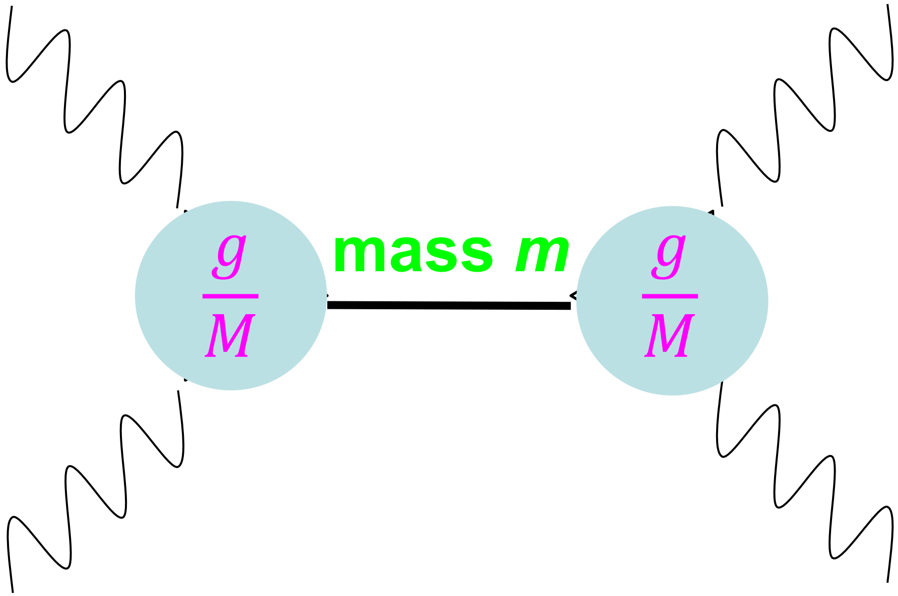
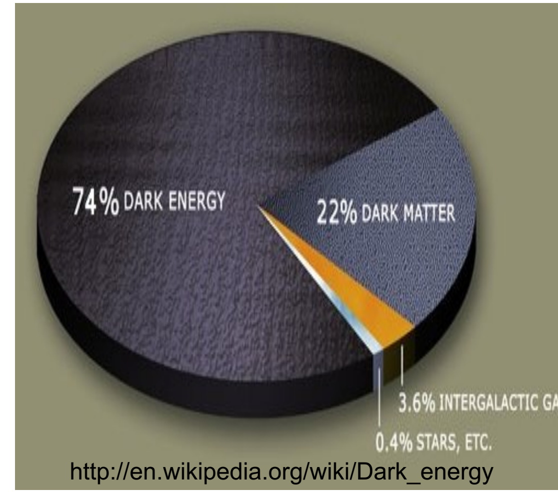
Perspective to search for dark components in the Universe with coherent photon collisions

Kensuke Homma
Hiroshima University
On behalf of the SAPPHIRES collaboration

1. Challenge to direct detection of gravitationally coupling pseudo Nambu-Goldstone NGB (pNGB), dilaton
2. Two key enhancement factors in stimulated resonant scattering
3. Probing sub-eV pNGBs
4. Potential to probe 0.1 eV – 10 keV pNGBs
5. Summary

pNGBs can be dark components of the Universe





Scale symmetry breaking

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

If M~M$_{Planck}$, dilaton (Dark Energy)

mass 1.5-5.9 10^{-7} eV

PQ U(1) symmetry breaking

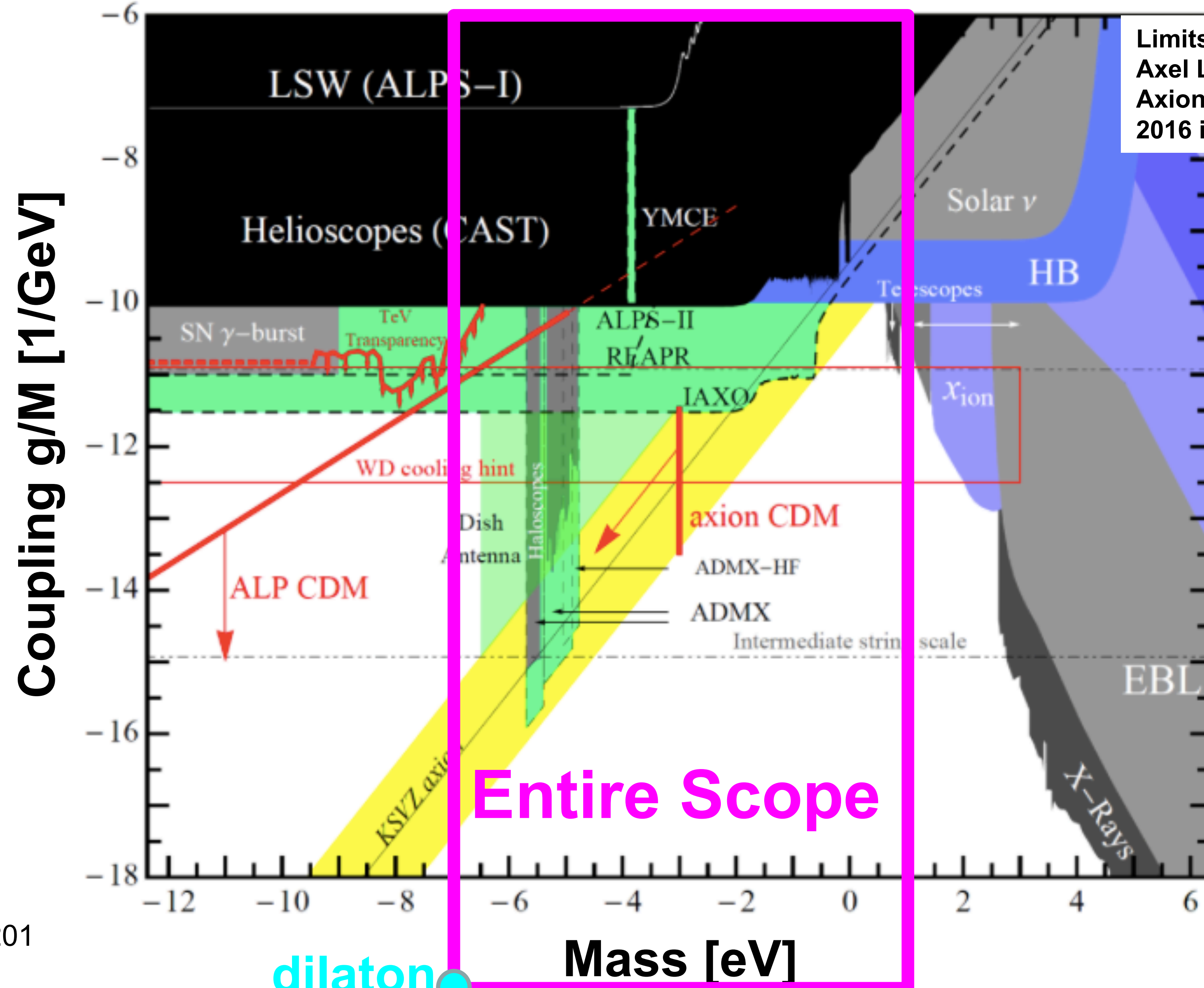
$$-\frac{1}{4}\frac{g}{M}F_{\mu\nu}\tilde{F}^{\mu\nu}\sigma$$

If M~M$_{GUT}$, axion (Cold Dark Matter)

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

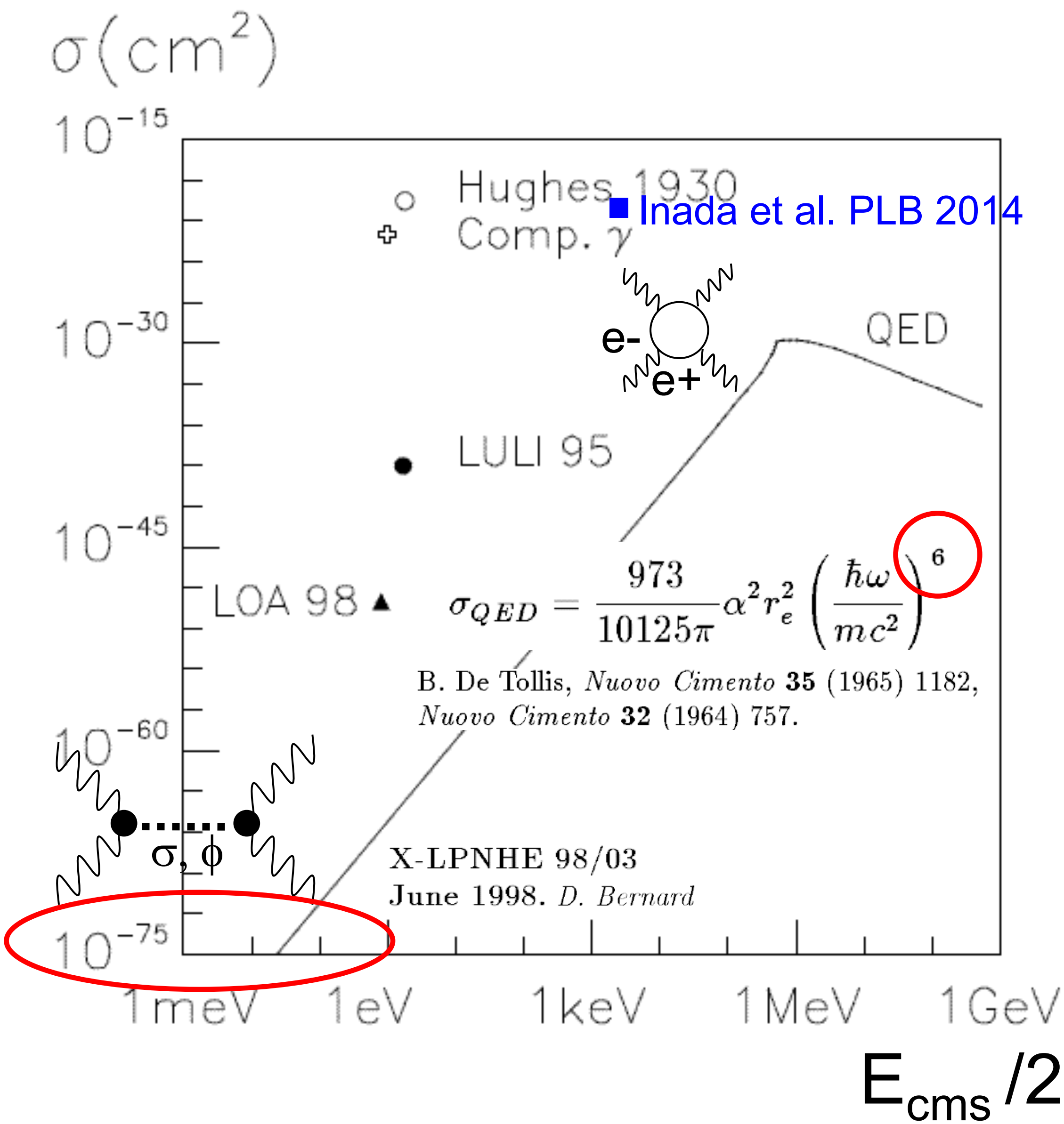
Two-loop self-energy correction
arXiv:1512.01360 [gr-qc]
Y. Fujii

Present upper bounds



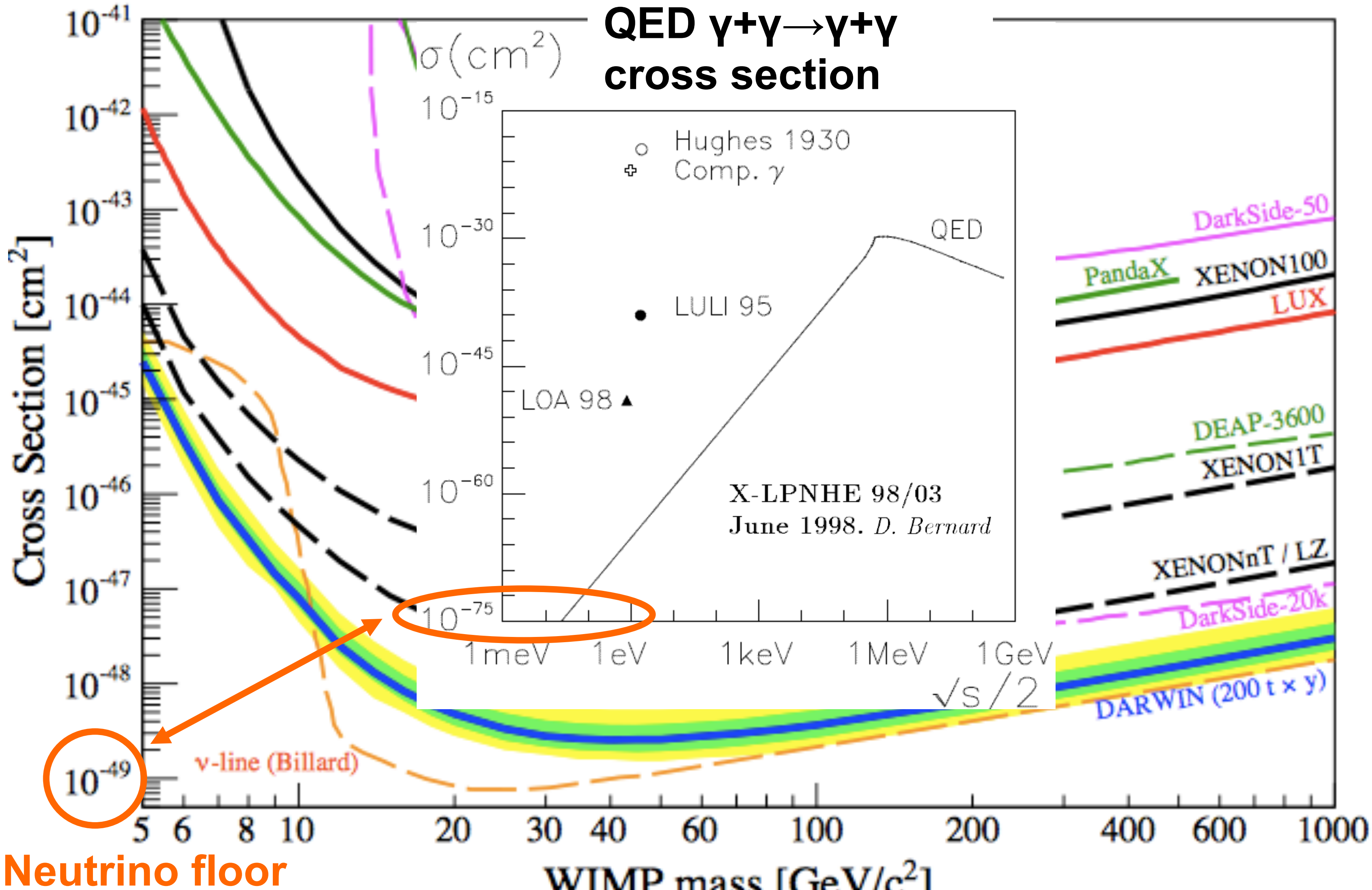
Limits shown by Axel Lindner Axion Dark Matter 2016 in Stockholm

Photon-photon interaction in sub-eV – MeV

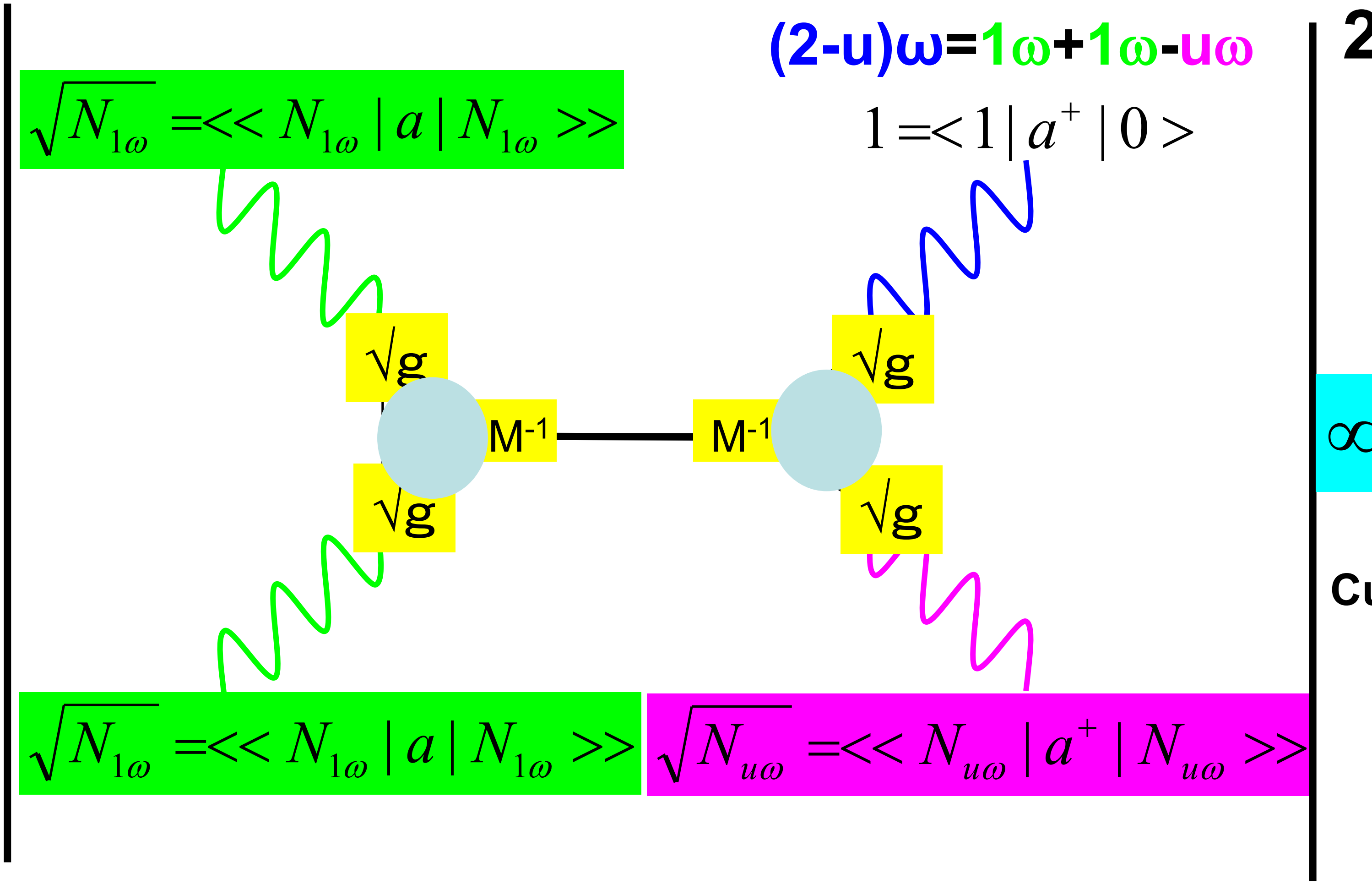


Complementarity to WIMP searches

arXiv:1606.07001 DARWIN collaboration



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



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

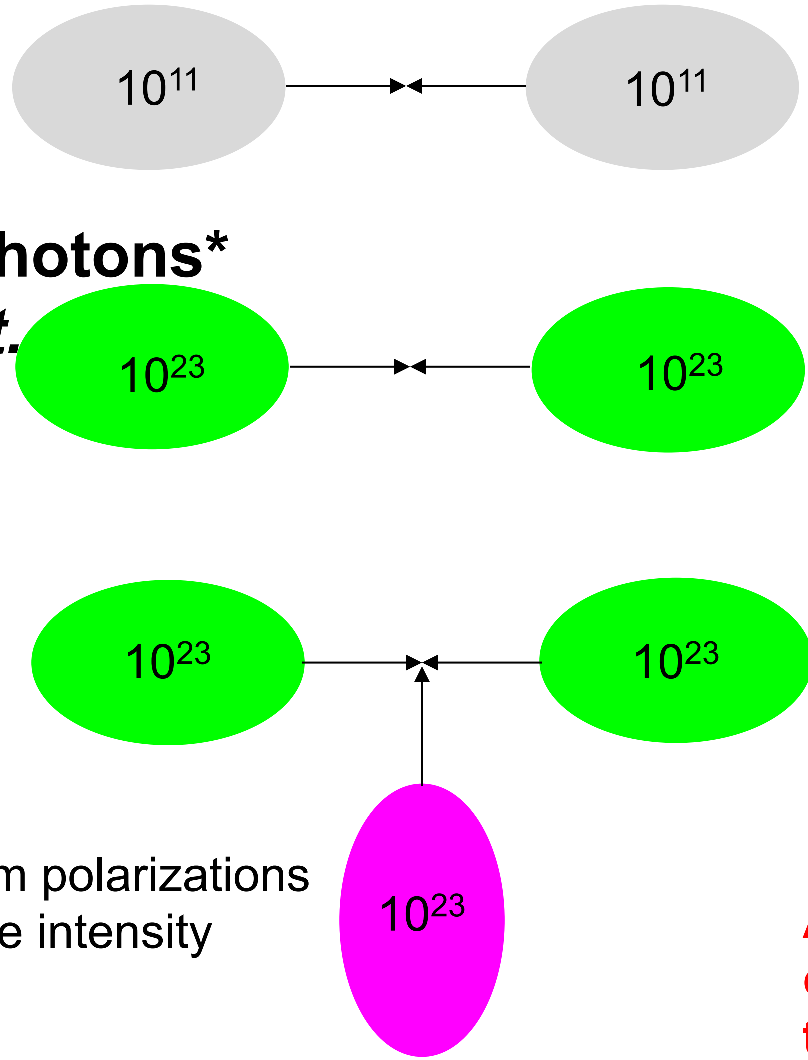
Cubic dependence

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

Comparison with charged particle colliders

Space-charge limitation exits

No limit on # of photons*
10^{23} ~ 200kJ@opt.



$(10^{11})^2$

$(10^{23})^2$

Inducement

$(10^{23})^3$

Accessibility to coupling even weaker than that of gravity

* Threshold for real vacuum polarizations far beyond the cutting-edge intensity

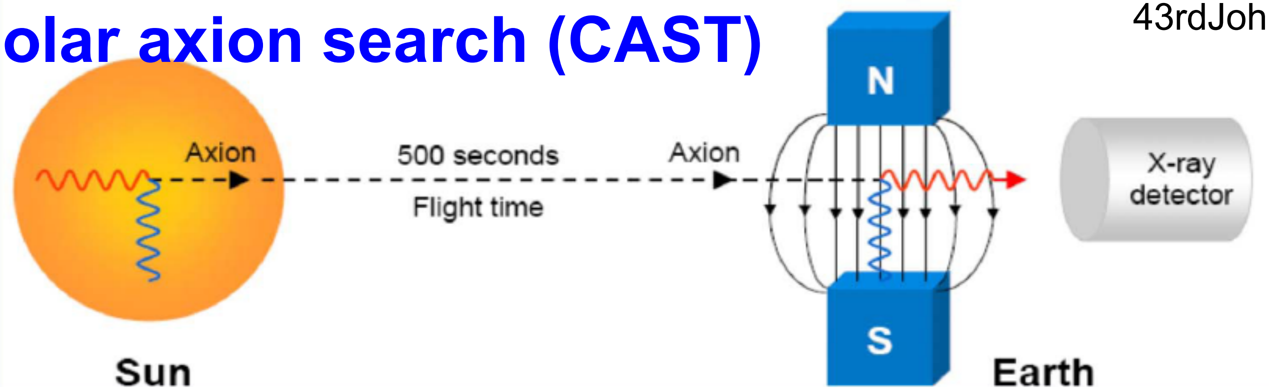
s-channel propagator cannot be implemented
- creation and decay points are spatially apart -

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

M^{-4} suppression !

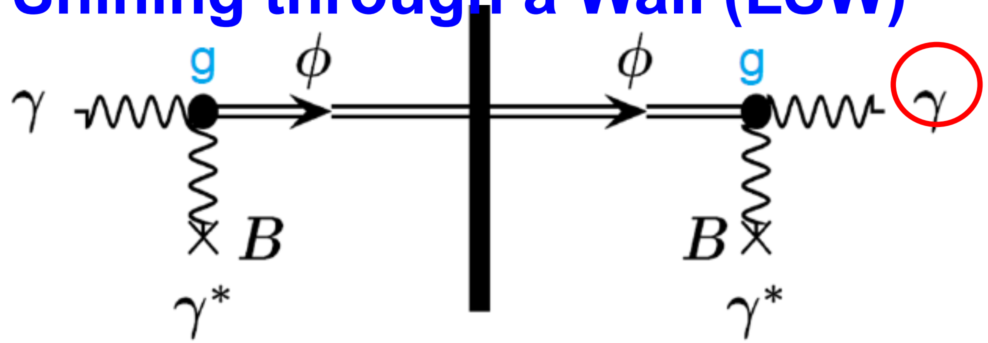
K. Homma@
43rdJohnHopkinsWorkshop

Solar axion search (CAST)



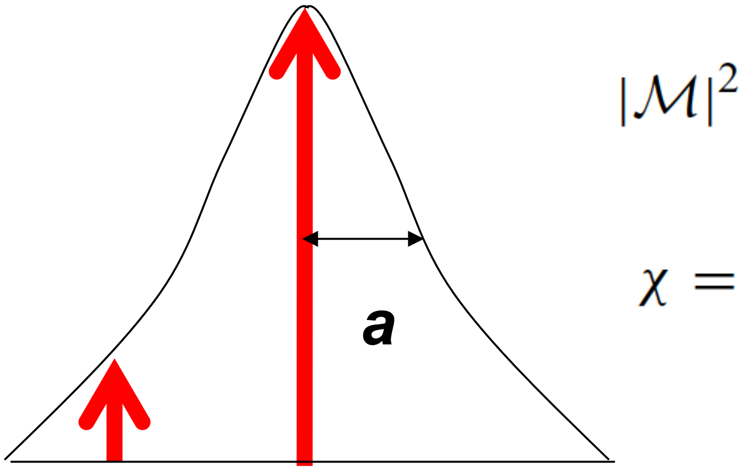
CAST, Theopisti Dafni, 7th Patras Workshop, Mykonos 2011

Light Shining through a Wall (LSW)



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

s-channel scattering contains resonance

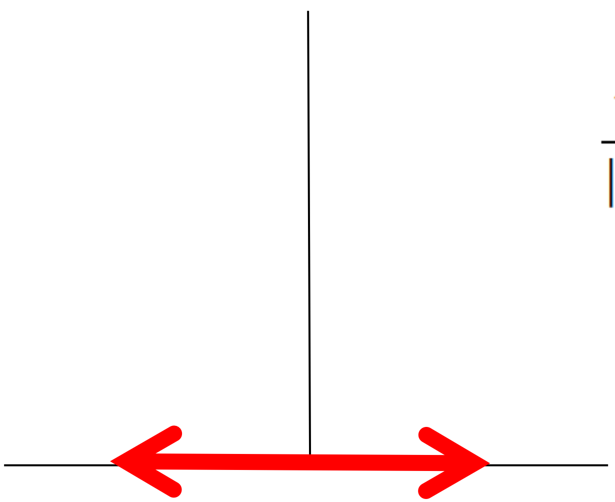


e.g. γ–γ Higgs factory

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

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

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



Collision in QPS within momentum-energy uncertainty

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

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

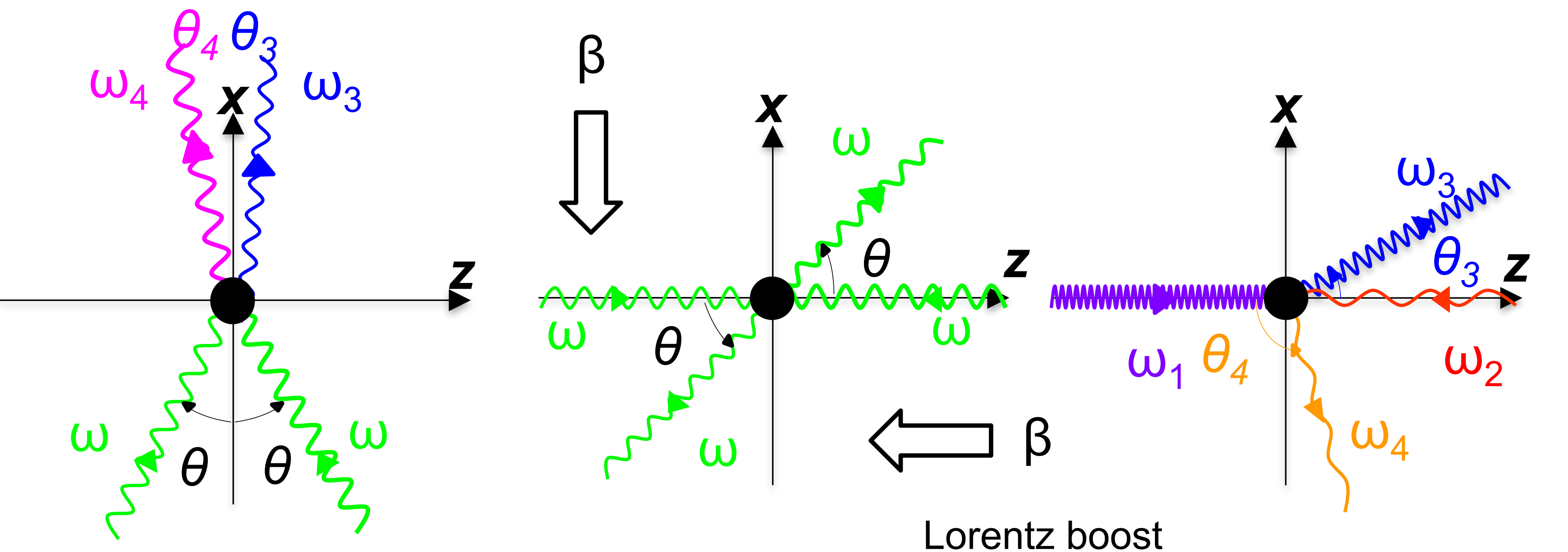
$$= \frac{(4\pi)^2}{2\eta a} 2a \tan^{-1}(\eta) = (4\pi)^2 \eta^{-1} \tan^{-1}(\eta)$$

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

Gain by M^2

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

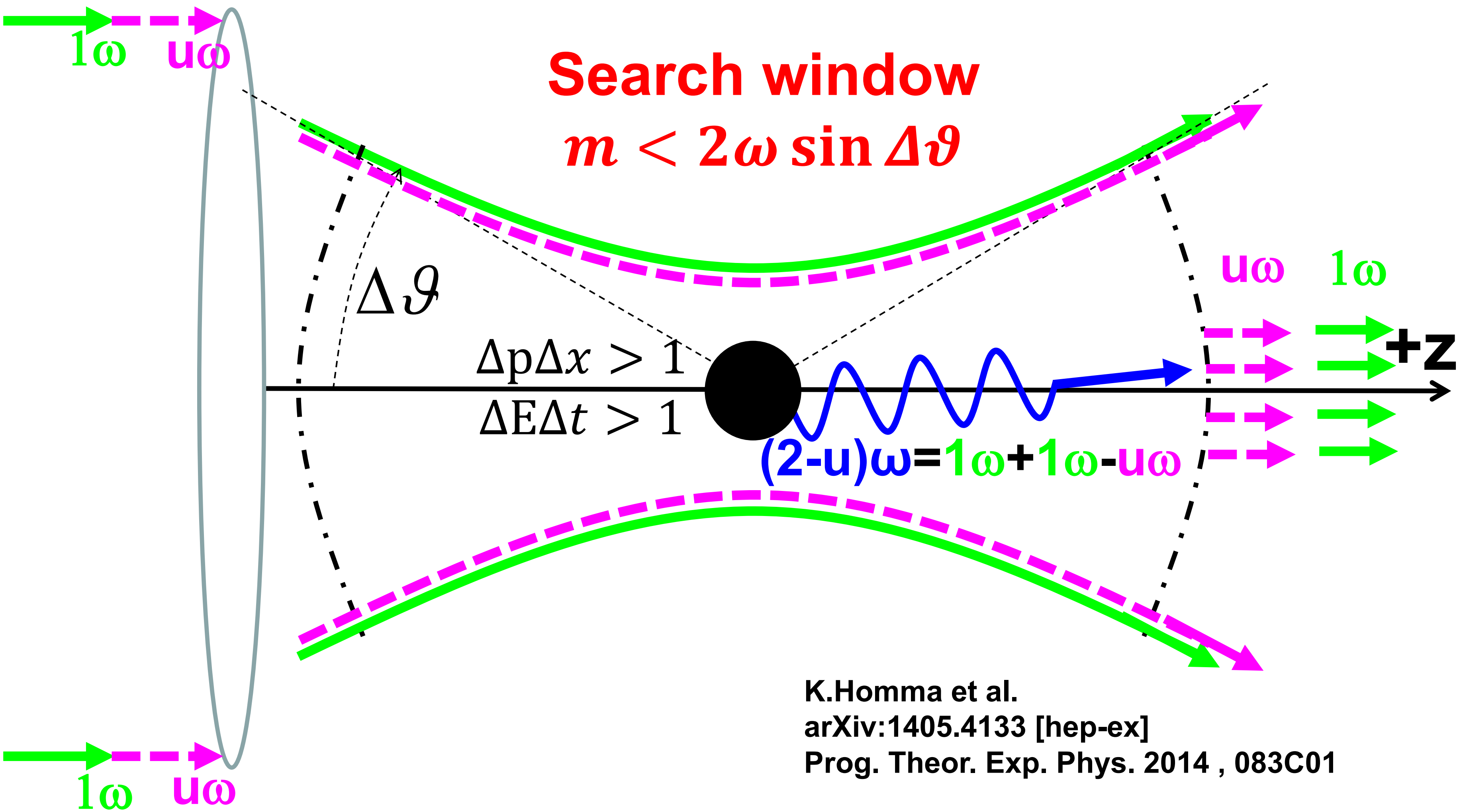
$E_{cms} = 2\omega$

High mass search

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

High mass search

QPS for low-mass pNGB



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

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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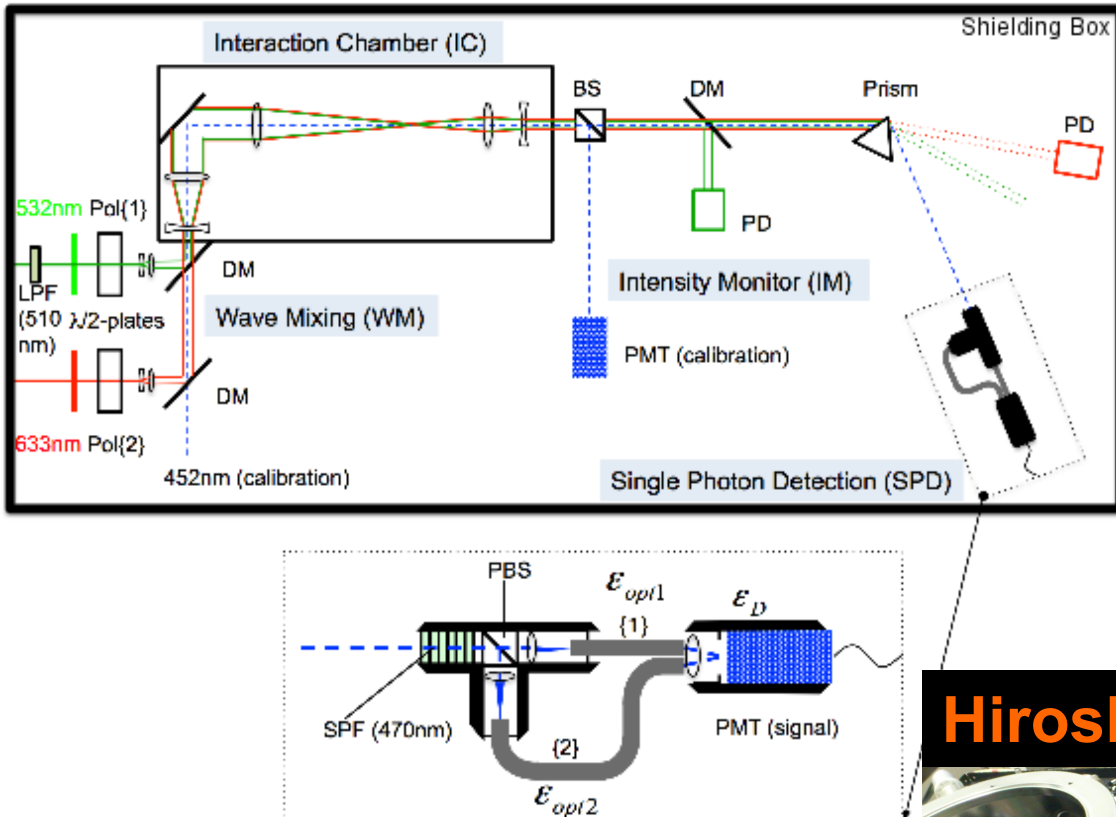
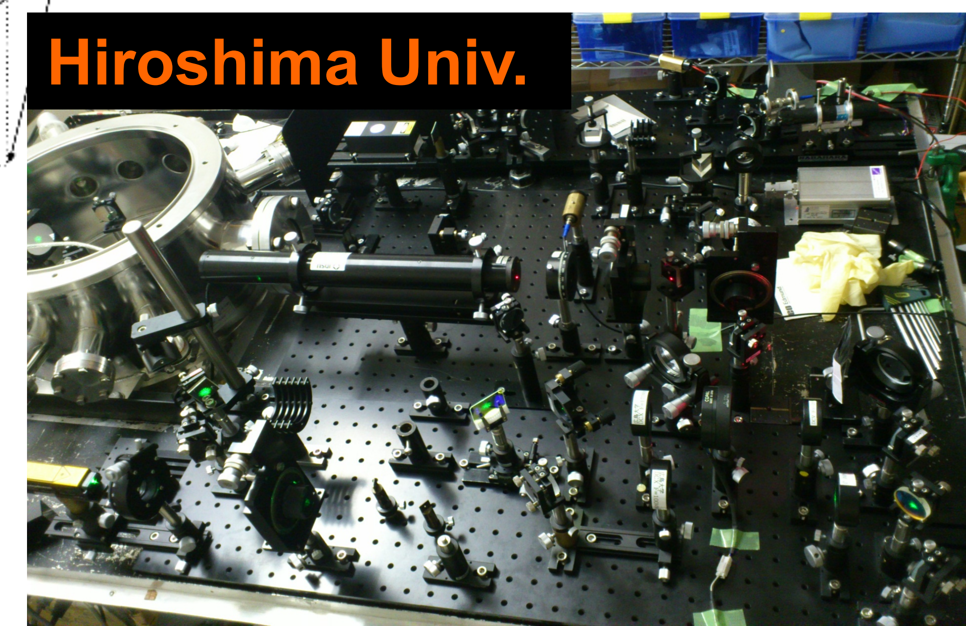
A search for sub-eV scalar fields coupling to two photons has been performed via four-wave mixing at a quasi-parallel laser collider for the first time. The experiment demonstrates the novel approach of searching for resonantly produced sub-eV scalar fields by combining two-color laser fields in the 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.

Pulse + CW lasers exp. @ Hiroshima Univ.

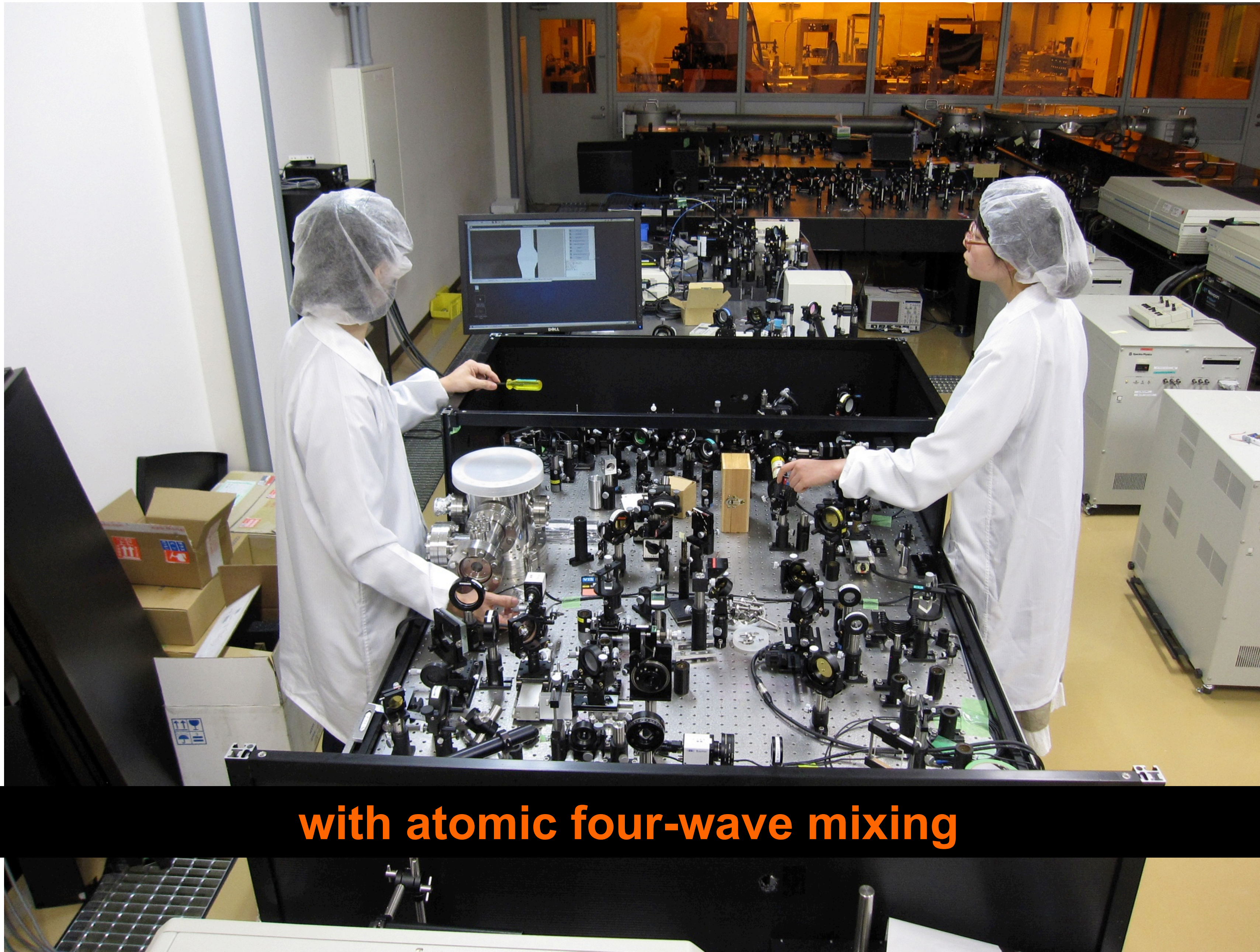




2019/06/05

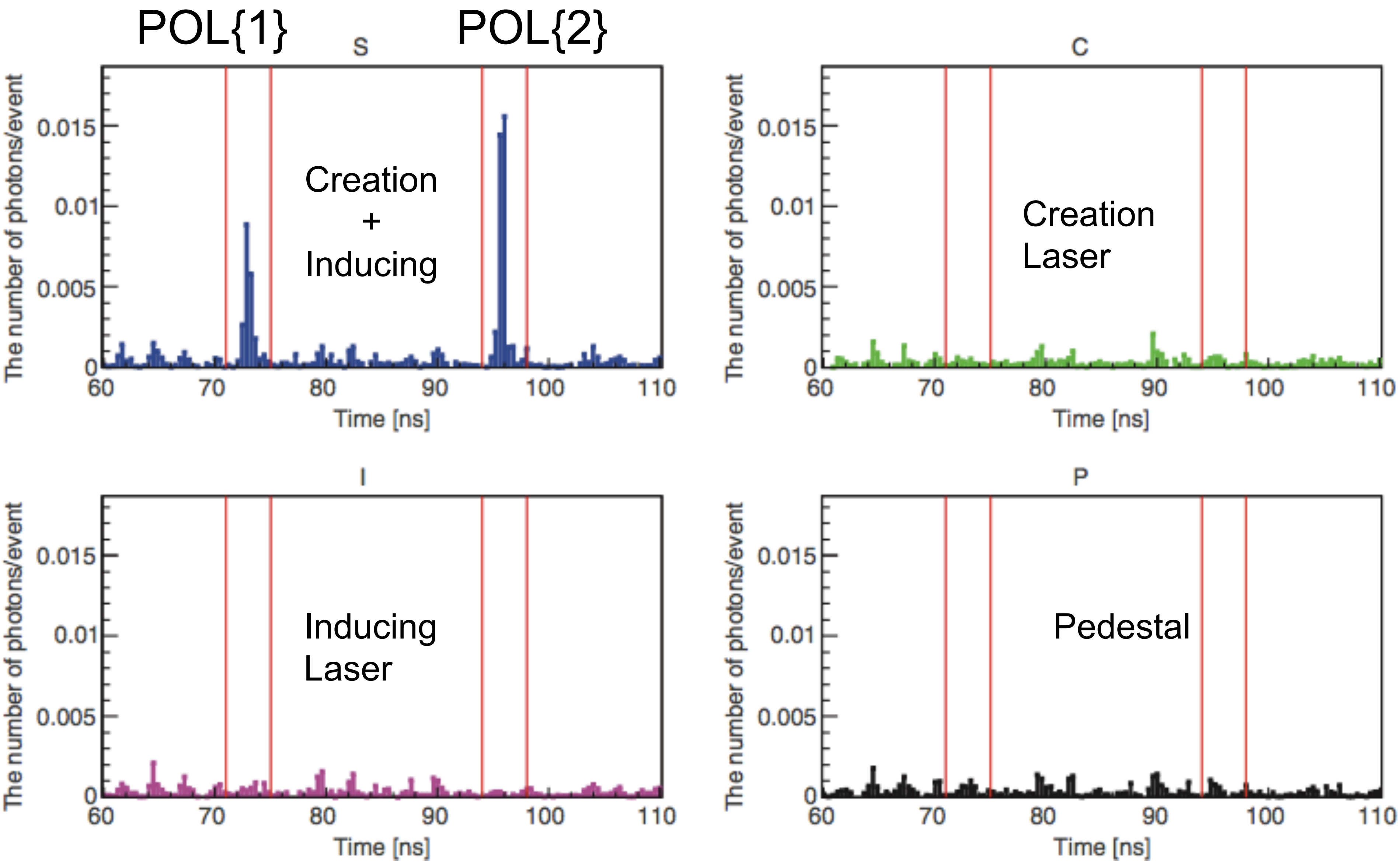
K. Homma@43rdJohnHopkinsWorkshop

Pulse + Pulse exp. Run I @ ICR, Kyoto Univ.



with atomic four-wave mixing

Time structures of the number of FWM photons

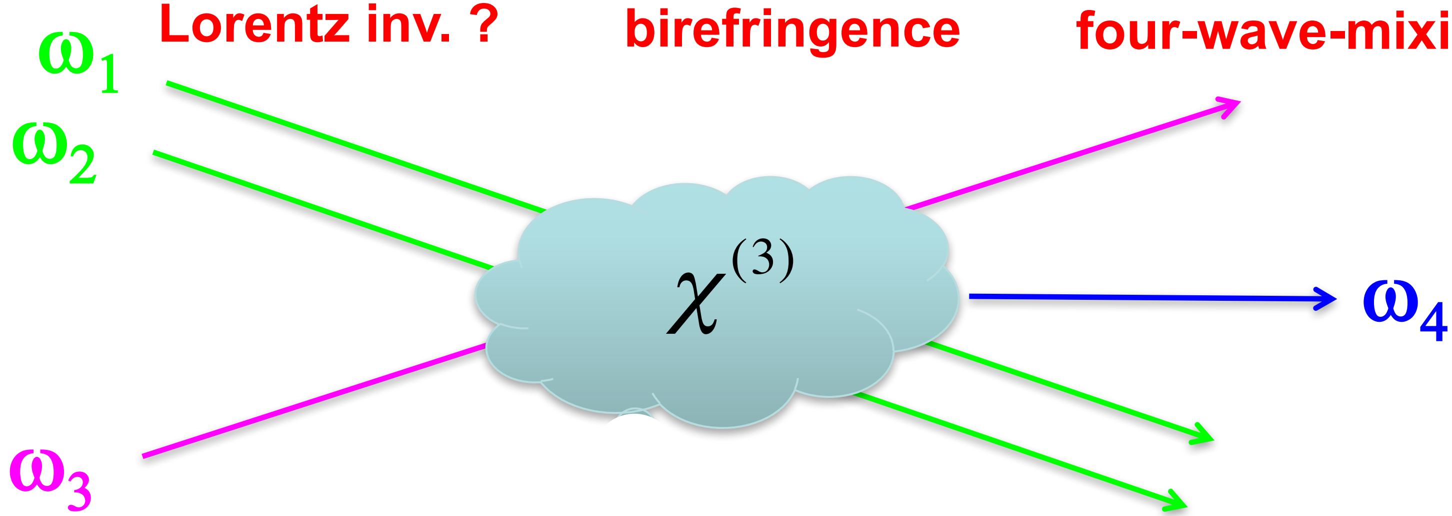


Four-Wave-Mixing in matter and vacuum

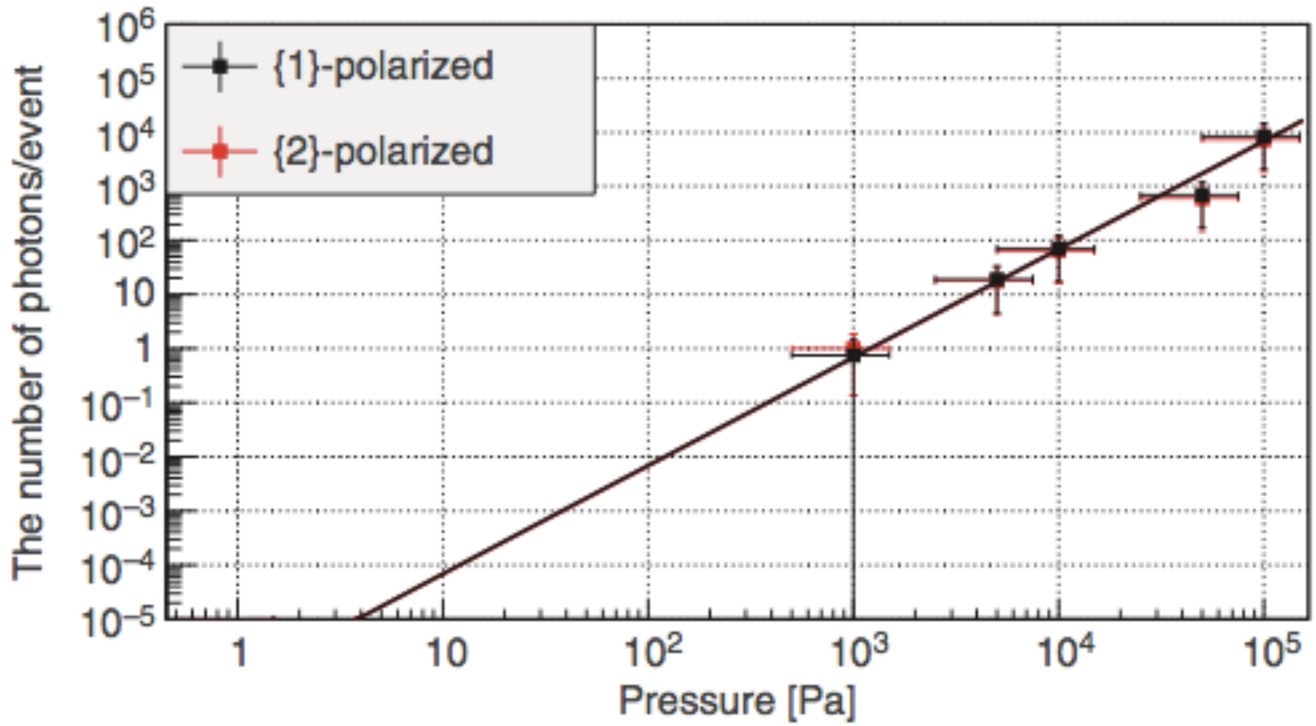
Susceptibility to electric field

$$P(\omega) = \varepsilon_0 (\chi^{(1)}(\omega) E + \chi^{(2)}(\omega) E^2 + \chi^{(3)}(\omega) E^3 + \cdots)$$

matter:	**dispersive refractive index**	**birefringence / frequency sum & difference**	**four-wave-mixing**
vacuum:	**violation of Lorentz inv. ?**	**vacuum birefringence**	**vacuum four-wave-mixing**



Pressure dependence of atomic FWM (corrected)



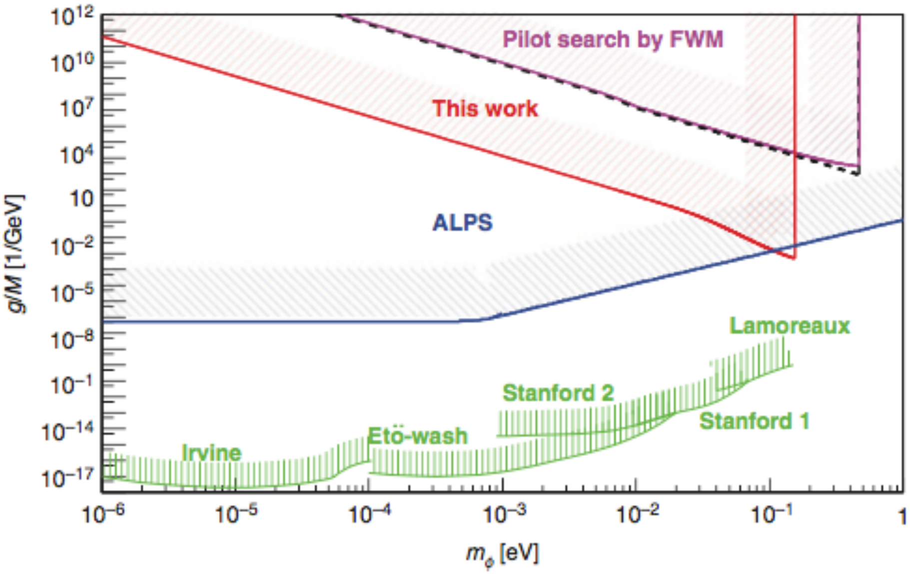
Quadratic pressure dependence is consistent with Chi^3 process

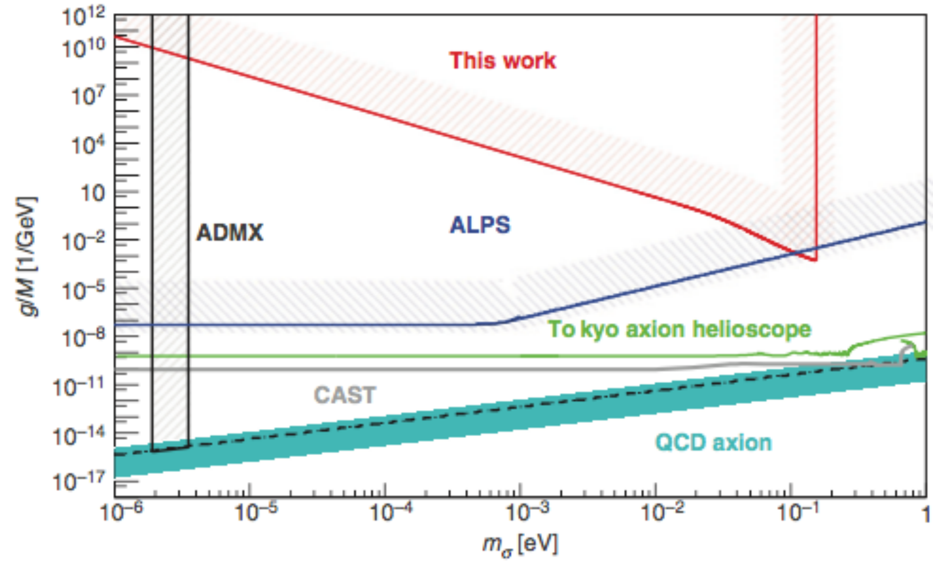
PTEP

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

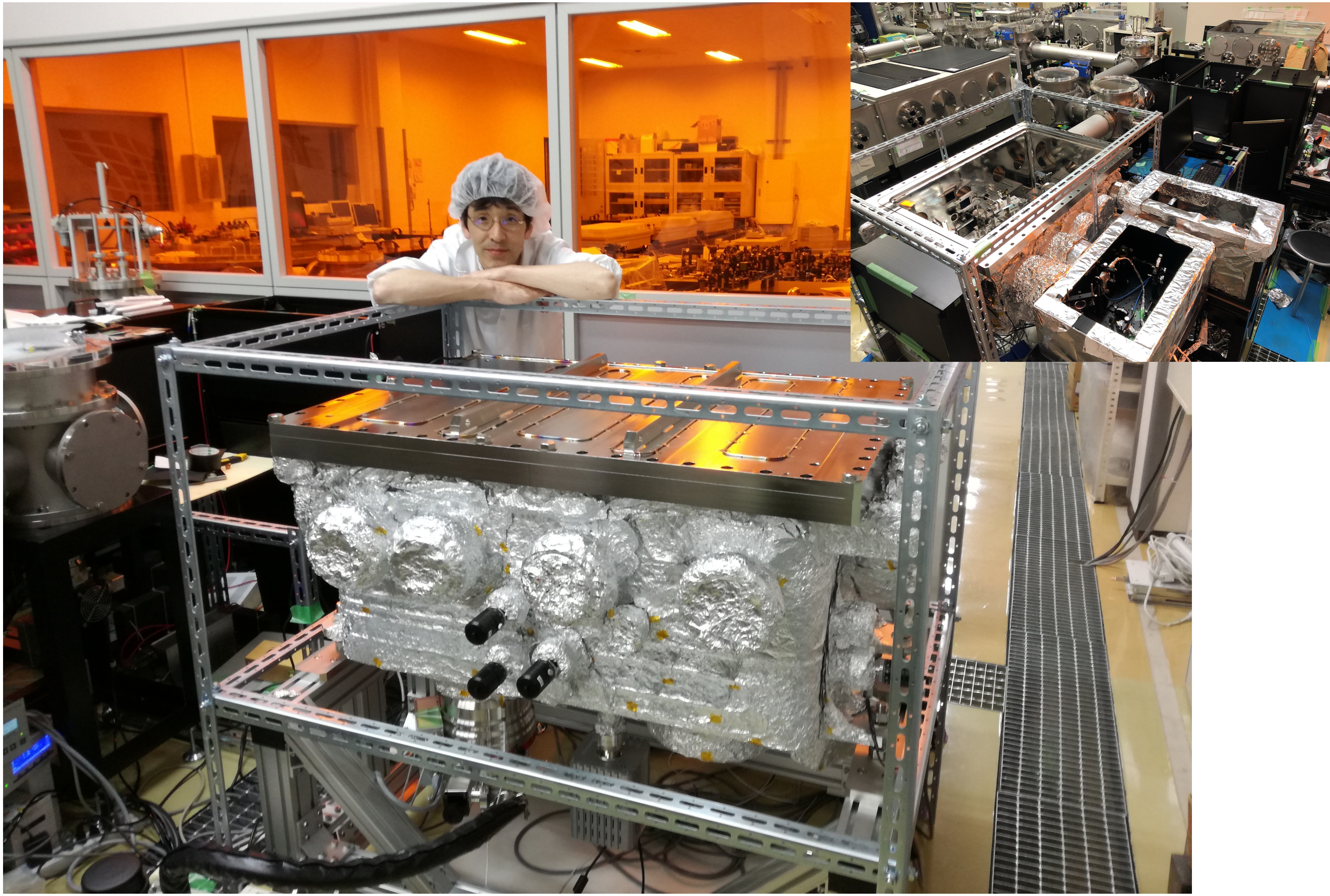
Search for sub-eV scalar and pseudoscalar resonances via four-wave mixing with a laser collider

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]

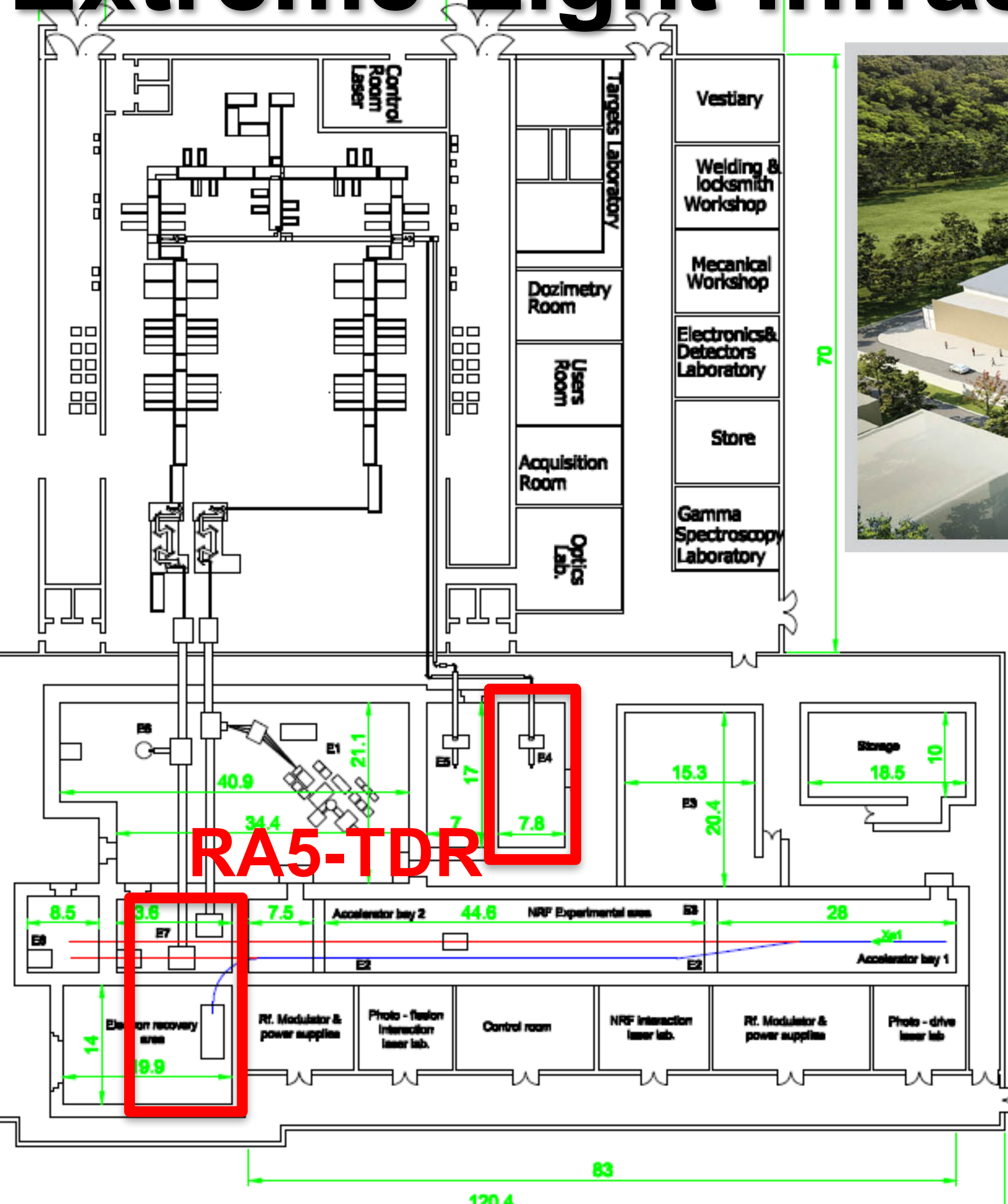




Higher intensity exp. Run II @ ICR, Kyoto



Extreme-Light-Infrastructure (ELI)



ELI-NP facility (280M€)

Comm. starts from 2019

2 x 10PW

2 x 1 PW

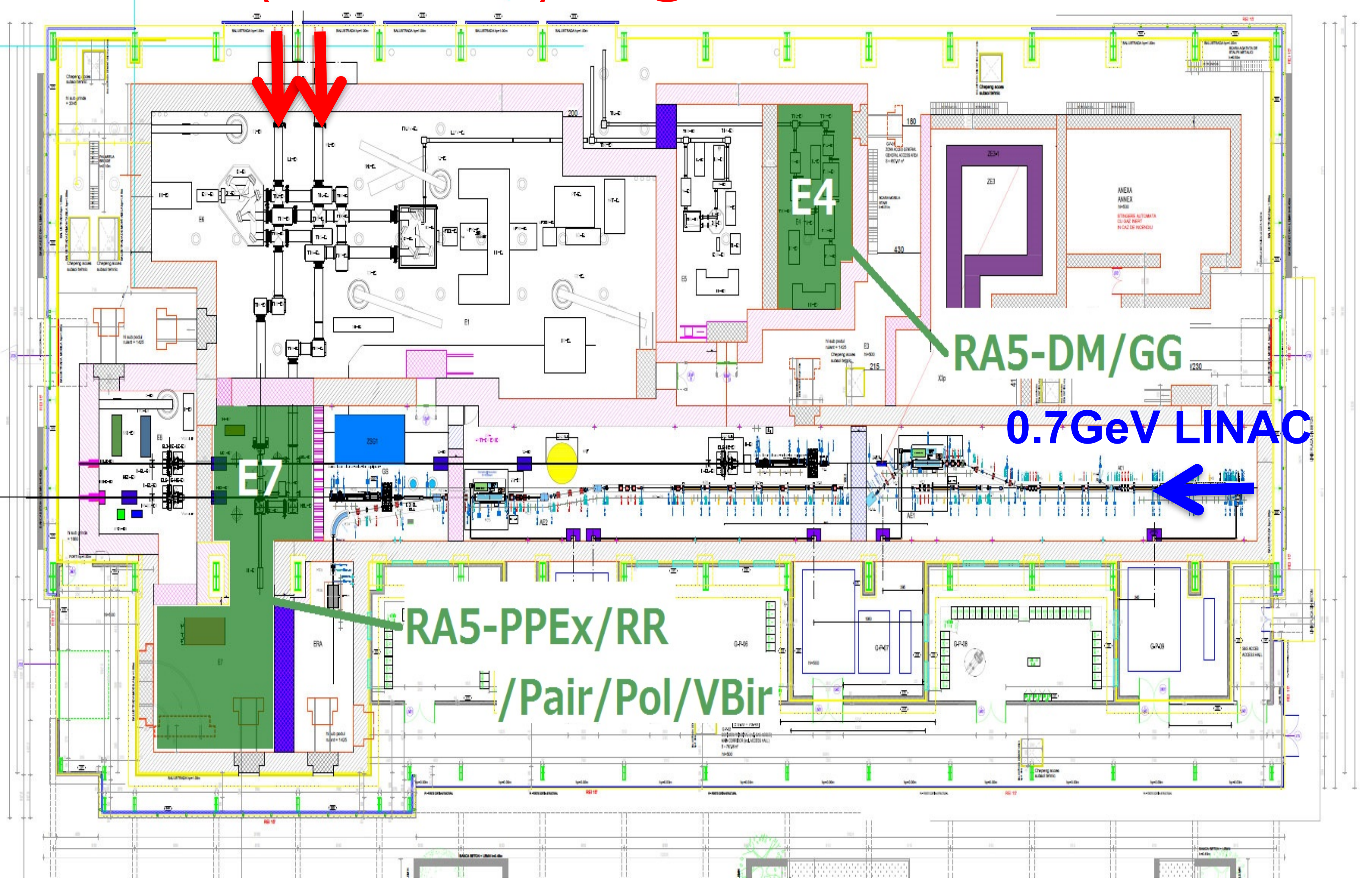
2 x 0.1 PW

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

ELI-NP as of June, 2017

ELI-NP declared achievement of 10 PW
on 13 Mar, 2019

10PW (10^{22-24}W/cm^2) x 2 @ 1 shot / min

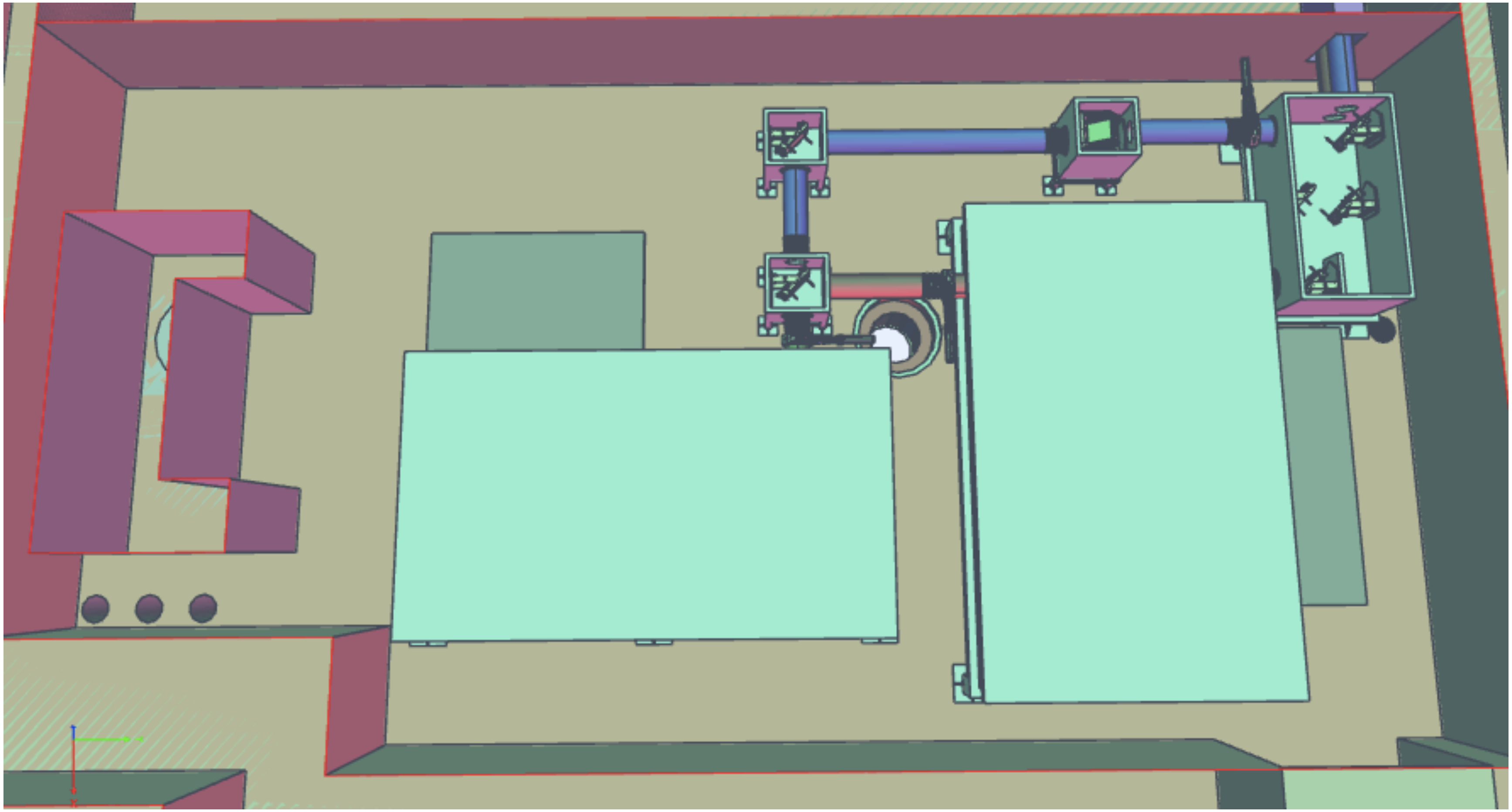


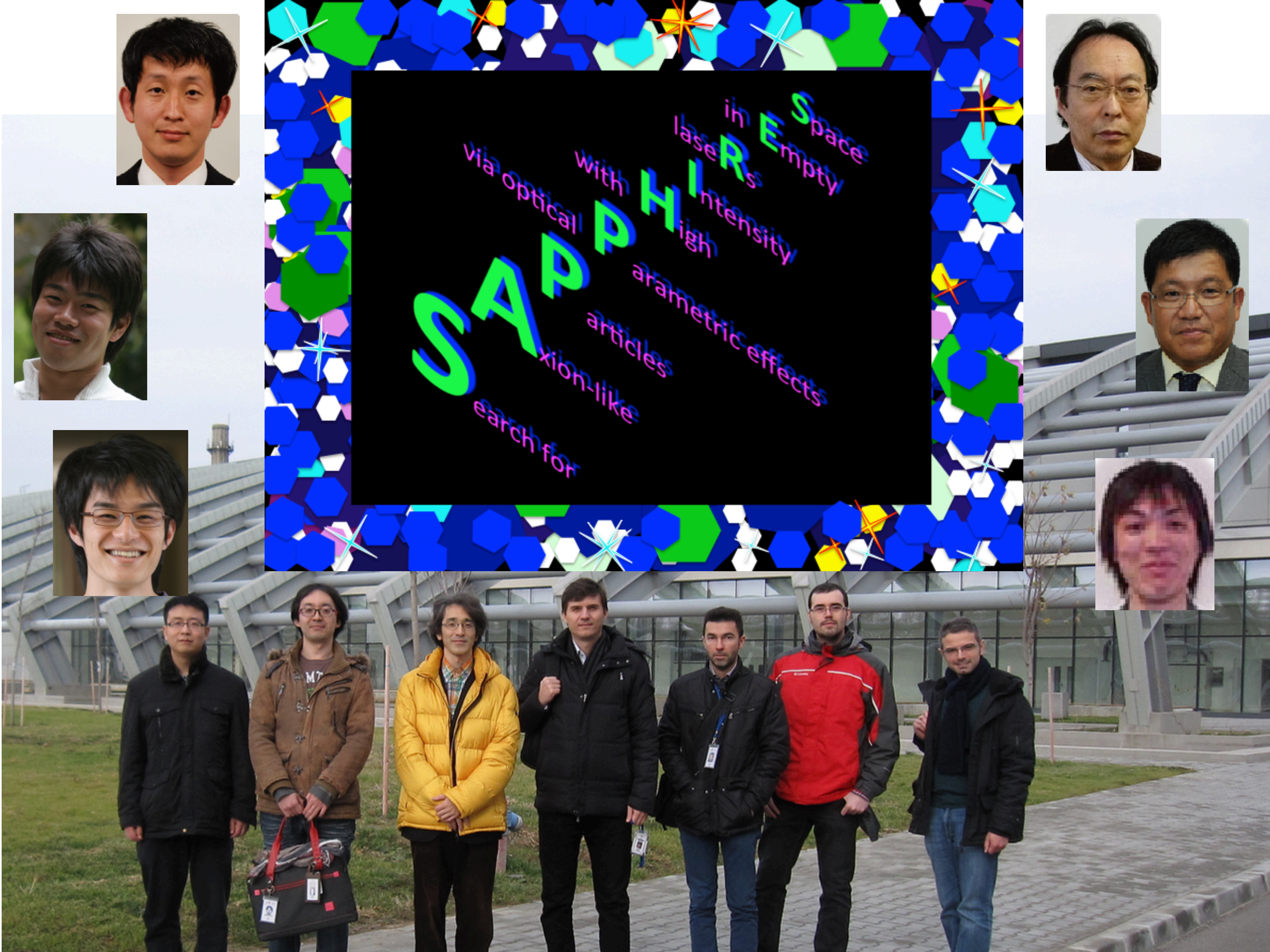
ELI-NP RA5 proposal for dark field search

HIGHLIGHTS OF RA5: COMBINED LASER – GAMMA EXPERIMENTS

Romanian Reports in Physics, Vol. 68, Supplement, P. S233–S274, 2016

K. HOMMA[1,2], O. TESILEANU[3], L. D'ALESSI[3], T. HASEBE[1], A. ILDERTON[4], T. MORITAKA[5], Y. NAKAMIYA[6], K. SETO[3], H. UTSUNOMIYA[7]




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

ICAN: 50J/100fs @ 10kHz

100-GeV Report:
Making the Ascent

There has been great progress on laser-driven plasma-based accelerators where electron beams can be accelerated to multi-GeV energy in centimeter-scale plasma driven by a 100-TW class ultrashort laser pulses thanks to the "laser wakefield accelerator" concept, pioneered by Tajima and Dawson in 1979. While to

date, worldwide research on laser-plasma accelerators is focused on the creation of compact particle and radiation sources for a wide range of applications in areas such as basic and medical sciences, the network of IZEST associate labs are undertaking to initiate the experimental research on large-scale laser-plasma accelerators with an aim at an ascent of electron beams energies toward 100-GeV. Experiments will be implemented by employing a multi-PW laser beam with a plasma accelerator consisting of injector and tens of meter-scale plasma waveguide. All of which will be inserted inside the Laser-Mega-Joule target chamber at CEA Bordeaux, implementing the PETAL beam which can deliver 3.5 kJ 500 fs pulses. Designs and implementation plans to accomplish 100 GeV acceleration within the framework of PETAL and LMJ are already underway. The first phase will be carried out in a 15-m beamline, followed in the second phase using a 30-m beamline for further high-energy acceleration with PETAL at full-power capability.

Recently, for preparation and execution of the project, the international team has been organized under 6 working packages: Managing & Design, Injector, Plasma Waveguide, Diagnostics, Integration & Interaction, and Implementation. We also push forward 100 GeV ascent project in close collaboration with associate experiments for 10-GeV level energies at Strathclyde University, APRI, SIOM, and GSI with PW-class laser facilities.

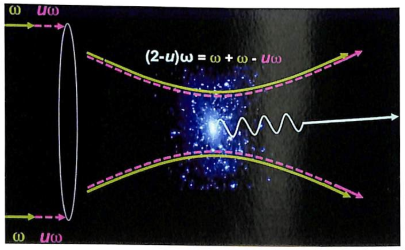
- K. Nakajima

Dark Fields Report:
Something from Nothing

Probing the nature of the quantum vacuum is indispensable in resolving the crucial problems in contemporary physics such as dark matter and dark energy in the universe.

To date, probing the vacuum has been limited to either the macroscopic space-time via astronomical observations or microscopic space-time points at high-energy particle collisions. With high-intensity lasers, however, we anticipate to be able to unveil the different aspects of the quantum vacuum at different space-time scales. With this in mind we launched the Dark Field working group within IZEST. The word "Dark" includes a broad sense: something undetected by conventional experimental approaches to date. Therefore, fundamental physics to be discussed within this working group covers weakly interacting phenomena such as Dark Matter/Dark Energy, nonlinear QED effects, and something which utilizes unique characters of the high-intensity as well as high-energy laser fields.

Among possible subjects, we are currently focusing on the search for weakly interacting low-mass bosons as a candidate of dark fields via quantum optical observables such as four-wave mixing where the nonlinear atomic process in matter is replaced by the nonlinearity caused



by a resonantly exchanged light boson in the vacuum (see image above).

Preliminary experimental trials to search for the four-wave mixing process are already on-going at Kyoto University in Japan and also the further test is planned at INRS in Canada under the association of IZEST.

- K. Homma

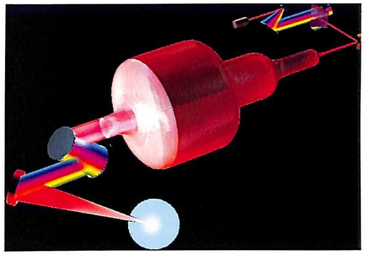
ICAN Report:
Can the future of accelerators be fibers?

Lasers are notorious for their poor efficiency. This is especially true for high peak power laser systems exhibiting wall-plug efficiency in the range of 1% at best.

For many utilizations requesting average power in the range of kW to 10 MW, like particle acceleration, this situation is economically unacceptable – even for research infrastructures – and seriously impairs the spread of important scientific and societal laser applications in science material science, environment, medicine and energy.

To solve this problem, the consortium ICAN (International Coherent Amplifying Network) has proposed to study a novel laser architecture known as CAN, (Coherent Amplification Network) that would guaranty, high peak (PW), high average (MW) powers while exhibiting a high wall plug efficiency, greater than 30%.

The CAN concept is based on the massive phasing of tens of thousands of diode pumped single mode lasers. Fiber amplifiers can produce very high average power, i.e. 10kW/fiber with excellent efficiency, i.e. 30%. In addition, because we can actuate individually each fiber we can have an handle on the phase and amplitude of each fiber output. As a consequence we can change the wavefront in phase and amplitude as necessary with



KHz bandwidth. The possibility to accelerate over short distances particles to high energy(GeV-TeV) with high efficiency, represents a watershed in science and societal applications with direct relevance to:
Proton Colliders (Tevatron, LHC), Neutron sources (SNS, ESS), Neutrino Sources(SNS, ESS), Radioactive Ion Beam (FRIB, Eurisol), Accelerator Driven Systems(Ch-ADS,MYRRHA), Electron linear collider, Muon collider, andFree Electron laser at 10kHz.

- G. Mourou

C3 Report:
Damageless Optics

The C³ pillar of IZEST is concerned with advancing the production of ultra-high laser pulses through the use of DamageLess (i.e. plasma based) Optics (DLO).

The partners of C³ have been advancing the use of such DLO for direct amplification of short laser pulses, either through Raman or Brillouin techniques, in experiments using the varied IZEST associated laboratories (Strathclyde, RAL, LULI, Jena, GSI, CEA-Saclay), and theoretical work has been pursued in parallel at Strathclyde, LULI, Düsseldorf, CELIA.

A workshop around these themes has been held at the University of Düsseldorf (Germany) from March 21 to March 22, 2013, with emphasis on "Manipulation and Amplification of short laser pulses on the road to Exa-Zettawatt Beam". This workshop gathered 42 participants from 9 countries and advances on all topics covered by C³ were presented, including progress on the realization of future major laser facilities like PETAL (France) where the C³ technology is aimed to be ultimately deployed.

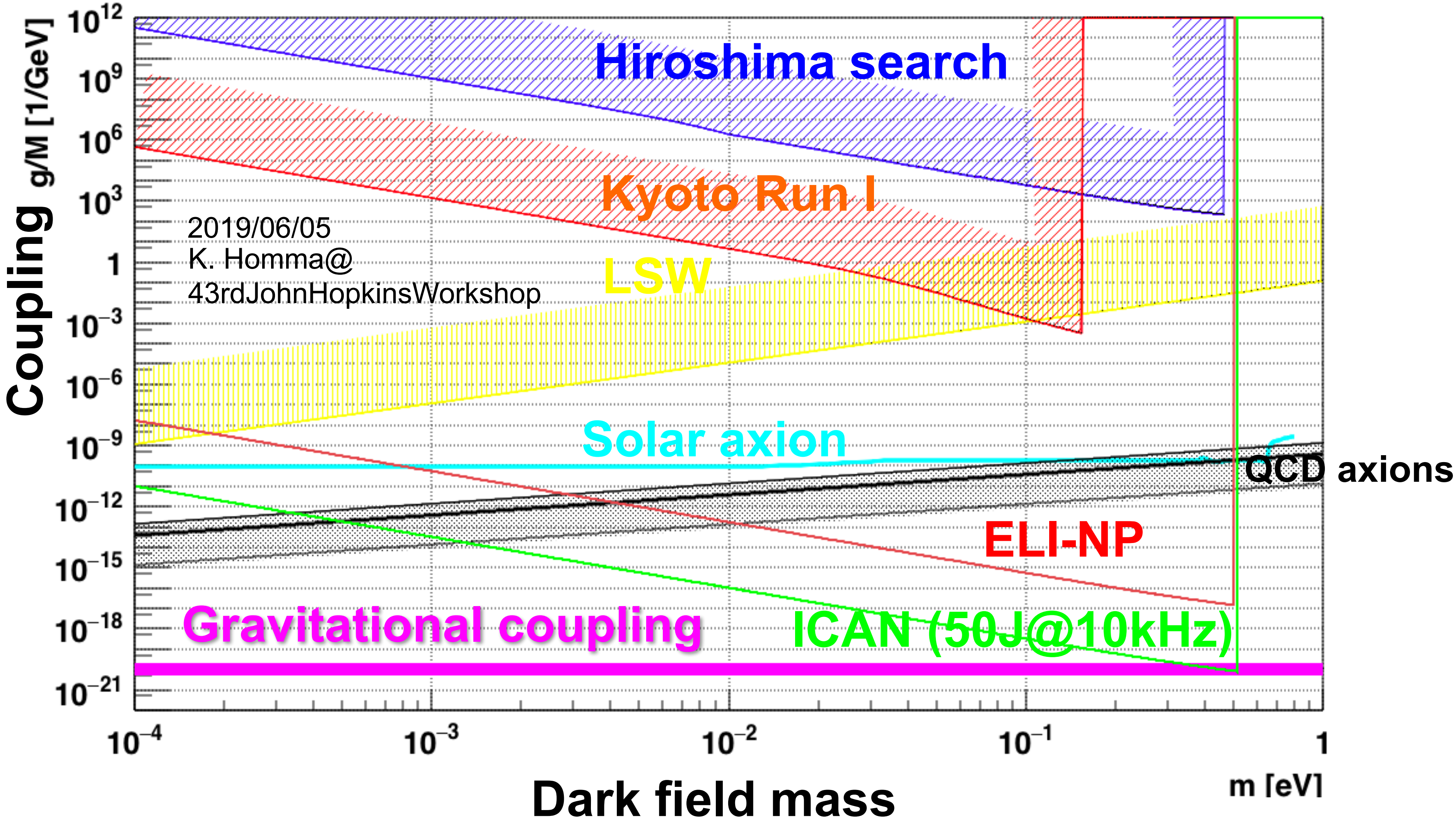
A summary of C³ methods, techniques and goals is being prepared to be written as part of the IZEST scientific case shaped in the form of a special issue of the European Journal of Physics (as offered by the editor). Several short (4 page) sections will detail the

main components of the C³ pilar: Raman and Brillouin amplification of ultra-intense light pulses, DLO for focusing such pulses, the intermediate laser facilities where C³ technology will be ramped up, and the large-scale future facilities where the production of the highest power pulses will ultimately be performed.

Contributors will be solicited on these various topics for papers to be ready by September 2013.

-J. Fuchs

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



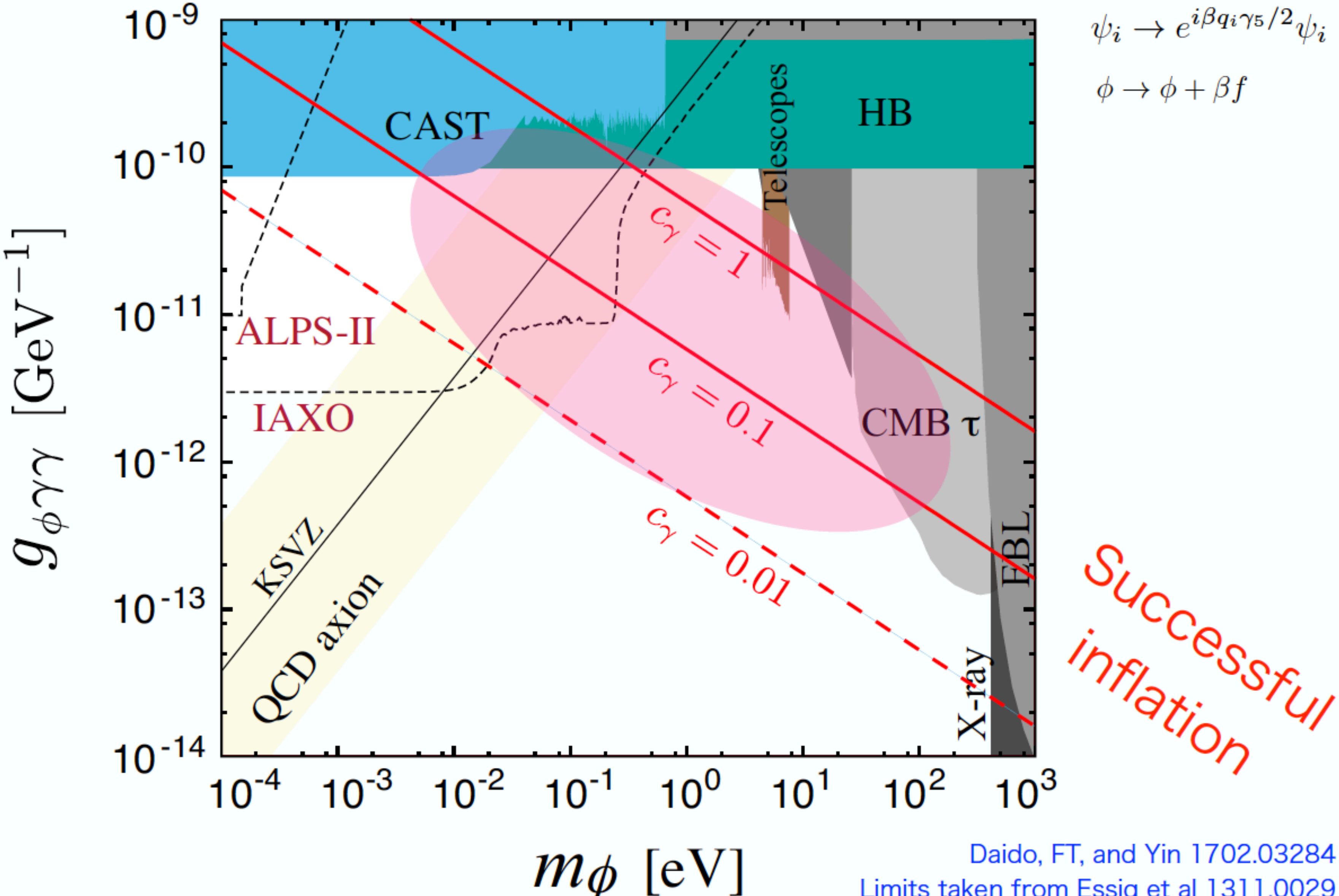
Inflaton (ALP) mass and coupling to photons

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

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

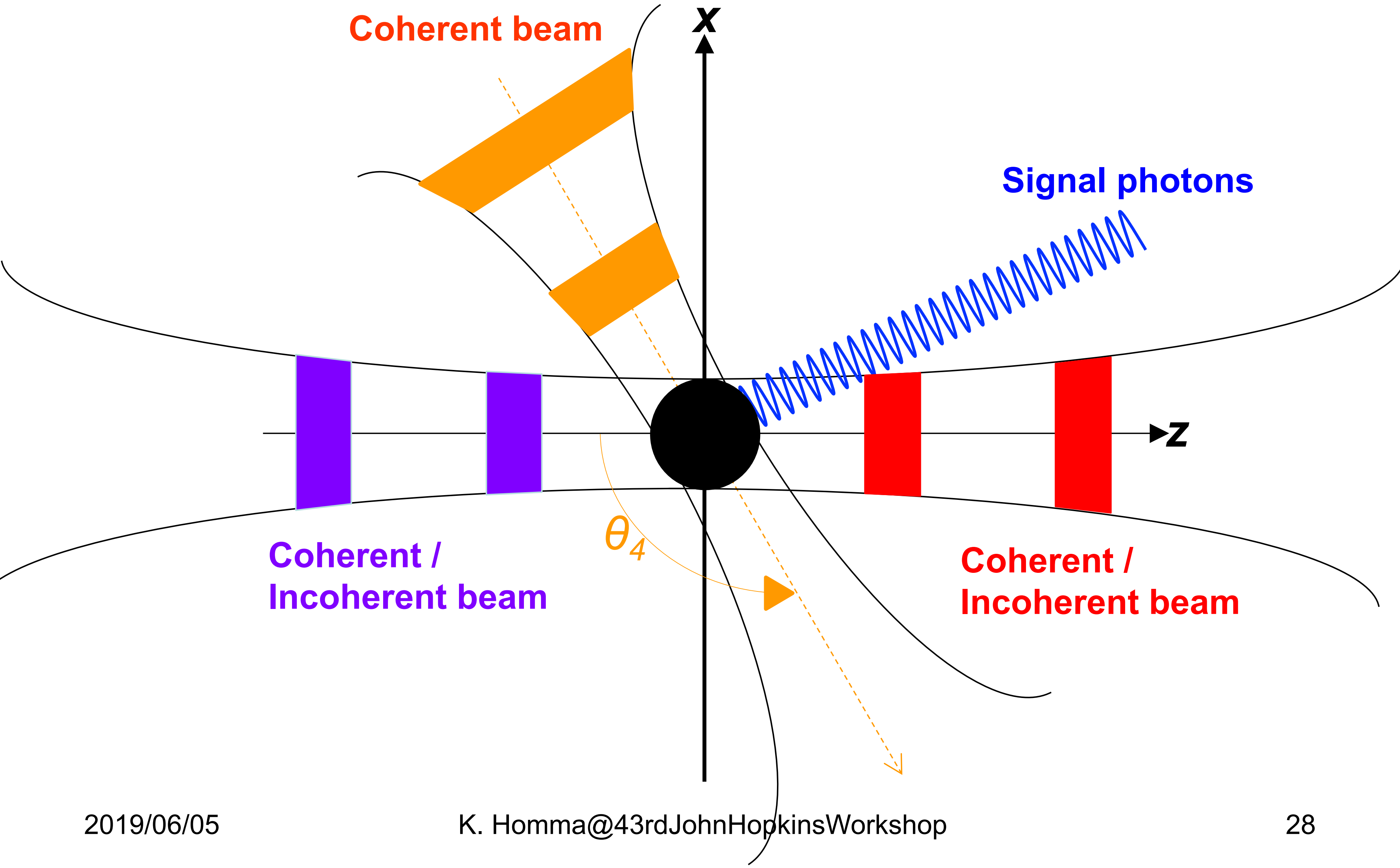
$$\psi_i \to e^{i\beta q_i \gamma_5/2}\psi_i$$

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

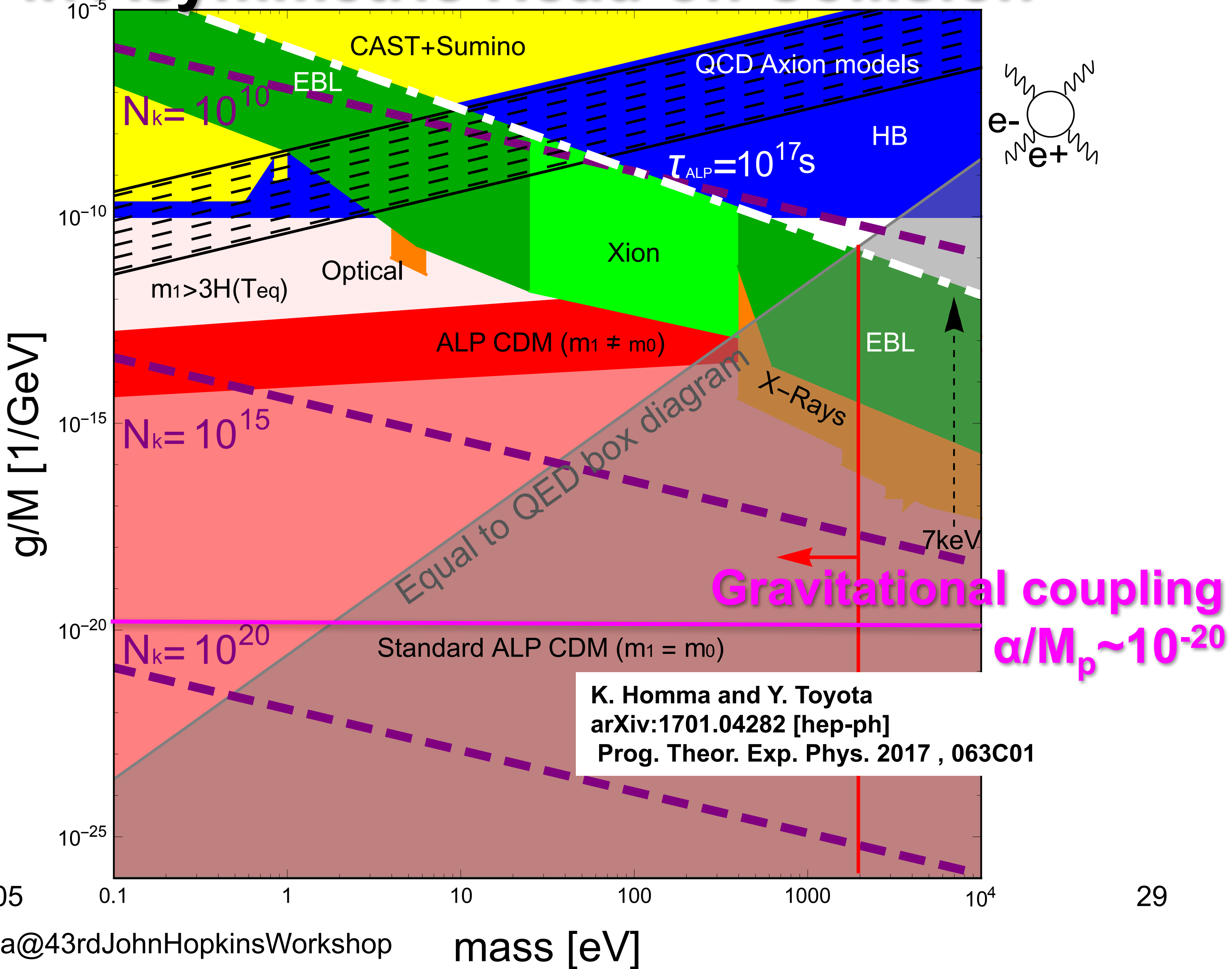


Daido, FT, and Yin 1702.03284
Limits taken from Essig et al 1311.0029

Extension to higher mass domains



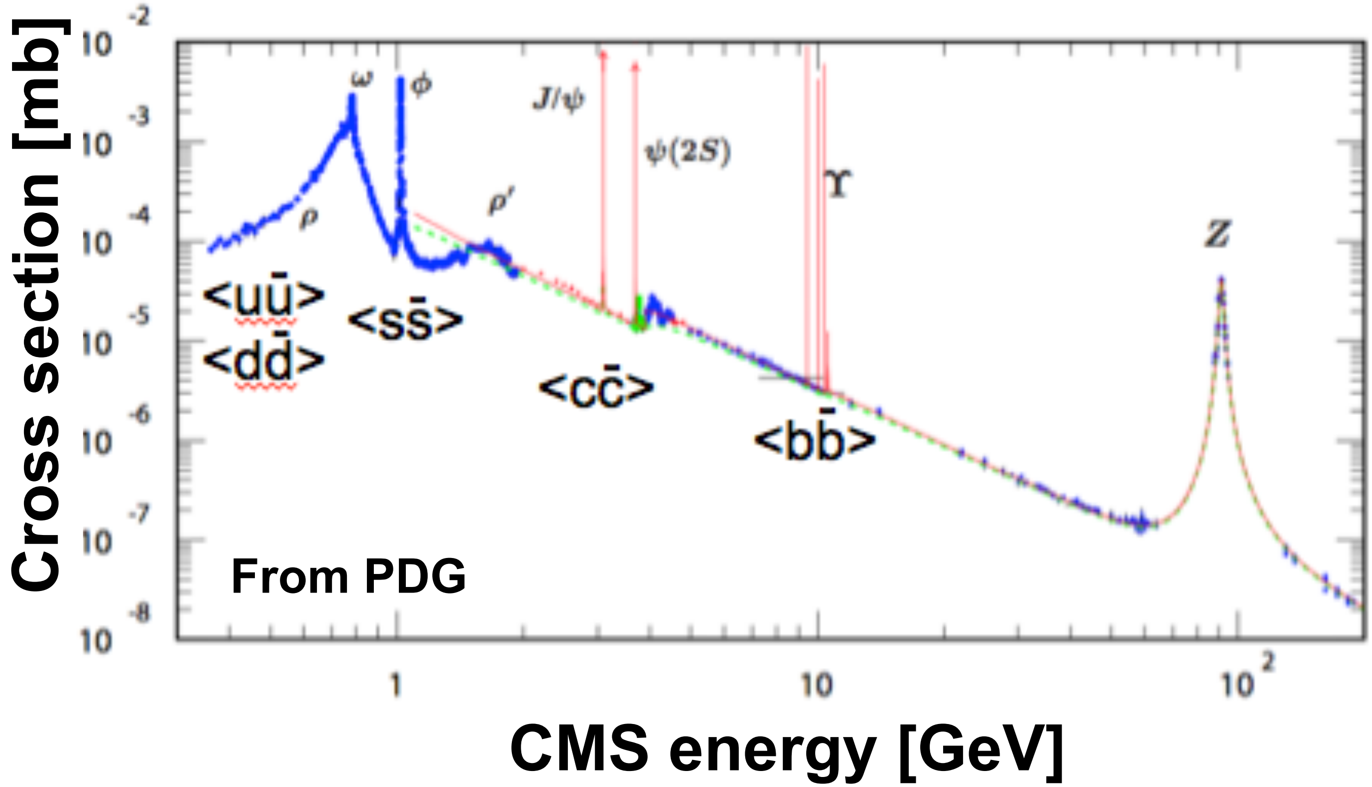
Sensitivity in sub-eV–10 keV mass domain in Asymmetric Head-on Collision

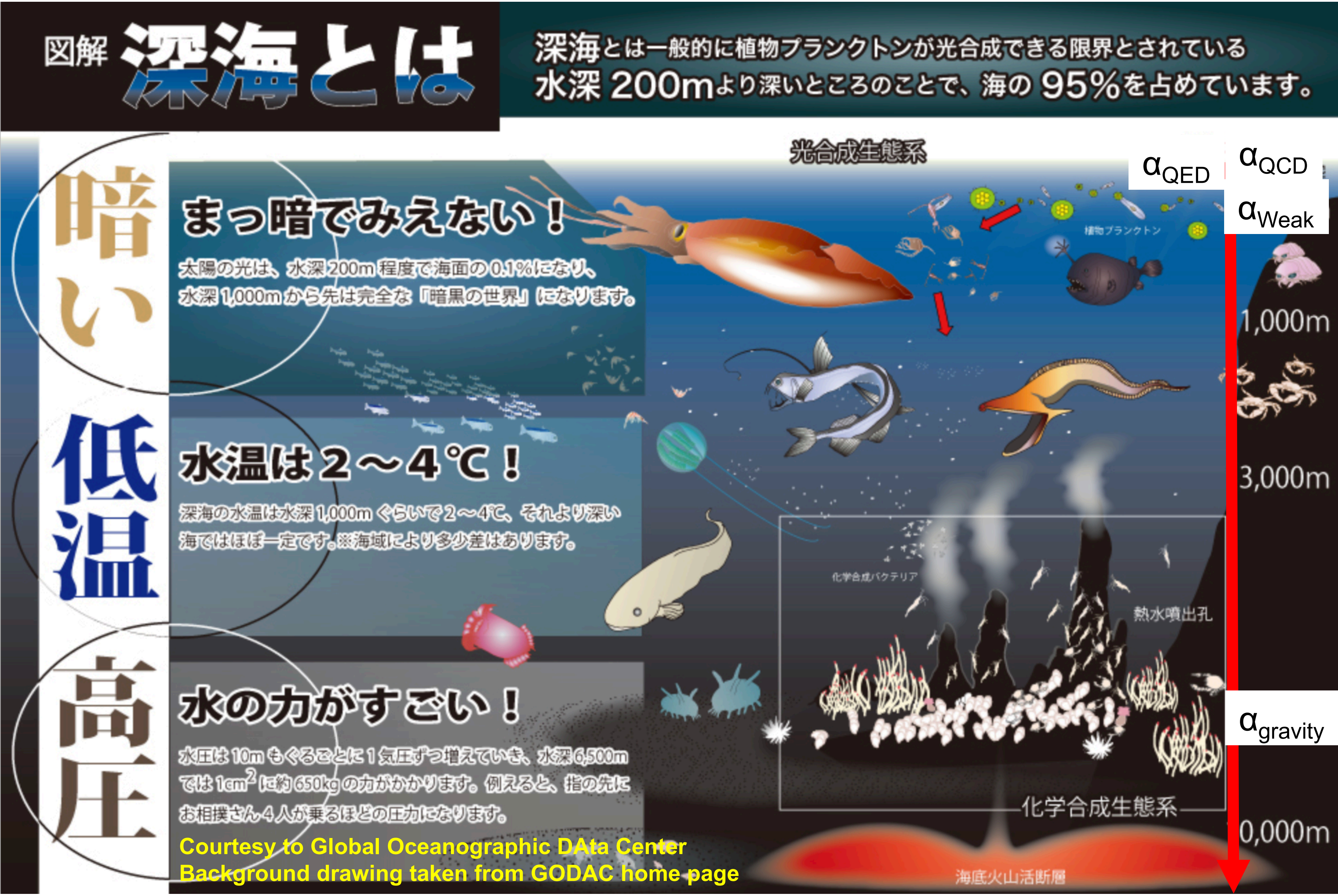


Summary

- Charged particle colliders discovered many SM resonance states in extremely strong coupling domains within only four orders of magnitude in CMS energy.

- Stimulated resonance scattering can provide proper windows for pNGB searches over $10^{-7} – 10^{3}$ eV in CMS energy.
  We have the ways to access gravitational coupling in scattering !




図解 深海とは
深海とは一般的に植物プランクトンが光合成できる限界とされている
水深 200mより深いところのことで、海の 95%を占めています。
光合成生態系
α_{QED}
α_{QCD}
α_{Weak}
暗い
まっ暗でみえない！
太陽の光は、水深200m 程度で海面の0.1%になり、
水深1,000m から先は完全な「暗黒の世界」になります。
植物プランクトン
1,000m
低温
水温は2～4℃！
深海の水温は水深1,000m ぐらいで2～4℃、それより深い
海ではほぼ一定です。※海域により多少差はあります。
3,000m
化学合成バクテリア
熱水噴出孔
高圧
水の力がすごい！
水圧は10m もぐるごとに1気圧ずつ増えていき、水深6,500m
では1cm2 に約650kg の力がかかります。例えると、指の先に
お相撲さん4人が乗るほどの圧力になります。
$\alpha_{gravity}$
化学合成生態系
0,000m
Courtesy to Global Oceanographic DAta Center
Background drawing taken from GODAC home page
海底火山活断層