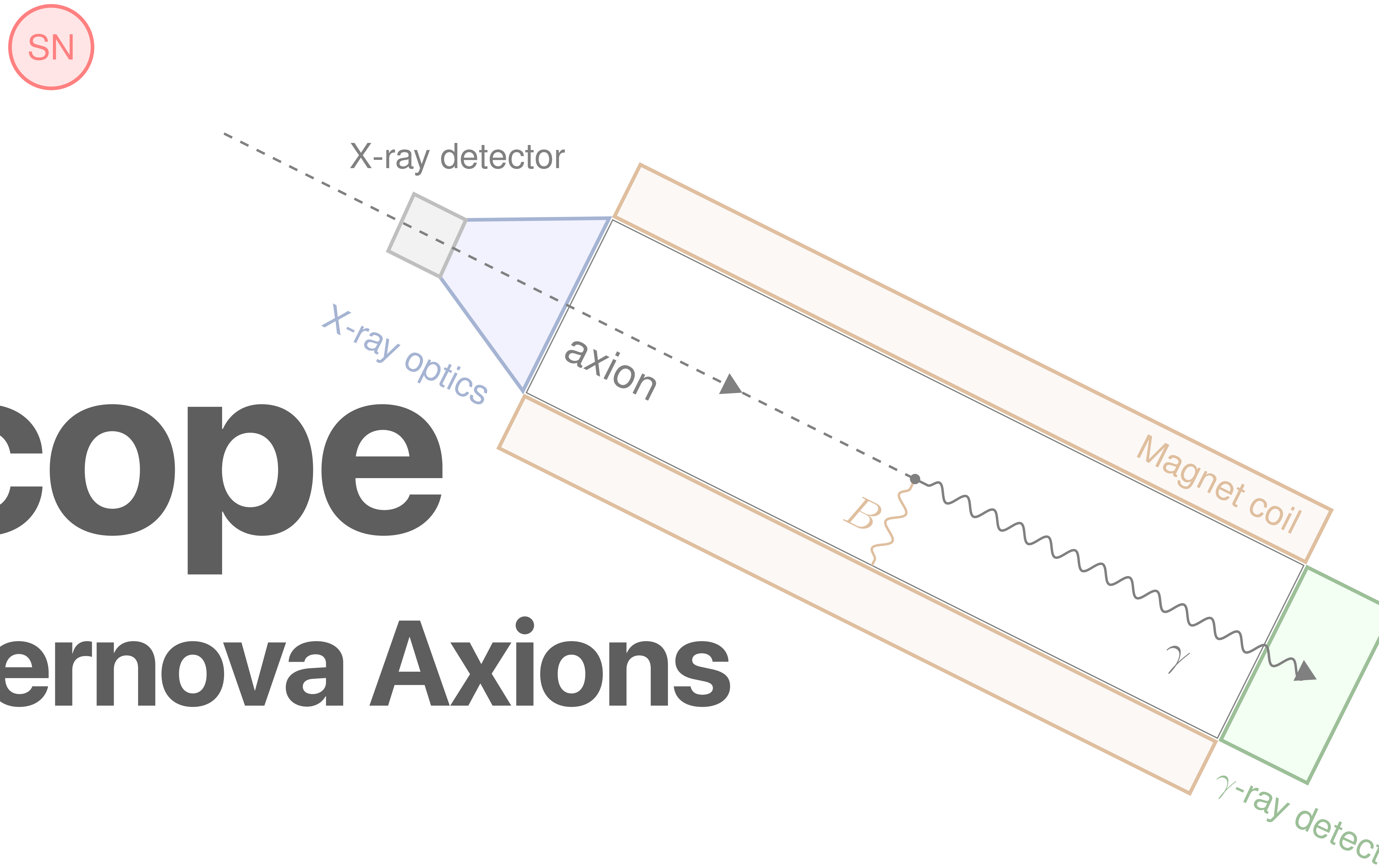

Supernova-scope

for the Direct Search of Supernova Axions

Koichi Hamaguchi (University of Tokyo)

@PRISMA Colloquium, JGU Mainz, April 17, 2024

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).

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- Postdoc and Junior Staff, DESY, 2002-2006
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- **Physics beyond the Standard Model (BSM), Cosmology and Astroparticle Physics**

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2004 12 12

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Recent Topics

- **Compact Stars × BSM Physics** (since 2018)
- **Axion × wormhole** (since 2021)
- **GUT models and proton decays** (since 2020)
- **Leptogenesis** (since Ph.D.)
- Extensions in the lepton sector (such as $U(1)_{\mu-\tau}$ model and g-2 motivated models)
- SUSY models and signatures at LHC
- etc.

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New Physics Directions in the LHC era and beyond

NEWFO

- **Compact Stars** × **BSM Physics** (since 2018)
  - **Neutron Star** × **Dark Matter**

    👉 I will talk about it **next week** @ MPI Heidelberg
    - arXiv 2309.02633, 2308.16066, 2204.02413, 2204.02238, 1905.02991, 1904.04667.
    - w/ Motoko Fujiwara, Natsumi Nagata, **Maura E. Ramirez-Quezada**, Keisuke Yanagi, Jiaming Zheng


Tokyo → TUM


Tokyo


Tokyo → Mainz

Tokyo →


Tokyo → TDLI

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  - **Neutron Star × Axion**
    - arXiv 1806.07151. w/ Natsumi Nagata, Keisuke Yanagi, Jiaming Zheng

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  - **Neutron Star × Axion**
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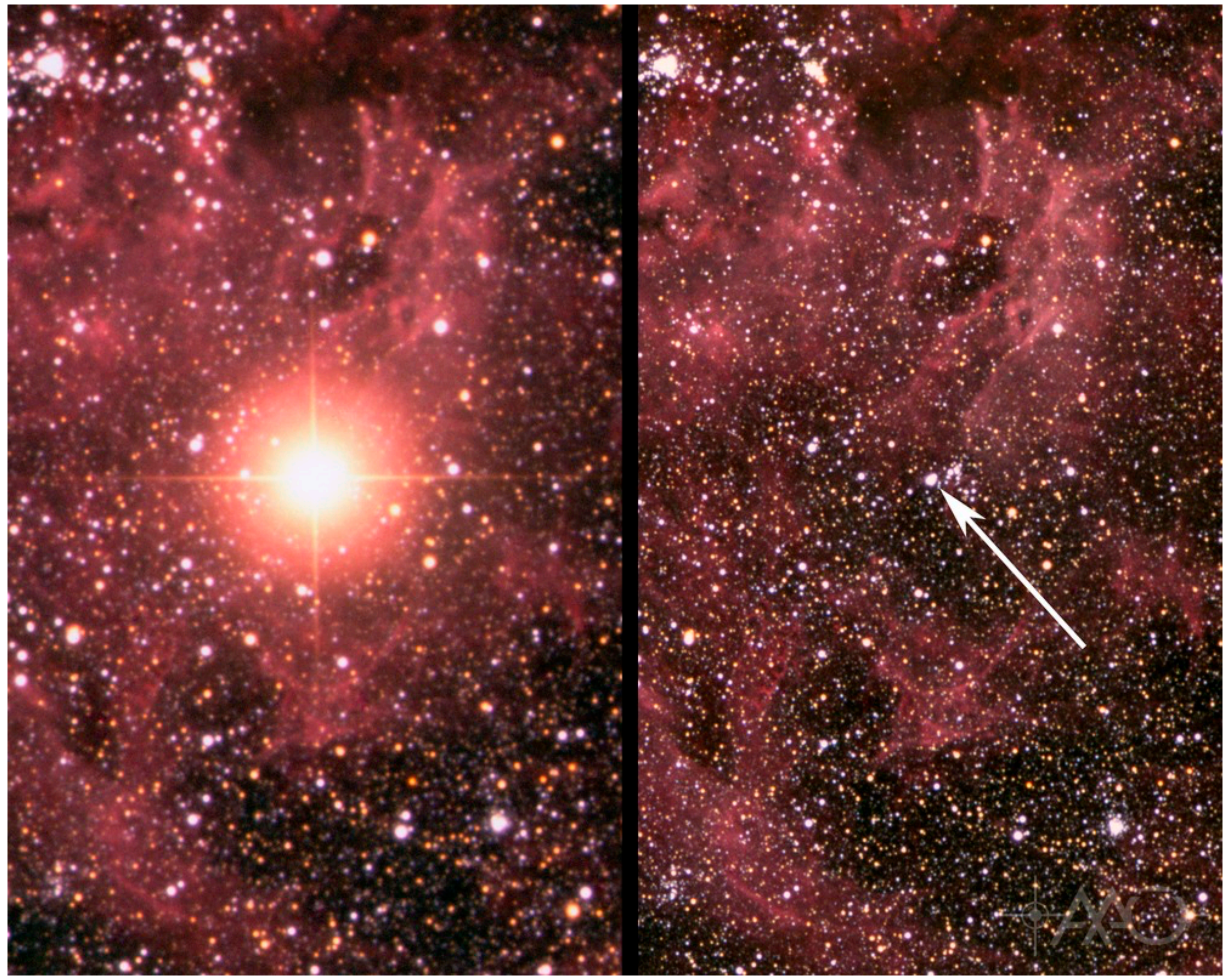
  - **Supernova × Axion**
    - arXiv 2008.03924. w/ S.Ge, T.Kanazawa, K.Ichimura, K.Ishidoshiro, Y.Kishimoto, N.Nagata, J.Zheng

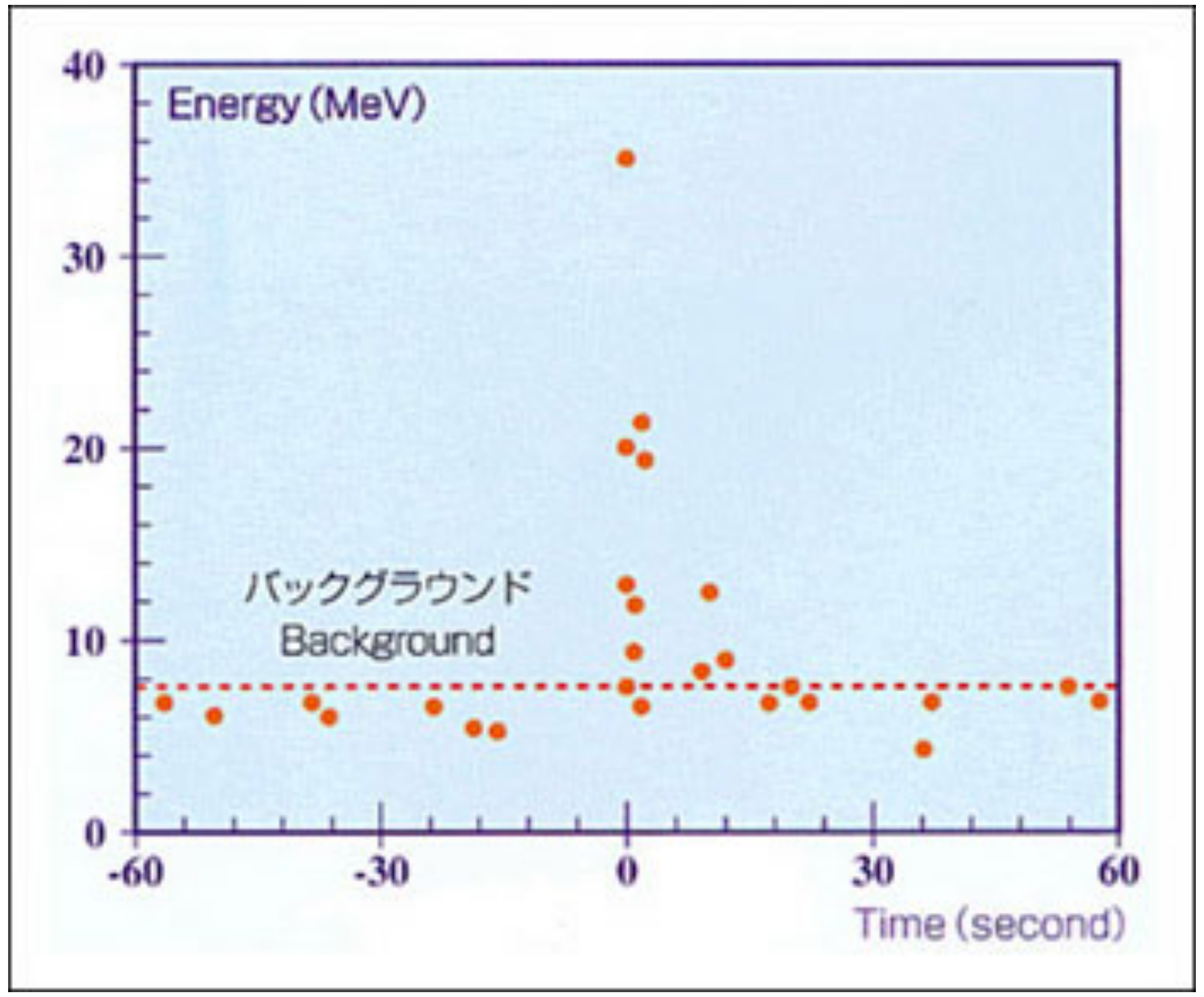
👉 **Today's Talk**

Toady's Main message

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

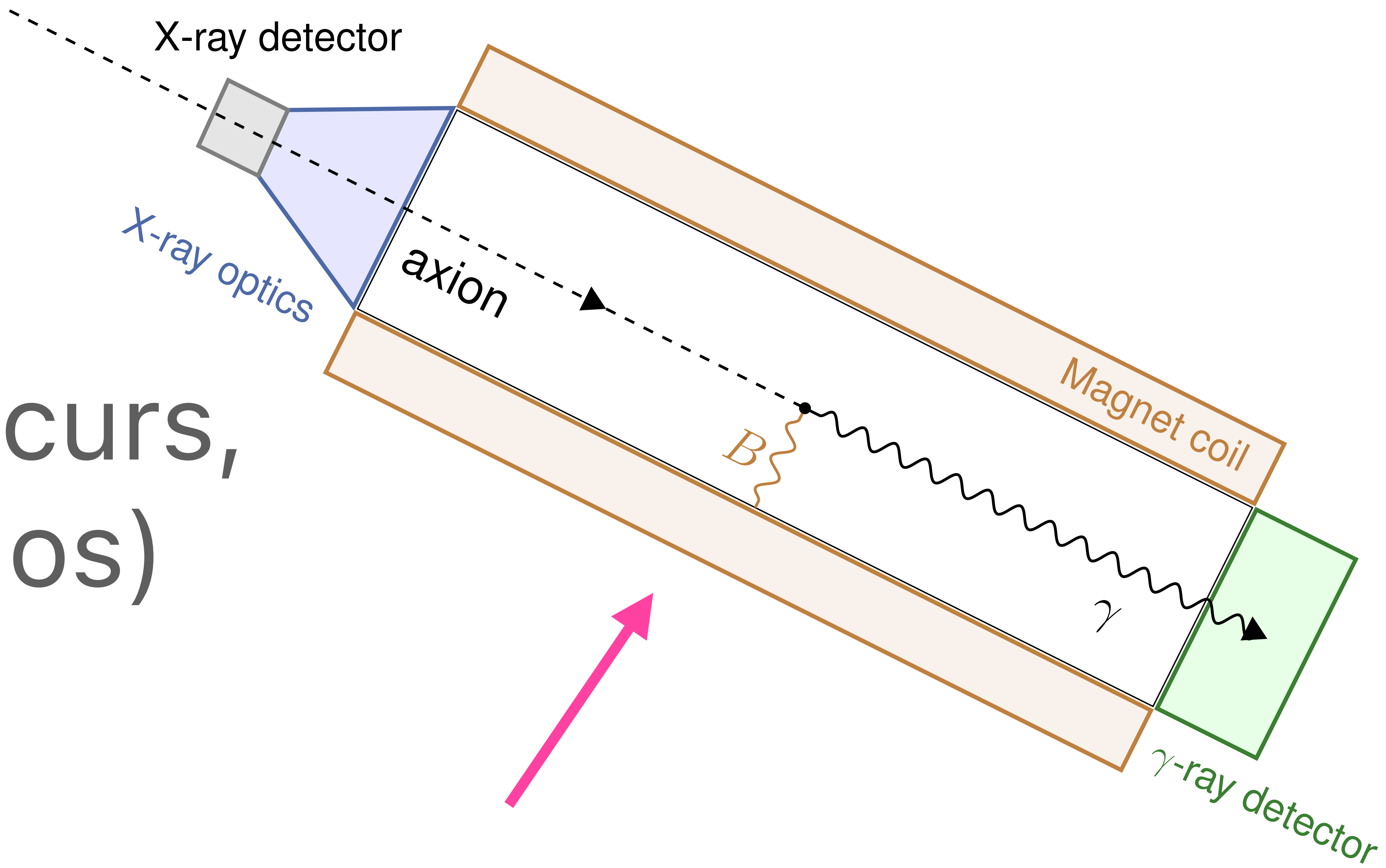
pioneered the new field of neutrino astronomy.
(Nobel Prize 2002)

What if the next nearby SN occurs?

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

Toady's Main message

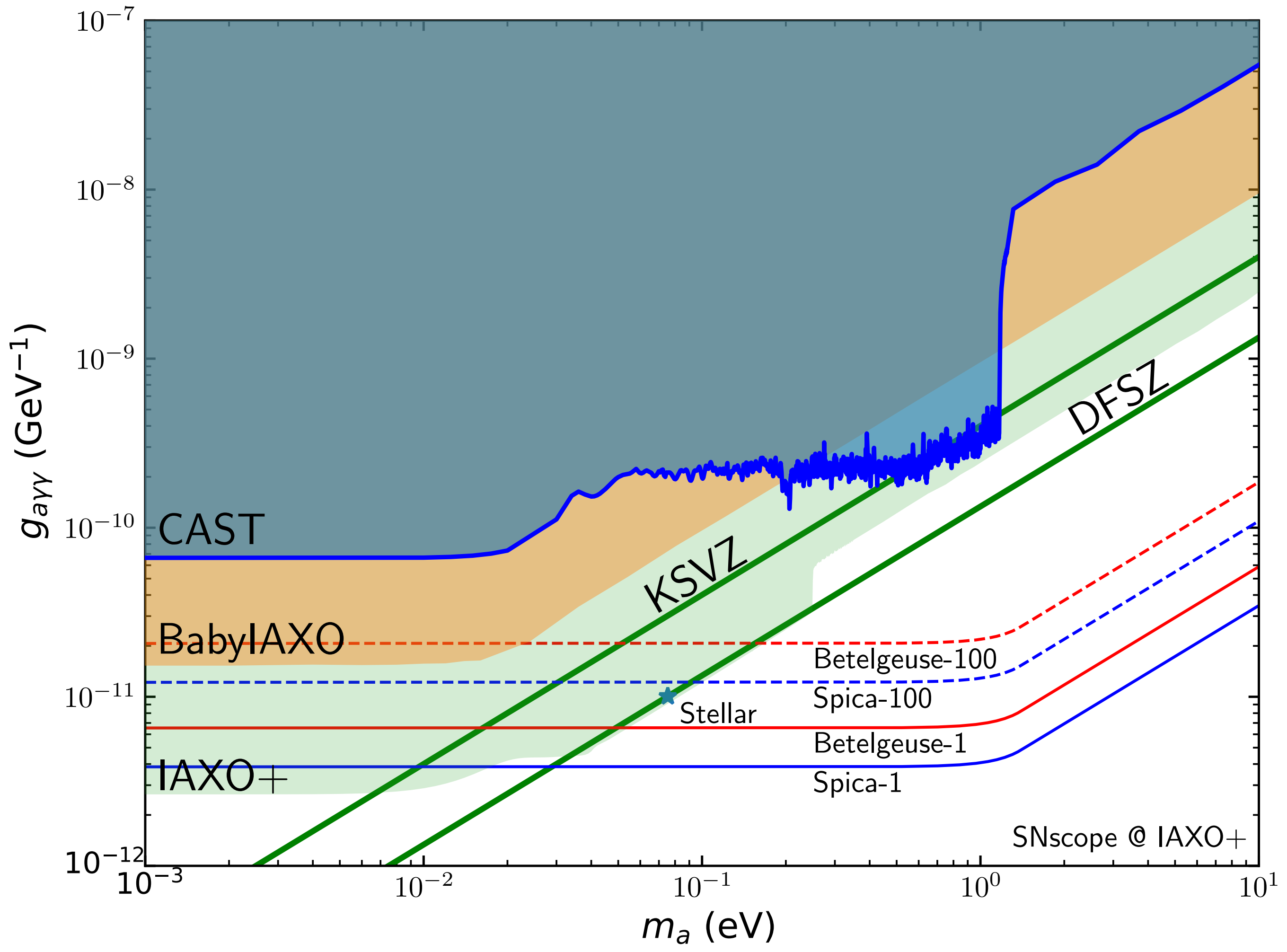
SN



- 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.

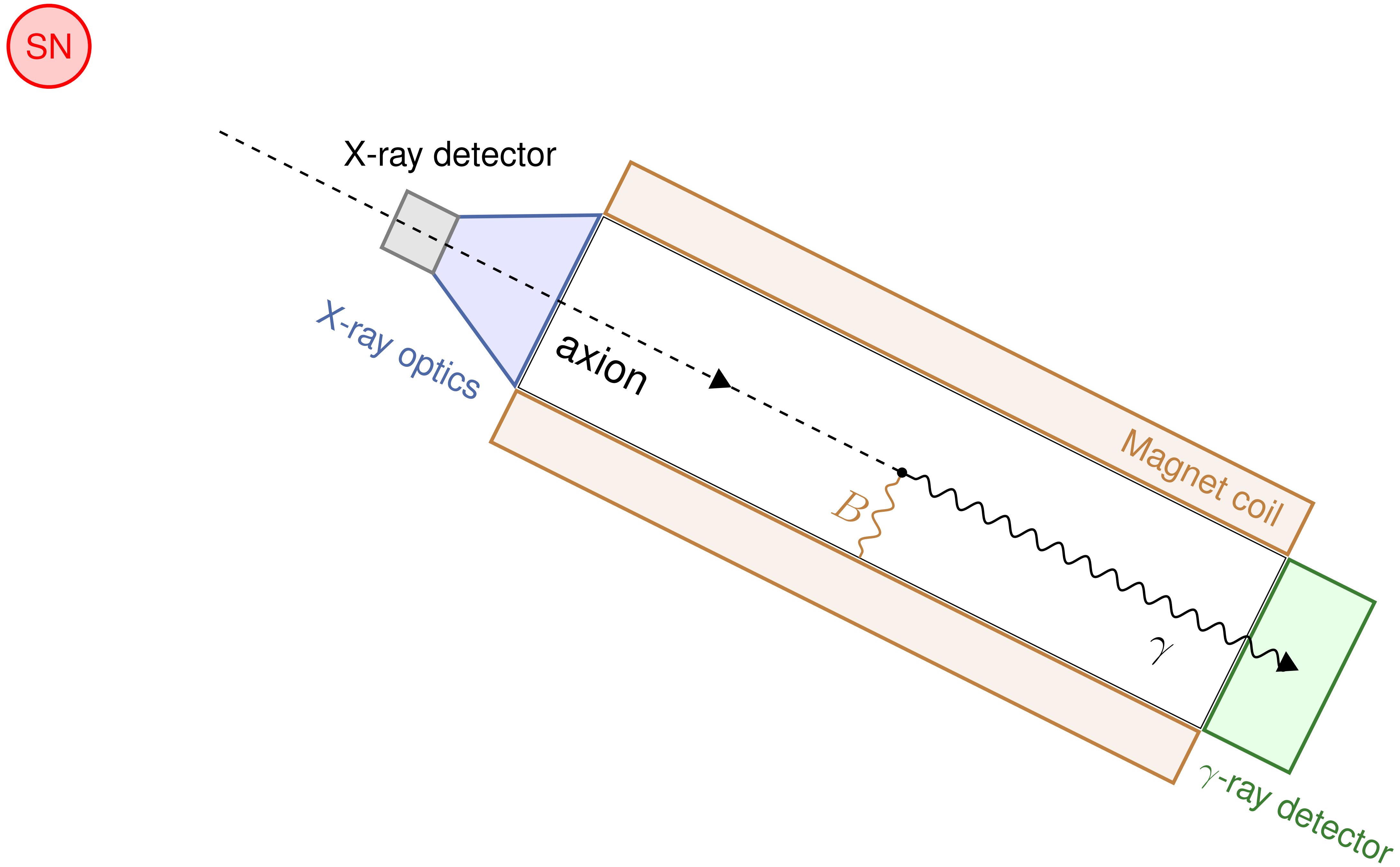


[arXiv:2008.03924] JCAP **11** (2020) 059.

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

Plan

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



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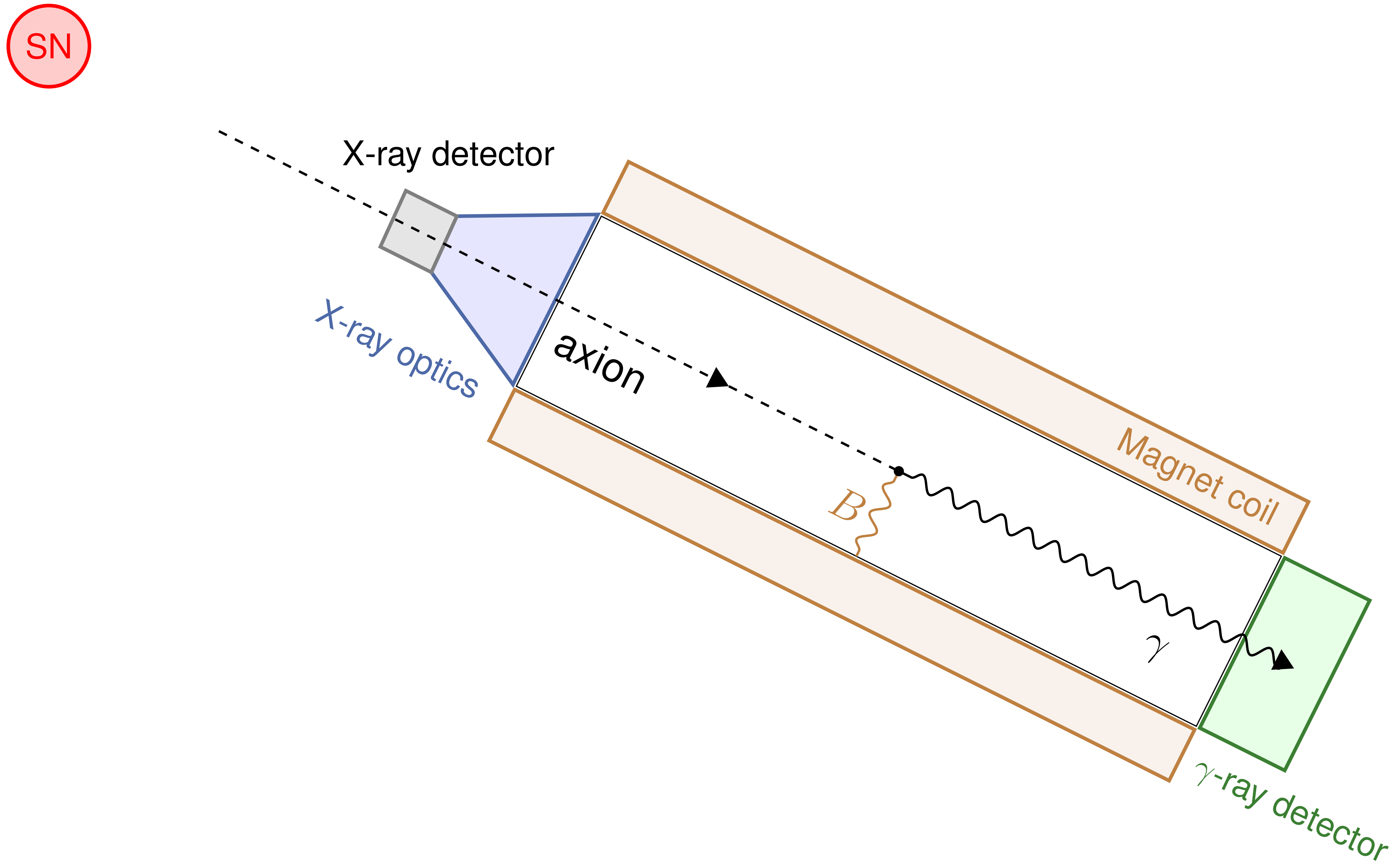
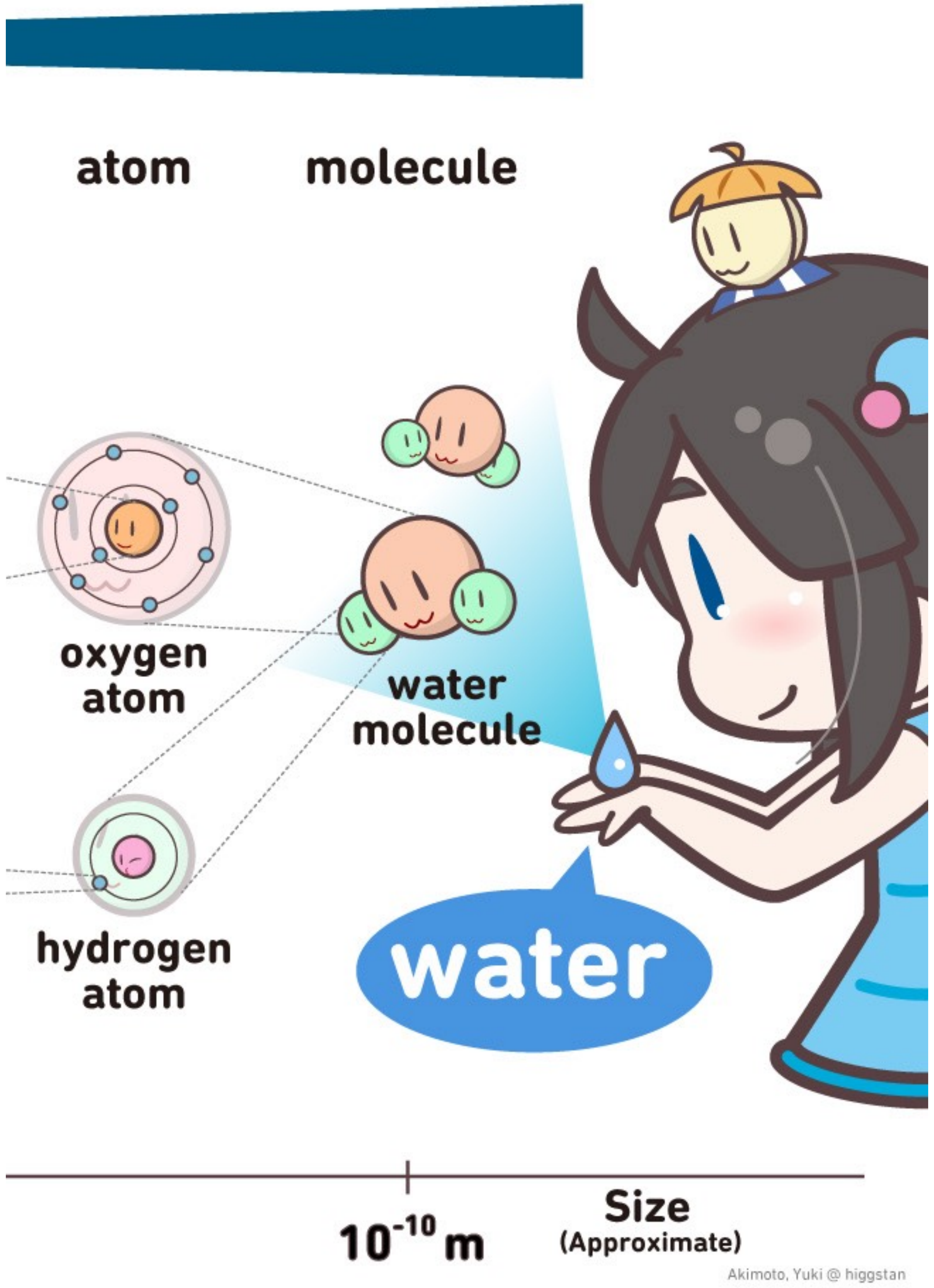


Introduction: **Standard Model**

elementary particles

Figs. from higgstan.com



Introduction: **Standard Model**

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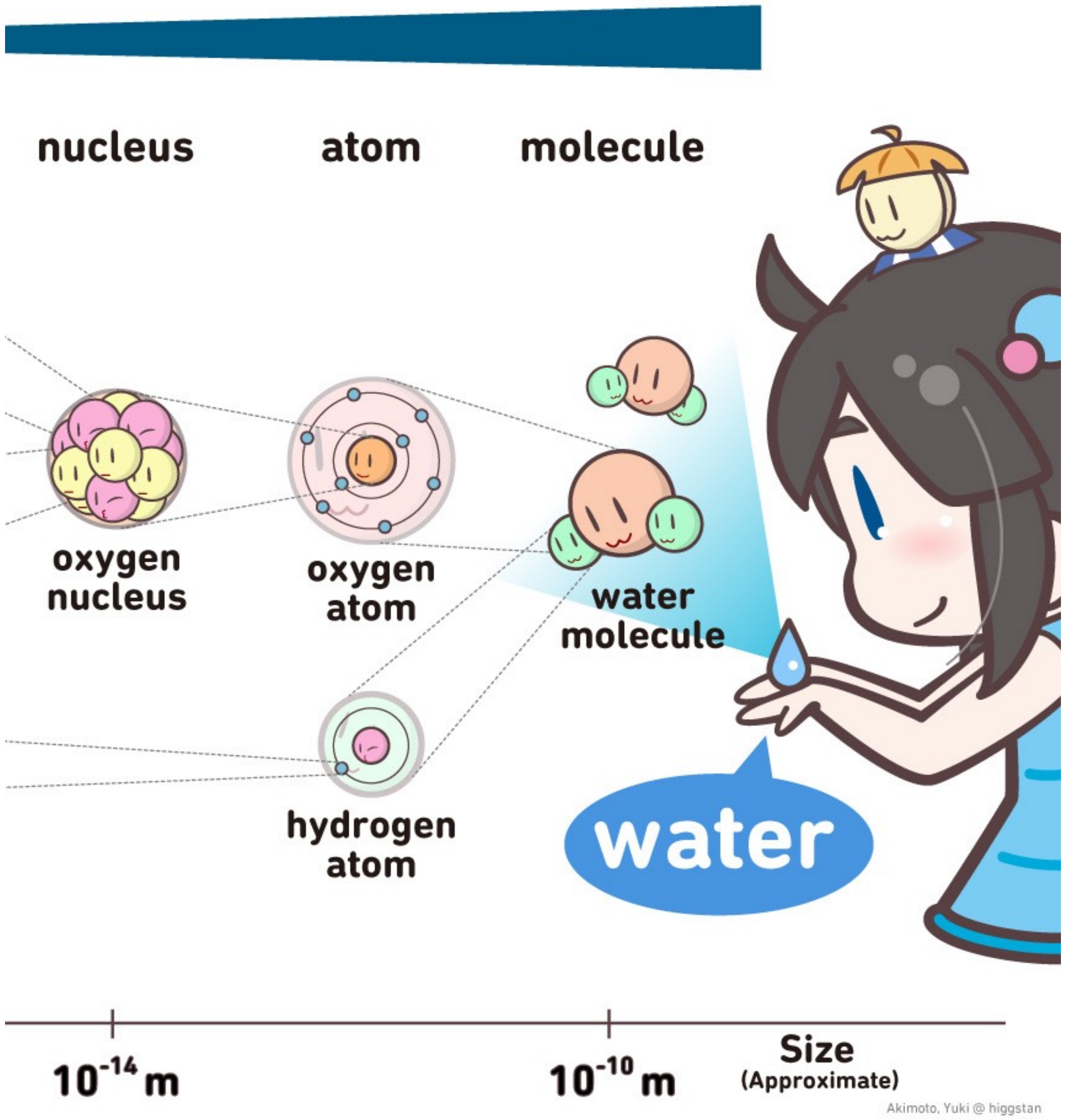

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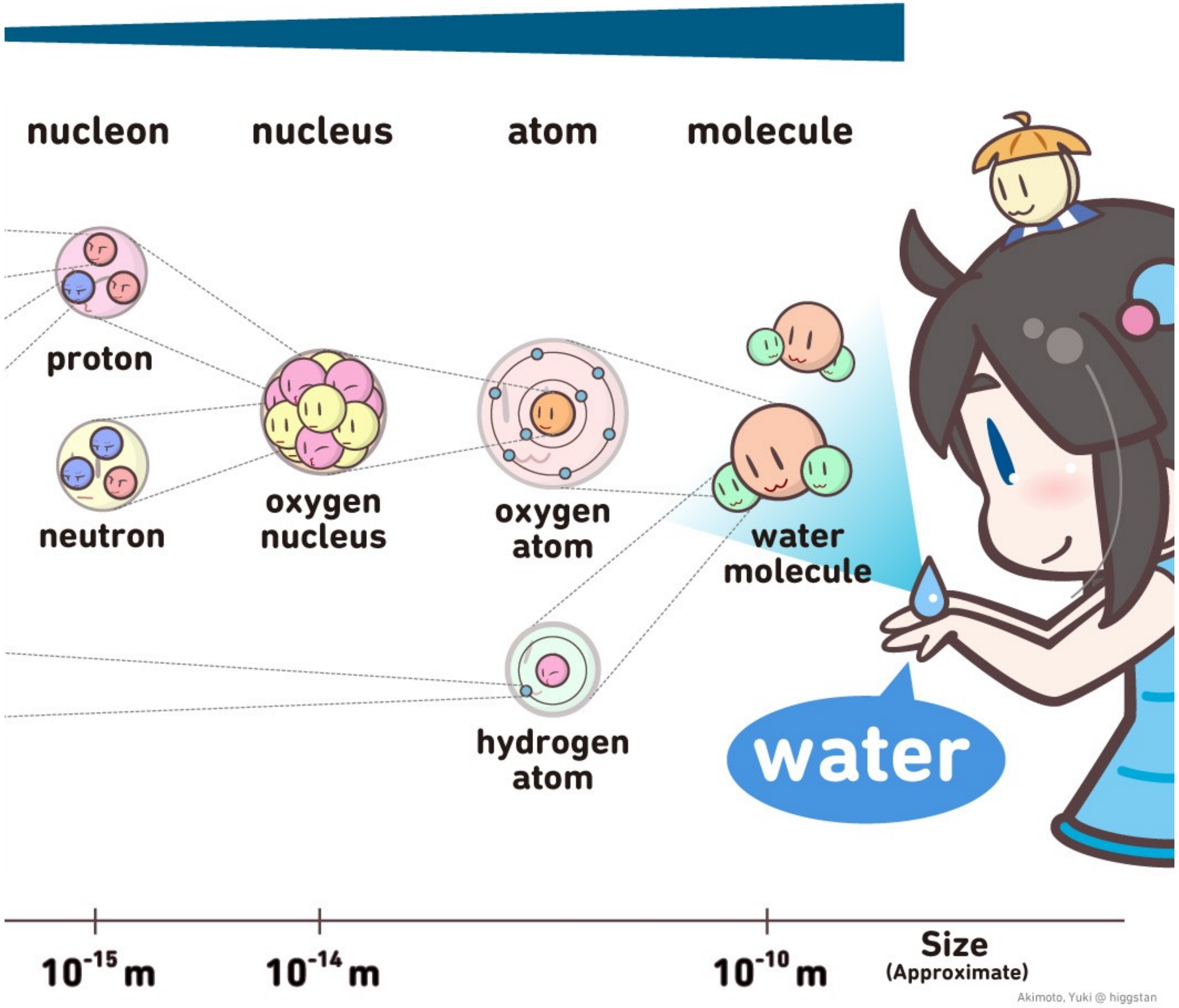

Introduction: **Standard Model**

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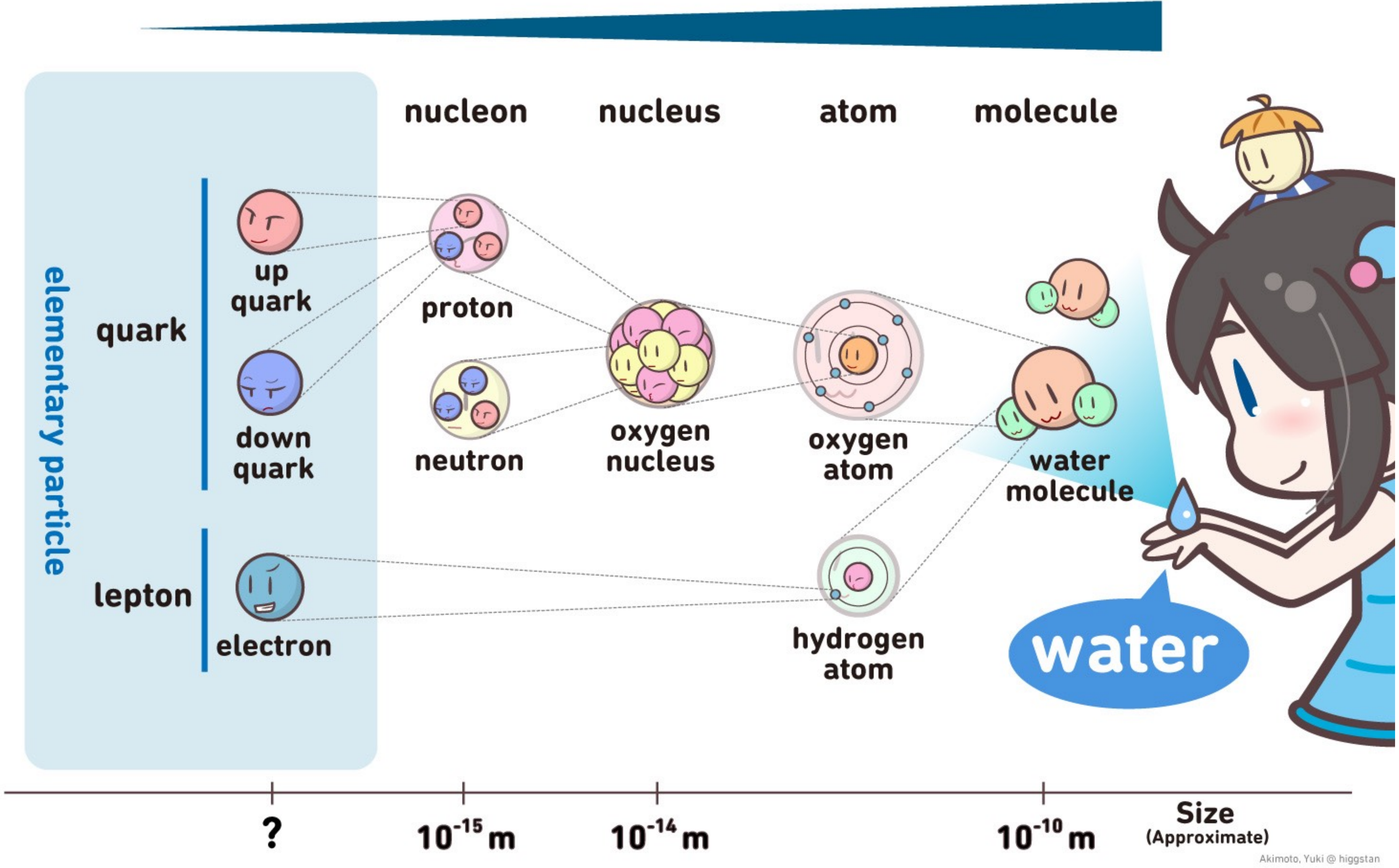

Introduction: **Standard Model**

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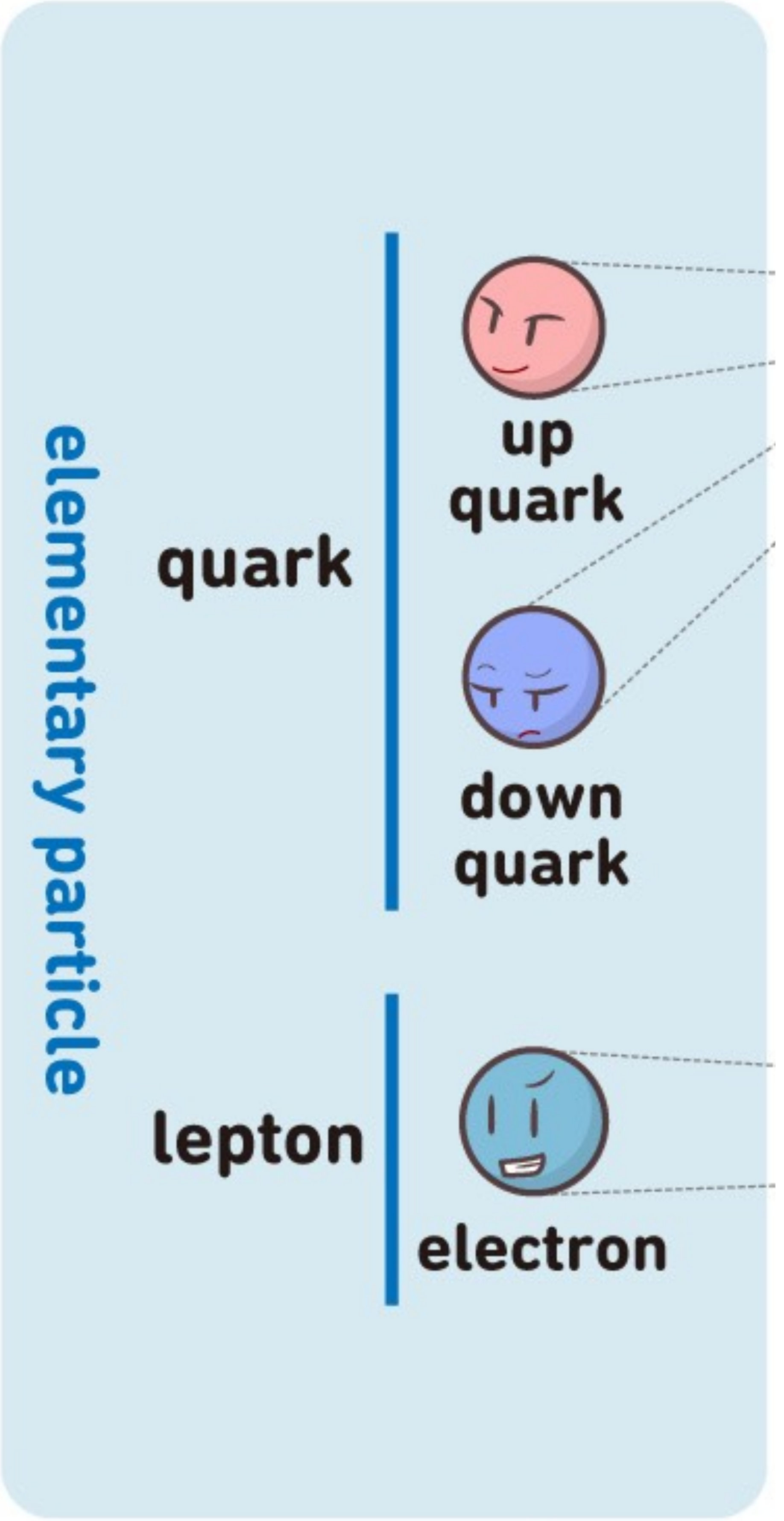

Introduction: **Standard Model**

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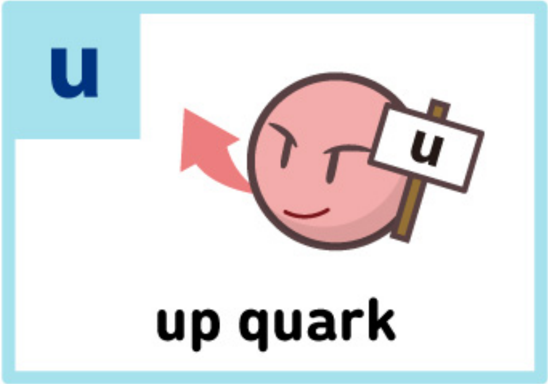
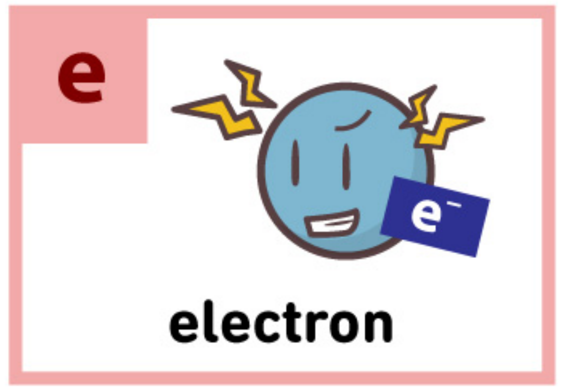
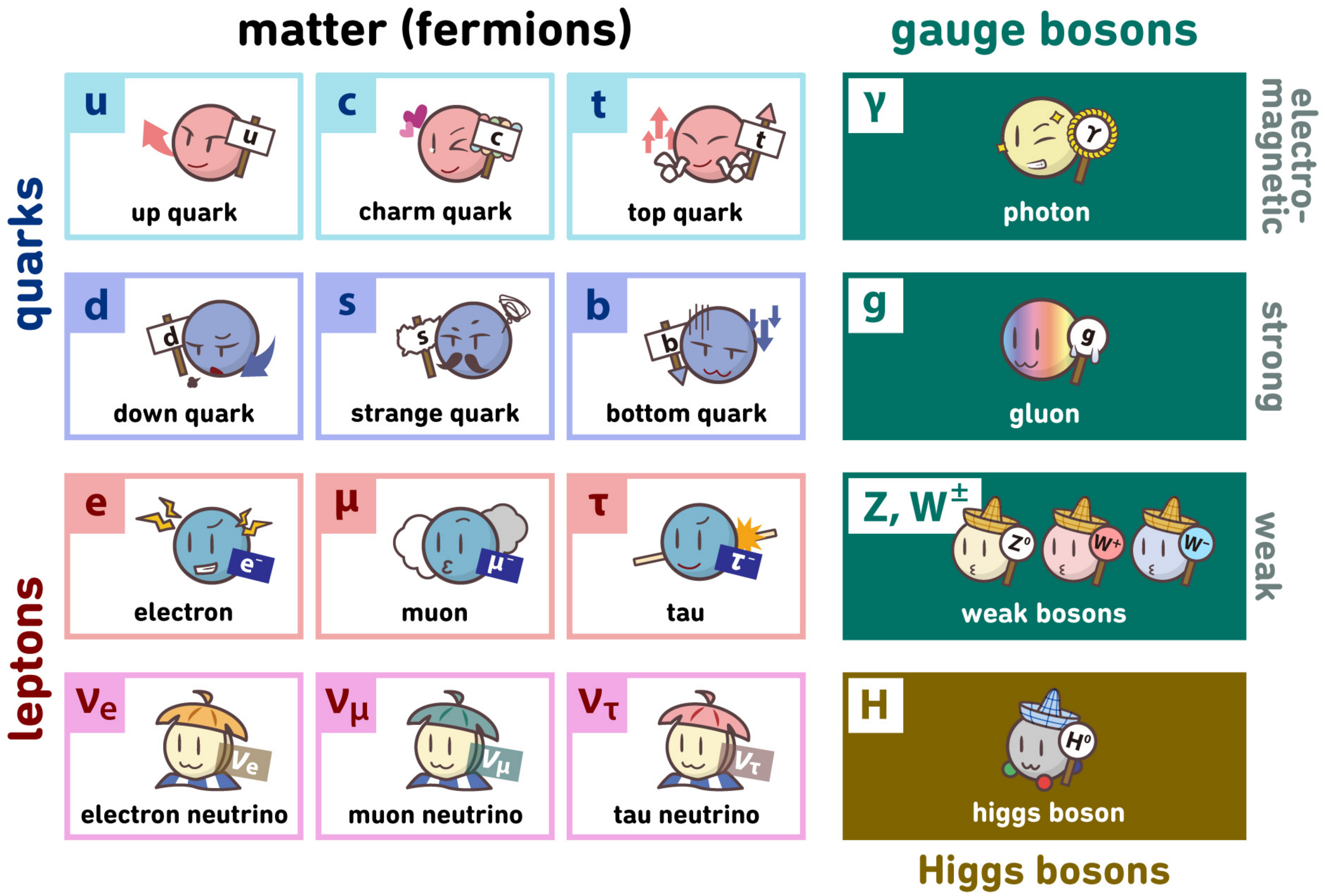




Introduction: **Standard Model**

Figs. from higgstan.com

Standard Model



Introduction: **Standard Model**

Standard Model

$$
\begin{aligned}
\mathscr{L} = &- \sum \frac{1}{4} F^{a}_{\mu\nu} F^{a\mu\nu} && \text{... gauge fields} \\
&+ \sum i\bar{\psi}\gamma^{\mu} D_{\mu}\psi && \text{... matter fields + gauge interactions} \\
&+ |D_{\mu}\phi|^{2} - V(\phi) && \text{... Higgs fields} \\
&+ \sum y\phi\bar{\psi}\psi + \mathrm{h.c.} && \text{... Yukawa interactions}
\end{aligned}
$$

It can explain the outcome of countless experiments in particle physics with remarkable accuracy.

The most successful theory of particle physics to date.

Introduction: **Standard Model**

Standard Model

$$
\begin{aligned}
\mathscr{L} = & -\sum \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} && \text{... gauge fields} \\
& + \sum i\bar{\psi}\gamma^\mu D_\mu \psi && \text{... matter fields + gauge interactions} \\
& + |D_\mu \phi|^2 - V(\phi) && \text{... Higgs fields} \\
& + \sum y\phi\bar{\psi}\psi + \mathrm{h.c.} && \text{... Yukawa interactions}
\end{aligned}
$$

But there are puzzles and problems that the Standard Model cannot explain, such as

- **Dark Matter,**
- **Matter-Antimatter asymmetry of the Universe,**
- **Inflation,**
- **Neutrino masses,**
- **Strong CP problem,** 👉
- **etc.**

Introduction: **Standard Model**

- **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.

It cannot be explained even by the anthropic discussion.

cf. The cosmological constant (CC) problem.
(The CC is small because, otherwise, humans would not exist to observe it.)

But humans can exist even if $\bar{\theta}$ is much larger.

Introduction: Axion

QCD

- **Strong CP problem**

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

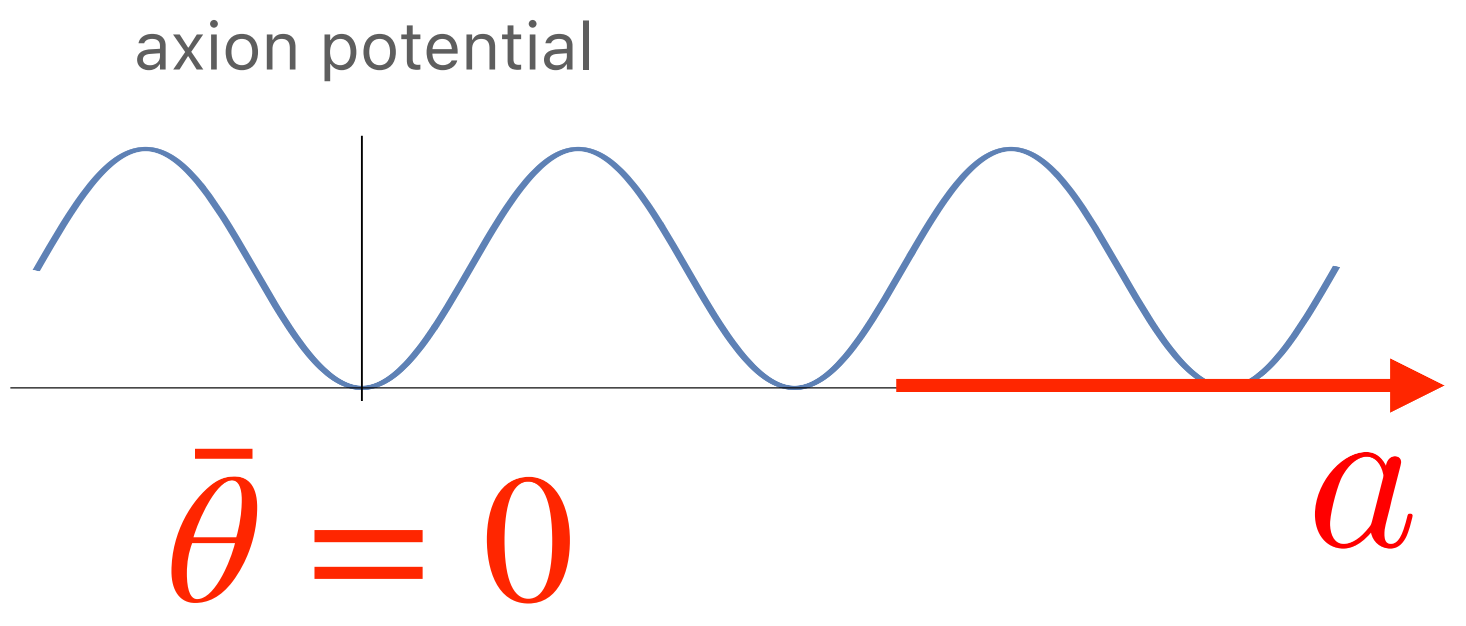
Experimental constraint (neutron EDM): $|\bar{\theta}| \lesssim 10^{-10}$

Why?

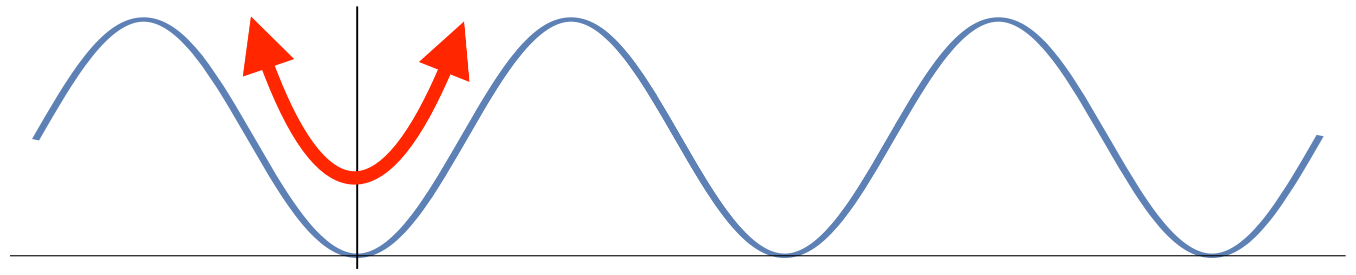
$$\left(\bar{\theta} = \theta + \sum_q \theta_q\right)$$

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

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



- Moreover, Axion can be the Dark Matter.



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

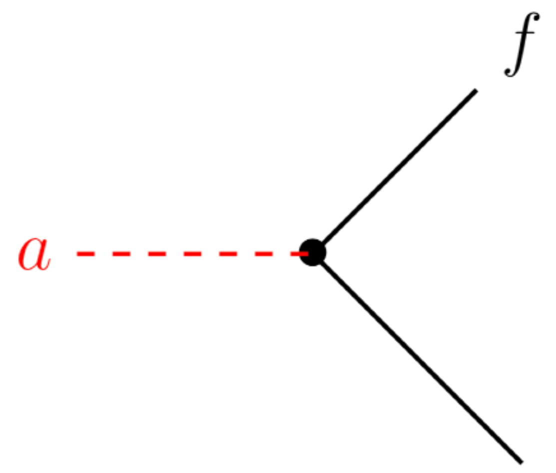
[Turner,'86]

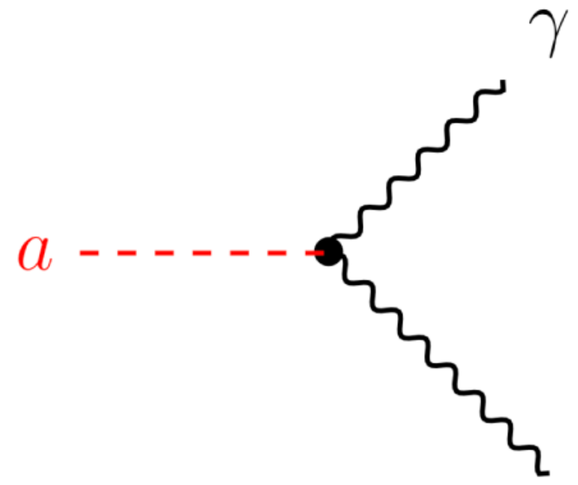
Introduction: Axion

QCD

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

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





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

- Axion's mass is also determined by f_a .

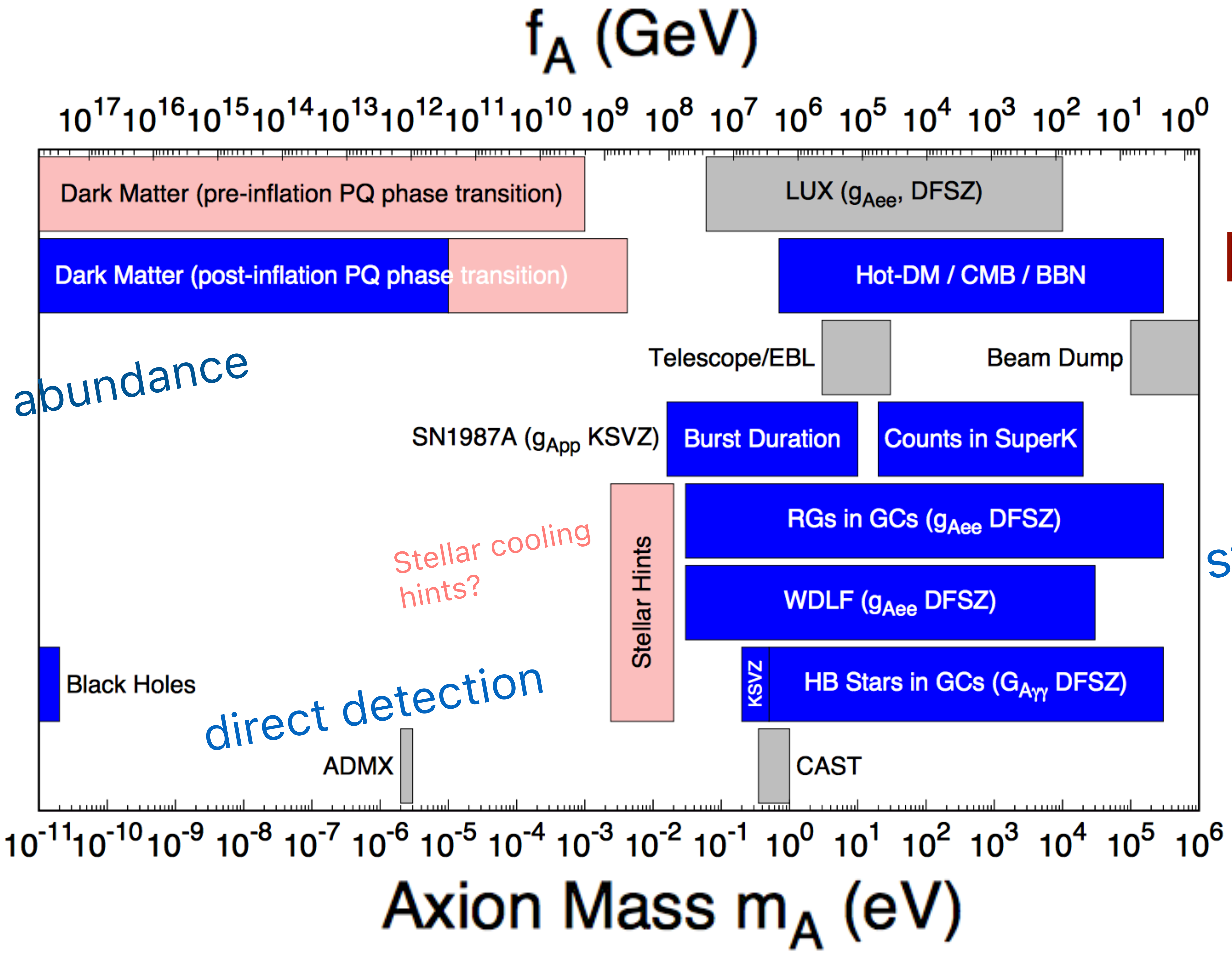
$$m_a = \frac{\sqrt{m_u m_d}}{m_u + m_d}\frac{f_\pi m_\pi}{f_a} \simeq 5.8 \times \left(\frac{10^9\ \text{GeV}}{f_a}\right)\ \text{meV}\,.$$

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

Introduction: **Axion**

QCD

Constraints



[Particle Data Group 2018]

Cosmology + DM abundance

Stellar cooling hints?

direct detection

stellar Coolings

Introduction: Axion

QCD

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.

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 to have a more direct method for detecting axions produced by stellar objects.

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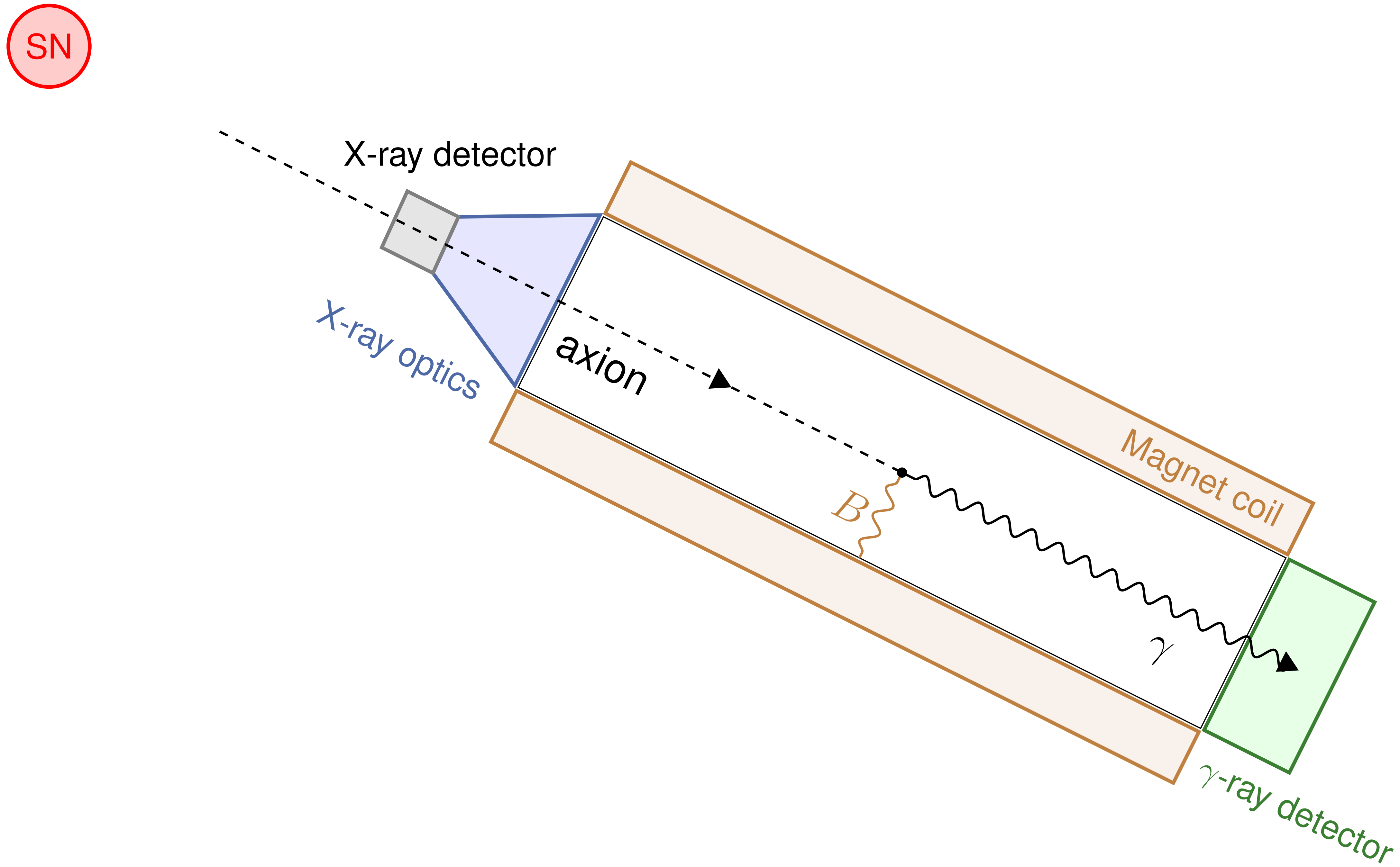
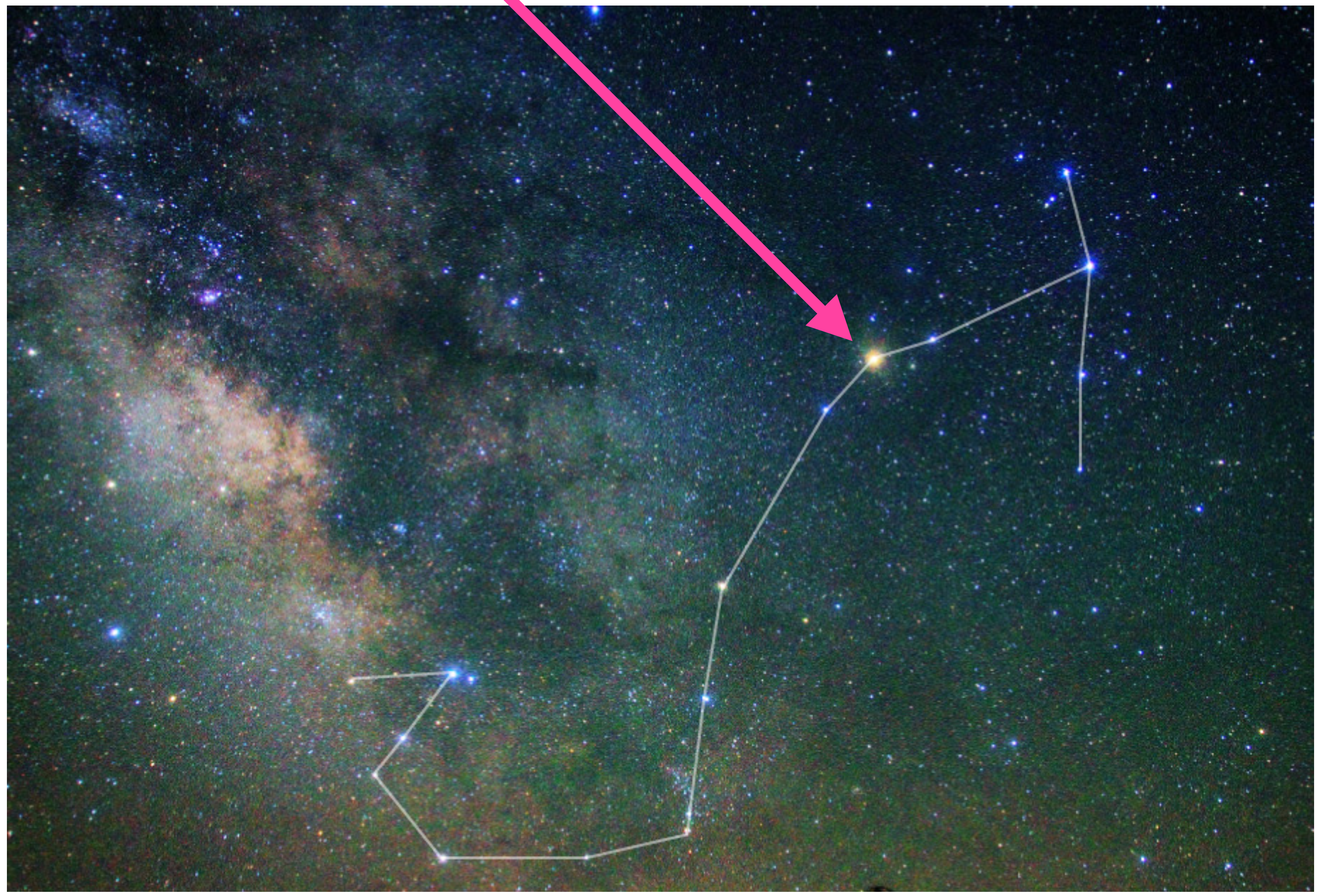


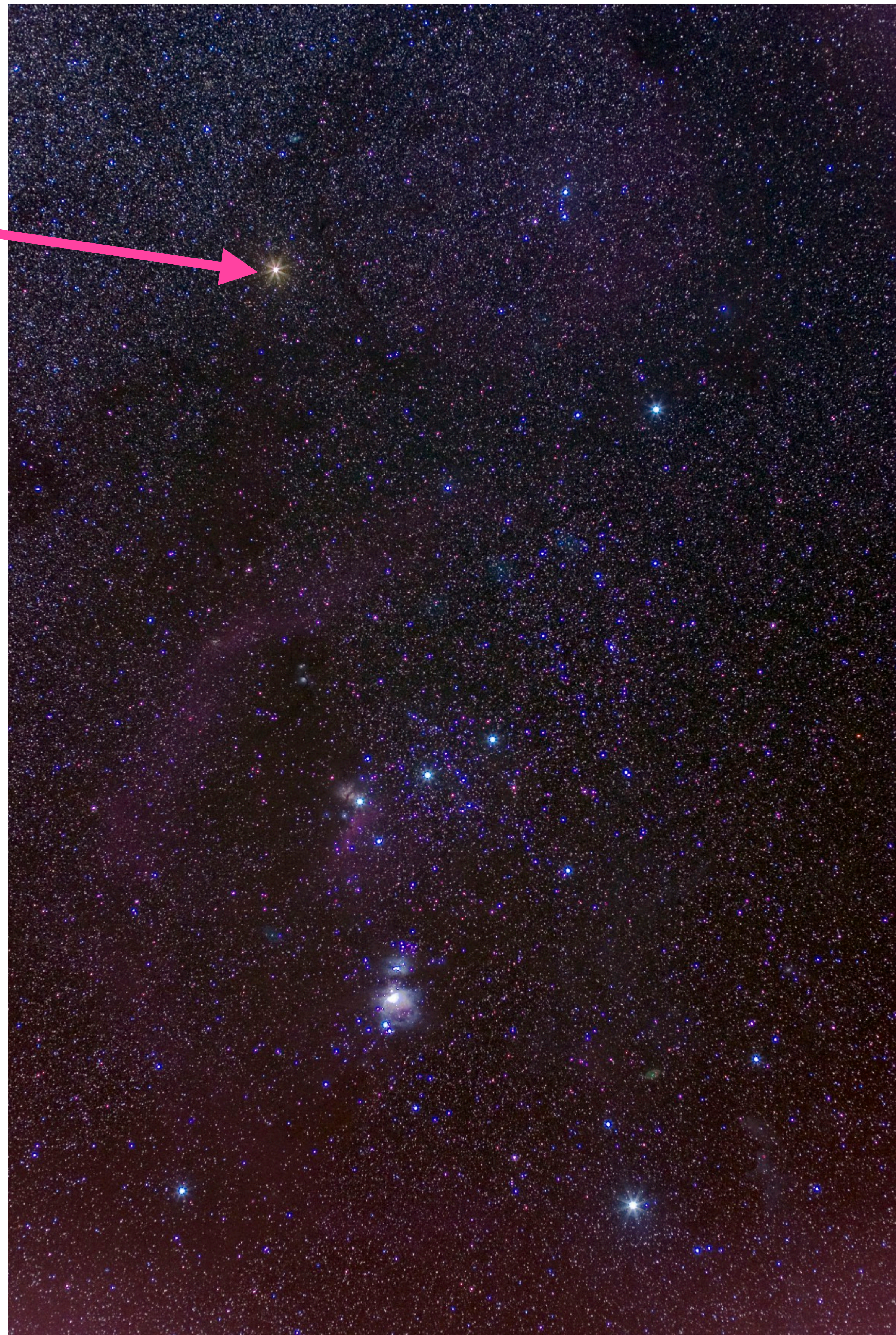
Nearby SN progenitor candidates

Antares
(~ 170 pc)



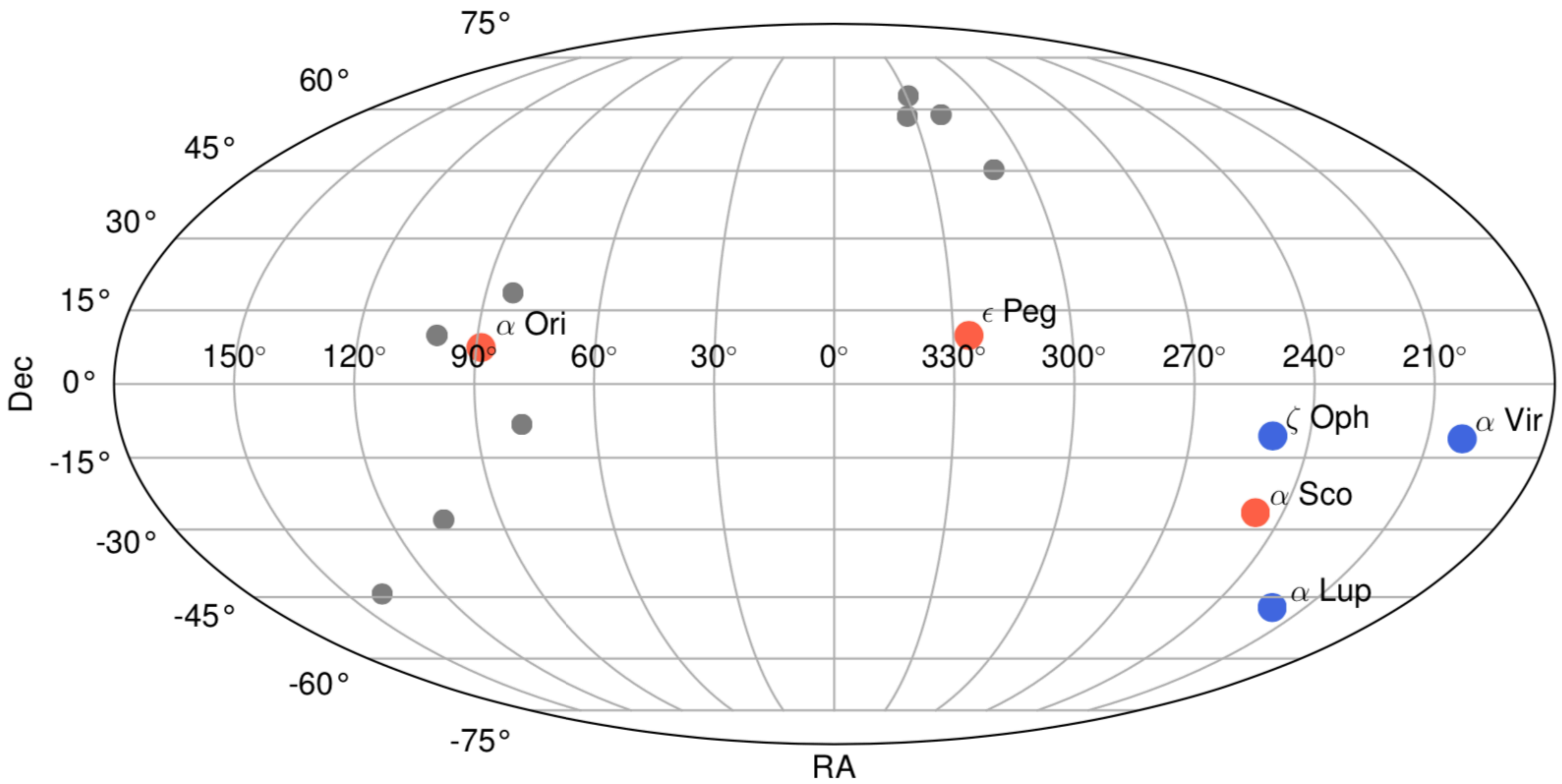
https://www.civillink.net/esozai/

Betelgeuse
(~ 200 pc)



Wikipedia

Nearby SN progenitor candidates



● ● $d < 250$ pc

● $d > 250$ pc

※ $M > 10M_\odot$ 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

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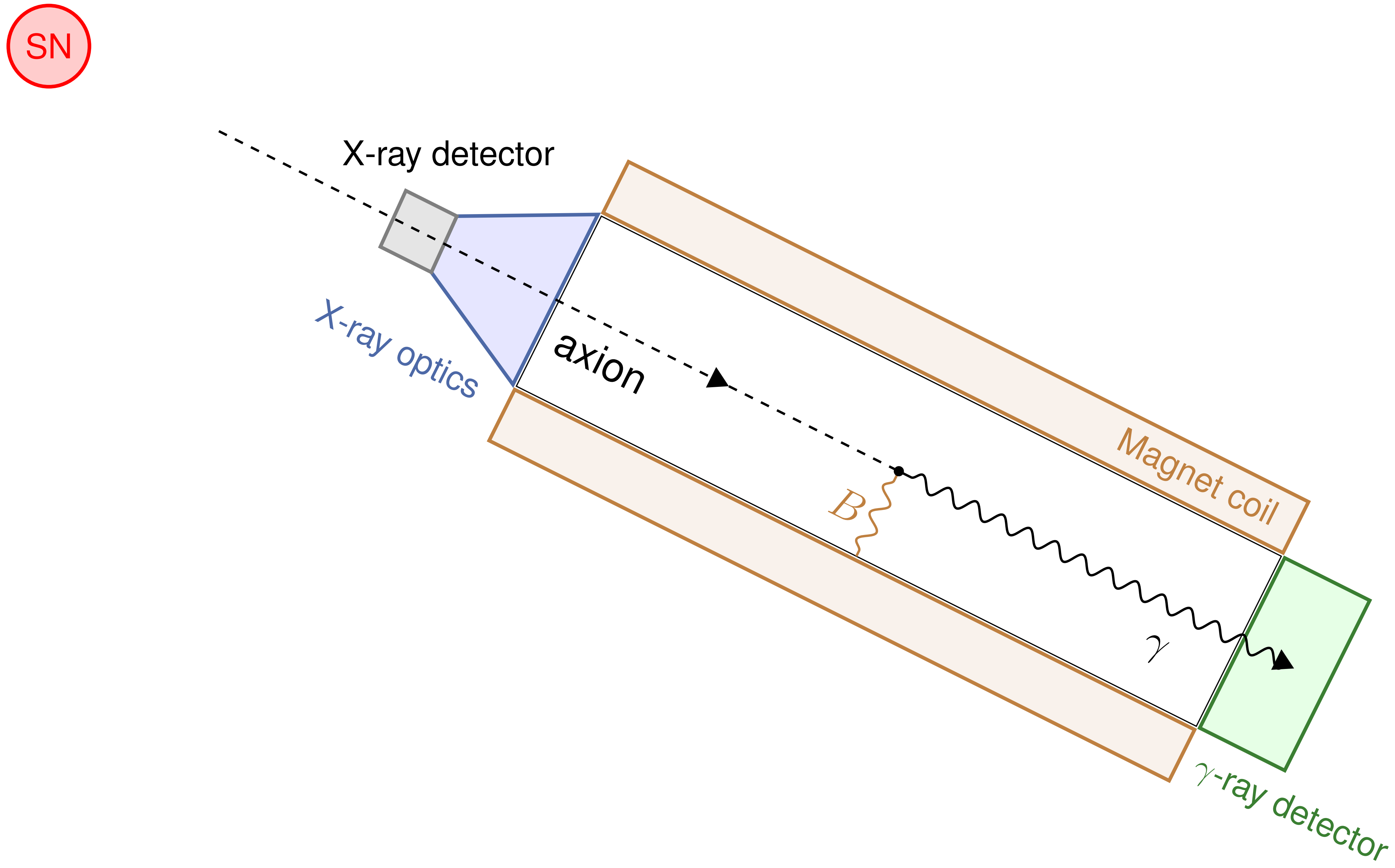
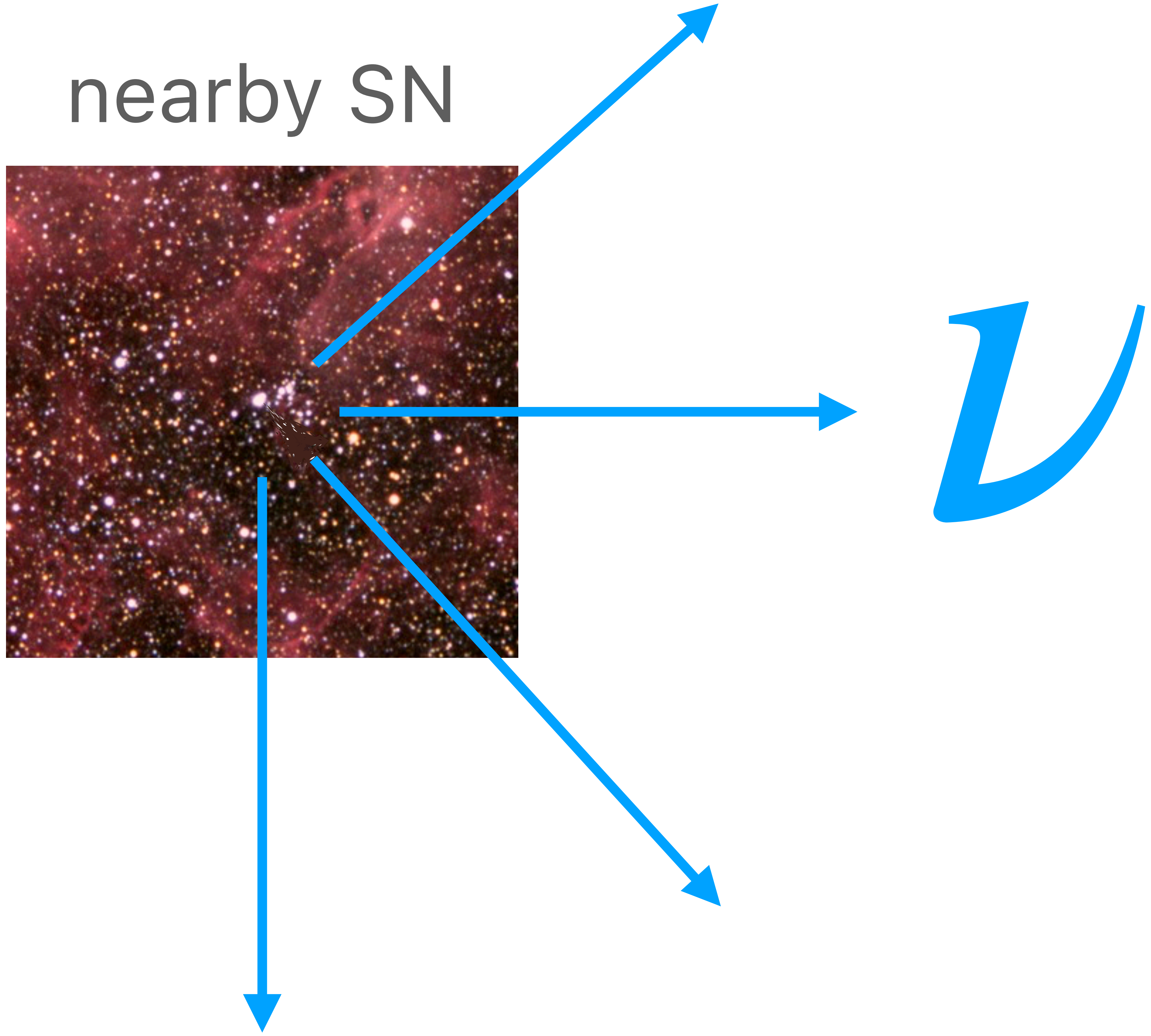


Supernova-scope

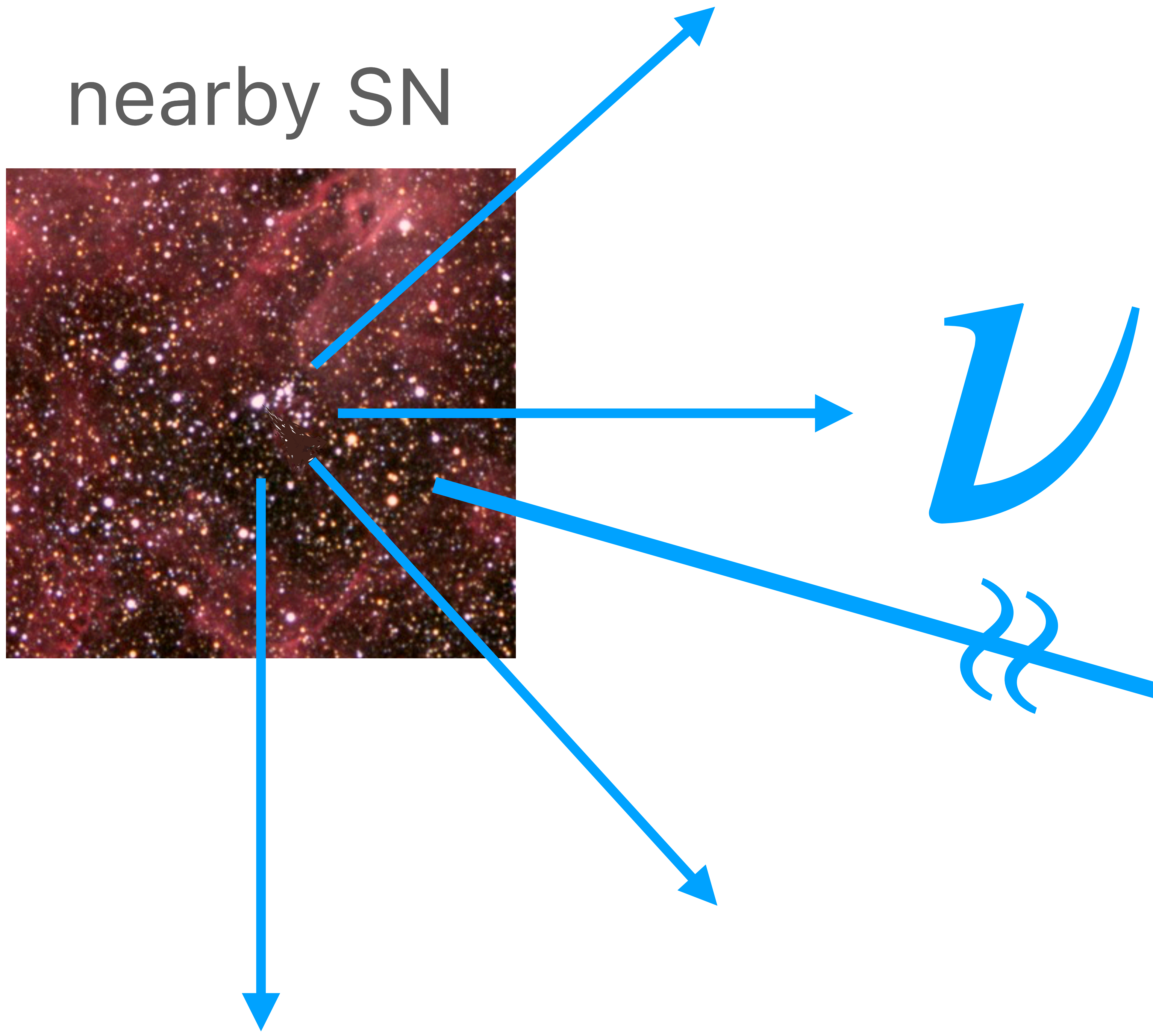
nearby SN

Supernova-scope

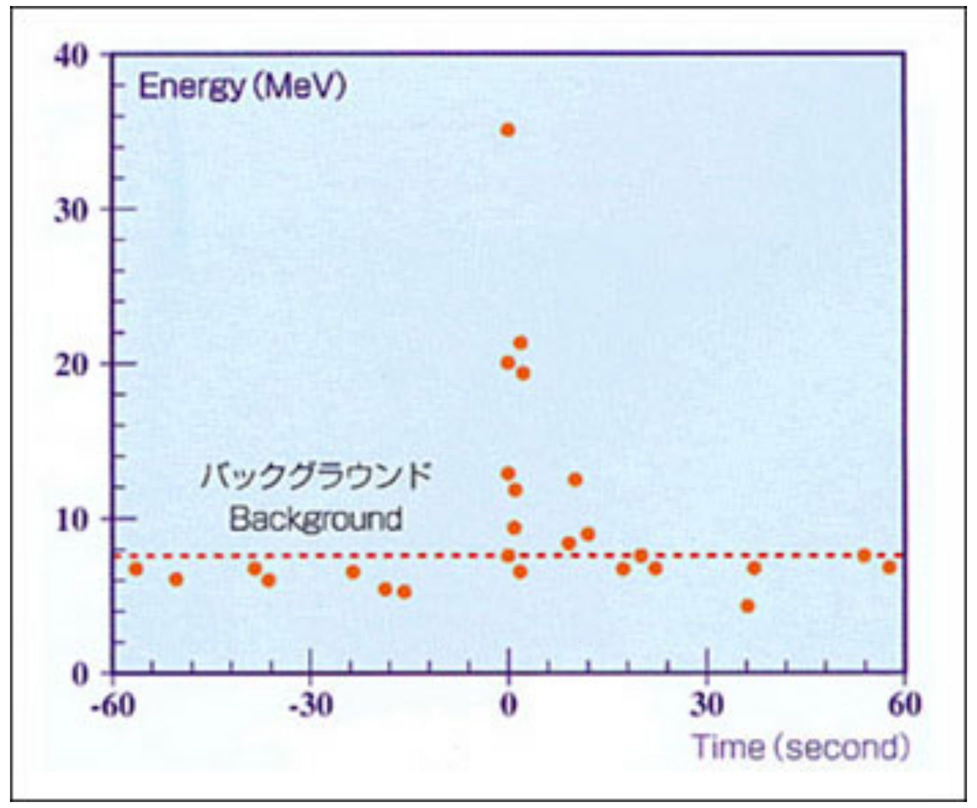


nearby SN

Supernova-scope



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



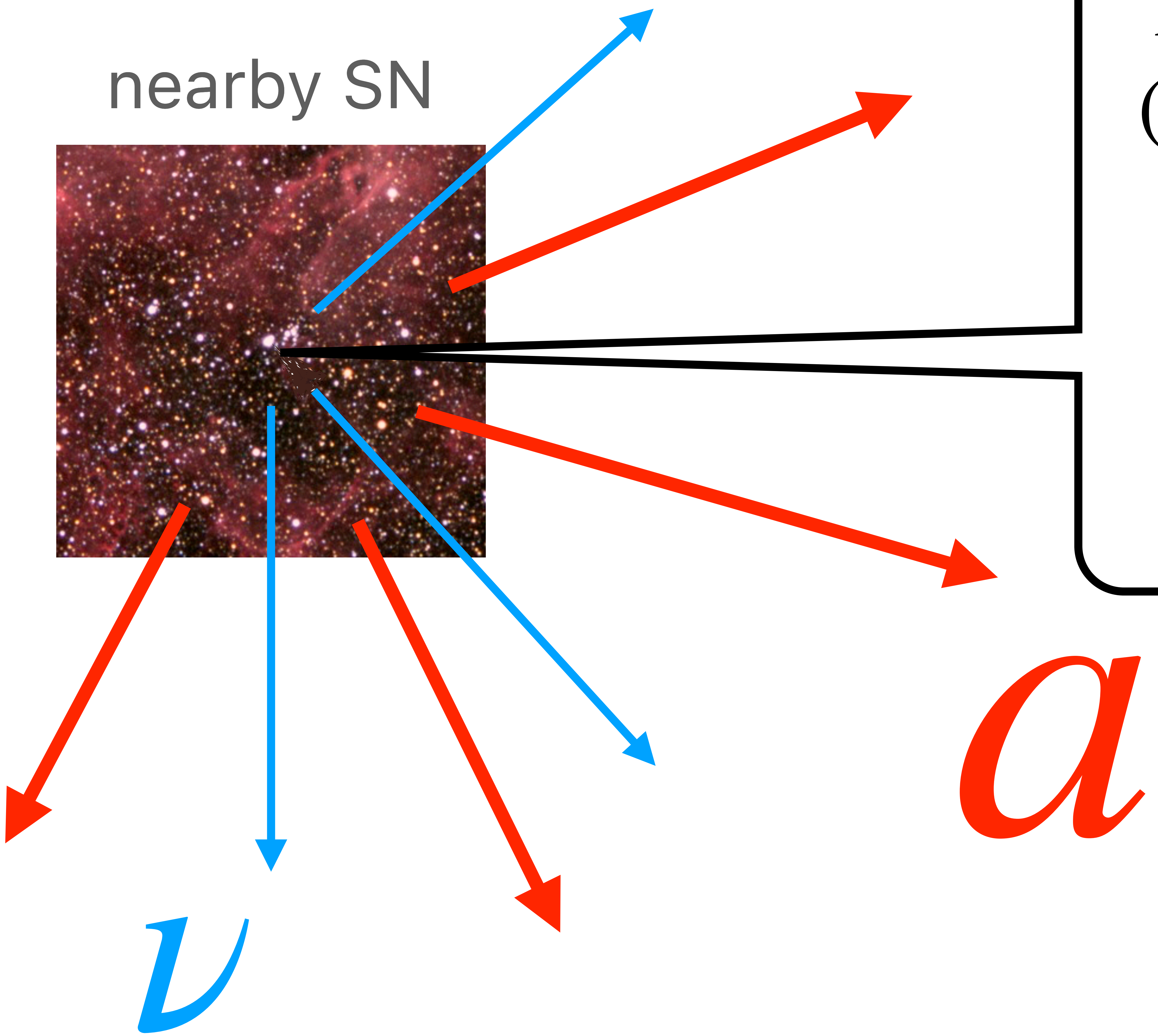
- SN1987A

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

- Future: various neutrino detectors

Supernova-scope

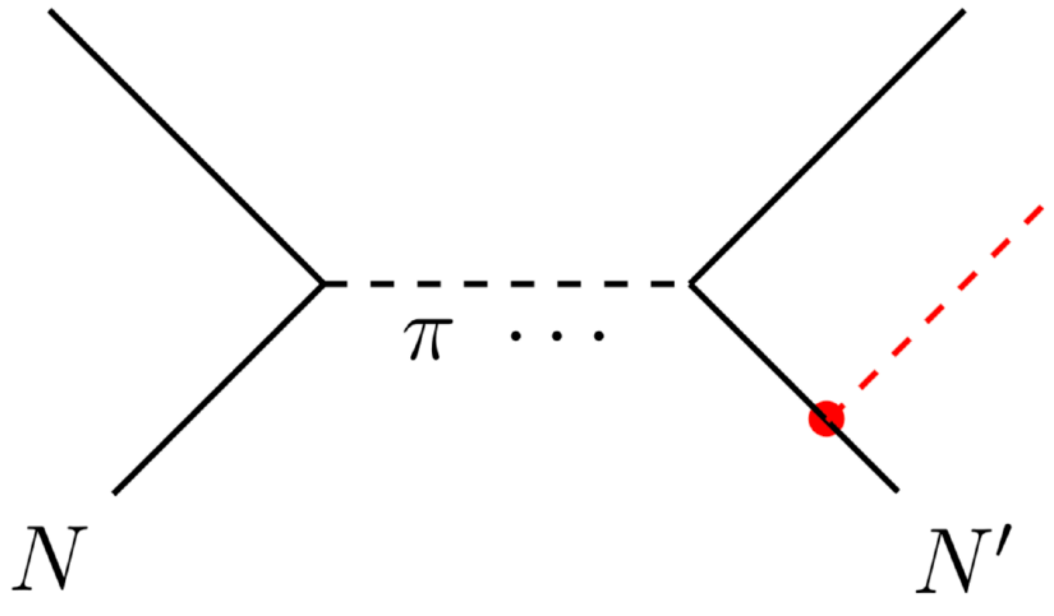
If the axion exists,...



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

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

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

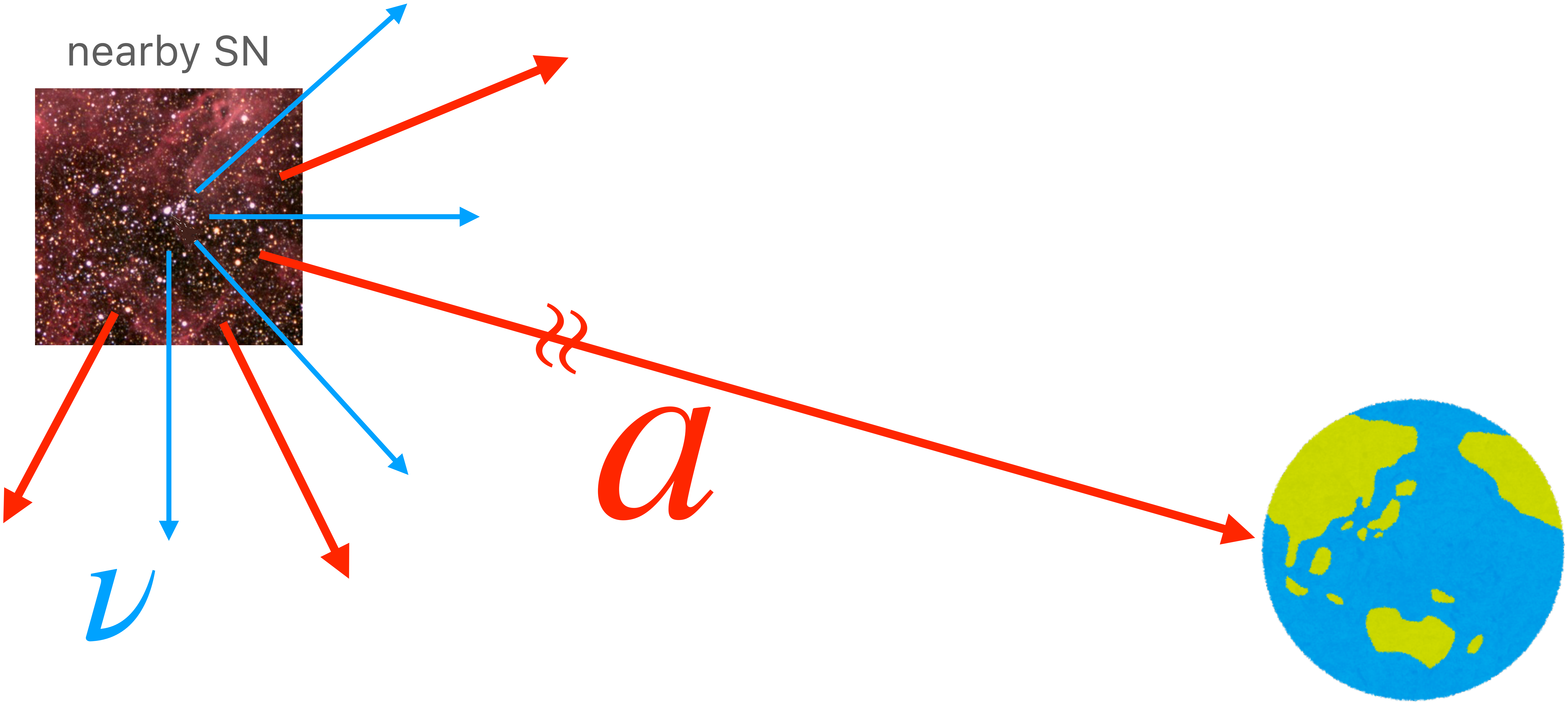


$$\begin{cases} C_p = -0.47 \\ C_n = -0.02 \end{cases} \quad \text{(KSVZ)}$$

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

Supernova-scope

If the axion exists,...

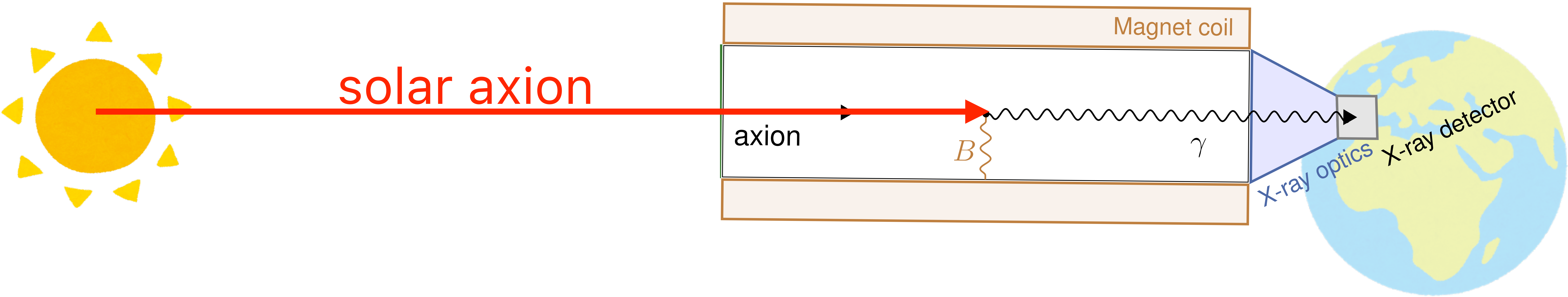


Supernova-scope

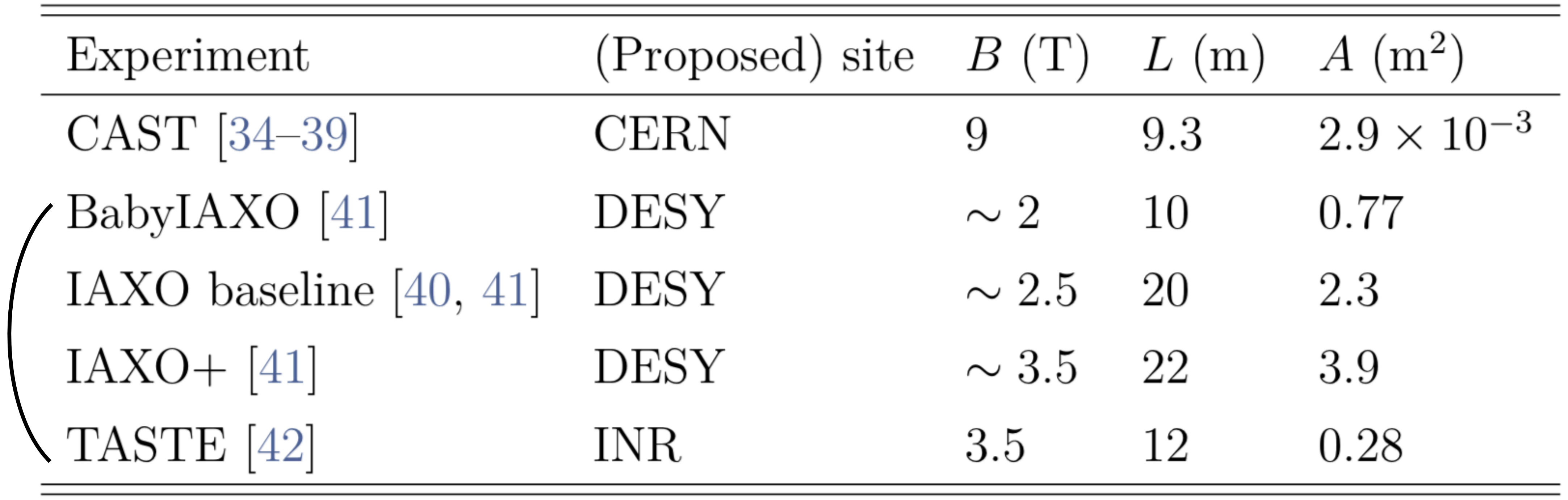
$$\mathscr{L}_{a\gamma\gamma} = \frac{1}{4}\frac{C_{a\gamma\gamma}}{f_a}\, a F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

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
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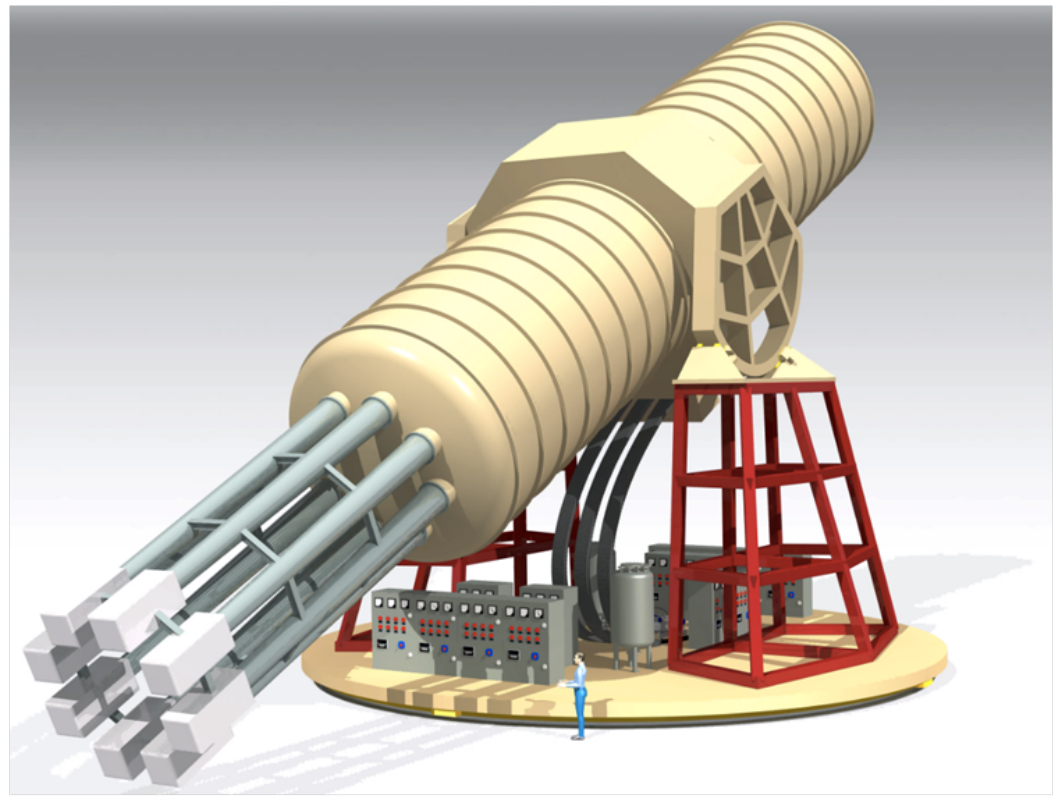
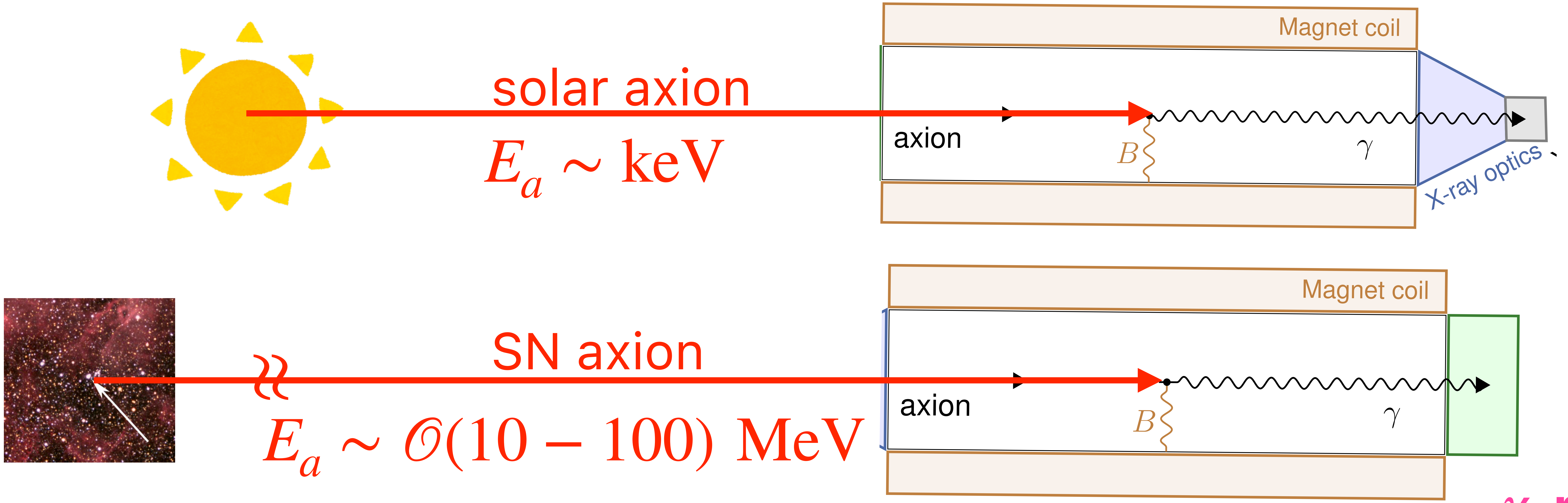


Fig. from IAXO homepage

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

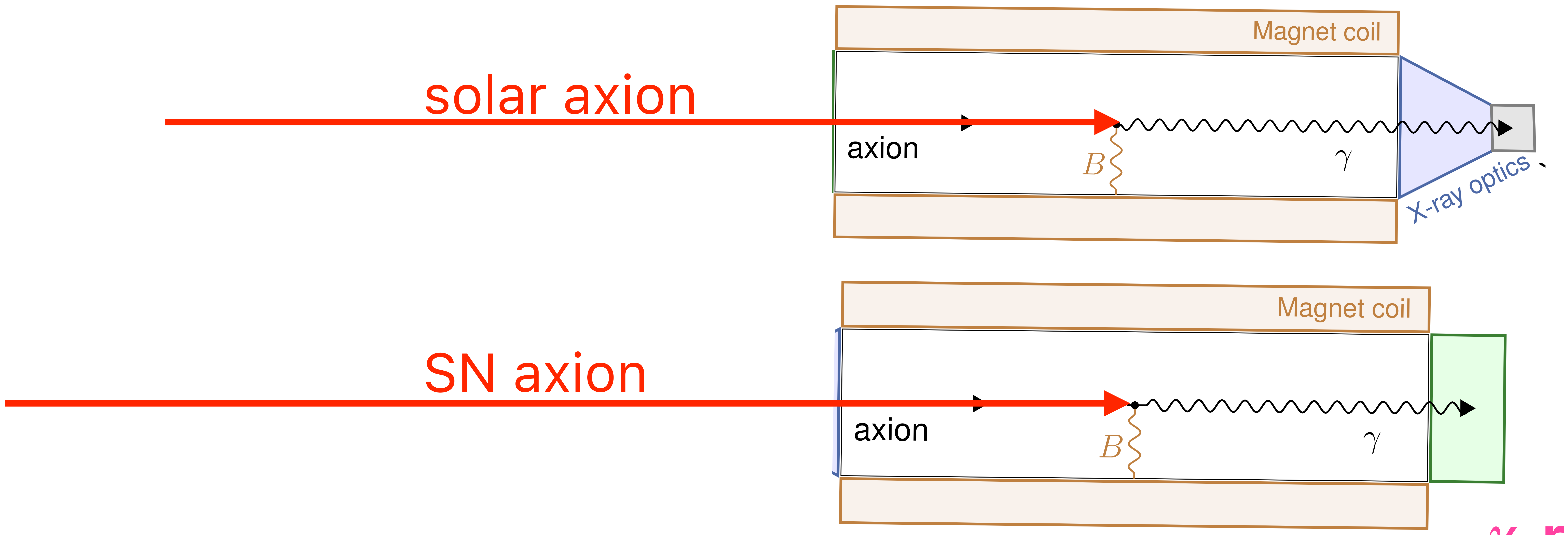
$E_a \sim \mathcal{O}(10-100)\ \mathrm{MeV}$

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



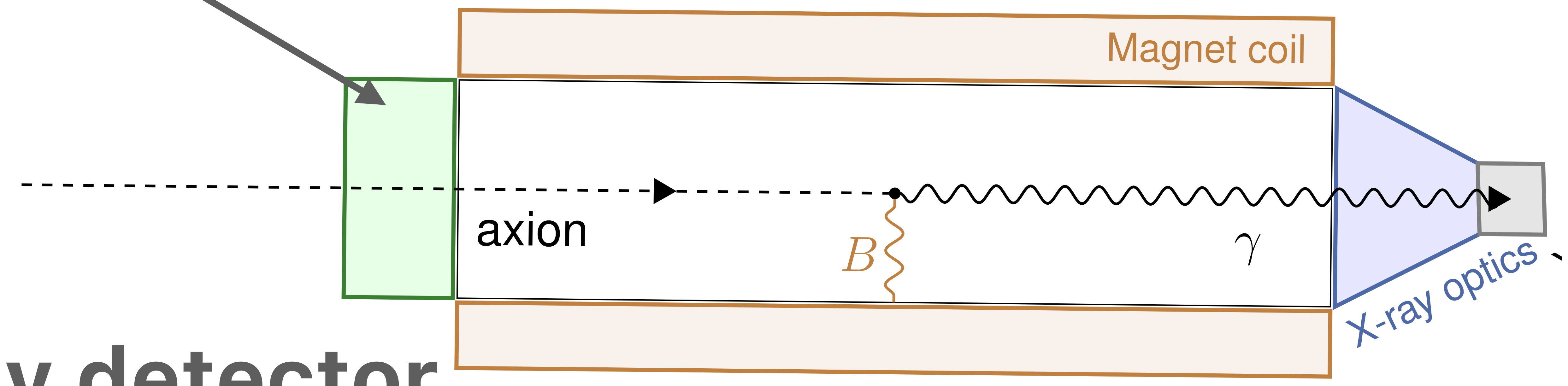
X-ray detector

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.



γ-ray detector

X-ray detector

Supernova-scope

S.Ge, K.Hamaguchi, K.Ichimura, K.Ishidoshiro, Y.Kanazawa, Y.Kishimoto, N.Nagata, J.Zheng.
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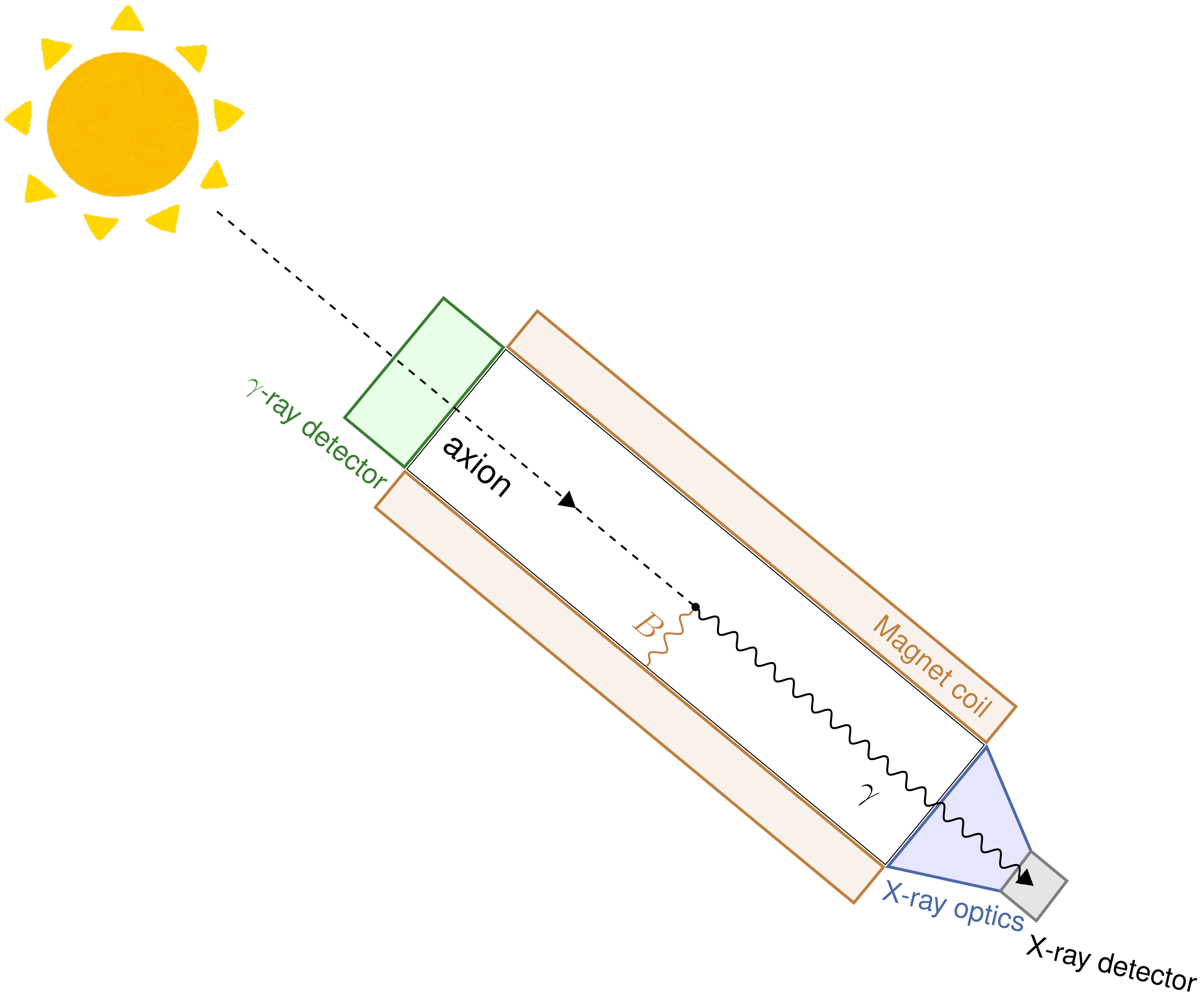
Normal operation time: It works as an axion helioscope.



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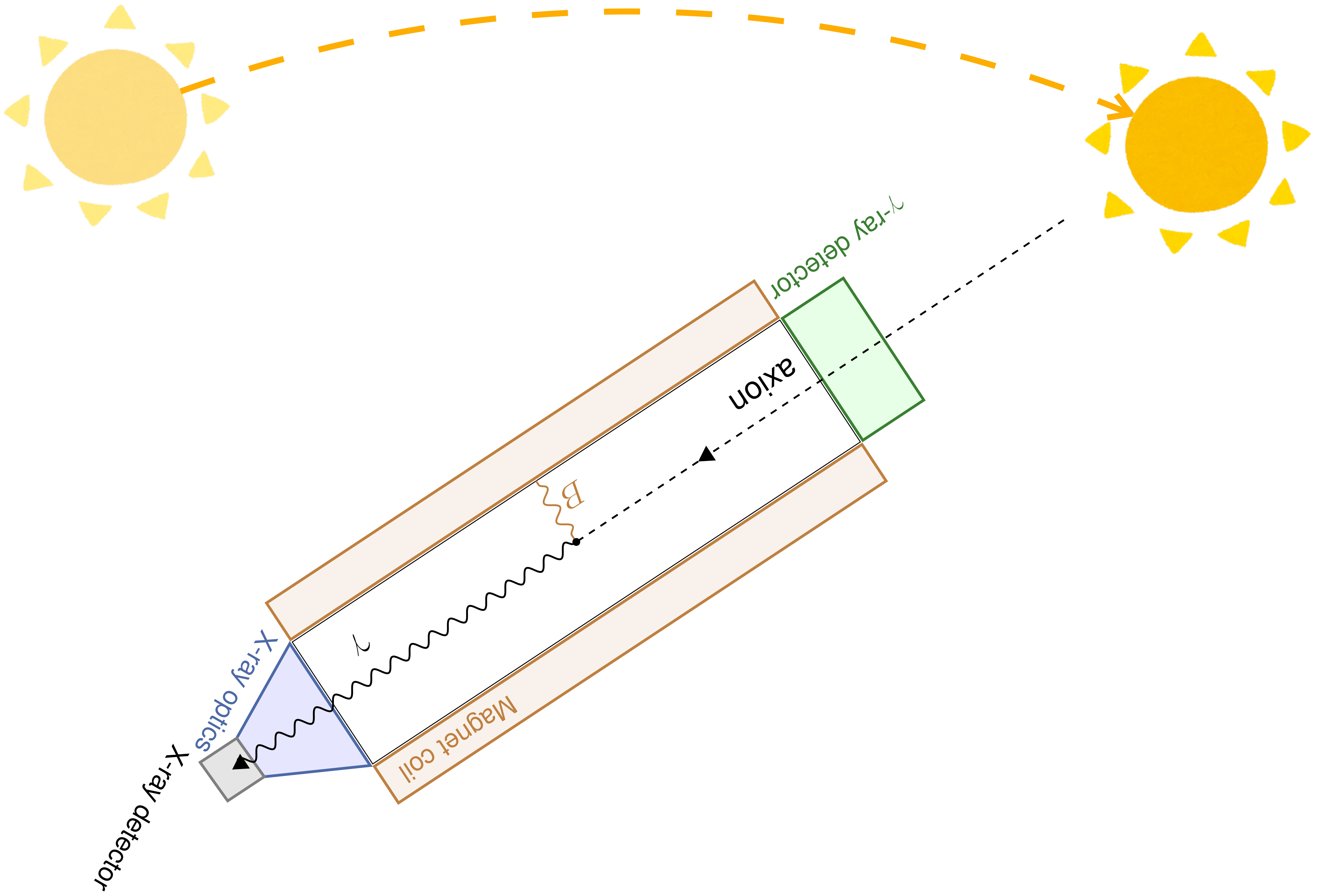

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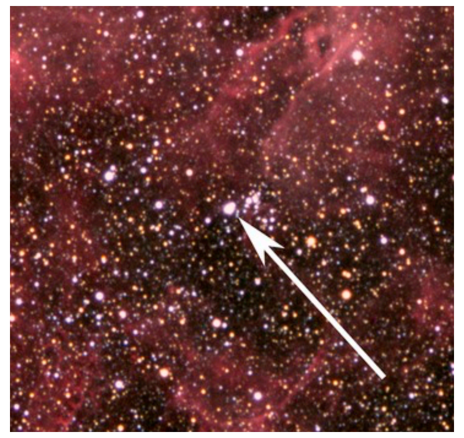
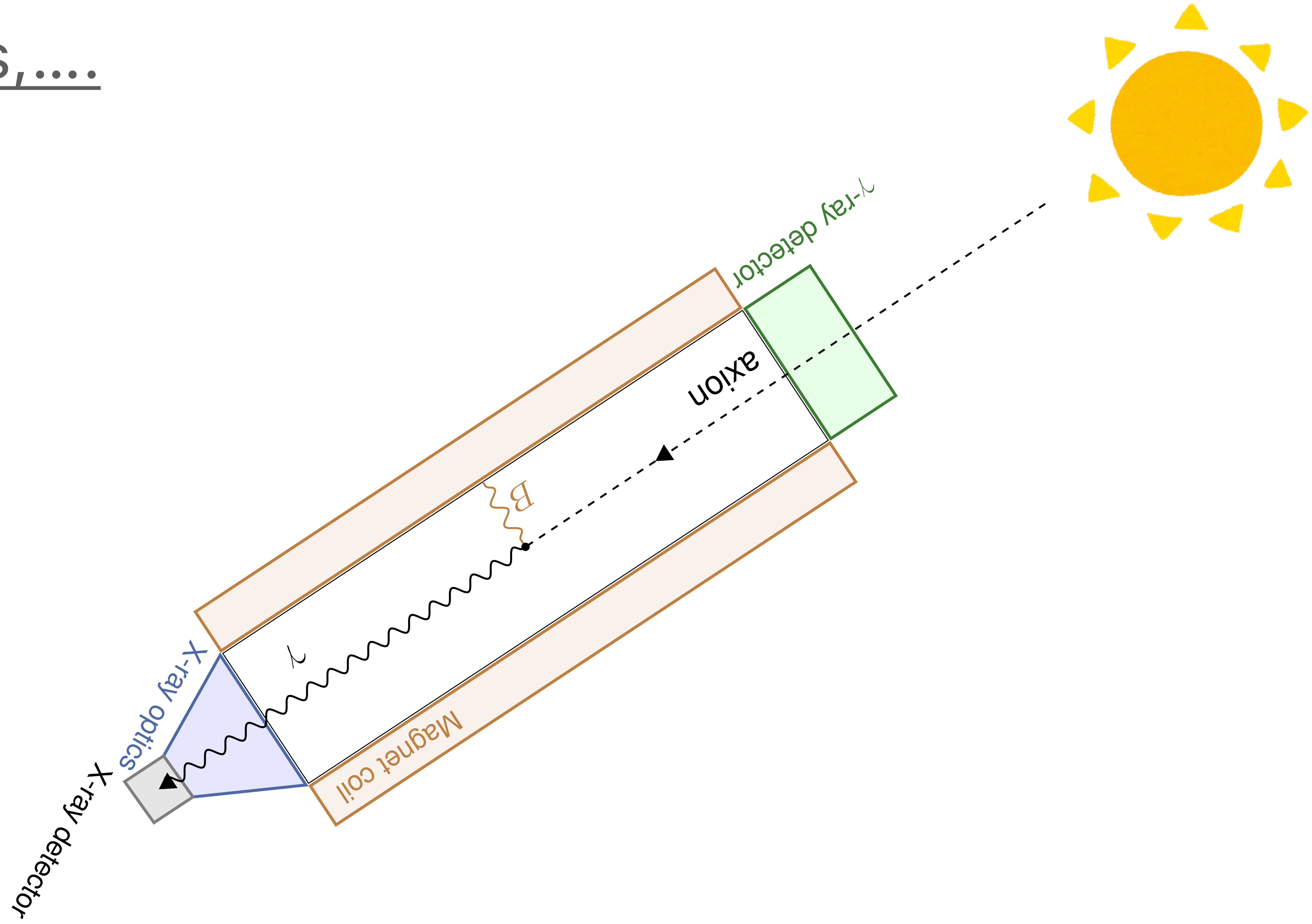
When a Supernova occurs,....





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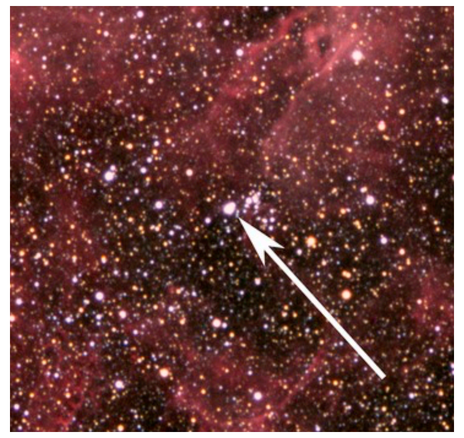

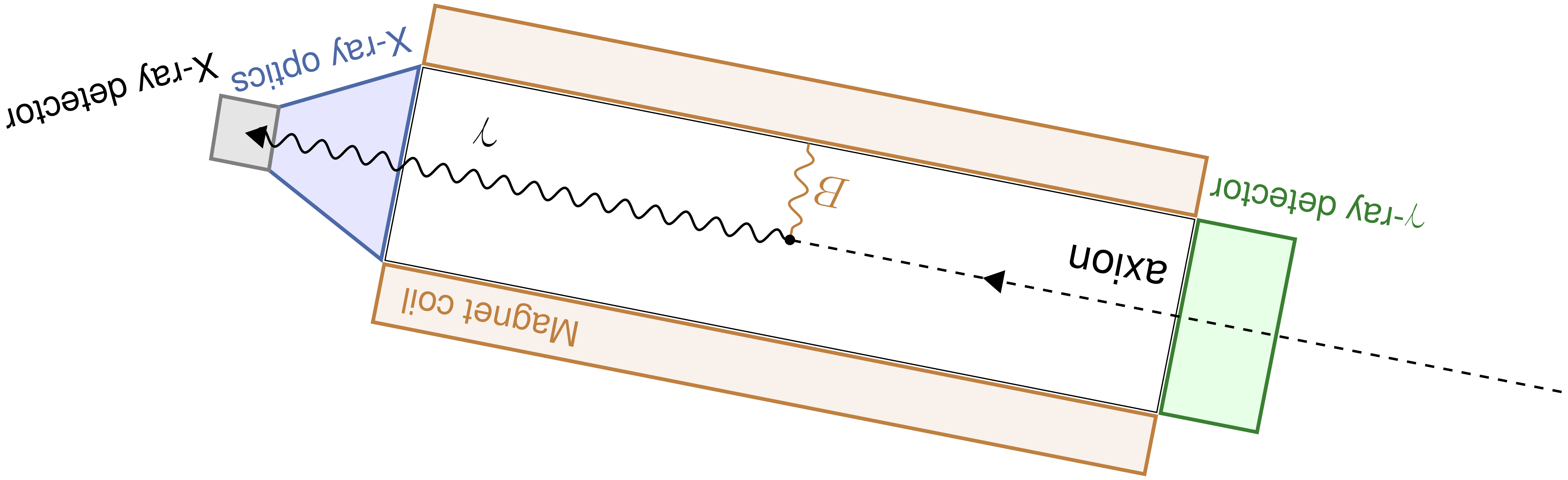

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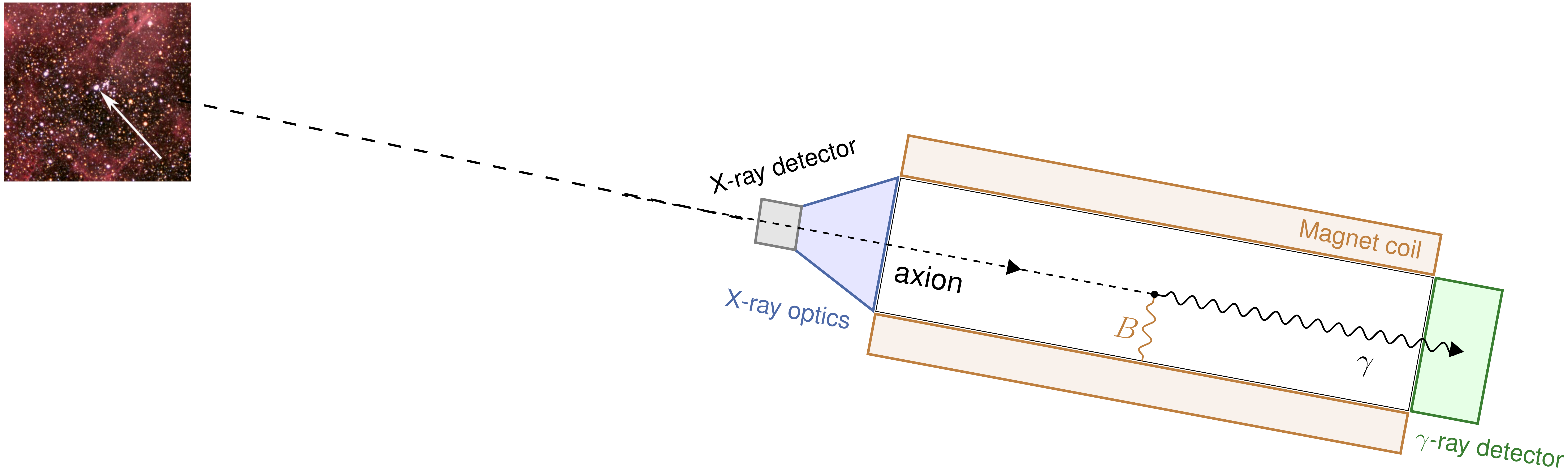

Axion Supernova-scope

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  - Event number
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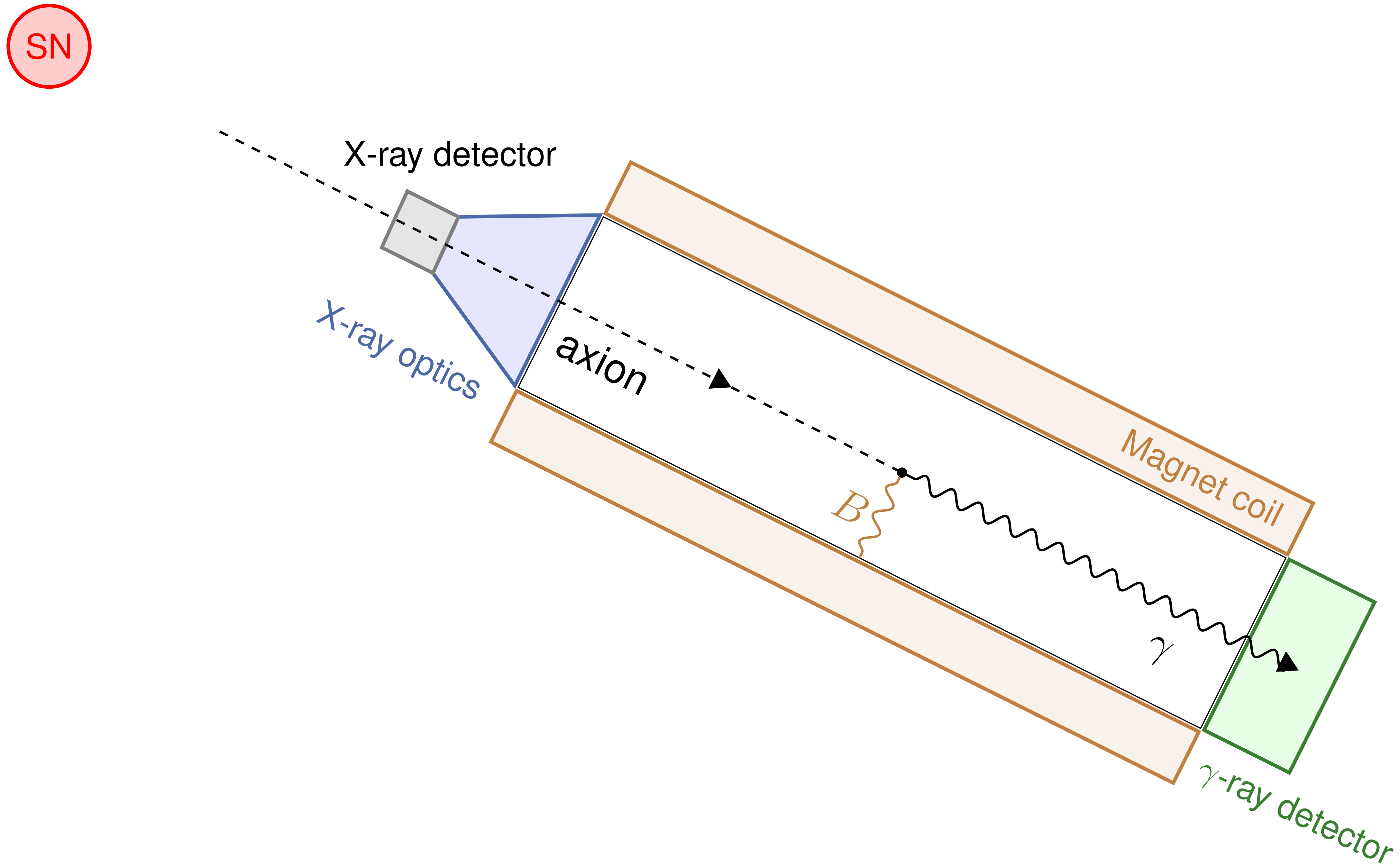
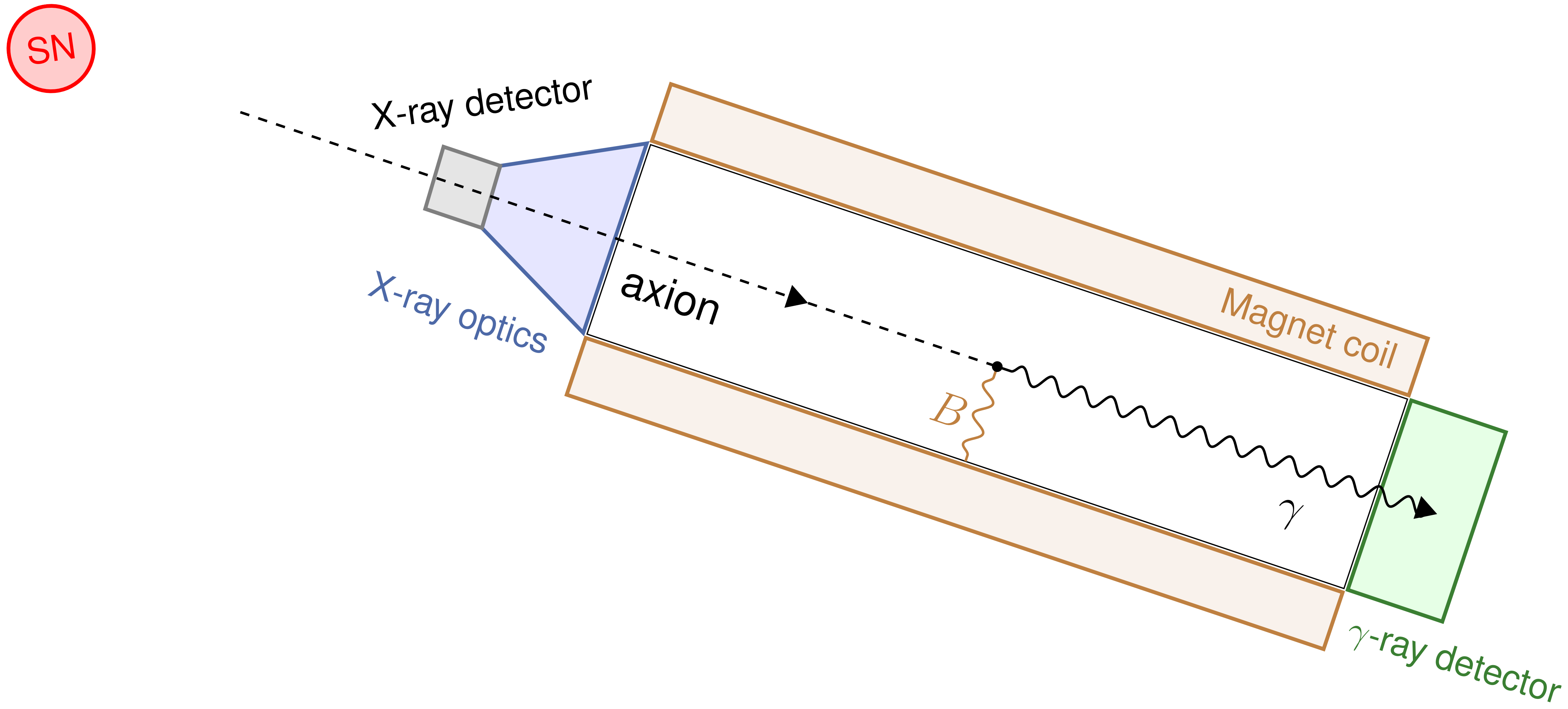


Pre-SN neutrino

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

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

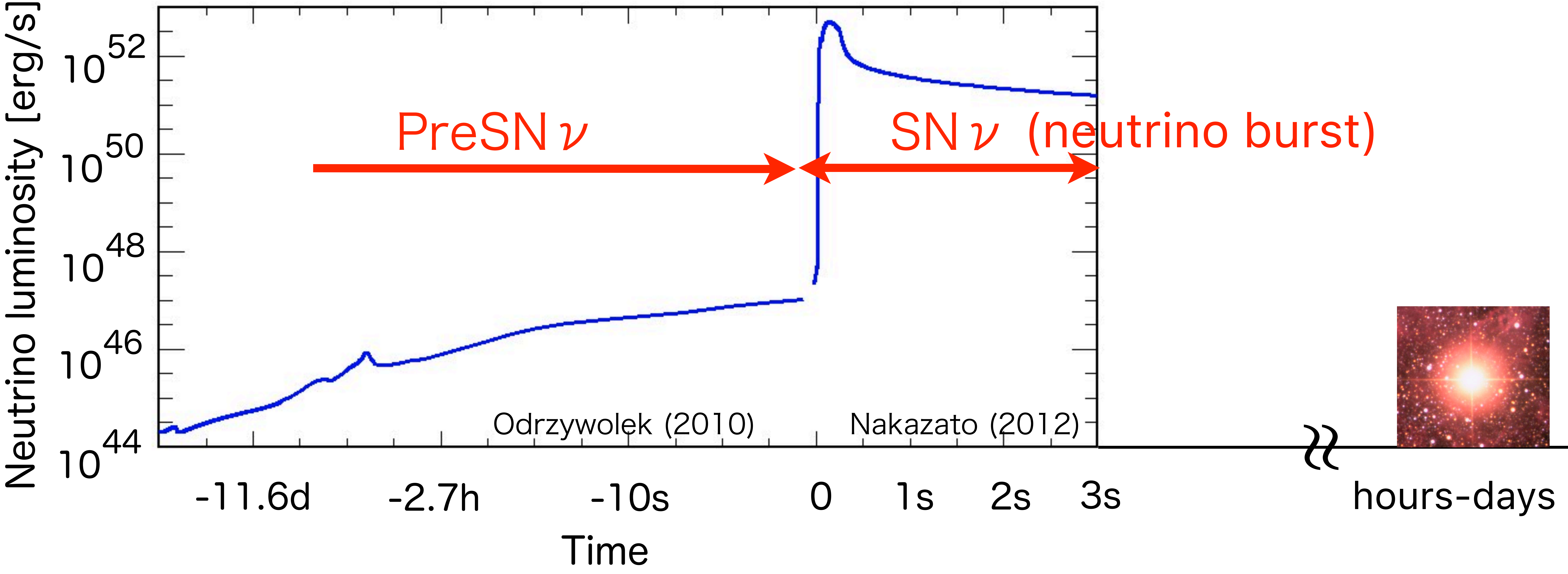


Figure from K.Ishidoshiro's talk in 2019.
https://www.lowbg.org/ugnd/workshop/sympo_all/201903_Sendai/

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

Pre-SN neutrino

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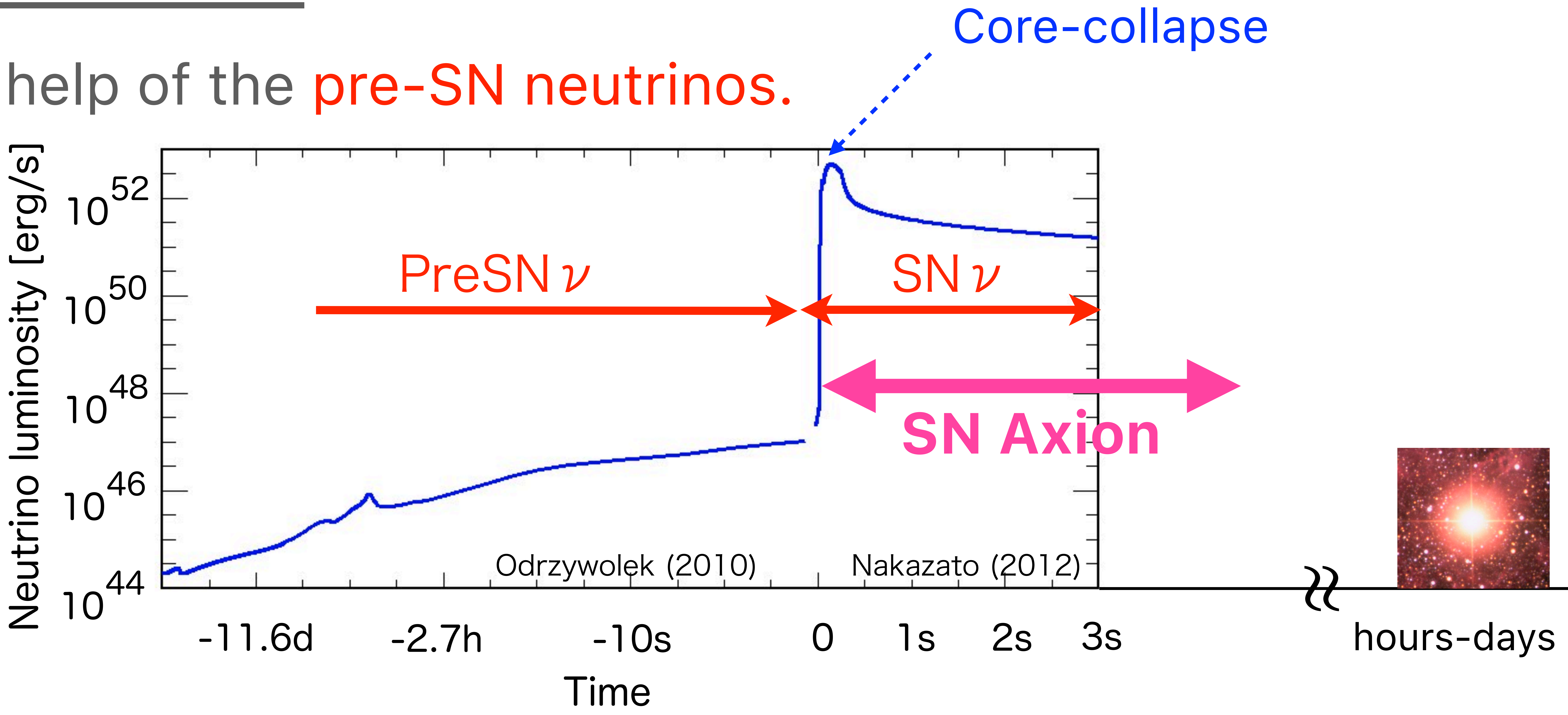

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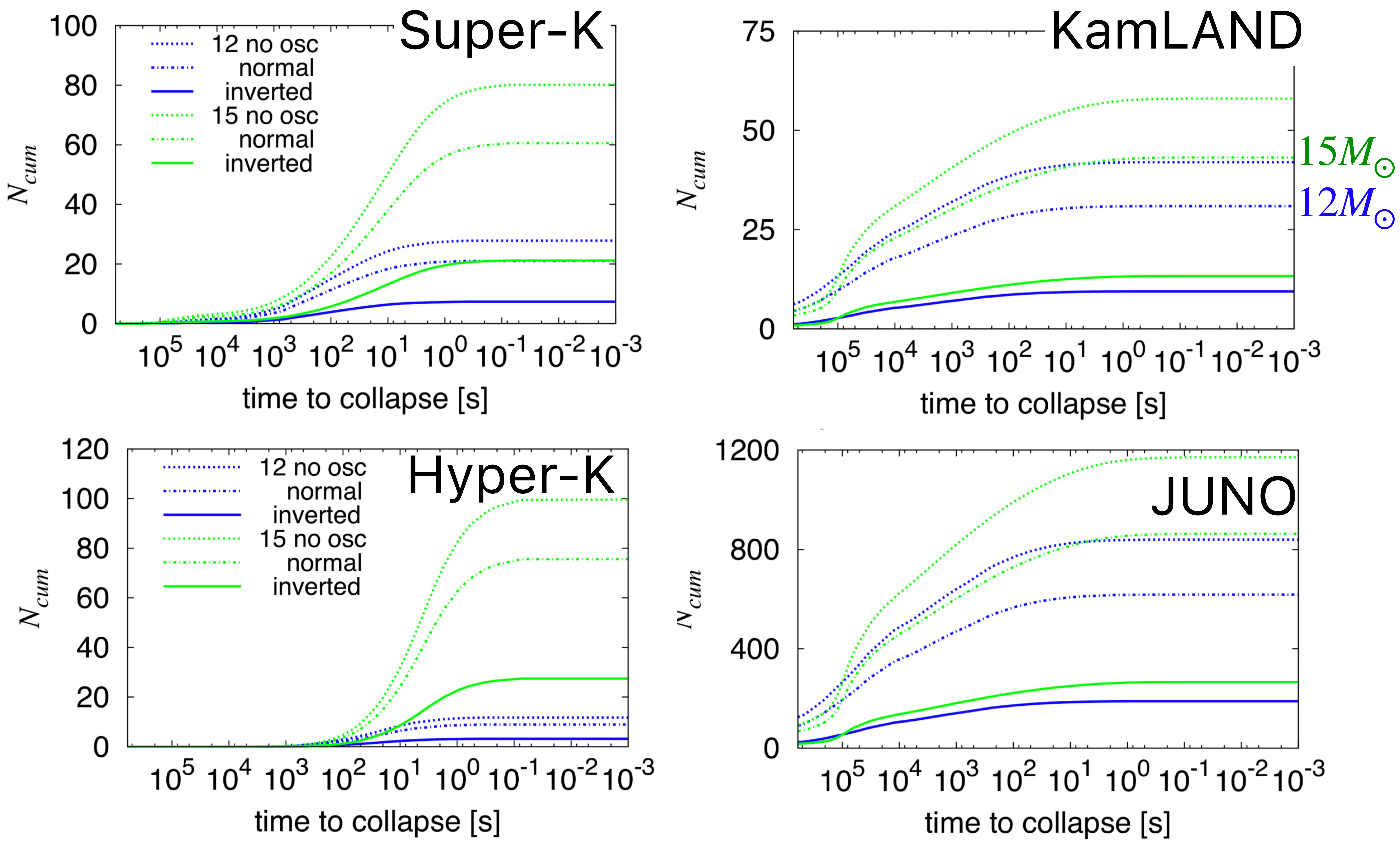
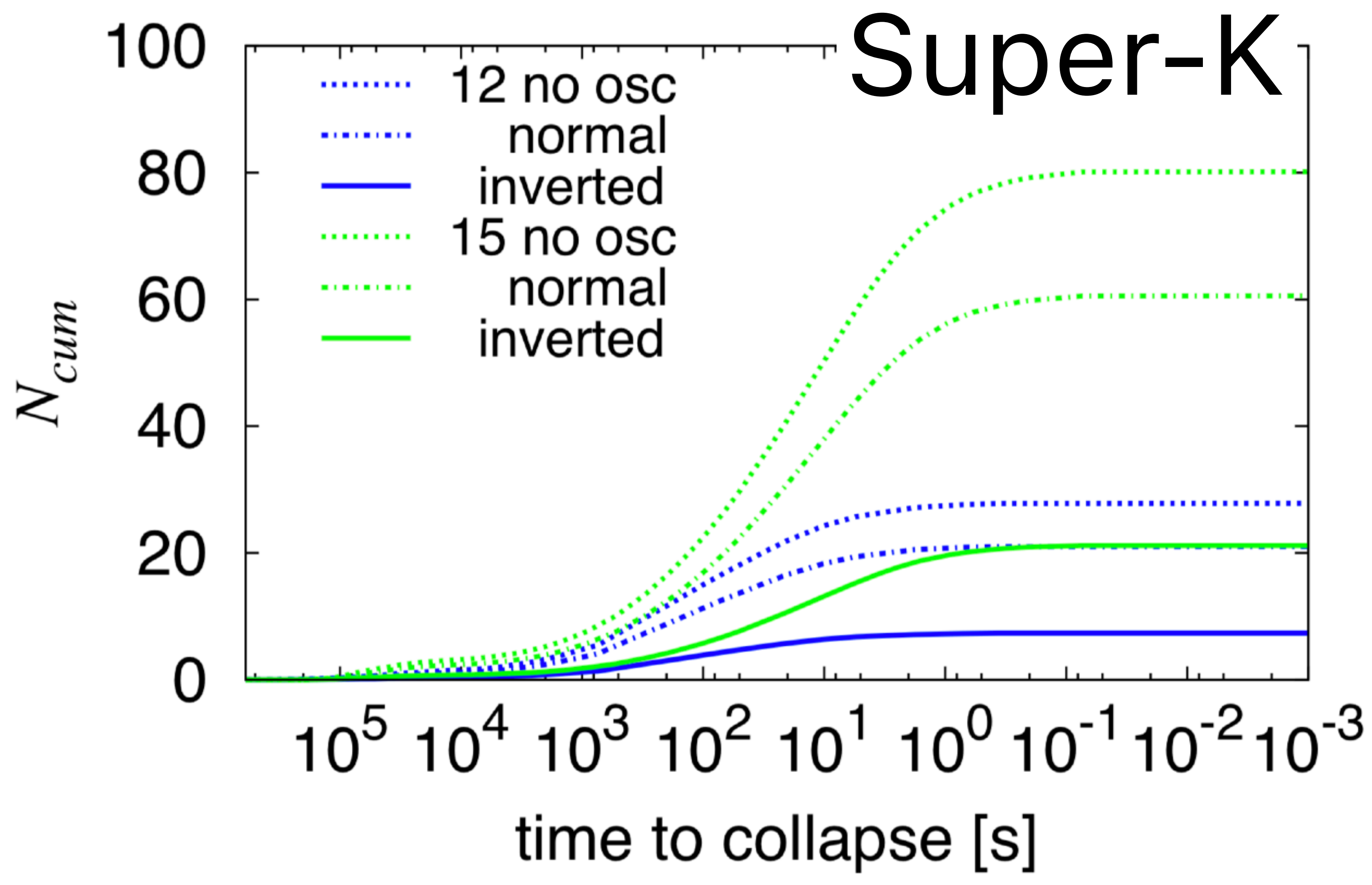
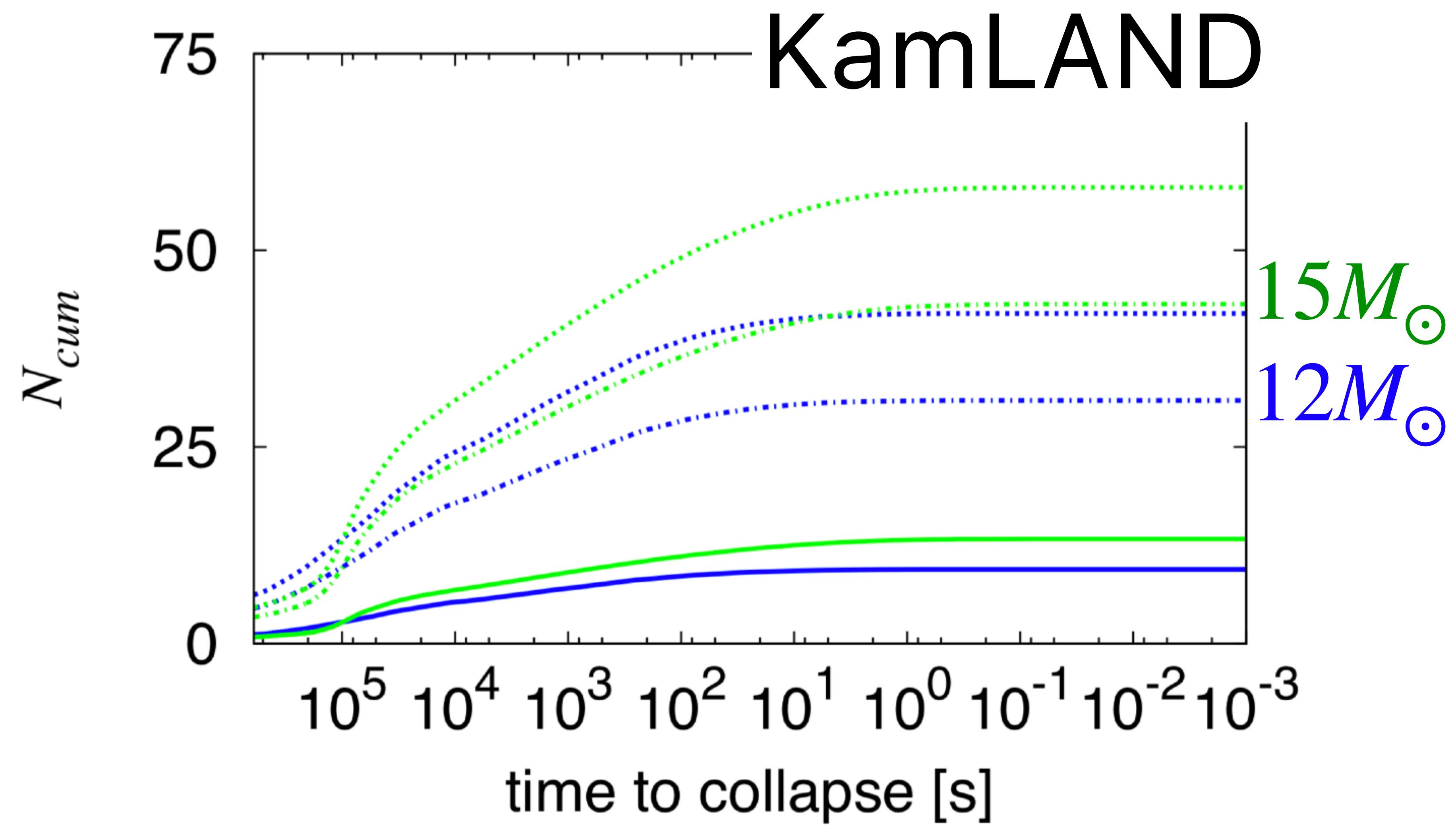


The cumulative numbers of expected pre-SN ν events for Fe-Core progenitor, $d = 200$ pc.

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

Pre-SN neutrino





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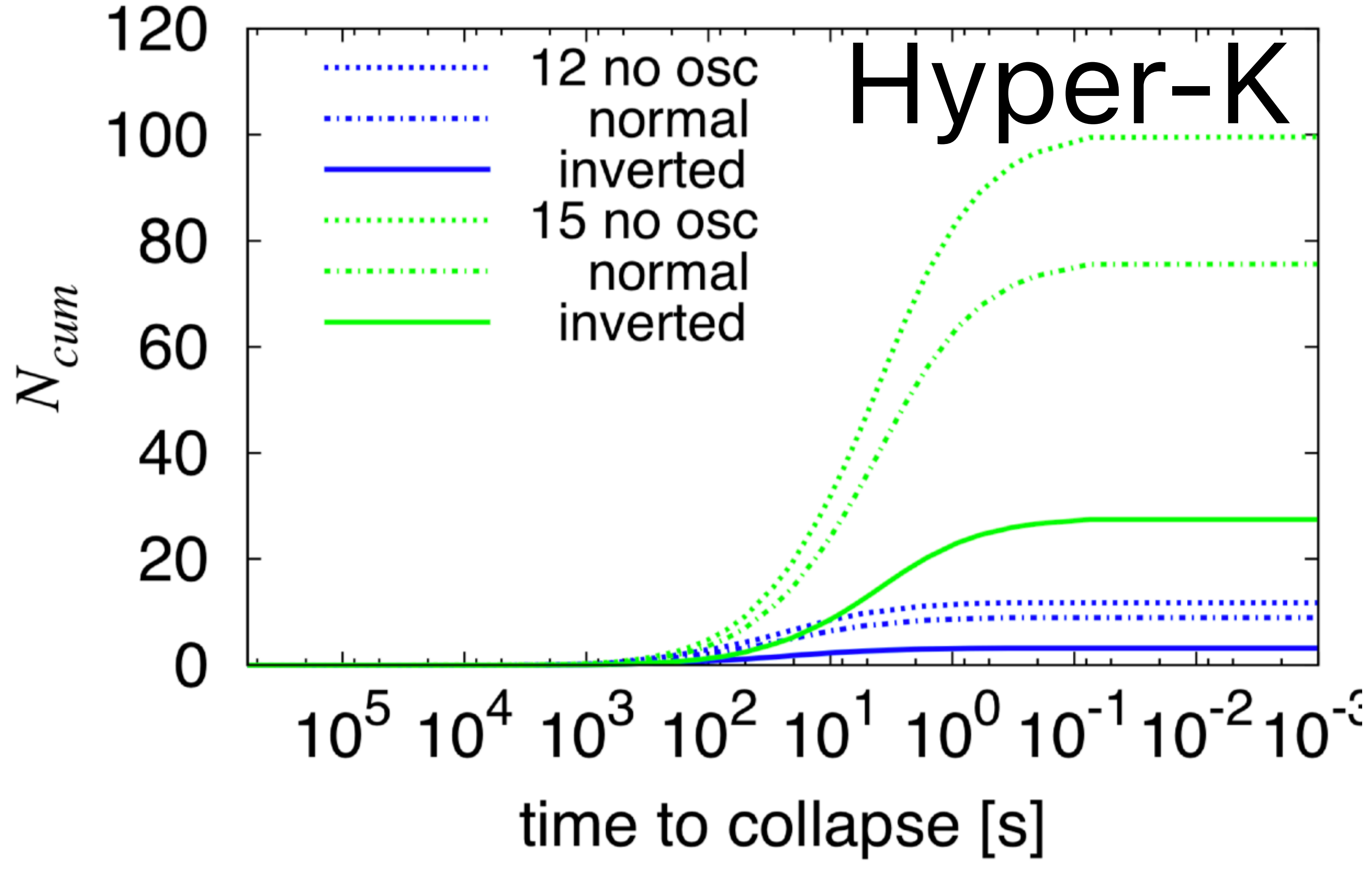
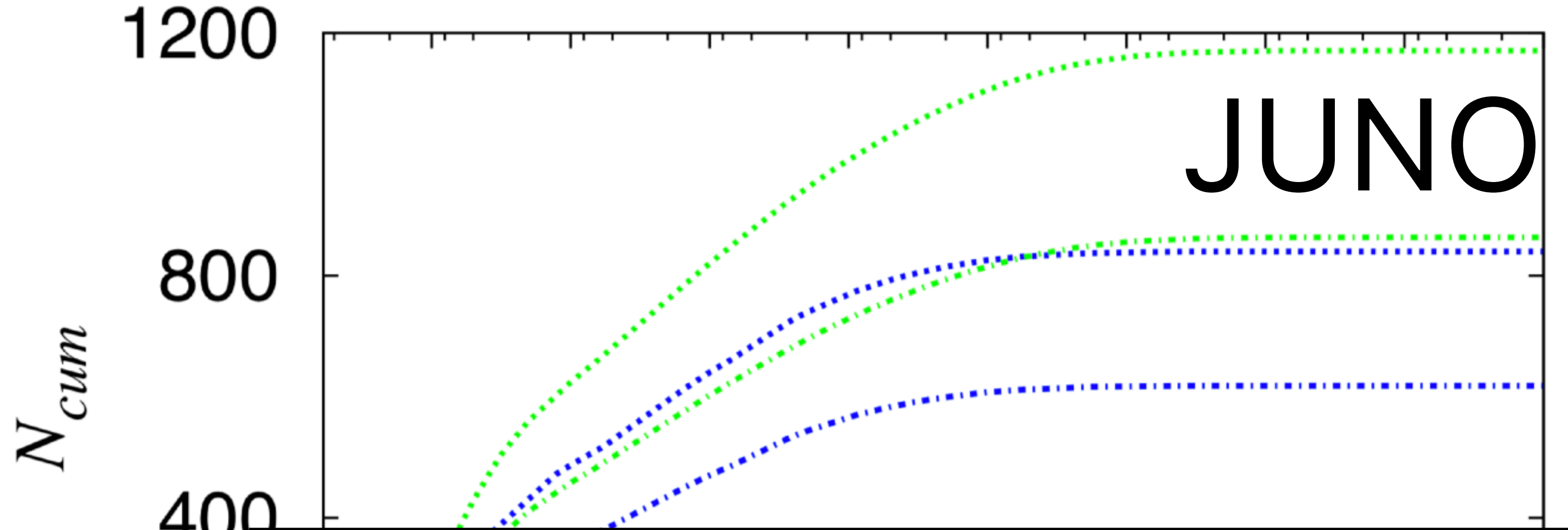




+ DUNE, SNO+,… global network for an early SN alarm

= Supernova Early Warning System (SNEWS)

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

SNEWS collaboration [2011.00035]

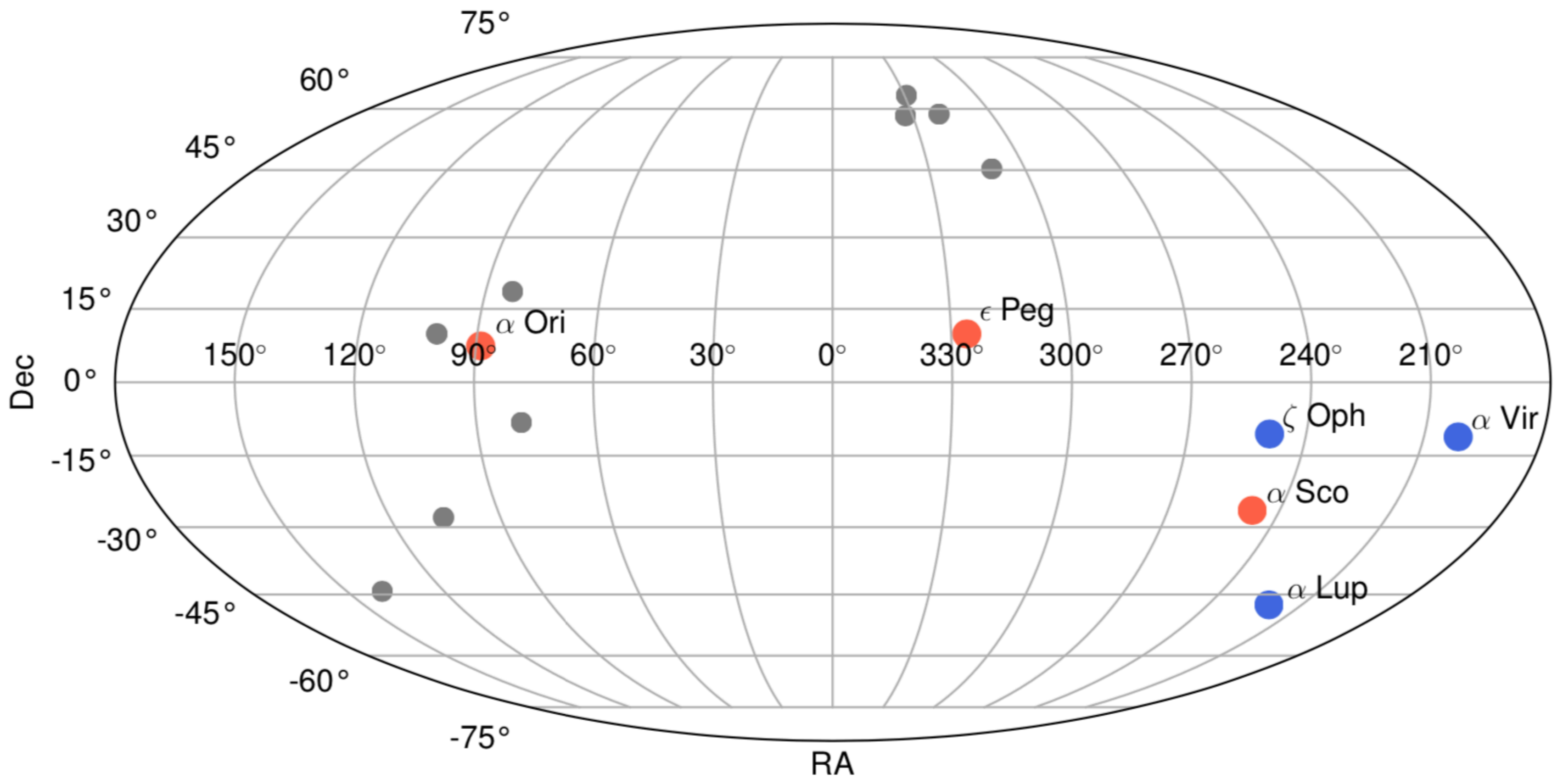
Pre-SN neutrino

- 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.

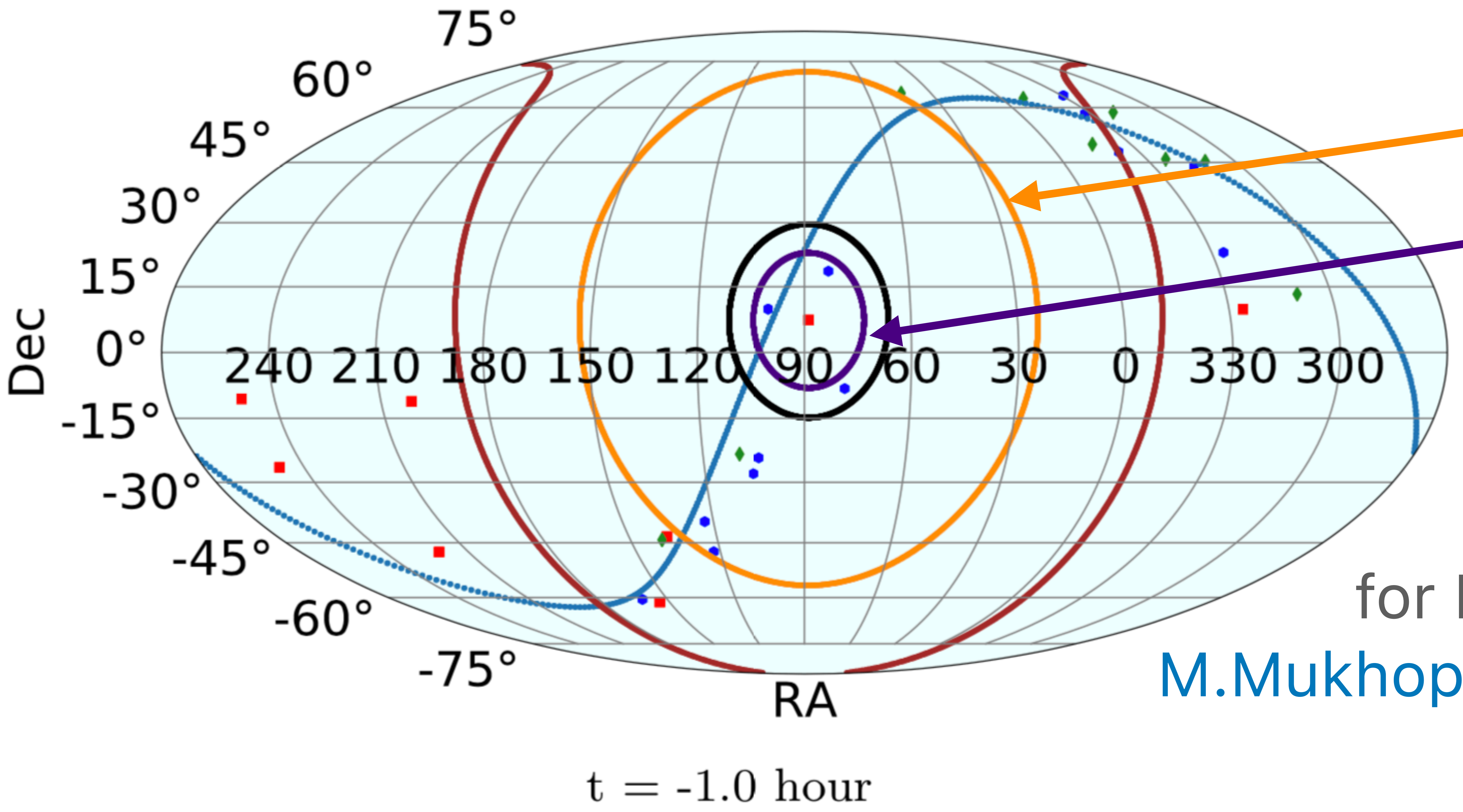
$M > 10M_\odot$ only.



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.



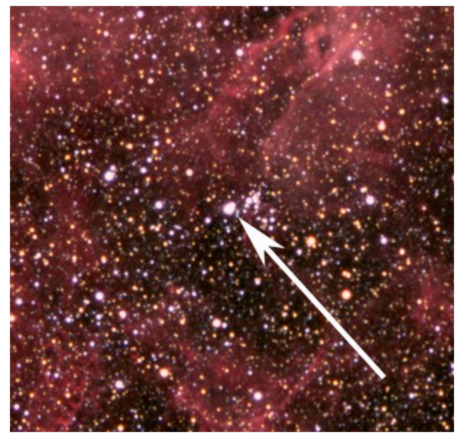
JUNO (68% C.L.)

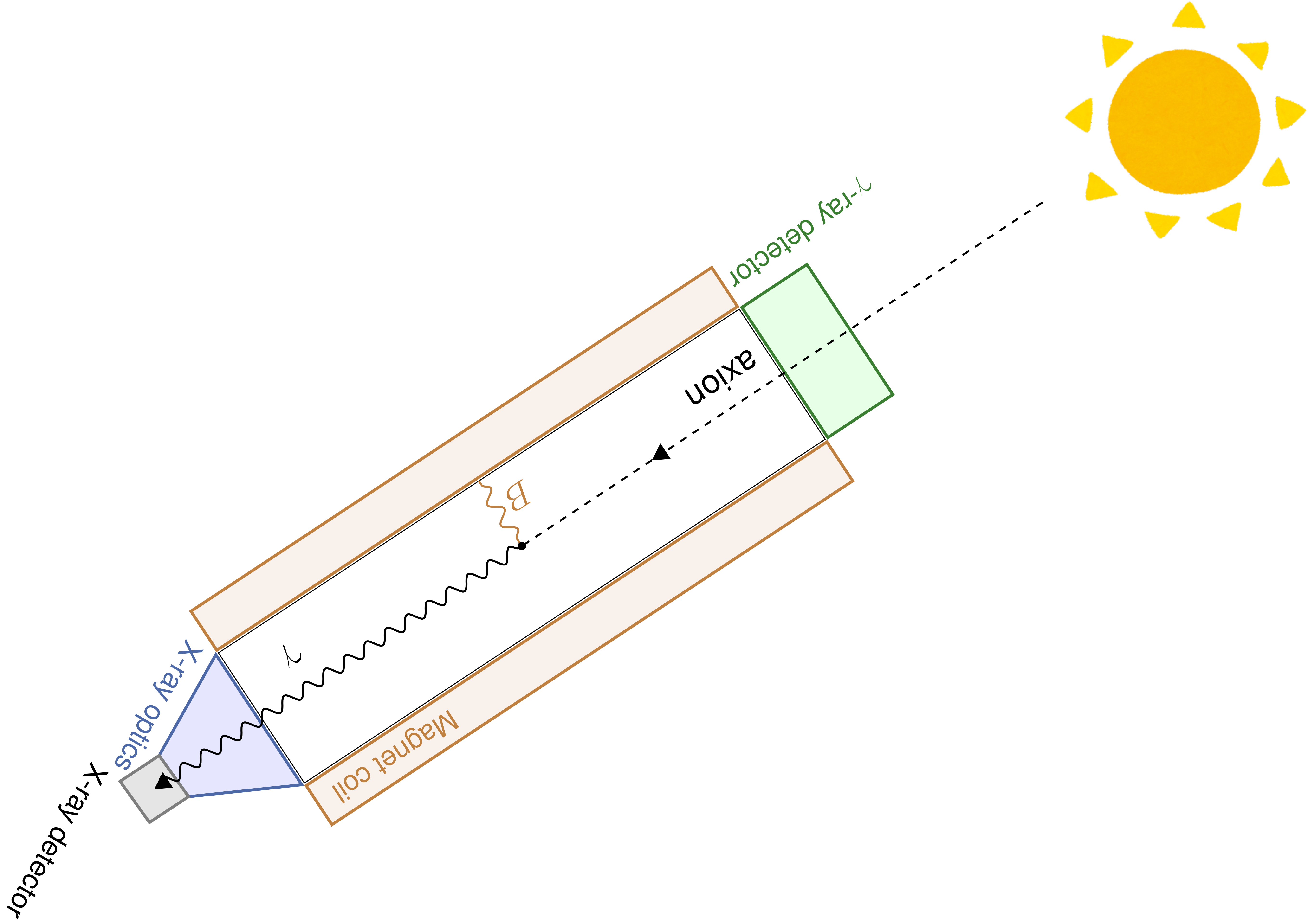
JUNO + Li (68% C.L.)

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

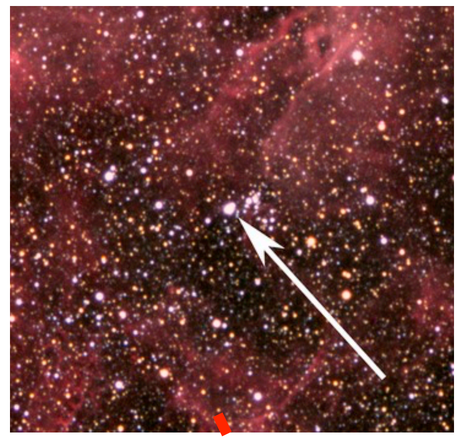
for Betelgeuse, $t = -1.0$ hour.

M.Mukhopadhyay et.al., [2004.02045]




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

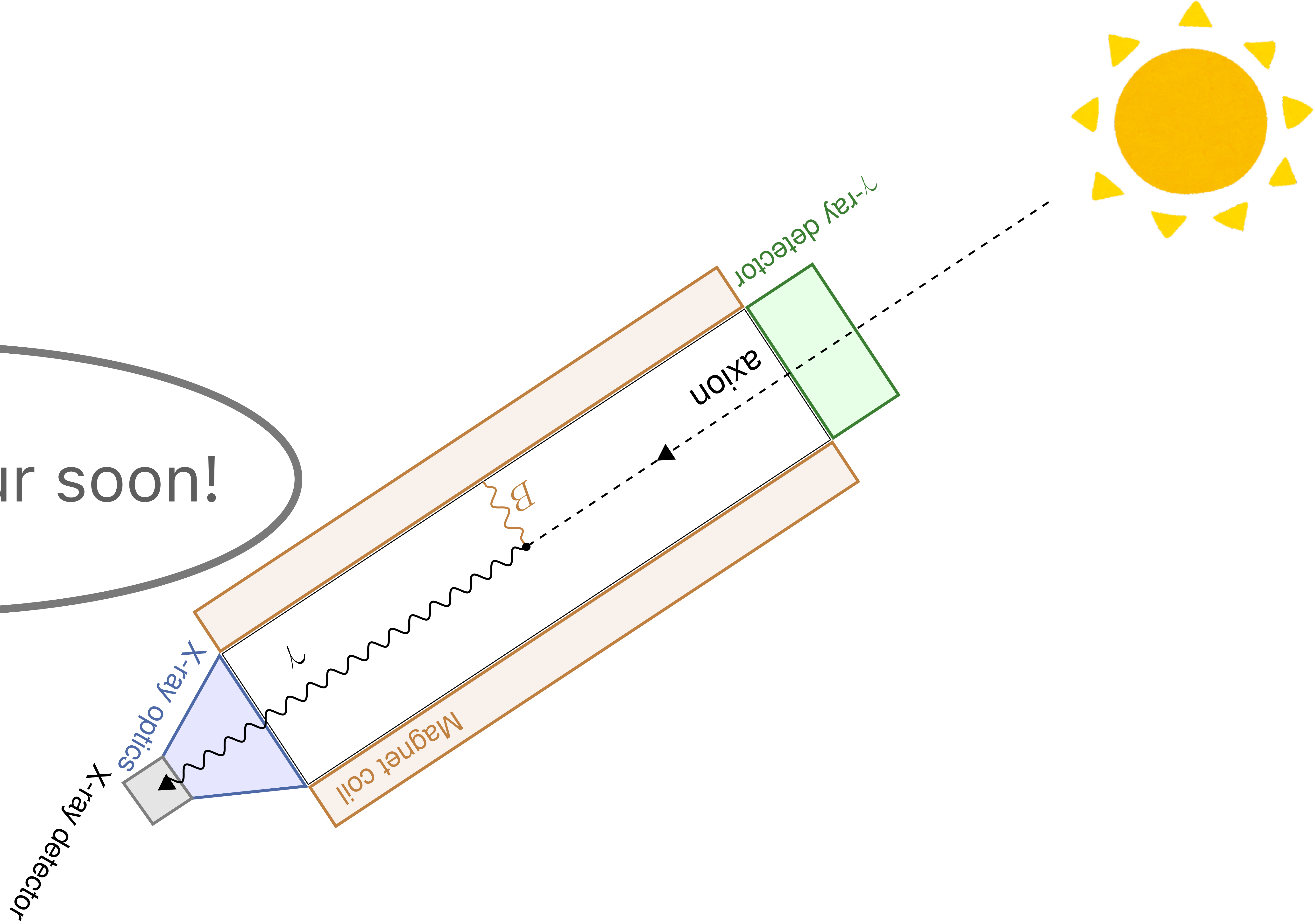
Once a pre-SN neutrino alert is received,



pre-SN ν

SNEWS

SN may occur soon!



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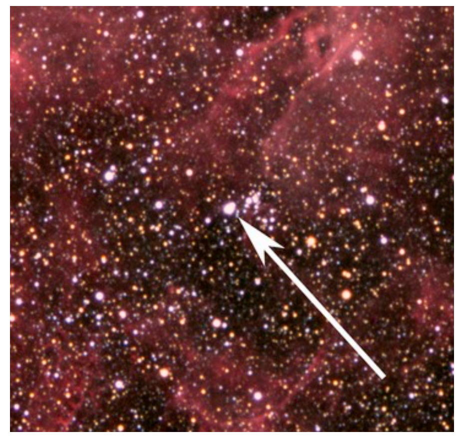

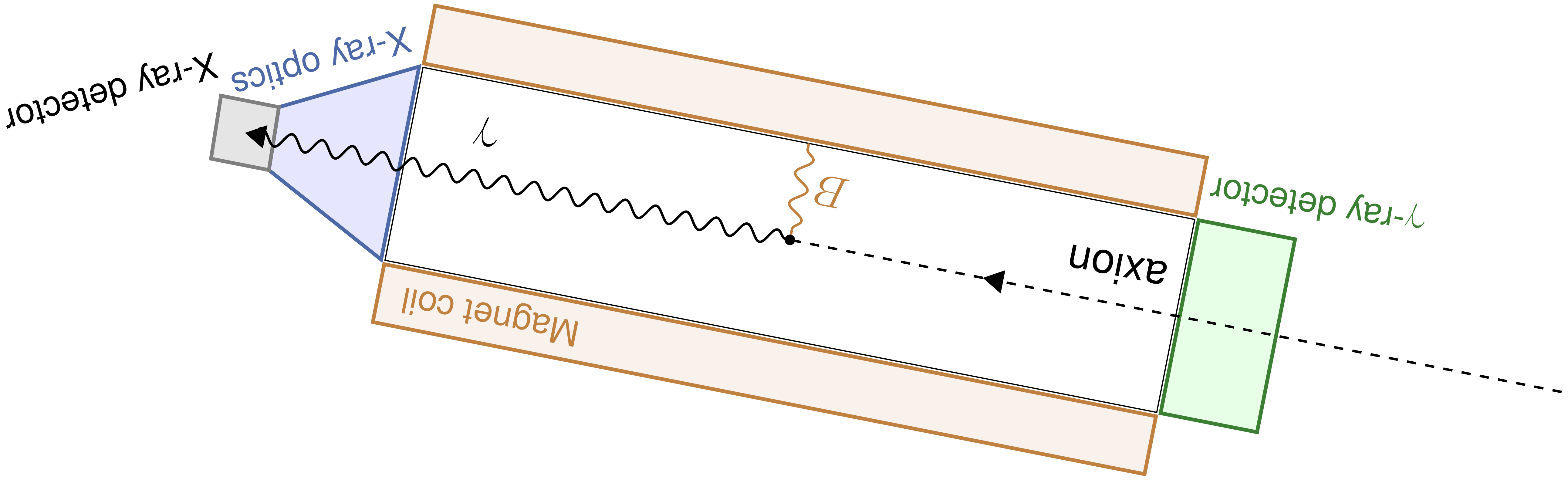

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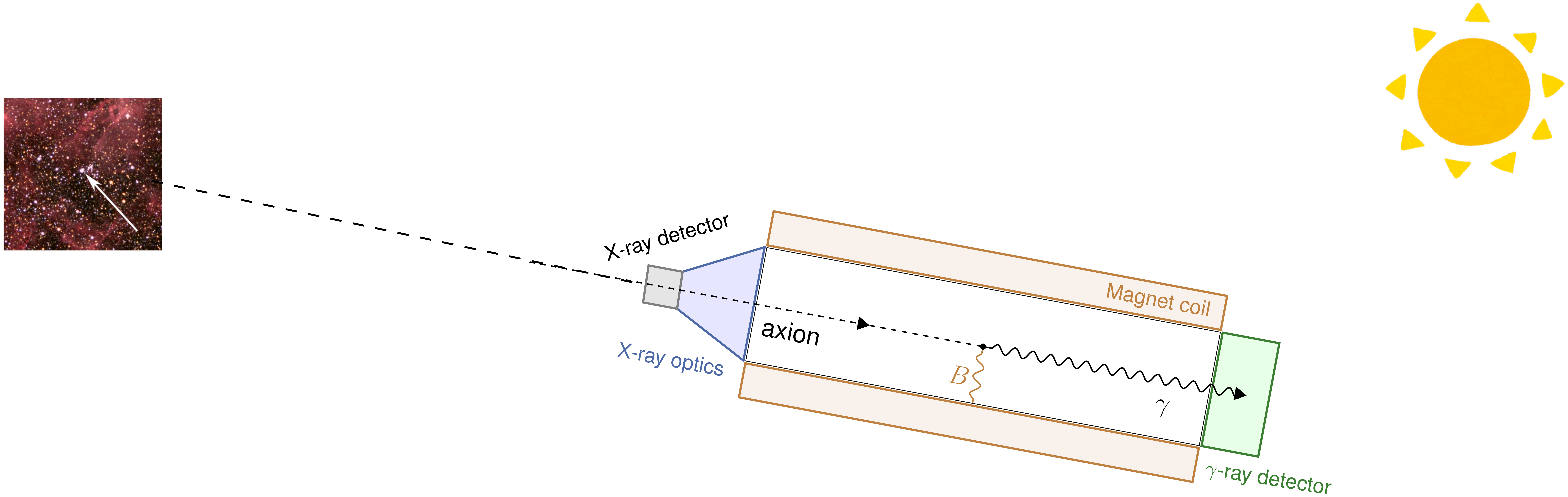

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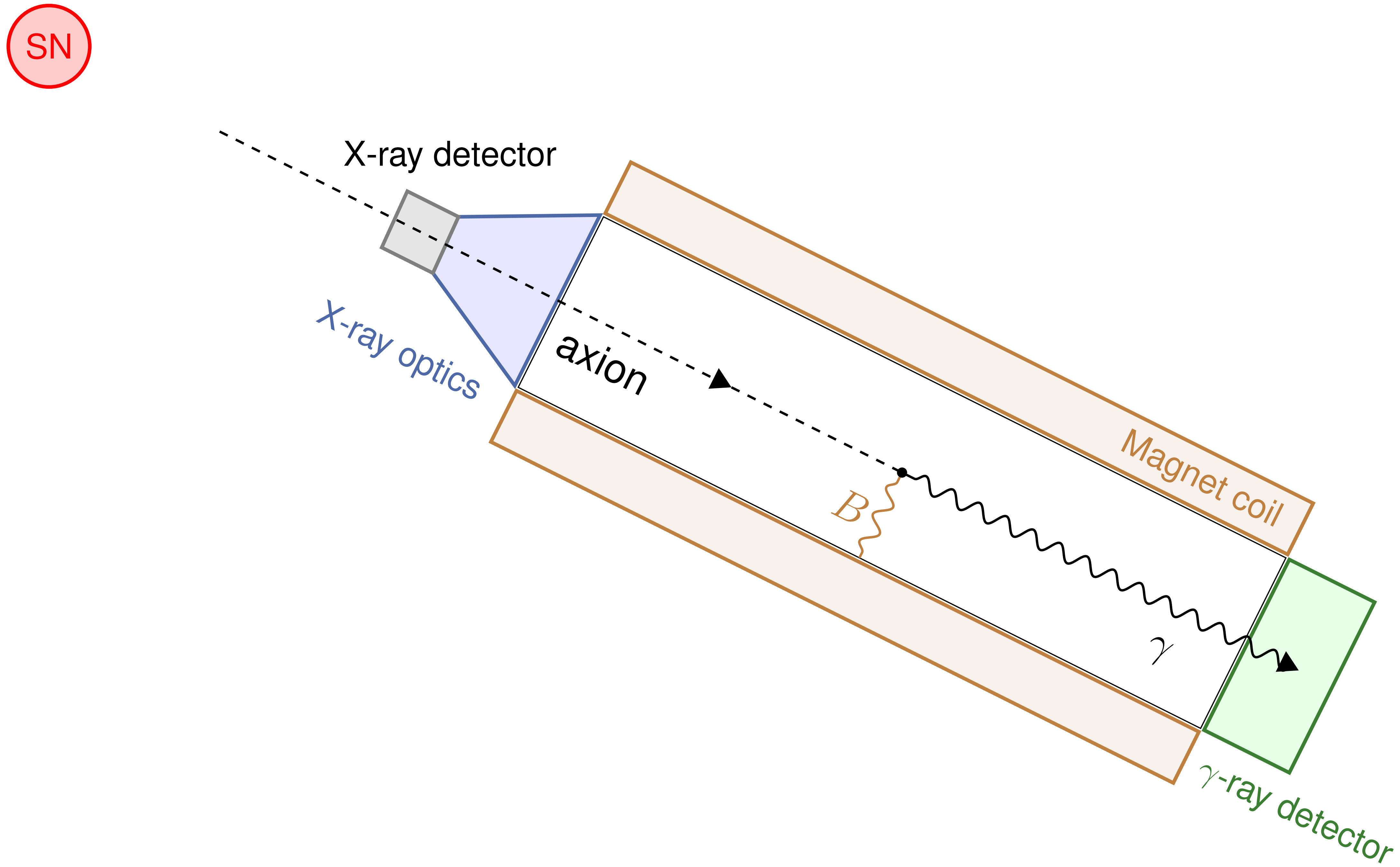


Observation time fraction

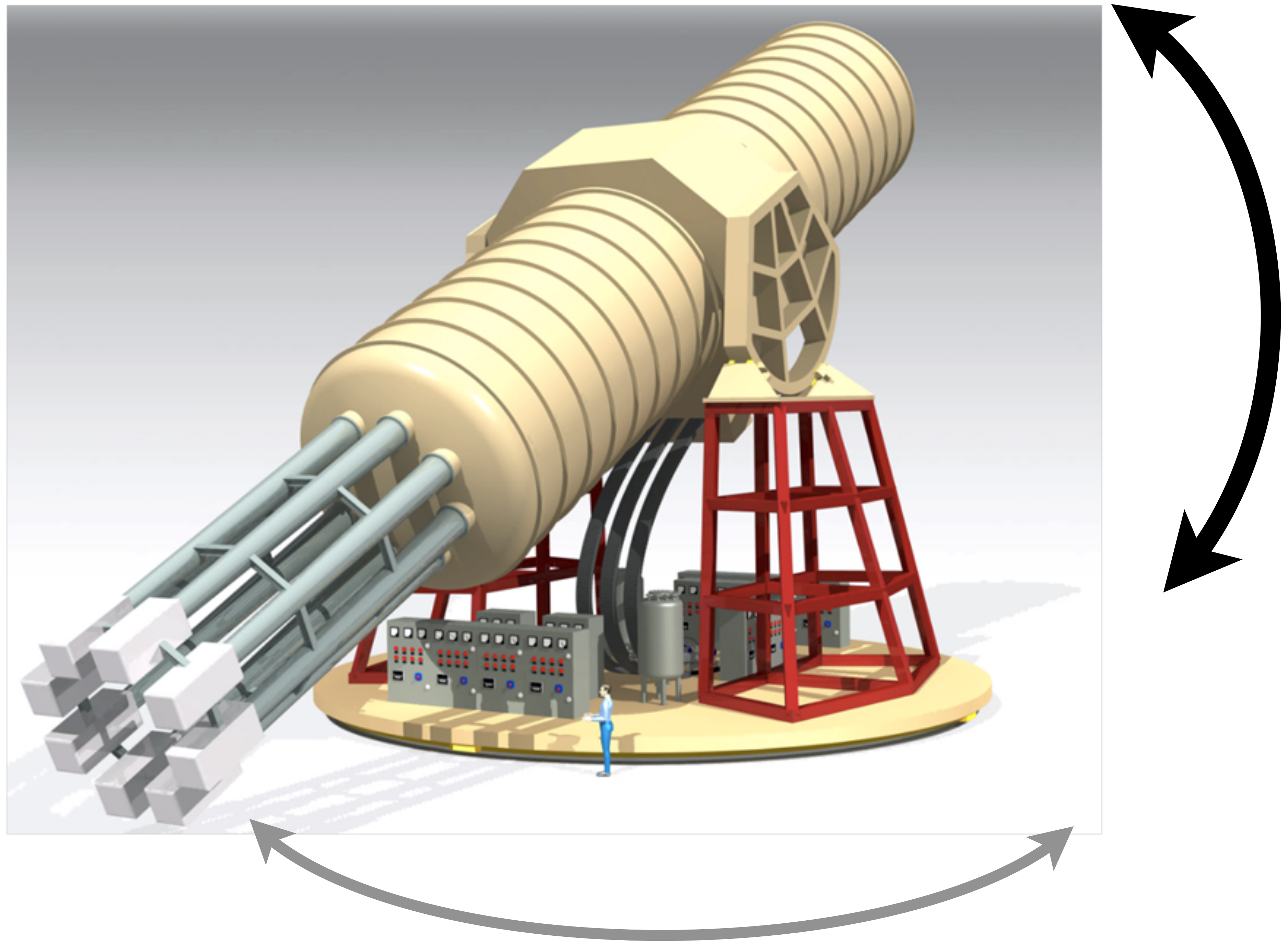


Fig. from IAXO homepage

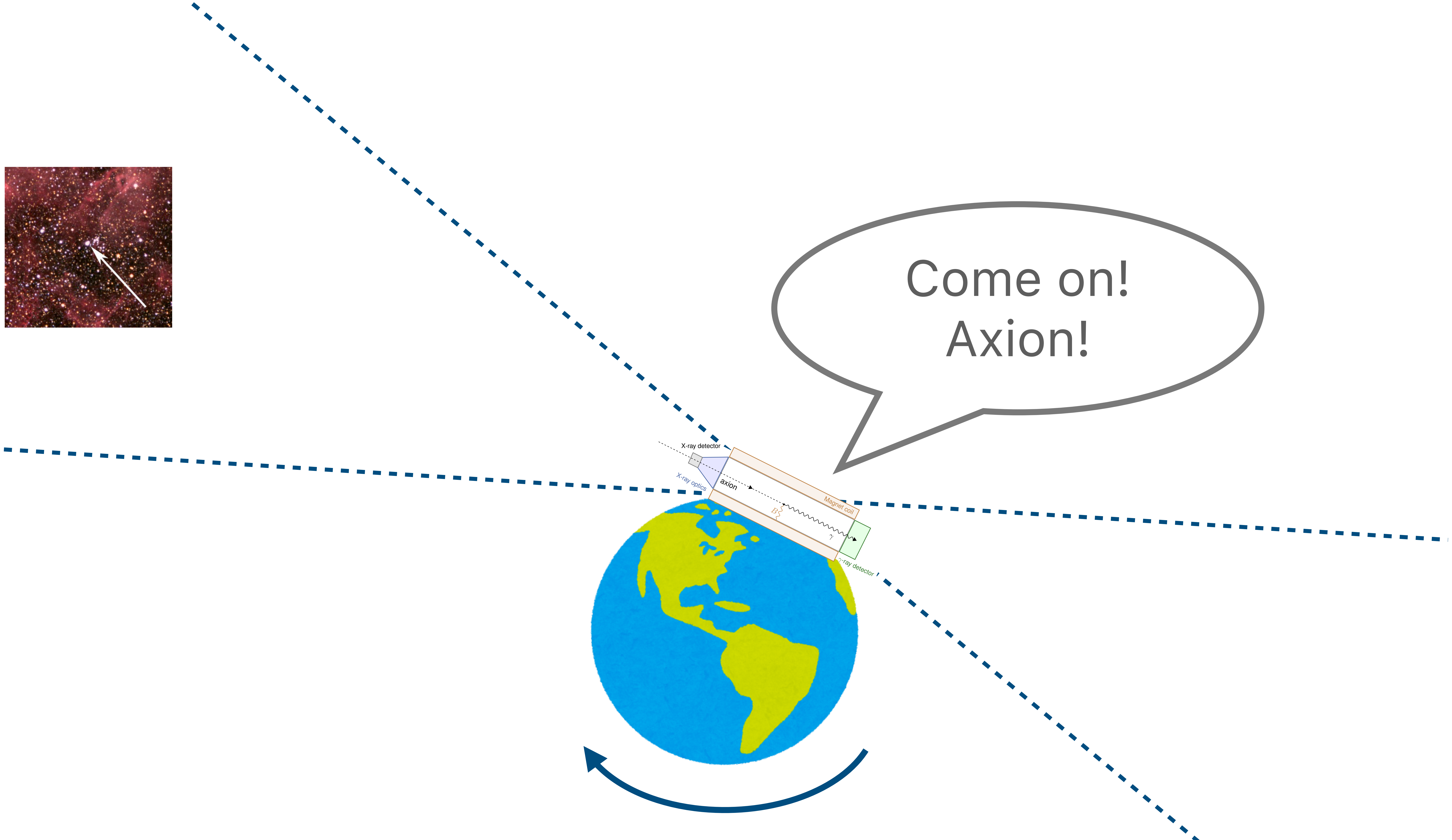
$$-\theta_{\max} \le \theta \le +\theta_{\max}$$

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

maximum elevation:

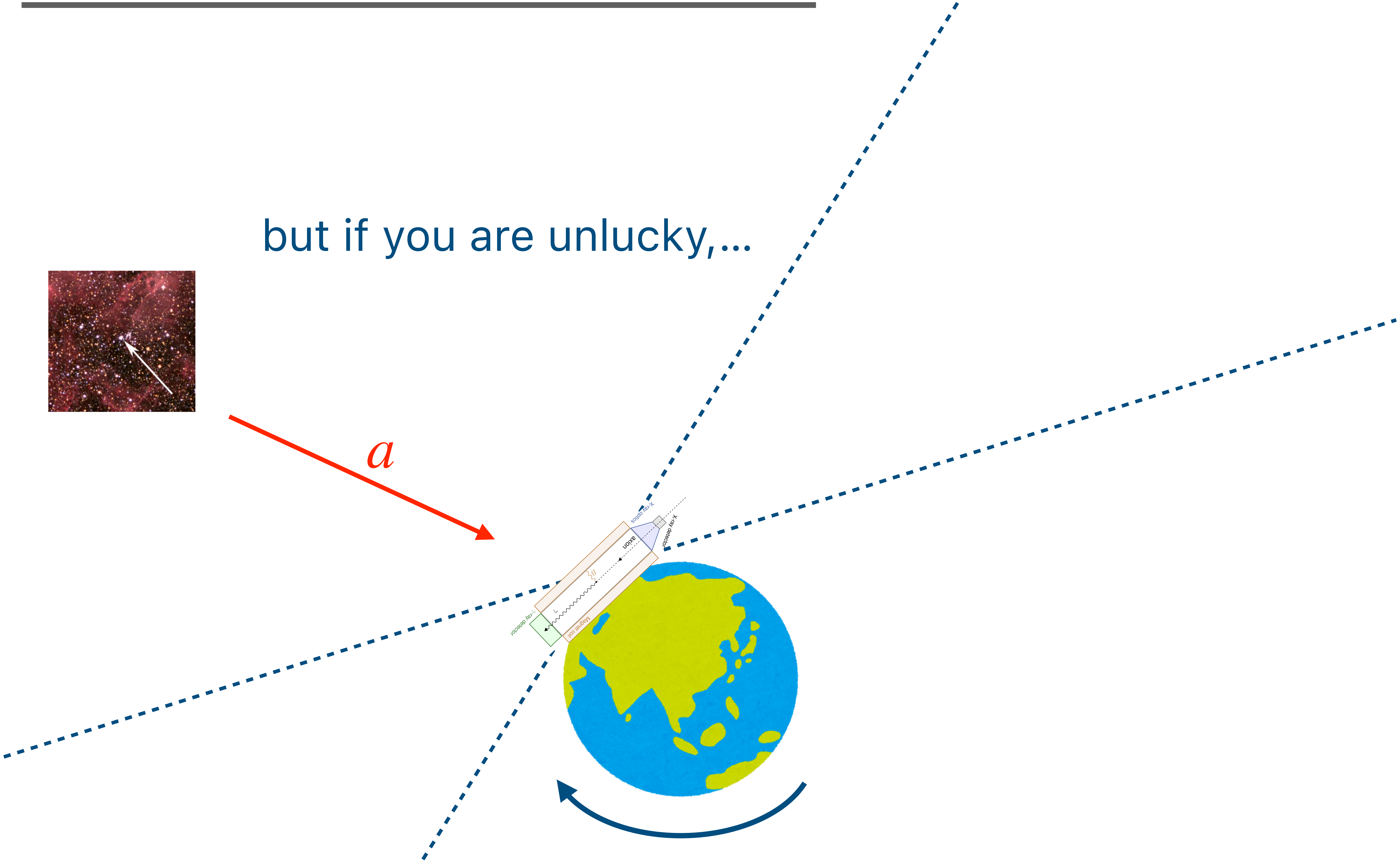
$$\theta_{\max} = \begin{cases} 25^\circ \text{ (IAXO)} \\ 20^\circ \text{ (TASTE)} \end{cases}$$

Observation time fraction



Observation time fraction

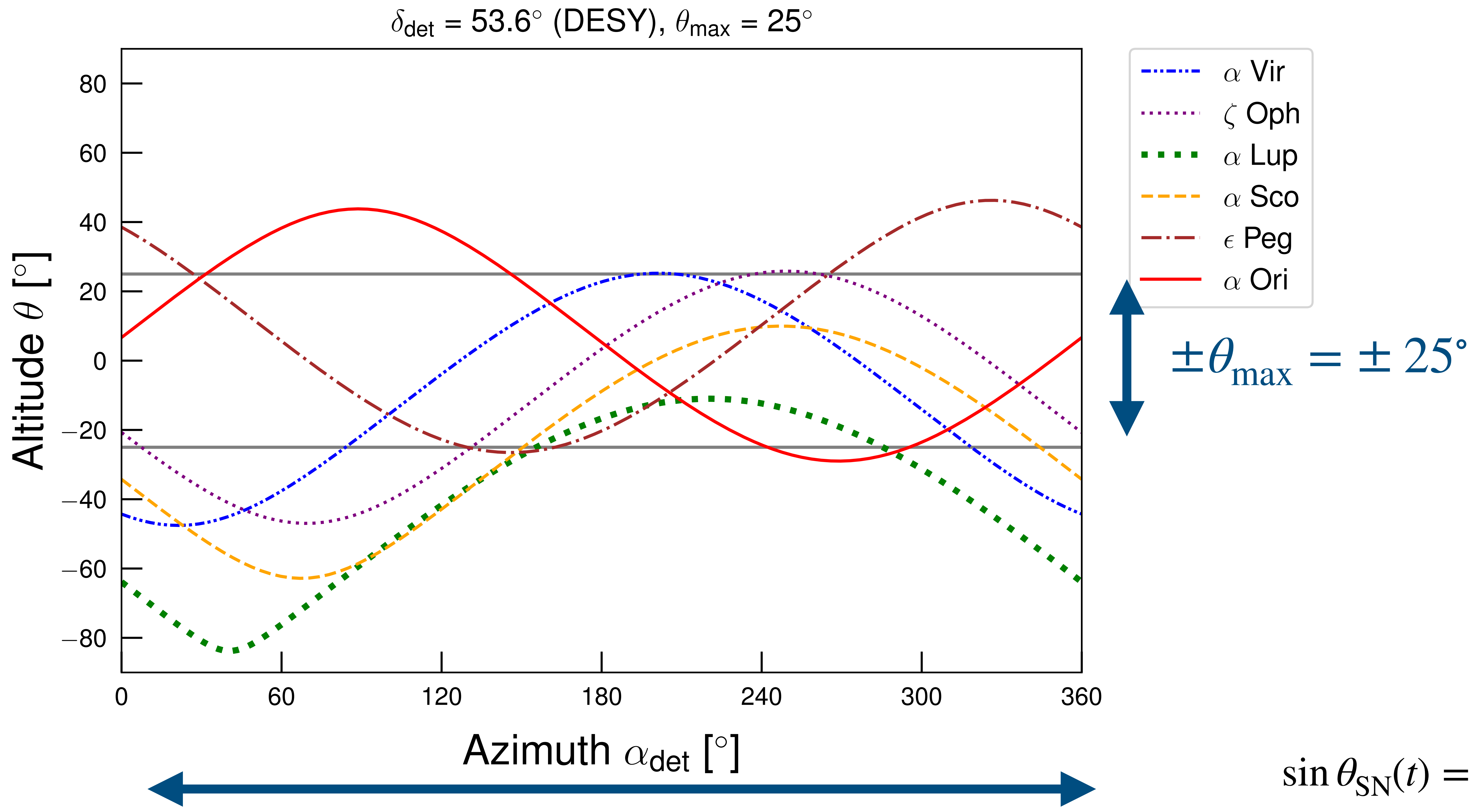
but if you are unlucky,…



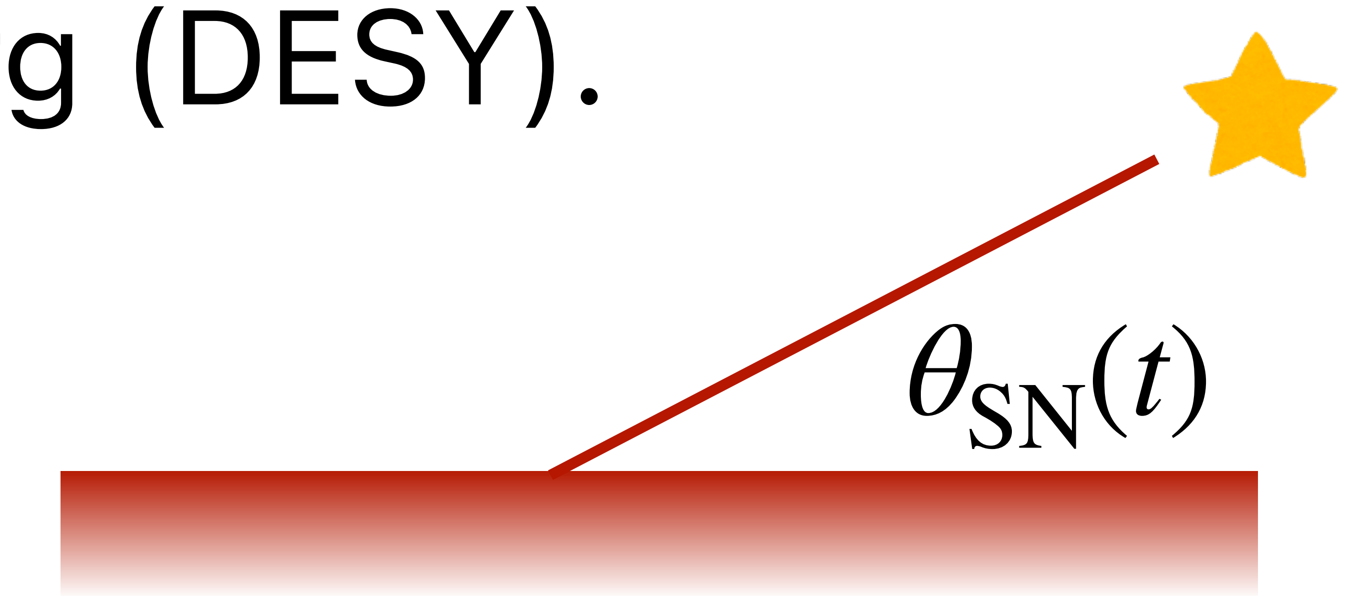
Observation time fraction

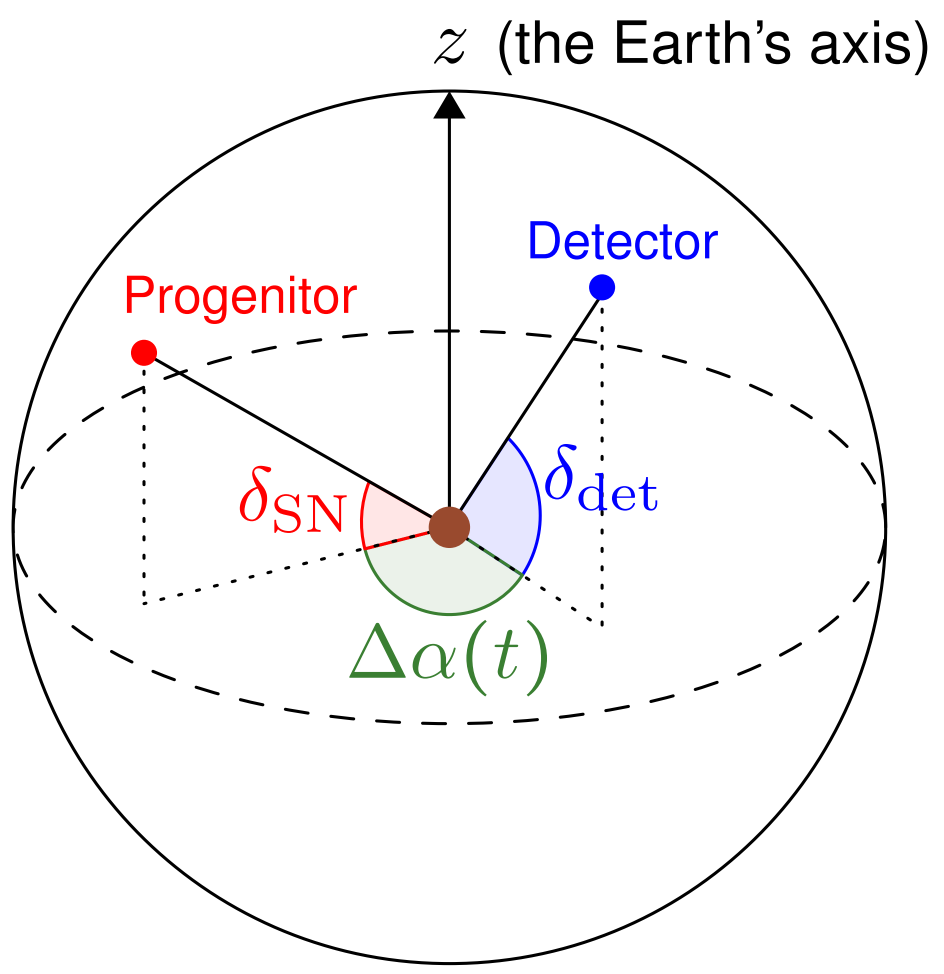
S.Ge, K.Hamaguchi, K.Ichimura, K.Ishidoshiro,
Y.Kanazawa, Y.Kishimoto, N.Nagata, J.Zheng.
[arXiv:2008.03924] JCAP **11** (2020) 059.

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



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.
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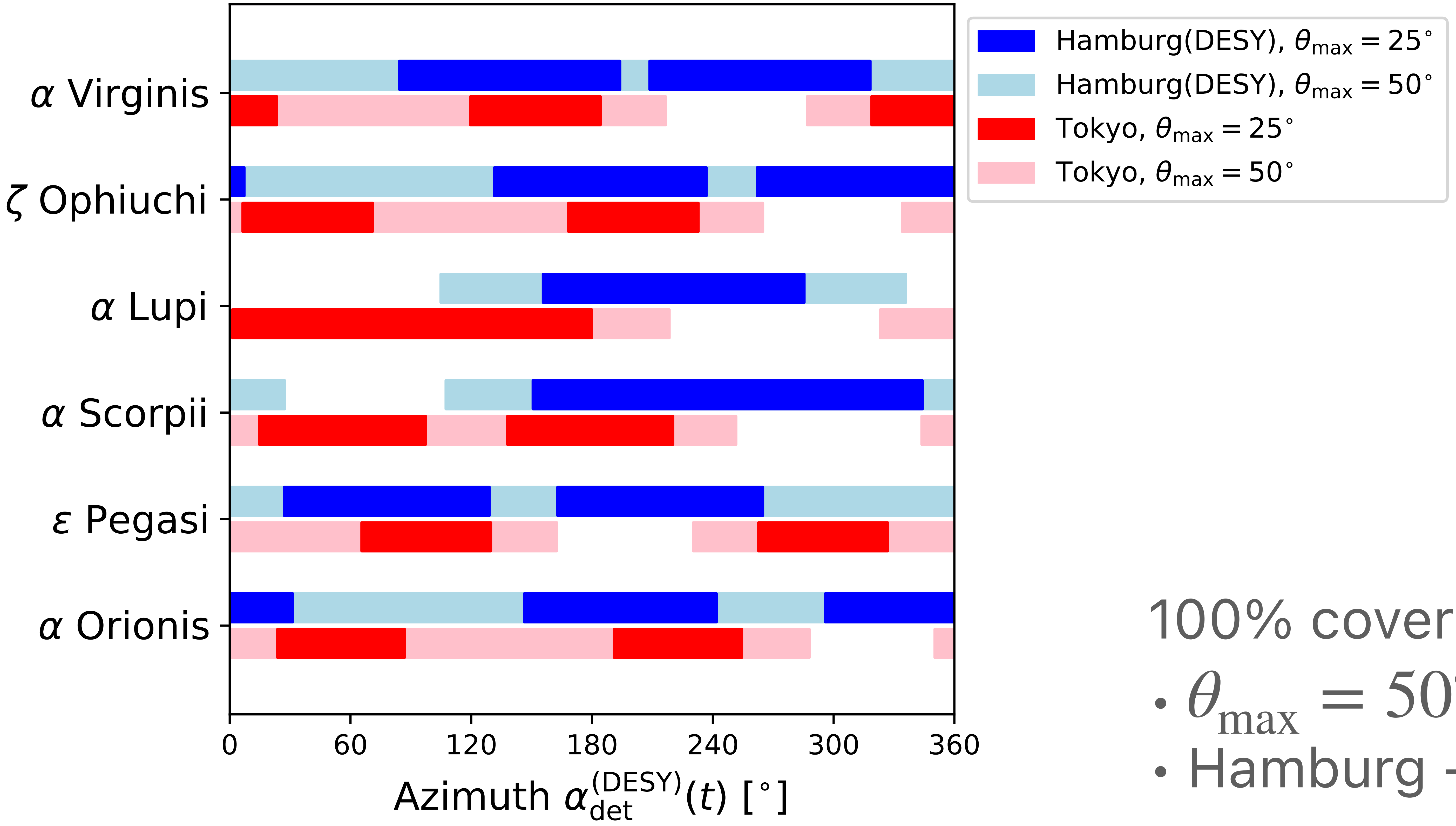
The time fraction can be increased by

- 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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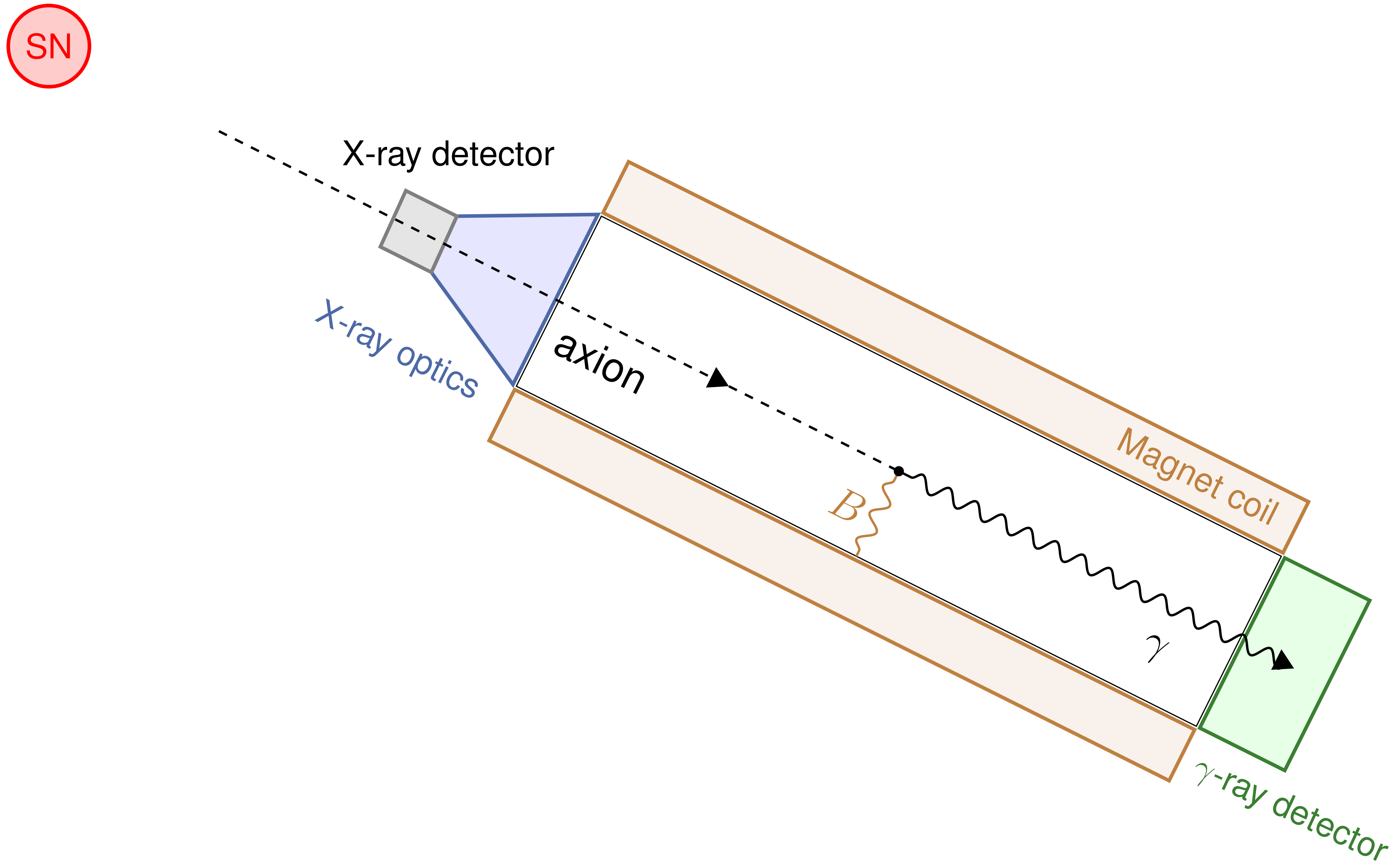
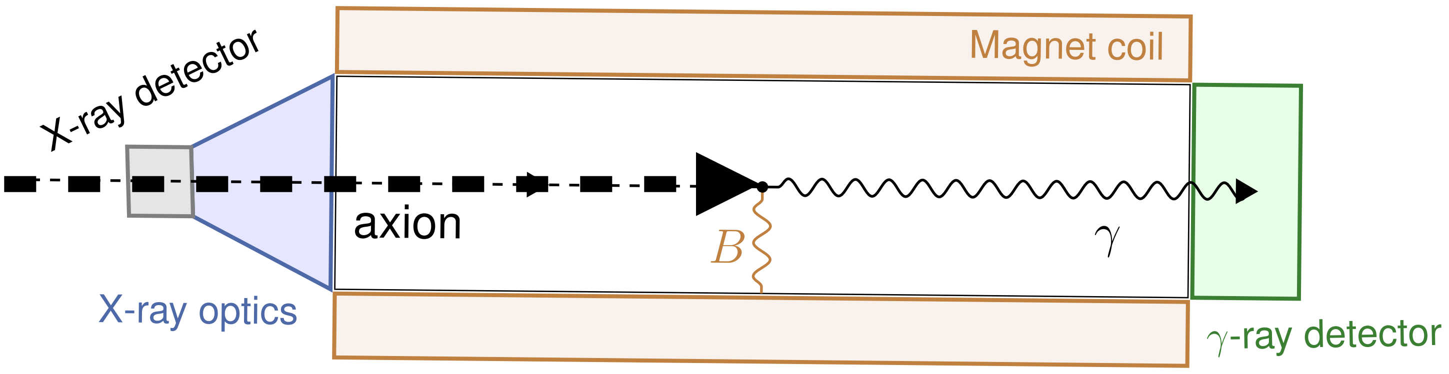
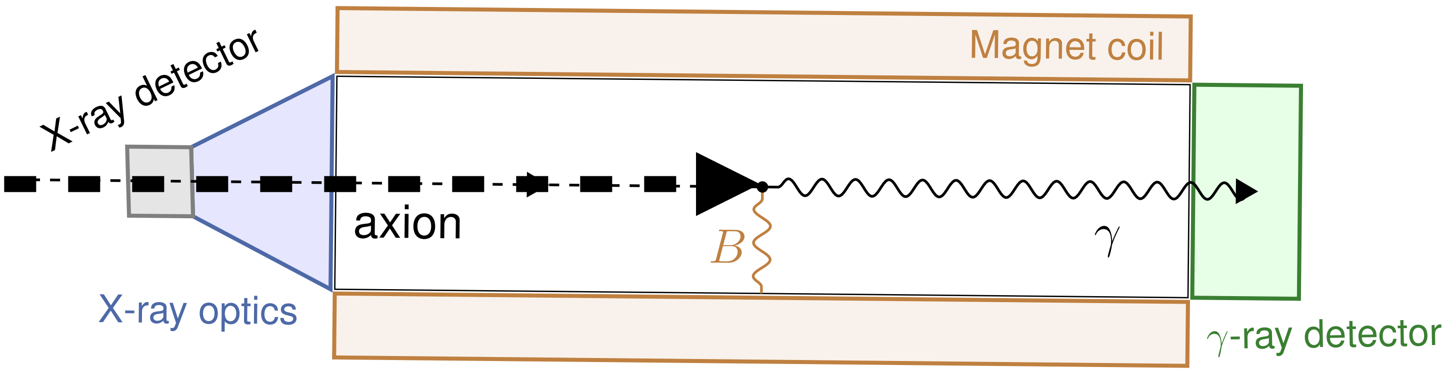


Event number



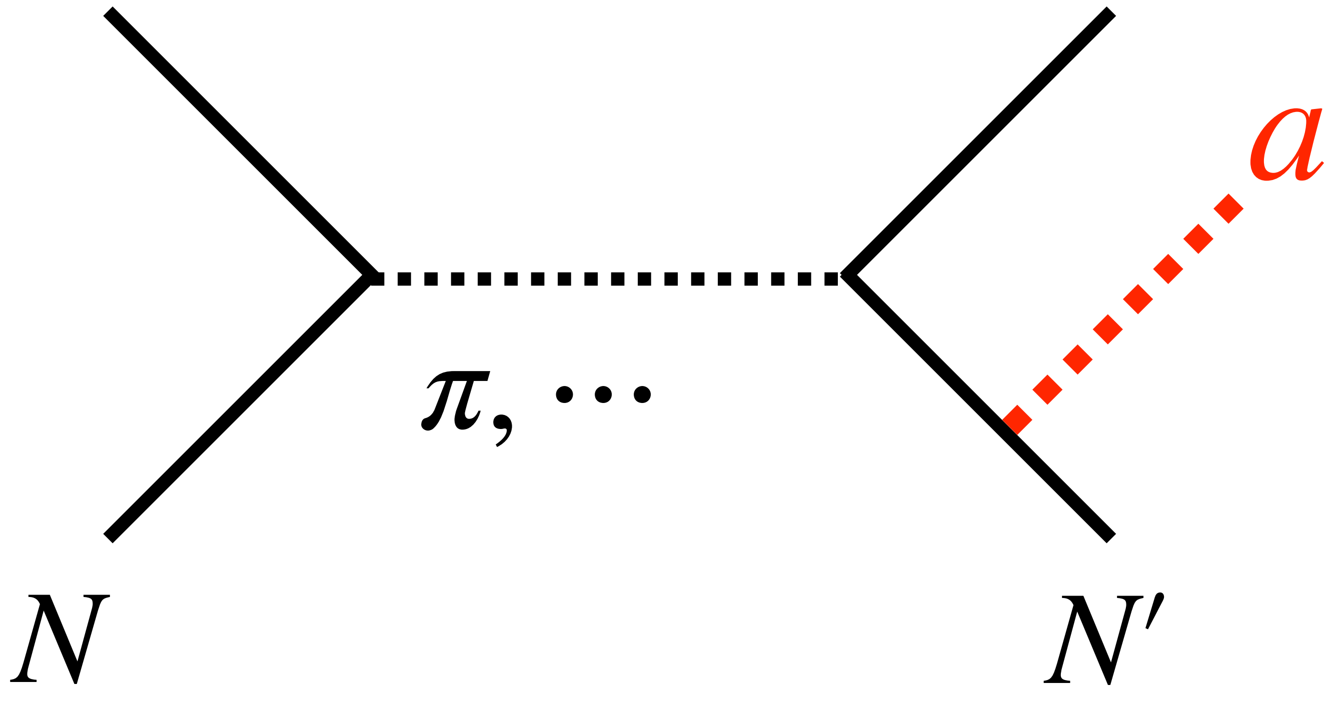
$$N_{\text{event}} = N_a^{\text{SN}} \times \frac{A}{4\pi d^2} \times P_{a\to\gamma}$$

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

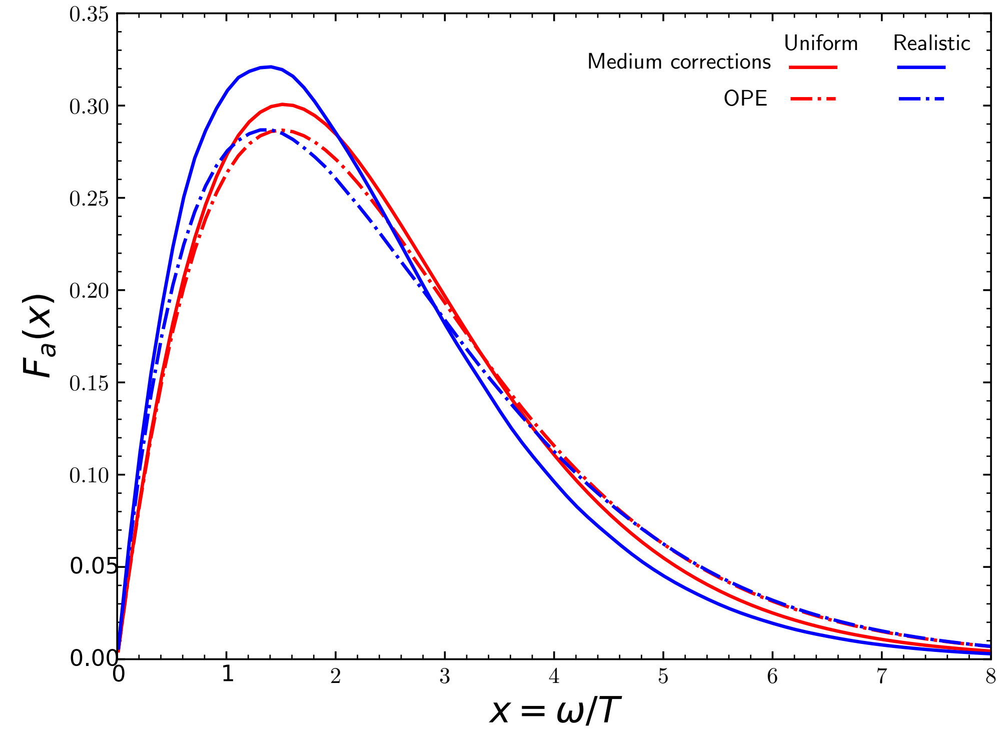
cf. more recent studies, P.Carenza+, 2010.02943, 2108.13726]

- 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,

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

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

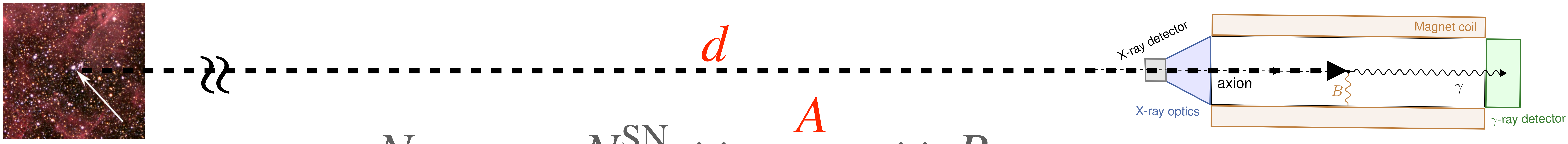
- We also include the temperature dependence, $\sim T^{5/2}$.
- The axion energy is $\langle E_a \rangle \simeq 2.3T$.



- Thus, the total number of axions from SN is

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

Event number



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

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

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
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Event number

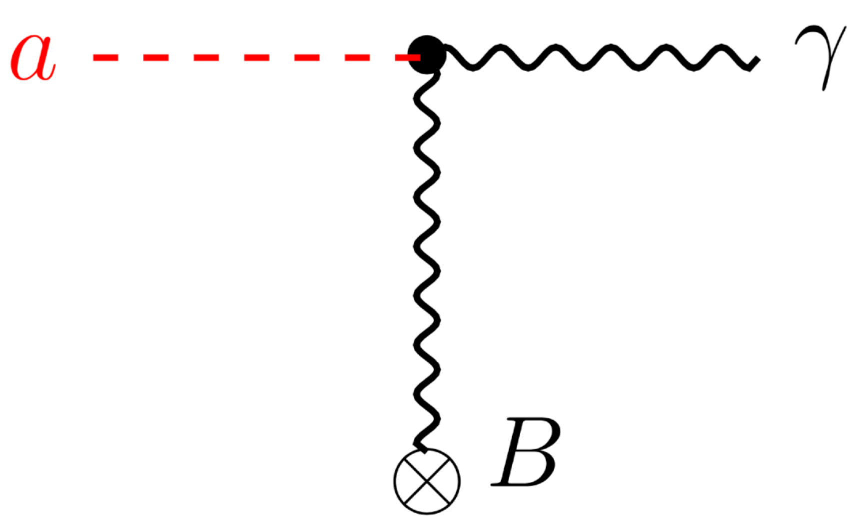
$$N_{\rm event} = N_a^{\rm SN} \times \frac{A}{4\pi d^2} \times P_{a\to\gamma}$$

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 $q = m_a^2/2E_a$.



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

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

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

After all,...

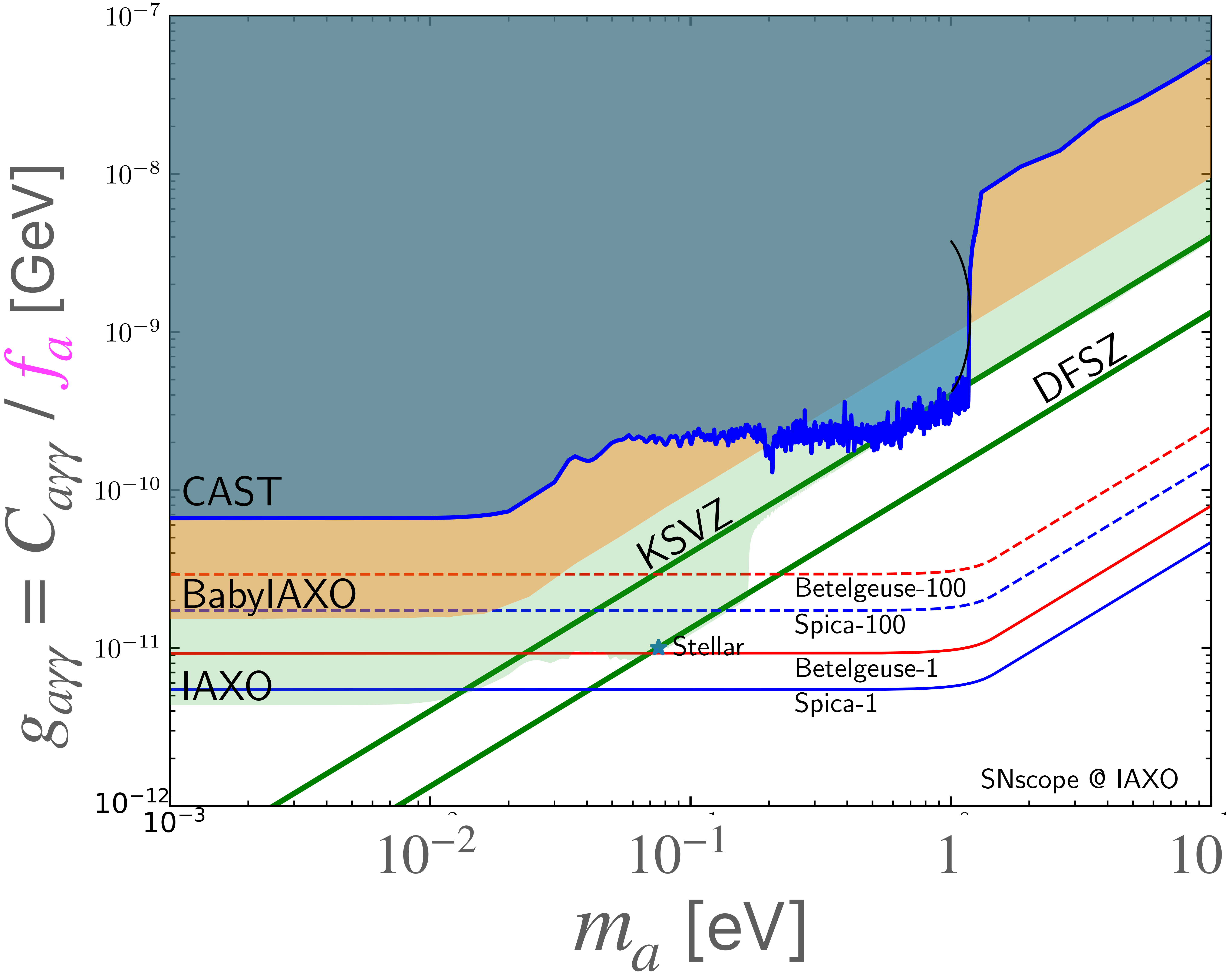
$$N_{\mathrm{event}} \simeq 1.0 \times \underbrace{\left(\frac{3\times 10^8\ \mathrm{GeV}}{f_a}\right)^4 \left(\frac{C_{N,\mathrm{eff}}}{0.37}\right)^2 \left(\frac{C_{a\gamma\gamma}}{\alpha/\pi}\right)^2}_{\text{axion model}} \times \underbrace{\left(\frac{150\ \mathrm{pc}}{d}\right)^2 \left(\frac{\Delta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

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

※ 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)

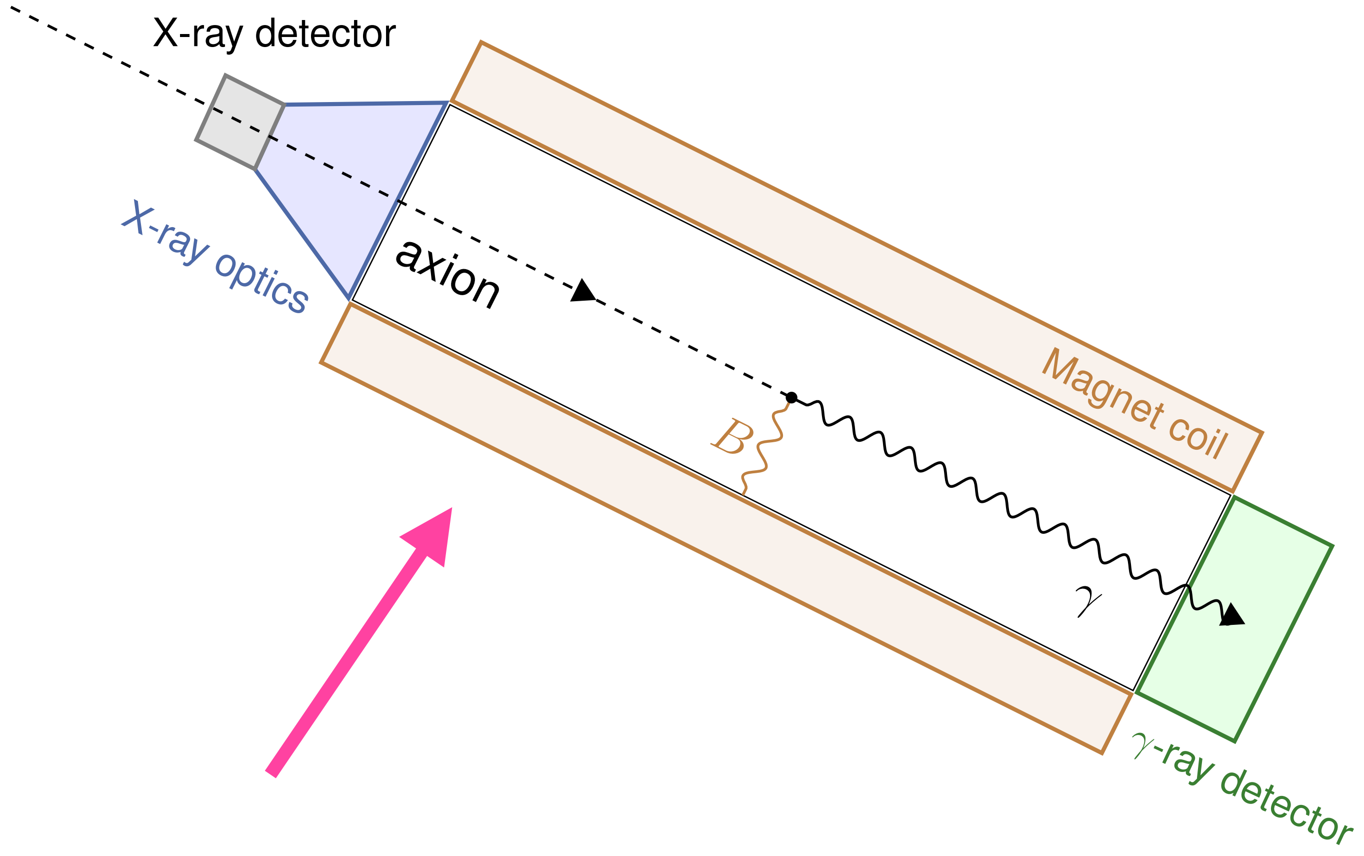
and Spica ($d \simeq 77$ pc)

- 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

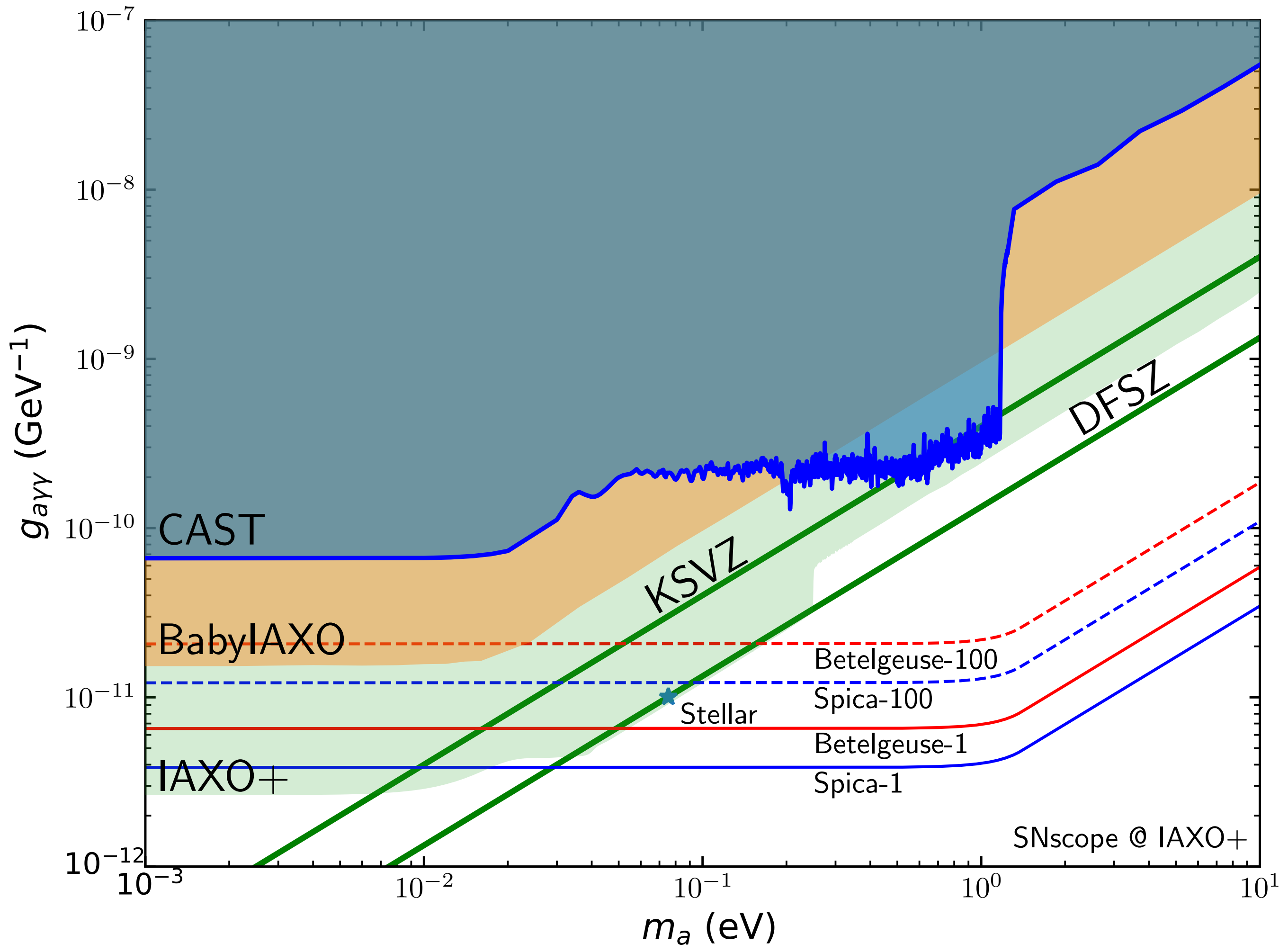


- If a nearby (< a few 100 pc) supernova (SN) occurs, a huge number of axions (in addition to neutrinos) may arrive at the Earth.

- 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.



[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]

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

Motivation: axion

Conventional Models

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

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

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---

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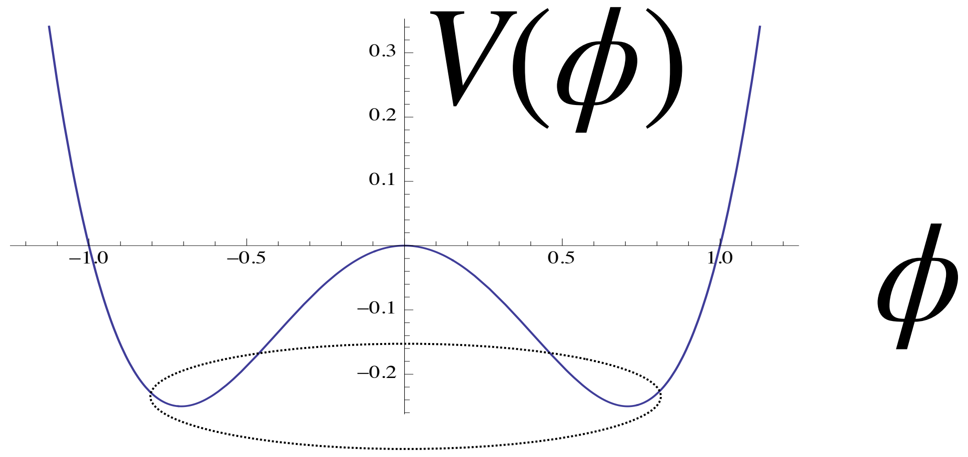
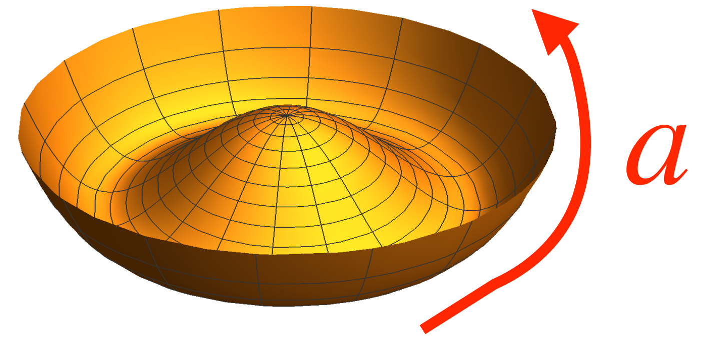
In all cases,...

ϕ : complex scalar (Peccei-Quinn field)

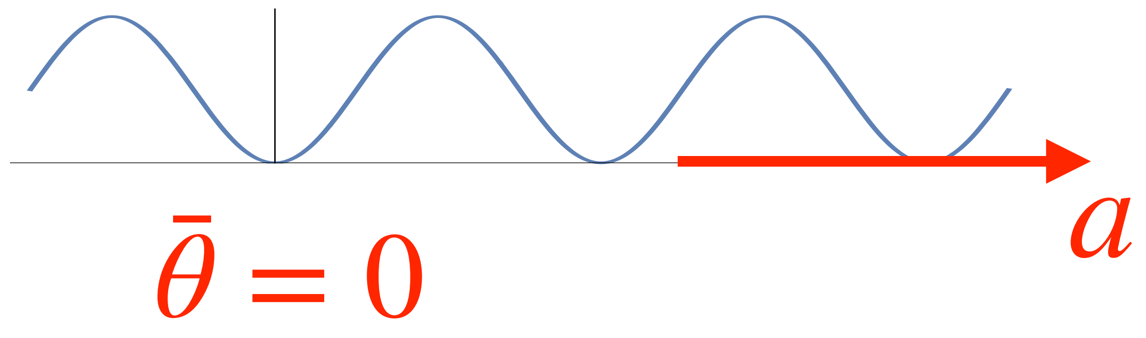
U(1)$_{\text{PQ}}$ ($\phi \to \phi e^{i\alpha}$) is spontaneously broken



Nambu-Goldstone boson = Axion



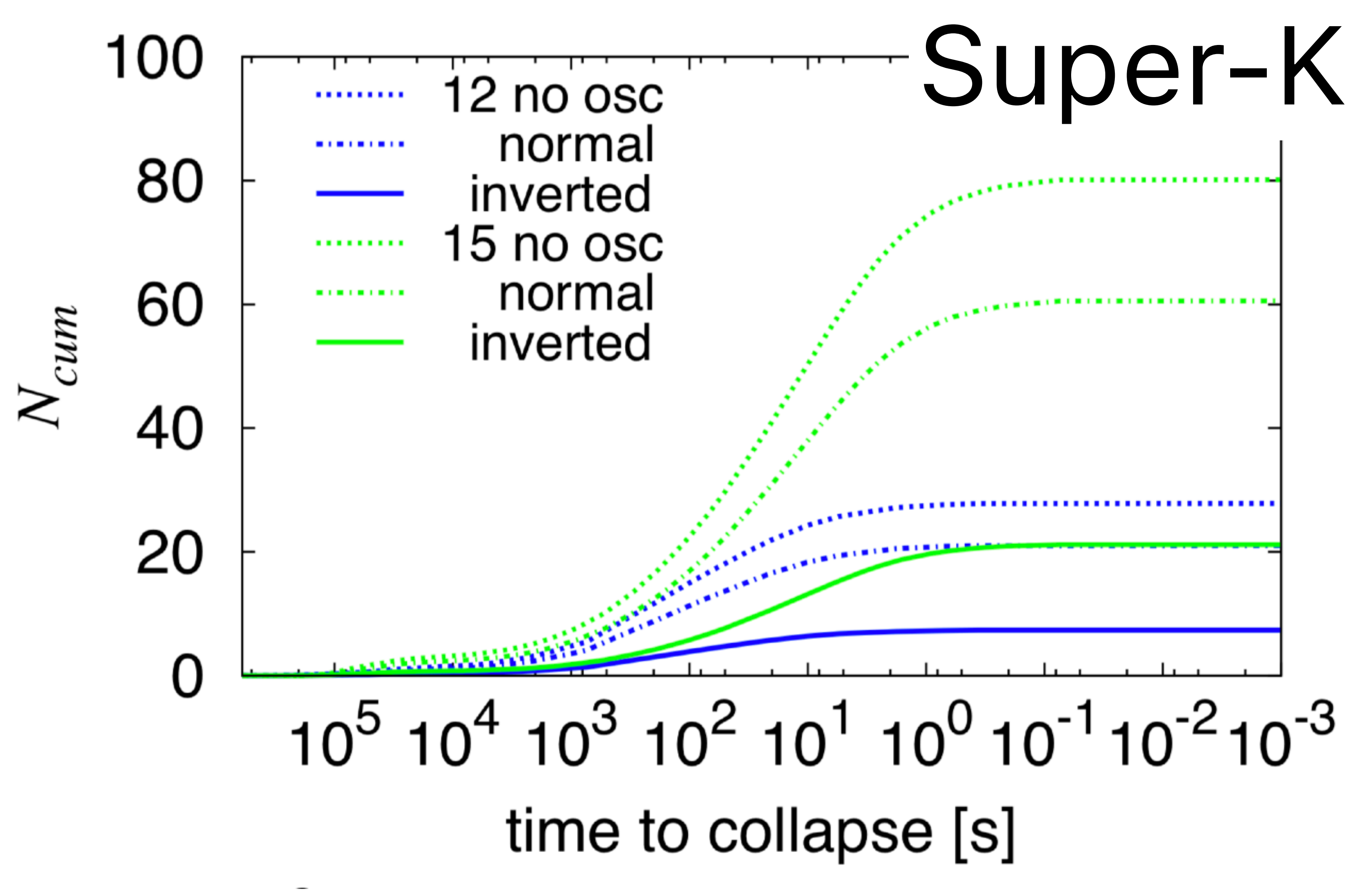
From anomaly, $\mathscr{L}_{\text{axion}} \ni \frac{\alpha_s}{8\pi}\frac{a}{f_a}G^a_{\mu\nu}\widetilde{G}^{a\mu\nu}$

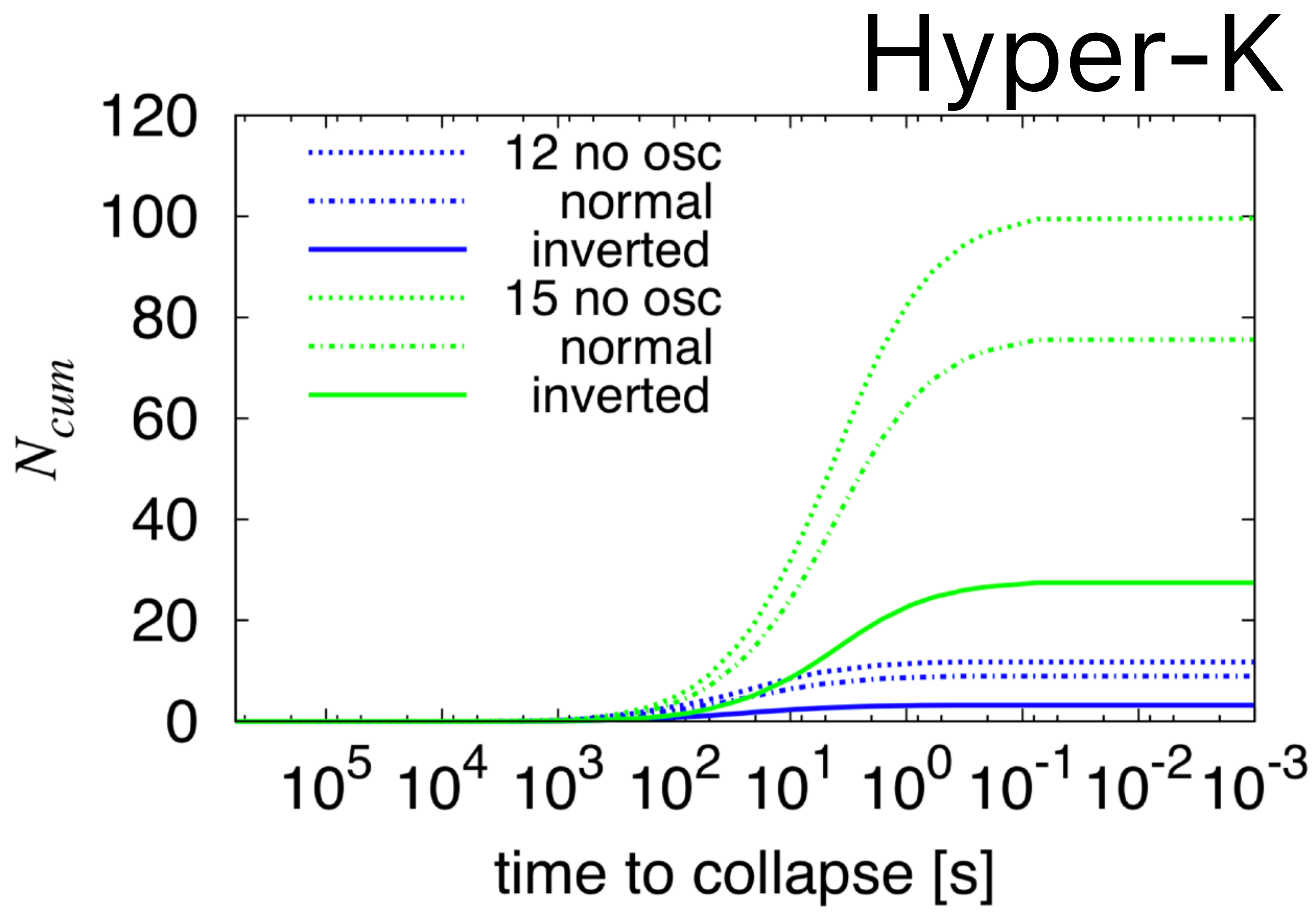


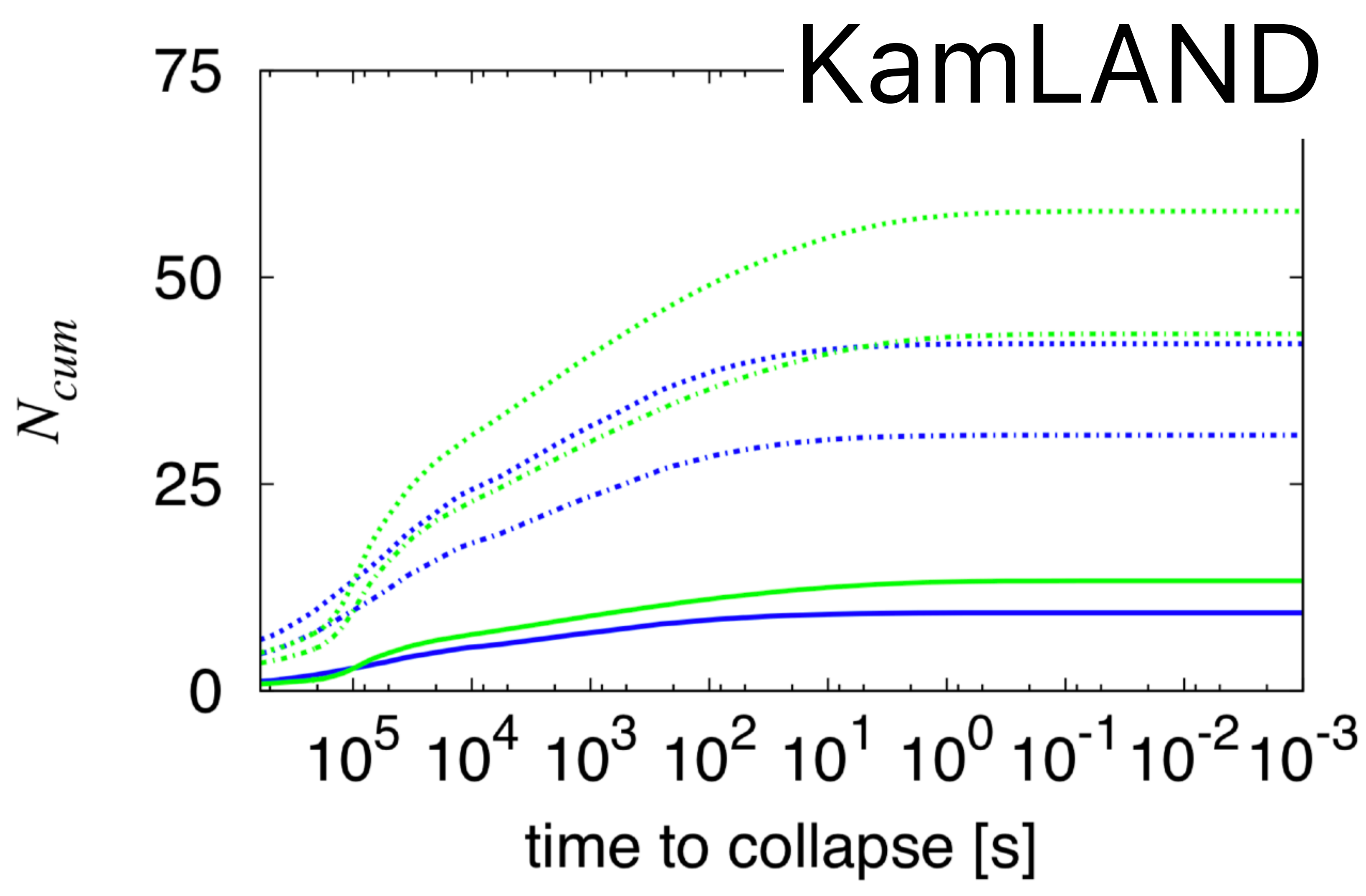
→ **Strong CP problem is solved.**

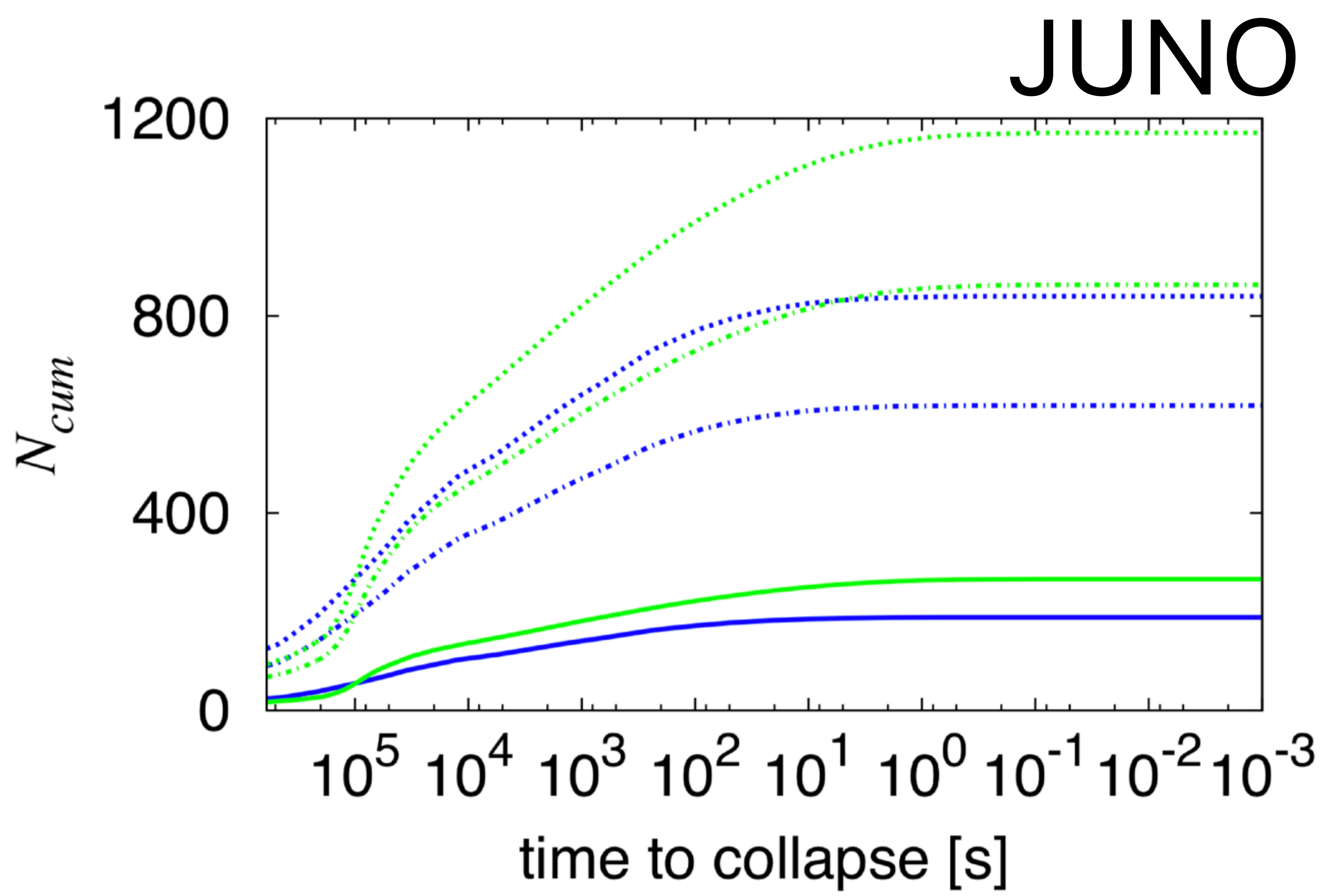
C. Kato et.al., [1506.02358].

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


Super-K


Hyper-K


KamLAND


JUNO

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

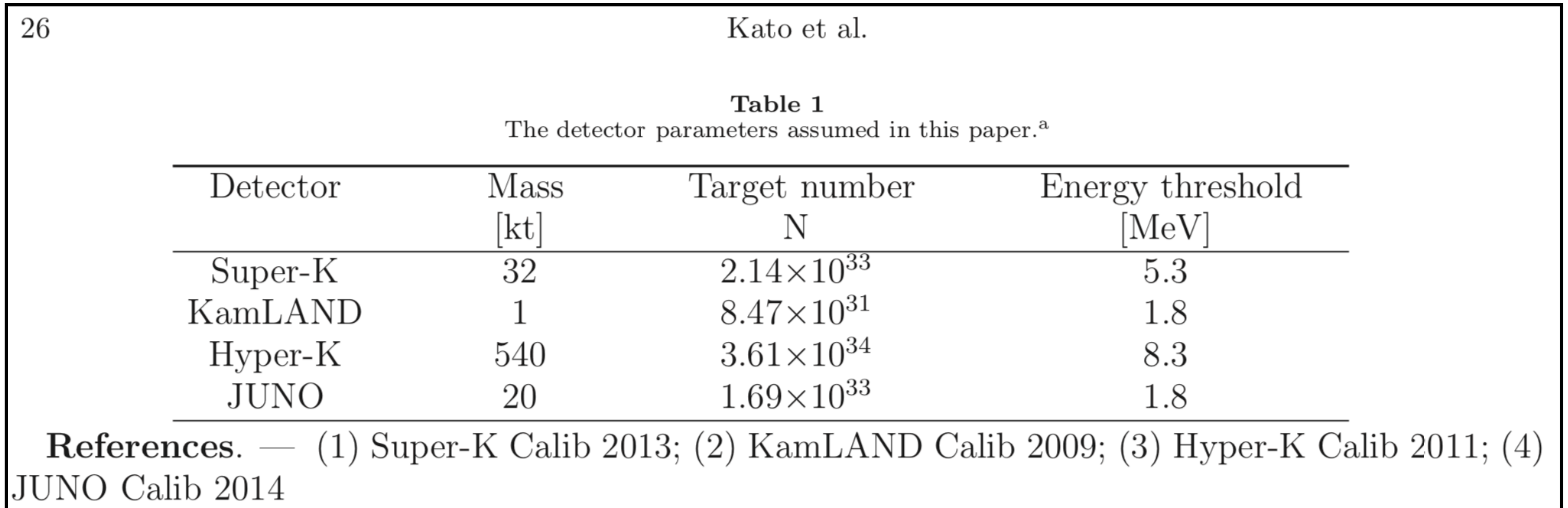
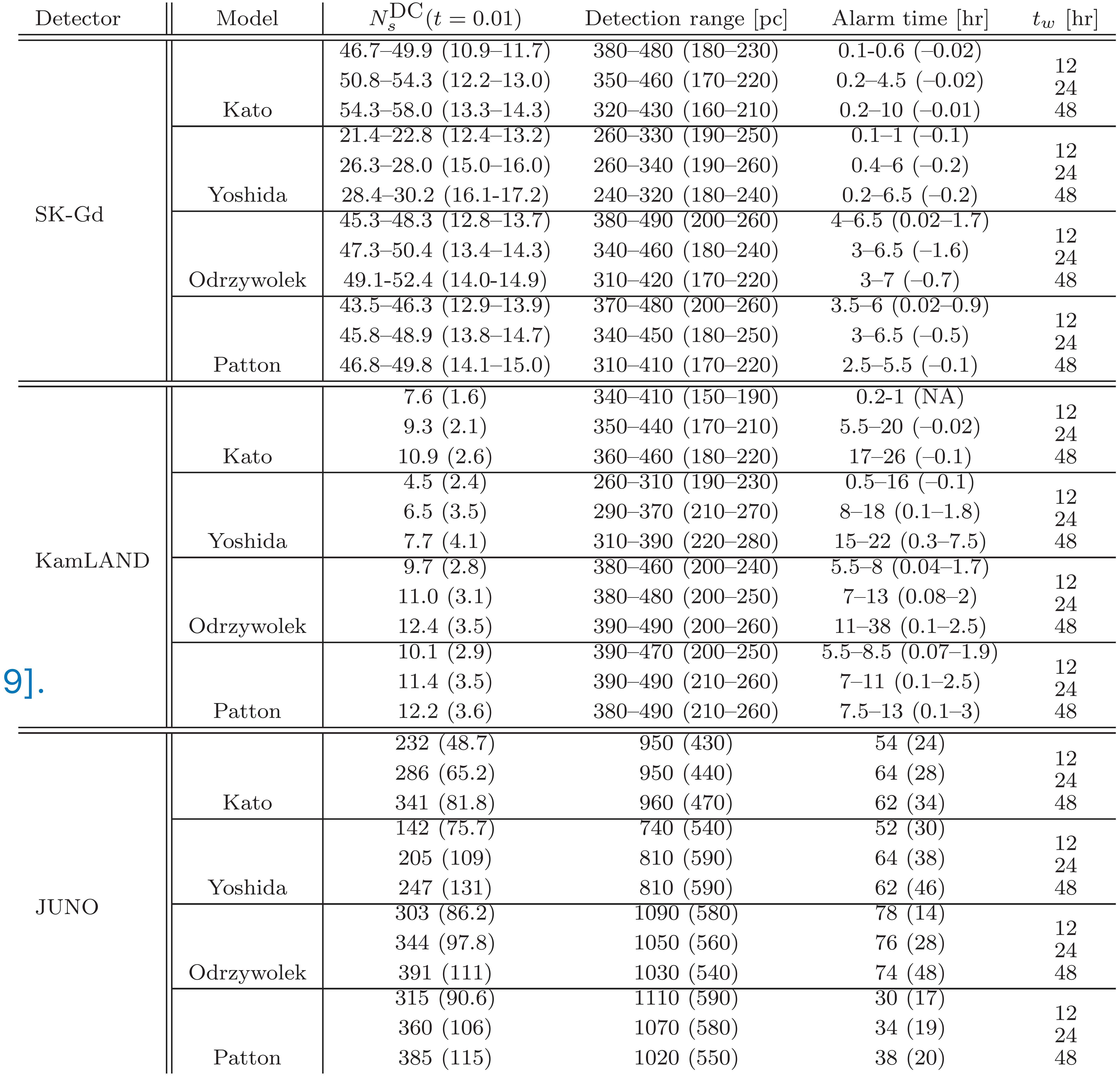

26 Kato et al.

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	$N_s^{\mathrm{DC}}(t = 0.01)$	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].

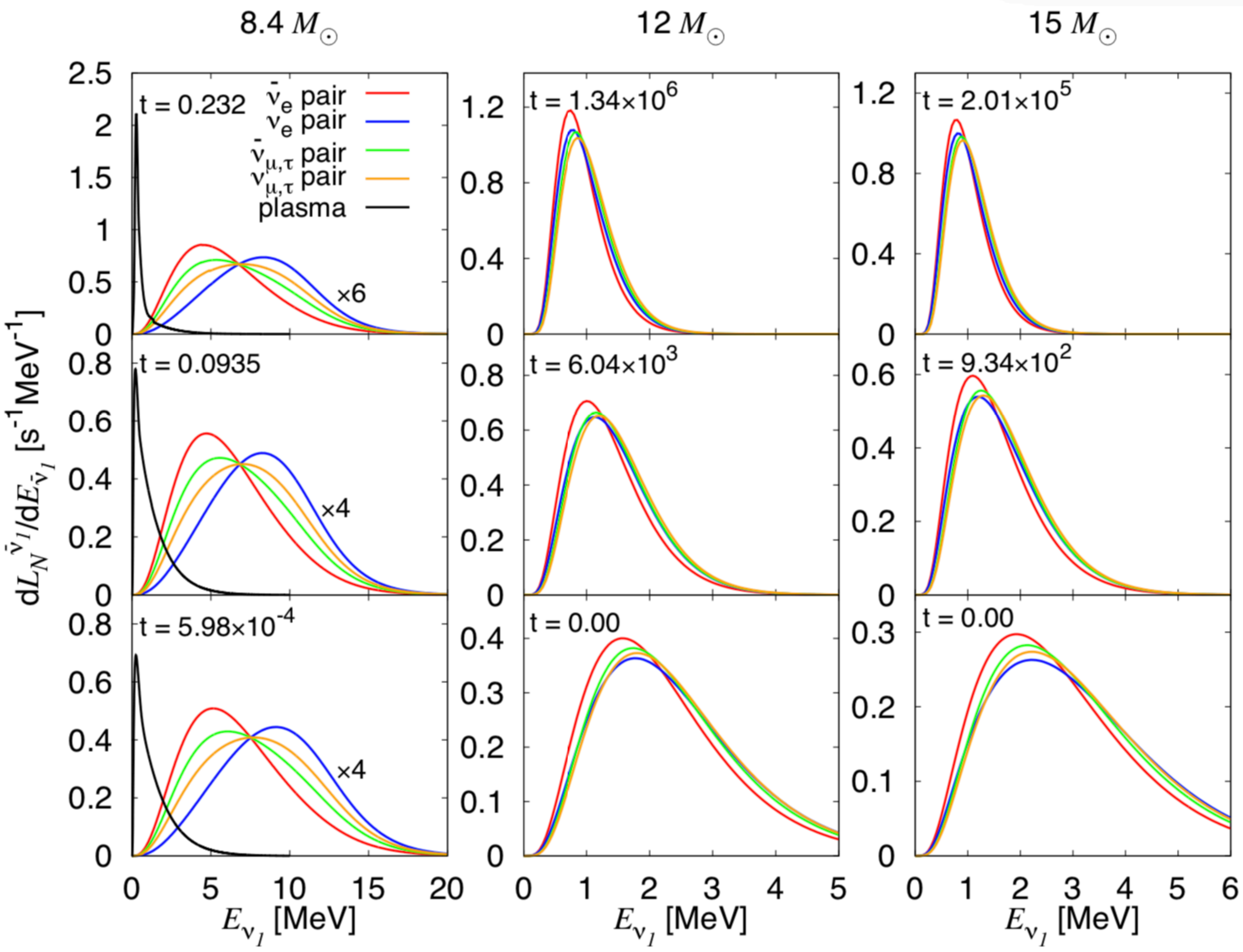


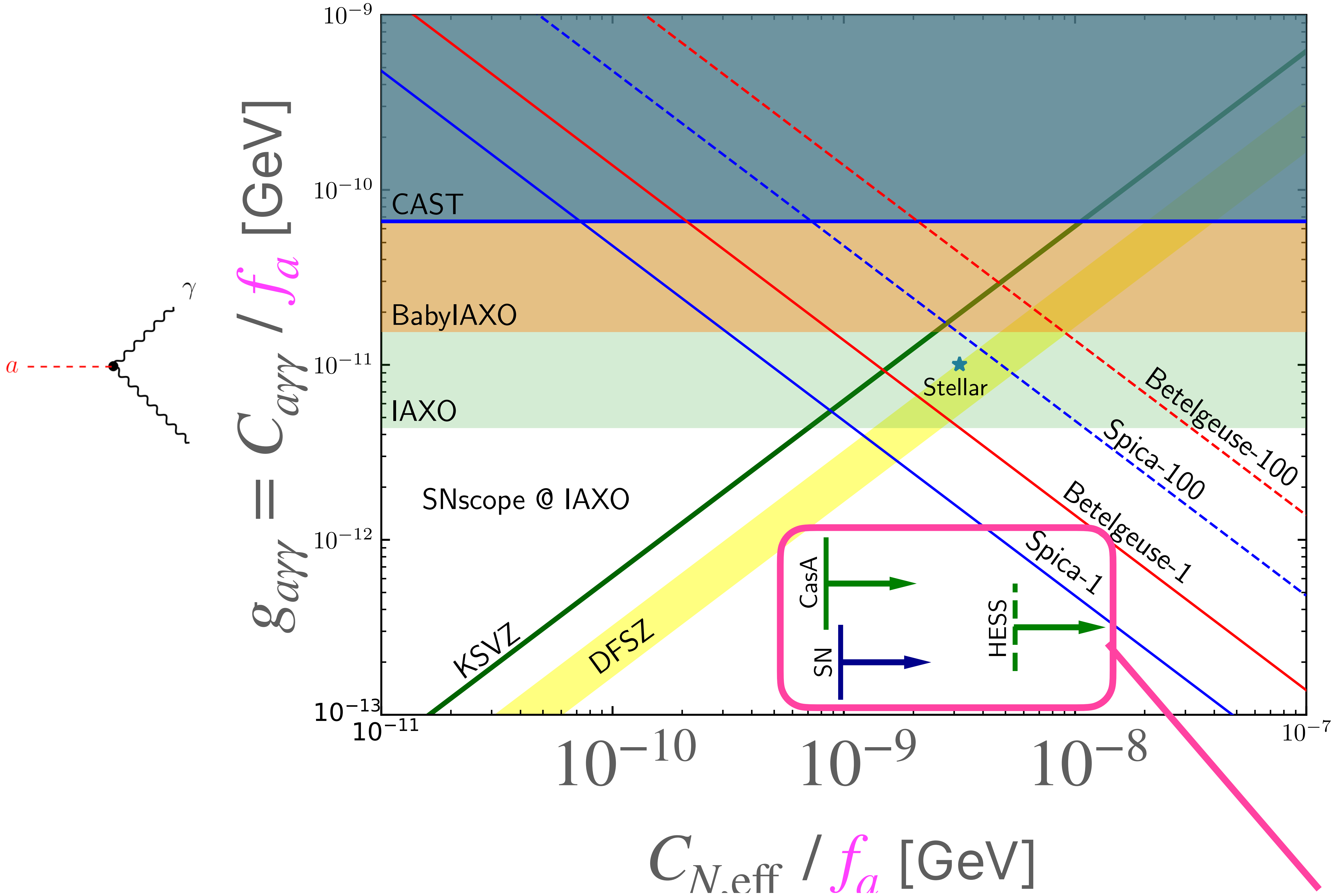
Figure 12. Normalized number spectra at different times for 8.4 $M_\odot$ (left panels), 12 $M_\odot$ (middle panels) and 15 $M_\odot$ (right panels). Red, blue, green and orange curves correspond, respectively, to $\bar{\nu}_e$ and ν_e from the pair annihilation and $\bar{\nu}_\mu/\bar{\nu}_\tau$ and 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].

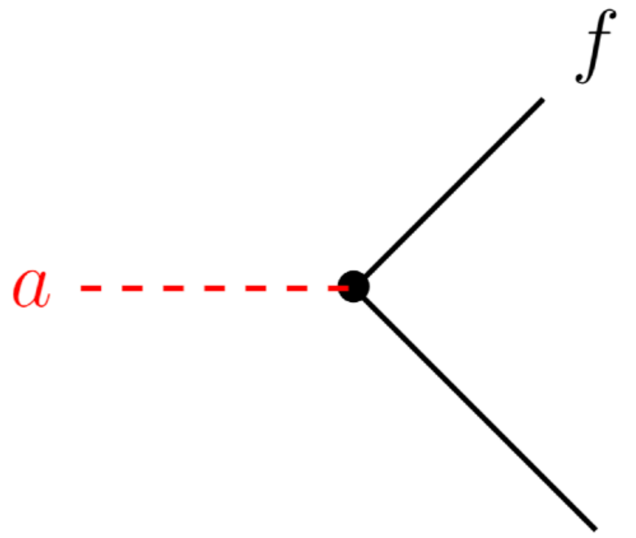
Event number

vs. stellar constraints

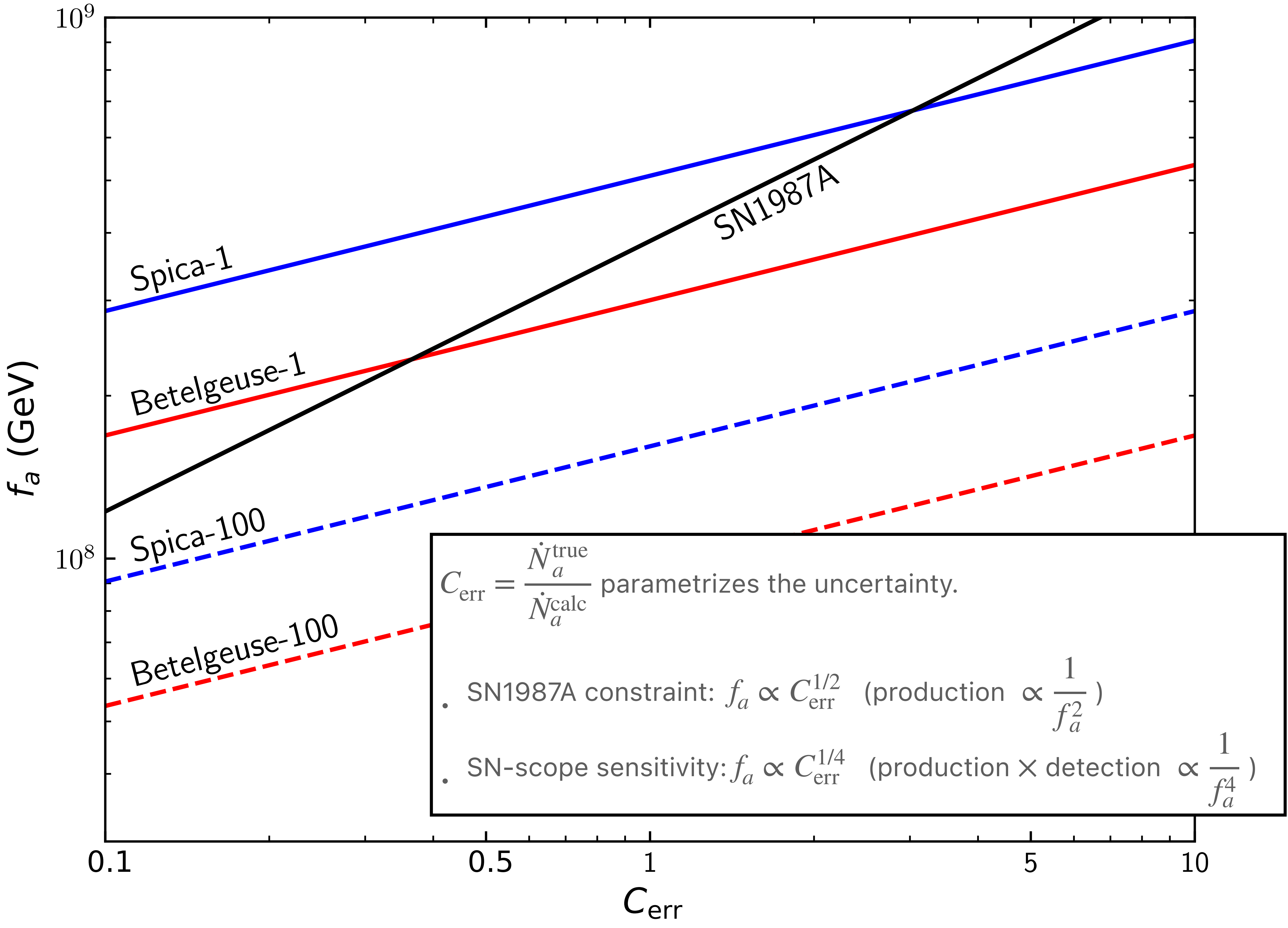
S.Ge, K.Hamaguchi, K.Ichimura, K.Ishidoshiro,
Y.Kanazawa, Y.Kishimoto, N.Nagata, J.Zheng.
[arXiv:2008.03924] JCAP **11** (2020) 059.



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



stellar
constraints



$C_{\mathrm{err}} = \dfrac{\dot N_a^{\mathrm{true}}}{\dot N_a^{\mathrm{calc}}}$ parametrizes the uncertainty.

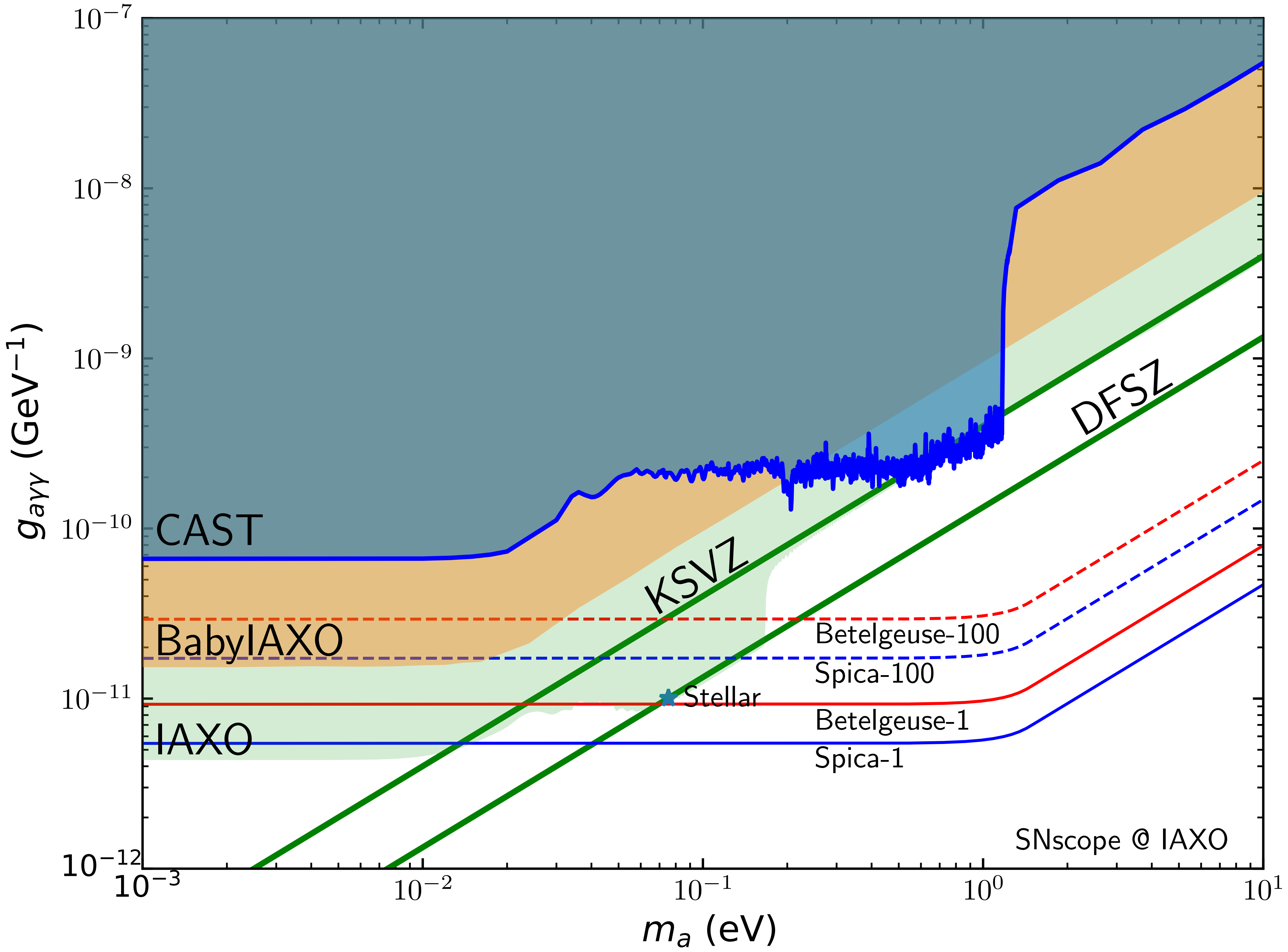
- SN1987A constraint: $f_a \propto C_{\mathrm{err}}^{1/2}$ (production $\propto \dfrac{1}{f_a^2}$)
- SN-scope sensitivity: $f_a \propto C_{\mathrm{err}}^{1/4}$ (production × detection $\propto \dfrac{1}{f_a^4}$)

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

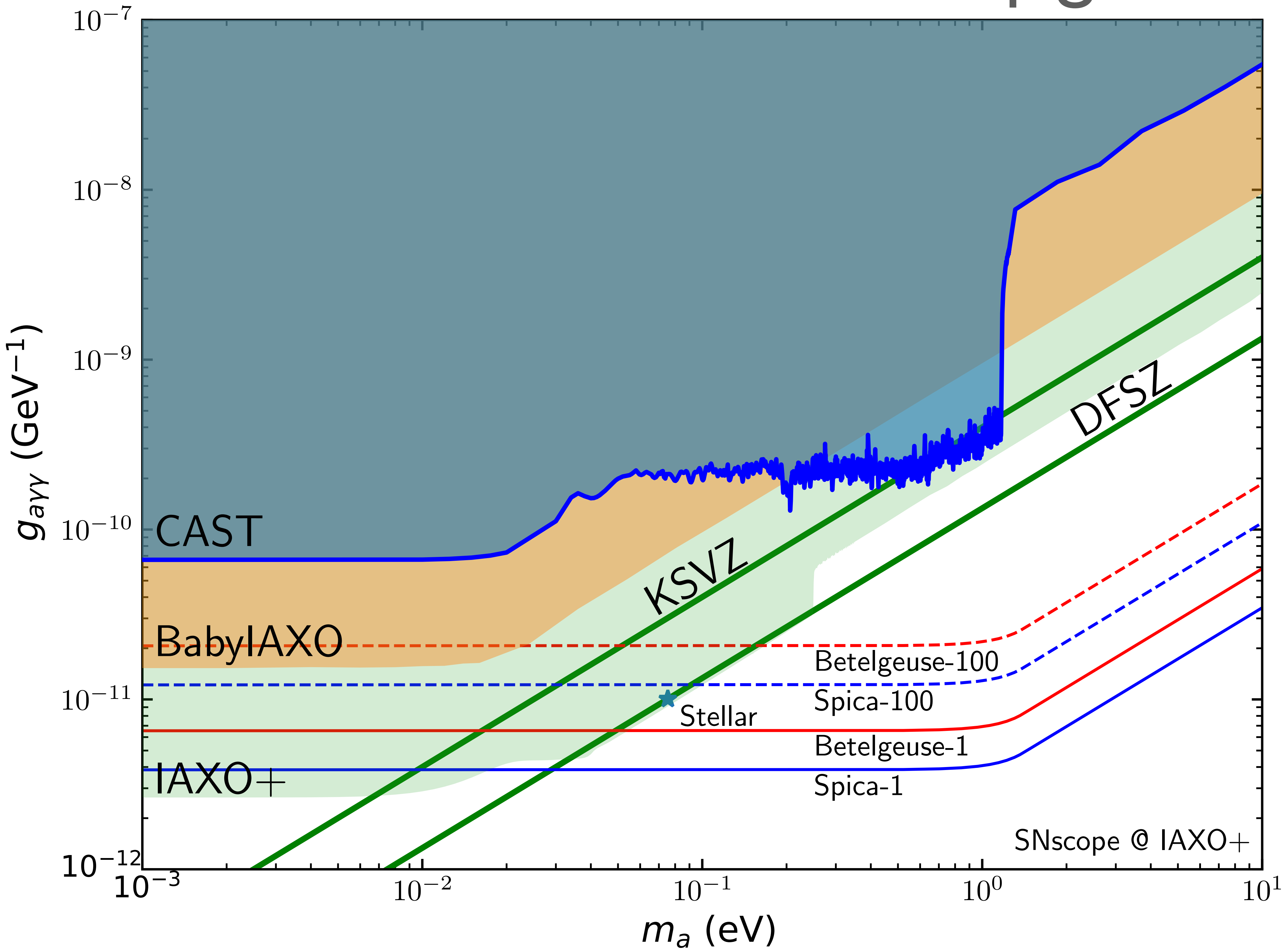
- $\mathcal{O}(1)$ events for Betelgeuse,
- $\mathcal{O}(10)$ events for Spica.

Event number

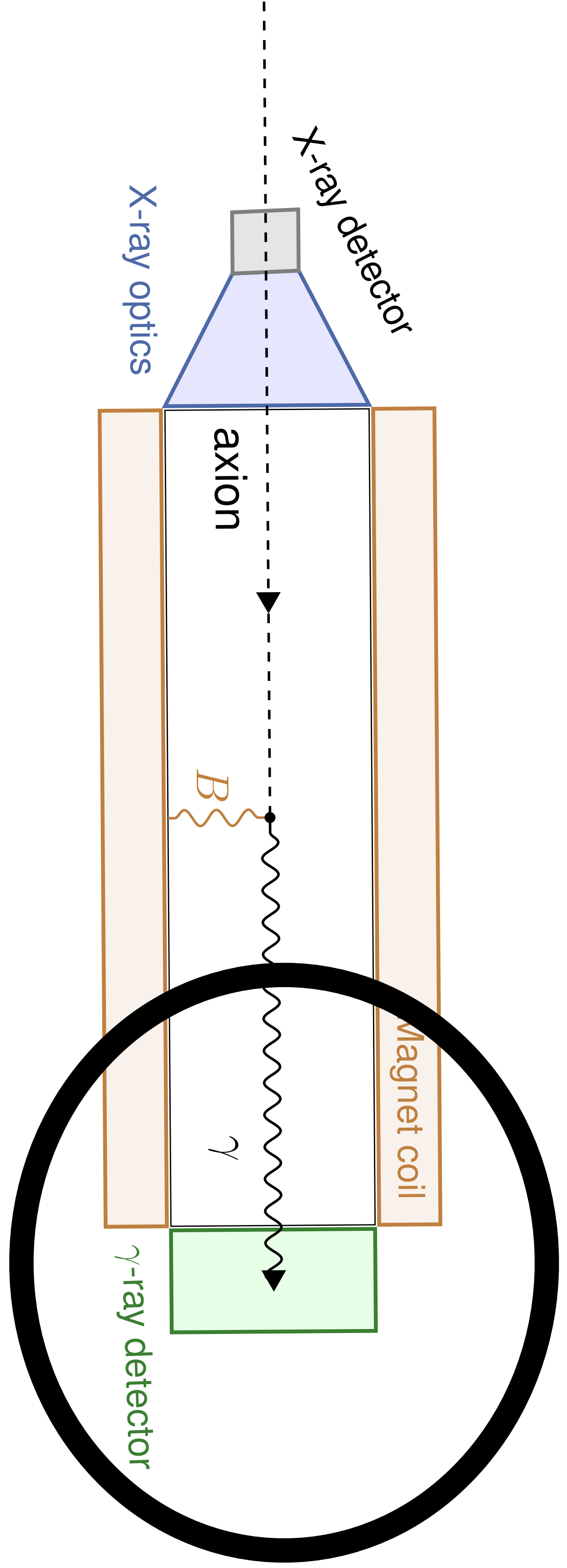
IAXO



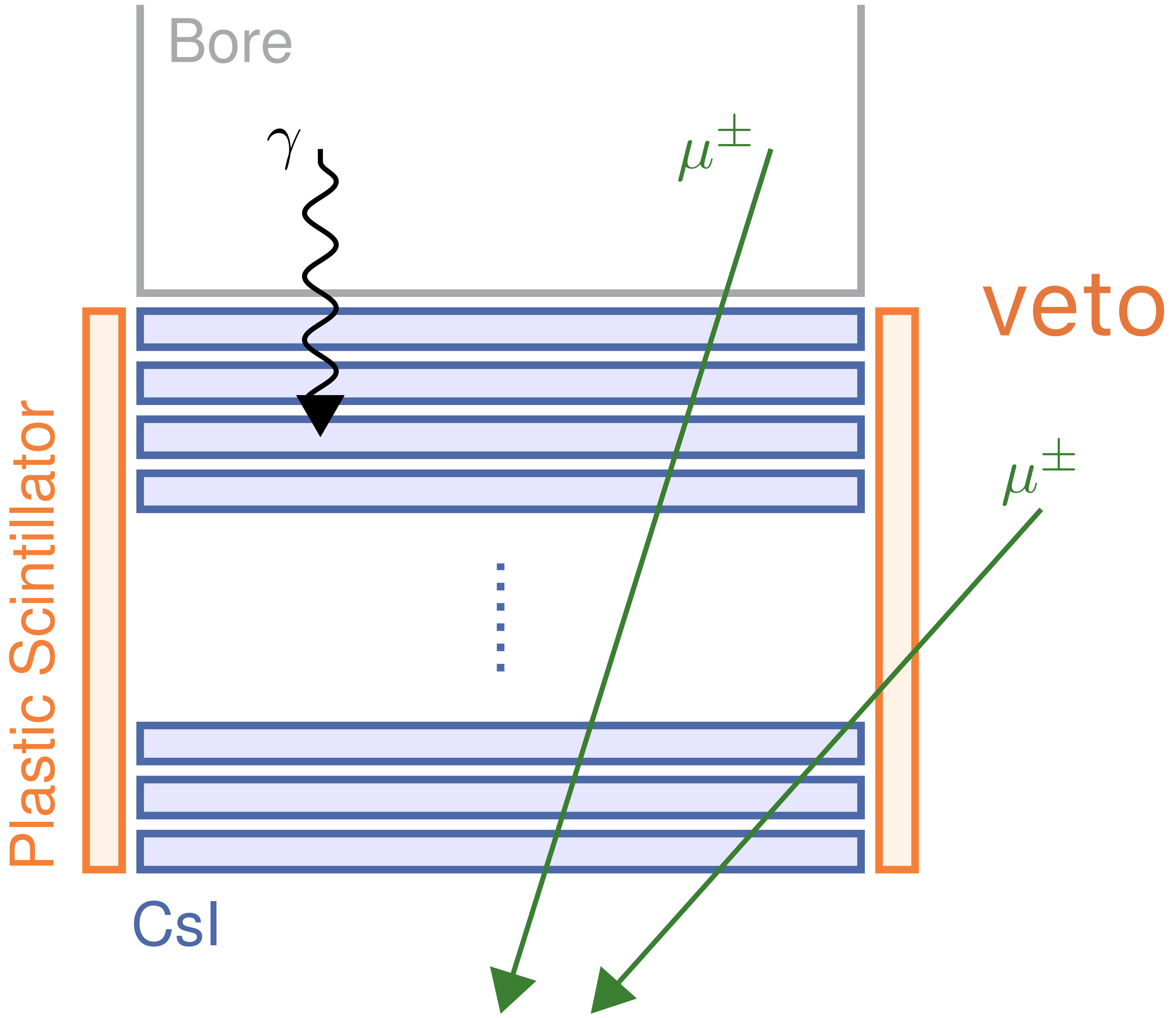
IAXO upgrade



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.

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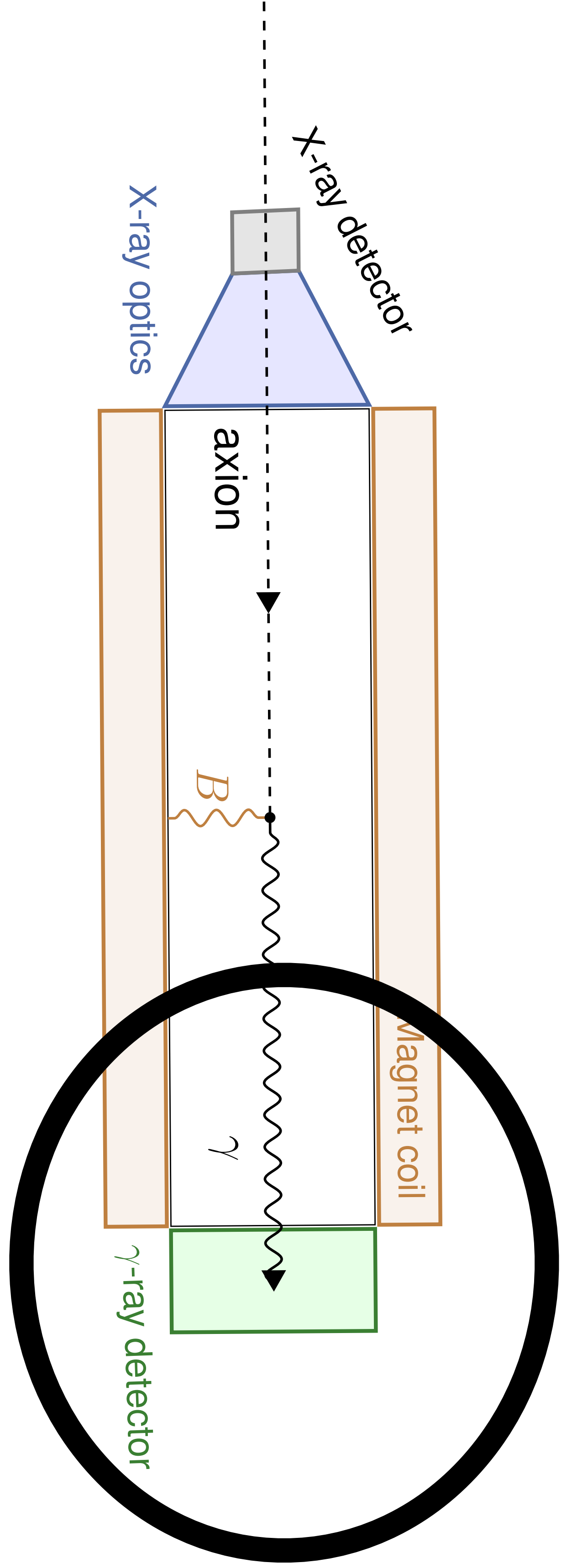
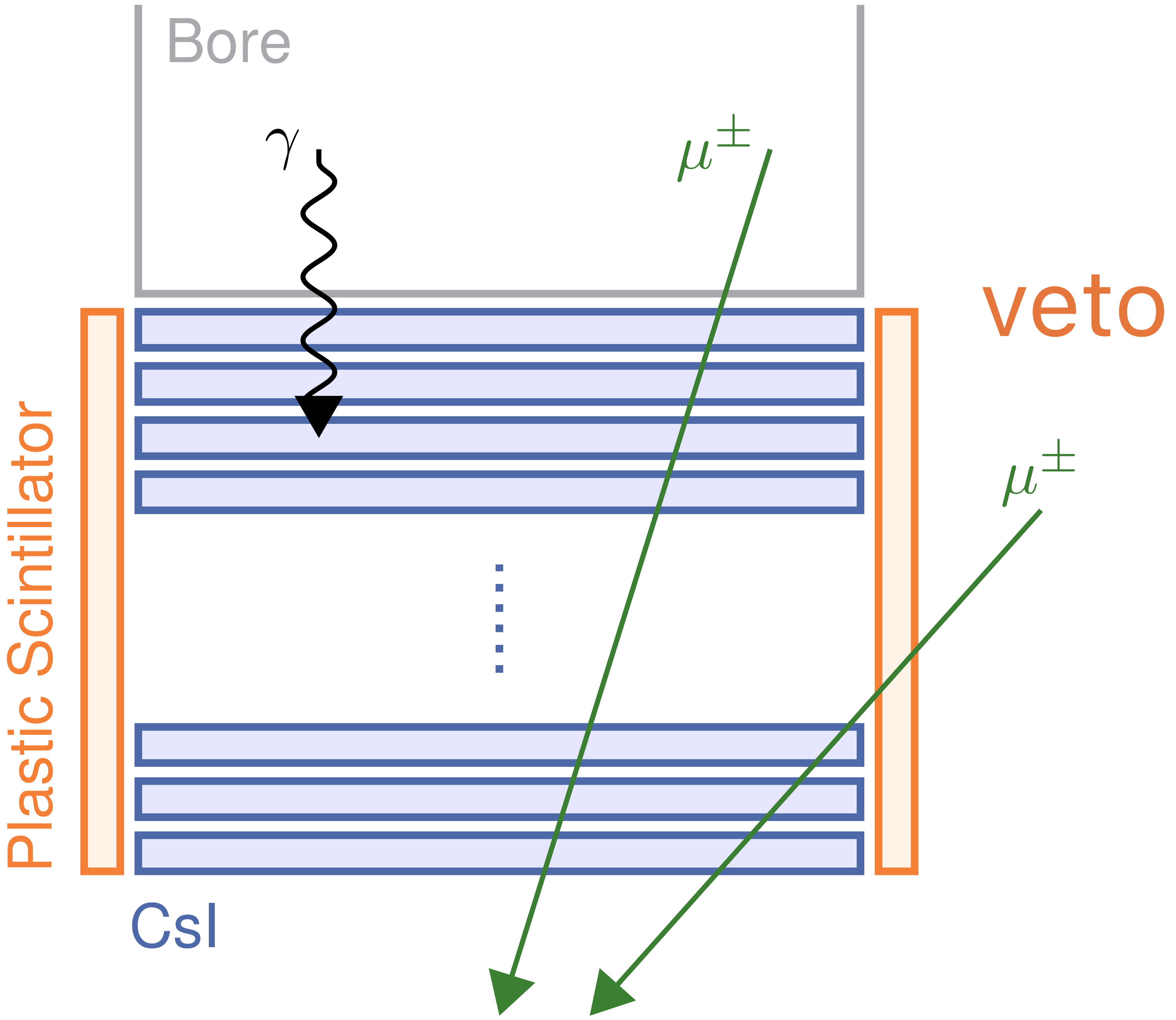
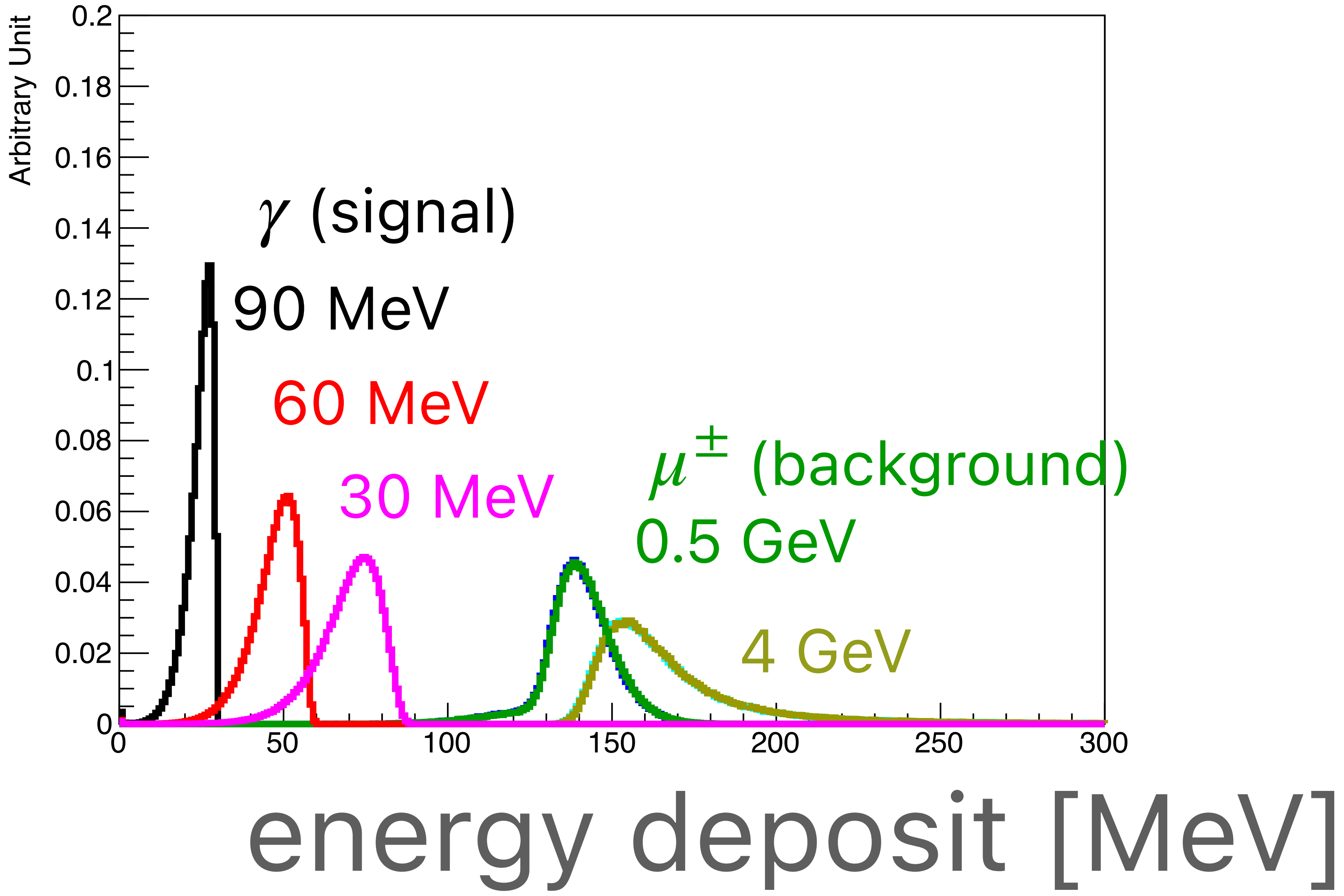
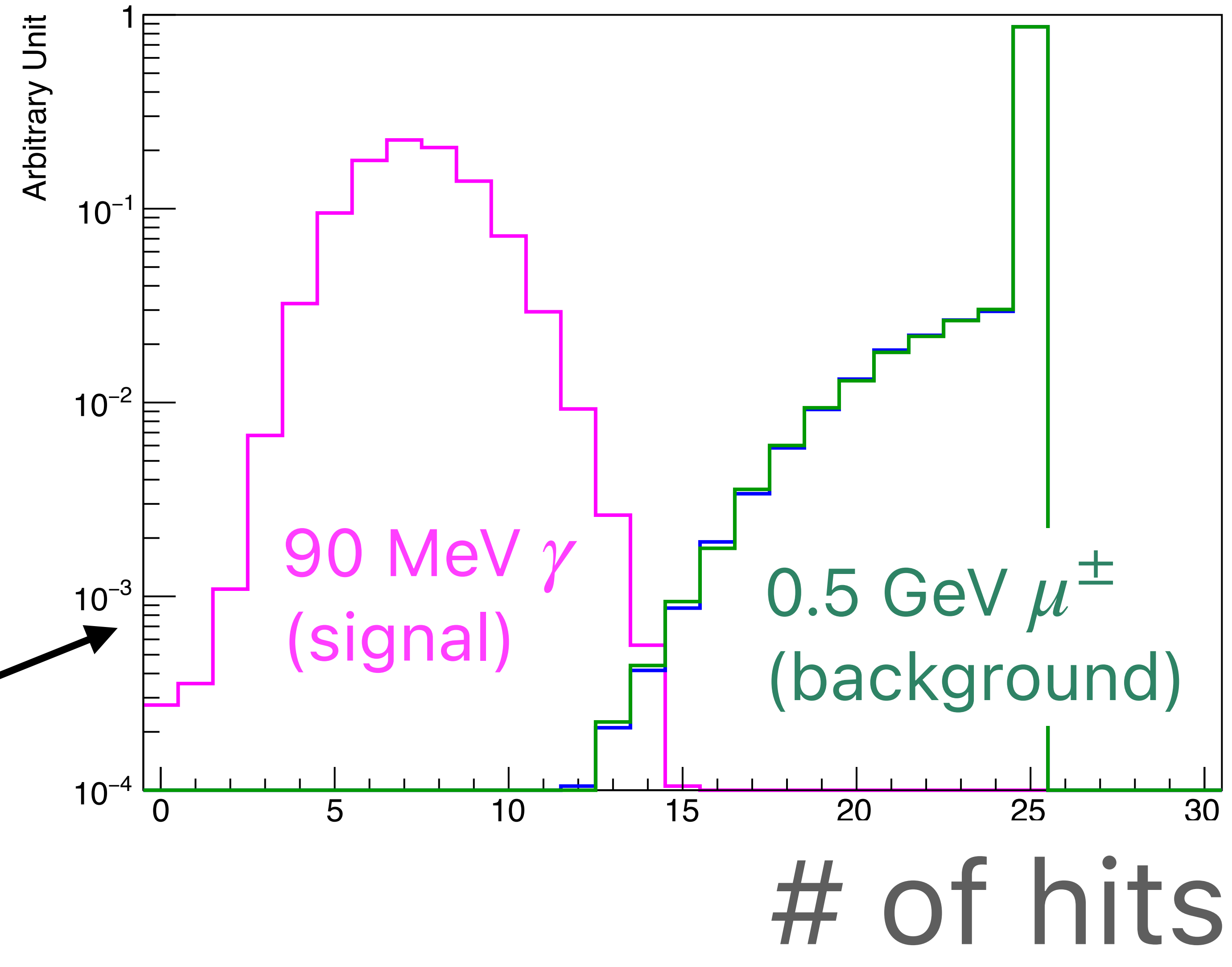


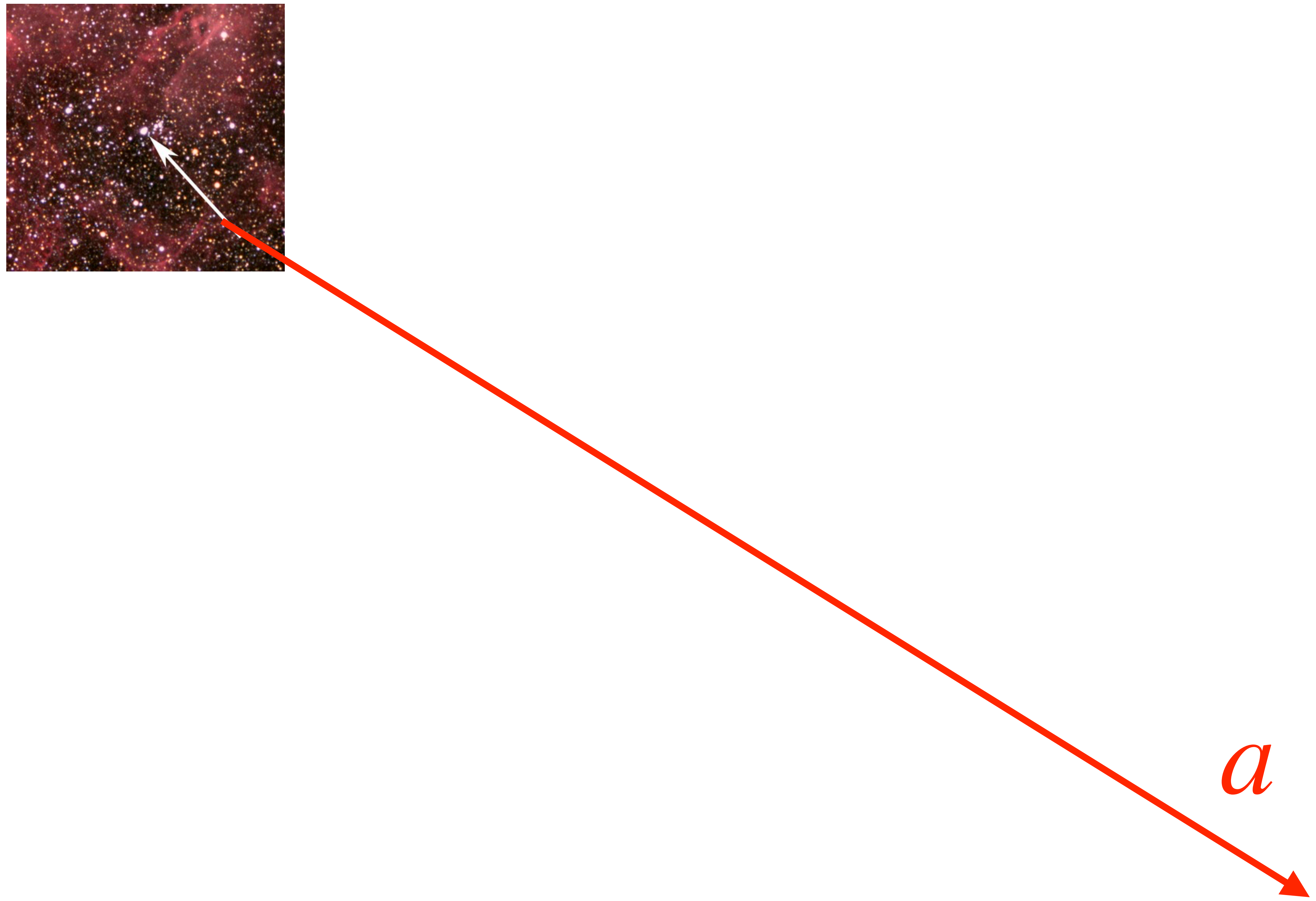


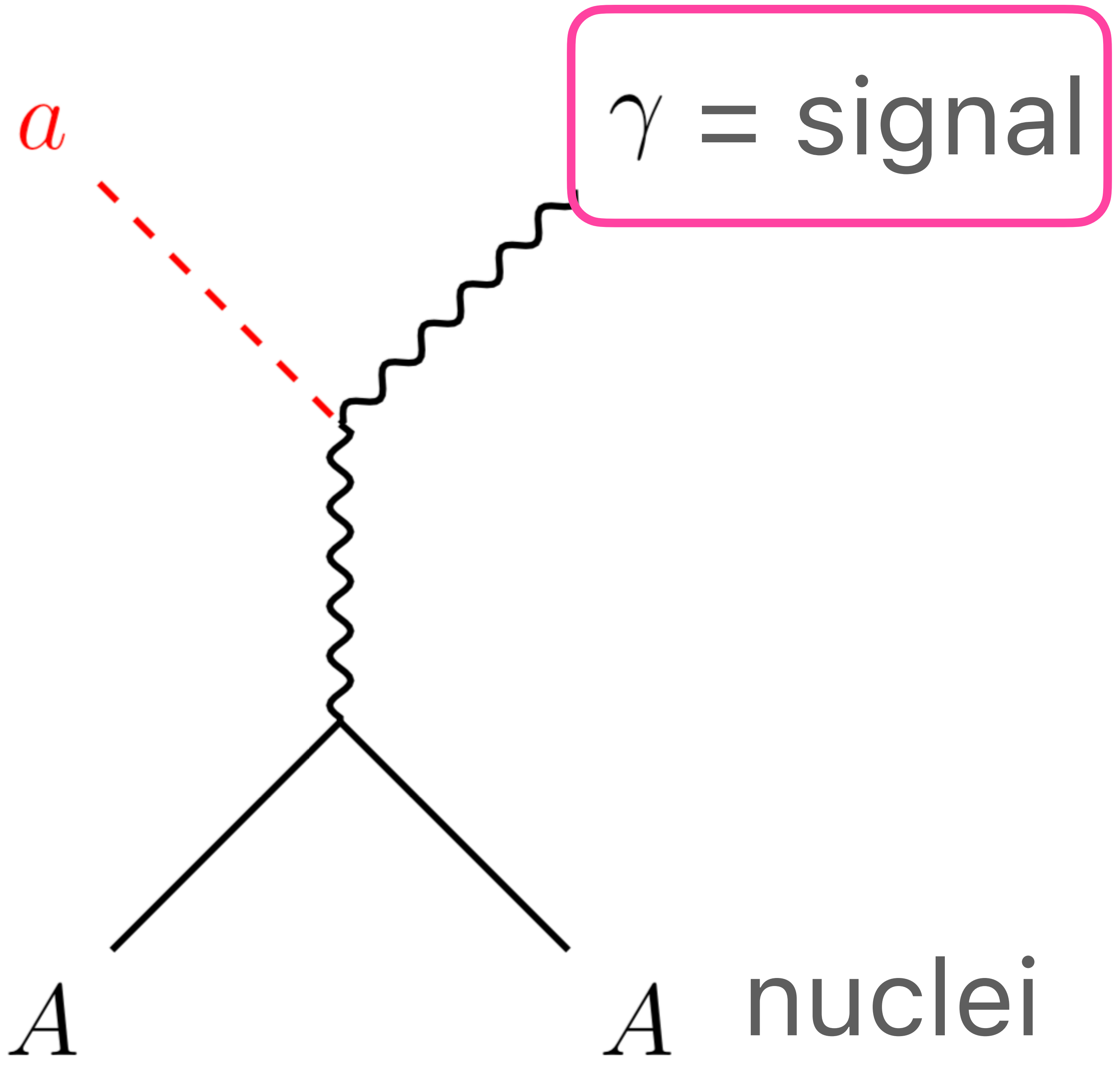




- O(1000) muon events in 10 sec.
- They can be rejected by energy deposit and # of hits.

What about the **inverse Primakoff** signal?





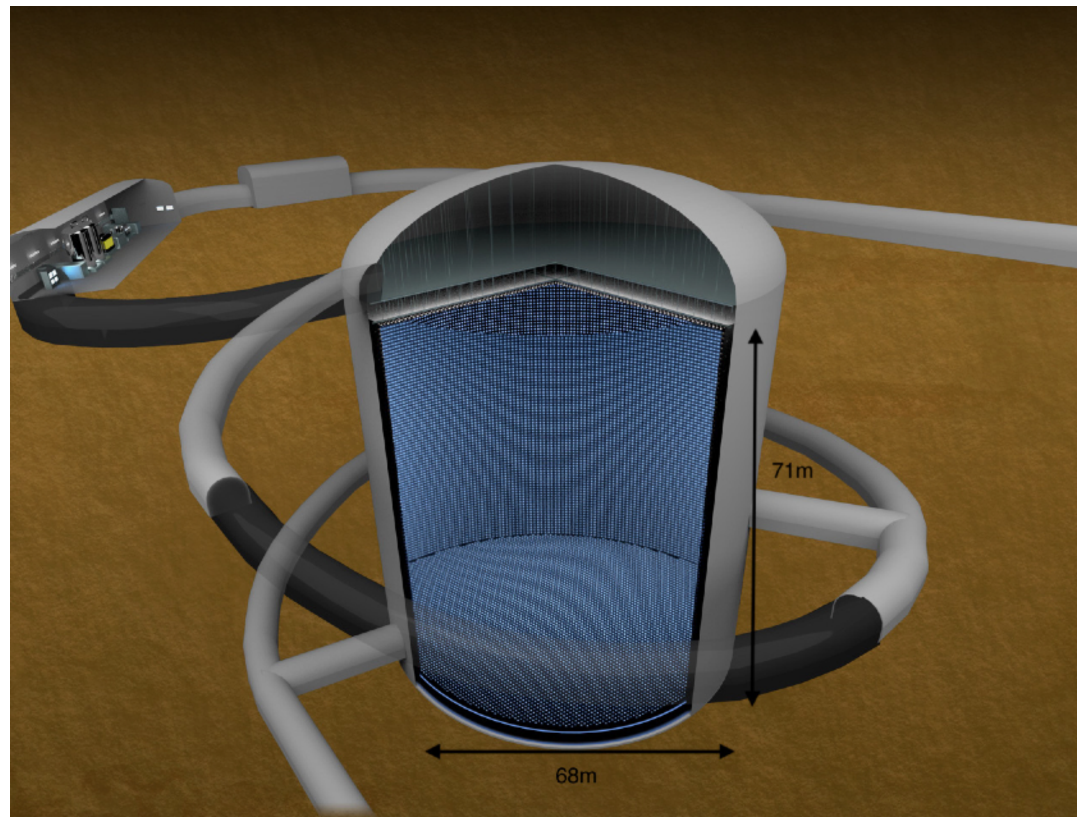
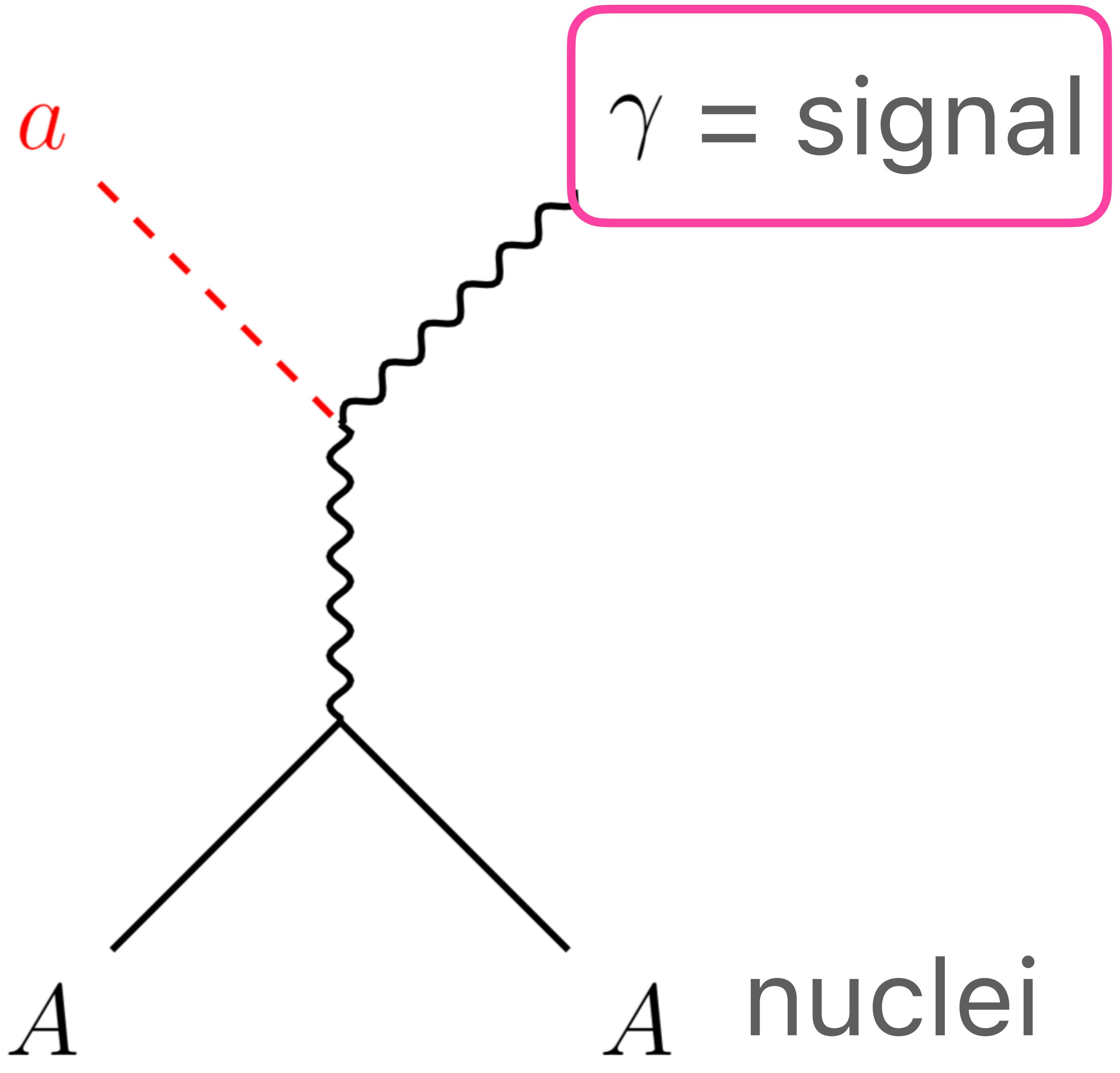


figure from Hyper-K homepage

What about the **inverse Primakoff** signal?



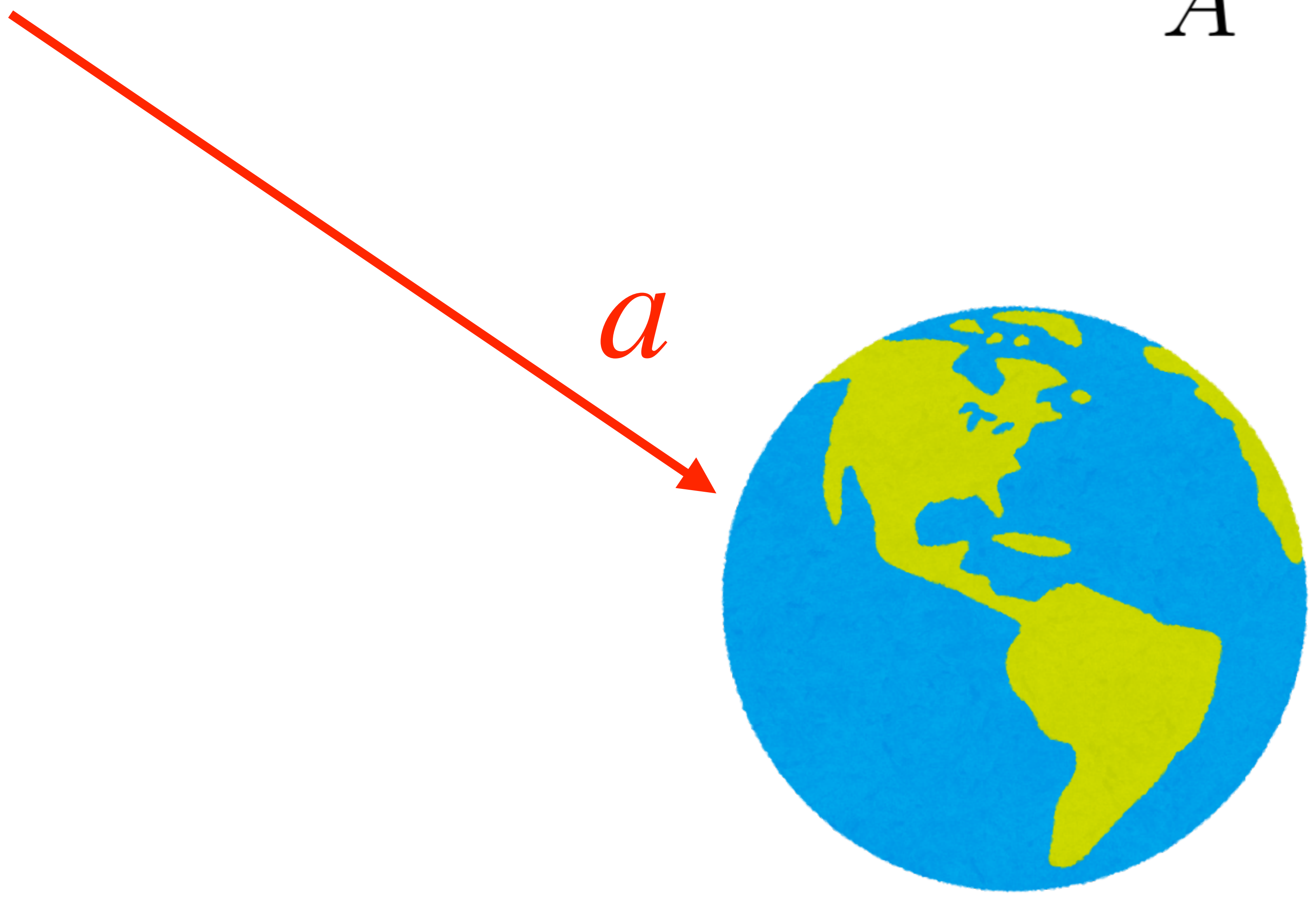
- SN-axion N_{event} at Hyper-K (187kt water)

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

$$N_{\text{event}} = \dot{N}_a \Delta t \times \frac{\sigma_{\text{el}}}{4\pi d^2} \times N_{\text{O}}$$

$$\simeq 1 \times \left(\frac{3 \times 10^8\ \text{GeV}}{f_a}\right)^4 \left(\frac{C_{N,\text{eff}}}{0.37}\right)^2 \left(\frac{g_{a\gamma\gamma} f_a}{\alpha/\pi}\right)^2 \left(\frac{\Delta t}{10\ \text{s}}\right) \left(\frac{d_{\text{SN}}}{100\ \text{pc}}\right)^{-2}$$

- No need to point to the progenitor.
- Difficulty to distinguish it from the huge number of neutrino burst events.



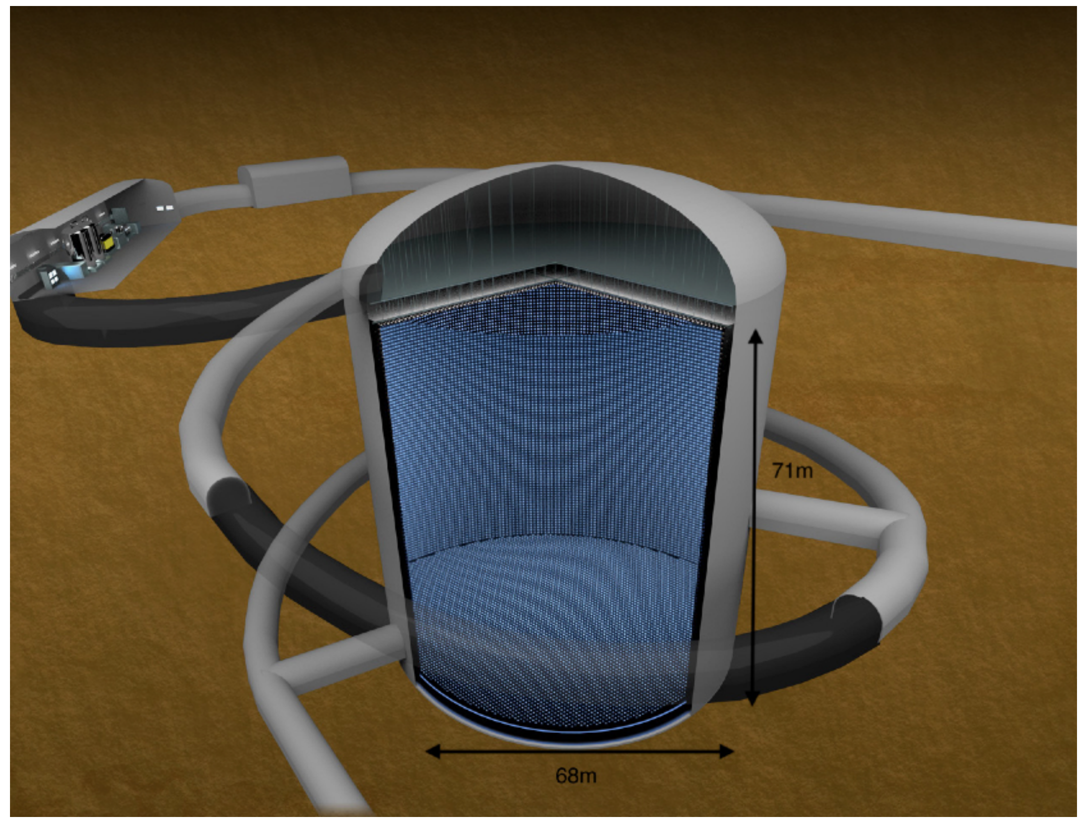


figure from Hyper-K homepage