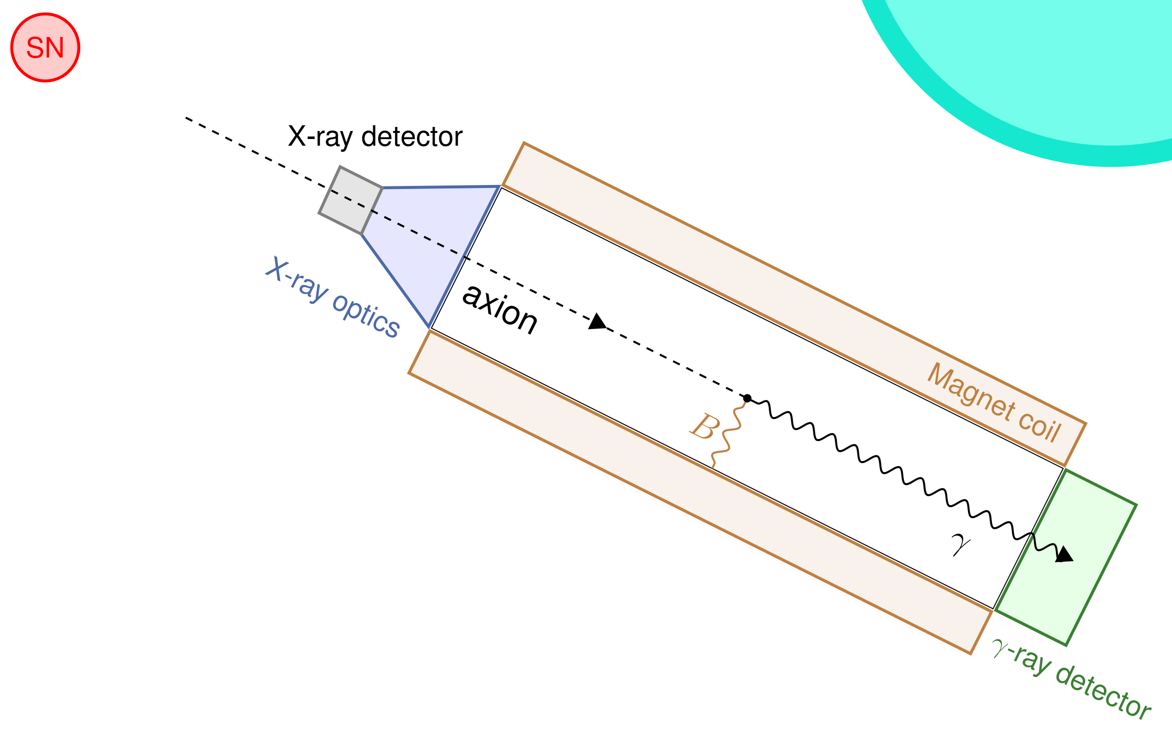
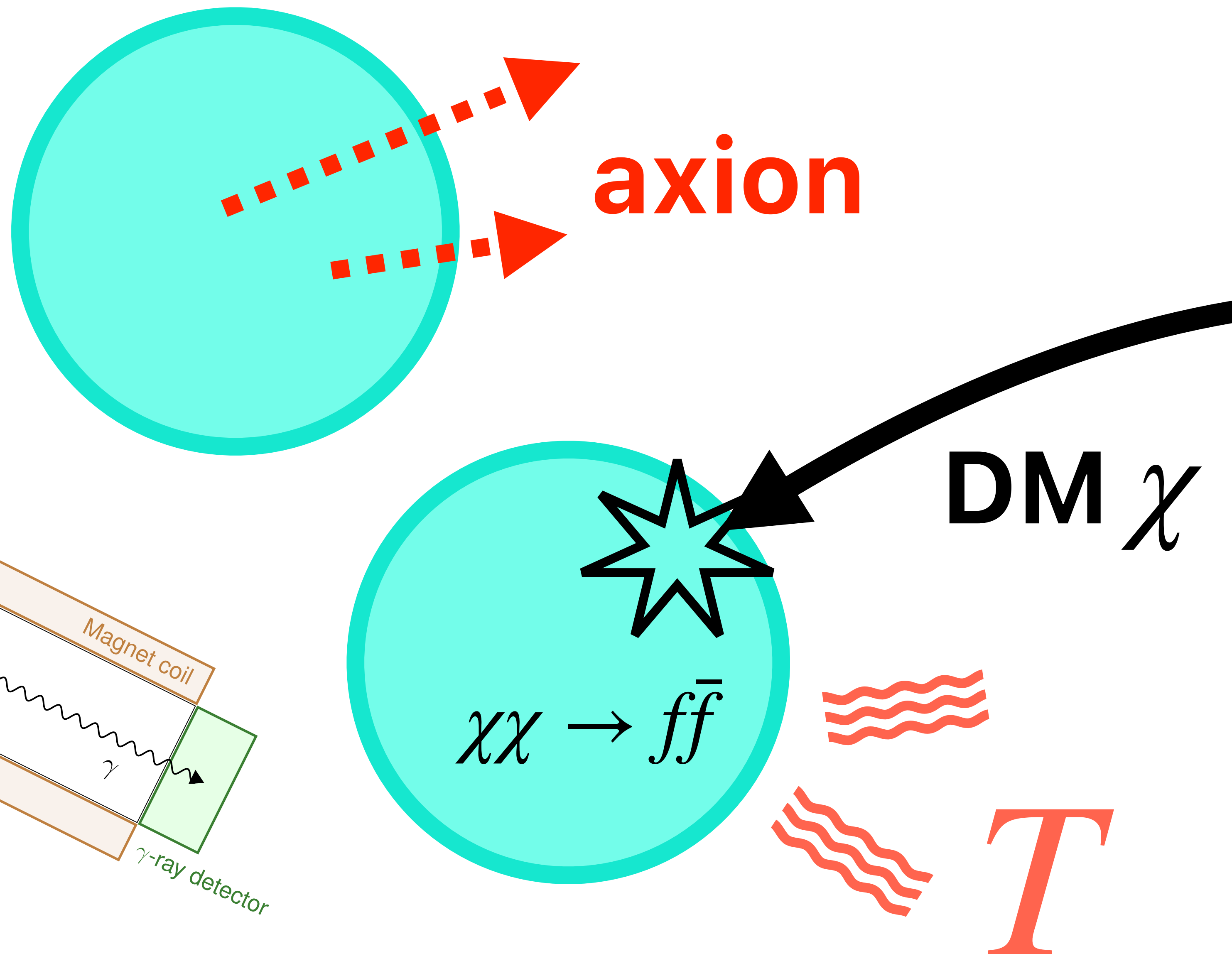
Exploring Physics Beyond the Standard Model via Temperature Observations of Neutron Stars

Koichi Hamaguchi (Tokyo U.)

@The Future is Whispering, NYCU, 25–27 June 2025





Based on the works with

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

(+ Shao-Feng Ge, Yoshiki Kanazawa, Koichi Ichimura, Koji Ishidoshiro, Yasuhiro Kishimoto, for the work on SN axion)

references

* **NS cooling by axion:** 1806.07151, 2502.18931 (👈 **New!)**
* **SN axion:** 2008.03924.
* **NS heating by DM:** arXiv 2309.02633, 2308.16066, 2204.02413, 2204.02238, 1905.02991, 1904.04667.

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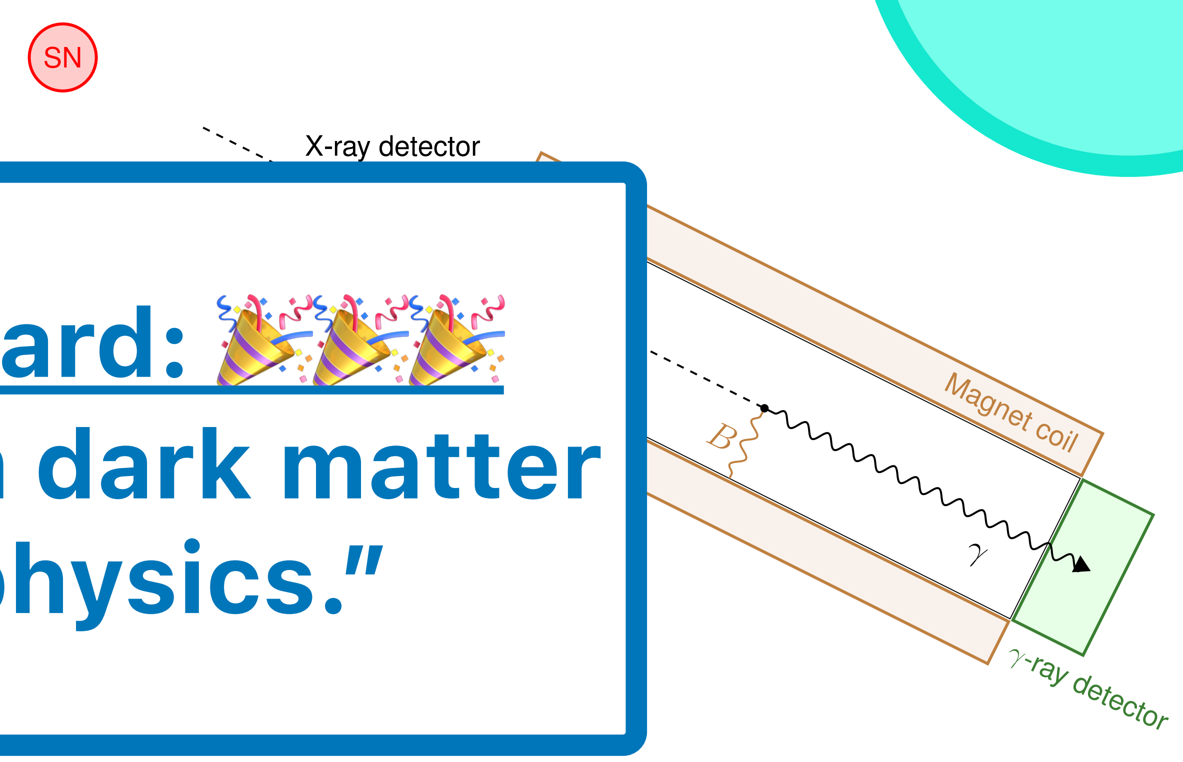

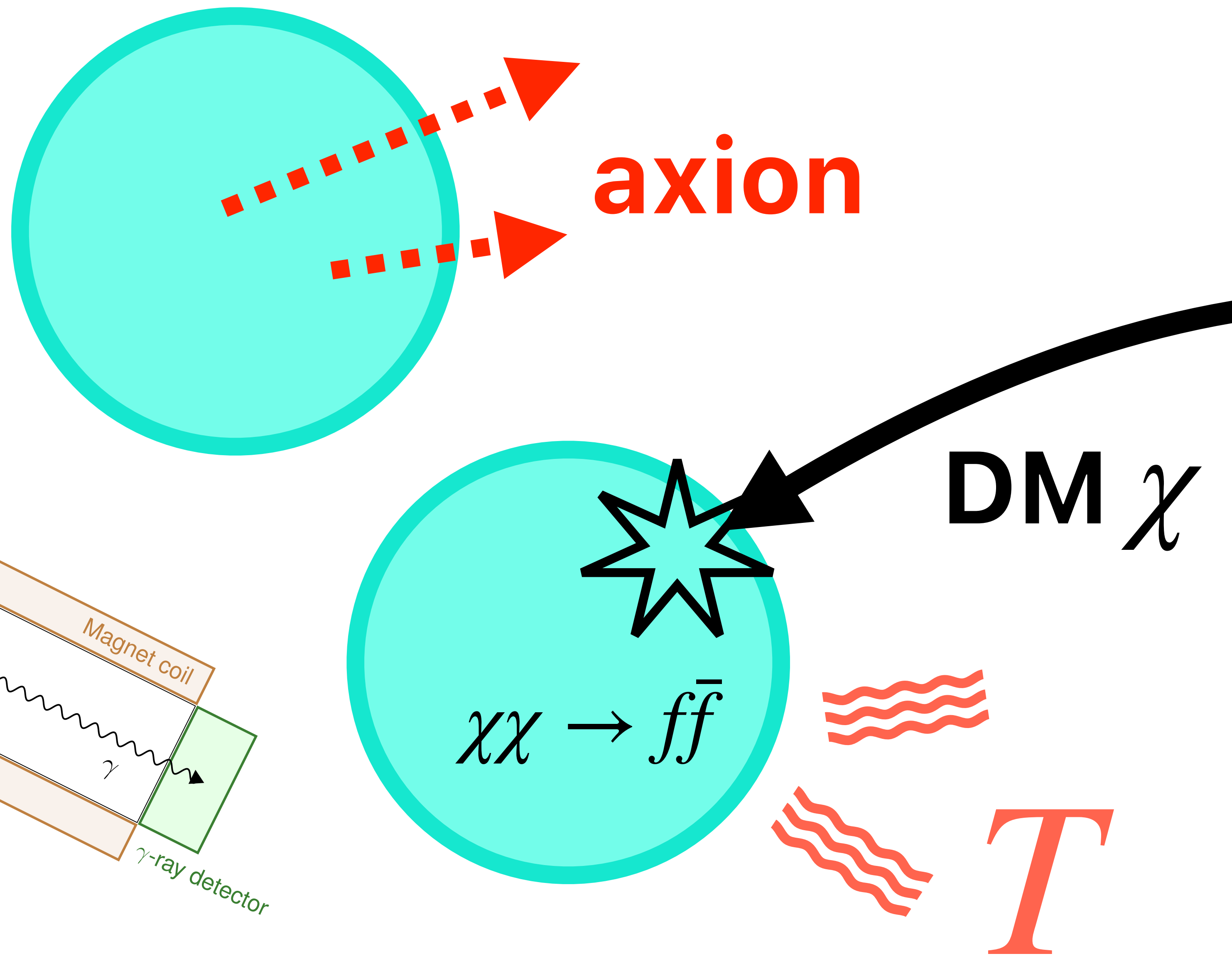

2024 AAPPS-JPS Award: 🎉🎉🎉
"Theoretical studies on dark matter and astroparticle physics."

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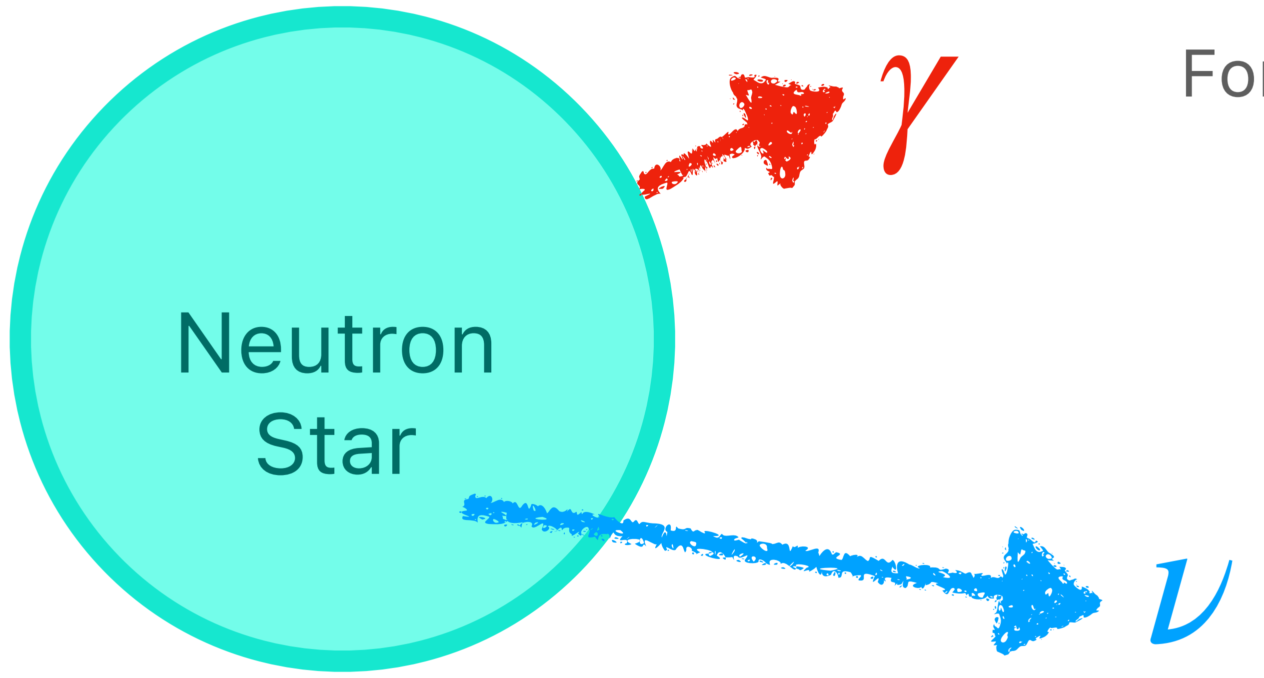
2025 JPS Young Scientist Award: 🎉🎉🎉
"Research on dark matter search through temperature observations of neutron stars."

Temperature evolution of isolated NS

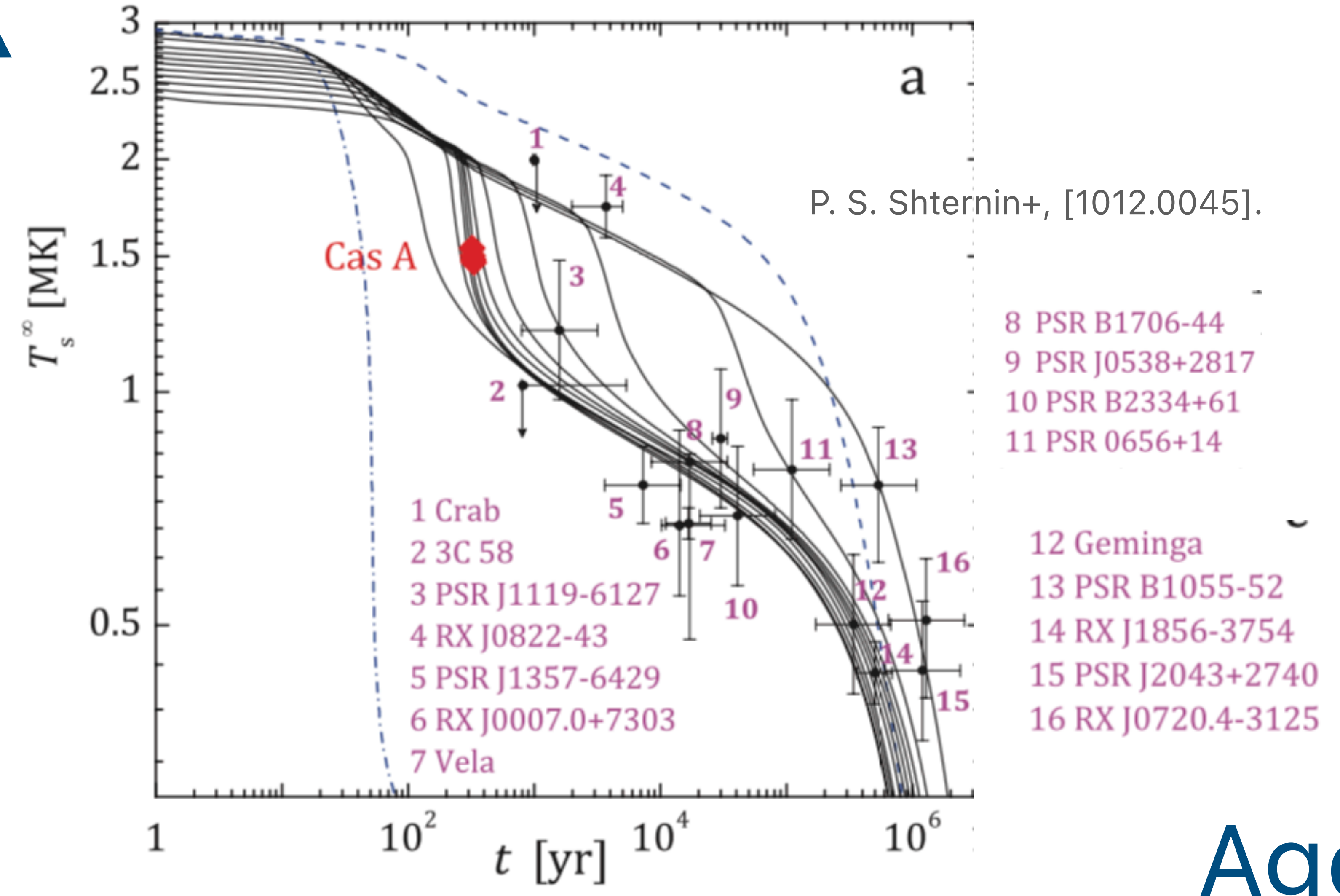
$$C\frac{dT}{dt} = -L_\nu - L_\gamma$$



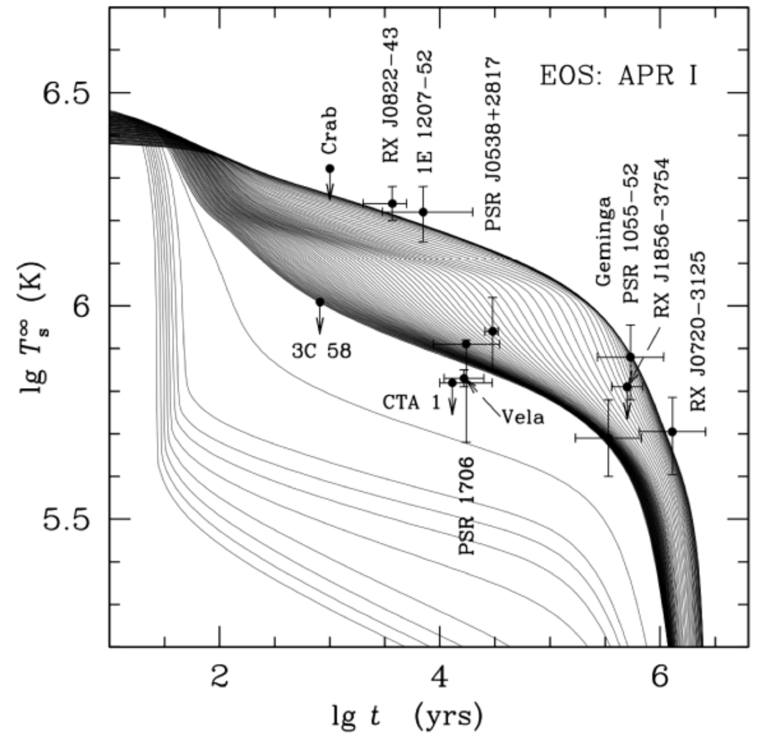
For reviews, e.g., D.G.Yakovlev+, astro-ph/0402143, D.Page+, astro-ph/0508056, 1302.6626

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

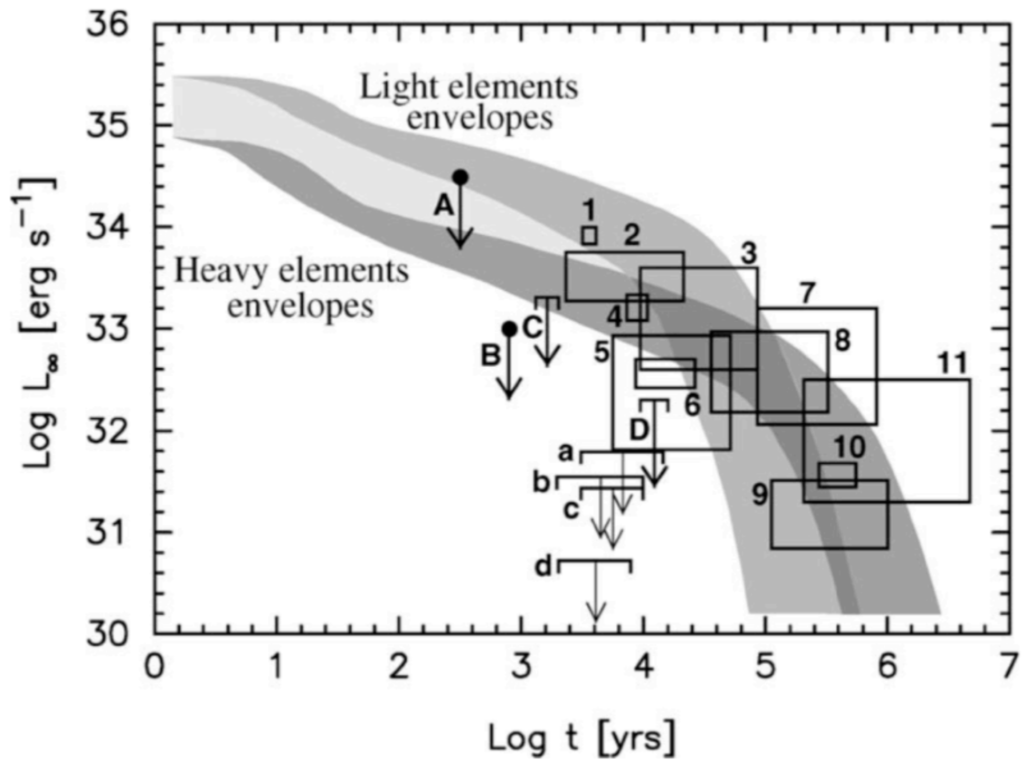
Surface Temperature



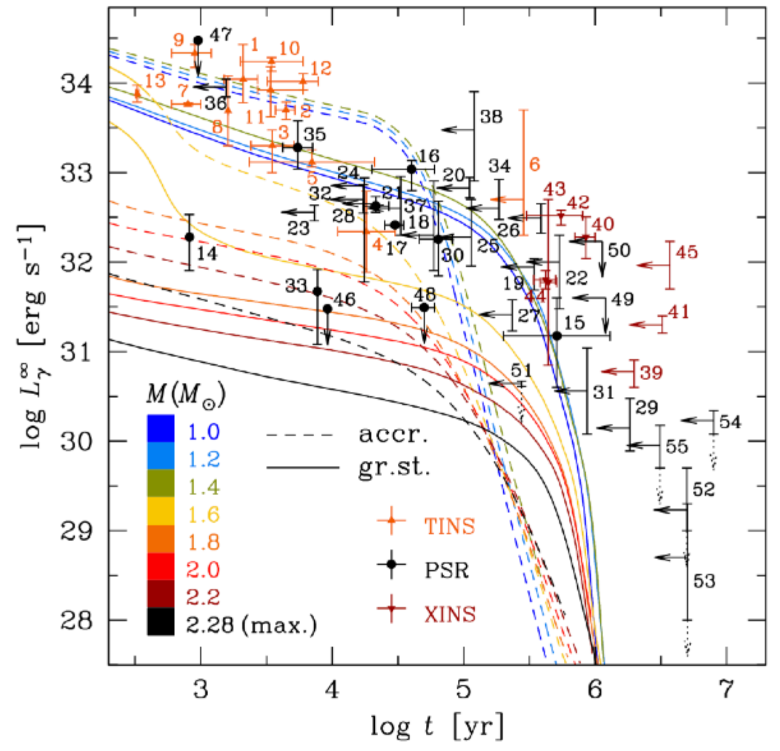
M. E. Gusakov, A. D. Kaminker, D. G. Yakovlev, O. Y. Gnedin
Mon.Not.Roy.Astron.Soc. **363** (2005) 555-562



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



A. Y. Potekhin+,2006.15004



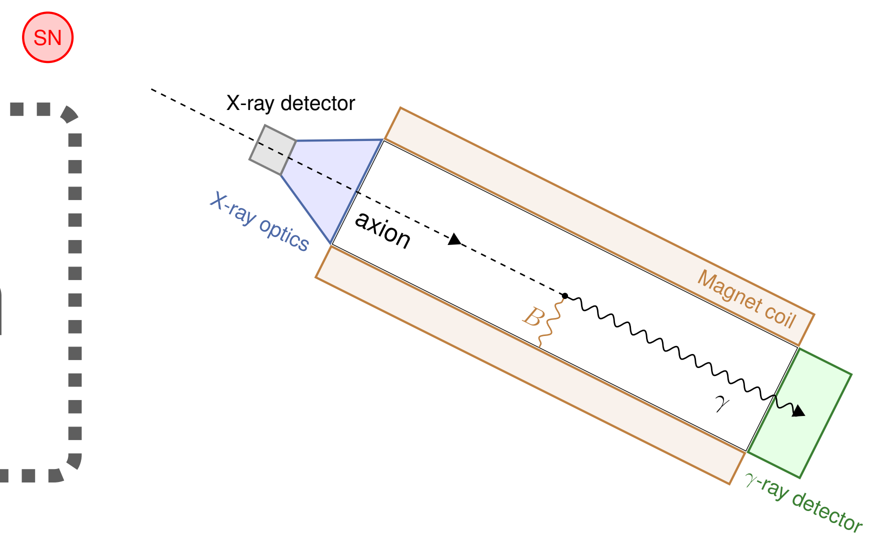
Ages of Neutron Stars

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

This talk

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

② (side remark) **Axion** from Supernova



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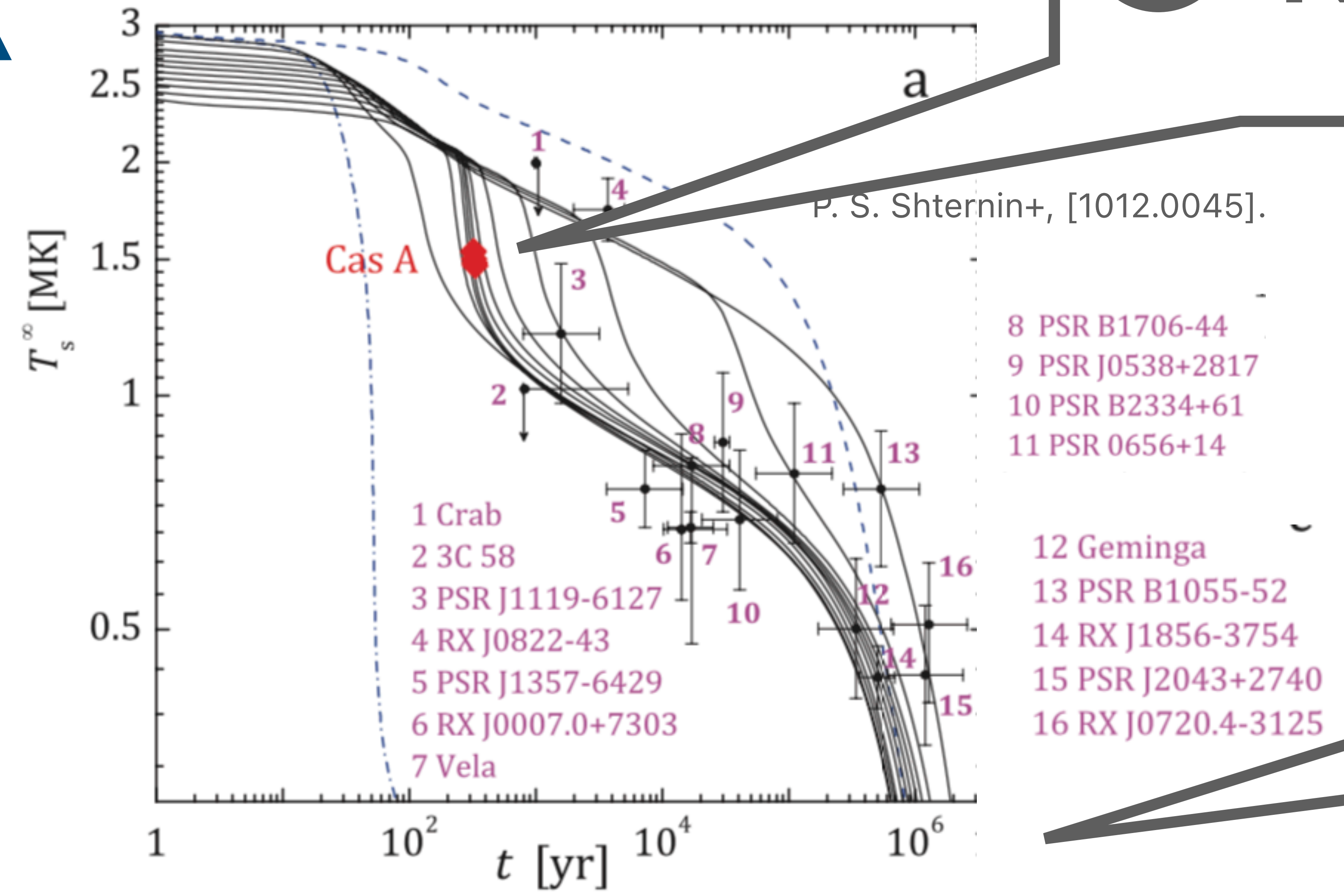
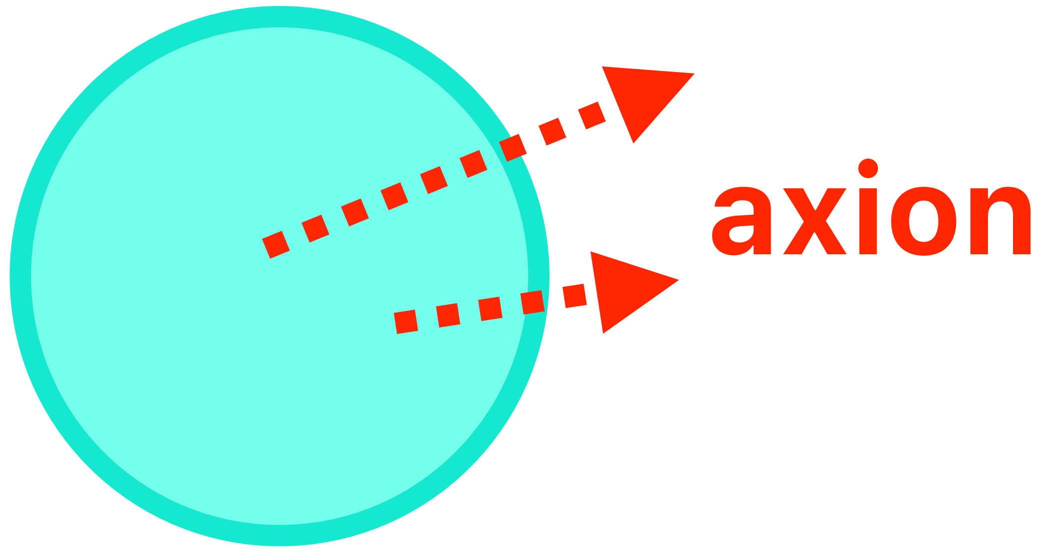


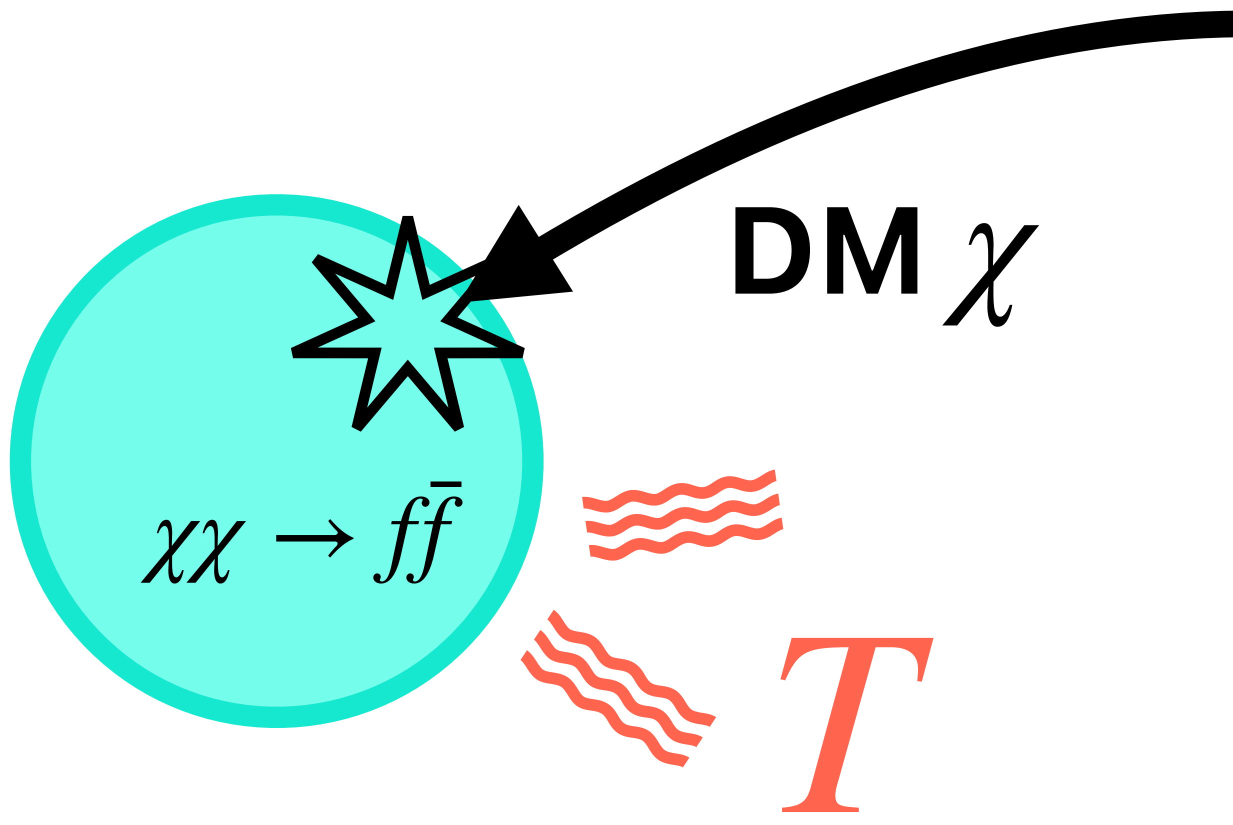
P. S. Shternin+, [1012.0045].

Age

① NS cooling by **Axion**



③ NS heating by **Dark Matter**



Plan

- Neutron Star
- NS Standard Cooling Theory
- BSM vs NS (and SN)
  - ① Cas A NS Cooling by axion
  - ② Side Remark: Supernova Axion
  - ③ NS Heating by DM

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Neutron Star

👉 cf. talk by Vedran Brdar yesterday

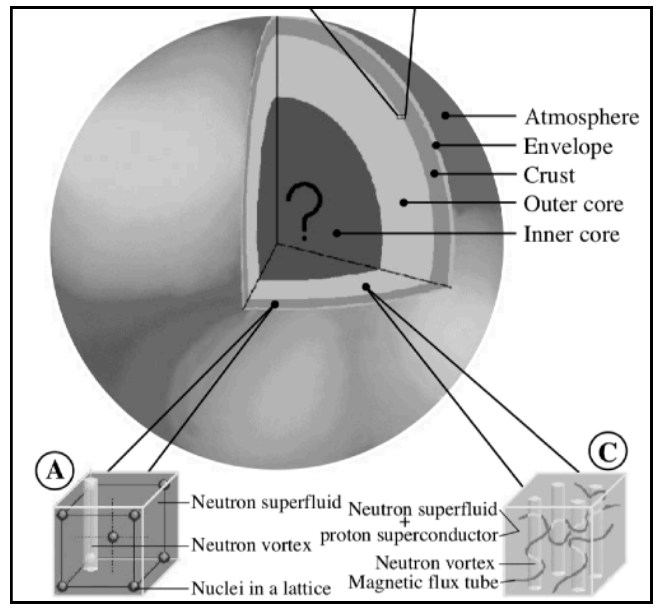

fig. from 1302.6626

Neutron Star

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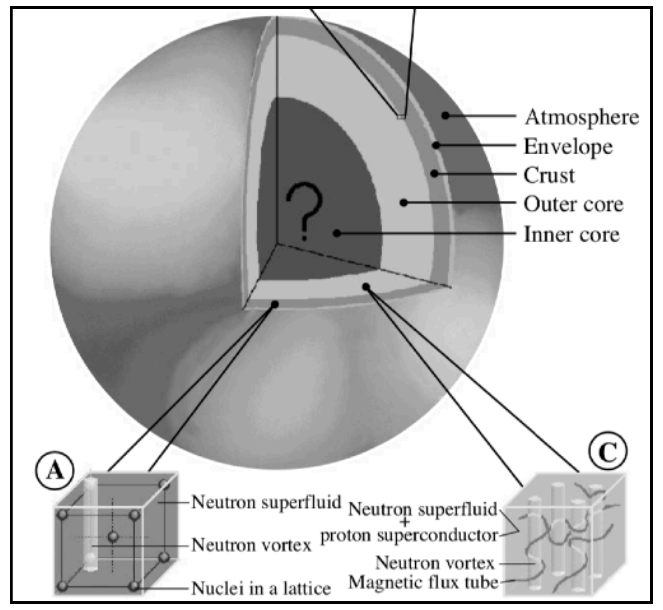

fig. from 1302.6626

- **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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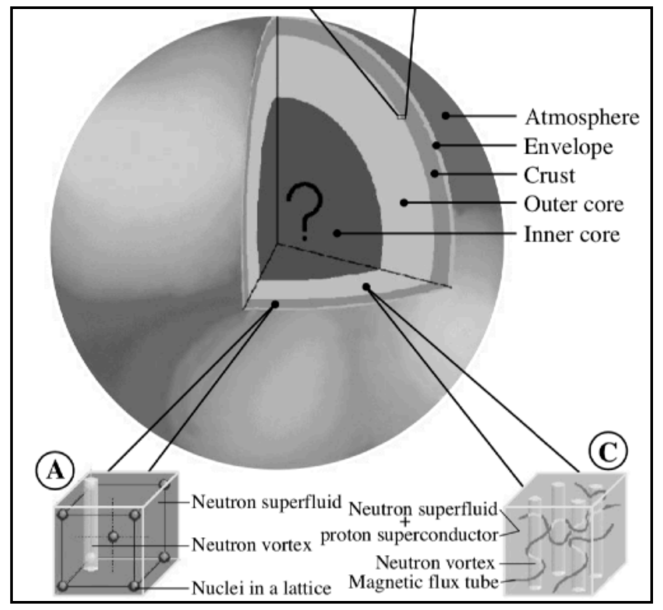

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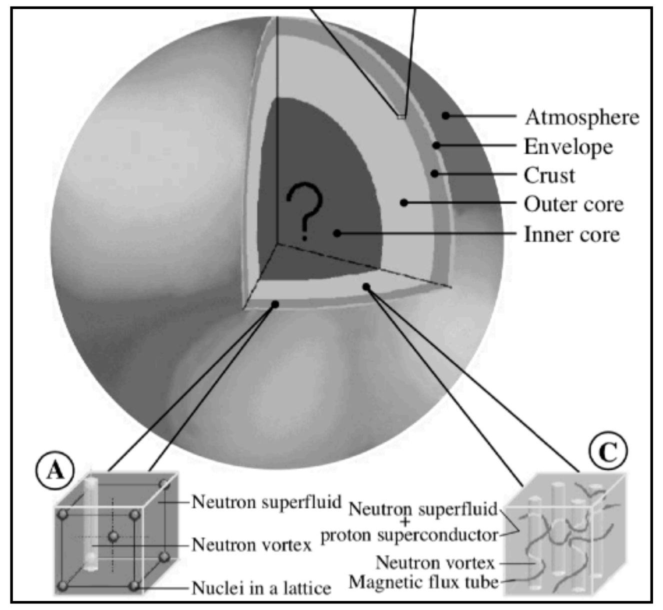

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- **Density**：$\bar{\rho} = \dfrac{M}{(4\pi/3)R^3} \simeq 7 \times 10^{14} \mathrm{g/cm^3}$

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

Neutron Star

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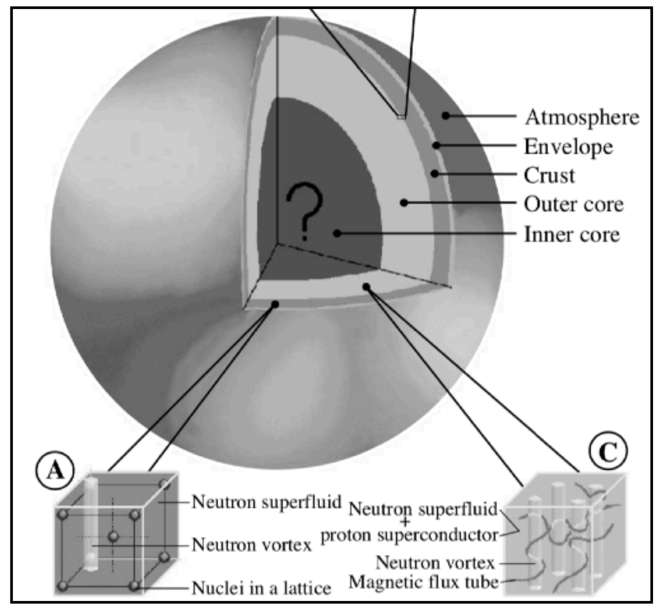

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Neutron Star

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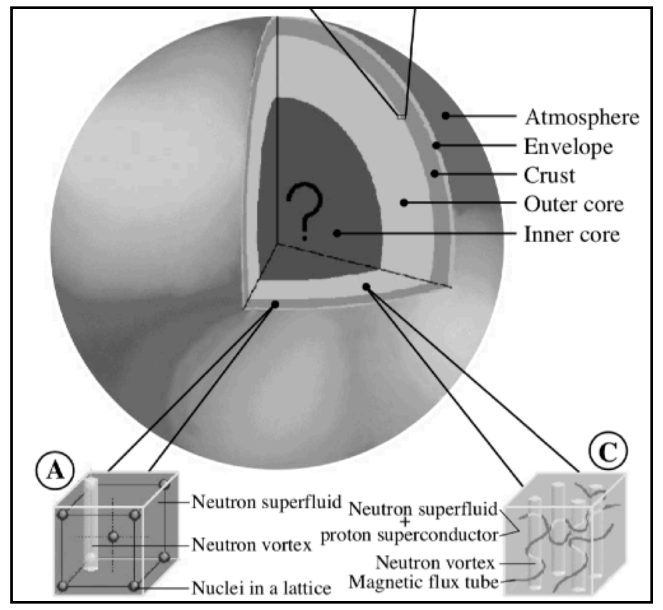

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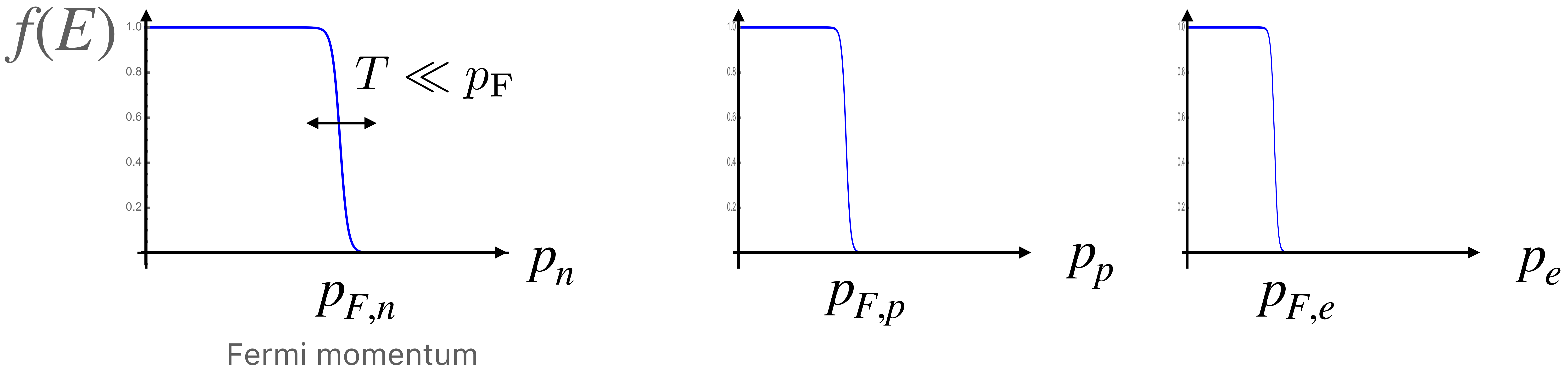

Neutron Star

👉 cf. talk by Vedran Brdar yesterday

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

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

Crab Pulsar

Neutron Star

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

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

> 3800 pulsars found so far.

ATNF pulsar catalogue:

Australia Telescope National Facility

HOME /

ATNF Pulsar Catalogue: Tu

ATNF Pulsar Catalogue Tutorial

Pages:

Introduction

1: The simplest query

Introduction
Last Update: 24th August 2023

This tutorial is a step by step introduction to t
this tutorial is to provide a complete coverage
without delving deeply into a discussion of wh
field.
A thorough coverage of the latter case can be
bottom of the main page. Alternatively, from t
hand side of the page which will link to the re

ATNF Pulsar Catalogue

Catalogue Version: 2.6.2

#	NAME		PSRJ		P0 (s)			P1		
1	J0002+6216	cwp+17	J0002+6216	cwp+17	0.1	0	cwp+17	6.0E-15	0	cwp+17
2	J0006+1834	cnt96	J0006+1834	cnt96	0.693748	0	dmo+24	2.097E-15	12	cn95
3	J0007+7303	aaa+09c	J0007+7303	aaa+09c	0.3158731909	3	awd+12	3.6E-13	1	awd+12
4	J0011+08	dsm+16	J0011+08	dsm+16	2.55287	0	dsm+16	*	0	*
5	J0012+5431	dcm+23	J0012+5431	dcm+23	3.02530070997	19	dcm+23	1.28e-16	0	dcm+23
6	B0011+47	dth78	J0014+4746	dth78	1.2	0	hlk+04	5.6E-16	1	hlk+04
7	J0021-0909	clh+20	J0021-0909	clh+20	2.31413082909	17	clh+20	1.0E-15	1	clh+20
8	J0023+0923	hrm+11	J0023+0923	hrm+11	0.003	0	aab+21a	1.1E-20	0	aab+21a
9	B0021-72C	mld+90	J0024-7204C	mld+90	0.006	0	frk+17	-5.0E-20	1	frk+17
10	B0021-72D	mlr+91	J0024-7204D	mlr+91	0.005	0	frk+17	-3.4E-21	1	frk+17
11	B0021-72E	mlr+91	J0024-7204E	mlr+91	0.004	0	frk+17	9.9E-20	0	frk+17
12	B0021-72F	mlr+91	J0024-7204F	mlr+91	0.003	0	frk+17	6.5E-20	0	frk+17
13	B0021-72G	rlm+95	J0024-7204G	rlm+95	0.004	0	frk+17	-4.2E-20	1	frk+17
14	B0021-72H	mlr+91	J0024-7204H	mlr+91	0.003	0	frk+17	-1.8E-21	1	frk+17
15	B0021-72I	mlr+91	J0024-7204I	mlr+91	0.003	0	frk+17	-4.6E-20	1	frk+17

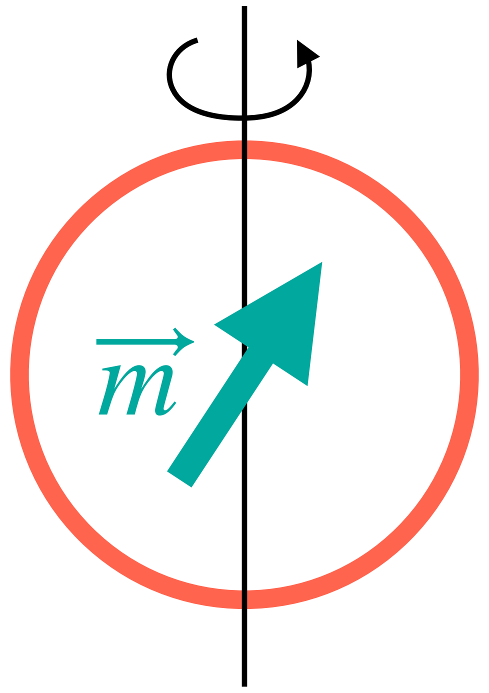
👉 cf. talk by Vedran Brdar yesterday

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

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

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

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

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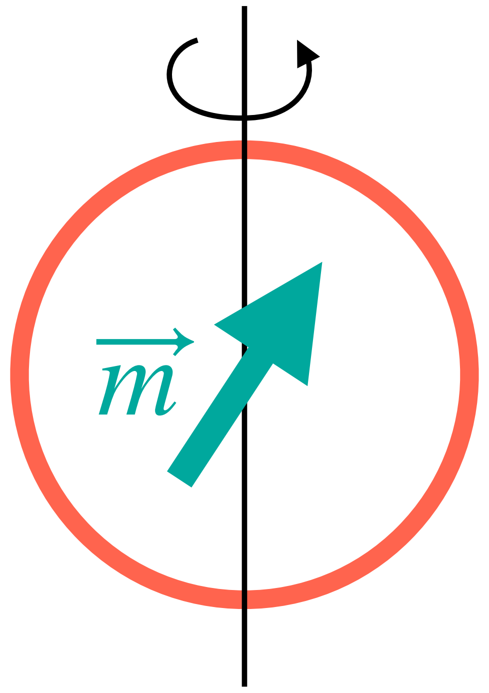

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https://commons.wikimedia.org/wiki/File:Chandra-crab.jpg

Crab Pulsar

Example: Crab Pulsar

- actual age: $\tau = 970$ yrs (from historical records of Supernova 1054.)
- spin down age: $P \simeq 0.033$ sec, $\dot{P} \simeq 4.2 \times 10^{-13} \Longrightarrow \tau_{\text{sd}} \simeq 1200$ yrs

Neutron Star

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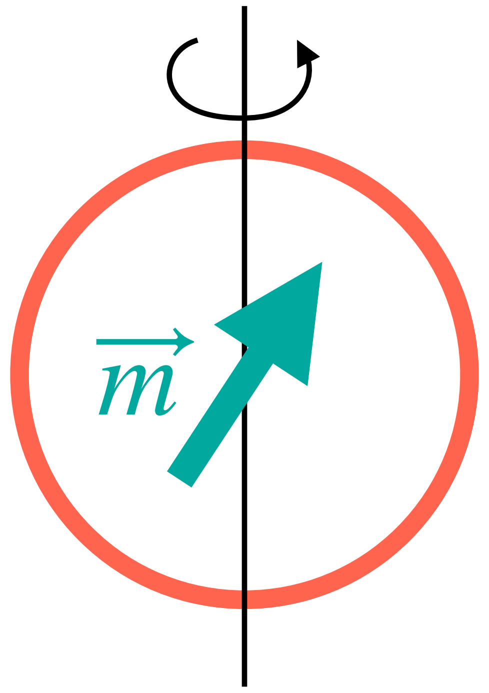
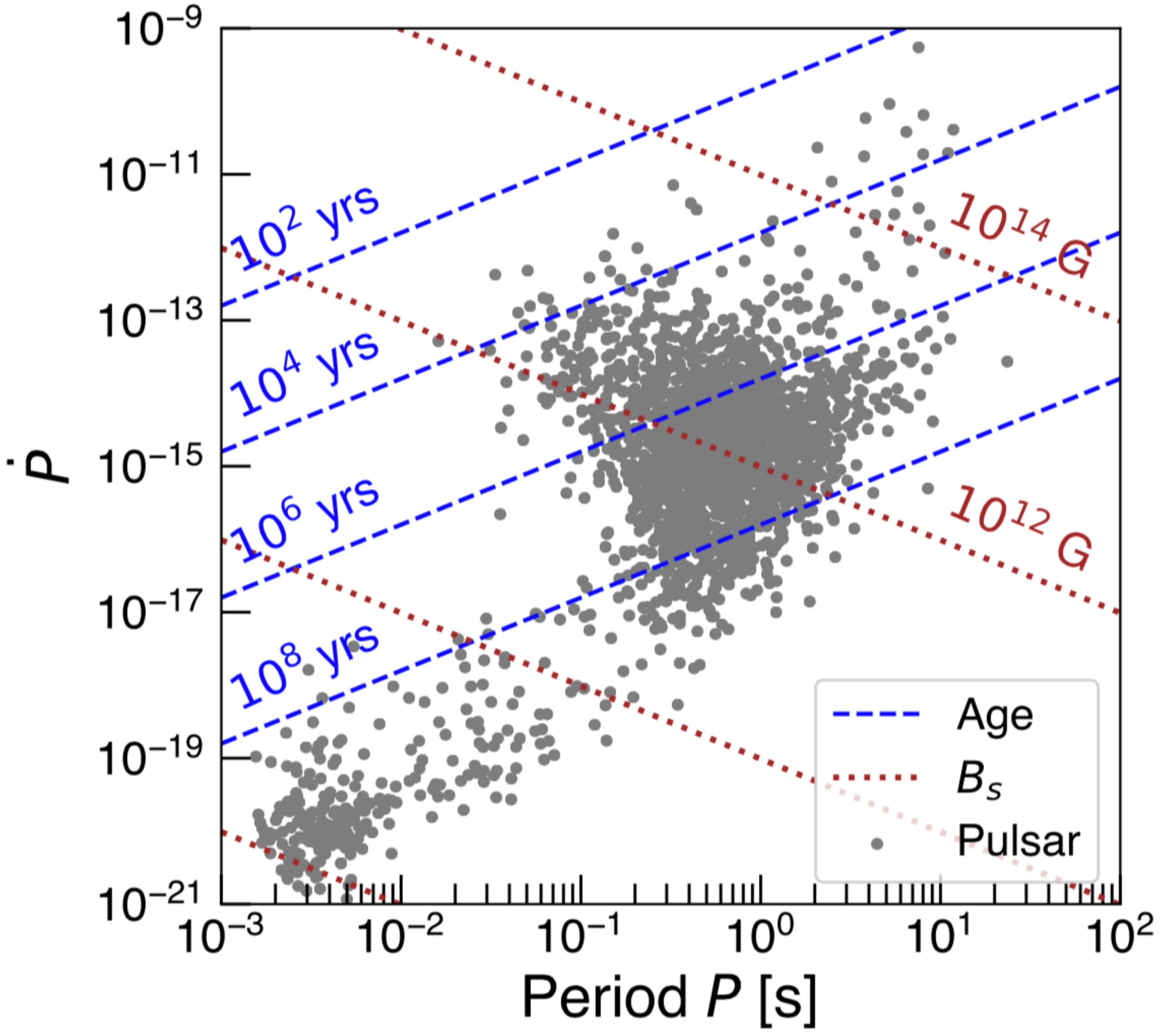
- **Magnetic Dipole Model**





$P - \dot{P}$ diagram

<=> Age and magnetic field of pulsars.

Fig. thanks to N.Natsumi.

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Crab Pulsar

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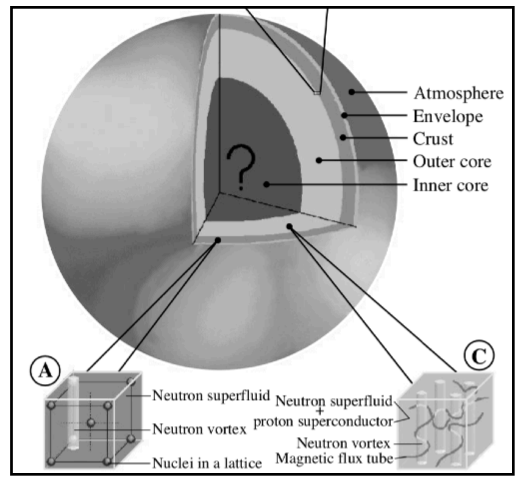

fig. from 1302.6626

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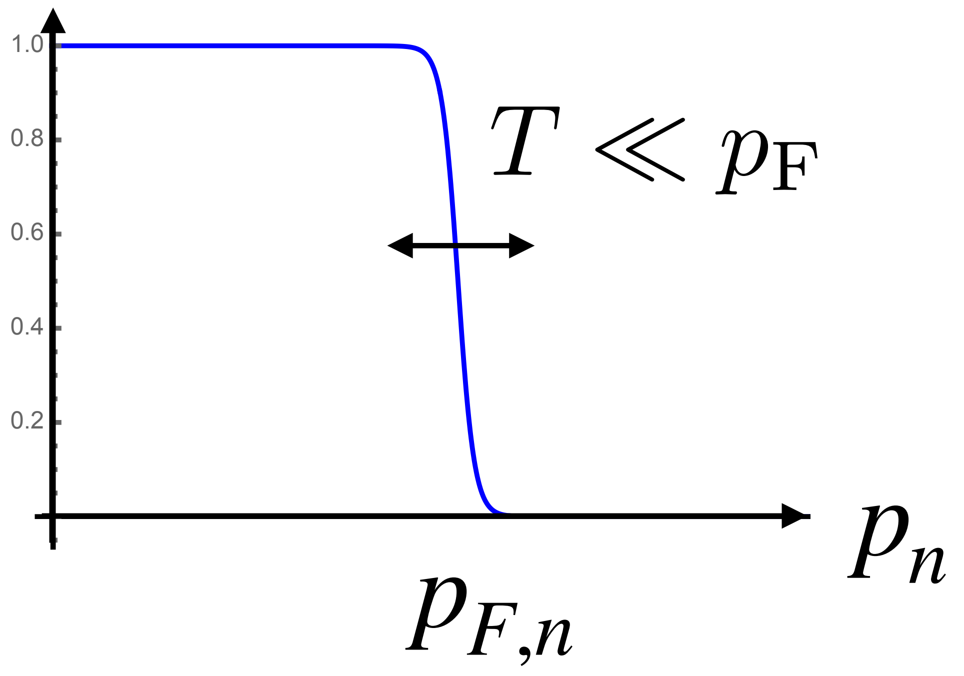

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In this talk, we will focus on
the temperatures of neutron stars
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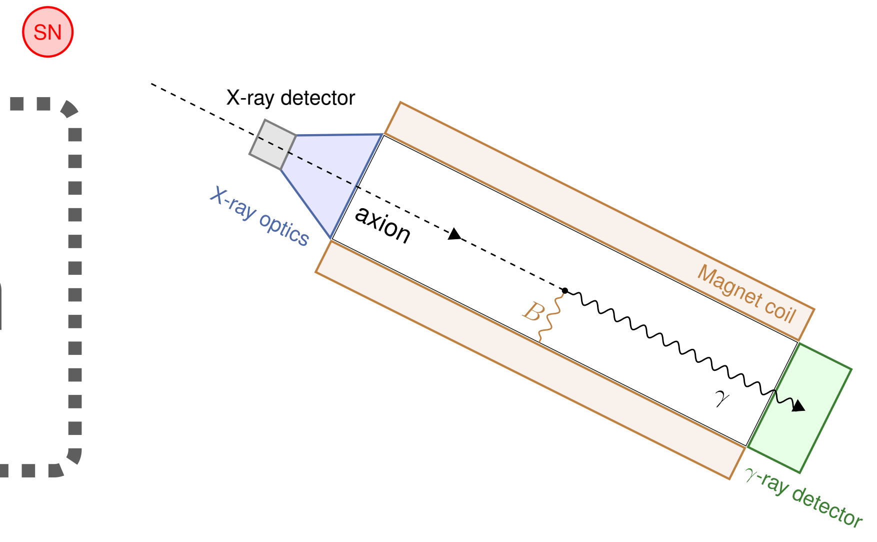
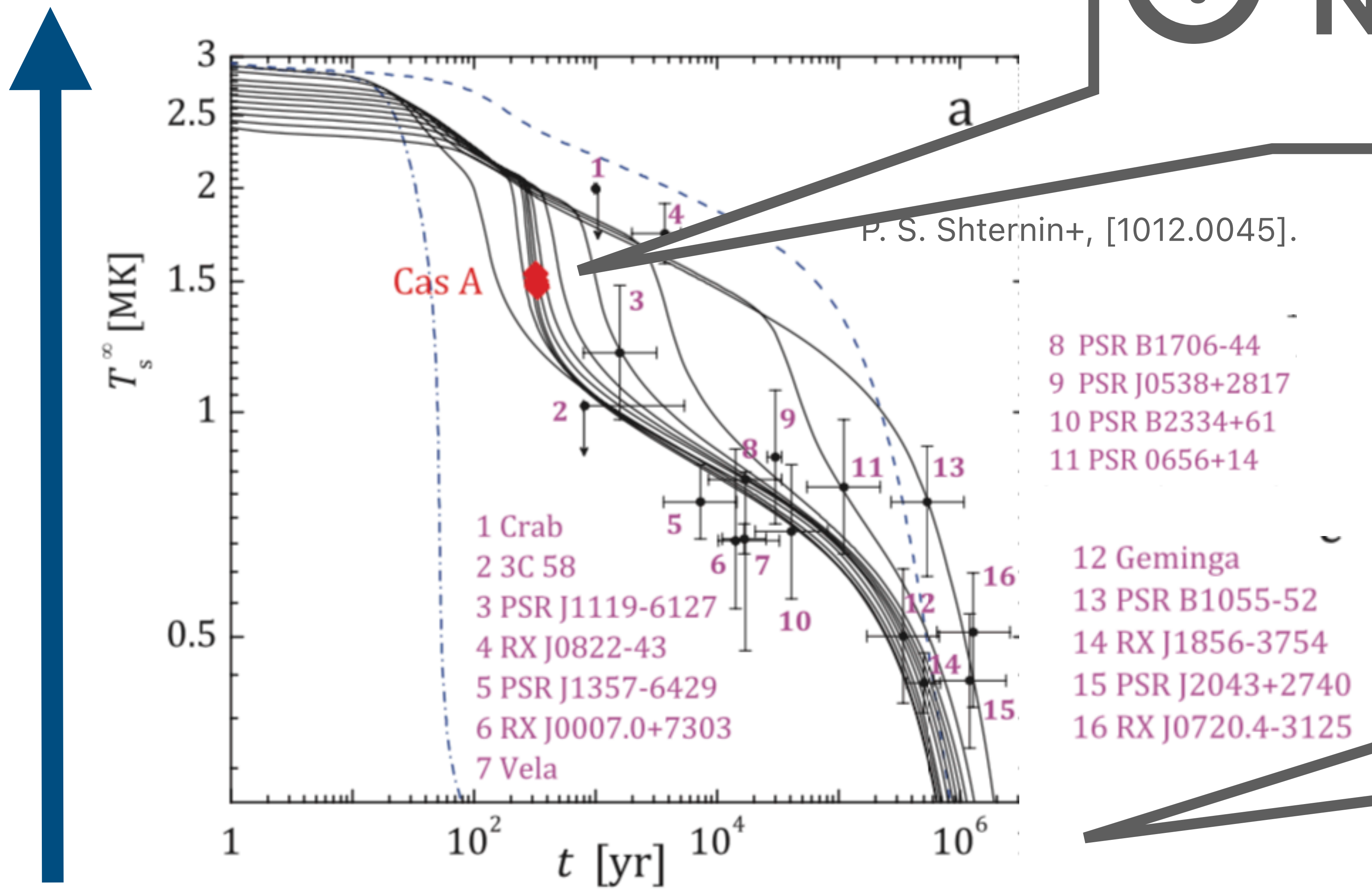
② (side remark) Axion from Supernova

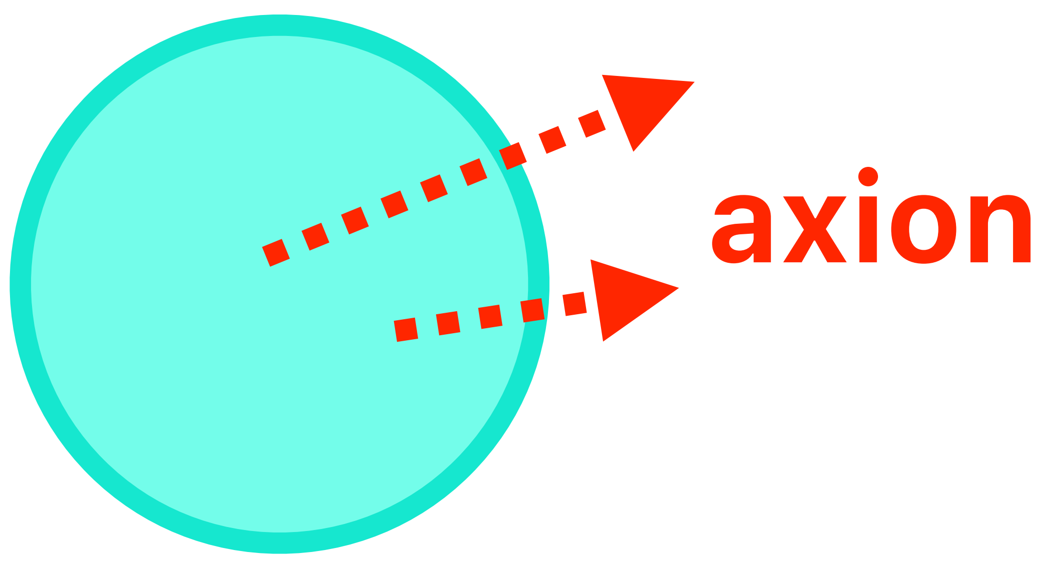


Surface Temperature

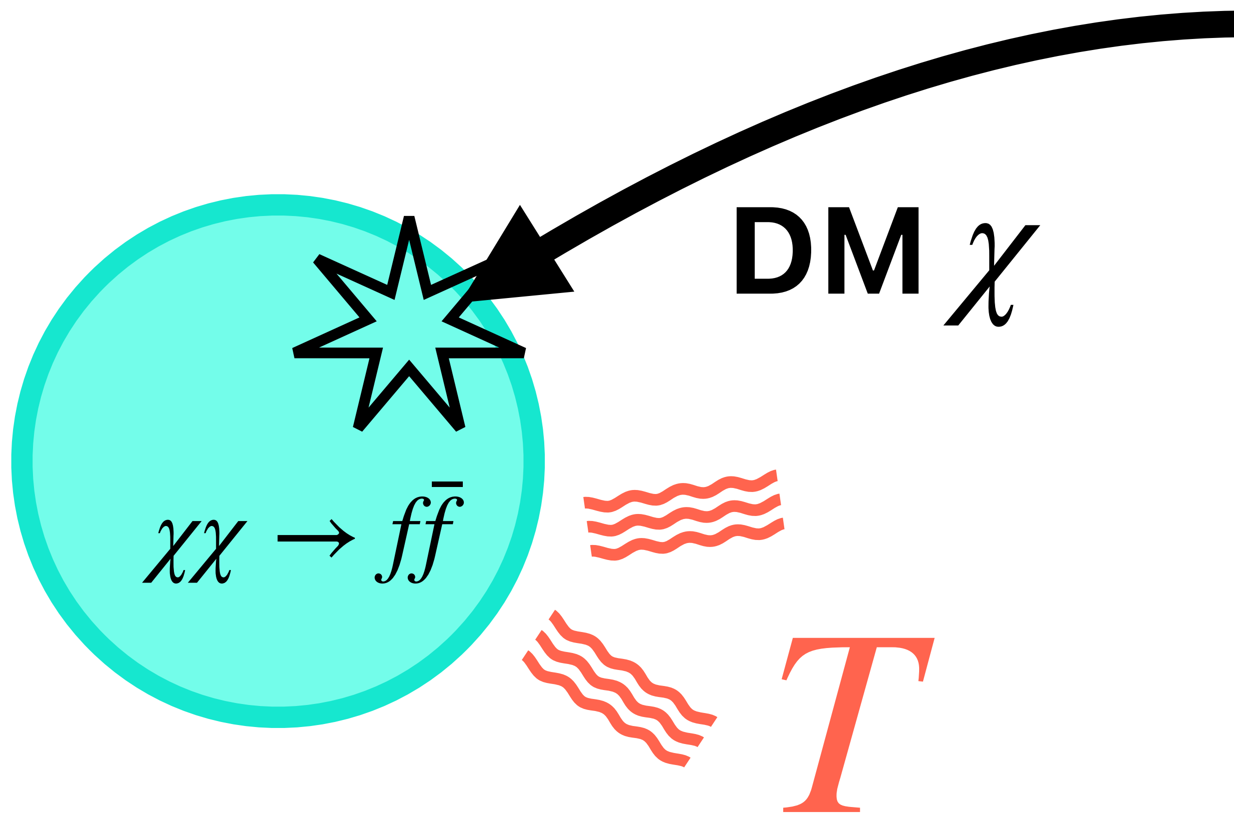


P. S. Shternin+, [1012.0045].

① NS cooling by Axion



③ NS heating by Dark Matter



Plan

- Neutron Star
- NS Standard Cooling Theory
- BSM vs NS (and SN)
  - ① Cas A NS Cooling by axion
  - ② Side Remark: Supernova Axion
  - ③ NS Heating by DM

A quick break... Any questions?

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NS Standard Cooling Theory

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

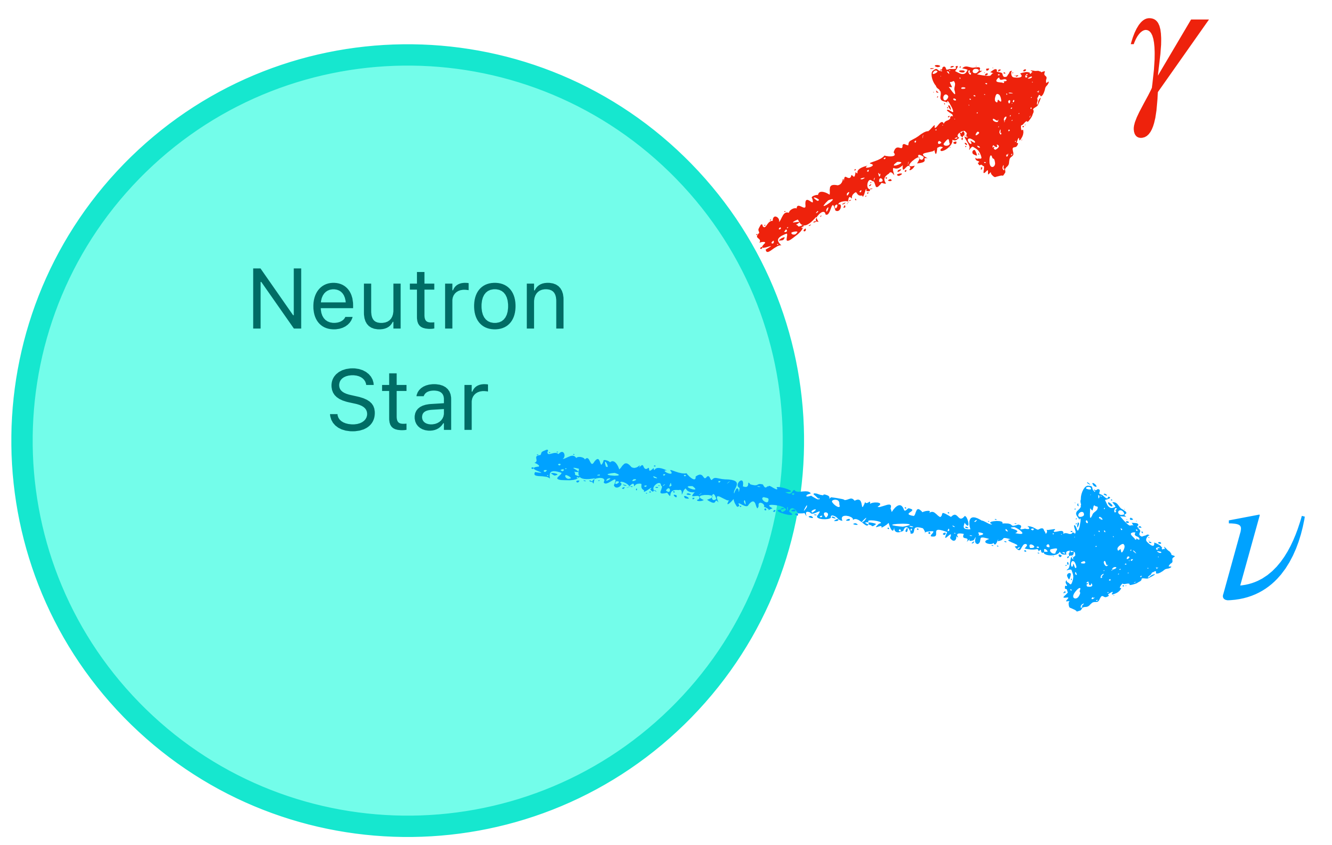
$$C\frac{dT}{dt} = -L_\nu - L_\gamma$$

RHS = Cooling Luminosity.

LHS = Temperature Evolution.

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

NS Standard Cooling Theory

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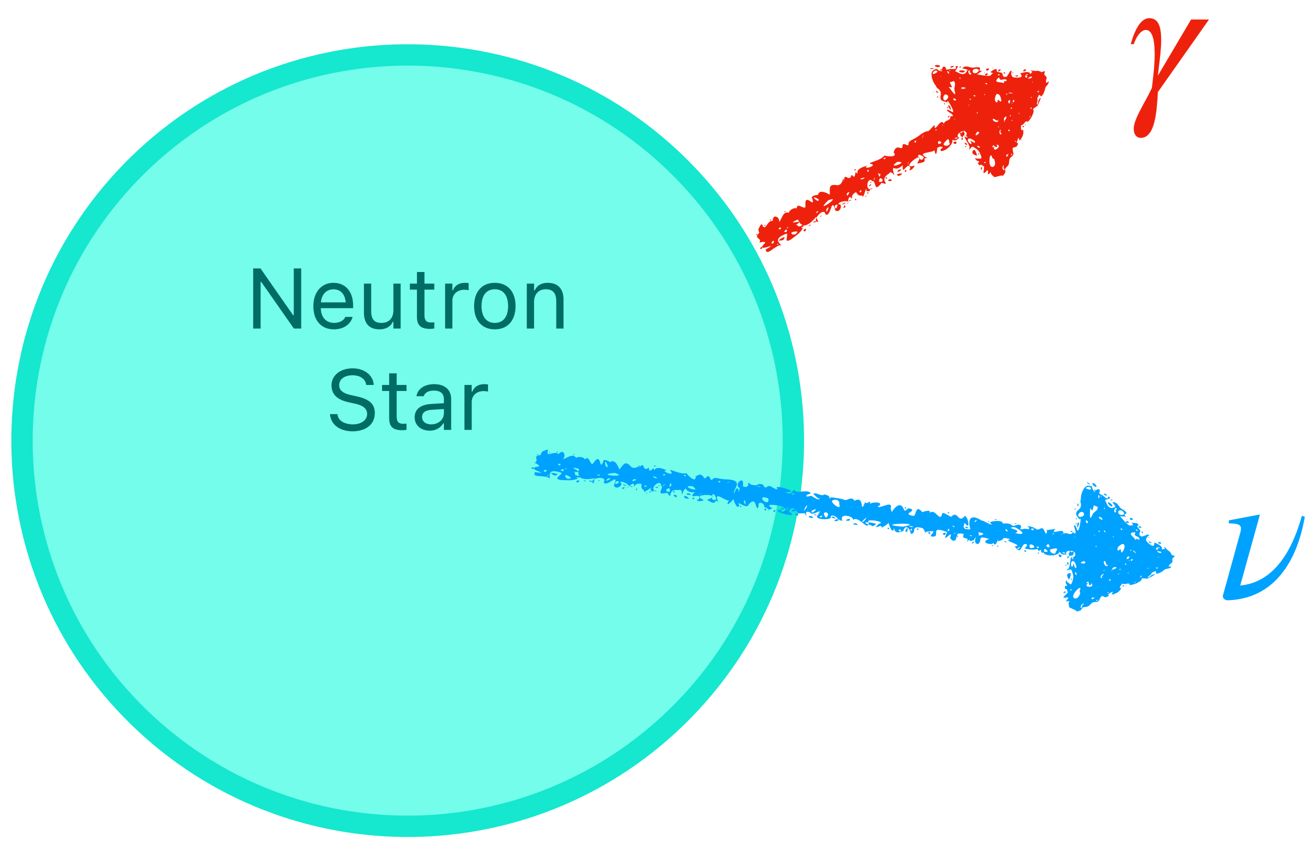
$$C\frac{dT}{dt} = -L_\nu - L_\gamma$$

Photon emission

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

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



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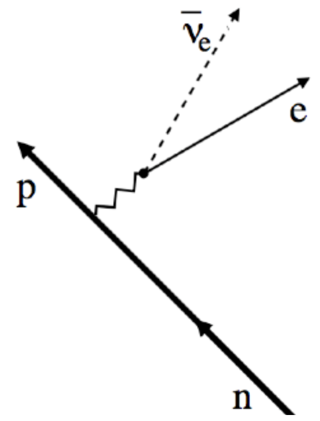
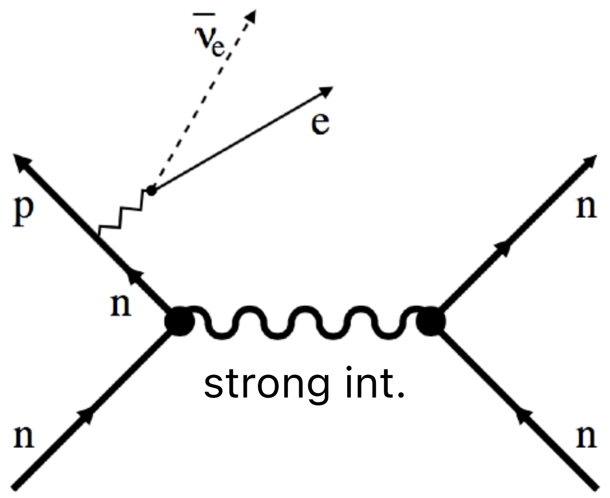
Neutrino emission
dominant for a young NS ($\tau \lesssim 10^5$ yrs)

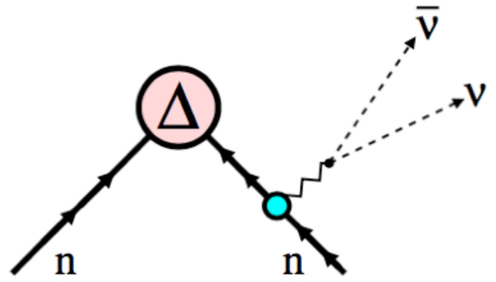
- Direct Urca

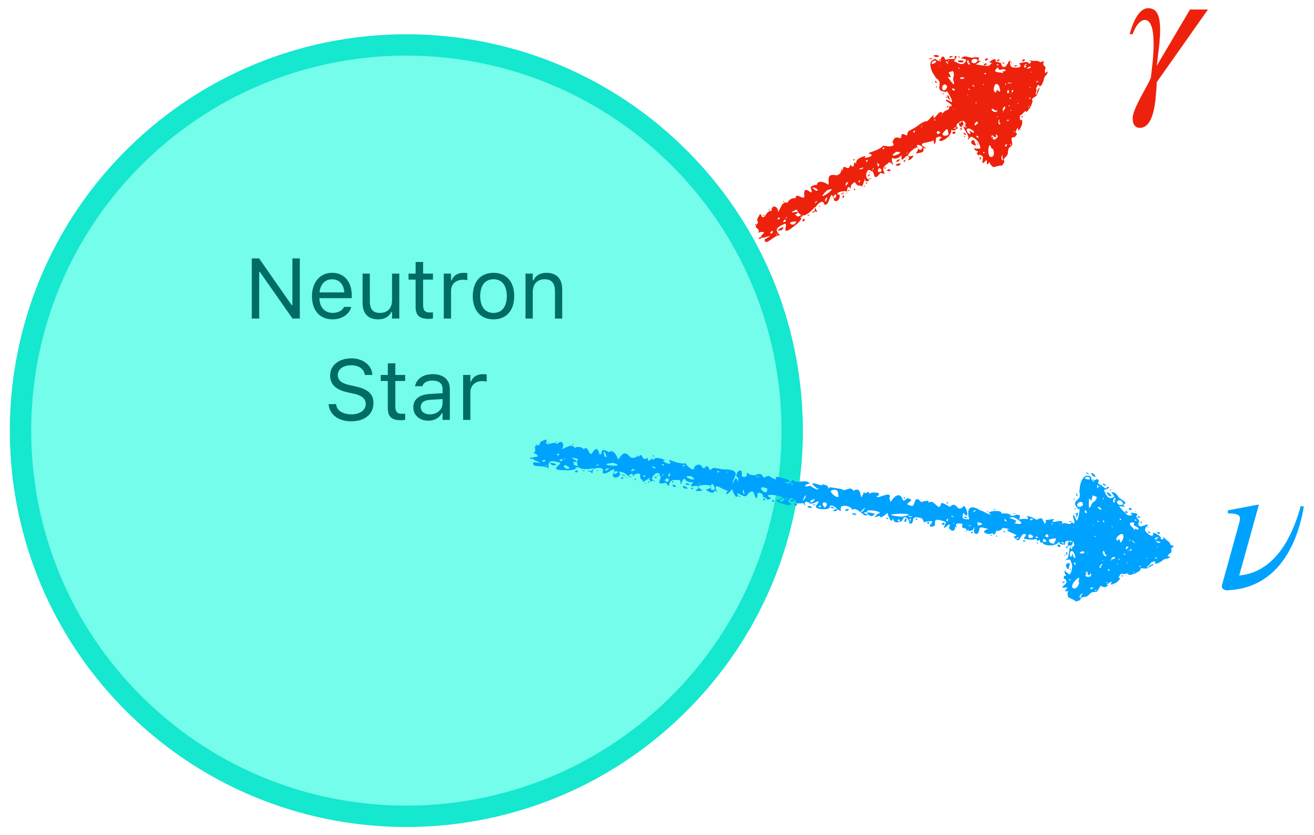


- Modified Urca
(& Bremsstrahlung)



- PBF





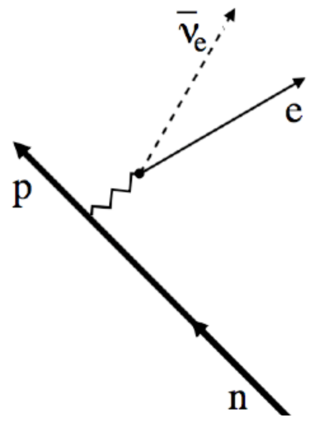
NS Standard Cooling Theory

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

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

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

- ~~Direct Urca~~

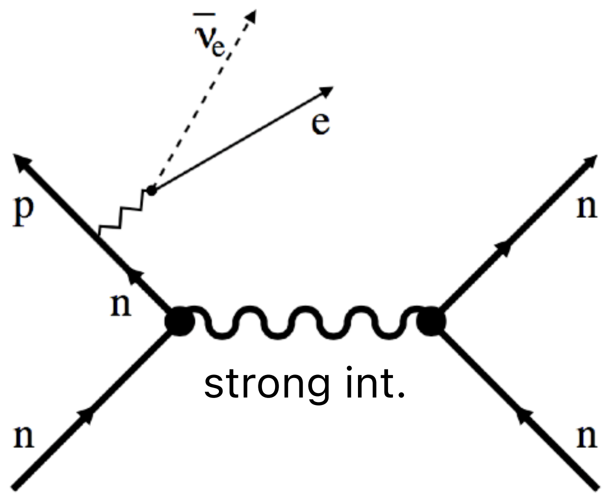


β decay and its inverse: $\begin{cases} n \to p + e^- + \bar{\nu}_e \\ p + e^- \to n + \nu_e \end{cases}$

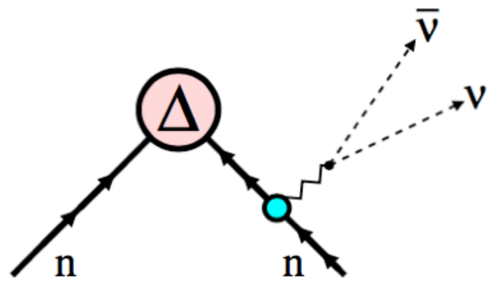
It does **NOT** work in typical NS because $p_{p,F} + p_{e,F} < p_{n,F}$.

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

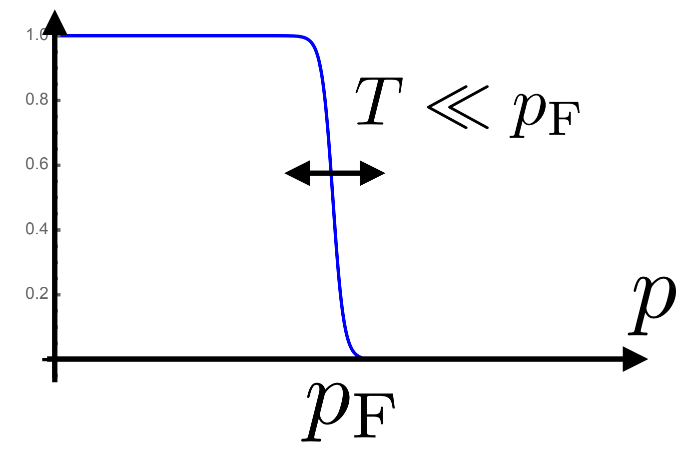
- Modified Urca
(& Bremsstrahlung)



- PBF



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



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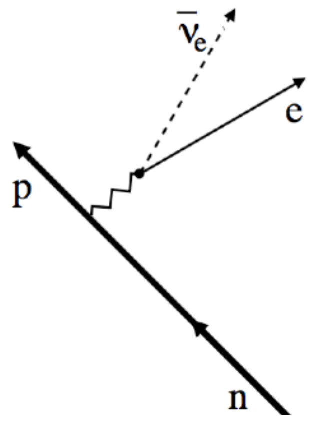
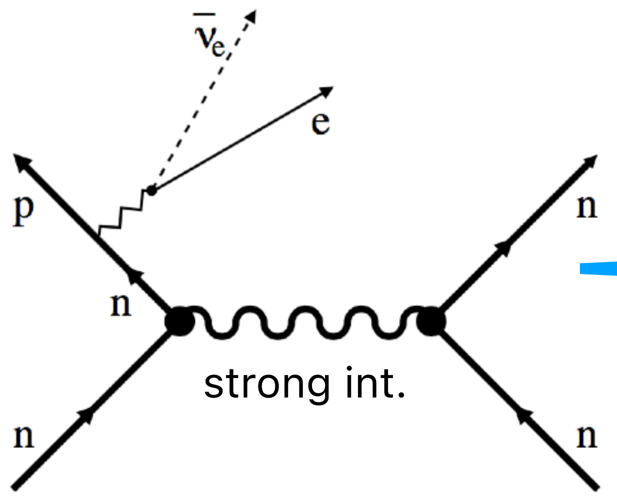
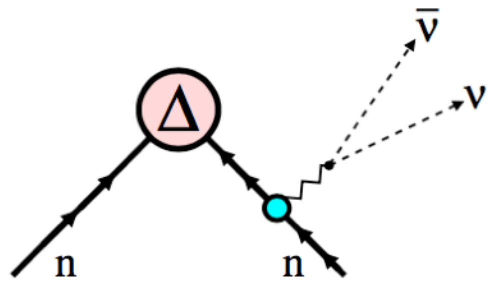


- **Modified Urca**
  (& Bremsstrahlung)



- PBF



Modified Urca

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

dominant process for $T > T_c$

NS Standard Cooling Theory

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

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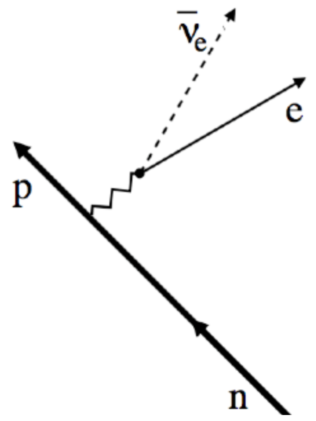
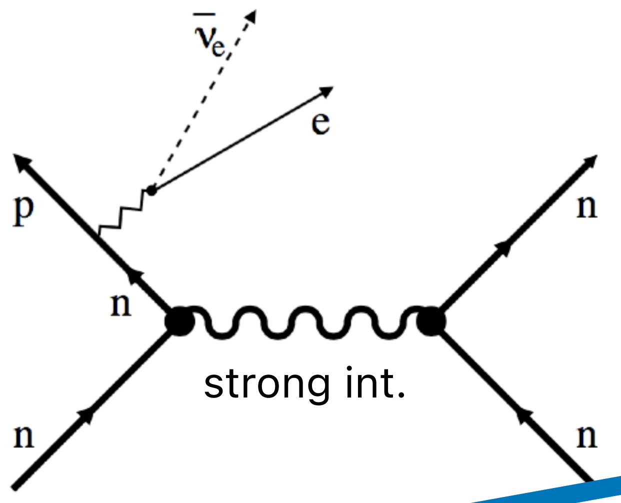
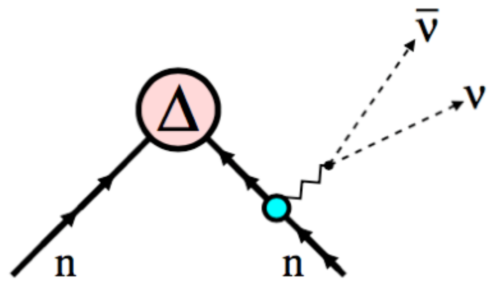


- **Modified Urca** (& Bremsstrahlung)

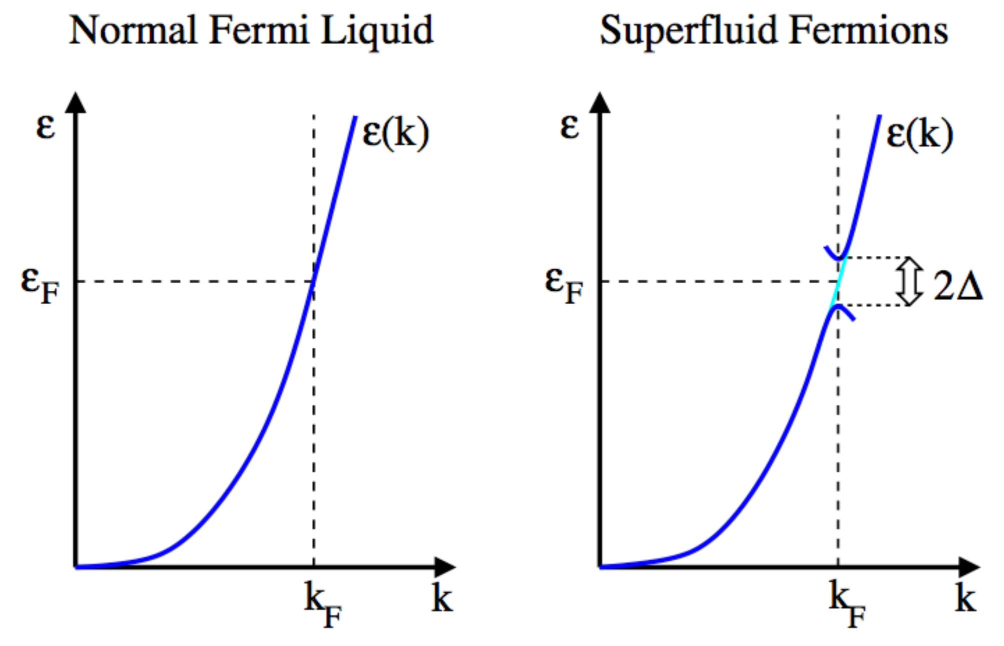


- **PBF**

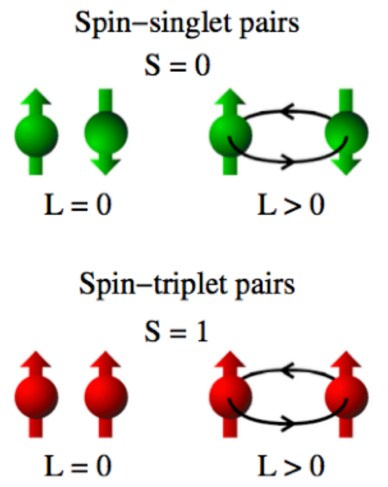


At $T < T_c$, Cooper pairing (p-p and n-n) occurs.

Superfluidity



$T > T_c$ $\quad$ $T < T_c$



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

- Heat capacity C is suppressed.
- **M.Urca** luminosity $L_{\nu,MU}$ is suppressed.
- **PBF** occurs at $T < T_c$.

NS Standard Cooling Theory

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

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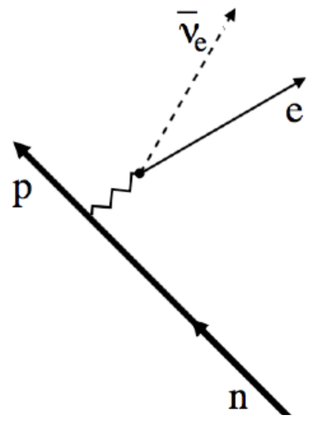

- **Modified Urca**
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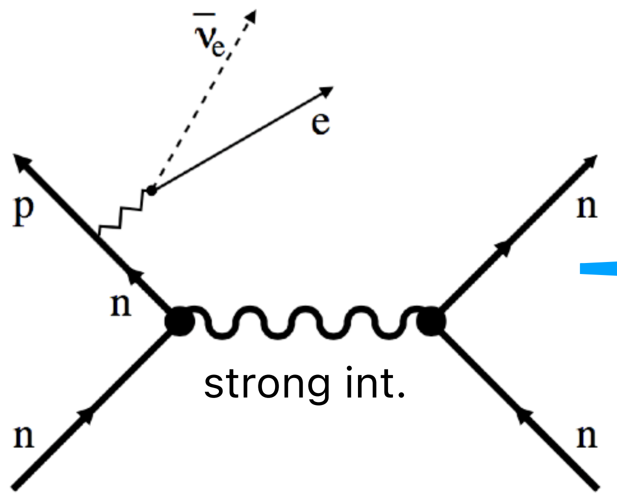

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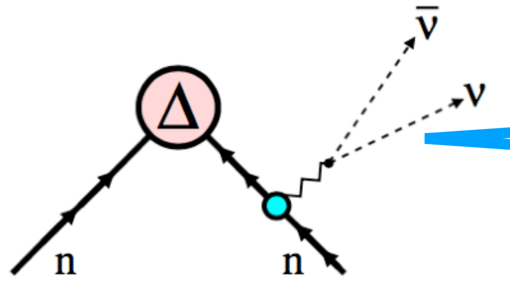
dominant process for $T > T_c$

- **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 $T < T_c$.

NS Standard Cooling Theory

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

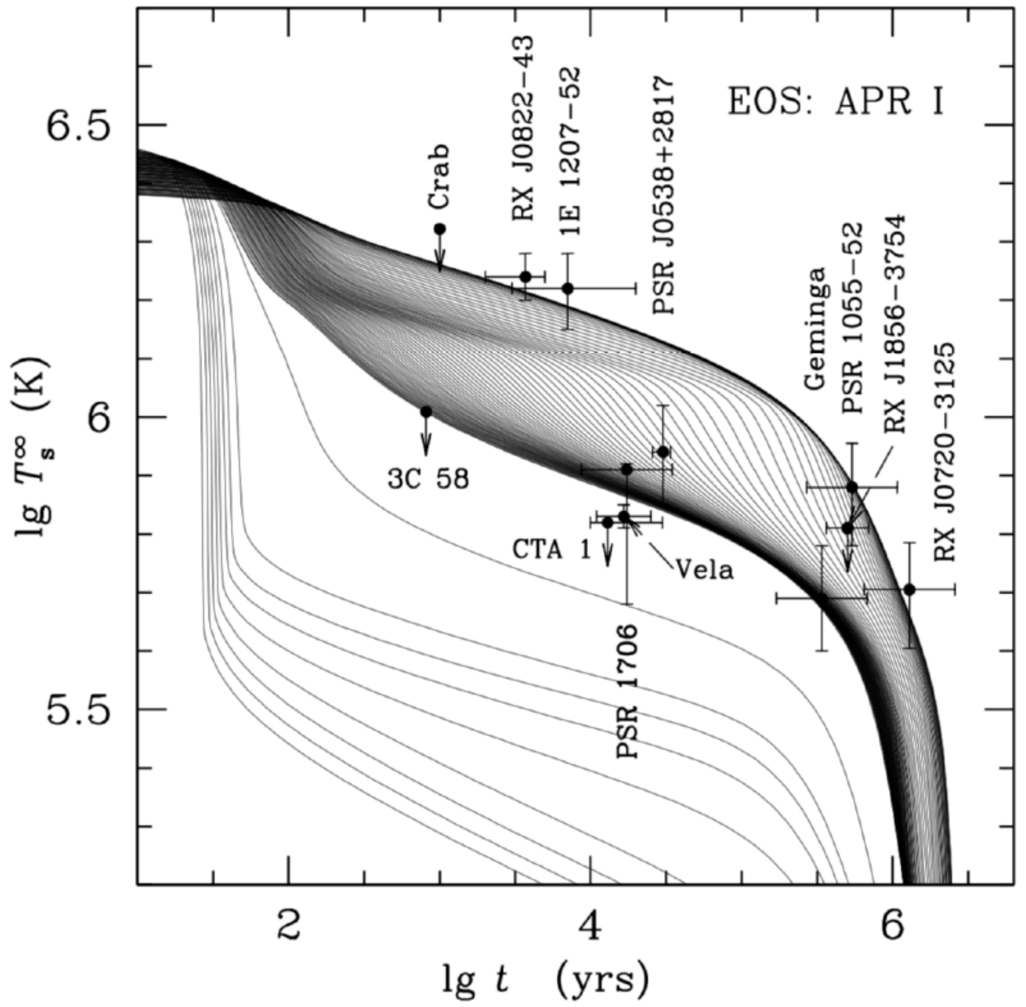
$$C\frac{dT}{dt} = -L_\nu - L_\gamma$$

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

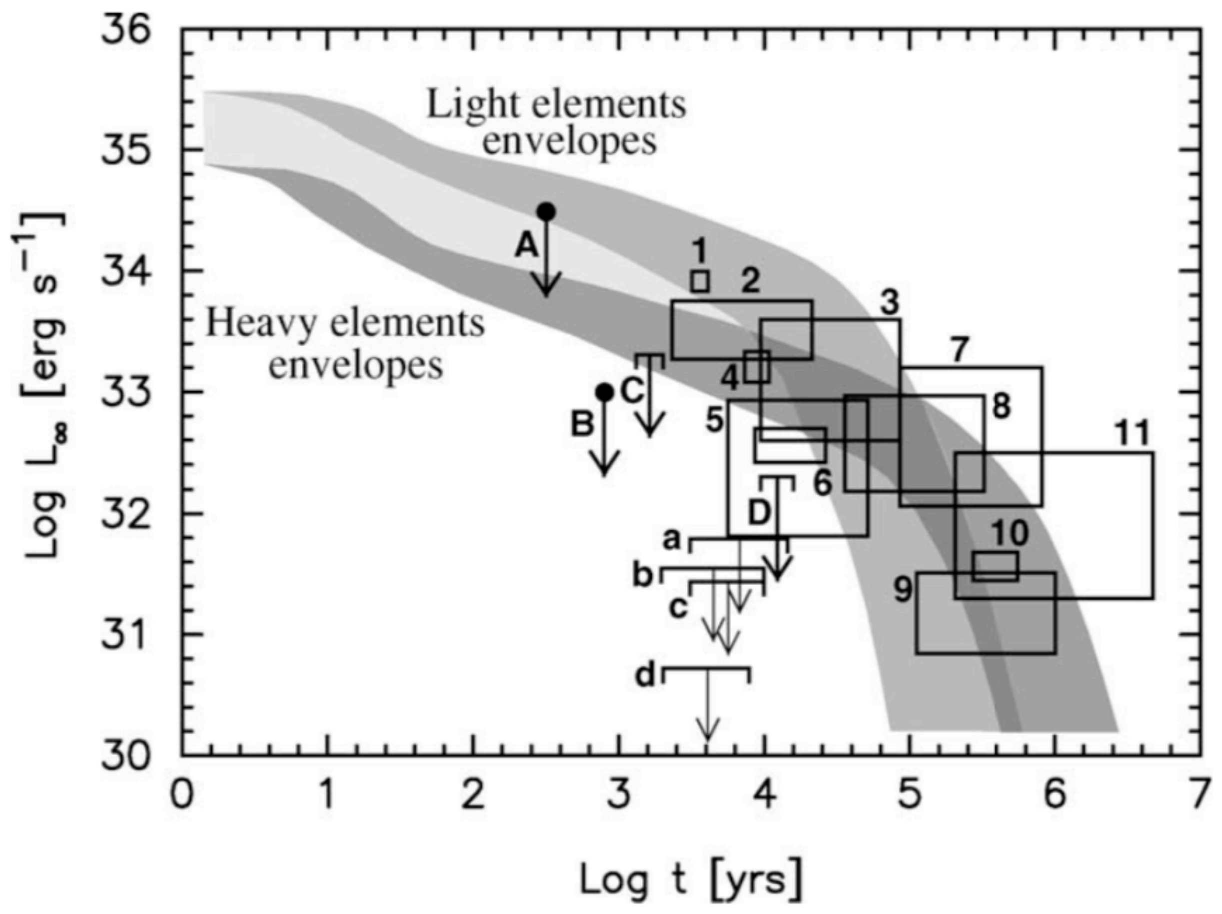
D.Page+, astro-ph/0403657,
M.E.Gusakov+, astro-ph/0404002,
D.Page+, 0906.1621

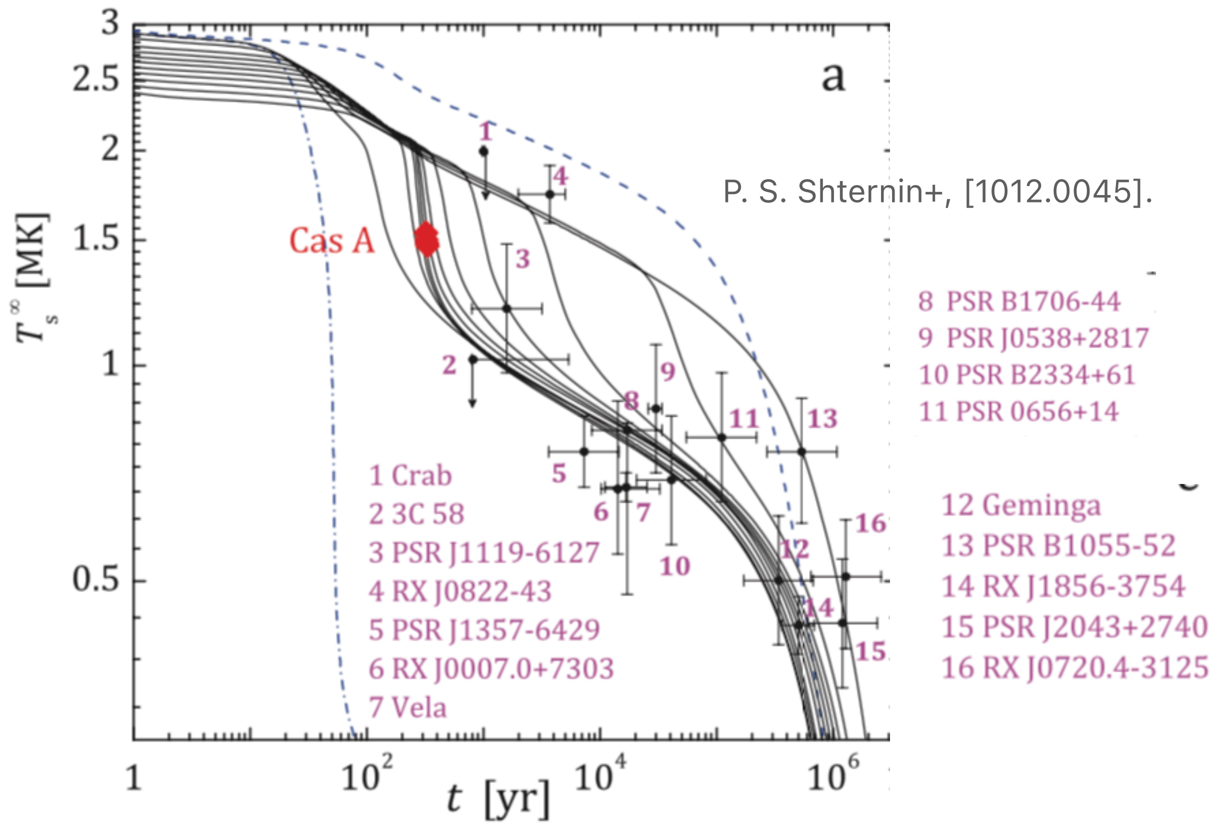
M. E. Gusakov, A. D. Kaminker, D. G. Yakovlev, O. Y. Gnedin

Mon.Not.Roy.Astron.Soc. **363** (2005) 555-562



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





Plan

- Neutron Star
- NS Standard Cooling Theory
- BSM vs NS (and SN)
    - ① Cas A NS Cooling by axion
    - ② Side Remark: Supernova Axion
    - ③ NS Heating by DM

A quick break again.
Any questions?

Plan

- Neutron Star
- NS Standard Cooling Theory
- BSM vs NS (and SN)
  - ① Cas A NS Cooling by **axion**
  - ② Side Remark: Supernova Axion
  - ③ NS Heating by DM

① Cas A NS Cooling by axion

KH, Nagata, Yanagi, Zheng, [1806.07151]
KH, Nagata, Zheng [2502.18931] **(update)**

Axion

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

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

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

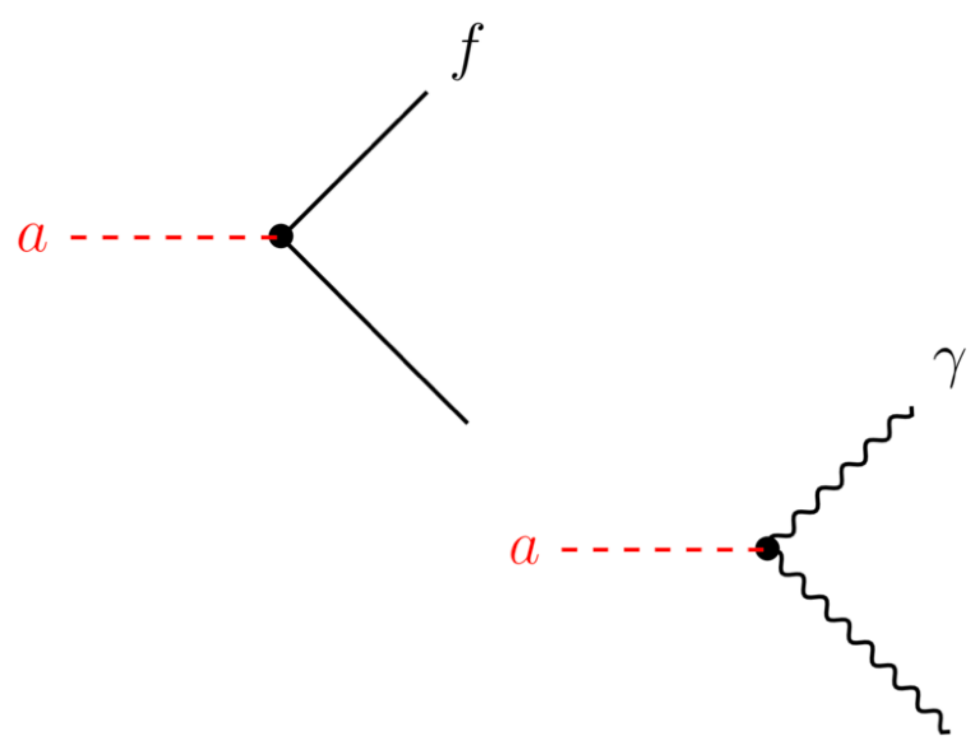
Experimental constraint (neutron EDM)

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

Why?

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

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

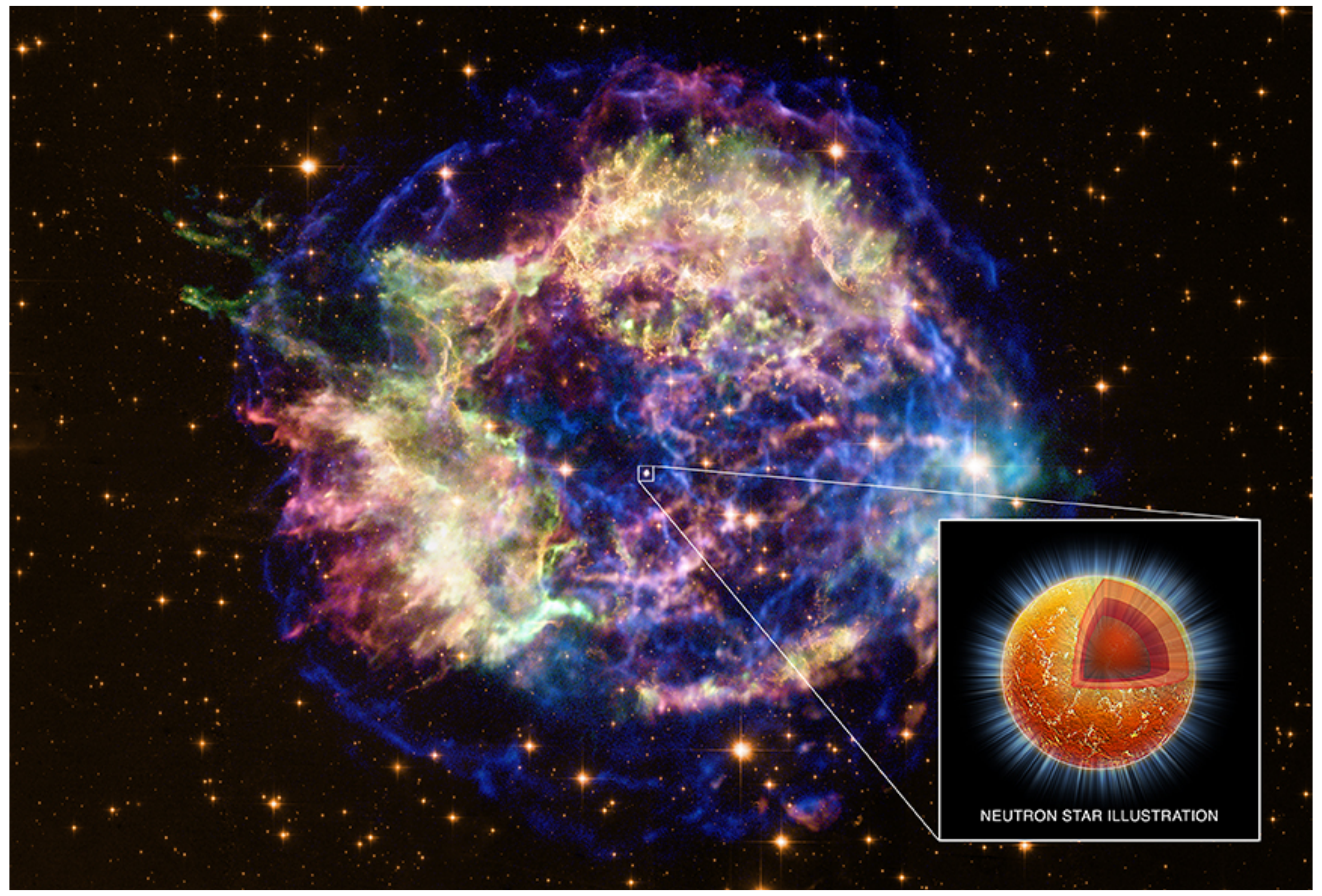


① Cas A NS Cooling by axion

KH, Nagata, Yanagi, Zheng, [1806.07151]
KH, Nagata, Zheng [2502.18931] **(update)**

What is Cas A NS?

- neutron star (NS) at the centre of the Cassiopeia A supernova remnant.
- ∼ 340 yrs old. (A young NS.)



Cassiopeia A (Cas A) supernova remnant and the NS at the center (Cas A NS).

Chandra found the NS in 1999.

① Cas A NS Cooling by axion

KH, Nagata, Yanagi, Zheng, [1806.07151]
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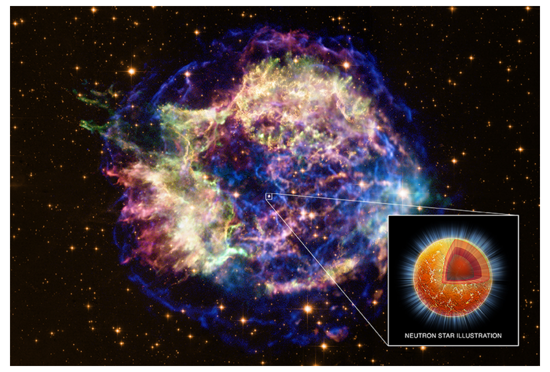
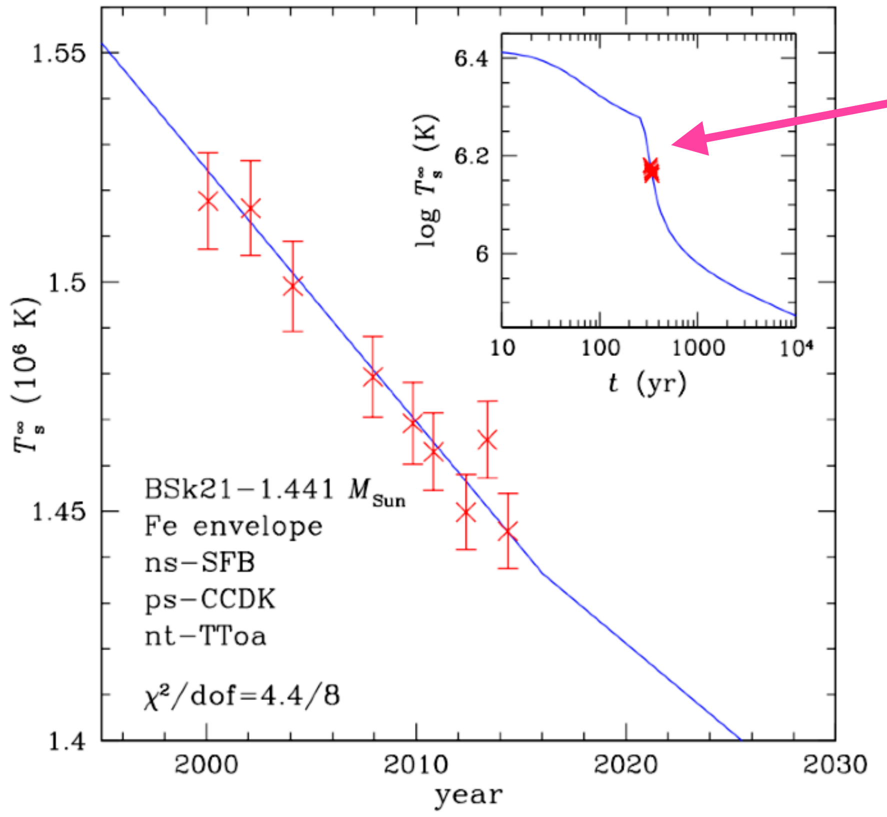


Why Cas A NS?

It is the only isolated NS whose **cooling has been observed in real time.**

- 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.

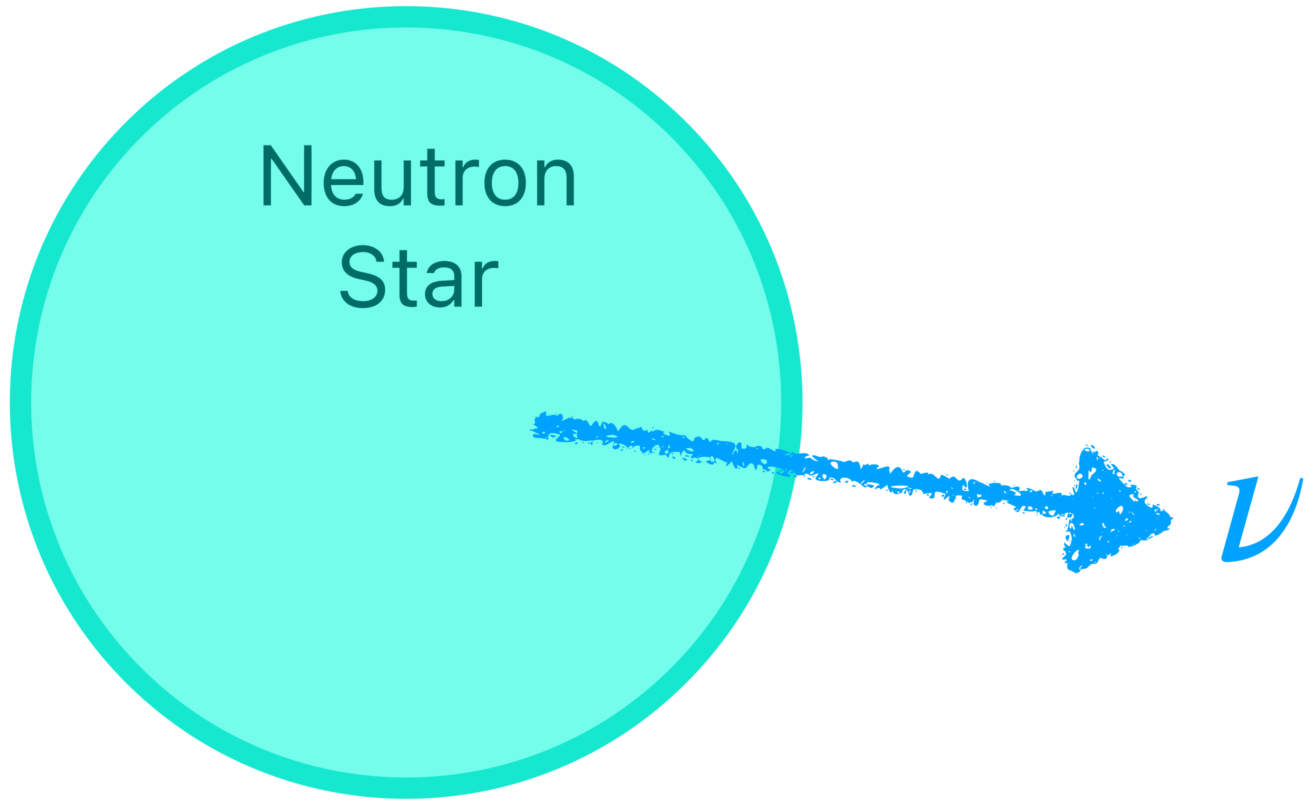
Fig. from W.C.G.Ho+, 1412.7759.

① Cas A NS Cooling by axion

KH, Nagata, Yanagi, Zheng, [1806.07151]
KH, Nagata, Zheng [2502.18931] **(update)**

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

negligible for $\tau \sim 300$ yrs

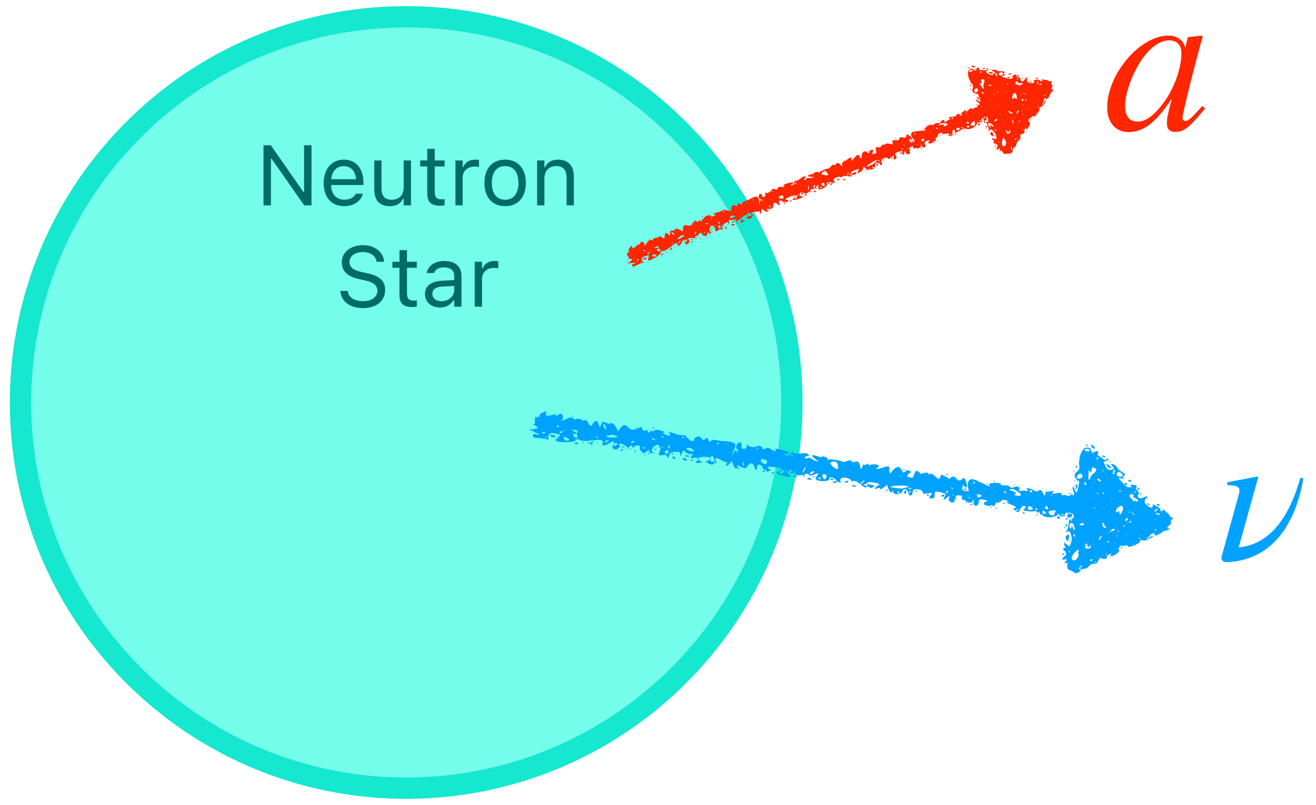


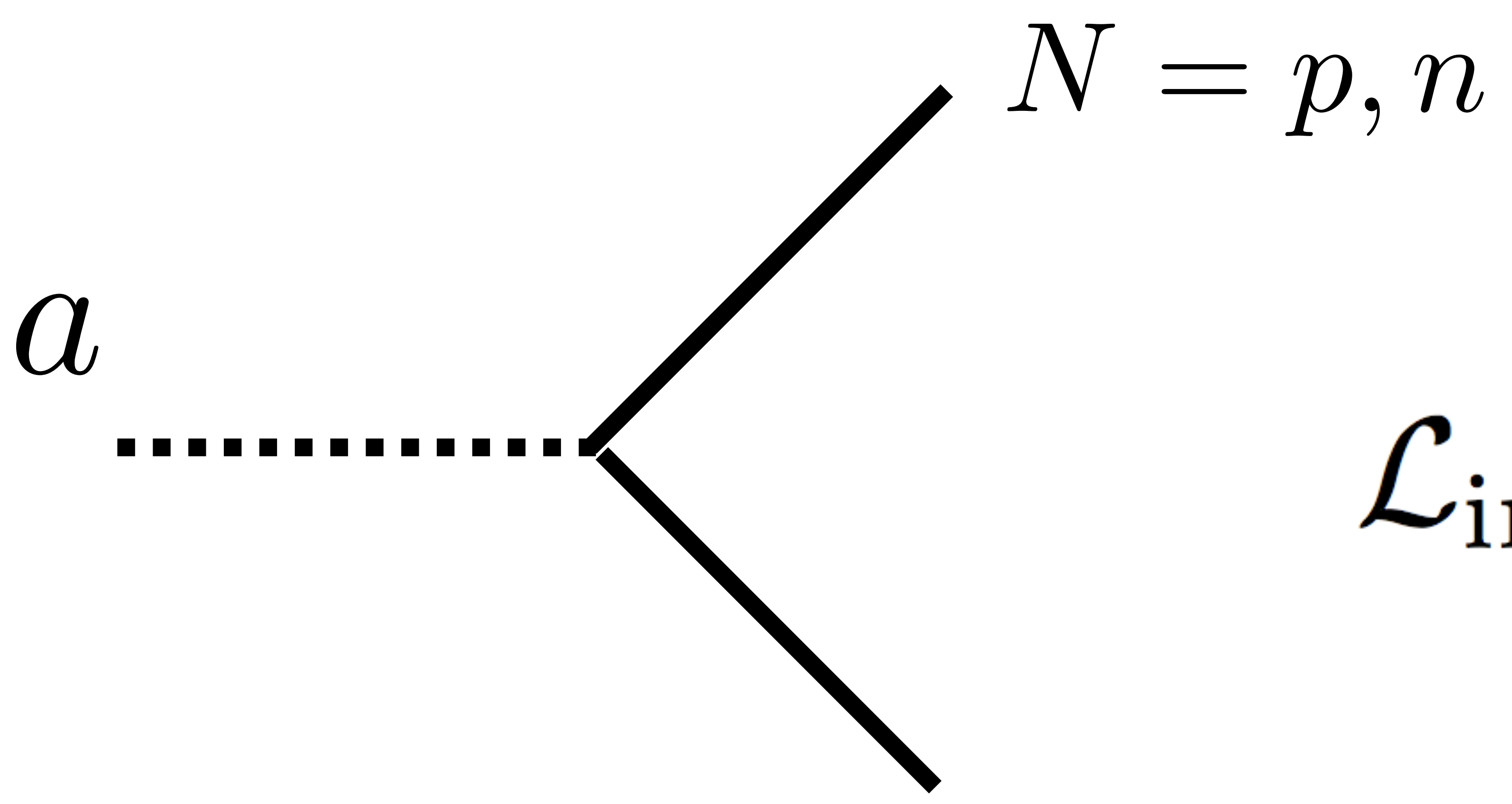
① Cas A NS Cooling by axion

KH, Nagata, Yanagi, Zheng, [1806.07151]
KH, Nagata, Zheng [2502.18931] **(update)**

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

axion emission





$$\mathcal{L}_{\rm int} = \sum_{N=p,n} \frac{C_N}{2f_a} \bar{N}\gamma^\mu\gamma_5 N \partial_\mu a$$

C_N : model−dependent parameter

$$\text{KSVZ:} \begin{cases} C_p = -0.47(3) \\ C_n = -0.02(3) \end{cases}$$

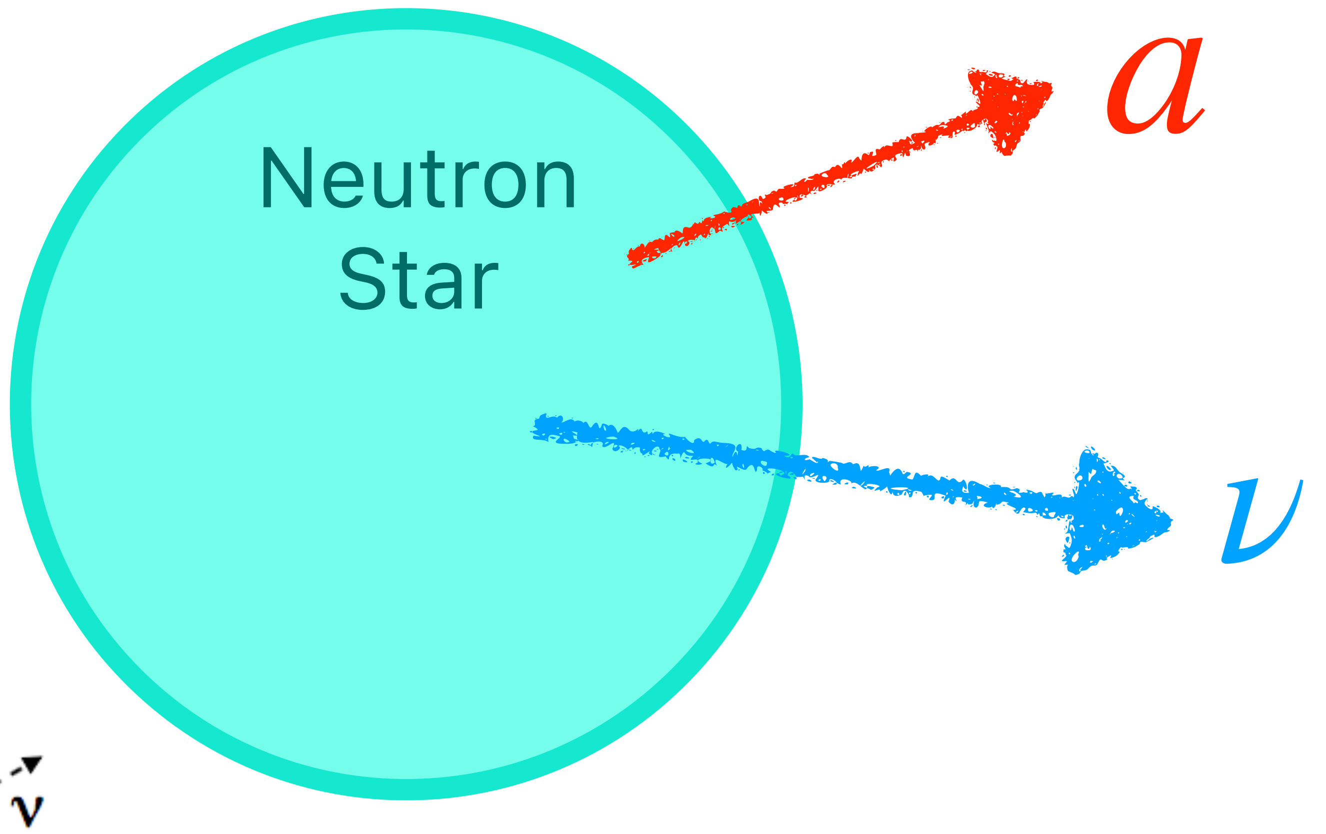
$$\text{DFSZ:} \begin{cases} C_p = -0.182(25) - 0.435\sin^2\beta \\ C_n = -0.160(25) - 0.414\sin^2\beta \end{cases}$$

① Cas A NS Cooling by axion

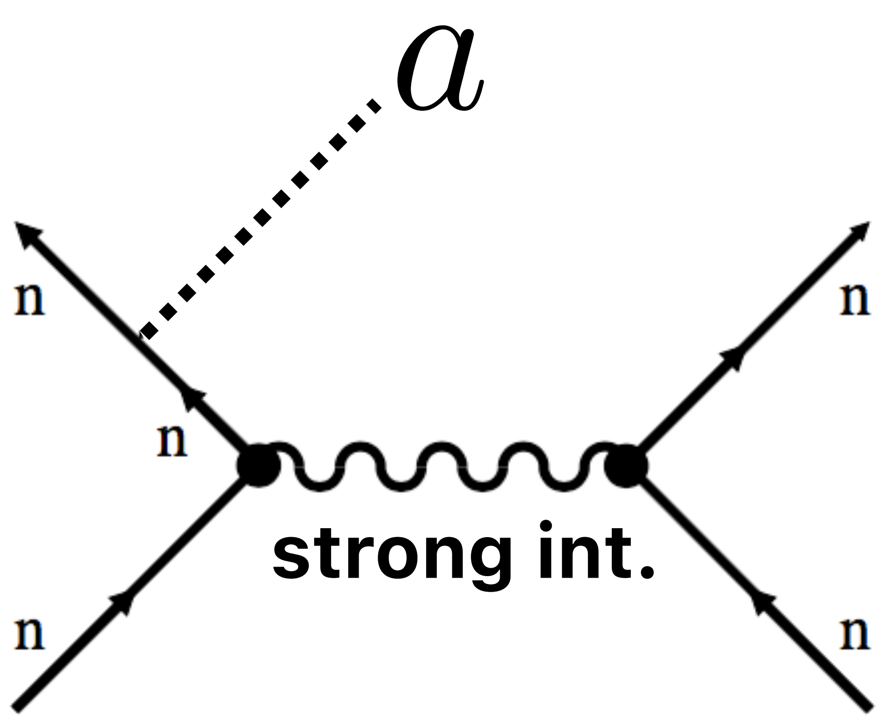
KH, Nagata, Yanagi, Zheng, [1806.07151]
KH, Nagata, Zheng [2502.18931] **(update)**

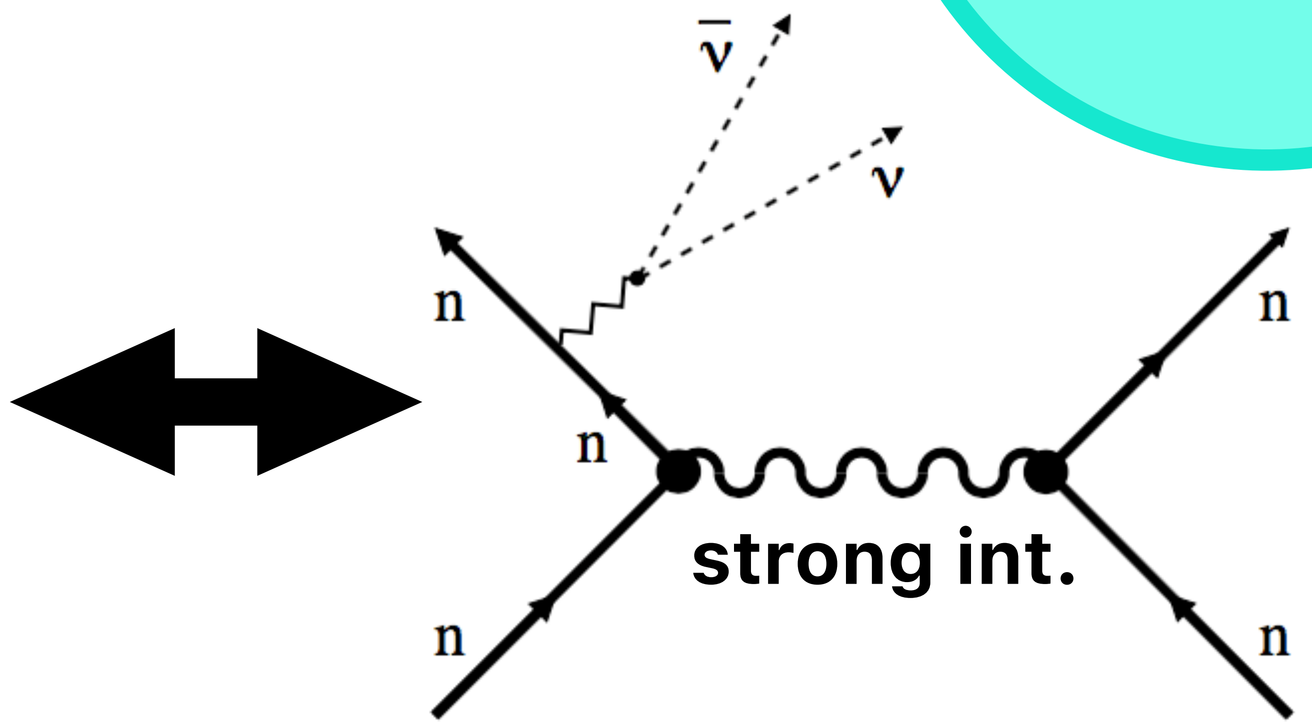
$$C\frac{dT}{dt} = -L_\nu - L_a$$

axion emission

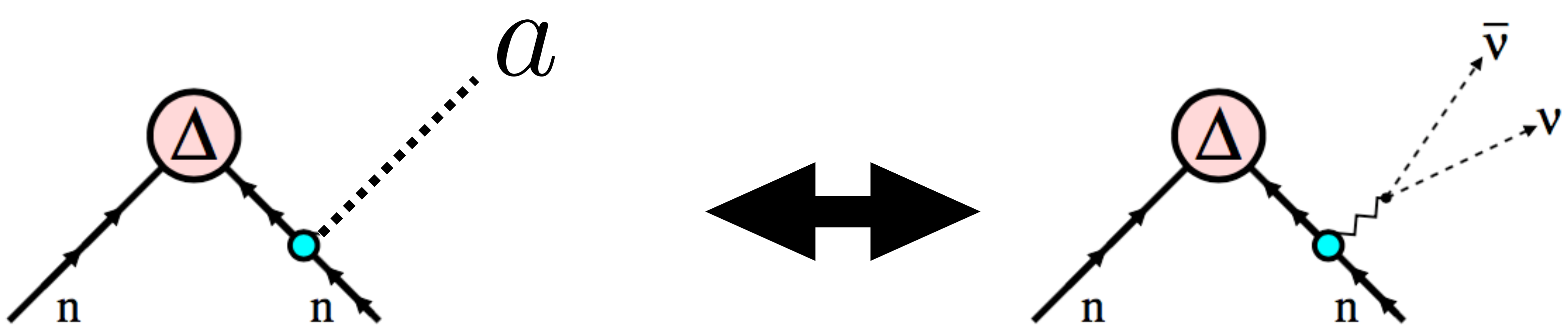


Bremsstrahlung axion emission





PBF axion emission



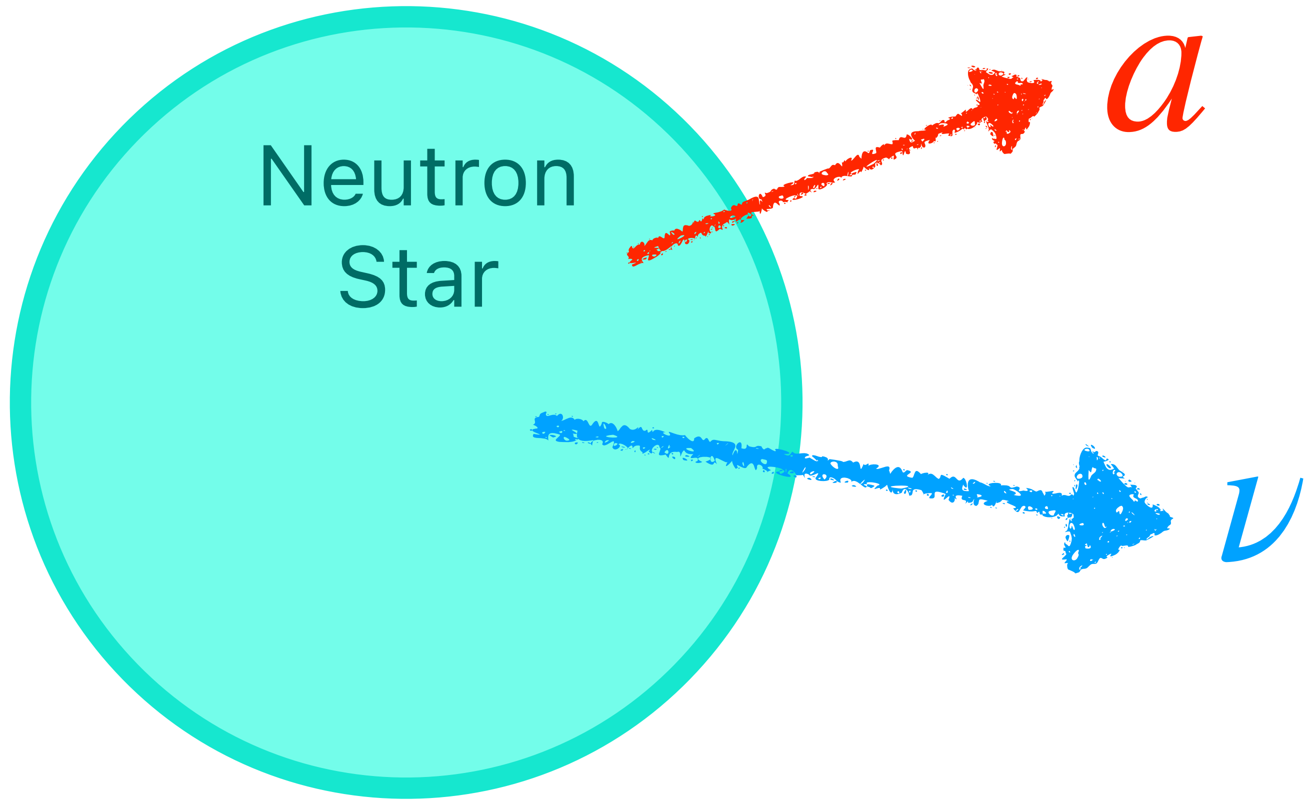
Brems.: N. Iwamoto, Phys. Rev. Lett. 53, 1198 (1984); N. Iwamoto,'89, '01.
PBF: A. Sedrakian, 1512.07828 [PRD]; J. Keller, A. Sedrakian,'12.

① Cas A NS Cooling by axion

KH, Nagata, Yanagi, Zheng, [1806.07151]
KH, Nagata, Zheng [2502.18931] **(update)**

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

axion emission



What we did:

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

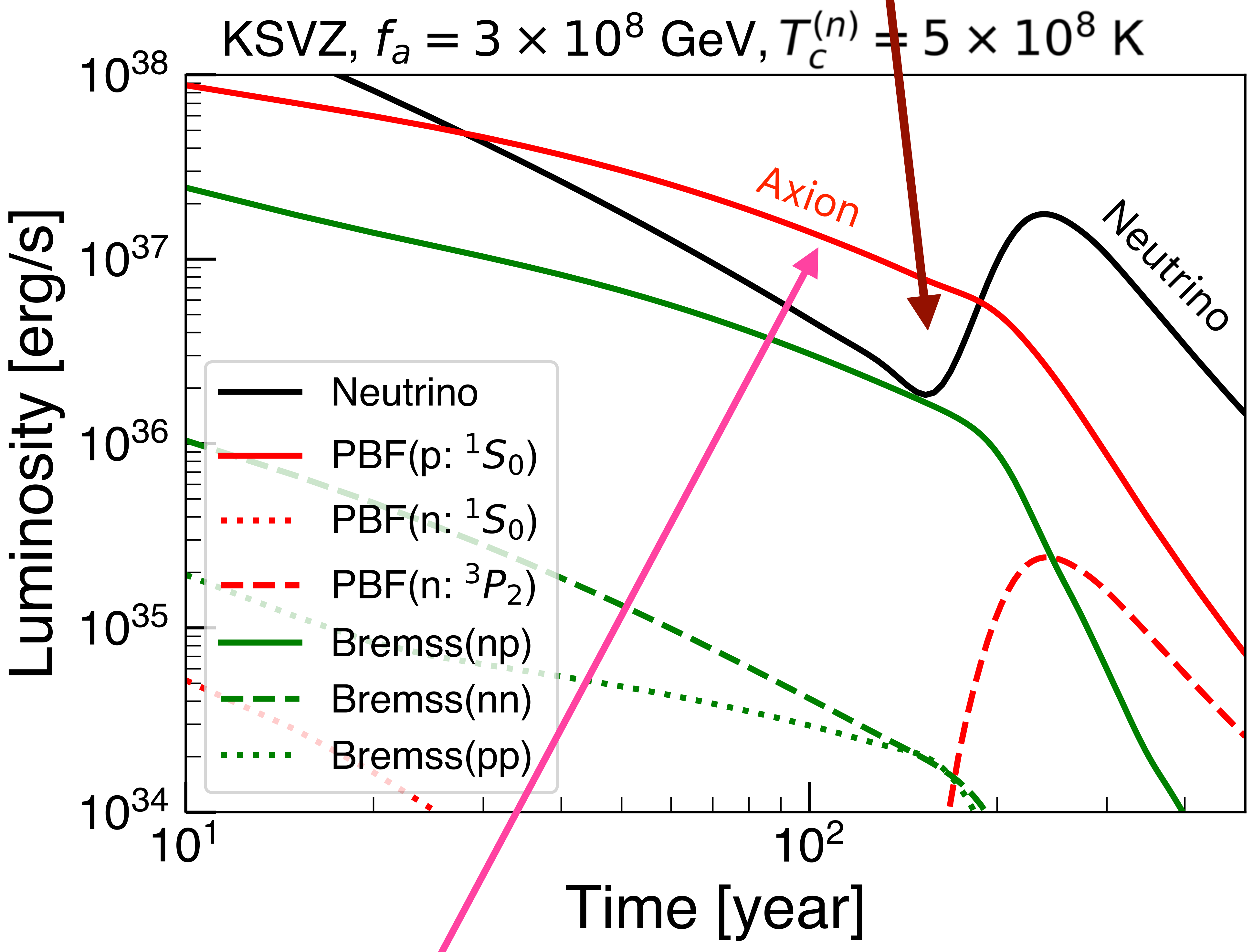
- APR EoS.
- NS mass $M = 1.4 M_\odot$
- gap models:
  - n-$^1S_0$ gap: SFB (doesn't matter)
  - p-$^1S_0$ gap: CCDK (doesn't matter as far as large enough)
  - n-$^3P_2$ gap: gap height $\Delta \propto T_c$ and width: free parameter.

① Cas A NS Cooling by axion

KH, Nagata, Yanagi, Zheng, [1806.07151]
KH, Nagata, Zheng [2502.18931] **(update)**

Results

phase transition
T = Tc



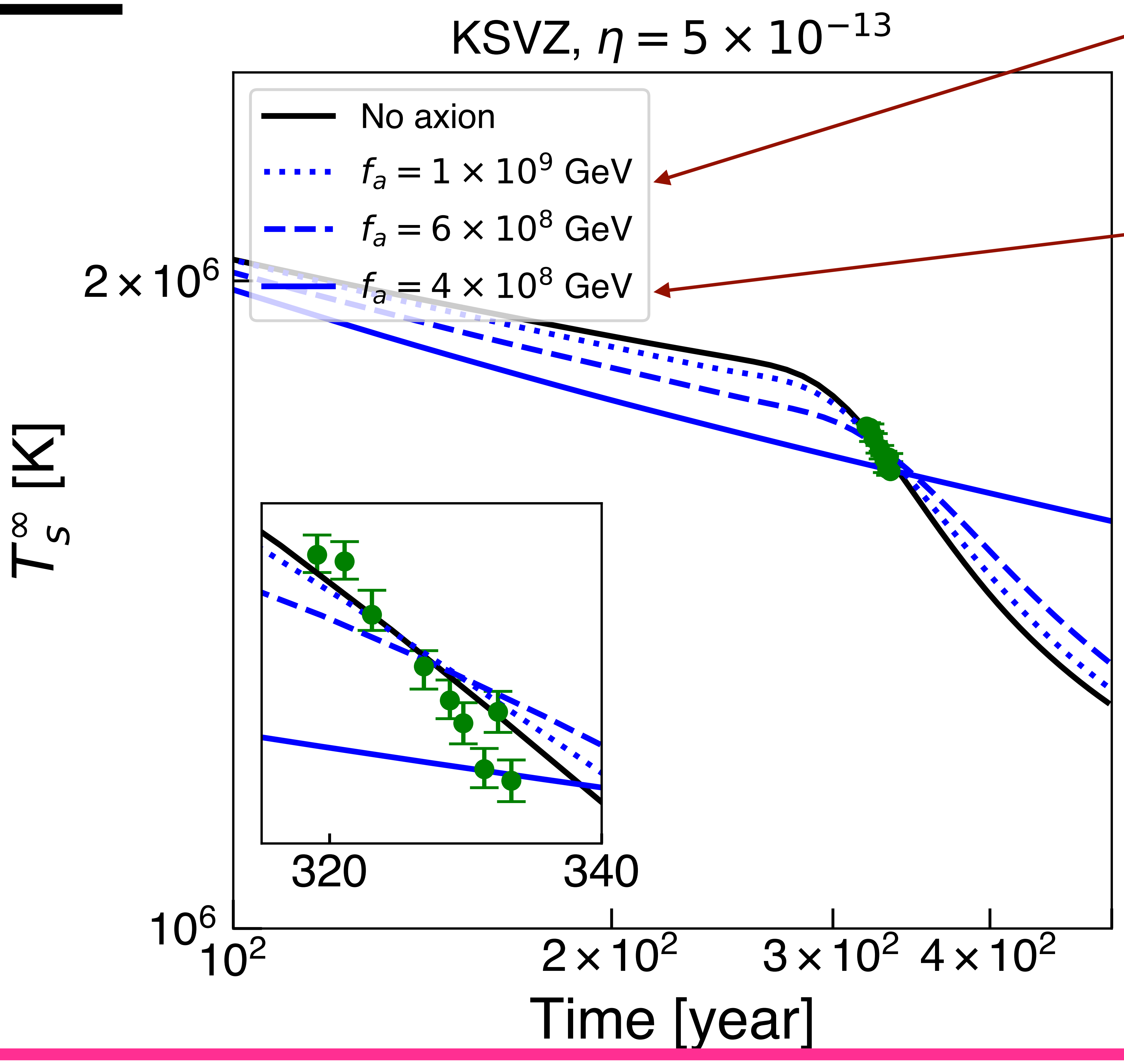
K. Hamaguchi,
N. Nagata,
K. Yanagi,
J. Zheng,
1806.07151

Axion emission can be as strong as neutrino emission.

① Cas A NS Cooling by axion

KH, Nagata, Yanagi, Zheng, [1806.07151]
KH, Nagata, Zheng [2502.18931] **(update)**

Results



$f_a = 1 \times 10^9$ GeV: can fit the data.

$f_a = 4 \times 10^8$ GeV: difficult to fit the data even by adjusting gap parameters.

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

$$\text{interaction} \propto \frac{1}{f_a}$$

obtained a new bound: $f_a \gtrsim 5 \times 10^8 \text{ GeV (KSVZ)}$

(for an envelope with a thin carbon layer)

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

① Cas A NS Cooling by axion

KH, Nagata, Yanagi, Zheng, [1806.07151]
KH, Nagata, Zheng [2502.18931] **(update)**

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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

INSPIRE search

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]

① Cas A NS Cooling by axion

KH, Nagata, Yanagi, Zheng, [1806.07151]
KH, Nagata, Zheng [2502.18931] **(update)**

update

KH, Nagata, Zheng [2502.18931]

02.18931v1 [hep-ph] 26 Feb 2025

Axion Emission from Proton Cooper Pairs in Neutron Stars

Koichi Hamaguchi[a,b*], Natsumi Nagata[a†], and Jiaming Zheng[‡]

[a]*Department of Physics, University of Tokyo, Bunkyo-ku, Tokyo 113–0033, Japan*
[b]*Kavli IPMU (WPI), University of Tokyo, Kashiwa, Chiba 277–8583, Japan*

Abstract

We investigate axion emission from singlet proton Cooper pairs in neutron stars, a process that dominates axion emission in young neutron stars in the KSVZ model. By re-deriving its emissivity, we confirm consistency with most existing literature, except for a recent study that exhibits a different dependence on the effective mass. This discrepancy results in more than an order-of-magnitude deviation in emissivity, significantly impacting constraints on the KSVZ axion from the cooling observations of the Cassiopeia A neutron star. Furthermore, we examine uncertainties arising from neutron-star equations of state and their role in the discrepancy, finding that the large deviation persists regardless of the choice of equations of state.

- Our results [1806.07151] : $f_a \gtrsim 5 \times 10^8$ GeV (KSVZ)
- Leinson [2105.14745] obtained a much weaker bound: $f_a \gtrsim 3 \times 10^7$ GeV (KSVZ).
- In this paper [2502.18931], we identified the source of this discrepancy as a different dependence on the effective nucleon mass, $m*$.
- Our re-derived formula is consistent with the one used in our previous analysis, as well as with other literature, implying that **our earlier result,** $f_a \gtrsim 5 \times 10^8$ GeV, **remains largely unchanged**.
- A more detailed and systematic update will be given in future work.

Plan

- Neutron Star
- NS Standard Cooling Theory
- BSM vs NS (and SN)
  - ① Cas A NS Cooling by **axion**
  - ② Side Remark: Supernova Axion
  - ③ NS Heating by DM

Any questions?

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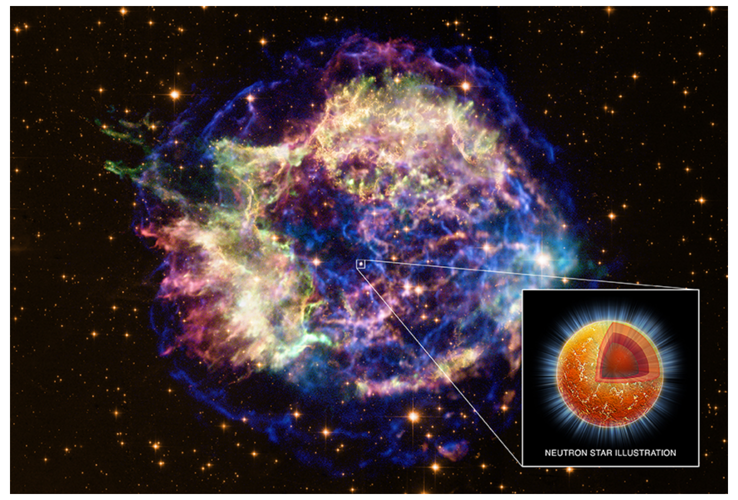
① Cas A NS Cooling by axion

② Side Remark: **Supernova Axion**

③ NS Heating by DM

② Side Remark

- **Cas A (supernova)**
  - 340 years ago
  - 3.4 kpc
  - NS found in 1999.



Chandra

② Side Remark

👉 cf. talks yesterday by
Jakob Ehring, Yu Min Yeh, Yen-Hsun Lin

- **Cas A (supernova)**
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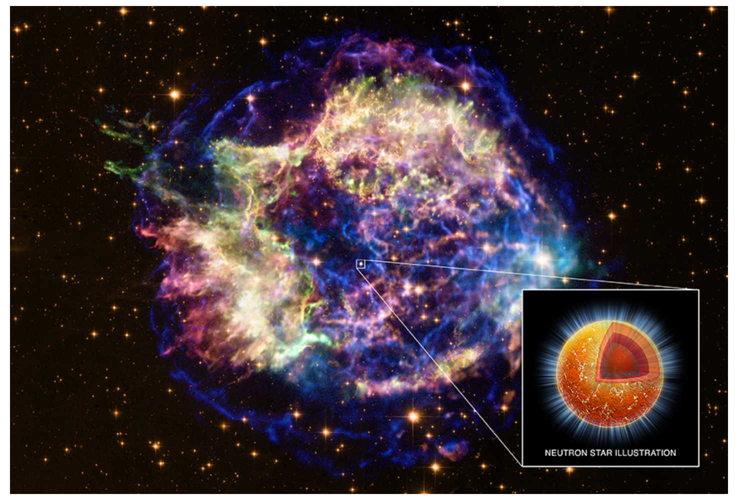
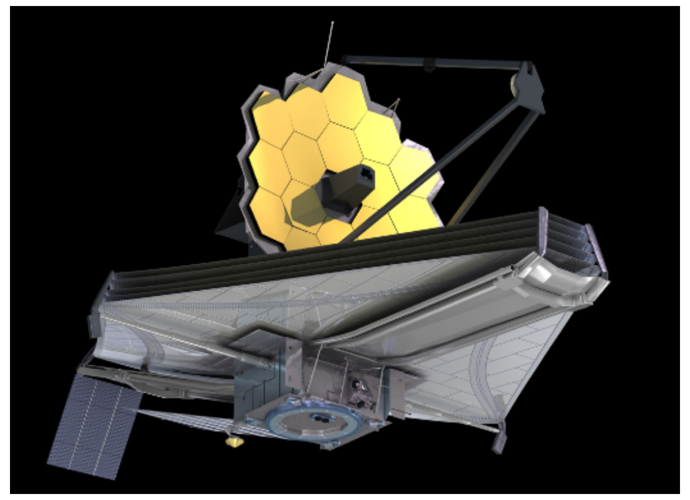


Chandra

- **SN1987A**
  - 38 years ago
  - 51 kpc
  - NS just found recently??



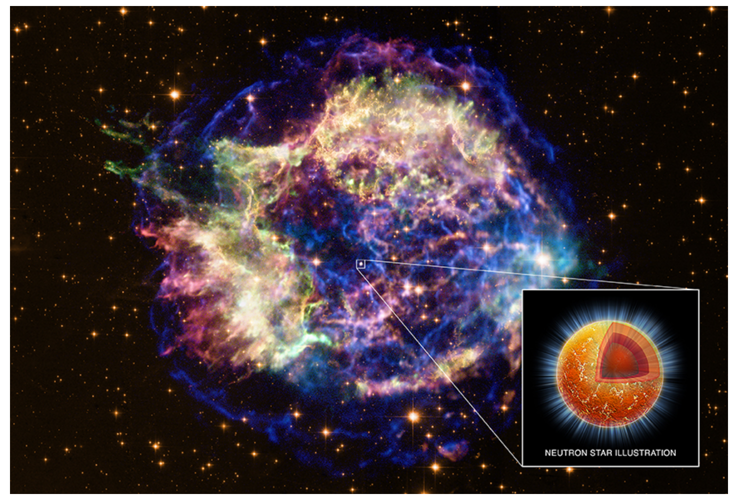
JWST

  - → More data on NS cooling (and axion?) in the next future?!

② Side Remark

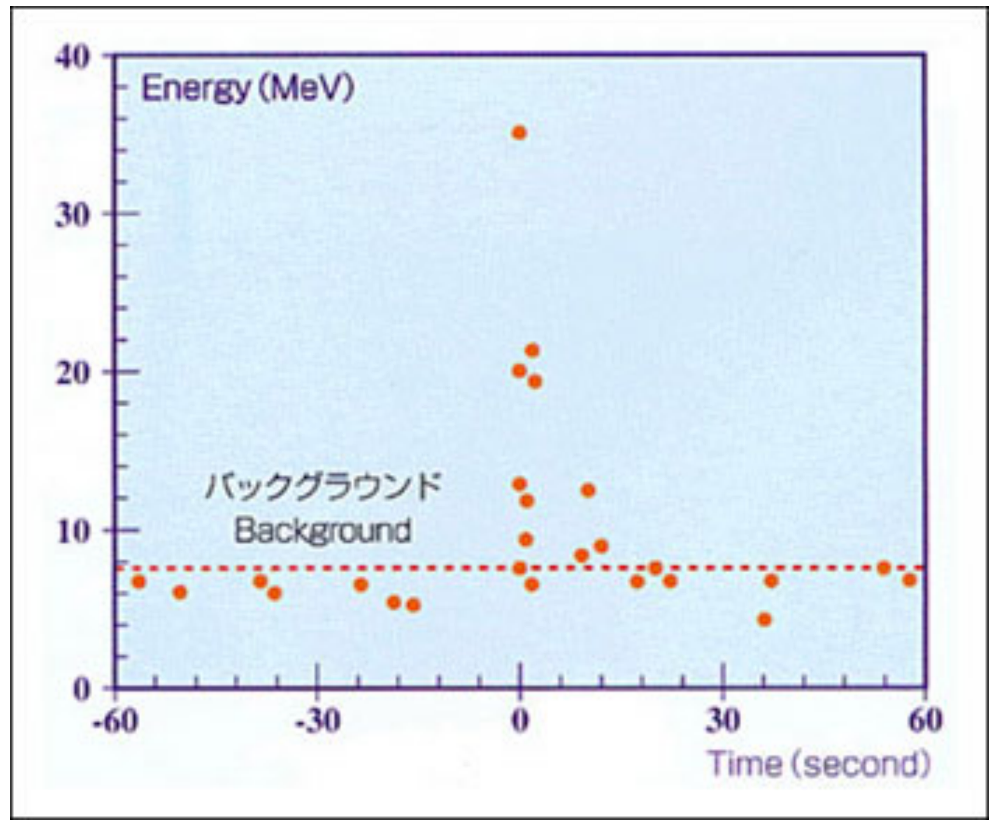
👉 cf. talks yesterday by
Jakob Ehring, Yu Min Yeh, Yen-Hsun Lin

- **Cas A (supernova)**
  - 340 years ago
  - 3.4 kpc
  - NS found in 1999.



Chandra

- **SN1987A**
  - 38 years ago
  - 51 kpc
  - **neutrino burst**



Kamiokande

http://www-sk.icrr.u-tokyo.ac.jp/sk/physics/supernova-e.html

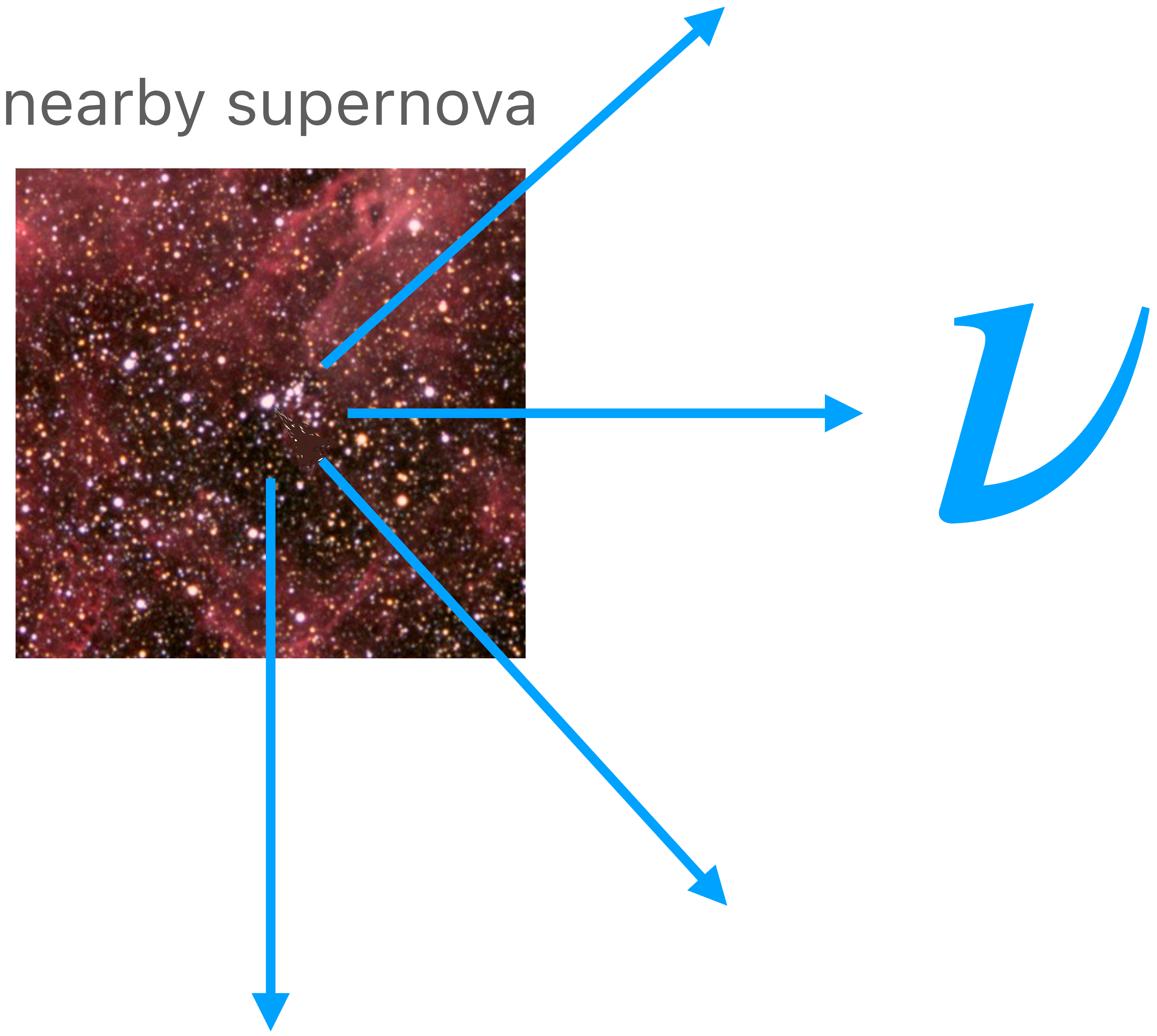
- What if **a nearby supernova** occurs in near future?

② Side Remark

👉 cf. talks yesterday by Jakob Ehring, Yu Min Yeh, Yen-Hsun Lin

- What if **a nearby supernova** occurs in near future?

nearby supernova



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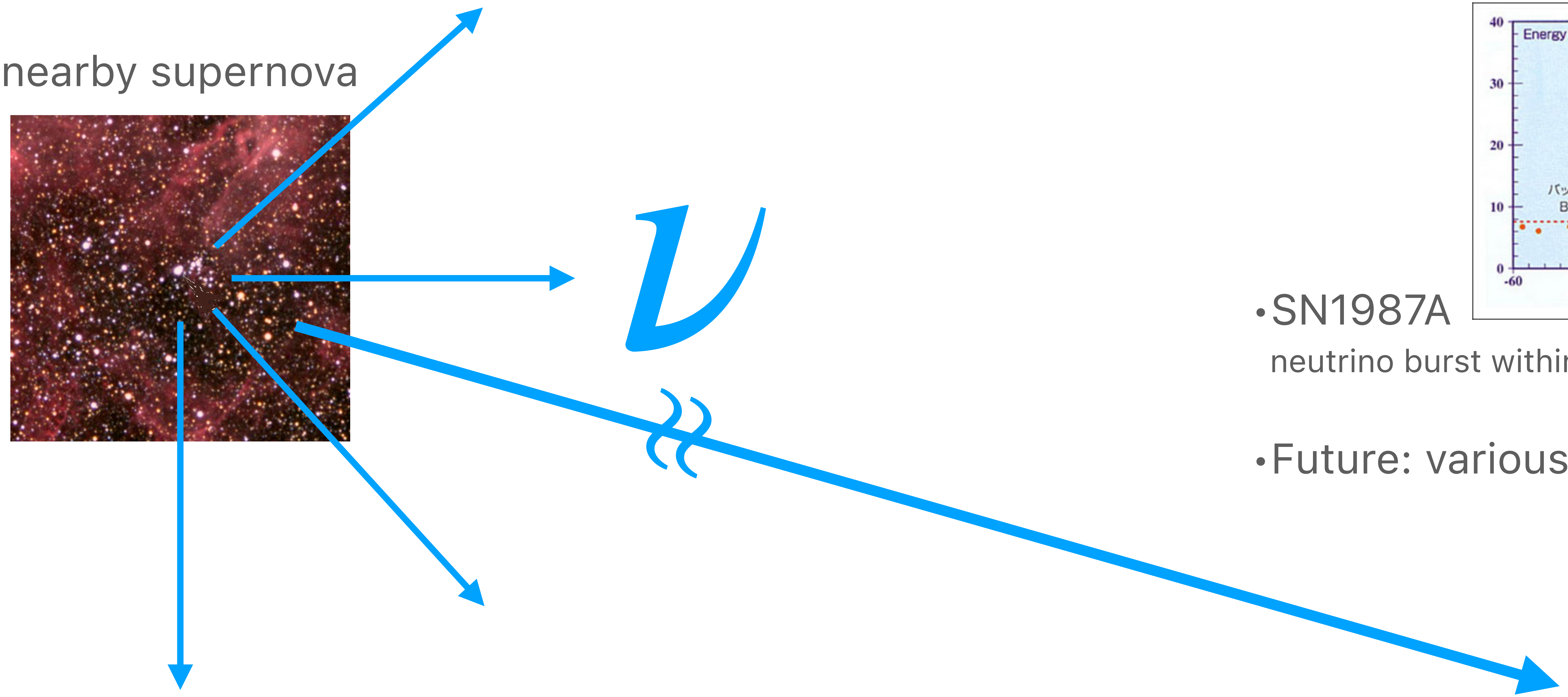
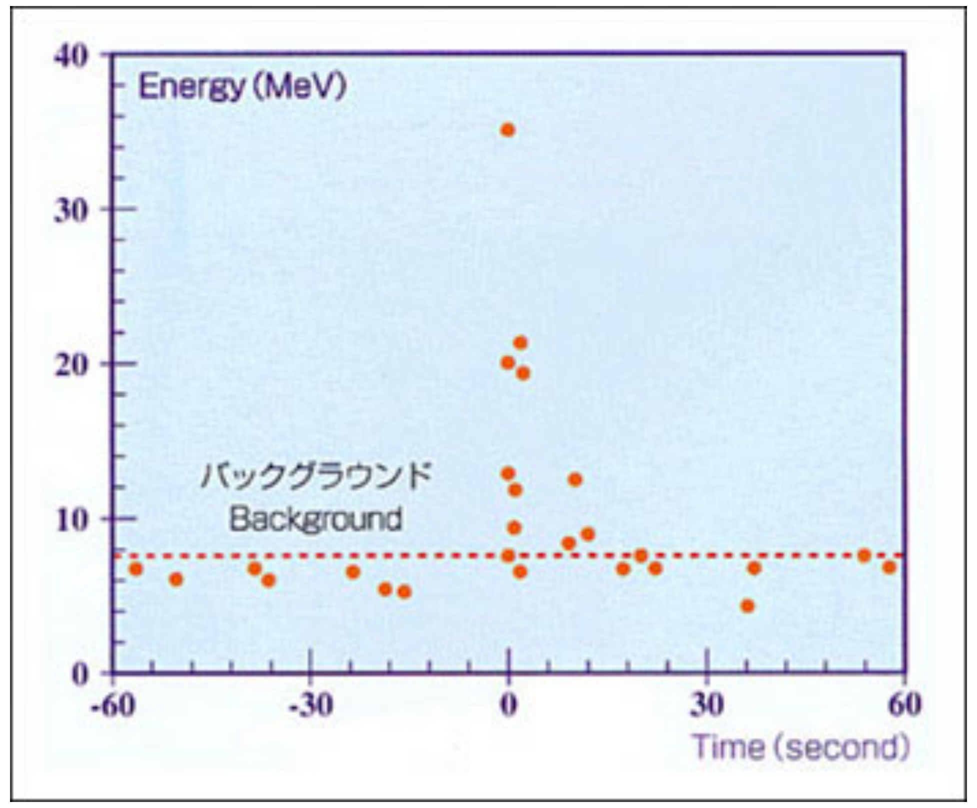
- What if **a nearby supernova** occurs in near future?

nearby supernova



http://www-sk.icrr.u-tokyo.ac.jp/sk/physics/supernova-e.html



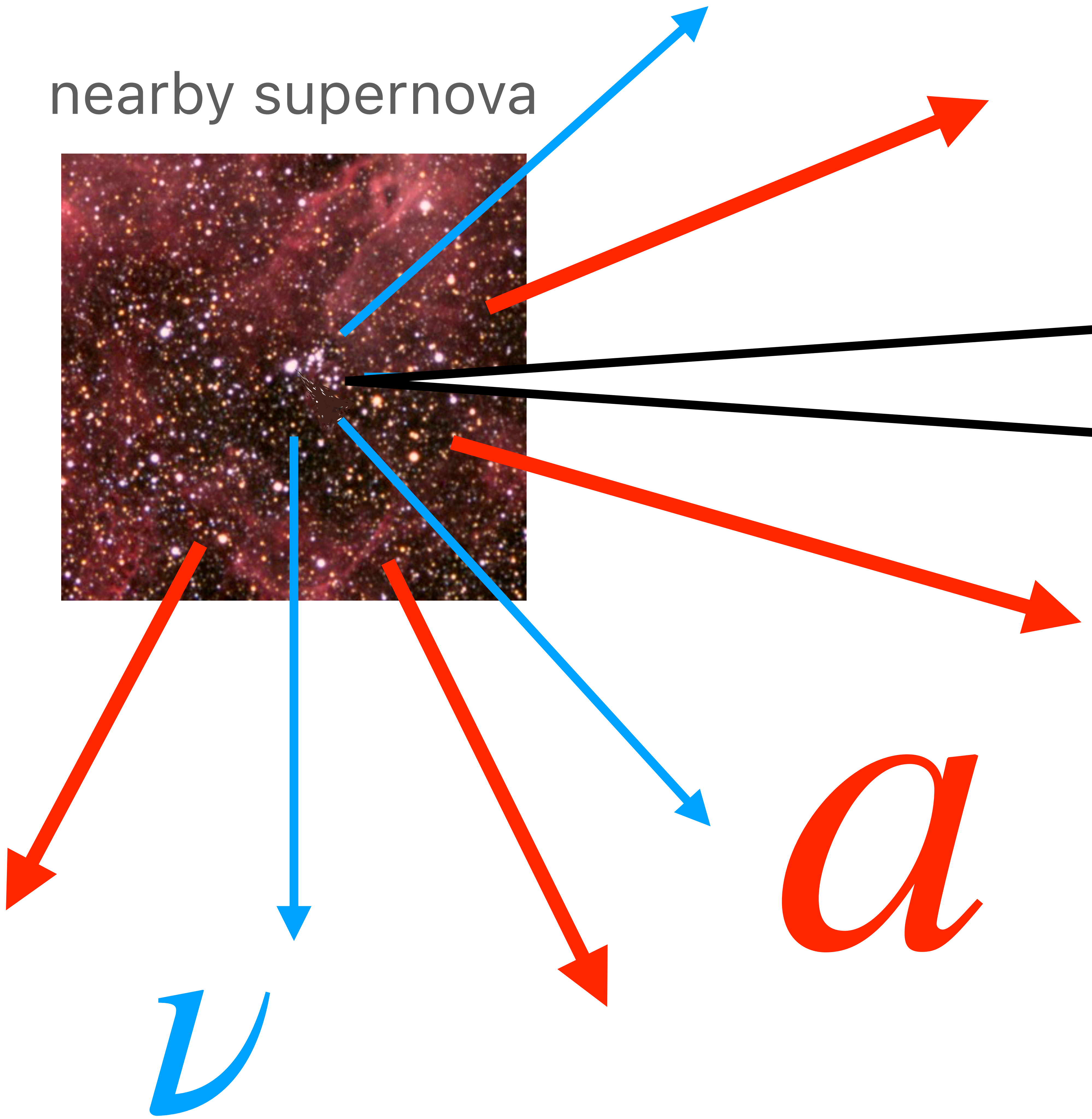
- SN1987A
  neutrino burst within $\Delta t \simeq 10$ sec.

- Future: various neutrino detectors

② Side Remark: Supernova Axion

- What if **a nearby supernova** occurs in near future?

nearby supernova

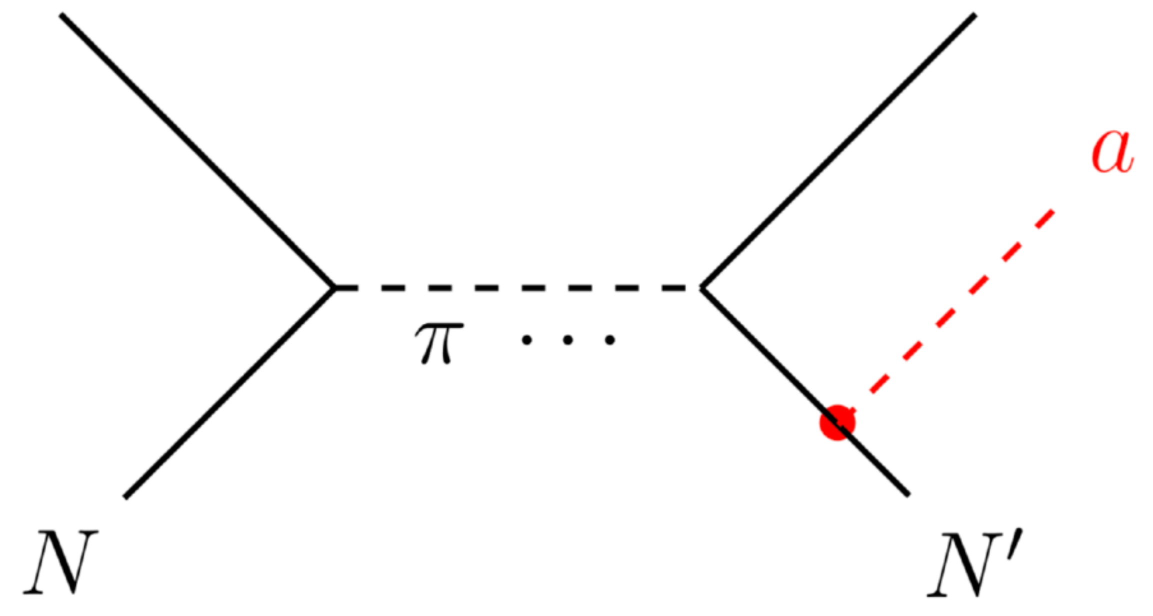


If the axion exists,...

$$NN' \rightarrow NN' + a$$

$$(N, N' = n, p)$$

$$\mathscr{L}_{aNN} = \sum_{N=n,p} \frac{C_N}{f_a} \bar{N}\gamma^\mu\gamma^5 N \partial_\mu a$$

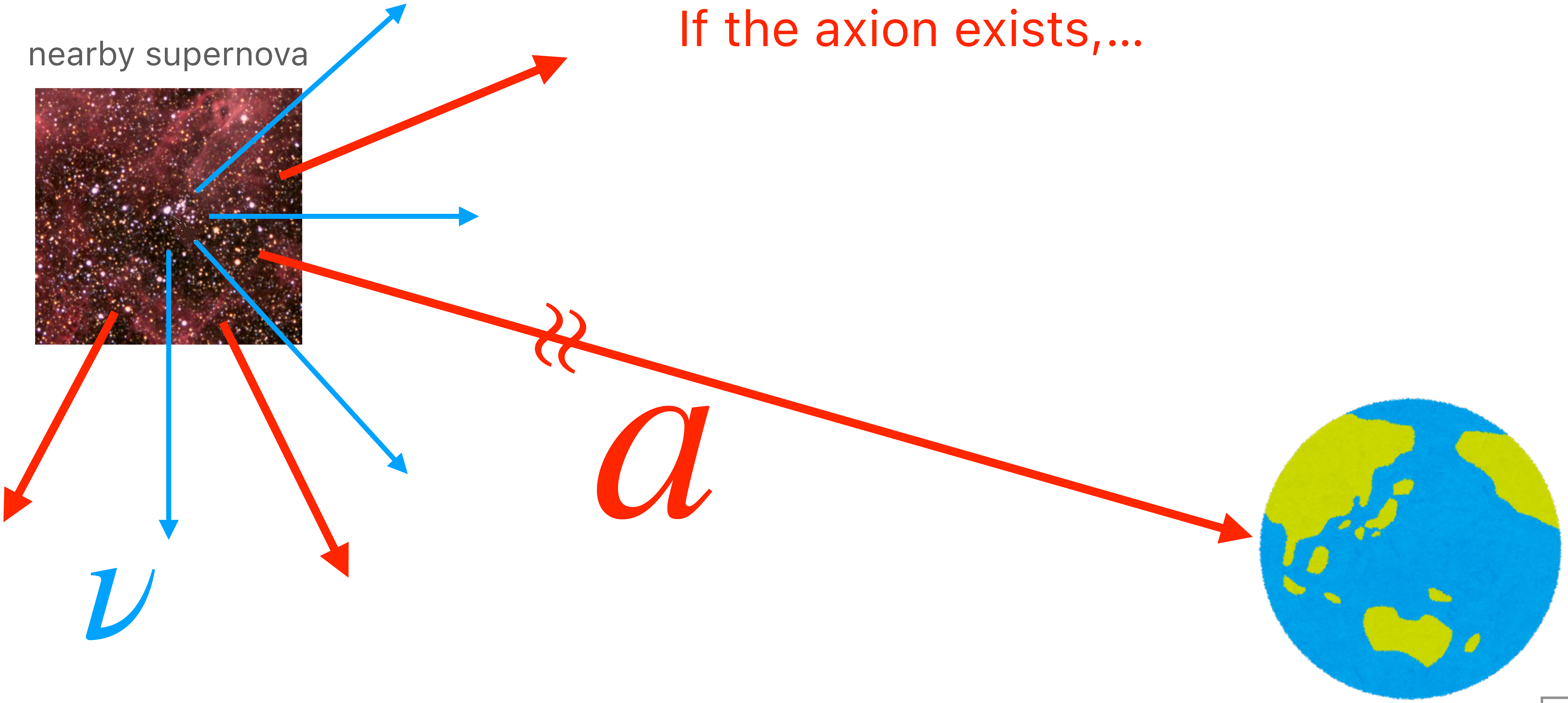


$$\begin{cases} C_p = -0.47 \\ C_n = -0.02 \end{cases} \quad \text{(KSVZ)}$$

$$\begin{cases} C_p = -0.182 - 0.435 \sin^2 \beta \\ C_n = -0.160 + 0.414 \sin^2 \beta \end{cases} \quad \text{(DFSZ)}$$

② Side Remark: Supernova Axion

- What if **a nearby supernova** occurs in near future?



② Side Remark: Supernova Axion

- What if **a nearby supernova** occurs in near future?

② Side Remark: Supernova Axion

- What if **a nearby supernova** occurs in near future?

- How do we know the timing of the SN in advance?
  👉Take the help of the pre-SN neutrinos.

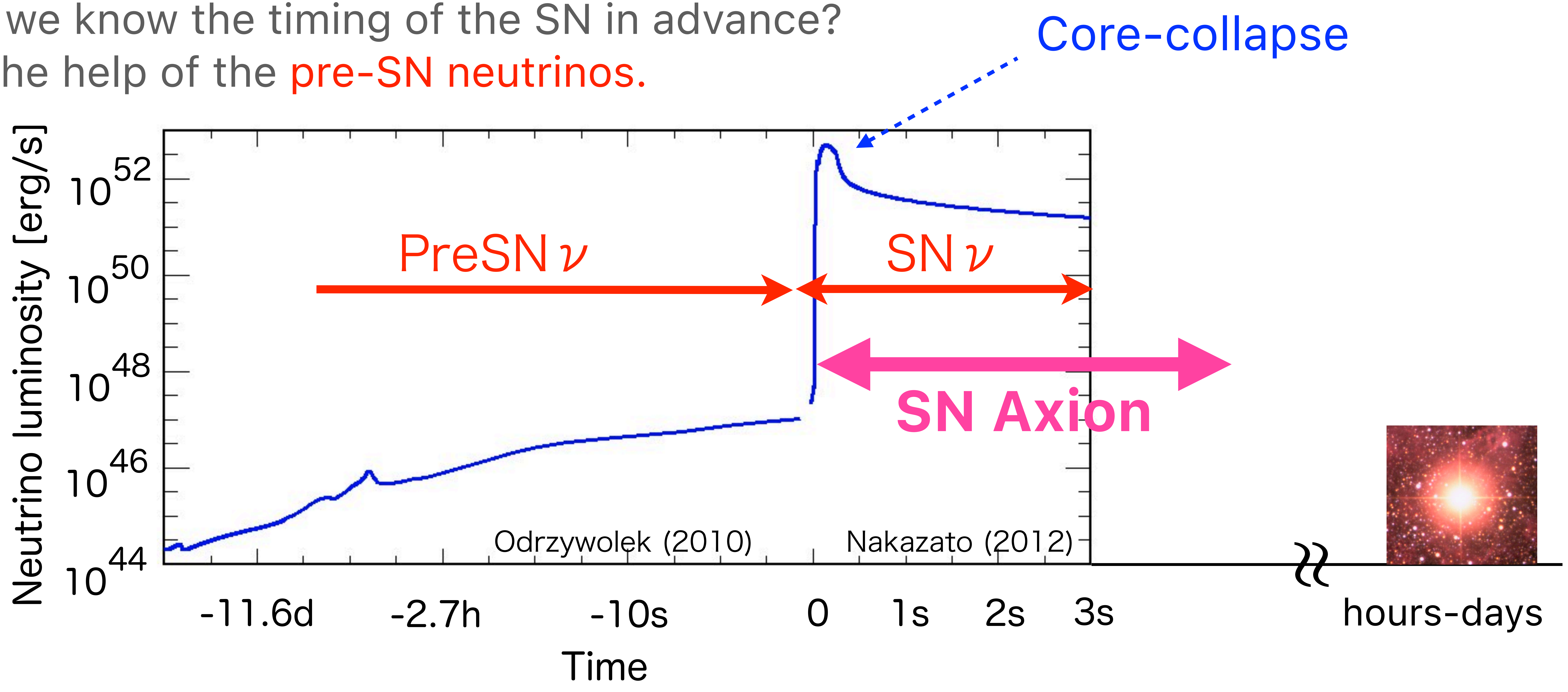
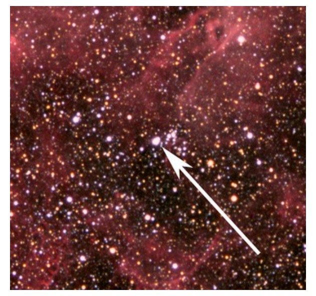


Figure from K.Ishidoshiro's talk in 2019.
https://www.lowbg.org/ugnd/workshop/sympo_all/201903_Sendai/
For a review of pre-SN neutrinos, see, e.g., C.Kato, K.Ishidoshiro, T.Yoshida [2006.02519].

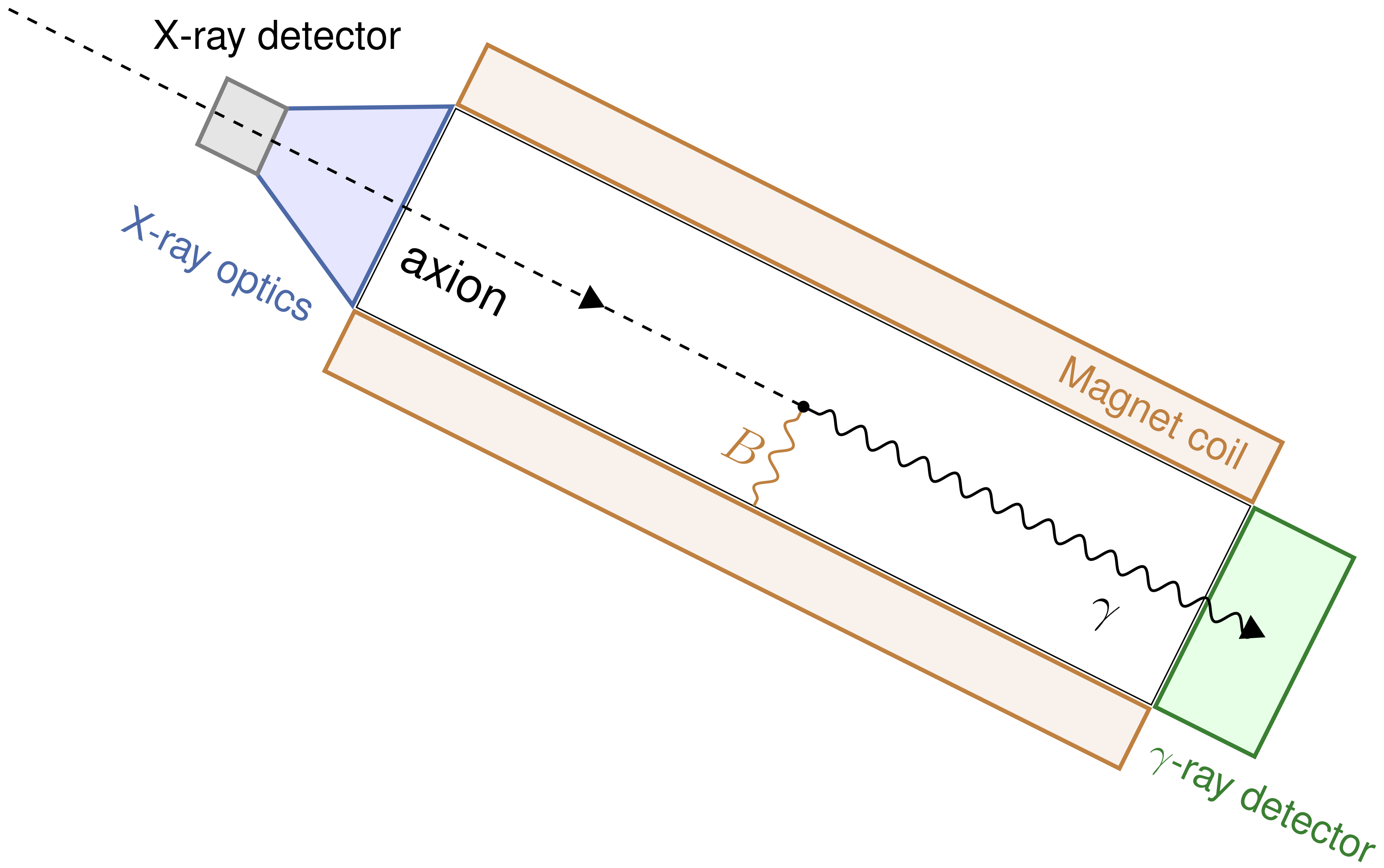
② Side Remark: Supernova Axion

S.Ge, K.Hamaguchi, K.Ichimura, K.Ishidoshiro, Y.Kanazawa, Y.Kishimoto, N.Nagata, J.Zheng.
[arXiv:2008.03924] JCAP **11** (2020) 059.

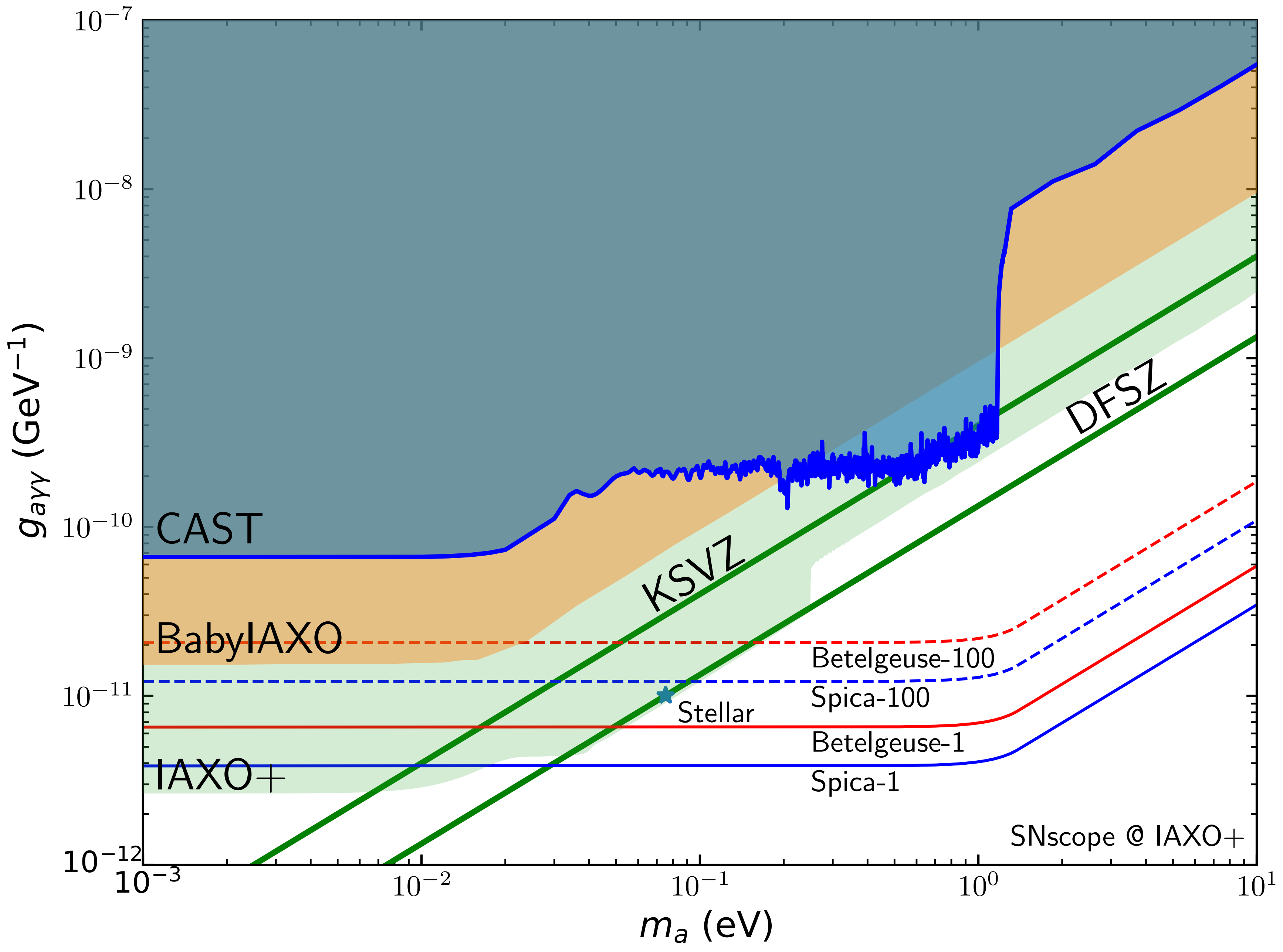
We have shown that, if a nearby (< a few 100pc) supernova (SN), such as Betelgeuse, occurs,..



...by using a "axion Supernova scope",
with the help of pre-SN neutrino alert,...



...SN axions may be detected!



👉 More details on backup slides.

Plan

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  - ② Side Remark: **Supernova Axion**
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Any questions?

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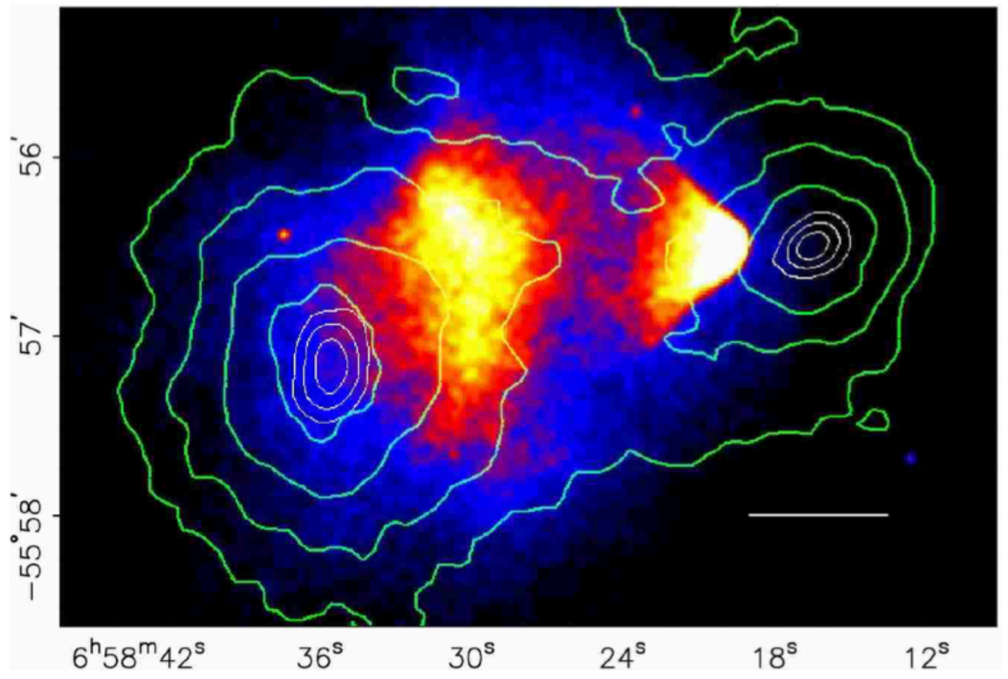
        - 3.1 Ideas
        - 3.2 back-of-envelope estimates
        - 3.3 advantages
        - 3.4 challenges

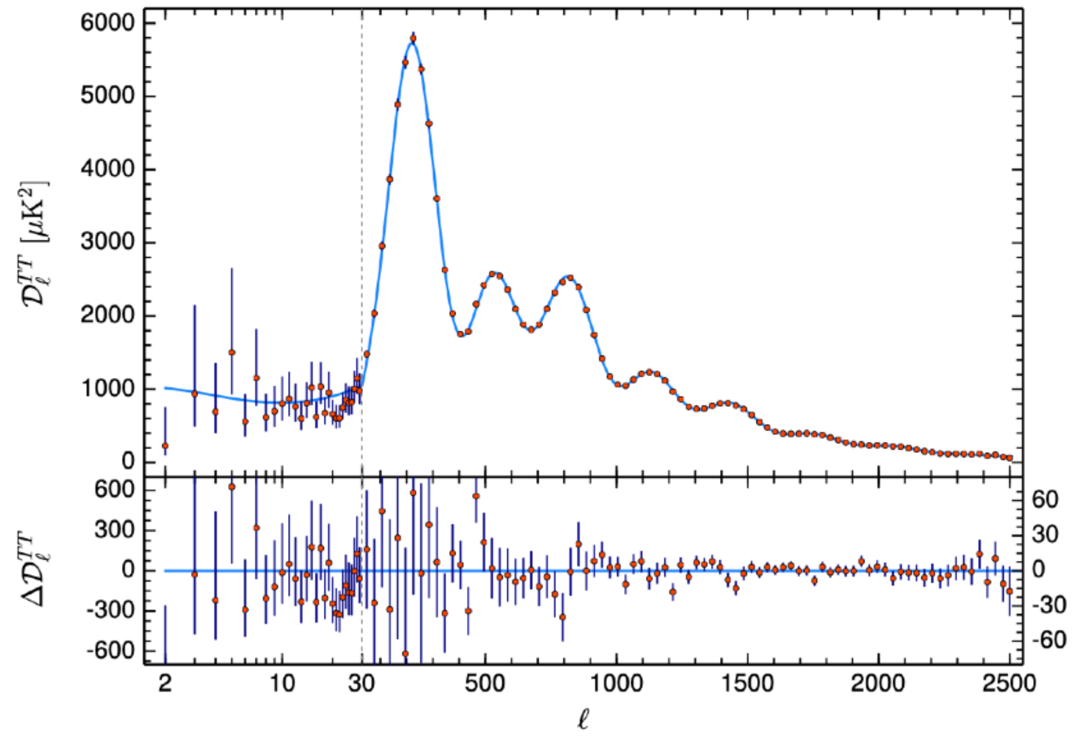
③ NS Heating by DM

Dark Matter

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



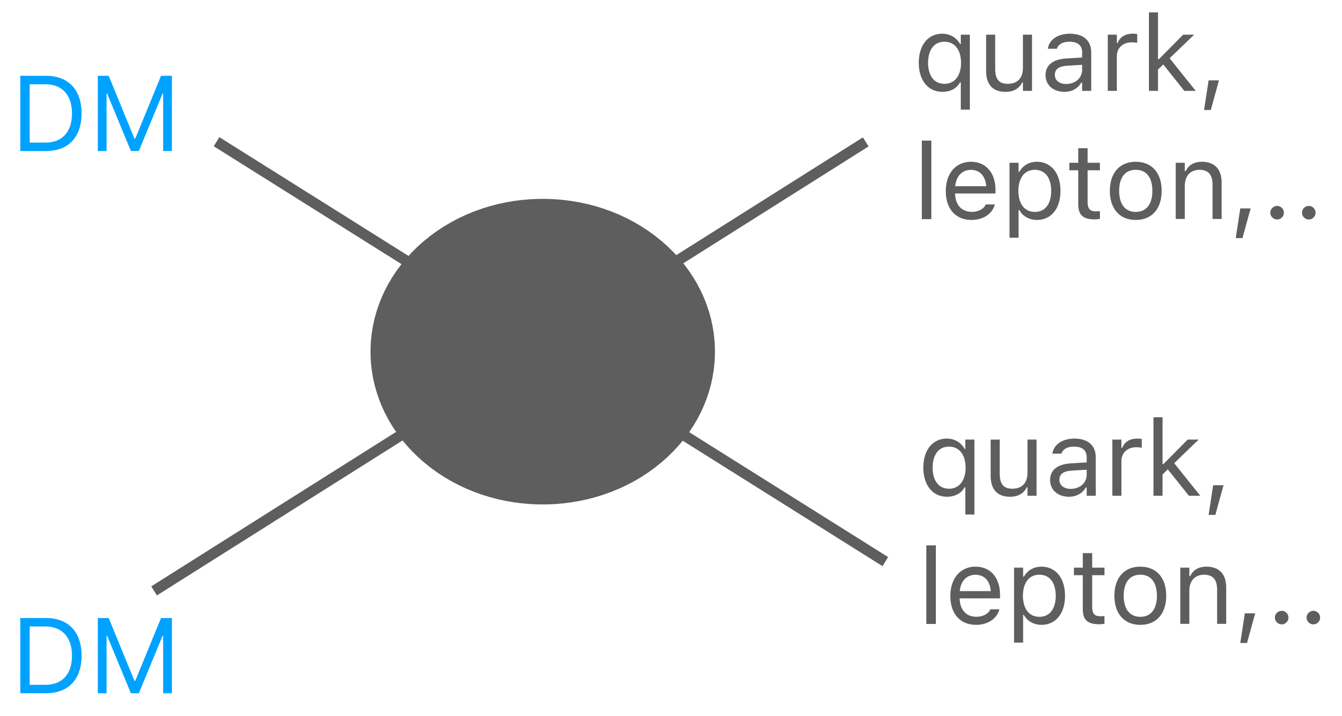
Bullet Cluster.
from astro-ph/0608407.



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, ...).



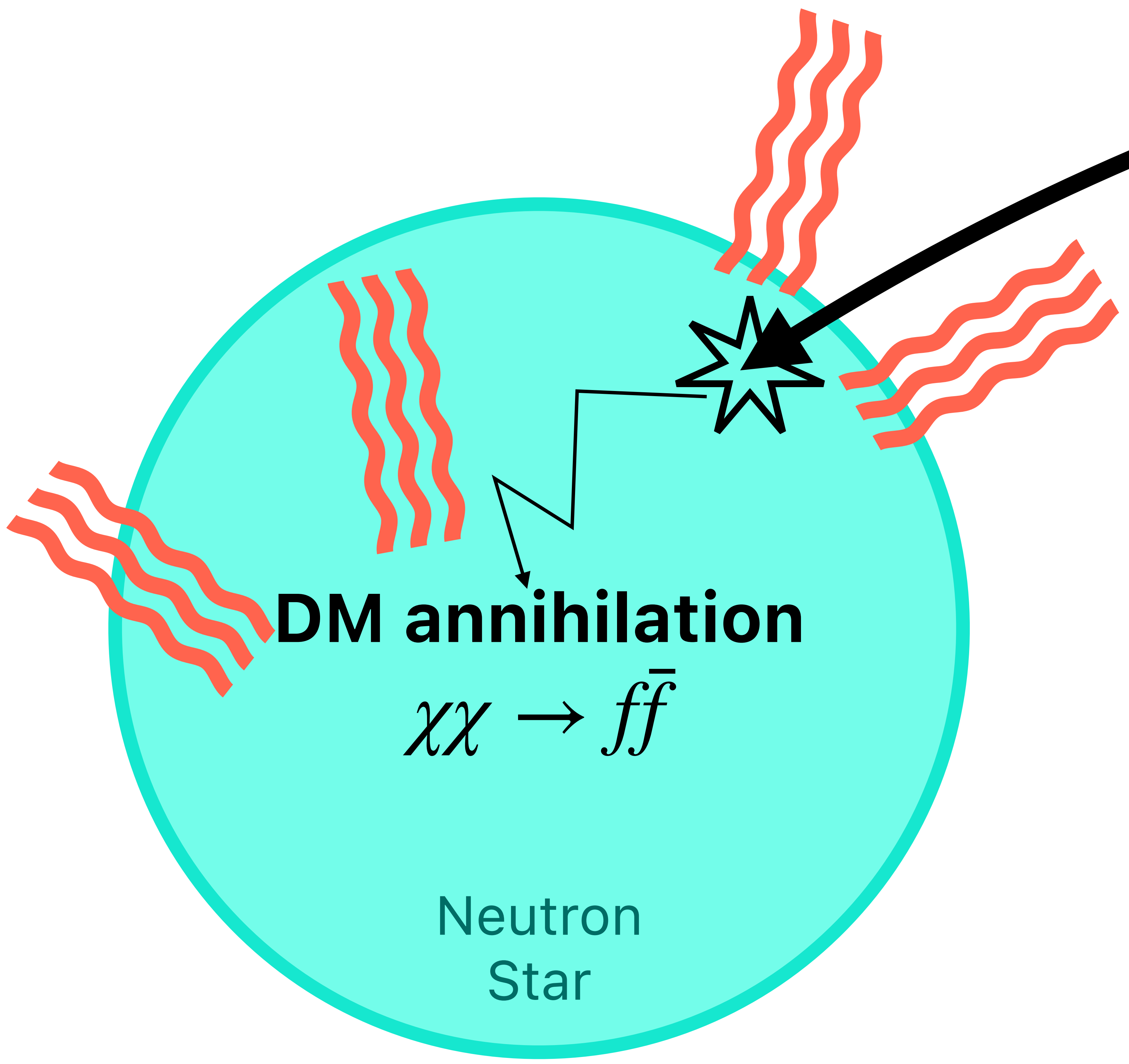
③ NS Heating by DM

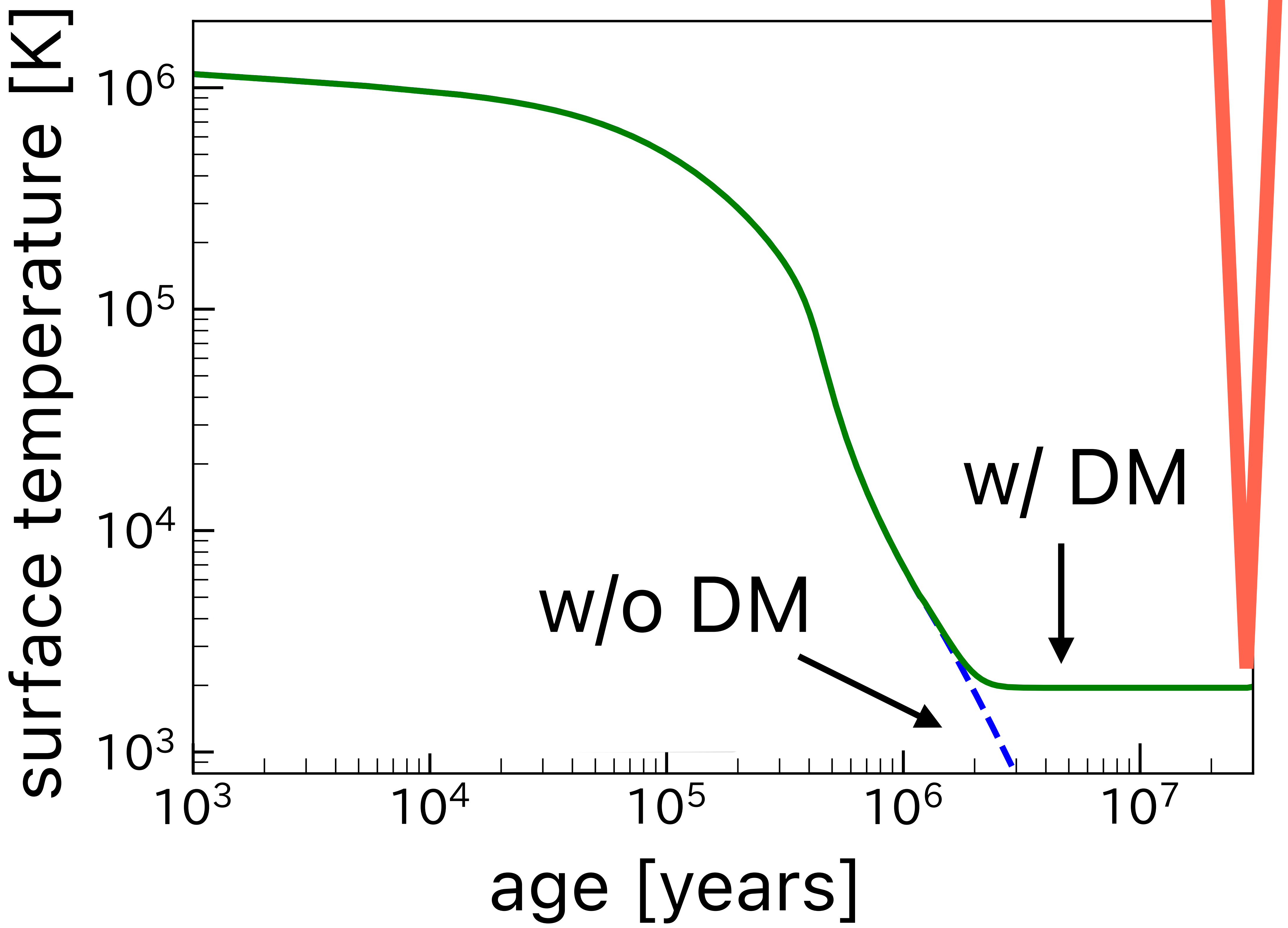
3.1. Idea

Kouvaris, 0708.2362
Baryakhtar+, 1704.01577

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

DM χ

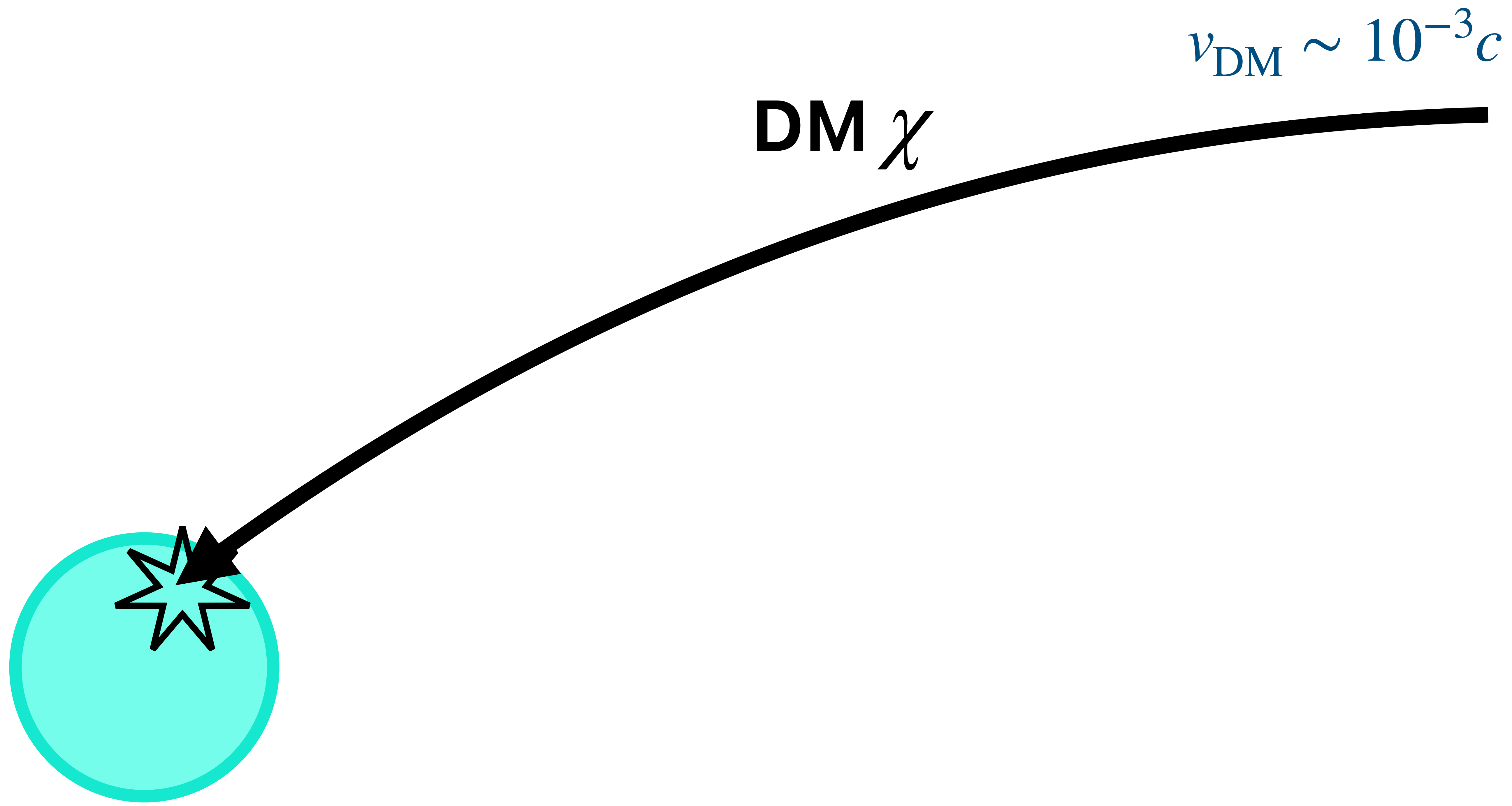




Old and warm NS = DM signal ?!

③ NS Heating by DM

3.2. back-of-envelope estimates



③ NS Heating by DM

3.2. back-of-envelope estimates

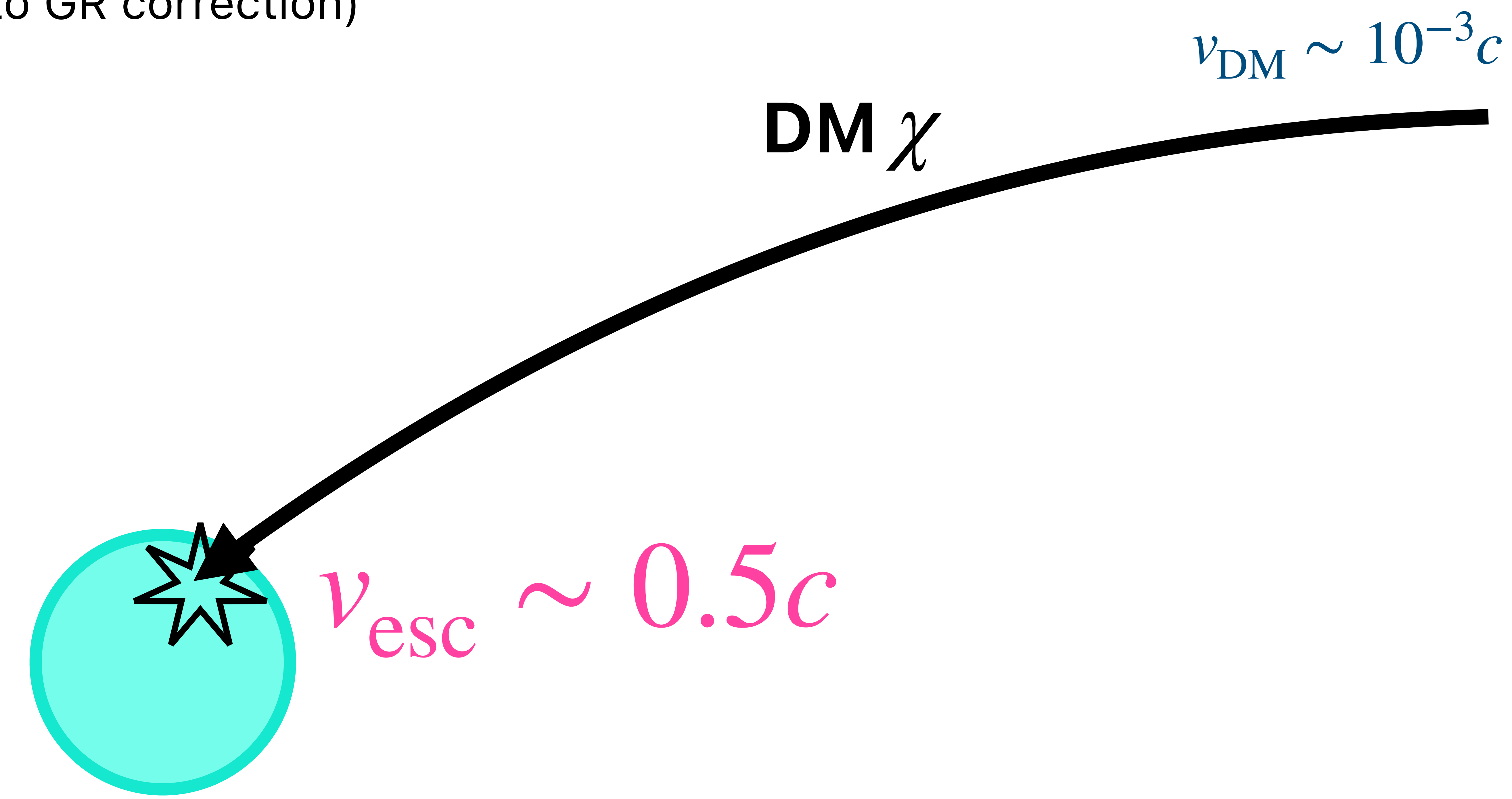
(1) DM velocity at the surface: $v_{\rm esc} \sim 0.5c$ (up to GR correction)

- From the energy conservation,

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

up to O(1) GR correction.

→ almost relativistic speed!

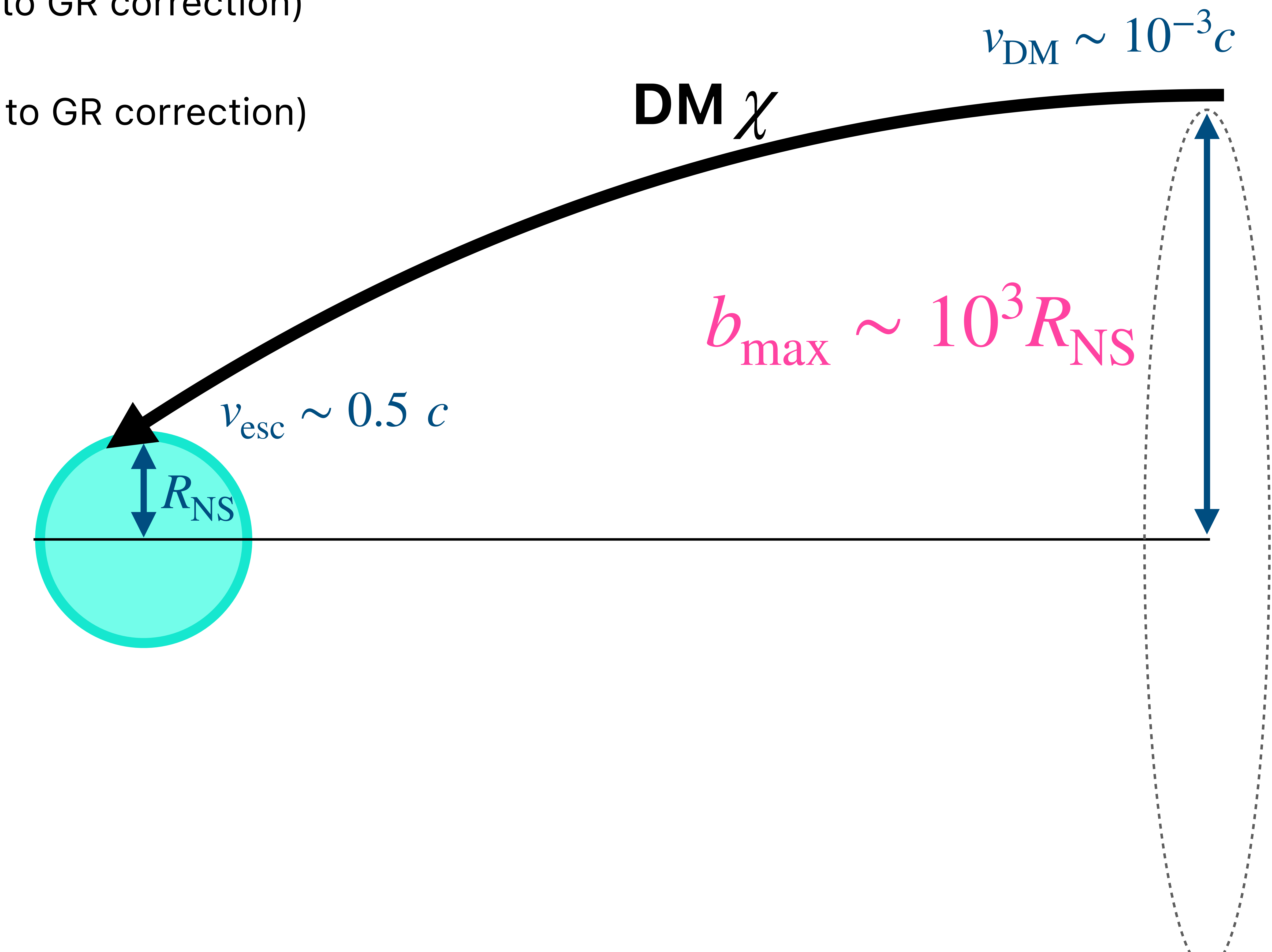


③ NS Heating by DM

3.2. 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)



- 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!

③ NS Heating by DM

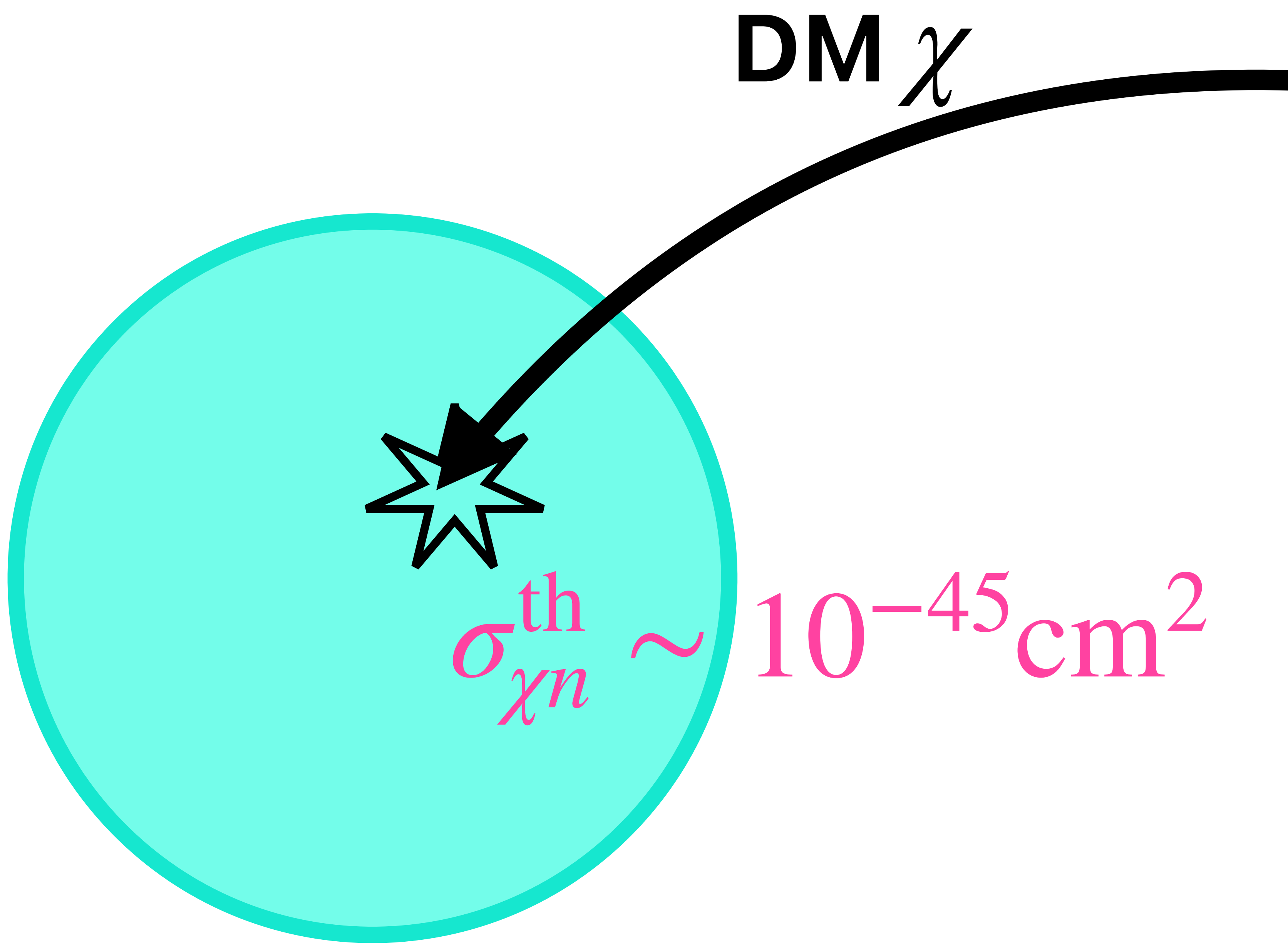
3.2. back-of-envelope estimates

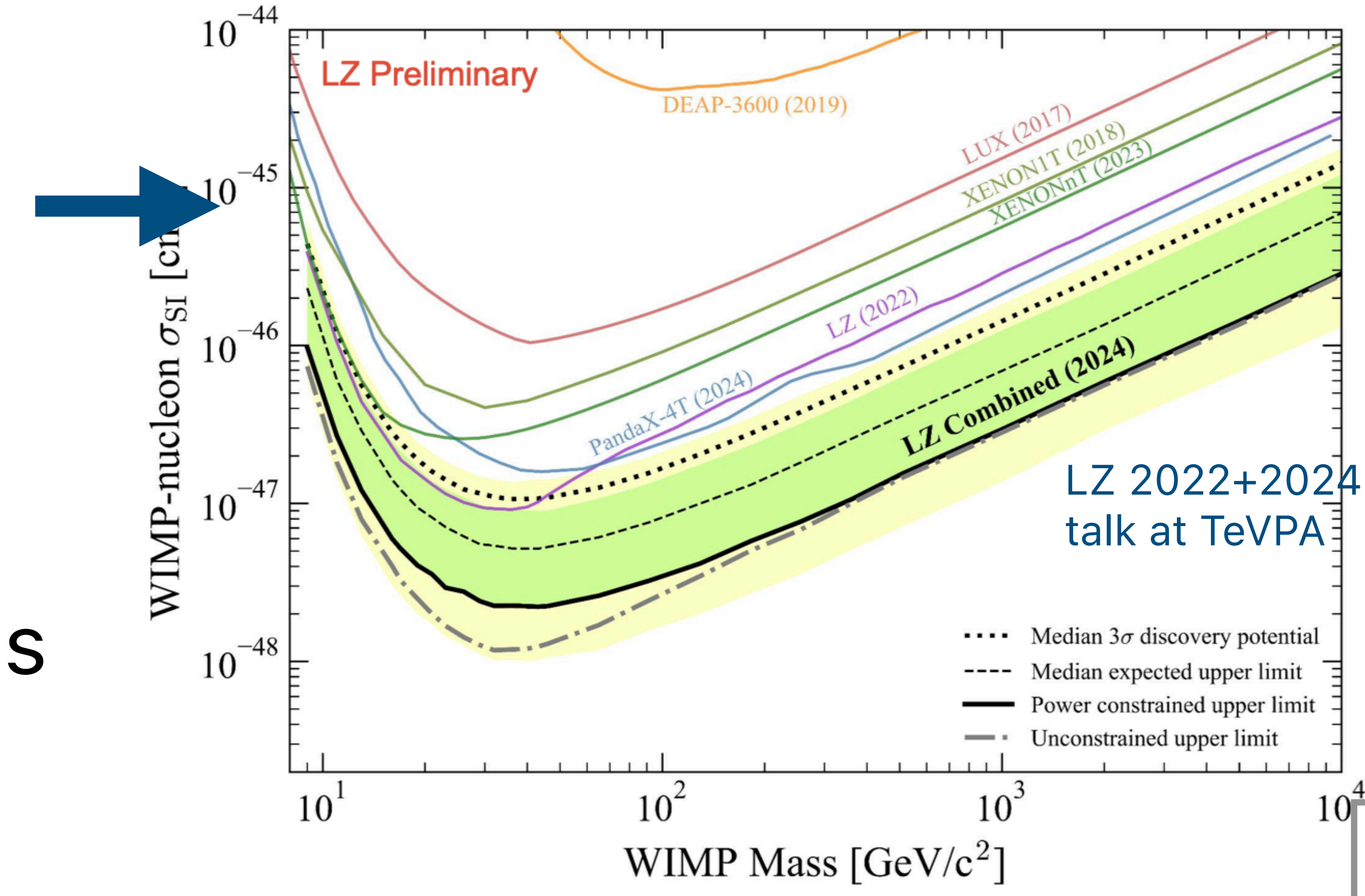
(1) DM velocity at the surface: $v_{\rm esc} \sim 0.5c$ (up to GR correction)

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

③ NS Heating by DM

3.2. back-of-envelope estimates

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

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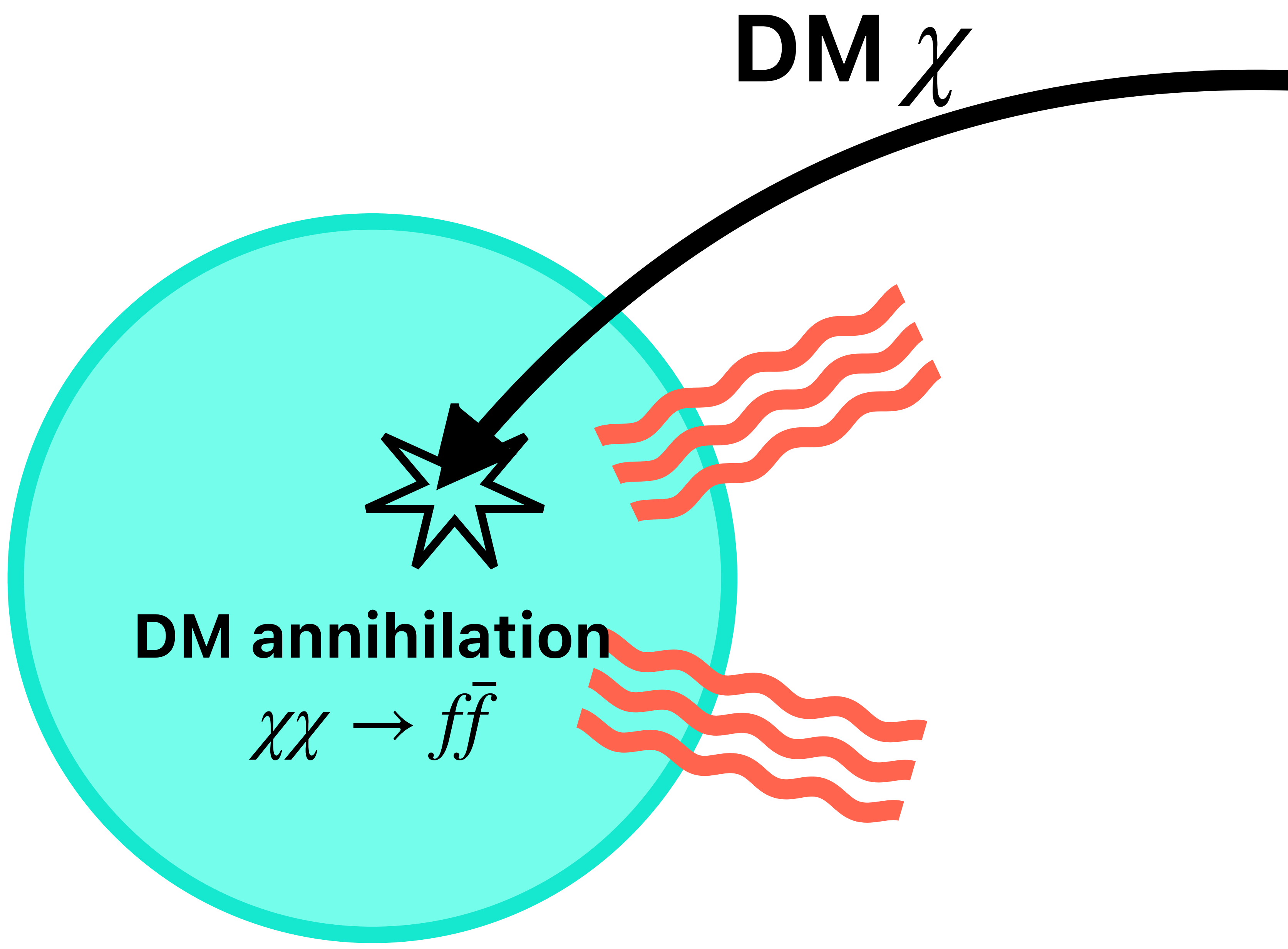
(3) Threshold cross section: $\sigma_{\chi n} > \sigma_{\chi n}^{\rm th} \sim \dfrac{1}{R_{\rm NS} n_N} \sim 10^{-45}\ {\rm cm}^2$

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



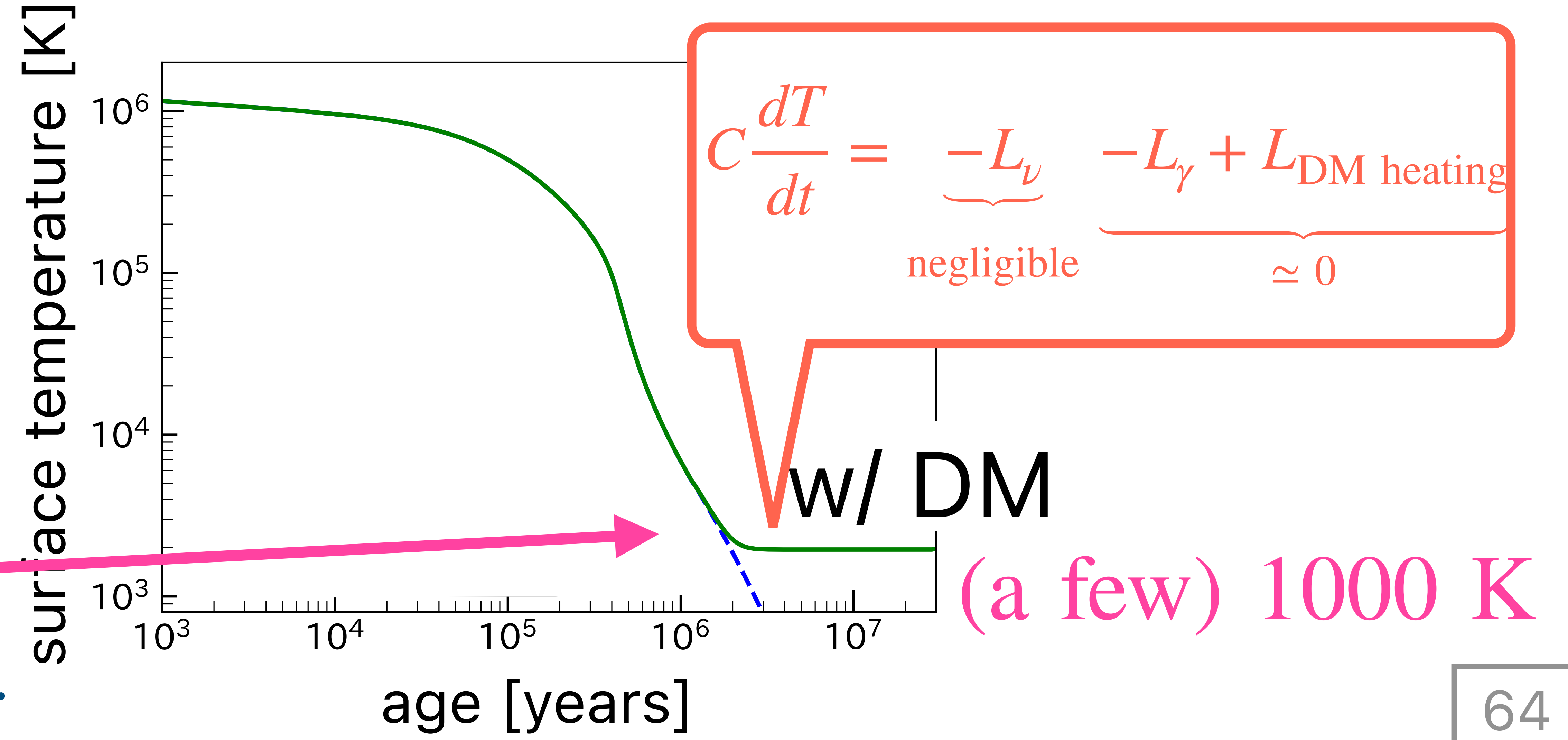
- The energy injection per time is estimated as

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

… independent of the DM mass!

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

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



③ NS Heating by DM

3.2. back-of-envelope estimates

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

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(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

(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.

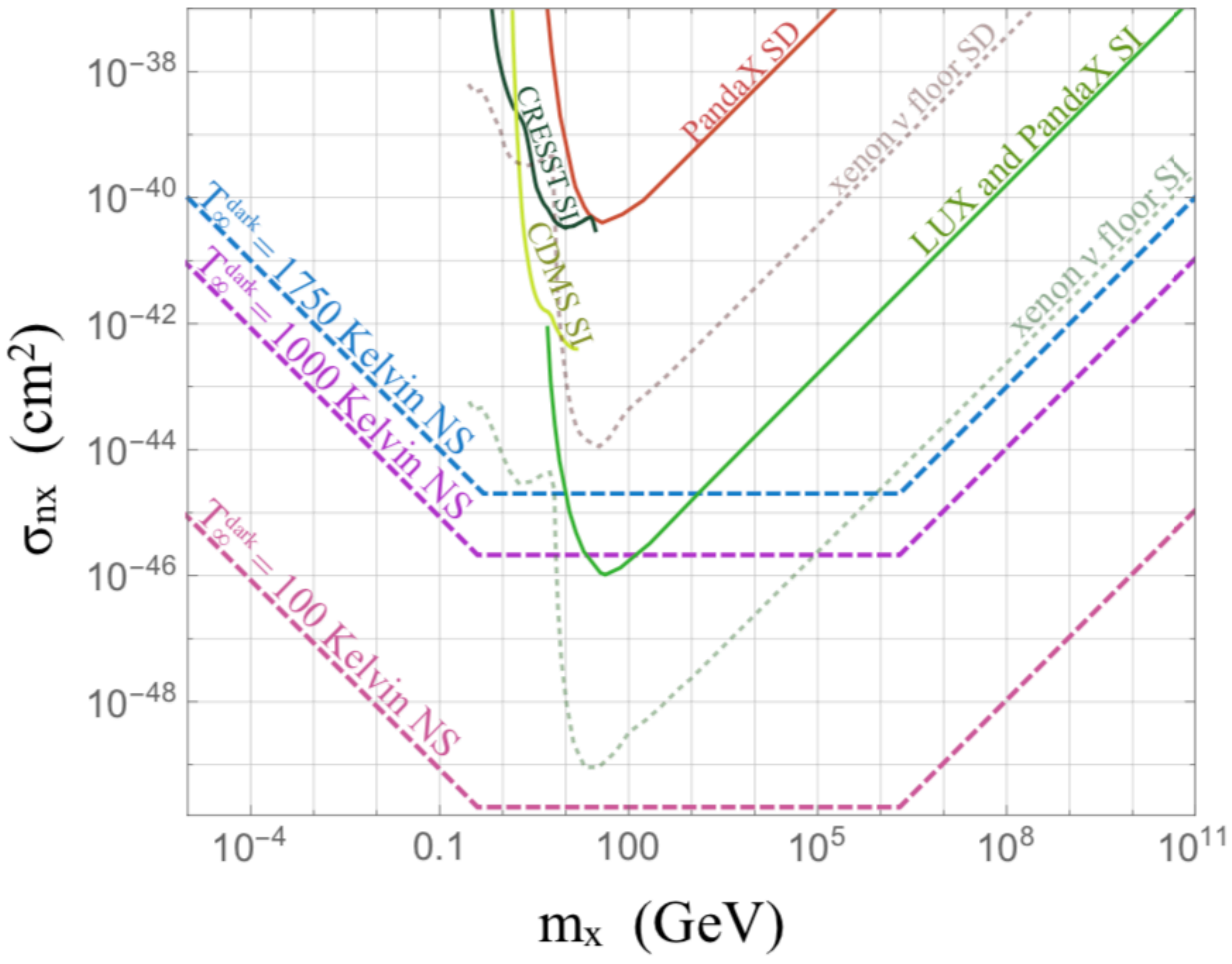

Fig. from Baryakhtar+, 1704.01577
(See also: N. F. Bell+, 2004.14888.)

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  3.4 challenges

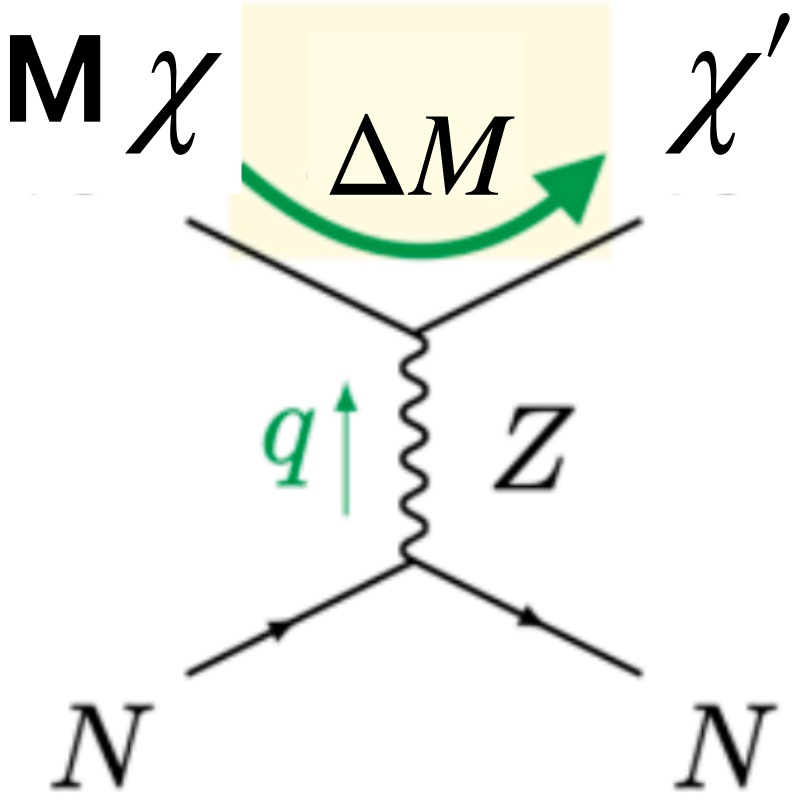
③ NS Heating by DM

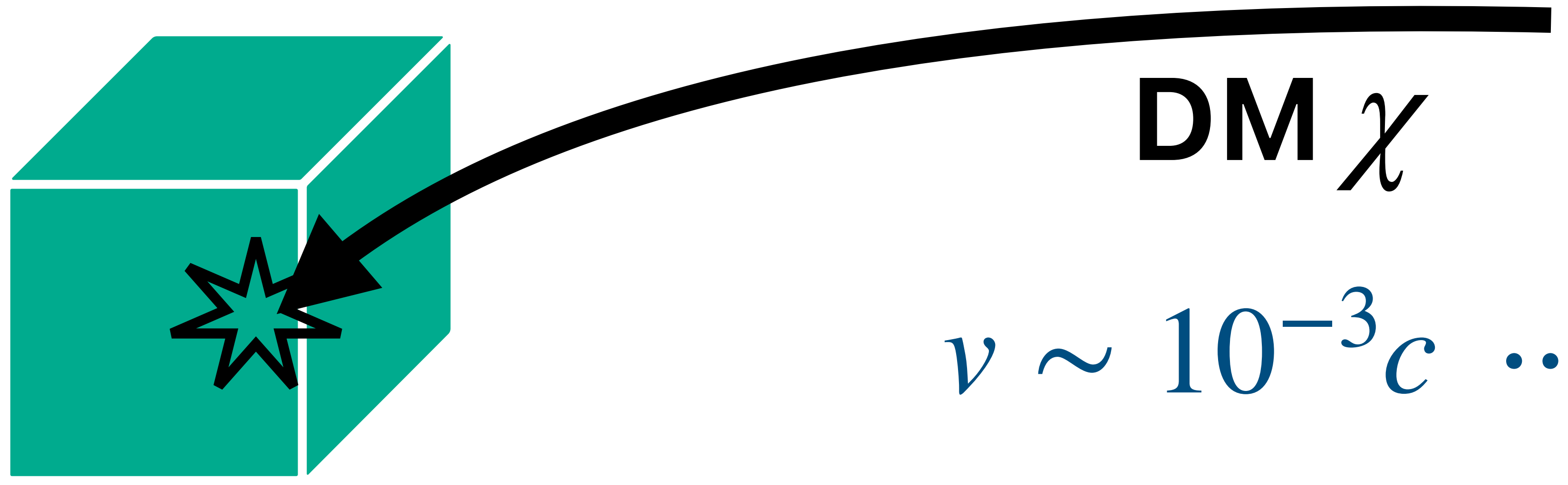
3.3. Advantages

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

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

inelastic scattering





direct detection experiments

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

NS

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

NS is much more sensitive to inelastic scattering.

③ NS Heating by DM

3.3. Advantages

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

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

example: Electroweak multiplet DM

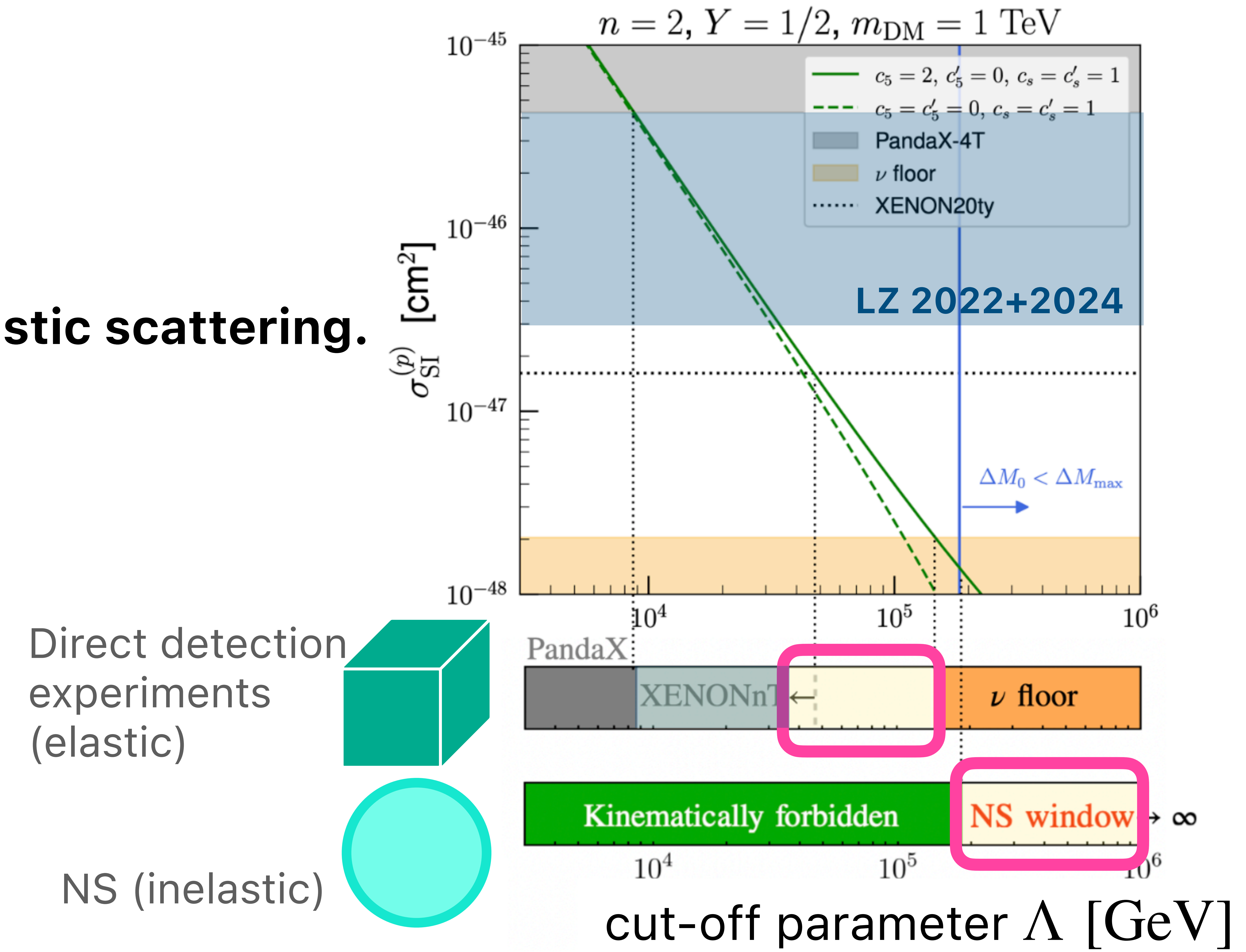
e.g., Wino and Higgsino in SUSY

dim-5 effective operators

w/ cut-off parameter Λ

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

Fujiwara, KH, Nagata, Zheng [2204.02238]



Direct detection and NS heating can play complementary roles.

③ NS Heating by DM

3.3. Advantages

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

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

(2) Multiple Targets: e, μ, p, n

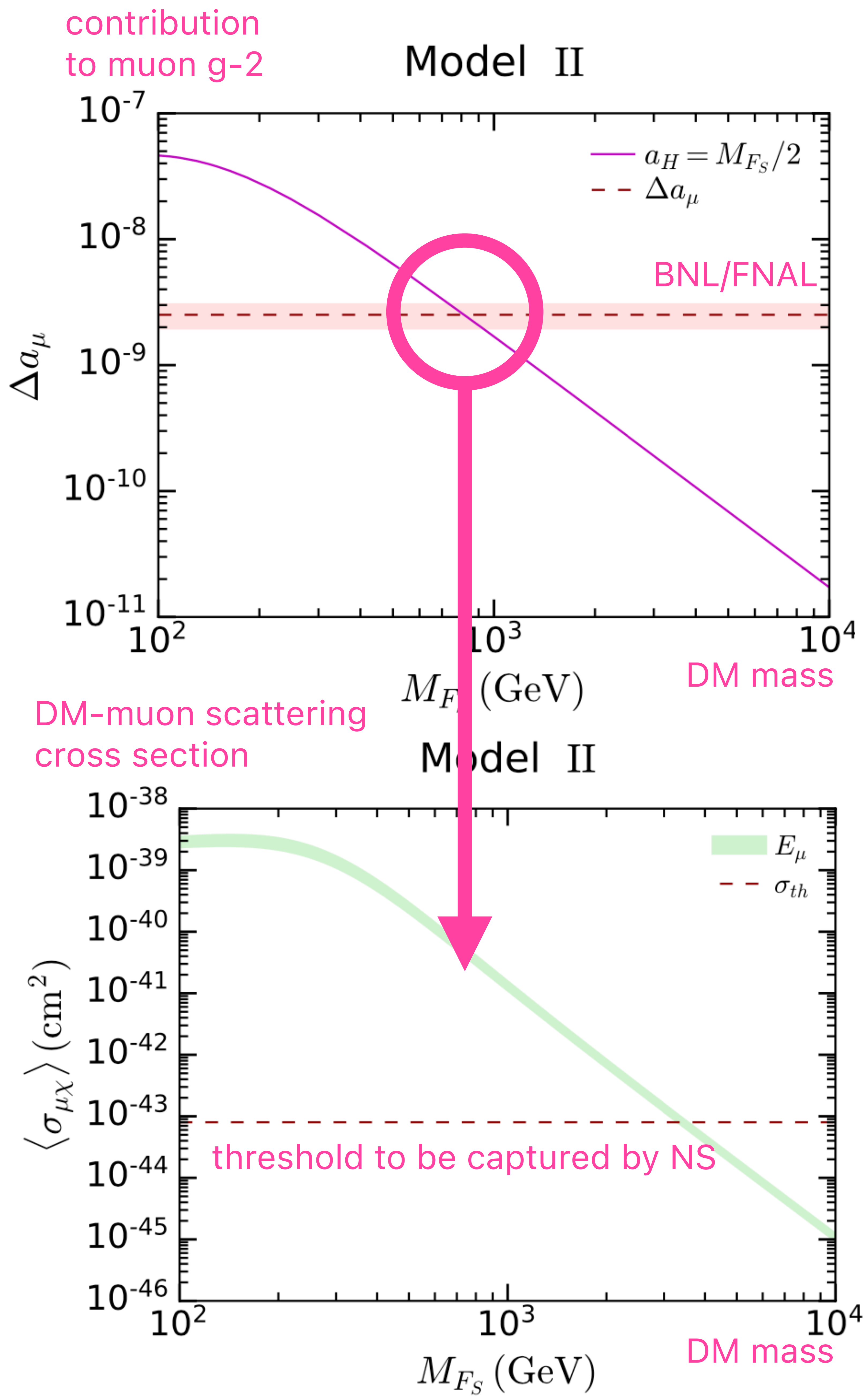
example: DM coupled only to muon.

KH, Nagata, Ramirez-Quezada [2204.02413]

Models motivated by the (then-considered) muon g-2 anomaly.

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

NS temperature may be a promising way.



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③ NS Heating by DM

3.4. challenges: internal heating

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

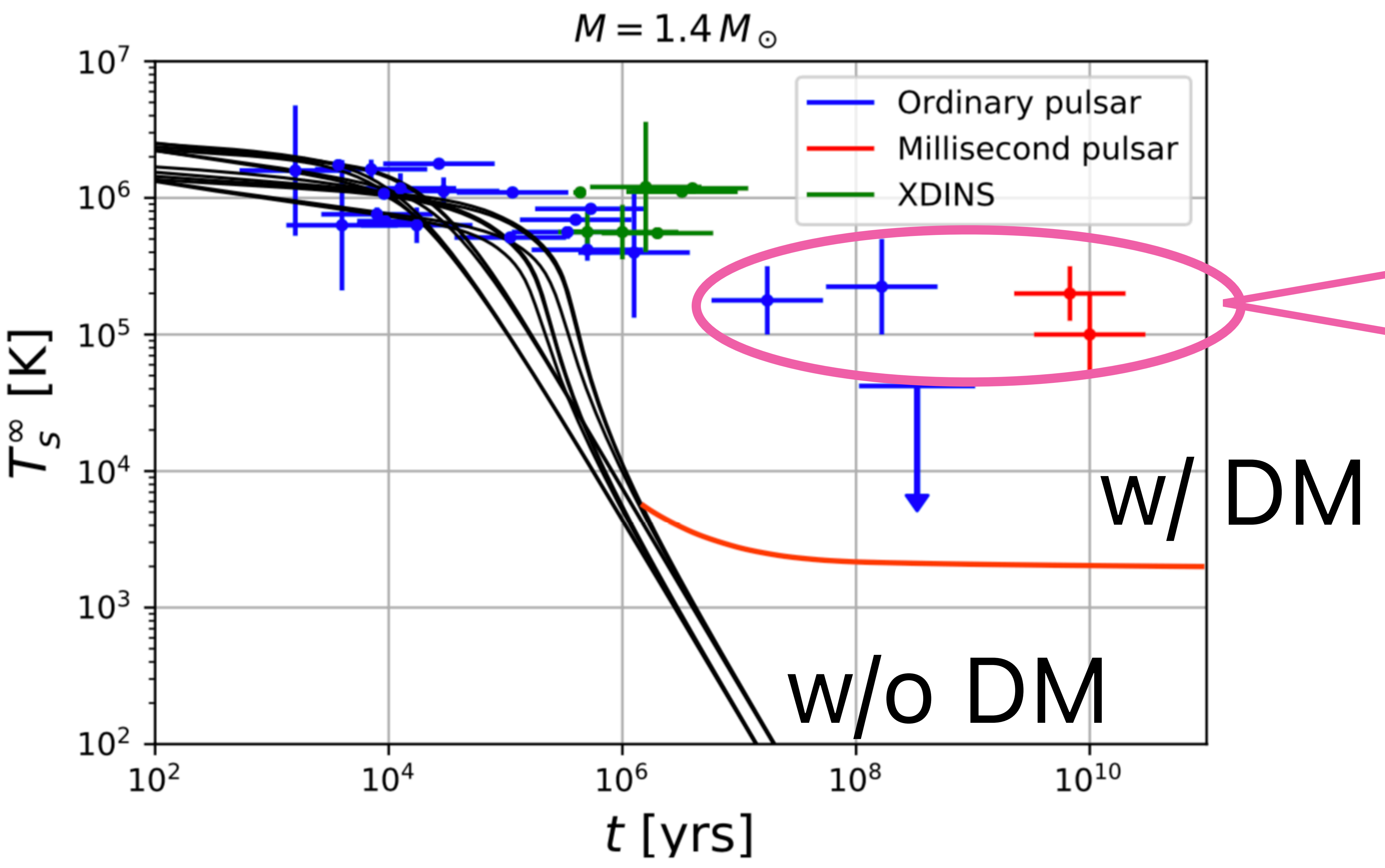


Fig. thanks to K.Yanagi.

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

③ NS Heating by DM

3.4. challenges: internal heating

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

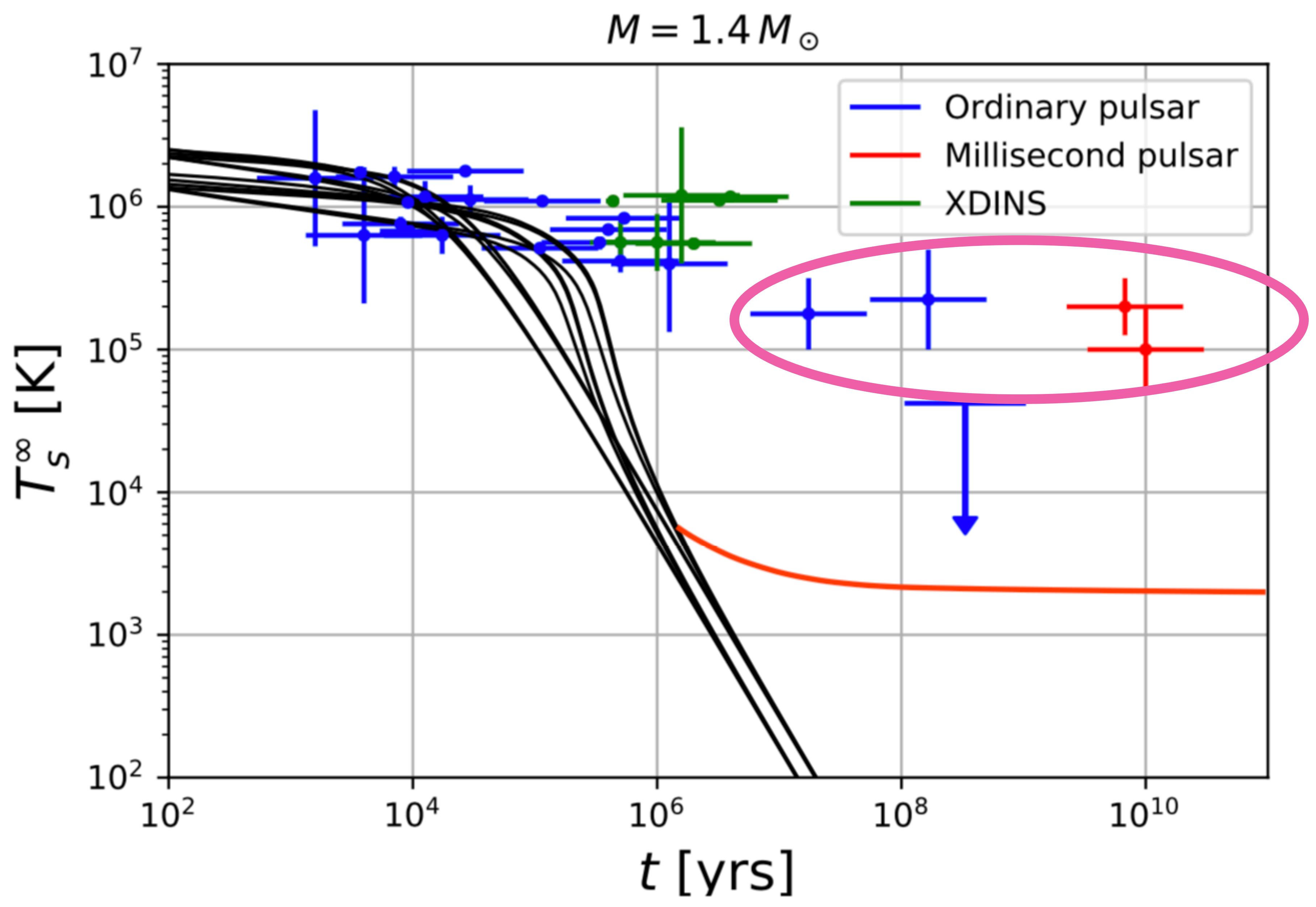


Fig. thanks to K.Yanagi.

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.

③ NS Heating by DM

3.4. challenges: internal heating

(1) Rotochemical heating

③ NS Heating by DM

3.4. challenges: internal heating

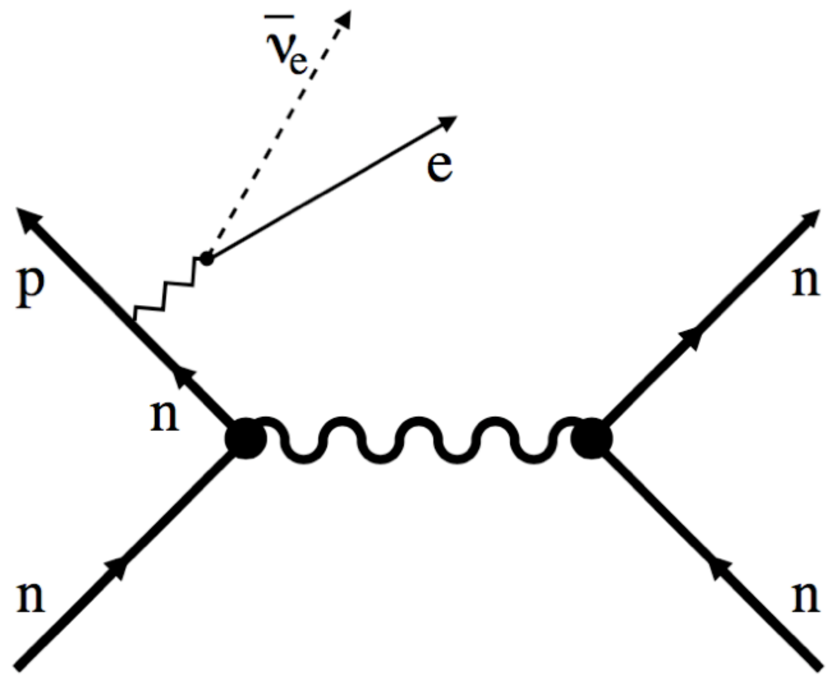
(1) Rotochemical heating

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

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

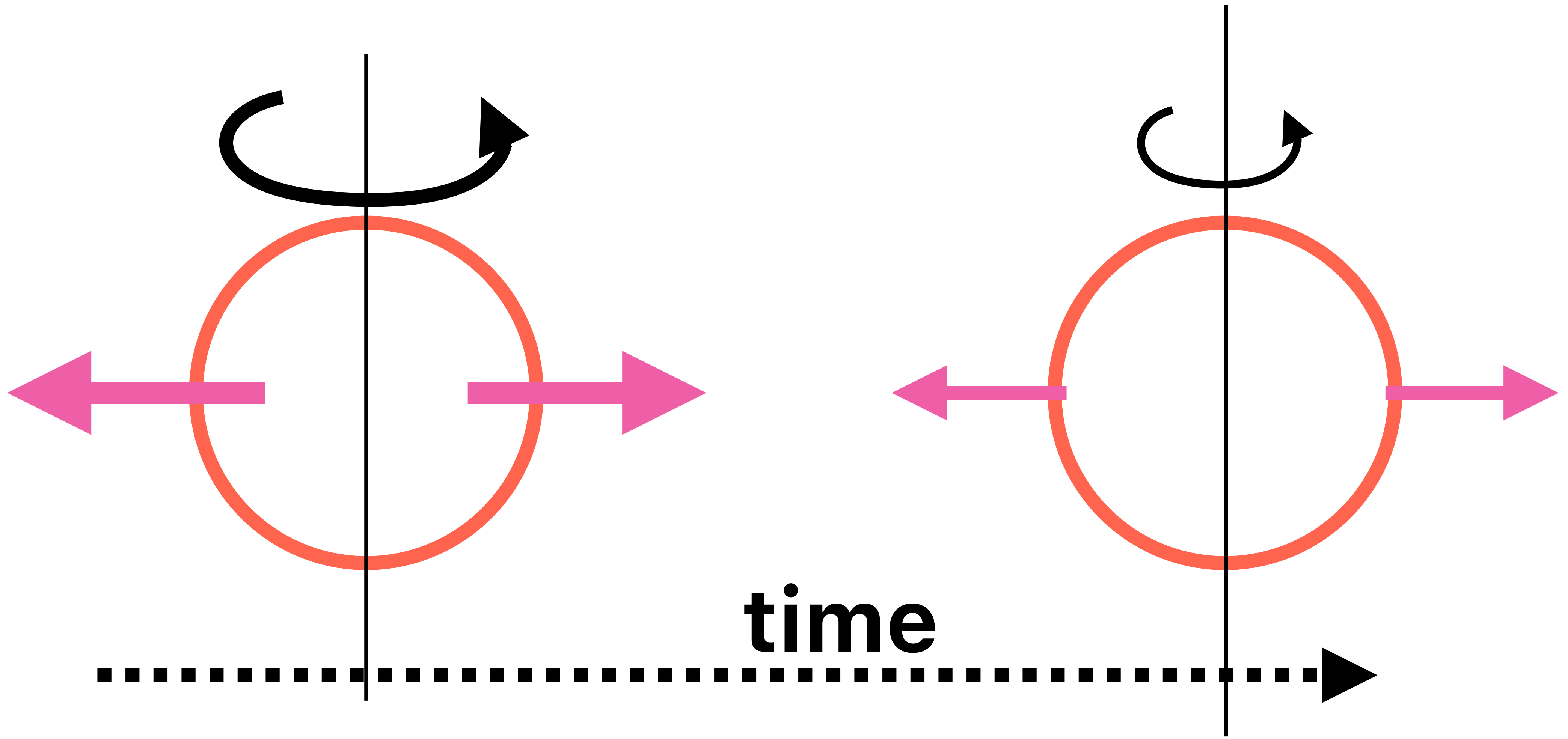
- In the minimal cooling, β-equilibrium is assumed.

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



- 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.

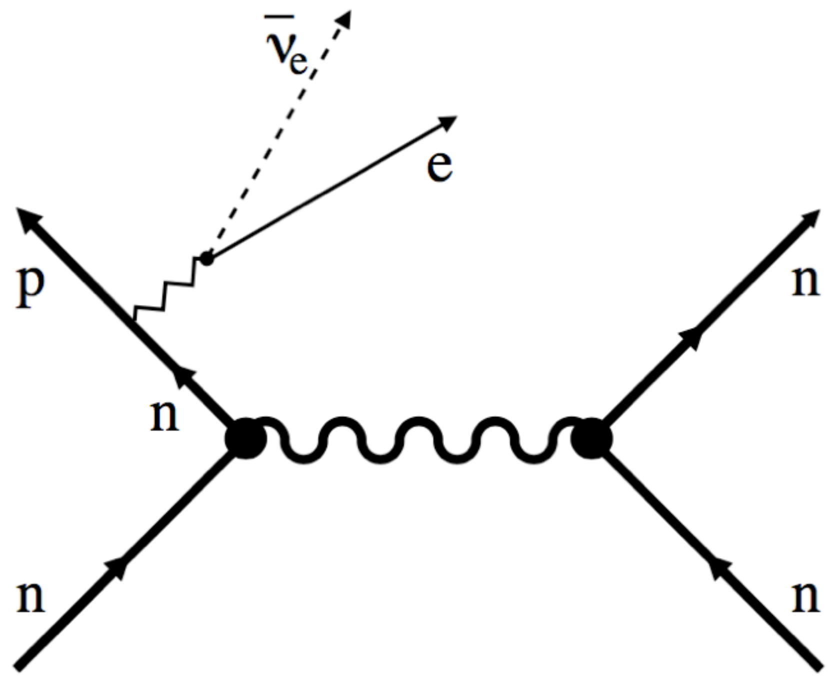
③ NS Heating by DM

3.4. 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.

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

- 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"**

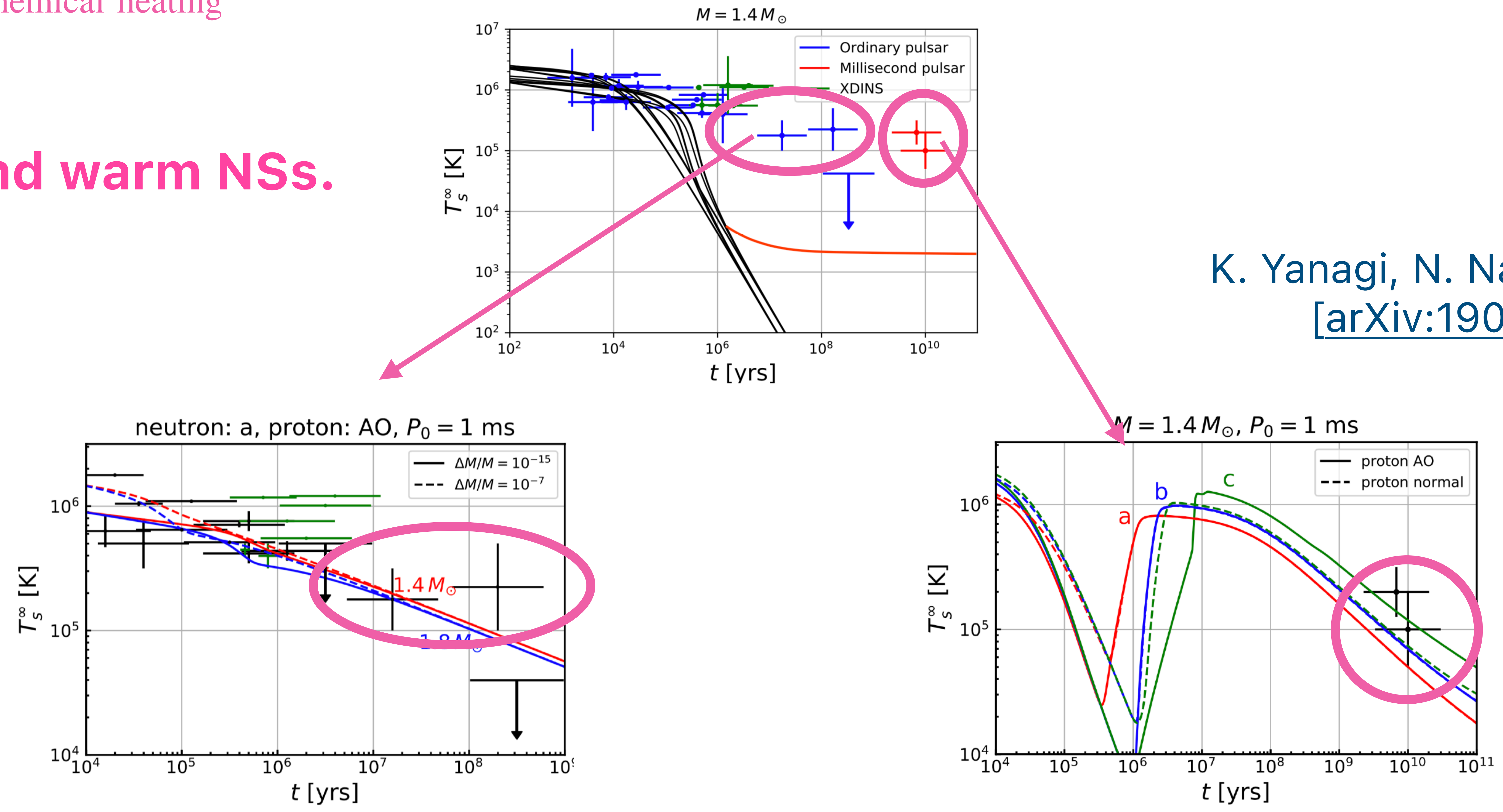
③ NS Heating by DM

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

③ NS Heating by DM

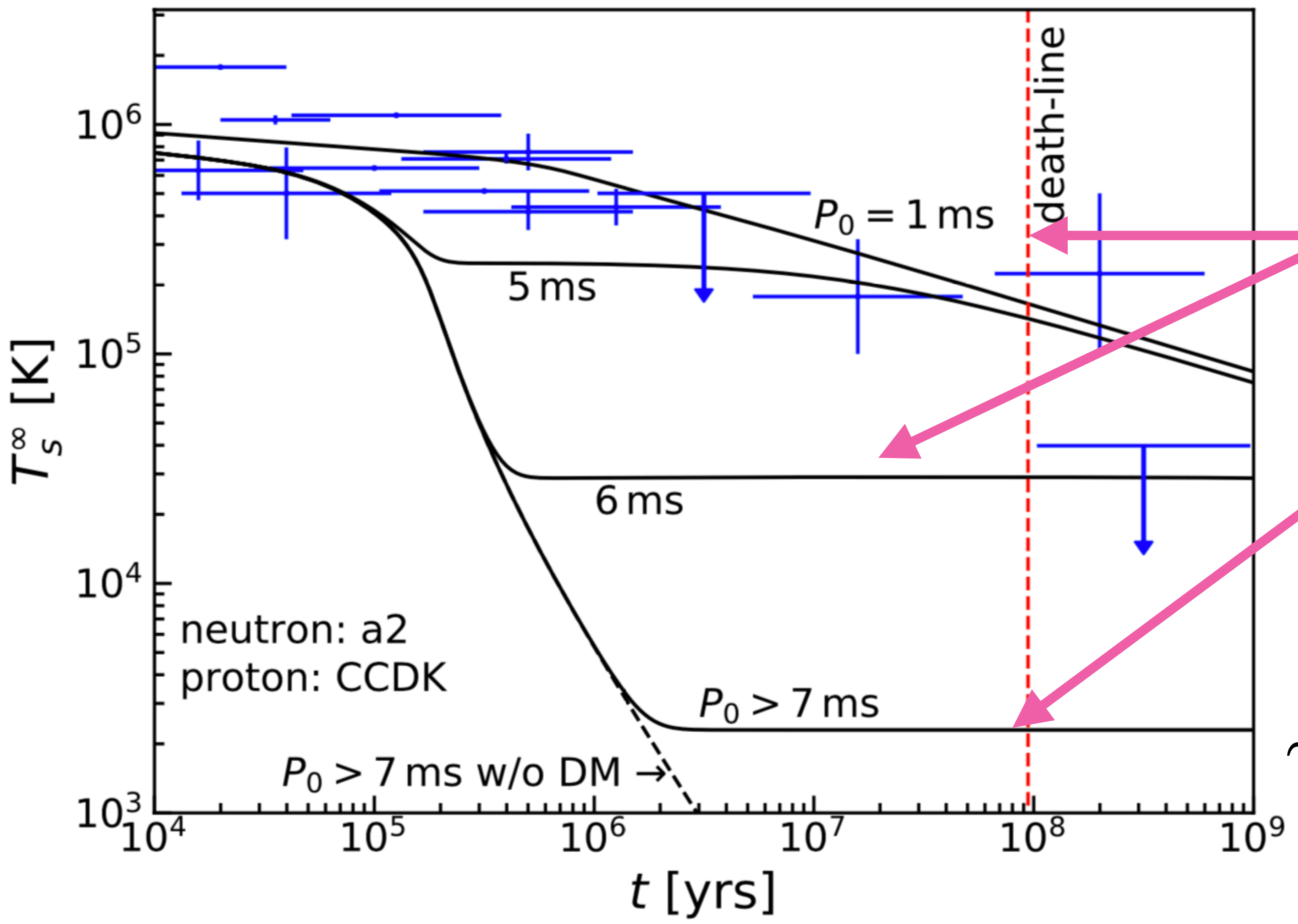
3.4. challenges: internal heating

(1)′ Rotochemical heating + DM heating

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

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

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



$\sim (2000 - 3000)K$

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.

③ NS Heating by DM

3.4. challenges: internal heating

(2) Vortex Creep heating

Alpar+, 1984, Shibazaki+, 1989

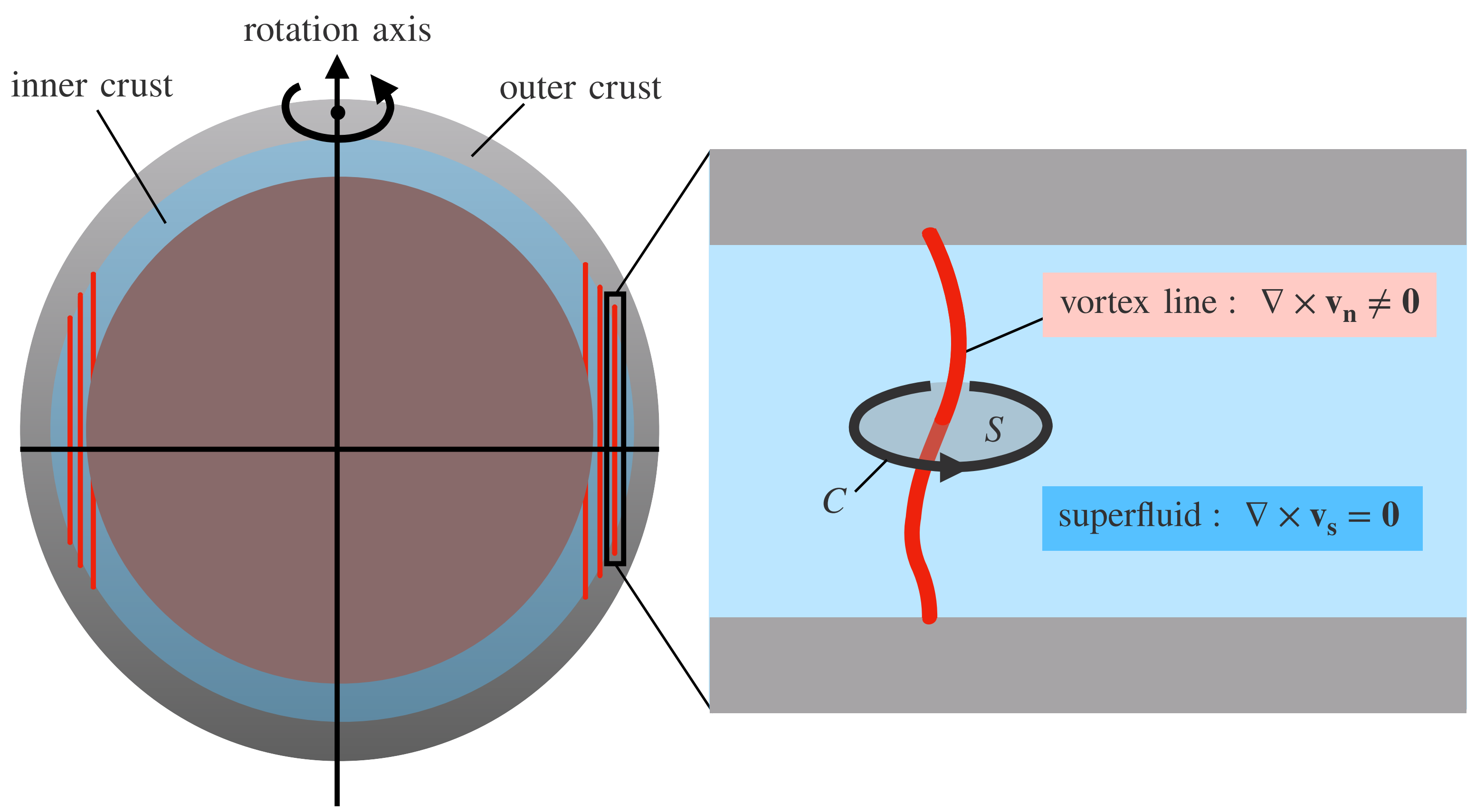
③ NS Heating by DM

3.4. challenges: internal heating

(2) Vortex Creep heating

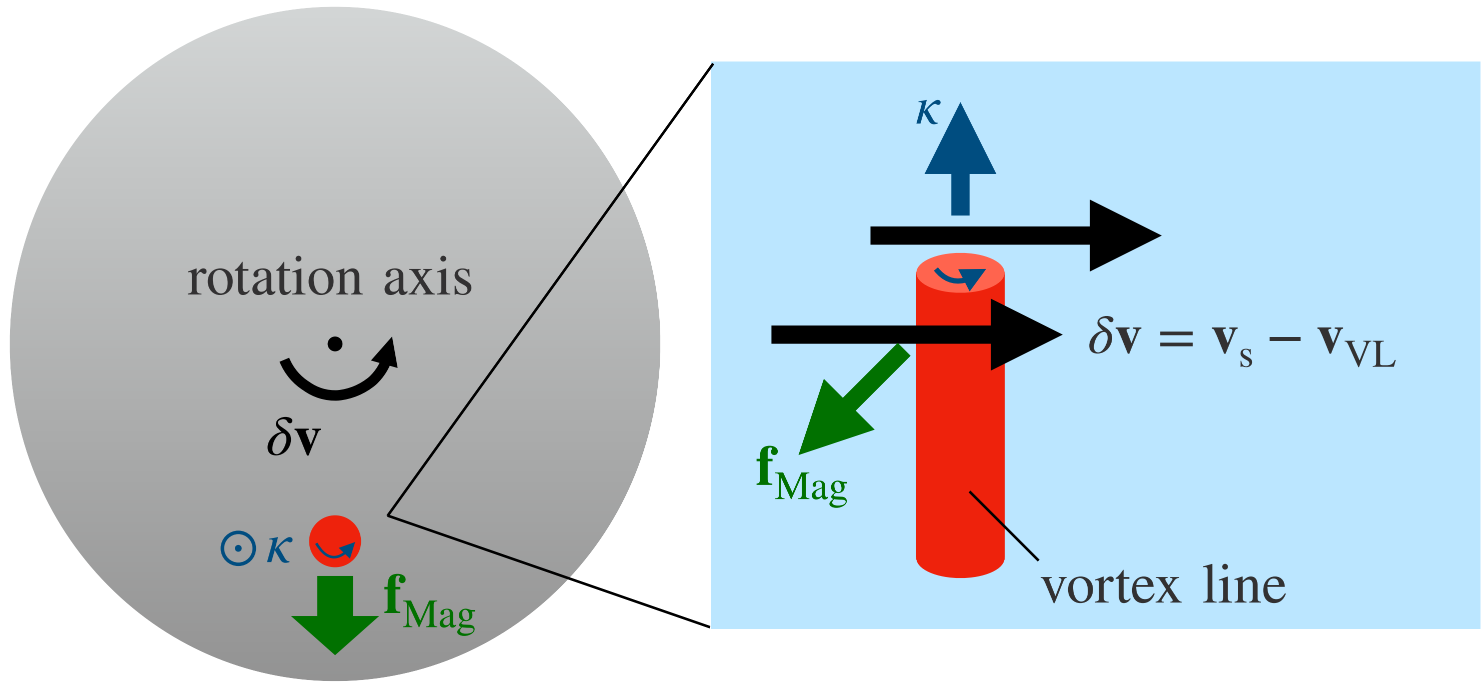
Alpar+, 1984, Shibazaki+, 1989

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



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

- 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**)

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

J : universal constant
Ω : NS angular velocity

③ NS Heating by DM

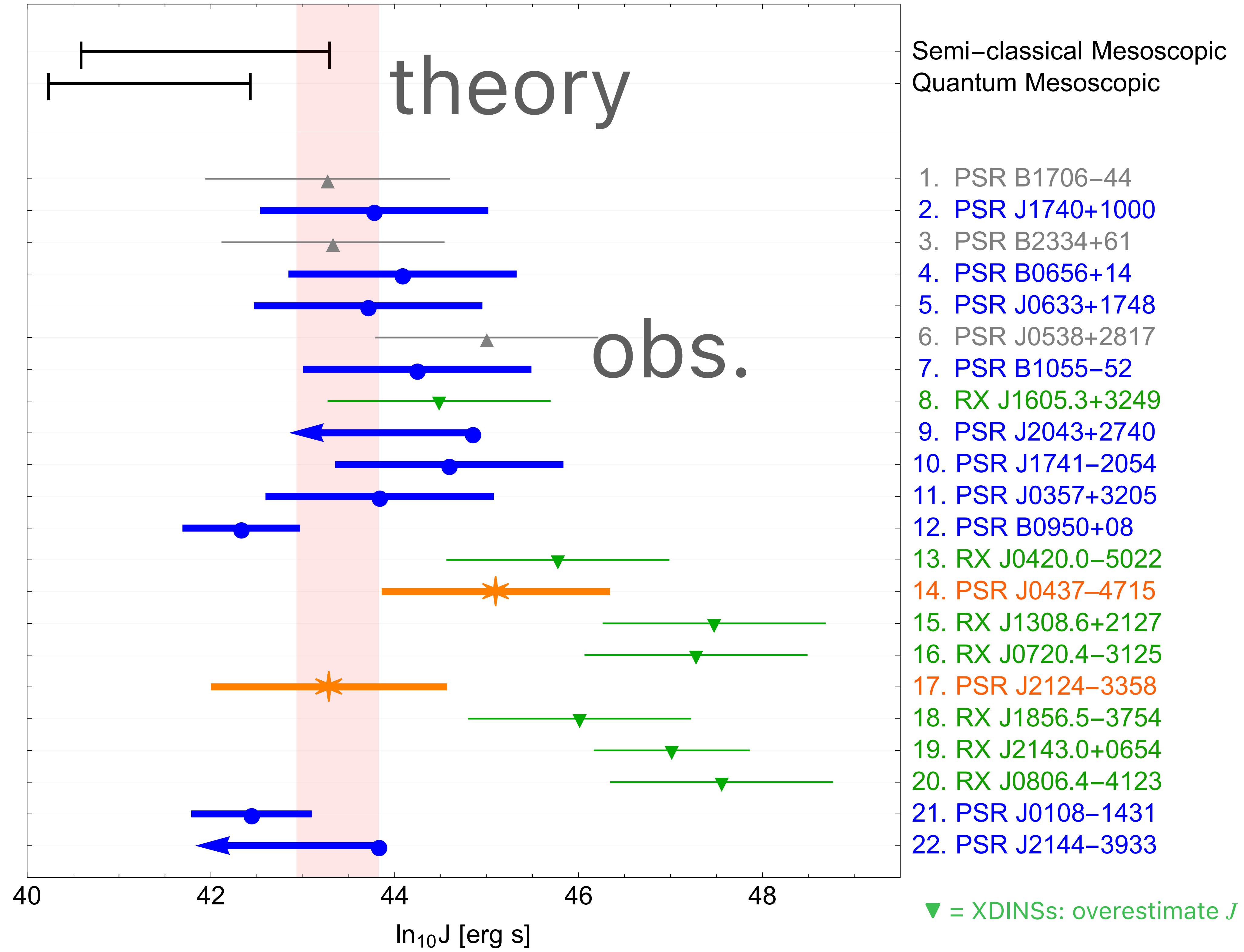
3.4. challenges: internal heating

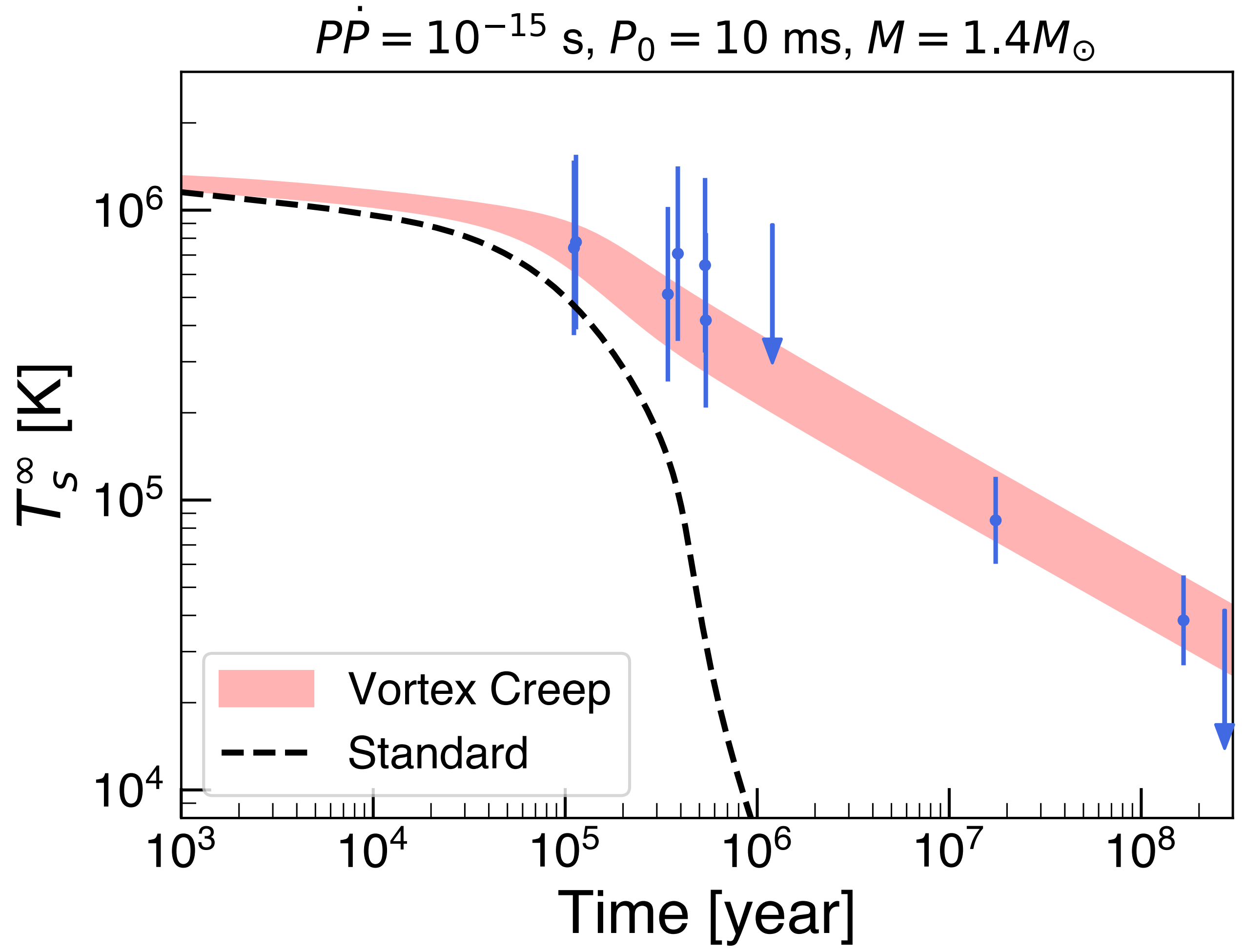
(2) Vortex Creep heating

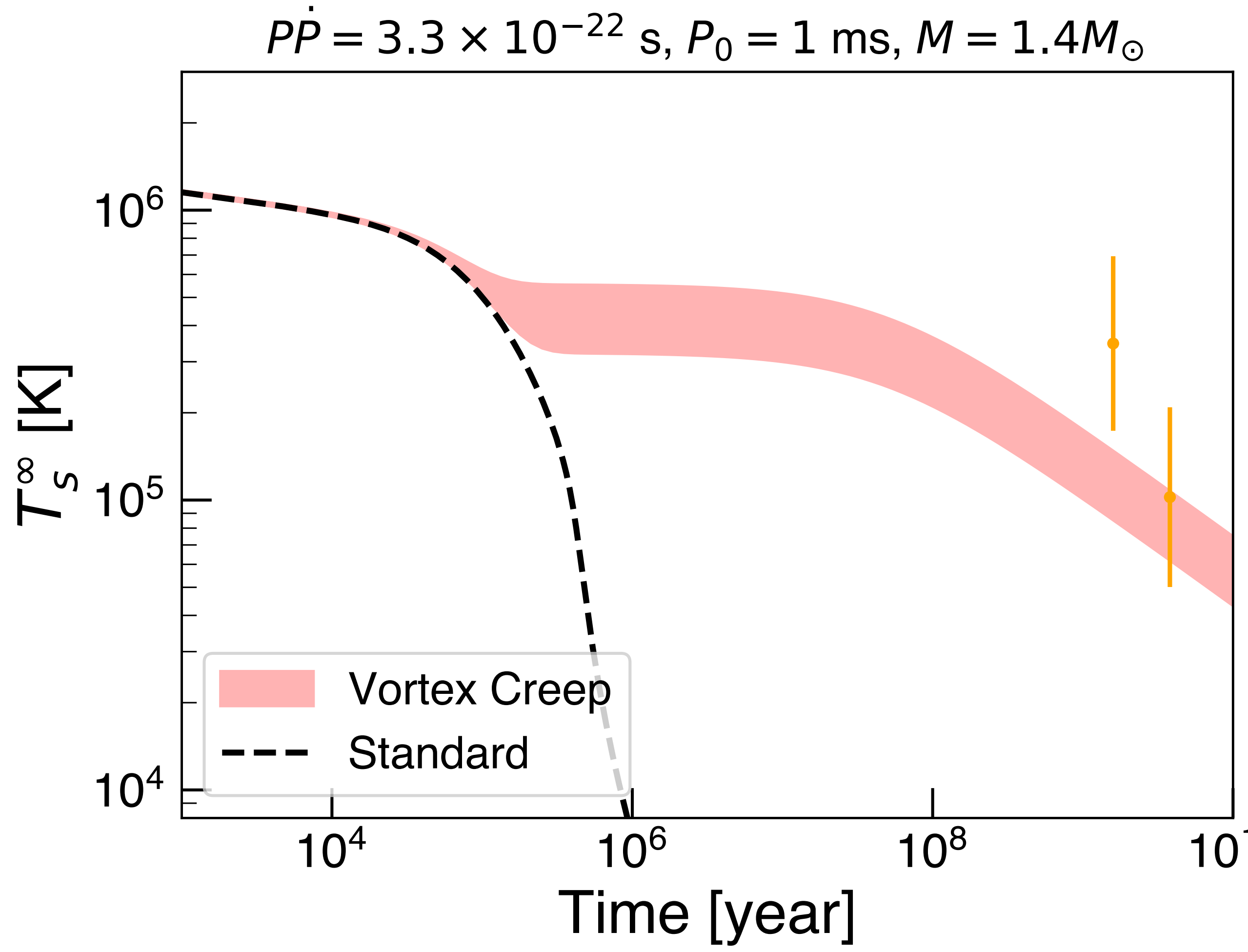
$$C\frac{dT}{dt} = -L_\nu - L_\gamma + L_{\text{vortex creep heating}}$$

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

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







▼ = XDINSs: overestimate J because of heating by decays of magnetic fields.

③ NS Heating by DM

3.4. challenges: internal heating

(2) Vortex Creep heating

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

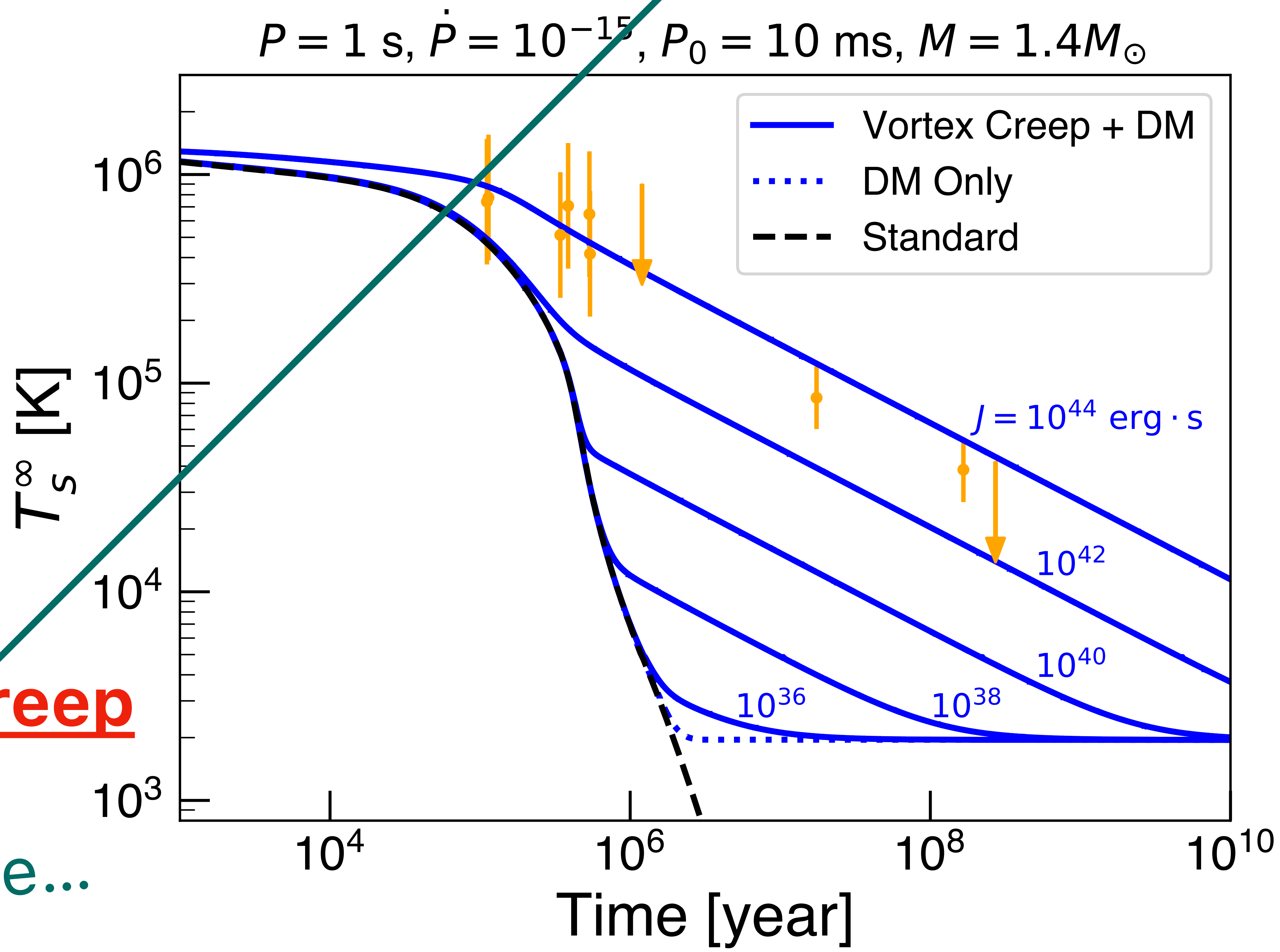
It can explain the old and warm NSs with a universal constant $J \sim 10^{43} - 10^{44}\ \text{erg}\cdot\text{s}$.

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

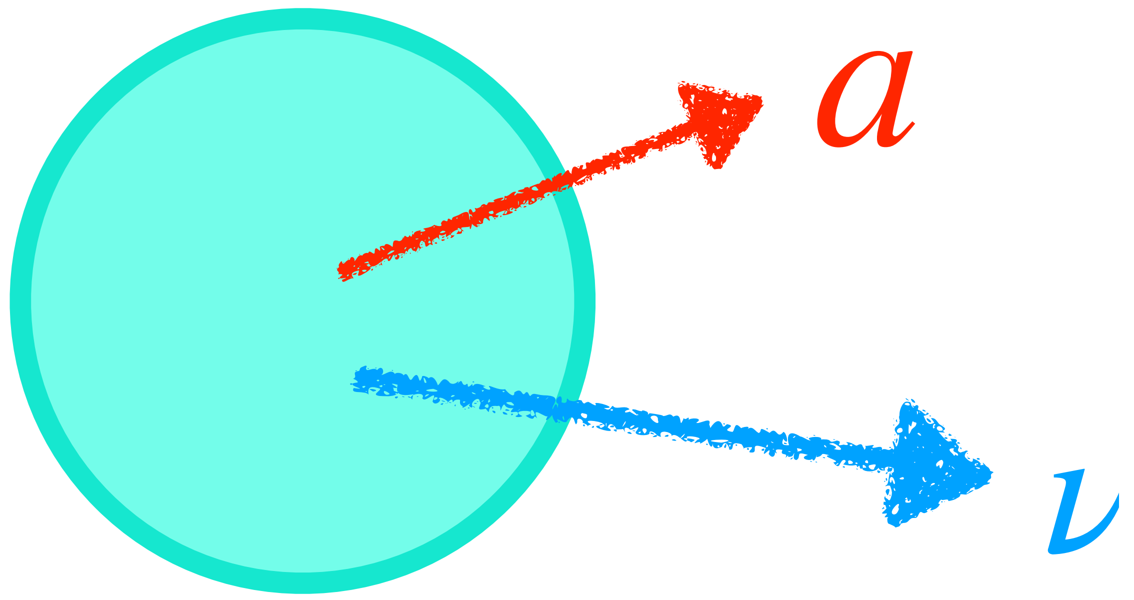
This may be a serious challenge...

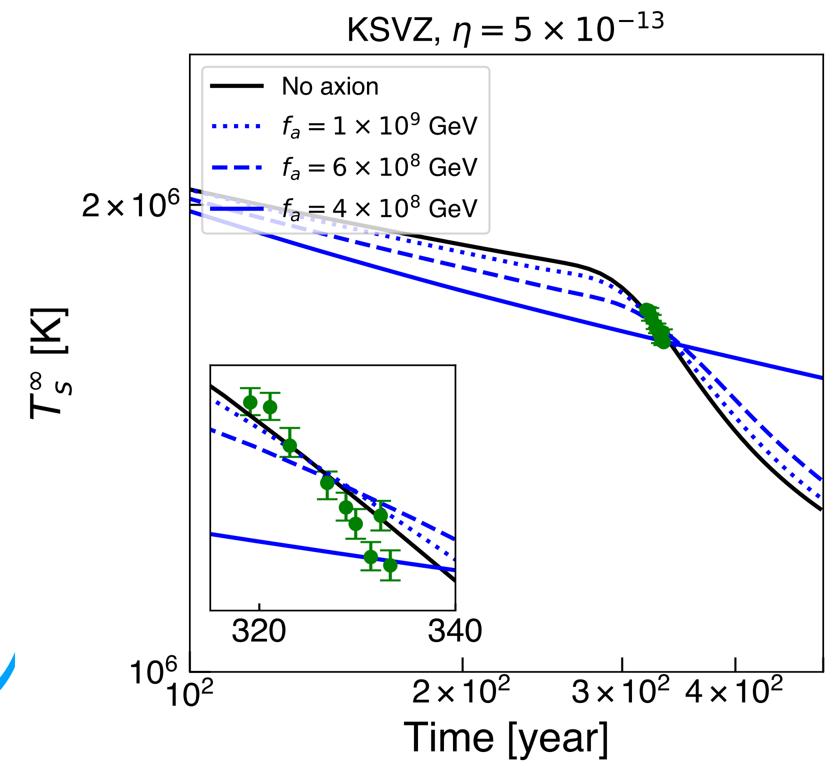
Summary

- Neutron Star
- NS Standard Cooling Theory

① Cas A NS Cooling by **axion**

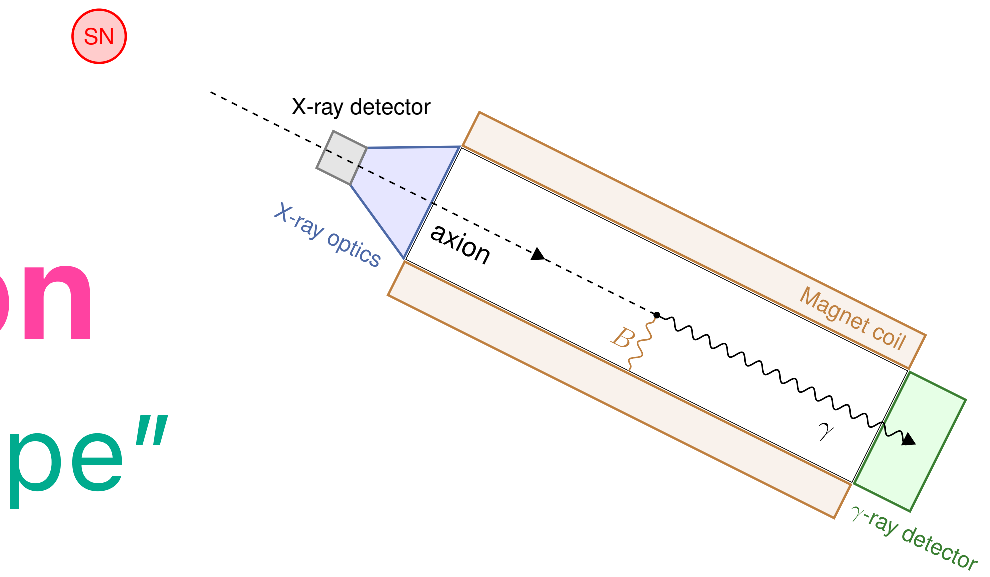
A new bound, $f_a > \mathcal{O}(10^8)$ GeV





② Side Remark: Supernova **Axion**

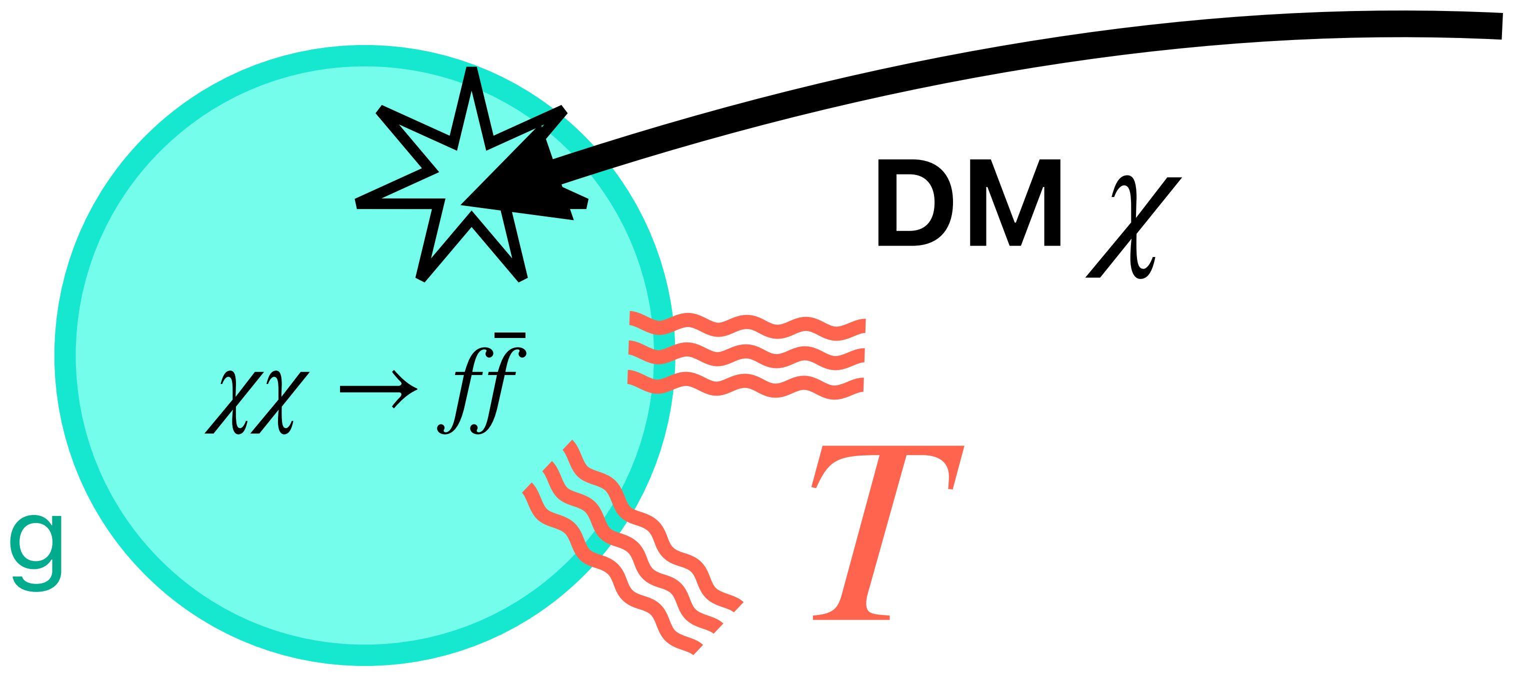
may be seen by a “Supernovascope”

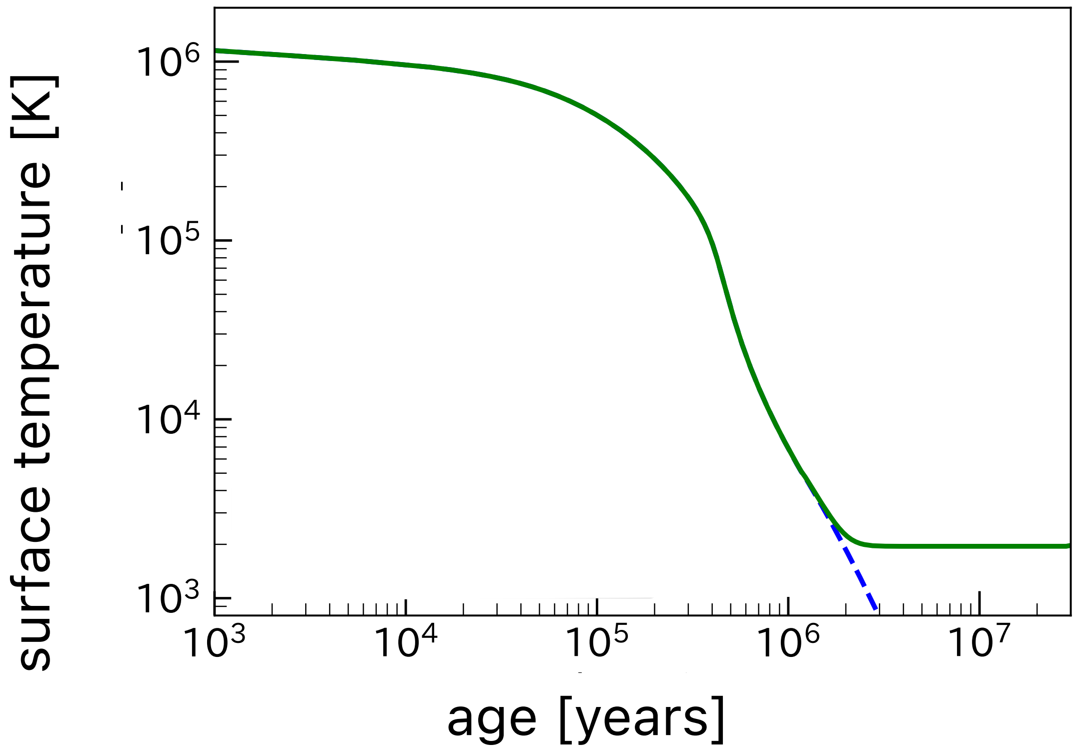


③ NS Heating by **DM**

examples

challenges: internal heating

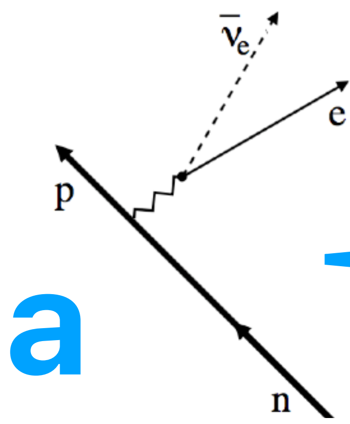




Backup

NS and Standard Cooling

- **Direct Urca**



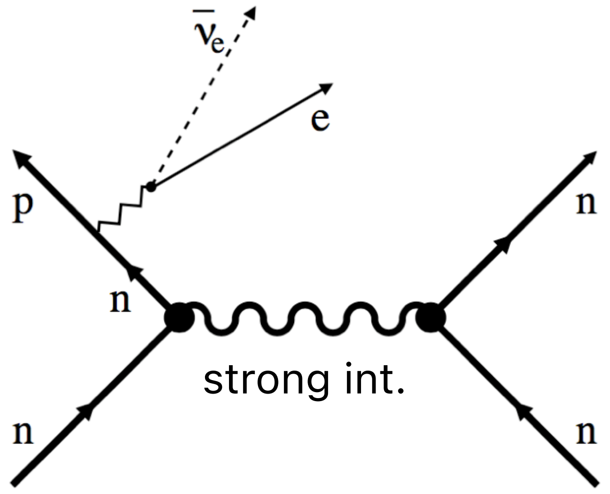
β decay and its inverse: $\begin{cases} n \to p + e^- + \bar{\nu}_e \\ p + e^- \to n + \nu_e \end{cases}$

It does **NOT** work in typical NS because $p_{p,F} + p_{e,F} < p_{n,F}$.

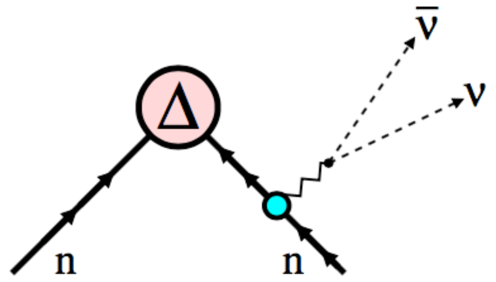
Discarded in “minimal cooling” scenario.

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

- Modified Urca (& Bremsstrahlung)



- PBF



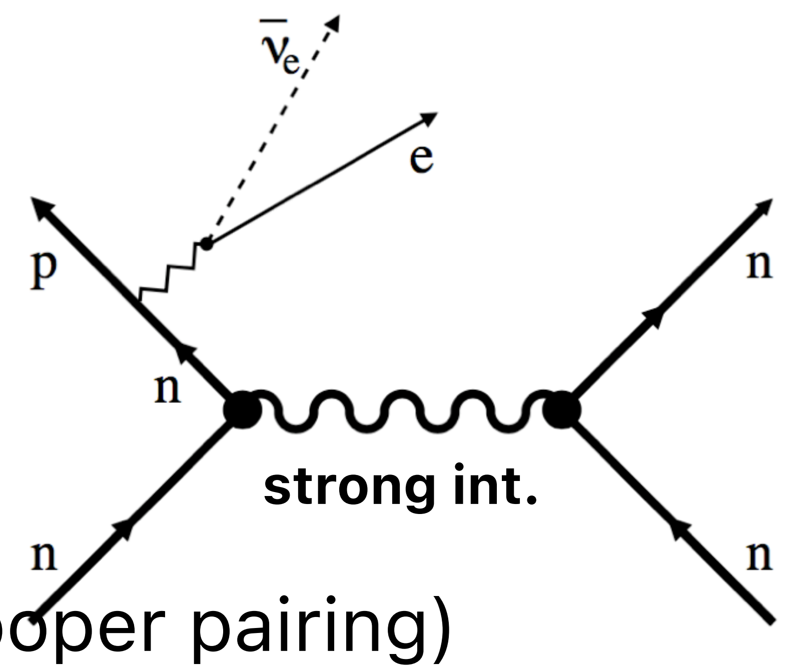
- From chemical eq., $\mu_n = \mu_p + \mu_e$, where $\mu_i = \sqrt{p_{i,F}^2 + m_{*i}^2}$
- Then, from the energy-momentum conservation,
  $|\vec{p}_{n,F}| < |\vec{p}_{p,F}| + |\vec{p}_{e,F}|$ must be satisfied, because…
  - For $n \to p + e$, only neutron around $\vec{p}_n \simeq \vec{p}_{n,F}$ are available.
  - This requires, $\sqrt{p_p^2 + m_{*p}^2} + \sqrt{p_e^2 + m_e^2} = E_n = \mu_n = \mu_p + \mu_e = \sqrt{p_{p,F}^2 + m_{*p}^2} + \sqrt{p_{e,F}^2 + m_e^2}$.
  - This requires $|\vec{p}_p| \simeq |\vec{p}_{p,F}|$ and $|\vec{p}_e| \simeq |\vec{p}_{e,F}|$. ($|\vec{p}_{p/e}| < p_{p/e,F}$ is Pauli-blocked.)
  - Thus, the three momentum, must satisfy $|\vec{p}_i| \simeq |\vec{p}_{i,F}|$ and $\vec{p_n} = \vec{p}_p + \vec{p}_e$,
    which is possible only if $|\vec{p}_{n,F}| < |\vec{p}_{p,F}| + |\vec{p}_{e,F}|$.

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



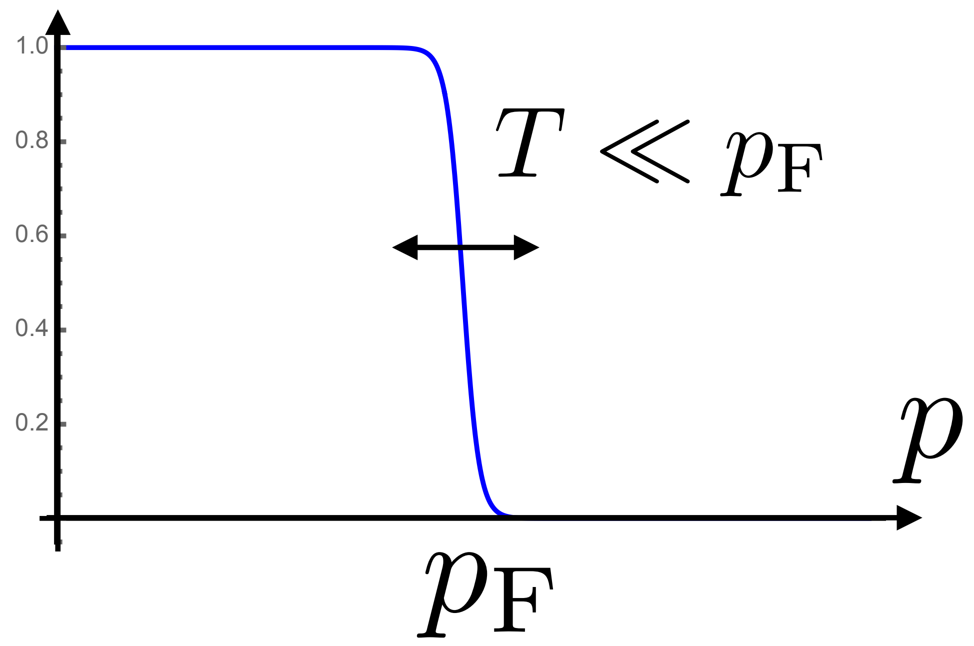
- Dominant process (before the onset of Cooper pairing)

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

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

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

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

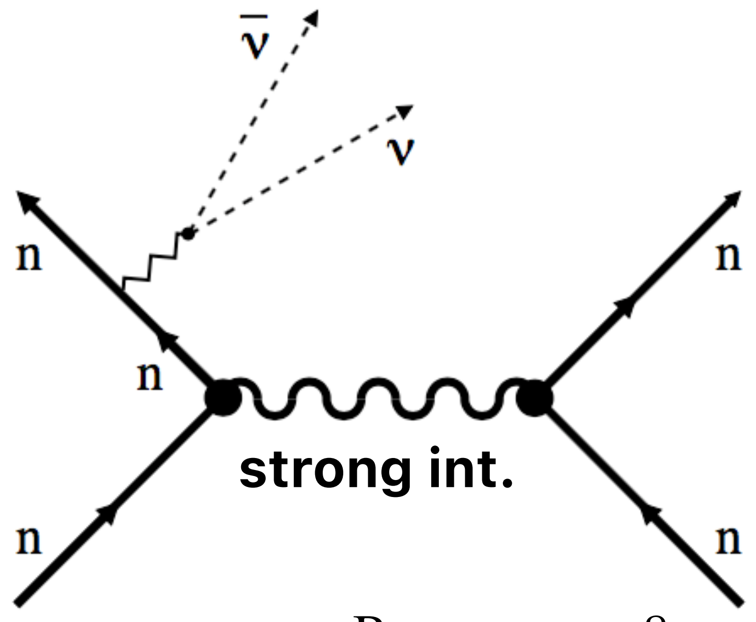


For reviews, e.g., D.G.Yakovlev+, astro-ph/0402143, D.Page+, astro-ph/0508056, 1302.6626

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

Neutrino emission

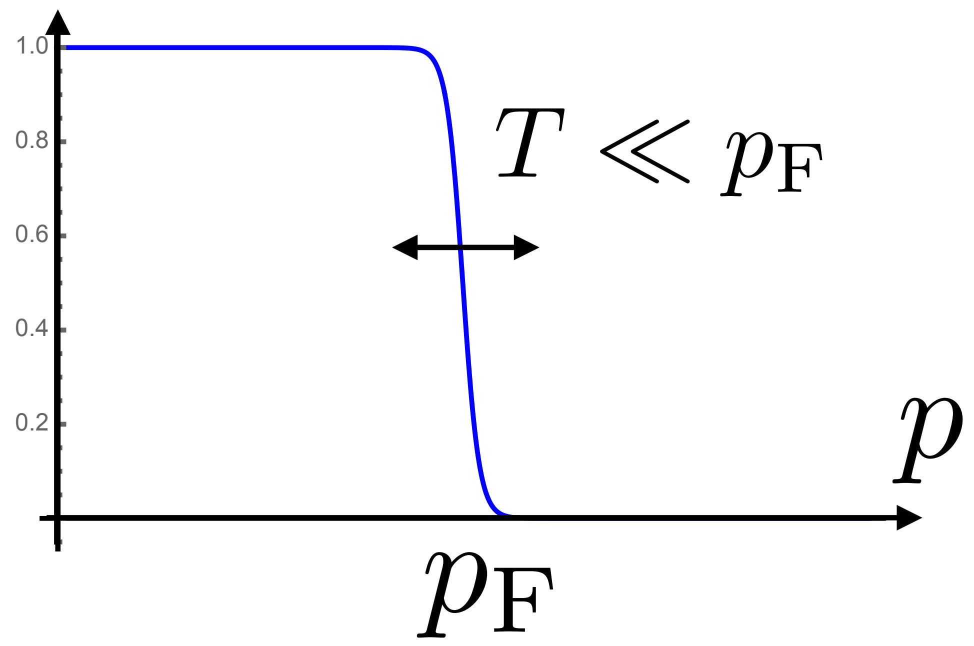
- ~~Direct Urca~~
- Modified Urca
- **Bremsstrahlung**
- PBF



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

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

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



Backup

Cas A NS cooling by axion

Cassiopeia A

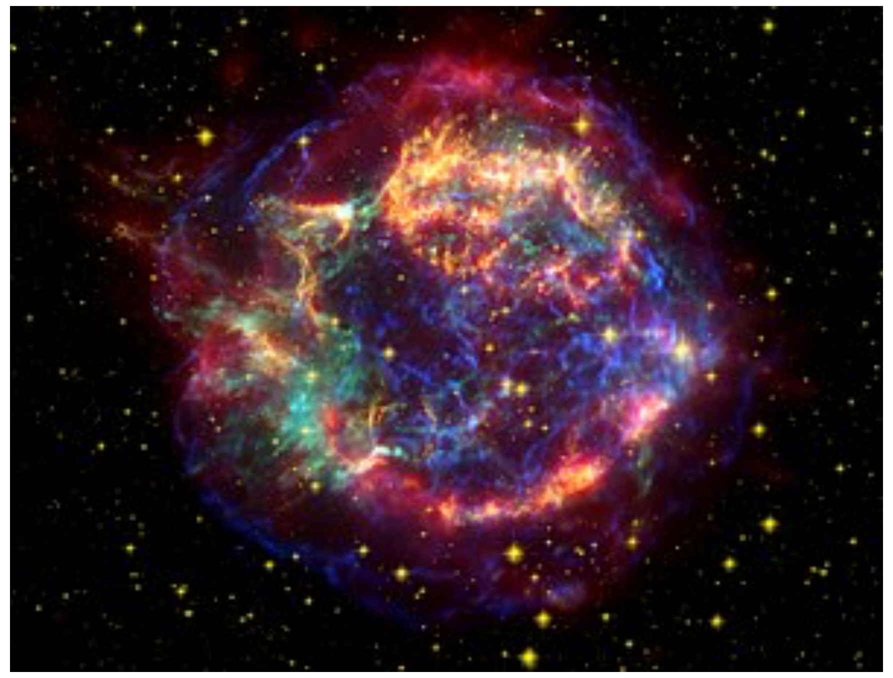
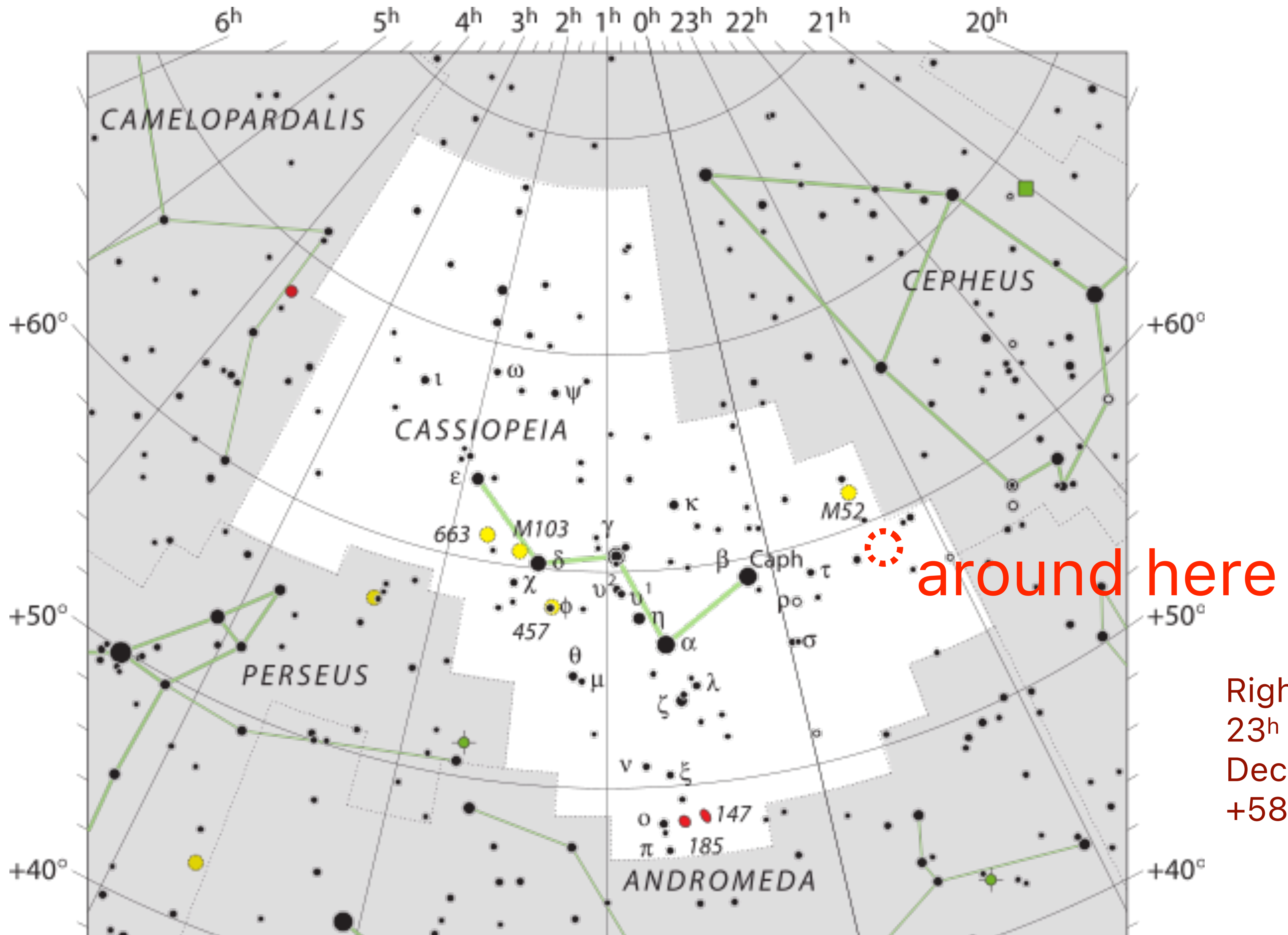


image from Wikipedia

- **What?** Supernova remnant (SNR)
- **Where?**
  In the constellation Cassiopeia.
  3.4 $^{+0.3}_{-0.1}$ kpc away [J.E.Reed et.al. '95] , within the Milky Way.



Right ascension
23h 23m 26s
Declination
+58° 48′

Cassiopeia A

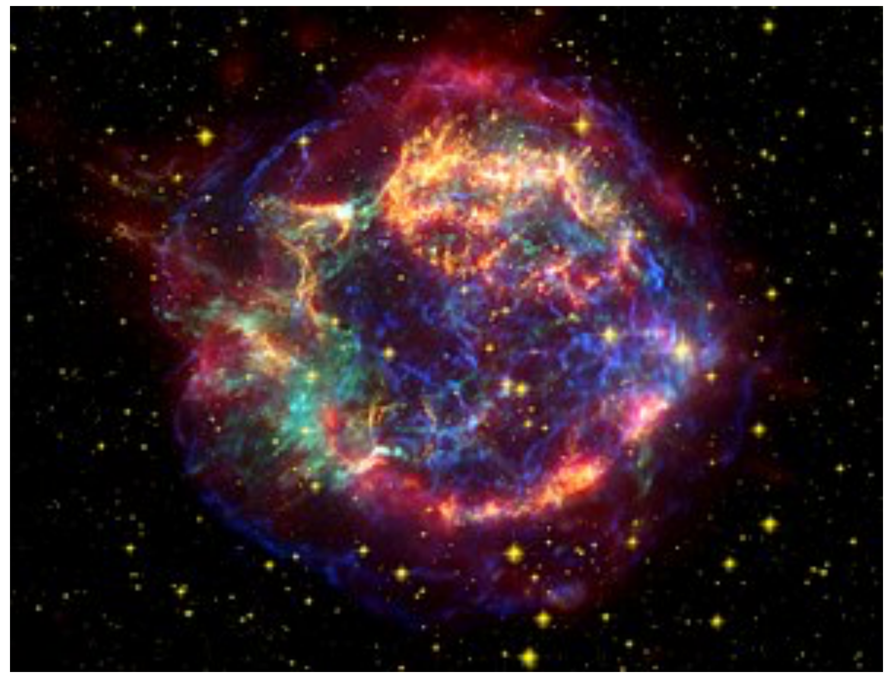


image from Wikipedia

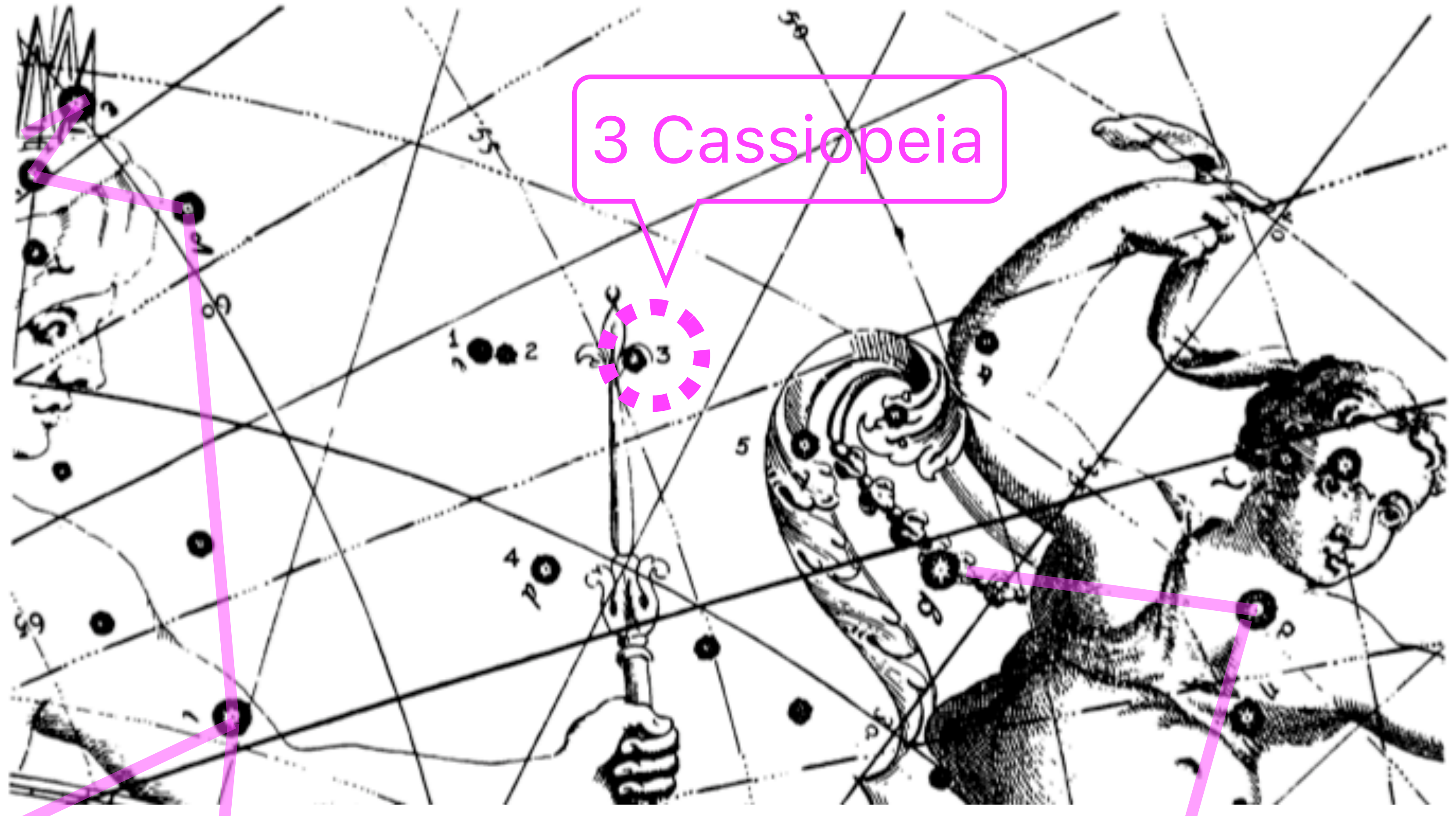
- **What?** Supernova remnant (SNR)
- **Where?**
  In the constellation Cassiopeia.
  3.4 $^{+0.3}_{-0.1}$ kpc away [J.E.Reed et.al. '95] , within the Milky Way.
- **When?**

  Explosion (light reached Earth) about 340 years ago.

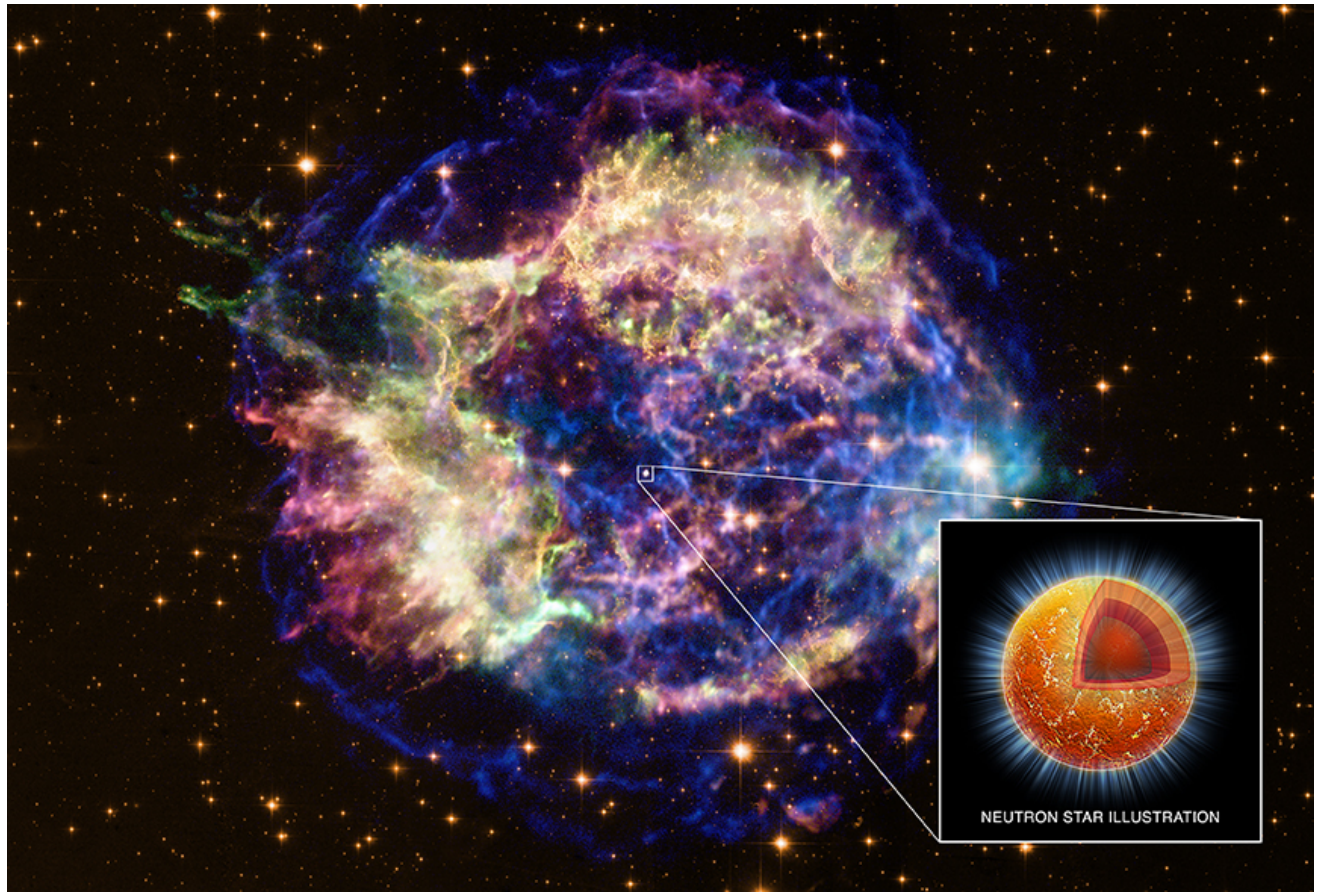
  - Remnant expansion suggests explosion dates of 1681 ± 19. [R.A.Fesen, et.al., '06]

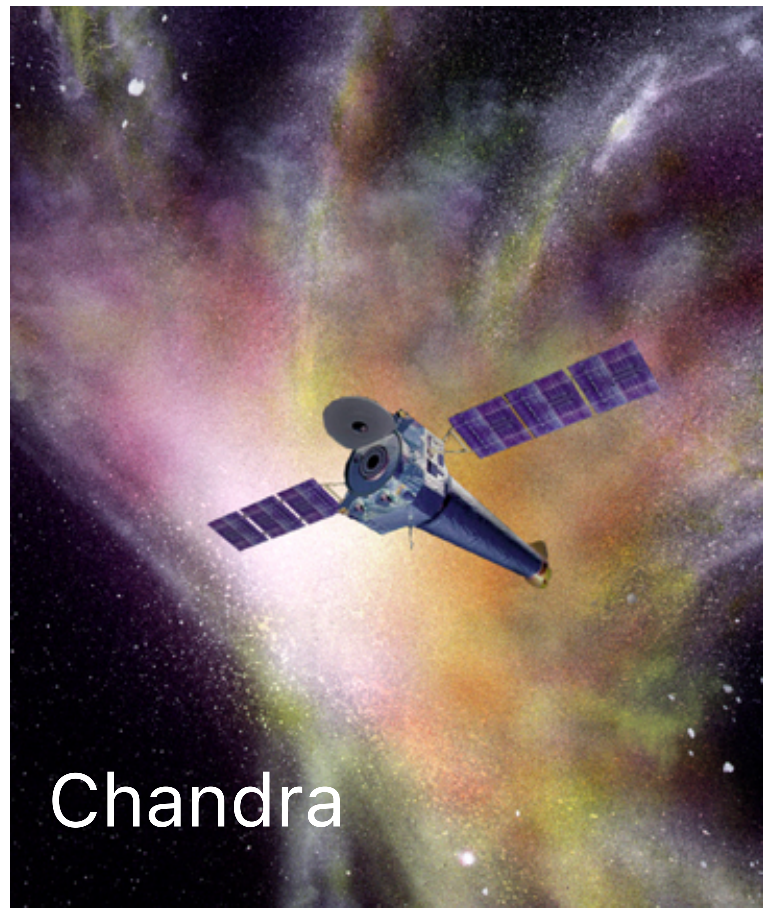
  - Cas A may be identical to the star 3 Cassiopeia, which was recorded by J. Flamsteed on August 16, 1680 and has been missed since then.

  [W. B. Ashworth, Jr. (1980); K. W. Kamper (1980); D. W. Hughes (1980).]



Cas A Neutron Star





images from Chandra's webpage

- In 1999, Chandra found a point source at the center of Cas A.
- X-ray spectrum is consistent with a thermal emission of **Neutron Star** with a carbon atmosphere, mass M = (1.4±0.3) Msun, and radius R = (11-13) km.

[W.C.G.Ho, C.O.Heinke, '09], [W.C.G.Ho, K.G.Elshamouty, C.O.Heinke, A.Y.Potekhin, '14].

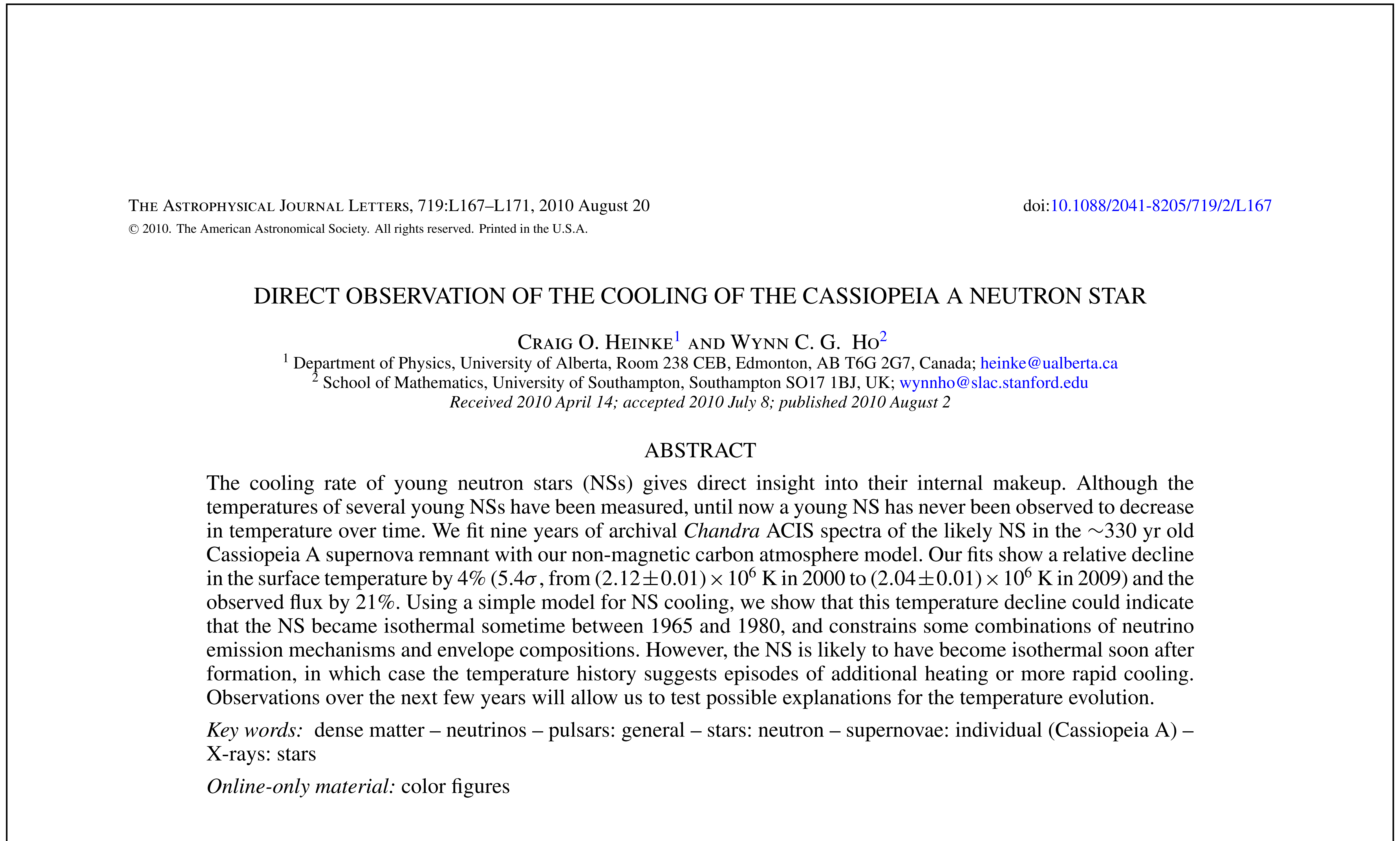
- and,.....

Cas A NS Cooling

- The **Cooling** is observed!

Cas A NS is the only isolated NS whose cooling has been observed in real time.

Temperature decreases by (3-4)% in 10 years.


The Astrophysical Journal Letters, 719:L167–L171, 2010 August 20 doi:10.1088/2041-8205/719/2/L167

DIRECT OBSERVATION OF THE COOLING OF THE CASSIOPEIA A NEUTRON STAR

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[2] School of Mathematics, University of Southampton, Southampton SO17 1BJ, UK; wynnho@slac.stanford.edu
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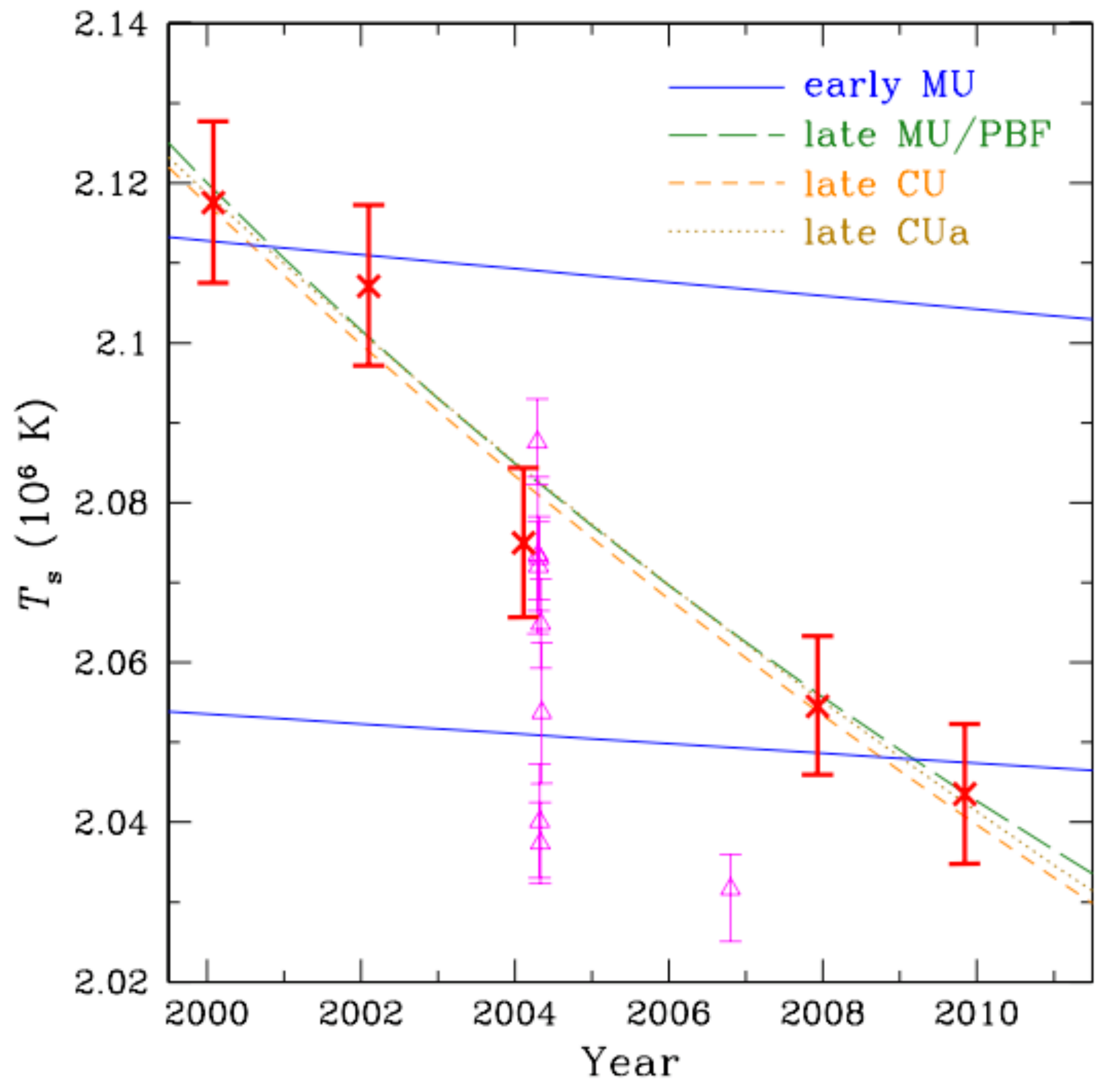
ABSTRACT

The cooling rate of young neutron stars (NSs) gives direct insight into their internal makeup. Although the temperatures of several young NSs have been measured, until now a young NS has never been observed to decrease in temperature over time. We fit nine years of archival *Chandra* ACIS spectra of the likely NS in the ~330 yr old Cassiopeia A supernova remnant with our non-magnetic carbon atmosphere model. Our fits show a relative decline in the surface temperature by 4% (5.4σ, from $(2.12\pm0.01)\times10^6$ K in 2000 to $(2.04\pm0.01)\times10^6$ K in 2009) and the observed flux by 21%. Using a simple model for NS cooling, we show that this temperature decline could indicate that the NS became isothermal sometime between 1965 and 1980, and constrains some combinations of neutrino emission mechanisms and envelope compositions. However, the NS is likely to have become isothermal soon after formation, in which case the temperature history suggests episodes of additional heating or more rapid cooling. Observations over the next few years will allow us to test possible explanations for the temperature evolution.

Key words: dense matter – neutrinos – pulsars: general – stars: neutron – supernovae: individual (Cassiopeia A) – X-rays: stars

Online-only material: color figures



Cas A NS Cooling

- The **Cooling** is observed!

Cas A NS is the only isolated NS whose cooling has been observed in real time.

Temperature decreases by (3-4)% in 10 years.

More Recent data:
W.C.G.Ho, K.G.Elshamouty, C.O.Heinke, A.Y.Potekhin, 1412.7759 (Phys.Rev.C)

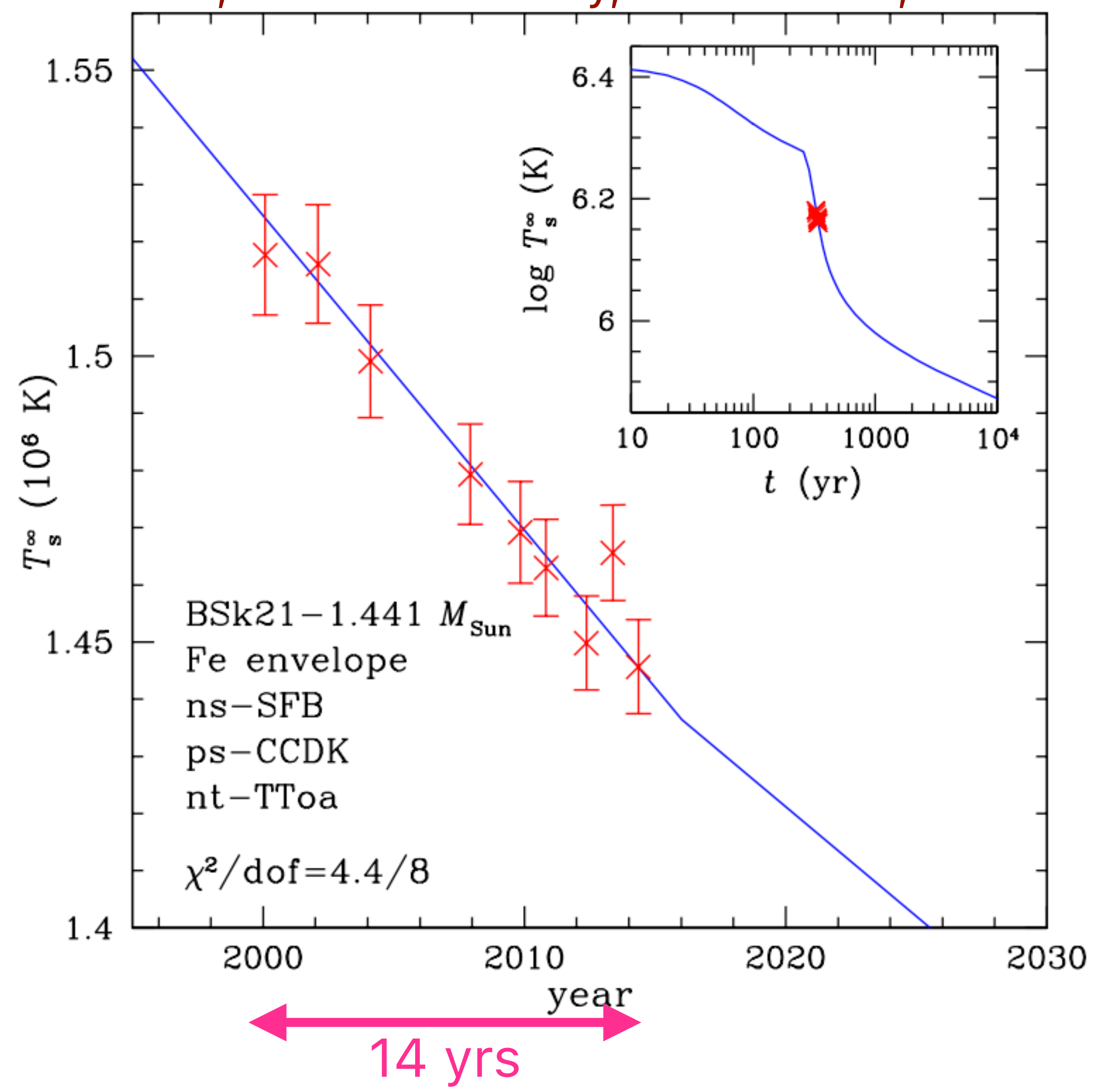


TABLE I. *Chandra* ACIS-S Graded mode temperatures.

ObsID	Year	$T_{\rm eff}$[a]
114	2000.08	$2.145^{+0.009}_{-0.008}$
1952	2002.10	$2.142^{+0.009}_{-0.008}$
5196	2004.11	$2.118^{+0.011}_{-0.007}$
(9117,9773)[b]	2007.93	$2.095^{+0.007}_{-0.010}$
(10935,12020)[b]	2009.84	$2.080^{+0.009}_{-0.008}$
(10936,13177)[b]	2010.83	$2.070^{+0.009}_{-0.009}$
14229	2012.37	$2.050^{+0.009}_{-0.008}$
14480	2013.38	$2.075^{+0.009}_{-0.009}$
14481	2014.36	$2.045^{+0.009}_{-0.009}$

[a] Errors are 1σ.
[b] The two ObsIDs, which were taken close together in time with the same instrument setup, are merged prior to spectral analysis.

Cas A NS Cooling (theory)

NS temperature evolution

$$C \frac{dT}{dt} = -L_\nu \propto T^8 \implies \boxed{T \propto t^{-1/6}}$$

C: $\propto T$

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

For Cas A NS observation,

$$\begin{cases} t \simeq 330 \text{ yrs} \\ \Delta t \simeq 10 \text{ yrs} \end{cases}$$

$$\implies \left.\frac{\Delta T}{T}\right|_{10\text{yrs}} \sim -\frac{1}{6} \cdot \frac{\Delta t}{t} \sim 0.5\%$$

surface temperature

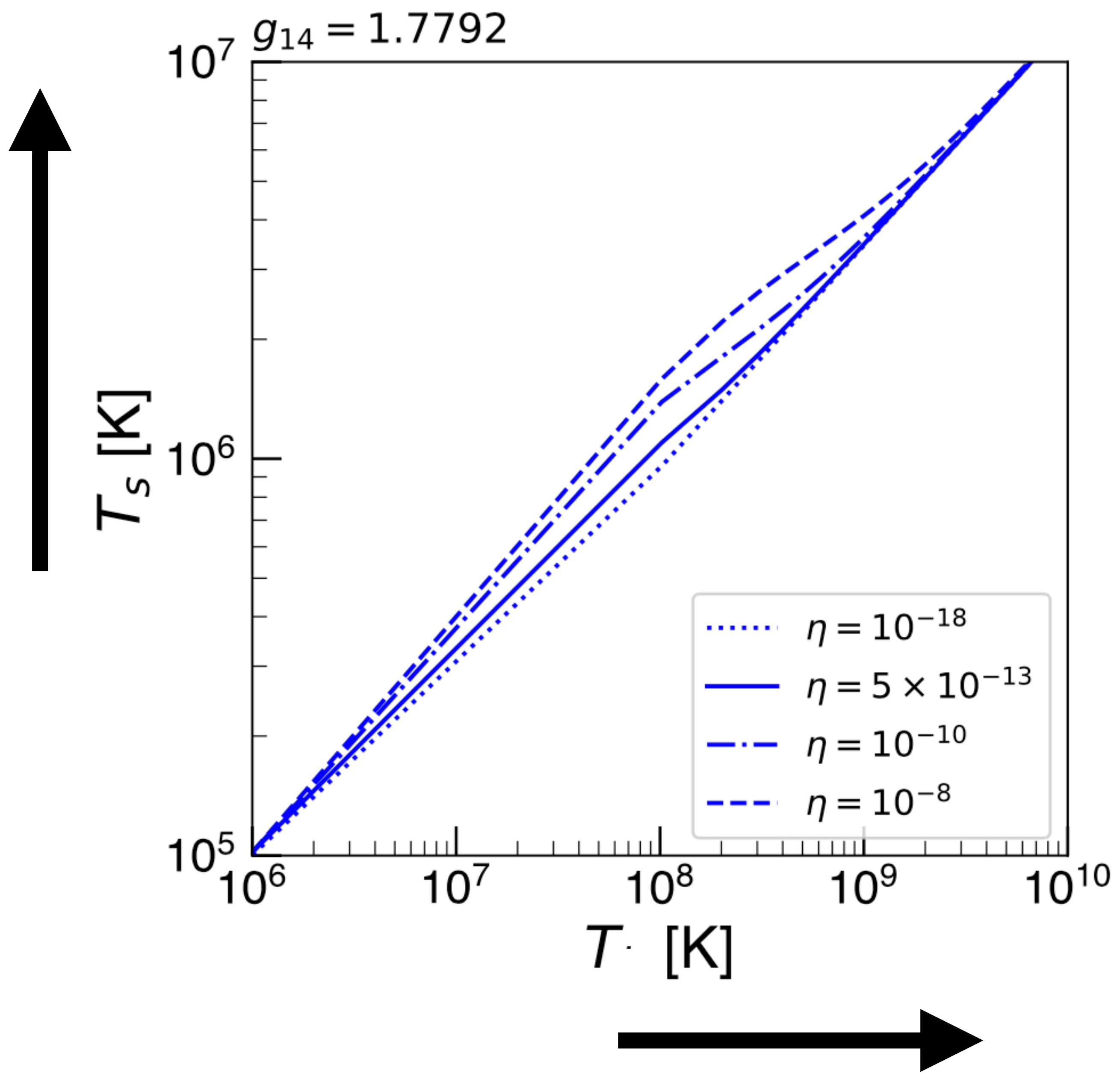
$$\implies \boxed{\left.\frac{\Delta T_s}{T_s}\right|_{10\text{yrs}} \sim 0.3\% \text{ !!}}$$

Cas A NS Cooling (theory)

NS surface is insulated from the hot interior by its envelope.

surface temperature (observed)

$T_s \sim T^\alpha \ (\alpha \sim 0.5)$



internal temperature

$\eta = g_{14}^2 \Delta M / M$

ΔM : mass of light elements

g_{14} : surface gravity in units of $10^{14}\mathrm{cm/s^2}$

$$\Longrightarrow \boxed{T \propto t^{-1/6}}$$

For Cas A NS observation,

$$\begin{cases} t \simeq 330 \text{ yrs} \\ \Delta t \simeq 10 \text{ yrs} \end{cases}$$

$$\Longrightarrow \left.\frac{\Delta T}{T}\right|_{10\mathrm{yrs}} \sim -\frac{1}{6} \cdot \frac{\Delta t}{t} \sim 0.5\%$$

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Cas A NS Cooling (theory)

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$$C\frac{dT}{dt} = -L_\nu \propto T^8 \quad \Longrightarrow \quad \boxed{T \propto t^{-1/6}}$$

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- (PBF)

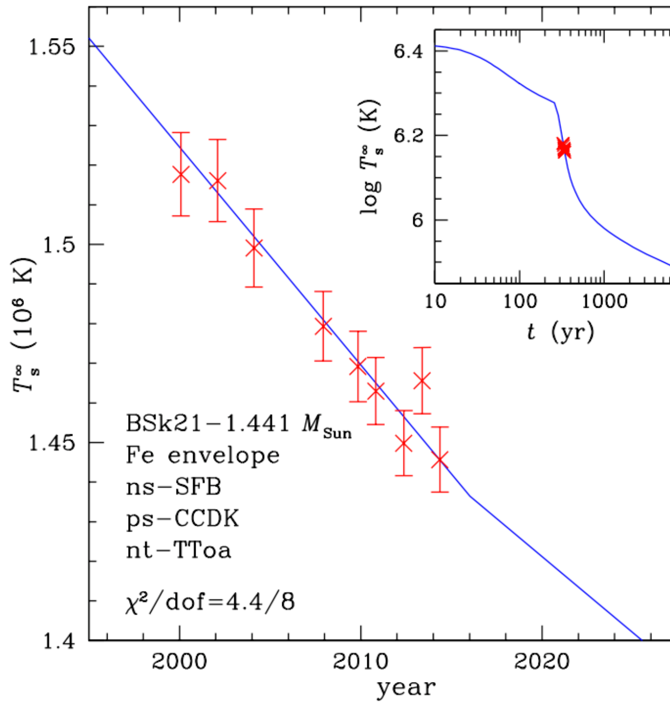
For Cas A NS observation,

$$\begin{cases} t \simeq 330 \text{ yrs} \\ \Delta t \simeq 10 \text{ yrs} \end{cases}$$

$$\Longrightarrow \left.\frac{\Delta T}{T}\right|_{10\text{yrs}} \sim -\frac{1}{6}\cdot\frac{\Delta t}{t} \sim 0.5\%$$

surface temperature

$$\Longrightarrow \boxed{\left.\frac{\Delta T_s}{T_s}\right|_{10\text{yrs}} \sim 0.3\% \text{ !!}}$$



much smaller than the observation, $\Delta T_s/T_s \sim$ (3-4)%.

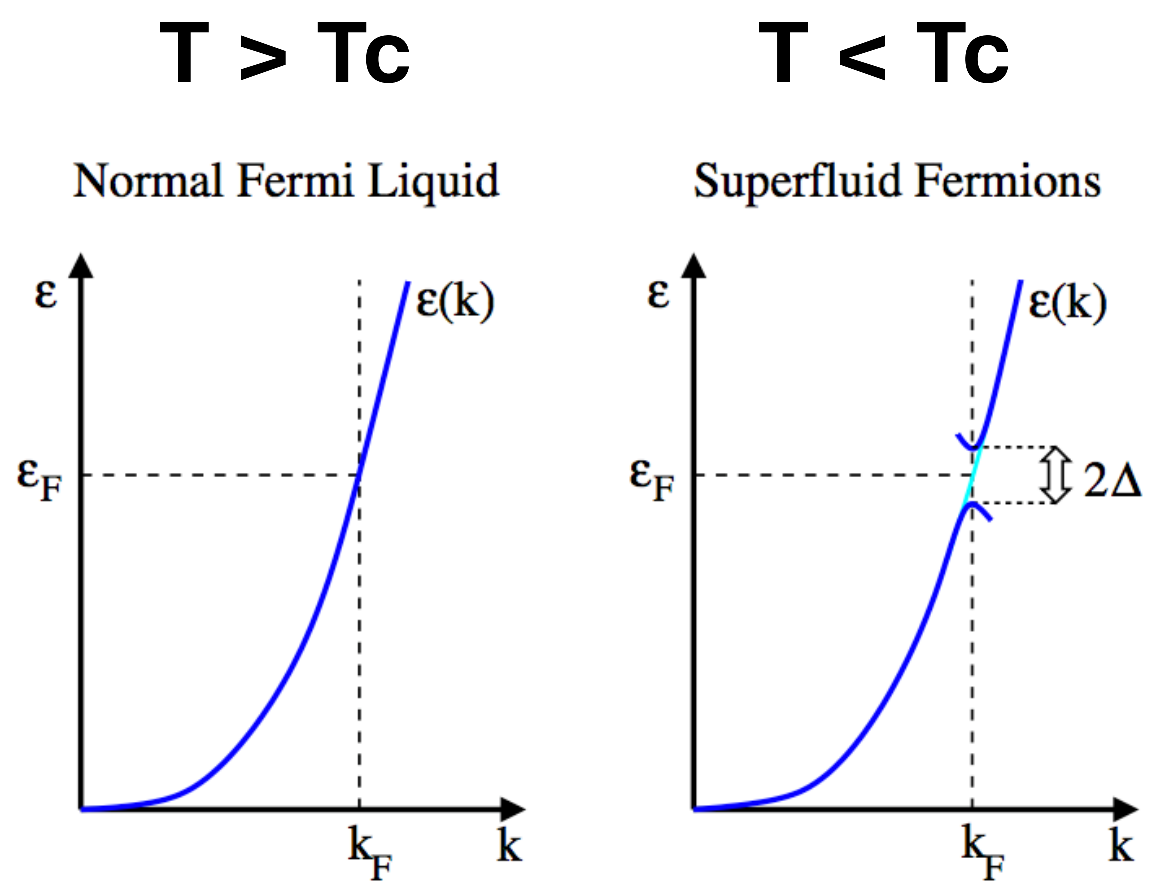
Cas A NS Cooling (theory)

NS temperature evolution

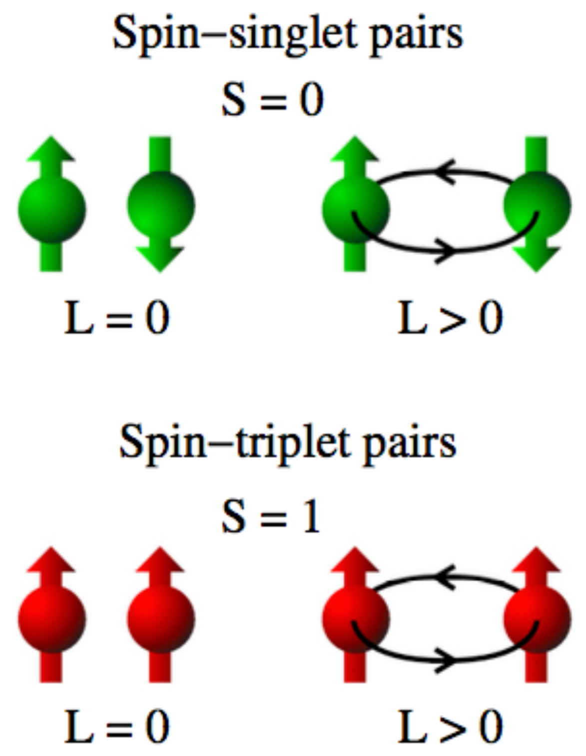
$$C\frac{dT}{dt} = -L_\nu$$

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

- At T < Tc, Cooper pairing occurs.



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



- M.Urca and Brems. are suppressed then.
- On the other hand, a new process, **Cooper pair breaking and formation (PBF),** is enhanced.

Figs. from Page et.al. 1302.6626

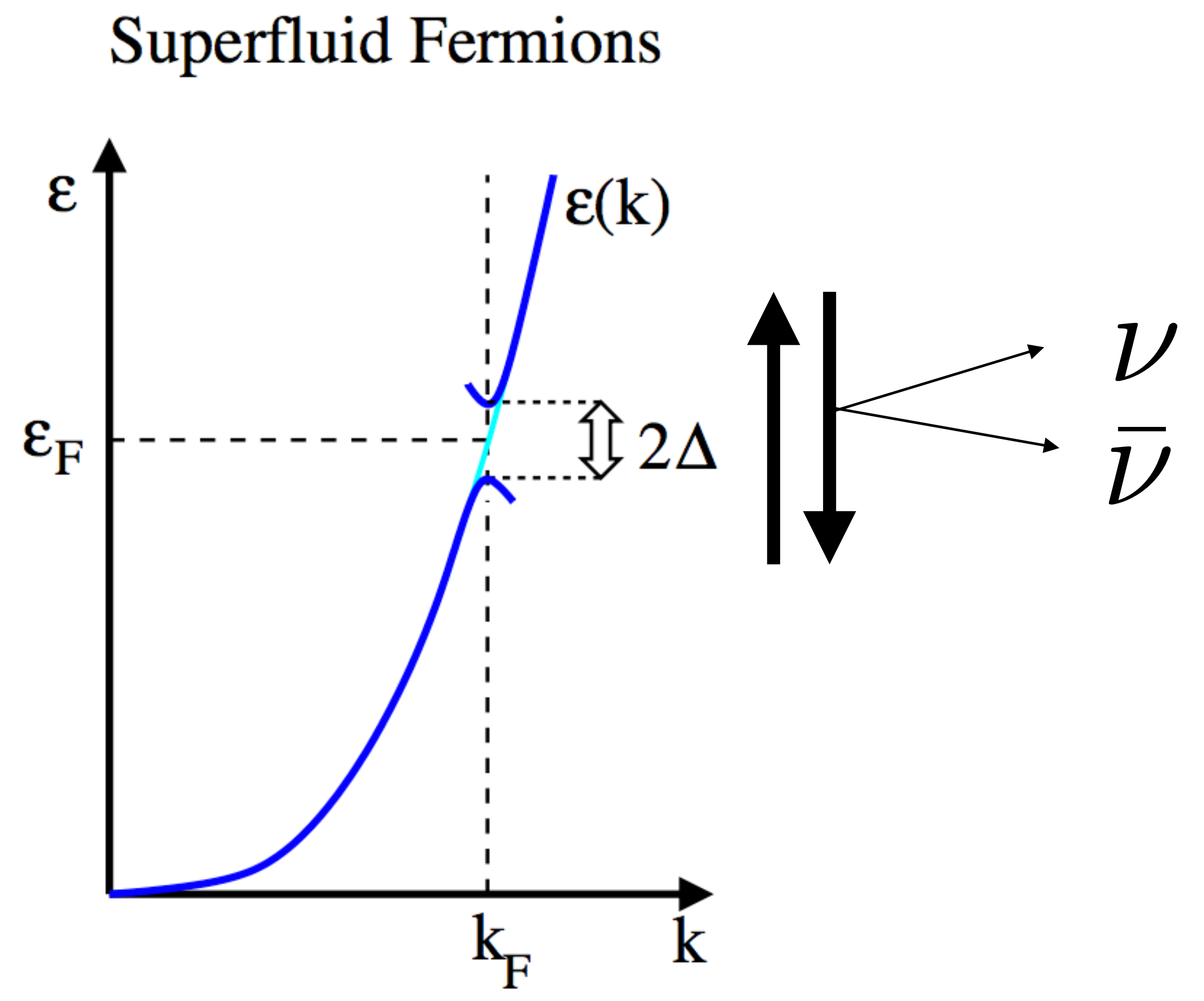
Cas A NS Cooling (theory)

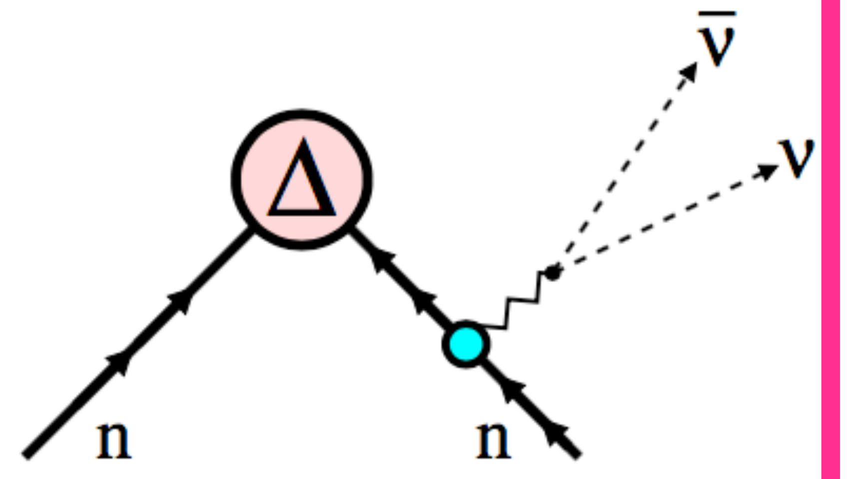
NS temperature evolution

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

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

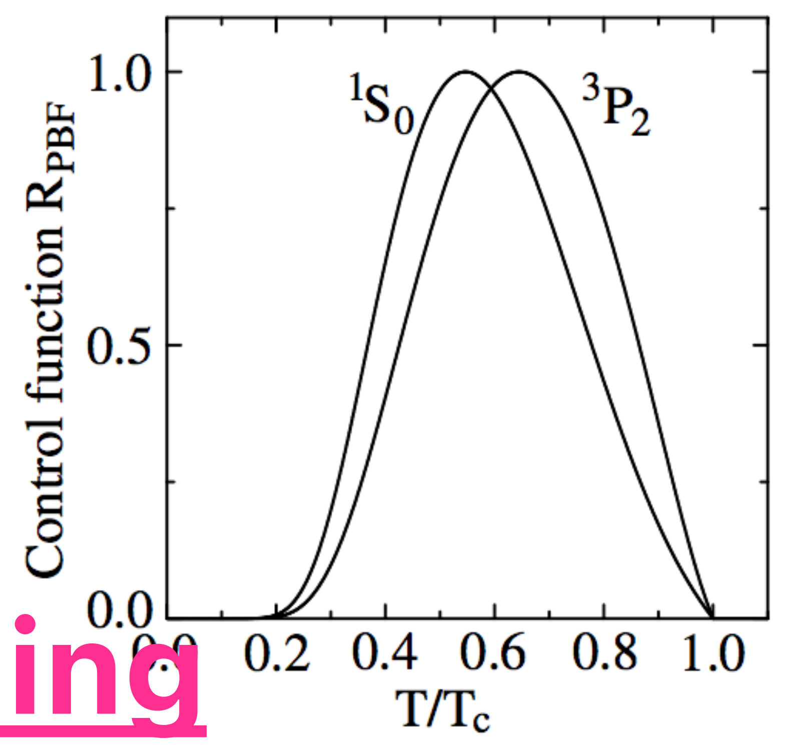
Cooper pair breaking and formation (PBF)





Effective only in a short period

- At T > Tc, no paring.
- At T << Tc, no pair breaking.



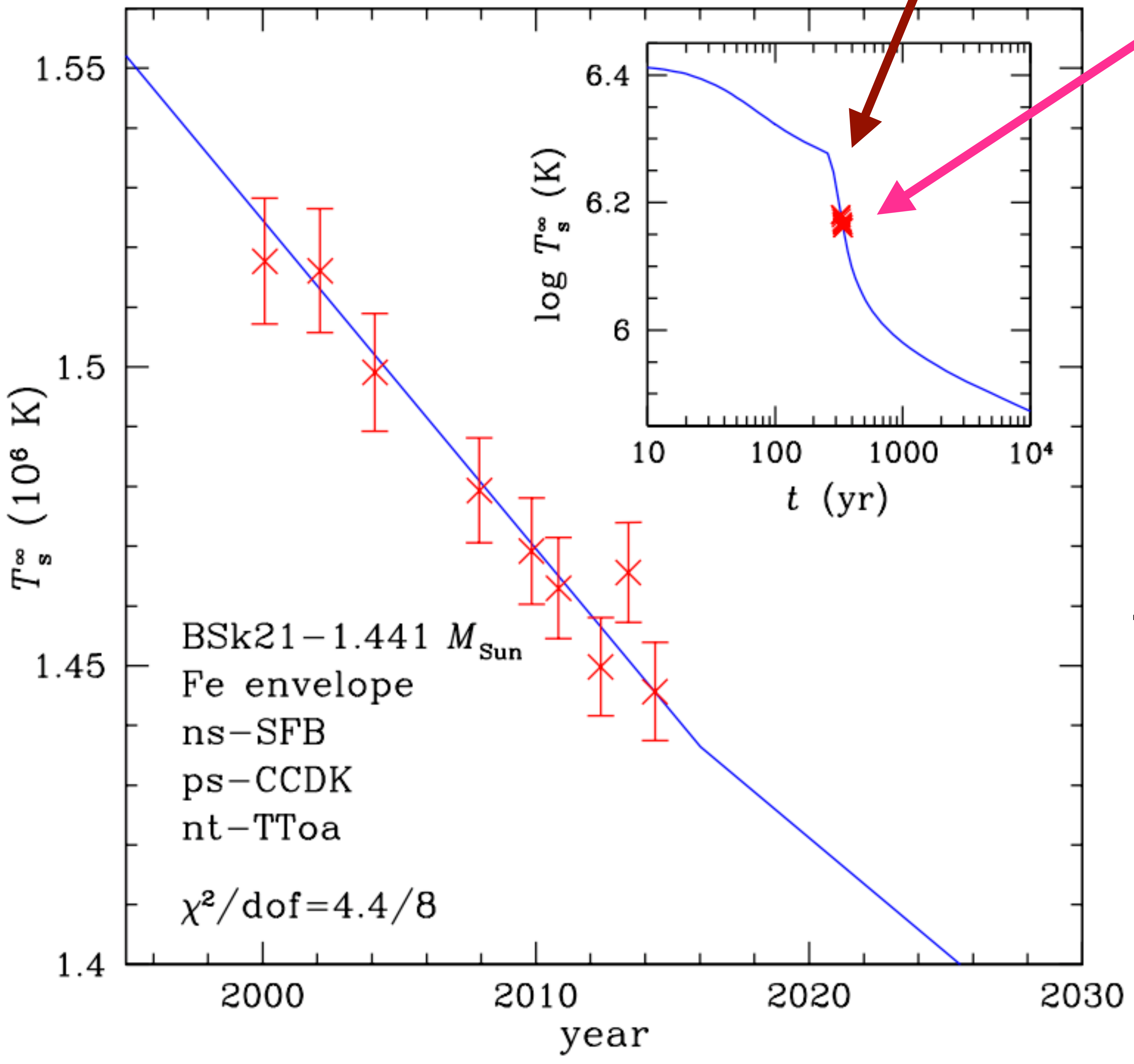
It triggers a sudden cooling at around T = Tc.

Figs. from Page et.al. 1302.6626

Cas A NS Cooling (theory)

phase transition
T = Tc

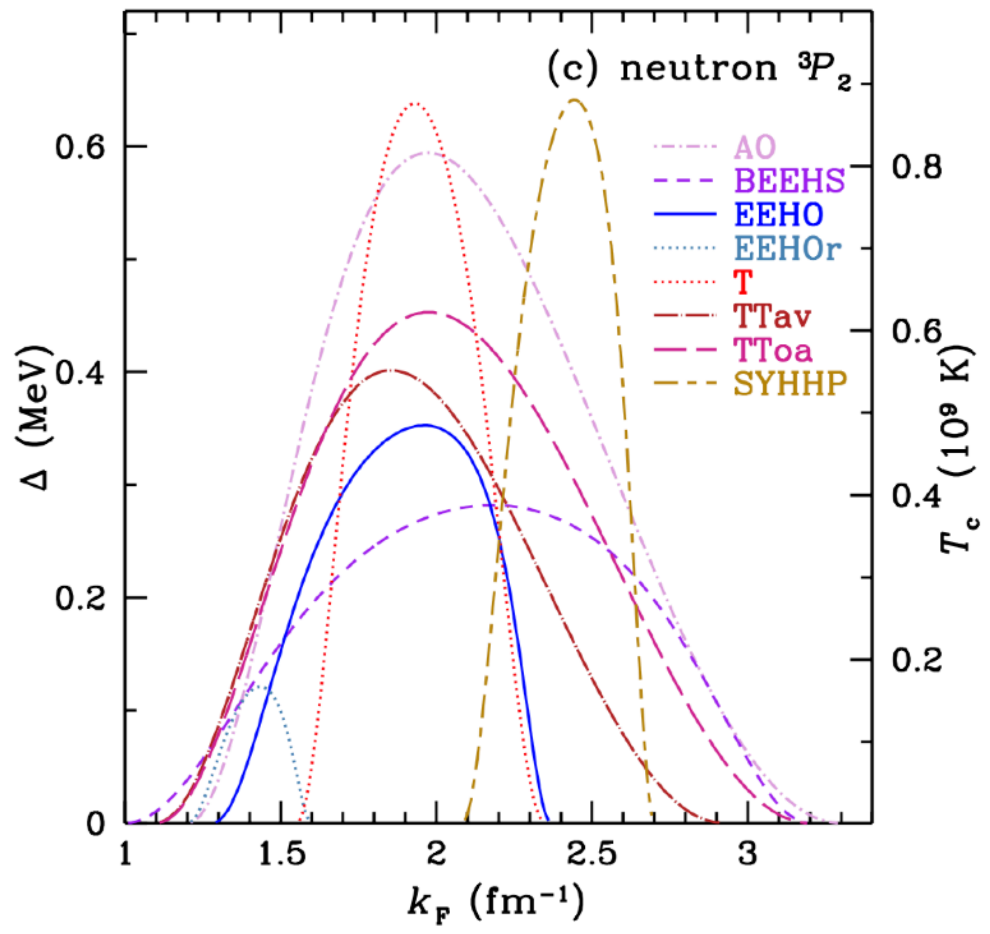
sudden, rapid cooling by PBF process.



W.C.G.Ho, K.G.Elshamouty, C.O.Heinke, A.Y.Potekhin, 1412.7759

- Neutron triplet (n-$^3P_2$) PBF is dominant.
- Large uncertainty in n-$^3P_2$ gap.

-> Parameters (in particular, Tc) are adjusted to fit the data.



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*
[4]*Joint Institute for Nuclear Astrophysics, National Superconducting Cyclotron Laboratory and, Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
(Received 29 November 2010; published 22 February 2011)

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].

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY LETTERS

Mon. Not. R. Astron. Soc. **412,** L108–L112 (2011) doi:10.1111/j.1745-3933.2011.01015.x

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

Peter S. Shternin,[1,2★] Dmitry G. Yakovlev,[1] Craig O. H
and Daniel J. Patnaude[5]

[1] *Ioffe Physical Technical Institute, Politekhnicheskaya 26, 194021 St Petersburg, Russia*
[2] *St Petersburg State Polytechnical University, Politechnicheskaya 29, 195251 St Petersburg, Russi*
[3] *Department of Physics, University of Alberta, Room 238 CEB, 11322-89 Avenue, Edmonton, AB*
[4] *School of Mathematics, University of Southampton, Southampton SO17 1BJ*
[5] *Smithsonian Astrophysical Observatory, Cambridge, MA 02138, USA*

Accepted 2011 January 12. Received 2011 January 12; in original form 2010 November 30

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 $T_{cn}(\rho)$ for the onset of neutron superfluidity [$T_{cn}(\rho)$ should have a wide peak with maximum ≈ (7–9) × 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.

ABSTRACT
According to recent results of Ho & Heink
tains a young (≈330-yr-old) neutron star (N
notable decline of the effective surface tem
Chandra observation which confirms the pr
naturally explained if neutrons have recent

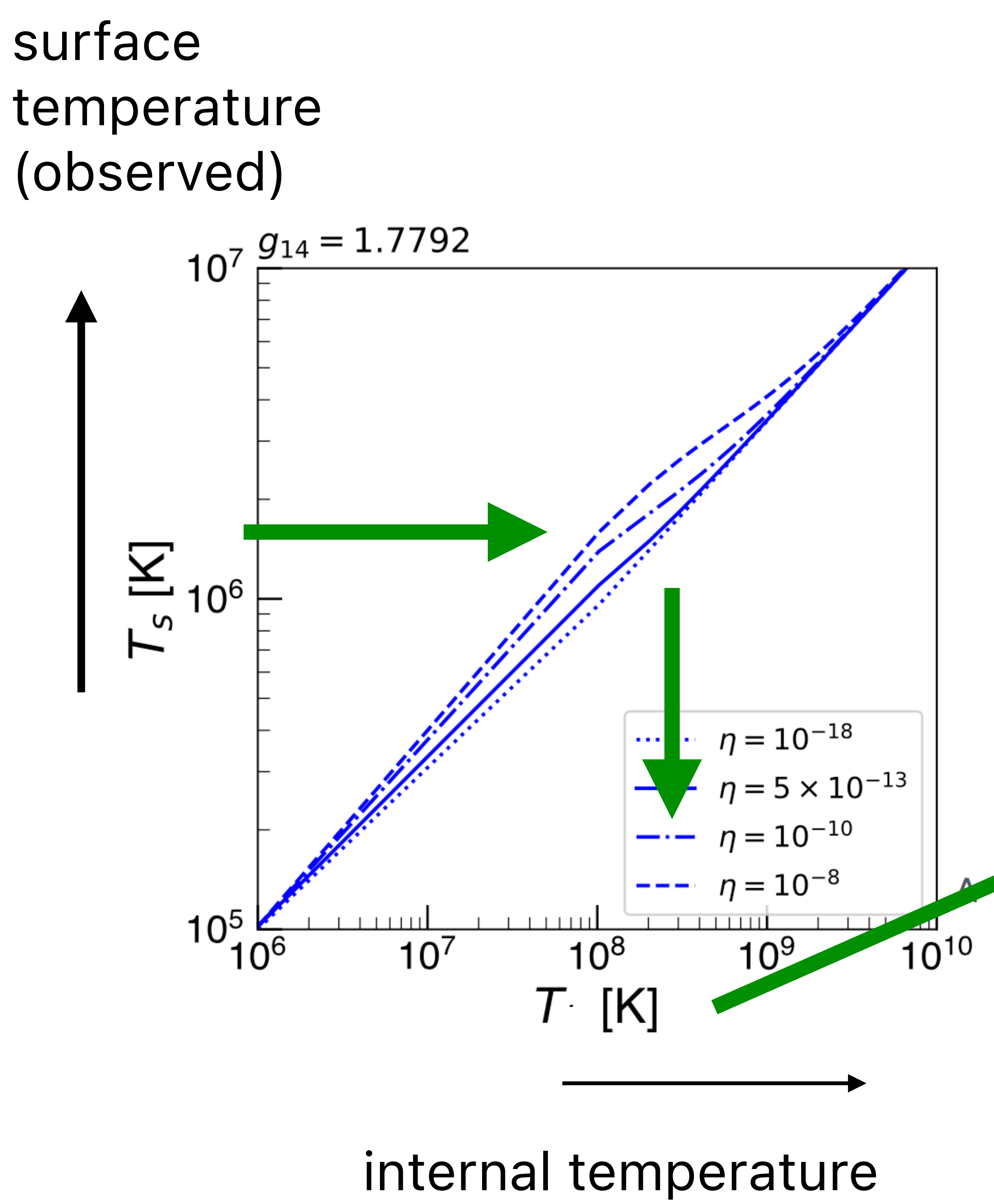
Alternative scenario to explain Cas A cooling

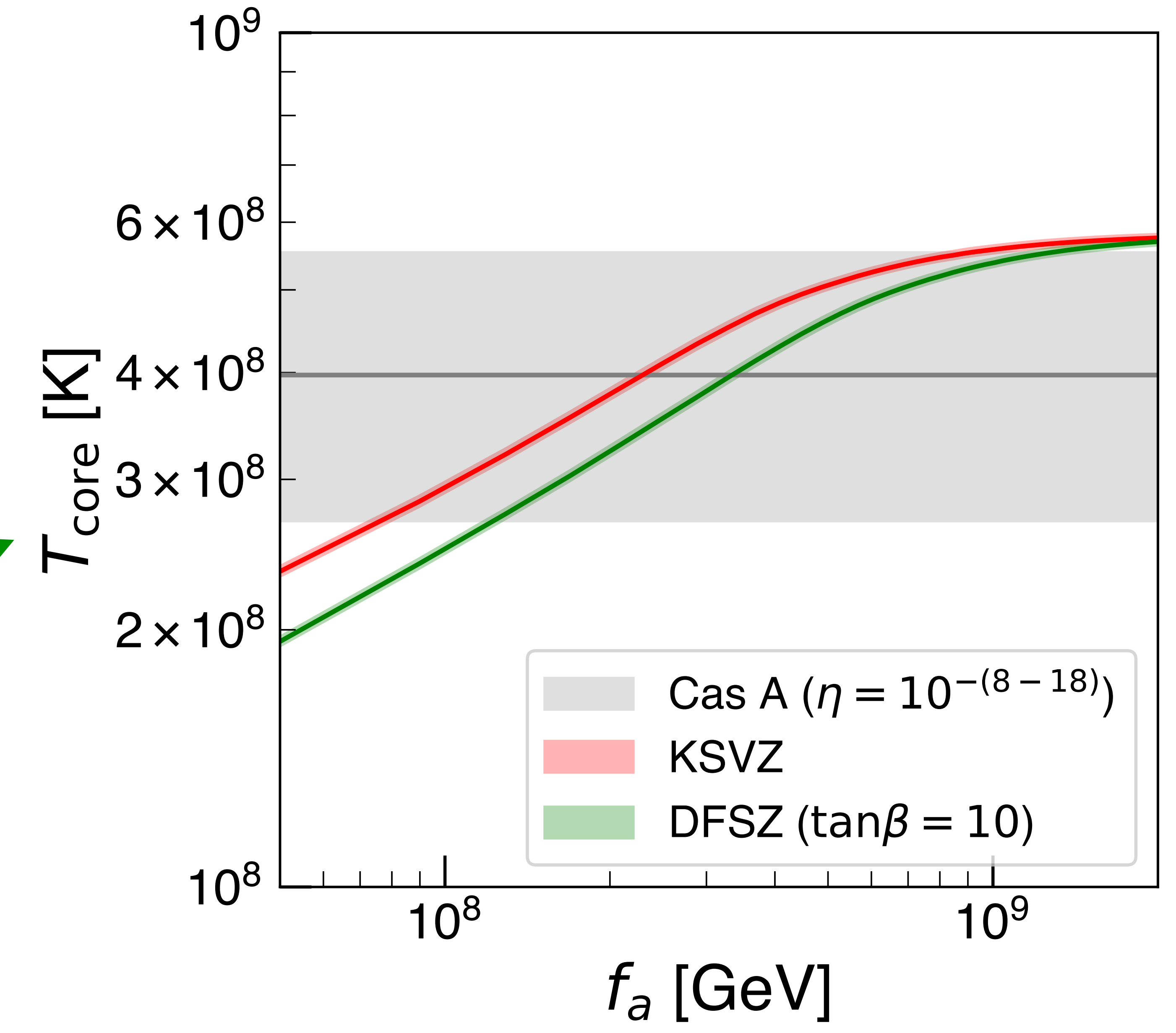
- longer thermal relaxation timescale in the crust or core
- etc

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;
T. Noda, M.-A. Hashimoto, N. Yasutake, T. Maruyama, T. Tatsumi, and M. Fujimoto, arXiv:1109.1080;
A. Sedrakian, arXiv:1303.5380;
D. Blaschke, H. Grigorian, and D. N. Voskresensky, arXiv:1308.4093;
A. Bonanno, M. Baldo, G. F. Burgio, and V. Urpin, arXiv:1311.2153;
L. B. Leinson, arXiv:1411.6833;
G. Taranto, G. F. Burgio, and H. J. Schulze, arXiv:1511.04243;
T. Noda, N. Yasutake, M.-a. Hashimoto, T. Maruyama, T. Tatsumi, and M. Y. Fujimoto, arXiv:1512.05468;
H. Grigorian, D. N. Voskresensky, and D. Blaschke, arXiv:1603.02634.

Cas A NS Cooling with axion

Remark: uncertainty from envelope



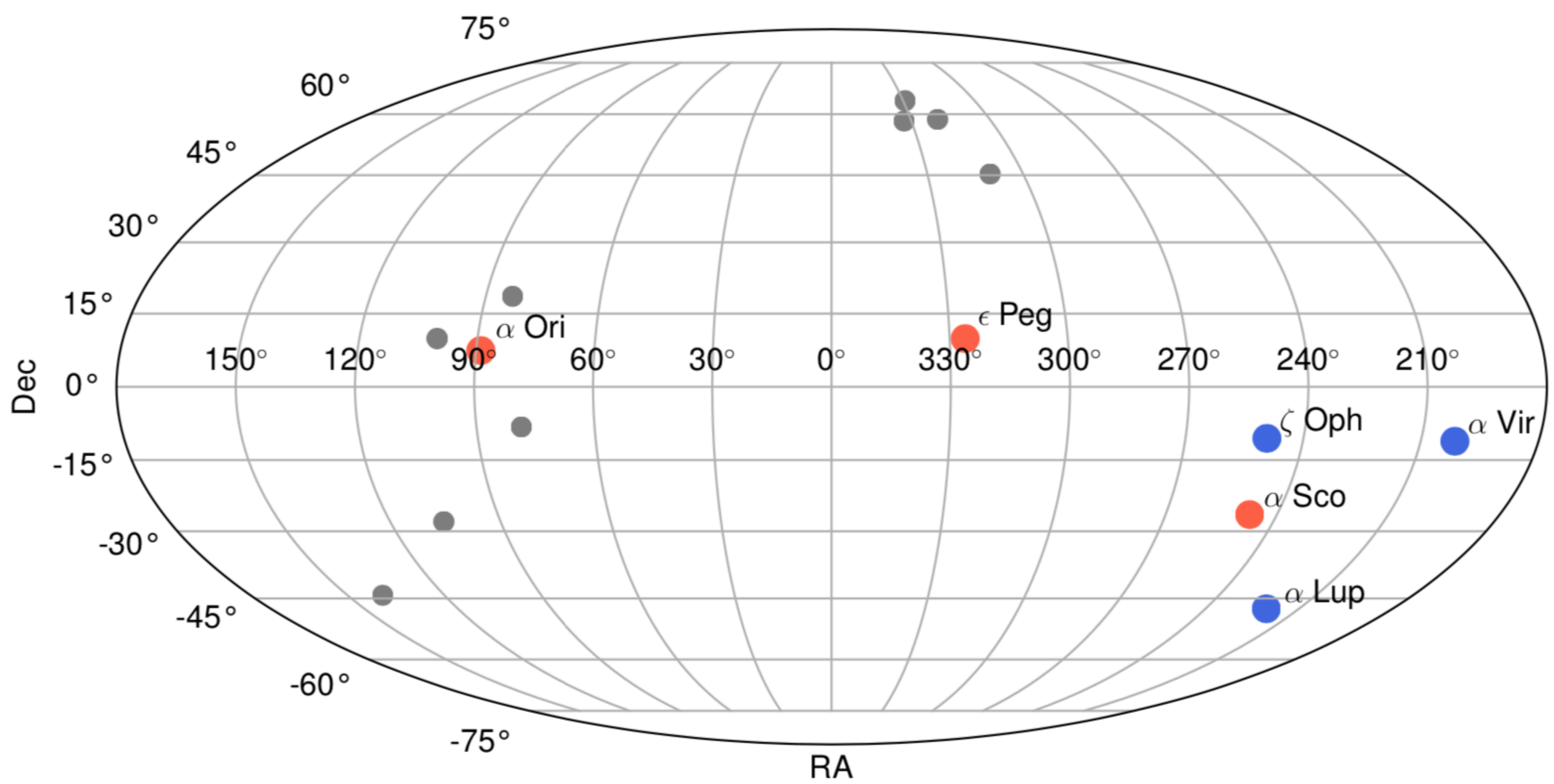


==> O(1) uncertainty in f_a bound.

Backup

SN-scope, SN axion

Nearby SN progenitor candidates



● ● $d < 250$ pc

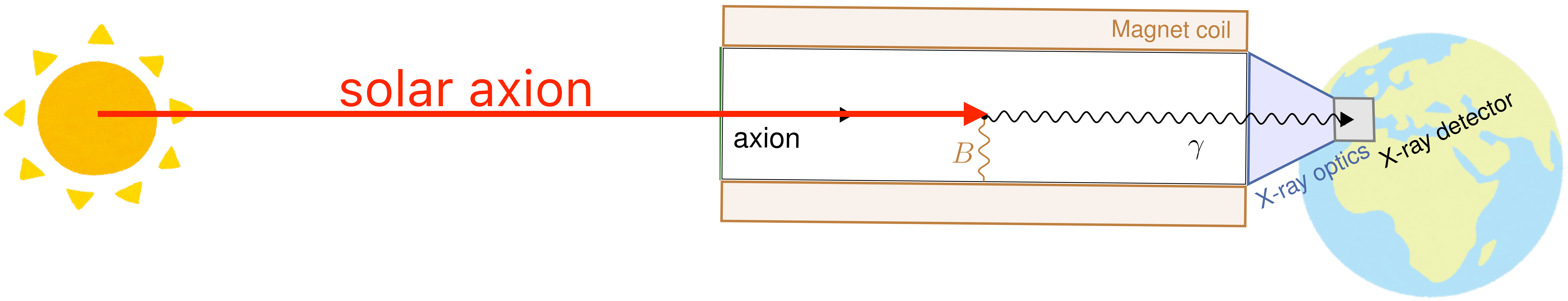
● $d > 250$ pc

※ $M > 10M_\odot$ only (more on this later)

HIP	Common Name	Distance (pc)	Mass ($M_\odot$)	RA (J2000)	Dec (J2000)
65474	Spica/α Virginis	77(4)	11.43 ± 1.15 [79]	13:25:11.58	−11:09:40.8
81377	ζ Ophiuchi	112(3)	20.0 [80]	16:37:09.54	−10:34:01.5
71860	α Lupi	142(3)	10.1 ± 1.0 [81]	14:41:55.76	−47:23:17.5
80763	Antares/α Scorpii	170(30)	11–14.3 [82]	16:29:24.46	−26:25:55.2
107315	Enif/ϵ Pegasi	211(8)	11.7(8) [81]	21:44:11.16	+09:52:30.0
27989	Betelgeuse/α Orionis	222^{+48}_{-34} [83]	$11.6^{+5.0}_{-3.9}$ [84]	05:55:10.31	+07:24:25.4

Supernova-scope

- Essentially the same as the Axion Helioscopes for the solar axion.



Axion Helioscopes

	Experiment	(Proposed) site	B (T)	L (m)	A (m^2)
on-going	CAST [34–39]	CERN	9	9.3	2.9×10^{-3}
next-gen.	BabyIAXO [41]	DESY	~ 2	10	0.77
next-gen.	IAXO baseline [40, 41]	DESY	~ 2.5	20	2.3
next-gen.	IAXO+ [41]	DESY	~ 3.5	22	3.9
next-gen.	TASTE [42]	INR	3.5	12	0.28

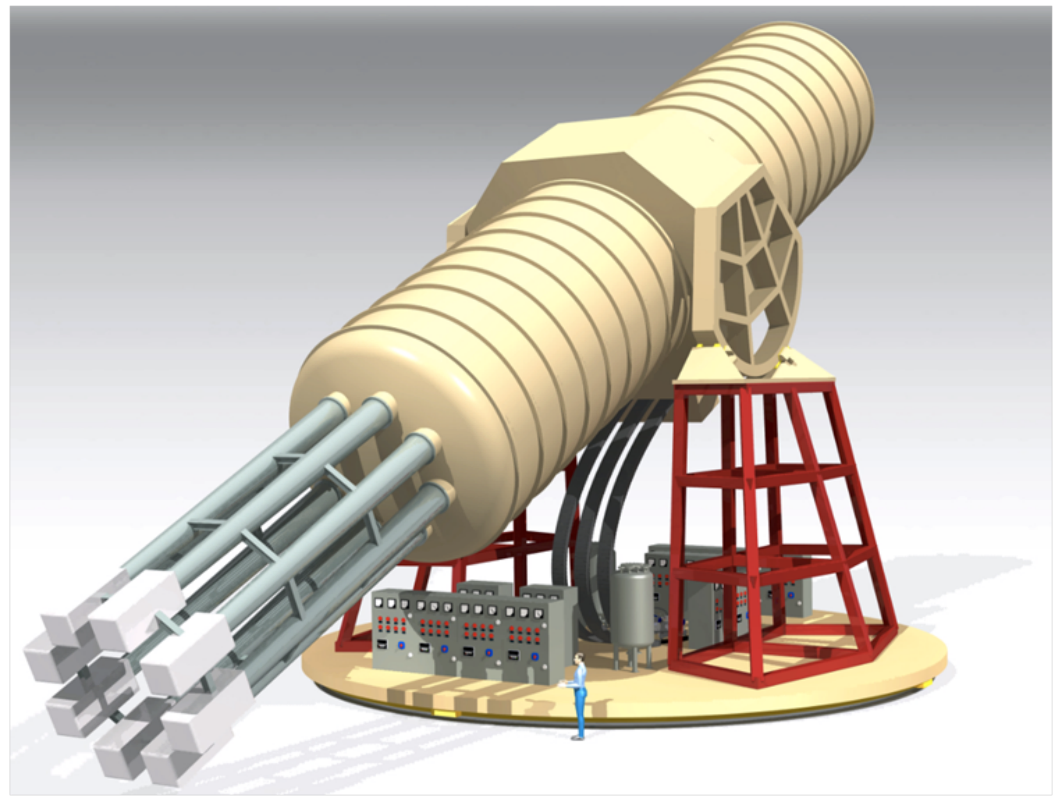
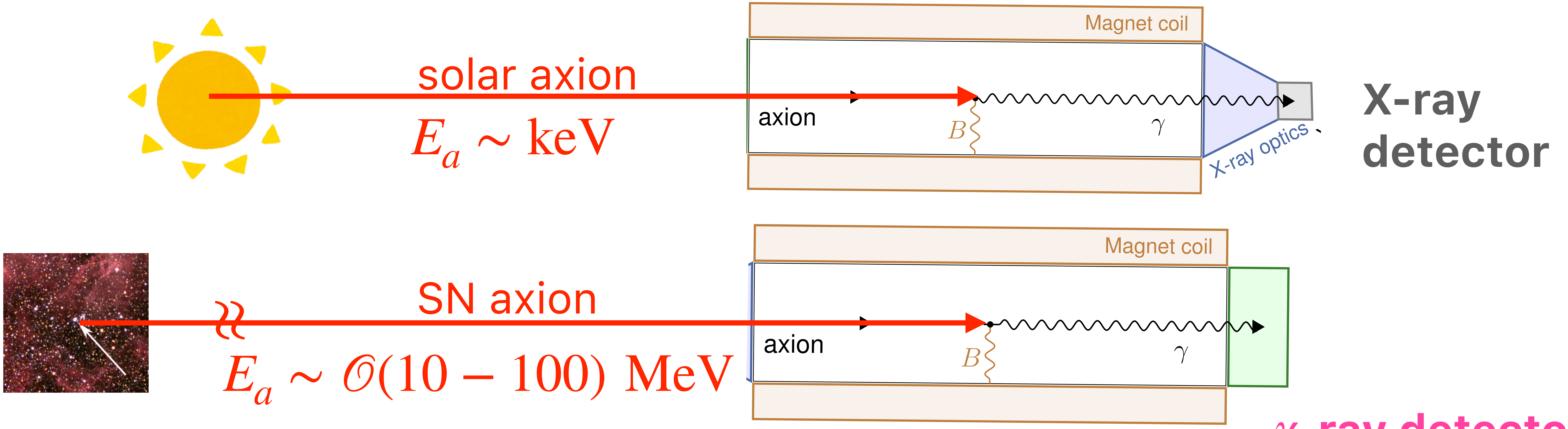


Fig. from IAXO homepage

Supernova-scope

- Essentially the same as the Axion Helioscopes for the solar axion.

- **But the axion energy is different.**



γ**-ray detector** is necessary.

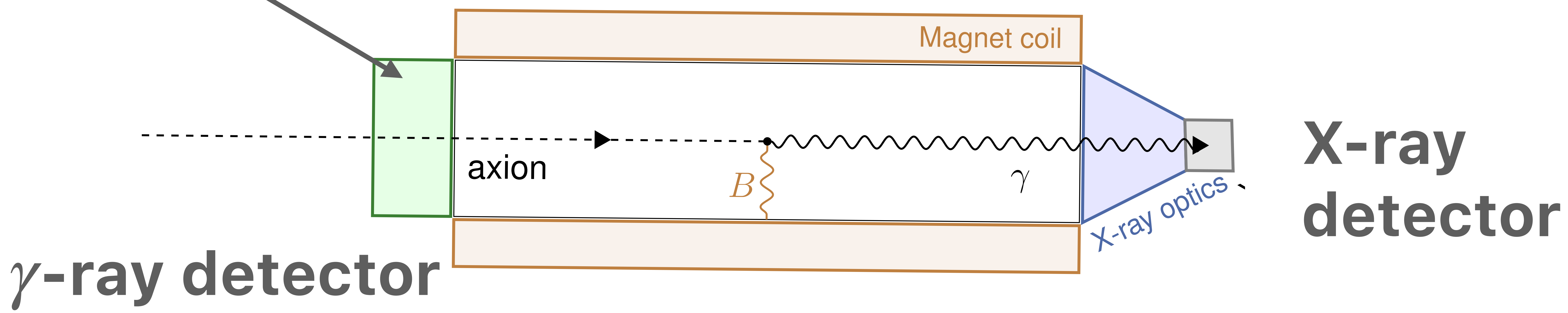
※ X-ray focusing optics doesn't work for γ-rays.

※ X-ray detector cannot measure the γ-ray energy, and hence the background rejection is difficult (see backup slide).

Supernova-scope

Idea: install a γ-ray detector at the opposite end to the X-ray detector.

S.Ge, K.Hamaguchi, K.Ichimura, K.Ishidoshiro, Y.Kanazawa, Y.Kishimoto, N.Nagata, J.Zheng.
[arXiv:2008.03924] JCAP **11** (2020) 059.

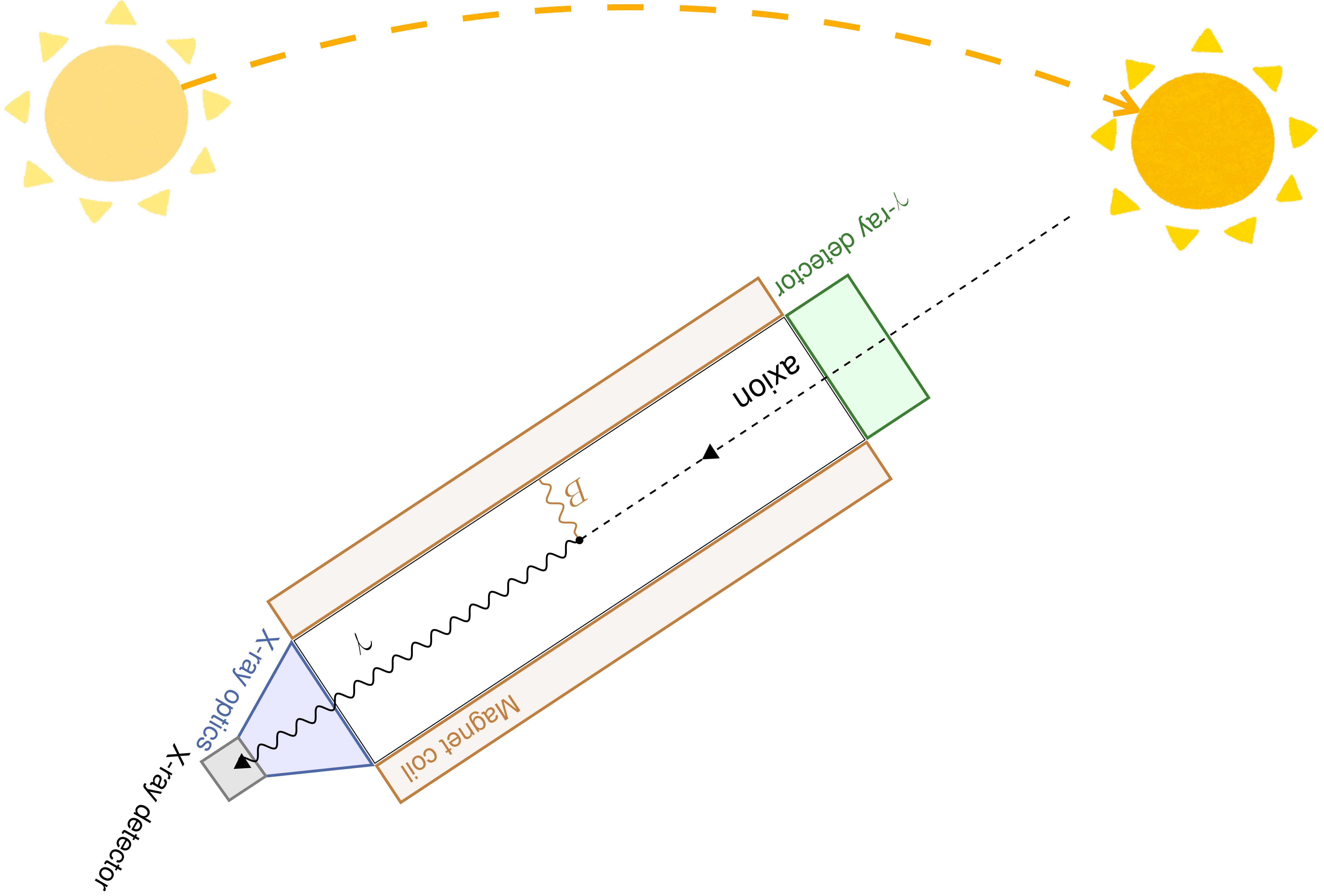


S.Ge, K.Hamaguchi, K.Ichimura, K.Ishidoshiro, Y.Kanazawa, Y.Kishimoto, N.Nagata, J.Zheng.
[arXiv:2008.03924] JCAP **11** (2020) 059.

Supernova-scope

Idea: install a γ-ray detector at the opposite end to the X-ray detector.

Normal operation time: It works as an axion helioscope.



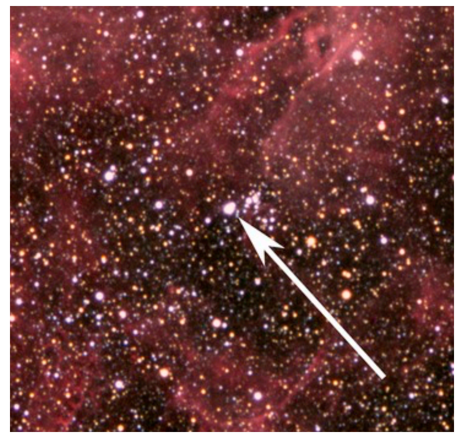
Supernova-scope

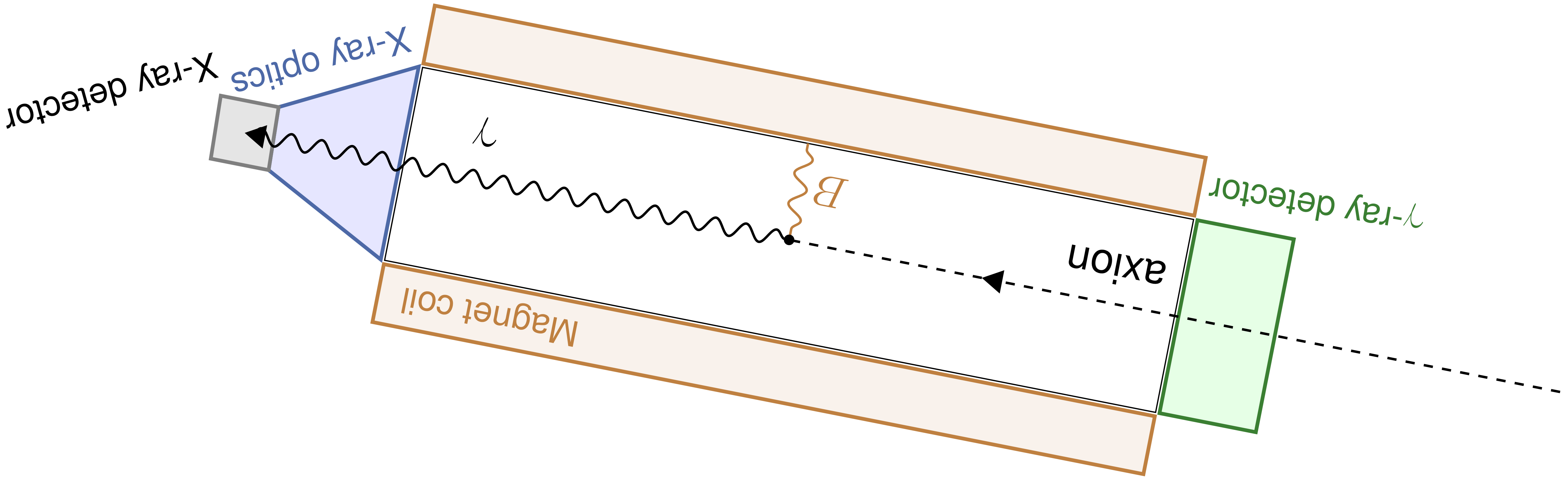
S.Ge, K.Hamaguchi, K.Ichimura, K.Ishidoshiro, Y.Kanazawa, Y.Kishimoto, N.Nagata, J.Zheng.
[arXiv:2008.03924] JCAP **11** (2020) 059.

Idea: install a γ-ray detector at the opposite end to the X-ray detector.

Normal operation time: It works as an axion helioscope.

When a Supernova occurs,....



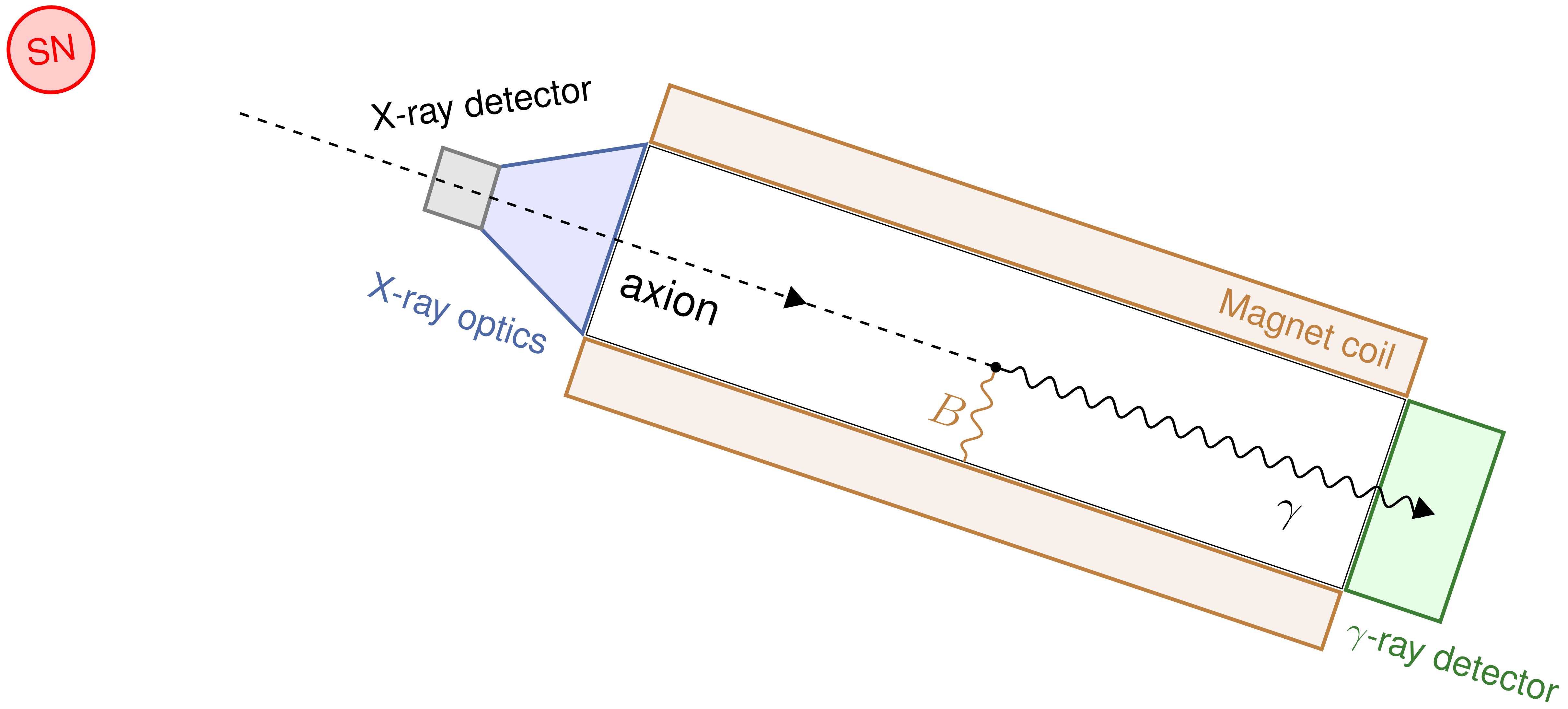


Pre-SN neutrino

The SN-scope has to be pointed to the exploding SN.

But SN-axions come within $\Delta t \sim 10\ \mathrm{sec}$. (cf. neutrino burst)

How do we know the timing of the SN in advance?



Pre-SN neutrino

Take the help of the pre-SN neutrinos.

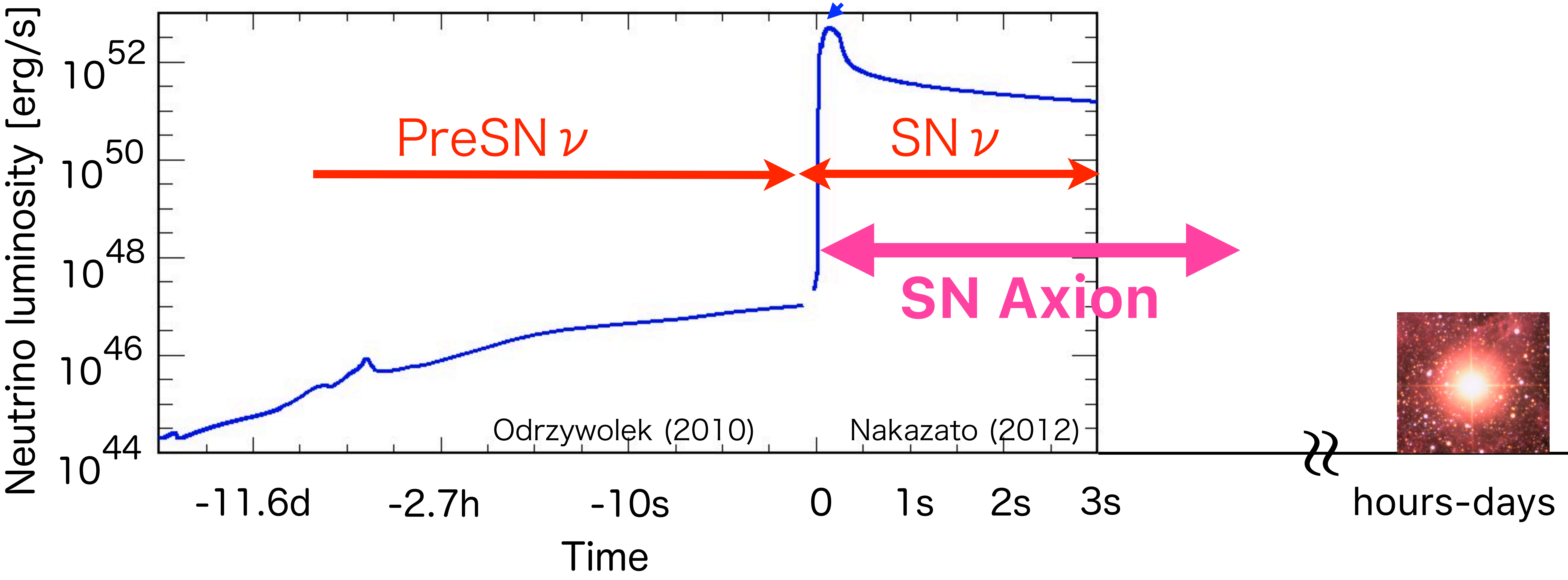
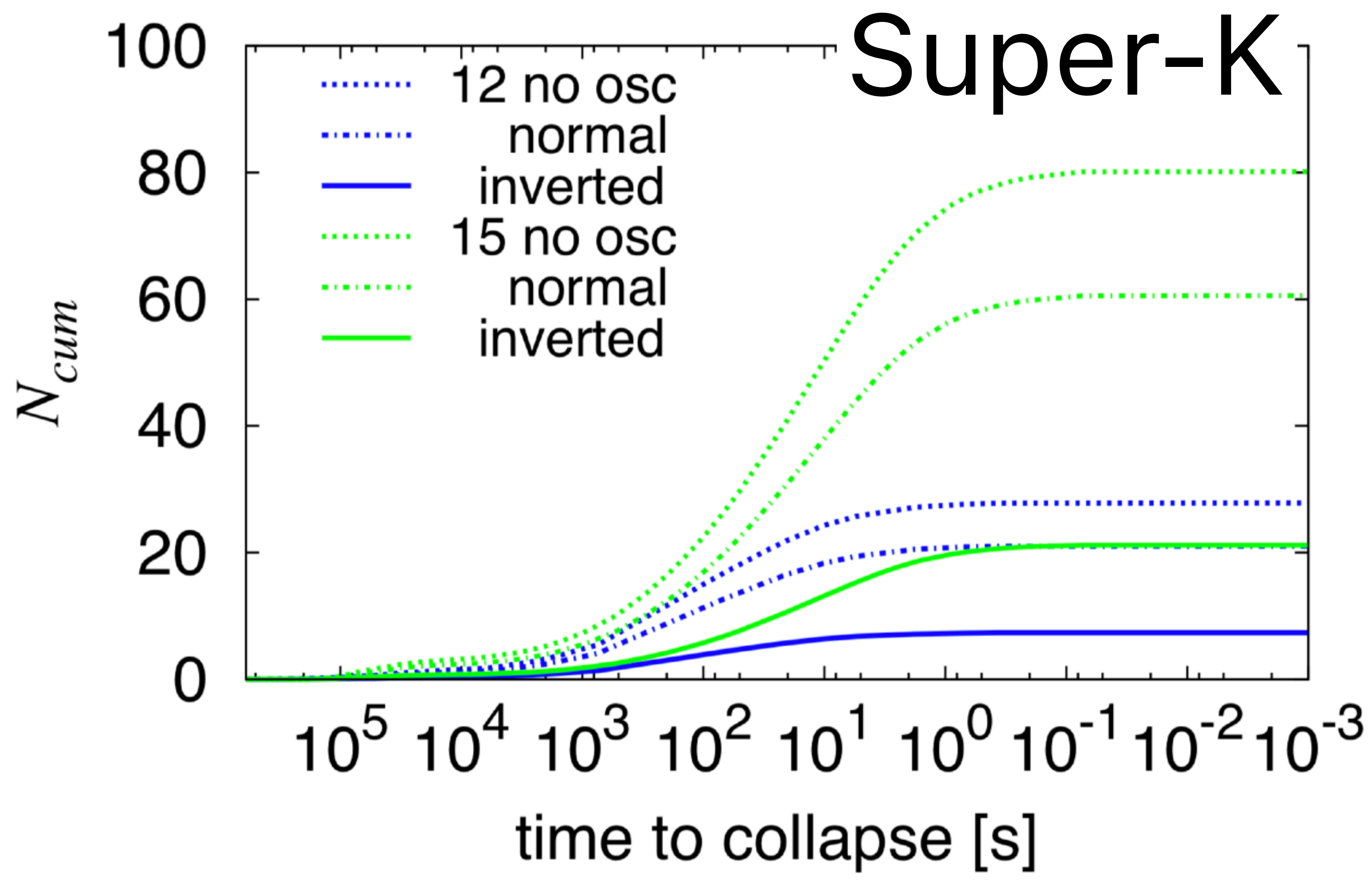
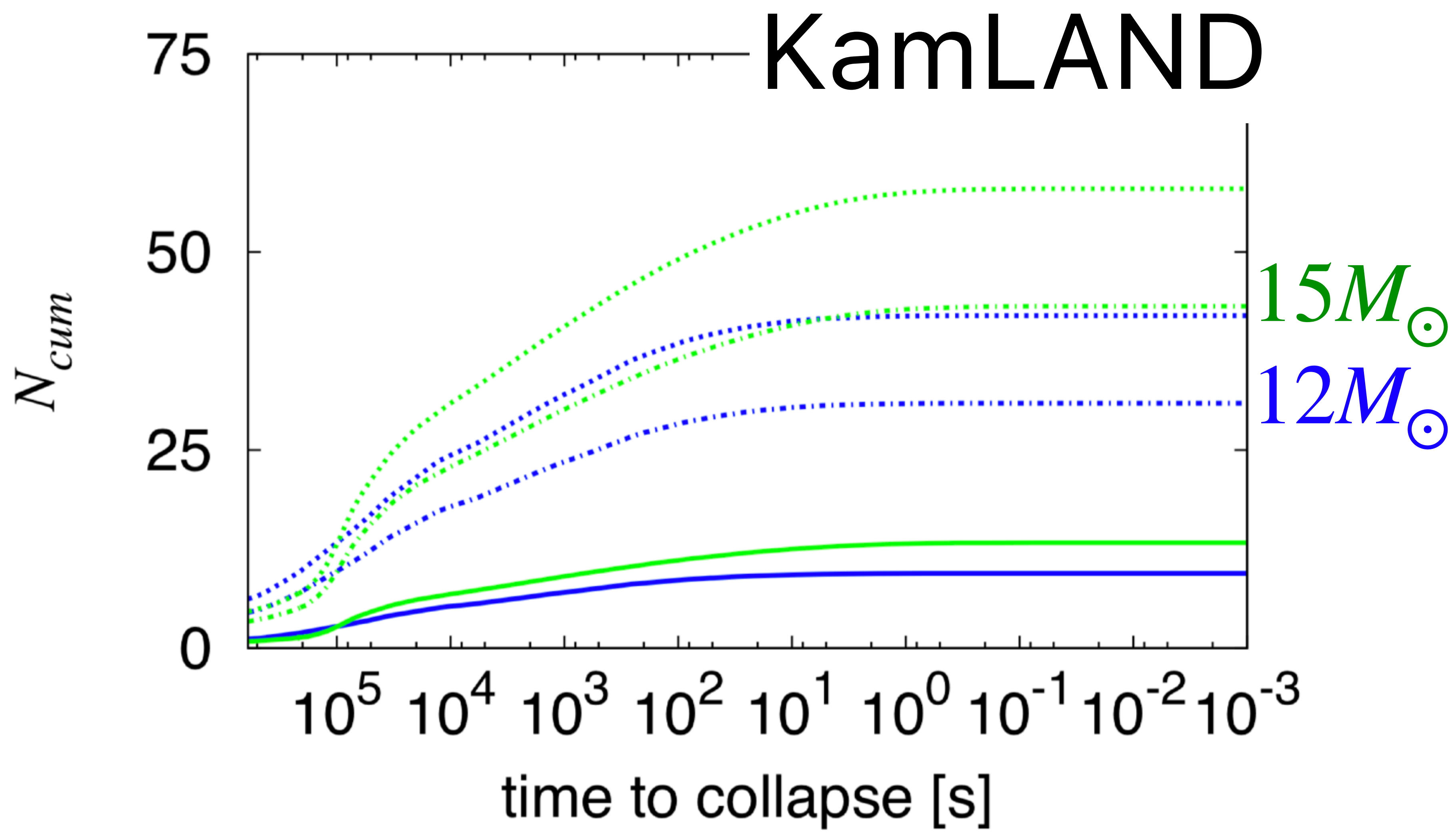


Figure from K.Ishidoshiro's talk in 2019.
https://www.lowbg.org/ugnd/workshop/sympo_all/201903_Sendai/

For a review of pre-SN neutrinos, see, e.g., C.Kato, K.Ishidoshiro, T.Yoshida [2006.02519].

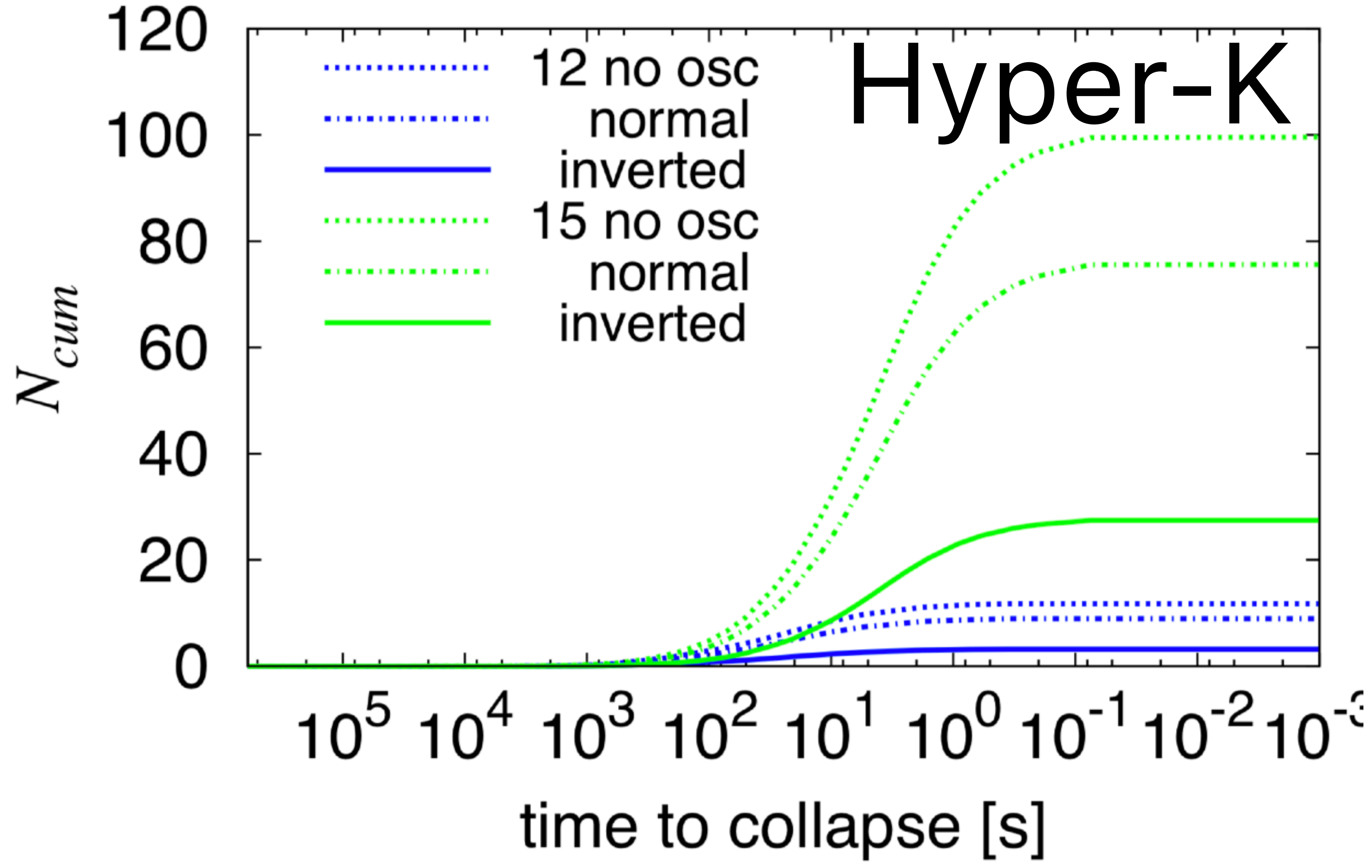
Pre-SN neutrino

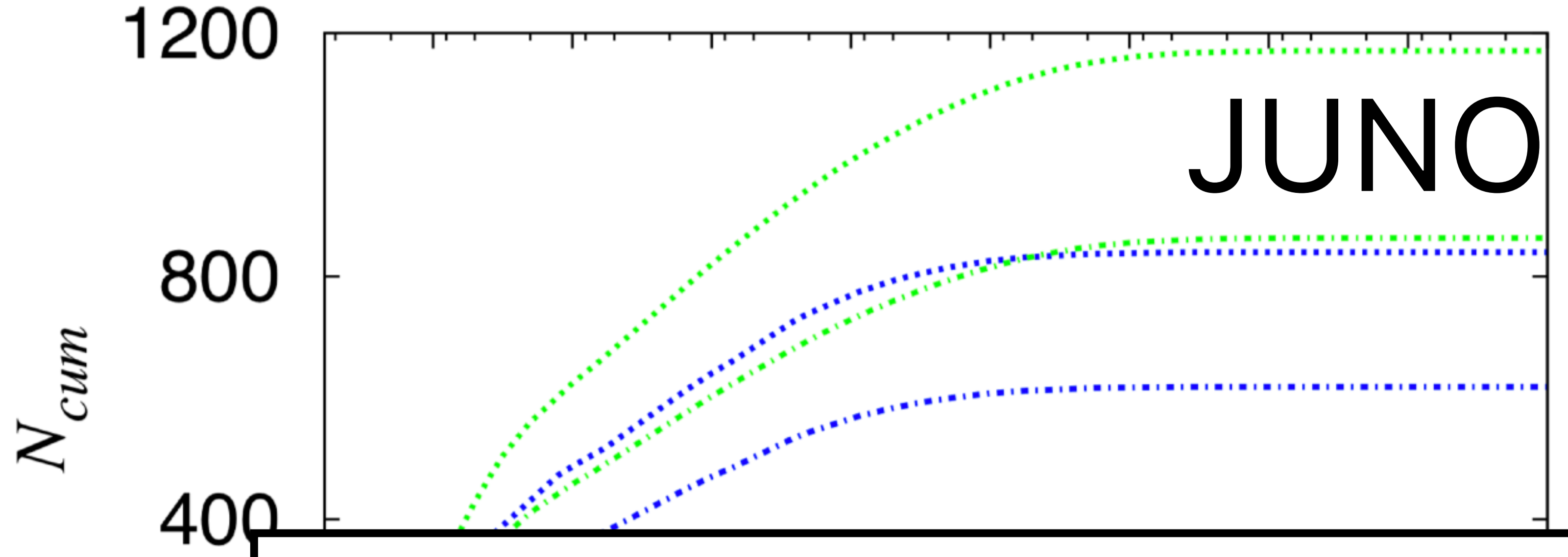




The cumulative numbers of expected pre-SN ν events for Fe-Core progenitor, $d = 200$ pc.

C. Kato et.al., [1506.02358].





+ DUNE, SNO+,... global network for an early SN alarm

= Supernova Early Warning System (SNEWS)

P. Antonioli et.al., [astro-ph/0406214].

SNEWS collaboration [2011.00035]

Pre-SN neutrino

- The pre-SN neutrinos can be detected (warning alert triggered) O(hours)-O(days) prior to the SN explosion ($d <$ a few 100 pc).

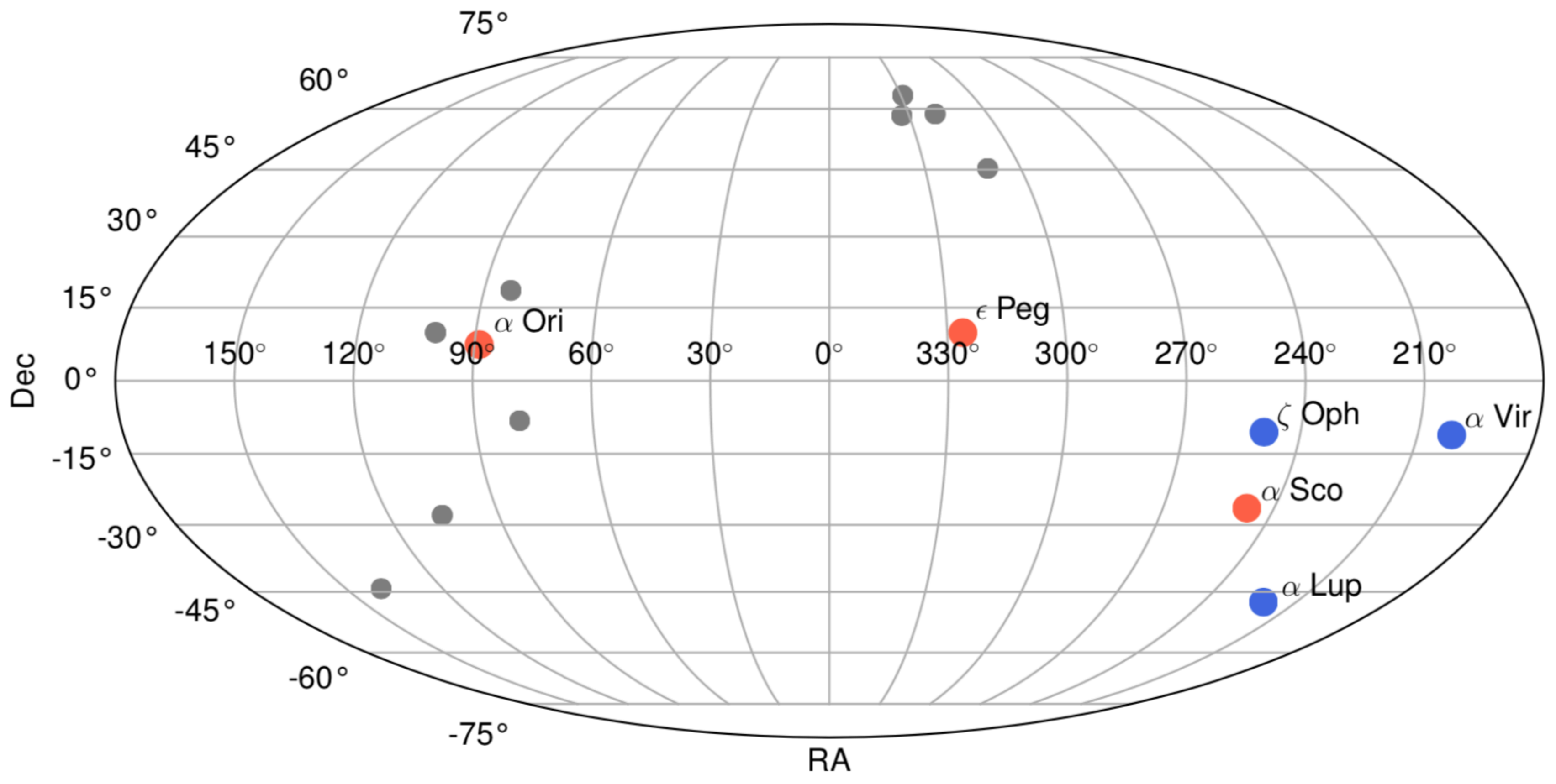
※ SN progenitors with $M < 10M_\odot$

→ Pre-SN ν flux is too small to be detected even for $d < 200$ pc.

C. Kato et.al., [1506.02358].

→ We discard them.

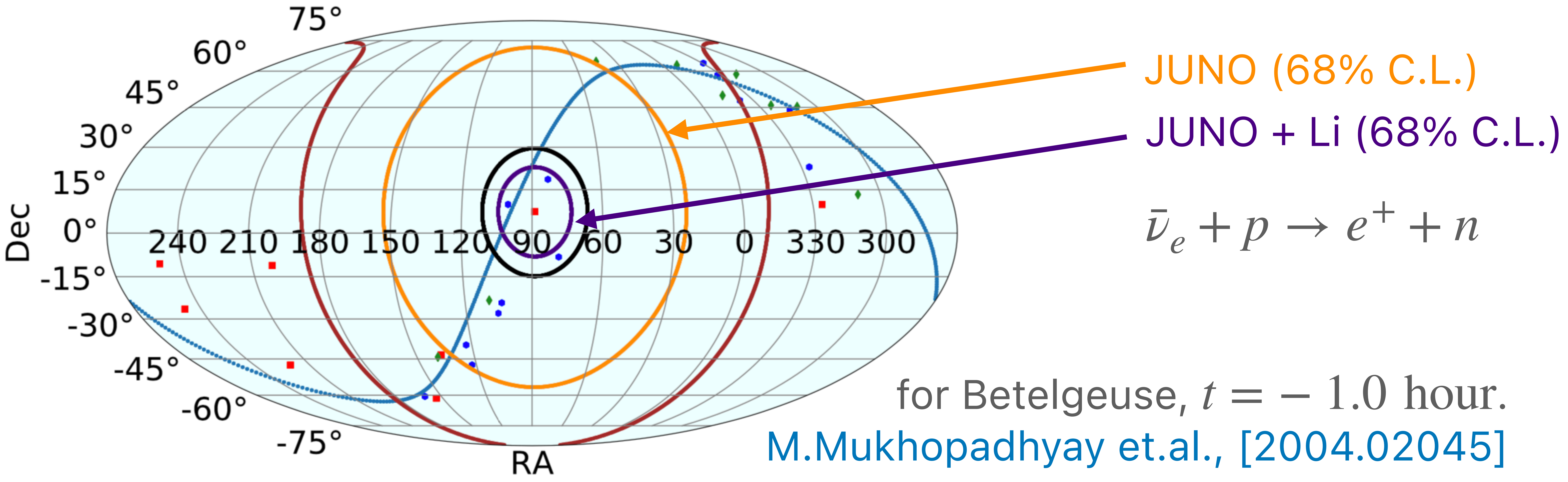
$M > 10M_\odot$ only.



Pre-SN neutrino

- The pre-SN neutrinos can be detected (warning alert triggered) O(hours)-O(days) prior to the SN explosion ($d <$ a few 100 pc).

- It is in principle possible to estimate the location of the SN candidate on the sky.



t = -1.0 hour

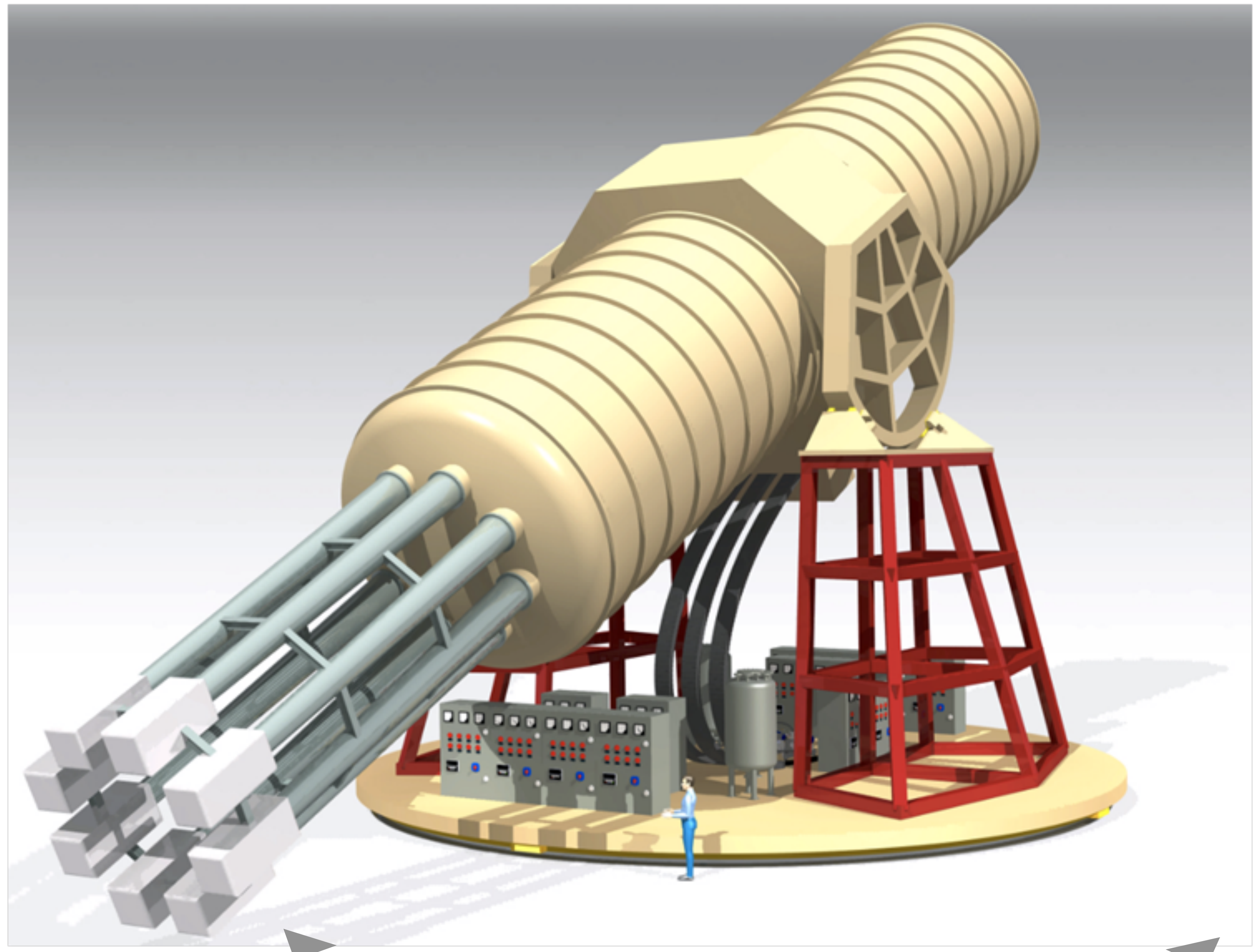
$$\bar{\nu}_e + p \to e^+ + n$$

for Betelgeuse, $t = -1.0$ hour.

M.Mukhopadhyay et.al., [2004.02045]

Observation time fraction

Fig. from IAXO homepage



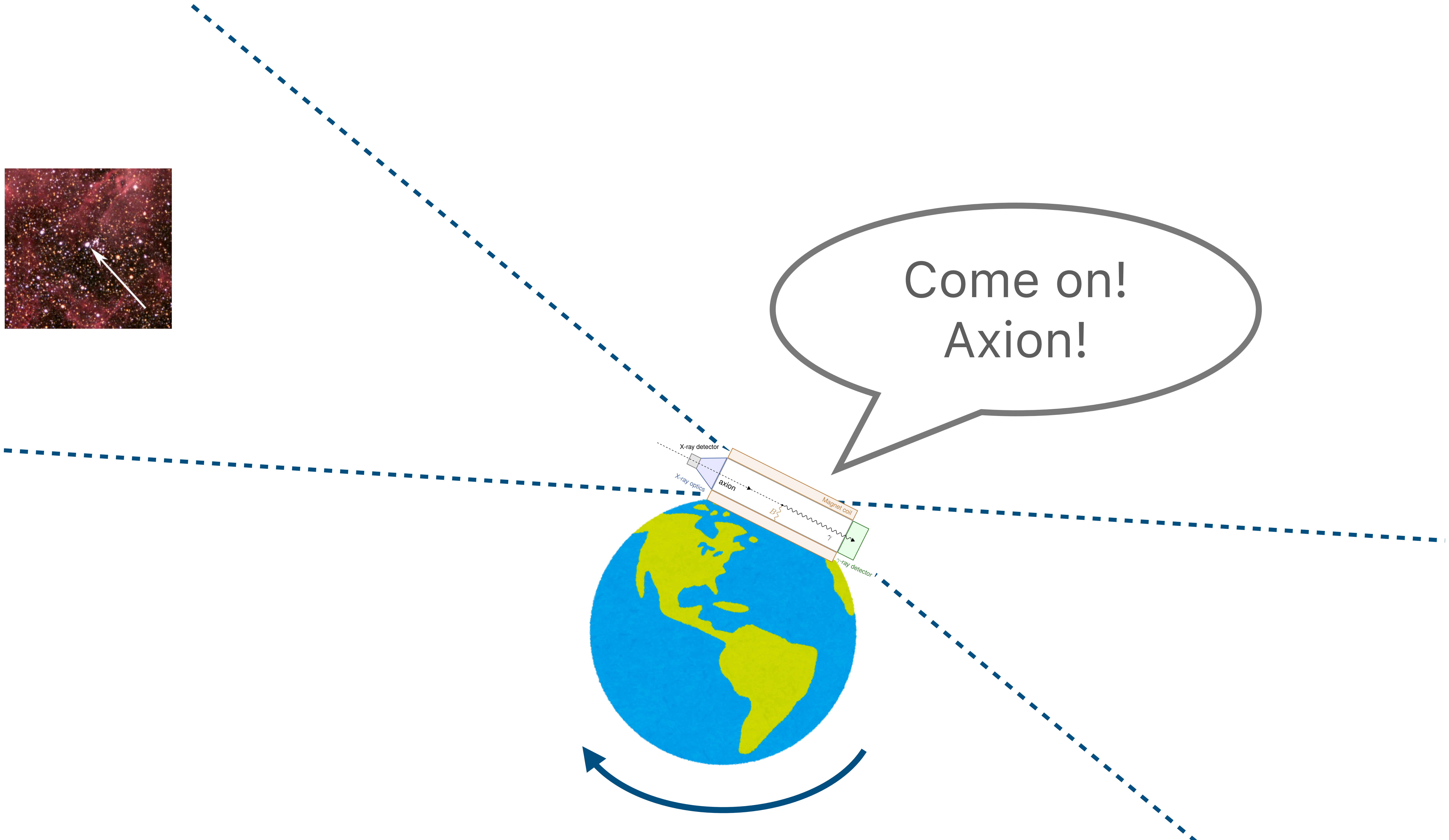
$$-\theta_{\max} \le \theta \le +\theta_{\max}$$

$$0 \le \phi \le 360^\circ$$

maximum elevation:

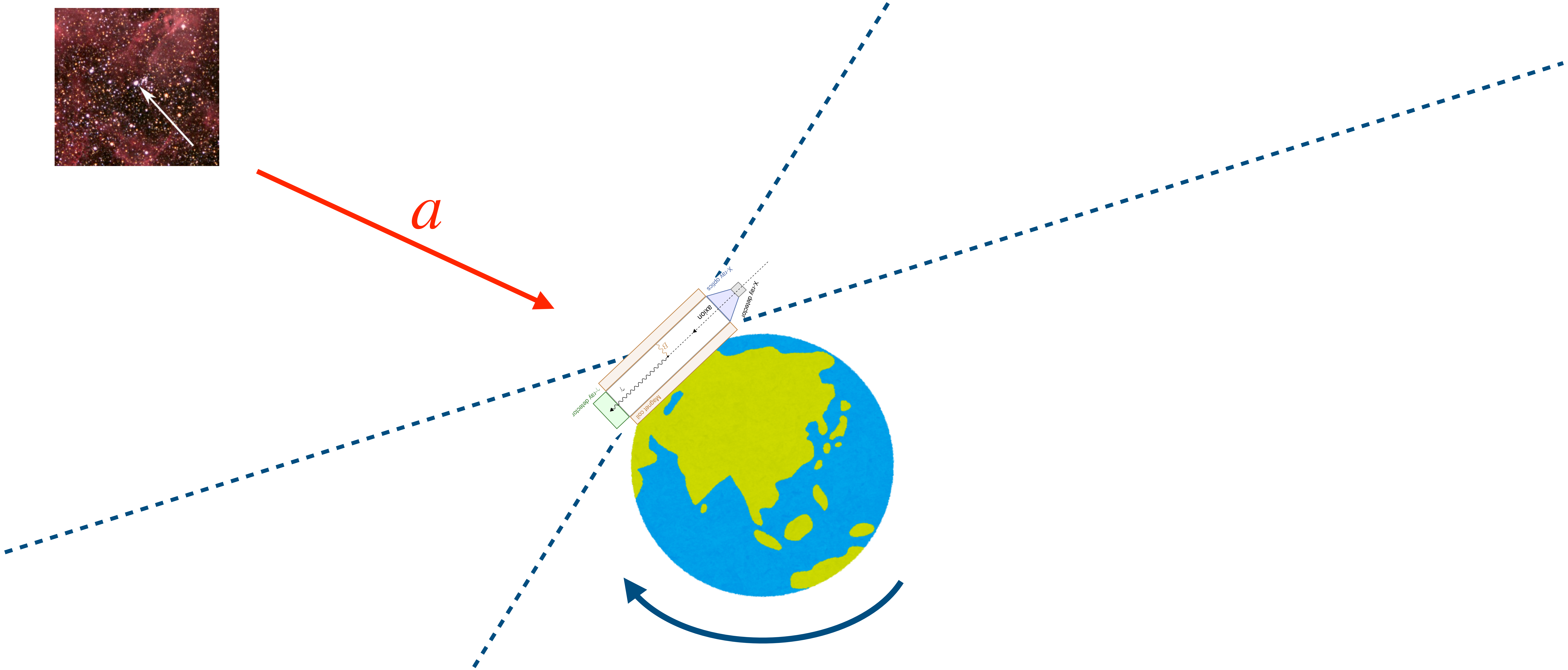
$$\theta_{\max} = \begin{cases} 25^\circ \text{ (IAXO)} \\ 20^\circ \text{ (TASTE)} \end{cases}$$

Observation time fraction



Observation time fraction

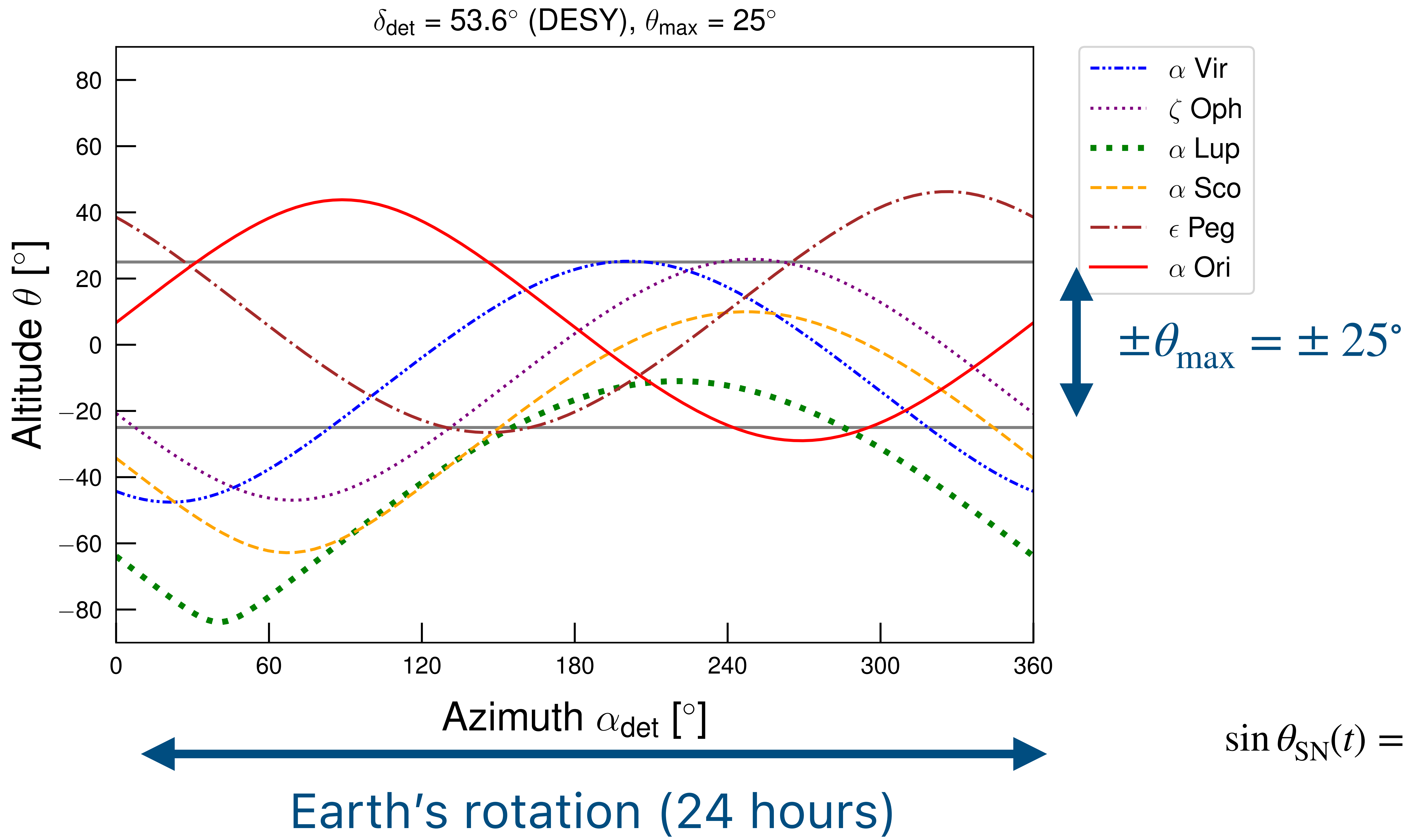
but if you are unlucky,...

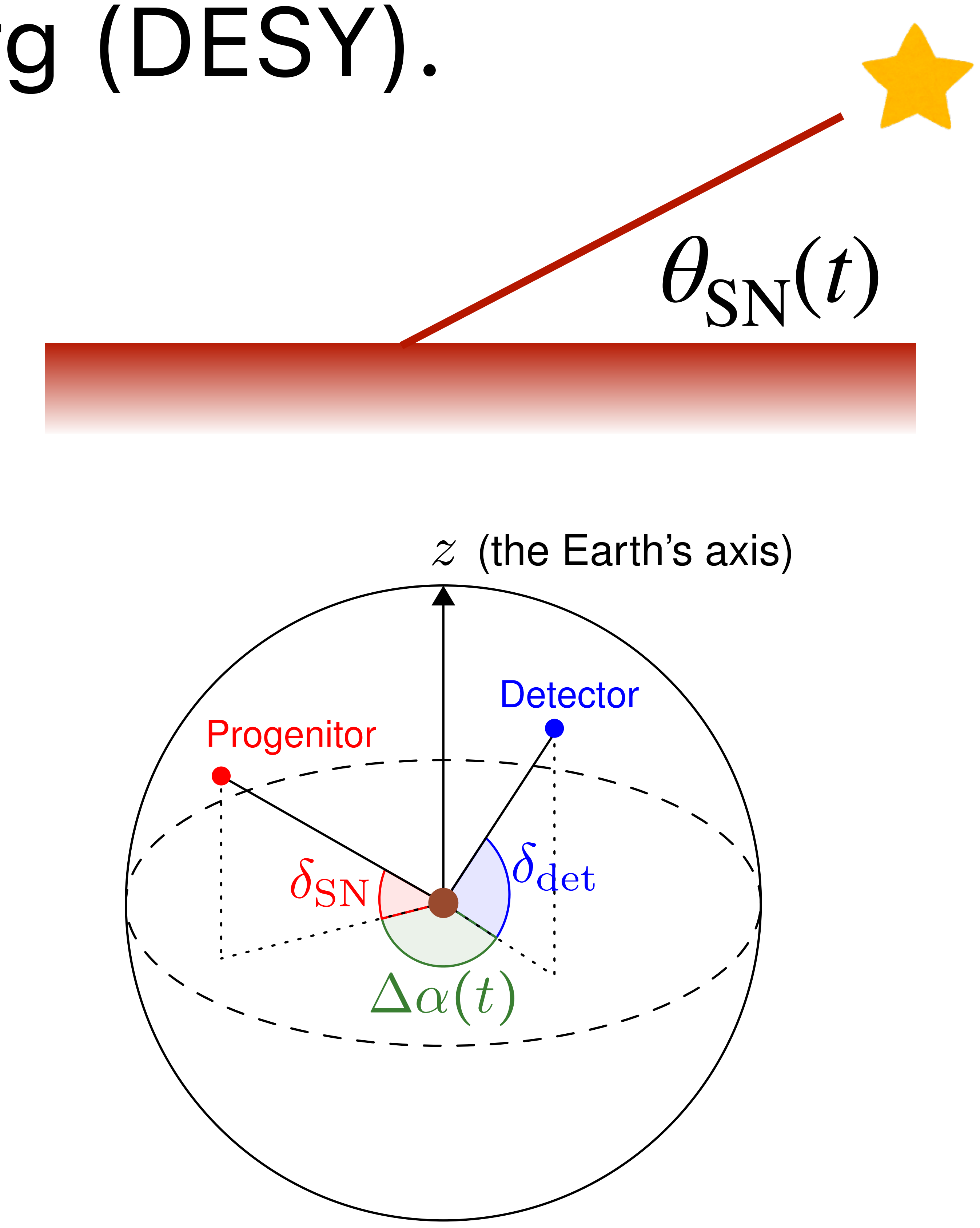


Observation time fraction

S.Ge, K.Hamaguchi, K.Ichimura, K.Ishidoshiro, Y.Kanazawa, Y.Kishimoto, N.Nagata, J.Zheng.
[arXiv:2008.03924] JCAP **11** (2020) 059.

The altitude of the progenitors $\theta_{SN}(t)$ seen from Hamburg (DESY).





$$\sin\theta_{SN}(t) = \cos\delta_{SN}\cos\delta_{det}\cos\Delta\alpha(t) + \sin\delta_{SN}\sin\delta_{det}\,.$$

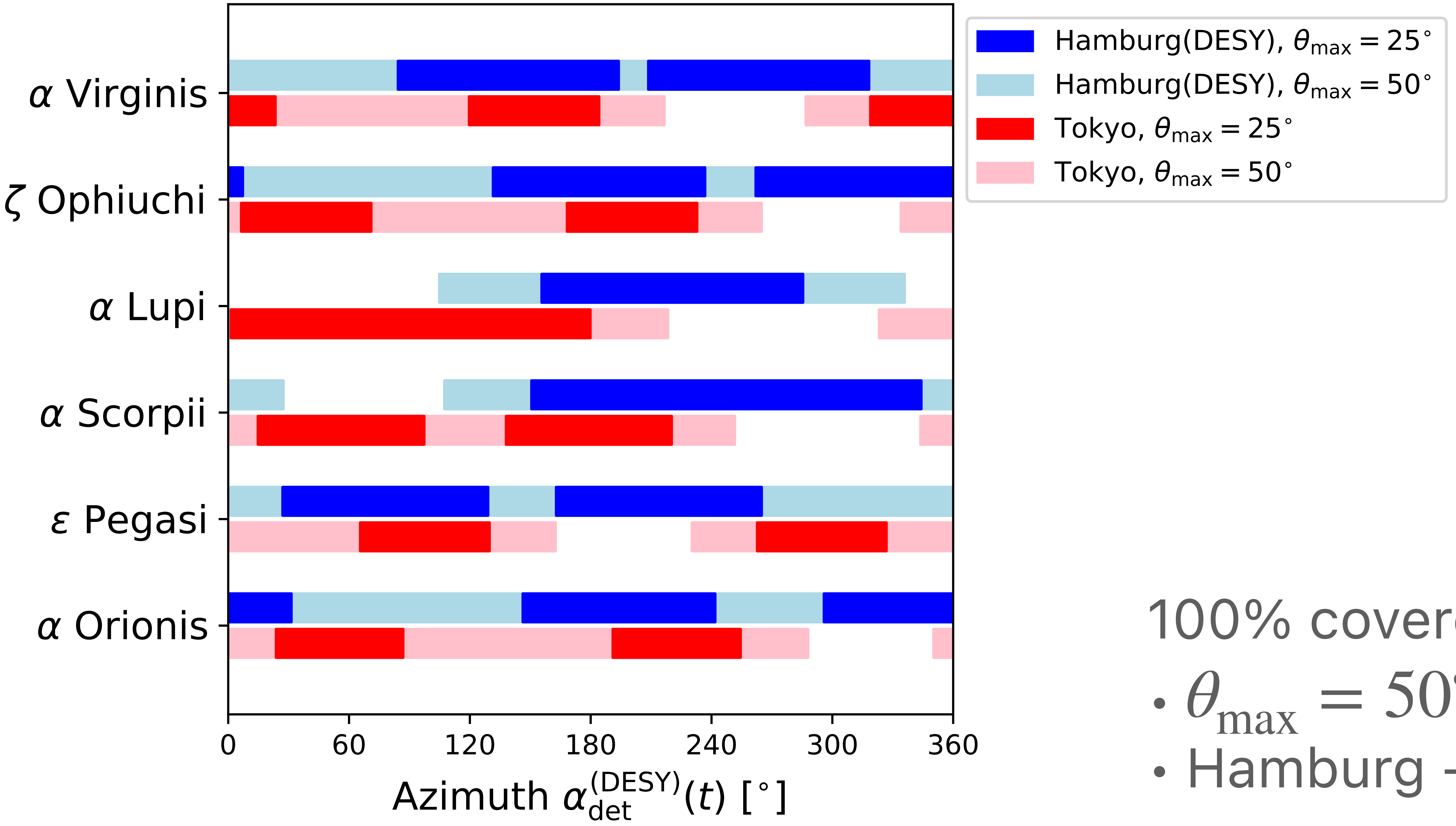
Observational time fraction > 50% for all the progenitors except α Lupi.

Observation time fraction

S.Ge, K.Hamaguchi, K.Ichimura, K.Ishidoshiro,
Y.Kanazawa, Y.Kishimoto, N.Nagata, J.Zheng.
[arXiv:2008.03924] JCAP **11** (2020) 059.

The time fraction can be increased by

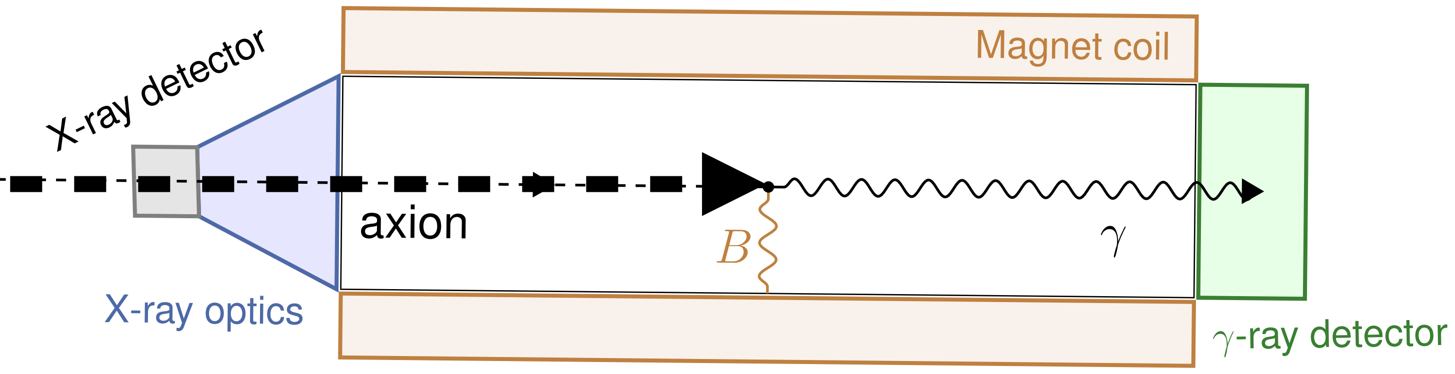
- increasing the maximum elevation $\theta_{\rm max}$ and/or
- two SN-scopes at different observation points (e.g., Hamburg and Tokyo)



100% covered if

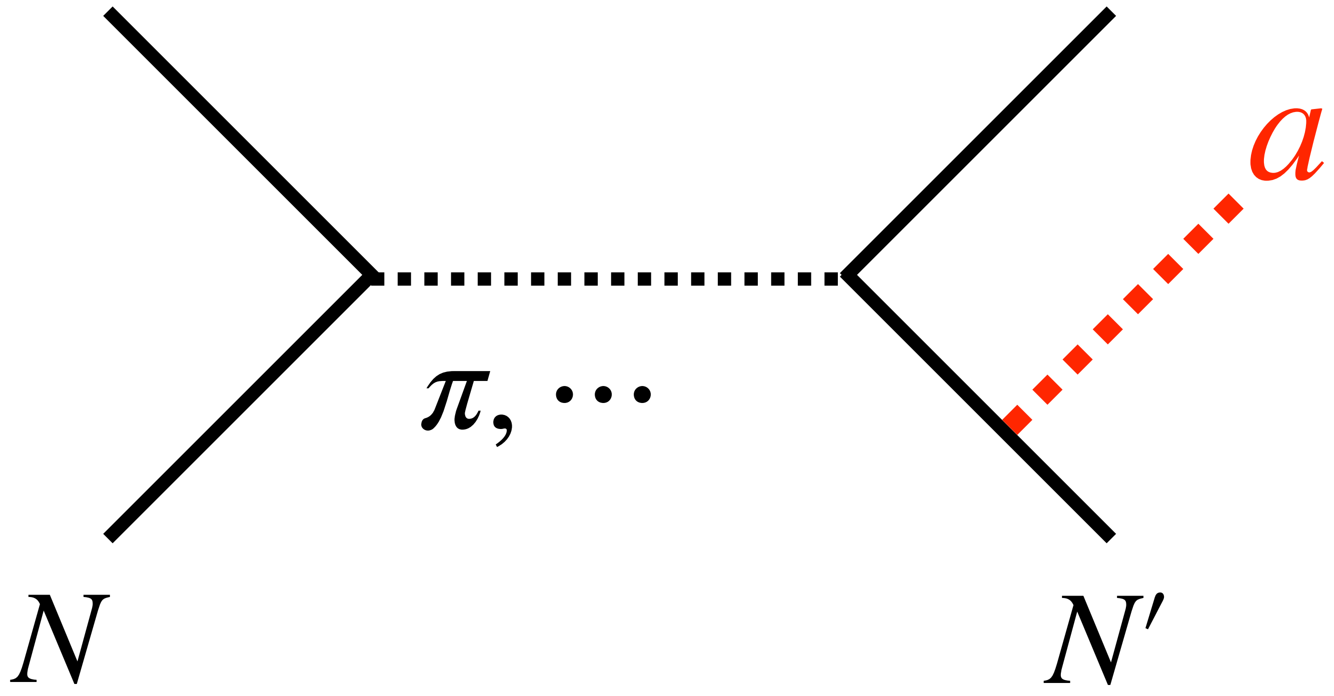
- $\theta_{\rm max} = 50^\circ$
- Hamburg + Tokyo.

Event number



$$N_{\text{event}} = N_a^{\text{SN}} \times \frac{A}{4\pi d^2} \times P_{a\to\gamma}$$

$$NN' \to NN' + a$$
$$(N, N' = n, p)$$



$$\mathscr{L}_{aNN} = \sum_{N=n,p} \frac{C_N}{f_a} \bar{N}\gamma^\mu\gamma^5 N \partial_\mu a$$

$$\begin{cases} C_p = -0.47 \\ C_n = -0.02 \end{cases} \text{(KSVZ)}$$

$$\begin{cases} C_p = -0.182 - 0.435\sin^2\beta \\ C_n = -0.160 + 0.414\sin^2\beta \end{cases} \text{(DFSZ)}$$

Production

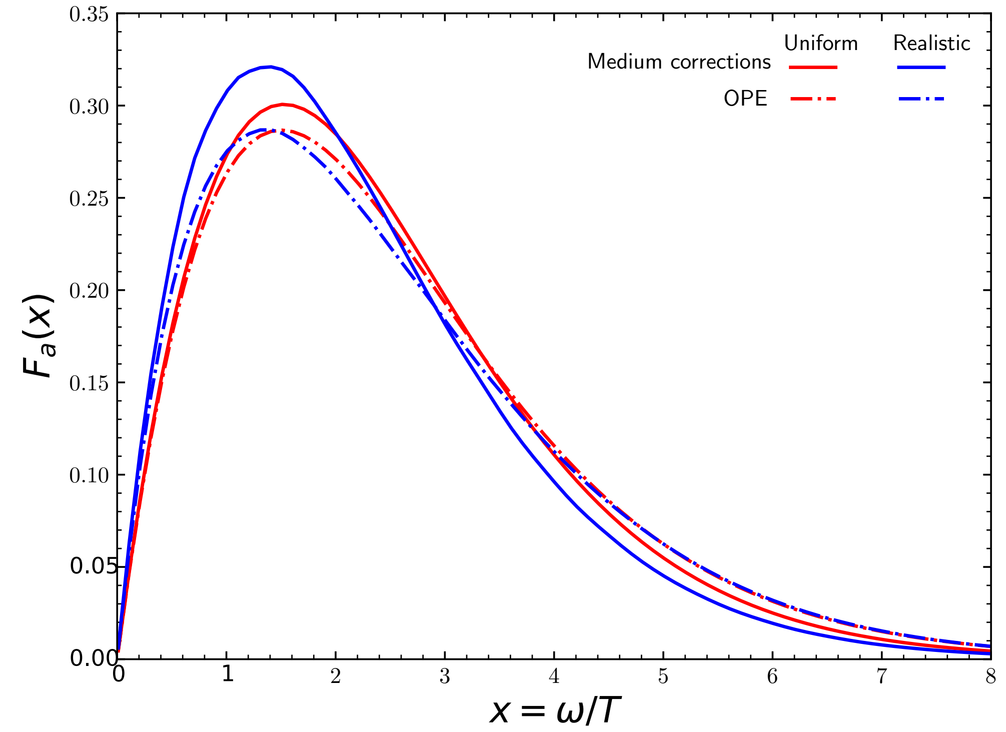
cf. more recent studies, P.Carenza+, 2010.02943, 2108.13726]

- For the axion luminosity, we follow [P.Carenza et.al., 1906.11844], which includes various corrections to the one-pion exchange approximation.
  At the post-bounce time 1sec,

$$L_a \simeq 2.42 \times 10^{70}\, \text{erg} \cdot \text{s}^{-1} \times \left(\frac{m_N}{f_a}\right)^2 C_{N,\text{eff}}^2,$$

where $C_{N,\text{eff}}^2 \equiv C_n^2 + 0.61 C_p^2 + 0.53 C_n C_p$.

- We also include the temperature dependence, $\sim T^{5/2}$.
- The axion energy is $\langle E_a \rangle \simeq 2.3T$.



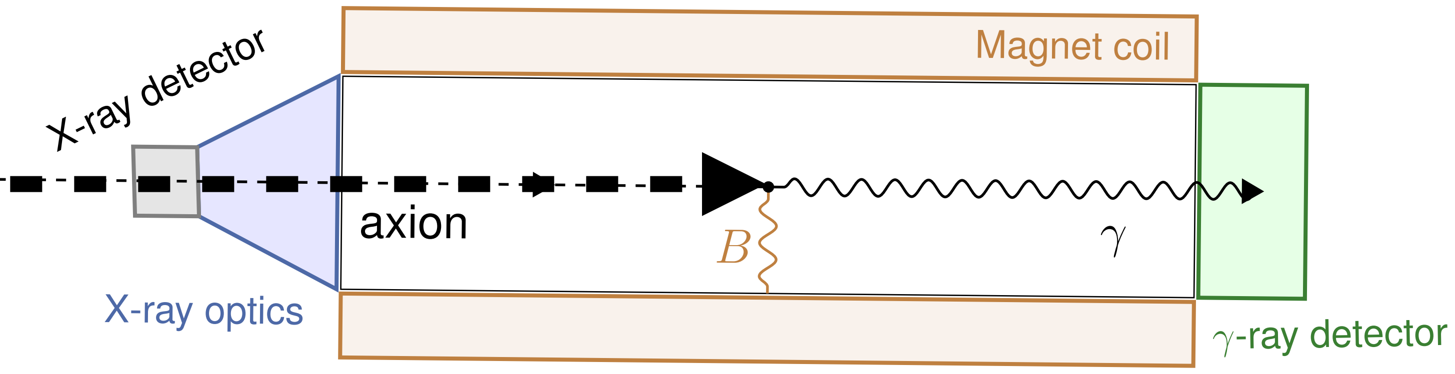
- Thus, the total number of axions from SN is

$$N_a^{\text{SN}} = \dot{N}_a \Delta t = \frac{L_a}{\langle E_a \rangle}\Delta t \simeq 3 \times 10^{57} \left(\frac{3\times 10^8\ \text{GeV}}{f_a}\right)^2 \left(\frac{C_{N,\text{eff}}}{0.37}\right)^2 \left(\frac{\Delta t}{10\ \text{s}}\right)\left(\frac{T}{30\ \text{MeV}}\right)^{5/2}$$

KSVZ

Event number

d

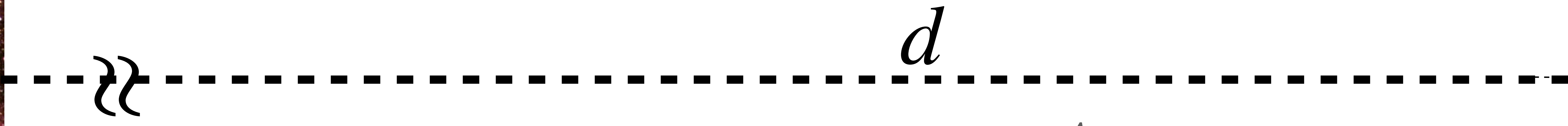


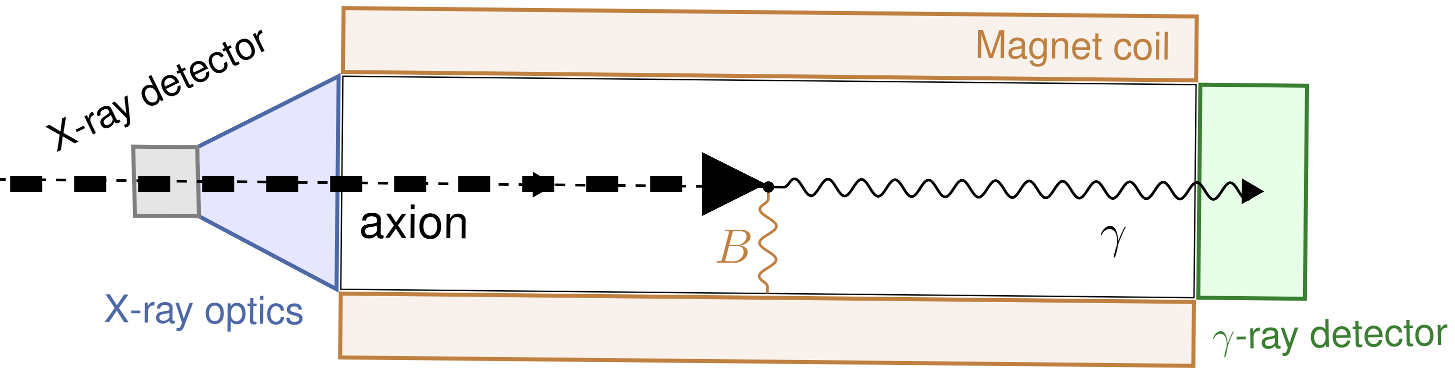
$$N_{\text{event}} = N_a^{\text{SN}} \times \frac{A}{4\pi d^2} \times P_{a\to\gamma}$$

$$\frac{A}{4\pi d^2} = 8.5\times 10^{-39}\left(\frac{A}{2.3\ \text{m}^2}\right)\left(\frac{150\ \text{pc}}{d}\right)^2$$

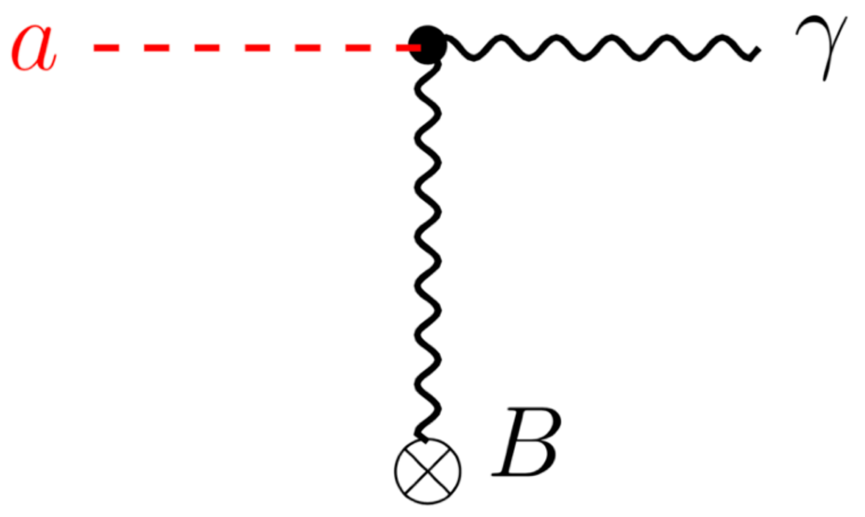
Experiment	(Proposed) site	B (T)	L (m)	A (m^2)
CAST [34–39]	CERN	9	9.3	2.9×10^{-3}
BabyIAXO [41]	DESY	~ 2	10	0.77
IAXO baseline [40, 41]	DESY	~ 2.5	20	2.3
IAXO+ [41]	DESY	~ 3.5	22	3.9
TASTE [42]	INR	3.5	12	0.28

Event number





$$N_{\text{event}} = N_a^{\text{SN}} \times \frac{A}{4\pi d^2} \times P_{a\to\gamma}$$



$$\mathcal{L}_{a\gamma\gamma} = \frac{1}{4}\frac{C_{a\gamma\gamma}}{f_a} a F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

Detection

$$P = \frac{1}{4}\left(\frac{C_{a\gamma\gamma}}{f_a}BL\right)^2\left(\frac{\sin\left(qL/2\right)}{qL/2}\right)^2$$

$$= 3.6\times 10^{-20}\left(\frac{C_{a\gamma\gamma}}{\alpha/\pi}\right)^2\left(\frac{3\times 10^8\ \text{GeV}}{f_a}\right)^2\left(\frac{B}{2.5\ \text{T}}\right)^2\left(\frac{L}{20\ \text{m}}\right)^2\left(\frac{\sin\left(qL/2\right)}{qL/2}\right)^2$$

where $q = m_a^2/2E_a$.

Experiment	(Proposed) site	B (T)	L (m)	A (m^2)
CAST [34–39]	CERN	9	9.3	2.9×10^{-3}
BabyIAXO [41]	DESY	~ 2	10	0.77
IAXO baseline [40, 41]	DESY	~ 2.5	20	2.3
IAXO+ [41]	DESY	~ 3.5	22	3.9
TASTE [42]	INR	3.5	12	0.28

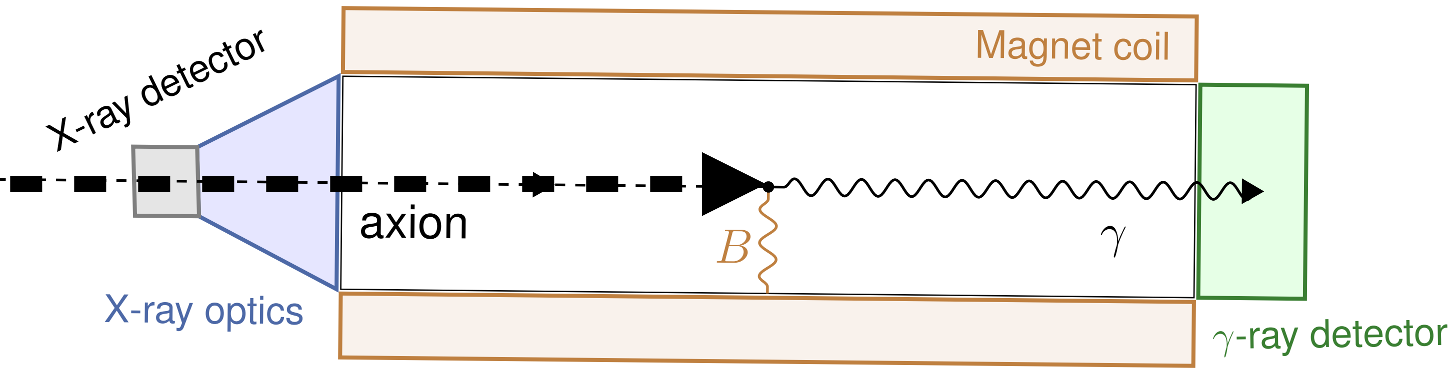
suppression factor

for $m_a \gtrsim \sqrt{\frac{2\langle E_a\rangle}{L}}$.

($a \leftrightarrow \gamma$ oscillation)

Event number

d



$$N_{\rm event} = N_a^{\rm SN} \times \frac{A}{4\pi d^2} \times P_{a\to\gamma}$$

After all,...

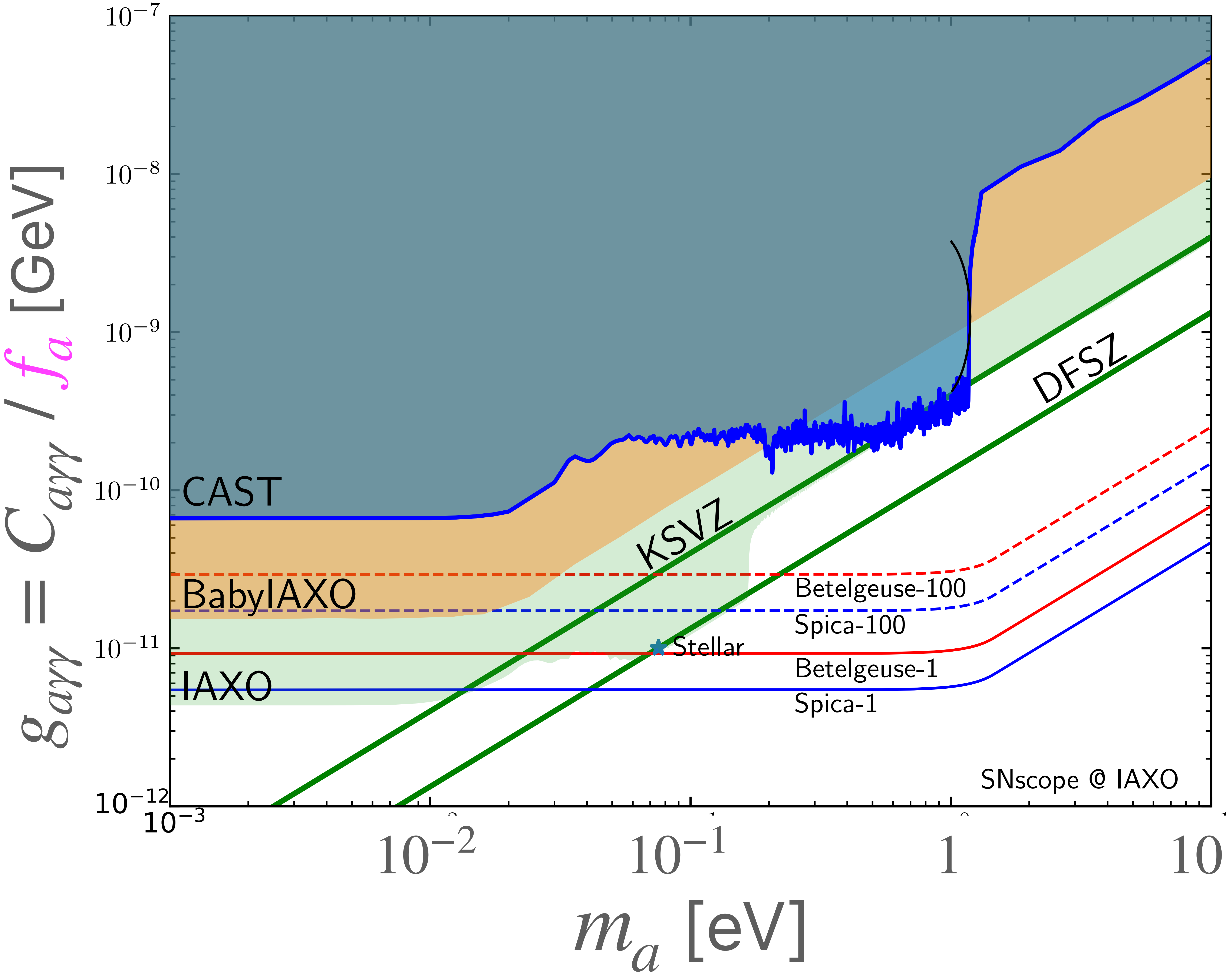
$$N_{\rm event} \simeq 1.0 \times \underbrace{\left(\frac{3\times 10^8~{\rm GeV}}{f_a}\right)^4 \left(\frac{C_{N,{\rm eff}}}{0.37}\right)^2 \left(\frac{C_{a\gamma\gamma}}{\alpha/\pi}\right)^2}_{\text{axion model}} \times \underbrace{\left(\frac{150~{\rm pc}}{d}\right)^2 \left(\frac{\Delta t}{10~{\rm s}}\right) \left(\frac{T}{30~{\rm MeV}}\right)^{5/2}}_{\rm SN}$$

$$\times \underbrace{\left(\frac{A}{2.3~{\rm m}^2}\right) \left(\frac{B}{2.5~{\rm T}}\right)^2 \left(\frac{L}{20~{\rm m}}\right)^2}_{\rm detector} \times \left(\frac{\sin(qL/2)}{qL/2}\right)^2 .$$

※ We expect roughly O(1)~10 uncertainty, especially from SN part.

Event number

S.Ge, K.Hamaguchi, K.Ichimura, K.Ishidoshiro,
Y.Kanazawa, Y.Kishimoto, N.Nagata, J.Zheng.
[arXiv:2008.03924] JCAP **11** (2020) 059.



$N_{\text{event}} = 1 \sim 100$

for Betelgeuse ($d \simeq 220$ pc)

and Spica ($d \simeq 77$ pc)

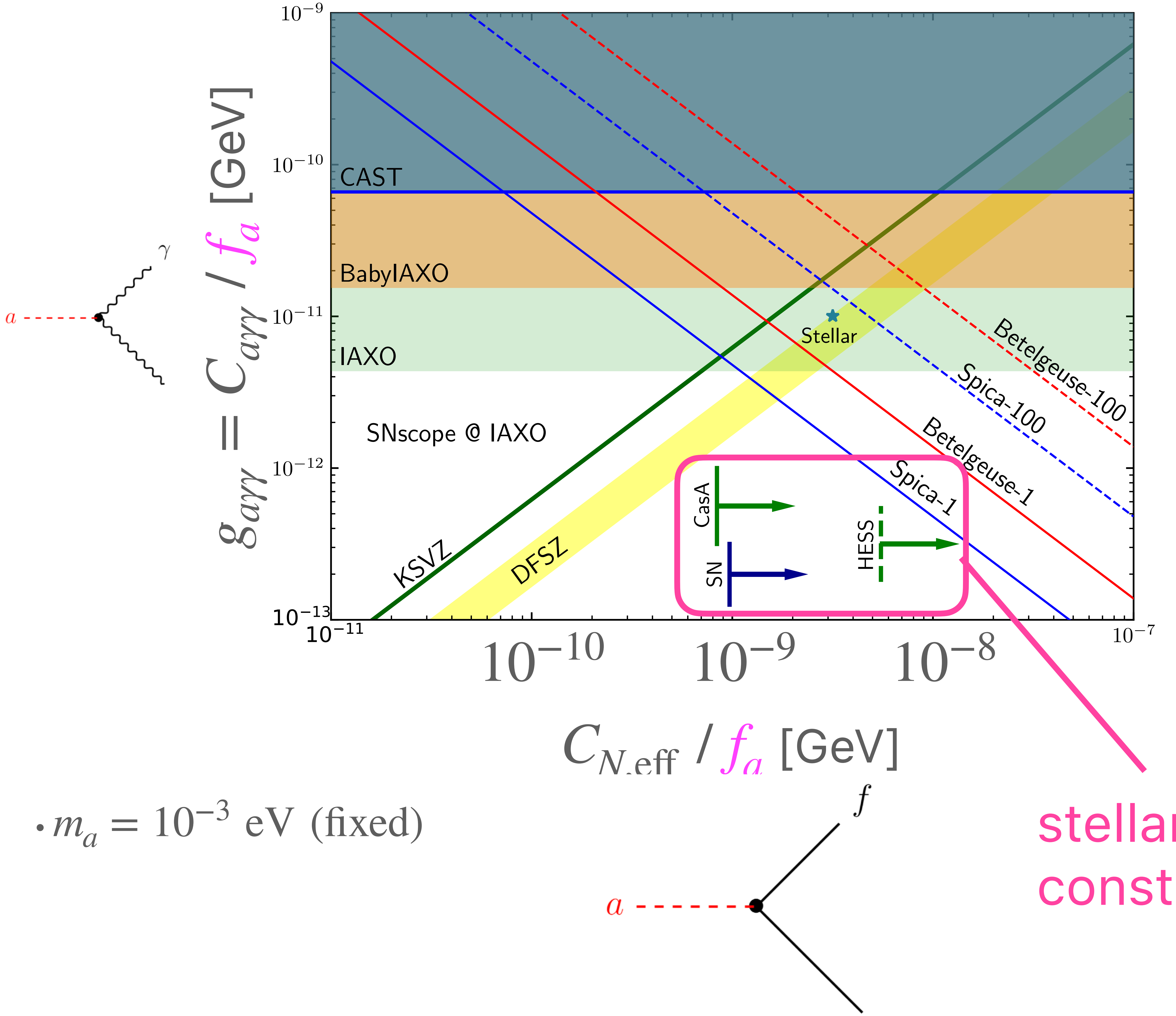
- Axion coupling: KSVZ model
  ($C_{N,\text{eff}} = 0.37$ and $C_{a\gamma\gamma} = \alpha/\pi$)
- Axion mass: free parameter (ALPs-like)

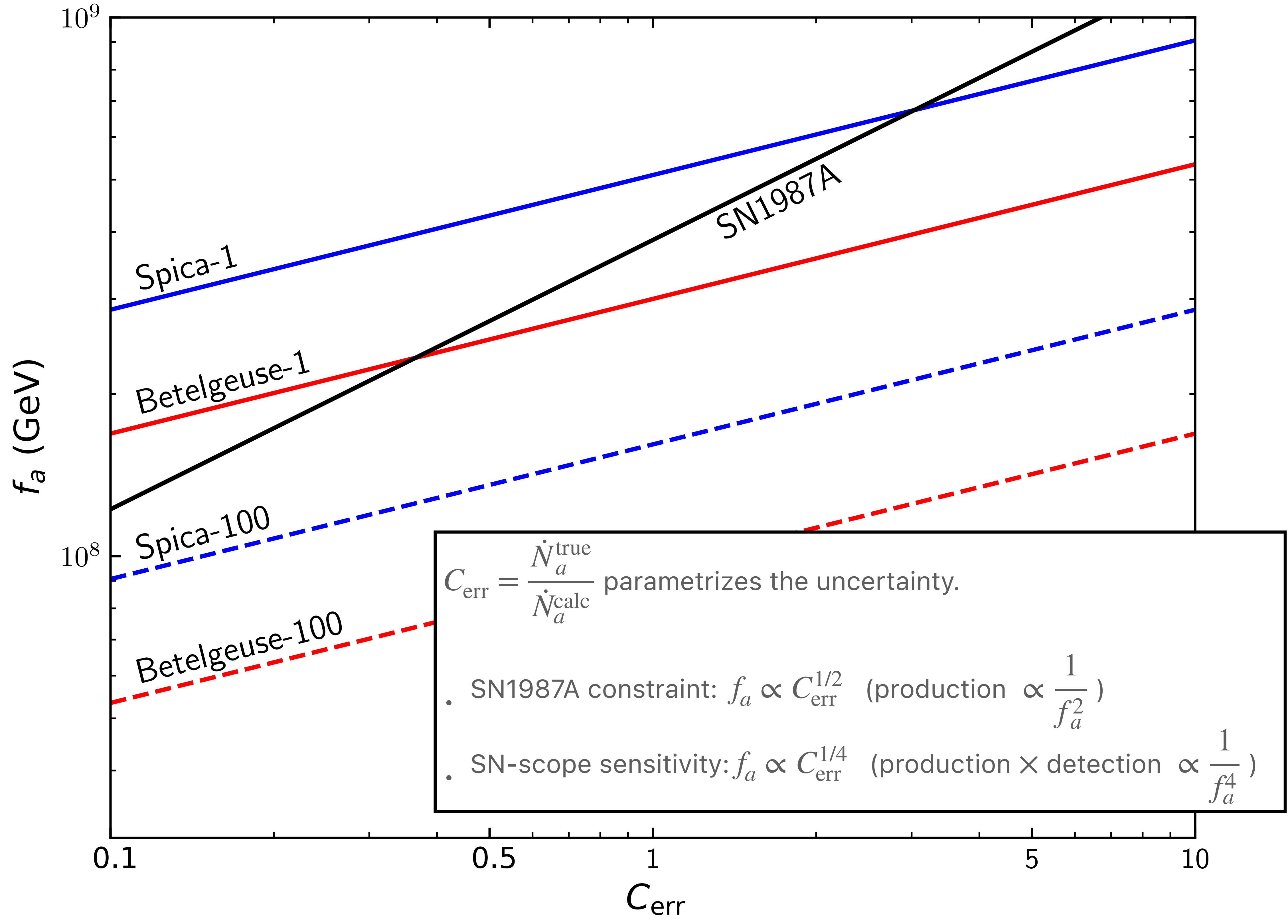
- Better sensitivity than helioscopes for large mass,
  because of higher axion energy
  ($E_a^{\text{SN}} \sim 70$ MeV $\gg$ $E_a^{\text{sun}} \sim$ a few keV).

- For small mass region, both solar axion and SN-axion may be discovered.

Event number vs. stellar constraints

S.Ge, K.Hamaguchi, K.Ichimura, K.Ishidoshiro, Y.Kanazawa, Y.Kishimoto, N.Nagata, J.Zheng. [arXiv:2008.03924] JCAP **11** (2020) 059.



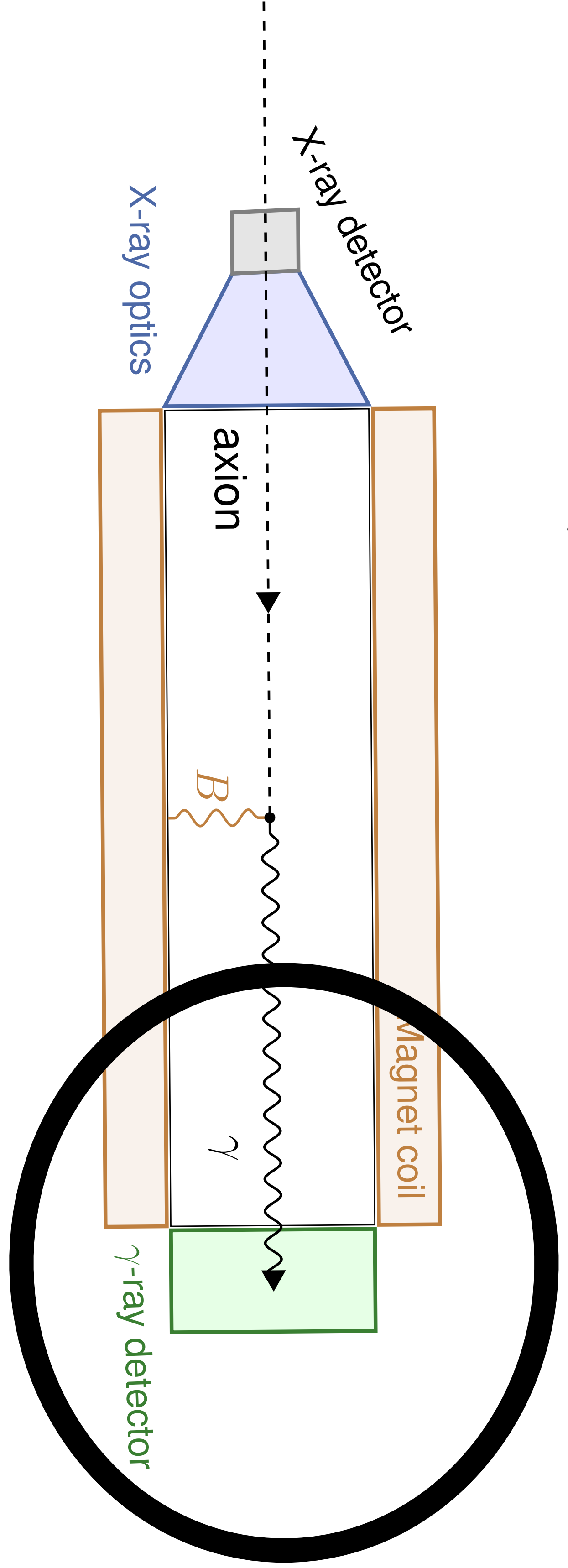


- $m_a = 10^{-3}$ eV (fixed)

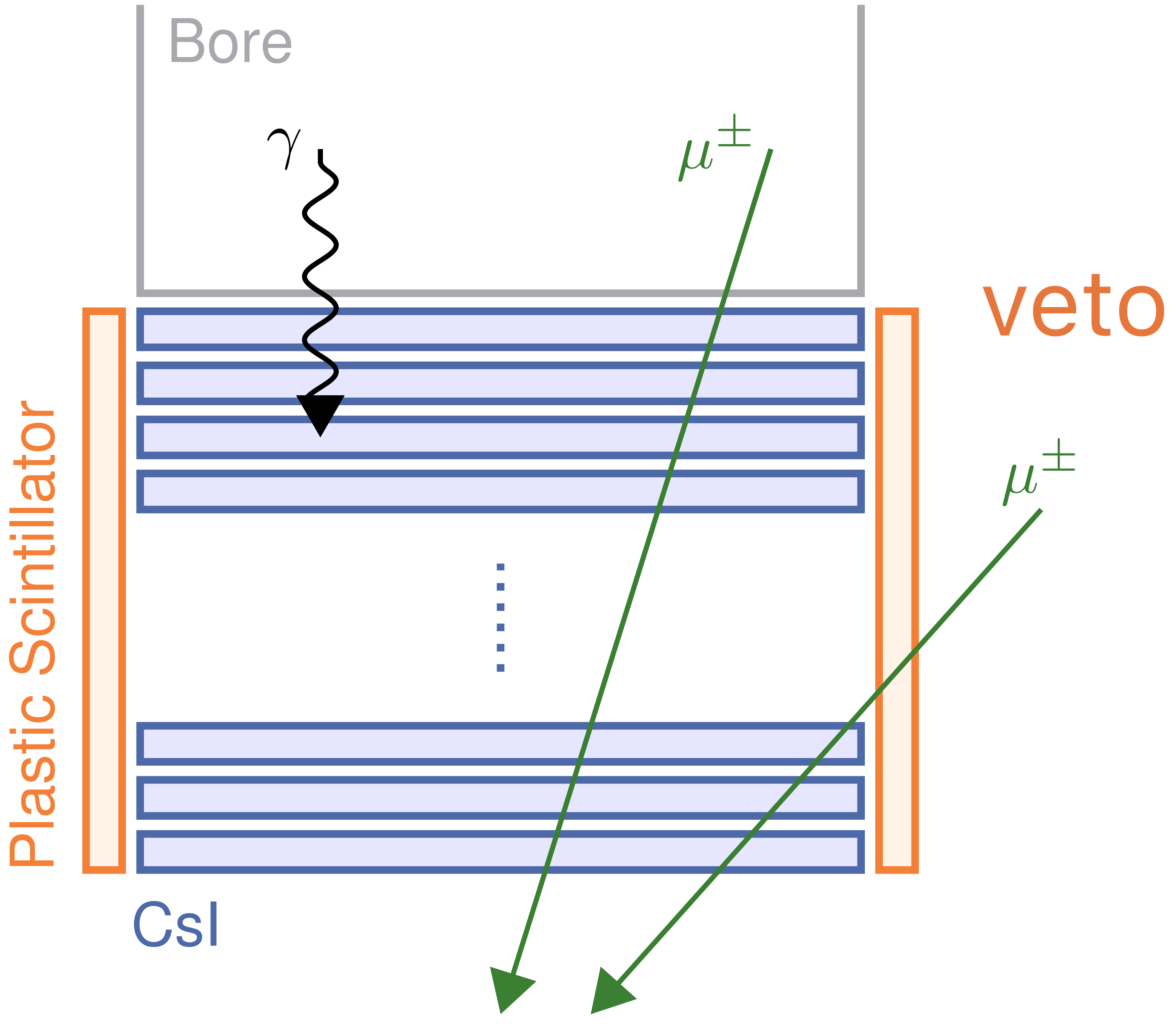
stellar constraints

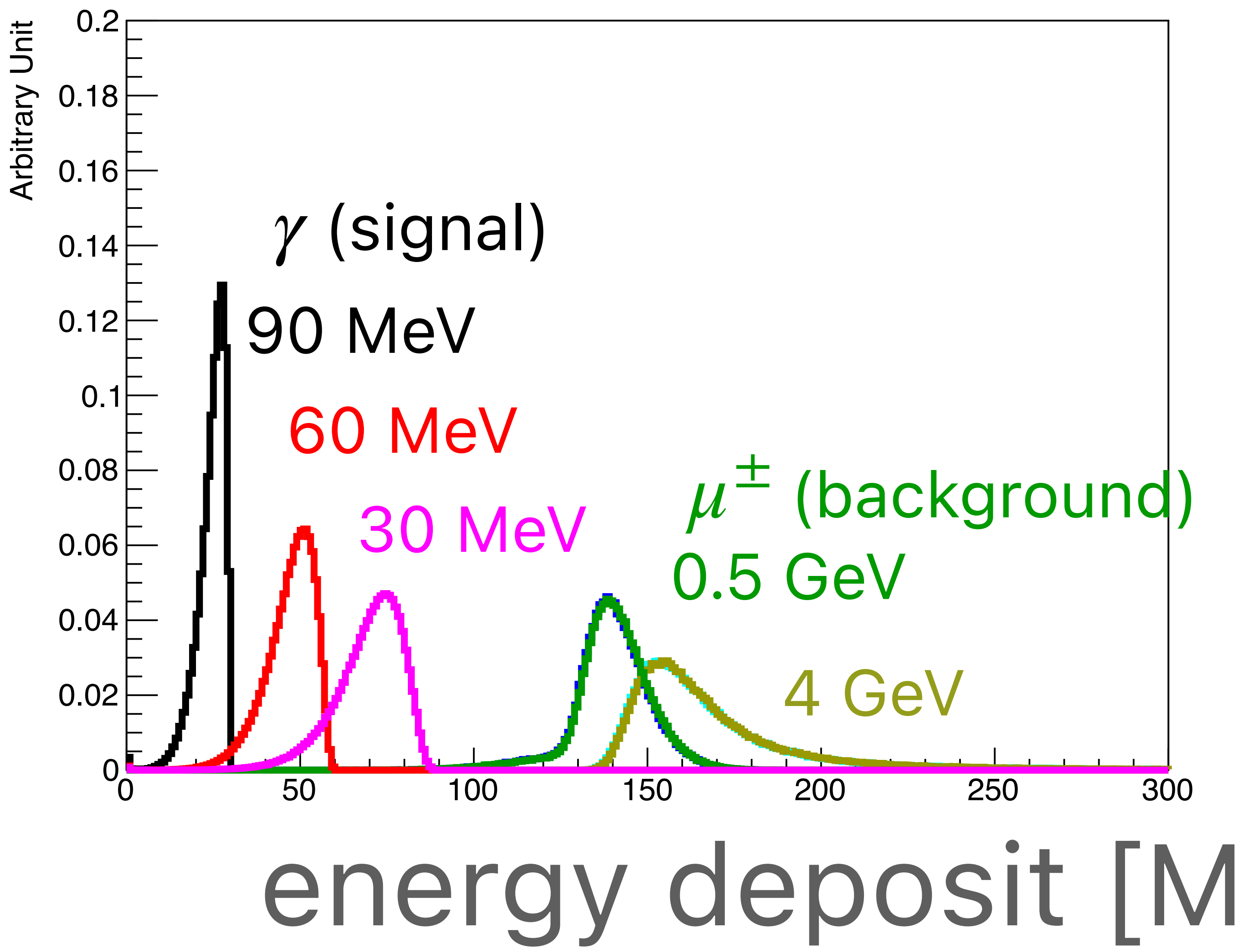
For $C_{\rm err} \simeq 0.1 - 0.3$,
- $\mathcal{O}(1)$ events for Betelgeuse,
- $\mathcal{O}(10)$ events for Spica.

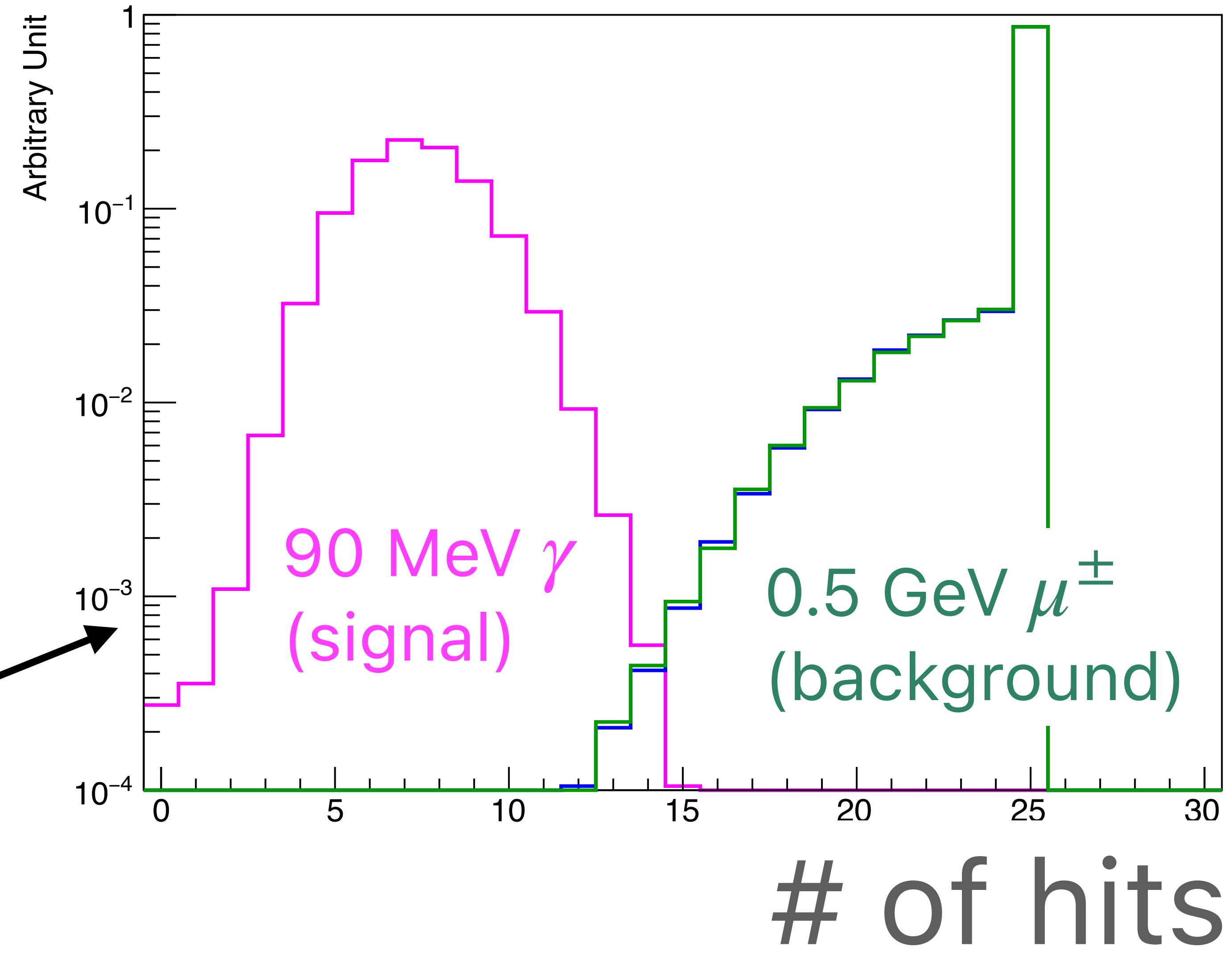
S.Ge, K.Hamaguchi, K.Ichimura, K.Ishidoshiro, Y.Kanazawa, Y.Kishimoto, N.Nagata, J.Zheng.
[arXiv:2008.03924] JCAP **11** (2020) 059.



A design for the gamma-ray detector







- O(1000) muon events in 10 sec.
- They can be rejected by energy deposit and # of hits.

Backup

NS and DM

observational feasibility

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

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

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[1] *Centre for High Energy Physics, Indian Institute of Science, C. V. Raman Avenue, Bengaluru 560012, India*

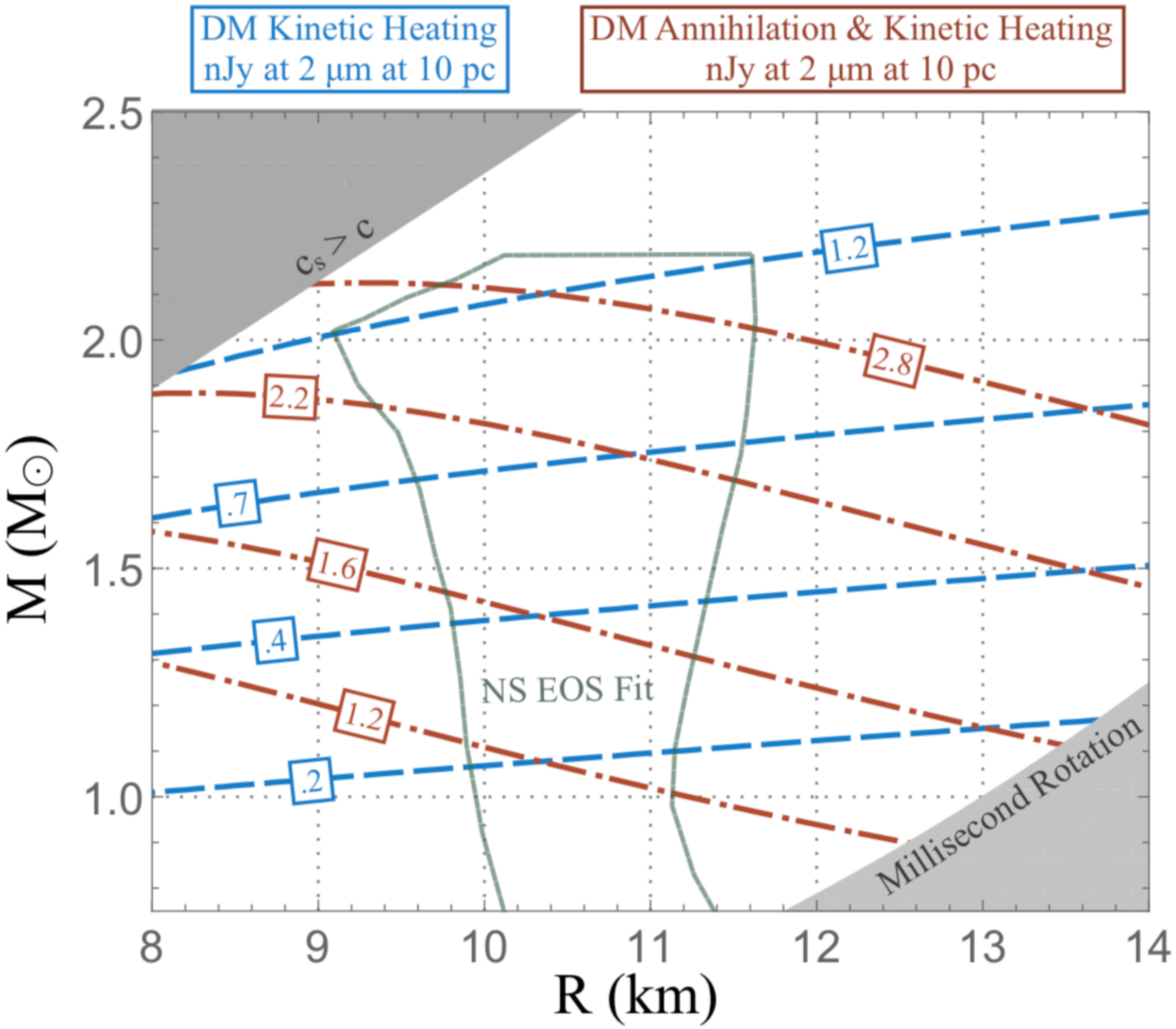
(Dated: March 13, 2024)

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

- 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