Direct & Indirect Probes of Axion with Supernova-scope & Muon g-2

Shao-Feng Ge

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SFG, Hamaguchi, Ichimura, Ishidoshiro, Kanazawa, Kishimoto, Nagata, Zheng, JCAP 11 (2020) 059

SFG, Xiao-Dong Ma, Pedro Pasquini, Eur.Phys.J.C 81 (2021) 9, 787

上海交通大學 SHANGHAI JIAO TONG UNIVERSITY

Axions 2022
November 23, 2022

李政道研究所 Tsung-Dao Lee Institute

Outline

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1) **Brief overview**

2) **Supernova Axion Direct Search @ SN-scope**

SFG, Hamaguchi, Ichimura, Ishidoshiro, Kanazawa, Kishimoto, Nagata, Zheng
JCAP 11 (2020) 059 [2008.03924 [hep-ph]]

3) **Dark Axion Portal @ Muon g-2**

SFG, Xiao-Dong Ma, Pedro Pasquini
Eur.Phys.J.C 81 (2021) 9, 787 [2104.03276 [hep-ph]]

Strong CP & Neutron EDM

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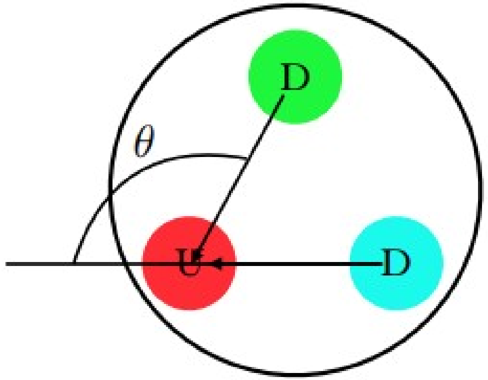
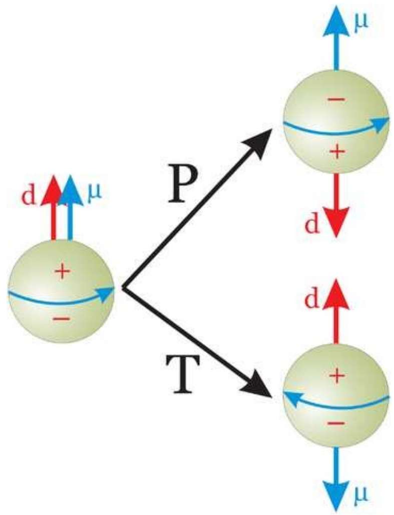
$$\mathcal{L} \supset \frac{\theta g_s^2}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu}$$



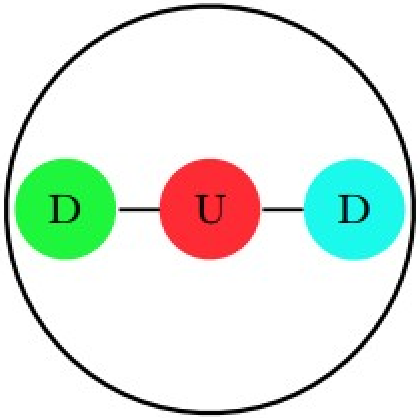


$$P: \quad d \to -d, \qquad s \to s.$$

Maximally violated by Weak Interactions

$$T: \quad d \to d, \qquad s \to -s.$$

CP



$$d_n \sim 3 \times \mathbf{10^{-16}}\,\overline{\theta}\,\mathrm{e\ cm}$$

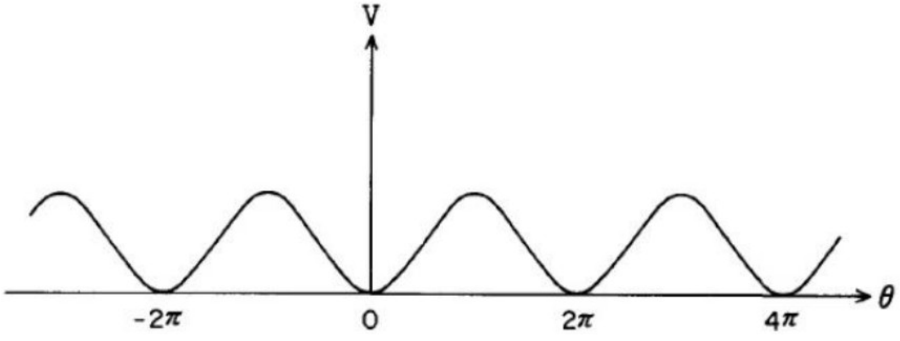
$$\leq \mathbf{10^{-26}}\ \mathrm{e\,cm}$$

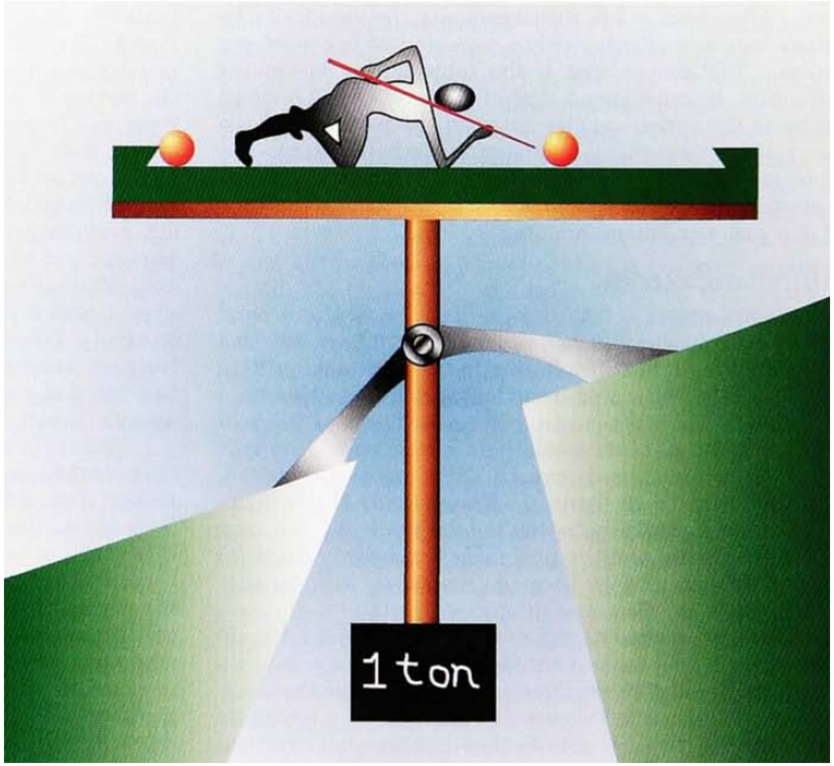
Axion

$$\mathcal{L} = \left(a + \frac{\bar{\theta} f_a}{\xi}\right) \frac{\xi g_s^2}{32 f_a \pi^2} \left\langle G_a^{\mu\nu} \widetilde{G}^a_{\mu\nu} \right\rangle$$

Sikivie [Physics Today '96]

$$V_{\rm eff} = \cos\left(\bar{\theta} + \xi \frac{\langle a \rangle}{f_a}\right)$$





Weinberg 78', Wilczek 78'

$$f_a$$

Axion Searches

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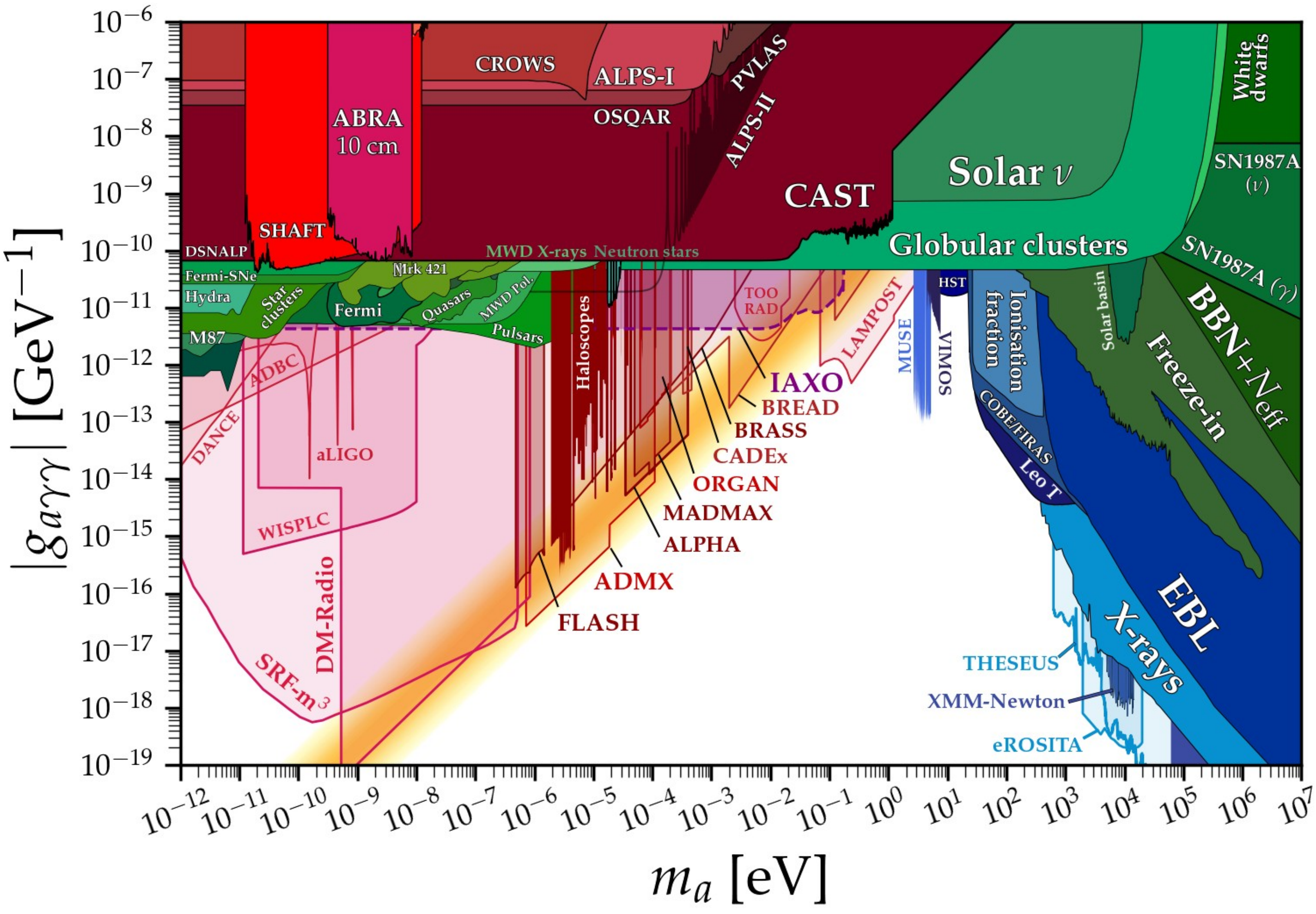

https://cajohare.github.io/AxionLimits/docs/ap.html

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Axion SN-scope

SFG, Hamaguchi, Ichimura, Ishidoshiro, Kanazawa, Kishimoto, Nagata, Zheng
JCAP 11 (2020) 059 [2008.03924 [hep-ph]]

Helioscope

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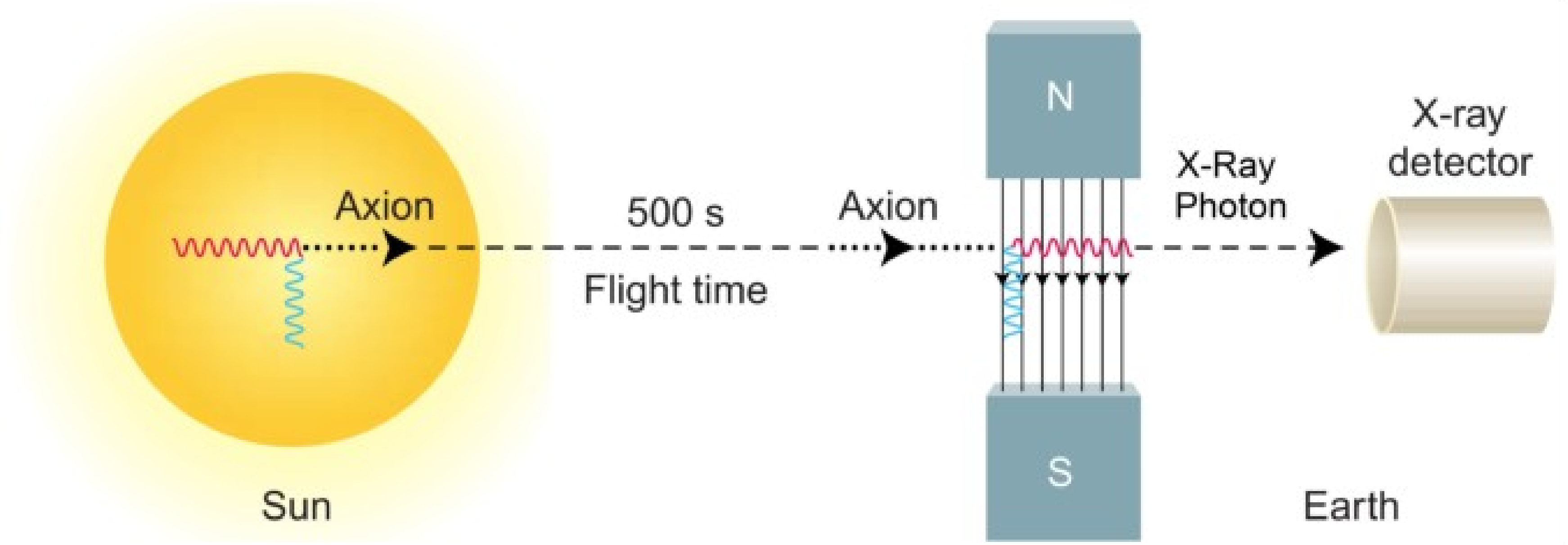

Science magazine Vol. 308 (2005)

- **Monochromatic Axion**

$$p(d, {}^3\mathrm{He})a \quad \Rightarrow \quad a + d \to n + p$$

5.5MeV

Aagaman Bhusal, Nick Houston, Tianjun Li
Phys.Rev.Lett. 126 (2021) 9, 091601 [2004.02733]

Helioscope

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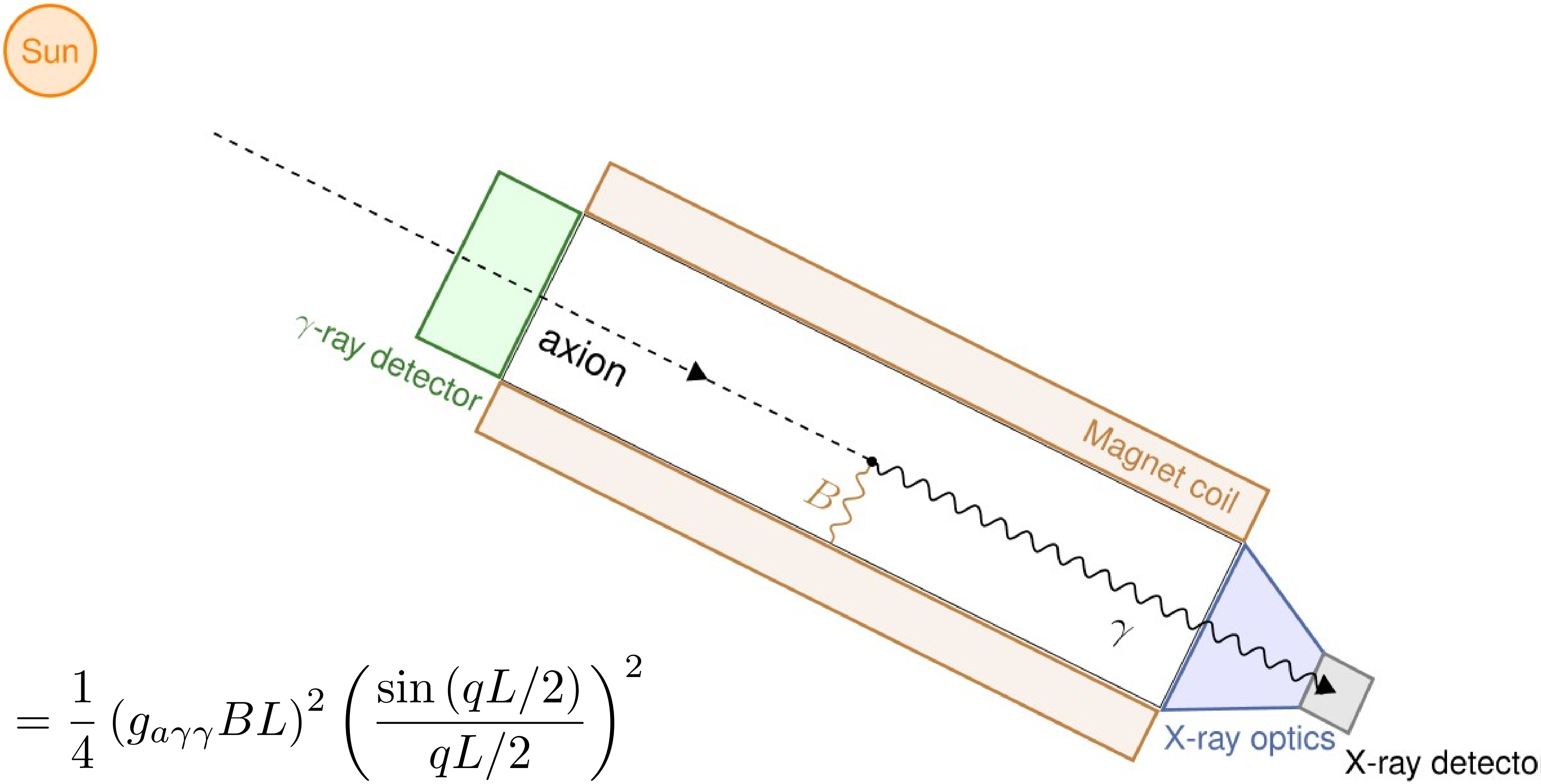

$$P = \frac{1}{4}(g_{a\gamma\gamma} B L)^2 \left(\frac{\sin(qL/2)}{qL/2}\right)^2$$

$$q = |m_a^2 - m_\gamma^2|/(2\omega)$$

Supernova-scope

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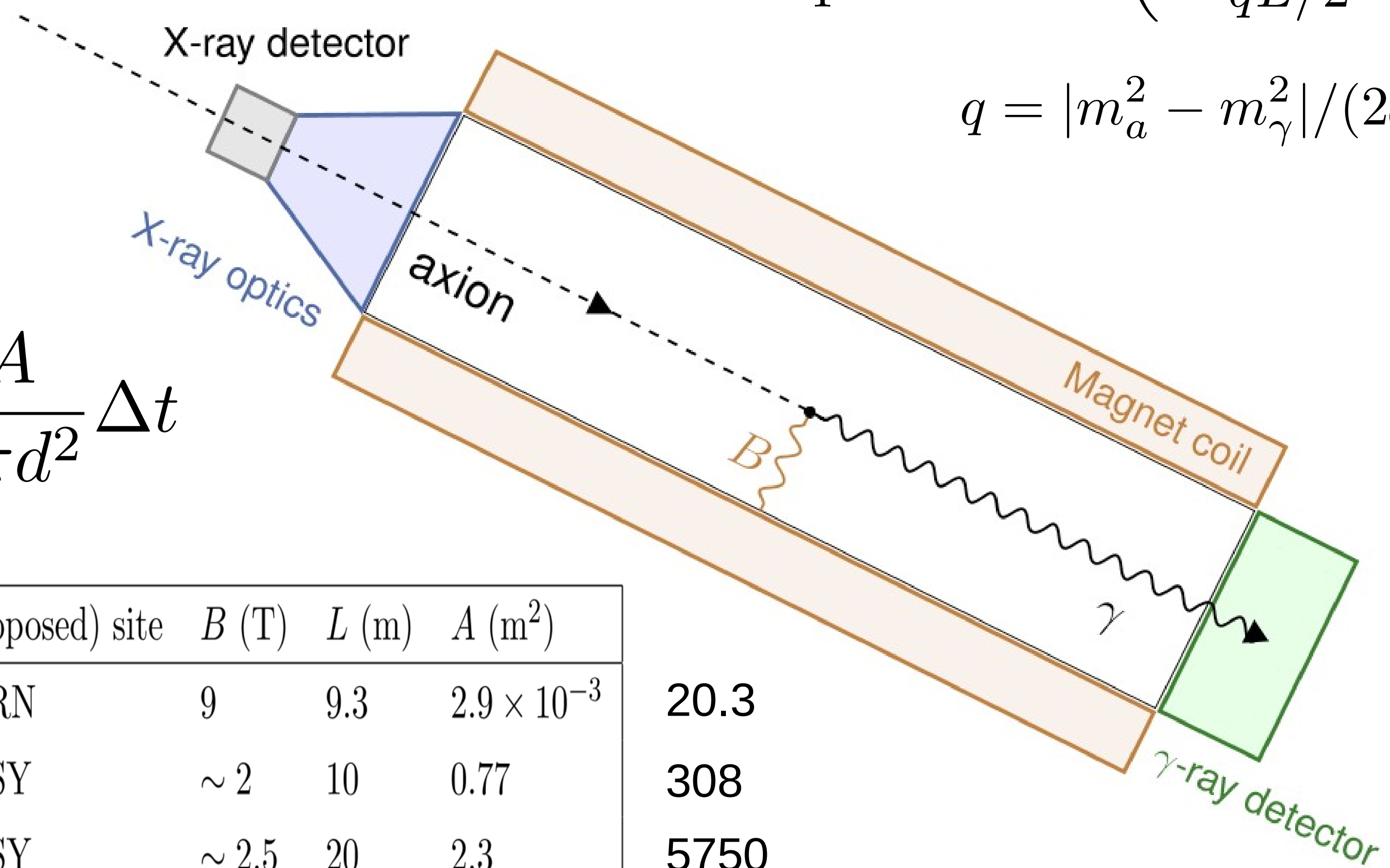
SN

$$P = \frac{1}{4}\left(g_{a\gamma\gamma} B L\right)^2 \left(\frac{\sin\left(qL/2\right)}{qL/2}\right)^2$$

$$q = |m_a^2 - m_\gamma^2|/(2\omega)$$



$$N \approx P \dot{N}_a \frac{A}{4\pi d^2} \Delta t$$

Experiment	(Proposed) site	B (T)	L (m)	A (m^2)	
CAST [34–39]	CERN	9	9.3	2.9×10^{-3}	20.3
BabyIAXO [41]	DESY	~ 2	10	0.77	308
IAXO baseline [40, 41]	DESY	~ 2.5	20	2.3	5750
IAXO+ [41]	DESY	~ 3.5	22	3.9	23123
TASTE [42]	INR	3.5	12	0.28	494

Supernova Alerts

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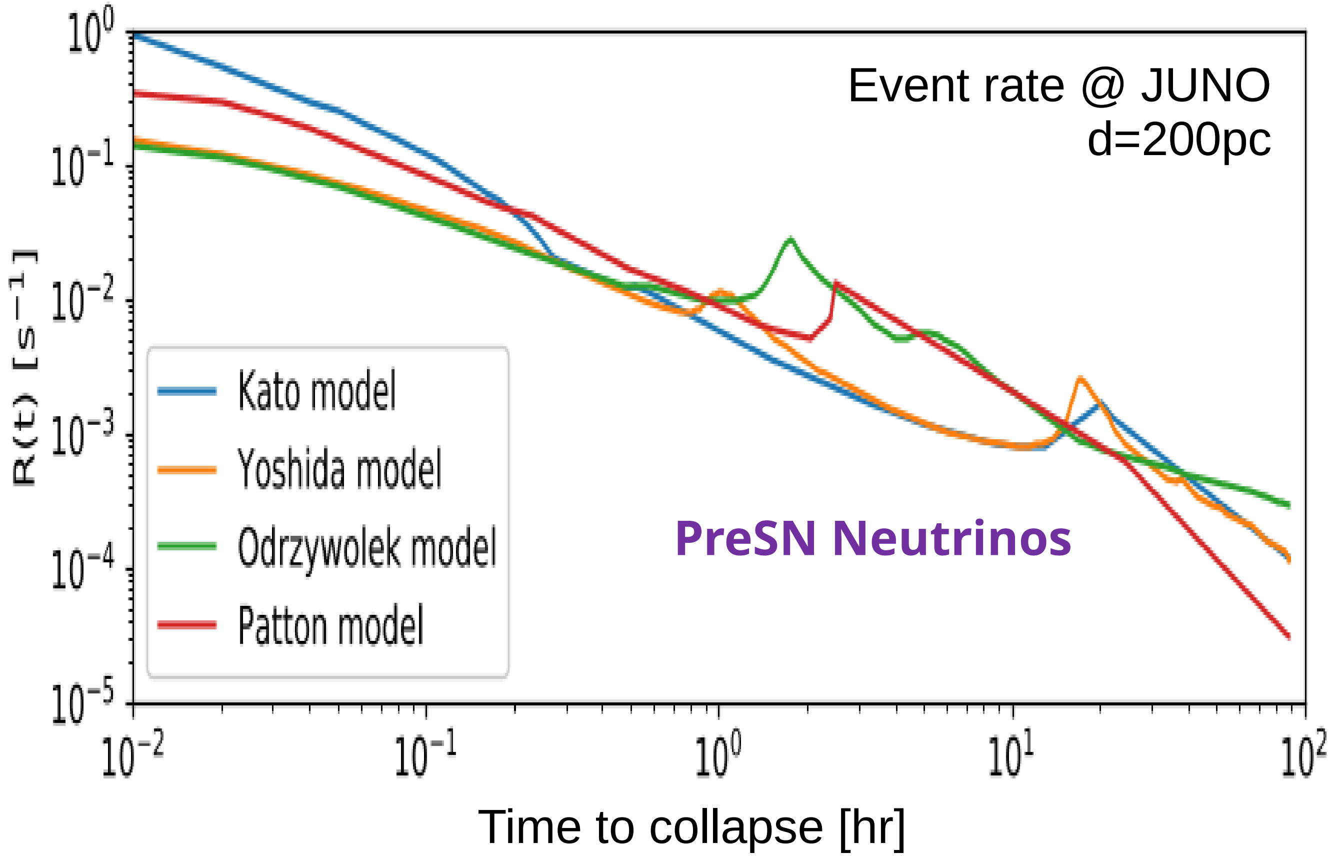

PreSN @ **KamLAND/SK**: **O(1) hour** alert for SNs with 300pc

JUNO: **20~70** hours within 500pc (w/o angular resolving)

SNEW 2.0:

Kato, Ishidoshiro & Yoshida [2006.02519]

Supernova Candidates

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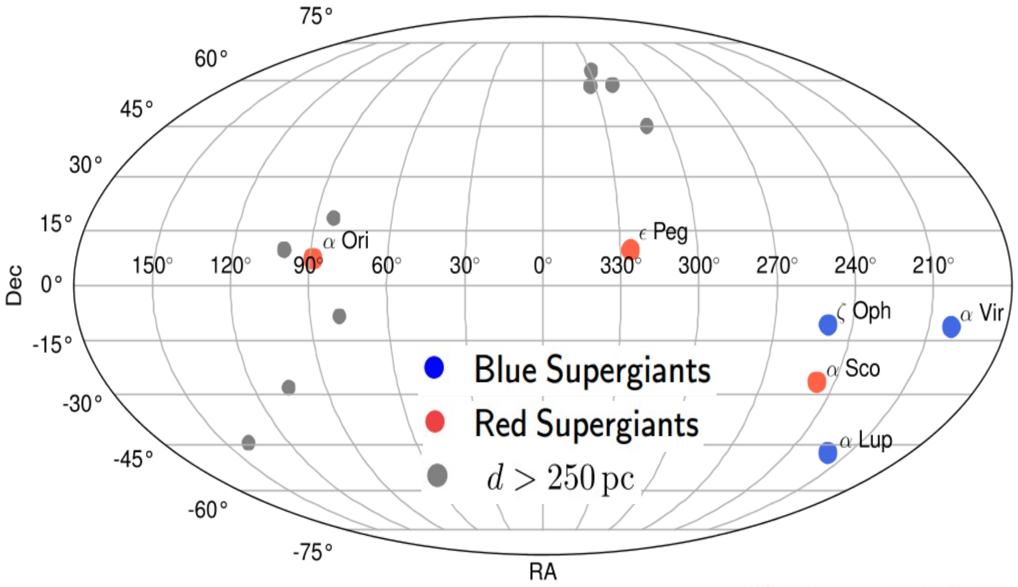

$$M > 10 M_\odot\,, \quad d < 250\,\mathrm{pc}$$

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

Sky Survey Coverage

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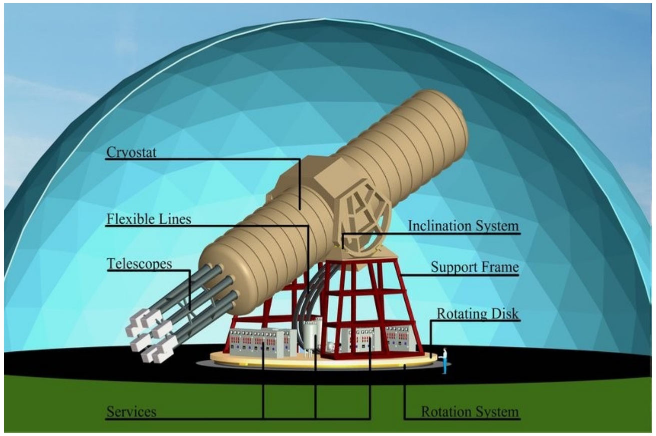
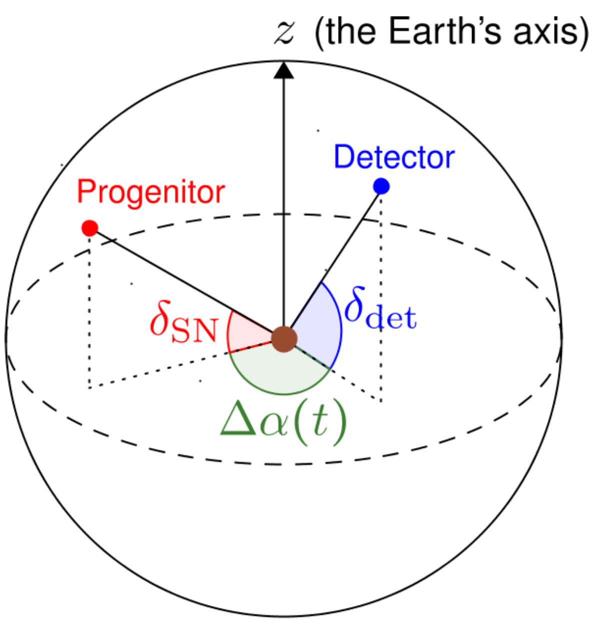
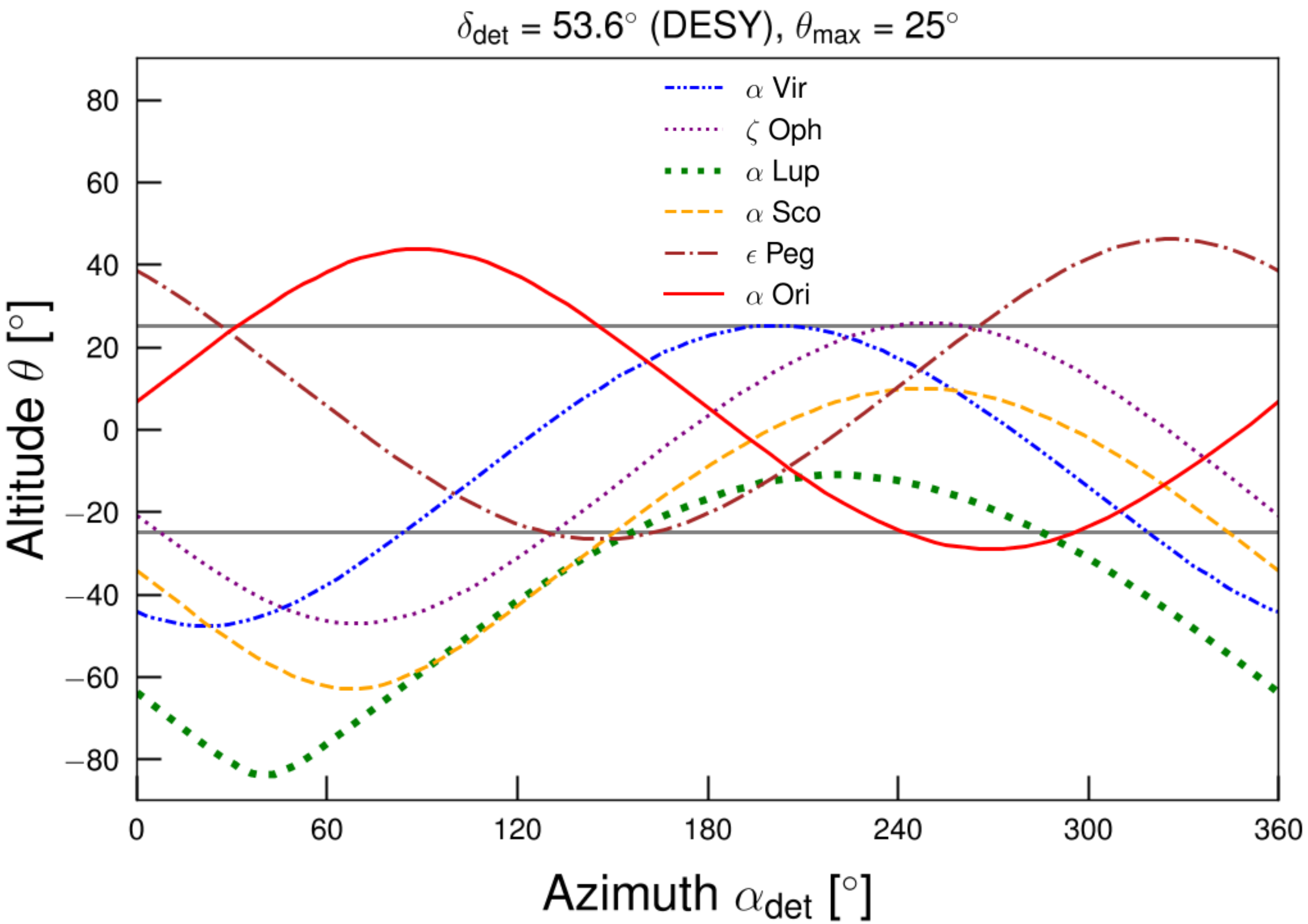


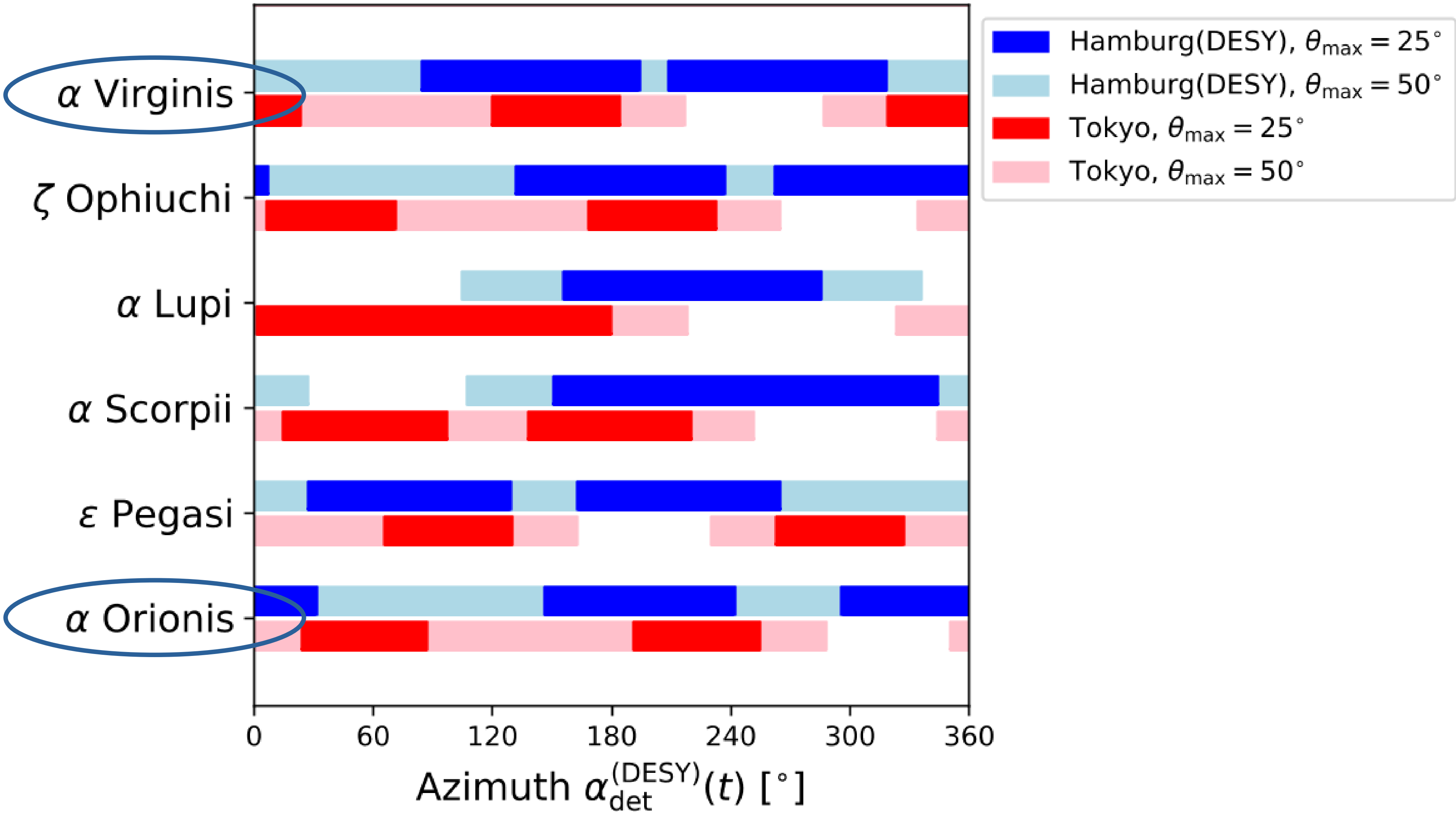
Shilon et al [1308.2526]





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

Time Coverage



Better to have 2 detectors @ different locations!

Supernova Axion

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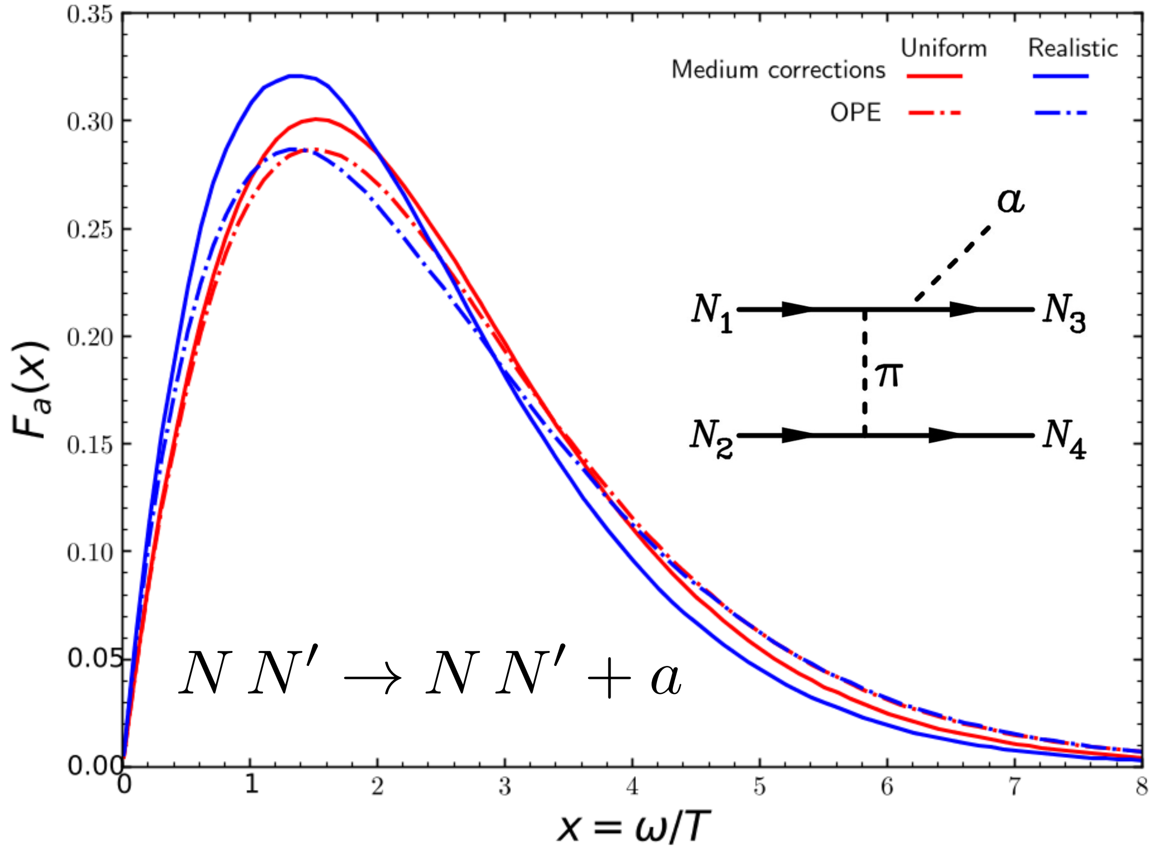
$$\sum_{N=p,n} \frac{C_N}{2f_a} \bar{N}\gamma^\mu\gamma_5 N\partial_\mu a$$

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

$$C_{N,\mathrm{eff}}^2 \equiv C_n^2 + 0.61C_p^2 + 0.53C_nC_p$$



$$\frac{dN_a}{d\omega dt dV} = \frac{1}{4\pi^{7/2}f_a^2}\left(\frac{g_A}{2f_\pi}\right)^4 n_B\rho\,\omega\sqrt{m_N T}e^{-\omega/T}s(\omega/T)$$

Carenza, Fischer, Giannotti, Guo, Martinez-Pinedo, Mirizzi
JCAP10(2019)016 [1906.11844]

SNscope Projection @ IAXO

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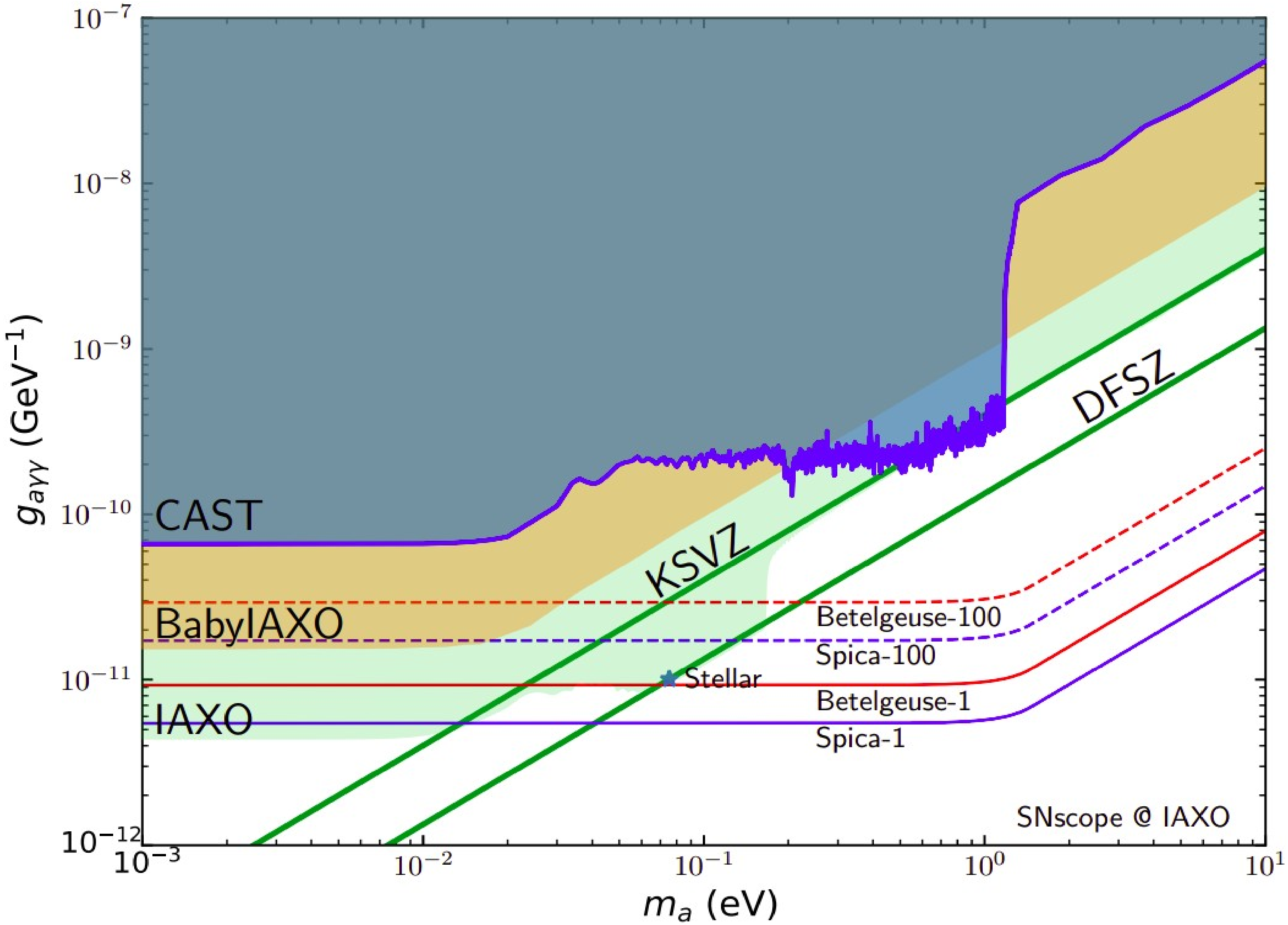

$$C_{N,\text{eff}} = 0.37 \text{ (KSVZ)} \qquad C_{a\gamma\gamma} \equiv g_{a\gamma\gamma} f_a = \alpha/\pi$$

SNscope Projection @ IAXO+

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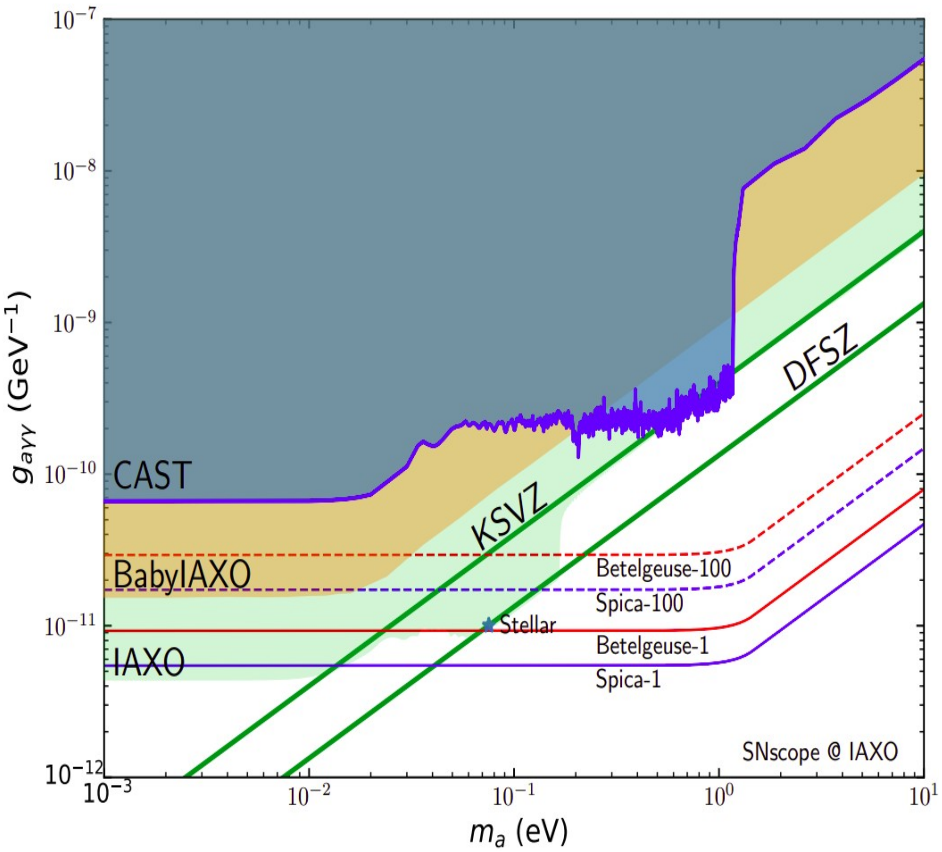
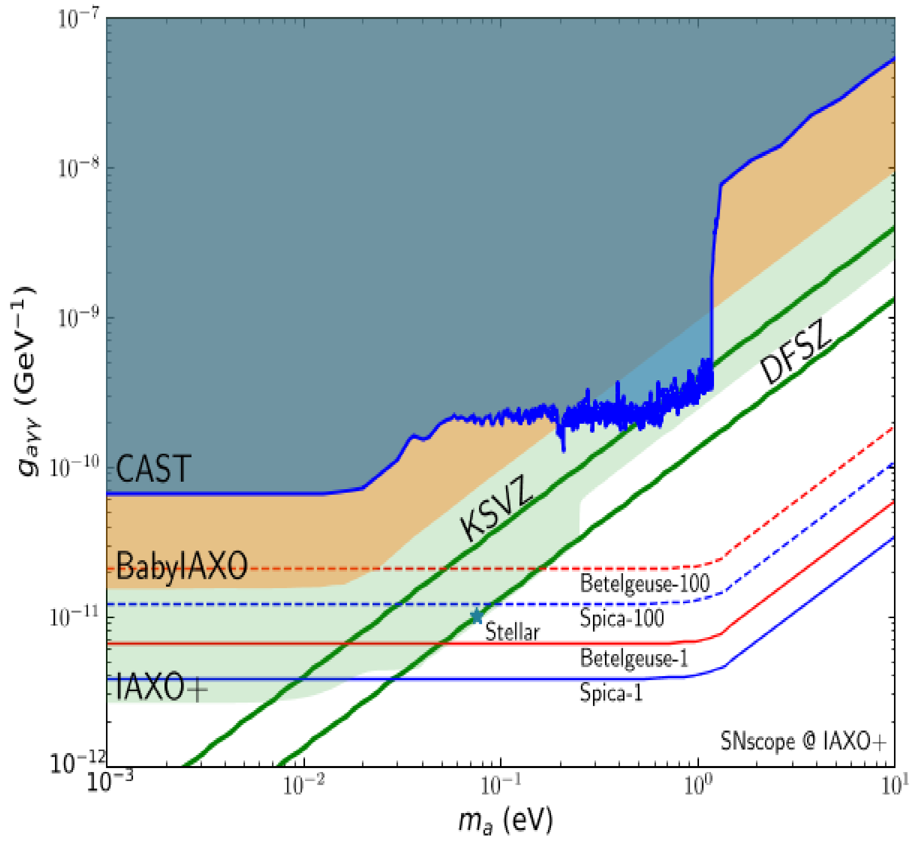
$$P = \frac{1}{4} (g_{a\gamma\gamma} B L)^2 \left(\frac{\sin (qL/2)}{qL/2} \right)^2$$





$$C_{N,\text{eff}} = 0.37 \ (\text{KSVZ})$$

$$C_{a\gamma\gamma} \equiv g_{a\gamma\gamma} f_a = \alpha/\pi$$

Supernova Projection @ IAXO

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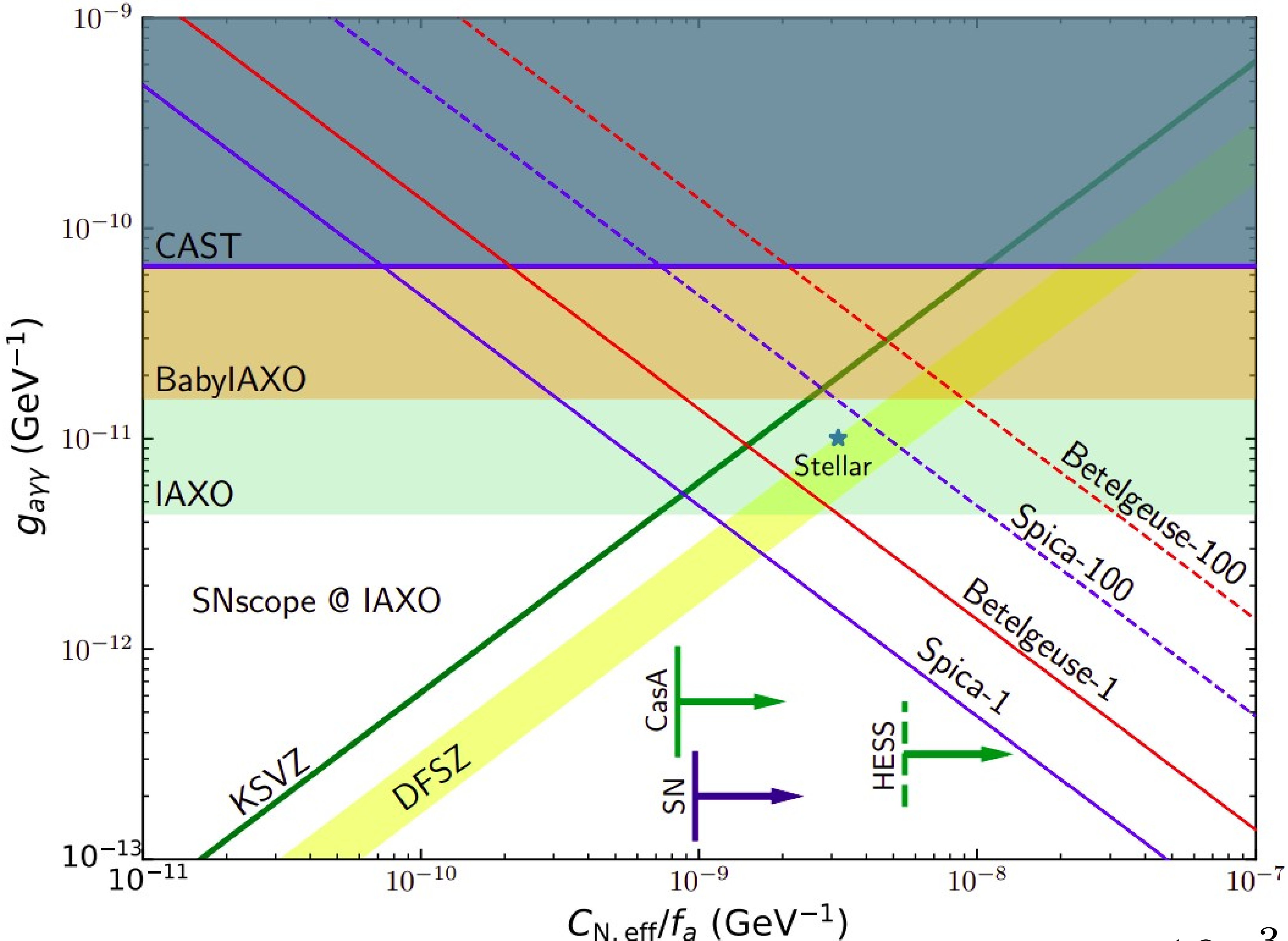
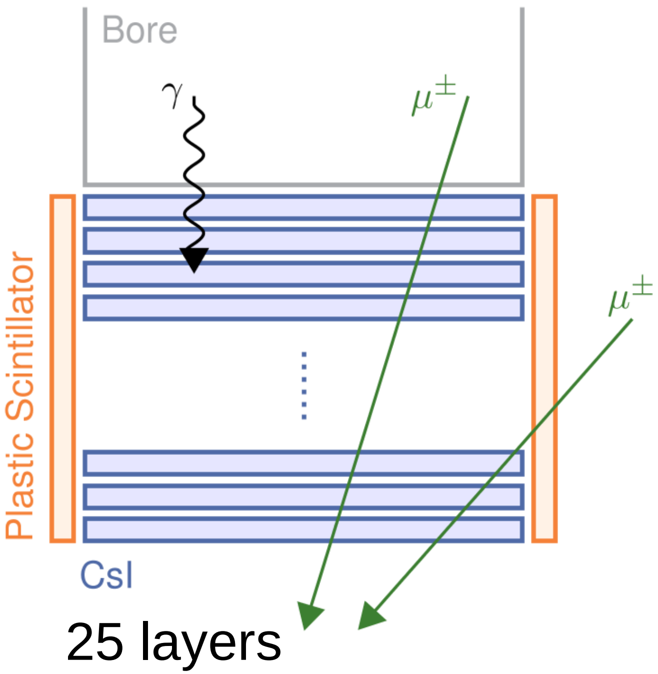
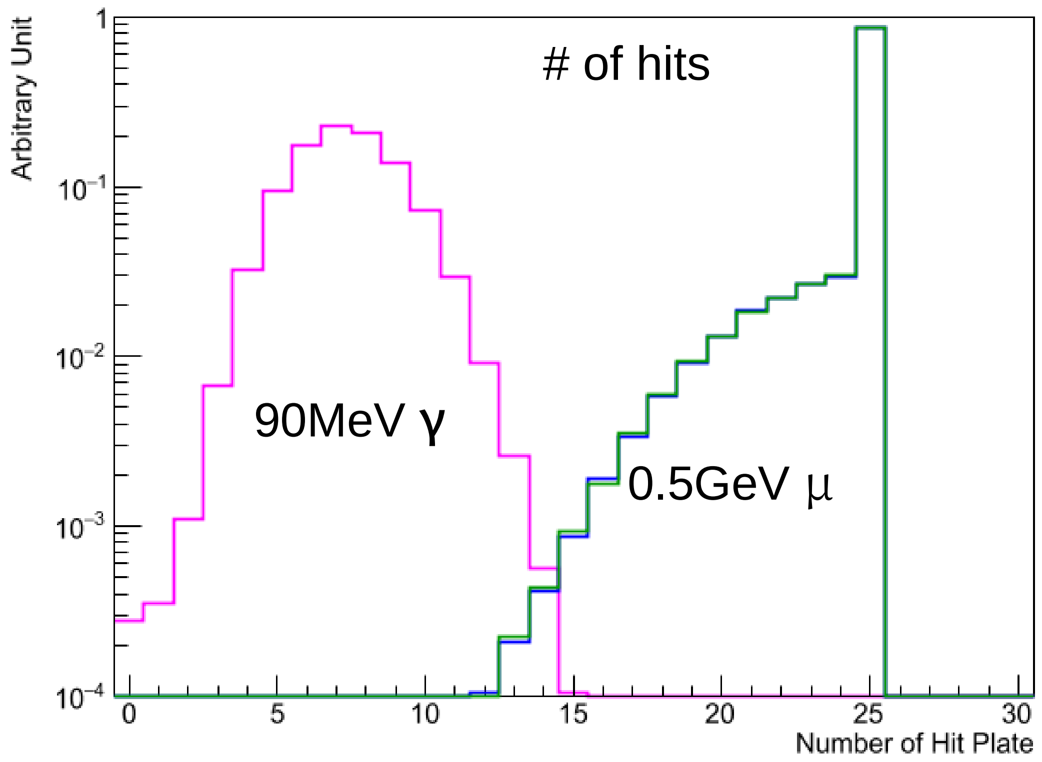


$$m_a = 10^{-3}\ \mathrm{eV}$$

Backgrounds





- Trajectory
- Energy deposit

$N_{\rm hit} \leq 12$

$\mathcal{O}(10^{-4})$ reduction of 0.5 GeV muon

$\geq 99.5\%$ acceptance of the 90 MeV γ

Muon g-2

Eur. Phys. J. C (2021) 81:787
https://doi.org/10.1140/epjc/s10052-021-09571-1

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article -Theoretical Physics

Probing the dark axion portal with muon anomalous magnetic moment

Shao-Feng Ge[1,2,a], **Xiao-Dong Ma**[1,2,b], **Pedro Pasquini**[1,2,c]

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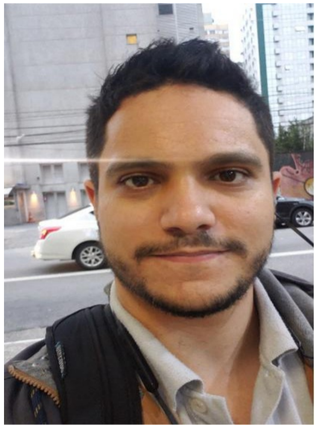
[2] Key Laboratory for Particle Astrophysics and Cosmology (MOE) and Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai 200240, China



SFG, Xiao-Dong Ma, Pedro Pasquini
Eur.Phys.J.C 81 (2021) 9, 787 [2104.03276 [hep-ph]]

Muon g-2 @ Fermilab

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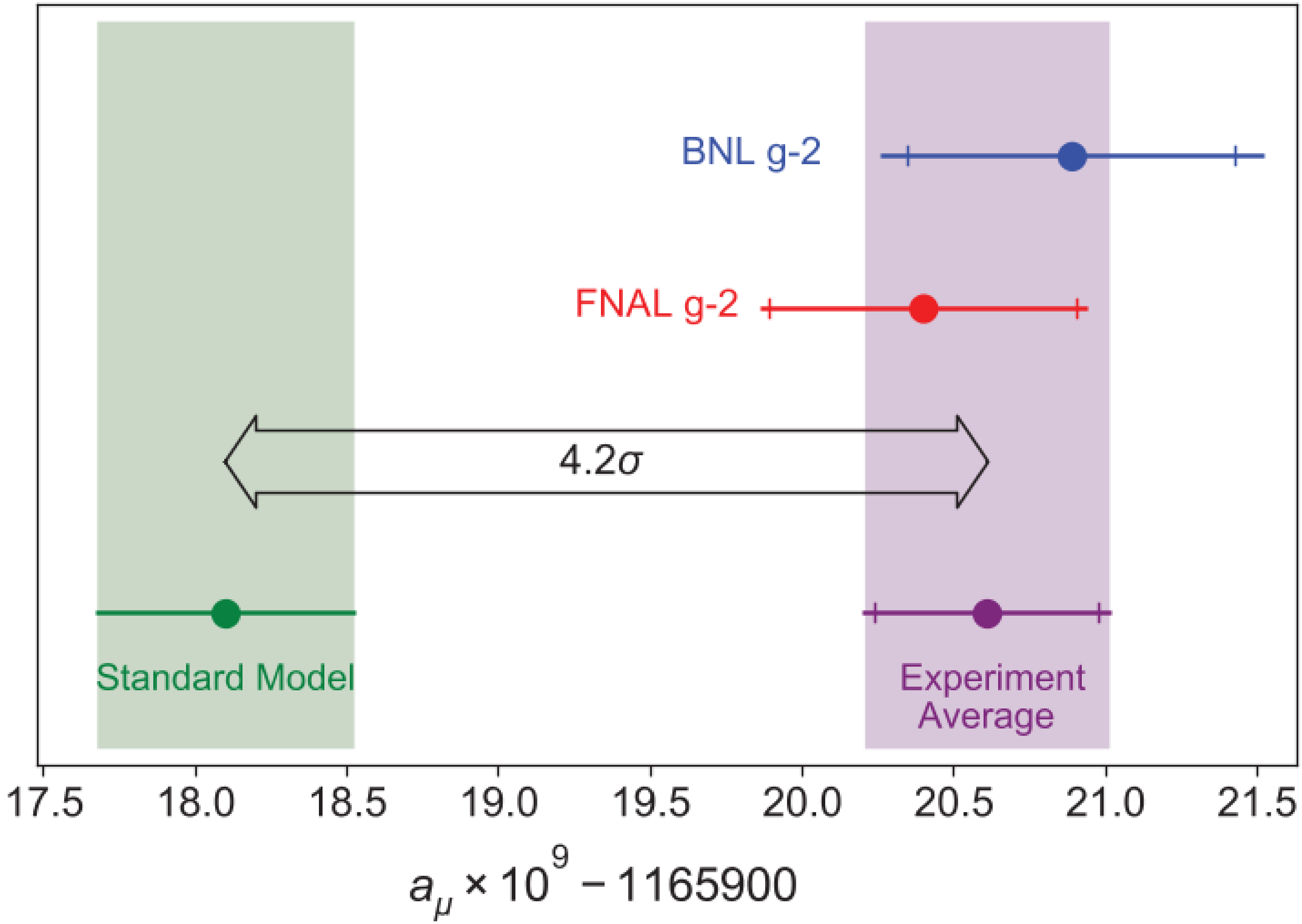

Phys.Rev.Lett. 126 (2021) 14, 141801 [2104.03281]

New Physics behind Muon g-2

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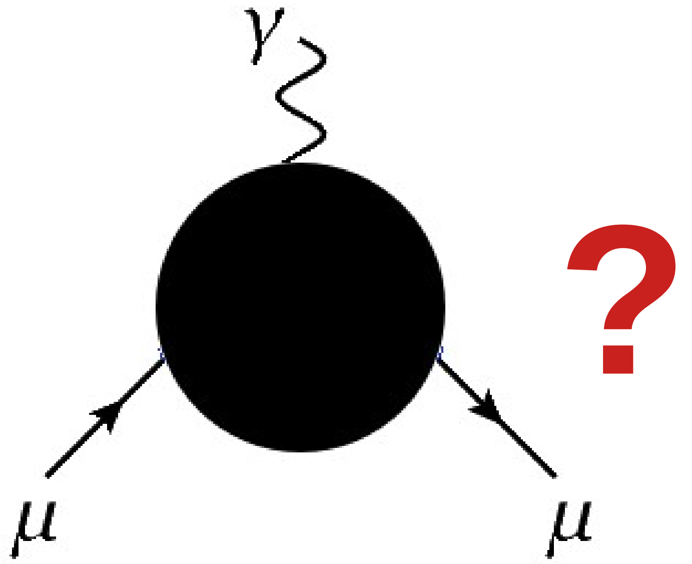
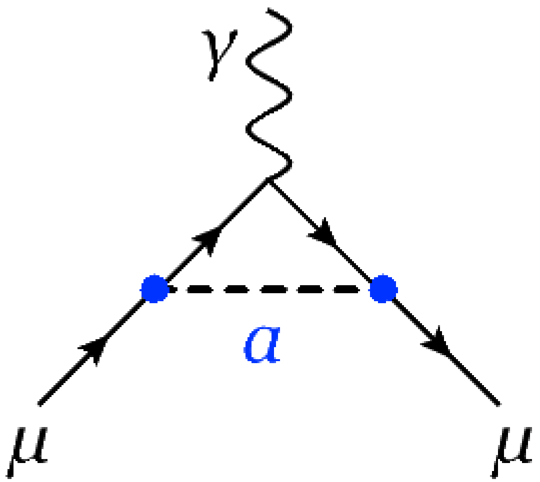


- Muon g-2 is a blackbox
- It cannot probe new physics directly
- Any interpretation relies on theoretical assumptions

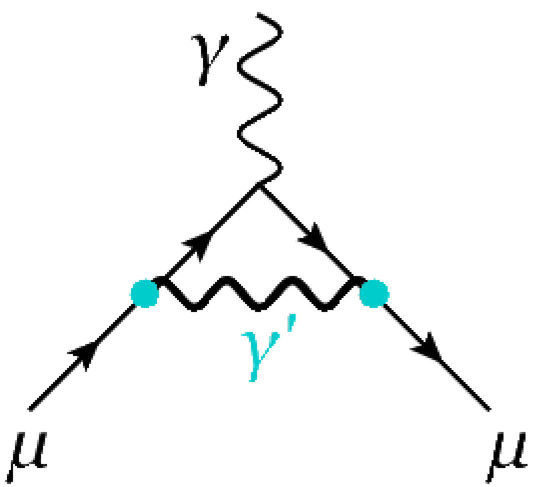
Axion or Dark Photon Alone



$$a_\mu^a = \frac{(y_a^\mu)^2}{4\pi^2}\frac{m_\mu^2}{m_a^2}F_a\left(\frac{m_\mu}{m_a}\right),$$

$$F_a(\eta) \equiv -\frac{1}{2}\int_0^1 \mathrm{d}x \frac{x^3}{(1-x)(1-\eta^2 x)+\eta^2 x}.$$

$$\eta \equiv m_\mu/m_a$$



$$a_\mu^{\gamma'} = \frac{\epsilon^2 e^2}{4\pi^2}\frac{m_\mu^2}{m_{\gamma'}^2}F_{\gamma'}\left(\frac{m_\mu}{m_{\gamma'}}\right),$$

$$F_{\gamma'}(\eta) \equiv \frac{1}{2}\int_0^1 \mathrm{d}x \frac{2x^2(1-x)}{(1-x)(1-\eta^2 x)+\eta^2 x},$$

$$\eta \equiv m_\mu/m_{\gamma'}$$

Dark Photon Explanation

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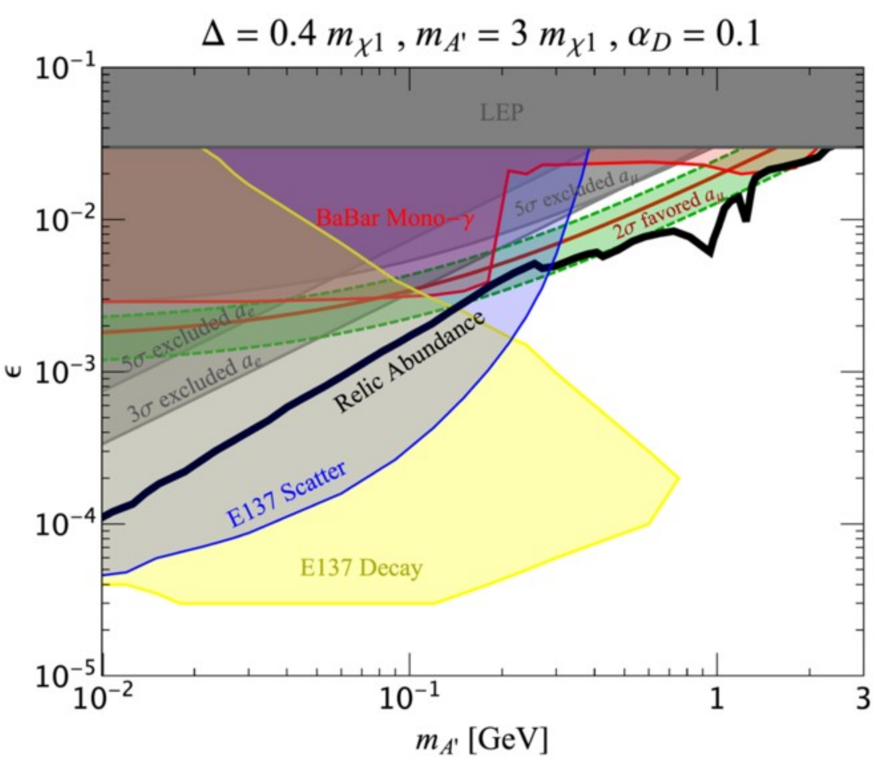
Mohlabeng, Phys.Rev.D 99 (2019) 11, 115001 [1902.05075]

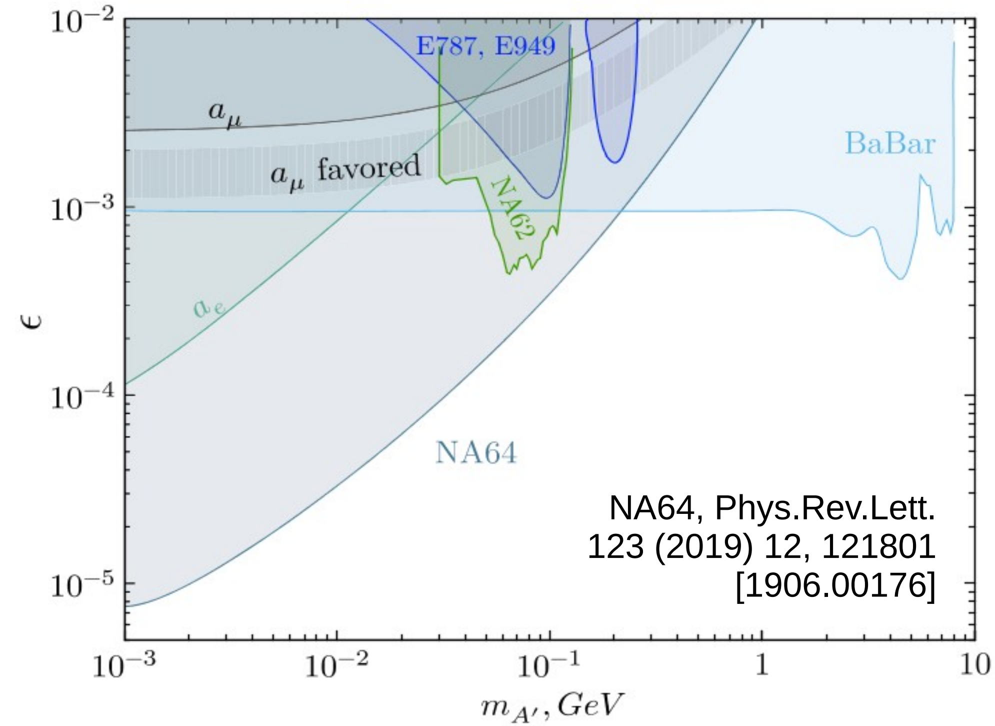
Revisiting the dark photon explanation of the muon anomalous magnetic moment

Gopolang Mohlabeng*
Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA

(Received 13 March 2019; published 3 June 2019)

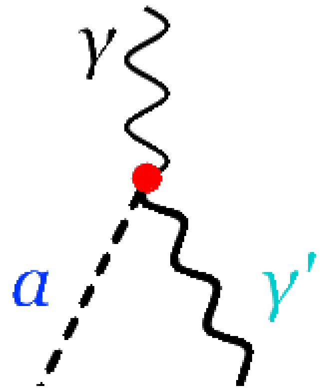
A massive $U(1)'$ gauge boson known as a "dark photon" or A', has long been proposed as a potential explanation for the discrepancy observed between the experimental measurement and theoretical determination of the anomalous magnetic moment of the muon ($g_\mu - 2$) anomaly. Recently, experimental results have excluded this possibility for a dark photon exhibiting exclusively visible or invisible decays. In this work, we





NA64, Phys.Rev.Lett. 123 (2019) 12, 121801 [1906.00176]

Dark Axion Portal



$$\mathcal{L}_{\rm int} = \frac{\alpha_s}{8\pi}\frac{a}{f_a} G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}$$

$$+\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

$$+\sum_f \frac{C_f}{2f_a}\bar{f}\gamma^\mu\gamma_5 f \partial_\mu a$$

$\Rightarrow$

$$\frac{1}{2} C_{a\gamma\gamma'} a F^{\mu\nu}\widetilde{X}_{\mu\nu}$$

$$+y^\mu_a a \bar{\mu}(i\gamma_5)\mu$$

$$-\epsilon e \bar{\mu}\gamma^\nu \mu X_\nu$$

Kunio Kaneta, Hye-Sung Lee, Seokhoon Yun
Phys.Rev.Lett. 118 (2017) 10, 101802 [1611.01466]

Dark Axion Portal

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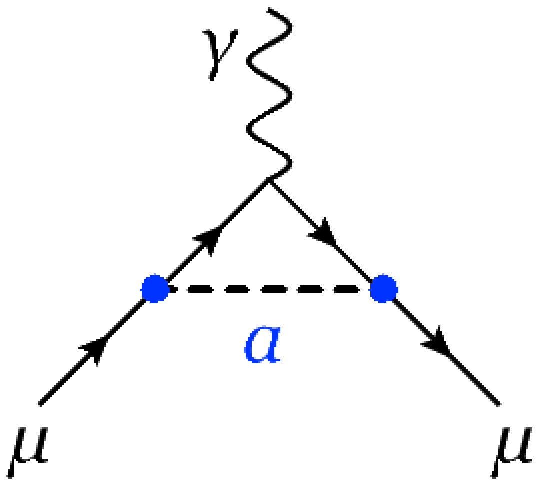

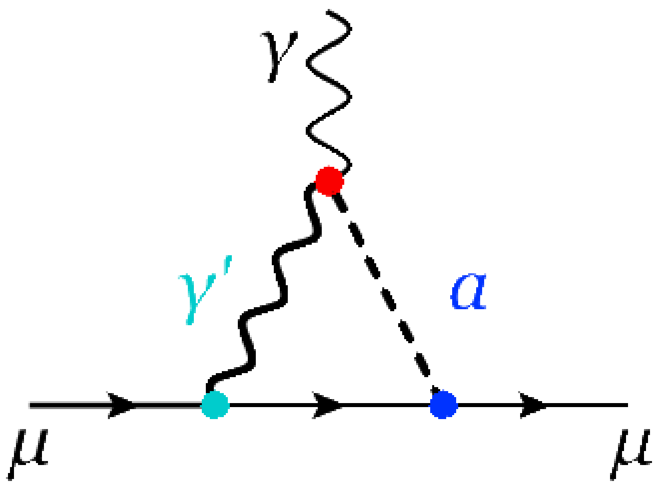

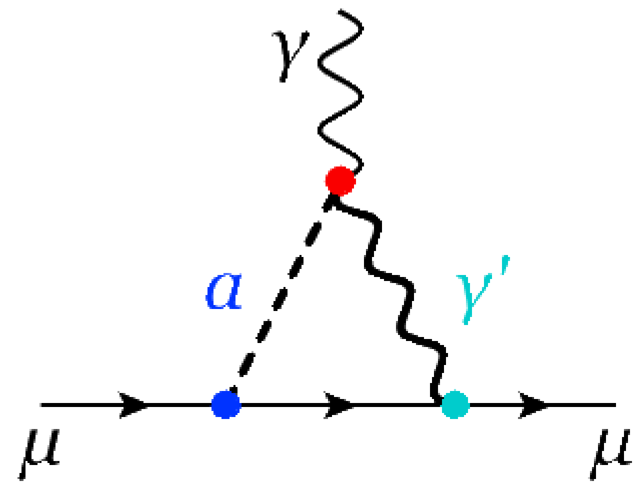

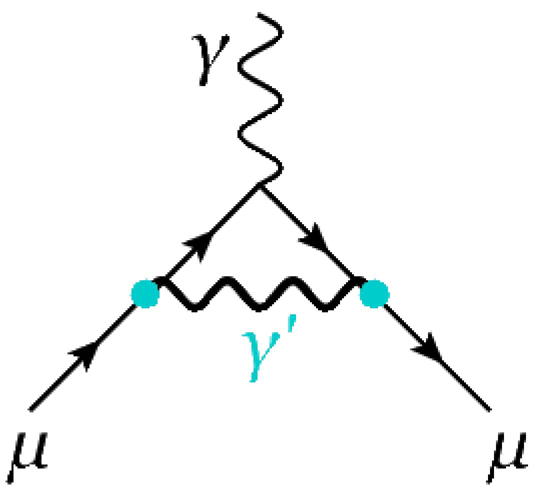

$$a_\mu = \frac{m_\mu}{4\pi^2} \epsilon y_a^\mu C_{a\gamma\gamma'} G,$$

$$G \equiv \int_0^1 dx \left[(1-x) \left(\ln \frac{\Lambda^2}{(1-x) m_a^2 + x^2 m_\mu^2} - \frac{1}{2} \right) - \frac{(1-x) m_{\gamma'}^2 + 2x^2 m_\mu^2}{m_a^2 - m_{\gamma'}^2} \ln \frac{(1-x) m_a^2 + x^2 m_\mu^2}{(1-x) m_{\gamma'}^2 + x^2 m_\mu^2} \right],$$

Make Axion Possible

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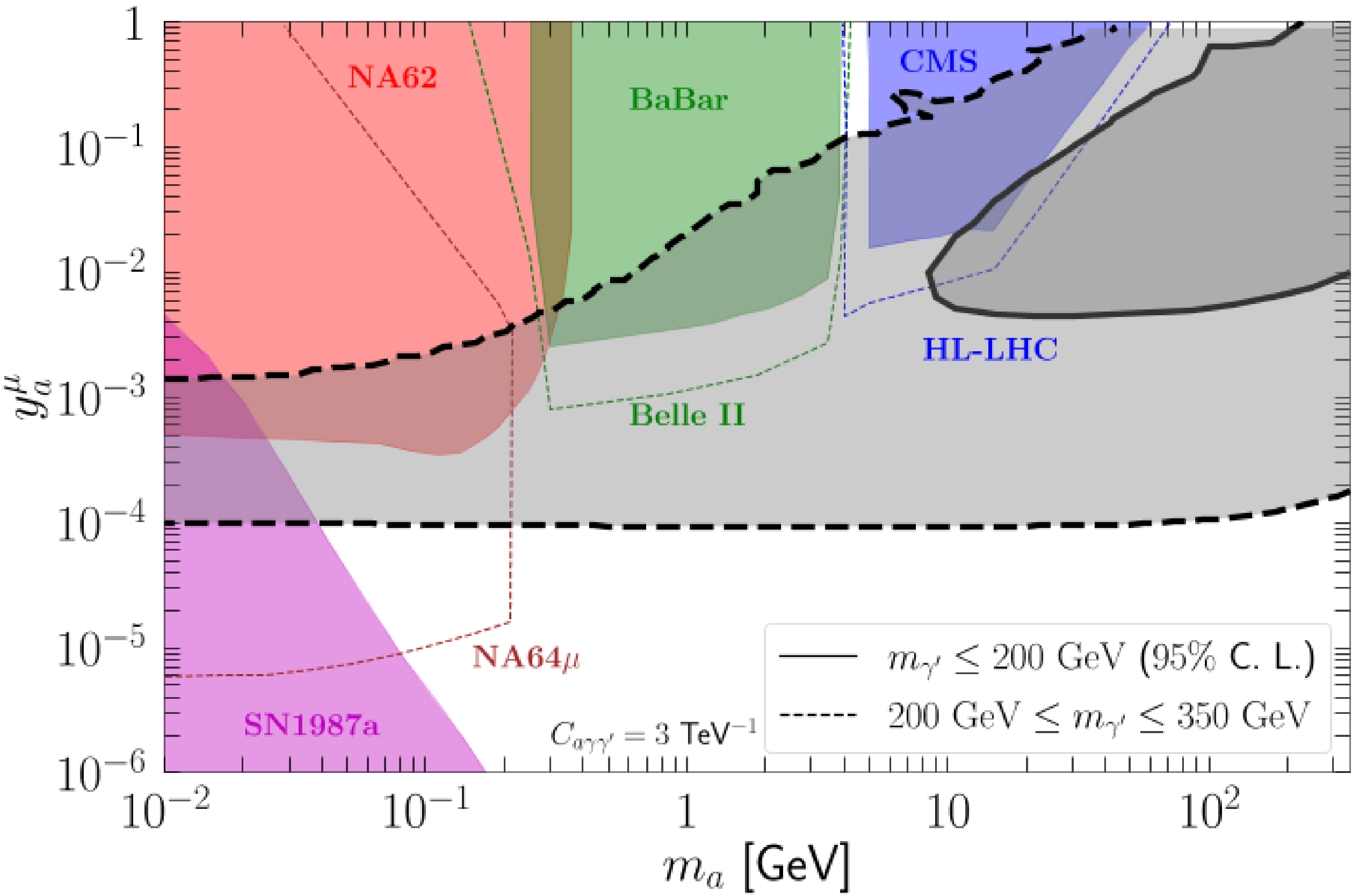

Make Axion Possible

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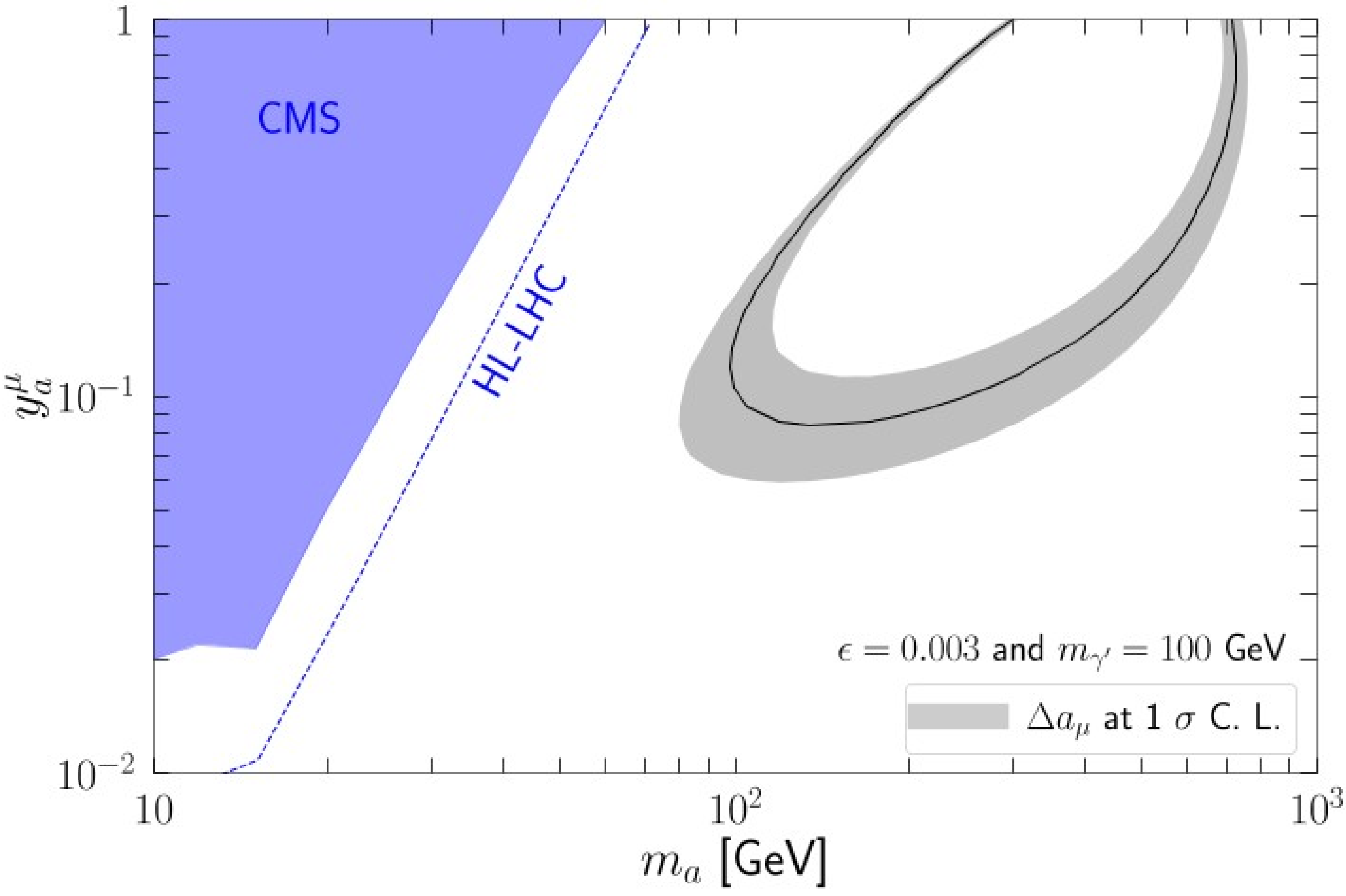
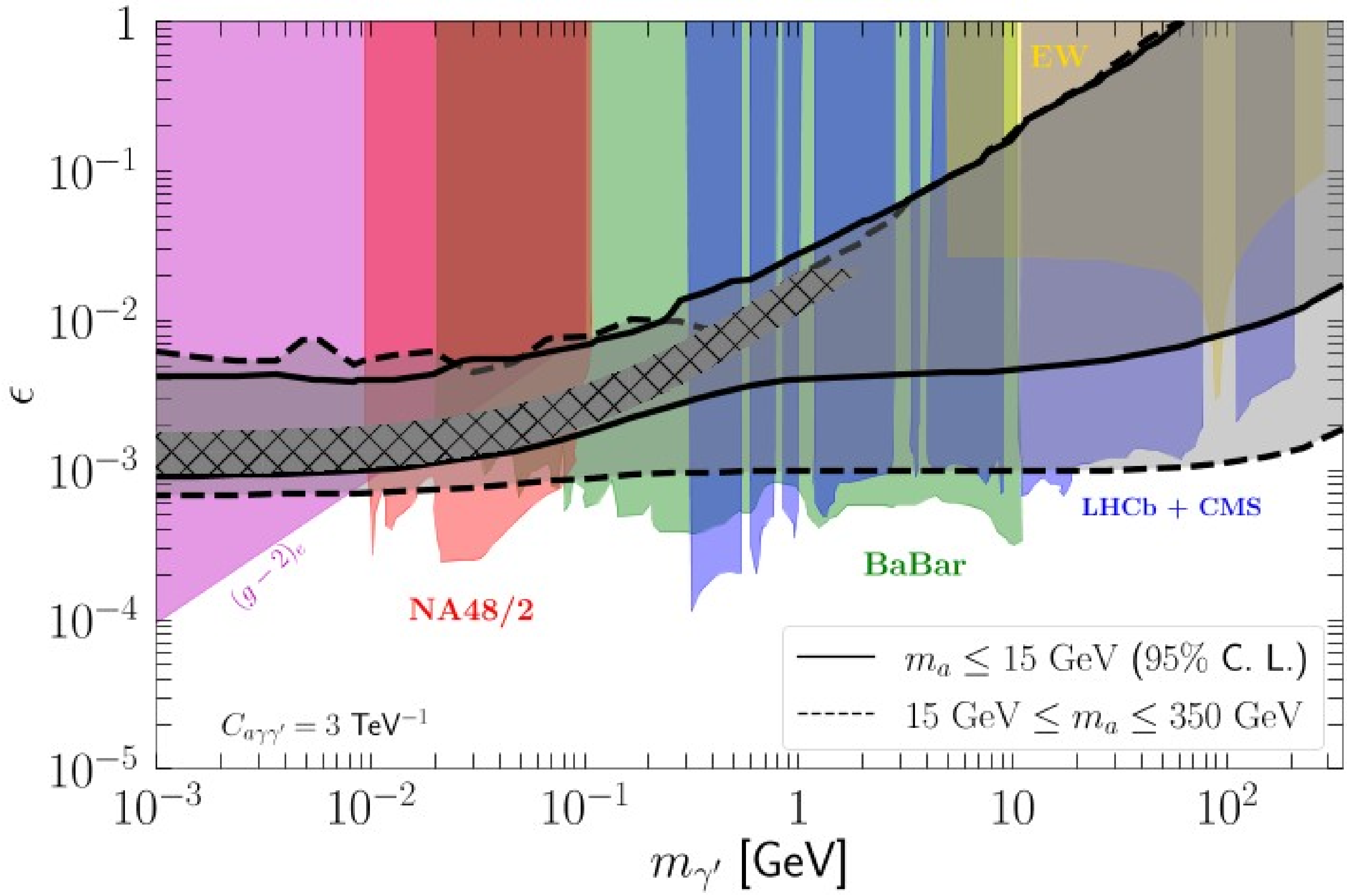
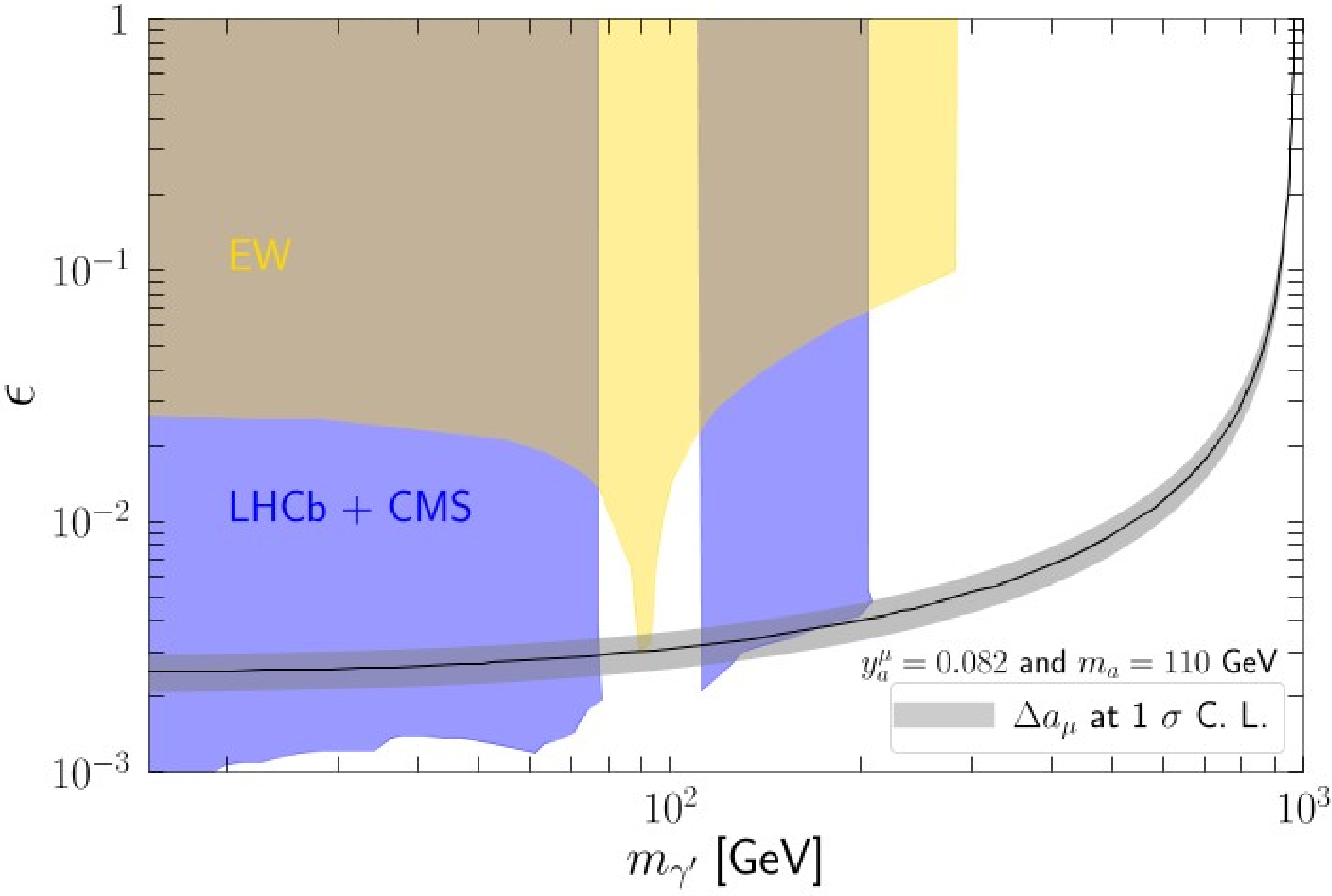


Extend Dark Photon



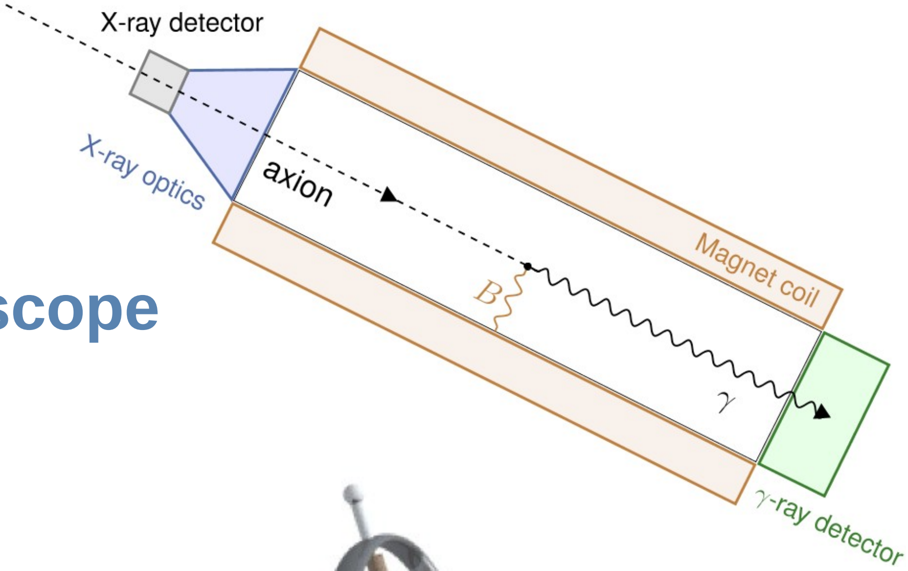
Extend Dark Photon



Summary

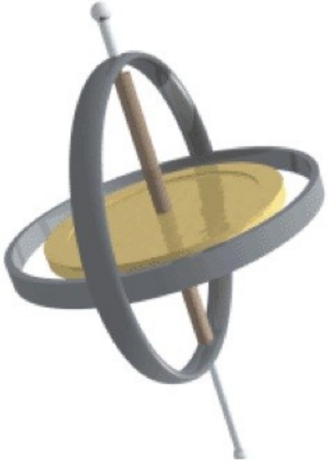
1) **Direct probe by SN-scope**

- **Double potential for helioscope**
- **Sensitive @ eV scale**



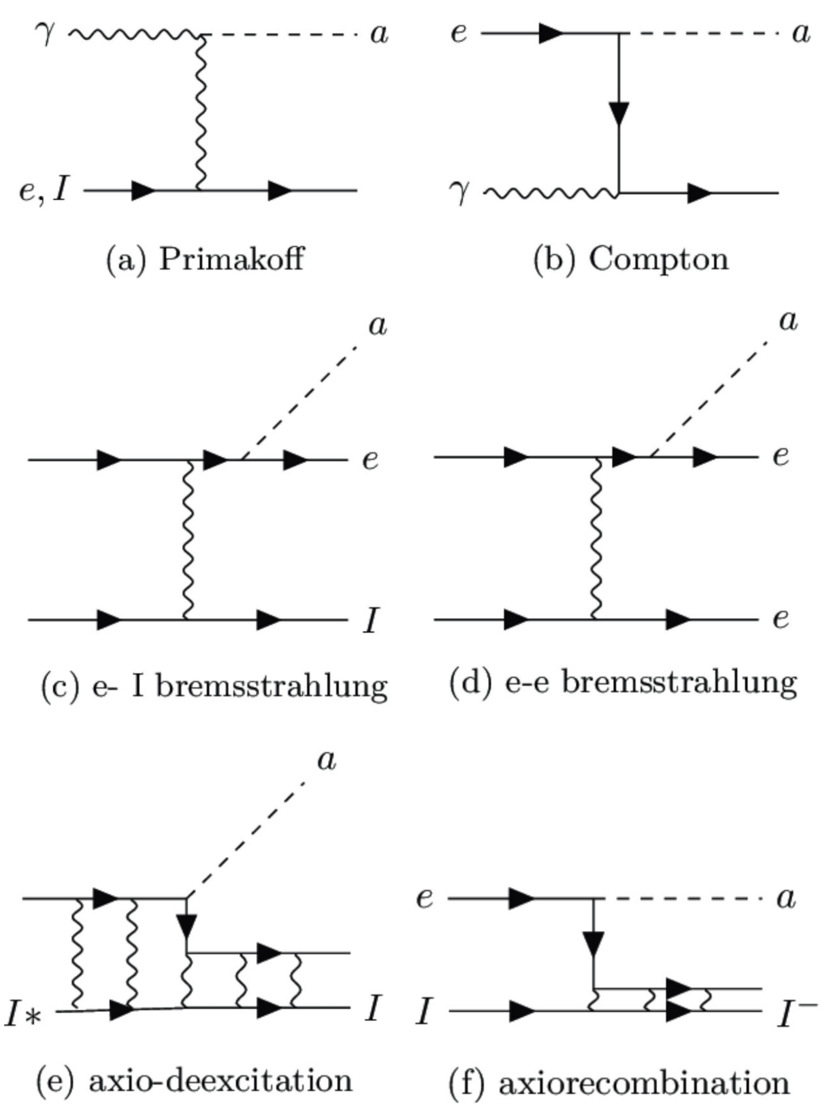
2) **Indirect probe by muon g-2**

- **Make axion scenario possible**
- **Extend the dark photon case**



Thank You

Solar Axion



$$\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \widetilde{F}^{\mu\nu} + \sum_f \frac{C_f}{2 f_a} \bar{f} \gamma^\mu \gamma_5 f \partial_\mu a$$