Exploring Physics Beyond the Standard Model via Temperature Observations of Neutron Stars

Koichi Hamaguchi (Tokyo U.)

@Nucleosynthesis and Evolution of Neutron Stars
Jan.27-30, 2025, Kyoto University

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Based on the works with

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

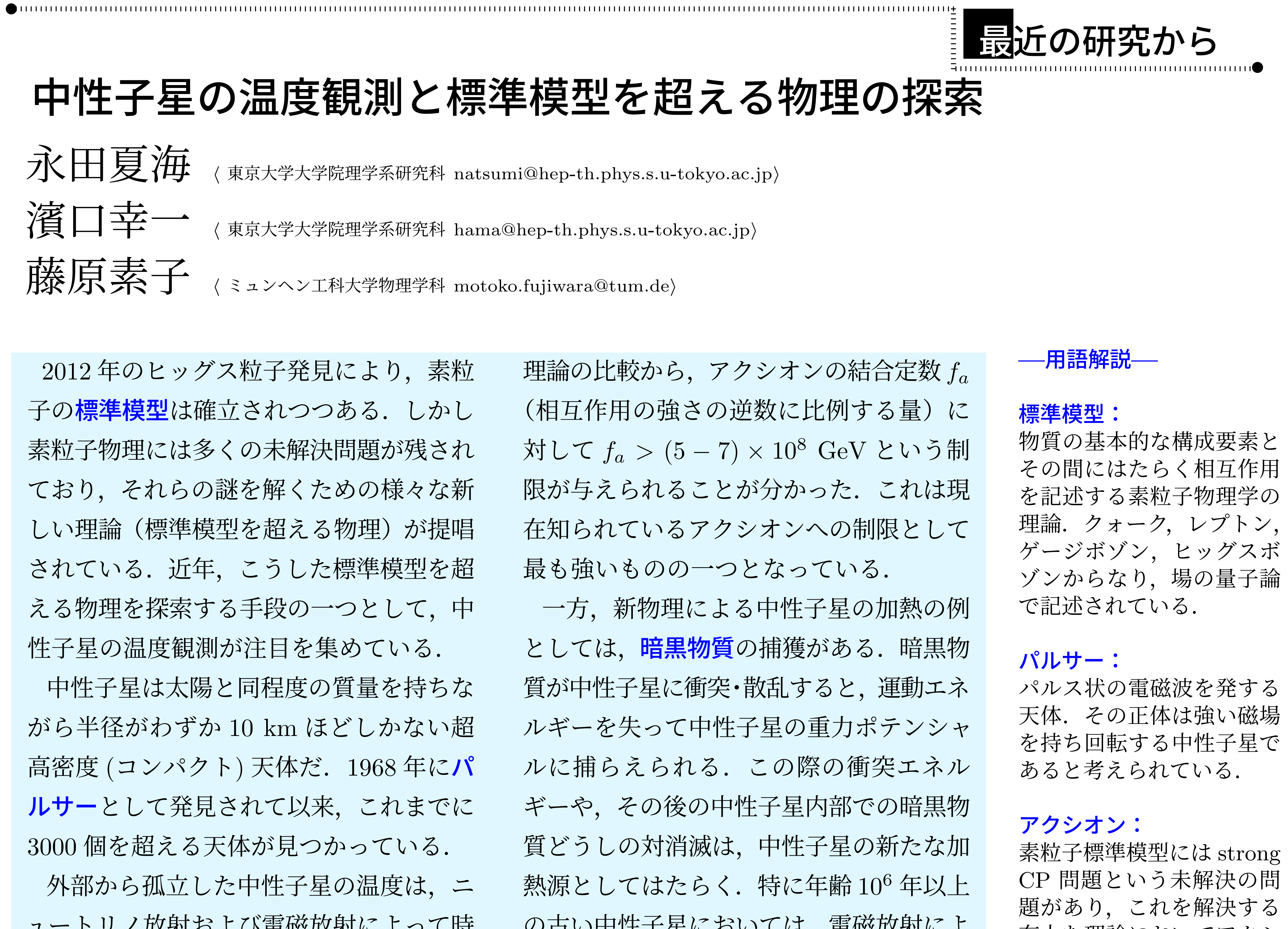
references

NS heating by DM: arXiv 2309.02633, 2308.16066, 2204.02413, 2204.02238, 1905.02991, 1904.04667.

NS cooling by axion: arXiv 1806.07151.

Exploring Physics Beyond the Standard Model via Temperature Observations of Neutron Stars

review article in 日本物理学会誌 (JPS, 2024)



最近の研究から

中性子星の温度観測と標準模型を超える物理の探索

永田夏海 〈東京大学大学院理学系研究科 natsumi@hep-th.phys.s.u-tokyo.ac.jp〉
濱口幸一 〈東京大学大学院理学系研究科 hama@hep-th.phys.s.u-tokyo.ac.jp〉
藤原素子 〈ミュンヘン工科大学物理学科 motoko.fujiwara@tum.de〉

2012年のヒッグス粒子発見により，素粒子の標準模型は確立されつつある．しかし素粒子物理には多くの未解決問題が残されており，それらの謎を解くための様々な新しい理論（標準模型を超える物理）が提唱されている．近年，こうした標準模型を超える物理を探索する手段の一つとして，中性子星の温度観測が注目を集めている．

中性子星は太陽と同程度の質量を持ちながら半径がわずか10 kmほどしかない超高密度(コンパクト)天体だ．1968年にパルサーとして発見されて以来，これまでに3000個を超える天体が見つかっている．

外部から孤立した中性子星の温度は，ニ

理論の比較から，アクシオンの結合定数 f_a（相互作用の強さの逆数に比例する量）に対して $f_a > (5-7) \times 10^8$ GeV という制限が与えられることが分かった．これは現在知られているアクシオンへの制限として最も強いものの一つとなっている．

一方，新物理による中性子星の加熱の例としては，暗黒物質の捕獲がある．暗黒物質が中性子星に衝突･散乱すると，運動エネルギーを失って中性子星の重力ポテンシャルに捕らえられる．この際の衝突エネルギーや，その後の中性子星内部での暗黒物質どうしの対消滅は，中性子星の新たな加熱源としてはたらく．特に年齢 10^6 年以上

—用語解説—

標準模型：
物質の基本的な構成要素とその間にはたらく相互作用を記述する素粒子物理学の理論．クォーク，レプトン，ゲージボゾン，ヒッグスボゾンからなり，場の量子論で記述されている．

パルサー：
パルス状の電磁波を発する天体．その正体は強い磁場を持ち回転する中性子星であると考えられている．

アクシオン：
素粒子標準模型には strong CP 問題という未解決の問題があり，これを解決する

Natsumi Nagata

(Tokyo U.)

🏆 **2024 AAPPS-JPS Award**

Motoko Fujiwara

(Toyama U.)

🏆 **2025 JPS Young Scientist Award**

Temperature evolution of isolated NS

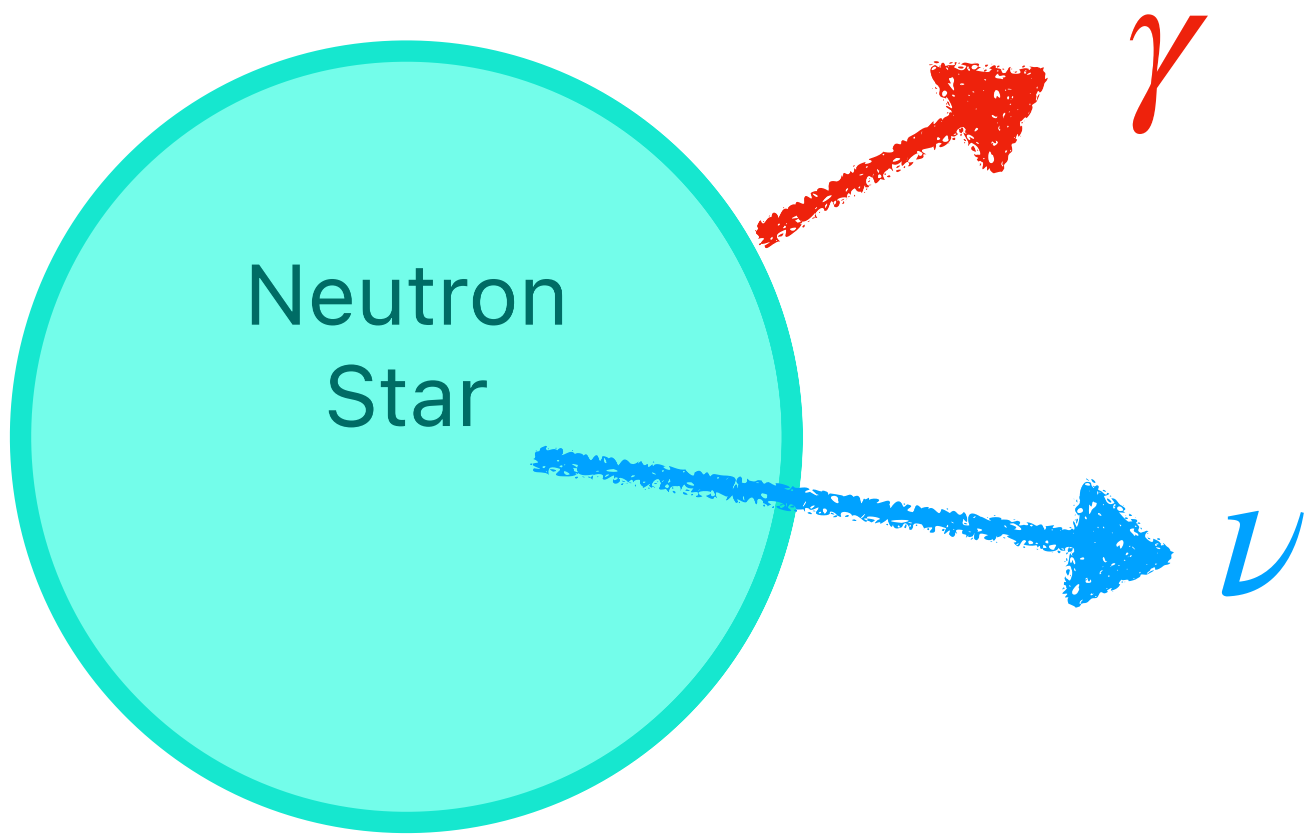
For reviews, e.g., D.G.Yakovlev+, astro-ph/0402143,
D.Page+, astro-ph/0508056, 1302.6626

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

Temperature Evolution.

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

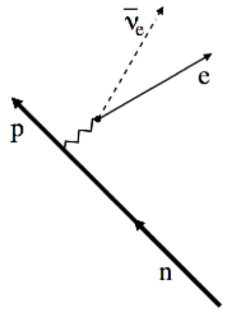
$C = C_n + C_p + C_e + C_\mu$



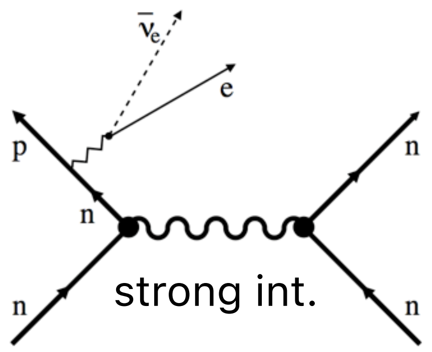
Neutrino emission

dominant for a **young** NS ($\tau \lesssim 10^5$ yrs)

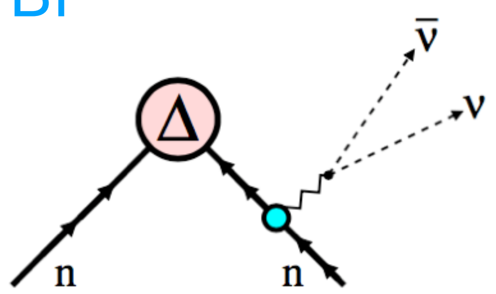
- Direct Urca



- Modified Urca (& Bremsstrahlung)



- PBF



Photon emission

dominant process for an **old** NS ($\tau \gtrsim 10^5$ yrs).

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

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

Temperature evolution of isolated NS

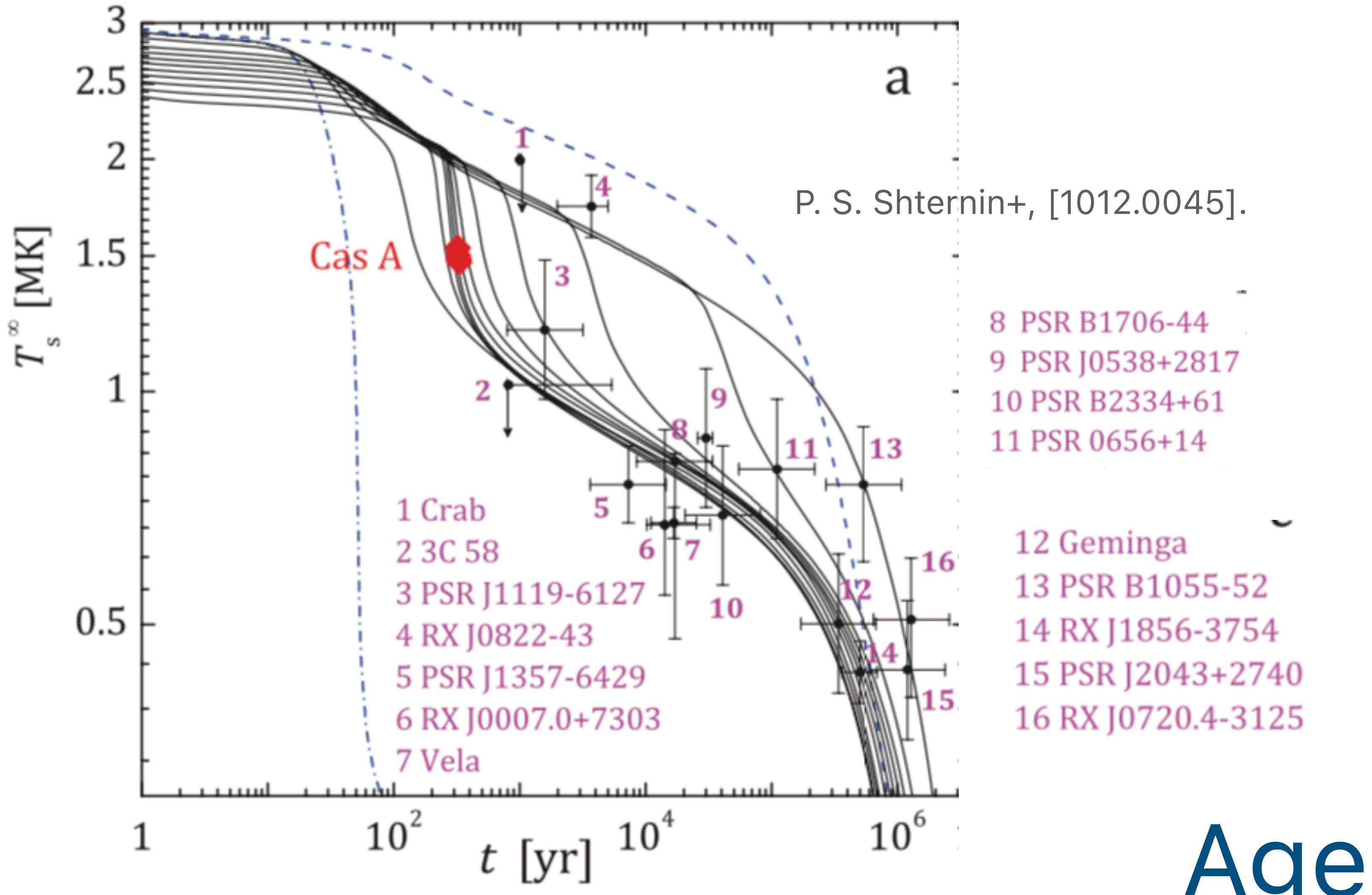
For reviews, e.g., D.G.Yakovlev+, astro-ph/0402143,
D.Page+, astro-ph/0508056, 1302.6626

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

The standard cooling scenario can successfully explain many isolated NS temperature observations.

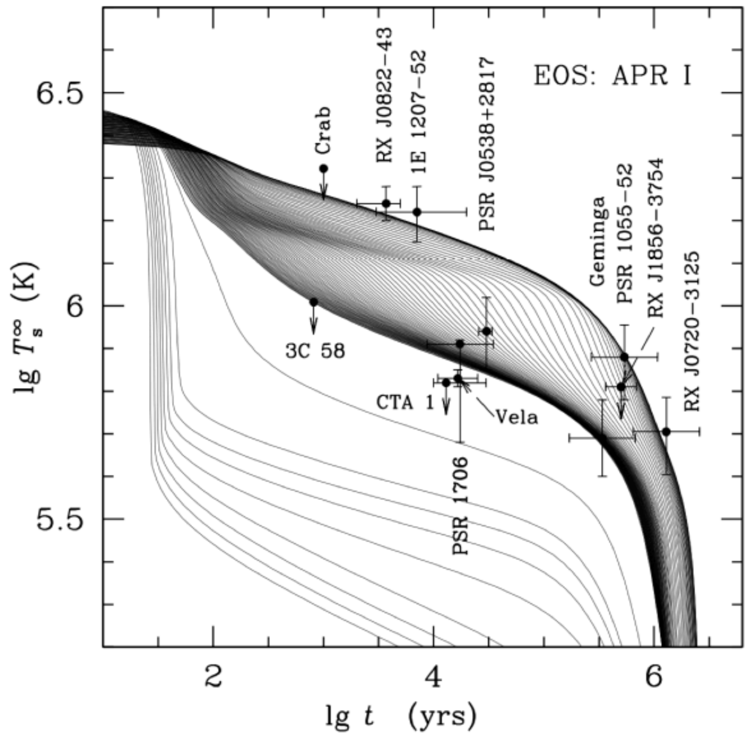
D.Page+, astro-ph/0403657,
M.E.Gusakov+, astro-ph/0404002,
D.Page+, 0906.1621

Surface Temperature

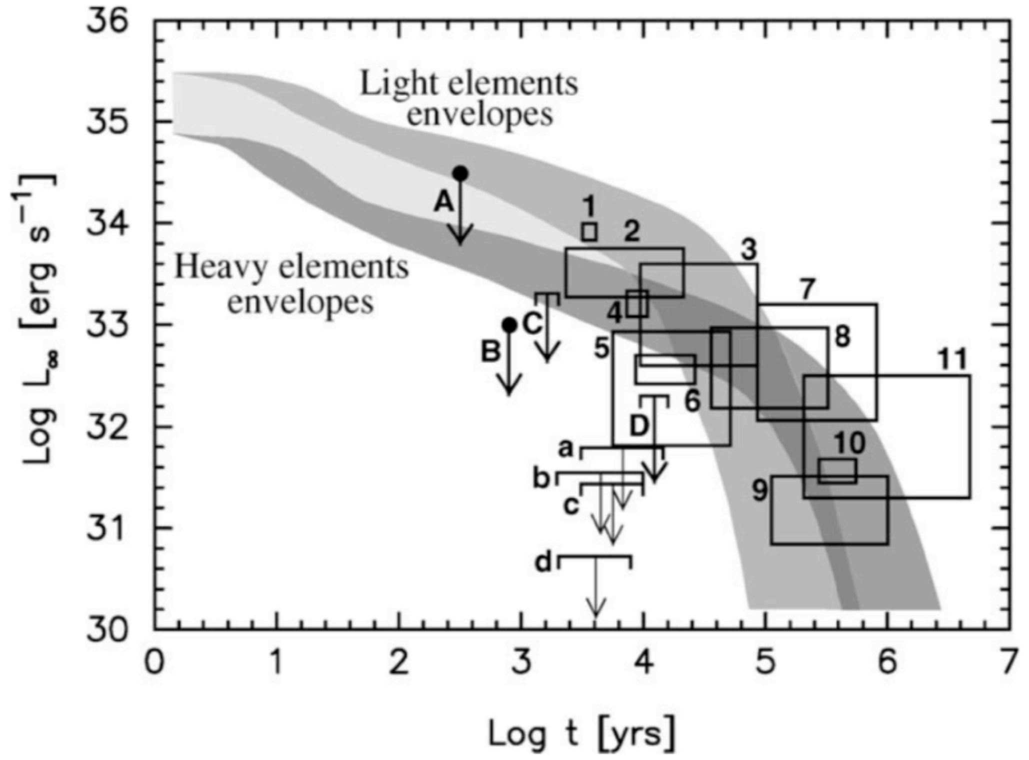


P. S. Shternin+, [1012.0045].

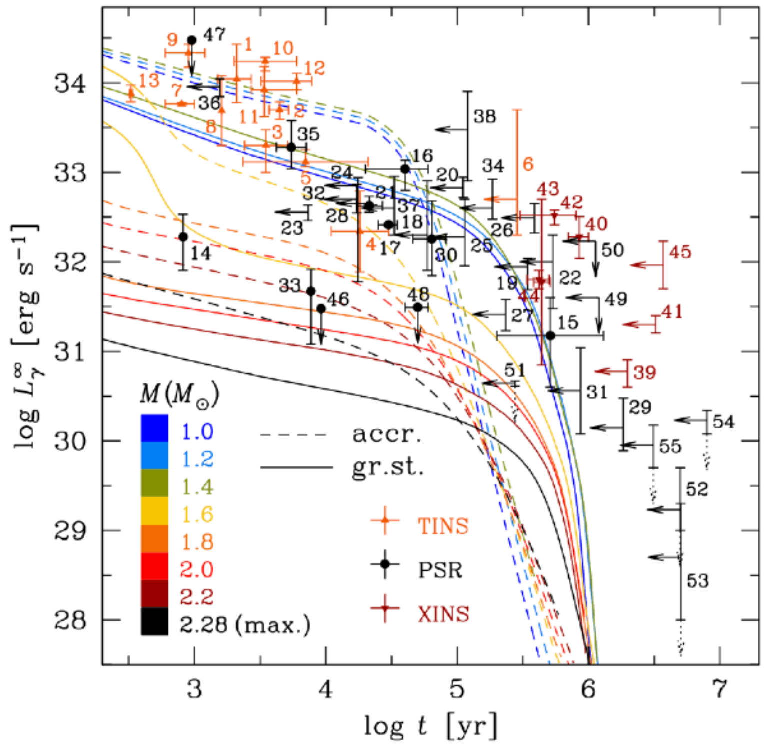
M. E. Gusakov, A. D. Kaminker, D. G. Yakovlev, O. Y. Gnedin
Mon.Not.Roy.Astron.Soc. **363** (2005) 555-562



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



A. Y. Potekhin+,2006.15004

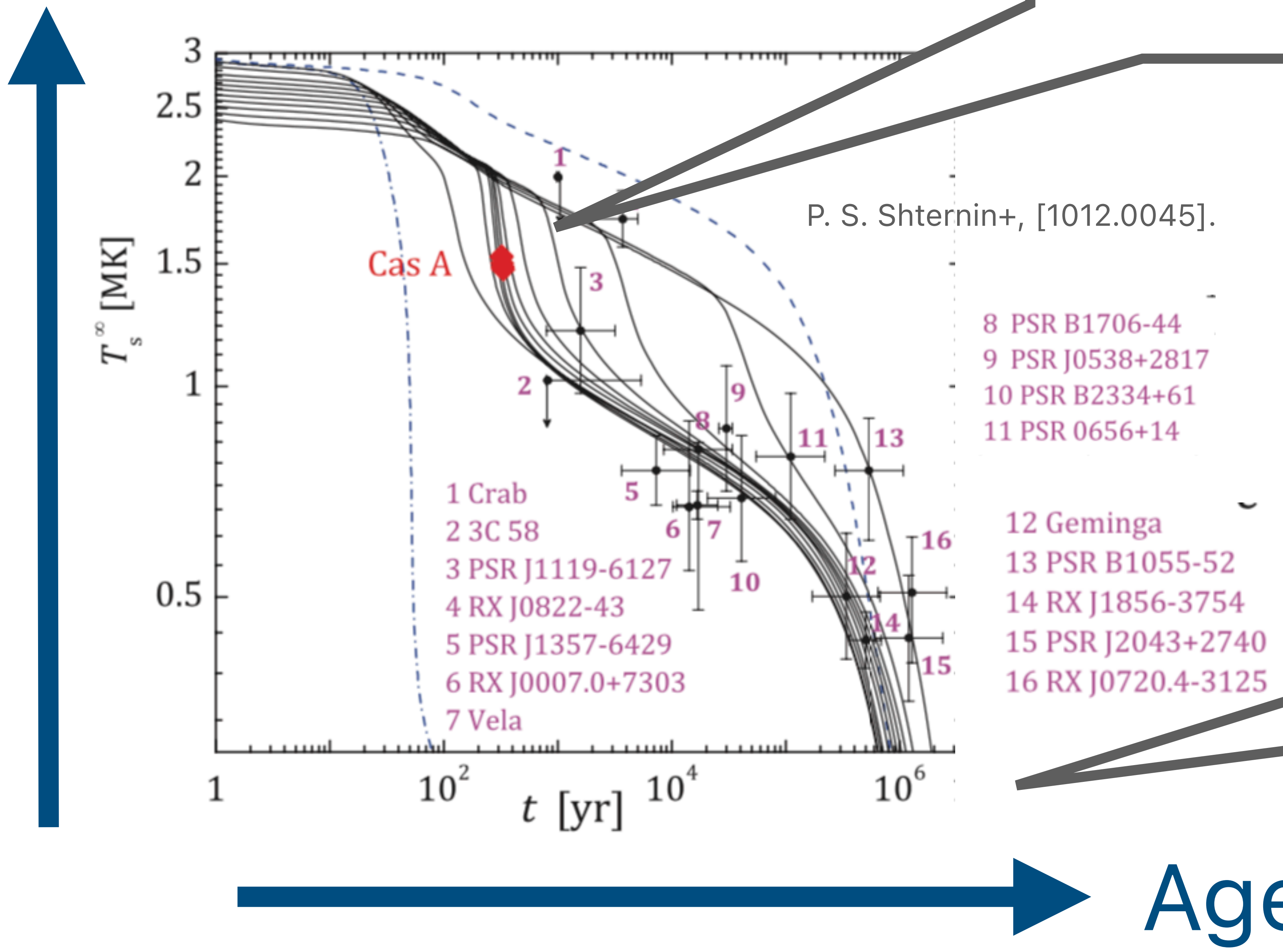


Ages of Neutron Stars

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

This talk

$$C\frac{dT}{dt} = -L_\nu - L_\gamma \pm L_{\text{new physics}}$$



Surface Temperature

Age

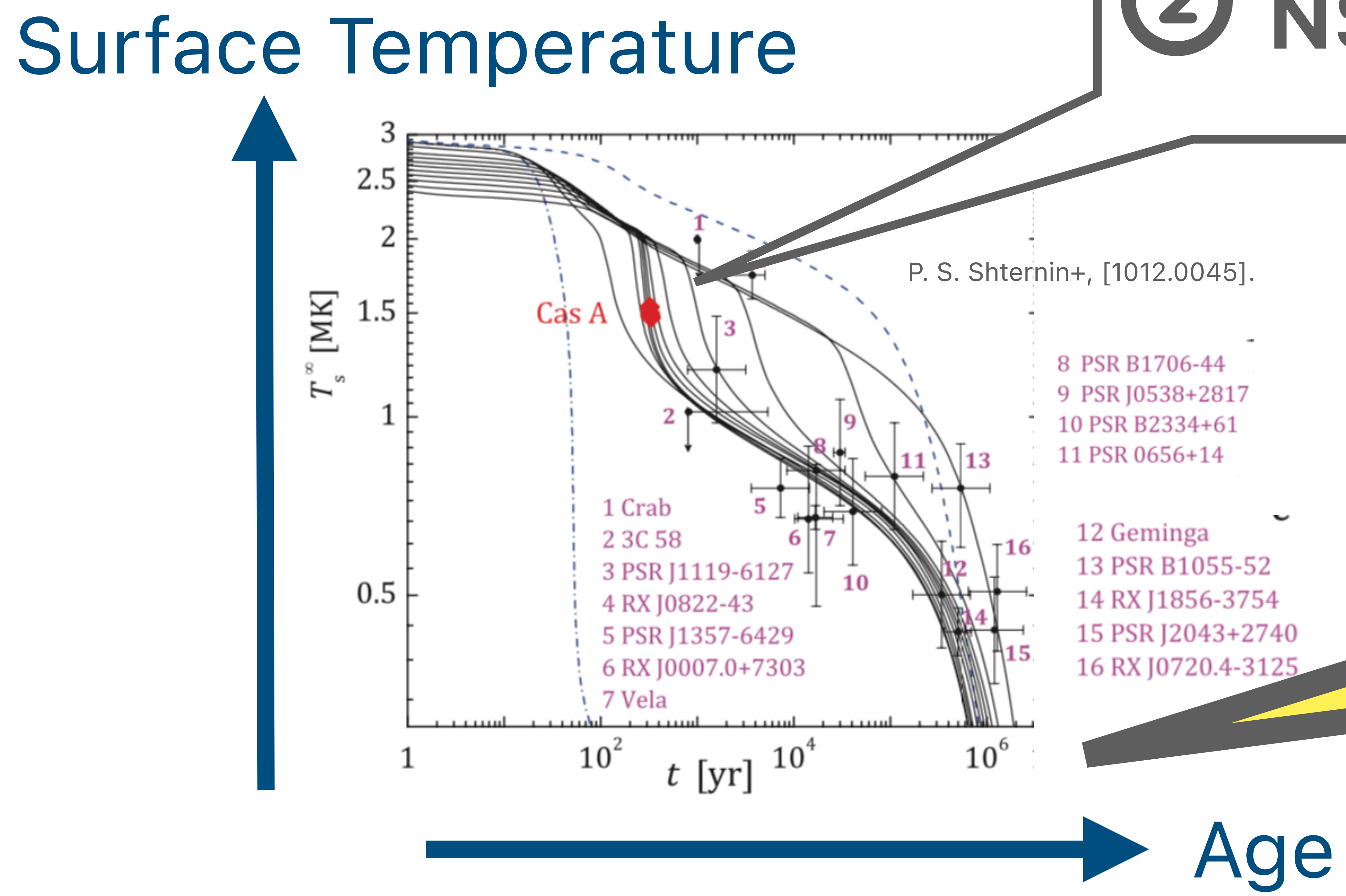
P. S. Shternin+, [1012.0045].

② **NS cooling by Axion**

① **NS heating by Dark Matter**

This talk

$$C\frac{dT}{dt} = -L_\nu - L_\gamma \pm L_{\text{new physics}}$$



P. S. Shternin+, [1012.0045].

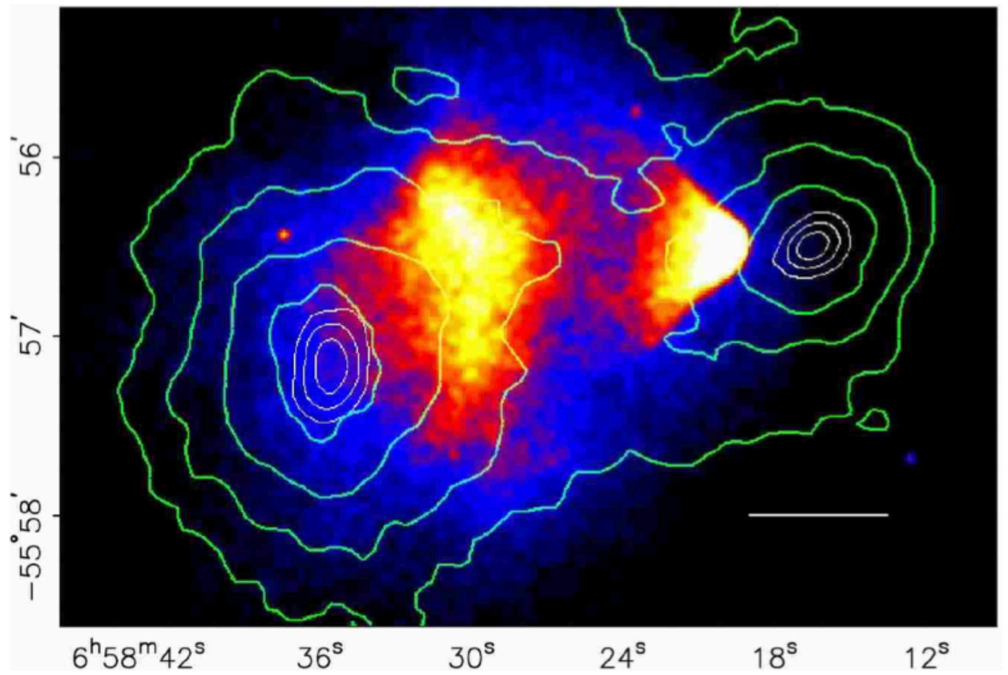
② **NS cooling by Axion**

① **NS heating by Dark Matter**

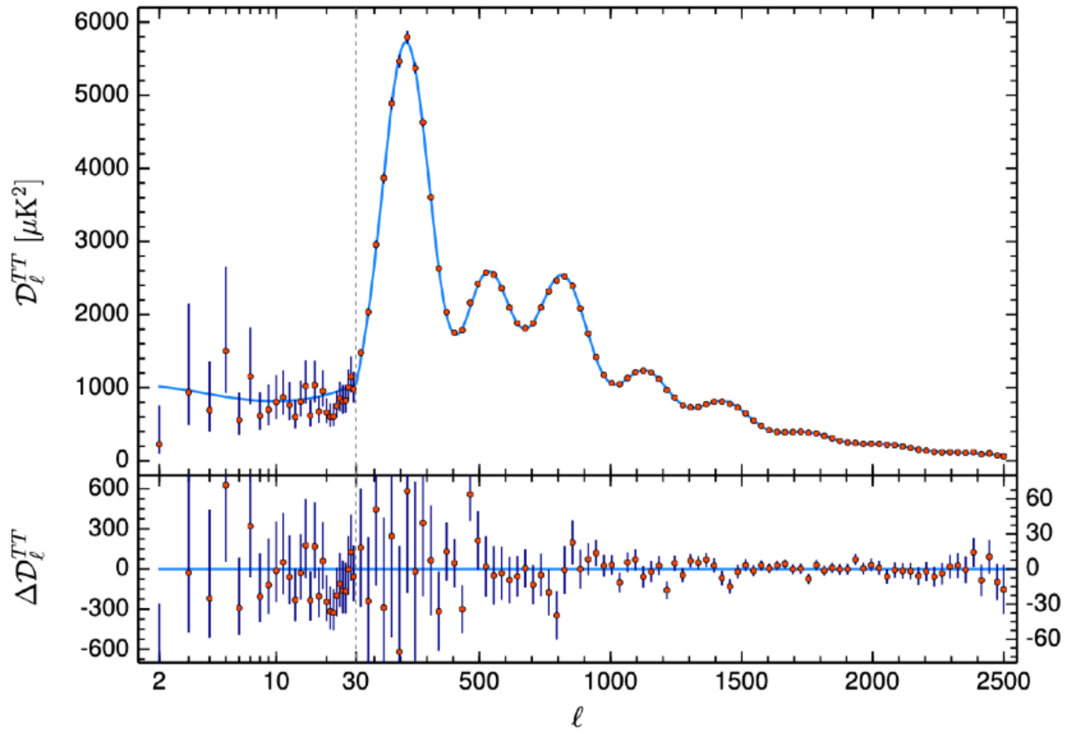
① NS heating by DM

Dark Matter

- Multiple evidence.
- Makes up ~26% of the universe's energy density.
- Electrically neutral.
- Various candidates: WIMPs, axions, PBHs, …



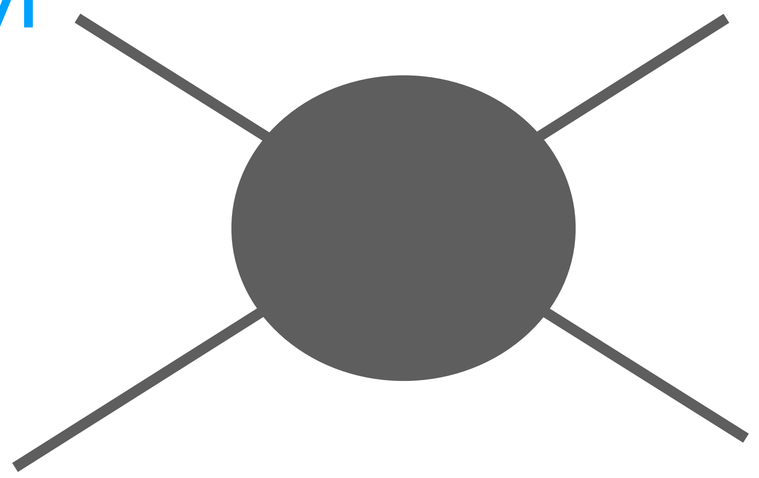
Bullet Cluster.
from astro-ph/0608407.



CMB anisotropy spectrum
from Planck 2018

Here, we focus on **WIMP = Weakly Interacting Massive Particle**

- Unknown particle.
- Stable.
- Typical mass: O(100 GeV)–O(1 TeV).
- Weakly interacts with Standard Model particles (quarks, leptons, ...).



DM

DM

quark,
lepton,..

quark,
lepton,..

① NS heating by DM

Basic Idea

Kouvaris, 0708.2362
Baryakhtar+, 1704.01577

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

Old and warm NS = DM signal ?!

① NS heating by DM

Basic Idea

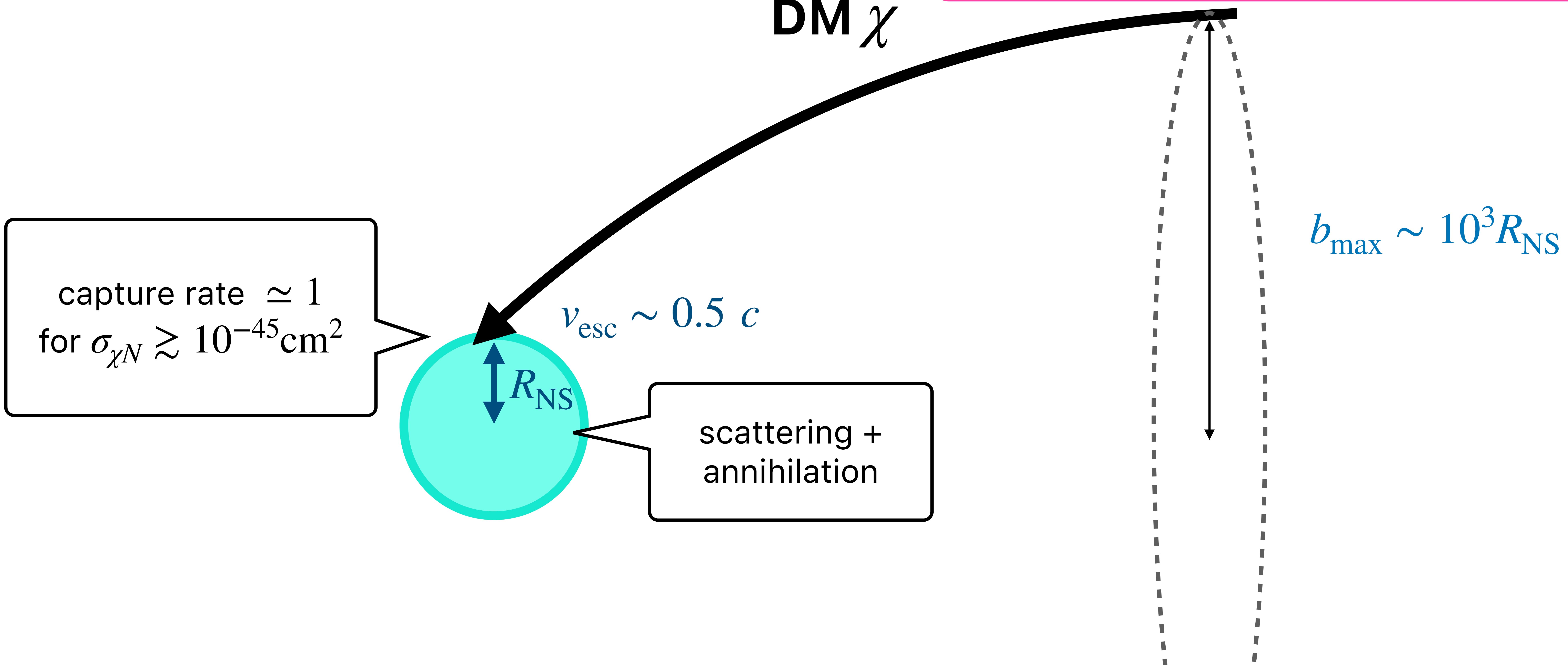
Kouvaris, 0708.2362
Baryakhtar+, 1704.01577

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

The energy injection per time:

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

… independent of the DM mass!



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

scattering +
annihilation

① NS heating by DM

Basic Idea

Kouvaris, 0708.2362
Baryakhtar+, 1704.01577

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

negligible for $\tau \gg 10^6$ years

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

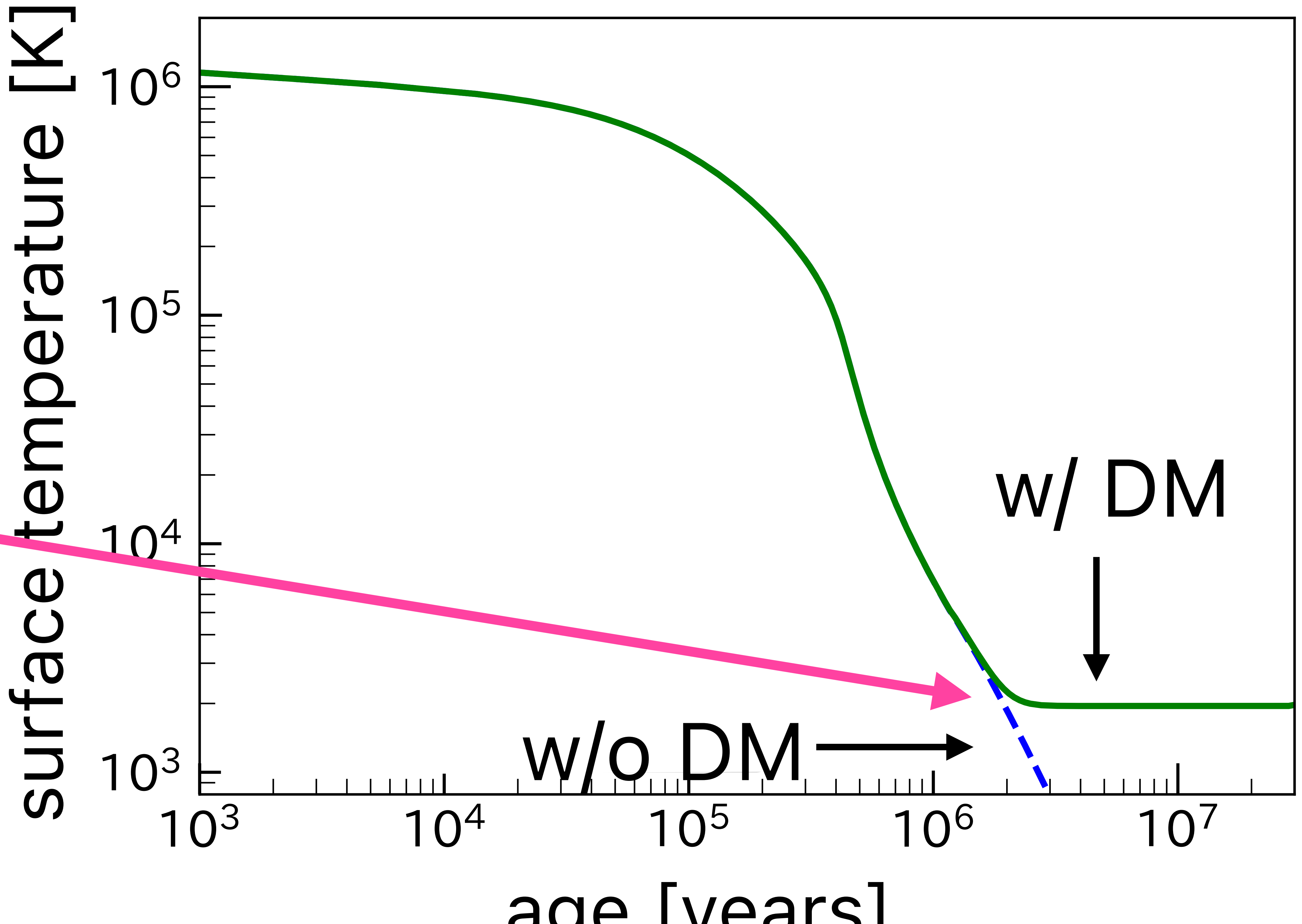
The energy injection per time:

$$L^{\mathrm{DM}}_{\mathrm{heatng}} = \dot{E}_{\mathrm{DM}} \sim \pi b^2_{\mathrm{max}} \cdot v_{\mathrm{DM}} \cdot \underbrace{n_{\mathrm{DM}} \cdot m_{\mathrm{DM}}}_{\rho_{\mathrm{DM}}} \sim 10^{22}\,\mathrm{erg/s}$$

… independent of the DM mass!

At late time, $L_\gamma \simeq L^{\mathrm{DM}}_{\mathrm{heating}}$

→ $T \sim$ (a few) 1000 K



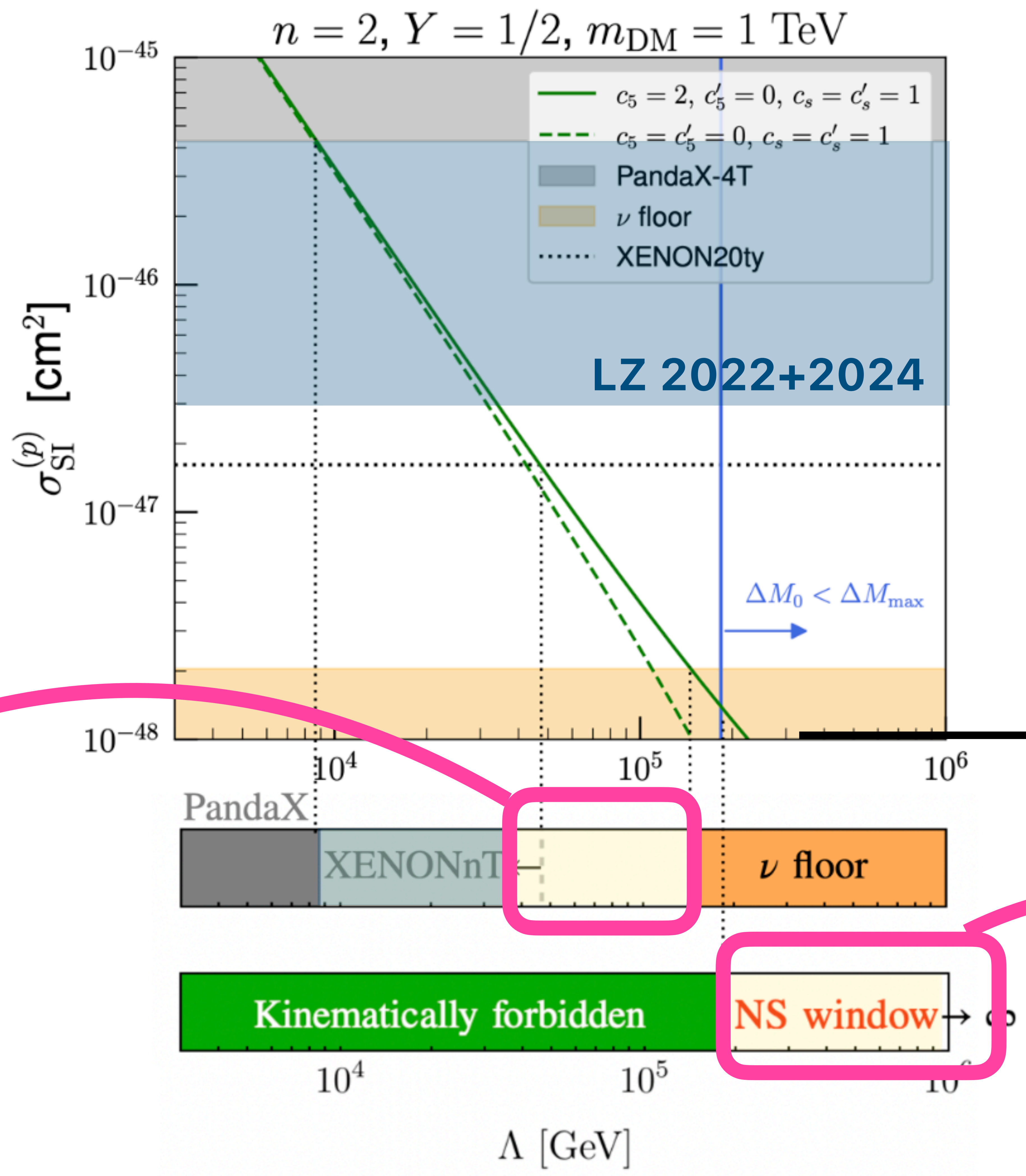
① NS heating by DM

Example

- **Electroweak multiplet DM**

  (A class of typical WIMP)

  e.g., Wino and Higgsino in SUSY



Fujiwara, KH, Nagata, Zheng [2204.02238]

cut-off parameter

Future DM direct detection experiments
(via elastic scattering)

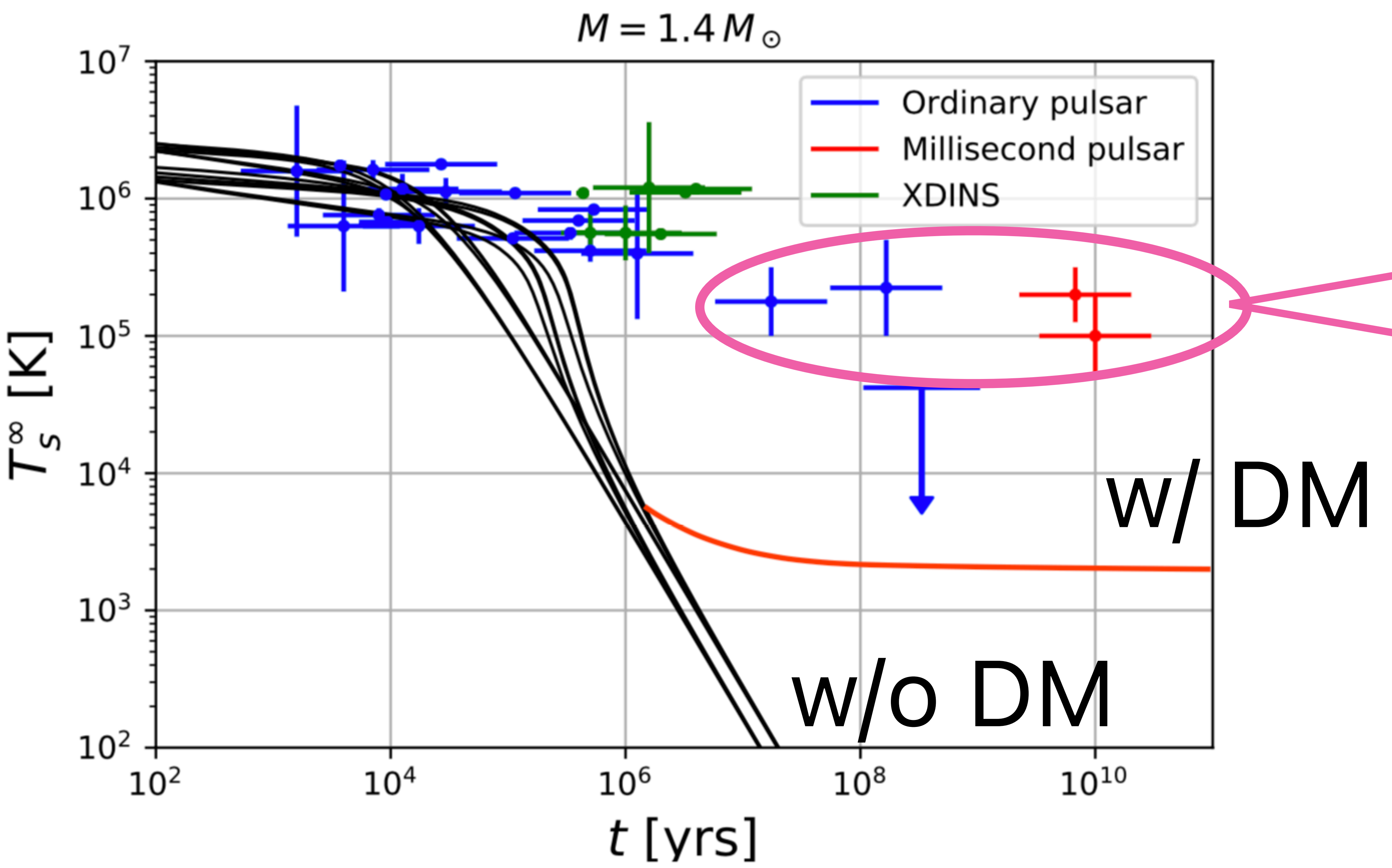
NS capture
(via inelastic scattering)

Direct detection and NS heating can play complementary roles.

① NS heating by DM

Challenge: Internal Heating

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



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

Fig. thanks to K.Yanagi.

① NS heating by DM

Challenge: Internal Heating

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

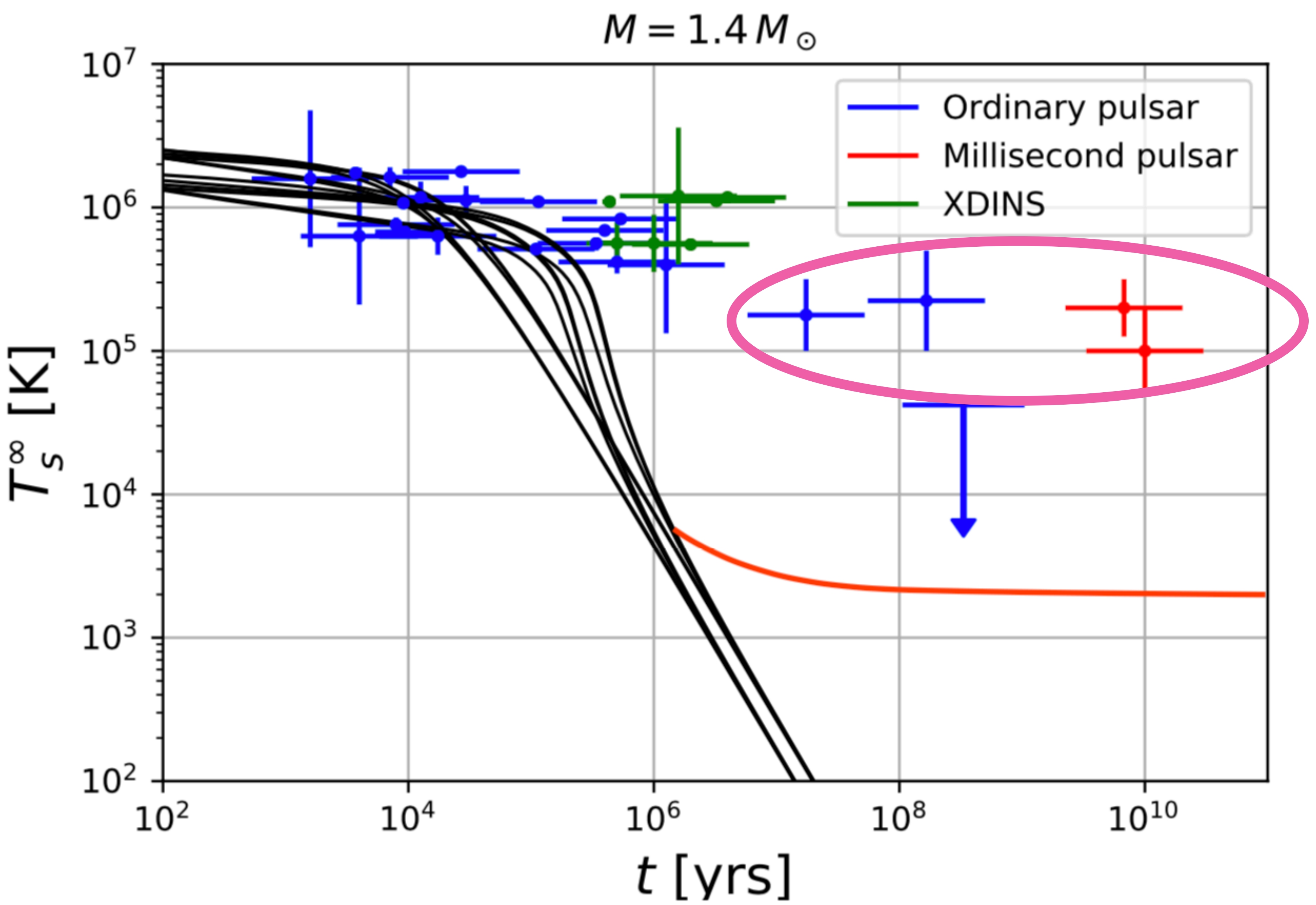


Fig. thanks to K.Yanagi.

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.

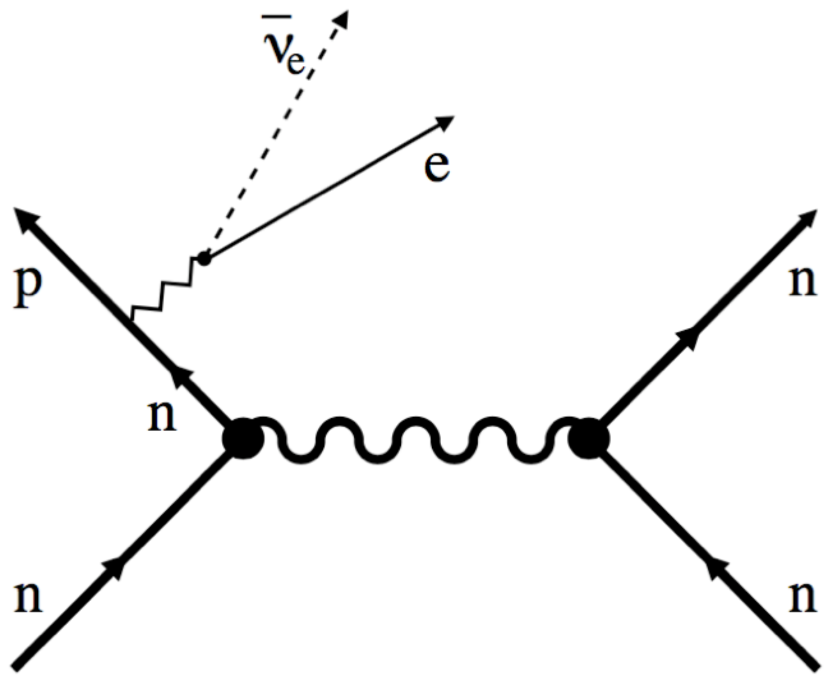
① NS heating by DM

Challenge: Internal Heating

(1) Rotochemical heating

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

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

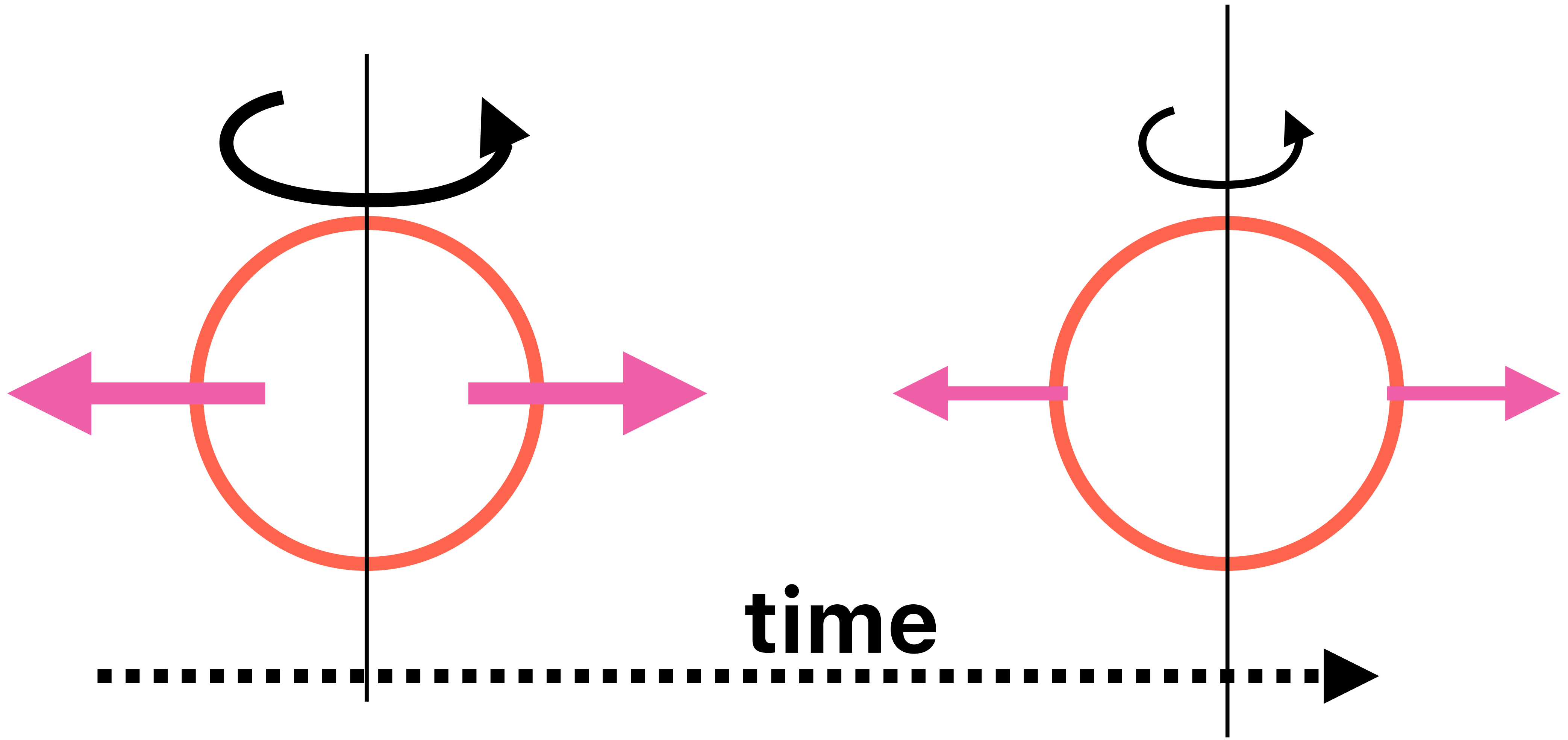


- In the minimal cooling, β-equilibrium is assumed.

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

- 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.

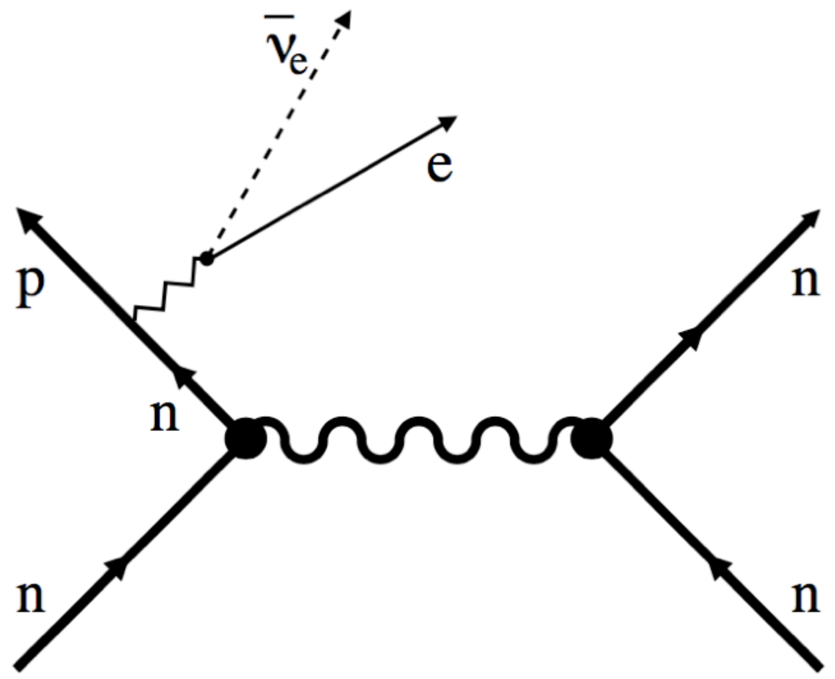
① NS heating by DM

Challenge: 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.

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

- 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**.

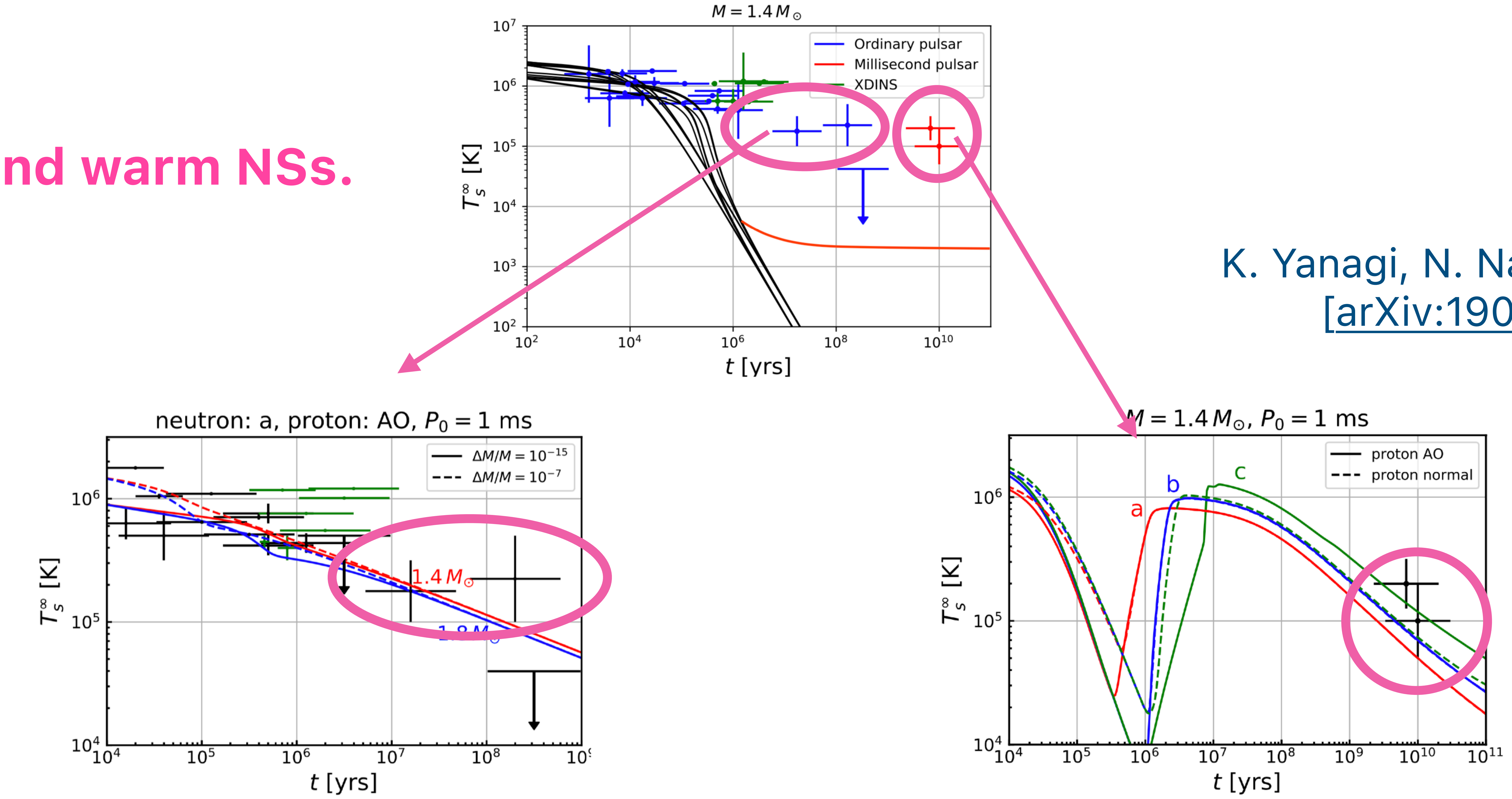
$$L_{\text{rotochemical heating}} = \int dV \left(\mu_n - \mu_p - \mu_e\right)\left(\Gamma_{n\to p+e} - \Gamma_{p+e\to n}\right) > 0.$$ **"Rotochemical heating"**

① NS heating by DM

Challenge: Internal Heating

(1) Rotochemical heating

It can explain the old and warm NSs.



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

① NS heating by DM

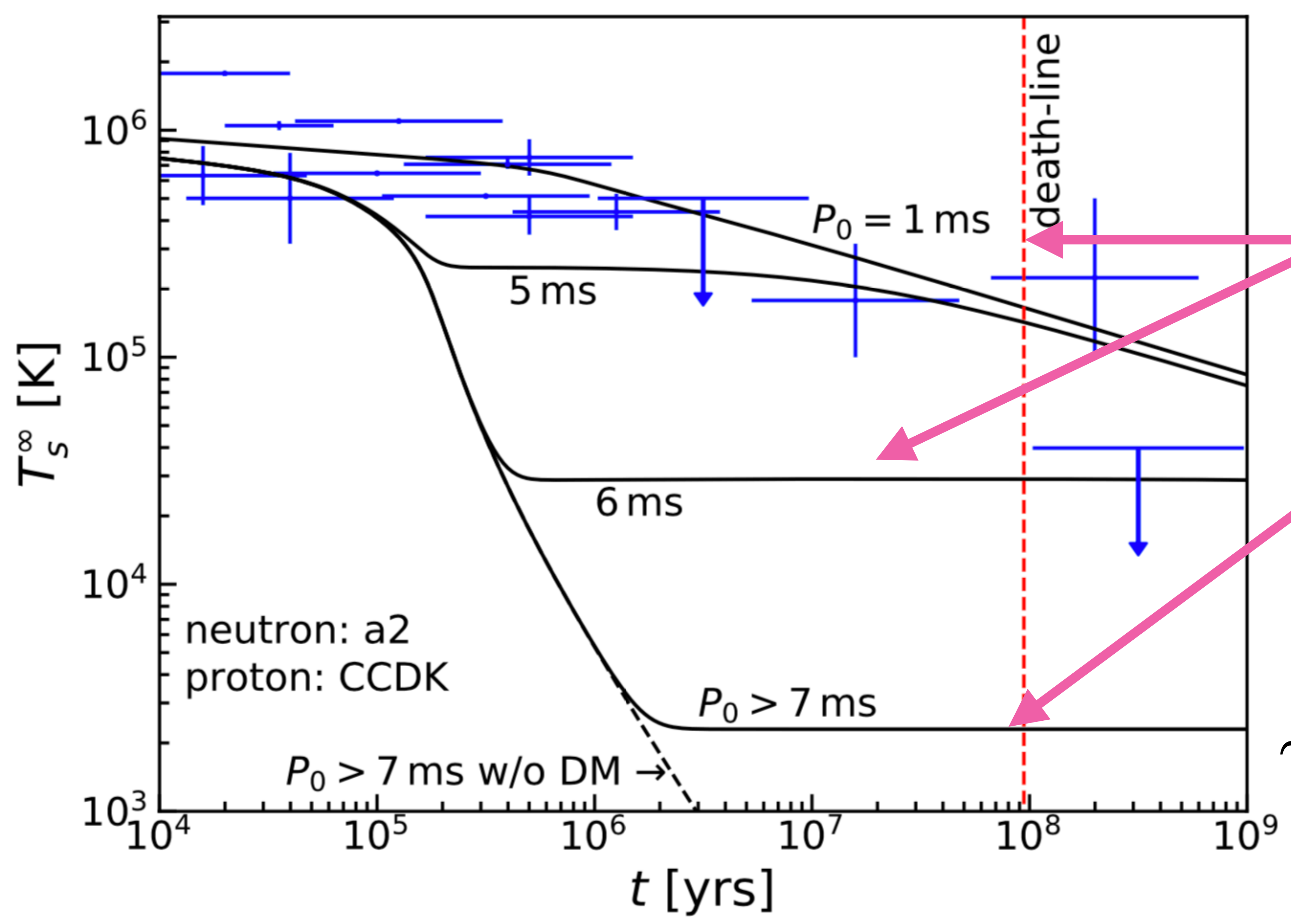
Challenge: Internal Heating

(1)′ Rotochemical heating + DM heating

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

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

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



$\sim (2000 - 3000)K$

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.**

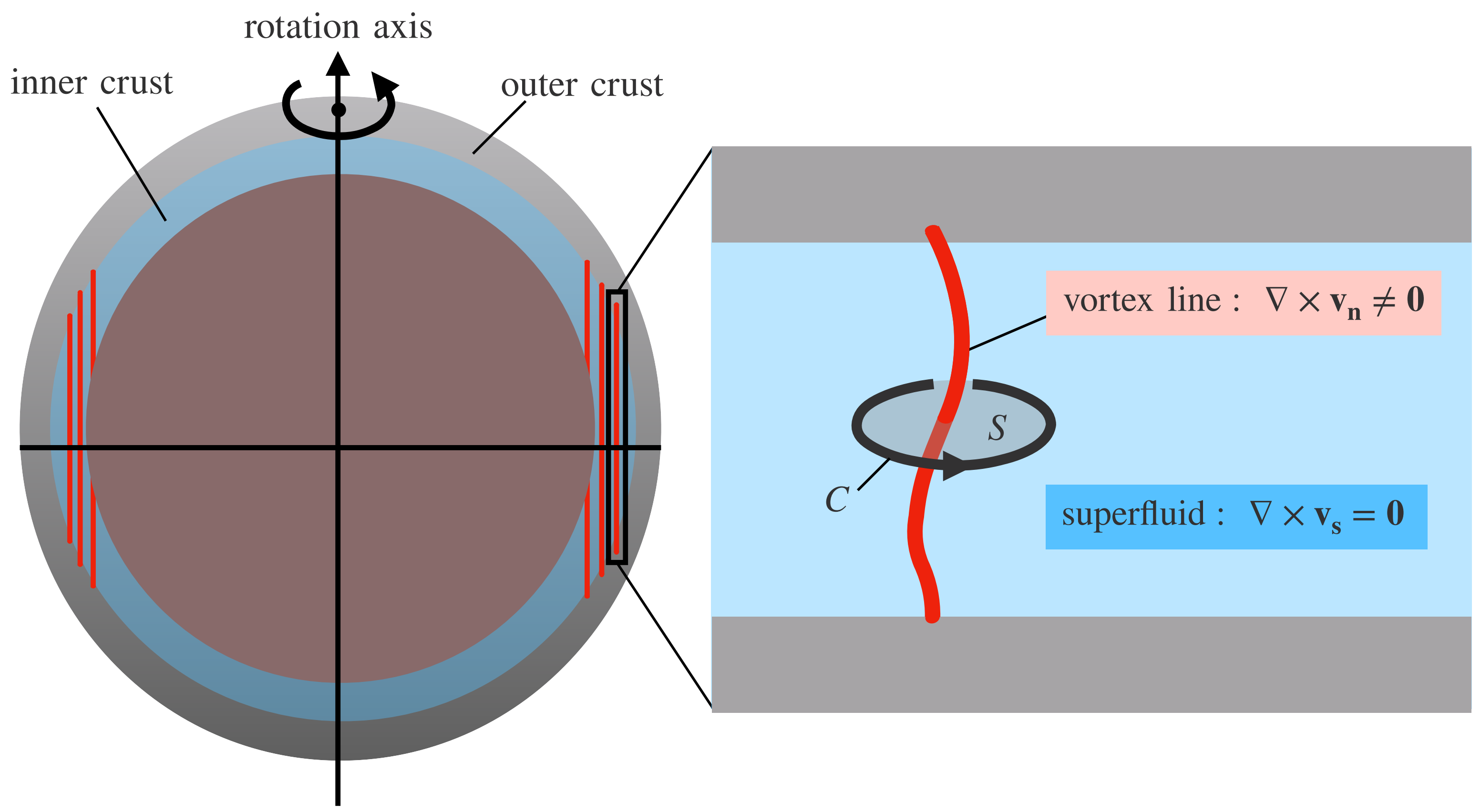
There is still a chance to see DM signal in this case.

① NS heating by DM

Challenge: Internal Heating

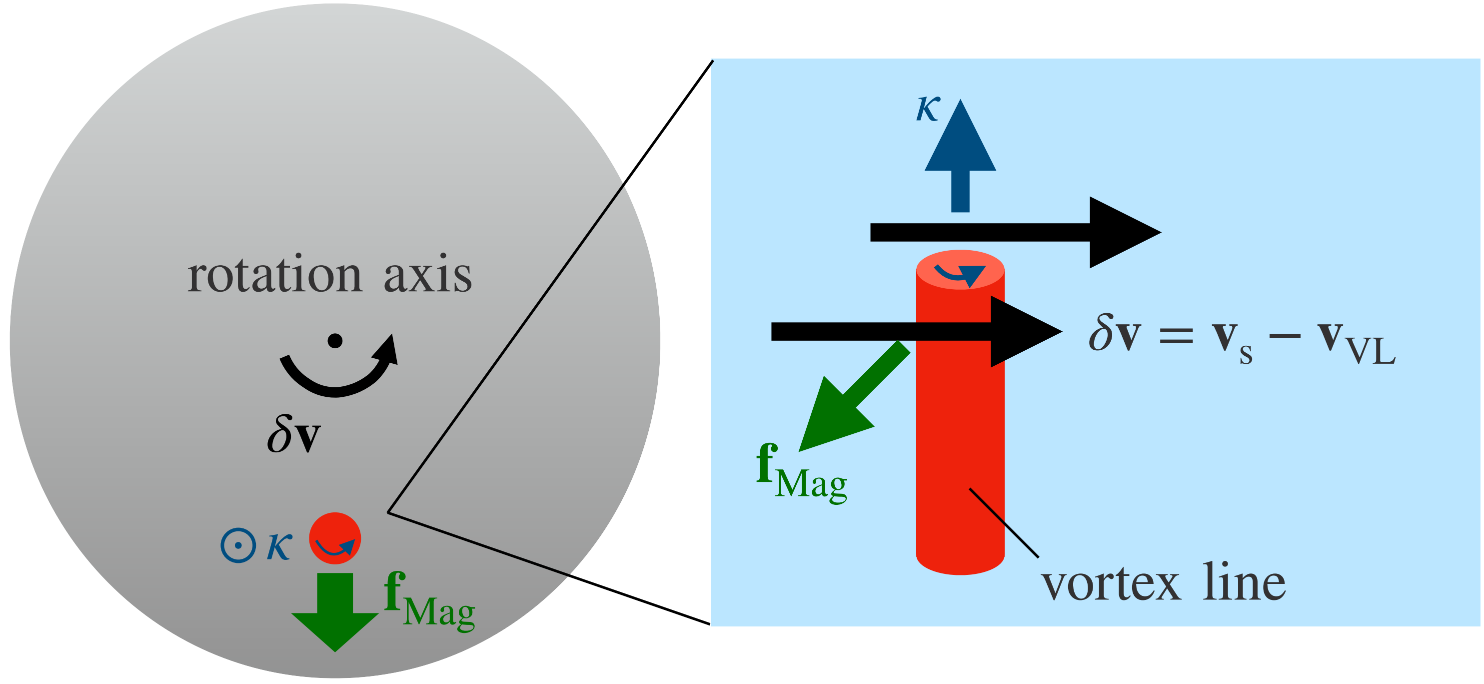
(2) Vortex Creep heating

Alpar+, 1984, Shibazaki+, 1989



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**)

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

J : universal constant
Ω : NS angular velocity

① NS heating by DM

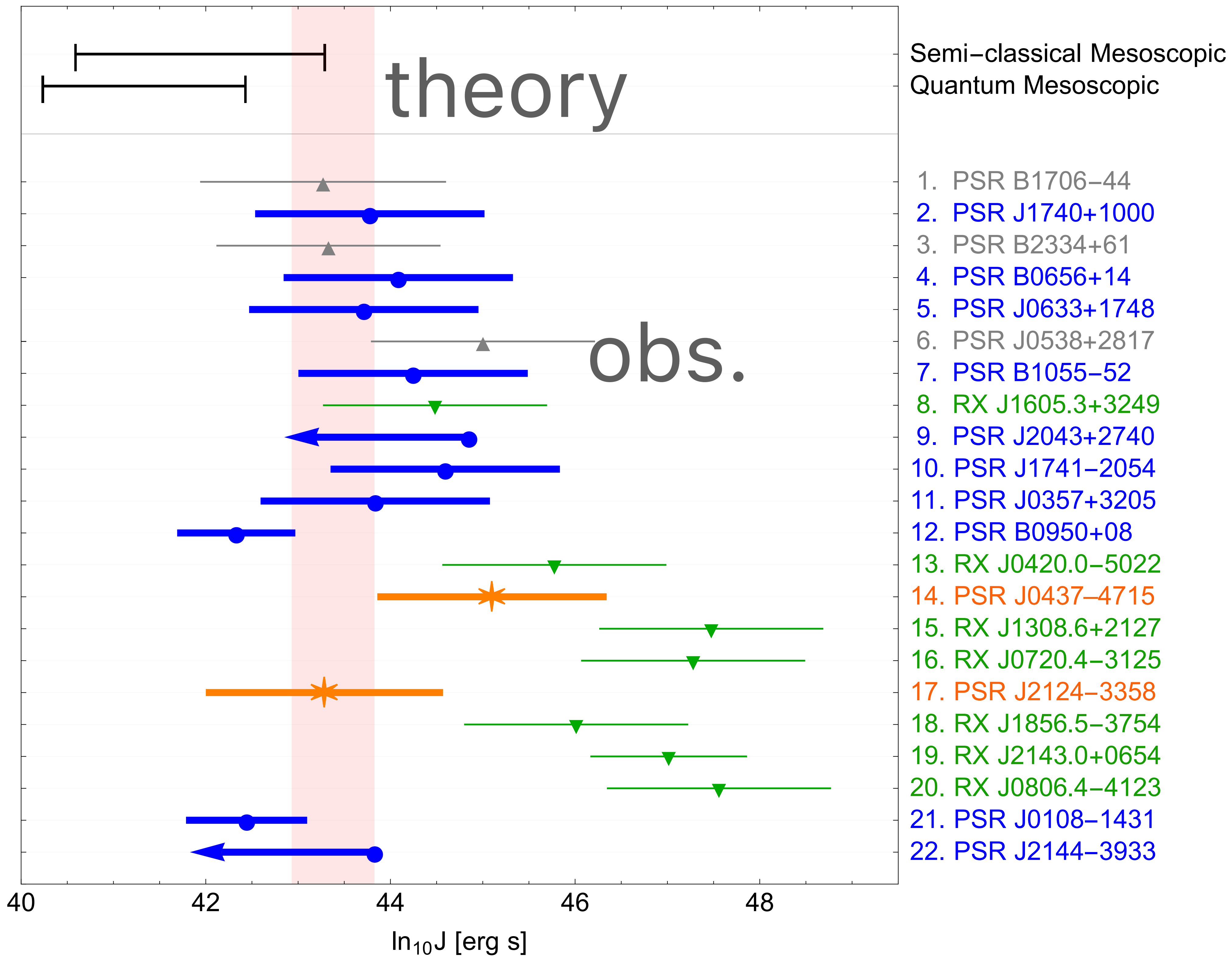
Challenge: Internal Heating

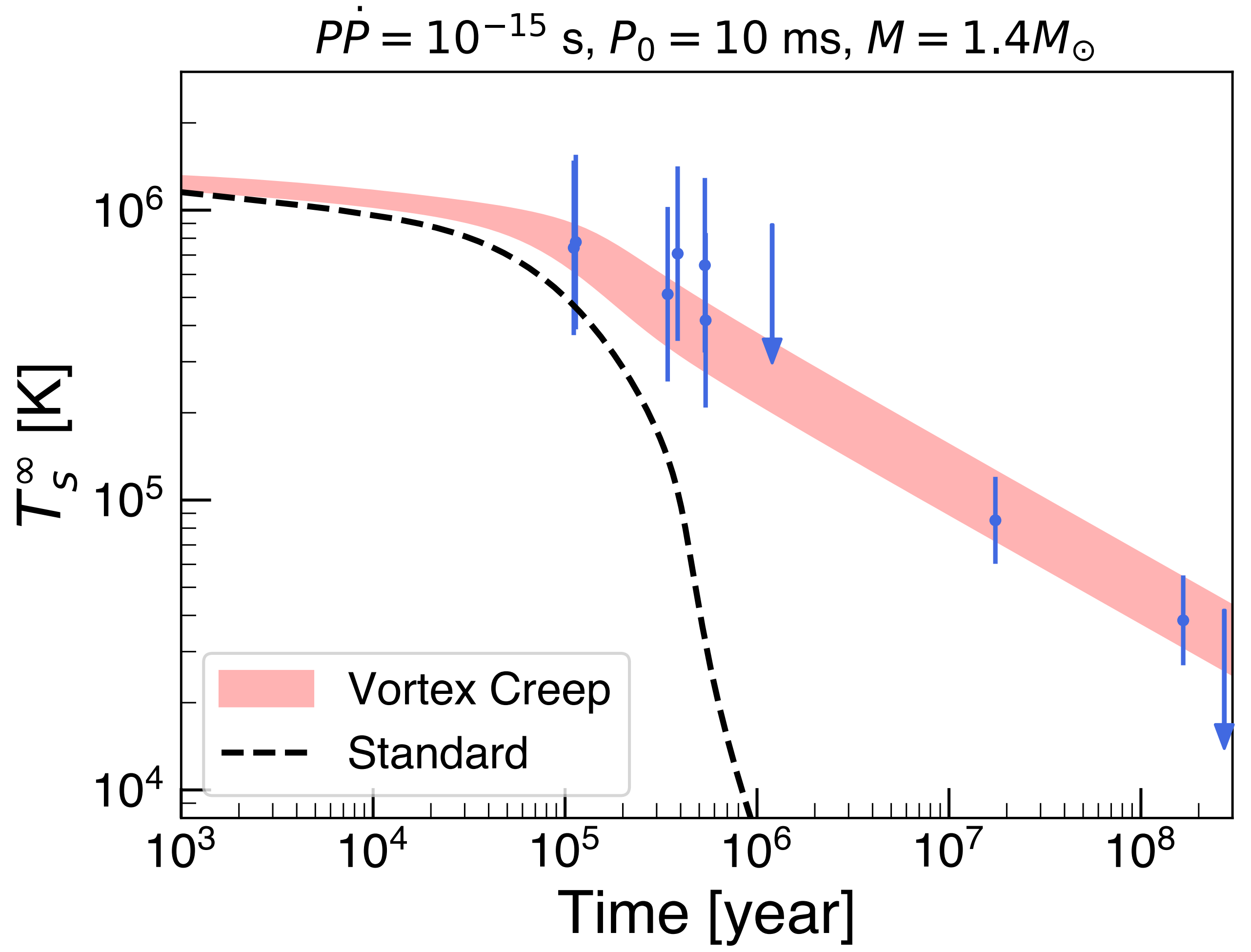
(2) Vortex Creep heating

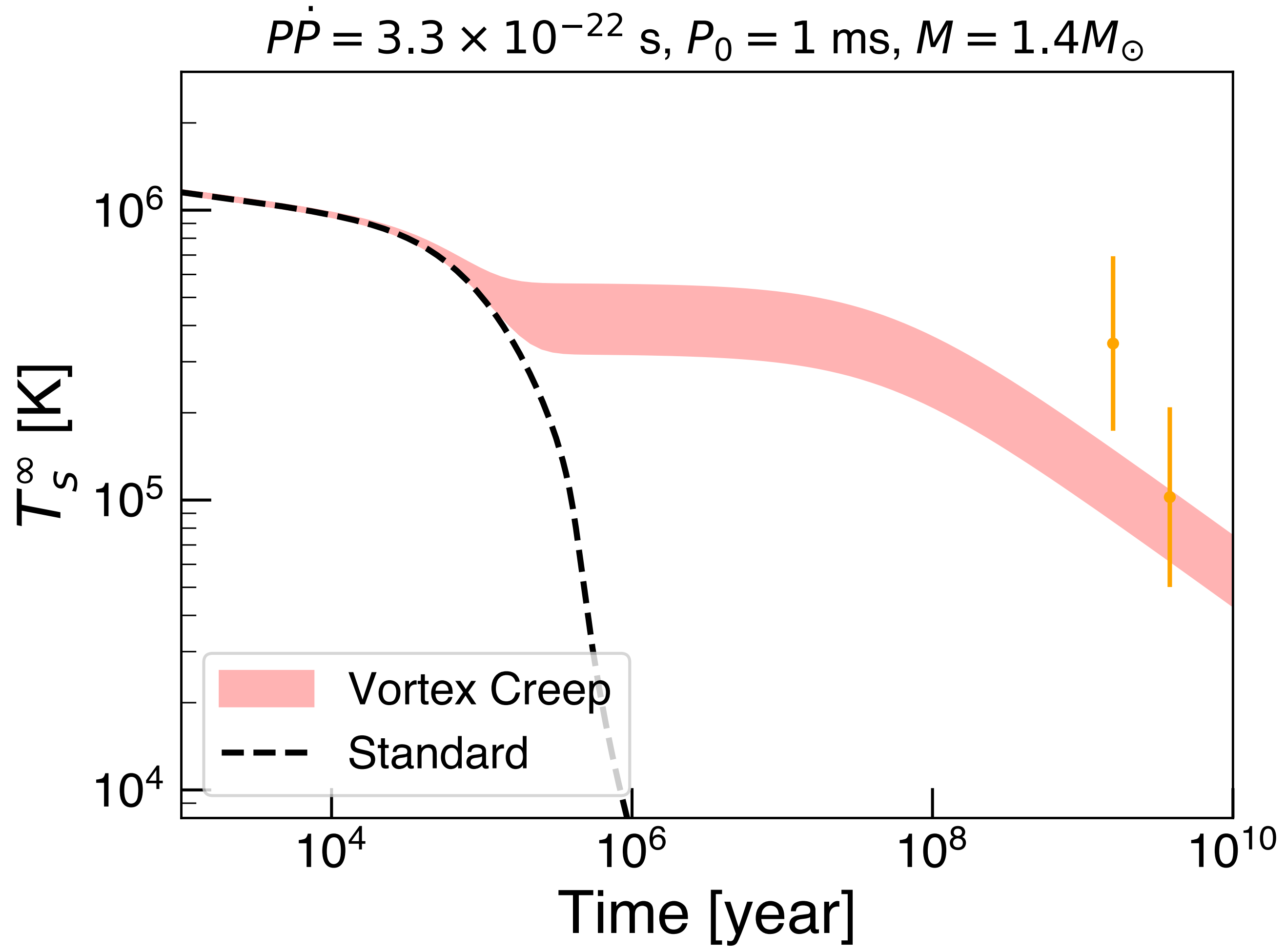
$$C\frac{dT}{dt} = -L_\nu - L_\gamma + L_{\text{vortex creep heating}}$$

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

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







① NS heating by DM

Challenge: 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 $J \sim 10^{43} - 10^{44}\ \mathrm{erg \cdot s}$.

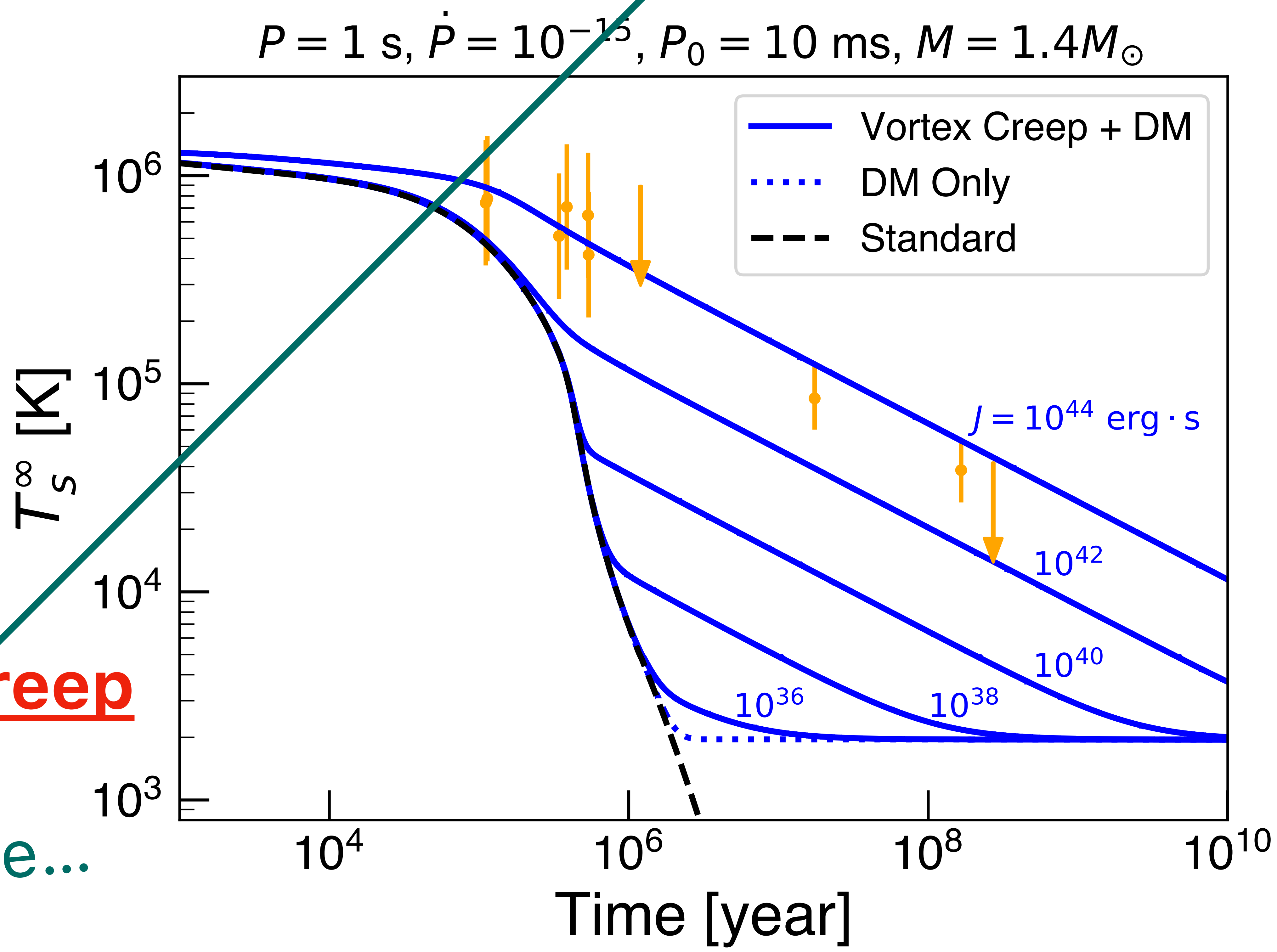
Fujiwara, KH, N. Nagata, Ramirez-Quezada [2308.16066]

(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 $J \lesssim 10^{38}\ \mathrm{erg \cdot s}$.



This may be a serious challenge...

① NS heating by DM

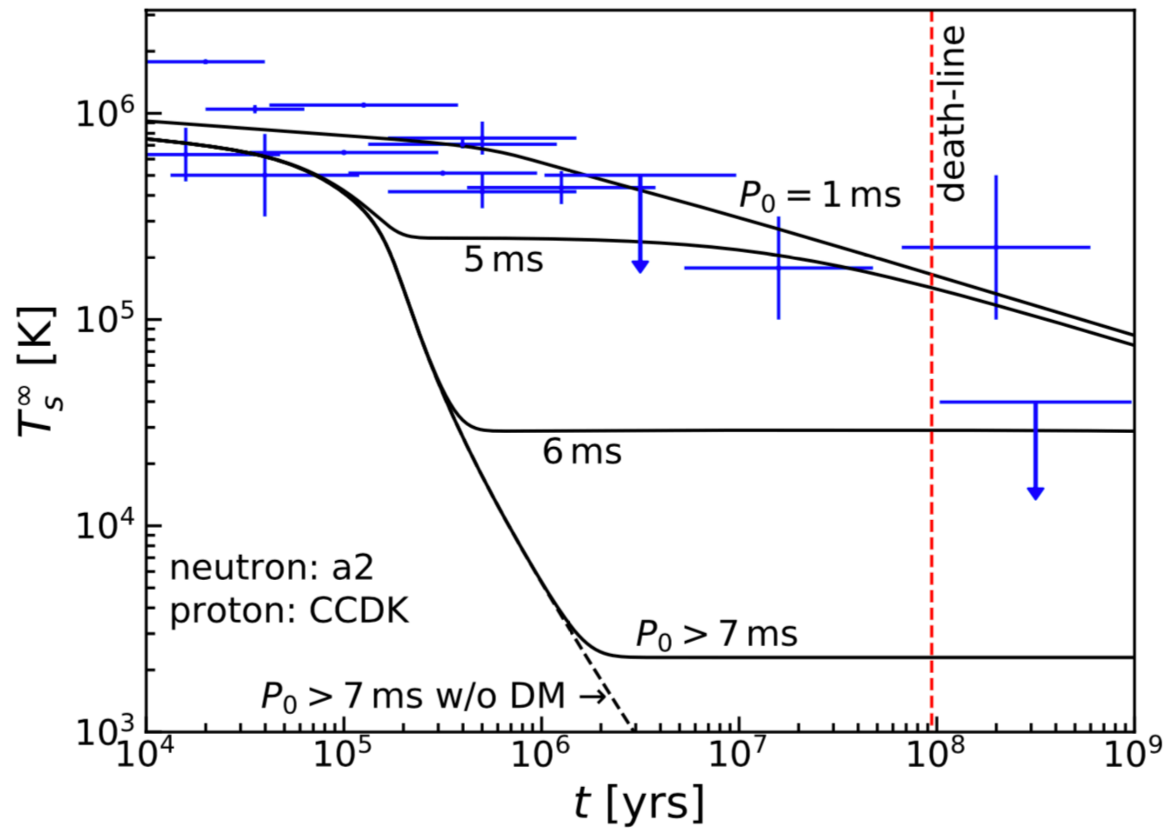
Challenge: Internal Heating

$$C\frac{dT}{dt} \simeq -L_\gamma + L_{\text{DM heating}} + \underline{L_{\text{internal heating}}}$$

(1) Rotochemical heating vs DM heating

KH, N. Nagata, K. Yanagi

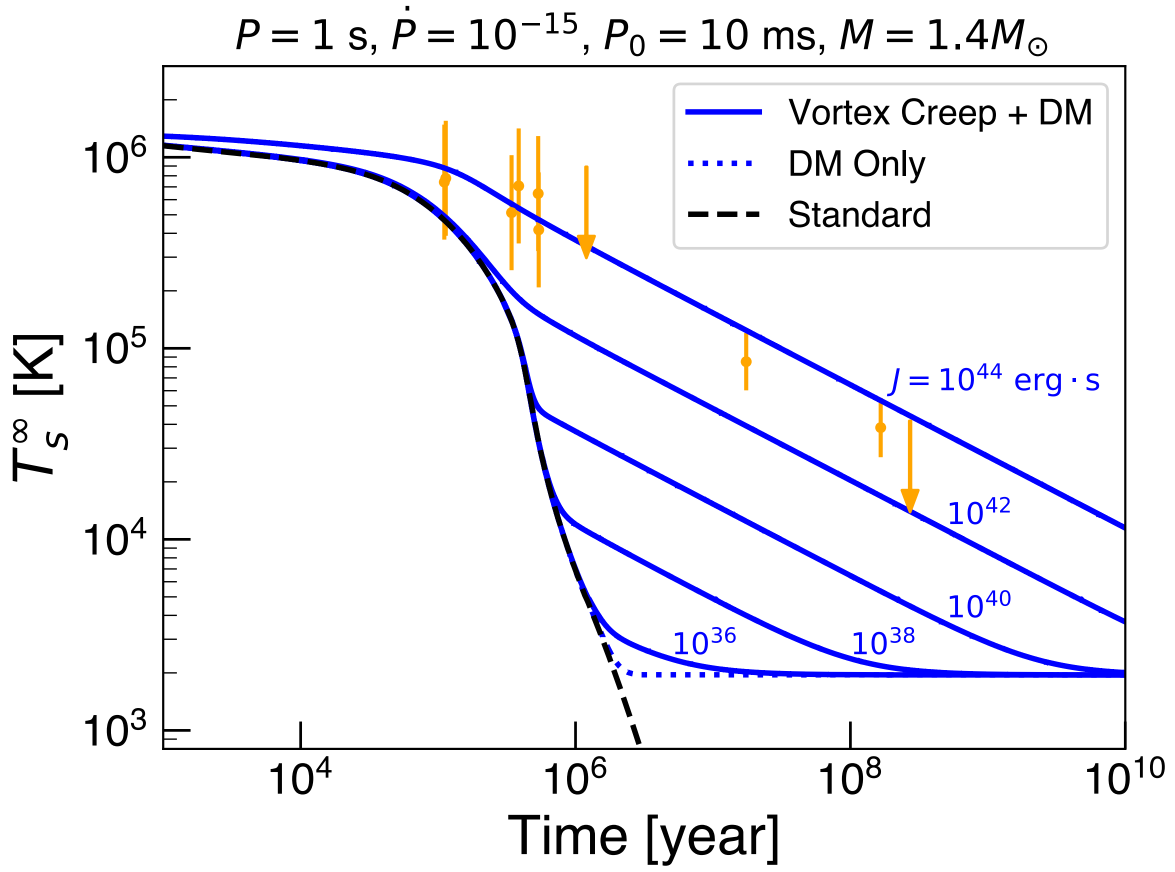
[1904.04667] +[1905.02991]



(2) Vortex Creep heating vs DM heating

M. Fujiwara, KH, N. Nagata, M. Ramirez-Quezada

[2308.16066] + [2309.02633]



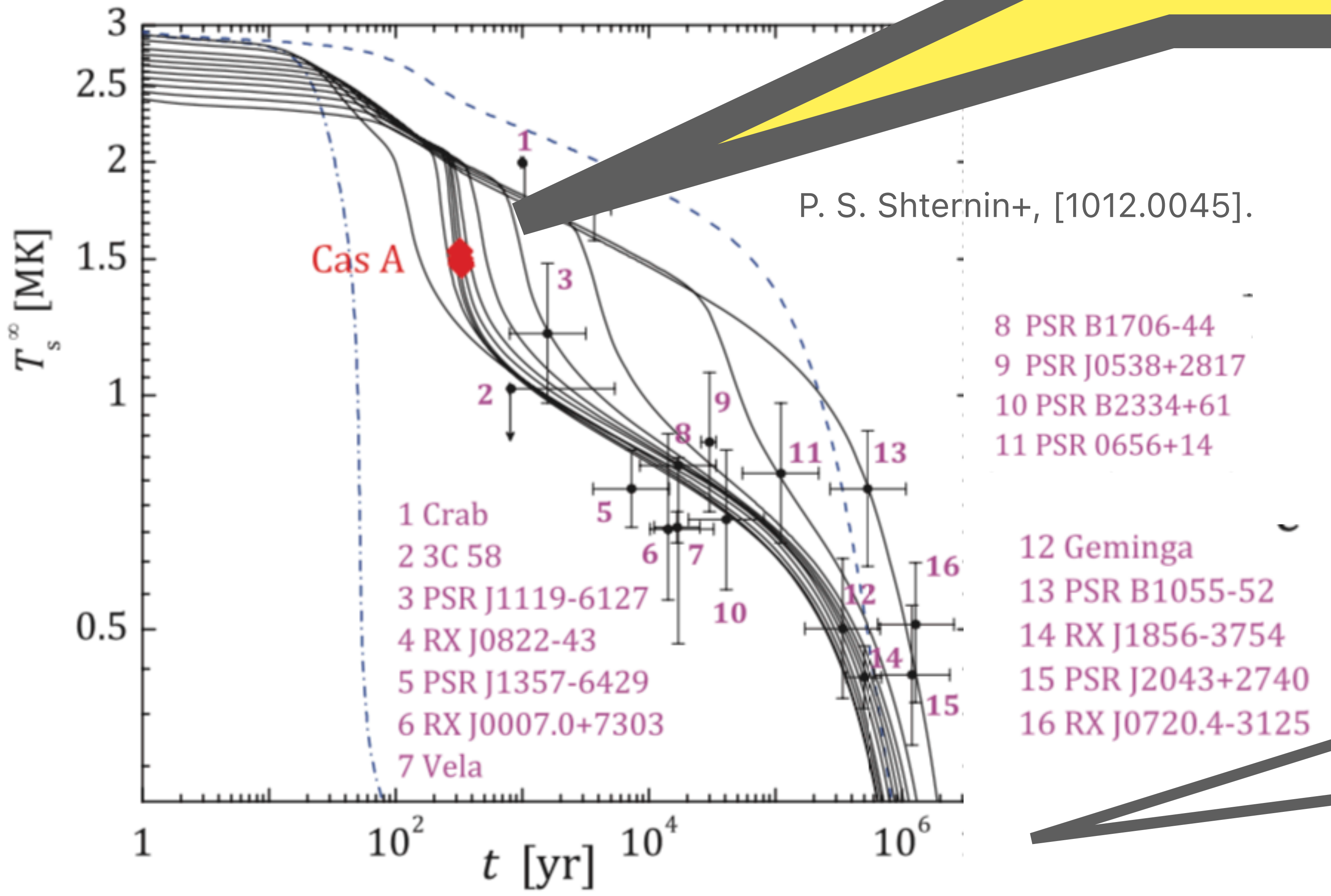
DM signal may be masked depending on the scenario and parameters.

→ Further studies of NSs, both theoretical and observational, are crucial for verification.

This talk

$$C\frac{dT}{dt} = -L_\nu - L_\gamma \pm L_{\text{new physics}}$$

Surface Temperature



P. S. Shternin+, [1012.0045].

② **NS cooling by Axion**

① **NS heating by Dark Matter**

Age

② NS cooling by axion

KH, Nagata, Yanagi, Zheng, [1806.07151]

Axion

- A hypothetical particle, introduced to solve the **strong CP problem in QCD.**
- Nambu-Goldstone boson.
- Very light: $m_a \ll 1\ \mathrm{eV}$.
- Very weak interaction with Standard Model particles.

interaction $\propto \frac{1}{f_a}, \quad f_a \gtrsim 10^8\ \mathrm{GeV}$.

$$\mathcal{L}_{\rm SM} \ni \frac{\alpha_s}{8\pi}\theta\, G^a_{\mu\nu}\widetilde{G}^{a\mu\nu} - \sum_q m_q \bar{q}\,\theta_q\, i\gamma_5 q$$

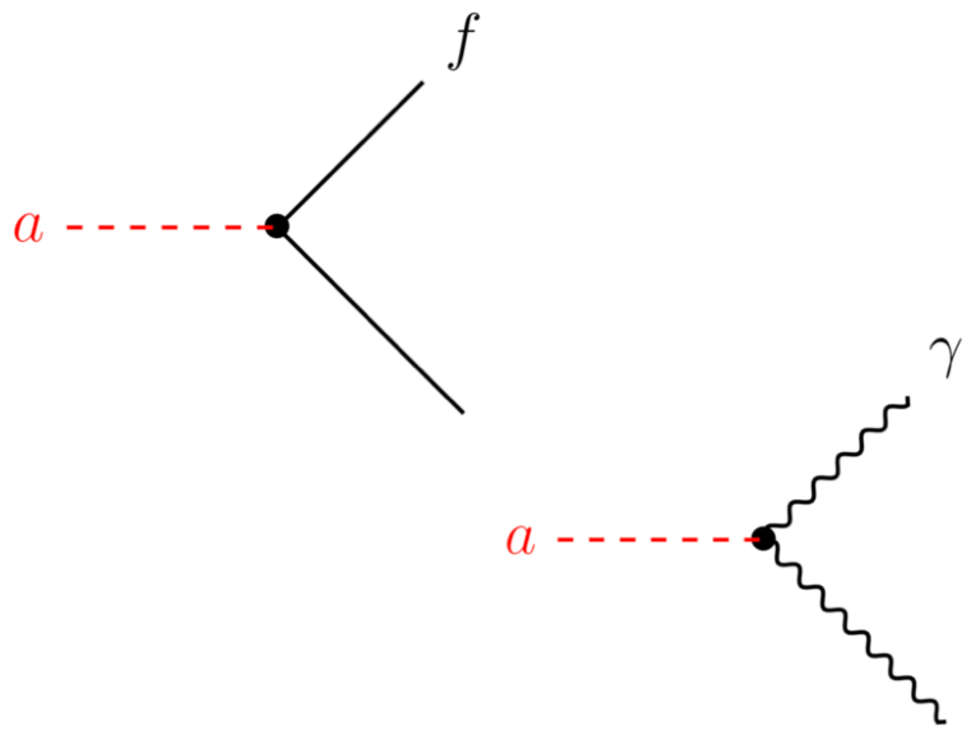
Experimental constraint (neutron EDM)

$$|\bar{\theta}| \lesssim 10^{-10} \qquad \left(\bar{\theta} = \theta + \sum_q \theta_q\right)$$

Why?

$$\mathcal{L}_{\rm int} = \frac{\alpha_s}{8\pi}\frac{a}{f_a}\underbrace{G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}}_{\text{gluon}} + \frac{1}{4}\frac{C_{a\gamma\gamma}}{f_a}a\underbrace{F_{\mu\nu}\widetilde{F}^{\mu\nu}}_{\text{photon}} + \sum_{\substack{f = \text{quarks,}\\ \text{leptons}}}\frac{1}{2}\frac{C_f}{f_a}\bar{f}\gamma^\mu\gamma_5 f\partial_\mu a\,.$$

$$C_{a\gamma\gamma} = \frac{\alpha}{2\pi}\left(\frac{E}{N} - \frac{2}{3}\frac{4m_d + m_u}{m_u + m_d}\right), \quad \begin{cases} C_q = 0 \quad \text{(KSVZ)} \\ C_{u,c,t} = \cos^2\beta/3, \quad C_{d,s,b} = \sin^2\beta/3 \quad \text{(DFSZ)} \end{cases}$$



② NS cooling by axion

KH, Nagata, Yanagi, Zheng, [1806.07151]

Cas A NS

- At the centre of the Cassiopeia A supernova remnant.
- ∼ 340 yrs old. (A young NS.)
- The only isolated NS whose **cooling has been observed in real time.**

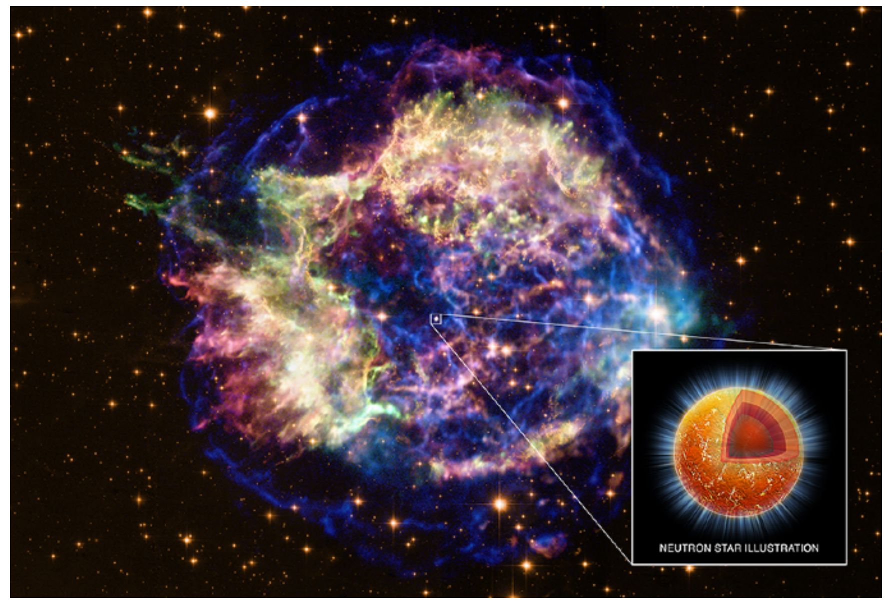


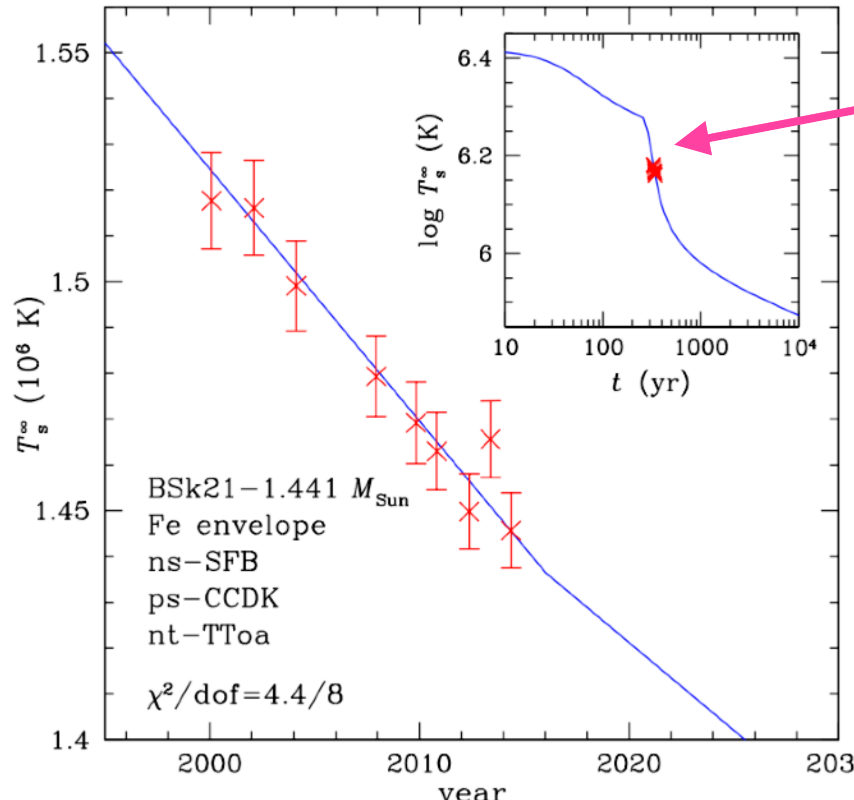
image from Wikipedia

- Temperature decreases by (3-4)% in 10 years.
- This rapid cooling is difficult to explain with M.Urca.
- It can be explained by the PBF process.
- **"Evidence of superfluidity in NS".**

D. Page +, 1011.6142 [Phys.Rev.Lett.].

P. S. Shternin +, 1012.0045 [MNRAS].

See also: Posselt+, 1311.0888, Posselt and G.G.Pavlov, 1808.00531, 2205.06552, W.C.G.Ho+. 1904.07505, Shternin+, 2211.02526.



phase transition $T = T_C$
sudden, rapid cooling by PBF neutrino emission.

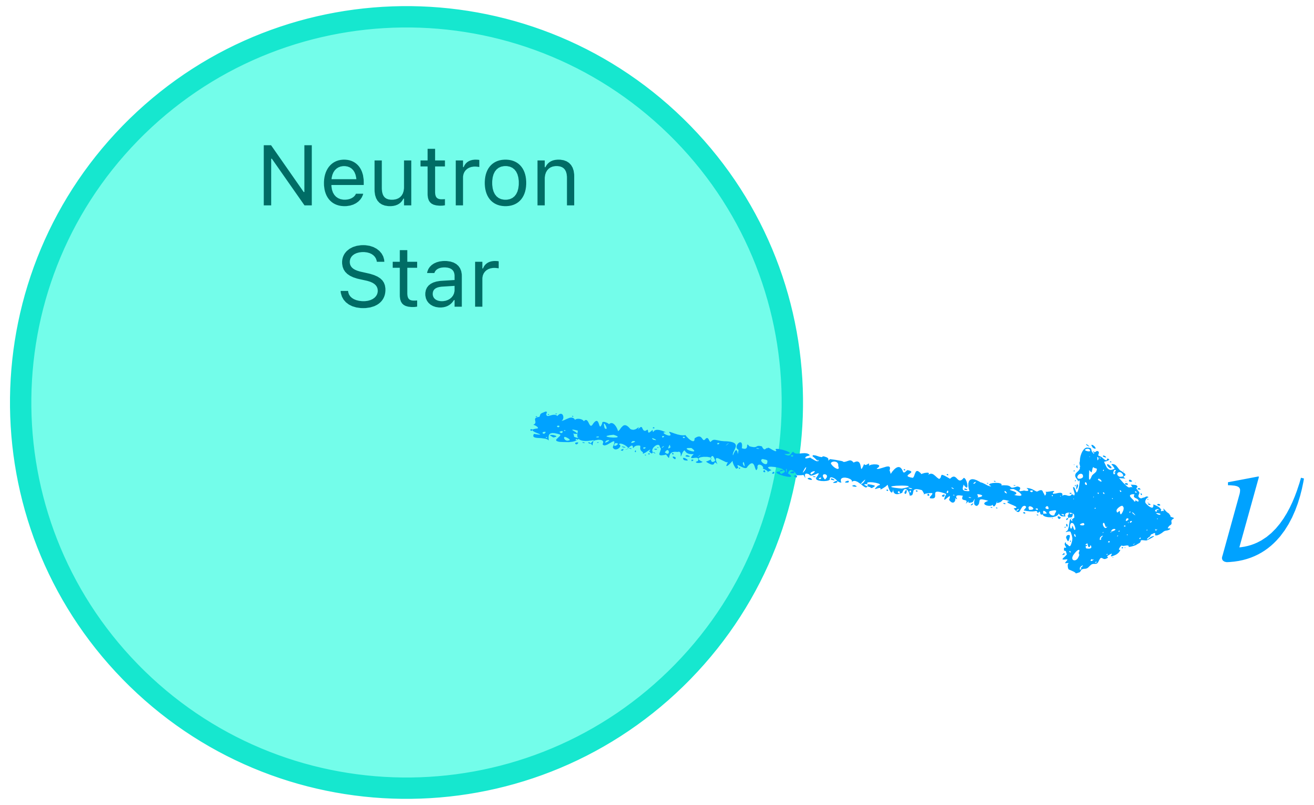
Fig. from W.C.G.Ho+, 1412.7759.

② NS cooling by axion

KH, Nagata, Yanagi, Zheng, [1806.07151]

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

negligible for $\tau \sim 300$ yrs

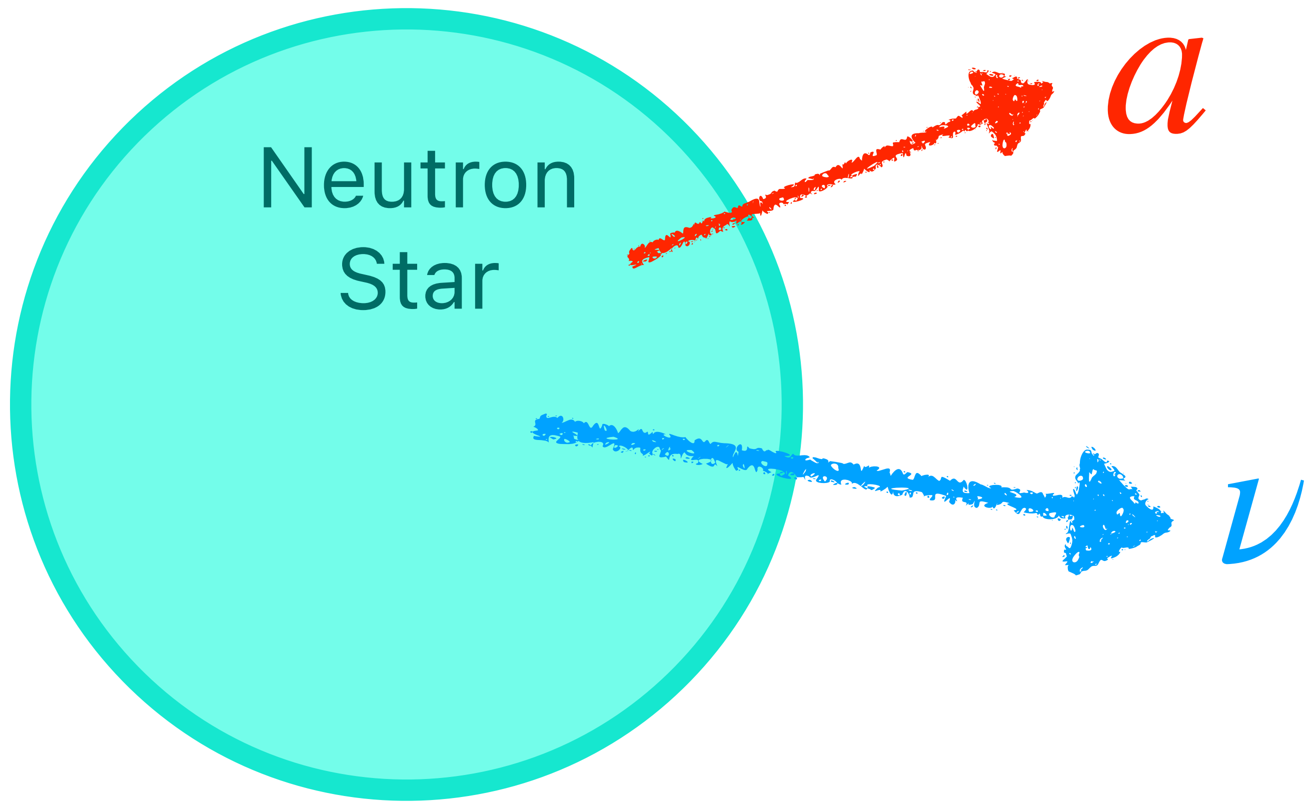


② NS cooling by axion

KH, Nagata, Yanagi, Zheng, [1806.07151]

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

axion emission



What we did:

- followed NS cooling **with axion emission** (Brems. and PBF).
  by modifying a public code NSCool.

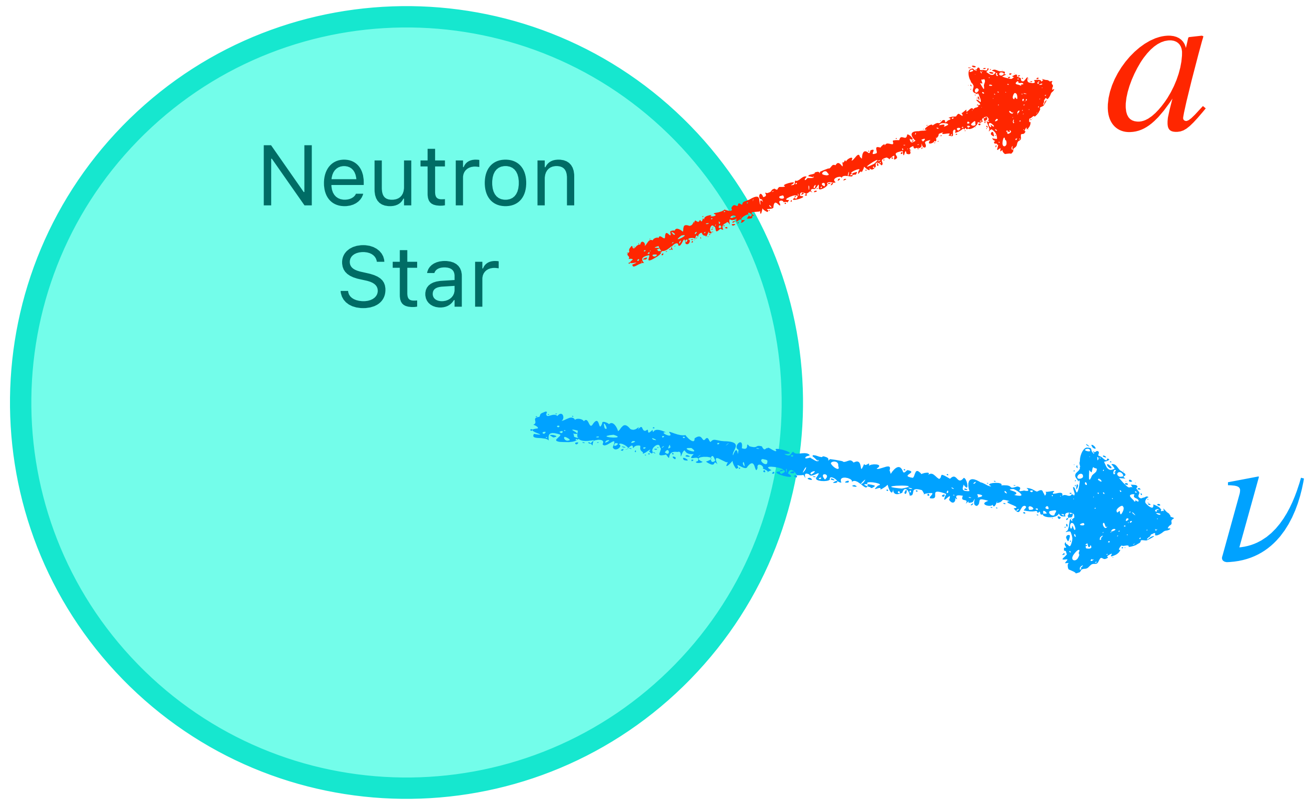
- APR EoS.
- NS mass $M = 1.4M_\odot$
- gap models:
  - n-$^1S_0$ gap: SFB (doesn't matter)
  - p-$^1S_0$ gap: CCDK (doesn't matter as far as large enough)
  - n-$^3P_2$ gap: gap height $\Delta \propto T_c$ and width: free parameter.

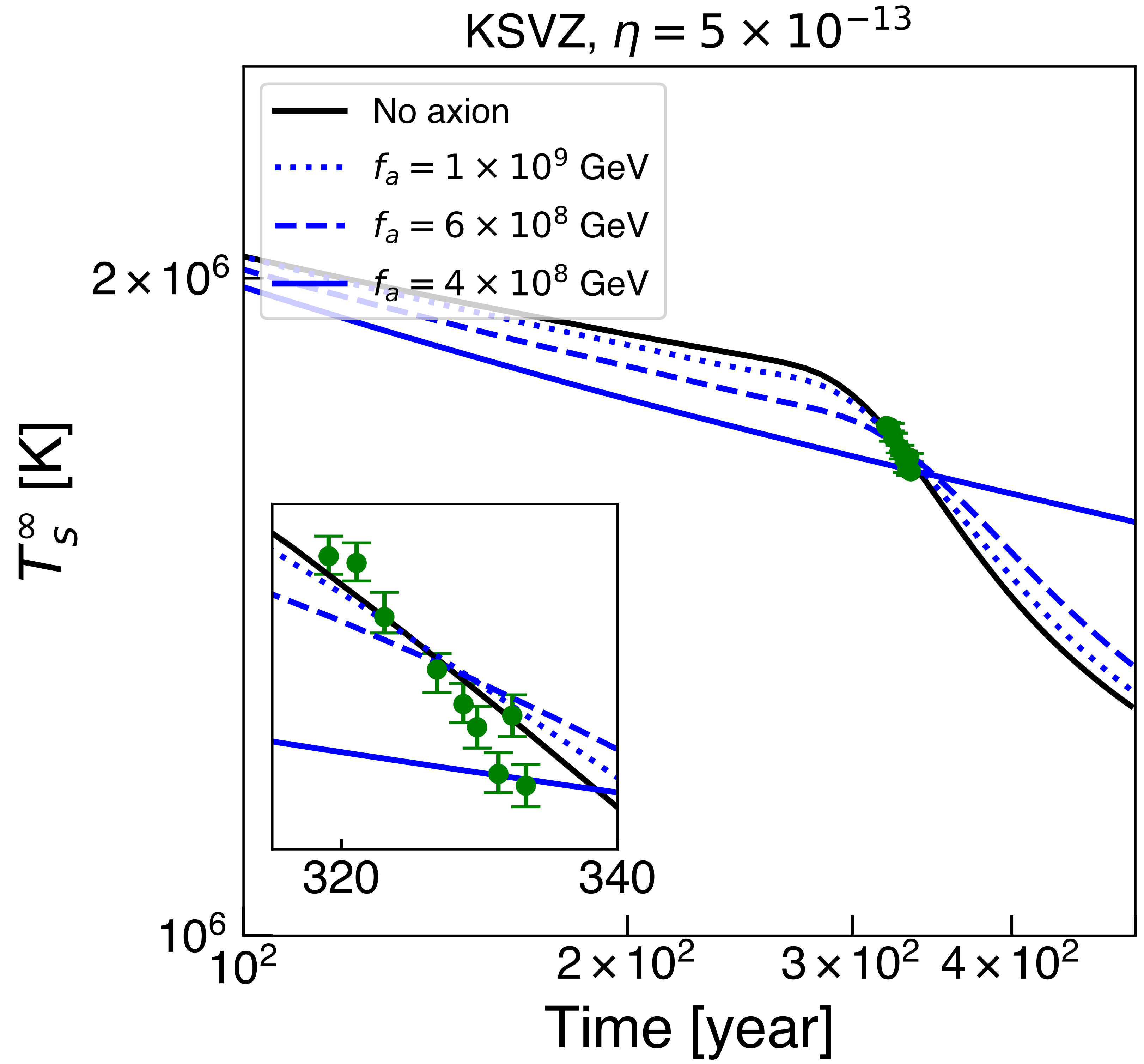
② NS cooling by axion

KH, Nagata, Yanagi, Zheng, [1806.07151]

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

axion emission





A new bound (KSVZ axion):

$$f_a \gtrsim 5 \times 10^8\ \mathrm{GeV}$$

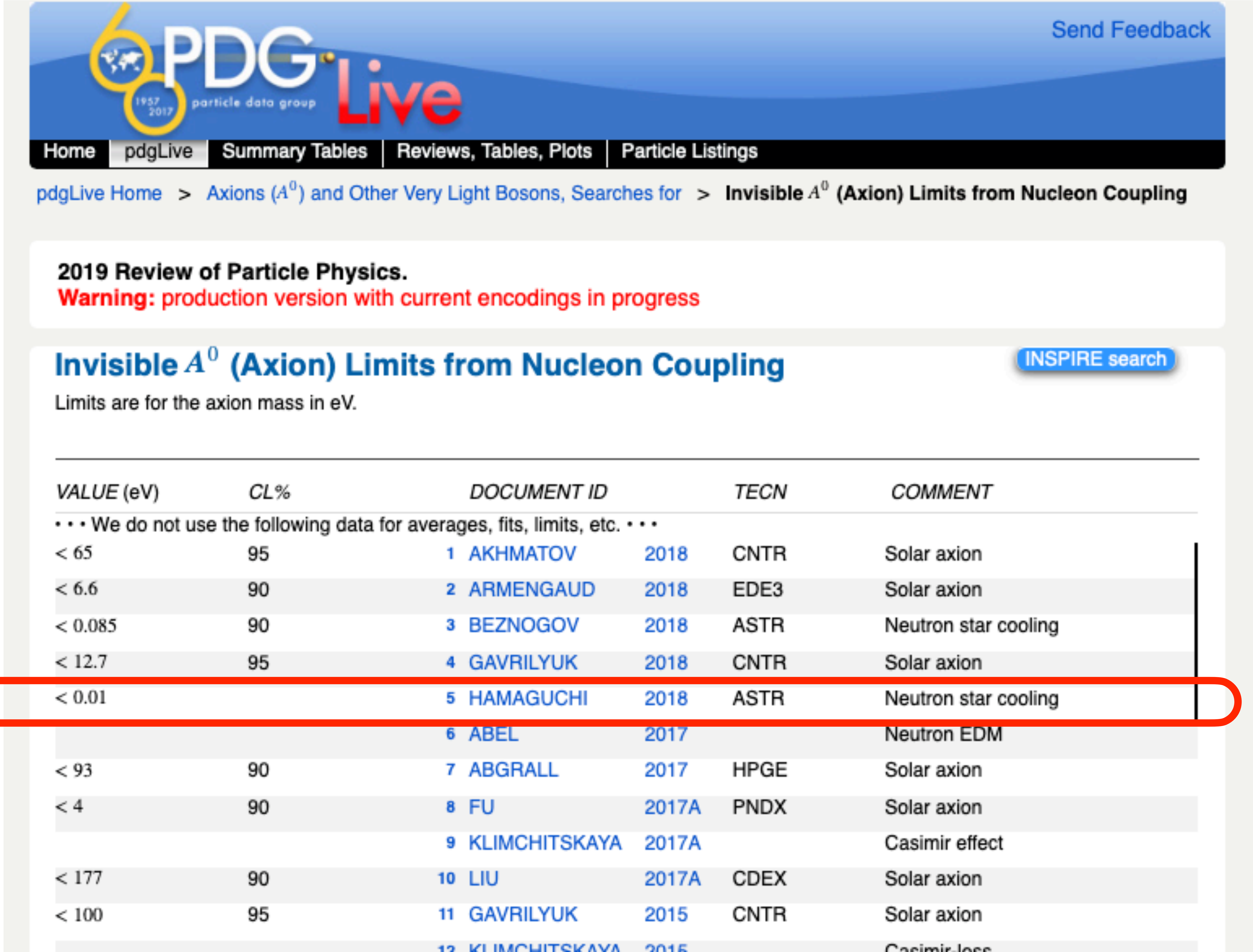
(for an envelope with a thin carbon layer)

cf. SN1987A bound: $f_a \gtrsim 4 \times 10^8\ \mathrm{GeV}$

NS cooling gives one of the strongest constraint on the axion models.

② NS cooling by axion

KH, Nagata, Yanagi, Zheng, [1806.07151]



pdgLive Home > Axions (A^0) and Other Very Light Bosons, Searches for > **Invisible A^0 (Axion) Limits from Nucleon Coupling**

2019 Review of Particle Physics.
Warning: production version with current encodings in progress

Invisible A^0 (Axion) Limits from Nucleon Coupling

Limits are for the axion mass in eV.

VALUE (eV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 65	95	1 AKHMATOV 2018	CNTR	Solar axion
< 6.6	90	2 ARMENGAUD 2018	EDE3	Solar axion
< 0.085	90	3 BEZNOGOV 2018	ASTR	Neutron star cooling
< 12.7	95	4 GAVRILYUK 2018	CNTR	Solar axion
< 0.01		5 HAMAGUCHI 2018	ASTR	Neutron star cooling
		6 ABEL 2017		Neutron EDM
< 93	90	7 ABGRALL 2017	HPGE	Solar axion
< 4	90	8 FU 2017A	PNDX	Solar axion
		9 KLIMCHITSKAYA 2017A		Casimir effect
< 177	90	10 LIU 2017A	CDEX	Solar axion
< 100	95	11 GAVRILYUK 2015	CNTR	Solar axion
		12 KLIMCHITSKAYA 2015		Casimir-less

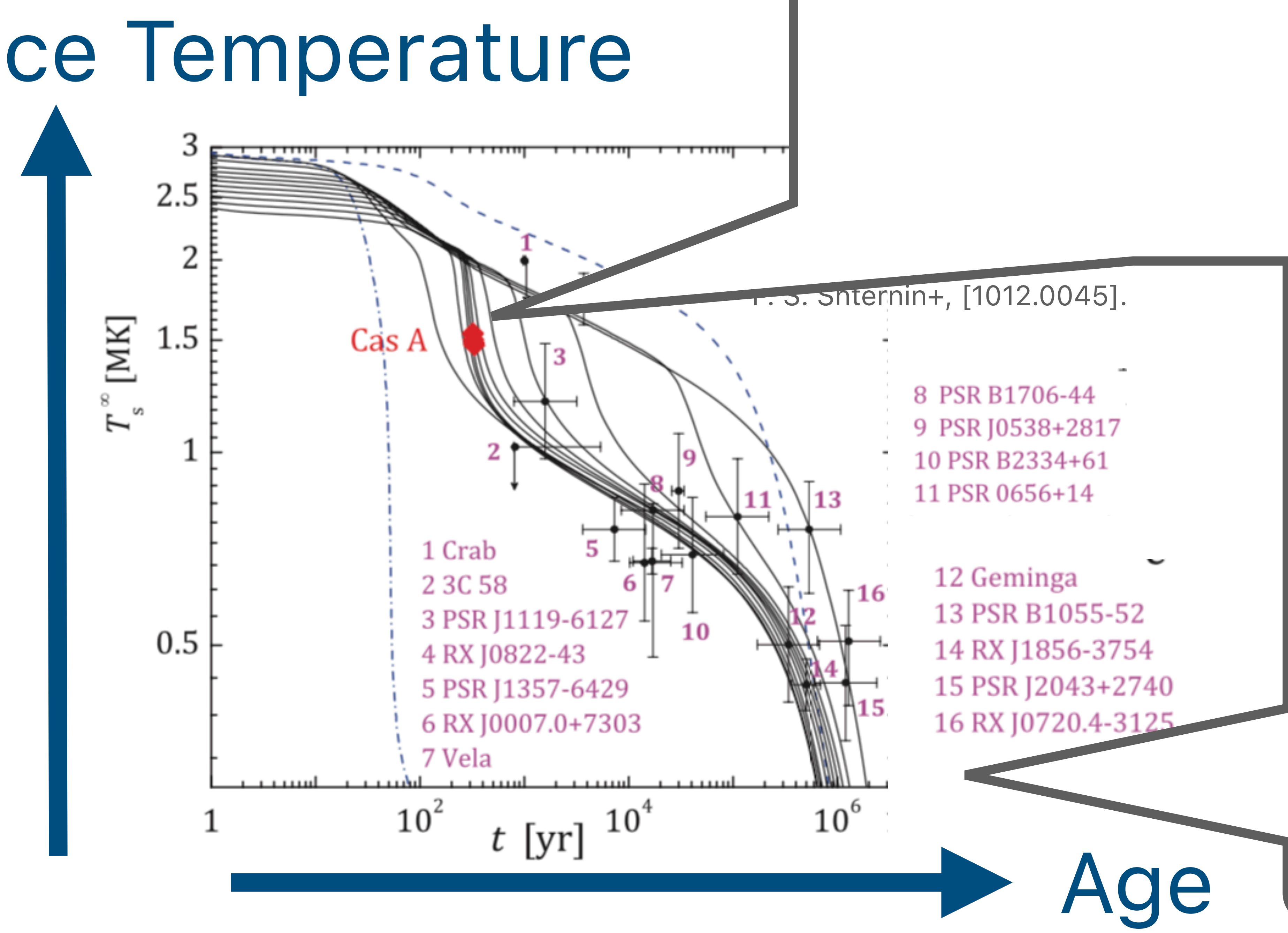
K. Hamaguchi, N. Nagata, K. Yanagi, J. Zheng, 1806.07151

See also:
- M. V. Beznogov+ [1806.07991].
- L. B. Leinson, [1909.03941] [2105.14745].
- Buschmann+, [2111.09892]

+ K. Hamaguchi, N. Nagata, J. Zheng, work in progress

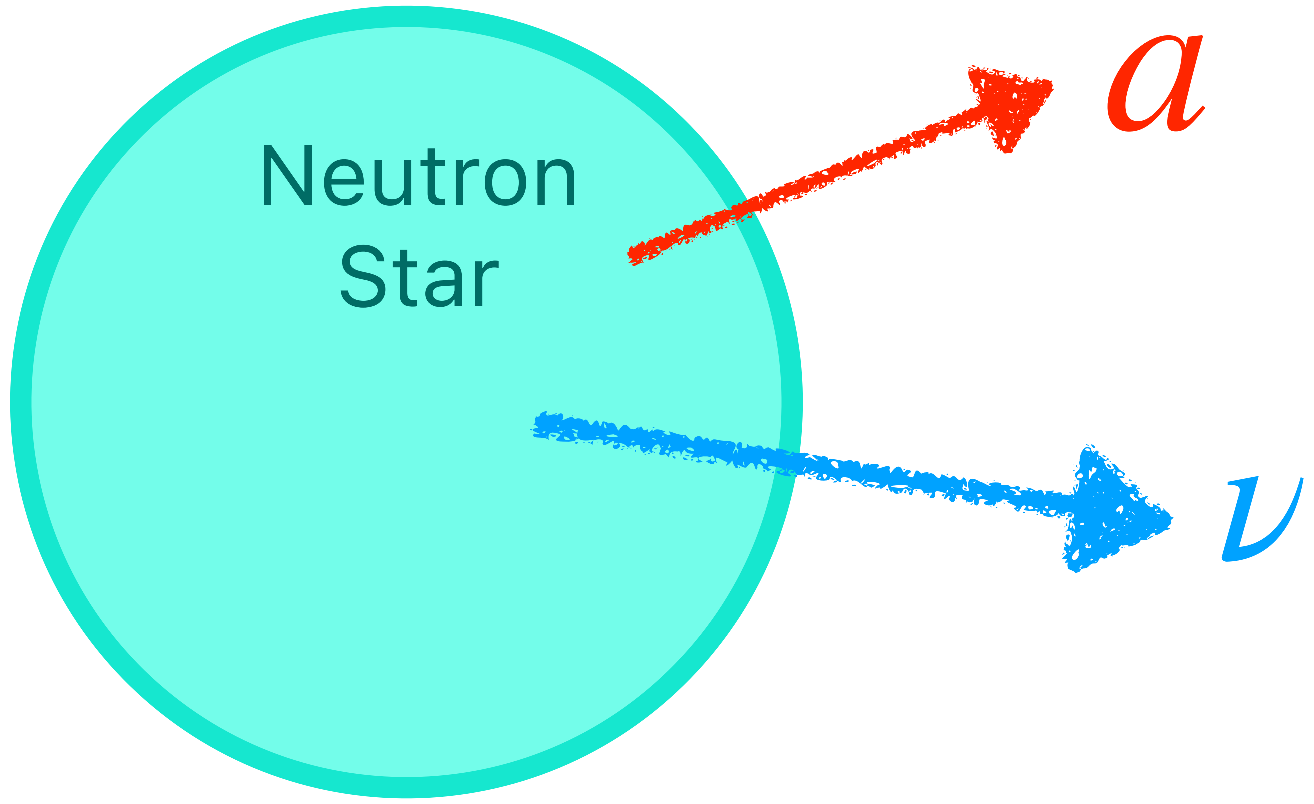
Summary

$$C\frac{dT}{dt} = -L_\nu - L_\gamma \pm L_{\text{new physics}}$$

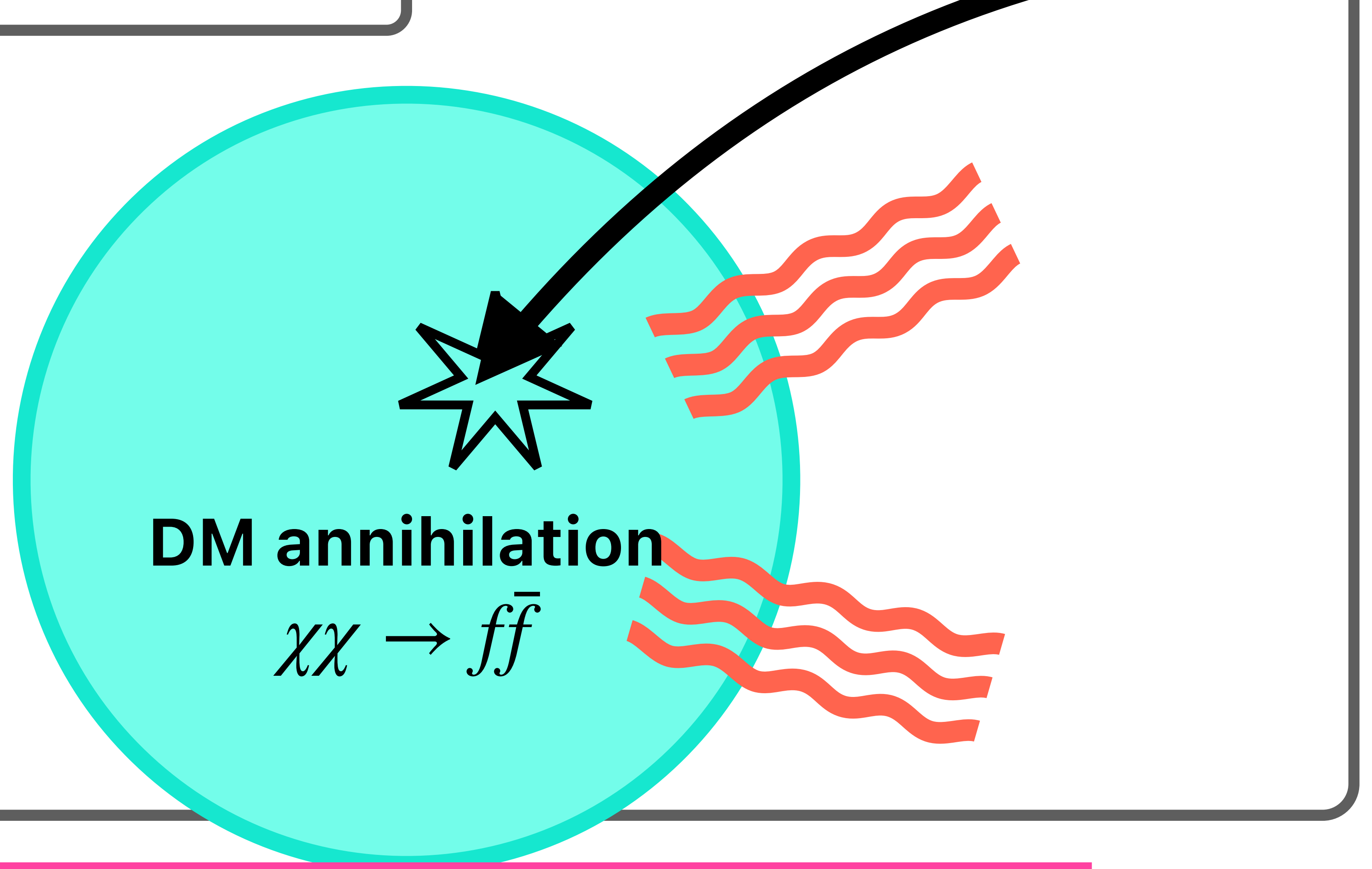


S. Shternin+, [1012.0045].

② NS cooling by **Axion**



① NS heating by **Dark Matter**



NS temperature observation may probe New Physics!

Backup slides

Old NS and DM

observational feasibility

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

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

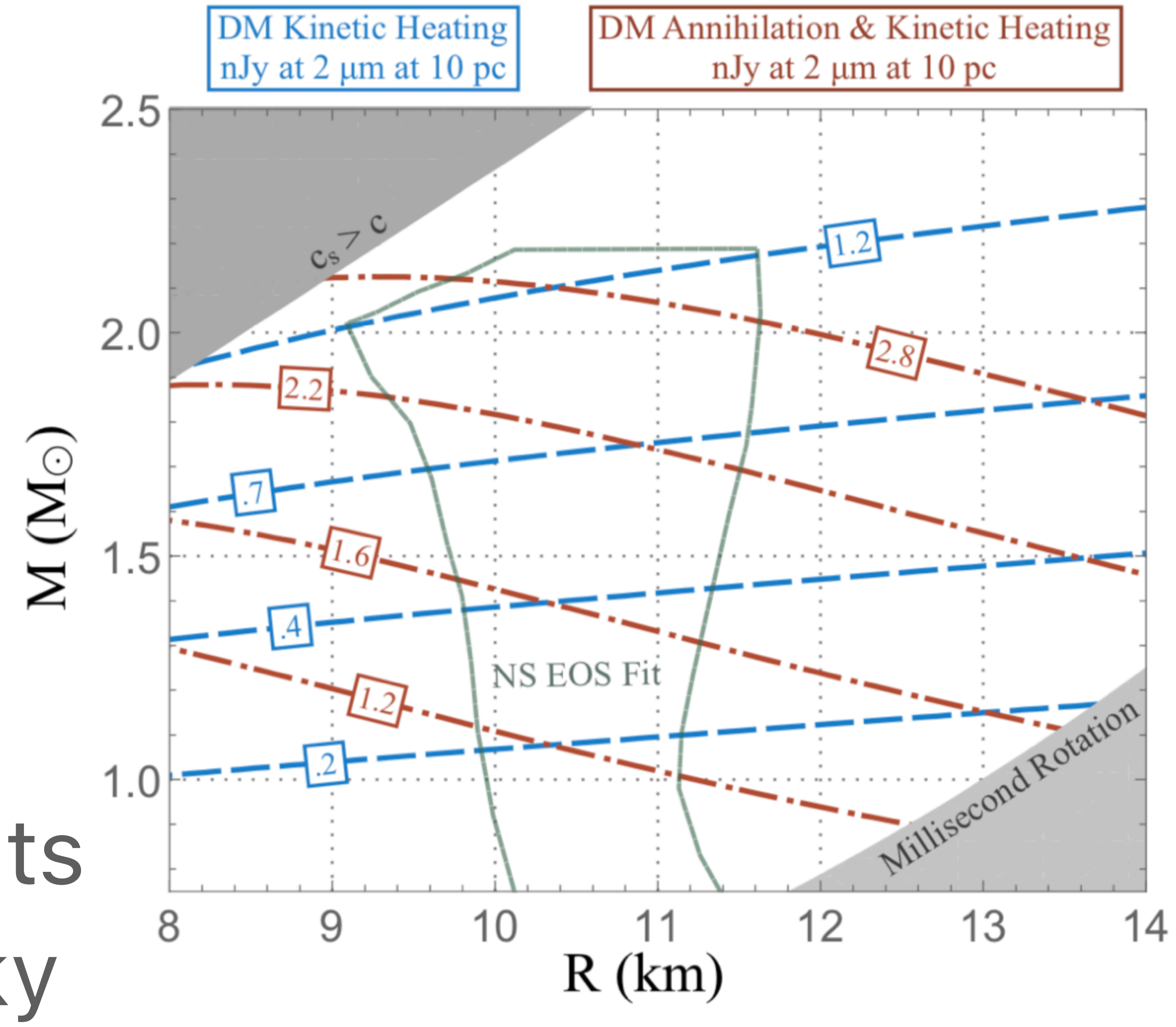
Nirmal Raj,[1,*] Prajwal Shivanna,[1,†] and Rachh Gaurav Niraj[1,‡]
[1] *Centre for High Energy Physics, Indian Institute of Science, C. V. Raman Avenue, Bengaluru 560012, India*

(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 distance from Earth, and find that potentially 30–40 of these may be inspected for late-stage

observational feasibility

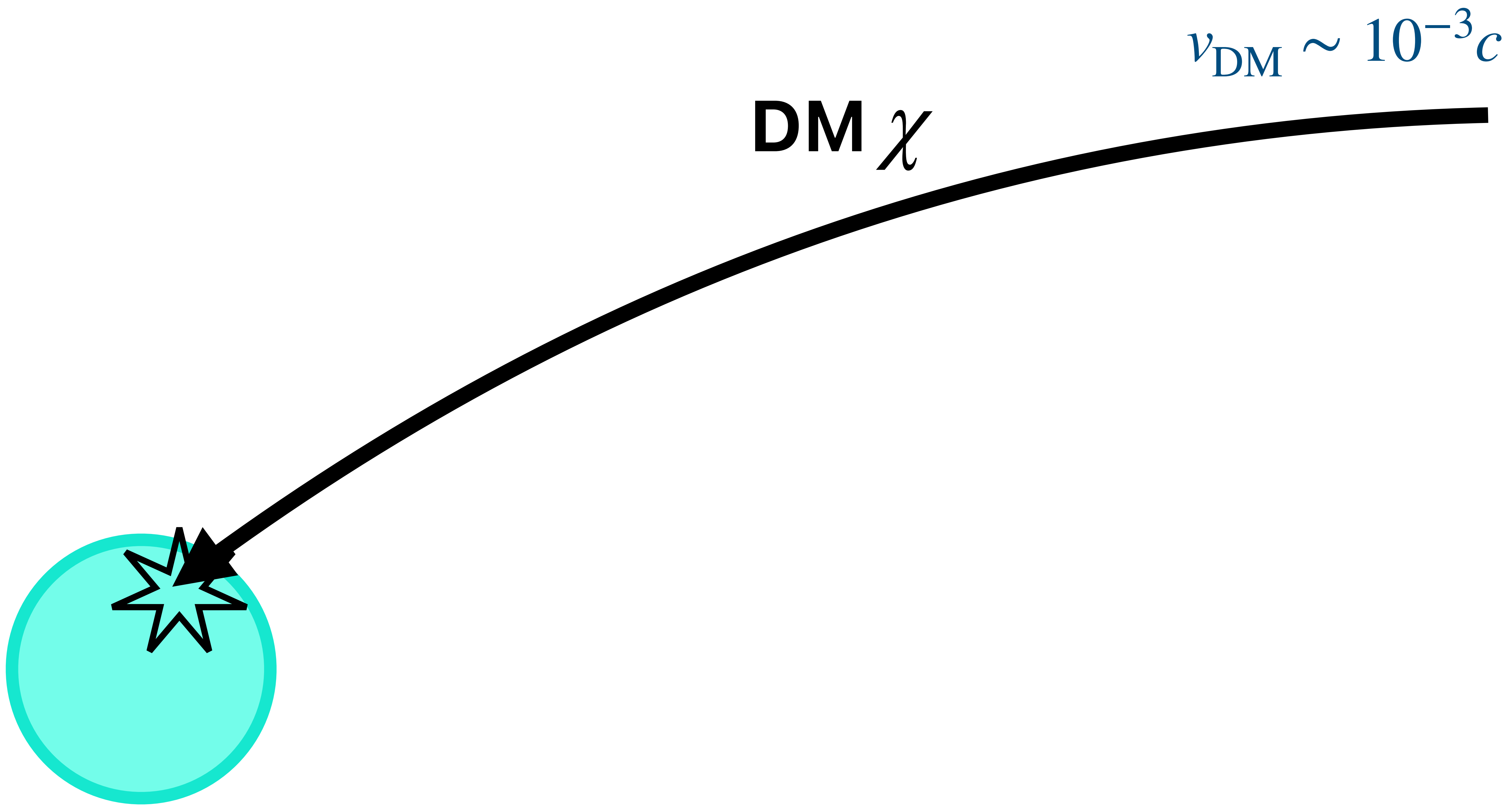
- See e.g., the discussion in M.Baryakhtar+, 1704.01577.
- O(1) old and cold NSs can be at $d = 10\text{pc}$.
- Radiation from a DM-heated NS there results in a spectral flux density of O(1) nanoJansky (nJy) at wavelength $\nu^{-1} = \mathcal{O}(1)\ \mu\text{m}$.
- Maybe within the sensitivity of the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



M.Baryakhtar+, 1704.01577

① NS heating by DM

Back-of-envelope estimates



① NS heating by DM

Back-of-envelope estimates

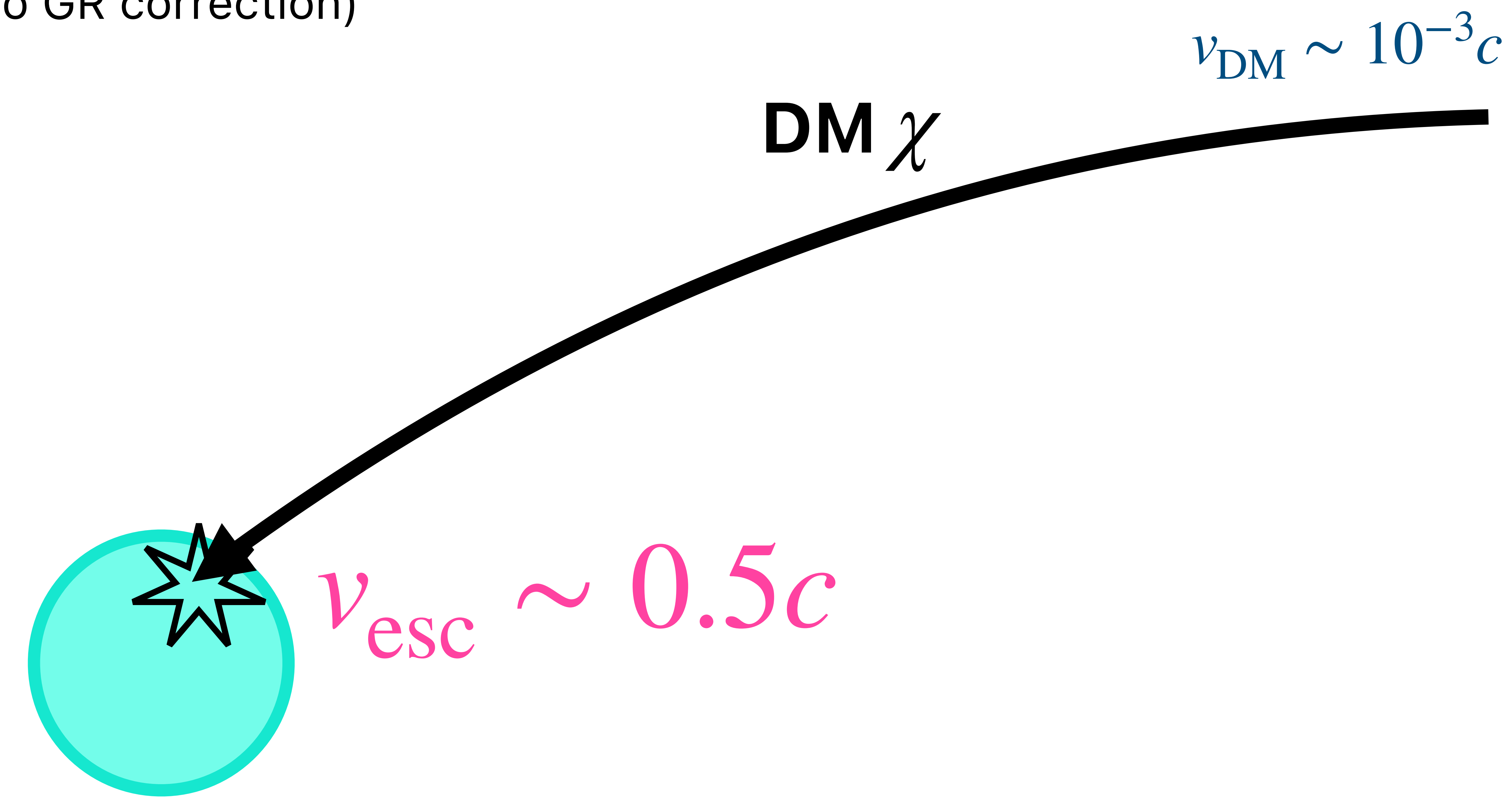
(1) DM velocity at the surface: $v_{\rm esc} \sim 0.5c$ (up to GR correction)

- 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!

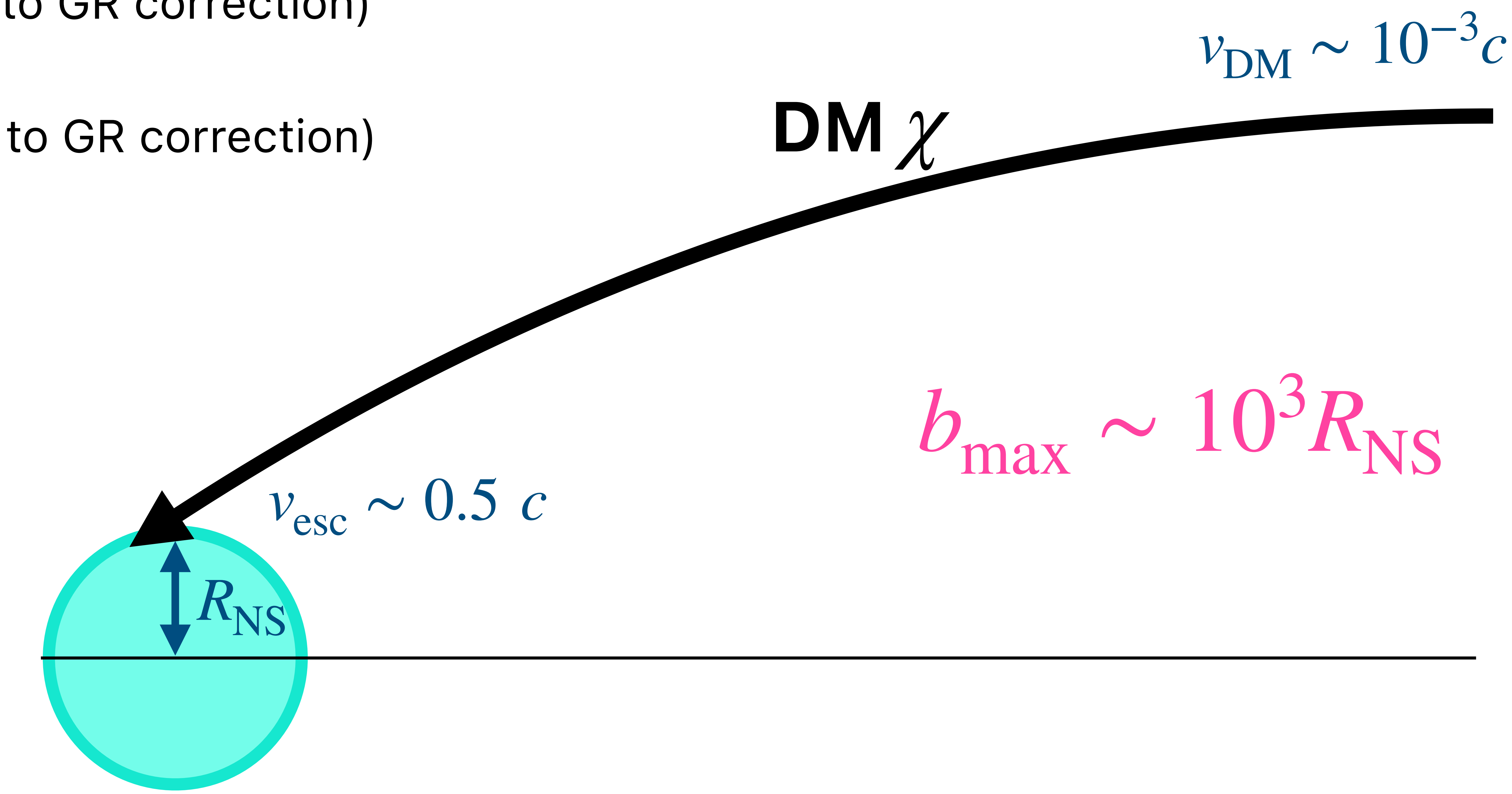


① NS heating by DM

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,

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

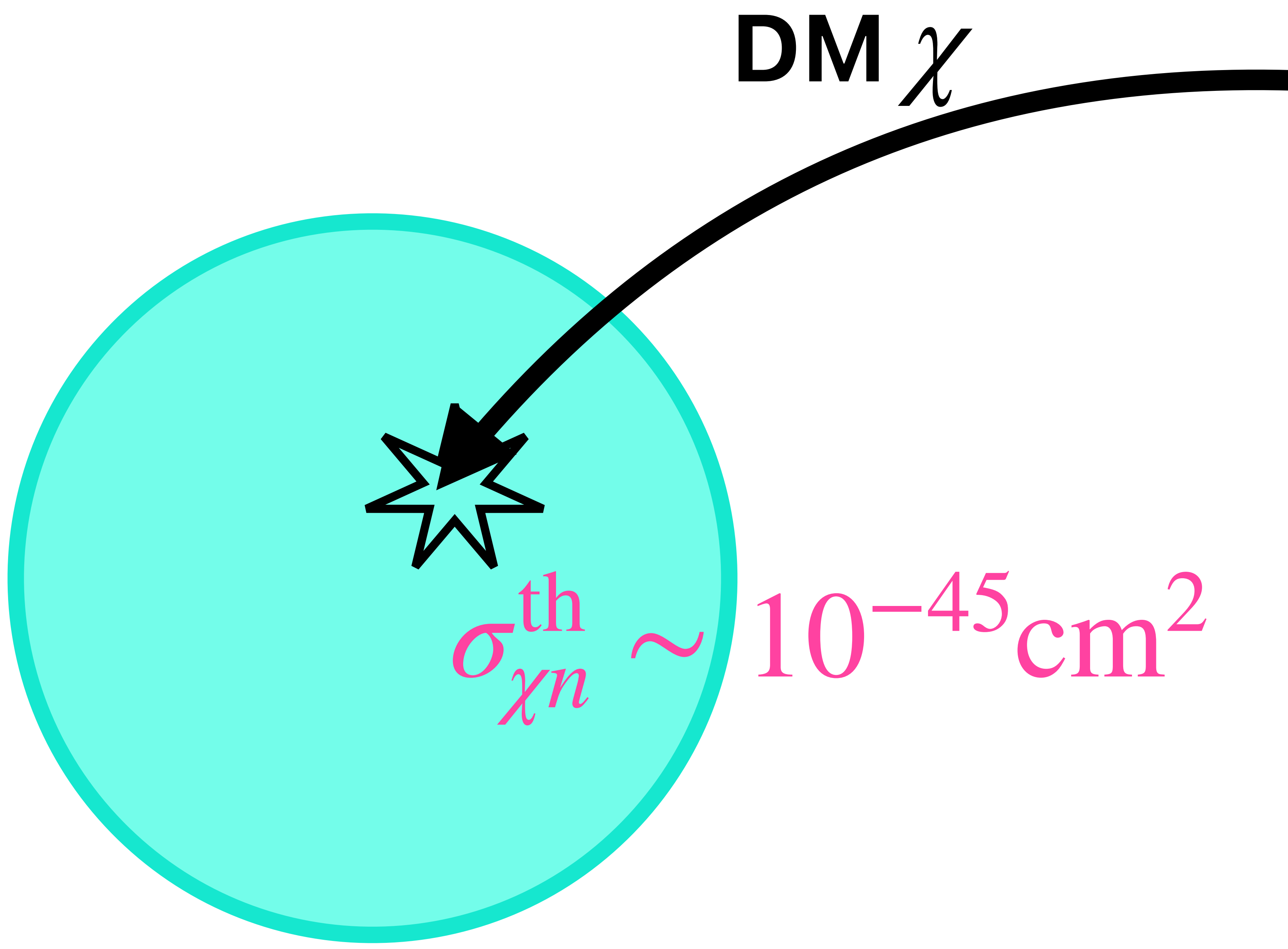
$$\therefore\quad b_{\rm max} \sim \frac{v_{\rm esc}}{v_{\rm DM}} R_{\rm NS} \sim 10^3\ R_{\rm NS}$$

up to O(1) GR correction.

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

① NS heating by DM

Back-of-envelope estimates



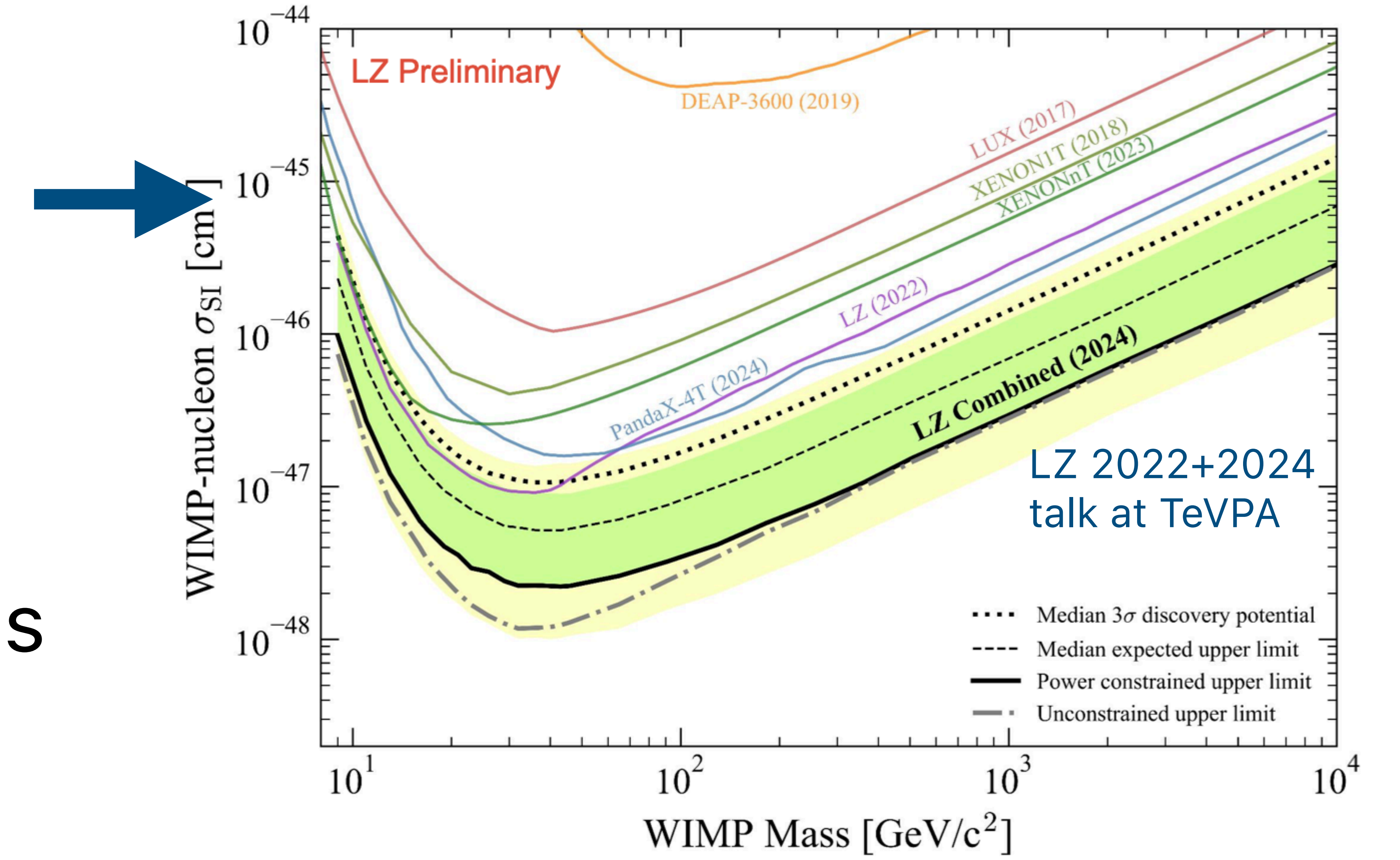
(1) DM velocity at the surface: $v_{\rm esc} \sim 0.5c$ (up to GR correction)

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

(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 $L \lesssim R_{\rm NS}$.

It is weaker than the current direct detection sensitivities, but there are still some advantages and complementarity 👉 more on this later.



LZ 2022+2024
talk at TeVPA

① NS heating by DM

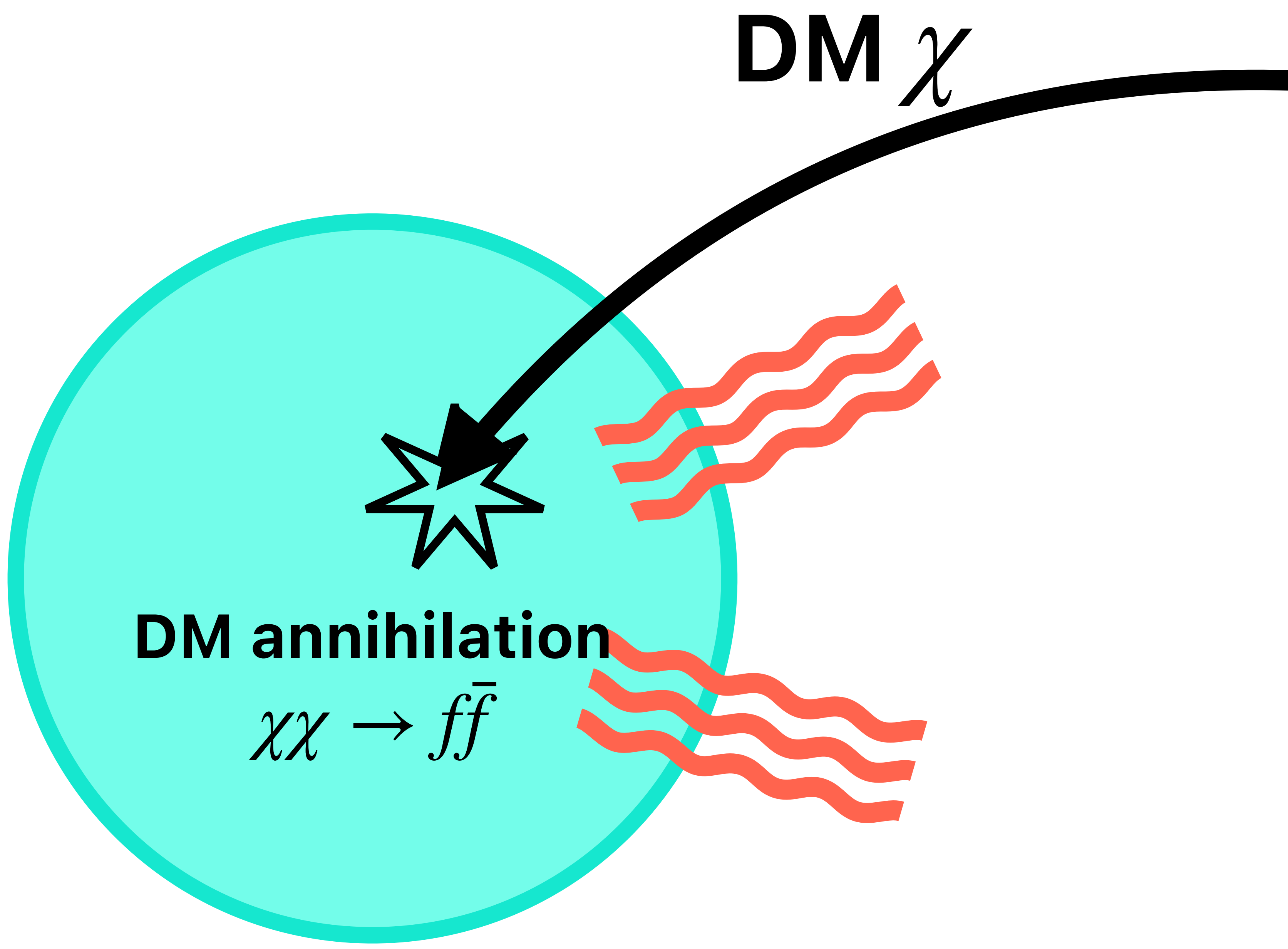
Back-of-envelope estimates

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

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

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

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



$T \sim$ (a few) 1000 K

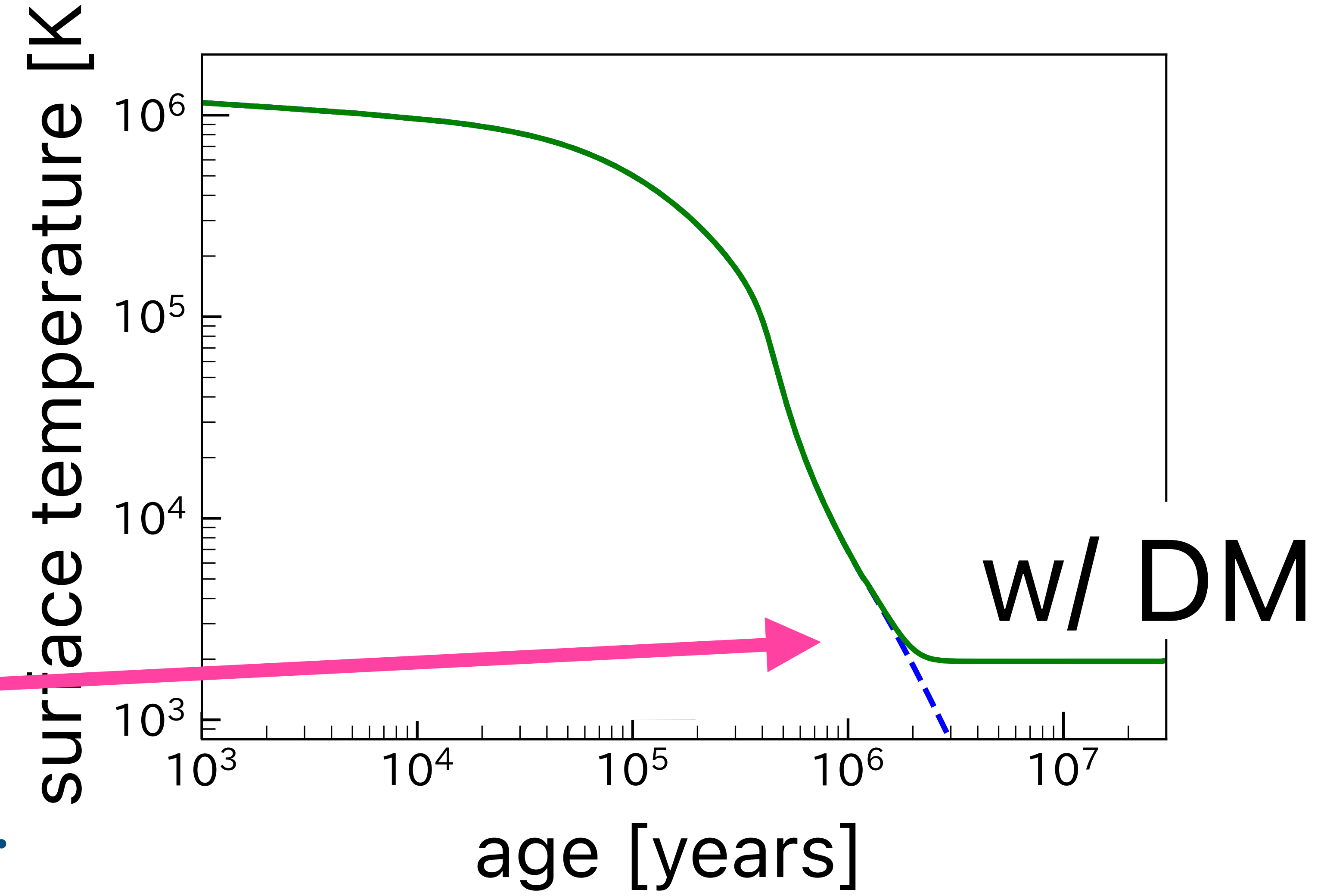
- The energy injection per time is estimated as

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

… independent of the DM mass!

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

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



① NS heating by DM

Back-of-envelope estimates

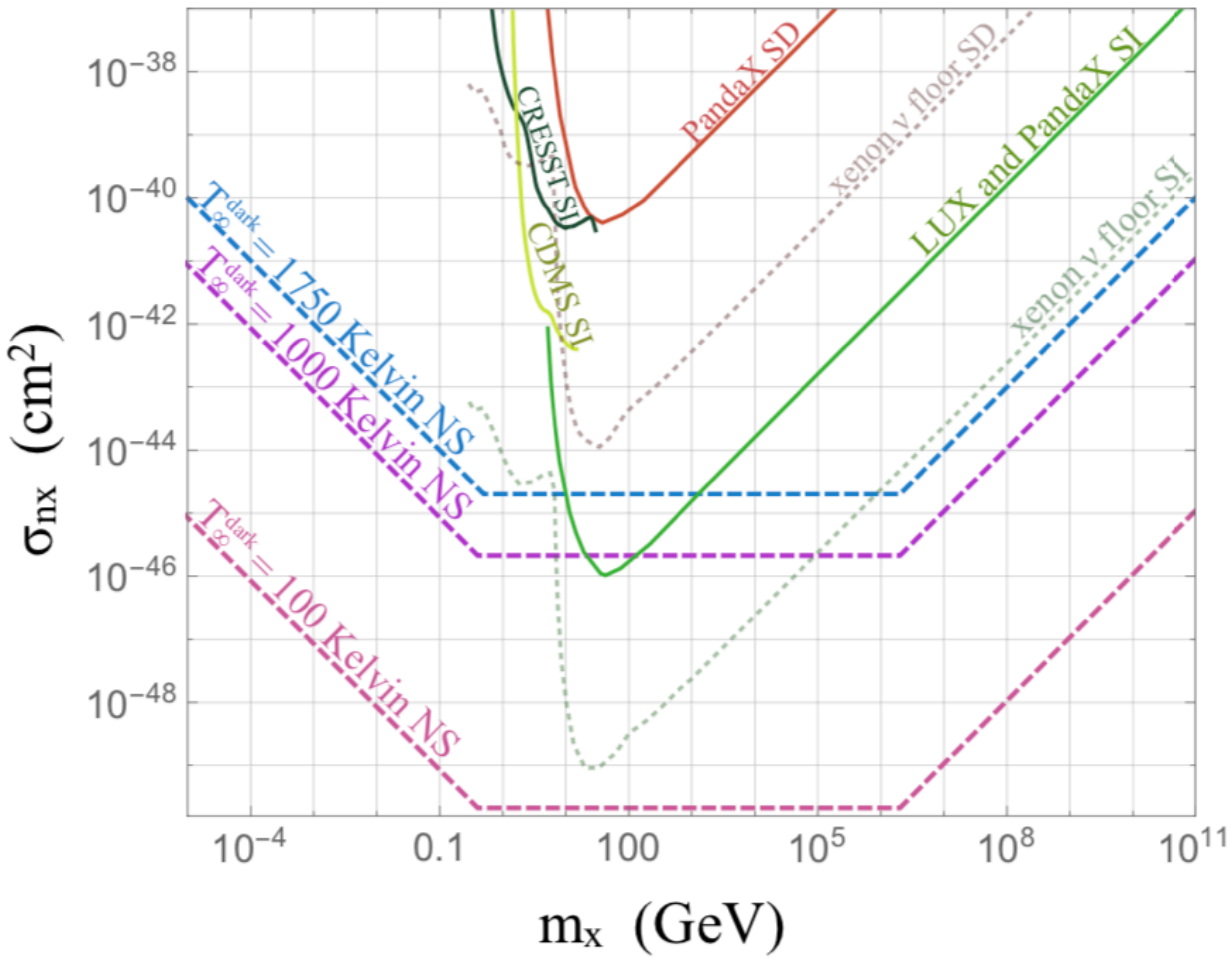
(1) DM velocity at the surface: $v_{\rm esc} \sim 0.5c$ (up to GR correction)

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

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

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

(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.)

① NS heating by DM

Example

- **Electroweak multiplet DM**

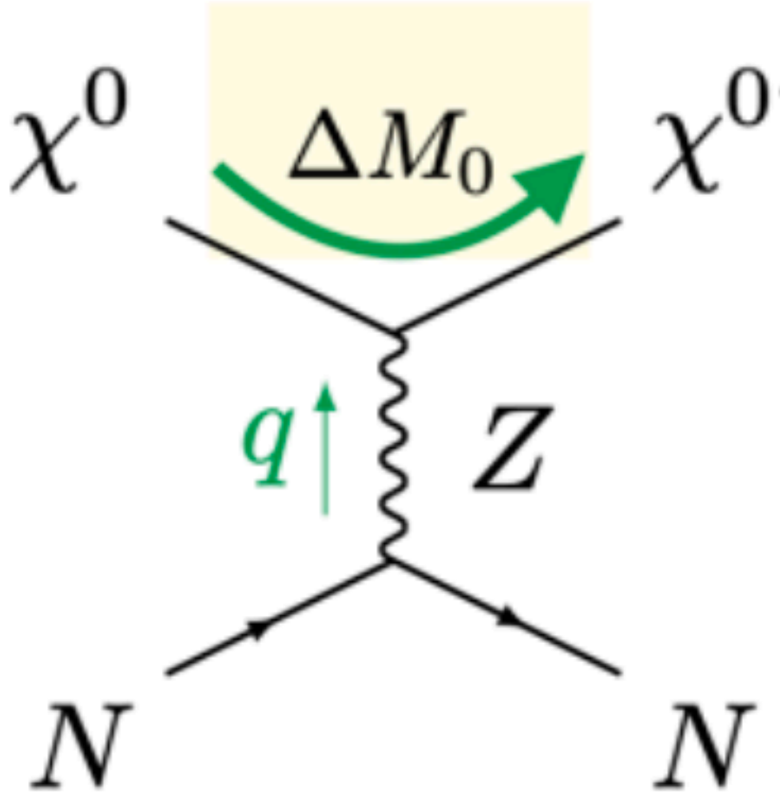
Fujiwara, KH, Nagata, Zheng [2204.02238]

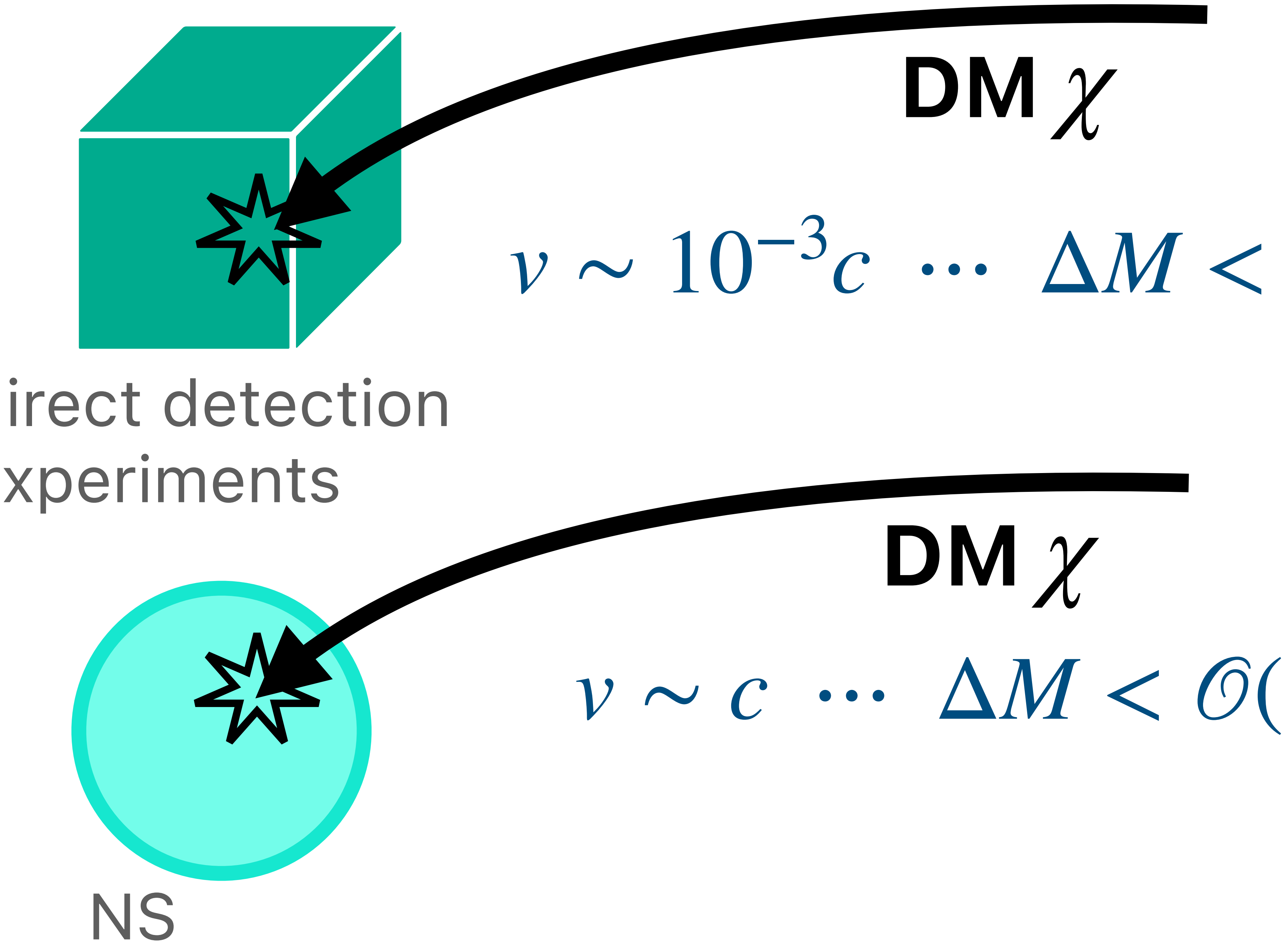
e.g., Wino and Higgsino in SUSY

The masses of the DM χ and its partner χ' are degenerate, $\Delta M \ll M_\chi$.

→ Inelastic scattering is important.

inelastic scattering





$v \sim 10^{-3}c \;\cdots\; \Delta M < \mathcal{O}(100)$ keV is necessary for inelastic scattering.

$v \sim c \;\cdots\; \Delta M < \mathcal{O}(100)$ MeV is necessary for inelastic scattering.

NS is much more sensitive to inelastic scattering.

Backup slides

Cas A SN and axion

3. Cas A NS Cooling by axion

KH, Nagata, Yanagi, Zheng, [1806.07151]

Motivation: **Axion**

Strong CP problem

$$\mathscr{L}_{\mathrm{SM}} \ni \frac{\alpha_s}{8\pi}\theta\, G^a_{\mu\nu}\widetilde{G}^{a\mu\nu} - \sum_q m_q \bar{q}\,\theta_q\, i\gamma_5 q$$

Experimental constraint (neutron EDM): $|\bar{\theta}| \lesssim 10^{-10}$

Why?

$$\left(\bar{\theta} = \theta + \sum_q \theta_q\right)$$

The most serious fine-tuning problem
in the Standard Model of particle physics.

(It cannot be explained even by the anthropic discussion.)

3. Cas A NS Cooling by axion

KH, Nagata, Yanagi, Zheng, [1806.07151]

Motivation: **Axion**

Strong CP problem

$$\mathscr{L}_{\rm SM} \ni \frac{\alpha_s}{8\pi} \boxed{\theta} G^a_{\mu\nu} \widetilde{G}^{a\mu\nu} - \sum_q m_q \bar{q}\, \theta_q\, i\gamma_5 q$$

Why?

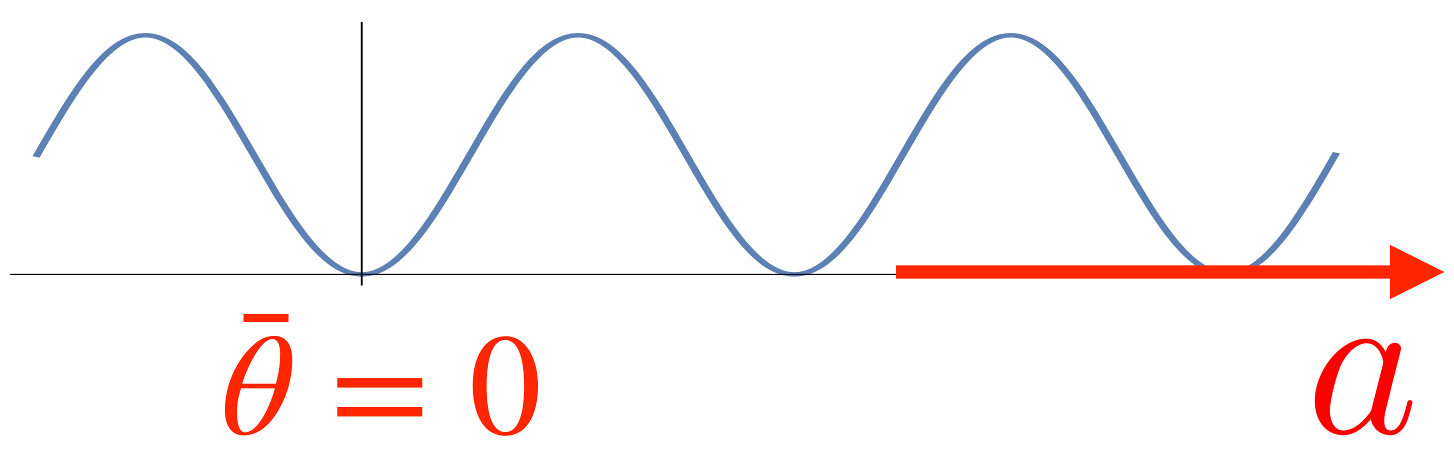
Experimental constraint (neutron EDM): $|\bar{\theta}| \lesssim 10^{-10}$

$$\left(\bar{\theta} = \theta + \sum_q \theta_q \right)$$

.....can be solved by the "Peccei-Quinn mechanism", [Peccei, Quinn,'77]
predicting a very light particle, Axion. [Weinberg,'78, Wilczek,'78]

$$\mathscr{L}_{\rm axion} \ni \frac{\alpha_s}{8\pi} \boxed{\frac{a}{f_a}} G^a_{\mu\nu} \widetilde{G}^{a\mu\nu}$$

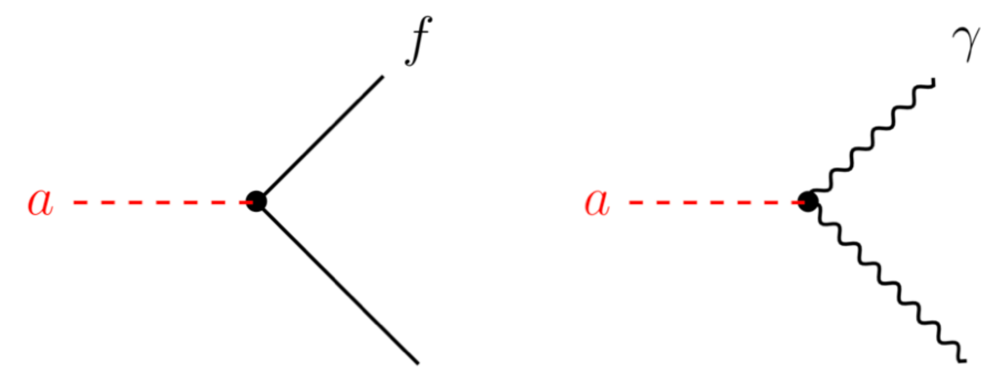
axion potential



- Axion's coupling is determined by the decay constant f_a .

$$\mathscr{L}_{\rm int} = \frac{\alpha_s}{8\pi} \frac{a}{f_a} \underbrace{G^{a\mu\nu} \widetilde{G}^a_{\mu\nu}}_{\text{gluon}} + \frac{1}{4} \frac{C_{a\gamma\gamma}}{f_a} a \underbrace{F_{\mu\nu} \widetilde{F}^{\mu\nu}}_{\text{photon}} + \sum_{\substack{f = \text{quarks,} \\ \text{leptons}}} \frac{1}{2} \frac{C_f}{f_a} \bar{f} \gamma^\mu \gamma_5 f \partial_\mu a \, .$$

$$C_{a\gamma\gamma} = \frac{\alpha}{2\pi} \left(\frac{E}{N} - \frac{2}{3} \frac{4m_d + m_u}{m_u + m_d} \right), \quad \begin{cases} C_q = 0 \quad (\text{KSVZ}) \\ C_{u,c,t} = \cos^2\beta/3, \quad C_{d,s,b} = \sin^2\beta/3 \quad (\text{DFSZ}) \end{cases}$$



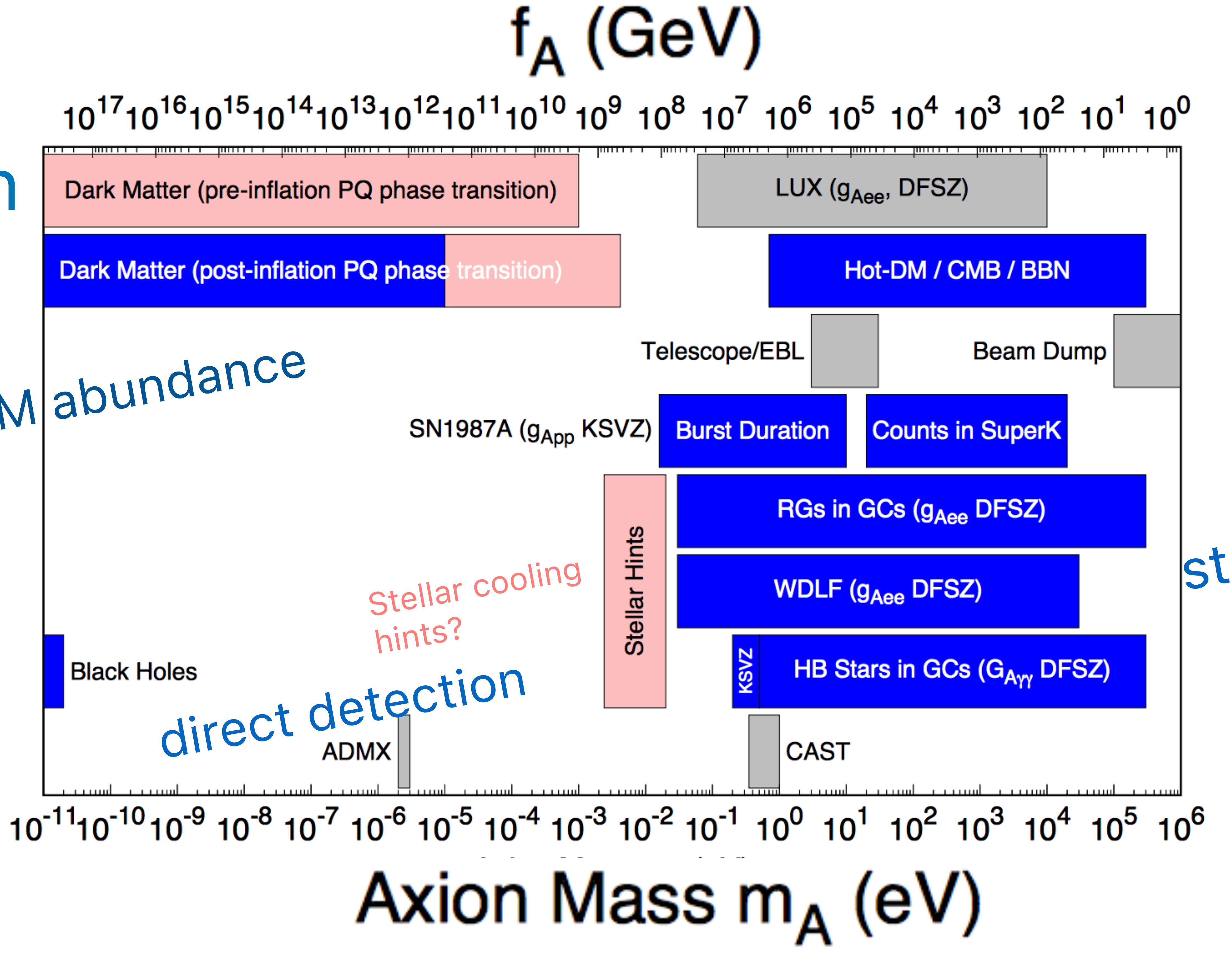
3. Cas A NS Cooling by axion

KH, Nagata, Yanagi, Zheng, [1806.07151]

Motivation: **Axion**

Constraints on axion

[Particle Data Group 2018]



Cosmology + DM abundance

Stellar cooling hints?

direct detection

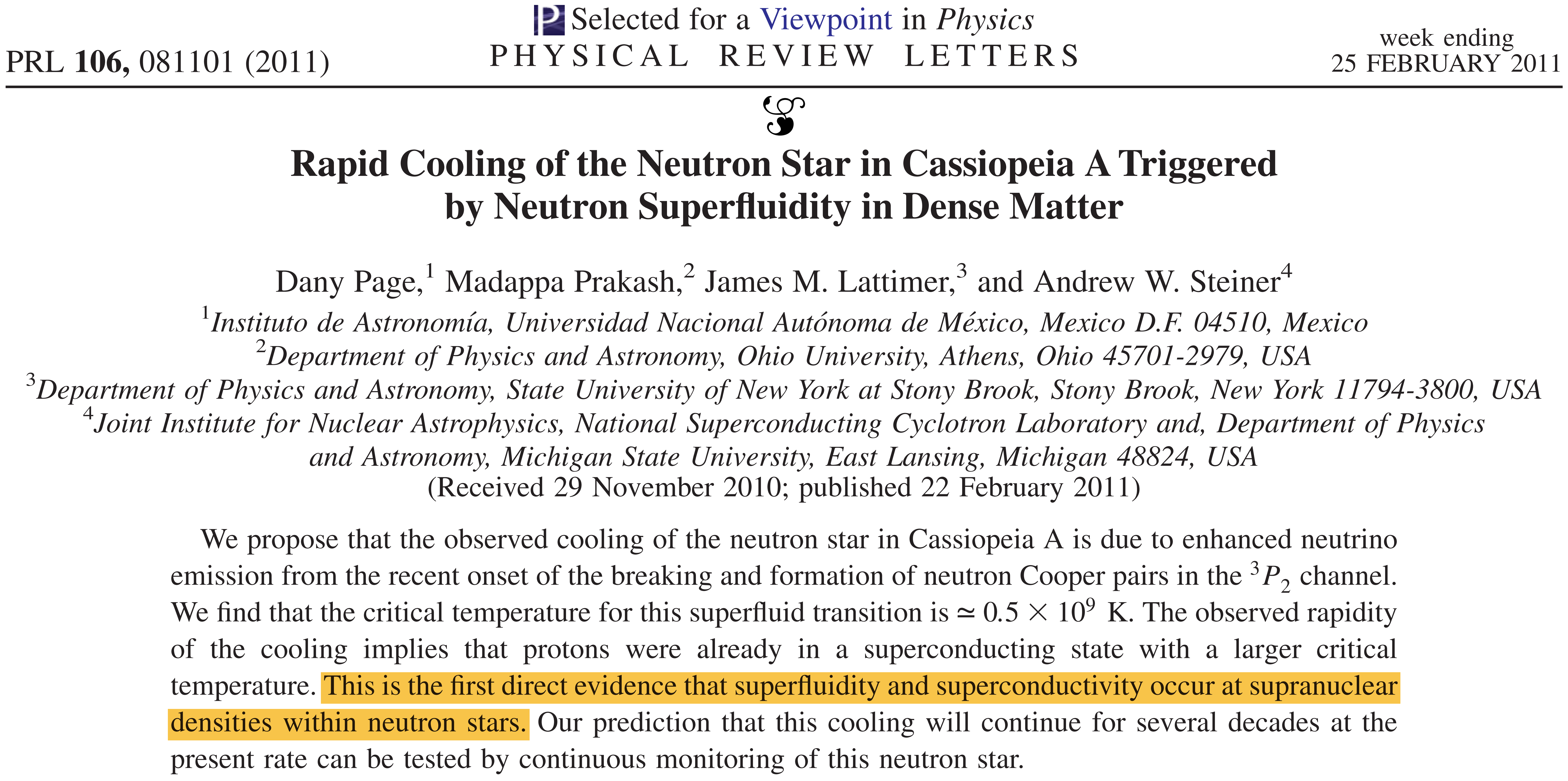
stellar Coolings

We obtained a **new bound** on the axion decay constant, $f_a > \mathcal{O}(10^8)$ GeV, by studying the **Cas A NS Cooling with axion.**

Cas A NS Cooling (theory)

- The observed Cas A NS cooling can be explained within **the standard NS Cooling theory.**
- Neutron **superfluidity** (and proton **superconductivity**) play key roles.

D. Page, M. Prakash, J. M. Lattimer, A. W. Steiner, 1011.6142 [Phys.Rev.Lett.].
P. S. Shternin, D. G. Yakovlev, C. O. Heinke, W. C. G. Ho, D. J. Patnaude, 1012.0045 [MNRAS].



Selected for a Viewpoint in *Physics*
PRL **106,** 081101 (2011) PHYSICAL REVIEW LETTERS week ending 25 FEBRUARY 2011

Rapid Cooling of the Neutron Star in Cassiopeia A Triggered by Neutron Superfluidity in Dense Matter

Dany Page,[1] Madappa Prakash,[2] James M. Lattimer,[3] and Andrew W. Steiner[4]
[1] *Instituto de Astronomía, Universidad Nacional Autónoma de México, Mexico D.F. 04510, Mexico*
[2] *Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701-2979, USA*
[3] *Department of Physics and Astronomy, State University of New York at Stony Brook, Stony Brook, New York 11794-3800, USA*
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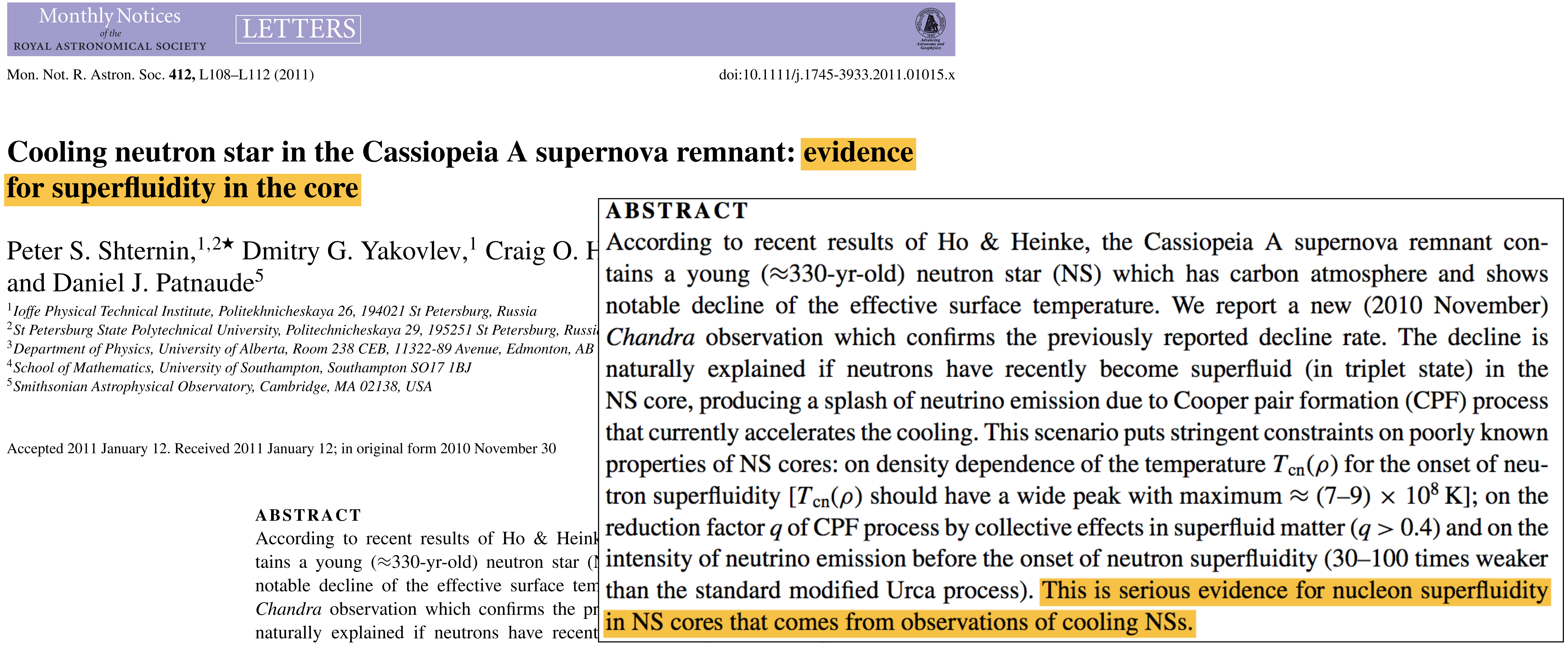
We propose that the observed cooling of the neutron star in Cassiopeia A is due to enhanced neutrino emission from the recent onset of the breaking and formation of neutron Cooper pairs in the $^3P_2$ channel. We find that the critical temperature for this superfluid transition is $\simeq 0.5 \times 10^9$ K. The observed rapidity of the cooling implies that protons were already in a superconducting state with a larger critical temperature. This is the first direct evidence that superfluidity and superconductivity occur at supranuclear densities within neutron stars. Our prediction that this cooling will continue for several decades at the present rate can be tested by continuous monitoring of this neutron star.

Cas A NS Cooling (theory)

- **The observed Cas A NS cooling can be explained within the standard NS Cooling theory.**
- Neutron **superfluidity** (and proton **superconductivity**) play key roles.

D. Page, M. Prakash, J. M. Lattimer, A. W. Steiner, 1011.6142 [Phys.Rev.Lett.].
P. S. Shternin, D. G. Yakovlev, C. O. Heinke, W. C. G. Ho, D. J. Patnaude, 1012.0045 [MNRAS].



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Cooling neutron star in the Cassiopeia A supernova remnant: evidence for superfluidity in the core

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ABSTRACT

According to recent results of Ho & Heinke, the Cassiopeia A supernova remnant contains a young (≈330-yr-old) neutron star (NS) which has carbon atmosphere and shows notable decline of the effective surface temperature. We report a new (2010 November) *Chandra* observation which confirms the previously reported decline rate. The decline is naturally explained if neutrons have recently become superfluid (in triplet state) in the NS core, producing a splash of neutrino emission due to Cooper pair formation (CPF) process that currently accelerates the cooling. This scenario puts stringent constraints on poorly known properties of NS cores: on density dependence of the temperature $T_{\mathrm{cn}}(\rho)$ for the onset of neutron superfluidity [$T_{\mathrm{cn}}(\rho)$ should have a wide peak with maximum $\approx (7\text{–}9) \times 10^8$ K]; on the reduction factor q of CPF process by collective effects in superfluid matter ($q > 0.4$) and on the intensity of neutrino emission before the onset of neutron superfluidity (30–100 times weaker than the standard modified Urca process). This is serious evidence for nucleon superfluidity in NS cores that comes from observations of cooling NSs.

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Alternative scenario to explain Cas A cooling

- longer thermal relaxation timescale in the crust or core
- etc

S.-H. Yang, C.-M. Pi, and X.-P. Zheng, arXiv:1103.1092;
R. Negreiros, S. Schramm, and F. Weber, arXiv:1103.3870;
D. Blaschke, H. Grigorian, D. N. Voskresensky, and F. Weber, arXiv:1108.4125;
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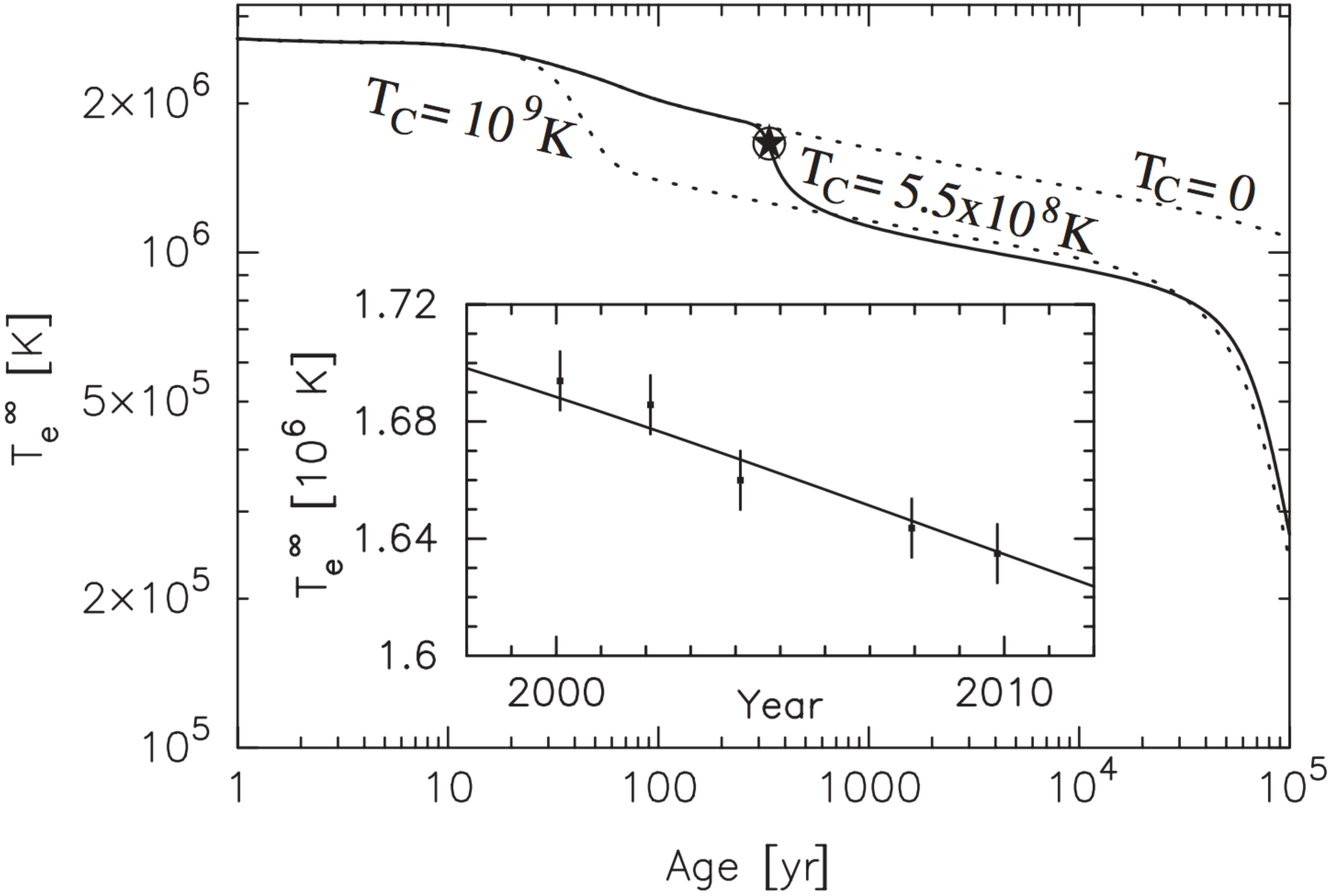
Minimal Cooling vs Cas A NS

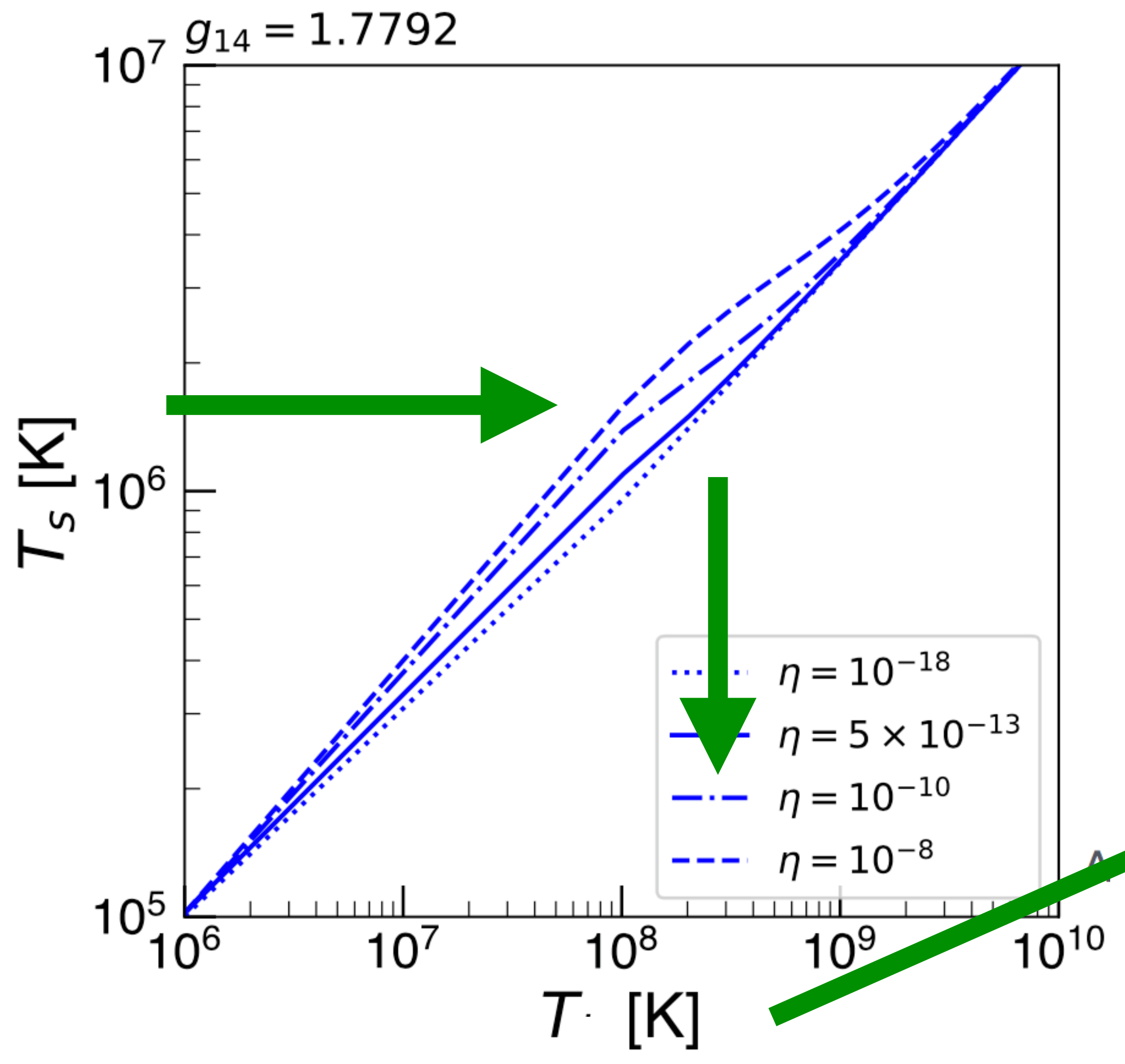


D. Page, M. Prakash, J. M. Lattimer, A. W. Steiner, 1011.6142 [Phys.Rev.Lett.].

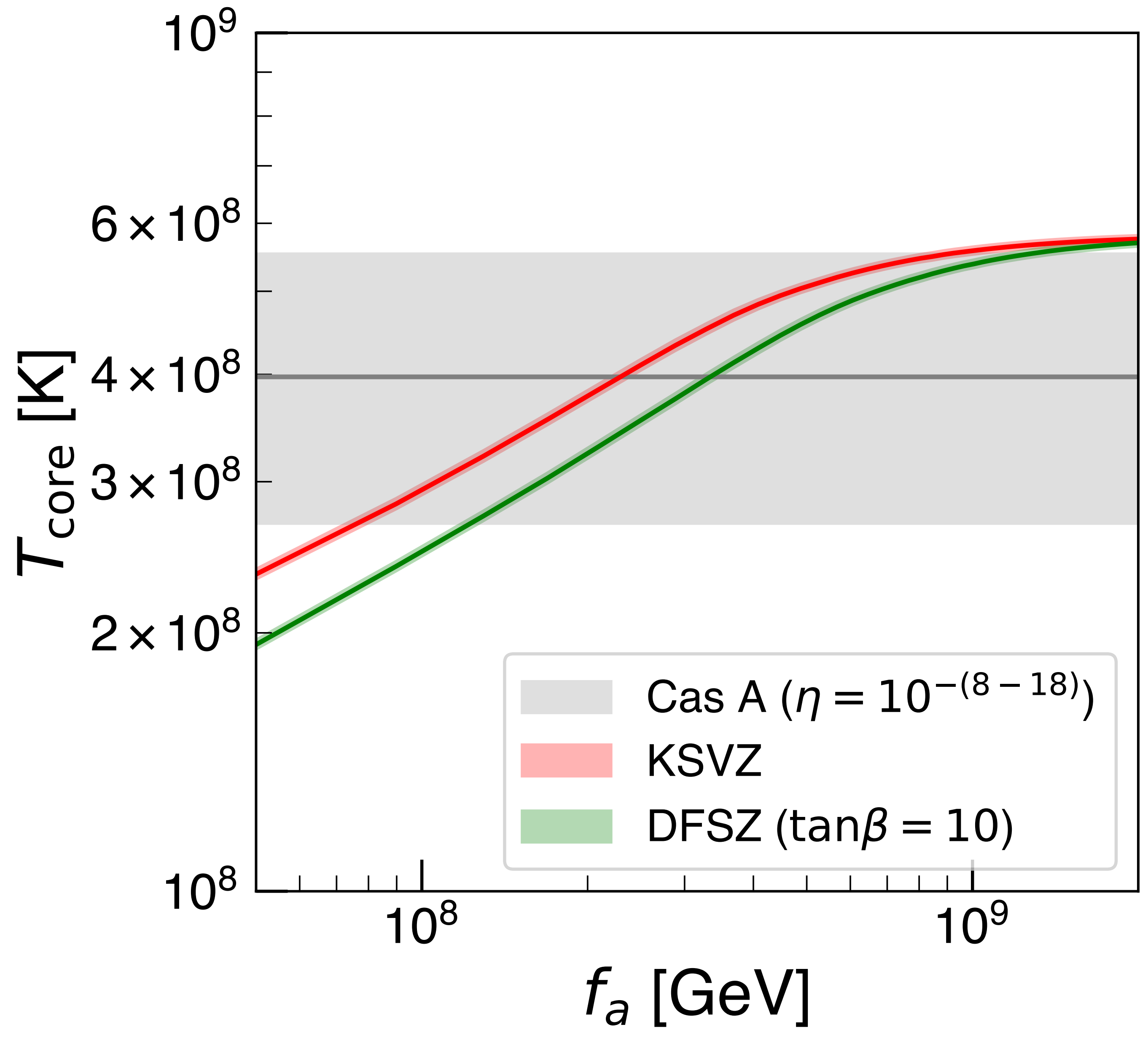
Cas A NS Cooling with axion

Remark: uncertainty from envelope

surface
temperature
(observed)



internal temperature



==> O(1) uncertainty in f_a bound.