Dark Matter Heating
vs.
Rotochemical Heating
in Old Neutron Stars

Koichi Hamaguchi (University of Tokyo)

Berkeley week at Kavli IPMU, January 16, 2020.

Based on

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

K. Yanagi, N. Nagata, KH, [arXiv:1904.04667] MNRAS (to be published)

cf. KH, N. Nagata, K. Yanagi, J. Zheng [arXiv:1806.07151], Phys.Rev. **D98** (2018) 103015. -> bound on **axion.**

Dark Matter Heating
vs.
Rotochemical Heating
in Old Neutron Stars

See also the **talk by Keisuke Yanagi** tomorrow.

Koichi Hamaguchi (University of Tokyo)

Berkeley week at Kavli IPMU, January 16, 2020.

Based on

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

K. Yanagi, N. Nagata, KH, [arXiv:1904.04667] MNRAS (to be published)

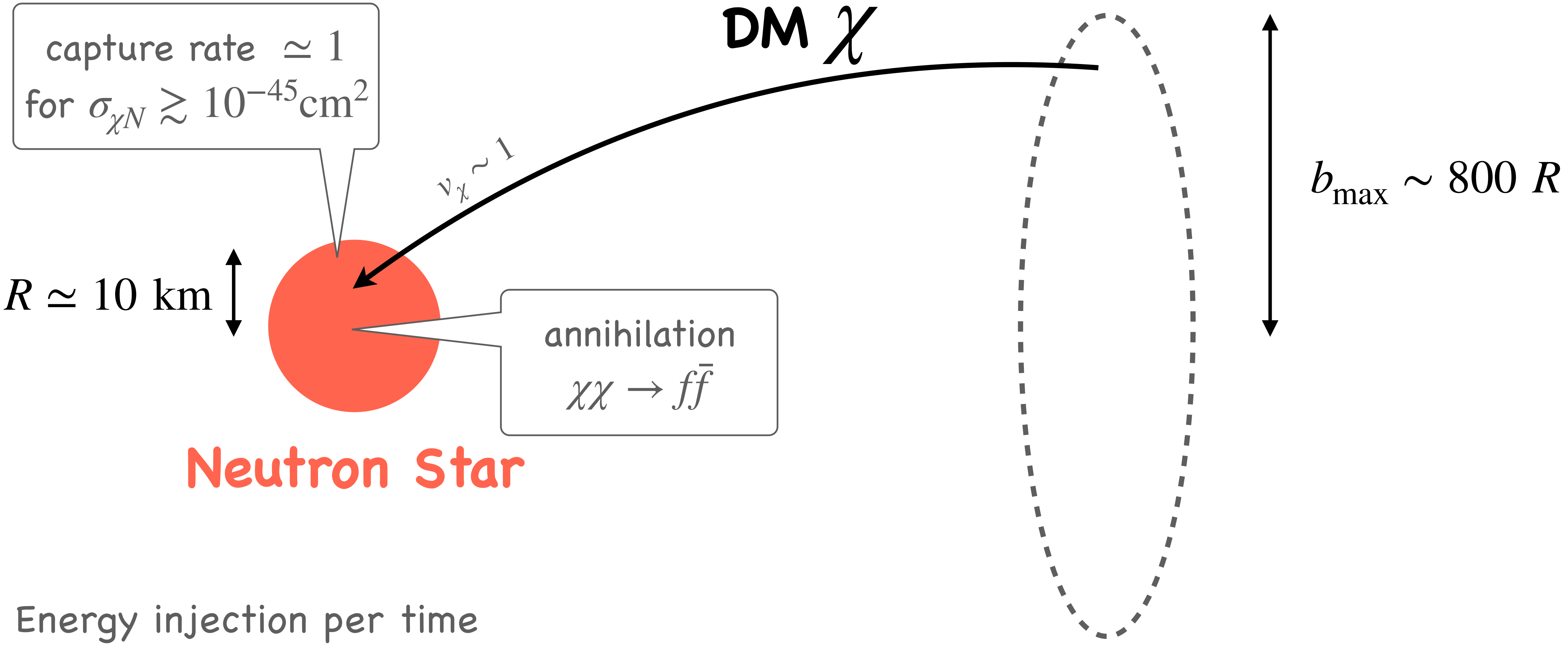
cf. KH, N. Nagata, K. Yanagi, J. Zheng [arXiv:1806.07151], Phys.Rev. **D98** (2018) 103015. -> bound on **axion.**

Introduction (outline of today's talk)

Introduction (outline of today's talk)

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

[C. Kouvaris, 0708.2362]



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

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

Neutron Star

Energy injection per time

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

(independent of DM mass)

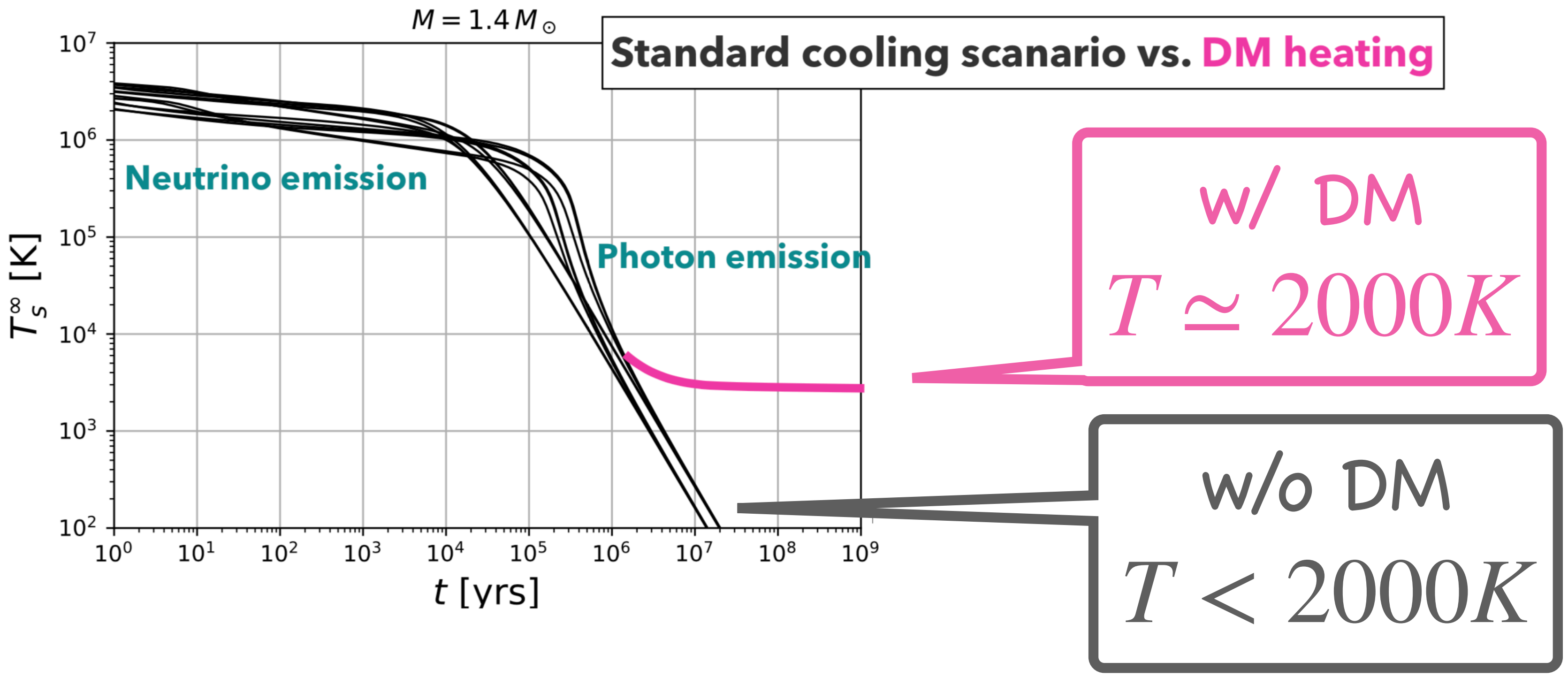
→ **DM heats NS !**

Introduction (outline of today's talk)

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,
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
C.-S. Chen+ 1804.03409
N. F. Bell+ 1807.02840
D. A. Camargo+ 1901.05474
N. F. Bell+ 1904.09803
KH, N.Nagata, K.Yanagi 1905.02991
R. Garani+ 1906.10145
J. F. Acevedo+, 1911.06334
A. Joglekar+, 1911.13293



Standard cooling scanario vs. DM heating

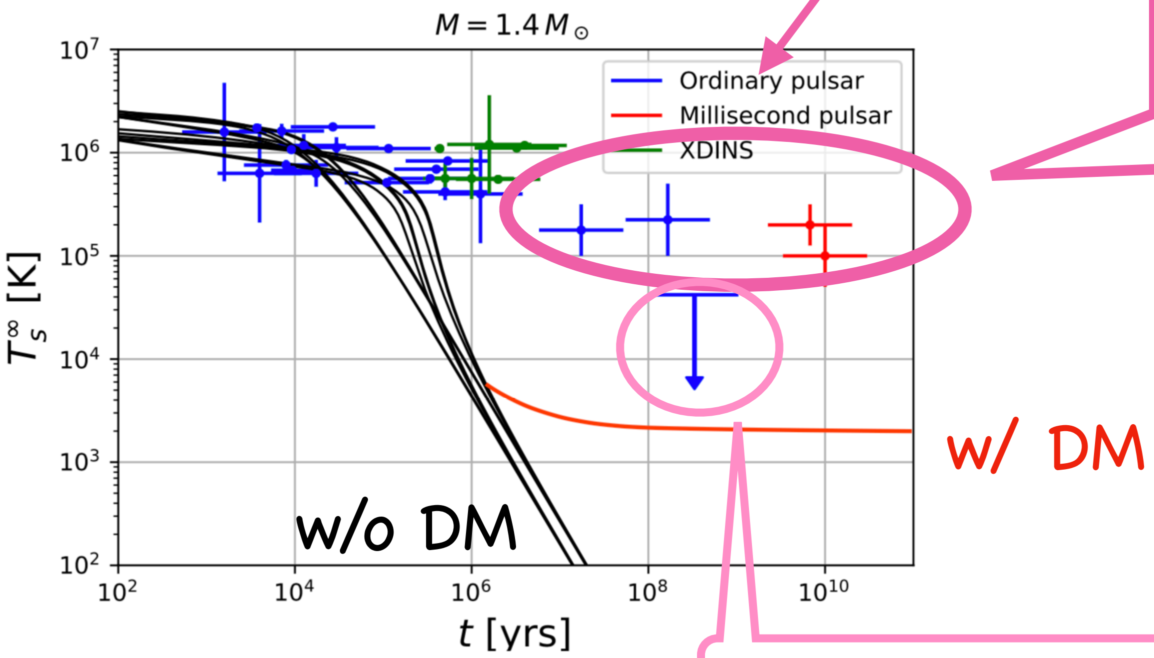
w/ DM
$T \simeq 2000K$

w/o DM
$T < 2000K$

Fig. thanks to **K.Yanagi.**

Introduction (outline of today's talk)

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!



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

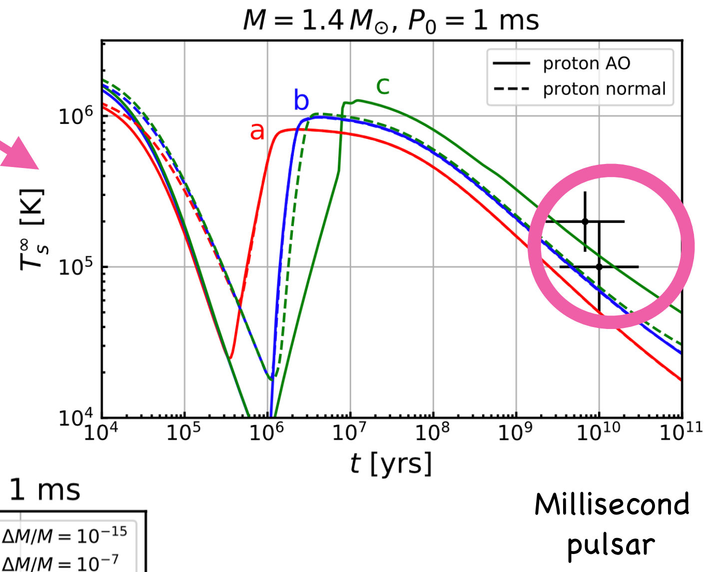
There are also cooler ones.

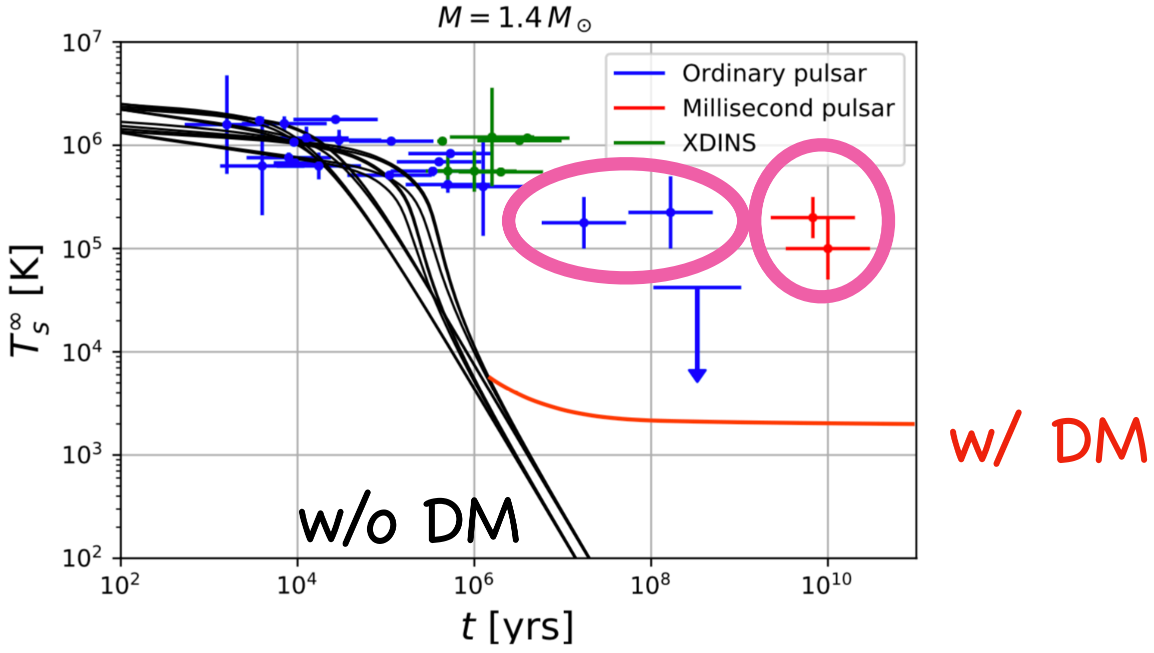
Fig. thanks to **K.Yanagi.**

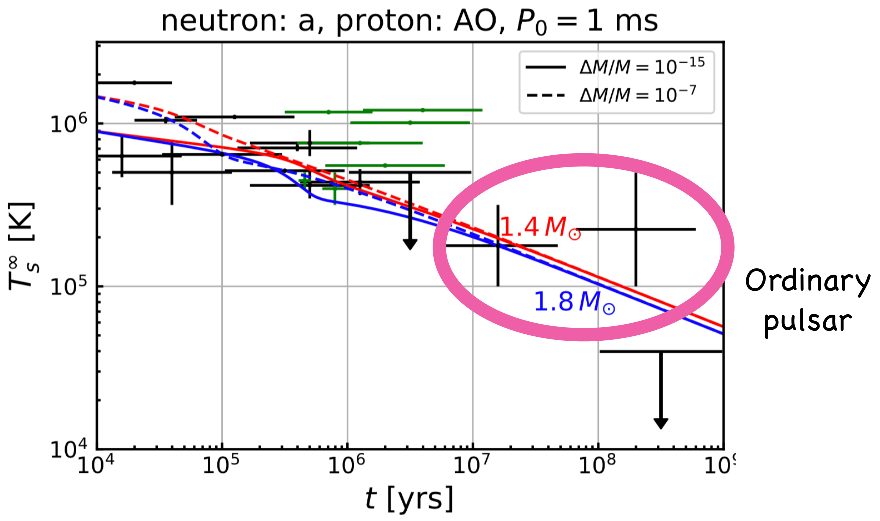
Introduction (outline of today's talk)

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!

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







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

Fig. thanks to **K.Yanagi.**

Introduction (outline of today's talk)

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!

In fact, **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?

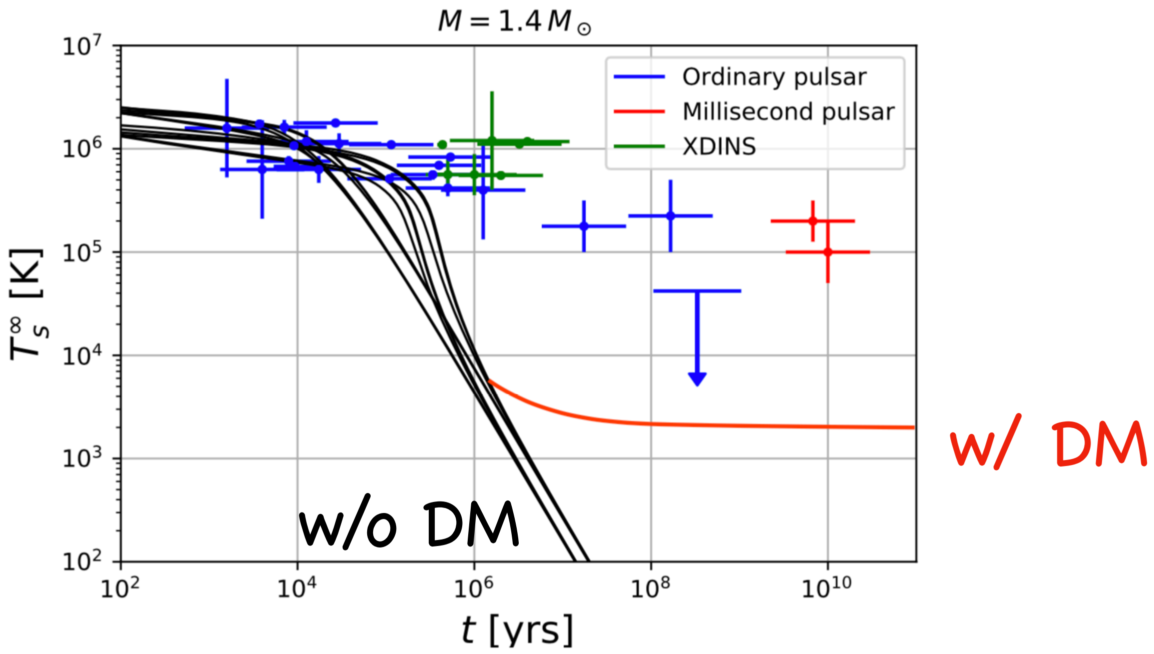


Fig. thanks to **K.Yanagi.**

Plan

0. Introduction

done

1. Neutron Star

2. Neutron Star Cooling and Heating

3. Summary

Neutron Star

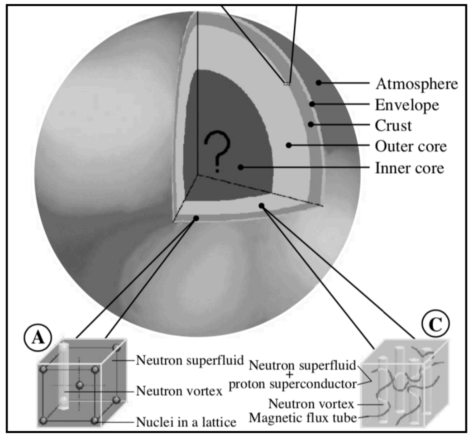


fig. from 1302.6626

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

heaviest one found recently: $M \simeq 2.14 M_\odot$ (pulsar MSP J0740+6620 [Nature, 2019 September])

Neutron Star

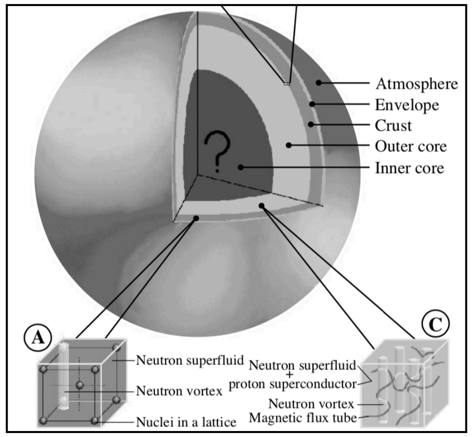
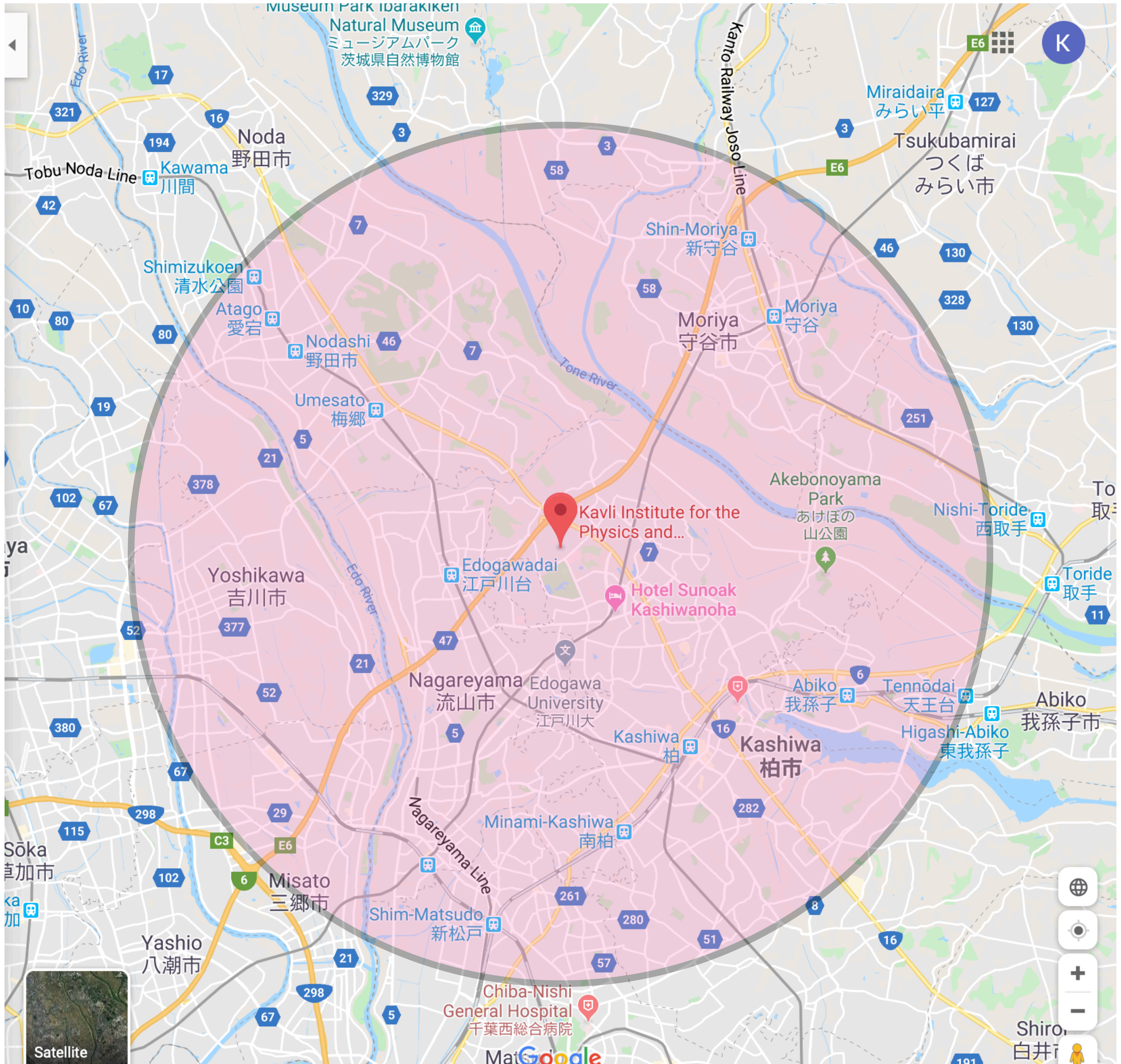


fig. from 1302.6626

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

  heaviest one found recently: $M \simeq 2.14 M_\odot$ (pulsar MSP J0740+6620 [Nature, 2019 September])

- **Radius** : $R \sim 10$ km



Neutron Star

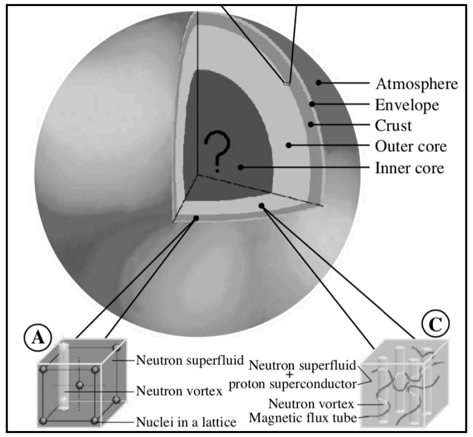


fig. from 1302.6626

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

  heaviest one found recently: $M \simeq 2.14 M_\odot$ (pulsar MSP J0740+6620 [Nature, 2019 September])

- **Radius** : $R \sim 10\ \text{km}$

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

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

Neutron Star

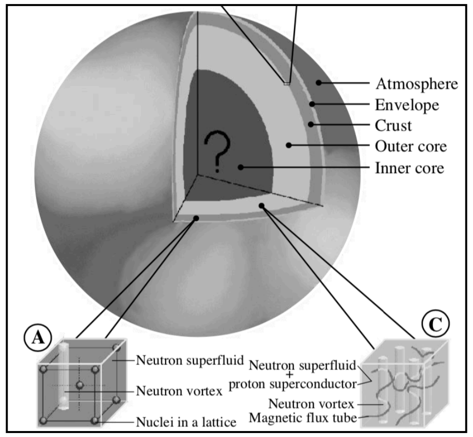


fig. from 1302.6626

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

  heaviest one found recently: $M \simeq 2.14 M_\odot$ (pulsar MSP J0740+6620 [Nature, 2019 September])

- **Radius** : $R \sim 10\ \text{km}$

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

- mostly composed of **neutrons,** + O(10%) **protons, electrons, muons.**

Neutron Star

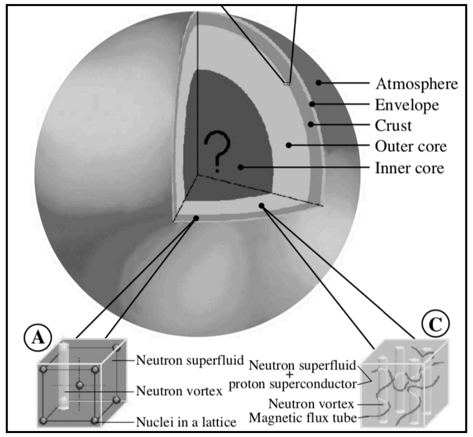


fig. from 1302.6626

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

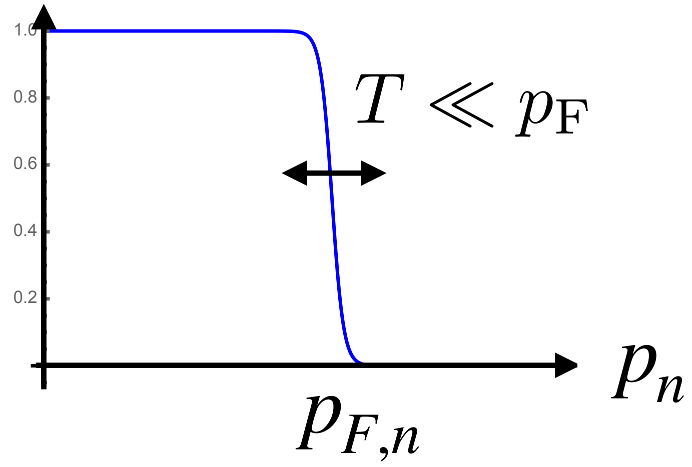
  heaviest one found recently: $M \simeq 2.14 M_\odot$ (pulsar MSP J0740+6620 [Nature, 2019 September])

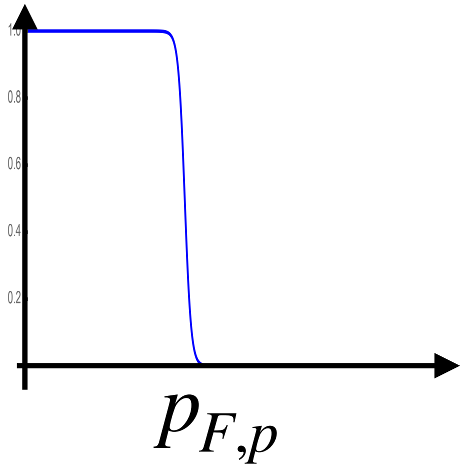
- **Radius** : $R \sim 10\ \mathrm{km}$

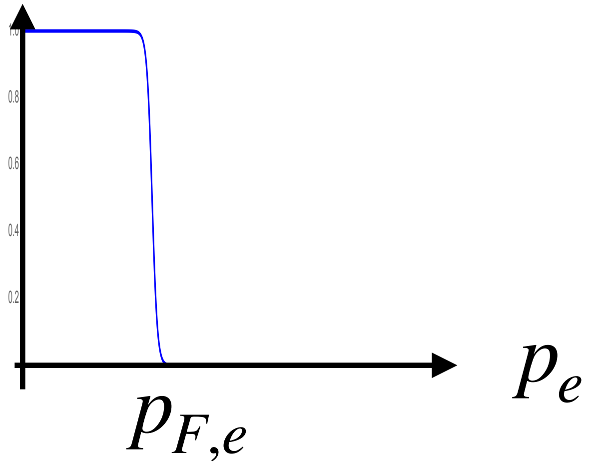
- **Density** : $\bar{\rho} = \dfrac{M}{(4\pi/3)R^3} \simeq 7 \times 10^{14} \mathrm{g/cm^3}$

- mostly composed of **neutrons,** + O(10%) **protons, electrons, muons.**

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







Neutron Star

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

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

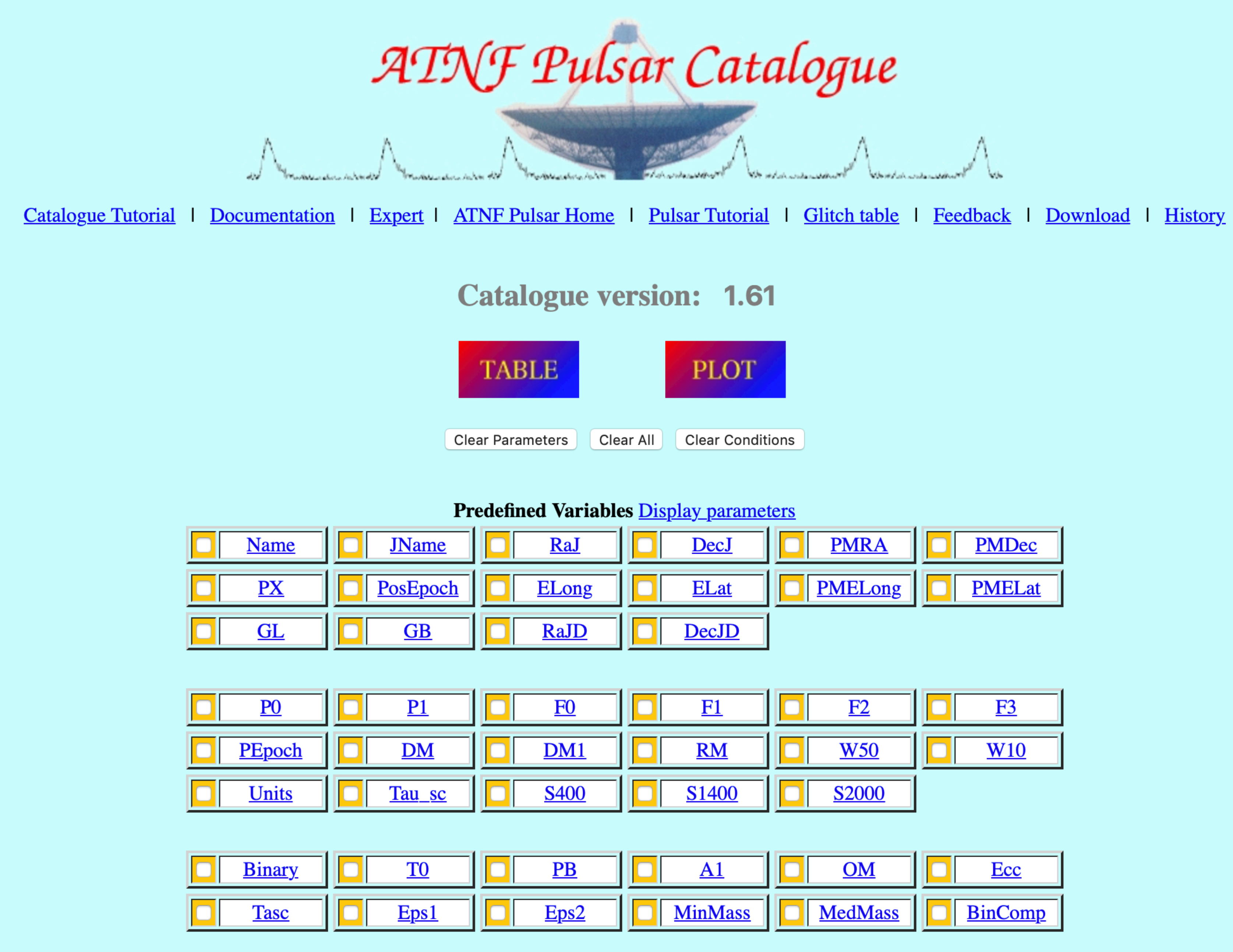
Crab Pulsar

Neutron Star

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

> 2700 pulsars found so far.

ATNF pulsar catalogue:



Catalogue version: 1.61

Predefined Variables Display parameters

☐ Name	☐ JName	☐ RaJ	☐ DecJ	☐ PMRA	☐ PMDec
☐ PX	☐ PosEpoch	☐ ELong	☐ ELat	☐ PMELong	☐ PMELat
☐ GL	☐ GB	☐ RaJD	☐ DecJD		
☐ P0	☐ P1	☐ F0	☐ F1	☐ F2	☐ F3
☐ PEpoch	☐ DM	☐ DM1	☐ RM	☐ W50	☐ W10
☐ Units	☐ Tau_sc	☐ S400	☐ S1400	☐ S2000	
☐ Binary	☐ T0	☐ PB	☐ A1	☐ OM	☐ Ecc
☐ Tasc	☐ Eps1	☐ Eps2	☐ MinMass	☐ MedMass	☐ BinComp

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

Crab Pulsar

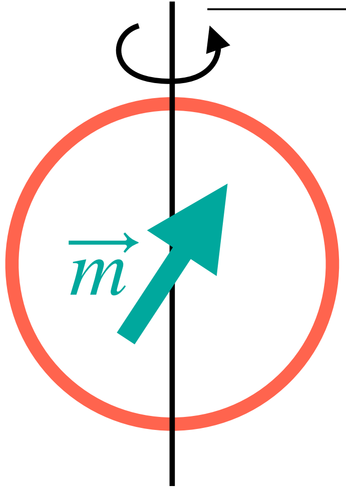
Neutron Star

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

Crab Pulsar

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

- **Magnetic Dipole Model**



Rotational energy loss ≃ magnetic dipole radiation

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

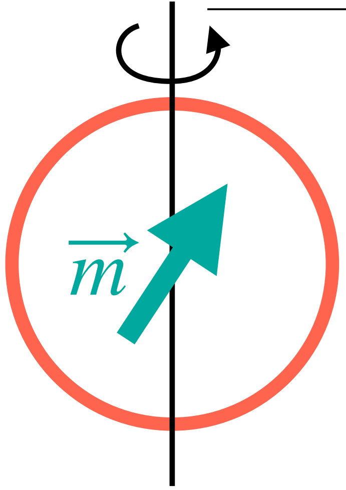
$$\Longrightarrow \quad t \simeq \frac{P_{\rm now}}{2\dot{P}_{\rm now}} \equiv \tau_{\rm sd}$$

spin down age / characteristic age

Neutron Star

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

- **Magnetic Dipole Model**



Rotational energy loss $\simeq$ magnetic dipole radiation

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

$$\Longrightarrow \qquad t \simeq \frac{P_{\rm now}}{2\dot{P}_{\rm now}} \equiv \tau_{\rm sd}$$

spin down age / characteristic age

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

Crab Pulsar

Example: Crab Pulsar

- actual age: $\tau = 965$ yrs (from historical records of SN1054.)
- spin down age: $P_{\rm now} \simeq 0.033$ sec, $\dot{P}_{\rm now} \simeq 4.2 \times 10^{-13} \Longrightarrow \tau_{\rm sd} \simeq 1200$ yrs

Plan

0. Introduction

1. Neutron Star

done

2. Neutron Star Cooling and Heating

3. Summary

Plan

0. Introduction

1. Neutron Star

2. Neutron Star Cooling and Heating

(i). $C\frac{dT}{dt} = -L_\nu - L_\gamma$ **Neutron Star Cooling**

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

(iii). $C\frac{dT}{dt} = -L_\nu - L_\gamma + L_{\text{rotochemical}}^{\text{heat}}$

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

Previous works

Our works

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

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

3. Summary

(i). NS Cooling

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

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

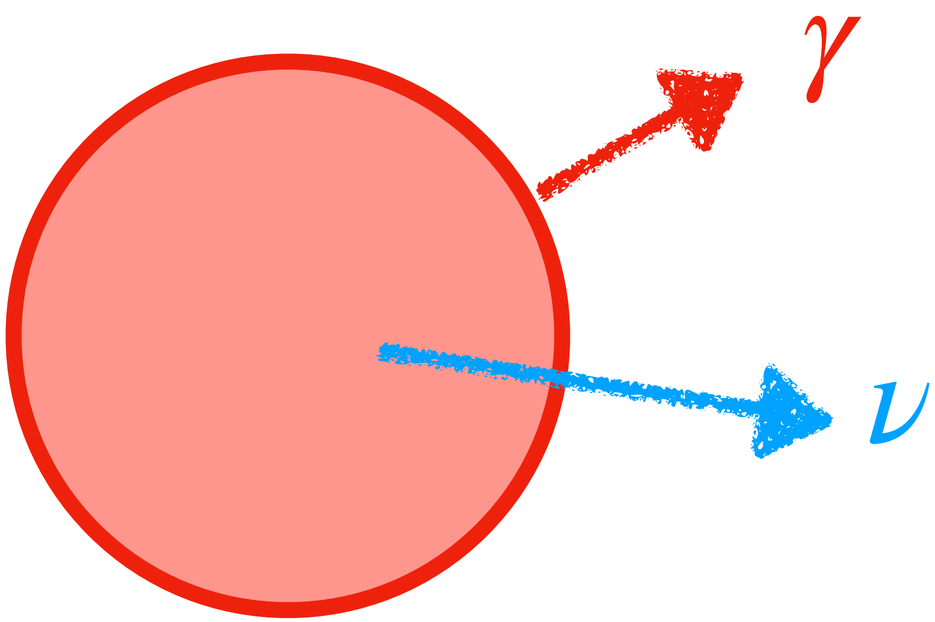
RHS = Cooling Luminosity.

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

LHS = Temperature Evolution.

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

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



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

(i). NS Cooling

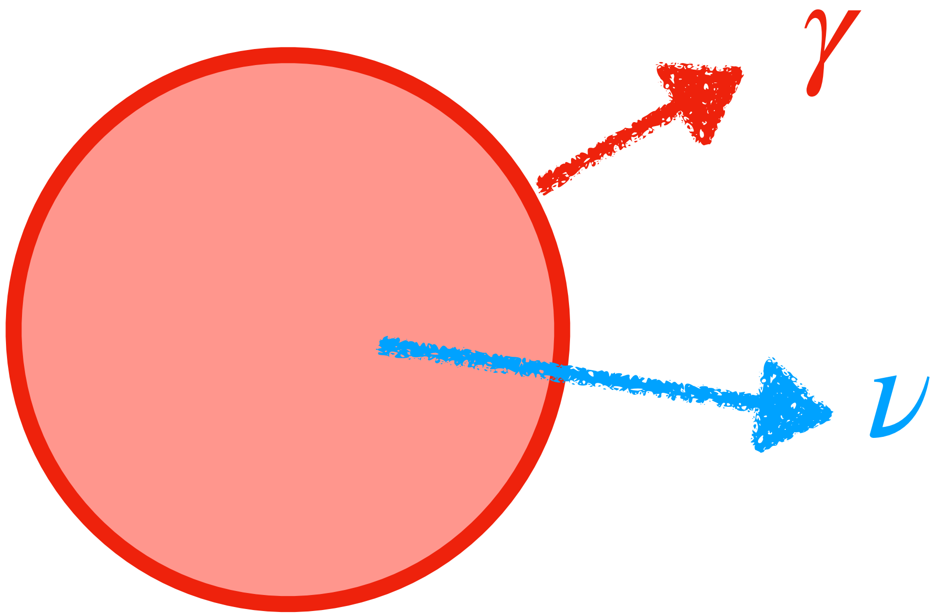
For reviews, e.g., D.G.Yakovlev+, astro-ph/0402143,
D.Page+, astro-ph/0508056, 1302.6626

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

Photon emission

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

dominant process at late time



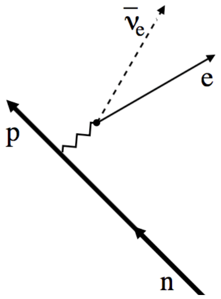
(i). NS Cooling

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

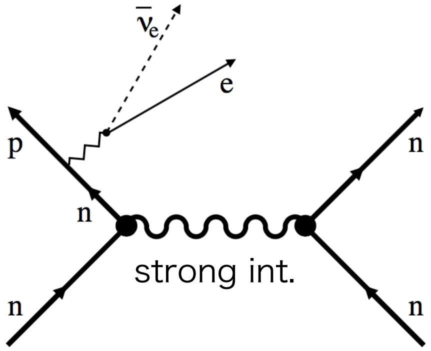
$$C\frac{dT}{dt} = -L_\nu - L_\gamma$$

Neutrino emission

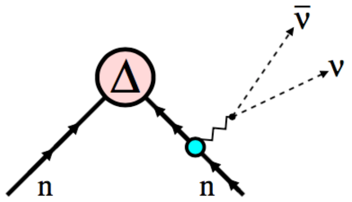
- Direct Urca

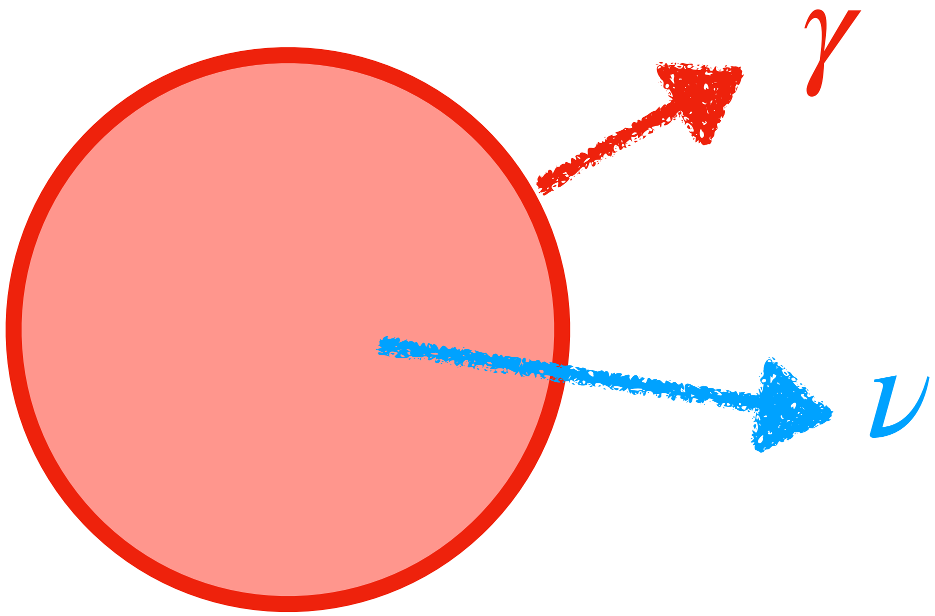


- Modified Urca
  (& Bremsstrahlung)



- PBF





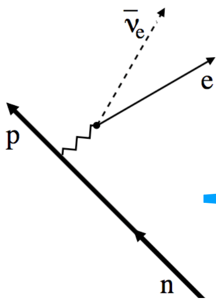
(i). NS Cooling

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~~

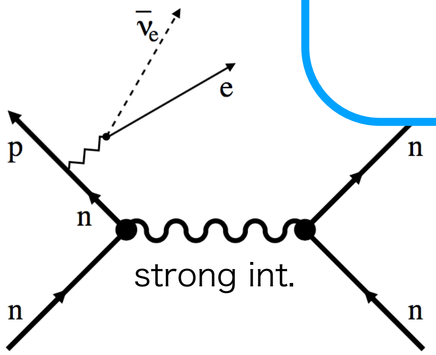


β decay and its inverse: $\begin{cases} n \to p + e^- + \bar{\nu}_e \\ p + e^- \to n + \nu_e \end{cases}$

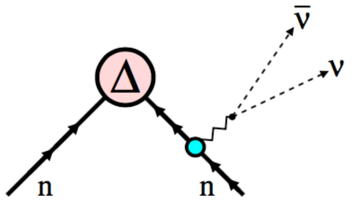
It does **NOT** work in typical NS because $p_p + p_e < p_n$.

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

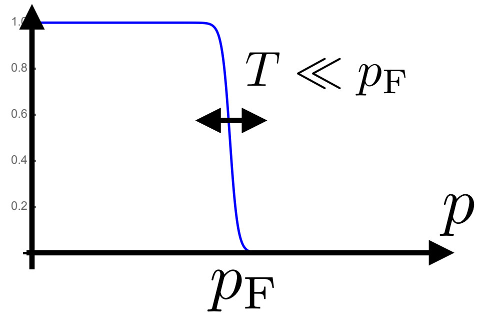
- Modified Urca
  (& Bremsstrahlung)



- PBF



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



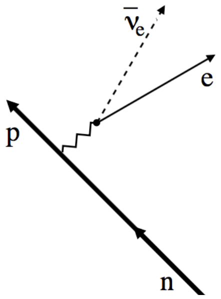
(i). NS Cooling

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

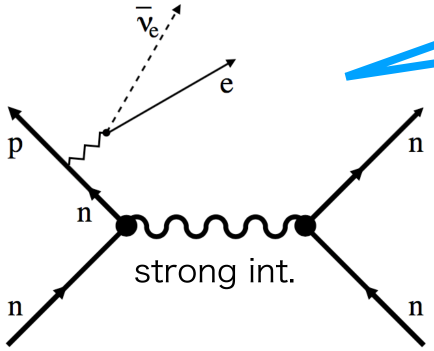
$$C\frac{dT}{dt} = -L_\nu - L_\gamma$$

Neutrino emission

- ~~Direct Urca~~



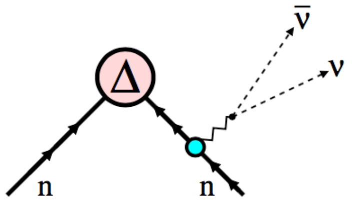
- Modified Urca (& Bremsstrahlung)



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

dominant process for $T > T_c$

- 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 $T < T_c$.

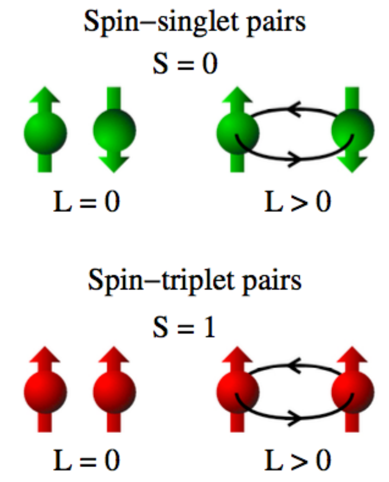
(i). NS Cooling

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

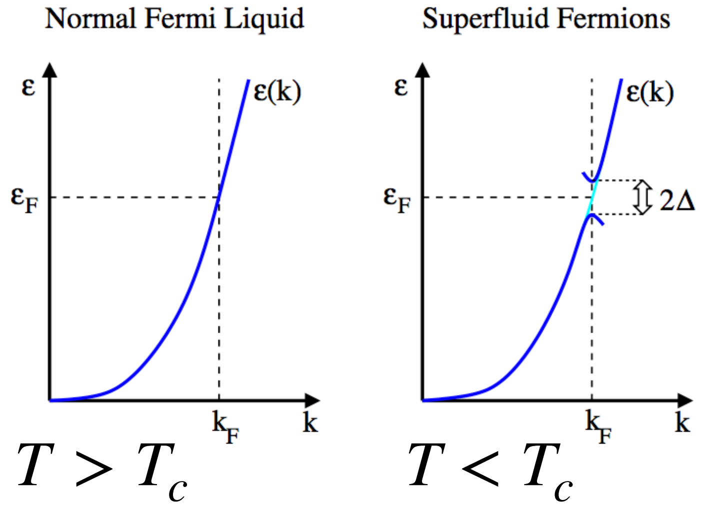
neutron singlet ($^1S_0$)
neutron triplet ($^3P_2$)
proton singlet ($^1S_0$)



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).



(i). NS Cooling

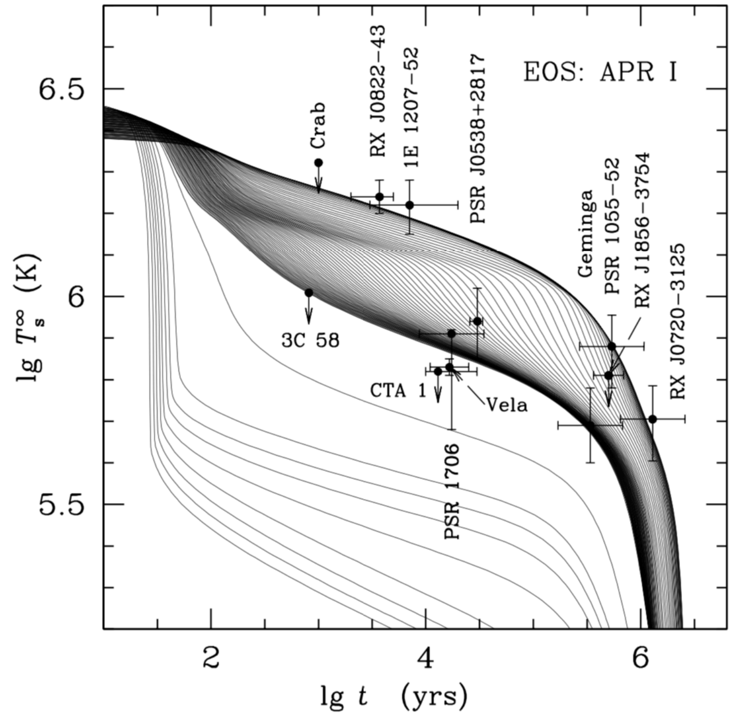
For reviews, e.g., D.G.Yakovlev+, astro-ph/0402143,
D.Page+, astro-ph/0508056, 1302.6626

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

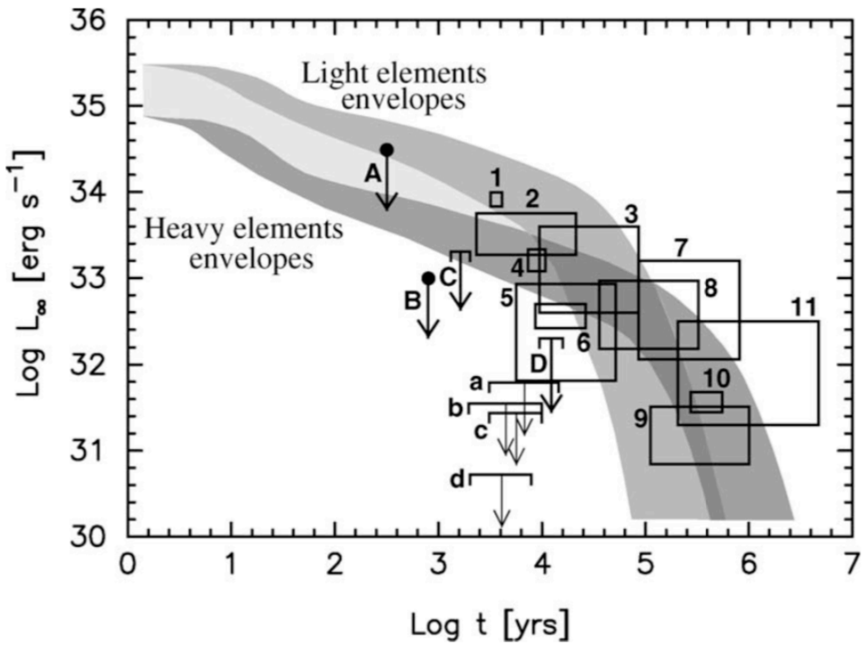
The minimal cooling scenario can successfully explain many NS temperature observations.

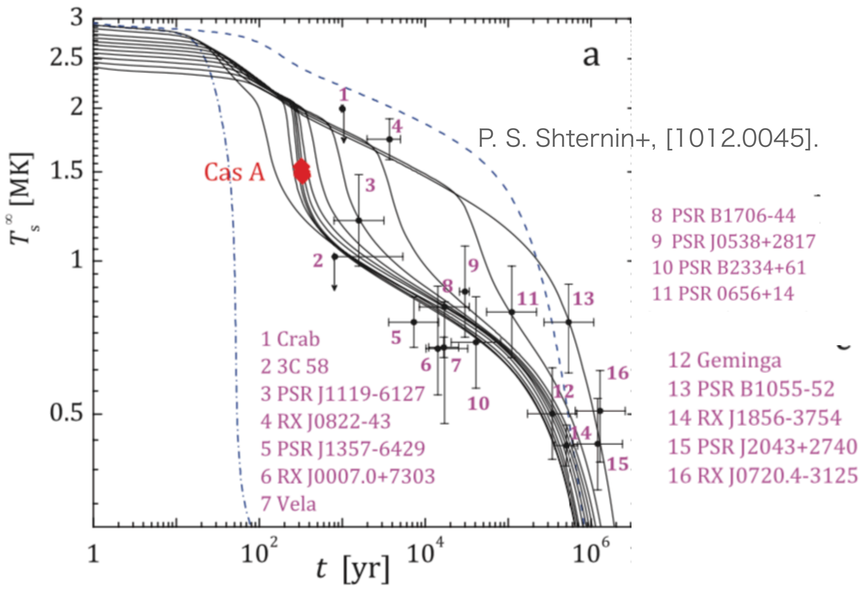
D.Page+, astro-ph/0403657,
M.E.Gusakov+, astro-ph/0404002,
D.Page+, 0906.1621

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





P. S. Shternin+, [1012.0045].

Plan

0. Introduction

1. Neutron Star

2. Neutron Star Cooling and Heating

(i). $$C\frac{dT}{dt} = -L_\nu - L_\gamma$$

done

(ii). $$\boxed{C\frac{dT}{dt} = -L_\nu - L_\gamma + L_{\text{DM}}^{\text{heat}}}$$

(iii). $$C\frac{dT}{dt} = -L_\nu - L_\gamma + L_{\text{rotochemical}}^{\text{heat}}$$

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

Previous works

Our works

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

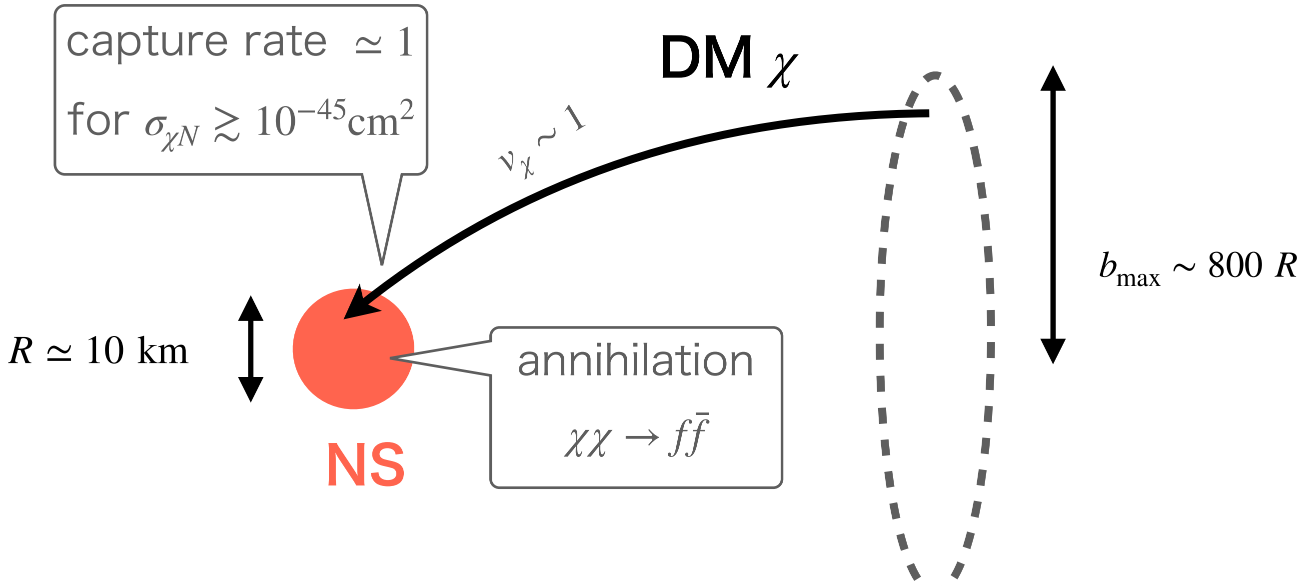
KH, N. Nagata, K. Yanagi, [1905.02991]

3. Summary

(ii). 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
C.-S. Chen+ 1804.03409
N. F. Bell+ 1807.02840
D. A. Camargo+ 1901.05474
N. F. Bell+ 1904.09803
KH, N.Nagata, K.Yanagi 1905.02991
R. Garani+ 1906.10145
J. F. Acevedo+, 1911.06334
A. Joglekar+, 1911.13293



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

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

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

Photon emission

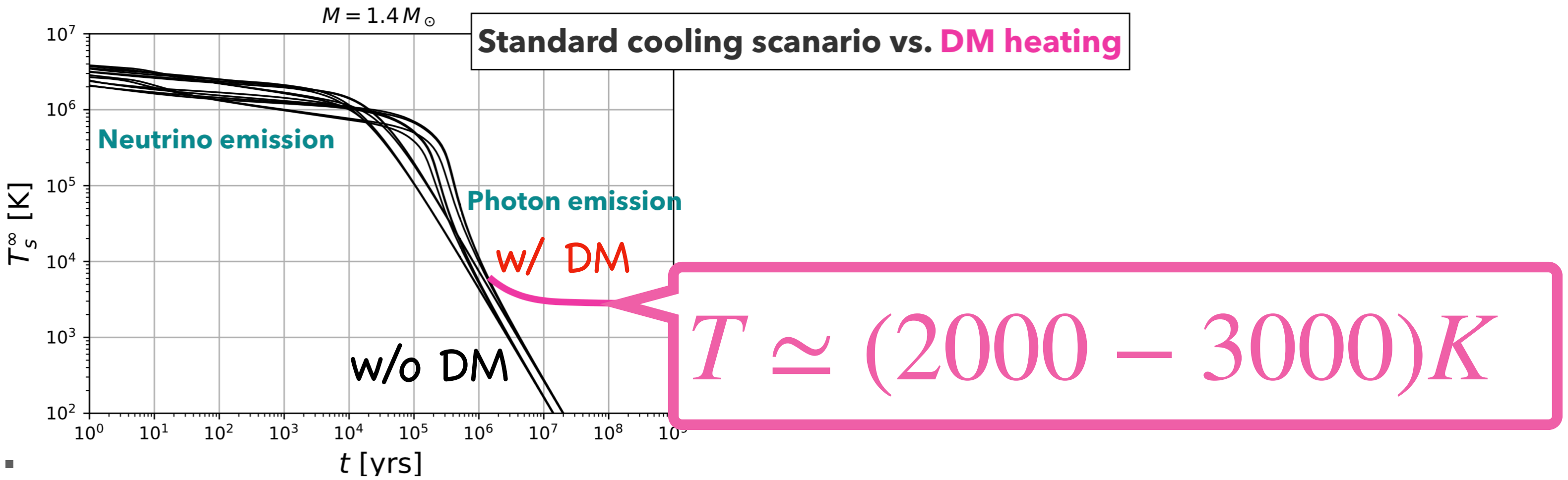
$$L_\gamma = 4\pi R^2 \sigma_{SB} T_s^4$$

dominant process at late time

DM heating

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

independent of the DM mass



Standard cooling scenario vs. DM heating

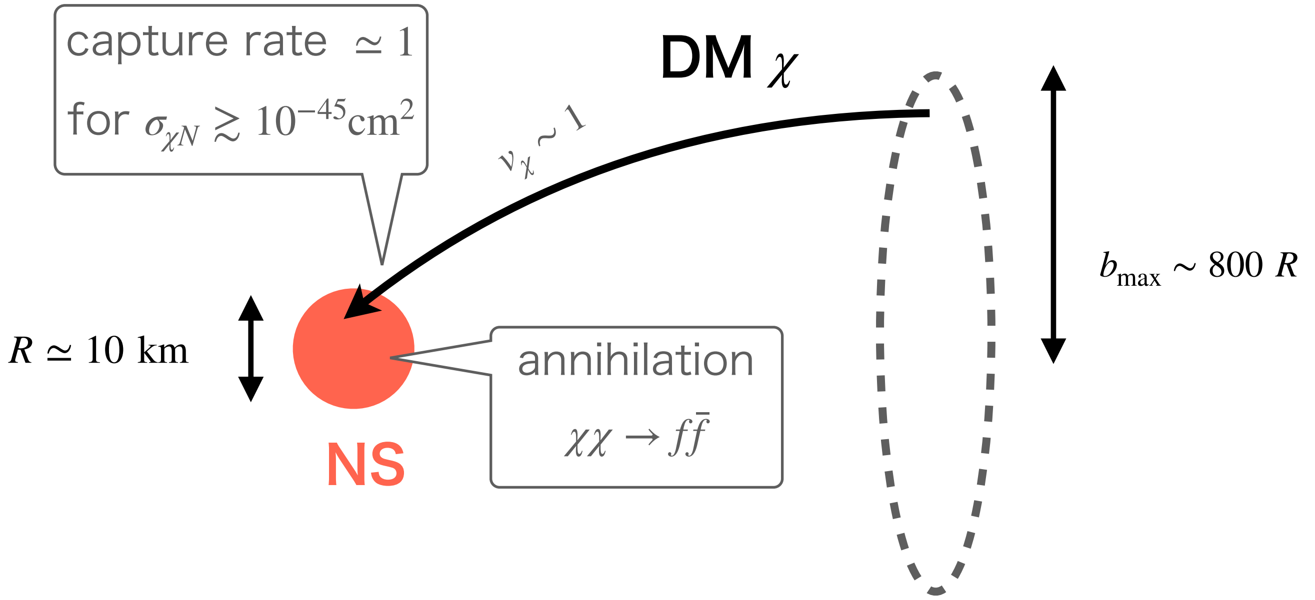
$$T \simeq (2000 - 3000)K$$

Fig. by K.Yanagi.

(ii). NS Heating by DM

C. Kouvaris 0708.2362,
G. Bertone+ 0709.1485,
C. Kouvaris+ 1004.0586,
A. de Lavallaz+ 1004.0629
. . .

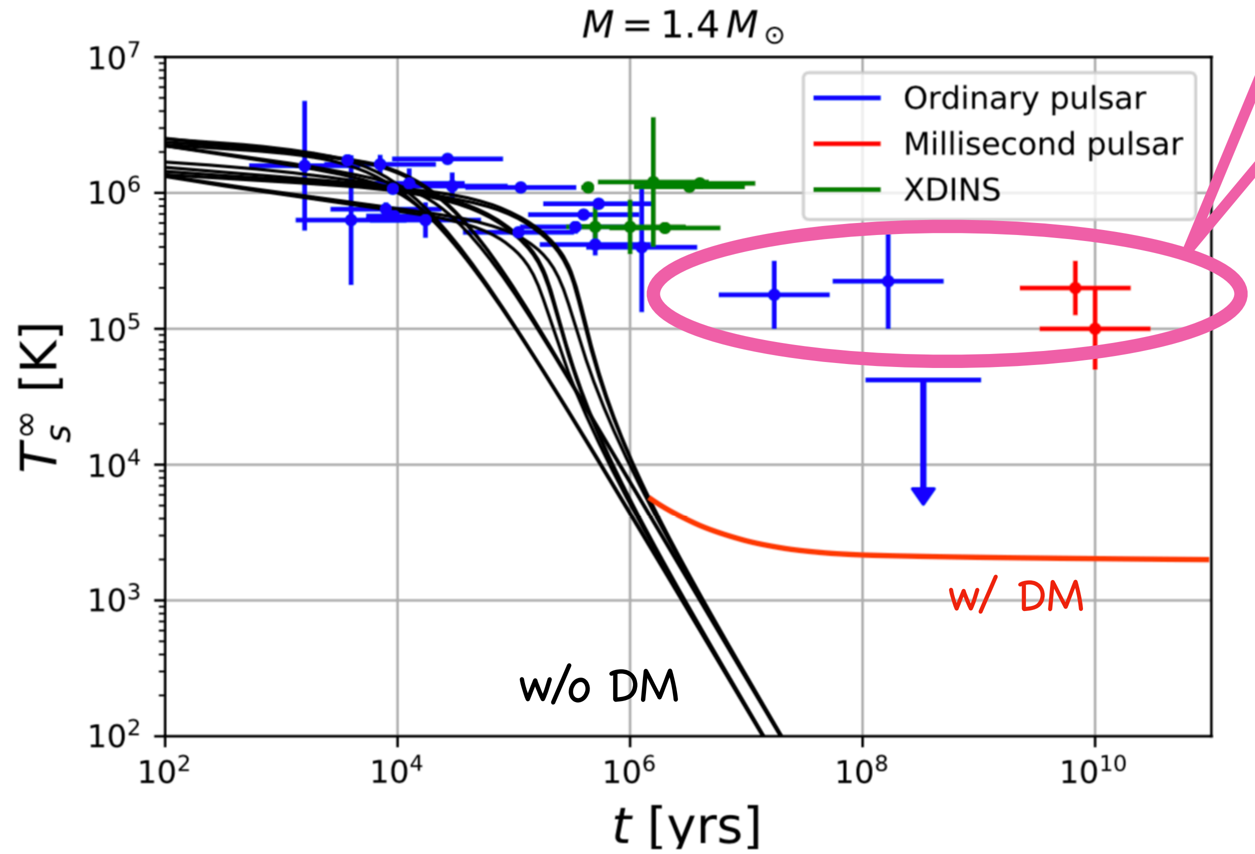
+ many recent works: e.g.,
J. Bramante+ 1703.04043
M. Baryakhtar+ 1704.01577
N. Raj+ 1707.09442
C.-S. Chen+ 1804.03409
N. F. Bell+ 1807.02840
D. A. Camargo+ 1901.05474
N. F. Bell+ 1904.09803
KH, N.Nagata, K.Yanagi 1905.02991
R. Garani+ 1906.10145
J. F. Acevedo+, 1911.06334
A. Joglekar+, 1911.13293



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

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

But,...



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

Plan

0. Introduction

1. Neutron Star

2. Neutron Star Cooling and Heating

(i). $C\dfrac{dT}{dt} = -L_\nu - L_\gamma$

(ii). $C\dfrac{dT}{dt} = -L_\nu - L_\gamma \; + L_{\text{DM}}^{\text{heat}}$

done

(iii). $C\dfrac{dT}{dt} = -L_\nu - L_\gamma \; + L_{\text{rotochemical}}^{\text{heat}}$

(iv). $C\dfrac{dT}{dt} = -L_\nu - L_\gamma \; + L_{\text{rotochemical}}^{\text{heat}} \; + L_{\text{DM}}^{\text{heat}}$

Previous works

Our works

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

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

3. Summary

(iii). Rotochemical Heating

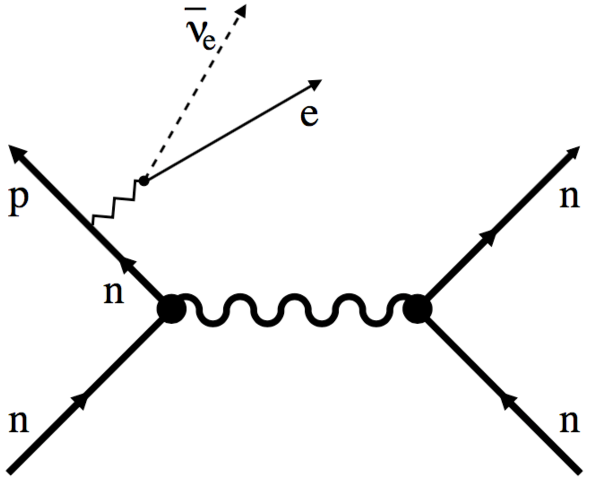
$$C\frac{dT}{dt} = -L_{\nu} - L_{\gamma} + L^{\mathrm{heat}}_{\mathrm{rotochemical}}$$

(iii). Rotochemical Heating

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

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

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

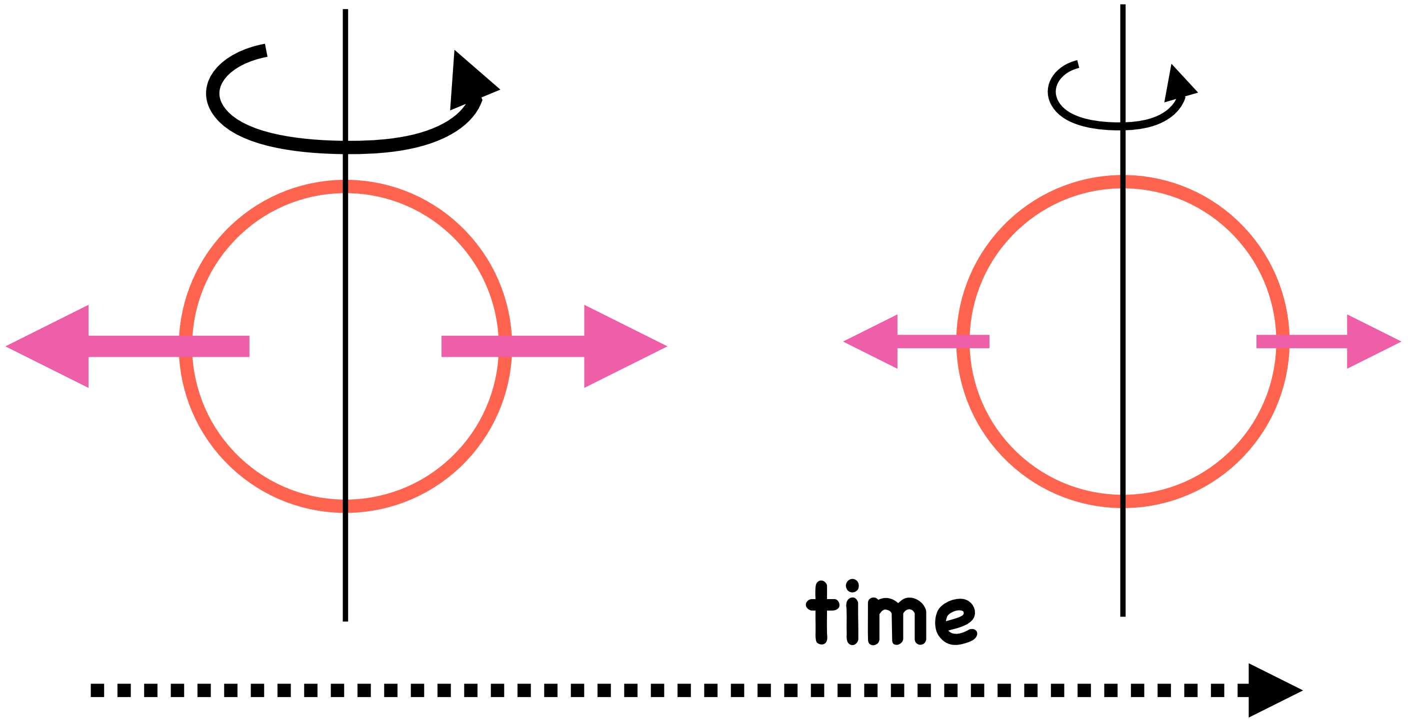


- In the minimal cooling, β-equilibrium is assumed.

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

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

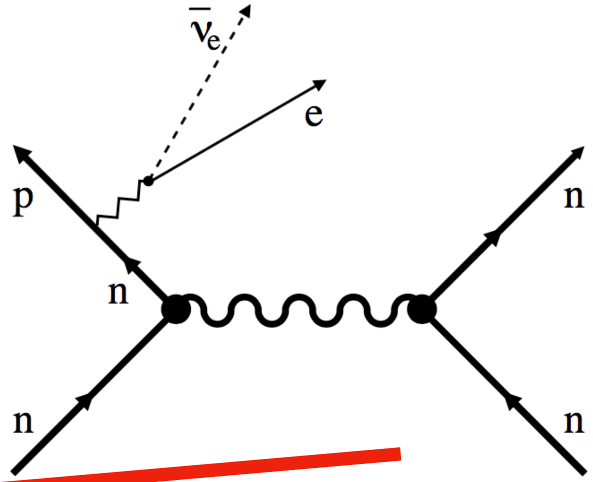
A.Reisenegger [astro-ph/9410035]



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.

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

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



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

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

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

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

A.Reisenegger [astro-ph/9410035]

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

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

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

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

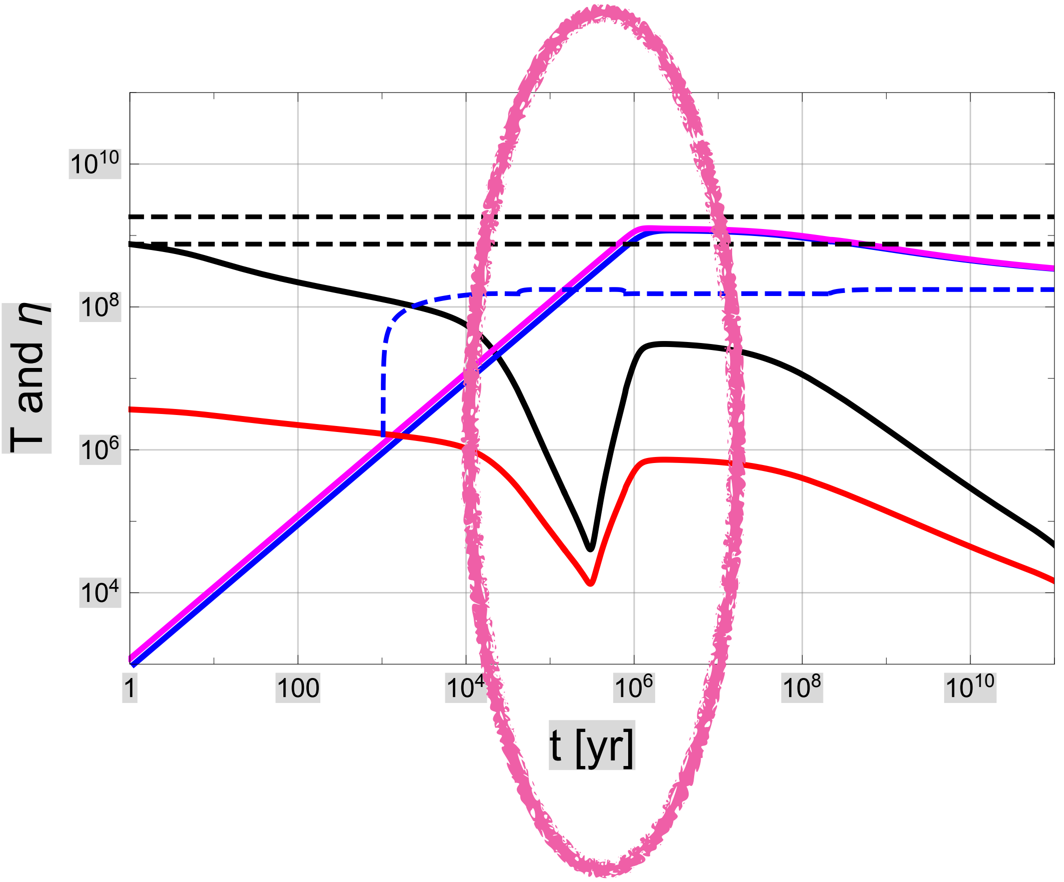
(iii). Rotochemical Heating

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

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

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

internal temperature T

surface temperature T_s

- The **superfluidity (pairing gap)** plays an important role.

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

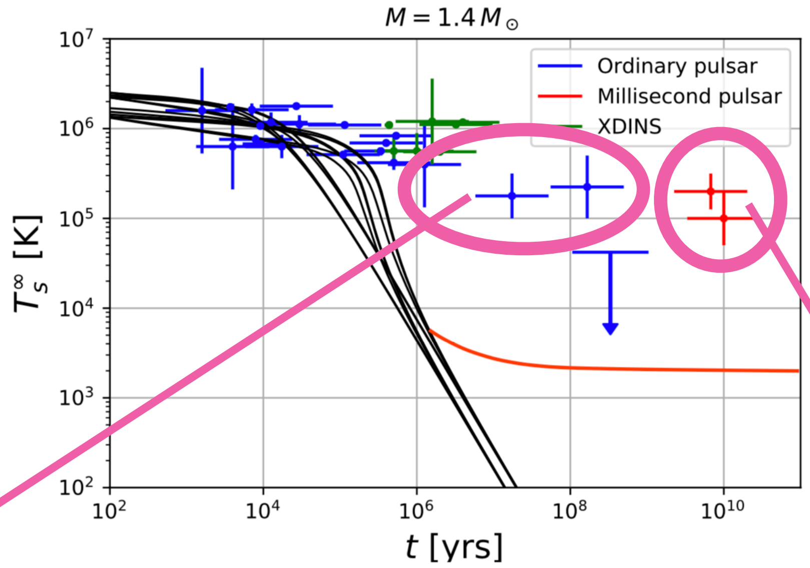
- Recently, we have updated the calculation.

  K. Yanagi, N. Nagata, KH, [arXiv:1904.04667] MNRAS (to be published)

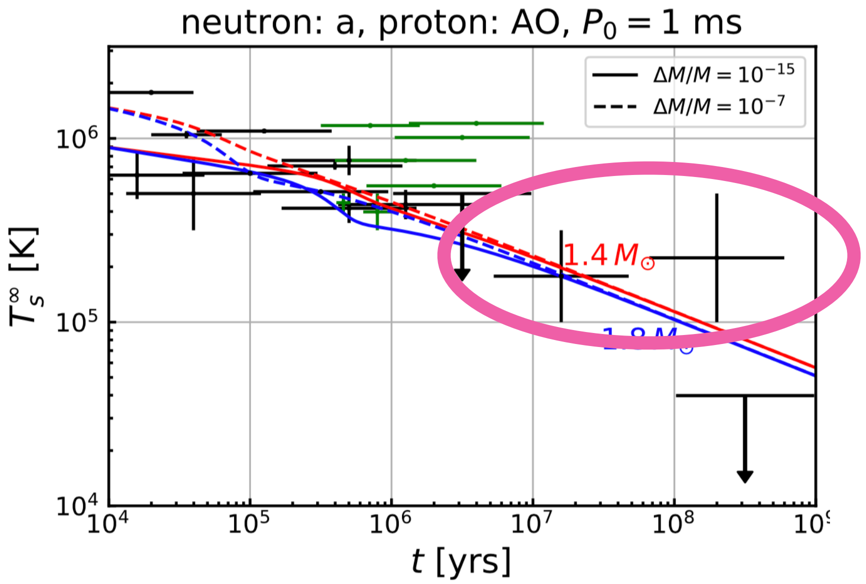
(iii). Rotochemical Heating $C\frac{dT}{dt} = -L_\nu - L_\gamma + L^{\mathrm{heat}}_{\mathrm{rotochemical}}$

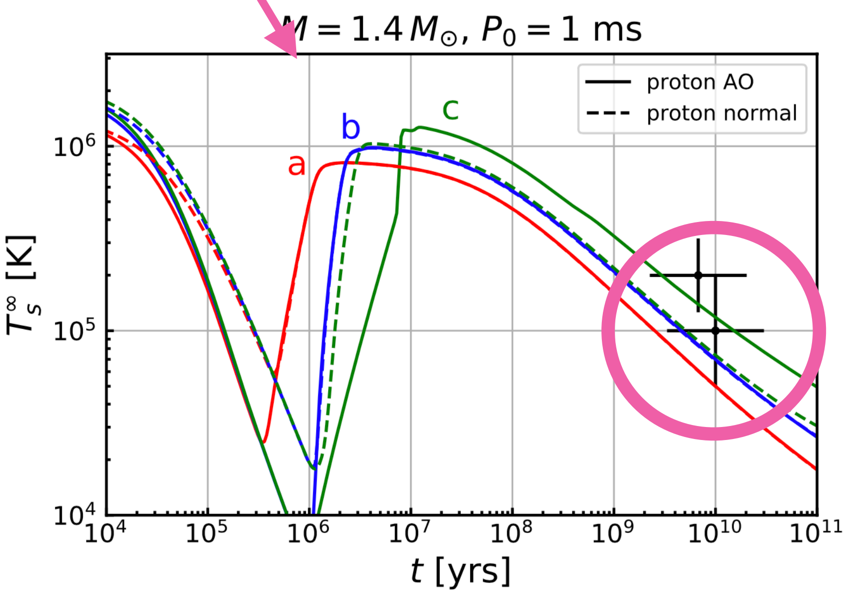
The rotochemical heating can explain the old and warm NSs.

NOTE: No exotic physics assumed. The same setting as the Standard Cooling.



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





Ordinary pulsar

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

Millisecond pulsar

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

Plan

0. Introduction

1. Neutron Star

2. Neutron Star Cooling and Heating

(i). $C\frac{dT}{dt} = -L_\nu - L_\gamma$

(ii). $C\frac{dT}{dt} = -L_\nu - L_\gamma \quad + L_{\text{DM}}^{\text{heat}}$

(iii). $C\frac{dT}{dt} = -L_\nu - L_\gamma \quad + L_{\text{rotochemical}}^{\text{heat}}$ done

Previous works

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

Our works

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

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

3. Summary

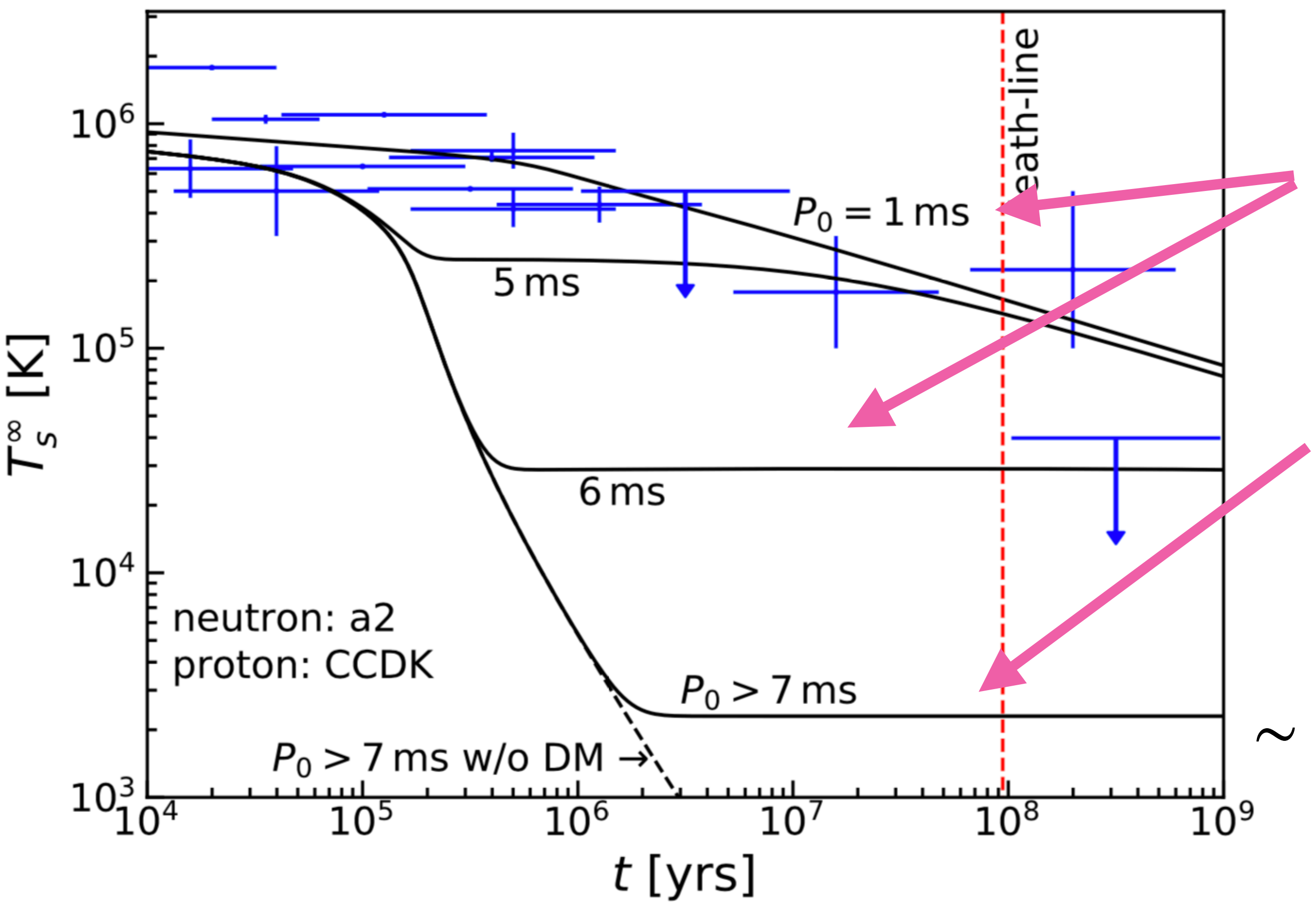
(iv). DM heating vs. Rotochemical heating

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

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

Result

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



$\sim (2000 - 3000)K$

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!**

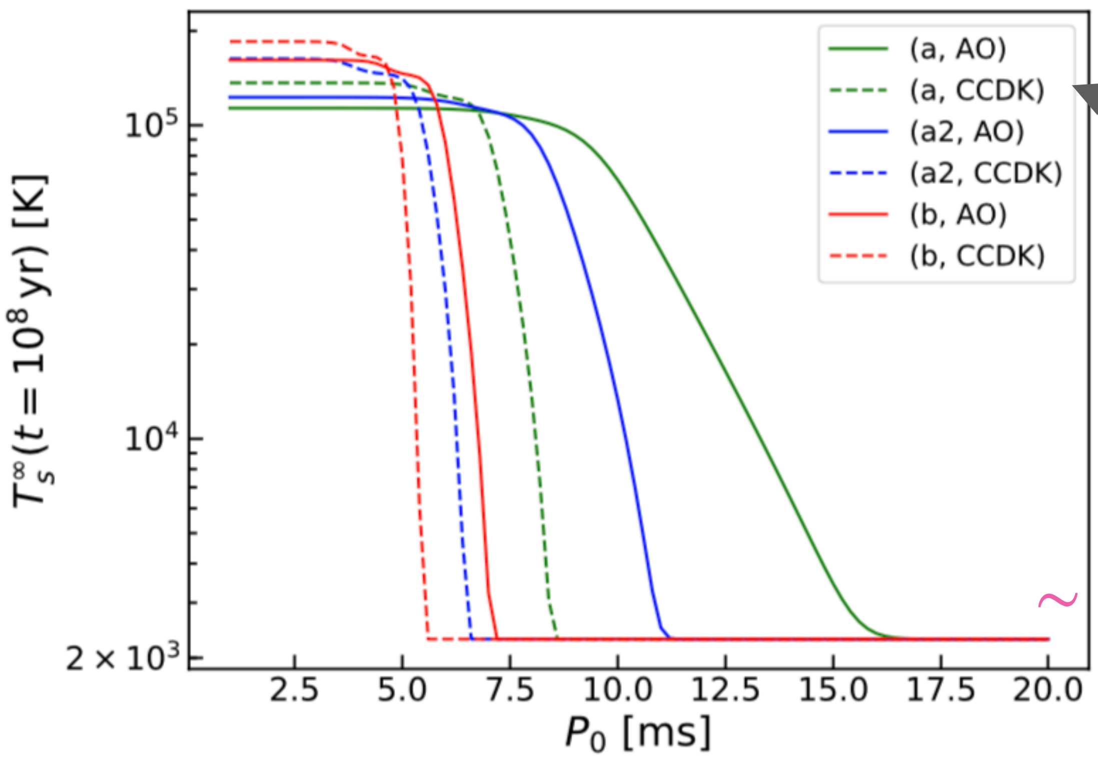
(iv). DM heating vs. Rotochemical heating

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

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

Result

Late time temperature



neutron/proton gap models

$\sim (2000-3000)K$

initial rotation period (P_0) dependence

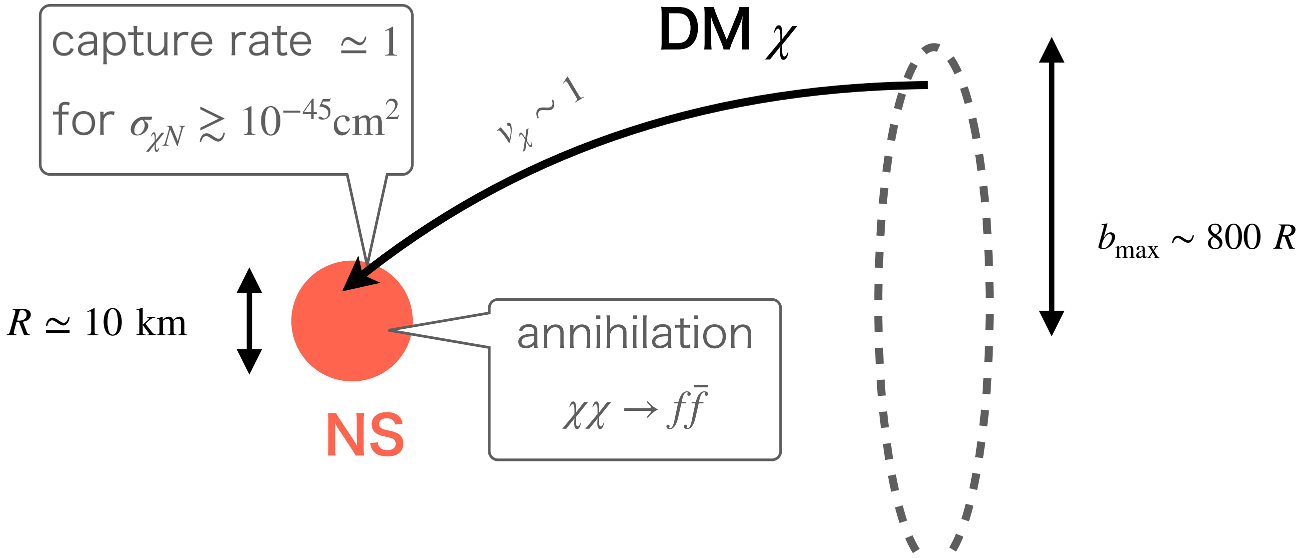
- **For large enough P_0 , DM signal is visible.**

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

  Currently no NS with such a low T is observed.

- **Conversely, discovery of a NS with $T < 2000\text{K}$ 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.

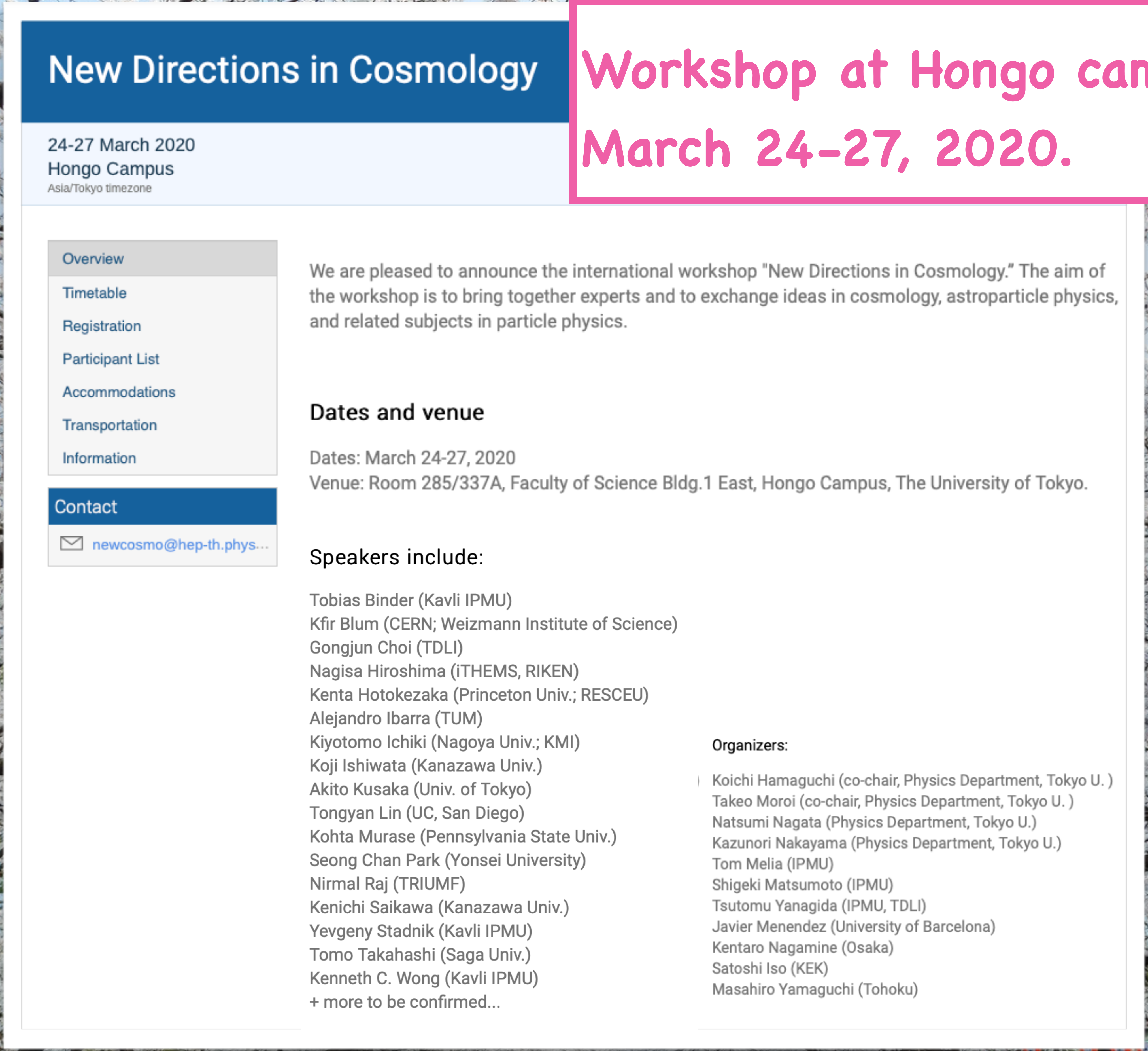
$$C\frac{dT}{dt} = -L_\nu - L_\gamma + L^{\text{heat}}_{\text{rotochemical}} + L^{\text{heat}}_{\text{DM}}$$

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.

Workshop at Hongo campus, March 24-27, 2020.



New Directions in Cosmology

24-27 March 2020
Hongo Campus
Asia/Tokyo timezone

We are pleased to announce the international workshop "New Directions in Cosmology." The aim of the workshop is to bring together experts and to exchange ideas in cosmology, astroparticle physics, and related subjects in particle physics.

Dates and venue

Dates: March 24-27, 2020
Venue: Room 285/337A, Faculty of Science Bldg.1 East, Hongo Campus, The University of Tokyo.

Speakers include:

Tobias Binder (Kavli IPMU)
Kfir Blum (CERN; Weizmann Institute of Science)
Gongjun Choi (TDLI)
Nagisa Hiroshima (iTHEMS, RIKEN)
Kenta Hotokezaka (Princeton Univ.; RESCEU)
Alejandro Ibarra (TUM)
Kiyotomo Ichiki (Nagoya Univ.; KMI)
Koji Ishiwata (Kanazawa Univ.)
Akito Kusaka (Univ. of Tokyo)
Tongyan Lin (UC, San Diego)
Kohta Murase (Pennsylvania State Univ.)
Seong Chan Park (Yonsei University)
Nirmal Raj (TRIUMF)
Kenichi Saikawa (Kanazawa Univ.)
Yevgeny Stadnik (Kavli IPMU)
Tomo Takahashi (Saga Univ.)
Kenneth C. Wong (Kavli IPMU)
+ more to be confirmed...

Organizers:

Koichi Hamaguchi (co-chair, Physics Department, Tokyo U.)
Takeo Moroi (co-chair, Physics Department, Tokyo U.)
Natsumi Nagata (Physics Department, Tokyo U.)
Kazunori Nakayama (Physics Department, Tokyo U.)
Tom Melia (IPMU)
Shigeki Matsumoto (IPMU)
Tsutomu Yanagida (IPMU, TDLI)
Javier Menendez (University of Barcelona)
Kentaro Nagamine (Osaka)
Satoshi Iso (KEK)
Masahiro Yamaguchi (Tohoku)

Backup

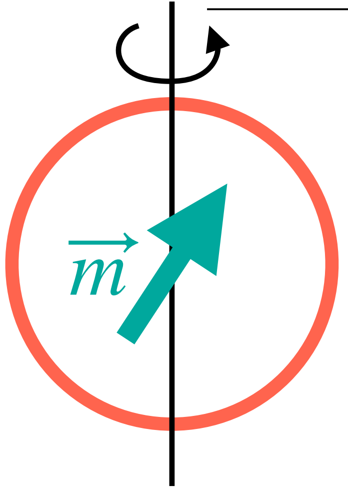
Neutron Star

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

Crab Pulsar

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

- **Magnetic Dipole Model**



Rotational energy loss $\simeq$ magnetic dipole radiation

$$\dot{E} = \frac{d}{dt}\left(\frac{1}{2}I\Omega^2\right) = -\frac{\sin^2\alpha}{6}R^6\Omega^4B_p^2$$

$$\begin{cases} I = \text{ moment of inertia} \\ \Omega = 2\pi/P = \text{ angular velocity} \\ P = \text{ rotation period} \\ B_p = \text{ magnetic field at the pole} \end{cases}$$

By solving this,

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

$$\Longrightarrow \quad t \simeq \frac{P_{\rm now}}{2\dot{P}_{\rm now}} \equiv \tau_{\rm sd}$$

spin down age / characteristic age

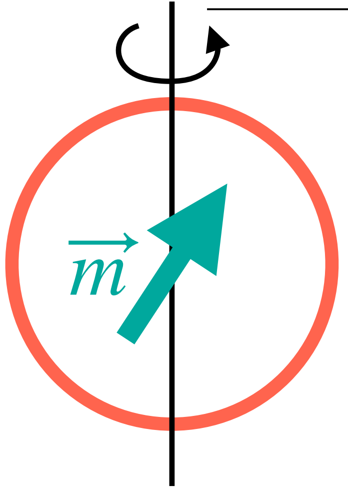
Neutron Star


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

Crab Pulsar

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

- **Magnetic Dipole Model**



Rotational energy loss $\simeq$ magnetic dipole radiation

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

By solving this,

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

$$\Longrightarrow \quad t \simeq \frac{P_{\rm now}}{2\dot{P}_{\rm now}} \equiv \tau_{\rm sd}$$

spin down age / characteristic age

Example: Crab Pulsar

- actual age: $\tau = 965$ yrs (from historical records of SN1054.)
- spin down age: $P \simeq 0.033$ sec, $\dot{P} \simeq 4.2 \times 10^{-13} \Longrightarrow \tau_{\rm sd} \simeq 1200$ yrs

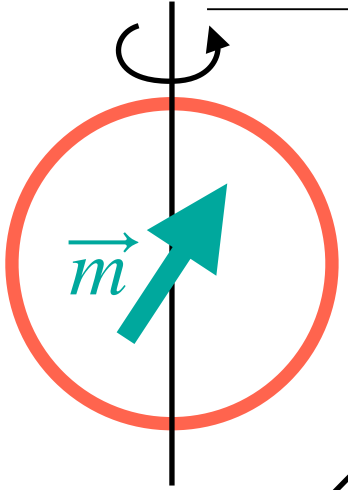
Neutron Star

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

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

Crab Pulsar

- **Magnetic Dipole Model**



Rotational energy loss ≃ magnetic dipole radiation

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

By solving this,

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

$$\Longrightarrow \qquad t \simeq \frac{P_{\rm now}}{2\dot{P}_{\rm now}} \equiv \tau_{\rm sd}$$

spin down age / characteristic age

The **magnetic field** can also be estimated from $P_{\rm now}$ and $\dot{P}_{\rm now}$.

$$B_p \simeq 1\times10^{20}{\rm G}\ \frac{1}{\sin\alpha}\left(\frac{P_{\rm now}\dot{P}_{\rm now}}{1\ \rm sec}\right)^{1/2} \times \left(\frac{10\ \rm km}{R}\right)^3\left(\frac{I}{10^{45}{\rm g}\cdot{\rm cm}^2}\right)^{1/2}$$

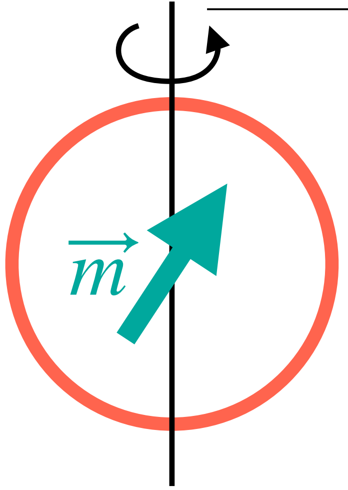
Neutron Star

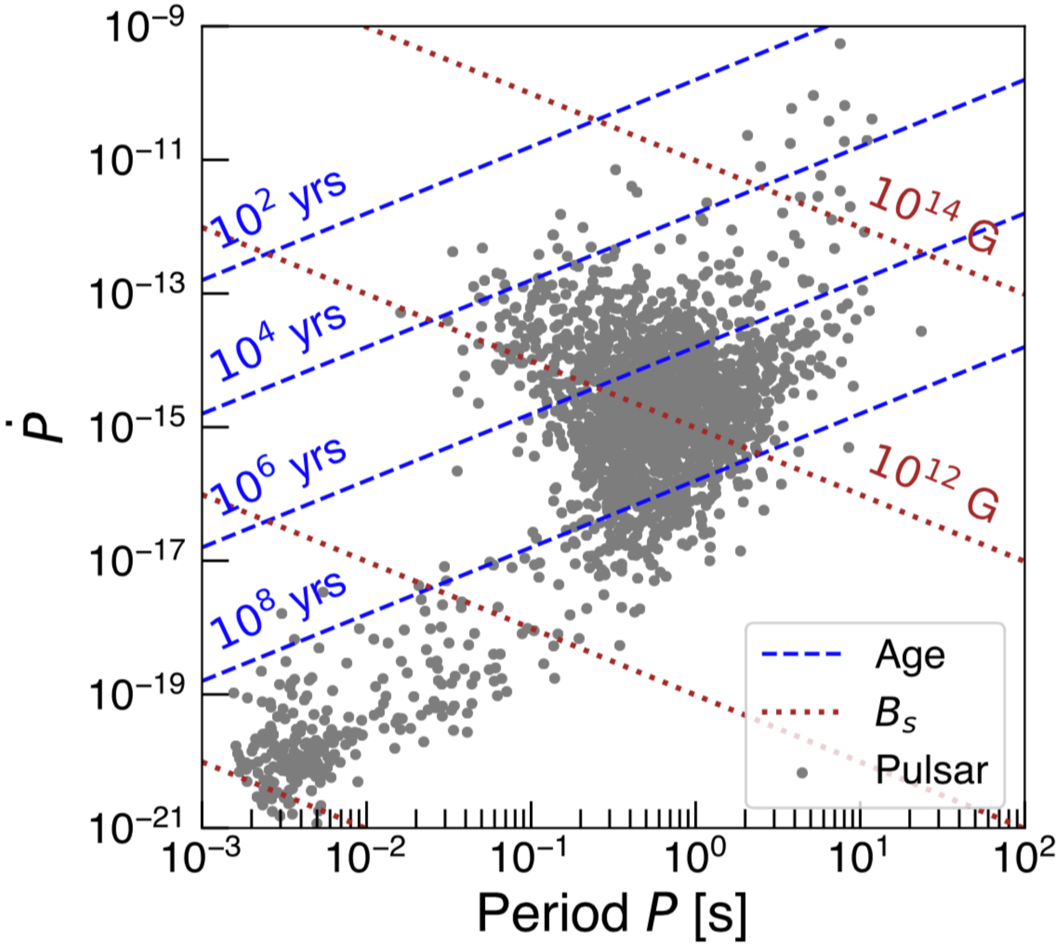
- Most of NSs are found as **pulsars.**

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

Crab Pulsar

- **Magnetic Dipole Model**





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

<=> Age and magnetic field of pulsars.

Fig. thanks to N.Natsumi.

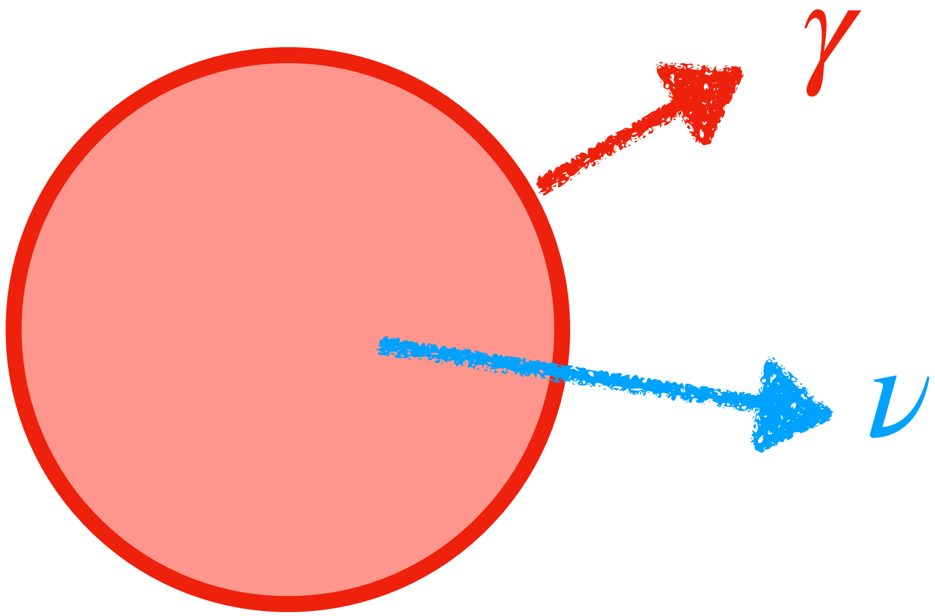
For reviews, e.g., D.G.Yakovlev+, astro-ph/0402143,
D.Page+, astro-ph/0508056, 1302.6626

(i). NS Cooling

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

Neutrino emission

- Direct Urca
- Modified Urca
- Bremsstrahlung
- PBF



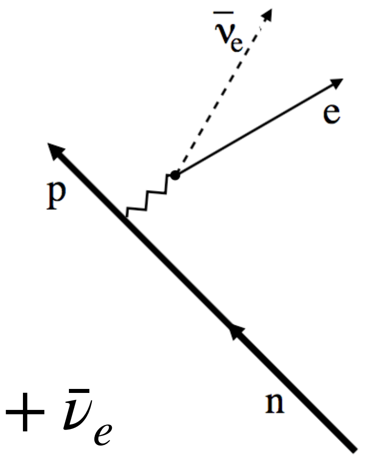
(i). NS Cooling

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

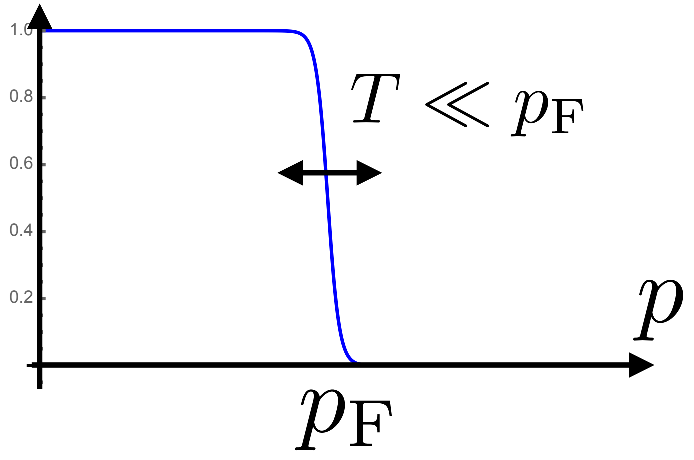


β decay and its inverse: $\begin{cases} n \to p + e^- + \bar{\nu}_e \\ p + e^- \to n + \nu_e \end{cases}$

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

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



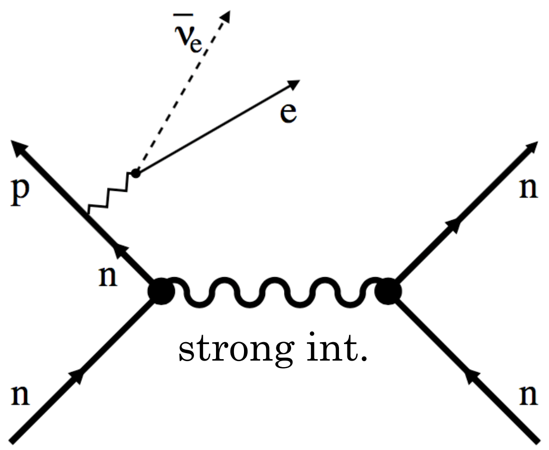
(i). NS Cooling

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



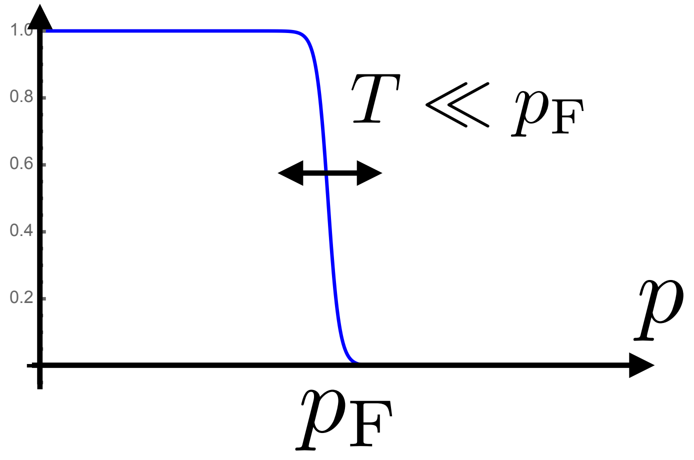
- Dominant process (before the onset of Cooper pairing)

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

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

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

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



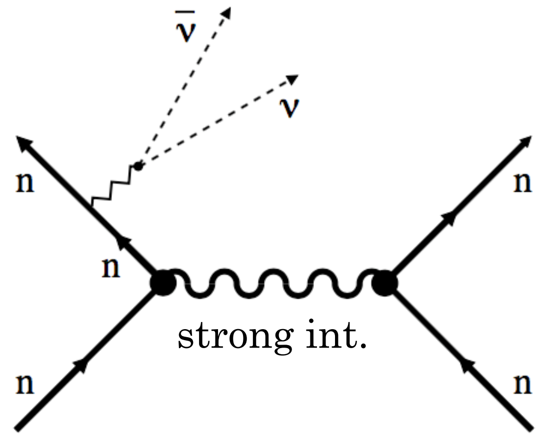
For reviews, e.g., D.G.Yakovlev+, astro-ph/0402143,
D.Page+, astro-ph/0508056, 1302.6626

(i). NS Cooling

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

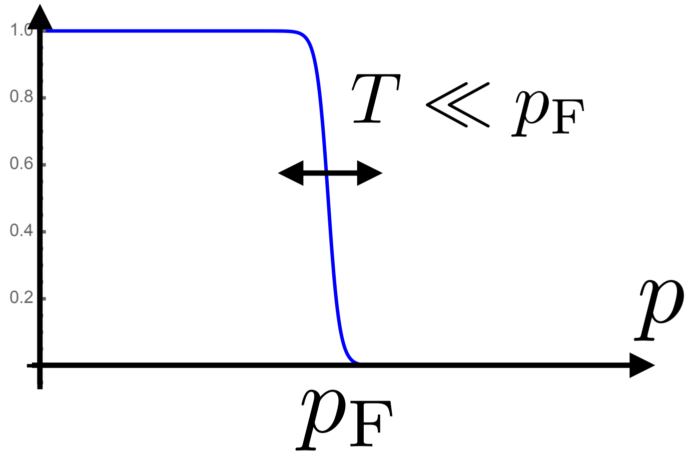
Neutrino emission

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



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

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



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

(i). NS Cooling

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

Neutrino emission

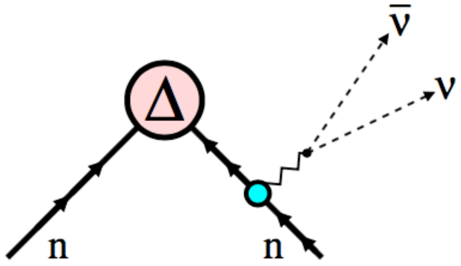
- ~~Direct Urca~~
- Modified Urca
- Bremsstrahlung
- **PBF**

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 $T < T_c$.



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

(i). NS Cooling

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

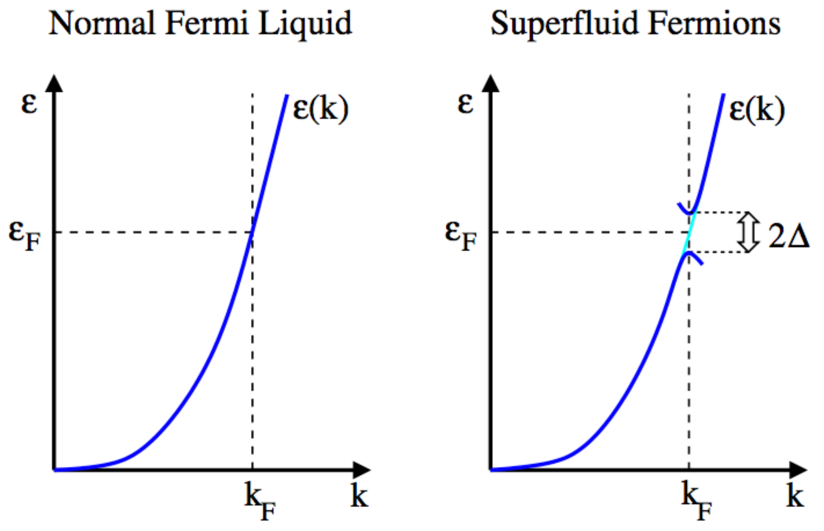
Neutrino emission

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

Superfuidity (pairing) plays important roles.

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

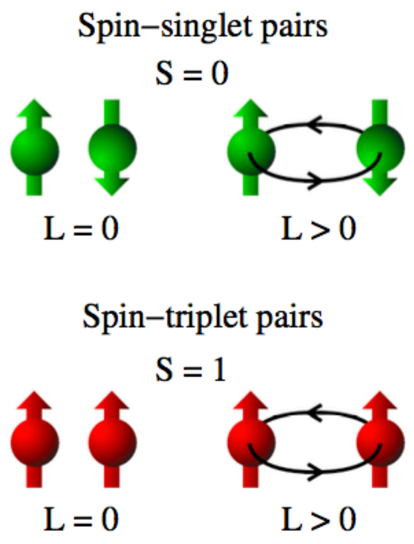
T > Tc **T < Tc**



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 ($^1S_0$)

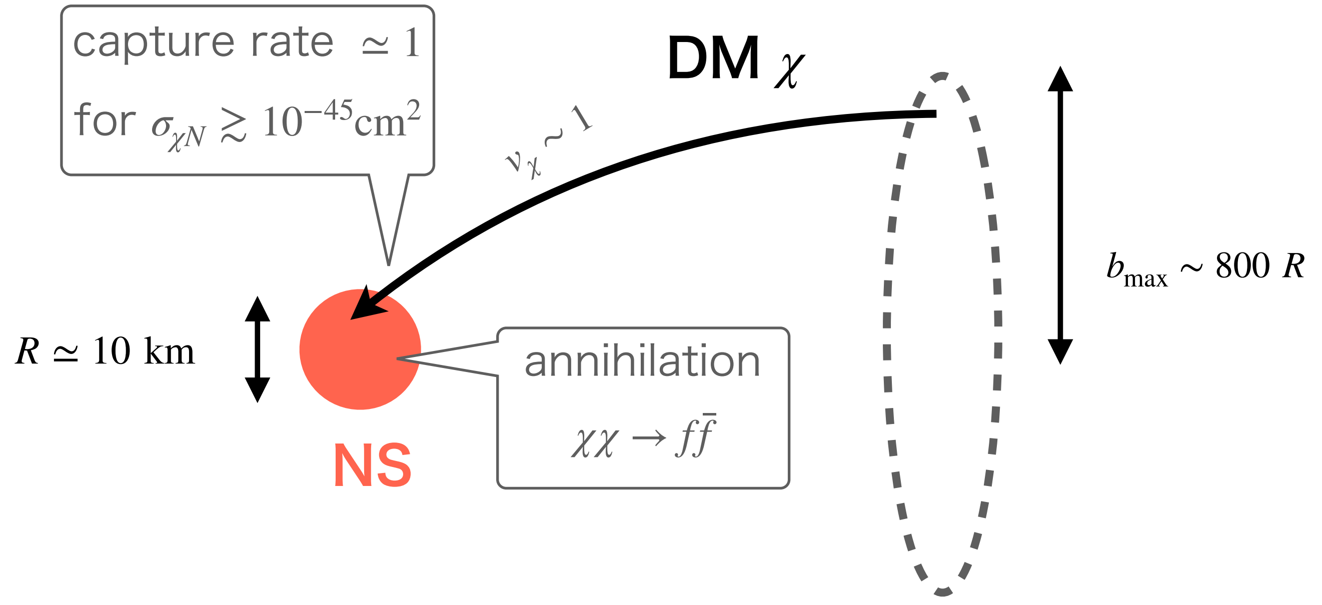


- Heat capacity C is suppressed. ($\sim e^{-\Delta/T}$)
- M.Urca luminosity $L_{\nu,MU}$ is suppressed. ($\sim e^{-\Delta/T}$)
- PBF occurs at $T < T_c$.
- It is also important for the "**rotochecmical heating**" (see below).

(ii). 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
C.-S. Chen+ 1804.03409
N. F. Bell+ 1807.02840
D. A. Camargo+ 1901.05474
N. F. Bell+ 1904.09803
KH, N.Nagata, K.Yanagi 1905.02991
R. Garani+ 1906.10145
J. F. Acevedo+, 1911.06334
A. Joglekar+, 1911.13293



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

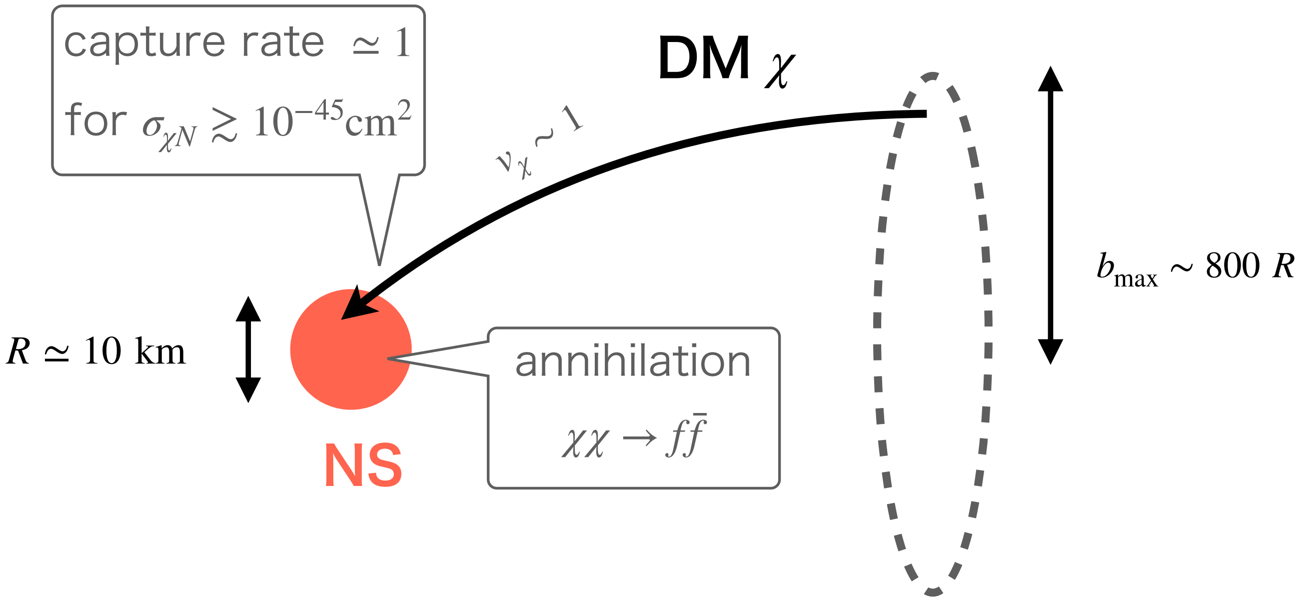
annihilation
$\chi\chi \to f\bar{f}$

- velocity : $v_\chi^\infty \simeq 10^{-3} \ \rightarrow \ v_\chi^{\text{surface}} \sim 1$
- mean free path $L_{\text{mfp}} < R$ for $\sigma_{\chi N} \gtrsim 10^{-45}\mathrm{cm}^2$ => capture probability $\simeq 1.$
- For old NSs, <u>accretion rate = annihilation rate.</u>

=> energy injection $L_{\text{DM}}^{\text{heat}} \sim \dot{N} m_\chi \sim \pi b_{\max}^2 \rho_\chi v_\chi^\infty \simeq 3 \times 10^{22} \mathrm{erg/s}$.

(independent of details of DM properties, such as mass, interactions,...)

(ii). NS Heating by DM



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

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

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
C.-S. Chen+ 1804.03409
N. F. Bell+ 1807.02840
D. A. Camargo+ 1901.05474
N. F. Bell+ 1904.09803
KH, N.Nagata, K.Yanagi 1905.02991
R. Garani+ 1906.10145
J. F. Acevedo+, 1911.06334
A. Joglekar+, 1911.13293

NS probe is advantageous in the sense that...

☑ $v_\chi \sim 1$ 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).

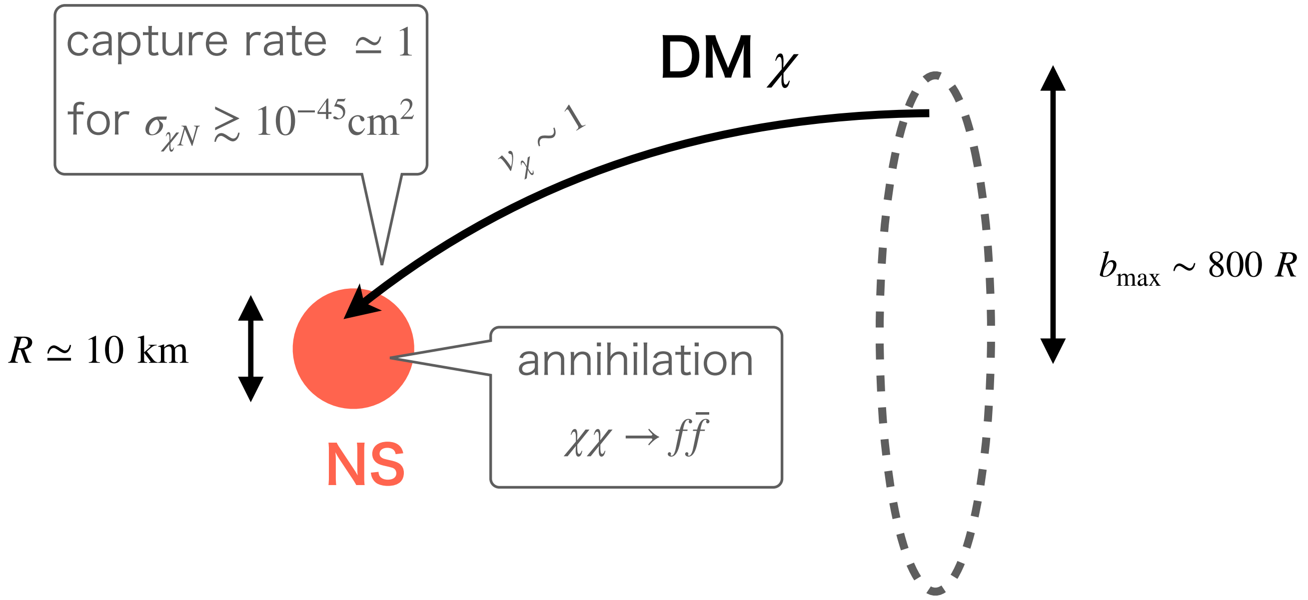
☑ It is also sensitive to lepton coupling (e and mu).

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

(ii). 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
C.-S. Chen+ 1804.03409
N. F. Bell+ 1807.02840
D. A. Camargo+ 1901.05474
N. F. Bell+ 1904.09803
KH, N.Nagata, K.Yanagi 1905.02991
R. Garani+ 1906.10145
J. F. Acevedo+, 1911.06334
A. Joglekar+, 1911.13293



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

DM χ

$v_\chi \sim 1$

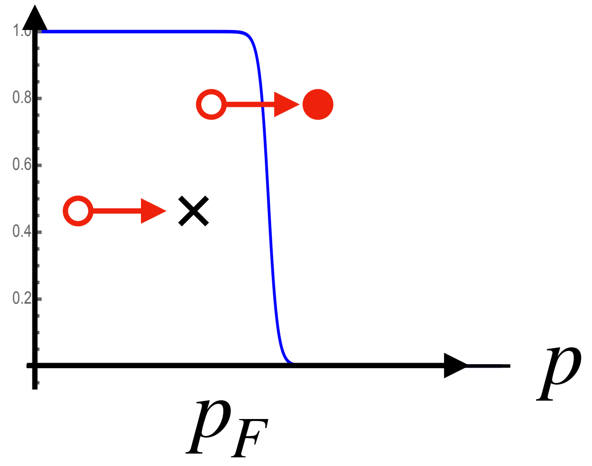
$b_{\max} \sim 800\ R$

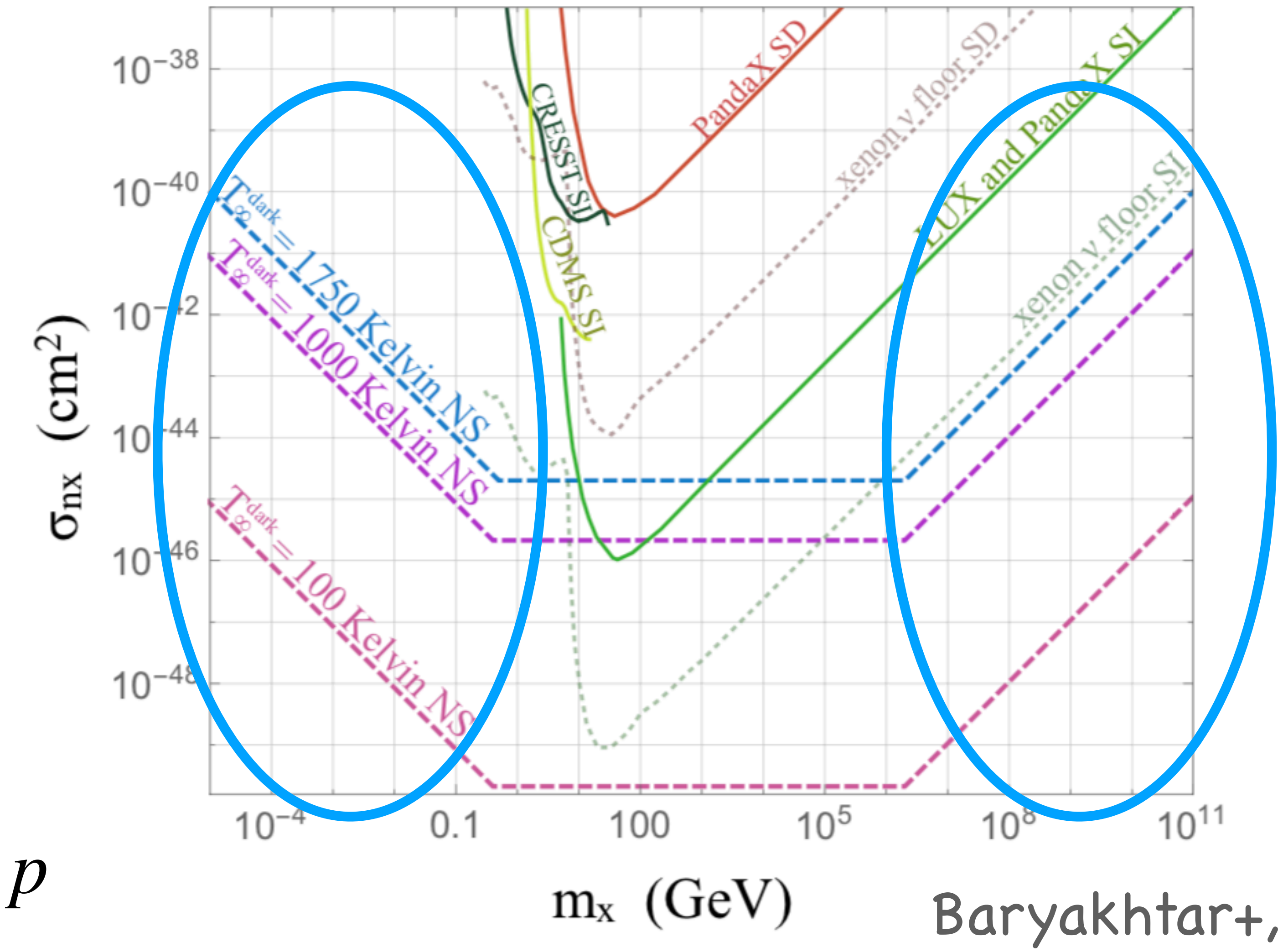
$R \simeq 10$ km

NS

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

For $m_\chi < 1$ GeV,
Pauli blocking prevents
scattering of low P
neutrons.



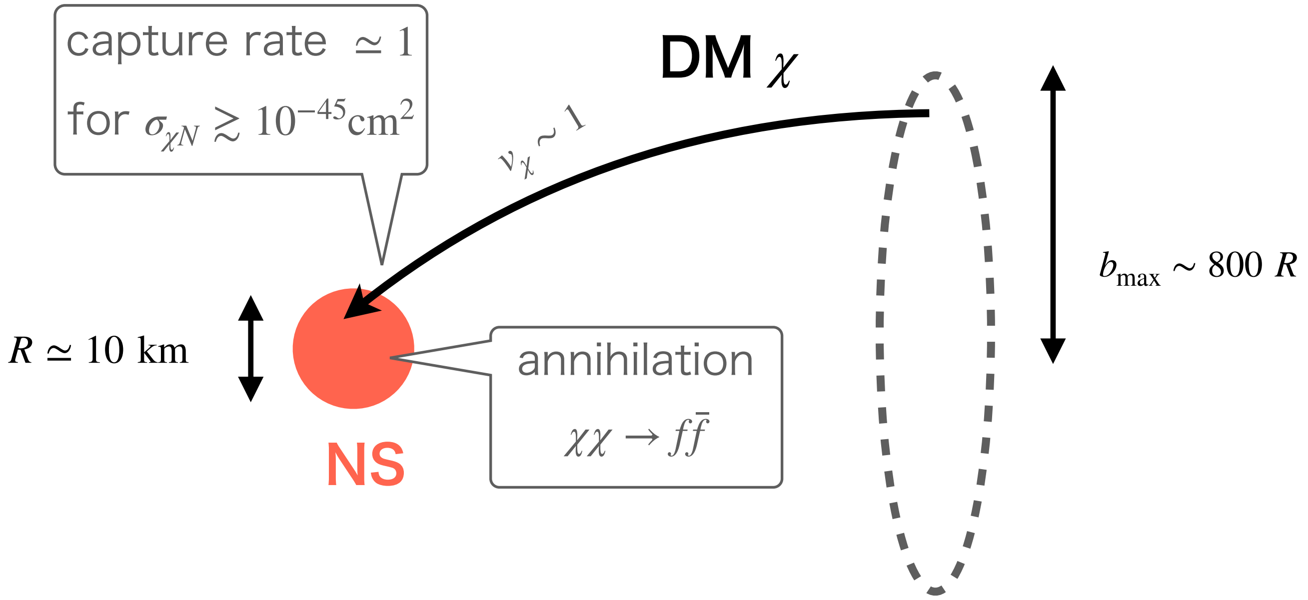


For $m_\chi > 100$ TeV,
single scattering is not
enough to catch DM.
→ multiple scattering.

Baryakhtar+, 1704.01577

(ii). 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
C.-S. Chen+ 1804.03409
N. F. Bell+ 1807.02840
D. A. Camargo+ 1901.05474
N. F. Bell+ 1904.09803
KH, N.Nagata, K.Yanagi 1905.02991
R. Garani+ 1906.10145


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

DM χ

$v_\chi \sim 1$

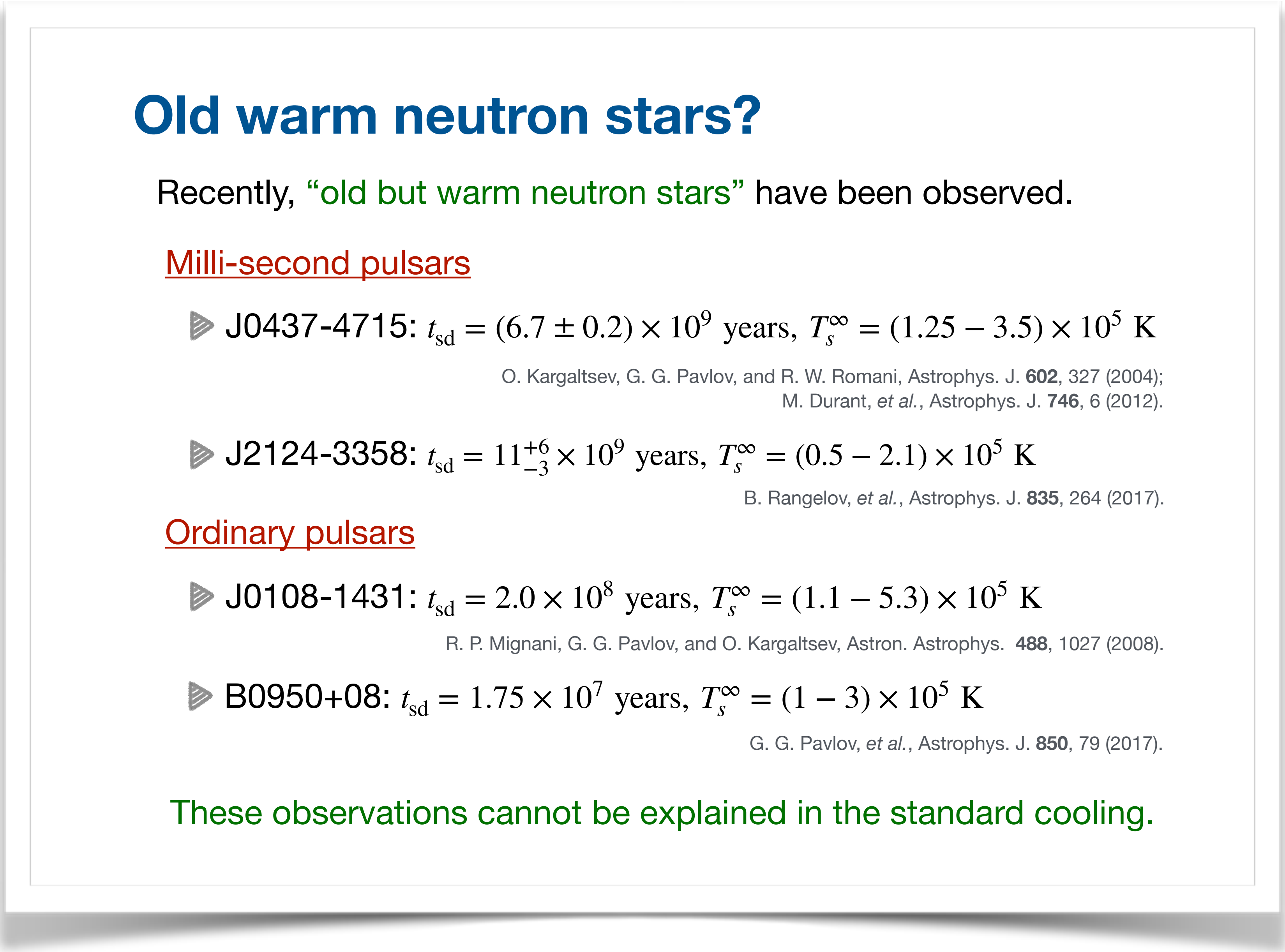
$b_{\max} \sim 800\ R$

$R \simeq 10$ km

NS

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

But,...


Old warm neutron stars?

Recently, "old but warm neutron stars" have been observed.

Milli-second pulsars

- J0437-4715: $t_{\mathrm{sd}} = (6.7 \pm 0.2) \times 10^9$ years, $T_s^\infty = (1.25 - 3.5) \times 10^5$ K

O. Kargaltsev, G. G. Pavlov, and R. W. Romani, Astrophys. J. **602**, 327 (2004);
M. Durant, *et al.*, Astrophys. J. **746**, 6 (2012).

- J2124-3358: $t_{\mathrm{sd}} = 11^{+6}_{-3} \times 10^9$ years, $T_s^\infty = (0.5 - 2.1) \times 10^5$ K

B. Rangelov, *et al.*, Astrophys. J. **835**, 264 (2017).

Ordinary pulsars

- J0108-1431: $t_{\mathrm{sd}} = 2.0 \times 10^8$ years, $T_s^\infty = (1.1 - 5.3) \times 10^5$ K

R. P. Mignani, G. G. Pavlov, and O. Kargaltsev, Astron. Astrophys. **488**, 1027 (2008).

- B0950+08: $t_{\mathrm{sd}} = 1.75 \times 10^7$ years, $T_s^\infty = (1 - 3) \times 10^5$ K

G. G. Pavlov, *et al.*, Astrophys. J. **850**, 79 (2017).

These observations cannot be explained in the standard cooling.

slide from N.Nagata

(iii). 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]**)

non-equilibrium

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

$$C\frac{dT^\infty}{dt} = -L^\infty_\nu - L^\infty_\gamma + L^\infty_H$$

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

chemical potential

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

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

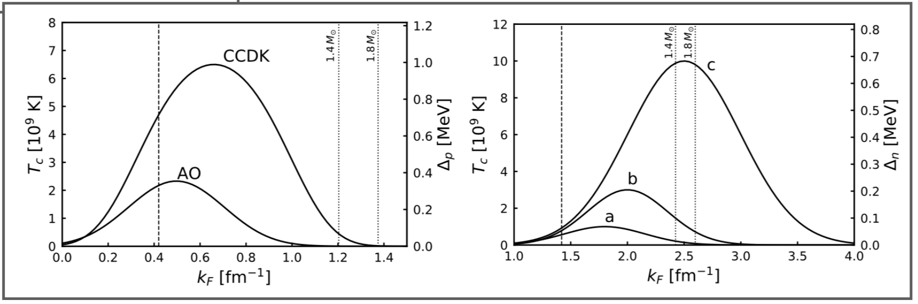
$$\Delta\Gamma_{M,N\ell} = \frac{Q^{(0)}_{M,N\ell}}{T(r)}\,I^N_{M,\Gamma}$$

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

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

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

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

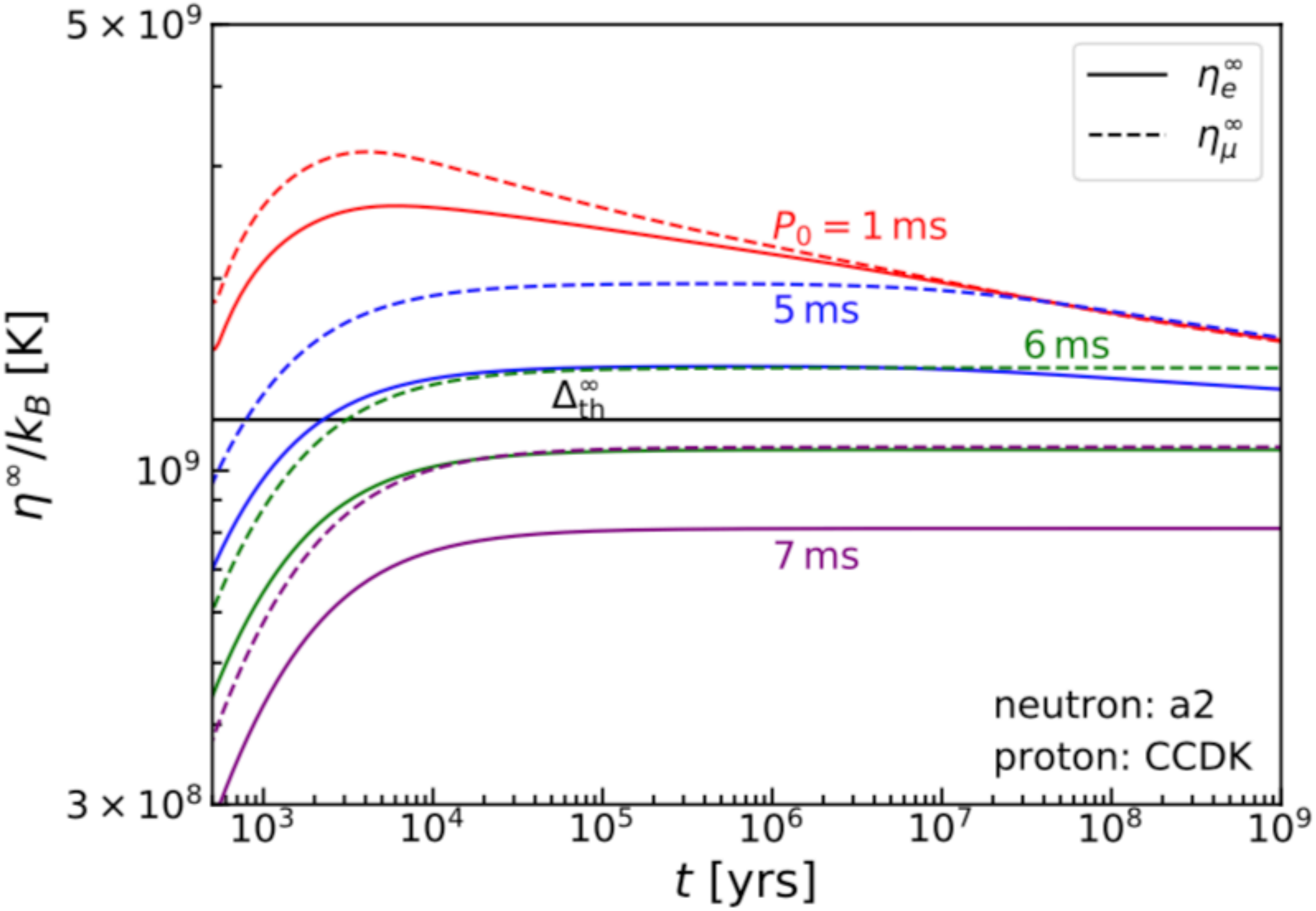


$$\tilde{N}\tilde{N} \rightarrow [NN] + \nu_\ell + \bar{\nu}_\ell$$

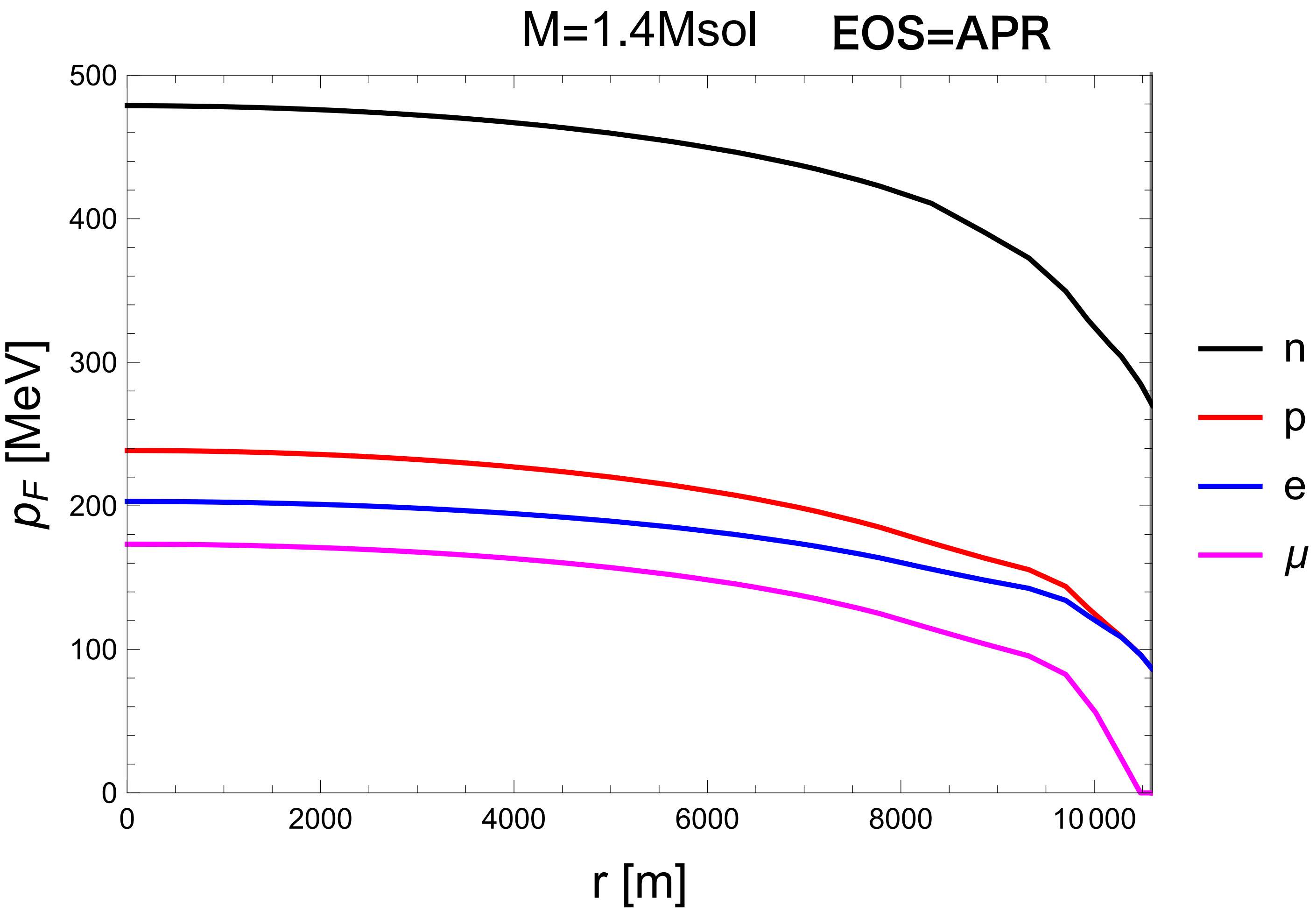
(iv). DM heating vs. Rotochemical heating

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

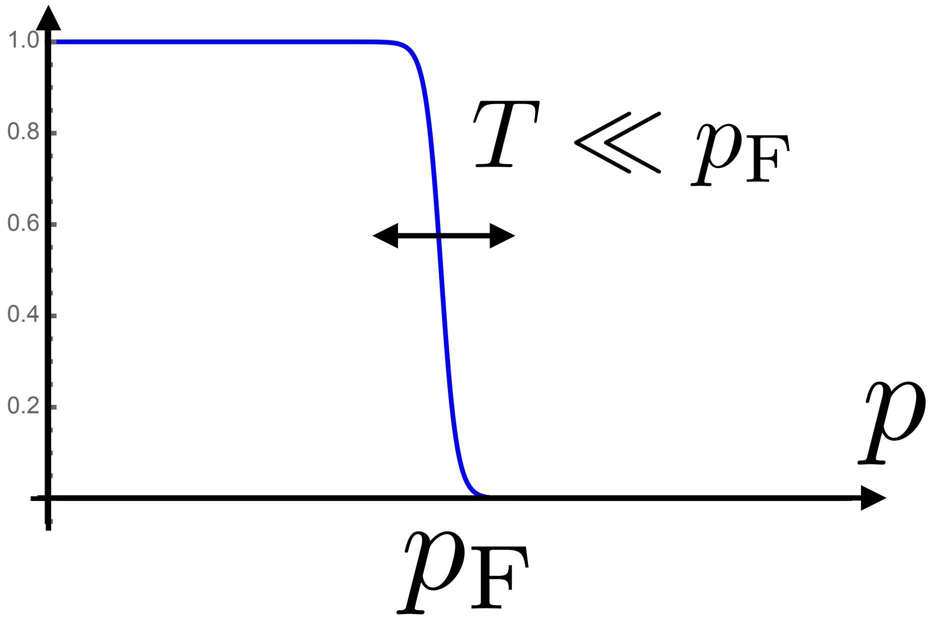
KH, N. Nagata, K. Yanagi, [1905.02991]



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



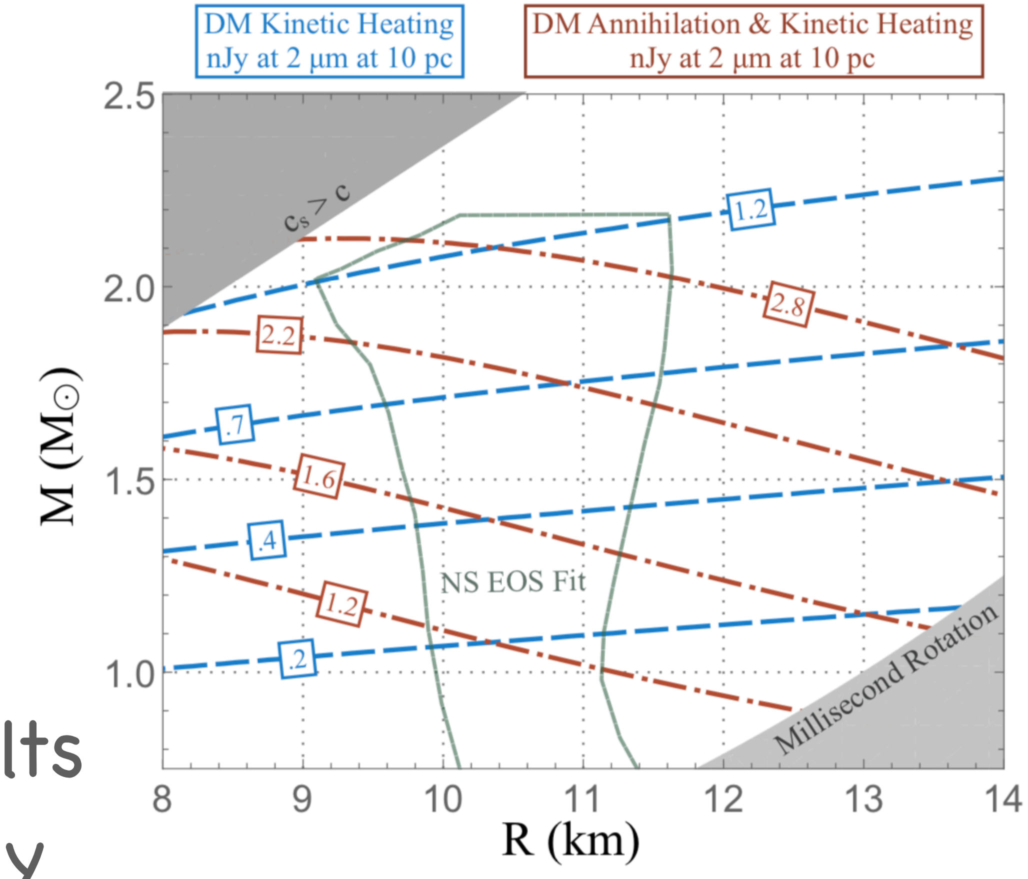
Fermi momentum $\sim \mathcal{O}(100)$ MeV



Fermi degenerate

observational feasibility

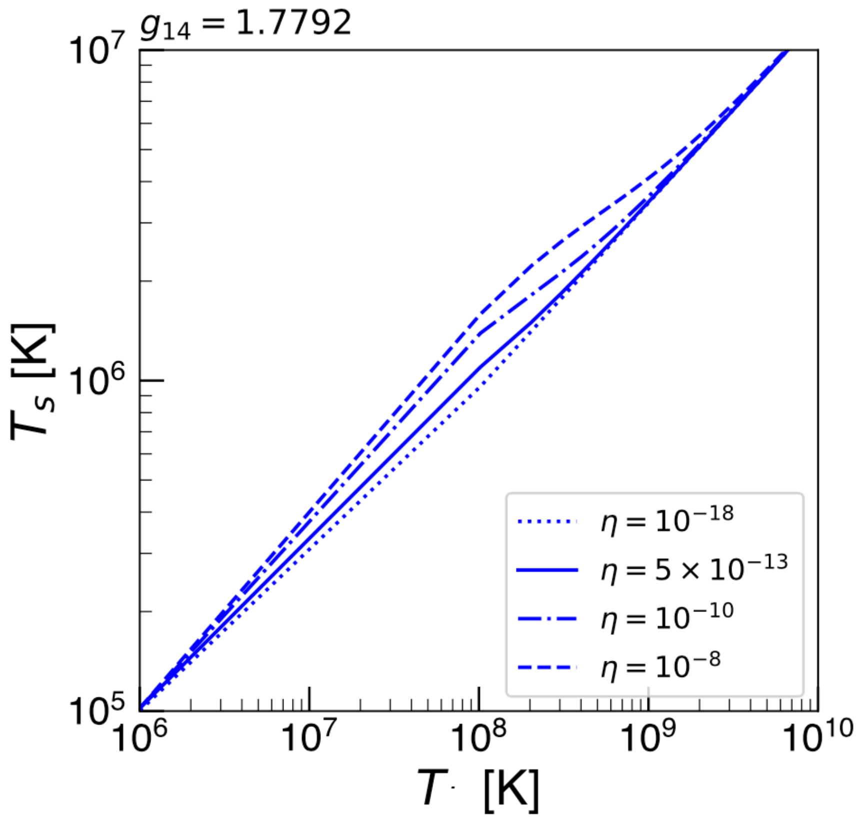
- See e.g., the discussion in M.Baryakhtar+, 1704.01577.
- O(1) old and cold NSs can be at $d = 10\text{pc}$.
- Radiation from a DM-heated NS there results in a spectral flux density of O(1) nanoJansky (nJy) at wavelength $\nu^{-1} = \mathcal{O}(1)\ \mu\text{m}$.
- Maybe within the sensitivity of the upcoming telescopes such as the JWST, TMT, and E-ELT.



M.Baryakhtar+, 1704.01577

$$\boxed{T_s \sim T^\alpha \ (\alpha \sim 0.5)}$$

surface
temperature
(observed)



internal temperature