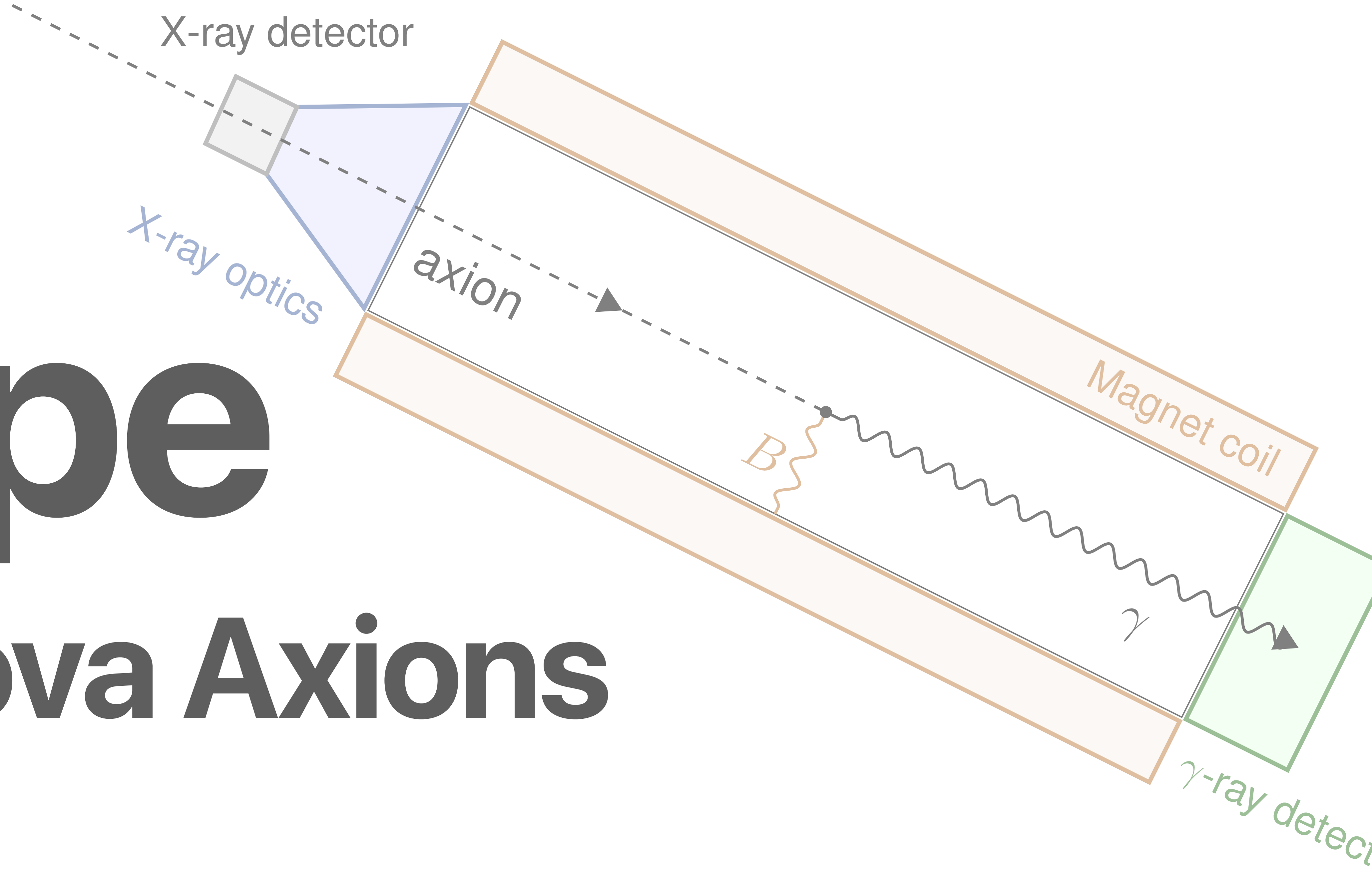


Supernova-scope

for the Direct Search of Supernova Axions

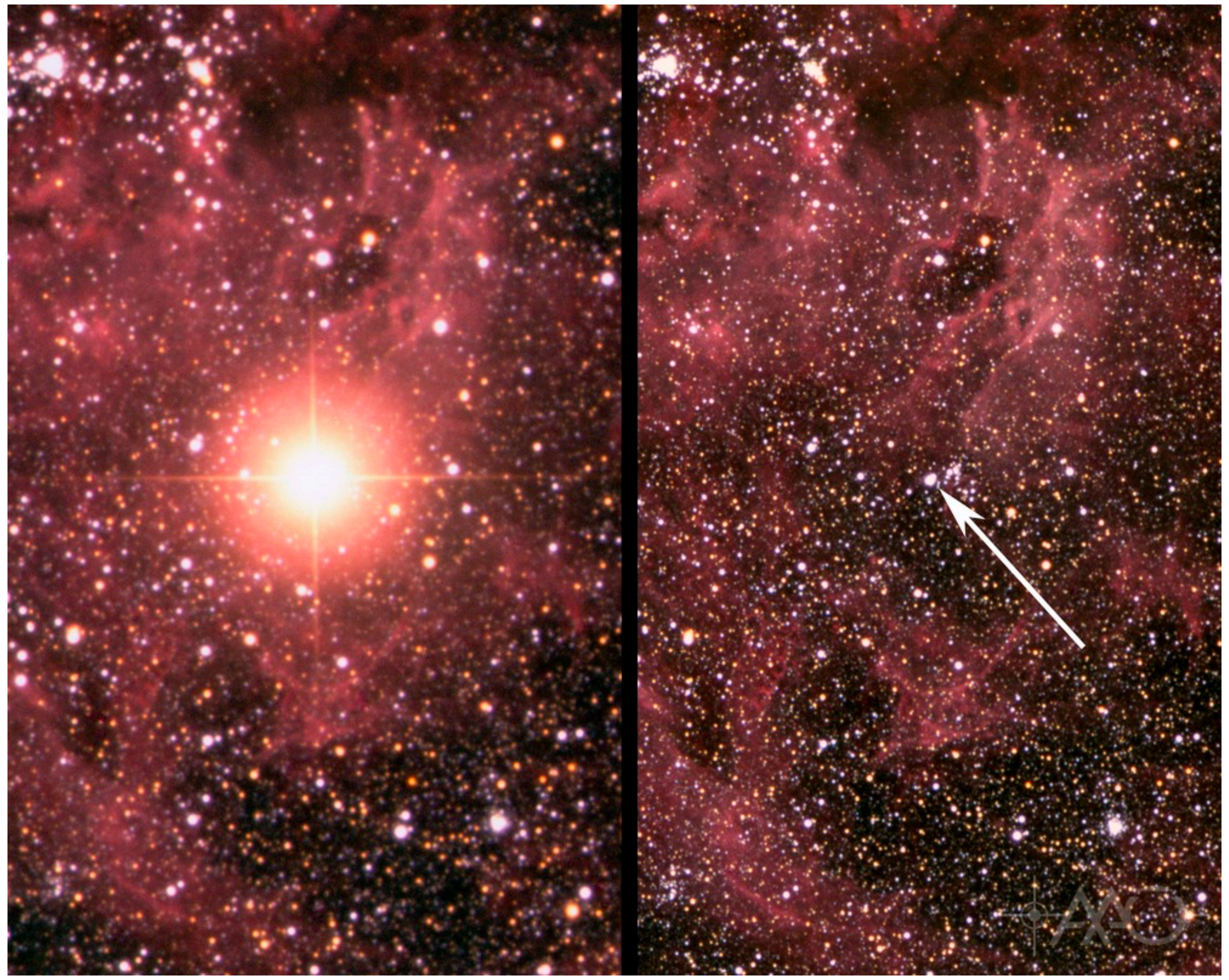
Koichi Hamaguchi (Tokyo U.)

@ 2022_Chung-Ang University BSM Workshop (online), February 7, 2021.

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

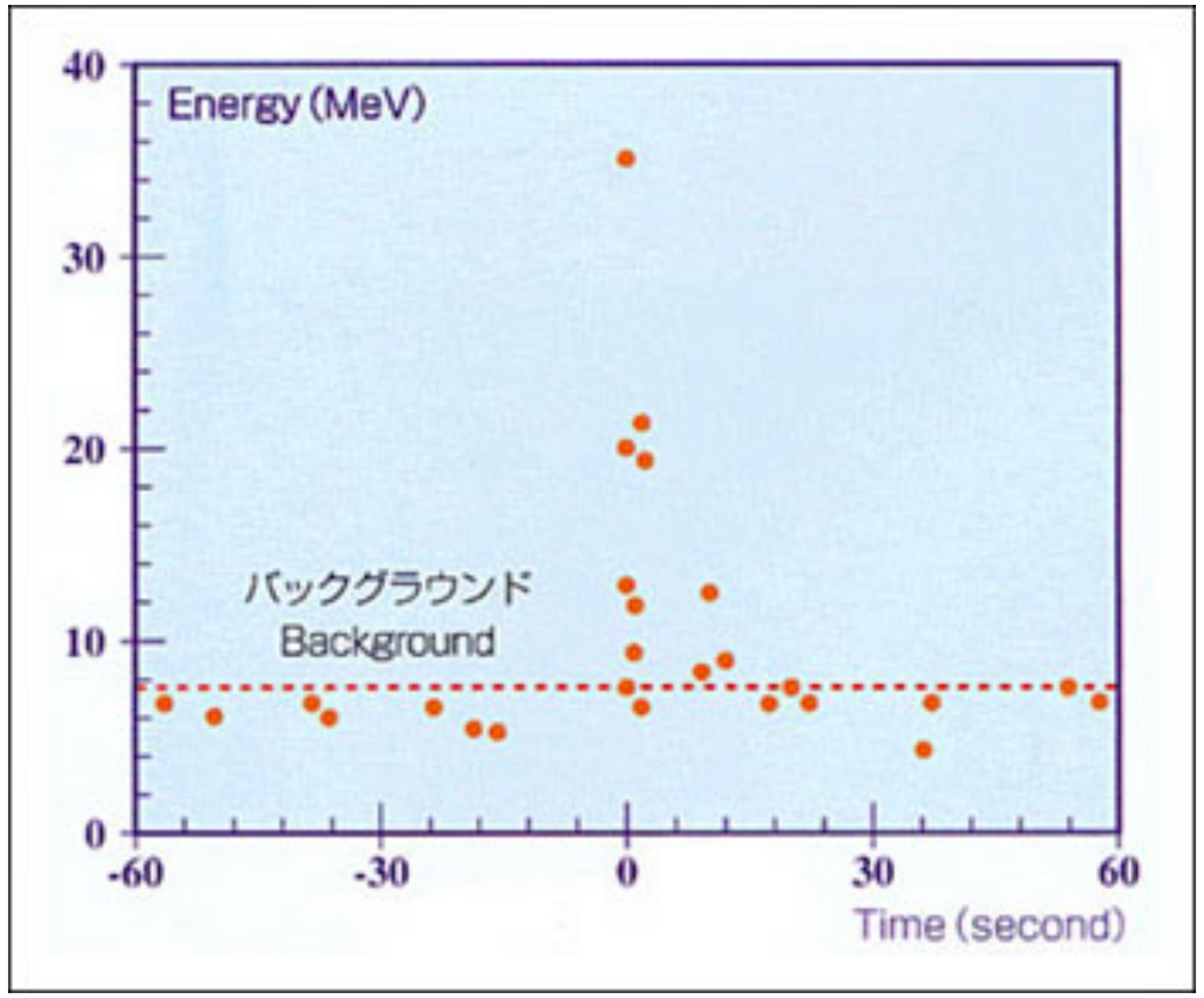
Shao-Feng Ge (TDLI), Koichi Hamaguchi (Tokyo), Koichi Ichimura (Tohoku),
Koji Ishidoshiro (Tohoku), Yoshiki Kanazawa (Tokyo), Yasuhiro Kishimoto (Tohoku),
Natsumi Nagata (Tokyo), Jiaming Zheng (TDLI).

Supernova 1987A (February 23, 1987)



before explosion

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



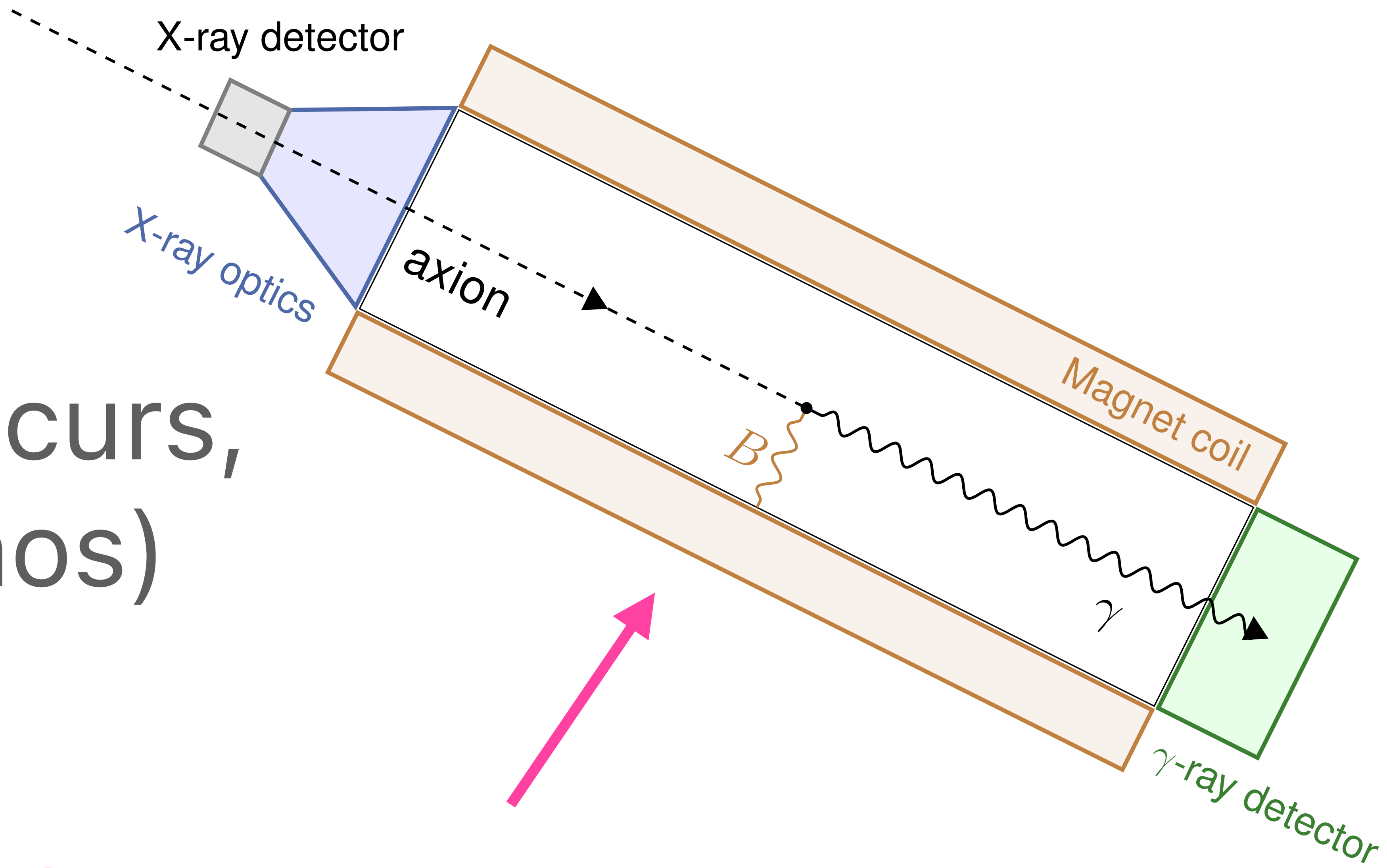
http://www-sk.icrr.u-tokyo.ac.jp/sk/physics/supernova-e.html

What if the next nearby SN occurs?

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

SN

Toady's Main message

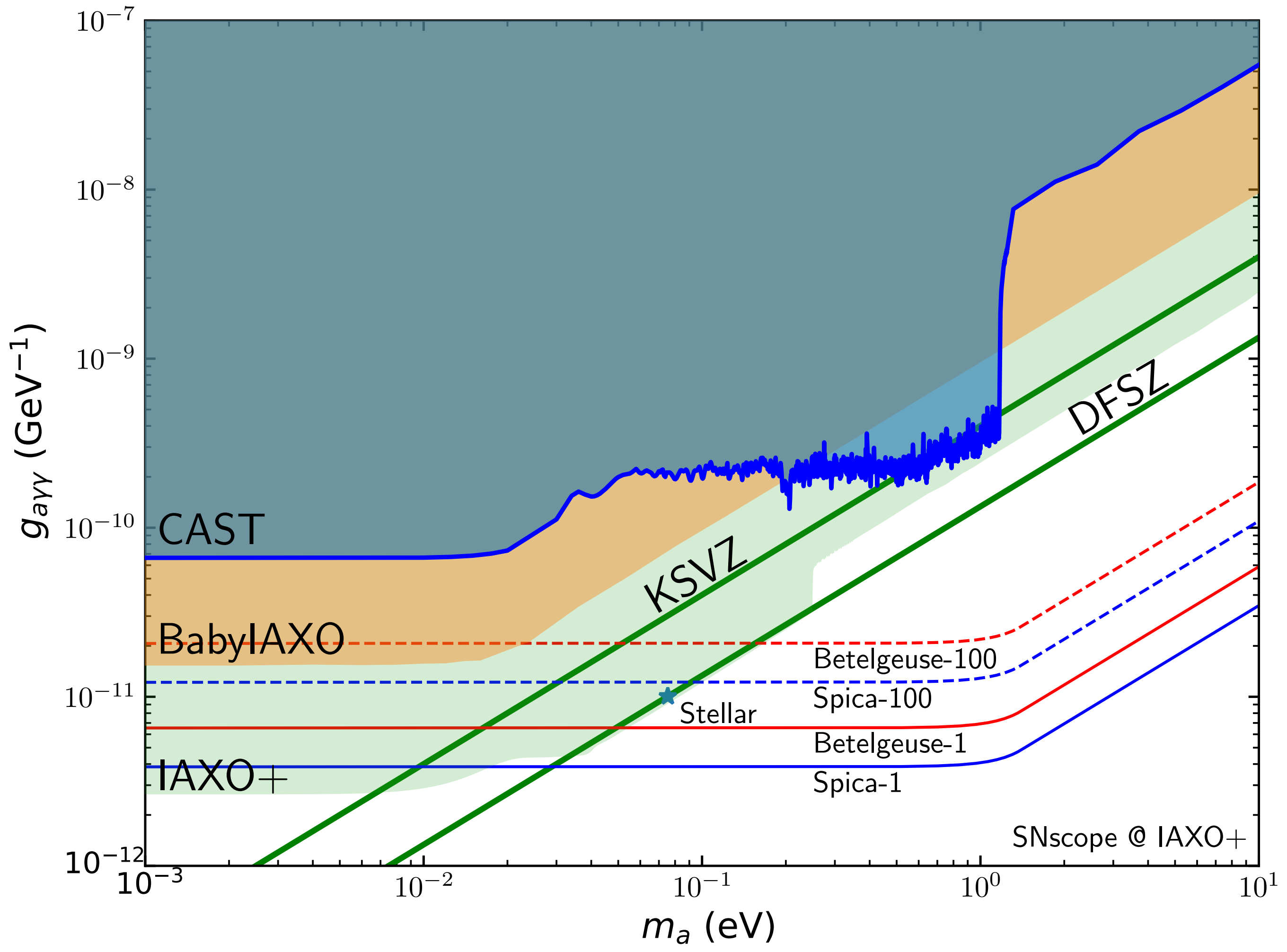


- If a nearby (< a few 100 pc) supernova (SN) occurs, a huge number of axions (in addition to neutrinos) may arrive at the Earth.

- 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).

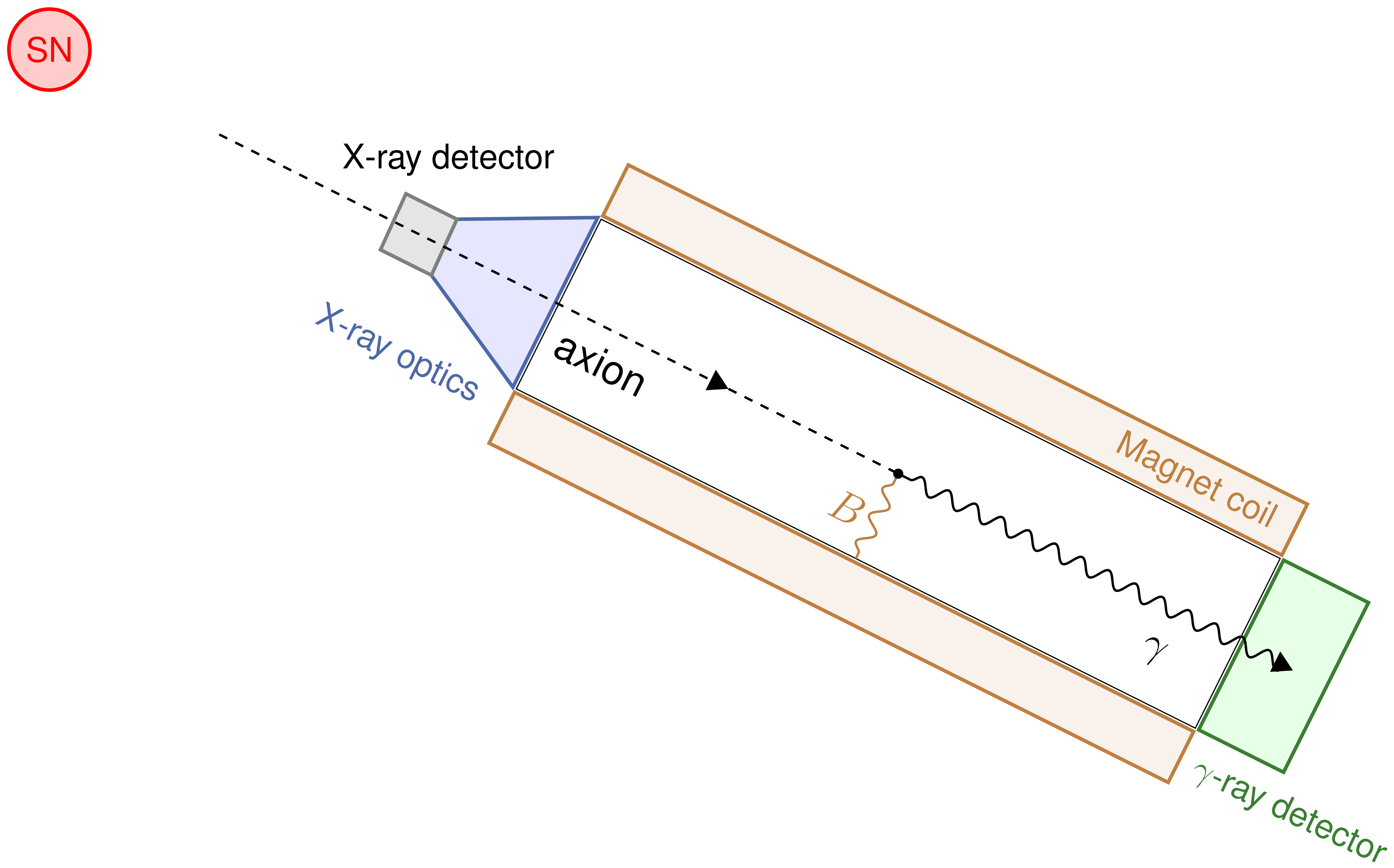
- SN-scopes based on the next-generation axion helioscopes (such as IAXO) have potential to detect O(1-100) SN axions.



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

Plan

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



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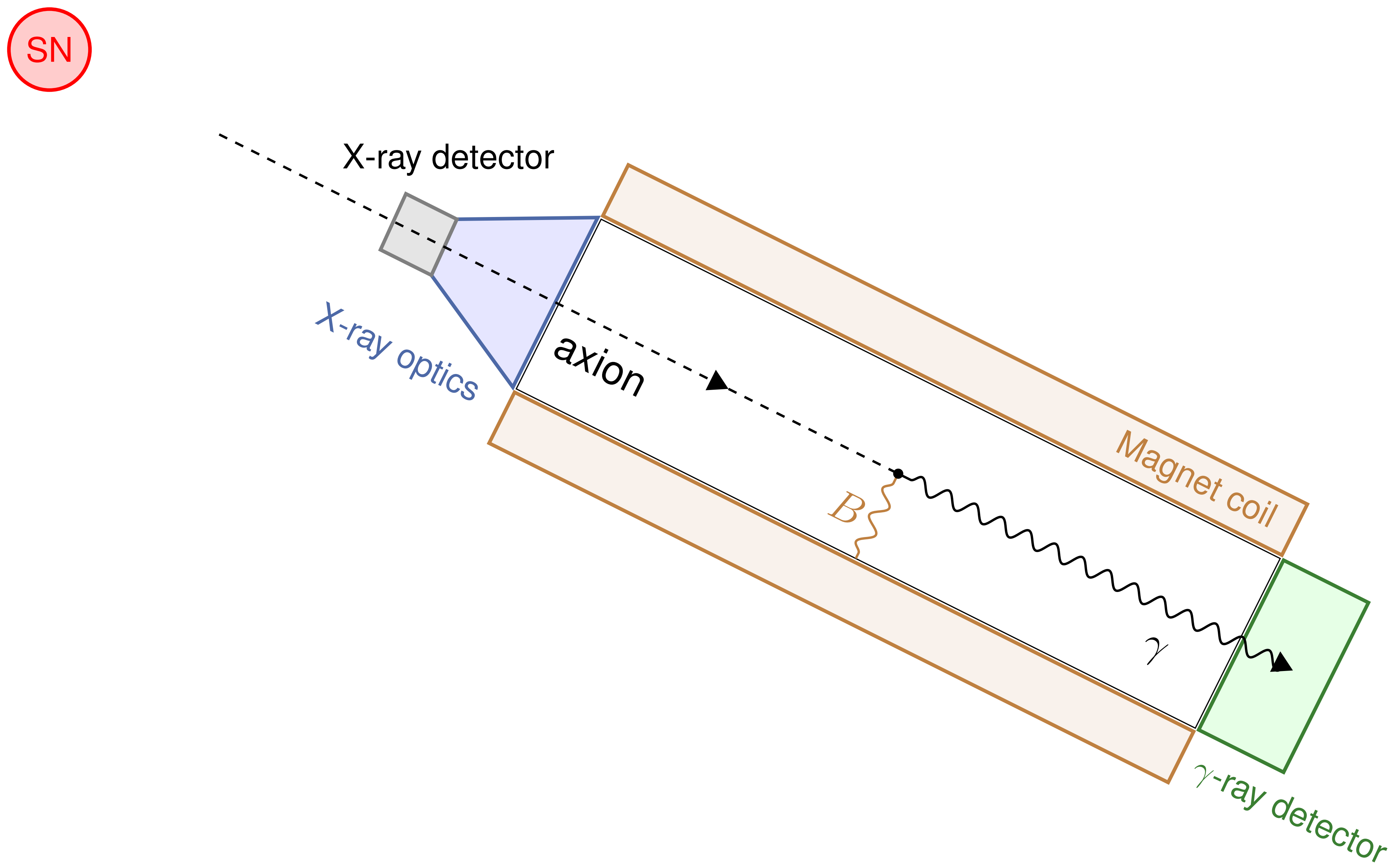


Motivation: mini-review of axion

- **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 SM.
It cannot be explained even by the anthropic discussion.

Motivation: mini-review of axion

- **Strong CP problem**

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

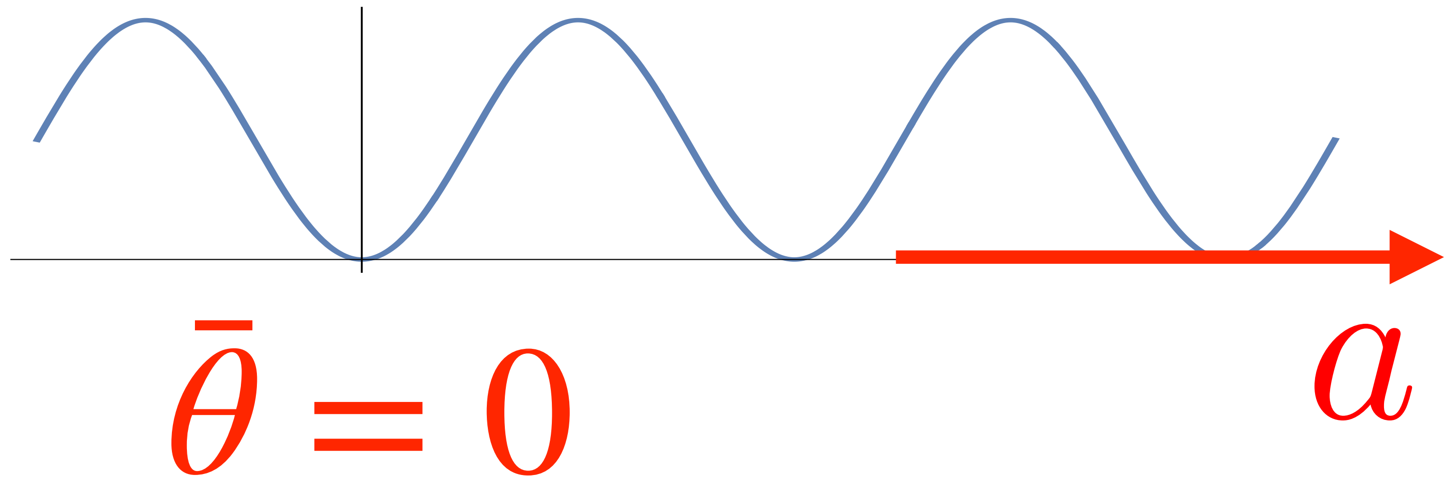
Why?

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

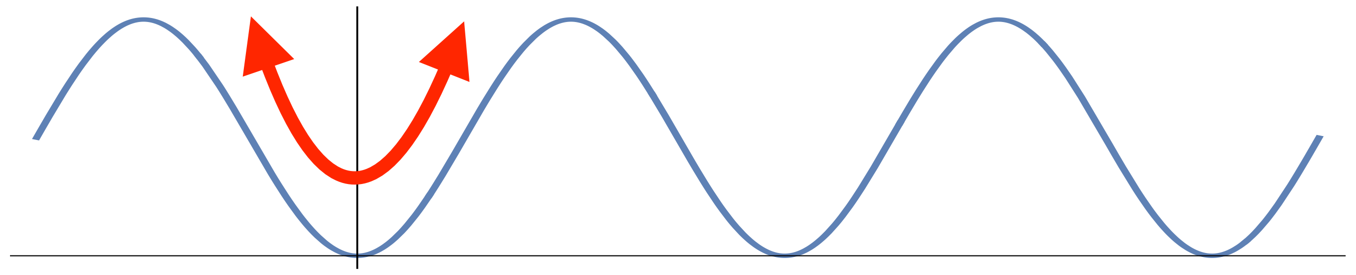
- It can be solved by the "Peccei-Quinn mechanism", [Peccei, Quinn,'77] predicting a very light particle, Axion. [Weinberg,'78, Wilczek,'78]

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

axion potential



- Moreover, Axion can be the Dark Matter.



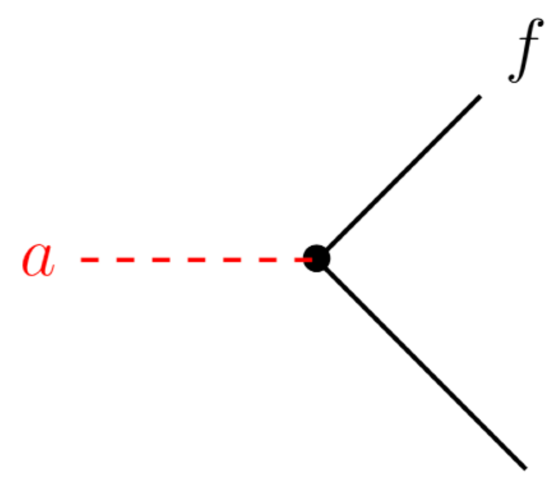
$$\Omega_a h^2 = 0.18\, \theta_i^2 \left(\frac{f_a}{10^{12}\,{\rm GeV}}\right)^{1.19}.$$

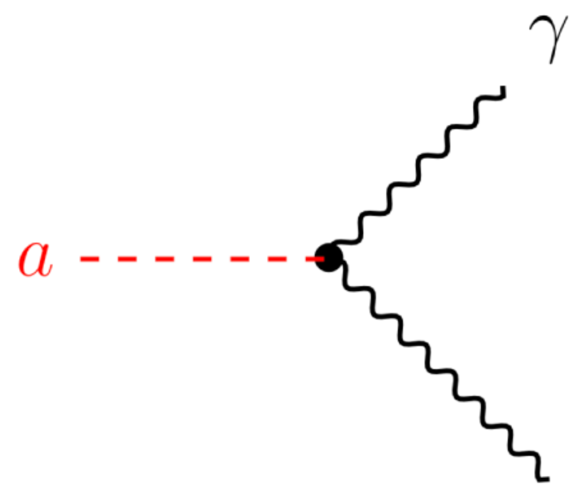
[Turner,'86]

Motivation: mini-review of axion

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

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





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

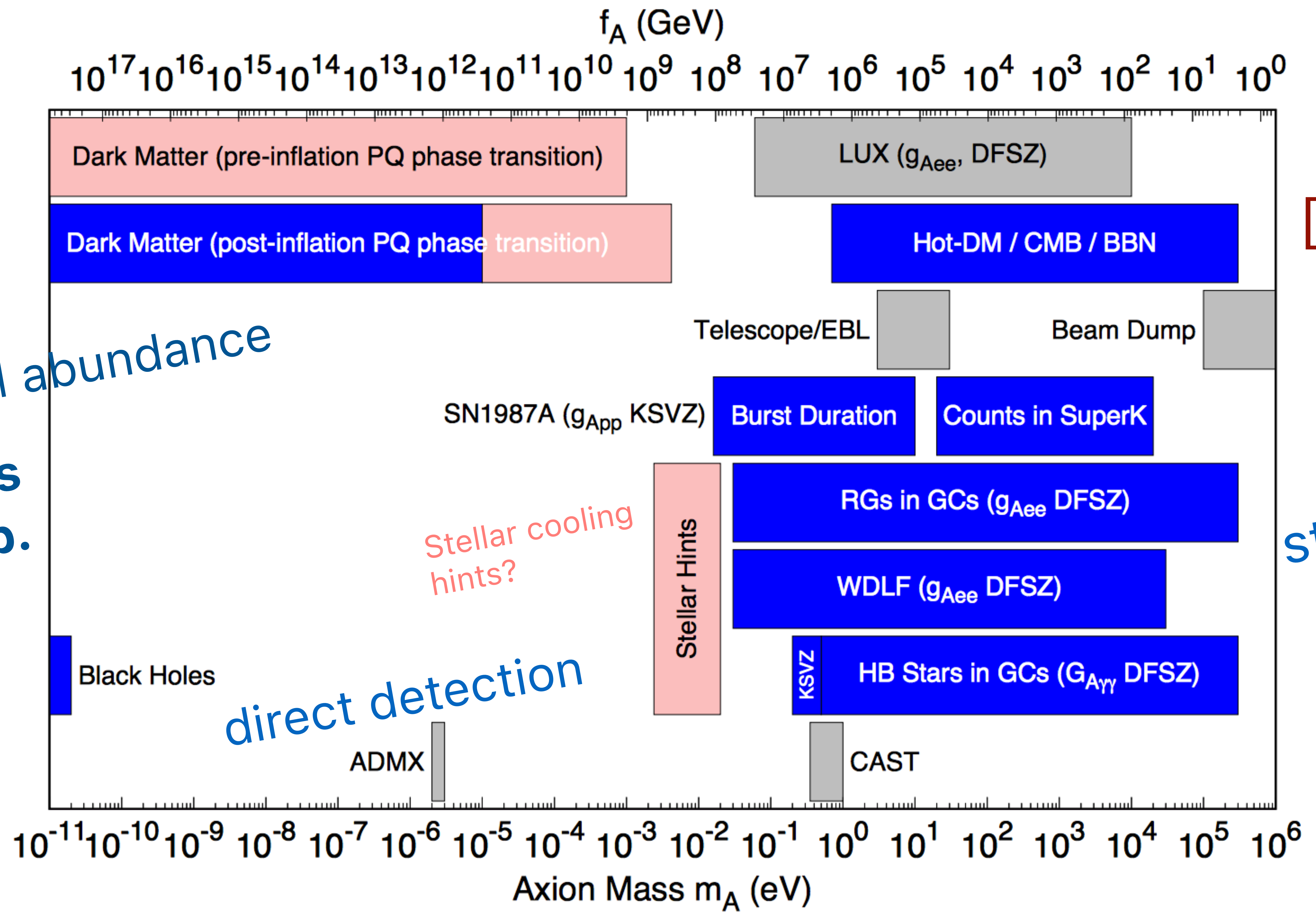
- Axion's mass is also determined by f_a .

$$m_a = \frac{\sqrt{m_u m_d}}{m_u + m_d}\frac{f_\pi m_\pi}{f_a} \simeq 5.8 \times \left(\frac{10^9\ \text{GeV}}{f_a}\right) \text{meV}\,.$$

- Roughly speaking, all parameters are determined by f_a up to O(1) model dependent parameters.

Motivation: mini-review of axion

Constraints



[Particle Data Group 2018]

Cosmology + DM abundance

👉 **several related talks in this workshop.**

Stellar cooling hints?

direct detection

stellar Coolings

Motivation: mini-review of axion

Constraints

- SN1987A: $f_a \gtrsim 4 \times 10^8\ \mathrm{GeV}$ (KSVZ) [P.Carenza et.al., 2019 + others]
- Neutron Star Cooling $f_a \gtrsim 5 \times 10^8\ \mathrm{GeV}$ (KSVZ)
  [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: $f_a \sim 8 \times 10^7\ \mathrm{GeV},\ \tan\beta \sim 0.28$ (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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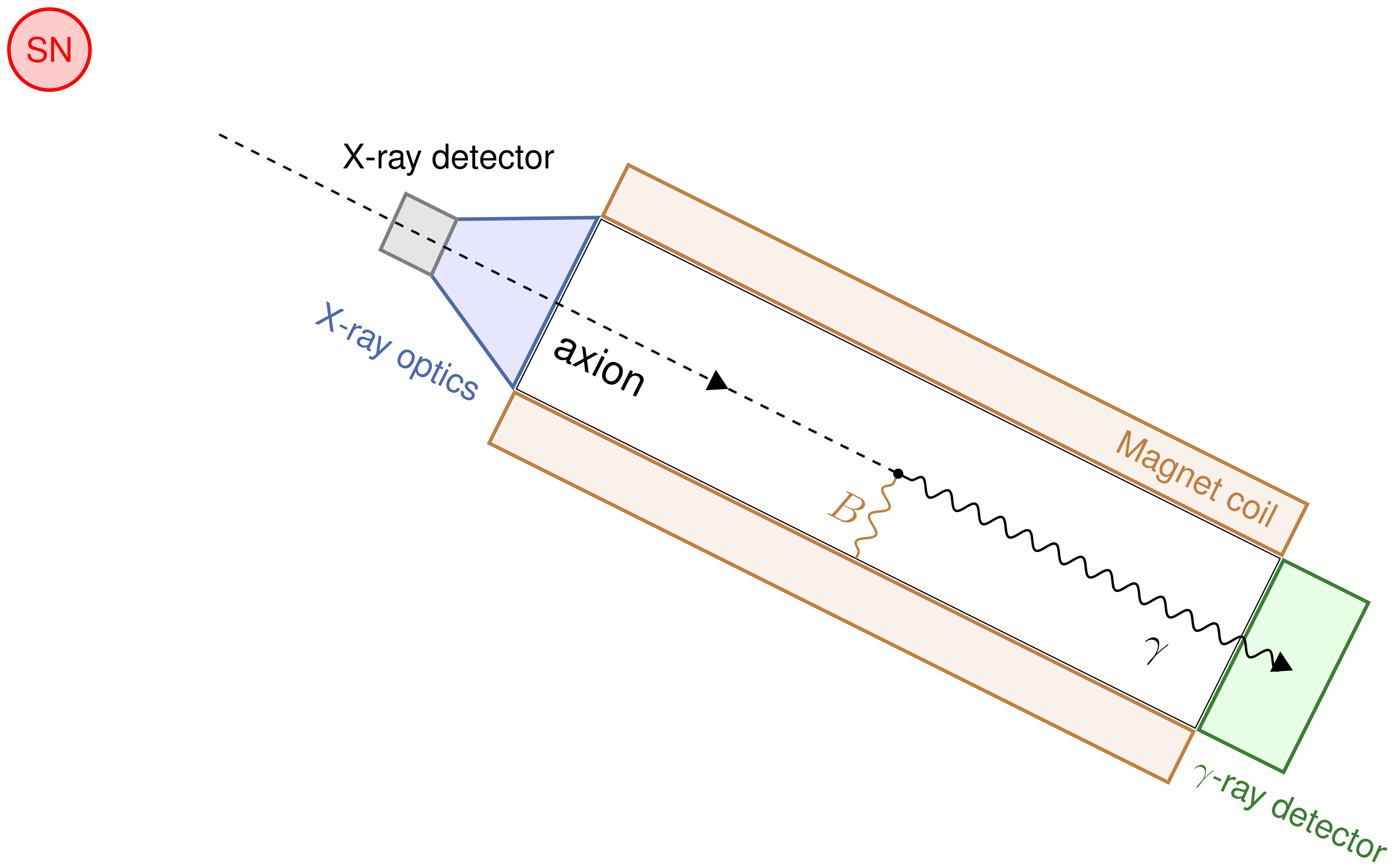
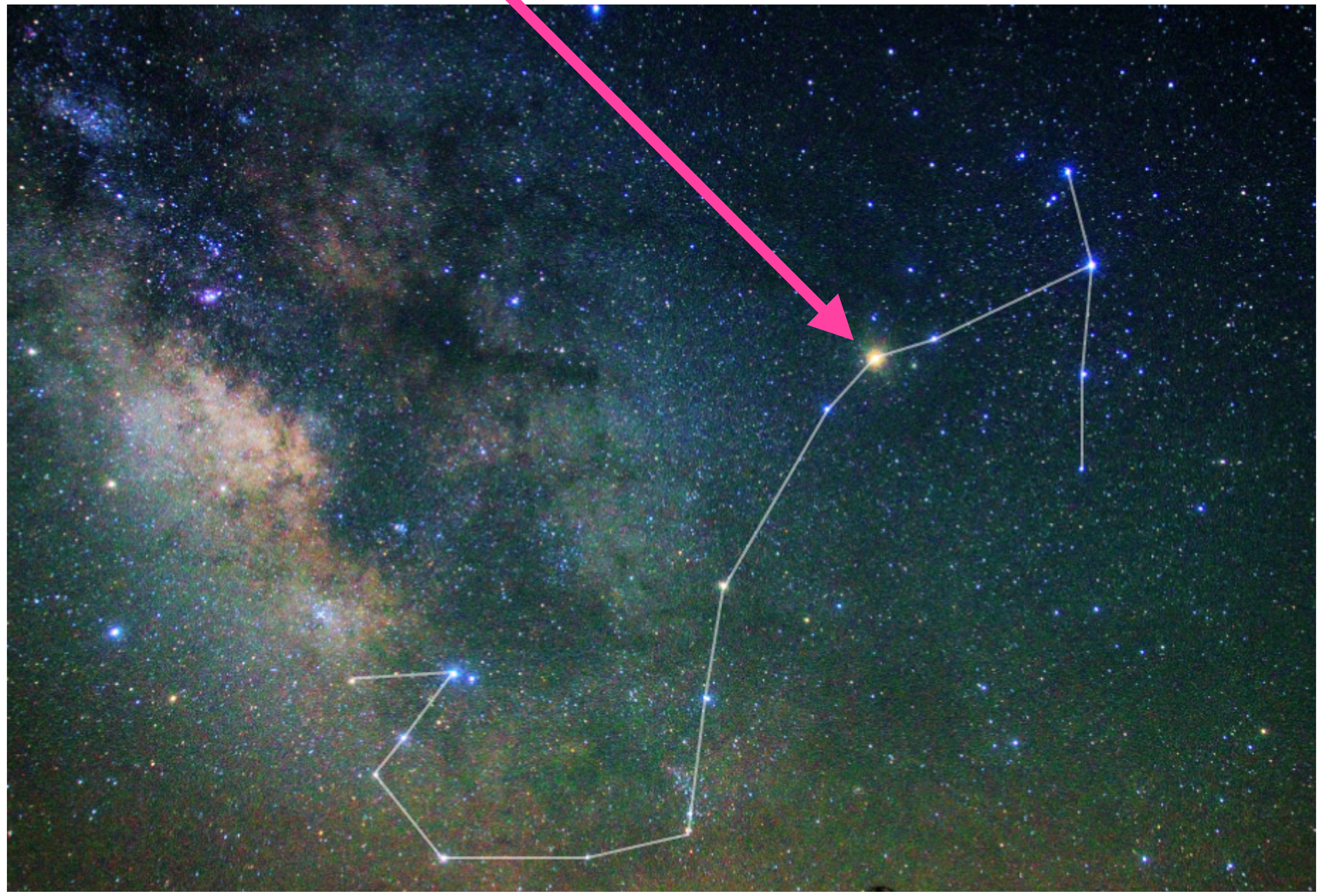


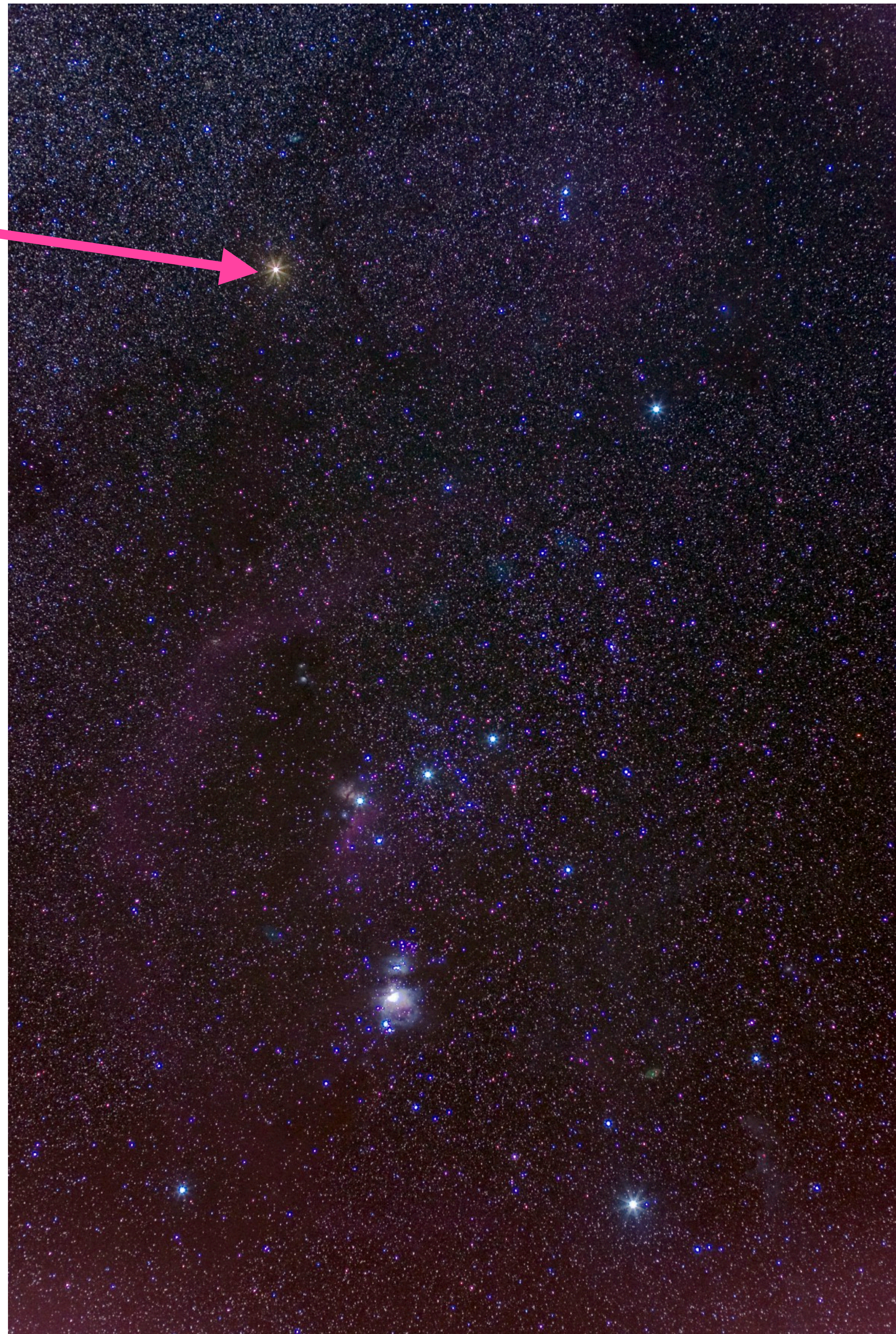
Nearby SN progenitor candidates

Antares
(~ 170 pc)



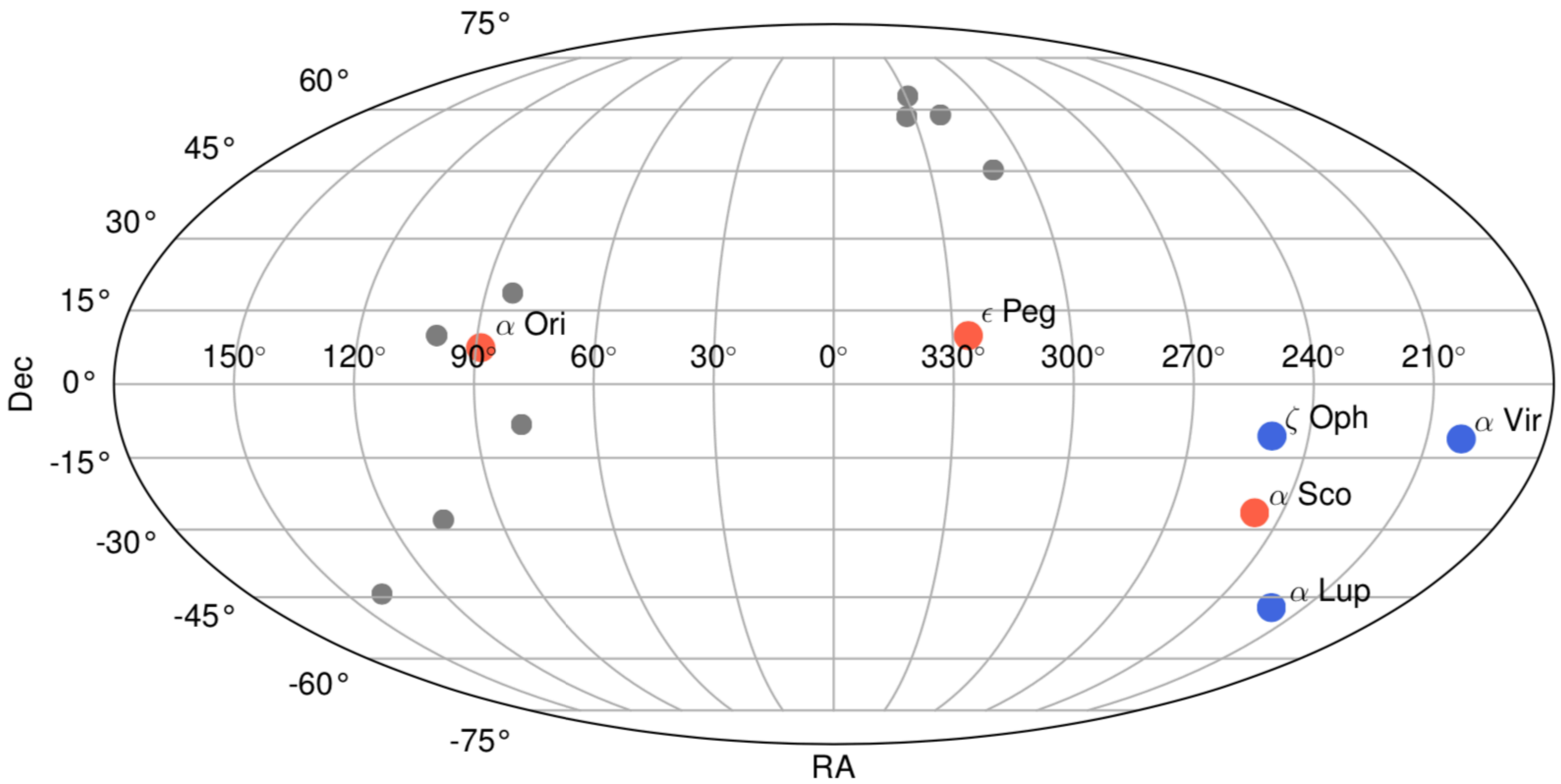
https://www.civillink.net/esozai/

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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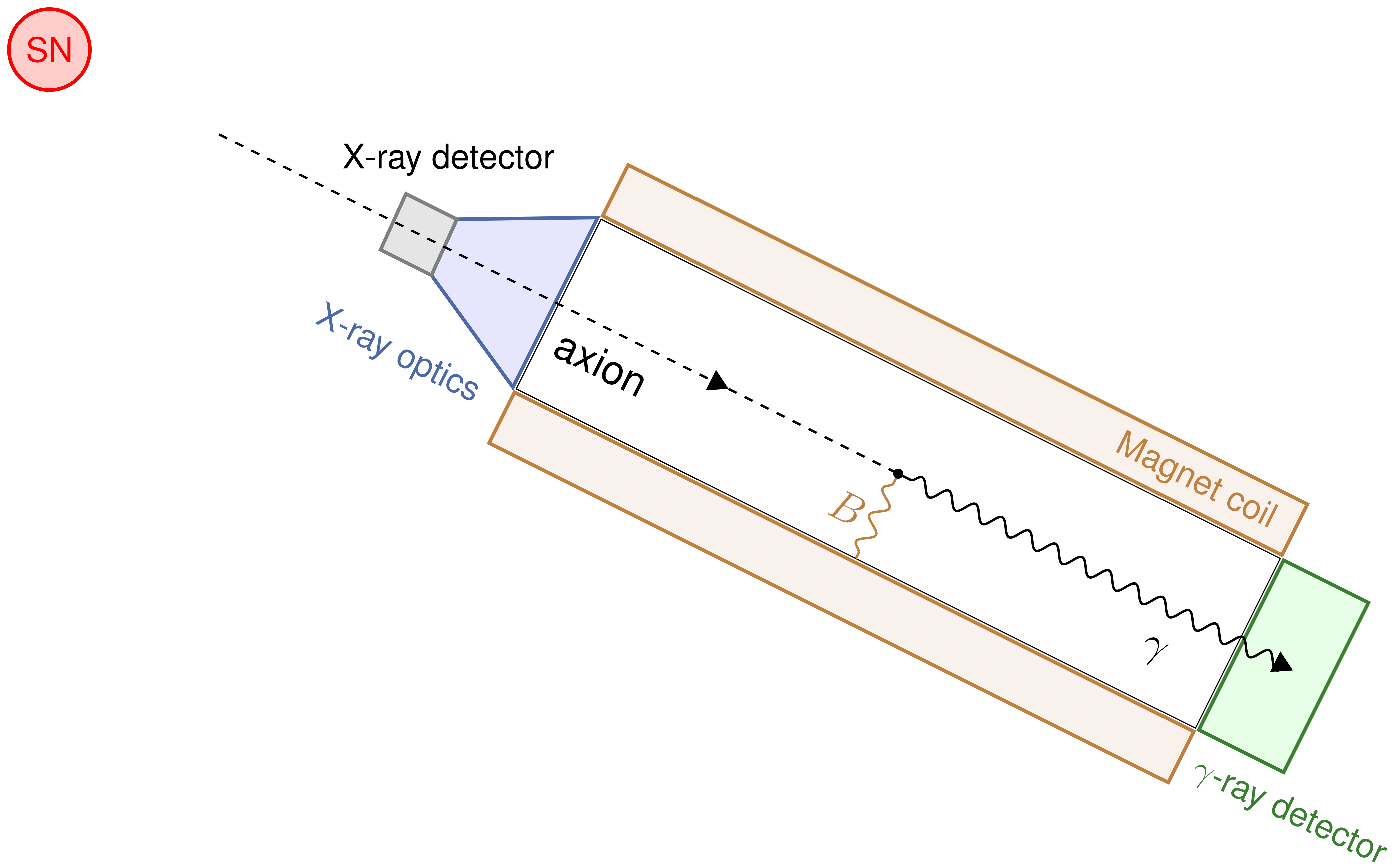
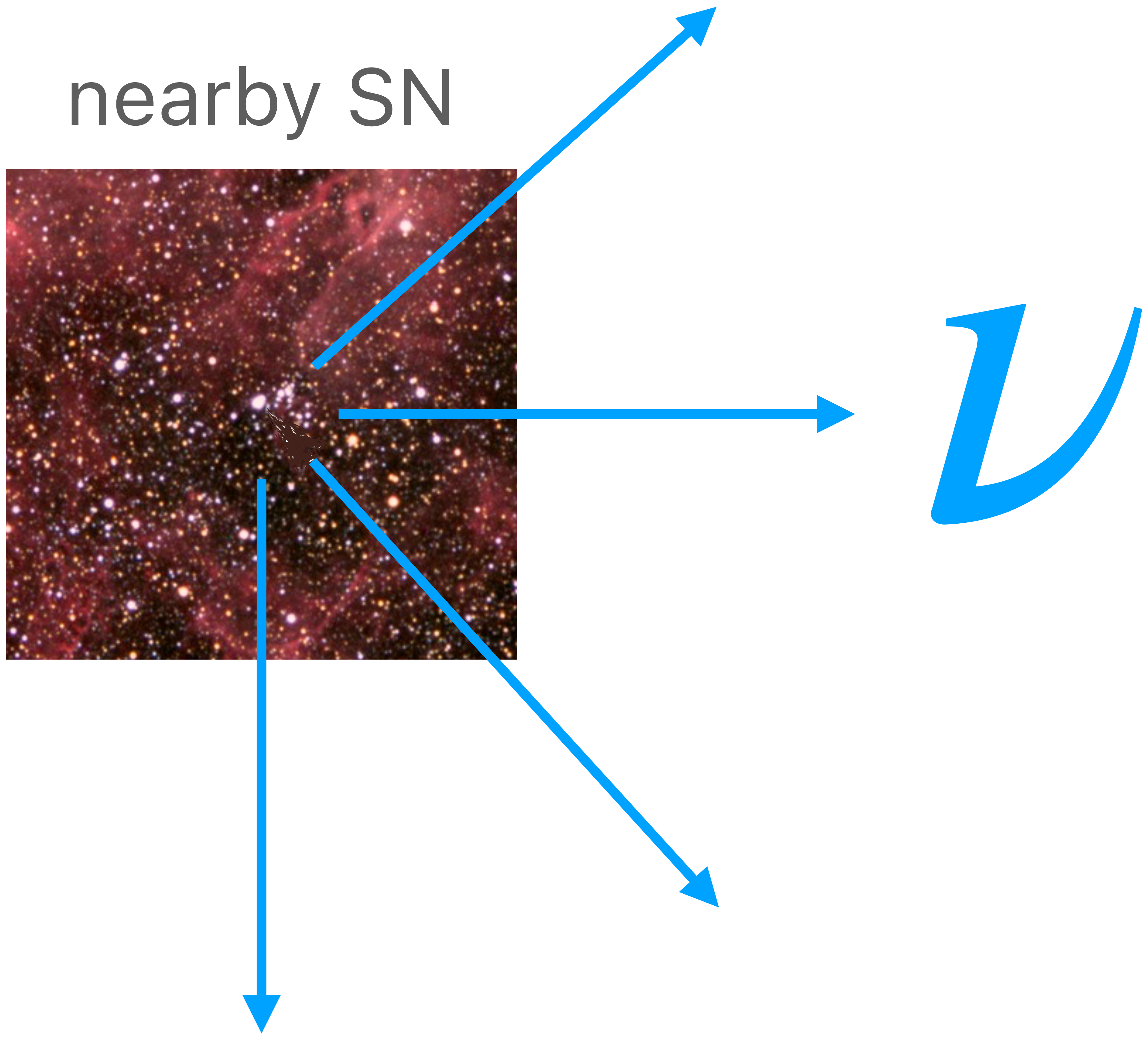


- **Summary**

Supernova-scope

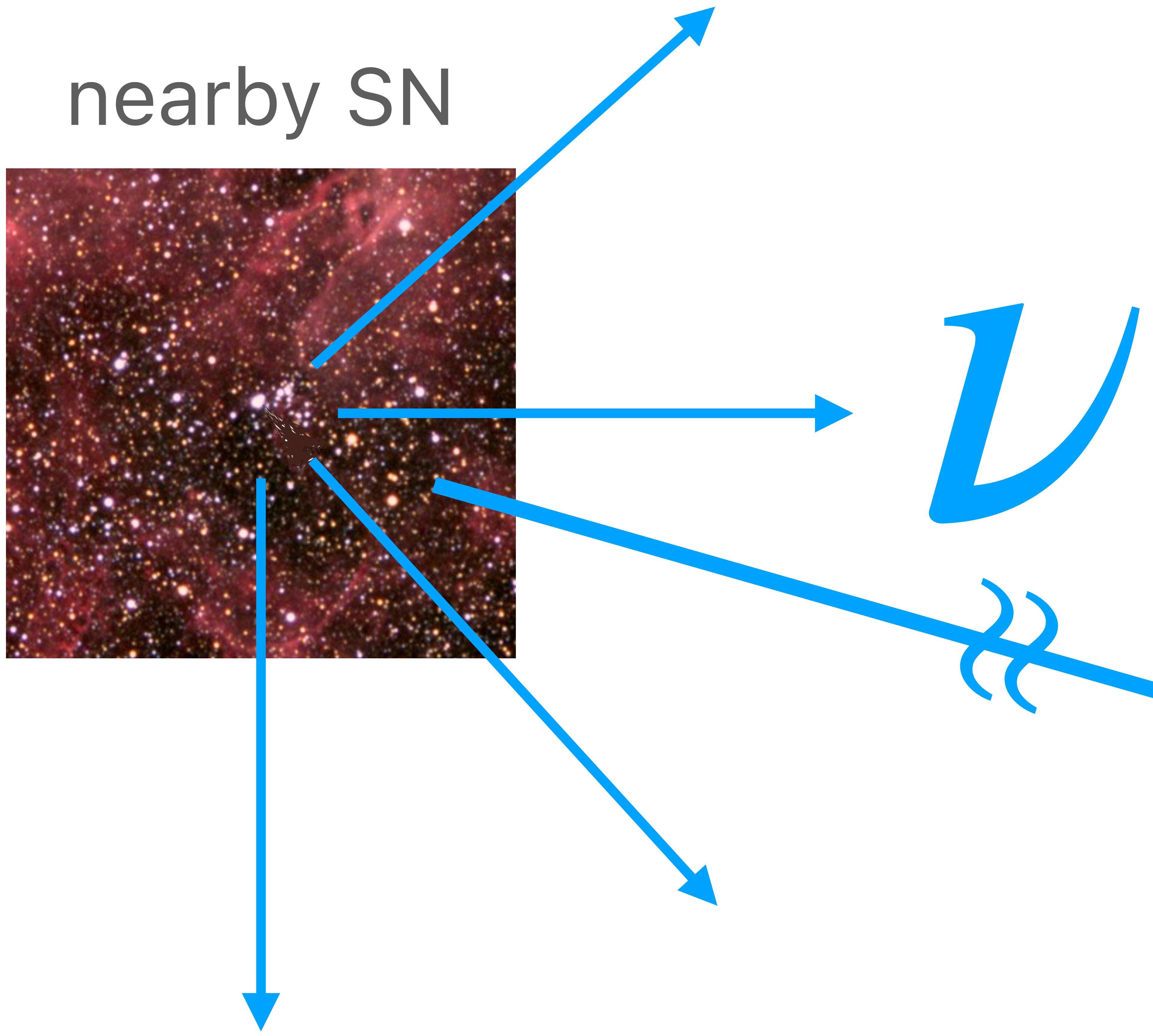
nearby SN

Supernova-scope

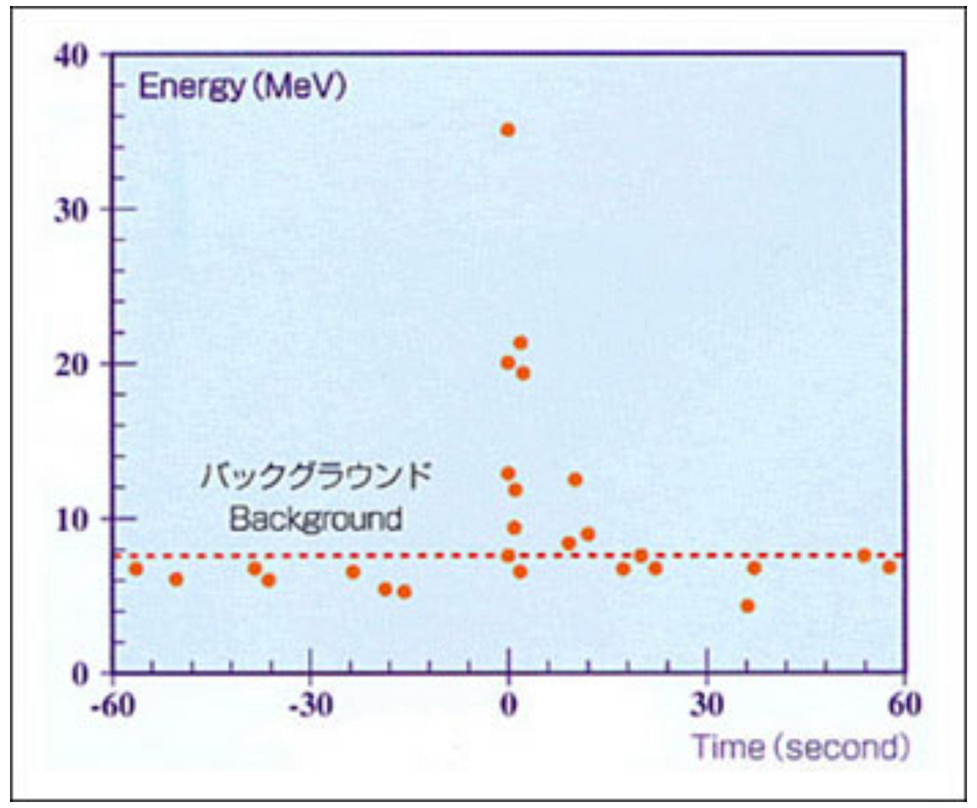


Supernova-scope

nearby SN



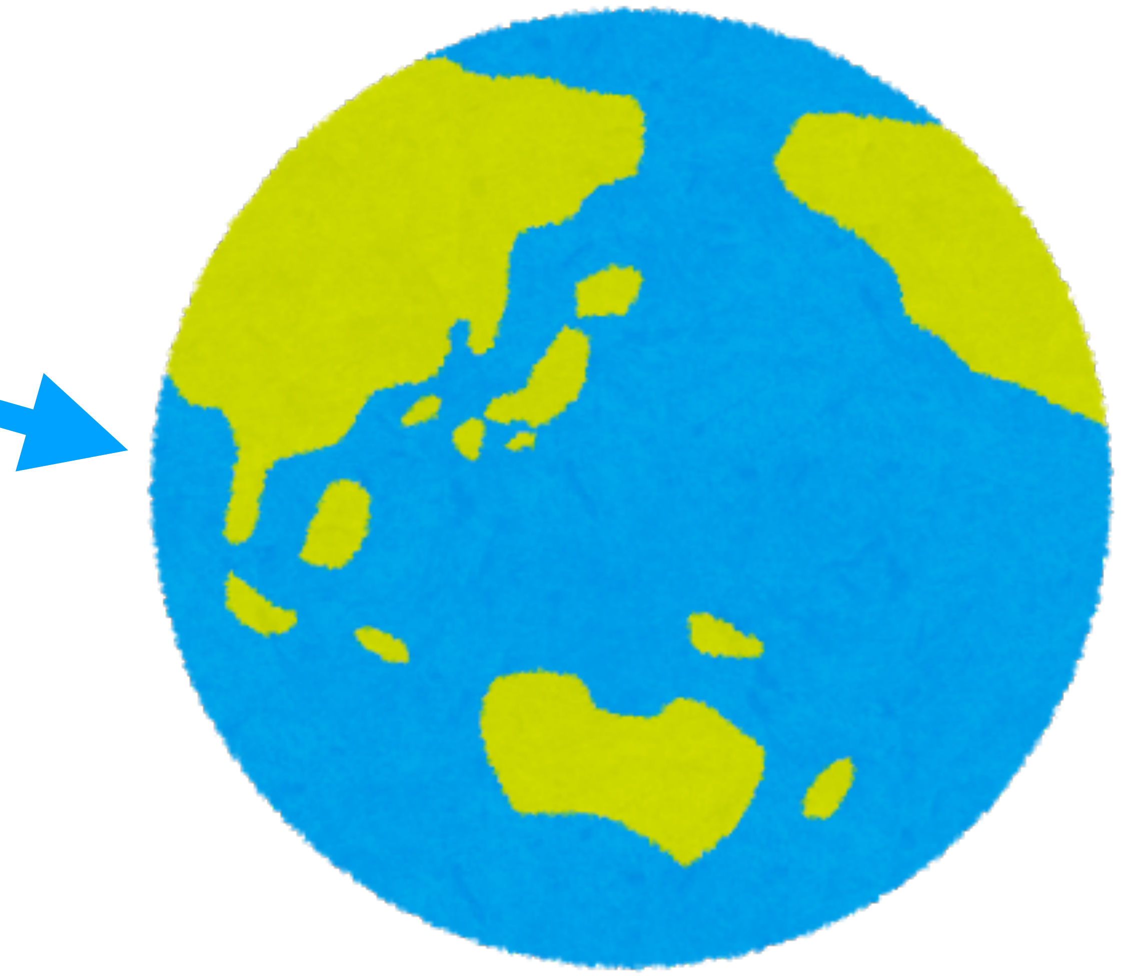
http://www-sk.icrr.u-tokyo.ac.jp/sk/physics/supernova-e.html



- SN1987A

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

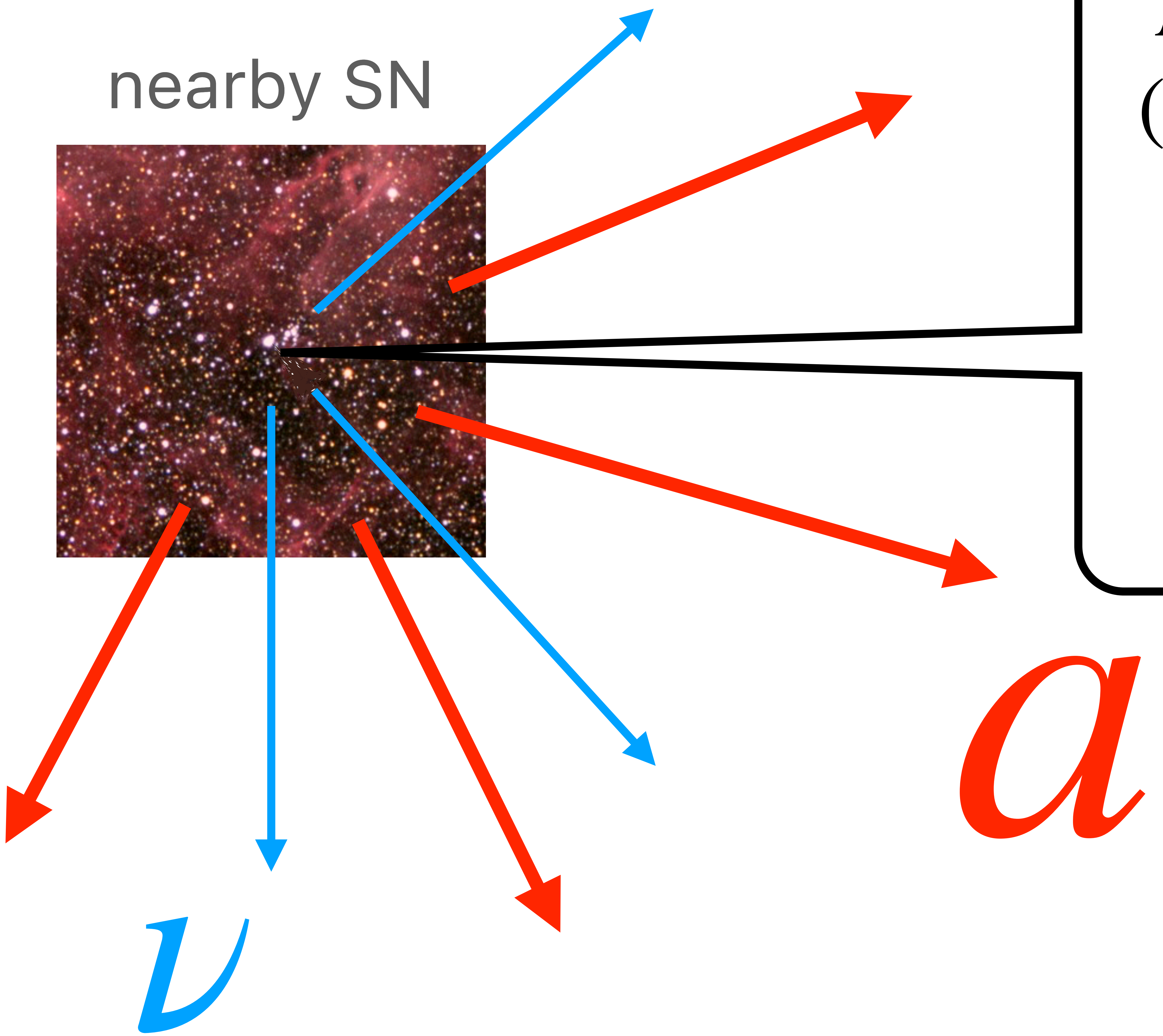
- Future: various neutrino detectors



Supernova-scope

If the axion exists,...

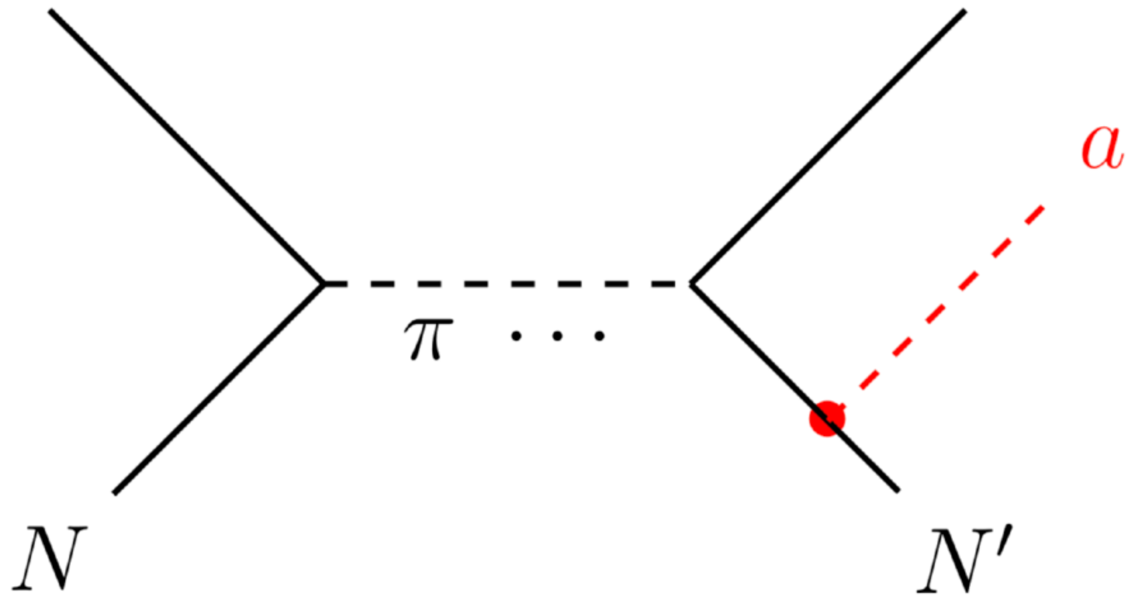
nearby SN



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

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

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

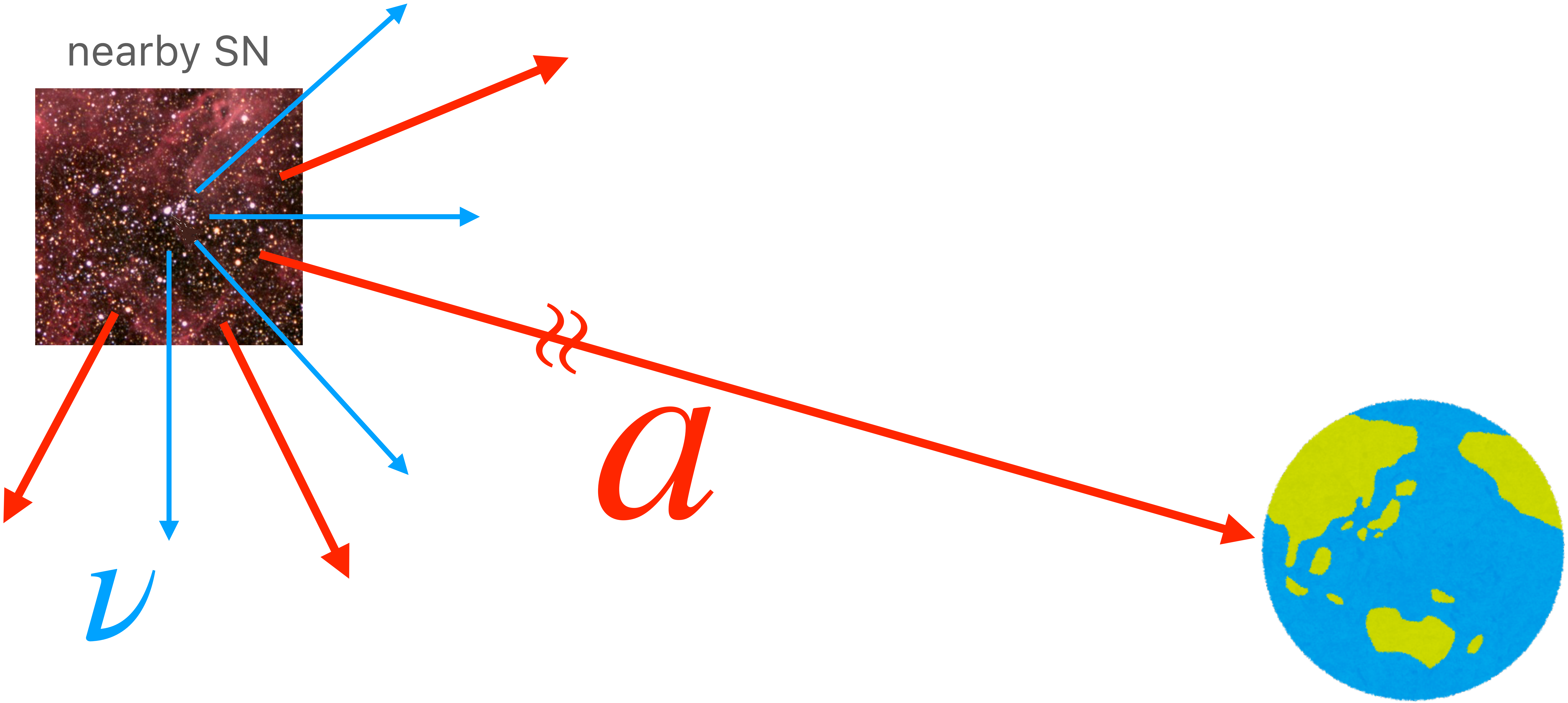


$$\begin{cases} C_p = -0.47 \\ C_n = -0.02 \end{cases} \text{(KSVZ)}$$

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

Supernova-scope

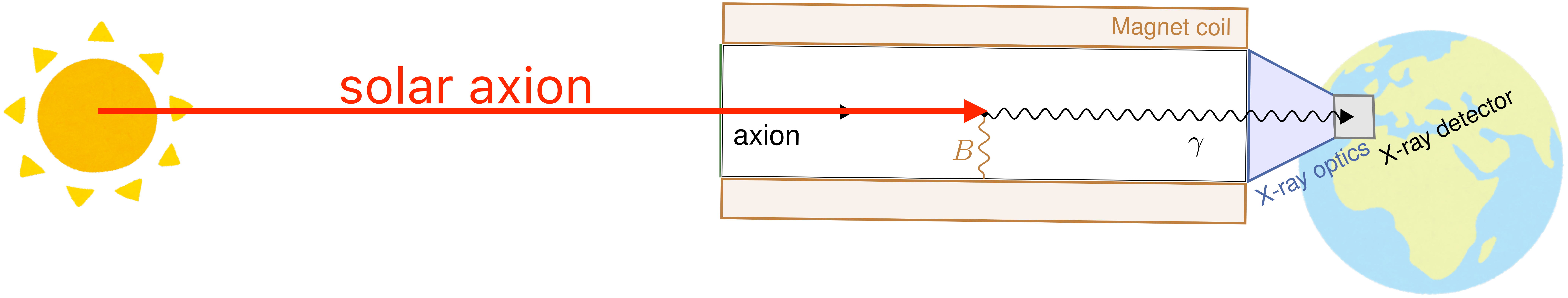
If the axion exists,...



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

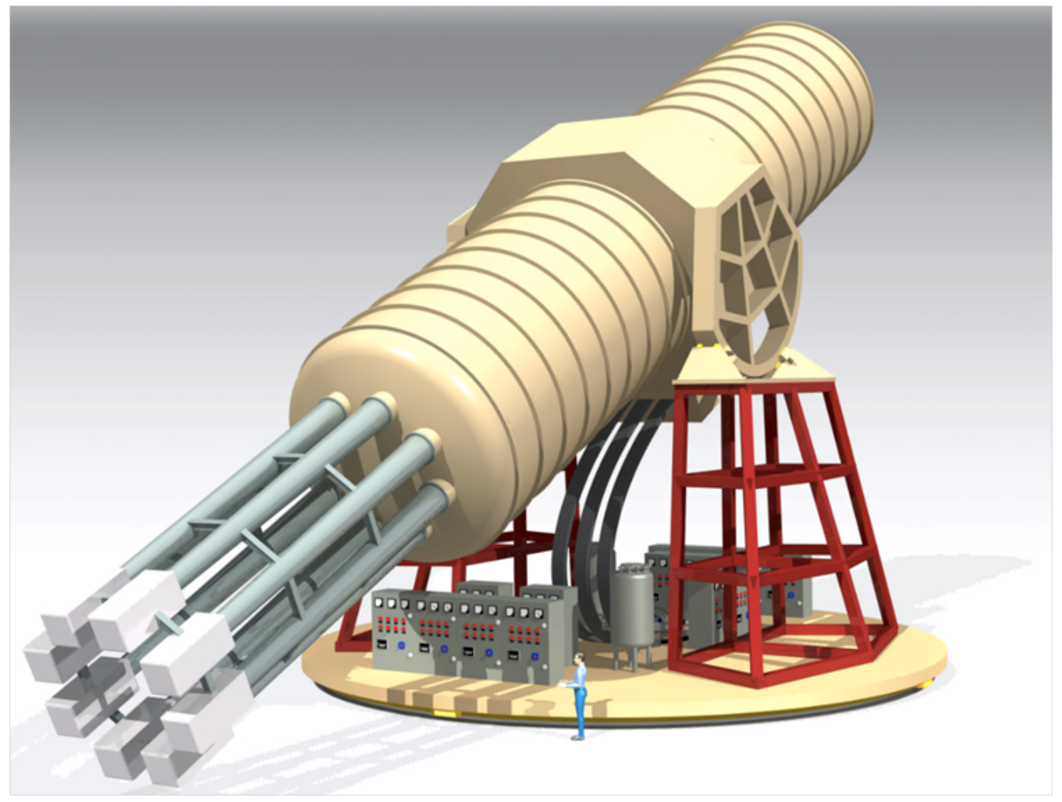
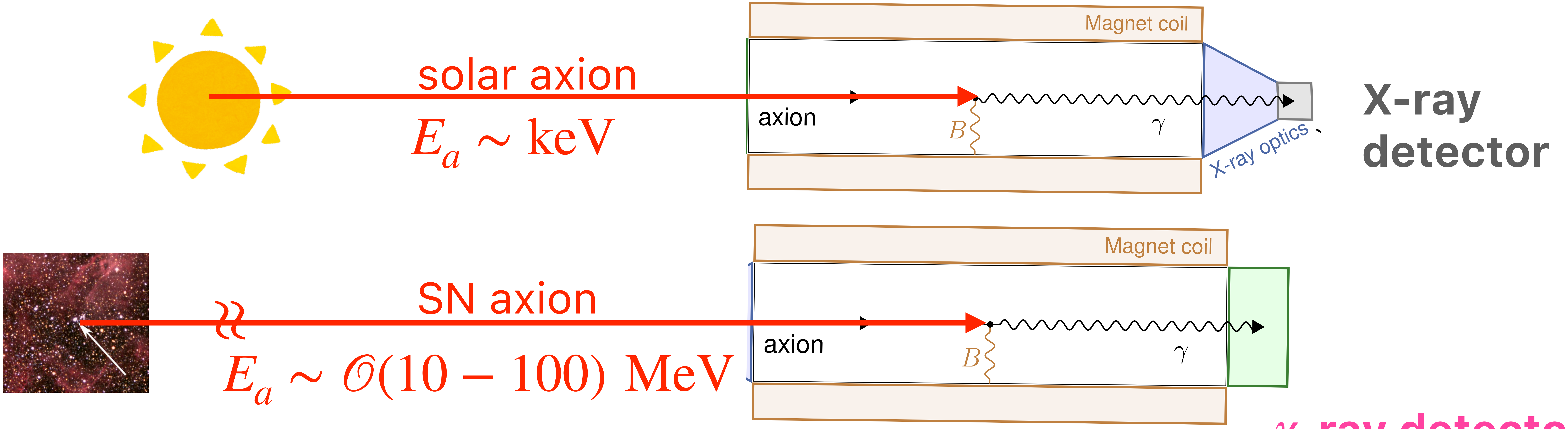


Fig. from IAXO homepage

Supernova-scope

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

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

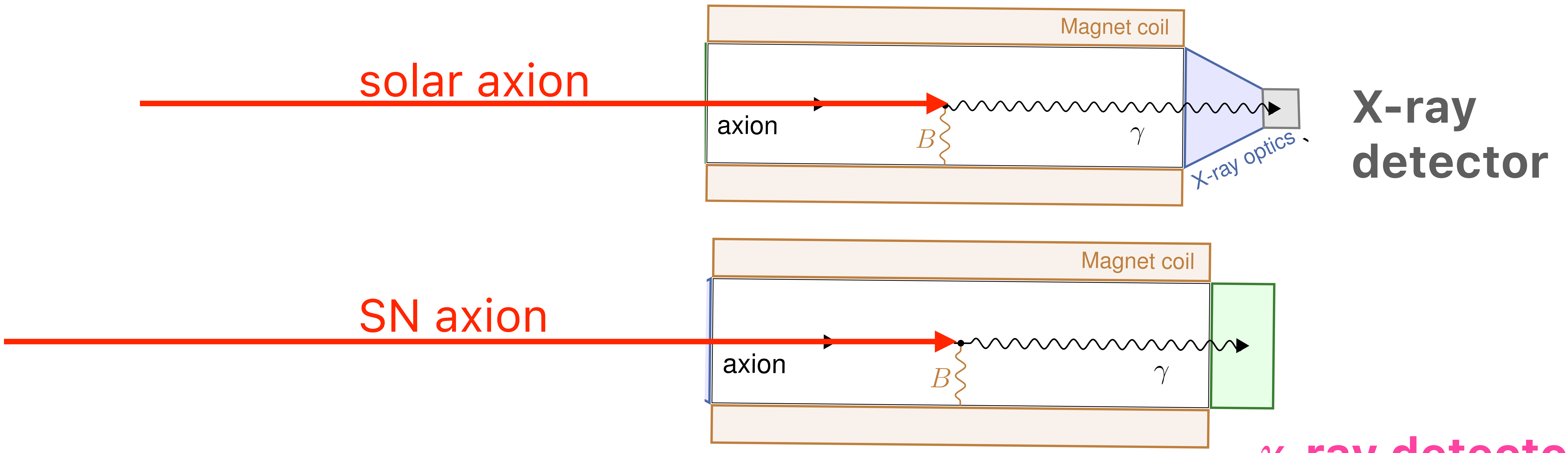


γ-ray detector is necessary.

※ 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
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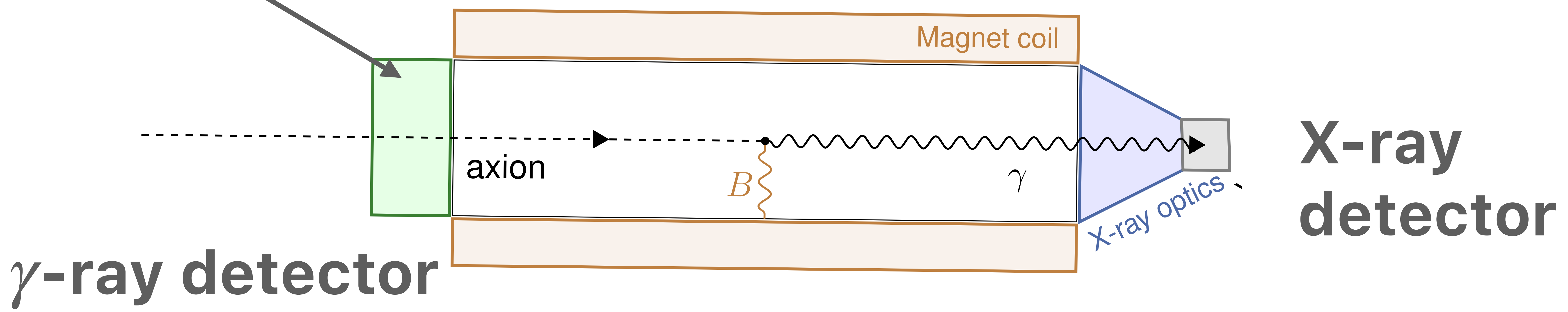
Supernova-scope

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.



Supernova-scope

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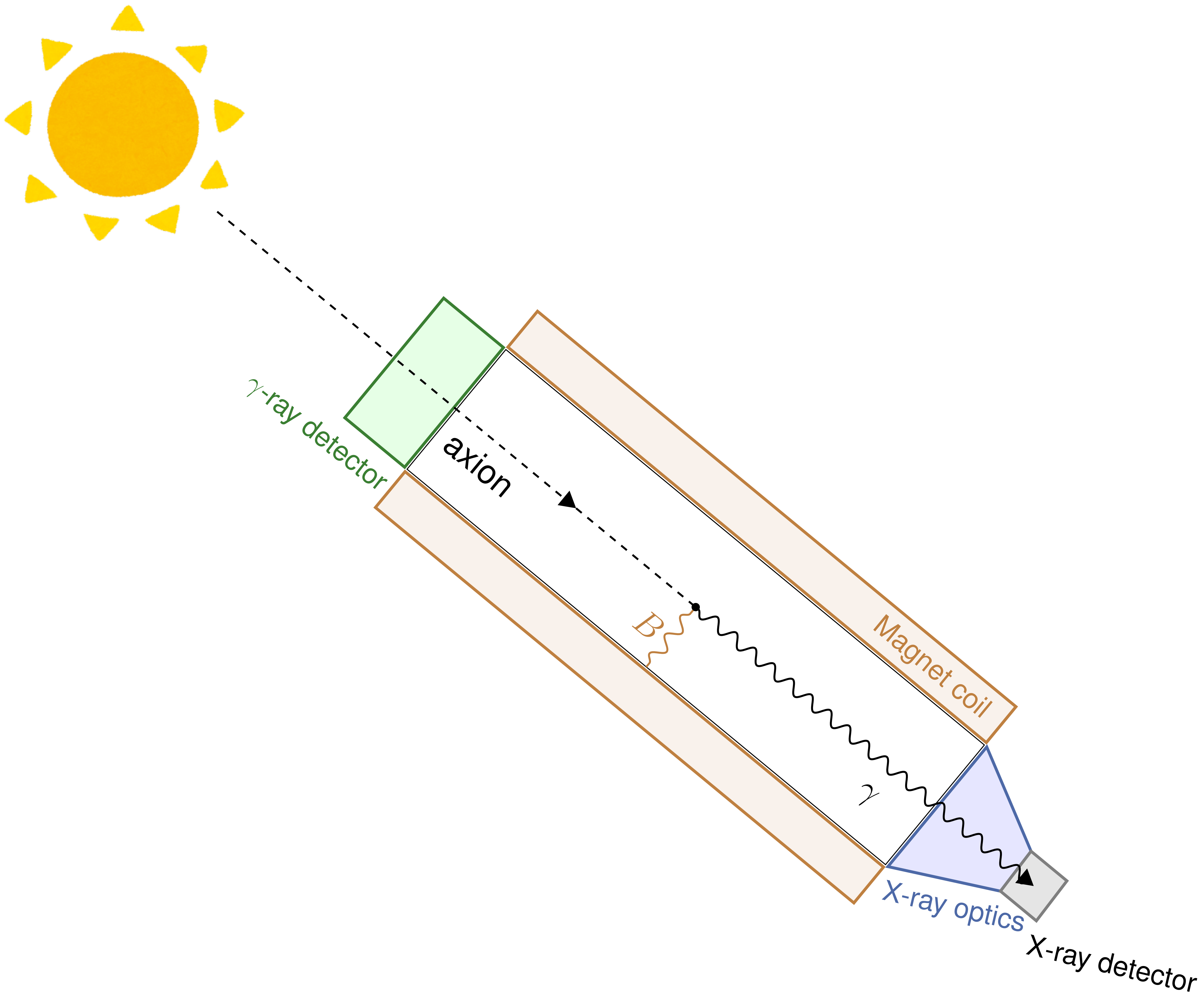
Normal operation time: It works as an axion helioscope.



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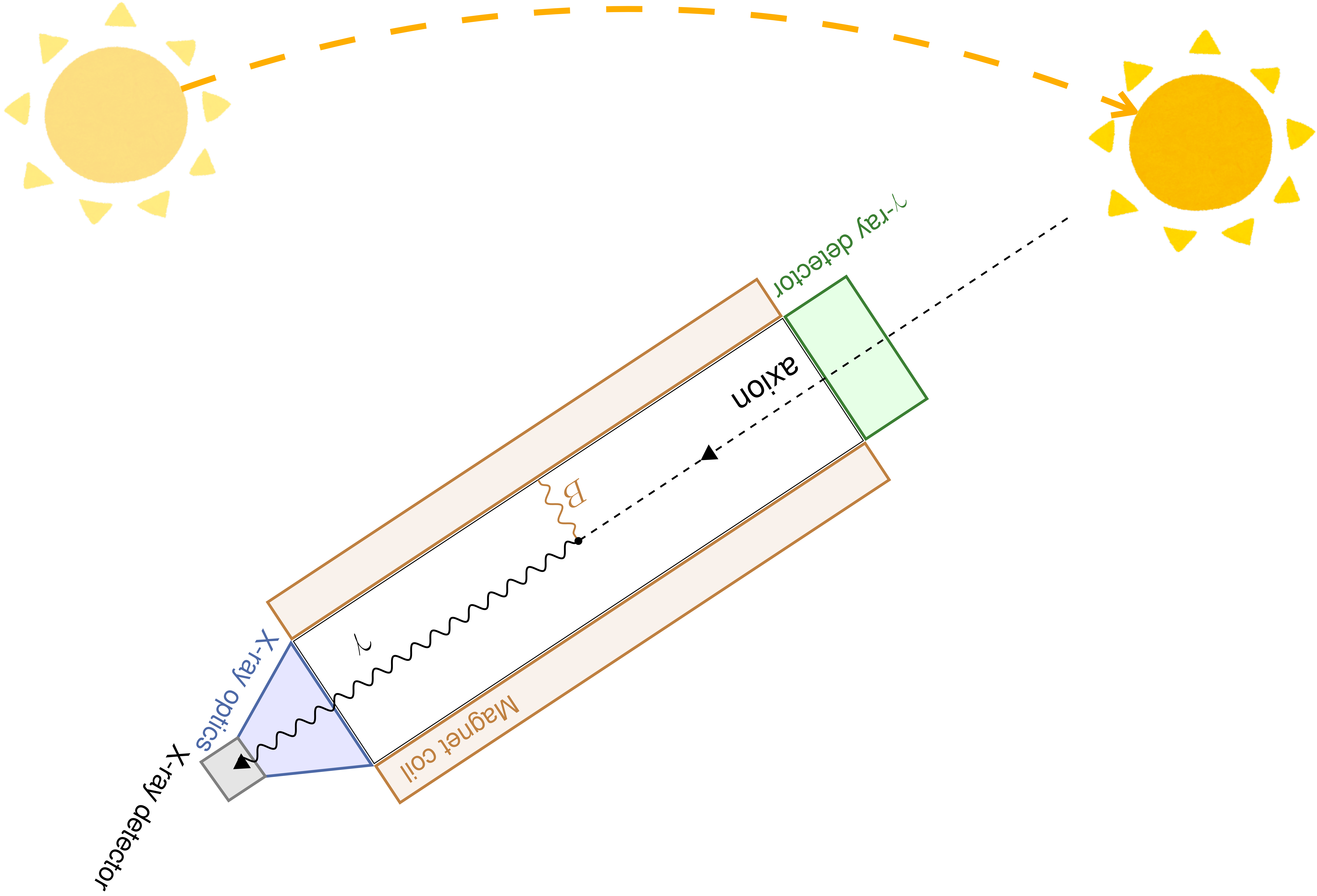

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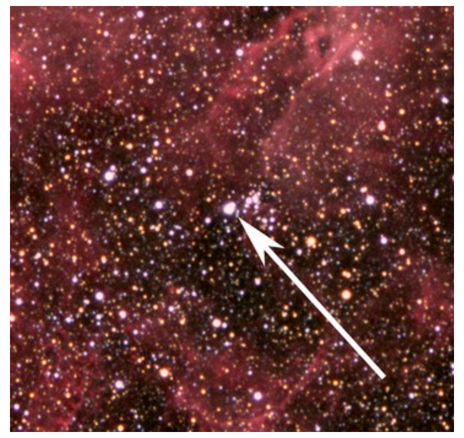
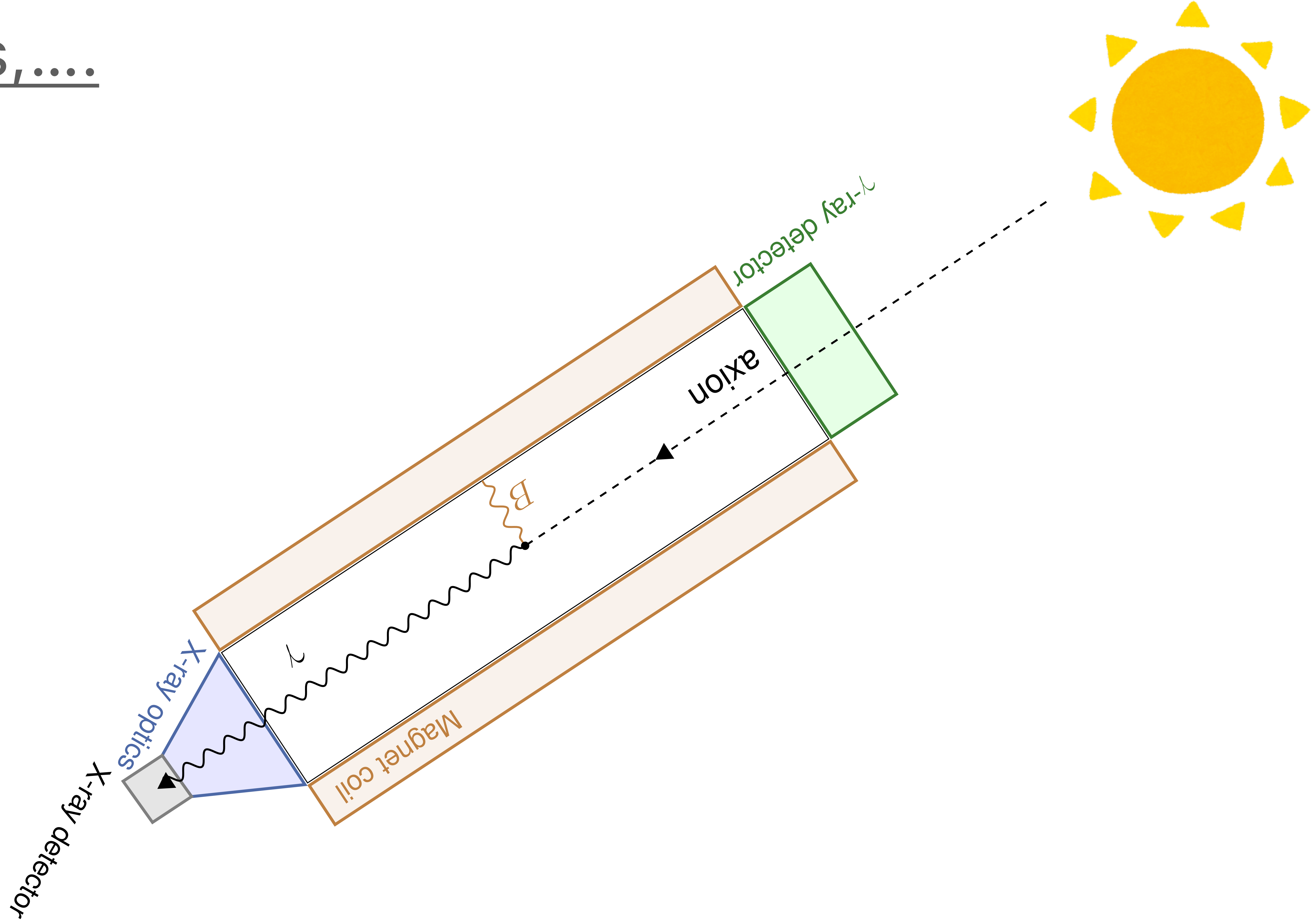
When a Supernova occurs,….





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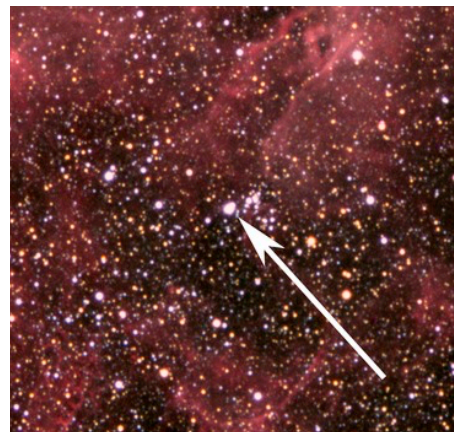

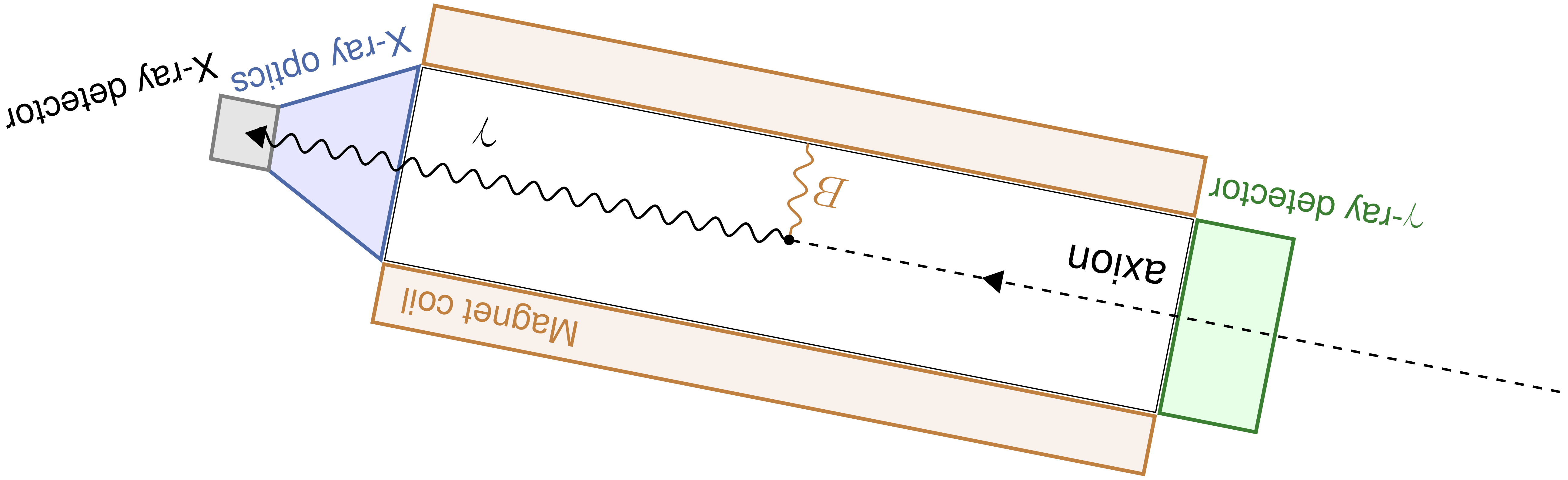

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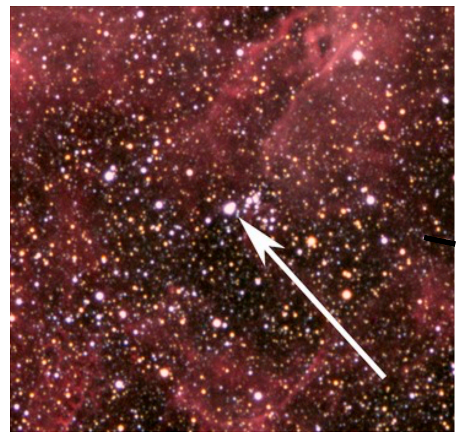

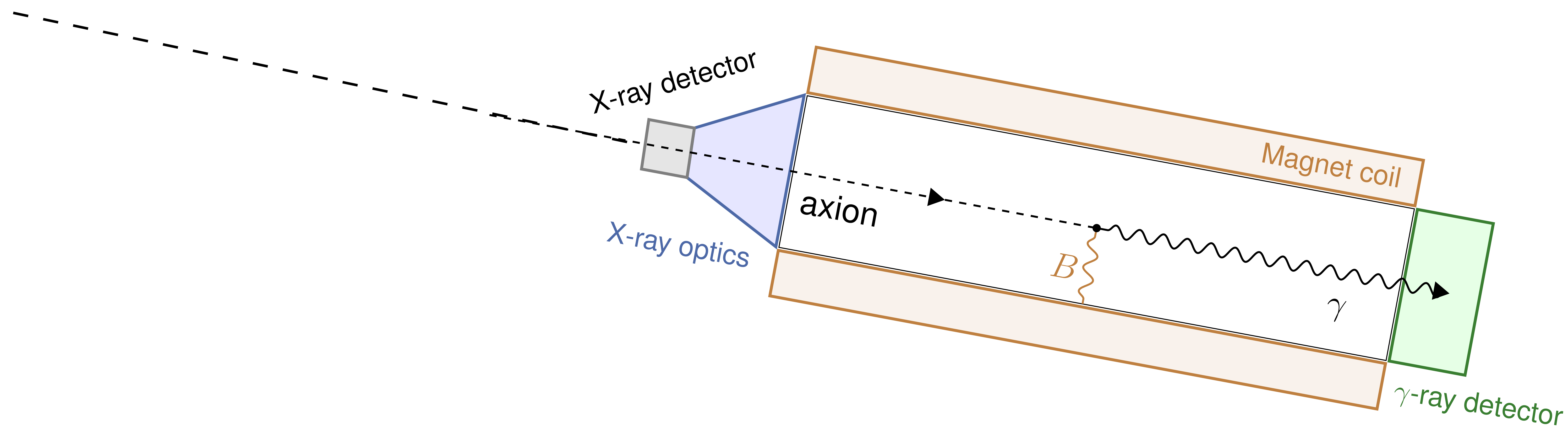

Axion Supernova-scope

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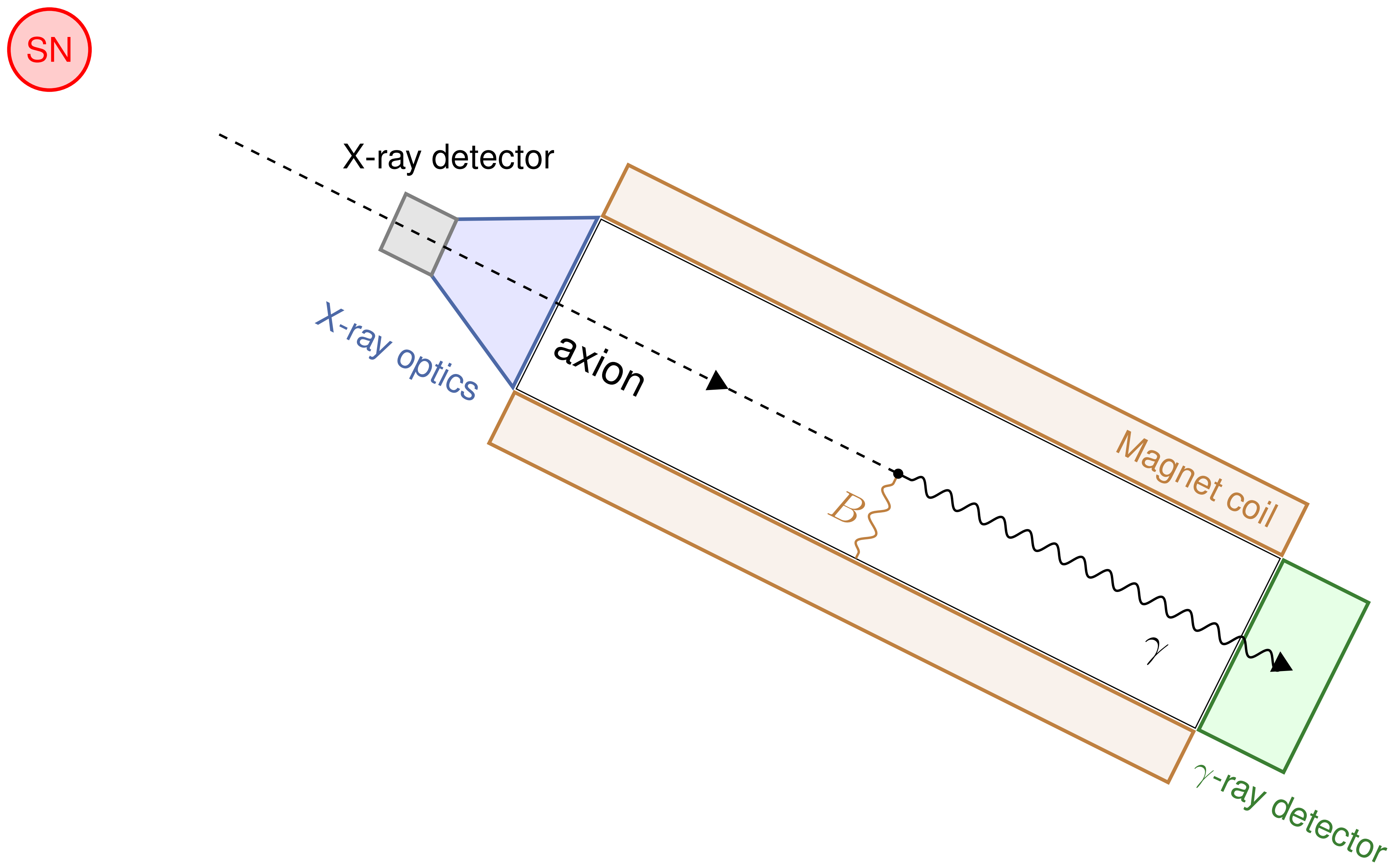
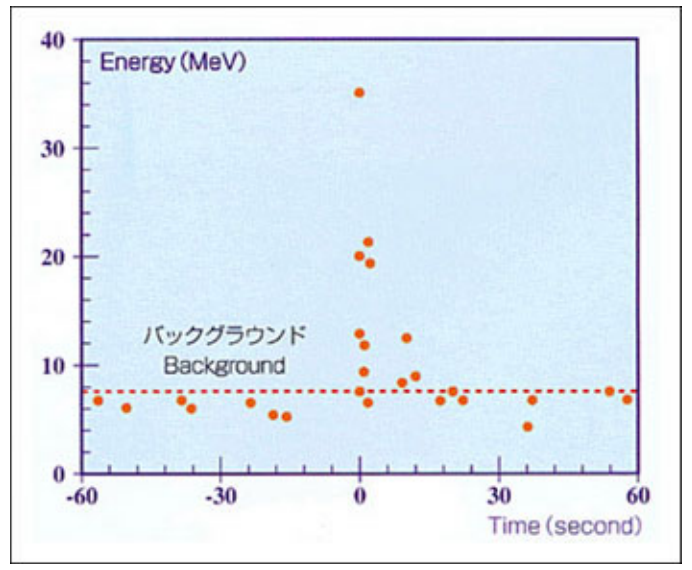


Pre-SN neutrino

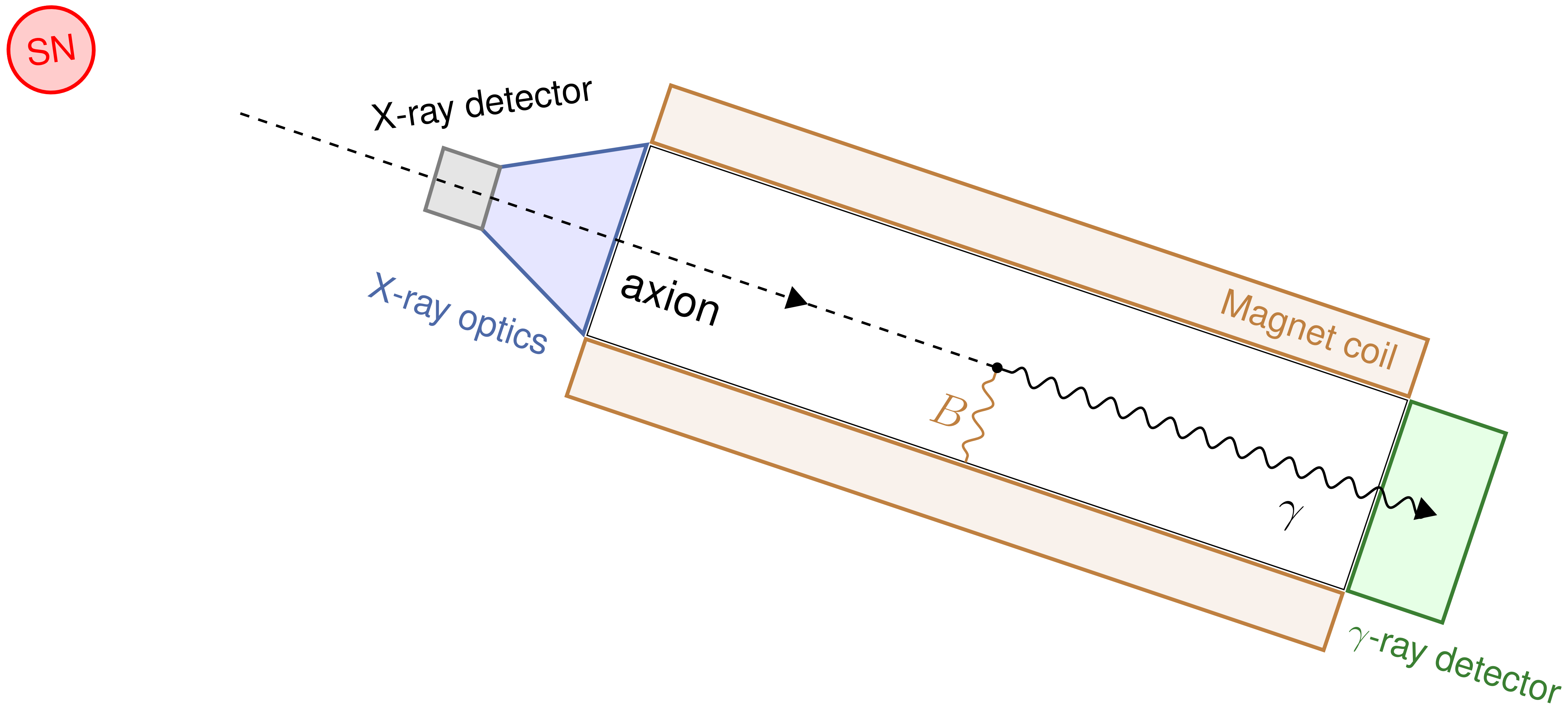
http://www-sk.icrr.u-tokyo.ac.jp/sk/physics/supernova-e.html



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

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

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



Pre-SN neutrino

Take the help of the pre-SN neutrinos.

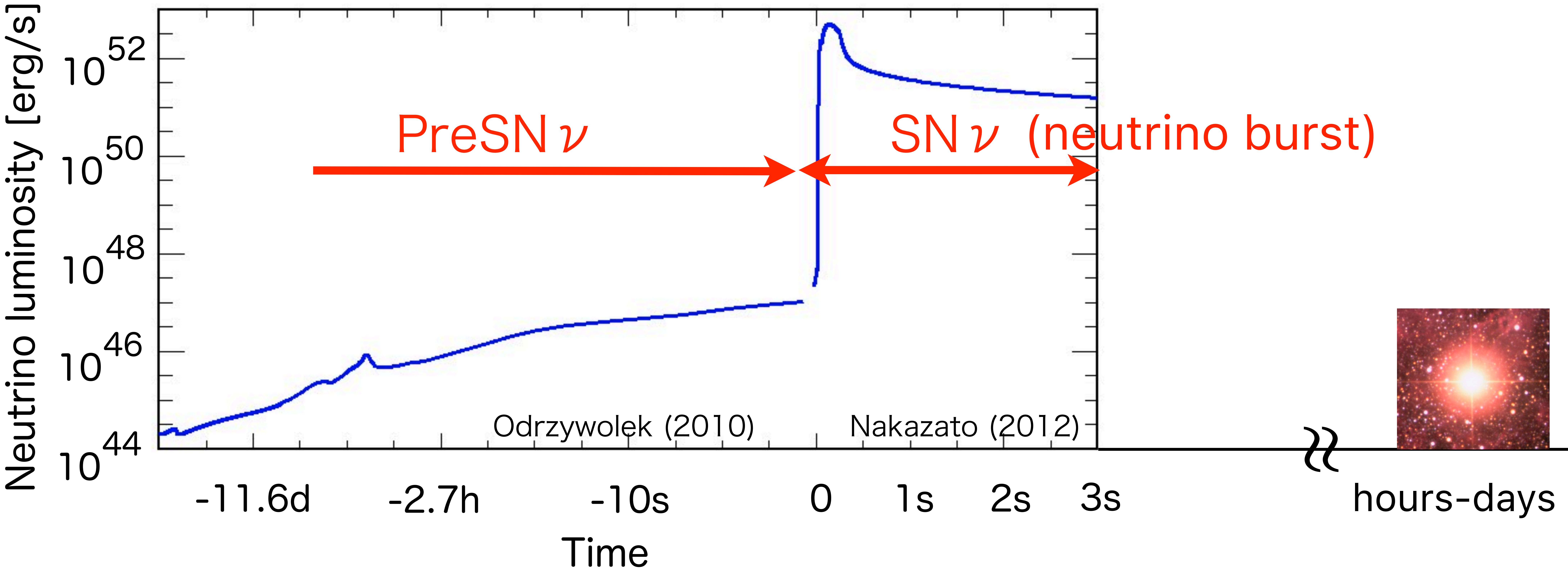
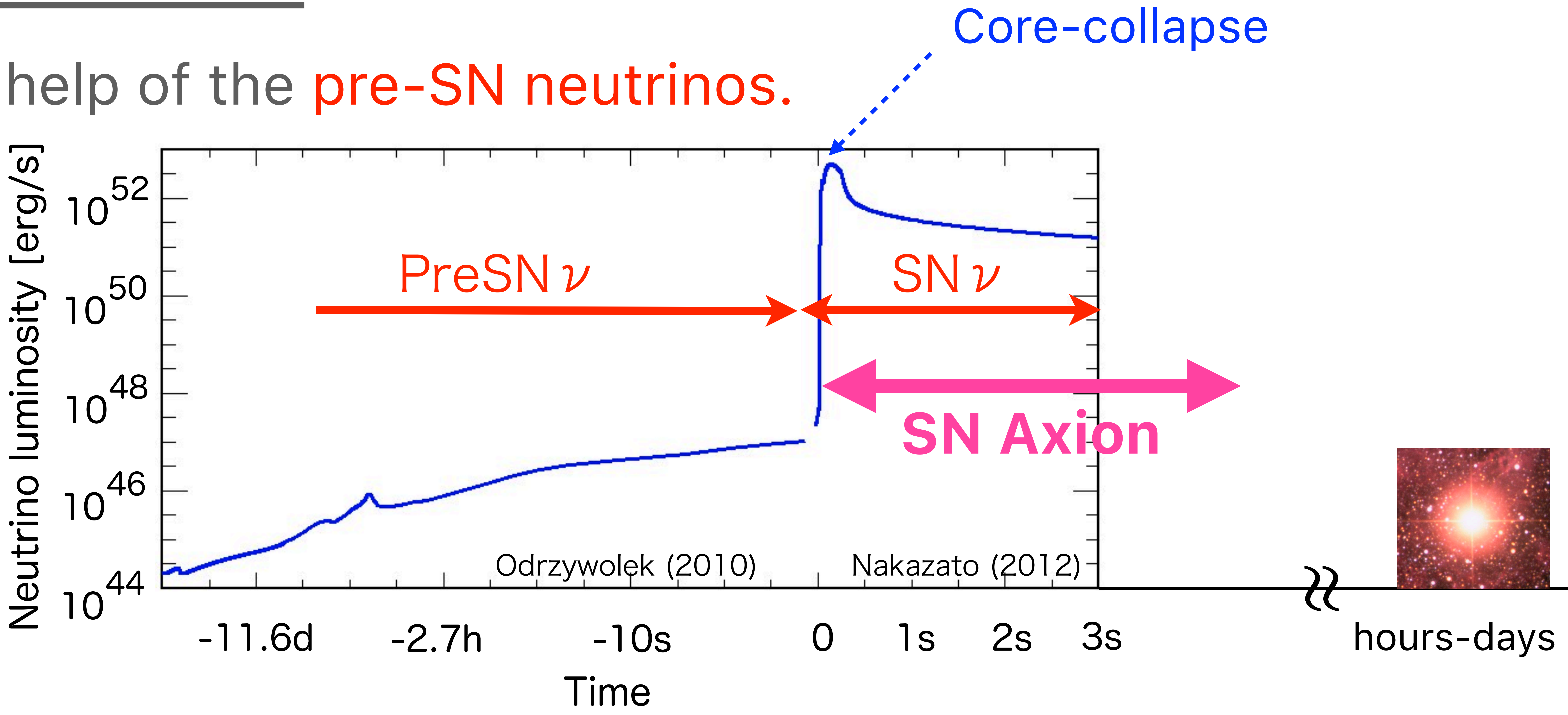


Figure from K.Ishidoshiro's talk in 2019.
https://www.lowbg.org/ugnd/workshop/sympo_all/201903_Sendai/

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

Pre-SN neutrino

Take the help of the pre-SN neutrinos.



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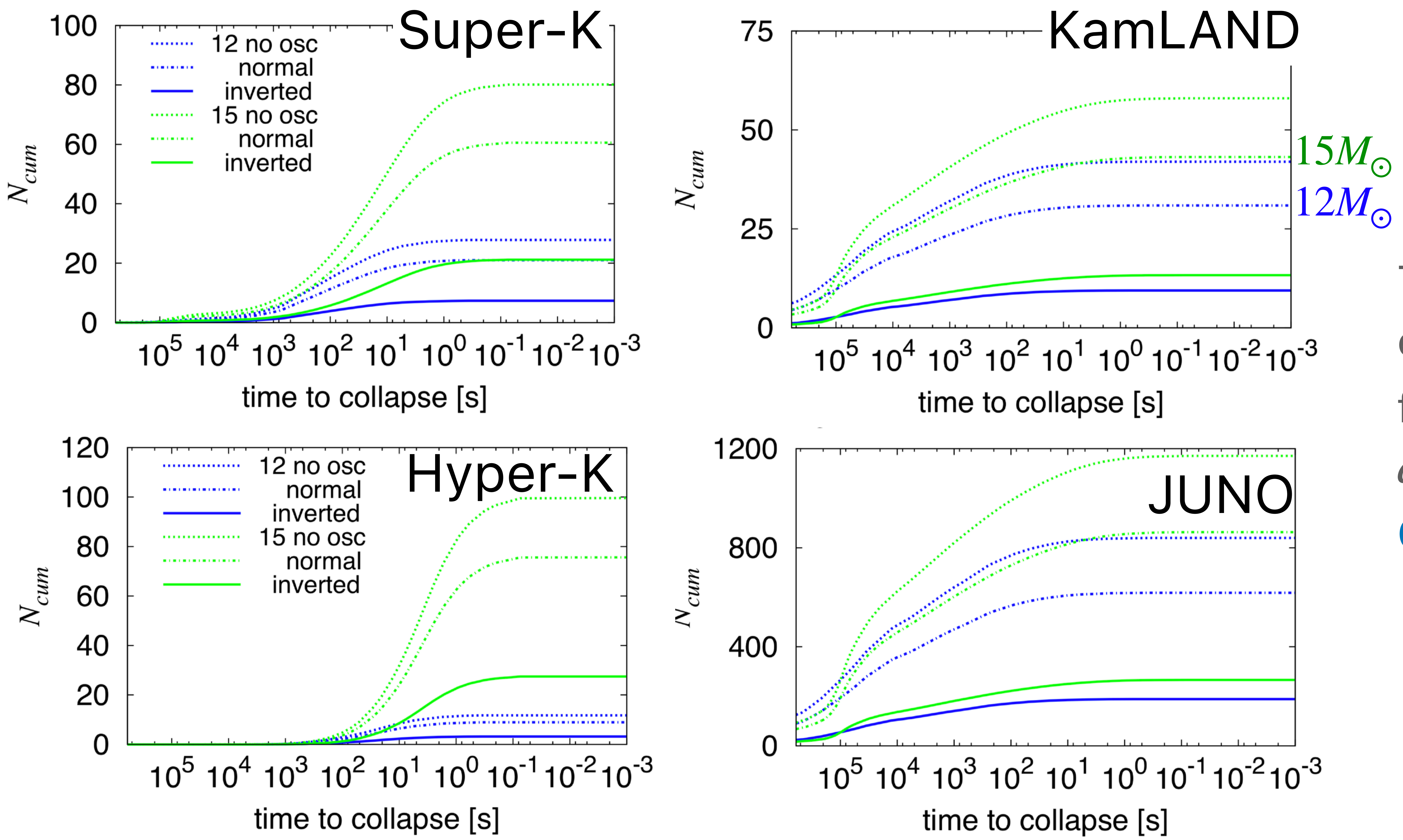
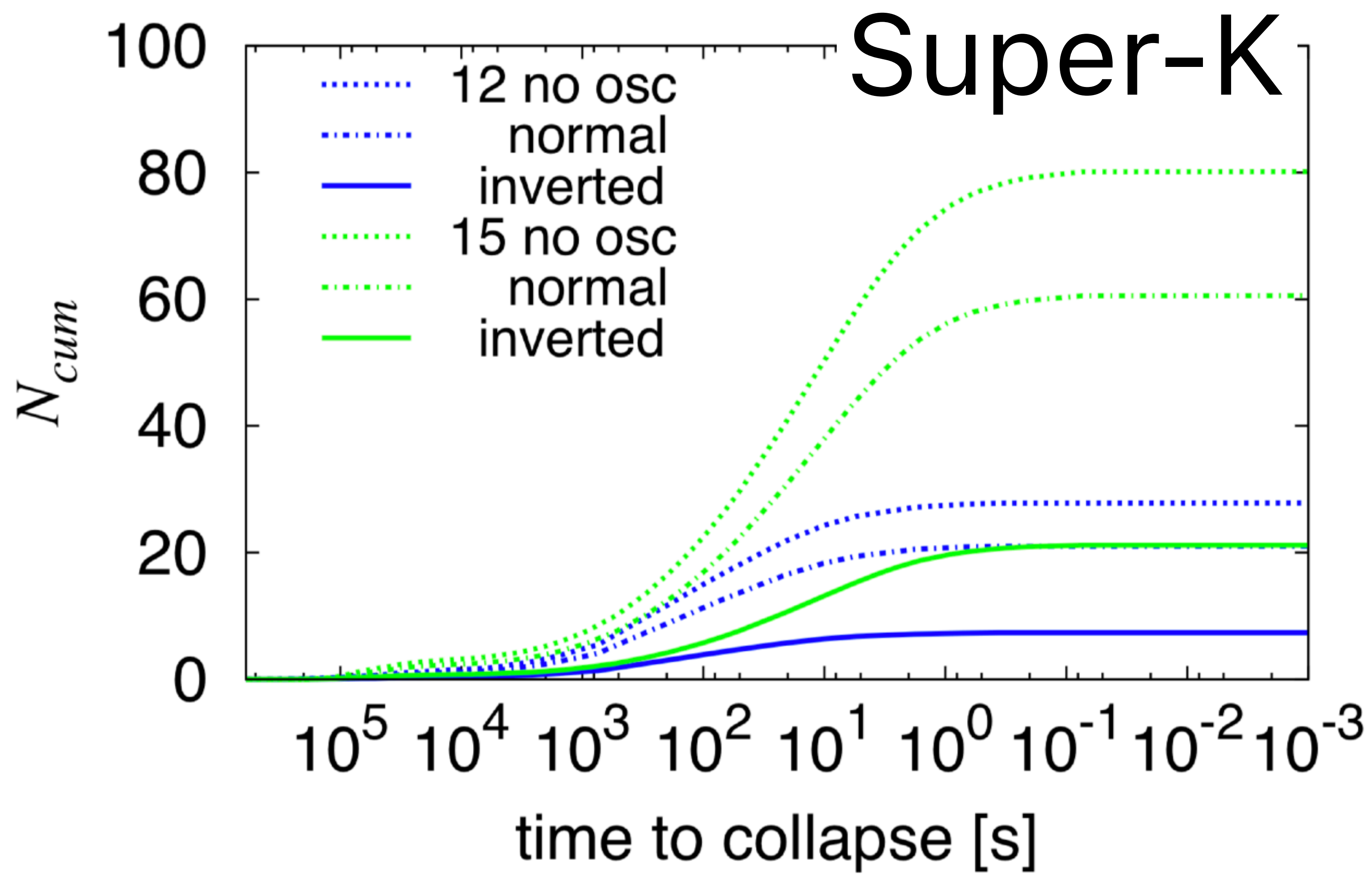
Pre-SN neutrino

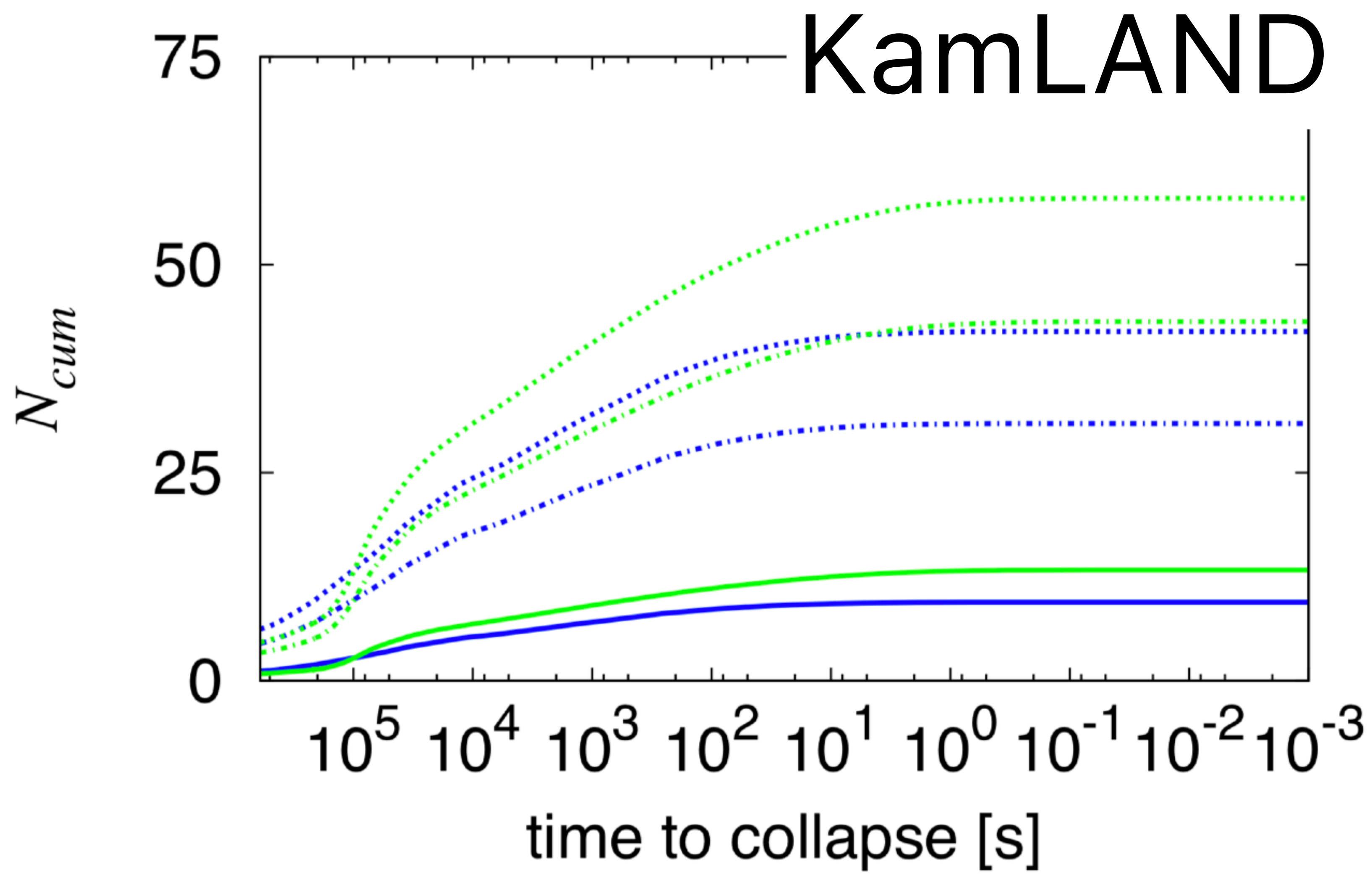


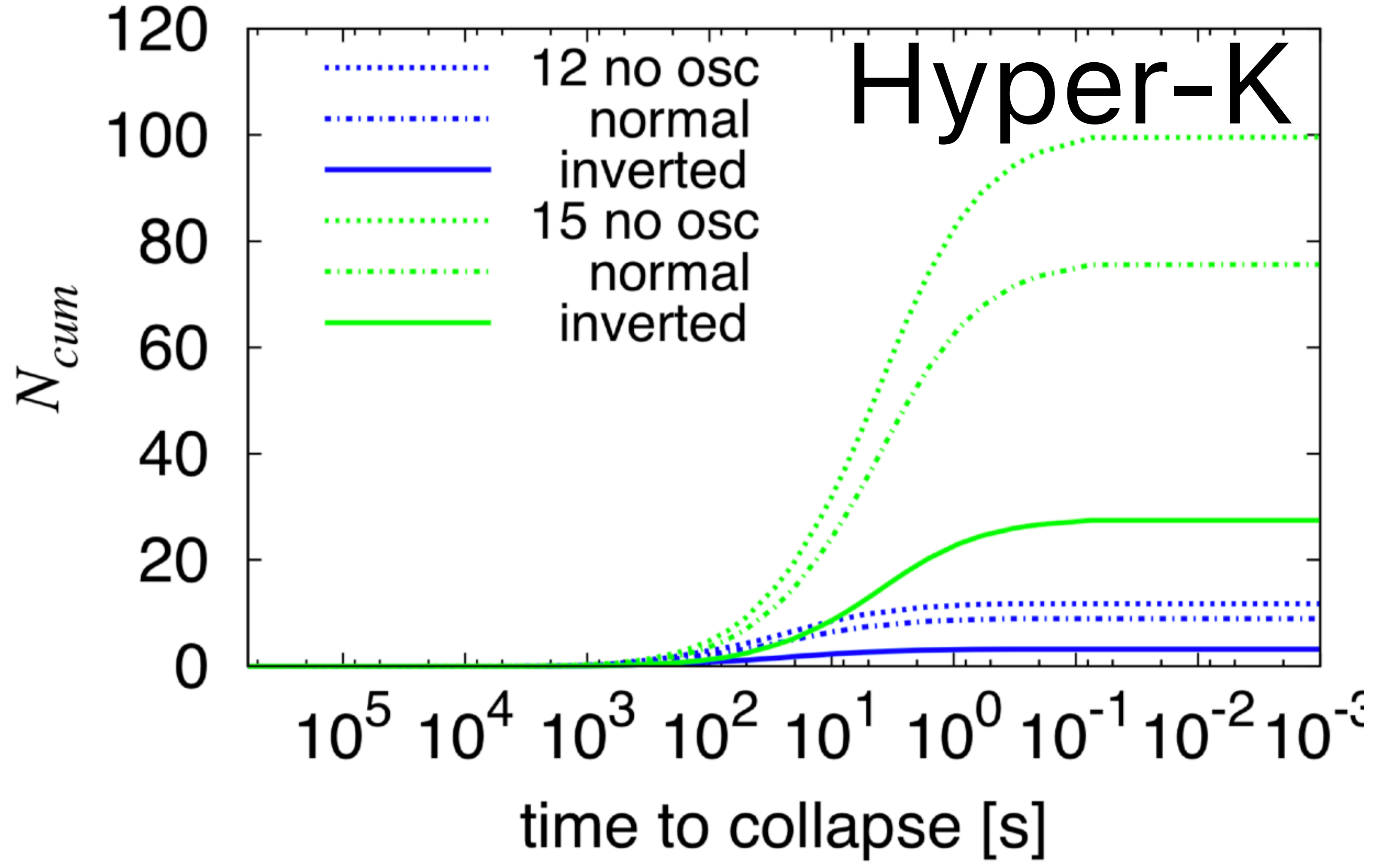
The cumulative numbers of expected pre-SN ν events for Fe-Core progenitor, $d = 200$ pc.

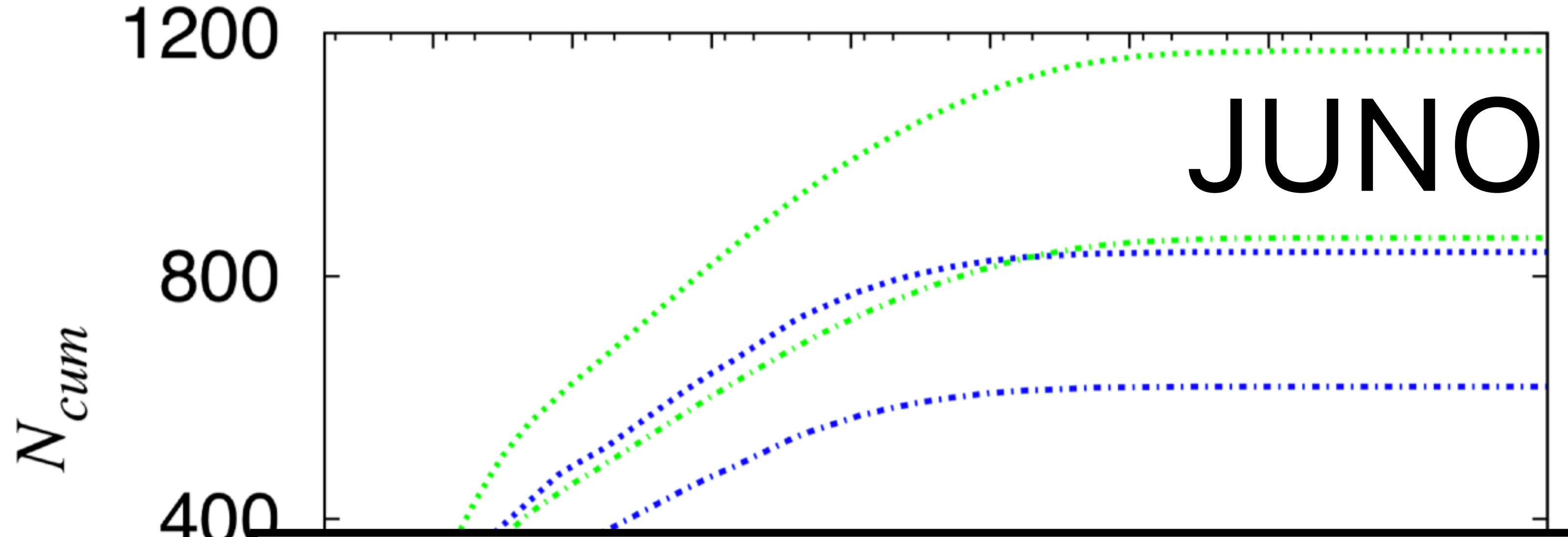
C. Kato et.al., [1506.02358].

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]

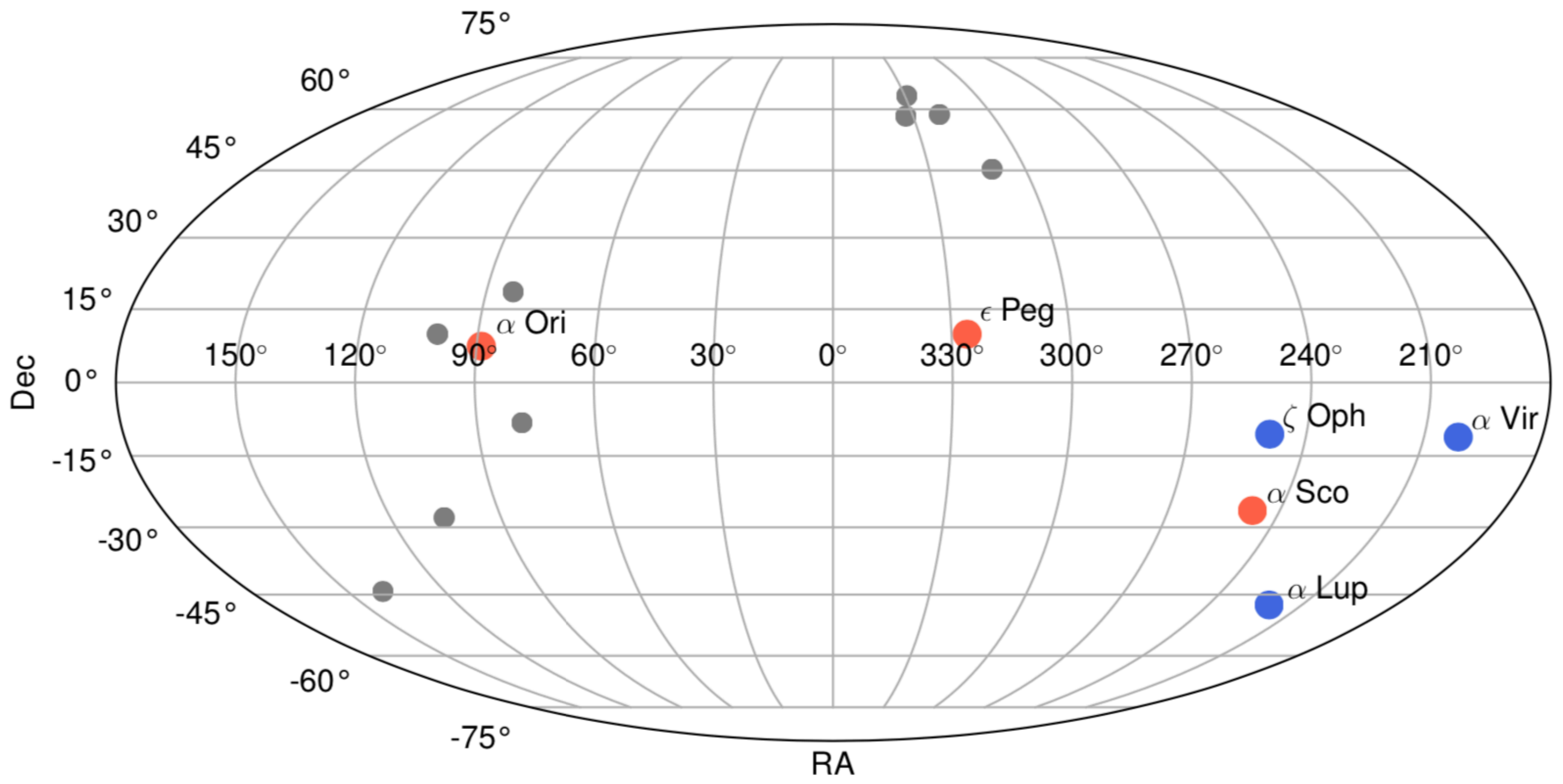
Pre-SN neutrino

- 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.

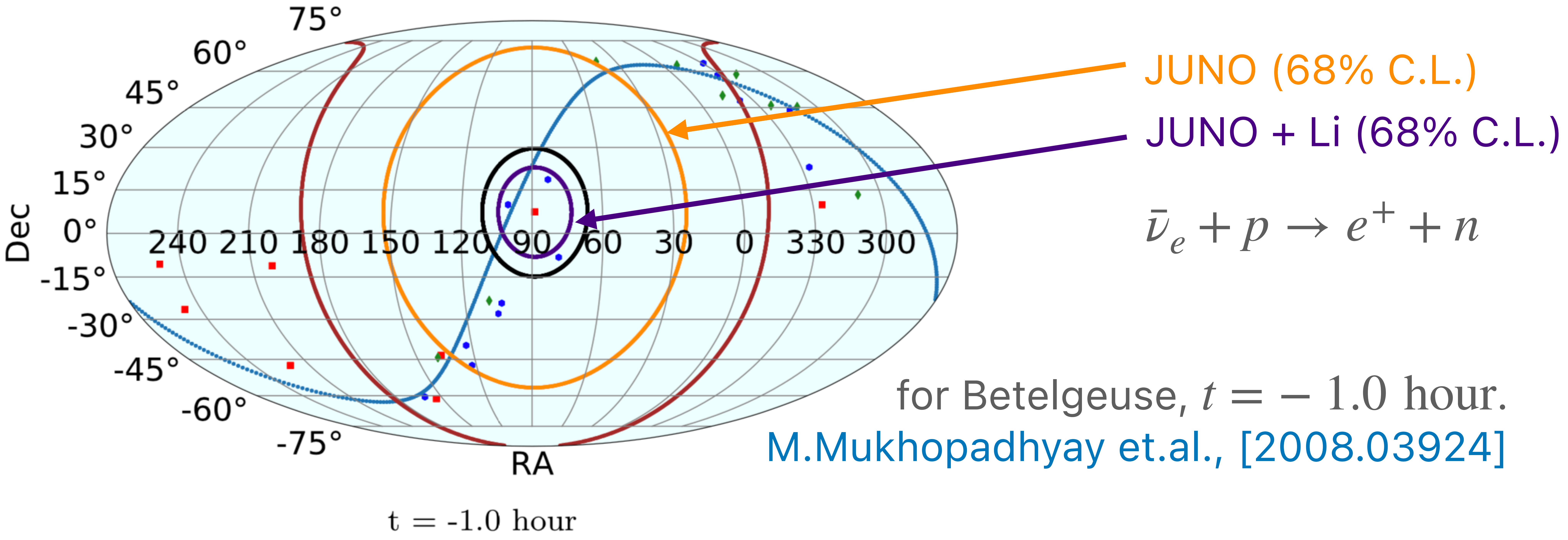
$M > 10M_\odot$ only.



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).

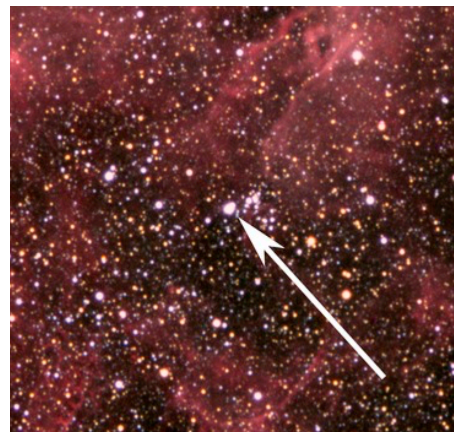
- It is in principle possible to estimate the location of the SN candidate on the sky.

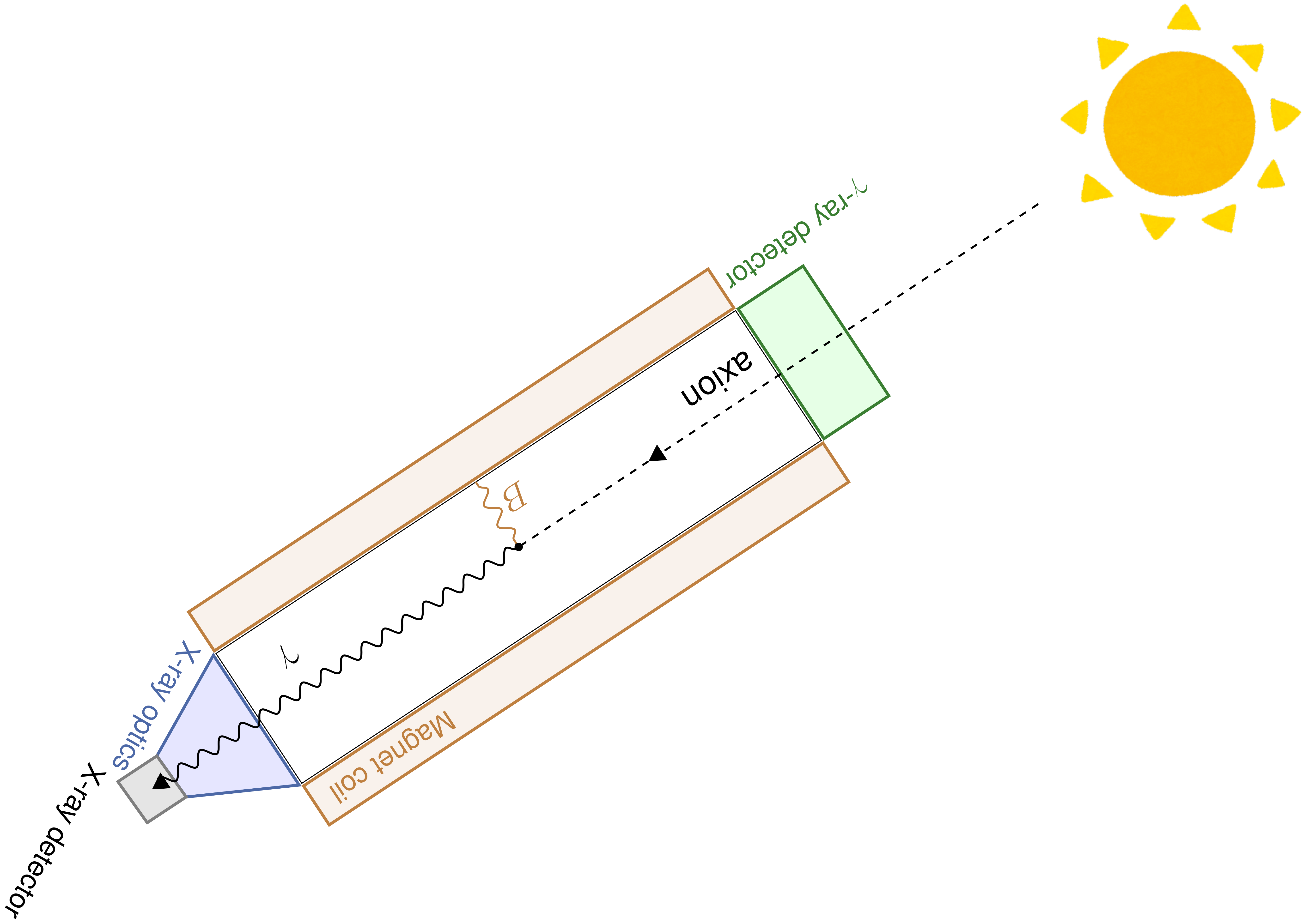


$$\bar{\nu}_e + p \to e^+ + n$$

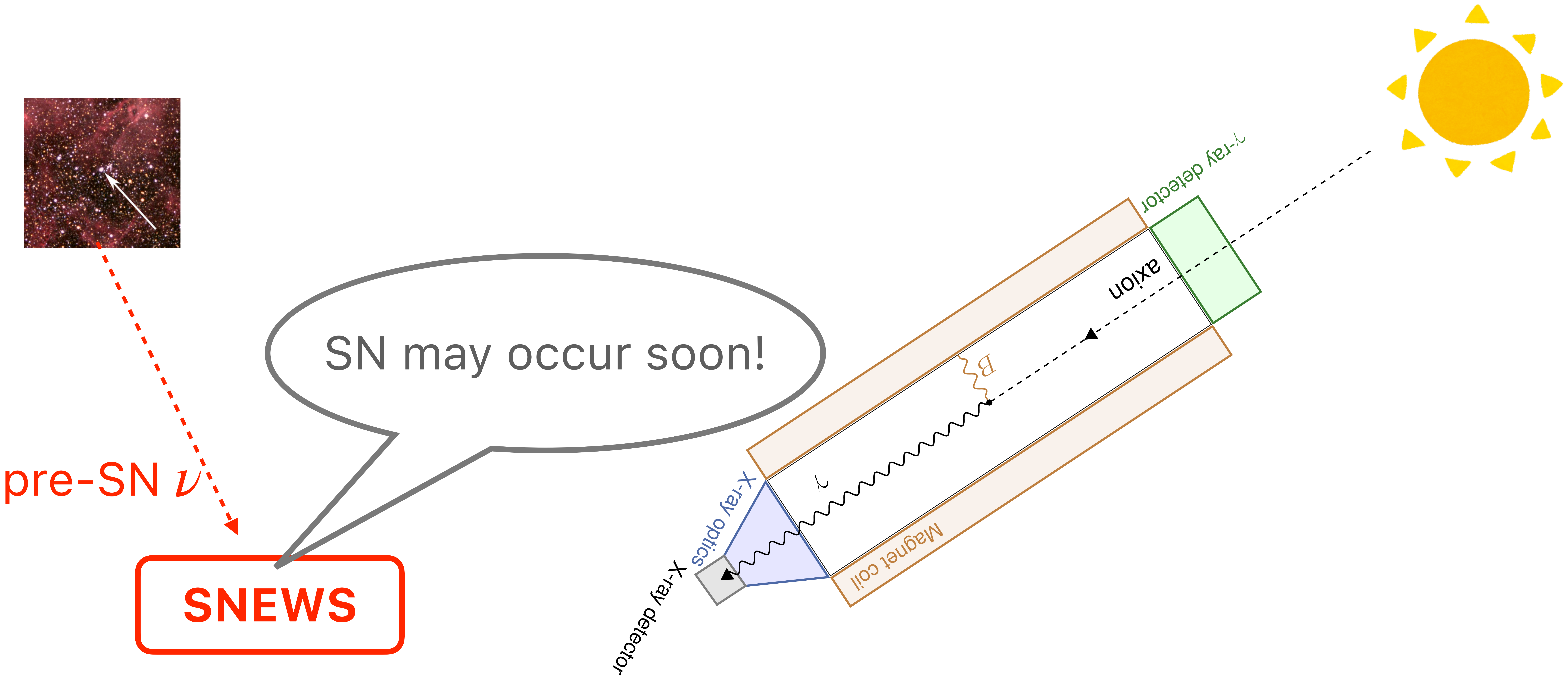
for Betelgeuse, $t = -1.0$ hour.

M.Mukhopadhyay et.al., [2008.03924]




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

Once a pre-SN neutrino alert is received,



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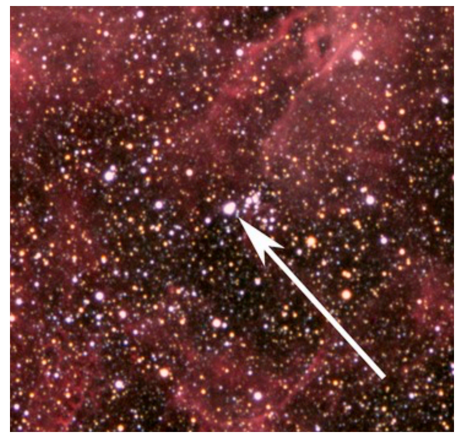

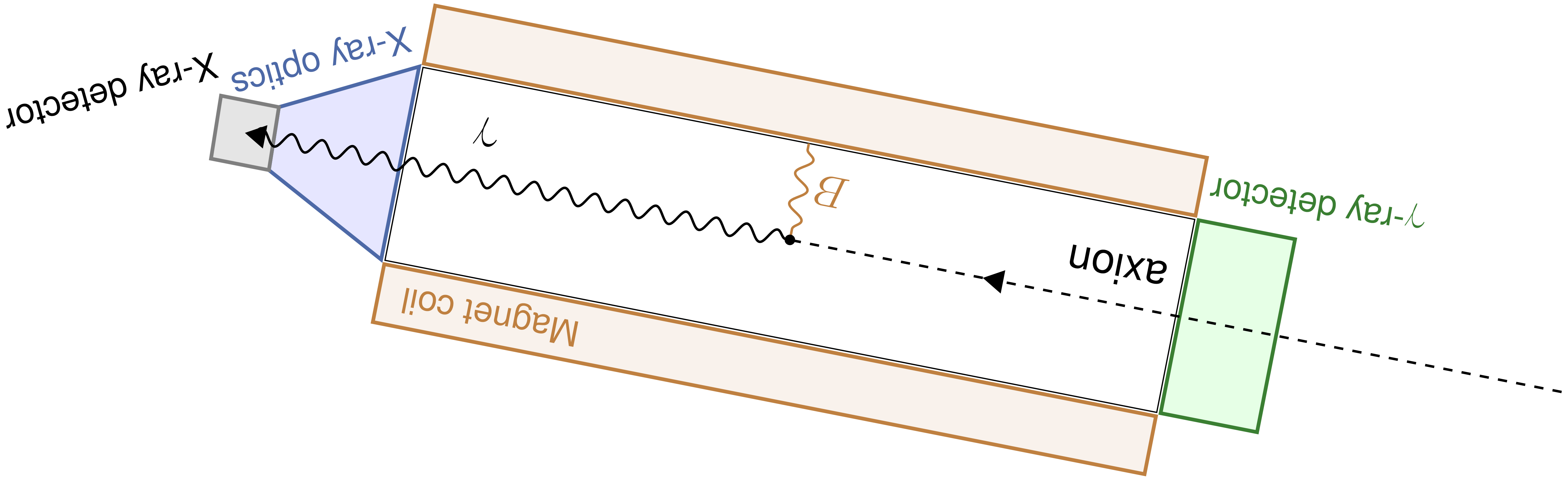

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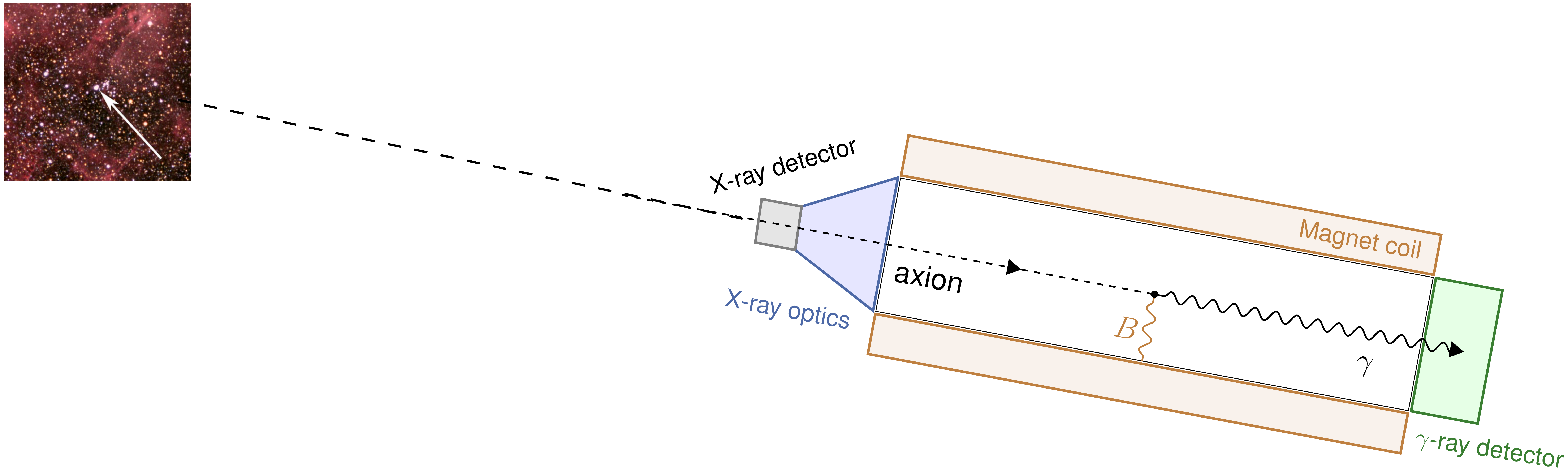
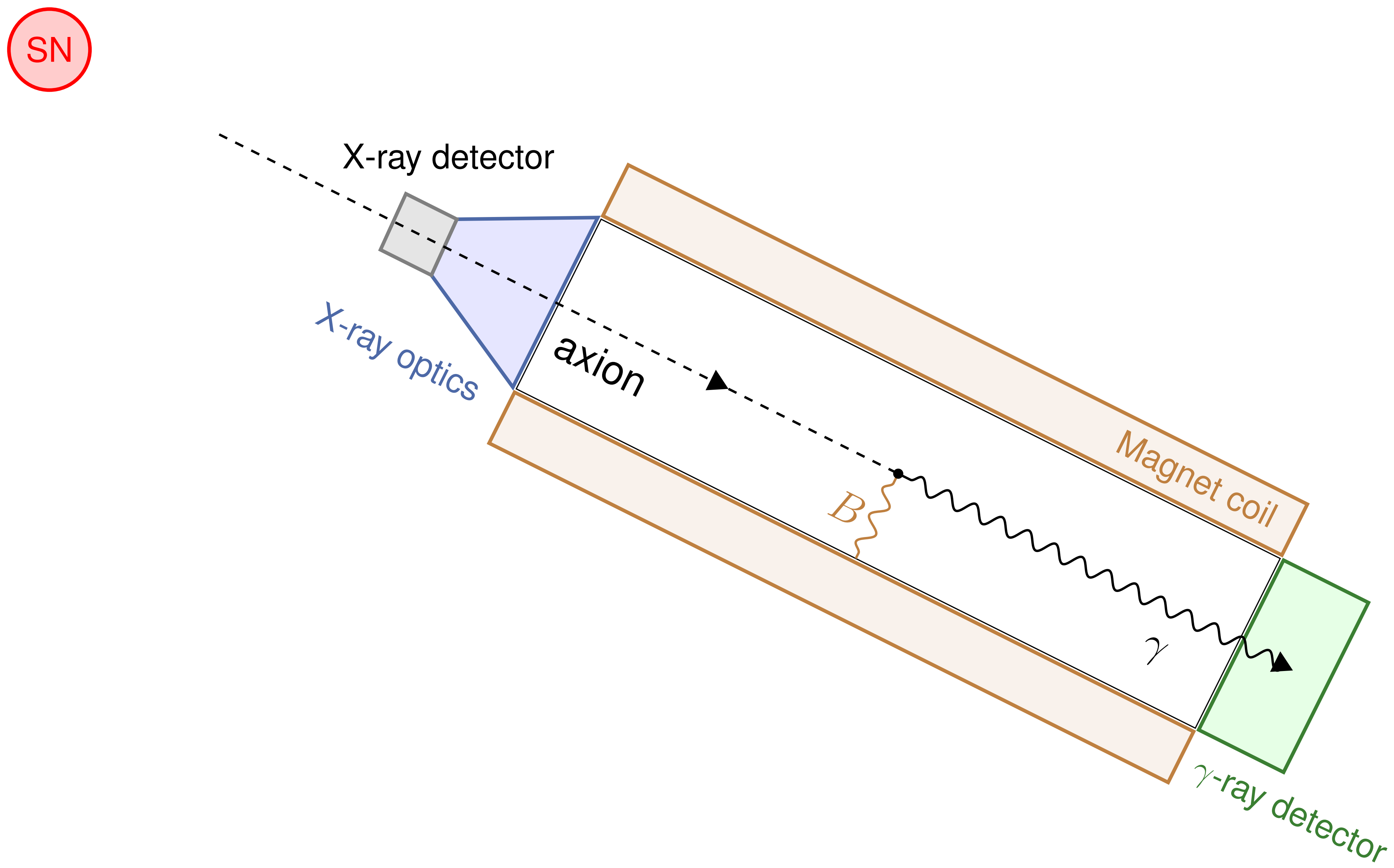


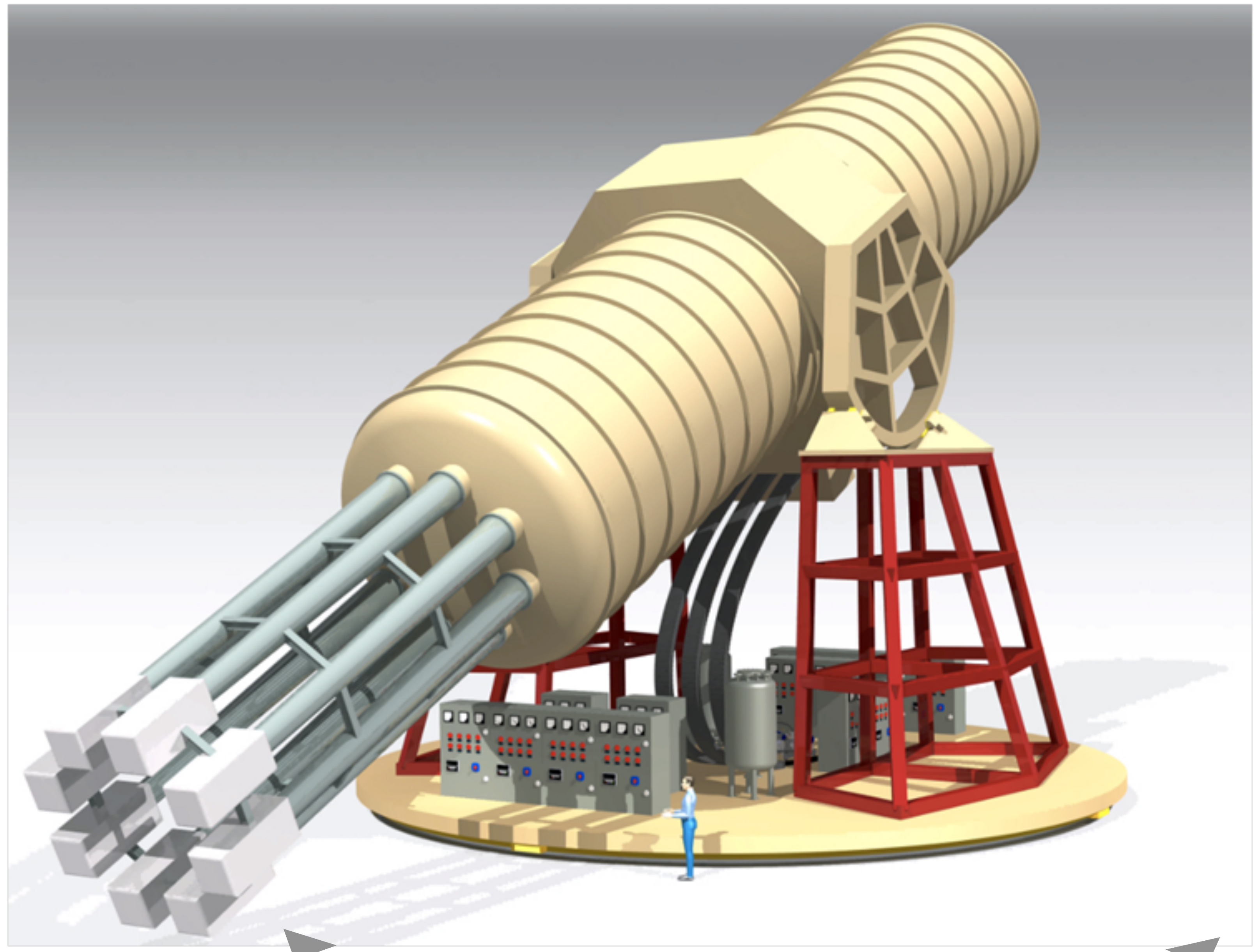
Plan

- **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



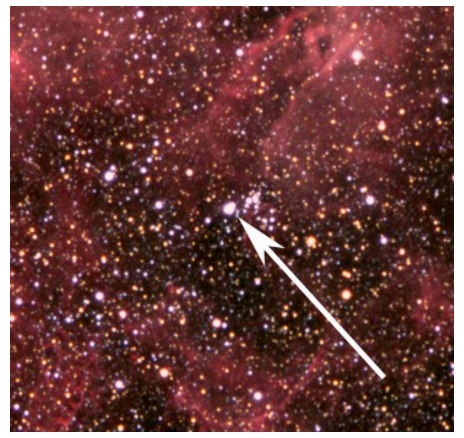
$$-\theta_{\max} \leq \theta \leq +\theta_{\max}$$

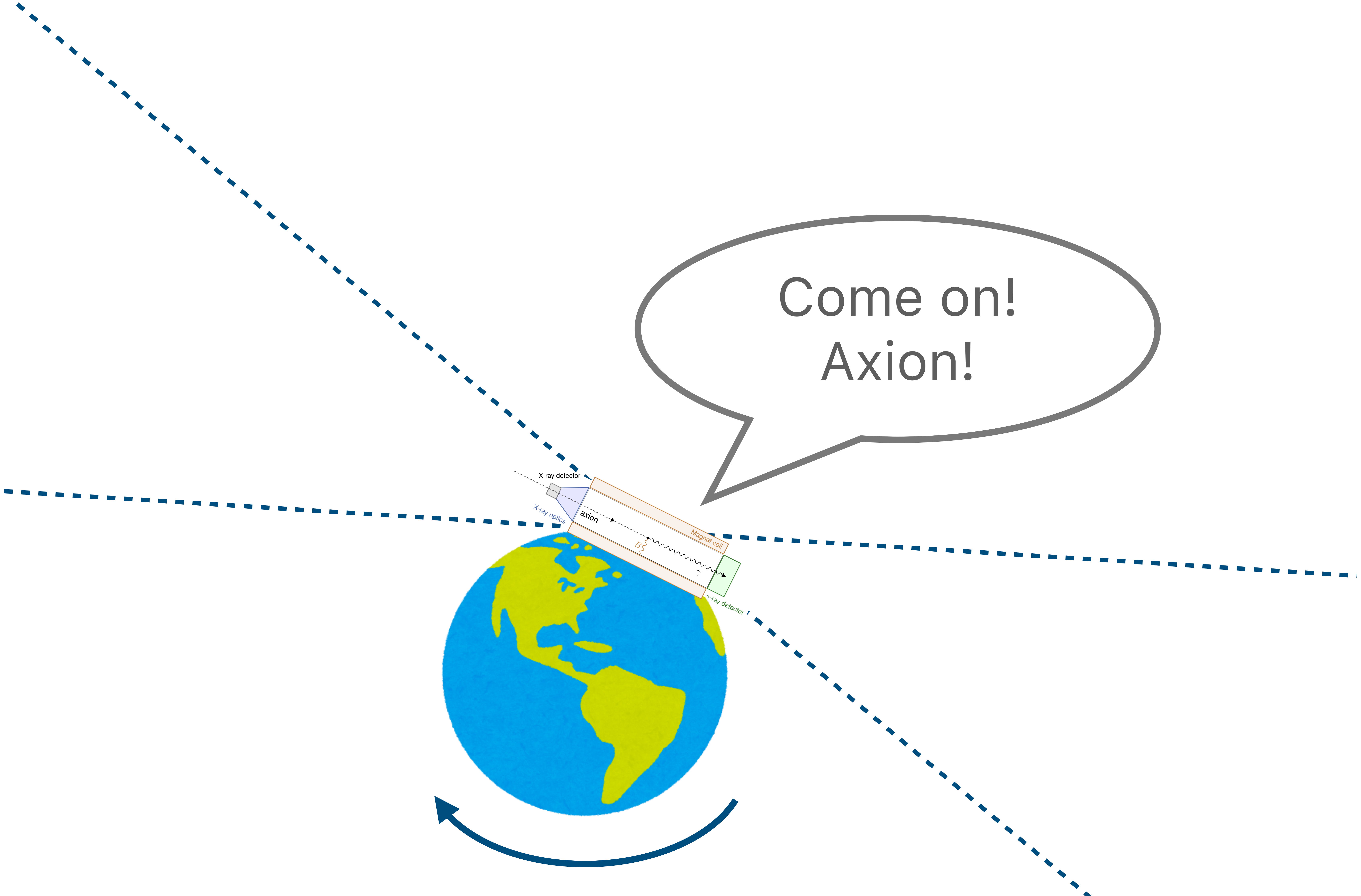
$$0 \leq \phi \leq 360^\circ$$

maximum elevation:

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

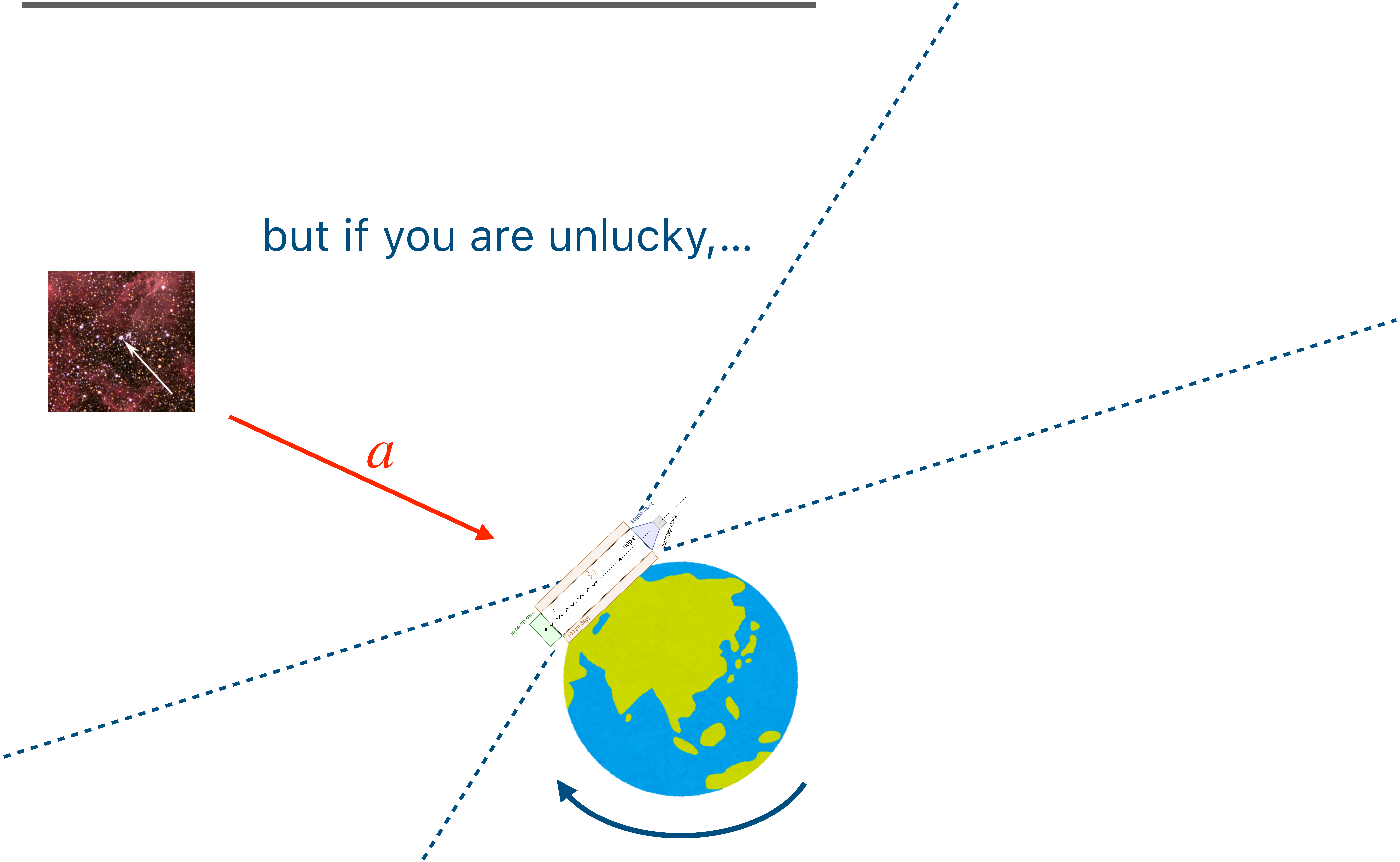
Observation time fraction





Observation time fraction

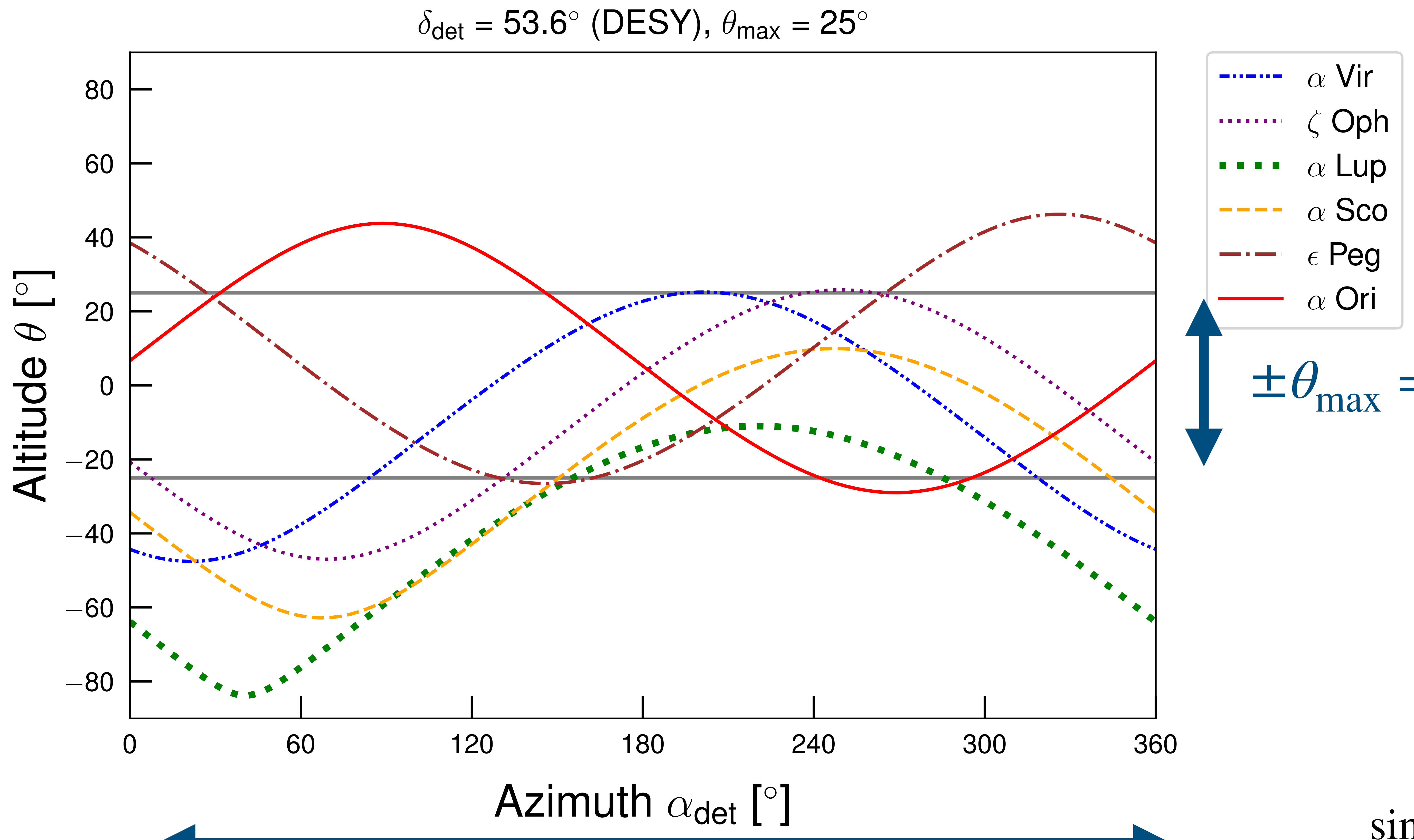
but if you are unlucky,...



Observation time fraction

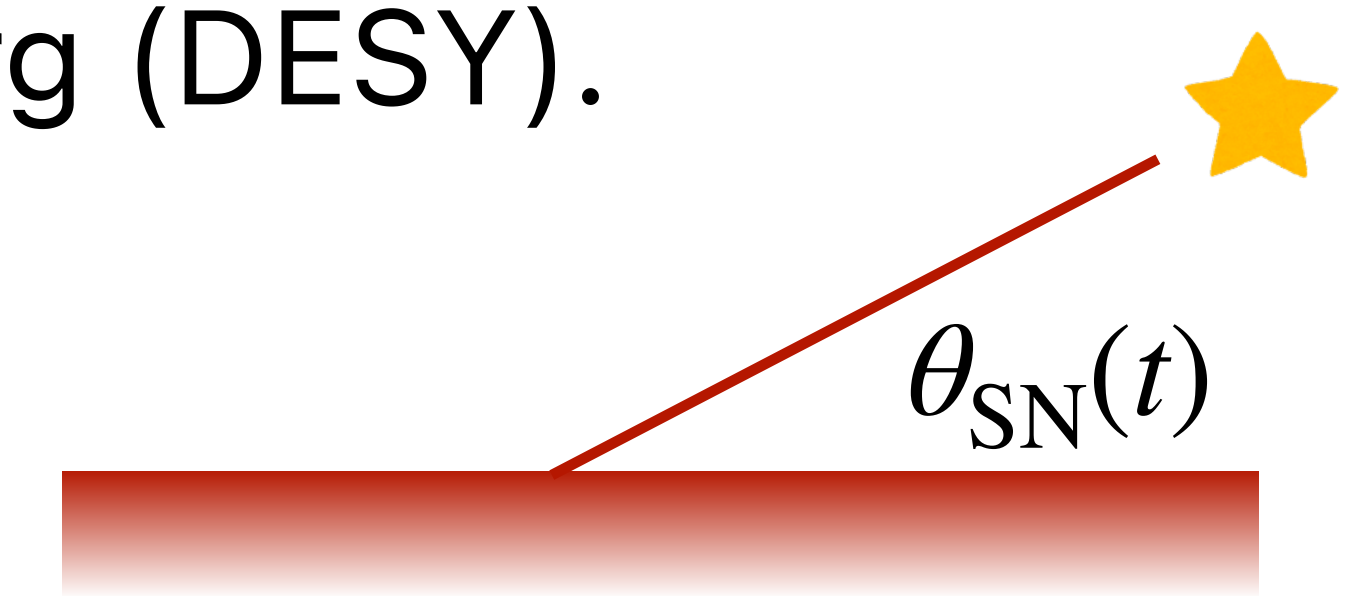
S.Ge, K.Hamaguchi, K.Ichimura, K.Ishidoshiro,
Y.Kanazawa, Y.Kishimoto, N.Nagata, J.Zheng.
[arXiv:2008.03924] JCAP **11** (2020) 059.

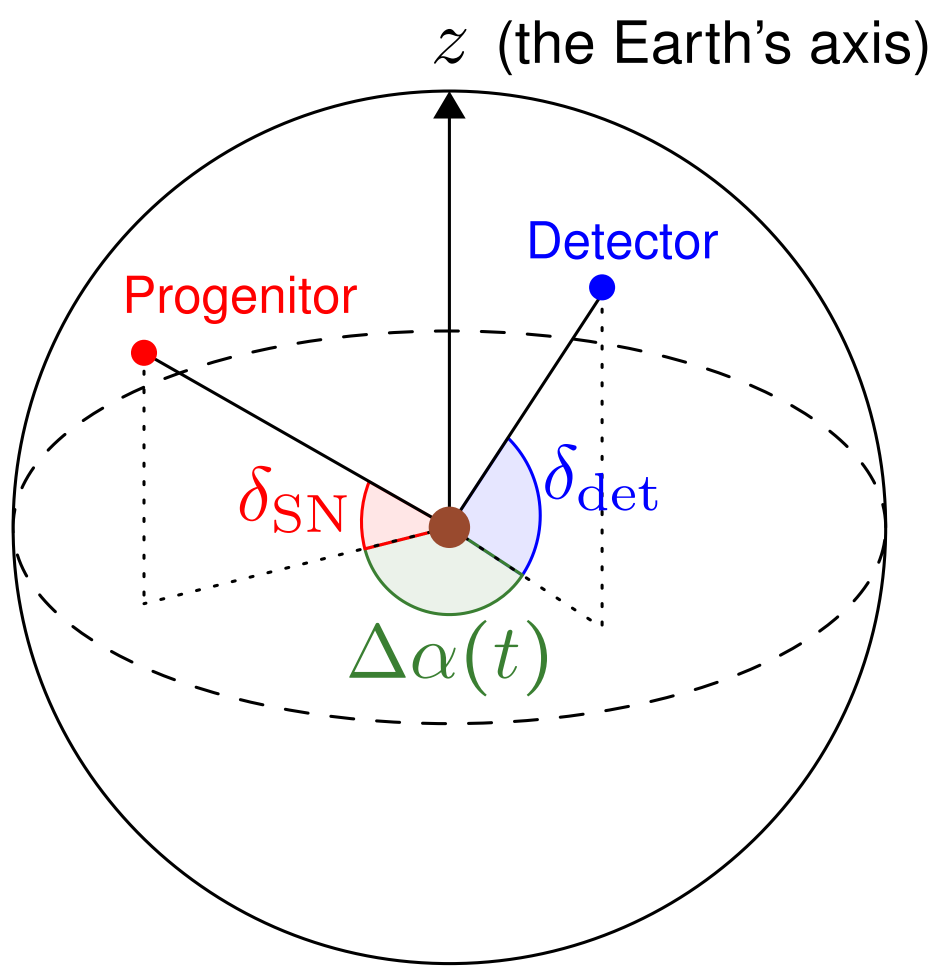
The altitude of the progenitors $\theta_{\rm SN}(t)$ seen from Hamburg (DESY).



$\pm\theta_{\rm max} = \pm 25^\circ$

Earth's rotation (24 hours)





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

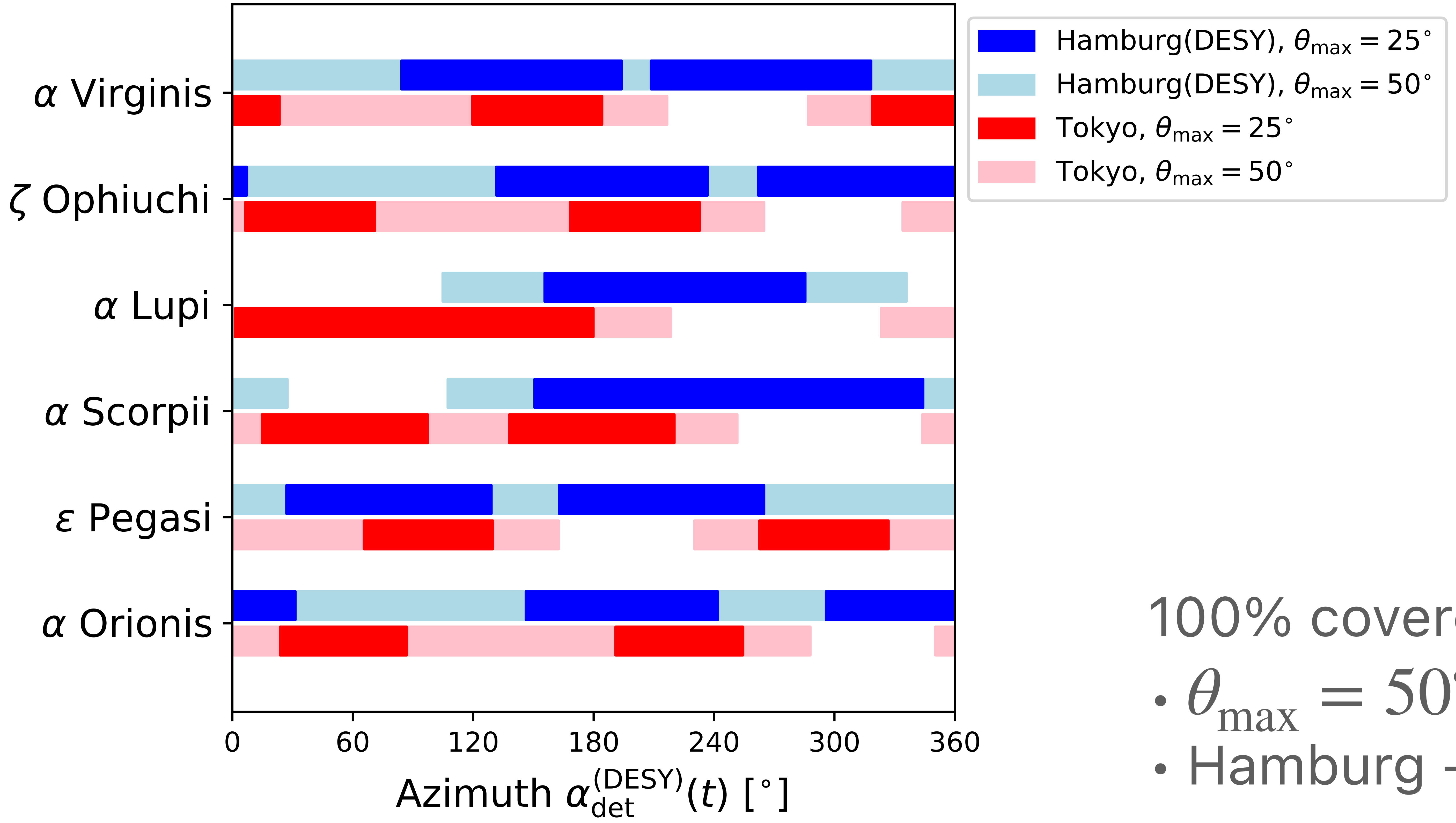
Observational time fraction > 50% for all the progenitors except α Lupi.

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 $\theta_{\rm max}$ 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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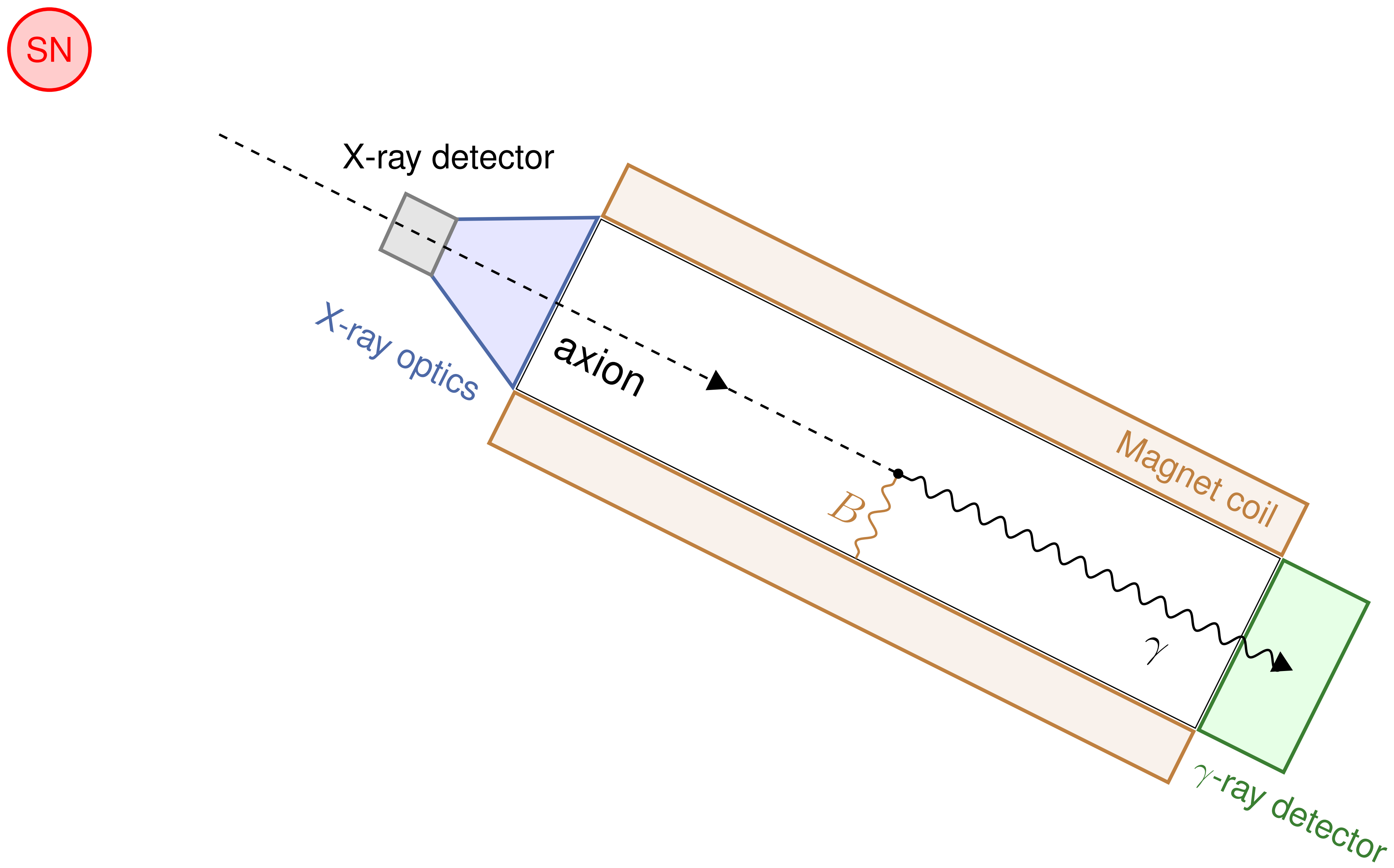
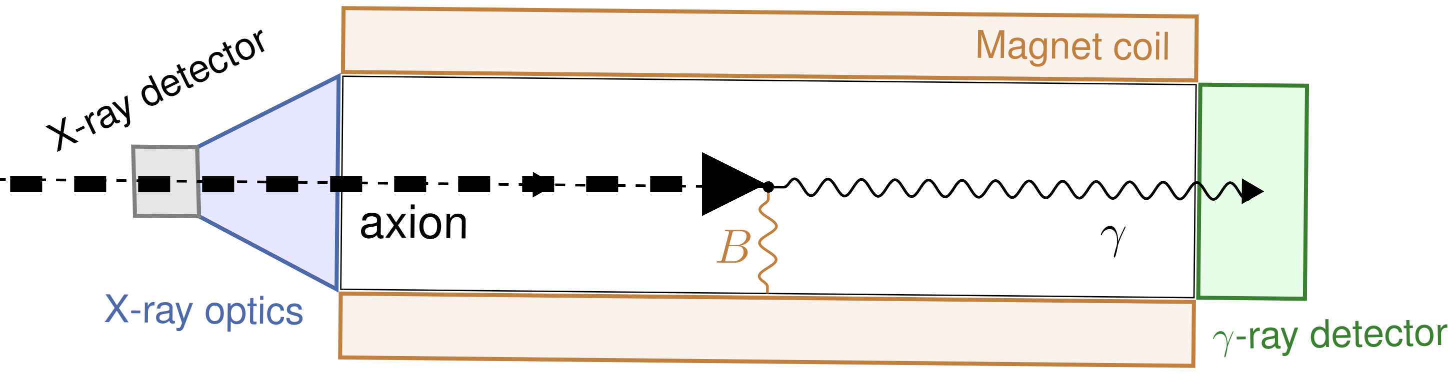
- **Summary**

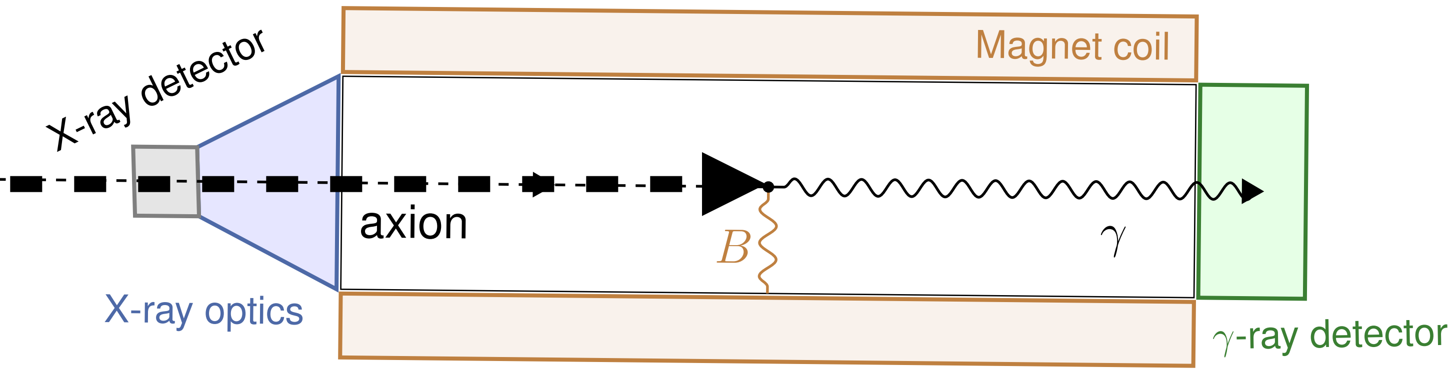


Event number



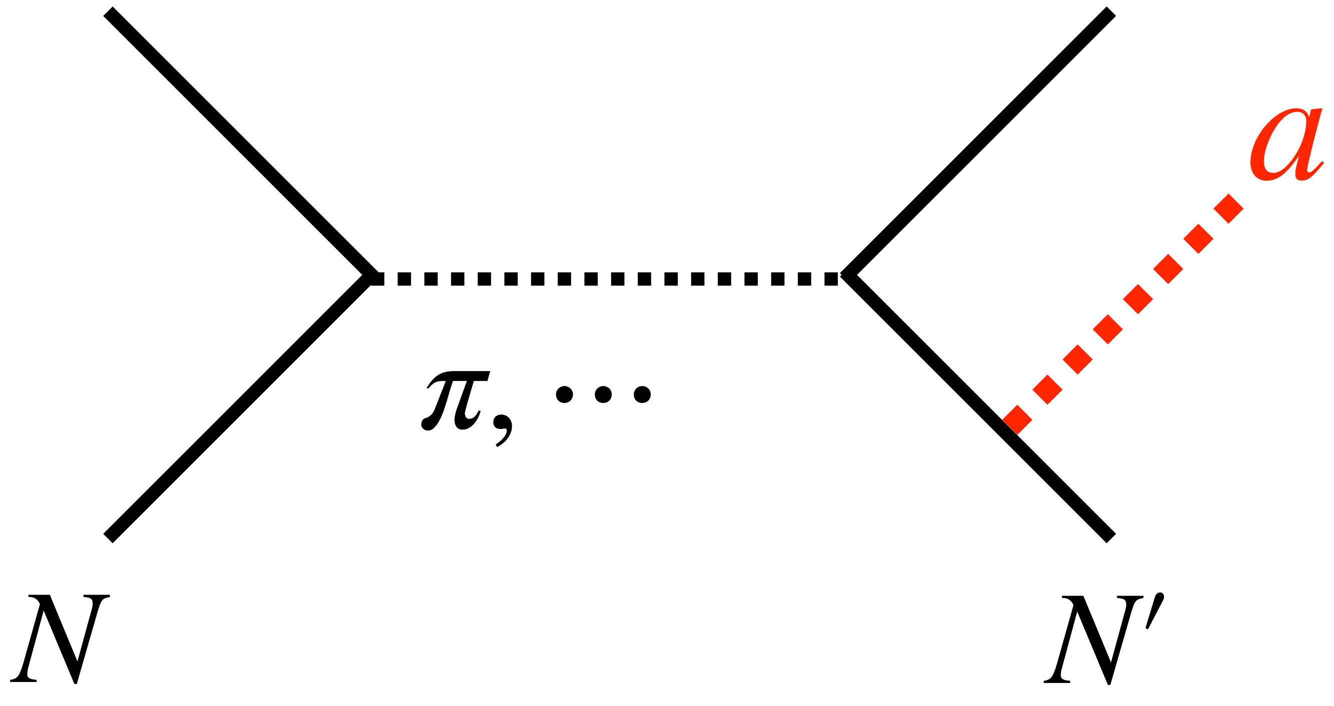
$$N_{\text{event}} = N_a^{\text{SN}} \times \frac{A}{4\pi d^2} \times P_{a\to\gamma}$$

Event number



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

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



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

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

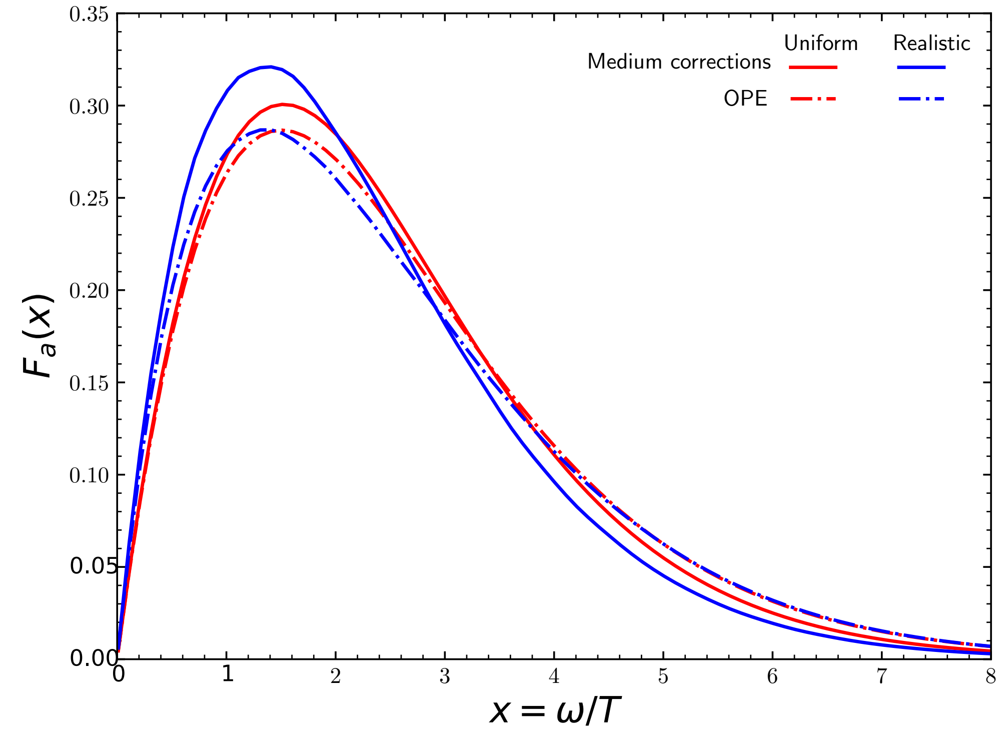
Production

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

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

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



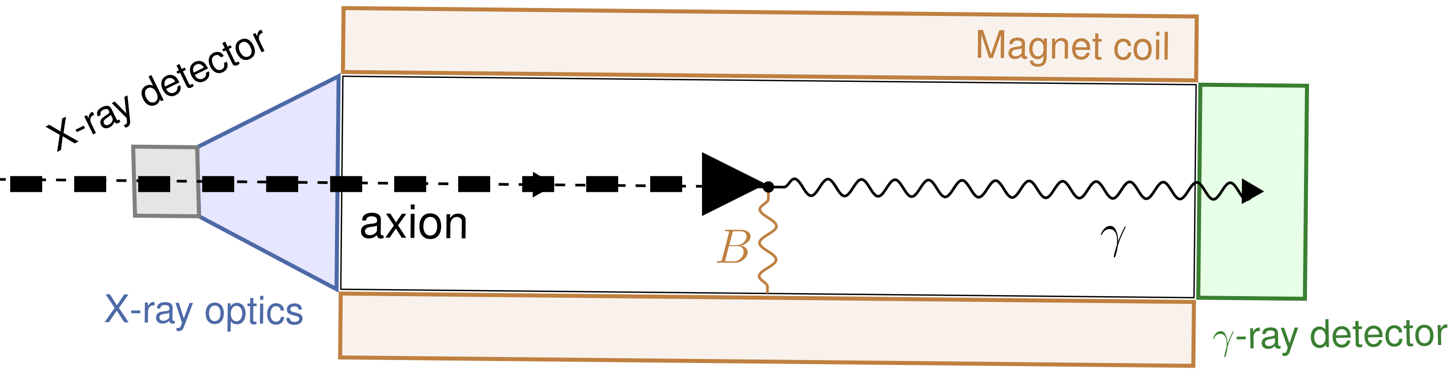
- Thus, the total number of axions from SN is

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

KSVZ

Event number

d



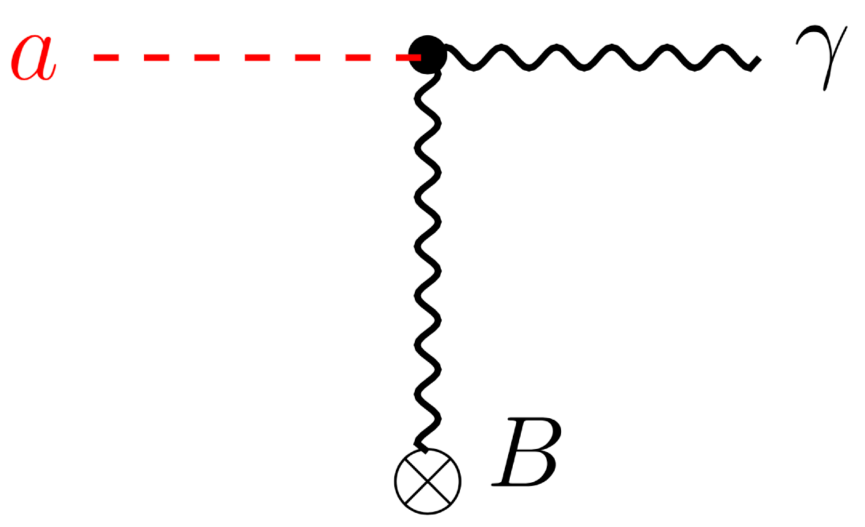
$$N_{\rm event} = N_a^{\rm SN} \times \frac{A}{4\pi d^2} \times P_{a\to\gamma}$$

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

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

Event number

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



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

Detection

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

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

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

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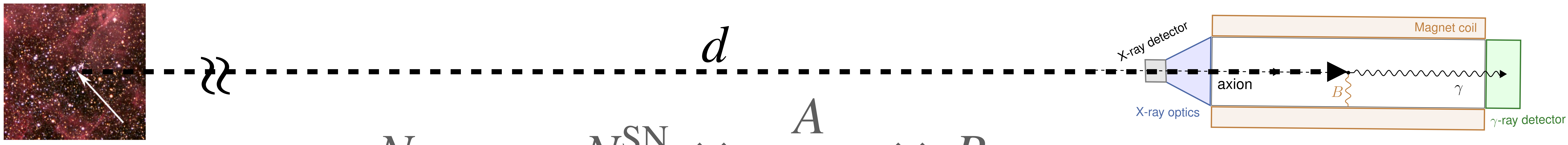
suppression factor

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

($a \leftrightarrow \gamma$ oscillation)

Event number



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

After all,...

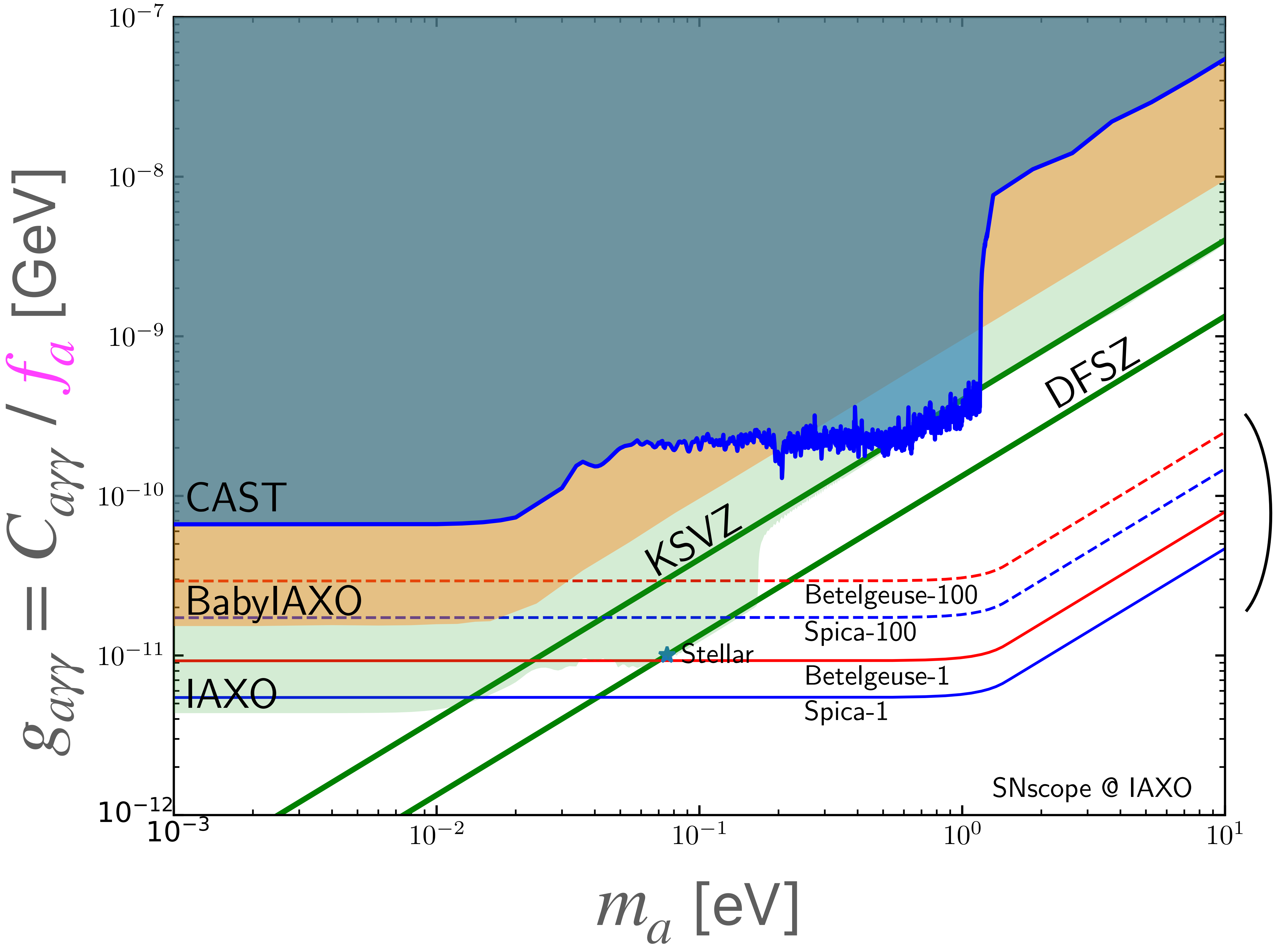
$$N_{\rm event} \simeq 1.0 \times \underbrace{\left(\frac{3\times 10^8\ {\rm GeV}}{f_a}\right)^4 \left(\frac{C_{N,{\rm eff}}}{0.37}\right)^2 \left(\frac{C_{a\gamma\gamma}}{\alpha/\pi}\right)^2}_{\text{axion model}} \times \underbrace{\left(\frac{150\ {\rm pc}}{d}\right)^2 \left(\frac{\Delta t}{10\ {\rm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

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

※ 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.

Event number

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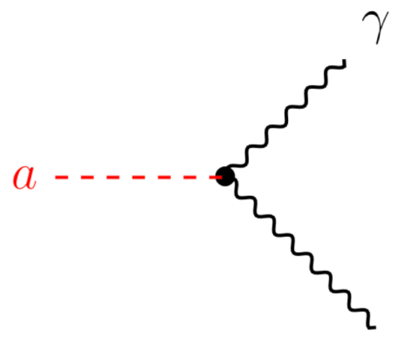
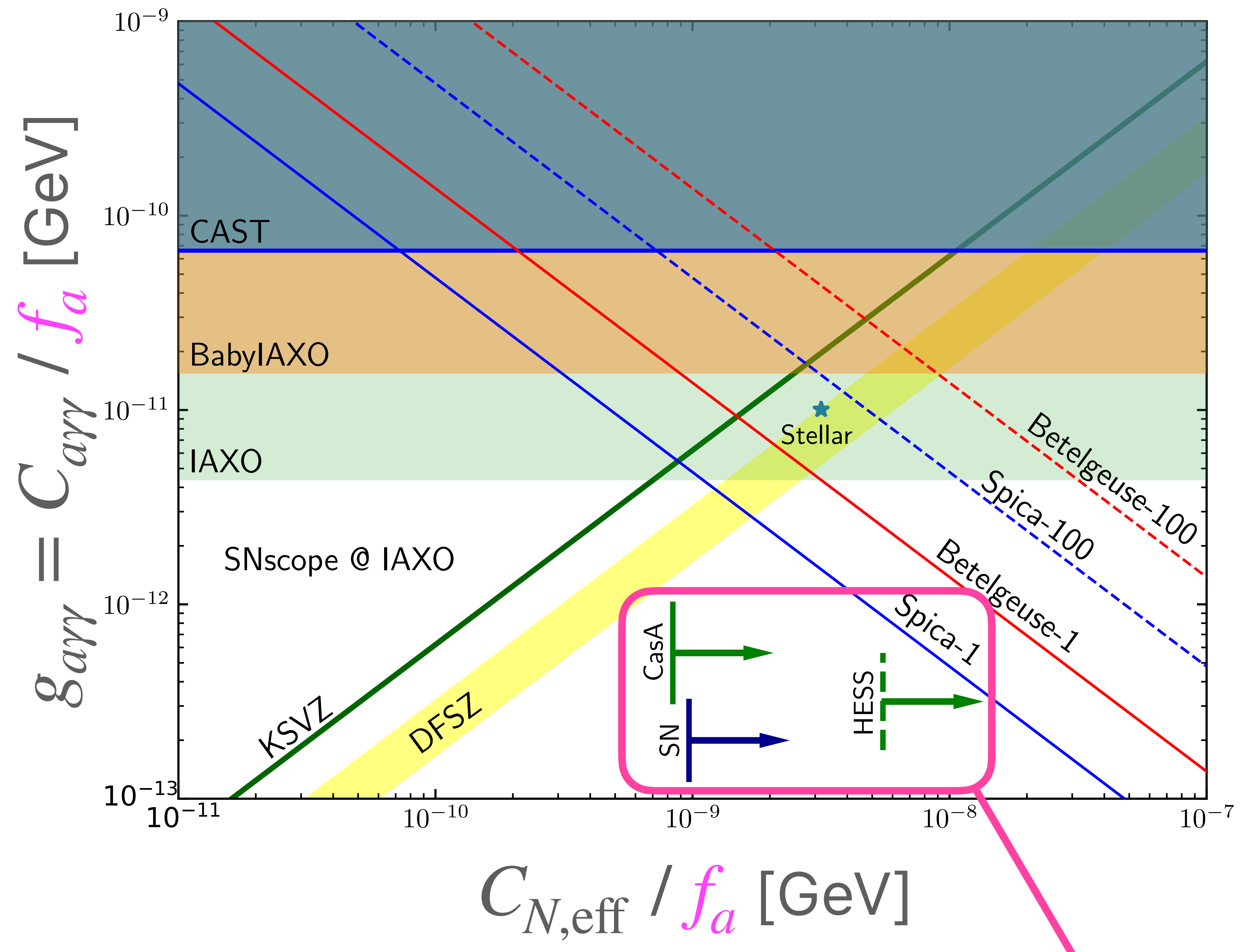
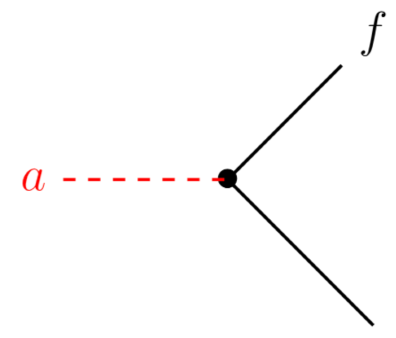
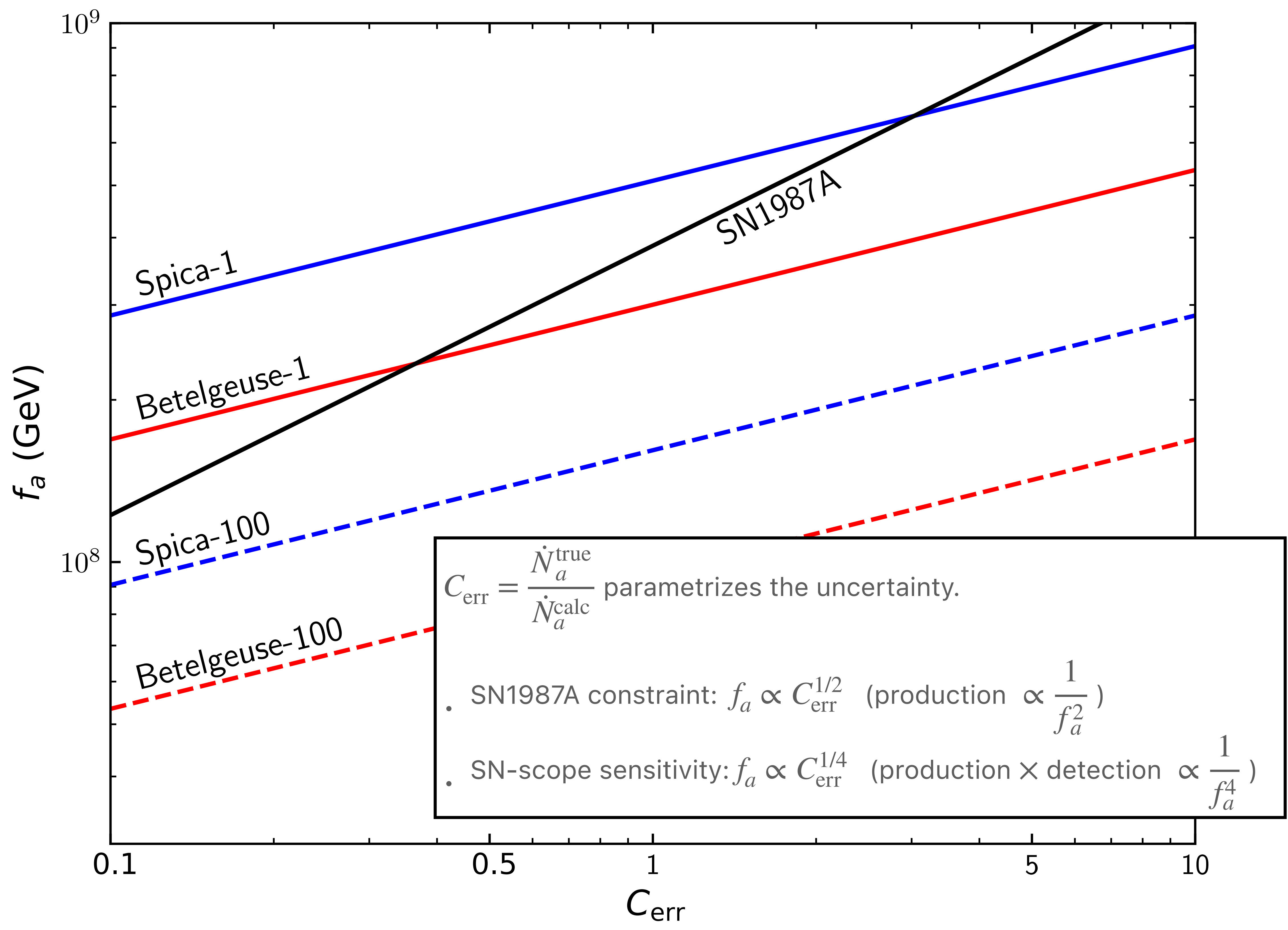
vs. stellar constraints







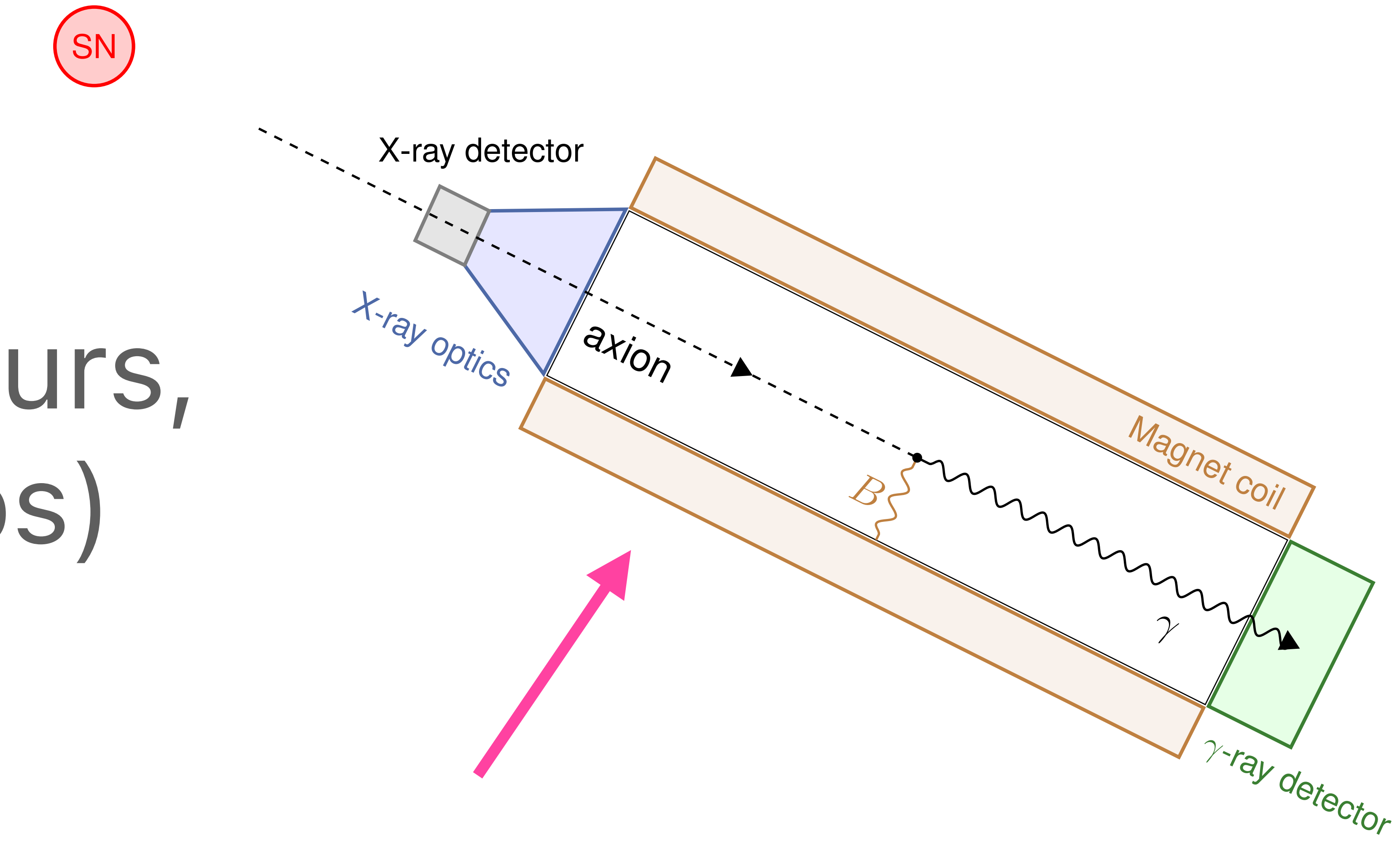
stellar constraints



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

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

Summary

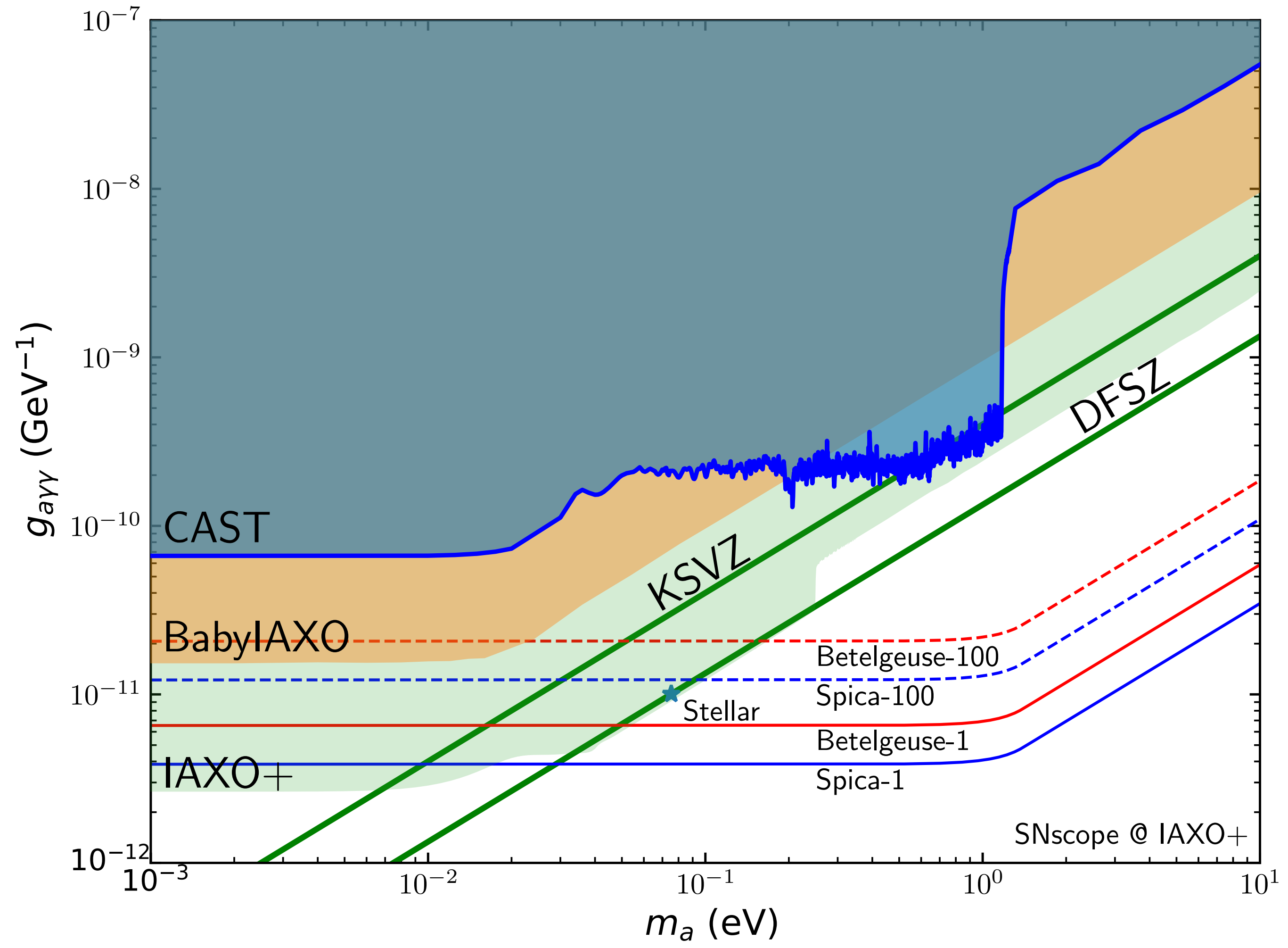


- If a nearby (< a few 100 pc) supernova (SN) occurs, a huge number of axions (in addition to neutrinos) may arrive at the Earth.

- 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!

backup

Motivation: axion

Conventional Models

- **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

- **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

---

cf. **Flaxion** model

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

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

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---

cf. **Flaxion** model

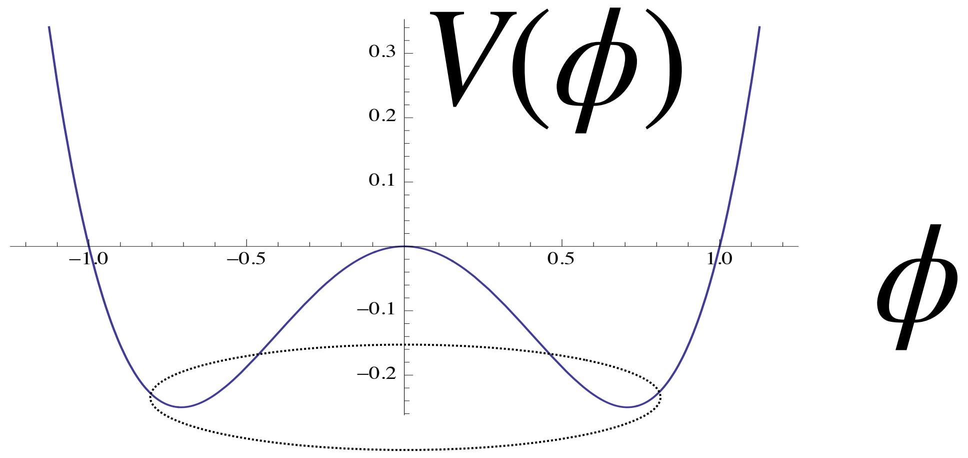
[Ema, Hamaguchi, Moroi, Nakayama,'16, Calibbi, Goertz, Redigolo, Ziegler, Zupan,'16]

$$\mathcal{L} = y_{ij}^d \left(\frac{\phi}{M}\right)^{n_{ij}^d} \overline{Q}_i H d_{Rj} + y_{ij}^u \left(\frac{\phi}{M}\right)^{n_{ij}^u} \overline{Q}_i \widetilde{H} u_{Rj}$$
$$+ y_{ij}^l \left(\frac{\phi}{M}\right)^{n_{ij}^l} \overline{L}_i H l_{Rj} + y_{i\alpha}^\nu \left(\frac{\phi}{M}\right)^{n_{i\alpha}^\nu} \overline{L}_i \widetilde{H} N_{R\alpha}$$
$$+ \frac{1}{2} y_{\alpha\beta}^N \left(\frac{\phi}{M}\right)^{n_{\alpha\beta}^N} M \overline{N_{R\alpha}^c} N_{R\beta} + \mathrm{h.c.}$$

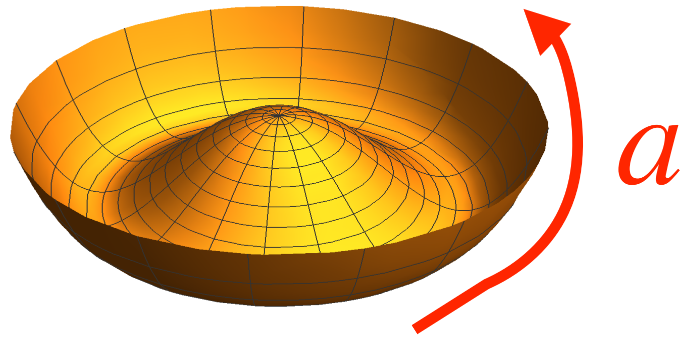
In all cases,...

ϕ : complex scalar (Peccei-Quinn field)

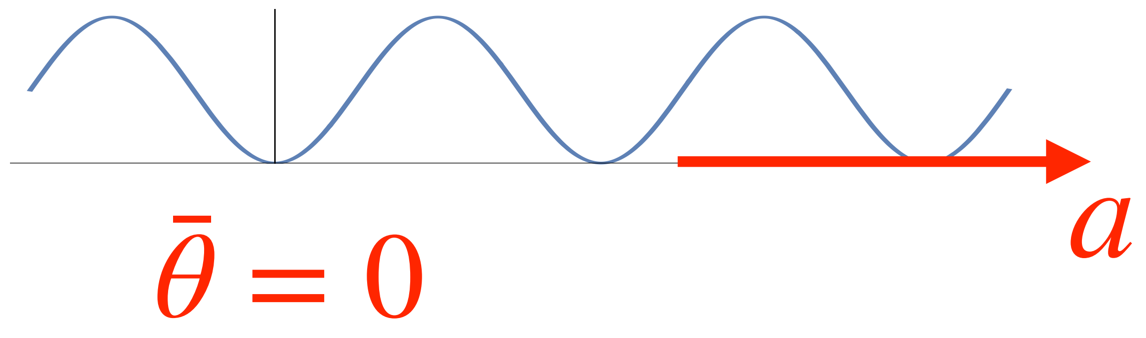
$U(1)_{PQ}$ ($\phi \to \phi e^{i\alpha}$) is spontaneously broken



Nambu-Goldstone boson = Axion



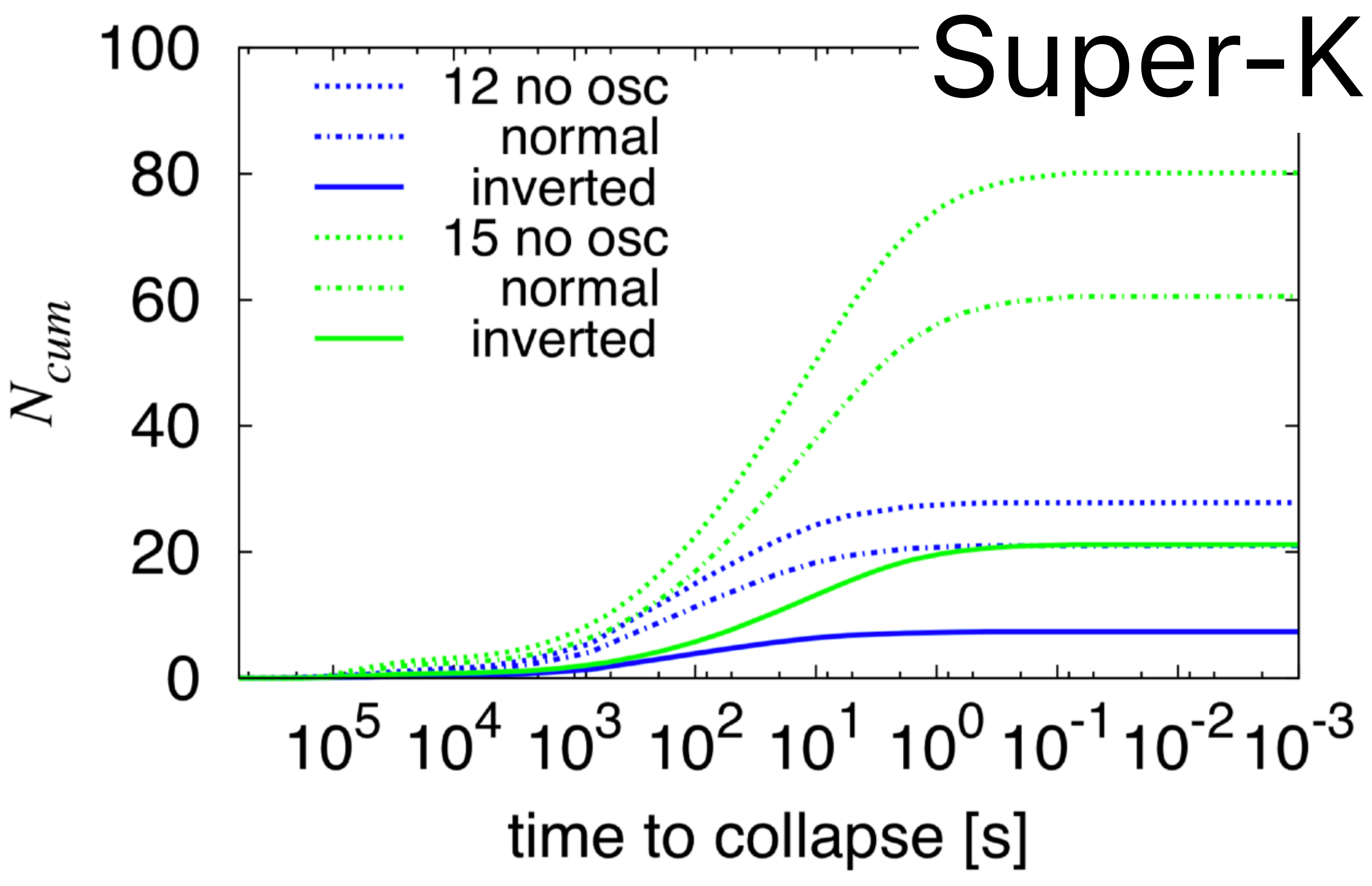
From anomaly, $\mathscr{L}_{\text{axion}} \ni \frac{\alpha_s}{8\pi}\frac{a}{f_a} G_{\mu\nu}^a \widetilde{G}^{a\mu\nu}$

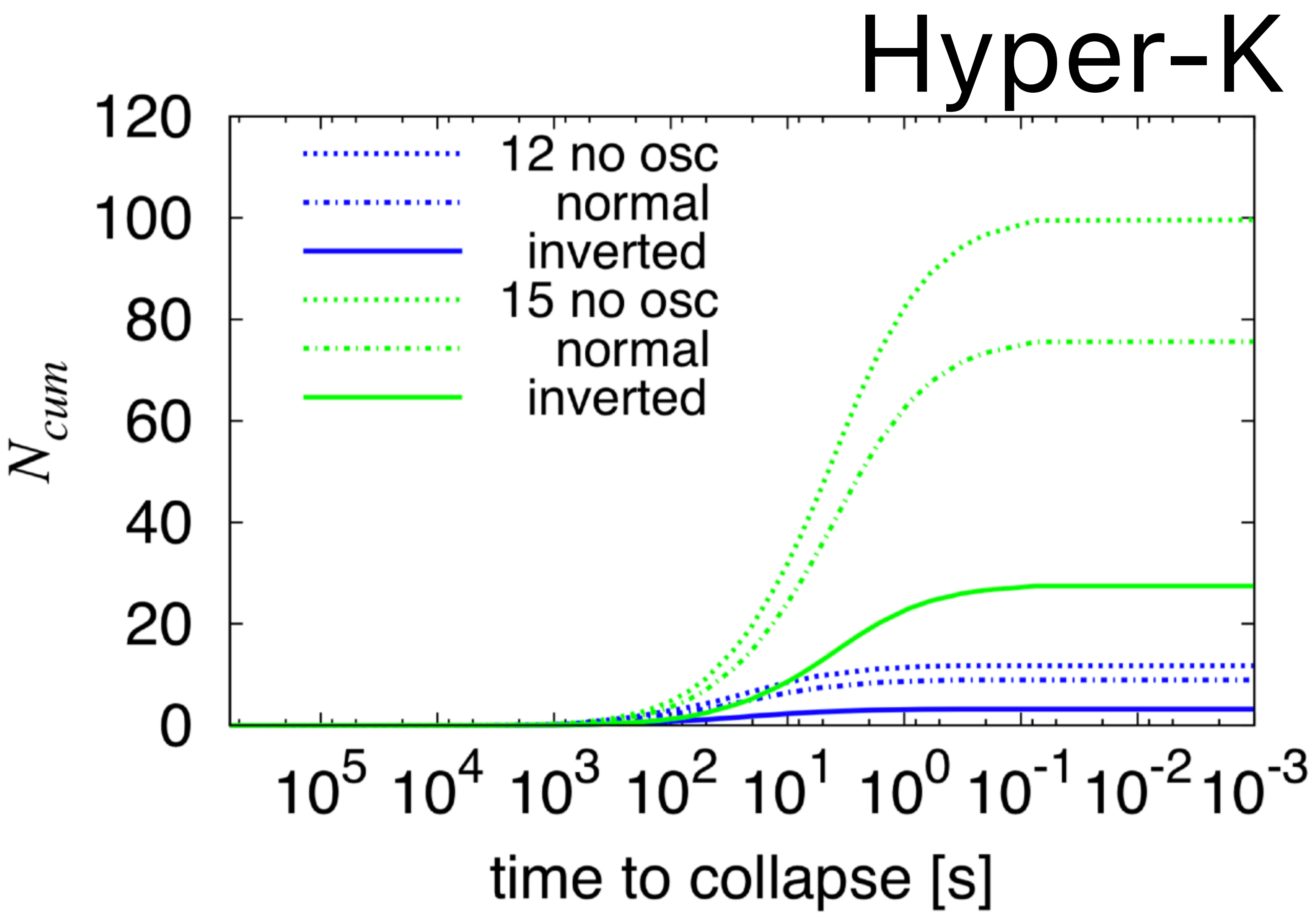


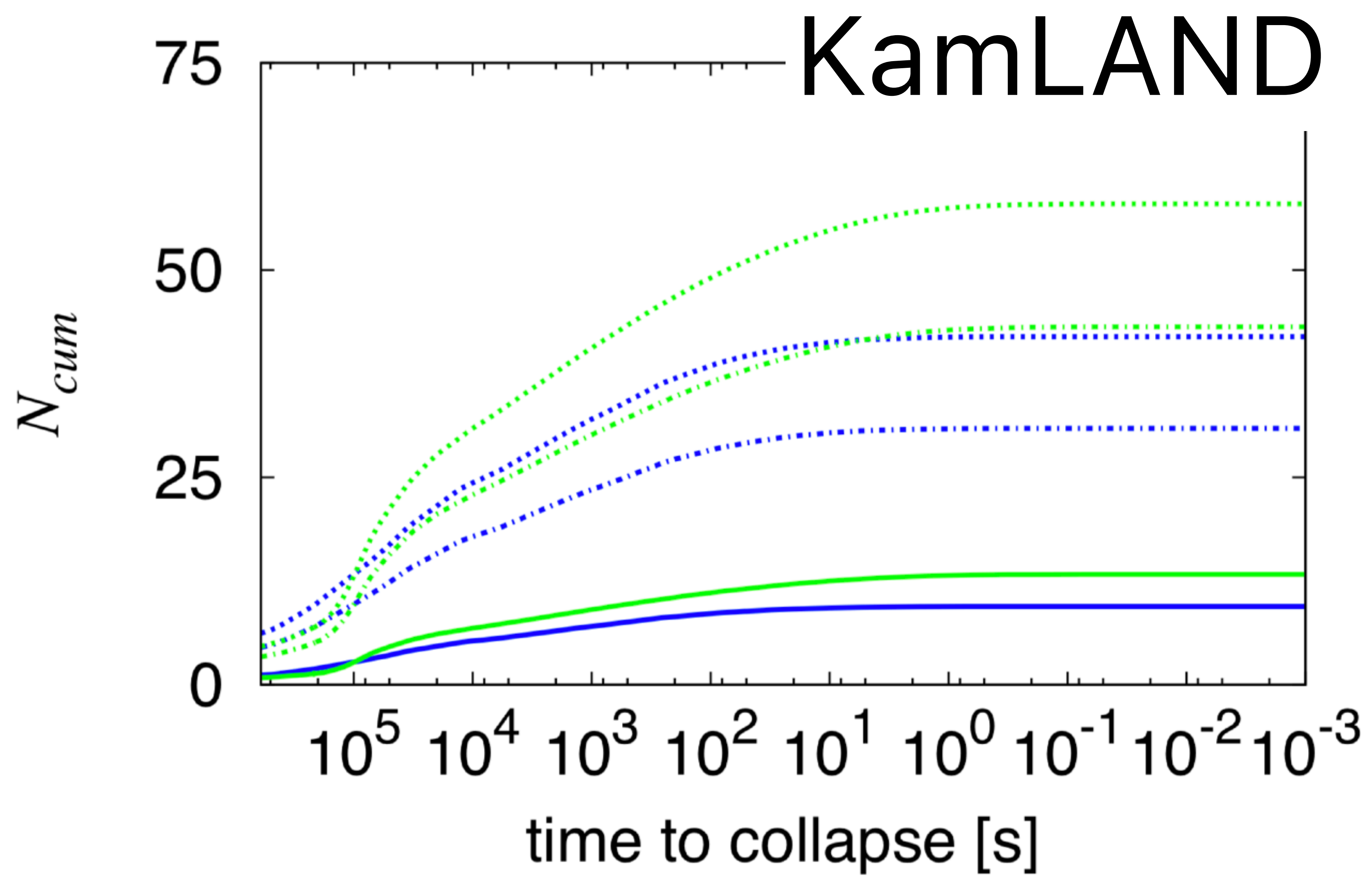
→ **Strong CP problem is solved.**

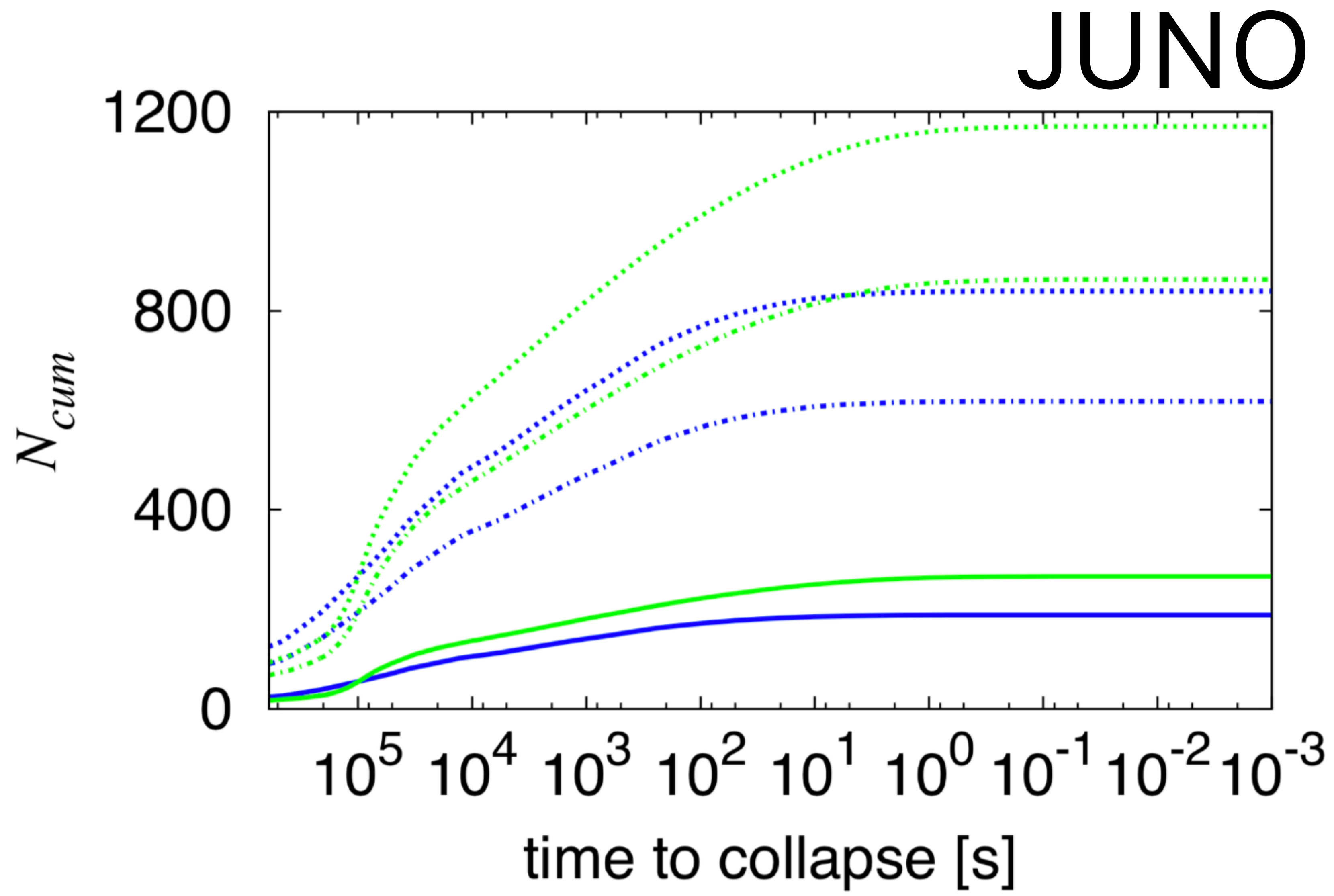
C. Kato et.al., [1506.02358].

The cumulative numbers of expected neutrino events for Fe-Core, $d = 200$ pc.









cf. The background at KamLAND is low ~ 1 event/day.

Table 1
The detector parameters assumed in this paper.[a]

Detector	Mass [kt]	Target number N	Energy threshold [MeV]
Super-K	32	2.14×10^{33}	5.3
KamLAND	1	8.47×10^{31}	1.8
Hyper-K	540	3.61×10^{34}	8.3
JUNO	20	1.69×10^{33}	1.8

References. — (1) Super-K Calib 2013; (2) KamLAND Calib 2009; (3) Hyper-K Calib 2011; (4) JUNO Calib 2014

Table 2 Detection ranges and alarm times for normal (inverted) mass ordering, where a false alarm rate is 1 yr^{-1}, for four pre-SN neutrino models with 15 $M_\odot$.

Detector	Model	$N_s^{DC}(t=0.01)$	Detection range [pc]	Alarm time [hr]	t_w [hr]
SK-Gd	Kato	46.7–49.9 (10.9–11.7)	380–480 (180–230)	0.1-0.6 (–0.02)	12
		50.8–54.3 (12.2–13.0)	350–460 (170–220)	0.2–4.5 (–0.02)	24
		54.3–58.0 (13.3–14.3)	320–430 (160–210)	0.2–10 (–0.01)	48
	Yoshida	21.4–22.8 (12.4–13.2)	260–330 (190–250)	0.1–1 (–0.1)	12
		26.3–28.0 (15.0–16.0)	260–340 (190–260)	0.4–6 (–0.2)	24
		28.4–30.2 (16.1-17.2)	240–320 (180–240)	0.2–6.5 (–0.2)	48
	Odrzywolek	45.3–48.3 (12.8–13.7)	380–490 (200–260)	4–6.5 (0.02–1.7)	12
		47.3–50.4 (13.4–14.3)	340–460 (180–240)	3–6.5 (–1.6)	24
		49.1-52.4 (14.0-14.9)	310–420 (170–220)	3–7 (–0.7)	48
	Patton	43.5–46.3 (12.9–13.9)	370–480 (200–260)	3.5–6 (0.02–0.9)	12
		45.8–48.9 (13.8–14.7)	340–450 (180–250)	3–6.5 (–0.5)	24
		46.8–49.8 (14.1–15.0)	310–410 (170–220)	2.5–5.5 (–0.1)	48
KamLAND	Kato	7.6 (1.6)	340–410 (150–190)	0.2-1 (NA)	12
		9.3 (2.1)	350–440 (170–210)	5.5–20 (–0.02)	24
		10.9 (2.6)	360–460 (180–220)	17–26 (–0.1)	48
	Yoshida	4.5 (2.4)	260–310 (190–230)	0.5–16 (–0.1)	12
		6.5 (3.5)	290–370 (210–270)	8–18 (0.1–1.8)	24
		7.7 (4.1)	310–390 (220–280)	15–22 (0.3–7.5)	48
	Odrzywolek	9.7 (2.8)	380–460 (200–240)	5.5–8 (0.04–1.7)	12
		11.0 (3.1)	380–480 (200–250)	7–13 (0.08–2)	24
		12.4 (3.5)	390–490 (200–260)	11–38 (0.1–2.5)	48
	Patton	10.1 (2.9)	390–470 (200–250)	5.5–8.5 (0.07–1.9)	12
		11.4 (3.5)	390–490 (210–260)	7–11 (0.1–2.5)	24
		12.2 (3.6)	380–490 (210–260)	7.5–13 (0.1–3)	48
JUNO	Kato	232 (48.7)	950 (430)	54 (24)	12
		286 (65.2)	950 (440)	64 (28)	24
		341 (81.8)	960 (470)	62 (34)	48
	Yoshida	142 (75.7)	740 (540)	52 (30)	12
		205 (109)	810 (590)	64 (38)	24
		247 (131)	810 (590)	62 (46)	48
	Odrzywolek	303 (86.2)	1090 (580)	78 (14)	12
		344 (97.8)	1050 (560)	76 (28)	24
		391 (111)	1030 (540)	74 (48)	48
	Patton	315 (90.6)	1110 (590)	30 (17)	12
		360 (106)	1070 (580)	34 (19)	24
		385 (115)	1020 (550)	38 (20)	48

C.Kato, K.Ishidoshiro, T.Yoshida [2006.02519].

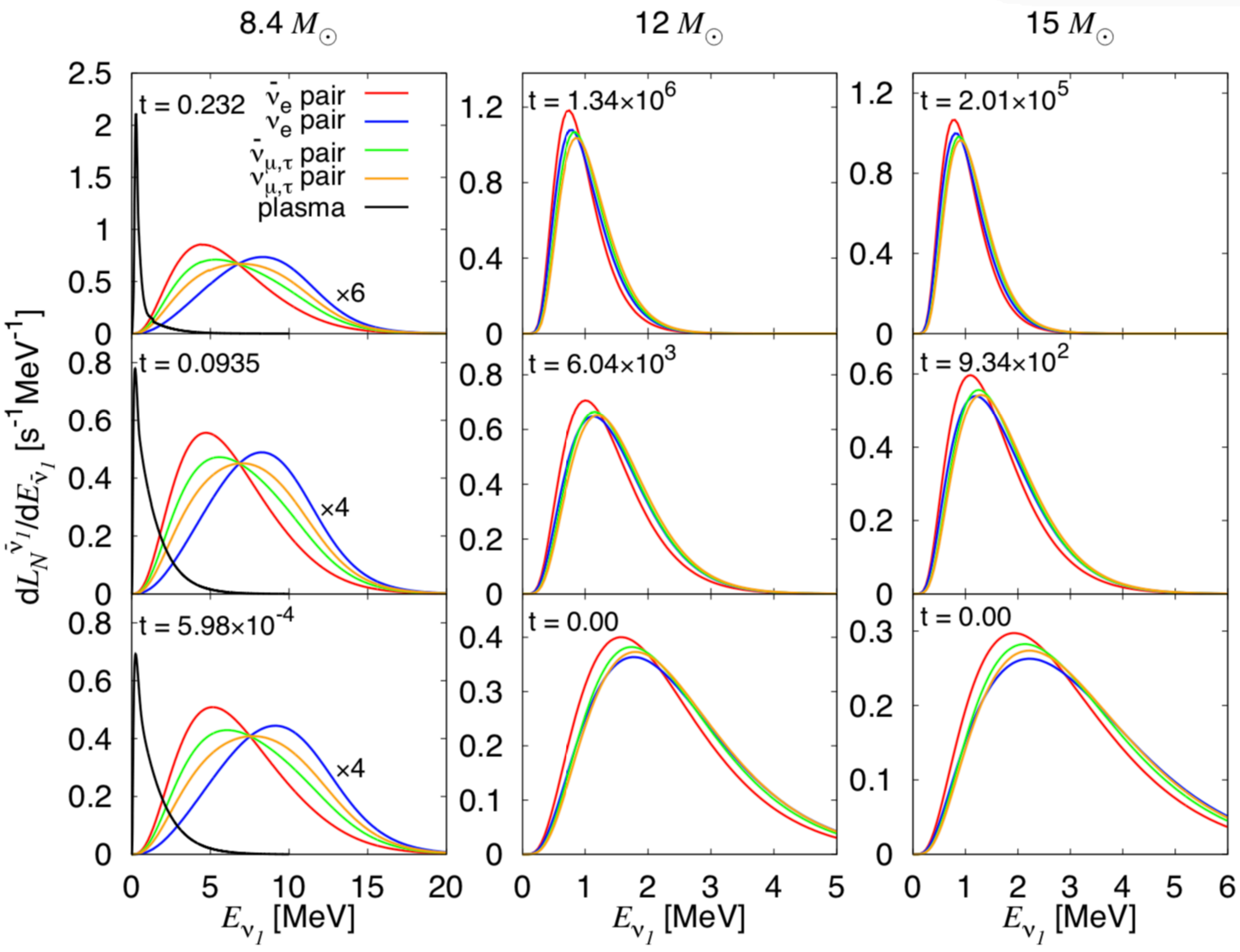
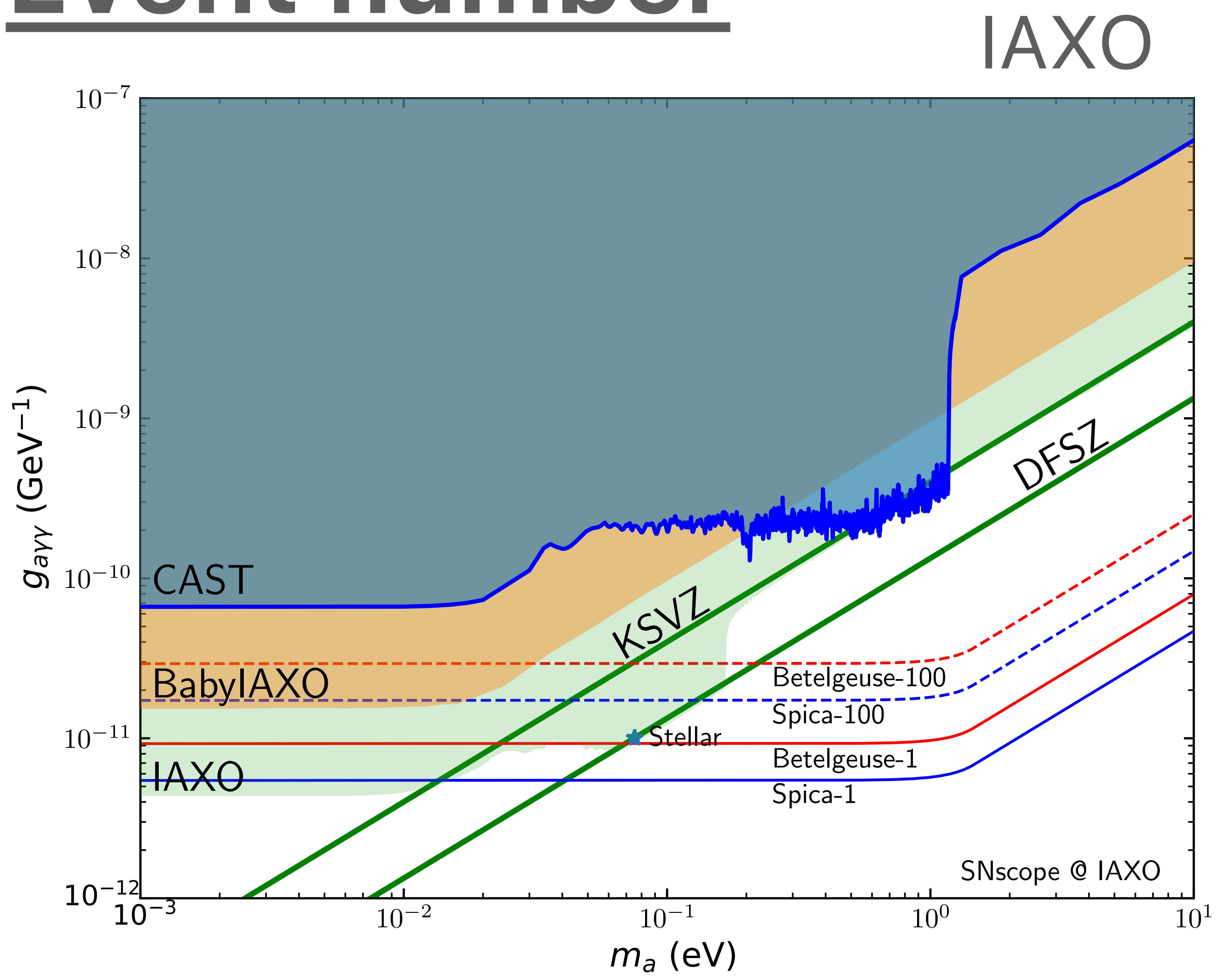
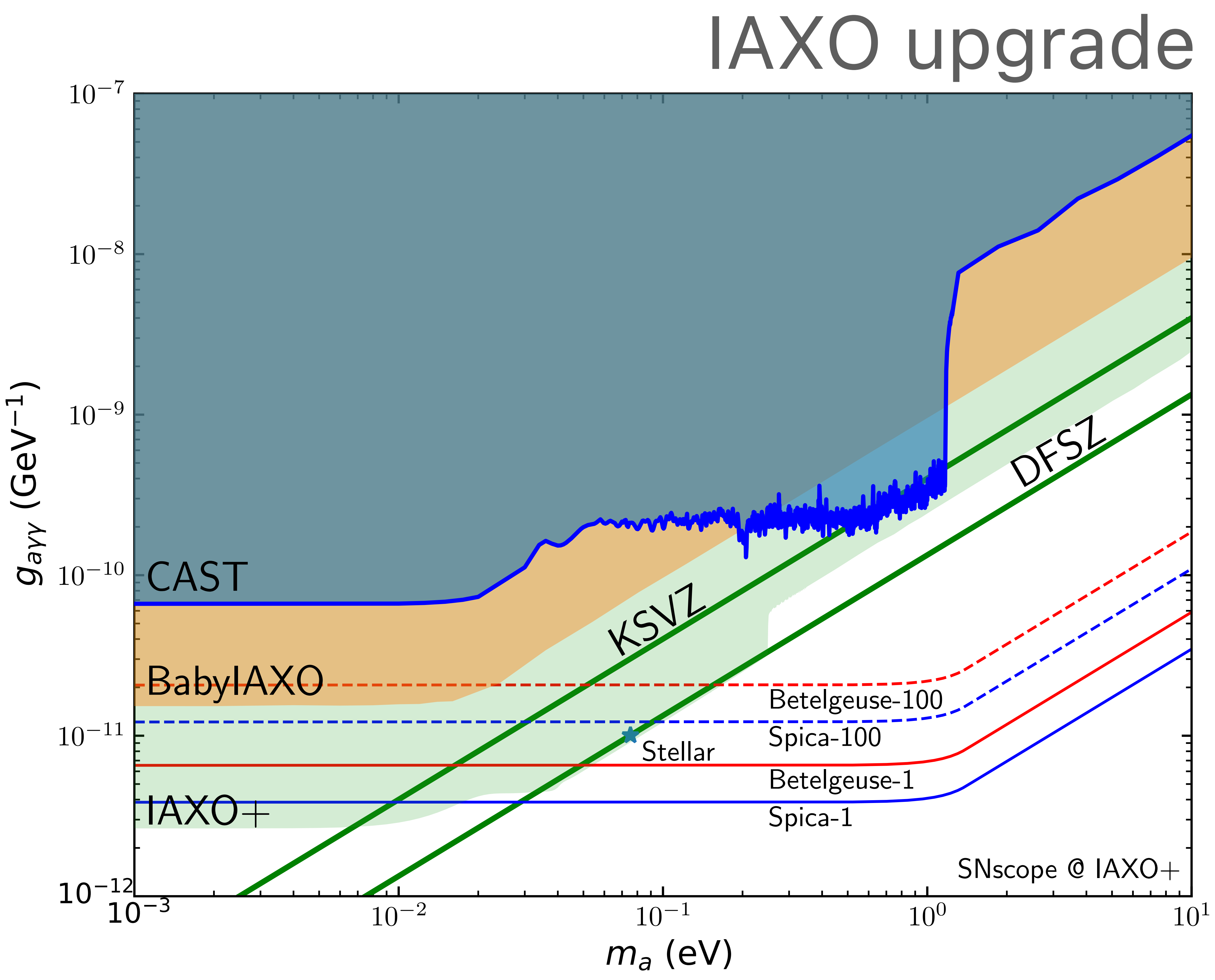


Figure 12. Normalized number spectra at different times for 8.4 M$_\odot$ (left panels), 12 M$_\odot$ (middle panels) and 15 M$_\odot$ (right panels). Red, blue, green and orange curves correspond, respectively, to $\bar{\nu}_e$ and ν_e from the pair annihilation and $\bar{\nu}_\mu/\bar{\nu}_\tau$ and ν_μ/ν_τ from the pair annihilation. All neutrinos have the identical spectrum after normalization for the plasmon decay as shown with black. For better visibility, all the lines but the black one in the left panels are multiplied by the factors indicated. Note that larger t's correspond to earlier times.

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

Event number





from P.Carenza et.al., 1906.11844]

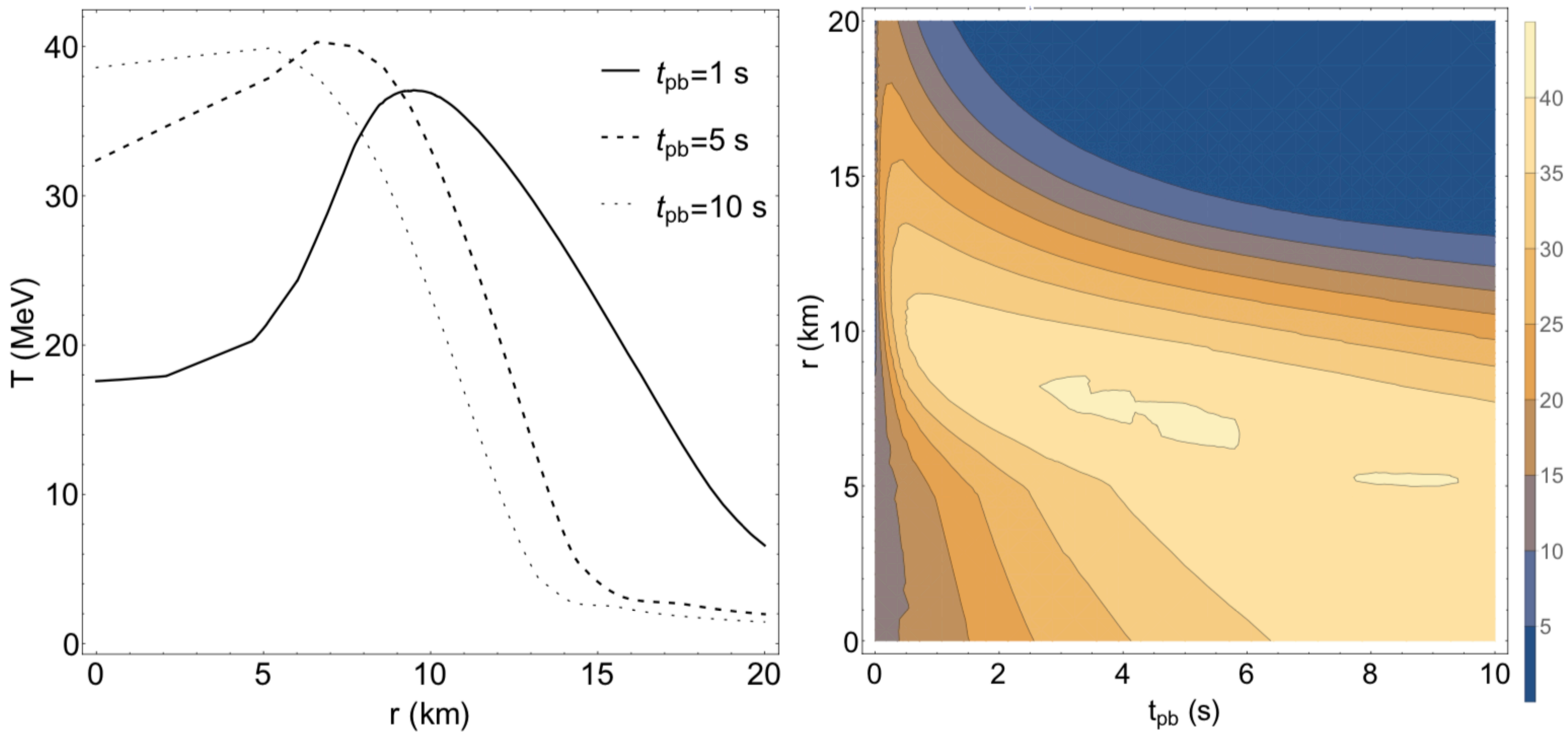


Figure 2. Left panel: Radial evolution of the temperature T at different post-bounce times $t_{\rm pb}$. Right panel: T behavior in the plane $t_{\rm pb}$-r.

from P.Carenza et.al., 1906.11844]

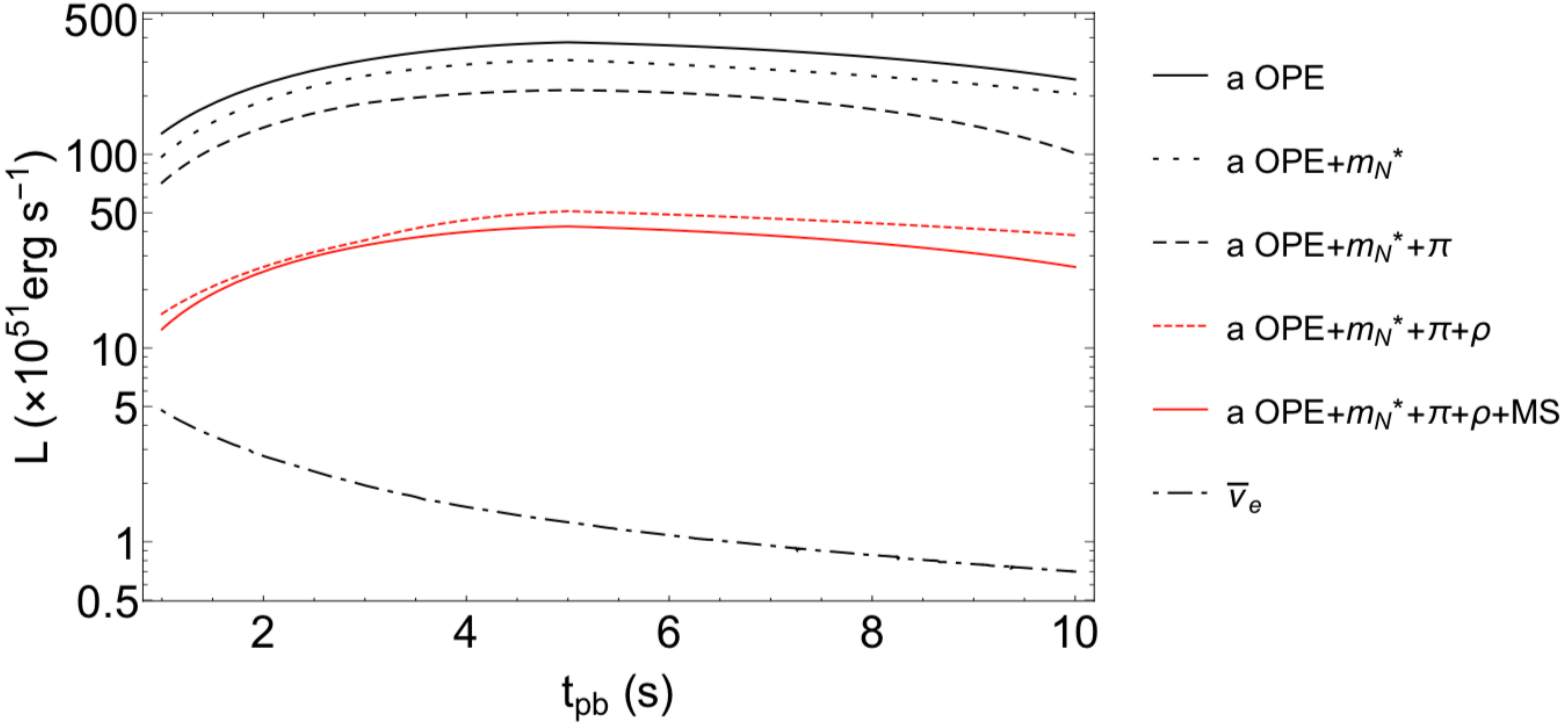


Figure 14. Time evolution of the axion luminosity L_a for $g_{an} = g_{ap} = 5 \times 10^{-10}$ for OPE (black continuous curve), and including the effective nucleon mass (black dot-dashed curve), a finite pion mass (black dotted curve), the exchange of the ϱ meson (red dotted curve), and multiple nucleon scatterings (red continuous curve), compared with the $\bar{\nu}_e$ luminosity (black dashed curve).

Improved axion emissivity from a supernova via nucleon-nucleon bremsstrahlung

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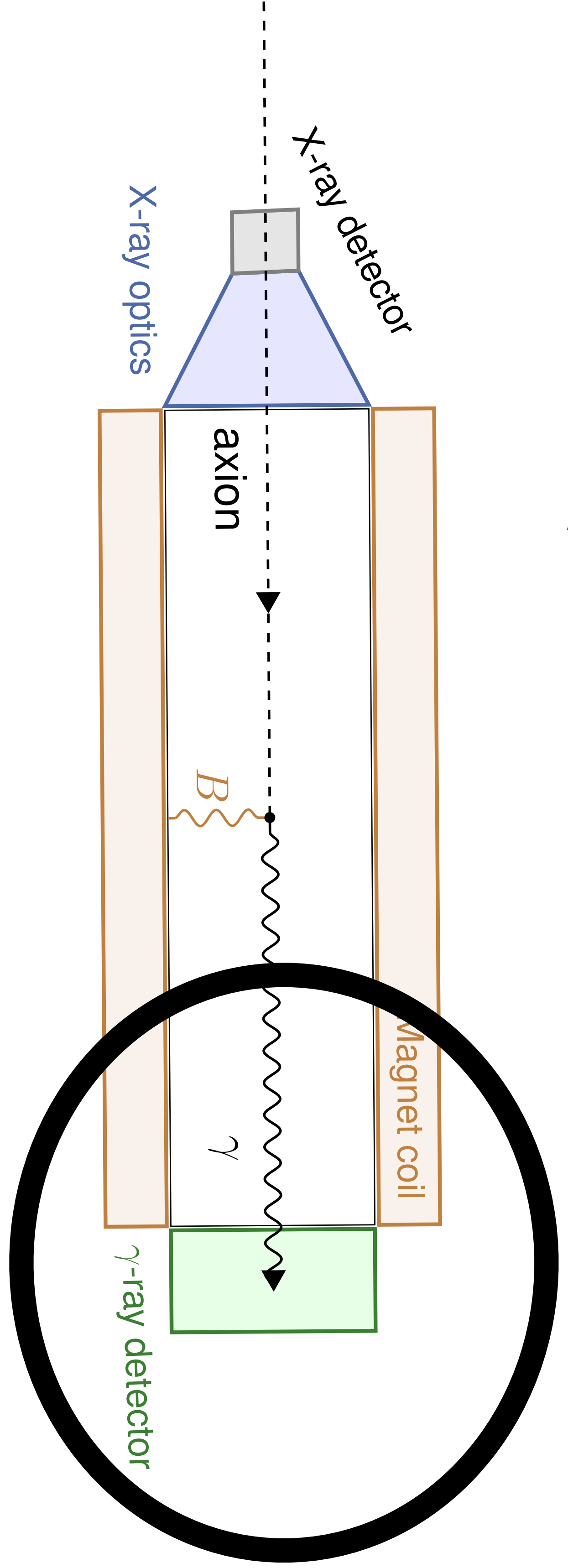
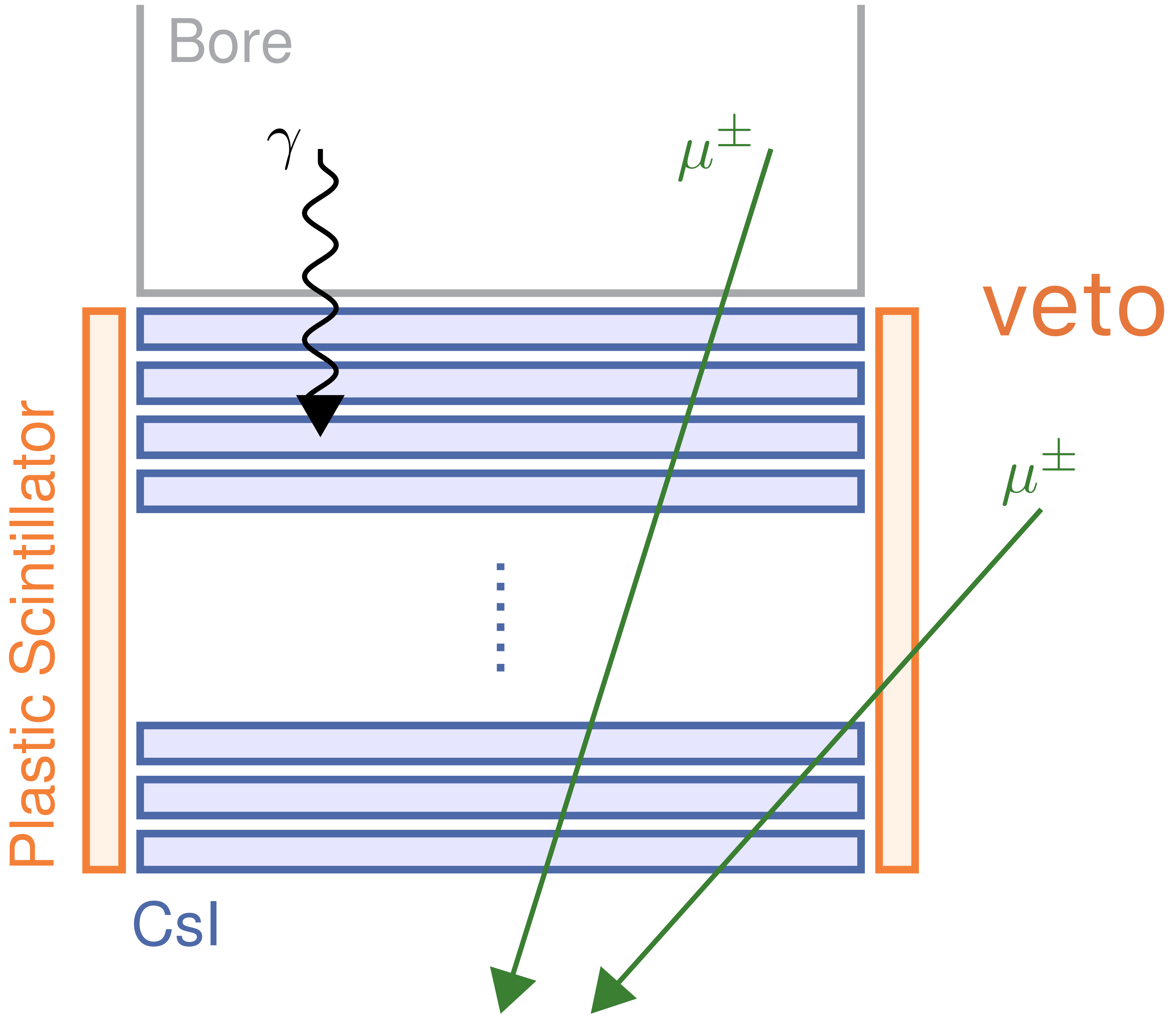
Abstract. The most efficient axion production mechanism in a supernova (SN) core is the nucleon-nucleon bremsstrahlung. This process has been often modeled at the level of the vacuum one-pion exchange (OPE) approximation. Starting from this naive recipe, we revise the calculation including systematically different effects, namely a non-vanishing mass for the exchanged pion, the contribution from the two-pions exchange, effective in-medium nucleon masses and multiple nucleon scatterings. Moreover, we allow for an arbitrary degree of nucleon degeneracy. A self consistent treatment of the axion emission rate including all these effects is currently missing. The aim of this work is to provide such an analysis. Furthermore, we demonstrate that the OPE potential with all the previous corrections gives rise to similar results as the on-shell T-matrix, and is therefore well justified for our and similar studies. We find that the axion emissivity is reduced by over an order of magnitude with respect to the basic OPE calculation, after all these effects are accounted for. The implications for the axion mass bound and the impact for the next generation experimental axion searches is also discussed.

cf. more recent works,
e.g.,
P.Carenza et.al., 2010.02943, 2108.13726,
K.Choi, H.J.Kim, H.Seong, C.S.Shin, 2110.01972.

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

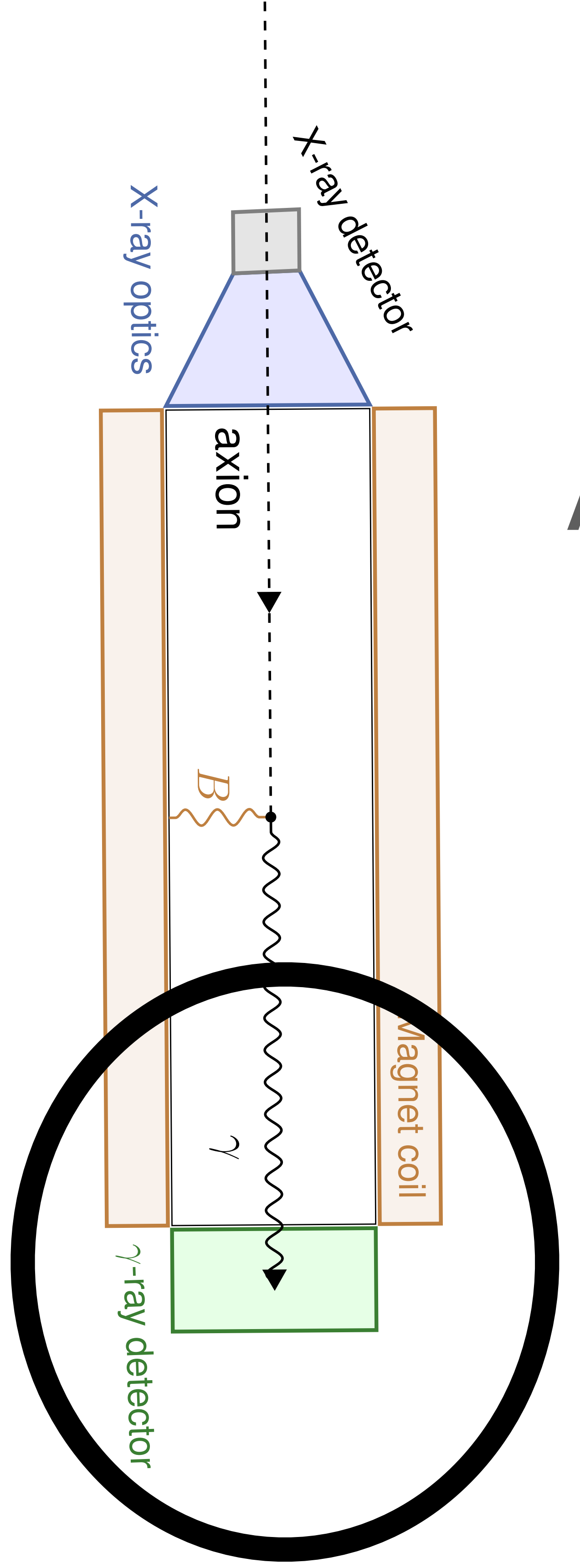


A design for the gamma-ray detector

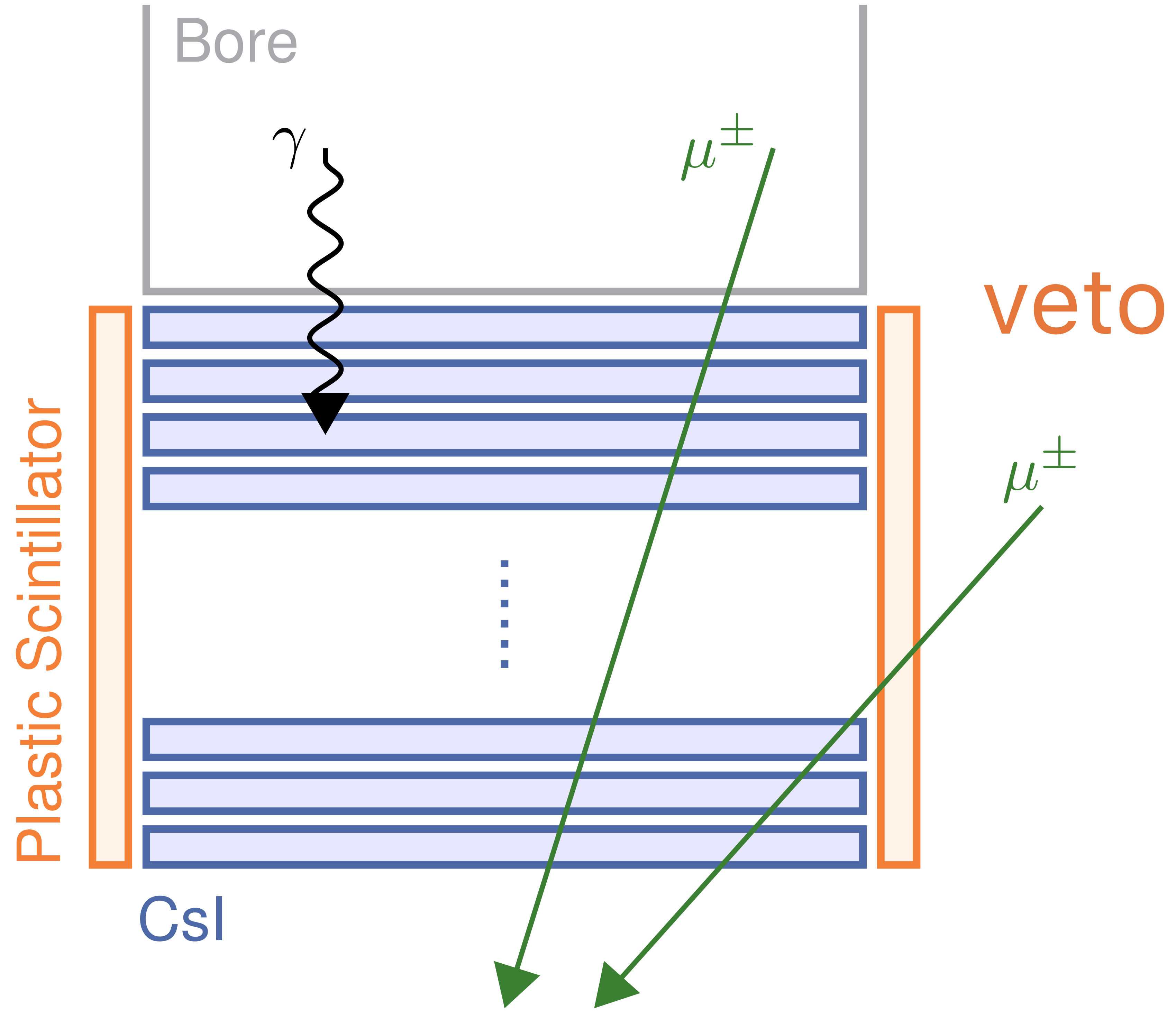


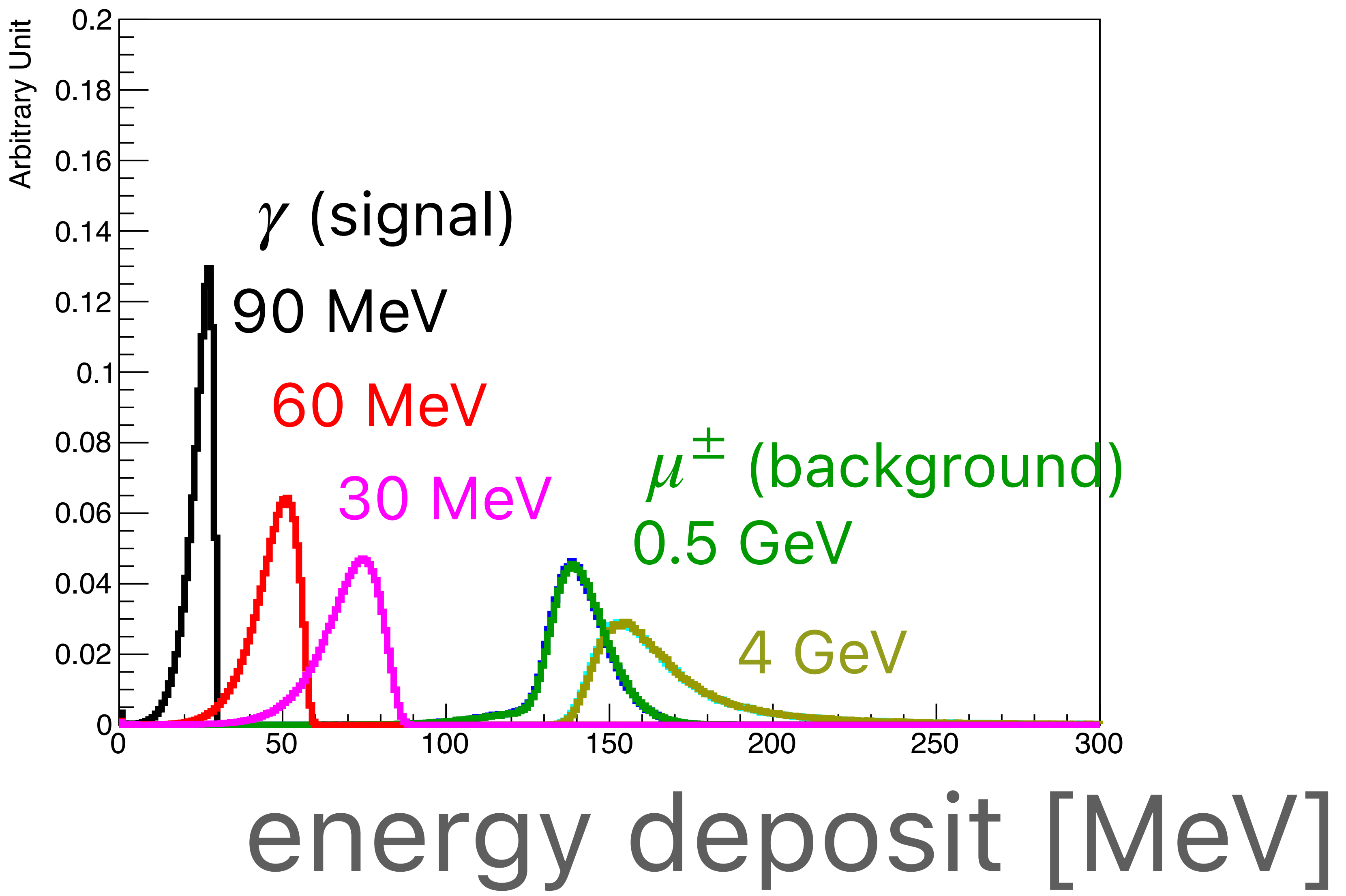
- O(1000) muon events in 10 sec.

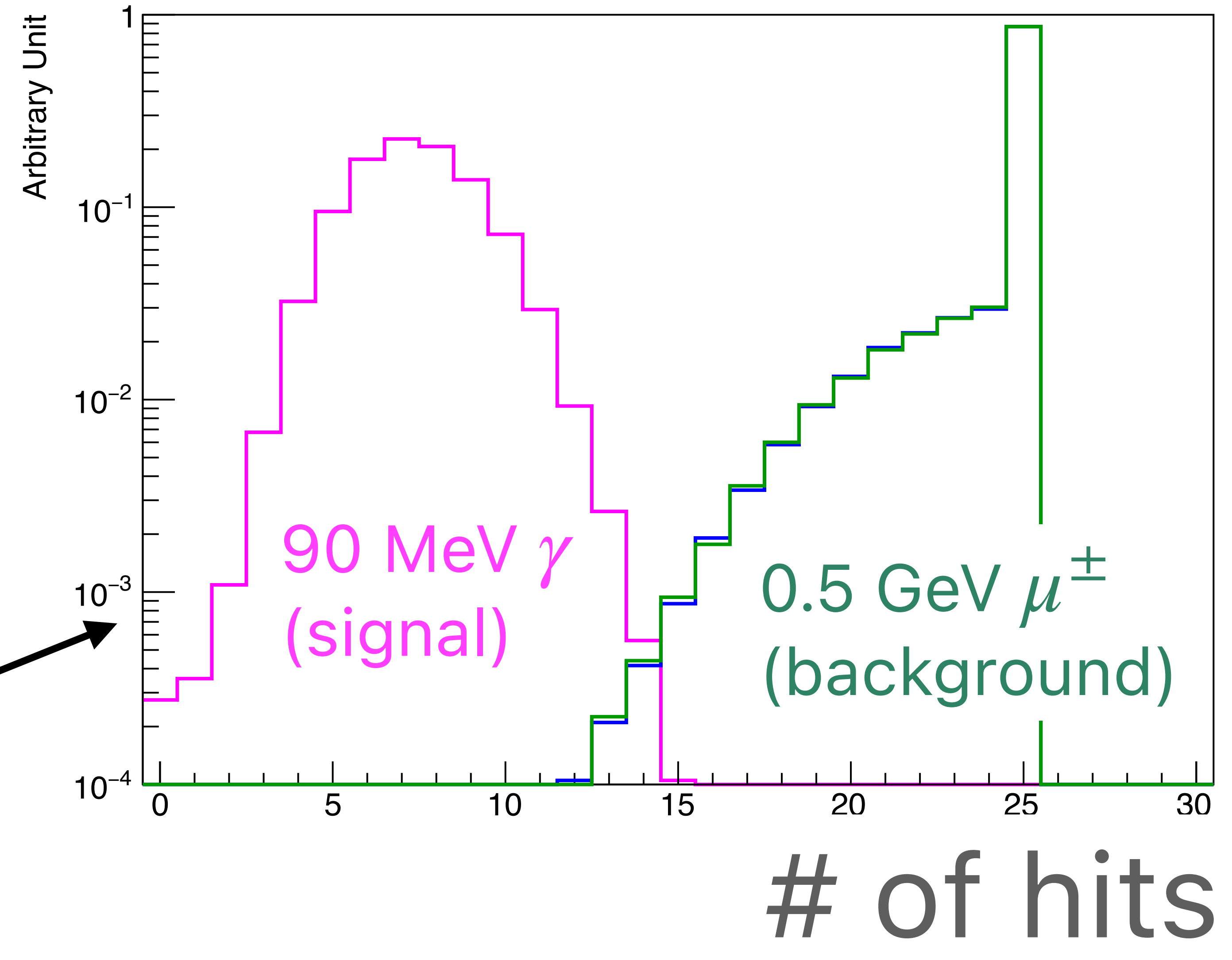
S.Ge, K.Hamaguchi, K.Ichimura, K.Ishidoshiro,
Y.Kanazawa, Y.Kishimoto, N.Nagata, J.Zheng.
[arXiv:2008.03924] JCAP **11** (2020) 059.



A design for the gamma-ray detector



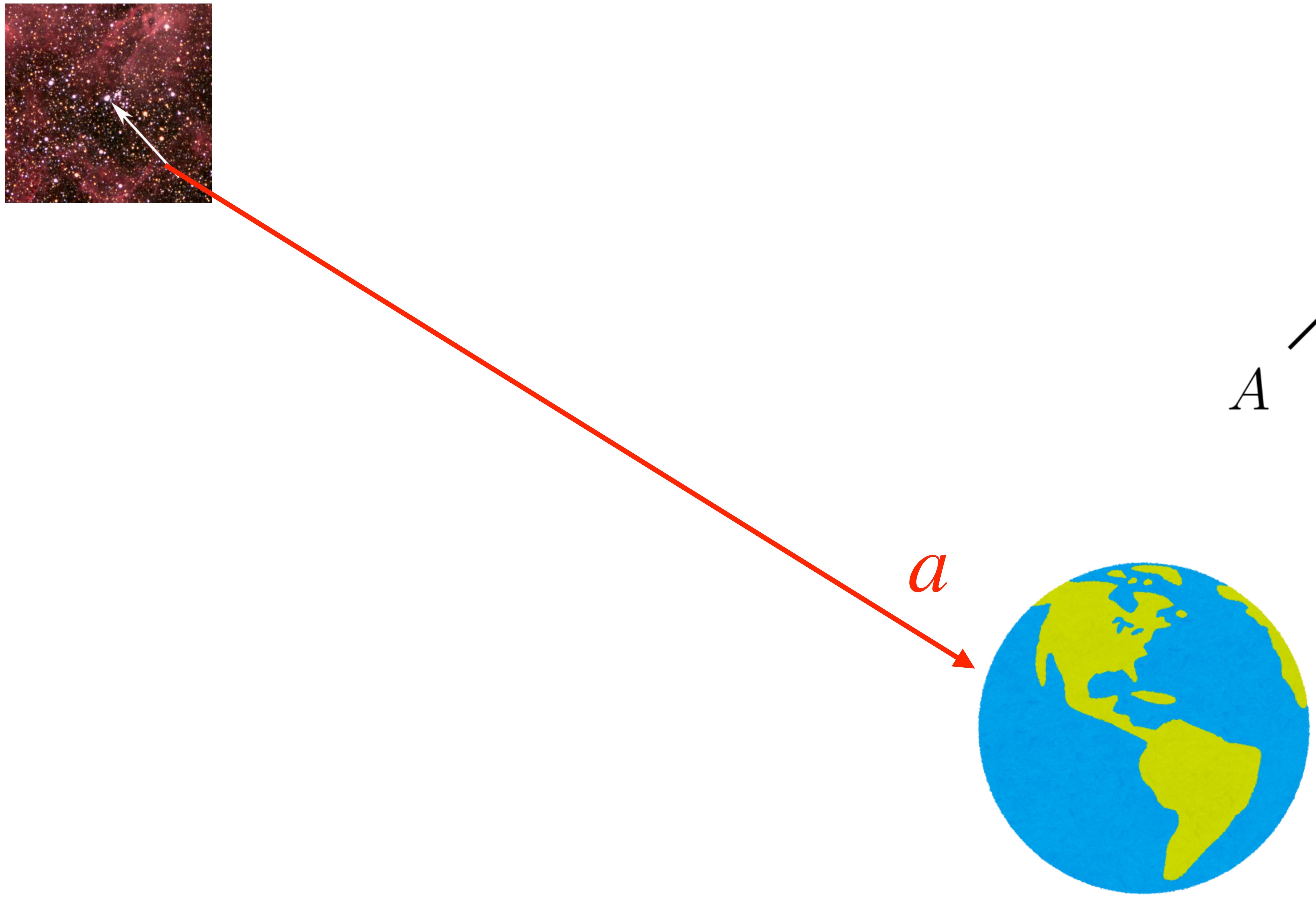


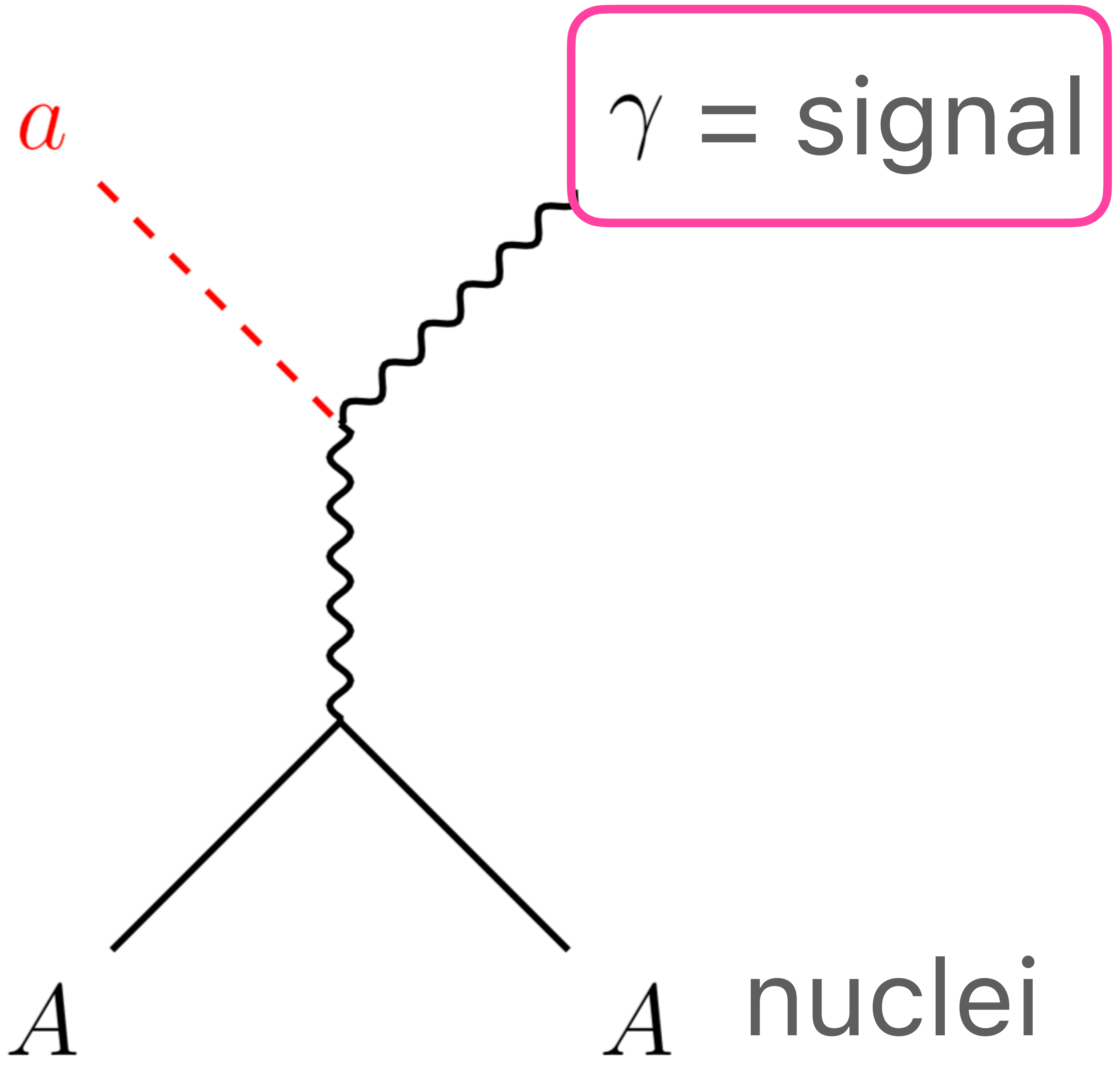


- O(1000) muon events in 10 sec.
- They can be rejected by <u>energy deposit</u> and <u># of hits</u>.

Inverse Primakoff

What about the **inverse Primakoff** signal?





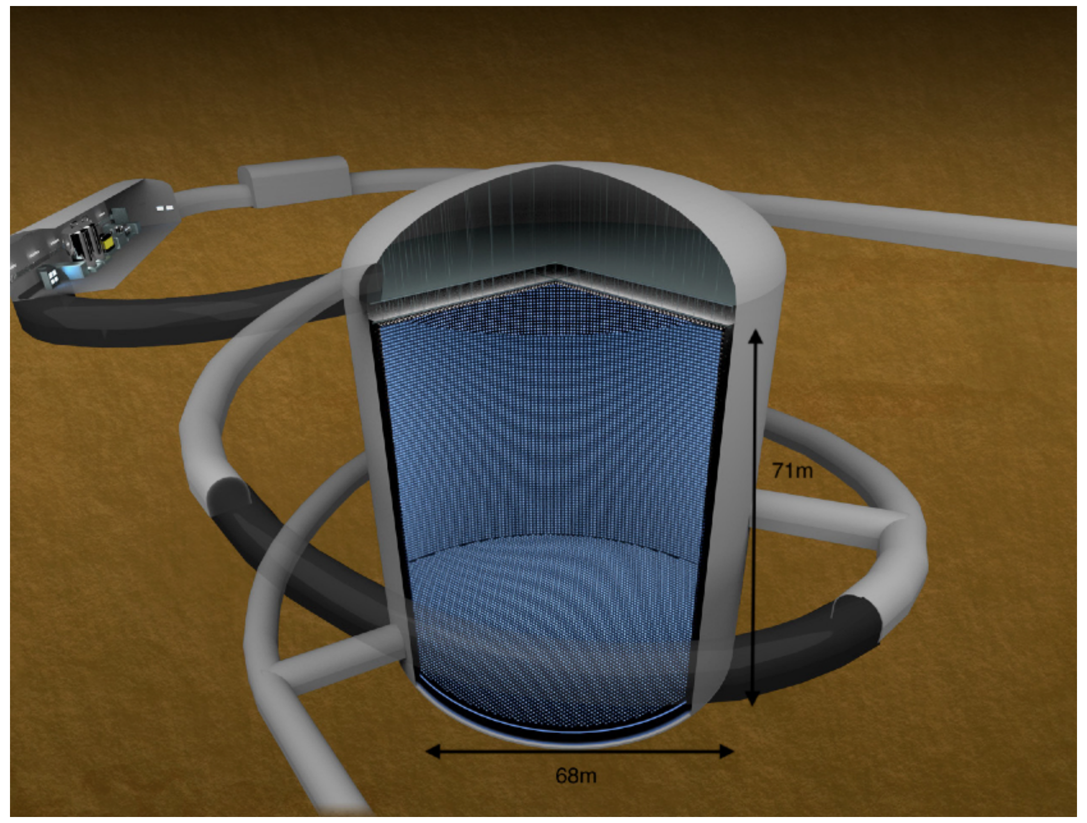
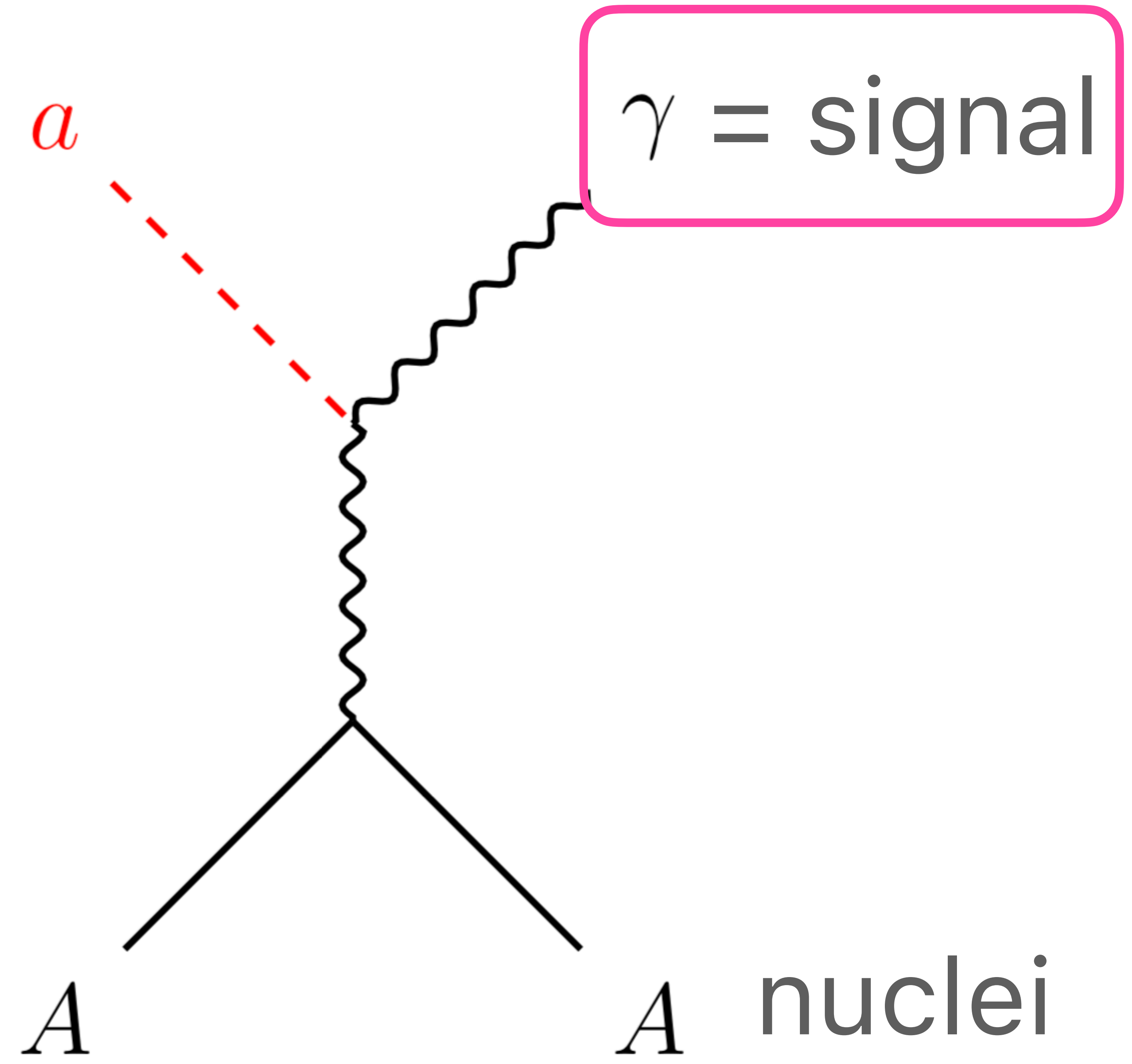


figure from Hyper-K homepage

What about the **inverse Primakoff** signal?



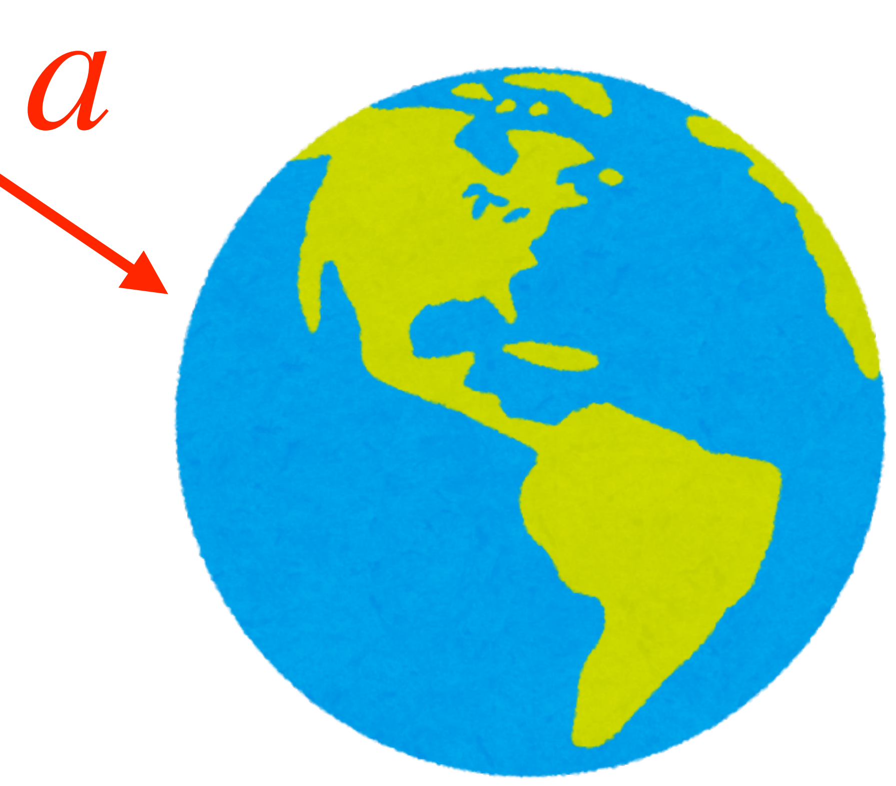
- SN-axion $N_{\rm event}$ at Hyper-K (187kt water)

T.Abe, KH, N.Nagata [2012.02508] PLB 2021

$$N_{\rm event} = \dot{N}_a \Delta t \times \frac{\sigma_{\rm el}}{4\pi d^2} \times N_{\rm O}$$
$$\simeq 1 \times \left(\frac{3\times 10^8~{\rm GeV}}{f_a}\right)^4 \left(\frac{C_{N,\rm eff}}{0.37}\right)^2 \left(\frac{g_{a\gamma\gamma} f_a}{\alpha/\pi}\right)^2 \left(\frac{\Delta t}{10~{\rm s}}\right) \left(\frac{d_{\rm SN}}{100~{\rm pc}}\right)^{-2}$$

- No need to point to the progenitor.

- Difficulty to distinguish it from the huge number of neutrino burst events.



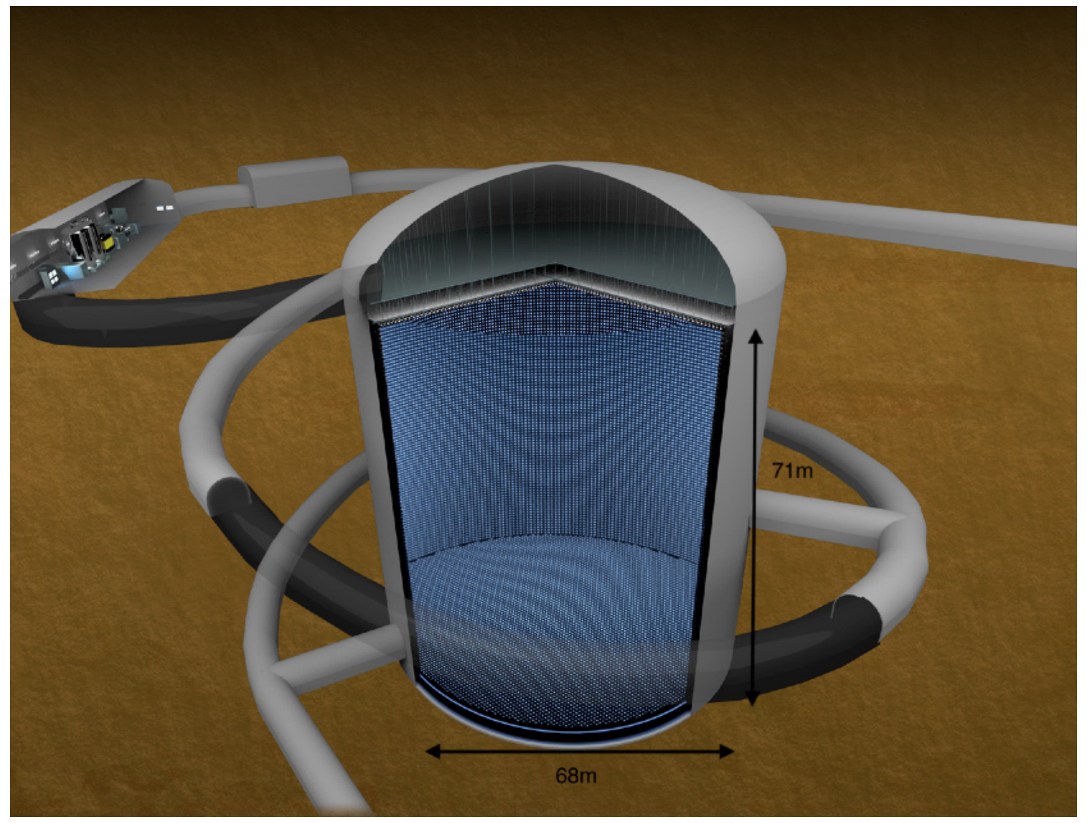


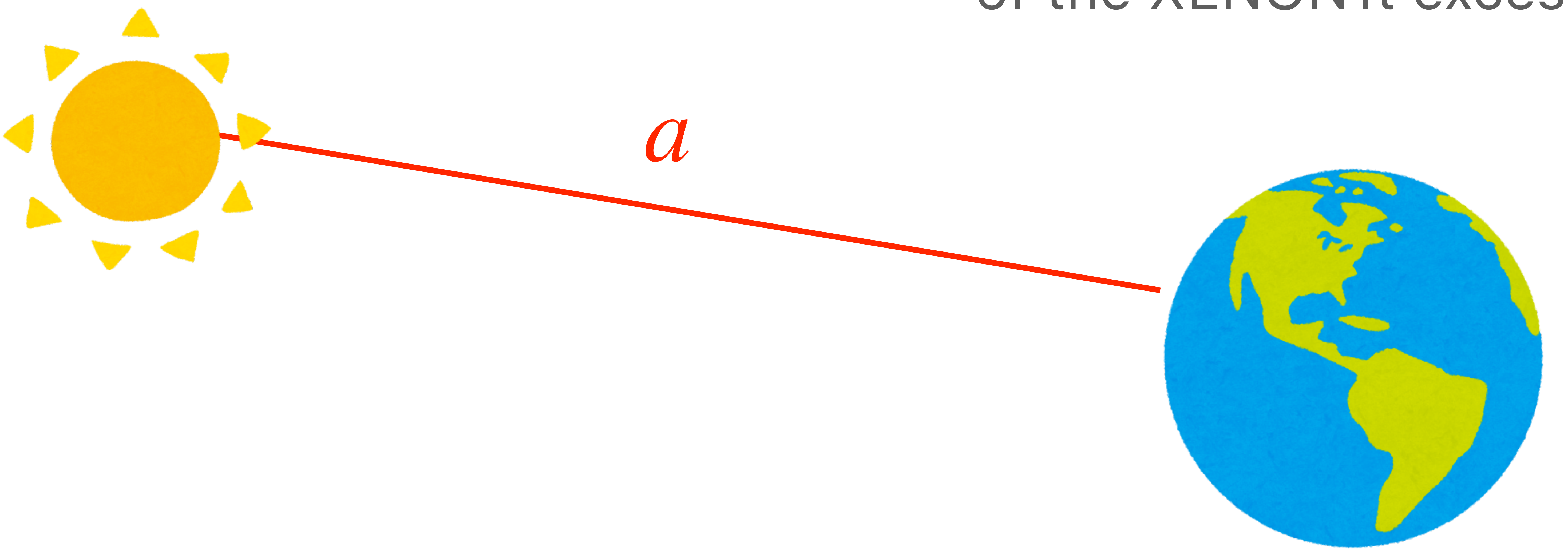
figure from Hyper-K homepage

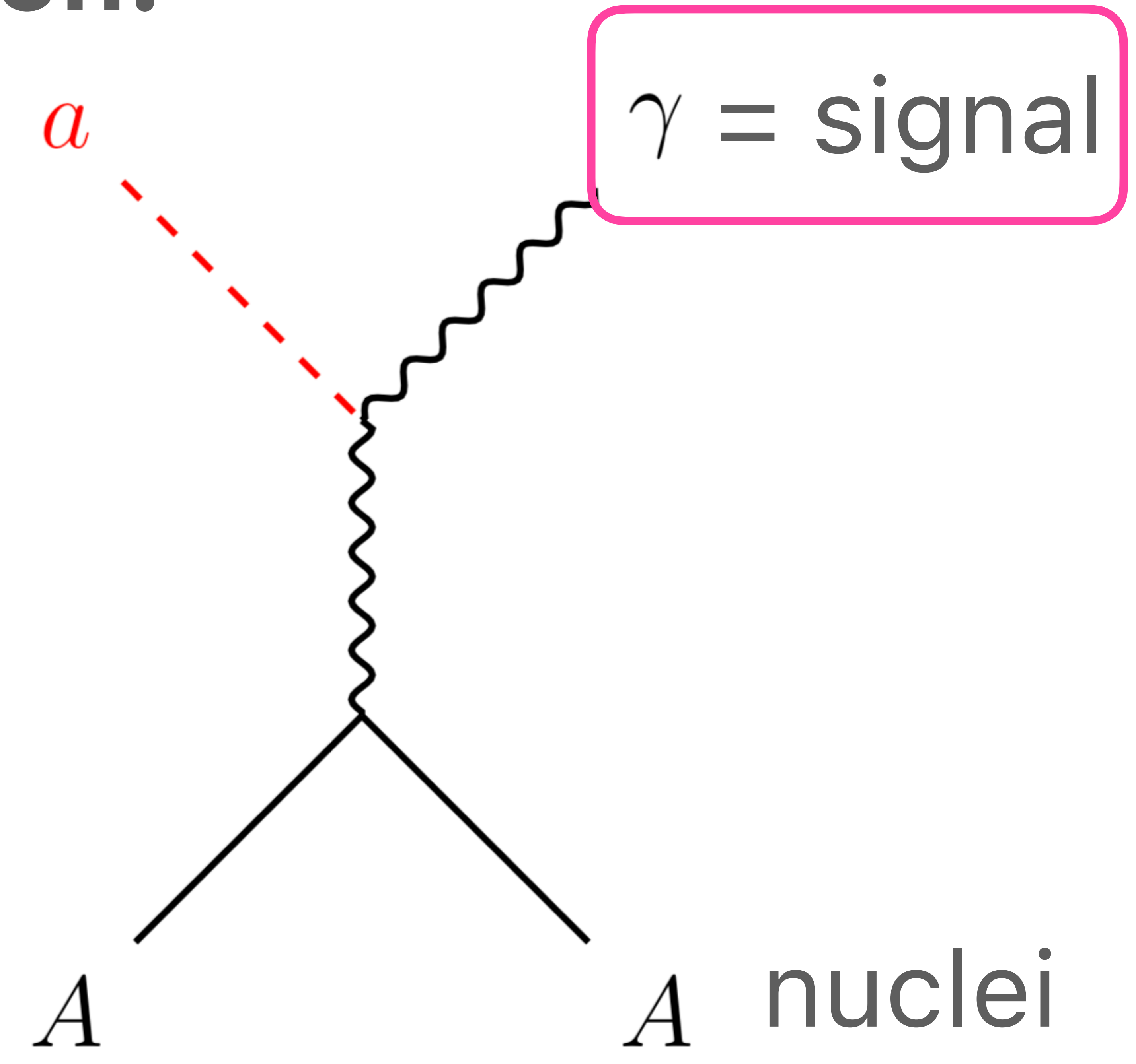
A comment on **inverse Primakoff scattering of axion.**

T.Abe, KH, N.Nagata [2012.02508] PLB 2021

- For low energy ($\lesssim \mathcal{O}(\mathrm{keV})$, e.g., solar axion), the atomic form factor is important.

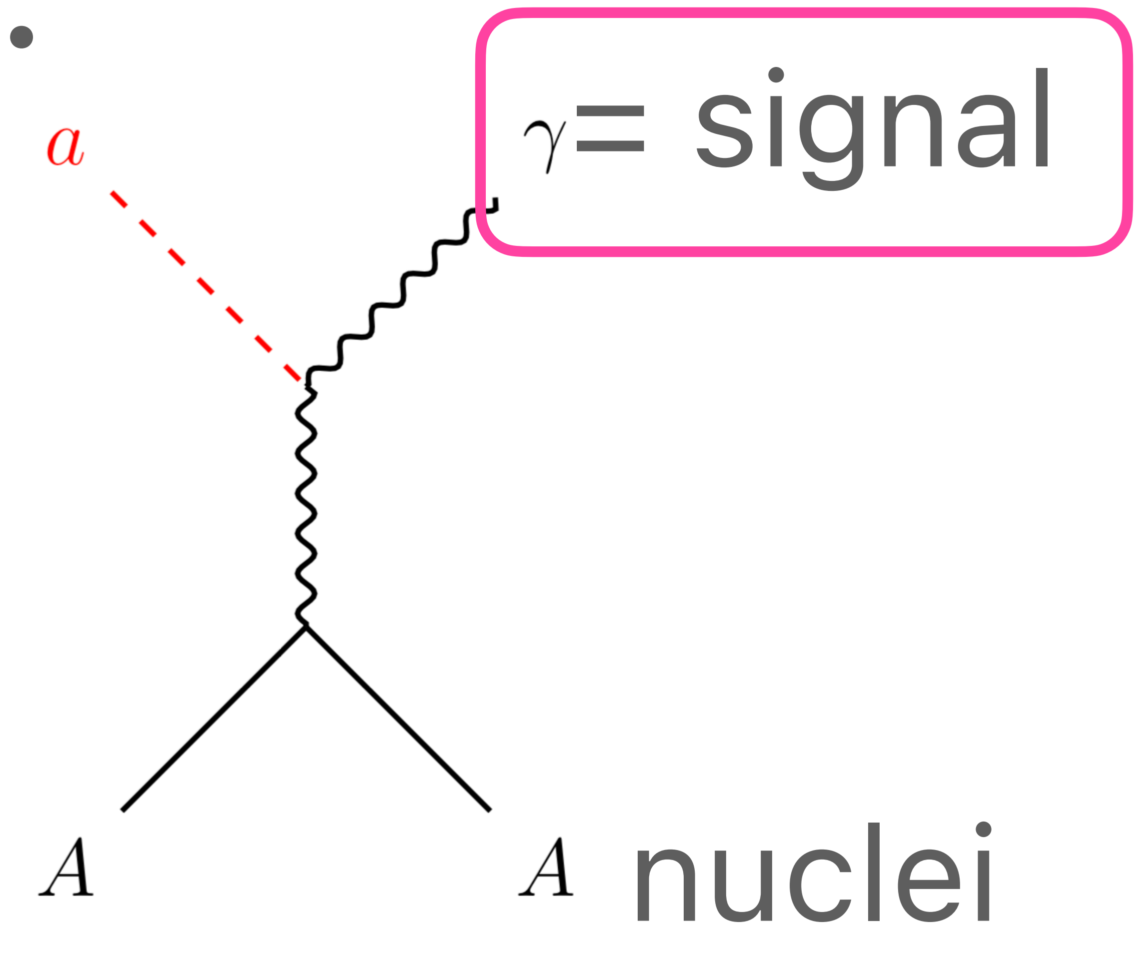
e.g., one of the interpretations of the XENON1t excess.





A comment on **inverse Primakoff scattering of axion.**

T.Abe, KH, N.Nagata [2012.02508] PLB 2021



- For low energy ($\lesssim \mathcal{O}(\mathrm{keV})$, e.g., solar axion), the atomic form factor is important.

  e.g., one of the interpretations of the XENON1t excess.

- Previous studies used a naive screened Coulomb potential.

- We reevaluated the cross section with a realistic form factor that is computed with a relativistic Hartree-Fock wave function.

- The scattering cross section was overestimated by more than an order of magnitude for axions with < O(10) keV energies.

- We also discussed the importance of the **inelastic scattering** for low energy.