Activity report from group E01

Theoretical research on new particle physics models and the evolution of the early universe unravelling the origin of matter

Koichi Hamaguchi (Tokyo U.)

@workshop 新学術「地下宇宙」領域研究会

(Unraveling the History of the Universe and Matter Evolution with Underground Physics)

May 20, 2021

Fig. from the pamphlet on the web pag

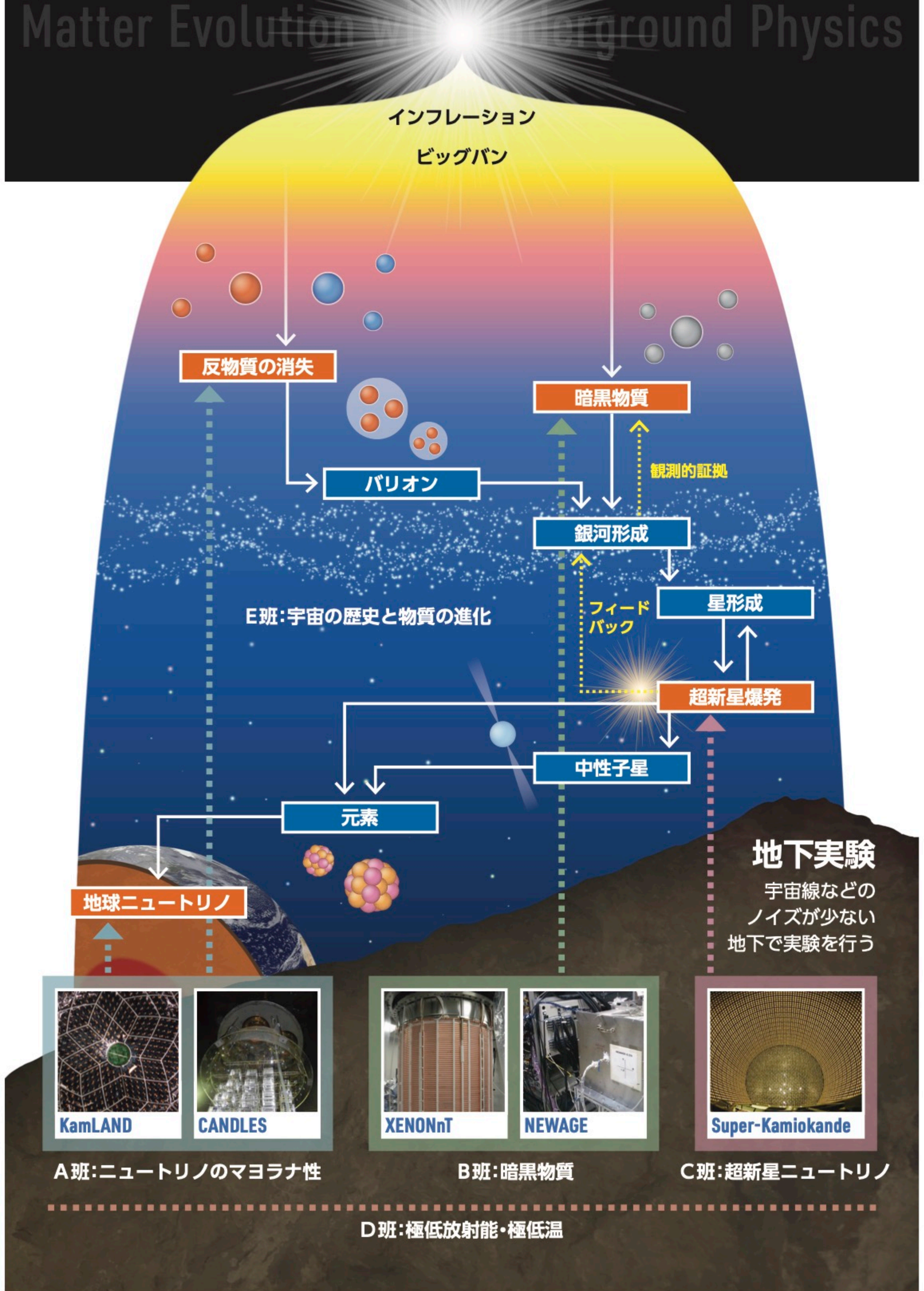
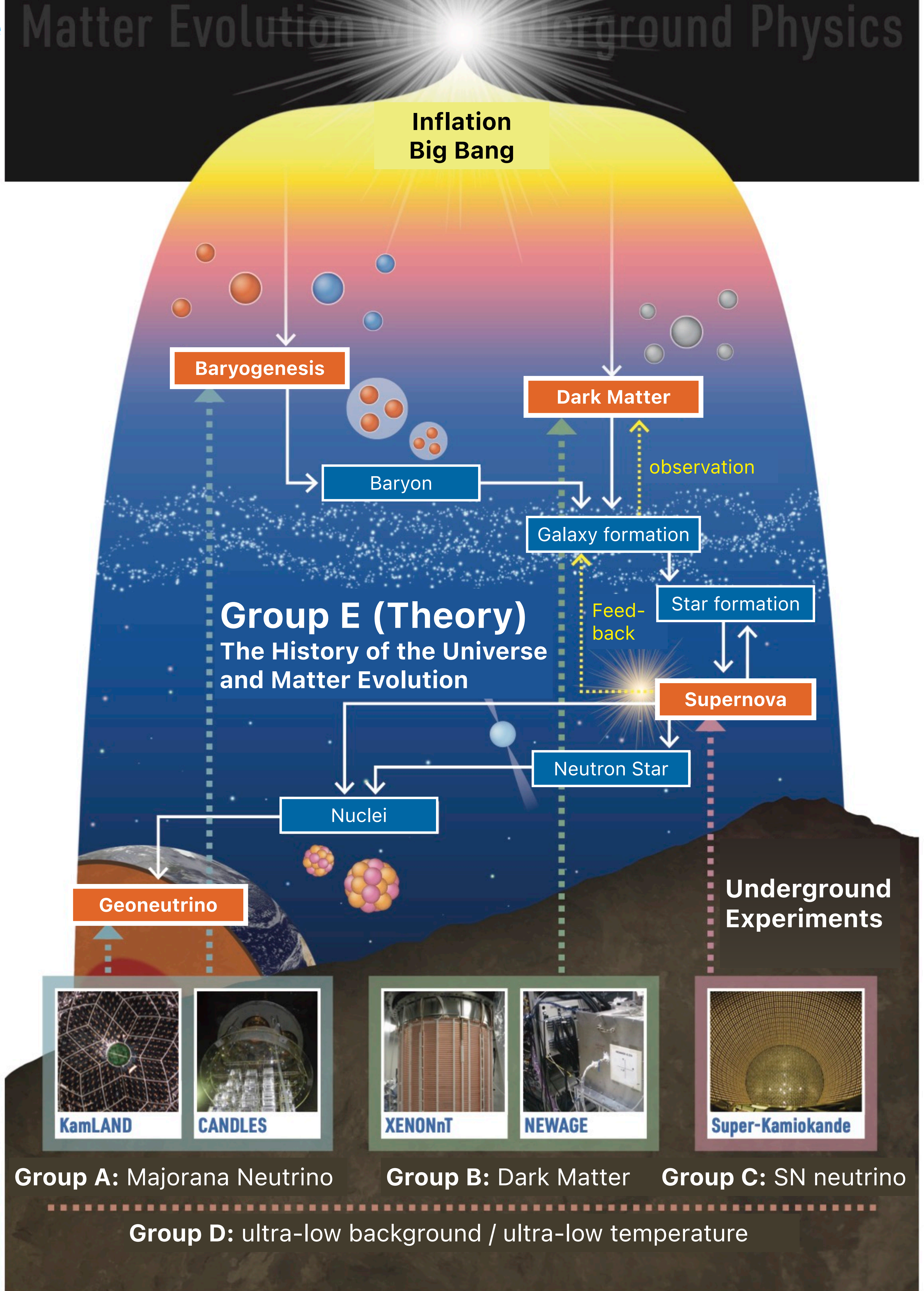


Fig. from the pamphlet on the web page (translated)



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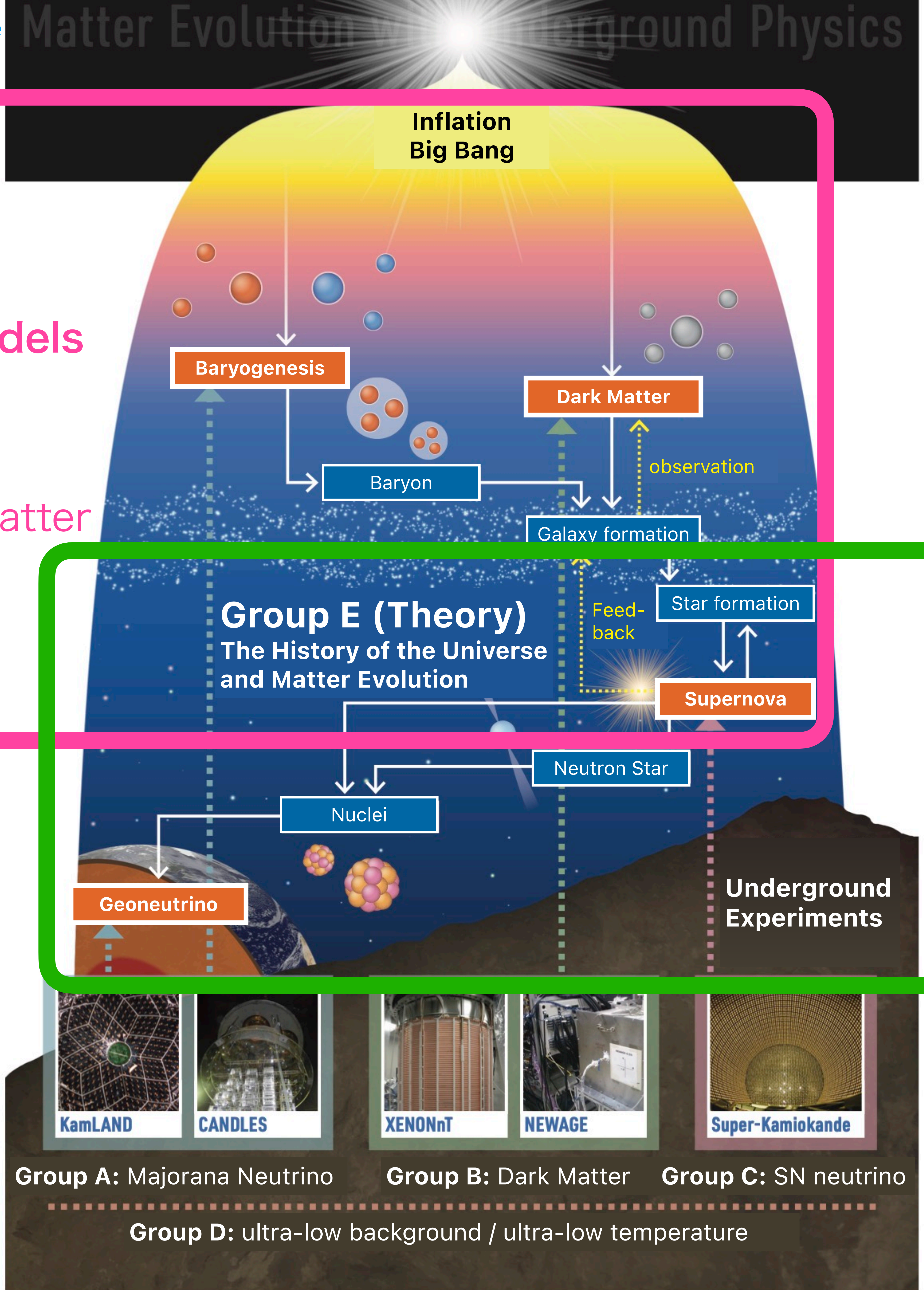

E01

Theoretical research on **new particle physics models and the evolution of the early universe** unravelling the origin of matter

E02

Theoretical research on **supernova neutrinos** in connection with **nuclear physics** and **cosmic chemical evolution**

Fig. from the pamphlet on the web page (translated)

E01

Theoretical research on
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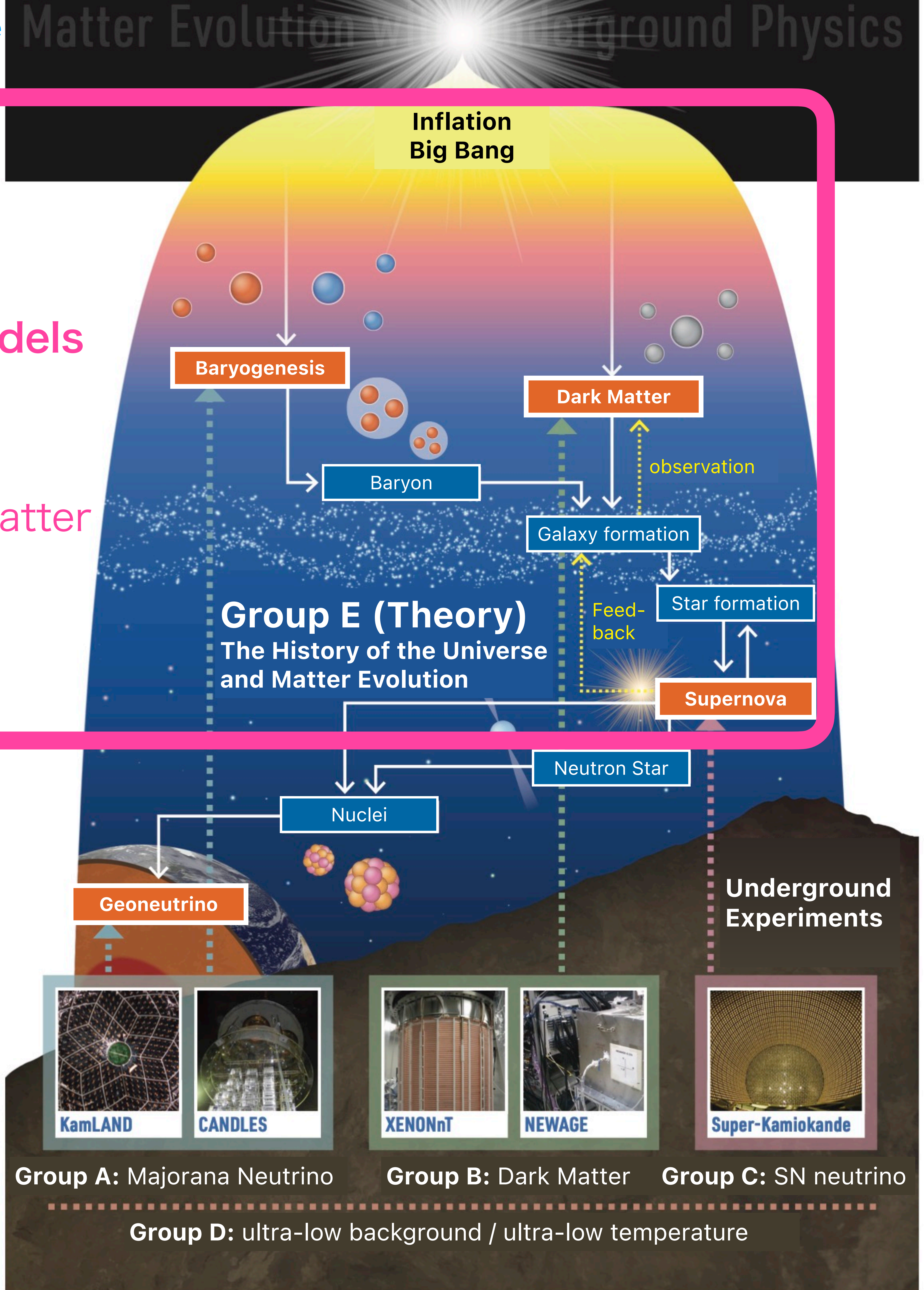

1. Matter > anti-matter and neutrino mass

2. Dark Matter

3. New particle physics models and the evolution of the early universe

Fig. from the pamphlet on the web page (translated)

E01

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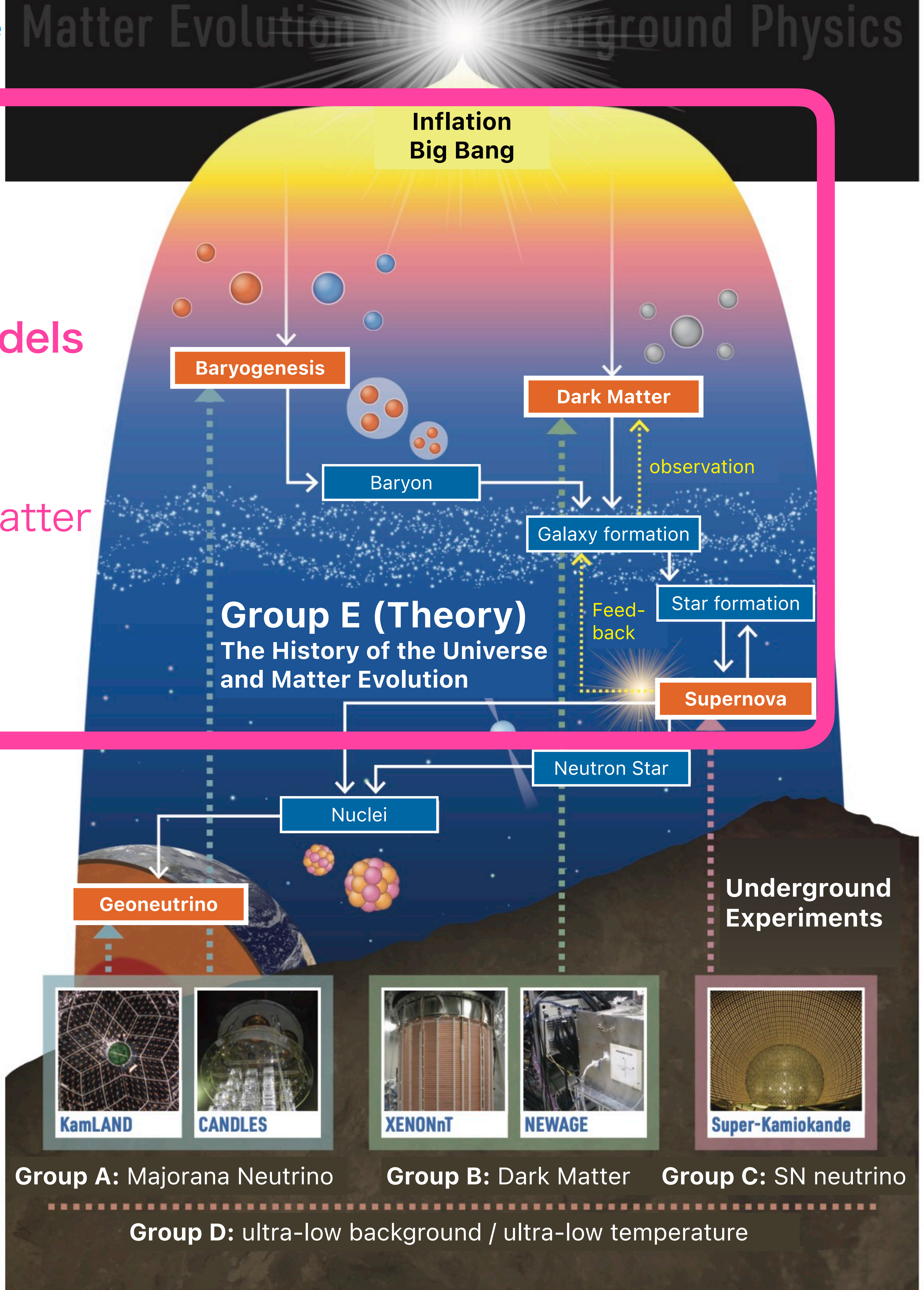

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Members

Koichi Hamaguchi (Tokyo U., PI)

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(IPMU, co-investigator)

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(Osaka, co-investigator)

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(IPMU & TDLI, co-investigator)

Wakutaka Nakano
(Tokyo U., postdoc, 2020-)

Fig. from the pamphlet on the web page (translated)

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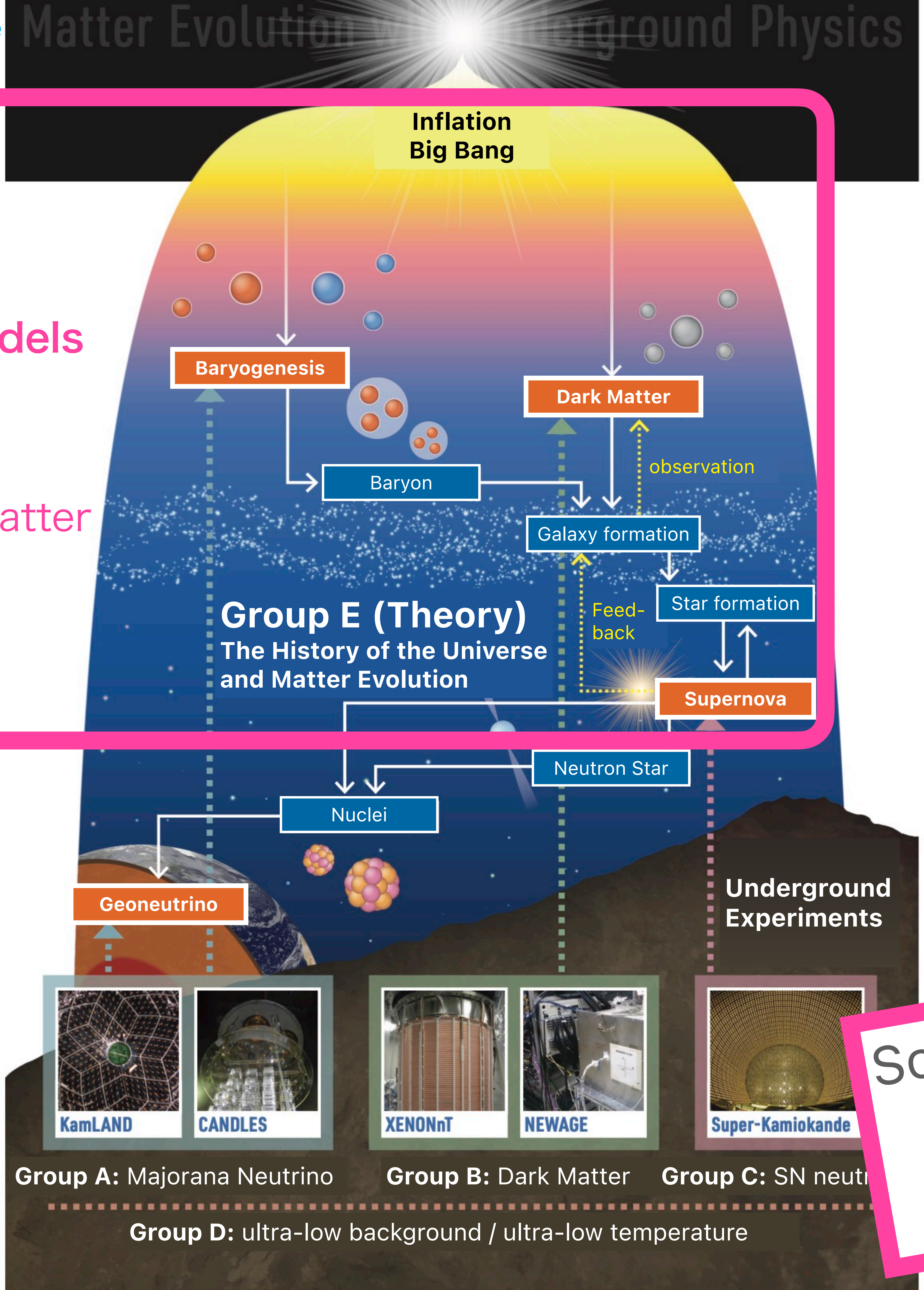

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So far (2019.7 — 2021.4)

- **53 papers** (40 published)
- **46 talks** (28 invited, 21 intl.)

Fig. from the pamphlet on the web page (translated)

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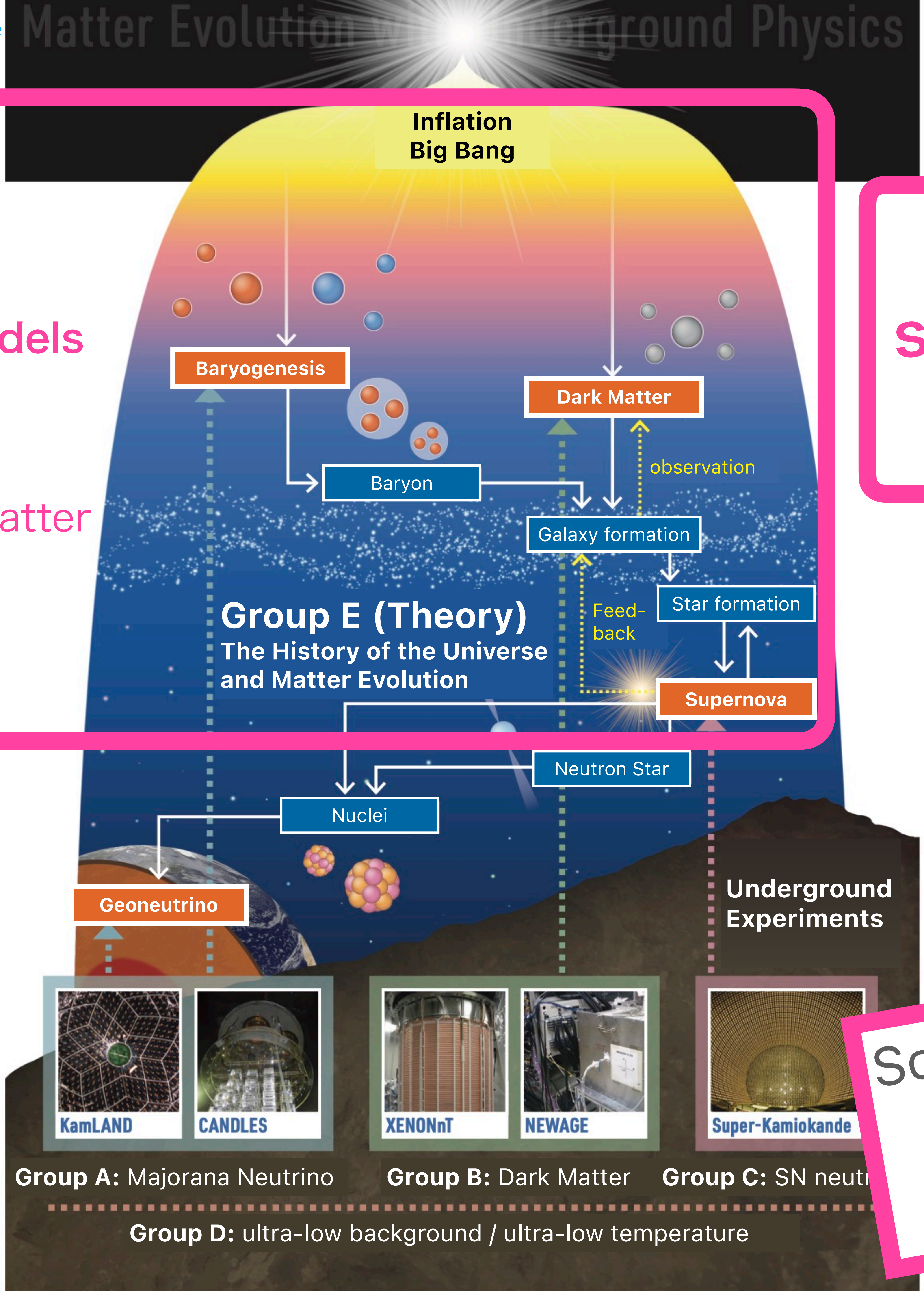

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see the next talks!

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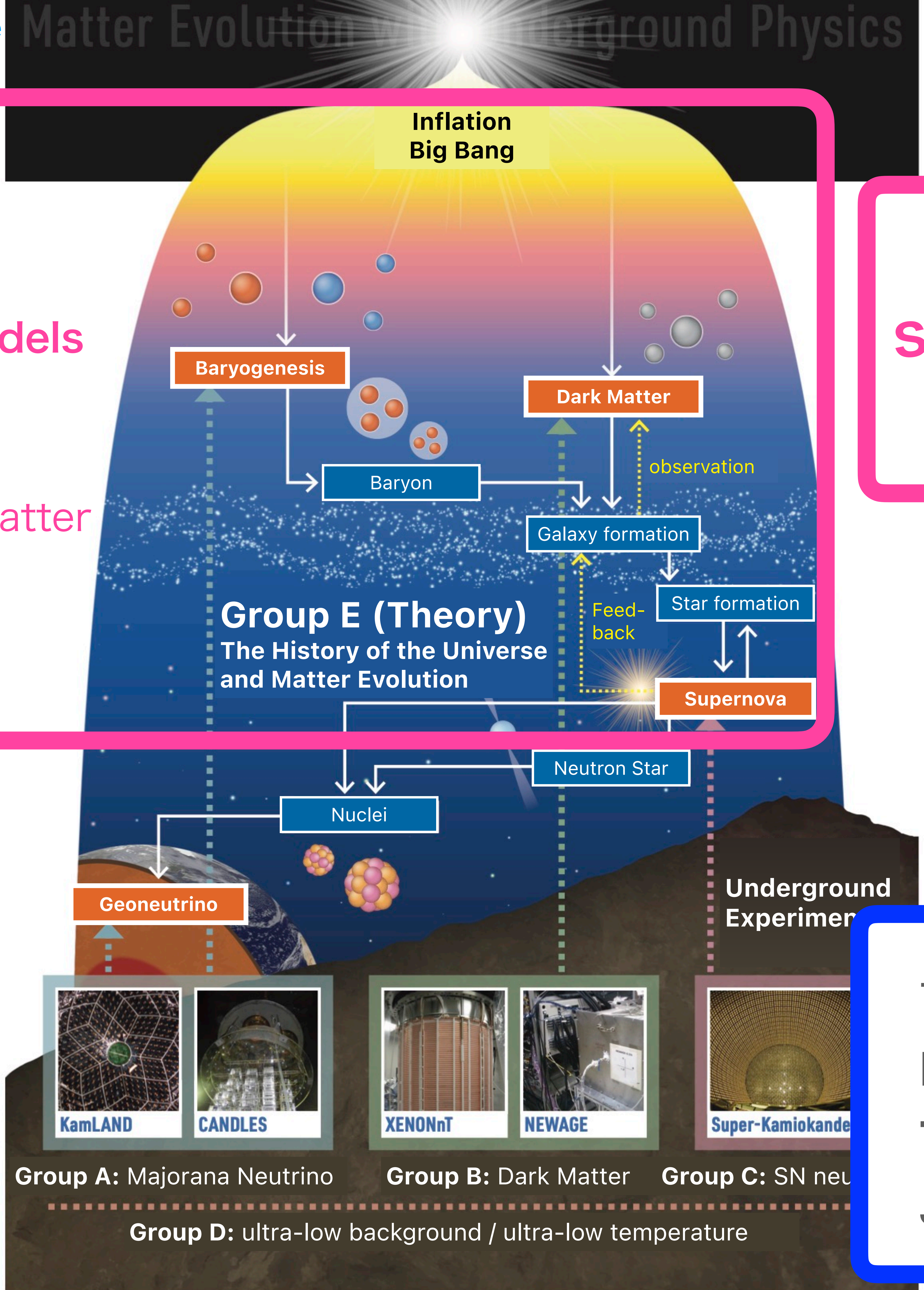

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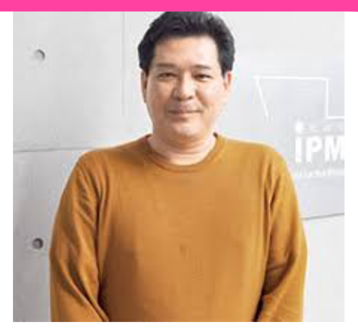

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(IPMU & TDLI, co-investigator)

Wakutaka Nakano
(Tokyo U., postdoc, 2020-)

+ Publicly offered research (公募研究)

Kentarou Mawatari
Tomoaki Ishiyama
Jun'ichi Yokoyama

see the next talks!

Fig. from the pamphlet on the web page (translated)

Cooperation in the Area (領域内連携)

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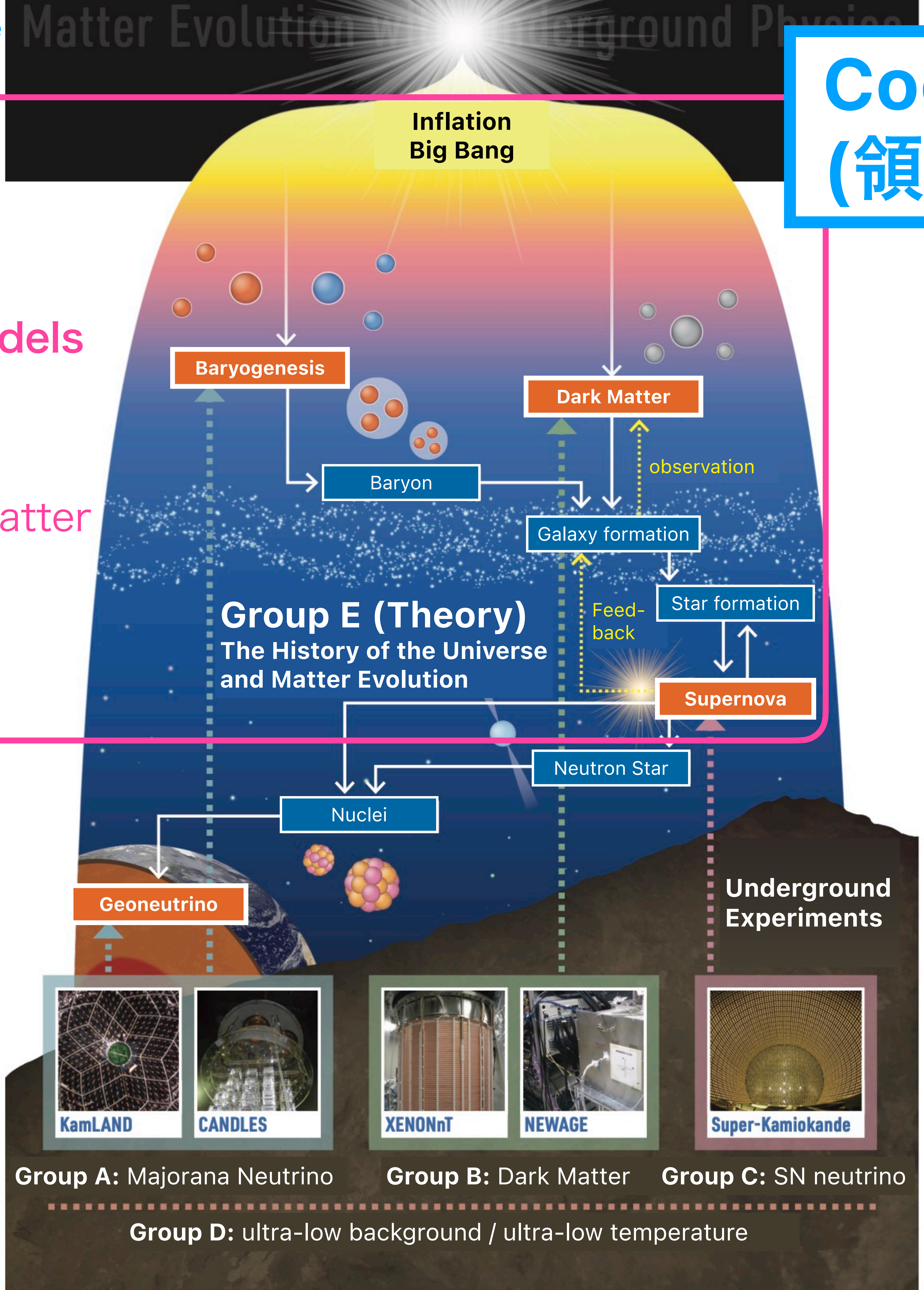

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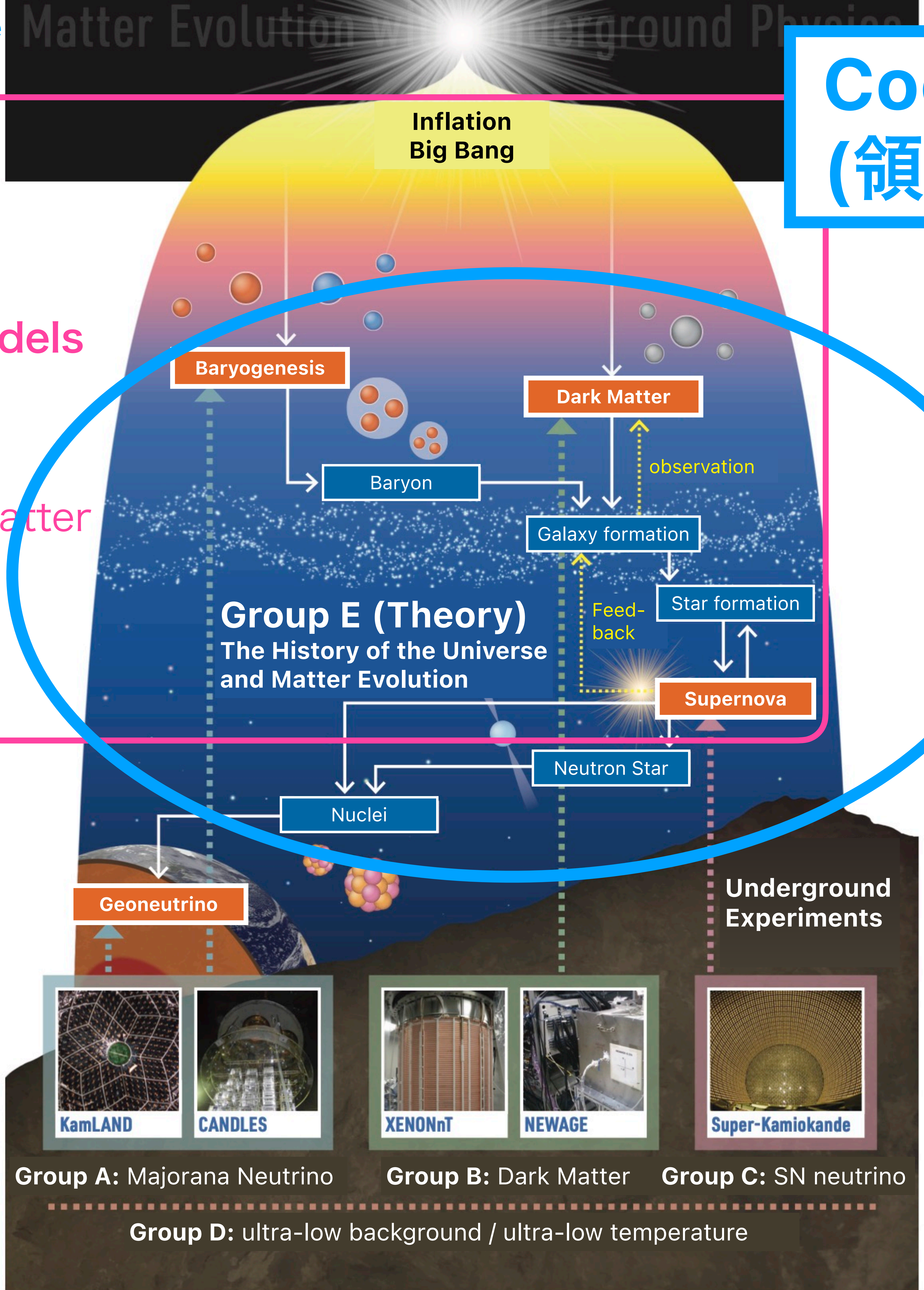

E01 + E02
Online Joint workshop (合同勉強会)

on BSM and SN

May 27, 2020.

K. Hamaguchi (**E01**)
H. Suzuki (**E02**)

Fig. from the pamphlet on the web page (translated)

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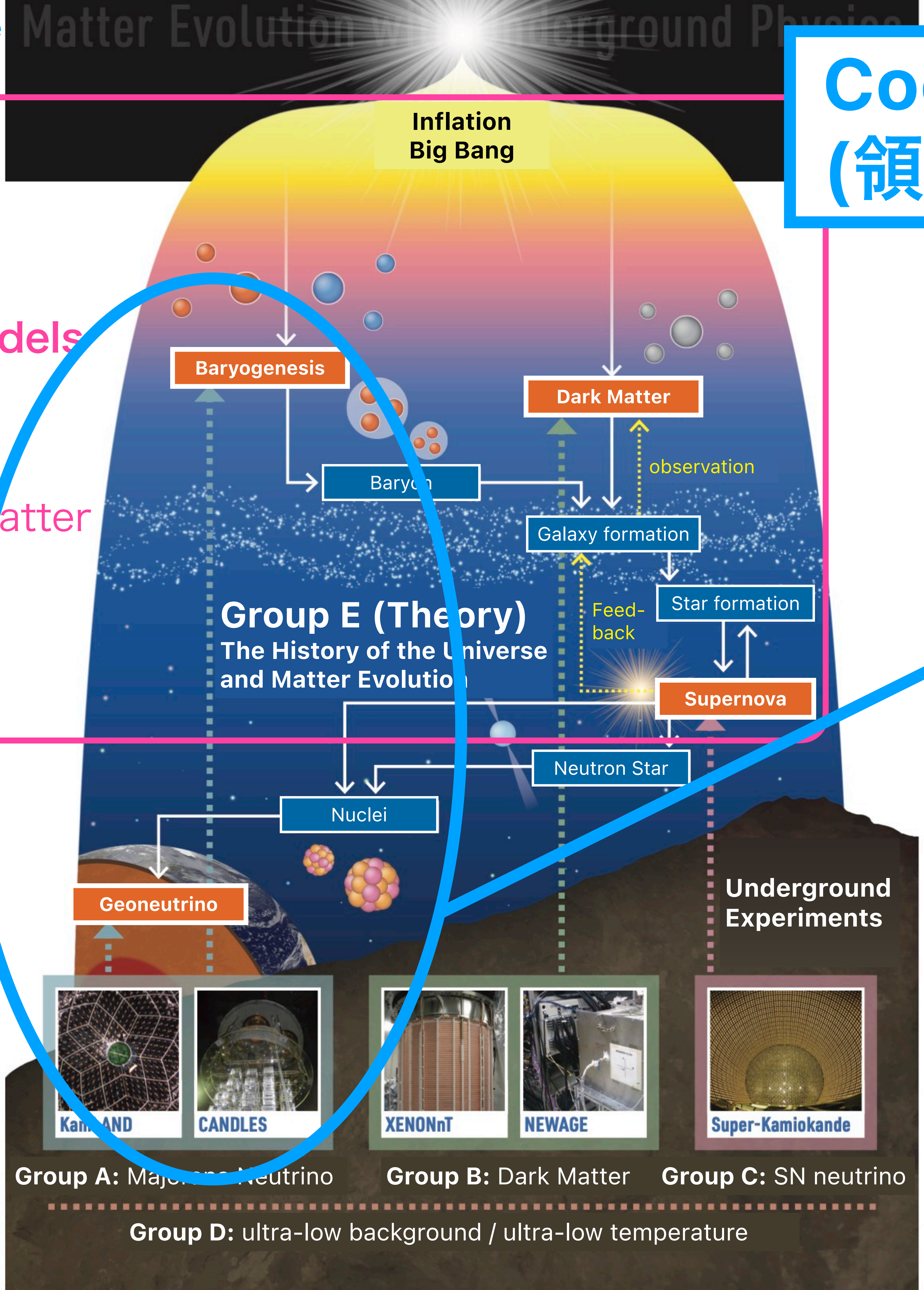

Online Workshop on $0\nu\beta\beta$ decay

Feb. 12, 15, 2021.

(>150 participants)

K. Hamaguchi (**E01**)

N. Hinohara (**A01** 公募)

W. Nakano (**E01**)

Fig. from the pamphlet on the web page (translated)

Cooperation in the Area (領域内連携)

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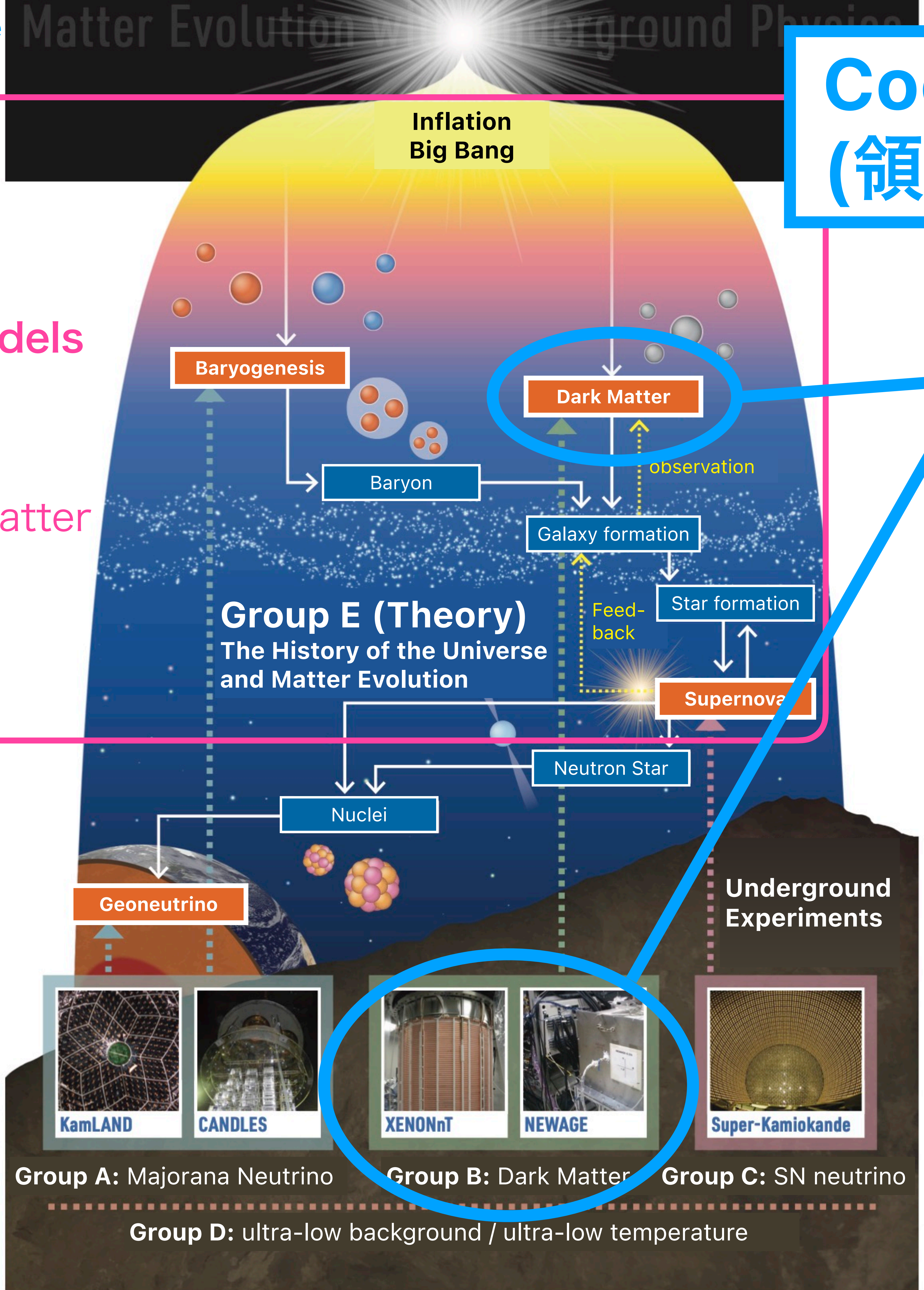

Collaboration on Migdal Effect.

[2009.05939, PTEP 2021]

K.Nakamura (**B02** 公募)

the previous talk

K.Miuchi (**B02**)

S.Kazama (**B01**)

Y.Shoji

M.Ibe

W.Nakano (**E01**)

Workshop

Nov.24 + Dec.9, 2020.

Fig. from the pamphlet on the web page (translated)

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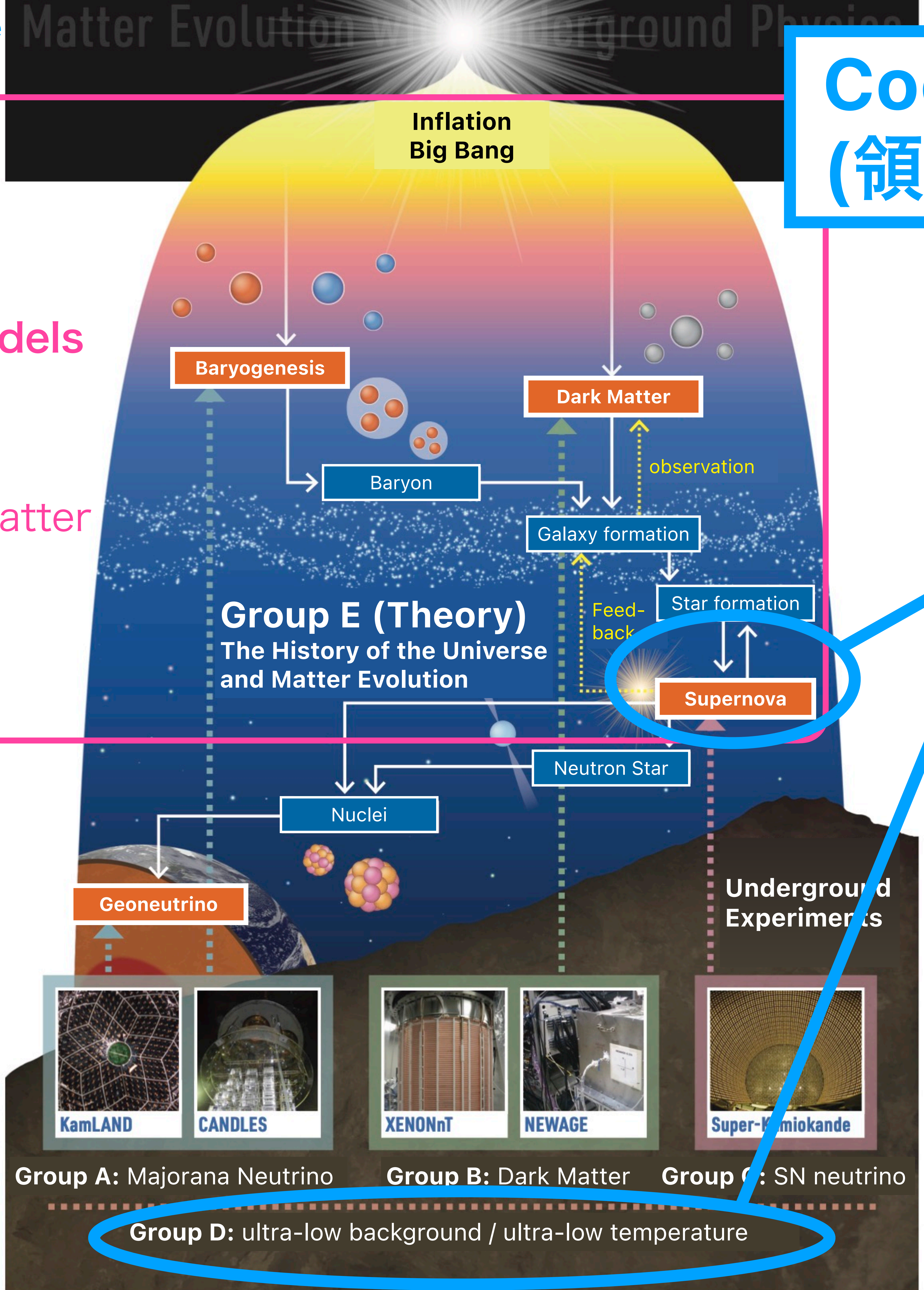

Collaboration on SN axion.

[2008.03924, JCAP 2020]

S.Ge
K.Hamaguchi (**E01**)
K.Ichimura (**D01**)
K.Ishidoshiro (**D02**)
Y.Kanazawa
Y.Kishimoto (**D02**)
N.Nagata
J.Zheng

(See below)

Supernova-scope

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

Supernova-scope

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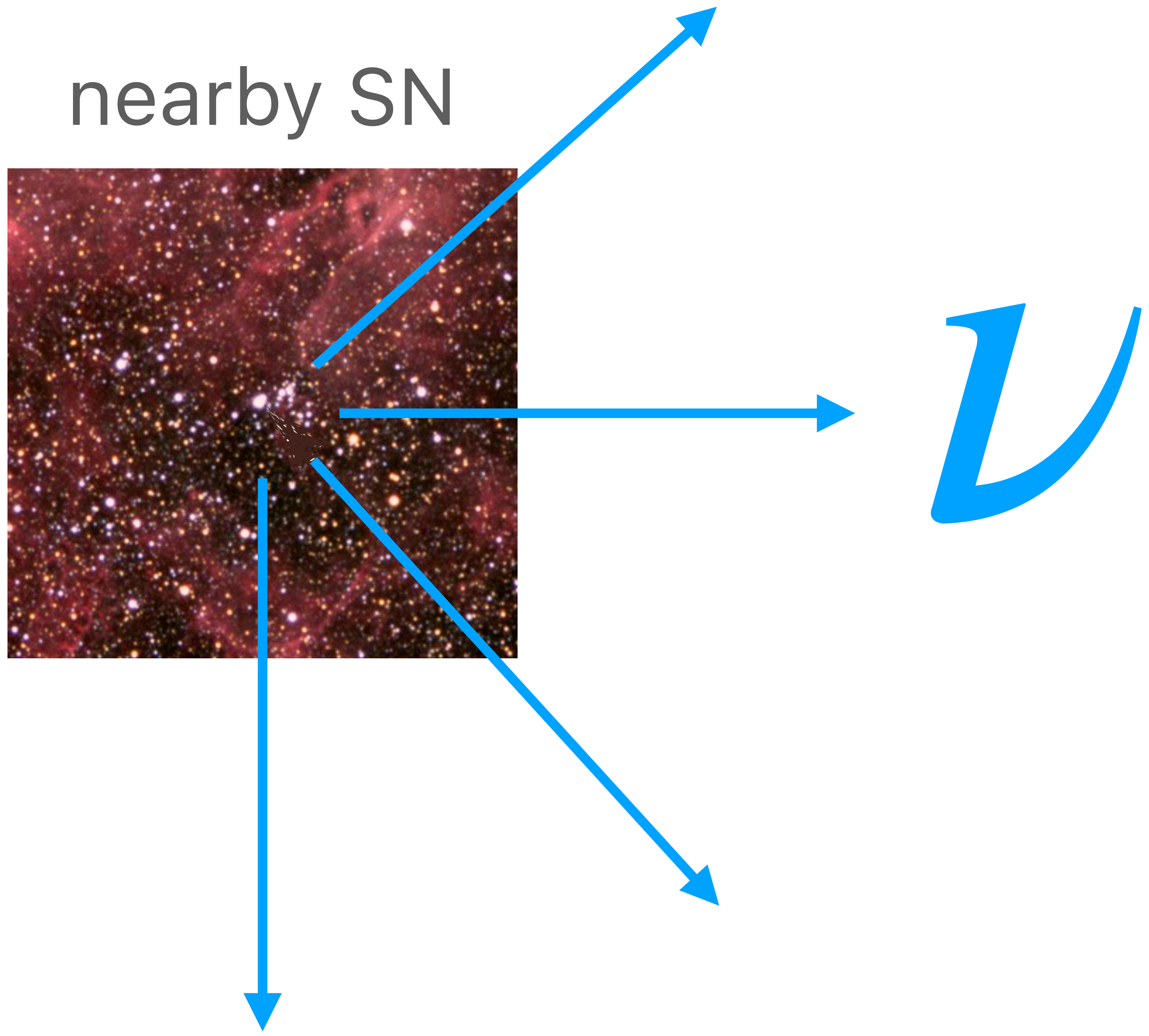
[arXiv:2008.03924] JCAP **11** (2020) 059.

nearby SN



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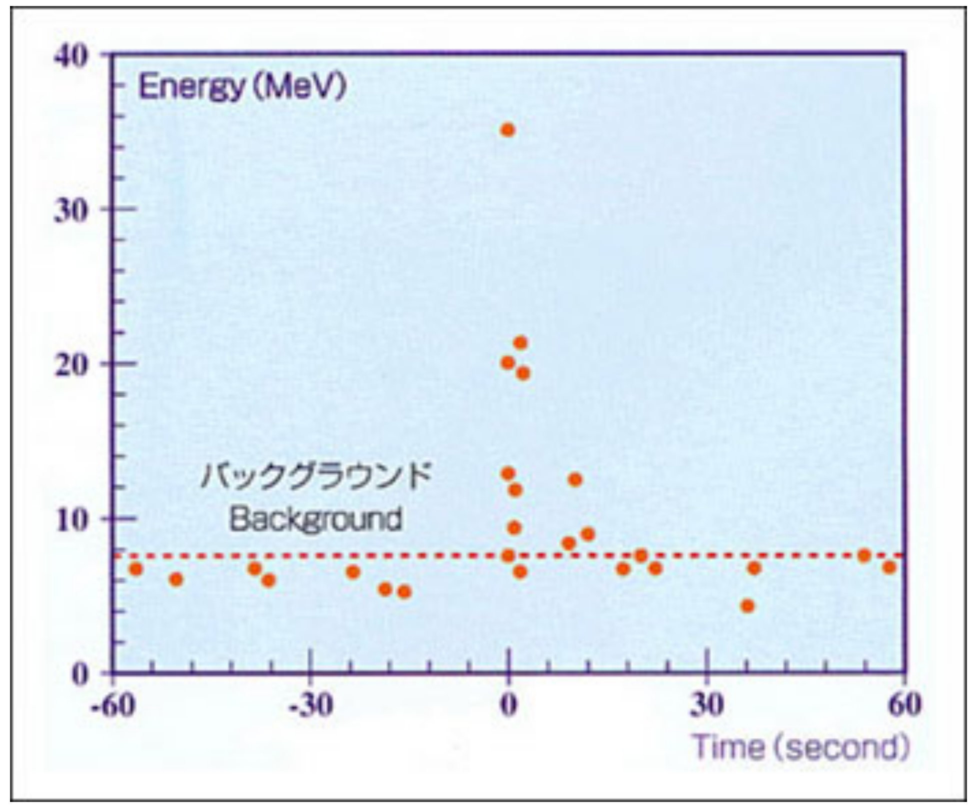
nearby SN

ν

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

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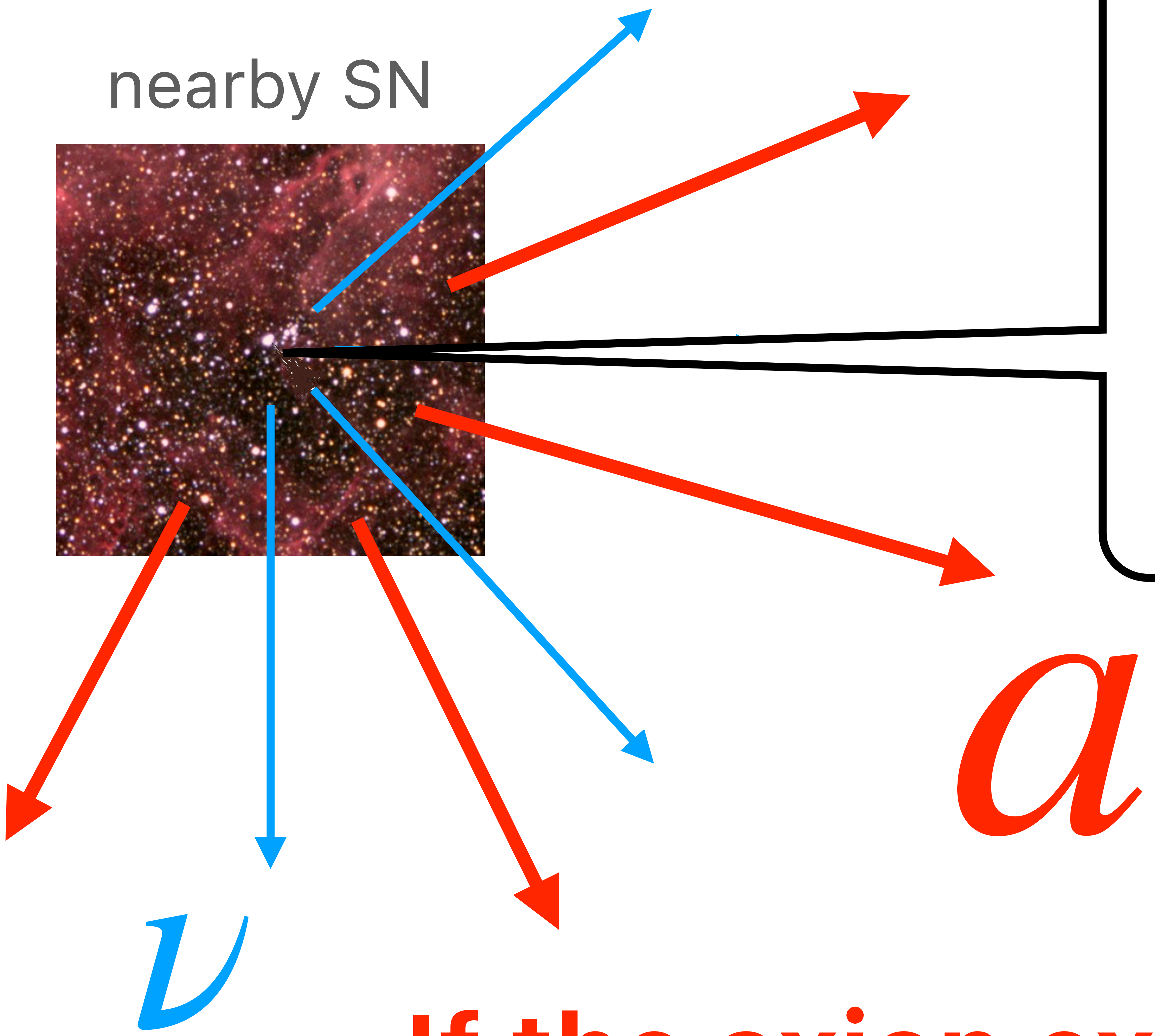
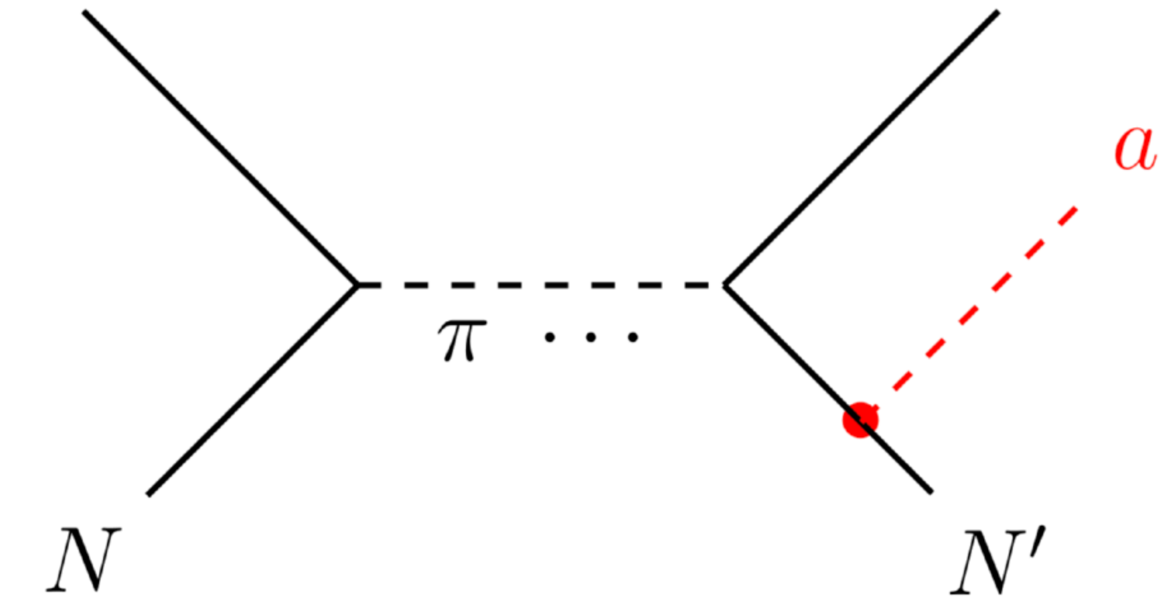
nearby SN



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

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



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

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

If the axion exists in nature,...

Supernova-scope

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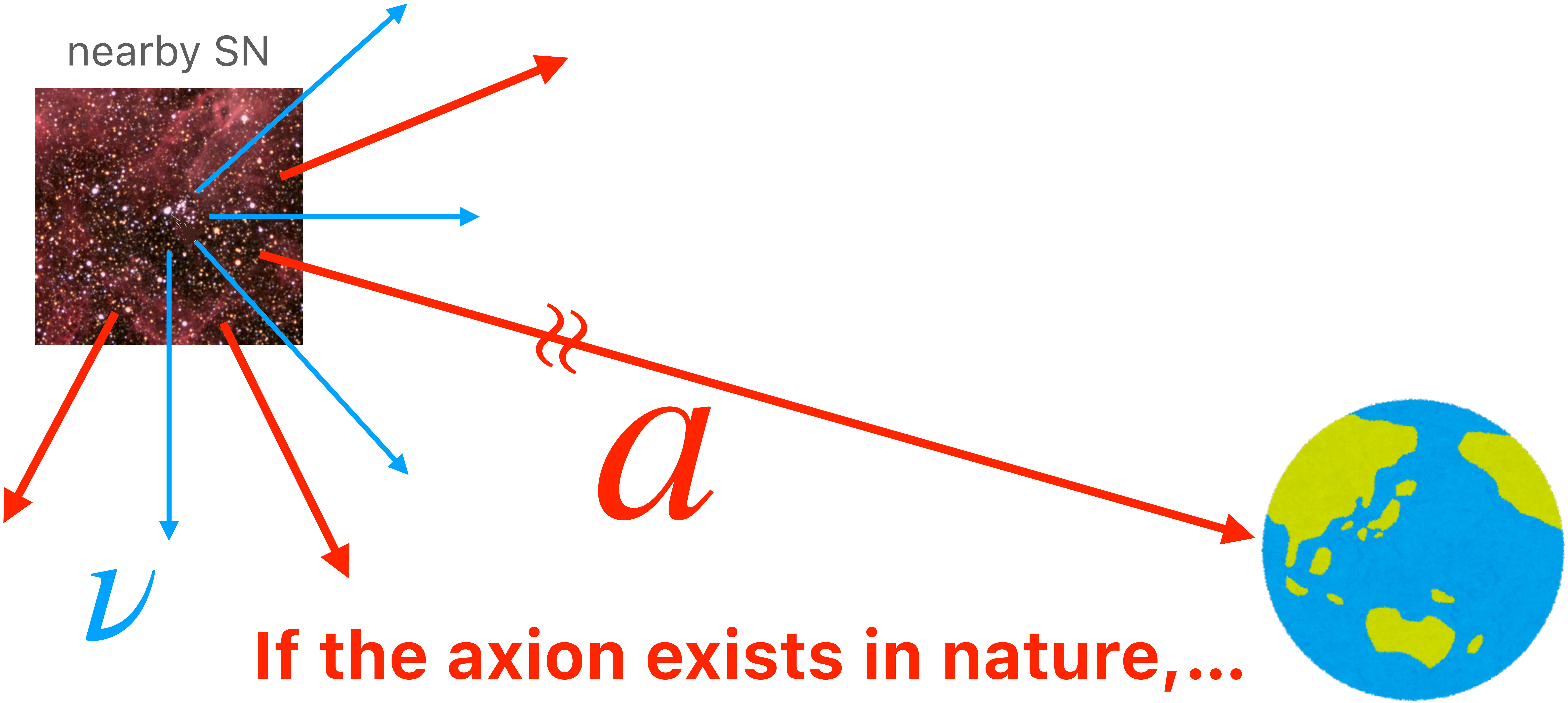

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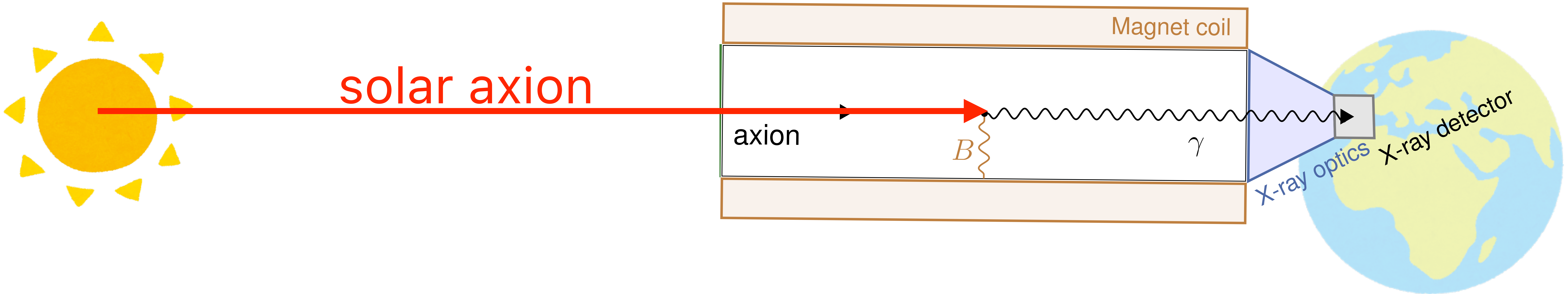
- Essentially the same as the Axion Helioscopes for the solar axion.



Axion Helioscopes

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

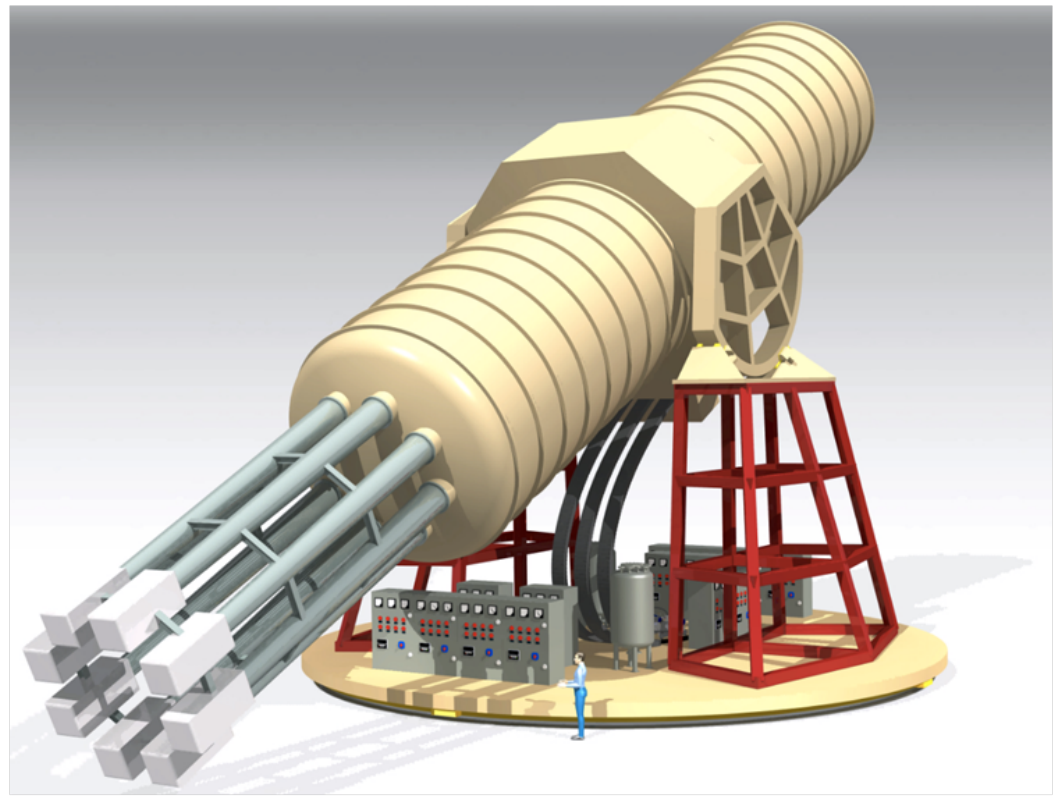
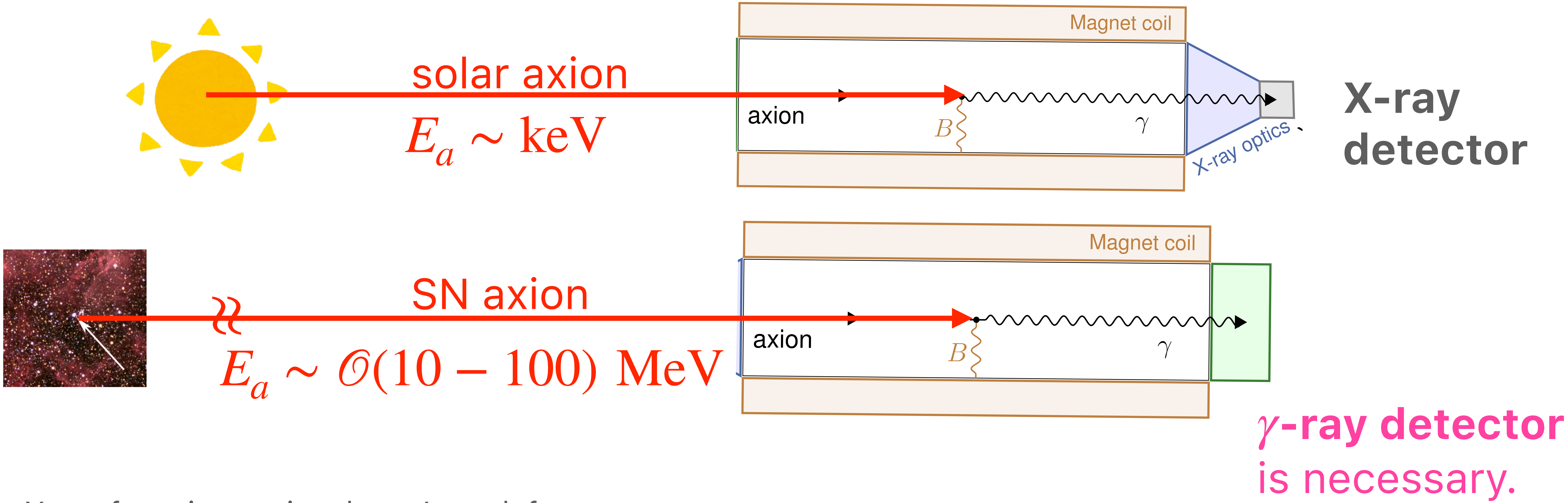


Fig. from IAXO homepage

Supernova-scope

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

- Essentially the same as the Axion Helioscopes for the solar axion.
- **But the axion energy is different.**



※ 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 below).

Supernova-scope

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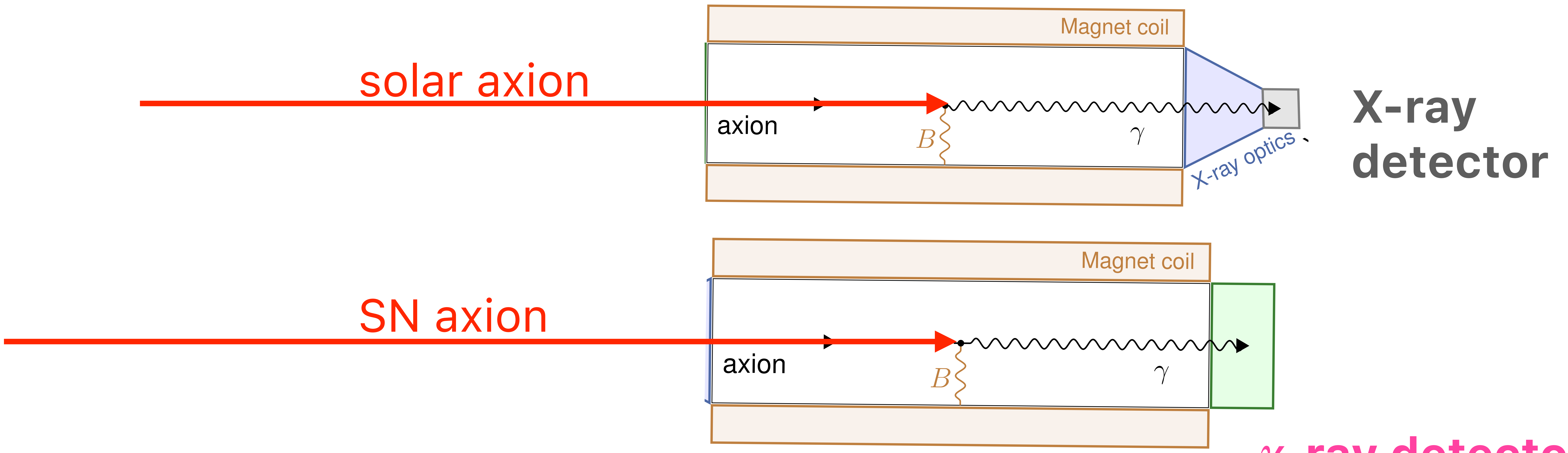

γ**-ray detector**
is necessary.

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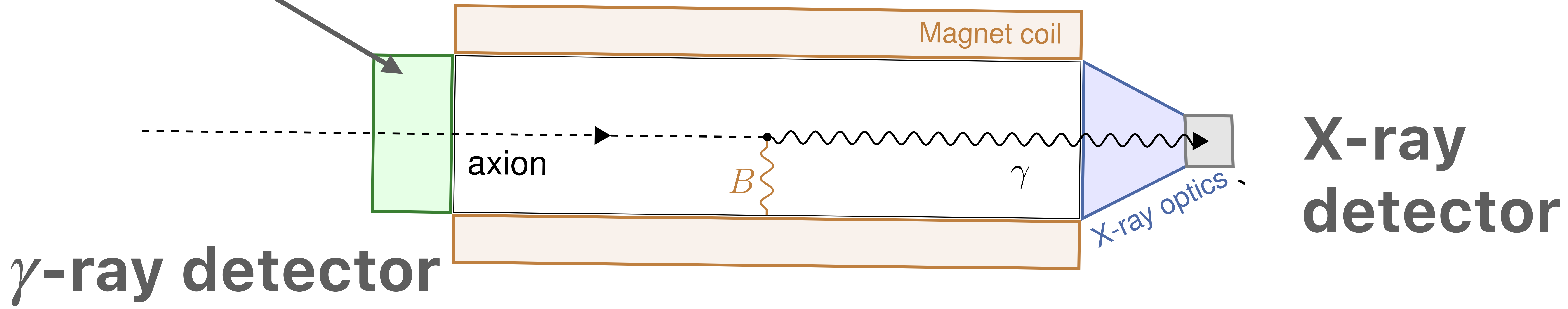
Supernova-scope

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



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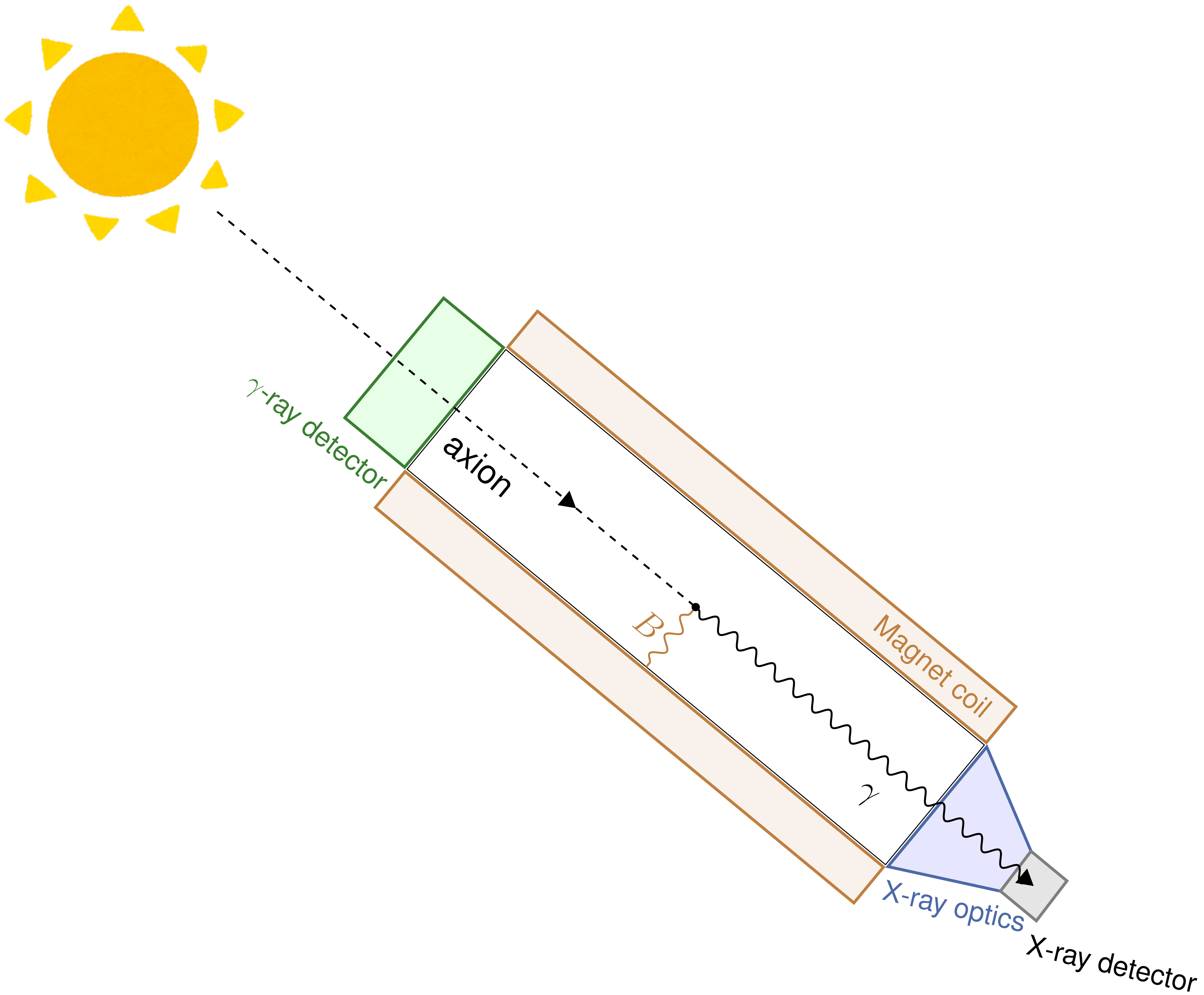
Idea: install a γ-ray detector at the opposite end to the X-ray detector.

Normal operation time: It works as an axion helioscope.



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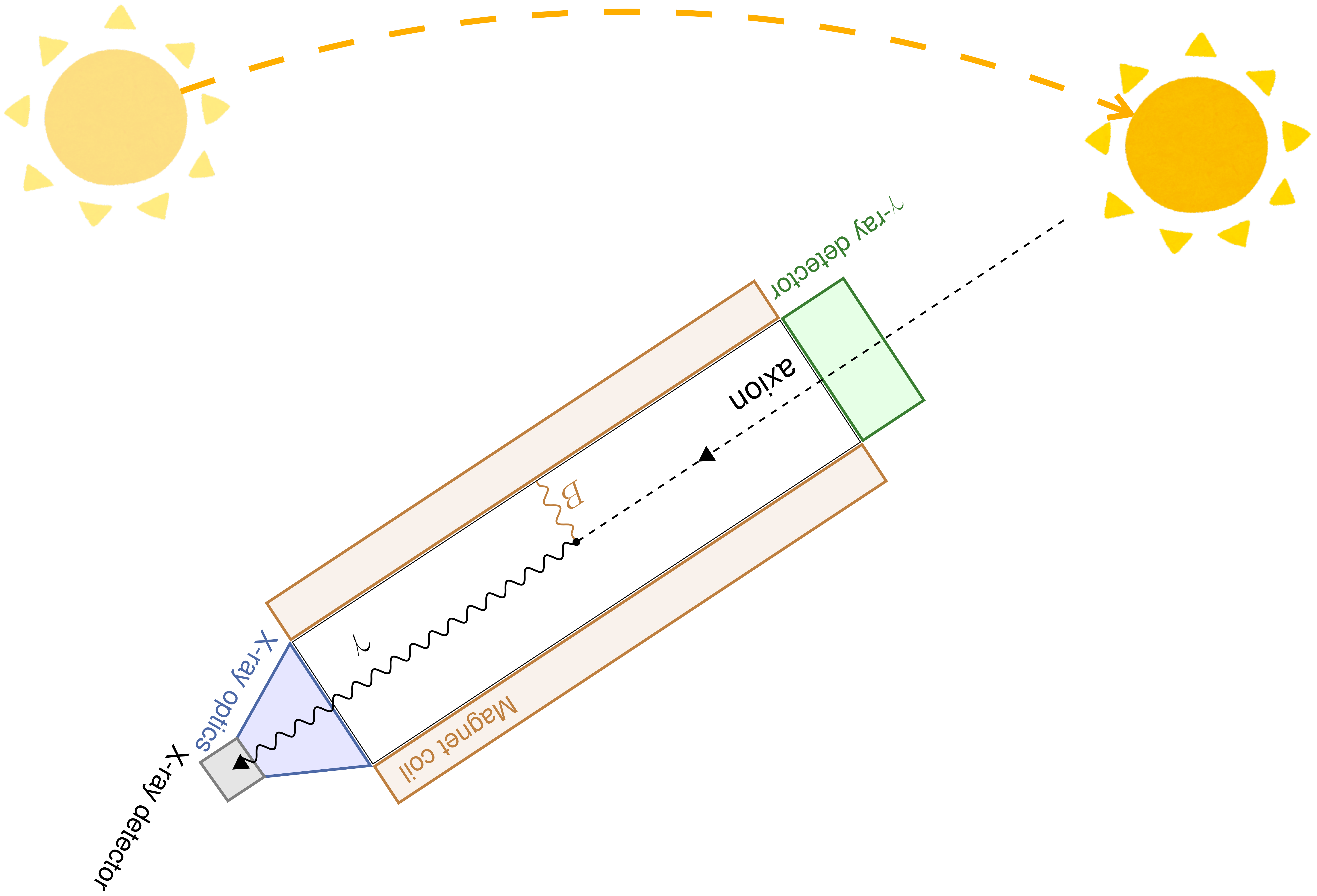

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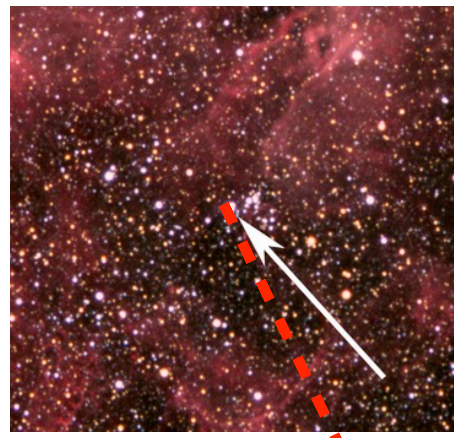
Supernova-scope

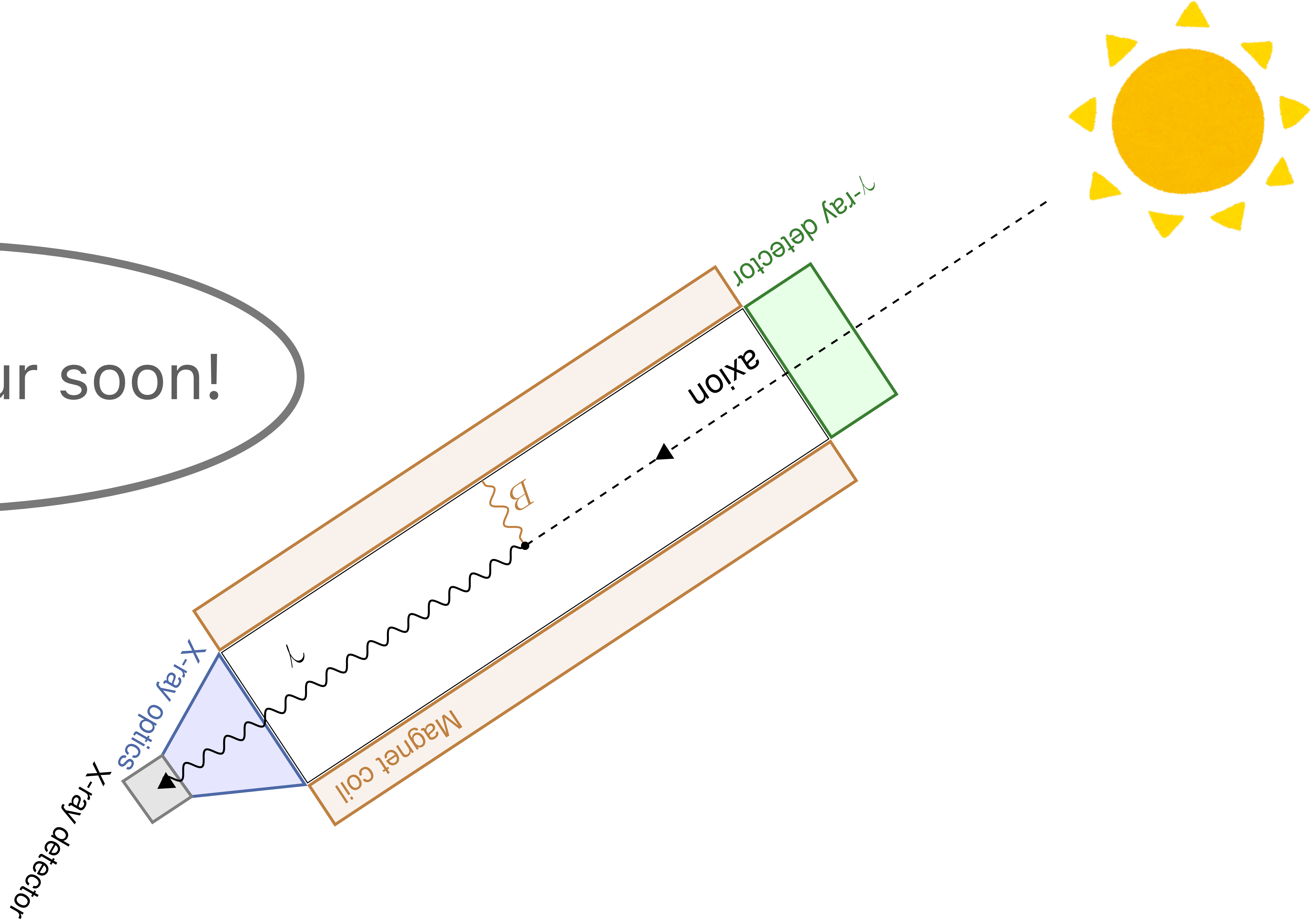
Once a pre-SN neutrino alert is received,



SN may occur soon!

pre-SN ν
alert

SNEWS



SNEWS collaboration [2011.00035]
For a review of pre-SN neutrinos,
see, e.g., C.Kato, K.Ishidoshiro, T.Yoshida [2006.02519].

Supernova-scope

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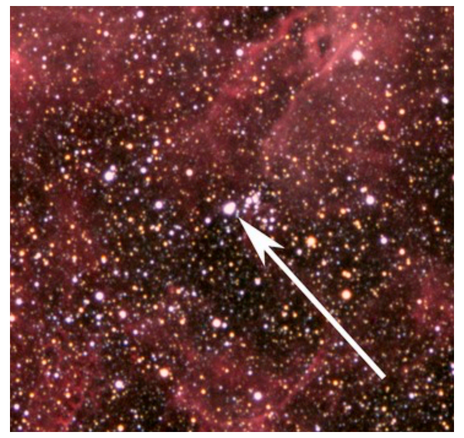

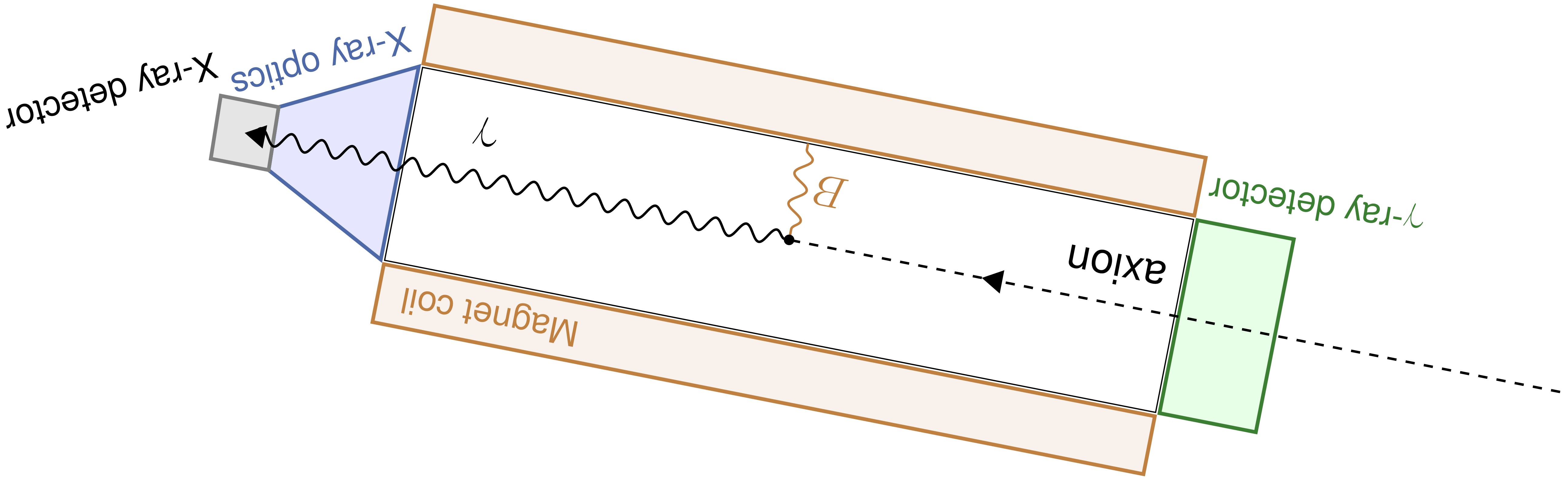

Supernova-scope

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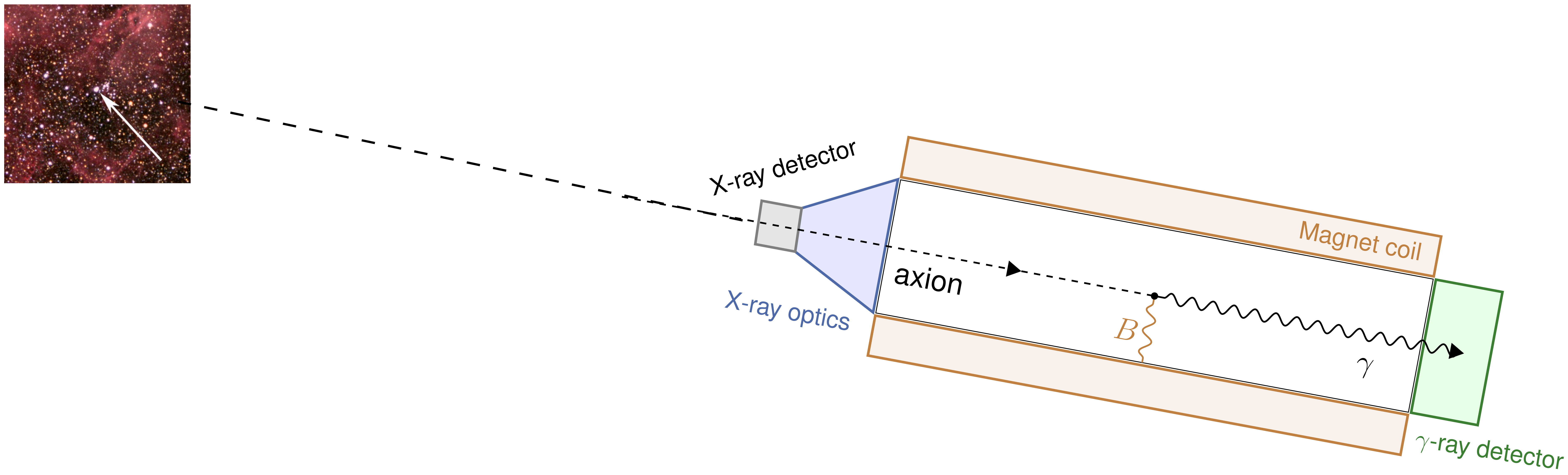


SN axion detection!

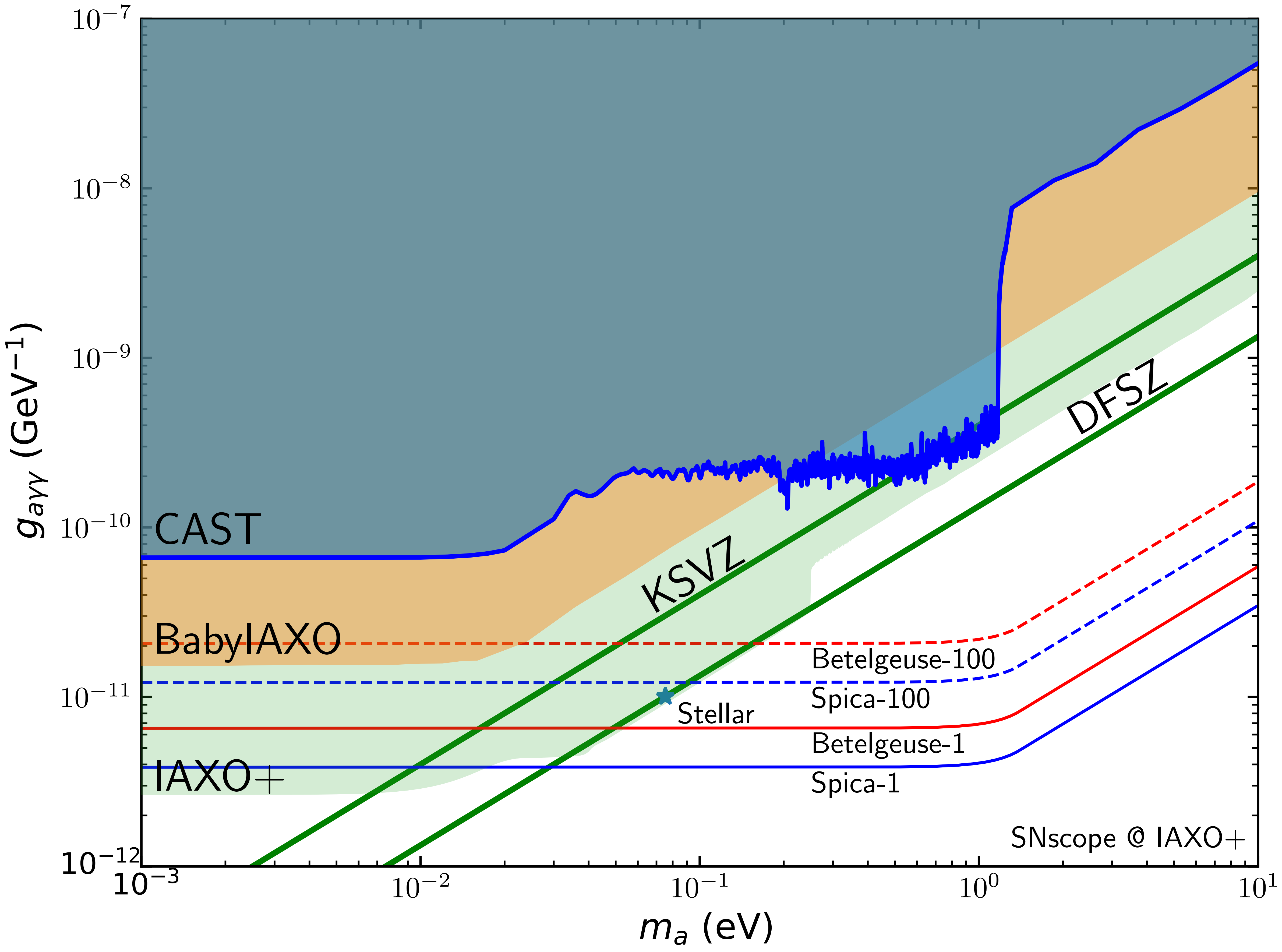
S.Ge, K.Hamaguchi, K.Ichimura, K.Ishidoshiro, Y.Kanazawa, Y.Kishimoto, N.Nagata, J.Zheng.
[arXiv:2008.03924] JCAP **11** (2020) 059.

Supernova-scope

We found that,

if a **nearby SN (< a few 100 pc)** occures,

SN-scopes based on the next-generation axion helioscopes (such as IAXO) have potential to detect **O(1-10) SN axions.**



For more details, see

- The **backup** slides
- **YouTube** (15 min.) by Jiaming Zheng: https://t.co/qSxjCNwiUL?amp=1
- **YouTube** (60 min.) by KH: https://t.co/UIP95kfPOt?amp=1

Fig. from the pamphlet on the web page (translated)

E01

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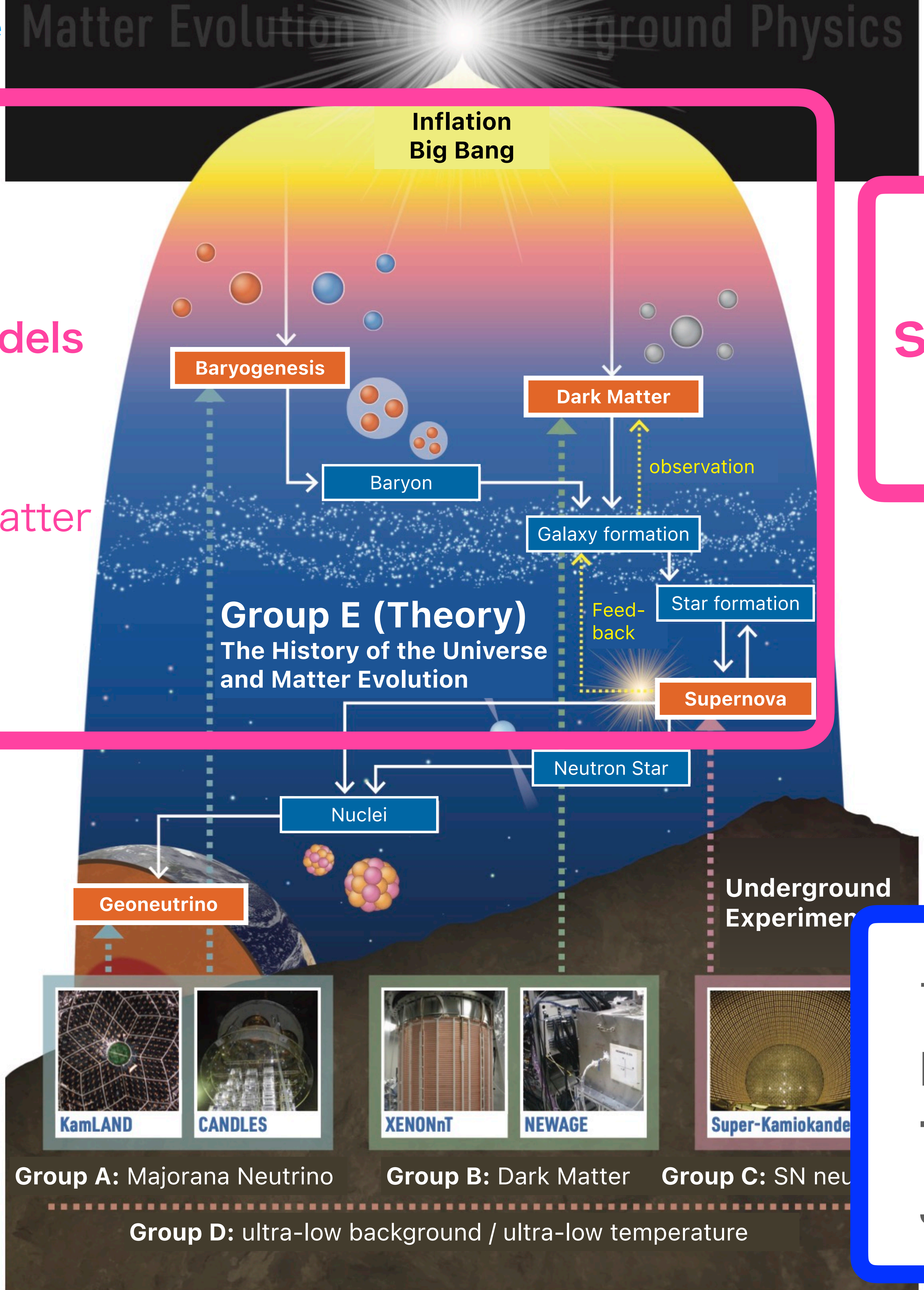
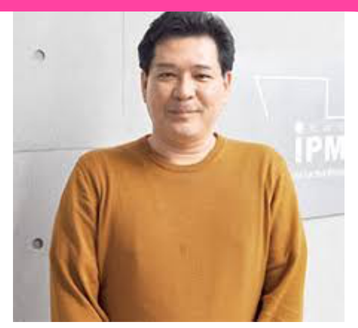
unravelling the origin of matter



1. **Matter > anti-matter** and neutrino mass
2. **Dark Matter**
3. New particle physics models and the evolution of the early universe

Members

Koichi Hamaguchi (Tokyo U., PI)



Shigeki Matsumoto
(IPMU, co-i

see the next talks!

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(Tokyo U., postdoc, 2020-)

+ Publicly offered research (公募研究)

Kentarou Mawatari
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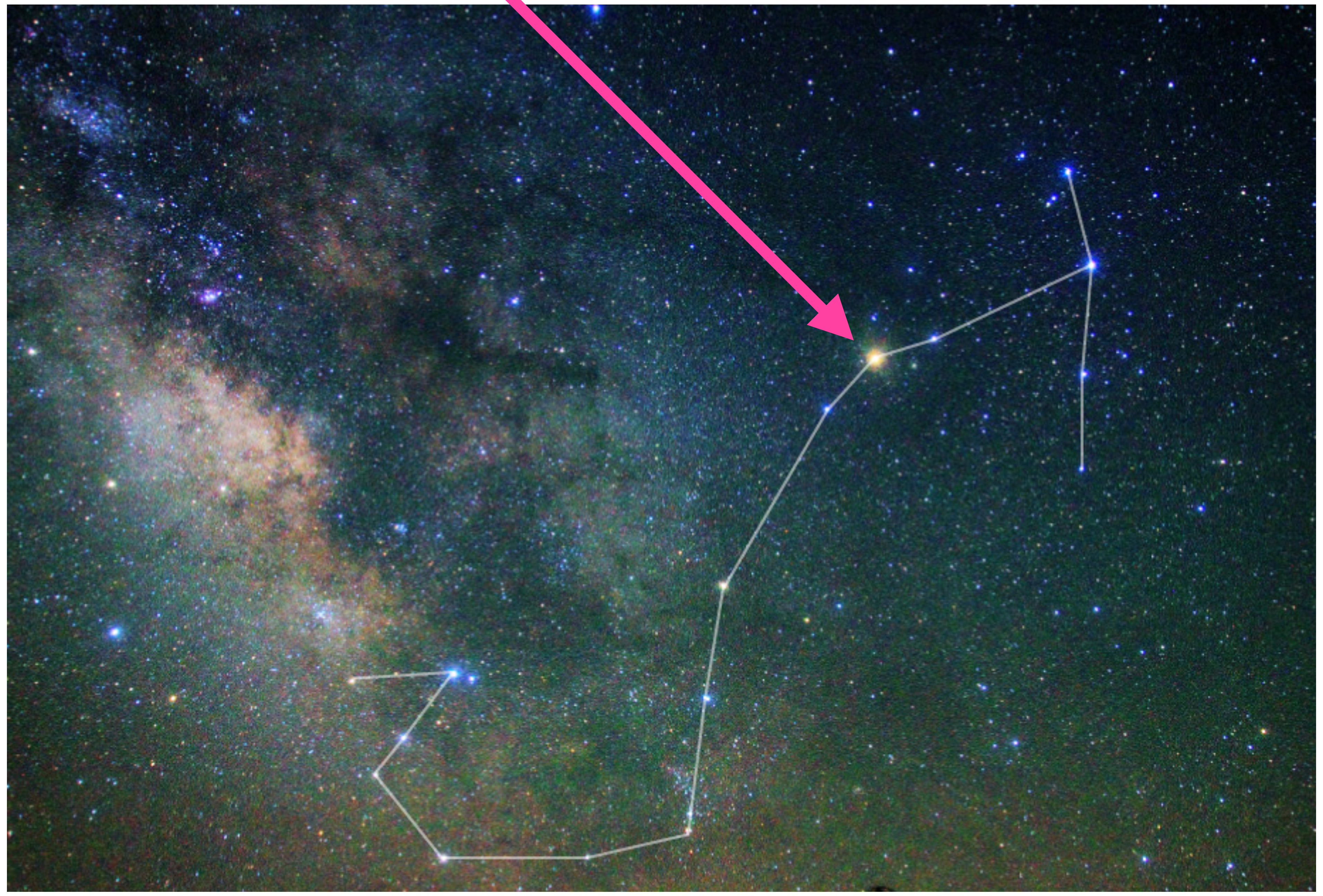
see the next talks!

- **Backup**

Nearby SN progenitor candidates

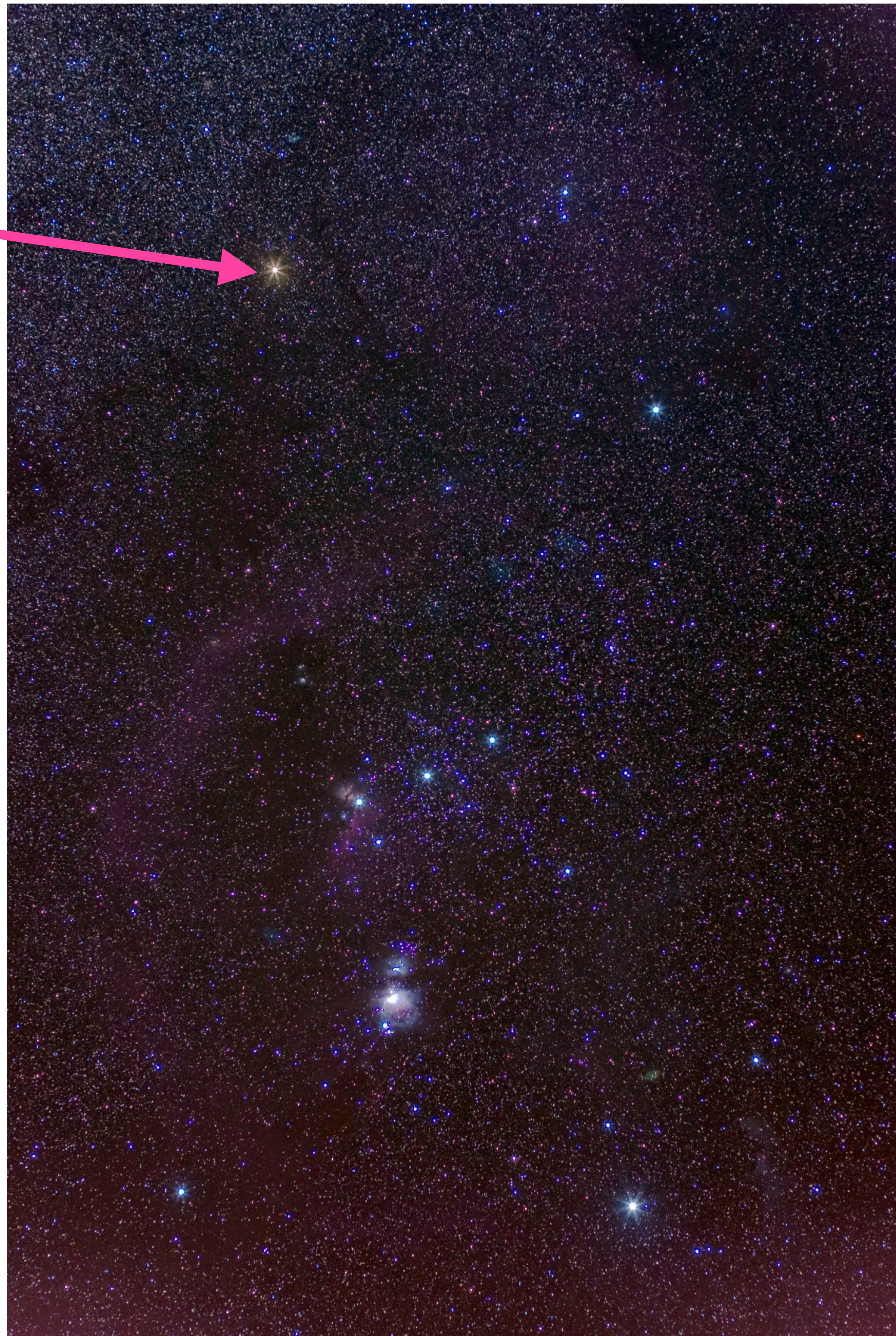
Antares
(~ 170 pc)



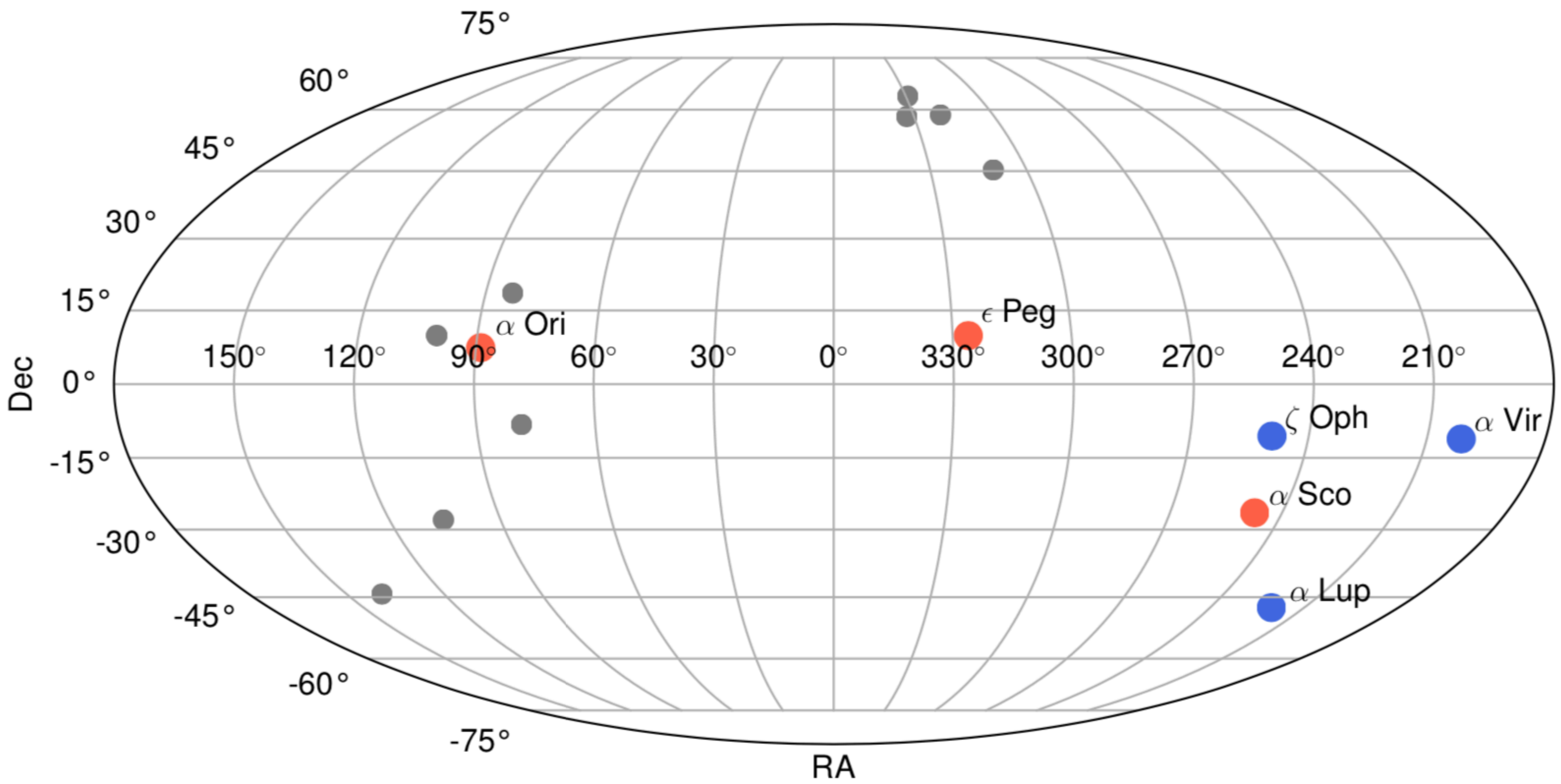
https://www.civillink.net/esozai/

Betelgeuse
(~ 200 pc)

Wikipedia



Nearby SN progenitor candidates



● ● $d < 250$ pc

● $d > 250$ pc

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

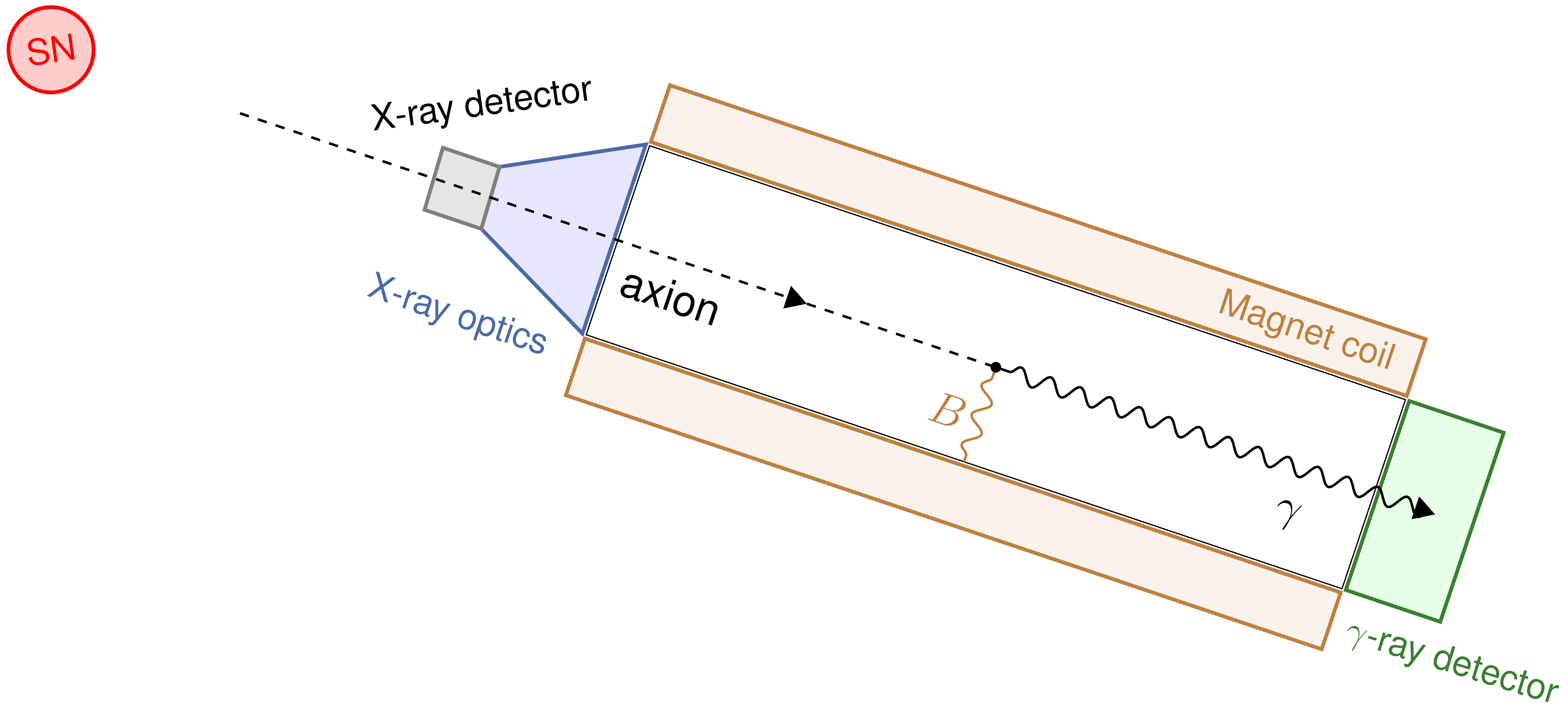
HIP	Common Name	Distance (pc)	Mass ($M_\odot$)	RA (J2000)	Dec (J2000)
65474	Spica/α Virginis	77(4)	11.43 ± 1.15 [79]	13:25:11.58	−11:09:40.8
81377	ζ Ophiuchi	112(3)	20.0 [80]	16:37:09.54	−10:34:01.5
71860	α Lupi	142(3)	10.1 ± 1.0 [81]	14:41:55.76	−47:23:17.5
80763	Antares/α Scorpii	170(30)	11–14.3 [82]	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

Pre-SN neutrino

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

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

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



Pre-SN neutrino

Take the help of the pre-SN neutrinos.

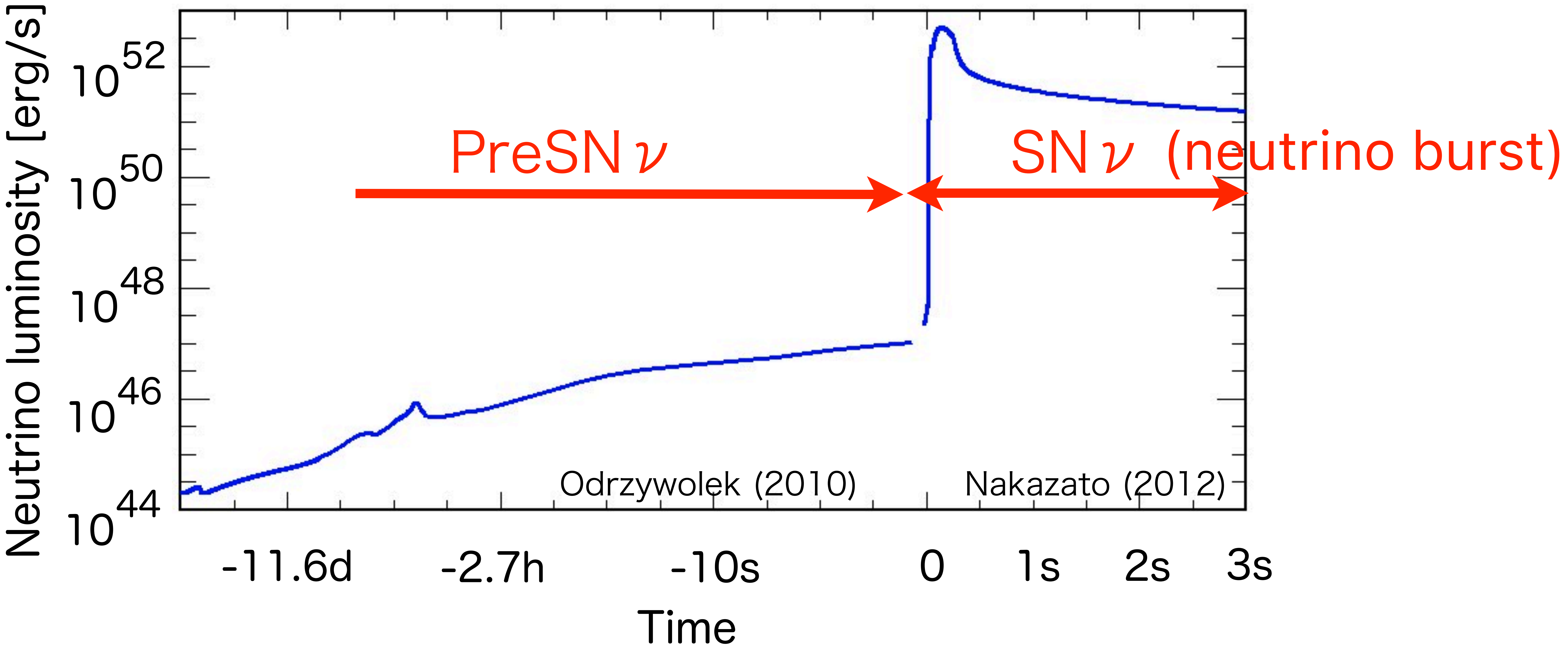
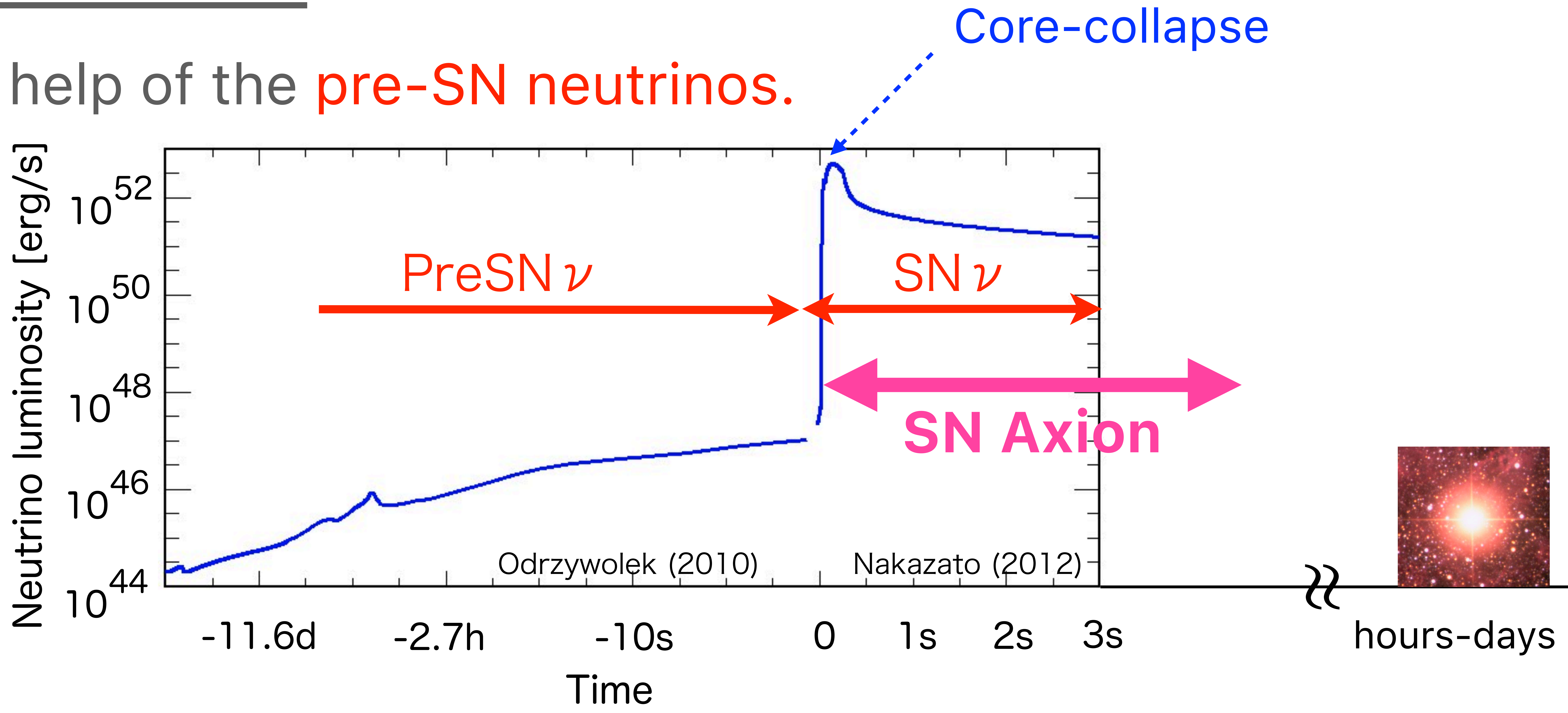


Figure from K.Ishidoshiro's talk in 2019.
https://www.lowbg.org/ugnd/workshop/sympo_all/201903_Sendai/

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

Pre-SN neutrino

Take the help of the pre-SN neutrinos.



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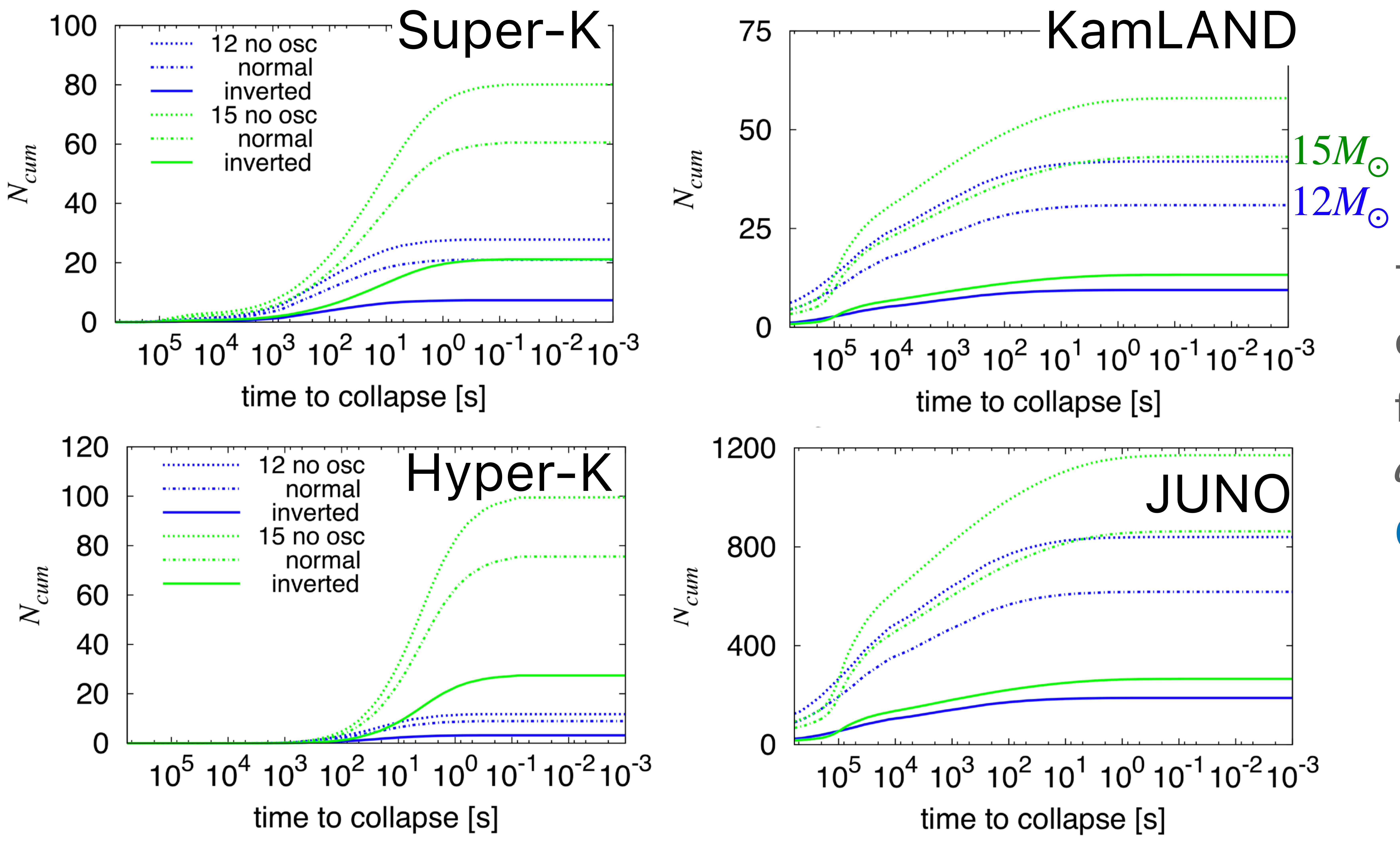
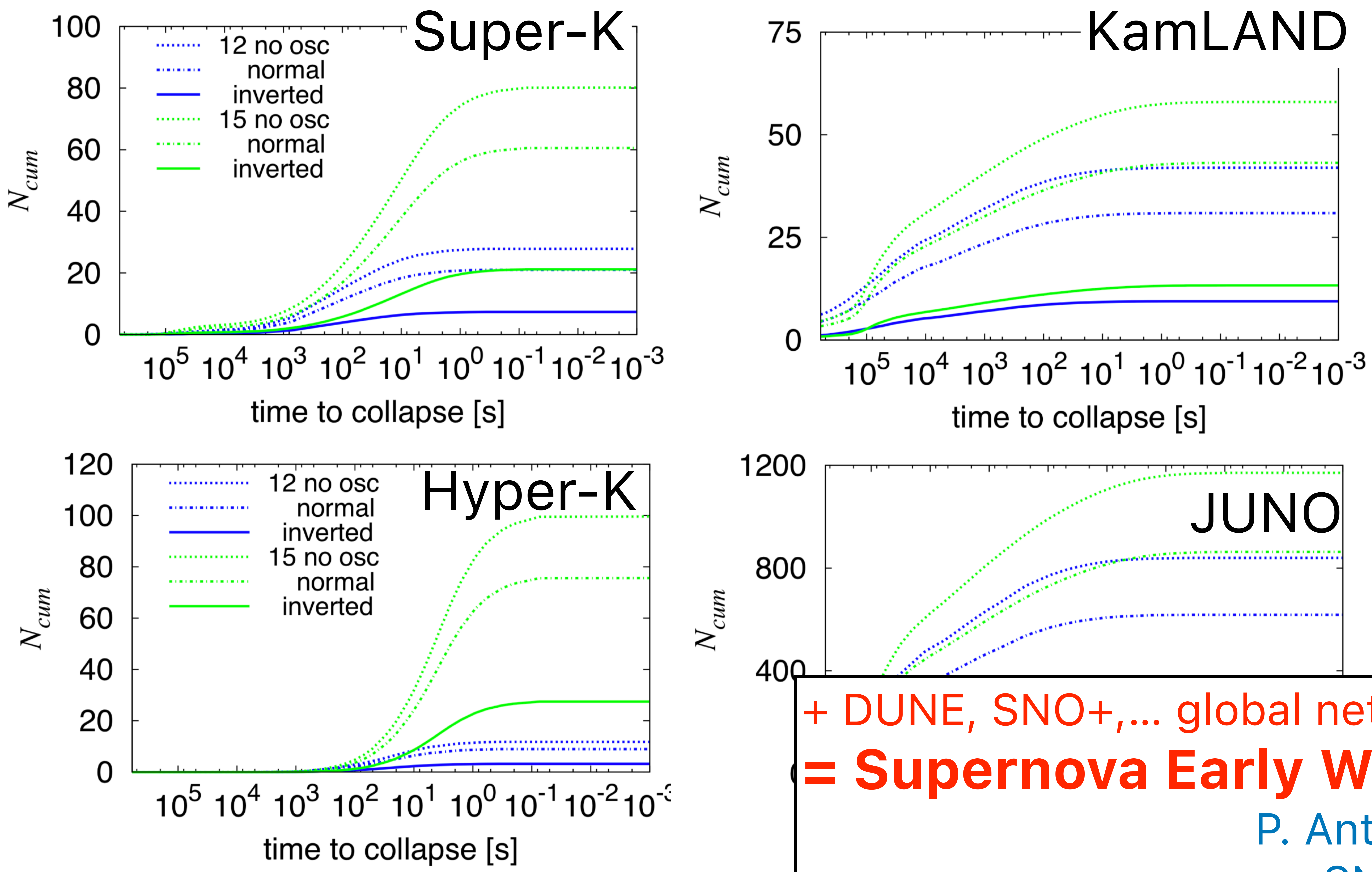
Pre-SN neutrino



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]

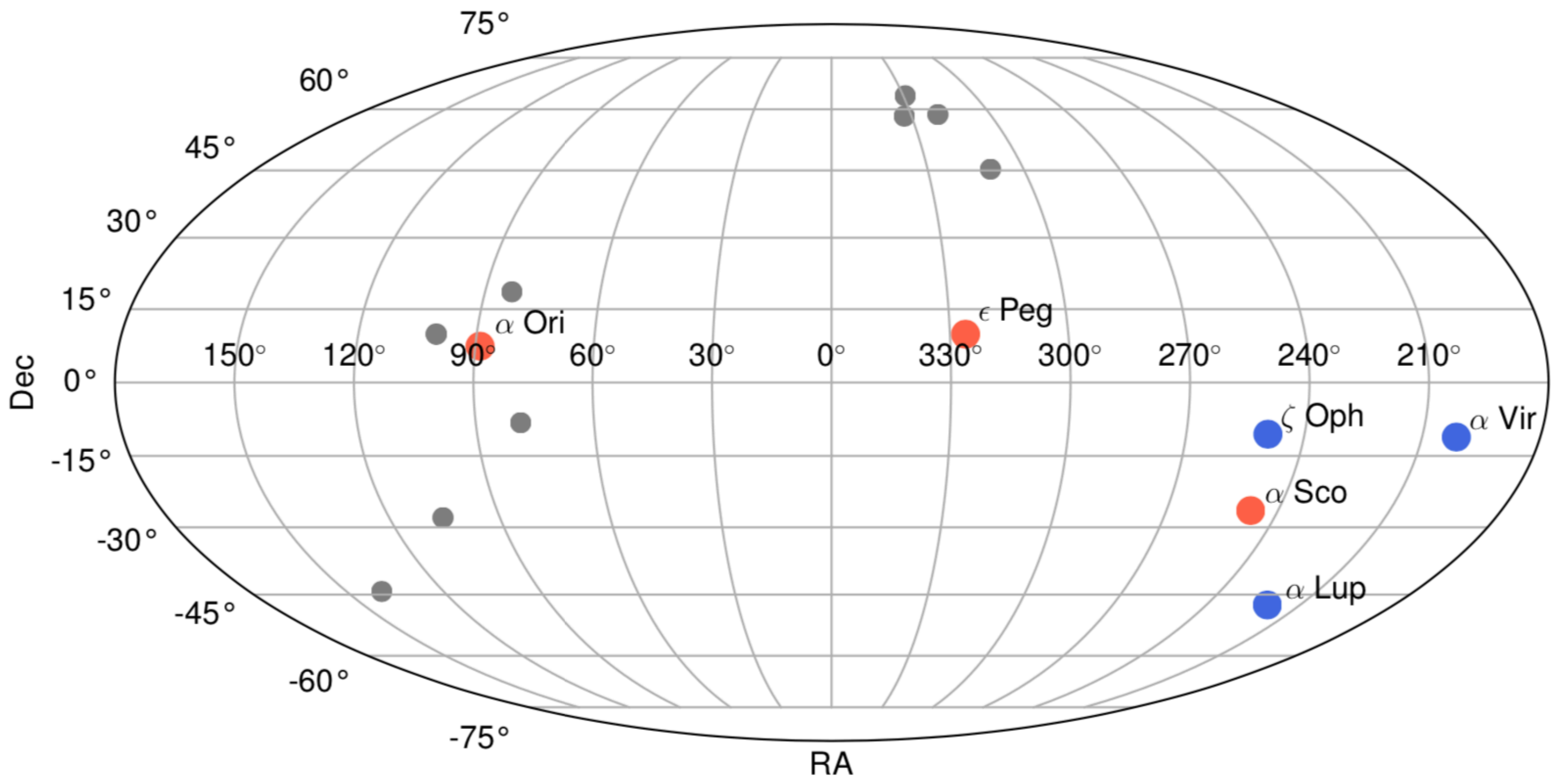
Pre-SN neutrino

- 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.

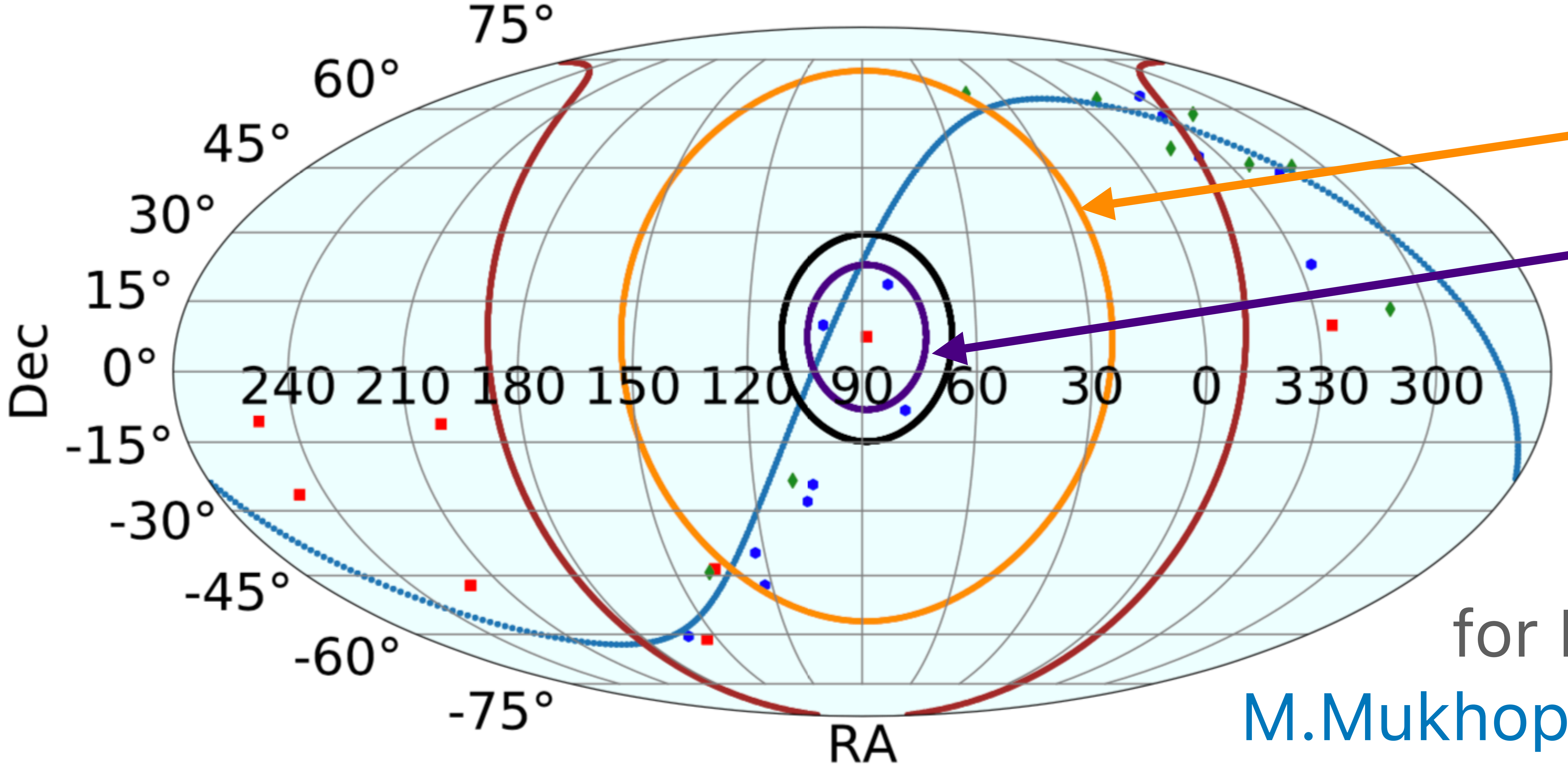
$M > 10M_\odot$ only.



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.



t = -1.0 hour

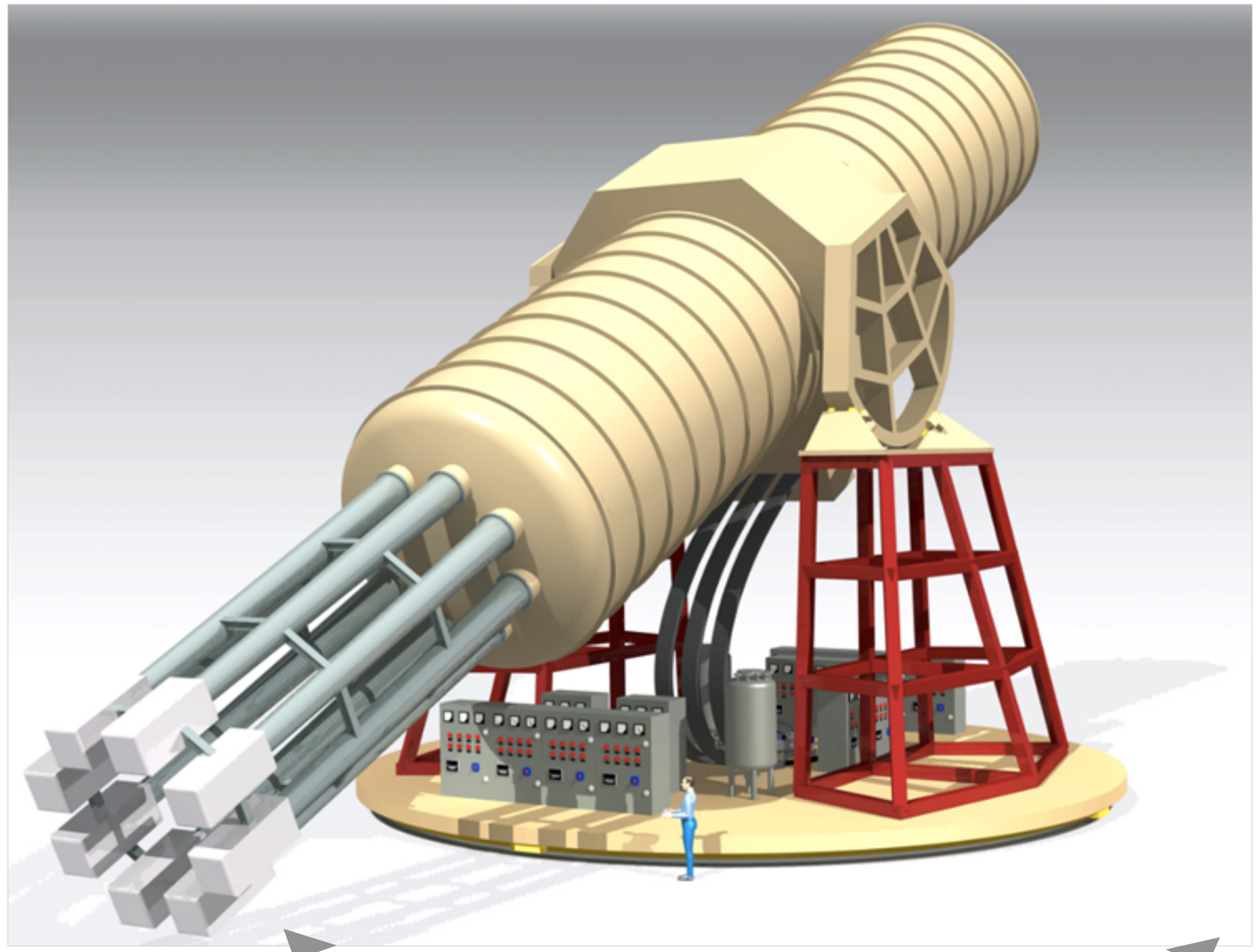
$\bar{\nu}_e + p \to e^+ + n$

for Betelgeuse, $t = -1.0$ hour.

M.Mukhopadhyay et.al., [2008.03924]

Observation time fraction

Fig. from IAXO homepage



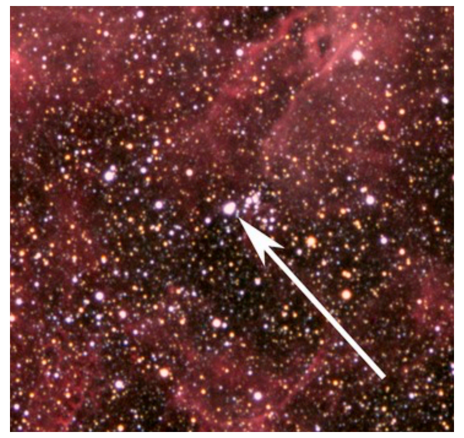
$$-\theta_{\max} \leq \theta \leq +\theta_{\max}$$

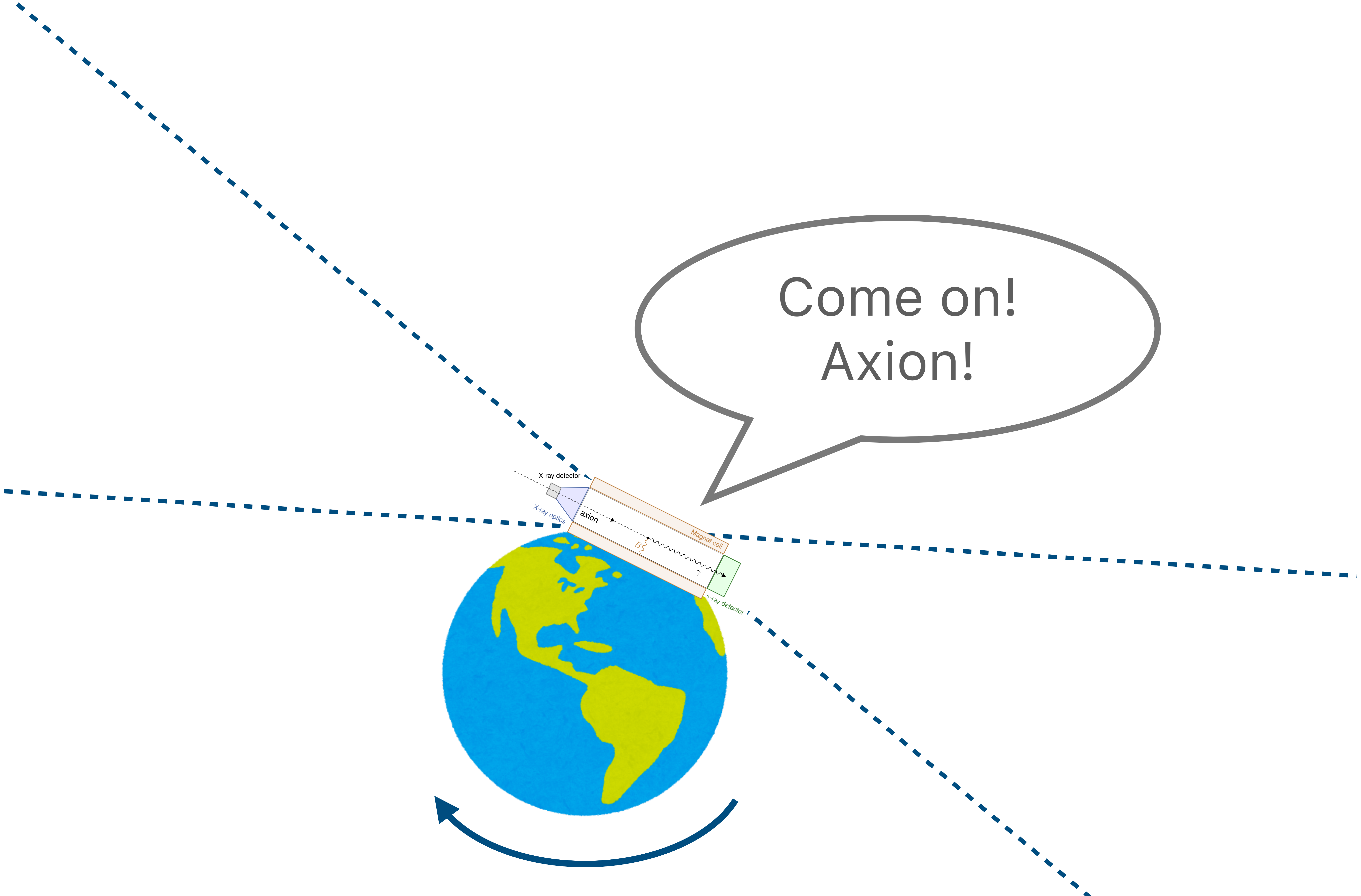
$$0 \leq \phi \leq 360^\circ$$

maximum elevation:

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

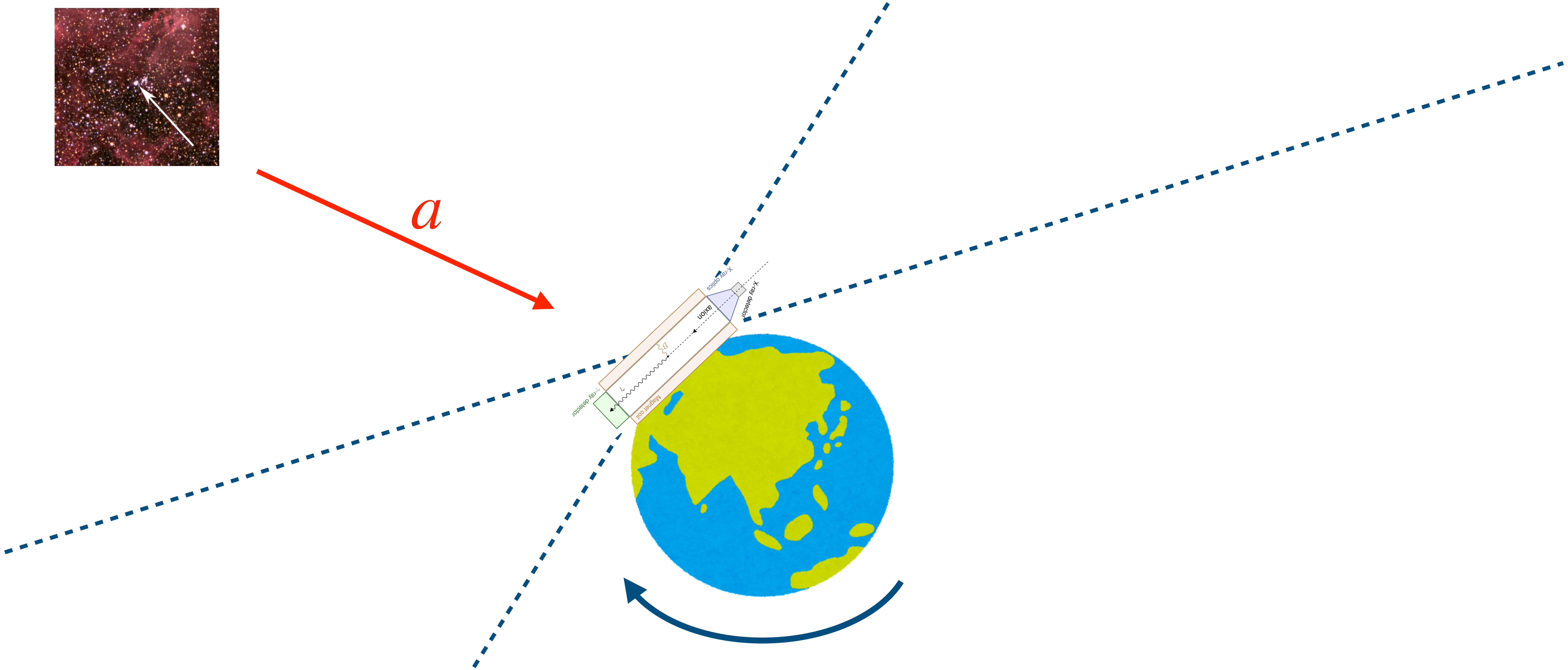
Observation time fraction





Observation time fraction

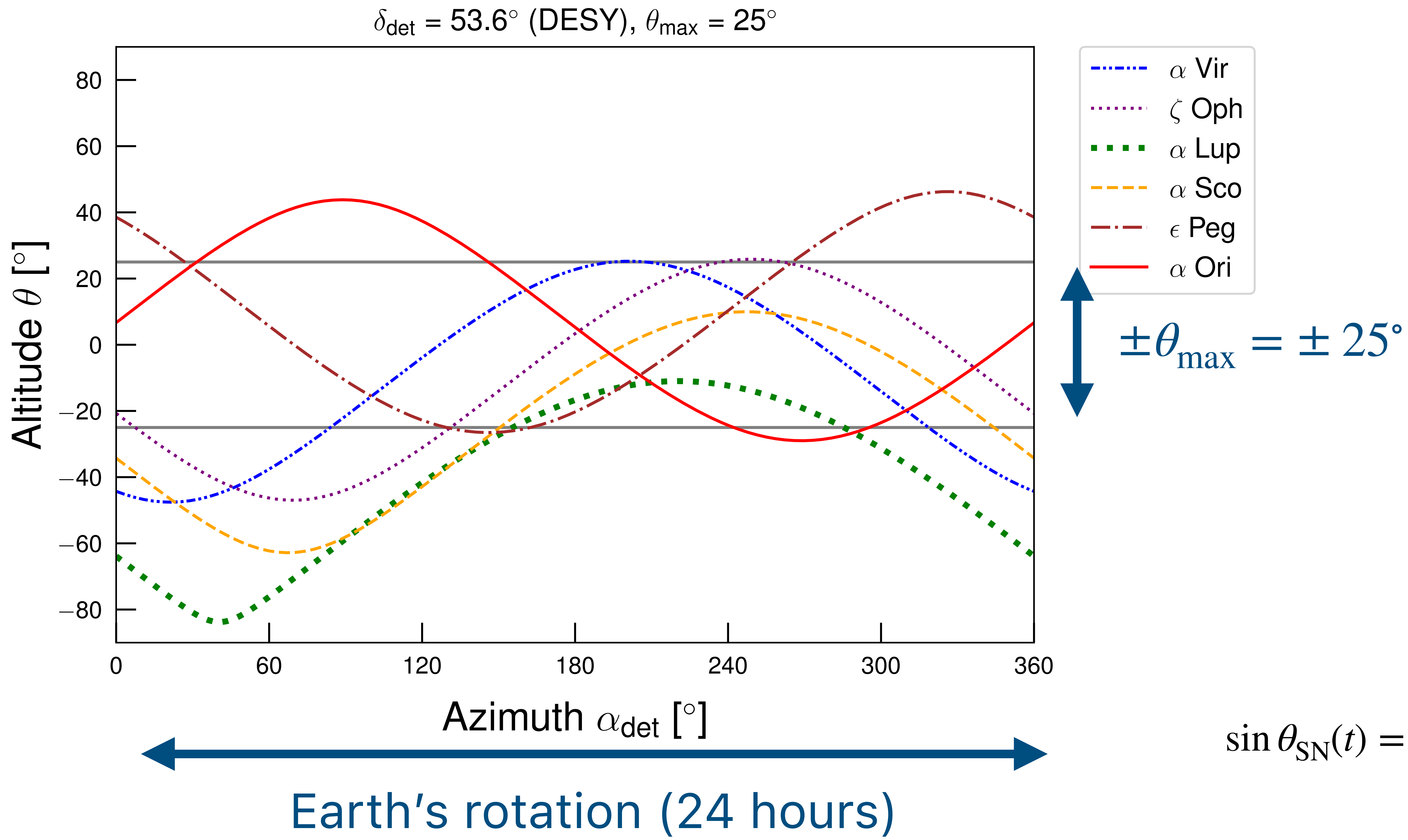
but if you are unlucky,...

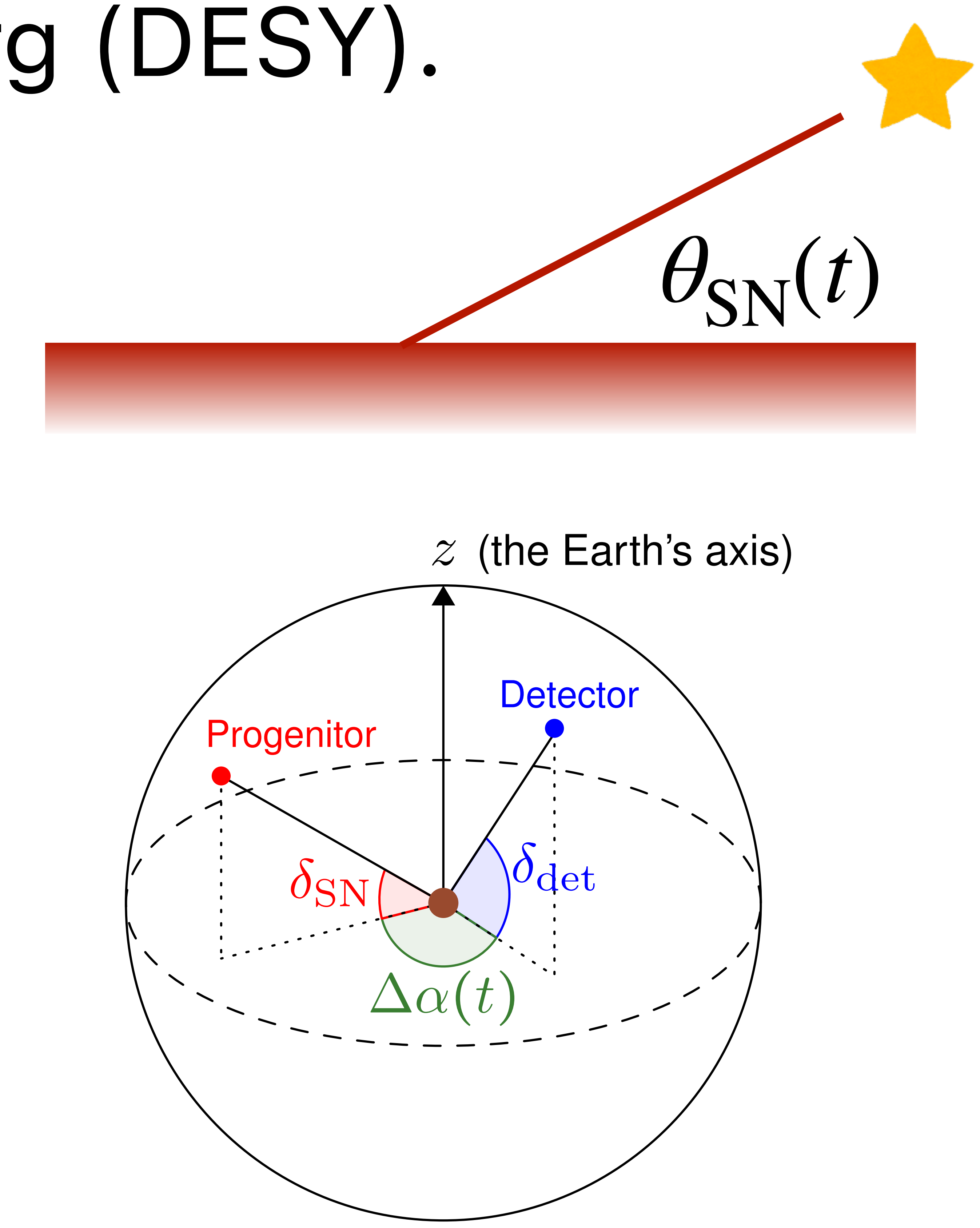


Observation time fraction

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 $\theta_{SN}(t)$ seen from Hamburg (DESY).





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

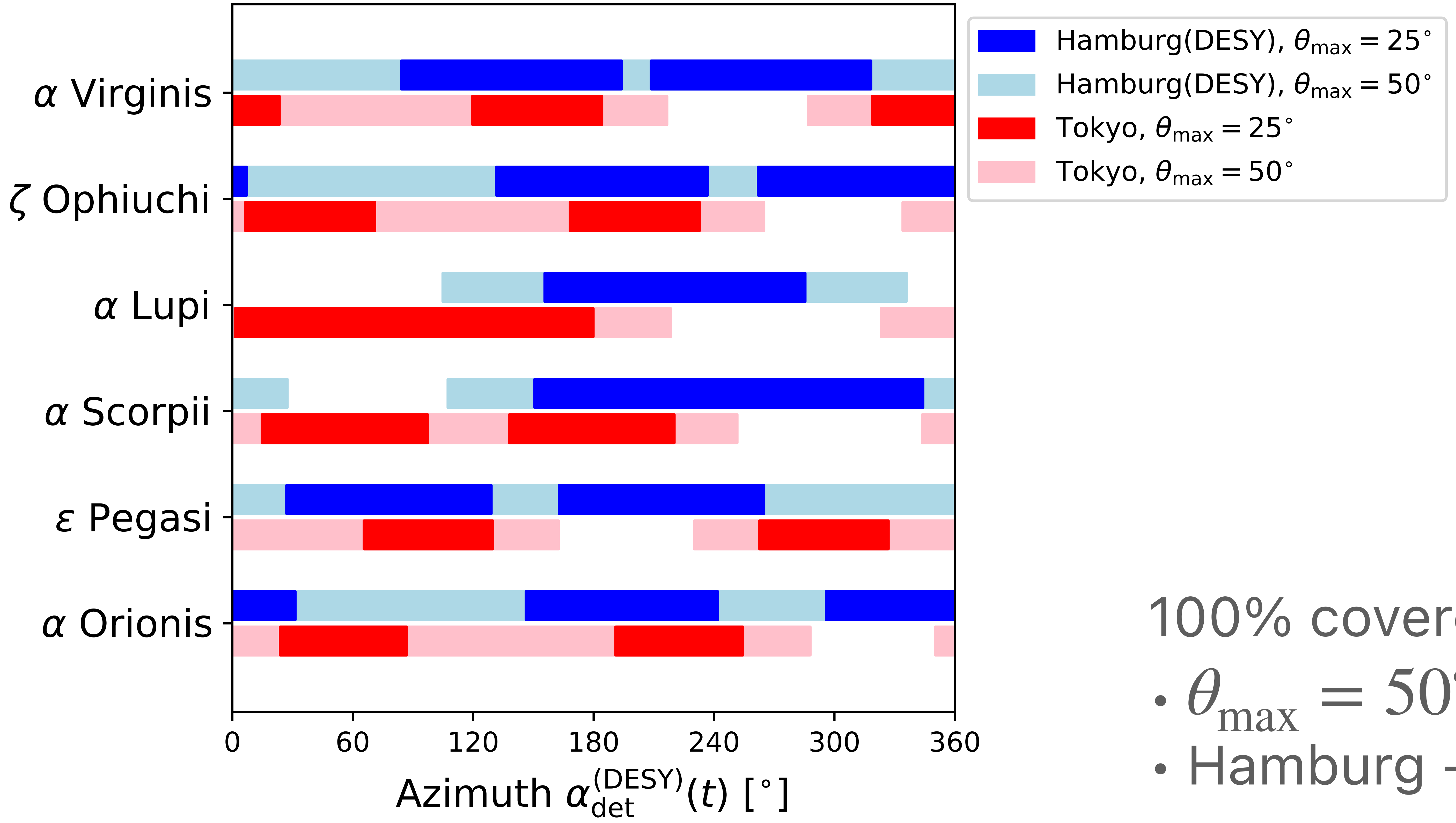
Observational time fraction > 50% for all the progenitors except α Lupi.

Observation time fraction

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

The time fraction can be increased by

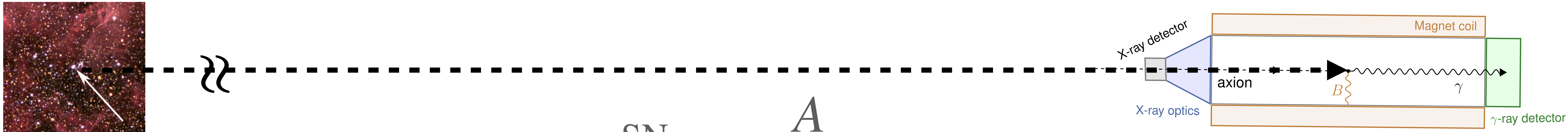
- increasing the maximum elevation $\theta_{\max}$ and/or
- two SN-scopes at different observation points (e.g., Hamburg and Tokyo)



100% covered if

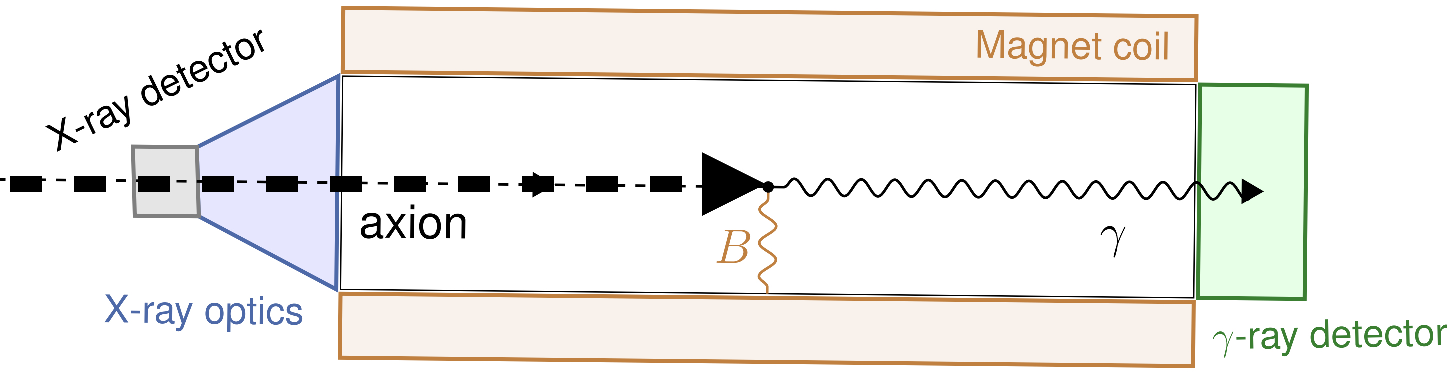
- $\theta_{\max} = 50^\circ$
- Hamburg + Tokyo.

Event number



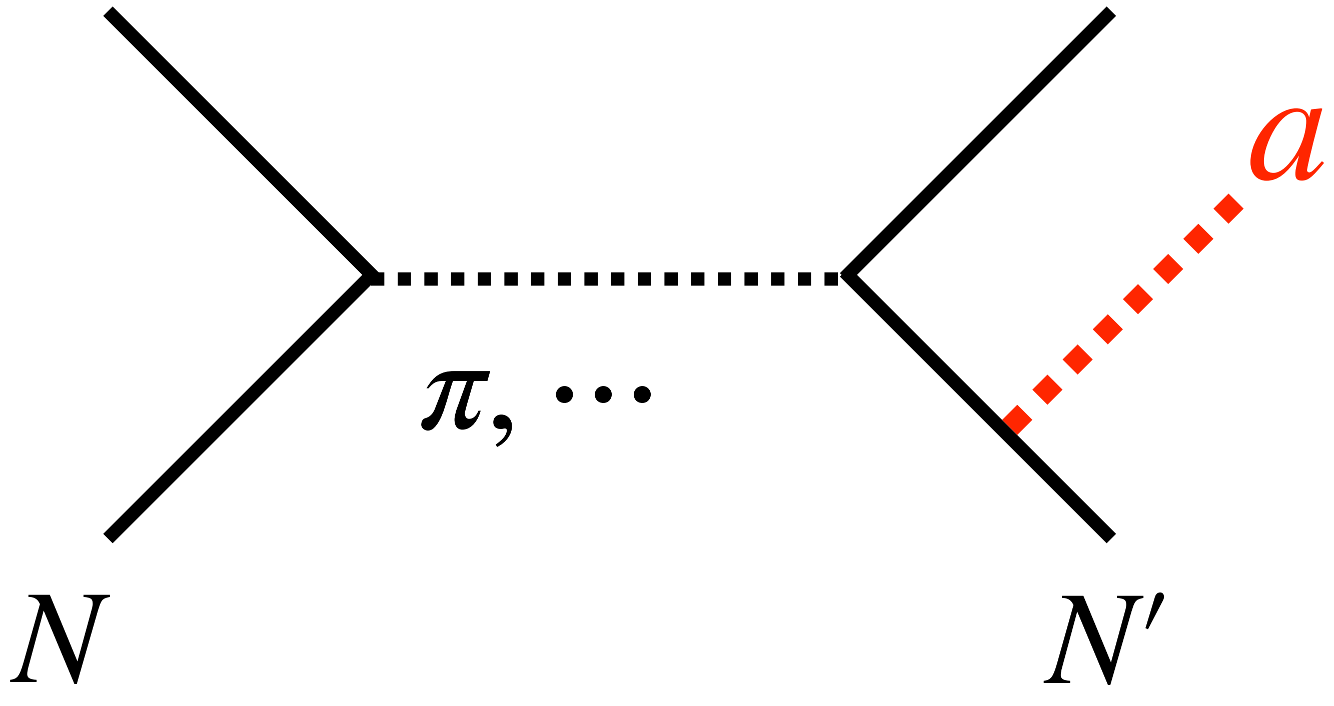
$$N_{\text{event}} = N_a^{\text{SN}} \times \frac{A}{4\pi d^2} \times P_{a\to\gamma}$$

Event number



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

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



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

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

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

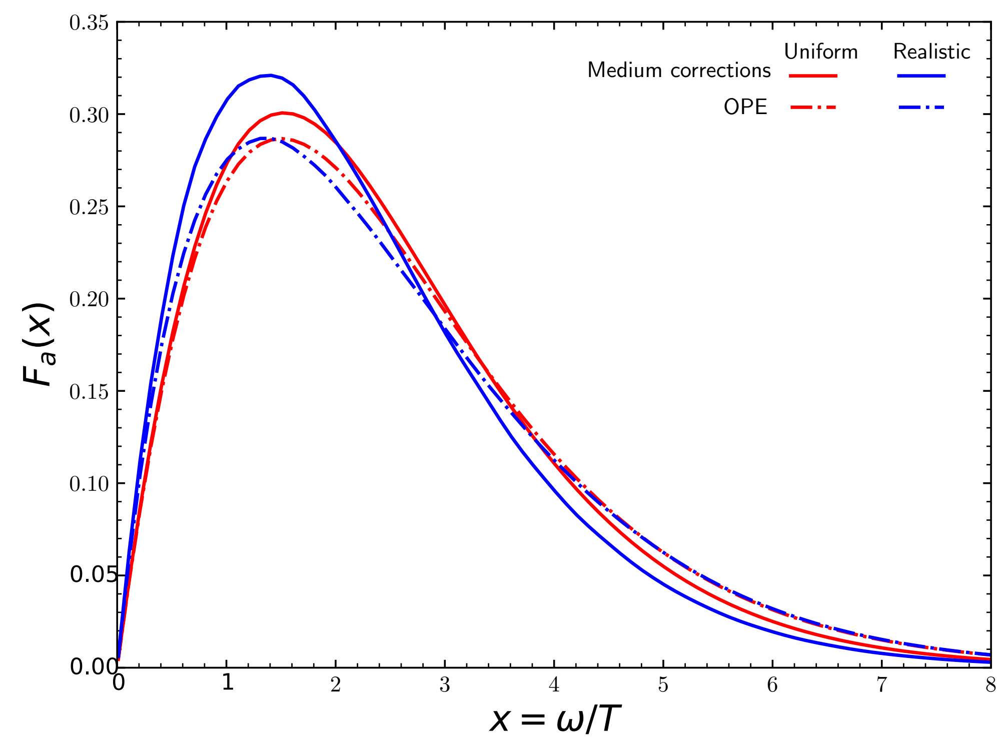
Production

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

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

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

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

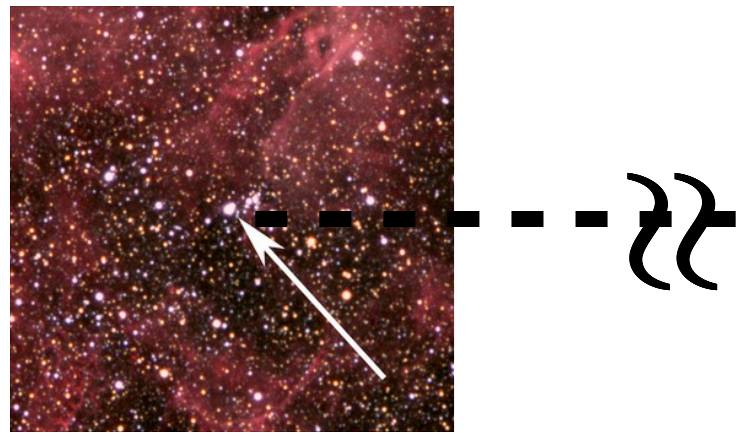


- Thus, the total number of axions from SN is

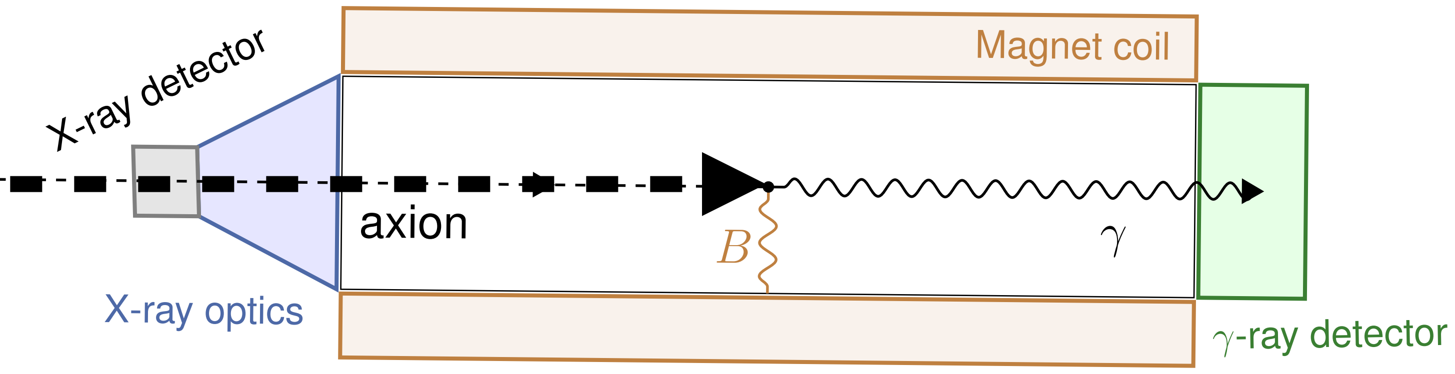
$$N_a^{\text{SN}} = \dot{N}_a \Delta t = \frac{L_a}{\langle E_a \rangle}\Delta t \simeq 3 \times 10^{57} \left(\frac{3\times 10^8\ \text{GeV}}{f_a}\right)^2 \left(\frac{C_{N,\text{eff}}}{0.37}\right)^2 \left(\frac{\Delta t}{10\ \text{s}}\right)\left(\frac{T}{30\ \text{MeV}}\right)^{5/2}$$

KSVZ

Event number



d

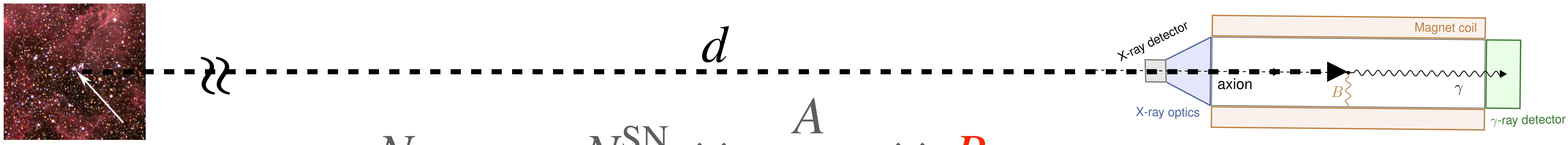


$$N_{\rm event} = N_a^{\rm SN} \times \frac{A}{4\pi d^2} \times P_{a\to\gamma}$$

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

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

Event number



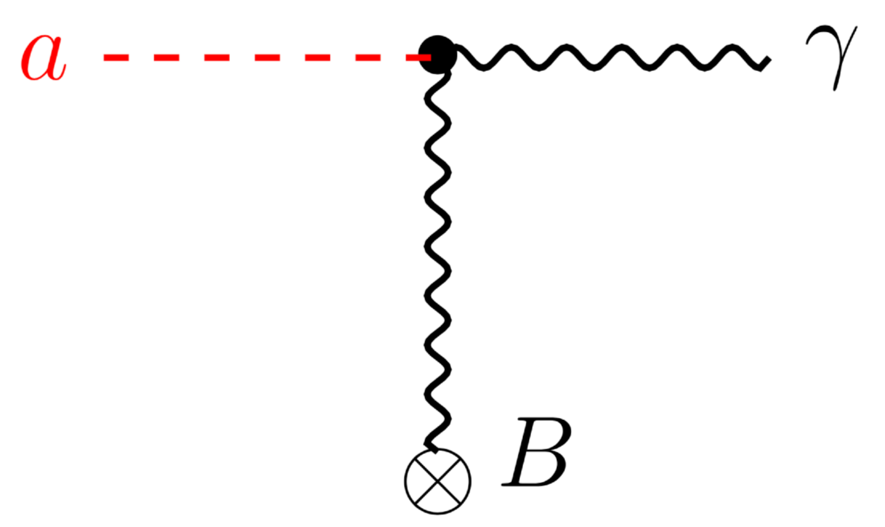
$$N_{\rm event} = N_a^{\rm SN} \times \frac{A}{4\pi d^2} \times P_{a\to\gamma}$$

Detection

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

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

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)
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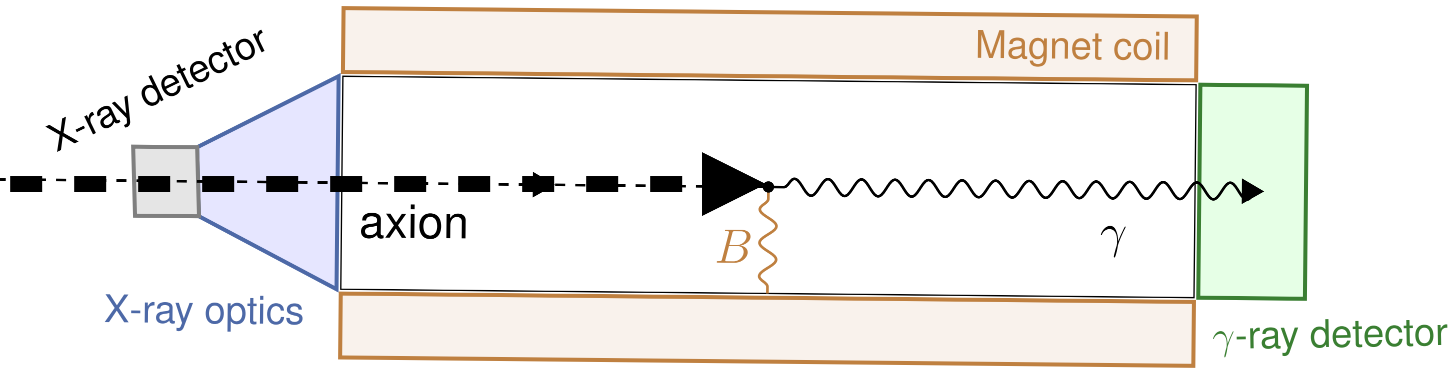
suppression factor

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

($a \leftrightarrow \gamma$ oscillation)

Event number

d



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

After all,...

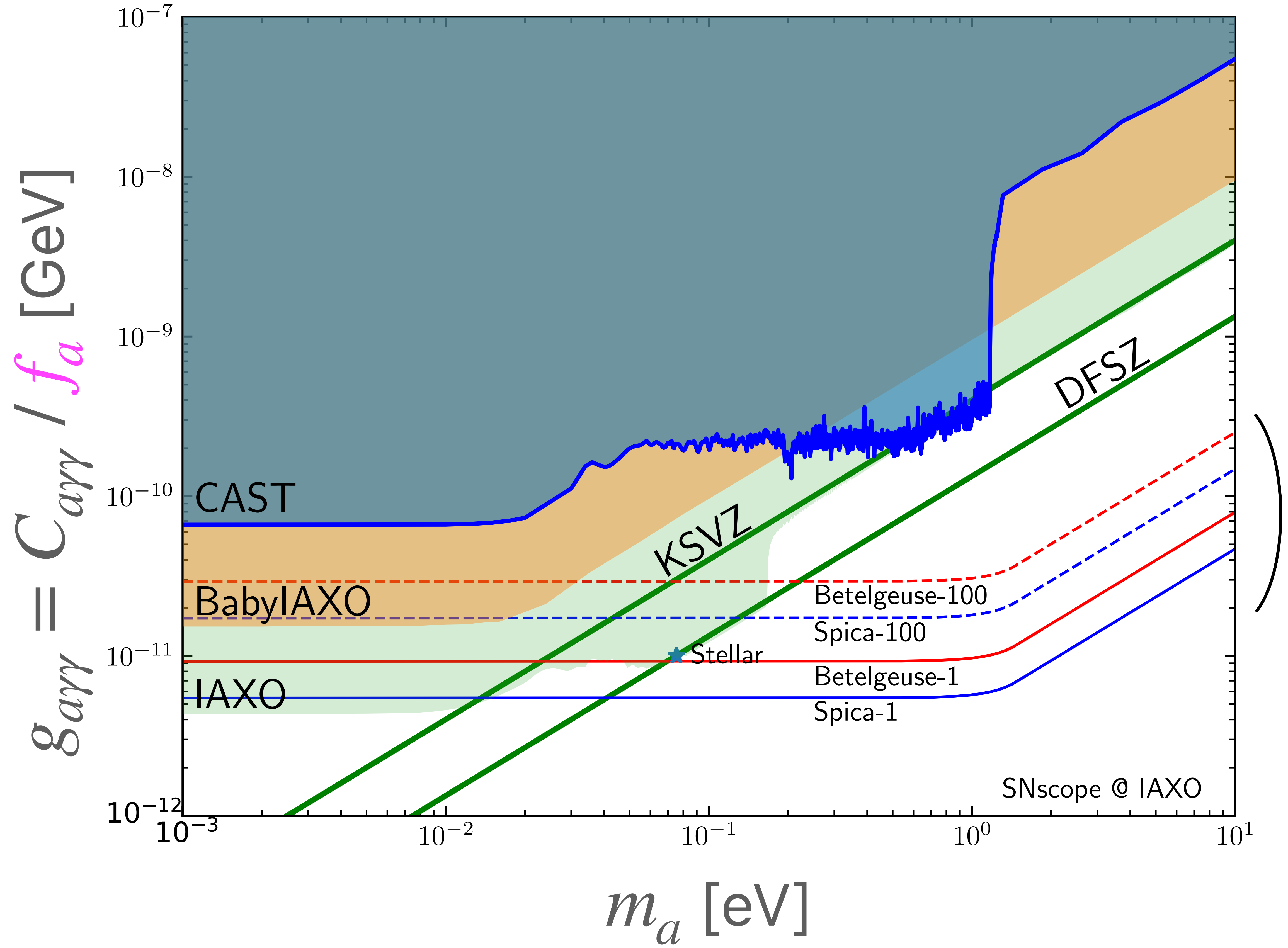
$$N_{\rm event} \simeq 1.0 \times \underbrace{\left(\frac{3\times 10^8~{\rm GeV}}{f_a}\right)^4 \left(\frac{C_{N,\rm eff}}{0.37}\right)^2 \left(\frac{C_{a\gamma\gamma}}{\alpha/\pi}\right)^2}_{\text{axion model}} \times \underbrace{\left(\frac{150~{\rm pc}}{d}\right)^2 \left(\frac{\Delta t}{10~{\rm s}}\right)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

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

※ 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)

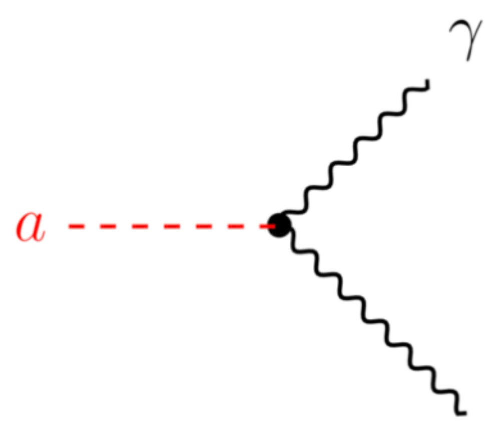
- Better sensitivity than helioscopes for large mass, because of higher axion energy ($E_a^{\text{SN}} \sim 70$ MeV $\gg$ $E_a^{\text{sun}} \sim$ a few keV).

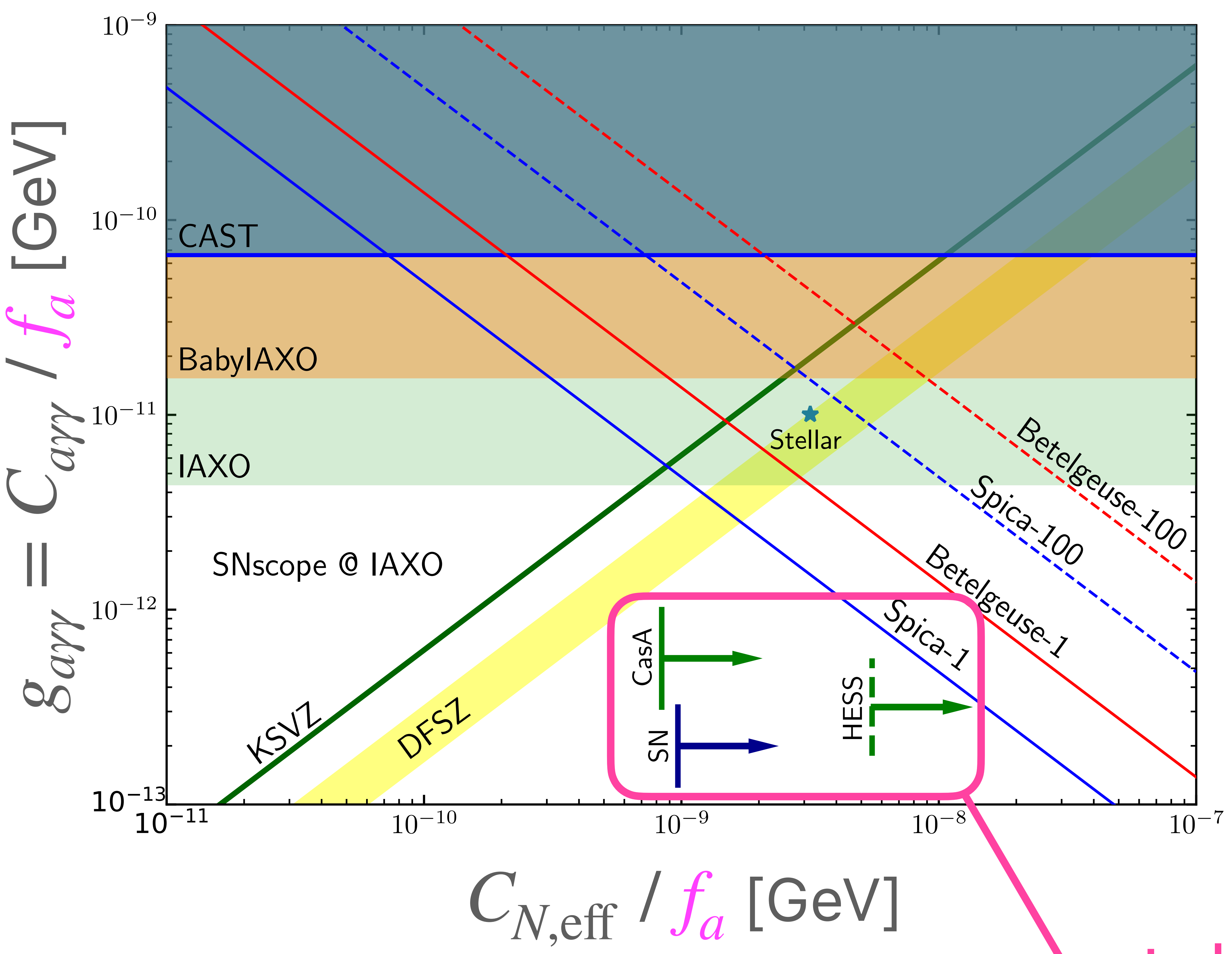
- For small mass region, both solar axion and SN-axion may be discovered.

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.

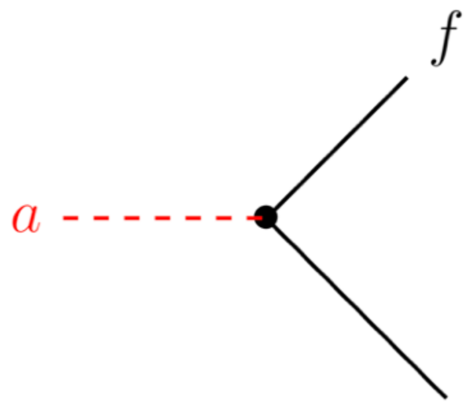
vs. stellar constraints





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

stellar constraints



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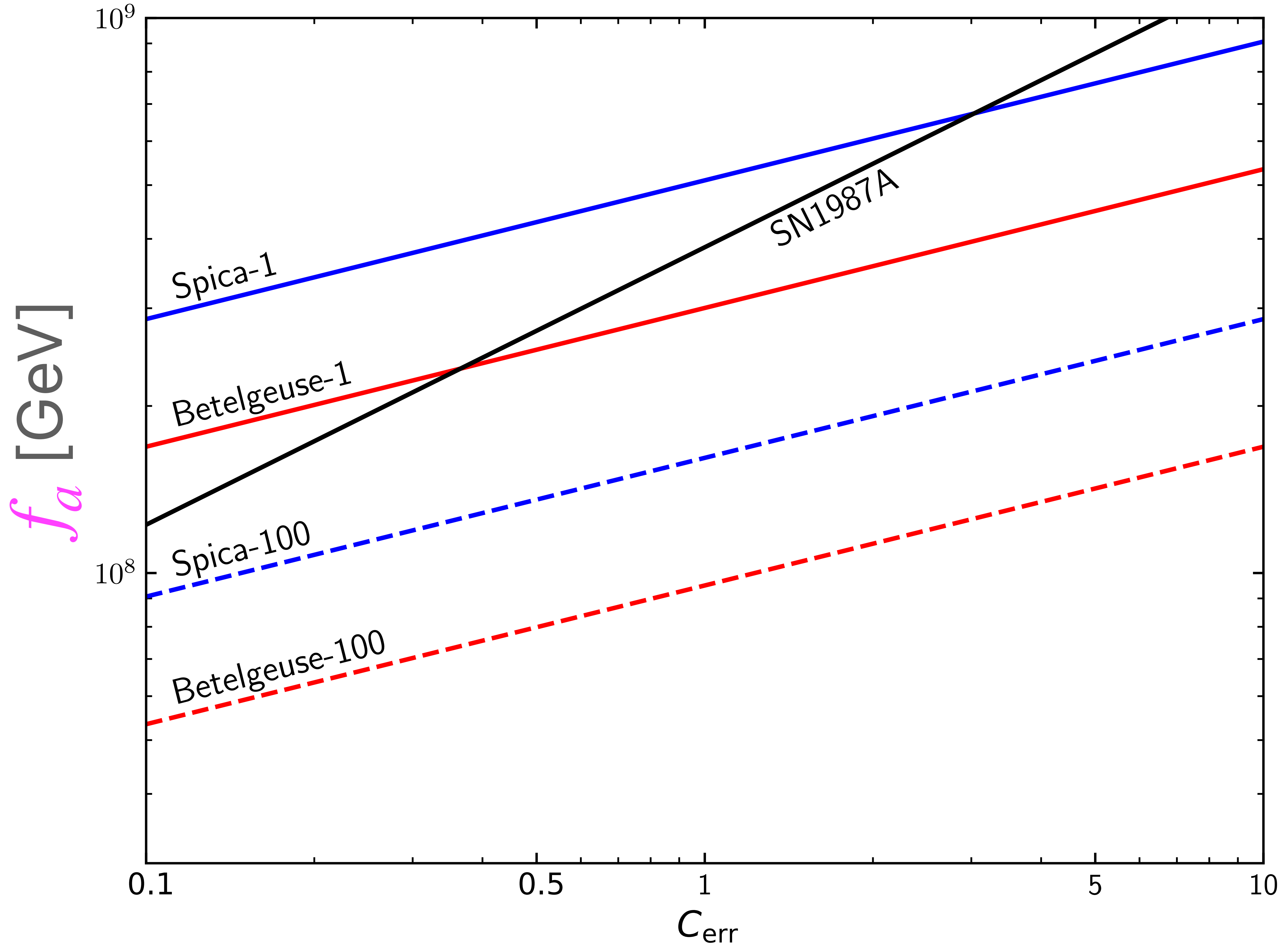
vs. stellar constraints



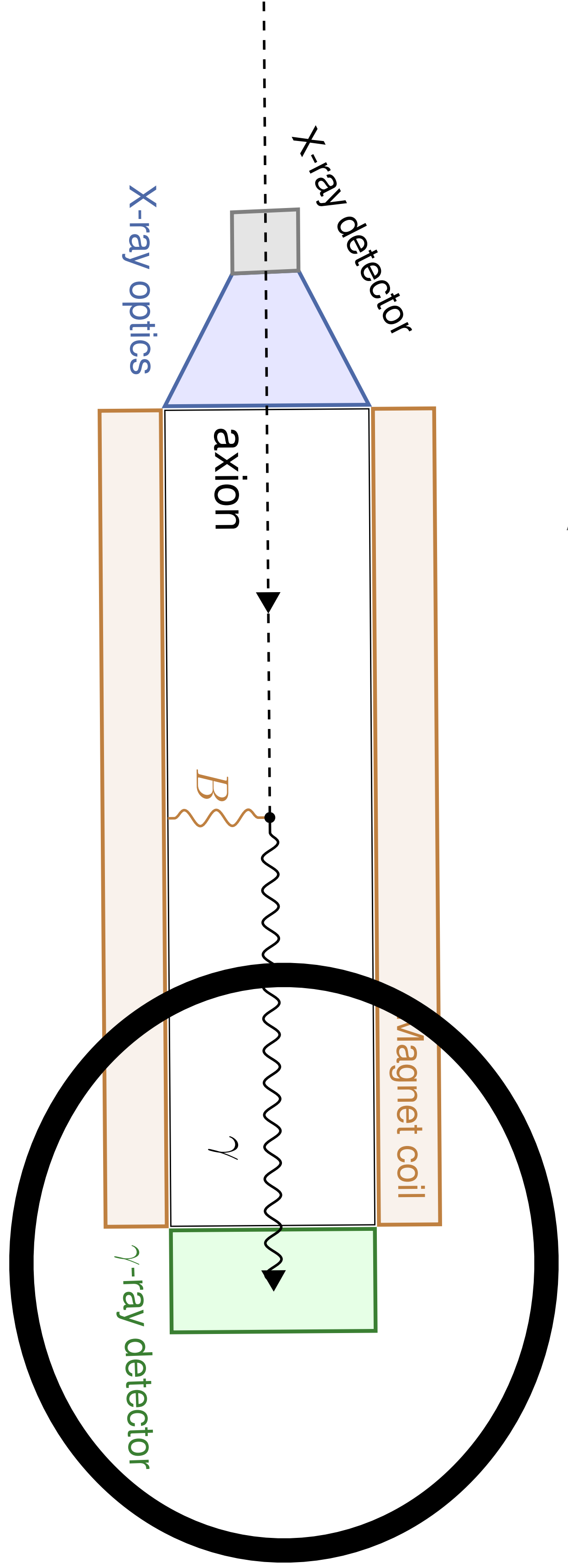
$C_{\rm err} = \dfrac{\dot{N}_a^{\rm true}}{\dot{N}_a^{\rm calc}}$ parametrizes the uncertainty.

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

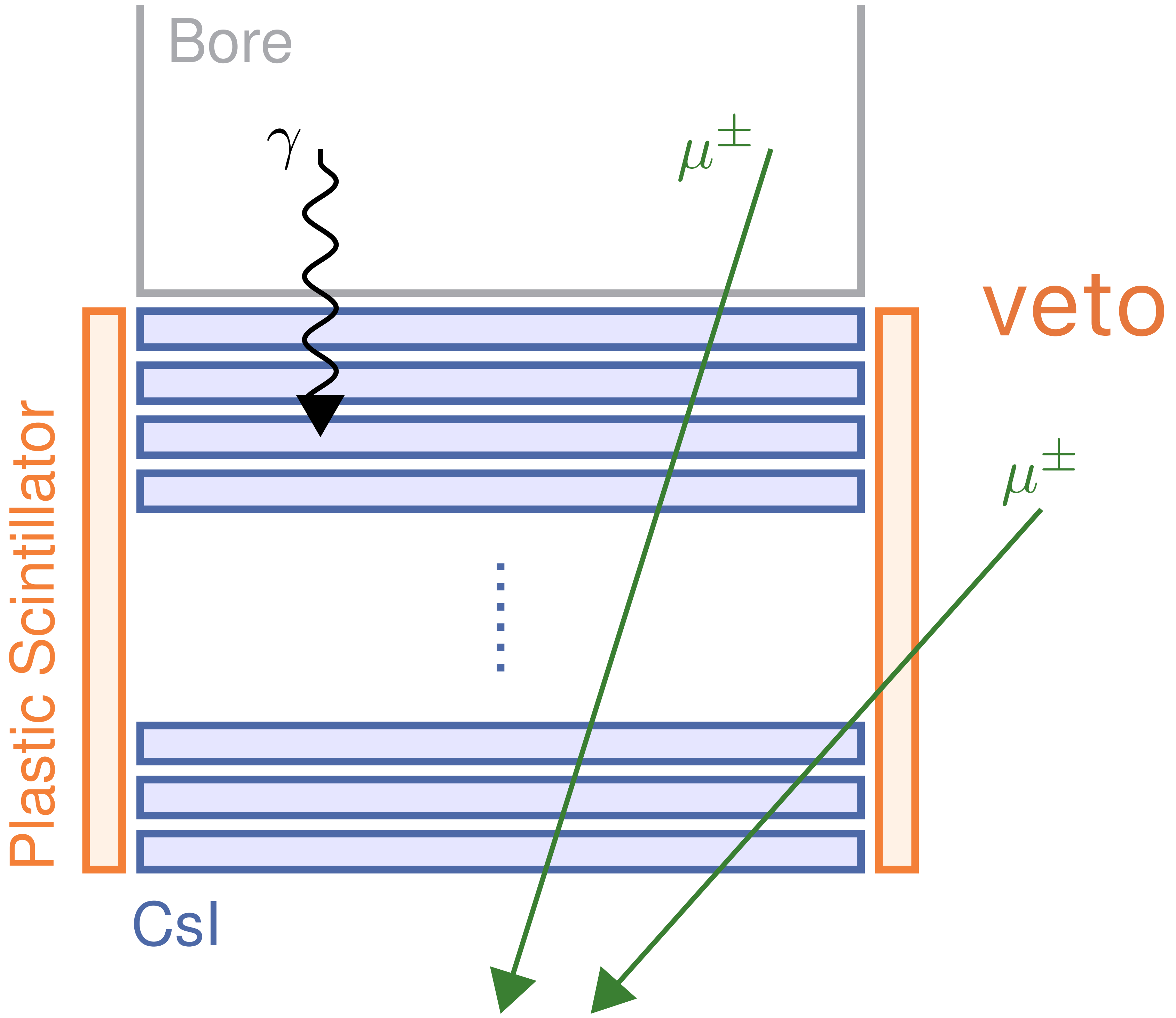
For $C_{\rm err} \simeq 0.1 - 0.3$,

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

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

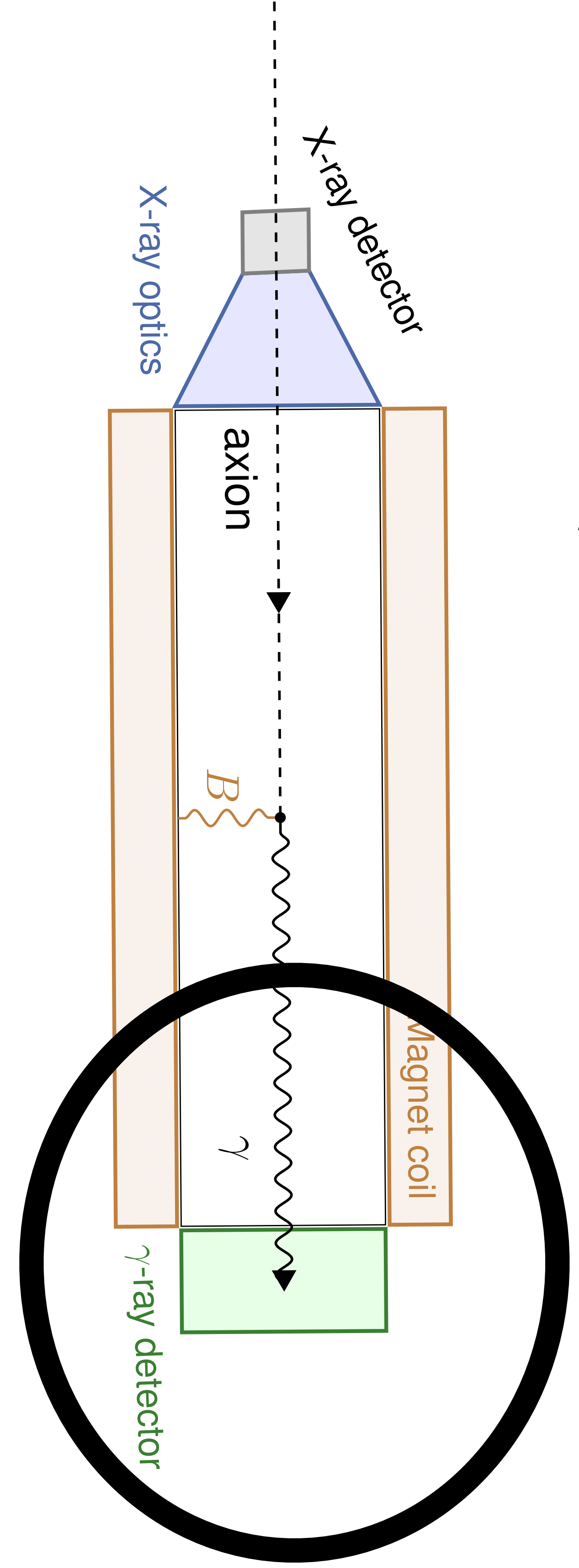


A design for the gamma-ray detector

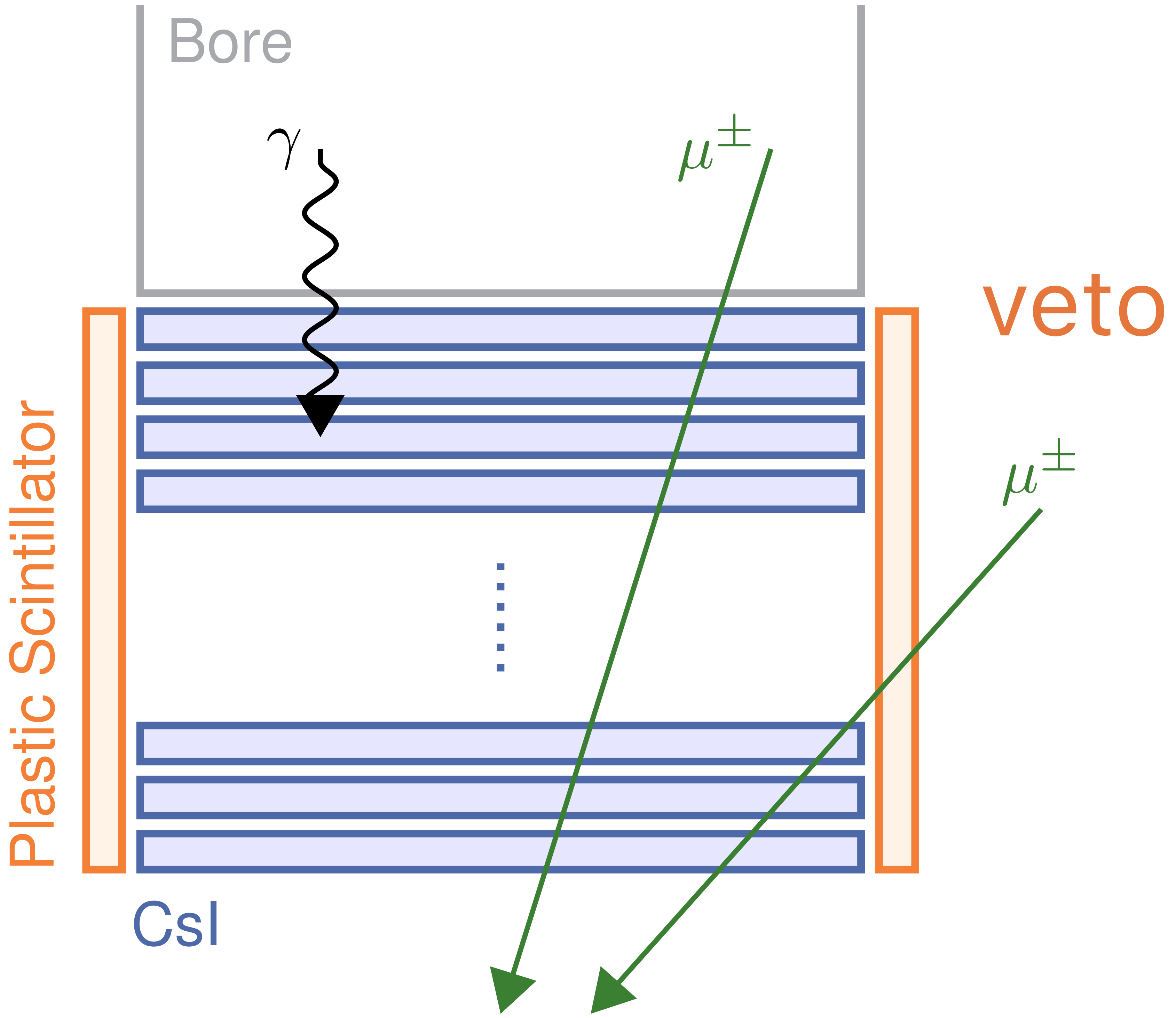


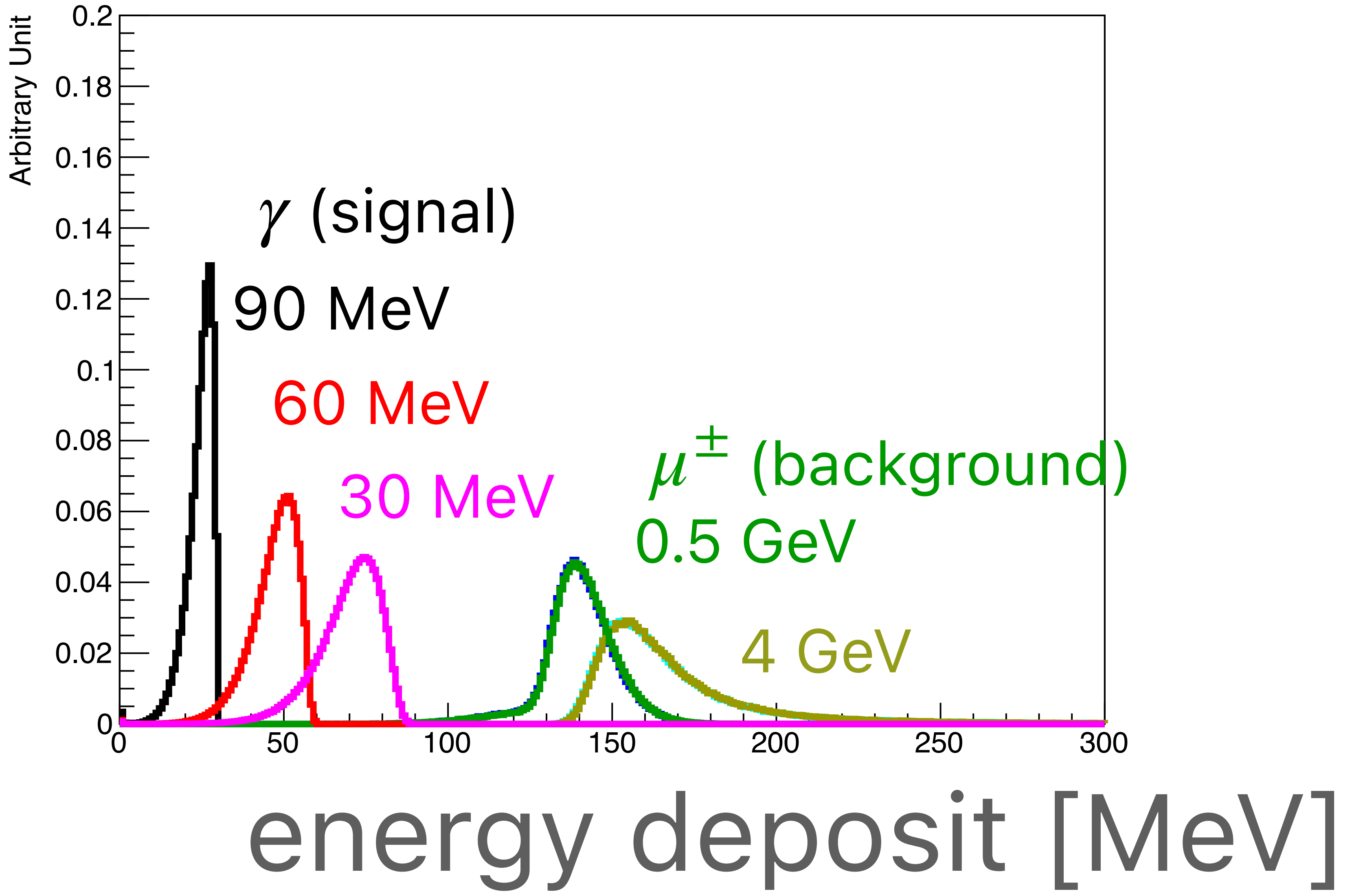
- O(1000) muon events in 10 sec.

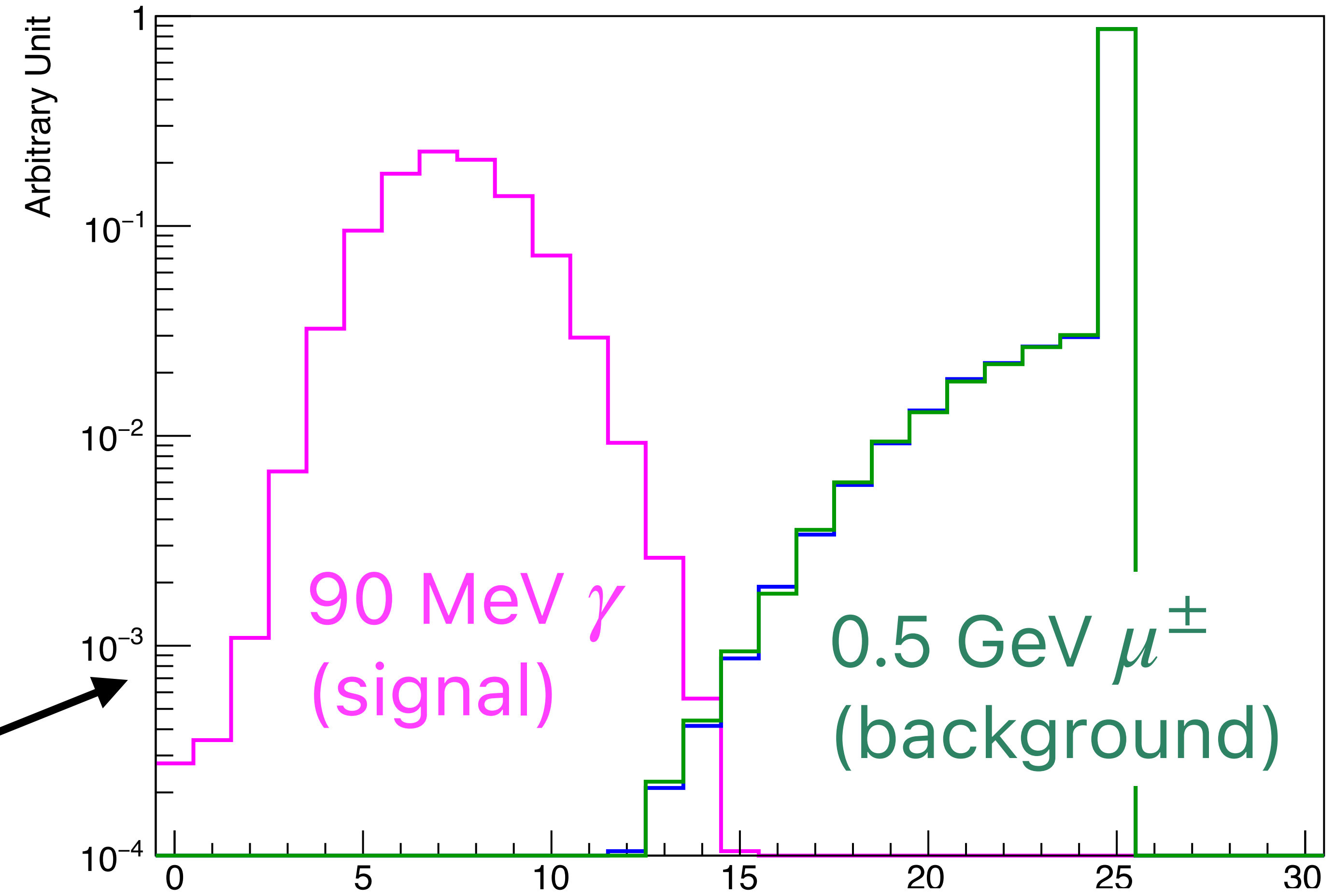
S.Ge, K.Hamaguchi, K.Ichimura, K.Ishidoshiro, Y.Kanazawa, Y.Kishimoto, N.Nagata, J.Zheng. [arXiv:2008.03924] JCAP **11** (2020) 059.



A design for the gamma-ray detector

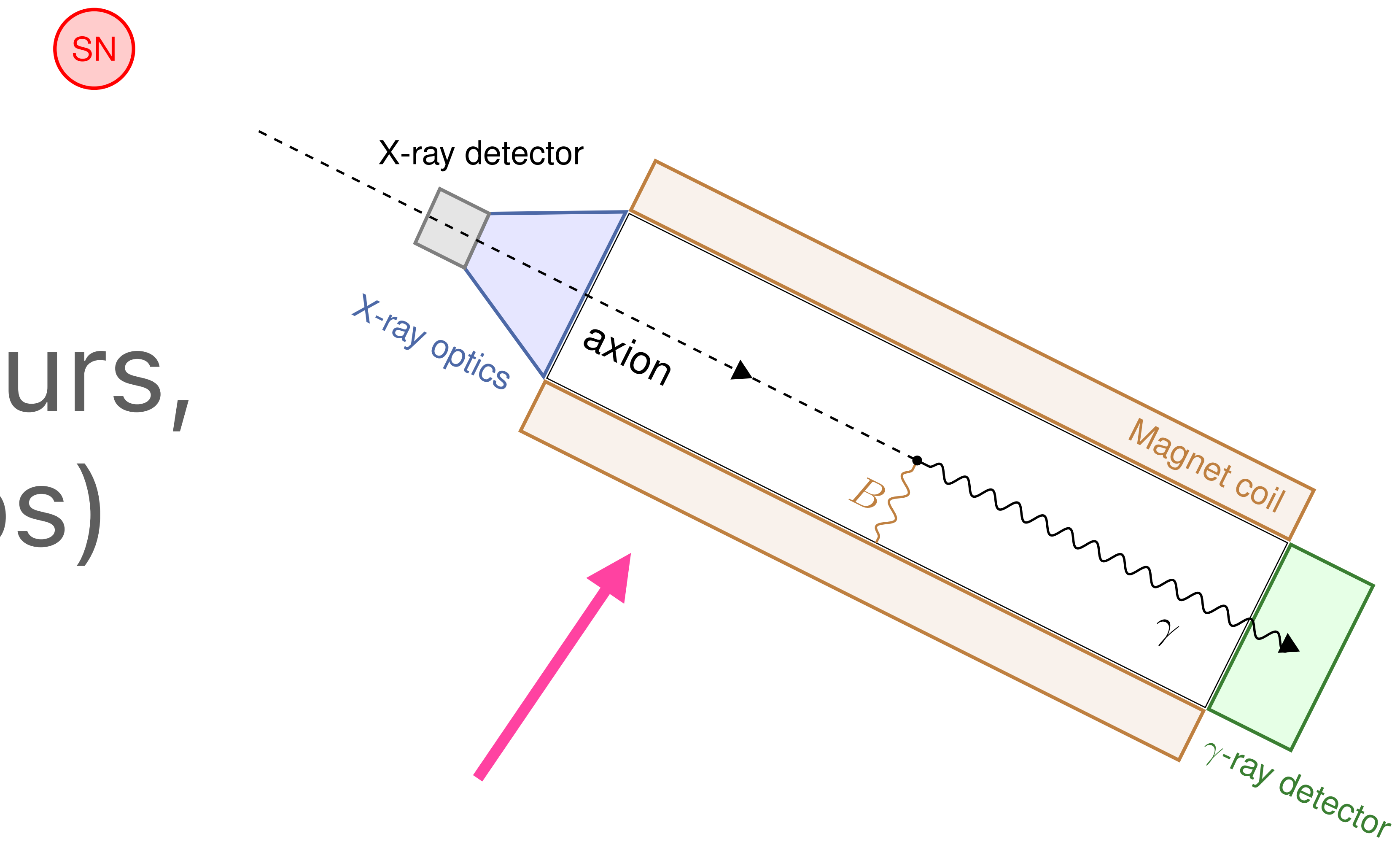






- O(1000) muon events in 10 sec.
- They can be rejected by energy deposit and # of hits.

Summary

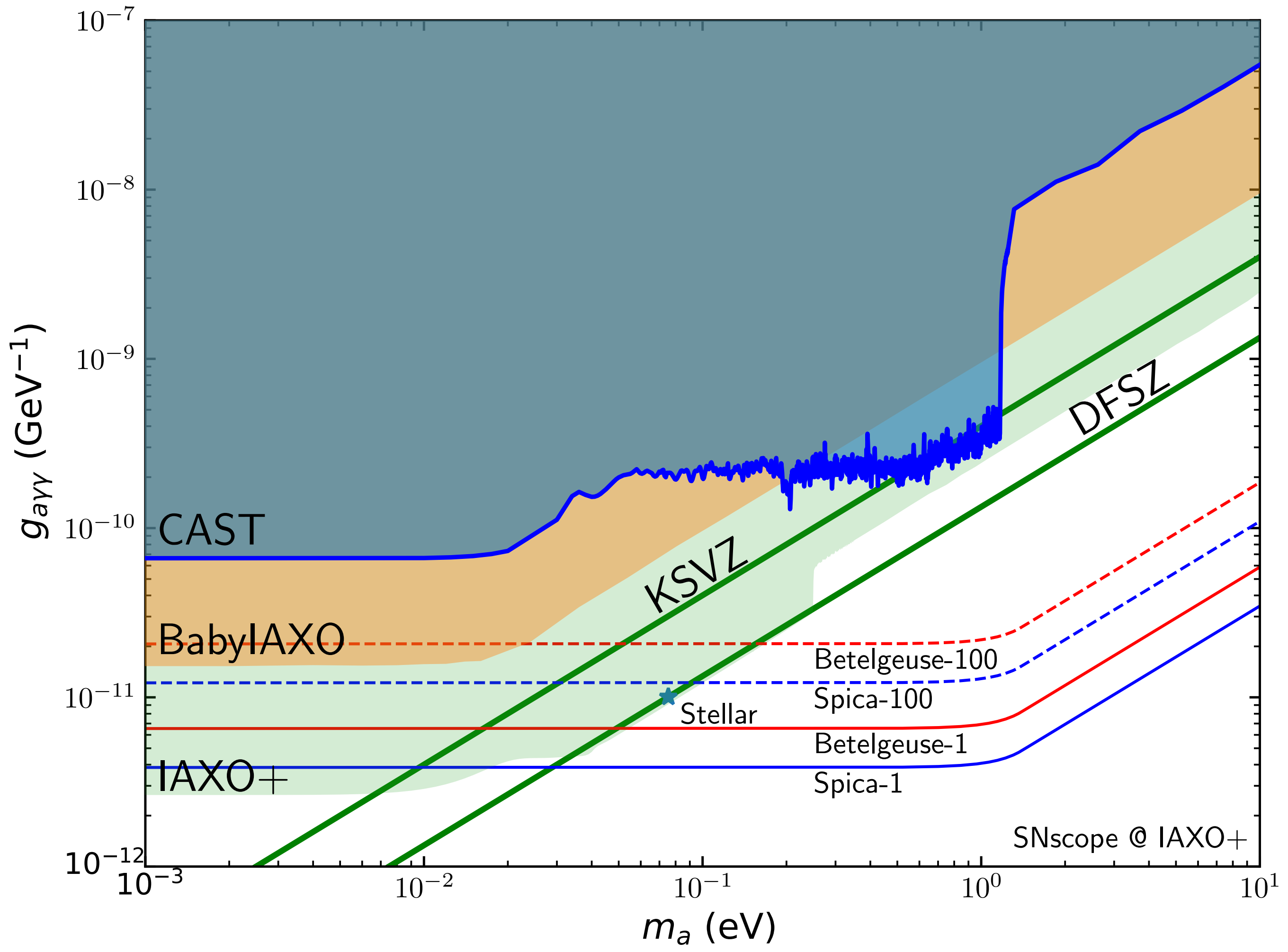


- If a nearby (< a few 100 pc) supernova (SN) occurs, a huge number of axions (in addition to neutrinos) may arrive at the Earth.

- 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!