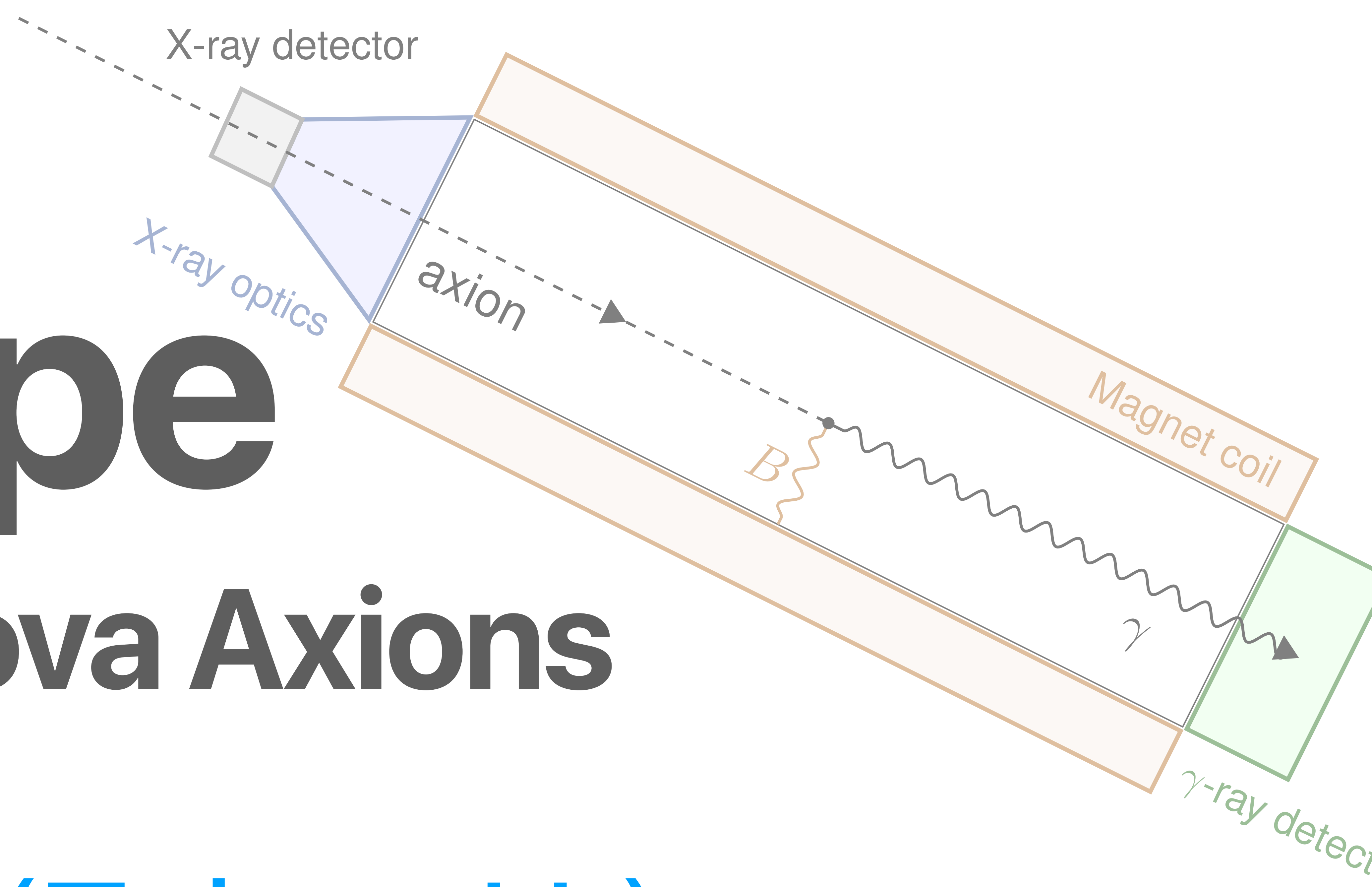


Supernova-scope

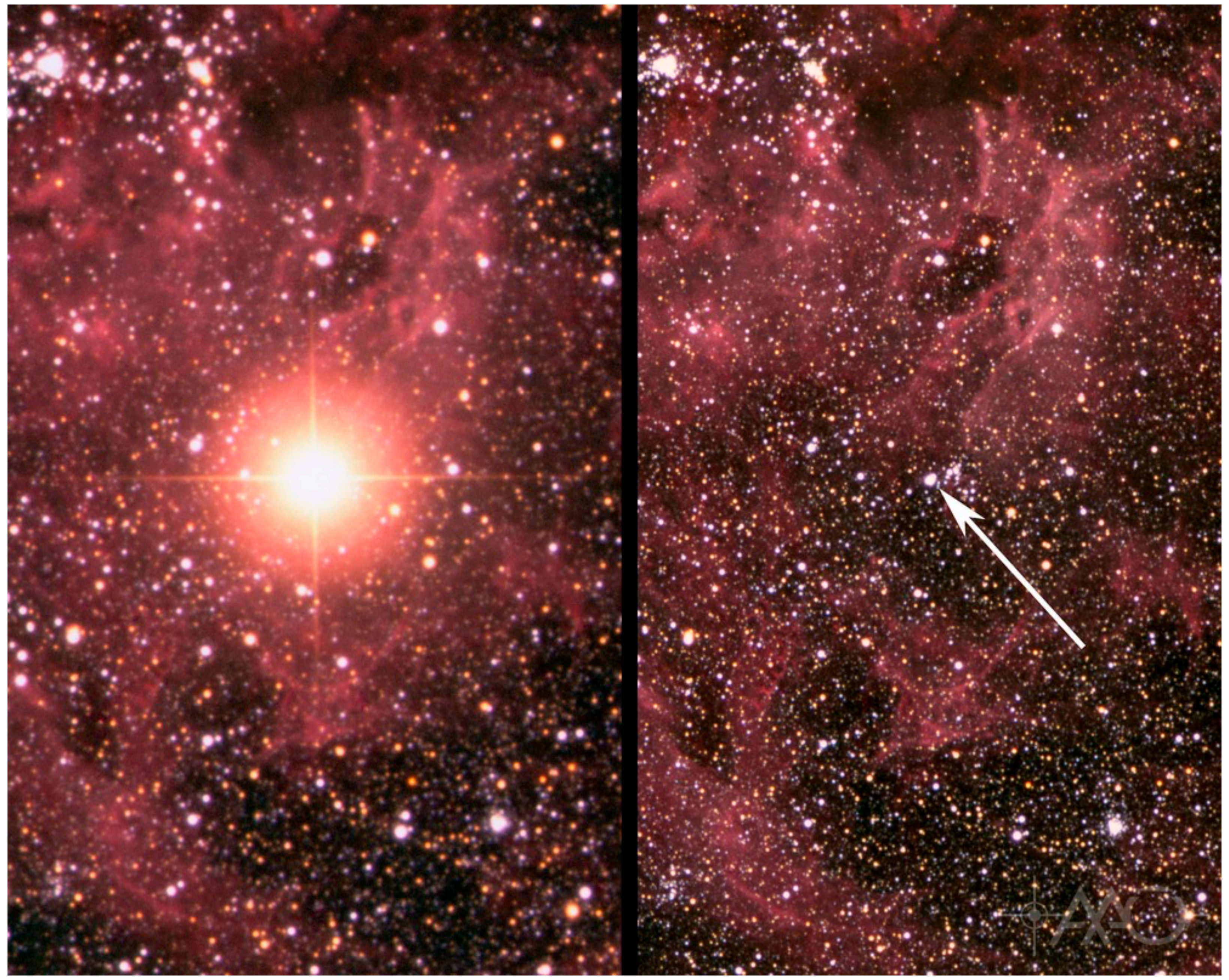
for the Direct Search of Supernova Axions

Koichi Hamaguchi (Tokyo U.)

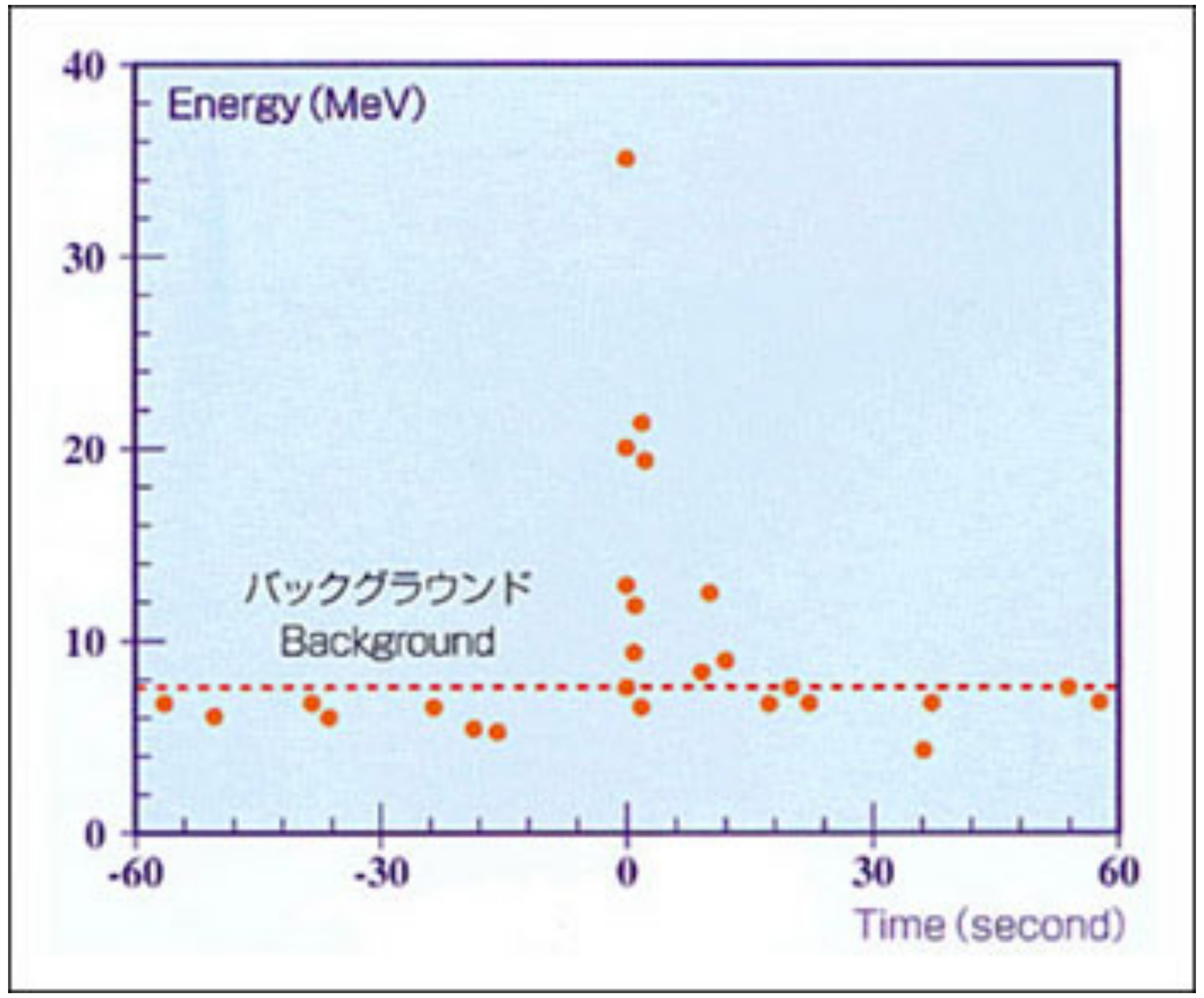
@ Windows on the Universe,
30th Anniversary of the Rencontres du Vietnam, ICISE, Quy Nhon, Aug. 10, 2023.

Based on [arXiv:2008.03924] JCAP **11** (2020) 059
Shao-Feng Ge (TDLI), Koichi Hamaguchi (Tokyo), Koichi Ichimura (Tohoku),
Koji Ishidoshiro (Tohoku), Yoshiki Kanazawa (Tokyo), Yasuhiro Kishimoto (Tohoku),
Natsumi Nagata (Tokyo), Jiaming Zheng (TDLI).

Supernova 1987A (February 23, 1987)



https://images.datacentral.org.au/malin/AAT/050a



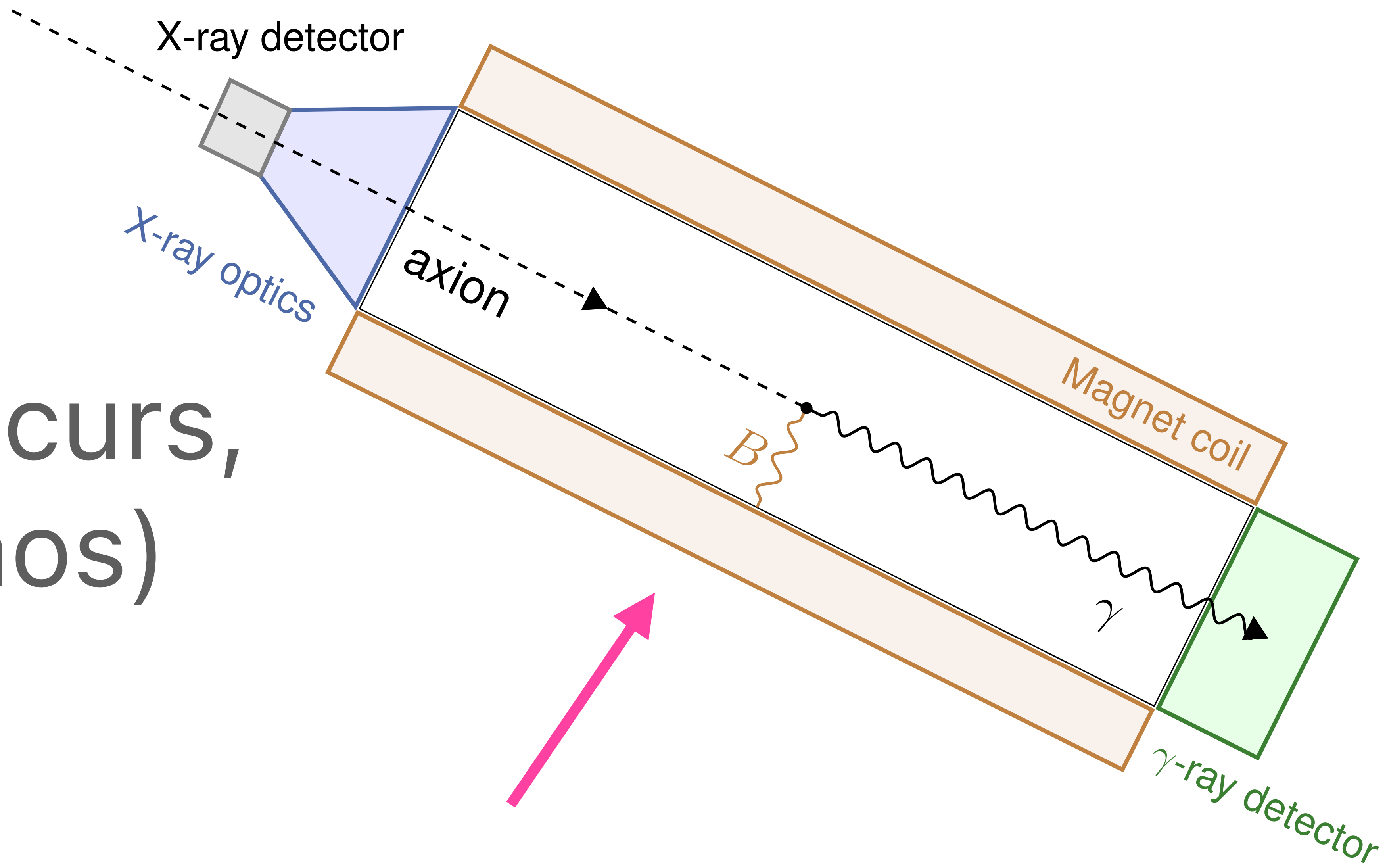
http://www-sk.icrr.u-tokyo.ac.jp/sk/physics/supernova-e.html

What if the next nearby SN occurs?

We could learn a lot about neutrino, supernova, and maybe...

Toady's Main message

SN

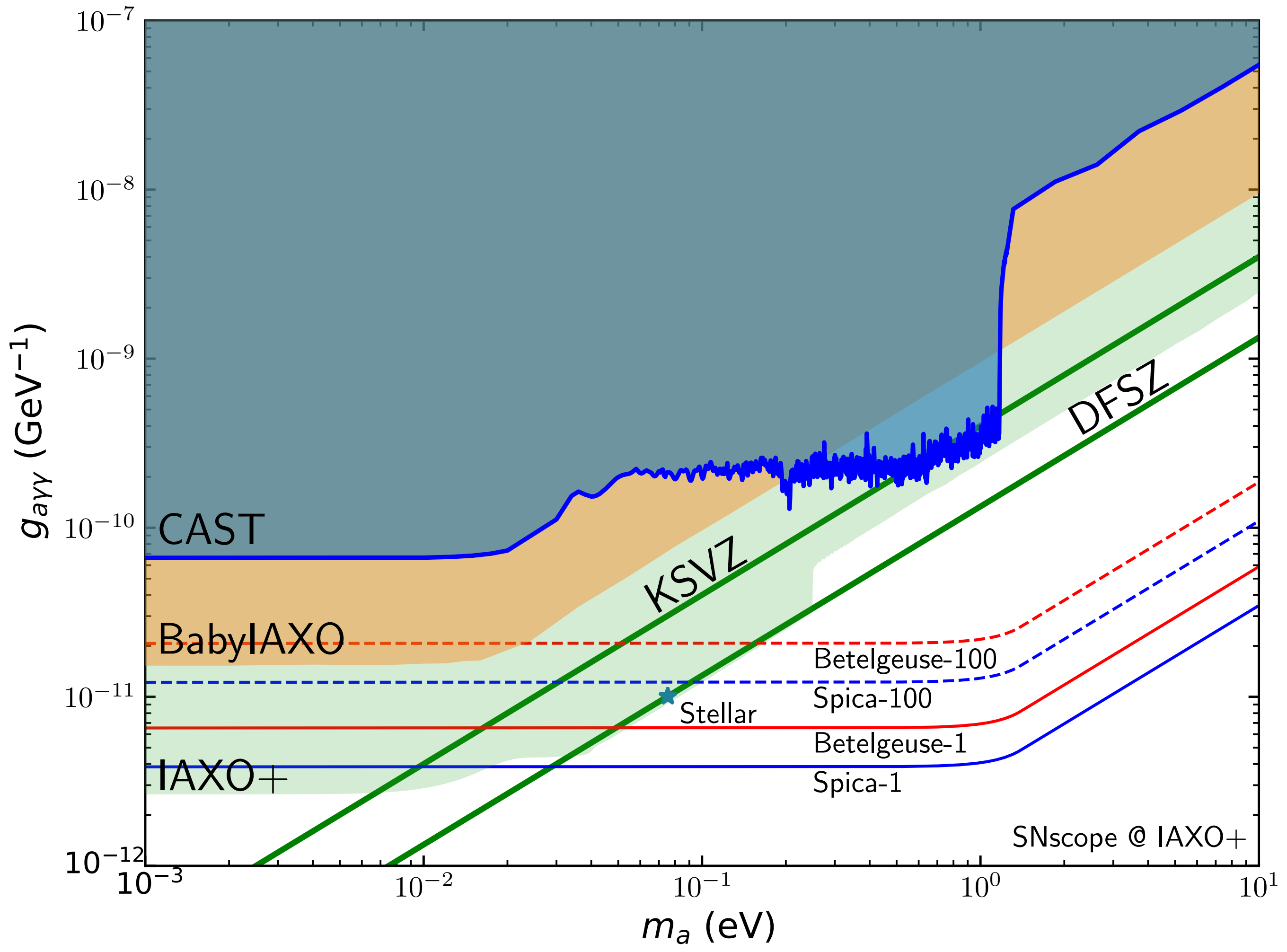


- If a nearby (< a few 100 pc) supernova (SN) occurs, a huge number of axions (in addition to neutrinos) may arrive at the Earth.

- 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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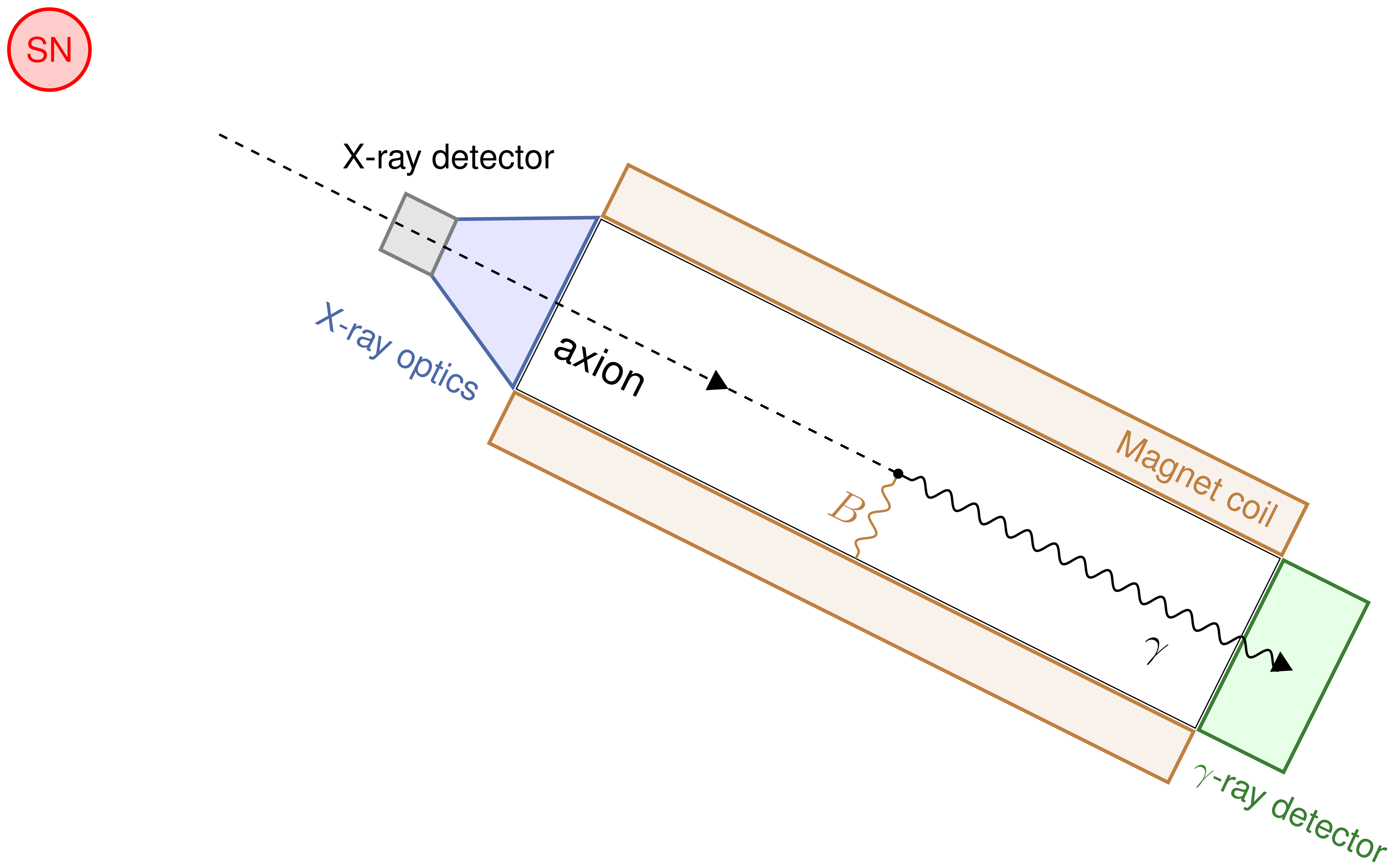
S.Ge, K.Hamaguchi, K.Ichimura, K.Ishidoshiro, Y.Kanazawa, Y.Kishimoto, N.Nagata, J.Zheng.

Plan

- **Motivation**: axion
- **Supernova Axion detection**
  - SN candidates
  - Supernova-scope
  - Pre-SN neutrino
  - Observation time fraction
  - Event number
- **Summary**



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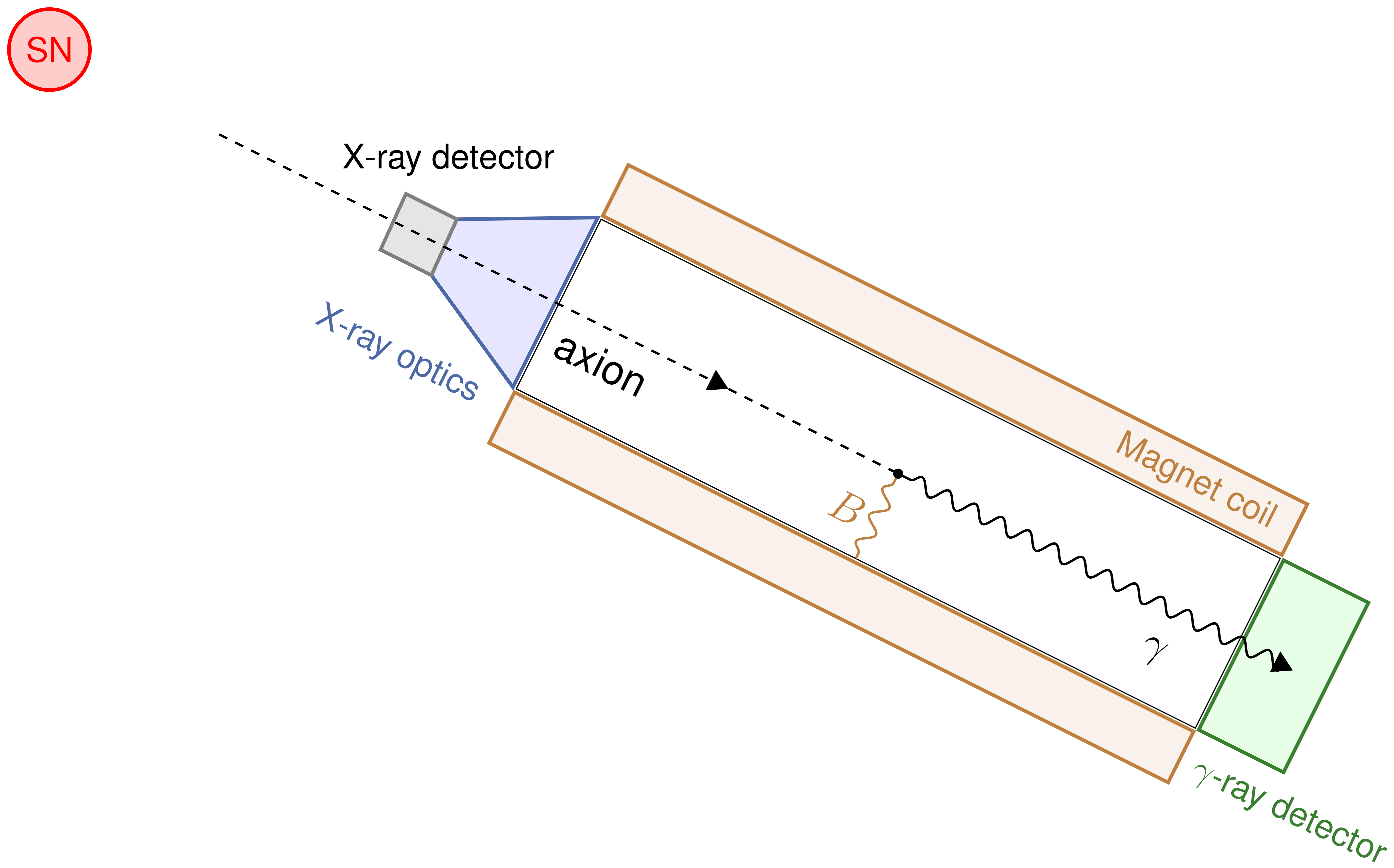

Motivation: Axion

QCD

➡Talks by **Andrew Long, Ngan Nguyen, Ranjan Laha, Boris Ivanov** (all today)

Strong CP problem

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

Why?

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

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

The most serious fine-tuning problem

in the Standard Model of particle physics.

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

Motivation: Axion

QCD

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Strong CP problem

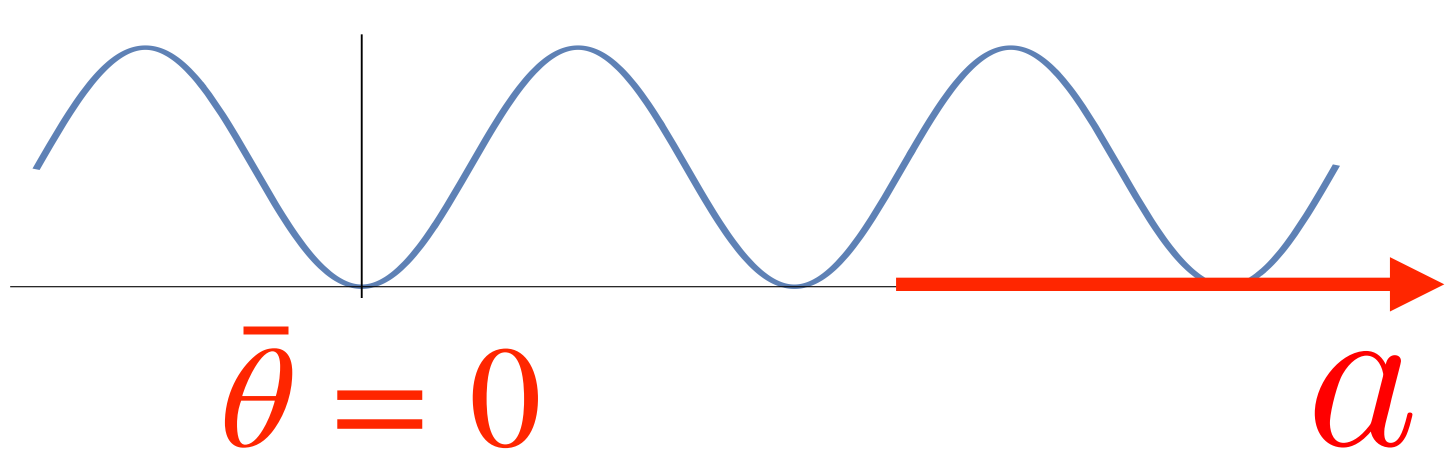
$$\mathscr{L}_{\rm SM} \ni \frac{\alpha_s}{8\pi}\theta G^a_{\mu\nu}\widetilde{G}^{a\mu\nu} - \sum_q m_q \bar{q}\,\theta_q\, i\gamma_5 q$$

Why?

Experimental constraint (neutron EDM): $|\bar{\theta}| \lesssim 10^{-10}$ $\left(\bar{\theta} = \theta + \sum_q \theta_q\right)$

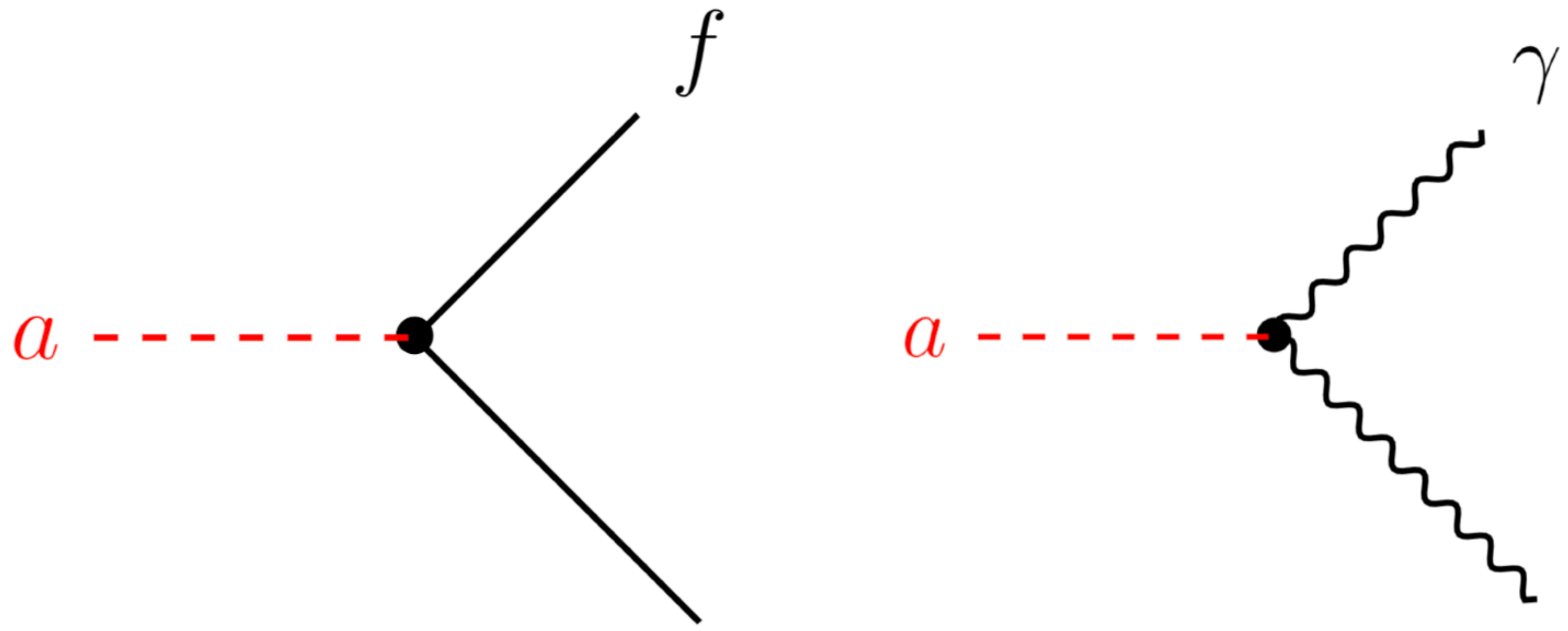
.....can be solved by the "Peccei-Quinn mechanism", [Peccei, Quinn,'77]
predicting a very light particle, Axion. [Weinberg,'78, Wilczek,'78]

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



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

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



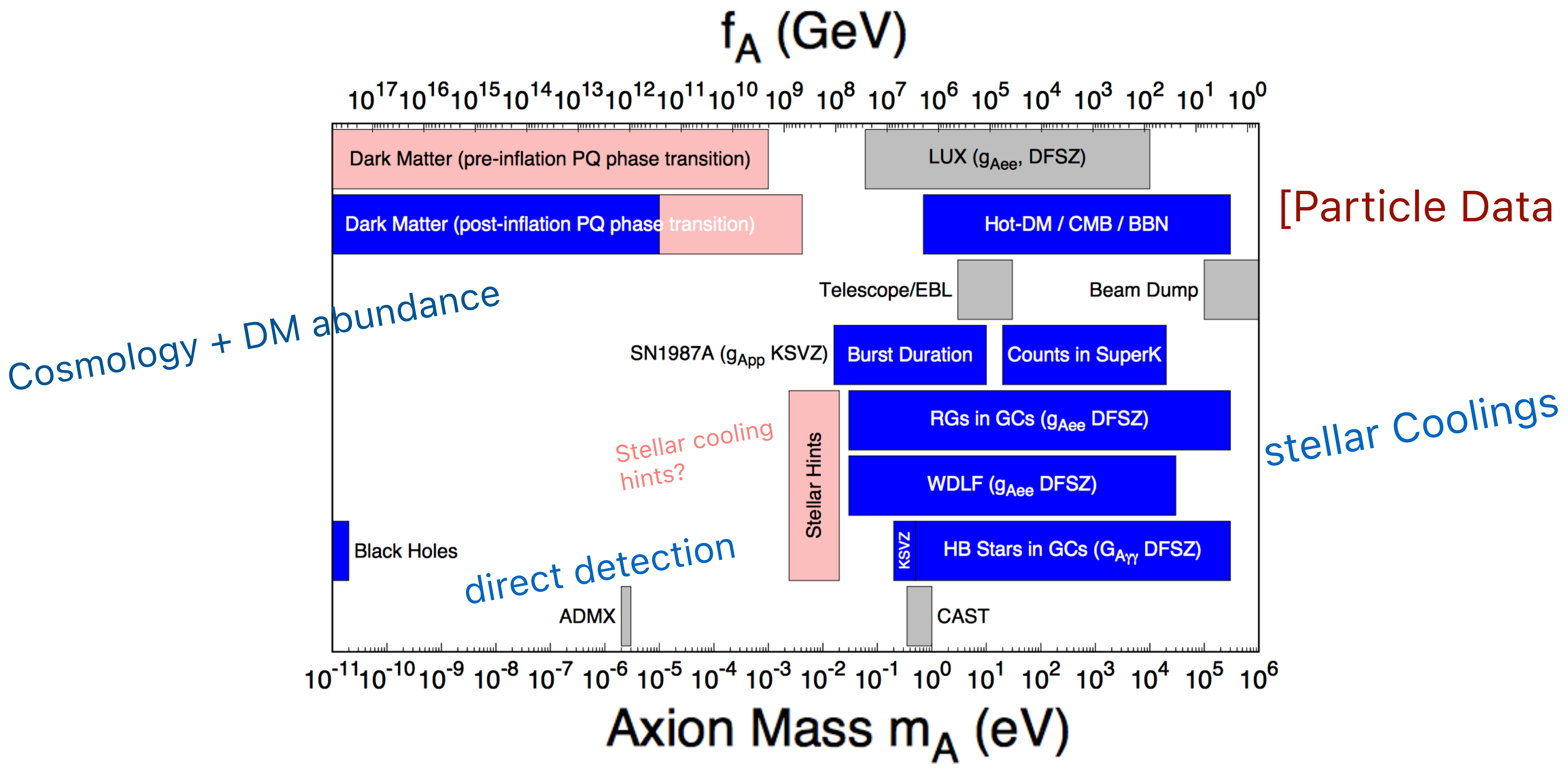
$$C_{a\gamma\gamma} = \frac{\alpha}{2\pi}\left(\frac{E}{N} - \frac{2}{3}\frac{4m_d + m_u}{m_u + m_d}\right), \quad \begin{cases} C_q = 0 \quad \text{(KSVZ)} \\ C_{u,c,t} = \cos^2\beta/3, \quad C_{d,s,b} = \sin^2\beta/3 \quad \text{(DFSZ)} \end{cases}$$

Motivation: Axion

QCD

➡Talks by **Andrew Long, Ngan Nguyen, Ranjan Laha, Boris Ivanov** (all today)

Constraints



[Particle Data Group 2018]

Motivation: Axion

QCD

➡Talks by **Andrew Long, Ngan Nguyen, Ranjan Laha, Boris Ivanov** (all today)

Constraints

- SN1987A: $f_a \gtrsim \mathcal{O}(10^8)$ GeV (KSVZ) [P.Carenza et.al., 2019 + others]
- Neutron Star Cooling $f_a \gtrsim \mathcal{O}(10^8)$ GeV [KH, N.Nagata, K.Yanagi, J.Zheng, 2018 + others]

But there are various uncertainties. [e.g., N.Bar, K.Blum, G.D'amico 2019]

There are also hints for stellar cooling.
preferred values: $f_a \sim 8 \times 10^7$ GeV, $\tan\beta \sim 0.28$ (DFSZ).
(SN1987A not included).
[M. M. Giannotti, I. G. Irastorza, J. Redondo, A. Ringwald, and K. Saikawa 2017]

It would be nice if there is more direct way of probing axions produced from the stellar objects.

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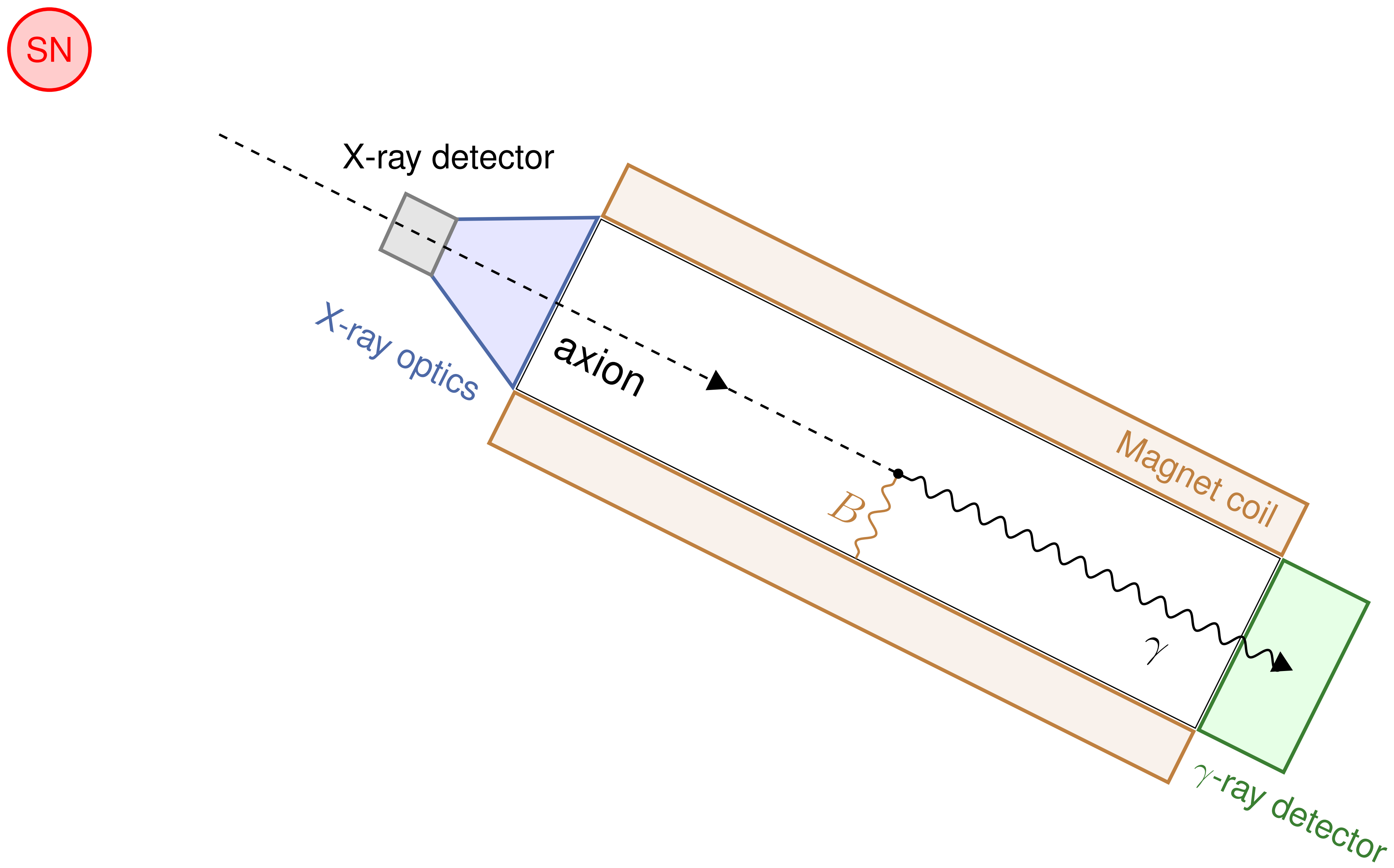
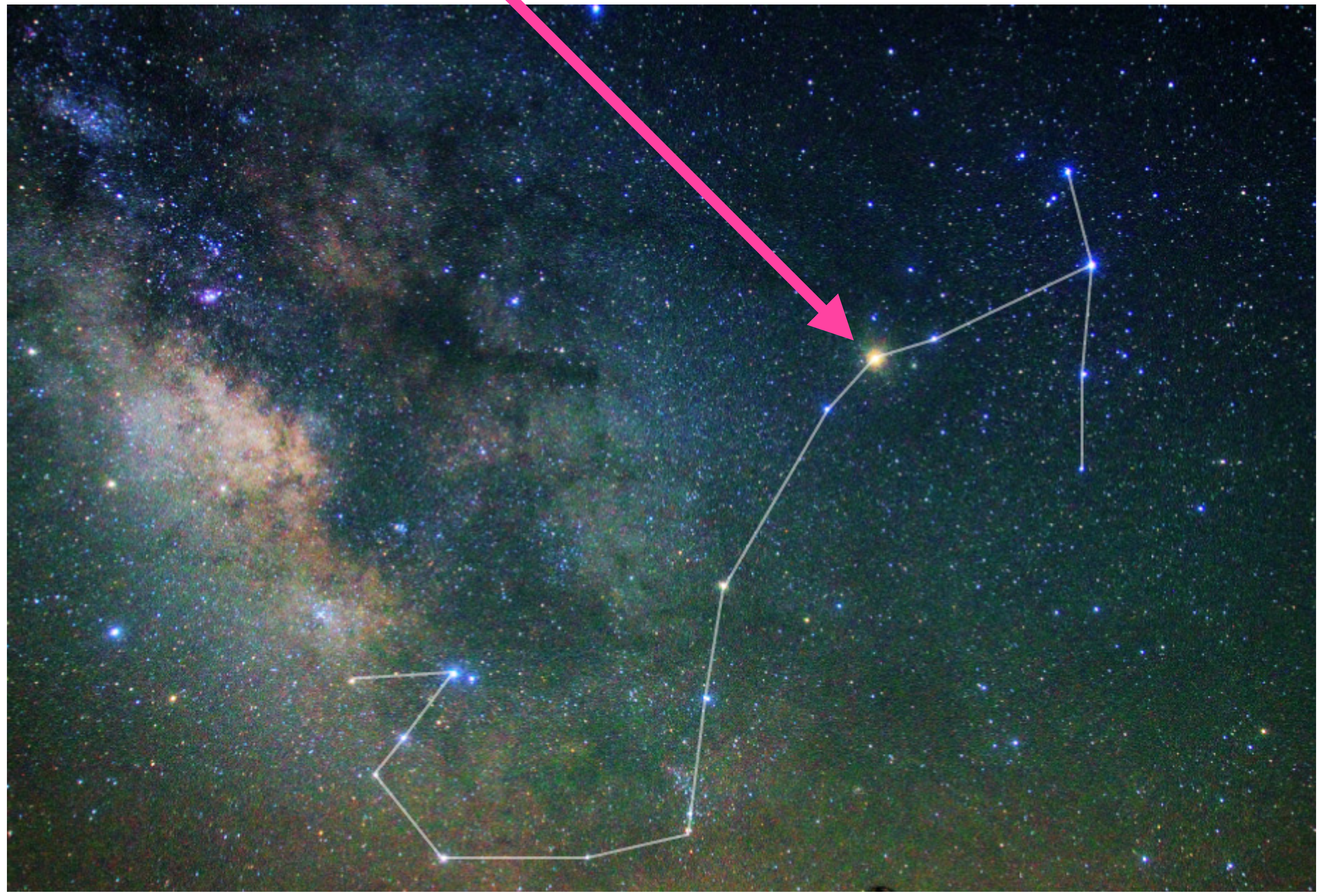


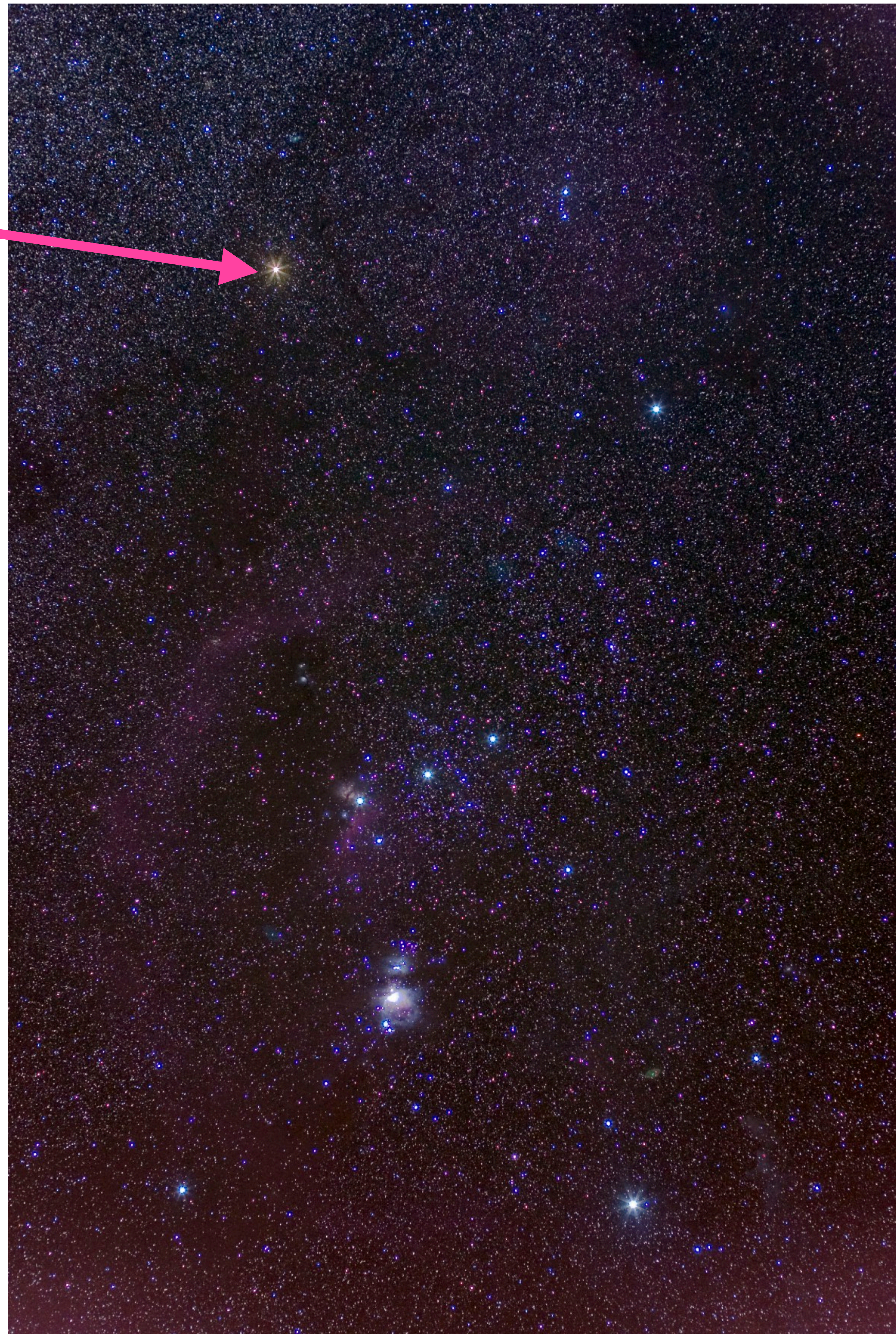
Nearby SN progenitor candidates

Antares
(~ 170 pc)



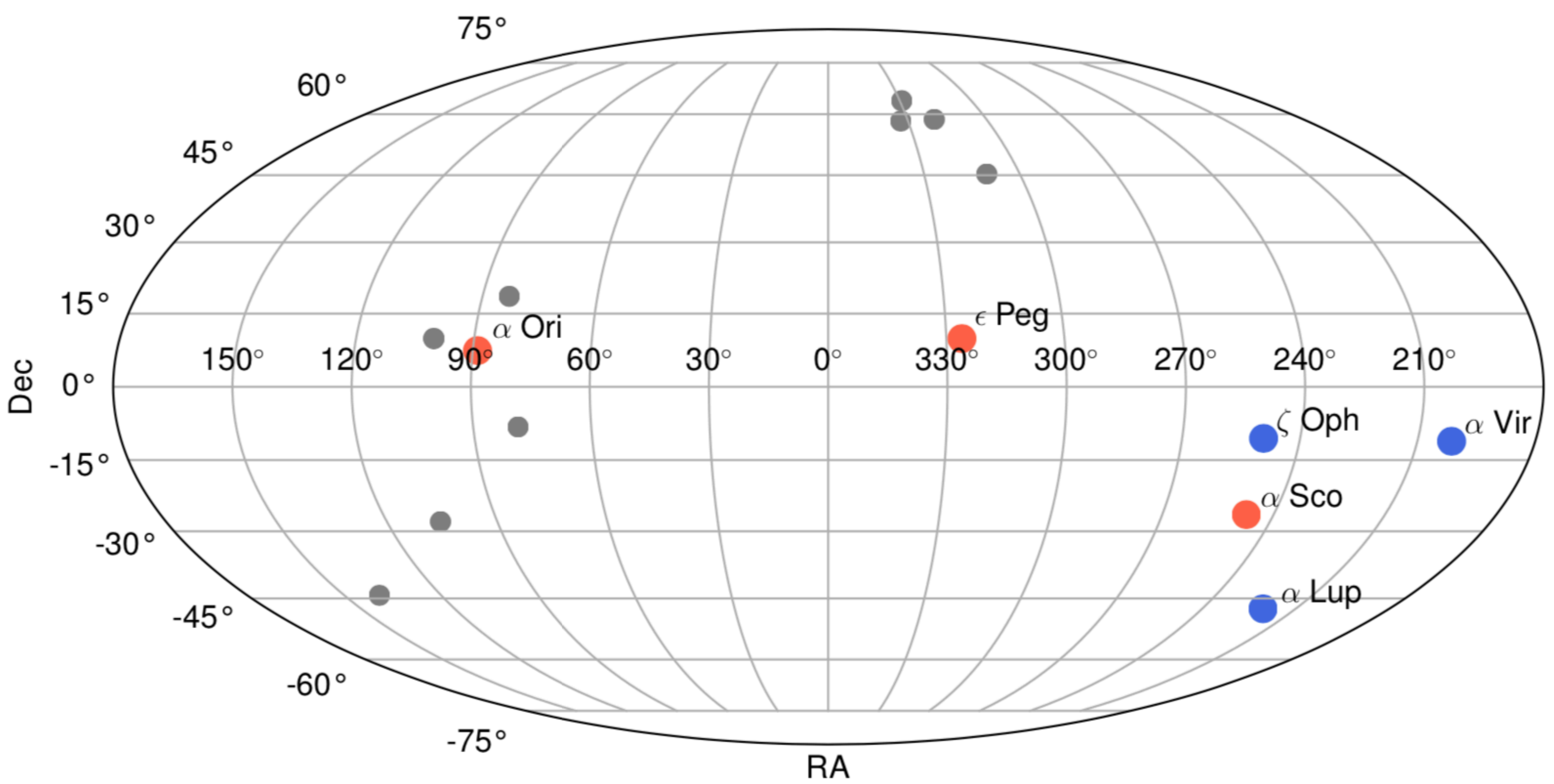
https://www.civillink.net/esozai/

Betelgeuse
(~ 200 pc)



Wikipedia

Nearby SN progenitor candidates



$d < 250$ pc

$d > 250$ pc

※ $M > 10 M_\odot$ 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

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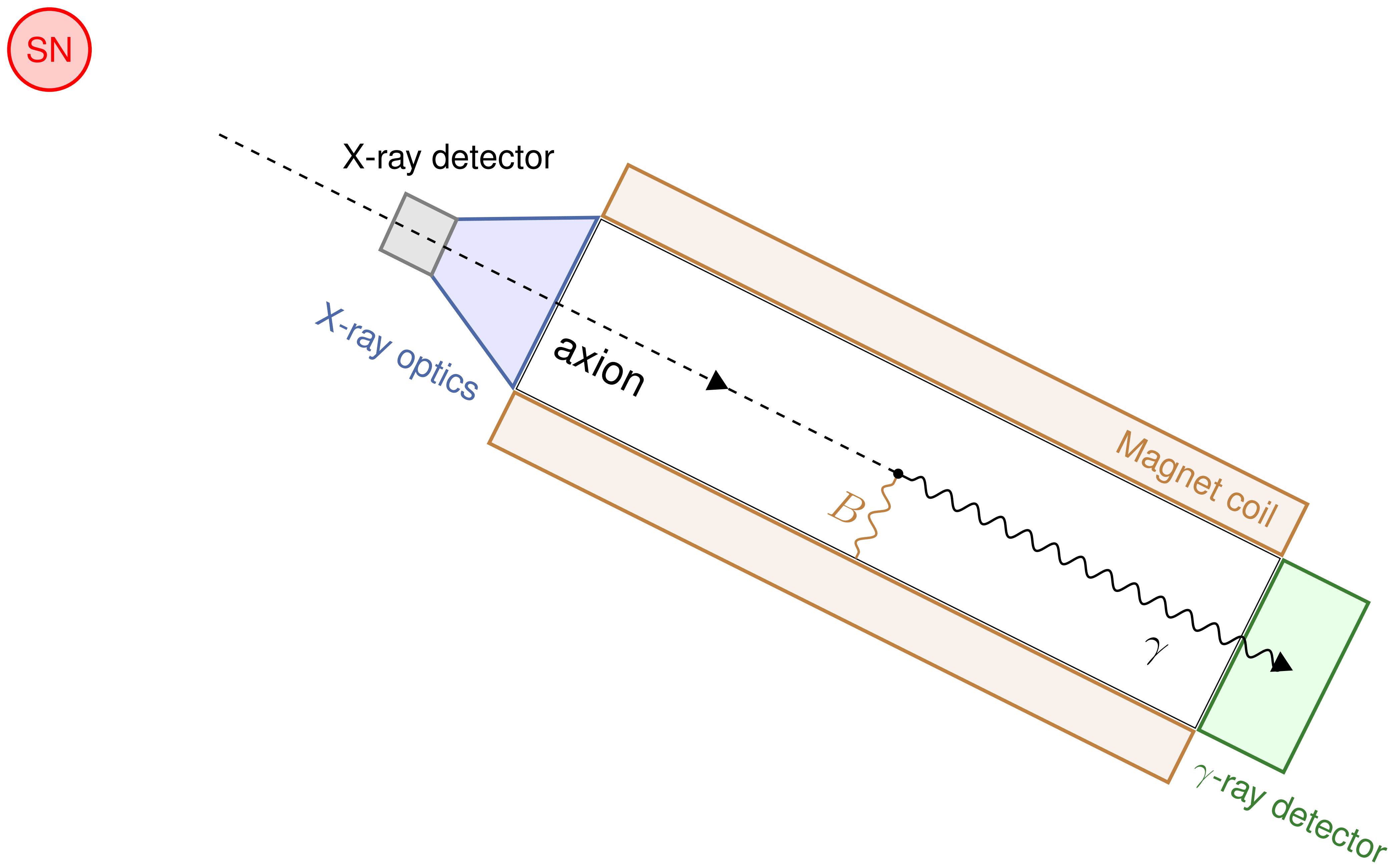
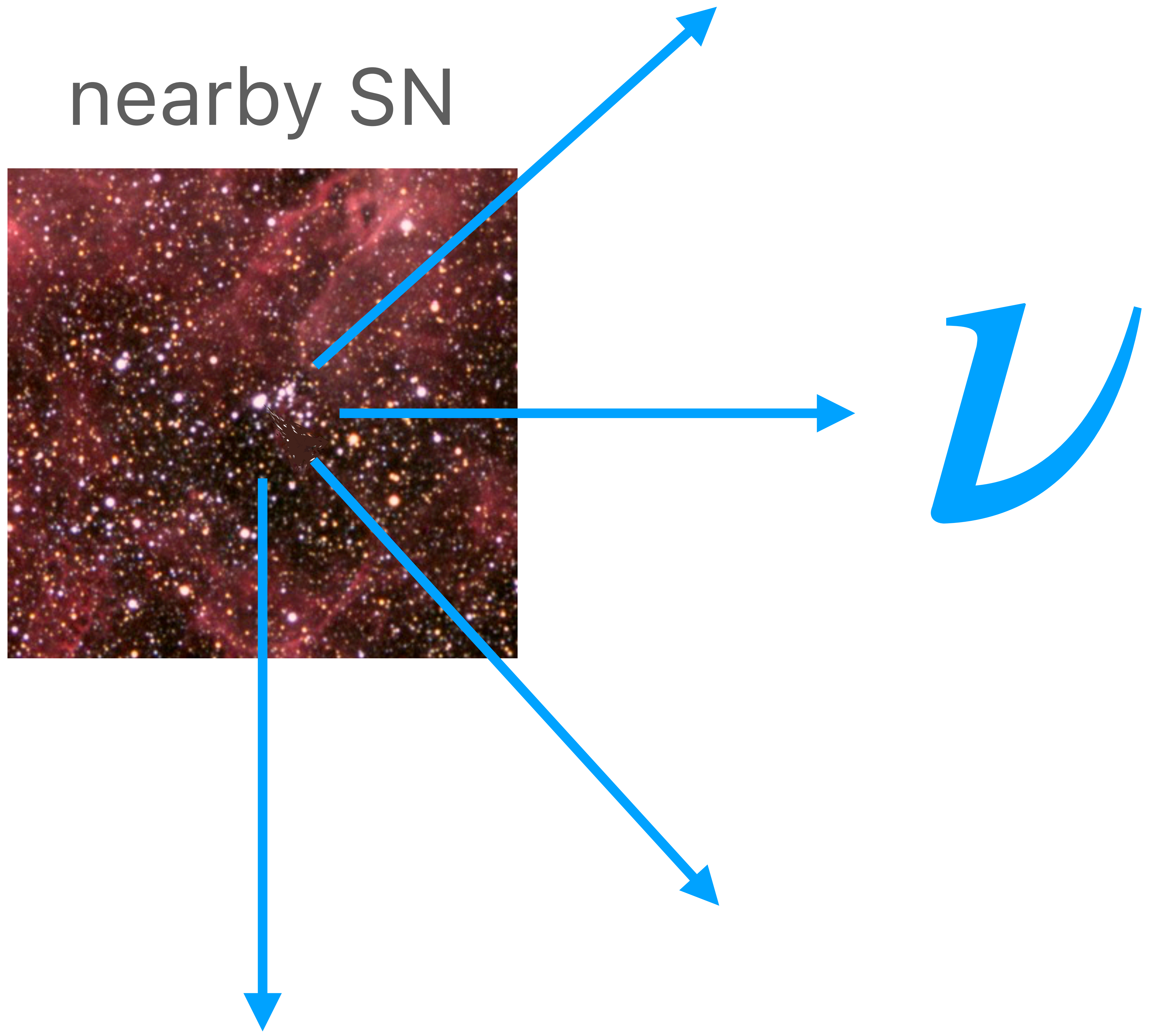


Supernova-scope

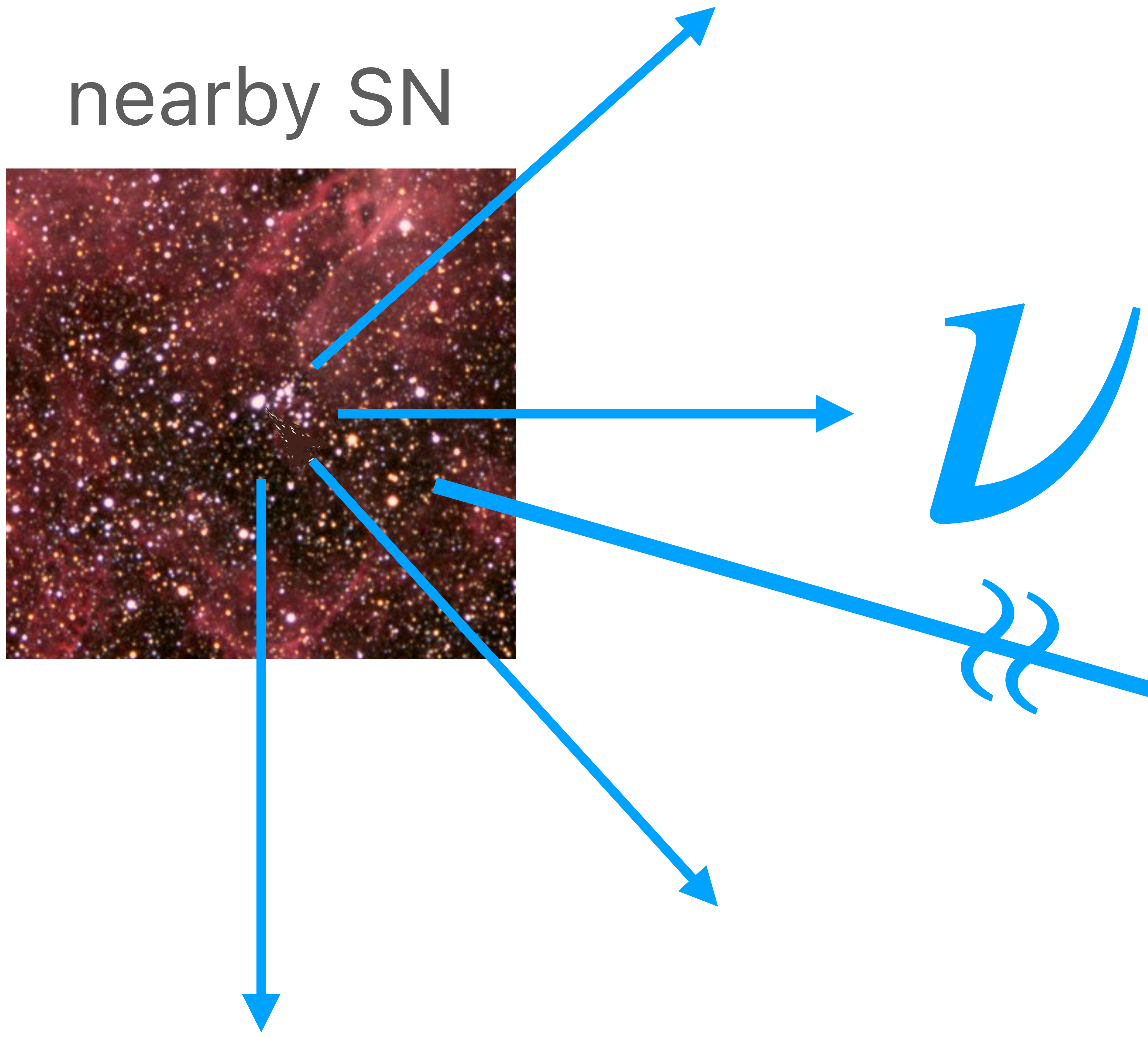
nearby SN

Supernova-scope

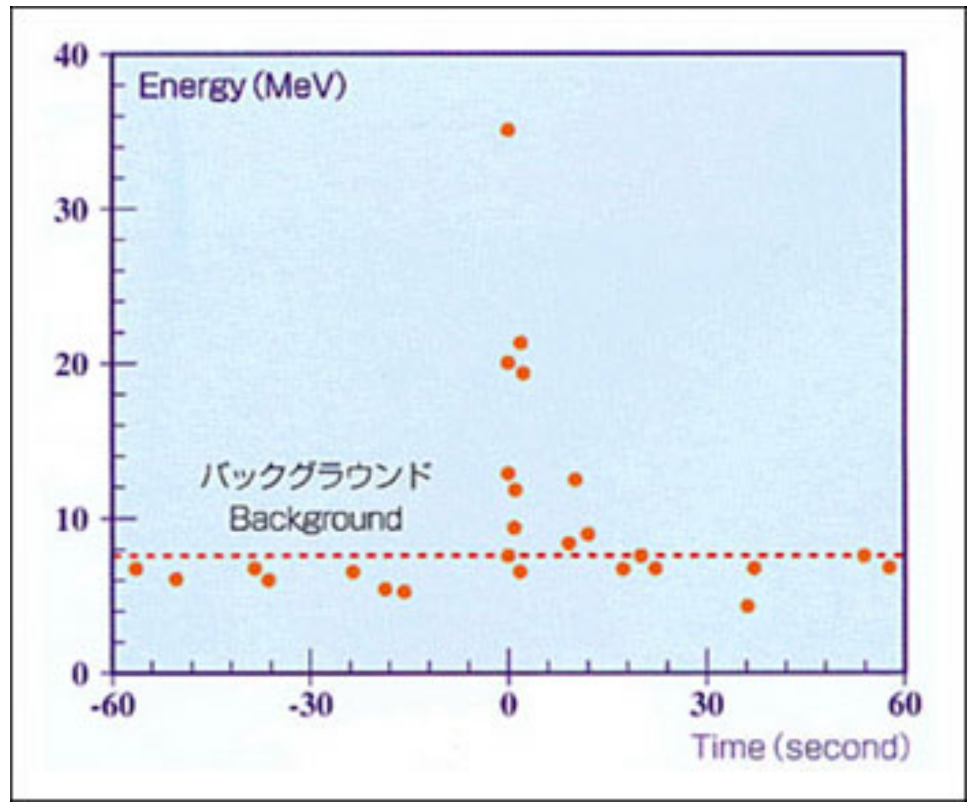


Supernova-scope

nearby SN



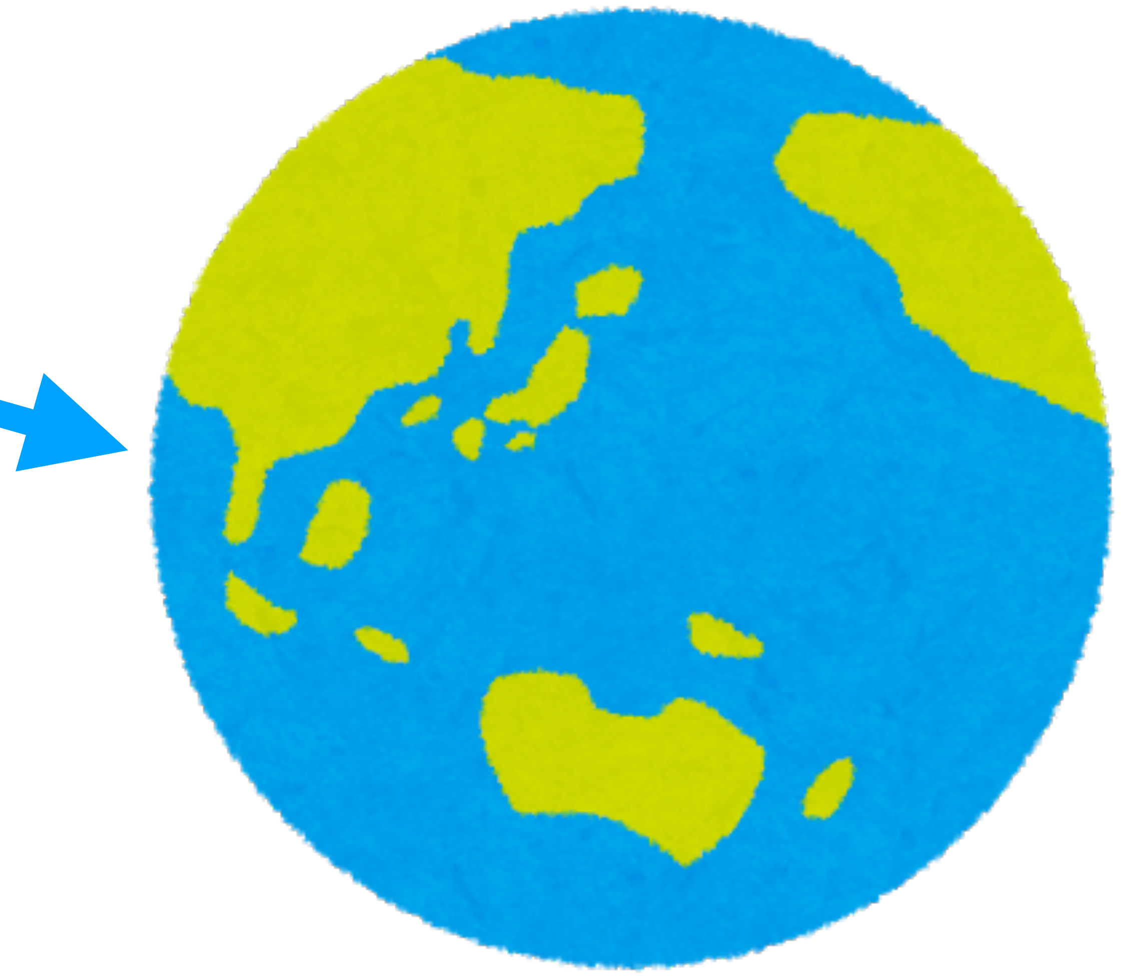
http://www-sk.icrr.u-tokyo.ac.jp/sk/physics/supernova-e.html



- SN1987A

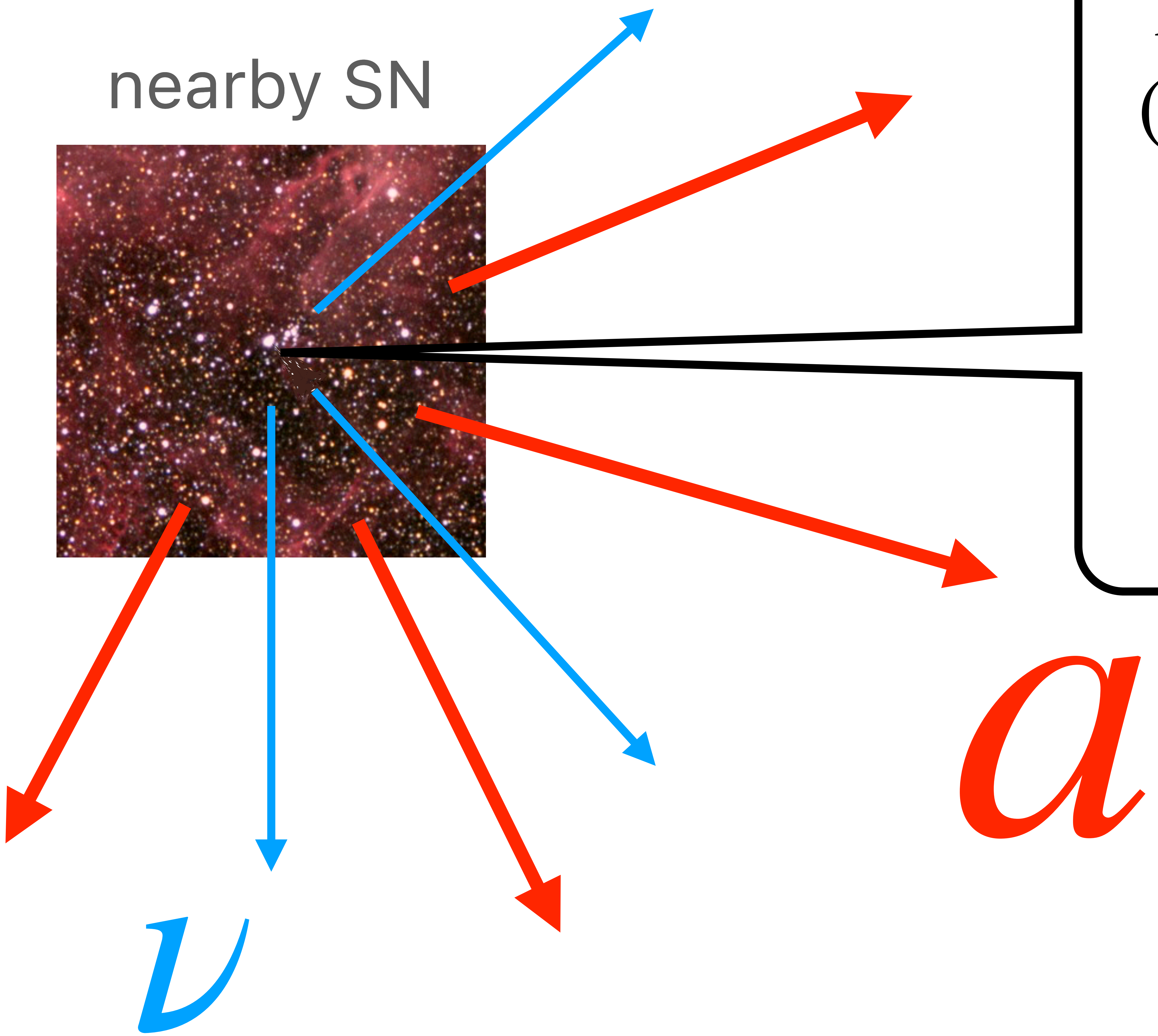
  neutrino burst within $\Delta t \simeq 10$ sec.

- Future: various neutrino detectors



Supernova-scope

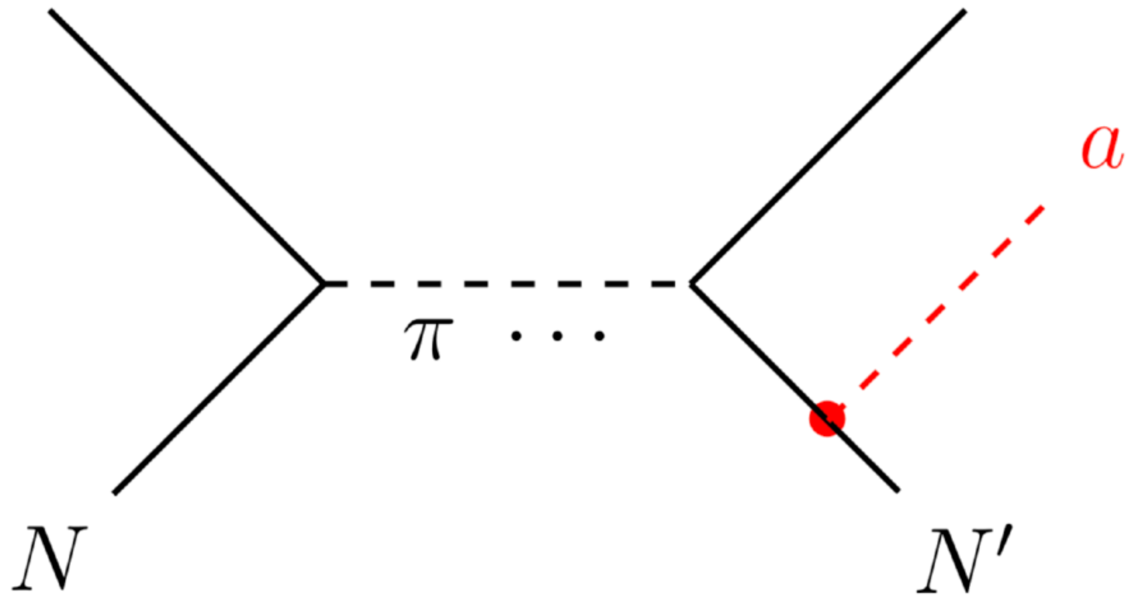
If the axion exists,...



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

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

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

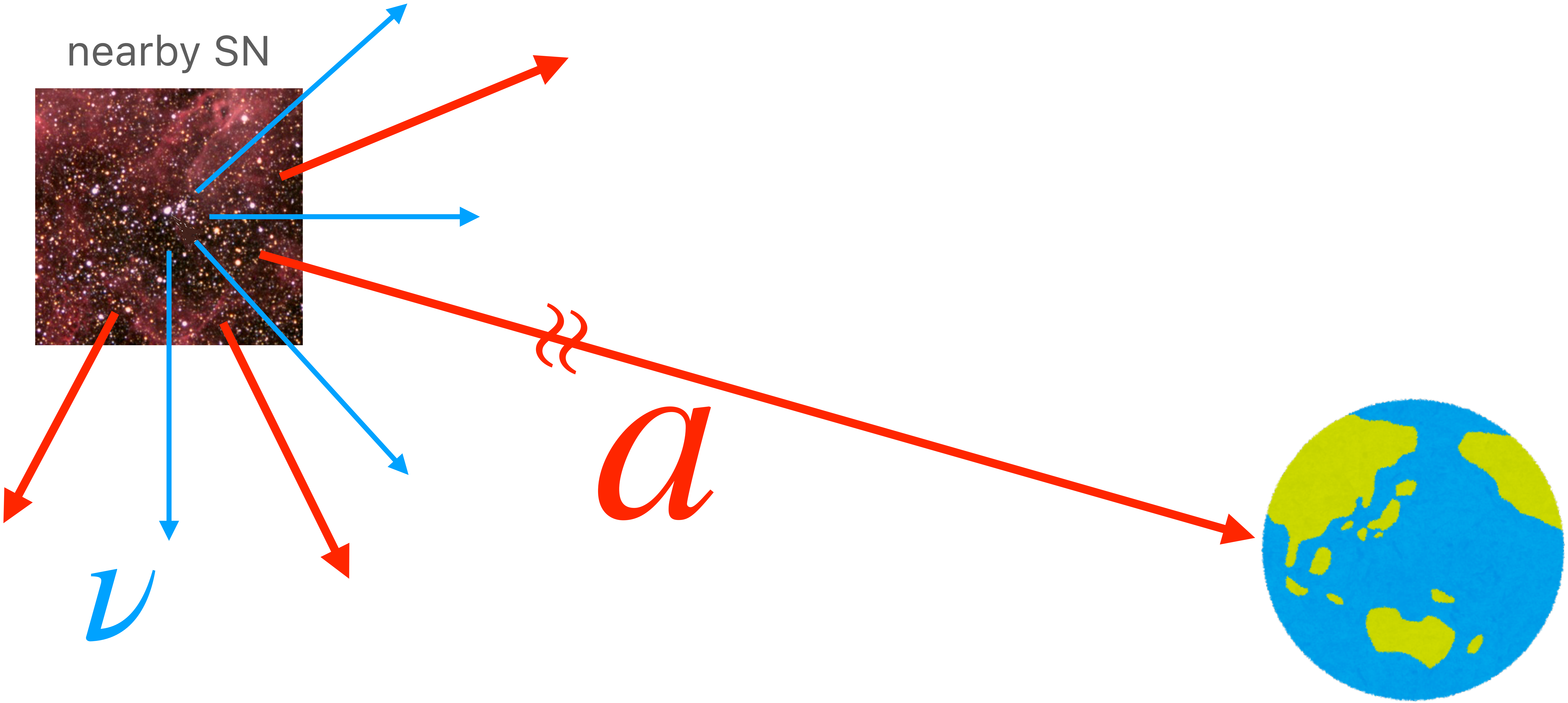


$$\begin{cases} C_p = -0.47 \\ C_n = -0.02 \end{cases} \text{(KSVZ)}$$

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

Supernova-scope

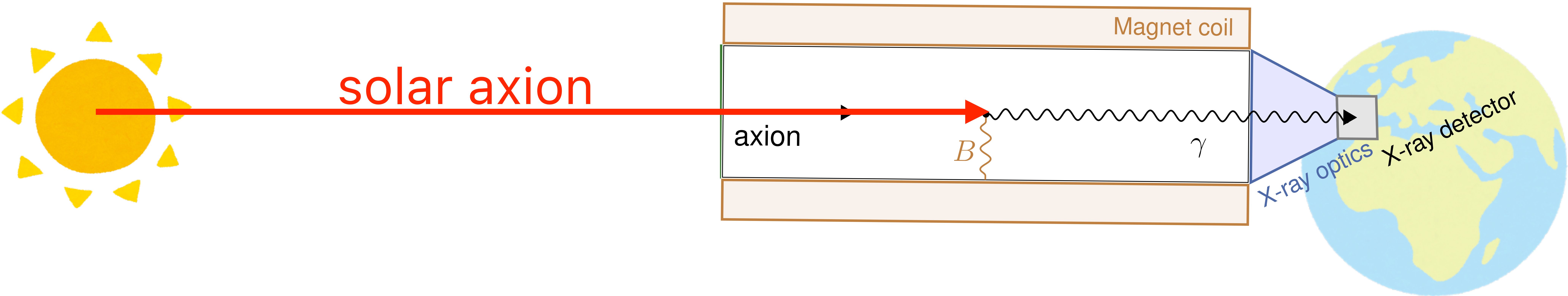
If the axion exists,...



Supernova-scope

Supernova-scope

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



Axion Helioscopes

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

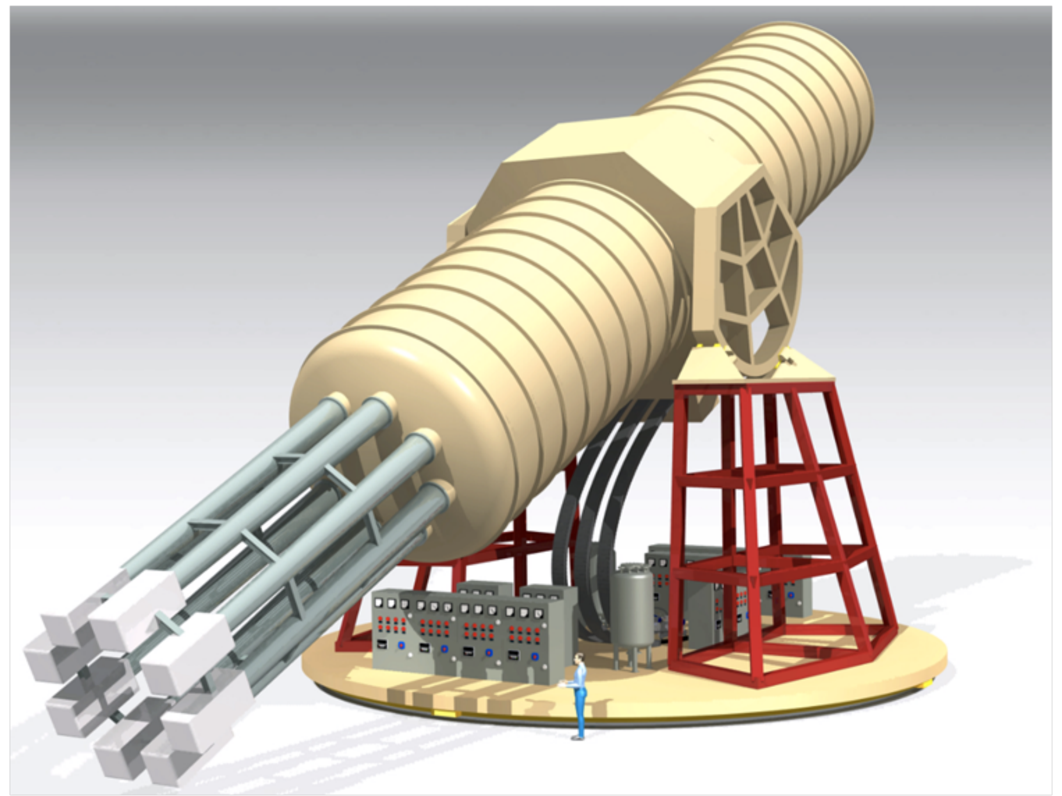
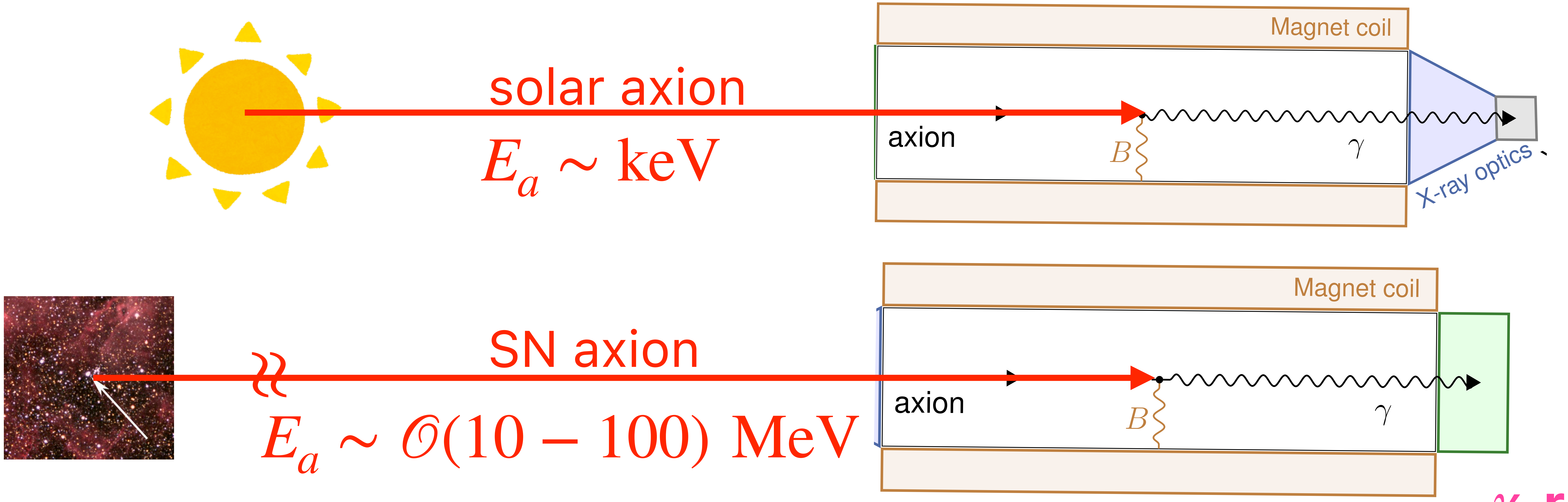


Fig. from IAXO homepage

Supernova-scope

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

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



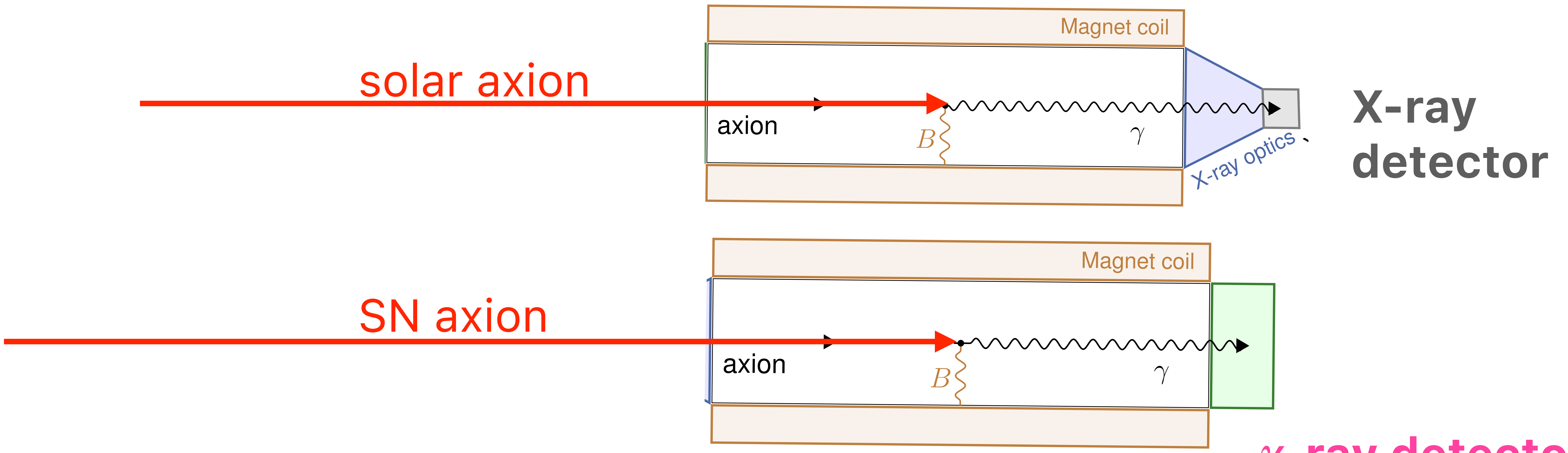
X-ray detector

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

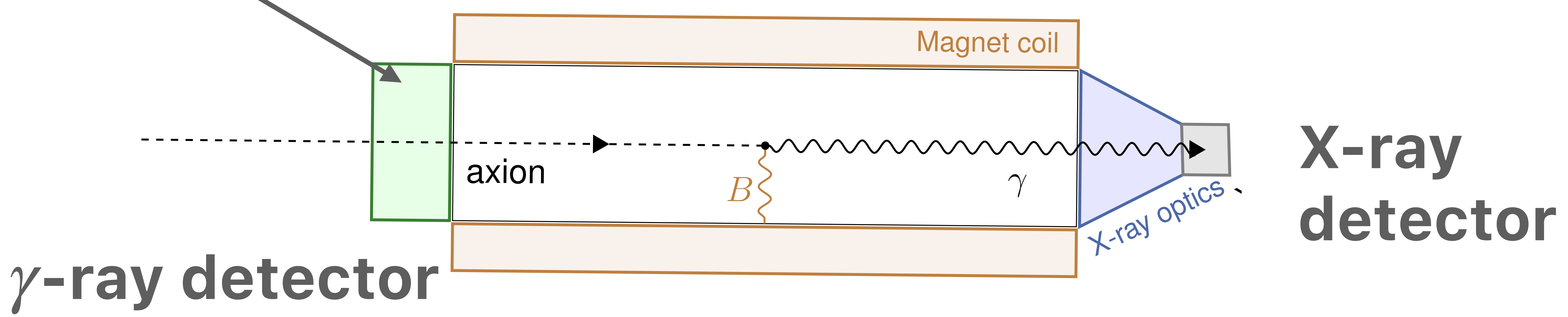


γ-ray detector is necessary.

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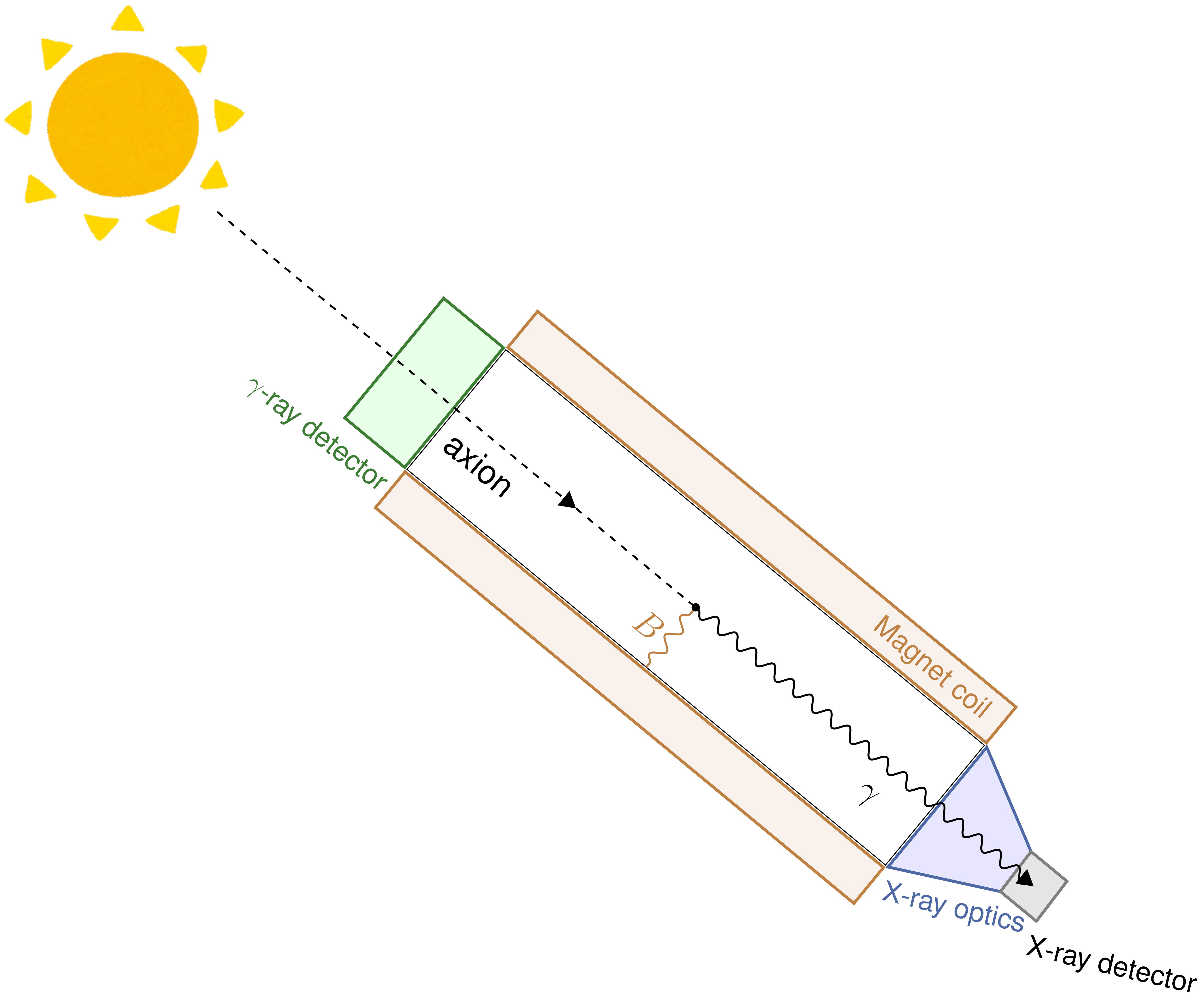
Idea: install a γ-ray detector at the opposite end to the X-ray detector.

Normal operation time: It works as an axion helioscope.



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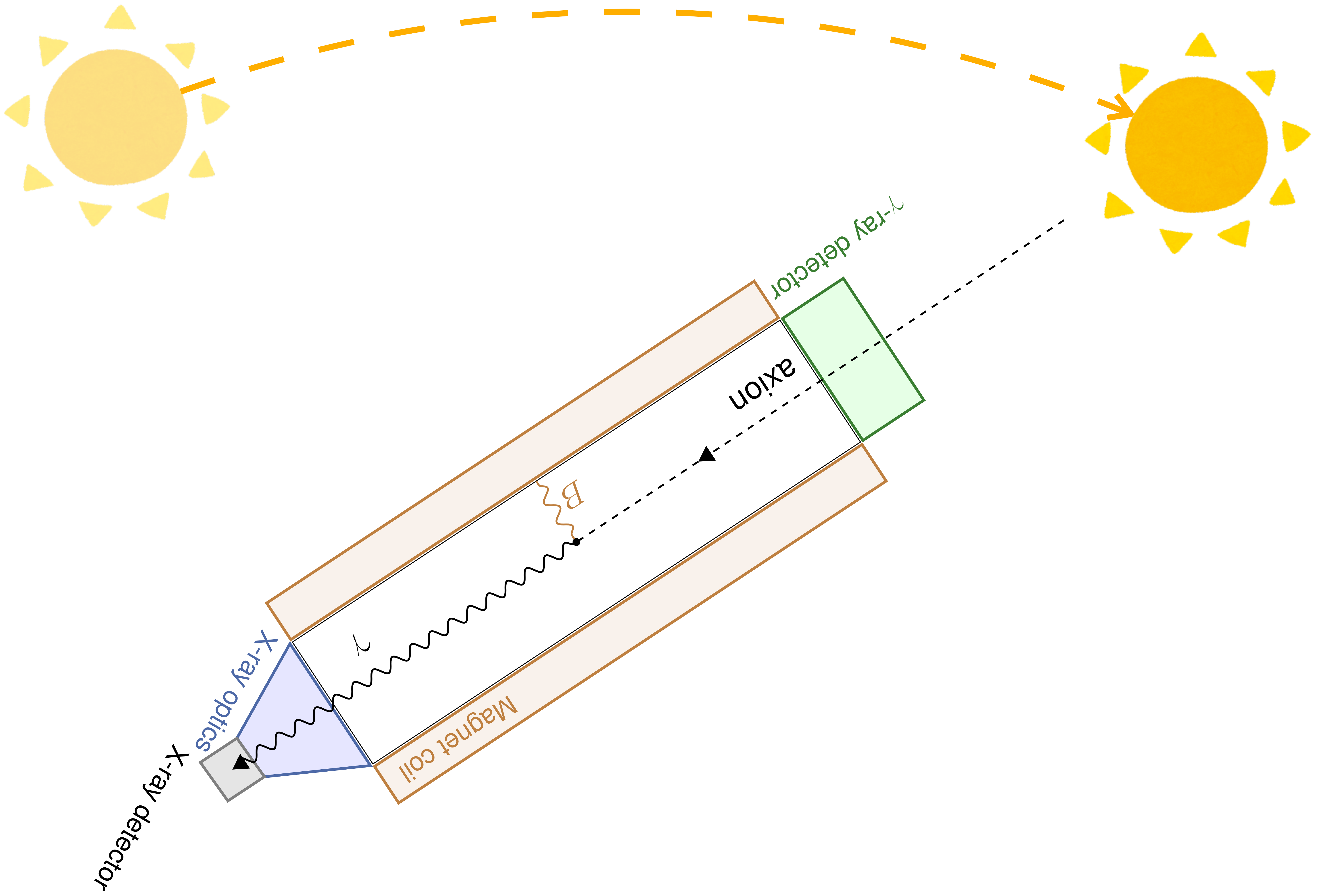

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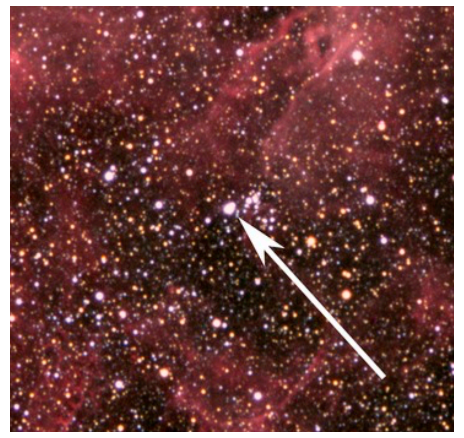
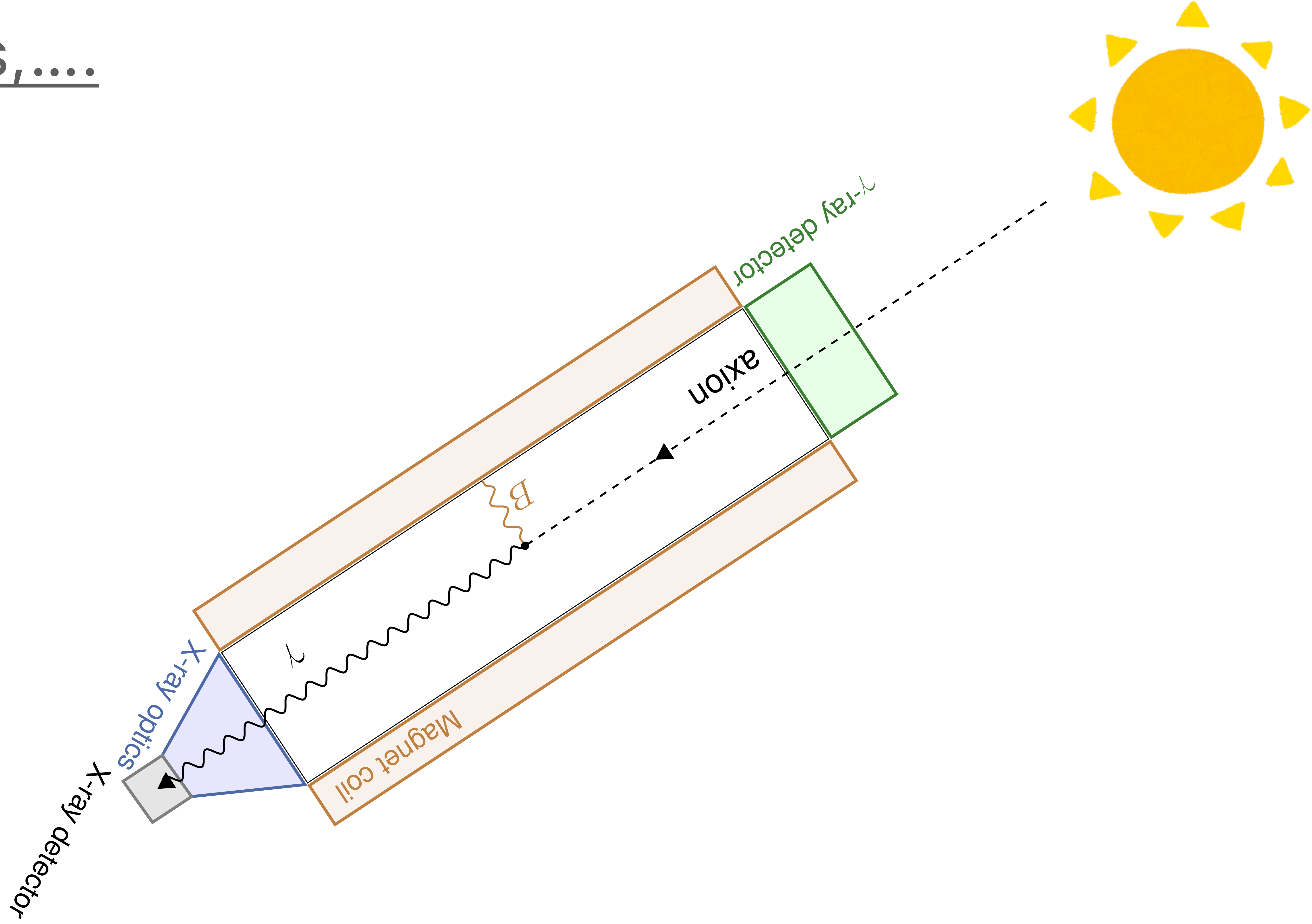
When a Supernova occurs,....





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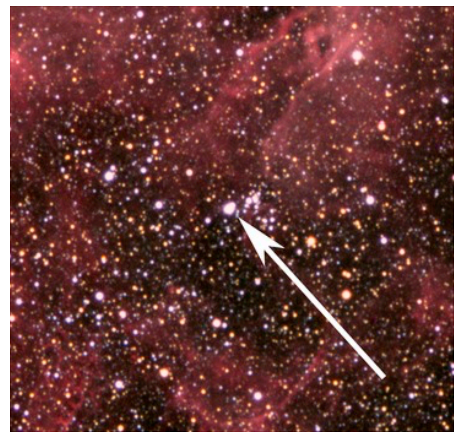

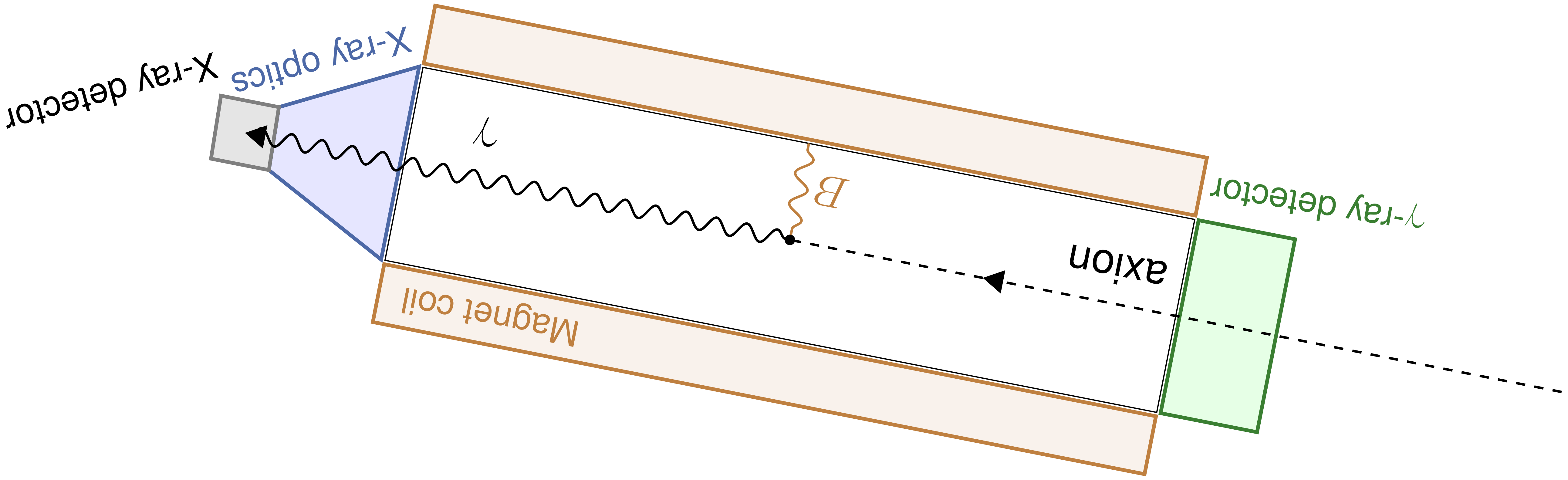

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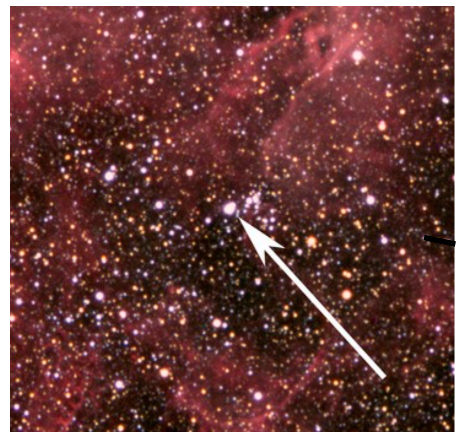

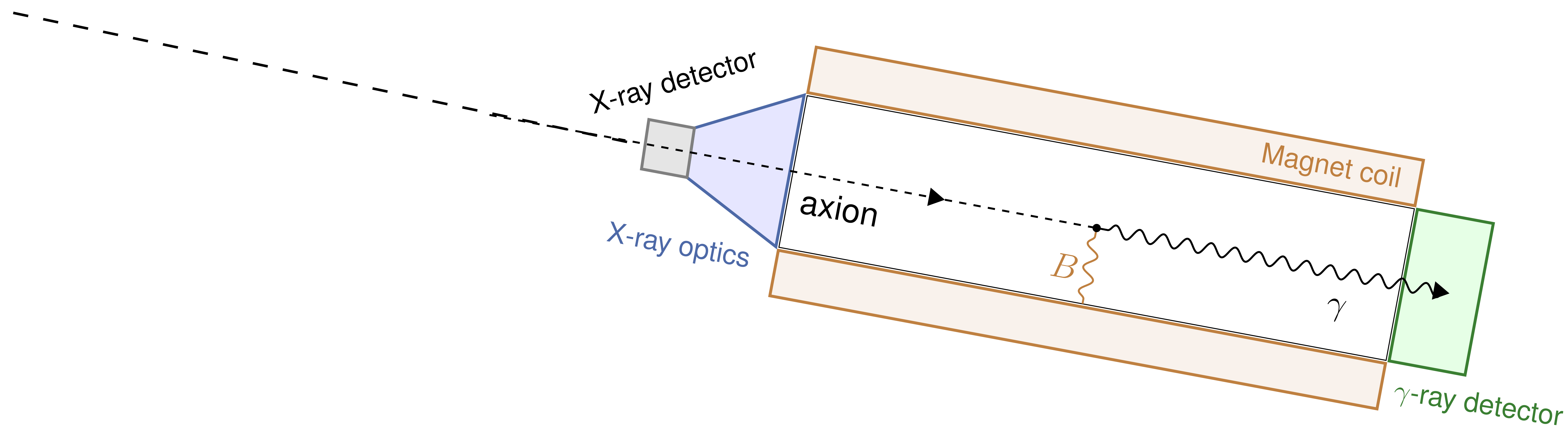

Axion Supernova-scope

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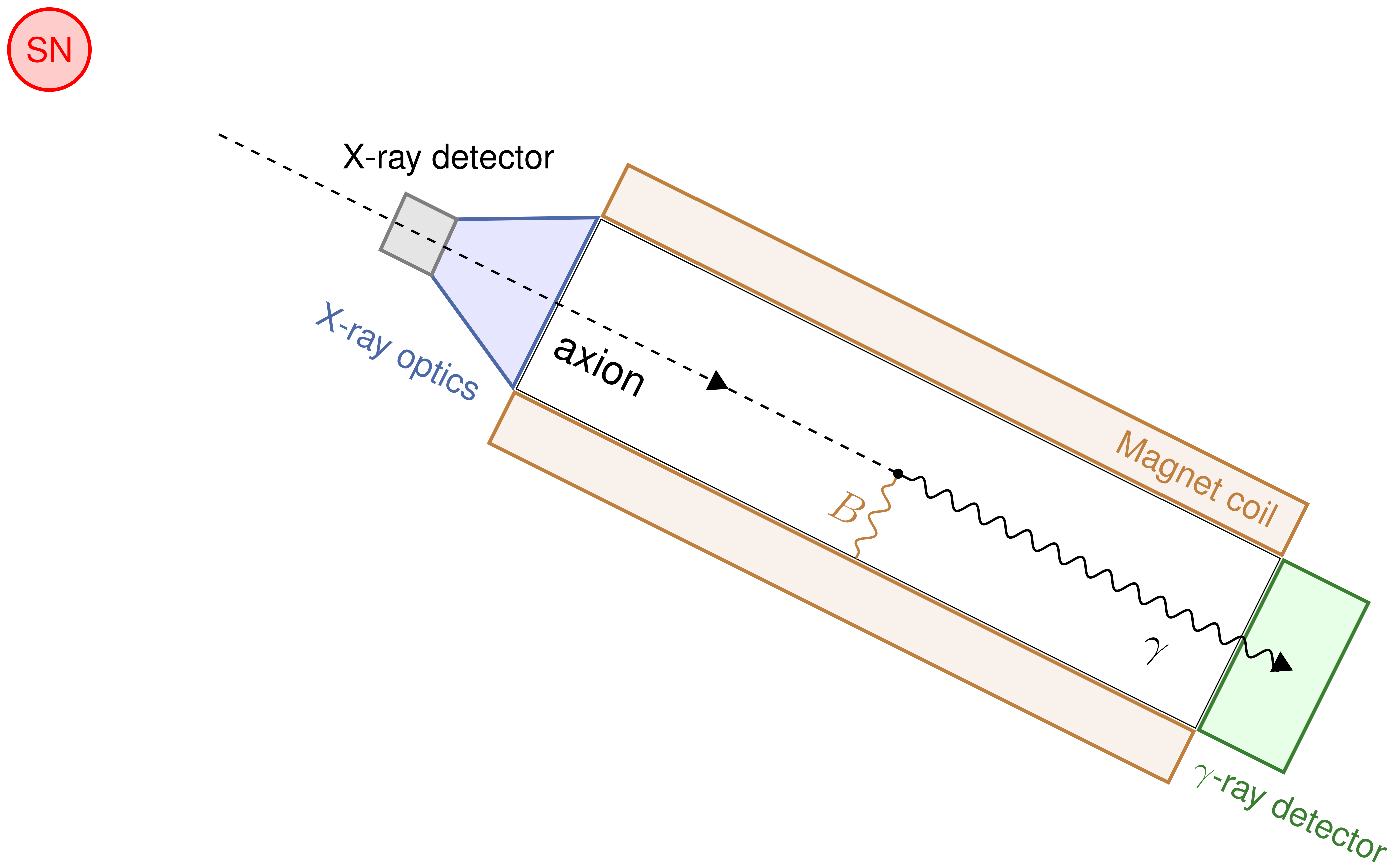
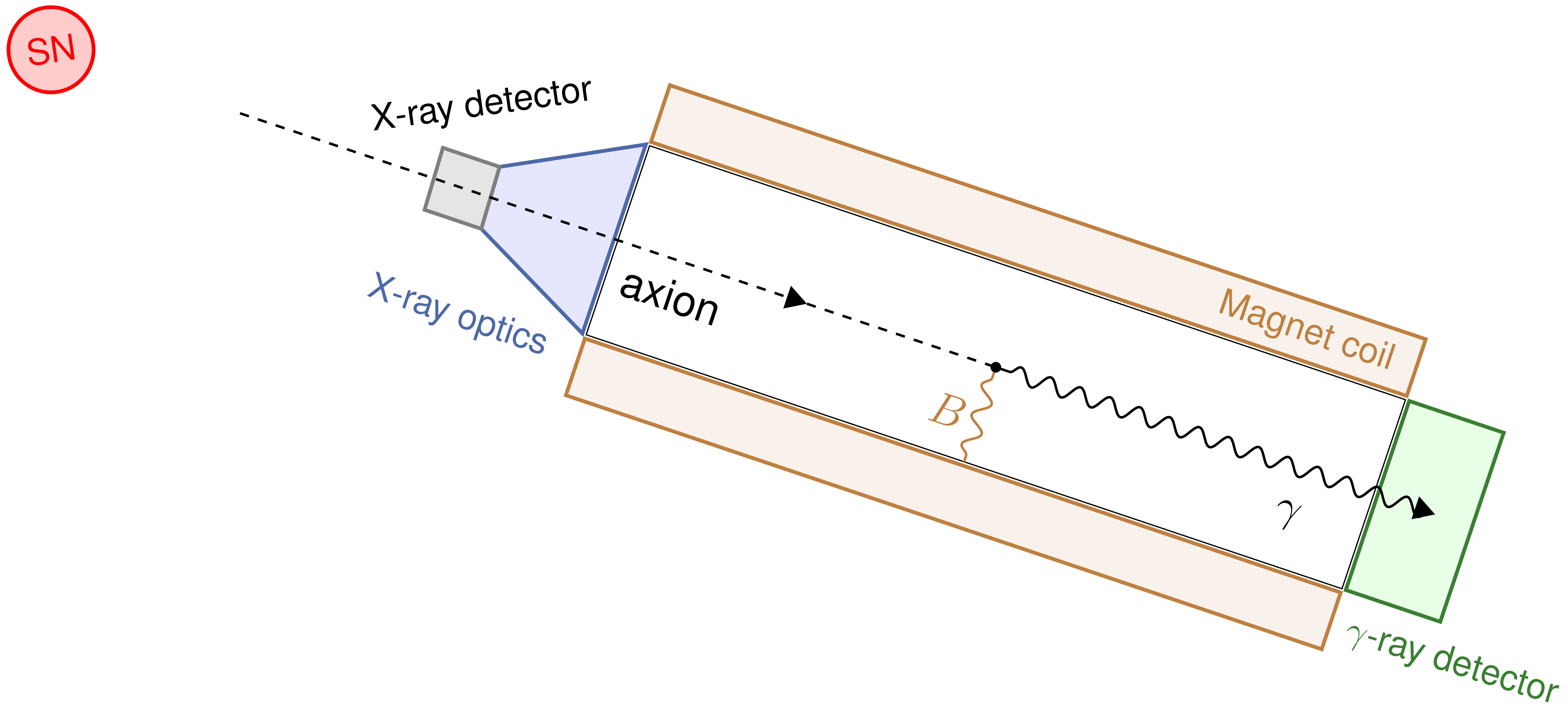


Pre-SN neutrino

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.

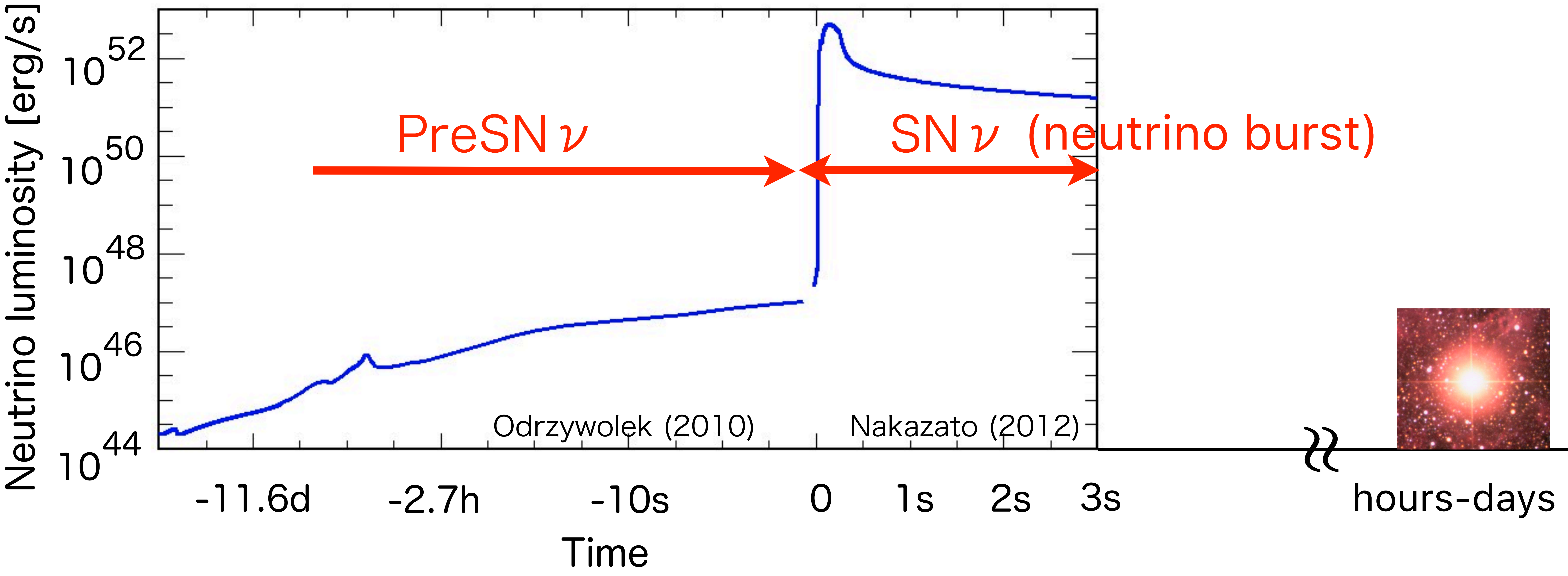


Figure from K.Ishidoshiro's talk in 2019.
https://www.lowbg.org/ugnd/workshop/sympo_all/201903_Sendai/

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

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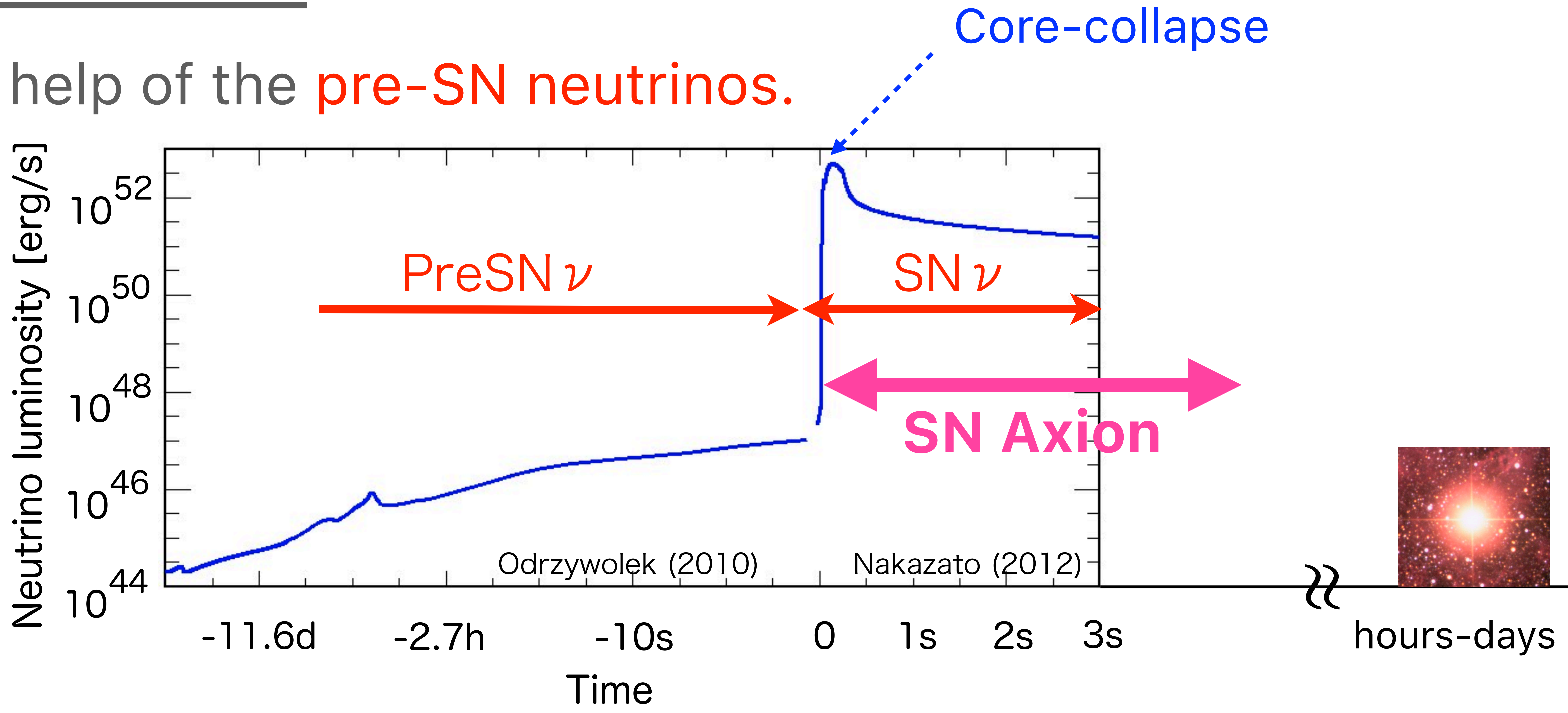

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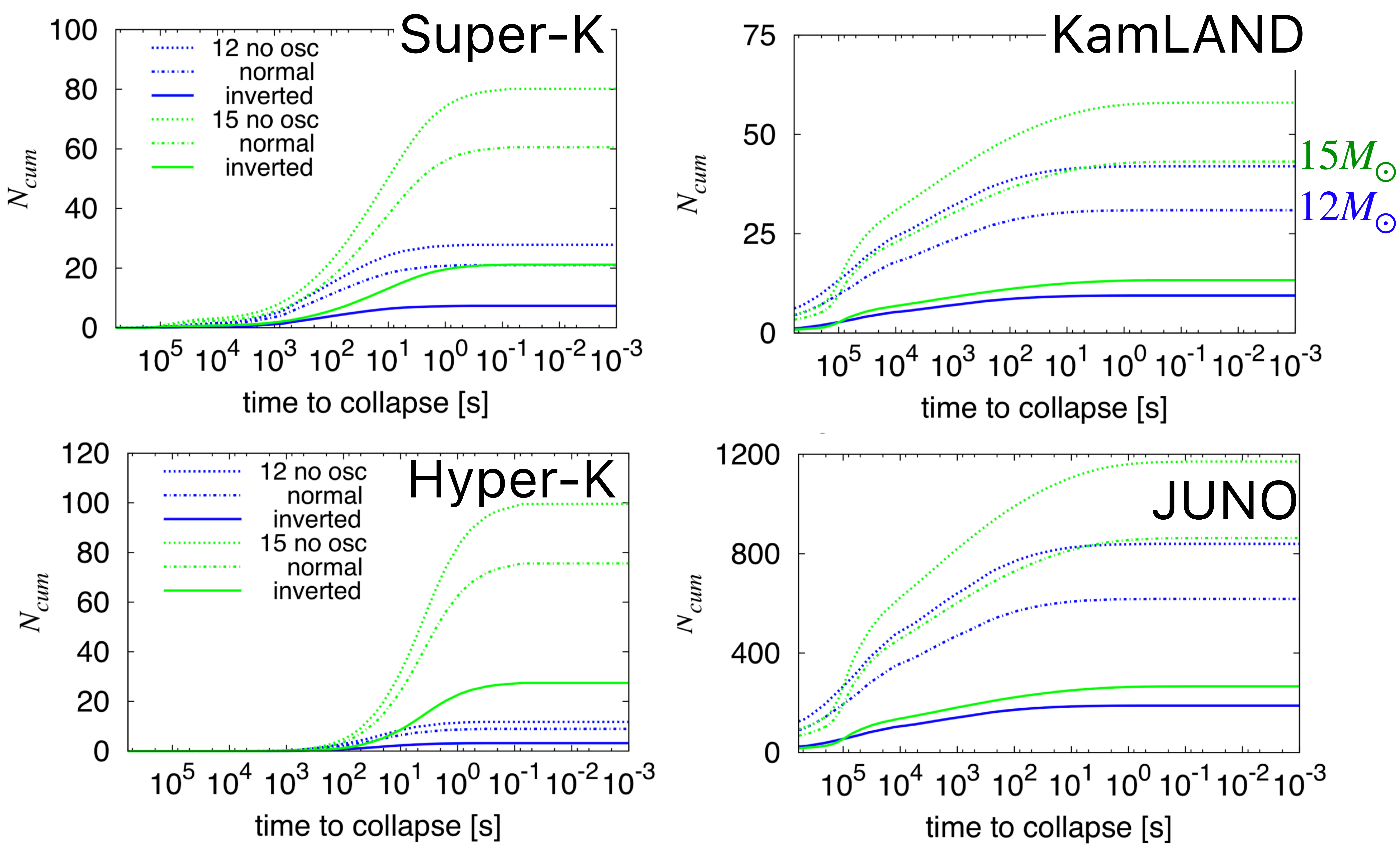


12 no osc
normal
inverted
15 no osc
normal
inverted
time to collapse [s]

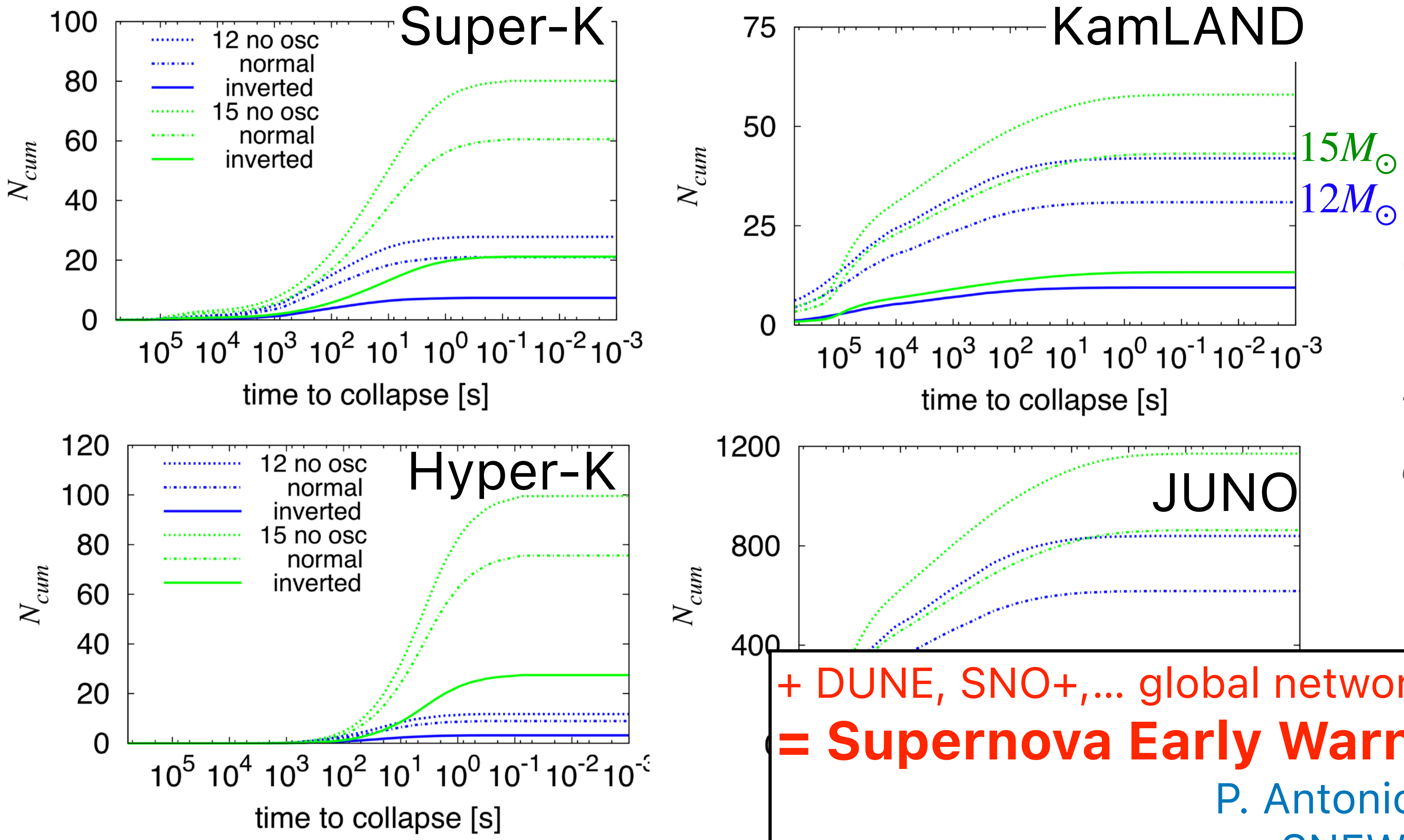
The cumulative numbers of expected pre-SN ν events for Fe-Core progenitor,

$d = 200$ pc.

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

➡ cf. Talk by **Sindhujha Kumaran** (Tuesday)

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).

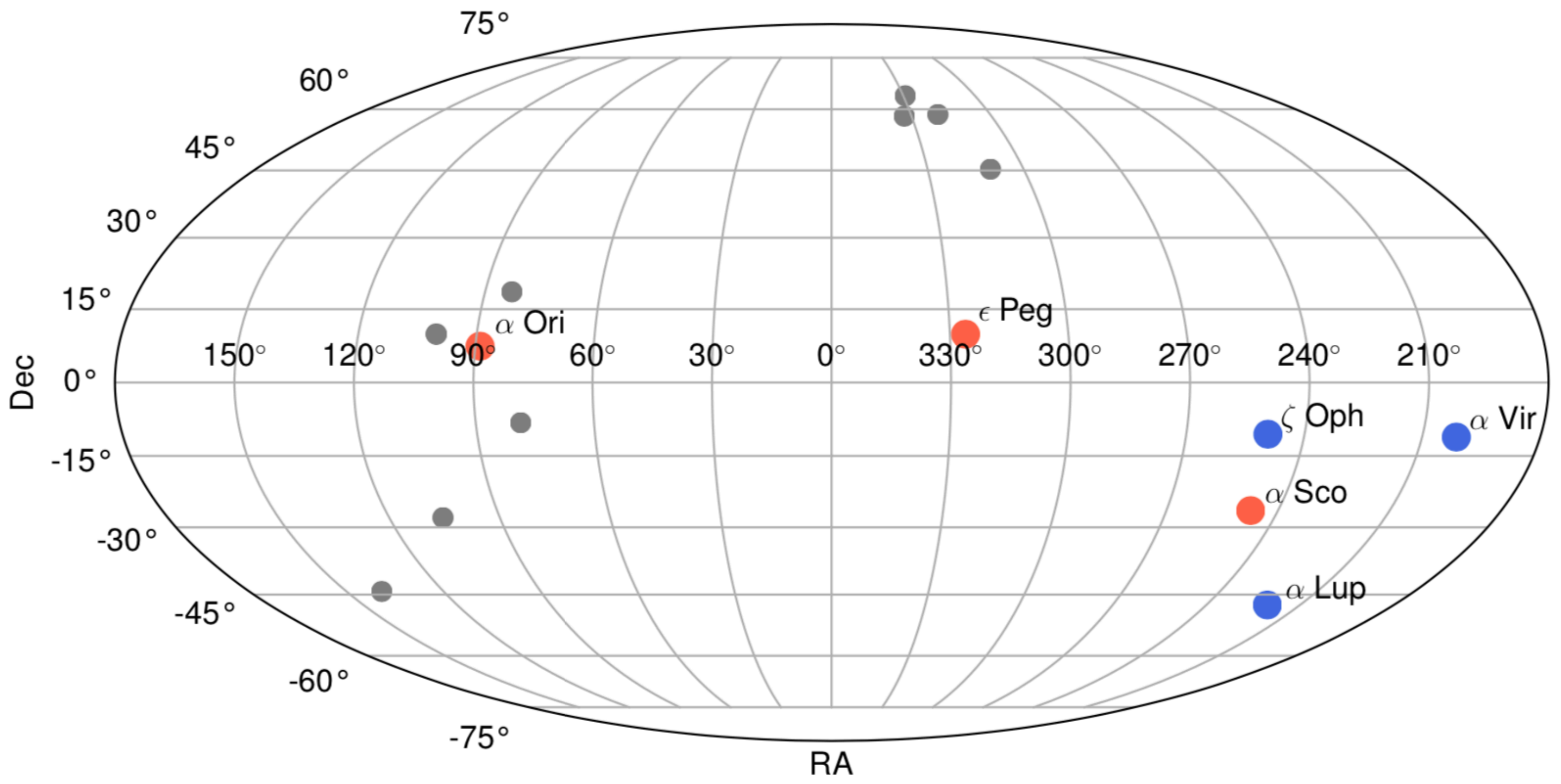
※ SN progenitors with $M < 10M_\odot$

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

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

→ We discard them.

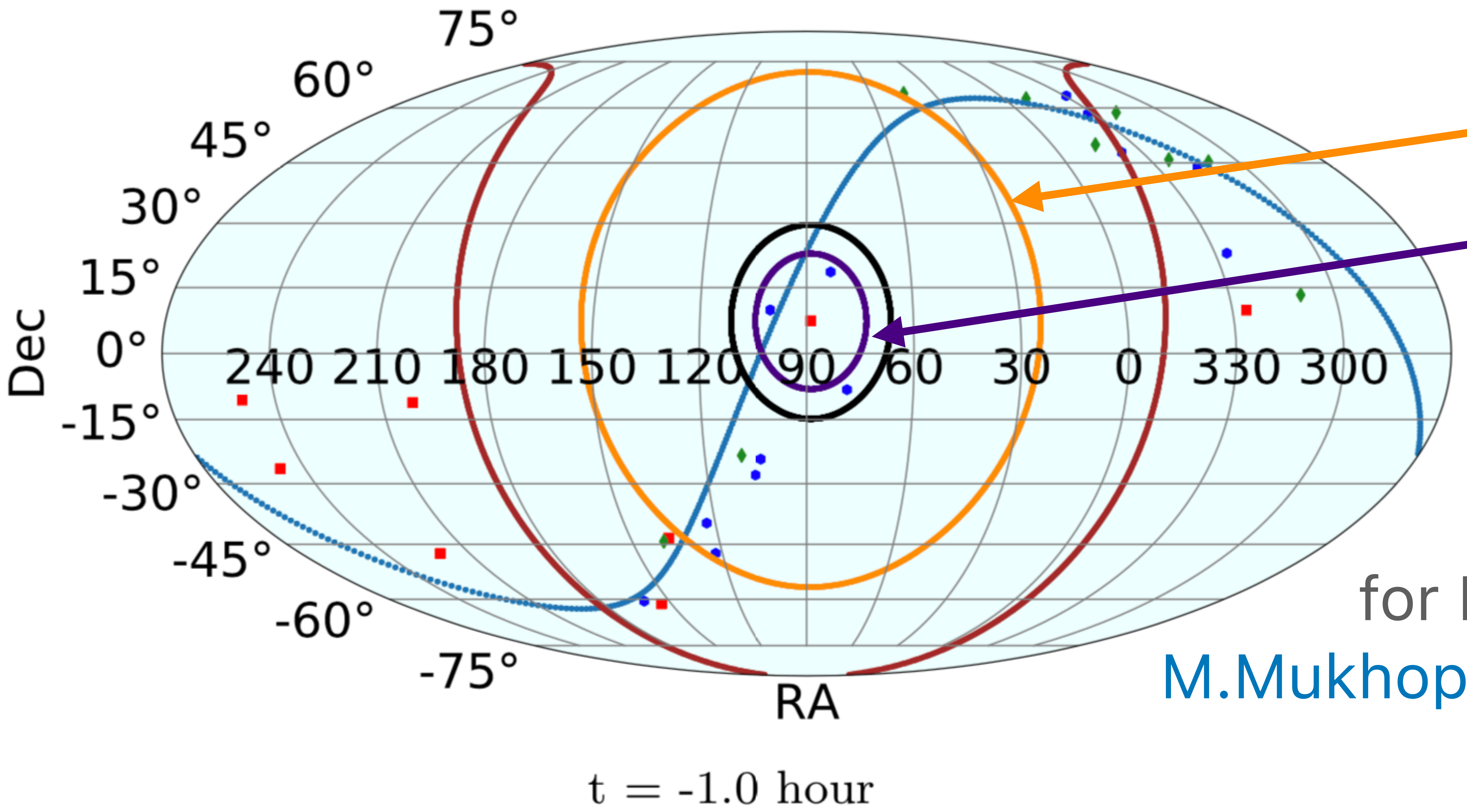
$M > 10M_\odot$ only.



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.



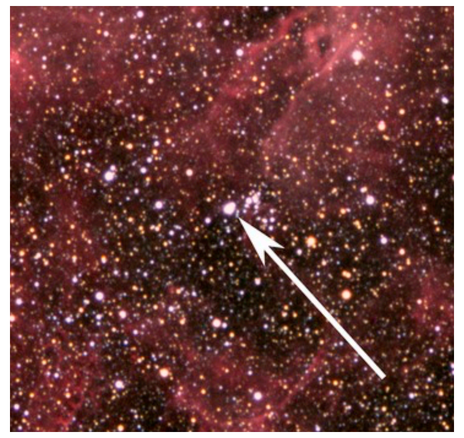
JUNO (68% C.L.)

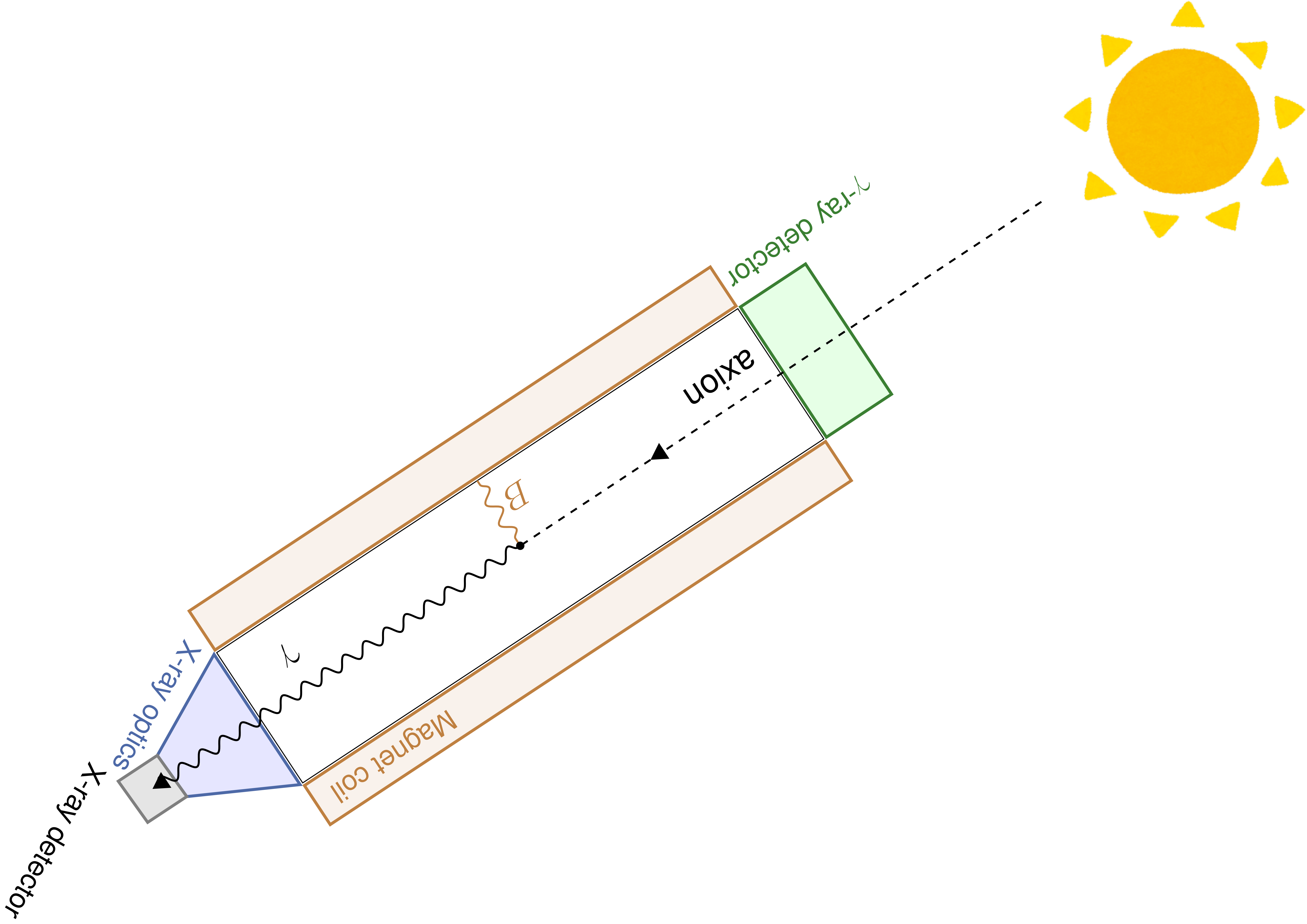
JUNO + Li (68% C.L.)

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

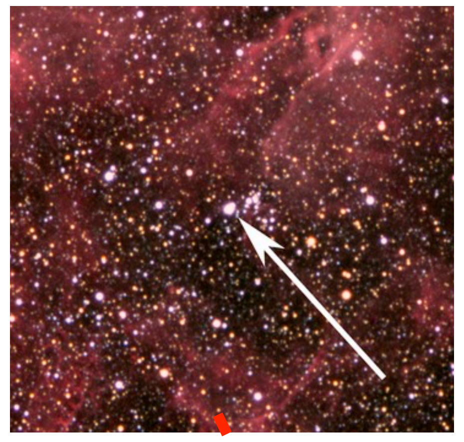
for Betelgeuse, $t = -1.0$ hour.

M.Mukhopadhyay et.al., [2004.02045]




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

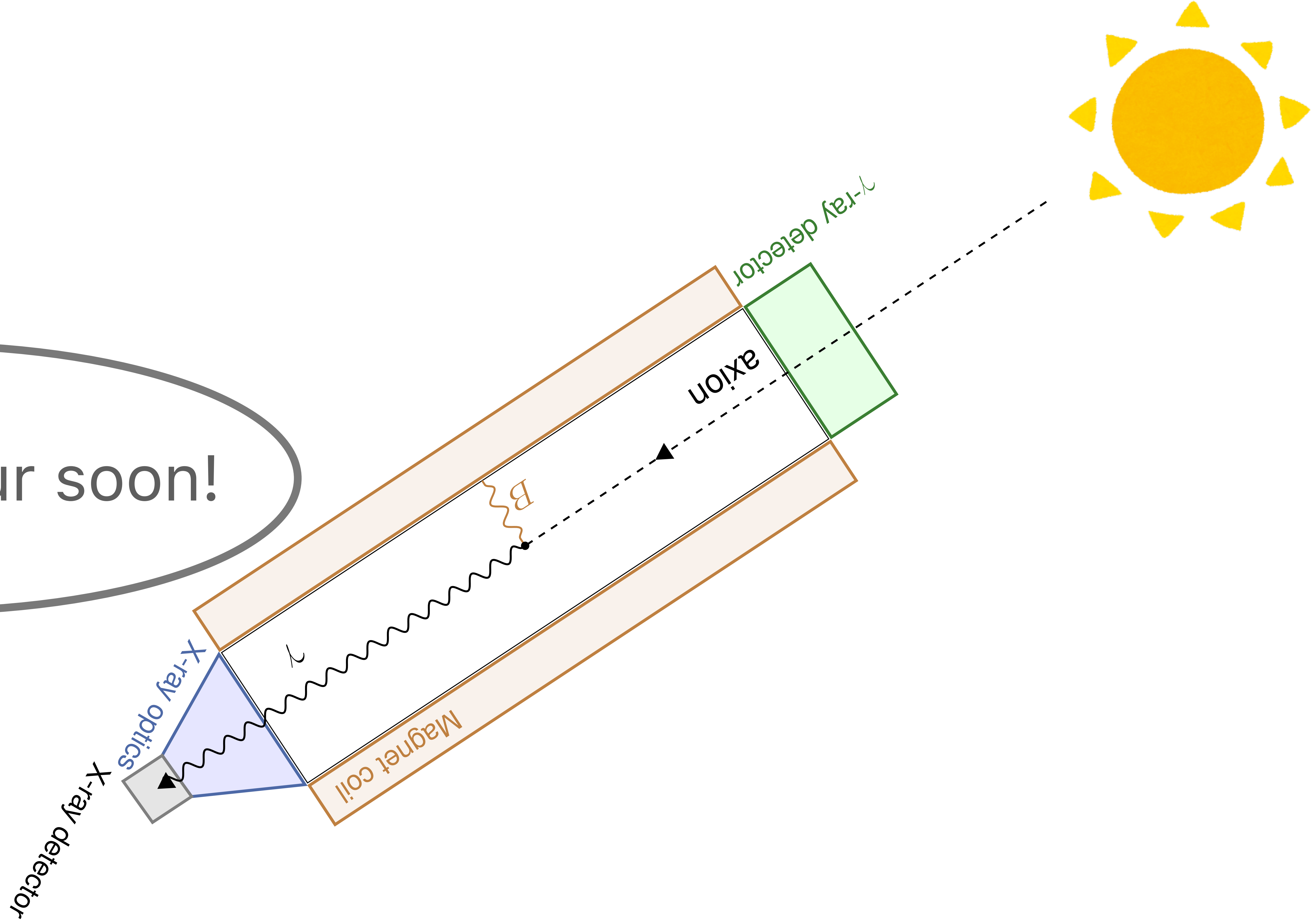
Once a pre-SN neutrino alert is received,



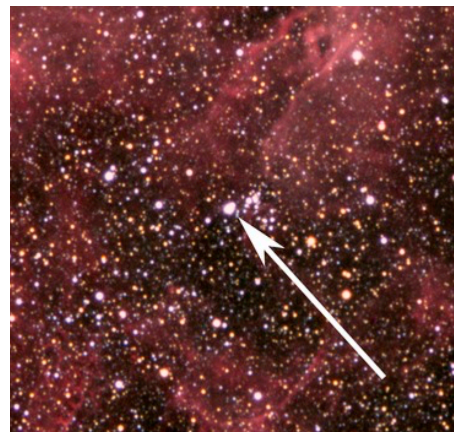
pre-SN ν

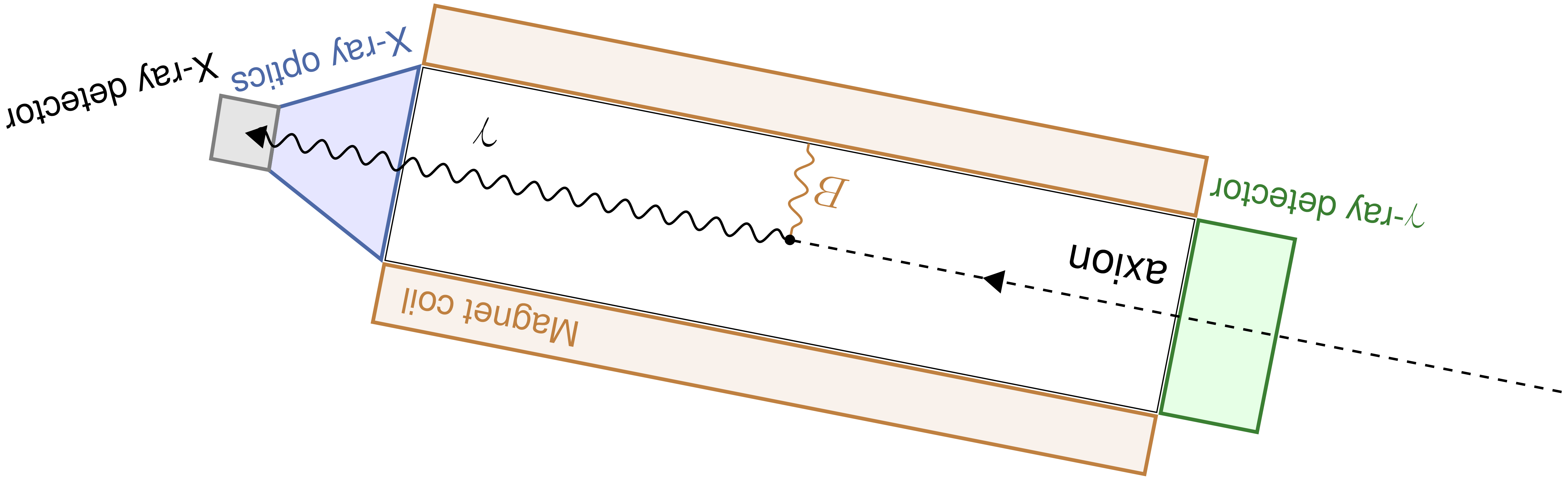
SN may occur soon!

SNEWS

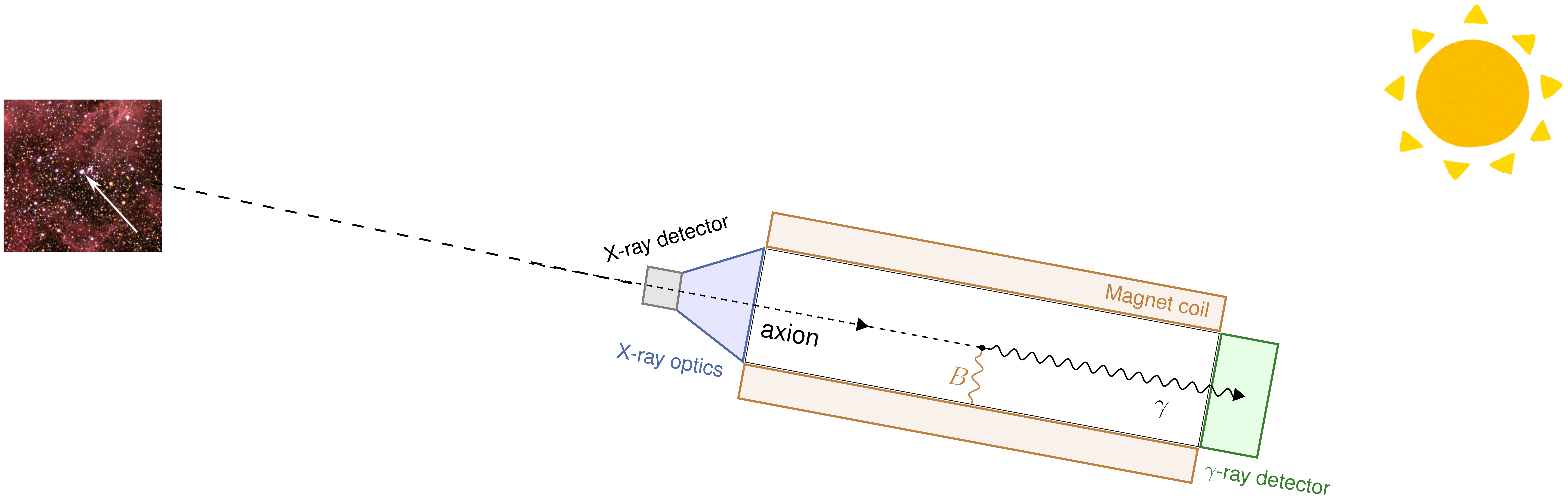


Once a pre-SN neutrino alert is received,



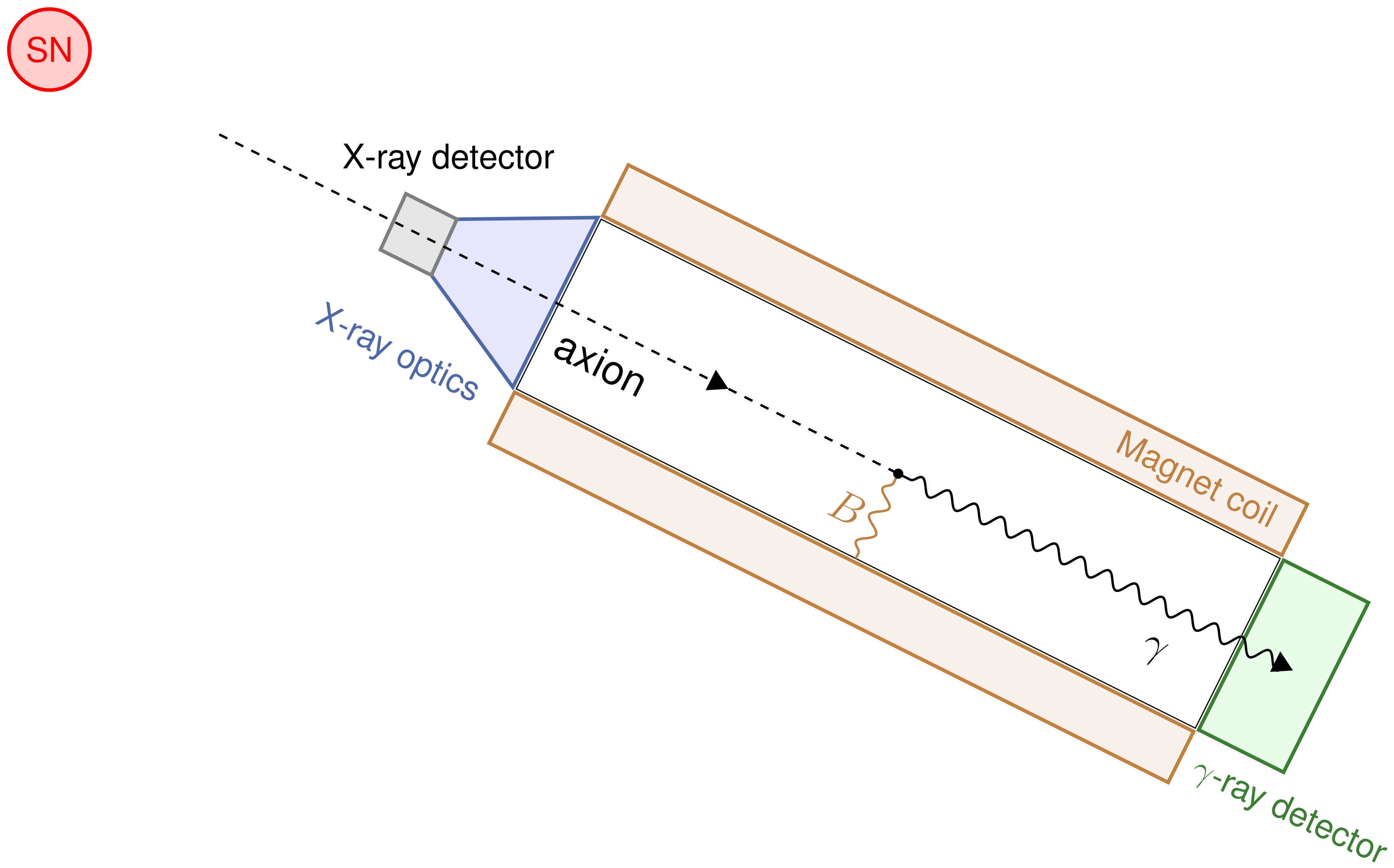


Once a pre-SN neutrino alert is received,



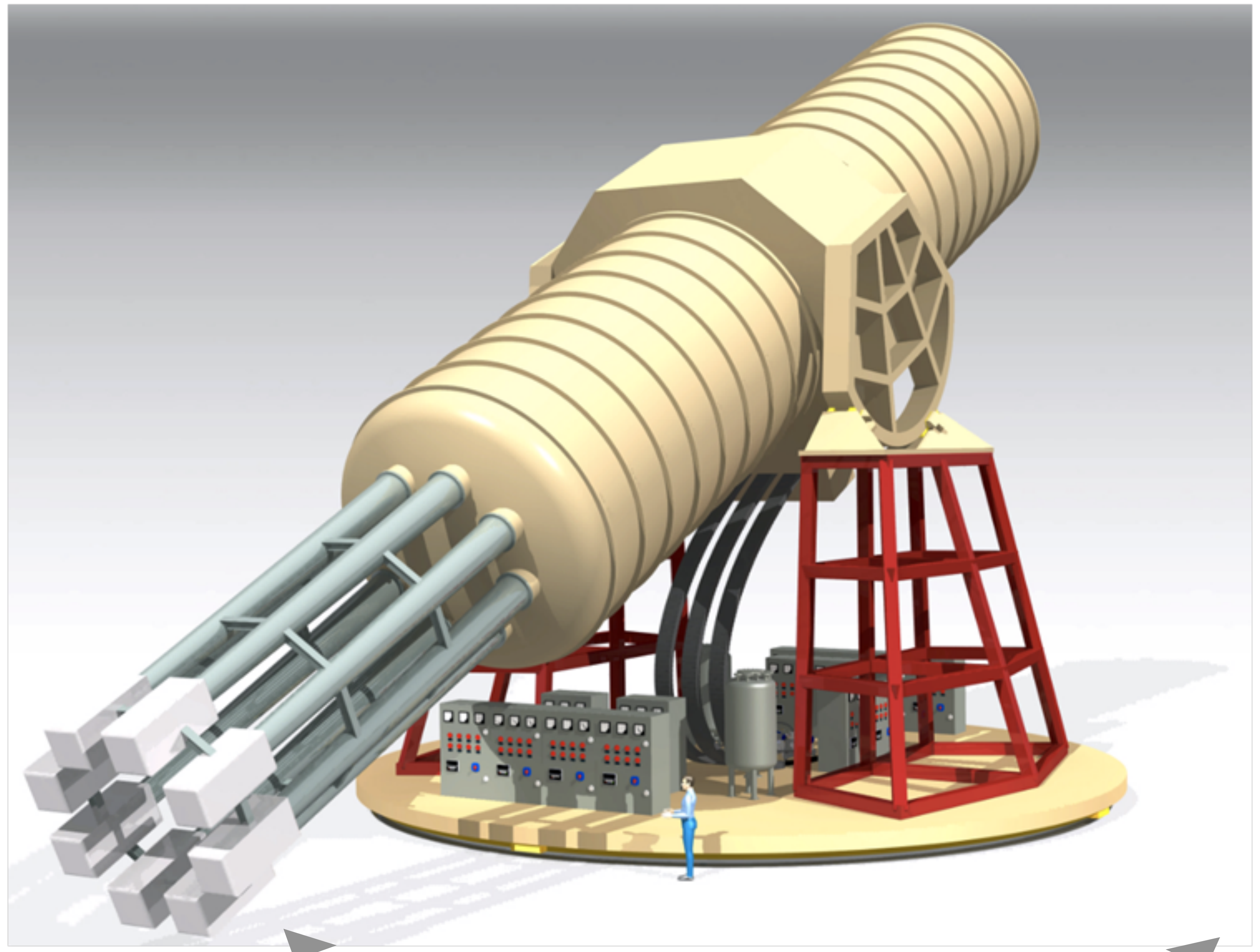
Plan

- **Motivation**: axion
- **Supernova Axion detection**
  - SN candidates
  - Supernova-scope
  - Pre-SN neutrino
  - Observation time fraction
  - Event number
- **Summary**



Observation time fraction

Fig. from IAXO homepage



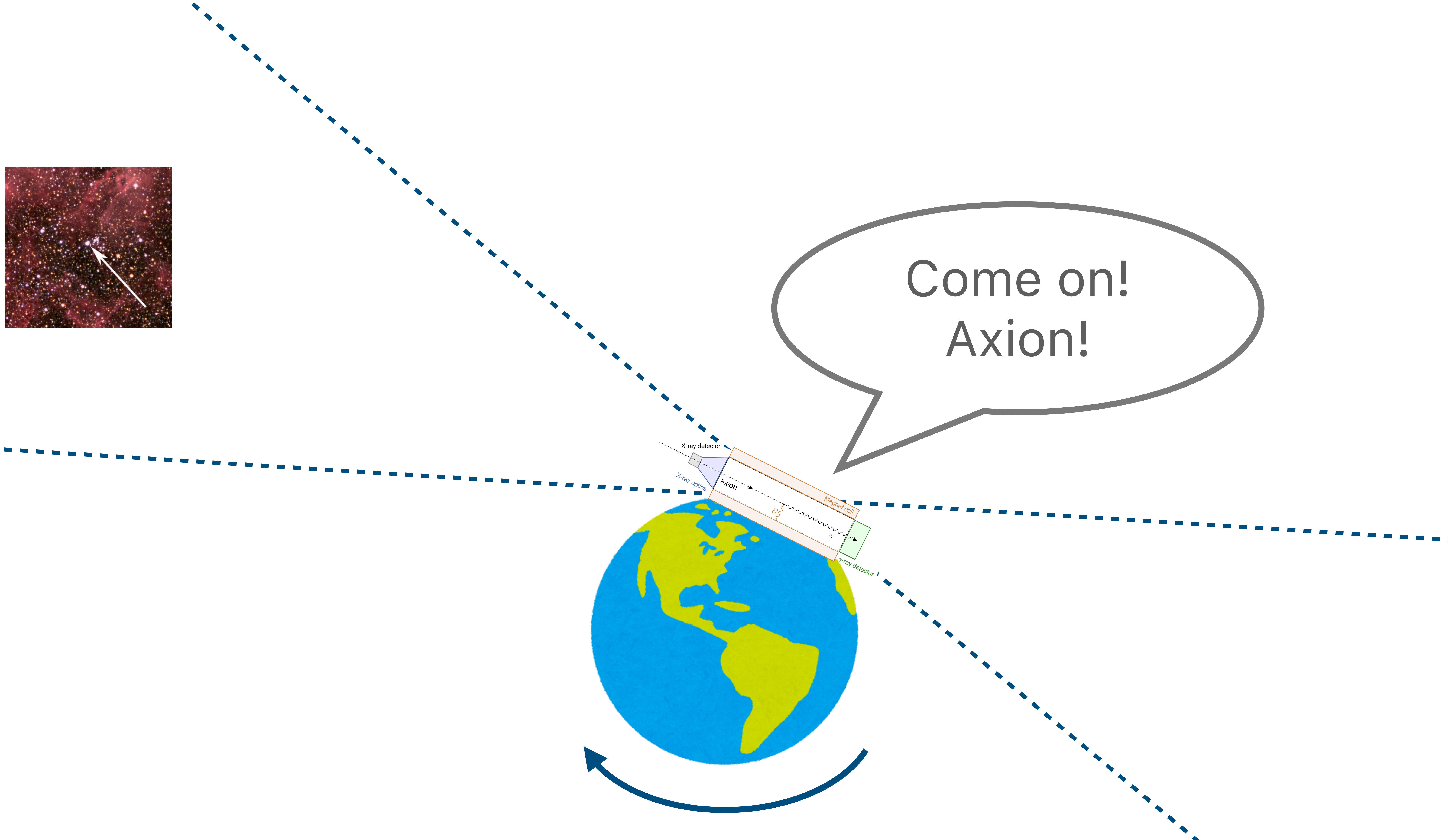
$$-\theta_{max} \leq \theta \leq +\theta_{max}$$

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

maximum elevation:

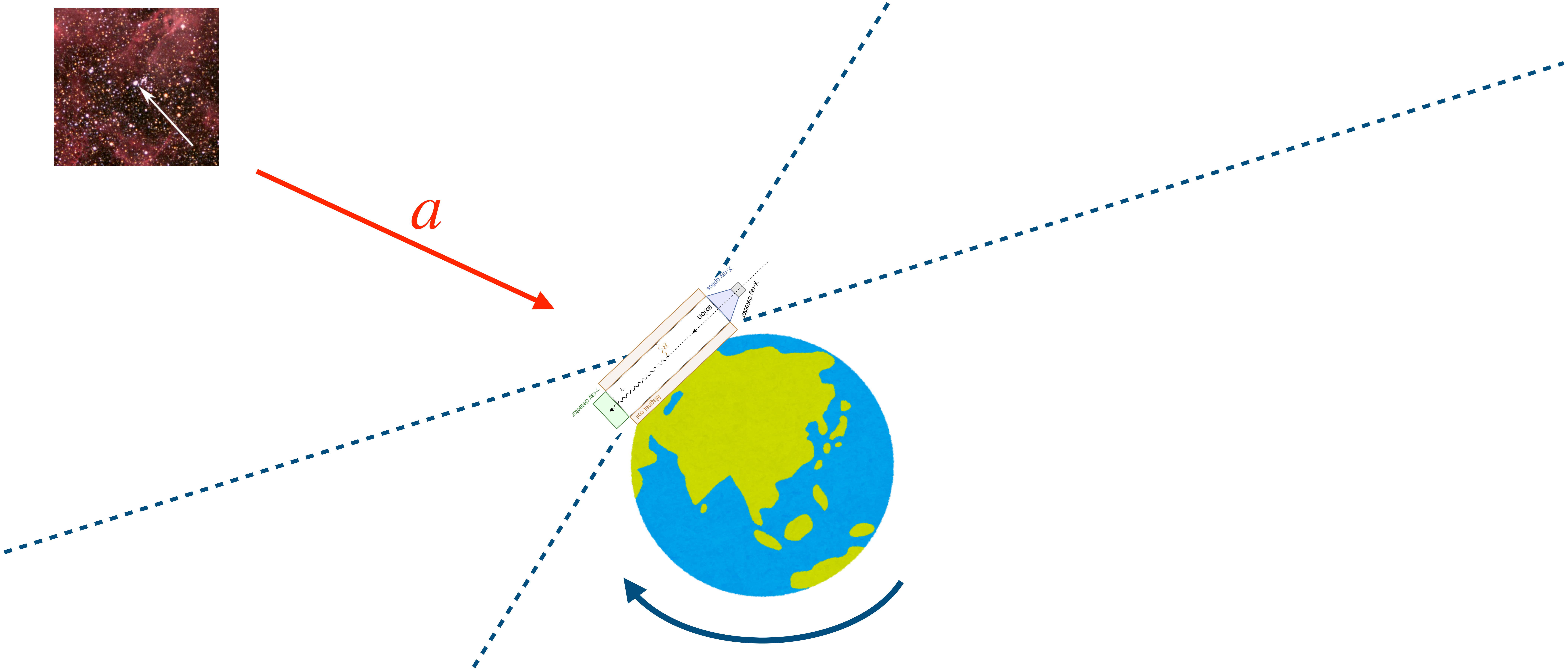
$$\theta_{max} = \begin{cases} 25^\circ \ (\mathrm{IAXO}) \\ 20^\circ \ (\mathrm{TASTE}) \end{cases}$$

Observation time fraction



Observation time fraction

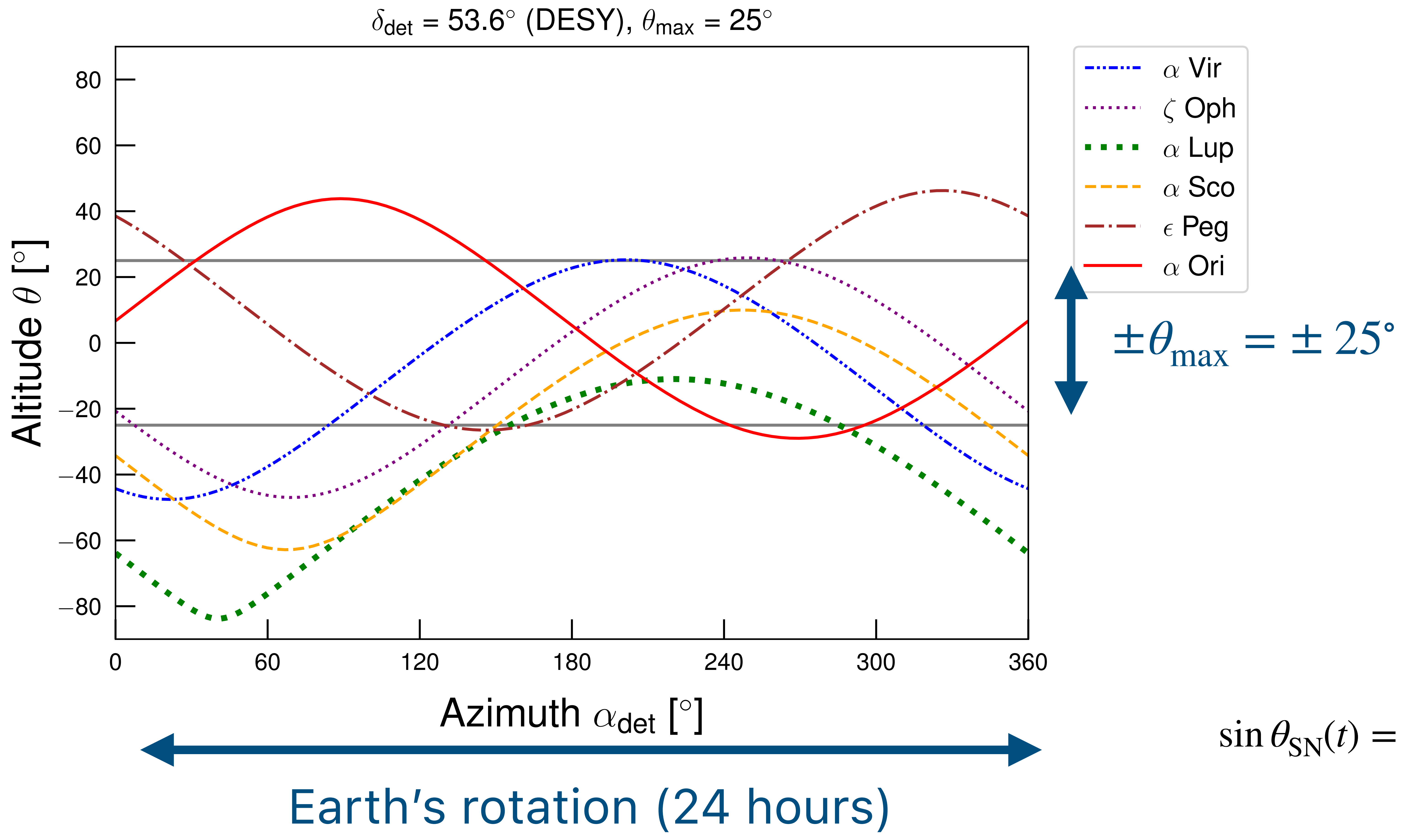
but if you are unlucky,...

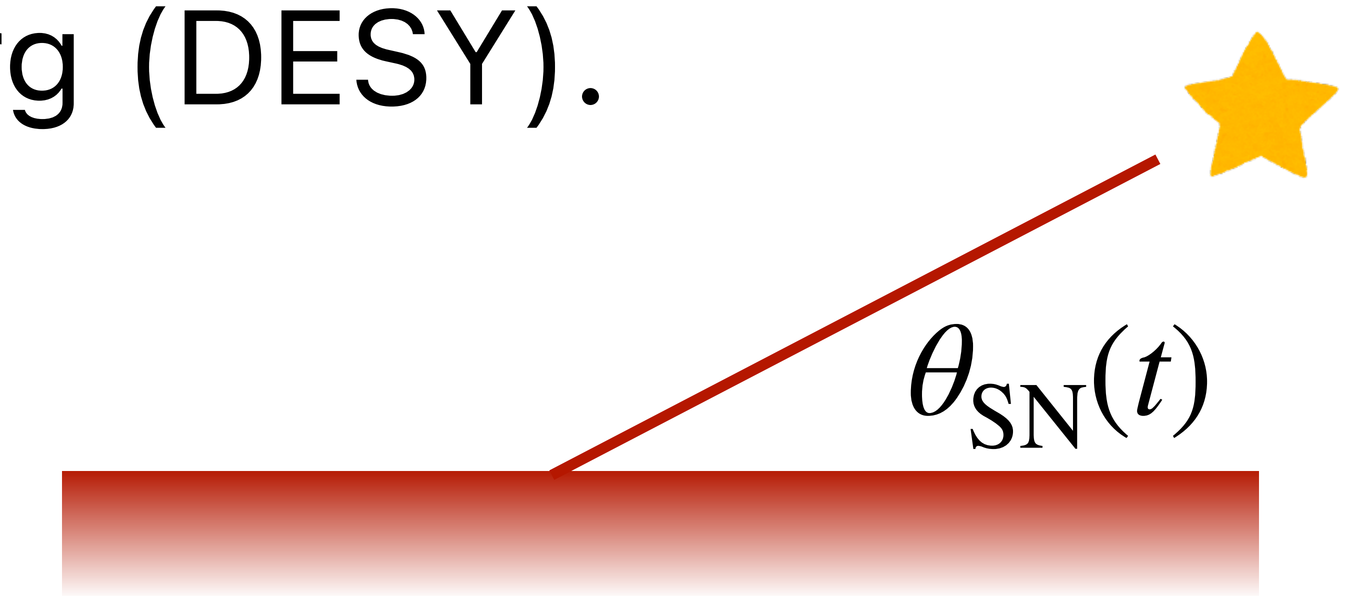


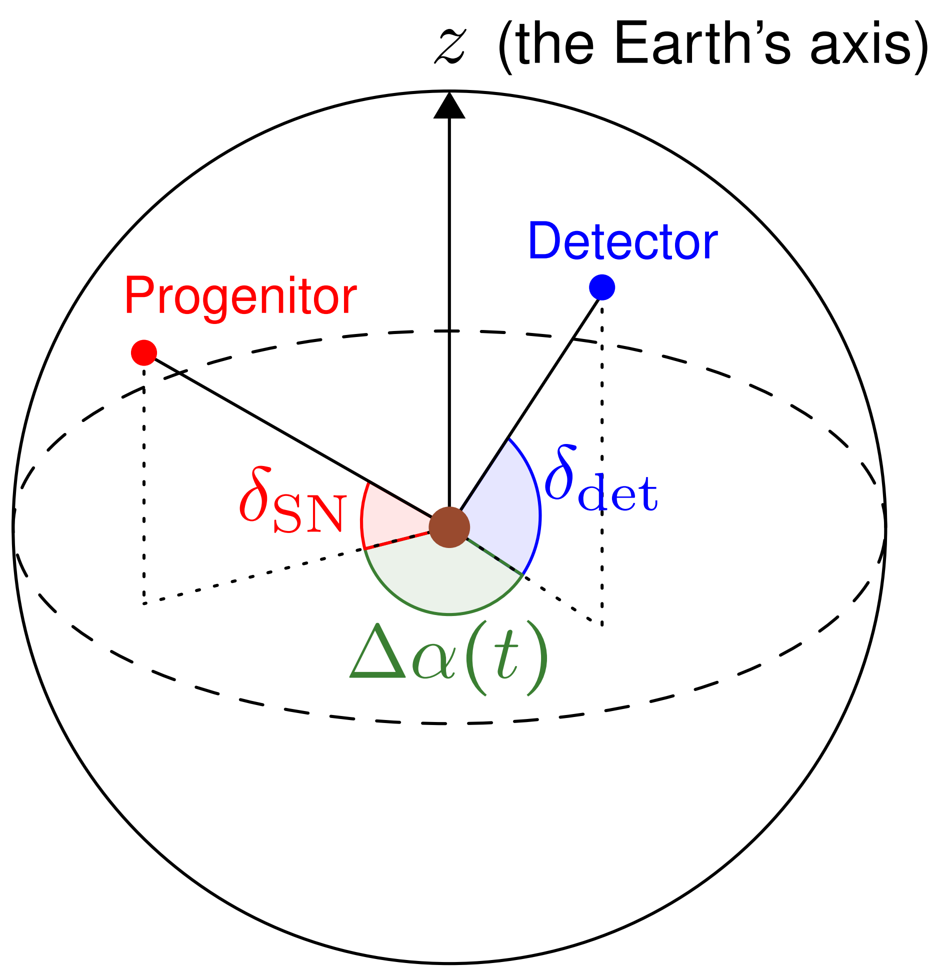
Observation time fraction

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

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







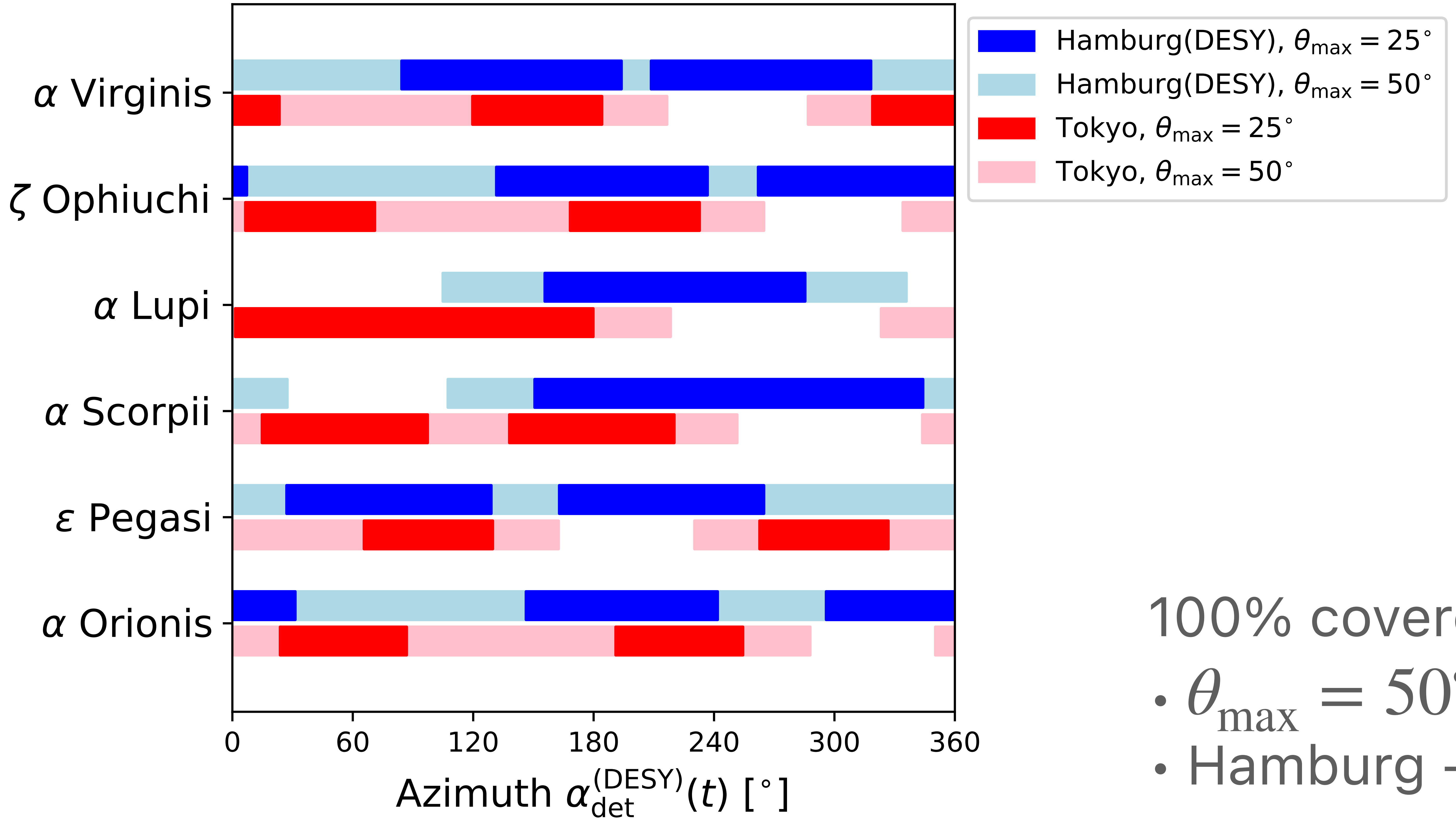
$$\sin\theta_{SN}(t) = \cos\delta_{SN}\cos\delta_{det}\cos\Delta\alpha(t) + \sin\delta_{SN}\sin\delta_{det}\,.$$

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

Observation time fraction

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

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



100% covered if
- $\theta_{\rm max} = 50^\circ$
- Hamburg + Tokyo.

Plan

- **Motivation**: axion
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  - Pre-SN neutrino
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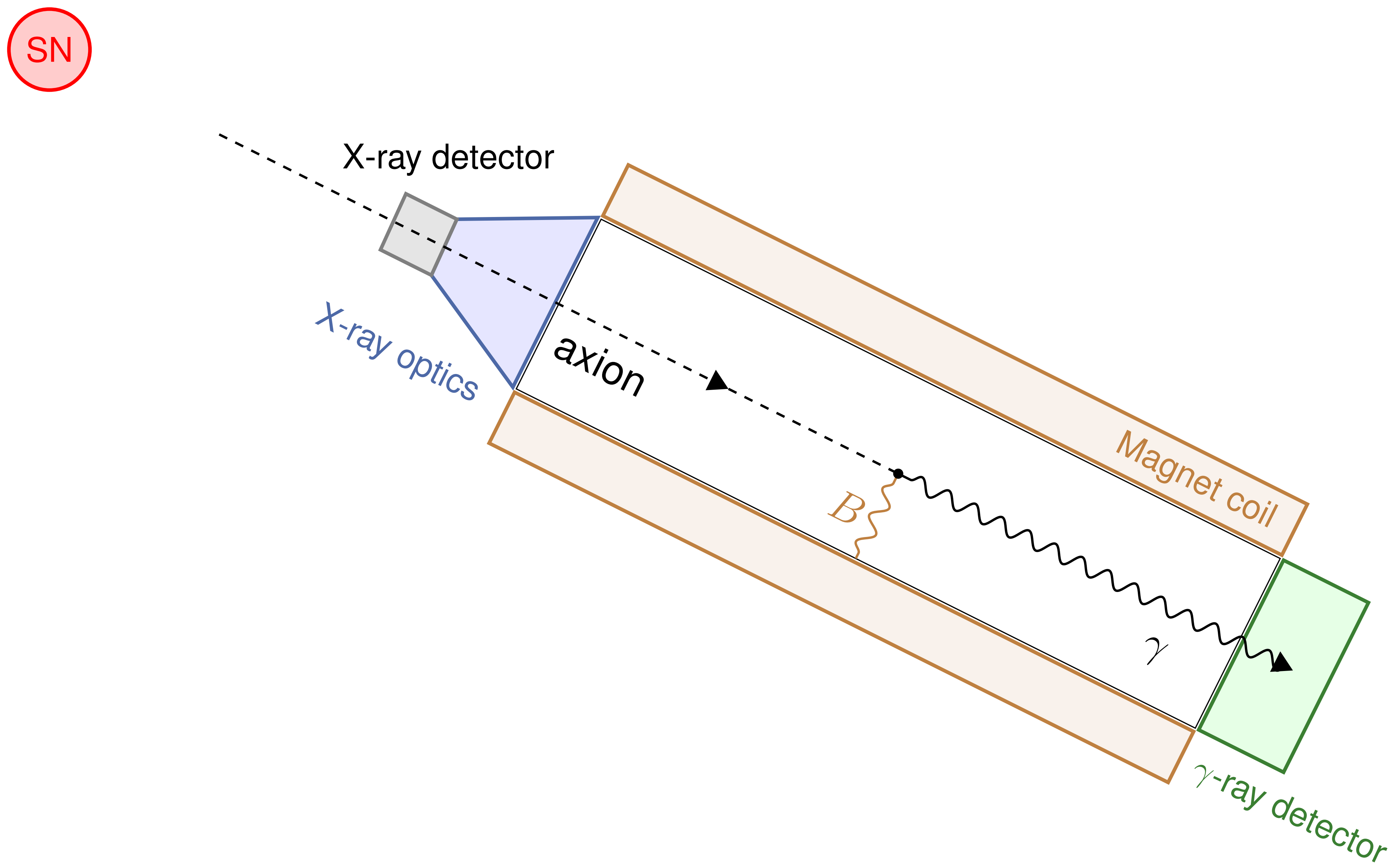
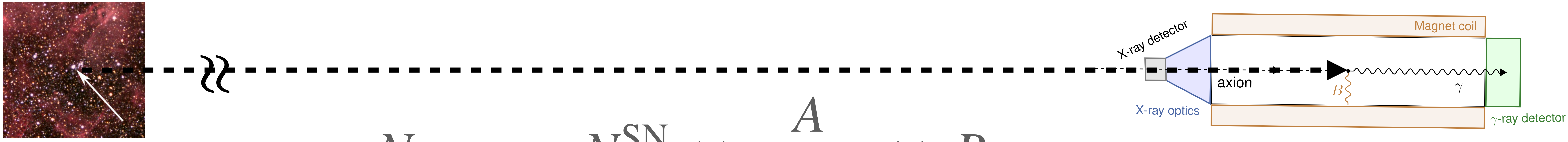
  - Event number
- **Summary**

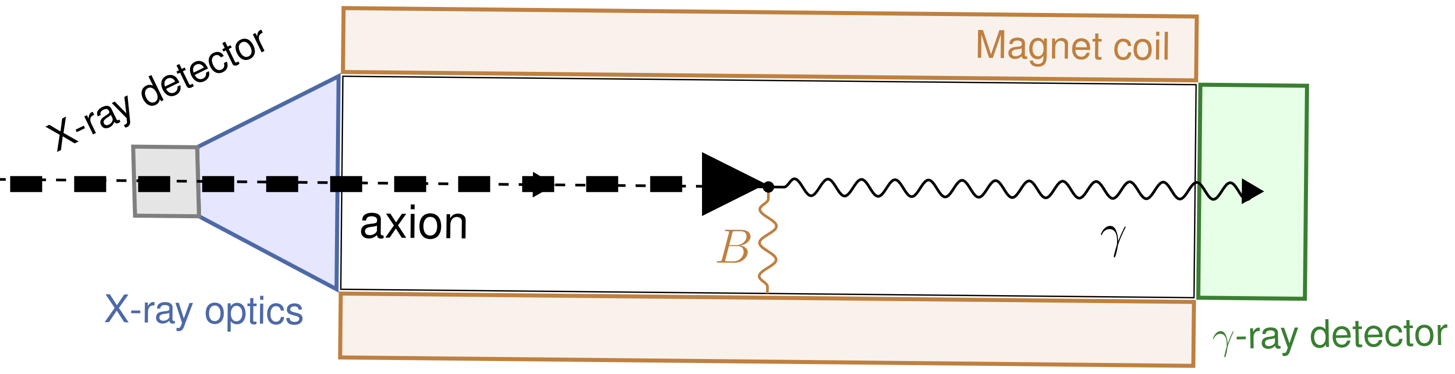


Event number



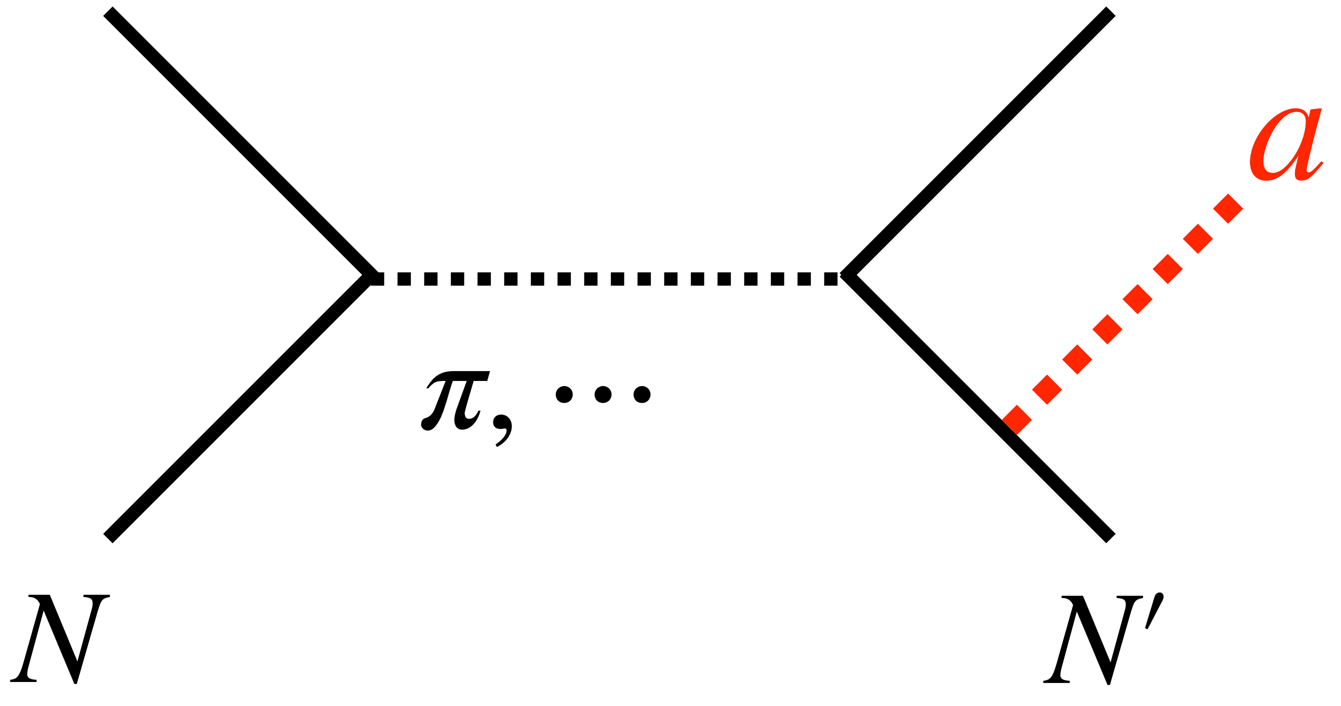
$$N_{\mathrm{event}} = N_a^{\mathrm{SN}} \times \frac{A}{4\pi d^2} \times P_{a\to\gamma}$$

Event number



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

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



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

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

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

Production

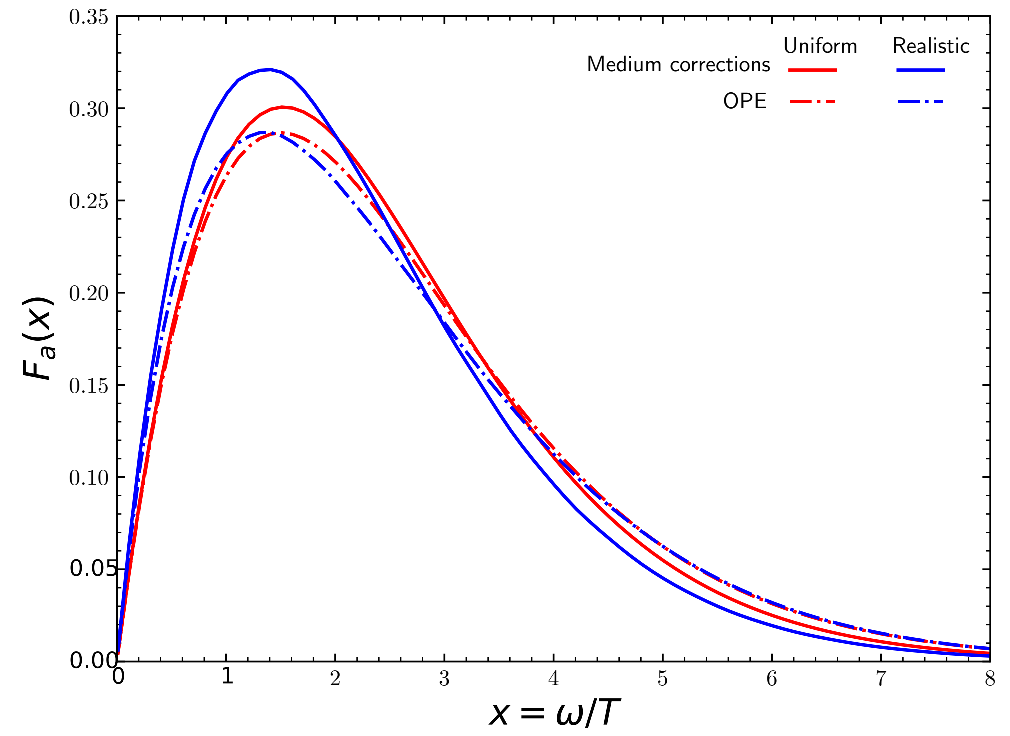
cf. more recent studies, P.Carenza+, 2010.02943, 2108.13726]

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

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

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 $\langle E_a \rangle \simeq 2.3T$.



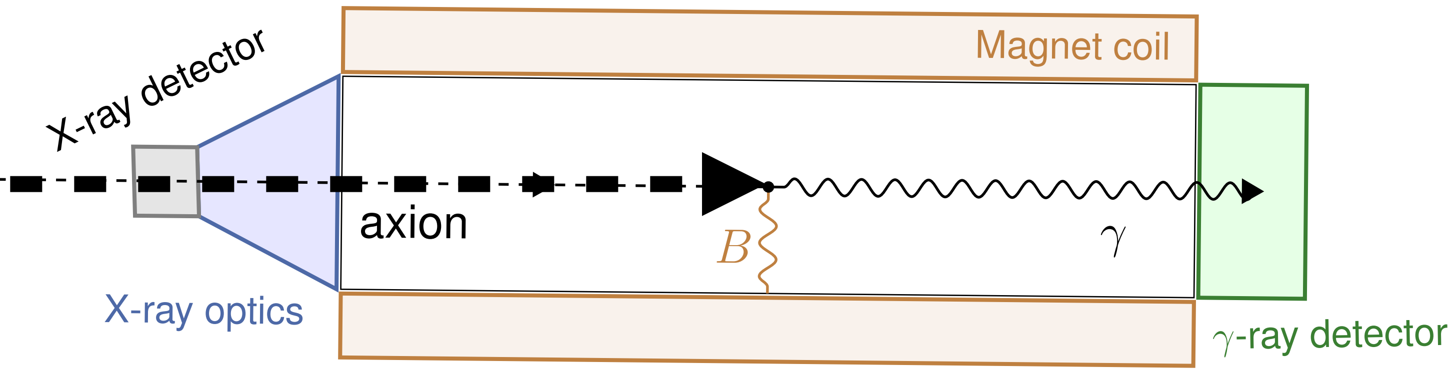
- Thus, the total number of axions from SN is

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

KSVZ

Event number

d



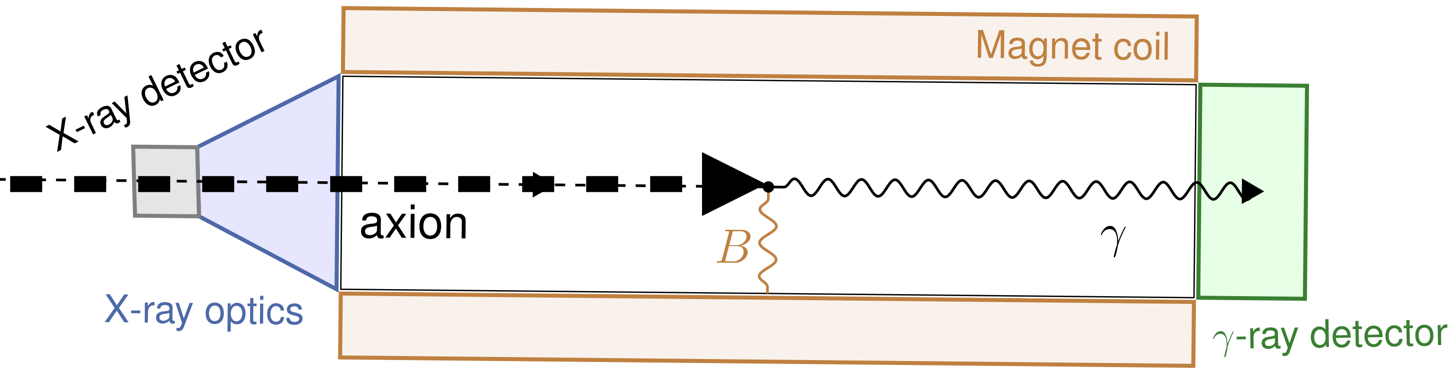
$$N_{\rm event} = N_a^{\rm SN} \times \frac{A}{4\pi d^2} \times P_{a\to\gamma}$$

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

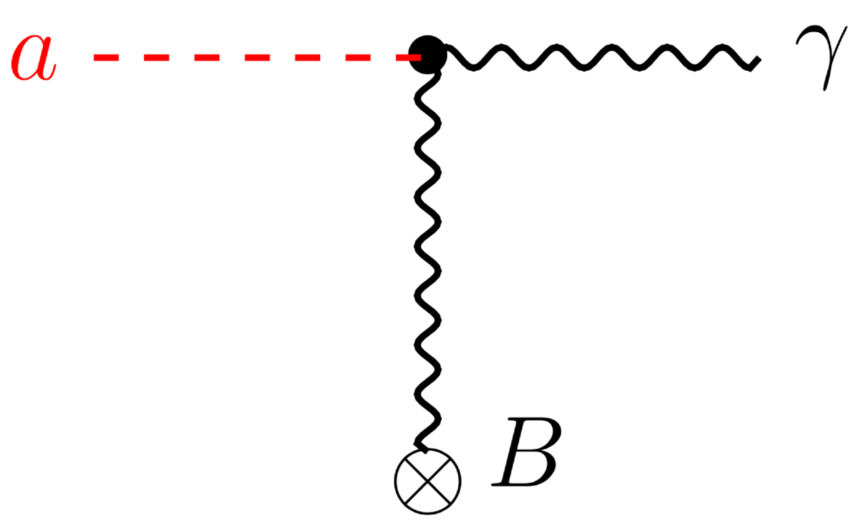
Experiment	(Proposed) site	B (T)	L (m)	A (m^2)
CAST [34–39]	CERN	9	9.3	2.9×10^{-3}
BabyIAXO [41]	DESY	~ 2	10	0.77
IAXO baseline [40, 41]	DESY	~ 2.5	20	2.3
IAXO+ [41]	DESY	~ 3.5	22	3.9
TASTE [42]	INR	3.5	12	0.28

Event number

d



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



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

Detection

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

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

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

Experiment	(Proposed) site	B (T)	L (m)	A (m^2)
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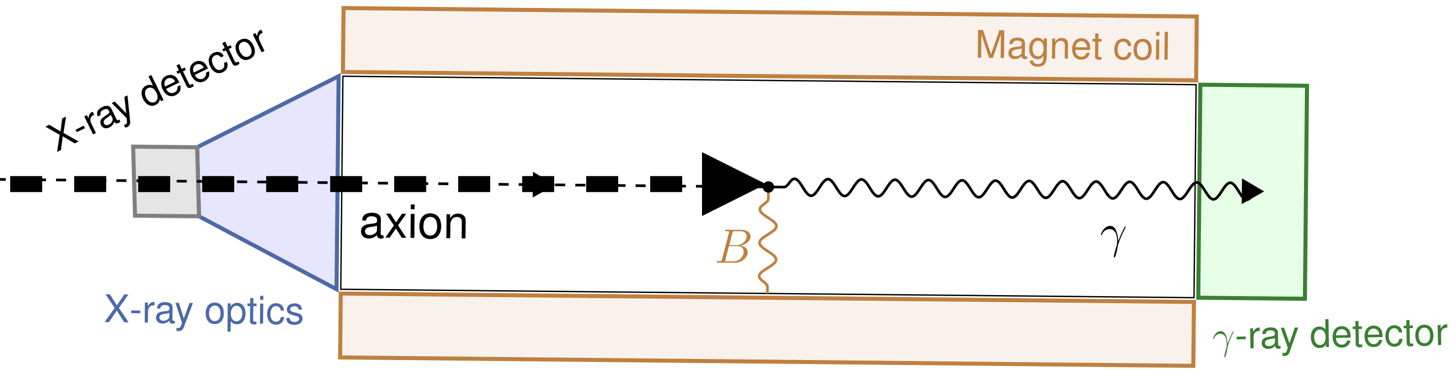
suppression factor

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,...

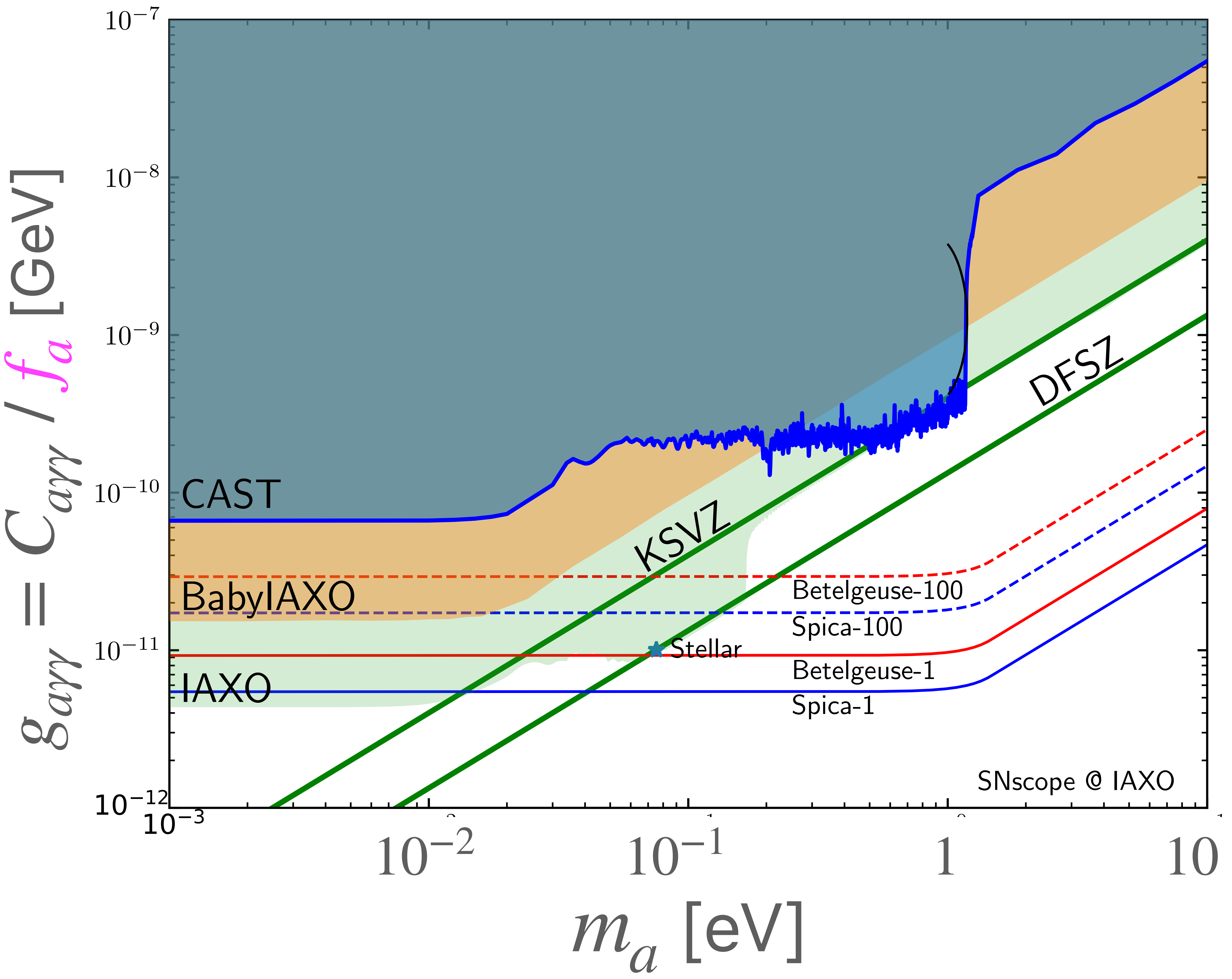
$$N_{\text{event}} \simeq 1.0 \times \underbrace{\left(\frac{3\times 10^8\ \text{GeV}}{f_a}\right)^4 \left(\frac{C_{N,\text{eff}}}{0.37}\right)^2 \left(\frac{C_{a\gamma\gamma}}{\alpha/\pi}\right)^2}_{\text{axion model}} \times \underbrace{\left(\frac{150\ \text{pc}}{d}\right)^2 \left(\frac{\Delta t}{10\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

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

※ 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.



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

for Betelgeuse ($d \simeq 220$ pc)

and Spica ($d \simeq 77$ pc)

- Axion coupling: KSVZ model ($C_{N,\rm eff} = 0.37$ 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 ($E_a^{\rm SN} \sim 70$ MeV $\gg$ $E_a^{\rm sun} \sim$ a few keV).
- For small mass region, both solar axion and SN-axion may be discovered.

Event number

vs. stellar constraints

S.Ge, K.Hamaguchi, K.Ichimura, K.Ishidoshiro,
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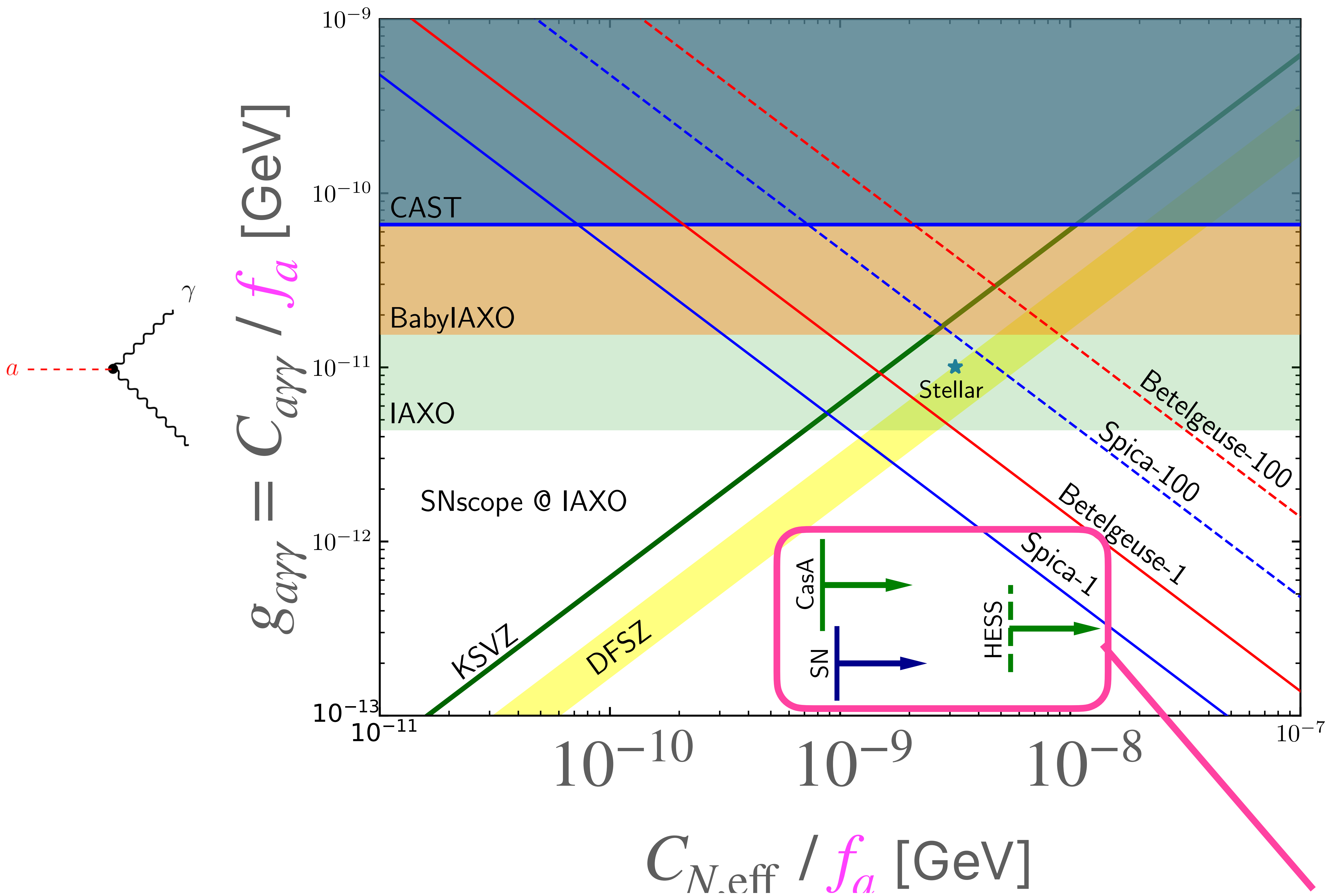
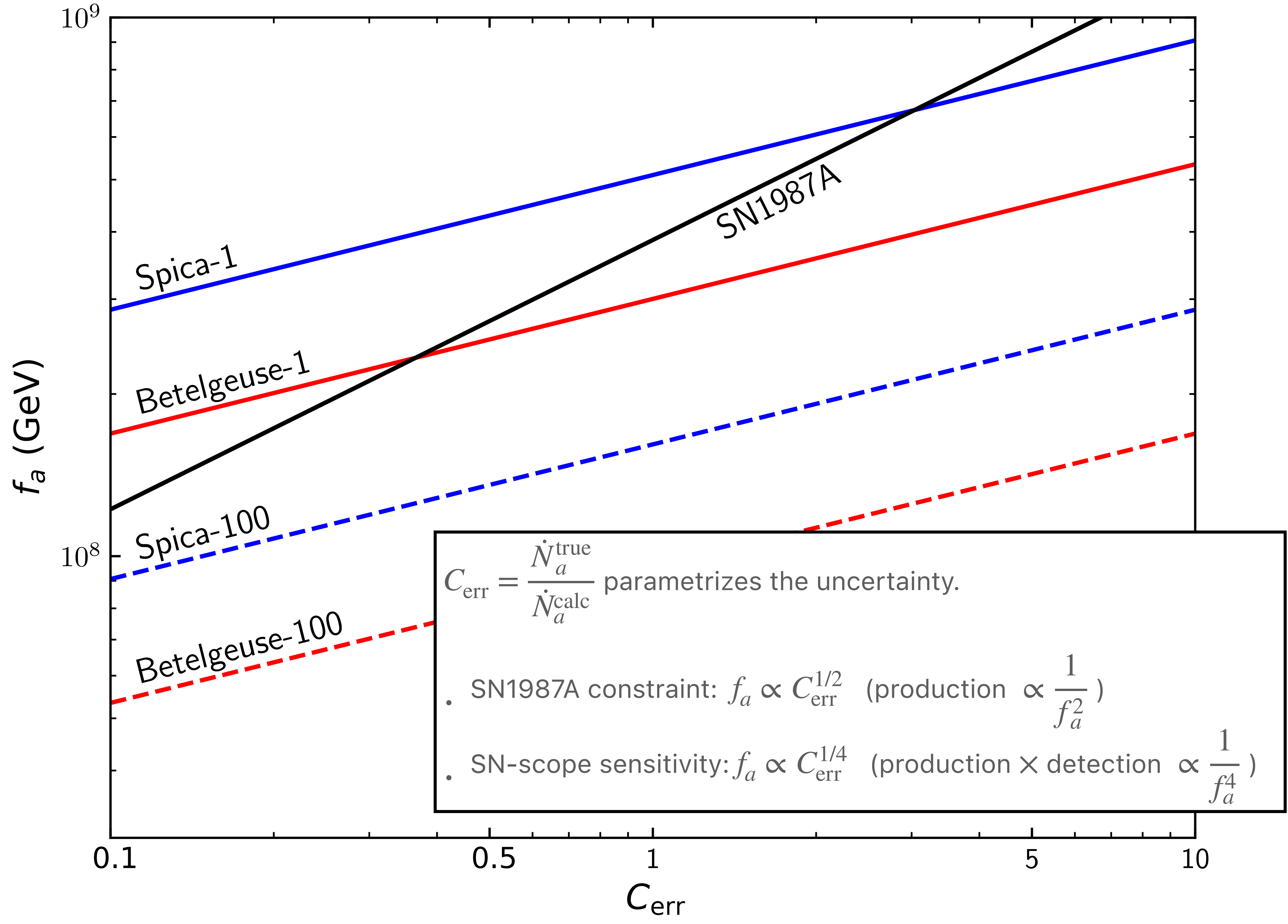
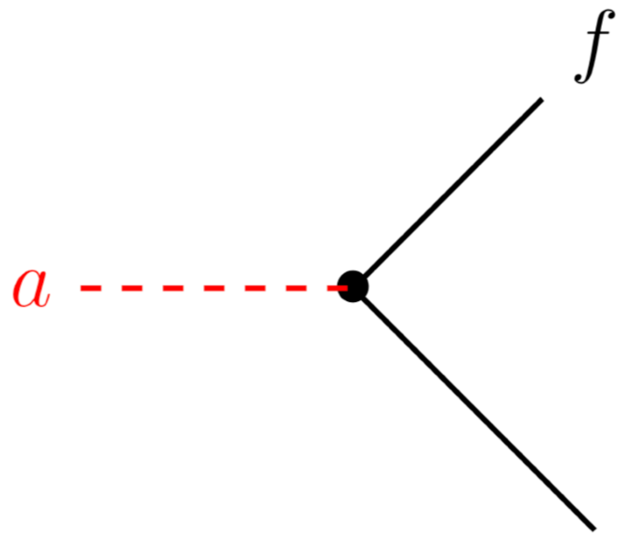




- $m_a = 10^{-3}$ eV (fixed)



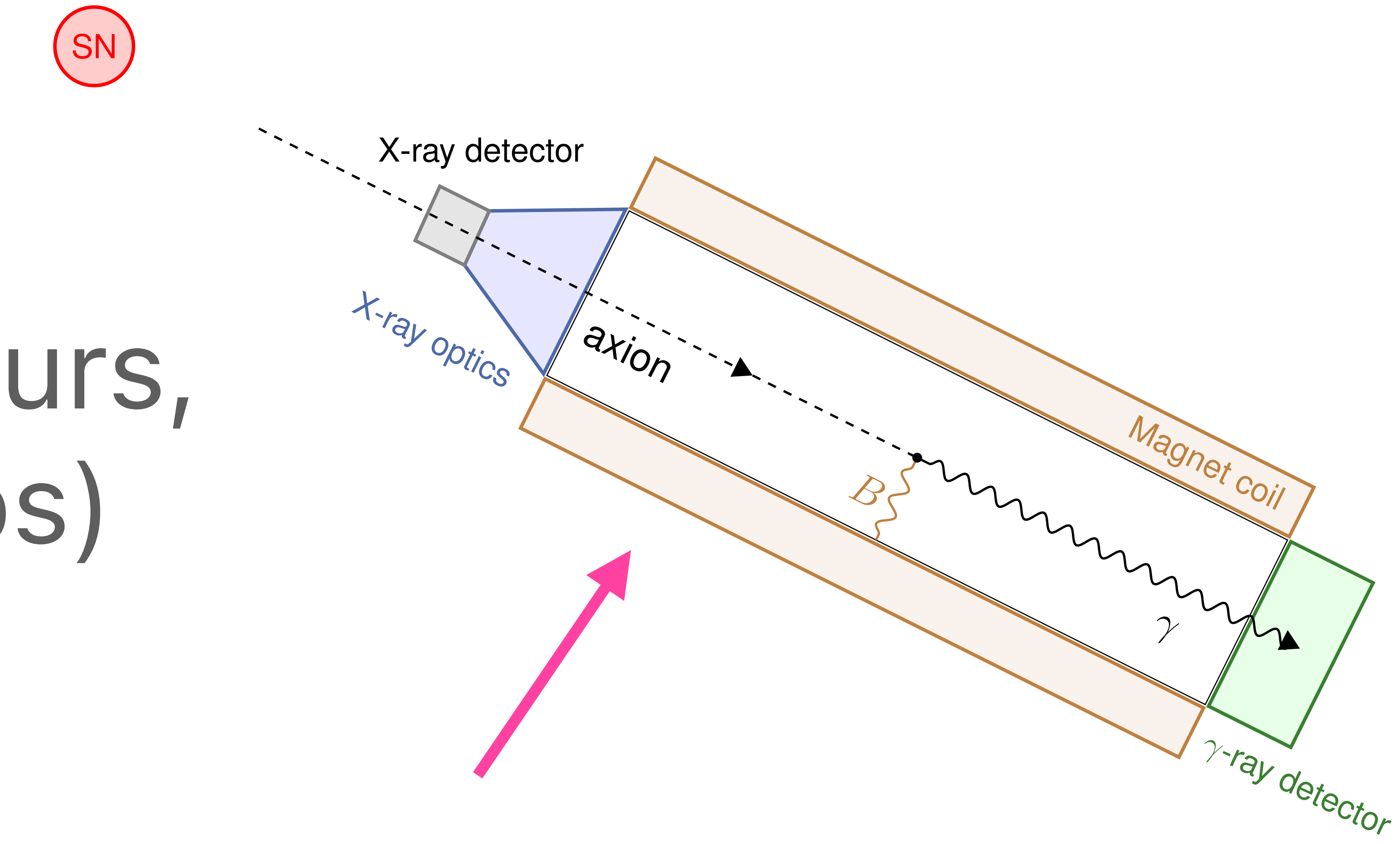
stellar constraints

For $C_{\rm err} \simeq 0.1 - 0.3$,

- $\mathcal{O}(1)$ events for Betelgeuse,
- $\mathcal{O}(10)$ events for Spica.

Summary

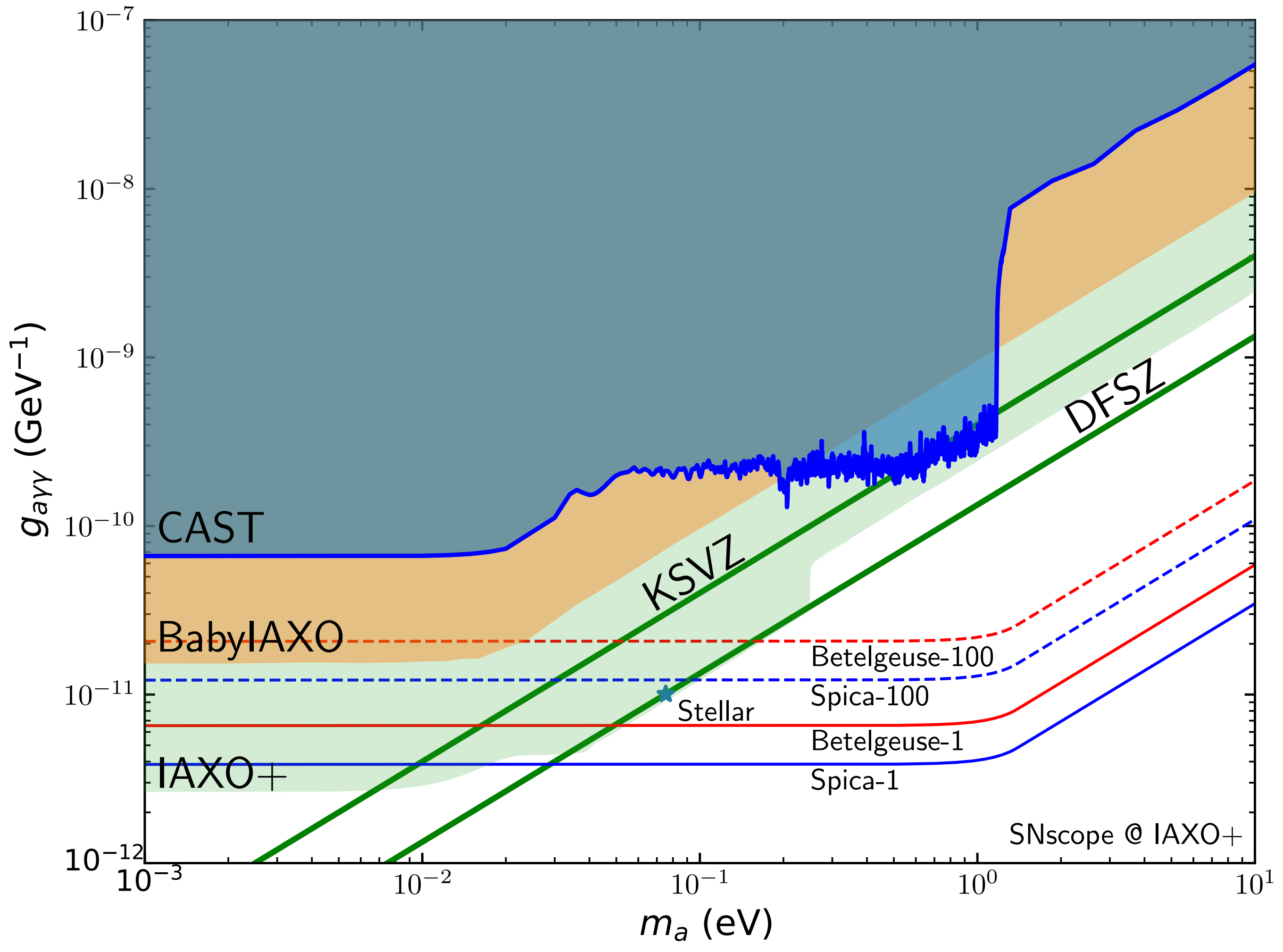
- If a nearby (< a few 100 pc) supernova (SN) occurs, a huge number of axions (in addition to neutrinos) may arrive at the Earth.



- 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.



[arXiv:2008.03924] JCAP **11** (2020) 059.

S.Ge, K.Hamaguchi, K.Ichimura, K.Ishidoshiro, Y.Kanazawa, Y.Kishimoto, N.Nagata, J.Zheng.

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