Perspective of searching for axion-like particles in the mass range 10^{-7} - 10^{3} eV with stimulated photon-photon collider

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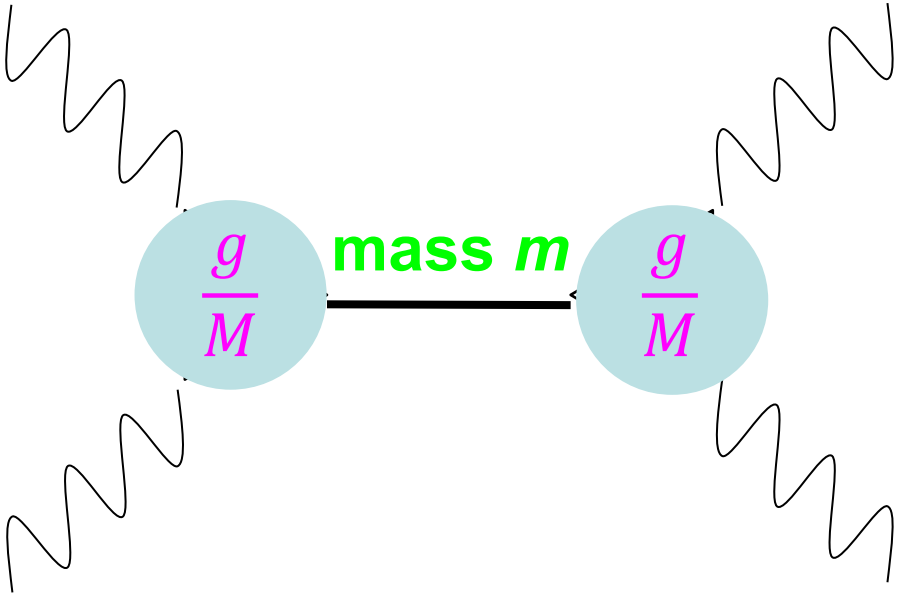
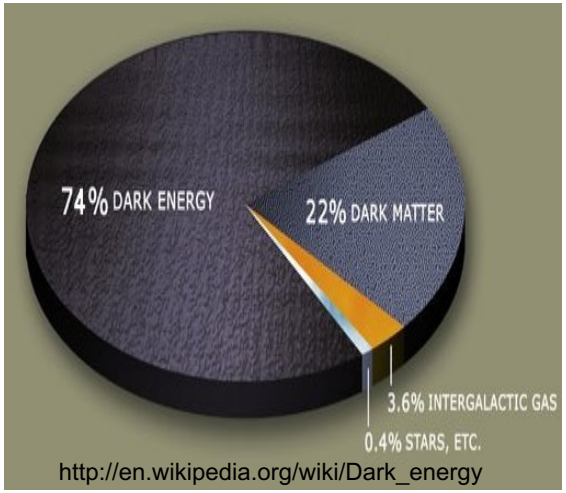
1. pseudo Nambu-Goldstone bosons as candidates for dark components in the Universe
2. Principle of stimulated resonant photon-photon scattering
3. Quick overview of experimental activities
4. Summary

pNGBs can be dark components of the Universe





http://en.wikipedia.org/wiki/Dark_energy

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

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

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

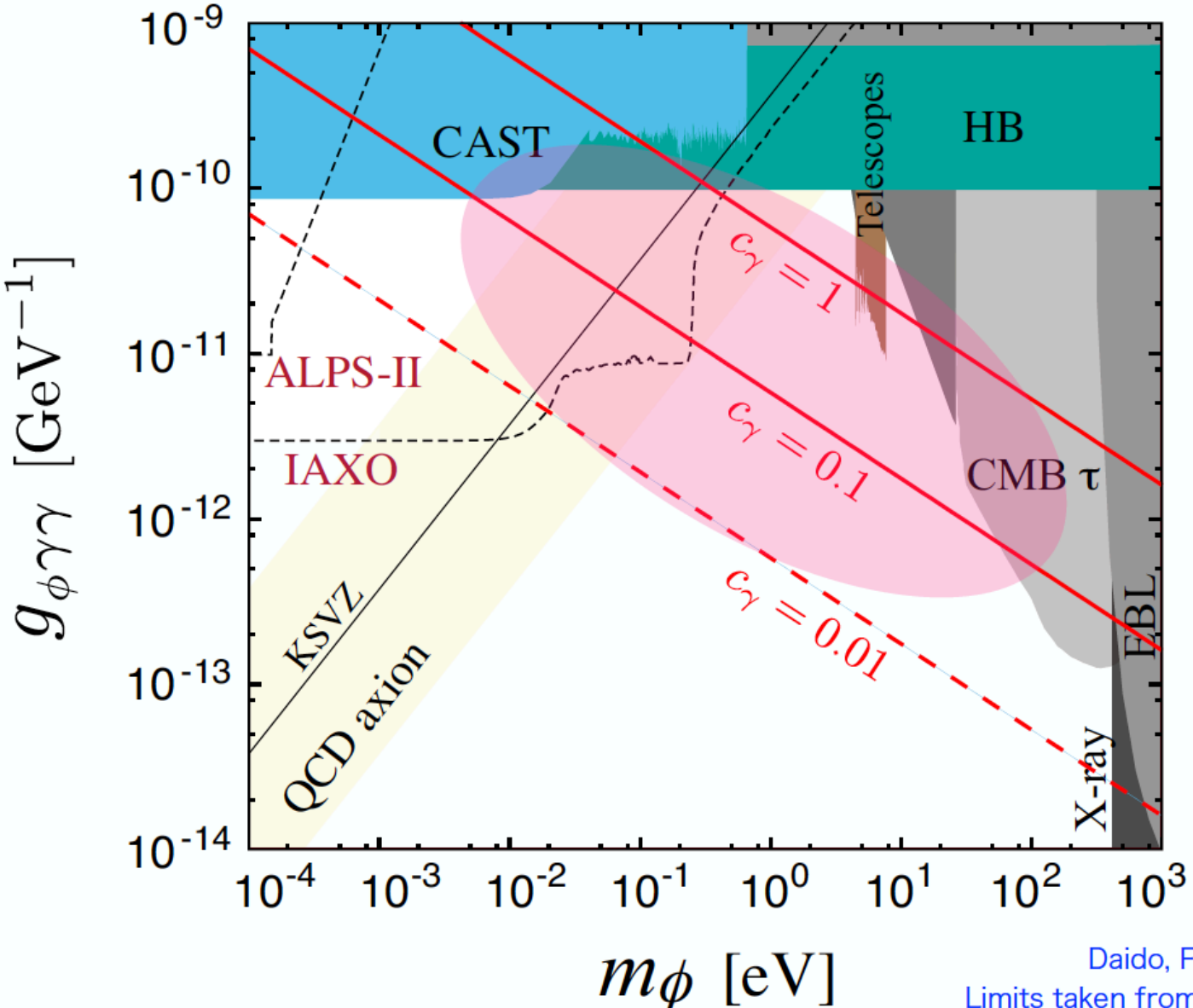
Inflaton (ALP) mass and coupling to photons

$$\mathcal{L} = \frac{g_{\phi\gamma\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad g_{\phi\gamma\gamma} = \frac{c_\gamma \alpha}{\pi f}$$

$$c_\gamma = \sum_i q_i Q_i^2$$

$$\psi_i \to e^{i\beta q_i \gamma_5/2}\psi_i$$

$$\phi \to \phi + \beta f$$

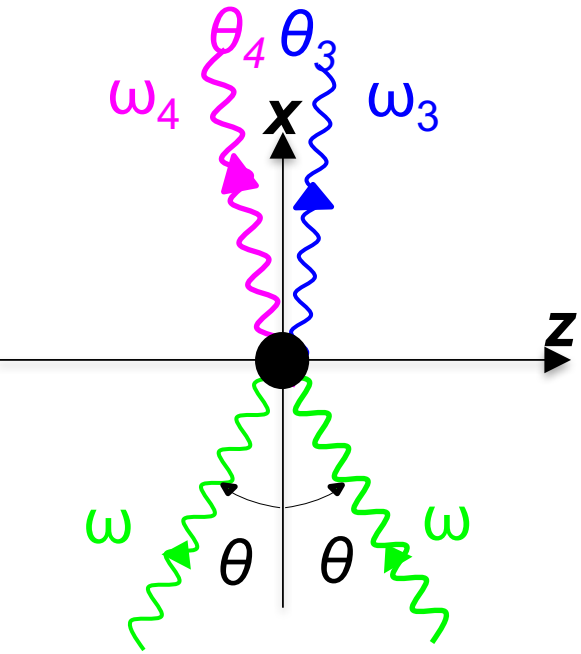


Successful inflation

Daido, FT, and Yin 1702.03284
Limits taken from Essig et al 1311.0029

Photon-photon collision systems

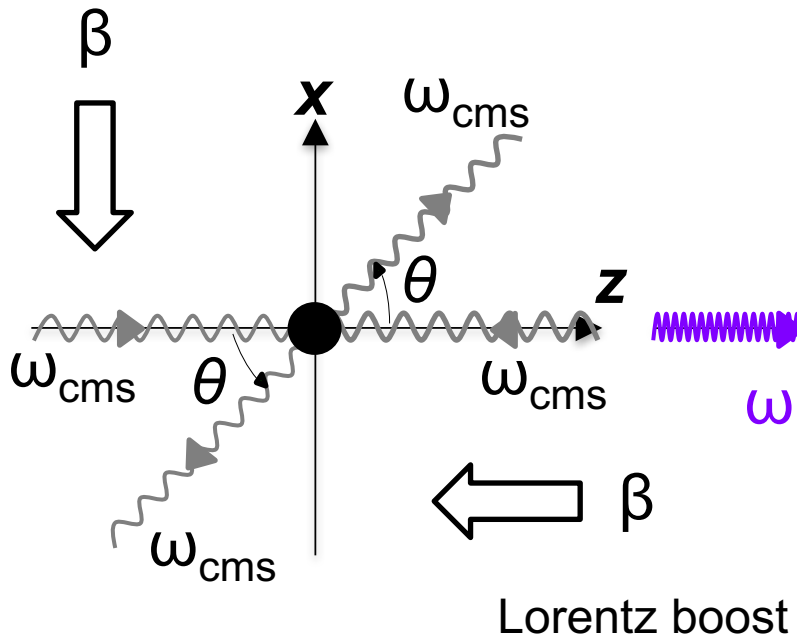
Quasi-Parallel collision System



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

Low mass search

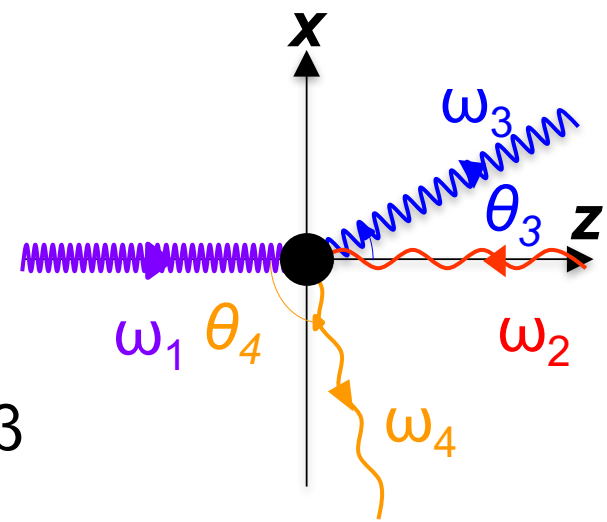
Center of Mass System



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

High mass search

Asymmetric Head-on collision System



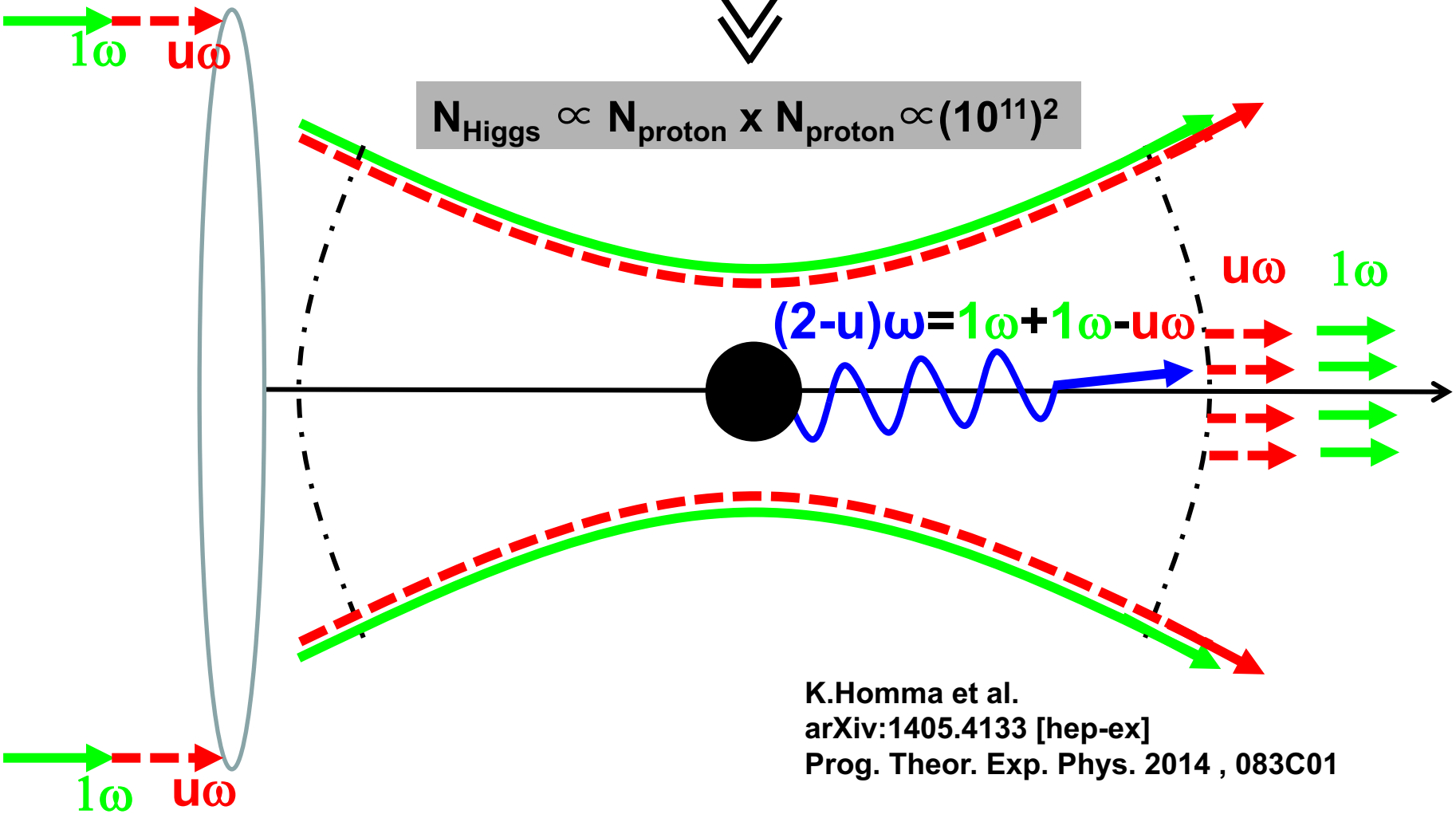
$$E_{cms} = 2\sqrt{\omega_1\omega_2}$$

High mass search

Stimulated photon-photon scattering

$N_{dark} \propto N_{creation} \times N_{creation} \times N_{induce} \propto (100J = 10^{20}{}_{opt.})^3$

$N_{Higgs} \propto N_{proton} \times N_{proton} \propto (10^{11})^2$



K.Homma et al.
arXiv:1405.4133 [hep-ex]
Prog. Theor. Exp. Phys. 2014 , 083C01

S-matrix for two-body interactions in stimulated resonant scattering

K.Homma, Y. Kirita
arXiv:1909.00983

$$S^{(2)} = \frac{i^2}{2}\int d^4x \int d^4y T[F_{\mu\nu}(x)F^{\mu\nu}\phi(x)F_{\rho\sigma}(y)F^{\rho\sigma}(y)\phi(y)]$$
$$N[F_{\mu\nu}(x)F^{\mu\nu}(x)F_{\sigma\rho}(y)F^{\sigma\rho}(y)\langle 0|T[\phi(x)\phi(y)]|0\rangle]$$

$$\propto a^\dagger_{\vec{i}} a^\dagger_{\vec{j}} a_{\vec{k}}\, a_{\vec{l}}$$

Scalar - 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**

$$\ll N_1| \ll N_4| \ll 1_3|S^{(2)}|N_1 \gg |N_4 \gg |0>$$
$$\propto \ll N_1| \ll N_4| \ll 1_3|a^\dagger_{\vec{i}} a^\dagger_{\vec{j}} a_{\vec{k}}\, a_{\vec{l}}\, |N_1 \gg |N_4 \gg |0>$$
$$\propto \sqrt{N_1}\sqrt{N_1}\sqrt{N_4} \ll N_1|N_1 \gg\ll N_4|N_4 \gg < 0|0>$$

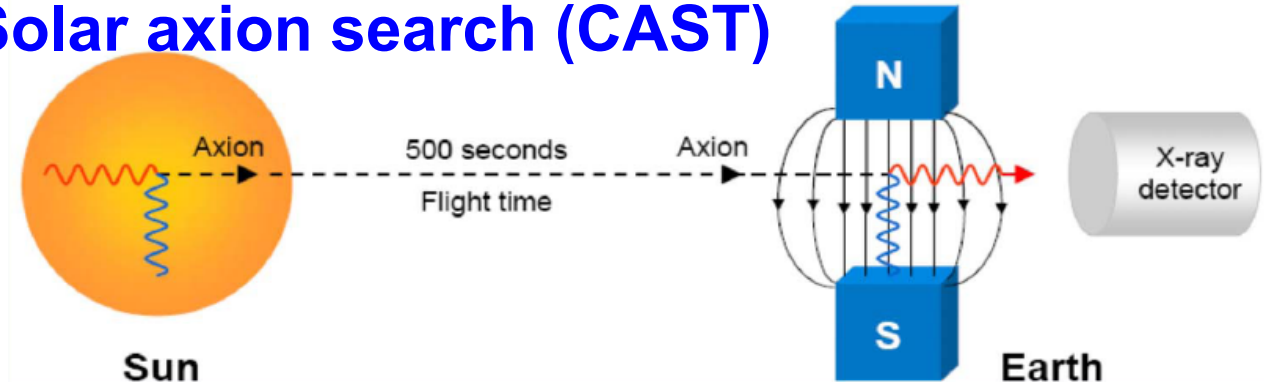
s-channel propagator cannot be implemented

- creation and decay points are spatially apart -

$$Rate \propto \left(\frac{g}{M}\right)^2_{creation} \times \left(\frac{g}{M}\right)^2_{decay}$$

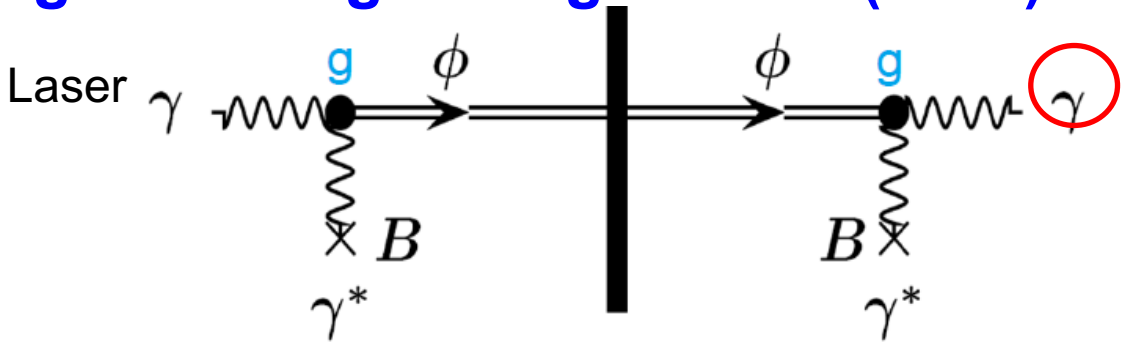
M^4 is huge !

Solar axion search (CAST)



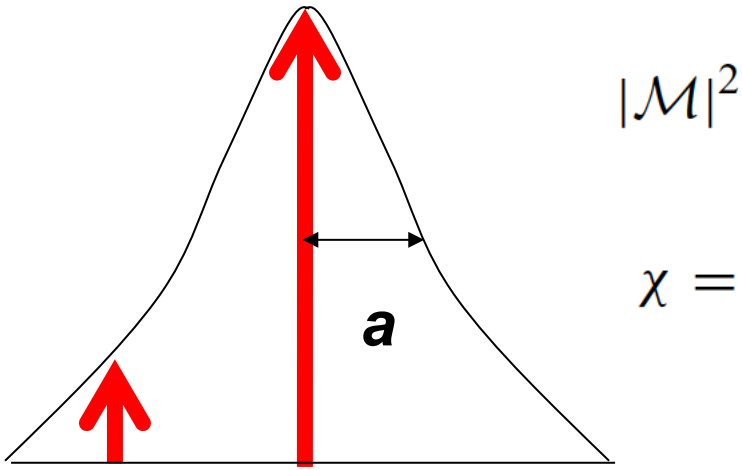
CAST, Theopisti Dafni, 7th Patras Workshop, Mykonos 2011

Light Shining through a Wall (LSW)



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

s-channel scattering contains resonance

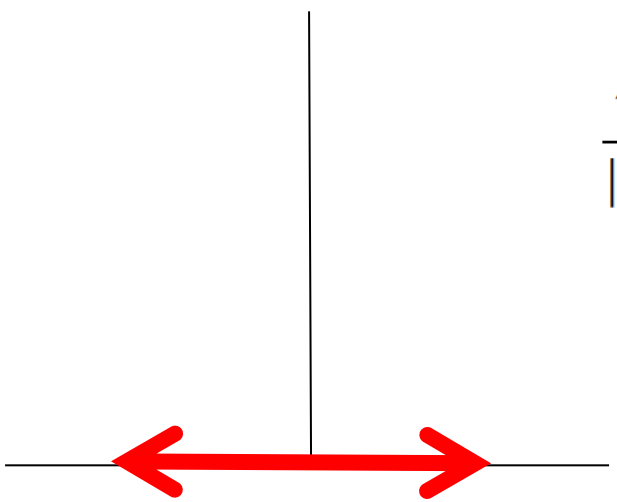


e.g. γ–γ Higgs factory

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

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

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



Collision in QPS within momentum-energy uncertainty

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

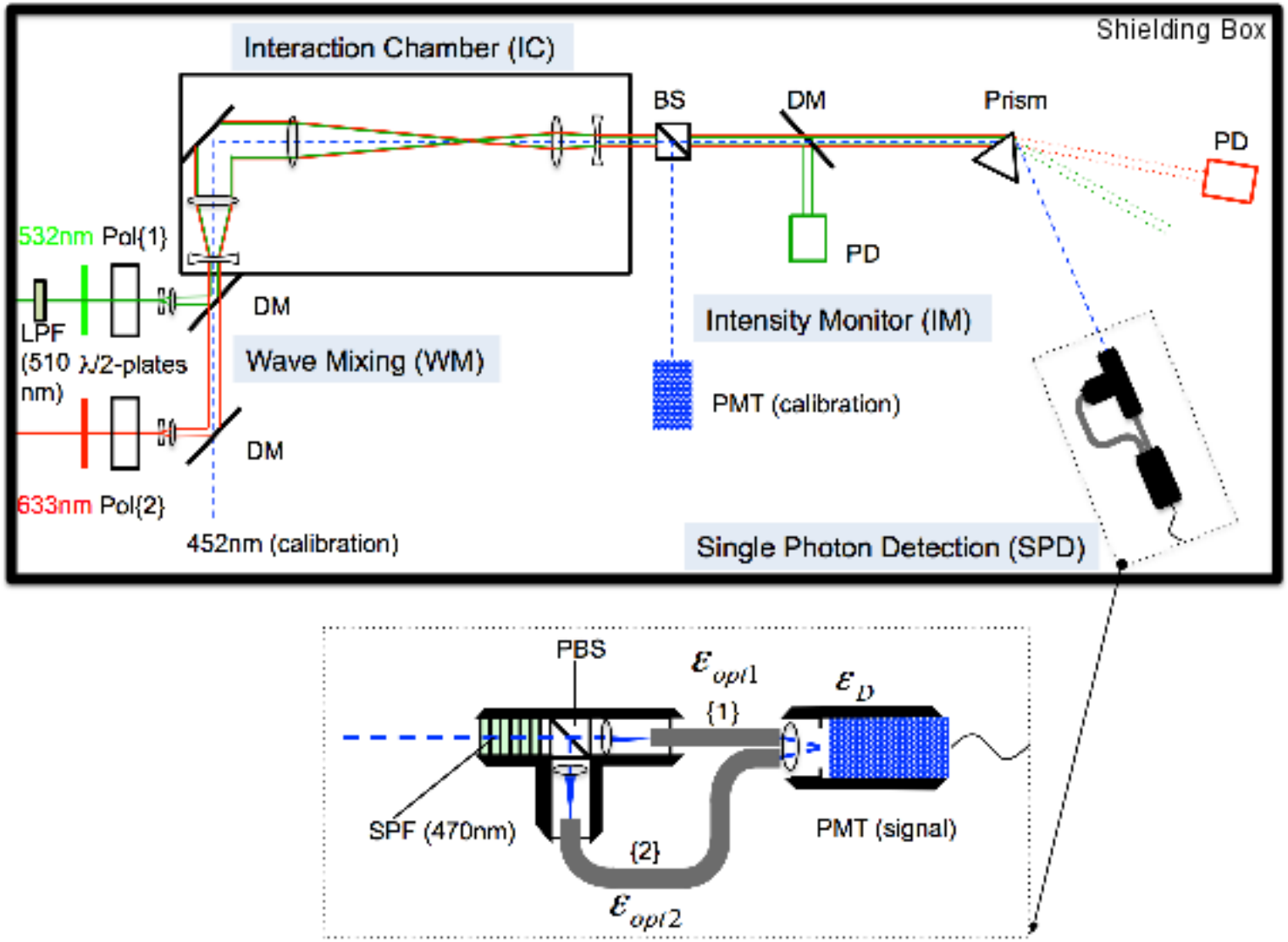
$$\overline{|\mathcal{M}|^2} = \frac{1}{\chi_+ - \chi_-}\int_{\chi_-}^{\chi_+} |\mathcal{M}|^2 d\chi$$

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

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

Gain by *M²*

The first search for scalar field with FWM



PTEP

Prog. Theor. Exp. Phys. **2014**, 083C01 (25 pages)
DOI: 10.1093/ptep/ptu087

The first search for sub-eV scalar fields via four-wave mixing at a quasi-parallel laser collider

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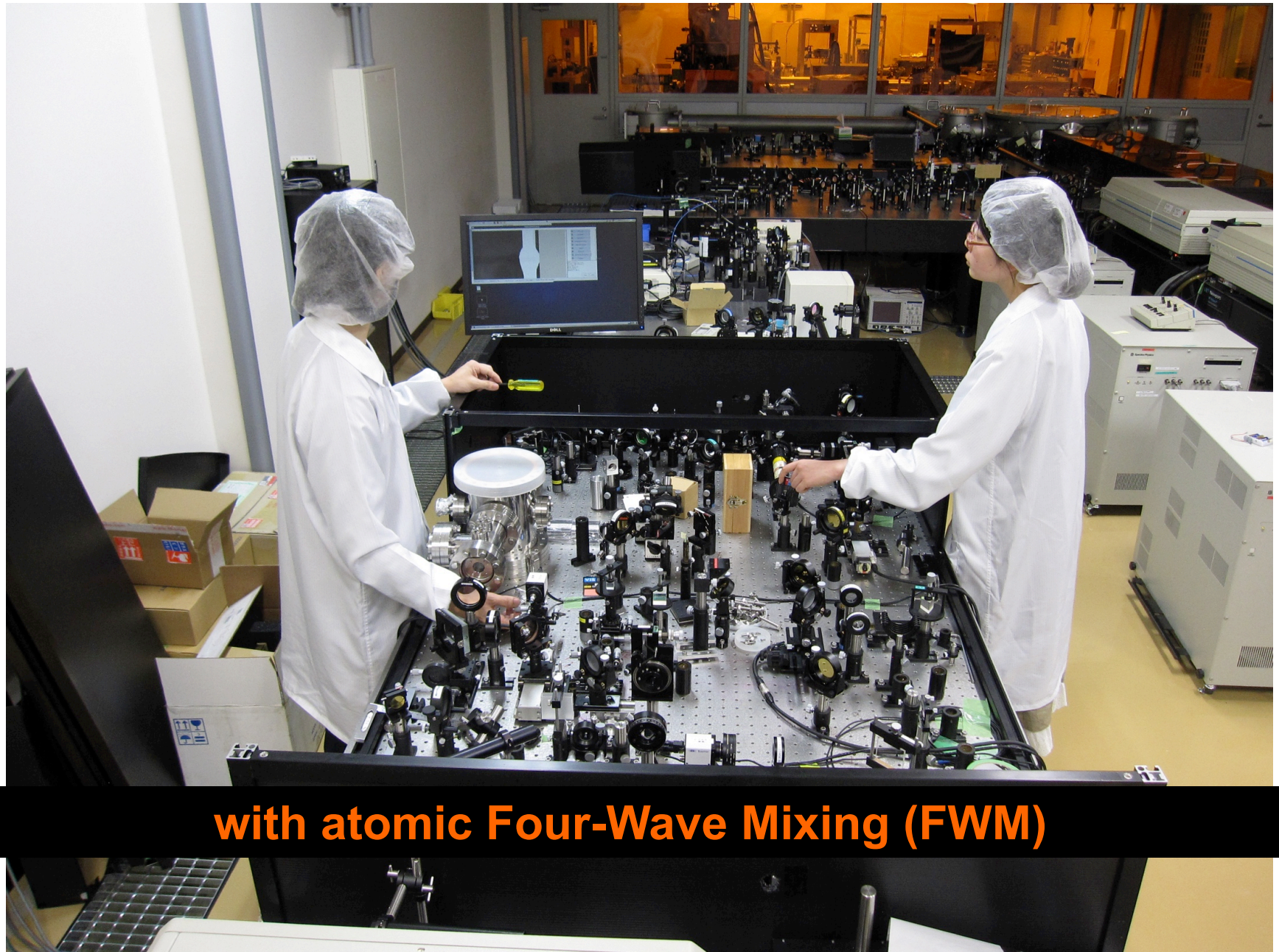
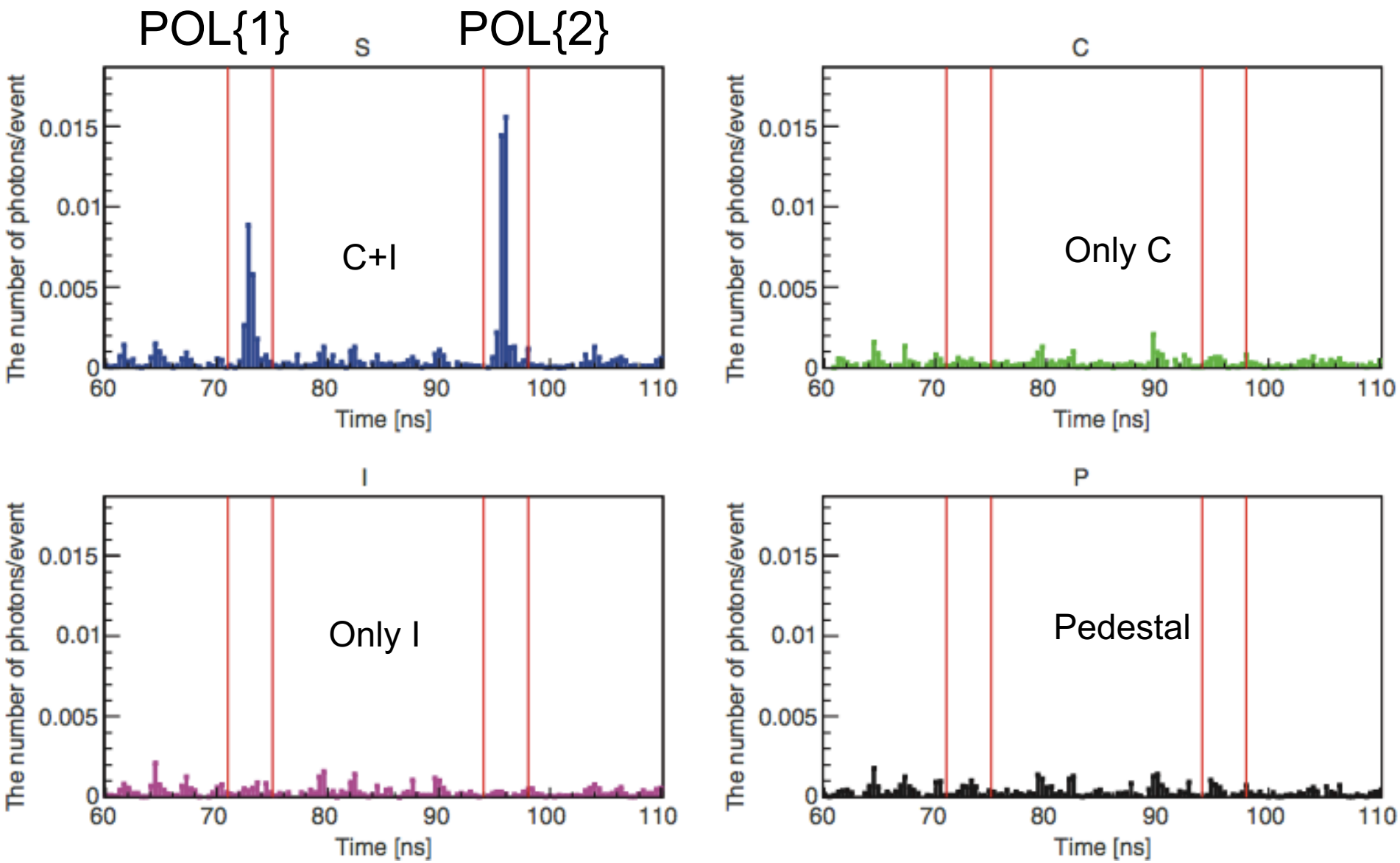
A search for sub-eV scalar fields coupling to two photons has been performed via four-wave mixing at a quasi-parallel laser collider for the first time. The experiment demonstrates the novel approach of searching for resonantly produced sub-eV scalar fields by combining two-color laser fields in the vacuum. The aim of this paper is to provide the concrete experimental setup and the analysis method based on specific combinations of polarization states between incoming and outgoing photons, which is extendable to higher-intensity laser systems operated at high repetition rates. No significant signal of four-wave mixing was observed by combining a 0.2 μJ/0.75 ns pulse laser and a 2 mW CW laser on the same optical axis. Based on the prescription developed for this particular experimental approach, we obtained the upper limit at a confidence level of 95% on the coupling–mass relation.

Run I at Kyoto-ICR

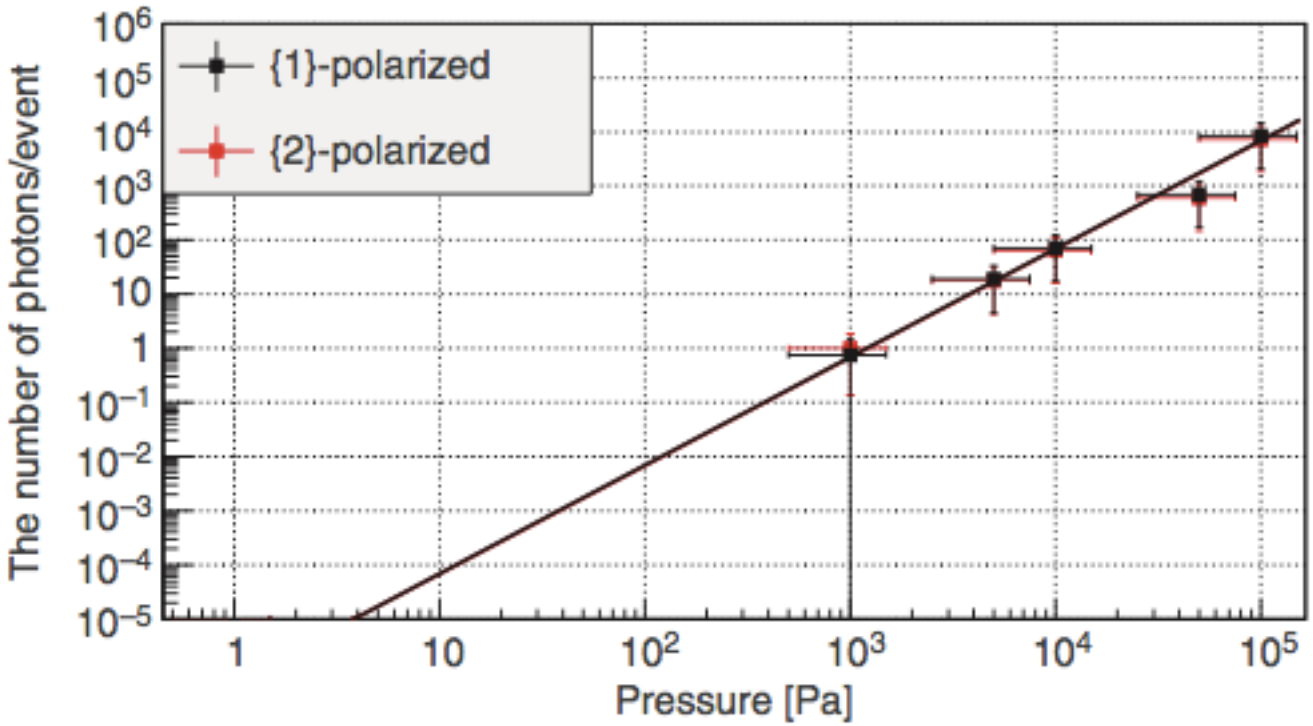


with atomic Four-Wave Mixing (FWM)

Time structures of the number of photons



Pressure dependence of atomic FWM (corrected)



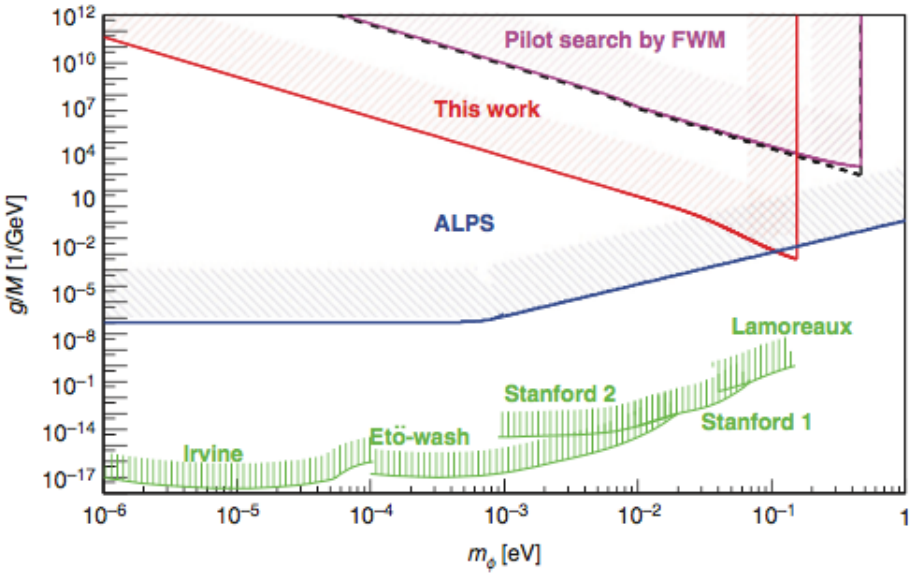
Quadratic pressure dependence is consistent with $\chi^{(3)}$ process

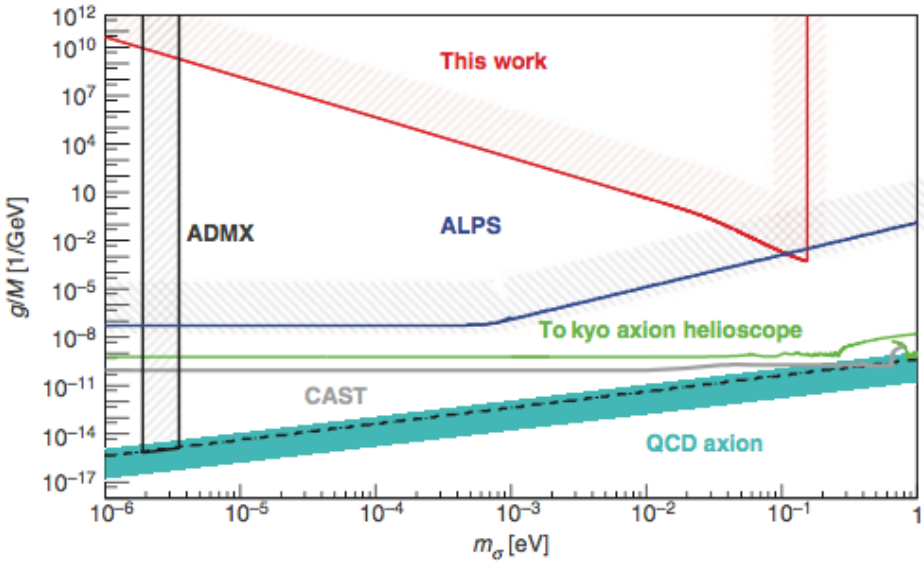
PTEP

Prog. Theor. Exp. Phys. **2015**, 073C01 (19 pages)
DOI: 10.1093/ptep/ptv101

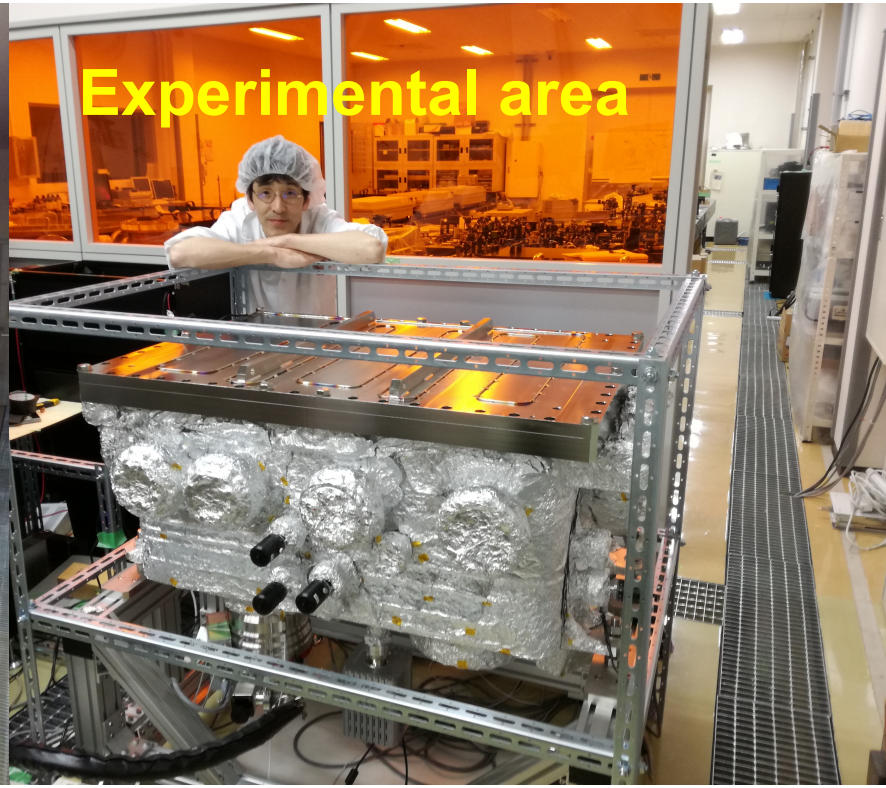
Search for sub-eV scalar and pseudoscalar resonances via four-wave mixing with a laser collider

Takashi Hasebe[1], Kensuke Homma[1,2,*], Yoshihide Nakamiya[3], Kayo Matsuura[1], Kazuto Otani[4], Masaki Hashida[3,5], Shunsuke Inoue[3,5], and Shuji Sakabe[3,5]

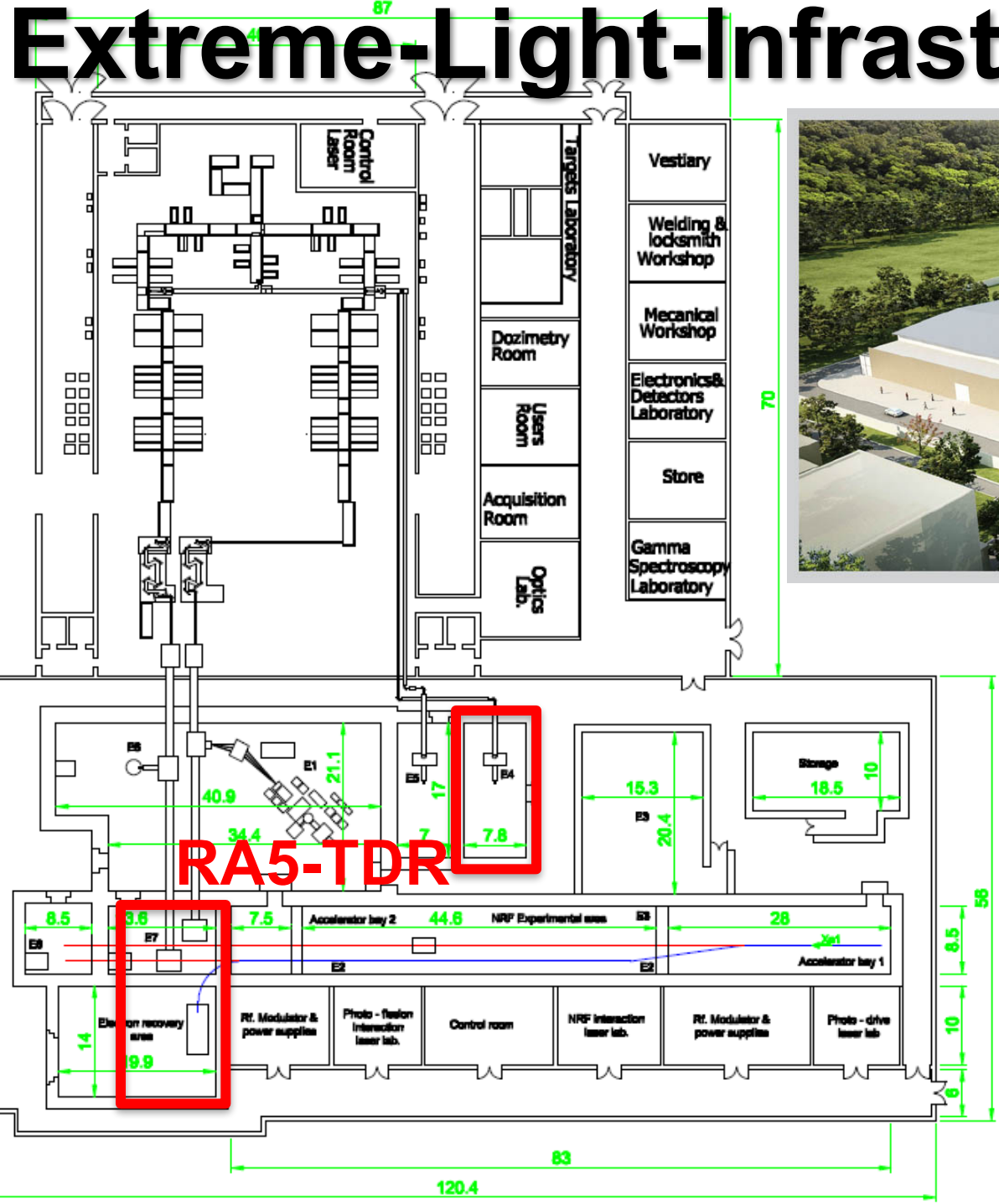




Run II with 10 TW at Kyoto-ICR



Extreme-Light-Infrastructure (ELI)



ELI-NP facility (280M€)

Comm. starts from 2019

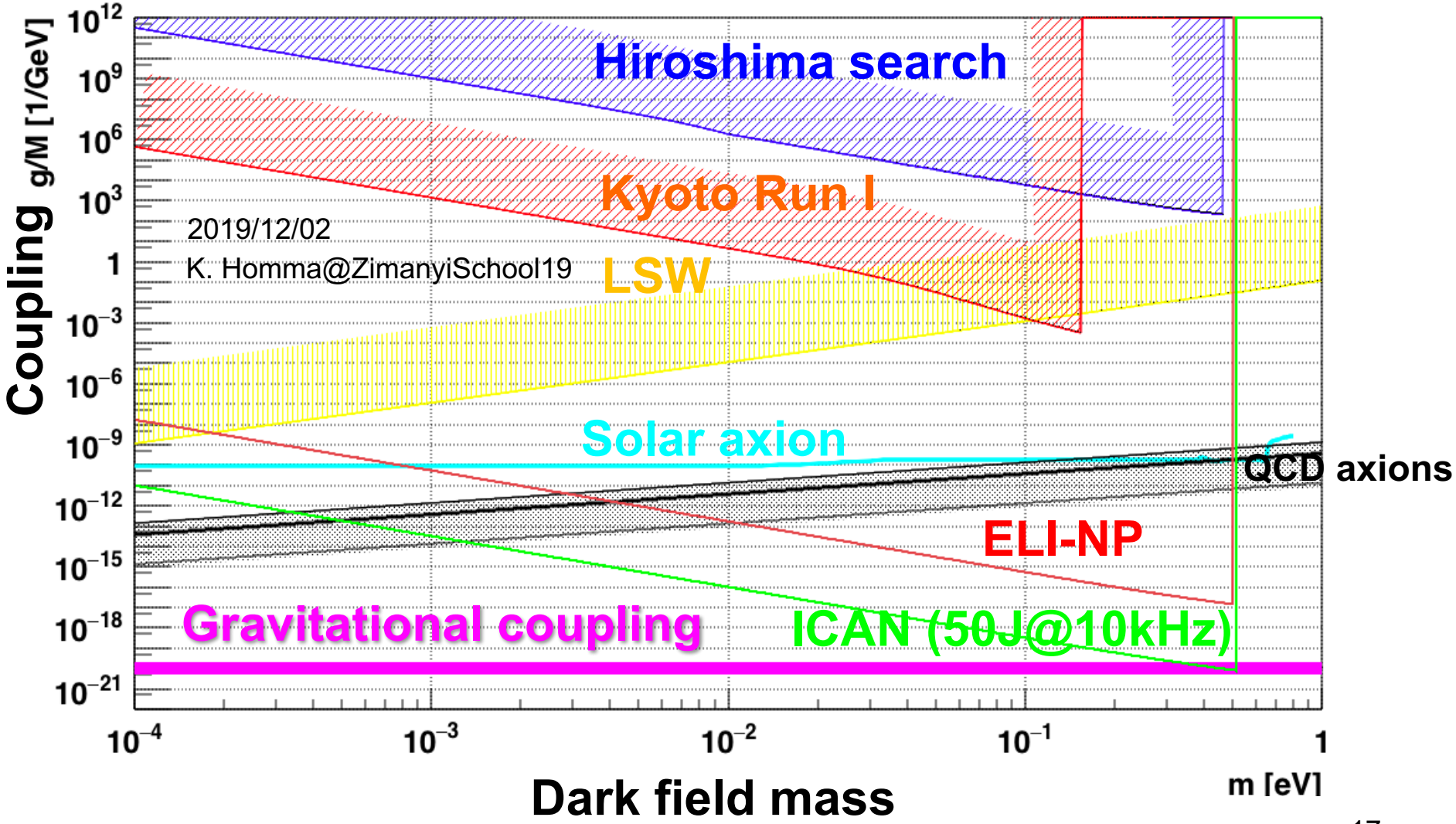
10 PW x 2

1 PW x 2

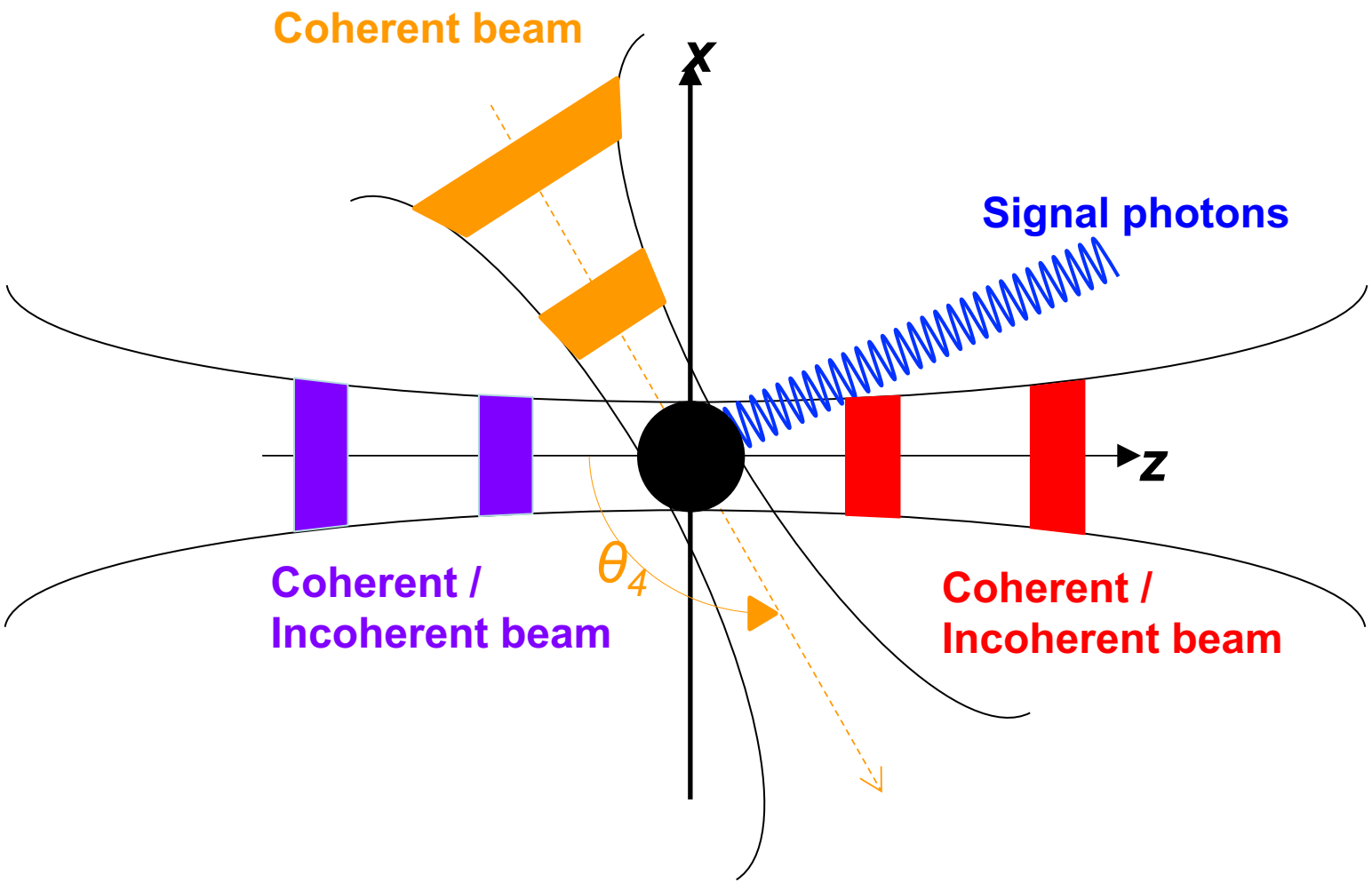
0.1 PW x 2

0.2-19.5 MeV gamma beam produced by ~700 MeV e- + laser

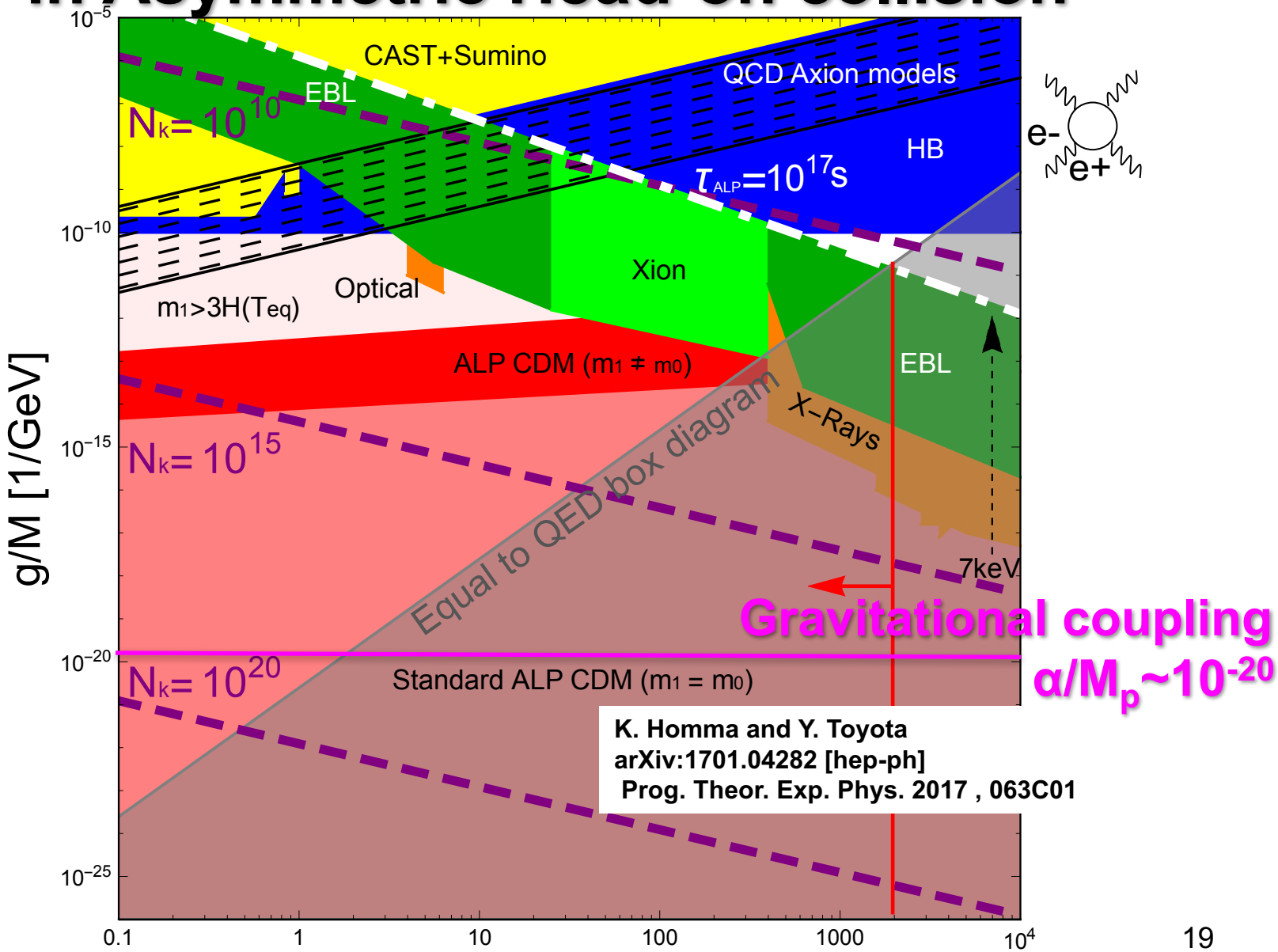
Sensitivity below sub-eV mass domain in Quasi-Parallel collision



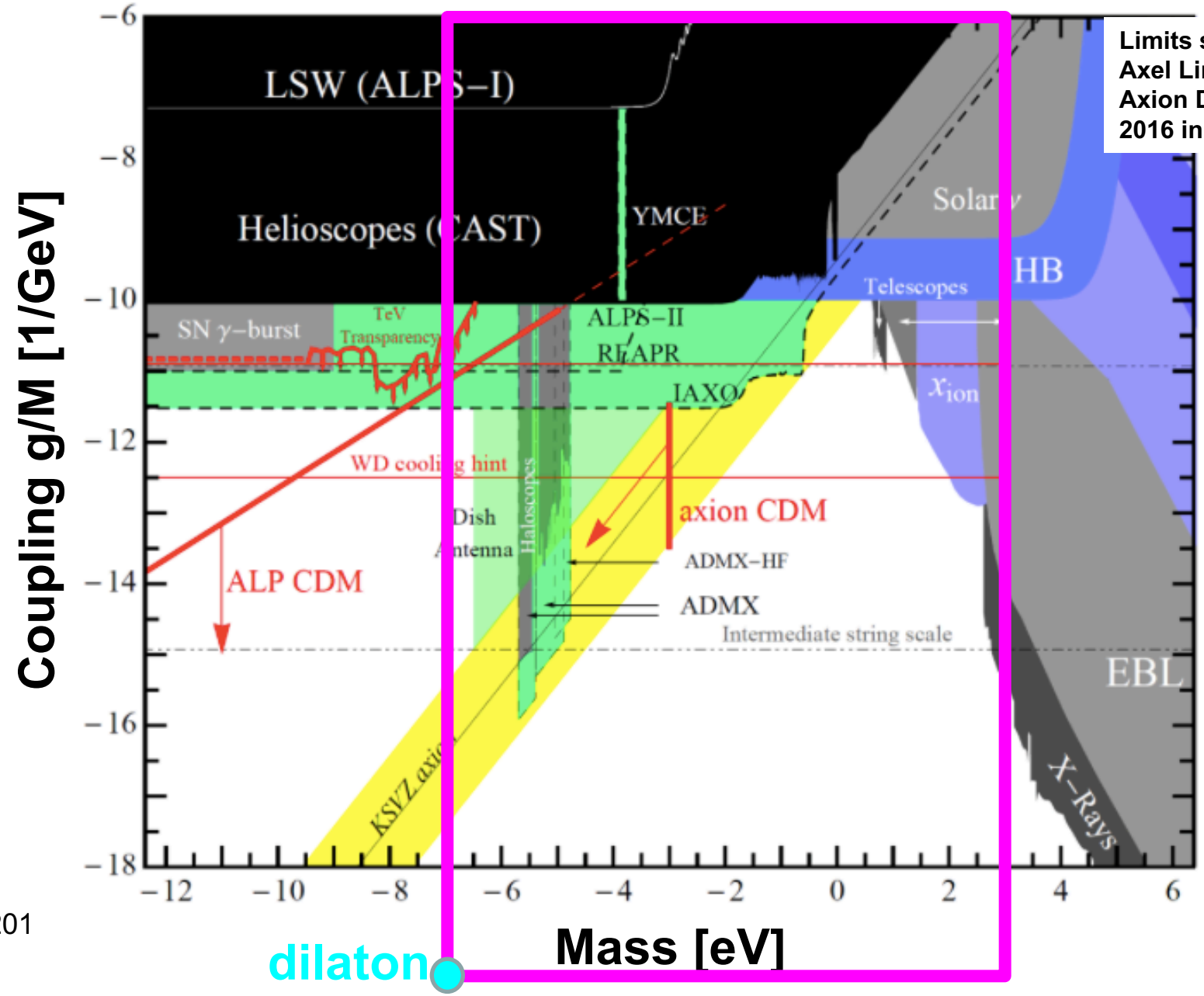
Asymmetric head-on collision for high-mass pNGB search



Sensitivity in 0.1 eV–10 keV mass domain in Asymmetric Head-on collision

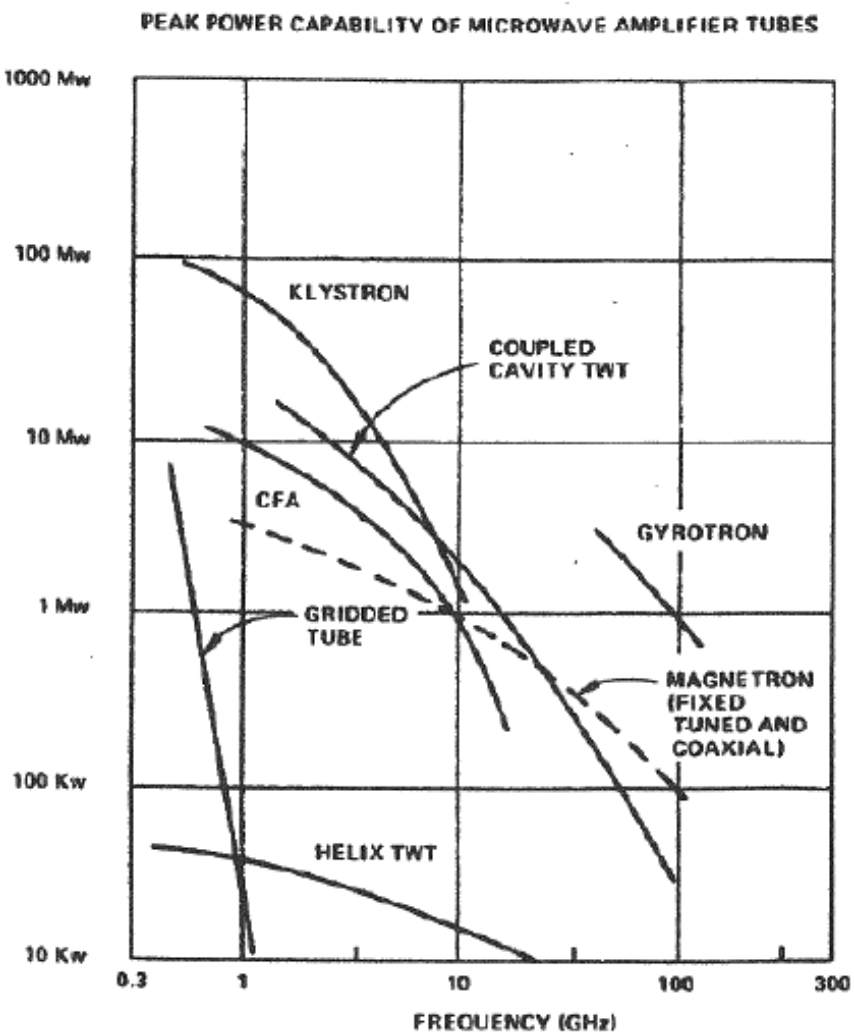


Entire scope by this method

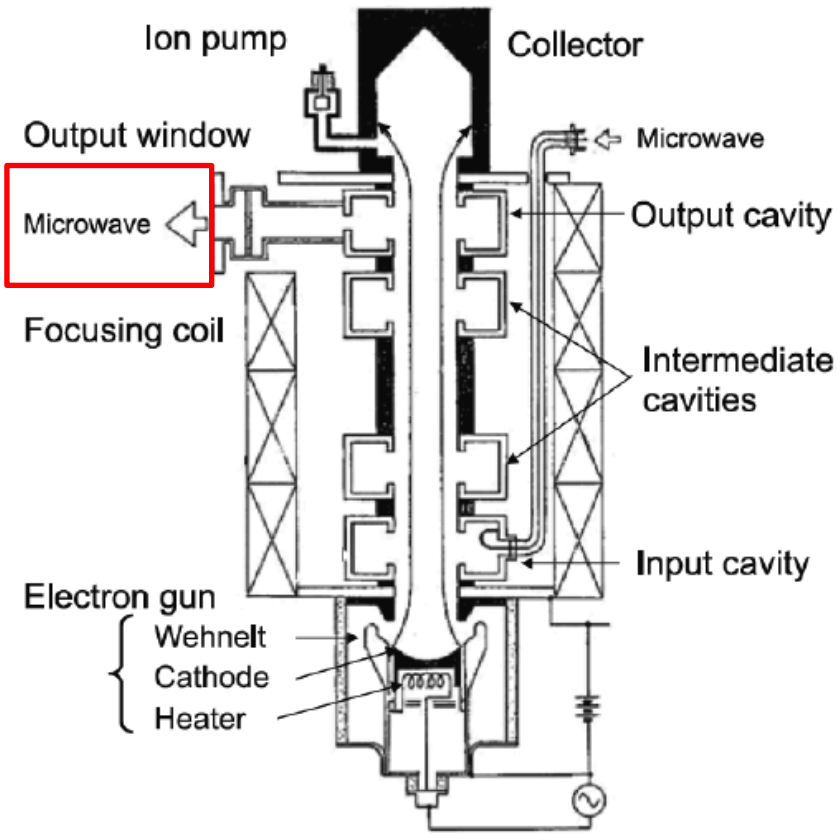


dilaton

Klystron as a 10^{-5} eV photon source



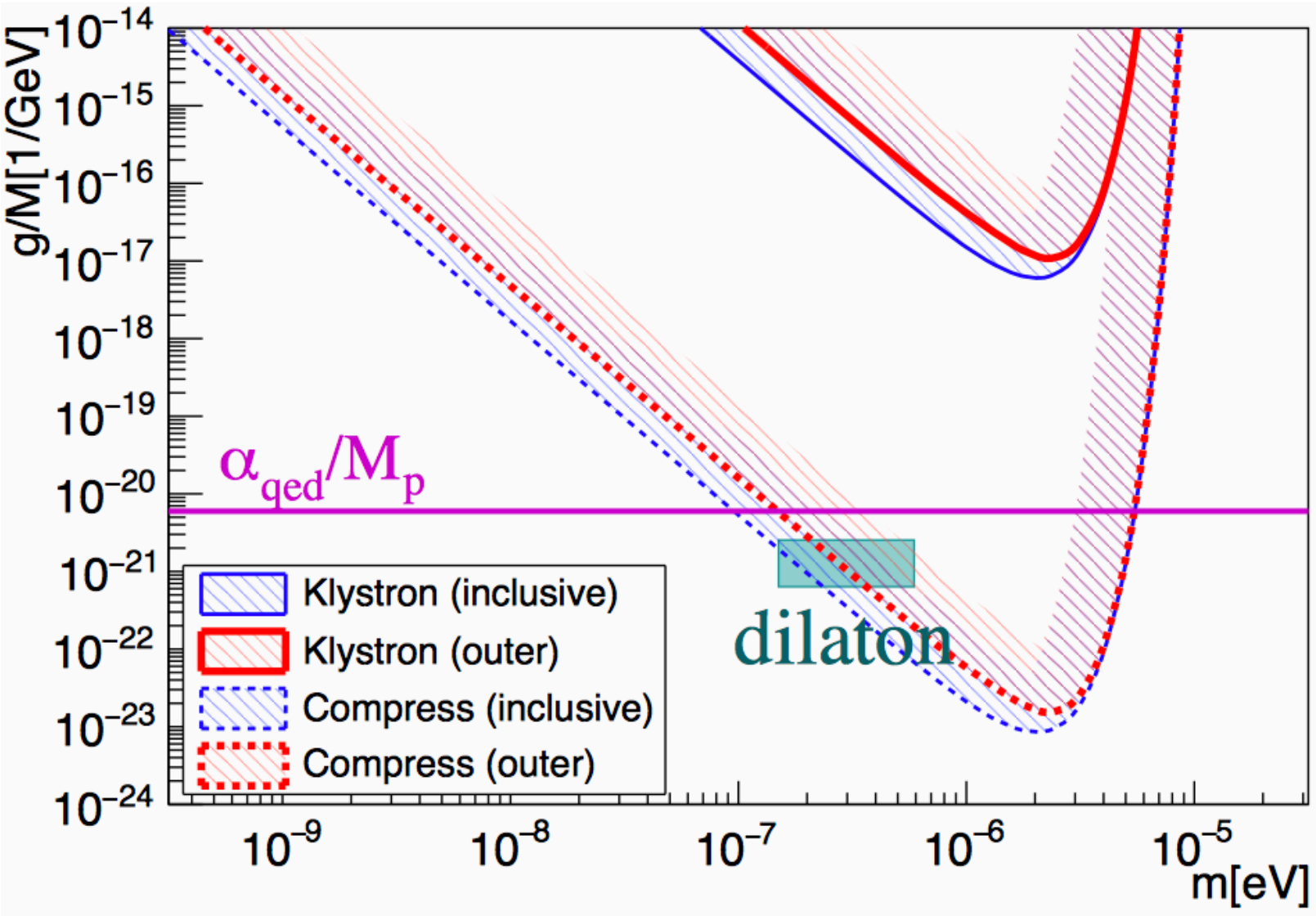
[3] Microwaves made simple: principles and applications/ the staff of the Microwave Training Institute, ed. By W. S. Cheung and F. H. Levin, Artech House, Boston 1985.



J.Plasma Fusion Res. Vol.86 (2010)

Can we reach dilaton ?

K.Homma, Y. Kirita
arXiv:1909.00983



Summary

- Charged particle collisions discovered SM particles in extremely strong coupling and high-mass domains over 10^5 – 10^{11} eV

- Stimulated photon-photon collider can provide windows in extremely weak coupling and low-mass domains over 10^{-7} – 10^3 eV

- Current technologies can provide the ways to access gravitational coupling strength in elementary scattering processes !