_1 + \nu_\ell$$

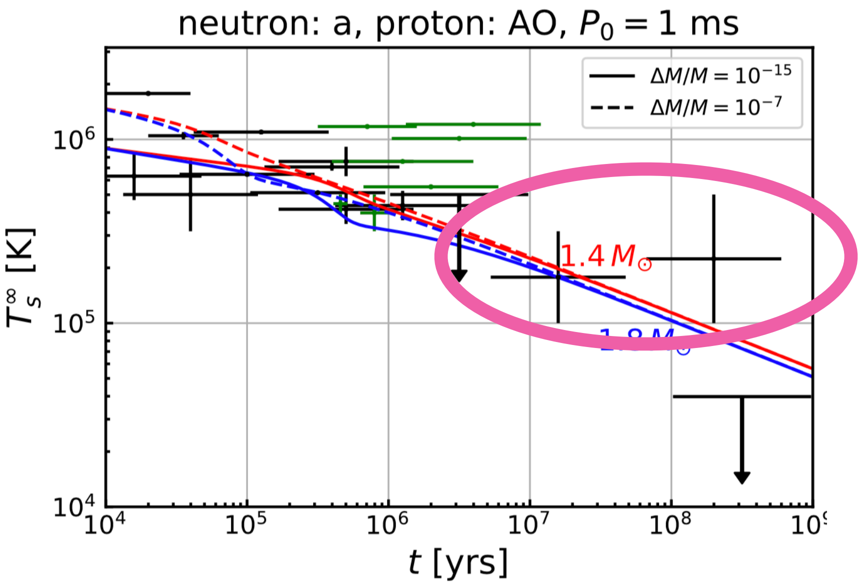
chemical potential

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

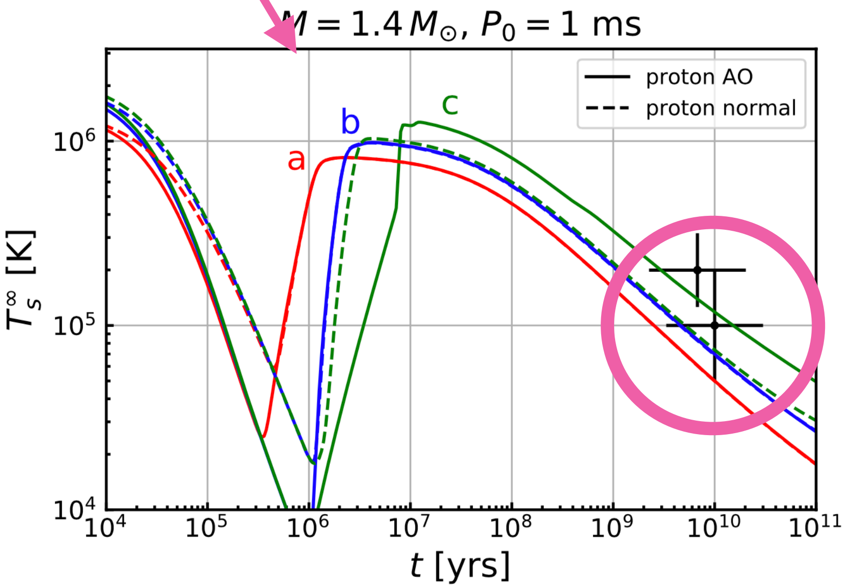
3. Rotochemical Heating $C\frac{dT}{dt} = -L_\nu - L_\gamma + L^{\text{heat}}_{\text{rotochemical}}$



K. Yanagi, N. Nagata, KH
[arXiv:1904.04667]



Ordinary pulsar
(typically $P \sim 1\text{s}$, $\dot{P} \sim 10^{-14}$, $B \sim 10^{12} G$)



Millisecond pulsar
(typically $P \sim 1\text{ms}$, $\dot{P} \sim 10^{-20}$, $B \sim 10^{8} G$)

The rotochemical heating can explain the old and warm NSs.

Plan

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done

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Previous works

4. $C\frac{dT}{dt} = -L_\nu - L_\gamma + L^{\text{heat}}_{\text{rotochemical}} + L^{\text{heat}}_{\text{DM}}$

Our works

K. Yanagi, N. Nagata, KH, [1904.04667]

KH, N. Nagata, K. Yanagi, [1905.02991]

5. Summary

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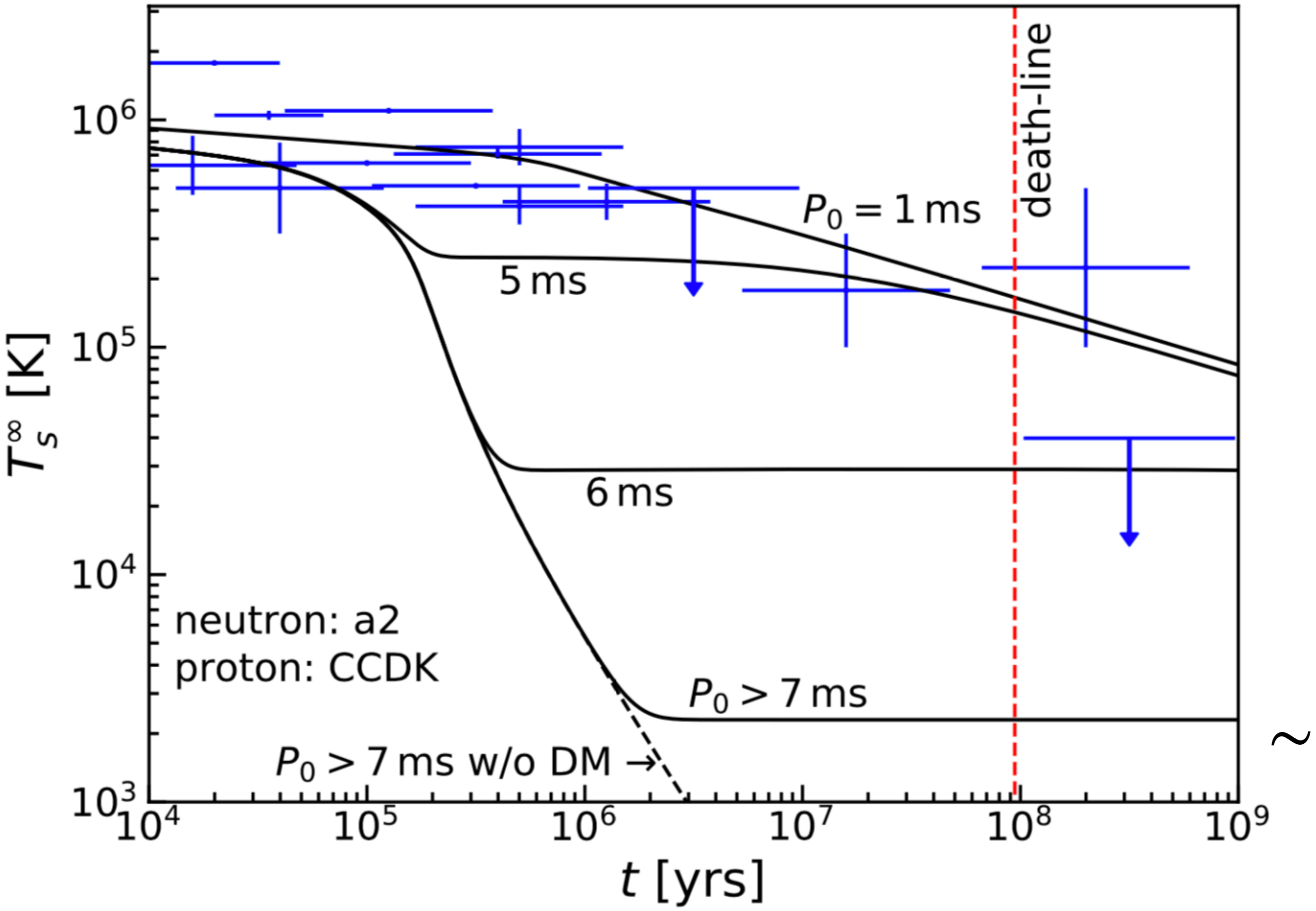
$$C\frac{dT}{dt} = -L_\nu - L_\gamma + L^{\text{heat}}_{\text{rotochemical}} + L^{\text{heat}}_{\text{DM}}$$

KH, N. Nagata, K. Yanagi, [1905.02991]

Result

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



$\sim (2000 - 3000)K$

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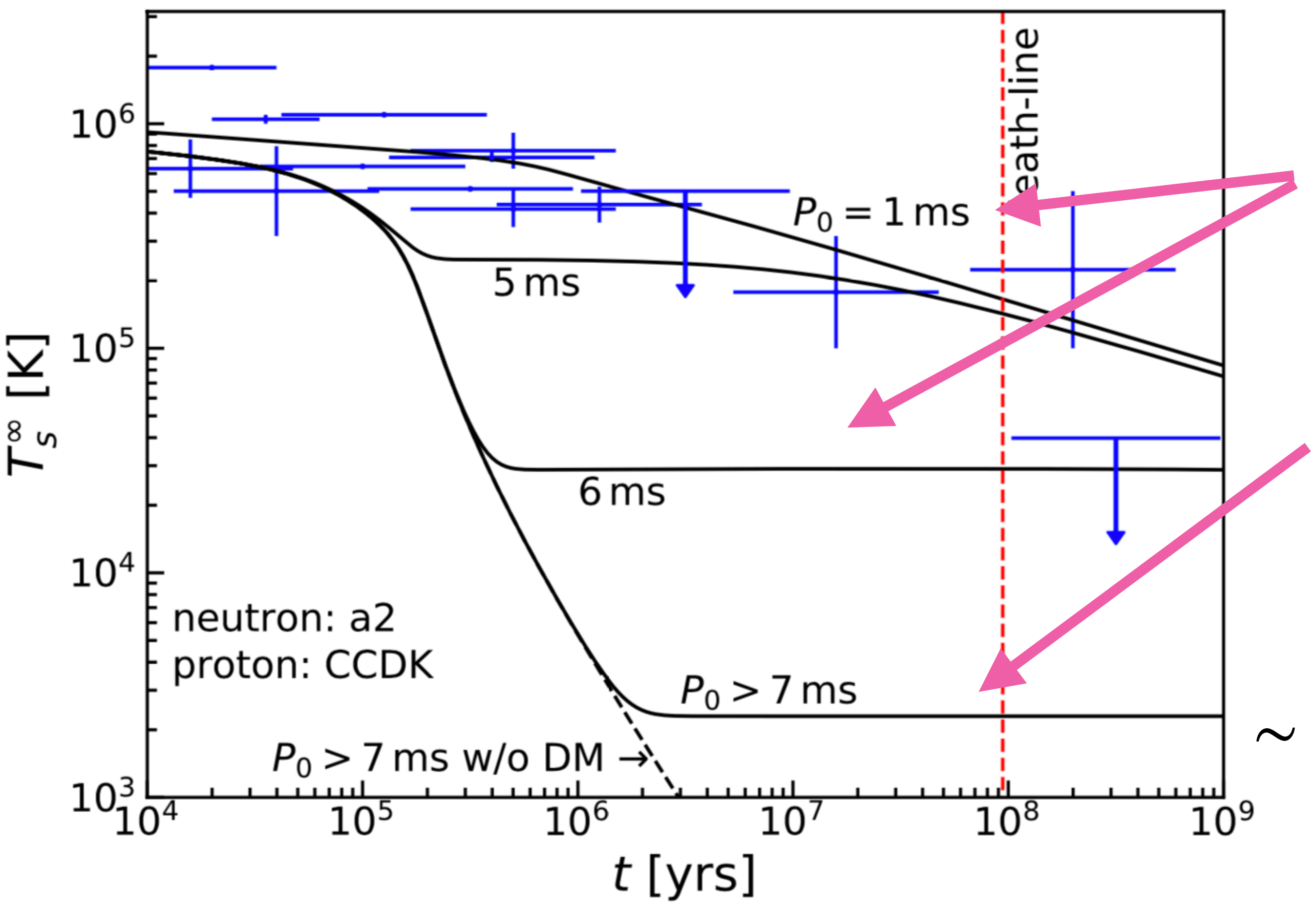

$\sim (2000 - 3000)K$

P_0 : **initial rotation period** is the key parameter.

- For a short P_0 , DM heating effect is invisible.
- **For a long P_0, DM heating effect is visible!**

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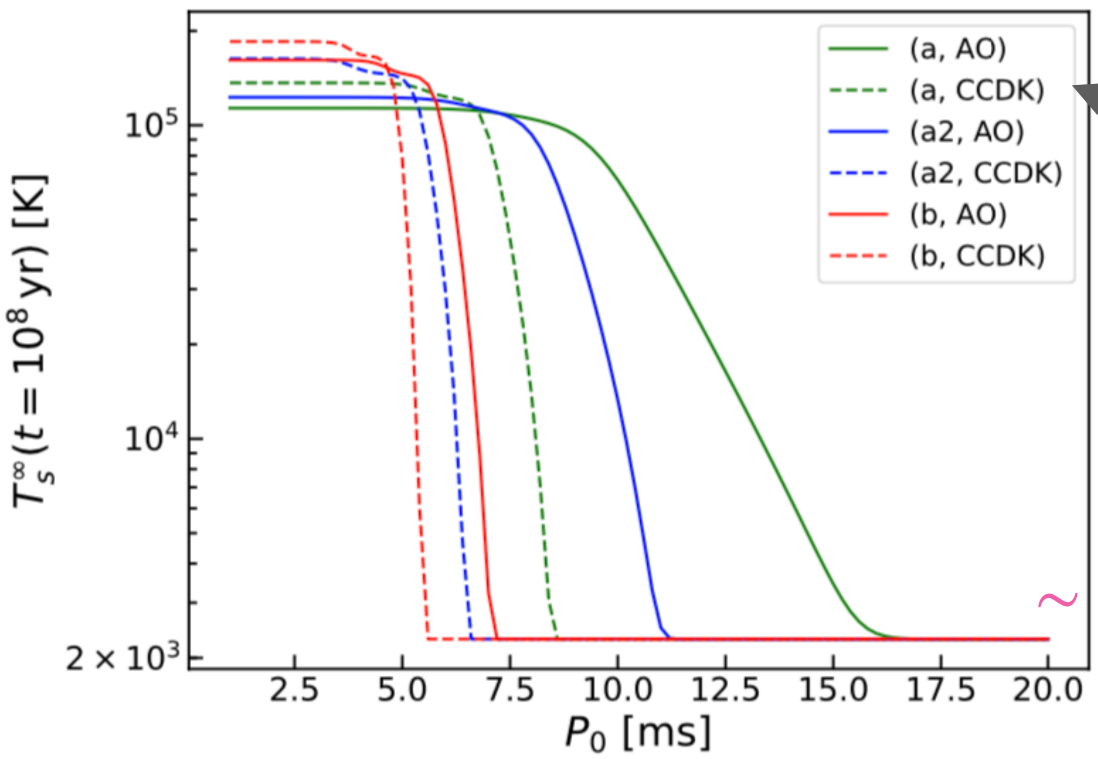
KH, N. Nagata, K. Yanagi, [1905.02991]

Result

Late time temperature



neutron/proton gap models

$\sim (2000-3000)K$

initial rotation period (P_0) dependence

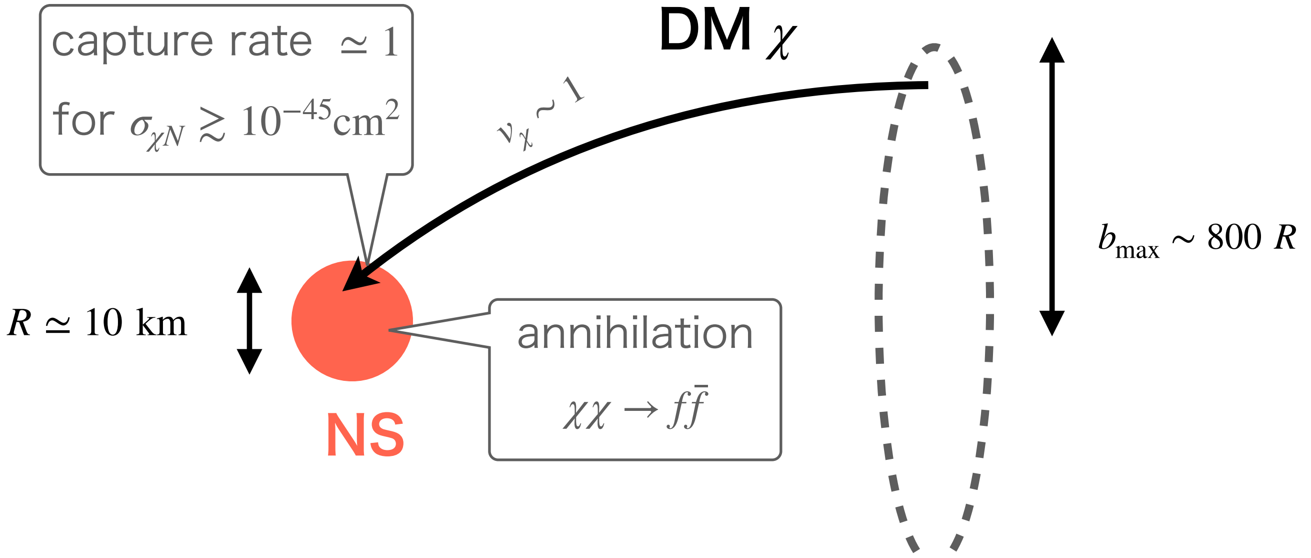
- **For large enough P_0 , DM signal is visible.**

  Recent studies suggest P_0 can indeed be very large. ($> 100\mathrm{ms}$). [cf. references in 1905.02991.]

  Currently no NS with such a low T is observed, but just because it is difficult to observe them.

- **Conversely, discovery of a NS with $T < 2000\mathrm{K}$ will exclude many DM models, such as Wino DM.**

Summary



- We studied NS temperature evolution in the presence of both rotochemical heating and DM heating.

$$C\frac{dT}{dt} = -L_\nu - L_\gamma + L^{\text{heat}}_{\text{rotochemical}} + L^{\text{heat}}_{\text{DM}}$$

and found that DM heating effect is indeed visible for a large initial rotation period P_0.

Future works

- application to concrete DM models.
- vs. other heating mechanisms. (cf. D.Gonzalez, 1005.5699)
- observational feasibility.

Advertisement:

Cosmology / Astroparicle Physics Workshop at Tokyo in March 2020.

- (tentative title) "New Directions in Cosmology"
- **March 25-27 (or 24-27), 2020**. (Pencil it on your calendar!)
- At **Tokyo U., Hongo campus**.
- Organizers:
  K.Hamaguchi (Co-chair), T.Moroi (Co-chair),
  S.Iso, S.Matsumoto, T.Melia, J.Menendez, K.Nagamine,
  N.Nagata, K.Nakayama, M.Yamaguchi, T.Yanagida.

Backup

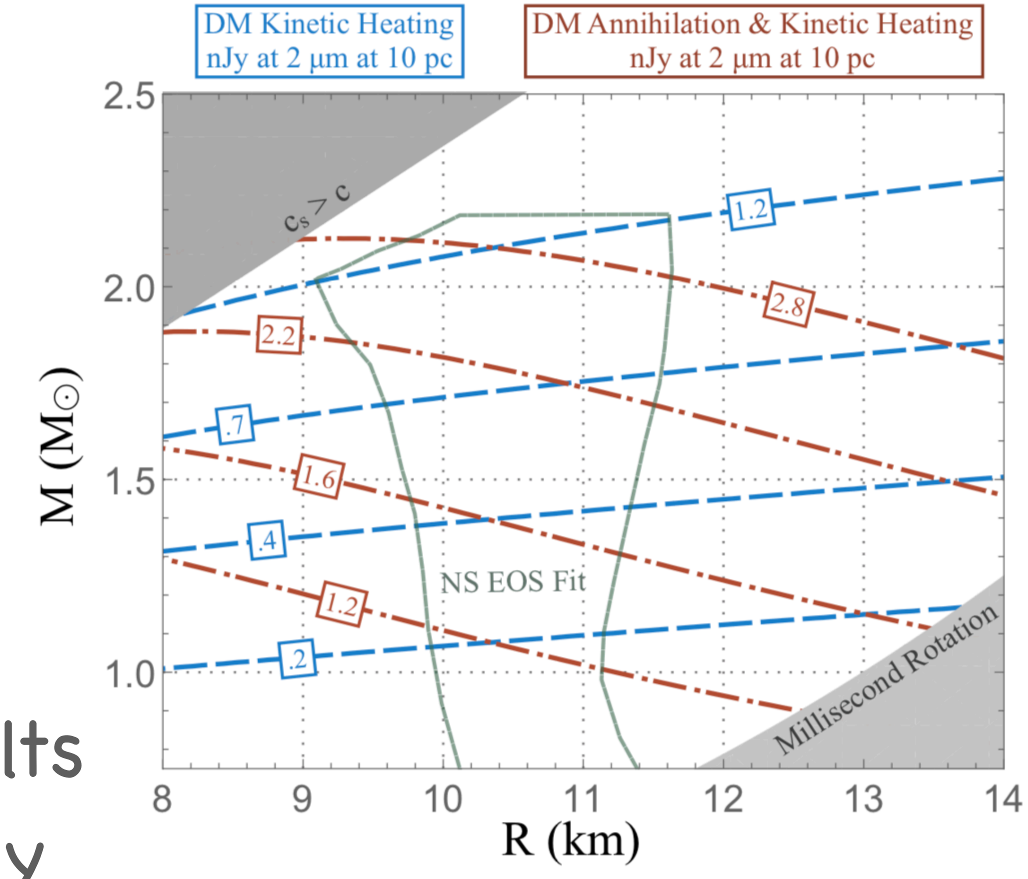
observational feasibility

- See e.g., the discussion in M.Baryakhtar+, 1704.01577.

- O(1) old and cold NSs can be at $d = 10\text{pc}$.

- Radiation from a DM-heated NS there results in a spectral flux density of O(1) nanoJansky (nJy) at wavelength $\nu^{-1} = \mathcal{O}(1)\ \mu\text{m}$.

- Maybe within the sensitivity of the upcoming telescopes such as the JWST, TMT, and E-ELT.



M.Baryakhtar+, 1704.01577