中性子星の温度観測と
標準模型を超える物理の探索

濱口幸一

@東京女子大学物理学セミナー 2026年4月23日

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)

参考文献

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

NS cooling by axion: 1806.07151, 2502.18391

SN axion: 2008.03924.

中性子星の温度観測と標準模型を超える物理の探索

🏆 2024 AAPPS-JPS Award 🏆

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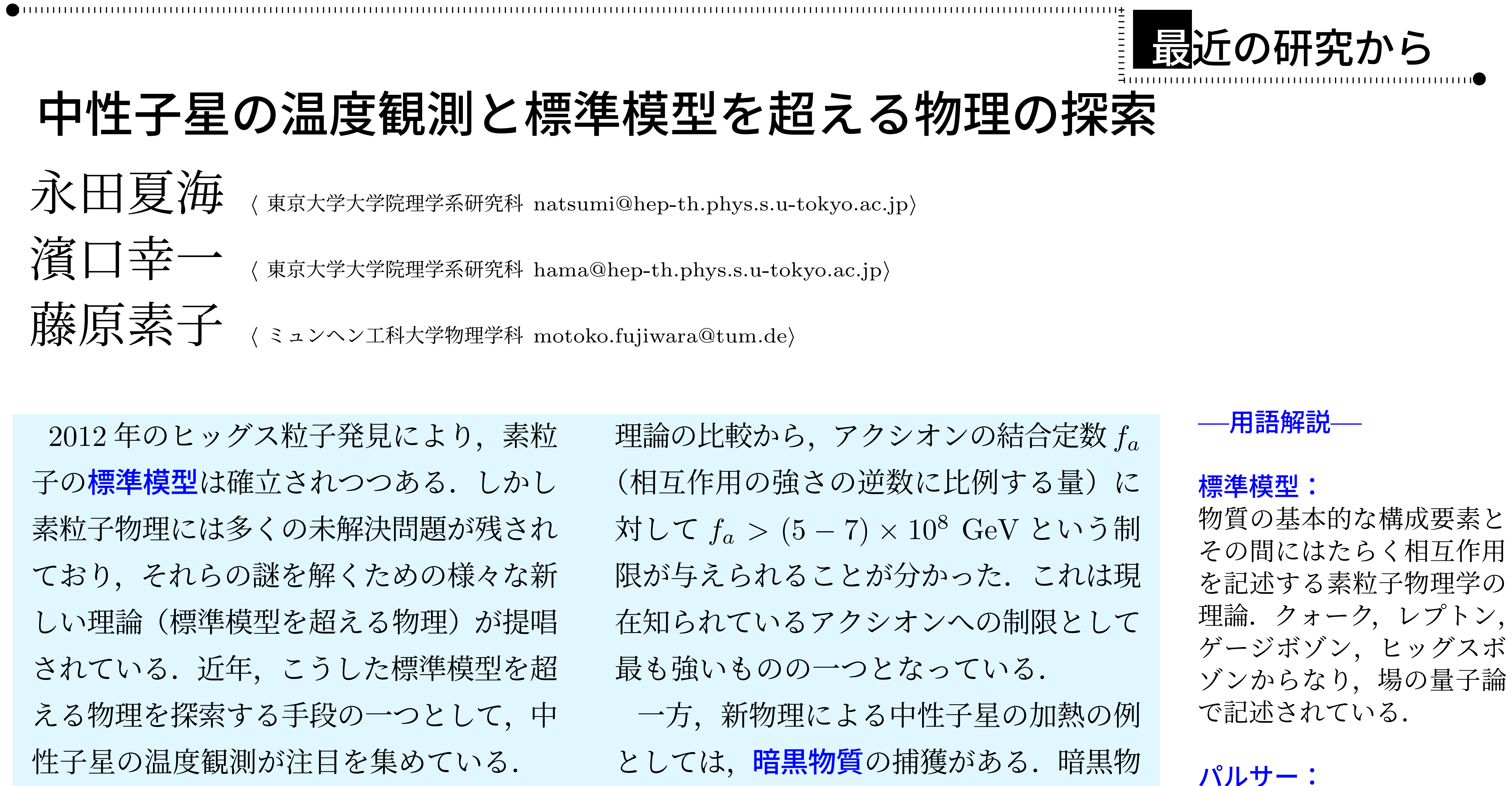
学会誌解説記事（リンク先から読めます）



最近の研究から

中性子星の温度観測と標準模型を超える物理の探索

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

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

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

一方，新物理による中性子星の加熱の例としては，**暗黒物質**の捕獲がある．暗黒物

—用語解説—

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

パルサー：

もくじ

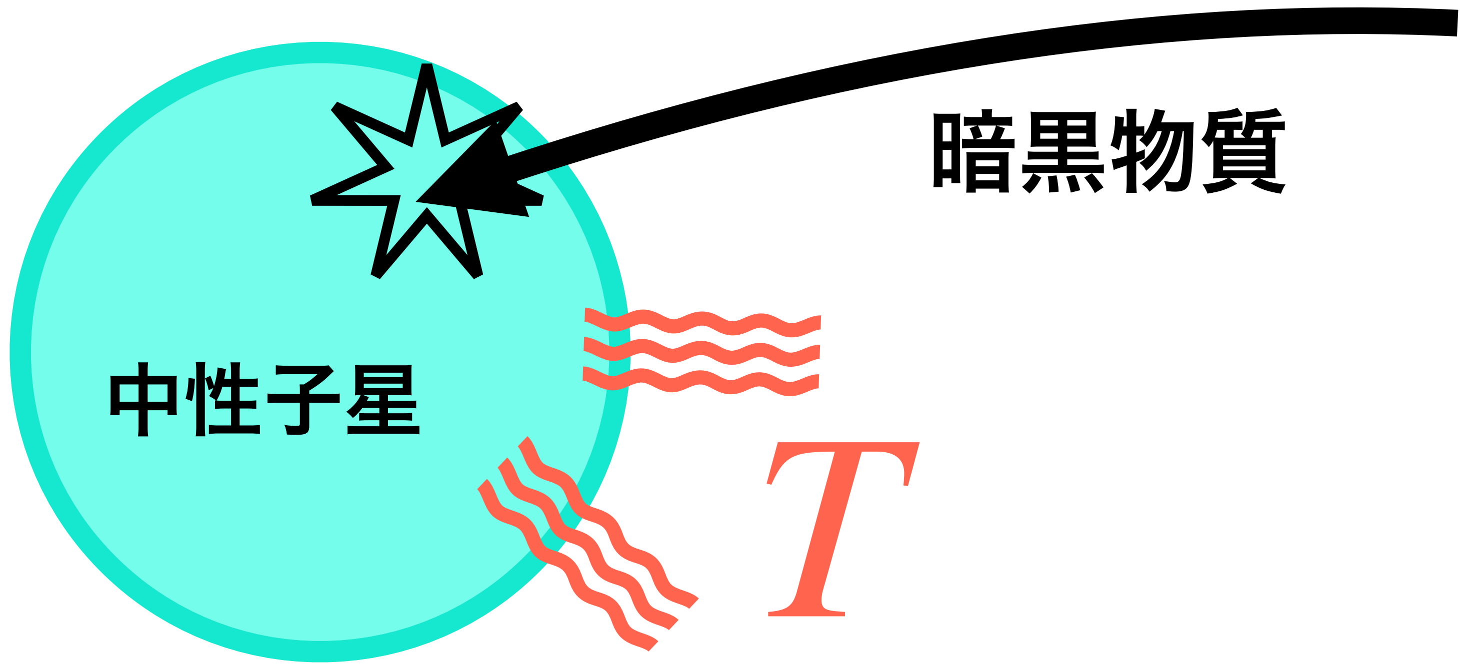
（尾田さんからのリクエストに沿って）

1. 前半 30+10分：物理学科以外の学部生向け

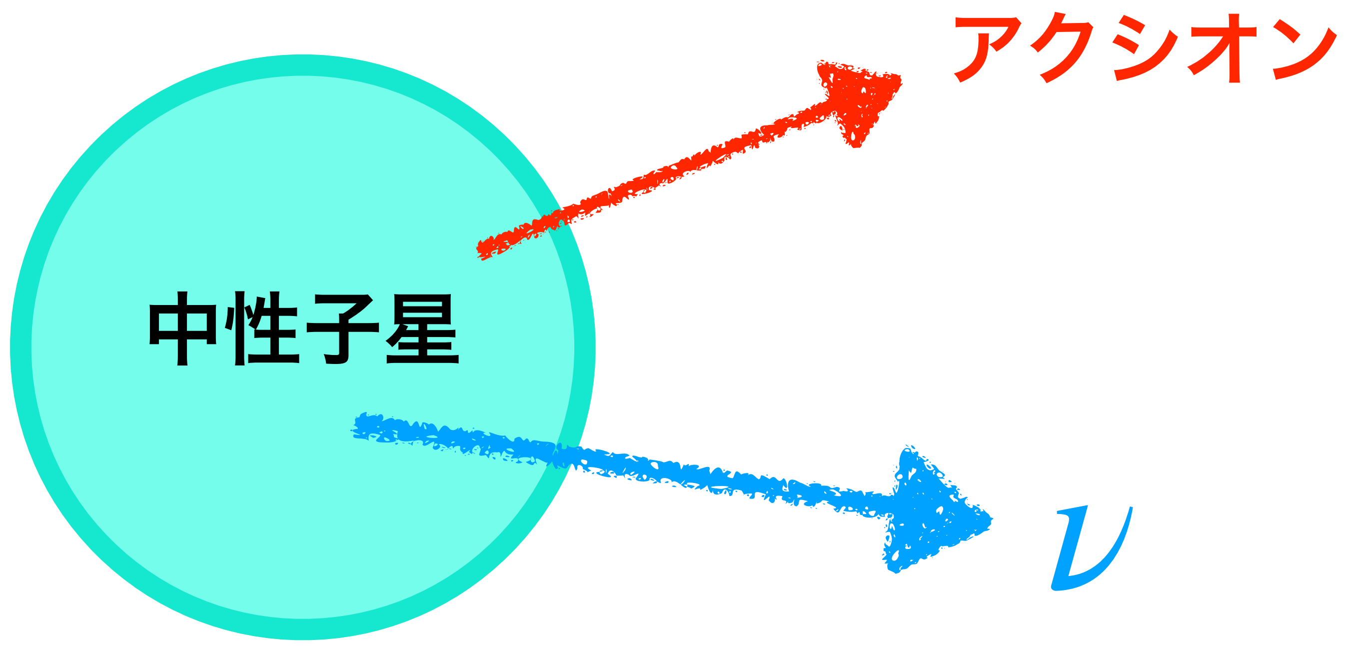
2. 後半 30+10分：大学院生以上向け

もくじ

1. 前半 30+10分：物理学科以外の学部生向け
    - **素粒子の標準模型、標準模型を超える物理**
    - **暗黒物質**
    - **中性子星**
    - **中性子星が暗黒物質で暖まる話**
    - **質疑応答**



2. 後半 30+10分：大学院生以上向け
    - **以下のどれか**
        - (a) 中性子星が暗黒物質で暖まる話、の続き
        - (b) 中性子星がアクシオンで冷える話
        - (c) 超新星からアクシオンがやってくる話



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    - **質疑応答**

質疑応答用に匿名で書き込める
ツール **Slido** を使います. QRコード👉
または適当なデバイスで「Slido」検索 → code **#1919184** で参加

とりあえず今、Slido に何か書いてみてください。
内容は問いません。　例「今日の朝ごはんは xxx だった」

もくじ

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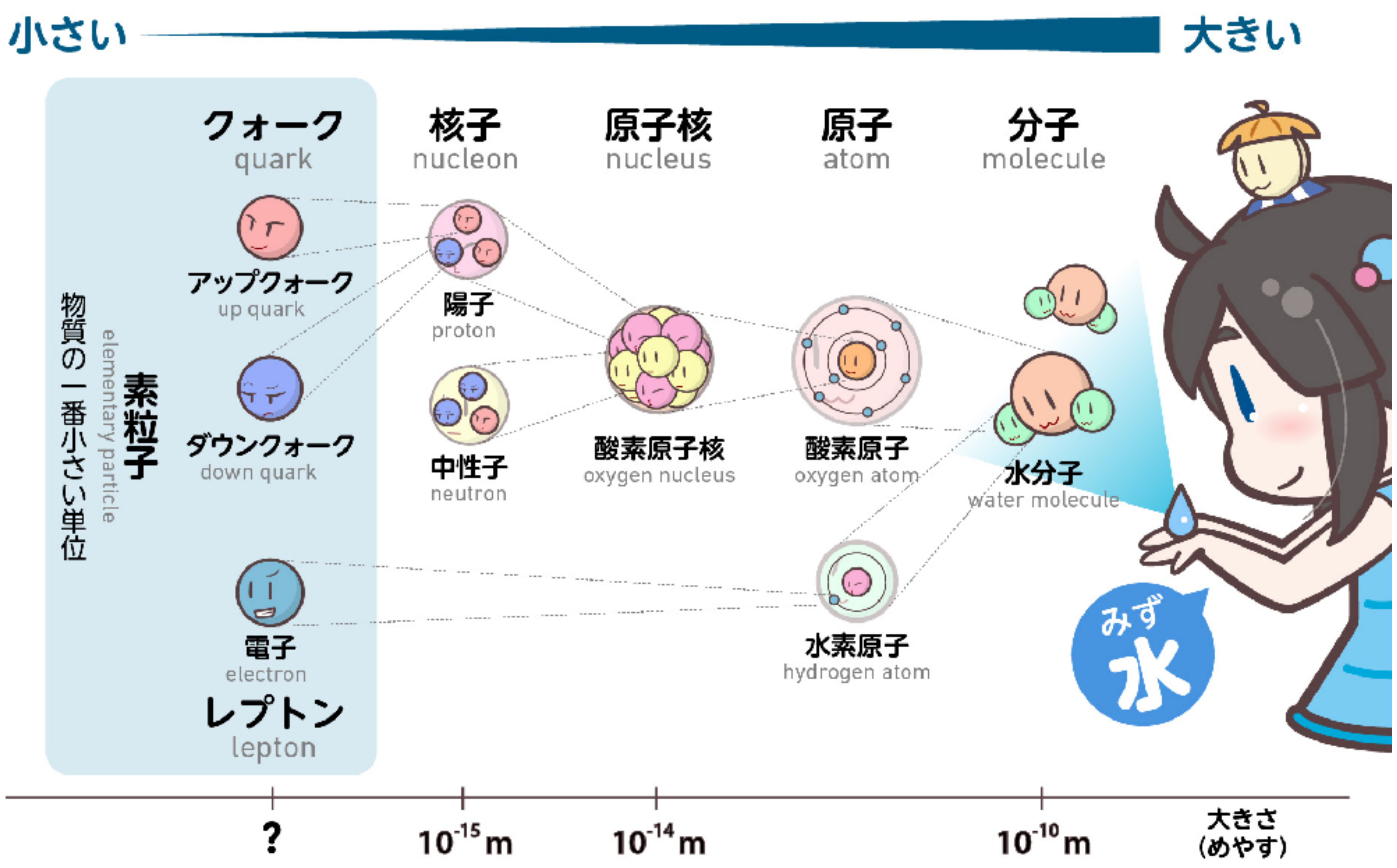
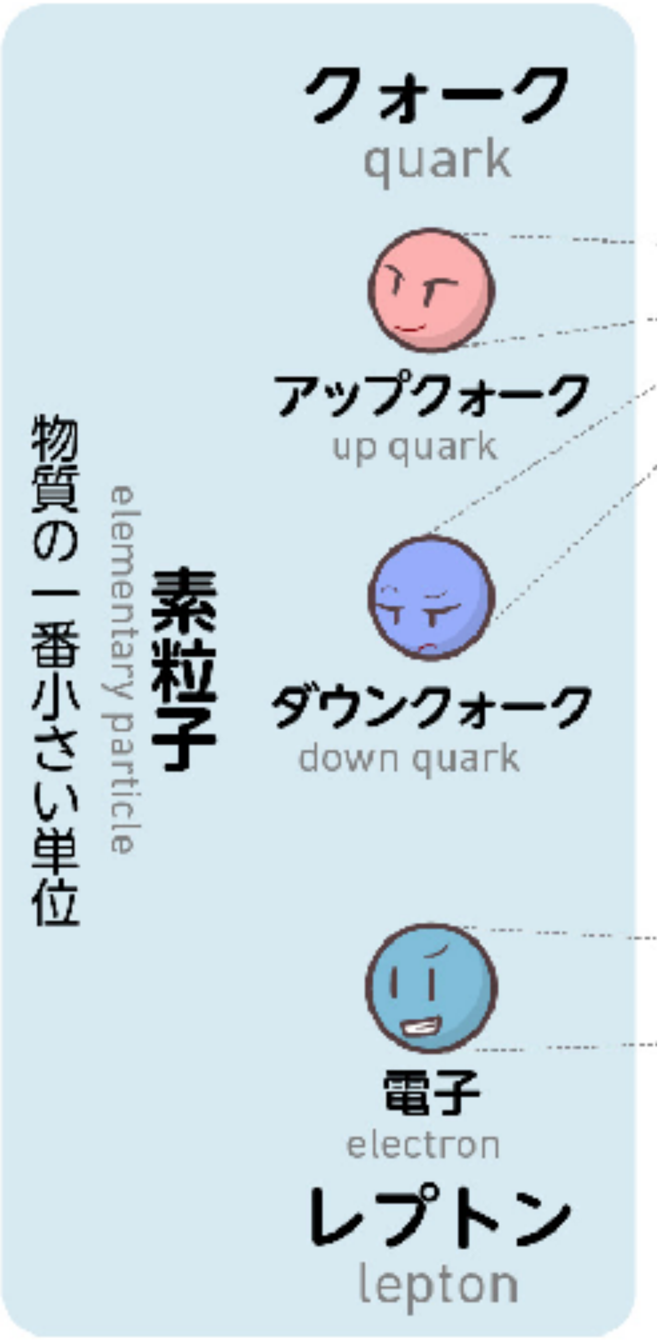
素粒子・・・物質の最小単位



ヒッグスたん
https://higgstan.com/

素粒子・・・物質の最小単位



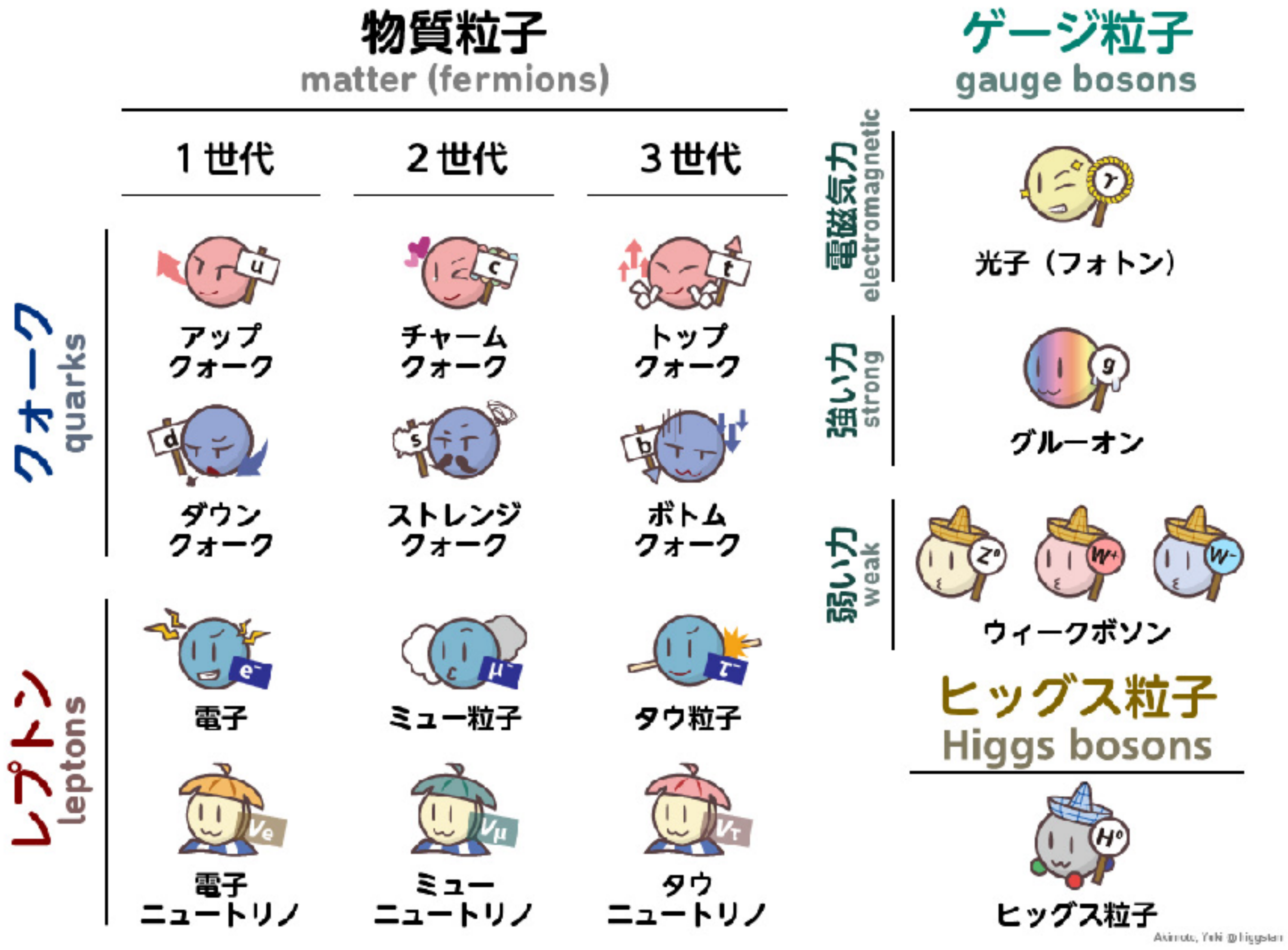
ヒッグスたん
https://higgstan.com/

アップ
クォーク

ダウン
クォーク

電子

素粒子の標準模型



ヒッグスたん
https://higgstan.com/

素粒子の標準模型

$$\mathscr{L} = -\sum \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu}$$ ⋯ gauge fields

$$+\sum i\bar{\psi}\gamma^\mu D_\mu \psi$$ ⋯ matter fields + gauge interactions

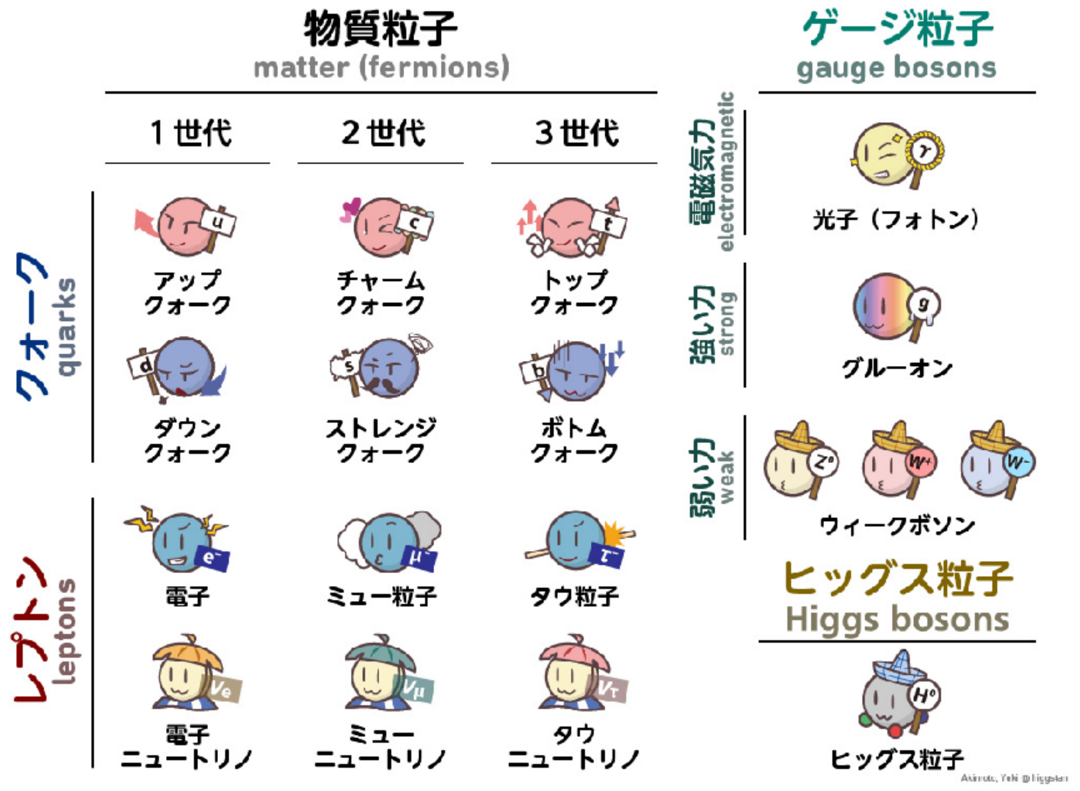
$$+|D_\mu \phi|^2 - V(\phi)$$ ⋯ Higgs fields

$$+\sum y\phi\bar{\psi}\psi + \mathrm{h.c.}$$ ⋯ Yukawa interactions

このたったの数行で無数の素粒子物理の実験事実を
とんでもない精度で記述出来ている。

現時点で最も成功している素粒子物理の理論。

素粒子の標準模型



$$\mathscr{L} = -\sum \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} \quad \cdots \text{ gauge fields}$$

$$+ \sum i\bar{\psi}\gamma^\mu D_\mu \psi \quad \cdots \text{ matter fields + gauge interactions}$$

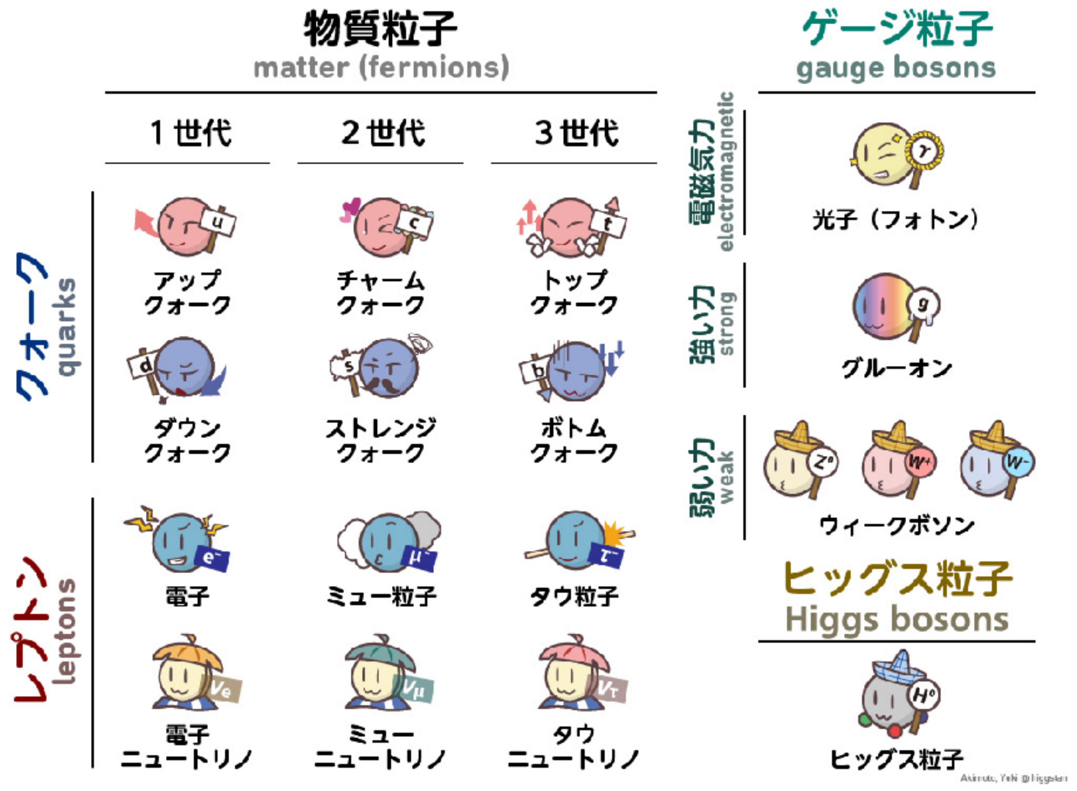
$$+ |D_\mu \phi|^2 - V(\phi) \quad \cdots \text{ Higgs fields}$$

$$+ \sum y\phi\bar{\psi}\psi + \mathrm{h.c.} \quad \cdots \text{ Yukawa interactions}$$

しかし、この標準模型では説明できない実験事実や未解決の謎がある

- 暗黒物質の謎
- 宇宙の物質と反物質の非対称性の謎
- インフレーション
- ニュートリノ質量
- Strong CP problem,
- などなど、、、

素粒子の標準模型



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- 宇宙の物質と反物質の非対称性の謎
- インフレーション
- ニュートリノ質量
- **Strong CP problem**, (後半時間があれば⋯)
- などなど、、、

もくじ

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暗黒物質：重力でしか見えない物質

正体は分からないけど、存在するという証拠は沢山ある。

- 銀河の回転速度
- 宇宙背景放射の非等方性の精密測定
- 宇宙の構造形成
- 弾丸銀河団
- ・・・

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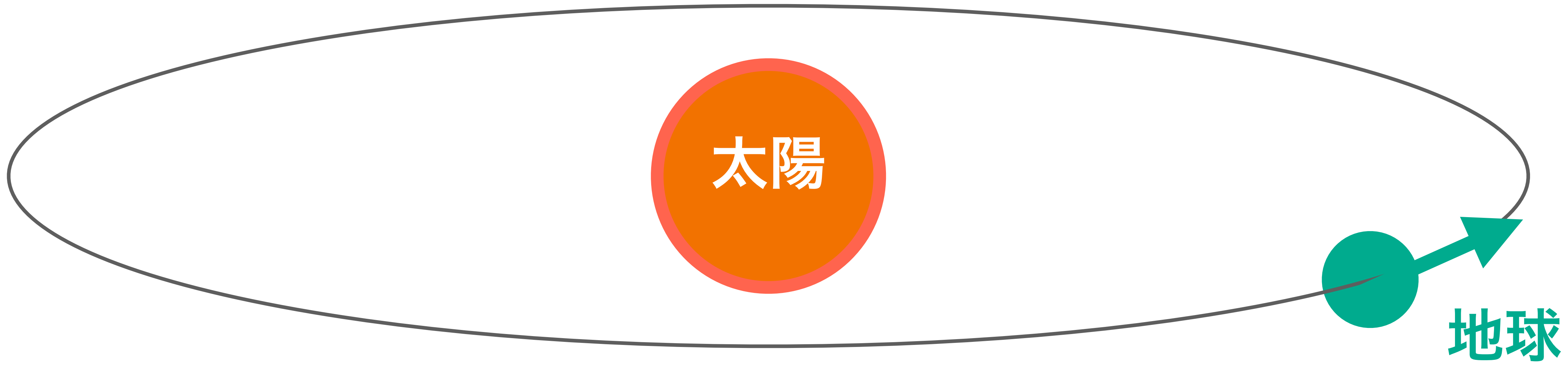

地球がグルグル回ってるのは
太陽が引力（重力）で引っ張っているから

写真は Reuter より
りくりゅう引退しちゃいますねぇ

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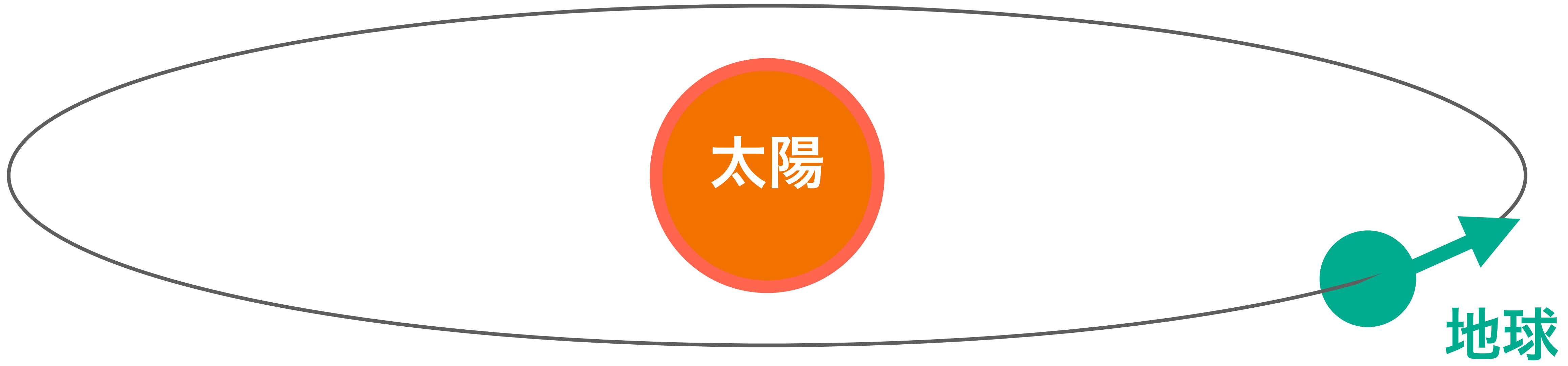

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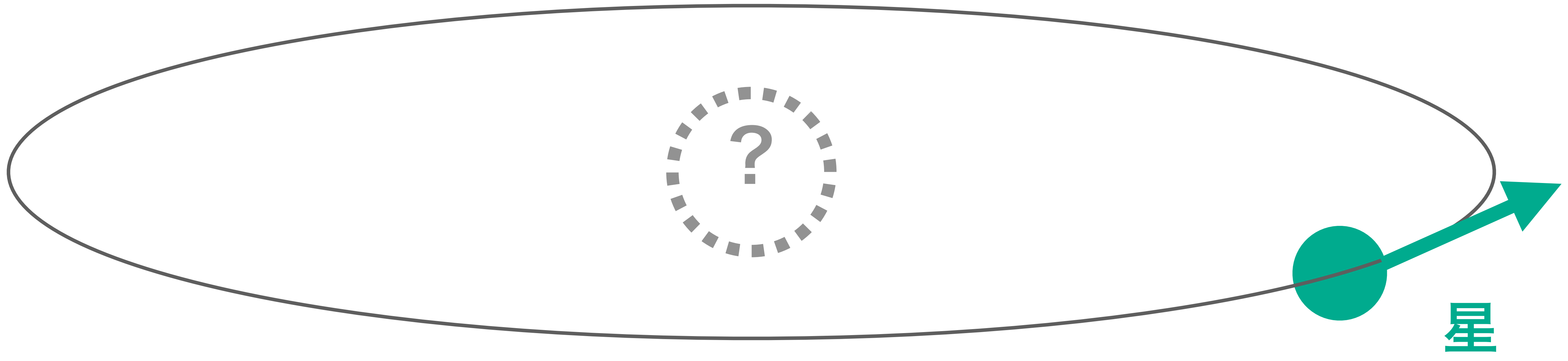
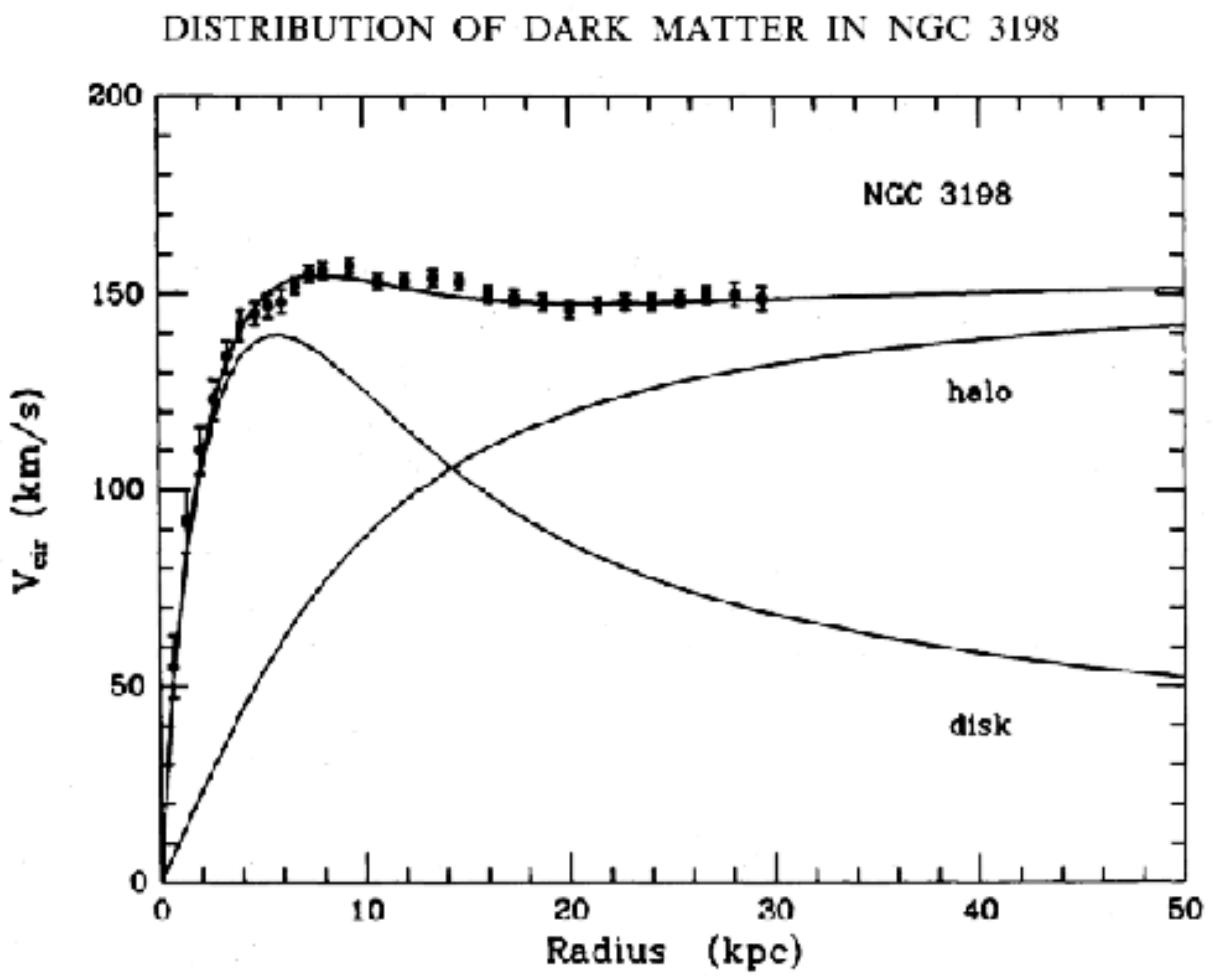


銀河の中の星たちもグルグル回っている。その動きを調べると、👉
見えている物質だけでは引力が足りないことが分かる。



暗黒物質：重力でしか見えない物質

正体は分からないけど、存在するという証拠は沢山ある。

- 銀河の回転速度

重い何か（重力源）があるはずだが
その正体はわからない・・・。
「暗黒物質」

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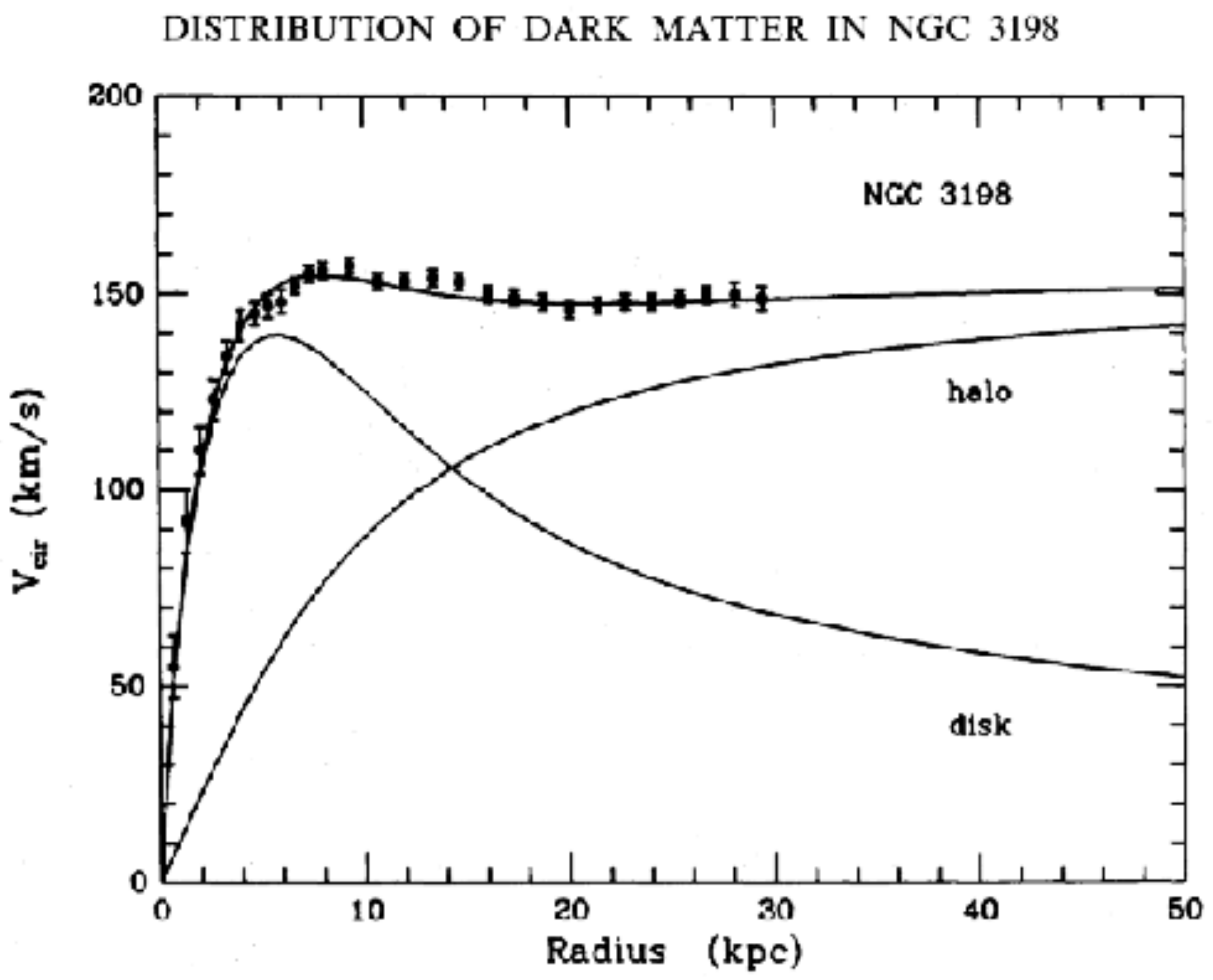
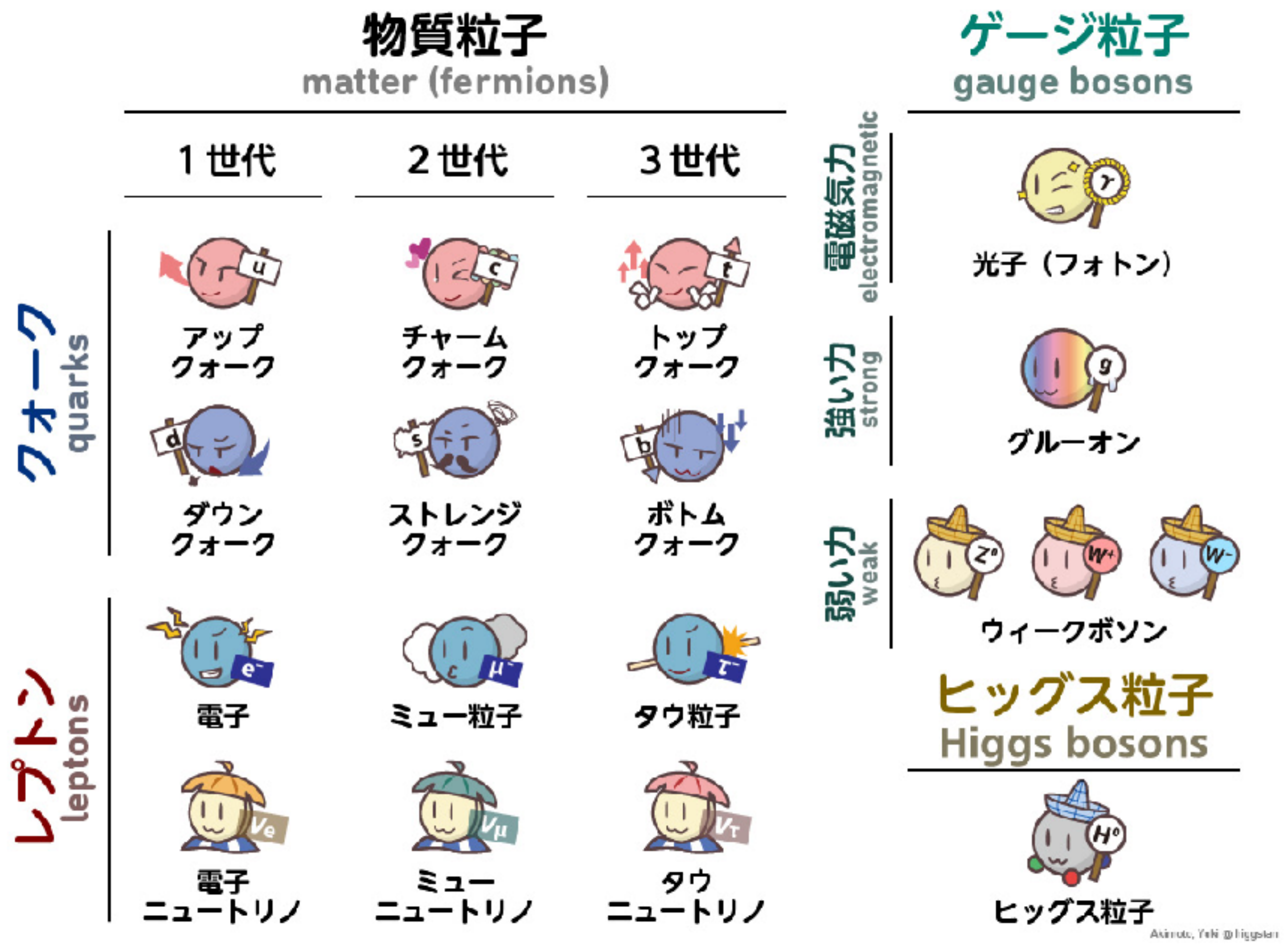


暗黒物質の正体は？

標準模型の中に
暗黒物質になれる粒子はない。

標準模型を超える新物理が必要！



＋

???

正体不明の新粒子

正体の候補：WIMP（弱い相互作用をする重い粒子）など

※WIMPについては後半、時間／質問があれば・・・

暗黒物質を探す

様々な探索方法が試みられている

- 地下実験（直接検出）
- 加速器実験
- 宇宙観測（間接検出）

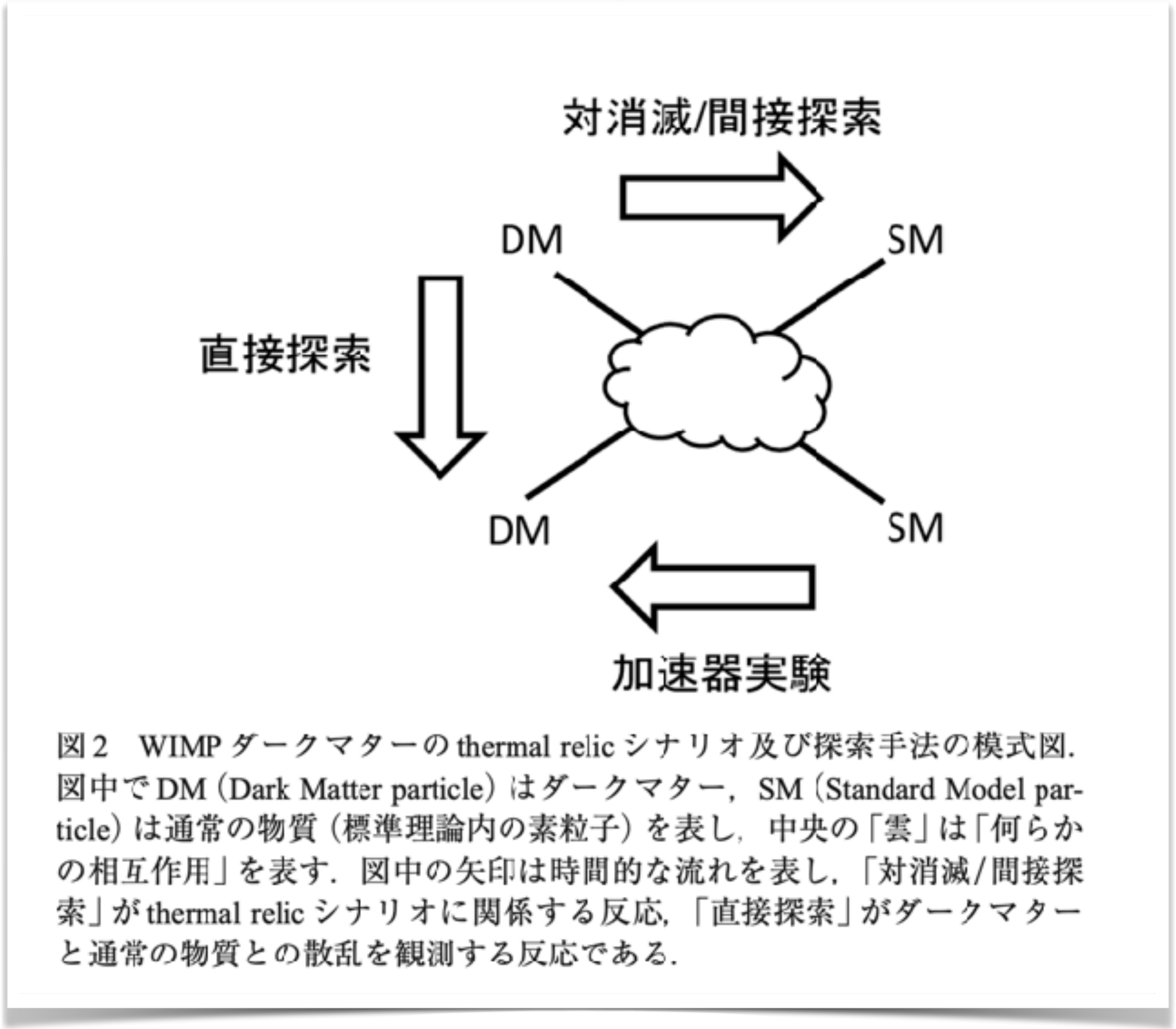


図 2　WIMP ダークマターの thermal relic シナリオ及び探索手法の模式図. 図中で DM（Dark Matter particle）はダークマター，SM（Standard Model particle）は通常の物質（標準理論内の素粒子）を表し，中央の「雲」は「何らかの相互作用」を表す．図中の矢印は時間的な流れを表し，「対消滅/間接探索」が thermal relic シナリオに関係する反応，「直接探索」がダークマターと通常の物質との散乱を観測する反応である．

学会誌解説記事（リンク先から読めます）より

今日は：

中性子星の温度観測を使った新しいアプローチについてお話しします。

もくじ

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    - **中性子星**
    - 中性子星が暗黒物質[illegible]まる話
    - 質疑応答

質疑応答用 Slido. QRコード👉
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中性子星

- **質量**：$M \sim (1-2)M_\odot$, ($M_\odot$ = 太陽質量 = 2×10^{30} kg)
- **半径**：$R \sim 10$ km

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- **平均密度：**$\bar{\rho} = \dfrac{M}{(4\pi/3)R^3} \simeq 7 \times 10^{14} \mathrm{g/cm}^3$　(スプーン一杯で10億トン！)

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- **ほぼ中性子で出来ている。** 10%くらい陽子, 電子 (ミューオン) もいる。

- ほとんどは**パルサー**として見つかっている。

パルサー：パルス状の電磁波を発する天体

その正体は強い磁場を持ち回転する中性子星であると考えられている.

現在までに2700個以上見つかっている。

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

かにパルサー

中性子星

- **質量：**$M \sim (1-2)M_\odot$, $(M_\odot =$ 太陽質量 $= 2 \times 10^{30}$ kg)
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今日は中性子星の温度に注目して
標準模型を超える物理にアプローチするお話

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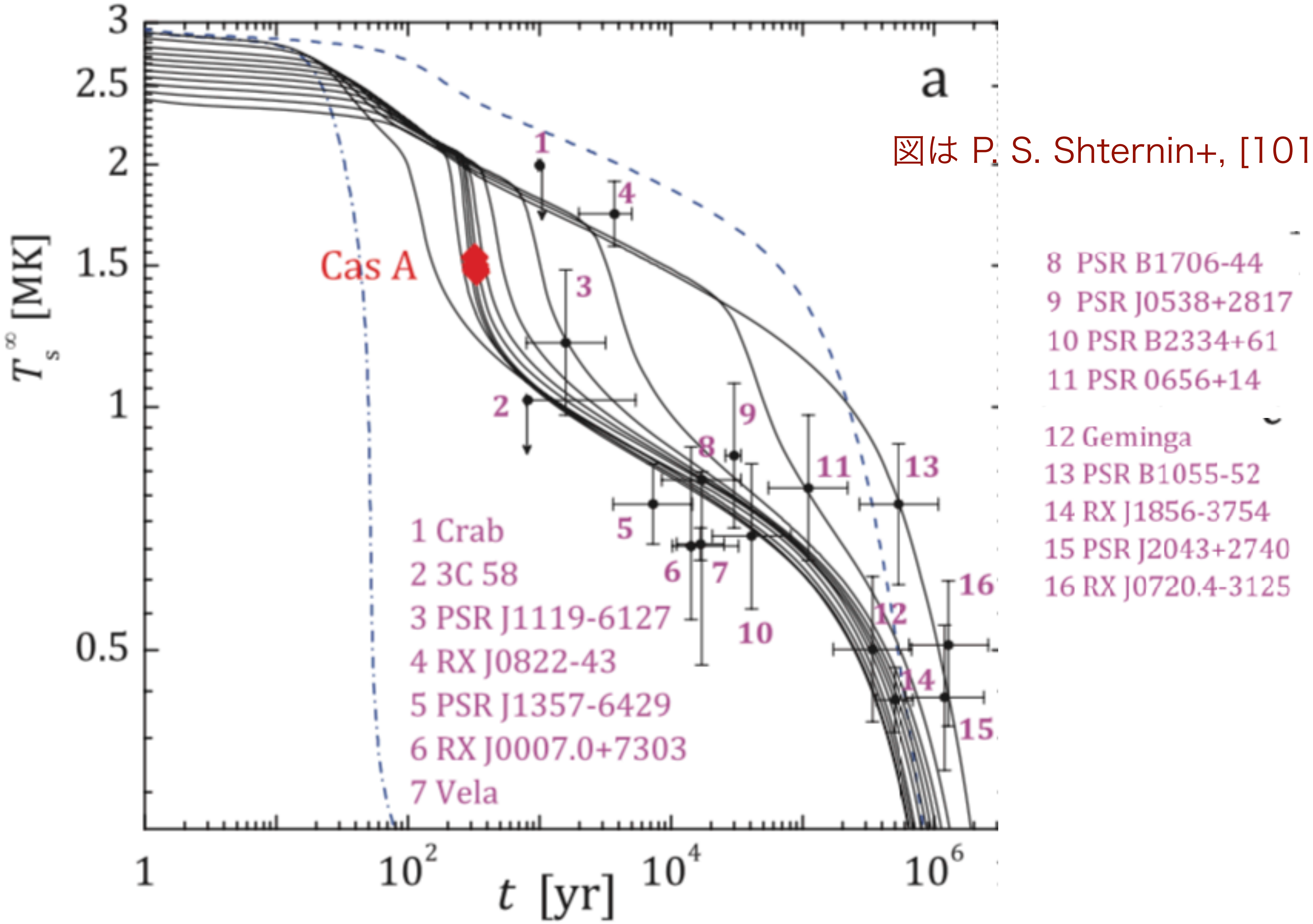
温度



図は P. S. Shternin+, [1012.0045]より。

年齢

今日は中性子星の温度に注目して
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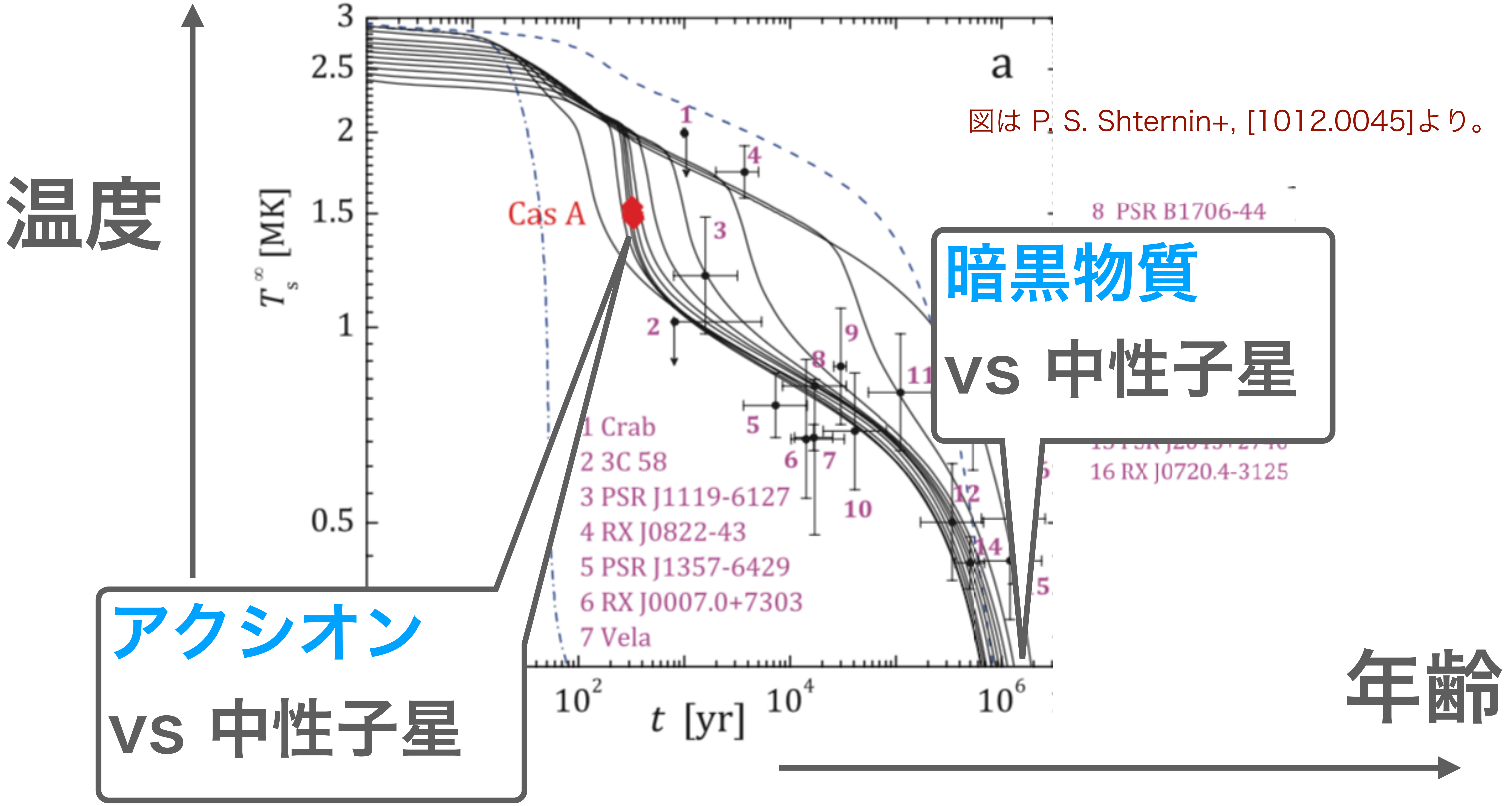

図は P. S. Shternin+, [1012.0045]より。

アクシオン
vs 中性子星

暗黒物質
vs 中性子星

- (後半時間があれば…)

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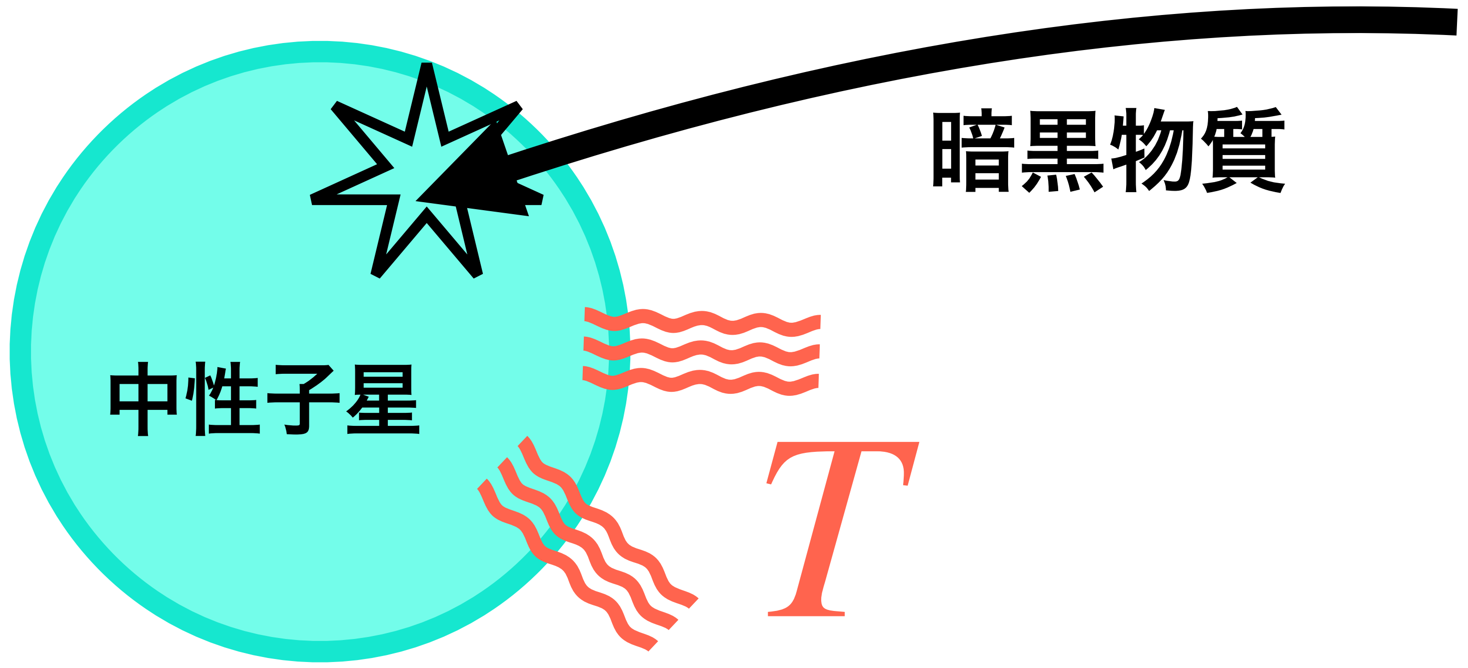

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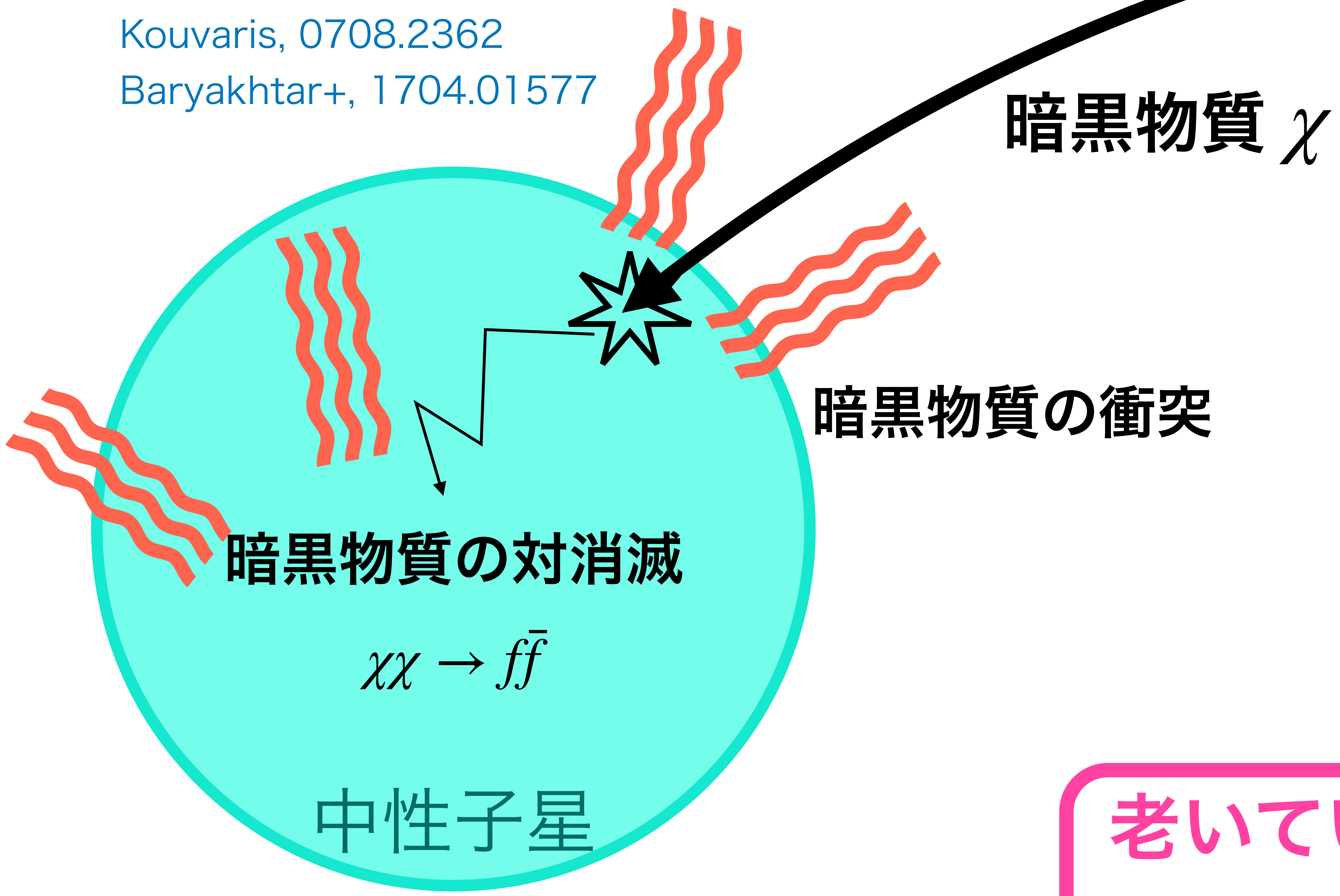
中性子星が暗黒物質で暖まる話

アイデアはとても簡単

Kouvaris, 0708.2362
Baryakhtar+, 1704.01577



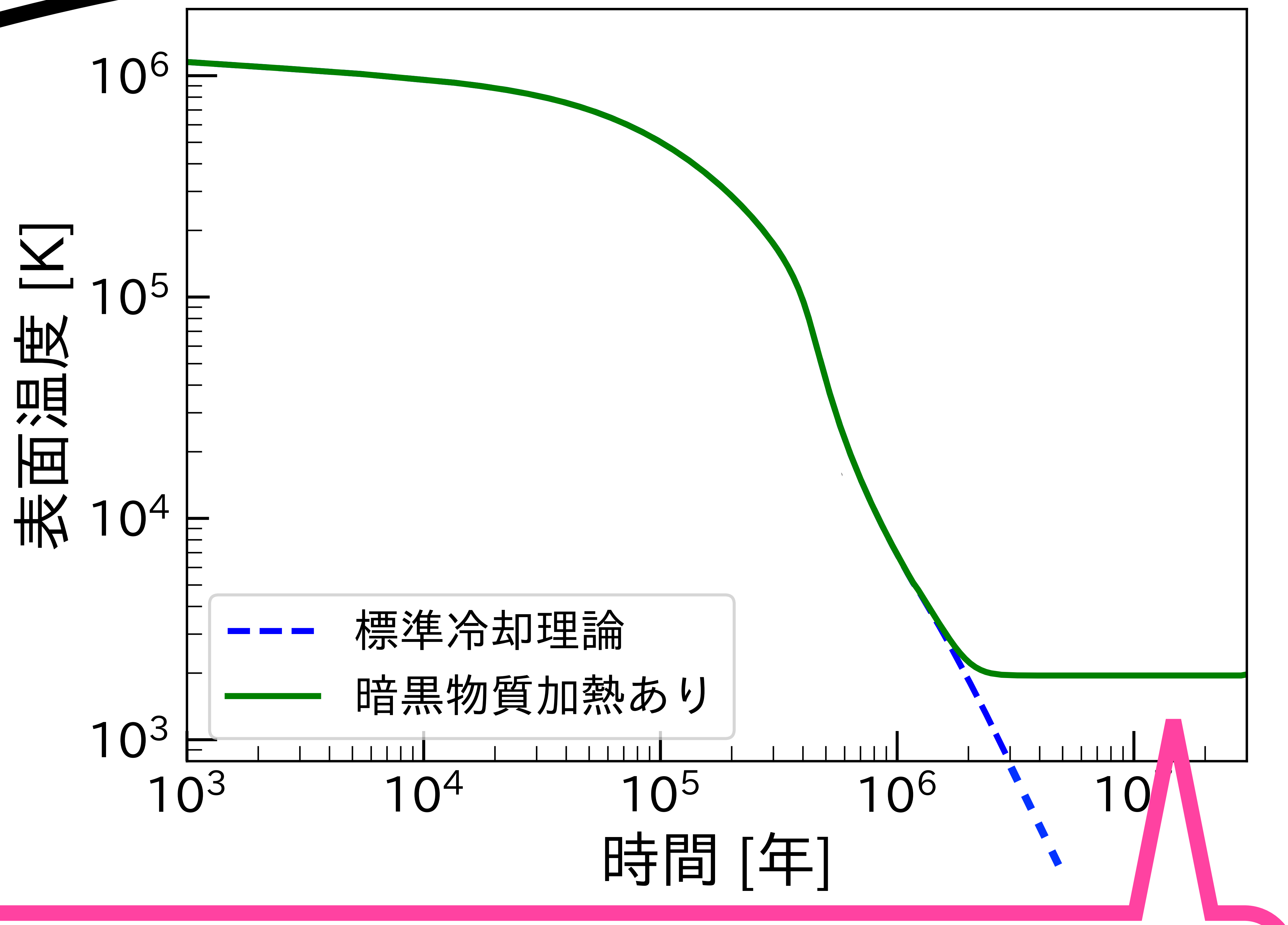
暗黒物質 χ

暗黒物質の衝突

暗黒物質の対消滅

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

中性子星



※ $f, \bar{f}$ は標準模型粒子（電子や陽子など）
すぐに中性子星に吸収されて熱になる

老いていて暖かい中性子星が見つかれば、
暗黒物質の間接証拠になるかも！

※ 今のところ観測の感度が足りていないが、将来可能性はあるかもしれない
M.Baryakhtar+, 1704.01577, G.N.Rachh+, 2403.07496

中性子星が暗黒物質で暖まる話

・・・と、ここまでは**先行研究**

ここから**自分の研究**：

😊 **嬉しい話**：直接検出実験と相補的！

Motoko Fujiwara，Natsumi Nagata，Maura E. Ramirez-Quezada，Jiaming Zheng　との共著
arXiv 2204.02413, 2204.02238.

😰 **困った話**：中性子星自身の内部加熱が邪魔をする…

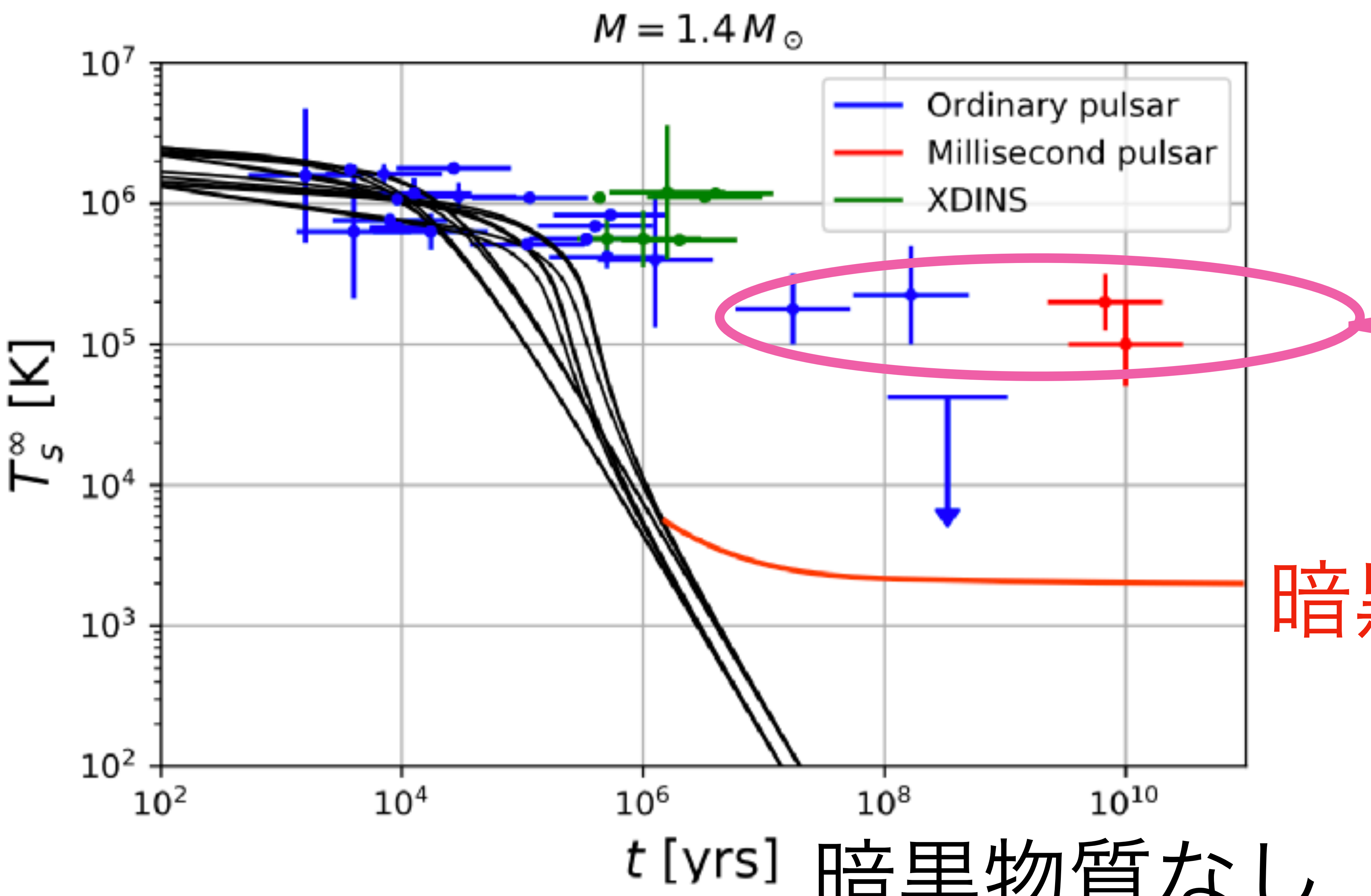
Motoko Fujiwara，Natsumi Nagata，Maura E. Ramirez-Quezada，Keisuke Yanagi との共著
arXiv 2309.02633, 2308.16066, 1905.02991, 1904.04667.

ここでは**困った話**を１つだけ紹介。

中性子星が暗黒物質で暖まる話

困った話

実は…老いていていてとても暖かい ($T \gg 2000K$) 中性子星がいくつか観測されている。



暗黒物質加熱でも標準冷却理論でも、
これらを説明できない。

暗黒物質あり

暗黒物質なし
(標準冷却理論)

Fig. thanks to K.Yanagi.

中性子星が暗黒物質で暖まる話

困った話

実は…老いていてとても暖かい ($T \gg 2000K$) 中性子星がいくつか観測されている。

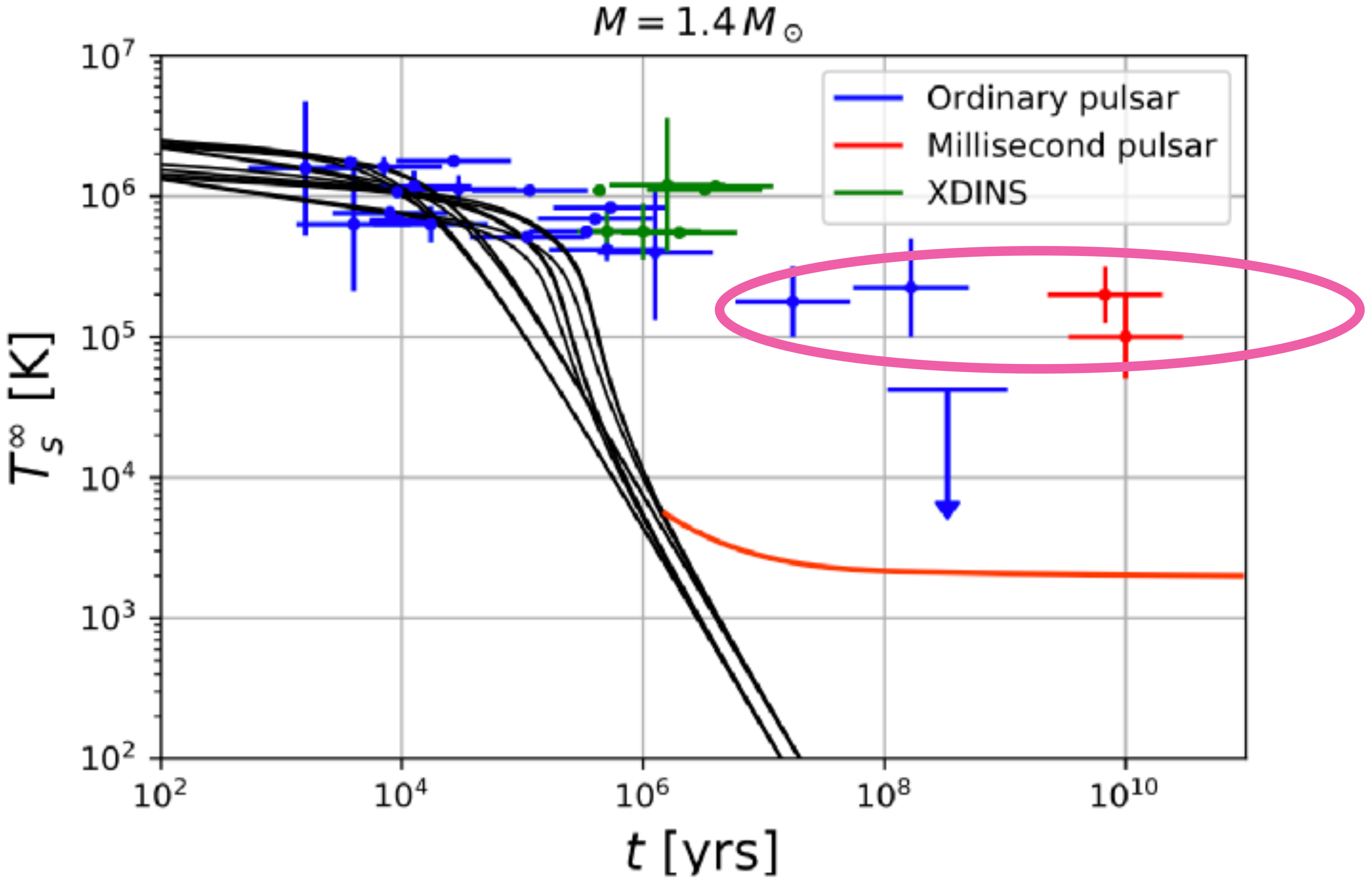


Fig. thanks to K.Yanagi.

さらに、これらの中性子星の温度を説明できる、中性子星自身による内部加熱のメカニズムがいくつか提案されている。

（例：rotochemical加熱、渦糸クリープ加熱）

そこで、これらの機構を再検討し、暗黒物質による中性子星加熱への影響を調べた。

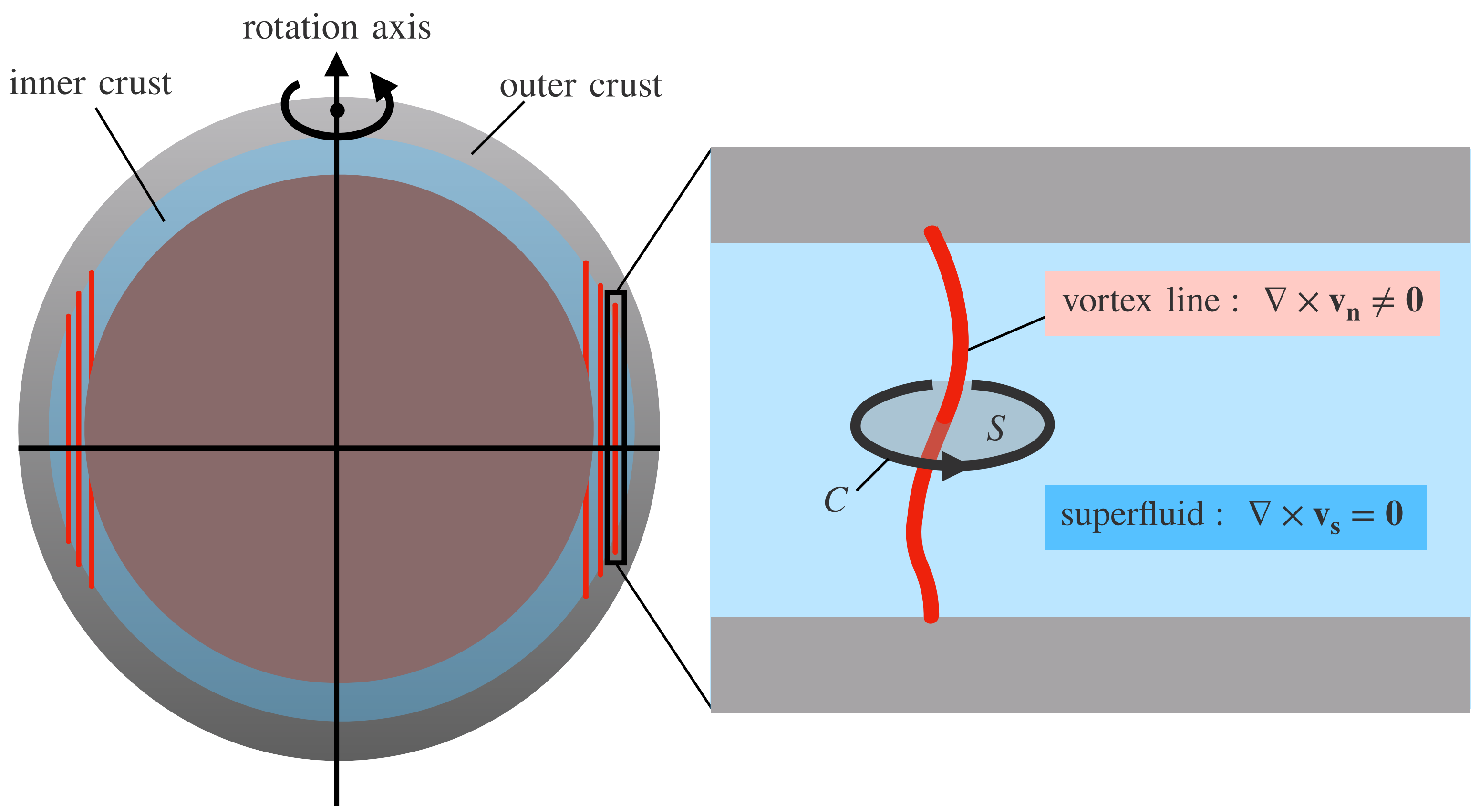
Motoko Fujiwara，Natsumi Nagata，Maura E. Ramirez-Quezada，Keisuke Yanagi との共著
arXiv 2309.02633, 2308.16066, 1905.02991, 1904.04667.

中性子星が暗黒物質で暖まる話

中性子星の渦糸加熱

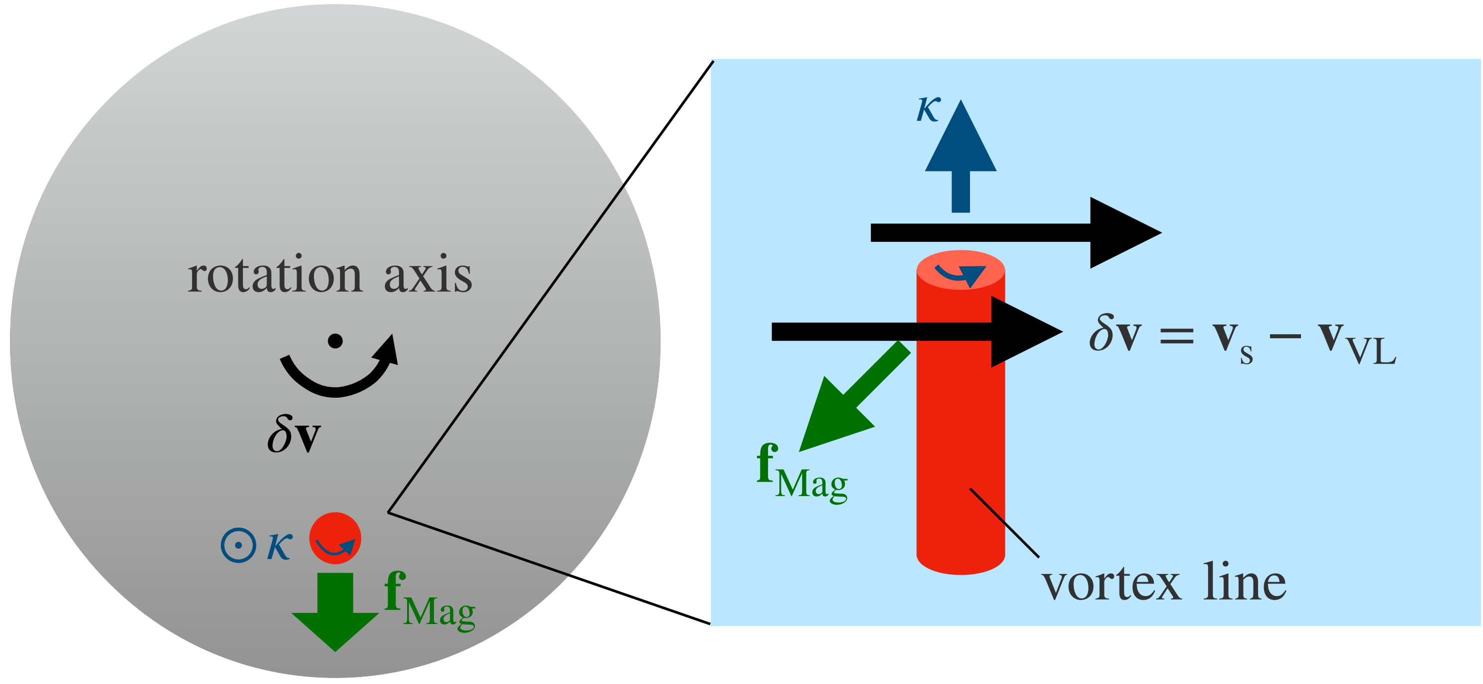
Alpar+, 1984, Shibazaki+, 1989

- クーパー対（超流動による）
- → 回転する中性子星の中に**渦糸**が形成される



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

- 外殻成分の自転の減速により、渦糸にマグナス力が働く
- → 渦糸が外側に移動し始める（**渦糸クリープ**)



- 超流動成分に蓄えられていた回転エネルギーが、熱に変わっていく(**渦糸クリープ加熱**)

$$L = J|\dot{\Omega}|$$

L …渦糸による加熱の強さ（luminosity)
J …普遍定数
$\dot{\Omega}$ …中性子星の角速度の時間変化

中性子星が暗黒物質で暖まる話

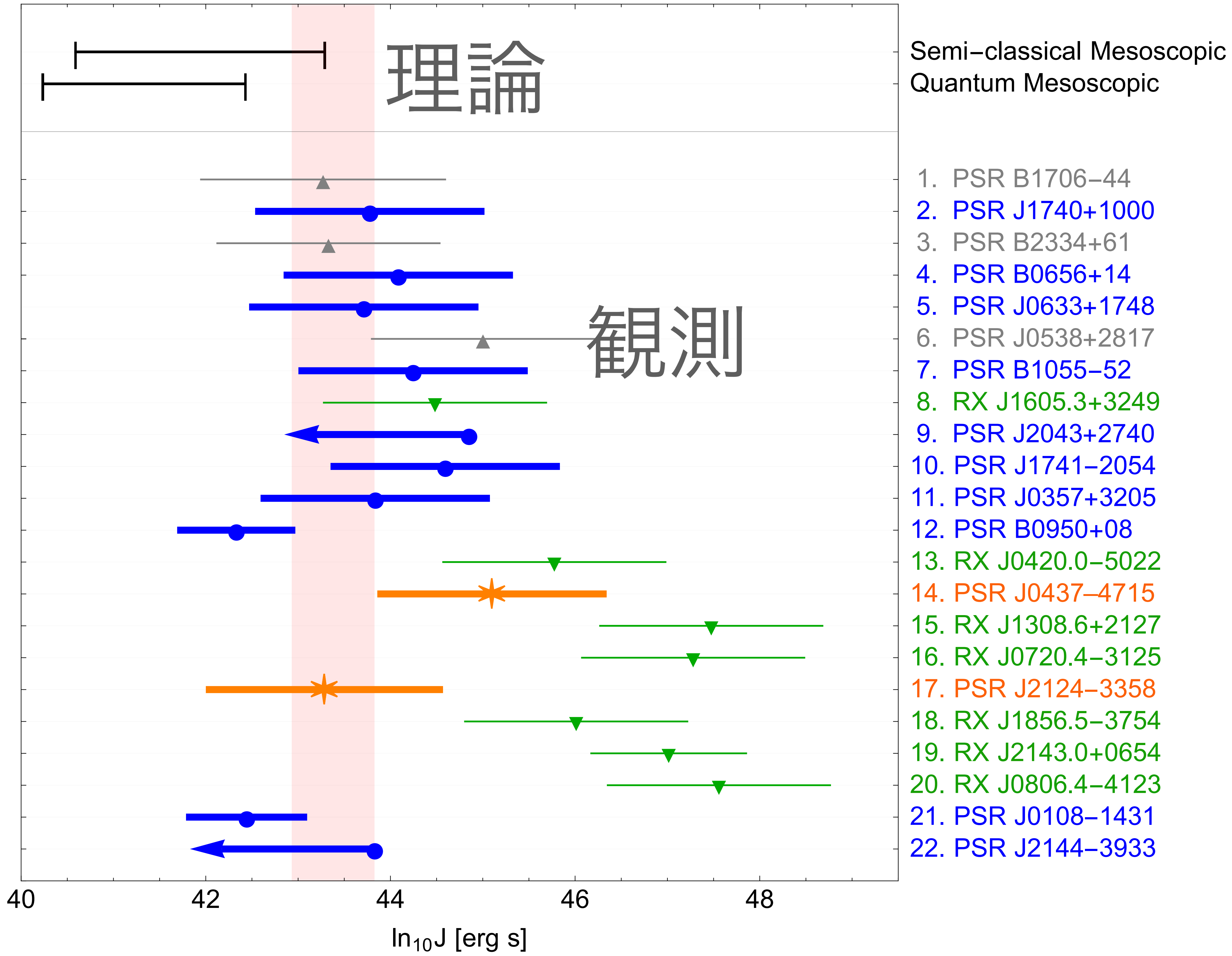
中性子星の渦糸加熱

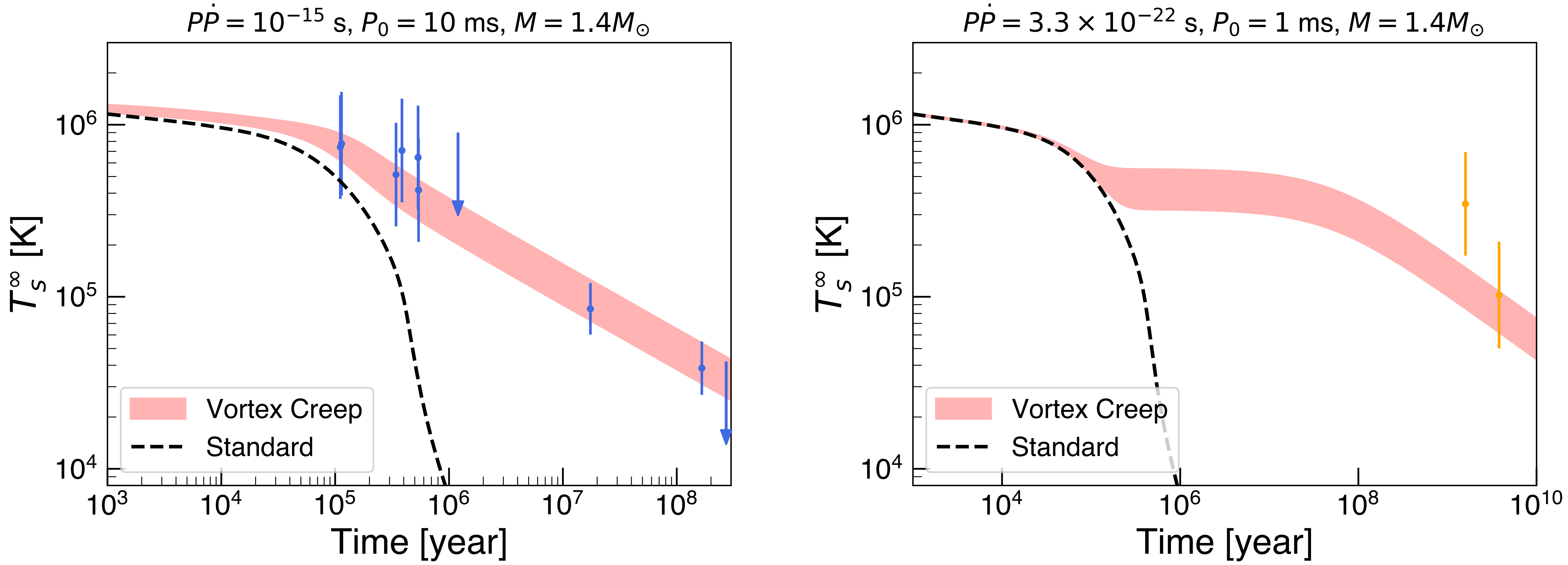
$$C\frac{dT}{dt} = -L_\nu - L_\gamma \quad +L_{\text{vortex creep heating}}$$

$$L = J|\dot{\Omega}| \begin{cases} L & \text{…渦糸による加熱の強さ（luminosity）} \\ J & \text{…普遍定数} \\ \dot{\Omega} & \text{…中性子星の角速度の時間変化} \end{cases}$$

普遍定数 $J \sim 10^{43} - 10^{44}\,\mathrm{erg \cdot s}$を使って、老いていて暖かい中性子星を説明できることがわかった。

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





中性子星が暗黒物質で暖まる話

中性子星の渦糸加熱

$$L = J|\dot{\Omega}| \quad \begin{cases} L & \text{…渦糸による加熱の強さ（luminosity)} \\ J & \text{…普遍定数} \\ \dot{\Omega} & \text{…中性子星の角速度の時間変化} \end{cases}$$

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

普遍定数 $J \sim 10^{43} - 10^{44} \text{erg} \cdot \text{s}$を使って、老いていて暖かい中性子星を説明できることがわかった。

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

中性子星の渦糸加熱 + 暗黒物質加熱

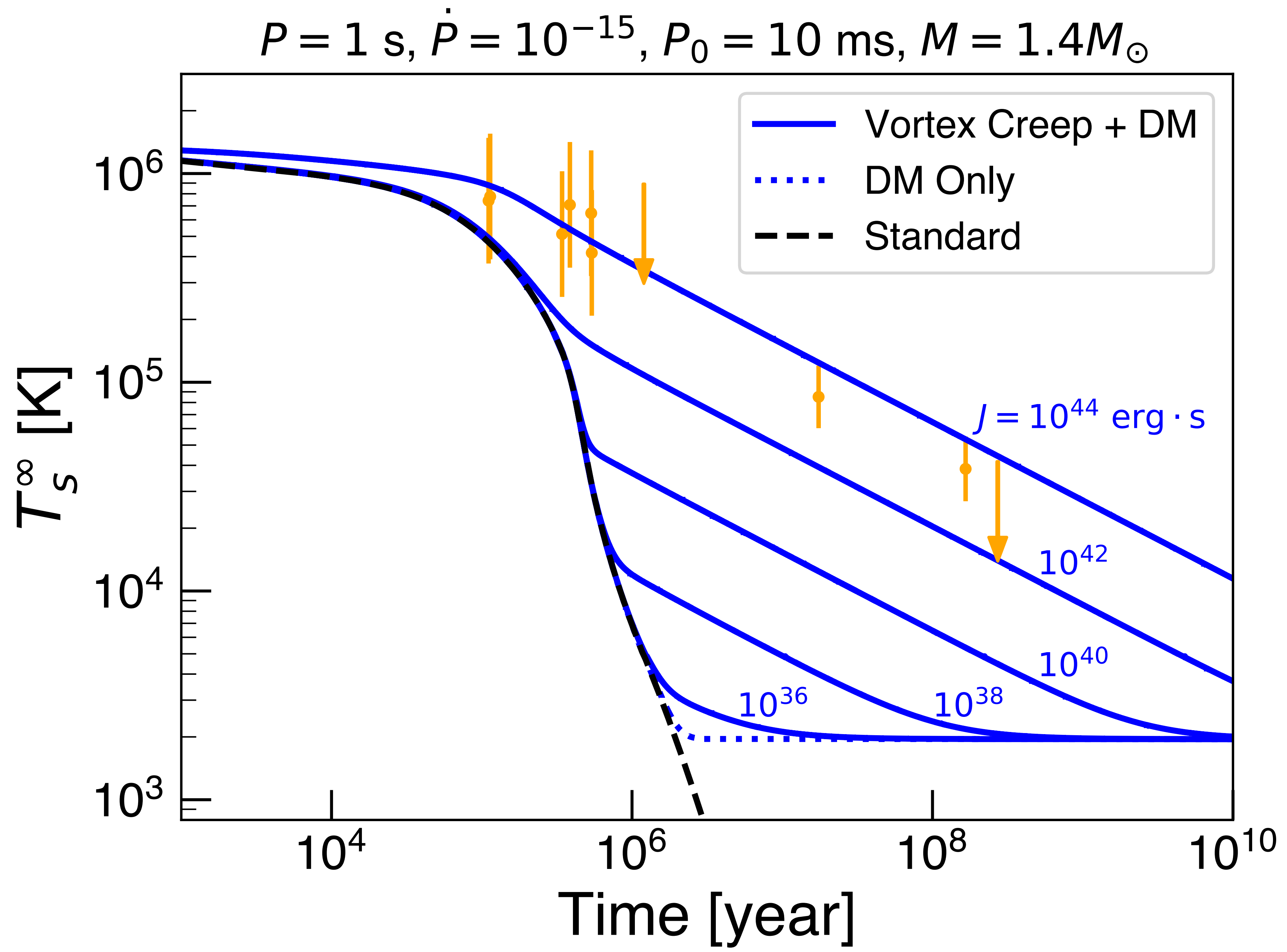
Fujiwara, KH, N. Nagata, Ramirez-Quezada [2309.02633]

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

暗黒物質による加熱の効果は $J \lesssim 10^{38} \ \text{erg} \cdot \text{s}$

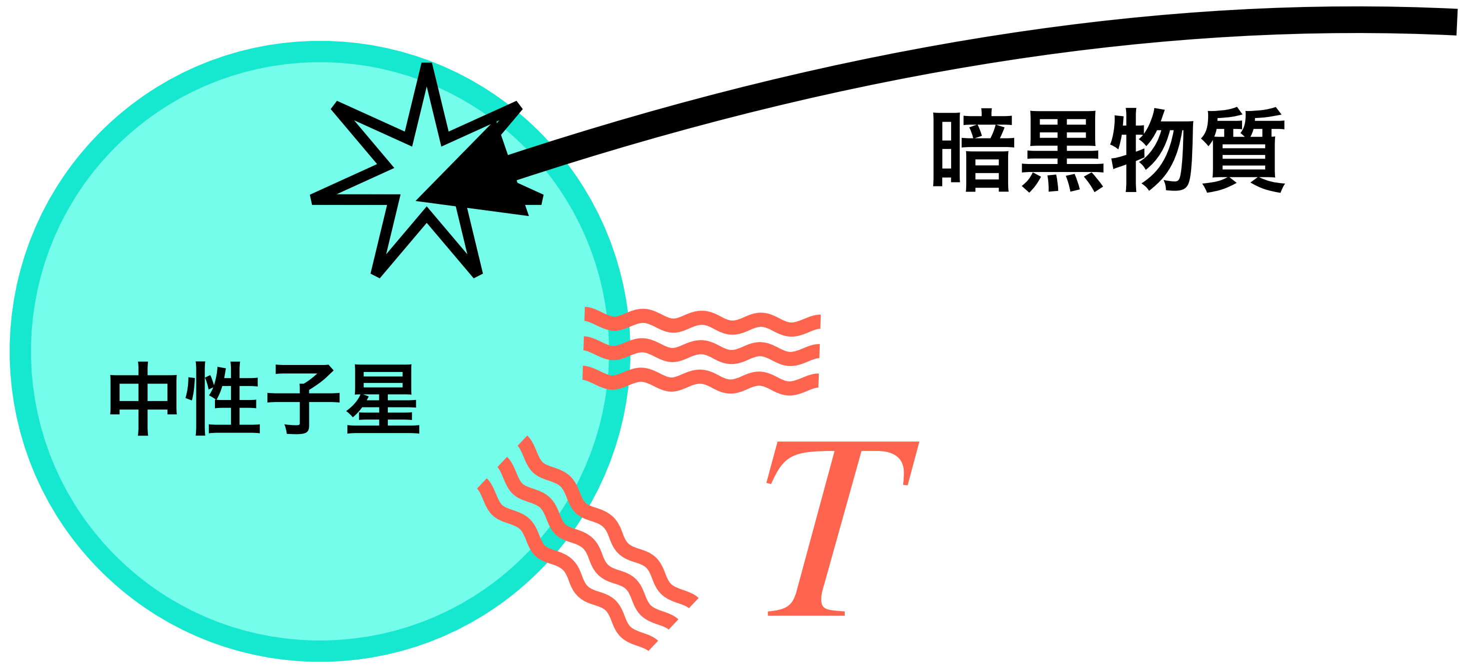
でない限り、渦糸クリープ加熱に埋もれてしまう。

これは、中性子星の温度観測による暗黒物質探索にとっては
深刻な問題かもしれない、、、。👉 今後のさらなる検証が重要。



もくじ

1. 前半 30+10分：物理学科以外の学部生向け
    - **素粒子の標準模型、標準模型を超える物理**
    - **暗黒物質**
    - **中性子星**
    - **中性子星が暗黒物質で暖まる話**
    - **質疑応答**
2. 後半 30+10分：大学院生以上向け



質疑応答用 Slido. QRコード👉
または適当なデバイスで「Slido」検索
→ code #1919184 で参加

もくじ

2. 後半 30+10分：大学院生以上向け
   - **以下のどれか**
     (a) **中性子星が暗黒物質で暖まる話、の続き** **(スライド英語ですゴメンなさい)**
     (b) **中性子星がアクシオンで冷える話**
     (c) **超新星からアクシオンがやってくる話** **(スライド英語ですゴメンなさい)**

投票用 Slido. QRコード👉
または適当なデバイスで「Slido」検索
→ code #1919184 で参加

(a) 中性子星が暗黒物質で暖まる話、の続き

Based on the works with

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

参考文献

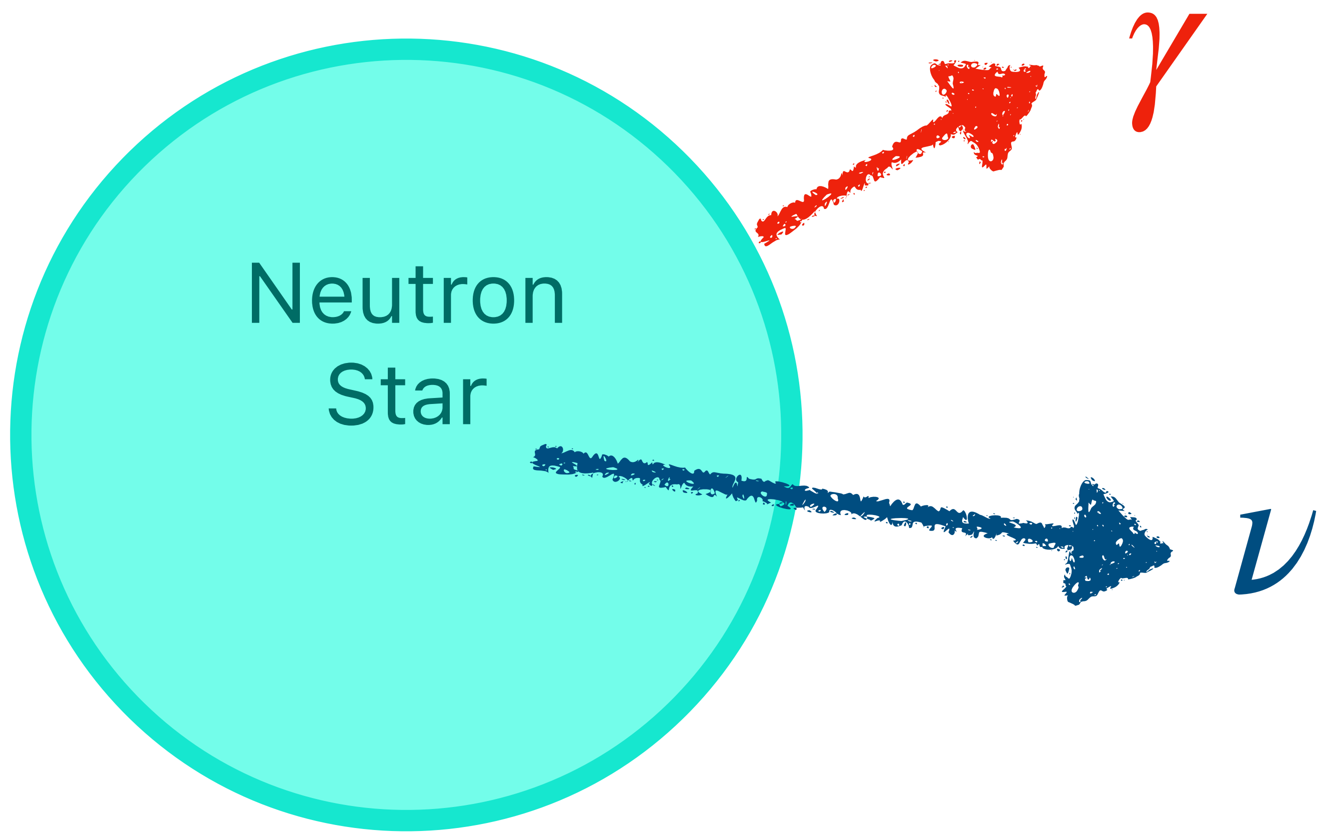
NS heating by DM: arXiv 2309.02633, 2308.16066, 2204.02413, 2204.02238, 1905.02991, 1904.04667.

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.

$C = \dfrac{dE_{\mathrm{thermal}}}{dT}$ (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).

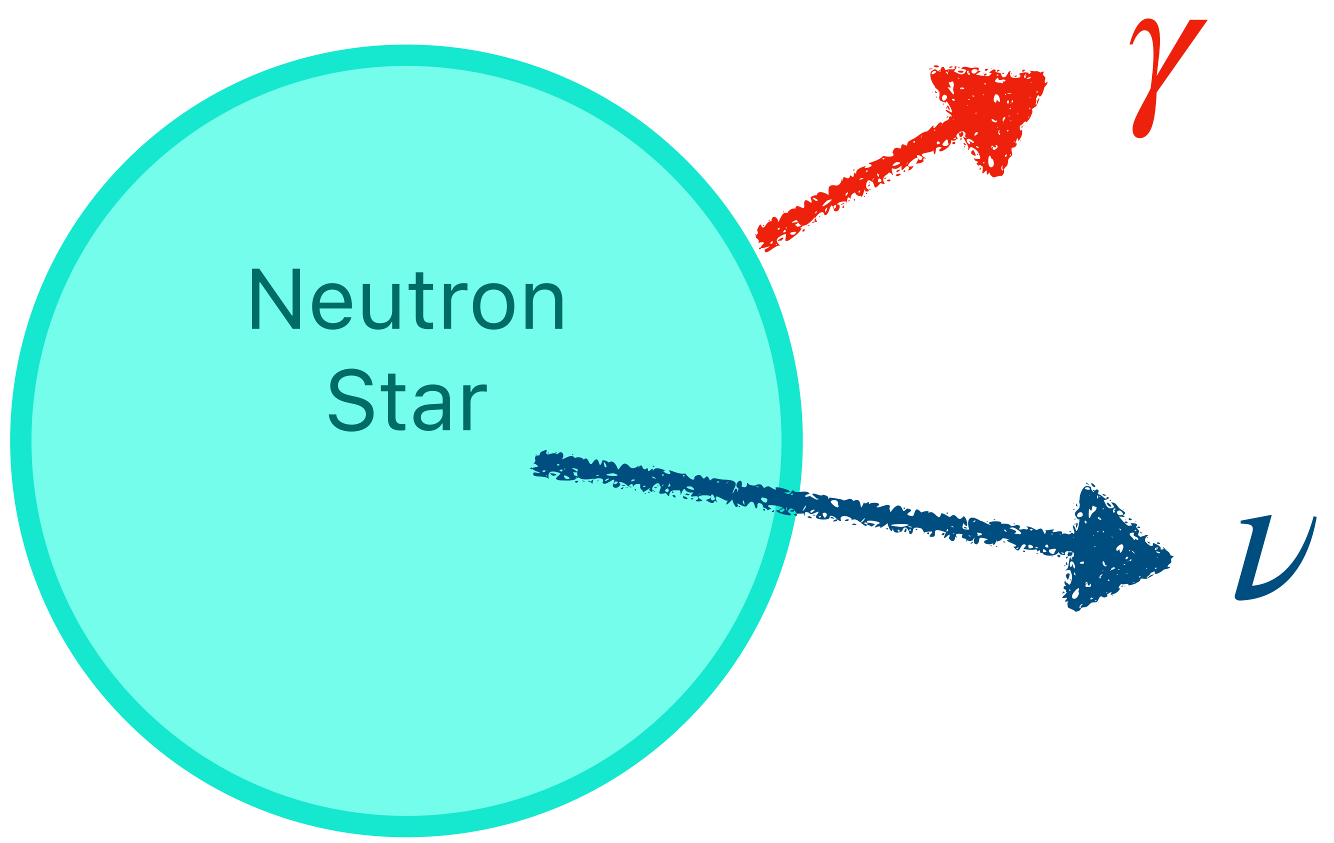
NS Standard Cooling Theory

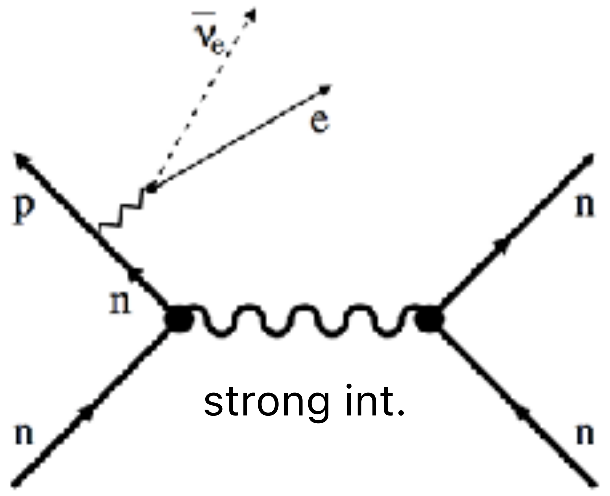
For reviews, e.g., D.G.Yakovlev+, astro-ph/0402143,
D.Page+, astro-ph/0508056, 1302.6626

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

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

Neutrino emission is the dominant process.

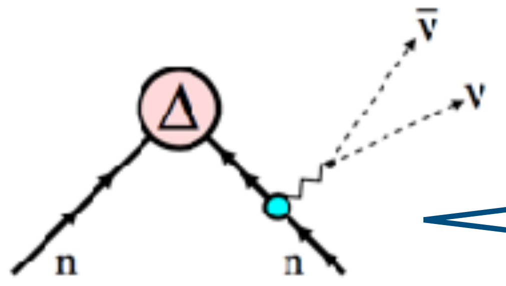




Modified Urca (& Bremsstrahlung)

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

Dominant process for $T > T_c$.



PBF (Cooper-pair breaking and formation)

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

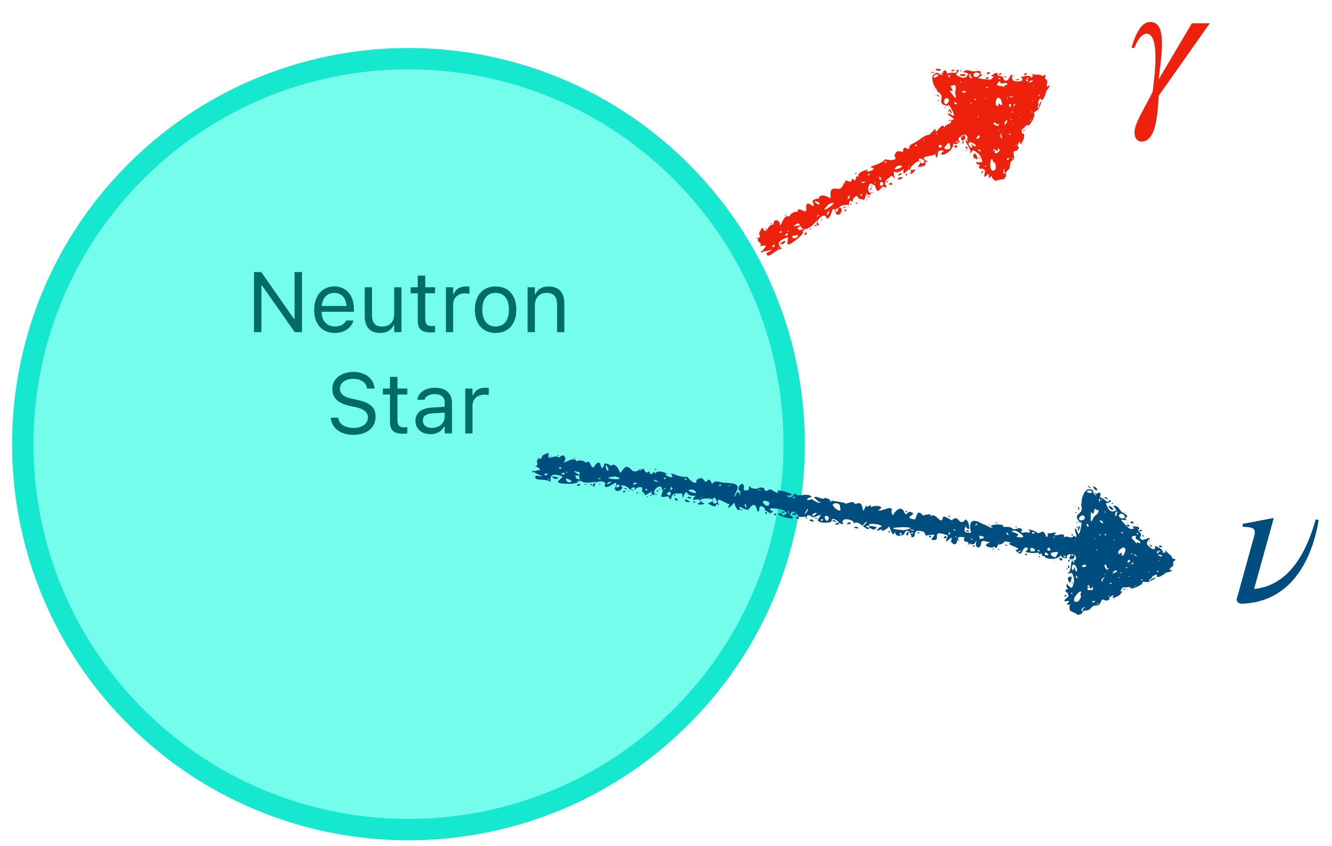
($\tilde{N}$: quasi-paticle, $[\tilde{N}\tilde{N}]$: Cooper-pair)

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

NS Standard Cooling Theory

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

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



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

Photon emission is the dominant process.

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

NS Standard Cooling Theory

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

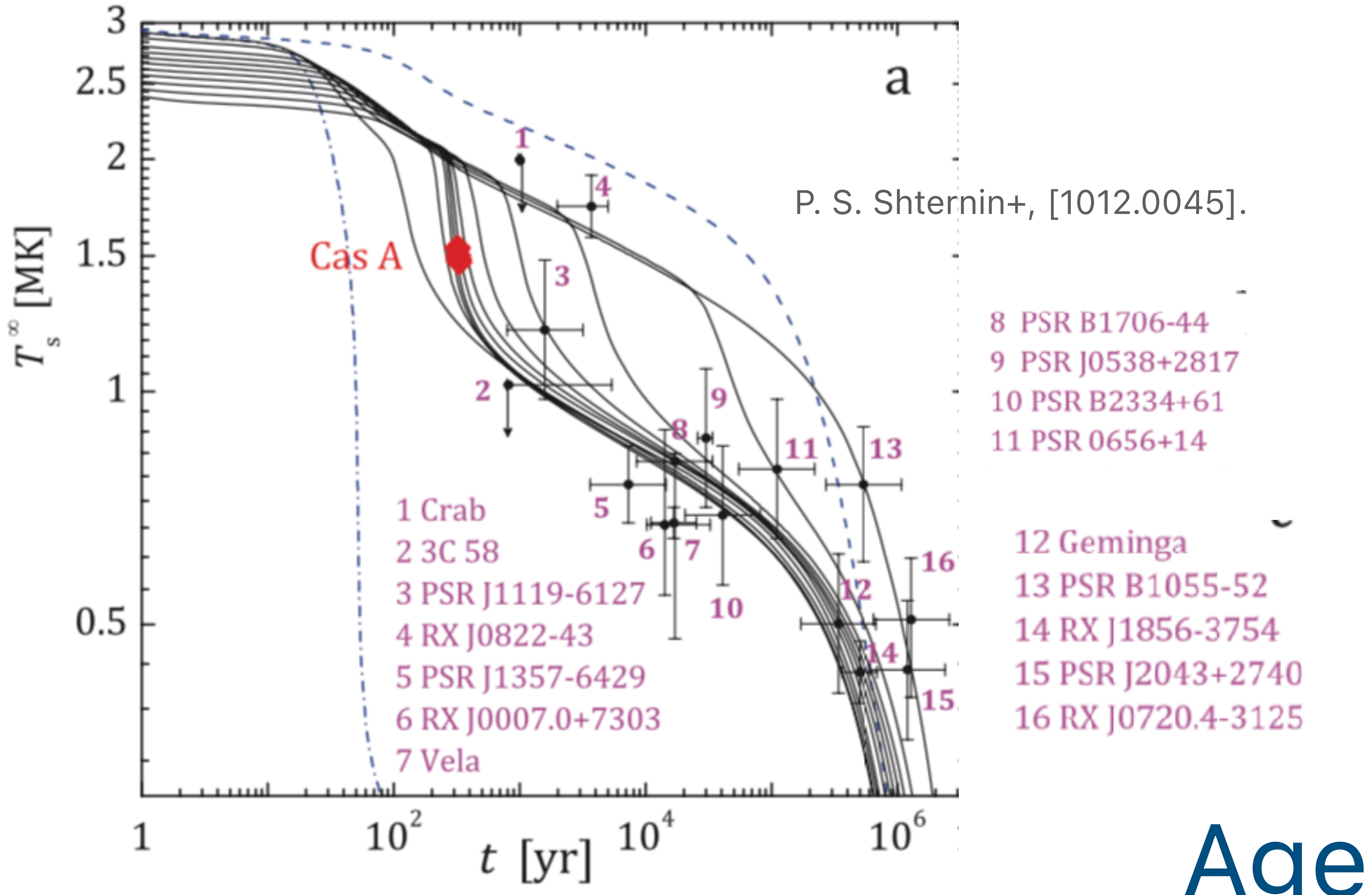
$$C\frac{dT}{dt} = -L_\nu - L_\gamma$$

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

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

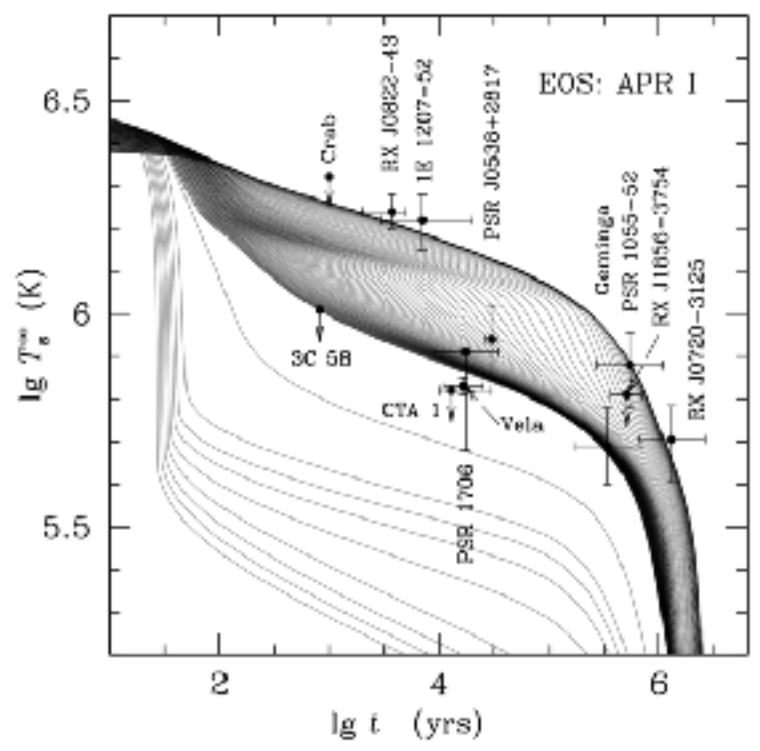
👉 **More on this later.**

Surface Temperature

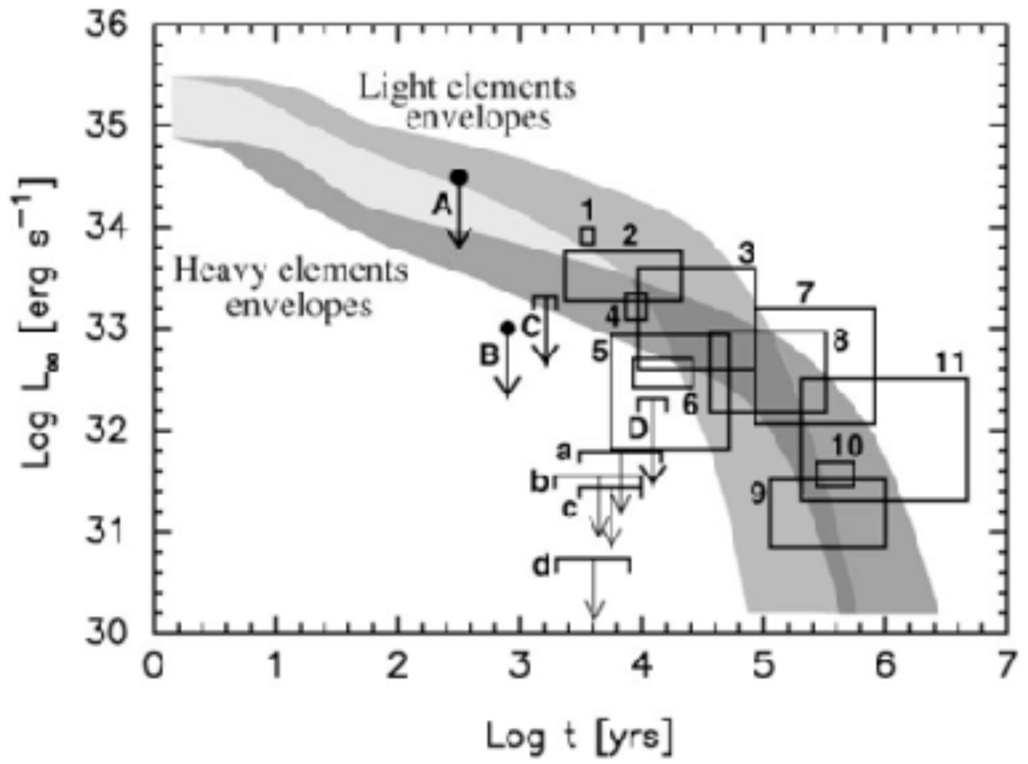


P. S. Shternin+, [1012.0045].

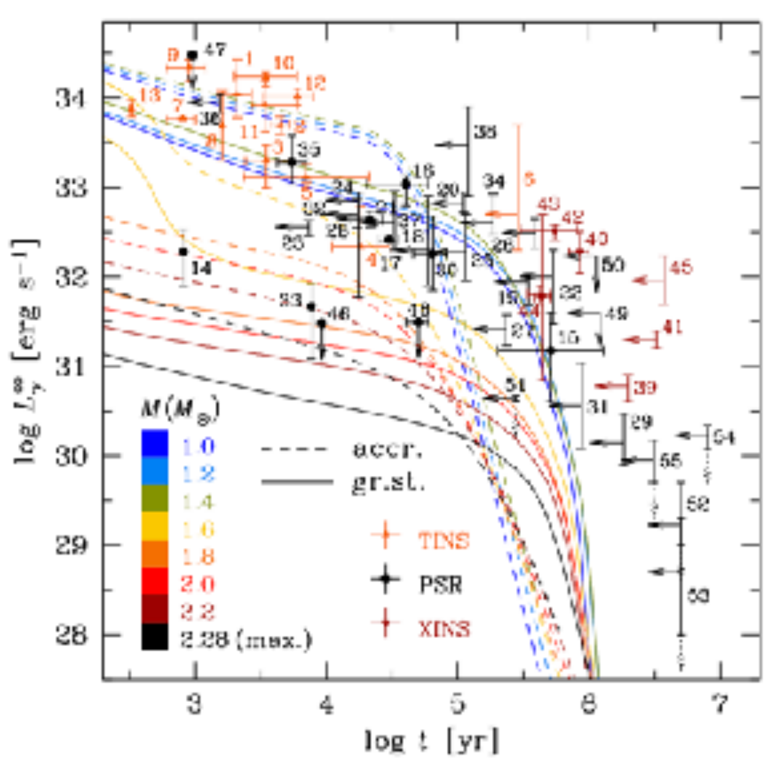
M. E. Gusakov, A. D. Kaminker, D. G. Yakovlev, O. Y. Gnedin
Mon.Not.Roy.Astron.Soc. **363** (2005) 555-562



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



A. Y. Potekhin+,2006.15004

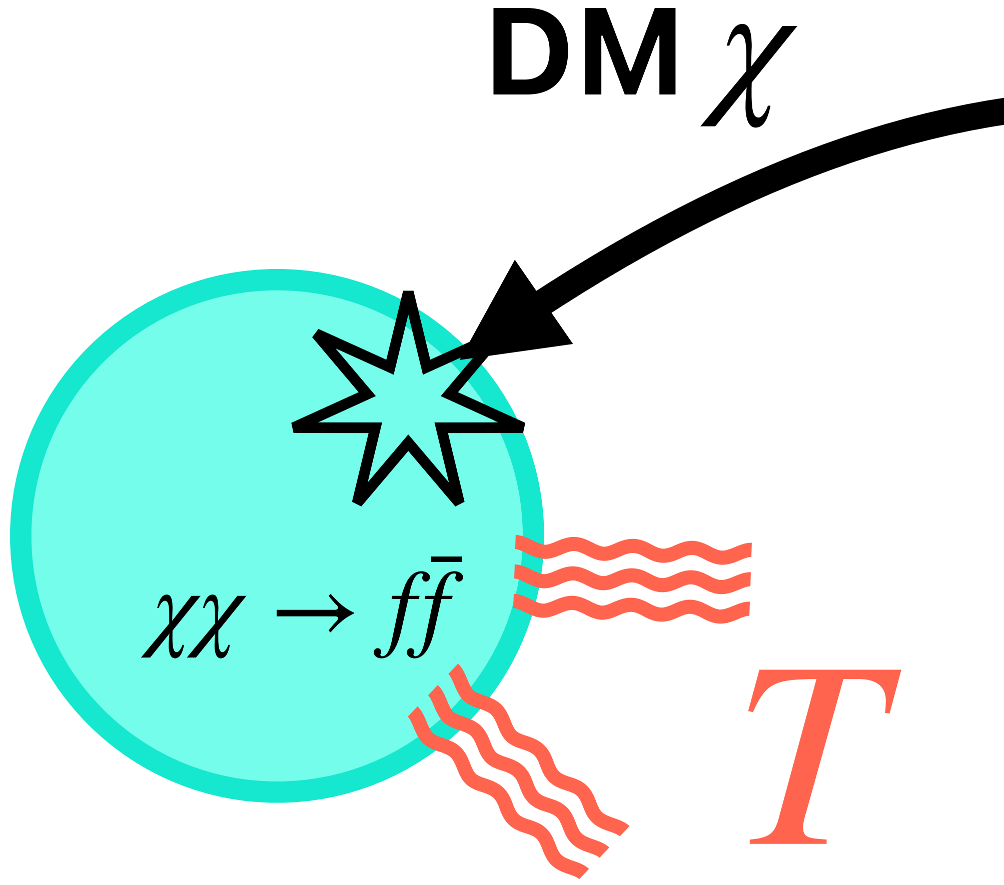


Ages of Neutron Stars

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

Plan

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



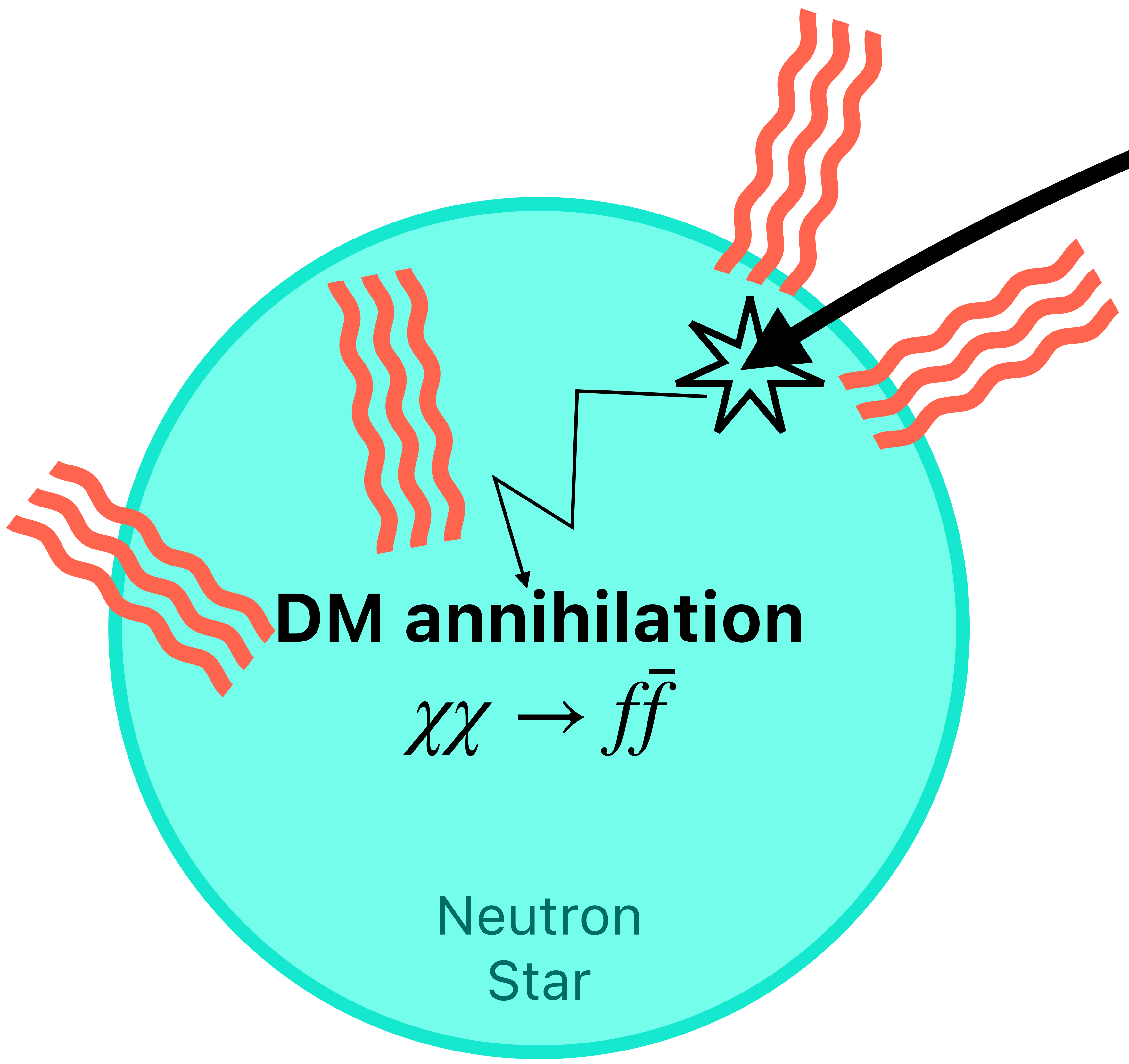
Dark Matter Heating of NS

Basic Idea

Kouvaris, 0708.2362
Baryakhtar+, 1704.01577

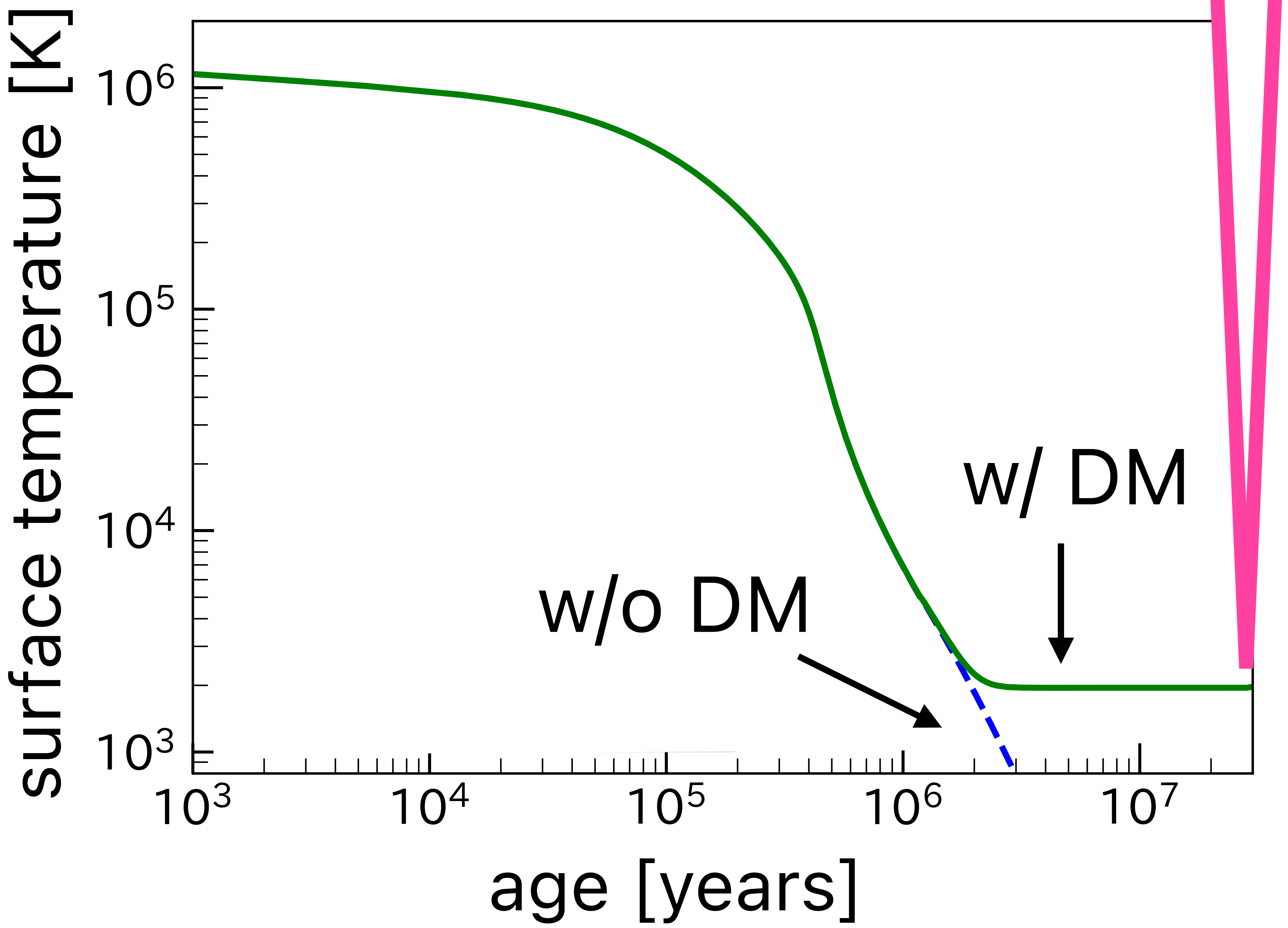
$$C\frac{dT}{dt} = \underbrace{-L_\nu}_{\ll L_\gamma} \underbrace{-L_\gamma + L_{\mathrm{DM\ heating}}}_{\simeq 0}$$

DM χ



DM annihilation

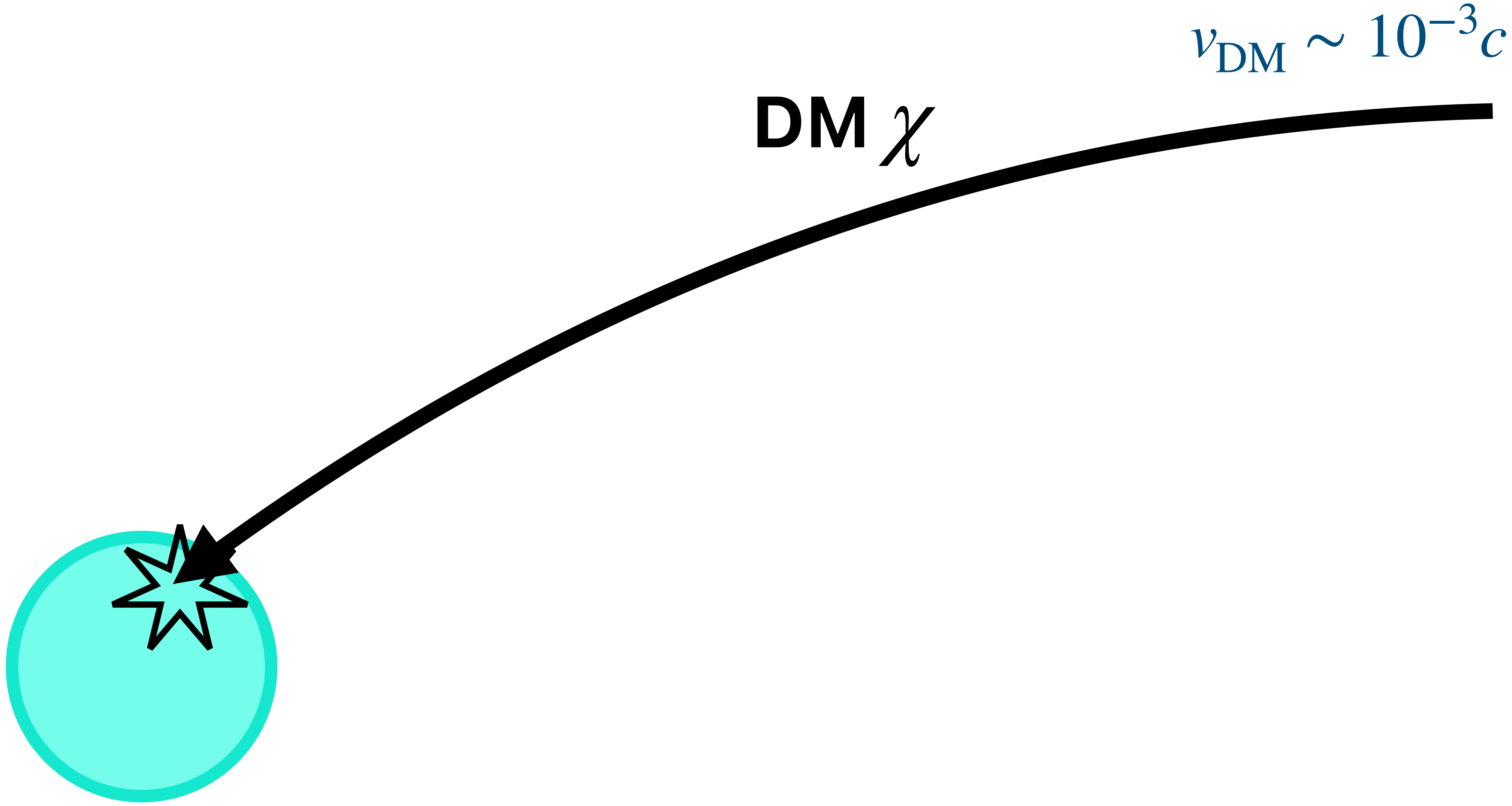
$\chi\chi \to f\bar{f}$



Old and warm NS = DM signal ?!

Dark Matter Heating of NS

Back-of-envelope estimates



Dark Matter Heating of NS

Back-of-envelope estimates

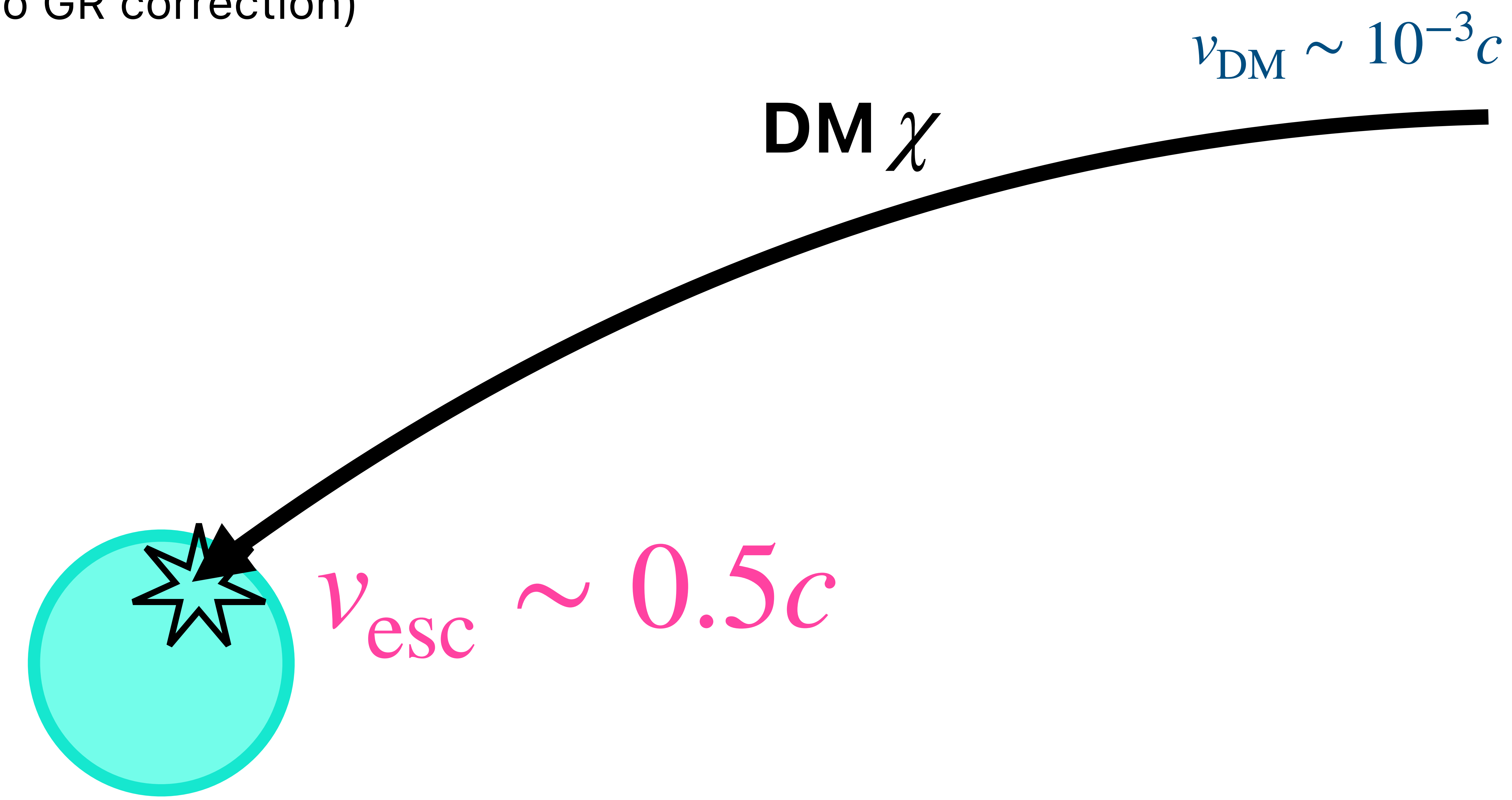
(1) DM velocity at the surface: $v_{\rm esc} \sim 0.5c$ (up to GR correction)

- From the energy conservation,

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

  up to O(1) GR correction.

  → almost relativistic speed!

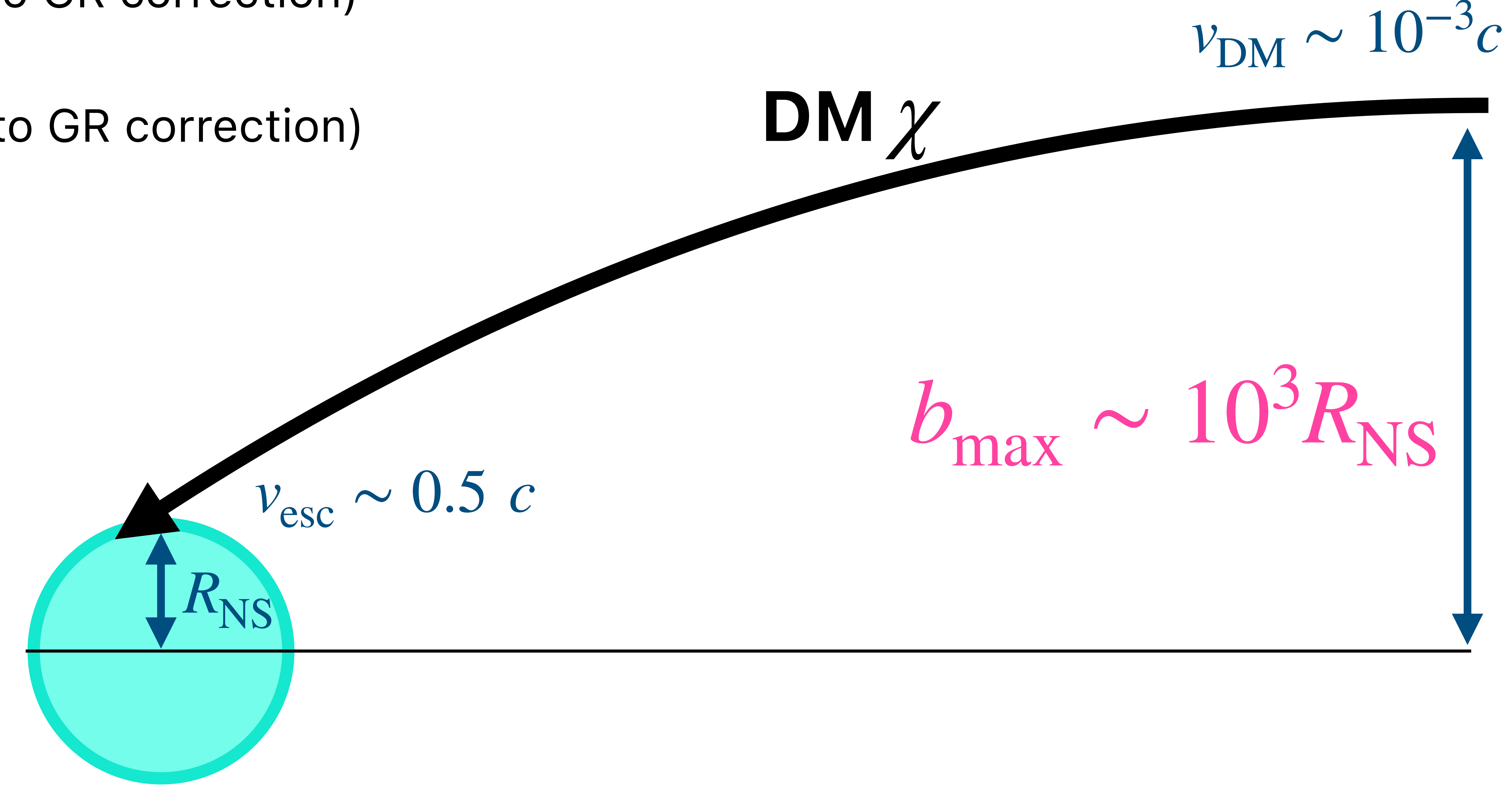


Dark Matter Heating of NS

Back-of-envelope estimates

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

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



- From the angular momentum conservation,

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

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

up to O(1) GR correction.

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

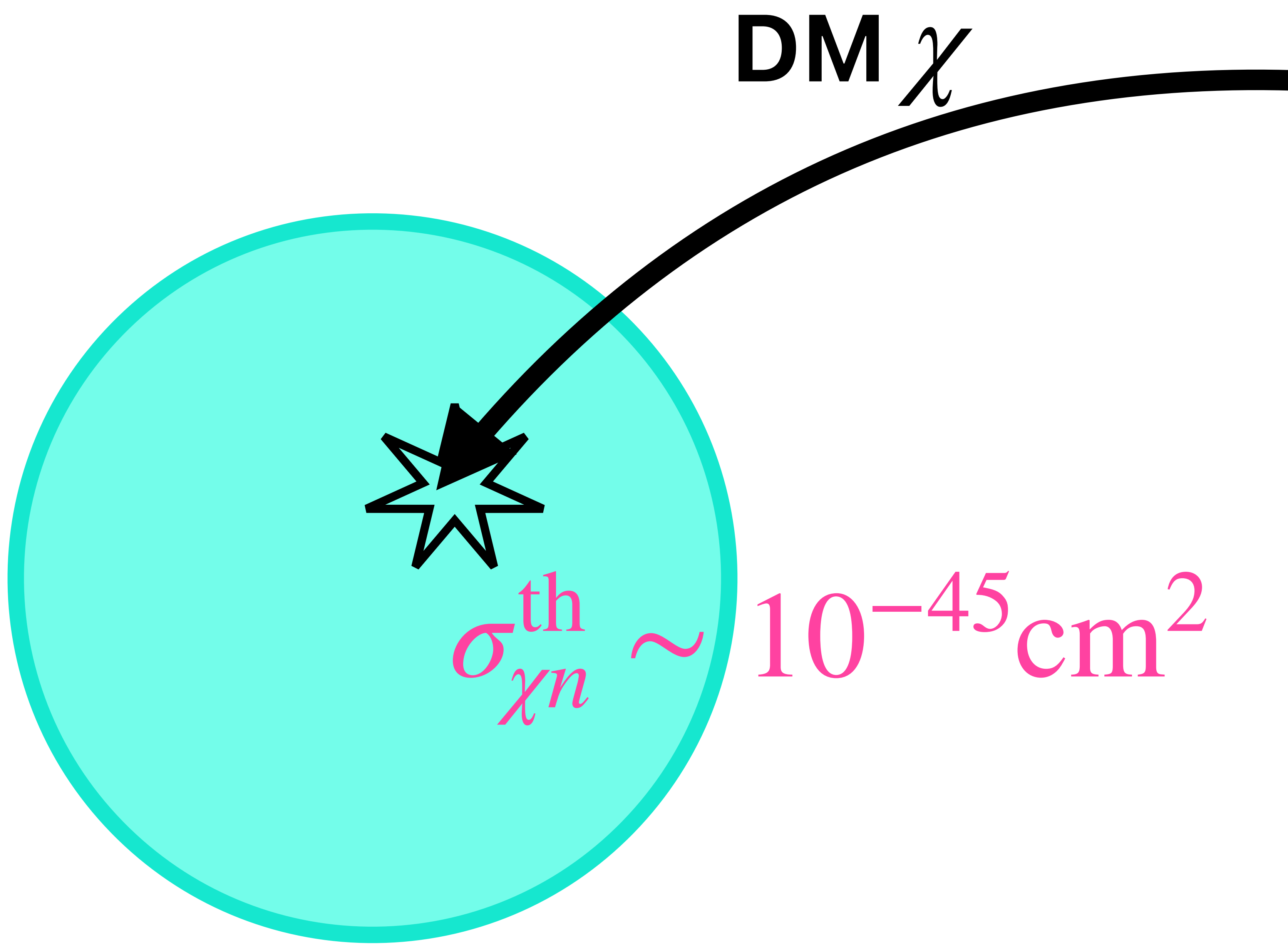
Dark Matter Heating of NS

Back-of-envelope estimates

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

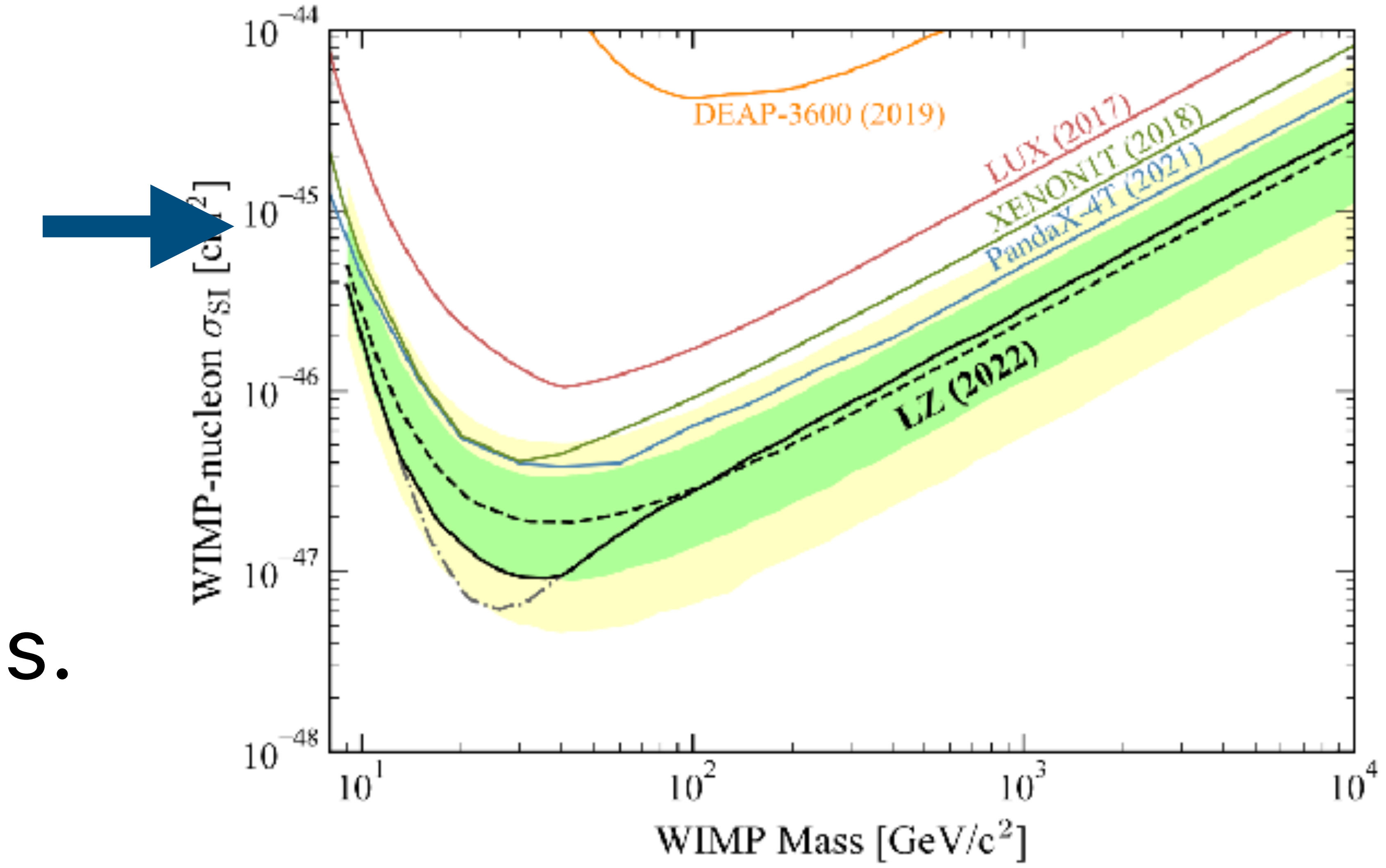
(2) Impact factor: $b_{\max} \sim \dfrac{v_{\mathrm{esc}}}{v_{\mathrm{DM}}} R_{\mathrm{NS}} \sim 10^3\ R_{\mathrm{NS}}$ (up to GR correction)

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



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

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



Dark Matter Heating of NS

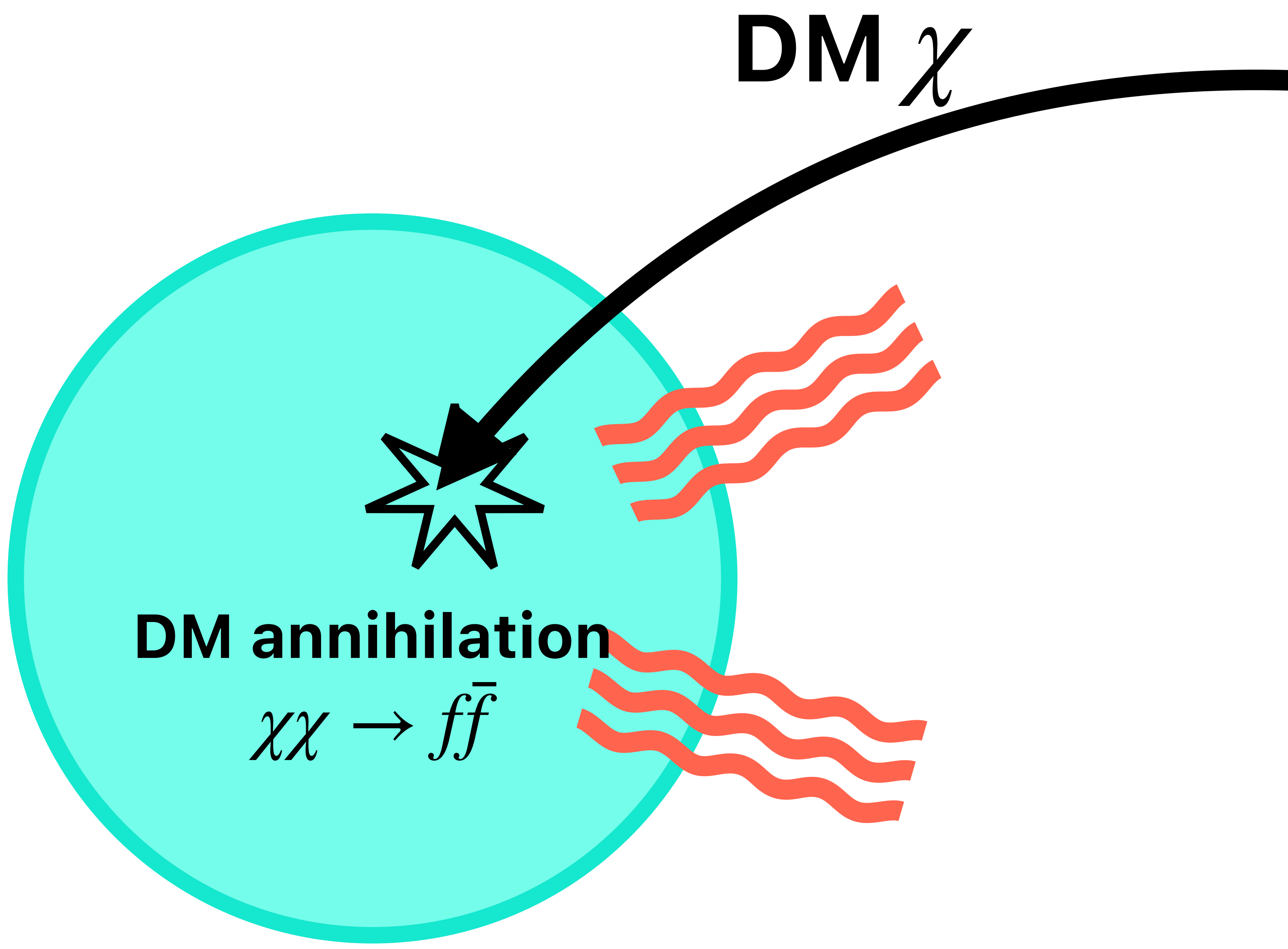
Back-of-envelope estimates

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

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

(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: $T \sim \text{a few } 1000\ {\rm K}$



$T \sim \text{(a few) } 1000\ {\rm K}$

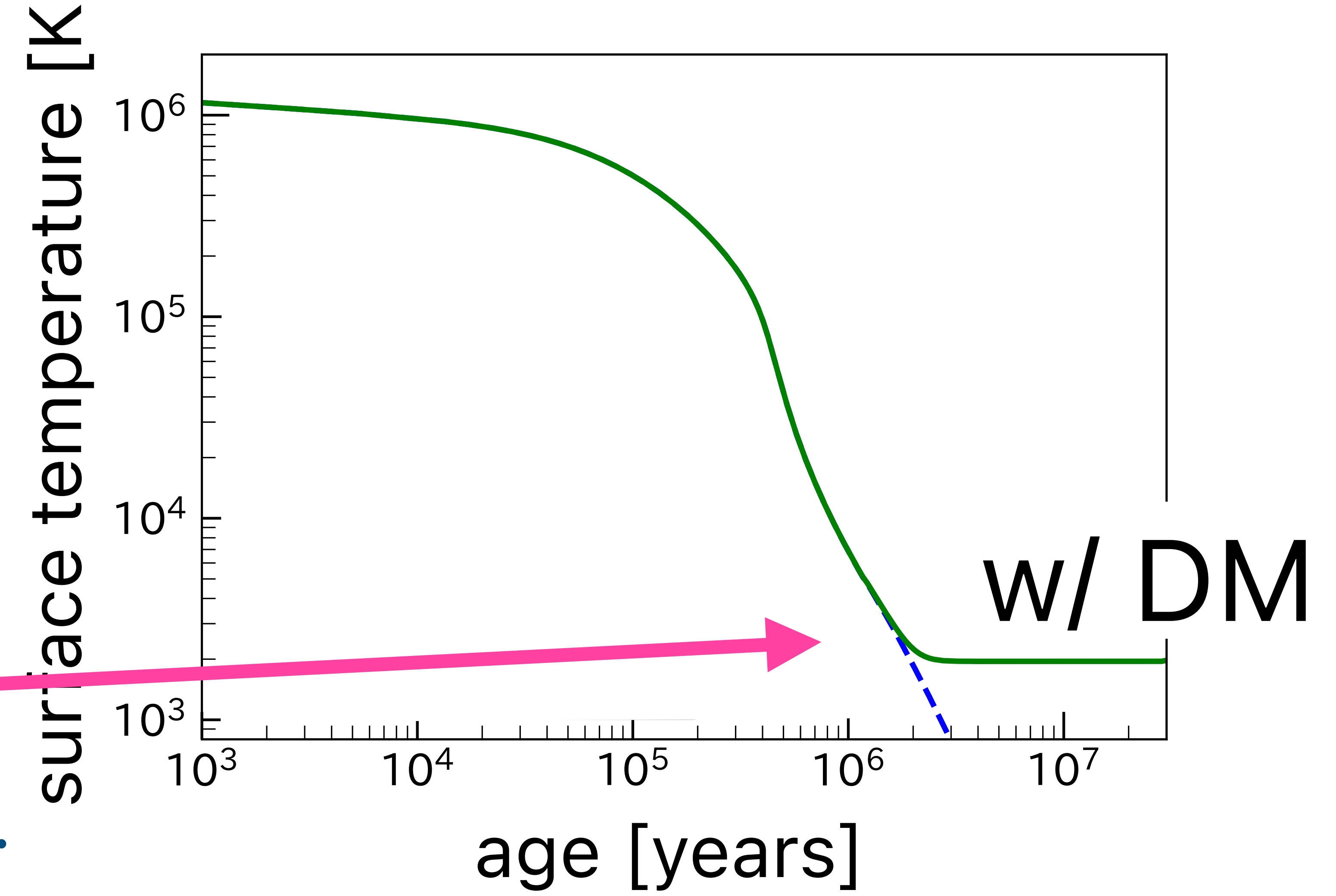
- The energy injection per time is estimated as

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

… independent of the DM mass!

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

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



Dark Matter Heating of NS

Back-of-envelope estimates

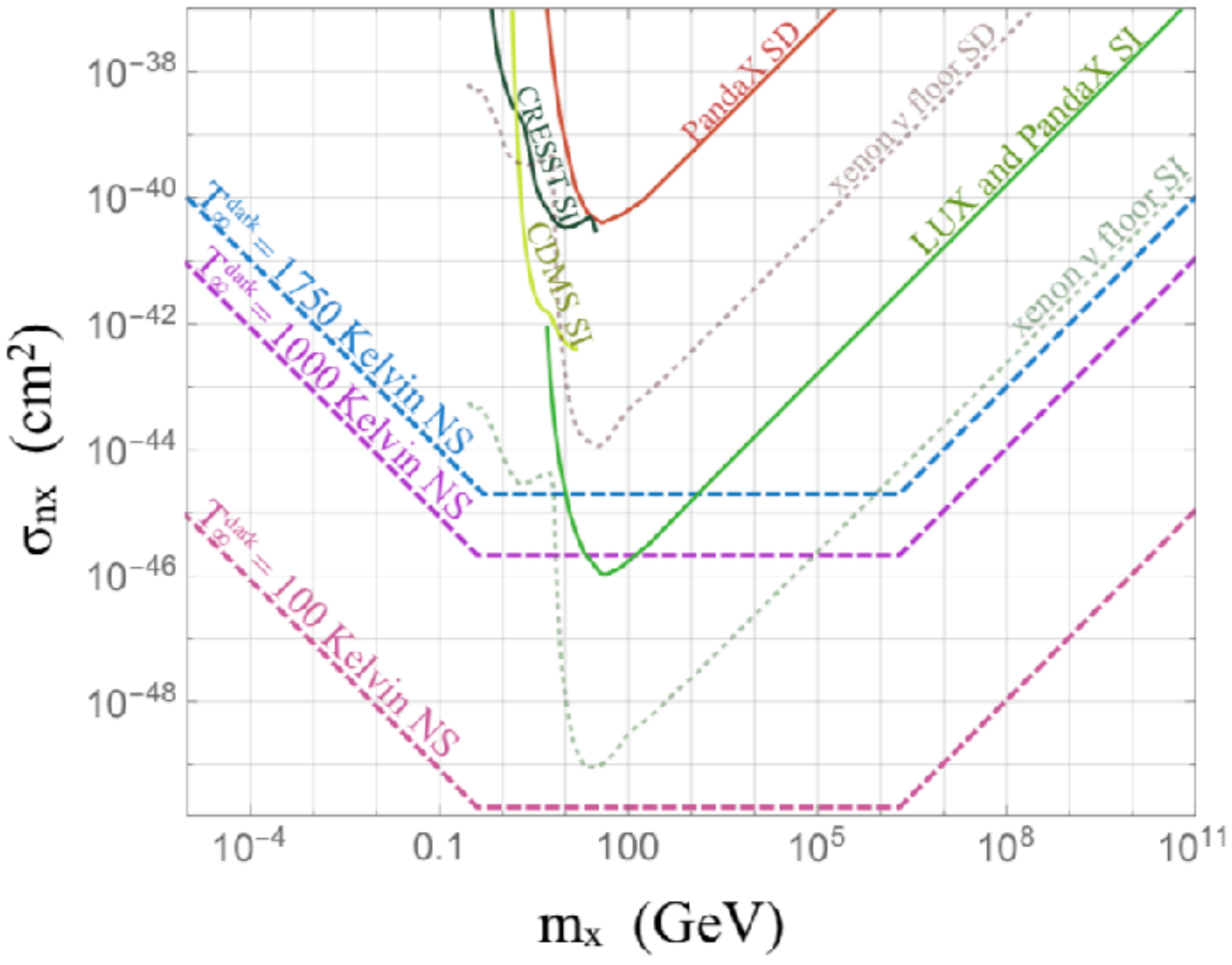
(1) DM velocity at the surface: $v_{\mathrm{esc}} \sim 0.5c$ (up to GR correction)

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

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

(4) Resultant surface temperature: $T \sim \text{a few } 1000\ \mathrm{K}$

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



- 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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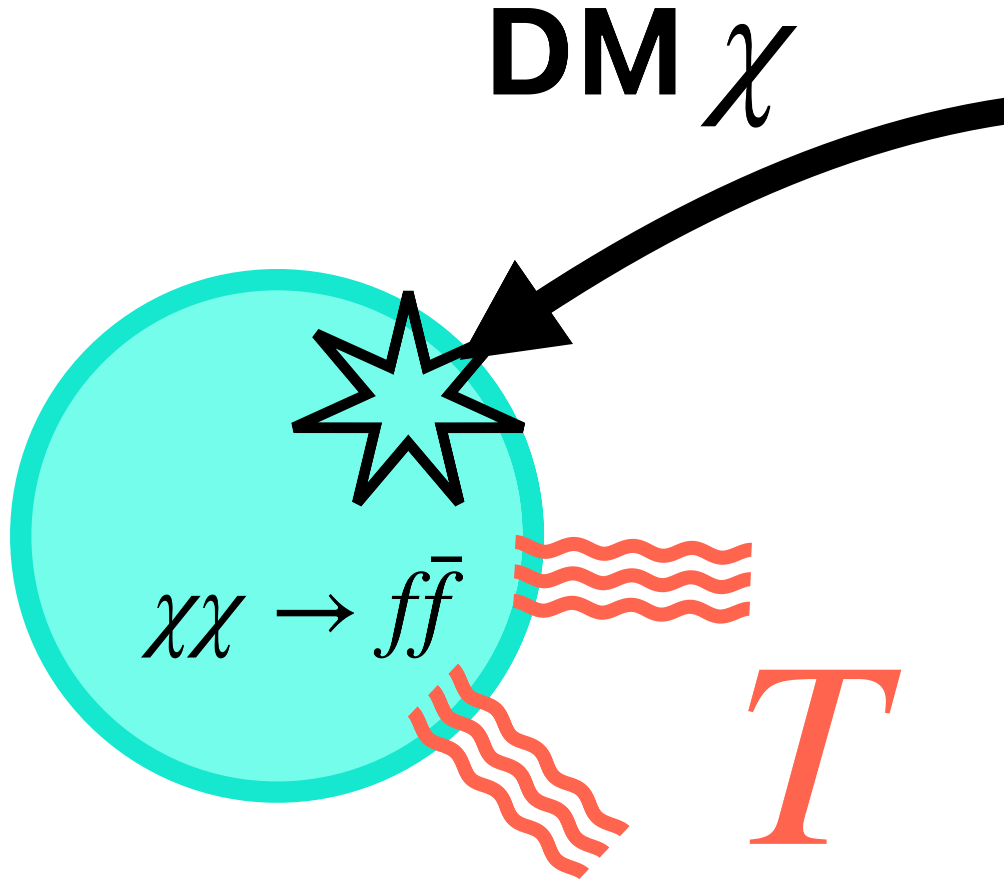


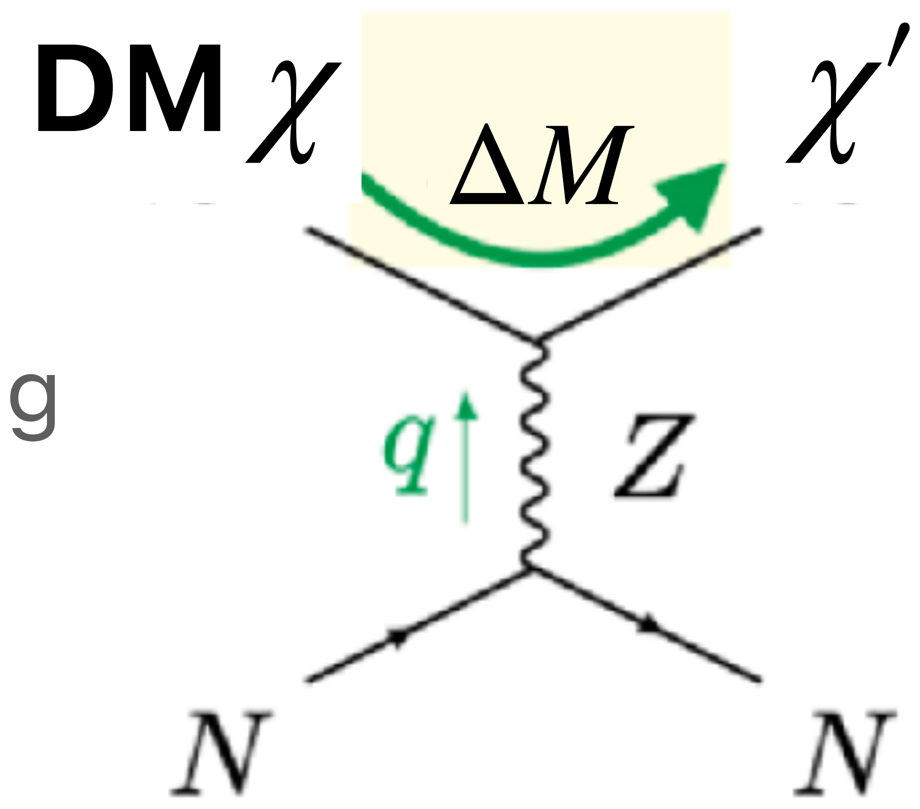
Dark Matter Heating of NS

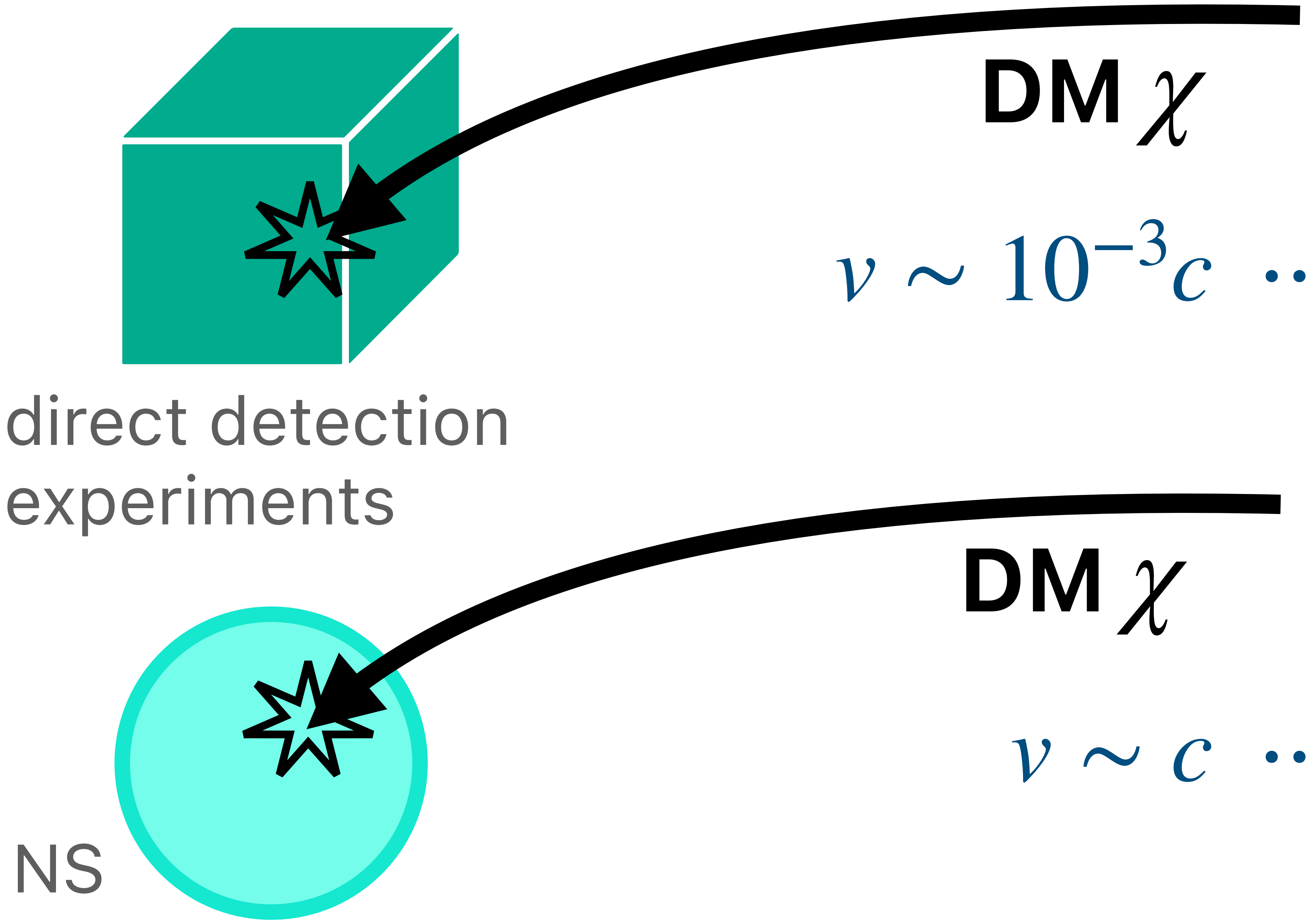
Advantages

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

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

inelastic scattering





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

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

NS is much more sensitive to inelastic scattering.

Dark Matter Heating of NS

Advantages

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

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

example: Electroweak multiplet DM

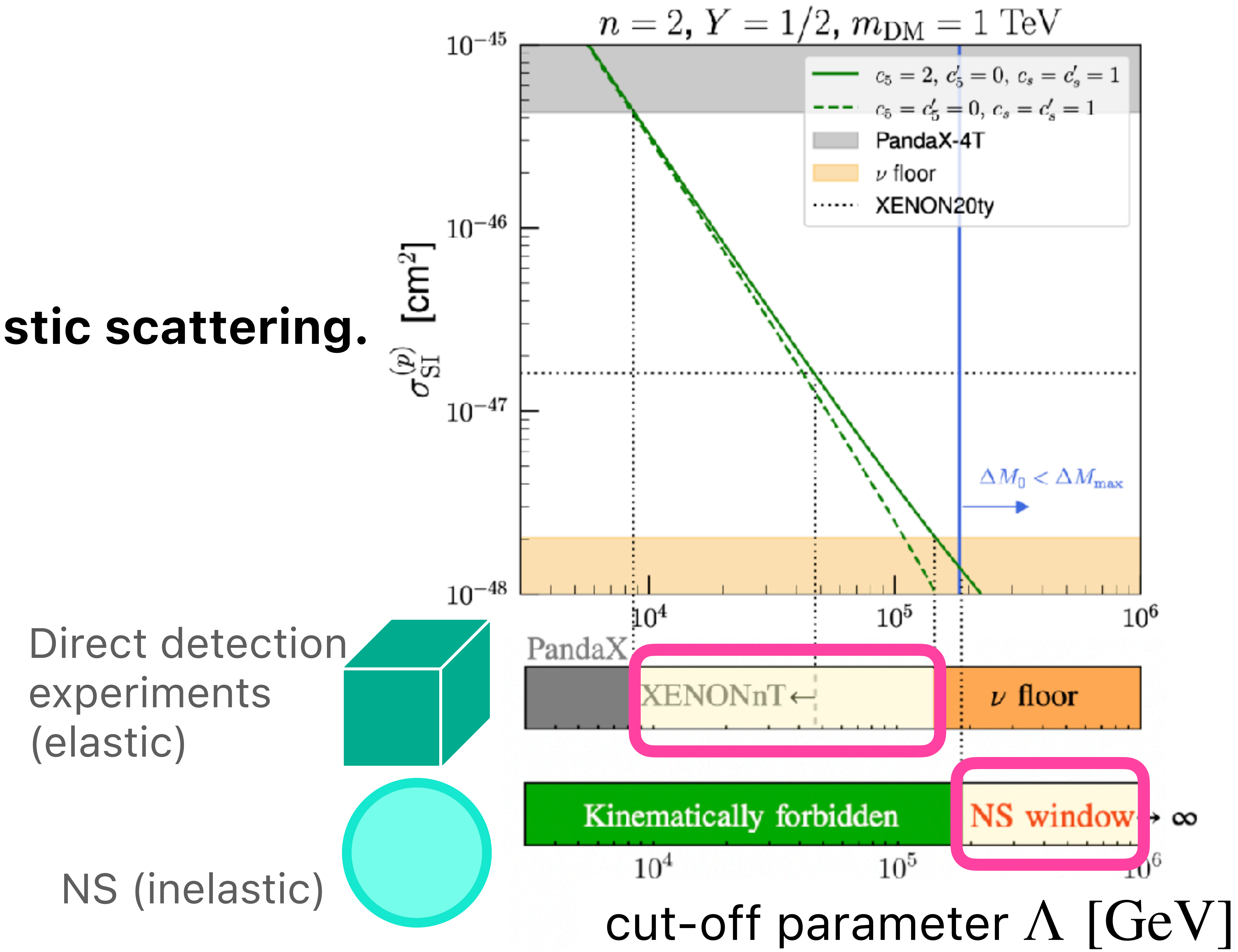
e.g., Wino and Higgsino in SUSY

dim-5 effective operators

w/ cut-off parameter Λ

$$\mathcal{L}_5 = -\frac{c_5}{\Lambda}\sum_m (-1)^{j+m}\eta_{-m}\chi_m |H|^2$$

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



Direct detection and NS heating can play complementary roles.

Fujiwara, KH, Nagata, Zheng [2204.02238]

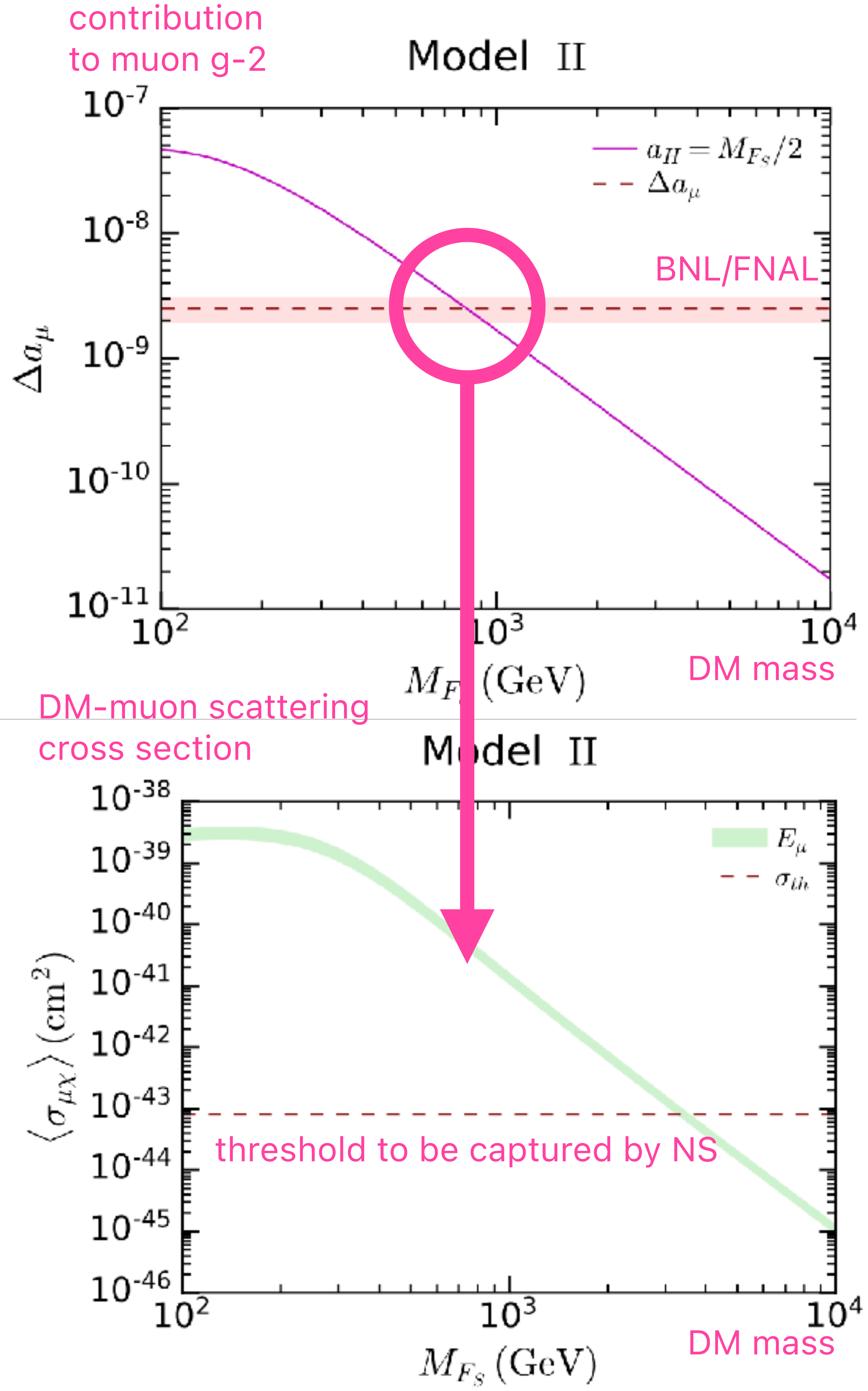
Dark Matter Heating of NS

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]

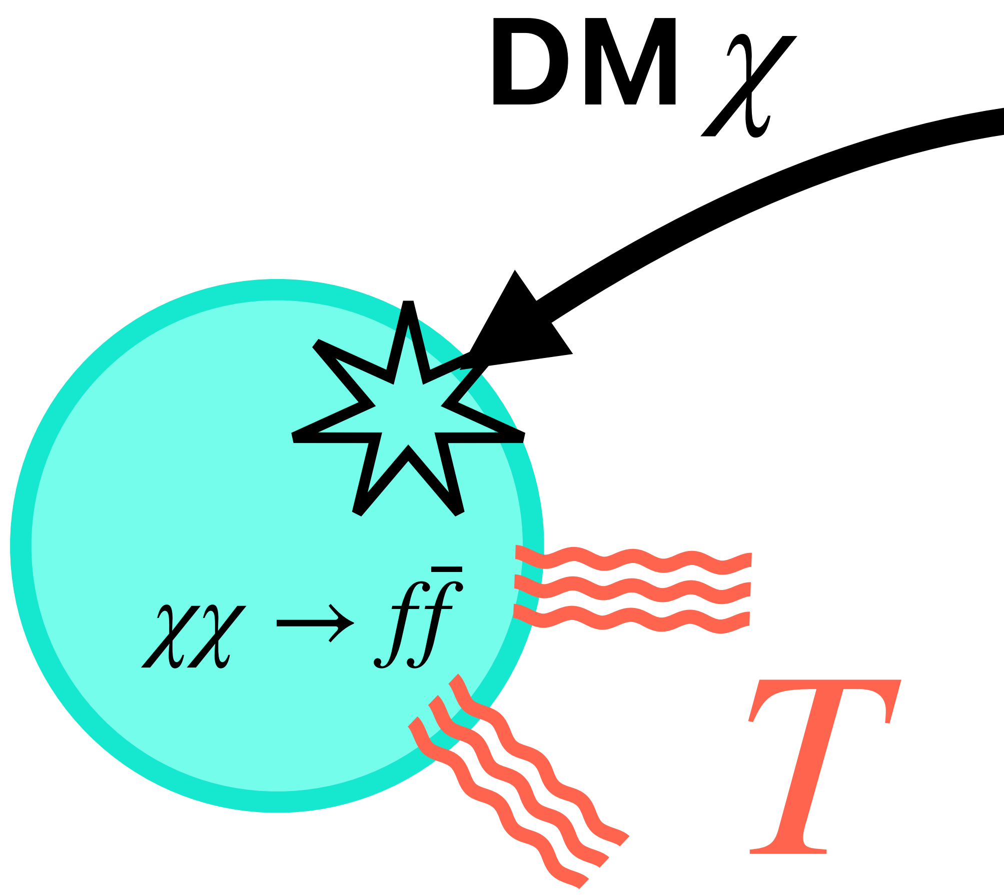
Models motivated by the muon g-2 anomaly.

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

NS temperature may be a promising way.

Plan

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



Dark Matter Heating of NS

Challenges: Internal Heating

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

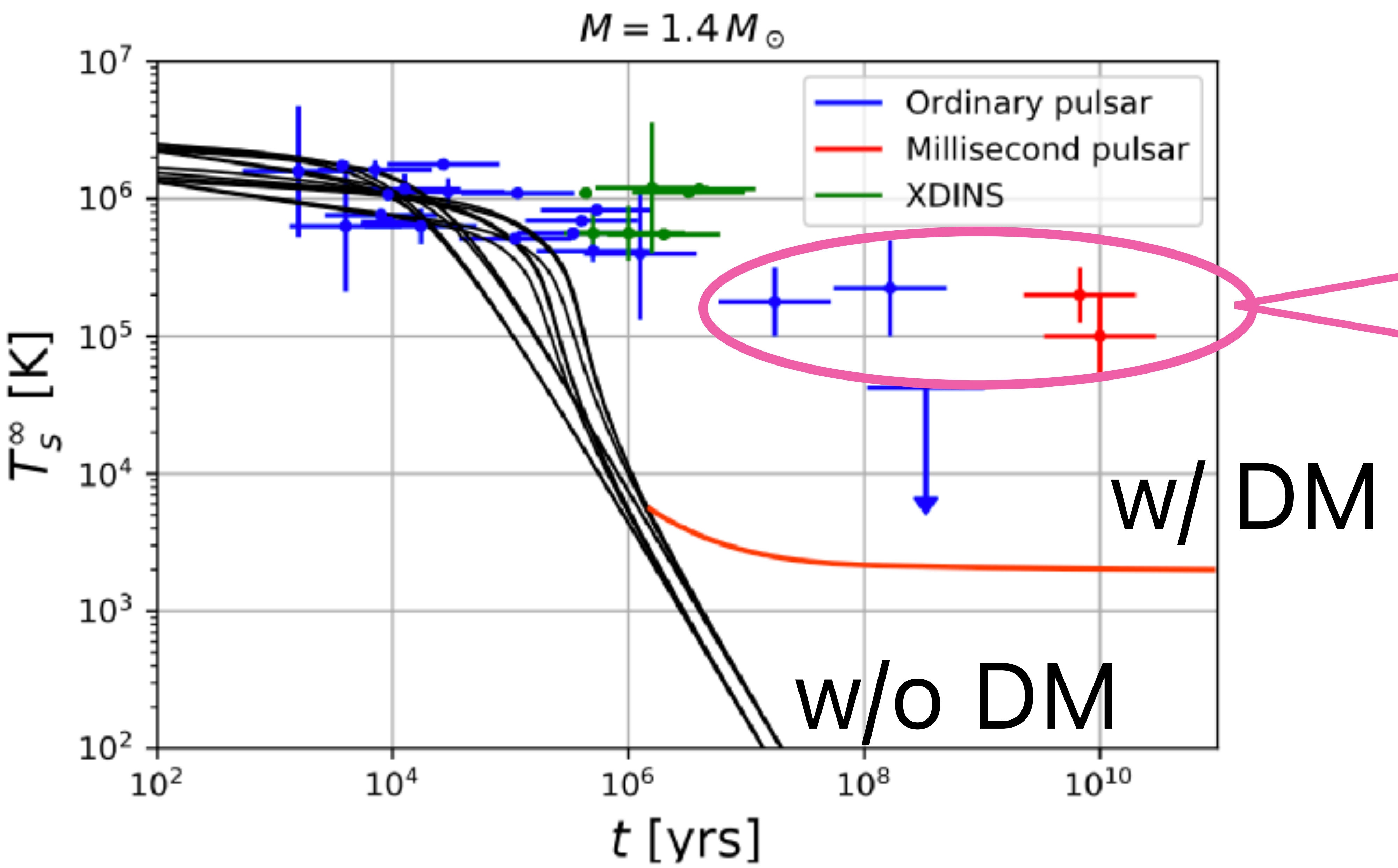


Fig. thanks to K.Yanagi.

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

Dark Matter Heating of NS

Challenges: Internal Heating

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

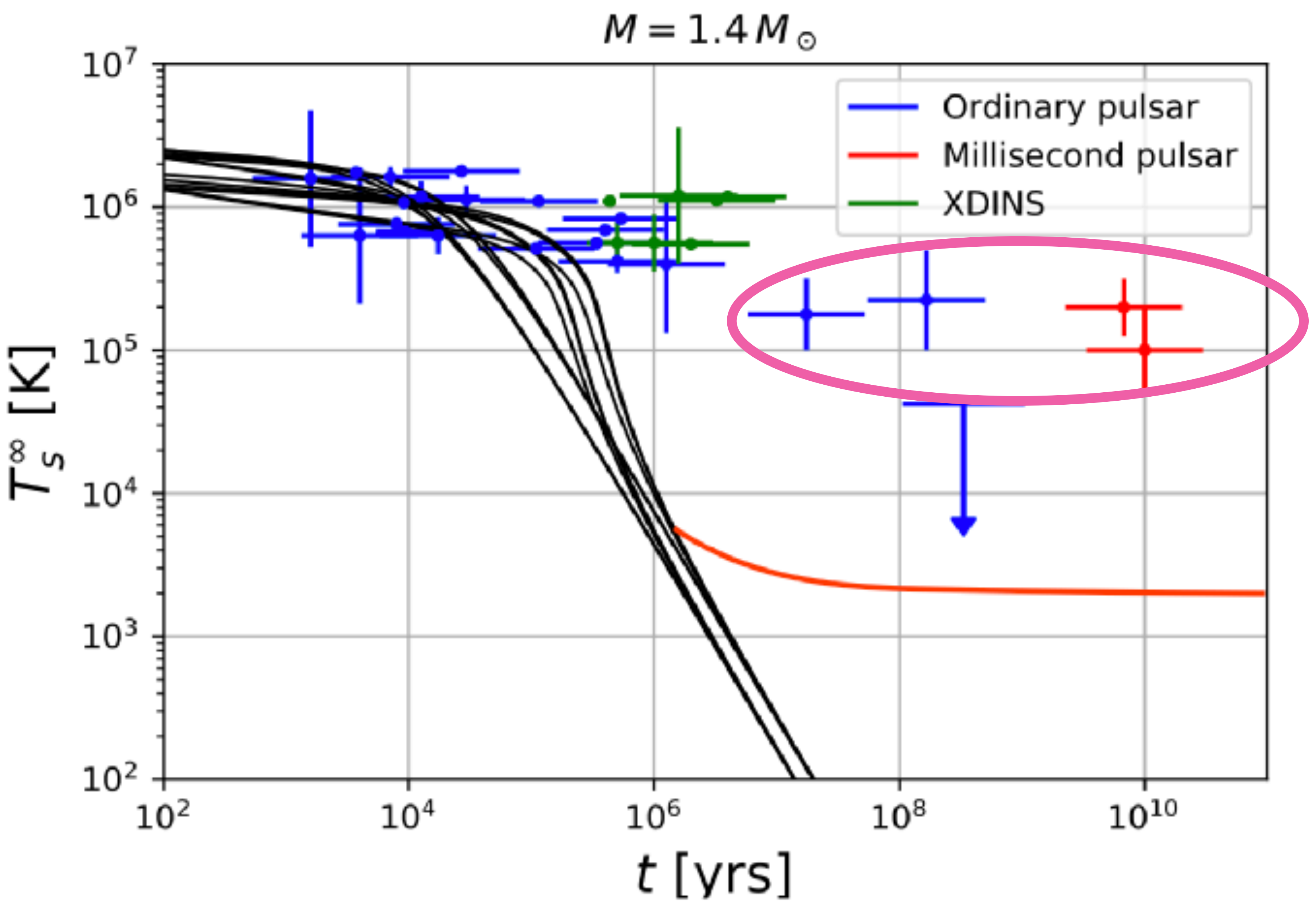


Fig. thanks to K.Yanagi.

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

(1) Rotochemical heating

(2) Vortex creep heating

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

Dark Matter Heating of NS

Challenges: Internal Heating

(1) **Rotochemical heating**

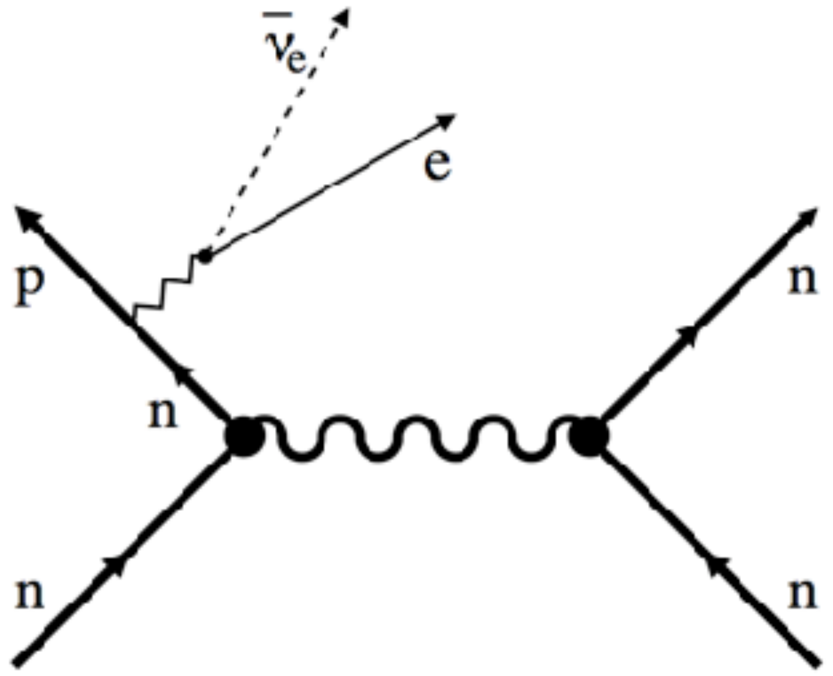
Dark Matter Heating of NS

Challenges: Internal Heating

(1) Rotochemical heating

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

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

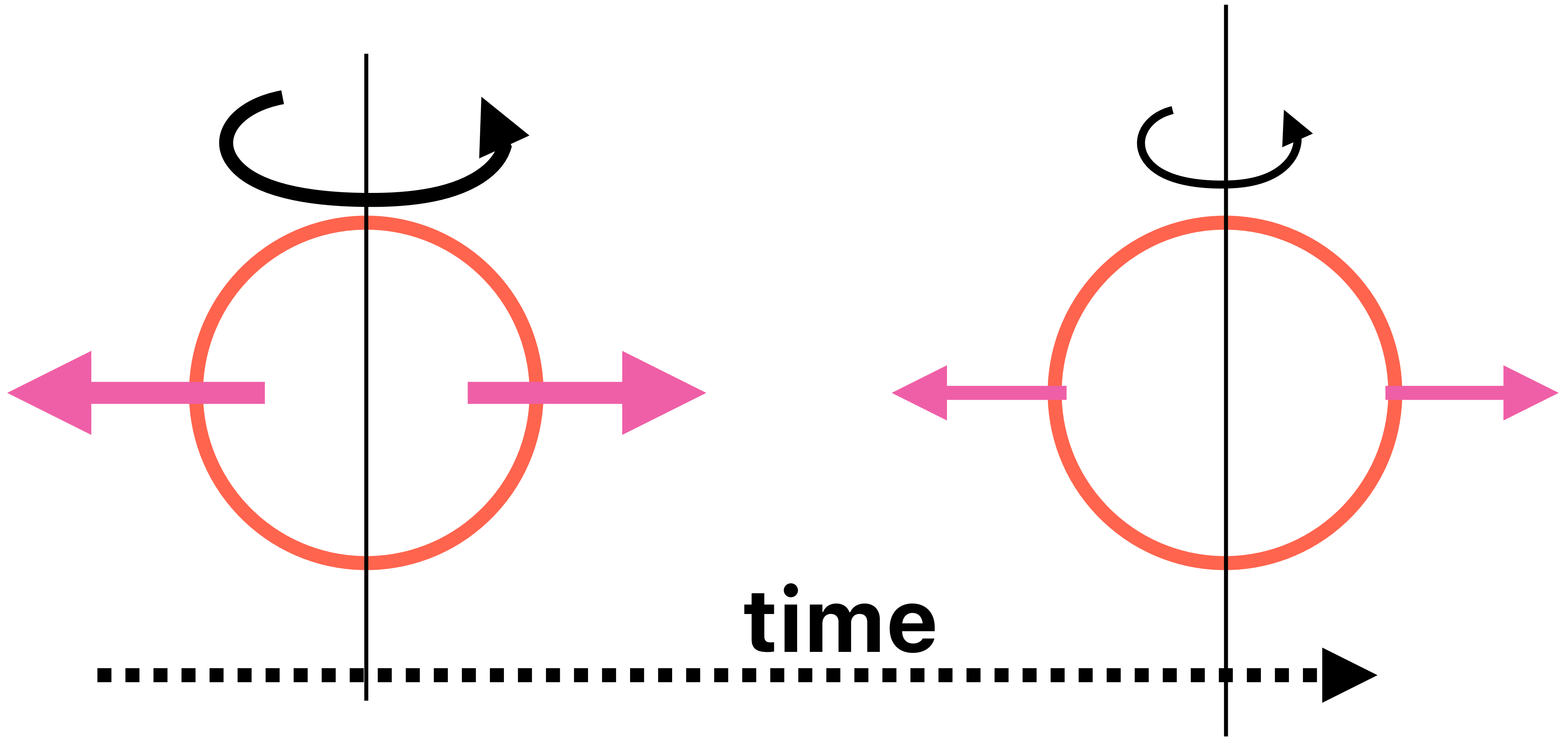


- In the minimal cooling, β-equilibrium is assumed.

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

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

A.Reisenegger [astro-ph/9410035]



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

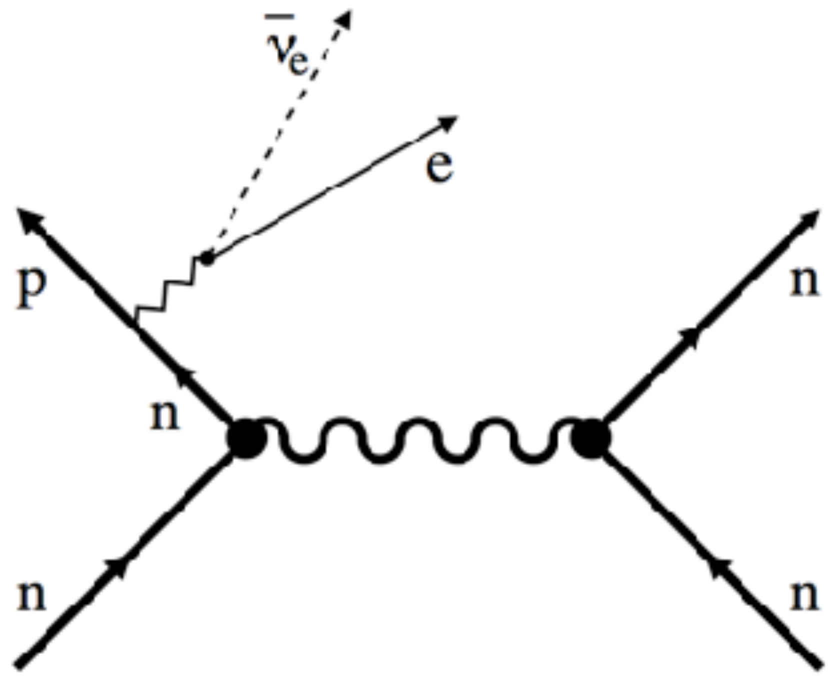
Dark Matter Heating of NS

Challenges: Internal Heating

(1) Rotochemical heating

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

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



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

A.Reisenegger [astro-ph/9410035]

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

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

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

Dark Matter Heating of NS

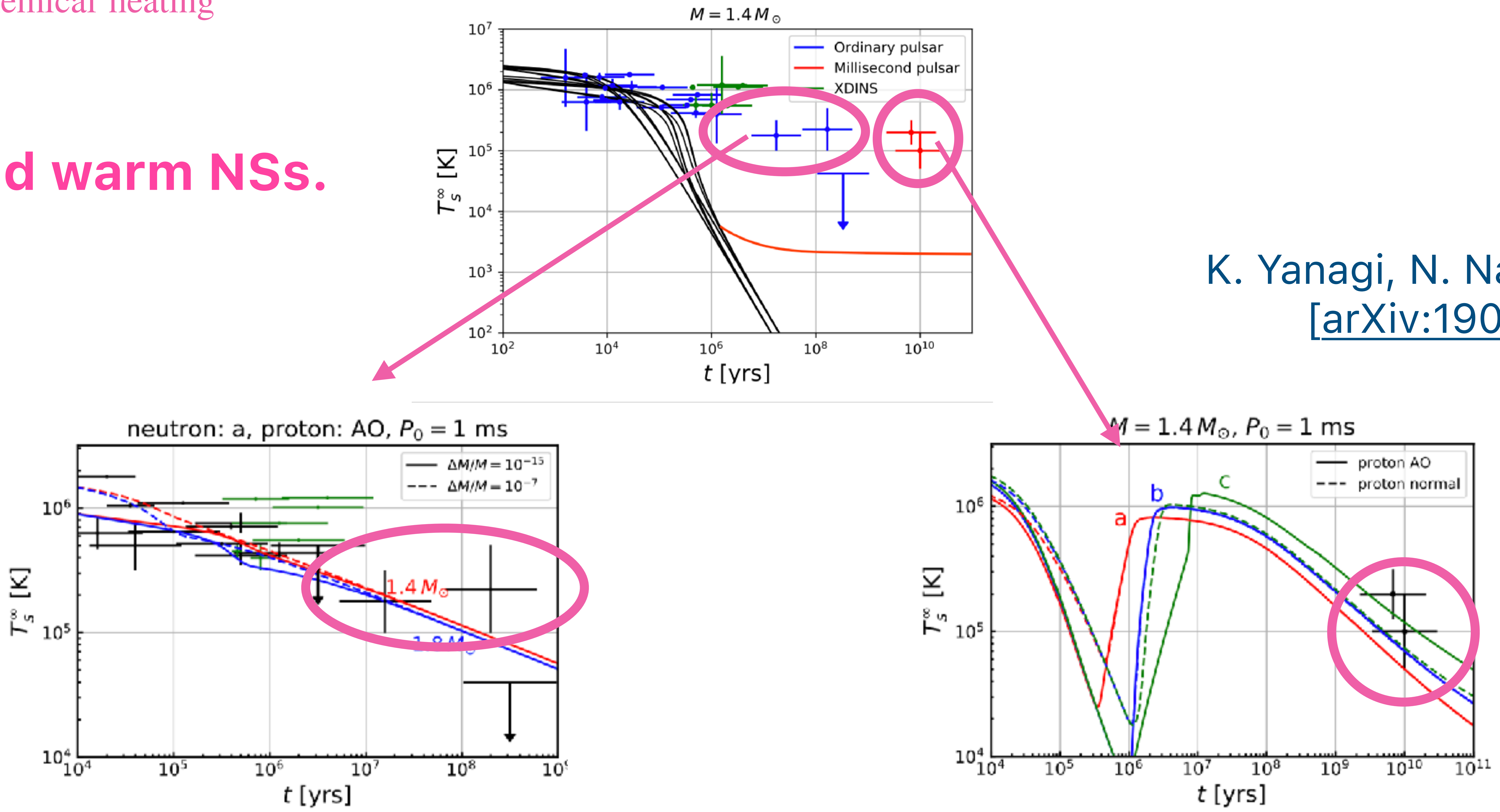
Challenges: Internal Heating

(1) Rotochemical heating

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

It can explain the old and warm NSs.

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



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

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

Dark Matter Heating of NS

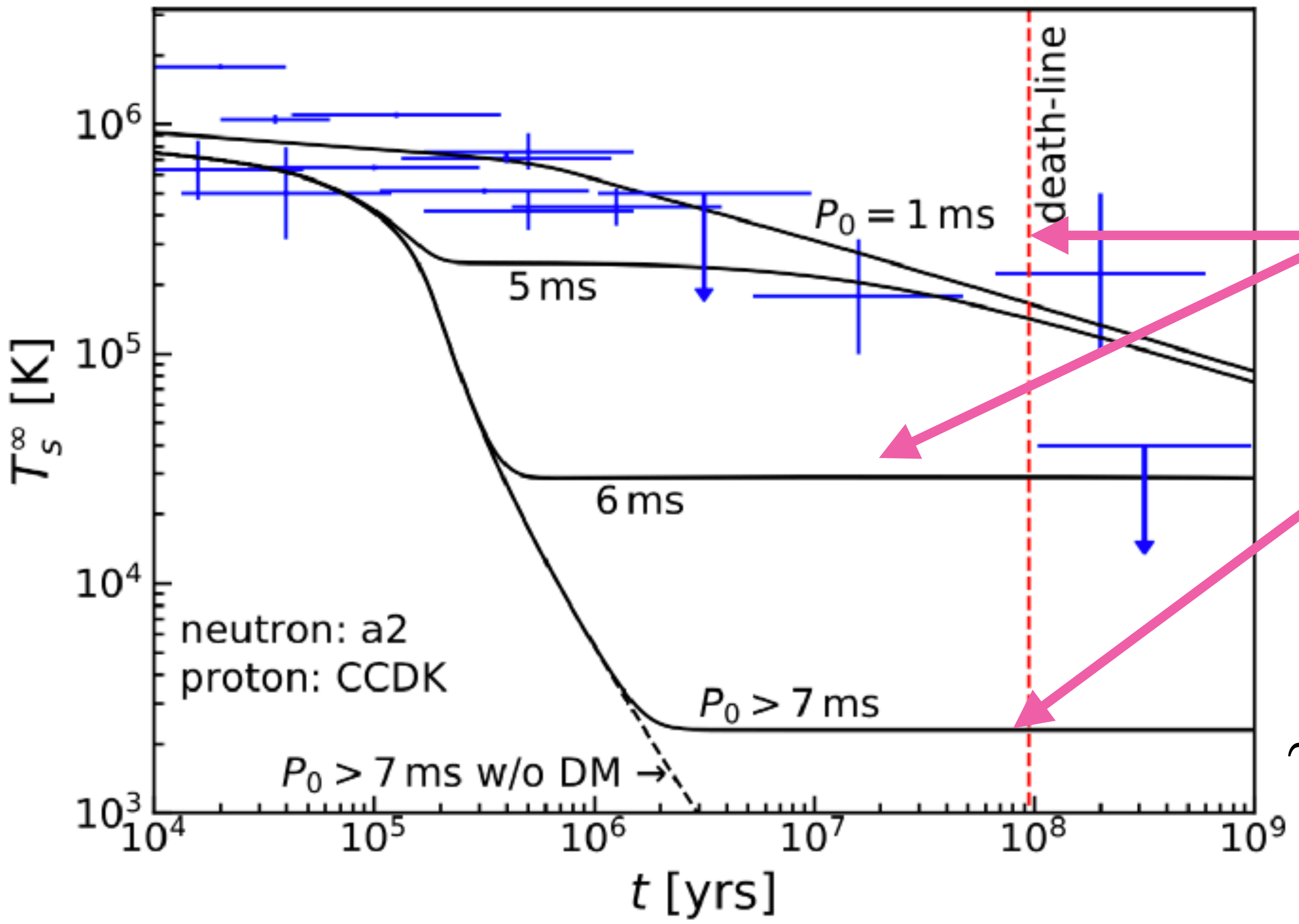
Challenges: Internal Heating

(1)′ Rotochemical heating + DM heating

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

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

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



$\sim (2000 - 3000)K$

P_0 **: initial rotation period**

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

There is still a chance…

Dark Matter Heating of NS

Challenges: Internal Heating

(2) Vortex Creep heating

Alpar+, 1984, Shibazaki+, 1989

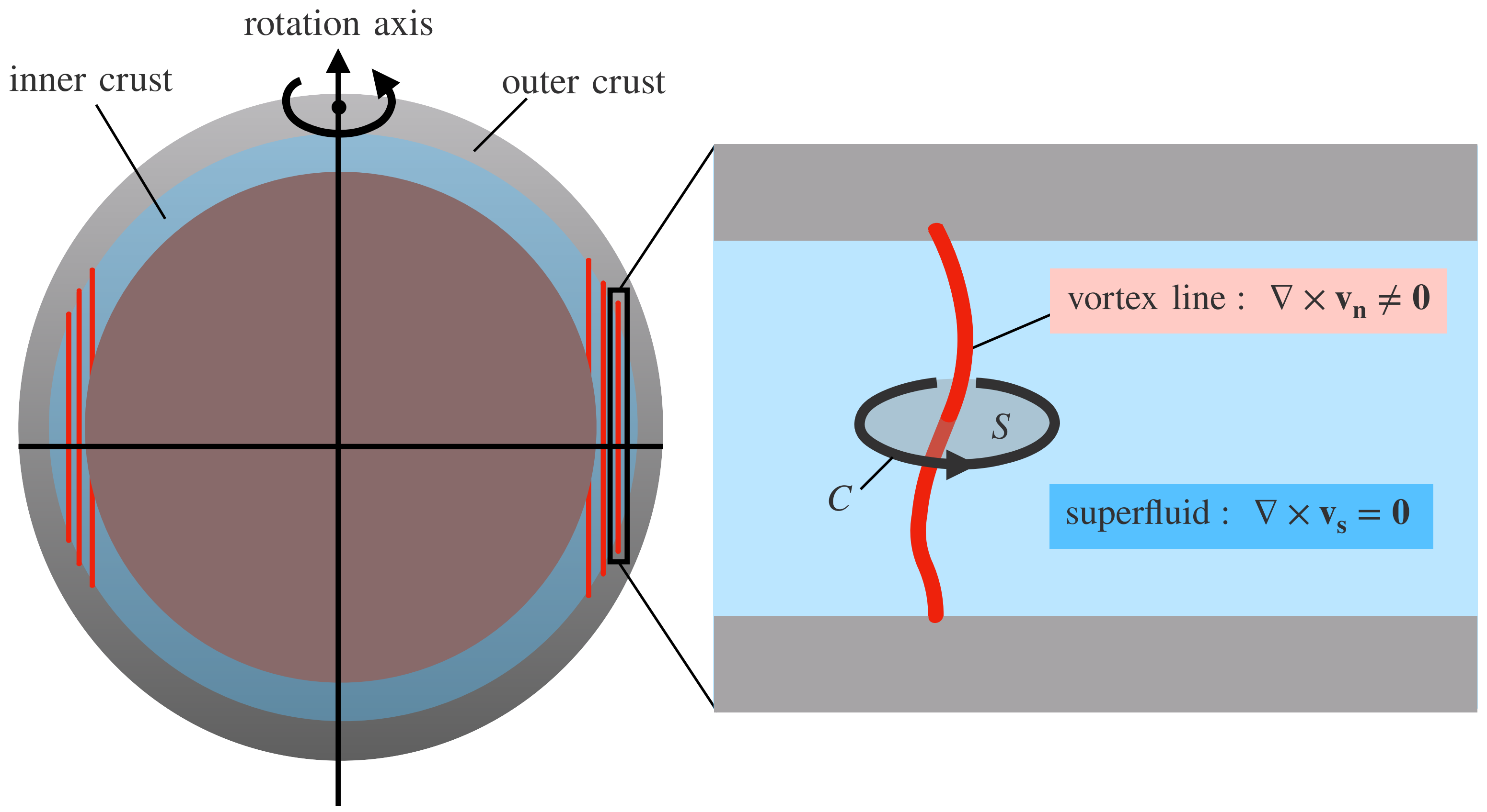
Dark Matter Heating of NS

Challenges: Internal Heating

(2) Vortex Creep heating

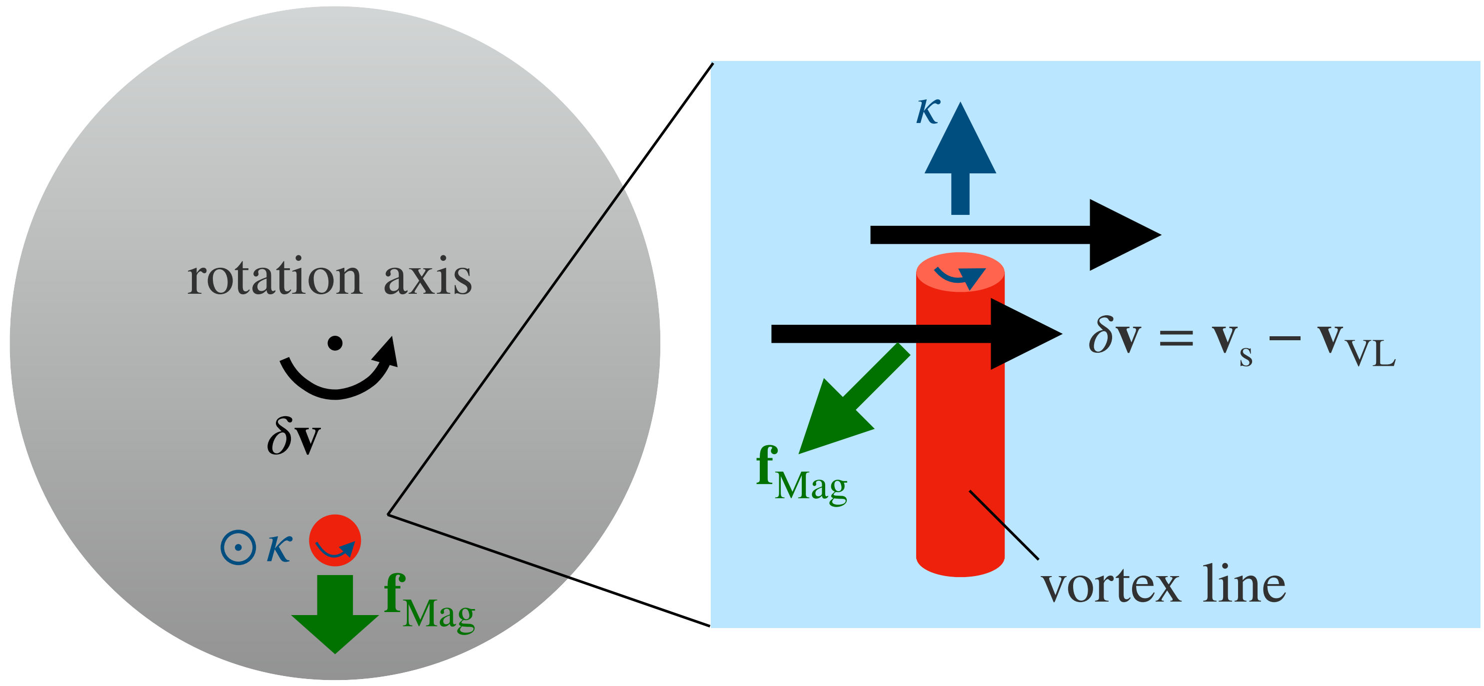
Alpar+, 1984, Shibazaki+, 1989

- 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

Dark Matter Heating of NS

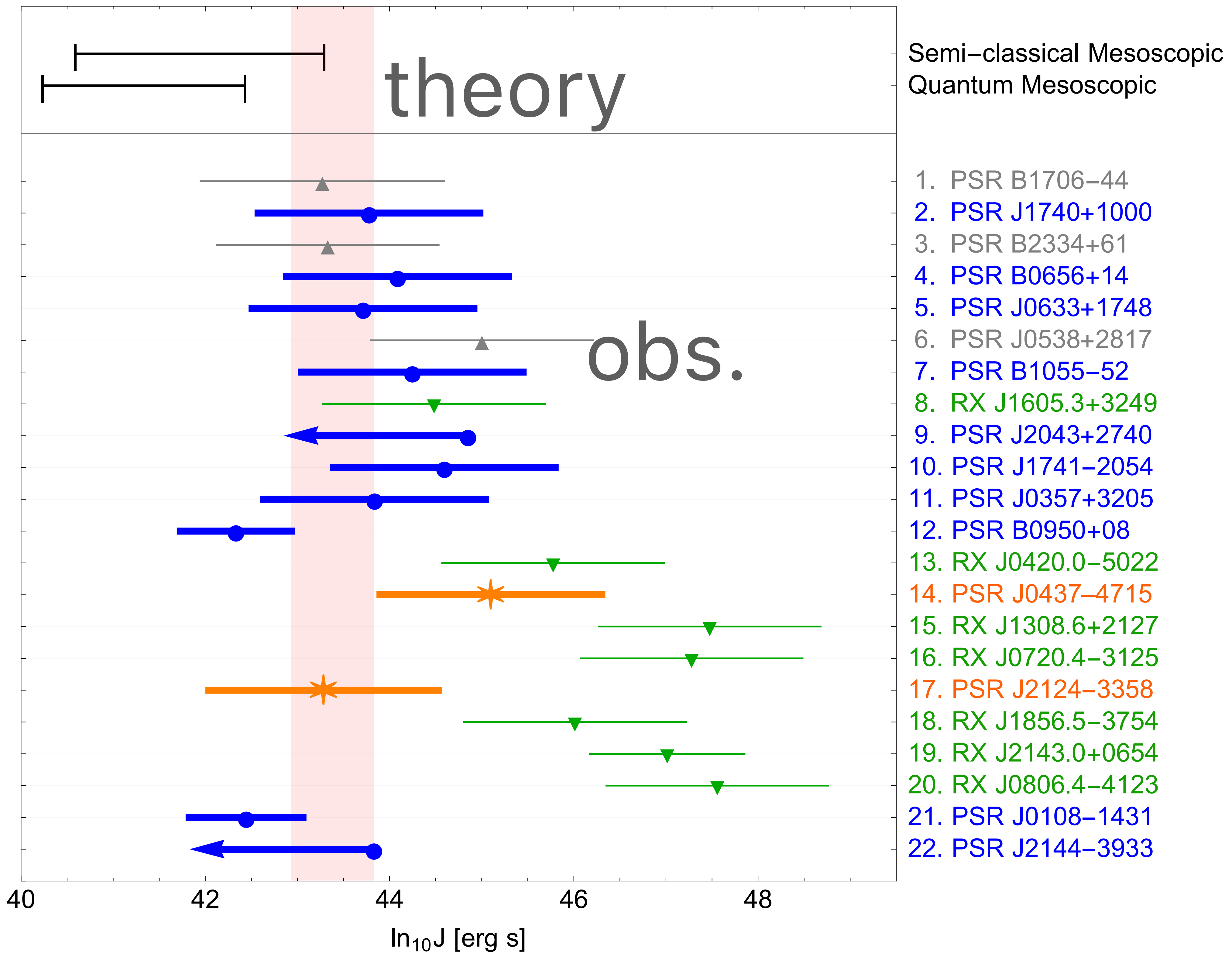
Challenges: Internal Heating

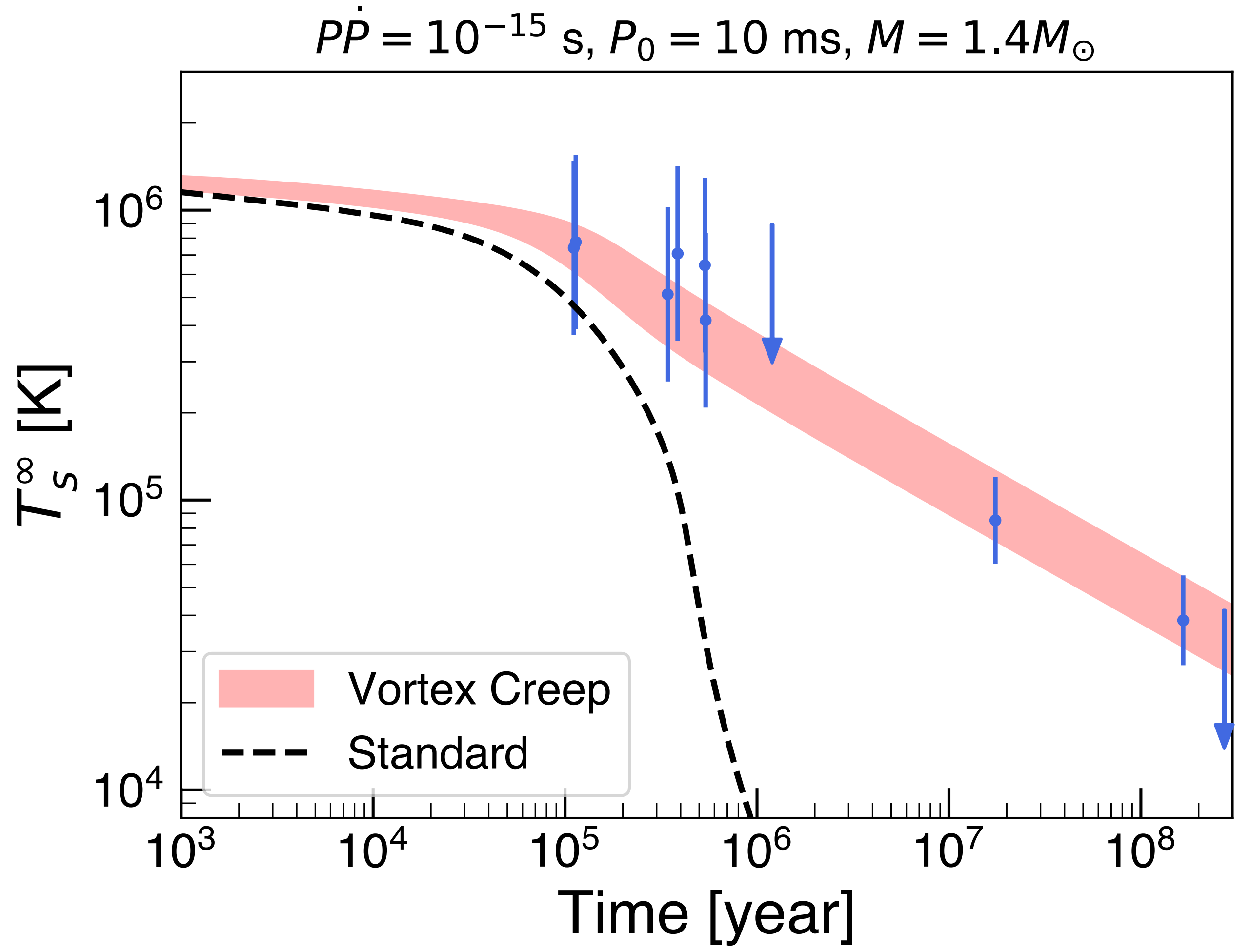
(2) Vortex Creep heating

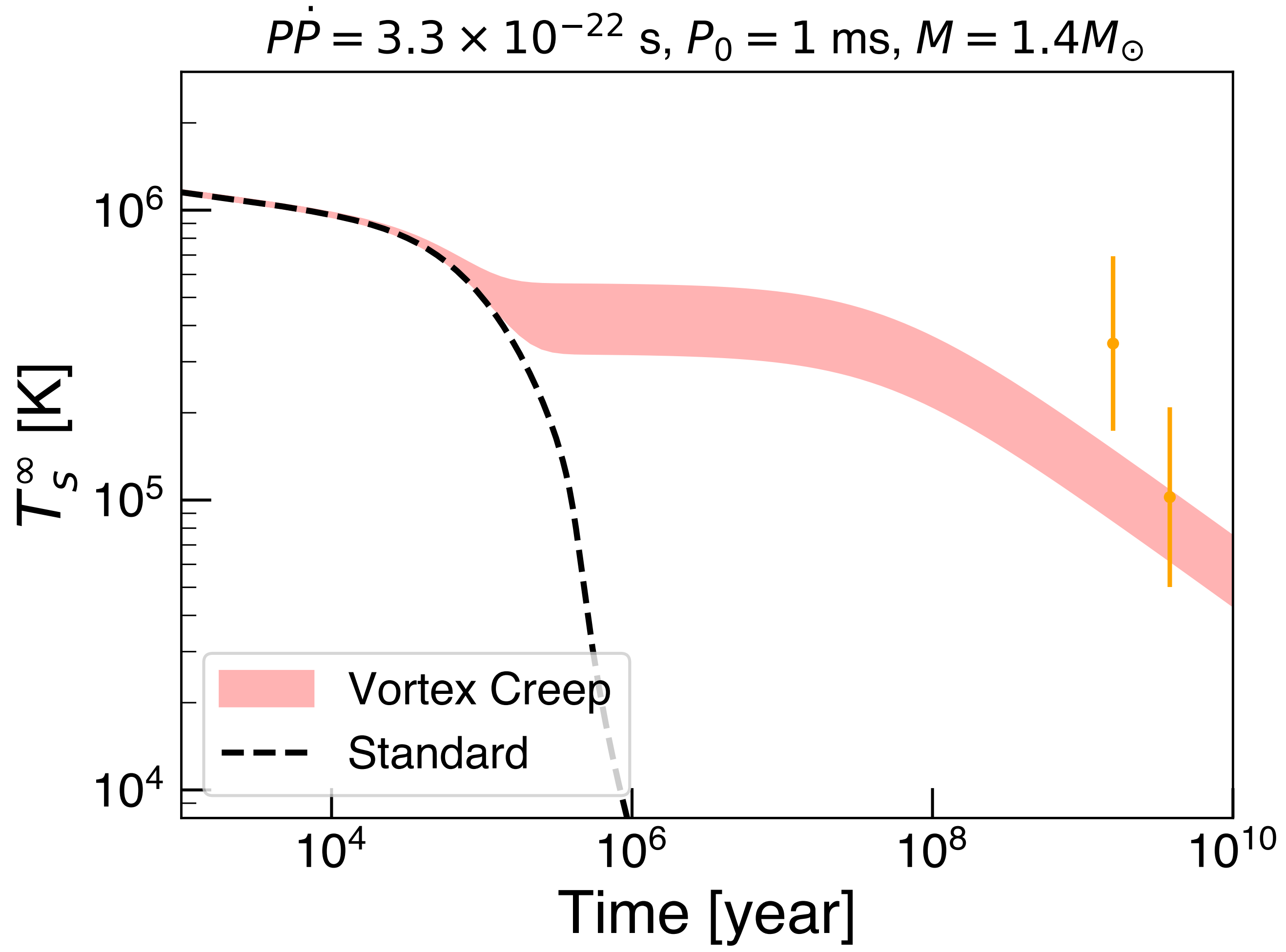
$$C\frac{dT}{dt} = -L_\nu - L_\gamma + L_{\text{vortex creep heating}}$$

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

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







Dark Matter Heating of NS

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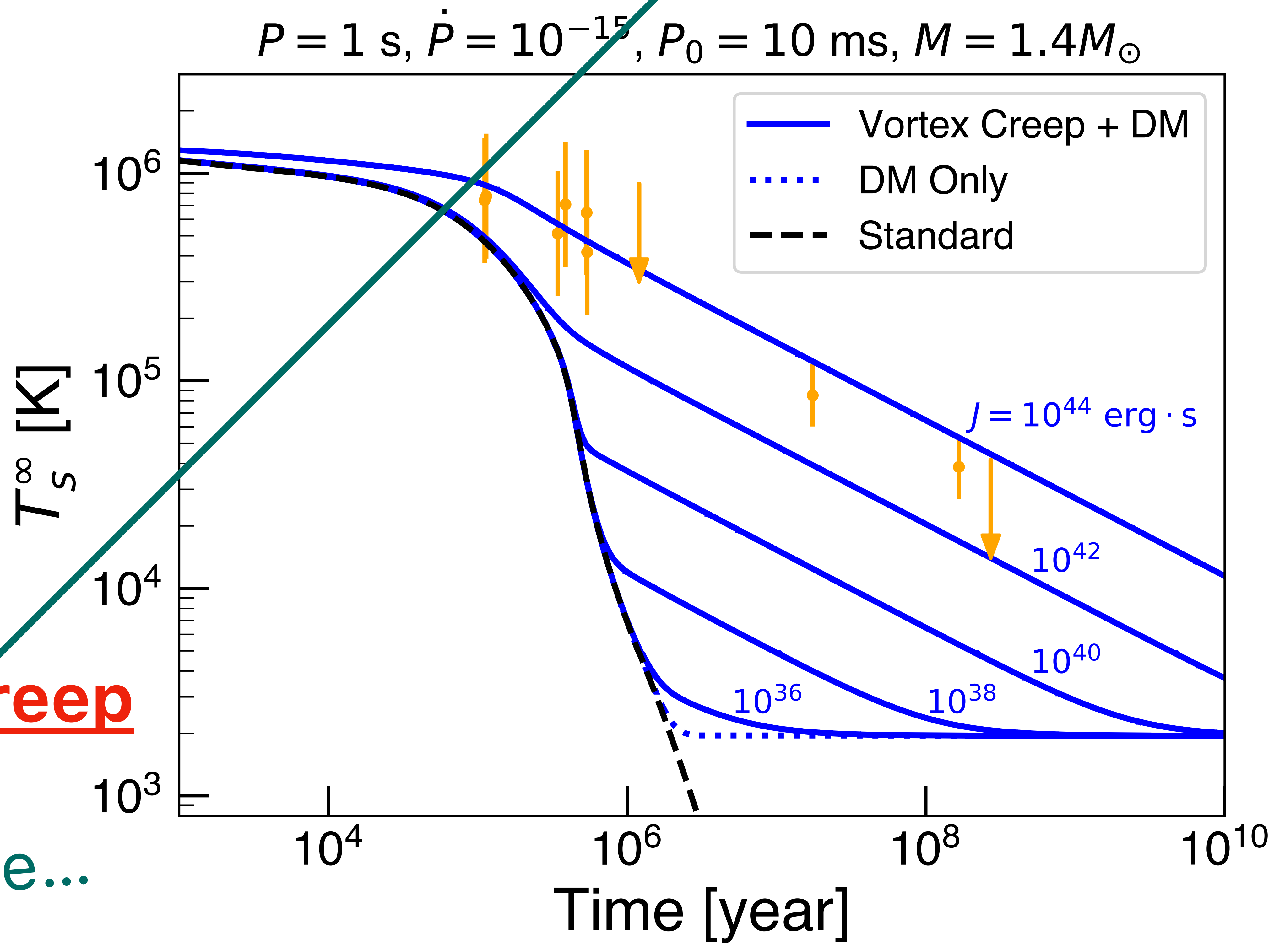
Fujiwara, KH, N. Nagata, Ramirez-Quezada [2308.16066]

(2)′ Vortex Creep heating + DM heating

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

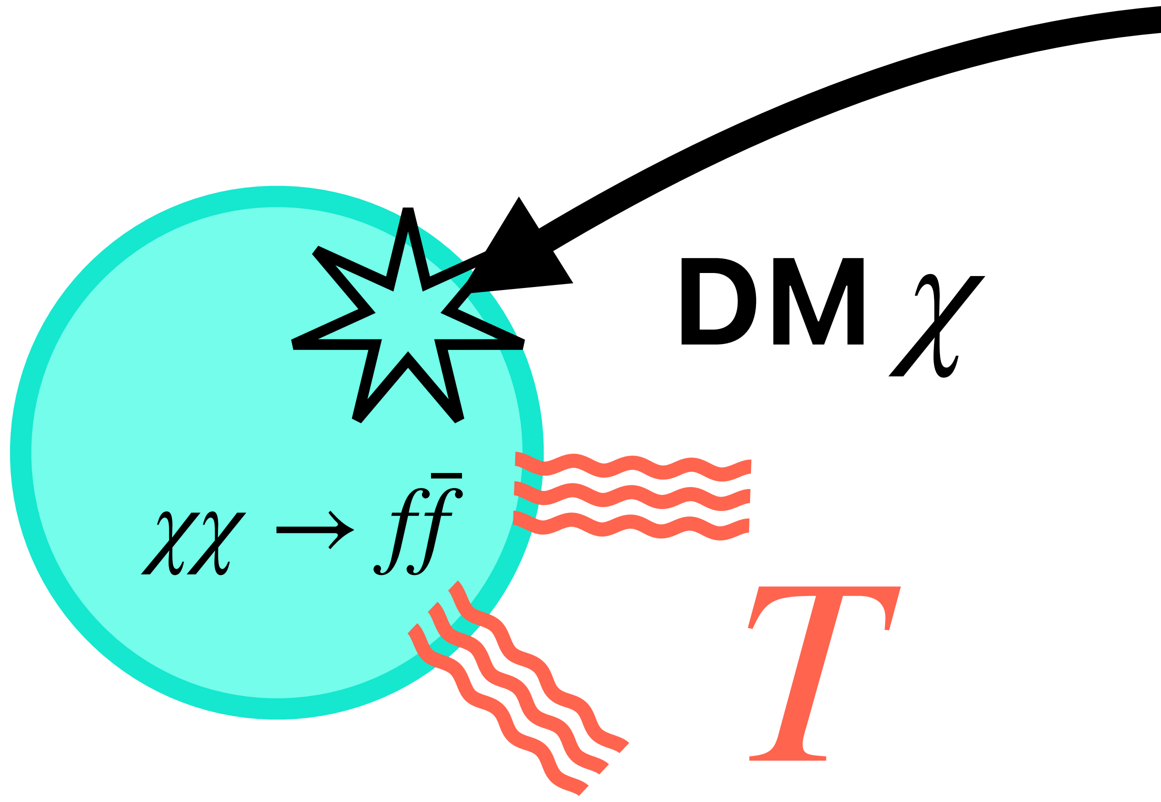
$$C\frac{dT}{dt} = -L_\nu - L_\gamma + L_{\text{vortex creep heating}} + L_{\text{DM heating}}$$

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


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

This may be a serious challenge...

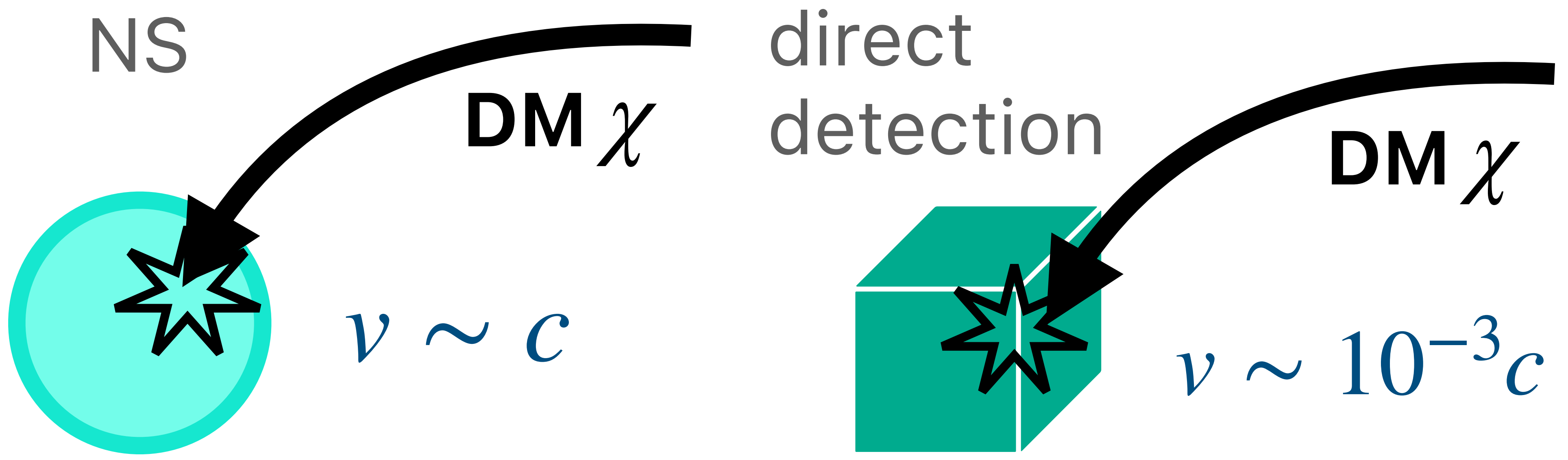
Summary



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

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

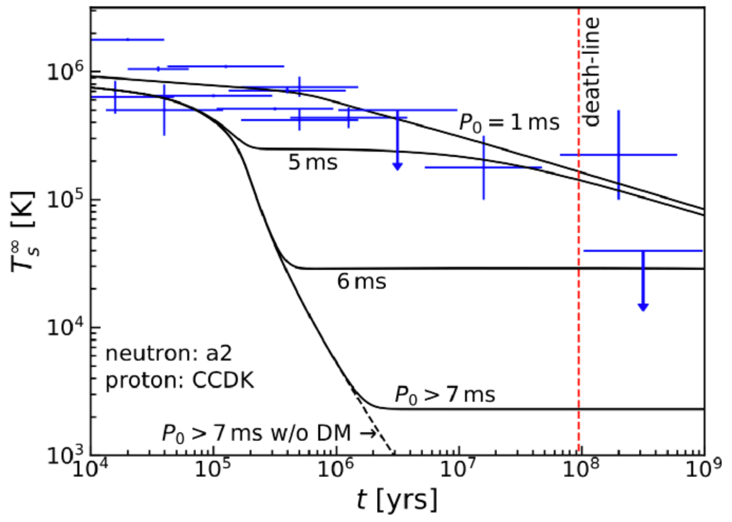
  (2) Multiple Targets: e, μ, p, n
  👉 It can probe, e.g., DM coupled only to **muon**.



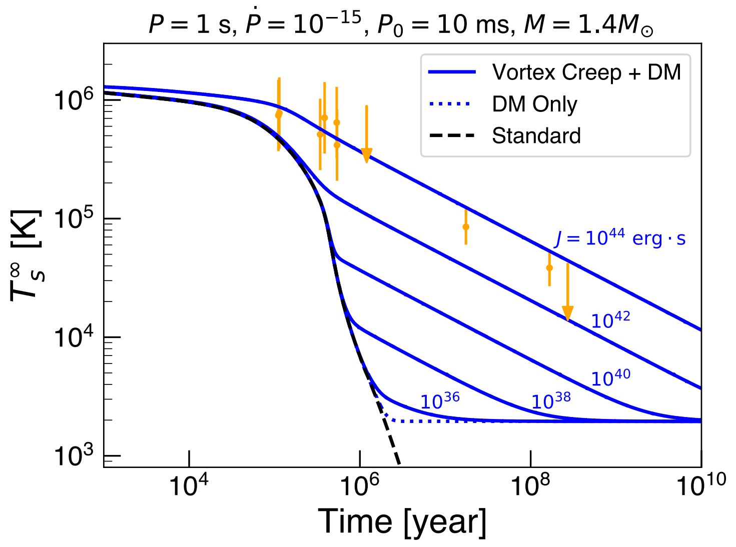
- **Challenges**:

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

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



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



(b) 中性子星がアクシオンで冷える話

Based on the works with

Natsumi Nagata, Keisuke Yanagi, Jiaming Zheng

参考文献

NS cooling by axion: 1806.07151, 2502.18391

(b) 中性子星がアクシオンで冷える話

1. 中性子星

2. アクシオン vs Cas A 中性子星

based on KH, N. Nagata, K. Yanagi, J. Zheng, [arXiv:1806.07151]

(1) アクシオン mini review

(2) Cas A 中性子星の cooling

(3) Cas A 中性子星の cooling とアクシオン

(4) 「アクシオン vs Cas A 中性子星」のまとめ

(1) アクシオン mini review

- **Strong CP 問題**

$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi}\theta\, F_a^{\mu\nu}\widetilde{F}_{a\mu\nu}, \quad \bar{\theta} = \theta + \arg\det m_q$$

$\underline{|\bar{\theta}| \lesssim 10^{-10}}$ <u>from neutron EDM</u>

中性子電気双極子モーメント

Why?

(1) アクシオン mini review

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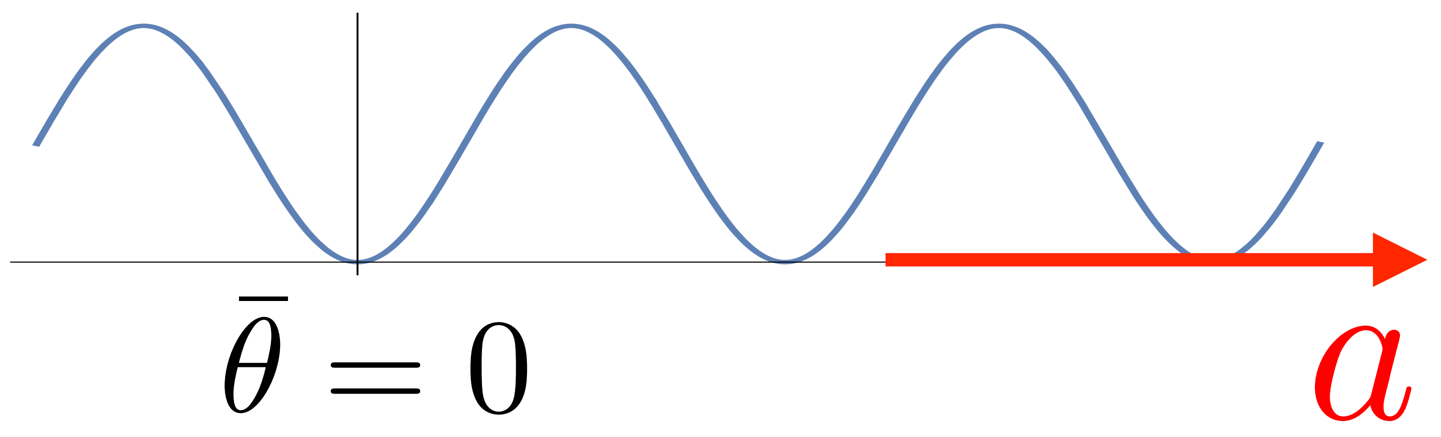
中性子電気双極子モーメント

Why?

- Peccei-Quinn 機構で解決出来る。 [Peccei, Quinn,’77]

軽い粒子**アクシオン**の存在を予言 [Weinberg,’78, Wilczek,’78]

$$\mathcal{L} = \frac{\alpha_s}{8\pi}\boxed{\frac{a}{f_a}}\, F_a^{\mu\nu}\tilde{F}_{a\mu\nu}$$



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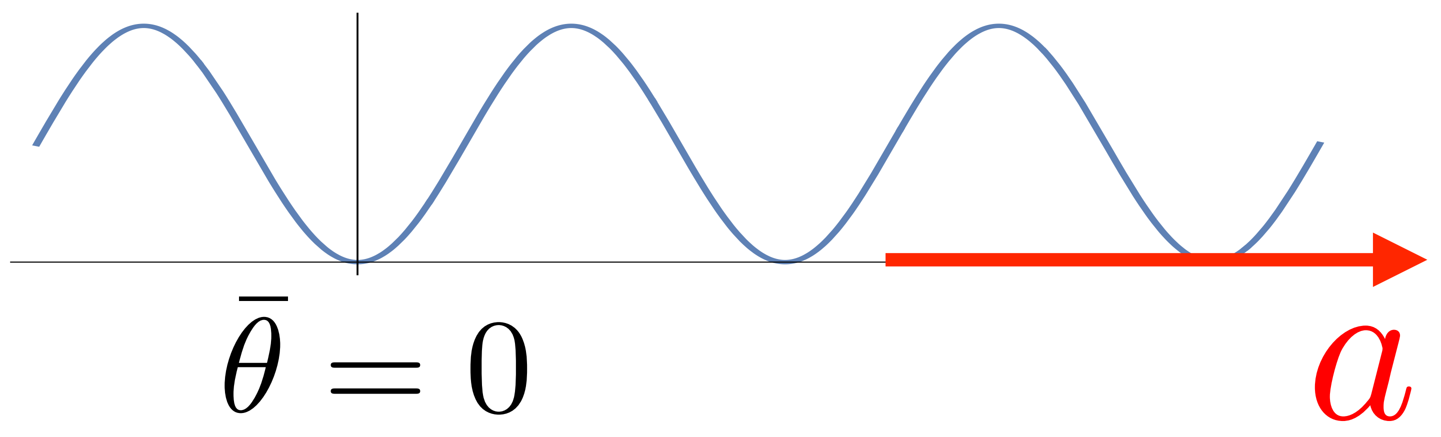
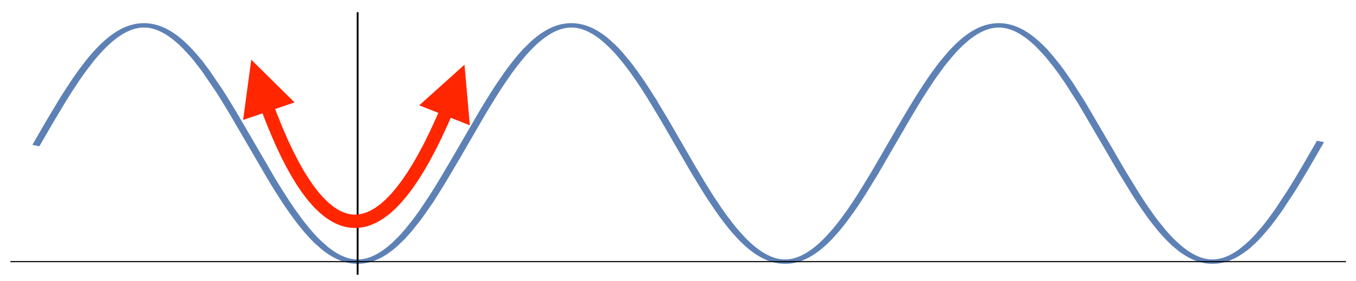


- アクシオンは暗黒物質の候補でもある！



$$\Omega_a h^2 = 0.18\,\theta_i^2 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{1.19}.$$

[Turner,'86]

(1) アクシオン mini review

アクシオンで良く議論されるのは、
だいたいこの２つのどちらか：

- **KSVZ axion model** [Kim,'79, Shifman, Vainshtein, Zakharov,'80]

$$\mathcal{L} = |\partial\phi|^2 + (\lambda\phi\bar{Q}Q + h.c.) - V(|\phi|)$$

  - $Q, \bar{Q}$: heavy vector-like quarks

新たな重いクォークを導入

- **DFSZ axion model** [Dine, Fischler, Srednicki,'81, Zhitnitski,'80]

$$\mathcal{L} = |\partial\phi|^2 + (\mu\phi H_u H_d + h.c.) - V(|\phi|, H_u, H_d)$$

  - 2 Higgs doublet H_u, H_d ヒッグス場を２つ導入

(宣伝) Flaxion model

[Ema, Hamaguchi, Moroi, Nakayama,'16, Calibbi, Goertz, Redigolo, Ziegler, Zupan,'16]

$$\begin{aligned}\mathcal{L} = {} & y^d_{ij}\left(\frac{\phi}{M}\right)^{n^d_{ij}} \overline{Q}_i H d_{Rj} + y^u_{ij}\left(\frac{\phi}{M}\right)^{n^u_{ij}} \overline{Q}_i \widetilde{H} u_{Rj} \\ & + y^l_{ij}\left(\frac{\phi}{M}\right)^{n^l_{ij}} \overline{L}_i H l_{Rj} + y^\nu_{i\alpha}\left(\frac{\phi}{M}\right)^{n^\nu_{i\alpha}} \overline{L}_i \widetilde{H} N_{R\alpha} \\ & + \frac{1}{2} y^N_{\alpha\beta}\left(\frac{\phi}{M}\right)^{n^N_{\alpha\beta}} M \overline{N^c_{R\alpha}} N_{R\beta} + \mathrm{h.c.}\end{aligned}$$

標準模型の色んな問題を同時に
解決する、アクシオンを含む模型

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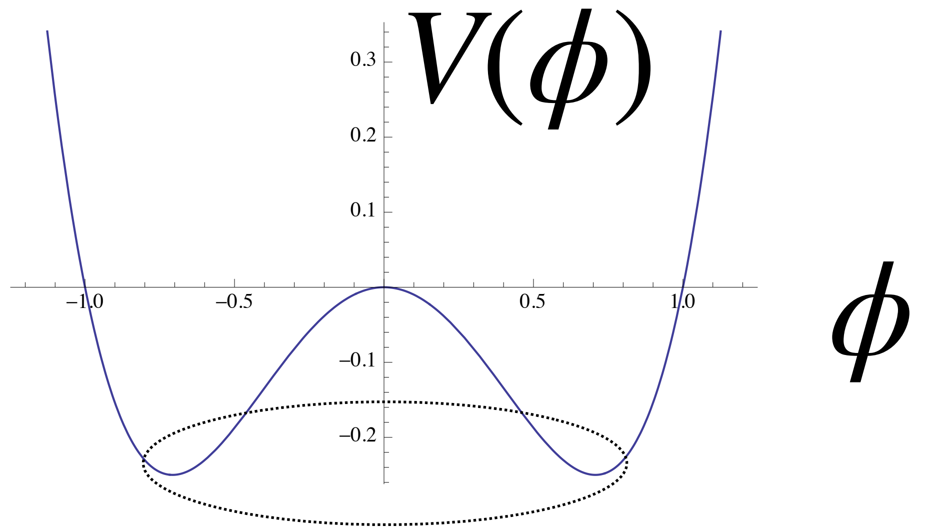
標準模型の色んな問題を同時に
解決する、アクシオンを含む模型

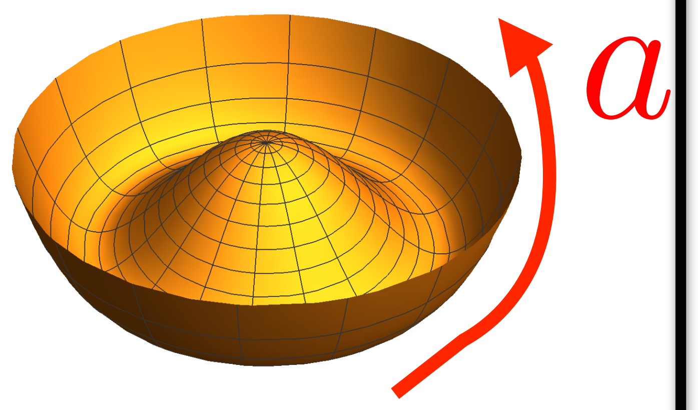
いずれの場合も

- ϕ 複素スカラー場 (Peccei-Quinn場)

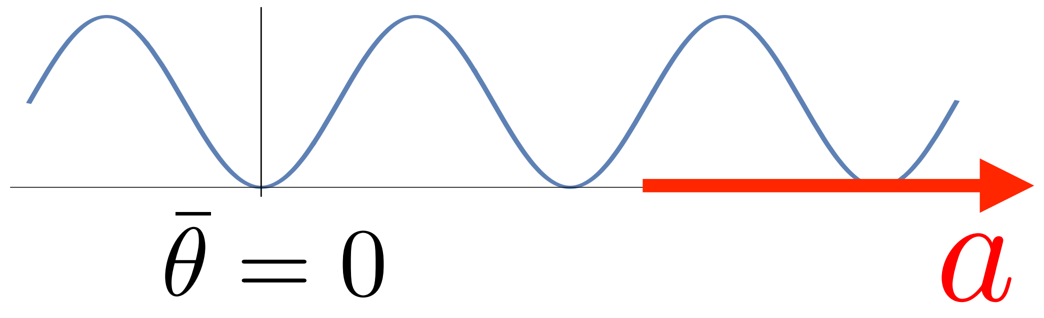
U(1)$_{\text{PQ}}$対称性($\phi \to \phi e^{i\alpha}$)の自発的破れ



- ϕ の位相方向
= 南部-Goldstone boson
= アクシオン



- アノマリーにより $\mathcal{L} = \frac{\alpha_s}{8\pi}\frac{a}{f_a}F^{\mu\nu}_a\tilde{F}_{a\mu\nu}$



strong CP 問題の解決！

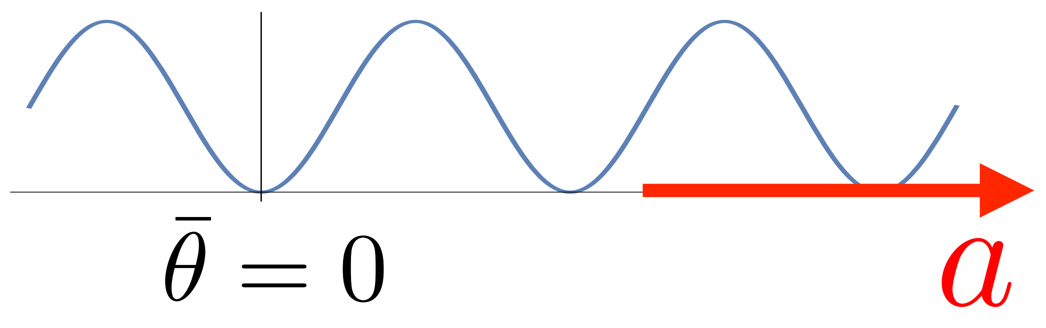
(1) アクシオン mini review

$$\mathcal{L} = \frac{\alpha_s}{8\pi}\frac{a}{f_a}F_a^{\mu\nu}\tilde{F}_{a\mu\nu}$$

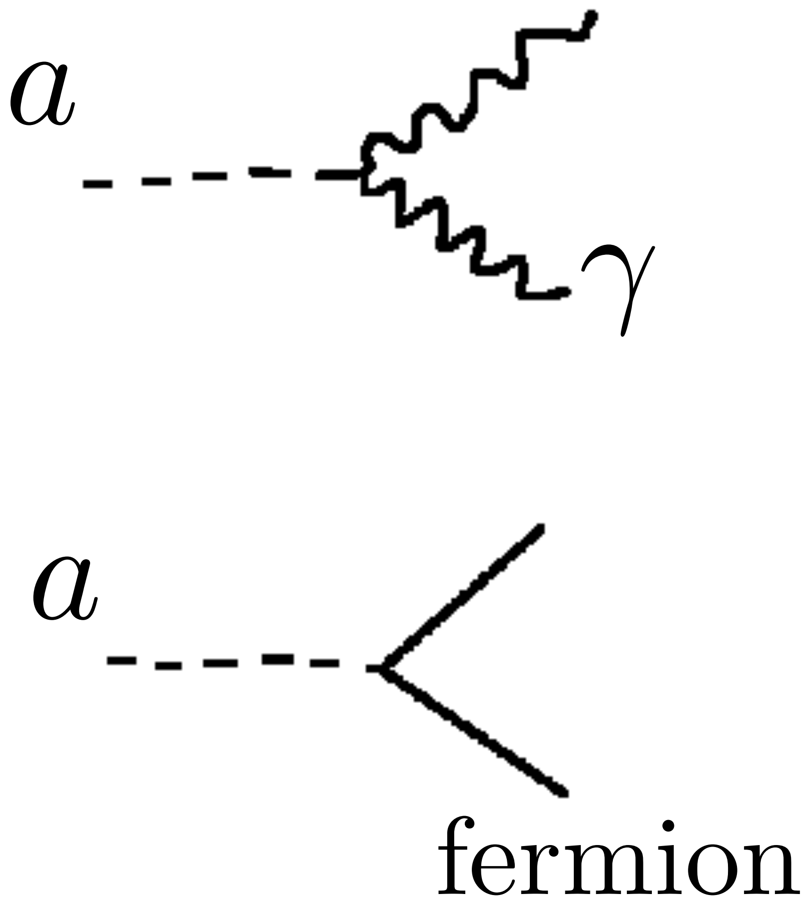
- アクシオンの**結合の強さは** f_a で決まる。

$$m_a \simeq 6\times 10^{-6}\,\mathrm{eV}\left(\frac{10^{12}\,\mathrm{GeV}}{f_a}\right)$$

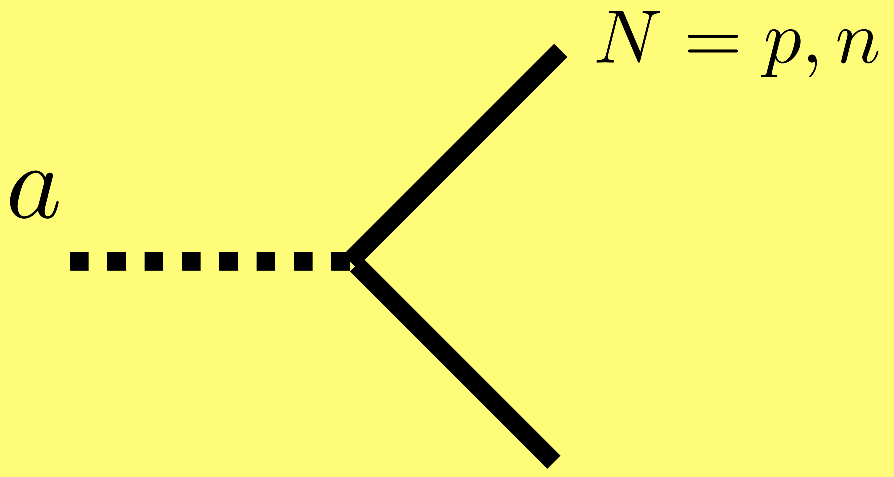
- アクシオンの**質量**も(ほぼ)これで決まる。



- 模型を決めれば**標準模型粒子との結合**も決まる。



例えば中性子星で重要な核子との相互作用は：



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

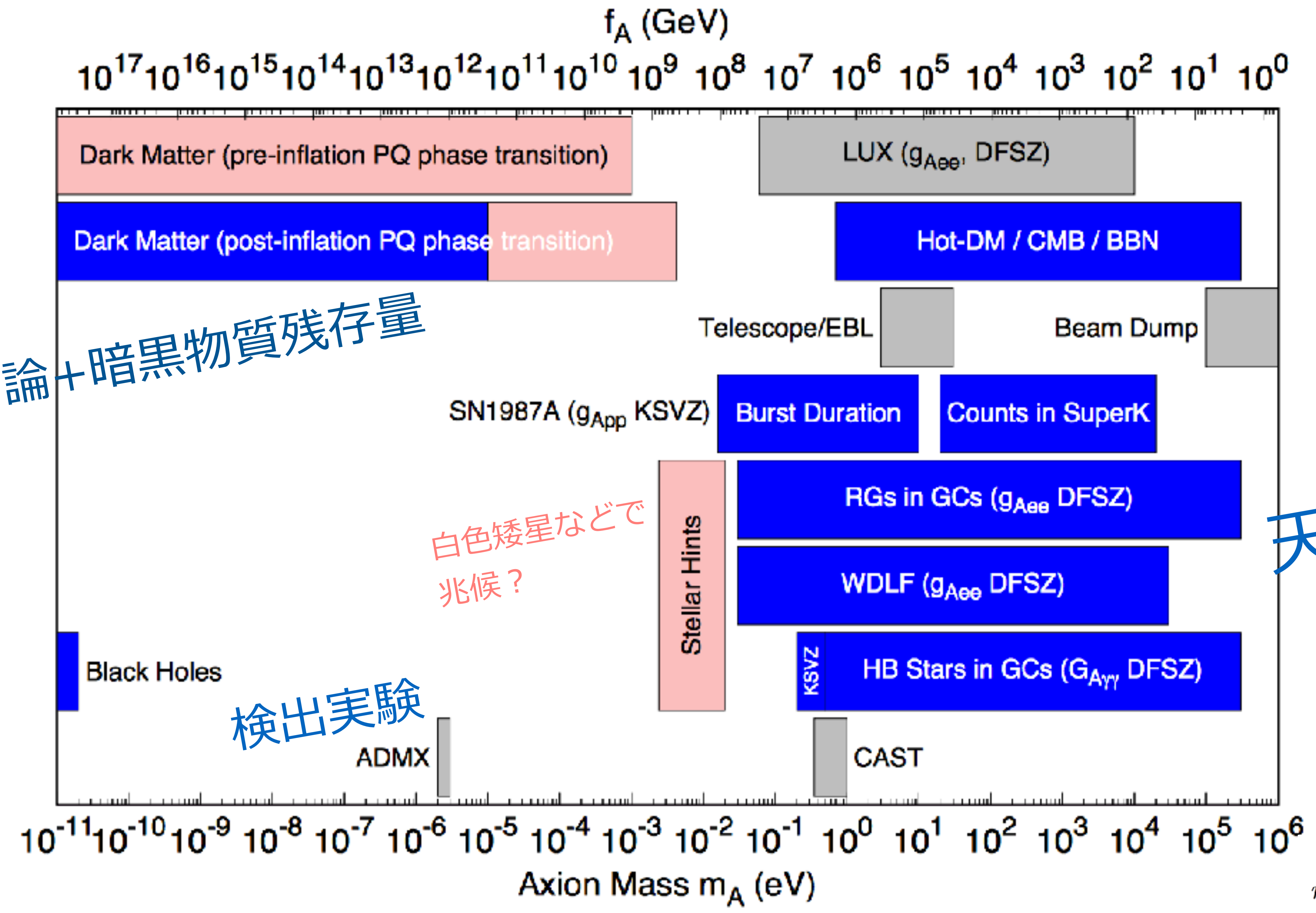
$$\text{KSVZ:}\begin{cases} C_p = -0.47(3) \\ C_n = -0.02(3) \end{cases}$$

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

大雑把には、O(1)係数を除いてだいたい全て f_a の１パラメータで決まる。

(1) アクシオン mini review

PDG 2018



宇宙論+暗黒物質残存量

白色矮星などで
兆候？

検出実験

天体観測

$$m_a \simeq 6\times10^{-6}\,\mathrm{eV}\left(\frac{10^{12}\,\mathrm{GeV}}{f_a}\right)$$

制限

$$10^{8}\ \mathrm{GeV}\ \lesssim\ f_a\ \lesssim\ 10^{12}\ \mathrm{GeV}$$

(b) 中性子星がアクシオンで冷える話

1. 中性子星

2. アクシオン vs Cas A 中性子星

based on KH, N. Nagata, K. Yanagi, J. Zheng, [arXiv:1806.07151]

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(2) Cas A 中性子星の cooling

- Cas A 中性子星 Cooling (観測)
- Cas A 中性子星 Cooling (理論)

(3) Cas A 中性子星の cooling とアクシオン

(4) 「アクシオン vs Cas A 中性子星」のまとめ

Cas A (カシオペヤ座A)

- <u>What?</u>　超新星残骸

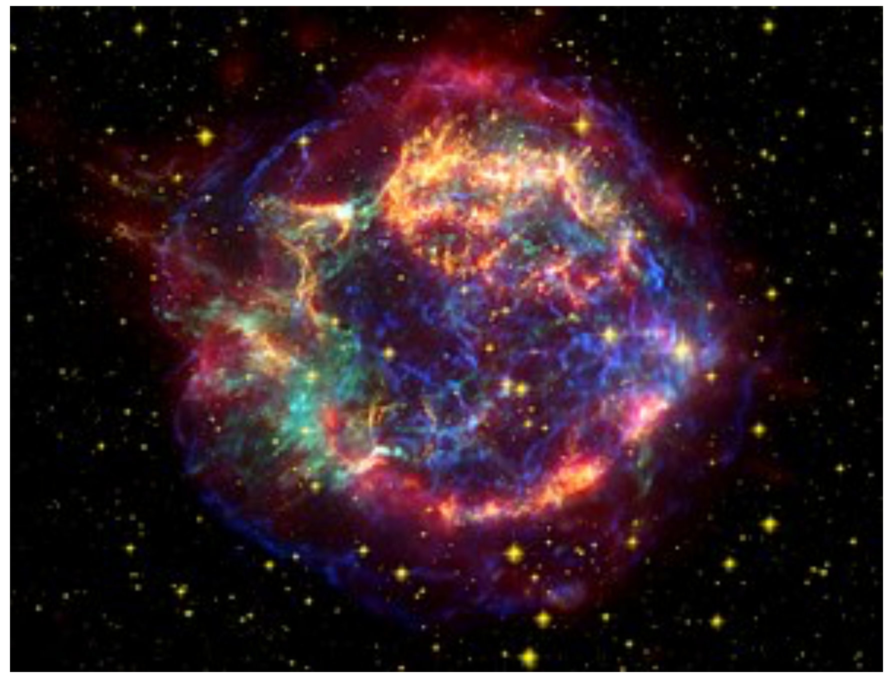


image from Wikipedia

Cas A (カシオペヤ座A)

- **What?**　超新星残骸
- **Where?**

  カシオペヤ座にある。

  地球から 3.4 $^{+0.3}_{-0.1}$ kpc [J.E.Reed et.al. '95] 、 銀河系内。

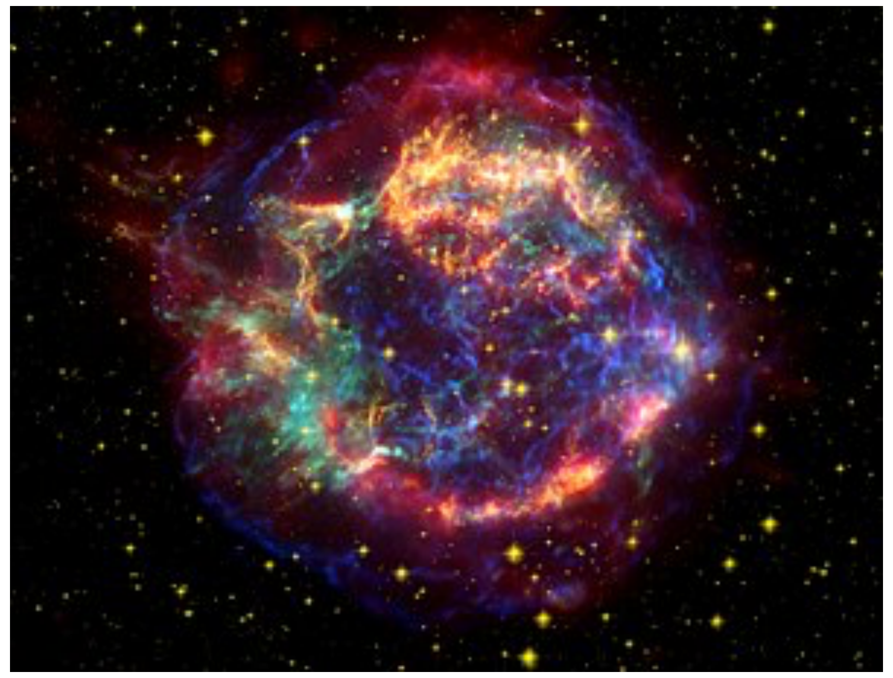
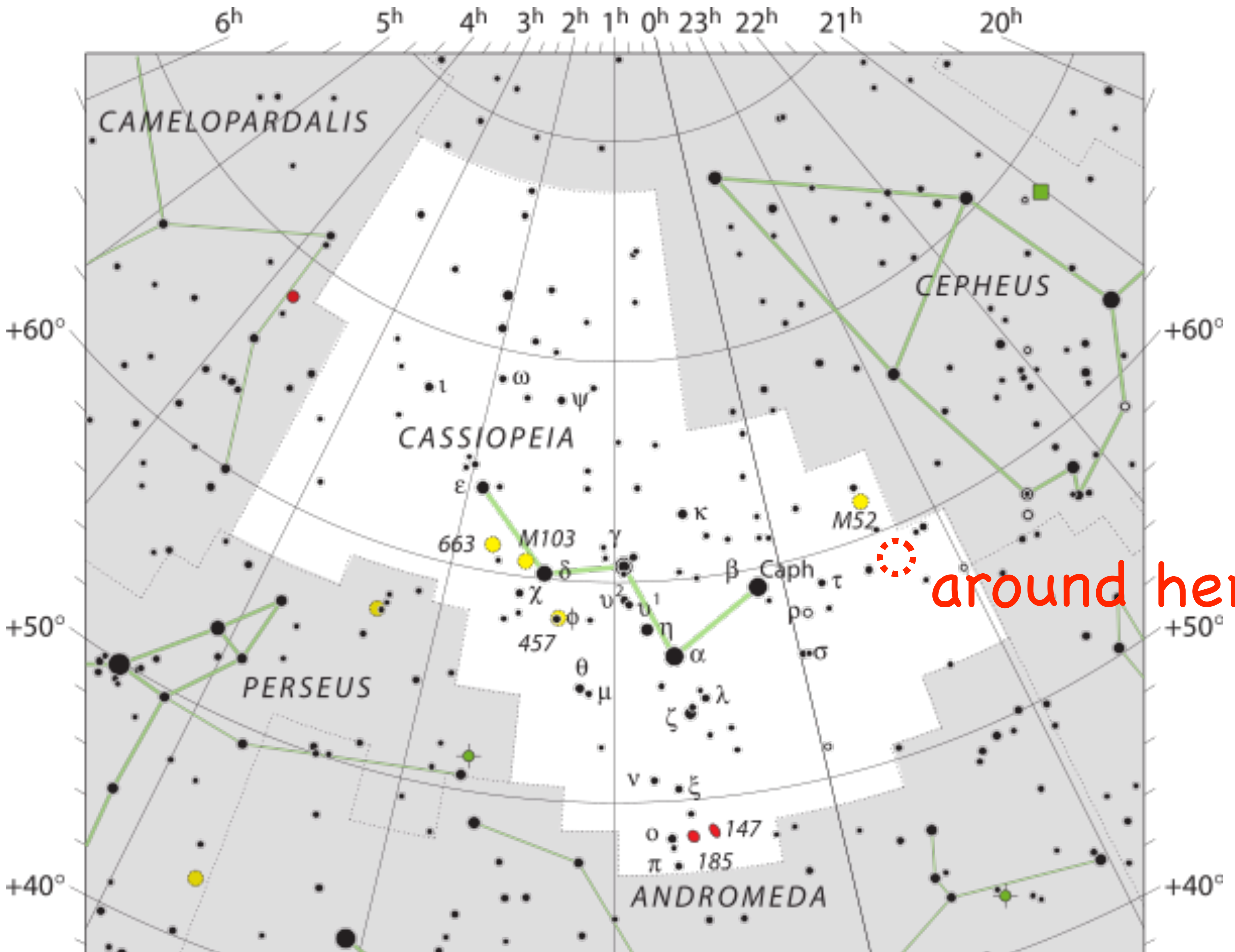


image from Wikipedia



around here

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

Cas A (カシオペヤ座A)

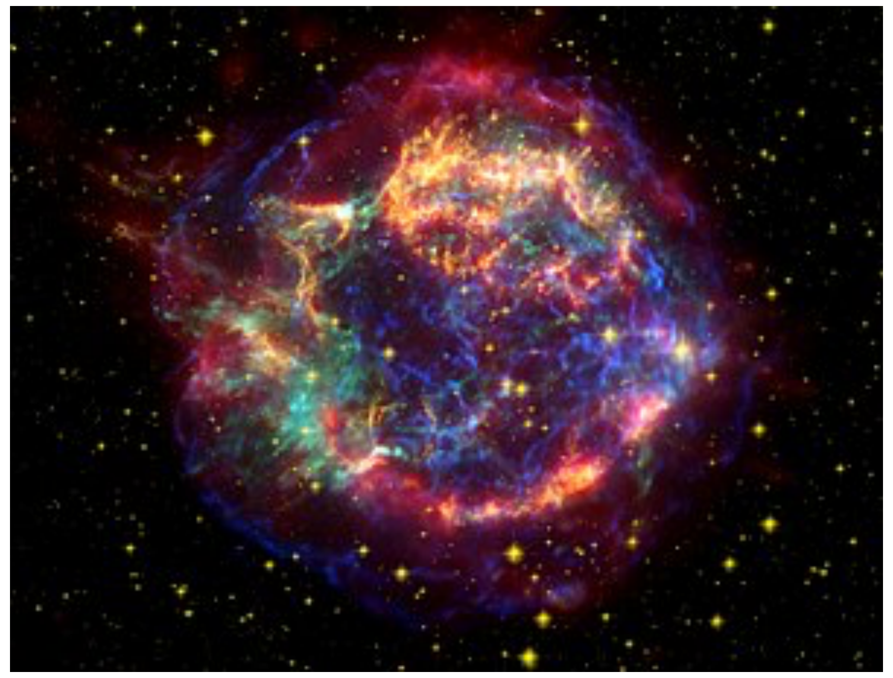


image from Wikipedia

- **What?**　超新星残骸
- **Where?**

  カシオペヤ座にある。

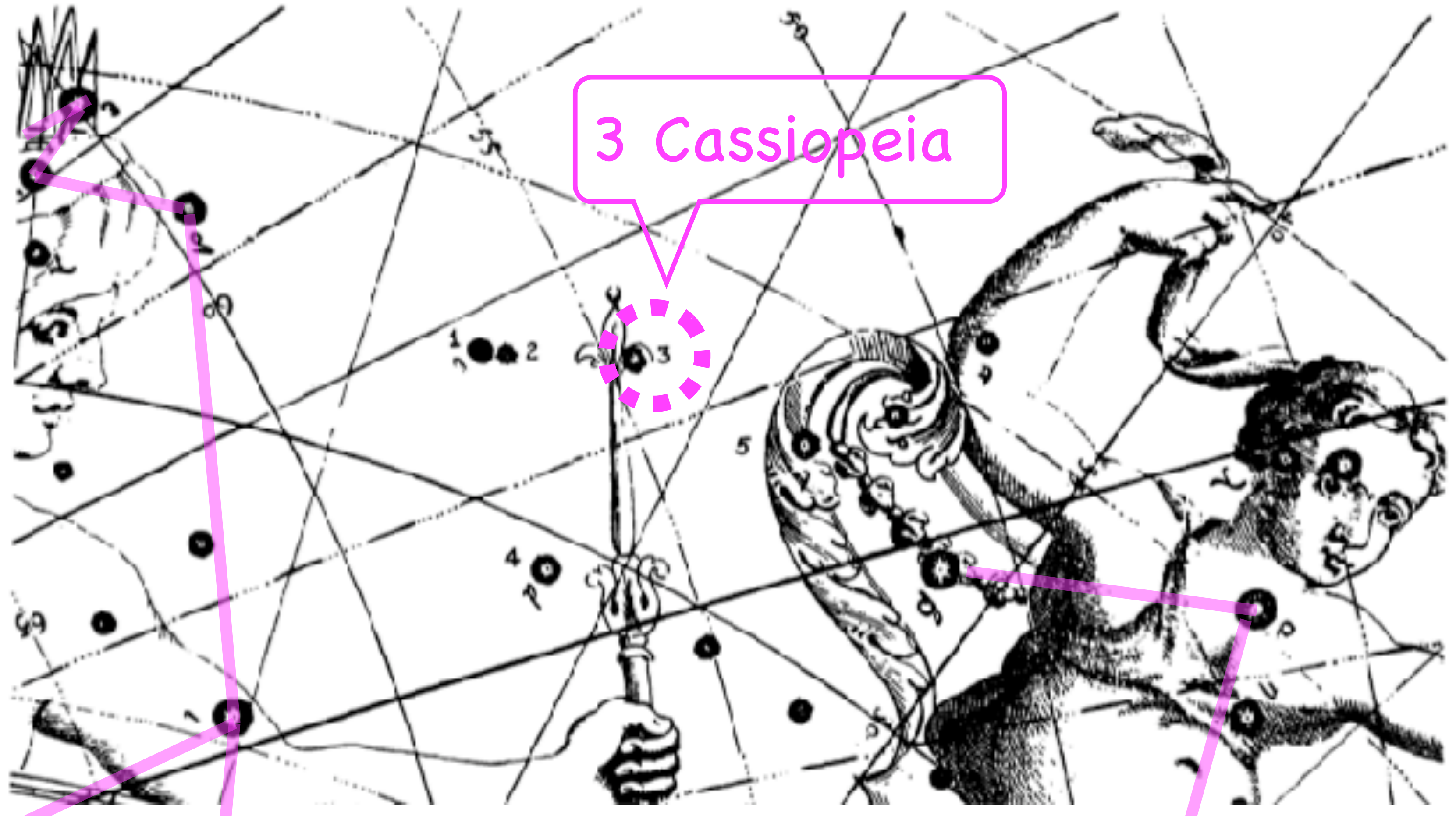
  地球から 3.4 $^{+0.3}_{-0.1}$ kpc [J.E.Reed et.al. '95] .、 銀河系内。
- **When?**

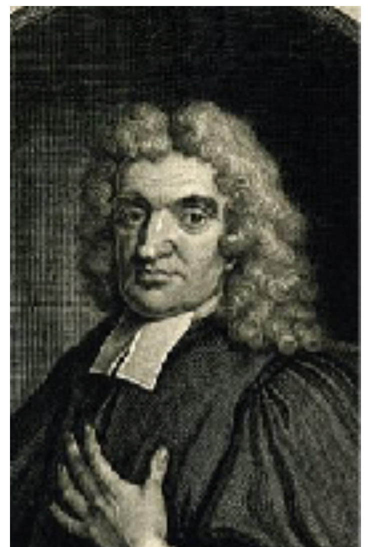
  超新星爆発 (の光が地球に届いたの) は 約 340 年前.

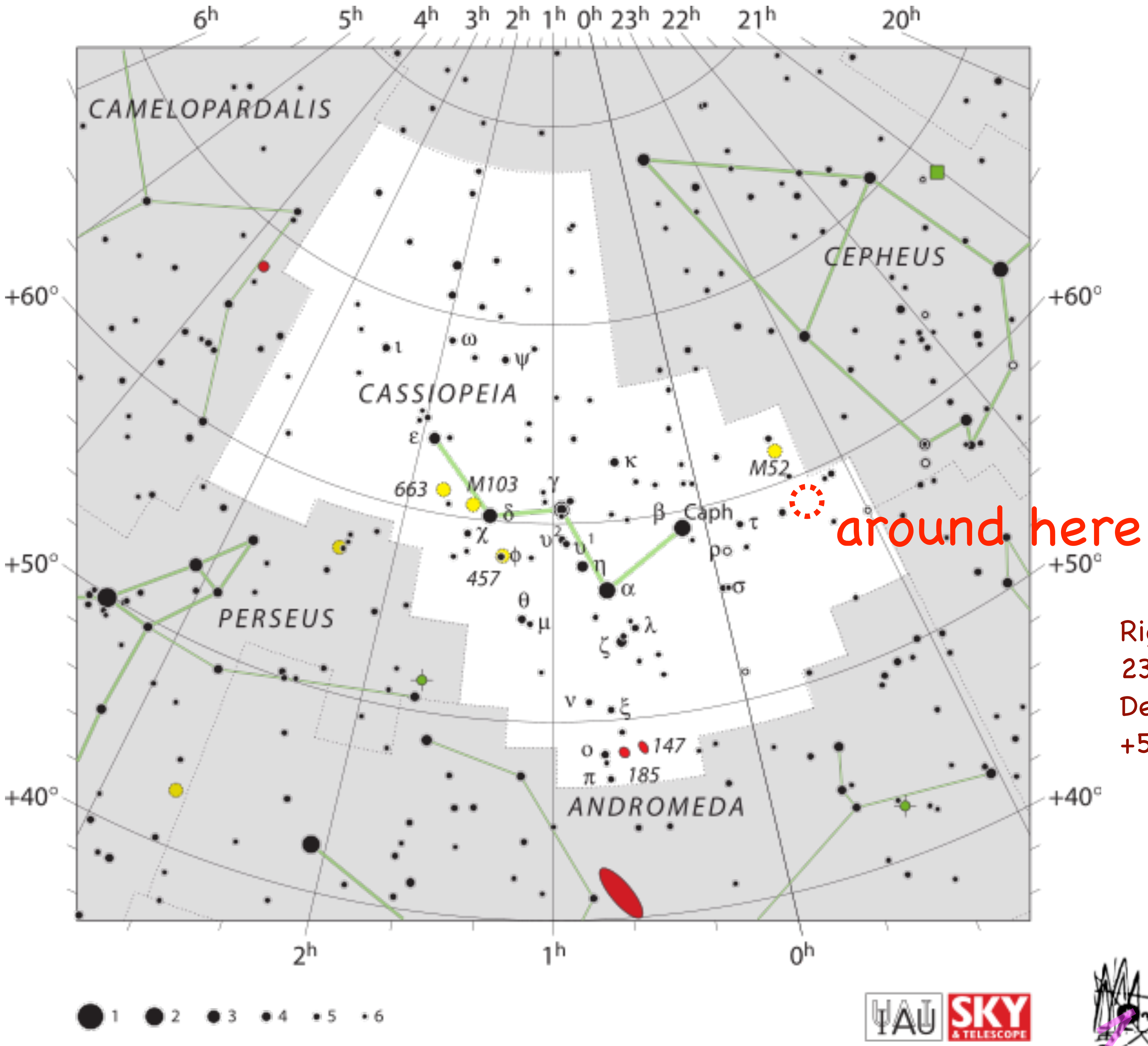
  - 超新星残骸の運動から推定した爆発の年は 1681 ± 19. [R.A.Fesen, et.al., '06]
  - イングランド初代王室天文官の John Flamsteed が1680年8月16日に Cassiopeia 3番星という星を記録。

    ==> その後は観測されていない。

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

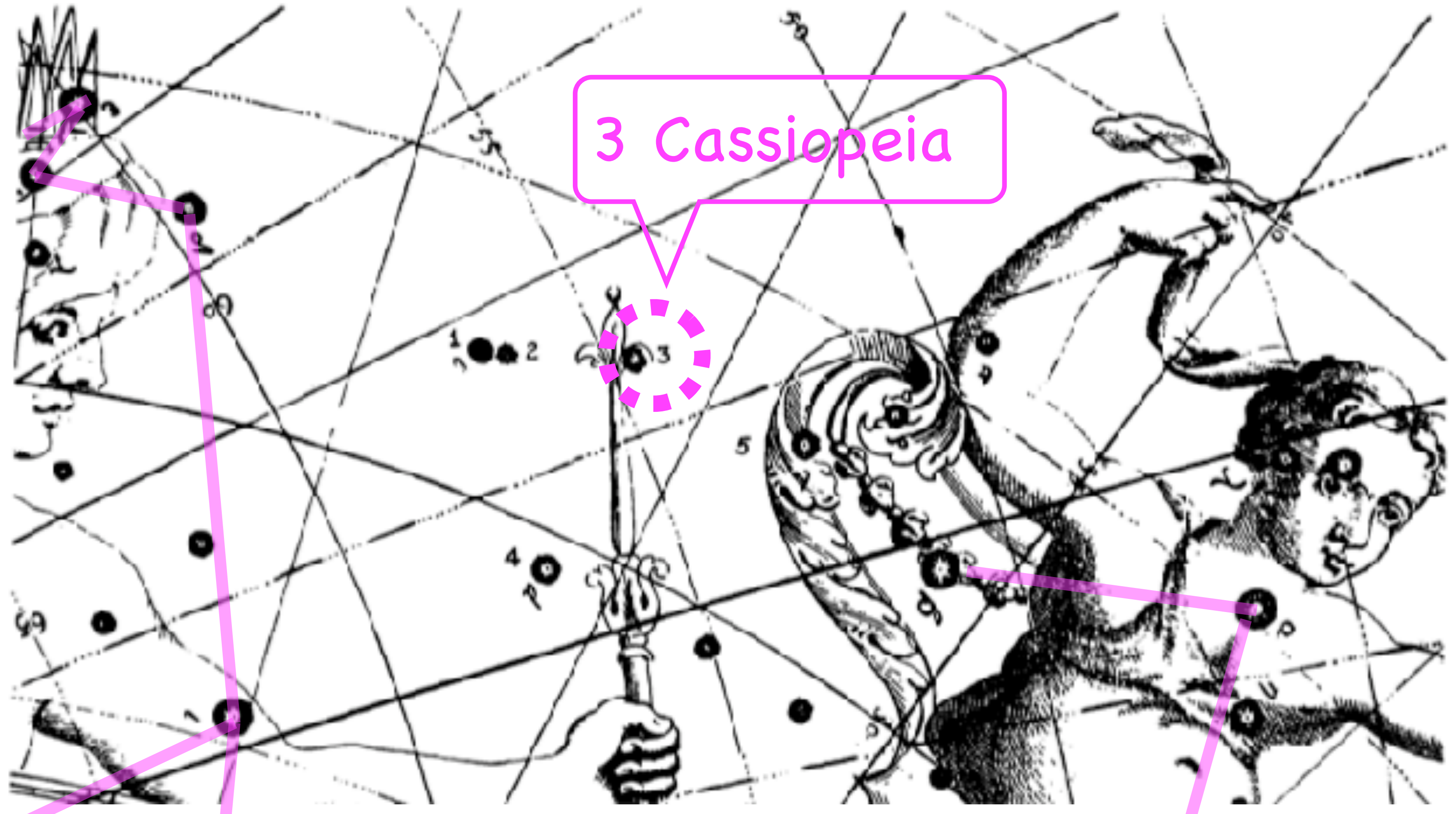



John Flamsteed
(Newtonと色々もめたらしい…)

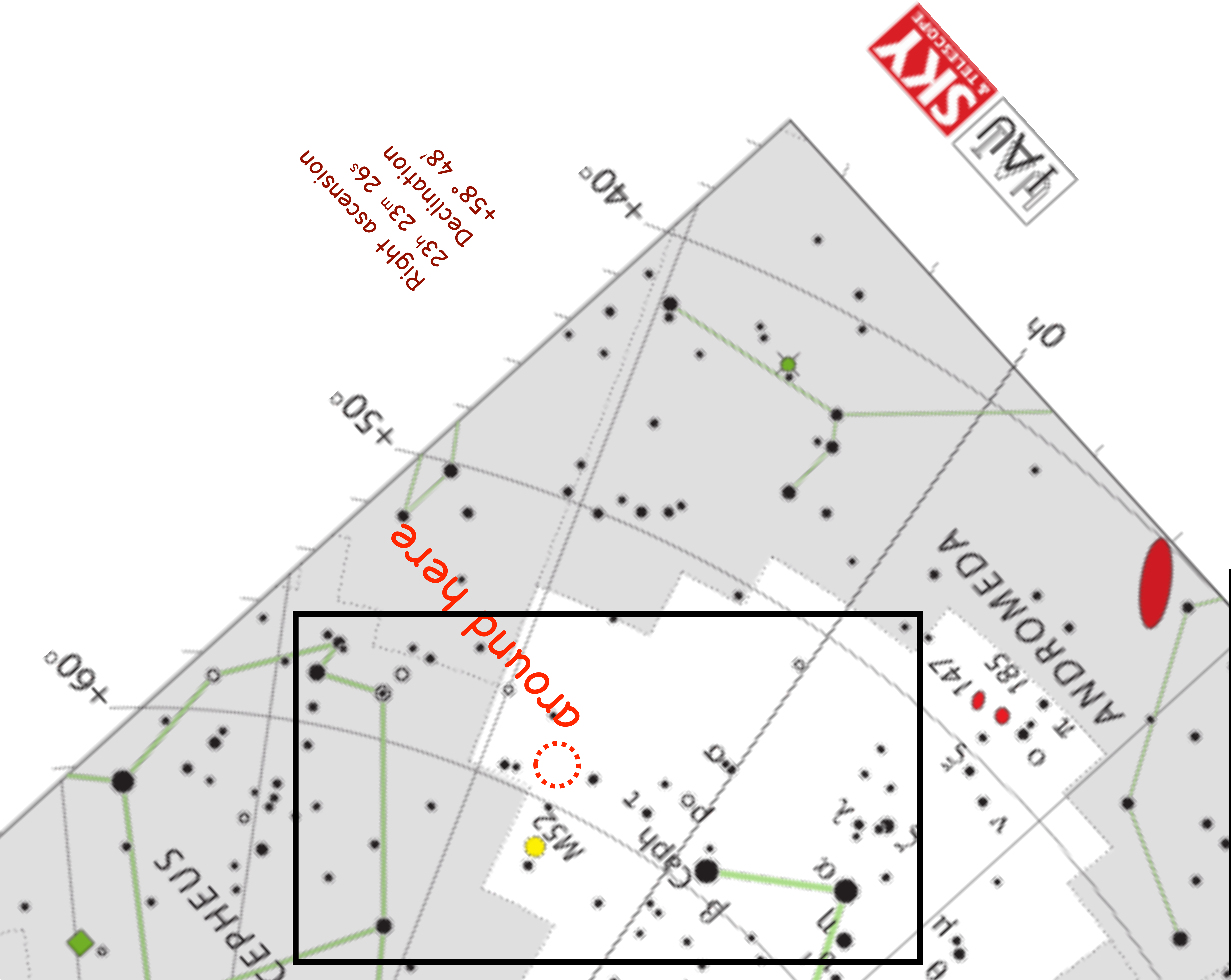


around here

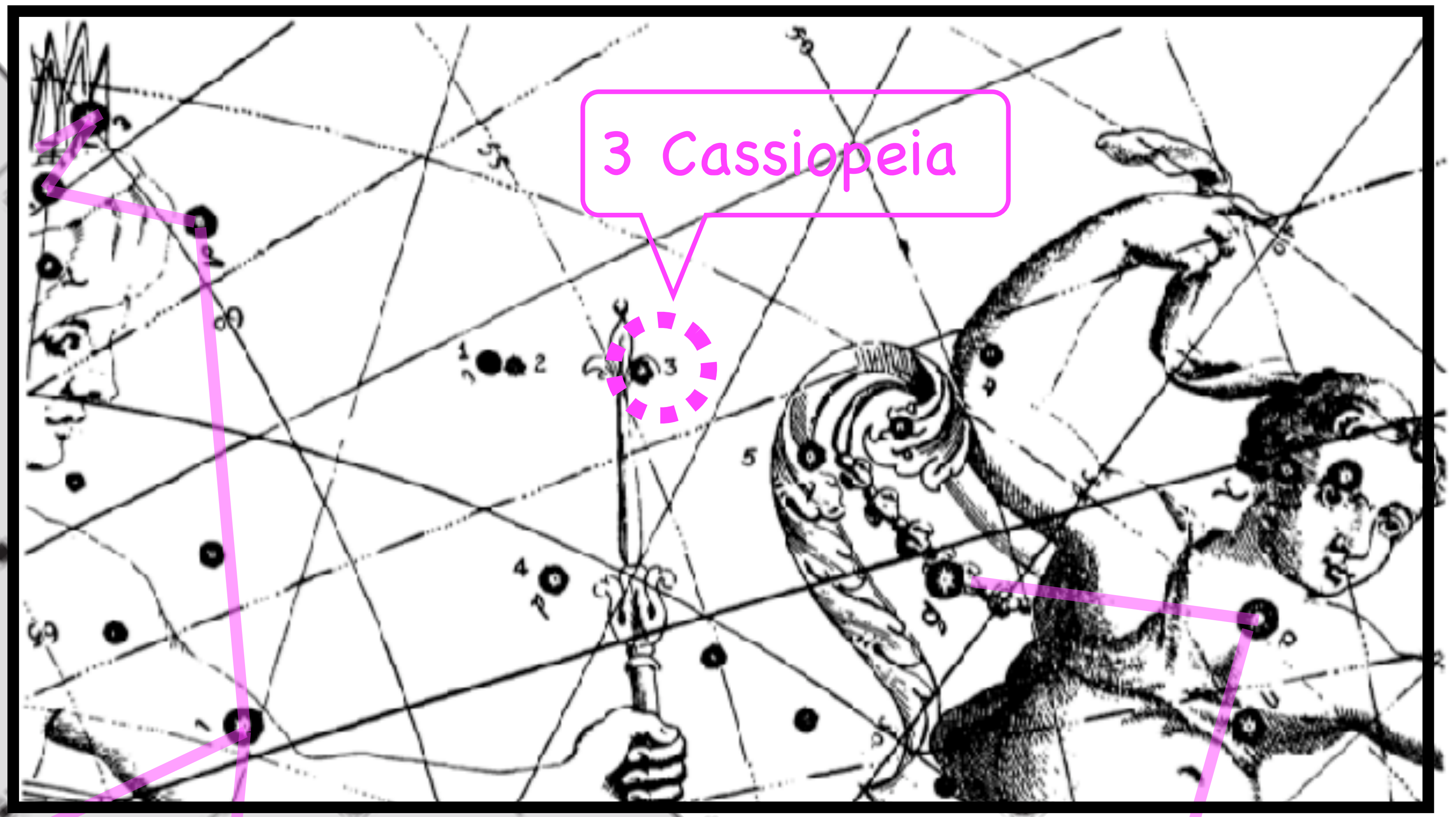
Right ascension
$23^h\ 23^m\ 26^s$
Declination
+58° 48′


3 Cassiopeia

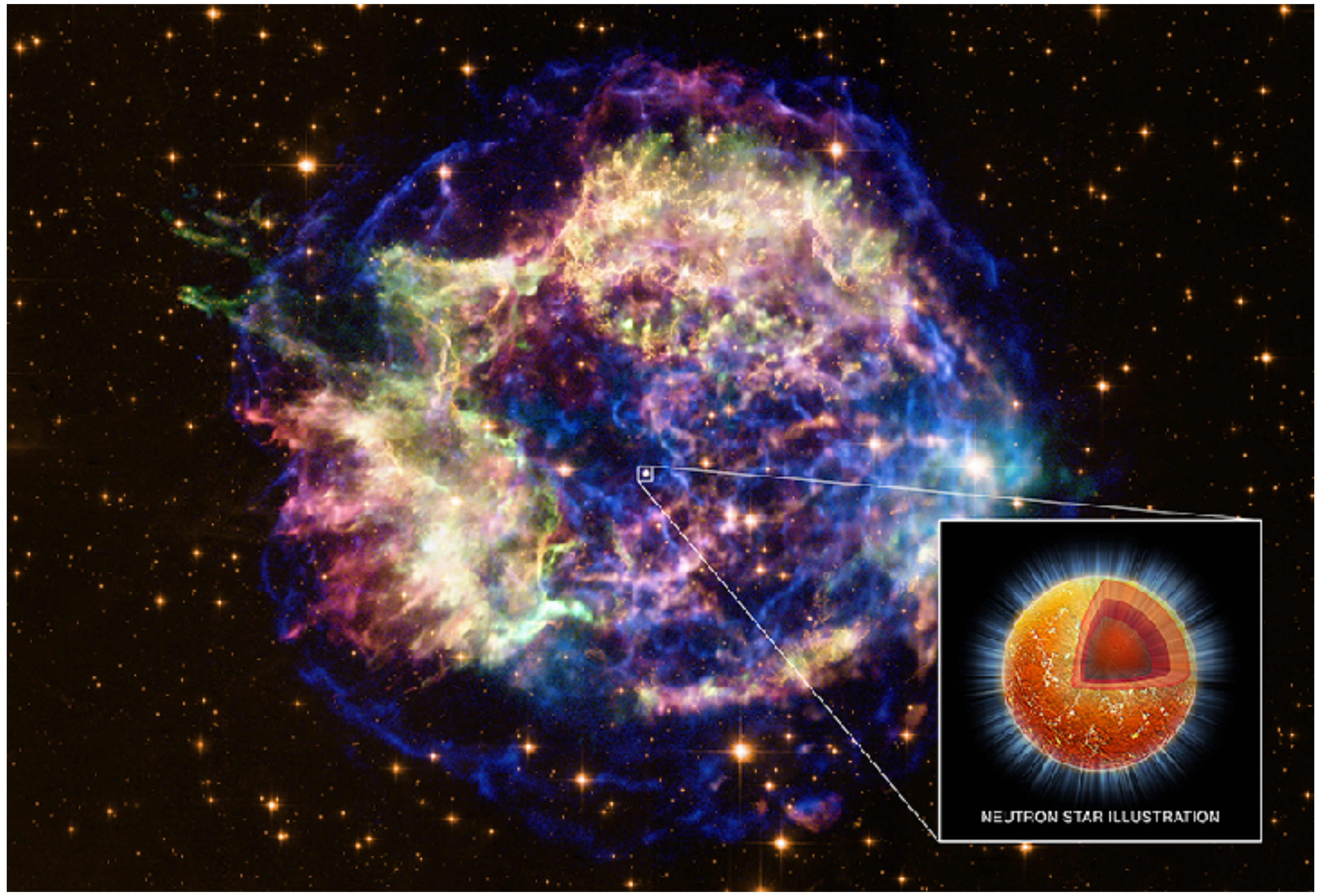
Right ascension
23h 23m 26s
Declination
+58° 48'



around here



Cas A 中性子星



images from Chandra's webpage

- 1999年, チャンドラX線天文衛星が Cas A の中心に暗い点源を発見
- X線スペクトラムは **中性子星** の thermal emission とconsistent.

(質量 $M = (1.4 \pm 0.3) M_{\odot}$, 半径 $R = (11 - 13)\ \mathrm{km}$. Carbon 大気モデルの仮定)

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

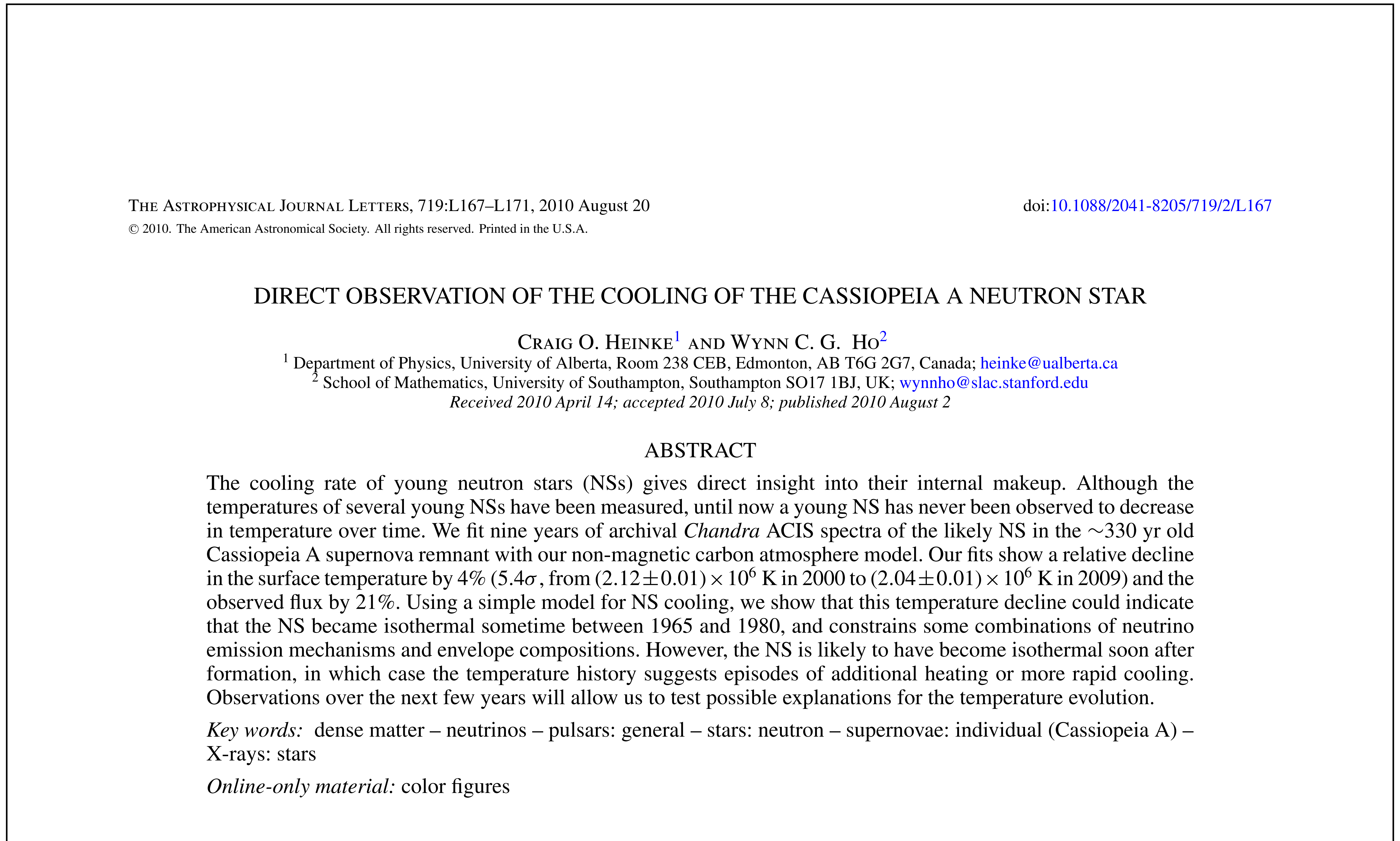
- **さらに・・・**

Cas A NS cooling

- 中性子星の**表面温度の減少 (cooling)** が直接観測された。

(* cooling が直接観測されている孤立中性子星は今のところこの Cas A NS だけ。)

温度の減少は、10年で数%



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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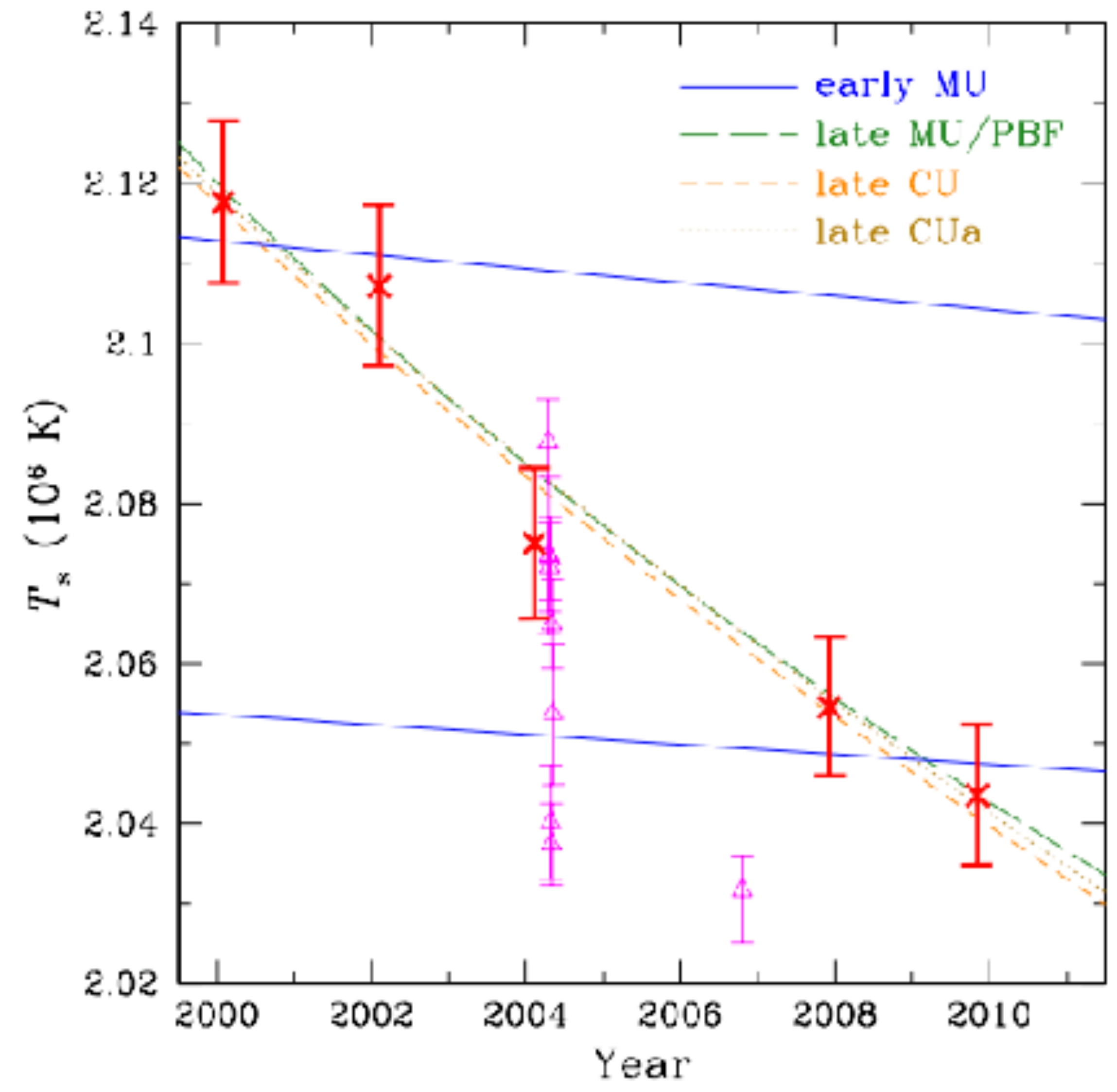
ABSTRACT

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

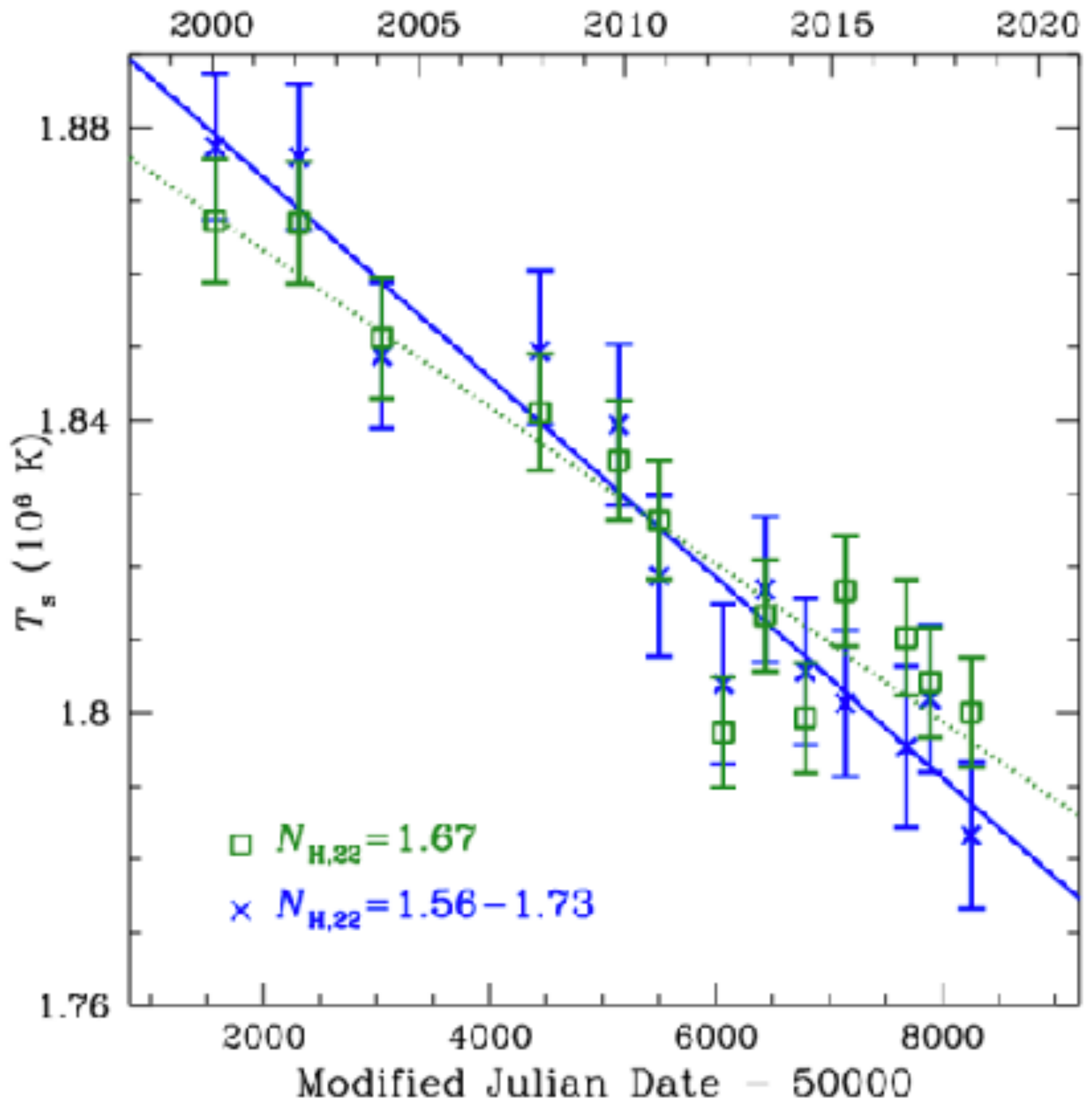
- 中性子星の表面温度の減少 (cooling) が直接観測された。

(* cooling が直接観測されている孤立中性子星は今のところこの Cas A NS だけ。)

温度の減少は、10年で数%

More Recent data:

M. Beznogov, P. Chang, C. O. Heinke, W. C. Ho, D. Page, D. J. Patnaude, M. Wijngaarden [arXiv:1901.01012]



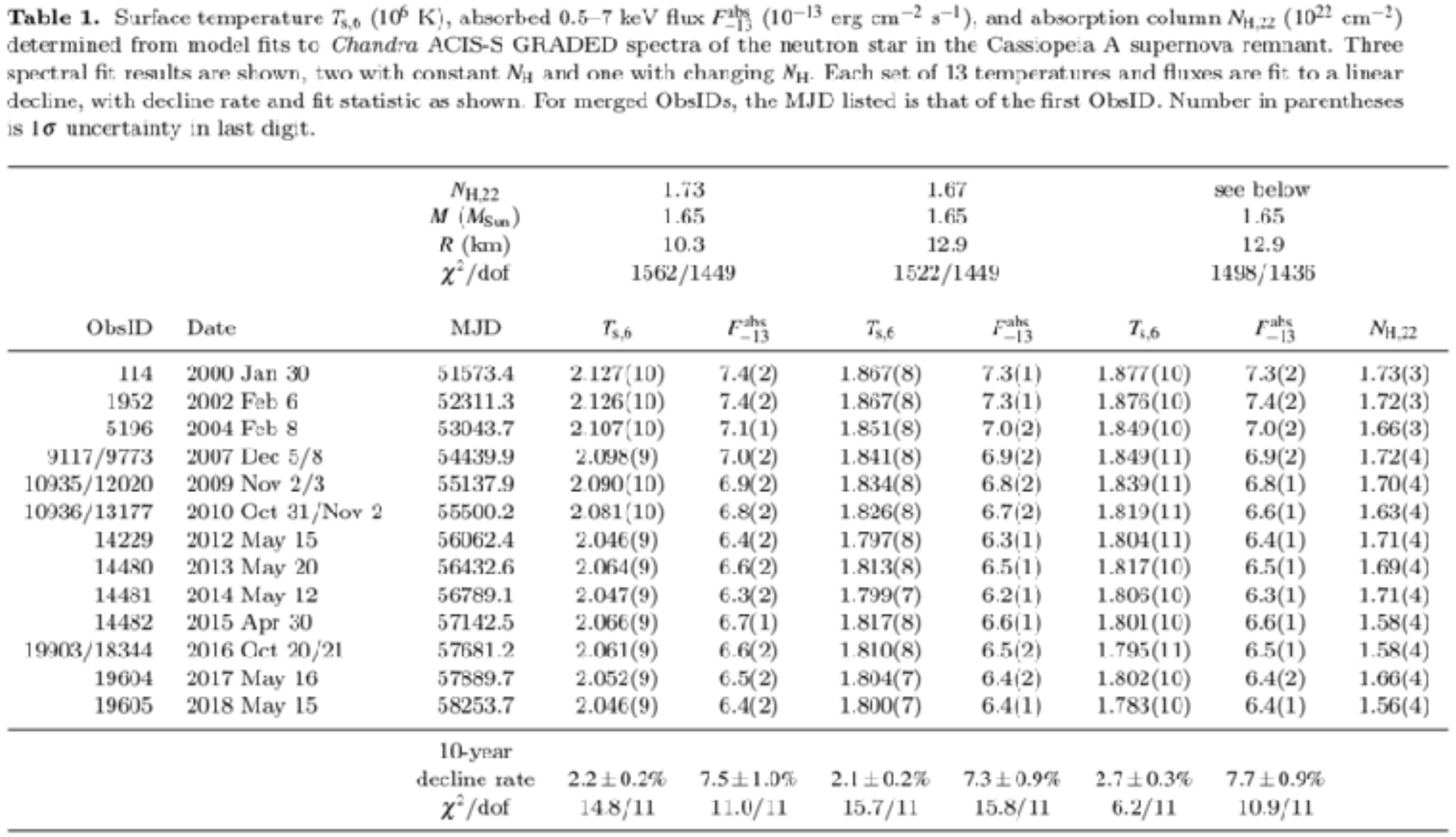


Table 1. Surface temperature $T_{s,6}$ (10^6 K), absorbed 0.5–7 keV flux $F^{\rm abs}_{-13}$ (10^{-13} erg cm^{-2} s^{-1}), and absorption column $N_{\rm H,22}$ (10^{22} cm^{-2}) determined from model fits to *Chandra* ACIS-S GRADED spectra of the neutron star in the Cassiopeia A supernova remnant. Three spectral fit results are shown, two with constant $N_{\rm H}$ and one with changing $N_{\rm H}$. Each set of 13 temperatures and fluxes are fit to a linear decline, with decline rate and fit statistic as shown. For merged ObsIDs, the MJD listed is that of the first ObsID. Number in parentheses is 1σ uncertainty in last digit.

		$N_{\rm H,22}$	1.73		1.67		see below		
		M ($M_{\rm Sun}$)	1.65		1.65		1.65		
		R (km)	10.3		12.9		12.9		
		χ^2/dof	1562/1449		1522/1449		1498/1436		
ObsID	Date	MJD	$T_{s,6}$	$F^{\rm abs}_{-13}$	$T_{s,6}$	$F^{\rm abs}_{-13}$	$T_{s,6}$	$F^{\rm abs}_{-13}$	$N_{\rm H,22}$
114	2000 Jan 30	51573.4	2.127(10)	7.4(2)	1.867(8)	7.3(1)	1.877(10)	7.3(2)	1.73(3)
1952	2002 Feb 6	52311.3	2.126(10)	7.4(2)	1.867(8)	7.3(1)	1.876(10)	7.4(2)	1.72(3)
5196	2004 Feb 8	53043.7	2.107(10)	7.1(1)	1.851(8)	7.0(2)	1.849(10)	7.0(2)	1.66(3)
9117/9773	2007 Dec 5/8	54439.9	2.098(9)	7.0(2)	1.841(8)	6.9(2)	1.849(11)	6.9(2)	1.72(4)
10935/12020	2009 Nov 2/3	55137.9	2.090(10)	6.9(2)	1.834(8)	6.8(2)	1.839(11)	6.8(1)	1.70(4)
10936/13177	2010 Oct 31/Nov 2	55500.2	2.081(10)	6.8(2)	1.826(8)	6.7(2)	1.819(11)	6.6(1)	1.63(4)
14229	2012 May 15	56062.4	2.046(9)	6.4(2)	1.797(8)	6.3(1)	1.804(11)	6.4(1)	1.71(4)
14480	2013 May 20	56432.6	2.064(9)	6.6(2)	1.813(8)	6.5(1)	1.817(10)	6.5(1)	1.69(4)
14481	2014 May 12	56789.1	2.047(9)	6.3(2)	1.799(7)	6.2(1)	1.806(10)	6.3(1)	1.71(4)
14482	2015 Apr 30	57142.5	2.066(9)	6.7(1)	1.817(8)	6.6(1)	1.801(10)	6.6(1)	1.58(4)
19903/18344	2016 Oct 20/21	57681.2	2.061(9)	6.6(2)	1.810(8)	6.5(2)	1.795(11)	6.5(1)	1.58(4)
19604	2017 May 16	57889.7	2.052(9)	6.5(2)	1.804(7)	6.4(2)	1.802(10)	6.4(2)	1.66(4)
19605	2018 May 15	58253.7	2.046(9)	6.4(2)	1.800(7)	6.4(1)	1.783(10)	6.4(1)	1.56(4)
		10-year decline rate	2.2 ± 0.2%	7.5 ± 1.0%	2.1 ± 0.2%	7.3 ± 0.9%	2.7 ± 0.3%	7.7 ± 0.9%	
		χ^2/dof	14.8/11	11.0/11	15.7/11	15.8/11	6.2/11	10.9/11	

(b) 中性子星がアクシオンで冷える話

1. 中性子星

2. アクシオン vs Cas A 中性子星

based on KH, N. Nagata, K. Yanagi, J. Zheng, [arXiv:1806.07151]

(1) アクシオン mini review

(2) Cas A 中性子星の cooling

- Cas A 中性子星 Cooling (観測)
- Cas A 中性子星 Cooling (理論)

(3) Cas A 中性子星の cooling とアクシオン

(4) 「アクシオン vs Cas A 中性子星」のまとめ

Cas A NS Cooling (理論)

中性子星の温度発展の式

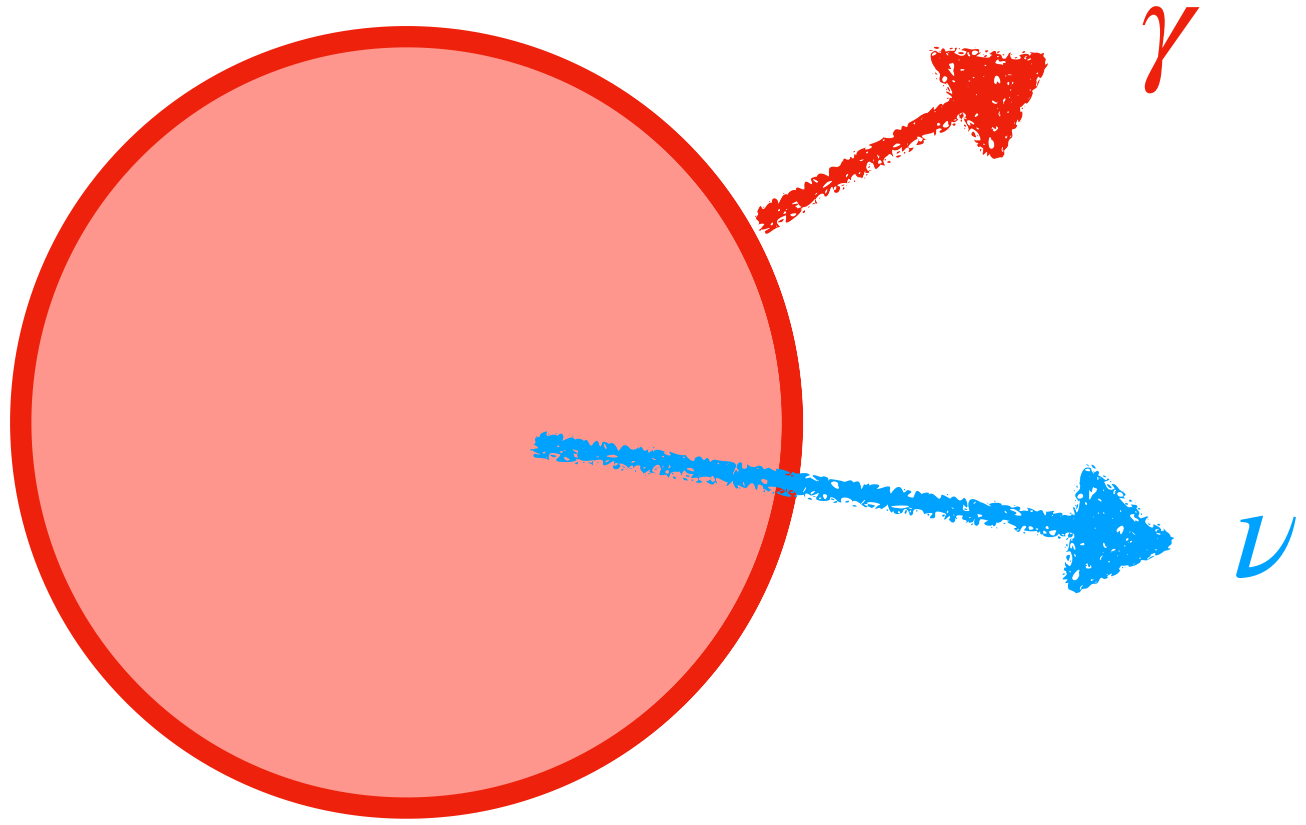
$$C\frac{dT}{dt} = -L_\nu - L_\gamma$$

Photon emission
luminosity. (dE_γ/dt)

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

Neutrino emission
luminosity. (dE_ν/dt)

Heat Capacity of the NS.
$C = dE_{\rm thermal}/dT$



※ assuming isothermal state $T(r) \propto e^{-\phi(r)}$ for simplicity.
In the numerical calculation, we followed $T(r,t)$.

Cas A NS Cooling (理論)

中性子星の温度発展の式

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

Photon emission
luminosity. (dE_γ/dt)

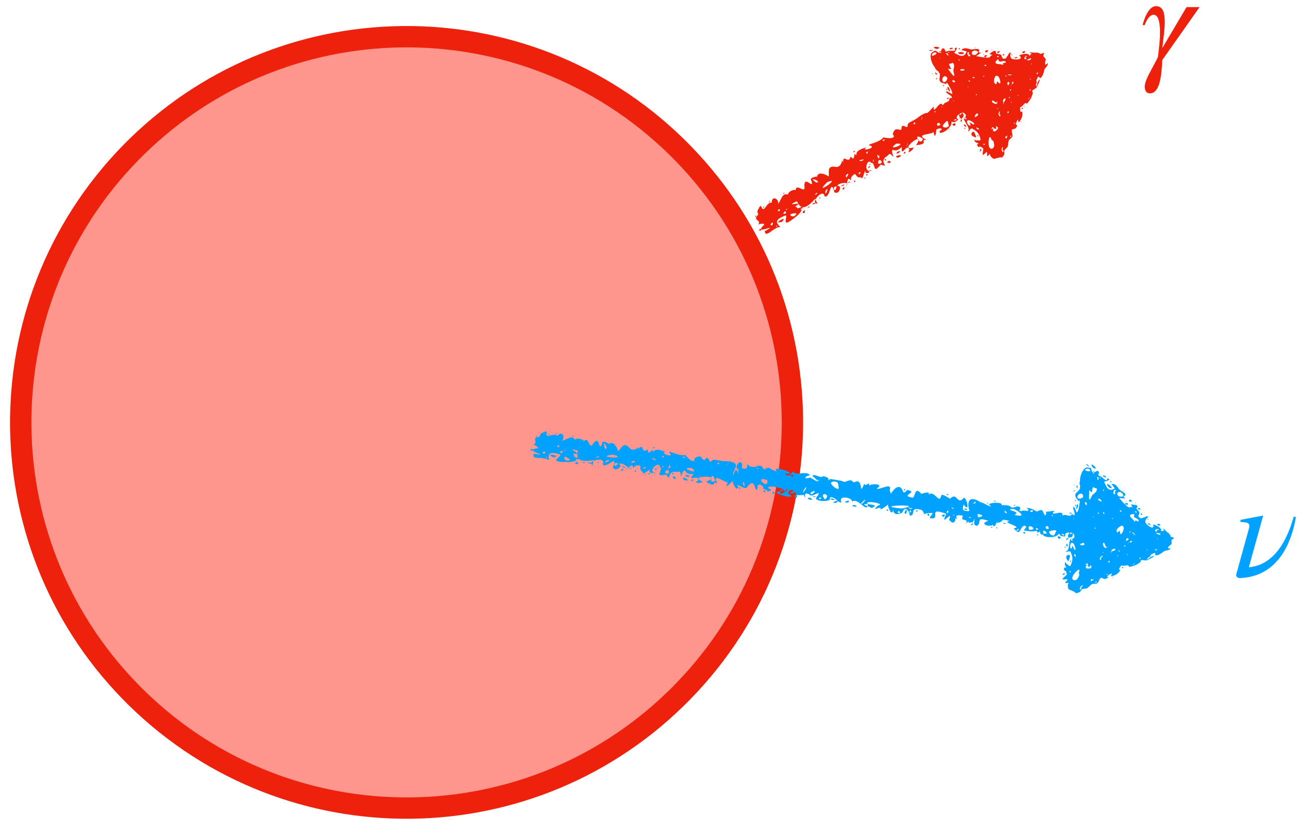
$$L_\gamma = 4\pi R^2 \sigma_{\mathrm{SB}} T_s^4$$

Neutrino emission
luminosity. (dE_ν/dt)

Heat Capacity of the NS.
C = dE_{thermal}/dT

$$L_\gamma \ll L_\nu \quad \text{for} \quad t \lesssim 10^6 \text{ years}$$

Cas A NS ($t \sim 300$ yrs) の場合は
photon emission は無視できる



Cas A NS Cooling (理論)

中性子星の温度発展の式

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luminosity. (dE_ν/dt)

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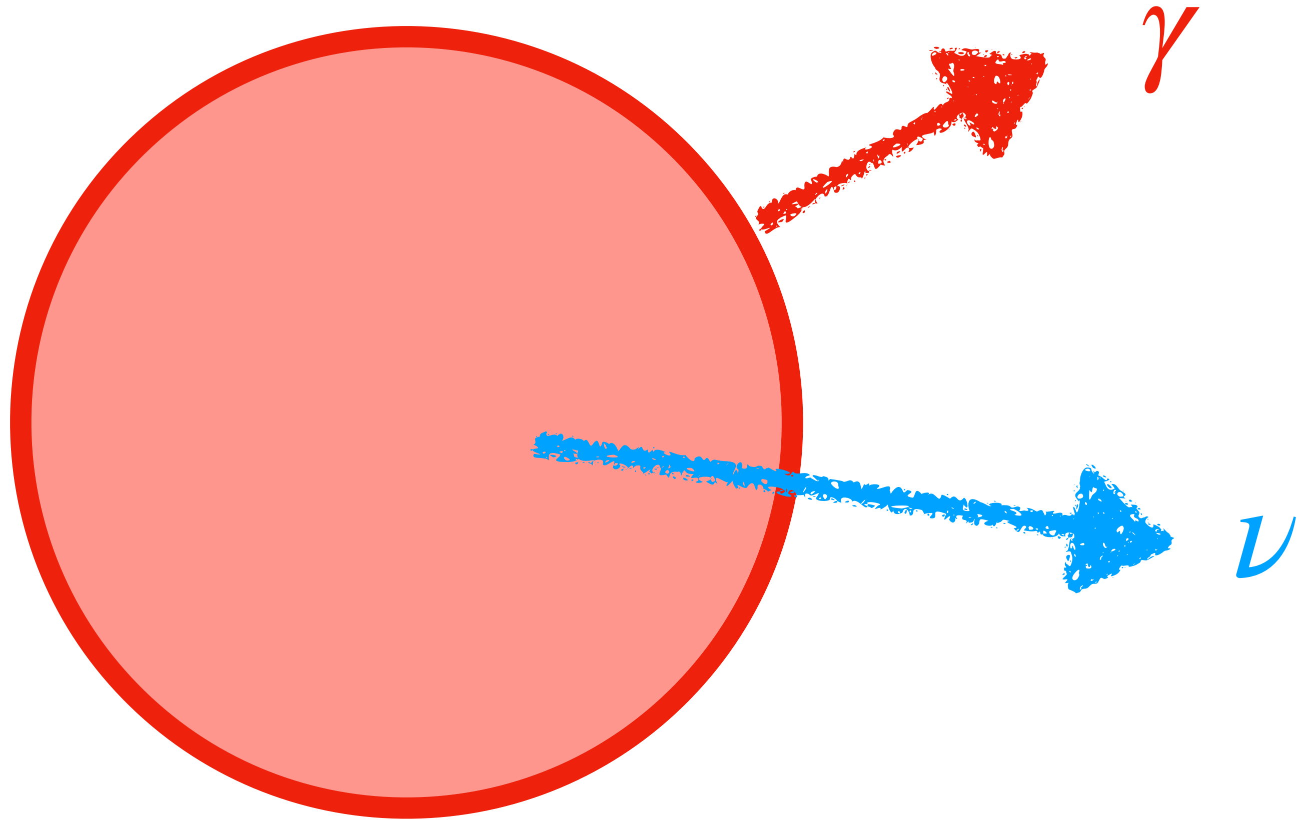
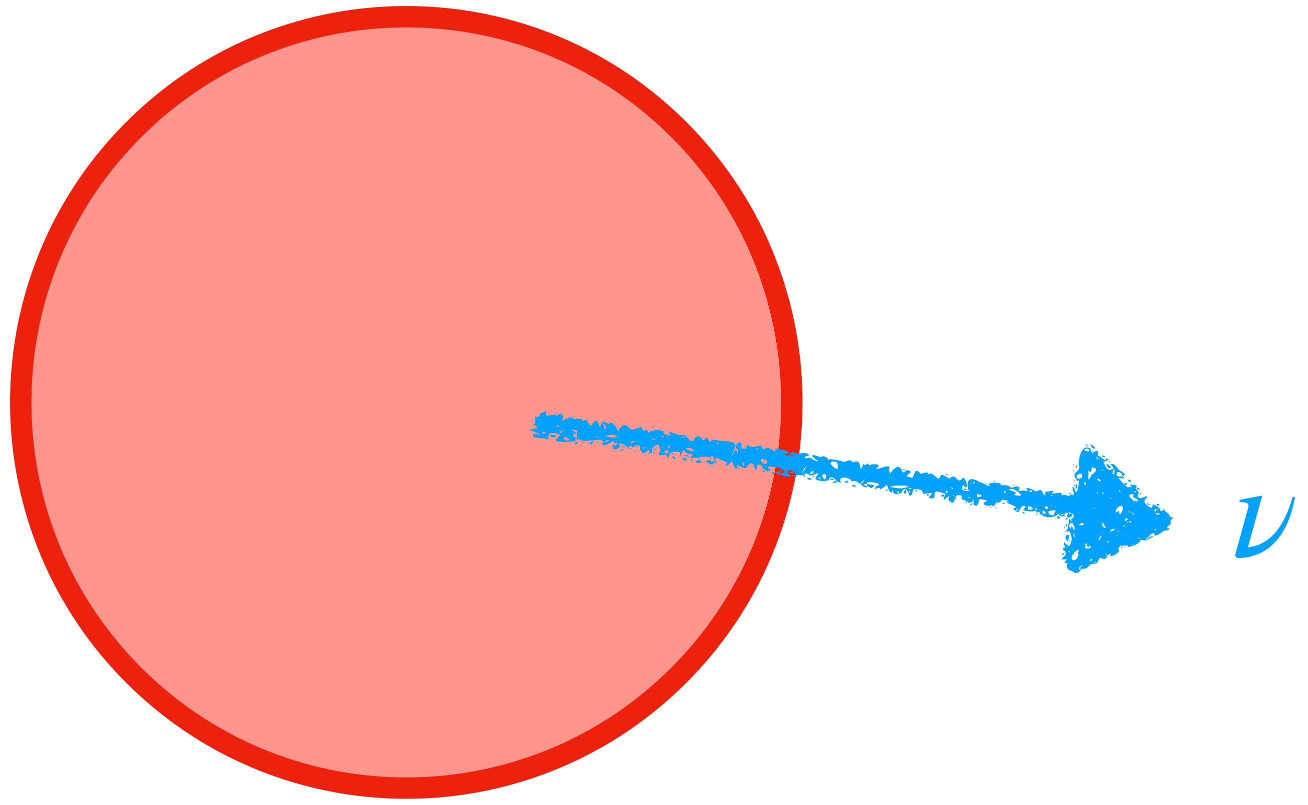


Cas A NS Cooling (理論)

中性子星の温度発展の式

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

- Direct Urca
- Modified Urca
- Bremsstrahlung
- PBF



Cas A NS Cooling (理論)

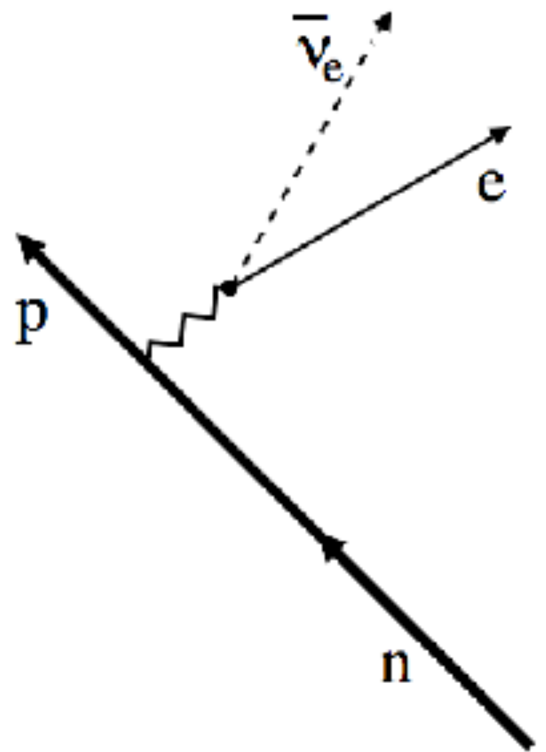
中性子星の温度発展の式

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

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

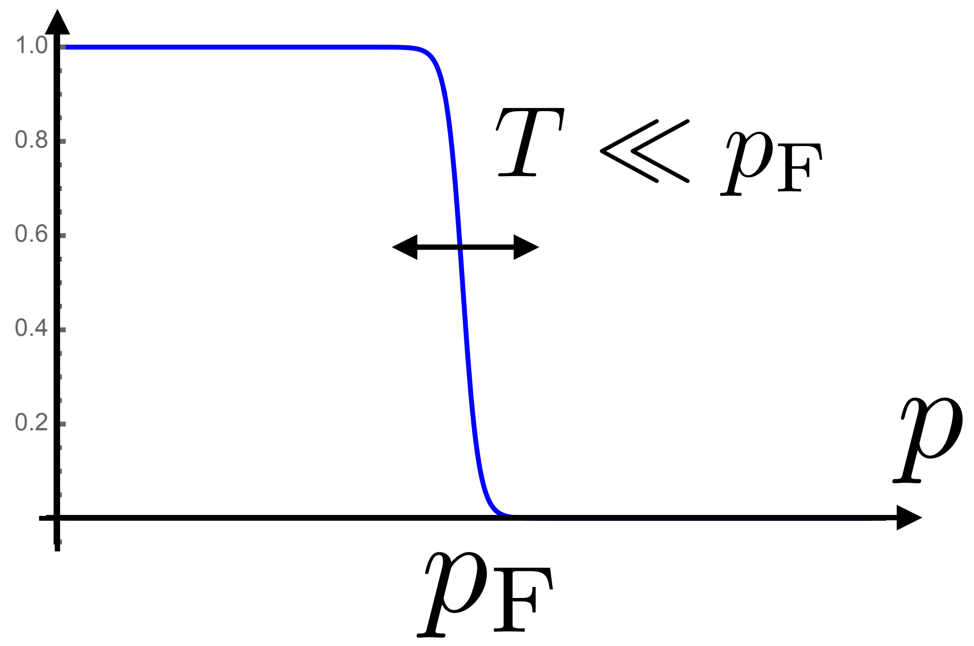
β 崩壊とその逆過程

$$\begin{cases} n \;\rightarrow\; p + e^- + \bar{\nu}_e \\ p + e^- \;\rightarrow\; n + \nu_e \end{cases}$$



- 運動量保存から $p_{F,p} + p_{F,e} > p_{F,n}$ が必要。
  重い中性子星でのみ発動。Cas A NS では unlikely.
- 仮に発動したとしても、年齢300年くらいでの温度が低くなりすぎて、**観測値を説明出来ない**。

※ 中性子、陽子、電子、全て**フェルミ縮退**している。



Cas A NS Cooling (理論)

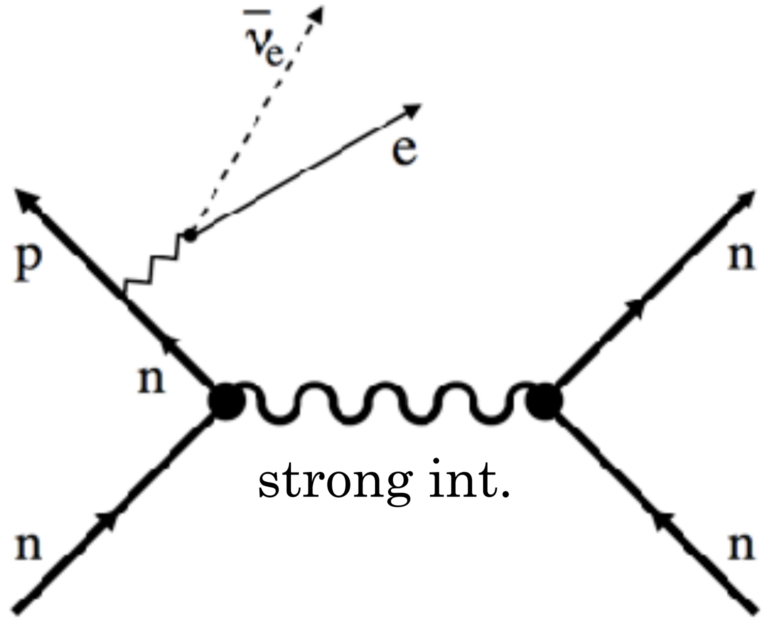
中性子星の温度発展の式

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

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

$$\begin{cases} n + N \;\to\; p + N + e^- + \bar{\nu}_e \\ p + N + e^- \;\to\; n + N + \nu_e \end{cases}$$

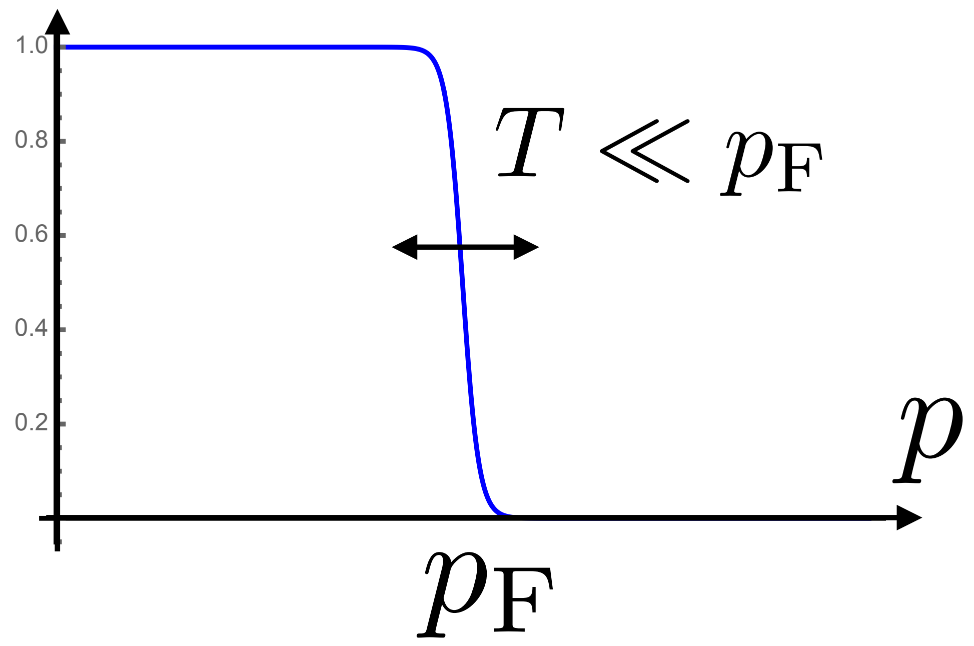
$$(N = n \text{ or } p)$$



- **Dominant process** (before the onset of Cooper pairing)
- $L_\nu^{\mathrm{MU}} \propto T^8$

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

※ 中性子、陽子、電子、全て**フェルミ縮退**している。



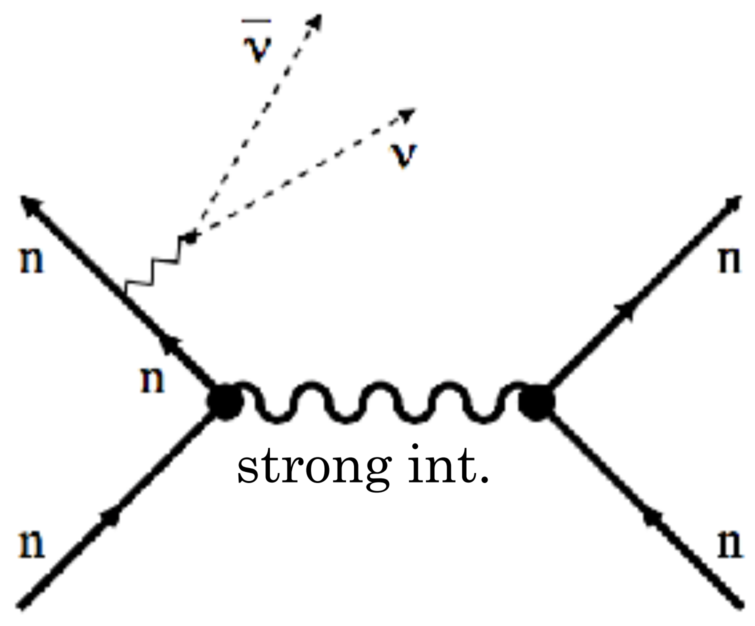
Cas A NS Cooling (理論)

中性子星の温度発展の式

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

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

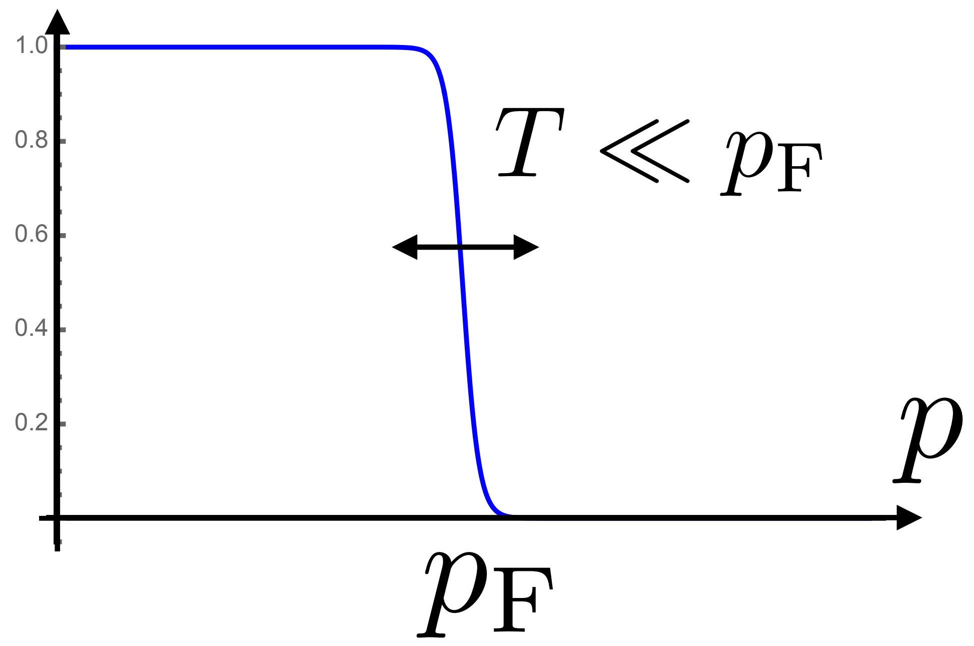
$$N + N' \;\rightarrow\; N + N' + \nu + \bar{\nu}$$
$$(N, N' = n \text{ or } p)$$



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

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

※ 中性子、陽子、電子、全て
フェルミ縮退している。



Cas A NS Cooling (理論)

中性子星の温度発展の式

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

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

また後で戻ってきます。

Cas A NS Cooling (理論)

中性子星の温度発展の式

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

$\propto T$

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

For Cas A NS observation,

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

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

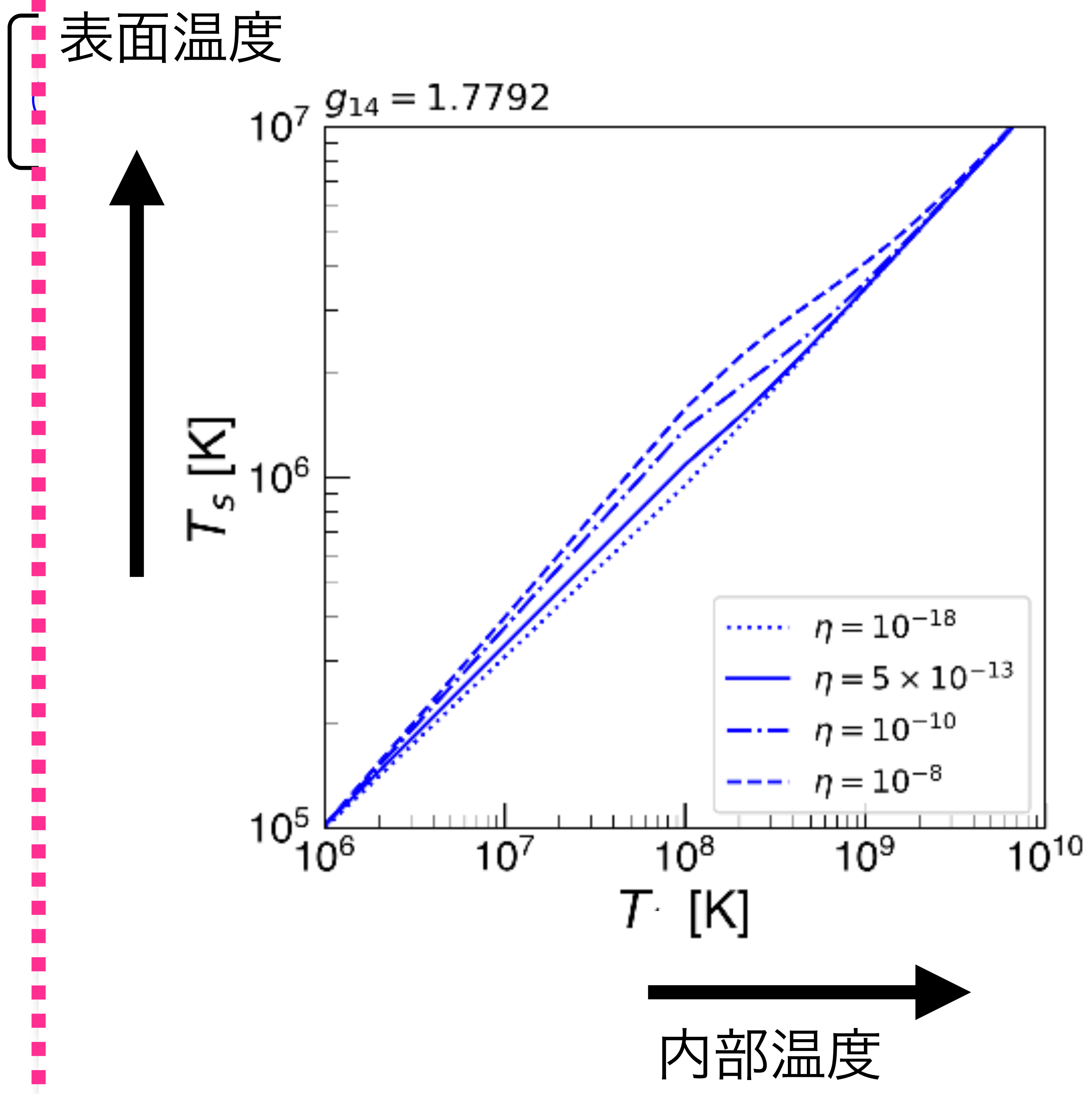
surface temperature

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

Cas A NS Cooling (理論)

表面温度と内部温度

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



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

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,

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

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

surface temperature

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

Cas A NS Cooling (理論)

中性子星の温度発展の式

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

$\propto T$

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

For Cas A NS observation,

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

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surface temperature

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

観測されている温度減少 $\Delta T_s/T_s \sim (3-4)\,\%$ に比べて遅すぎる！

Cas A NS Cooling (理論)

中性子星の温度発展の式

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

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

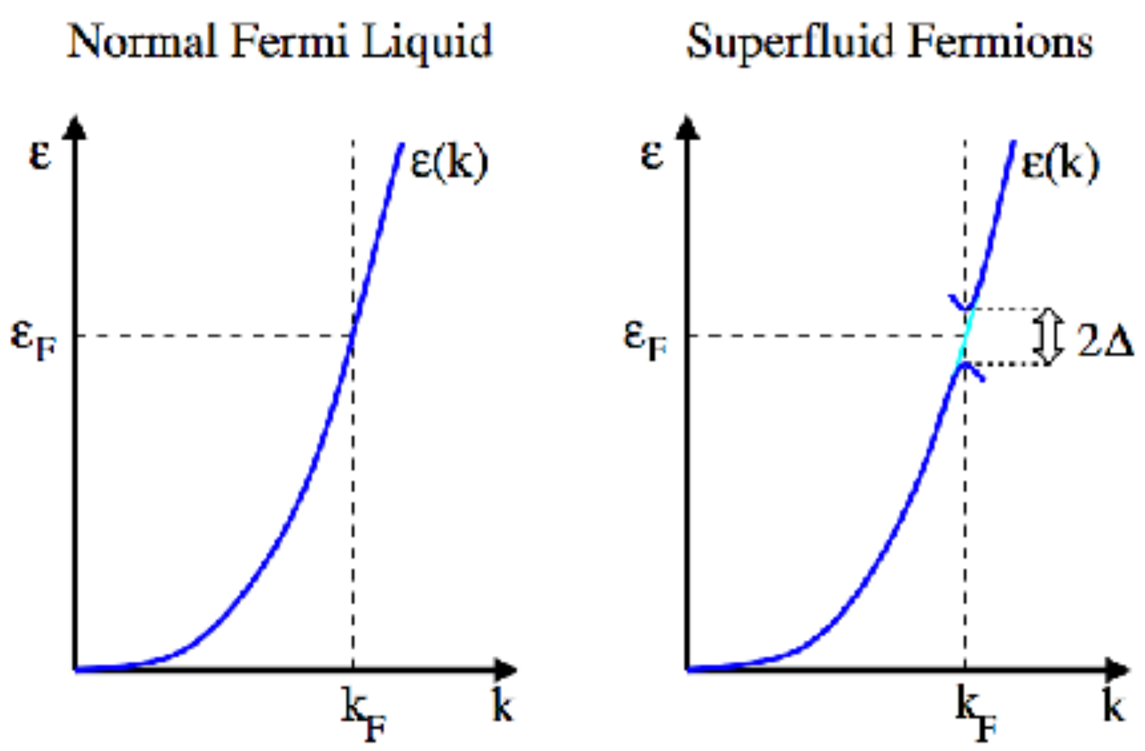
Cas A NS Cooling (理論)

中性子星の温度発展の式

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

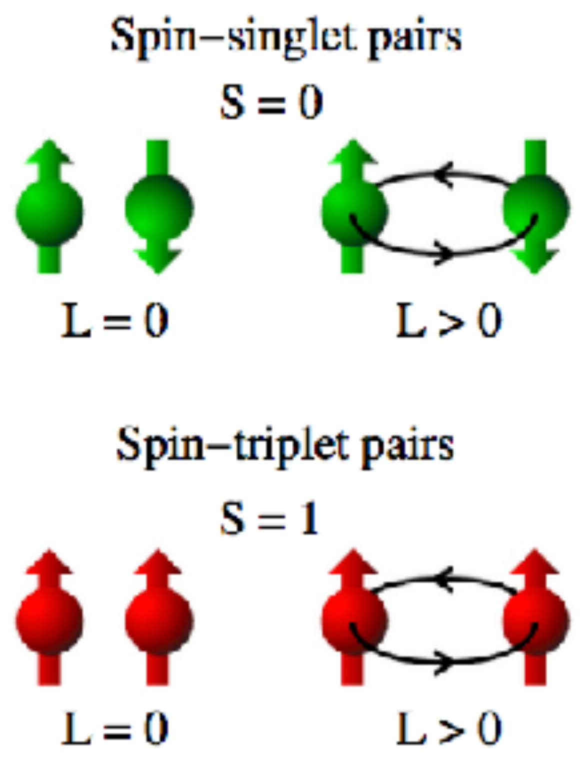
- ~~Direct Urca~~
- Modified Urca
- Bremsstrahlung
- **PBF**

- 中性子星内では温度が下がると核子が**クーパー対**を形成する。



T > Tc T < Tc

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



- M.Urca と Brems. は suppress される.
- 一方、新たなプロセスである **Cooper pair breaking and formation (PBF)** が発動。

Figs. from Page et.al. 1302.6626

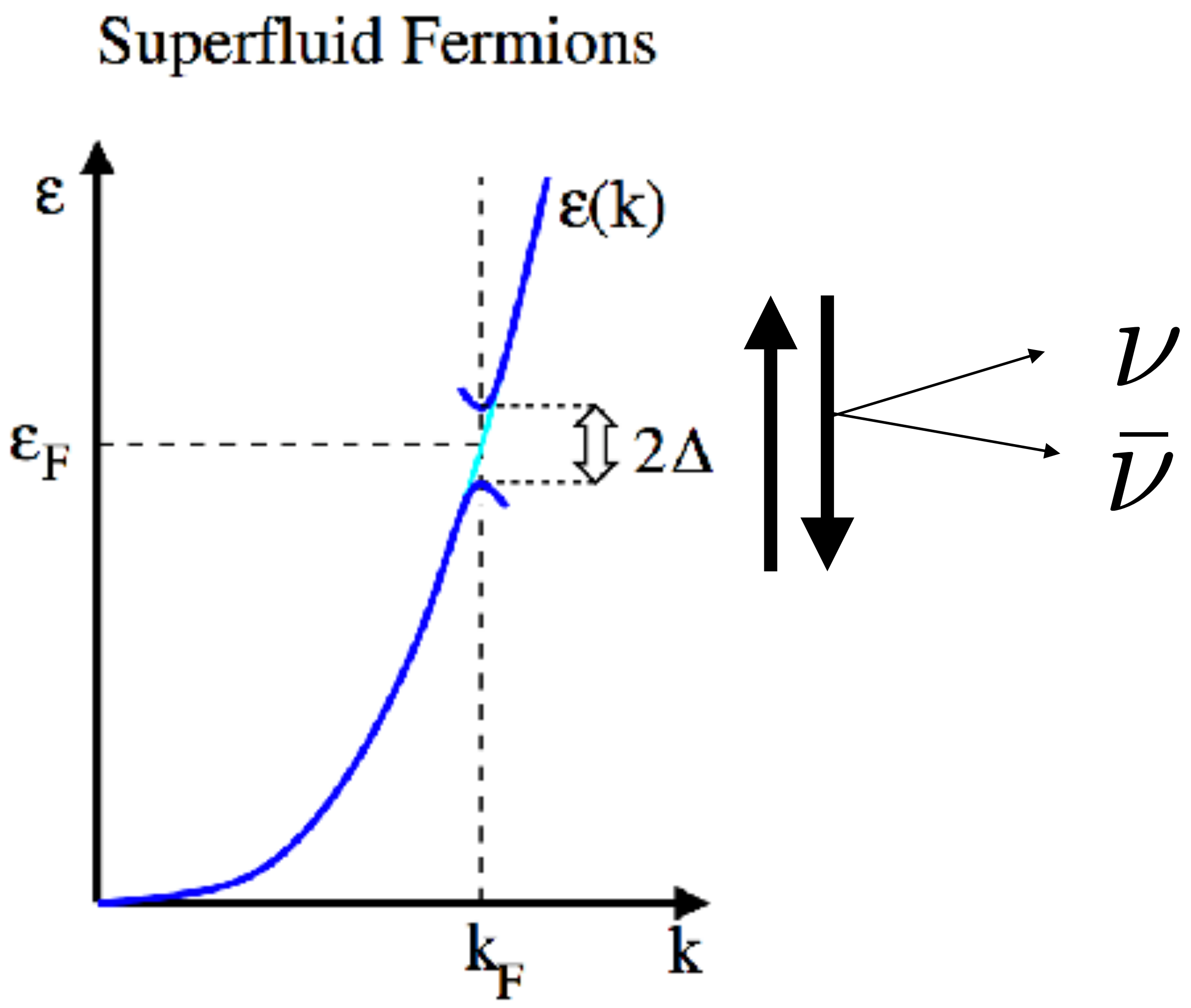
Cas A NS Cooling (理論)

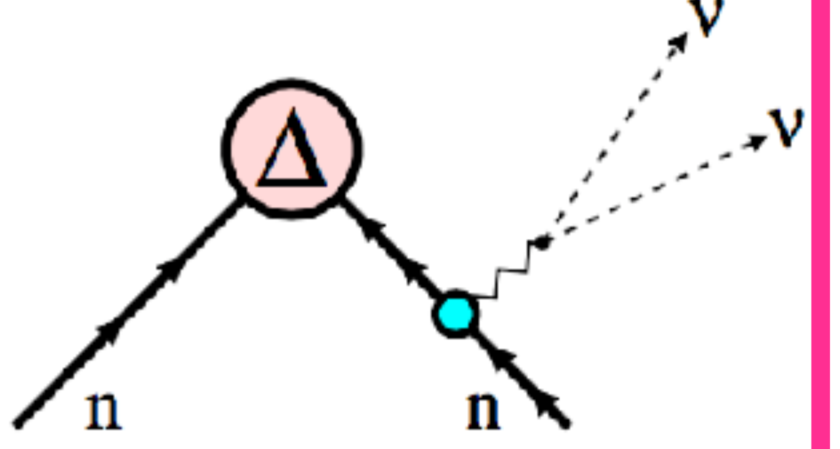
中性子星の温度発展の式

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

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

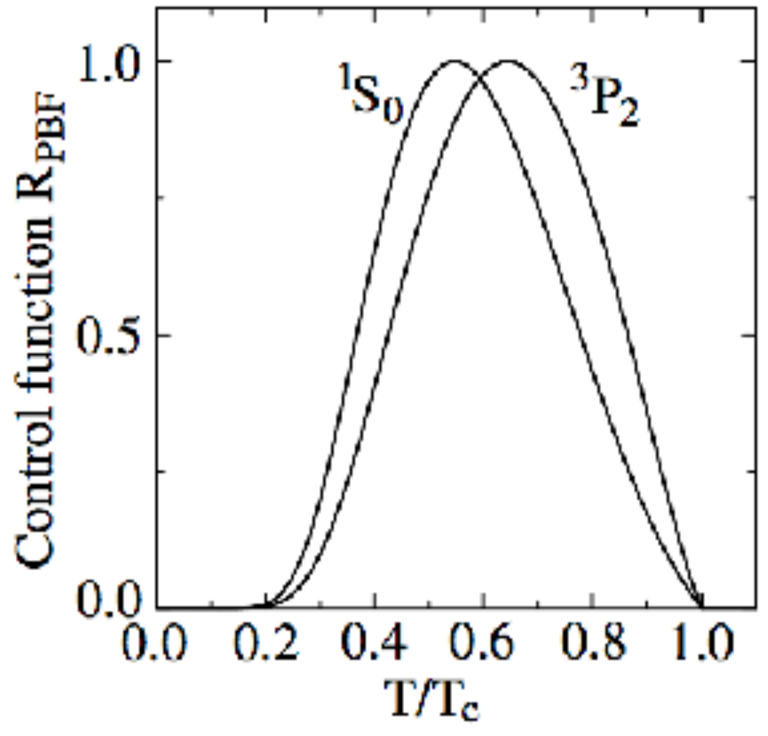
Cooper pair breaking and formation (PBF)





短い温度領域でのみ急激に働く

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



T=Tc 付近で、急激な温度減少を引き起こせる。

Figs. from Page et.al. 1302.6626

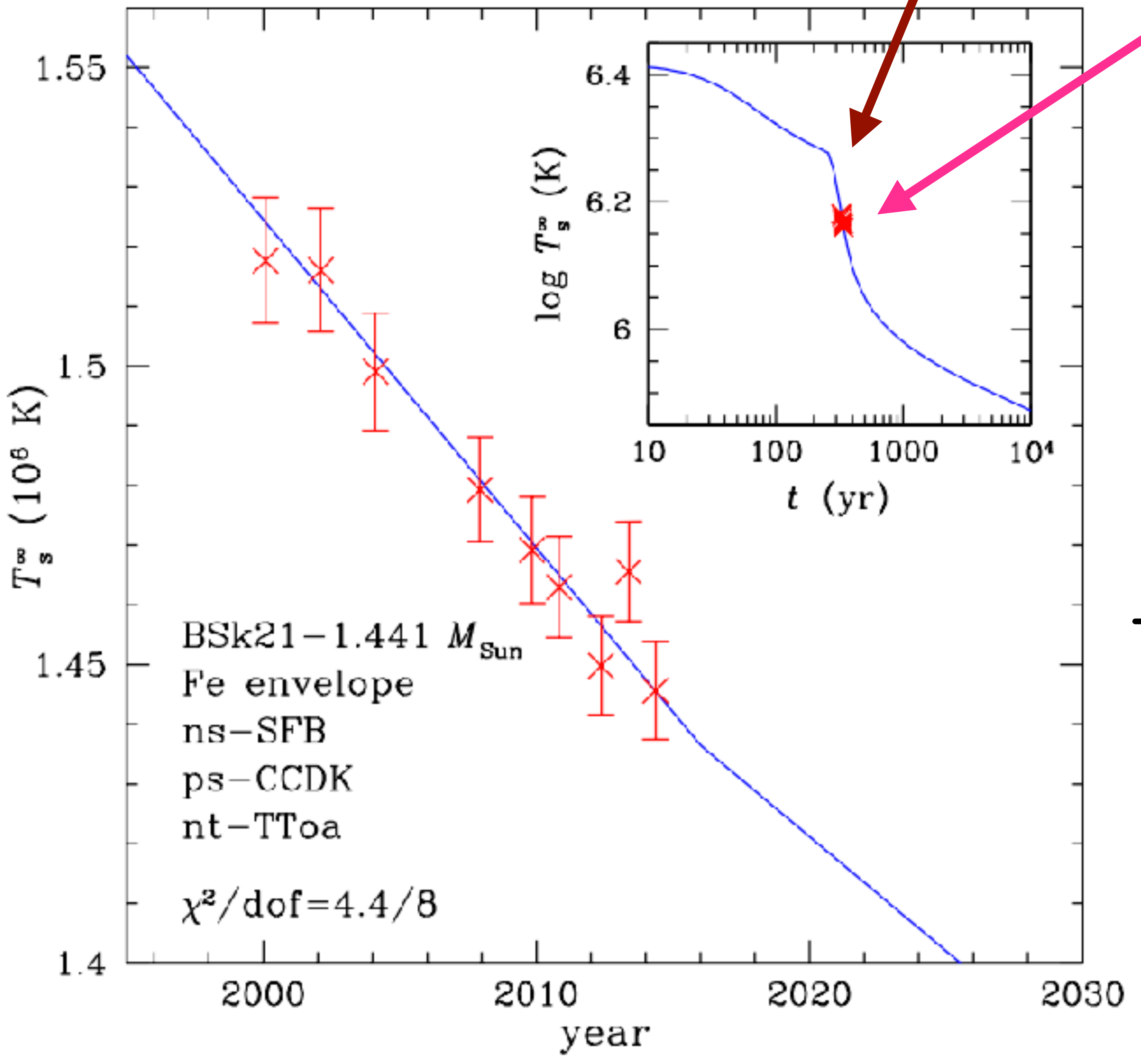
Cas A NS Cooling (理論)

超流動相転移

T = Tc

PBF process による

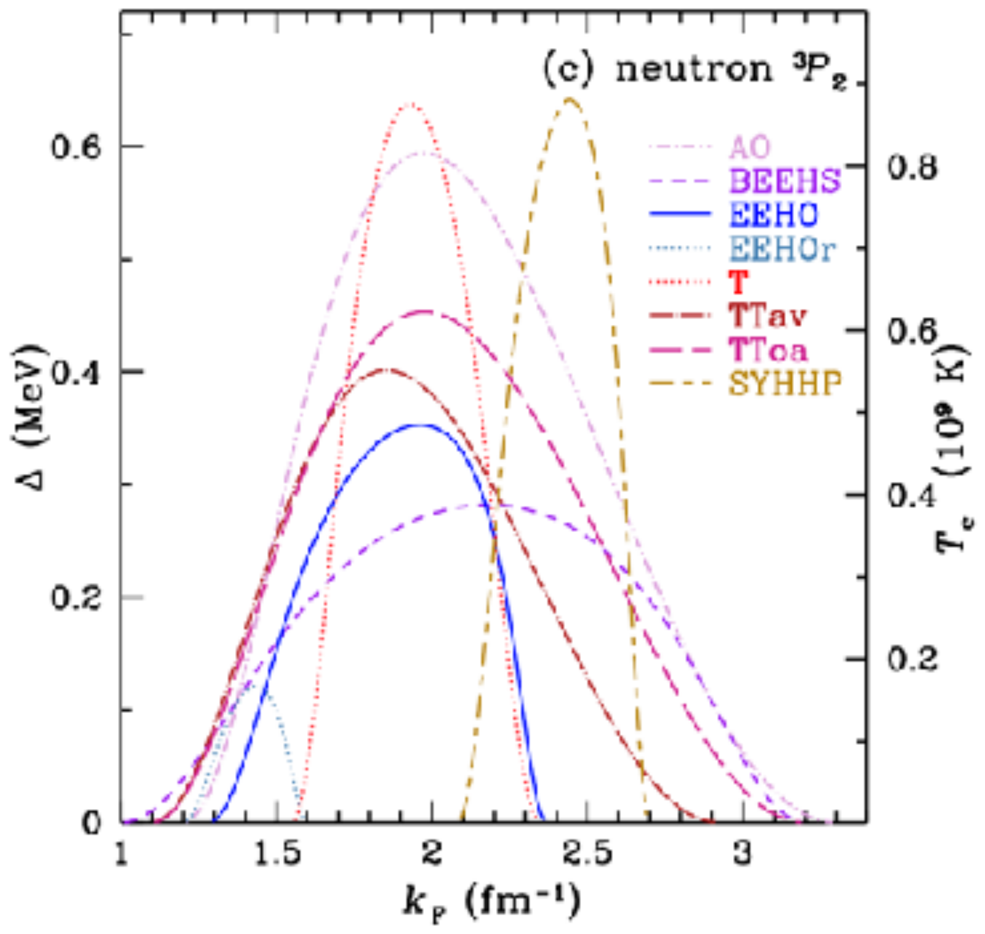
急激な cooling



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.



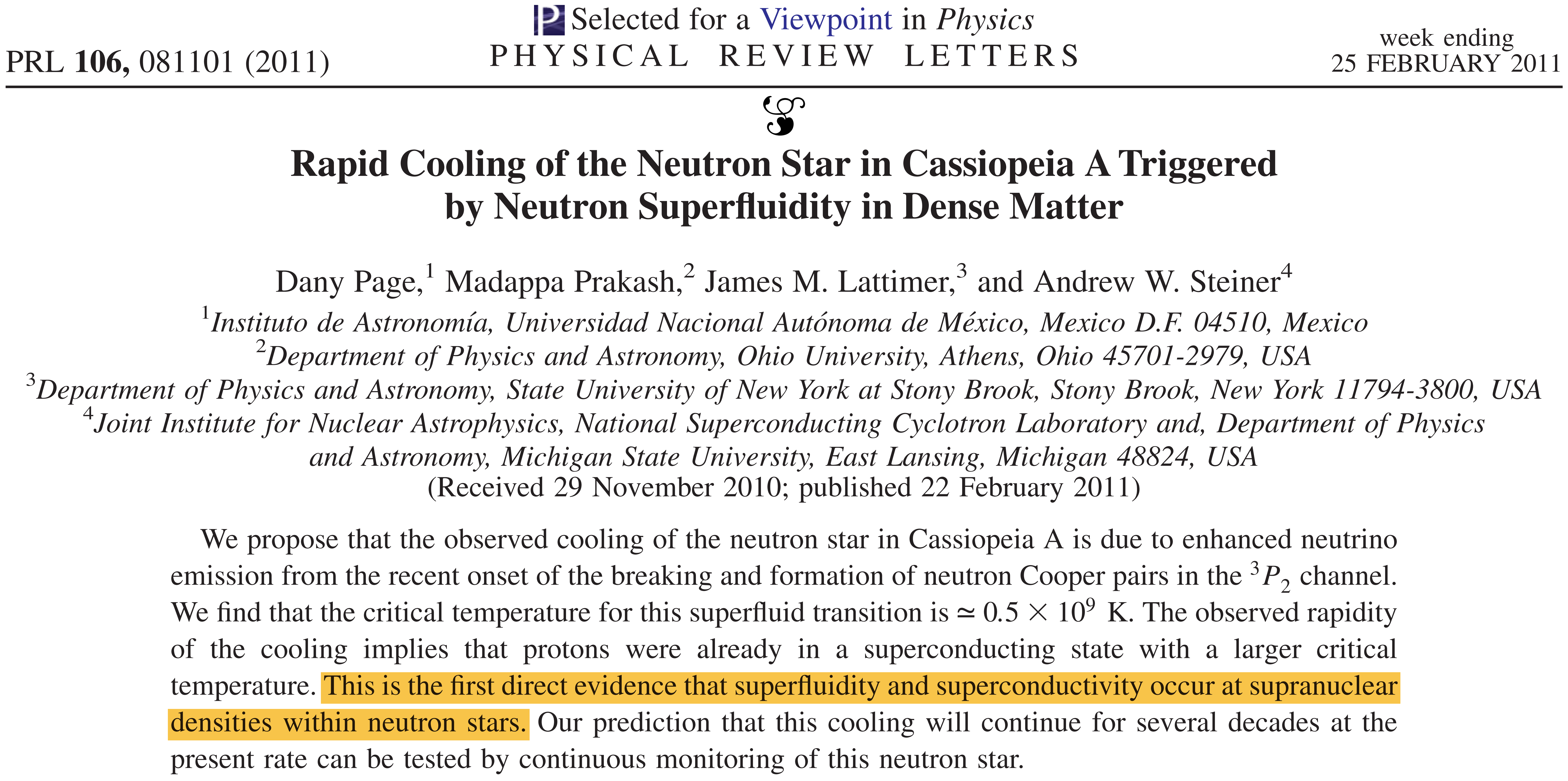
Cas A NS Cooling (理論)

- Cas A 中性子星の温度減少は、

中性子星の**標準冷却理論**で説明しうる。

- 鍵を握るのは**中性子の超流動** (と陽子の超伝導)

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 (理論)

- Cas A 中性子星の温度減少は、
中性子星の**標準冷却理論**で説明しうる。

- 鍵を握るのは**中性子の超流動** (と陽子の超伝導)

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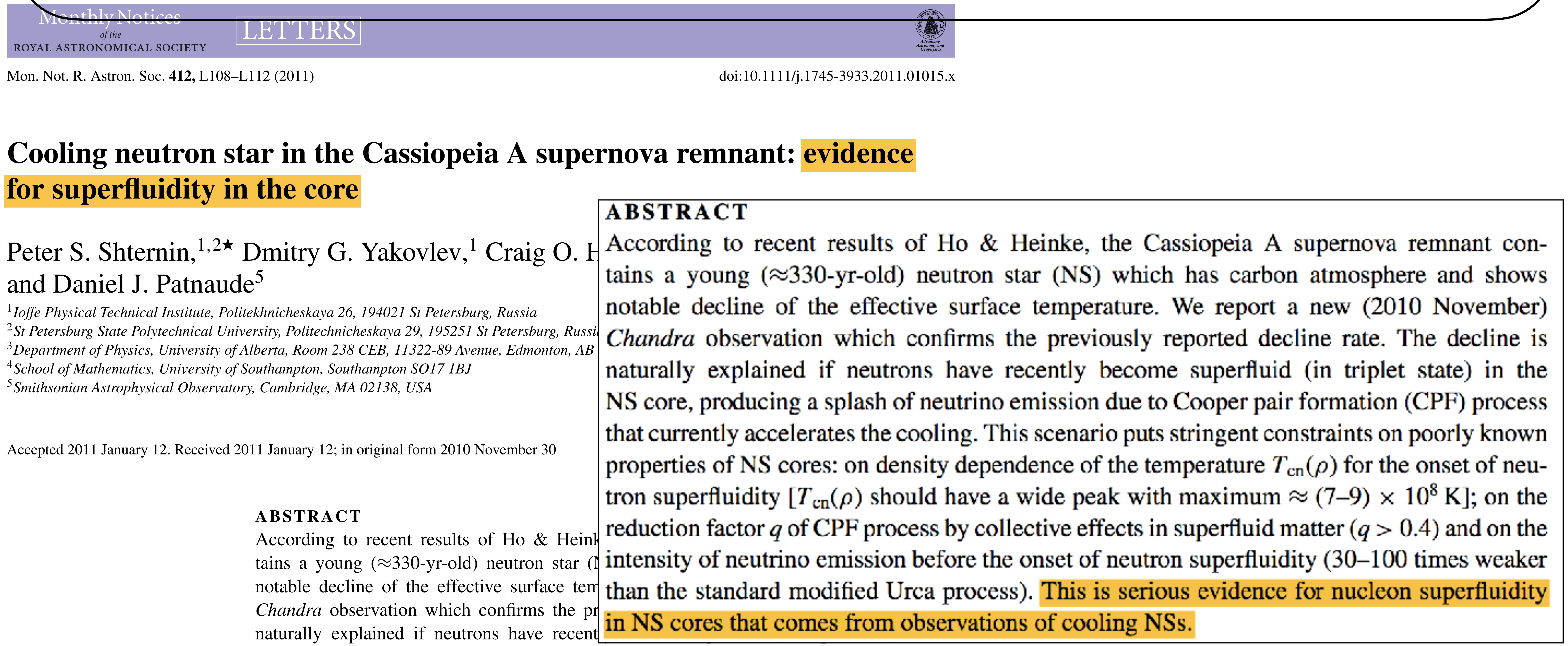

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY LETTERS

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 $T_{\rm cn}(\rho)$ for the onset of neutron superfluidity [$T_{\rm cn}(\rho)$ 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 (
notable decline of the effective surface tem
Chandra observation which confirms the pr
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(b) 中性子星がアクシオンで冷える話

1. 中性子星

2. アクシオン vs Cas A 中性子星

based on KH, N. Nagata, K. Yanagi, J. Zheng, [arXiv:1806.07151]

(1) アクシオン mini review

(2) Cas A 中性子星の cooling
- Cas A 中性子星 Cooling (観測)
- Cas A 中性子星 Cooling (理論)

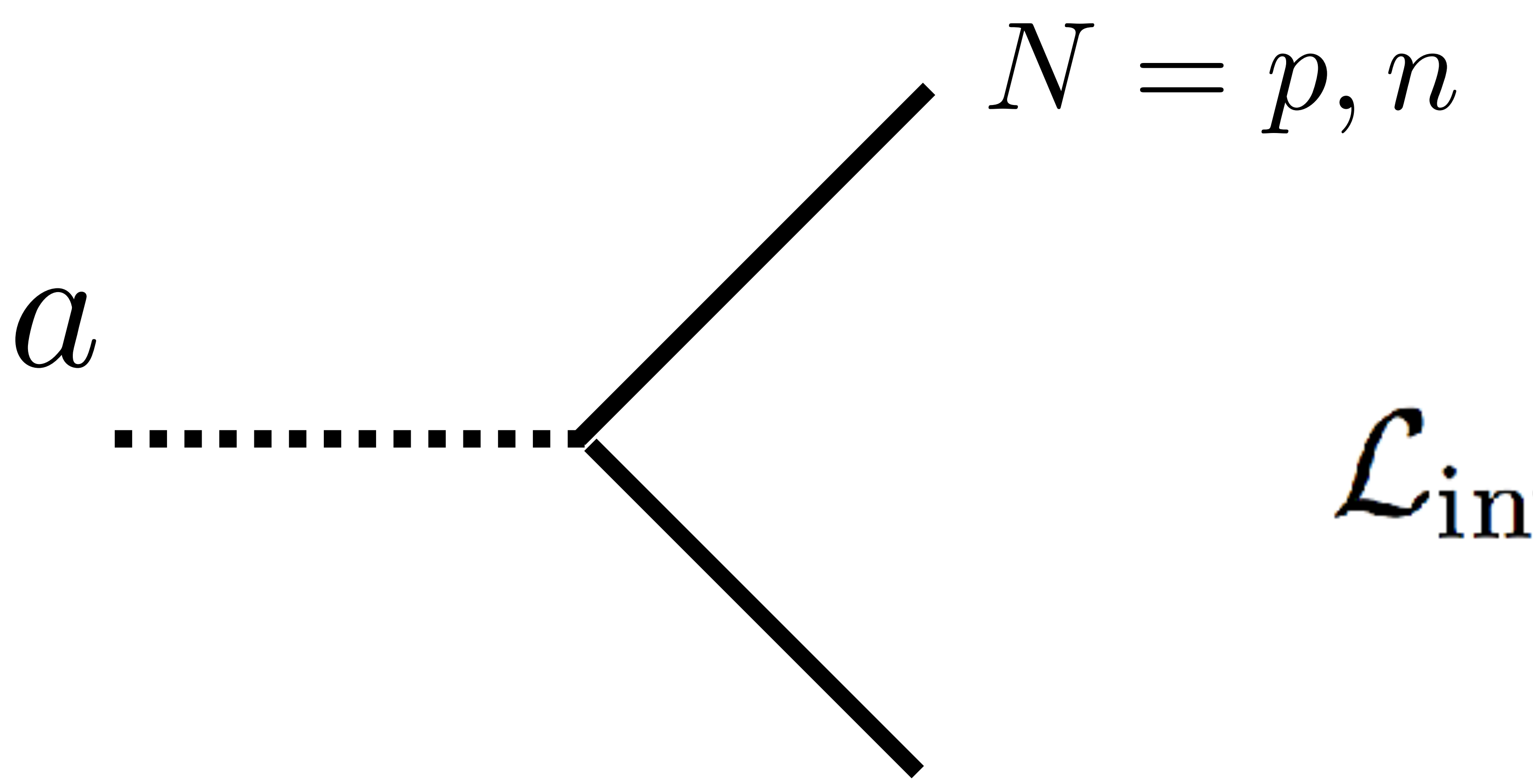
(3) Cas A 中性子星の cooling とアクシオン

(4) 「アクシオン vs Cas A 中性子星」のまとめ

Cas A 中性子星の cooling と axion

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

axion emission



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

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

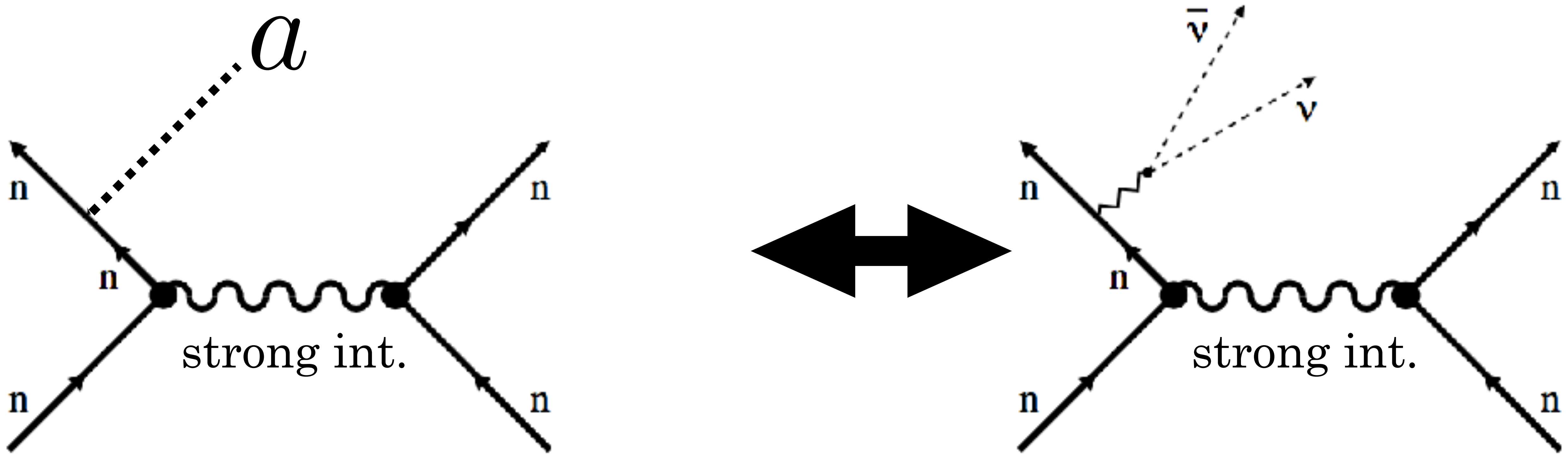
$$\text{DFSZ:} \begin{cases} C_p = -0.182(25) - 0.435\sin^2\beta \\ C_n = -0.160(25) - 0.414\sin^2\beta \end{cases}$$

Cas A 中性子星の cooling と axion

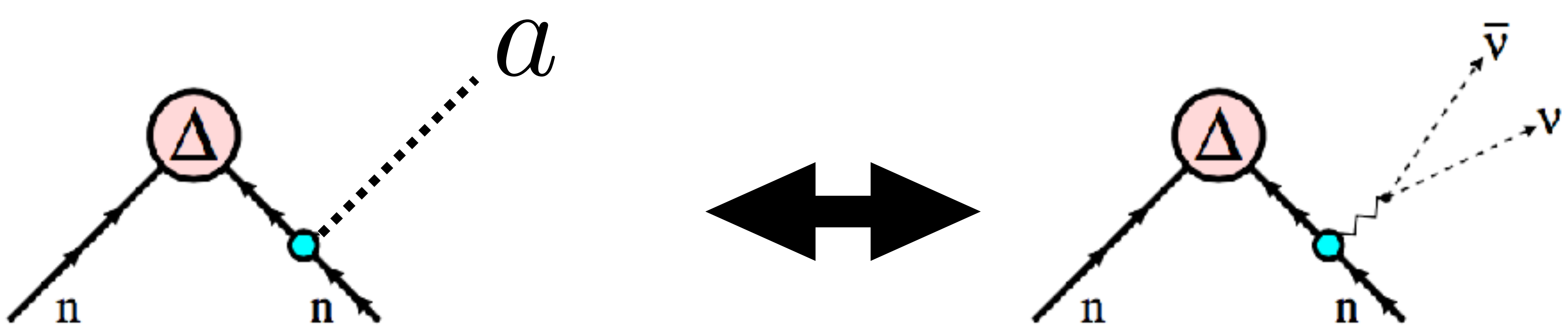
$$C\frac{dT}{dt} = -L_\nu - L_a$$

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.

Cas A 中性子星の cooling と axion

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

axion emission

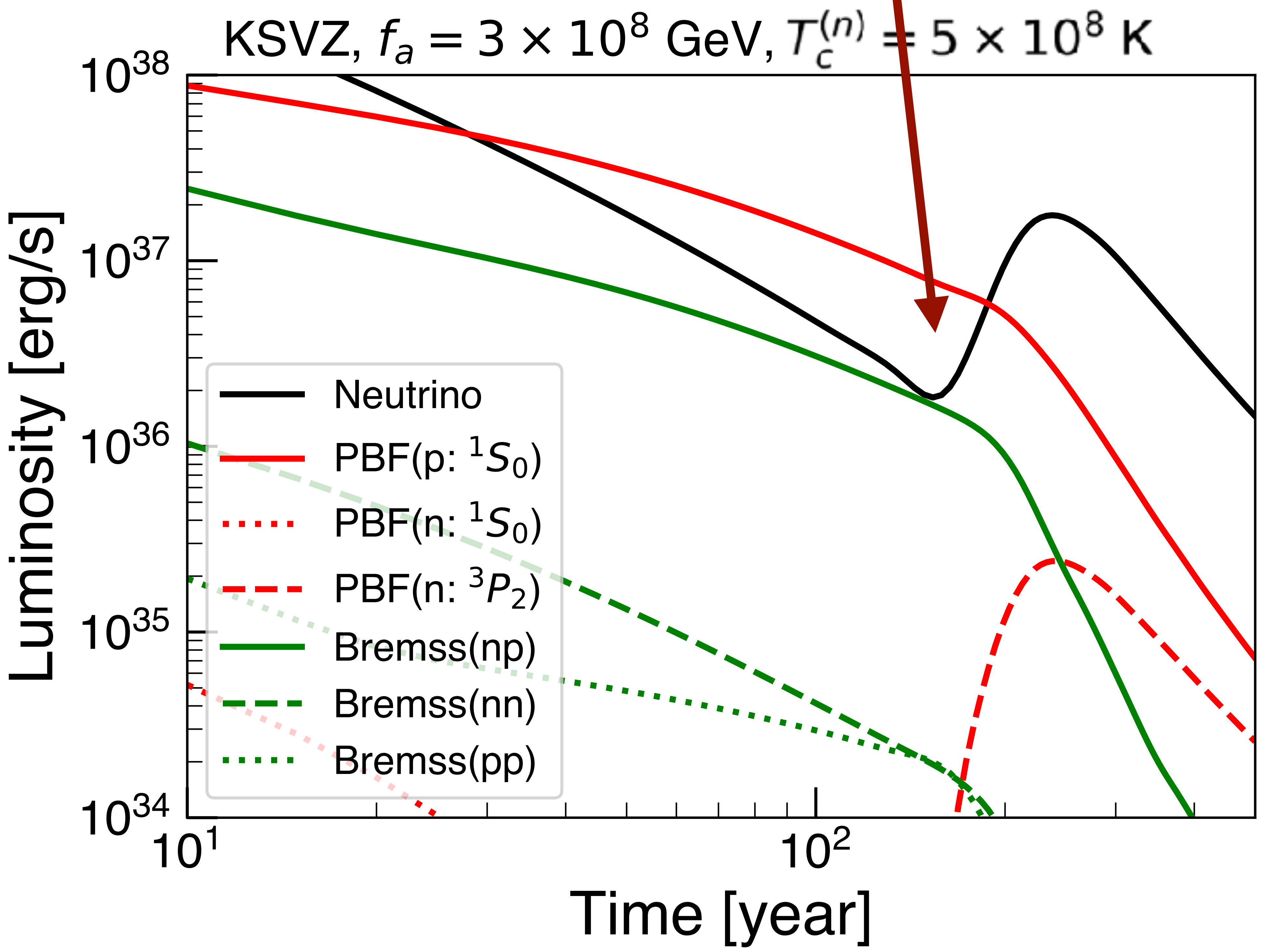
我々がやったこと

- followed NS cooling **with axion emission** (Brems. and PBF).
  by modifying a public code NSCool.
- APR EoS.
- NS mass M = 1.4 Msun.
- 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.

Cas A 中性子星の cooling と axion

Results

phase transition
T = Tc

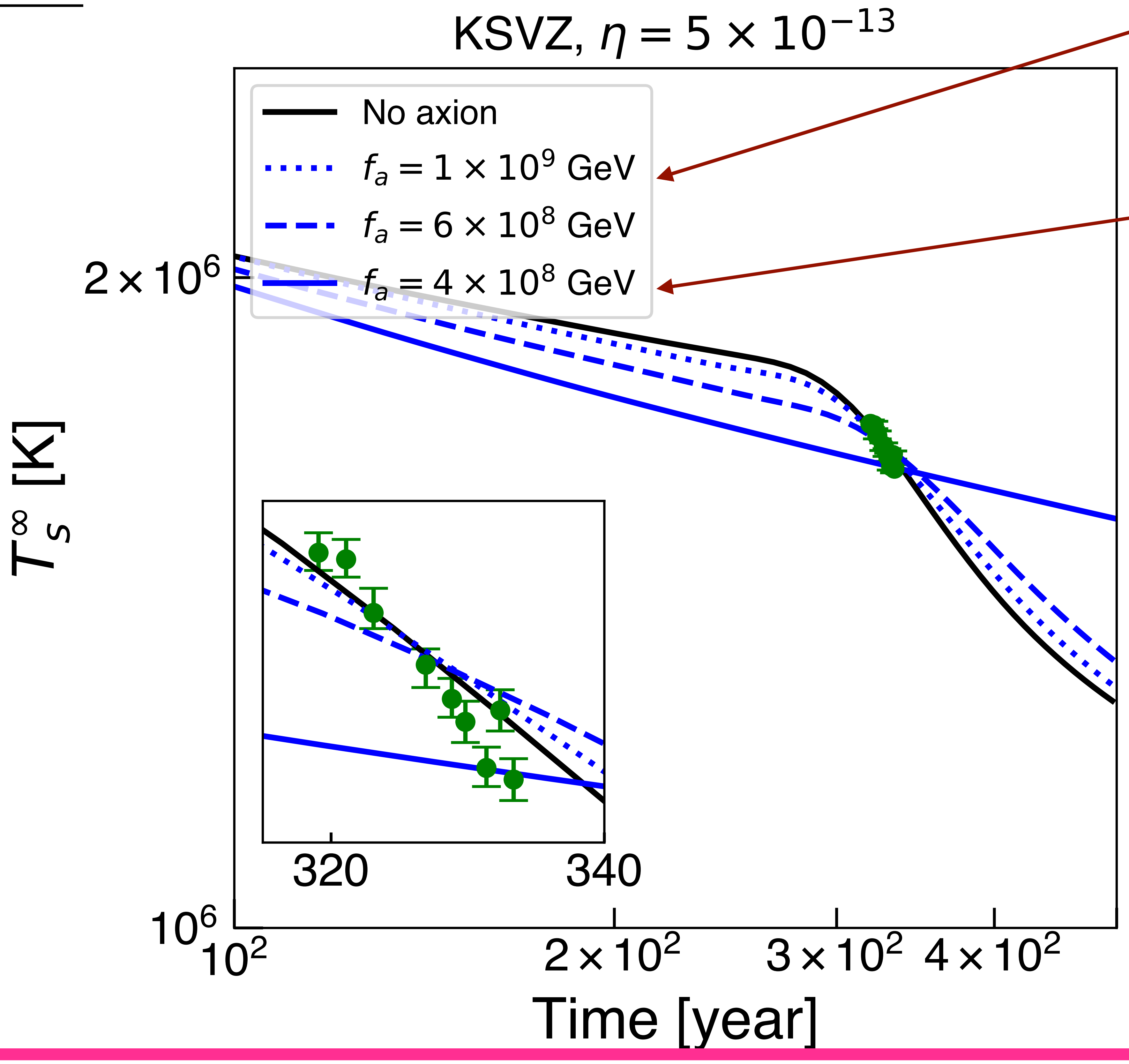


K. Hamaguchi,
N. Nagata,
K. Yanagi,
J. Zheng,
1806.07151

Axion emission は neutrino emission より大きくなり得る。

Cas A 中性子星の cooling と axion

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.

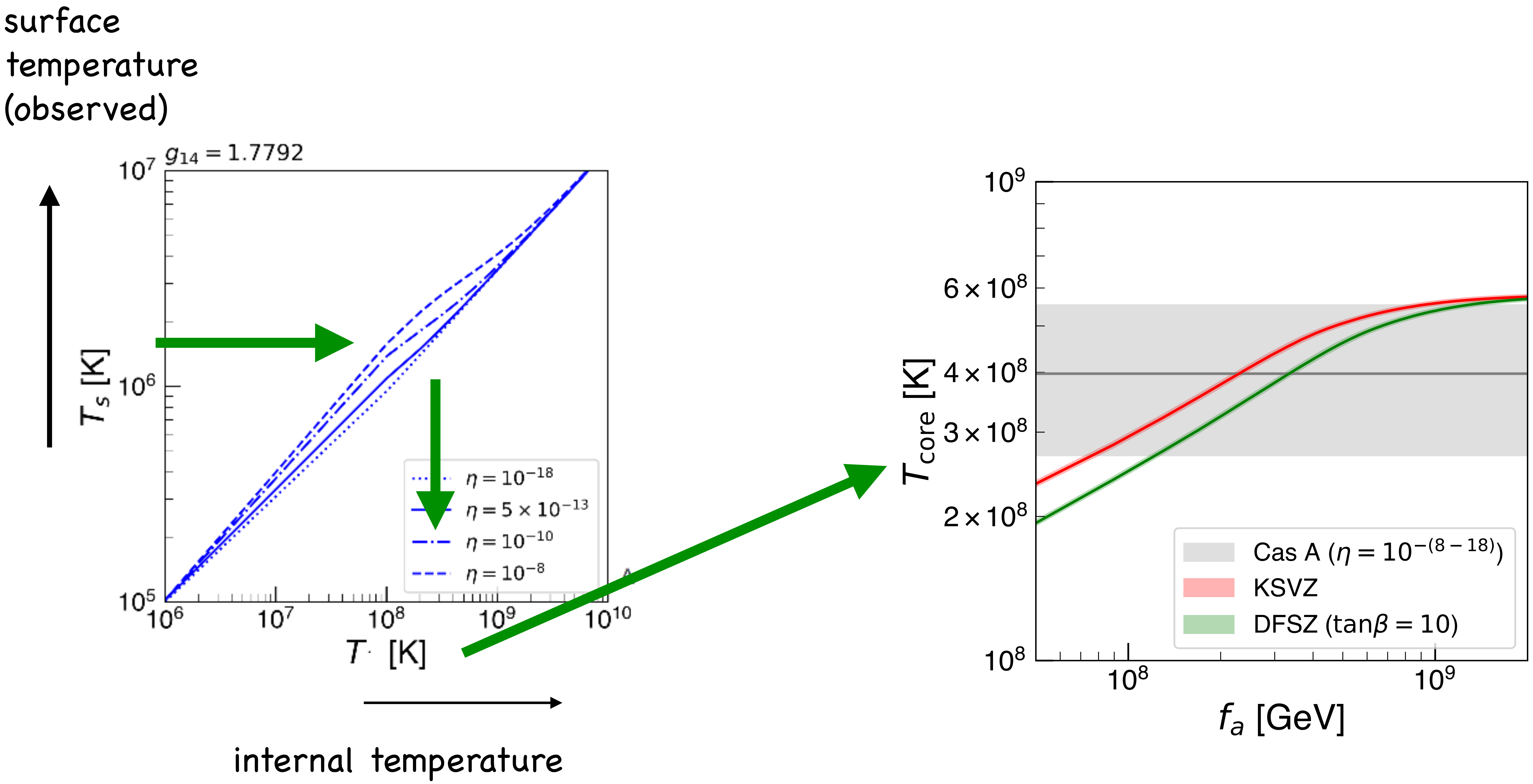
K. Hamaguchi,
N. Nagata,
K. Yanagi,
J. Zheng,
1806.07151

新たな制限 $f_a \gtrsim \mathcal{O}(10^8)$ GeV (KSVZ) を得た

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

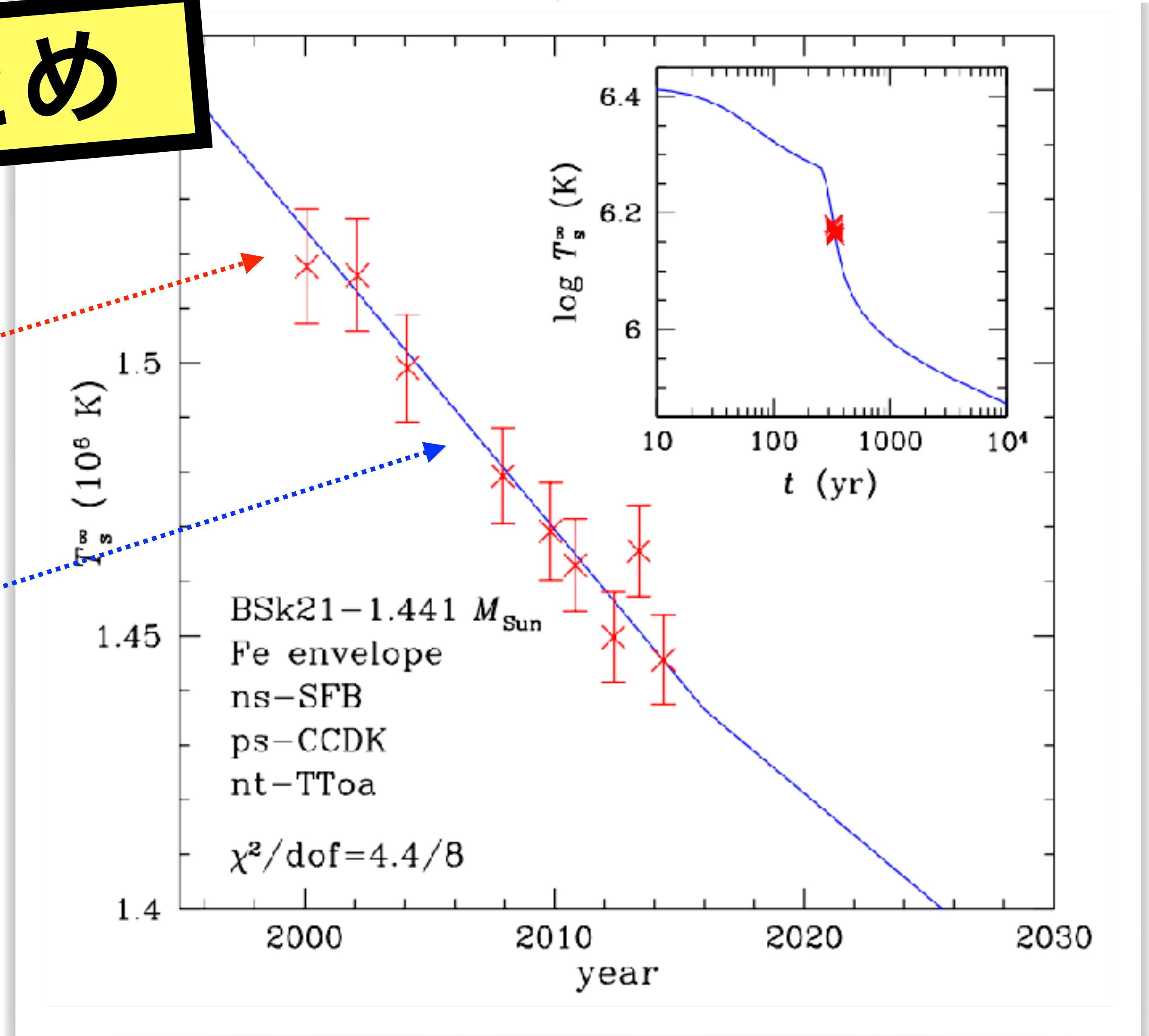
Cas A 中性子星の cooling と axion

注：ただし, envelope による O(1) 不定生あり



「アクシオン vs Cas A 中性子星」まとめ

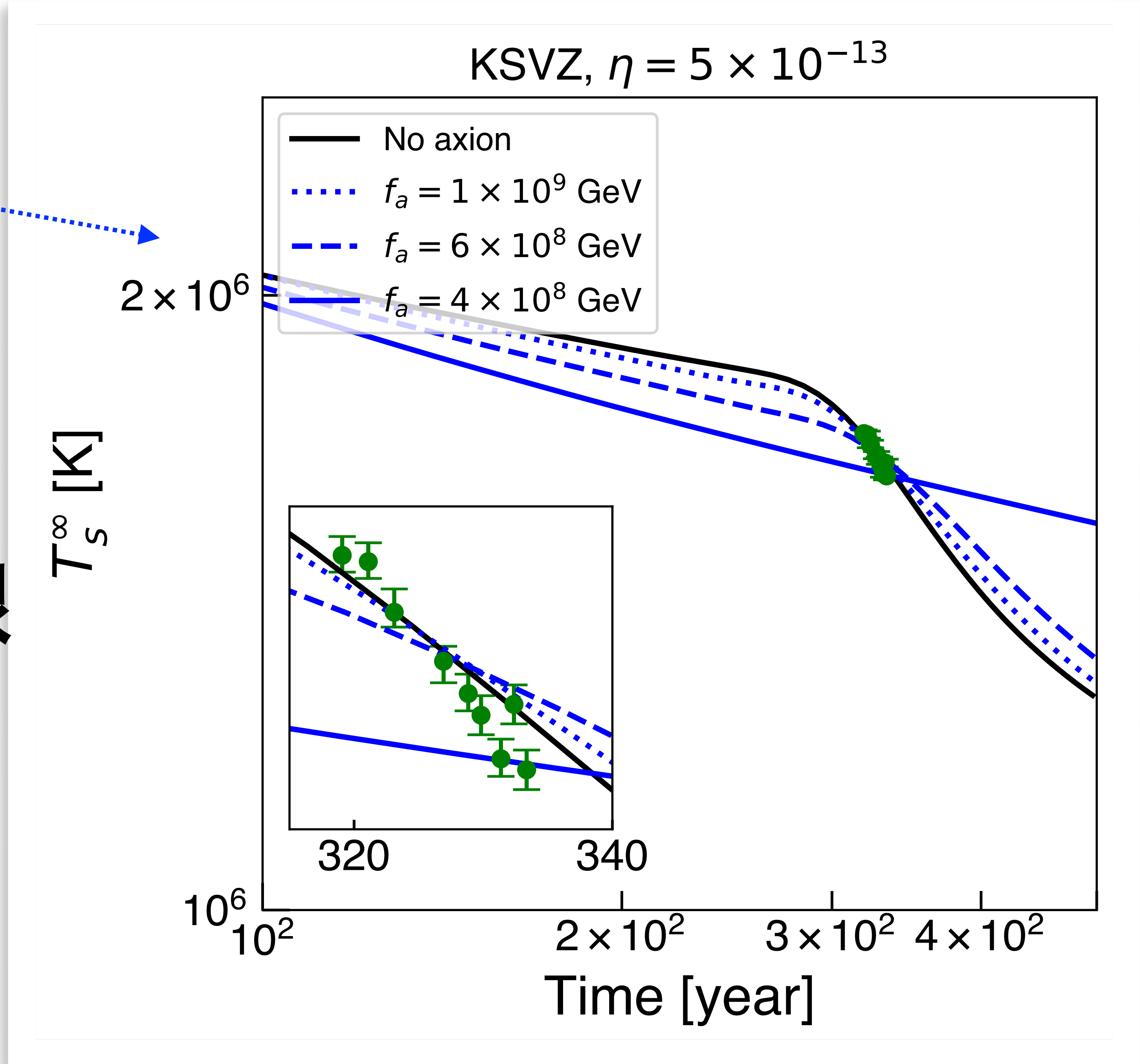
W.C.G.Ho, K.G.Elshamouty, C.O.Heinke, A.Y.Potekhin, 1412.7759



- **Cas A 中性子星の表面温度の減少**が観測されている.
- 中性子星の標準冷却理論で説明可能。

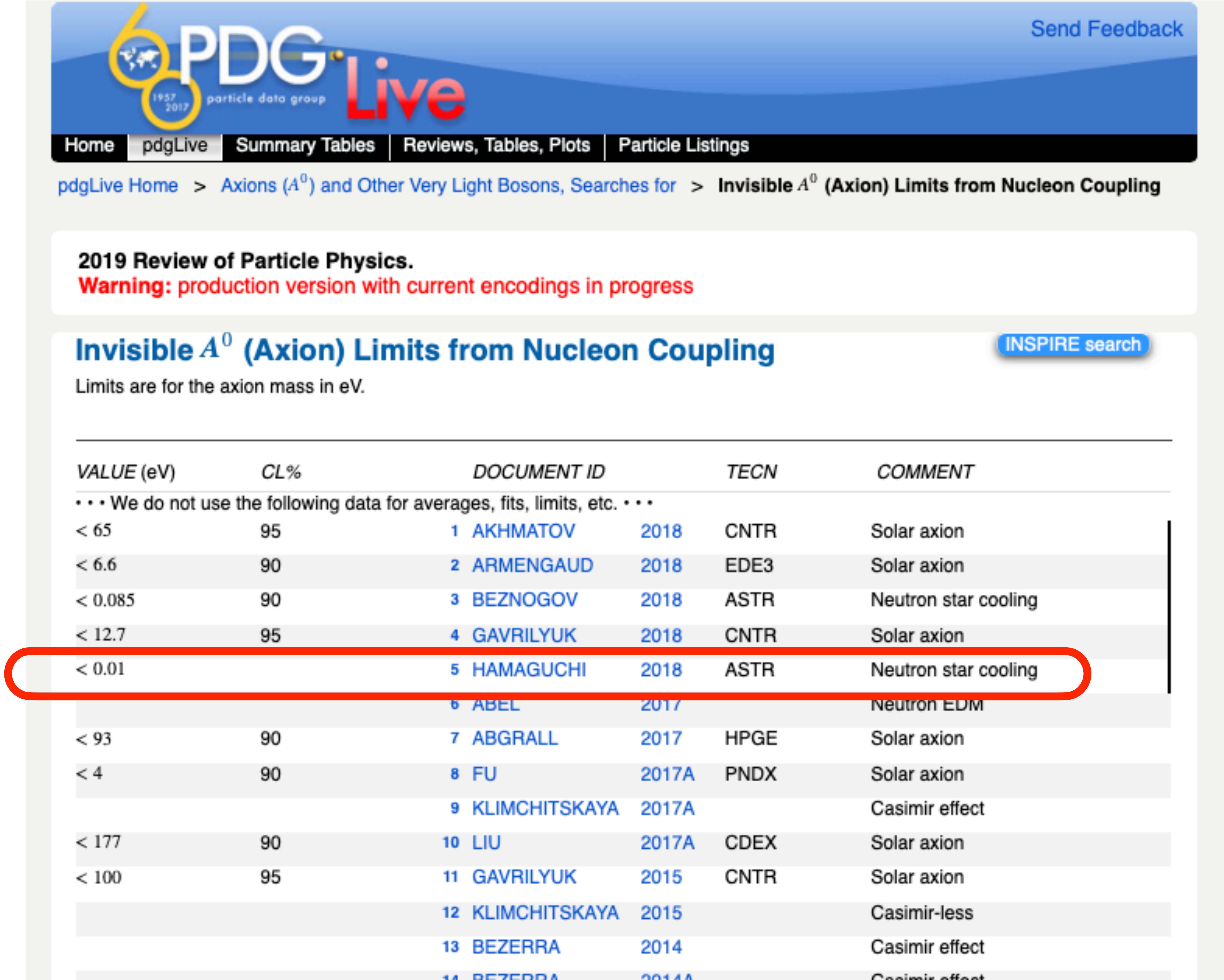
- もし **axion** のような余計な冷却源があると冷却曲線が変わってしまう。
- 我々は axion emission 込みで Cas A 中性子星の温度発展を解析し、**axion decay constant に対する新たな制限 $f_a > O(10^8)$ GeV を得た。**

(これまで最強だったSN1987Aからの制限と独立で同程度に強い.)



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

「アクシオン vs Cas A 中性子星」まとめ



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

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

Invisible A^0 (Axion) Limits from Nucleon Coupling

Limits are for the axion mass in eV.

VALUE (eV)	*CL%*		*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 65	95	1	AKHMATOV	2018	CNTR	Solar axion
< 6.6	90	2	ARMENGAUD	2018	EDE3	Solar axion
< 0.085	90	3	BEZNOGOV	2018	ASTR	Neutron star cooling
< 12.7	95	4	GAVRILYUK	2018	CNTR	Solar axion
< 0.01		5	HAMAGUCHI	2018	ASTR	Neutron star cooling
		6	ABEL	2017		Neutron EDM
< 93	90	7	ABGRALL	2017	HPGE	Solar axion
< 4	90	8	FU	2017A	PNDX	Solar axion
		9	KLIMCHITSKAYA	2017A		Casimir effect
< 177	90	10	LIU	2017A	CDEX	Solar axion
< 100	95	11	GAVRILYUK	2015	CNTR	Solar axion
		12	KLIMCHITSKAYA	2015		Casimir-less
		13	BEZERRA	2014		Casimir effect
		14	BEZERRA	2014A		Casimir effect

cf. 関連研究
- M.V.Beznogov+ [arXiv:1806.07991]
- L.B.Leinson [arXiv:1909.03941]

(c) 超新星からアクシオンがやってくる話

Based on the works with

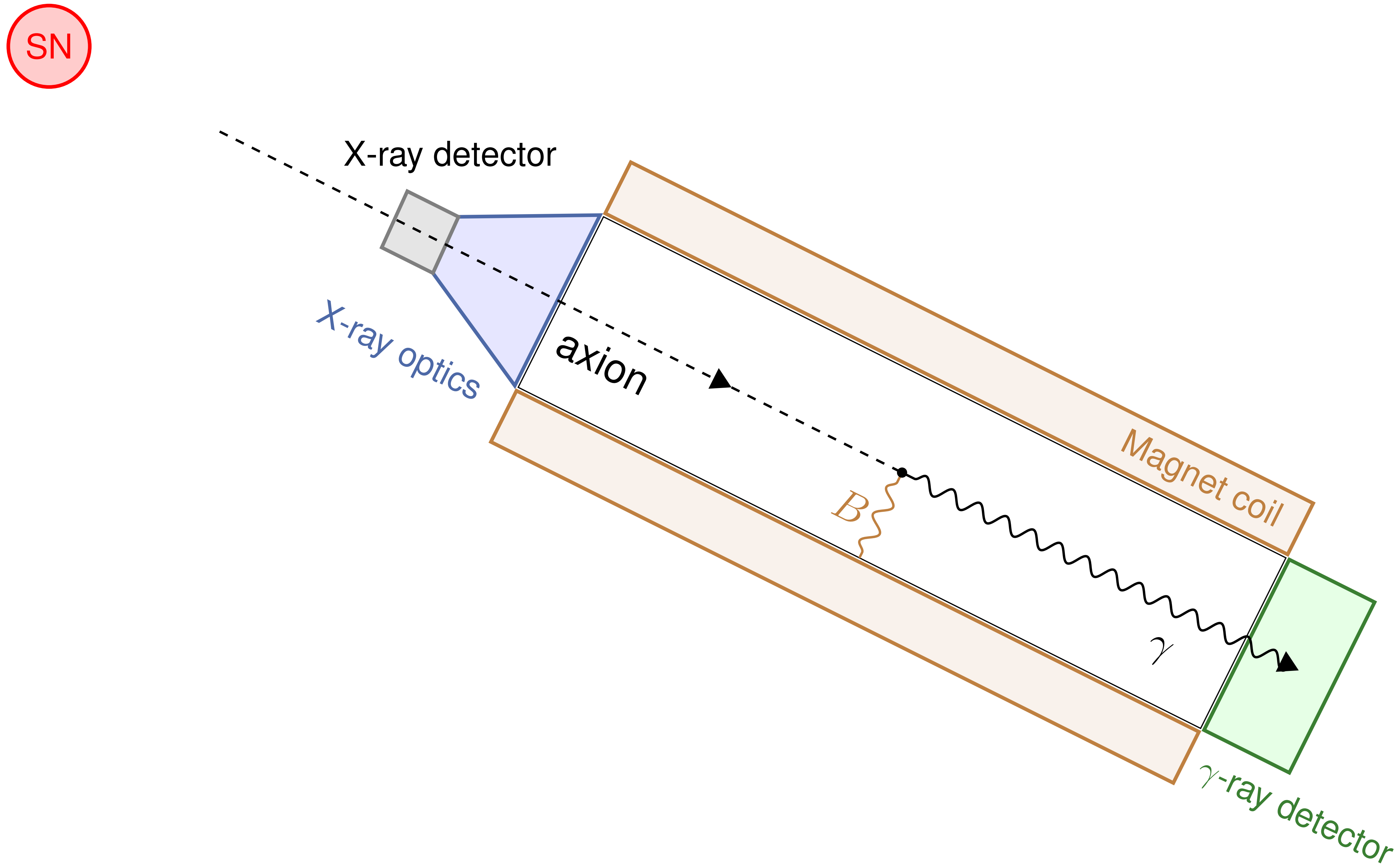
Shao-Feng Ge, Koichi Ichimura, Koji Ishidoshiro, Yoshiki Kanazawa, Yasuhiro Kishimoto, Natsumi Nagata, Jiaming Zheng,

参考文献

SN axion: 2008.03924.

Plan

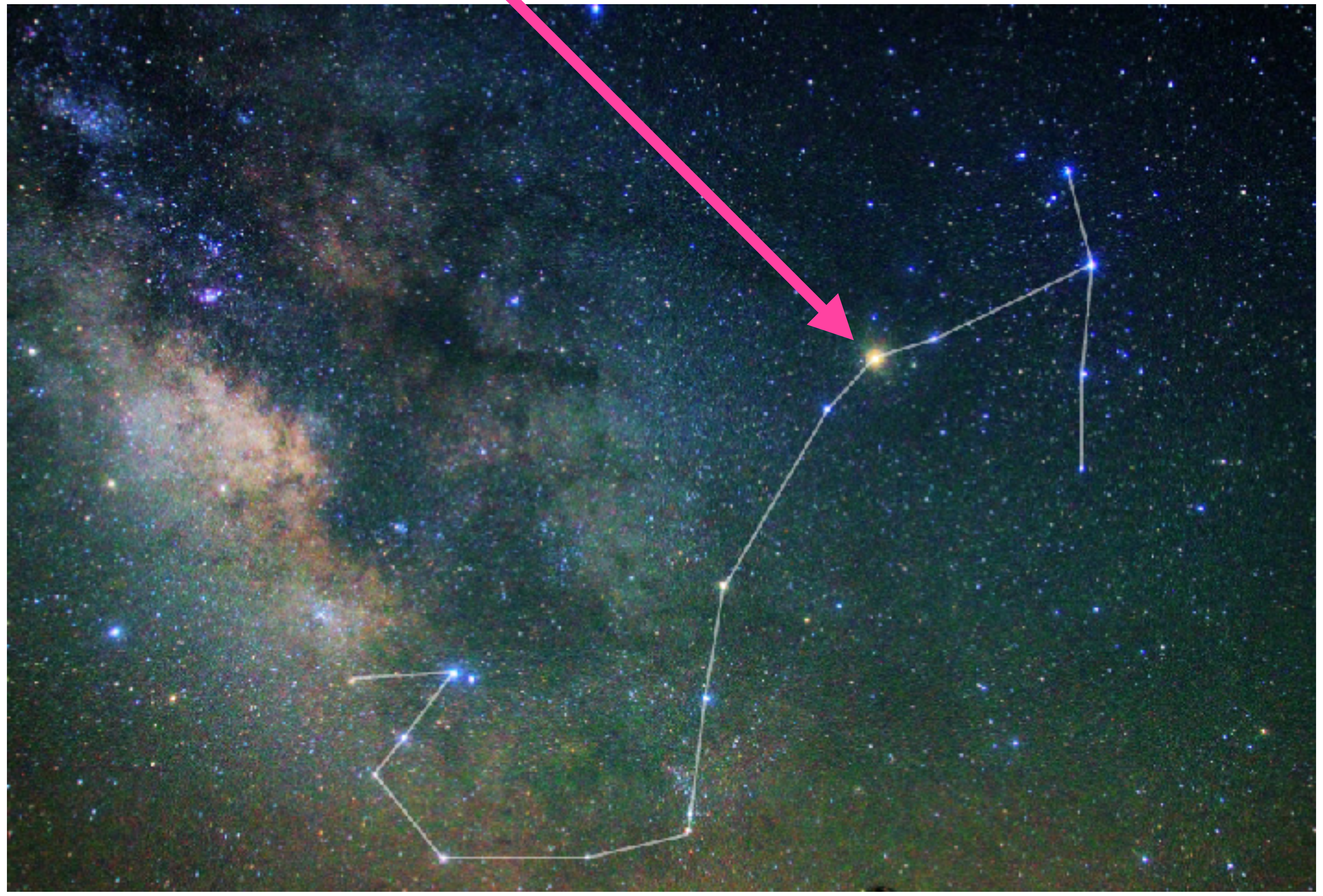
- **Introduction: Standard Model and Axion**
- **Supernova Axion detection**
  - SN candidates
  - Supernova-scope
  - Pre-SN neutrino
  - Observation time fraction
  - Event number
- **Summary**



Nearby SN progenitor candidates

Antares

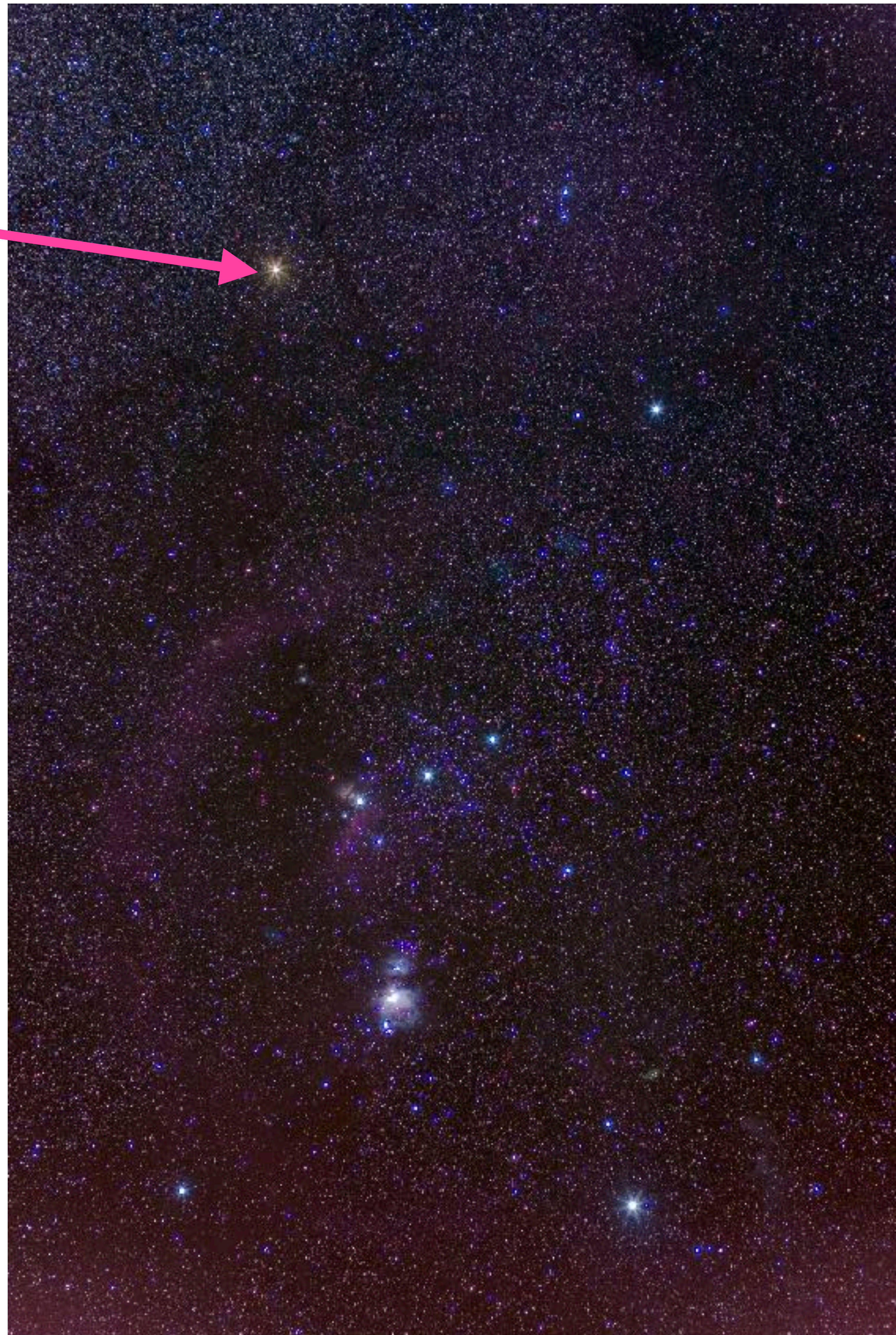
(~ 170 pc)



https://www.civillink.net/esozai/

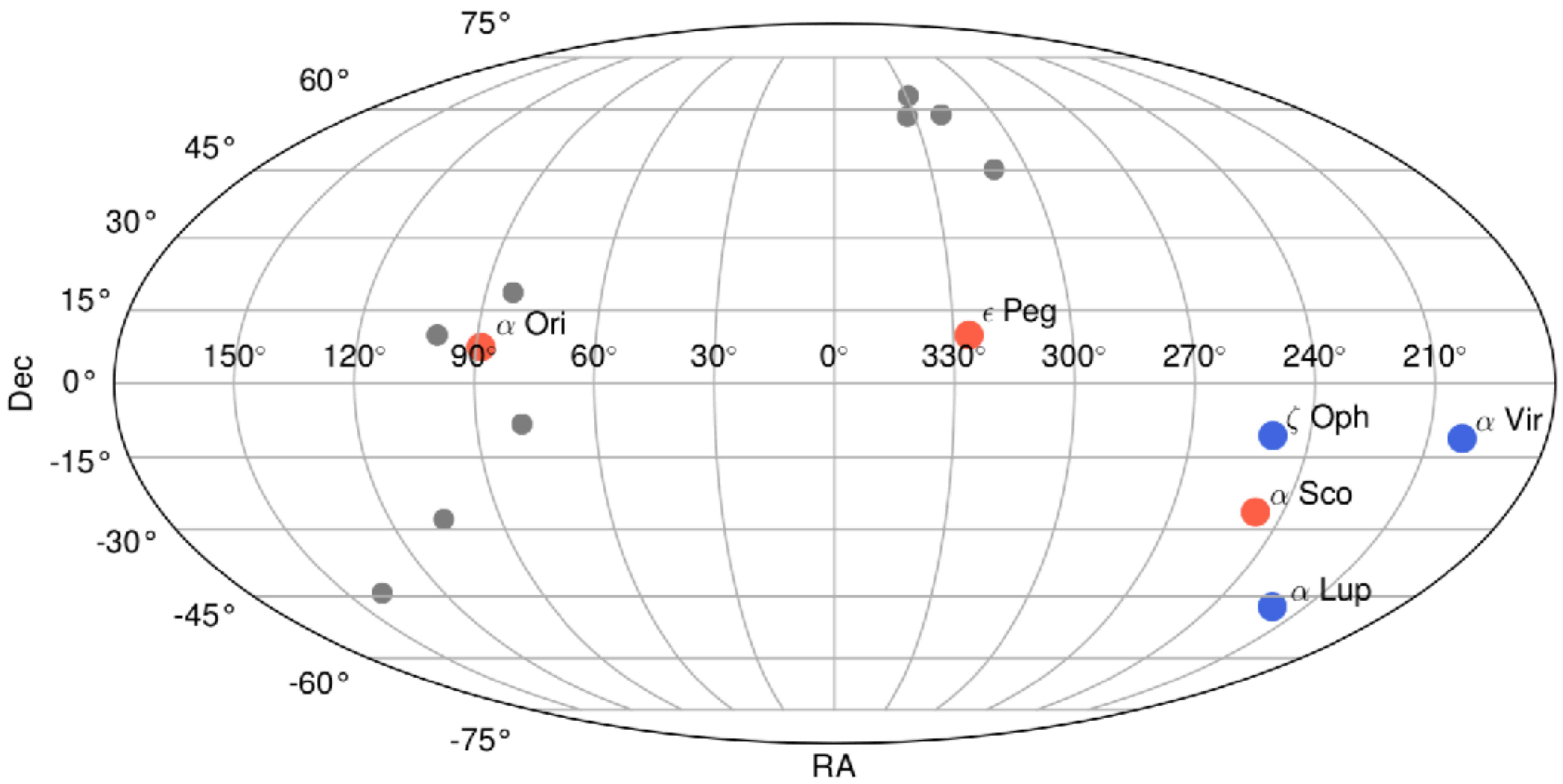
Betelgeuse

(~ 200 pc)



Wikipedia

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

Plan

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  - SN candidates
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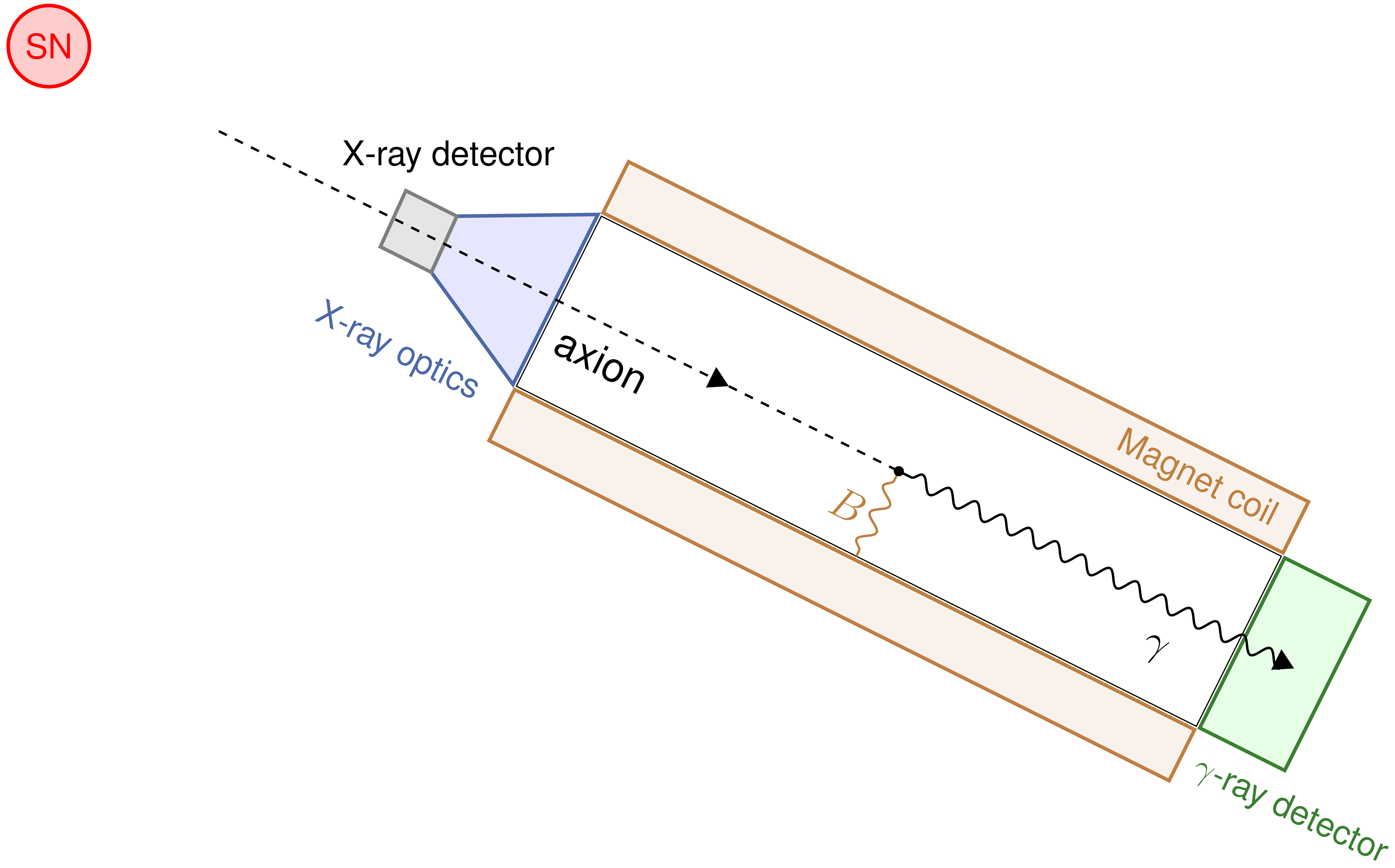
  - Observation time fraction
  - Event number
- **Summary**

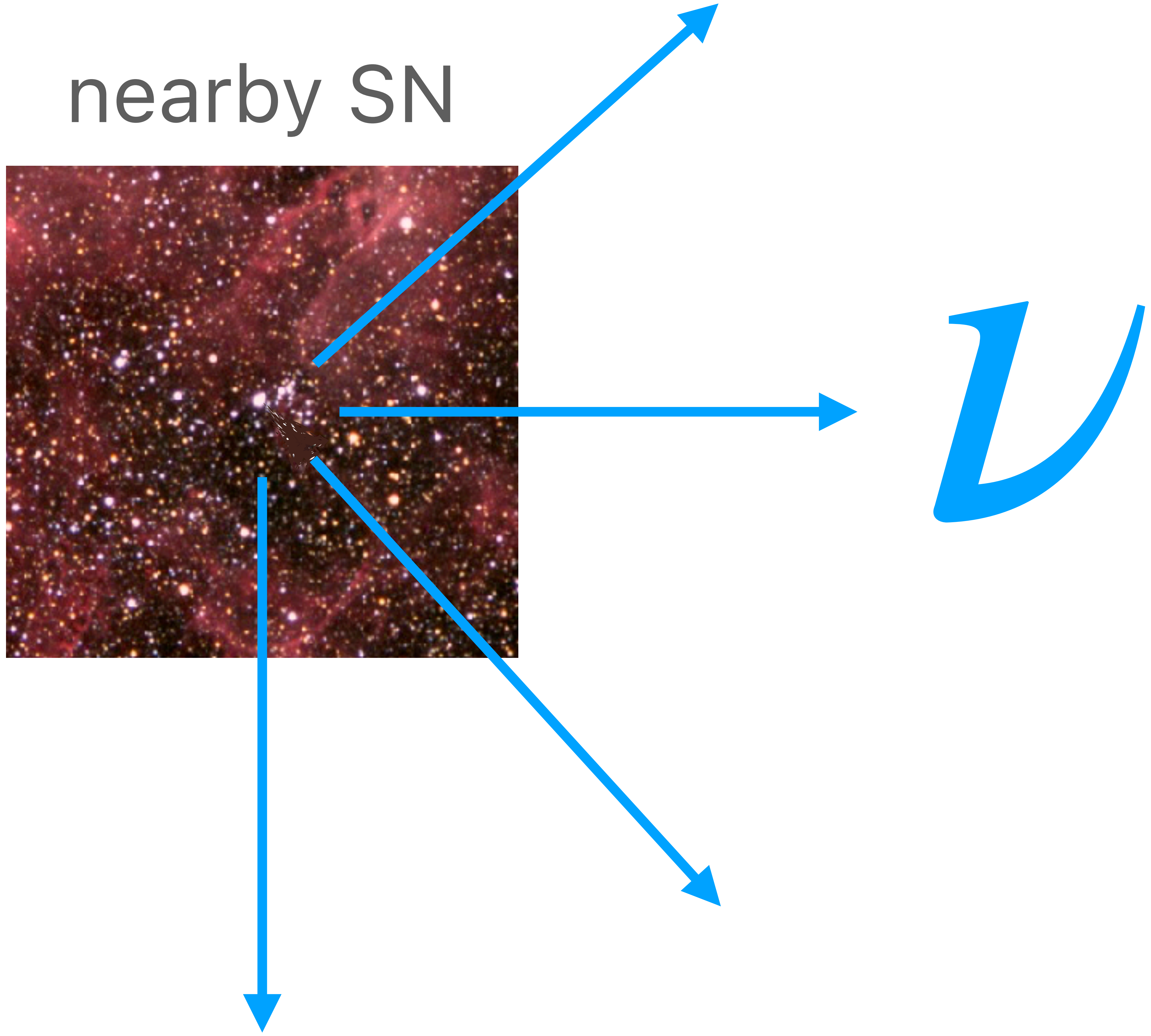


Supernova-scope

nearby SN

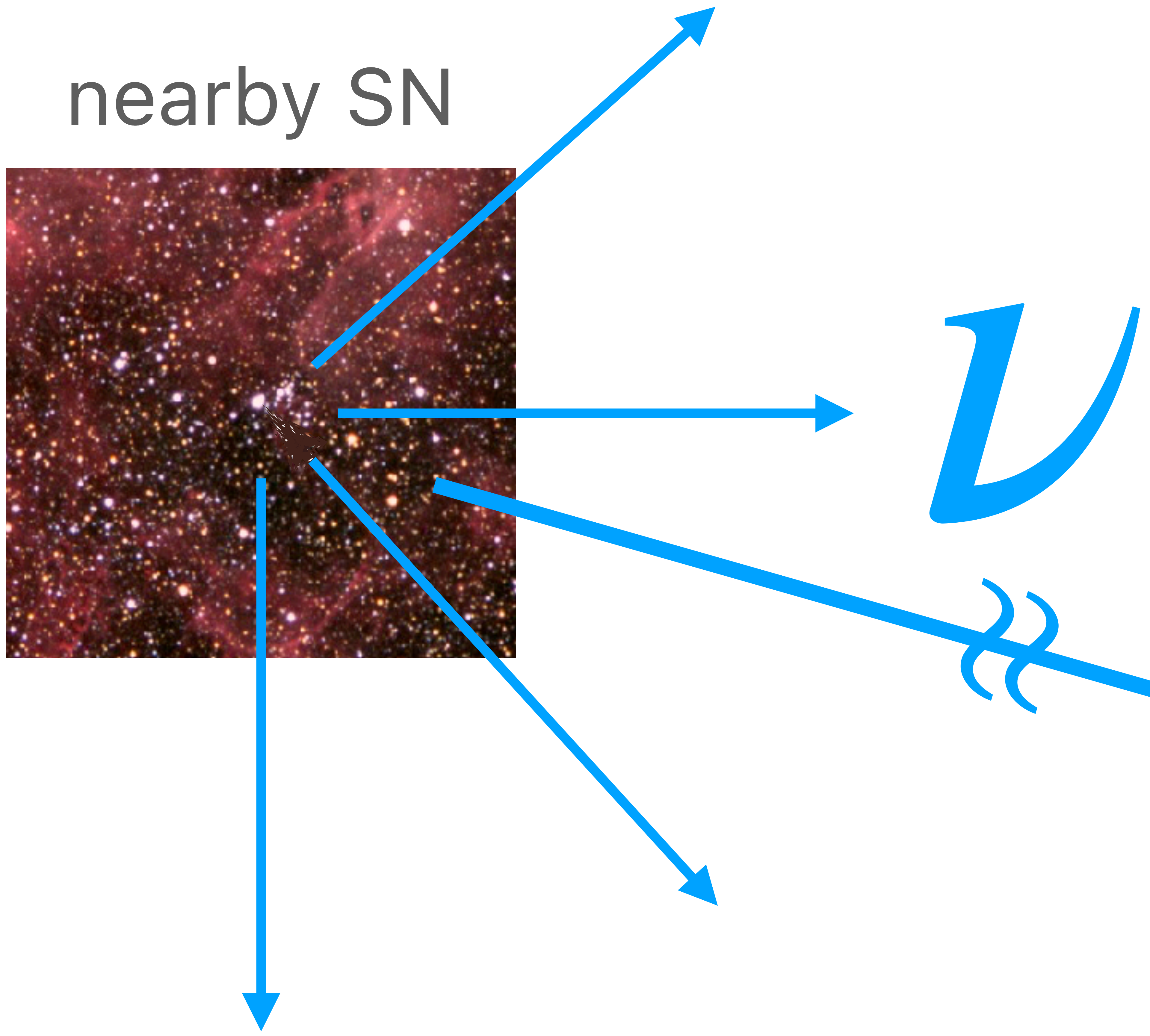
Supernova-scope

nearby SN

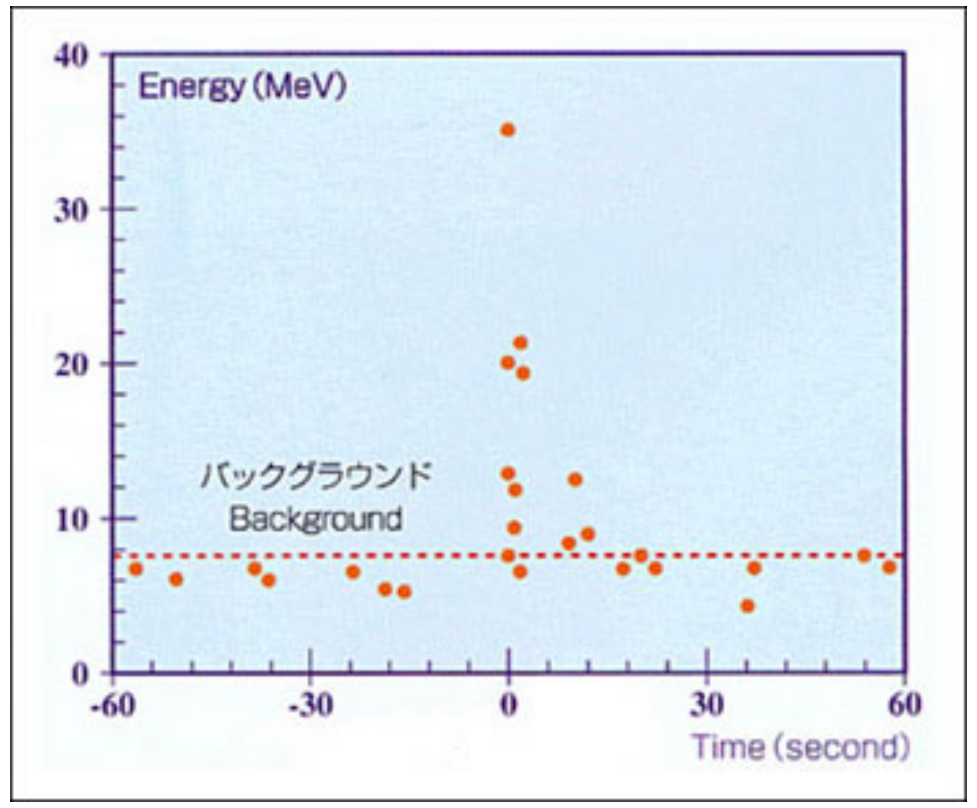


Supernova-scope

nearby SN



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



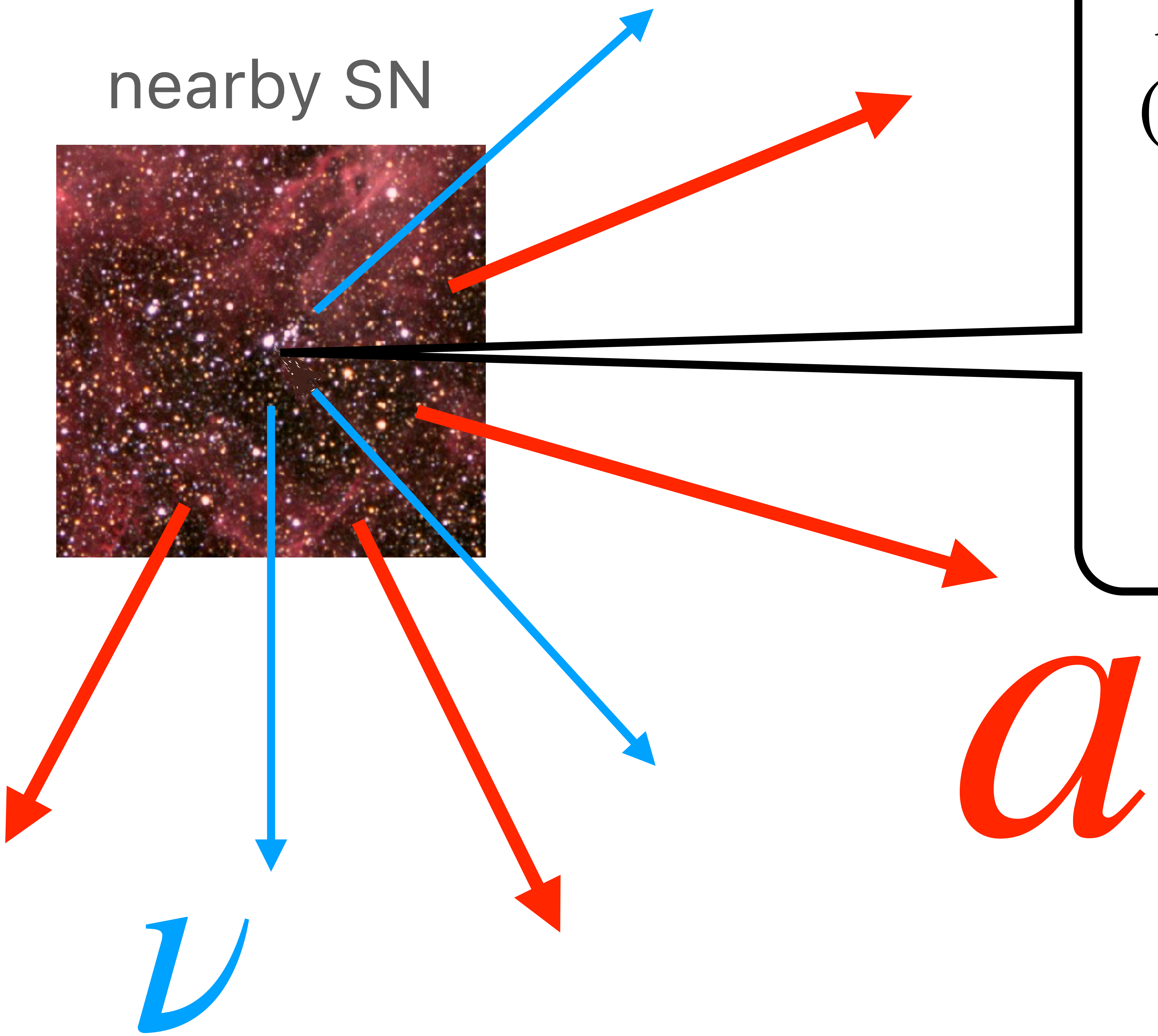
- SN1987A

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

- Future: various neutrino detectors

Supernova-scope

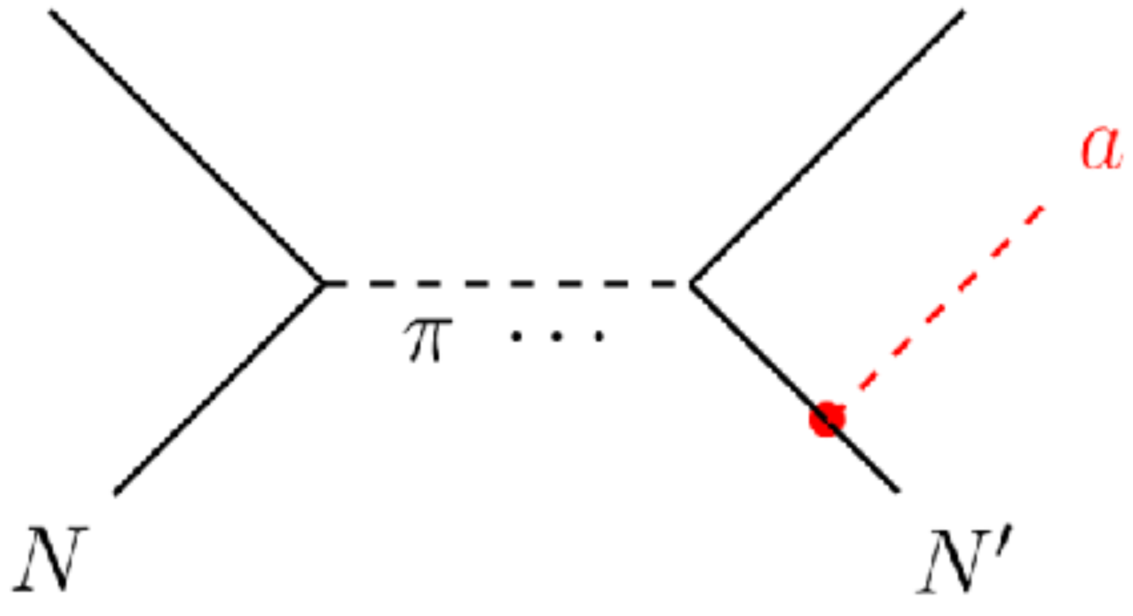
If the axion exists,...



$$NN' \to NN' + a$$

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

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



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

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

Supernova-scope

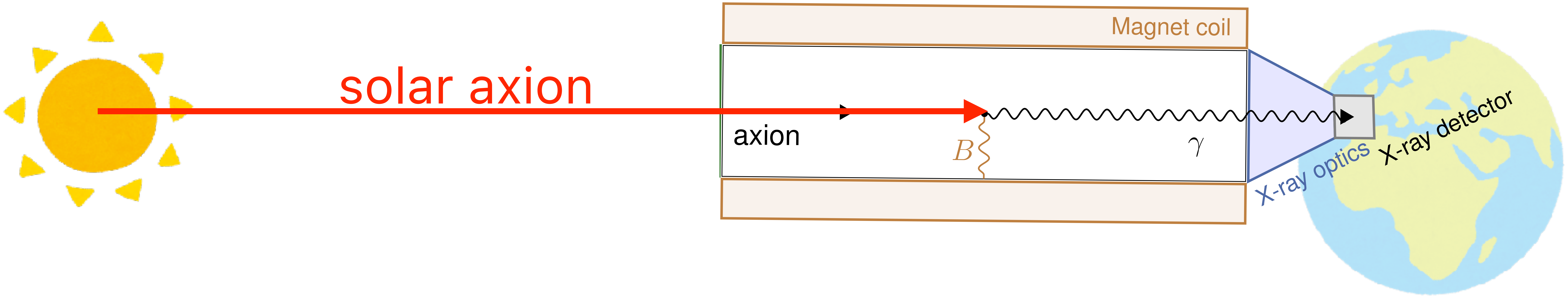
If the axion exists,...

Supernova-scope

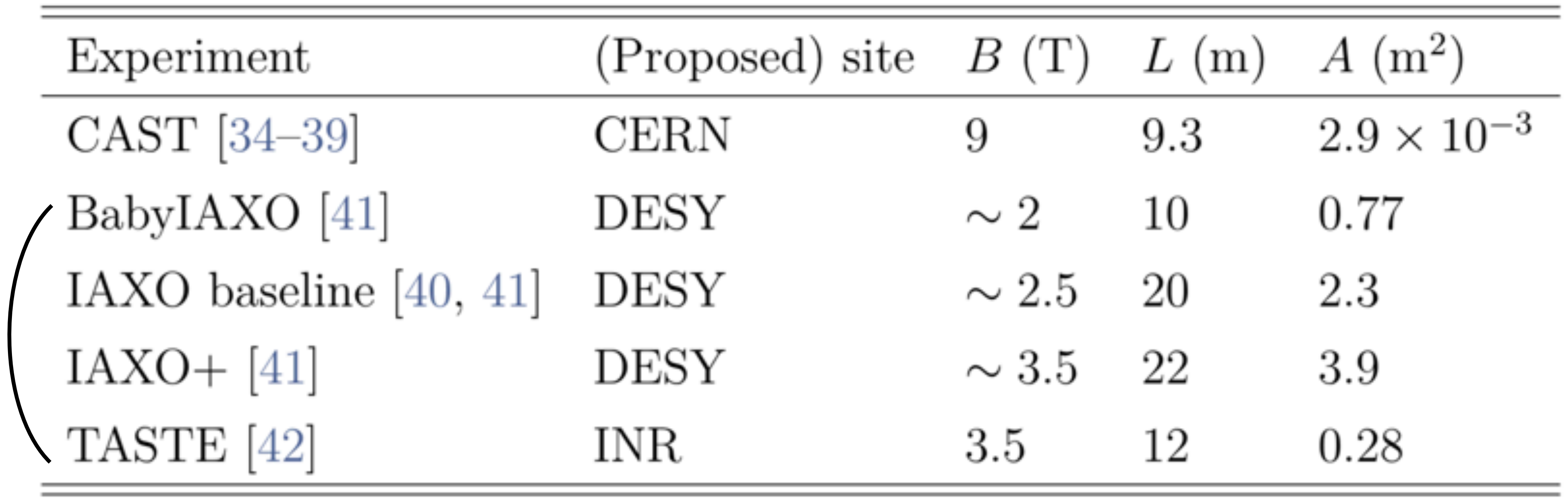
$$\mathcal{L}_{a\gamma\gamma} = \frac{1}{4}\frac{C_{a\gamma\gamma}}{f_a} a F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

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
	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

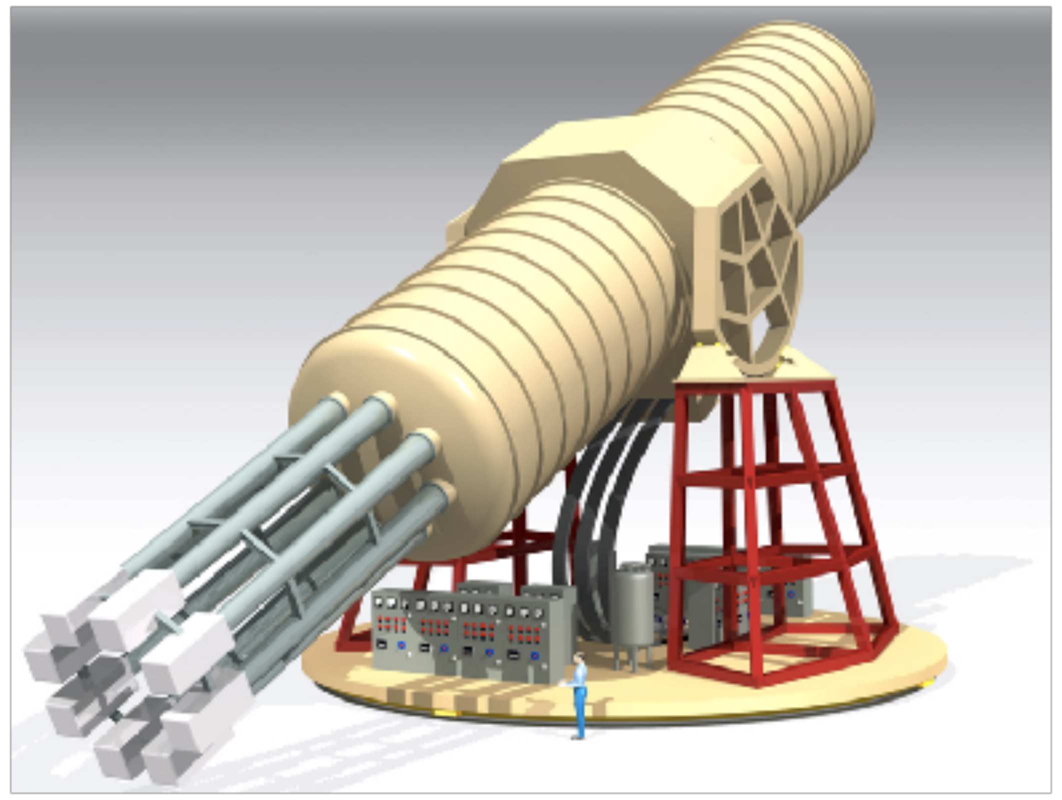
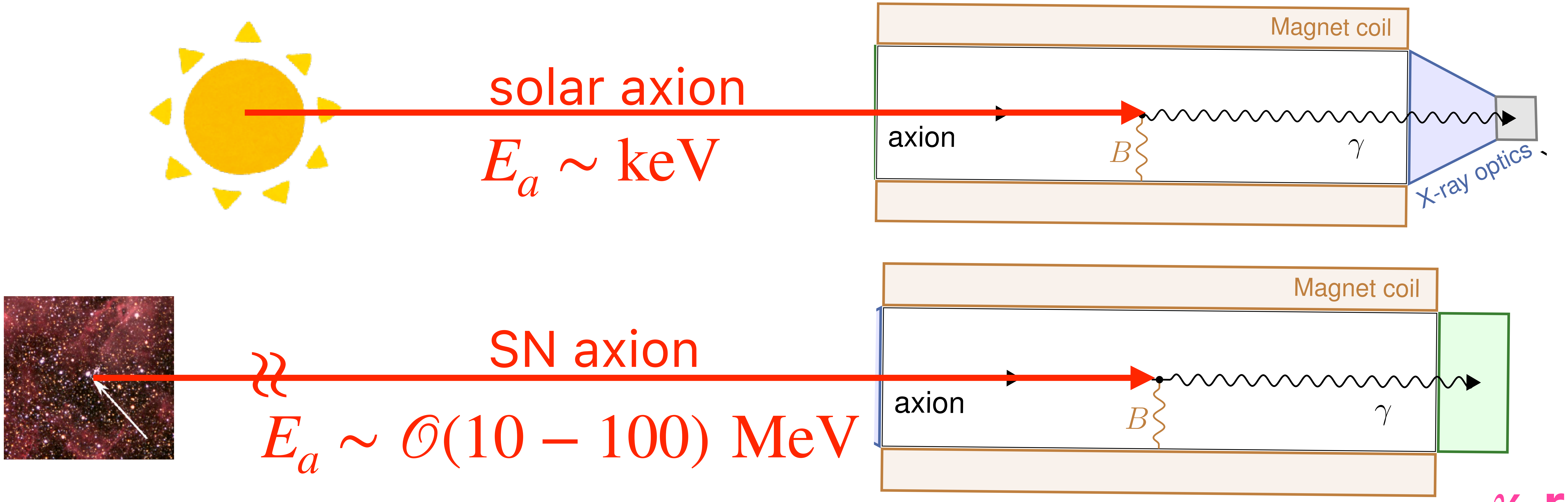


Fig. from IAXO homepage

Supernova-scope

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

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



solar axion

$E_a \sim \mathrm{keV}$

X-ray detector

SN axion

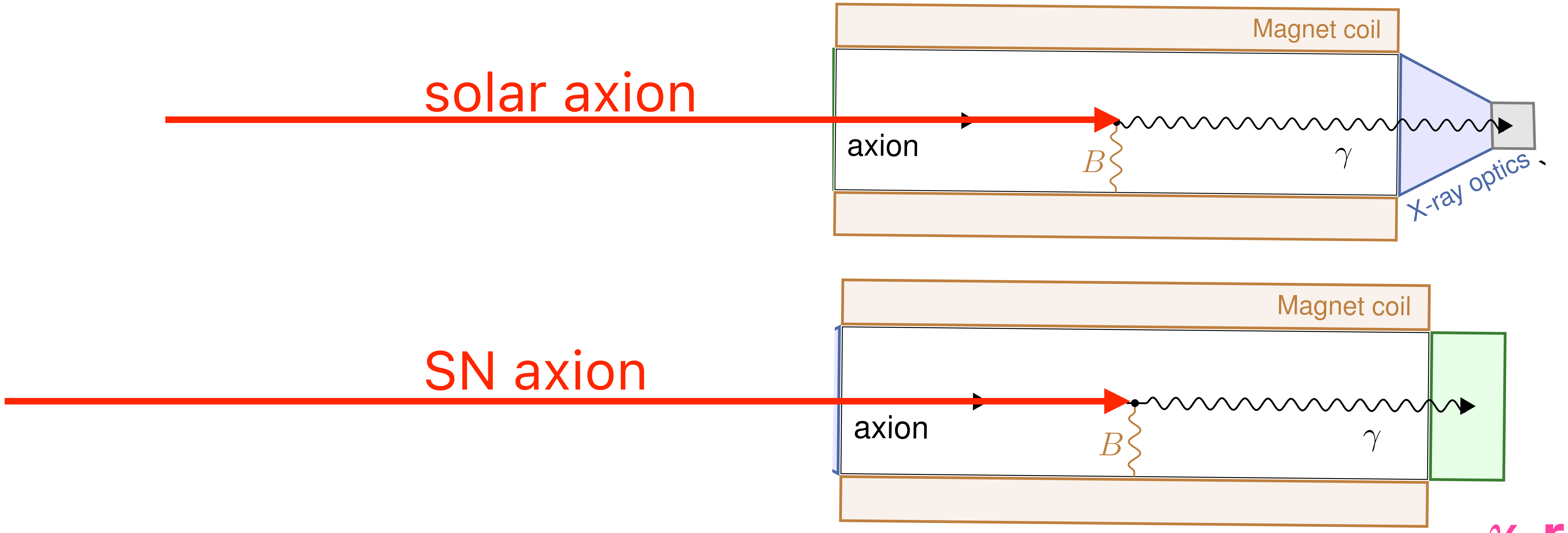
$E_a \sim \mathcal{O}(10-100)\ \mathrm{MeV}$

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



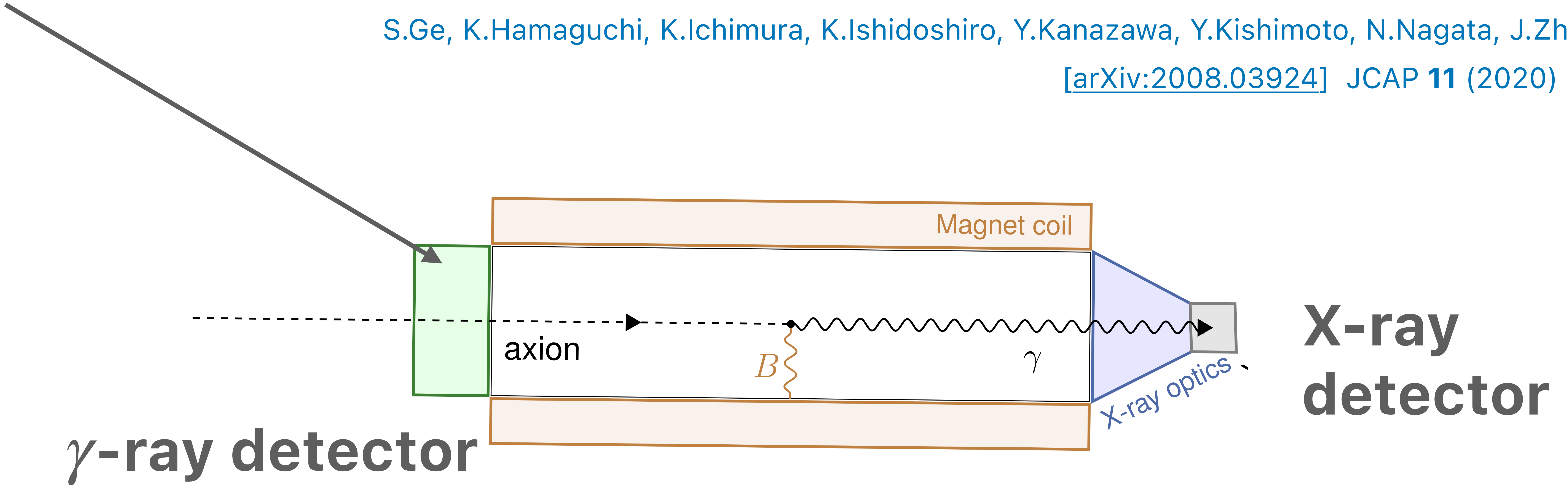
X-ray detector

γ-ray detector is necessary.

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.



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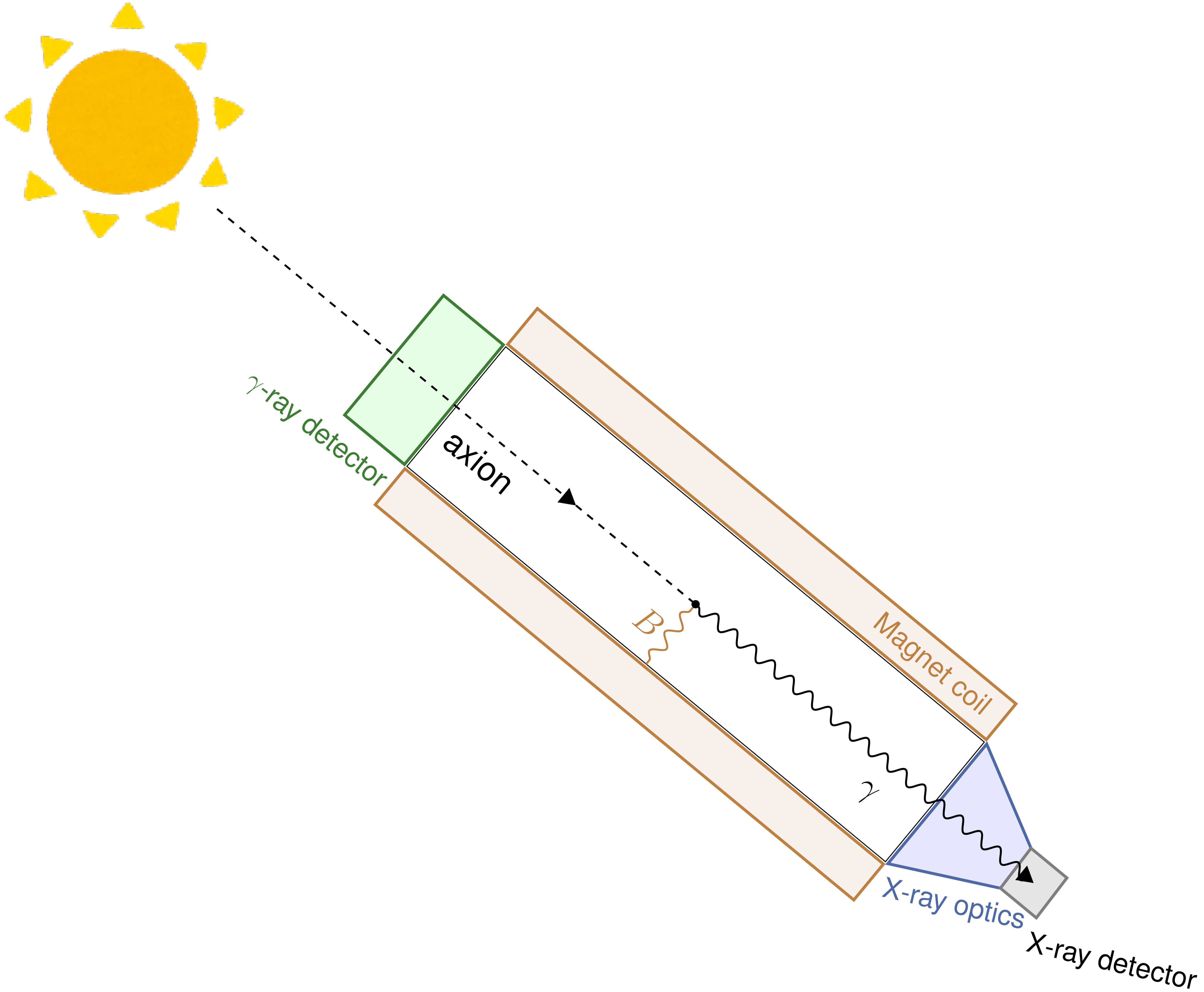
Normal operation time: It works as an axion helioscope.



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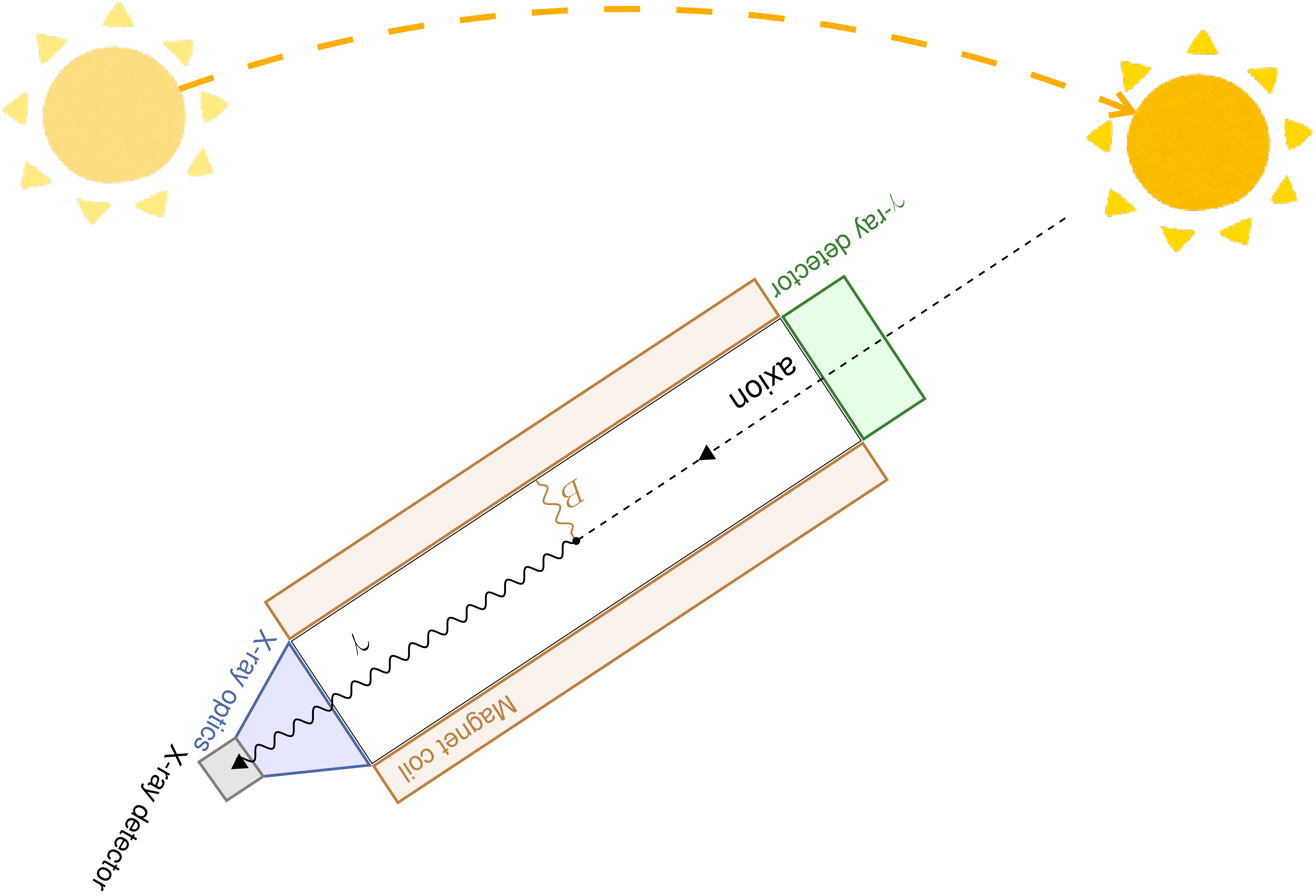

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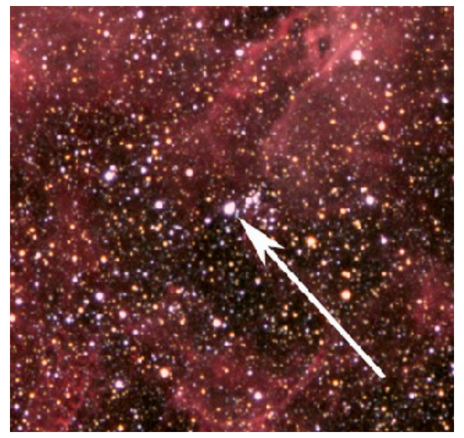
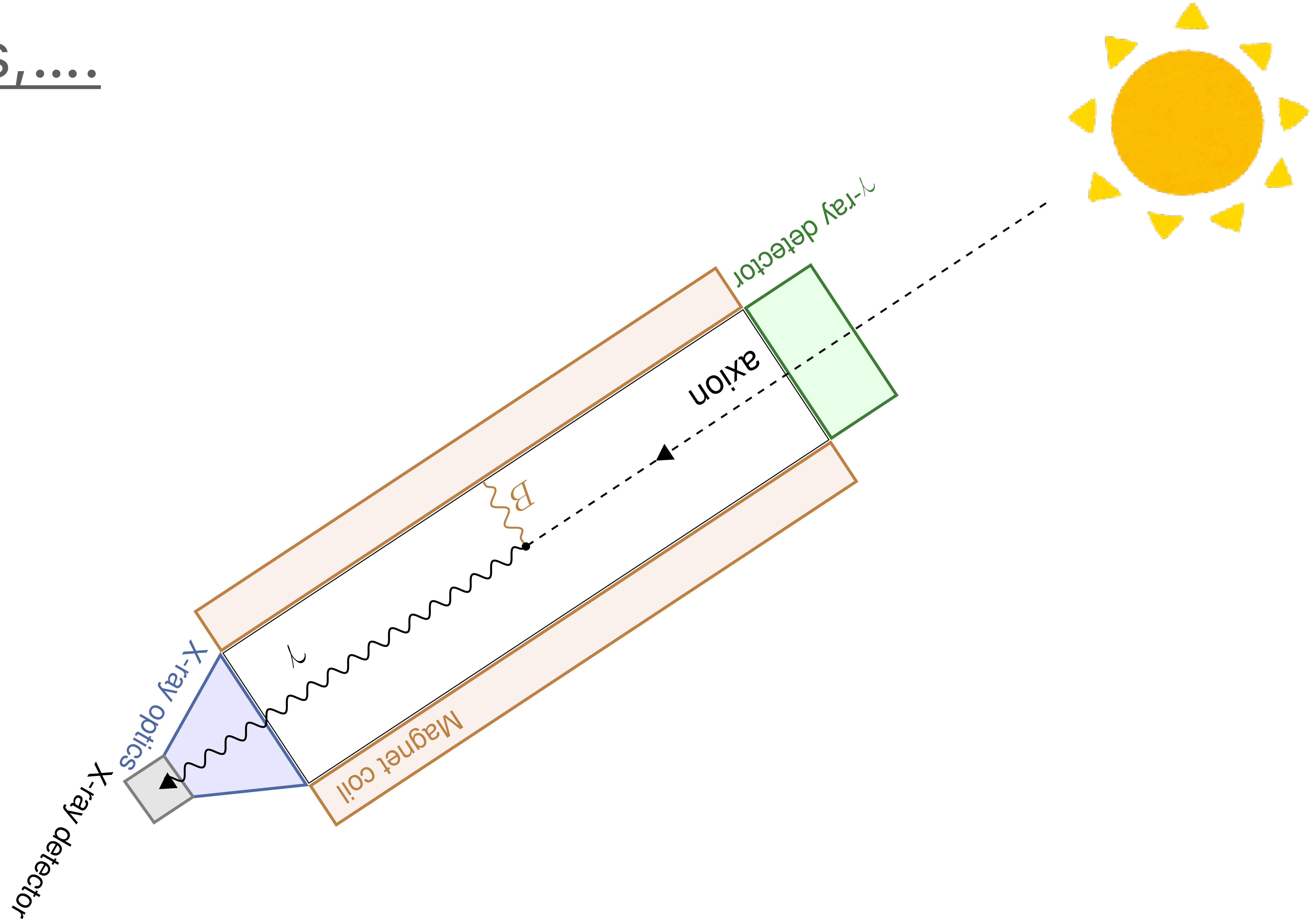
When a Supernova occurs,….





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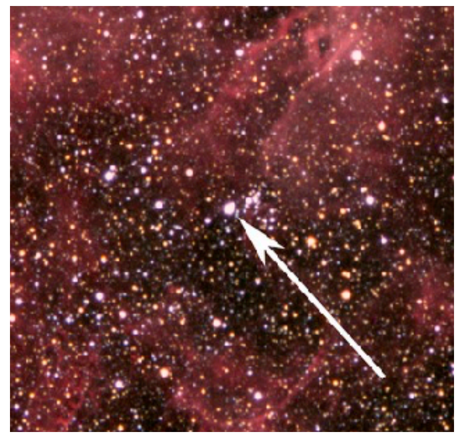

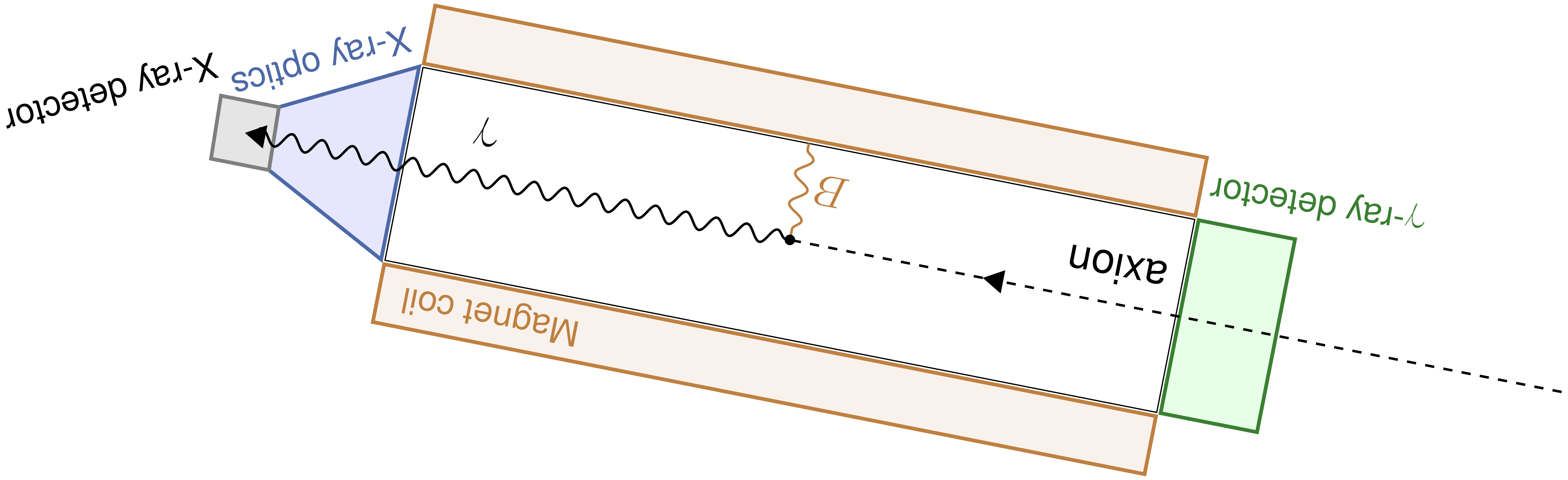

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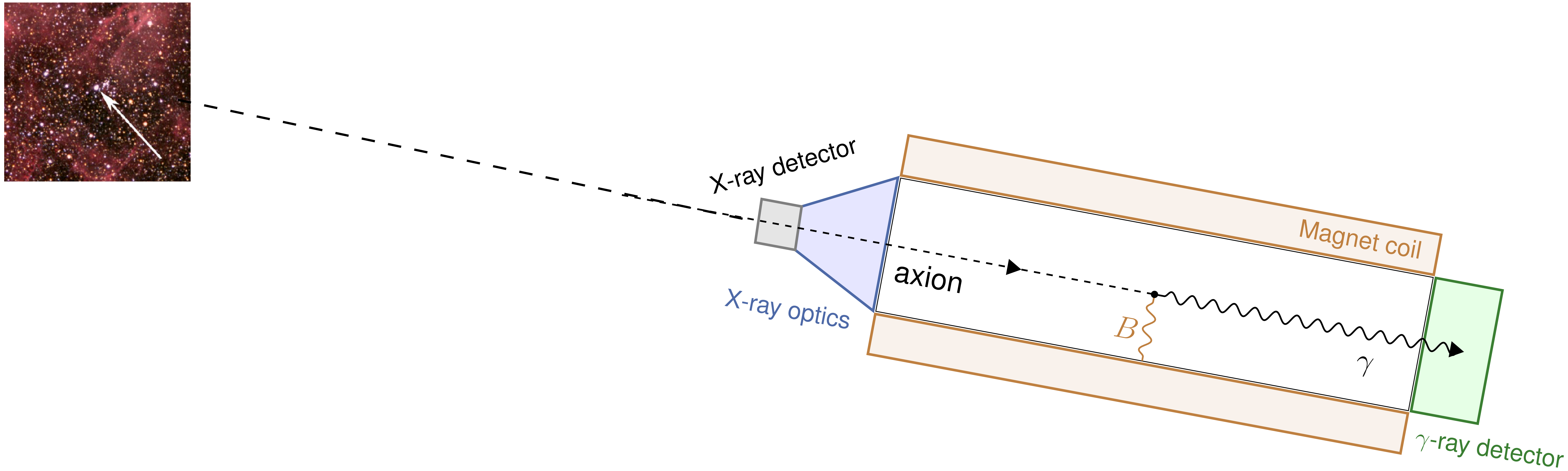

Axion Supernova-scope

Plan

- **Introduction: Standard Model and Axion**
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  - Pre-SN neutrino
  - Observation time fraction
  - Event number
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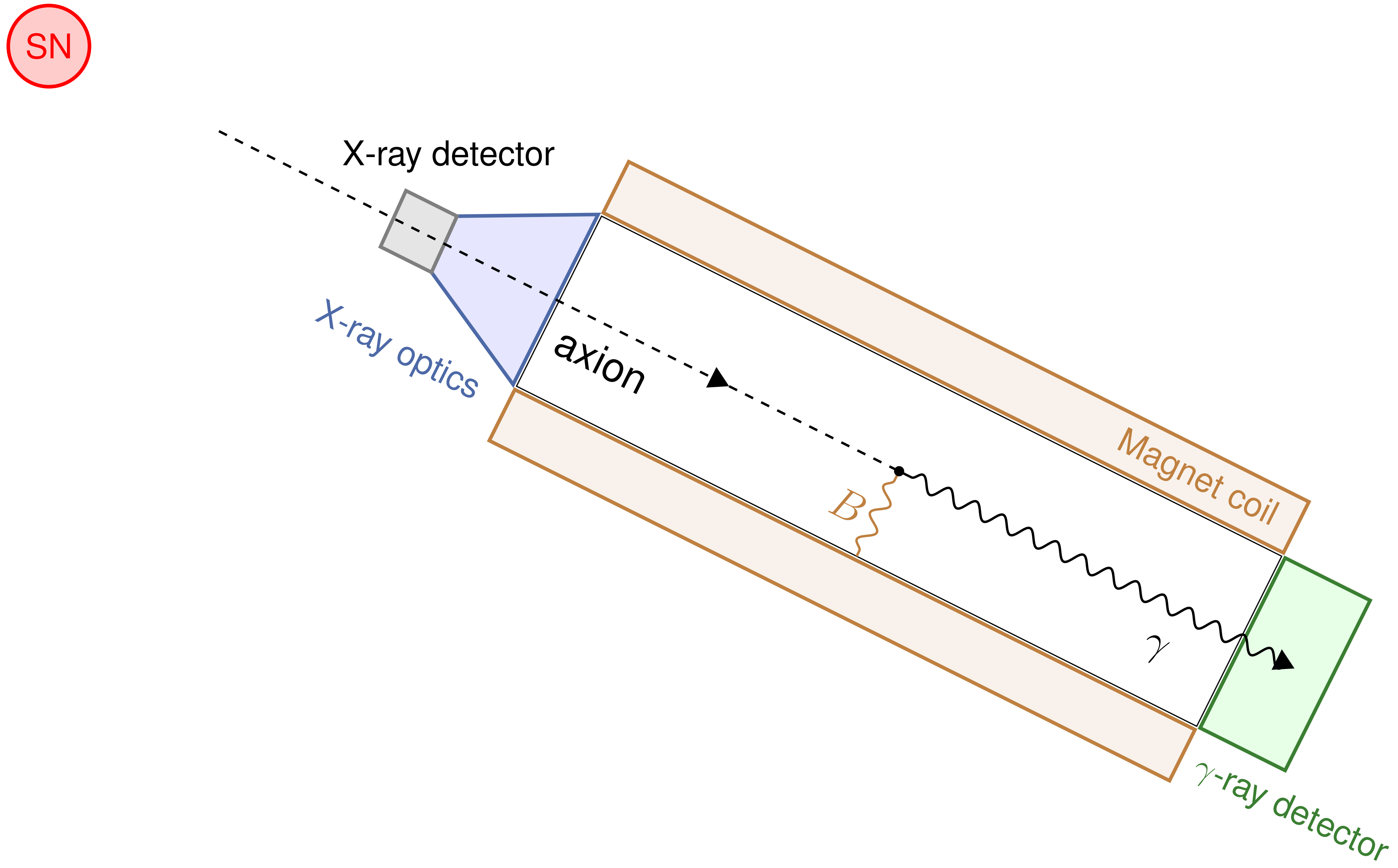
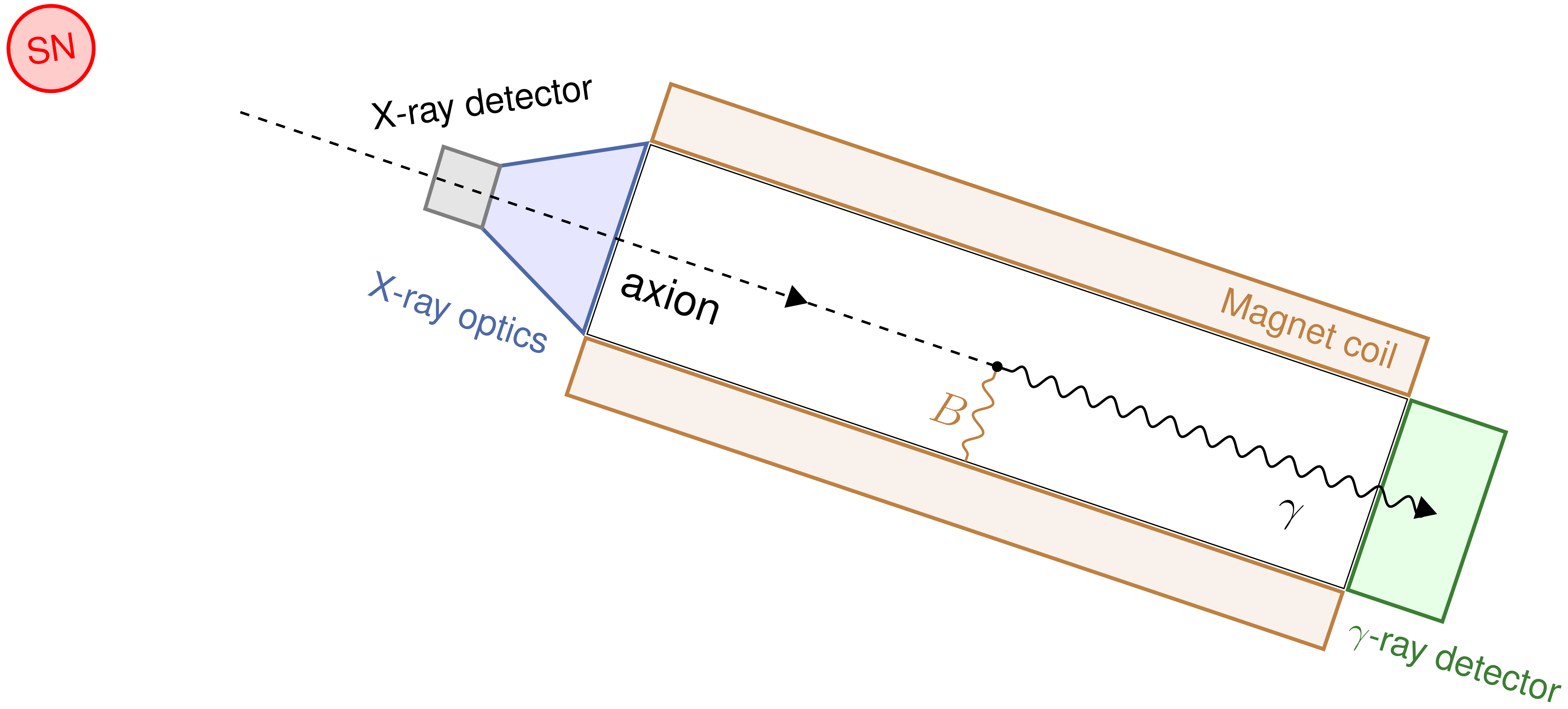


Pre-SN neutrino

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.

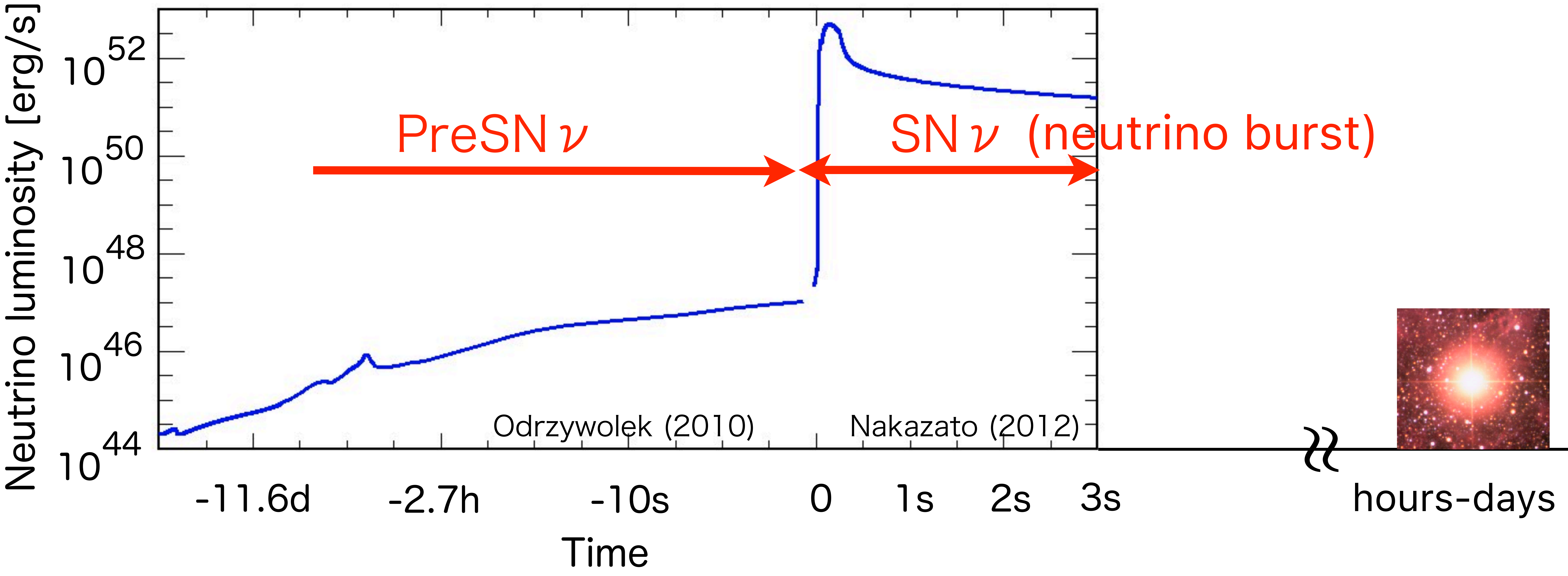


Figure from K.Ishidoshiro's talk in 2019.
https://www.lowbg.org/ugnd/workshop/sympo_all/201903_Sendai/

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

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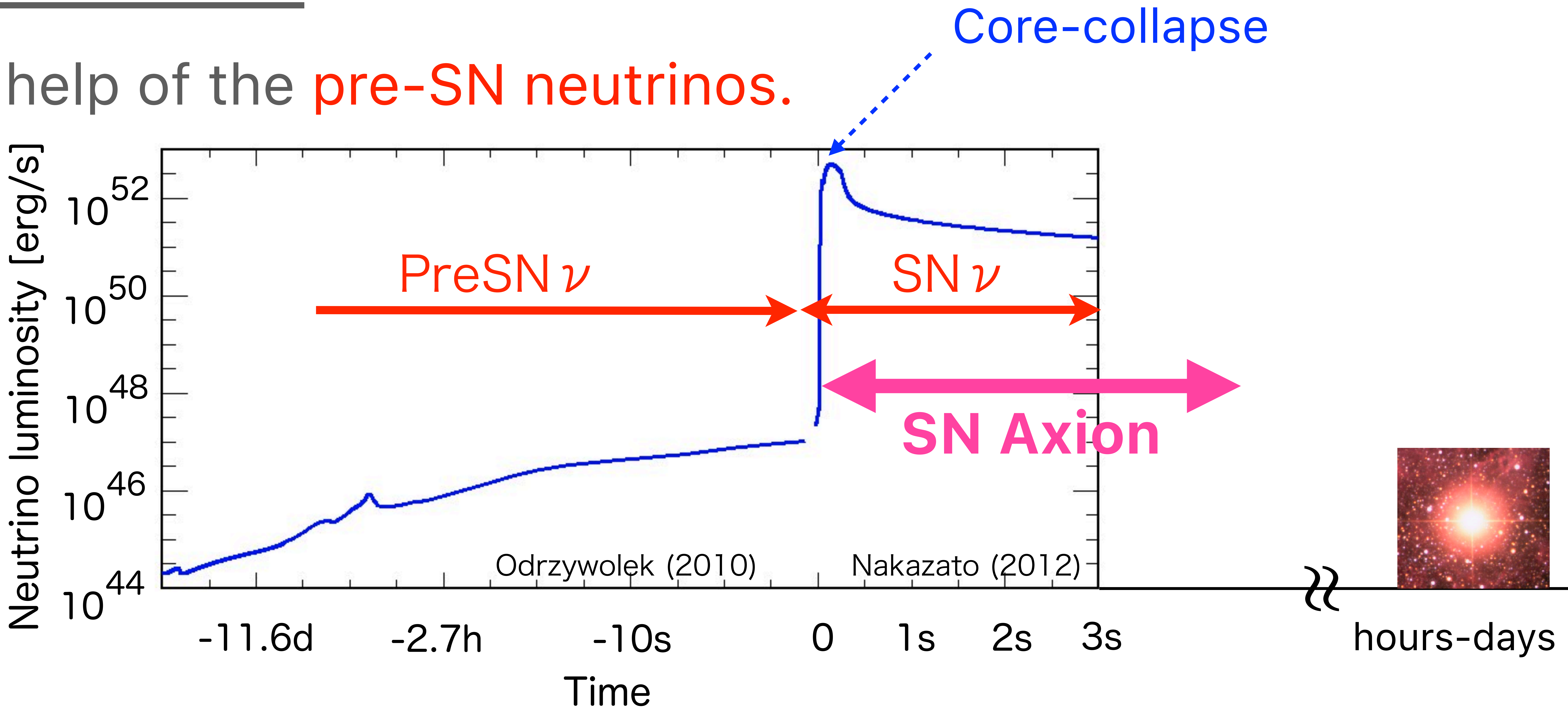

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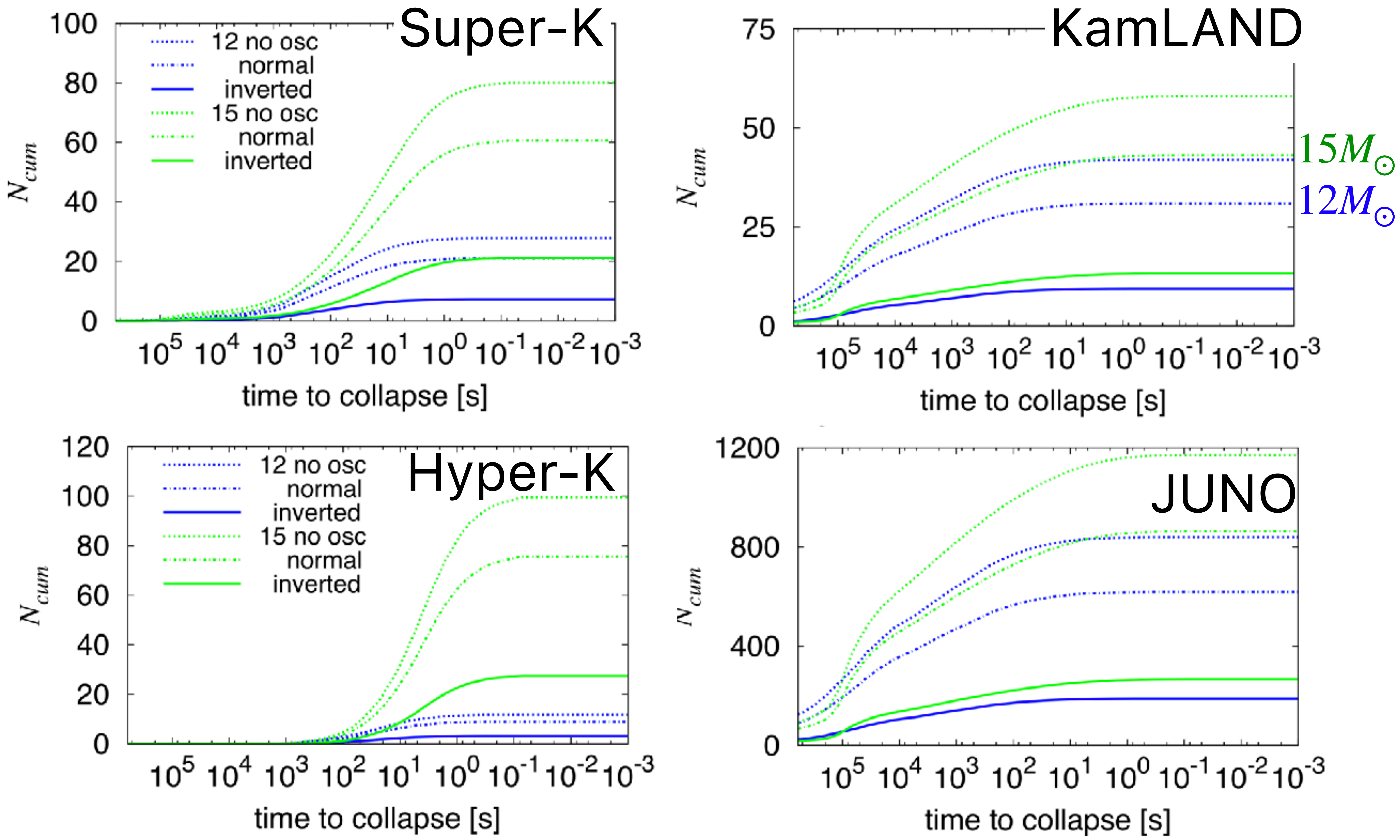
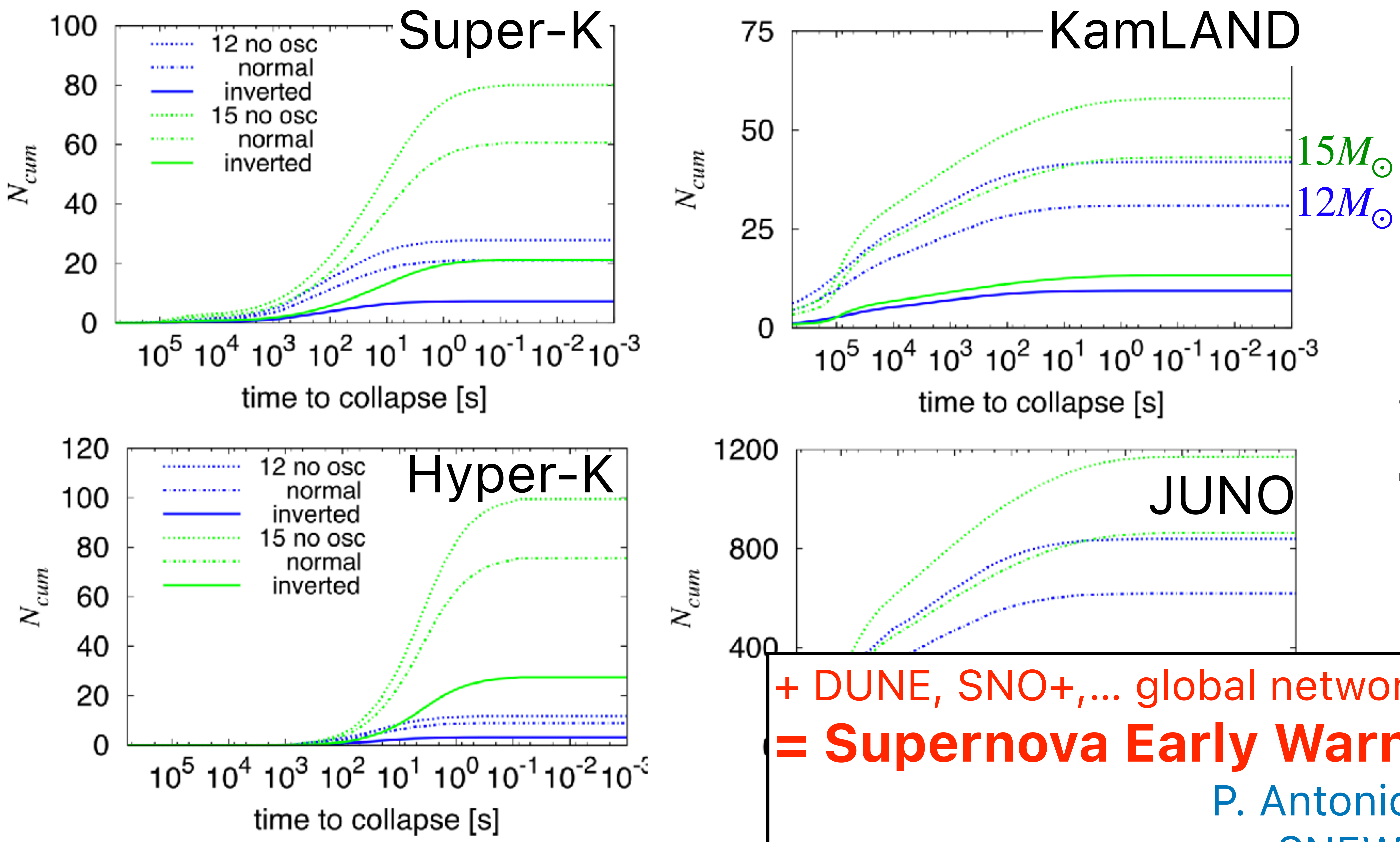


The cumulative numbers of expected pre-SN ν events for Fe-Core progenitor, $d = 200$ pc.

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

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).

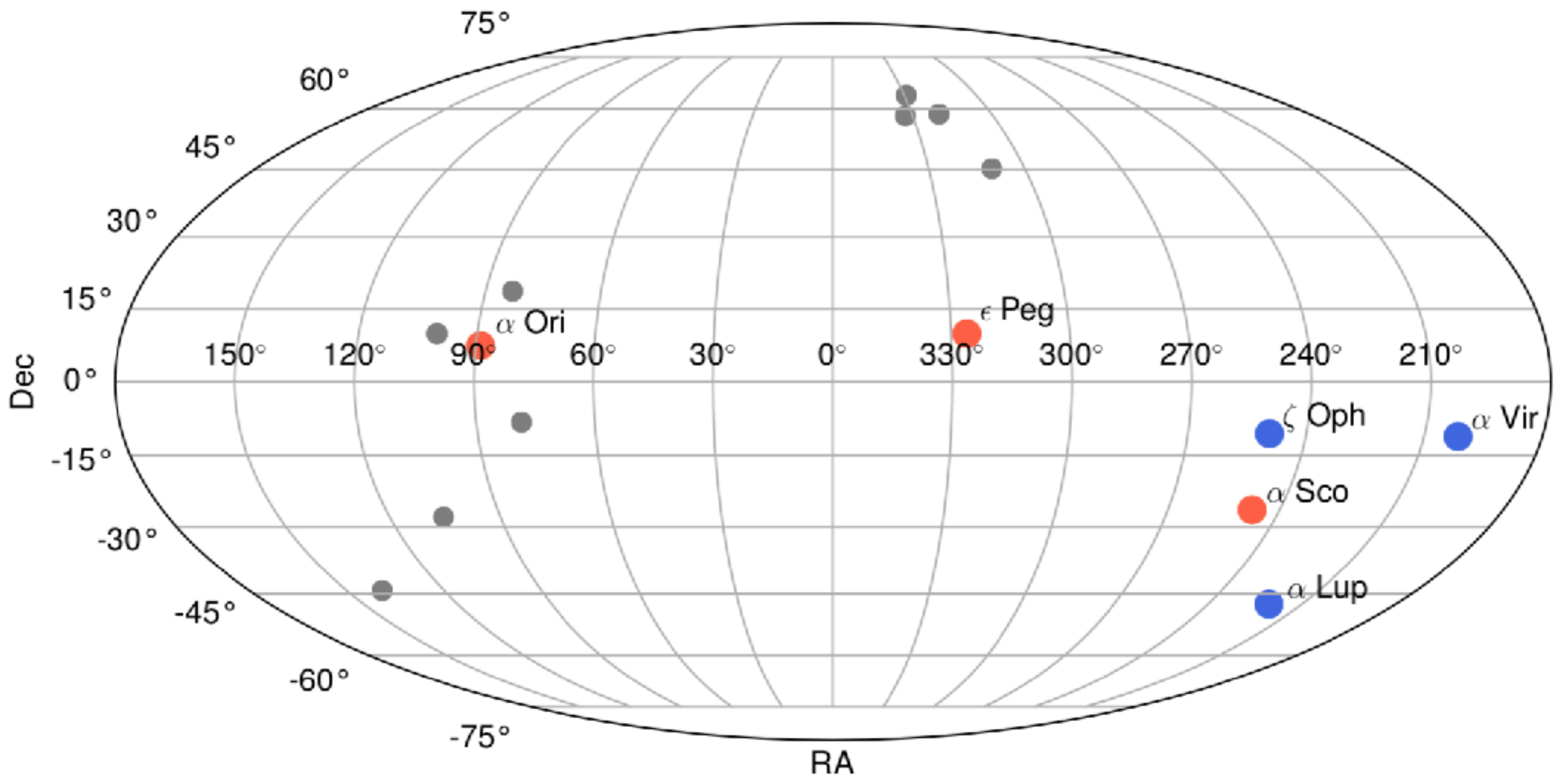
※ SN progenitors with $M < 10M_\odot$

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

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

→ We discard them.

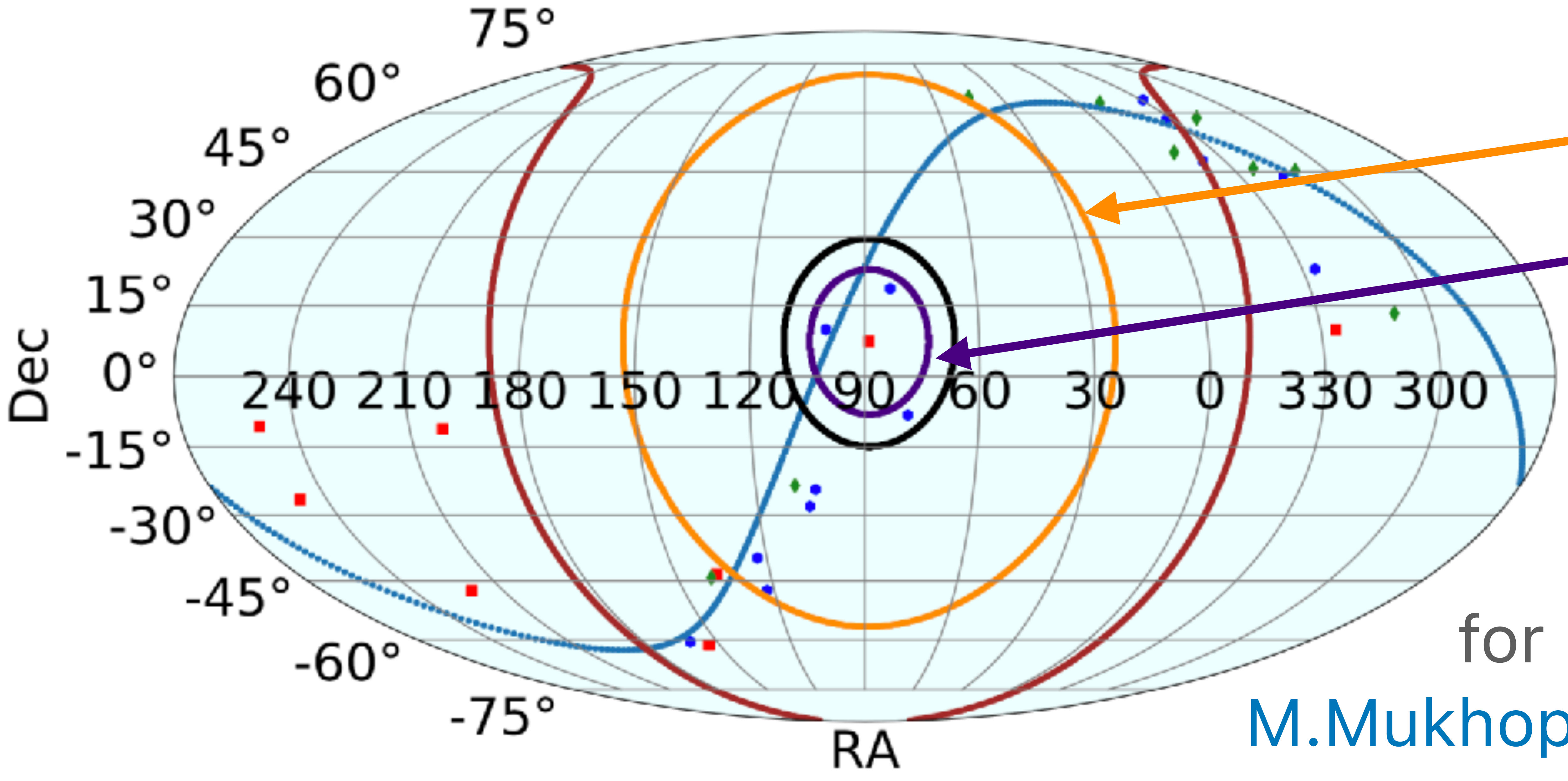
$M > 10M_\odot$ only.



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

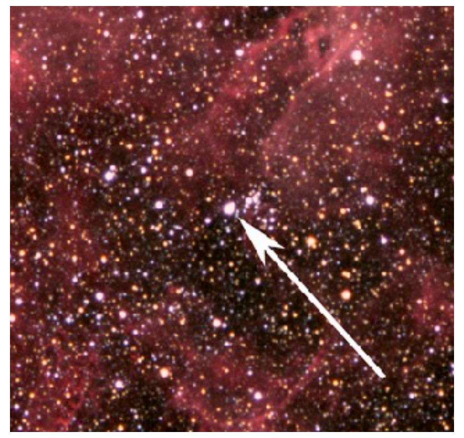
JUNO (68% C.L.)

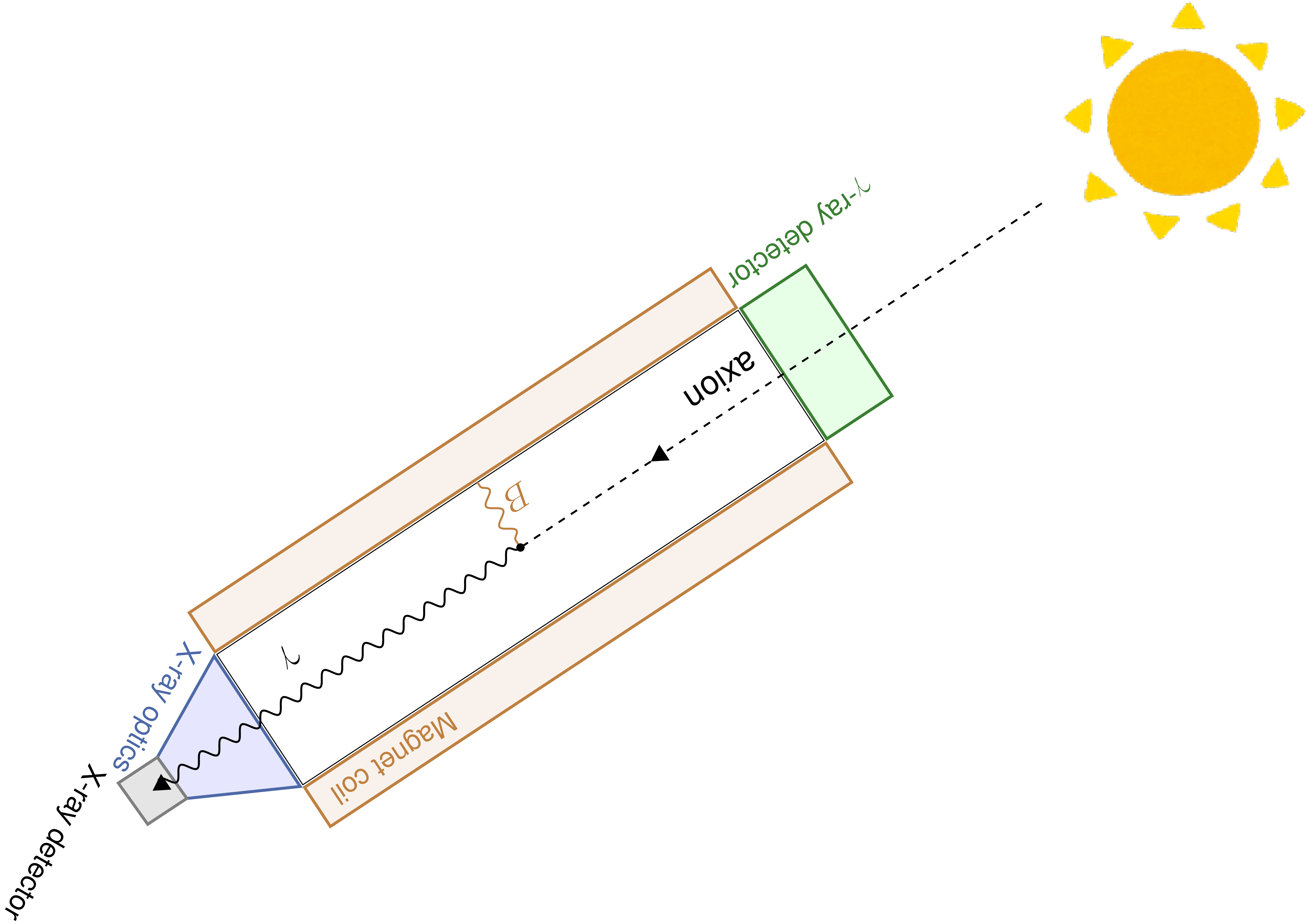
JUNO + Li (68% C.L.)

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

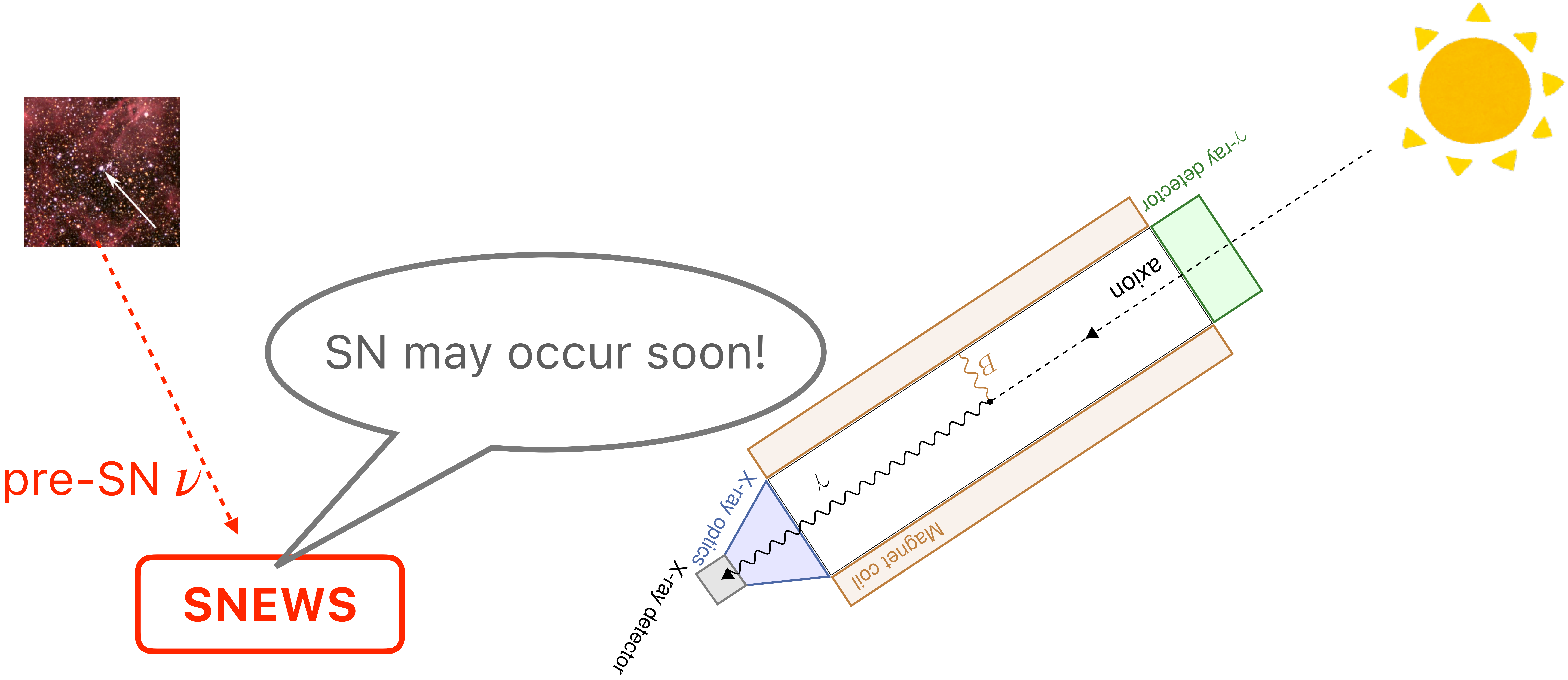
for Betelgeuse, $t = -1.0$ hour.

M.Mukhopadhyay et.al., [2004.02045]




γ-ray detector
axion
B
γ
X-ray optics
X-ray detector
Magnet coil

Once a pre-SN neutrino alert is received,

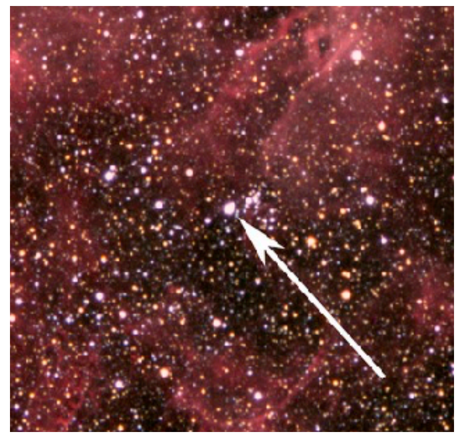


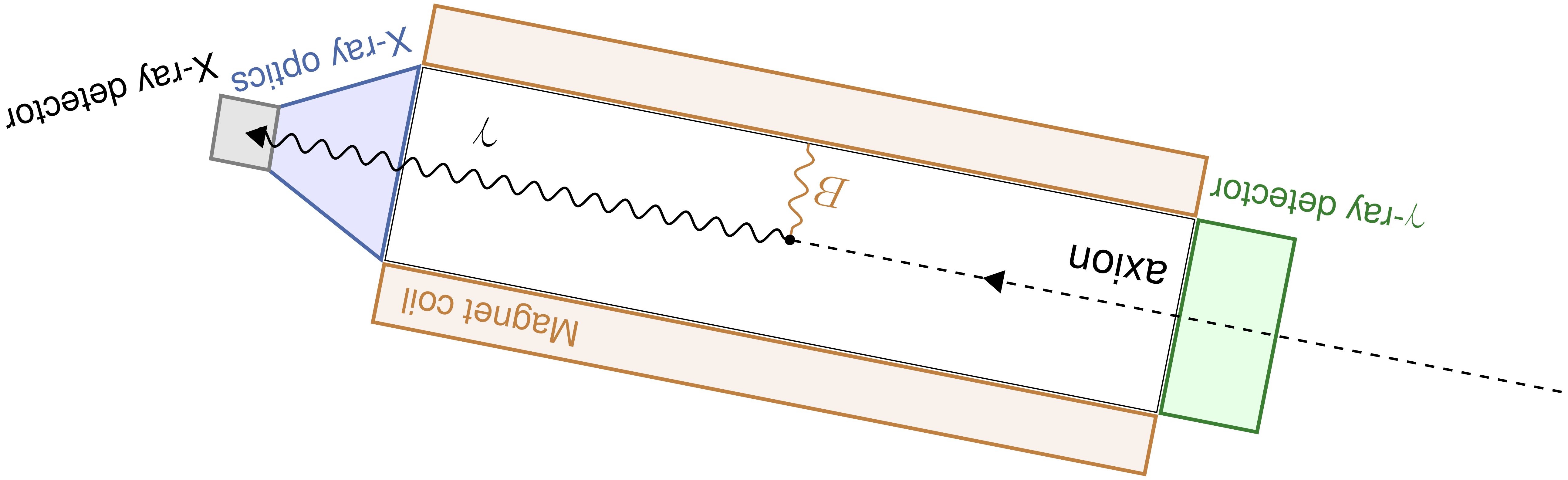
pre-SN ν

SNEWS

SN may occur soon!

Once a pre-SN neutrino alert is received,





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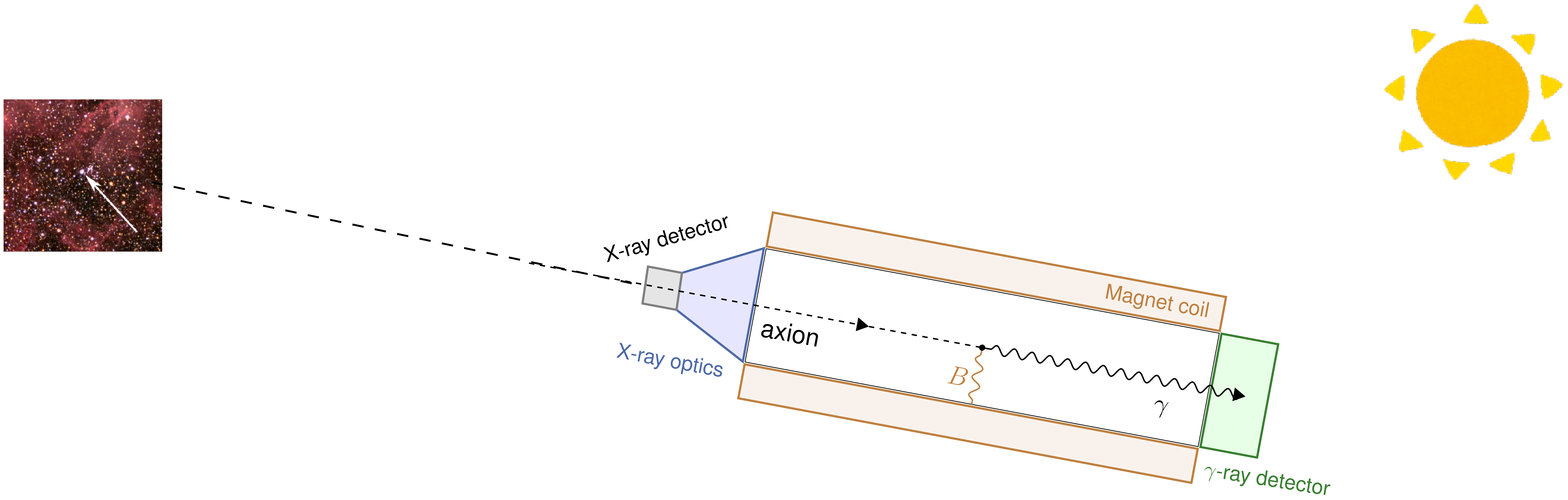

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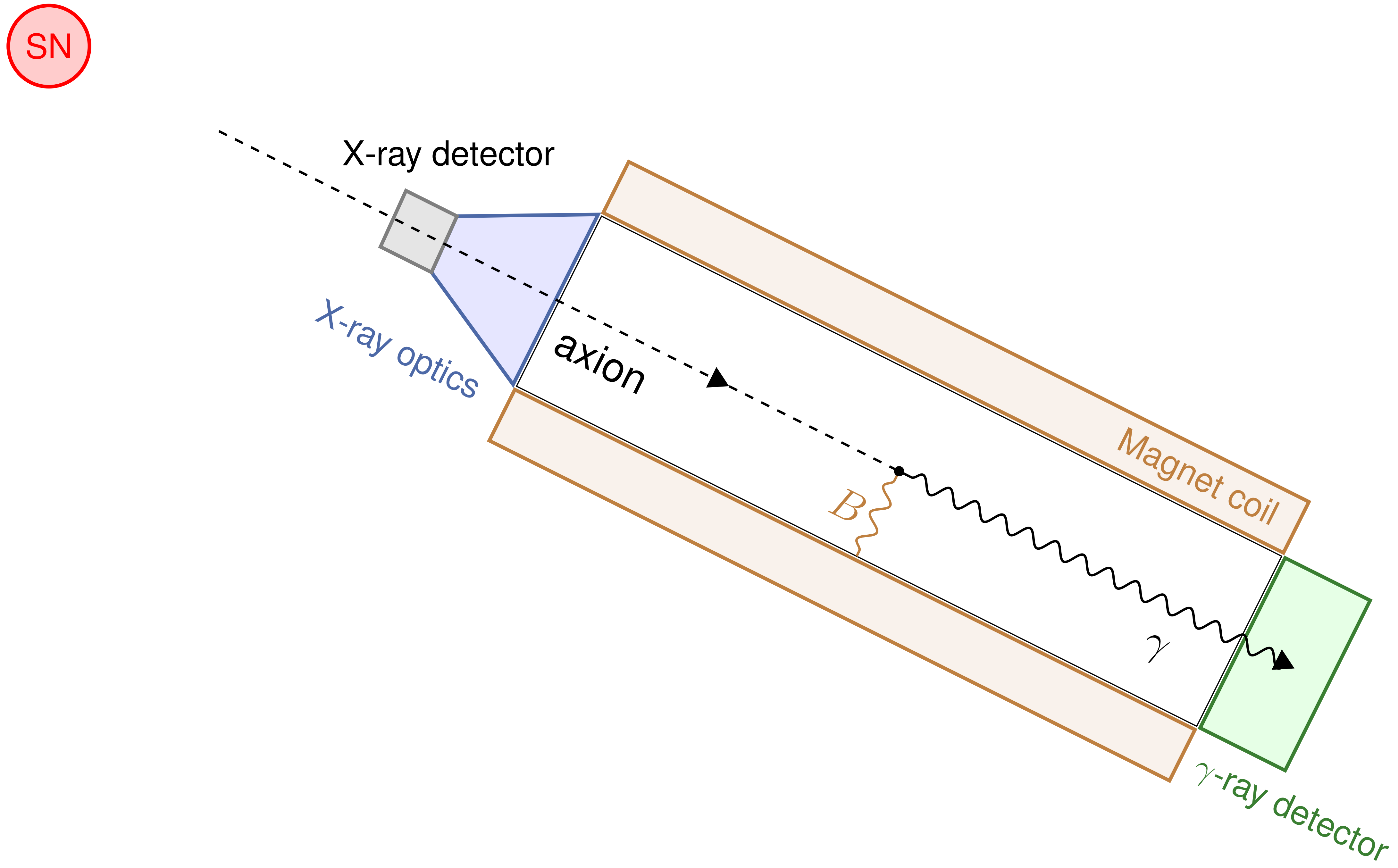
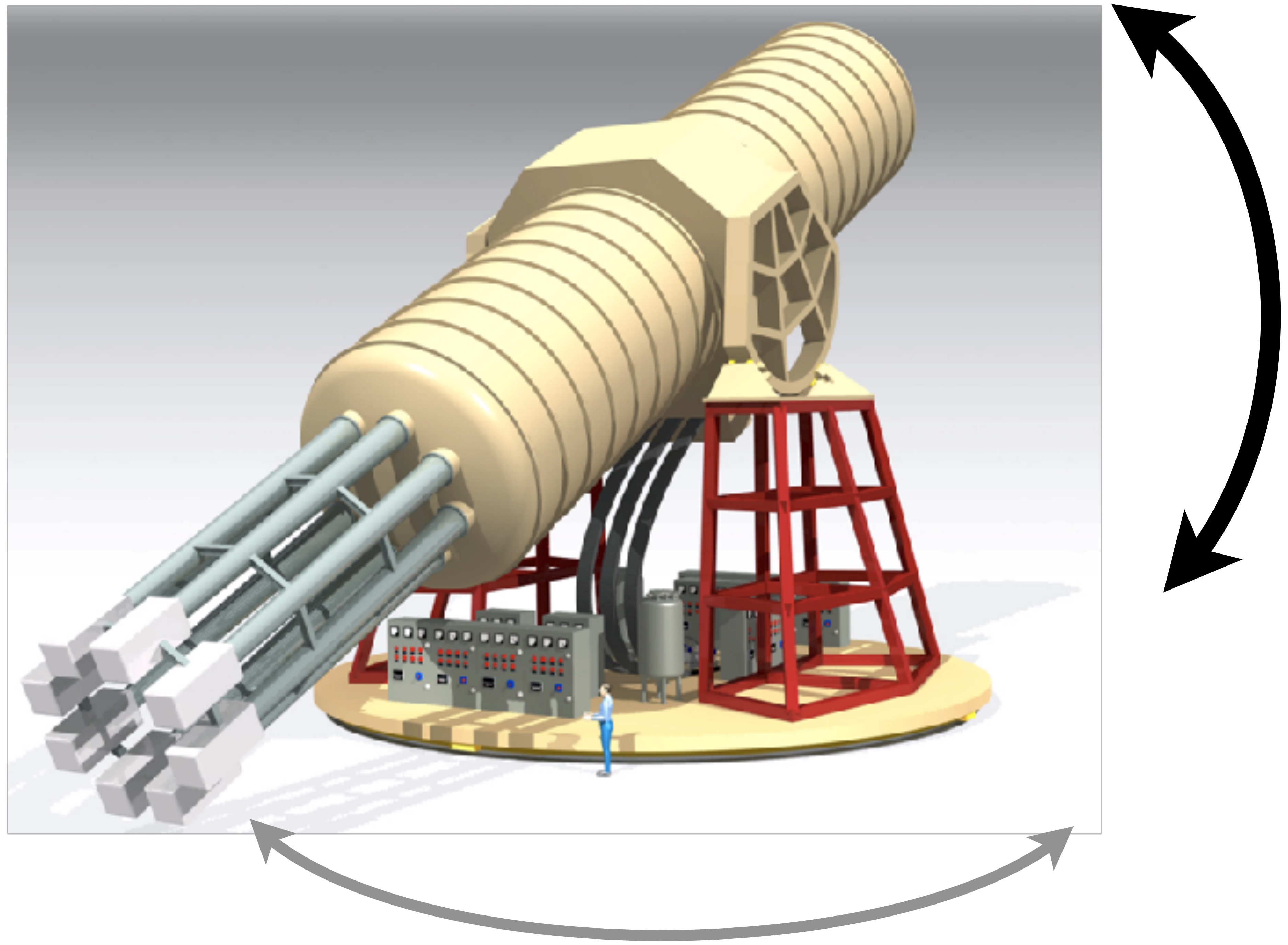


Observation time fraction

Fig. from IAXO homepage



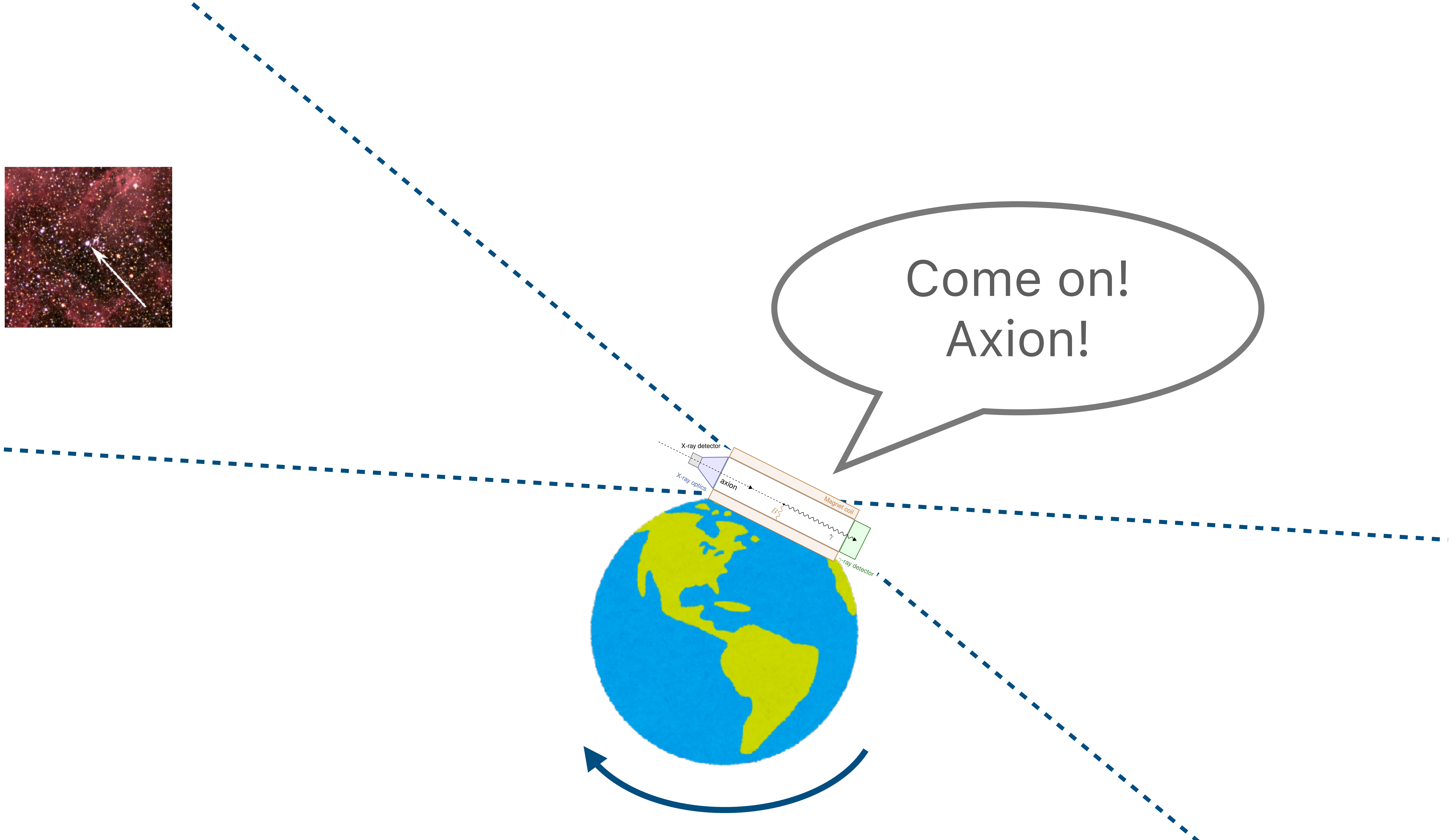
$$-\theta_{\max} \leq \theta \leq +\theta_{\max}$$

$$0 \leq \phi \leq 360^\circ$$

maximum elevation:

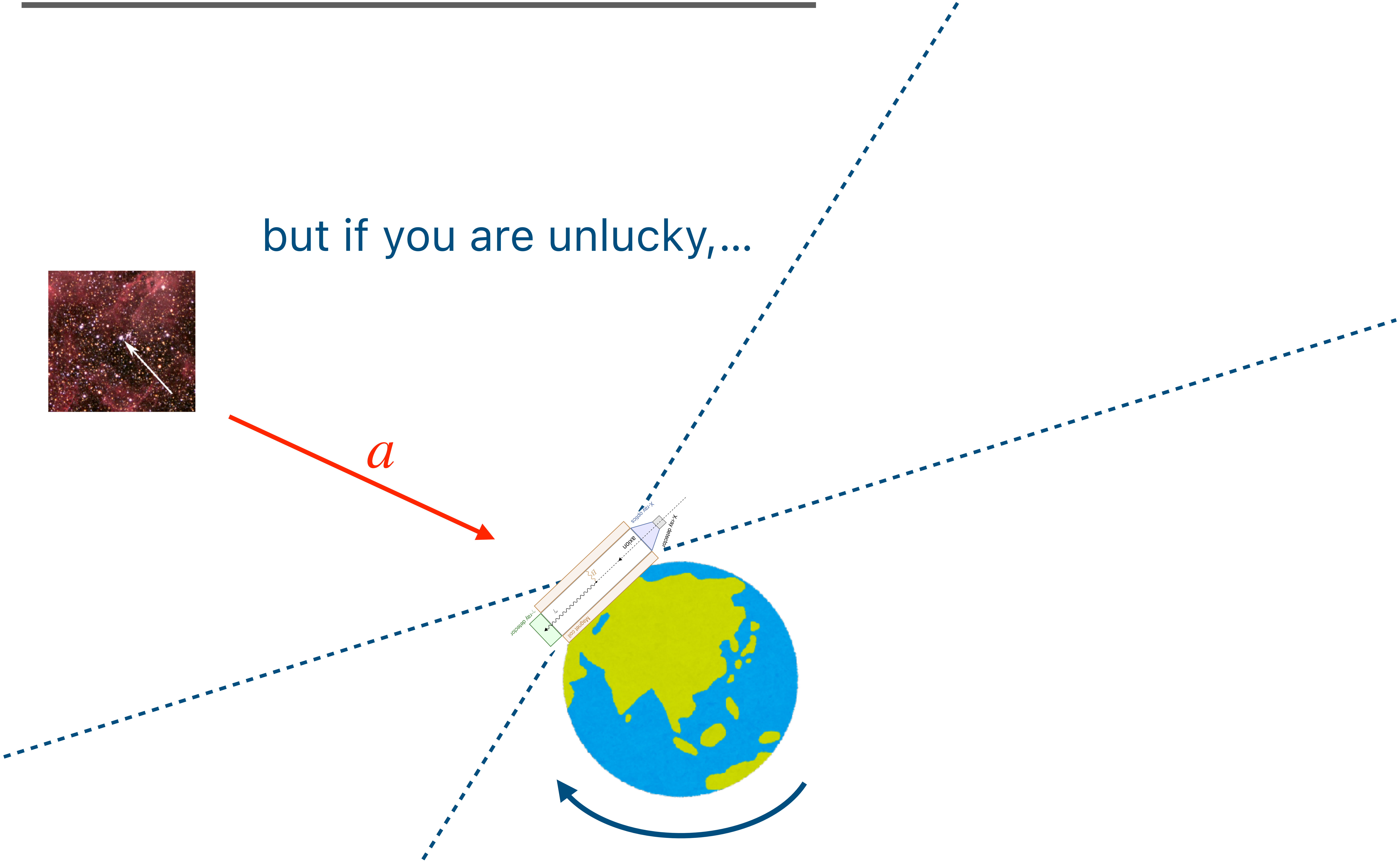
$$\theta_{\max} = \begin{cases} 25^\circ \text{ (IAXO)} \\ 20^\circ \text{ (TASTE)} \end{cases}$$

Observation time fraction



Observation time fraction

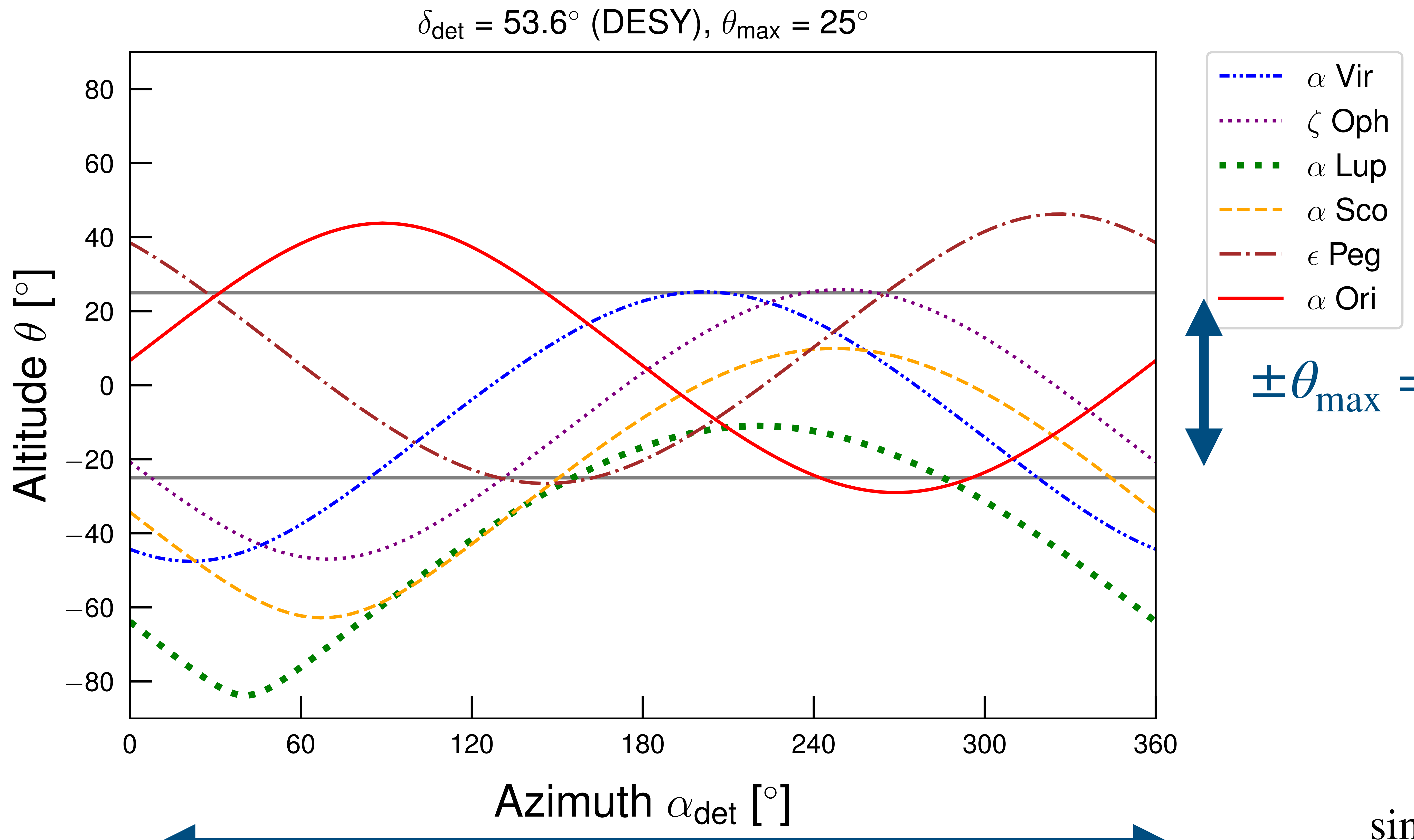
but if you are unlucky,...



Observation time fraction

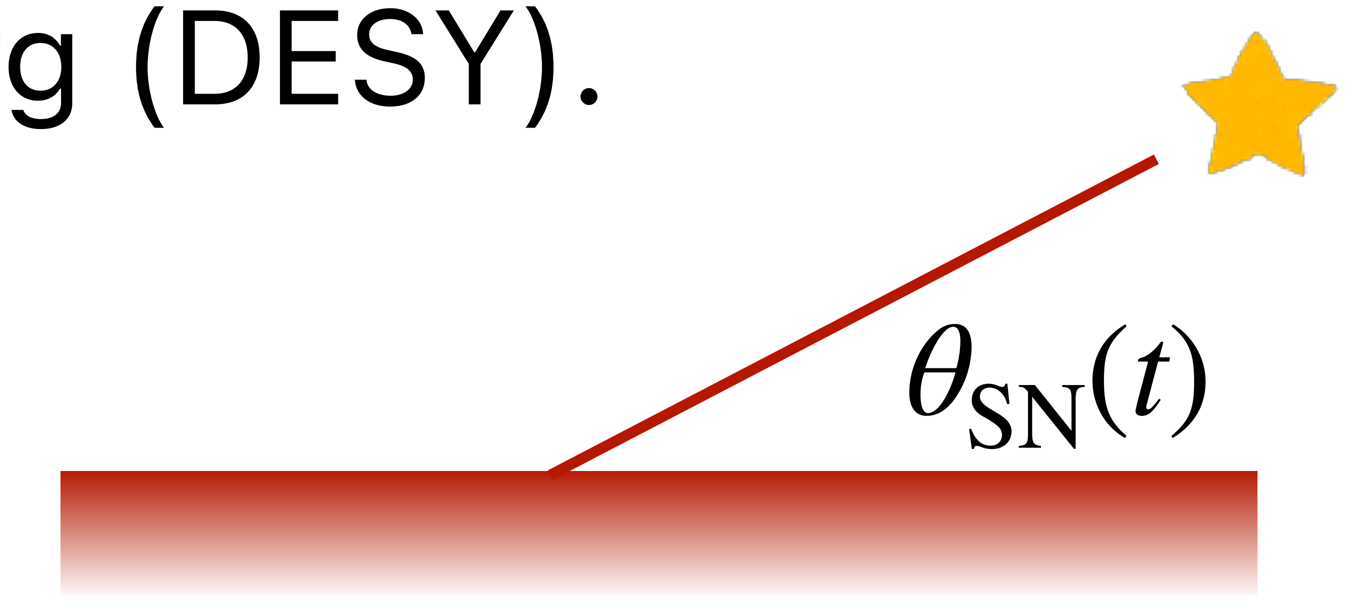
S.Ge, K.Hamaguchi, K.Ichimura, K.Ishidoshiro,
Y.Kanazawa, Y.Kishimoto, N.Nagata, J.Zheng.
[arXiv:2008.03924] JCAP **11** (2020) 059.

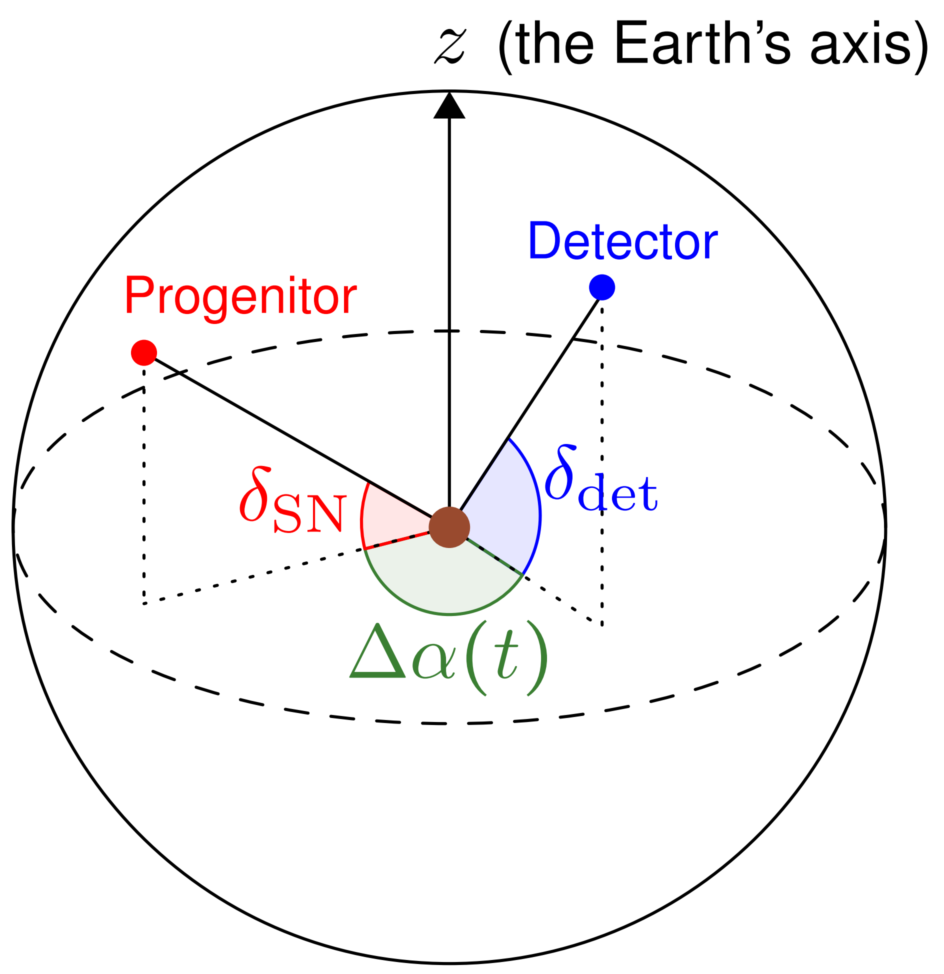
The altitude of the progenitors $\theta_{\rm SN}(t)$ seen from Hamburg (DESY).



$\pm\theta_{\rm max} = \pm 25°$

Earth's rotation (24 hours)





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

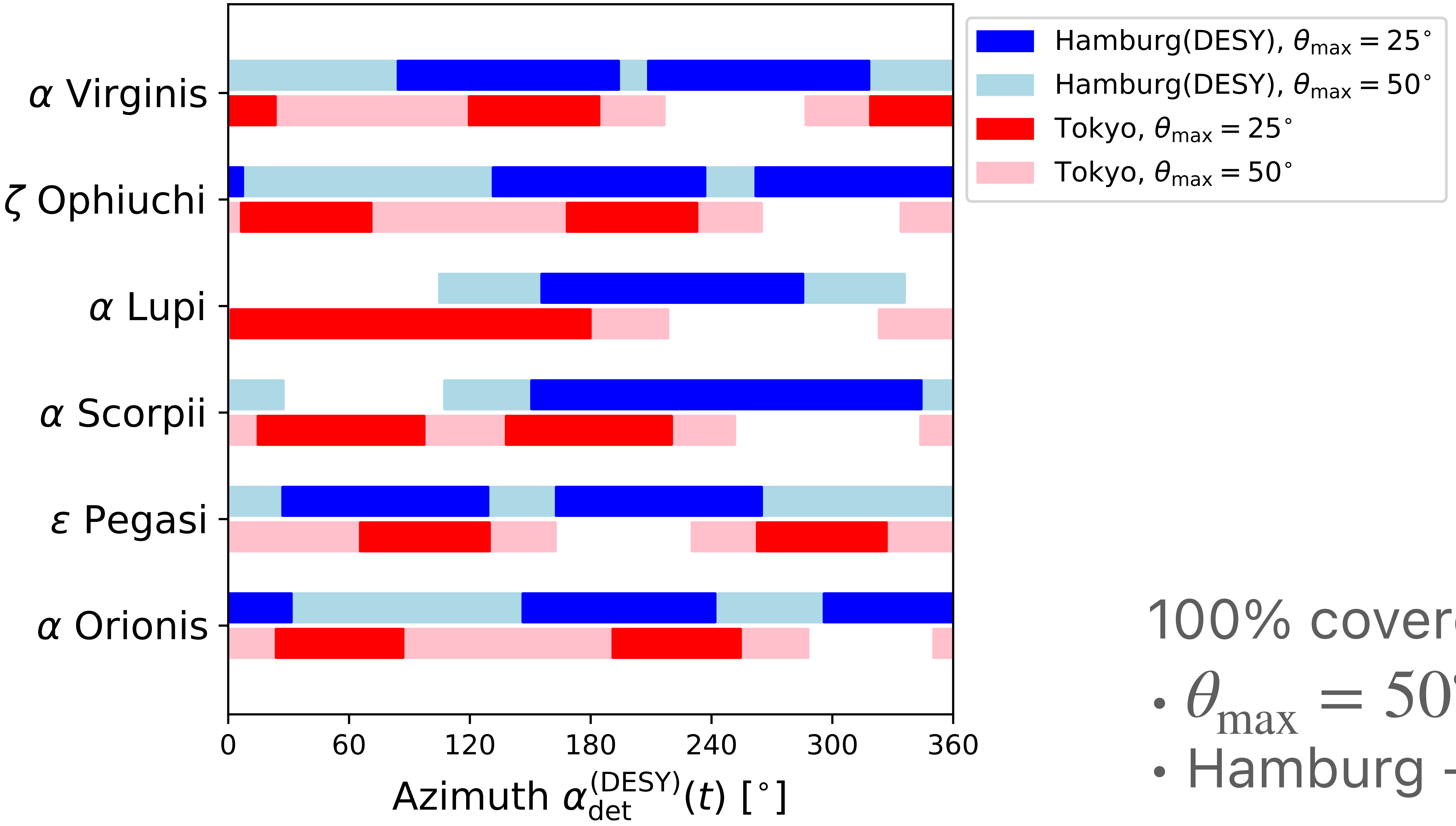
Observational time fraction > 50% for all the progenitors except α Lupi.

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



100% covered if

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

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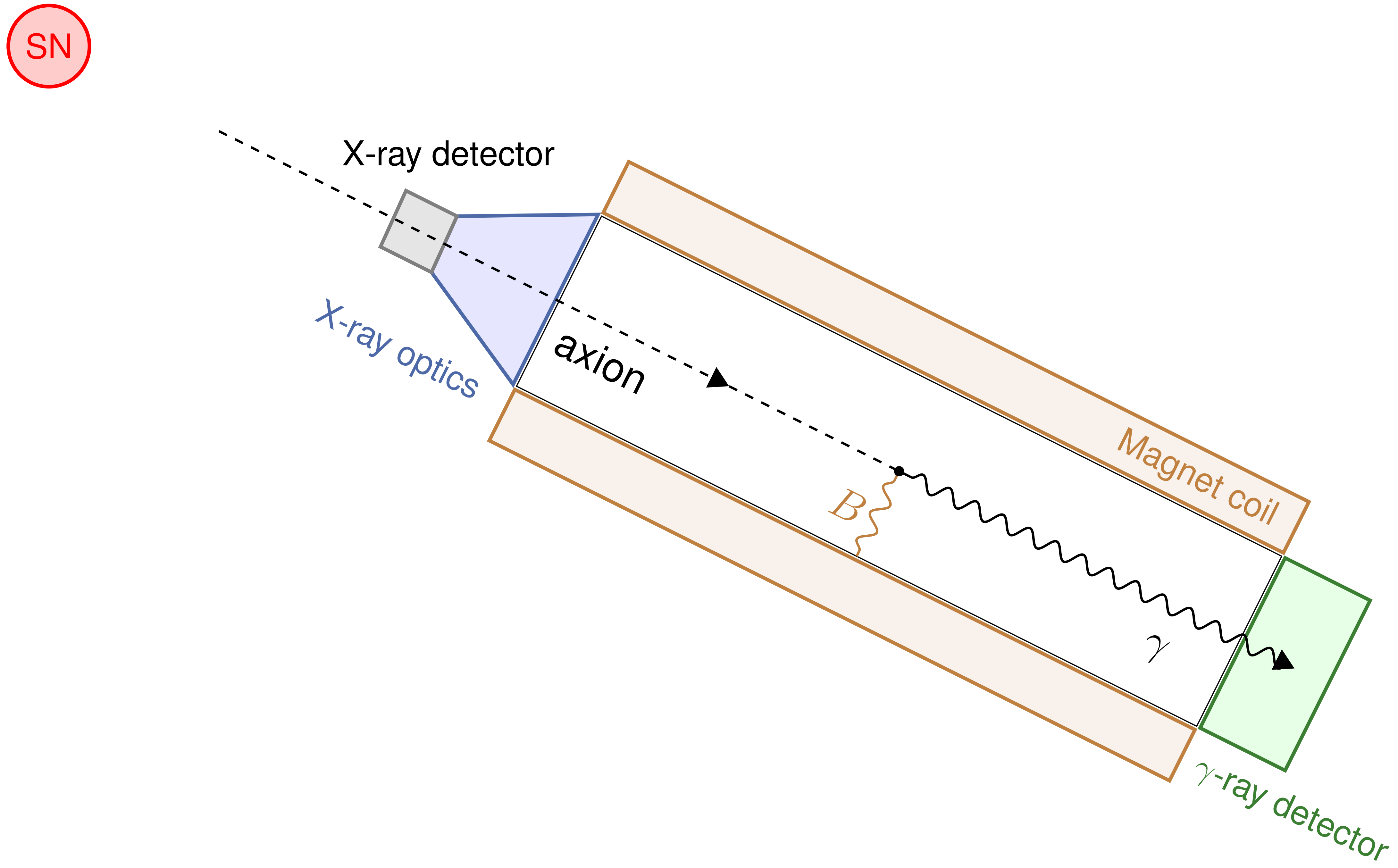
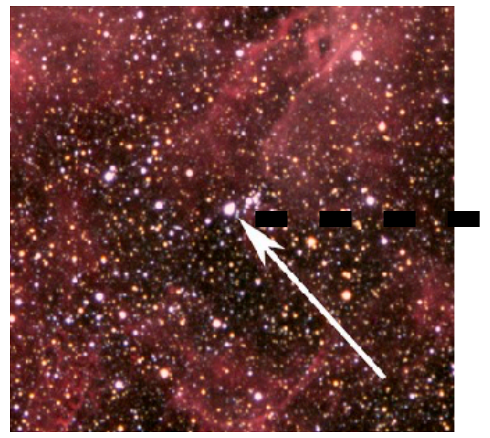
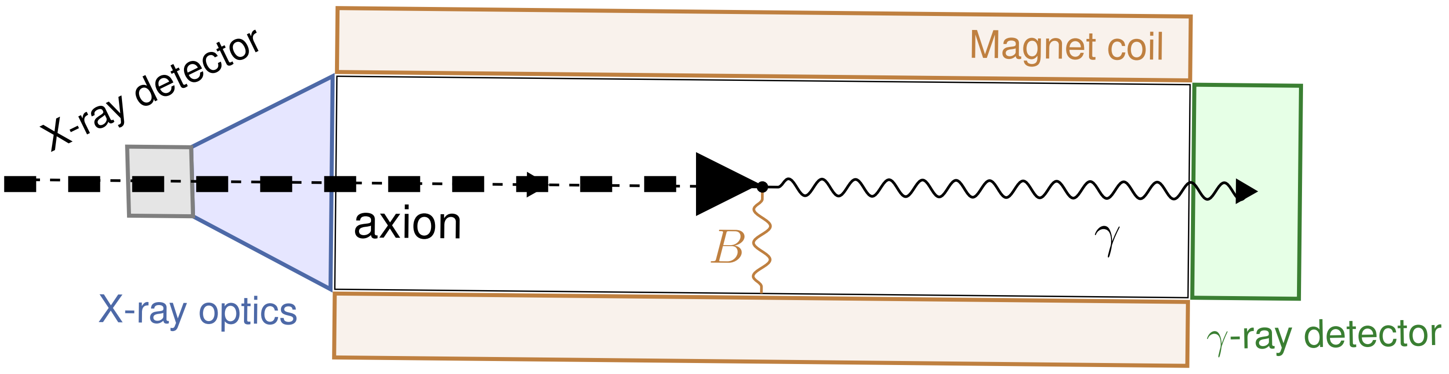


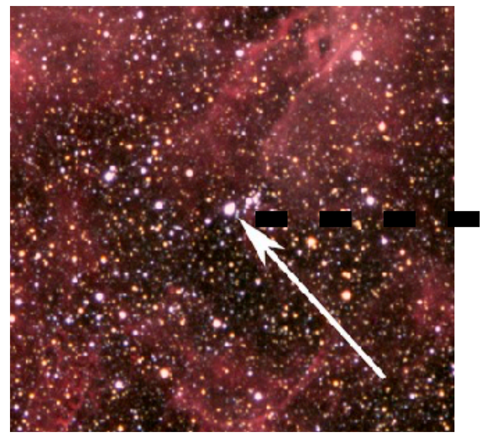
Event number

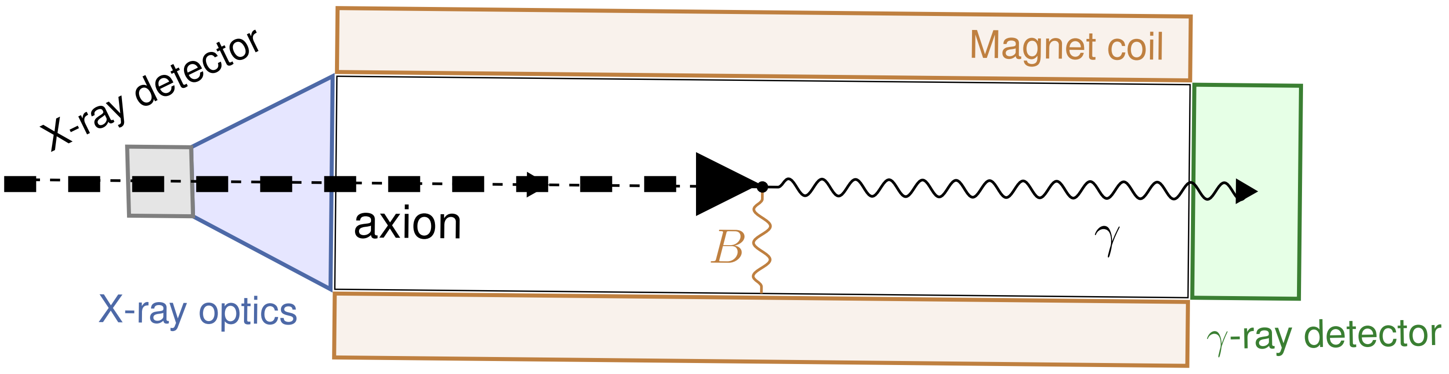




$$N_{\mathrm{event}} = N_a^{\mathrm{SN}} \times \frac{A}{4\pi d^2} \times P_{a\to\gamma}$$

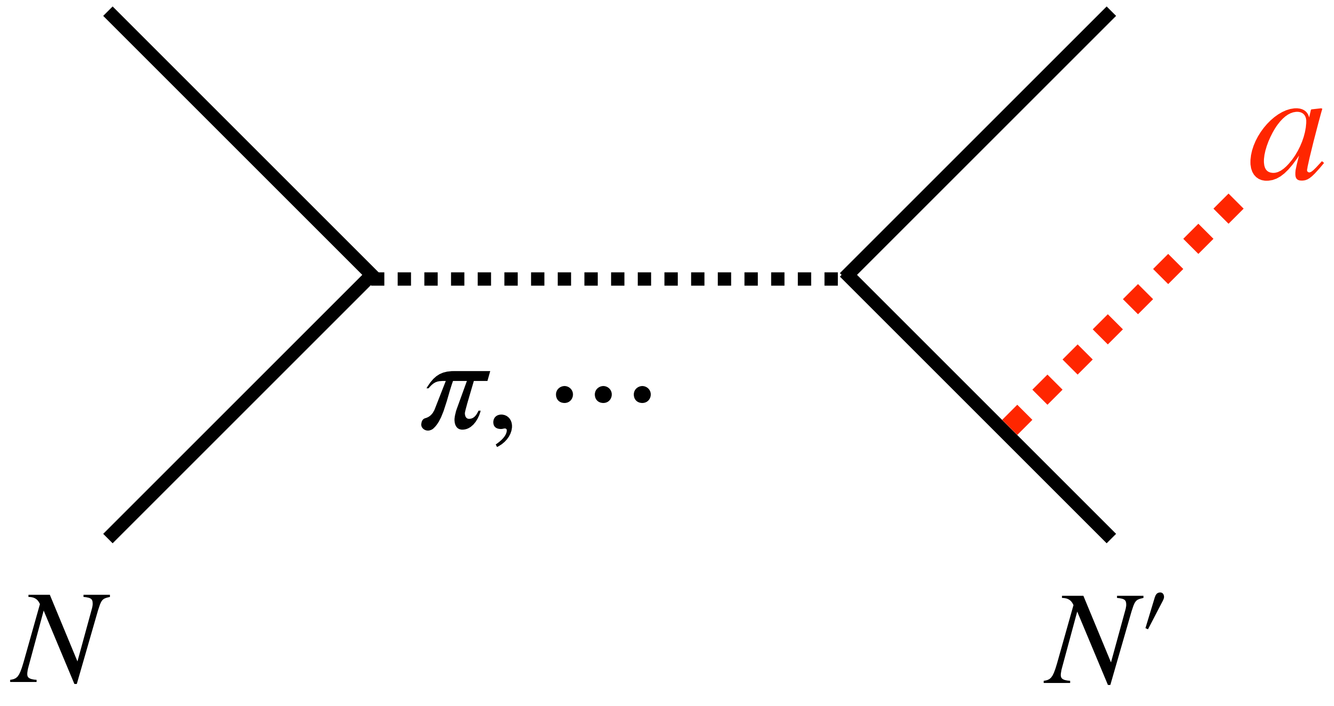
Event number





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

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



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

$$\begin{cases} C_p = -0.47 \\ C_n = -0.02 \end{cases} \text{(KSVZ)}$$
$$\begin{cases} C_p = -0.182 - 0.435\sin^2\beta \\ C_n = -0.160 + 0.414\sin^2\beta \end{cases} \text{(DFSZ)}$$

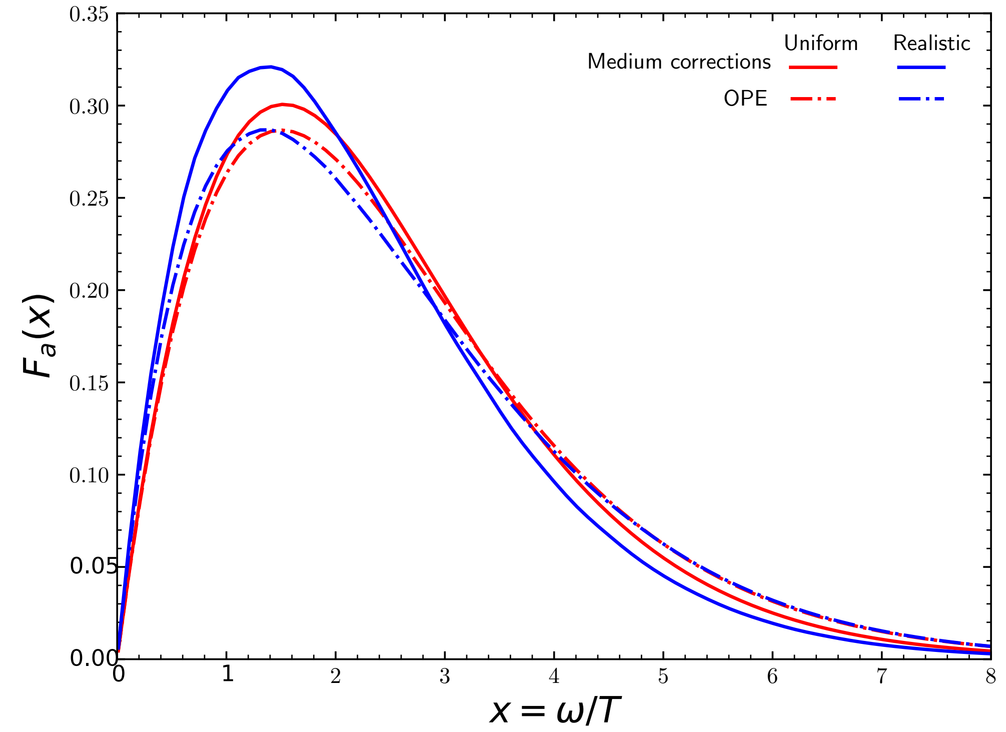
Production

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,

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

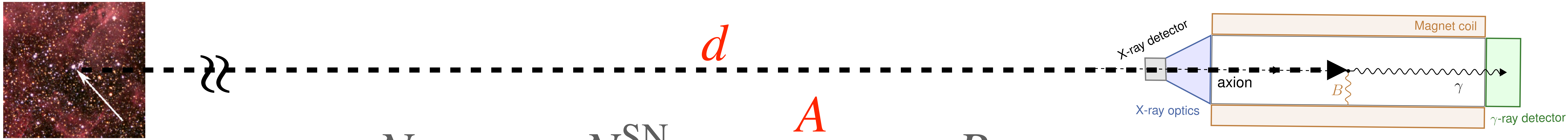
  where $C_{N,\rm eff}^2 \equiv C_n^2 + 0.61 C_p^2 + 0.53 C_n C_p$.
- We also include the temperature dependence, $\sim T^{5/2}$.
- The axion energy is $\langle E_a\rangle \simeq 2.3T$.



- Thus, the total number of axions from SN is

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

Event number



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

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

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

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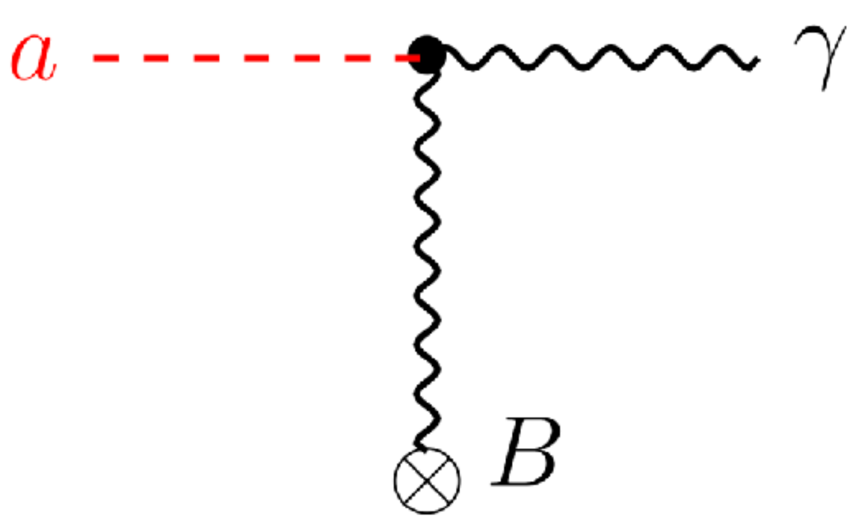


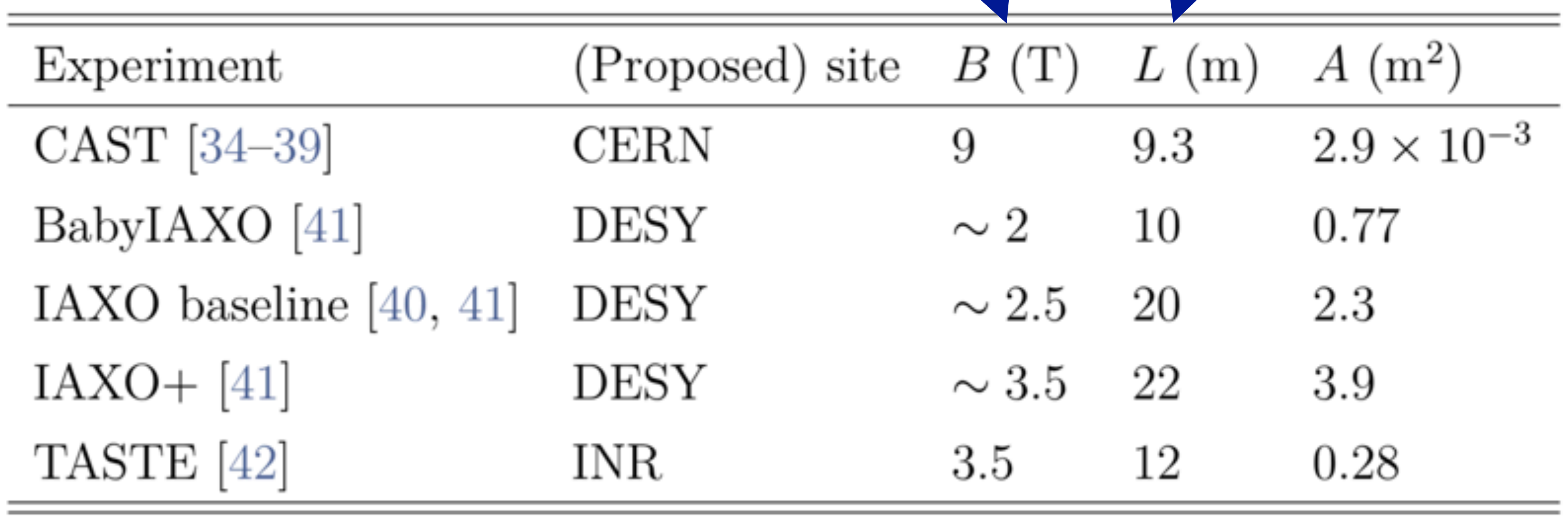
$$\mathscr{L}_{a\gamma\gamma} = \frac{1}{4}\frac{C_{a\gamma\gamma}}{f_a} a F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

Detection

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

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

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



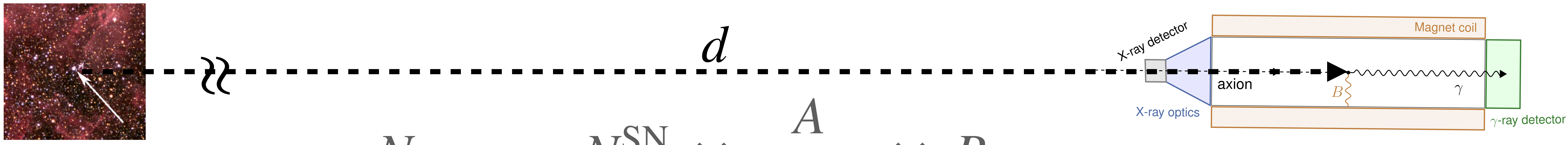
Experiment	(Proposed) site	B (T)	L (m)	A (m^2)
CAST [34–39]	CERN	9	9.3	2.9×10^{-3}
BabyIAXO [41]	DESY	~ 2	10	0.77
IAXO baseline [40, 41]	DESY	~ 2.5	20	2.3
IAXO+ [41]	DESY	~ 3.5	22	3.9
TASTE [42]	INR	3.5	12	0.28

suppression factor

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

($a \leftrightarrow \gamma$ oscillation)

Event number



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

After all,…

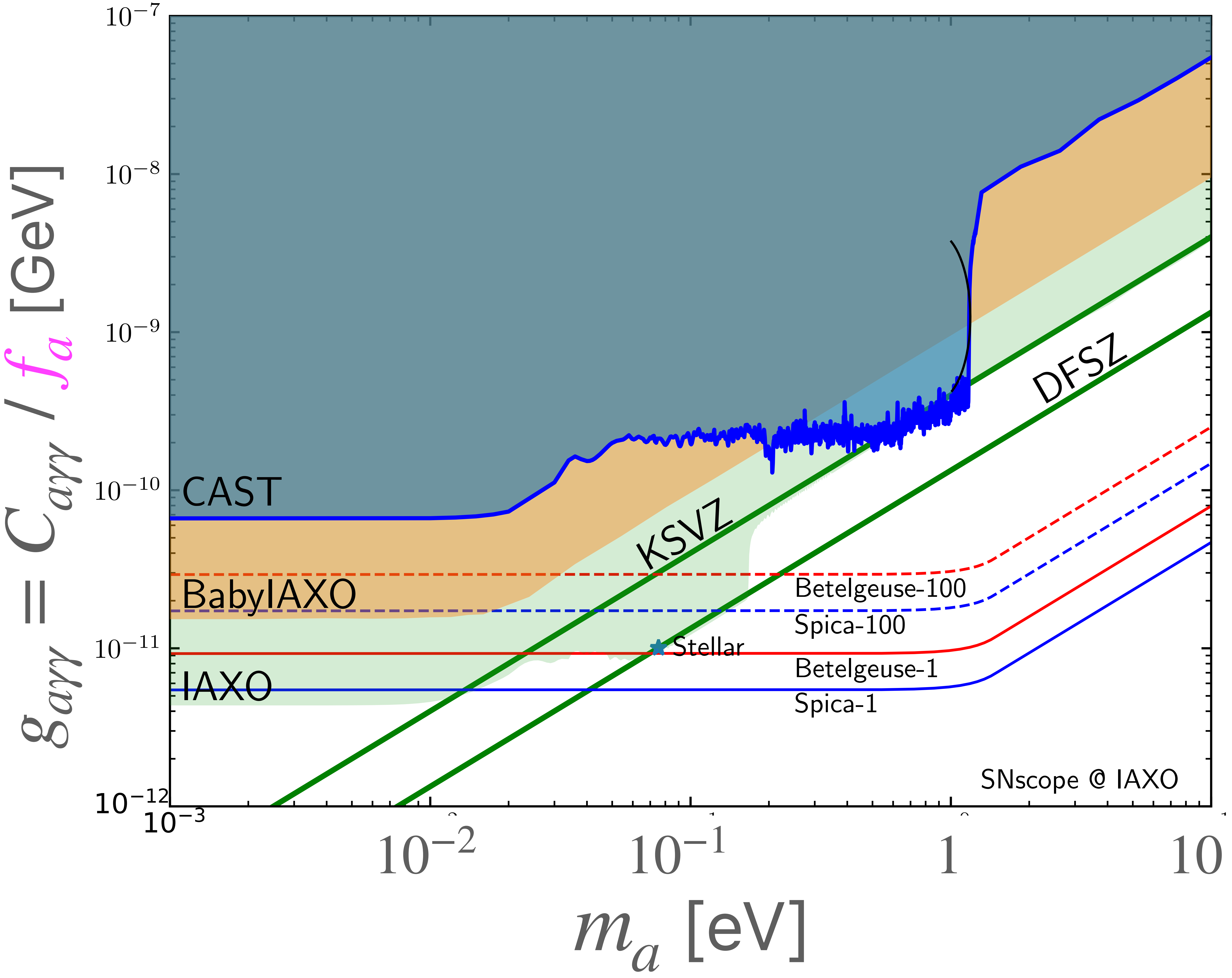
$$N_{\text{event}} \simeq 1.0 \times \underbrace{\left(\frac{3\times 10^8\ \text{GeV}}{f_a}\right)^4 \left(\frac{C_{N,\text{eff}}}{0.37}\right)^2 \left(\frac{C_{a\gamma\gamma}}{\alpha/\pi}\right)^2}_{\text{axion model}} \times \underbrace{\left(\frac{150\ \text{pc}}{d}\right)^2 \left(\frac{\Delta t}{10\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

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

※ 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)

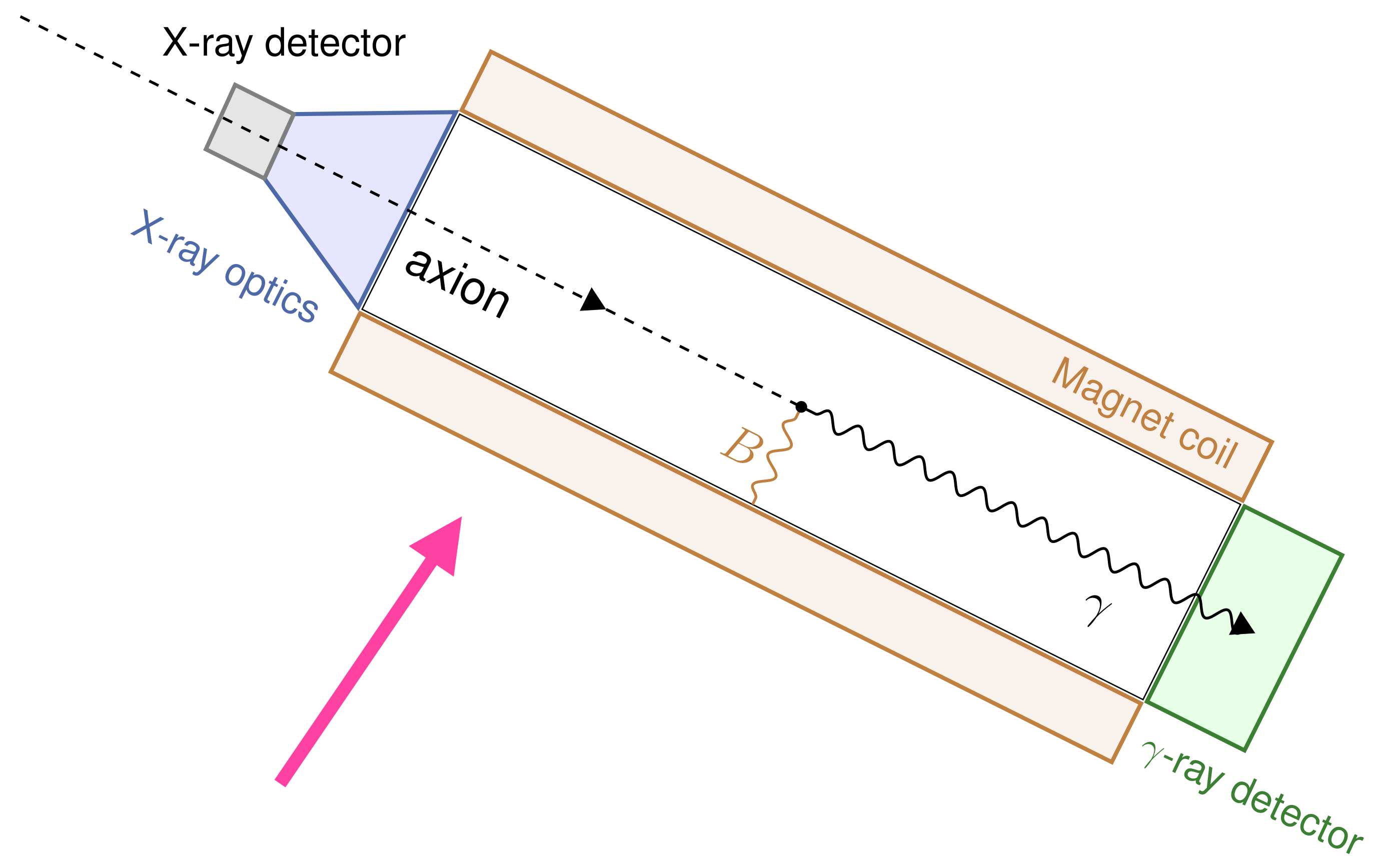
and Spica ($d \simeq 77$ pc)

- 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.

Summary

SN

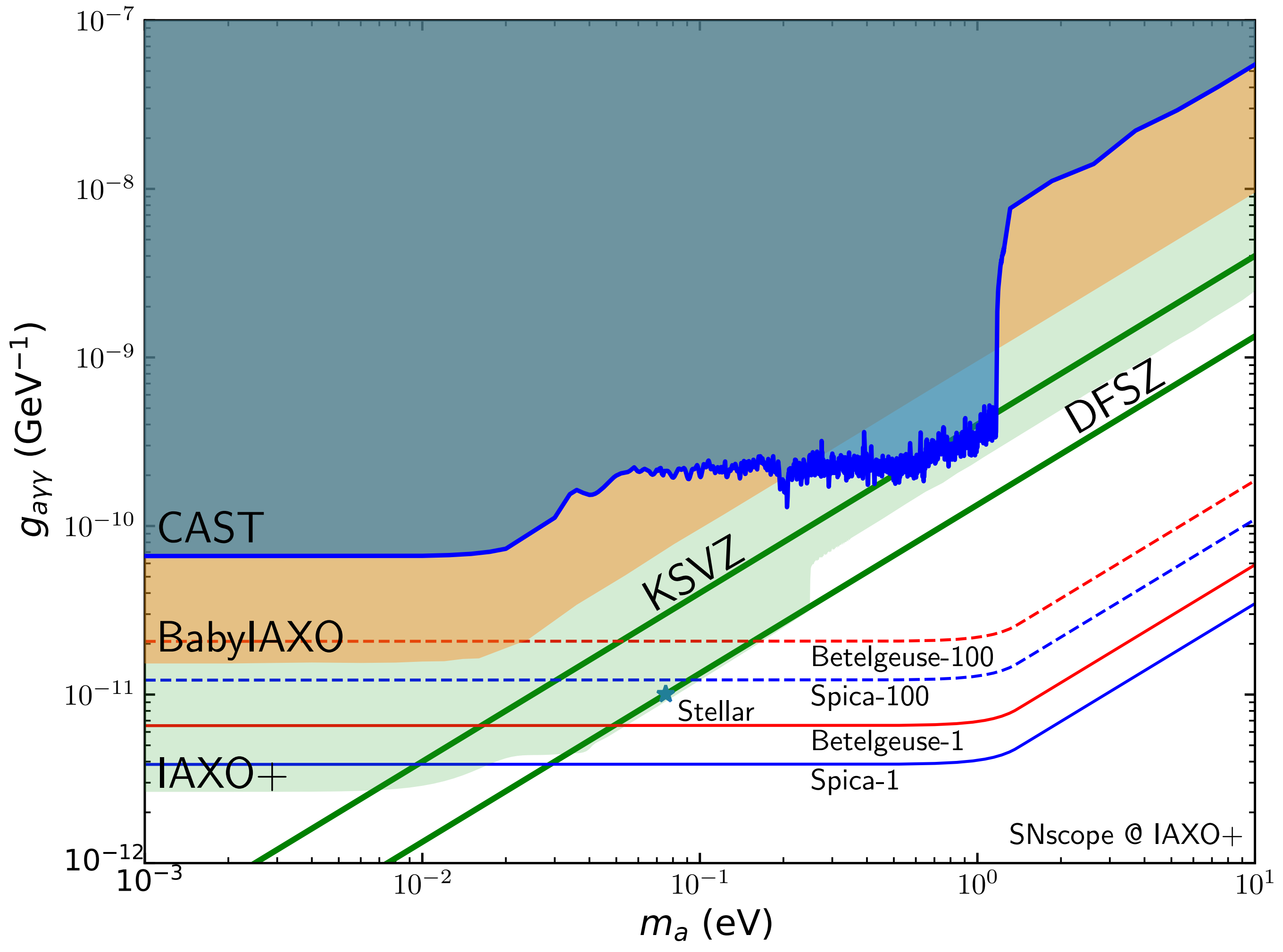


- If a nearby (< a few 100 pc) supernova (SN) occurs, a huge number of axions (in addition to neutrinos) may arrive at the Earth.

- Those SN axions may be detected by an axion Supernova-scope with the help of pre-SN neutrino alert.

Similar idea in: G.G.Raffelt, J.Redondo, N.Viaux Maira (2011), I.G.Irastorza, J.Redondo (2018).

- SN-scopes based on the next-generation axion helioscopes (such as IAXO) have potential to detect O(1-100) SN axions.



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A nearby SN is so rare —— it would be a once in a lifetime opportunity for directly detecting SN axions!