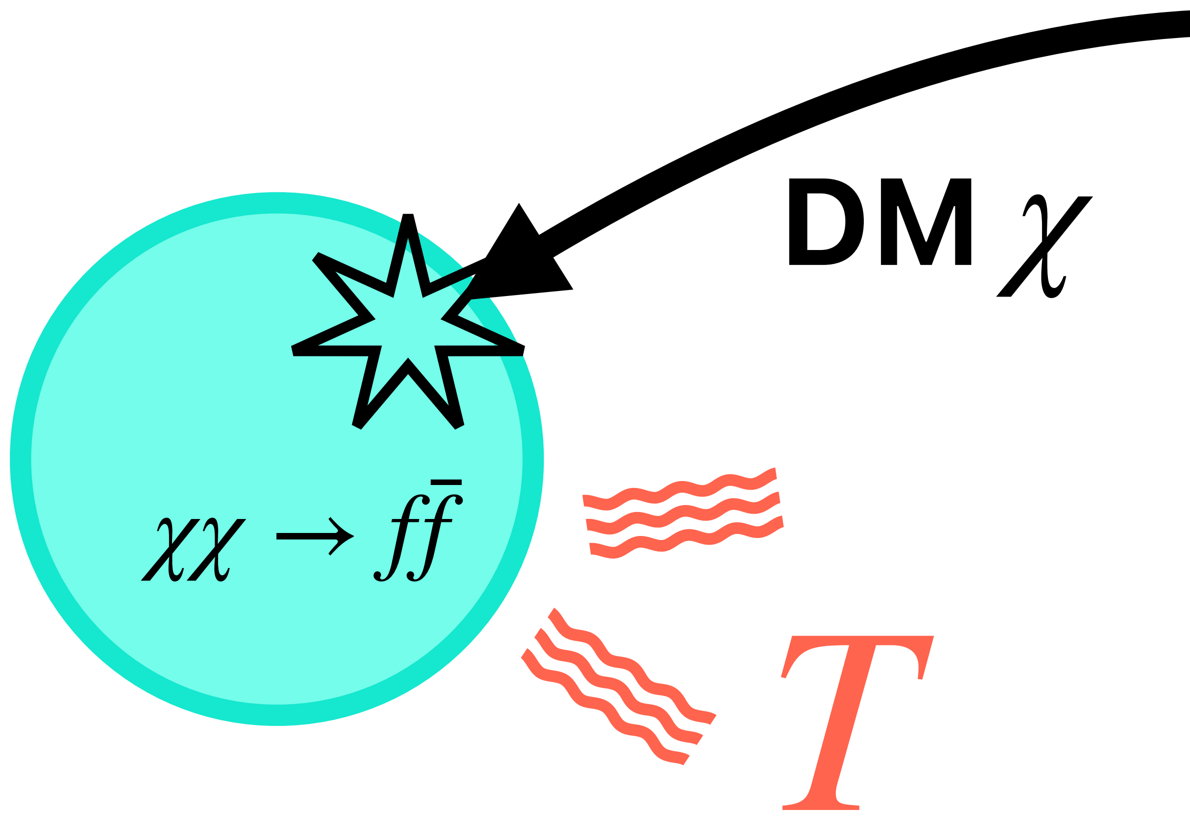
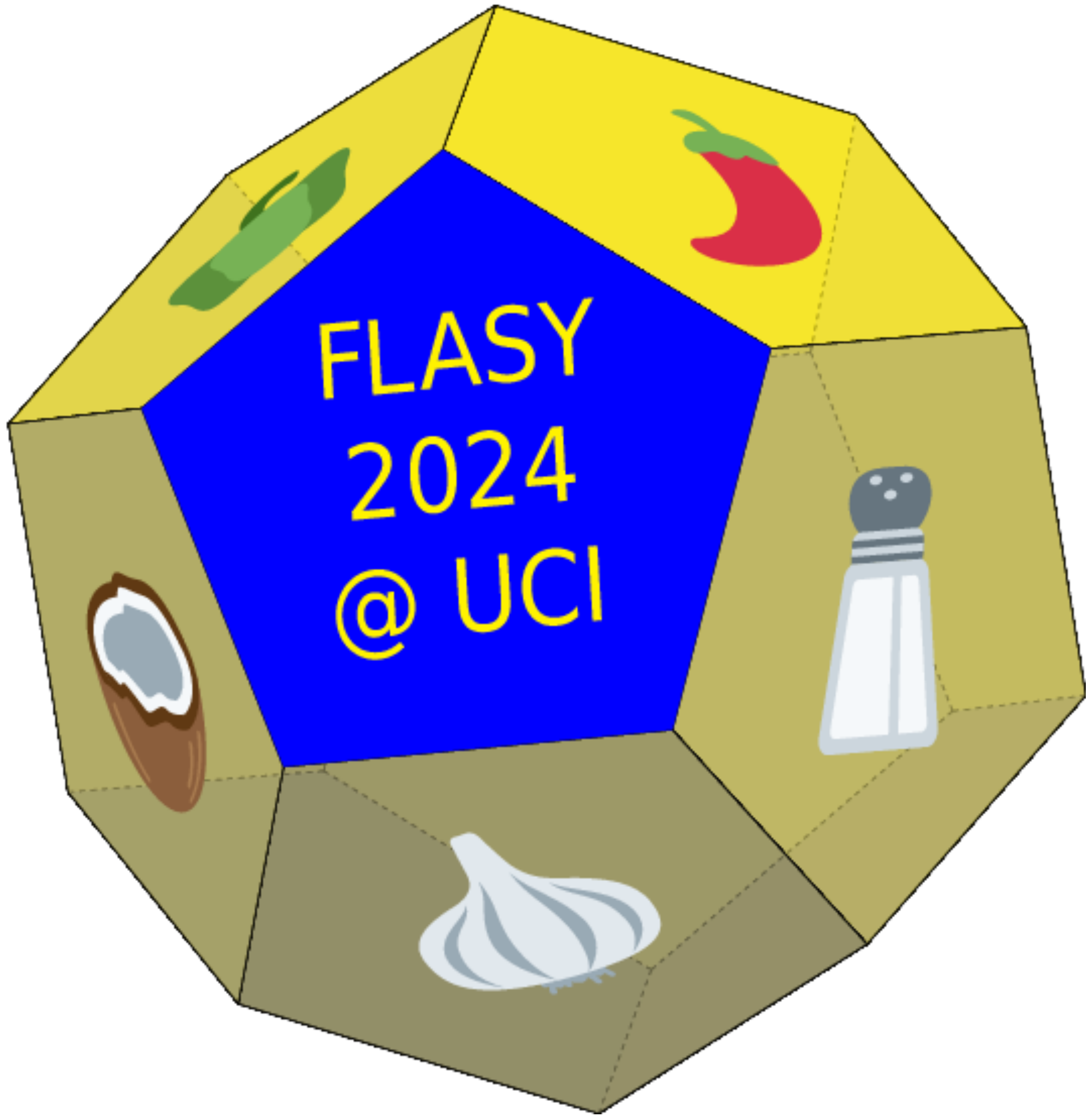
Dark Matter Heating of Neutron Stars: Advantages and Challenges



Koichi Hamaguchi (Tokyo U.)

@FLASY 2024

24–28 June 2024, Irvine, CA



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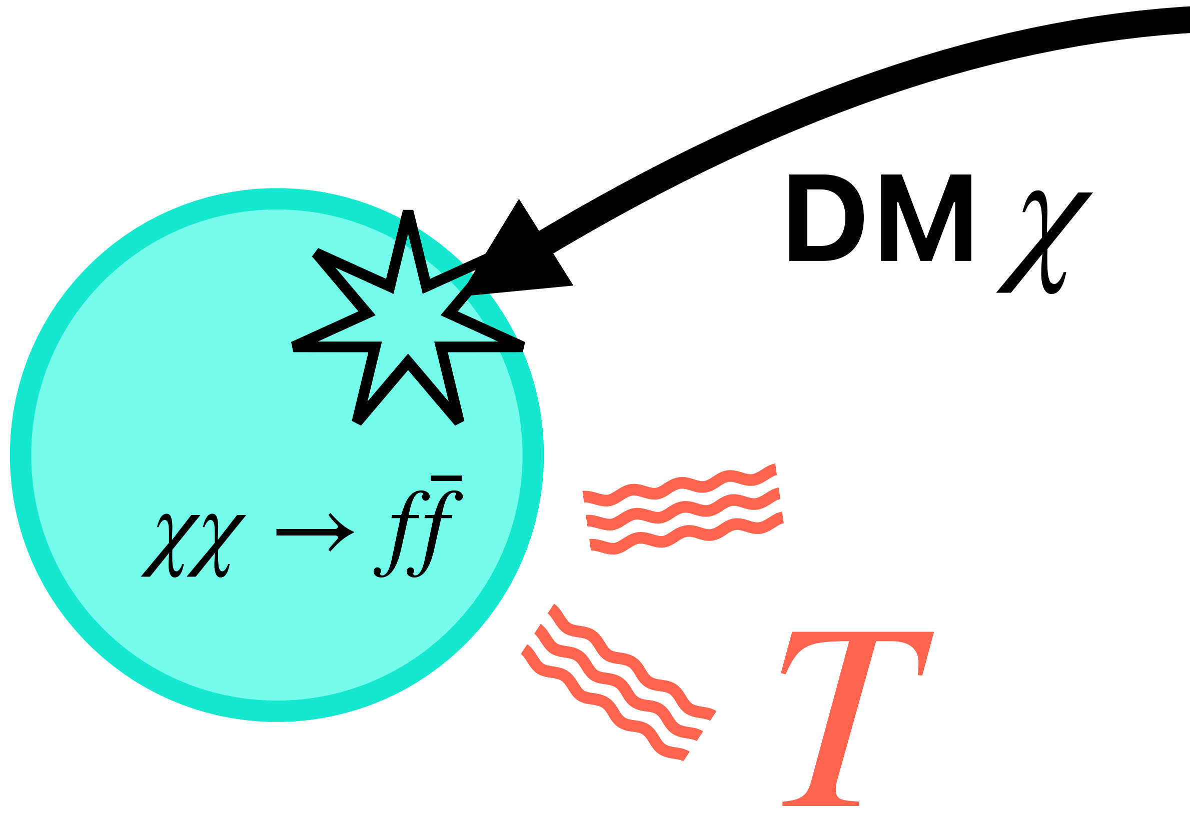

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Based on

arXiv 2309.02633, 2308.16066, 2204.02413, 2204.02238, 1905.02991, 1904.04667,

w/ Motoko Fujiwara, Natsumi Nagata, Maura E. Ramirez-Quezada, Keisuke Yanagi, Jiaming Zheng.

Plan

- **Neutron Star and its Cooling**
- **Dark Matter Heating of Neutron Stars**
  - Basic Idea and back-of-envelope estimates
  - Advantages
  - Challenges

- **Summary**

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Neutron Star

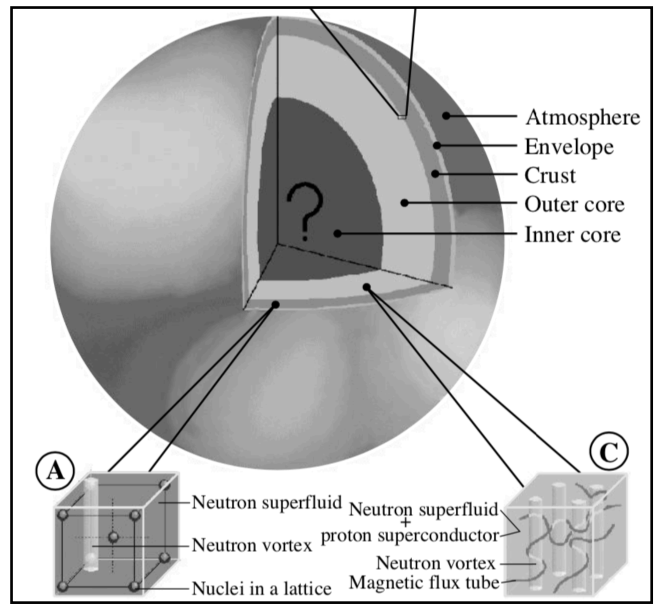

fig. from 1302.6626

Neutron Star

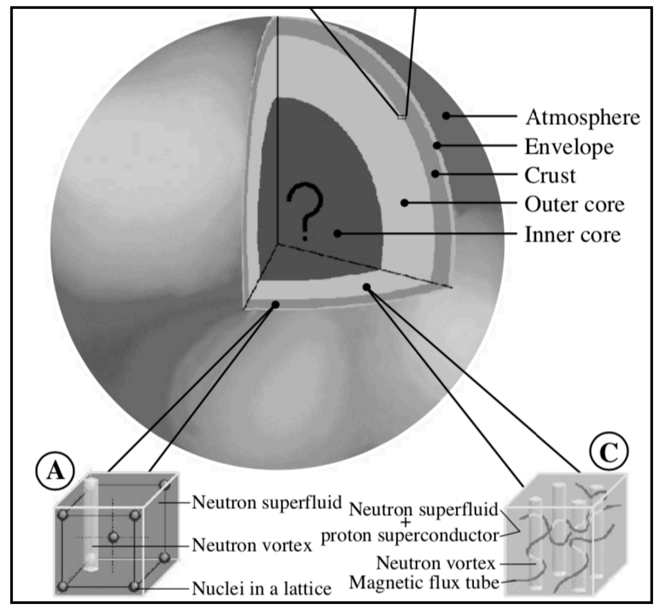

fig. from 1302.6626

- **Mass**：$M \sim (1-2)M_\odot$ ($M_\odot$ = solar mass)

heaviest one found so far: $M \simeq 2.35 M_\odot$（pulsar PSR J0952-0607 [arXiv:2207.05124])

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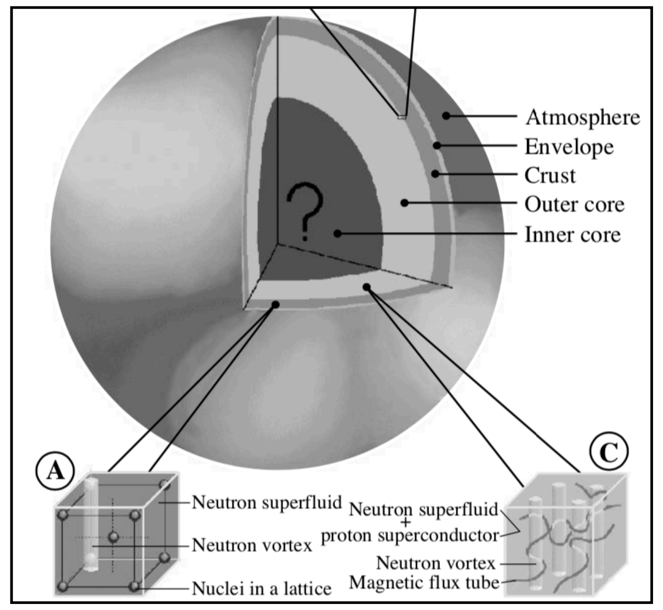

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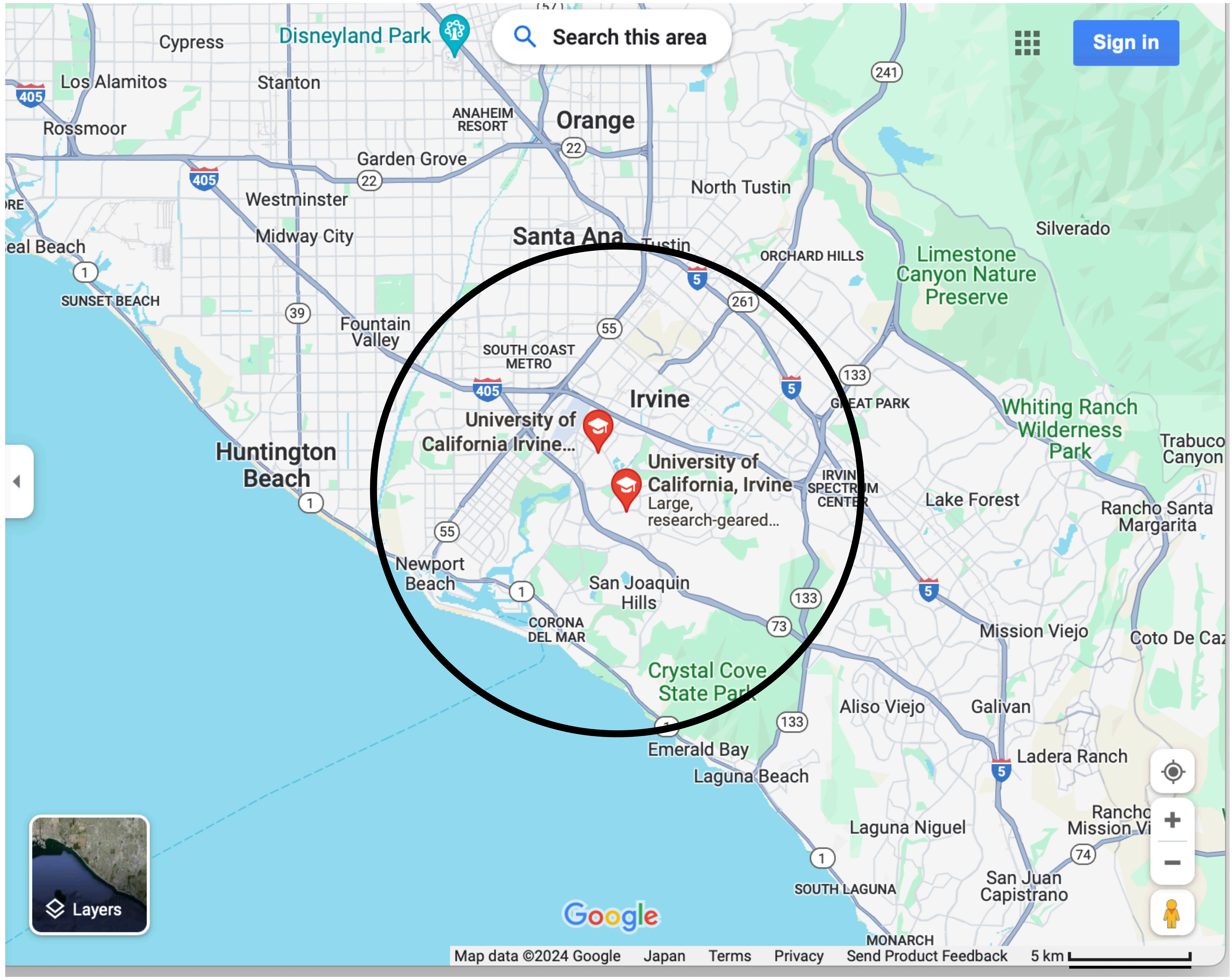
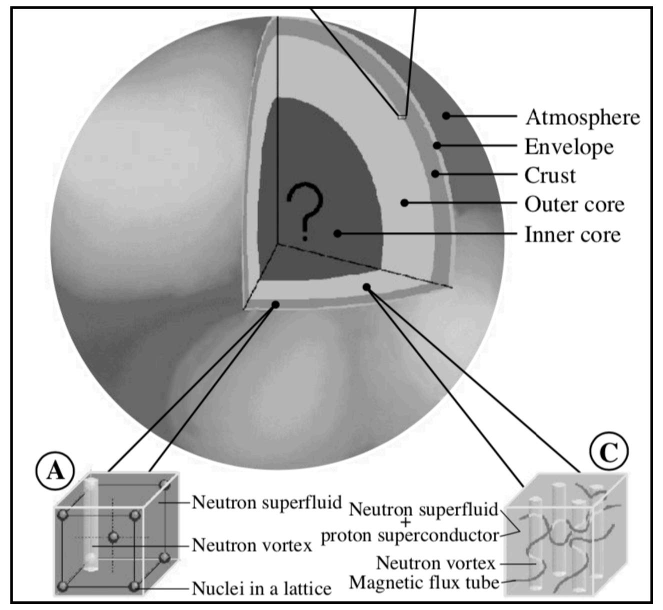
- **Radius：**$R \sim 10$ km



Neutron Star



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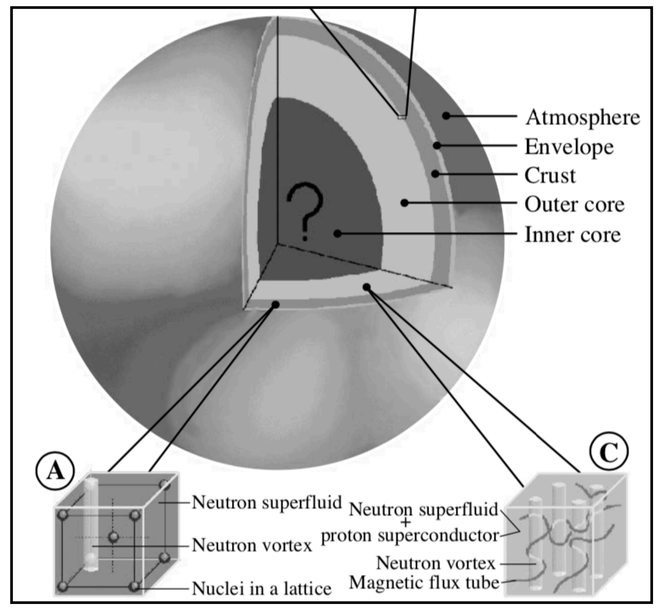
- **Radius**：$R \sim 10$ km

- **Density**：$\bar{\rho} = \dfrac{M}{(4\pi/3)R^3} \simeq 7 \times 10^{14}\mathrm{g/cm^3}$

cf. nuclear density $\sim 3 \times 10^{14}\mathrm{g/cm^3}$

Neutron Star



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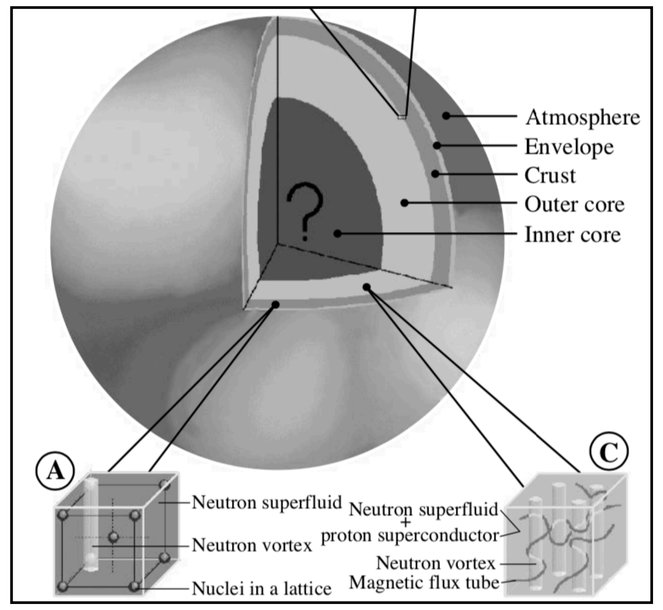
Neutron Star



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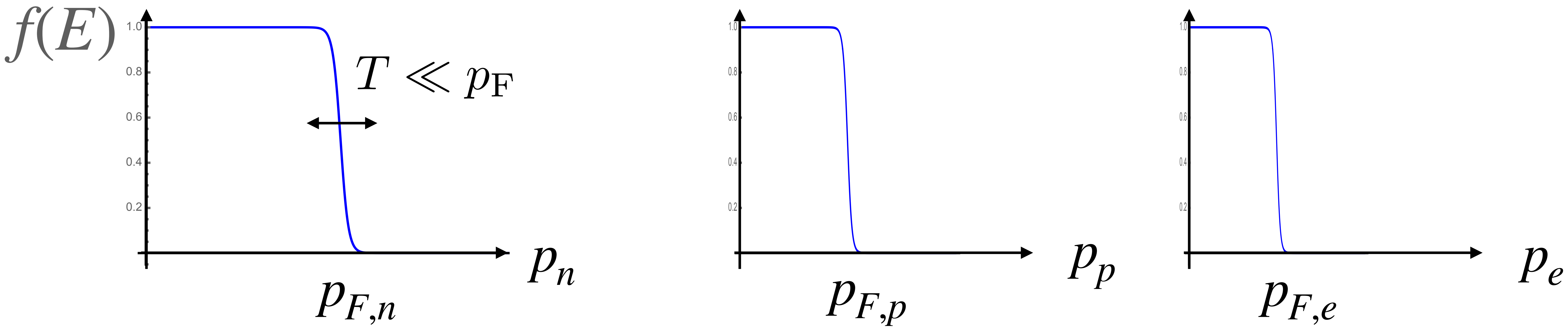
- Neutrons, protons, and electrons are all **Fermi degenerate**.



Fermi momentum

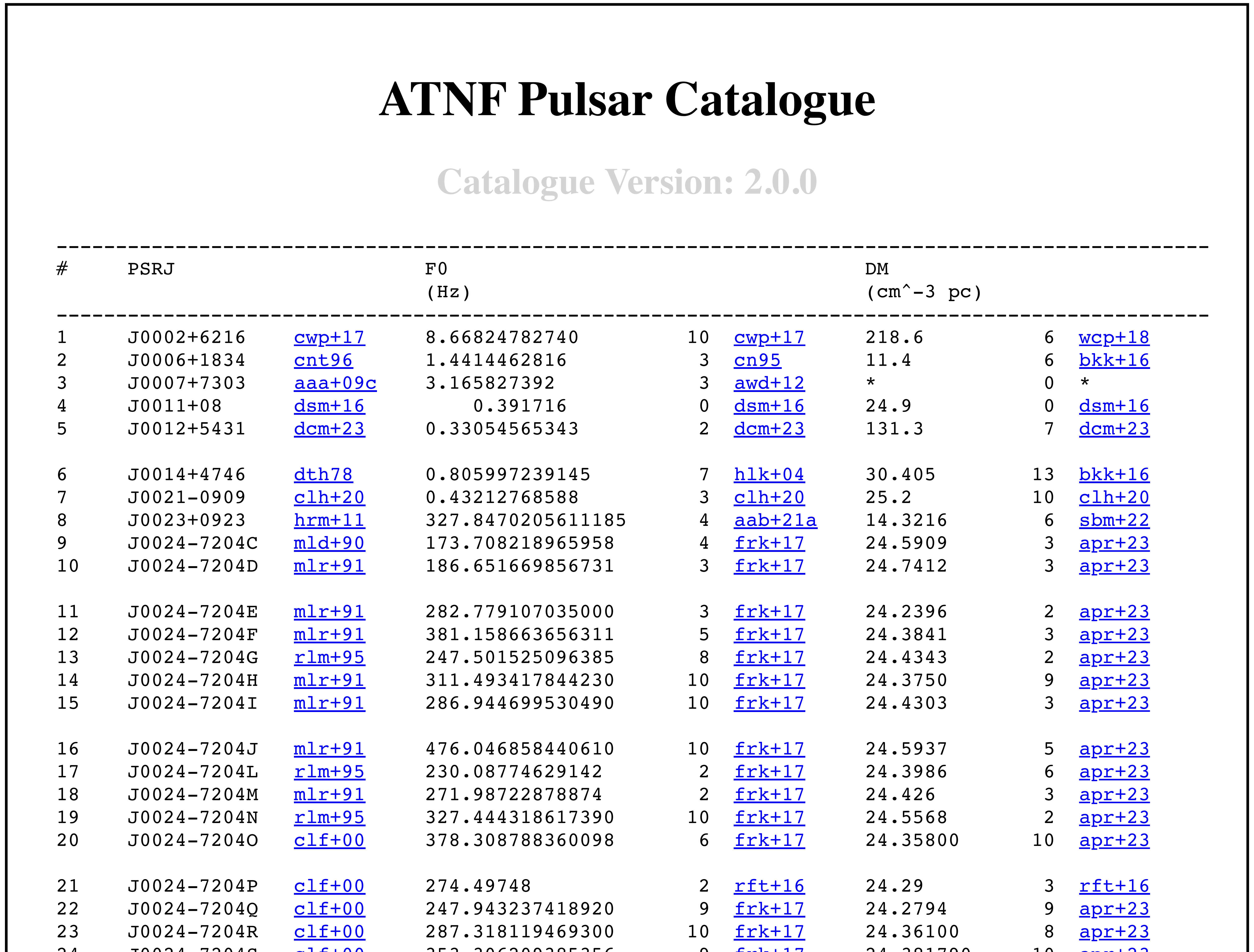
Neutron Star

https://commons.wikimedia.org/wiki/File:Chandra-crab.jpg
Crab Pulsar

- Most of NSs are found as **pulsars**.

> 3400 pulsars found so far.

👉 ATNF pulsar catalogue:



ATNF Pulsar Catalogue

Catalogue Version: 2.0.0

```
-------------------------------------------------------------------------------------------------
#      PSRJ                       F0                                    DM
                                  (Hz)                                  (cm^-3 pc)
-------------------------------------------------------------------------------------------------
1      J0002+6216     cwp+17      8.66824782740          10  cwp+17     218.6          6  wcp+18
2      J0006+1834     cnt96       1.4414462816            3  cn95       11.4           6  bkk+16
3      J0007+7303     aaa+09c     3.165827392             3  awd+12     *              0  *
4      J0011+08       dsm+16          0.391716            0  dsm+16     24.9           0  dsm+16
5      J0012+5431     dcm+23      0.33054565343           2  dcm+23     131.3          7  dcm+23

6      J0014+4746     dth78       0.805997239145          7  hlk+04     30.405        13  bkk+16
7      J0021-0909     clh+20      0.43212768588           3  clh+20     25.2          10  clh+20
8      J0023+0923     hrm+11      327.8470205611185       4  aab+21a    14.3216        6  sbm+22
9      J0024-7204C    mld+90      173.708218965958        4  frk+17     24.5909        3  apr+23
10     J0024-7204D    mlr+91      186.651669856731        3  frk+17     24.7412        3  apr+23

11     J0024-7204E    mlr+91      282.779107035000        3  frk+17     24.2396        2  apr+23
12     J0024-7204F    mlr+91      381.158663656311        5  frk+17     24.3841        3  apr+23
13     J0024-7204G    rlm+95      247.501525096385        8  frk+17     24.4343        2  apr+23
14     J0024-7204H    mlr+91      311.493417844230       10  frk+17     24.3750        9  apr+23
15     J0024-7204I    mlr+91      286.944699530490       10  frk+17     24.4303        3  apr+23

16     J0024-7204J    mlr+91      476.046858440610       10  frk+17     24.5937        5  apr+23
17     J0024-7204L    rlm+95      230.08774629142         2  frk+17     24.3986        6  apr+23
18     J0024-7204M    mlr+91      271.98722878874         2  frk+17     24.426         3  apr+23
19     J0024-7204N    rlm+95      327.444318617390       10  frk+17     24.5568        2  apr+23
20     J0024-7204O    clf+00      378.308788360098        6  frk+17     24.35800      10  apr+23

21     J0024-7204P    clf+00      274.49748               2  rft+16     24.29          3  rft+16
22     J0024-7204Q    clf+00      247.943237418920        9  frk+17     24.2794        9  apr+23
23     J0024-7204R    clf+00      287.318119469300       10  frk+17     24.36100       8  apr+23
```

Neutron Star

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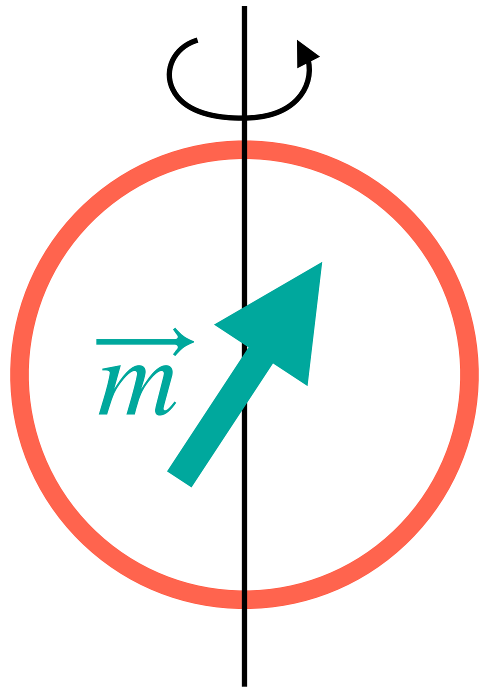
- **Magnetic Dipole Model**



Rotational energy loss ≃ magnetic dipole radiation

$$\dot{E} = \frac{d}{dt}\left(\frac{1}{2}I\Omega^2\right) = -\frac{\sin^2\alpha}{6}R^6\Omega^4B_p^2 \quad \begin{cases} I = \text{ moment of inertia} \\ \Omega = 2\pi/P = \text{ angular velocity} \\ P = \text{ rotation period} \\ B_p = \text{ magnetic field at the pole} \end{cases}$$

By solving this,

$$P(t) = \sqrt{P_0^2 + (P_\text{now}\dot{P}_\text{now})\,t} \qquad P_0 = \text{ initial period}$$

$$\implies \quad t \simeq \frac{P_\text{now}}{2\dot{P}_\text{now}} \equiv \tau_\text{sd}$$ **spin down age / characteristic age**

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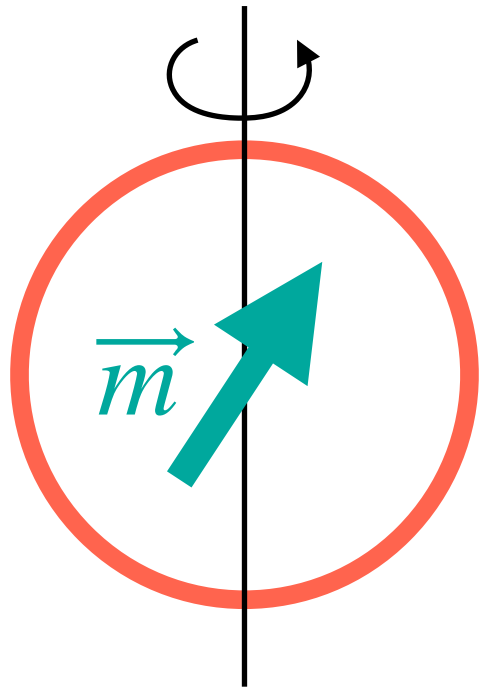

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Example: Crab Pulsar

- actual age: $\tau = 970\ \text{yrs}$ (from historical records of Supernova 1054.)
- spin down age: $P \simeq 0.033\ \text{sec},\ \dot{P} \simeq 4.2\times10^{-13} \Longrightarrow \tau_\text{sd} \simeq 1200\ \text{yrs}$

Neutron Star

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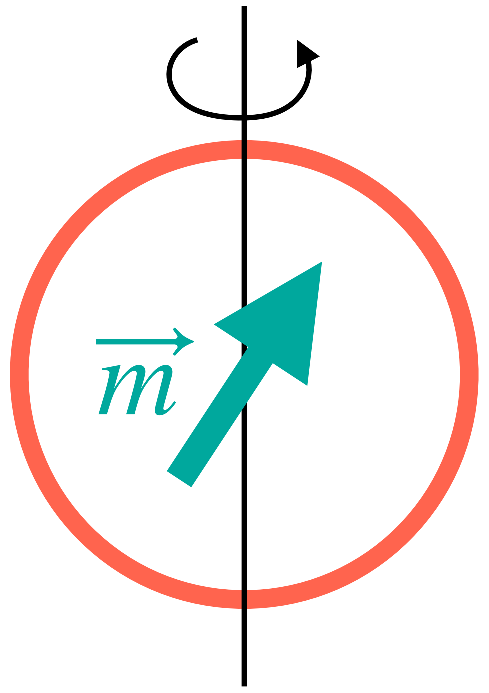
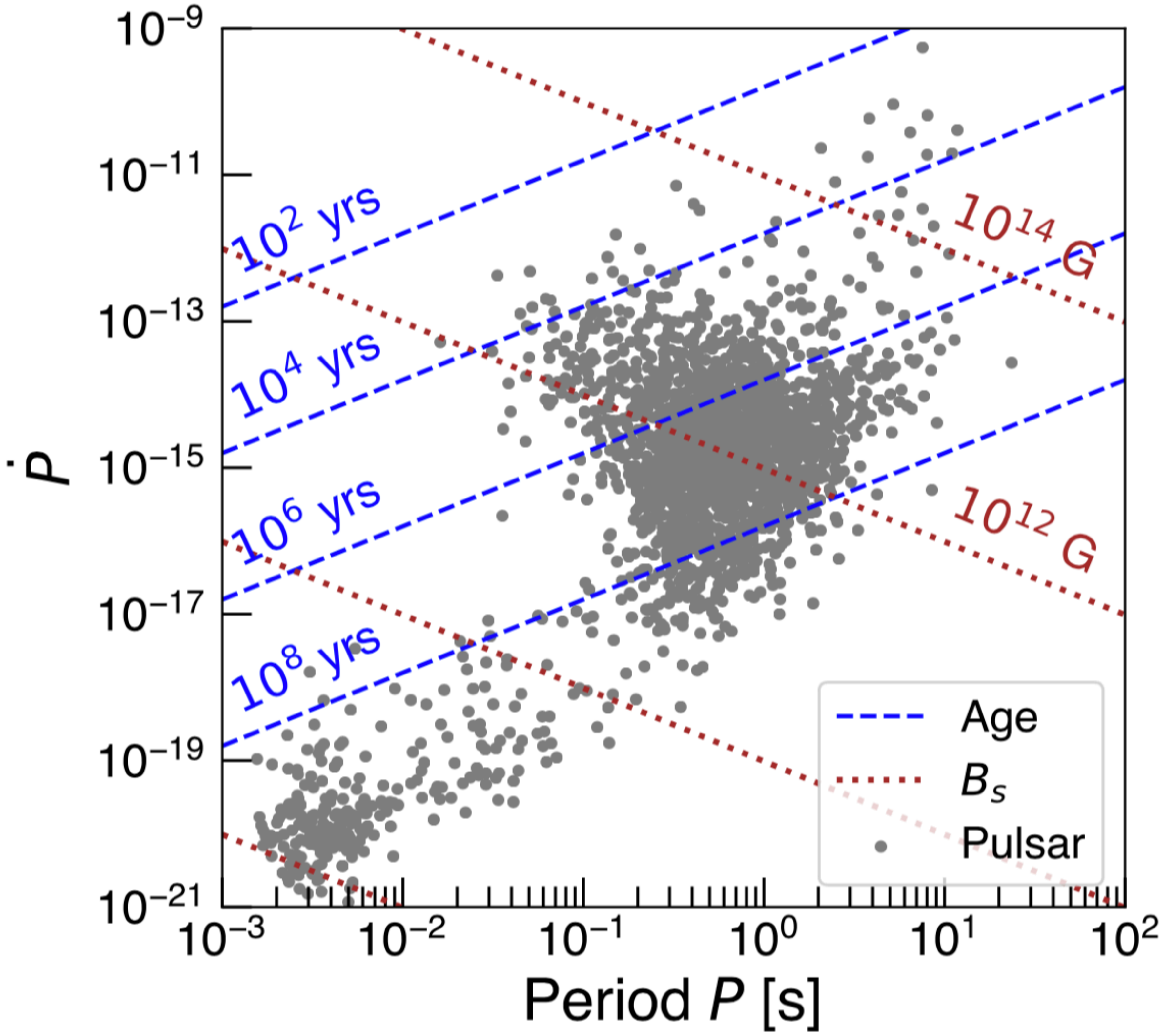




$\boxed{P - \dot{P} \text{ diagram}}$

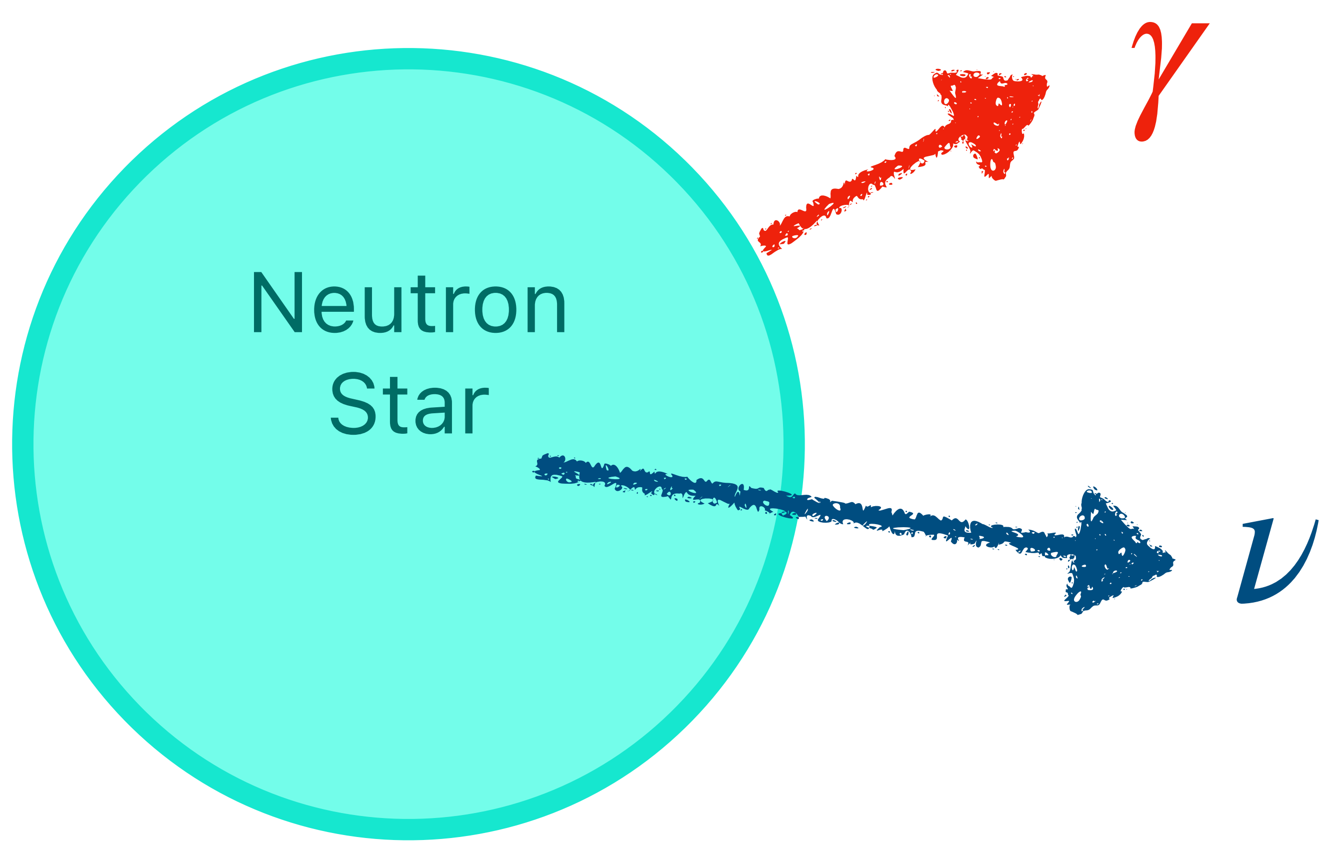
<=> Age (and magnetic field) of pulsars.

Fig. thanks to N.Nagata.

NS Standard Cooling Theory

For reviews, e.g., D.G.Yakovlev+, astro-ph/0402143,
D.Page+, astro-ph/0508056, 1302.6626

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



※ assuming isothermal state $T(r) \propto e^{-\Phi(r)}$ for simplicity (valid for $t \gtrsim 100$ sec).

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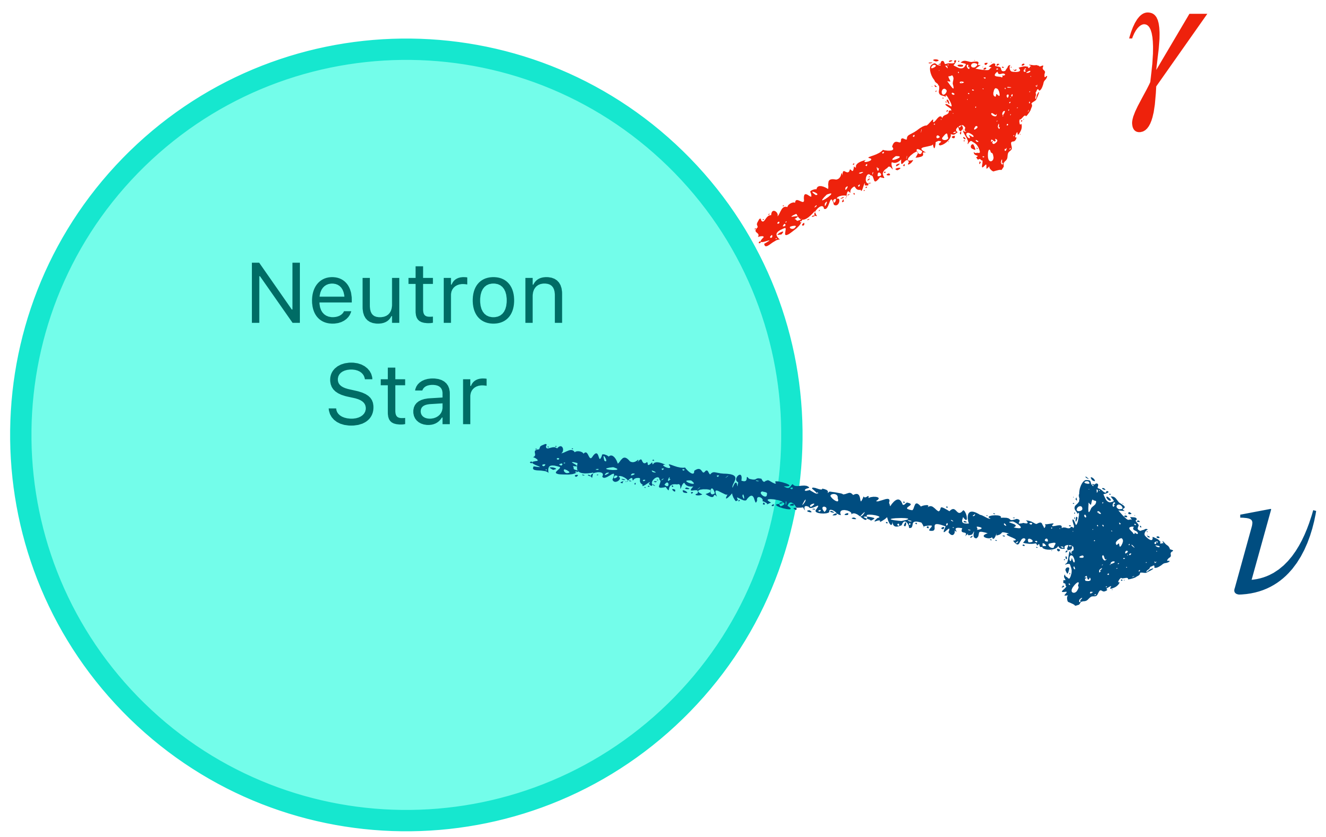

LHS = Temperature Evolution.

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

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

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RHS = Cooling Luminosity.

LHS = Temperature Evolution.

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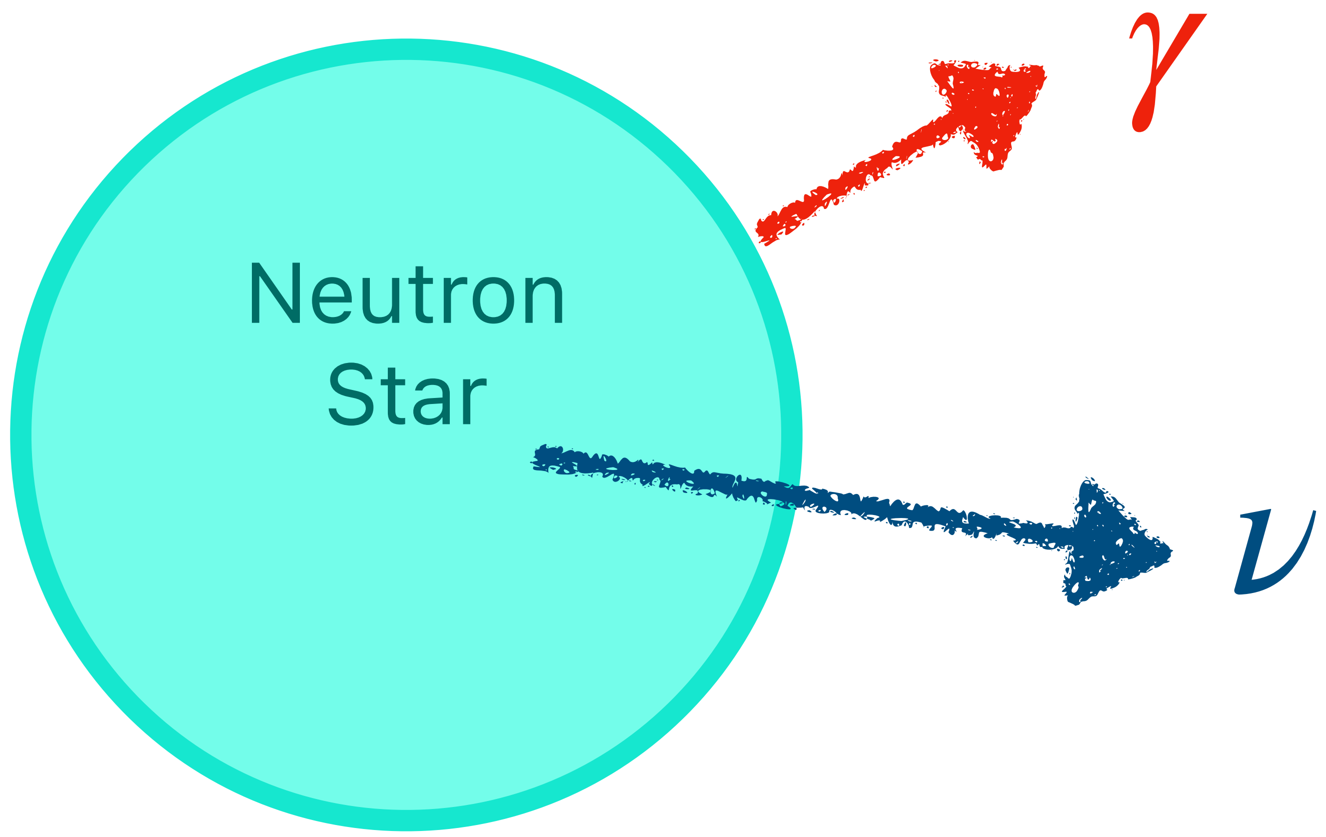

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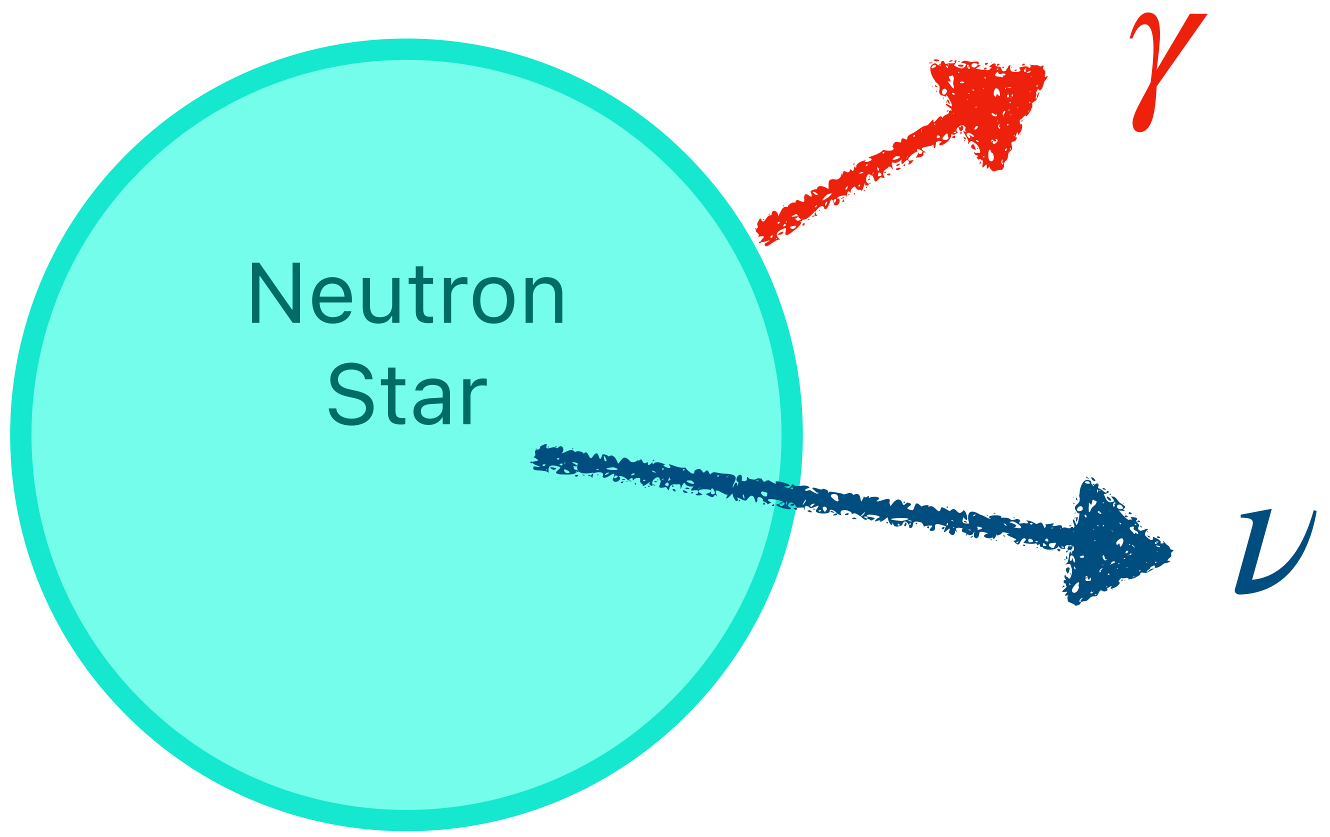
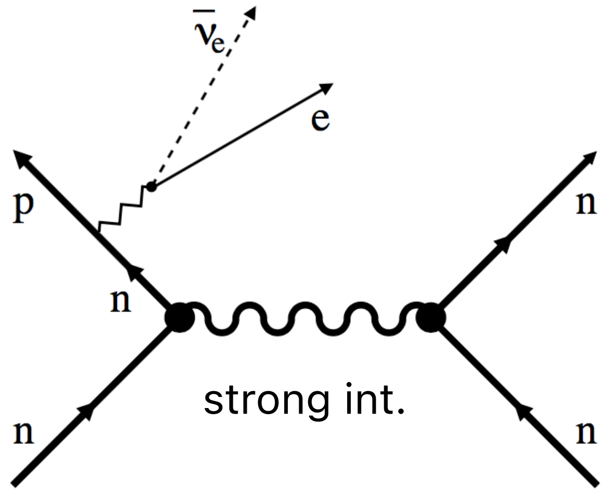
$$C\frac{dT}{dt} = -\boxed{L_\nu} - L_\gamma$$

For a **young NS** $(\tau \lesssim 10^5\ \mathrm{yrs})$

Neutrino emission is the dominant process.

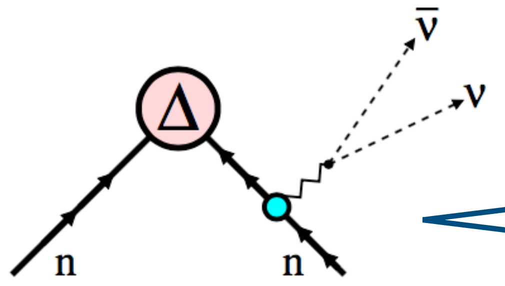




Modified Urca (& Bremsstrahlung)

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

Dominant process for $T > T_c$.



PBF (Cooper-pair breaking and formation)

$$\begin{cases} [\tilde{N}\tilde{N}] \to \tilde{N} + \tilde{N} \\ \tilde{N} + \tilde{N} \to [\tilde{N}\tilde{N}] + \nu + \bar{\nu} \end{cases}$$

($\tilde{N}$: quasi-paticle, $[\tilde{N}\tilde{N}]$: Cooper-pair)

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

NS Standard Cooling Theory

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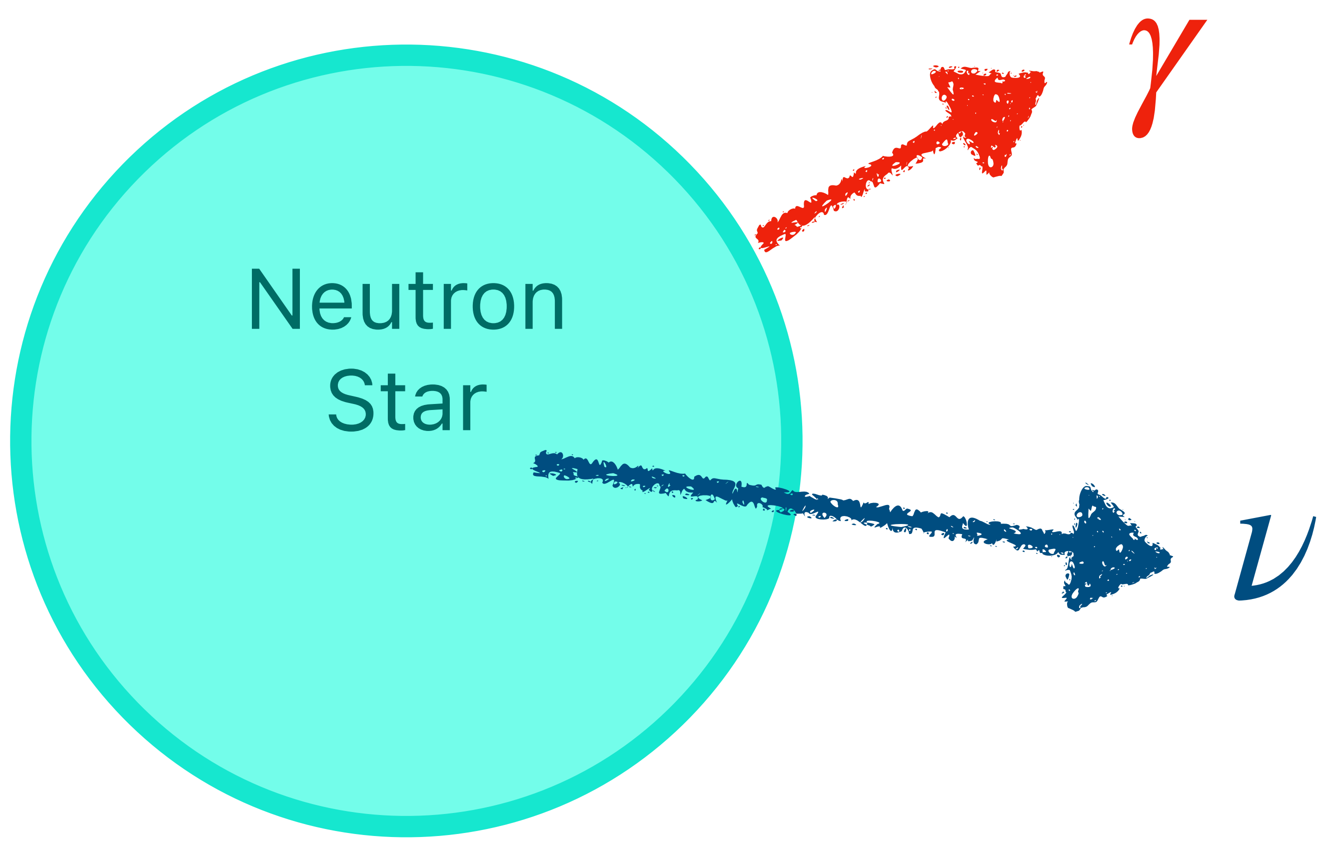
D.Page+, astro-ph/0508056, 1302.6626

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



For an **old NS** ($\tau \gtrsim 10^5$ yrs).

Photon emission is the dominant process.

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

NS Standard Cooling Theory

For reviews, e.g., D.G.Yakovlev+, astro-ph/0402143,
D.Page+, astro-ph/0508056, 1302.6626

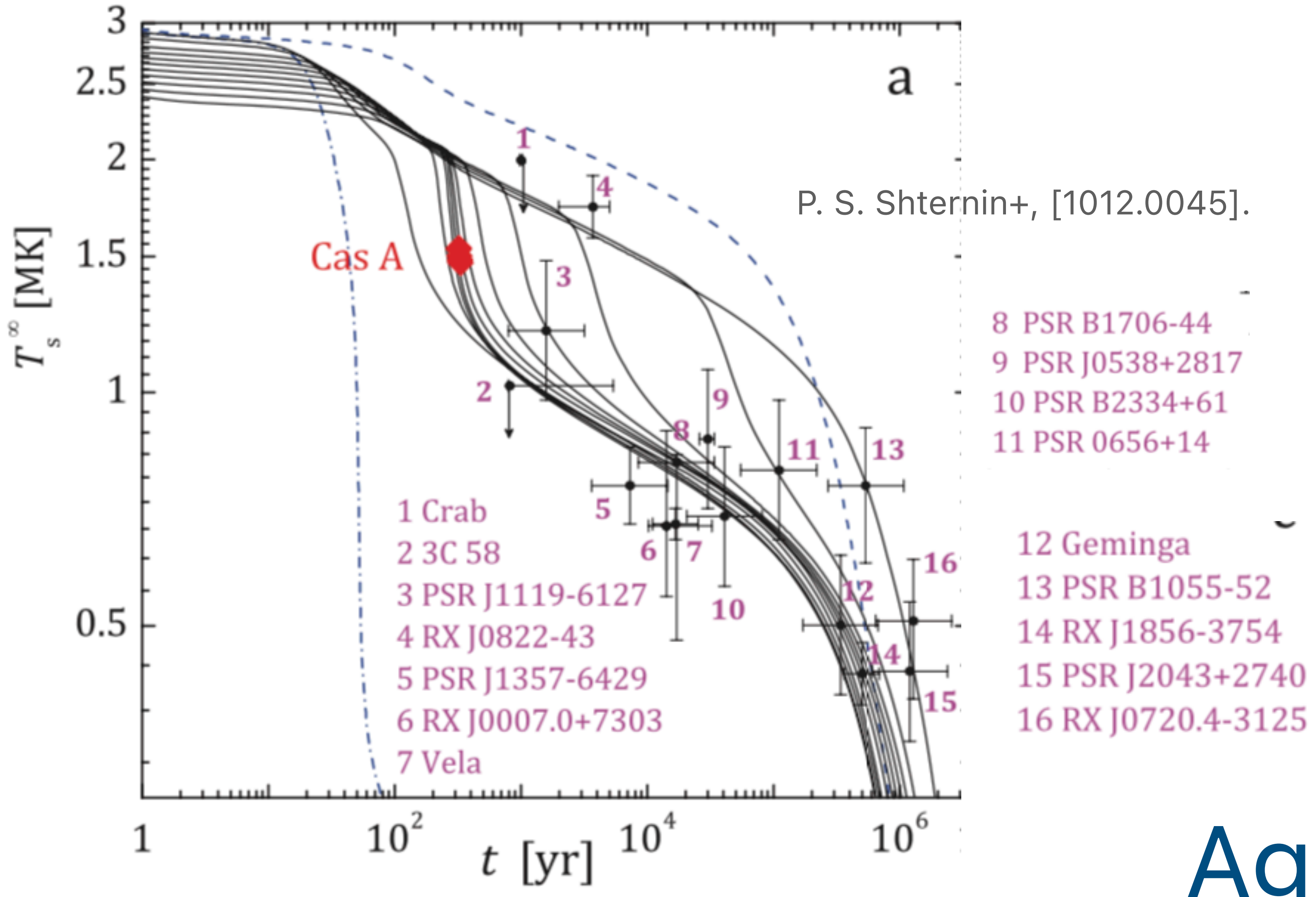
$$C\frac{dT}{dt} = -L_\nu - L_\gamma$$

The minimal cooling scenario can successfully explain many NS temperature observations.

D.Page+, astro-ph/0403657,
M.E.Gusakov+, astro-ph/0404002,
D.Page+, 0906.1621

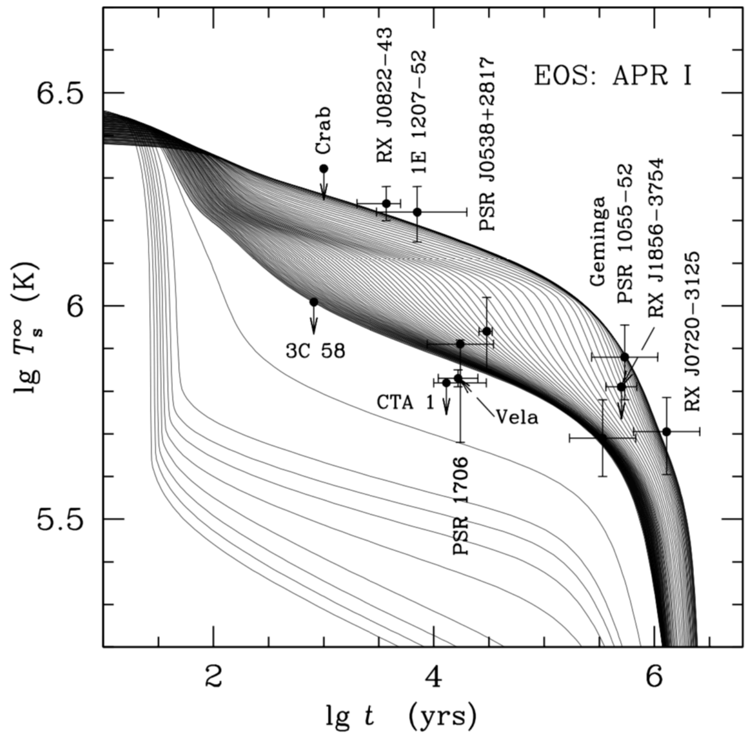
👉 **More on this later.**

Surface Temperature

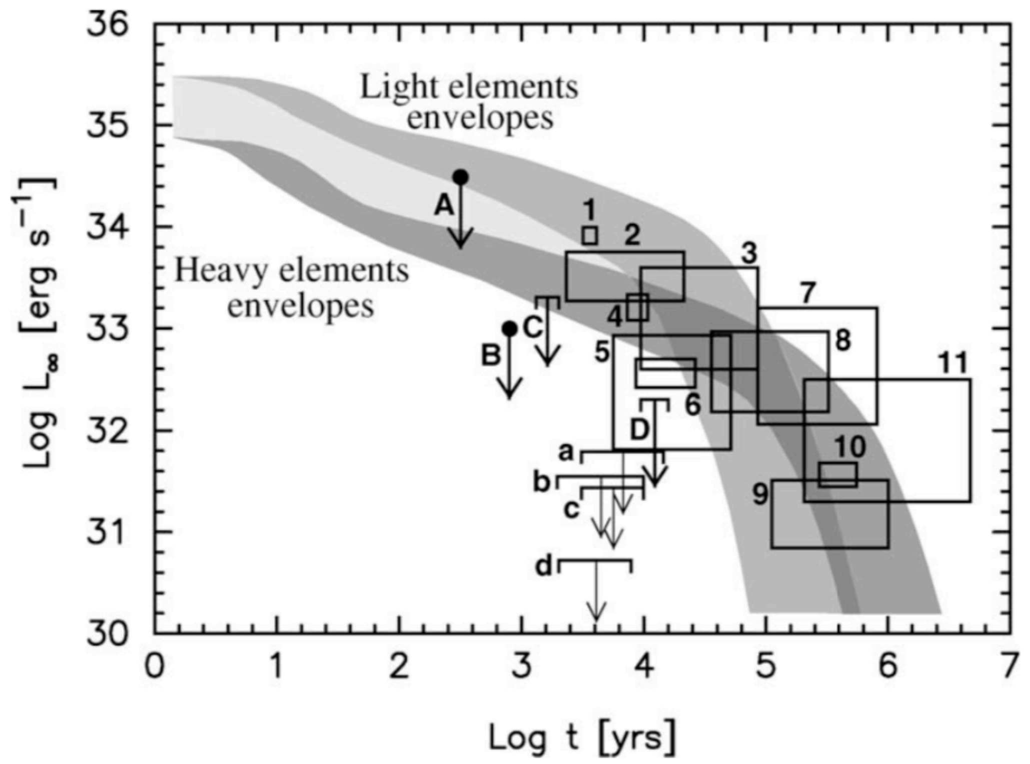


P. S. Shternin+, [1012.0045].

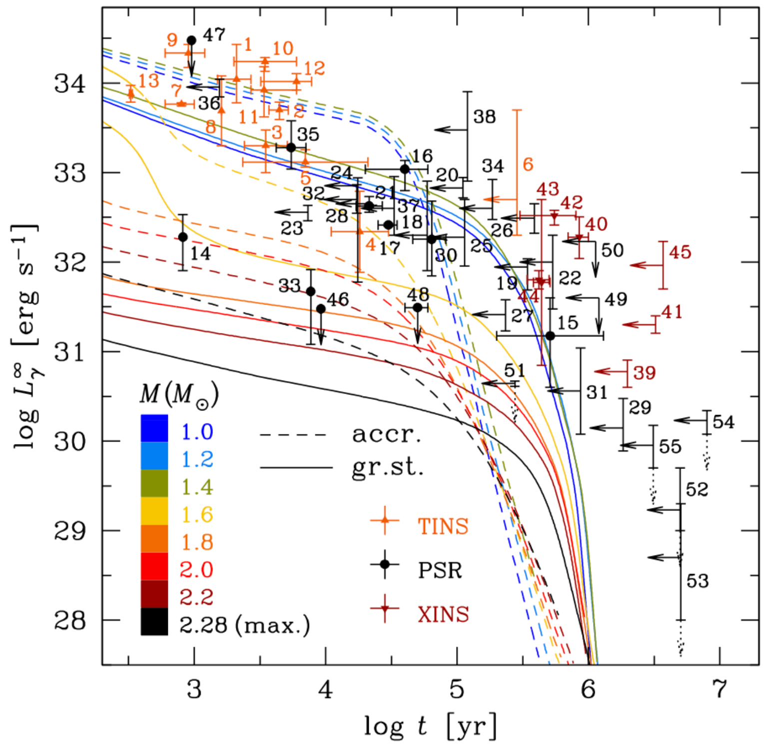
M. E. Gusakov, A. D. Kaminker, D. G. Yakovlev, O. Y. Gnedin
Mon.Not.Roy.Astron.Soc. **363** (2005) 555-562



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



A. Y. Potekhin+,2006.15004



Ages of Neutron Stars

estimated by spin-down age $\tau_{\rm sd} = P/(2\dot{P})$ or kinematics.

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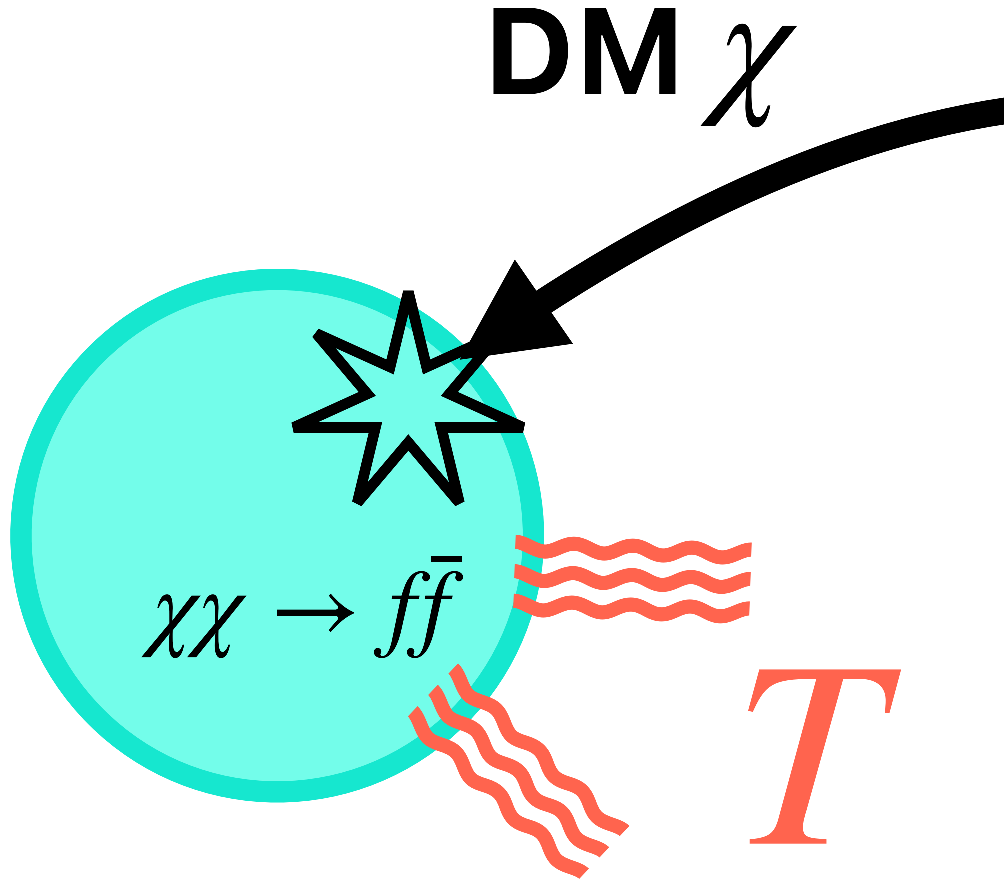
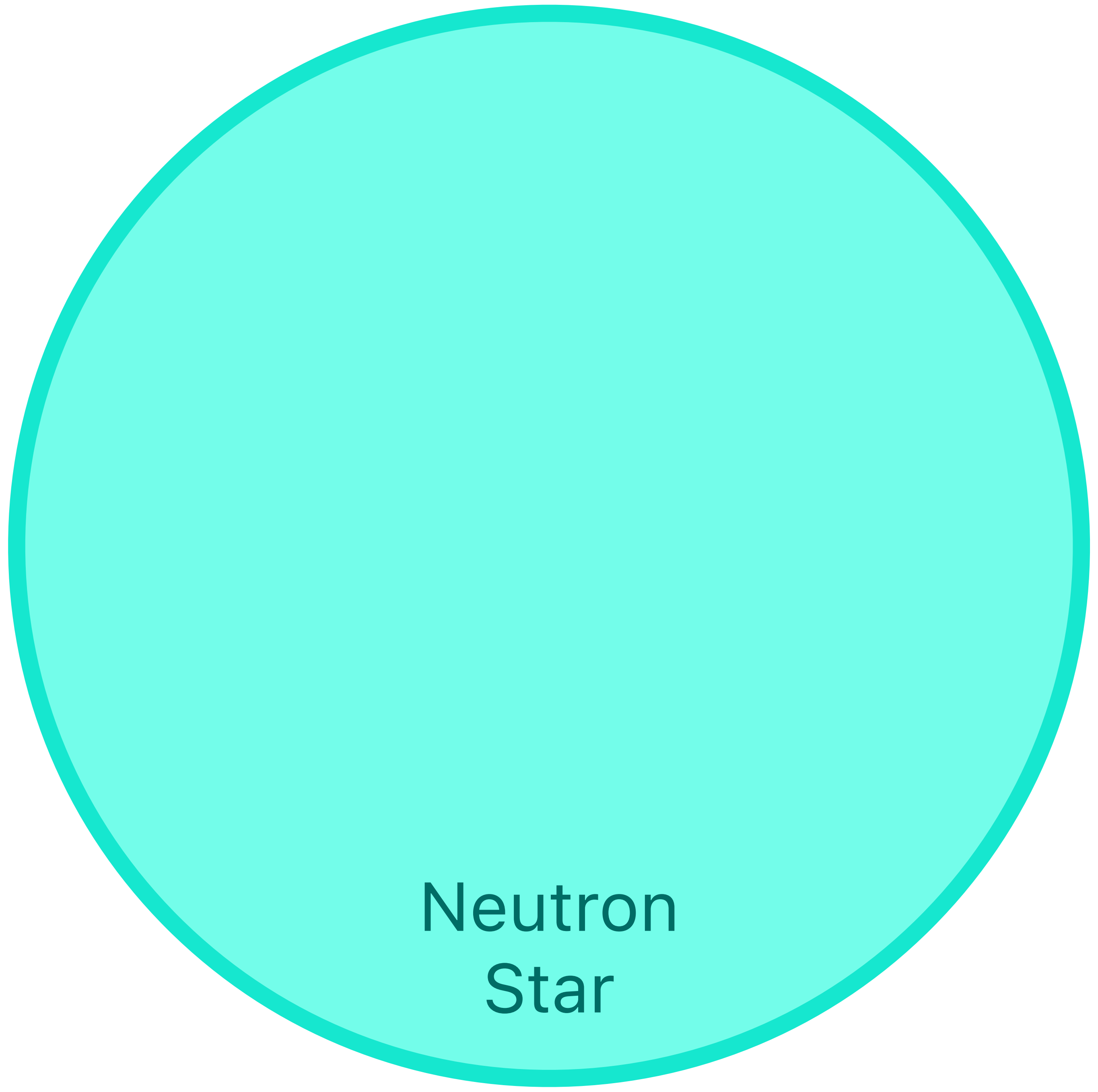


Dark Matter Heating of NS

Basic Idea

Kouvaris, 0708.2362
Baryakhtar+, 1704.01577



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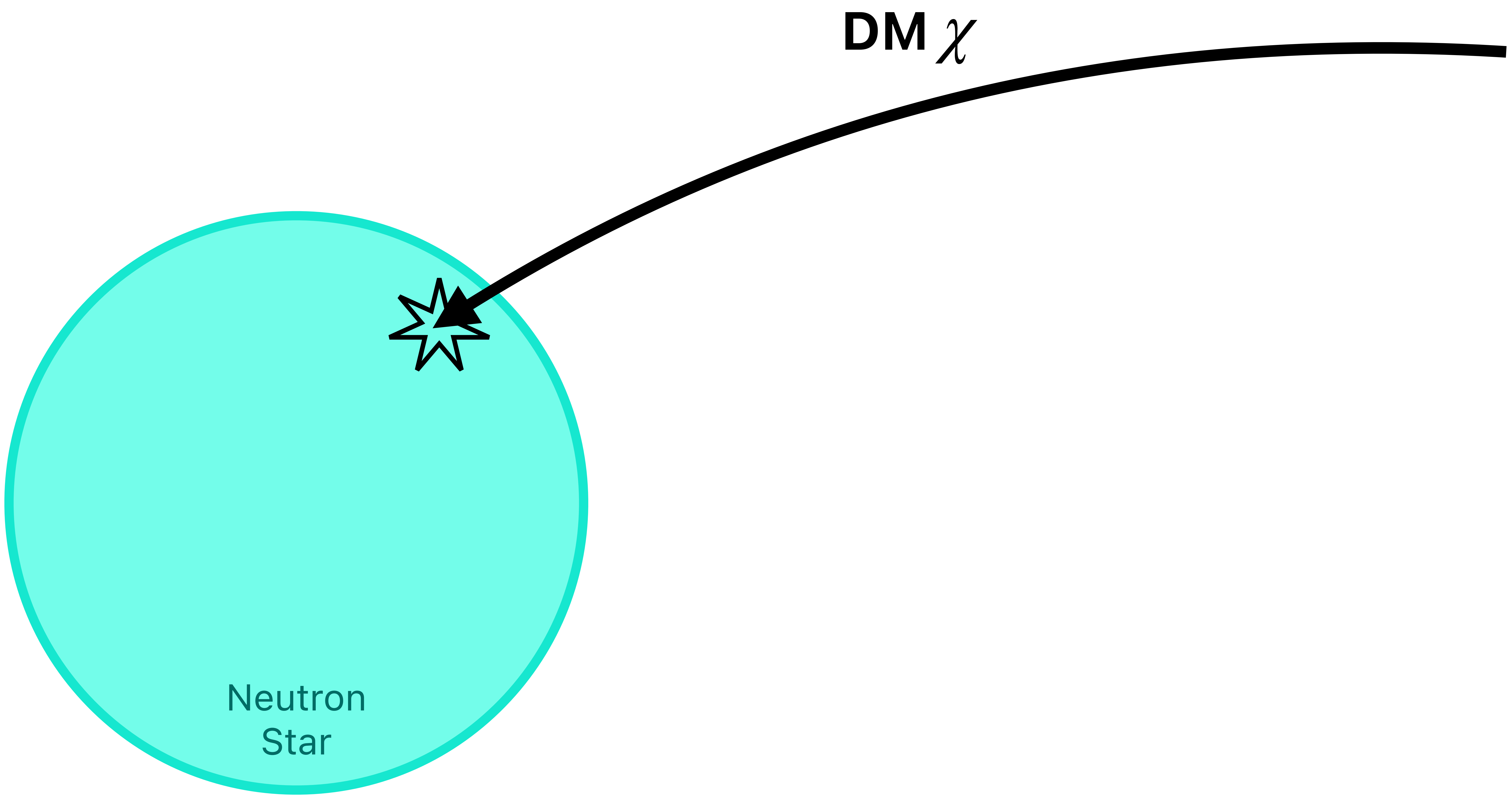

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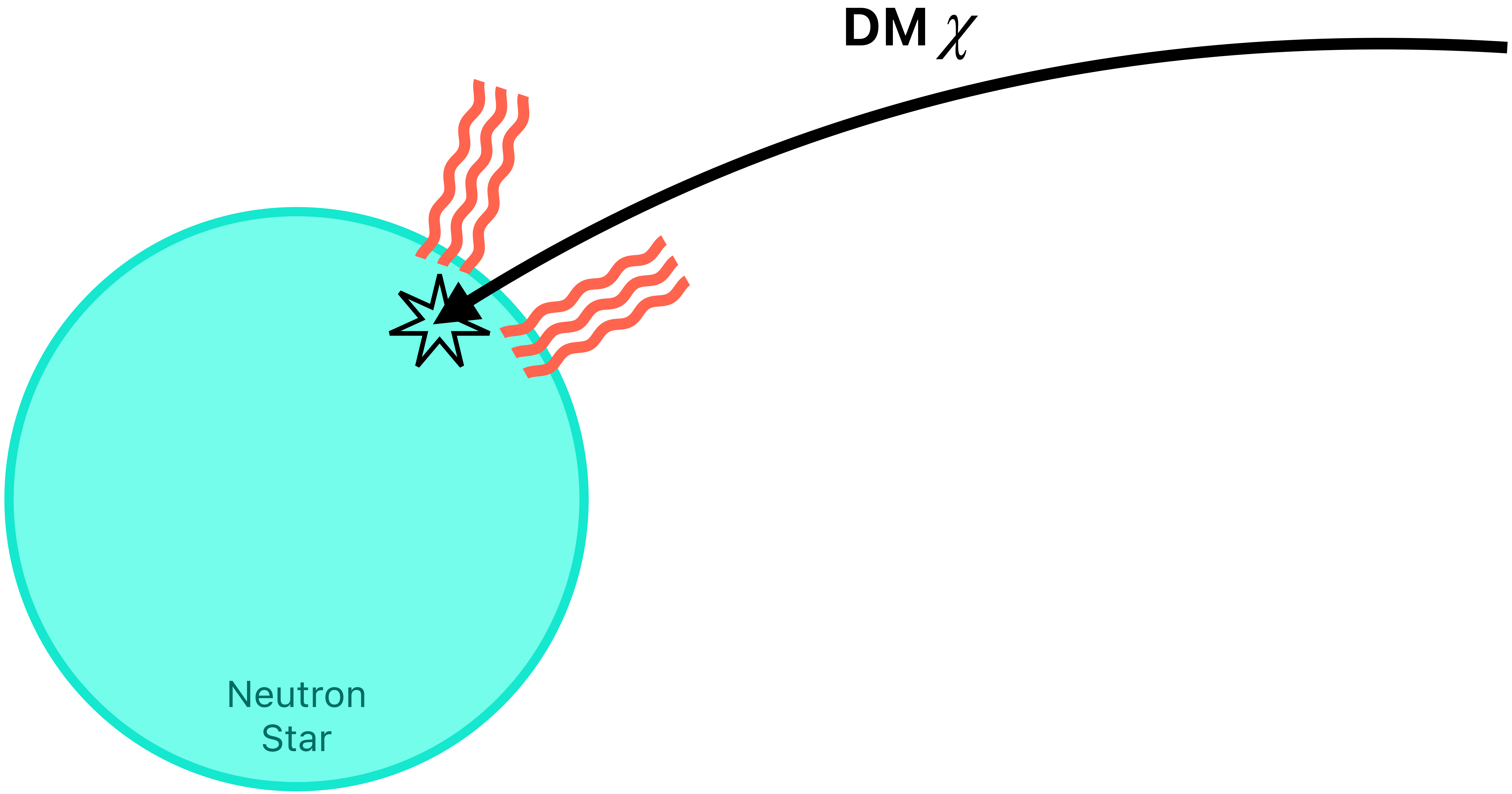

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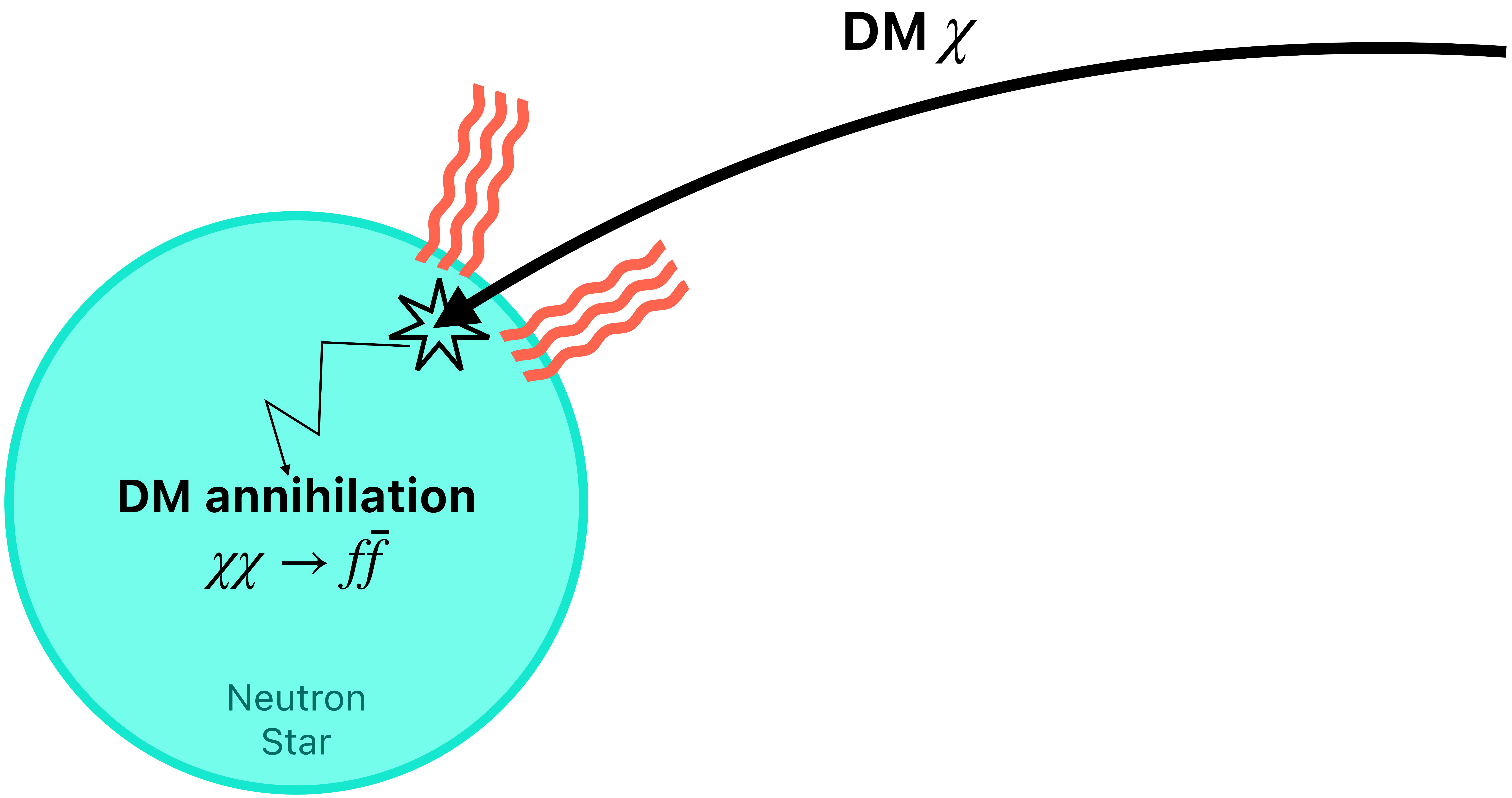

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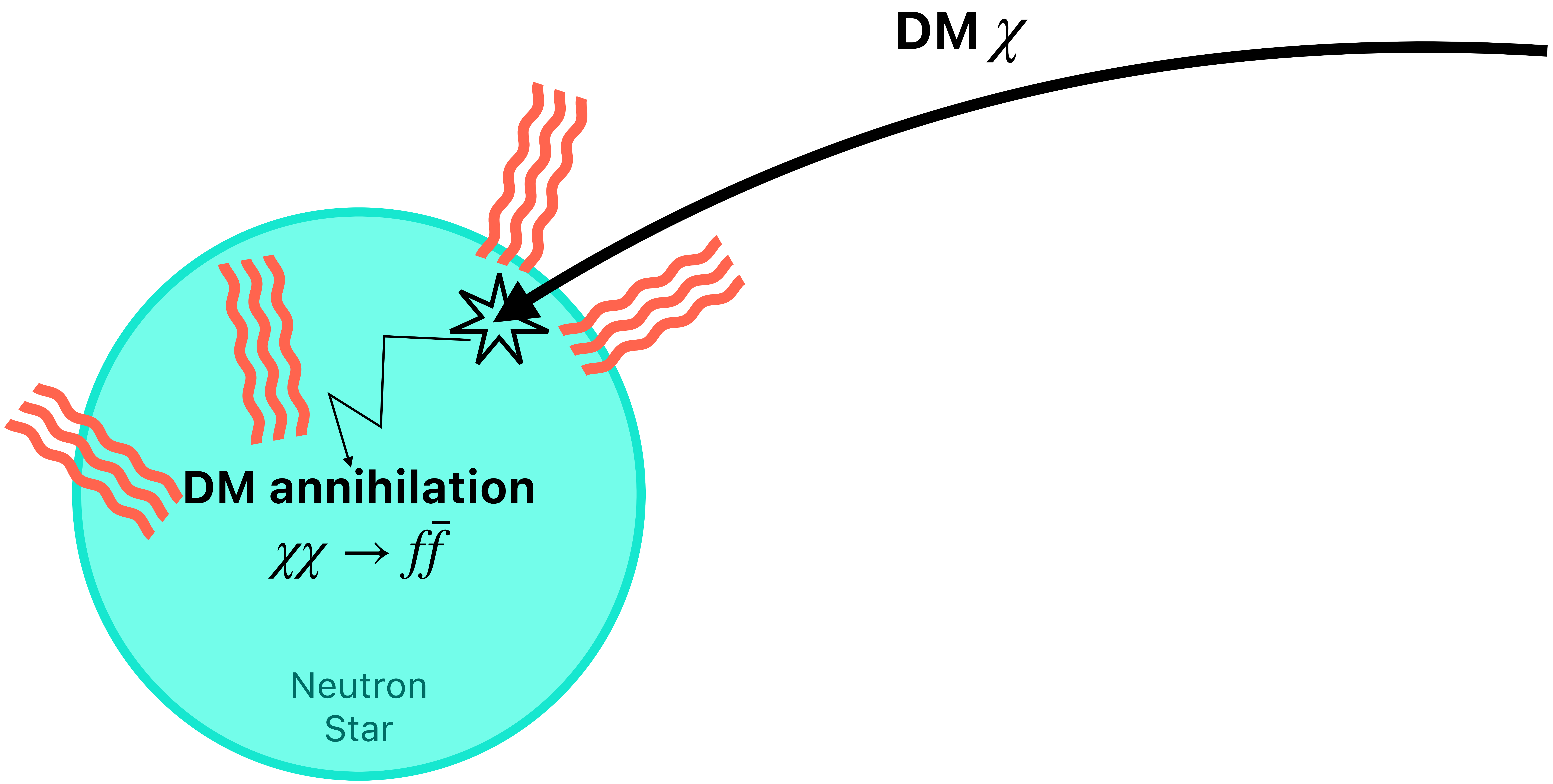

DM χ

DM annihilation

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

Neutron Star

Dark Matter Heating of NS

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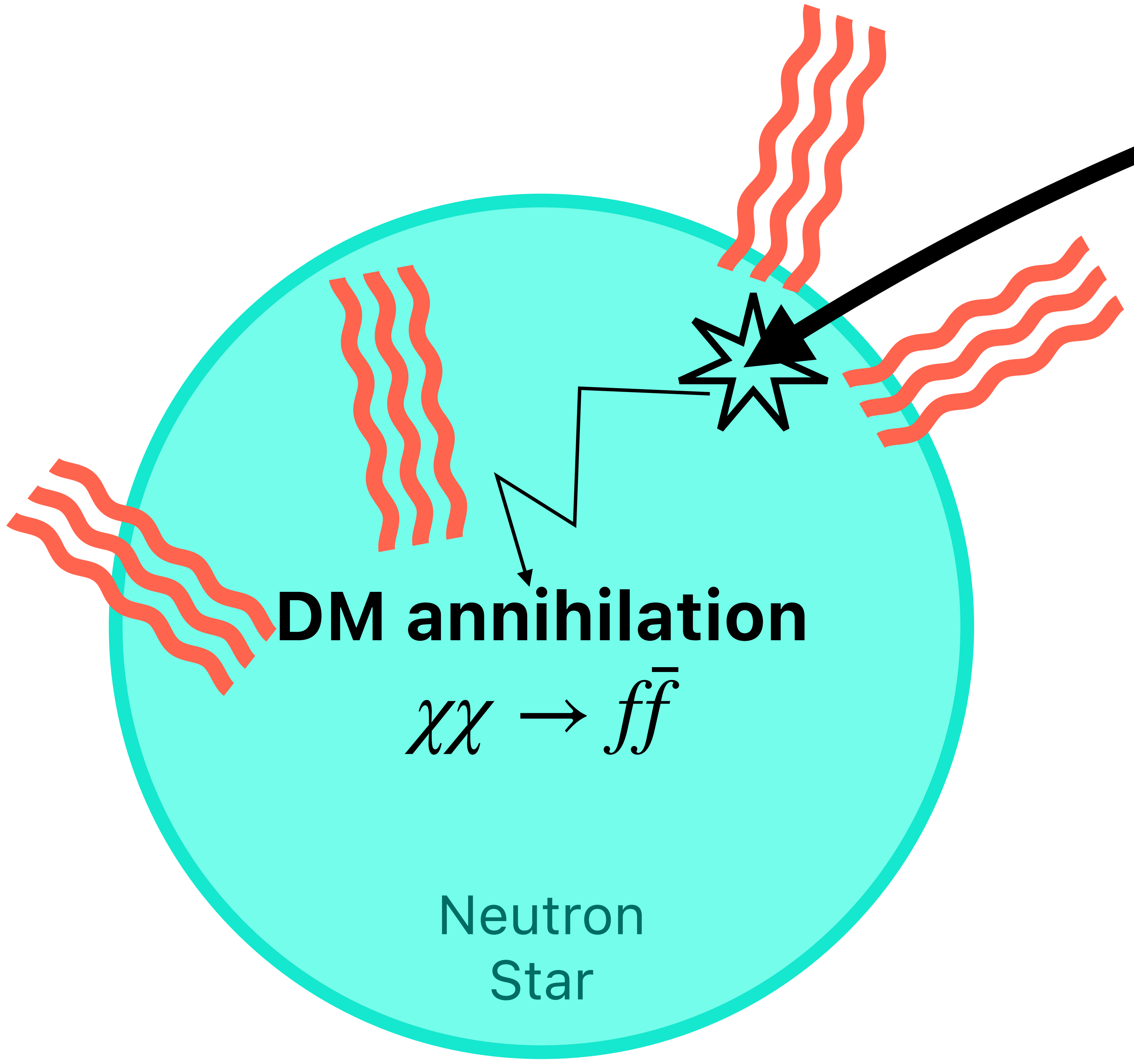
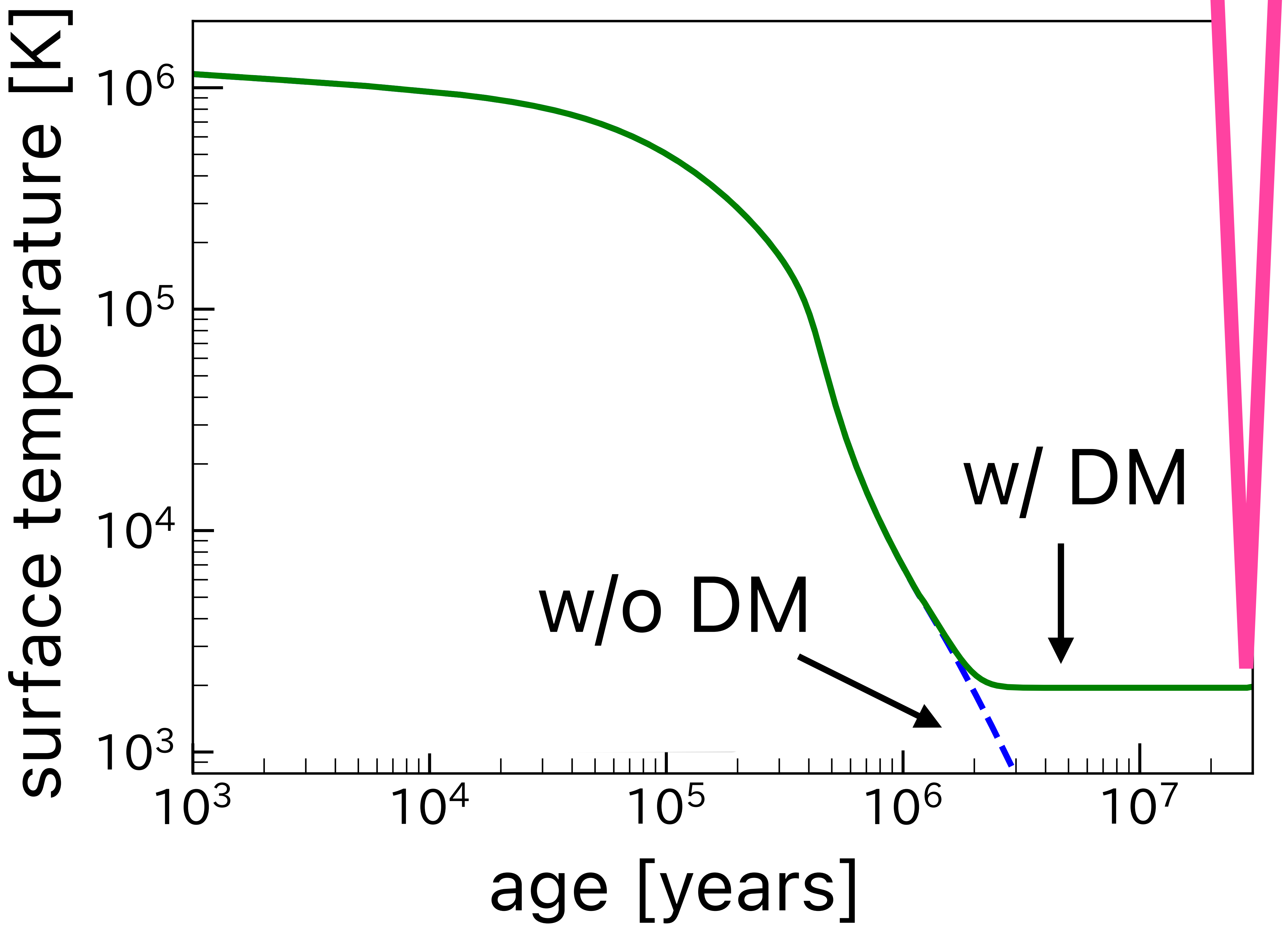
$$C\frac{dT}{dt} = \underbrace{-L_\nu}_{\ll L_\gamma} \underbrace{-L_\gamma + L_{\text{DM heating}}}_{\simeq 0}$$

DM χ

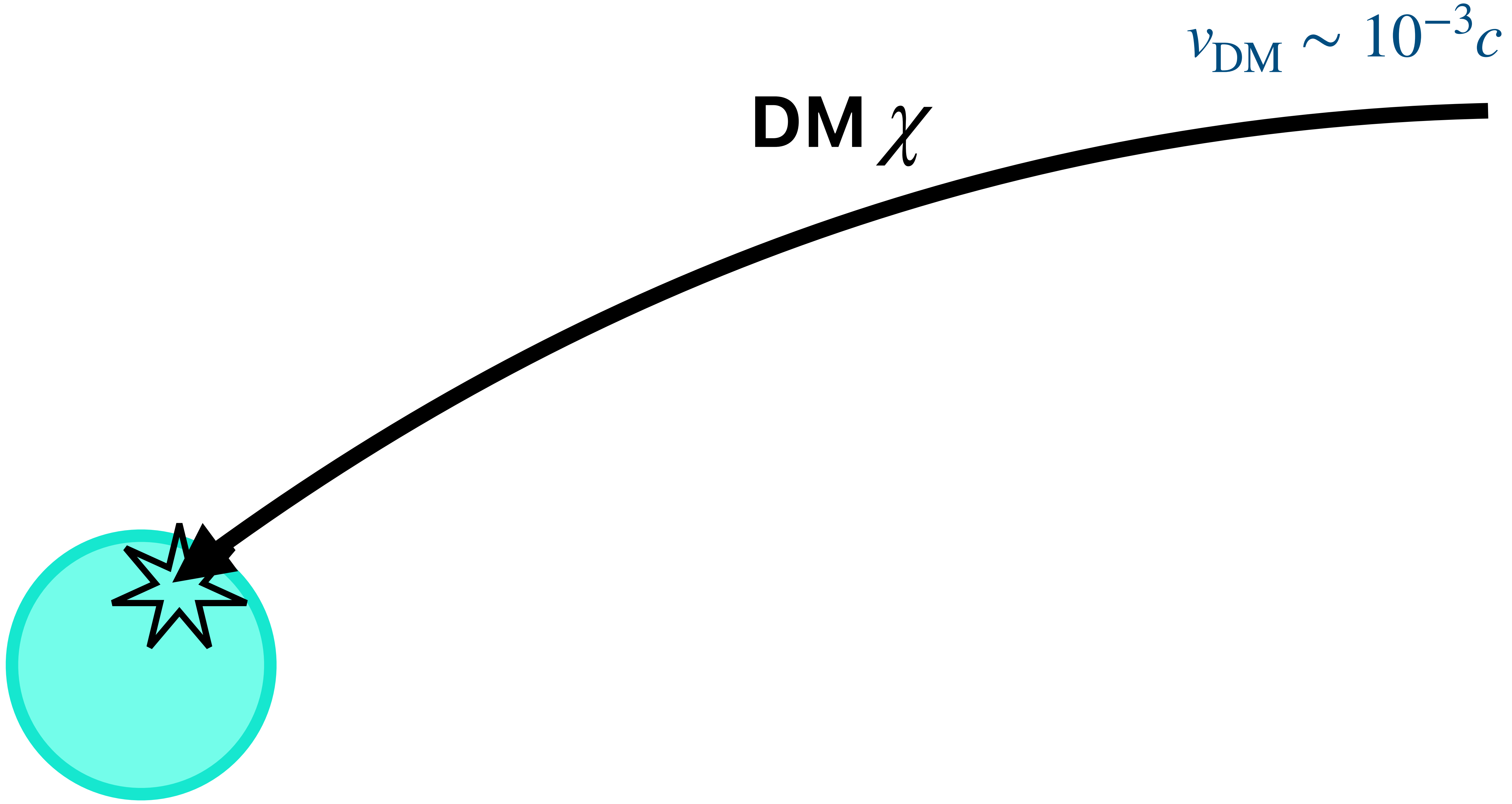




Old and warm NS = DM signal ?!

Dark Matter Heating of NS

Back-of-envelope estimates



Dark Matter Heating of NS

Back-of-envelope estimates

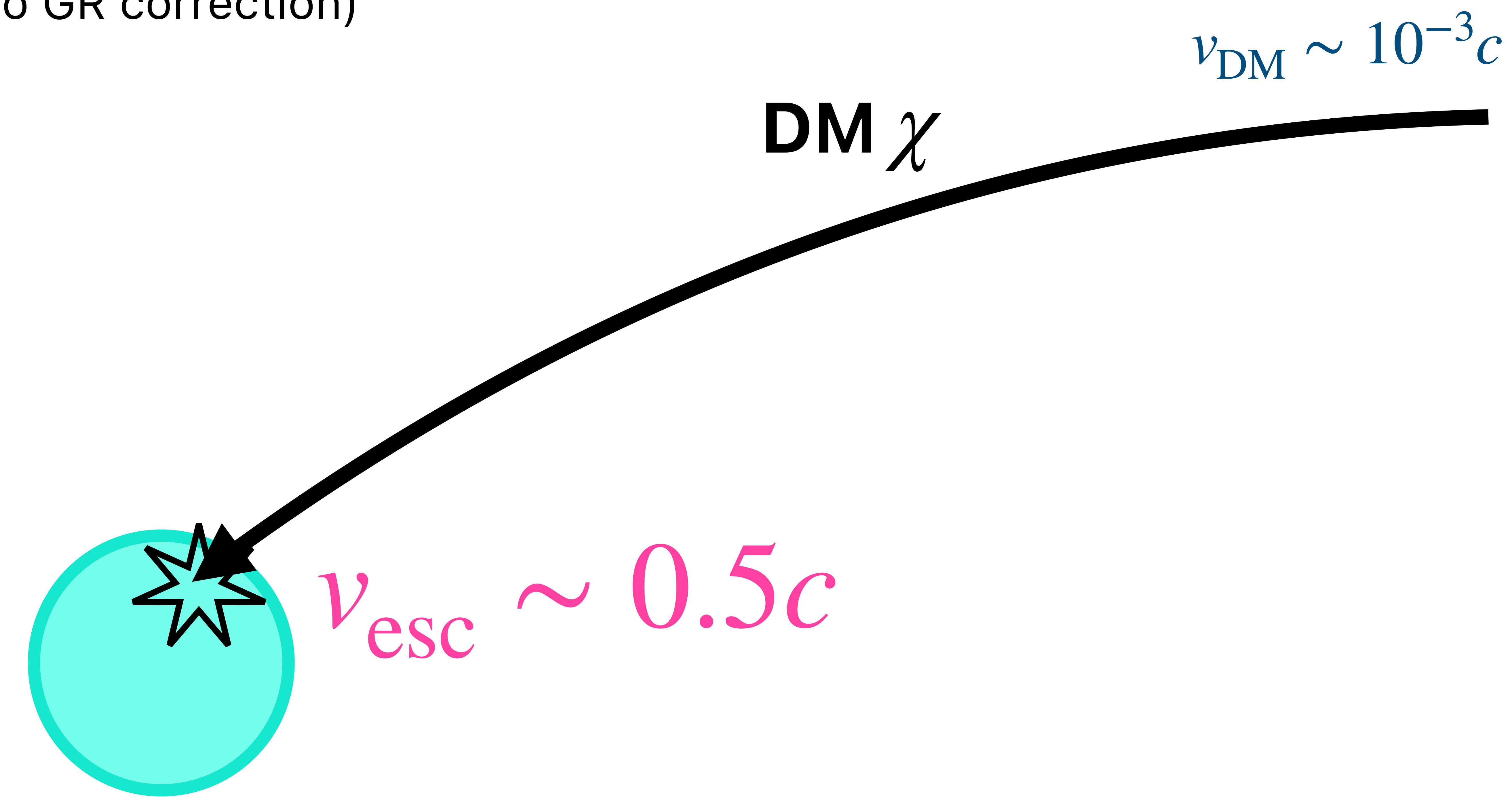
(1) DM velocity at the surface: $v_{\rm esc} \sim 0.5c$ (up to GR correction)

- From the energy conservation,

  escape velocity $v_{\rm esc} \sim \sqrt{\dfrac{2GM_{\rm NS}}{R_{\rm NS}}} \sim 0.5\ c$

  up to O(1) GR correction.

  → almost relativistic speed!

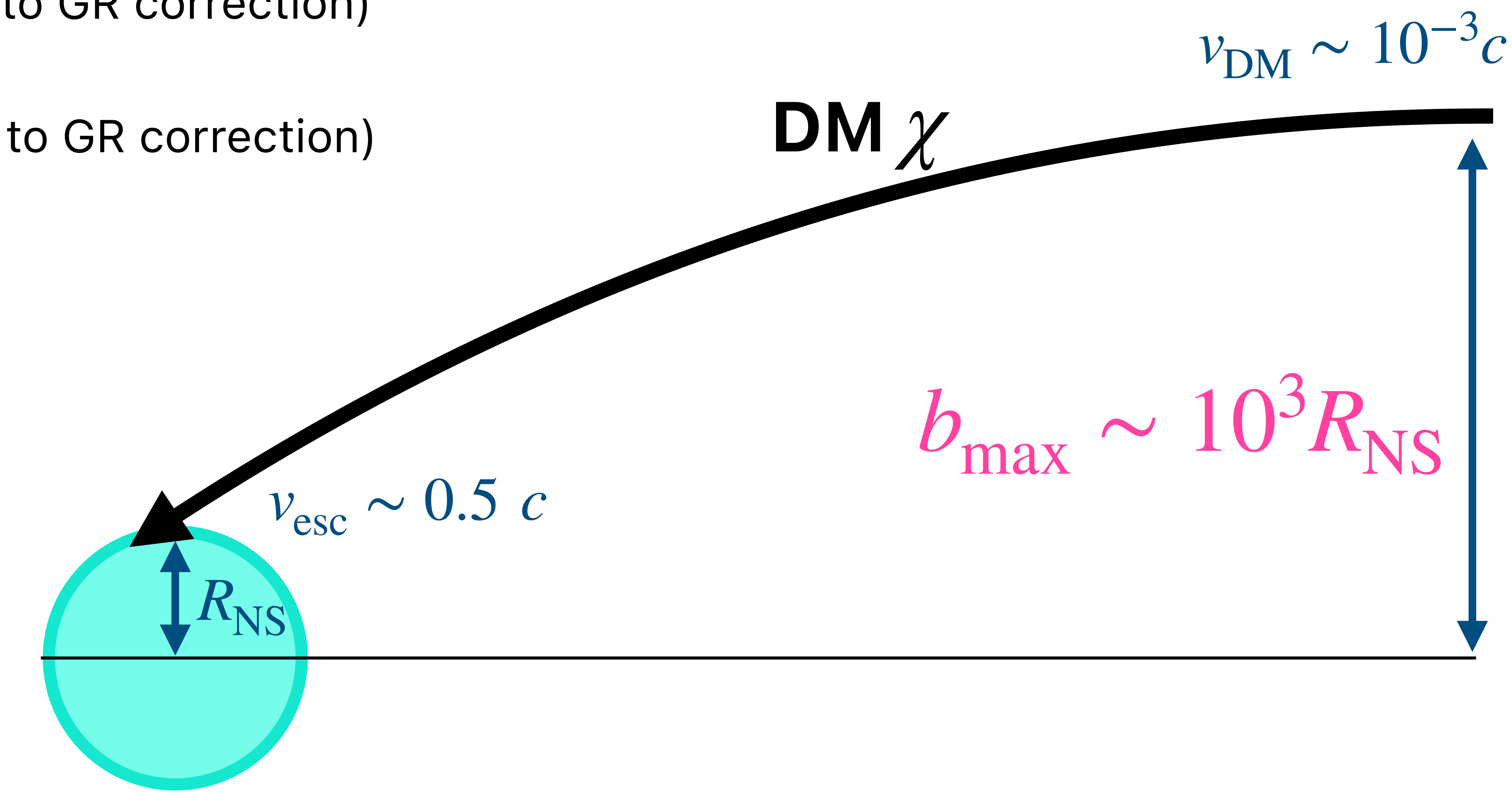


Dark Matter Heating of NS

Back-of-envelope estimates

(1) DM velocity at the surface: $v_{\rm esc} \sim 0.5c$ (up to GR correction)

(2) Impact factor: $b_{\rm max} \sim \frac{v_{\rm esc}}{v_{\rm DM}} R_{\rm NS} \sim 10^3\ R_{\rm NS}$ (up to GR correction)



- From the angular momentum conservation,

$$b_{\rm max} v_{\rm DM} \sim R_{\rm NS} v_{\rm esc}$$

$$\therefore \quad b_{\rm max} \sim \frac{v_{\rm esc}}{v_{\rm DM}} R_{\rm NS} \sim 10^3\ R_{\rm NS}$$

up to O(1) GR correction, $e^{-\Phi(R_{\rm NS})} = (1 - 2GM_{\rm NS}/R_{\rm NS})^{-1/2} \sim 1.2.$

→ $\sim \mathcal{O}(10^6)$ flux enhancement!

Dark Matter Heating of NS

Back-of-envelope estimates

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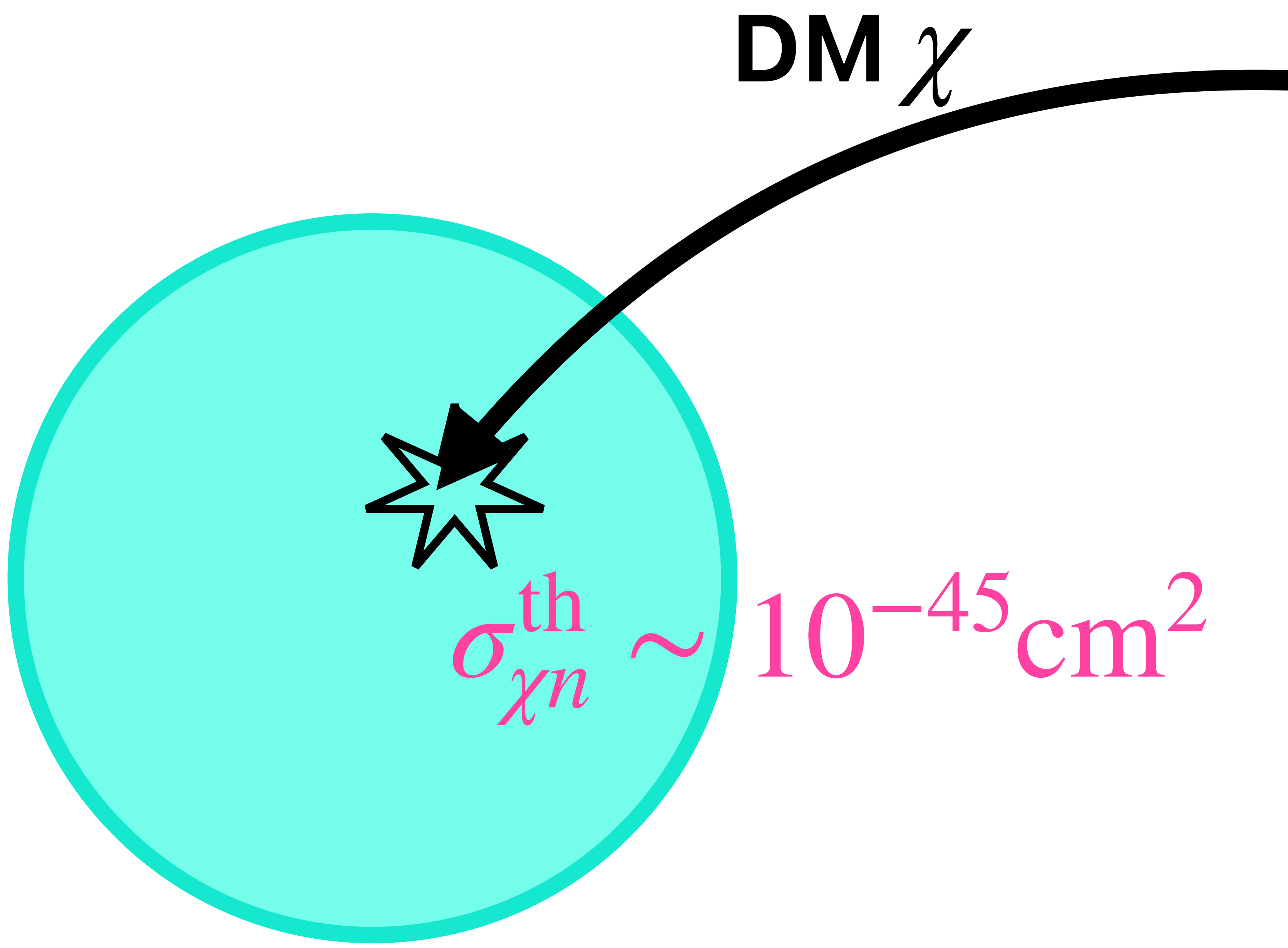
(3) Threshold cross section: $\sigma_{\chi n} > \sigma_{\chi n}^{\rm th} \sim \dfrac{1}{R_{\rm NS} n_N} \sim 10^{-45}\ {\rm cm}^2$

- Assuming DM-neutron scattering, the mean free path is $L \sim 1/(\sigma_{\chi n} n_N)$ where $n_N \sim 4 \times 10^{38}/{\rm cm}^3$ is the neutron density, and the scatterings occur if $L \lesssim R_{\rm NS}$.



Dark Matter Heating of NS

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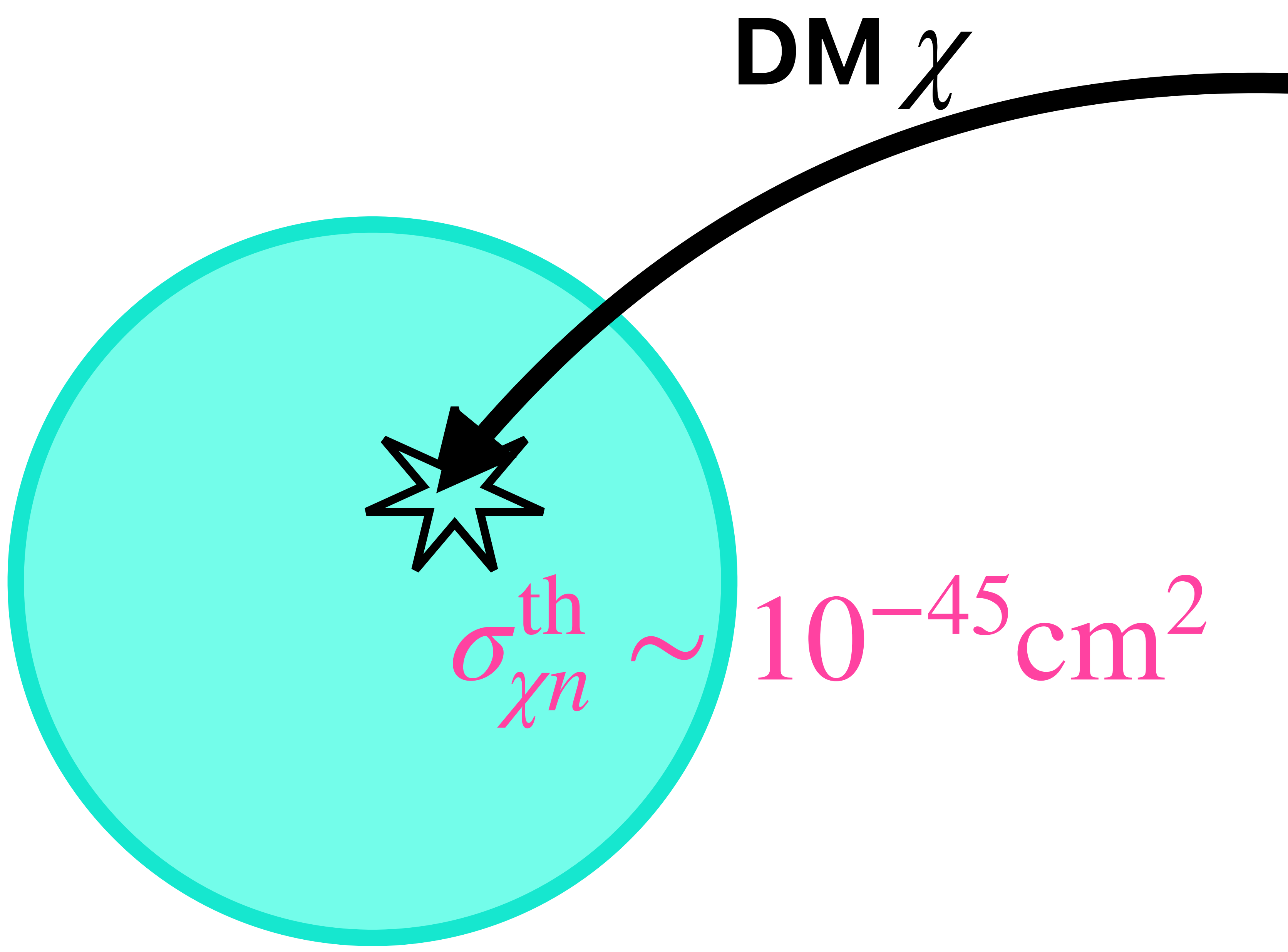
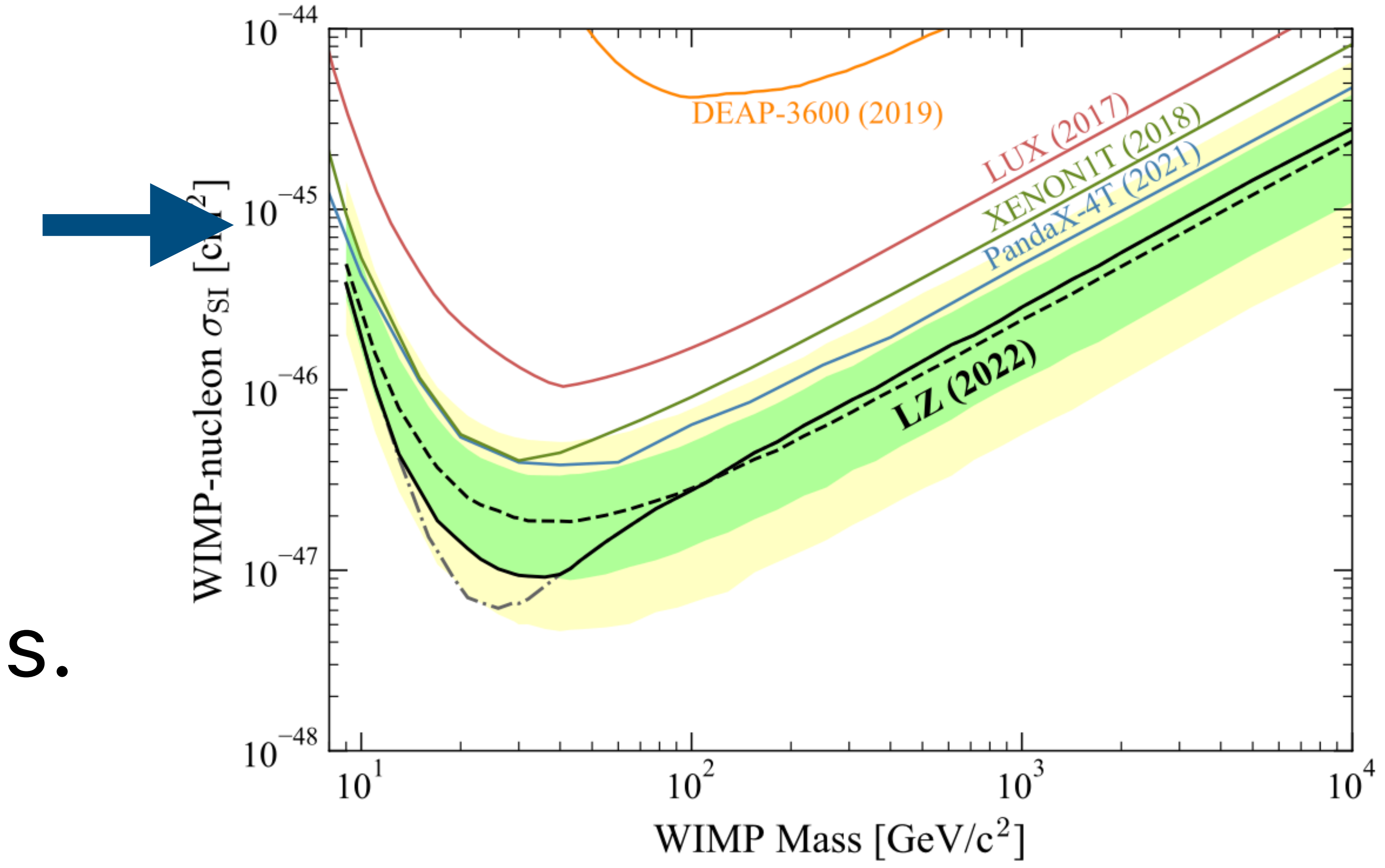


$\sigma_{\chi n}^{\rm th} \sim 10^{-45}{\rm cm}^2$



… comparable or slightly weaker than
the current direct detection sensitivities.
(but some advantages 👉 more later.)

Dark Matter Heating of NS

Back-of-envelope estimates

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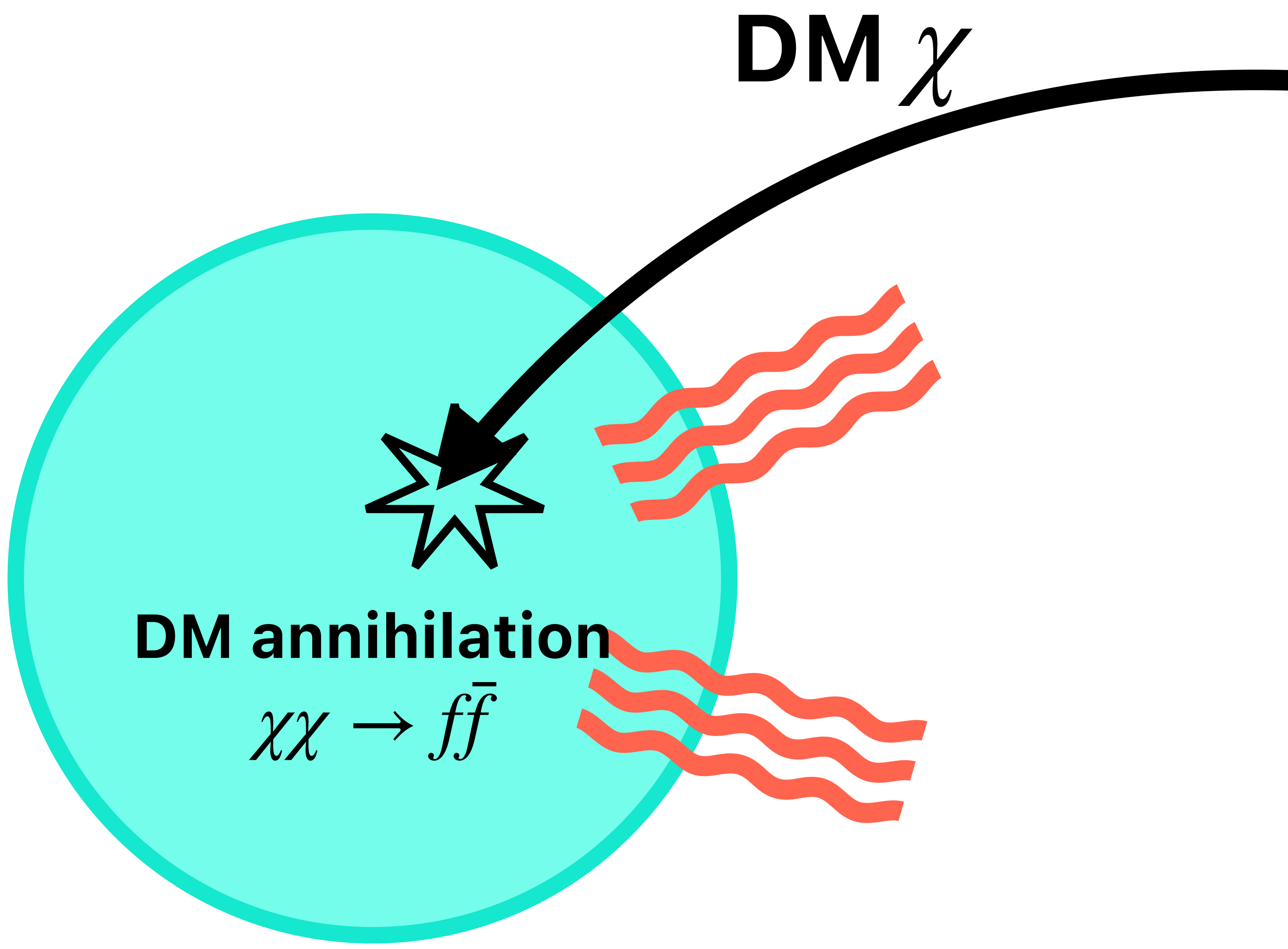
(4) Resultant surface temperature: $T \sim$ a few 1000 K



$T \sim$ (a few) 1000 K

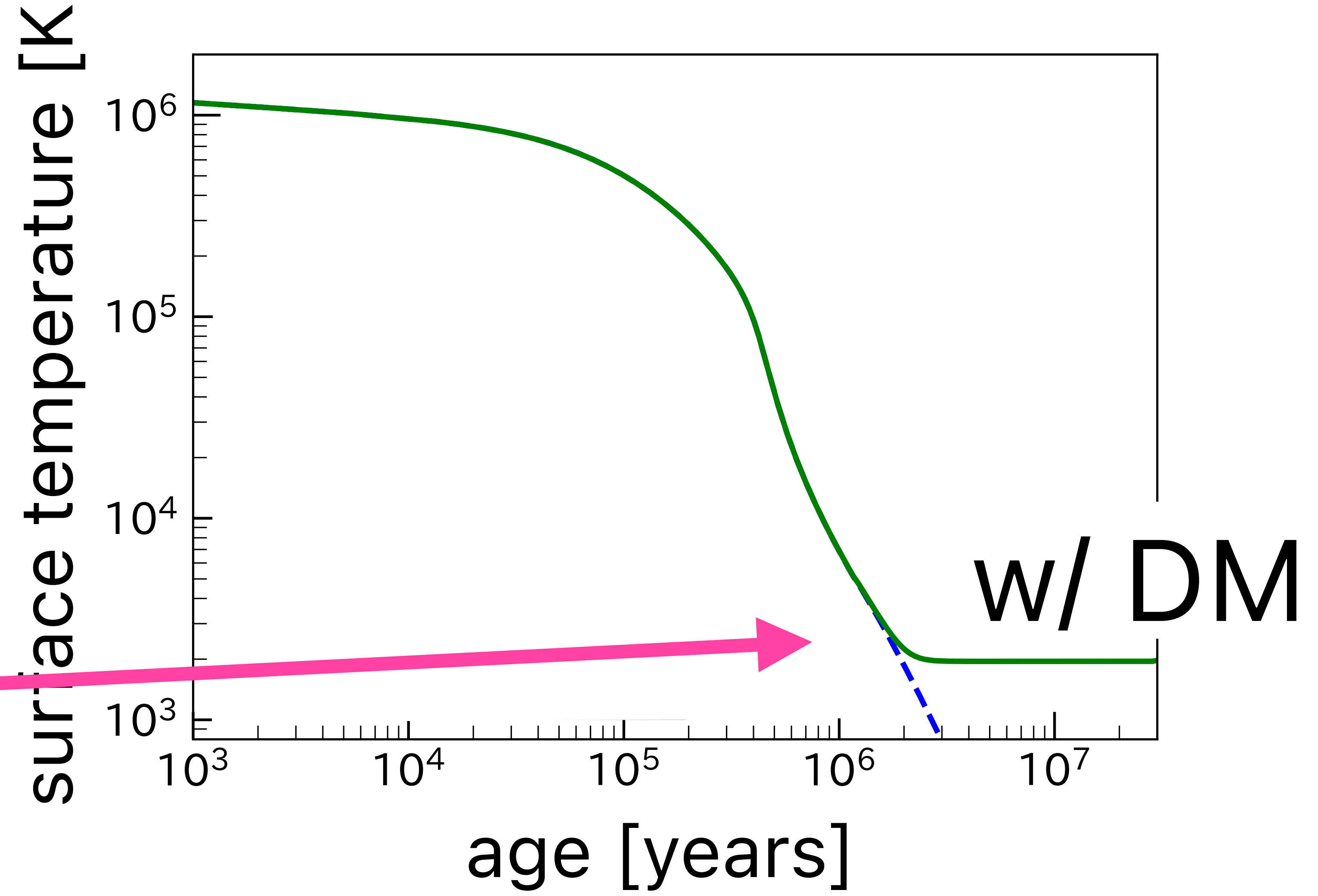
- The energy injection per time is estimated as

$$L_{\rm DM\ heatng} = \dot{E}_{\rm DM} \sim \pi b_{\rm max}^2 \cdot v_{\rm DM} \cdot \underbrace{n_{\rm DM} \cdot m_{\rm DM}}_{\rho_{\rm DM}} \sim 10^{22} {\rm erg/s}$$

… independent of the DM mass!

For an old enough NS with $\tau \gtrsim 10^6$ yrs,

$$L_{\rm DM\ heating} \sim L_\gamma = 4\pi R_{\rm NS}^2 \sigma_{\rm SB} T^4 \quad \Longrightarrow \quad T \sim \text{a few 1000 K}.$$



Dark Matter Heating of NS

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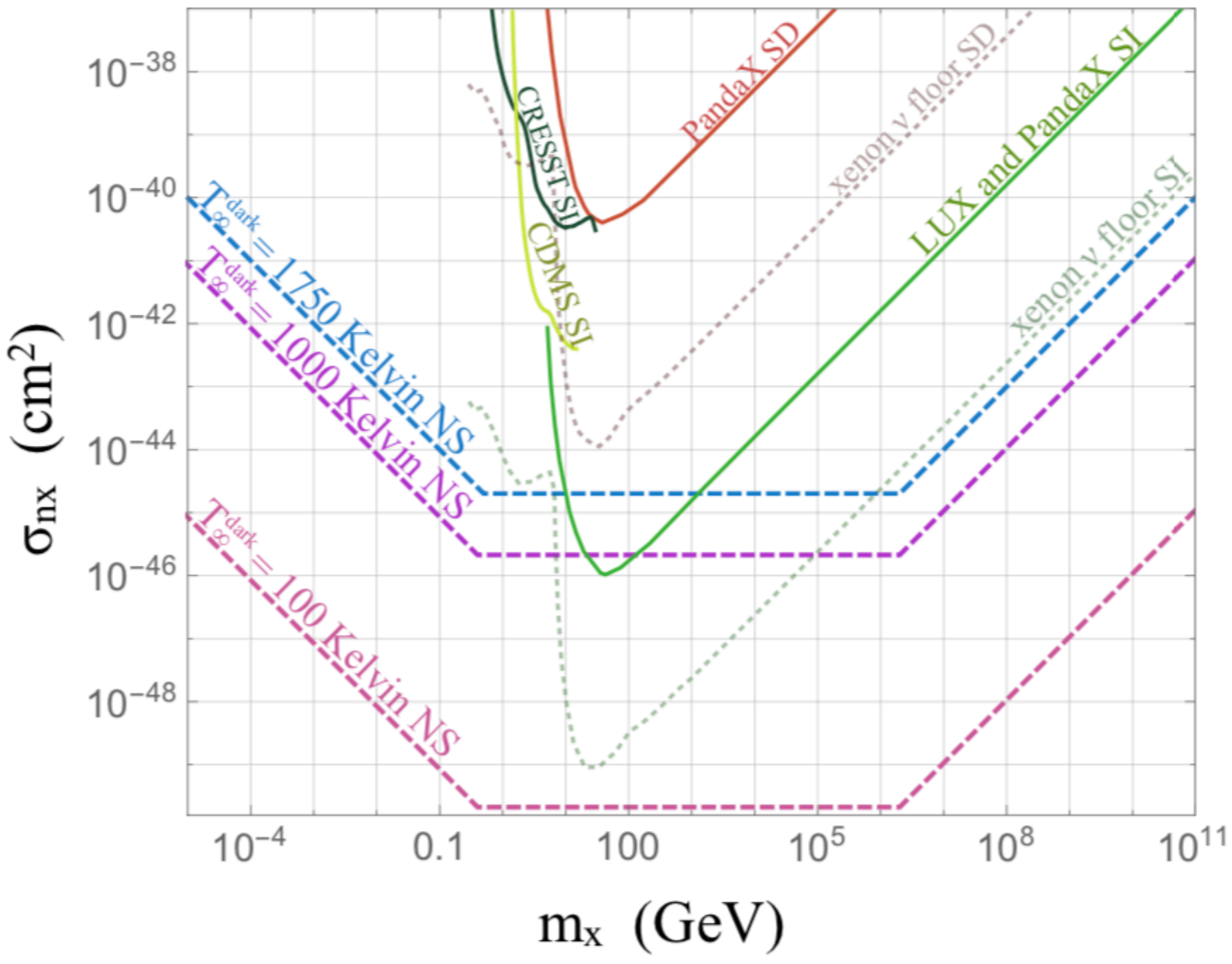
(5) Typical mass range: $\mathcal{O}(0.1\ {\rm GeV}) - \mathcal{O}(1000\ {\rm TeV})$.

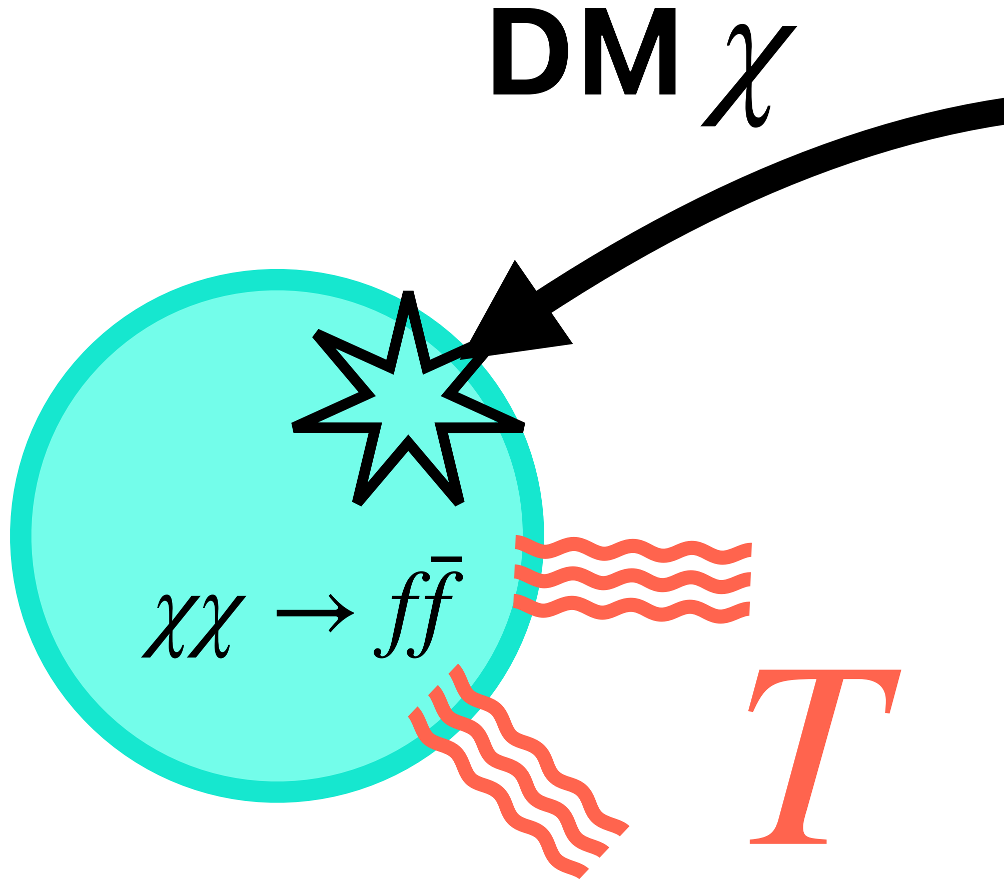


- For < 0.1 GeV, Pauli blocking suppresses scatterings.
- For > 1000 TeV, a single scattering is not enough to catch DM.

Fig. from Baryakhtar+, 1704.01577
(See also: N. F. Bell+, 2004.14888.)

Plan

- Neutron Star and its Cooling
- **Dark Matter Heating of Neutron Stars**
  - Basic Idea and back-of-envelope estimates
  - **Advantages**
  - Challenges
- Summary

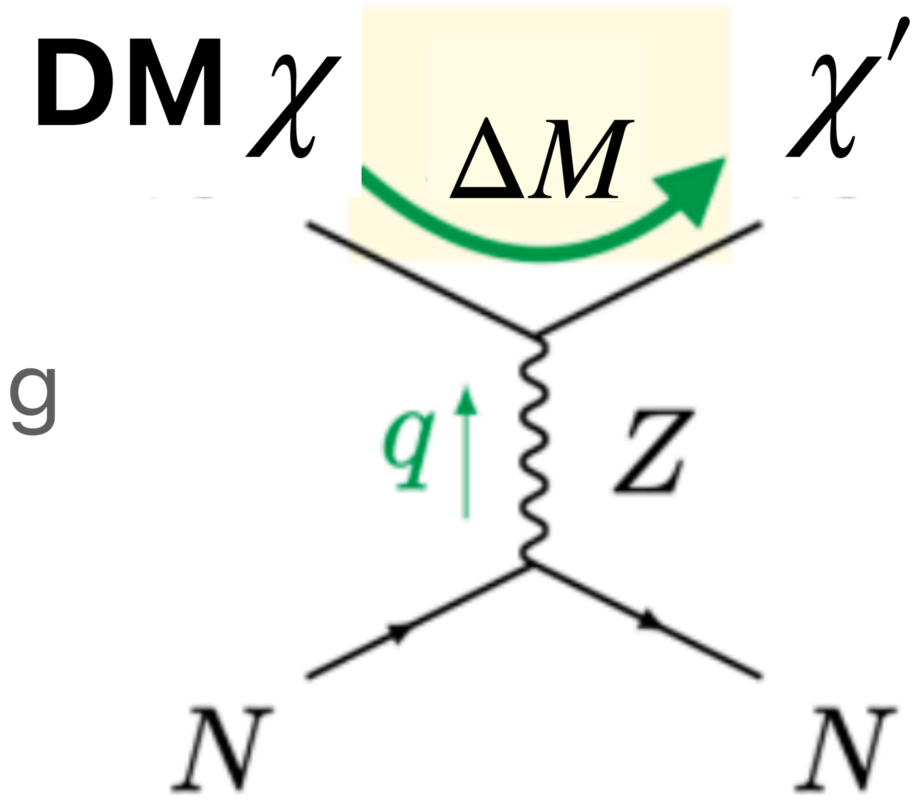


Dark Matter Heating of NS

Advantages

(1) Large Kinetic Energy $(v \sim c)$

👉 **This is advantageous for, e.g., inelastic scattering.**



inelastic
scattering

Dark Matter Heating of NS

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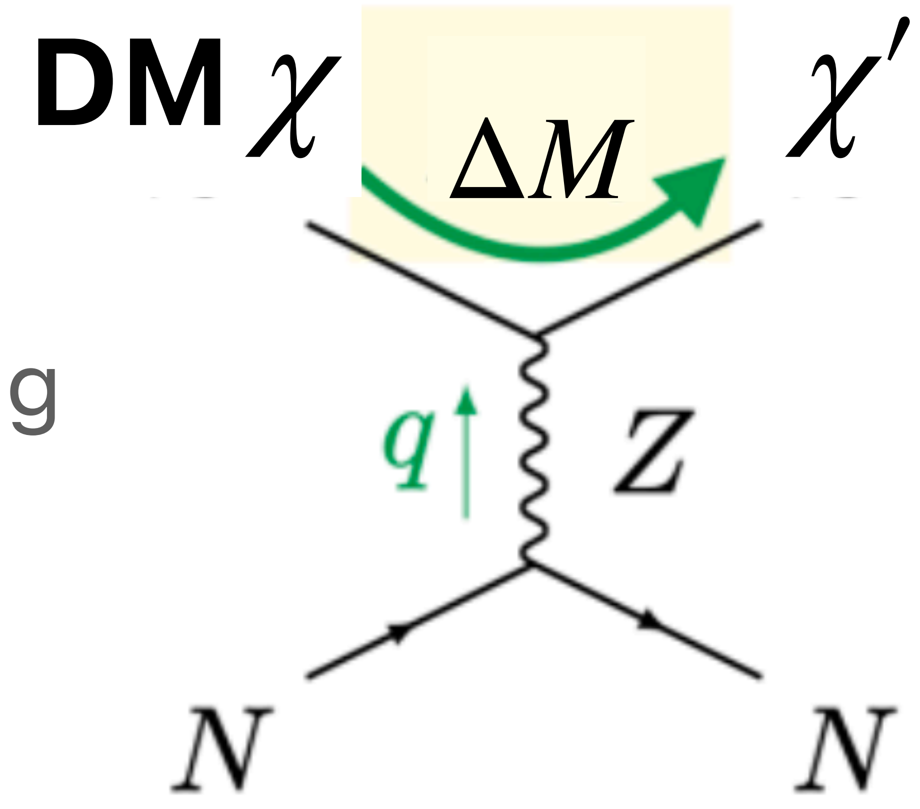
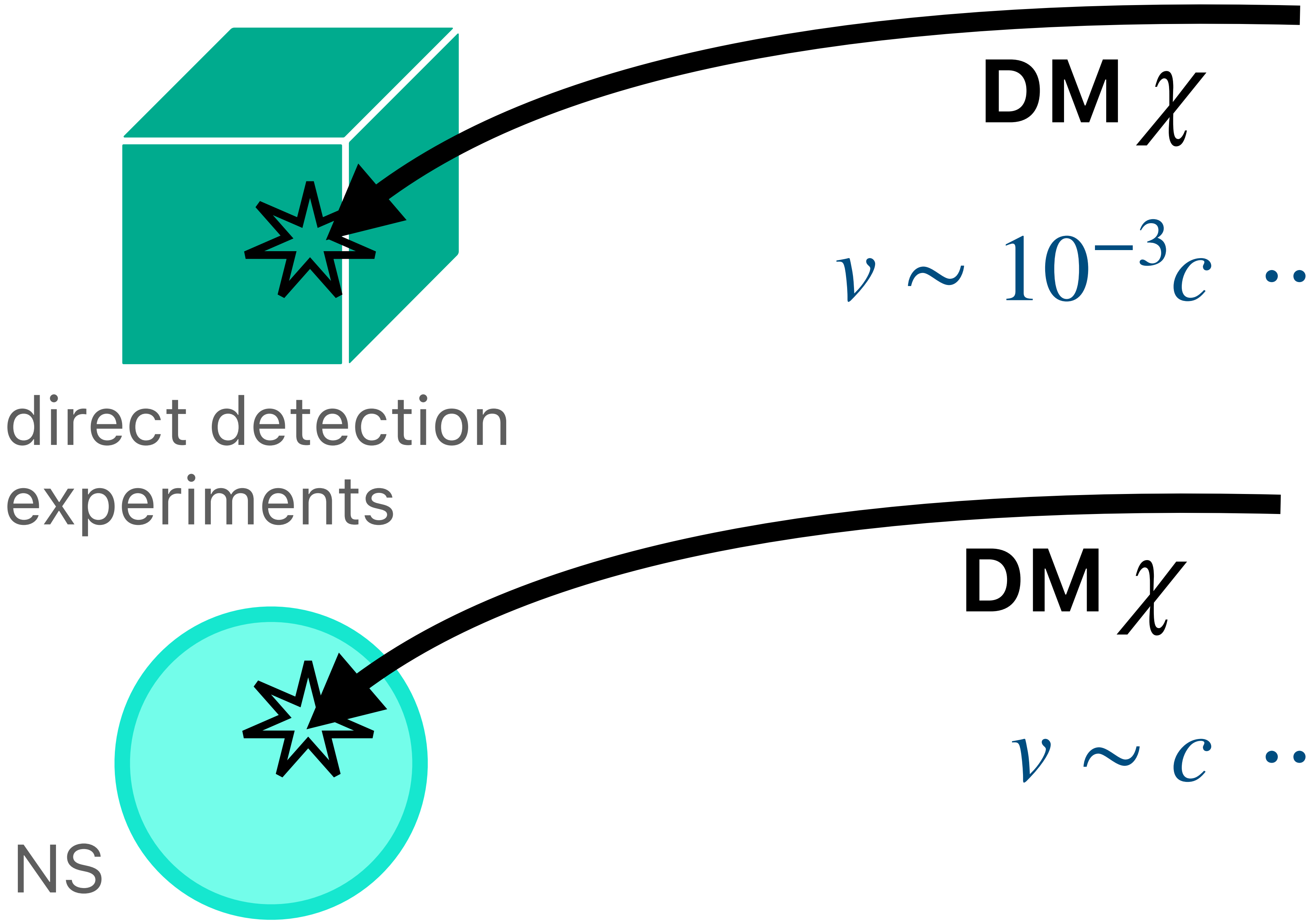
inelastic scattering





$v \sim 10^{-3}c$ ⋯ inelastic scattering occurs for $\Delta M < \mathcal{O}(100)$ keV

$v \sim c$ ⋯ inelastic scattering occurs for $\underline{\Delta M < \mathcal{O}(100)\ \mathrm{MeV}}$

NS is much more sensitive to inelastic scattering.

Dark Matter Heating of NS

Advantages

(1) Large Kinetic Energy $(v \sim c)$

👉 **This is advantageous for, e.g., inelastic scattering.**

example: Electroweak multiplet DM

e.g., Wino and Higgsino in SUSY

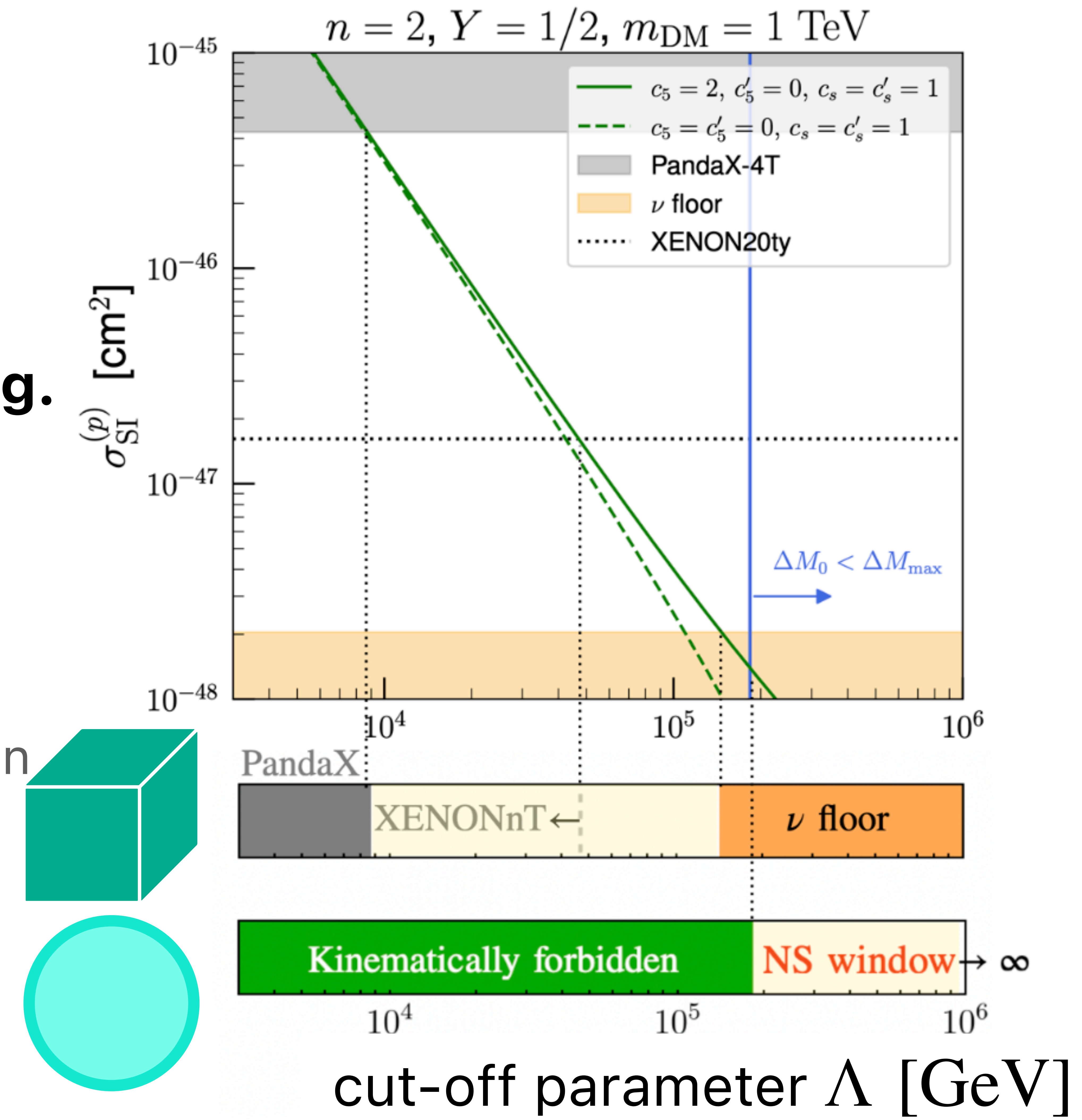
dim-5 effective operators

w/ cut-off parameter Λ

$$\mathcal{L}_5 = -\frac{c_5}{\Lambda}\sum_m (-1)^{j+m}\eta_{-m}\chi_m |H|^2 - \frac{c'_5}{\Lambda}\sum_{m,n}(-1)^{j+m}\eta_{-m}(T_a)_{mn}\chi_n H^\dagger\tau_a H \quad + \text{h.c.}$$

Direct detection experiments (elastic)

NS (inelastic)



Fujiwara, KH, Nagata, Zheng [2204.02238]

Dark Matter Heating of NS

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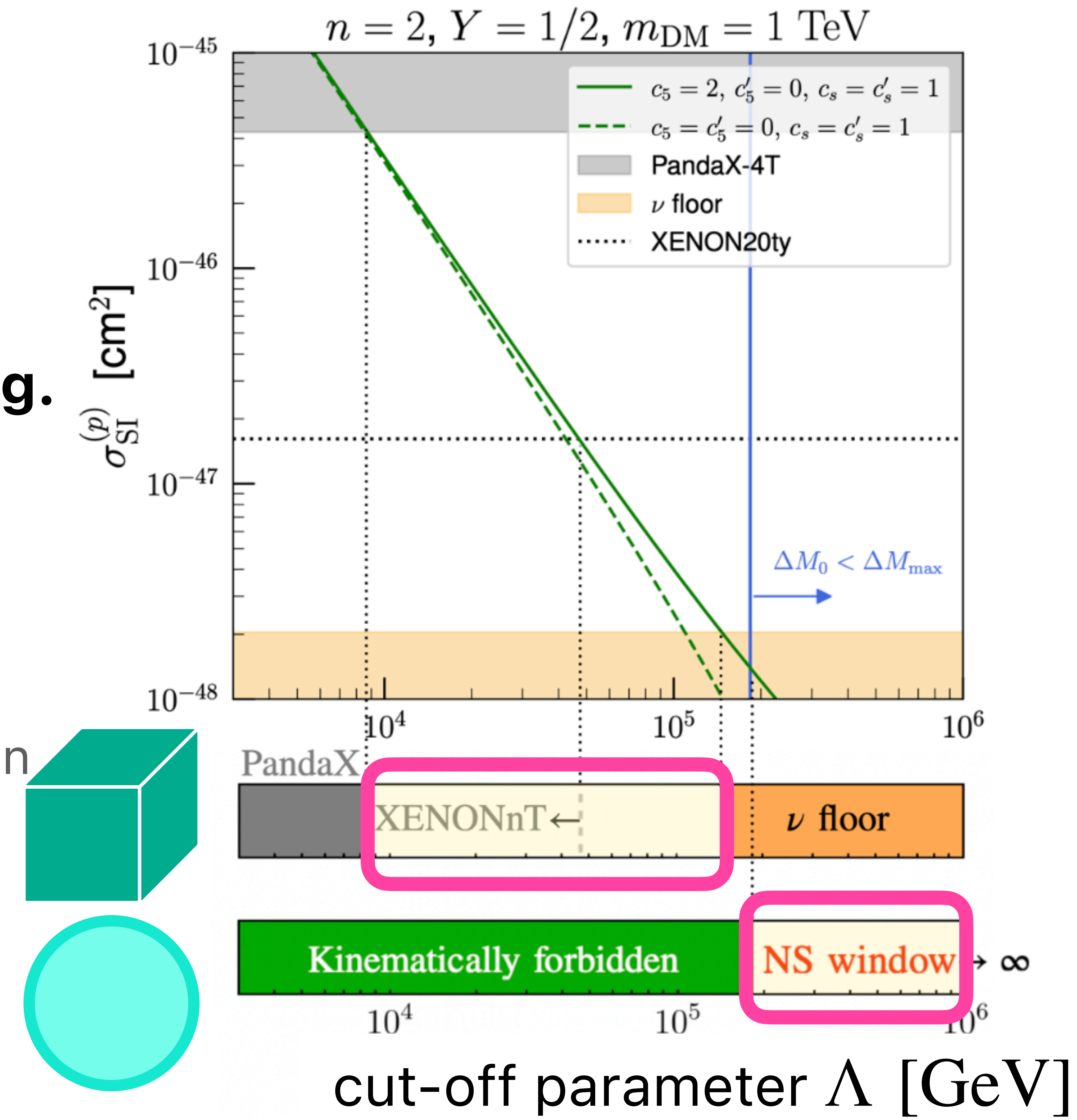


Direct detection experiments (elastic)

NS (inelastic)

Direct detection and NS heating can play complementary roles.

Dark Matter Heating of NS

Advantages

(2) Multiple Targets: e, μ, p, n

example: DM coupled only to muon.

KH, Nagata, Ramirez-Quezada [2204.02413]

Models motivated by the muon g-2 anomaly.

Field	Spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
χ_S	1/2	**1**	**1**	0	−
$\widetilde{L}$	0	**1**	**2**	−1/2	−
$\widetilde{\bar{e}}$	0	**1**	**1**	1	−

$$\mathcal{L}_{\rm mass} = -\left(\frac{1}{2}M_{F_S}\chi_S\chi_S + {\rm h.c.}\right) - M^2_{\widetilde{L}}|\widetilde{L}|^2 - M^2_{\widetilde{\bar{e}}}|\widetilde{\bar{e}}|^2 \ ,$$

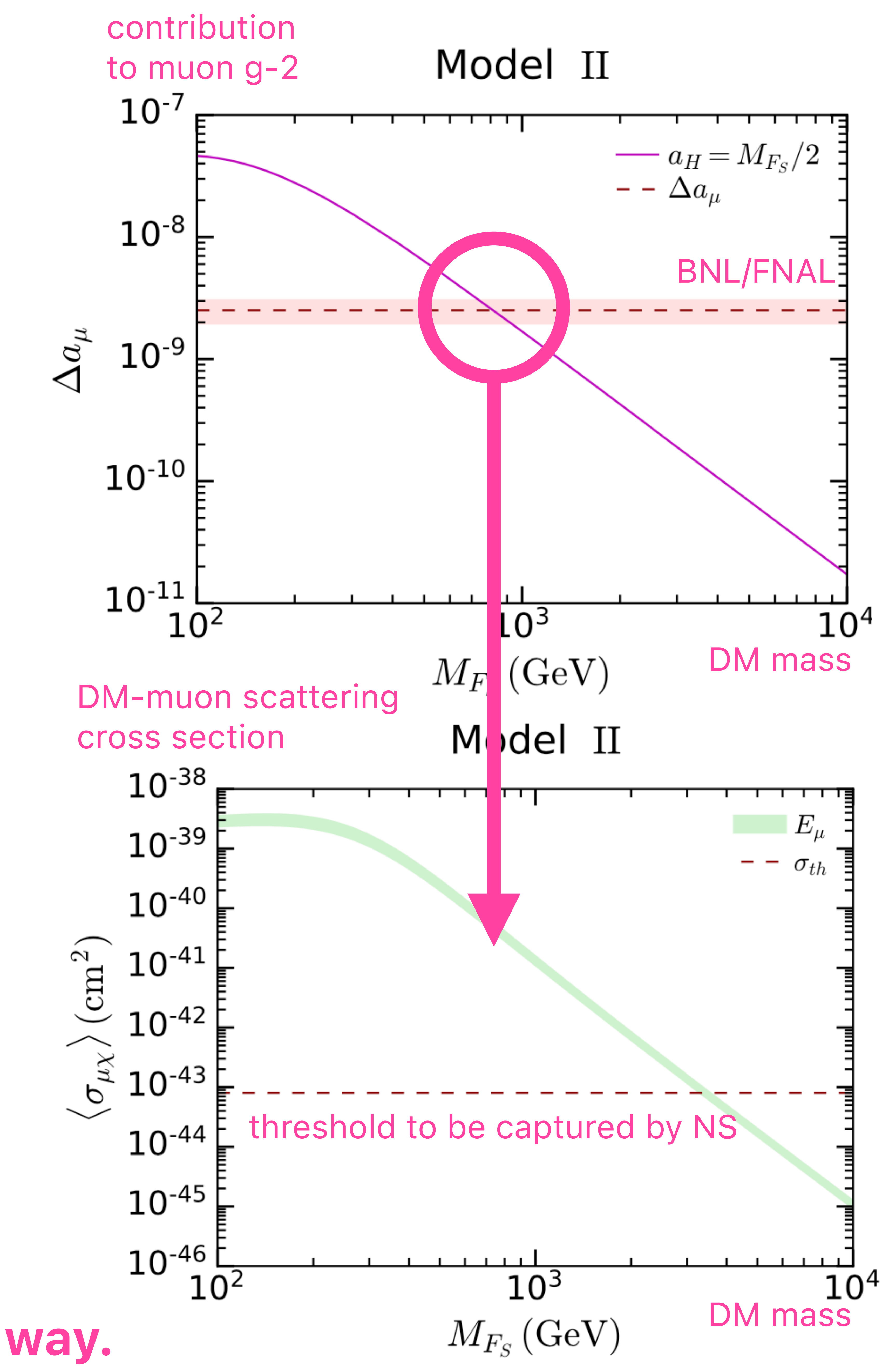
$$\mathcal{L}_{\rm Yukawa} = -y_1\, \chi_S L_\mu \widetilde{L}^\dagger - y_2\, \chi_S \mu_R^c \widetilde{\bar{e}}^\dagger + {\rm h.c.} \ ,$$

$$\mathcal{L}_{\rm tri} = -a_H\, \widetilde{\bar{e}}\widetilde{L}H^\dagger + {\rm h.c.} \ ,$$

$$\mathcal{L}_{\rm quart} = -\sum_{f=L,\bar{e}} \lambda_f |\widetilde{f}|^2|H|^2 - \lambda'_L \widetilde{L}^\dagger\tau_a\widetilde{L}H^\dagger\tau_a H + \dots \ .$$

→ A large parameter space will remain unexplored in the LHC and DM direct searches.

NS temperature may be a promising way.



contribution to muon g-2

BNL/FNAL

DM mass

DM-muon scattering cross section

threshold to be captured by NS

DM mass

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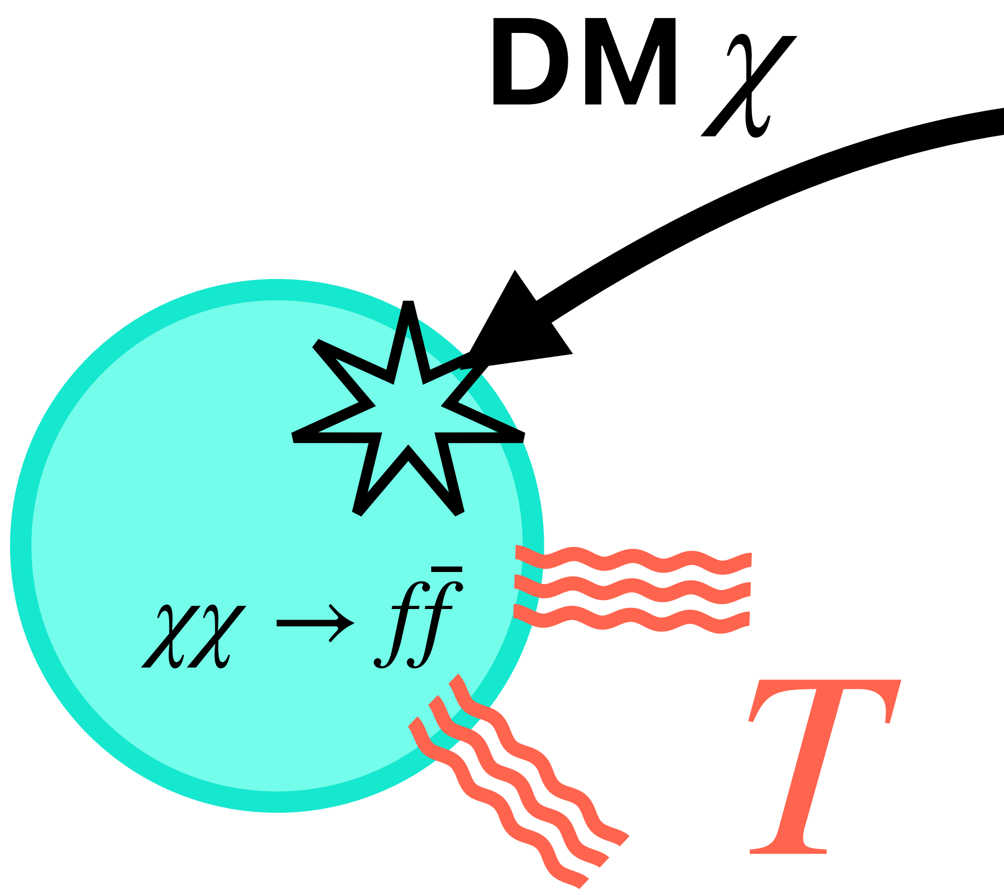

Dark Matter Heating of NS

Challenges: Internal Heating

Actually... some old and warmer ($T \gg 2000K$) NSs have been observed.

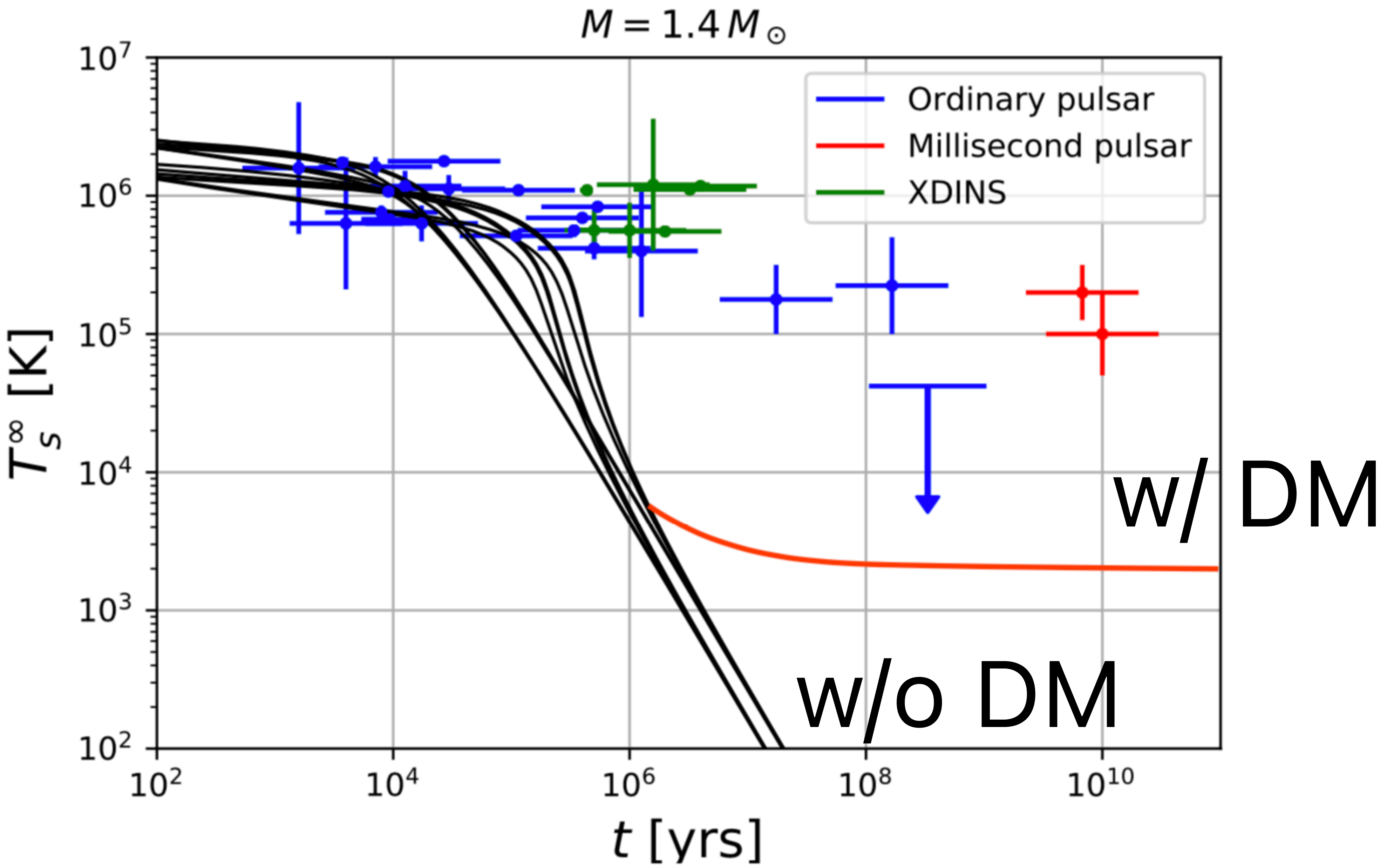

Fig. thanks to K.Yanagi.

Dark Matter Heating of NS

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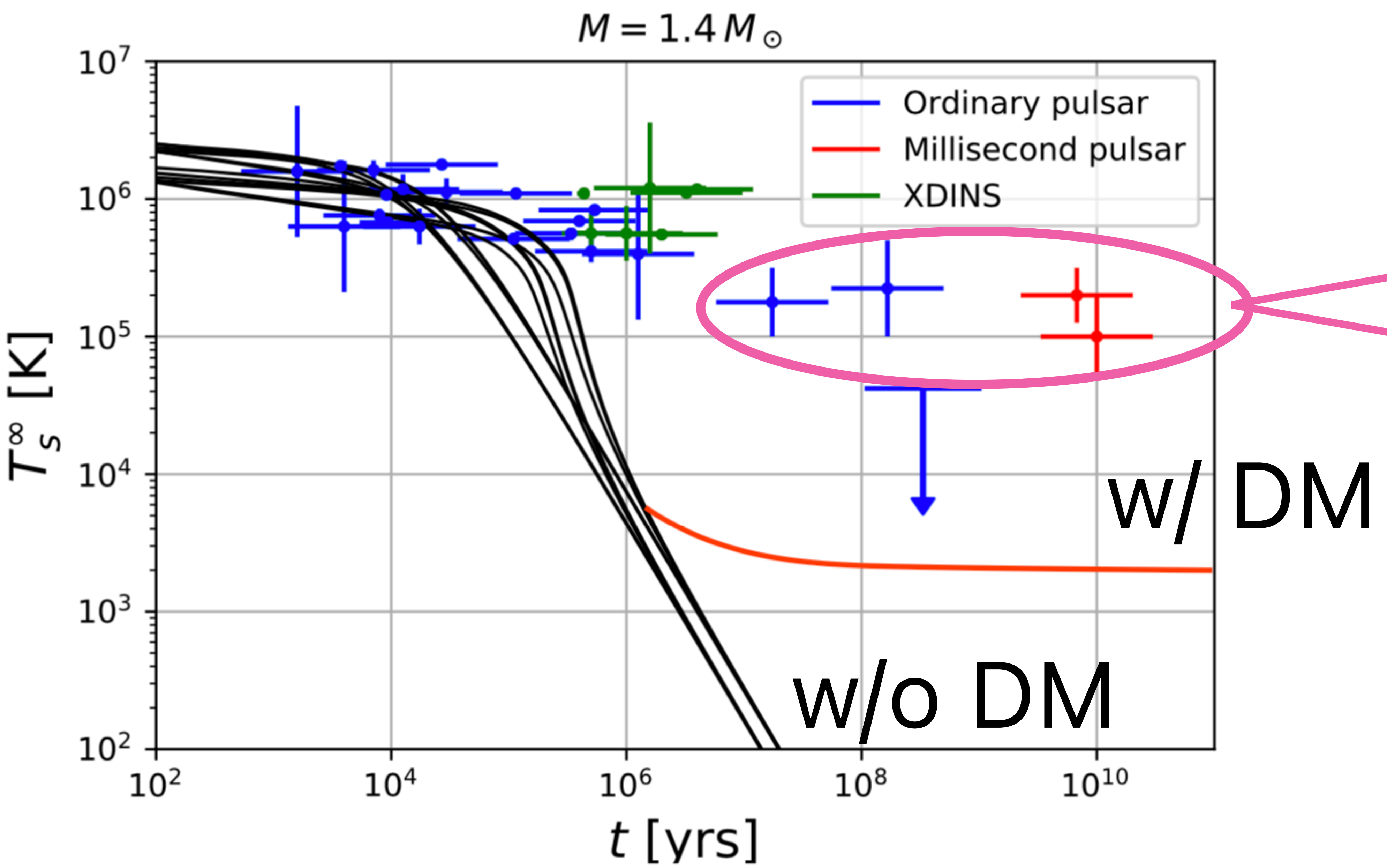


Neither DM nor standard NS cooling can explain those old and warm NSs.

Fig. thanks to K.Yanagi.

Dark Matter Heating of NS

Challenges: Internal Heating

Actually... some old and warmer ($T \gg 2000K$) NSs have been observed.

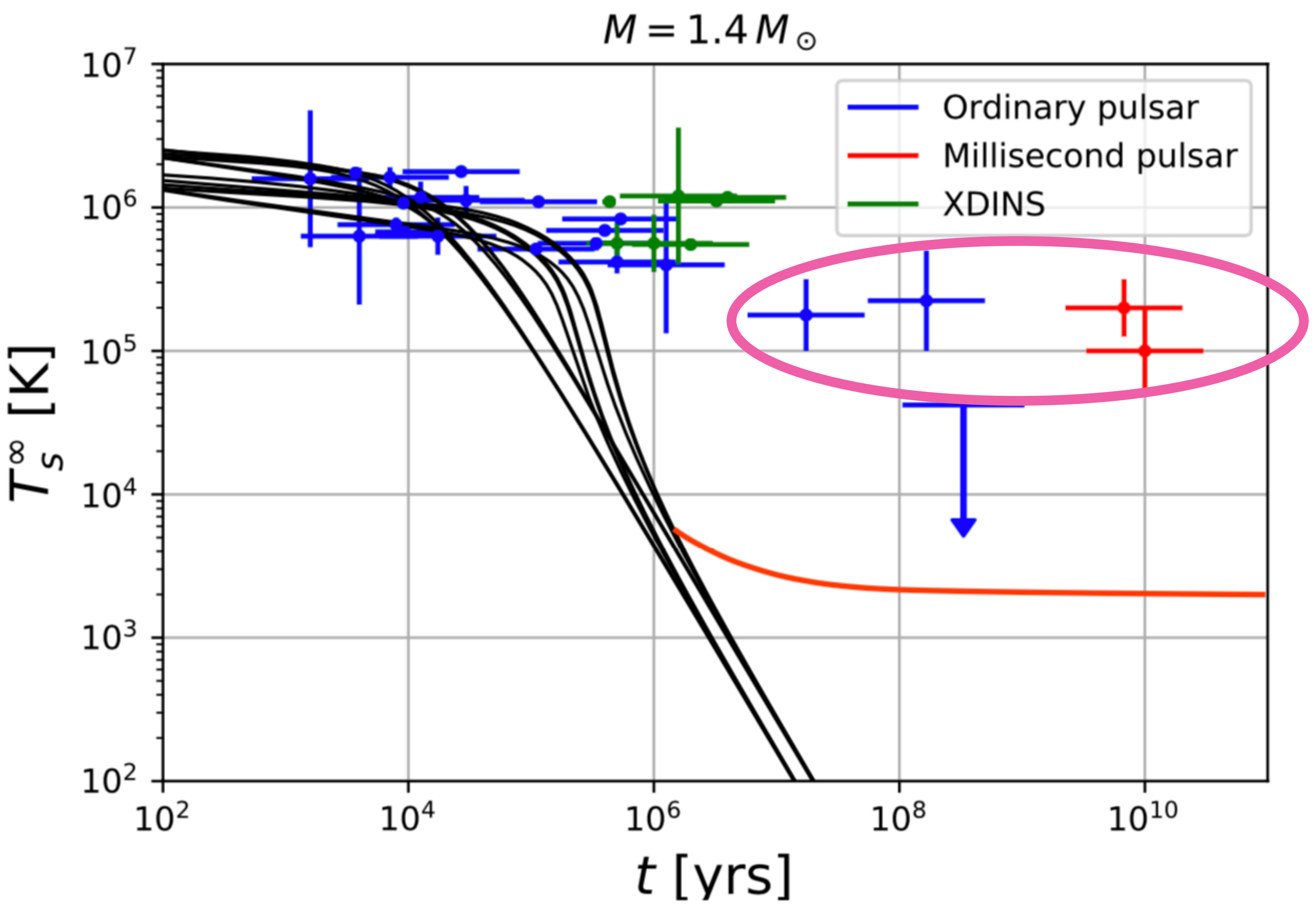


Fig. thanks to K.Yanagi.

There are some **internal NS heating mechanisms** that can explain those NS temperatures, such as

(1) Rotochemical heating

(2) Vortex creep heating

We revisited those mechanisms and investigated their **implications for the DM heating** of NS.

Dark Matter Heating of NS

Challenges: Internal Heating

(1) **Rotochemical heating**

Dark Matter Heating of NS

Challenges: Internal Heating

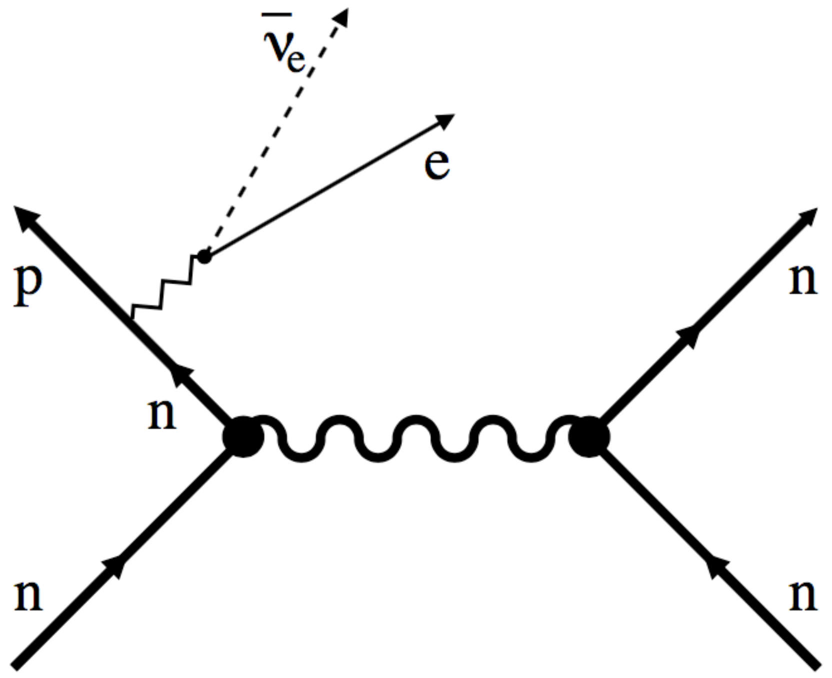
(1) Rotochemical heating

- 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.

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



Dark Matter Heating of NS

Challenges: Internal Heating

(1) Rotochemical heating

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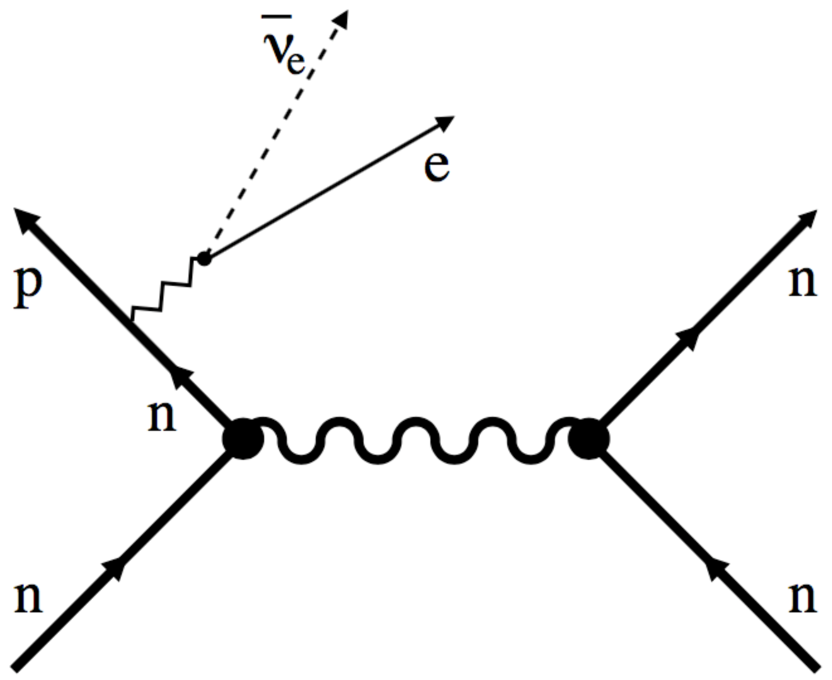
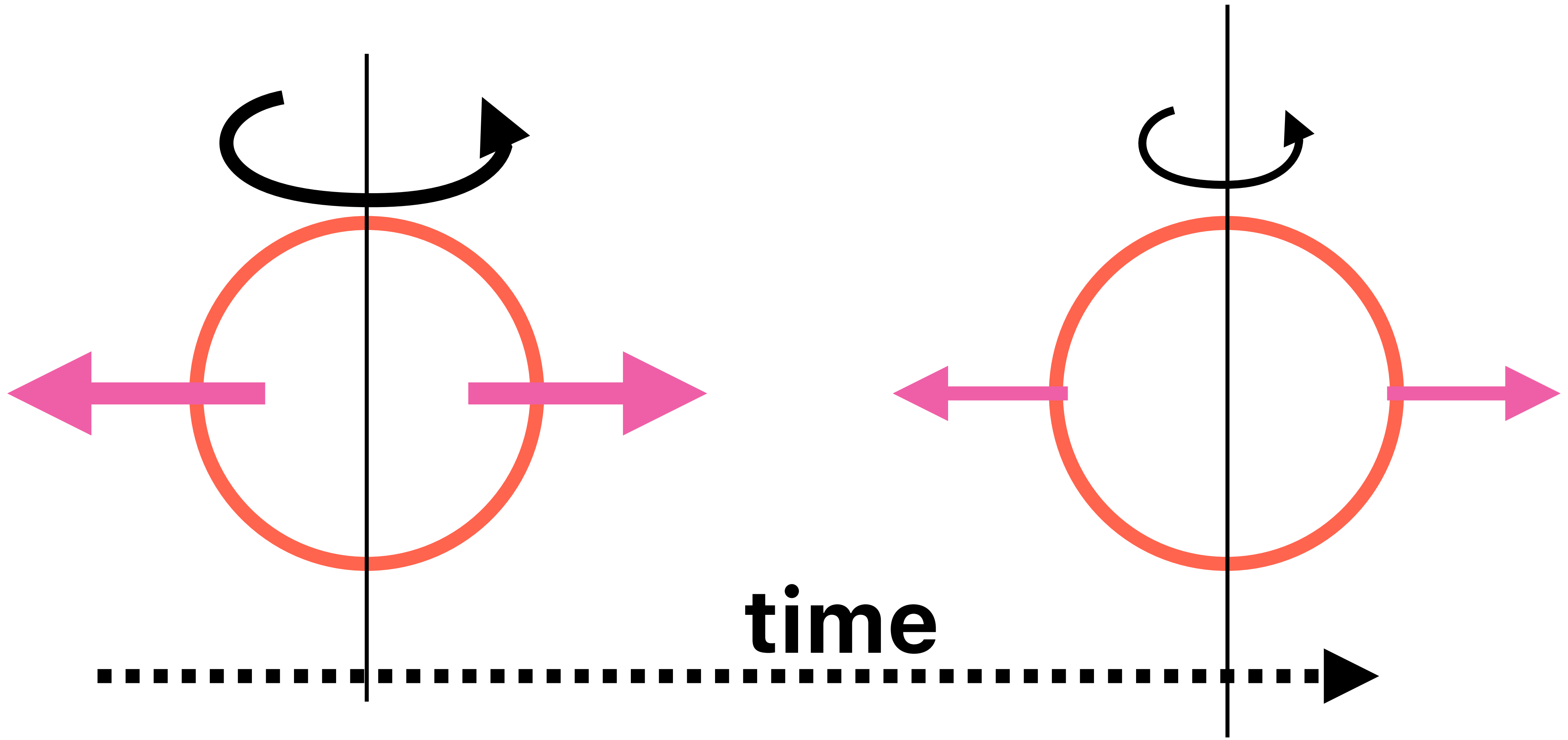


- In the minimal cooling, β-equilibrium is assumed.

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

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

A.Reisenegger [astro-ph/9410035]



spin-down weakens the centrifugal force.
→ pressure changes.
→ chemical eq. condition changes
→ at low T,
the modified Urca process (slow, $\sim T^8$)
can no longer maintain the equilibrium.

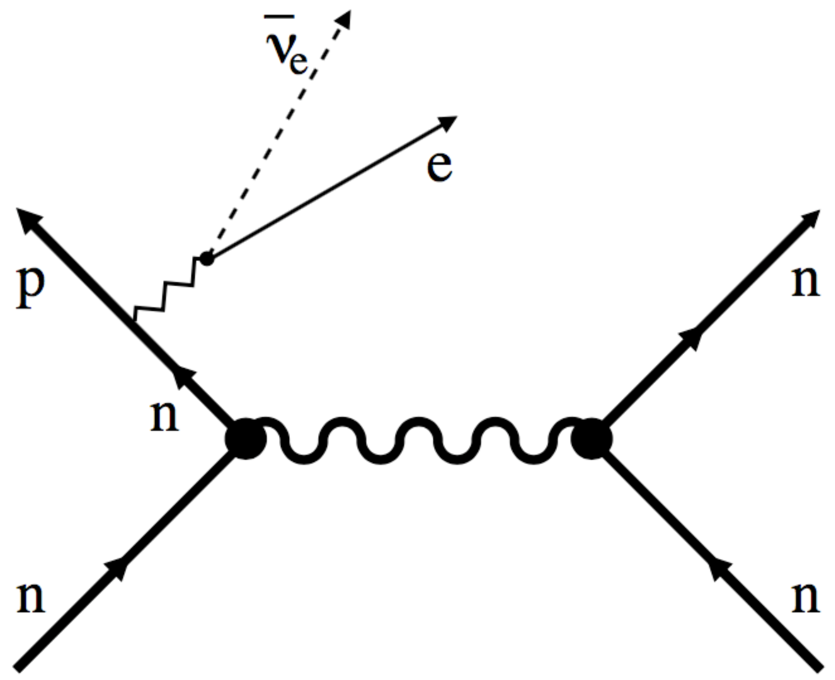
Dark Matter Heating of NS

Challenges: Internal Heating

(1) Rotochemical heating

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

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



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

A.Reisenegger [astro-ph/9410035]

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

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

$$L_{\text{rotochemical heating}} = \int dV \left(\mu_n - \mu_p - \mu_e\right)\left(\Gamma_{n\to p+e} - \Gamma_{p+e\to n}\right) > 0.$$ **"Rotochemical heating"**

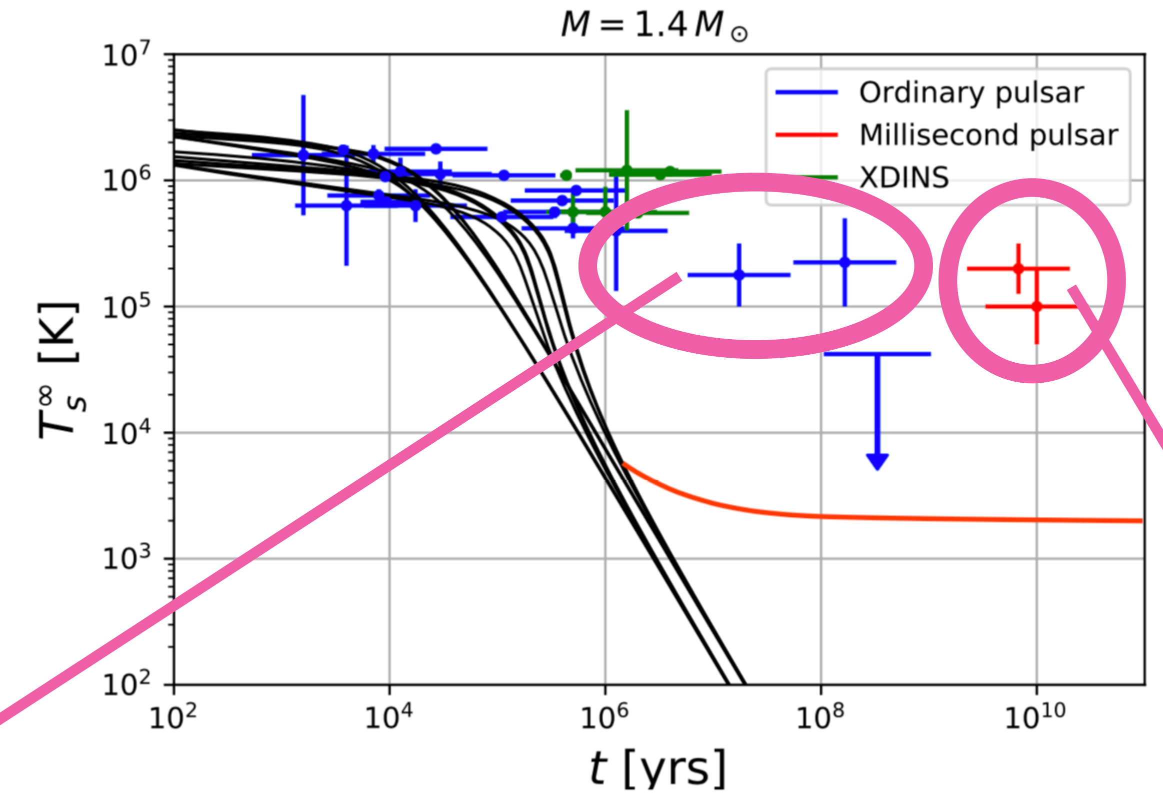
Dark Matter Heating of NS

Challenges: Internal Heating

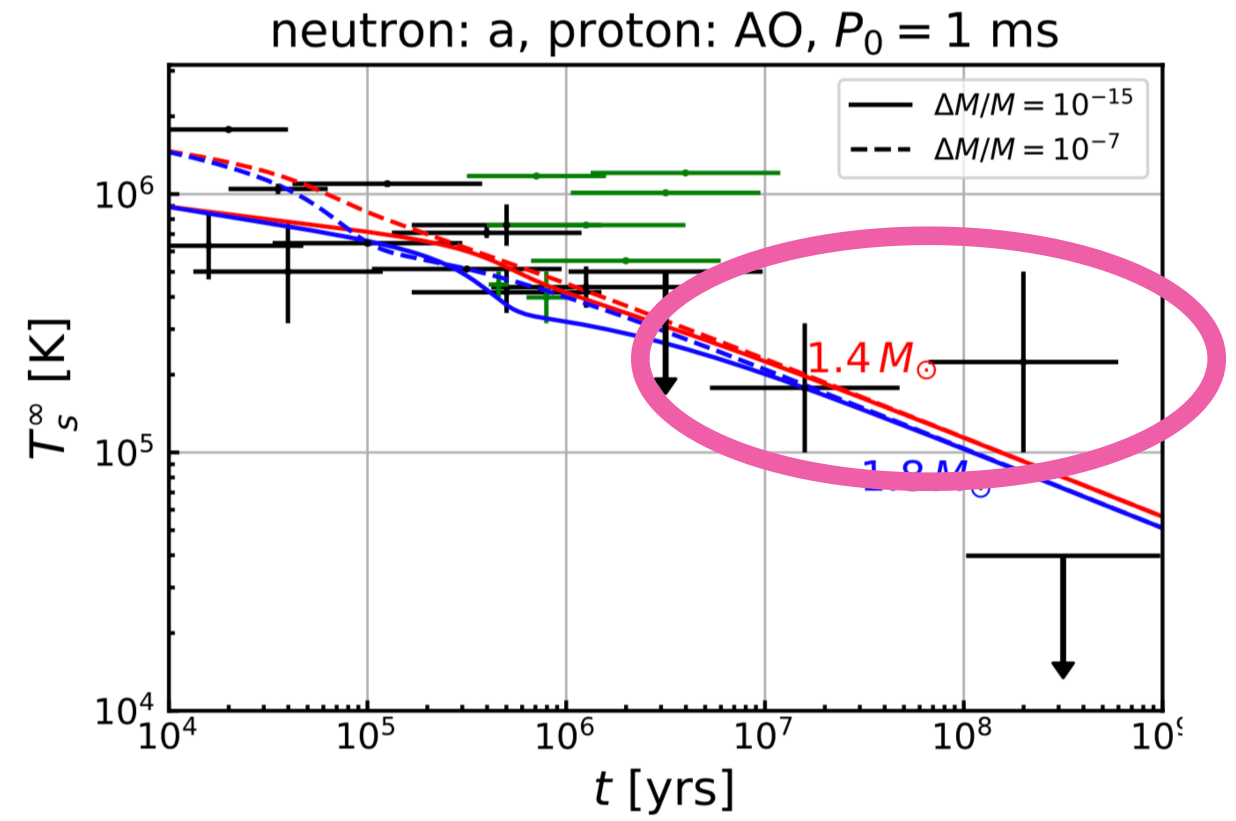
(1) Rotochemical heating

$$C\frac{dT}{dt} = -L_\nu - L_\gamma + L_{\text{rotochemical heating}}$$

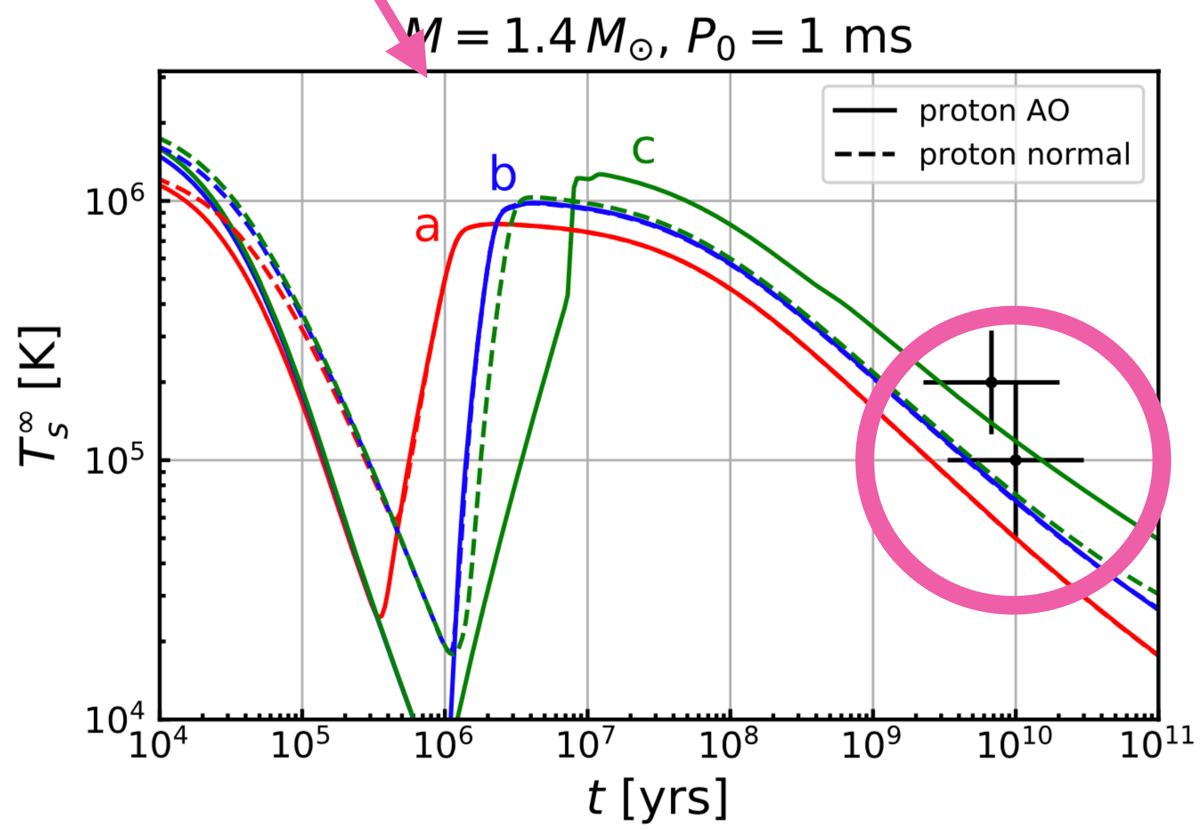
It can explain the old and warm NSs.



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

Dark Matter Heating of NS

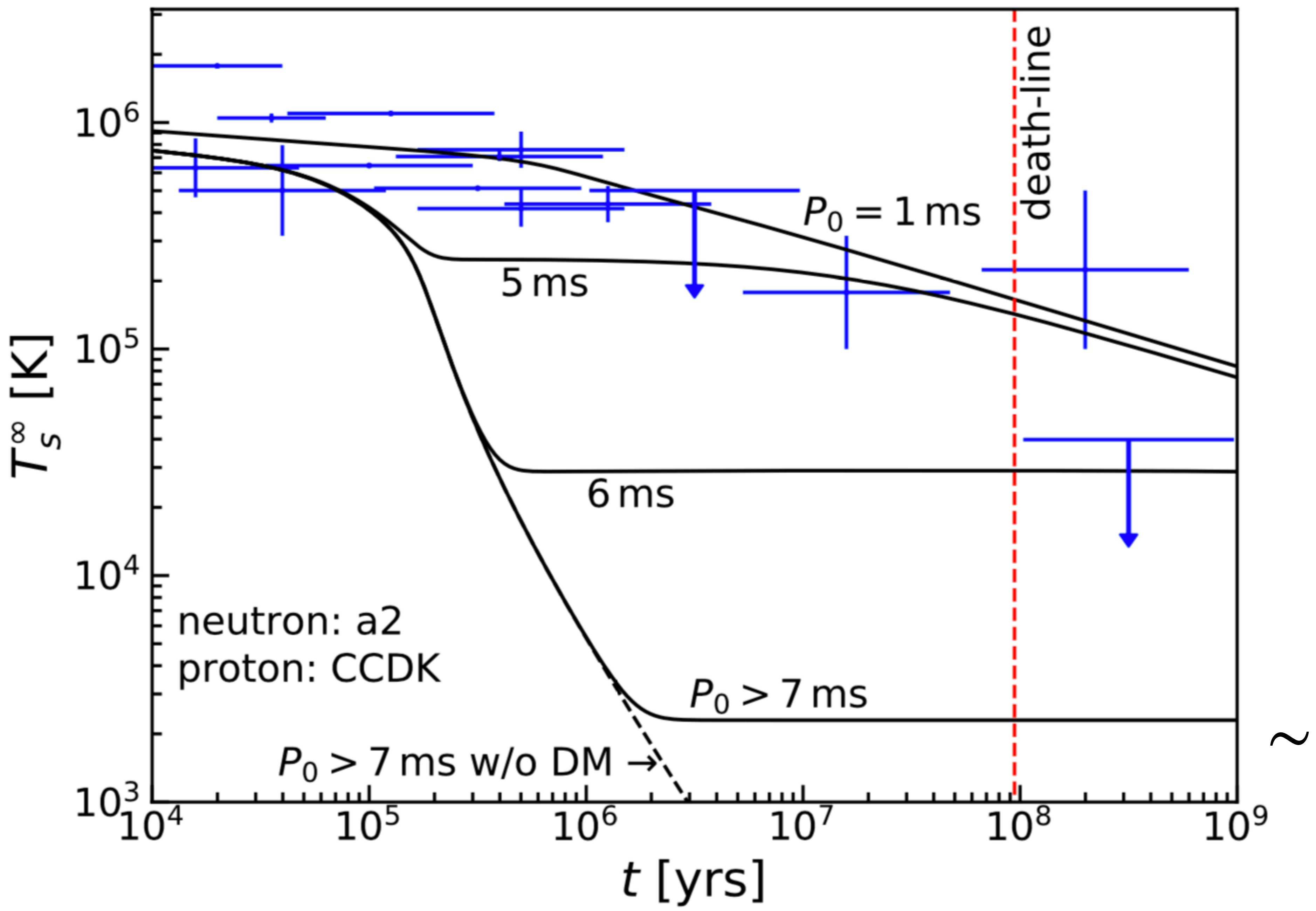
Challenges: Internal Heating

(1)′ Rotochemical heating + DM heating

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

$$C\frac{dT}{dt} = -L_\nu - L_\gamma + L_{\text{rotochemical heating}} + L_{\text{DM heating}}$$

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



$\sim (2000 - 3000) K$

Dark Matter Heating of NS

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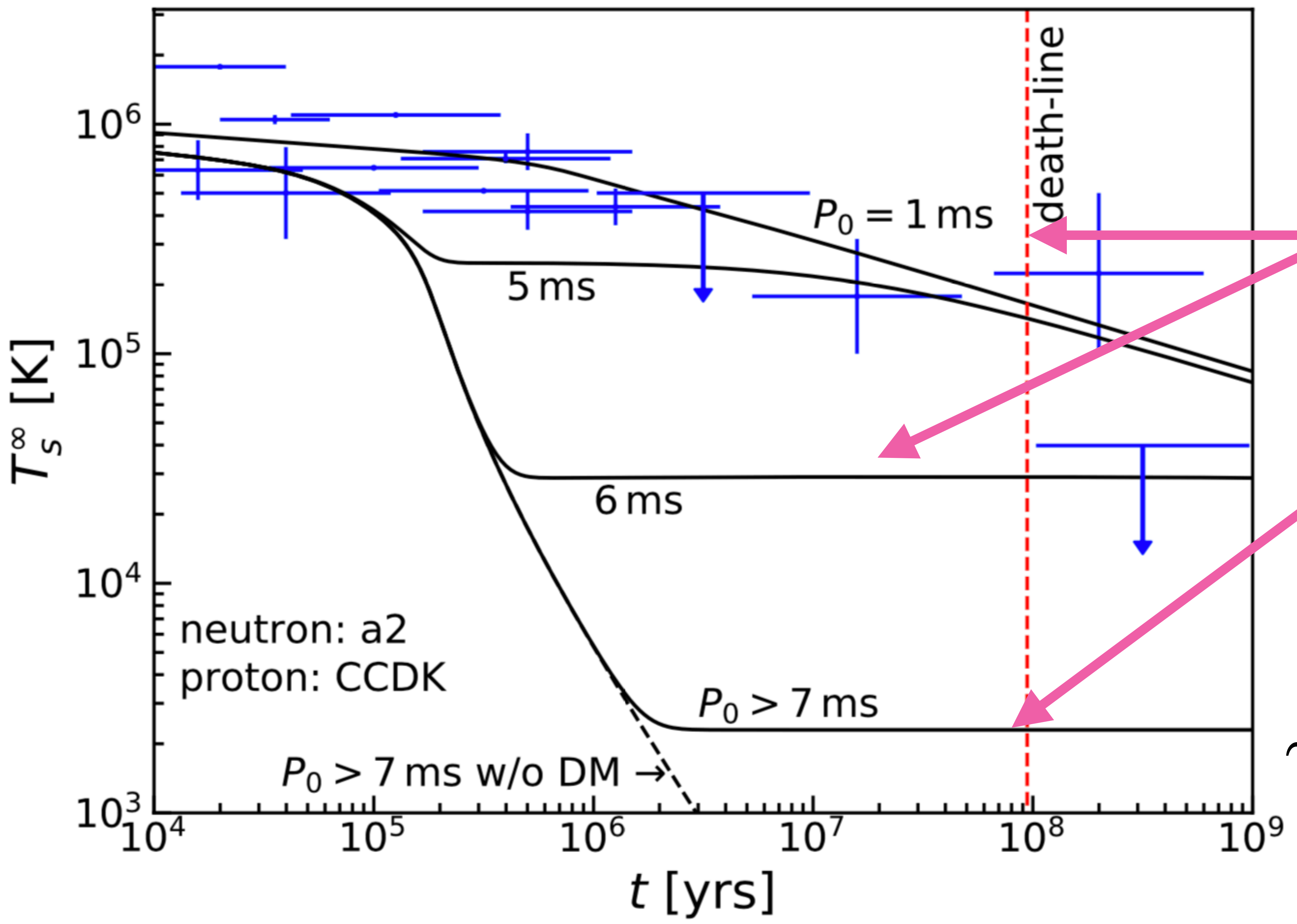

$\sim (2000 - 3000)K$

P_0 **: initial rotation period**

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

Dark Matter Heating of NS

Challenges: Internal Heating

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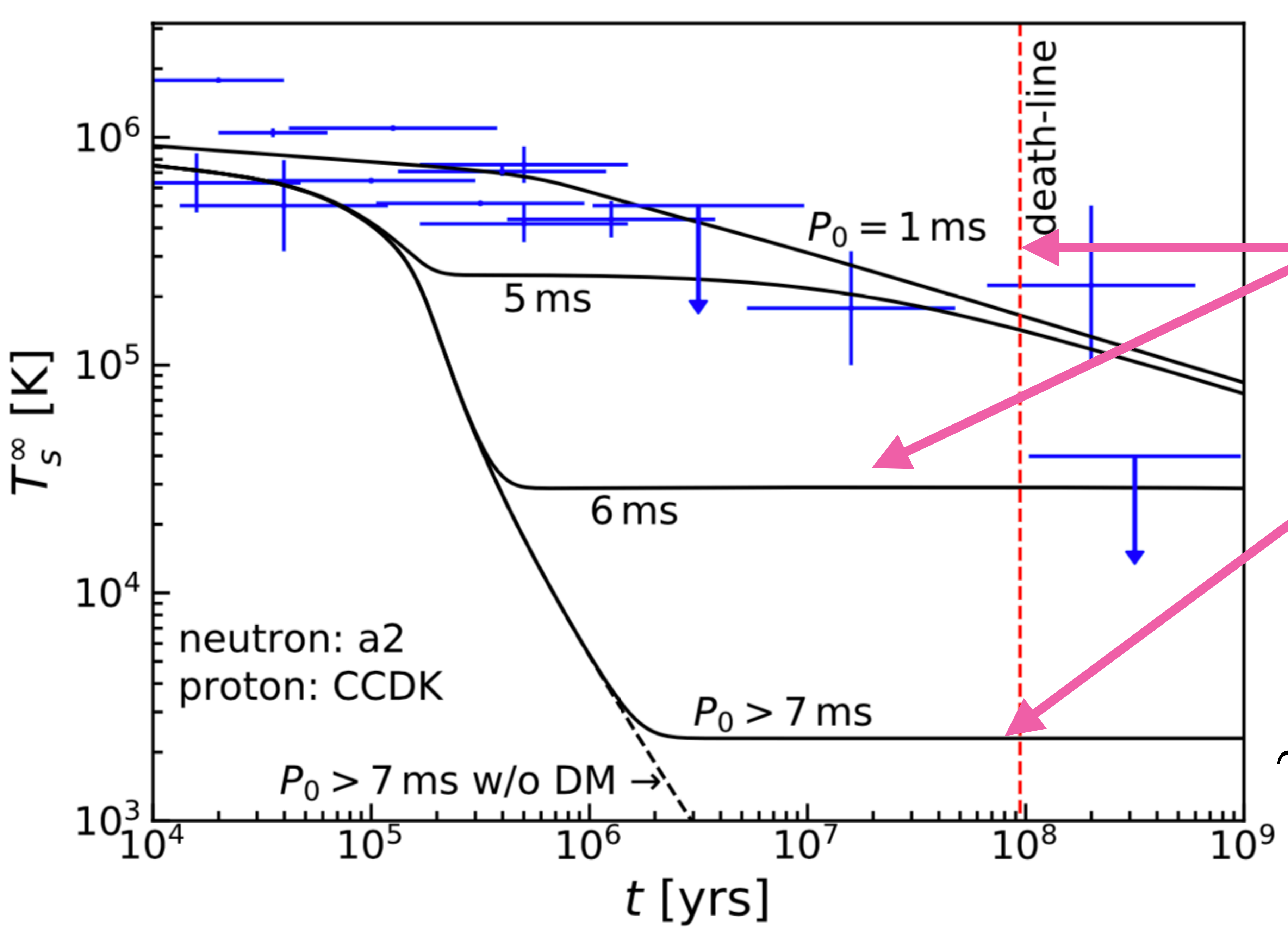

$\sim (2000 - 3000)K$

P_0 **: initial rotation period**

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

There is still a chance…

Dark Matter Heating of NS

Challenges: Internal Heating

(2) Vortex Creep heating

Alpar+, 1984, Shibazaki+, 1989

Dark Matter Heating of NS

Challenges: Internal Heating

(2) Vortex Creep heating

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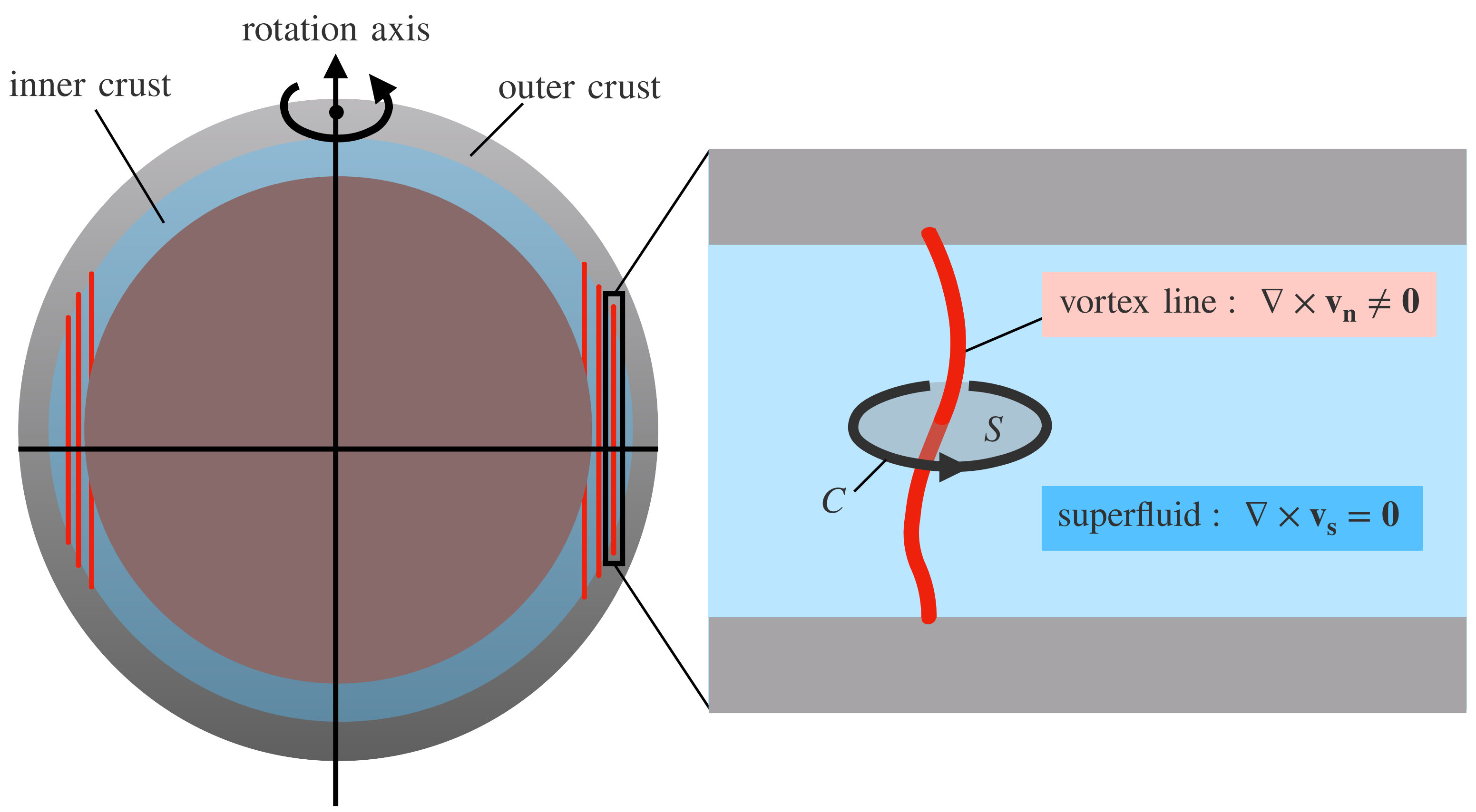
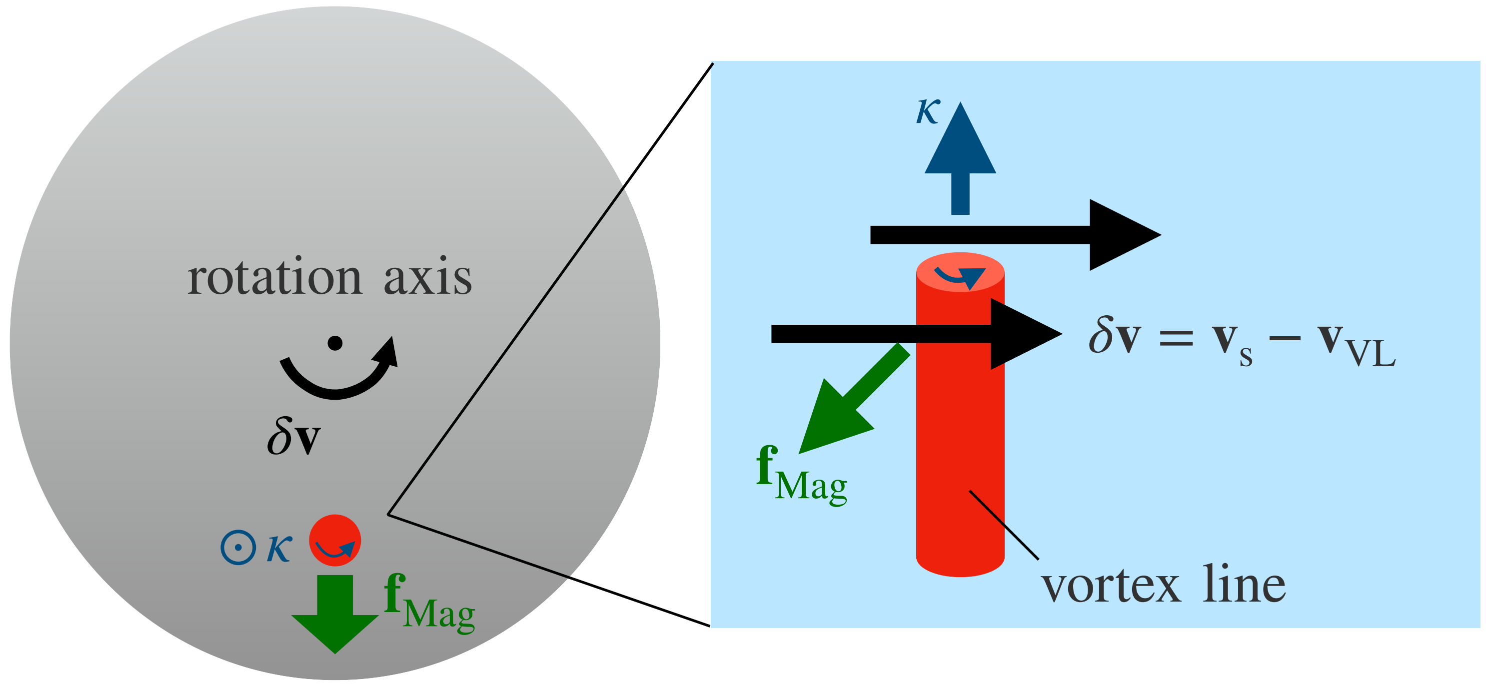


Figs. from Fujiwara, KH, N. Nagata, and Ramirez-Quezada [2308.16066]

- Cooper pairs (superfluidity)
  → **vortex lines** are formed in a rotating NS.



- The slow-down of the outer crust component induces a Magnus force on vortex lines.
  → vortex lines start to move outwards. (**vortex creep**)

- The rotational energy stored in the superfluid component is dissipated as heat (**vortex creep heating**)

$$L_{\text{vortex creep heating}} = J|\dot{\Omega}|$$

J : universal constant

Ω : NS angular velocity

Dark Matter Heating of NS

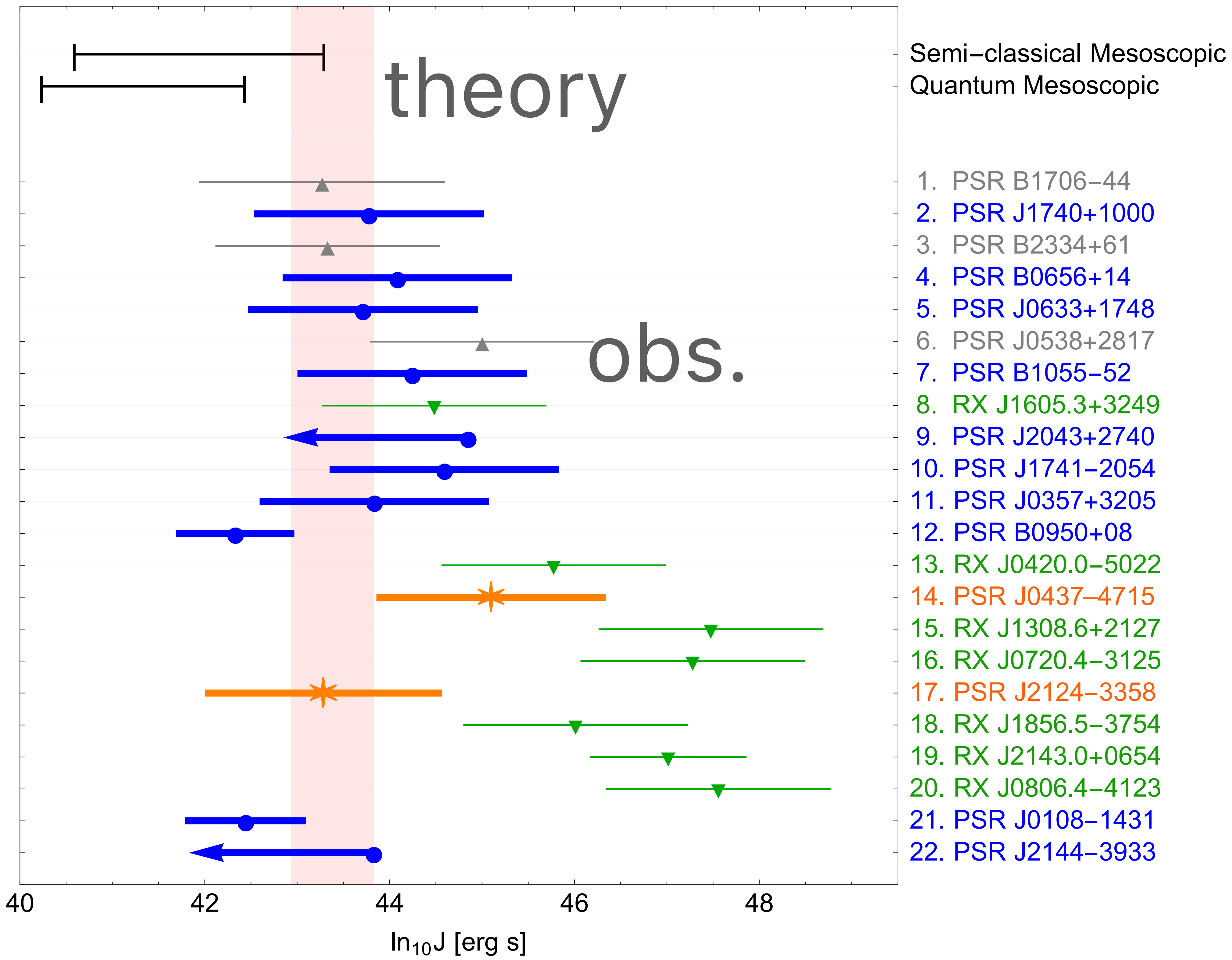
Challenges: Internal Heating

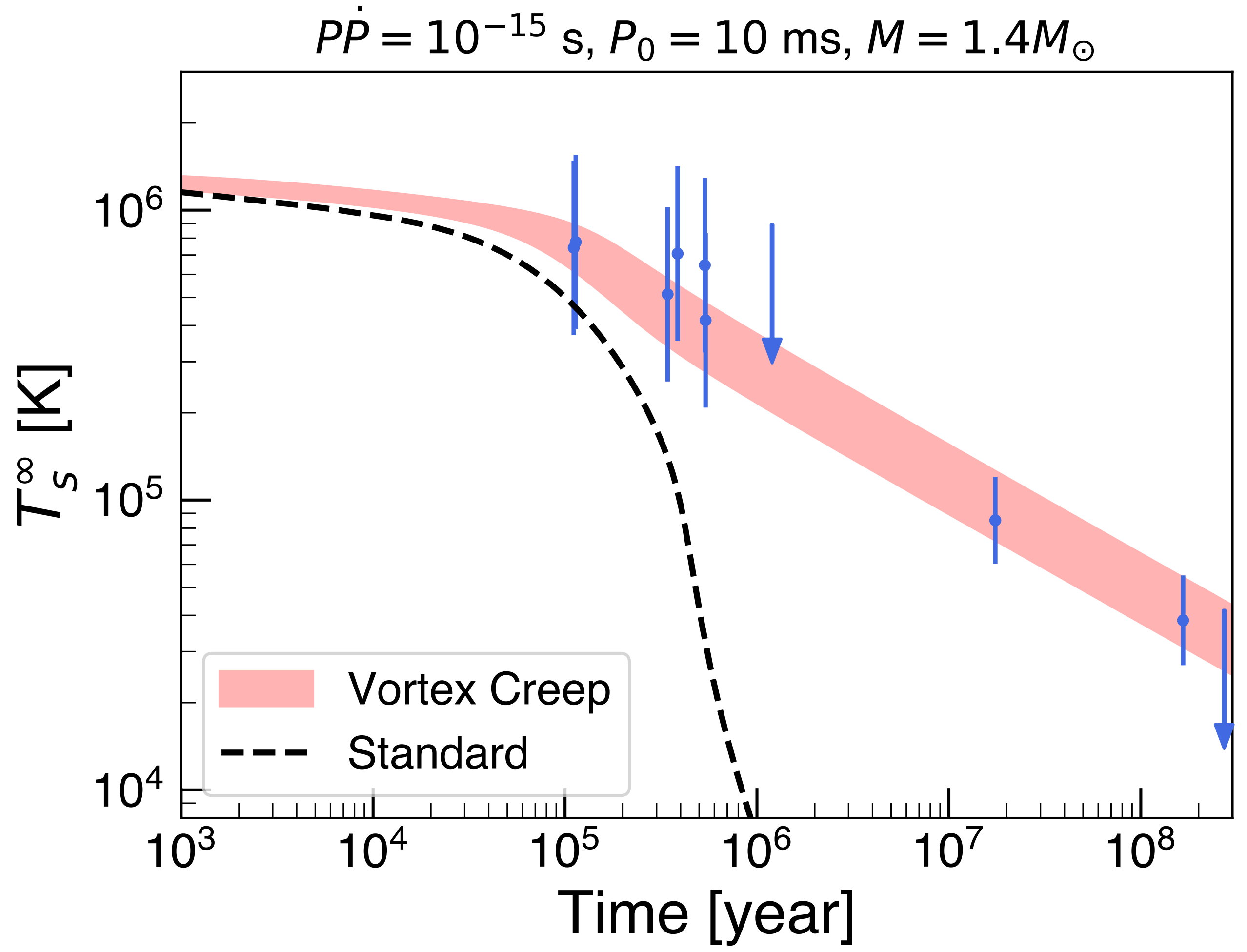
(2) Vortex Creep heating

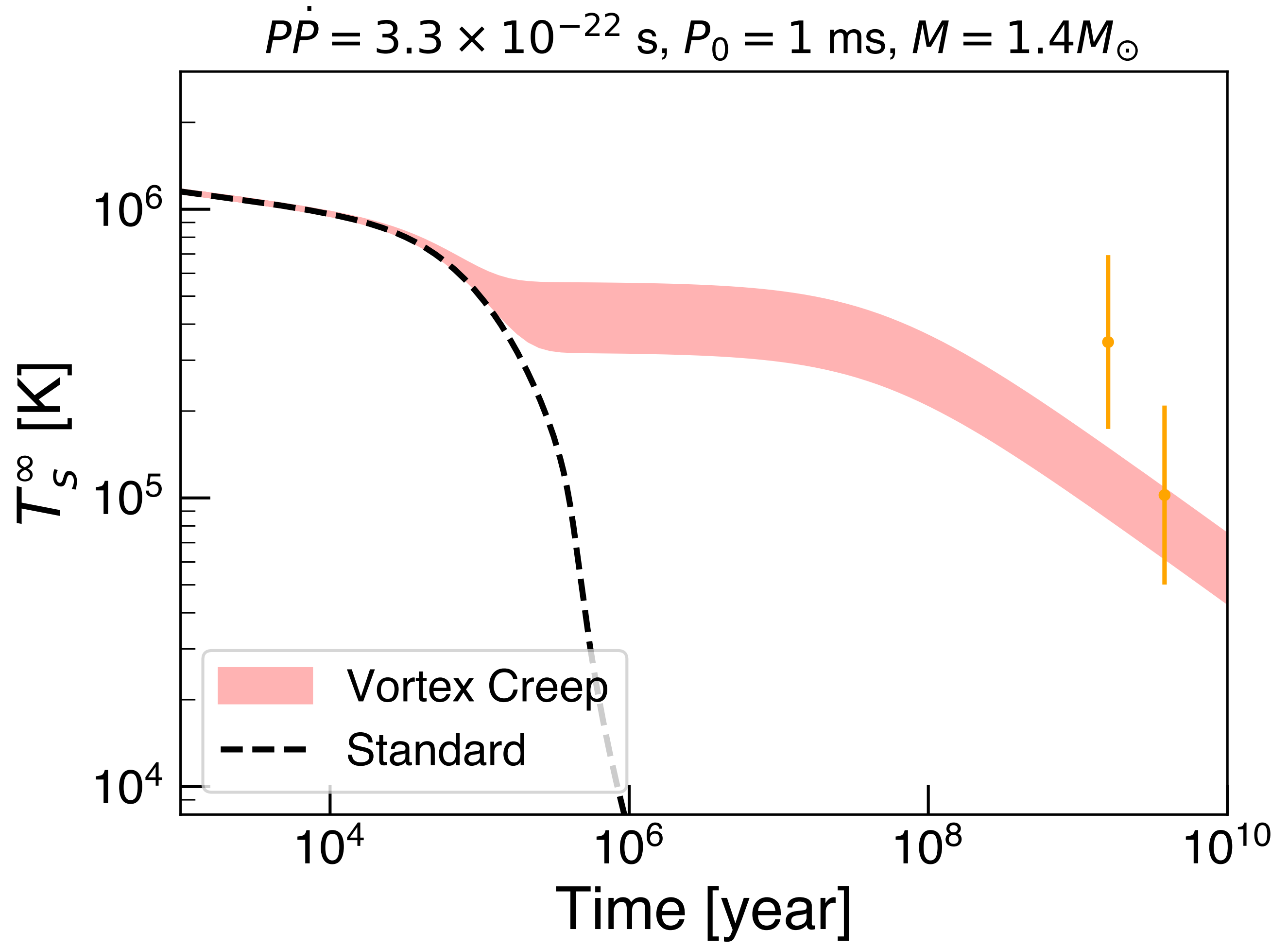
$$C\frac{dT}{dt} = -L_\nu - L_\gamma + L_{\text{vortex creep heating}}$$

It can explain the old and warm NSs with a universal constant $J \sim 10^{43} - 10^{44}$ erg · s .

Fujiwara, KH, N. Nagata, Ramirez-Quezada [2308.16066]







Dark Matter Heating of NS

Challenges: Internal Heating

(2) Vortex Creep heating

$$C\frac{dT}{dt} = -L_\nu - L_\gamma + L_{\text{vortex creep heating}}$$

It can explain the old and warm NSs with a universal constant $J \sim 10^{43} - 10^{44}$ erg $\cdot$ s .

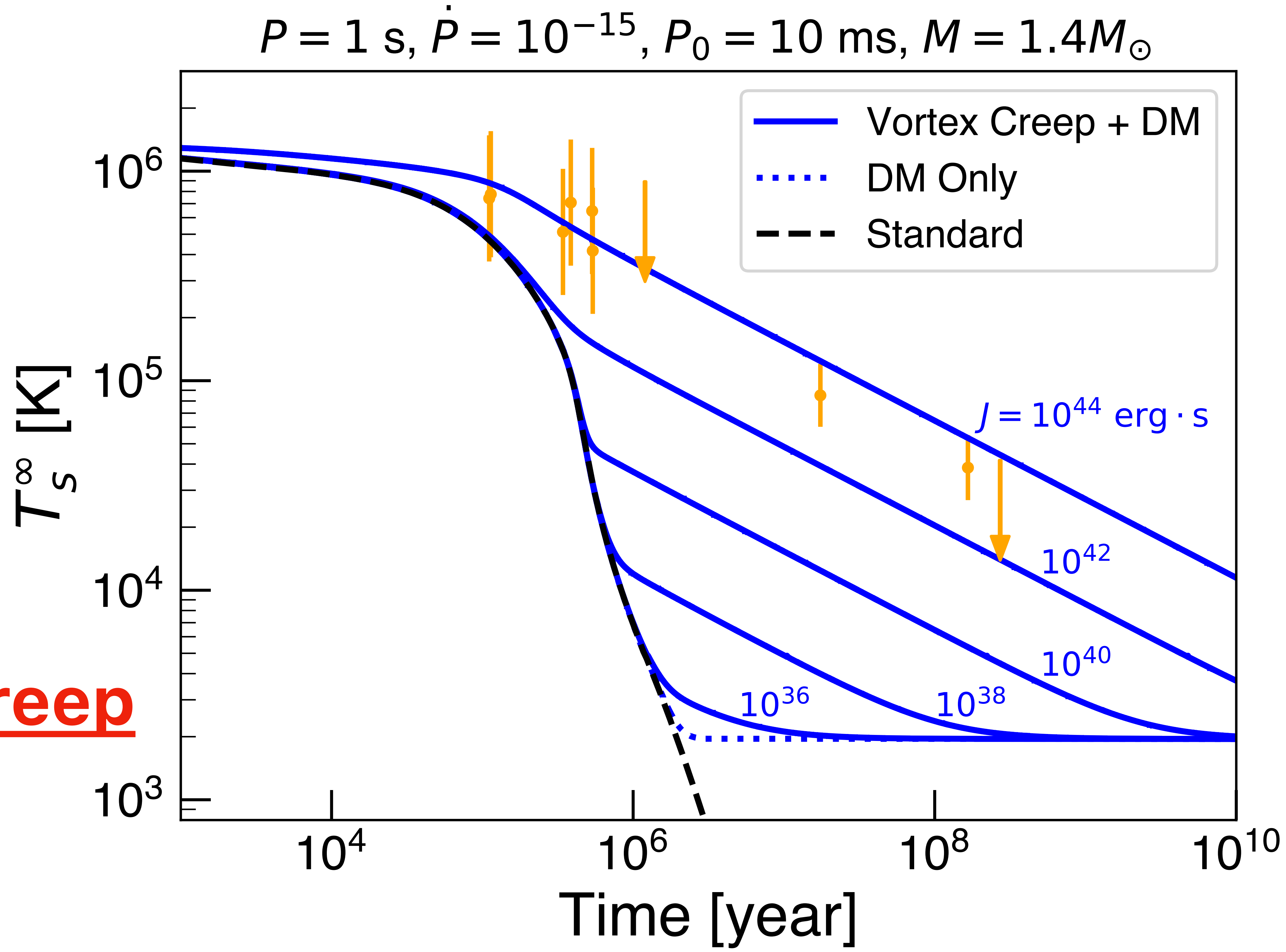
Fujiwara, KH, N. Nagata, Ramirez-Quezada [2308.16066]

(2)′ Vortex Creep heating + DM heating

Fujiwara, KH, N. Nagata, Ramirez-Quezada [2309.02633]

$$C\frac{dT}{dt} = -L_\nu - L_\gamma + L_{\text{vortex creep heating}} + L_{\text{DM heating}}$$

The DM heating is masked under the vortex creep heating unless $J \lesssim 10^{38}$ erg $\cdot$ s.



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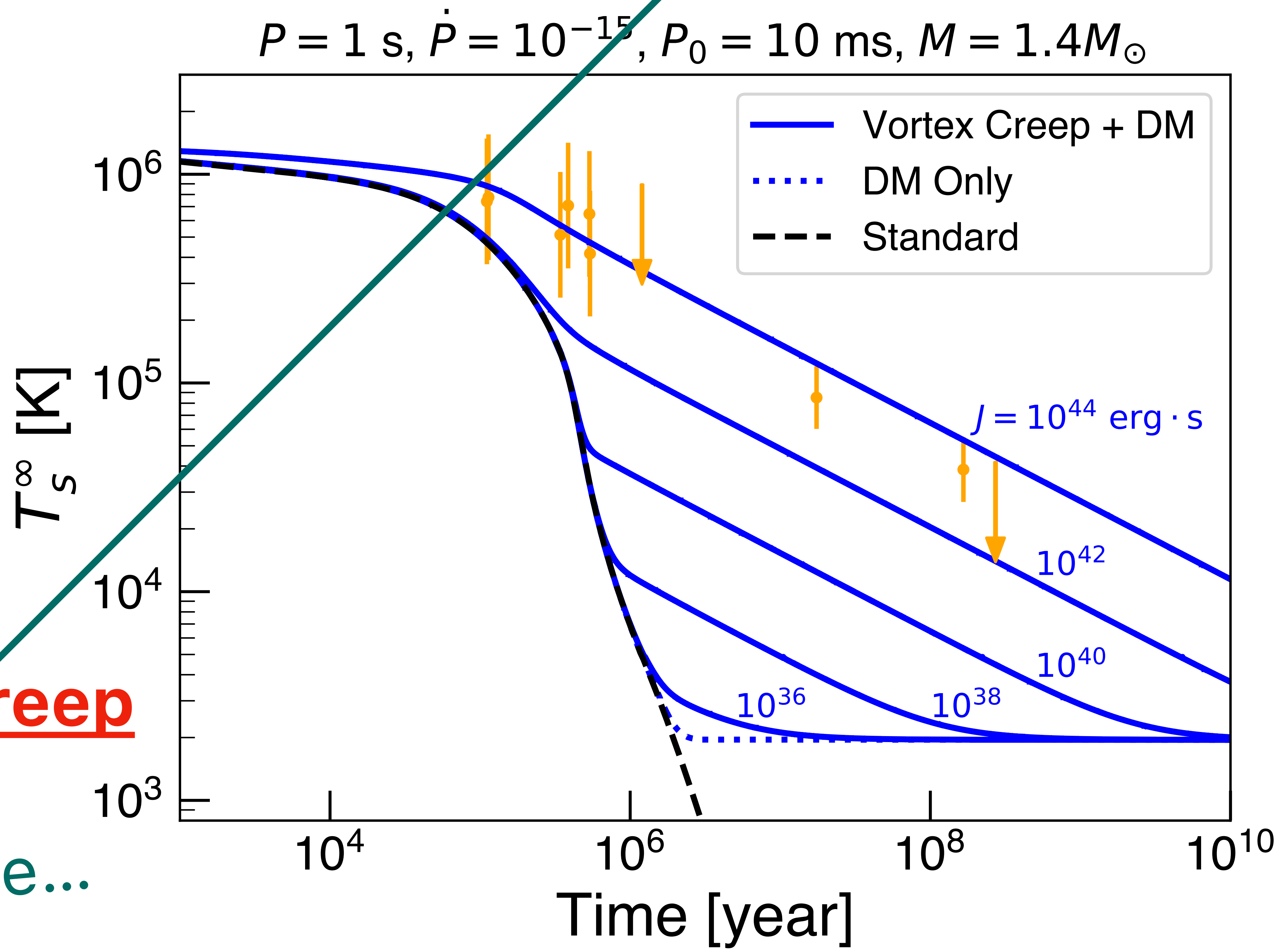
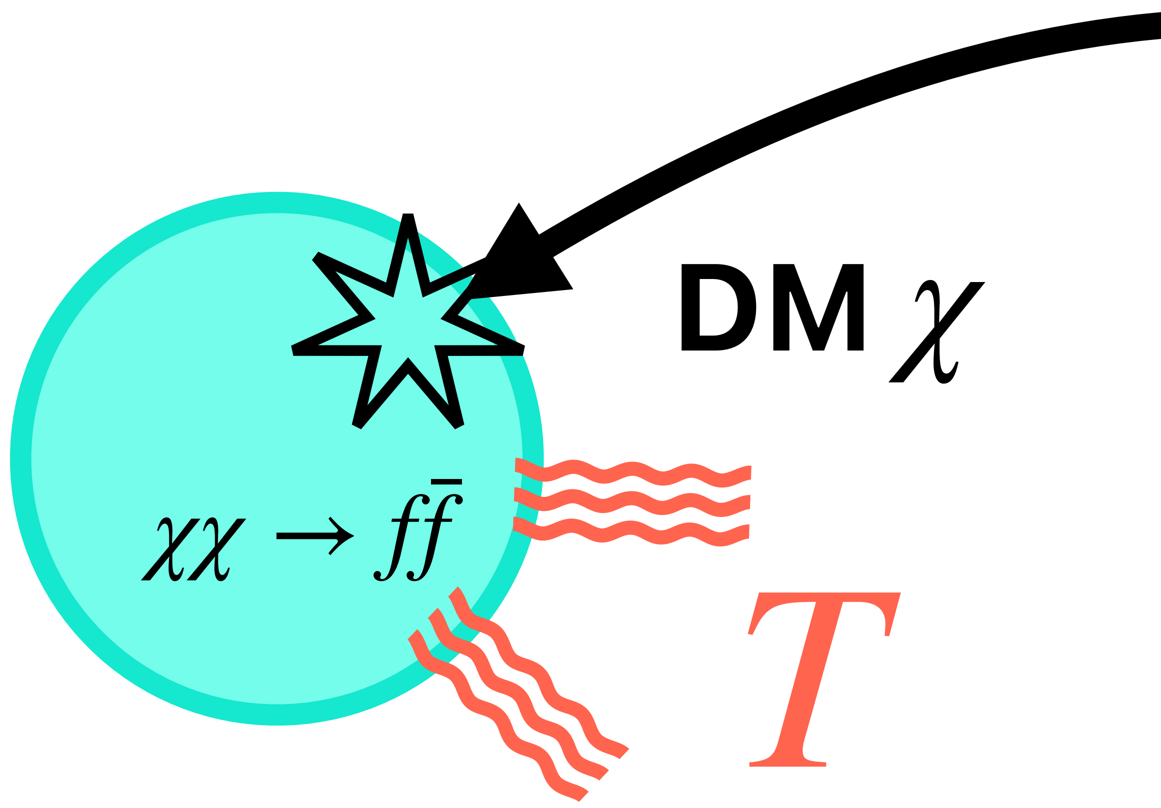

$P = 1$ s, $\dot{P} = 10^{-15}$, $P_0 = 10$ ms, $M = 1.4 M_\odot$

The DM heating is masked under the vortex creep heating unless $J \lesssim 10^{38}\ \mathrm{erg\cdot s}$.

This may be a serious challenge…

Summary

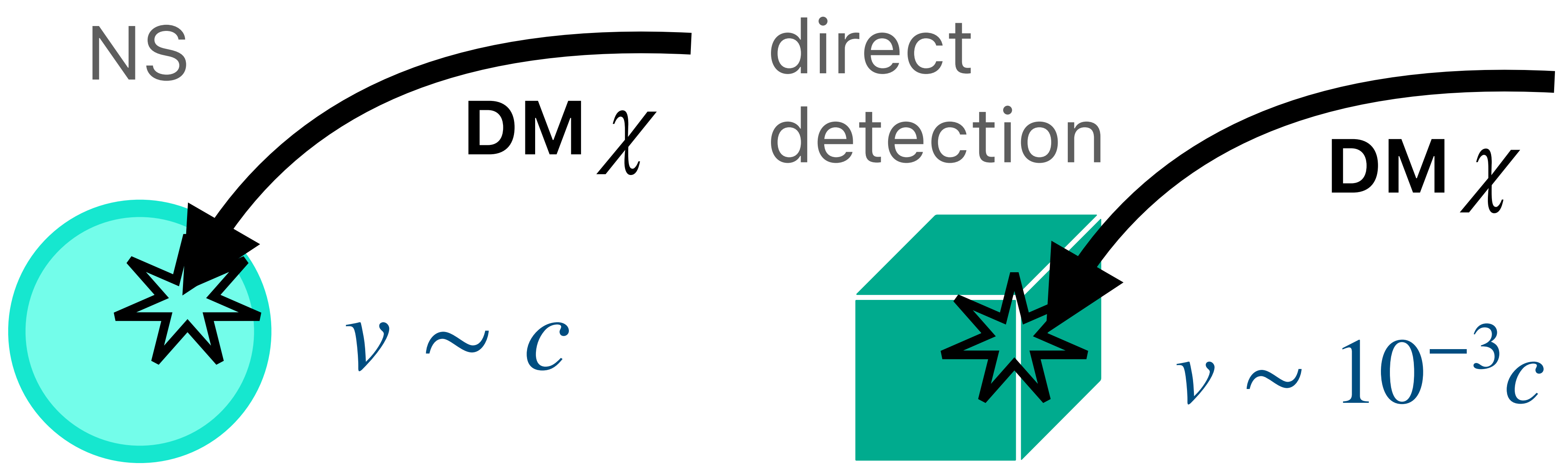
- **NS Heating** is an interesting alternative probe of **Dark Matter**.



- **Advantages**:

  (1) Large Kinetic Energy ($v \sim c$)
  👉 advantageous for, e.g., **inelastic scattering**.

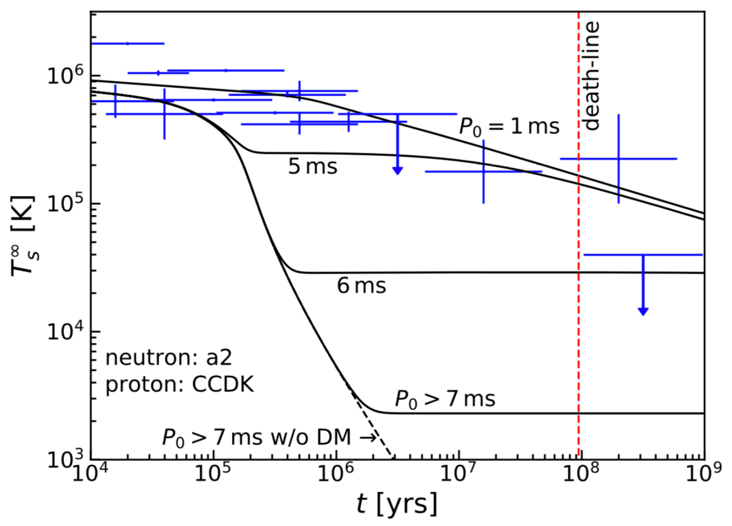
  (2) Multiple Targets: e, μ, p, n
  👉 It can probe, e.g., DM coupled only to **muon**.



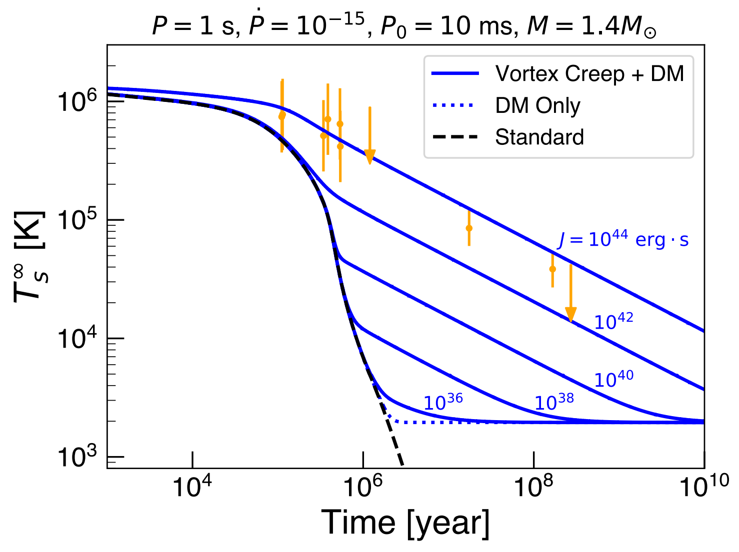
- **Challenges**:

  Some old and warm ($T \gg 2000K$) NSs have been observed, implying additional **internal heating mechanisms**.

  (1) **Rotochemical Heating**
  👉 For a long P_0, DM heating effect is visible.



  (2) **Vortex Creep Heating**
  👉 If this is the dominant heating mechanism, DM heating is masked.



Backup

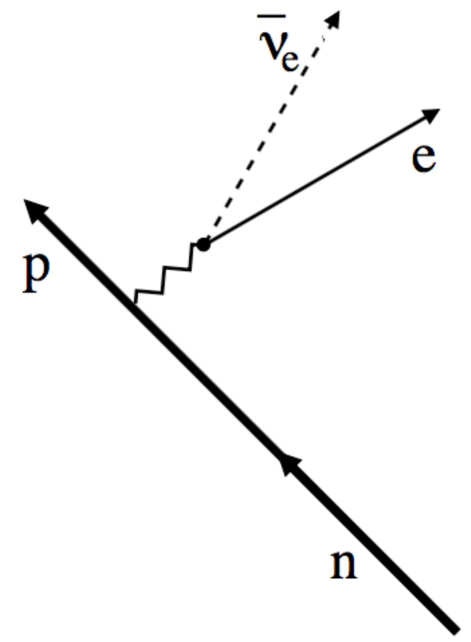
NS and Standard Cooling

For reviews, e.g., D.G.Yakovlev+, astro-ph/0402143,
D.Page+, astro-ph/0508056, 1302.6626

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

Neutrino emission

- **Direct Urca**
- Modified Urca
- Bremsstrahlung
- PBF

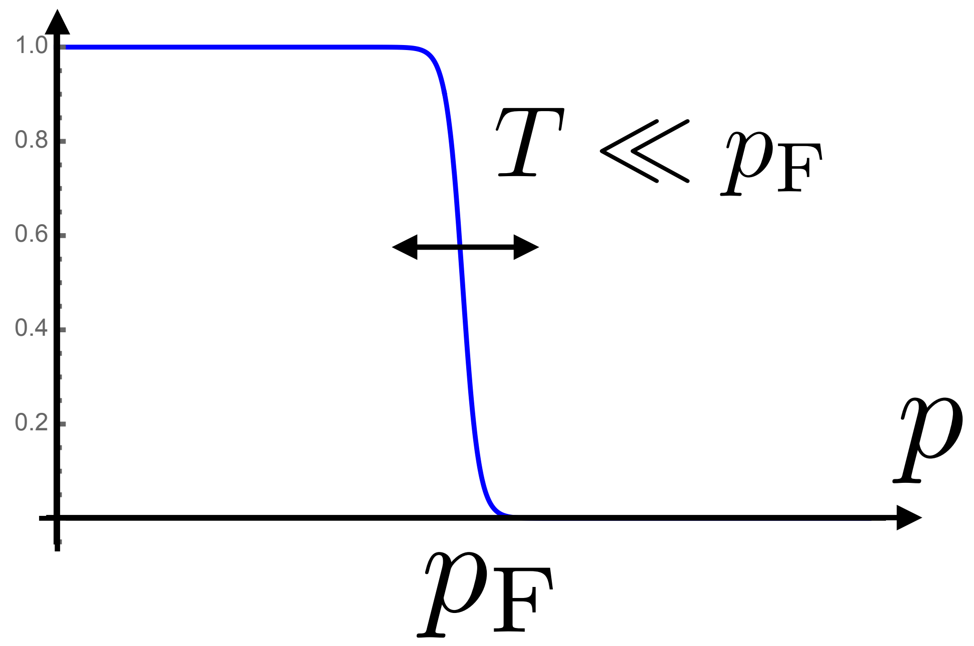


β decay and its inverse: $\begin{cases} n \rightarrow p + e^- + \bar{\nu}_e \\ p + e^- \rightarrow n + \nu_e \end{cases}$

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

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



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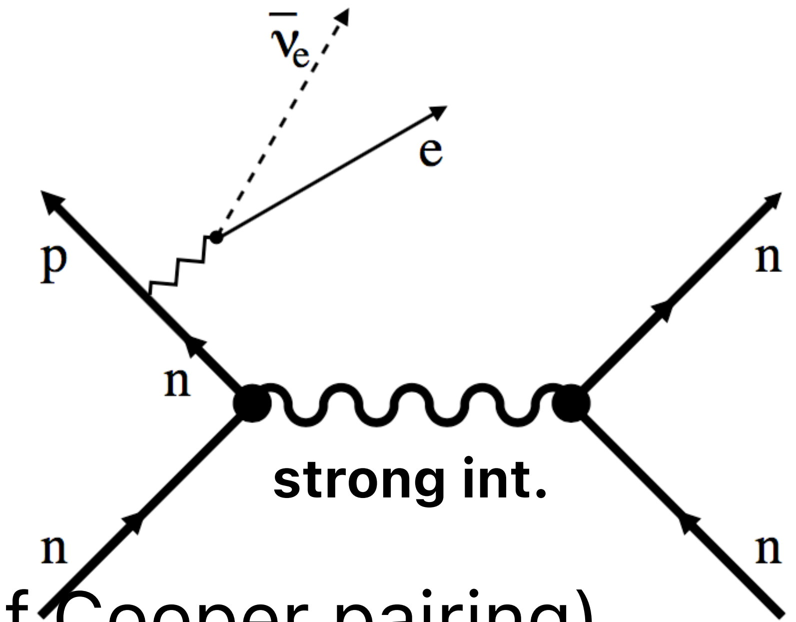


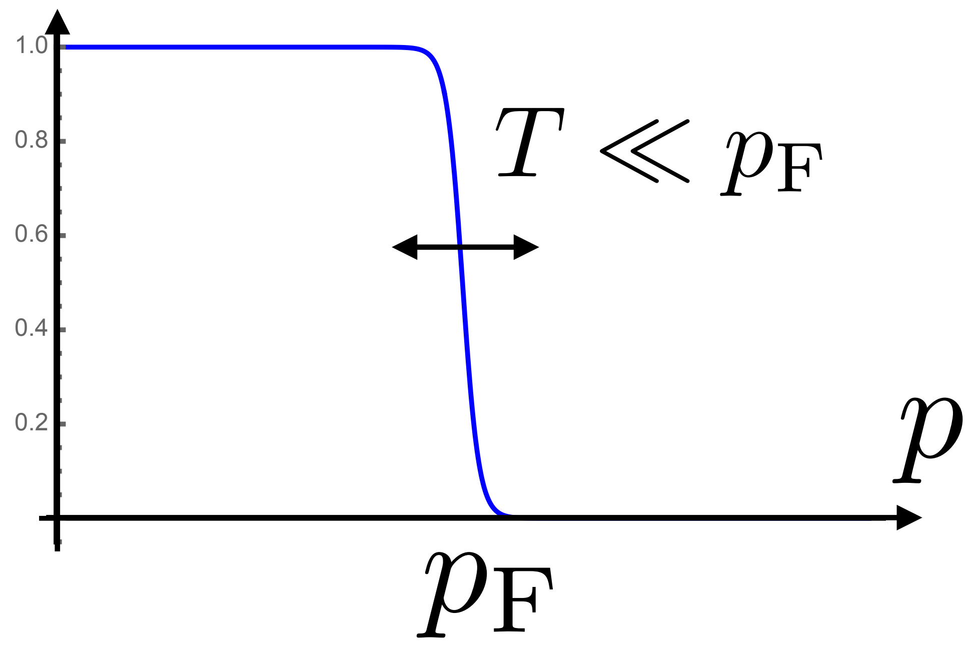
- Dominant process (before the onset of Cooper pairing)

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

$$L_\nu^{\mathrm{MU}} \sim T^8$$

$$L_\nu^{\mathrm{MU}} \sim \underbrace{\int d^3p_n}_{T} \underbrace{\int d^3p_N}_{T} \cdot \underbrace{\int d^3p_p}_{T} \underbrace{\int d^3p_N}_{T} \underbrace{\int d^3p_e}_{T} \cdot \underbrace{\int d^3p_\nu \delta^4(p_i - p_f) E_\nu}_{T^3}$$

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

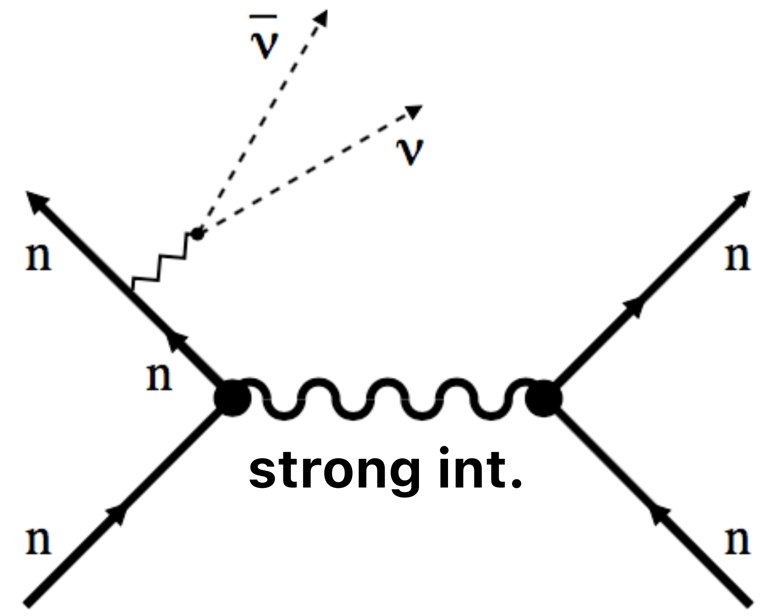


For reviews, e.g., D.G.Yakovlev+, astro-ph/0402143,
D.Page+, astro-ph/0508056, 1302.6626

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

Neutrino emission

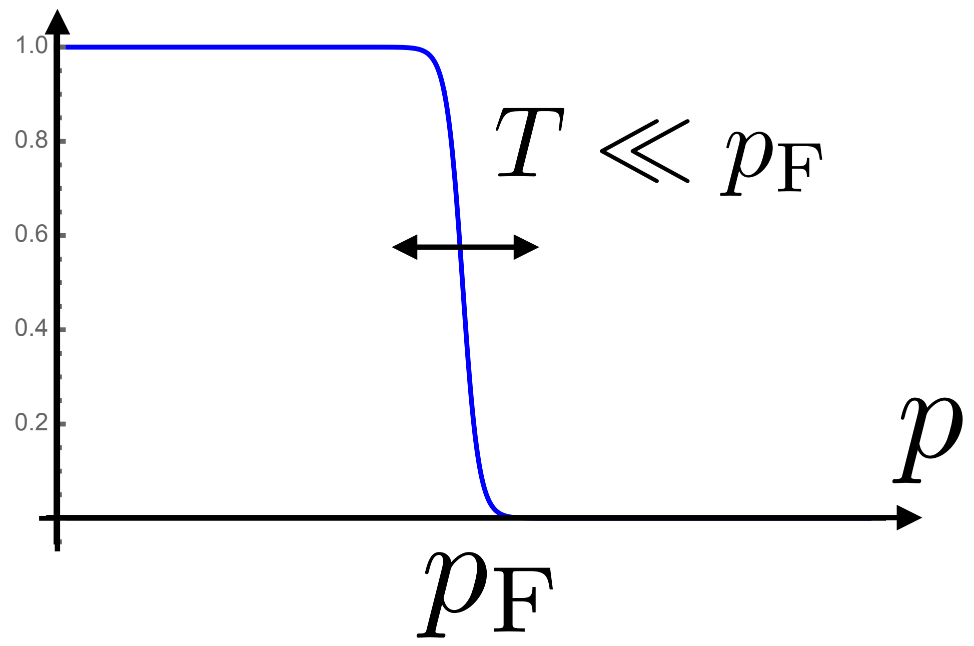
- ~~Direct Urca~~
- Modified Urca
- **Bremsstrahlung**
- PBF



- similarly, $L_\nu^{\mathrm{Brems.}} \sim T^8$

$$L_\nu^{\mathrm{Brems}} \sim \mathcal{O}(0.01) L_\nu^{\mathrm{MU}}$$

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



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D.Page+, astro-ph/0508056, 1302.6626

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

Neutrino emission

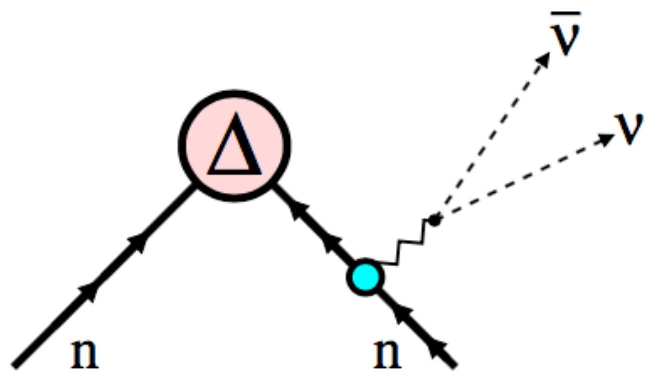
- ~~Direct Urca~~
- Modified Urca
- Bremsstrahlung
- **PBF**

PBF (Cooper-pair breaking and formation)

$$\begin{cases} [\tilde{N}\tilde{N}] \to \tilde{N} + \tilde{N} \\ \tilde{N} + \tilde{N} \to [\tilde{N}\tilde{N}] + \nu + \bar{\nu} \end{cases}$$

($\tilde{N}$: quasi-paticle, $[\tilde{N}\tilde{N}]$: Cooper-pair)

Important for $T < T_c$.



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

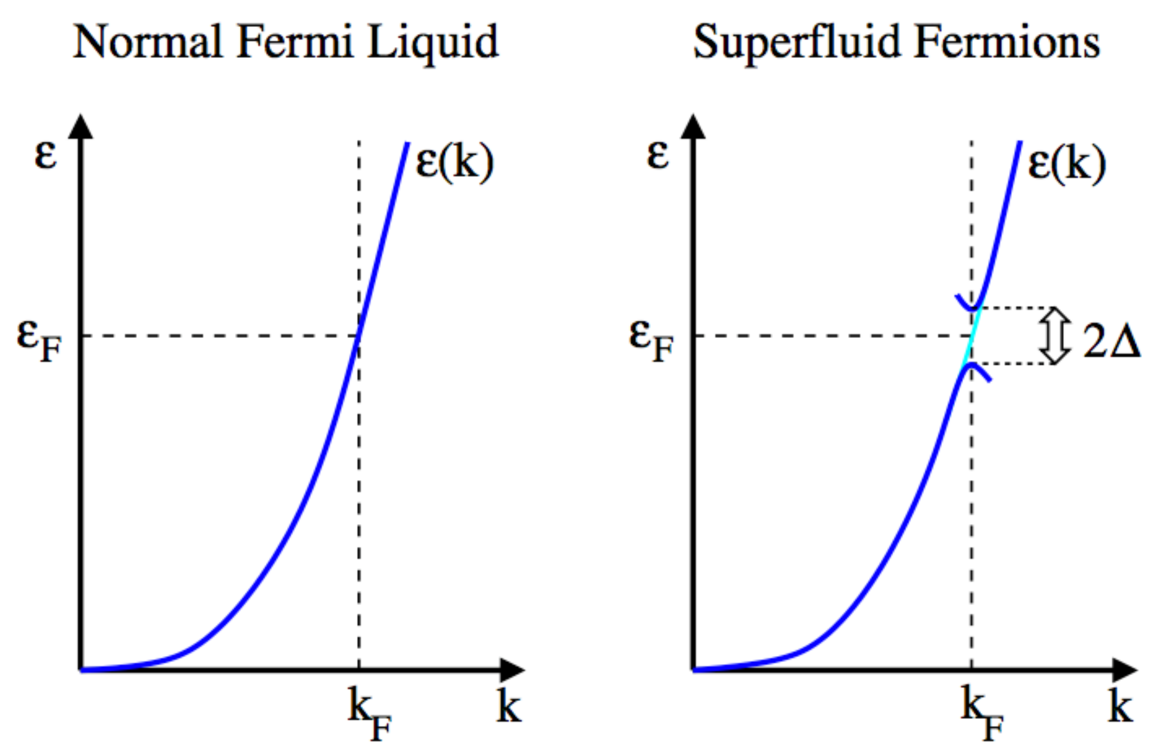
Neutrino emission

- ~~Direct Urca~~
- Modified Urca
- Bremsstrahlung
- PBF

Superfuidity (pairing) plays important roles.

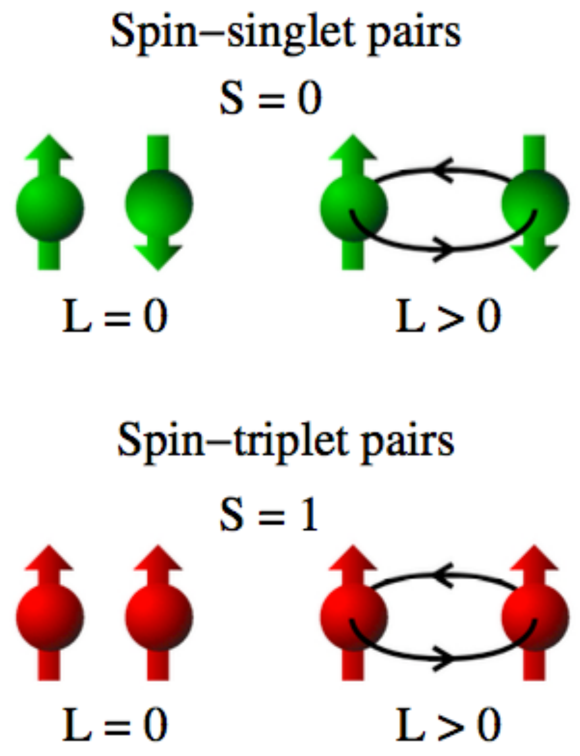
- At **T < Tc,** Cooper pairing occurs.

T > Tc **T < Tc**



Figs. from Page et.al. 1302.6626

$$\varepsilon(p) \simeq \sqrt{\Delta^2 + v_F^2(p-p_F)^2}$$



neutron singlet ($^1S_0$)
neutron triplet ($^3P_2$)
proton singlet ($^1S_0$)

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

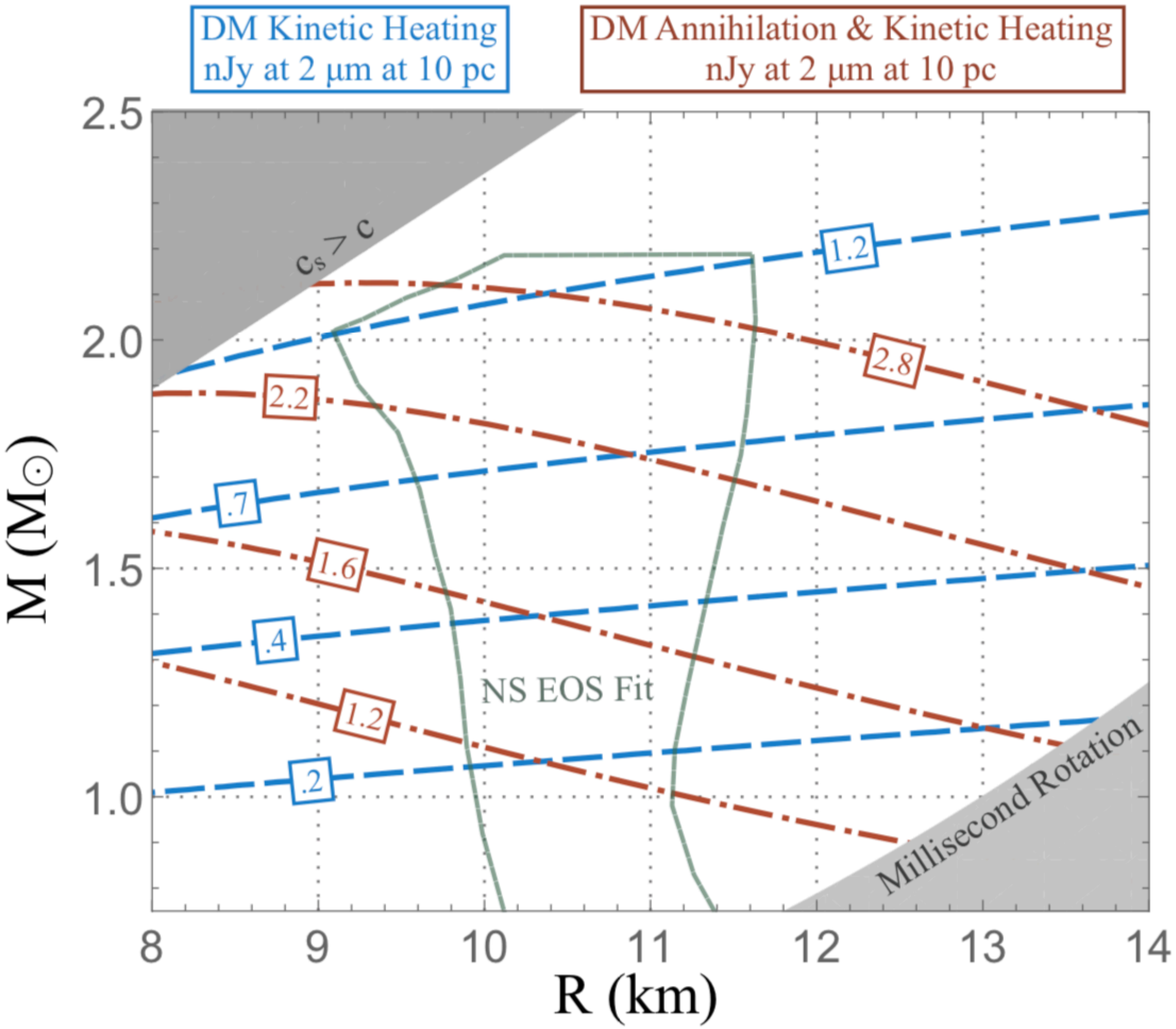
Backup

NS and DM

observational feasibility

- https://arxiv.org/abs/1704.01577

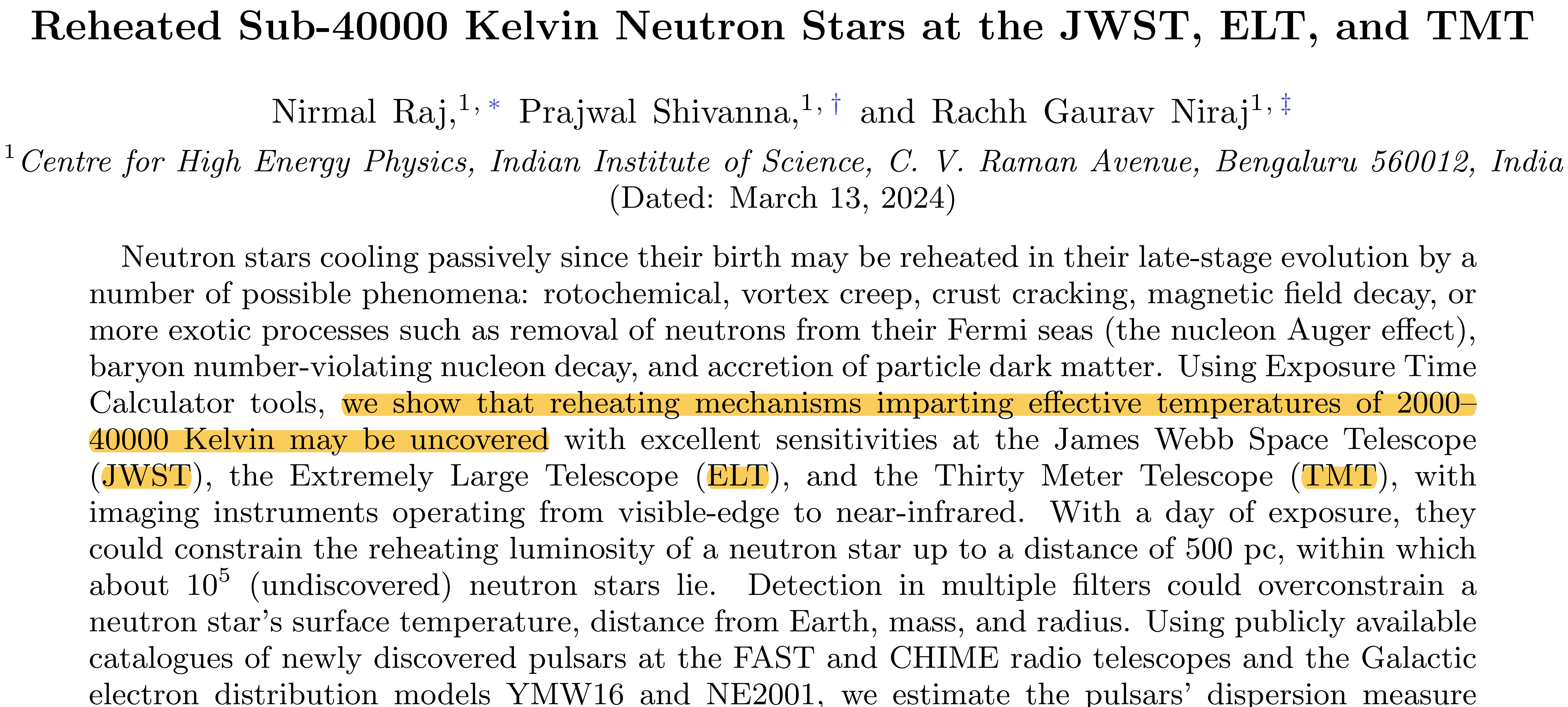
- O(1) old and cold NSs can be at $d = 10\text{pc}$.
- Radiation from a DM-heated NS there results in a spectral flux density of O(1) nanoJansky (nJy) at wavelength $\nu^{-1} = \mathcal{O}(1)\ \mu\text{m}$.
- Maybe within the sensitivity of the upcoming telescopes such as the JWST, TMT, and E-ELT.



M.Baryakhtar+, 1704.01577

observational feasibility

- https://arxiv.org/abs/2403.07496



Reheated Sub-40000 Kelvin Neutron Stars at the JWST, ELT, and TMT

Nirmal Raj,[1,*] Prajwal Shivanna,[1,†] and Rachh Gaurav Niraj[1,‡]
[1] *Centre for High Energy Physics, Indian Institute of Science, C. V. Raman Avenue, Bengaluru 560012, India*

(Dated: March 13, 2024)

Neutron stars cooling passively since their birth may be reheated in their late-stage evolution by a number of possible phenomena: rotochemical, vortex creep, crust cracking, magnetic field decay, or more exotic processes such as removal of neutrons from their Fermi seas (the nucleon Auger effect), baryon number-violating nucleon decay, and accretion of particle dark matter. Using Exposure Time Calculator tools, we show that reheating mechanisms imparting effective temperatures of 2000–40000 Kelvin may be uncovered with excellent sensitivities at the James Webb Space Telescope (JWST), the Extremely Large Telescope (ELT), and the Thirty Meter Telescope (TMT), with imaging instruments operating from visible-edge to near-infrared. With a day of exposure, they could constrain the reheating luminosity of a neutron star up to a distance of 500 pc, within which about 10^5 (undiscovered) neutron stars lie. Detection in multiple filters could overconstrain a neutron star's surface temperature, distance from Earth, mass, and radius. Using publicly available catalogues of newly discovered pulsars at the FAST and CHIME radio telescopes and the Galactic electron distribution models YMW16 and NE2001, we estimate the pulsars' dispersion measure

Backup

NS and DM: rotochemical

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

- We have updated the calculation, including for the first time

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

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

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

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

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

non-equilibrium

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

chemical potential

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

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

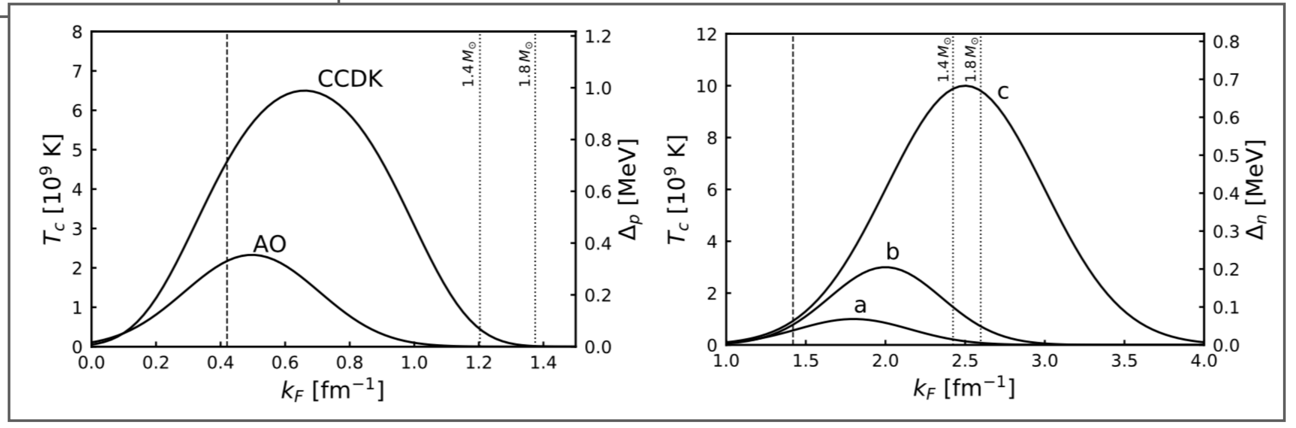
$$\Delta\Gamma_{M,N\ell} = \frac{Q_{M,N\ell}^{(0)}}{T(r)}\,I_{M,\Gamma}^N$$

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

$$Q_{M,N\ell} = Q_{M,N\ell}^{(0)}\,I_{M,\epsilon}^N$$

$$I_{M,\epsilon}^N = \frac{60480}{11513\pi^8}\frac{1}{A_0^N}\int\prod_{j=1}^{5}\frac{d\Omega_j}{4\pi}\int_0^\infty dx_\nu\int_{-\infty}^{\infty}dx_n dx_p dx_{N_1} dx_{N_2}\,x_\nu^3\cdot f(z_n)f(z_p)f(z_{N_1})f(z_{N_2})$$
$$\times\left[f(x_\nu-\xi_\ell-z_n-z_p-z_{N_1}-z_{N_2}) + f(x_\nu+\xi_\ell-z_n-z_p-z_{N_1}-z_{N_2})\right]\delta^3\left(\sum_{j=1}^{5}\boldsymbol{p}_j\right), \quad (18)$$

$$I_{M,\Gamma}^N = \frac{60480}{11513\pi^8}\frac{1}{A_0^N}\int\prod_{j=1}^{5}\frac{d\Omega_j}{4\pi}\int_0^\infty dx_\nu\int_{-\infty}^{\infty}dx_n dx_p dx_{N_1} dx_{N_2}\,x_\nu^2\cdot f(z_n)f(z_p)f(z_{N_1})f(z_{N_2})$$
$$\times\left[f(x_\nu-\xi_\ell-z_n-z_p-z_{N_1}-z_{N_2}) - f(x_\nu+\xi_\ell-z_n-z_p-z_{N_1}-z_{N_2})\right]\delta^3\left(\sum_{j=1}^{5}\boldsymbol{p}_j\right), \quad (19)$$

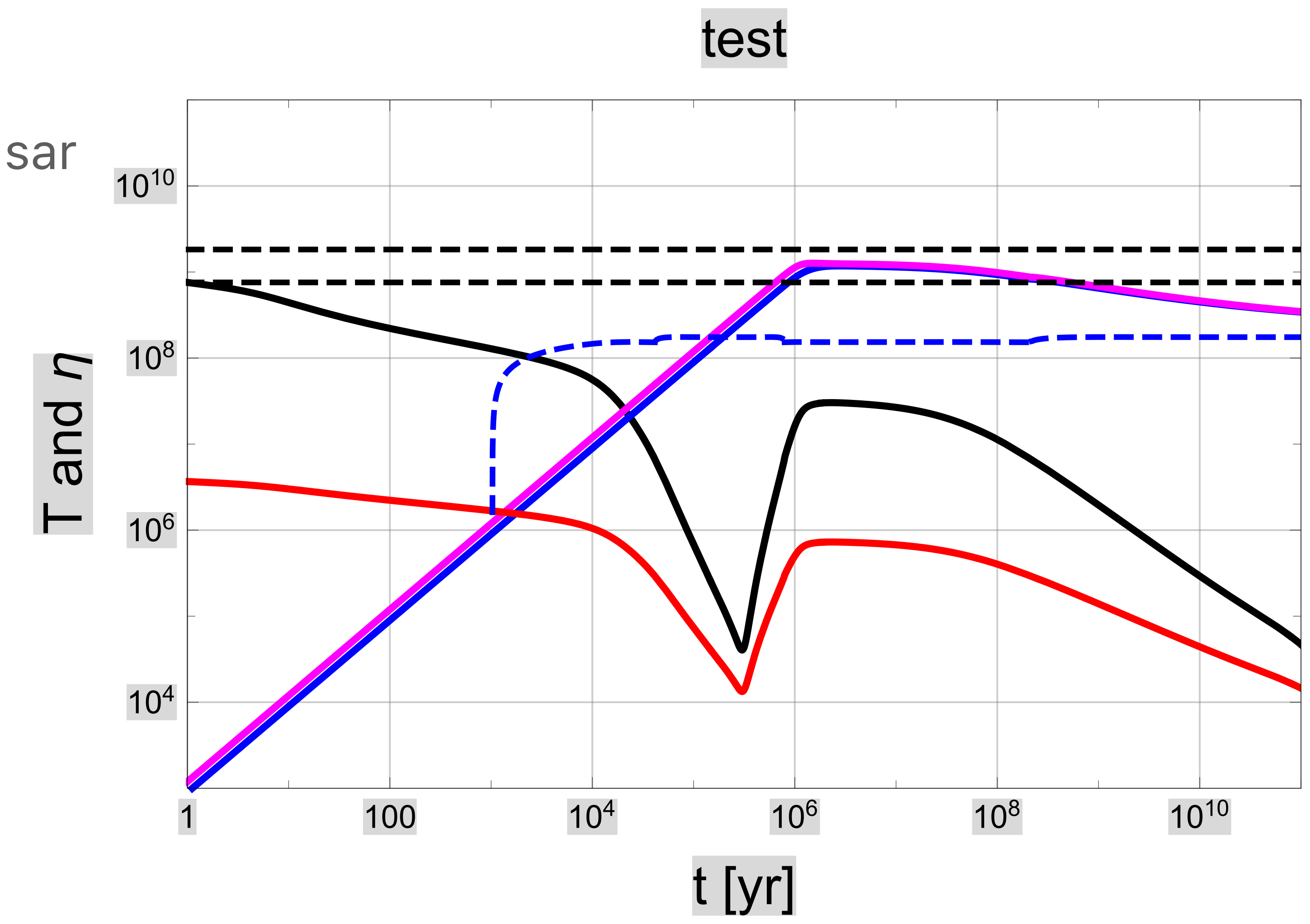


$$\tilde{N}\tilde{N} \longrightarrow [NN] + \nu_\ell + \bar{\nu}_\ell$$

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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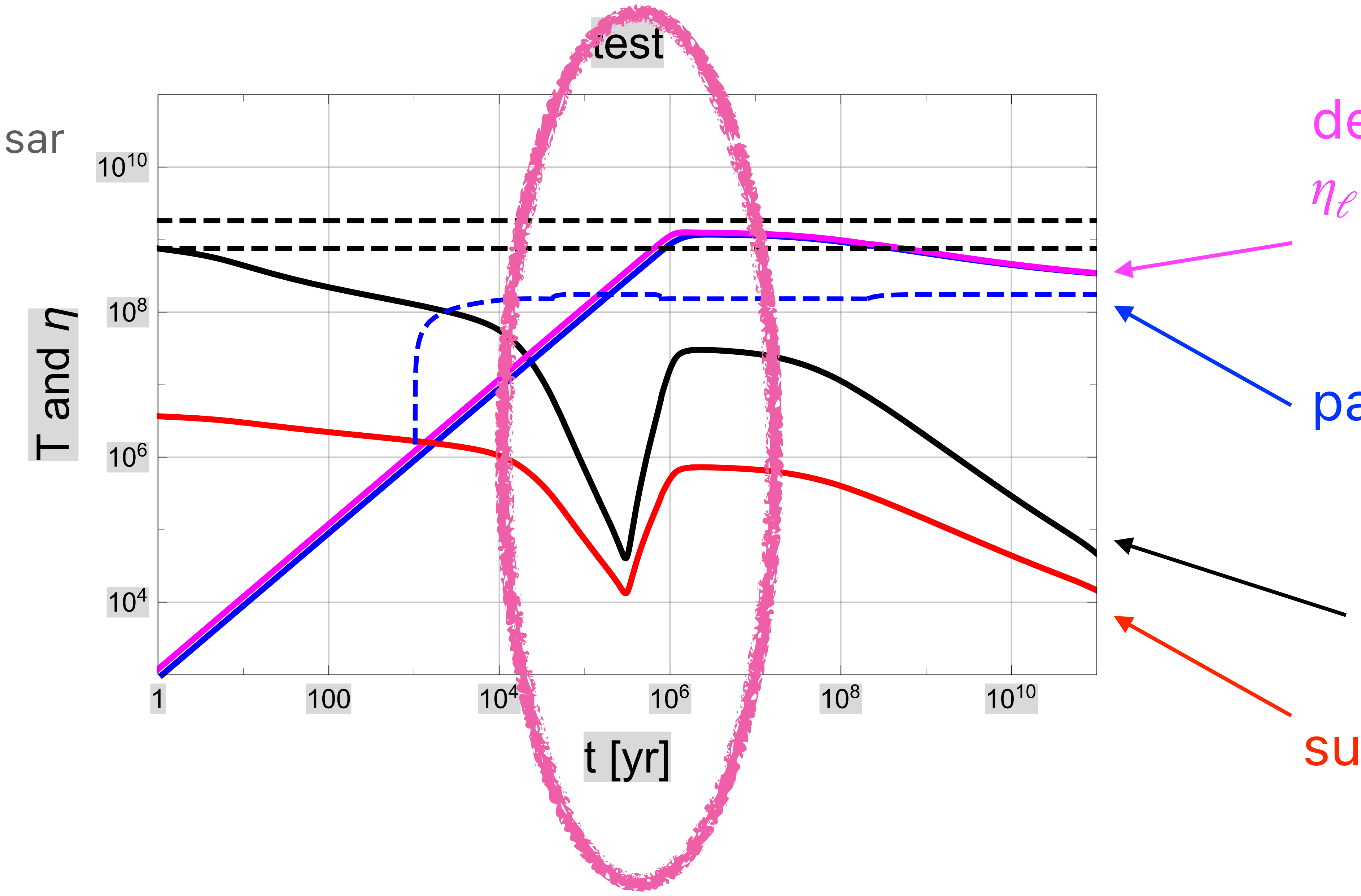


deviation from β-eq.
$\eta_\ell = \mu_n - \mu_p - \mu_\ell \ (\ell = e, \mu)$

pairing gap Δ

internal temperature T

surface temperature T_s

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

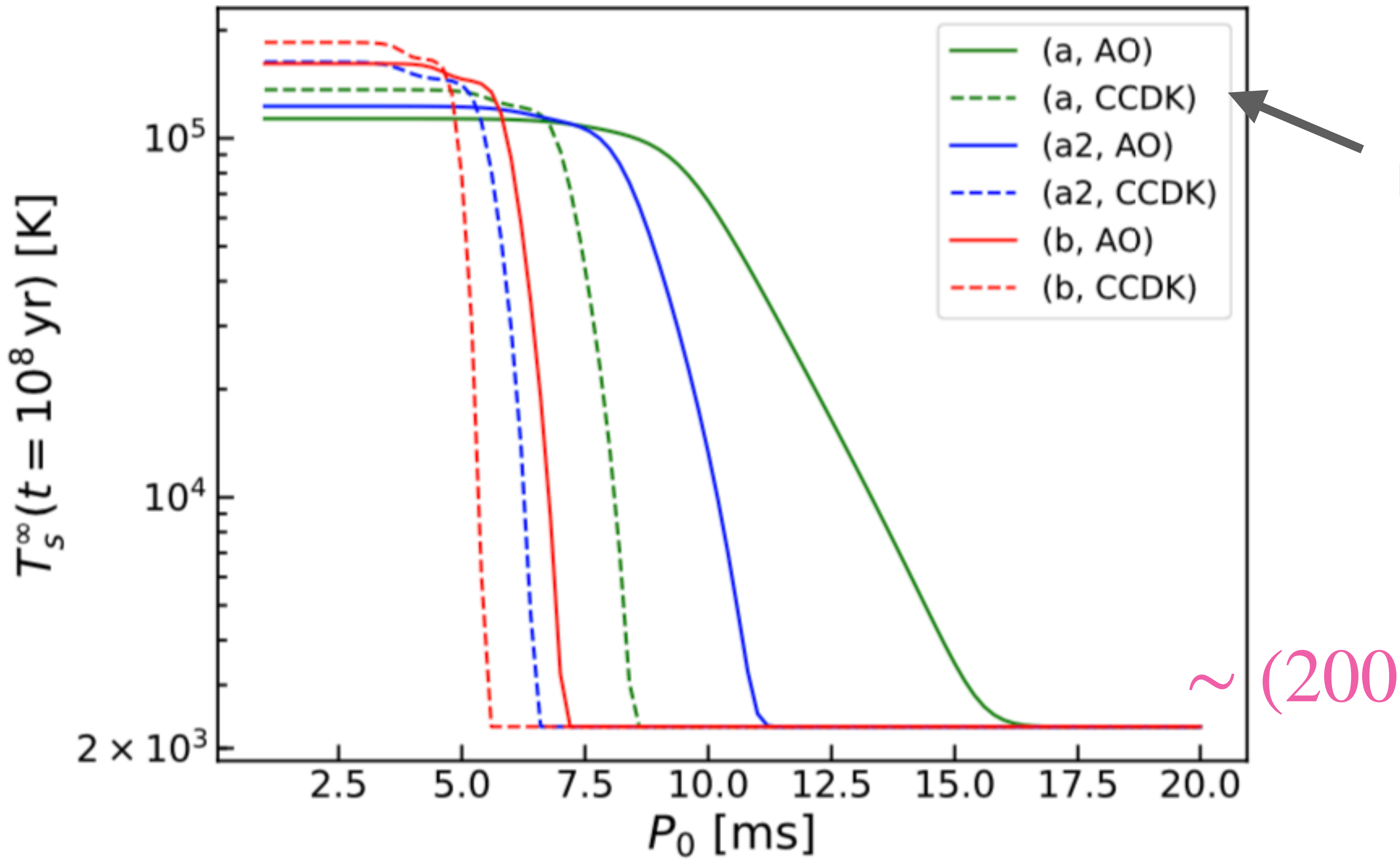
DM heating vs. Rotochemical heating

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

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