Probing weakly coupling pseudo Nambu-Goldstone bosons with stimulated resonant photon-photon colliders

Kensuke Homma partly on behalf of the SAPPHIRES collaboration

SAPPHIRES (KH et al.), arXiv:2105.01224 (accepted by JHEP 2021)

Kensuke Homma[1], Yuri Kirita[1], Masaki Hashida[2, 3], Yusuke Hirahara[1], Shunsuke Inoue[2, 3], Fumiya Ishibashi[1], Yoshihide Nakamiya[2, 4], Liviu Neagu[4, 5], Akihide Nobuhiro[1], Takaya Ozaki[1], Madalin-Mihai Rosu[4], Shuji Sakabe[2, 3], and Ovidiu Tesileanu[4]

[1]Graduate School of Advanced Science and Engineering, Hiroshima University, Kagamiyama, Higashi-Hiroshima 739-8526, Japan
[2]Institute for Chemical Research, Kyoto University Uji, Kyoto 611-0011, Japan
[3]Graduate School of Science, Kyoto University, Sakyouku, Kyoto 606-8502, Japan
[4]Extreme Light Infrastructure-Nuclear Physics (ELI-NP) / Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH), 30 Reactorului St., P.O. Box MG-6, Bucharest-Magurele, Judetul Ilfov, RO-077125, Romania
[5]National Institute for Laser, Plasma and Radiation Physics, 409 Atomistilor PO Box MG-36, 077125, Magurele, Jud. Ilfov, Romania

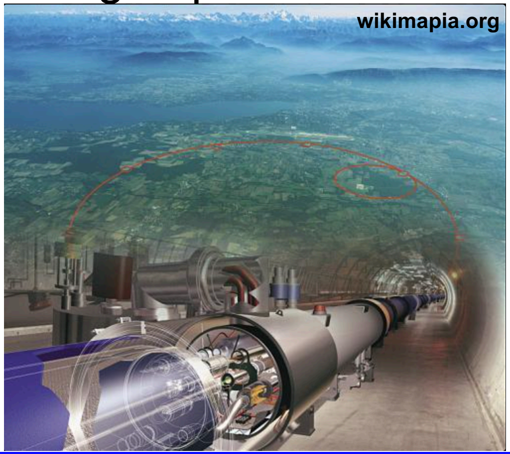
KH and K. Kirita, JHEP 09 (2020) 095
T. Katsuragawa, S. Matsuzaki, KH, arXiv: 2107.00478 [gr-qc]

1. **Pseudo Nambu-Goldstone bosons: axion**
2. **Search results with lasers**
3. **Pseudo Nambu-Goldstone bosons: dilaton**
4. **Prospect of dilaton search with klystron**
5. **Summary**

Approaches to different mass - coupling domains

Coupling

Charged particle collider

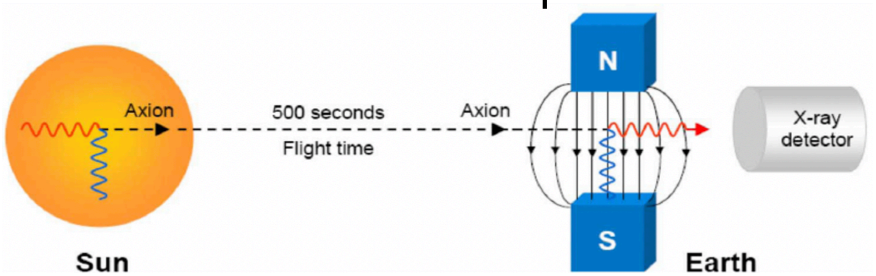


Photons, electrons, muons, neutrinos discovered in fixed target particle collisions and cosmic-rays in early days

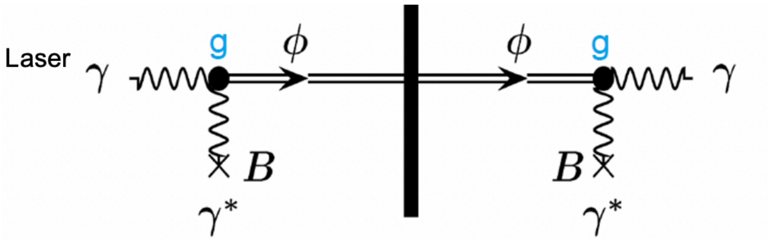
Novel approach

Mass

Photon-based Axion-like particle search

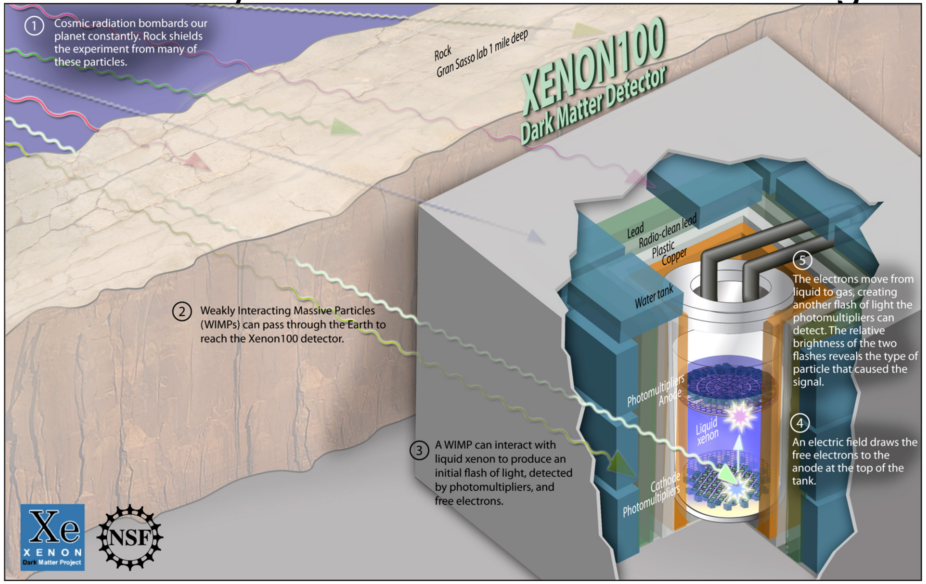


CAST, Theopisti Dafni, 7th Patras Workshop, Mykonos 2011



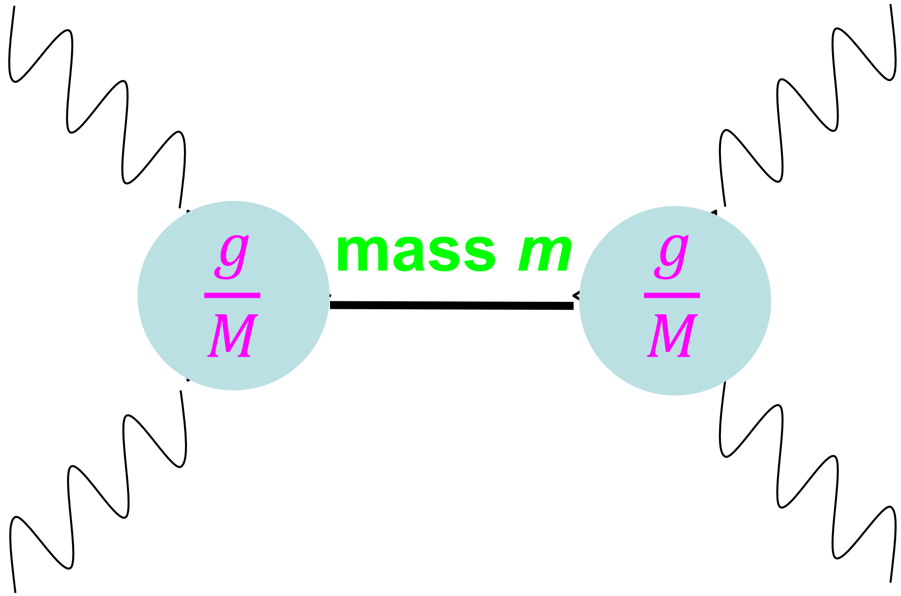
Okun 1982, Skivie 1983, Ansel'm 1985, Van Bibber et al. 1987

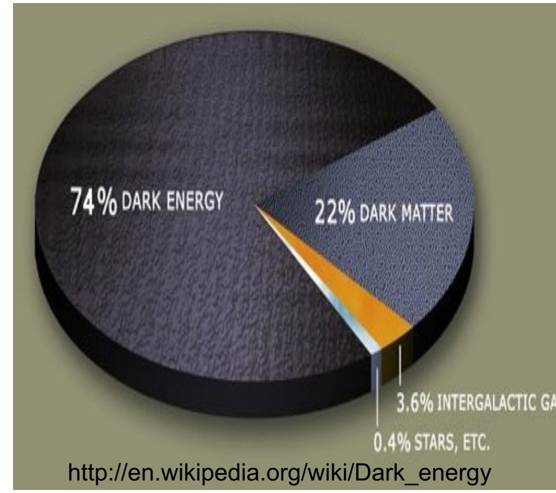
Recoil by dark matter collisions in target



https://www.nsf.gov/news/mmg/media/images/xenon_h.jpg

Pseudo Nambu-Goldstone bosons are light !





Scale symmetry breaking

$$-\frac{1}{4}\frac{g}{M}F_{\mu\nu}F^{\mu\nu}\phi$$

If $M \sim M_{Planck}$, dilaton (Dark Energy)

mass 1.5-5.9 10^{-7} eV

PQ U(1) symmetry breaking

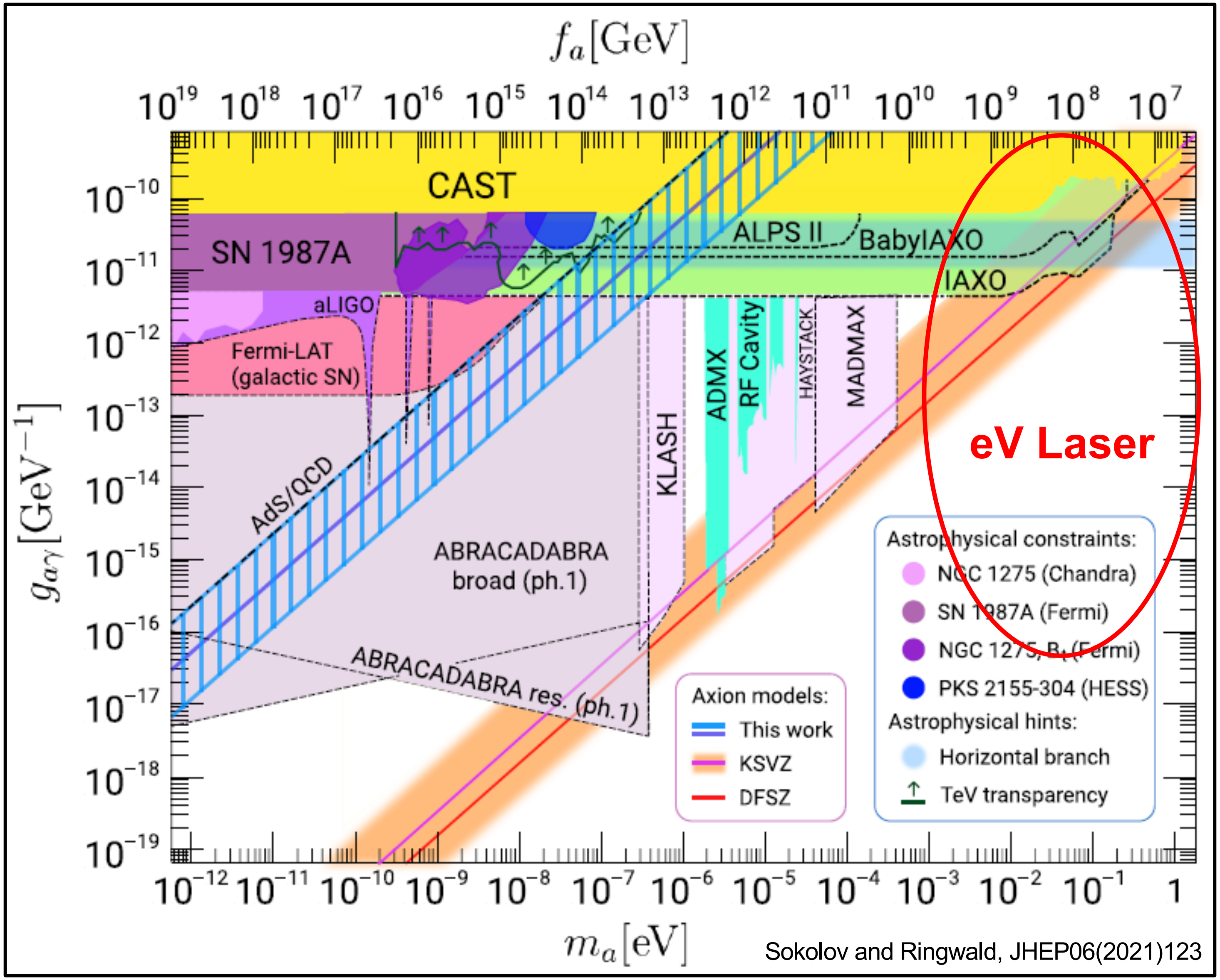
$$-\frac{1}{4}\frac{g}{M}F_{\mu\nu}\tilde{F}^{\mu\nu}\sigma$$

If $M \sim M_{GUT}$, axion (Cold Dark Matter)

mass 10^{-4}-10^{-6} eV

Two-loop self-energy correction
arXiv:1512.01360 [gr-qc]
Y. Fujii

Target mass-coupling domains



Sokolov and Ringwald, JHEP06(2021)123

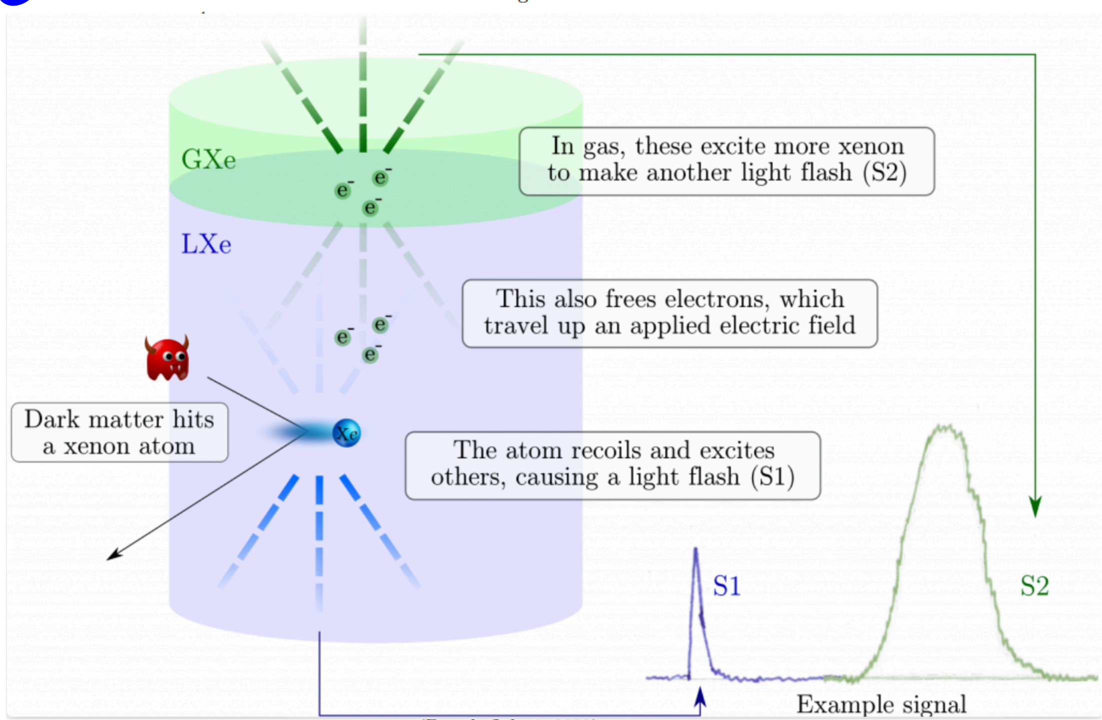
Electronic recoil indicates 0.1-100 eV solar axions?

Observation of Excess Electronic Recoil Events in XENON1T

E. Aprile,[1] J. Aalbers,[2] F. Agostini,[3] M. Alfonsi,[4] L. Althueser,[5] F. D. Amaro,[6] V. C. Antochi,[2]
E. Angelino,[7] J. R. Angevaare,[8] F. Arneodo,[9] D. Barge,[2] L. Baudis,[10] B. Bauermeister,[2] L. Bellagamba,[3]
M. L. Benabderrahmane,[9] T. Berger,[11] A. Brown,[10] E. Brown,[11] S. Bruenner,[8] G. Bruno,[9] R. Budnik,[12,*]
C. Capelli,[10] J. M. R. Cardoso,[6] D. Cichon,[13] B. Cimmino,[14] M. Clark,[15] D. Coderre,[16] A. P. Colijn,[8]
J. Conrad,[2] J. P. Cussonneau,[17] M. P. Decowski,[8] A. Depoian,[15] P. Di Gangi,[3] A. Di Giovanni,[9] R. [illegible]
S. Diglio,[17] A. Elykov,[16] G. Eurin,[13] A. D. Ferella,[18,19] W. Fulgione,[7,19] P. Gaemers,[8] [illegible]
M. Galloway,[10,‡] F. Gao,[1] L. Grandi,[21] C. Hasterok,[13] C. Hils,[4] K. Hiraide,[22] L. [illegible] J. Howlett,[1]
M. Iacovacci,[14] Y. Itow,[23] F. Joerg,[13] N. Kato,[22] S. Kazama,[23,§] M. Kobaya[illegible] A. Kopec,[15]
H. Landsman,[12] R. F. Lang,[15] L. Levinson,[12] Q. Lin,[1] S. Lin[illegible] F. Lombardi,[6]
J. Long,[21] J. A. M. Lopes,[6,¶] E. López Fune,[20] C. Ma[illegible] A. Mancuso,[3] L. Manenti,[9]
A. Manfredini,[10] F. Marignetti,[14] T. Marrodán Undag[illegible] J. Masbou,[17] D. Masson,[16]
S. Mastroianni,[14] M. Messina,[19] K. Miuchi,[25] K. [illegible] Molinario,[19] K. Morå,[1,2] S. Moriyama,[22]
Y. Mosbacher,[12] M. Murra,[5] J. Nagan[illegible] U. Oberlack,[4] K. Odgers,[11] J. Palacio,[13,17] B. Pelssers,[2]
R. Peres,[10] J. Pienaar,[21] V. Pizz[illegible] J. Qin,[15] H. Qiu,[12] D. Ramírez García,[16] S. Reichard,[10]
A. Rocchetti,[16] N. Rup[illegible] G. Sartorelli,[3] N. Šarčević,[16] M. Scheibelhut,[4] J. Schreiner,[13]
D. Schulte,[5] M[illegible] Lavina,[20] M. Selvi,[3] F. Semeria,[3] P. Shagin,[27] E. Shockley,[21,**]
M. Silva,[6] H. Sim[illegible] Takeda,[22] C. Therreau,[17] D. Thers,[17] F. Toschi,[16] G. Trinchero,[7] C. Tunnell,[27]
M. [illegible] G. [illegible] H. Wang,[28] Y. Wei,[26] C. Weinheimer,[5] M. Weiss,[12] D. Wenz,[4] C. Wittweg,[5]
[illegible] Yamashita,[23,22] J. Ye,[26,††] G. Zavattini,[3,‡‡] Y. Zhang,[1] T. Zhu,[1] and J. P. Zopounidis[20]
(XENON Collaboration)
X. Mougeot[29]

arXiv:2006.09721v2 [hep-ex] 30 Jun 2020

Dark Matter Discovered ?



(Dated: July 1, 2020)

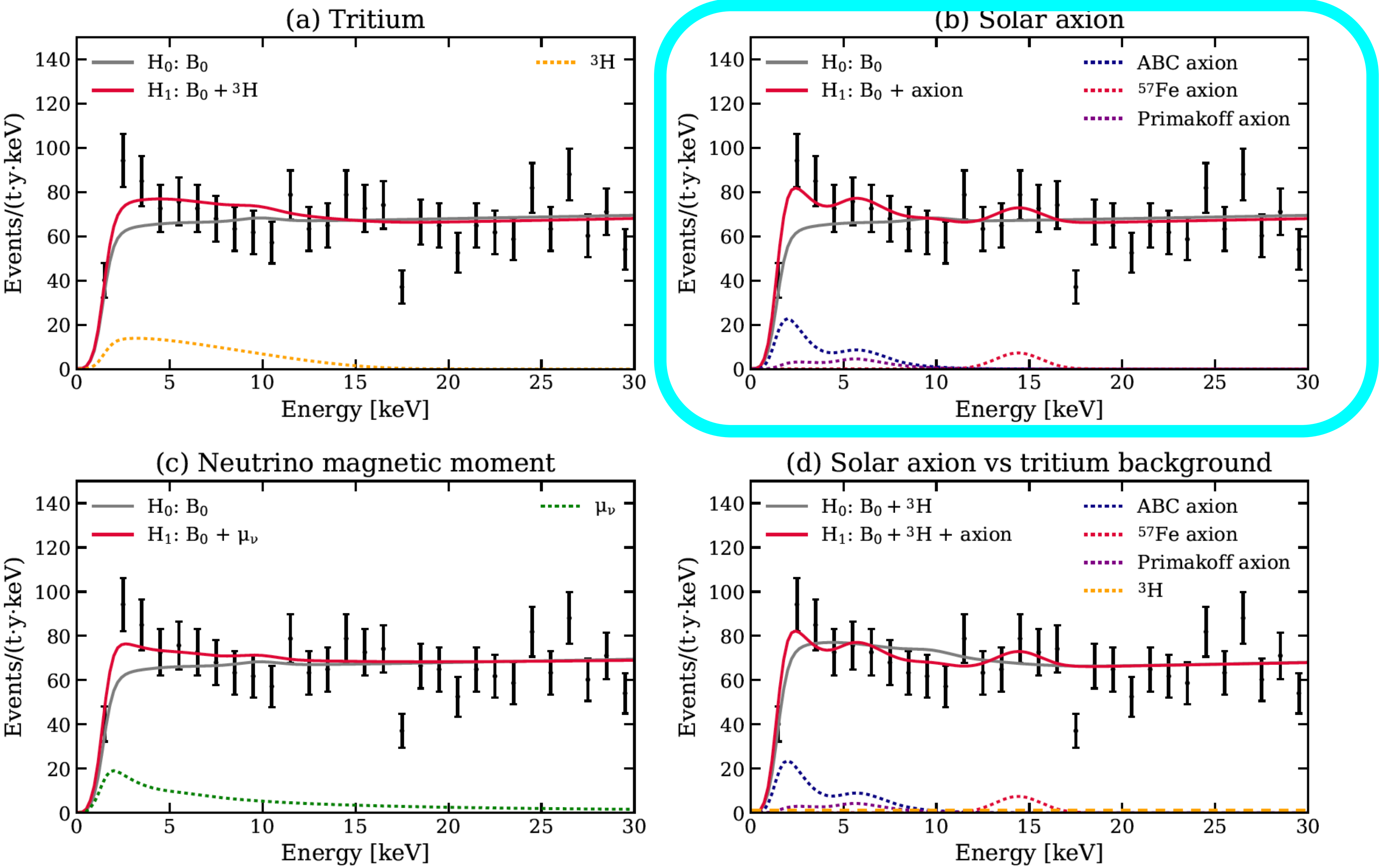


FIG. 7. Fits to the data under various hypotheses. The null and alternative hypotheses in each scenario are denoted by gray (solid) and red (solid) lines, respectively. For the tritium (a), solar axion (b), and neutrino magnetic moment (c) searches, the null hypothesis is the background model B_0 and the alternative hypothesis is B_0 plus the respective signal. Contributions from selected components in each alternative hypothesis are illustrated by dashed lines. Panel (d) shows the best fits for an additional statistical test on the solar axion hypothesis, where an unconstrained tritium component is included in both null and alternative hypotheses. This tritium component contributes significantly to the null hypothesis, but its best-fit rate is negligible in the alternative hypothesis, which is illustrated by the orange dashed line in the same panel.

XENON1T's claim

For the DFSZ model, we find $m_a \sim 0.1$–$4.1\ \mathrm{eV}/c^2$ and $\cos^2\beta_{\mathrm{DFSZ}} \sim 0.01$–$1$ would be consistent with this work. Alternatively, under the KSVZ model, $m_a \sim 46$–$56\ \mathrm{eV}/c^2$ and $E = 6$ would be similarly consistent. These model-

$$g_{ae} = \frac{m_e}{3 f_a} \cos^2\beta_{\mathrm{DFSZ}},$$

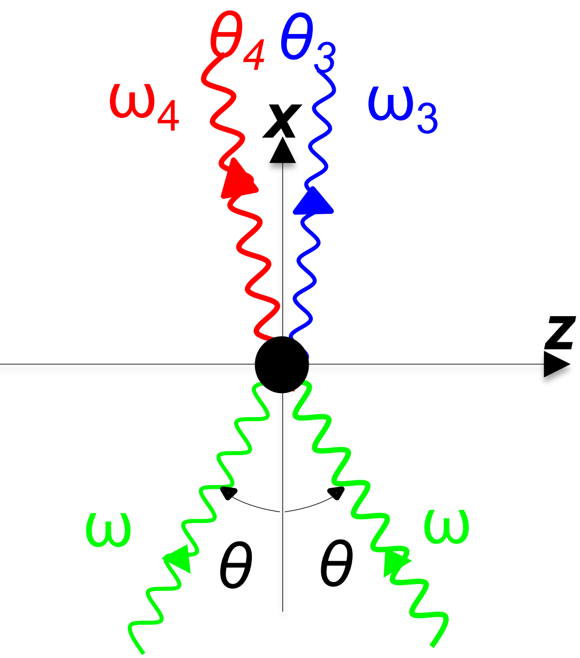
$$\tan(\beta_{\mathrm{DFSZ}}) = \left(\frac{X_u}{X_d}\right)^{1/2}$$

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - \frac{2}{3}\,\frac{4+z}{1+z}\right)$$

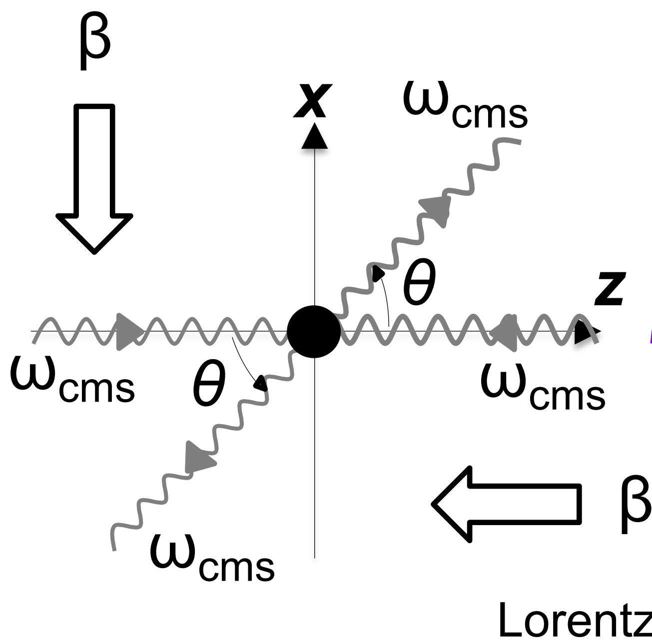
$$z = m_u / m_d,$$

Photon-photon collision systems

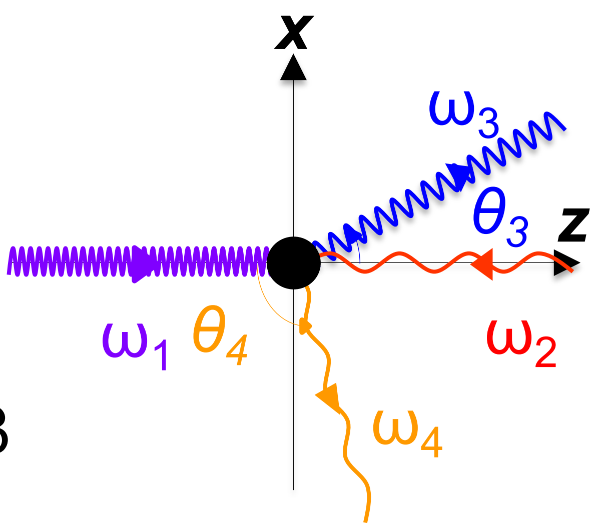
Quasi-Parallel collision System



Center of Mass System



Asymmetric Head-on collision System



$$E_{cms} = 2\omega \sin\theta$$

Low mass search

$$E_{cms} = 2\omega_{cms}$$

High mass search

$$E_{cms} = 2\sqrt{\omega_1 \omega_2}$$

High mass search

Scattering amplitude for two-body interactions in stimulated resonant scattering

$$S^{(2)} = \frac{i^2}{2}\int d^4x \int d^4y T[F_{\mu\nu}(x)F^{\mu\nu}\phi(x)F_{\rho\sigma}(y)F^{\rho\sigma}(y)\phi(y)]$$

$$N[F_{\mu\nu}(x)F^{\mu\nu}(x)F_{\sigma\rho}(y)F^{\sigma\rho}(y)\langle 0|T[\phi(x)\phi(y)]|0\rangle]$$

$\propto a^{\dagger}_{\vec{i}} a^{\dagger}_{\vec{j}} a_{\vec{k}}\, a_{\vec{l}}$ pNGB-propagator

Coherent state:

$$|N\rangle\rangle \equiv \exp(-N/2)\sum_{n=0}^{\infty}\frac{N^{n/2}}{\sqrt{n!}}|n\rangle \quad |n\rangle = \frac{1}{\sqrt{n!}}\left(a^{\dagger}\right)^{n}|0\rangle$$

$$\langle\langle N|N\rangle\rangle = 1 \quad \langle\langle N|\left(a^{\dagger}a\right)|N\rangle\rangle = N \quad a|N\rangle\rangle = \sqrt{N}|N\rangle\rangle, \quad \text{and} \quad \langle\langle N|a^{\dagger} = \sqrt{N}\langle\langle N|,$$

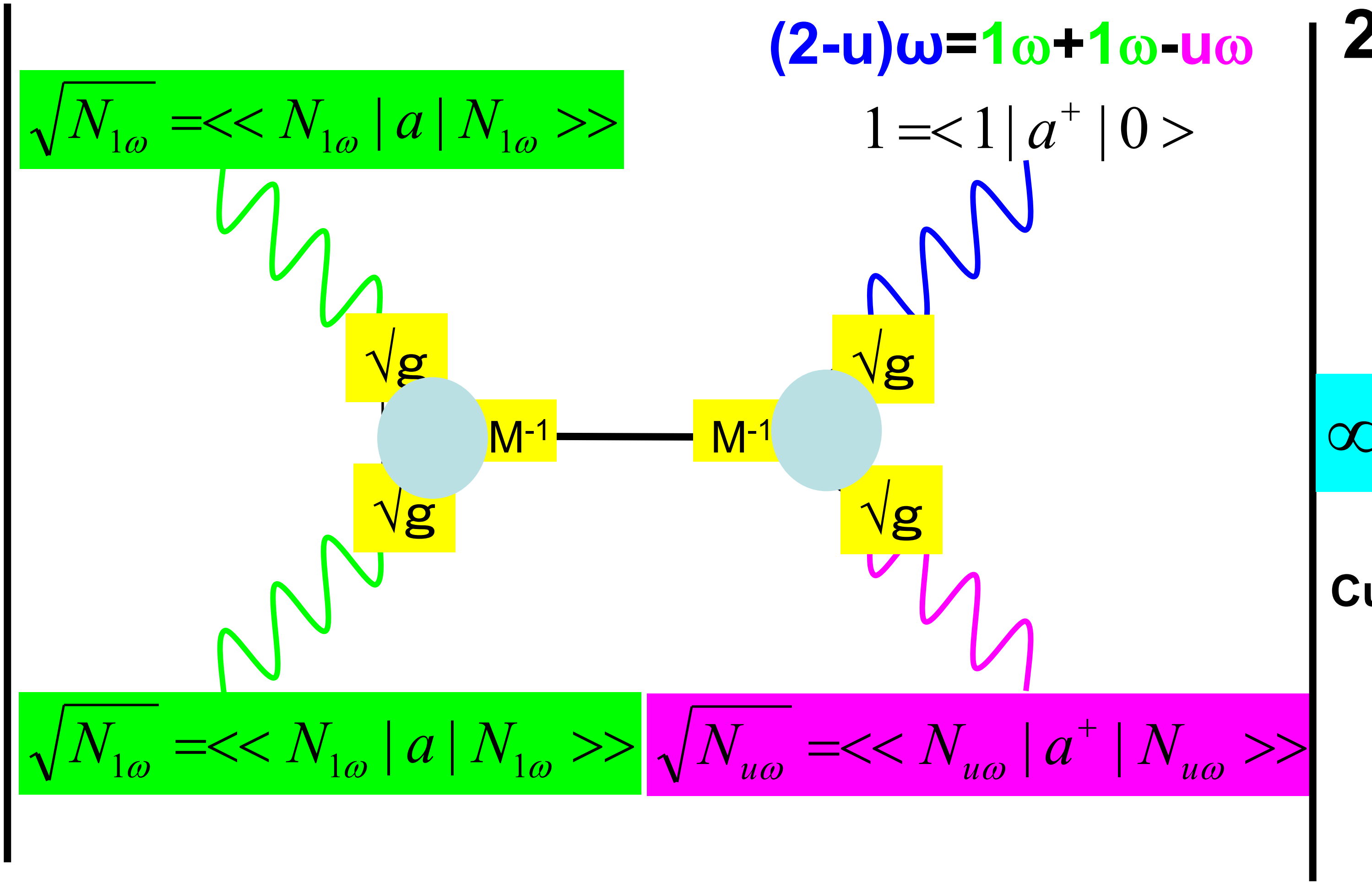
Transition amplitude: **1** + **1** → 3 + **4**

$$\ll N_1| \ll N_4| \ll 1_3|S^{(2)}|N_1 \gg |N_4 \gg |0>$$

$$\propto \ll N_1| \ll N_4| \ll 1_3|a^{\dagger}_{\vec{i}} a^{\dagger}_{\vec{j}} a_{\vec{k}}\, a_{\vec{l}}\, |N_1 \gg |N_4 \gg |0>$$

$$\propto \sqrt{N_1}\sqrt{N_1}\sqrt{N_4} \ll N_1|N_1 \gg\ll N_4|N_4 \gg< 0|0>$$

Enhanced rate by inducing laser field
- stimulated scattering in bkg laser field-



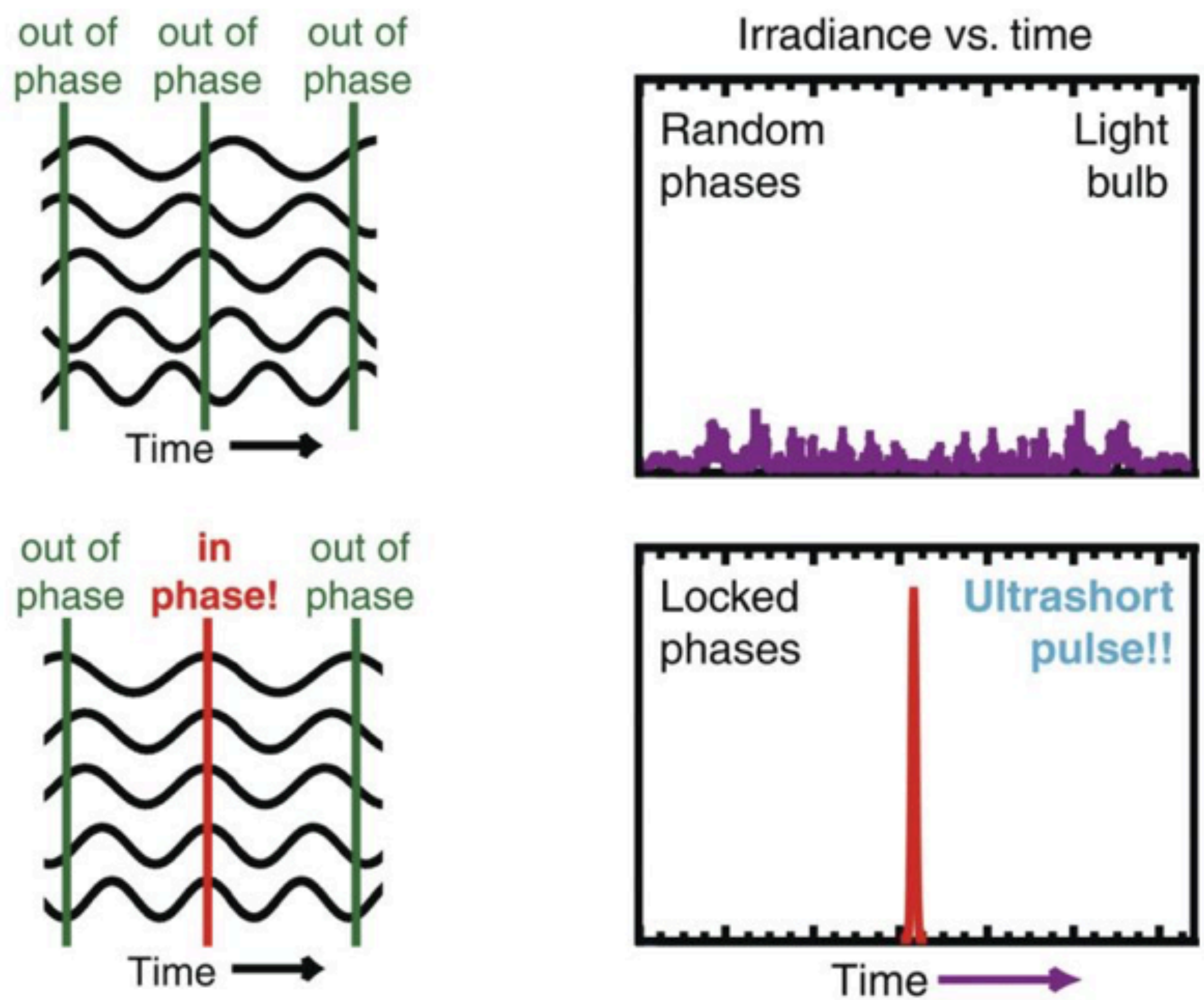
$\propto N^{2}_{1\omega} N_{u\omega}$

Cubic dependence

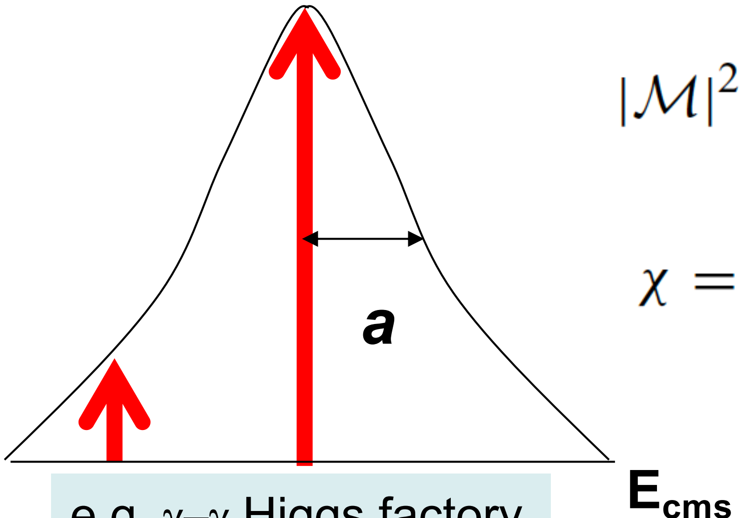
arXiv:1006.1762 [gr-qc]
Y. Fujii and K.Homma
Prog. Theor. Phys., 2011

Short pulse duration = Broad-band in energy

Figure quoted from https://www.newport.com/n/pulsed-laser-methods



s-channel scattering contains resonance

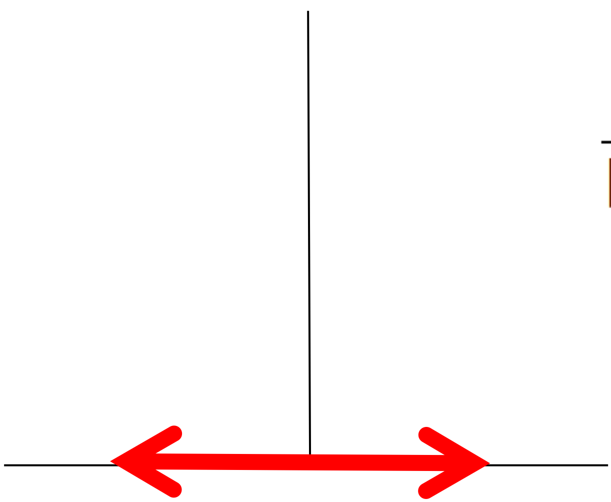


e.g. γ–γ Higgs factory

$$|\mathcal{M}|^2 \approx (4\pi)^2 \frac{a^2}{\chi^2 + a^2} \qquad a = \frac{\omega_r^2}{16\pi}\left(\frac{gm}{M}\right)^2$$

$$\chi = \omega^2 - \omega_r^2 \quad \omega_r^2 = \frac{m^2/2}{1 - \cos 2\vartheta}$$

$$\chi \gg a \rightarrow |\mathcal{M}|^2 \propto a^2 \propto M^{-4}$$
$$\omega = \omega_r \rightarrow |\mathcal{M}|^2 \propto (4\pi)^2$$



Collision in QPS within momentum-energy uncertainty

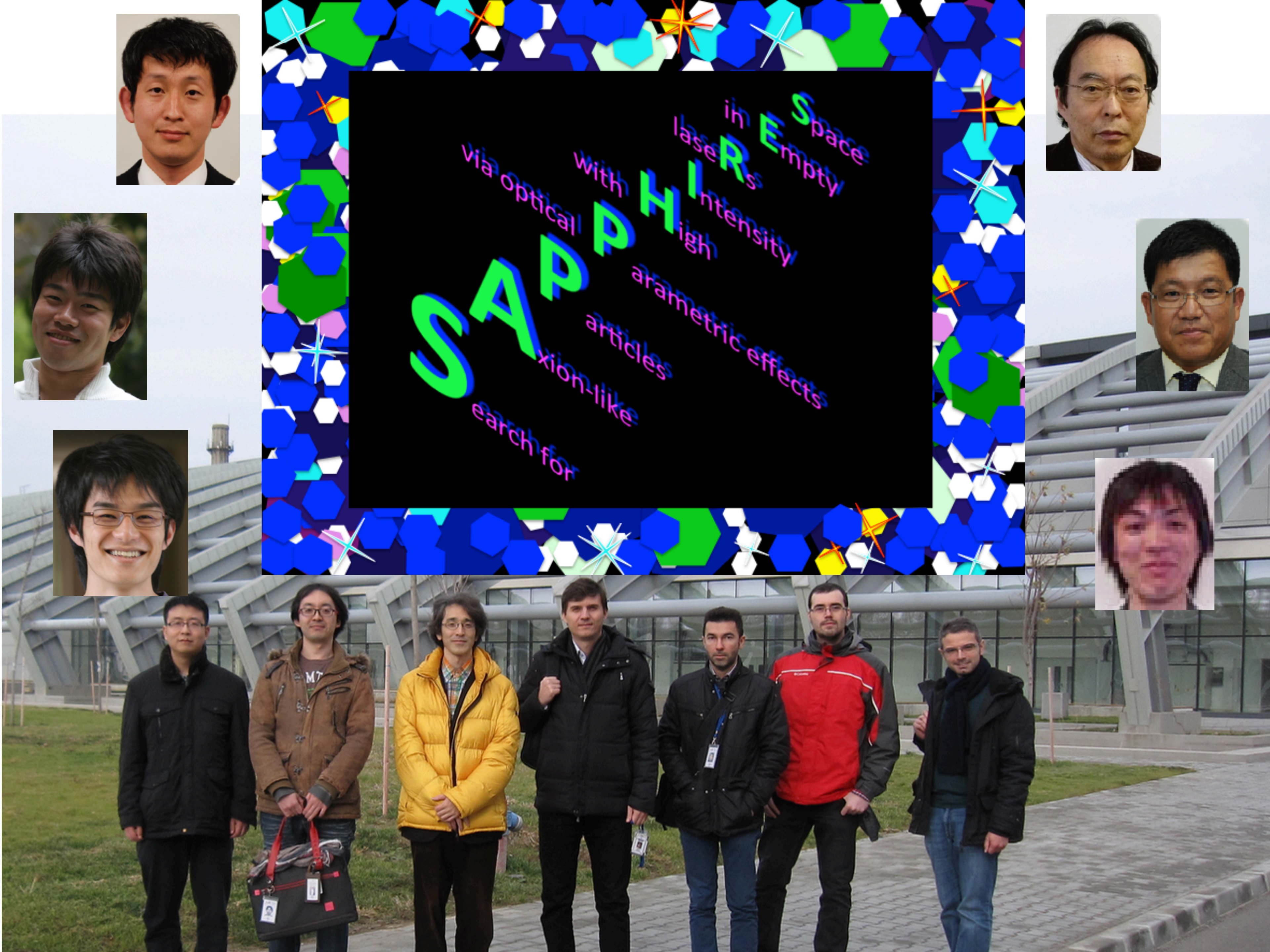
$$\chi_\pm \equiv \pm\eta a \text{ with } \eta \gg 1$$

$$\overline{|\mathcal{M}|^2} = \frac{1}{\chi_+ - \chi_-}\int_{\chi_-}^{\chi_+} |\mathcal{M}|^2 d\chi$$

$$= \frac{(4\pi)^2}{2\eta a} 2a \tan^{-1}(\eta) = (4\pi)^2 \eta^{-1} \tan^{-1}(\eta)$$

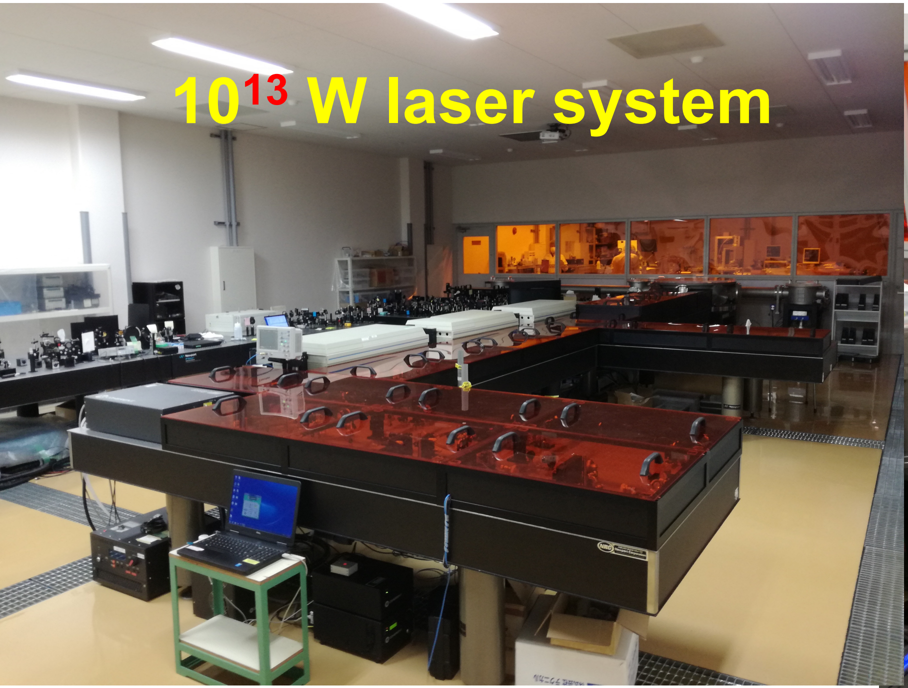
$$\approx (4\pi)^2 \eta^{-1} \frac{\pi}{2} = 8\pi^3 \frac{a}{|\chi_\pm|}$$

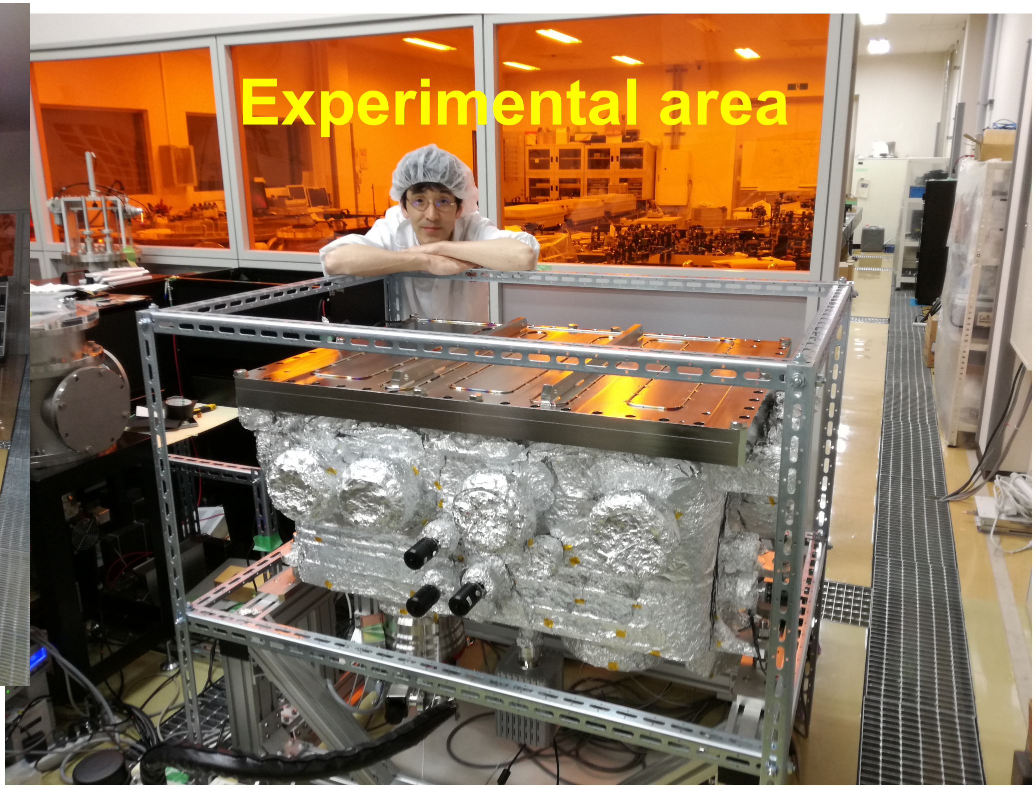
Gain by *M^2*



Search for
Axion-like
Particles
via optical
Parametric effects
with
High
Intensity
laseRs
in
Empty
Space

Searches at Ins. Chem. Res. in Kyoto Univ.





The air causes the stimulate scattering