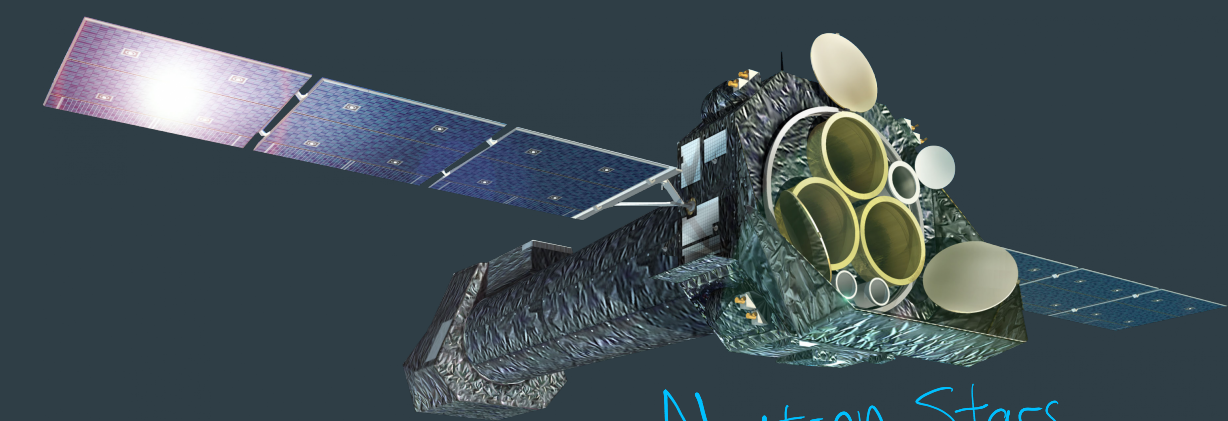


Probing the Wave Nature of Light New Physics

Chen Sun (孙晨) HIAS (杭高院)



Neutron Stars
Galaxy clusters



NS & BH Mergers



Quasars, SN
BAO

SN Remnant
Galaxy Rotation Curves
Sungayev-Zeldovich



Strong CP problem

Dark matter

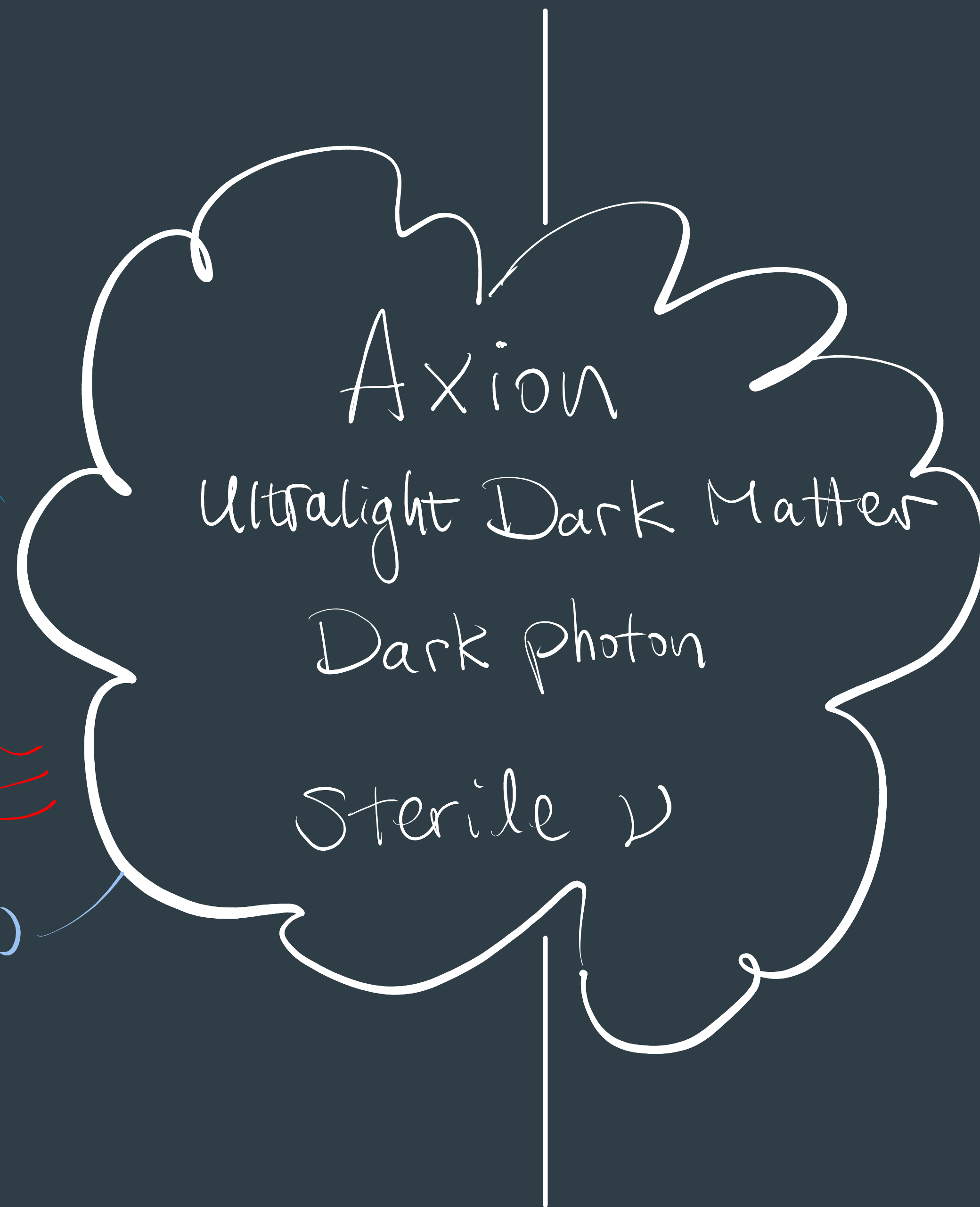
UV completion of gravity

Generation of neutrino mass

Baryon asymmetry

•
•
•

Neutron Stars
Galaxy clusters
Quasars, SN
BAO
SN Remnant
Galaxy Rotation Curves
Sungaei-Zeldovich
Binary Mergers. (BH, NS, ...)



Strong CP problem
Dark matter
UV completion of gravity
Generation of neutrino mass
Baryon asymmetry

Neutron Stars
Galaxy clusters
Quasars, SN
BAO
SN Remnant
Galaxy Rotation Curves
Sungaei-Zeldovich
Binary Mergers. (BH, NS, ...)

Axion

(QCD axion, axion DM,
ultralight DM, ALPs)

Strong CP problem

Dark matter

UV completion of gravity

Generation of neutrino mass

Baryon asymmetry

Why Axion?

a) Strong CP

b) Dark Matter

c) String / extra dimension

QCD Axion

$$\mathcal{L}_{SM} \supset \underbrace{-\frac{\theta_0}{32\pi^2} G \tilde{G}}_{\sim \mathcal{O}(1)} - \underbrace{\gamma_u \bar{Q} \tilde{H} u + \gamma_d \bar{Q} H d}_{\sim \mathcal{O}(1)}$$

$$\theta_{\text{phys}} := \theta_0 - \arg \det(\gamma_u \gamma_d)$$

$$\downarrow$$
$$n \varepsilon_{DM}$$

$$\downarrow$$
$$\theta_{\text{phys}} \lesssim 10^{-10} \quad \text{!}$$

QCD Axion

1) 10^{-10} Cancellation

2) SM: θ_{phys} { threshold at 3 loops } from δ_{CKM}
{ Running at 7 loops }

BSM: Running possible at 1 loop

→ Incompatible w/ "UV solutions"

QCD Axion

KSVZ

DFSZ

⋮

UV completion & low-energy axion EFT:
Buen-Abad, Fan, Reece, CS JHEP 09 (2021) 101

Resonance detection of QCD axion:
Seong, CS, Yun. JHEP 03 (2025) 071

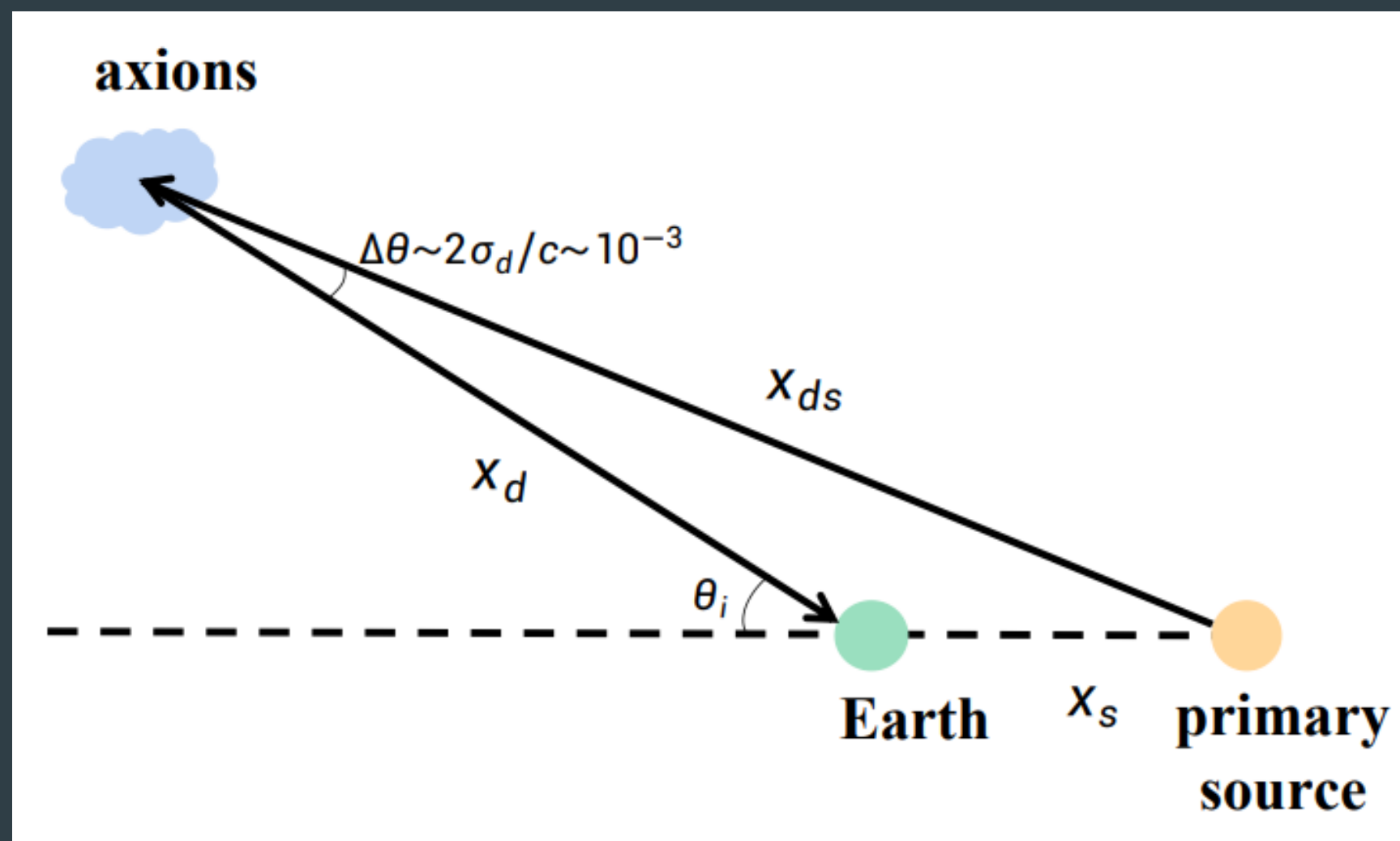
$V(\theta_{\text{phys}})$

Life Time

Axion DM



$$\tau_a \propto m_a^{-1} \left(\frac{m_a}{f_a} \right)^{-2} \gg 13 \text{ Gyr}$$



Axion DM induced SN Remnant echo signals:

Buen-Abad, Fan, **CS**

2110.13916 [Phys.Rev.D 105, 075006]

[see also

Sun, Schutz, Nambrath et al.

2110.13920 [Phys.Rev.D 105, 063007]

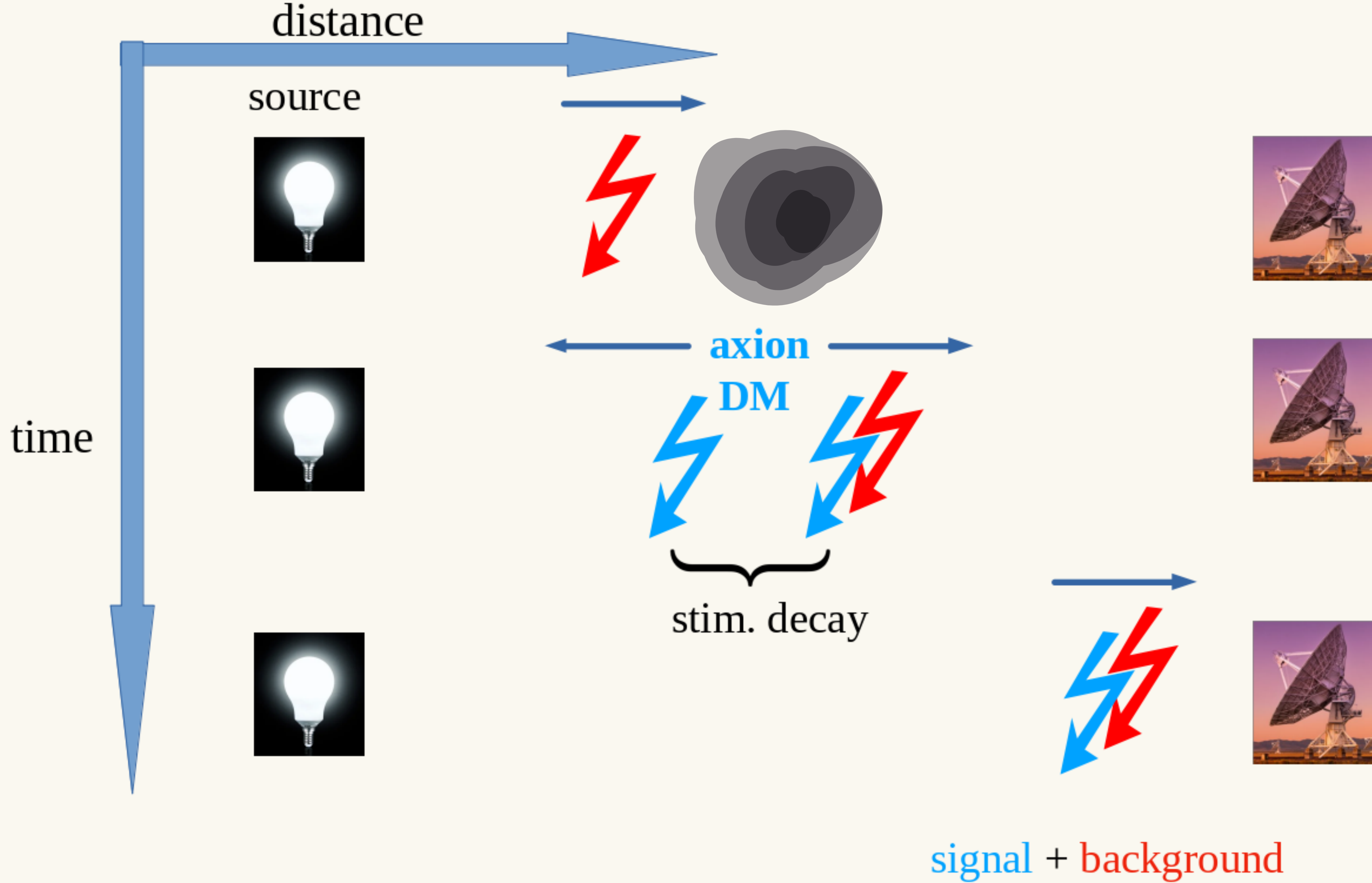
Arza, Guo, Wu, et al.

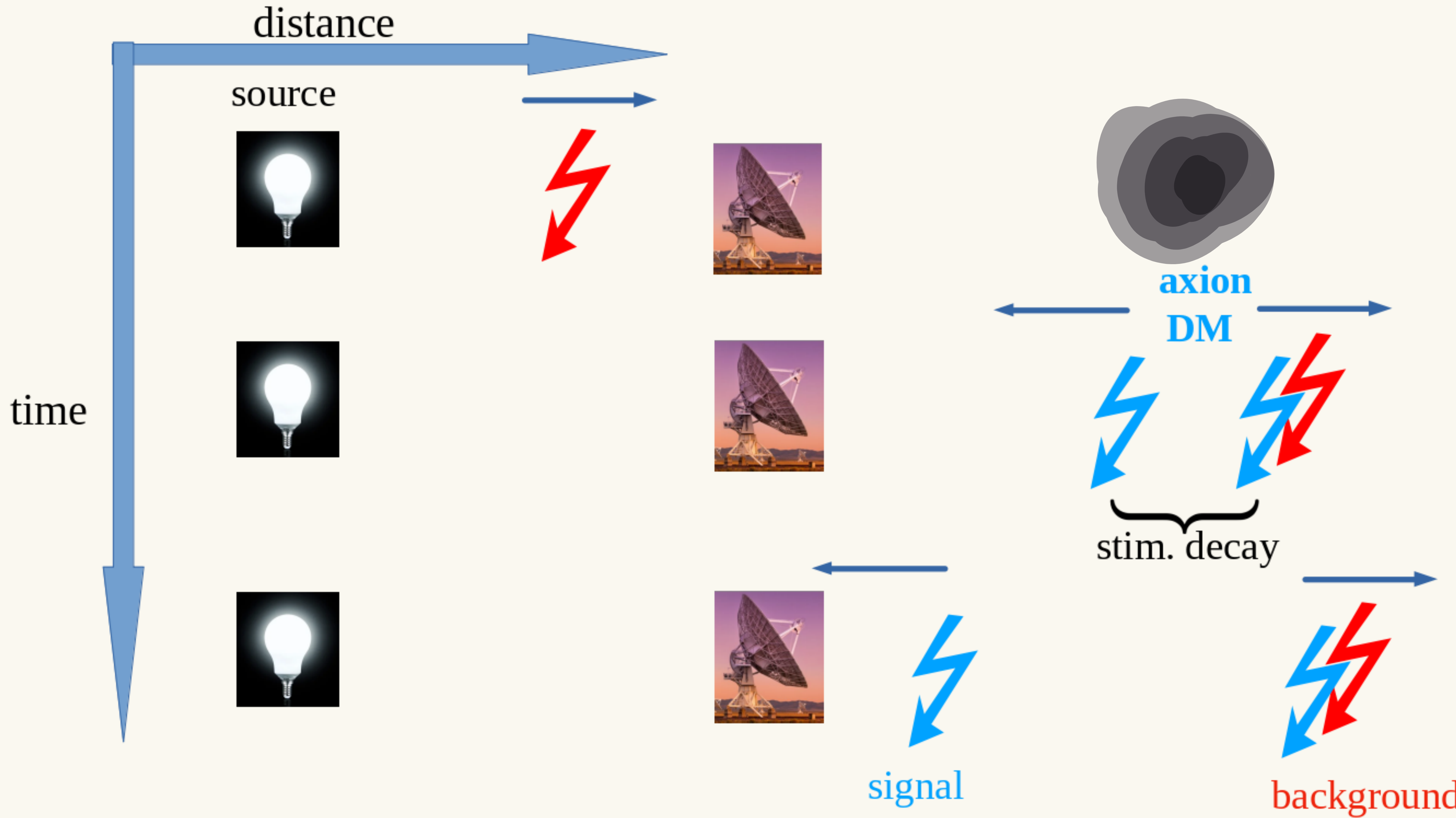
2309.06857 [Sci.Bull. 69 (2024) 2971]

Yang, Sun, Wang et al.

2502.08913 [Astrophys.J. 988 1,104]

...]

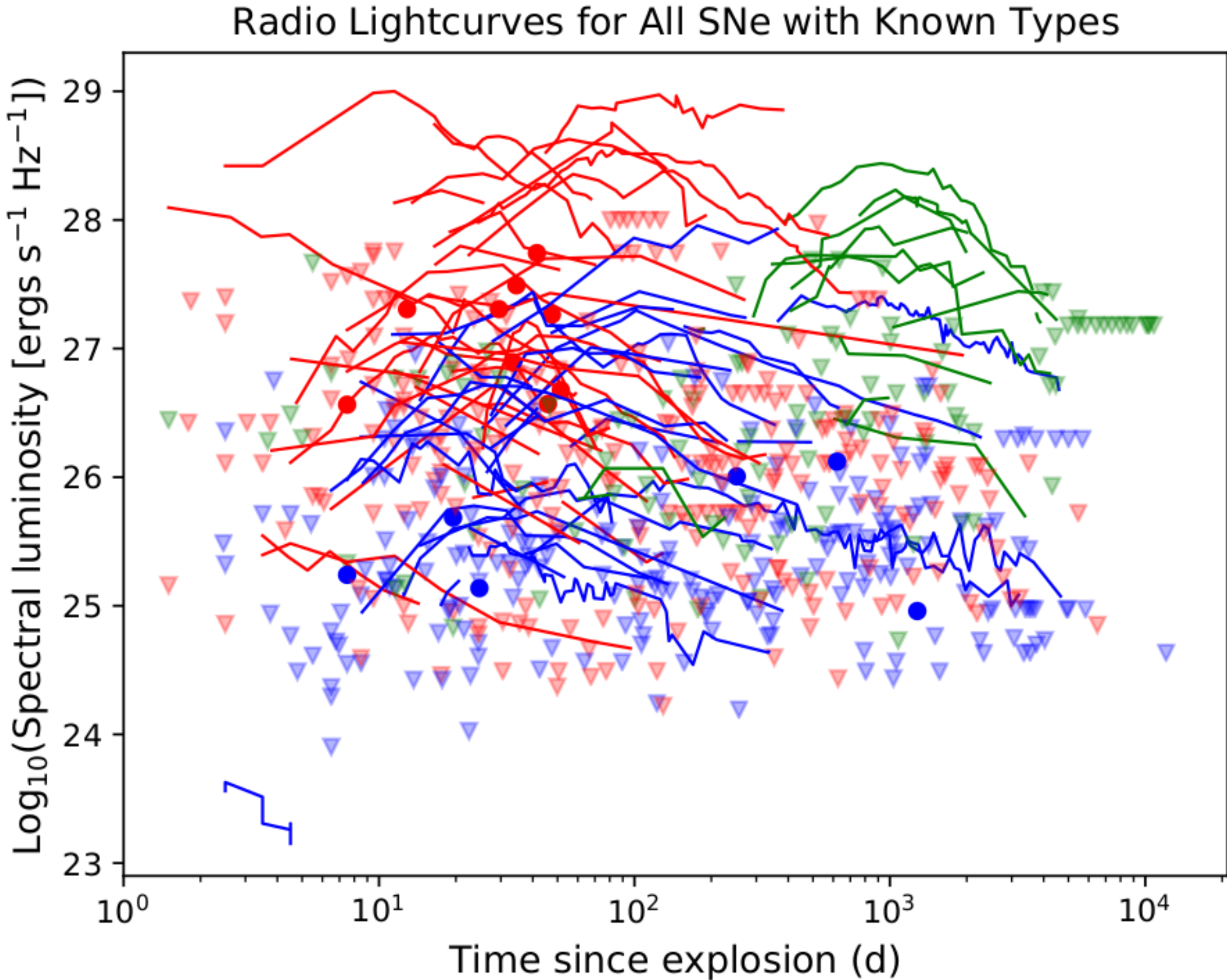
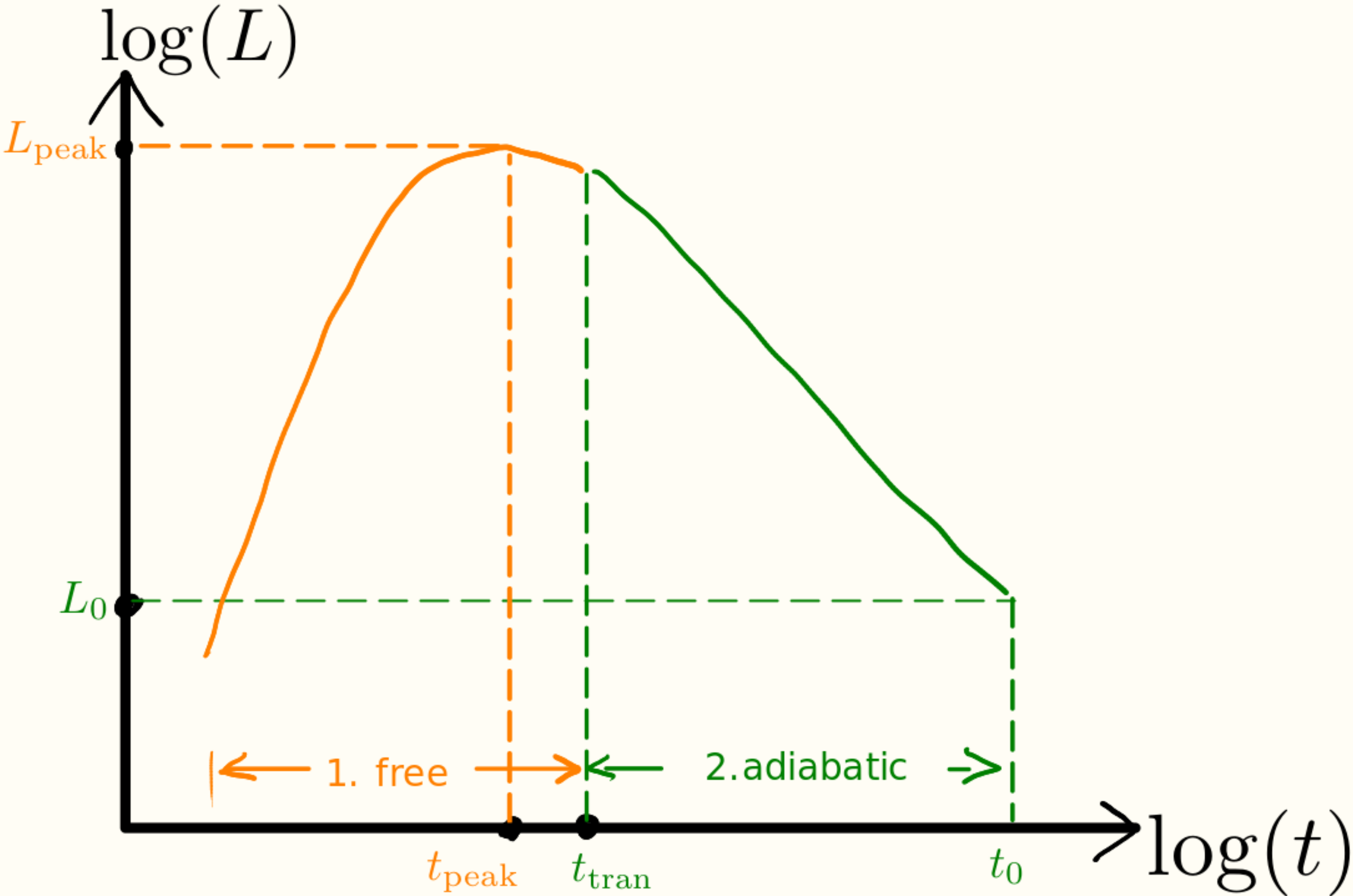


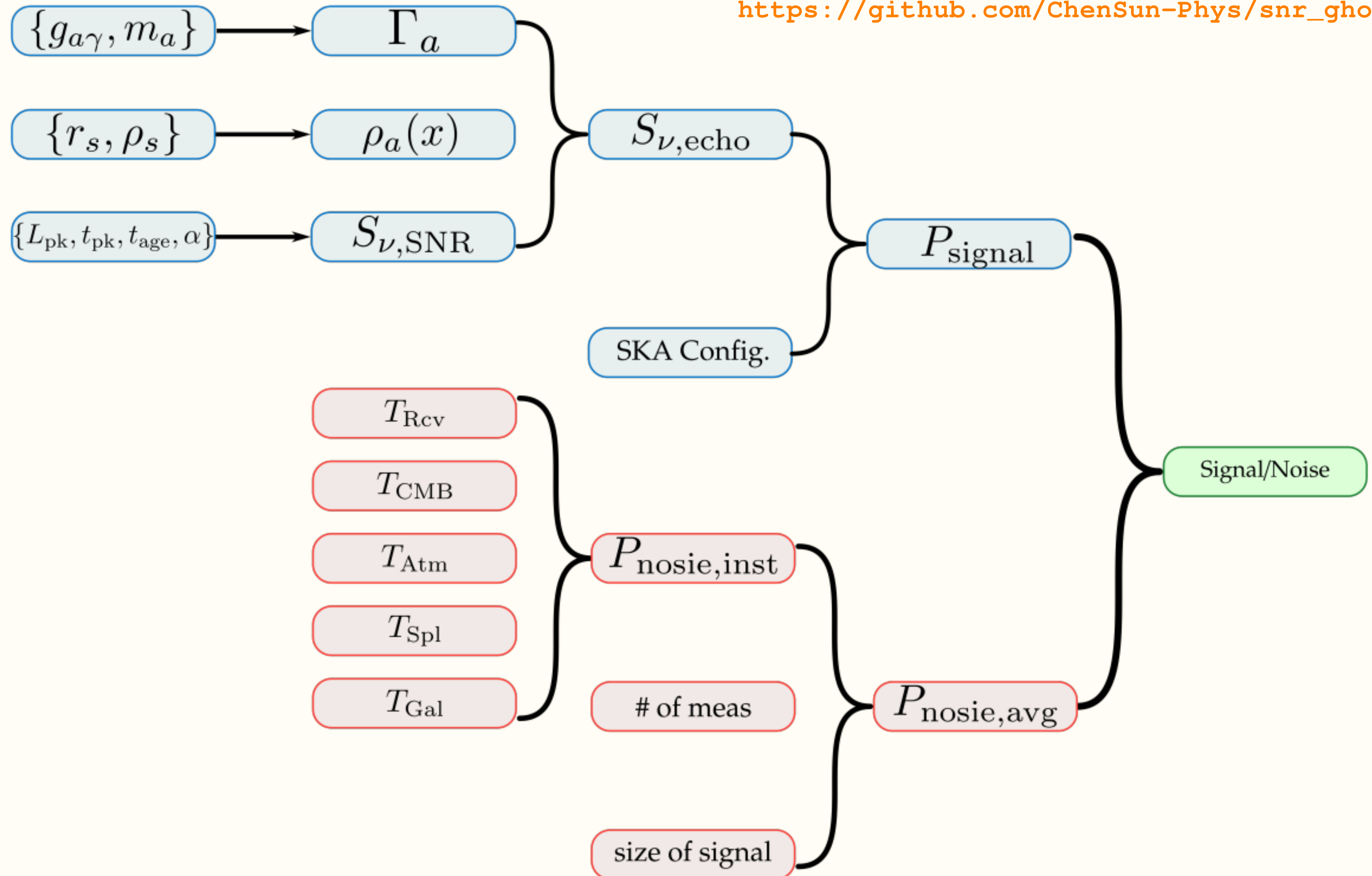


Green 2019

Table 1. 294 Galactic supernova remnants: summary data.

l	b	RA (J2000) (h m s)	Dec (° ')	size /arcmin	type	Flux at 1 GHz/Jy	spectral index	other name(s)
0.0	+0.0	17 45 44	-29 00	3.5×2.5	S	100?	0.8?	Sgr A East
0.3	+0.0	17 46 15	-28 38	15×8	S	22	0.6	
0.9	+0.1	17 47 21	-28 09	8	C	18?	varies	
1.0	-0.1	17 48 30	-28 09	8	S	15	0.6?	
1.4	-0.1	17 49 39	-27 46	10	S	2?	?	
1.9	+0.3	17 48 45	-27 10	1.5	S	0.6	0.6	
3.7	-0.2	17 55 26	-25 50	14×11	S	2.3	0.65	
	+0.3	17 52 55	-25 28	18	S?	3?	0.6	
2.5	-0.5	18 08 55	-27 02	38	S	2.22	0.62	





G39.7-2.0 (W50)

$(l, b) = (39.7^\circ, -2^\circ)$

$\theta_s = 85$ arcmin

$S_{1\text{GHz},s}^{(0)} = 85$ Jy (*)

$D = 4.9$ kpc

$t_{\text{age}} = 30,000\text{--}100,000$ years

$\alpha = 0.7$ (*)

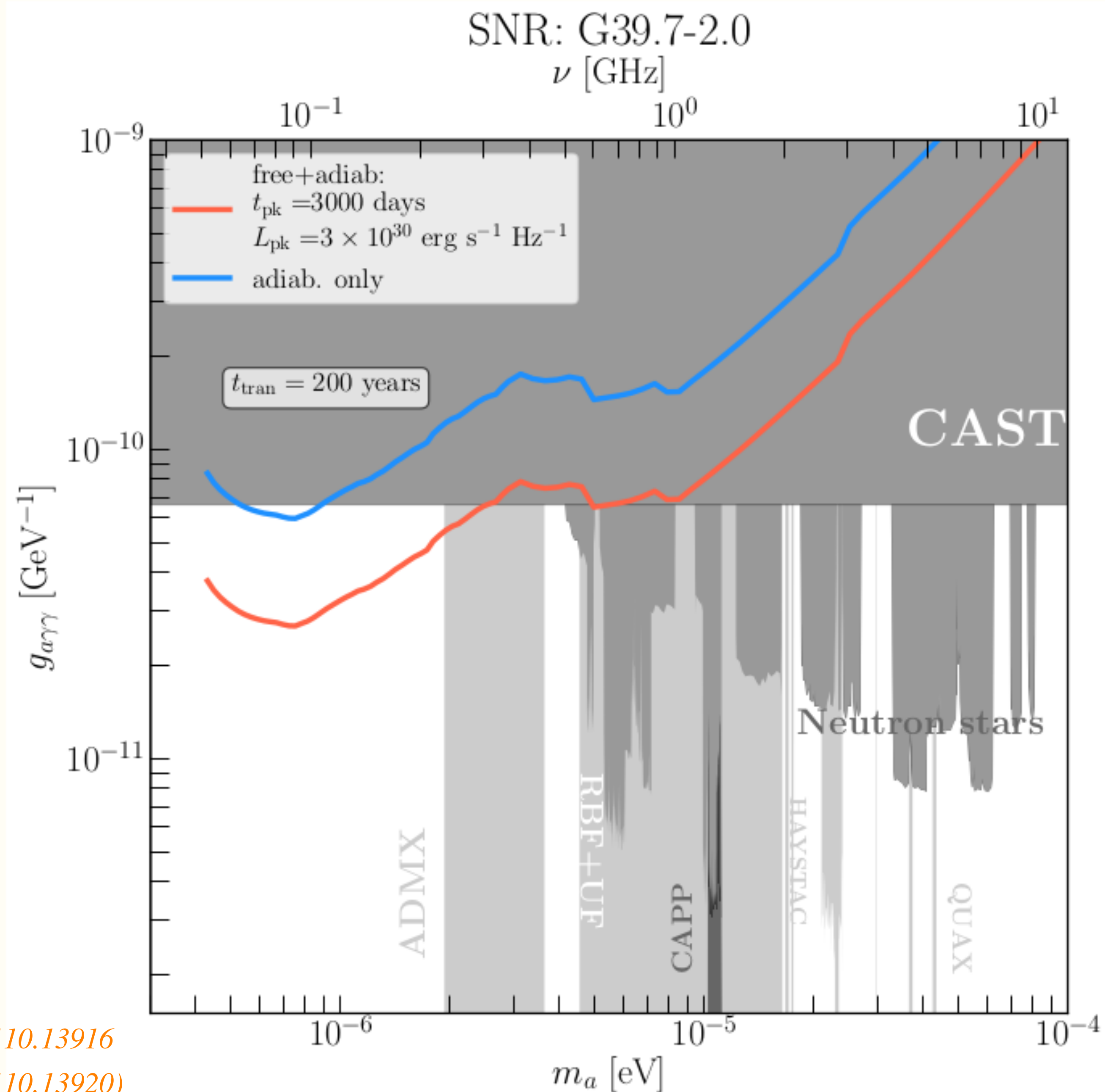
$\gamma = 1.92$

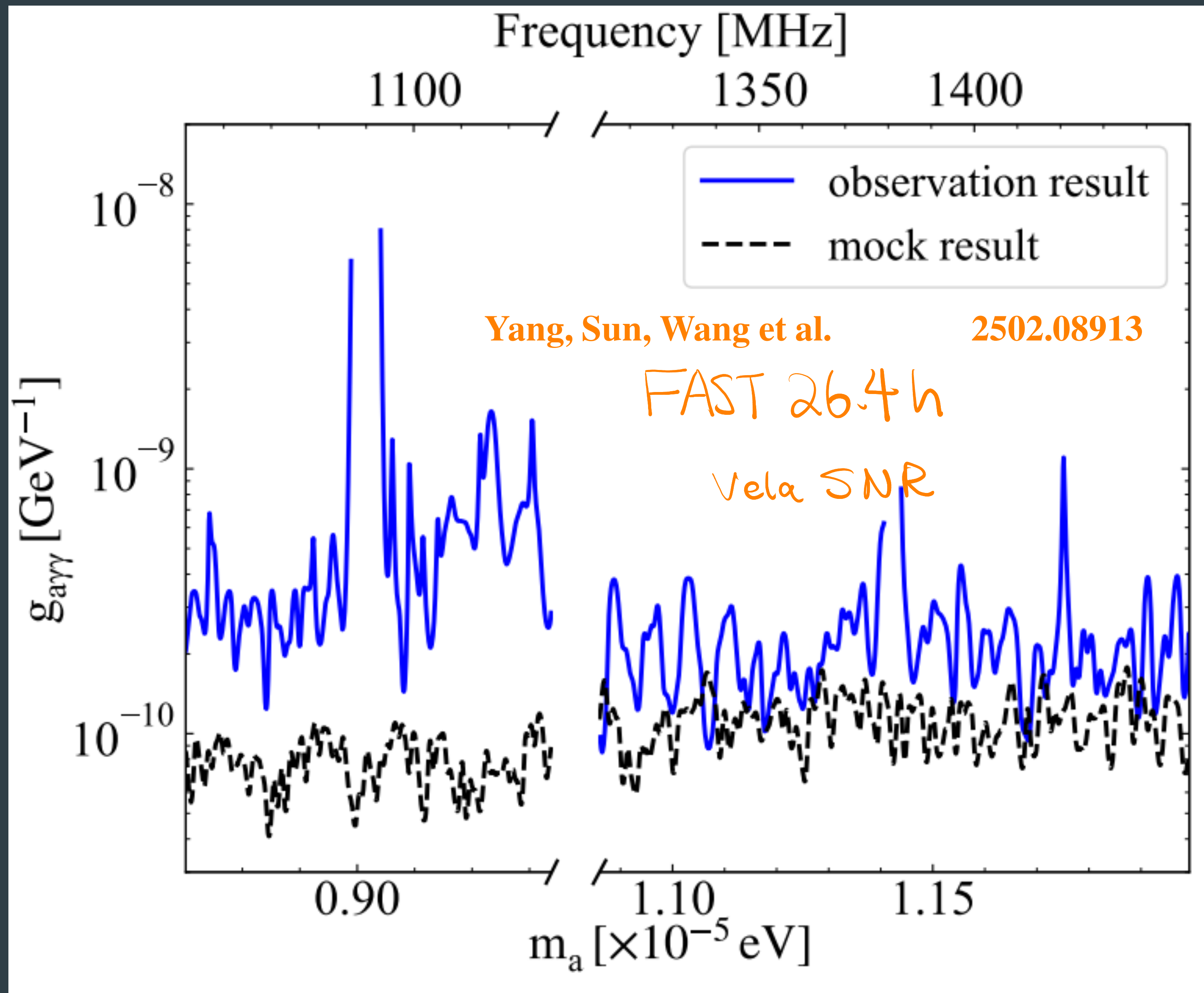
Buen-Abad, Fan, CS

(see also Sun, Schutz, Nambrath et al.

2110.13916

2110.13920)

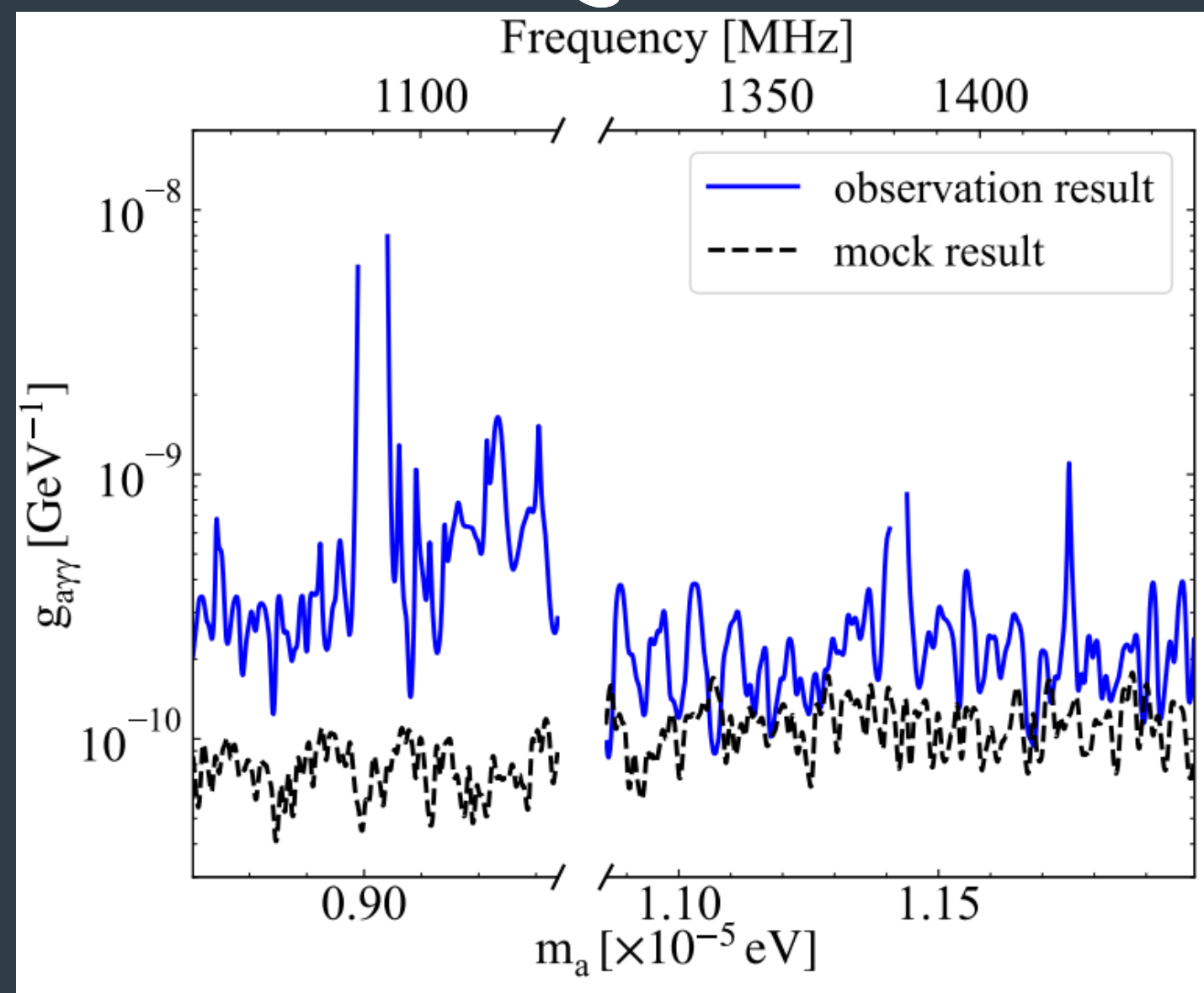




Life Time

Axion DM

$$\tau_a \propto m_a^{-1} \left(\frac{m_a}{f_a} \right)^{-2} \gg 13 \text{ Gyr}$$



Axion DM induced SN Remnant echo signals:

Buen-Abad, Fan, **CS**

2110.13916 [Phys.Rev.D 105]

[see also

Sun, Schutz, Nambrath et al.

2110.13920 [Phys.Rev.D 105]

Arza, Guo, Wu, et al.

2309.06857 [Sci.Bull. 69 2971]

Yang, Sun, Wang et al.

2502.08913 [Astrophys.J. 988]

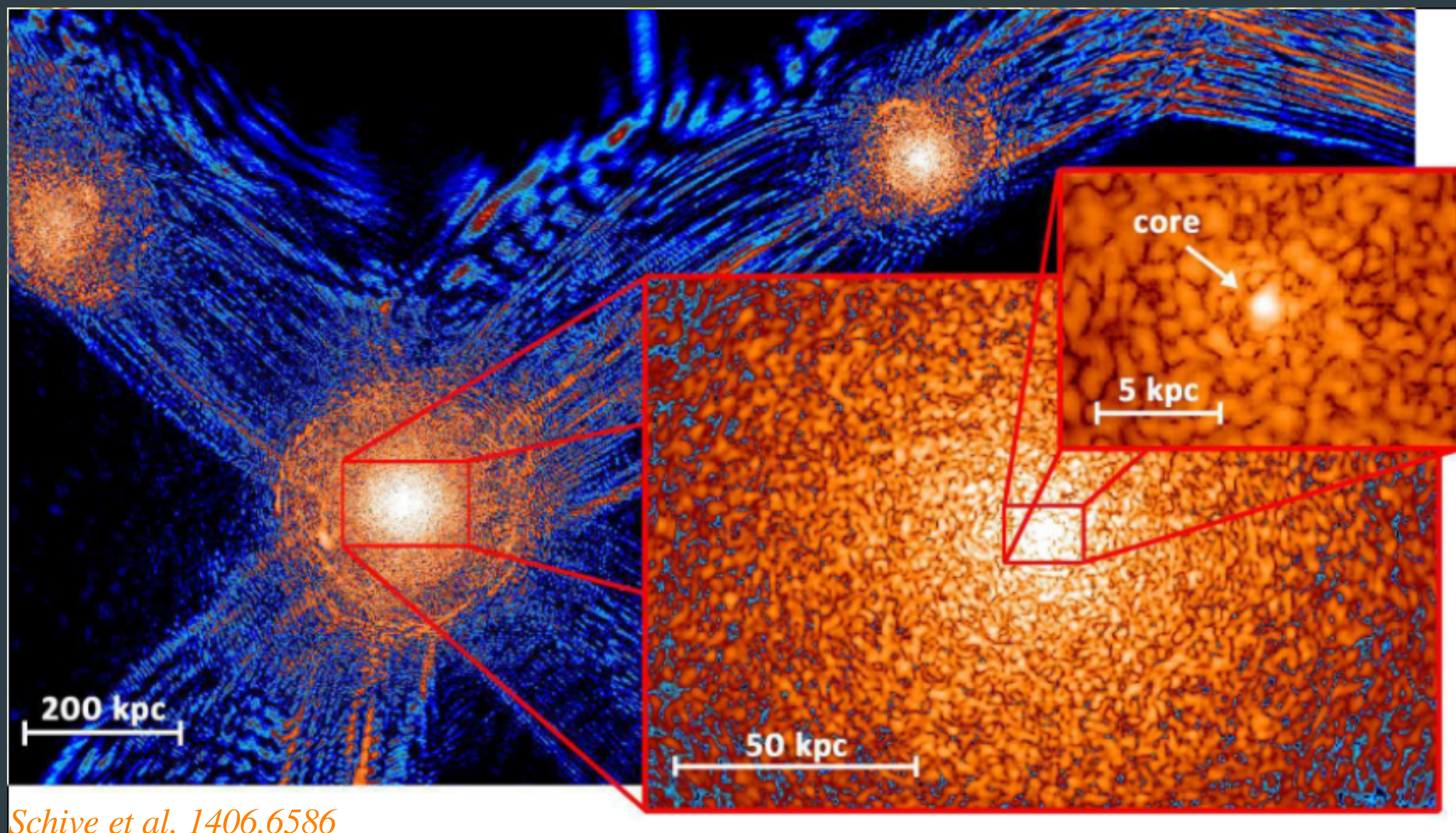
...]

FAST 26.4 h

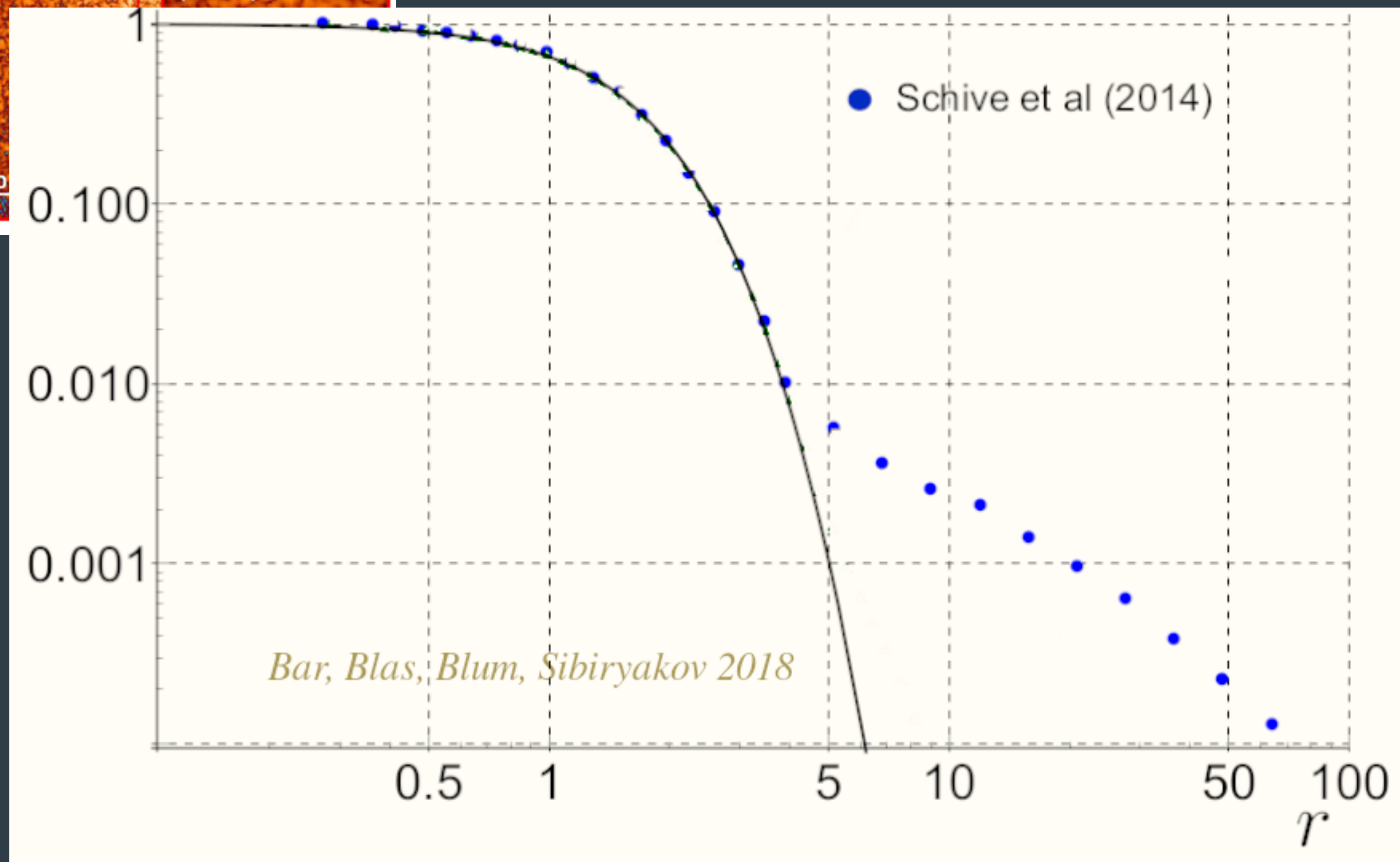
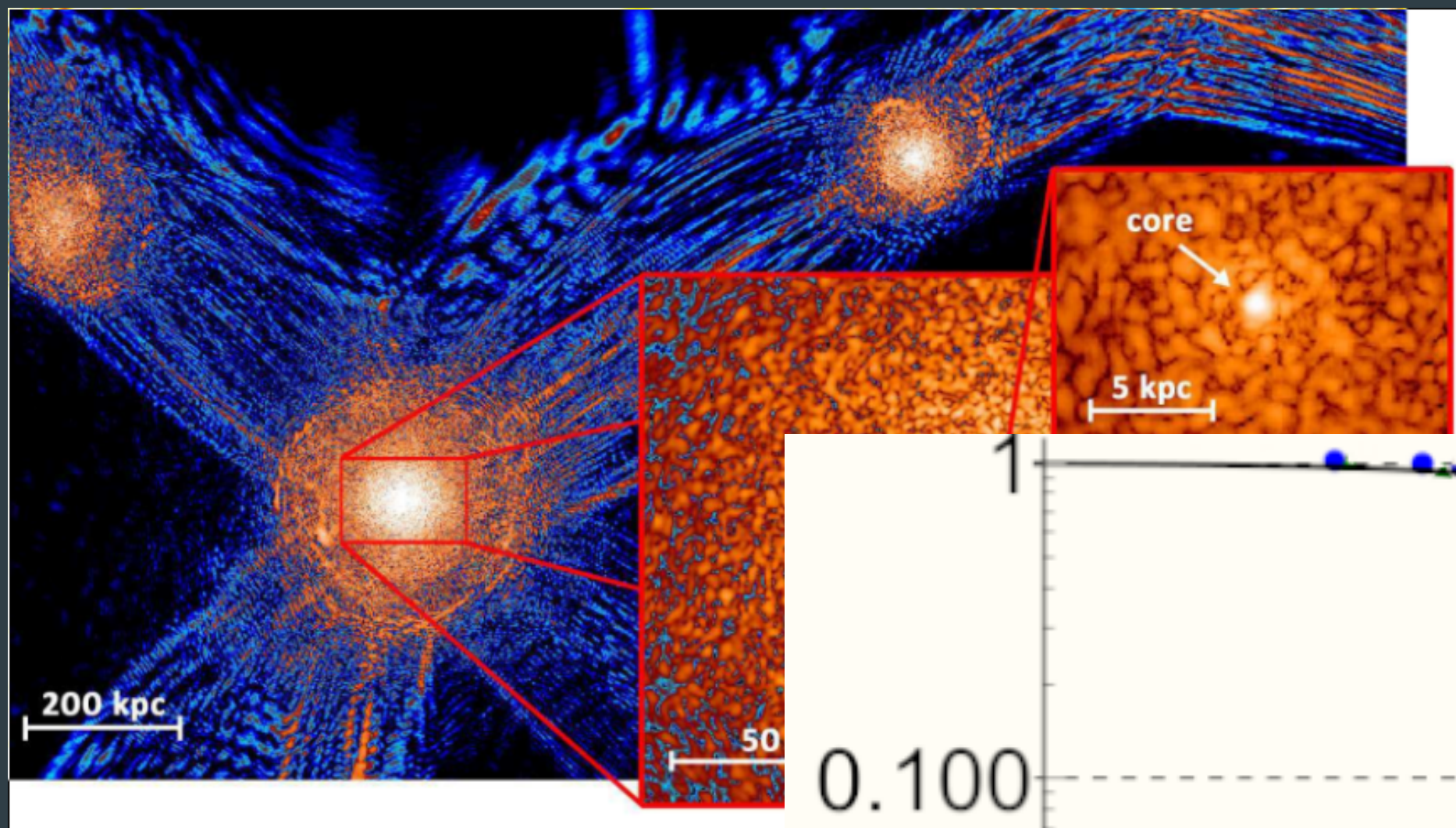
← Vela SNR

Structure formation

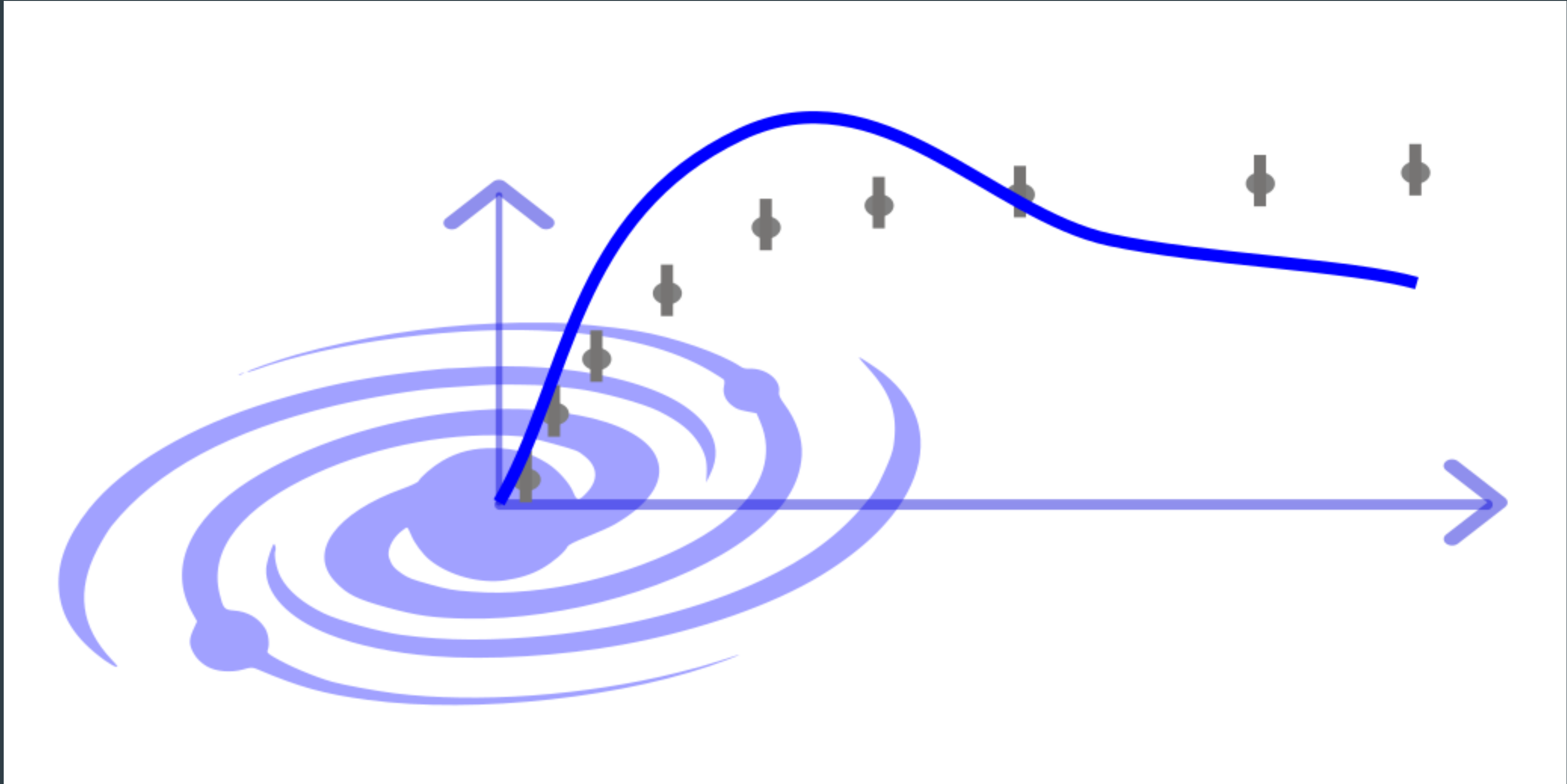
Axion DM

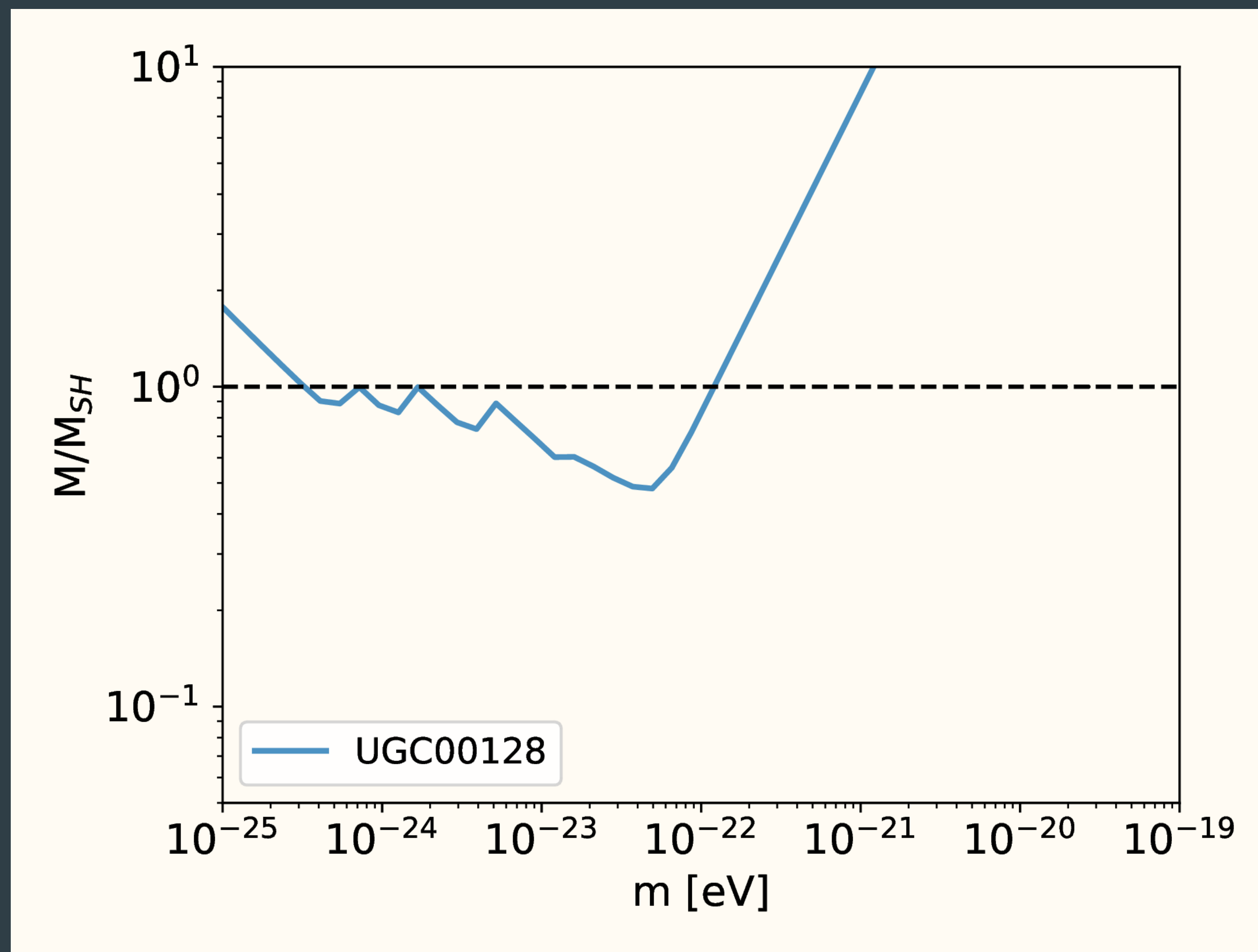


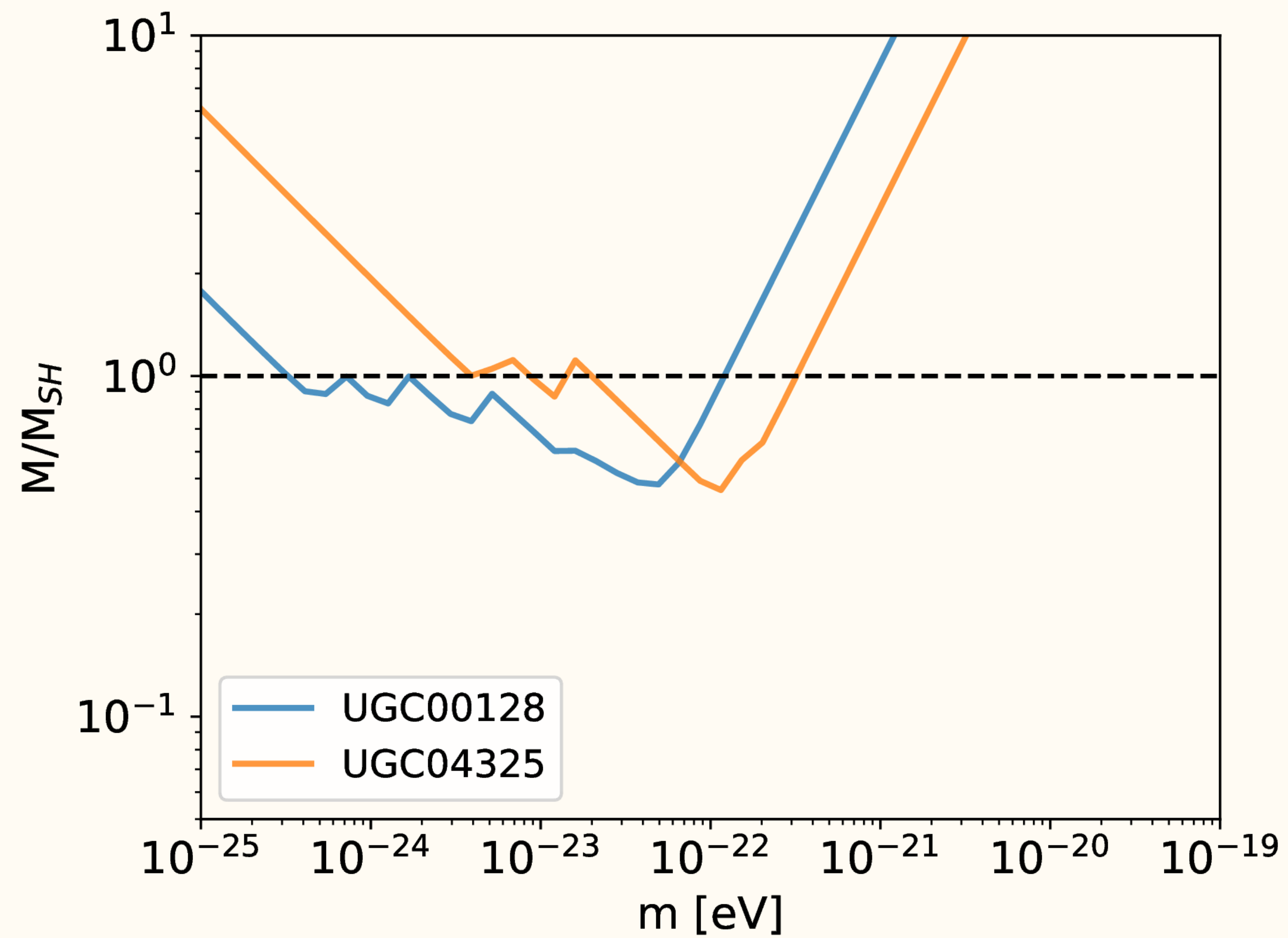
Schive et al. 1406.6586

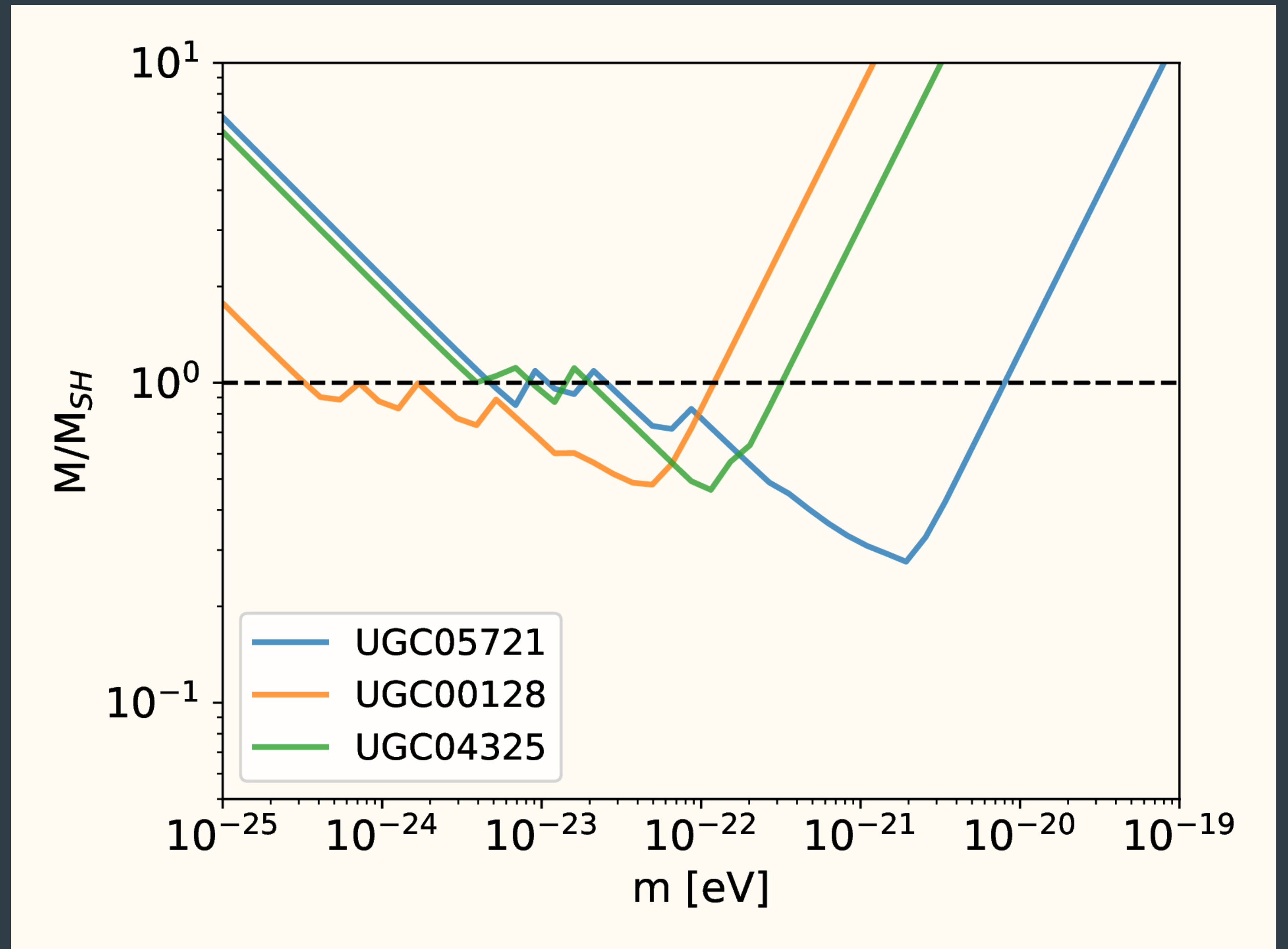


Name	T	D (Mpc)	Met.	i ($^{\circ}$)	$L_{[3.6]}$ ($10^9 L_{\odot}$)	R_{eff} (kpc)	Σ_{eff} ($L_{\odot} \text{ pc}^{-2}$)	R_d (kpc)	Σ_d ($L_{\odot} \text{ pc}^{-2}$)	M_{HI} ($10^9 M_{\odot}$)	R_{HI} (kpc)	V_f (km s^{-1})	Q	Ref.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
CamB	10	3.36 ± 0.26	2	65 ± 5	0.075 ± 0.003	1.21	7.9	0.47	66.2	0.016	...	...	2	1
D512-2	10	15.20 ± 4.56	1	56 ± 10	0.325 ± 0.022	2.37	9.2	1.24	93.9	0.108	...	...	3	2
D564-8	10	8.79 ± 0.28	2	63 ± 7	0.033 ± 0.004	0.72	10.1	0.45	30.8	0.039	...	...	3	2
D631-7	10	7.72 ± 0.18	2	59 ± 3	0.196 ± 0.009	1.22	20.9	0.70	115.0	0.385	...	57.7 ± 2.7	1	2, 3



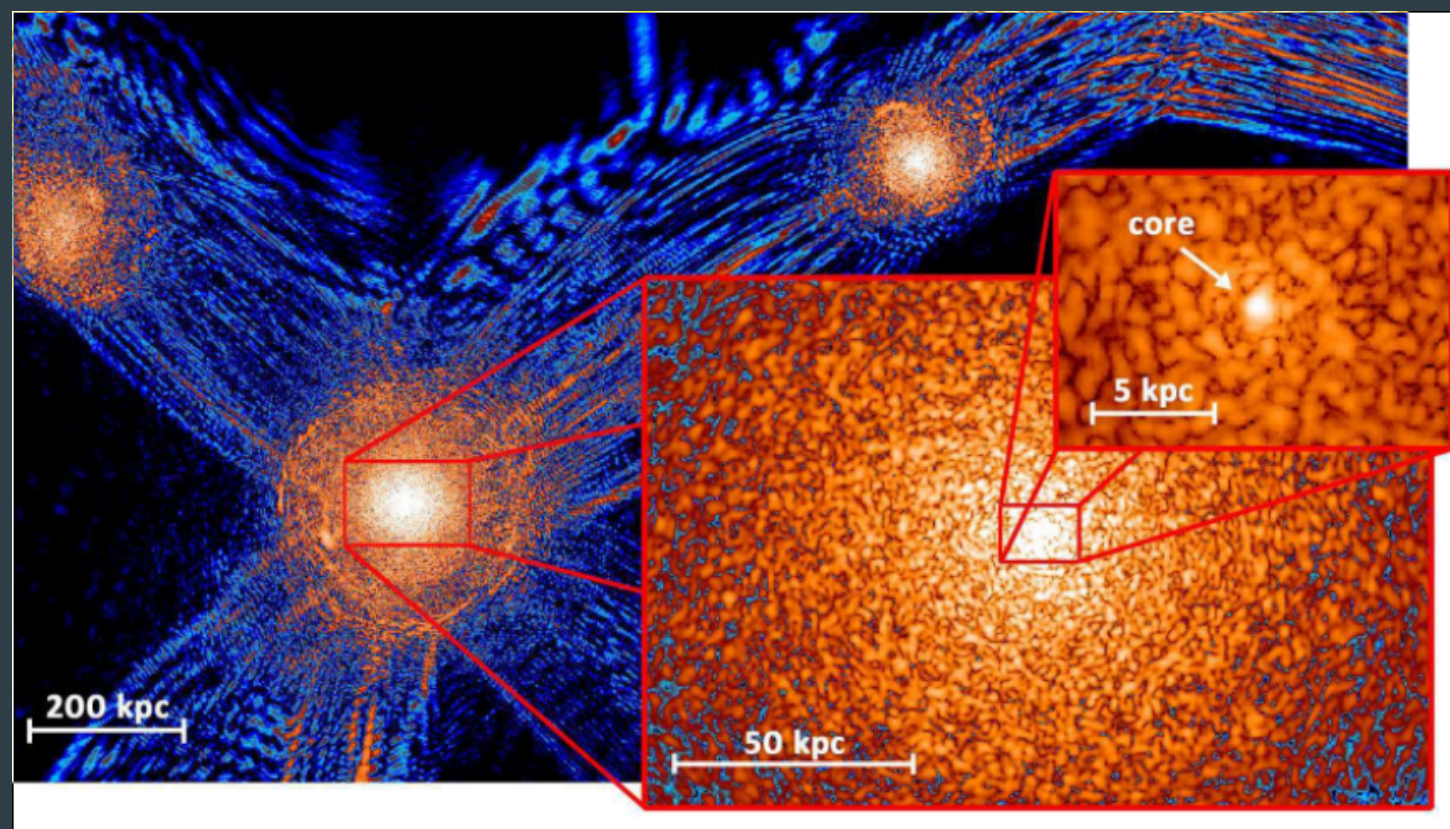




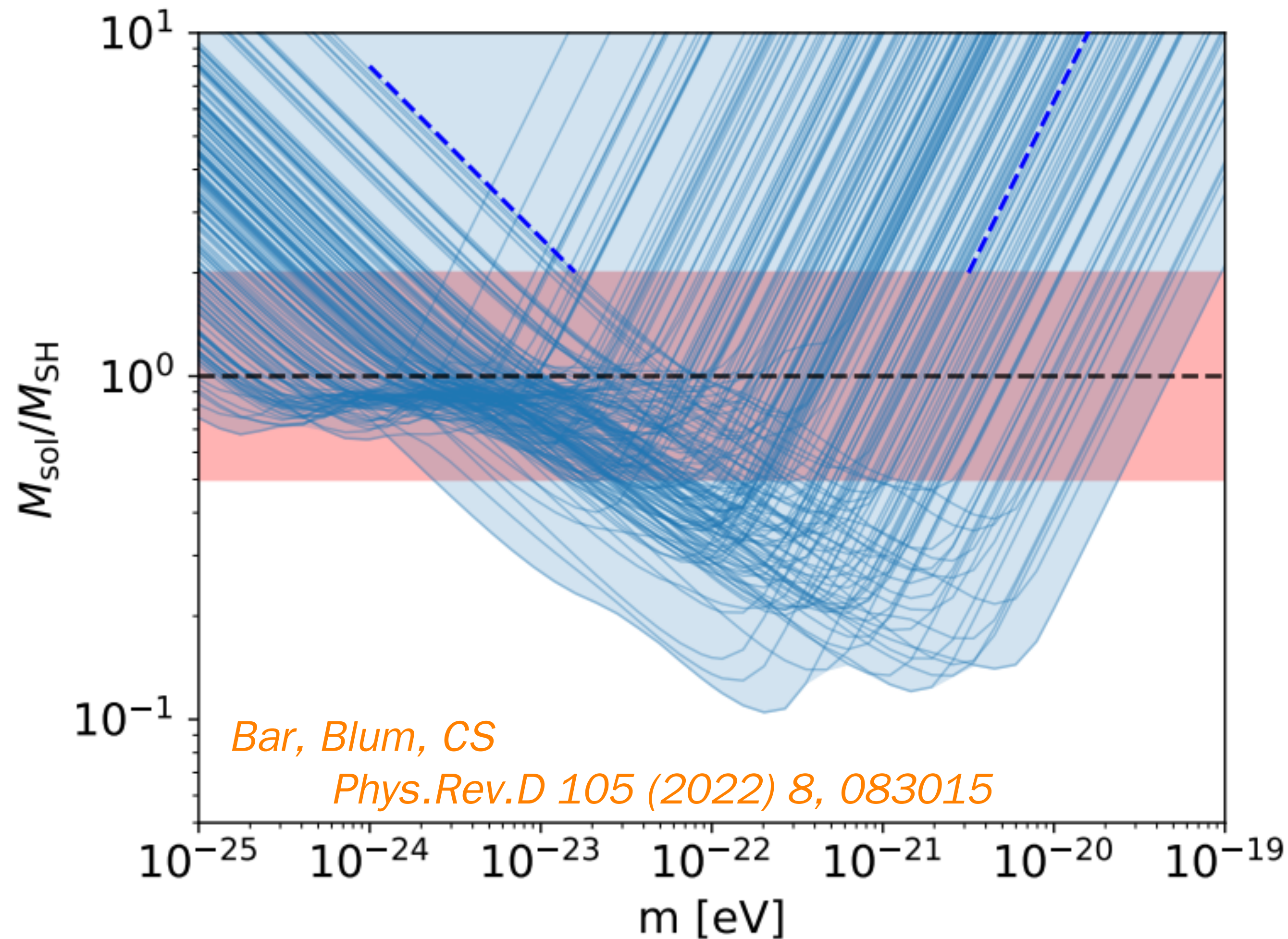


Structure formation

Axion DM

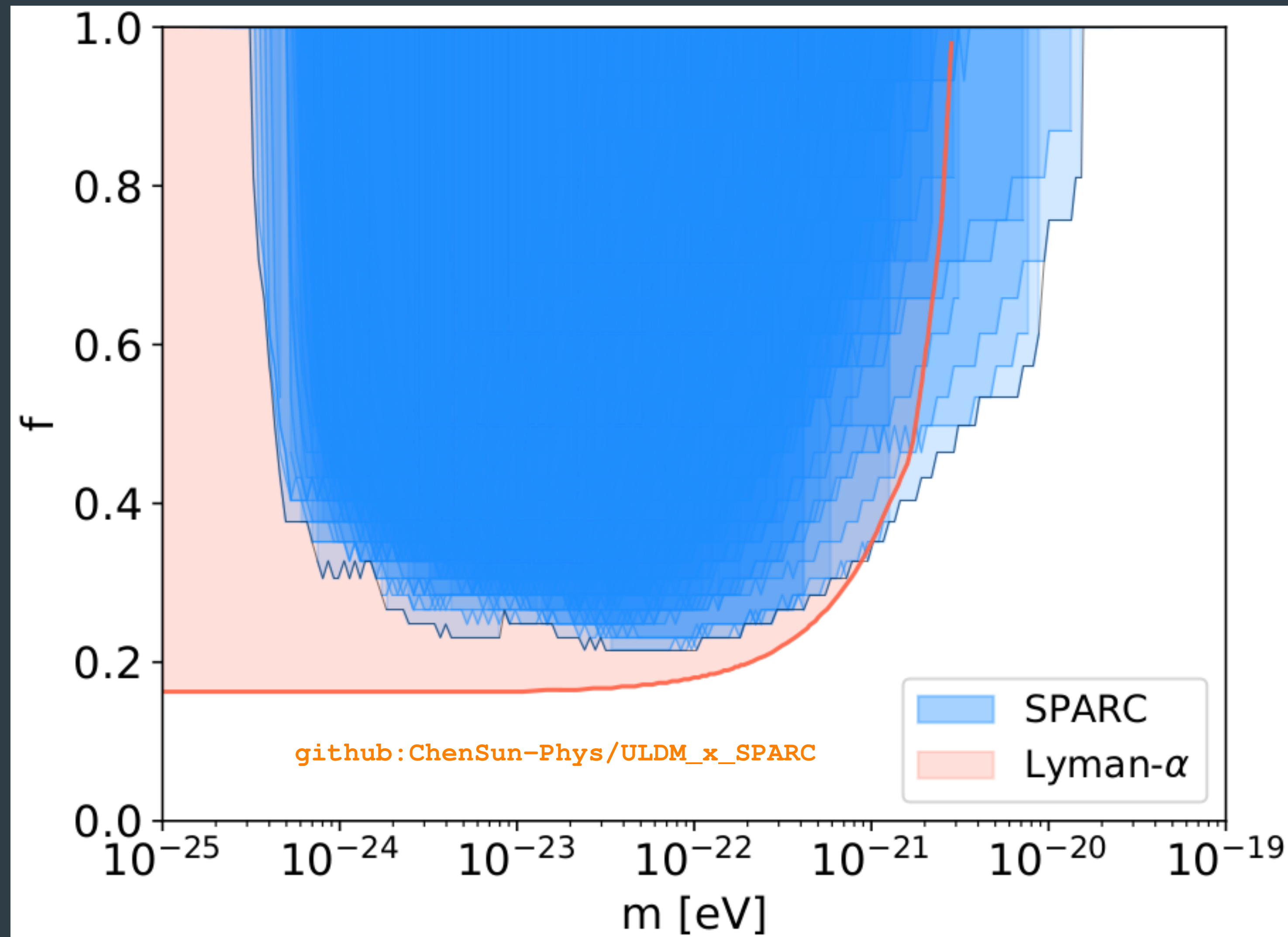


Schive et al. 1406.6586



Structure formation

Axion DM



production

1) pre-inflation ~~PQ~~

2) post-inflation ~~PQ~~

Boson Stars, and binary mergers:

Croon, Nelson, CS, Walker, Xianyu

Croon, Fan, CS

Guo, Sinha, CS

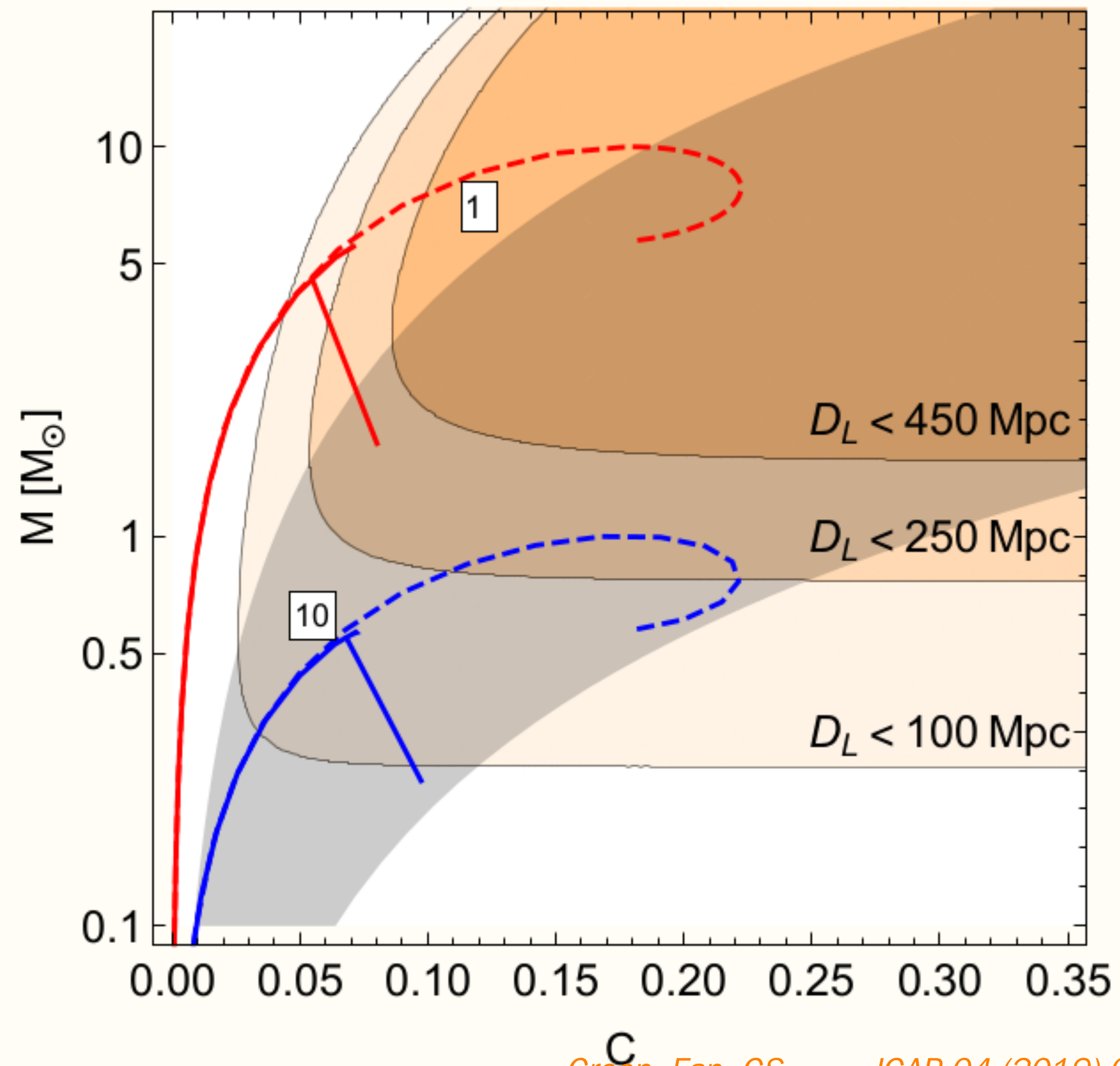
Guo, Sinha, CS et al.

Astrophys. J. Lett. 858

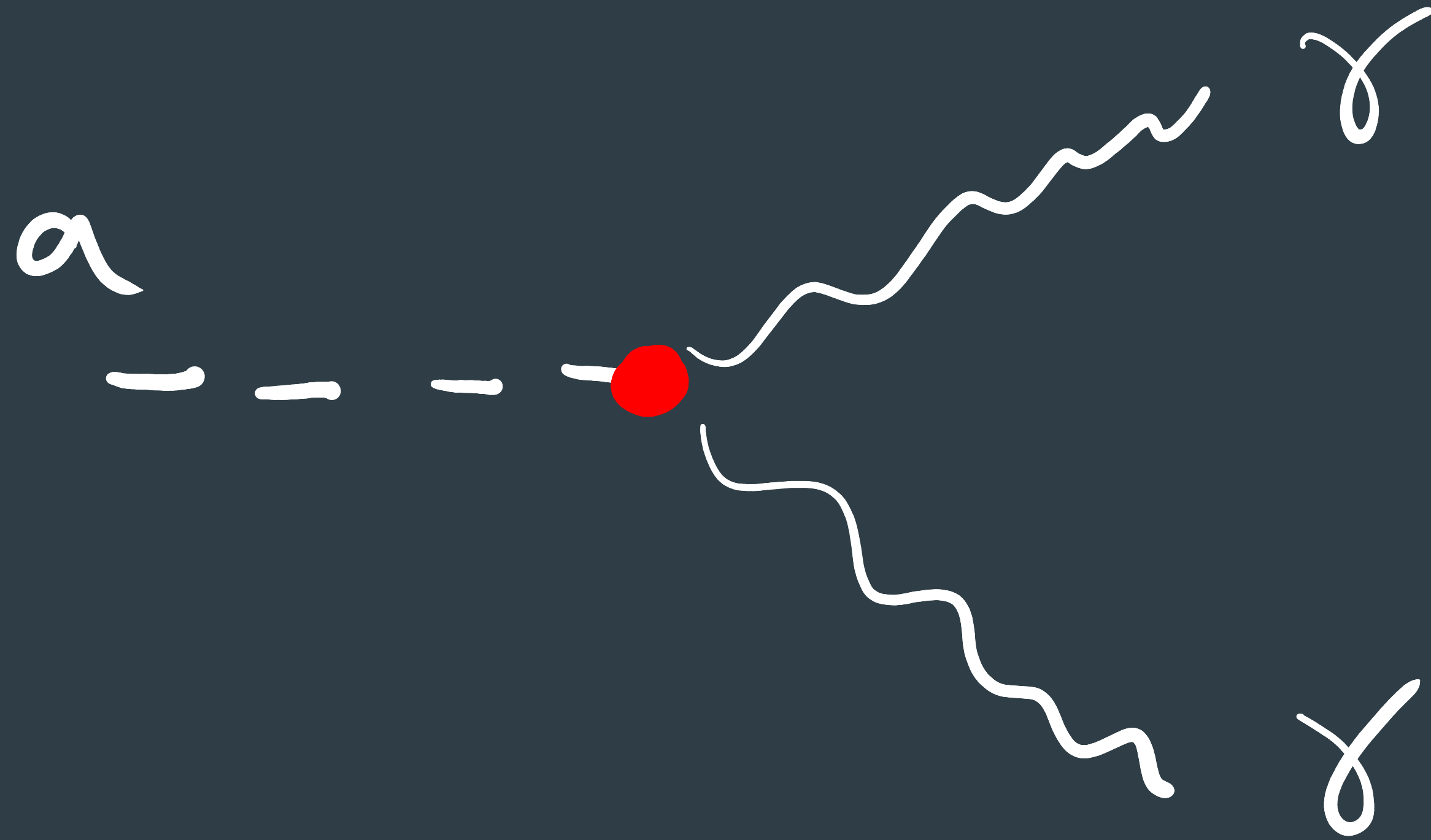
JCAP 04 (2019) 008

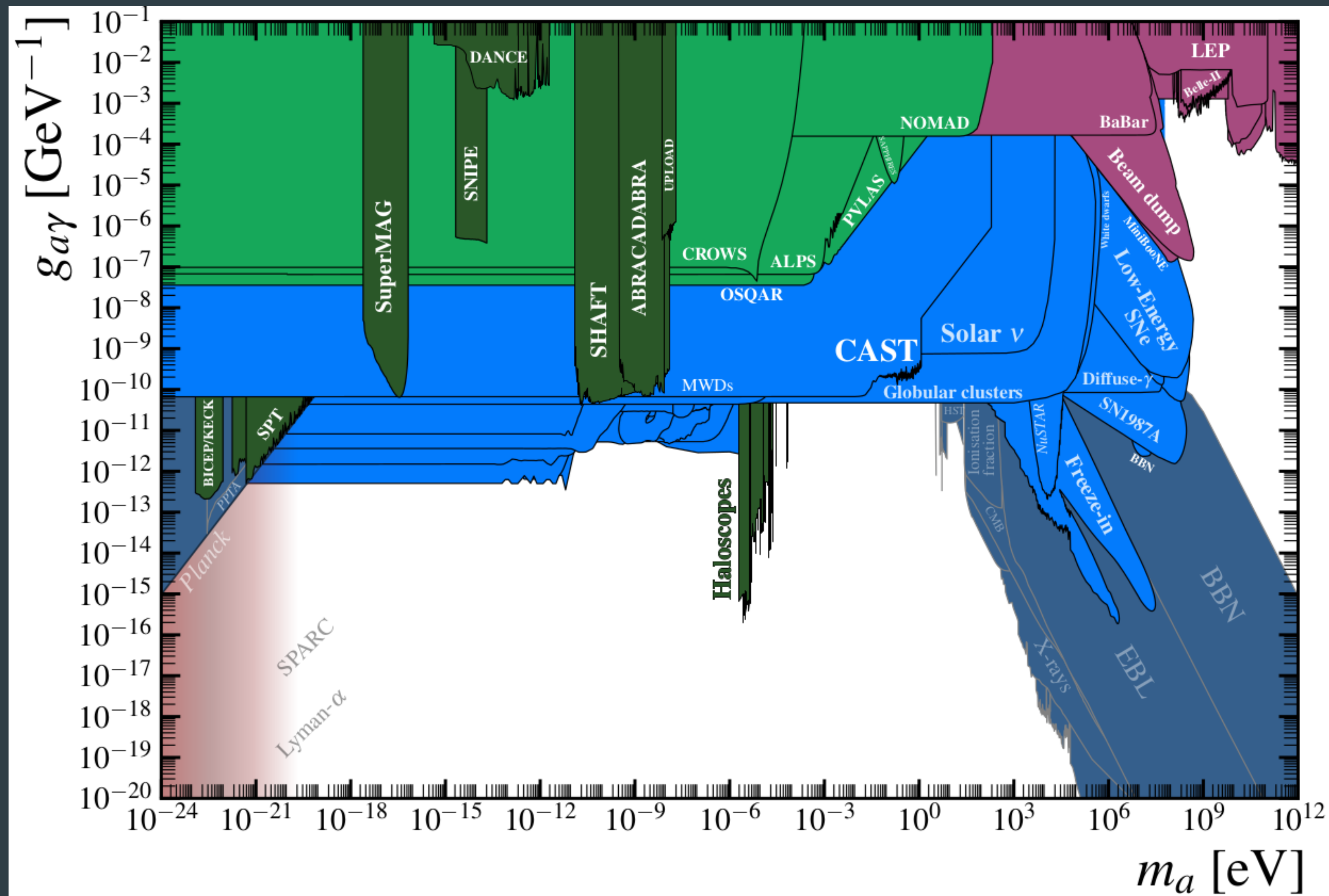
JCAP 09 (2019) 032

JCAP 10 (2021) 028



Non-Gravitational Channel





Axion-Photon

BAO, SNe, galaxy clusters

Buen-Abad, Fan, CS 2011.05993 (JHEP)

Supernova remnants (radio)

Buen-ABad, Fan, CS 2110.13916 (PRD)

Quasars (UV, X-ray)

Buen-Abad, Fan, CS 2309.07212 (JCAP)

Laboratory Search (laser)

Seong, CS, Yun 2308.10925 (PRD)

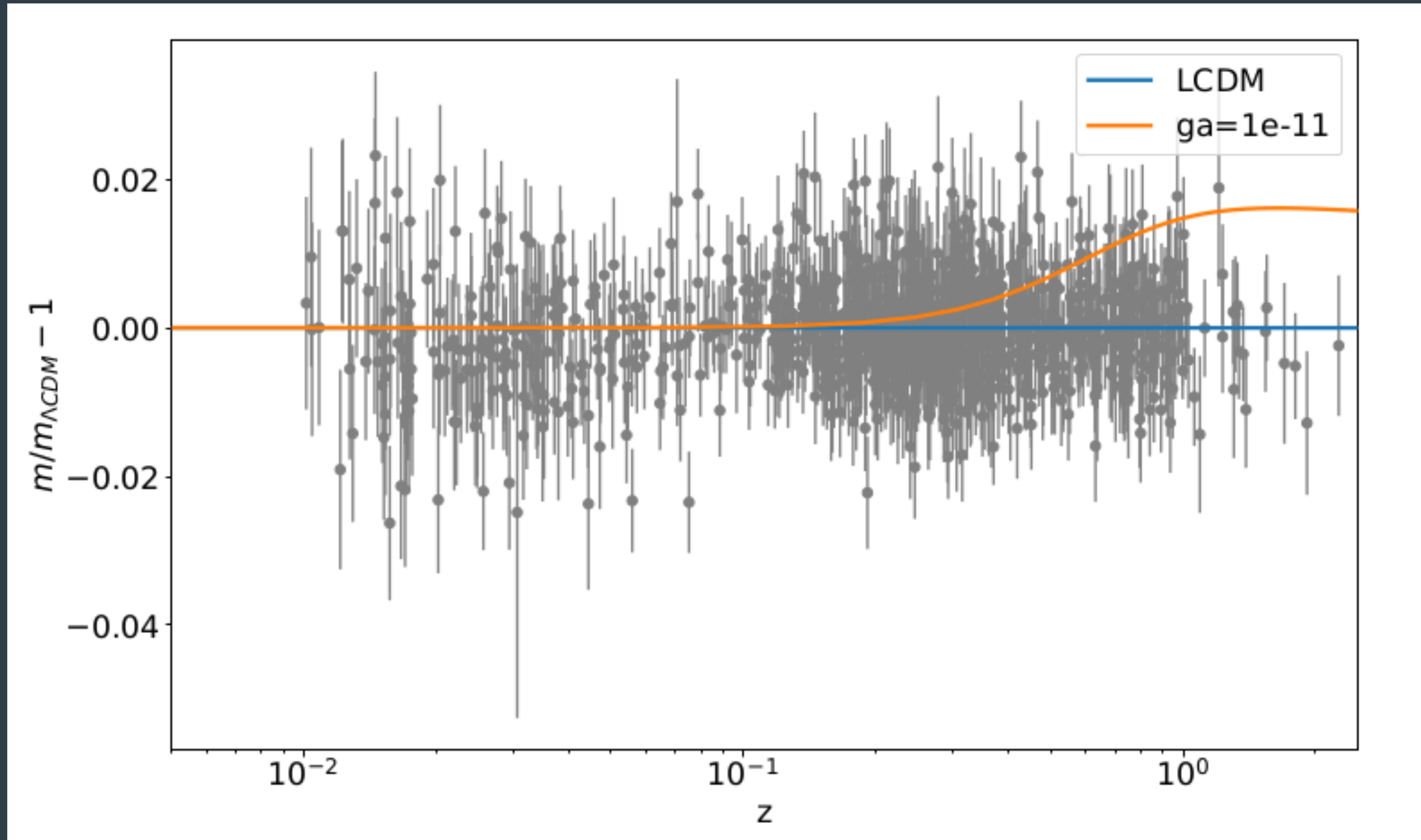
Solar axion (X-ray)

Seong, CS, Yun 2408.11103 (JHEP)

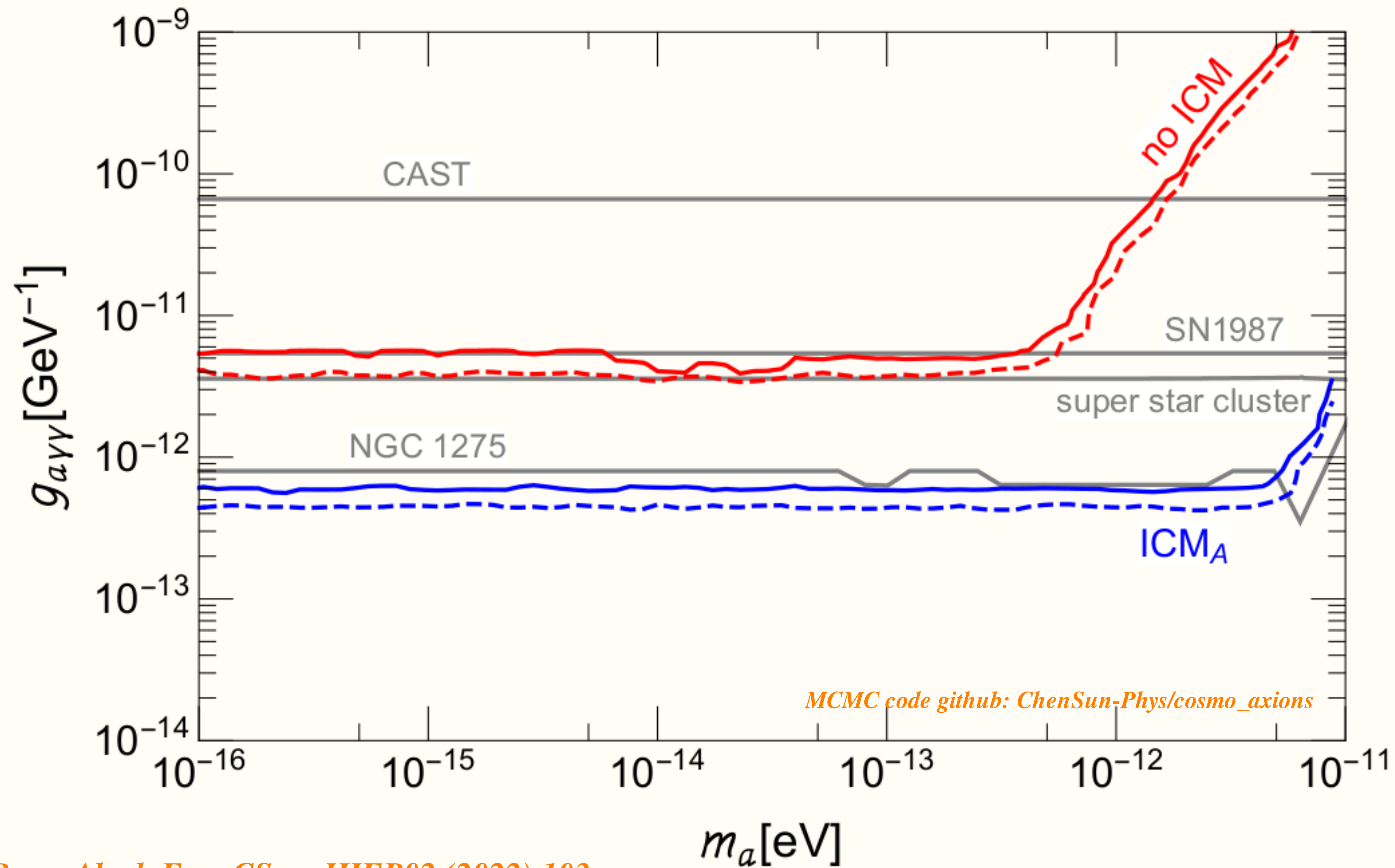
Pulsars (X-ray)

Fan, Li, CS 2501.12440 (PRL)

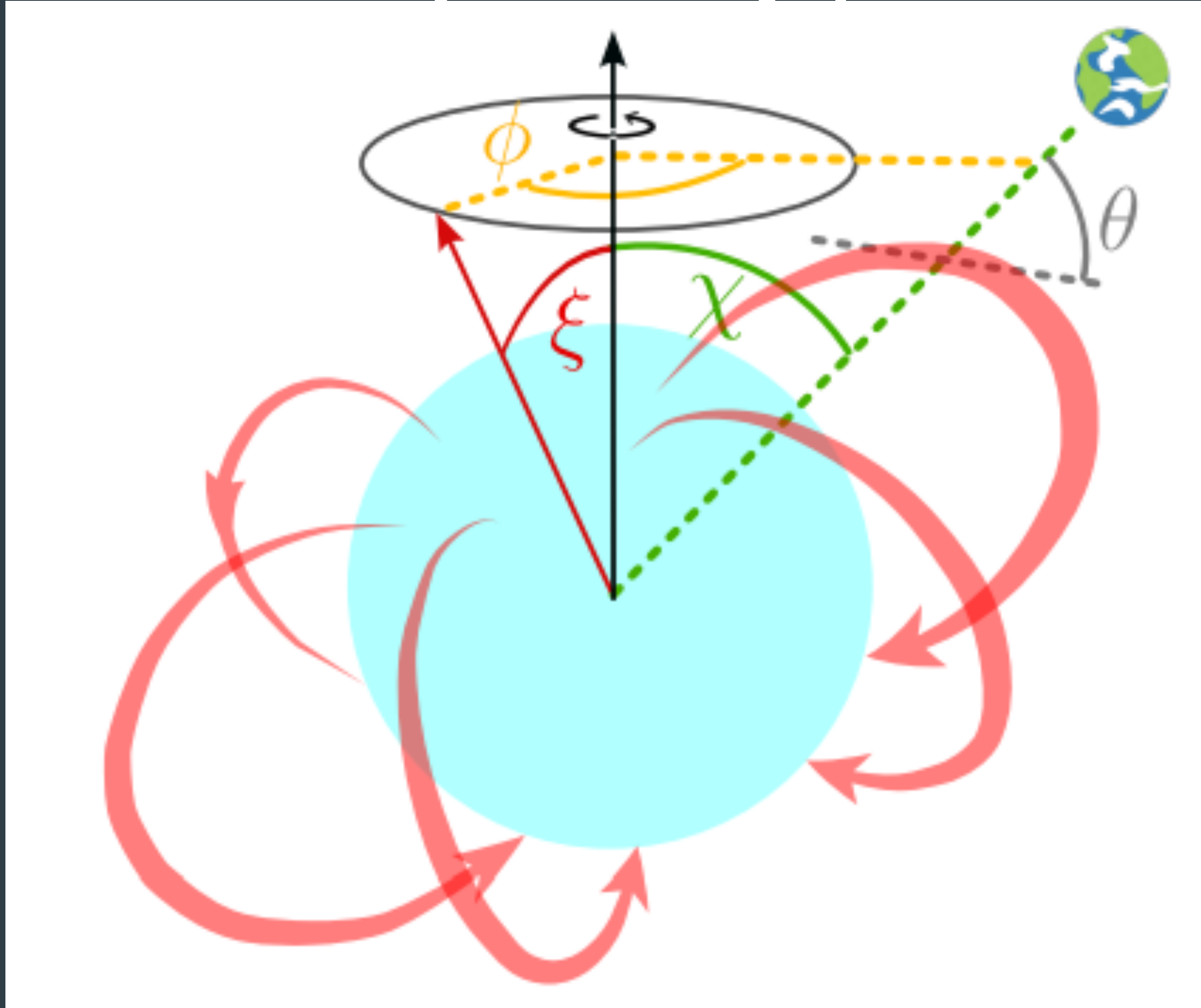
Cosmic Distance

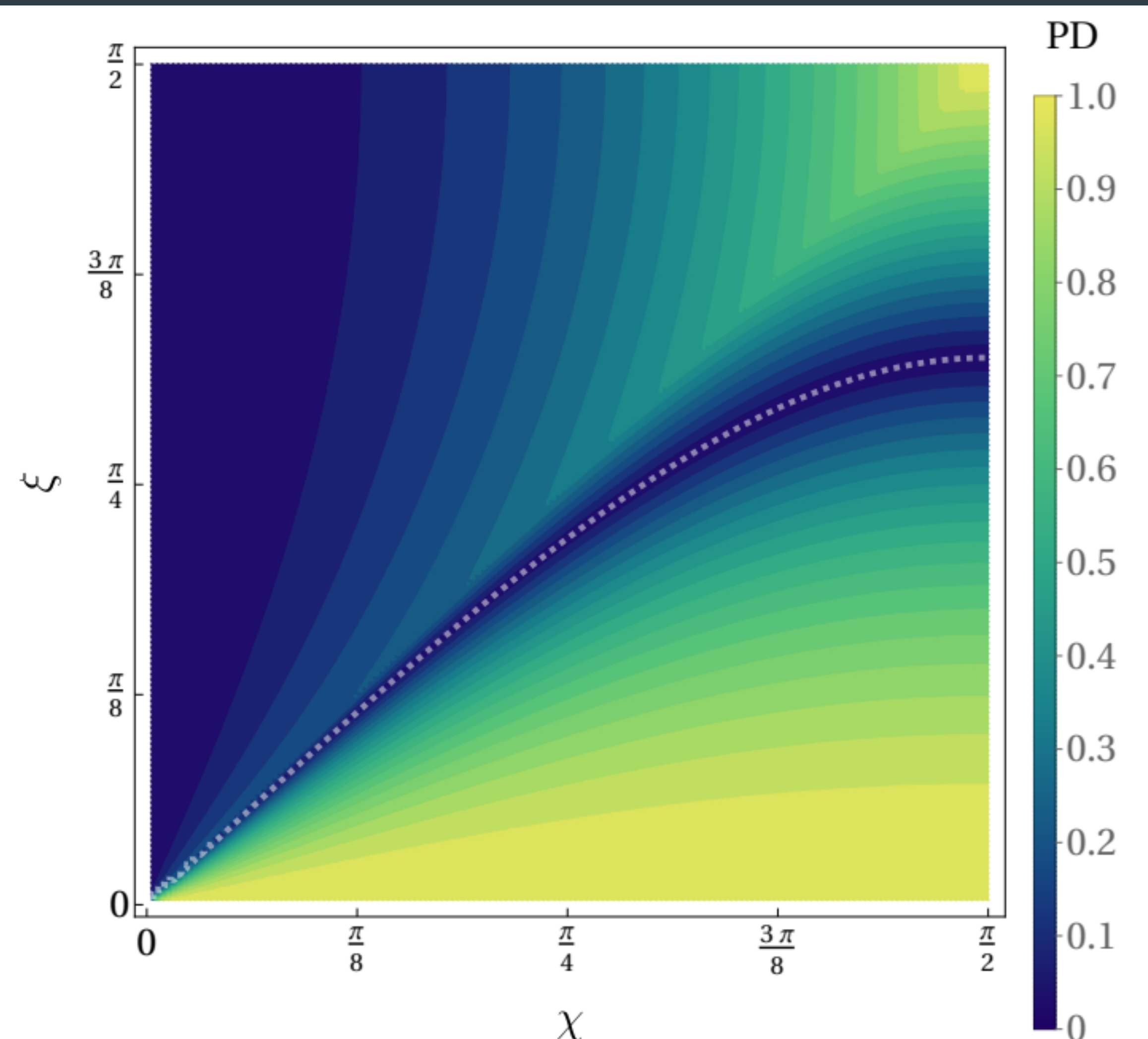
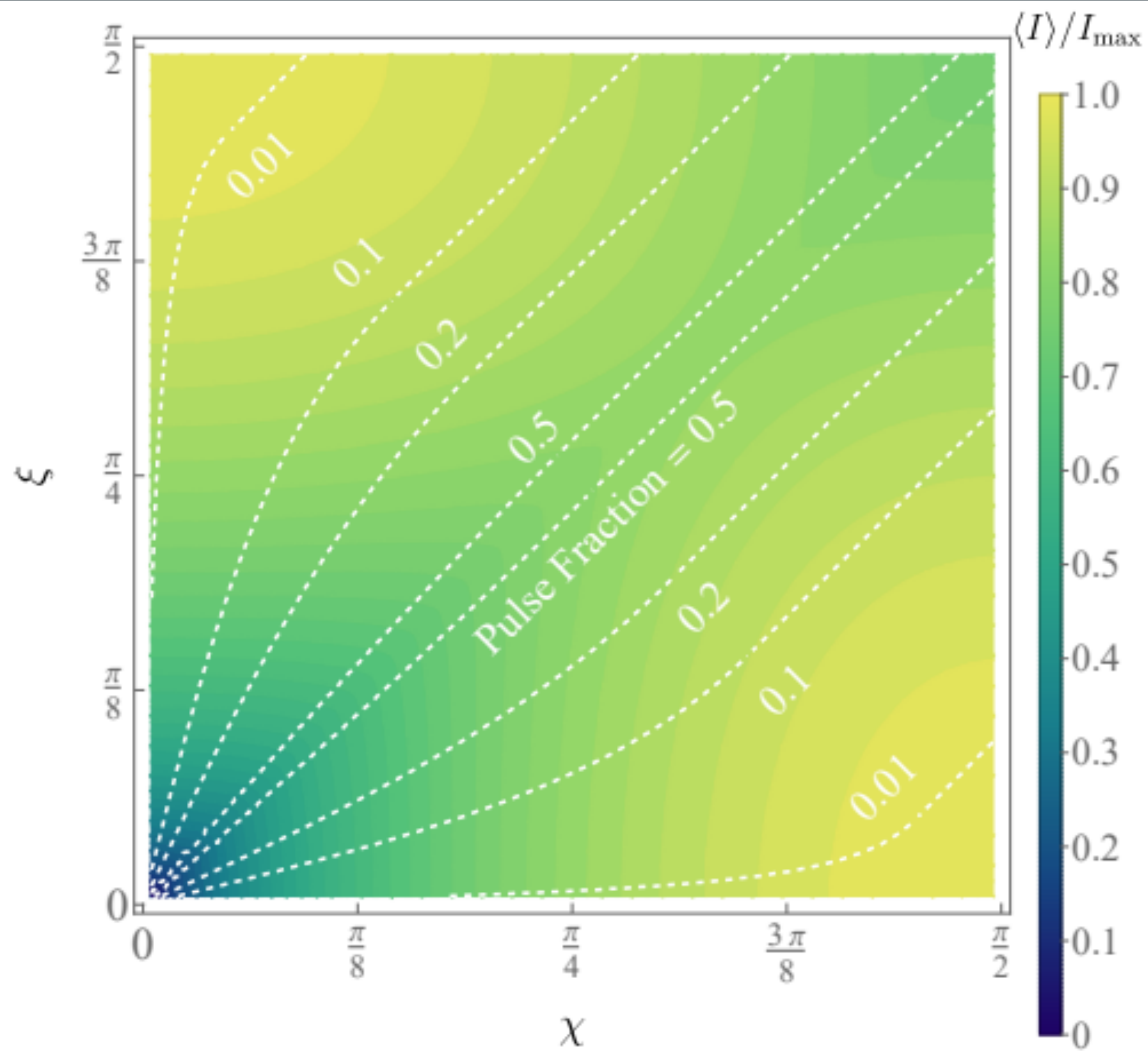


$$F(D_L) = P_{\gamma\gamma}(D_L) \frac{L}{4\pi D_L^2}$$



Neutron Star (X-ray)

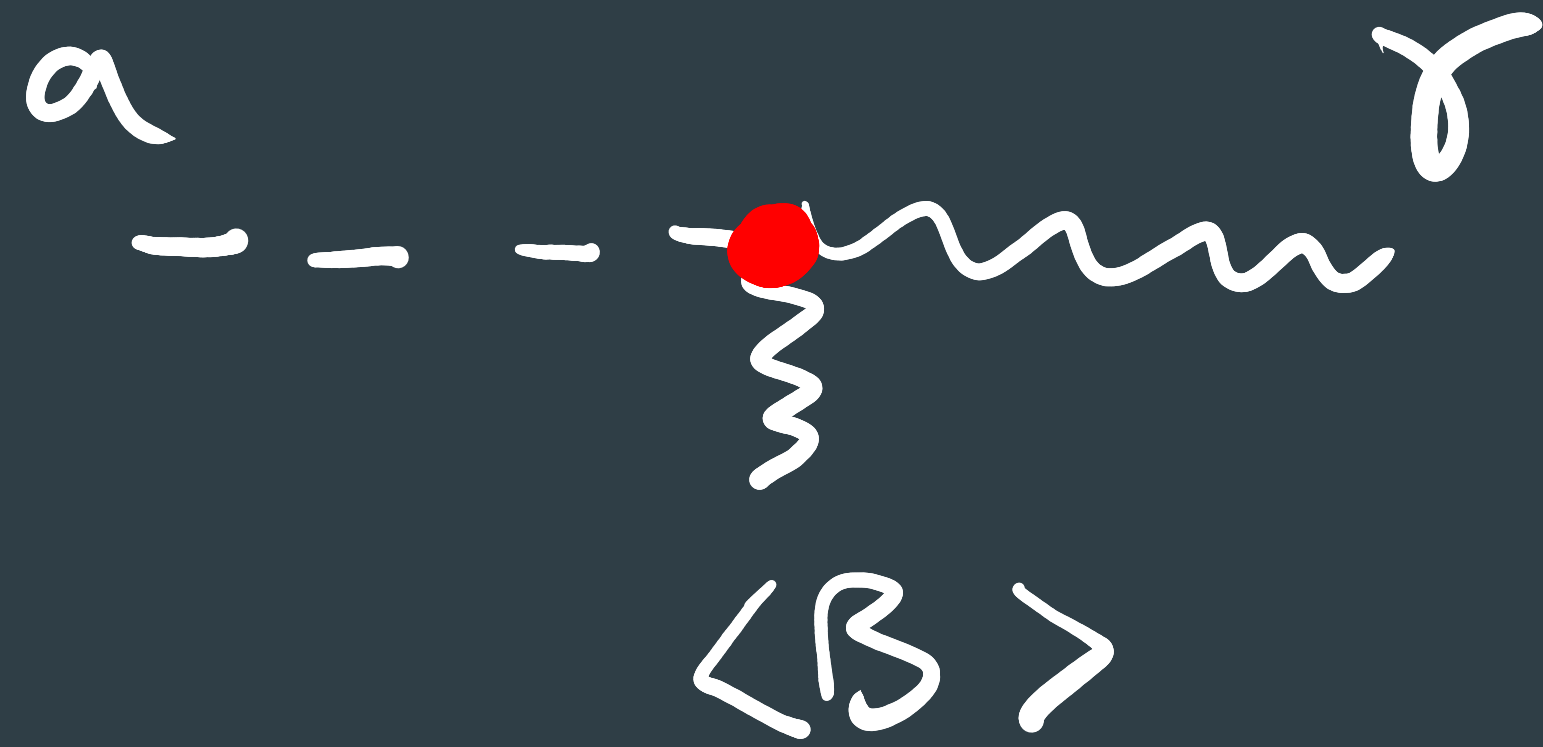




JiJi Fan, Lingfeng Li, CS

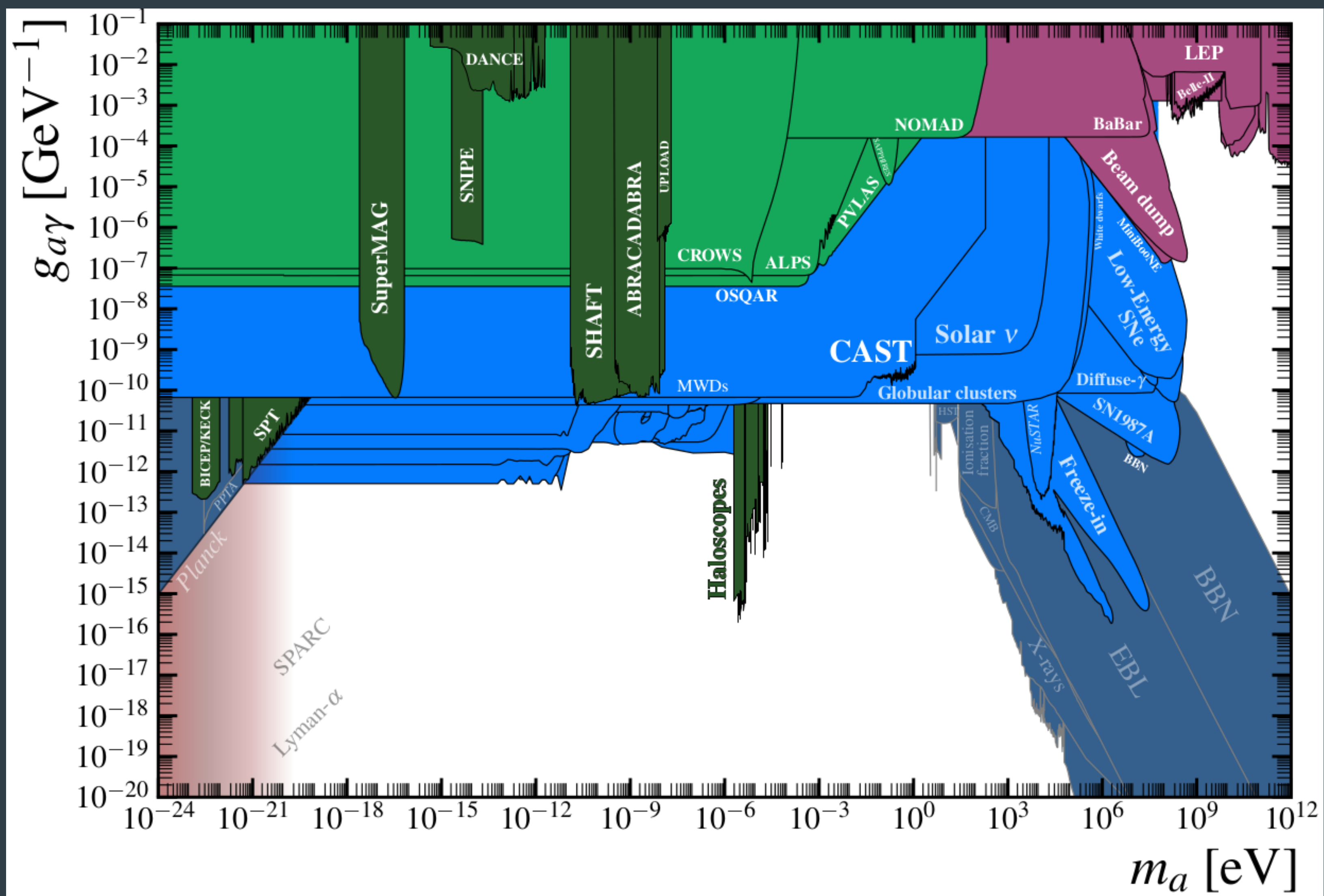
Phys.Rev.Lett. 135 (2025) 23, 231801

Future : eXTP, CATCH, etc.



$$P_{a \rightarrow \gamma} \propto \left(\frac{g_{a\gamma} B \omega}{m_a^2} \right)^2$$

large m_a



Axion

$$P_\mu P^\mu = m_a^2$$

Photon

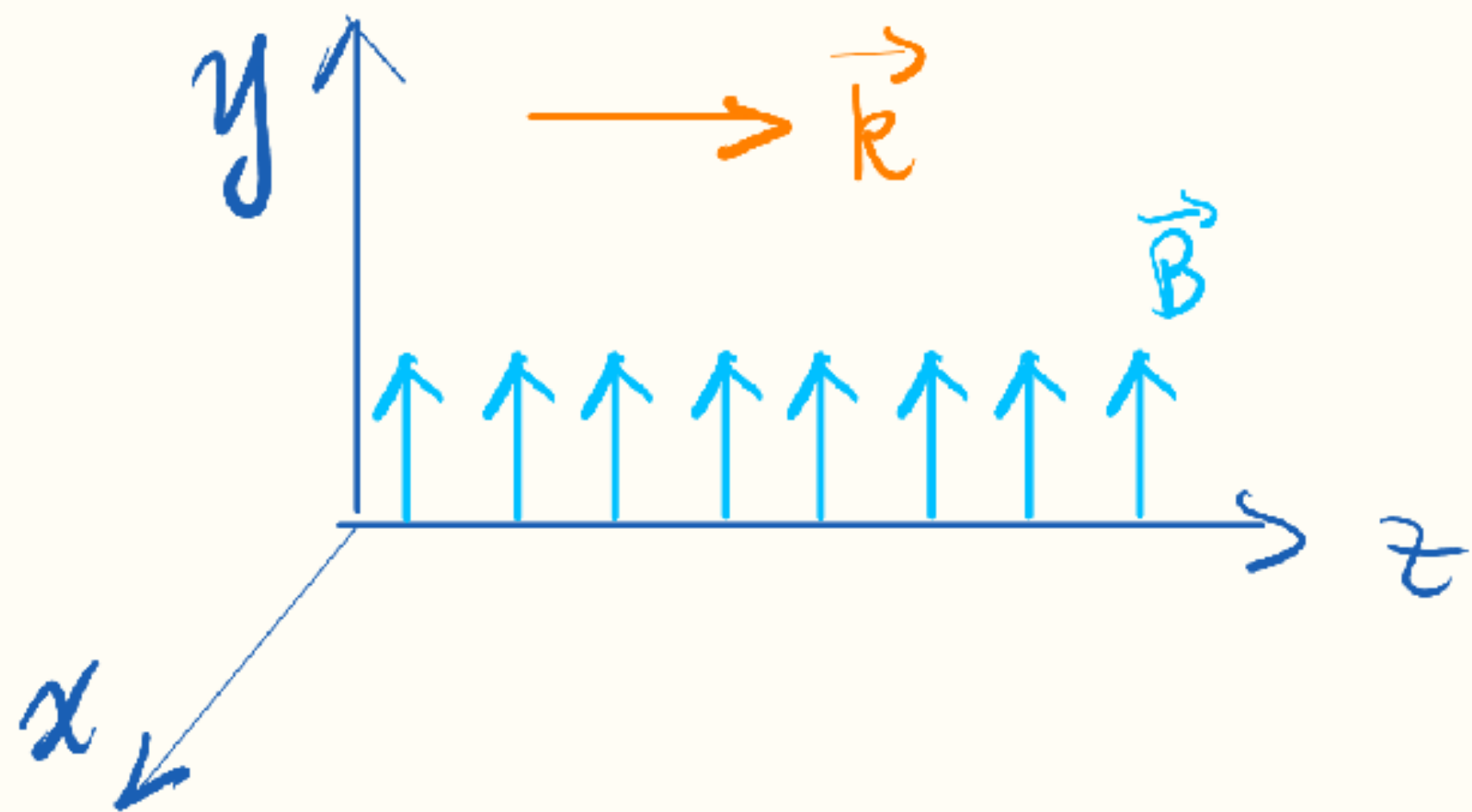
$$k_\mu k^\mu = 0$$

Mismatch

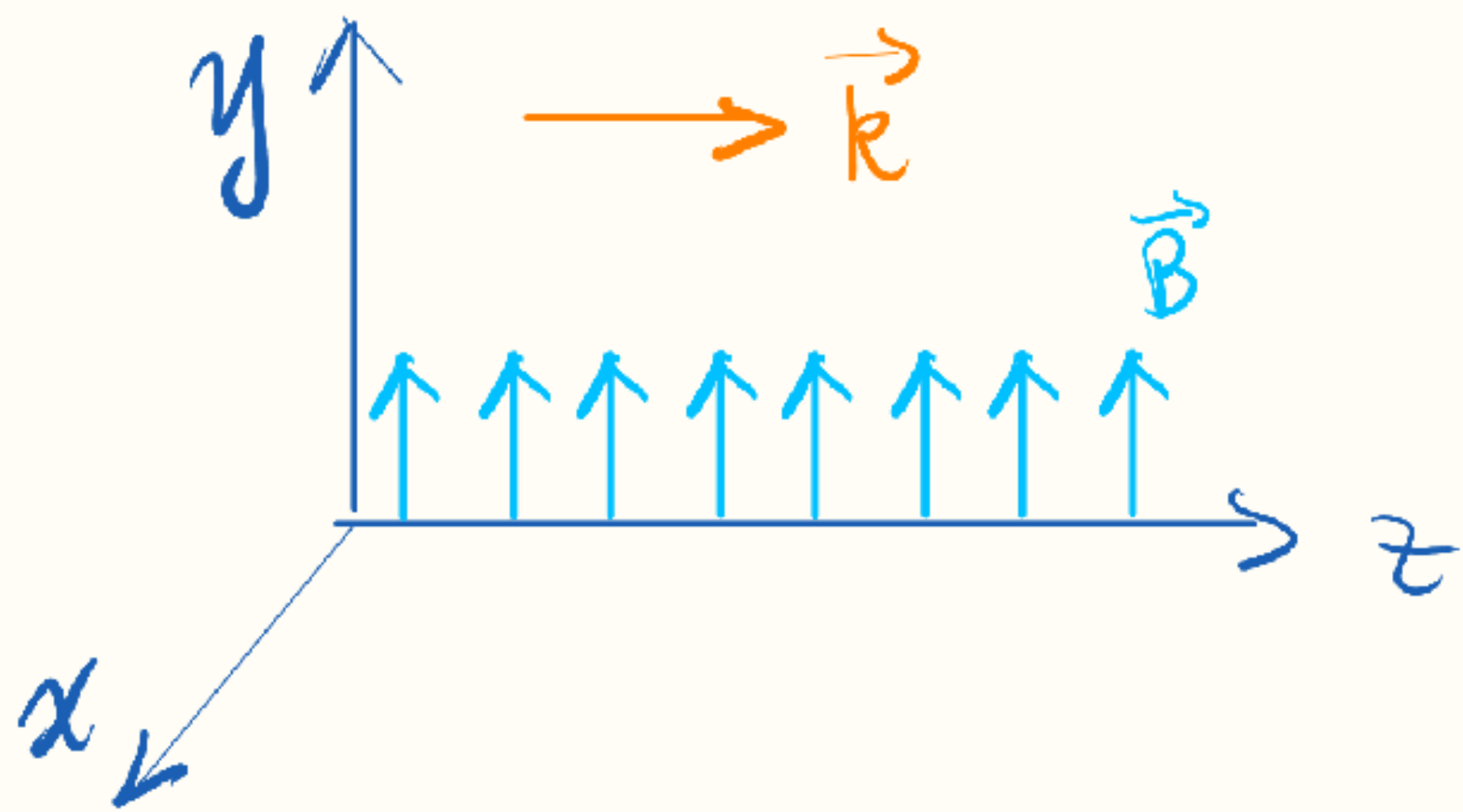


$$\text{Fix } |\vec{k}| = |\vec{p}| \Rightarrow E_\gamma - E_a \approx \frac{m_a^2}{2|\vec{k}|} \gg \frac{1}{L}$$

$\Rightarrow$ fast oscillation $a \leftrightarrow \gamma$.



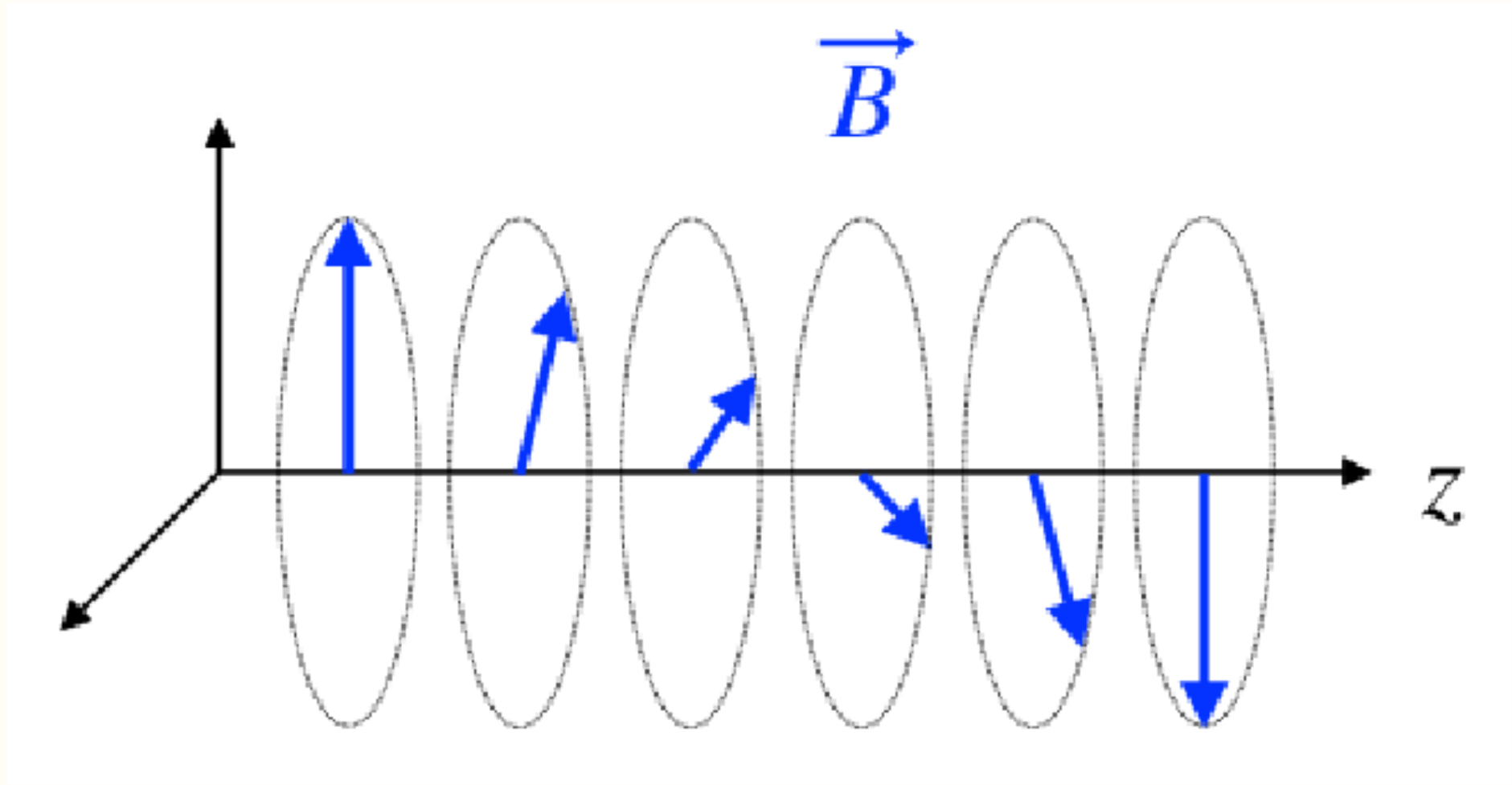
$$i\partial_z \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix} = \frac{1}{2\omega} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & g_{a\gamma}\omega B \\ 0 & g_{a\gamma}\omega B & m_a^2 \end{bmatrix} \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix},$$



$$\mathcal{M}_{a \rightarrow \gamma_y} = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} U \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i \frac{m_a^2}{2\omega} z} \end{bmatrix} U^\dagger \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

$$P_{a \rightarrow \gamma_y} = |\mathcal{M}_{a \rightarrow \gamma_y}|^2$$

$$\simeq \frac{g_{a\gamma}^2 B^2}{g_{a\gamma}^2 B^2 + m_a^4/4\omega^2} \sin^2 \left(\left(\frac{1}{2} \sqrt{g_{a\gamma}^2 B^2 + \frac{m_a^4}{4\omega^2}} \right) z \right)$$



$$i\partial_z \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix} = \frac{1}{2\omega} \begin{bmatrix} 0 & 0 & g_{a\gamma}\omega B s_\theta \\ 0 & 0 & g_{a\gamma}\omega B c_\theta \\ g_{a\gamma}\omega B s_\theta & g_{a\gamma}\omega B c_\theta & m_a^2 \end{bmatrix} \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix}$$

$$\theta = \theta(z)$$

$$V^\dagger i\partial_z \left(V(z) \begin{bmatrix} \gamma'_x \\ \gamma'_y \\ a' \end{bmatrix} \right) = \left(V^\dagger \begin{bmatrix} 0 & 0 & \frac{g_{a\gamma}B}{2}s_\theta \\ 0 & 0 & \frac{g_{a\gamma}B}{2}c_\theta \\ \frac{g_{a\gamma}B}{2}s_\theta & \frac{g_{a\gamma}B}{2}c_\theta & m_a^2/2\omega \end{bmatrix} V \right) \begin{bmatrix} \gamma'_x \\ \gamma'_y \\ a' \end{bmatrix}$$

$$\theta = \theta(z)$$

$$i\partial_z \begin{bmatrix} \gamma'_x \\ \gamma'_y \\ a' \end{bmatrix} = \left(\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & \frac{g_{a\gamma}B}{2} \\ 0 & \frac{g_{a\gamma}B}{2} & m_a^2/2\omega \end{bmatrix} - \textcolor{brown}{V}^\dagger i\partial_z \textcolor{brown}{V} \right) \begin{bmatrix} \gamma'_x \\ \gamma'_y \\ a' \end{bmatrix}$$

$$\theta = \theta(z)$$

$$i\partial_z \begin{bmatrix} \gamma''_x \\ \gamma''_y \\ a'' \end{bmatrix} = \begin{bmatrix} -\dot{\theta} & 0 & \frac{g_{a\gamma}B}{2\sqrt{2}} \\ 0 & \dot{\theta} & \frac{g_{a\gamma}B}{2\sqrt{2}} \\ \frac{g_{a\gamma}B}{2\sqrt{2}} & \frac{g_{a\gamma}B}{2\sqrt{2}} & m_a^2/2\omega \end{bmatrix} \begin{bmatrix} \gamma''_x \\ \gamma''_y \\ a'' \end{bmatrix}$$

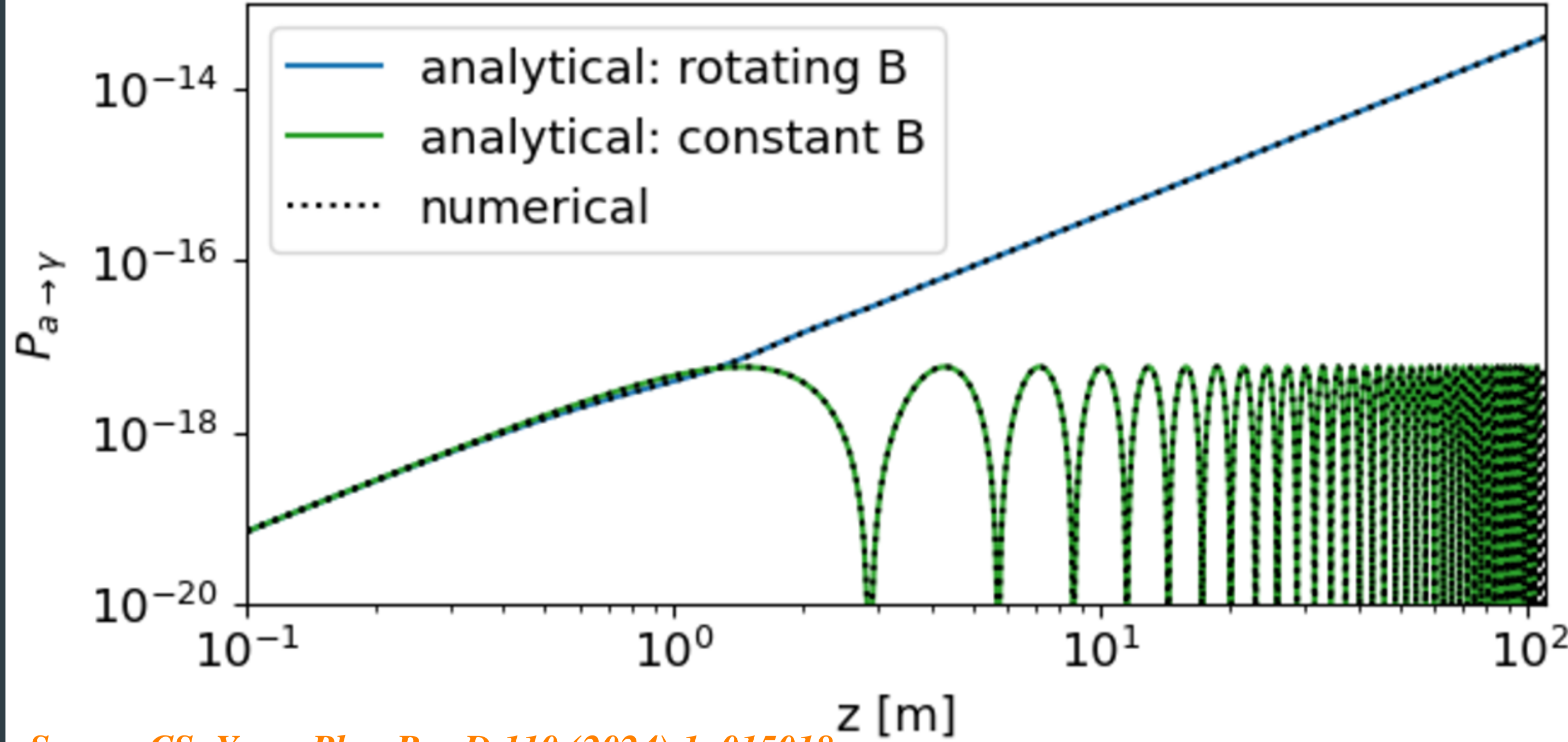
$$\theta = \theta(z)$$

$$i\partial_z \begin{bmatrix} \gamma''_x \\ \gamma''_y \\ a'' \end{bmatrix} = \begin{bmatrix} -\dot{\theta} & 0 & \frac{g_{a\gamma}B}{2\sqrt{2}} \\ 0 & \dot{\theta} & \frac{g_{a\gamma}B}{2\sqrt{2}} \\ \frac{g_{a\gamma}B}{2\sqrt{2}} & \frac{g_{a\gamma}B}{2\sqrt{2}} & m_a^2/2\omega \end{bmatrix} \begin{bmatrix} \gamma''_x \\ \gamma''_y \\ a'' \end{bmatrix}$$

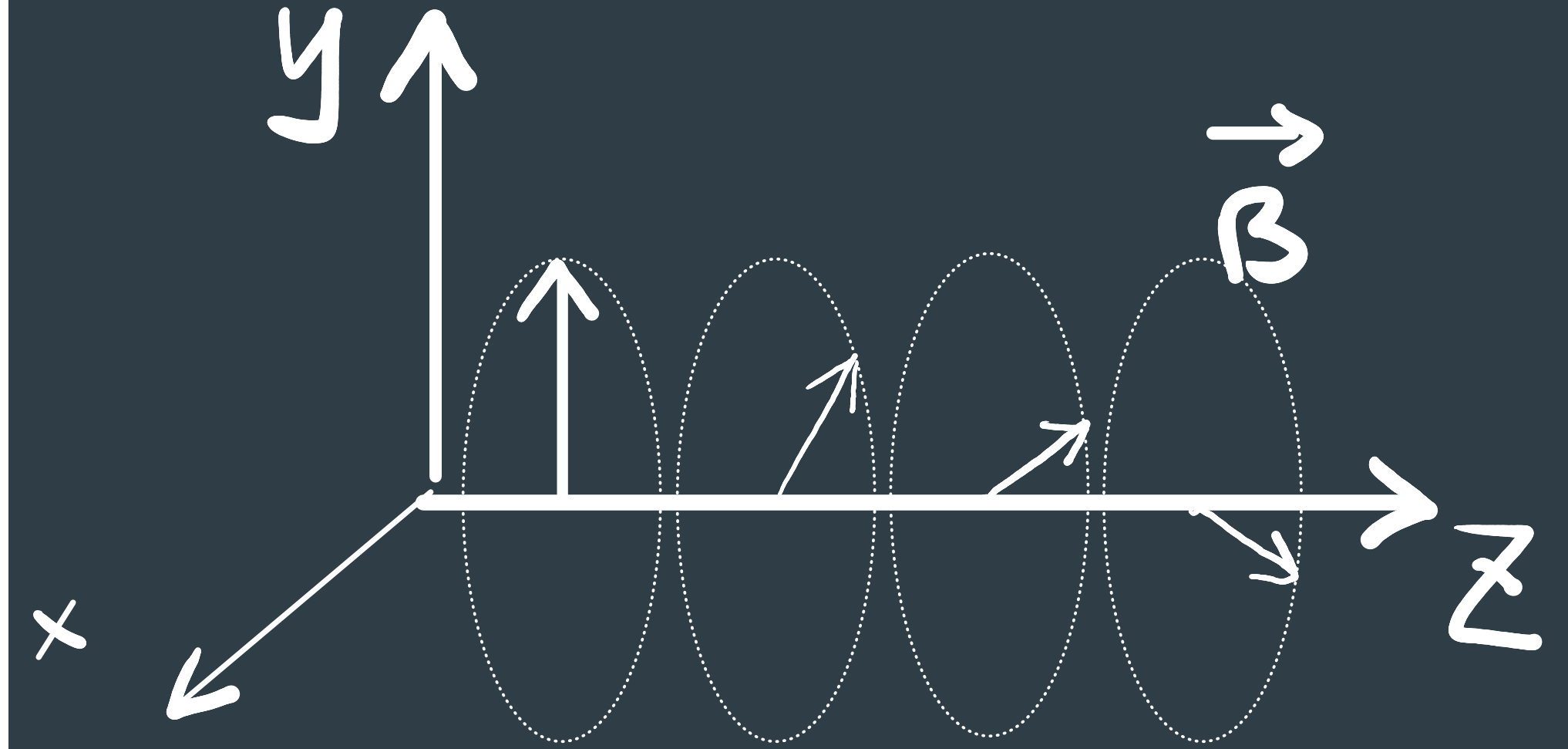
$$\theta = \theta(z)$$

$$P_{a\rightarrow\gamma} \simeq \sum_{\pm} \frac{g_{a\gamma}^2 B^2/2}{g_{a\gamma}^2 B^2/2 + (m_a^2/2\omega \pm \dot{\theta})^2} \sin^2 \left(\left(\frac{1}{2} \sqrt{\frac{g_{a\gamma}^2 B^2}{2} + (\frac{m_a^2}{2\omega} \pm \dot{\theta})^2} \right) z \right),$$

 [Github: ChenSun-Phys/axion-magnetic-resonance](https://github.com/ChenSun-Phys/axion-magnetic-resonance)



Seong, CS, Yun *Phys.Rev.D* 110 (2024) 1, 015018



$$P_{a \rightarrow \gamma} \simeq \sum_{\pm} \frac{g_{a\gamma}^2 B^2 / 2}{g_{a\gamma}^2 B^2 / 2 + (m_a^2 / 2\omega \pm \Omega)^2} \sin^2 \left(\left(\frac{1}{2} \sqrt{\frac{g_{a\gamma}^2 B^2}{2} + \left(\frac{m_a^2}{2\omega} \pm \Omega \right)^2} \right) z \right),$$

$$\alpha|0\rangle + e^{i\varphi(t)}\beta|1\rangle$$

Qubit



(Pauli X Gate)

↯ oscillation

MSW & (Avoided) level crossing

Atomic

Rabi flopping

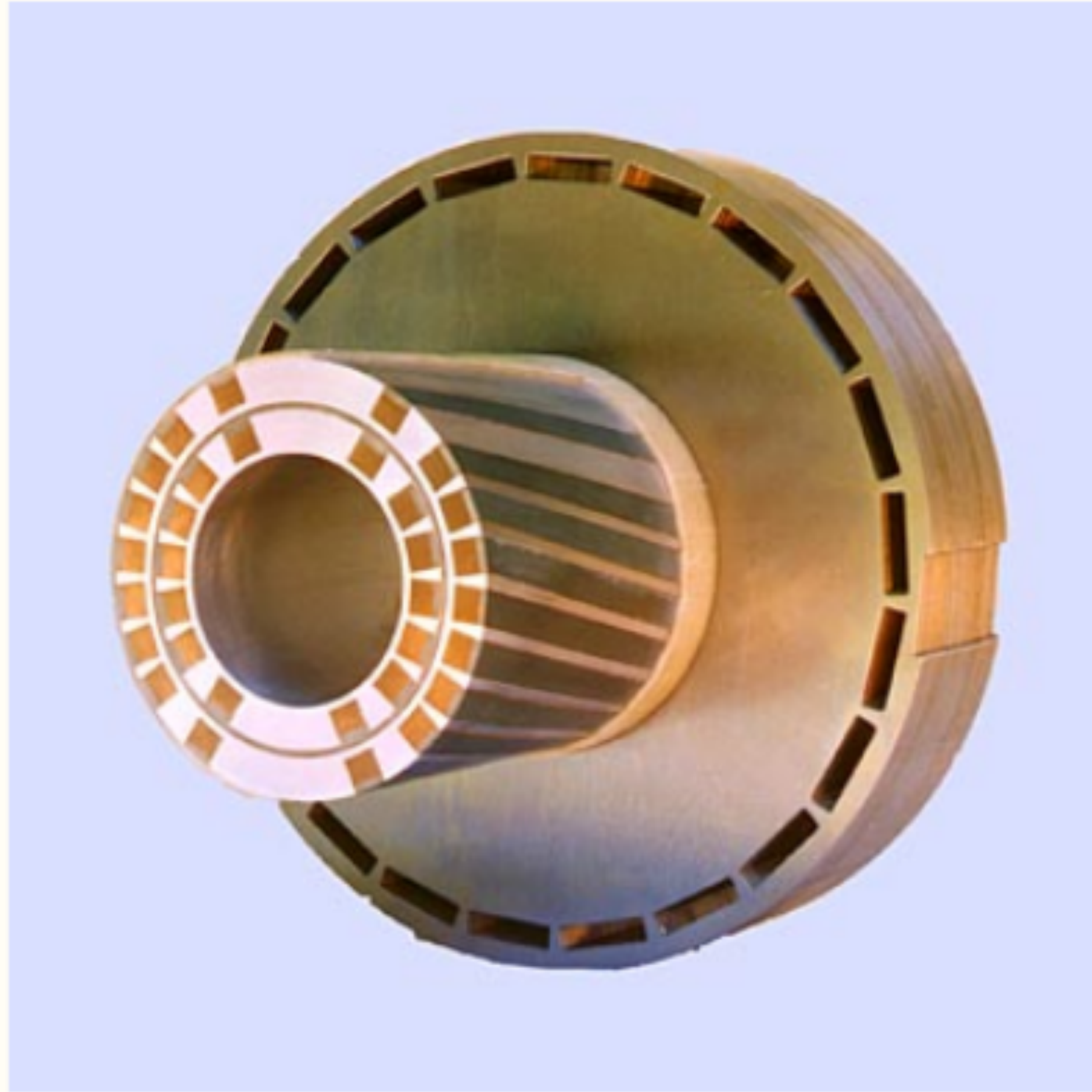
Nuclear

Nuclear Magnetic Resonance

Axion-photon

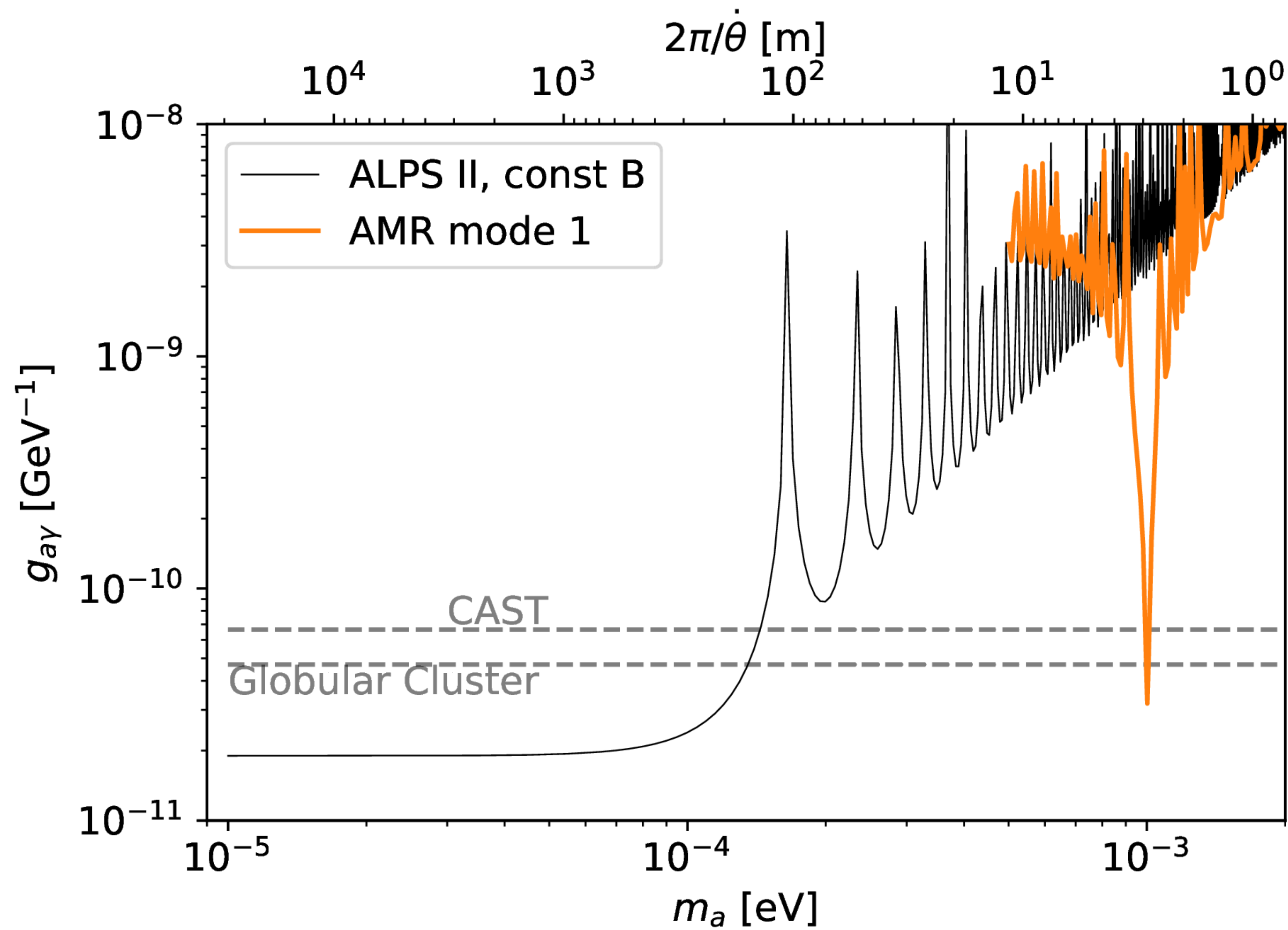
Axion Magnetic Resonance

Experimental Implications

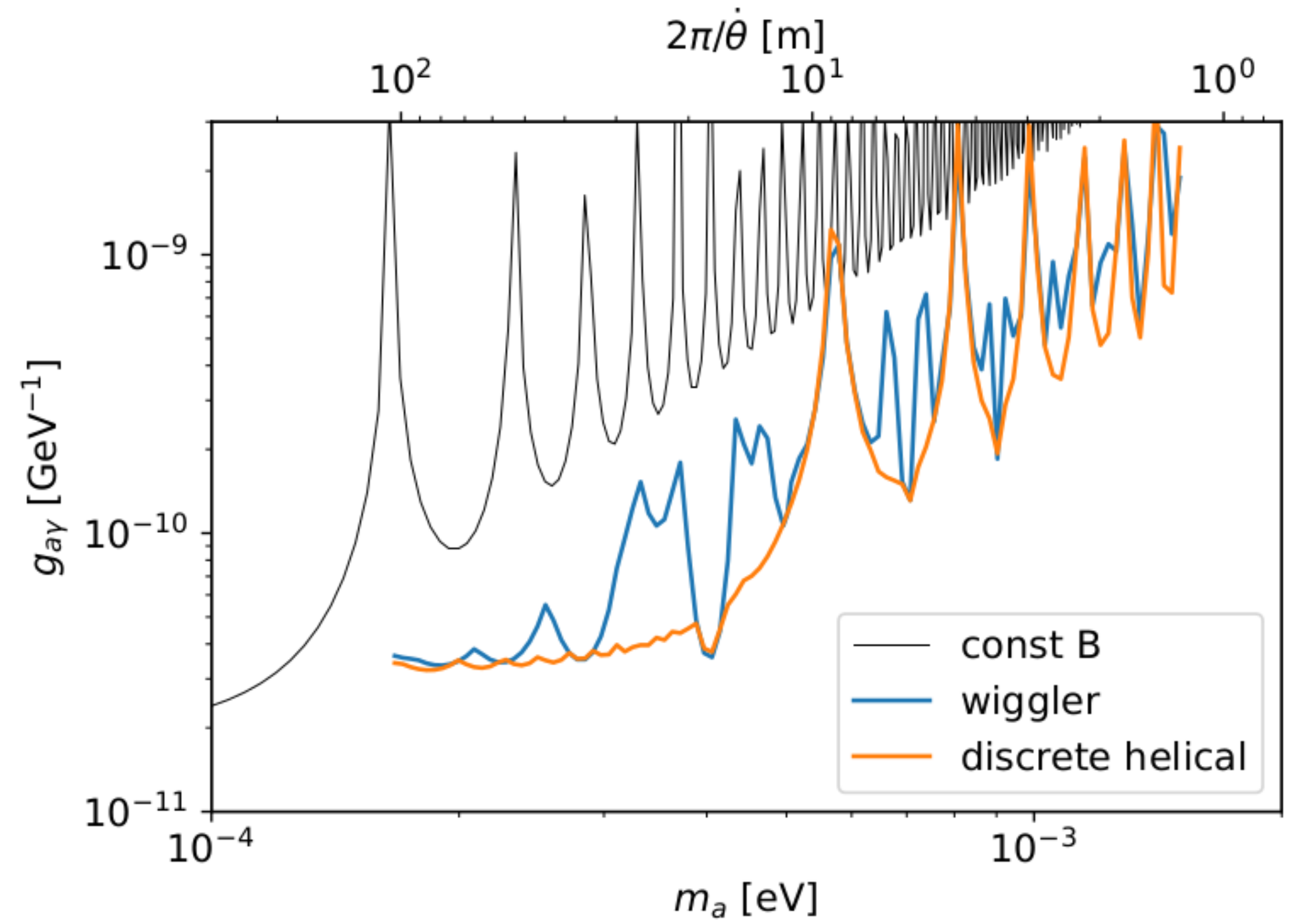
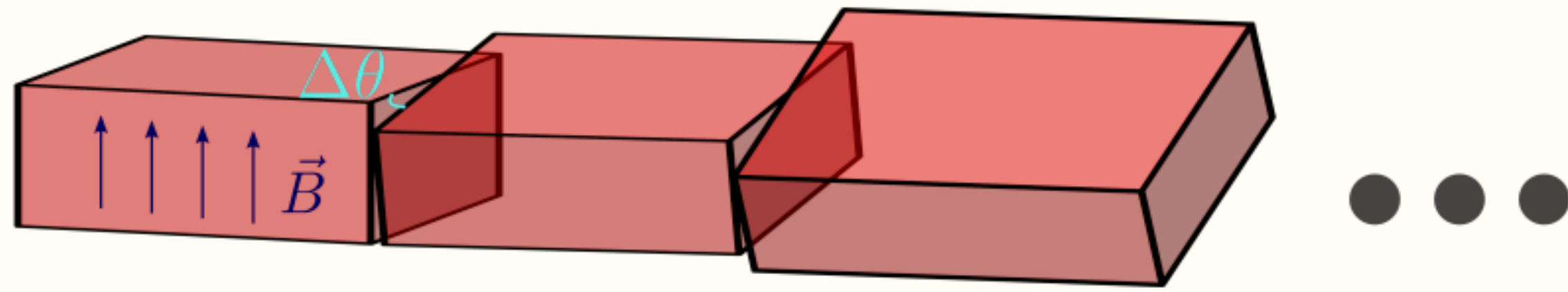


Magnets at Relativistic Heavy Ion Collider (RHIC), BNL:

- superconducting dipole magnet ~ 5 T
- 1740 magnets adopted by RHIC
- 30-/36-strand SC cable for...
... 80-100/130-180 mm apertures
- **B** field rotates 360 degrees in 2.4 meters
- designed to control proton spin for polarized proton colliding



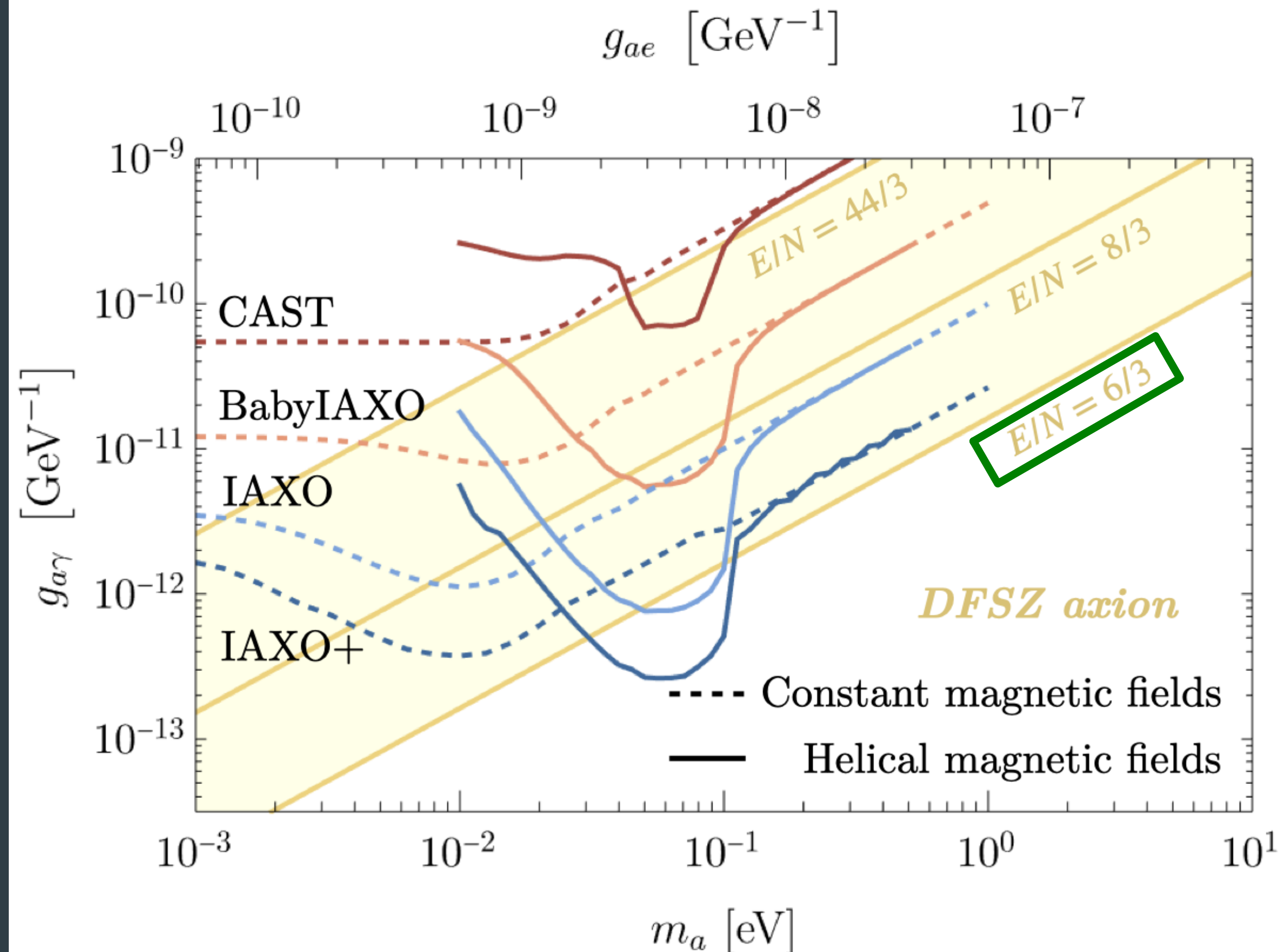
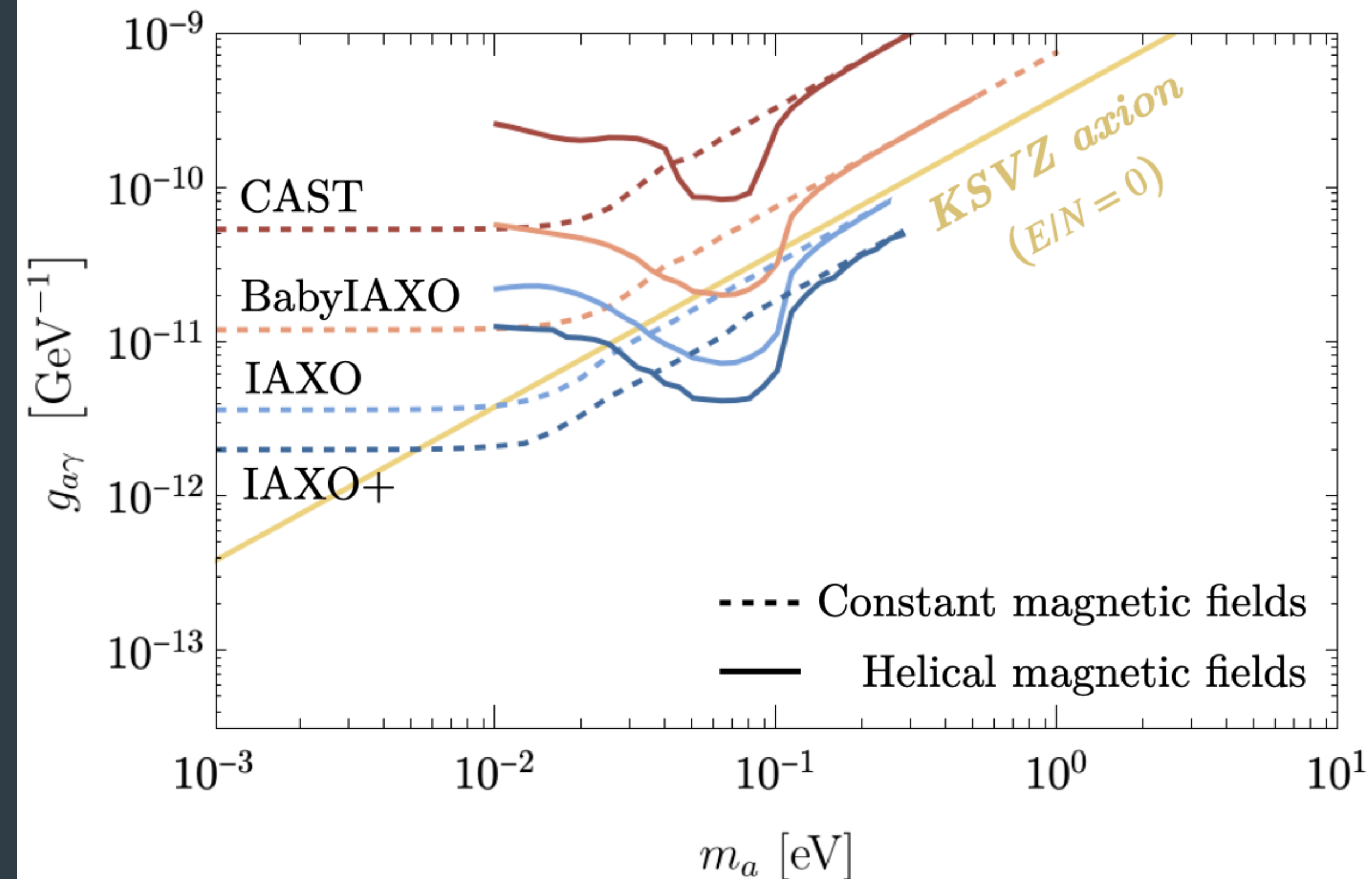
Scanning Different Axion Masses



QCD Axion

Seong, CS, Yun

JHEP 03 (2025) 071



$$g_{a\gamma} \sim \mathcal{O}(10^3 f_a^{-1})$$

$$g_{ae} \sim \mathcal{O}(f_a^{-1})$$

Conclusion

- a) Many UV theories predict low energy d.o.f. that exhibit **wave features**
- b) New astrophysical and cosmological observations **just start to probe** into interesting parameter region by leveraging such features.
 - supernova remnants (radio)
 - galaxy rotation curves (radio, NIR, optical)
 - binary mergers (GW)
 - cosmic distance (X-ray and optical)
 - neutron stars (X-ray spectrum, polarization, and pulsation)
 - ...
- c) There exist **new resonances** to further enhance the signal strength.

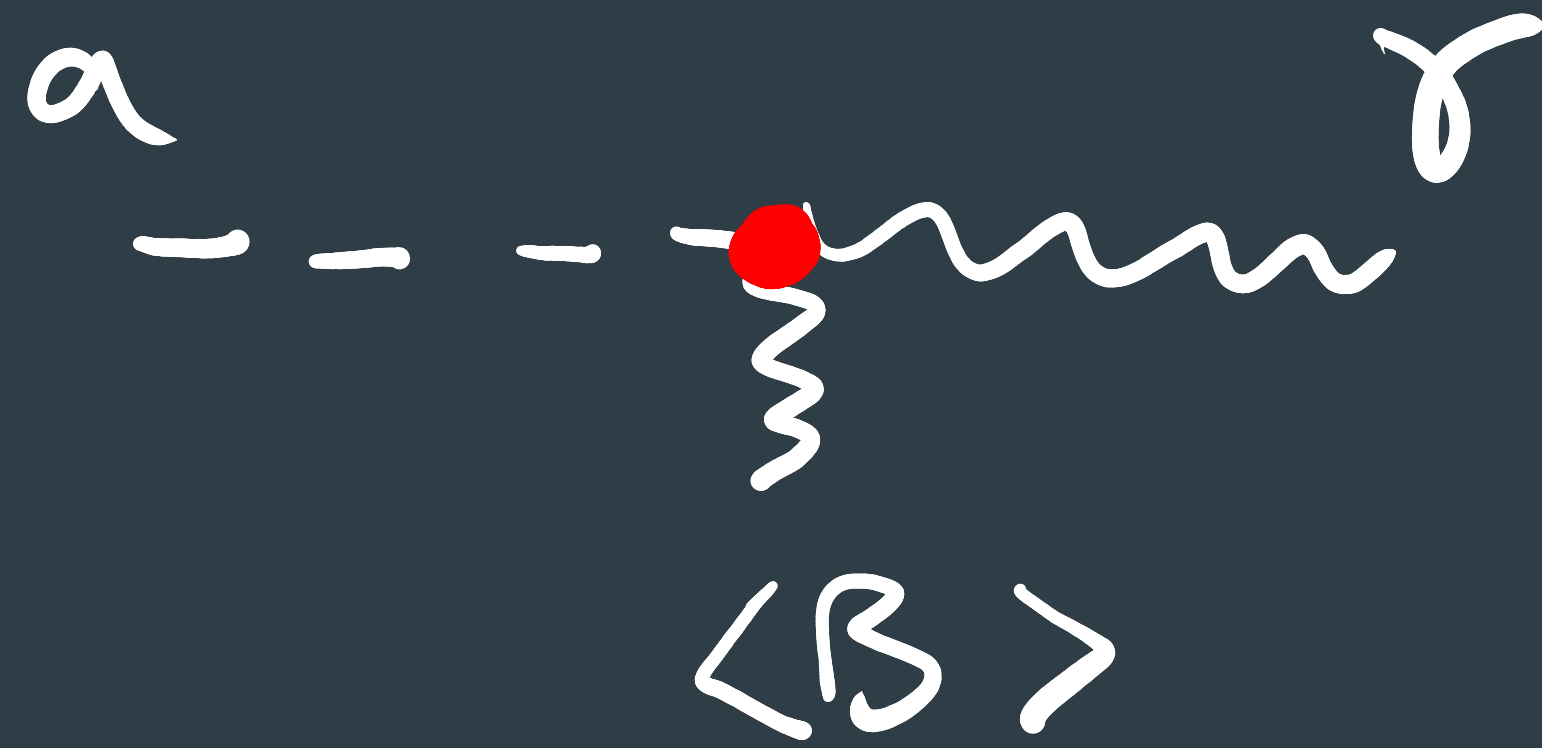
Thank you !

感谢垂听

欢迎各位老师来杭高院指导、交流

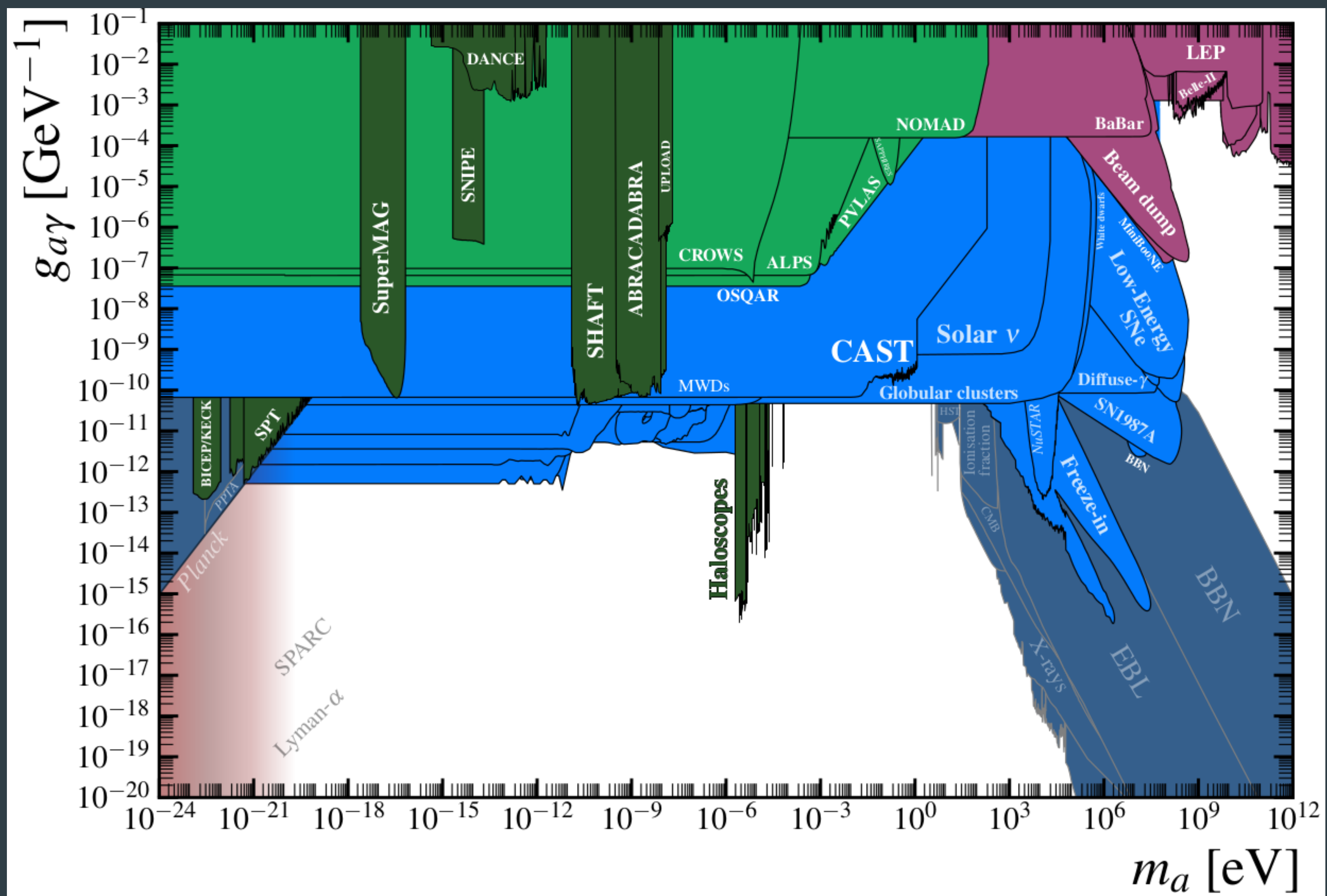
Back up Slides

Can we Do better
at large m_a ?



$$P_{a \rightarrow \gamma} \propto \left(\frac{g_{a\gamma} B \omega}{m_a^2} \right)^2$$

large m_a



Axion

$$P_\mu P^\mu = m_a^2$$

Photon

$$k_\mu k^\mu = 0$$

Mismatch

$$\text{Fix } |\vec{k}| = |\vec{p}| \Rightarrow E_\gamma - E_a \approx \frac{m_a^2}{2|\vec{k}|} \gg \frac{1}{L}$$

$\Rightarrow$ fast oscillation $a \leftrightarrow \gamma$.

Axion

$$P_\mu P^\mu = m_a^2$$

Photon

$$k_\mu k^\mu = m_\gamma^2$$

matched!

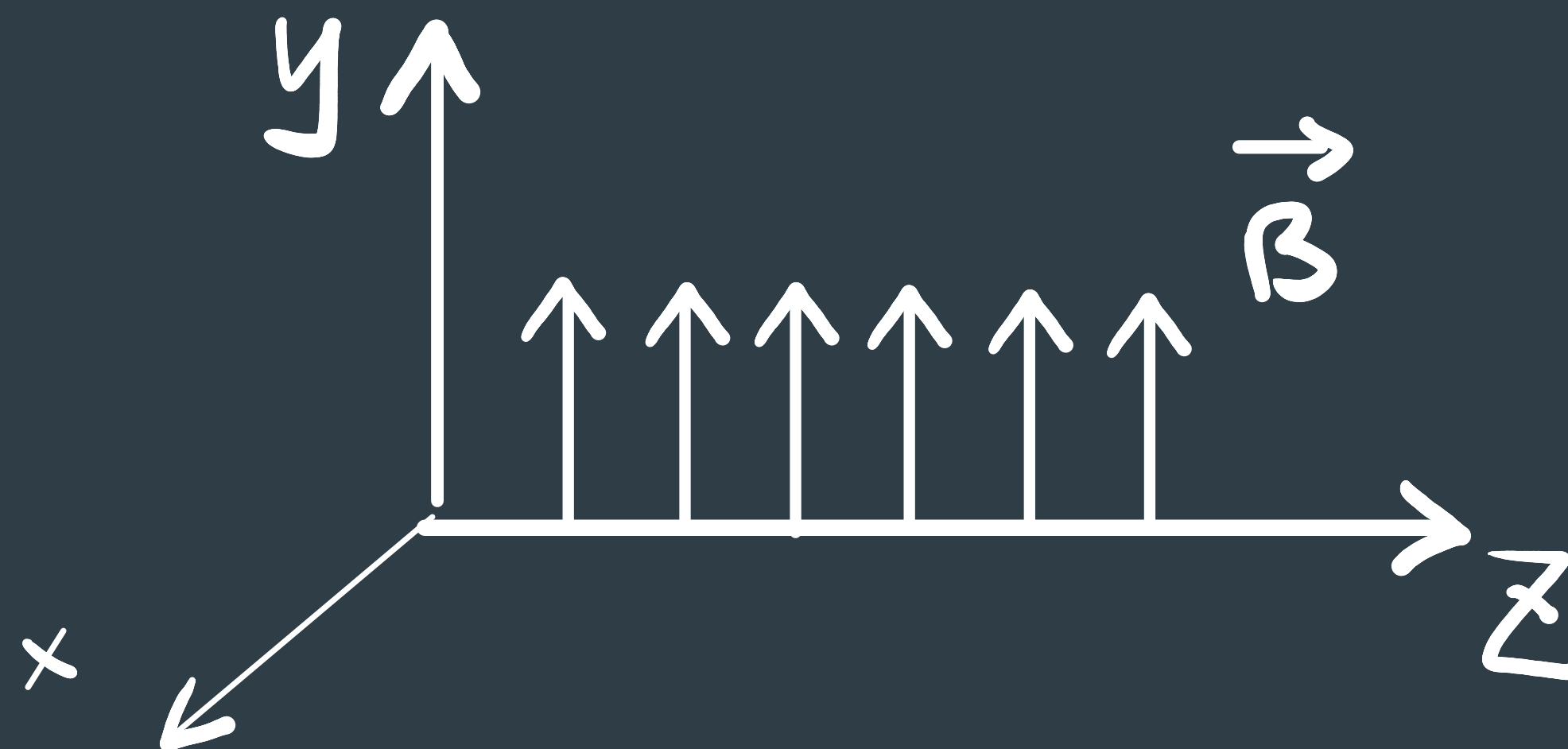
$$\text{Fix } |\vec{k}| = |\vec{p}| \Rightarrow E_\gamma - E_a \approx \frac{m_a^2 - m_\gamma^2}{2|\vec{k}|} \ll \frac{1}{L}$$

Modulating $\rightarrow$
B

$$\left\{ \begin{array}{l} \text{Amplitude} \\ \text{Orientation} \end{array} \right\} \otimes \left\{ \begin{array}{l} \text{time} \\ \text{space} \end{array} \right\}$$

$$\left\{ \begin{array}{l} \text{Amplitude} \\ \text{Orientation} \end{array} \right\} \otimes \left\{ \begin{array}{l} \text{time} \\ \text{space} \end{array} \right\}$$

$$\mathcal{L} \supset a \vec{E} \cdot \vec{B}$$



$$\mathcal{L} \supset a \vec{E} \cdot \vec{B} \sin(\Omega z)$$



"Wigner" Van Bibber et al. 1987

$$\mathcal{L} \supset a \vec{E} \cdot \vec{B} e^{i\Omega z}$$

$$\mathcal{L} \supset a \left(\vec{E} e^{i\Omega z} \right) \cdot \vec{B}$$

$$\mathcal{L} = a \underbrace{\left(\vec{E} e^{i\Omega z} \right)}_{\vec{k}' = \begin{pmatrix} E_y \\ \vec{k} + \Omega \end{pmatrix}} \cdot \vec{B}$$

$$\vec{k}' = \begin{pmatrix} E_y \\ \vec{k} + \Omega \end{pmatrix}$$

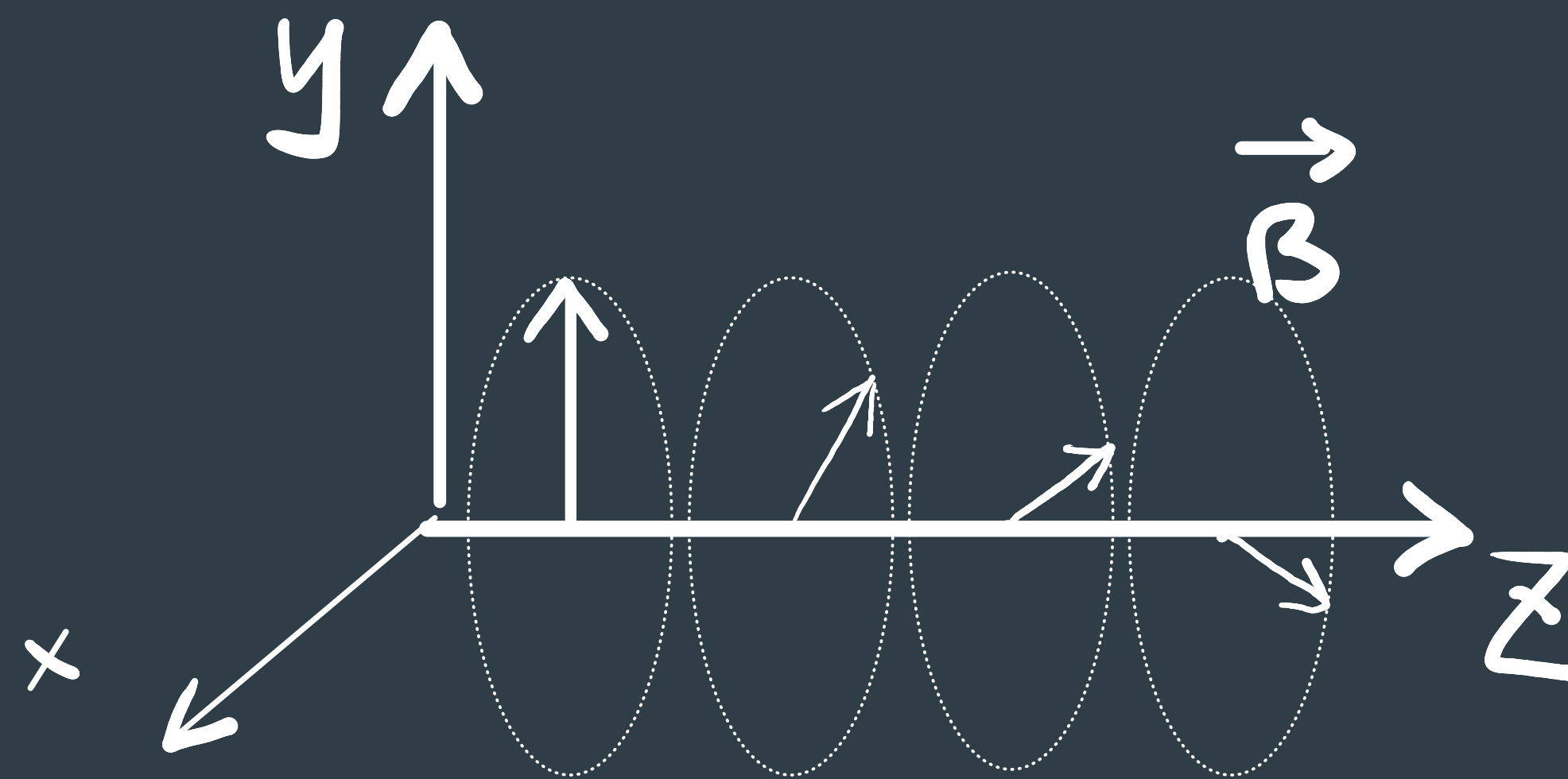
$$k'_\mu k'^\mu = \underbrace{k_\mu k^\mu}_{=0} + 2E_y \Omega + \underbrace{\Omega^2}_{\Omega \ll E_y}$$

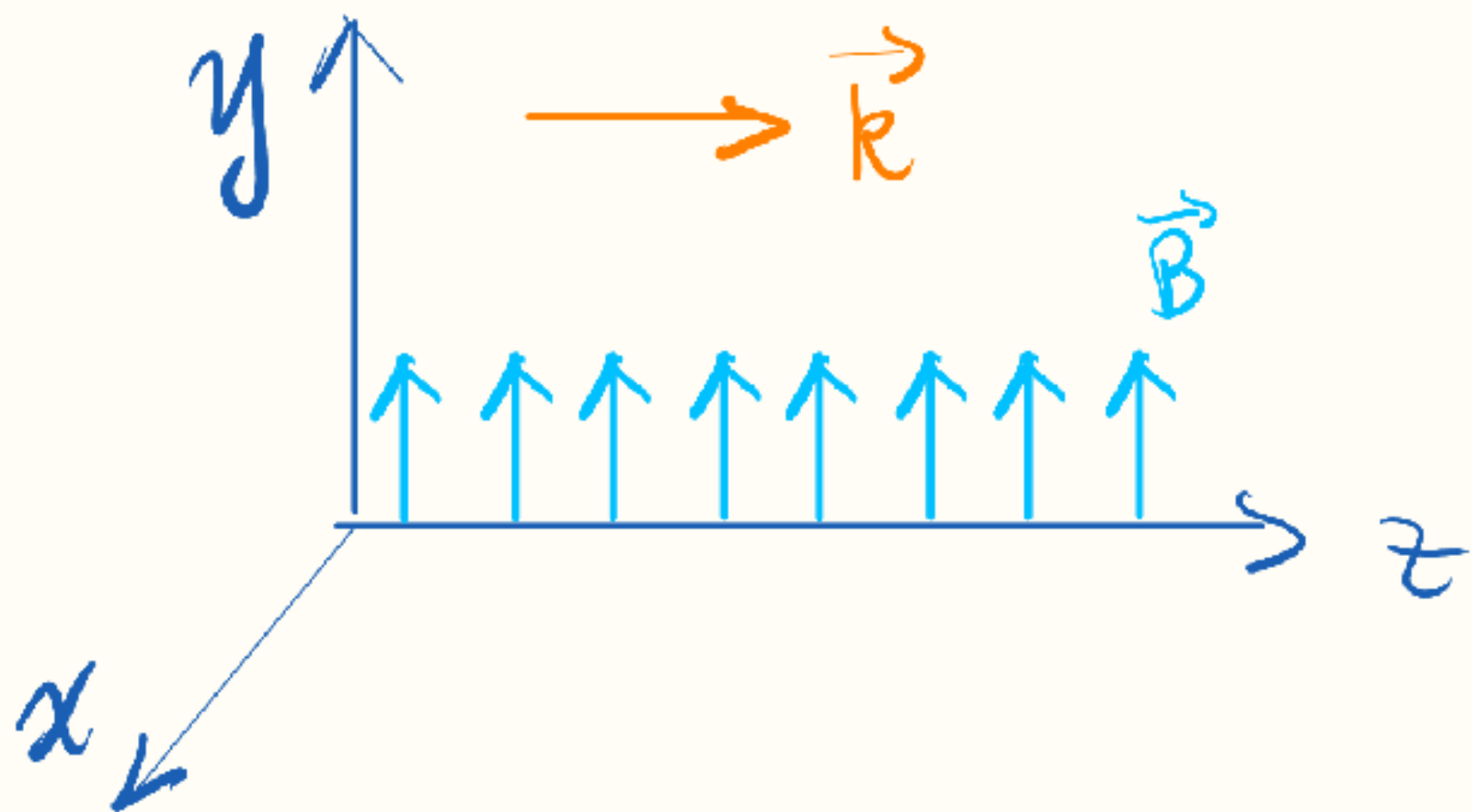
$$\mathcal{L} \supset a \left(\vec{E} e^{i\Omega z} \right) \cdot \vec{B}$$

$$\left. \begin{aligned} k'_\mu k'^\mu &= 2\bar{E}_\gamma \Omega \\ p_\mu p^\mu &= m_a^2 \end{aligned} \right\} \text{Match at } \Omega = \frac{m_a^2}{2\bar{E}_\gamma}$$

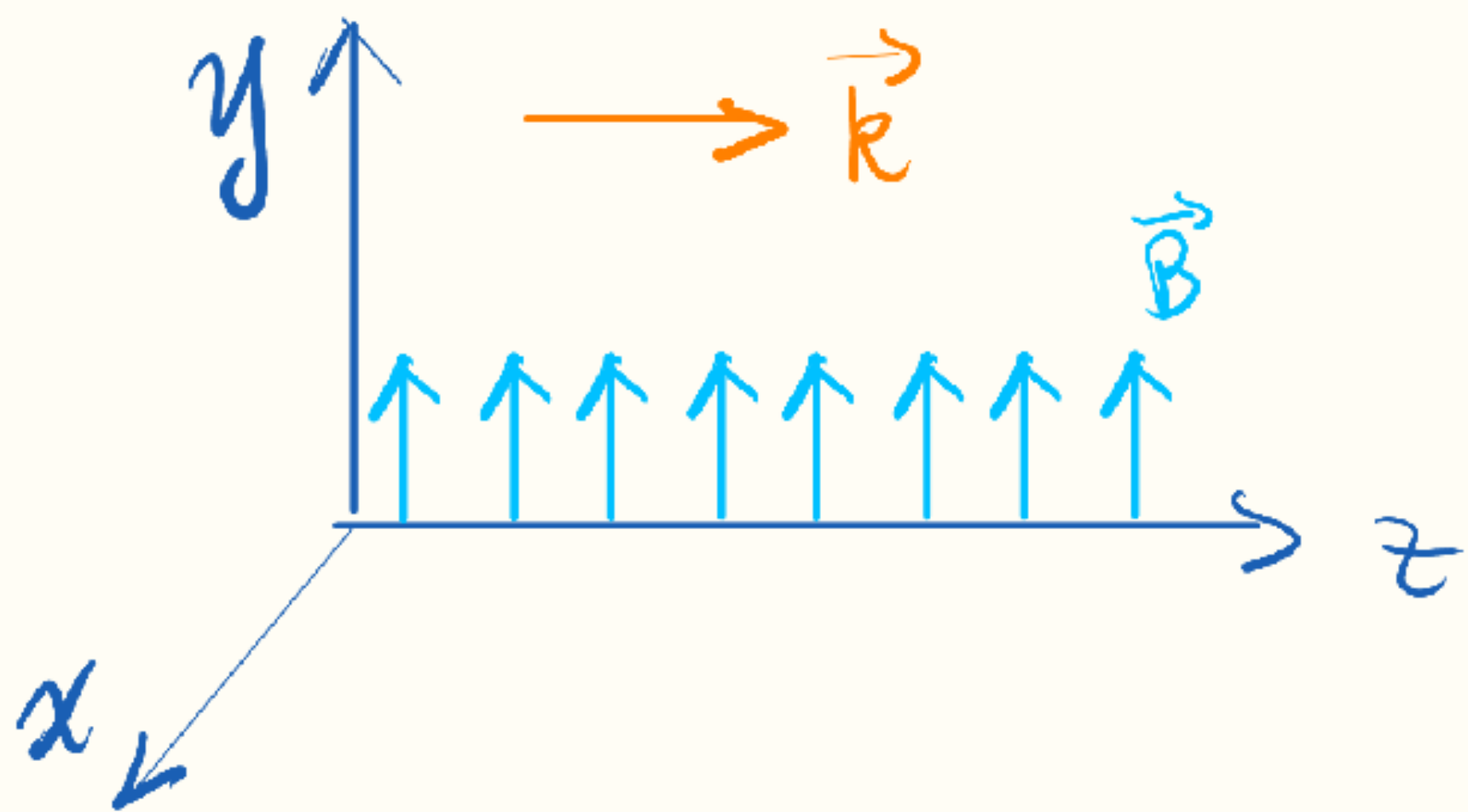
$$\left\{ \begin{array}{l} \text{Amplitude} \\ \text{Orientation} \end{array} \right\} \otimes \left\{ \begin{array}{l} \text{time} \\ \text{space} \end{array} \right\}$$

$$\mathcal{L} \supset a E_x \cdot B_x \sin(\Omega z) \\ + a E_y \cdot B_y \cos(\Omega z)$$

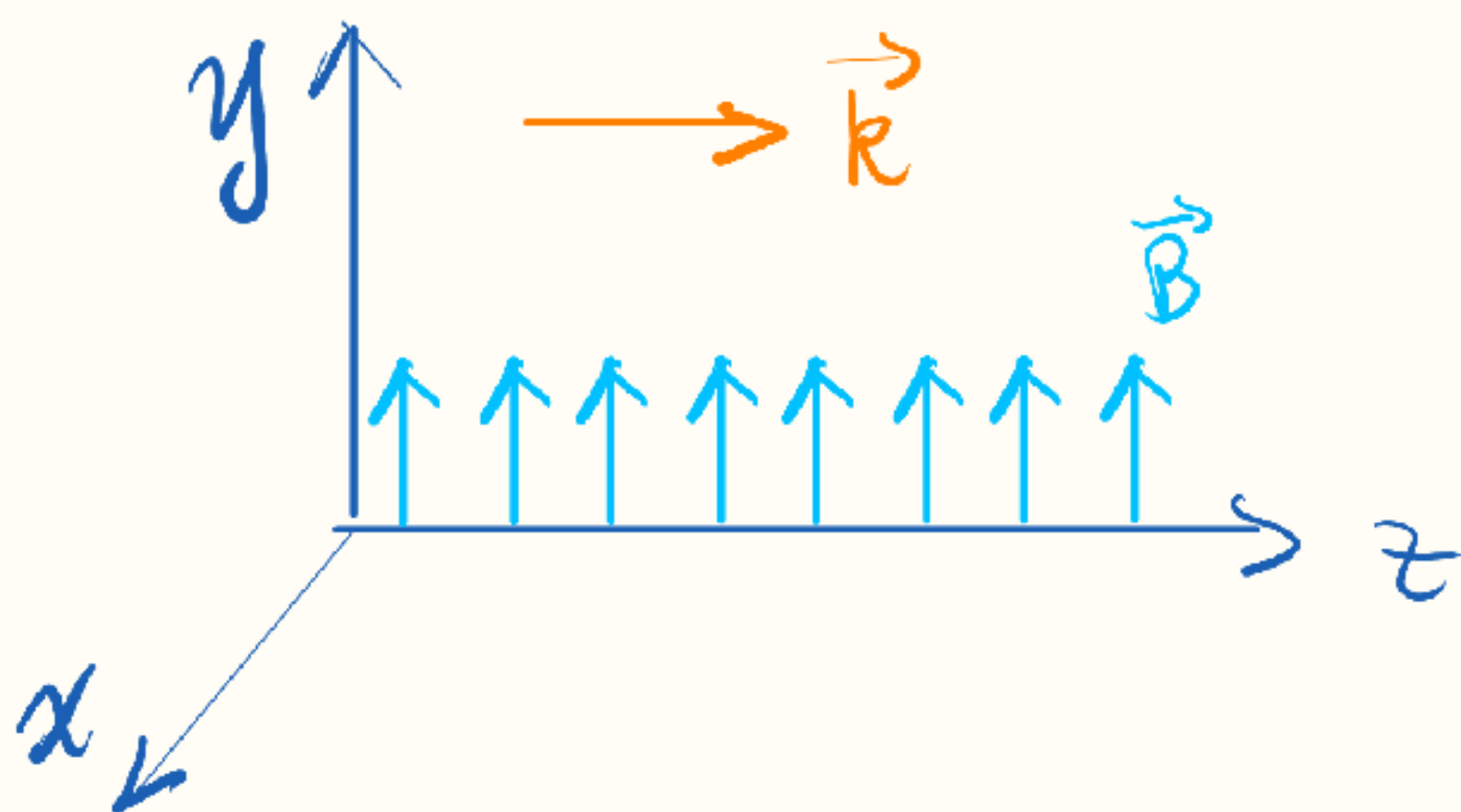




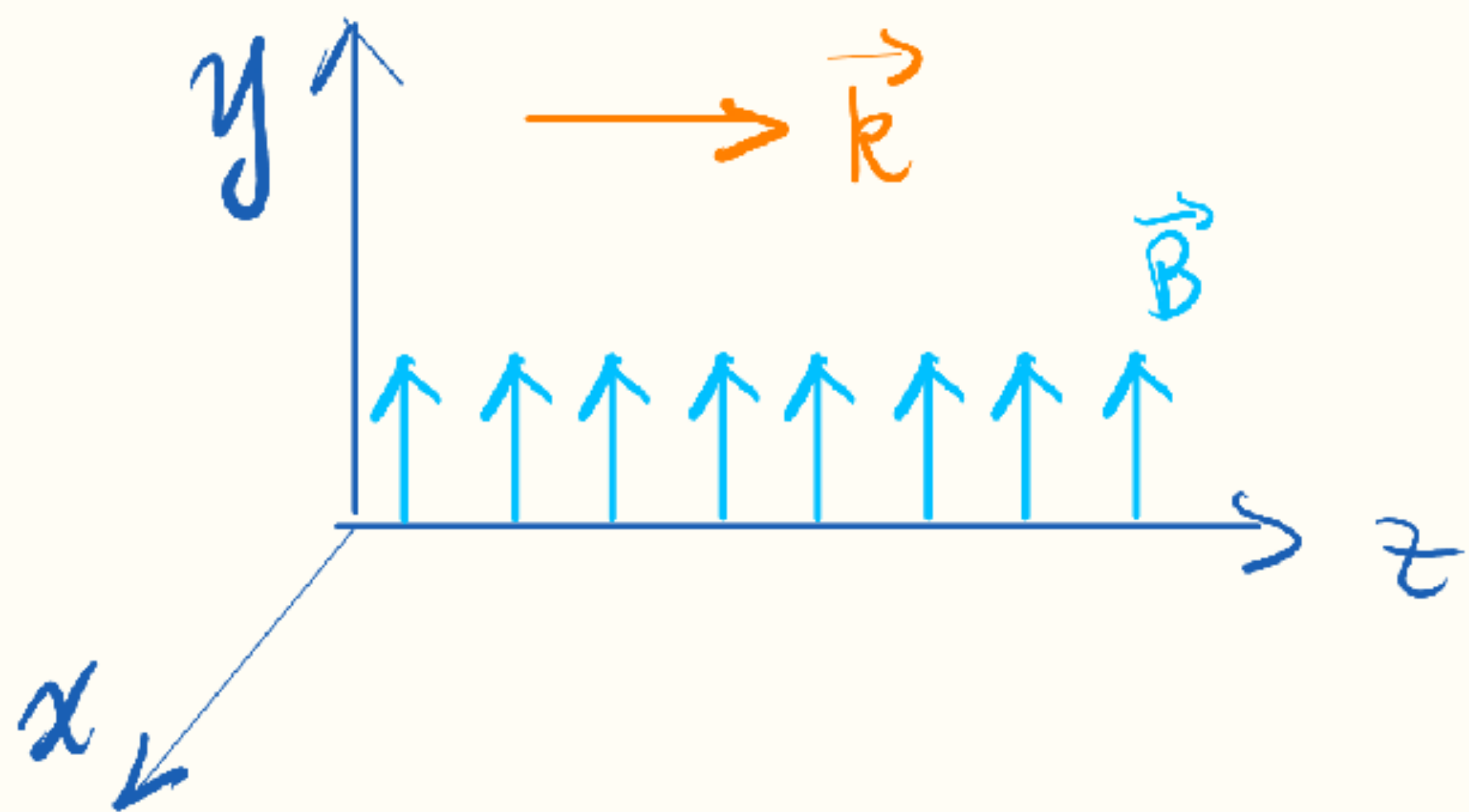
$$i\partial_z \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix} = \frac{1}{2\omega} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & g_{a\gamma}\omega B \\ 0 & g_{a\gamma}\omega B & m_a^2 \end{bmatrix} \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix},$$



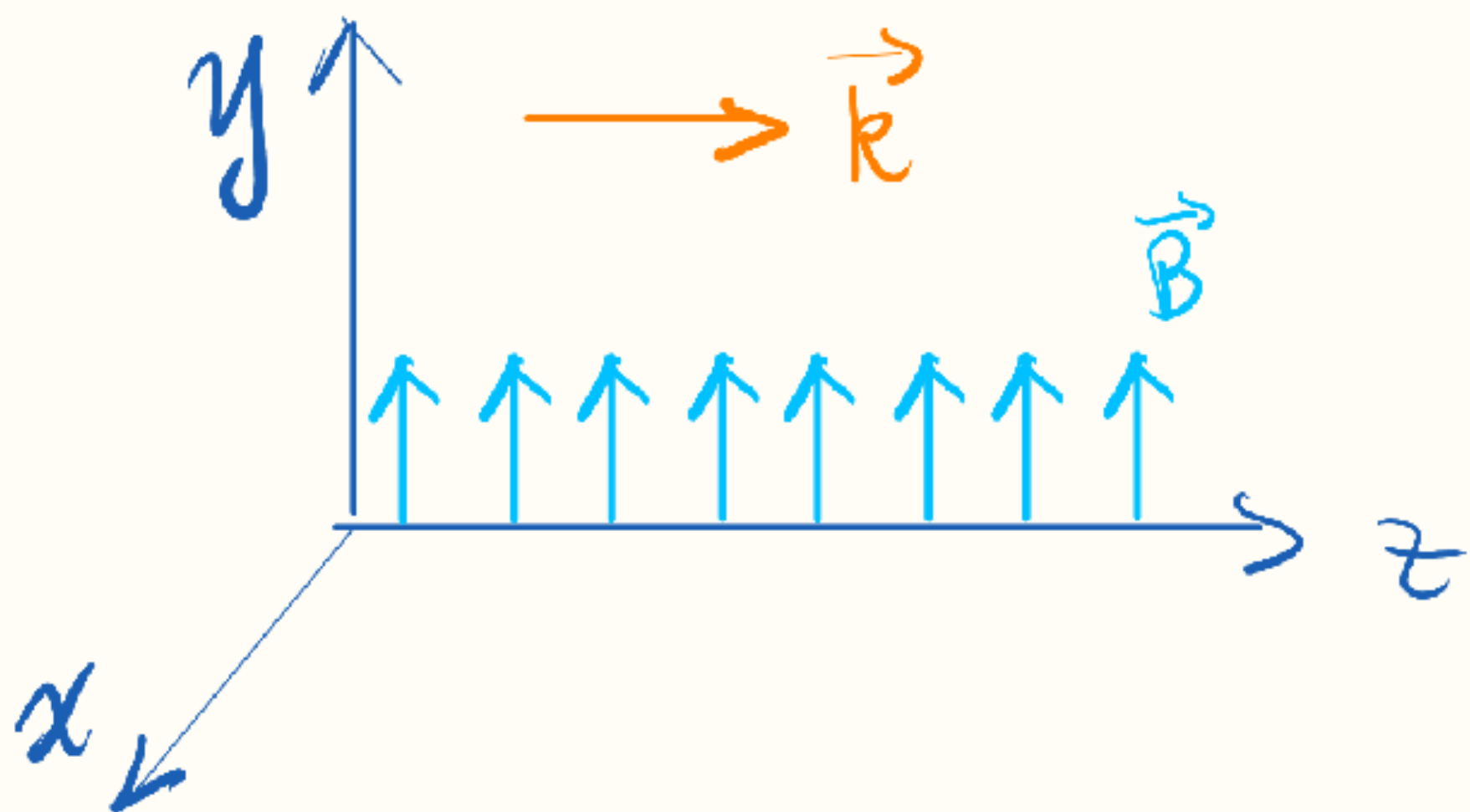
$$U^\dagger i\partial_z \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix} = \frac{1}{2\omega} \underbrace{U^\dagger \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & g_{a\gamma}\omega B \\ 0 & g_{a\gamma}\omega B & m_a^2 \end{bmatrix} U}_{\text{diagonal}} \underbrace{U^\dagger \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix}}_{\text{mass eigenbasis}},$$



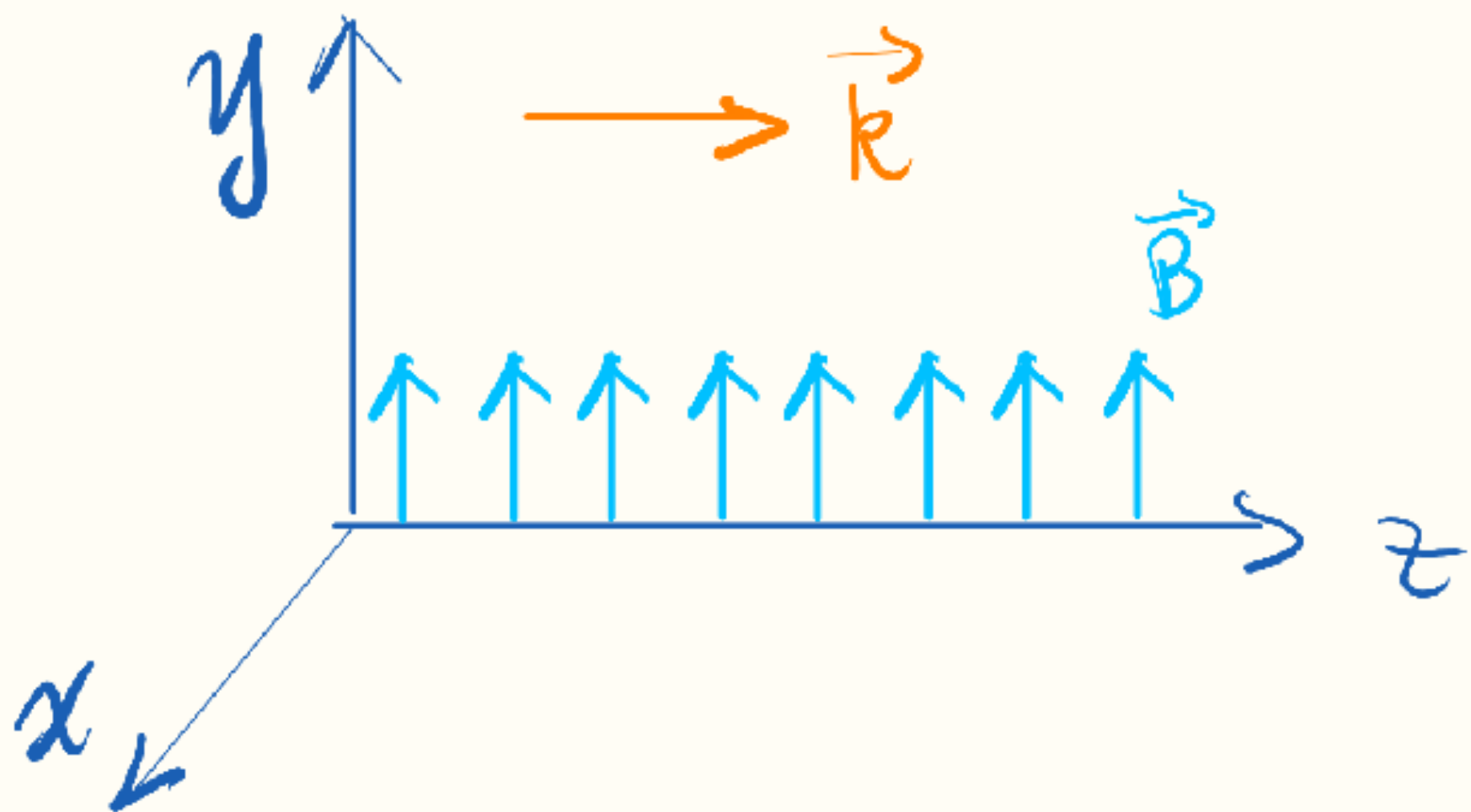
$$i\partial_z U^\dagger \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix} = \frac{1}{2\omega} \underbrace{U^\dagger \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & g_{a\gamma}\omega B \\ 0 & g_{a\gamma}\omega B & m_a^2 \end{bmatrix} U}_{\text{diagonal}} \underbrace{U^\dagger \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix}}_{\text{mass eigenbasis}},$$



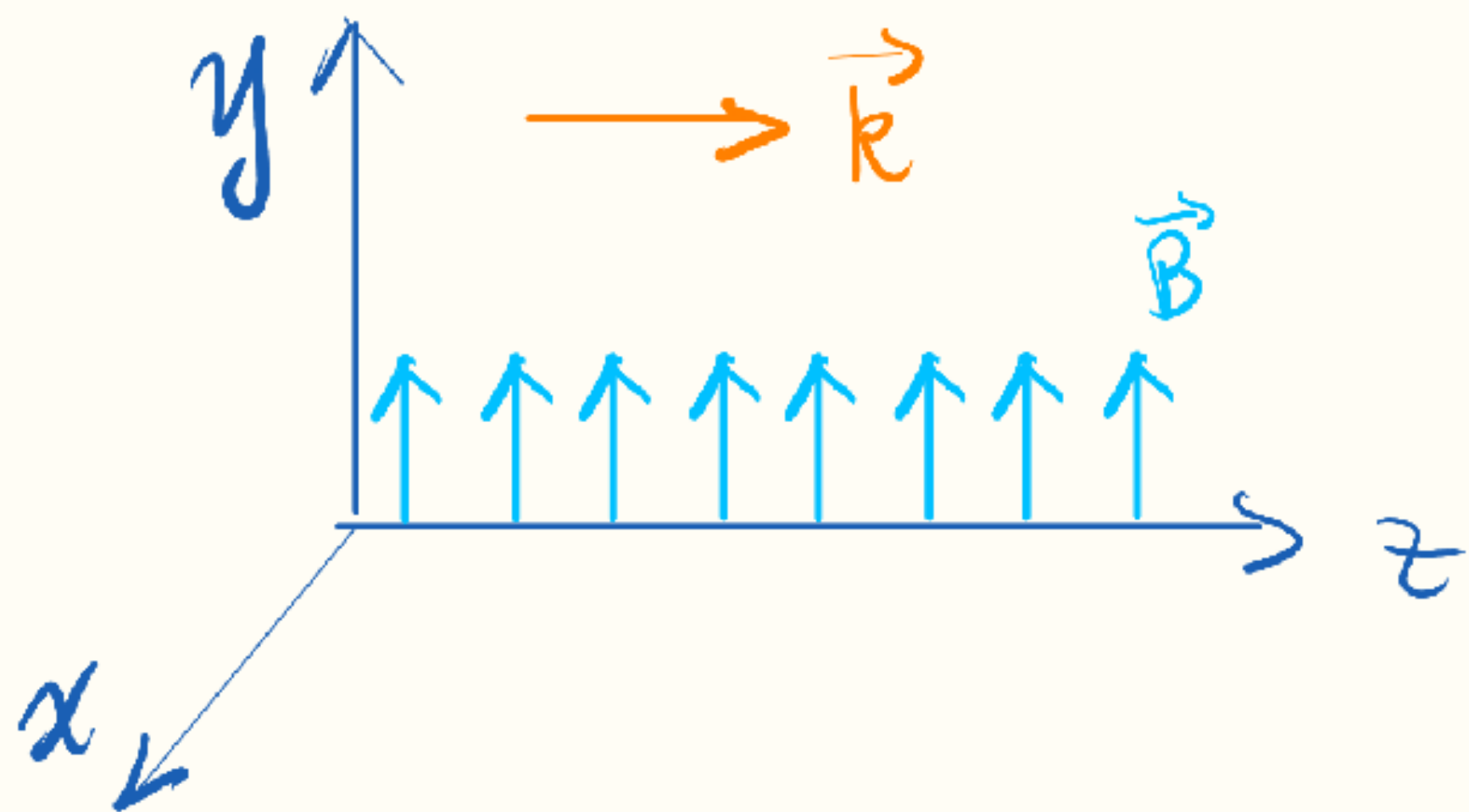
$$i\partial_z \begin{bmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{bmatrix} = \begin{bmatrix} m_1^2/2\omega & 0 & 0 \\ 0 & m_2^2/2\omega & 0 \\ 0 & 0 & m_3^2/2\omega \end{bmatrix} \begin{bmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{bmatrix}$$



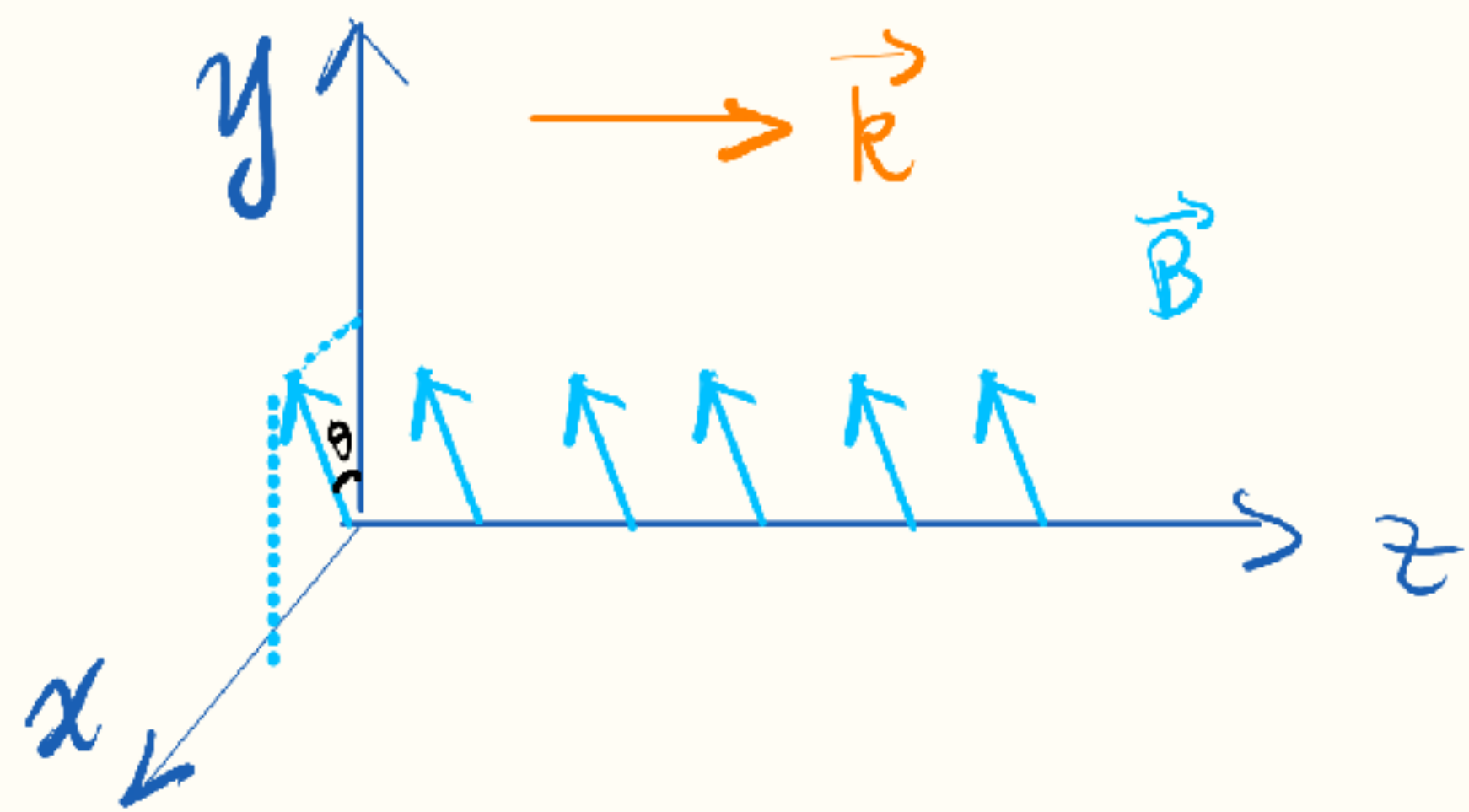
$$\begin{bmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{bmatrix} = \begin{bmatrix} e^{-i \frac{m_1^2}{2\omega} z} & 0 & 0 \\ 0 & e^{-i \frac{m_2^2}{2\omega} z} & 0 \\ 0 & 0 & e^{-i \frac{m_3^2}{2\omega} z} \end{bmatrix} \begin{bmatrix} \psi_1(0) \\ \psi_2(0) \\ \psi_3(0) \end{bmatrix}$$

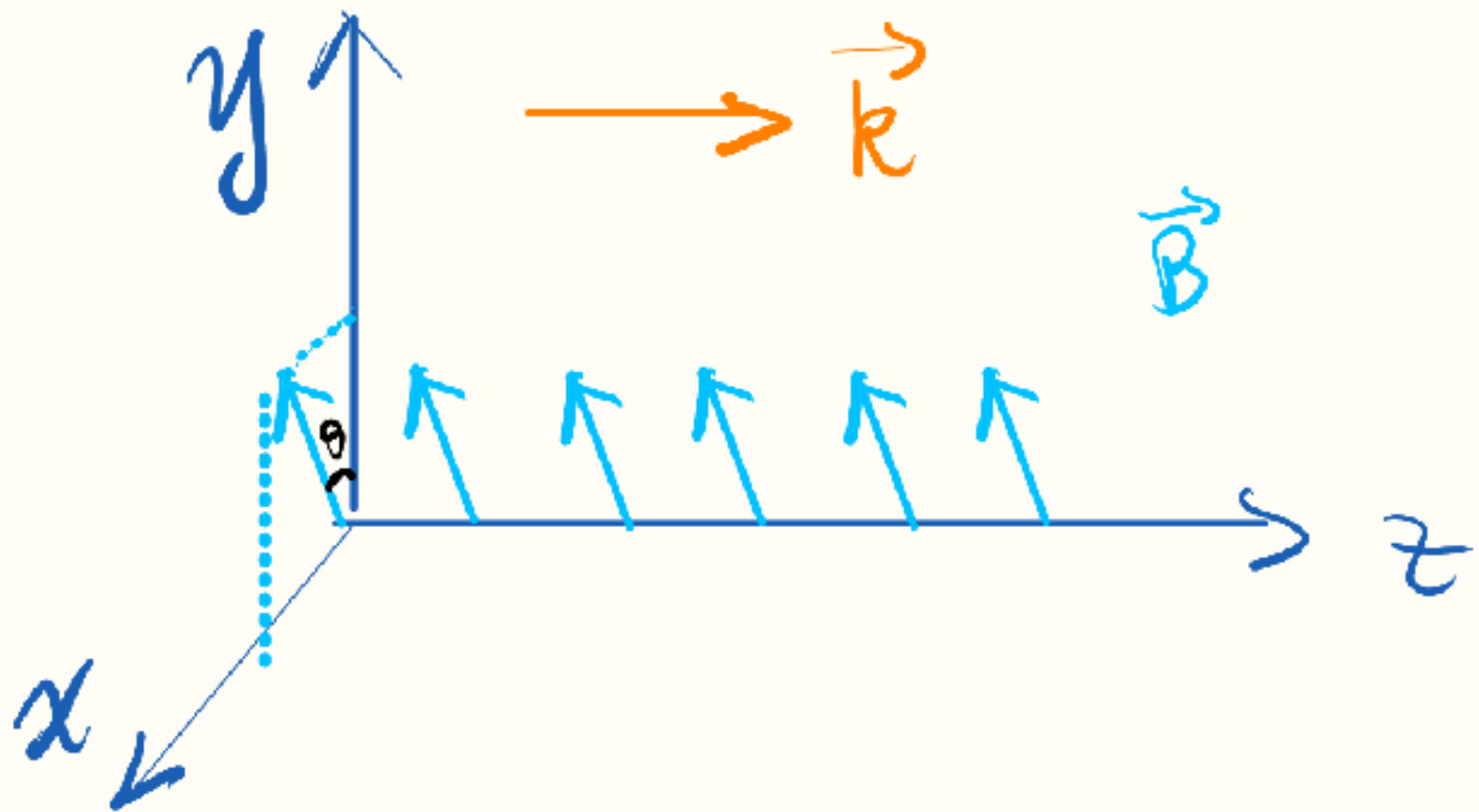


$$\begin{bmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{bmatrix} \approx \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i \frac{m_a^2}{2\omega} z} \end{bmatrix} \begin{bmatrix} \psi_1(0) \\ \psi_2(0) \\ \psi_3(0) \end{bmatrix}$$

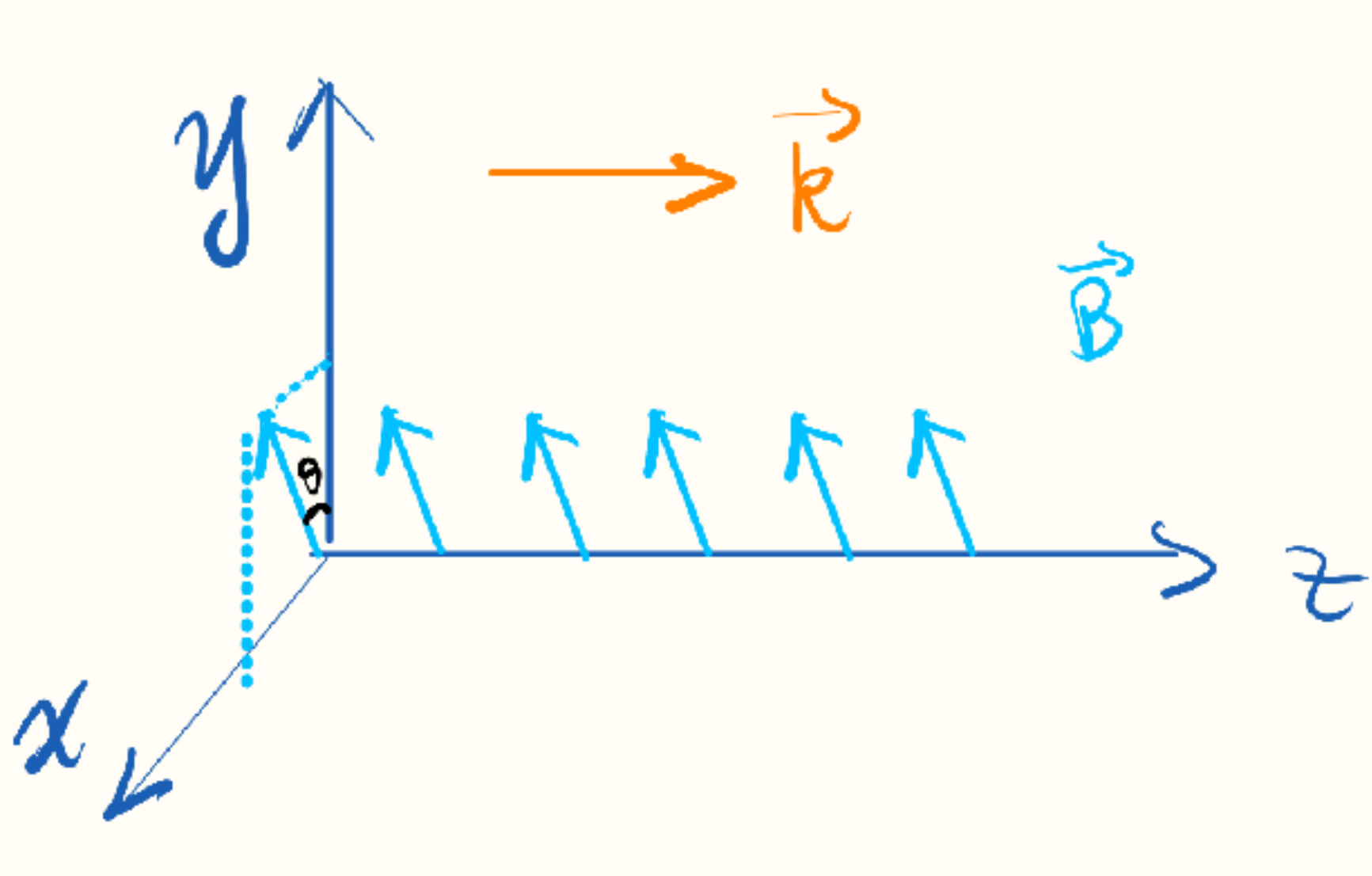


$$\begin{aligned}
 \mathcal{M}_{a \rightarrow \gamma_y} &= \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} U \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i \frac{m_a^2}{2\omega} z} \end{bmatrix} U^\dagger \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \\
 P_{a \rightarrow \gamma_y} &= |\mathcal{M}_{a \rightarrow \gamma_y}|^2 \\
 &\simeq \frac{g_{a\gamma}^2 B^2}{g_{a\gamma}^2 B^2 + m_a^4/4\omega^2} \sin^2 \left(\left(\frac{1}{2} \sqrt{g_{a\gamma}^2 B^2 + \frac{m_a^4}{4\omega^2}} \right) z \right)
 \end{aligned}$$





$$i\partial_z \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix} = \frac{1}{2\omega} \begin{bmatrix} 0 & 0 & g_{a\gamma}\omega B s_\theta \\ 0 & 0 & g_{a\gamma}\omega B c_\theta \\ g_{a\gamma}\omega B s_\theta & g_{a\gamma}\omega B c_\theta & m_a^2 \end{bmatrix} \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix}$$

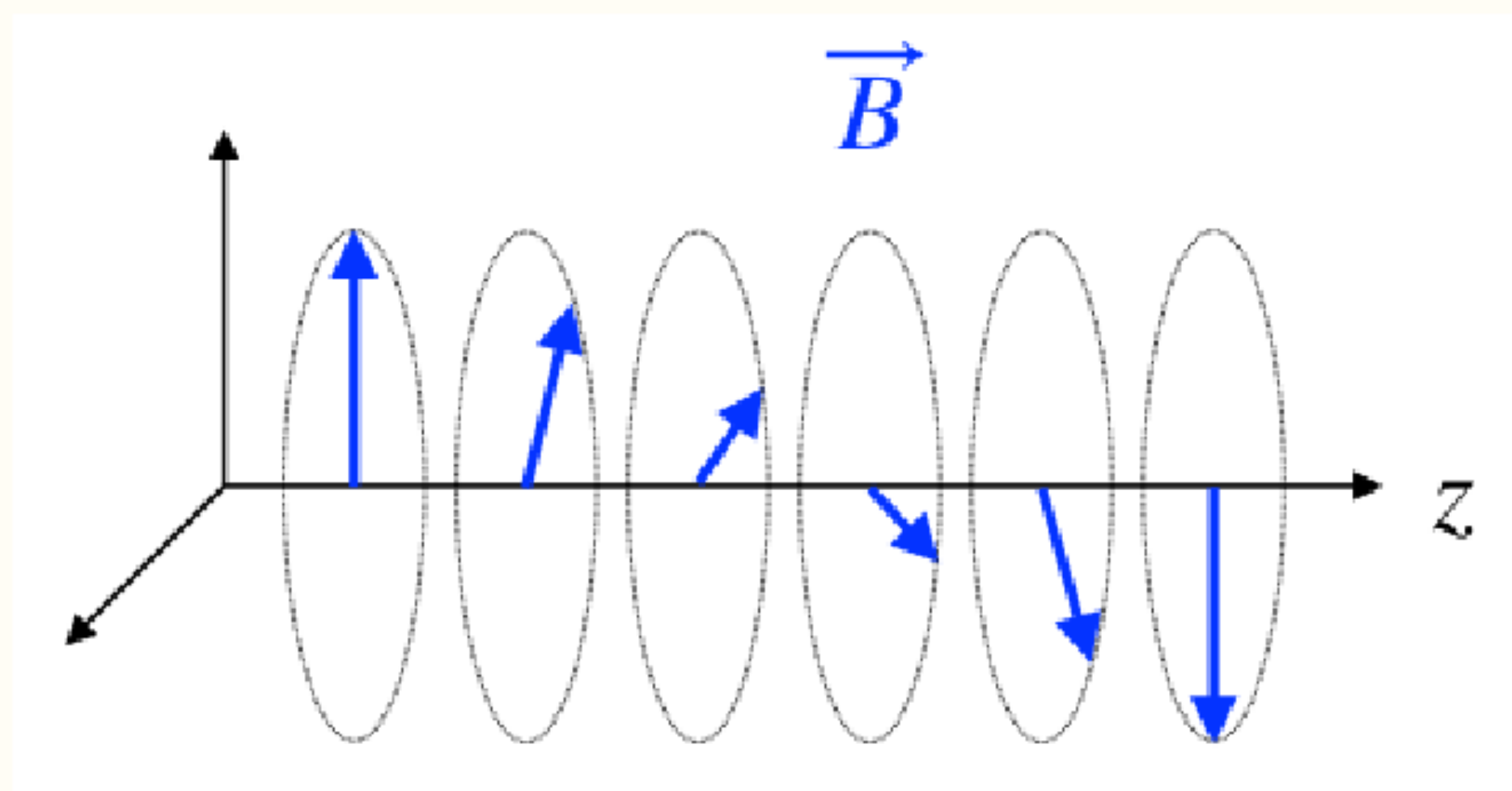


$$i\partial_z \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix} = \frac{1}{2\omega} \begin{bmatrix} 0 & 0 & g_{a\gamma}\omega B s_\theta \\ 0 & 0 & g_{a\gamma}\omega B c_\theta \\ g_{a\gamma}\omega B s_\theta & g_{a\gamma}\omega B c_\theta & m_a^2 \end{bmatrix} \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix}.$$

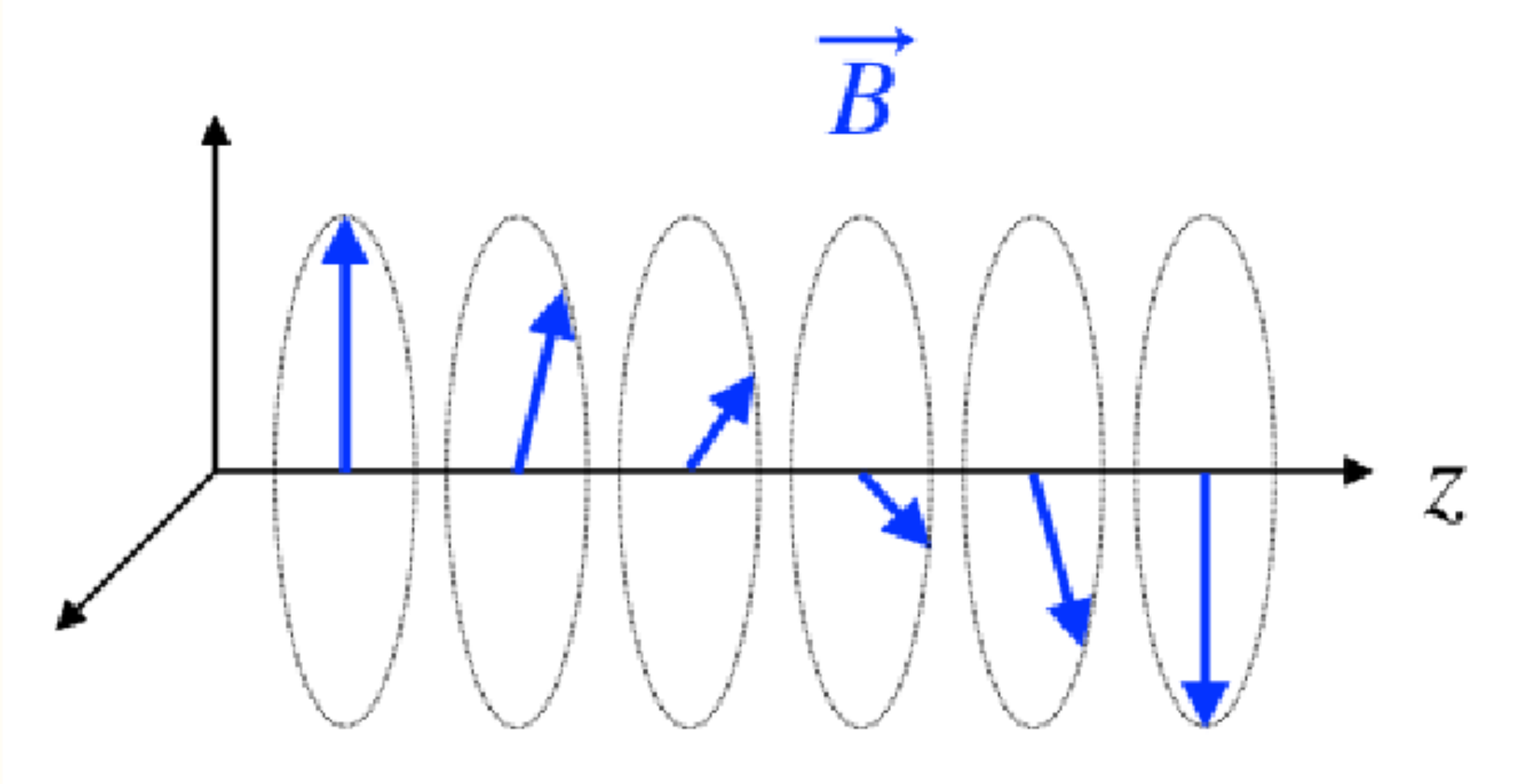
$$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & g_{a\gamma}\omega B \\ 0 & g_{a\gamma}\omega B & m_a^2 \end{bmatrix} = \begin{bmatrix} c_\theta & -s_\theta & 0 \\ s_\theta & c_\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 & 0 & g_{a\gamma}\omega B s_\theta \\ 0 & 0 & g_{a\gamma}\omega B c_\theta \\ g_{a\gamma}\omega B s_\theta & g_{a\gamma}\omega B c_\theta & m_a^2 \end{bmatrix} \begin{bmatrix} c_\theta & s_\theta & 0 \\ -s_\theta & c_\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$i\partial_z \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix} = \frac{1}{2\omega} \begin{bmatrix} 0 & 0 & g_{a\gamma}\omega B s_\theta \\ 0 & 0 & g_{a\gamma}\omega B c_\theta \\ g_{a\gamma}\omega B s_\theta & g_{a\gamma}\omega B c_\theta & m_a^2 \end{bmatrix} \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix}.$$

$$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & g_{a\gamma}\omega B \\ 0 & g_{a\gamma}\omega B & m_a^2 \end{bmatrix} = \underbrace{\begin{bmatrix} c_\theta & -s_\theta & 0 \\ s_\theta & c_\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{V^\dagger} \begin{bmatrix} 0 & 0 & g_{a\gamma}\omega B s_\theta \\ 0 & 0 & g_{a\gamma}\omega B c_\theta \\ g_{a\gamma}\omega B s_\theta & g_{a\gamma}\omega B c_\theta & m_a^2 \end{bmatrix} \underbrace{\begin{bmatrix} c_\theta & s_\theta & 0 \\ -s_\theta & c_\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}}_V$$

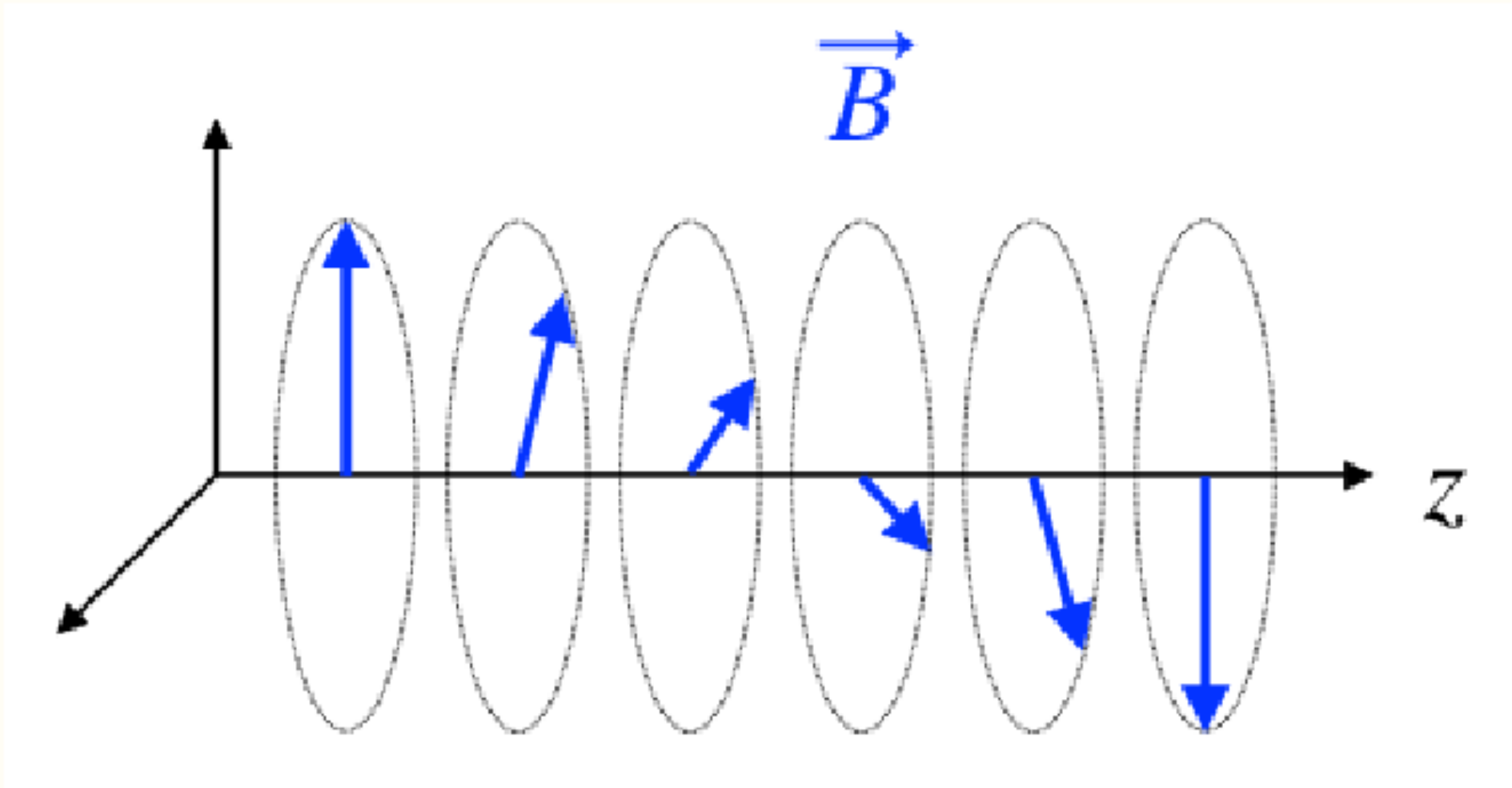


?



$$i\partial_z \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix} = \frac{1}{2\omega} \begin{bmatrix} 0 & 0 & g_{a\gamma}\omega B s_\theta \\ 0 & 0 & g_{a\gamma}\omega B c_\theta \\ g_{a\gamma}\omega B s_\theta & g_{a\gamma}\omega B c_\theta & m_a^2 \end{bmatrix} \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix},$$

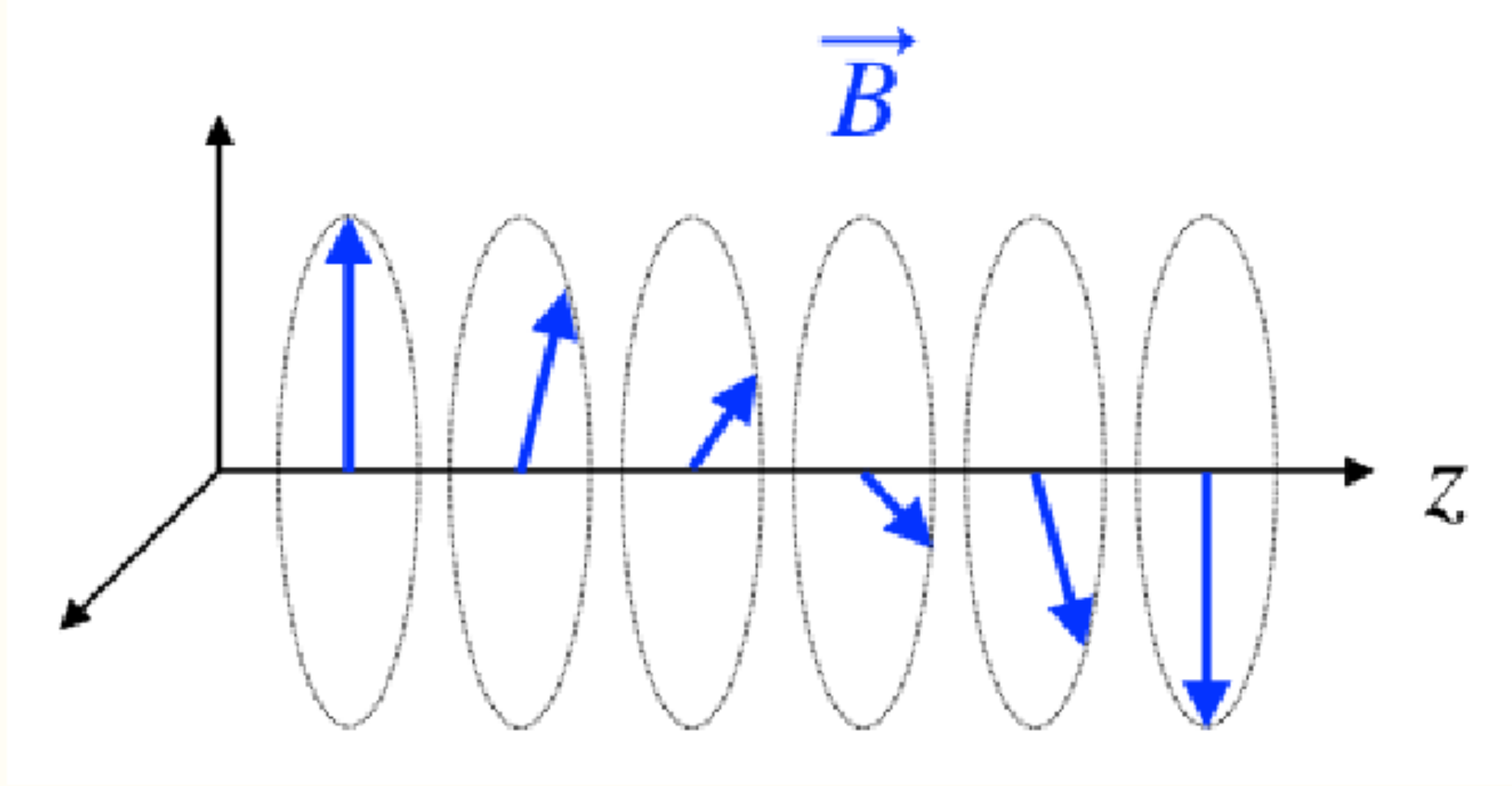
$$\theta = \theta(z)$$



$$i\partial_z \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix} = \frac{1}{2\omega} \begin{bmatrix} 0 & 0 & g_{a\gamma}\omega B s_\theta \\ 0 & 0 & g_{a\gamma}\omega B c_\theta \\ g_{a\gamma}\omega B s_\theta & g_{a\gamma}\omega B c_\theta & m_a^2 \end{bmatrix} \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix}$$

$$\theta = \theta(z)$$

$$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & g_{a\gamma}\omega B \\ 0 & g_{a\gamma}\omega B & m_a^2 \end{bmatrix} = \begin{bmatrix} c_\theta & -s_\theta & 0 \\ s_\theta & c_\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 & 0 & g_{a\gamma}\omega B s_\theta \\ 0 & 0 & g_{a\gamma}\omega B c_\theta \\ g_{a\gamma}\omega B s_\theta & g_{a\gamma}\omega B c_\theta & m_a^2 \end{bmatrix} \begin{bmatrix} c_\theta & s_\theta & 0 \\ -s_\theta & c_\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



$$i\partial_z \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix} = \frac{1}{2\omega} \begin{bmatrix} 0 & 0 & g_{a\gamma}\omega B s_\theta \\ 0 & 0 & g_{a\gamma}\omega B c_\theta \\ g_{a\gamma}\omega B s_\theta & g_{a\gamma}\omega B c_\theta & m_a^2 \end{bmatrix} \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix},$$

$$\theta = \theta(z)$$

$$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & g_{a\gamma}\omega B \\ 0 & g_{a\gamma}\omega B & m_a^2 \end{bmatrix} = \underbrace{\begin{bmatrix} c_\theta & -s_\theta & 0 \\ s_\theta & c_\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{V^\dagger(z)} \begin{bmatrix} 0 & 0 & g_{a\gamma}\omega B s_\theta \\ 0 & 0 & g_{a\gamma}\omega B c_\theta \\ g_{a\gamma}\omega B s_\theta & g_{a\gamma}\omega B c_\theta & m_a^2 \end{bmatrix} \underbrace{\begin{bmatrix} c_\theta & s_\theta & 0 \\ -s_\theta & c_\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{V(z)}$$

$$i\partial_z \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix} = \frac{1}{2\omega} \begin{bmatrix} 0 & 0 & g_{a\gamma}\omega Bs_\theta \\ 0 & 0 & g_{a\gamma}\omega Bc_\theta \\ g_{a\gamma}\omega Bs_\theta & g_{a\gamma}\omega Bc_\theta & m_a^2 \end{bmatrix} \begin{bmatrix} \gamma_x \\ \gamma_y \\ a \end{bmatrix},$$

$$\theta = \theta(z)$$

$$V^\dagger i\partial_z \left(V(z) \begin{bmatrix} \gamma'_x \\ \gamma'_y \\ a' \end{bmatrix} \right) = \left(V^\dagger \begin{bmatrix} 0 & 0 & \frac{g_{a\gamma}B}{2}s_\theta \\ 0 & 0 & \frac{g_{a\gamma}B}{2}c_\theta \\ \frac{g_{a\gamma}B}{2}s_\theta & \frac{g_{a\gamma}B}{2}c_\theta & m_a^2/2\omega \end{bmatrix} V \right) \begin{bmatrix} \gamma'_x \\ \gamma'_y \\ a' \end{bmatrix}$$

$$\theta = \theta(z)$$

$$i\partial_z \begin{bmatrix} \gamma'_x \\ \gamma'_y \\ a' \end{bmatrix} = \left(\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & \frac{g_{a\gamma}B}{2} \\ 0 & \frac{g_{a\gamma}B}{2} & m_a^2/2\omega \end{bmatrix} - \textcolor{brown}{V}^\dagger i\partial_z \textcolor{brown}{V} \right) \begin{bmatrix} \gamma'_x \\ \gamma'_y \\ a' \end{bmatrix}$$

$$\theta = \theta(z)$$

$$i\partial_z \begin{bmatrix} \gamma'_x \\ \gamma'_y \\ a' \end{bmatrix} = \begin{bmatrix} 0 & -i\dot{\theta} & 0 \\ i\dot{\theta} & 0 & \frac{g_{a\gamma}B}{2} \\ 0 & \frac{g_{a\gamma}B}{2} & m_a^2/2\omega \end{bmatrix} \begin{bmatrix} \gamma'_x \\ \gamma'_y \\ a' \end{bmatrix}$$

$$\theta = \theta(z)$$

$$i\partial_z \begin{bmatrix} \gamma_x'' \\ \gamma_y'' \\ a'' \end{bmatrix} = \begin{bmatrix} -\dot{\theta} & 0 & \frac{g_{a\gamma}B}{2\sqrt{2}} \\ 0 & \dot{\theta} & \frac{g_{a\gamma}B}{2\sqrt{2}} \\ \frac{g_{a\gamma}B}{2\sqrt{2}} & \frac{g_{a\gamma}B}{2\sqrt{2}} & m_a^2/2\omega \end{bmatrix} \begin{bmatrix} \gamma_x'' \\ \gamma_y'' \\ a'' \end{bmatrix}$$

$$\theta = \theta(z)$$

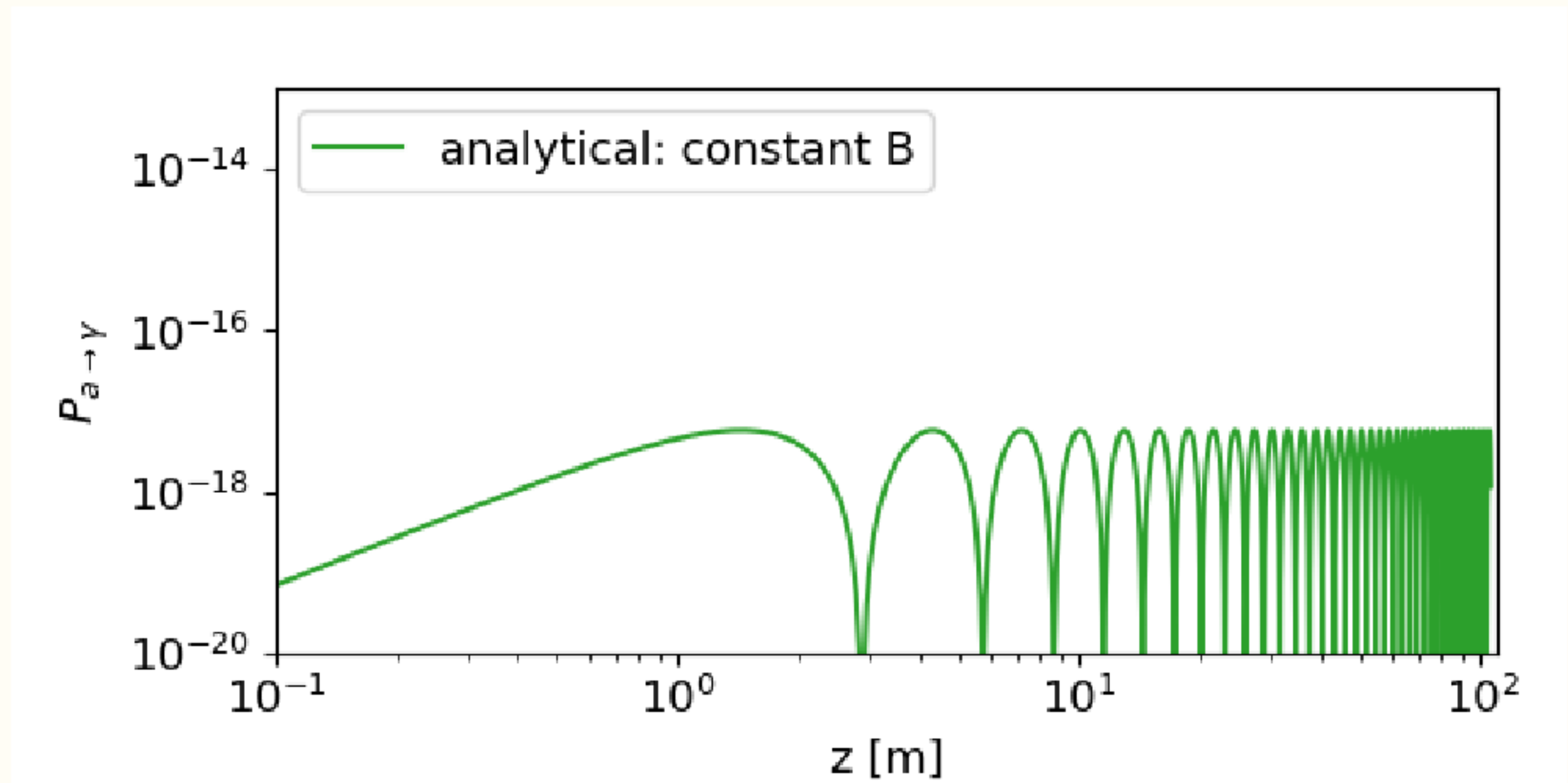
$$i\partial_z \begin{bmatrix} \gamma''_x \\ \gamma''_y \\ a'' \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & \frac{g_{a\gamma}B}{2} \\ 0 & \frac{g_{a\gamma}B}{2} & m_a^2/2\omega \end{bmatrix} \begin{bmatrix} \gamma''_x \\ \gamma''_y \\ a'' \end{bmatrix}$$

$$P_{a\rightarrow\gamma} \simeq \frac{g_{a\gamma}^2 B^2}{g_{a\gamma}^2 B^2 + m_a^4/(4\omega^2)} \sin^2 \left(\left(\frac{1}{2} \sqrt{g_{a\gamma}^2 B^2 + \frac{m_a^4}{4\omega^2}} \right) z \right),$$

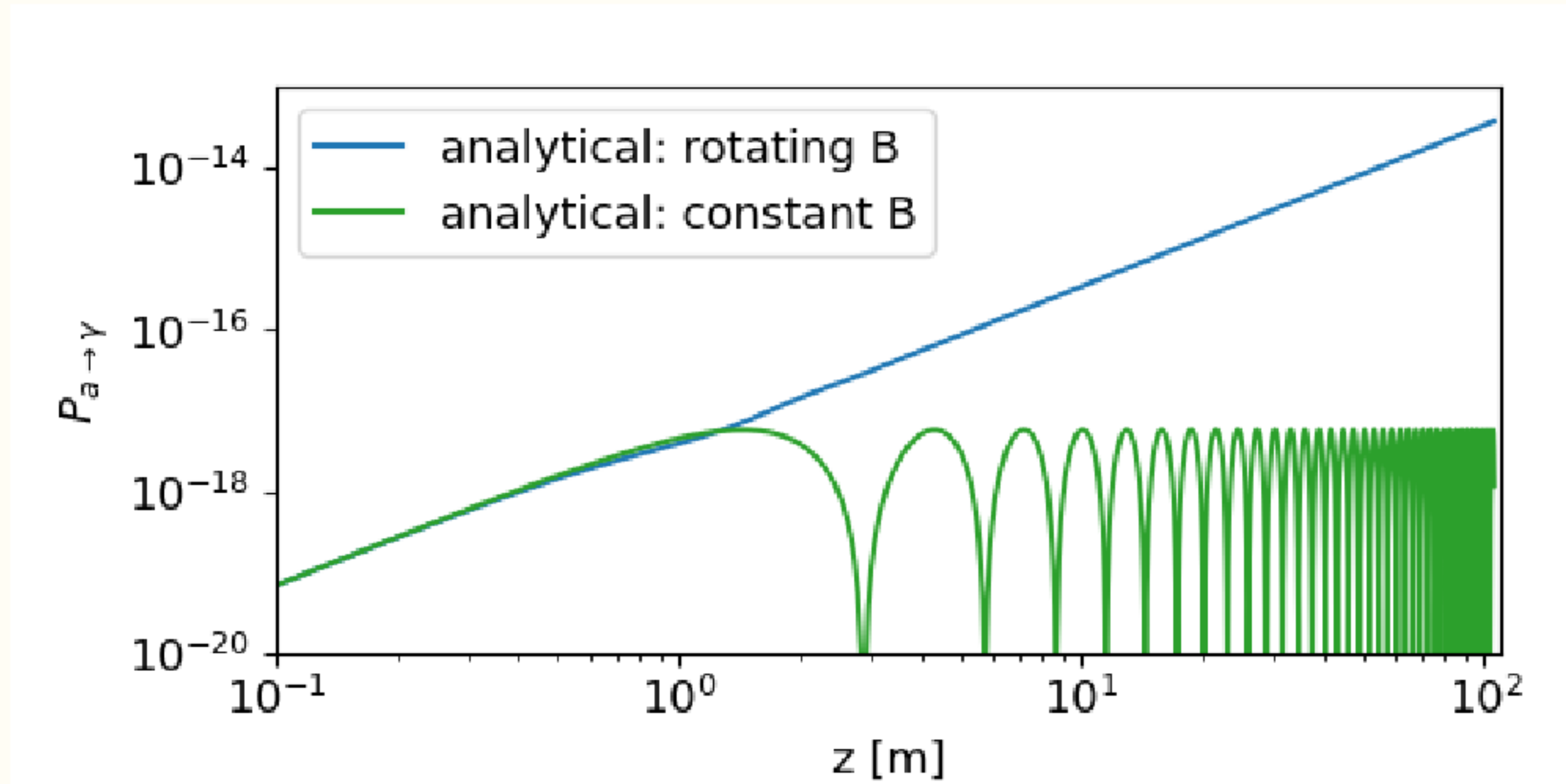
$$i\partial_z \begin{bmatrix} \gamma''_x \\ \gamma''_y \\ a'' \end{bmatrix} = \begin{bmatrix} -\dot{\theta} & 0 & \frac{g_{a\gamma}B}{2\sqrt{2}} \\ 0 & \dot{\theta} & \frac{g_{a\gamma}B}{2\sqrt{2}} \\ \frac{g_{a\gamma}B}{2\sqrt{2}} & \frac{g_{a\gamma}B}{2\sqrt{2}} & m_a^2/2\omega \end{bmatrix} \begin{bmatrix} \gamma''_x \\ \gamma''_y \\ a'' \end{bmatrix}$$

$$\theta = \theta(z)$$

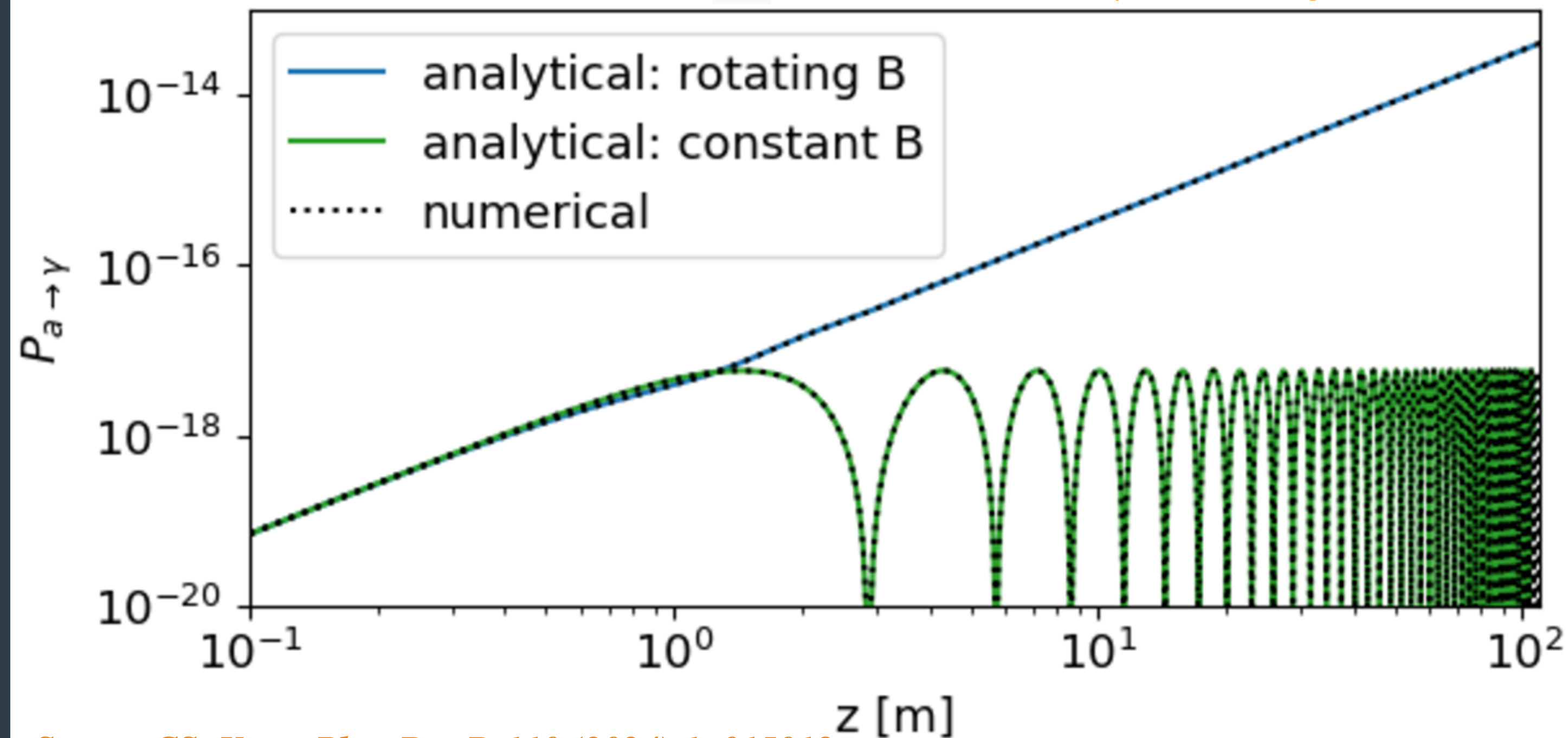
$$P_{a\rightarrow\gamma} \simeq \sum_{\pm} \frac{g_{a\gamma}^2 B^2/2}{g_{a\gamma}^2 B^2/2 + (m_a^2/2\omega \pm \dot{\theta})^2} \sin^2 \left(\left(\frac{1}{2} \sqrt{\frac{g_{a\gamma}^2 B^2}{2} + (\frac{m_a^2}{2\omega} \pm \dot{\theta})^2} \right) z \right),$$



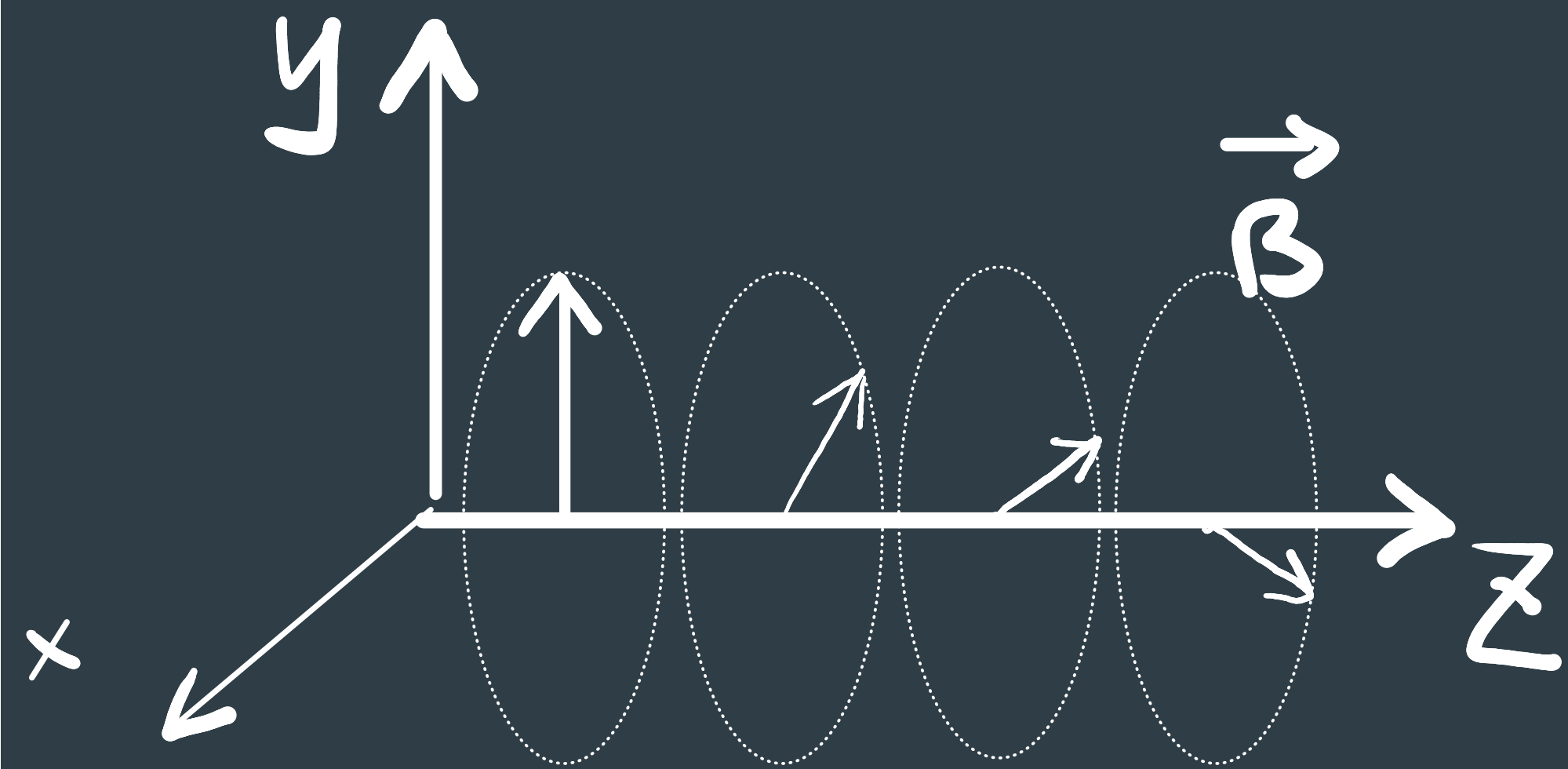
$$P_{a \rightarrow \gamma} \simeq \frac{g_{a\gamma}^2 B^2}{g_{a\gamma}^2 B^2 + m_a^4/(4\omega^2)} \sin^2 \left(\left(\frac{1}{2} \sqrt{g_{a\gamma}^2 B^2 + \frac{m_a^4}{4\omega^2}} \right) z \right),$$



$$P_{a \rightarrow \gamma} \simeq \sum_{\pm} \frac{g_{a\gamma}^2 B^2 / 2}{g_{a\gamma}^2 B^2 / 2 + (m_a^2 / 2\omega \pm \dot{\theta})^2} \sin^2 \left(\left(\frac{1}{2} \sqrt{\frac{g_{a\gamma}^2 B^2}{2} + \left(\frac{m_a^2}{2\omega} \pm \dot{\theta} \right)^2} \right) z \right),$$



Seong, CS, Yun *Phys.Rev.D* 110 (2024) 1, 015018



$$P_{a \rightarrow \gamma} \simeq \sum_{\pm} \frac{g_{a\gamma}^2 B^2 / 2}{g_{a\gamma}^2 B^2 / 2 + (m_a^2 / 2\omega \pm \Omega)^2} \sin^2 \left(\left(\frac{1}{2} \sqrt{\frac{g_{a\gamma}^2 B^2}{2} + \left(\frac{m_a^2}{2\omega} \pm \Omega \right)^2} \right) z \right),$$

$$\alpha|0\rangle + e^{i\varphi(t)}\beta|1\rangle$$

Qubit



(Pauli X Gate)

V oscillation

MSW & (Avoided) level crossing

Atomic

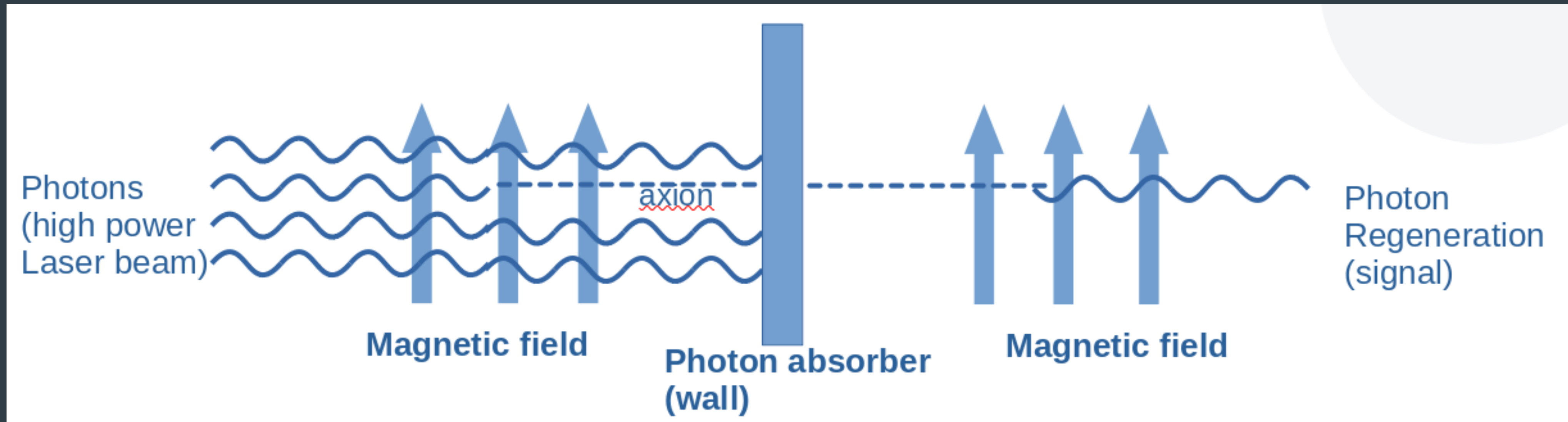
Rabi flopping

Nuclear

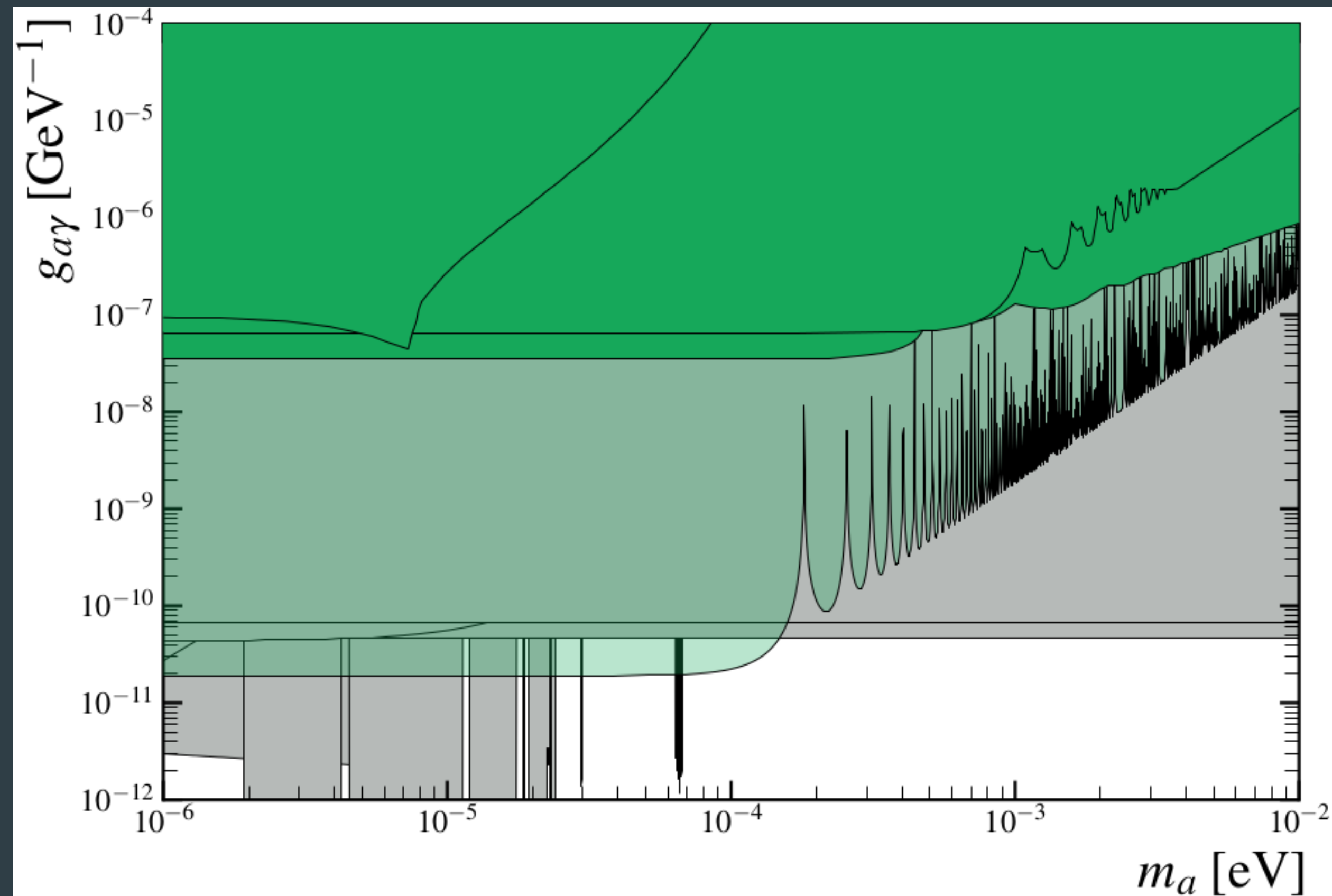
Nuclear Magnetic Resonance

Axion-photon

Axion Magnetic Resonance

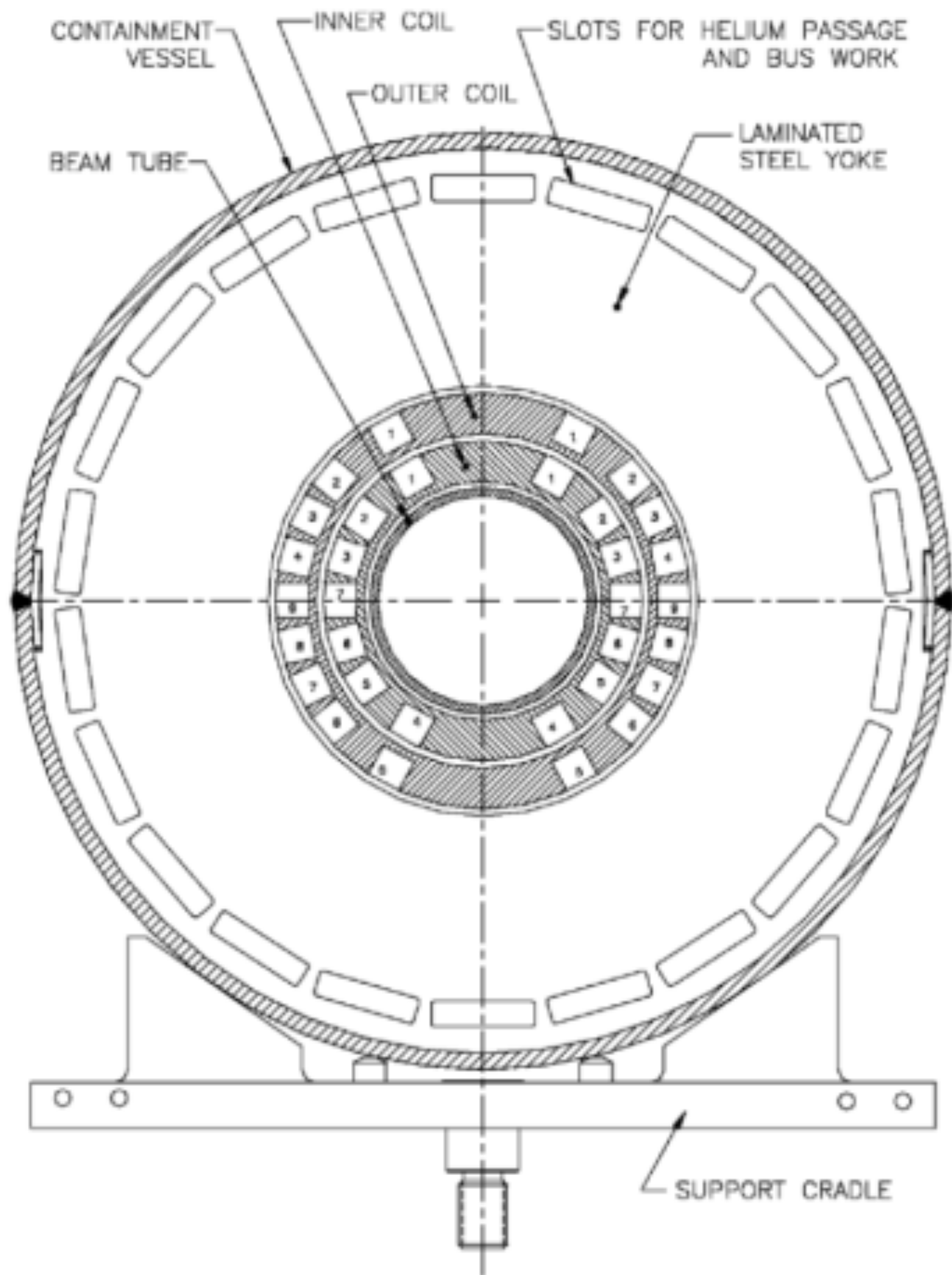


"Light Shining through Walls"



- 12 pieces of HERA dipole magnet,
- 106 m for production, 106 m for regen'
- continuous laser: 1064 nm, 30 W
- optical Fabry-Perot resonator:
 - + 5000 power build-up ~150 kW in prod' cavity
 - + 40000 power build-up in the regen' cavity
- detector: cryogenic superconducting microcalorimeter (TES)
- started data taking on May 23, 2023

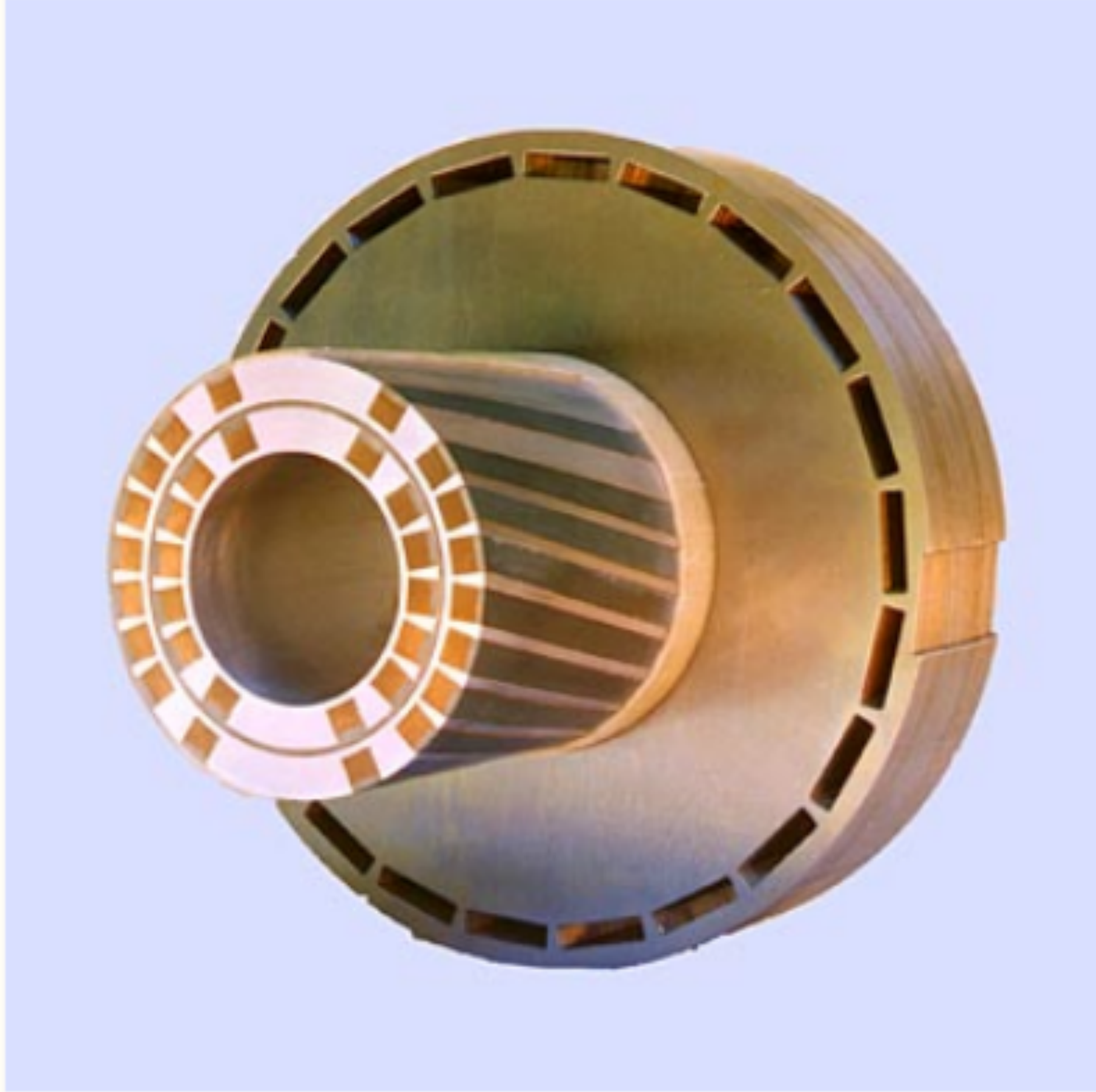
Experimental Implications



Magnets at Relativistic Heavy Ion Collider (RHIC), BNL:

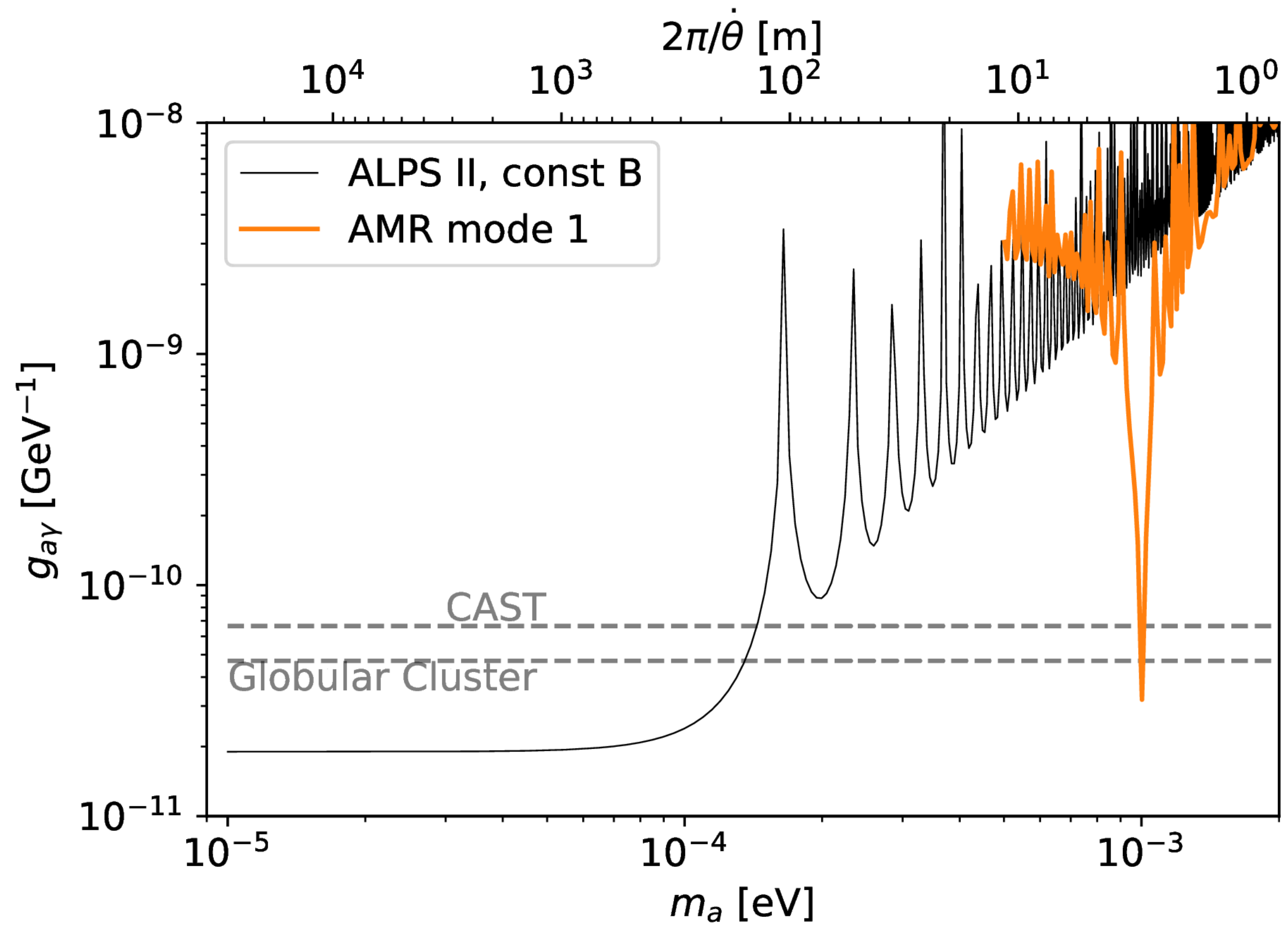
- superconducting dipole magnet ~ 5 T
- 1740 magnets adopted by RHIC
- 30-/36-strand SC cable for...
... 80-100/130-180 mm apertures

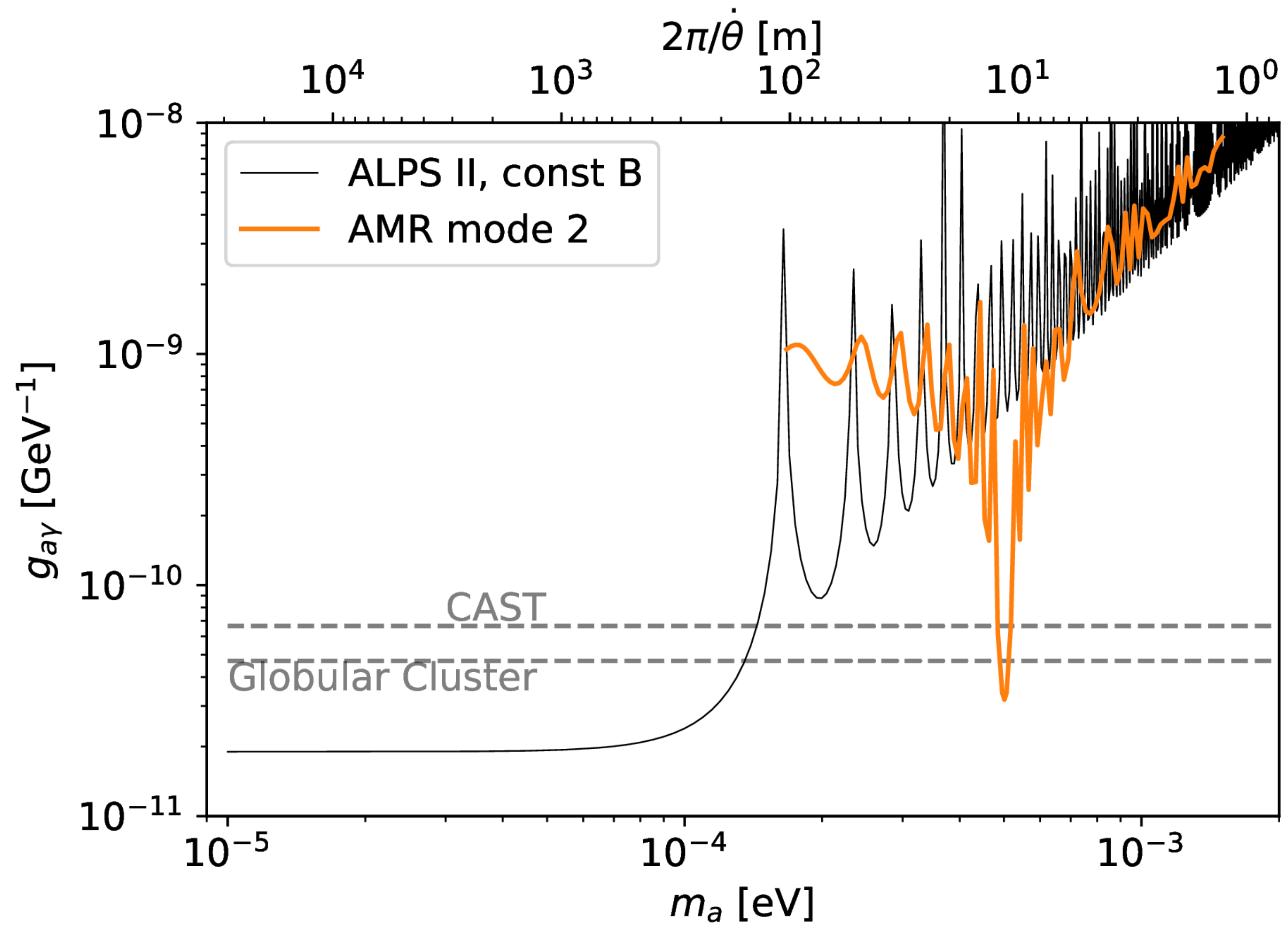
Experimental Implications

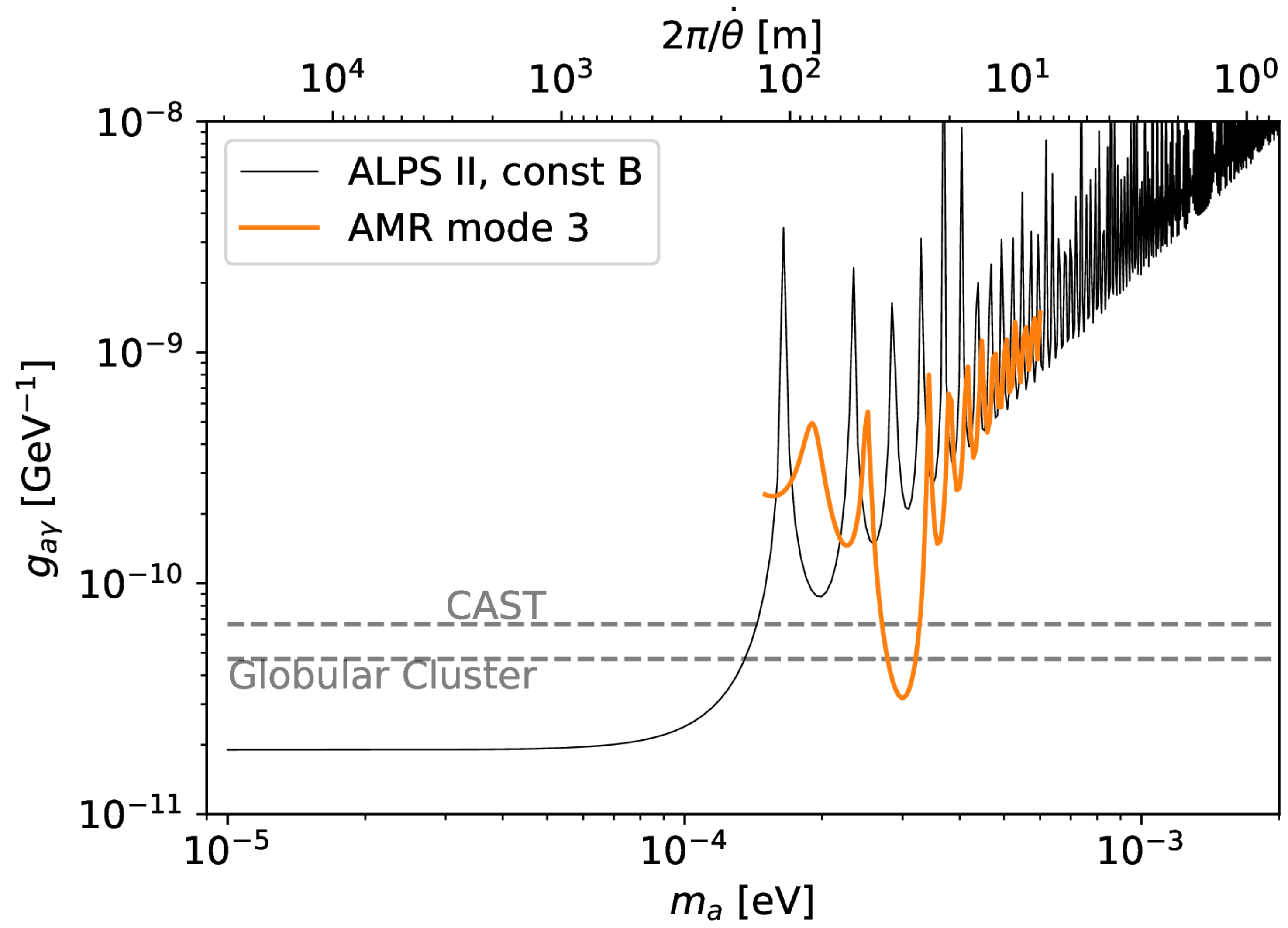


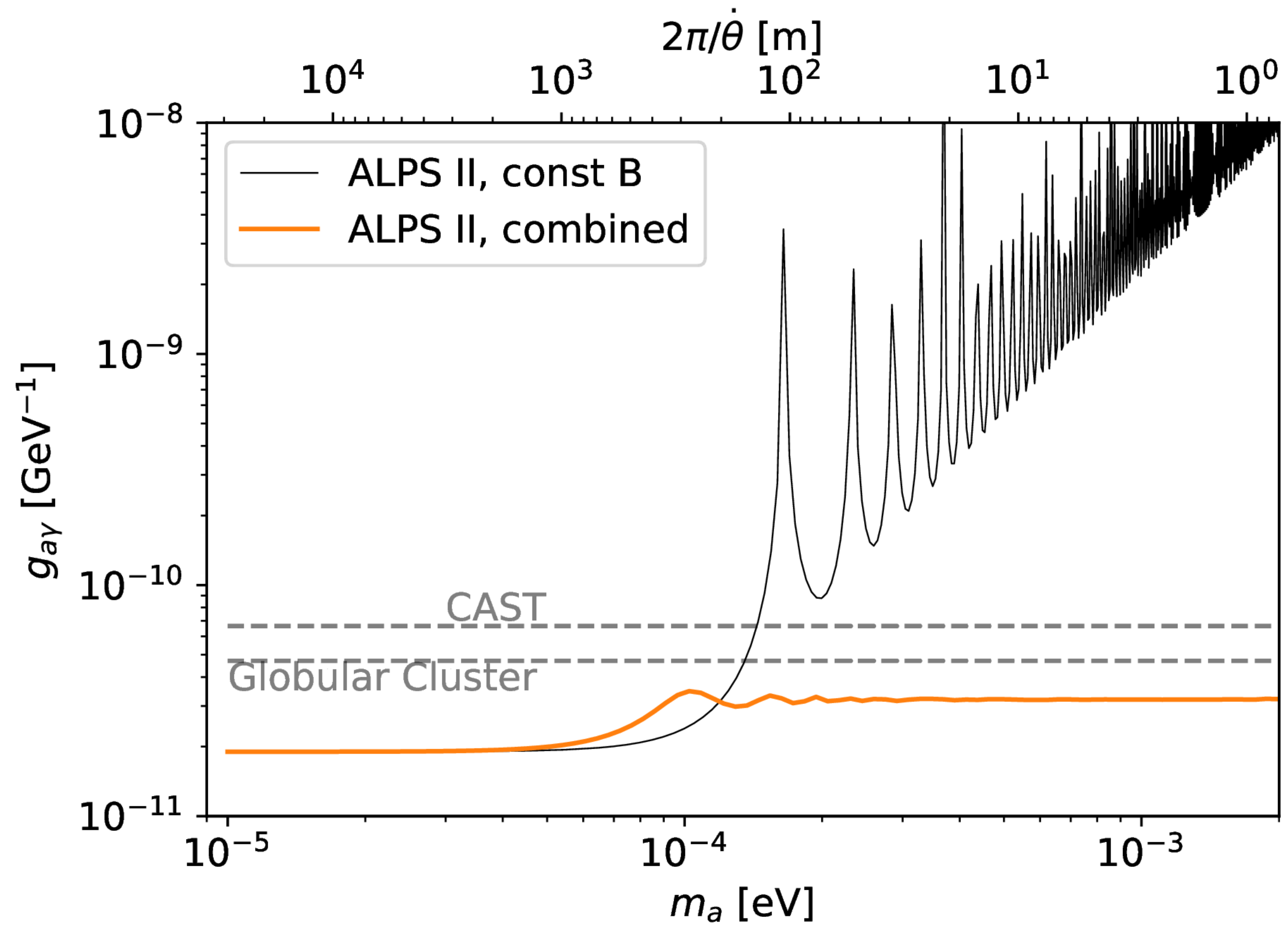
Magnets at Relativistic Heavy Ion Collider (RHIC), BNL:

- superconducting dipole magnet ~ 5 T
- 1740 magnets adopted by RHIC
- 30-/36-strand SC cable for...
... 80-100/130-180 mm apertures
- **B** field rotates 360 degrees in 2.4 meters
- designed to control proton spin for polarized proton colliding





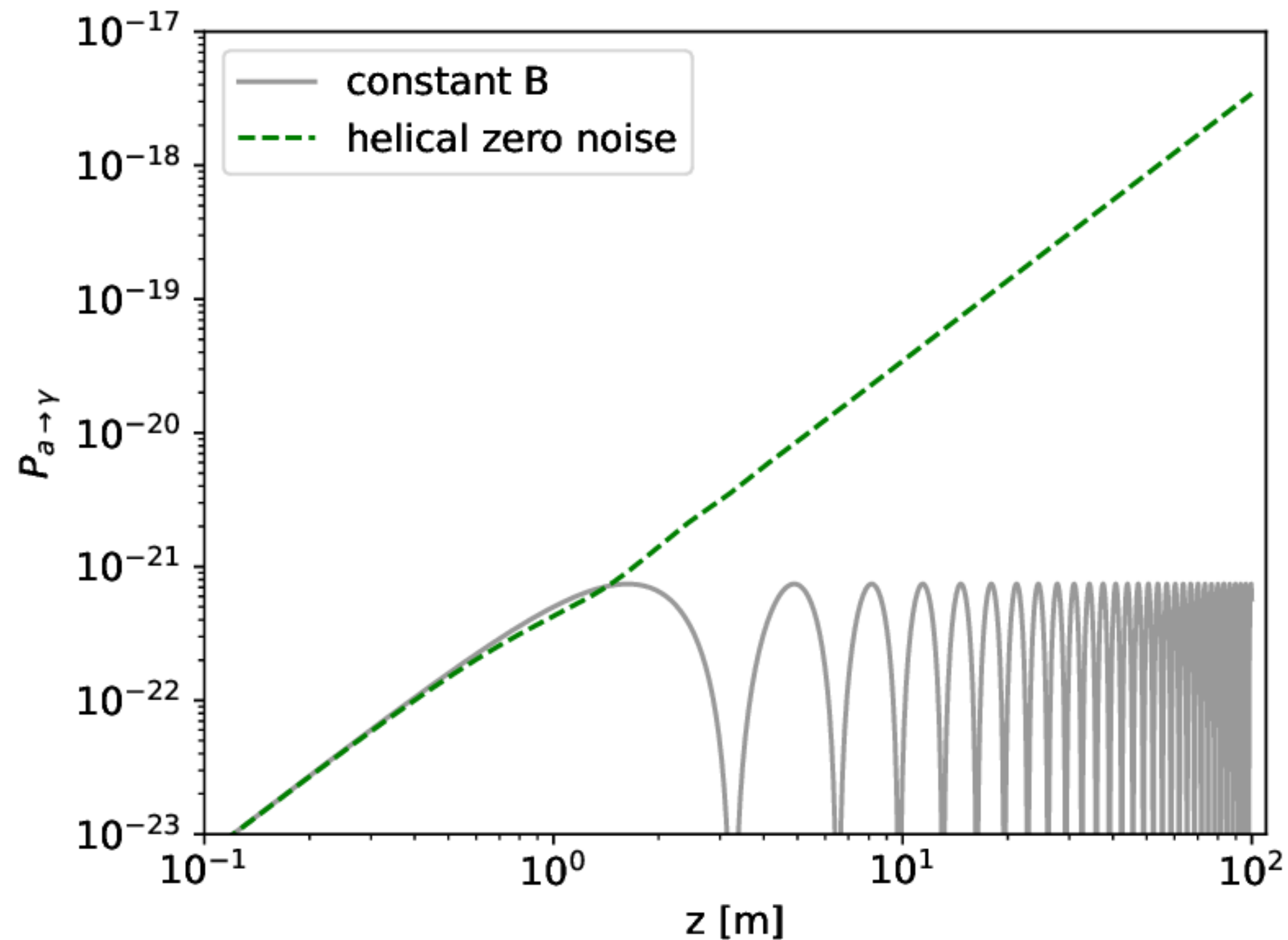




Noise :

Ω fluctuation

Experimental Implications – B regularity

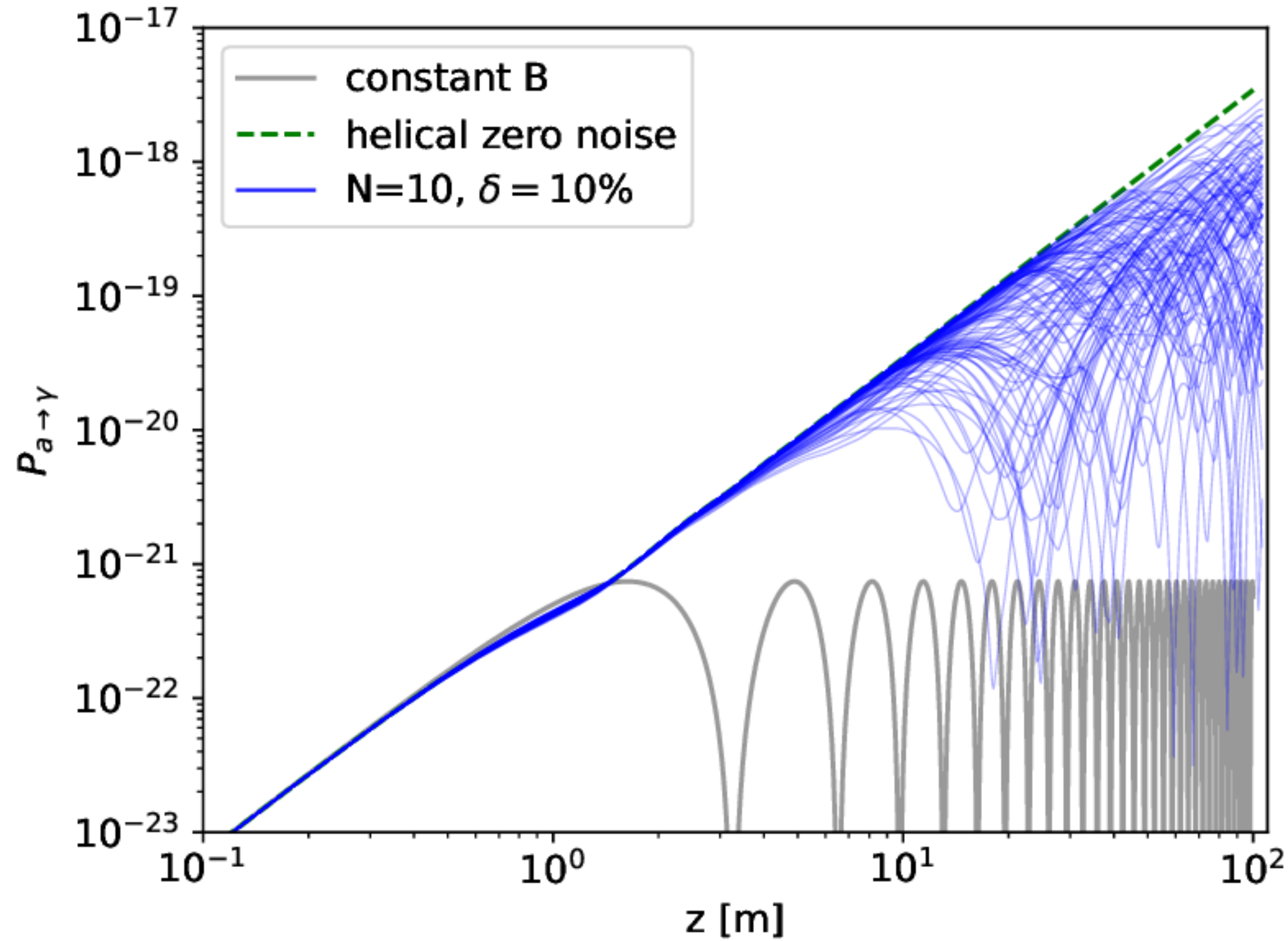


A simplified model:

- $\dot{\theta}$ takes N values along the whole baseline
larger $N \sim$ larger noise frequency
- in each interval, $\dot{\theta}(z) = \bar{\dot{\theta}} + \delta\dot{\theta}(z)$
larger $\delta\dot{\theta}/\bar{\dot{\theta}} \sim$ larger noise amplitude
- assume $\delta\dot{\theta}/\bar{\dot{\theta}}$ to be gaussian around zero

$$\theta = \Omega \cdot z \longrightarrow \theta = \dot{\theta}(z) \cdot z$$

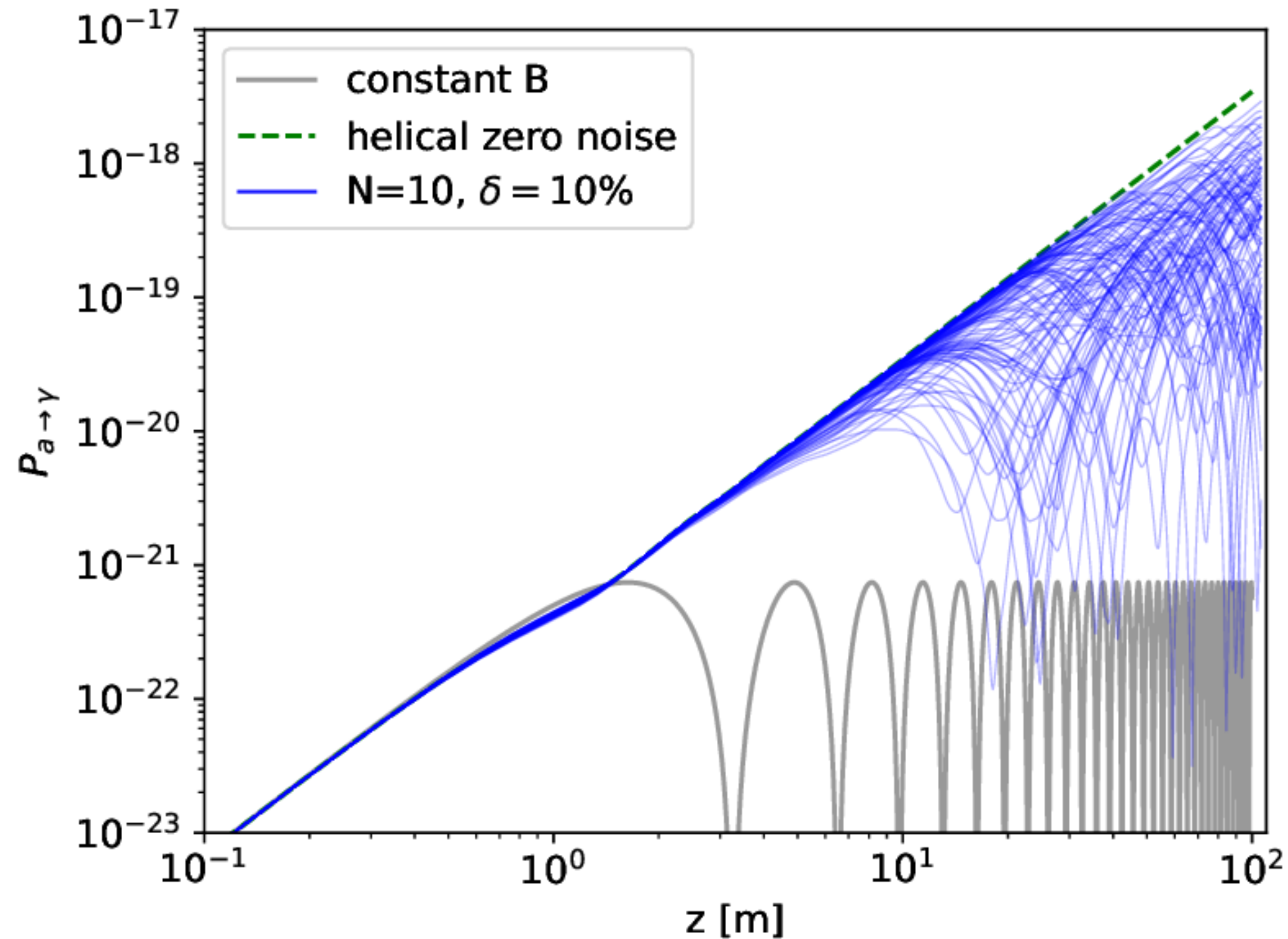
Experimental Implications – B regularity



A simplified model:

- $\dot{\theta}$ takes N values along the whole baseline
larger $N \sim$ larger noise frequency
- in each interval, $\dot{\theta}(z) = \bar{\dot{\theta}} + \delta\dot{\theta}(z)$
larger $\delta\dot{\theta}/\bar{\dot{\theta}} \sim$ larger noise amplitude
- assume $\delta\dot{\theta}/\bar{\dot{\theta}}$ to be gaussian around zero

Experimental Implications – B regularity

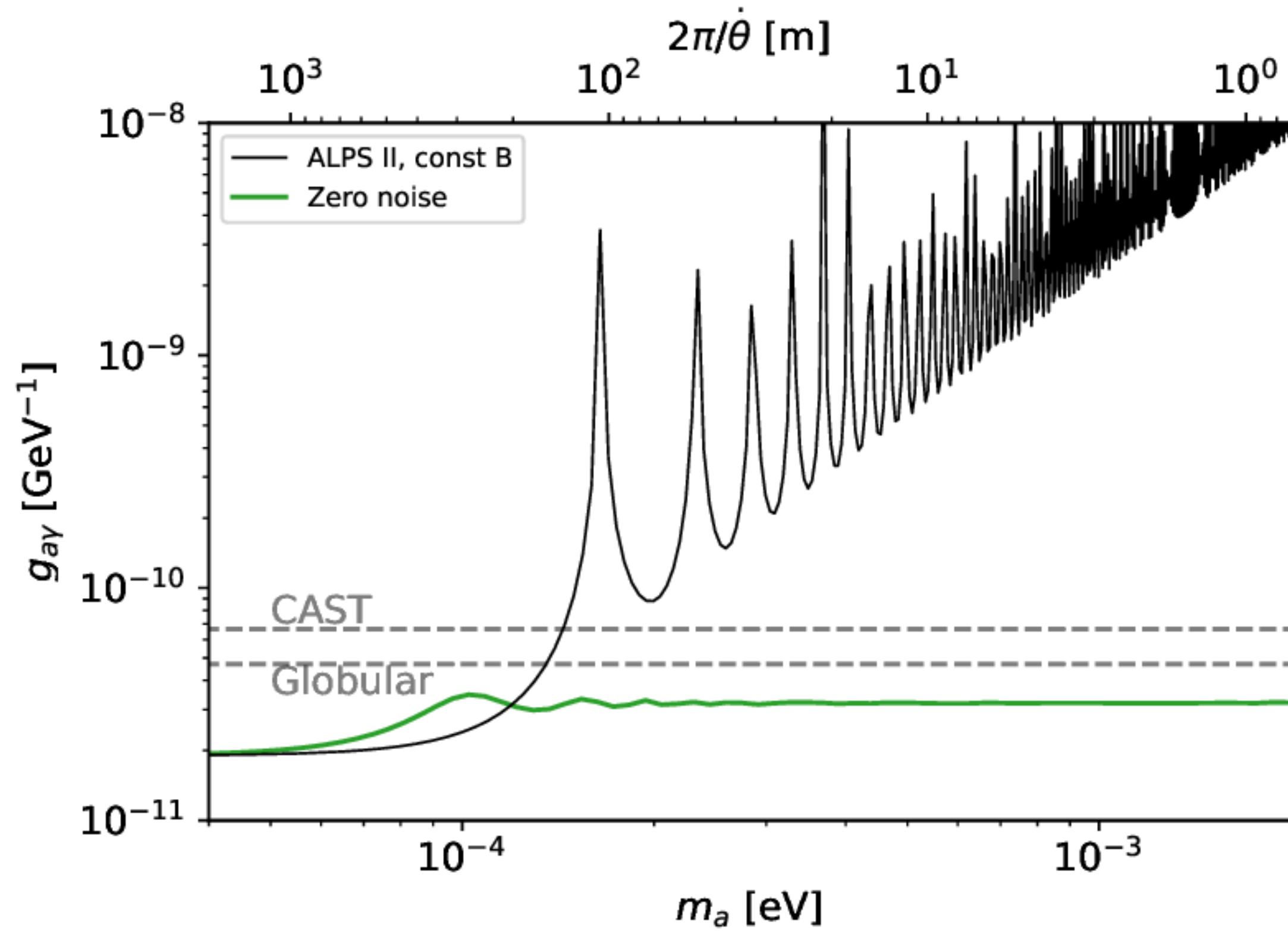


A simplified model:

- $\dot{\theta}$ takes N values along the whole baseline
larger $N \sim$ larger noise frequency
- in each interval, $\dot{\theta}(z) = \bar{\dot{\theta}} + \delta\dot{\theta}(z)$
larger $\delta\dot{\theta}/\bar{\dot{\theta}} \sim$ larger noise amplitude
- assume $\delta\dot{\theta}/\bar{\dot{\theta}}$ to be gaussian around zero

Repeat same exercise for different m_a

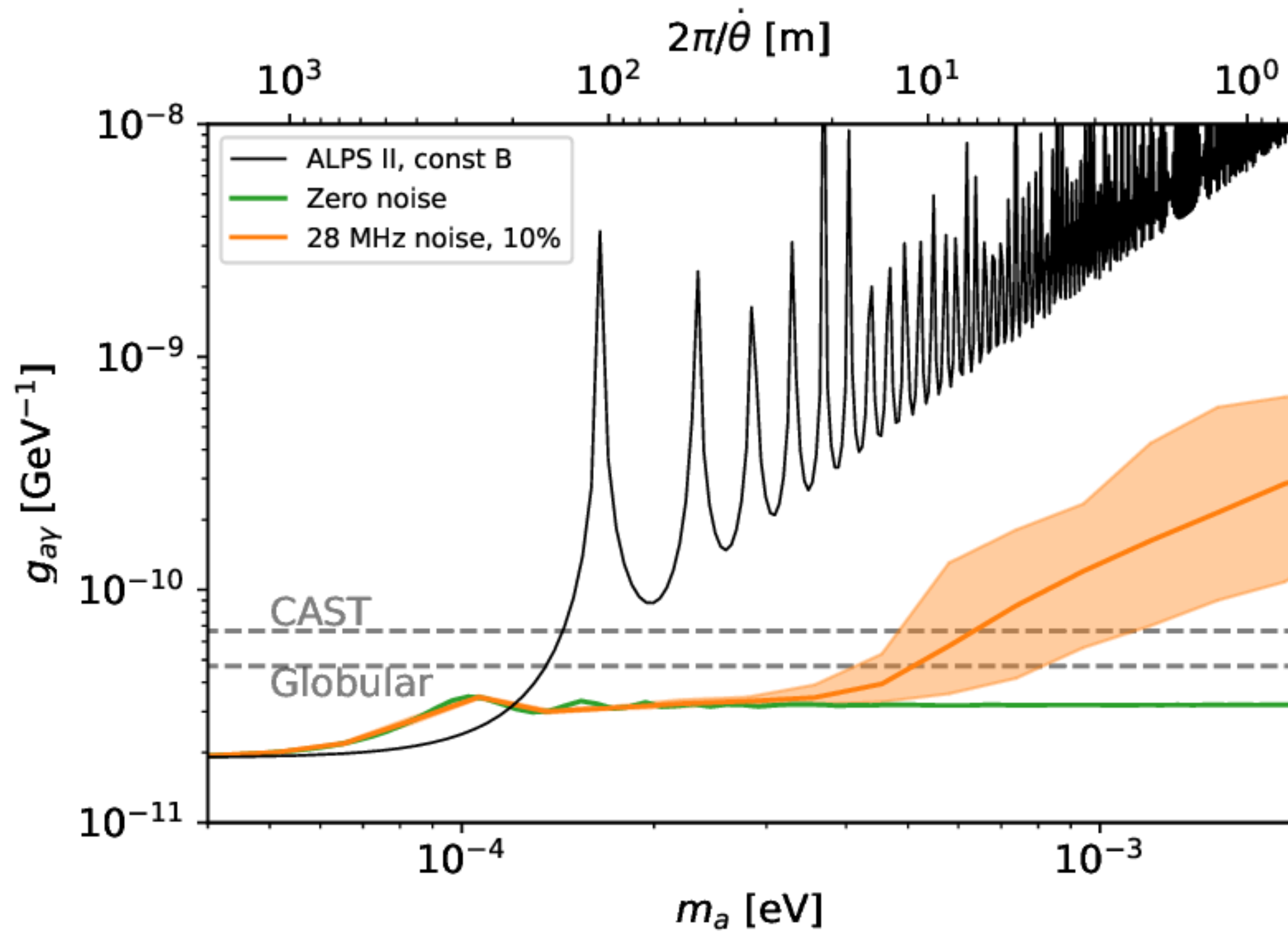
Experimental Implications – B regularity (cont'd)



A simplified model:

- Zero noise reach: AMR floor

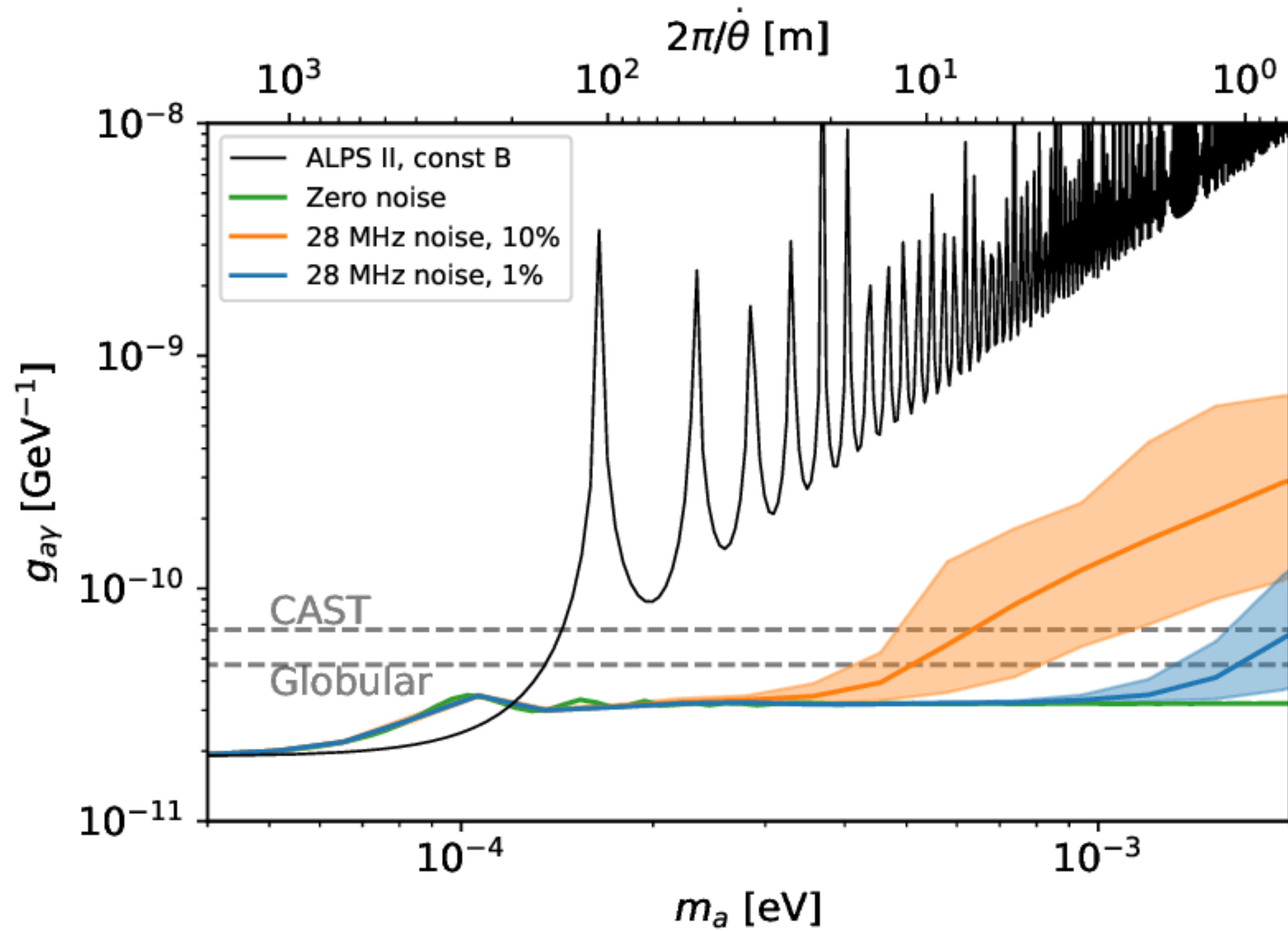
Experimental Implications – B regularity (cont'd)



A simplified model:

- Zero noise reach: AMR floor
- $N = 10$, $\delta = 10\%$

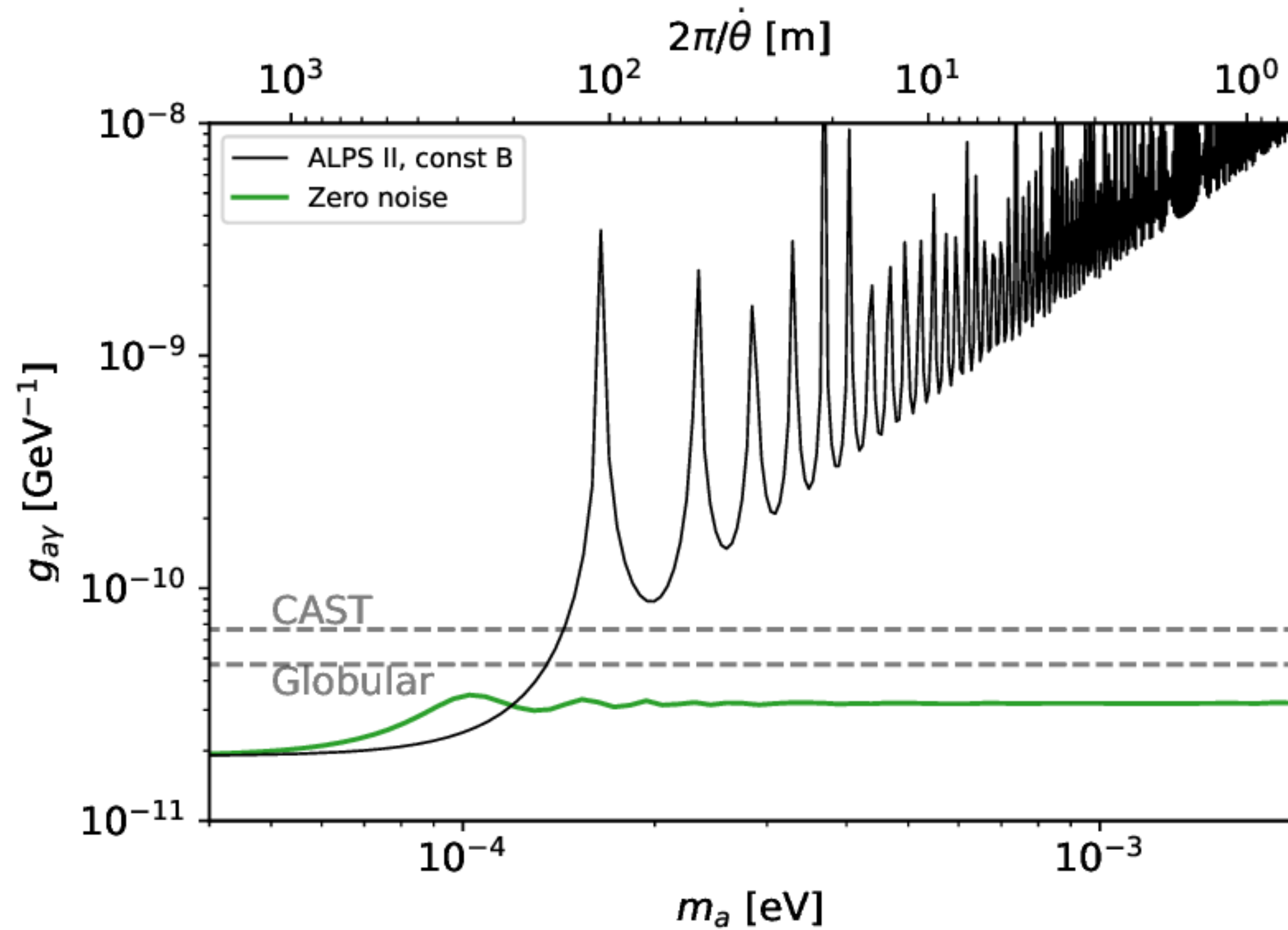
Experimental Implications – B regularity (cont'd)



A simplified model:

- Zero noise reach: AMR floor
- $N = 10$, $\delta = 10\%$
- $N = 10$, $\delta = 1\%$

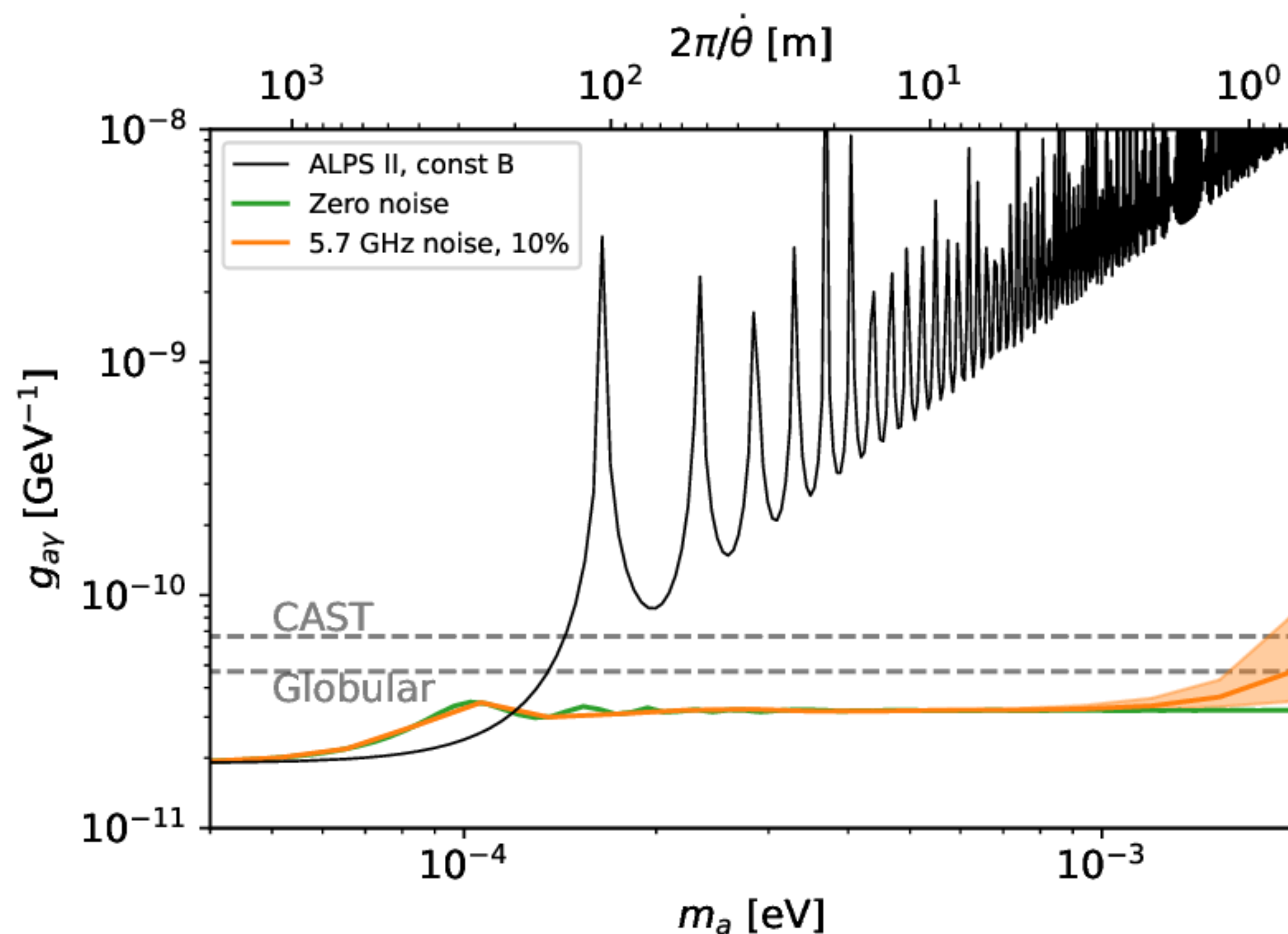
Experimental Implications – B regularity (cont'd)



A simplified model:

- Zero noise reach: AMR floor
- $N = 10$, $\delta = 10\%$
- $N = 10$, $\delta = 1\%$

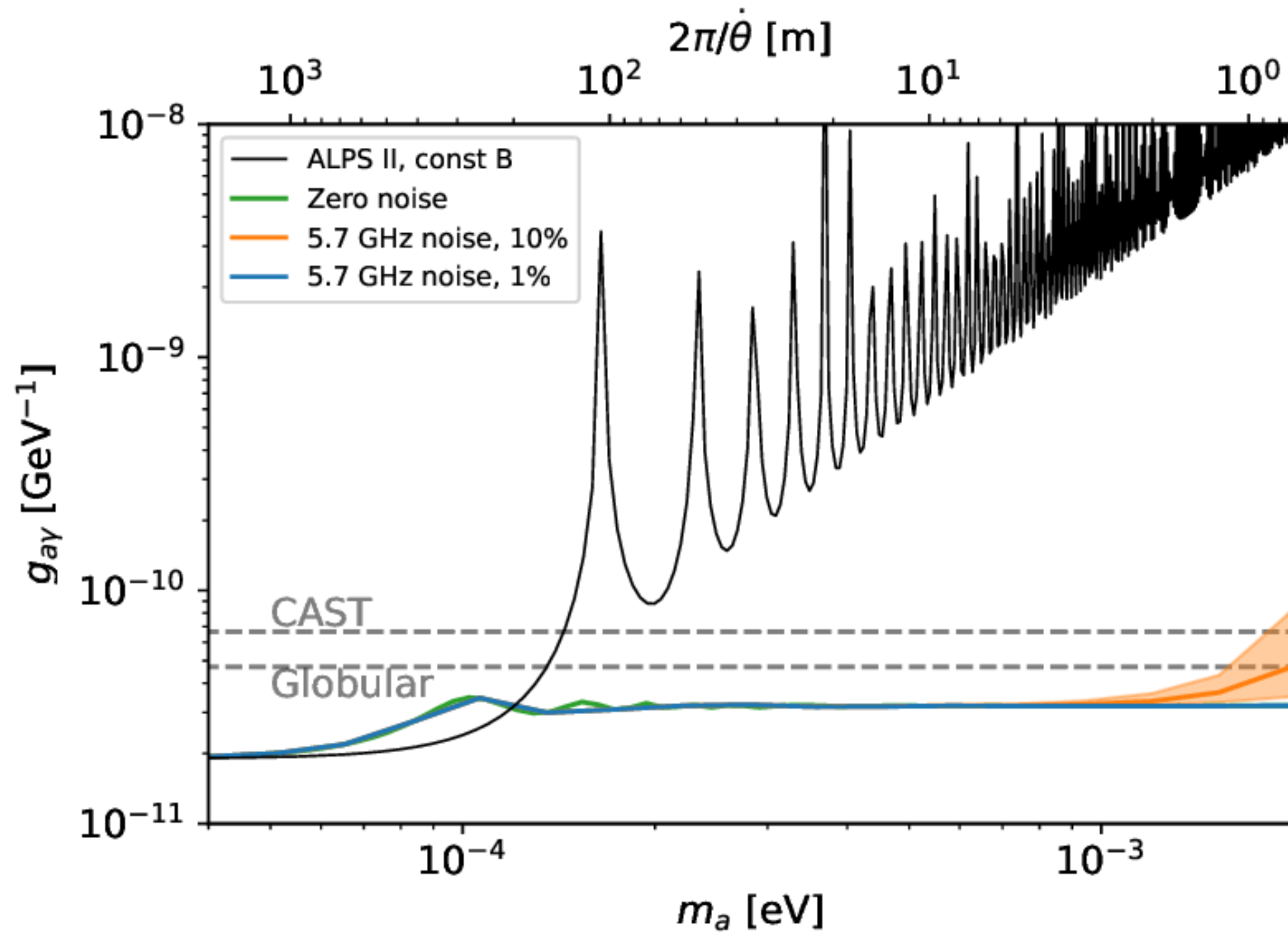
Experimental Implications – B regularity (cont'd)



A simplified model:

- Zero noise reach: AMR floor
- $N = 10$, $\delta = 10\%$
- $N = 10$, $\delta = 1\%$
- $N = 2000$, $\delta = 10\%$

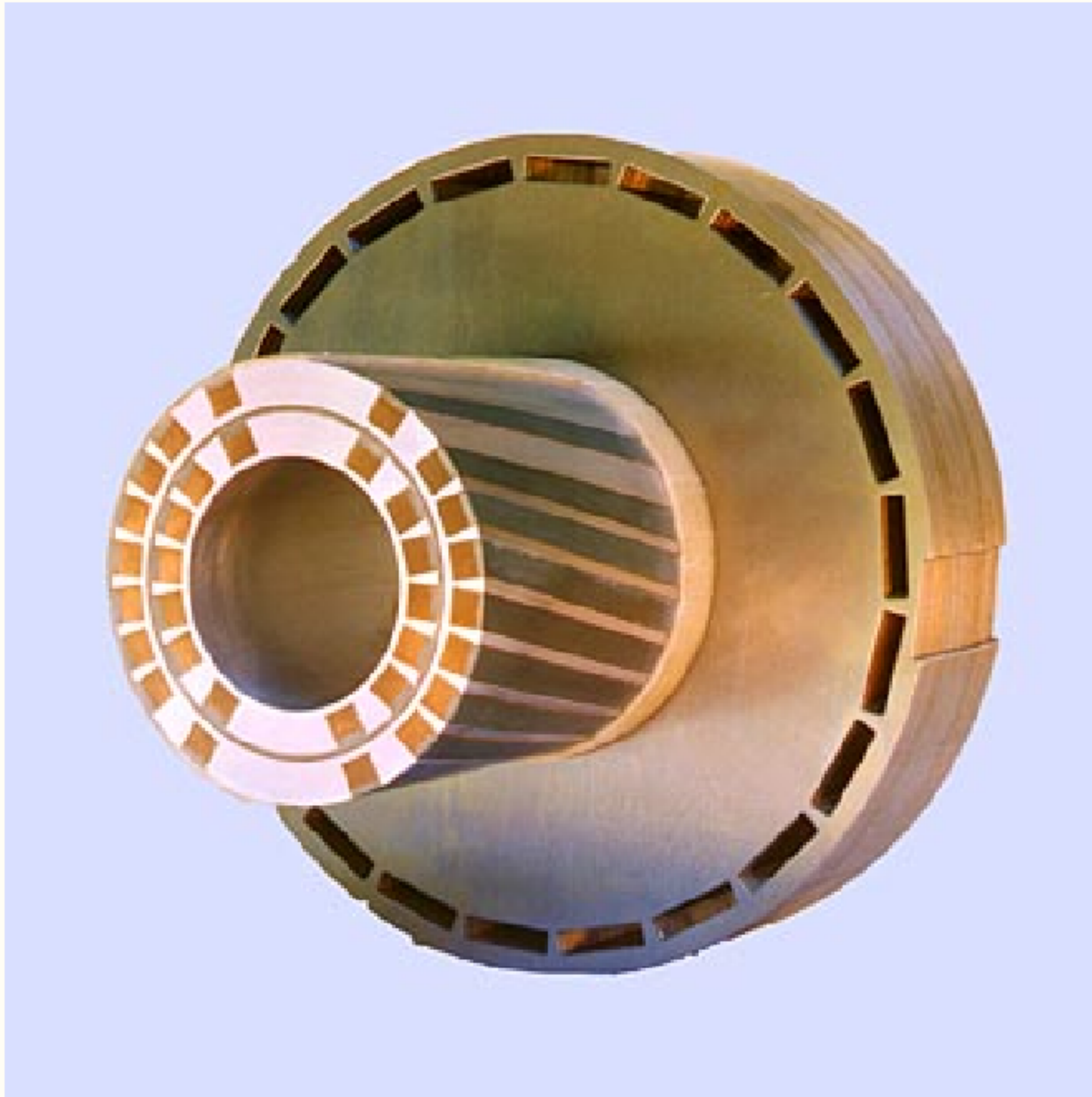
Experimental Implications – B regularity (cont'd)



A simplified model:

- Zero noise reach: AMR floor
- $N = 10$, $\delta = 10\%$
- $N = 10$, $\delta = 1\%$
- $N = 2000$, $\delta = 10\%$
- $N = 2000$, $\delta = 1\%$

Experimental Implications – B regularity (cont'd)



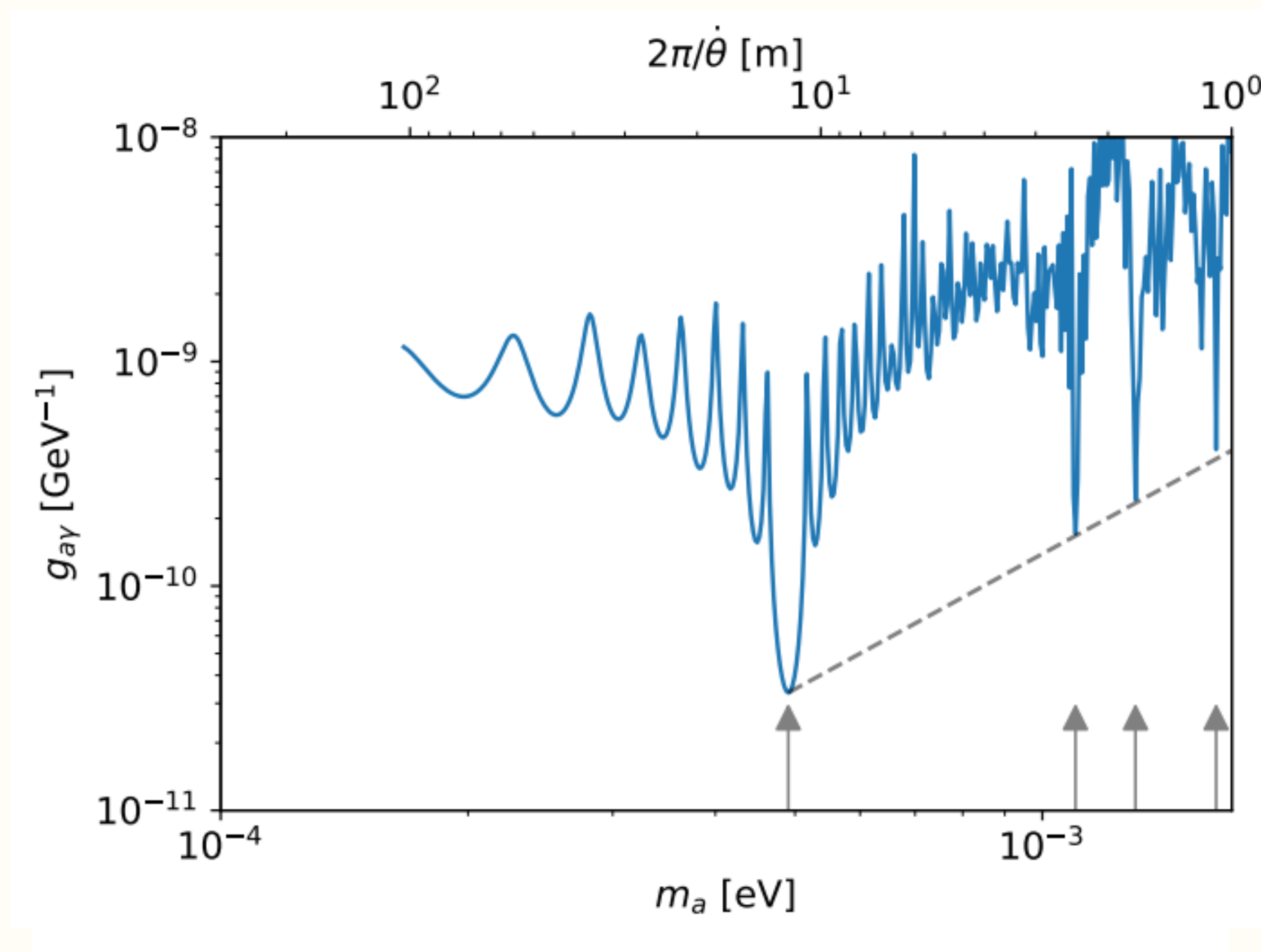
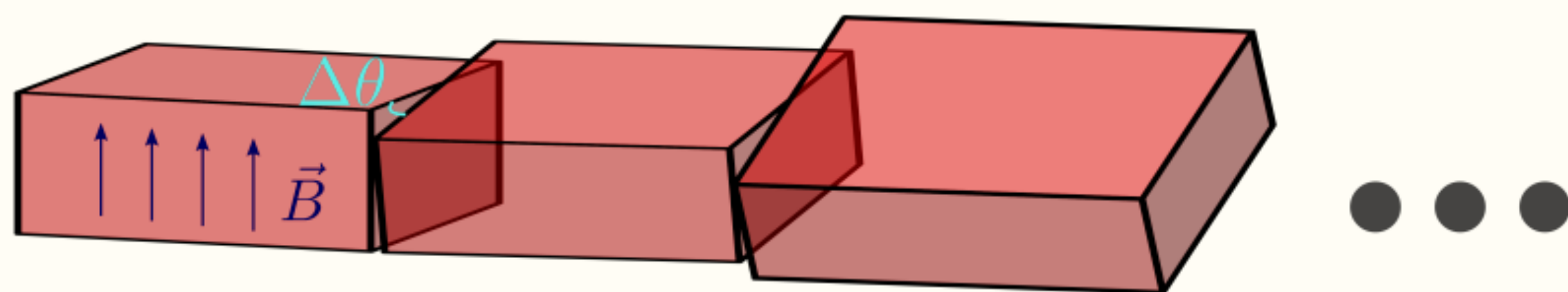
Magnets at Relativistic Heavy Ion Collider (RHIC), BNL:

- superconducting dipole magnet ~ 5 T
- 1740 magnets adopted by RHIC
- 30-/36-strand SC cable for...
... 80-100/130-180 mm apertures
- **B** field rotates 360 degrees in 2.4 meters
- designed to control proton spin for polarized proton colliding
- sub-percent error in field irregularity easily achieved:

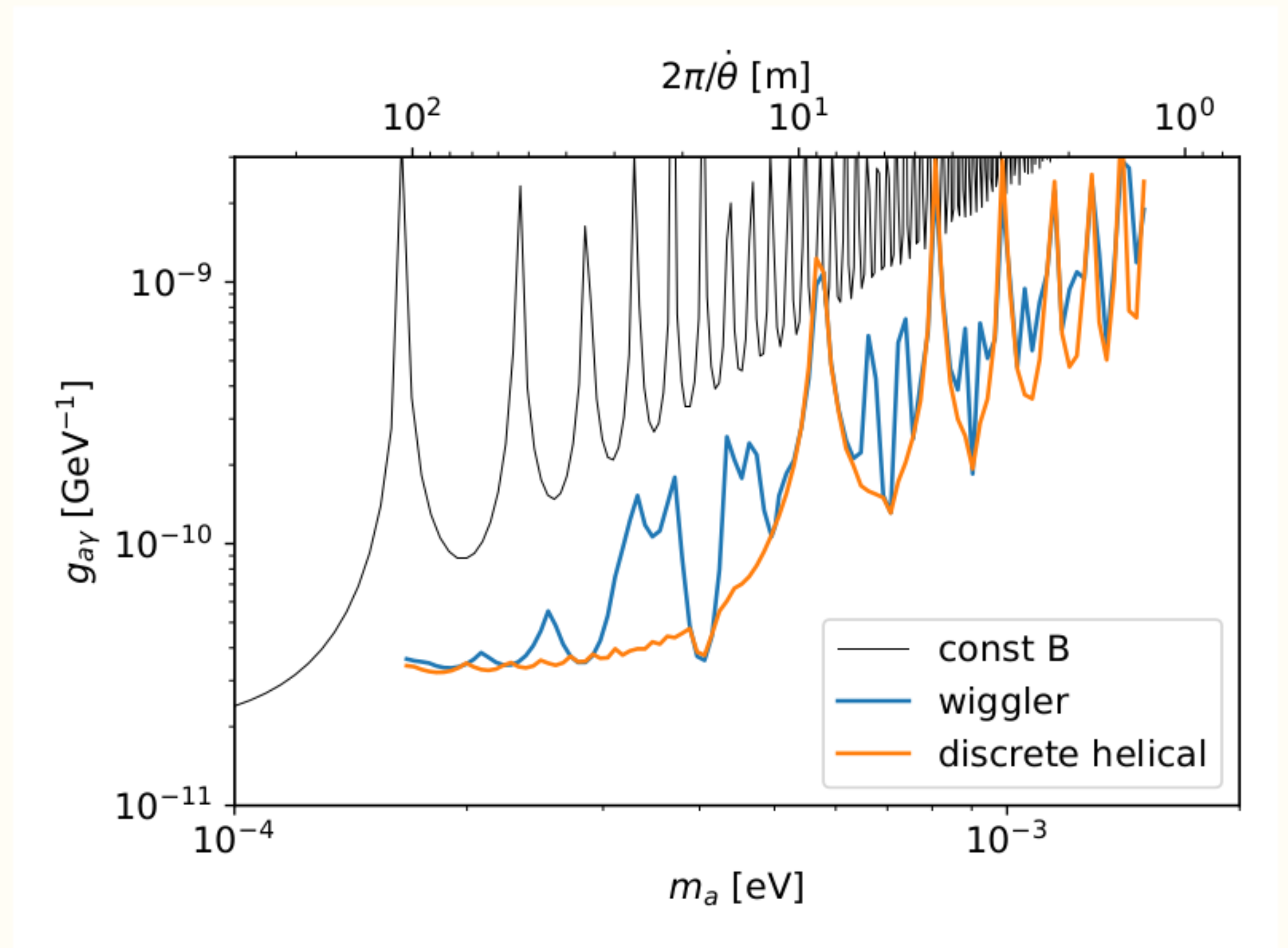
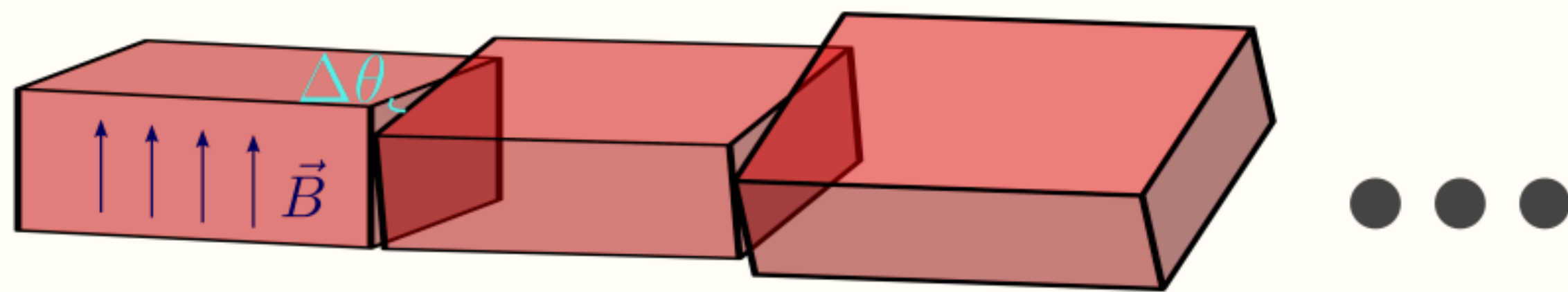
$$\int |\mathbf{B}| dz \approx 10 \text{ T} \cdot \text{m}$$

$$\left[\left(\int B_x(z) dz \right)^2 + \left(\int B_y(z) dz \right)^2 \right]^{1/2} < 0.05 \text{ T} \cdot \text{m}$$

Scanning Different Axion Masses



Scanning Different Axion Masses



Neutron Stars

Solar X-ray.

Galaxy clusters

Stellar mass distribution

Quasars, SN

BAO

SN Remnant

Galaxy Rotation Curves

Sunyaev-Zeldovich

Binary Mergers. (BH, NS, ...)

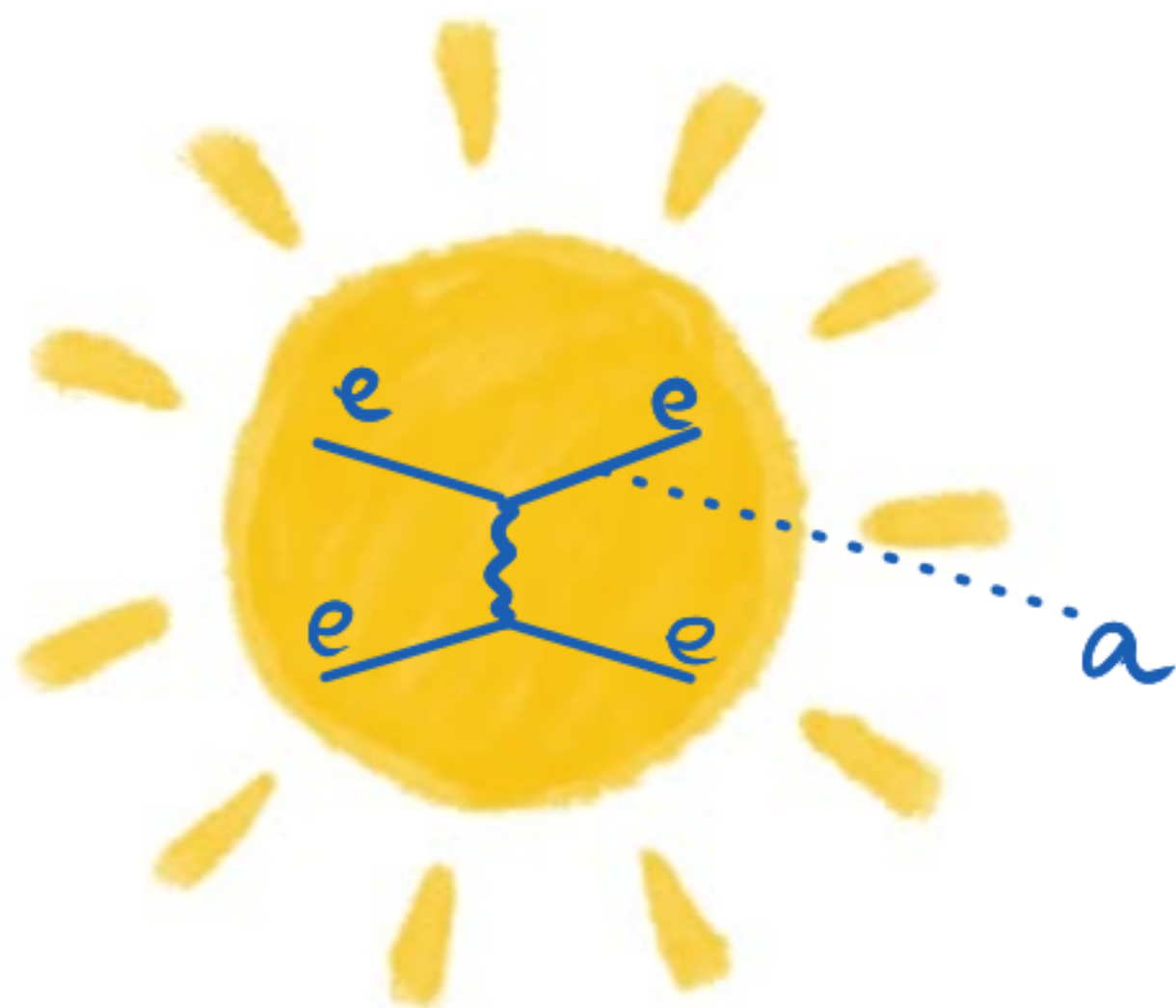
Axion

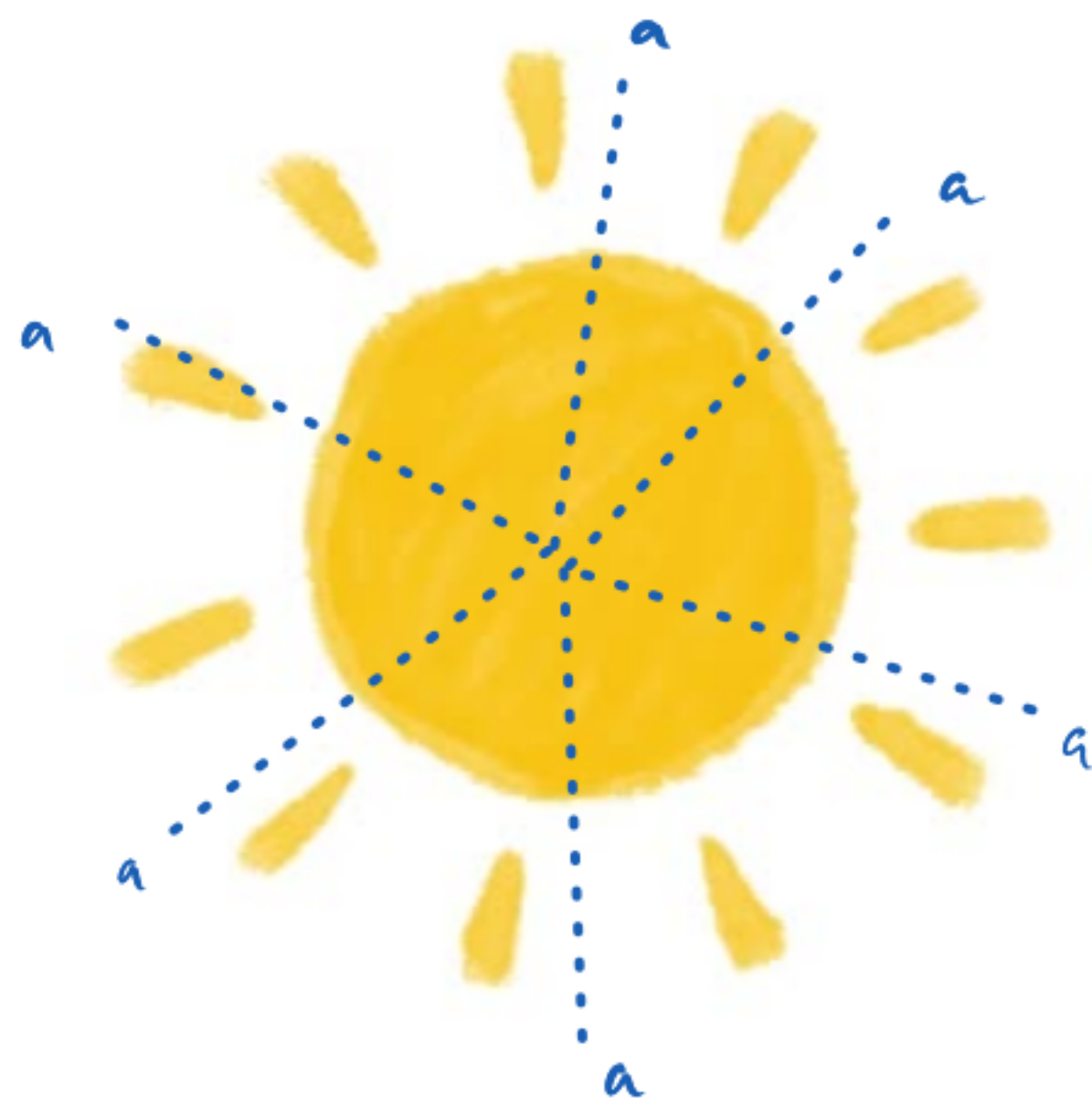
Dark photon

Sterile ν

⋮

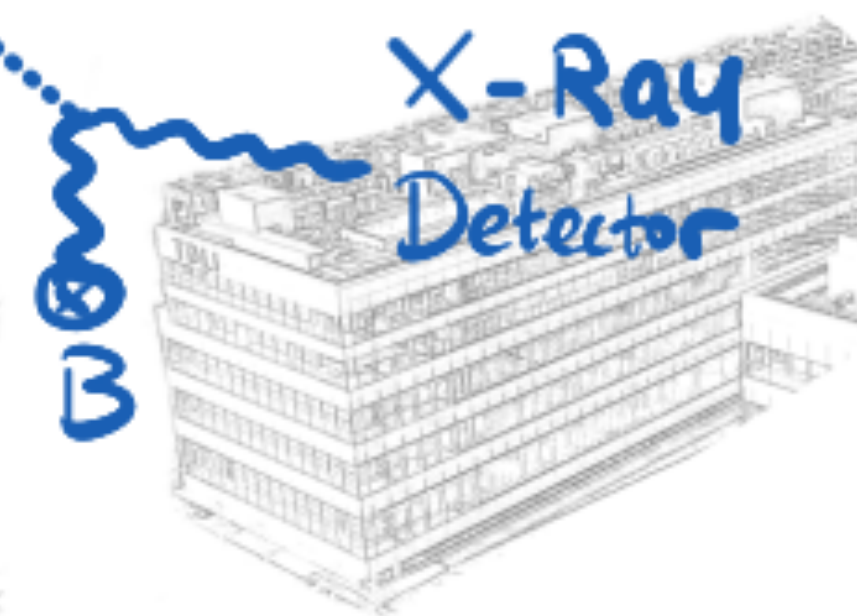








- BNL
- Sumico
- CAST
- IAXO



Resonance

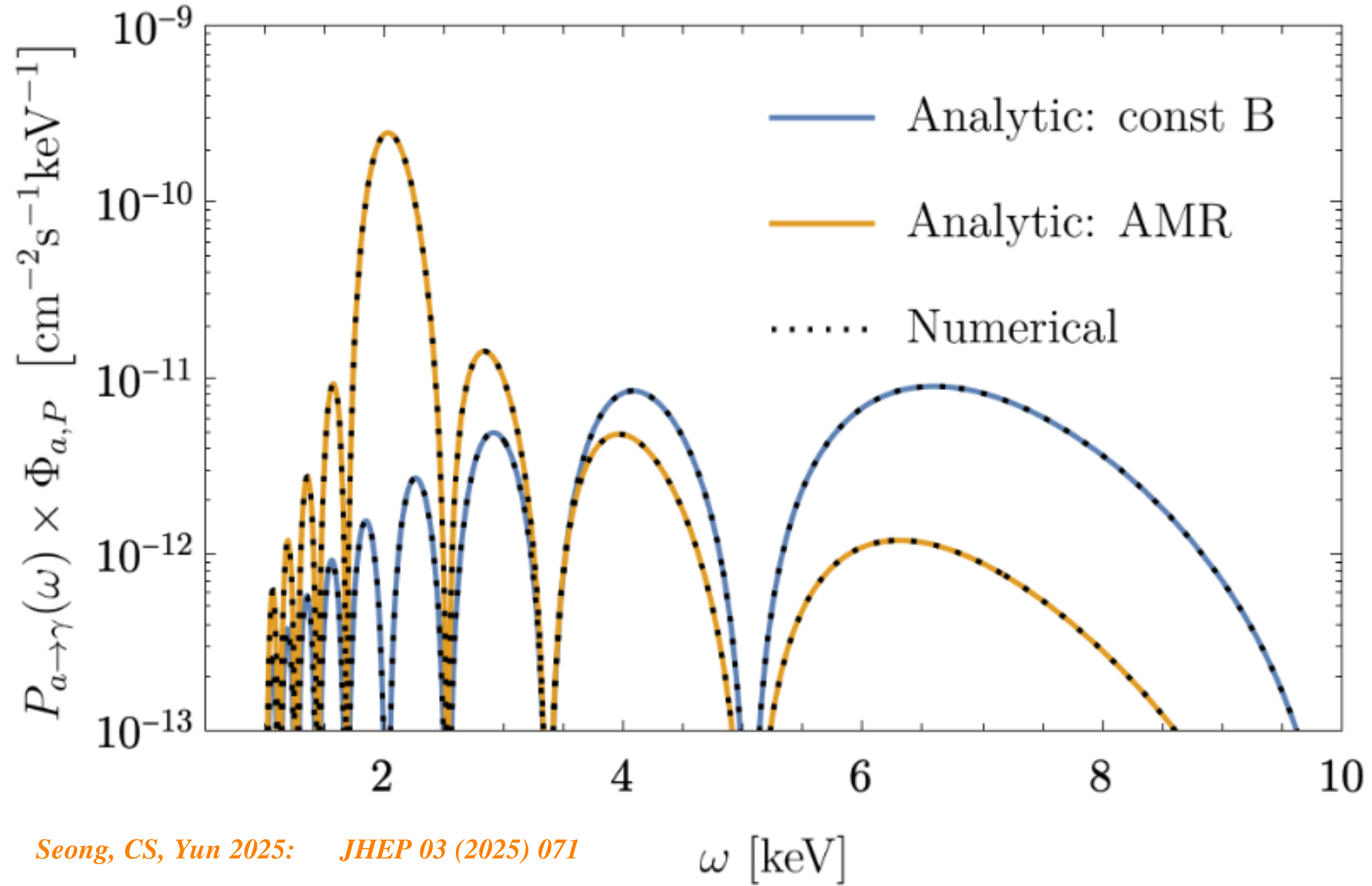
$$\Omega = \frac{m_a^2}{2W}$$

Laser

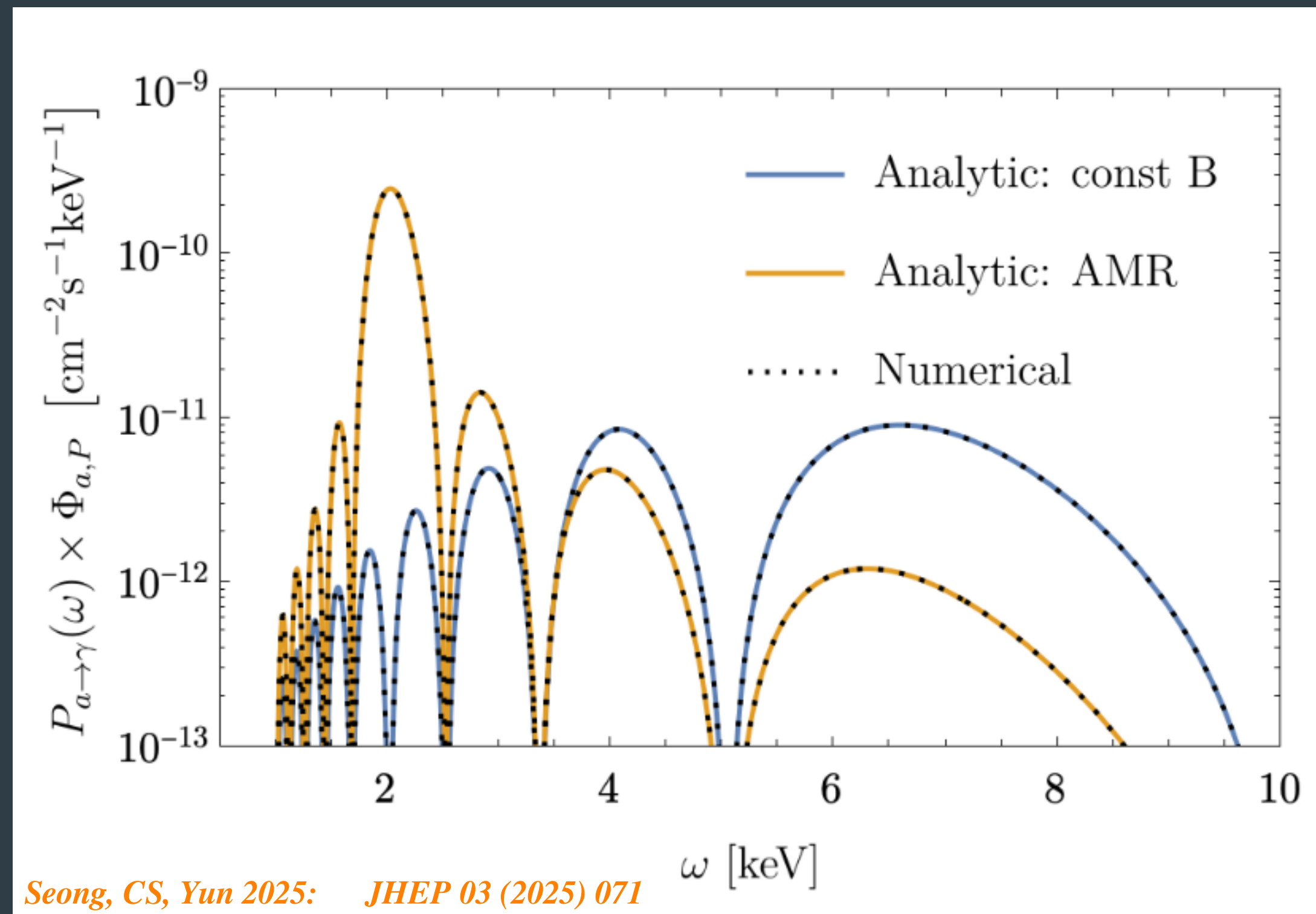
- W fixed
- Ω varied

Solar Axion

- W "varied"
- Ω fixed



Seong, CS, Yun 2025: JHEP 03 (2025) 071



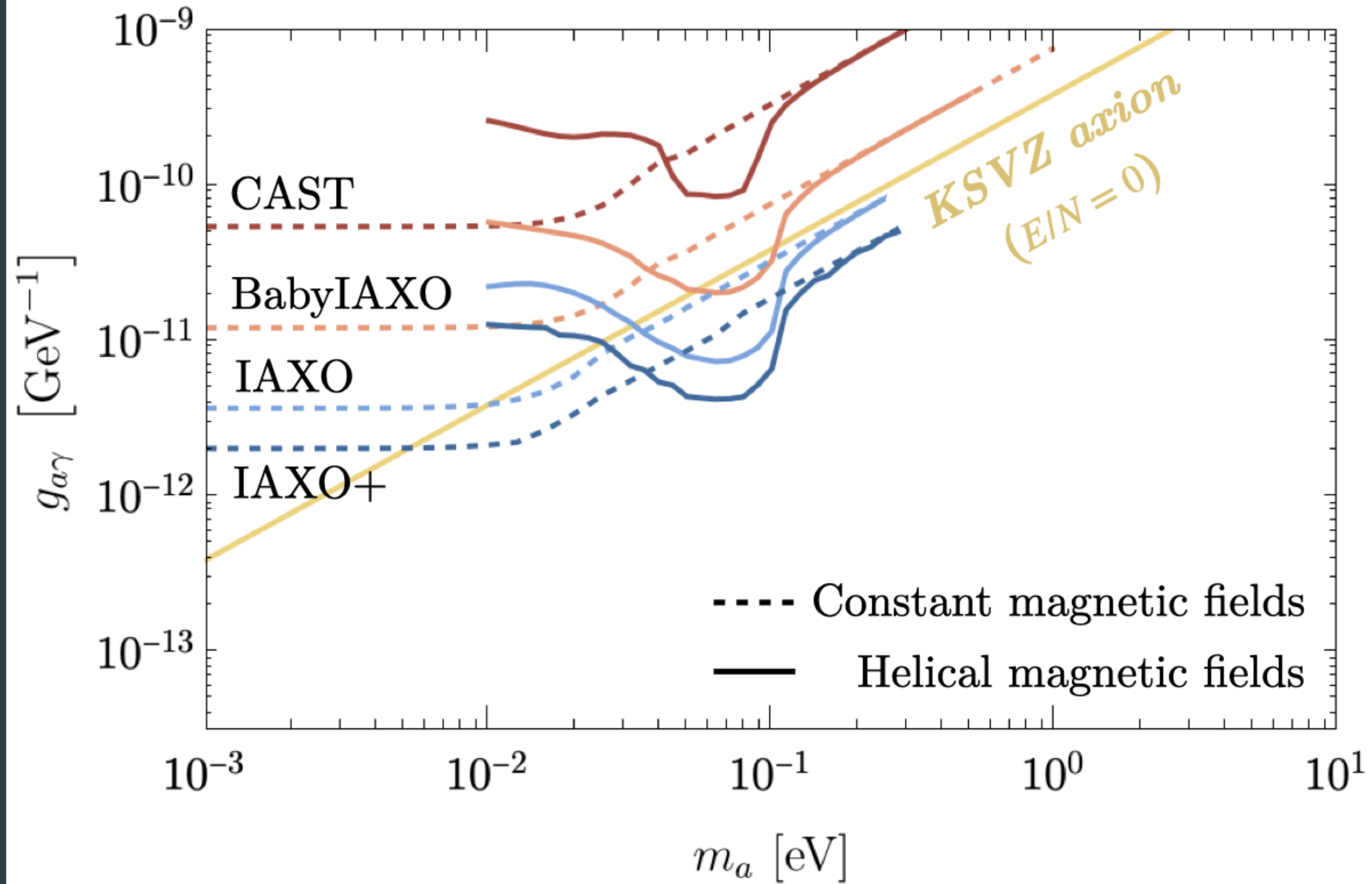
AMR:

$$\frac{d}{d\omega} P\left(\Omega = \frac{m_a^2}{2\omega}\right) \neq 0$$

plasma frequency:

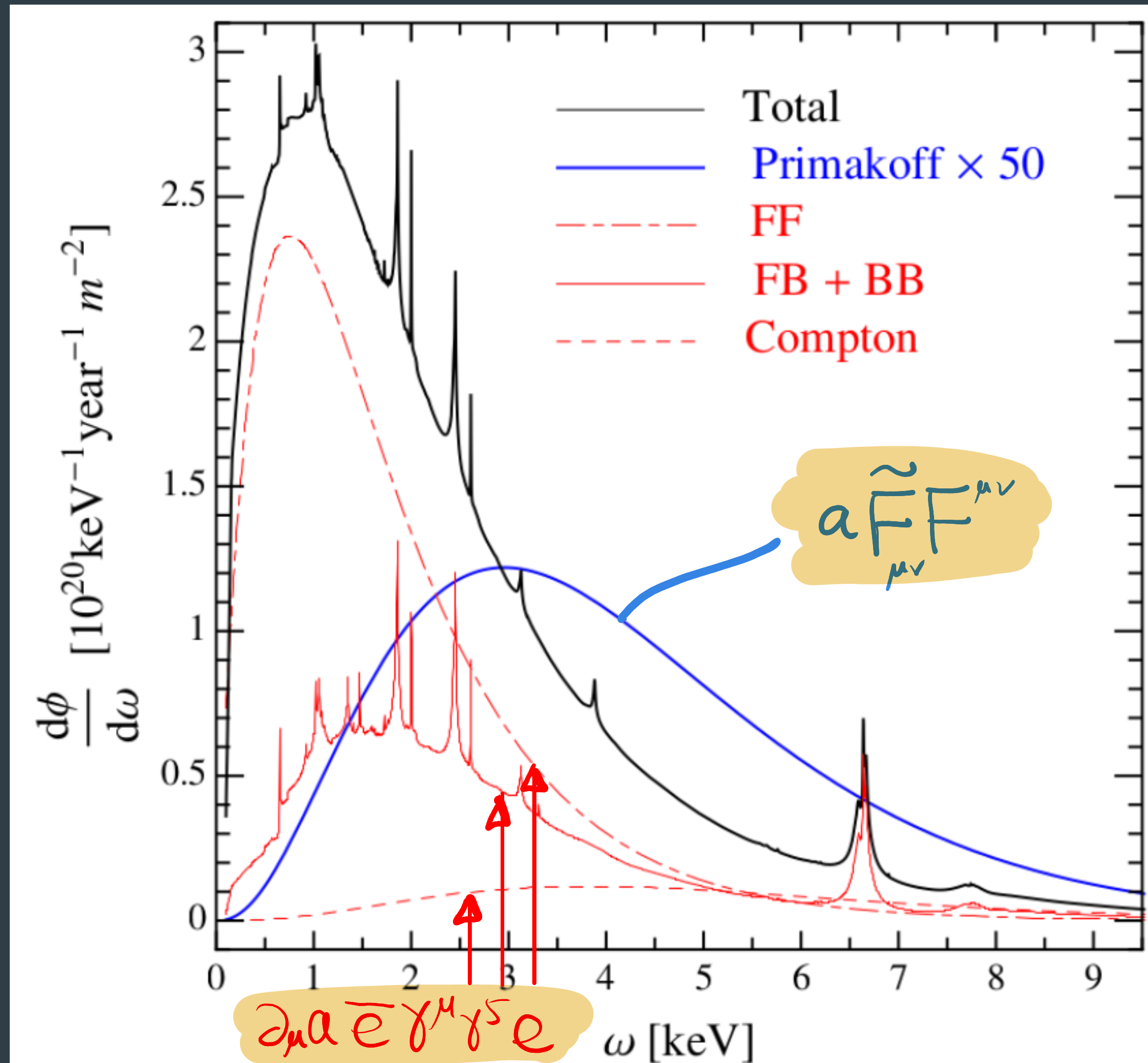
$$\frac{d}{d\omega} P(m_\gamma = m_a) = 0$$

KSVZ vs DFSZ



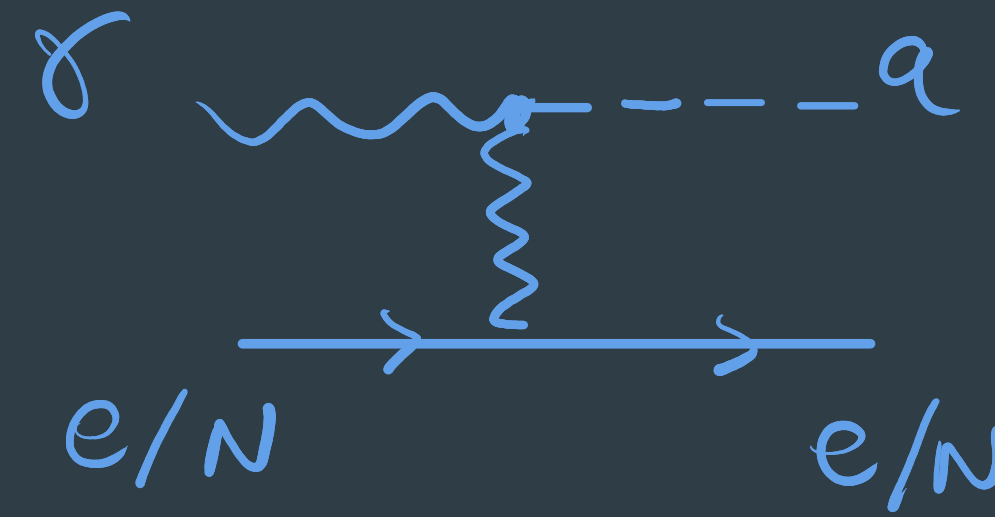
- $$g_{a\gamma, \text{eff}} \approx \frac{\alpha}{2\pi f_a} \left(\underbrace{\frac{E}{N}}_{\text{UV}} - \underbrace{1.92}_{\text{xPT}} + \mathcal{O}\left(\left(\frac{\text{keV}}{m_e}\right)^2\right) \right)$$

- DFSZ flux enhancement



Barth et al. 2013 1302.6283

KSVZ DFSZ

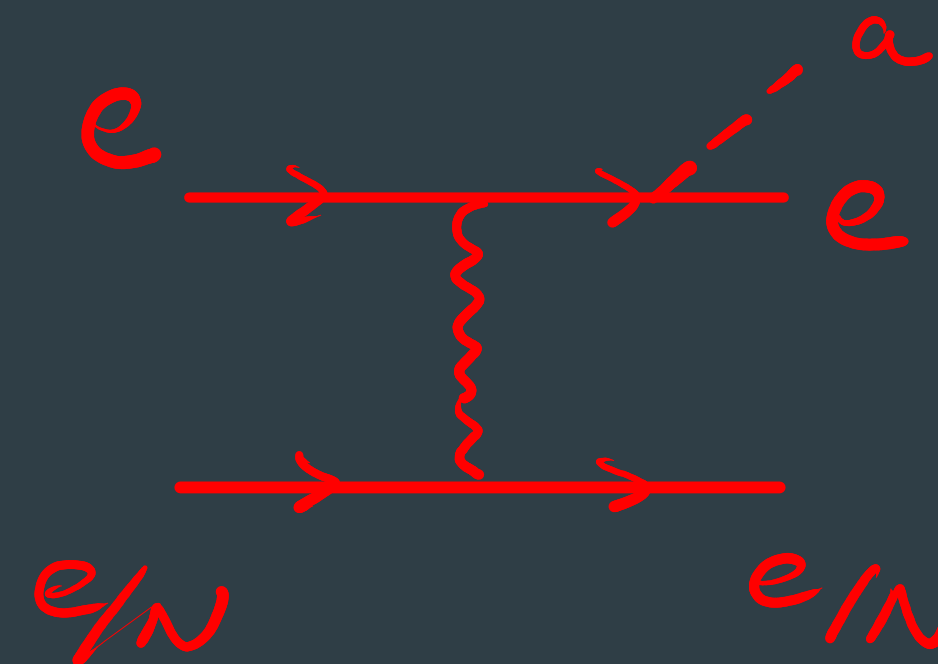


✓

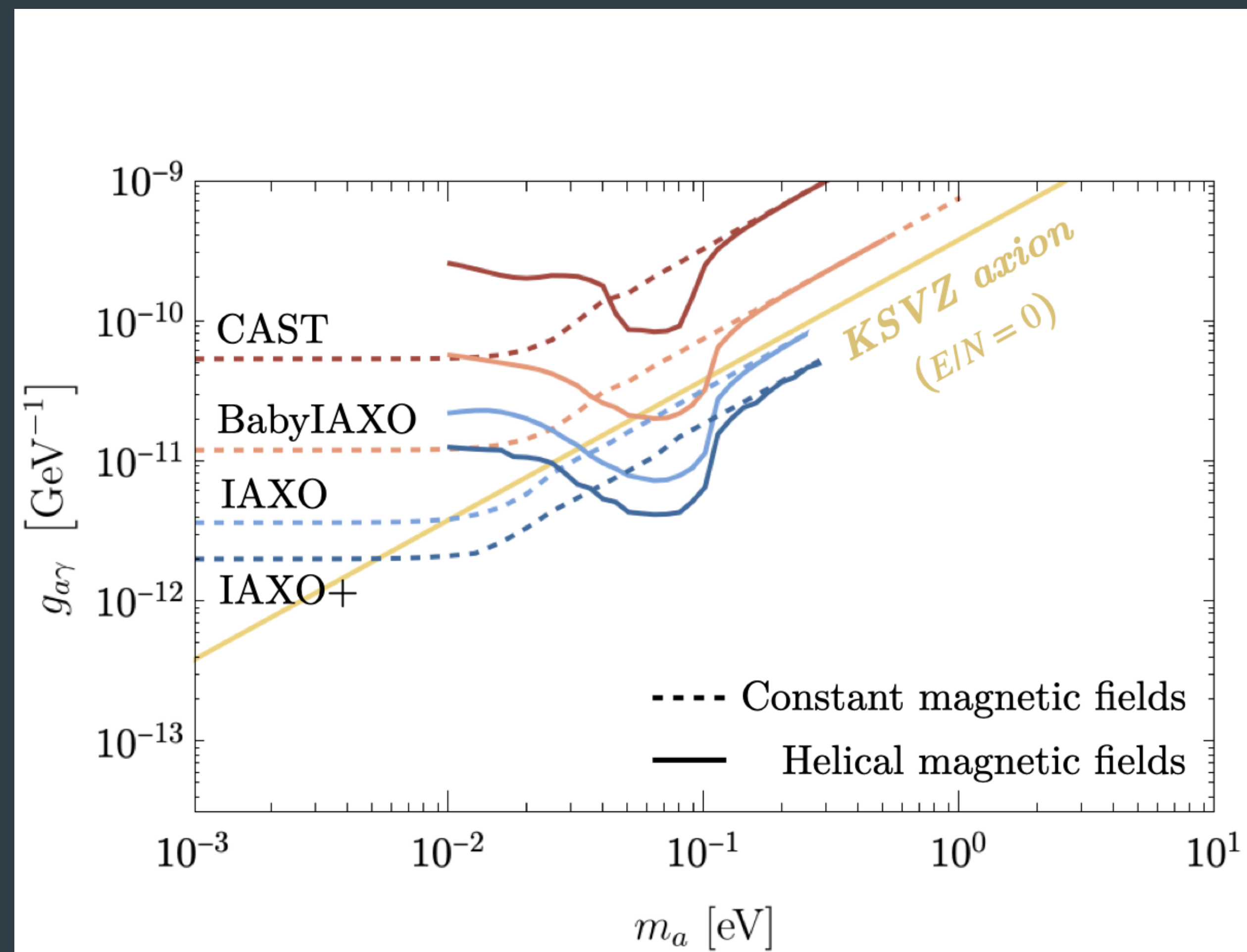
✓



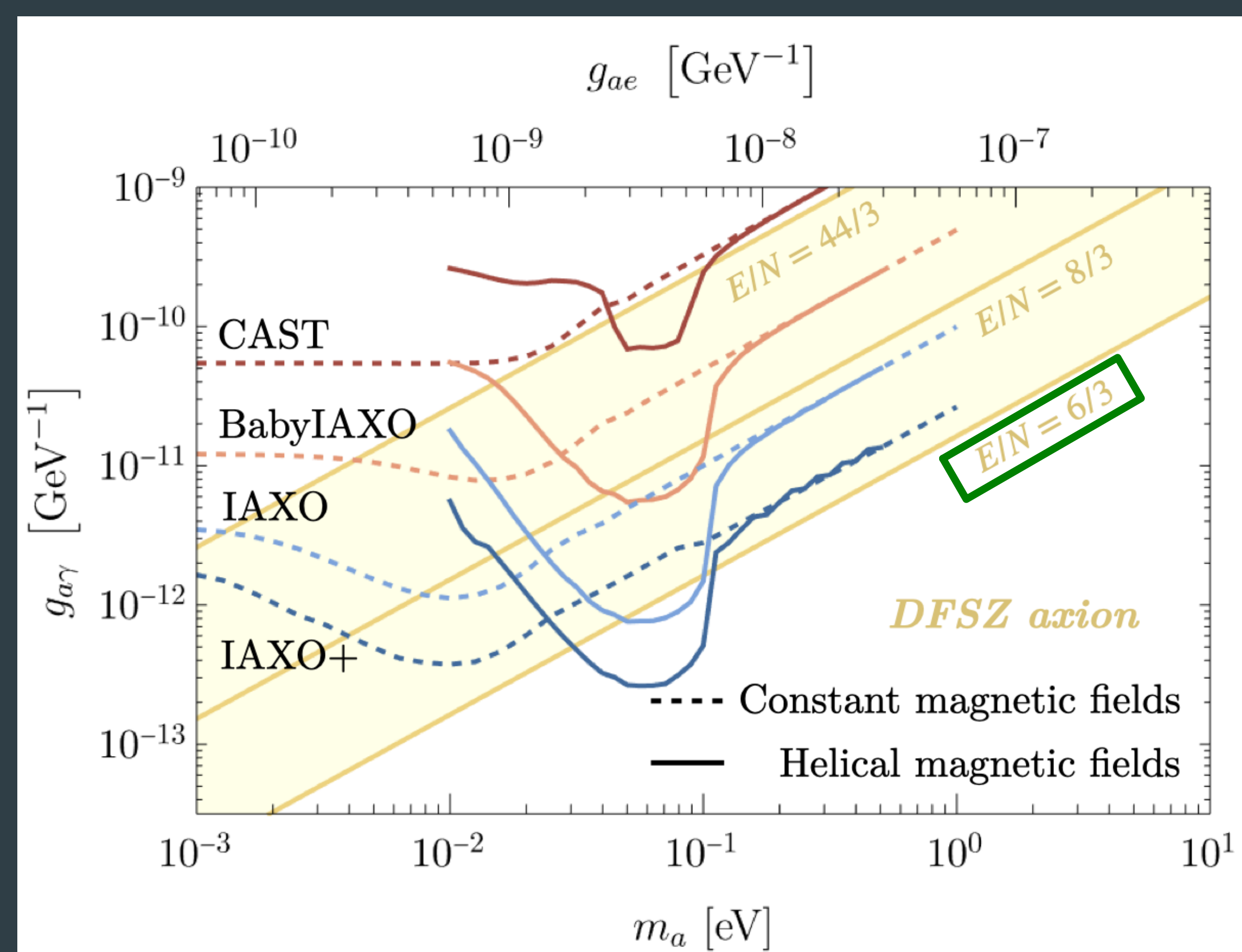
✓



✓



$$g_{a\gamma} \sim \mathcal{O}(10^3 f_a^{-1})$$



$$g_{ae} \sim \mathcal{O}(f_a^{-1})$$

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Sungaeu-Zeldovich

Neutron Stars GW

Binary Mergers (BH, NS, ...)

Axion

Dark photon

Asymmetric DM

Sterile ν

⋮

Solar X-ray

Neutron Stars X-ray

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BAO

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Galaxy Rotation Curves

Sunyaev-Zeldovich

Binary Mergers. (BH, NS, ...)

Axion

Dark photon

Sterile ν

⋮

Fan, Li, CS:

2501.12440

Solar X-ray

Neutron Stars

X-ray

BAO

Galaxy clusters

Stellar mass distribution

Quasars, SN

SN Remnant

Galaxy Rotation Curves

Sunyaev-Zeldovich

Binary Mergers (BH, NS, ...)

Axion

Dark photon

Sterile ν

⋮

Fuyuto, Kumar, Mereghetti, Sandner, CS

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