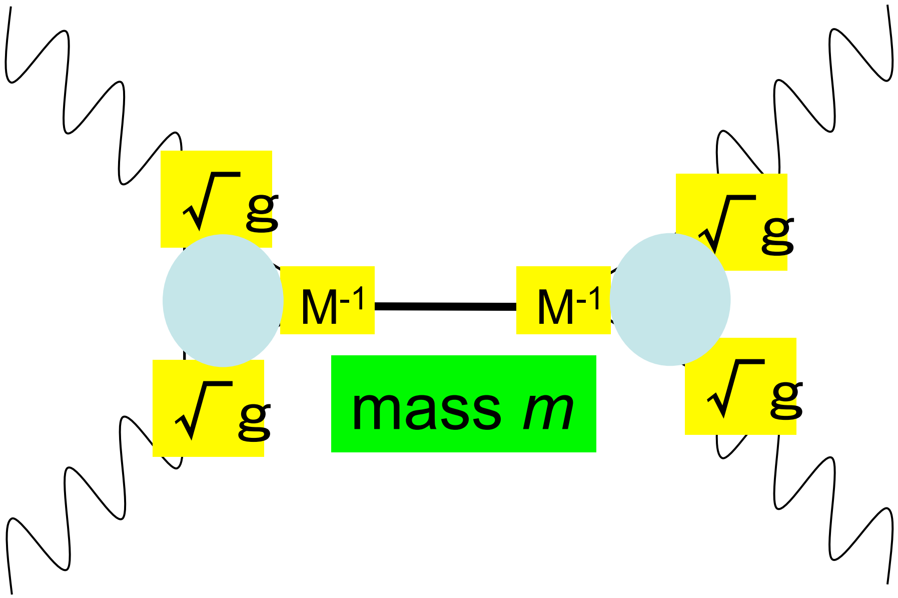
Searches for pseudo Nambu-Goldstone bosons by stimulated resonant photon-photon scatterings with high-intensity laser fields

Kensuke Homma
Hiroshima University
On behalf of the SAPPHIRES collaboration

1. Photon-photon interactions in SM and non-SM in different energy scales
2. Four-Wave-Mixing in the vacuum
3. Probing sub-eV pNGBs
4. Potential to probe 0.1 eV – 10 keV pNGBs
5. Comparison with WIMP searches
6. The SAPPHIRES collaboration

How much could pNGBs be light ?



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

$$gM^{-1}F^{\mu\nu}\tilde{F}_{\mu\nu}\sigma$$

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

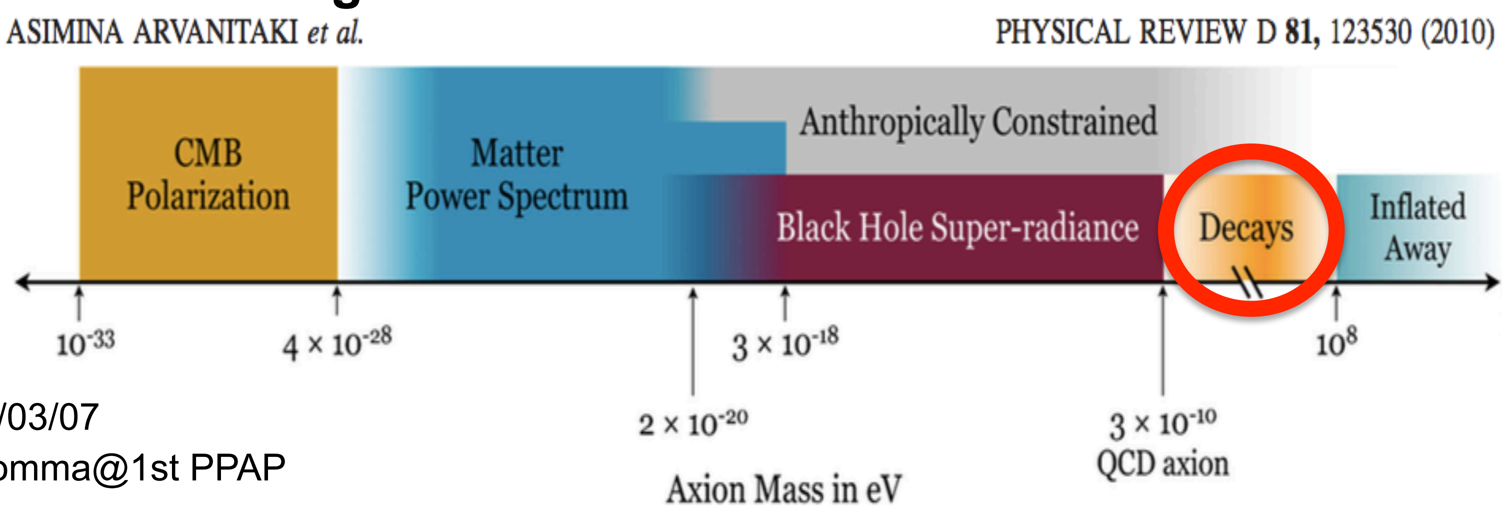
If $M \sim M_{Planck}$, dilaton (Dark Energy)

$$gM^{-1}F^{\mu\nu}F_{\mu\nu}\phi$$

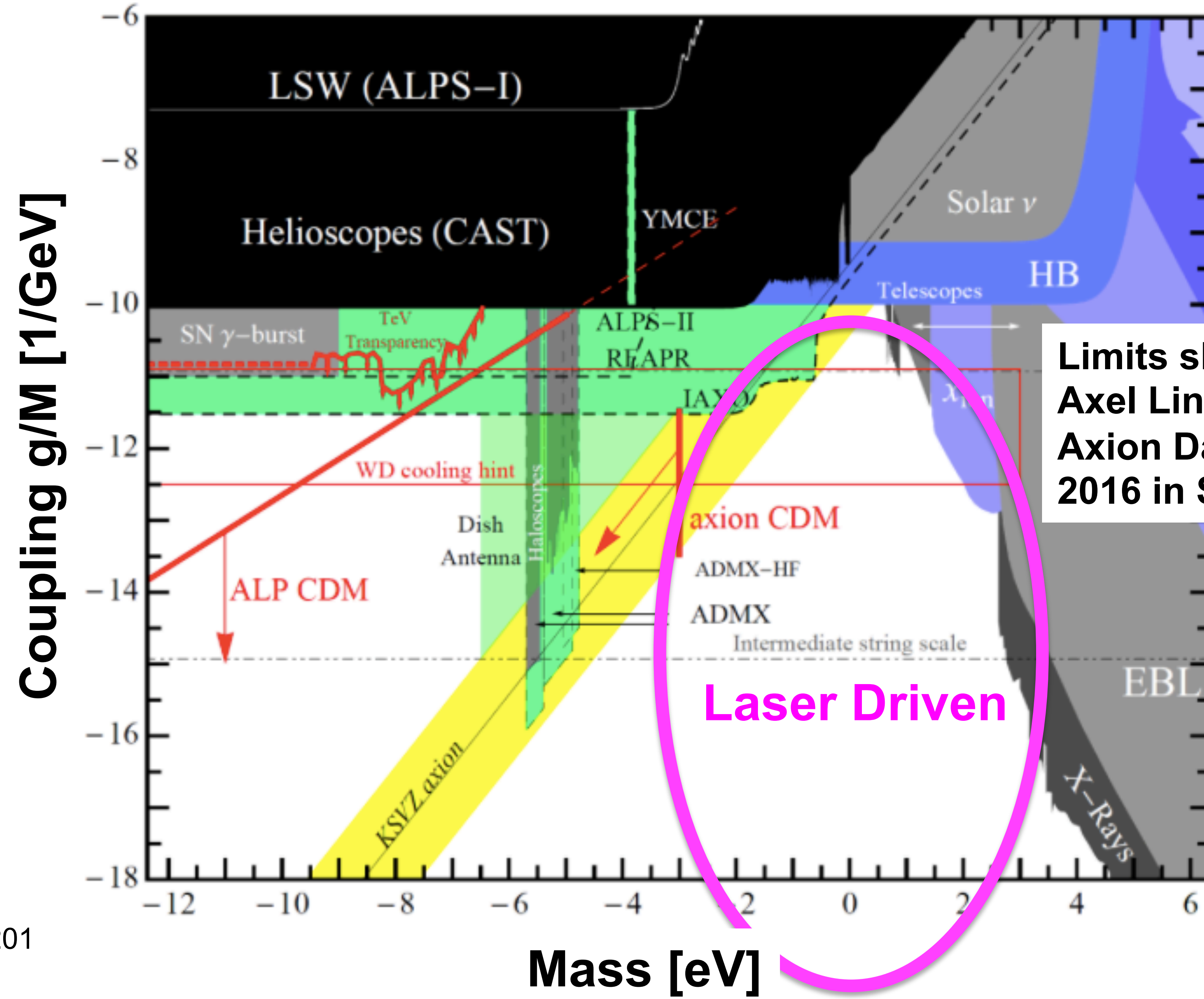
mass>10^{-9} eV

arXiv:1006.1762 [gr-qc]
Y. Fujii and K.Homma
Prog. Theo. Phys. 126, 531 (2011)

Plural pNGBs in the wide mass range can be a test of string-based theories ?



Present upper bounds



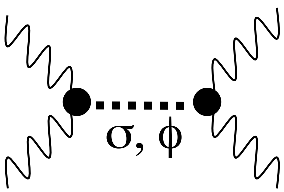
Limits shown by Axel Lindner Axion Dark Matter 2016 in Stockholm

Photon-Photon interactions over a wide energy range

Laser-Laser quantum interaction

High-energy particle interactions

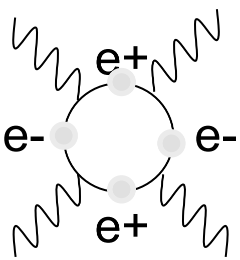
Very light field in the context of dark energy / matter



Undiscovered !

Below 1eV

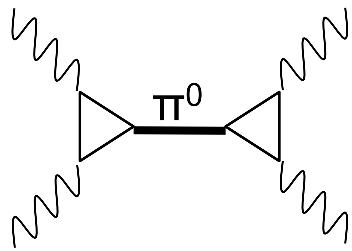
Interactions via QED (+QCD)



Not verified !

Below 1 MeV

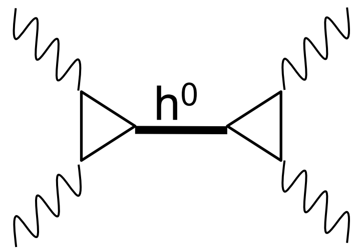
Chiral symmetry QCD int.



pseudoscalar

135 MeV

Gauge symmetry Electroweak int.

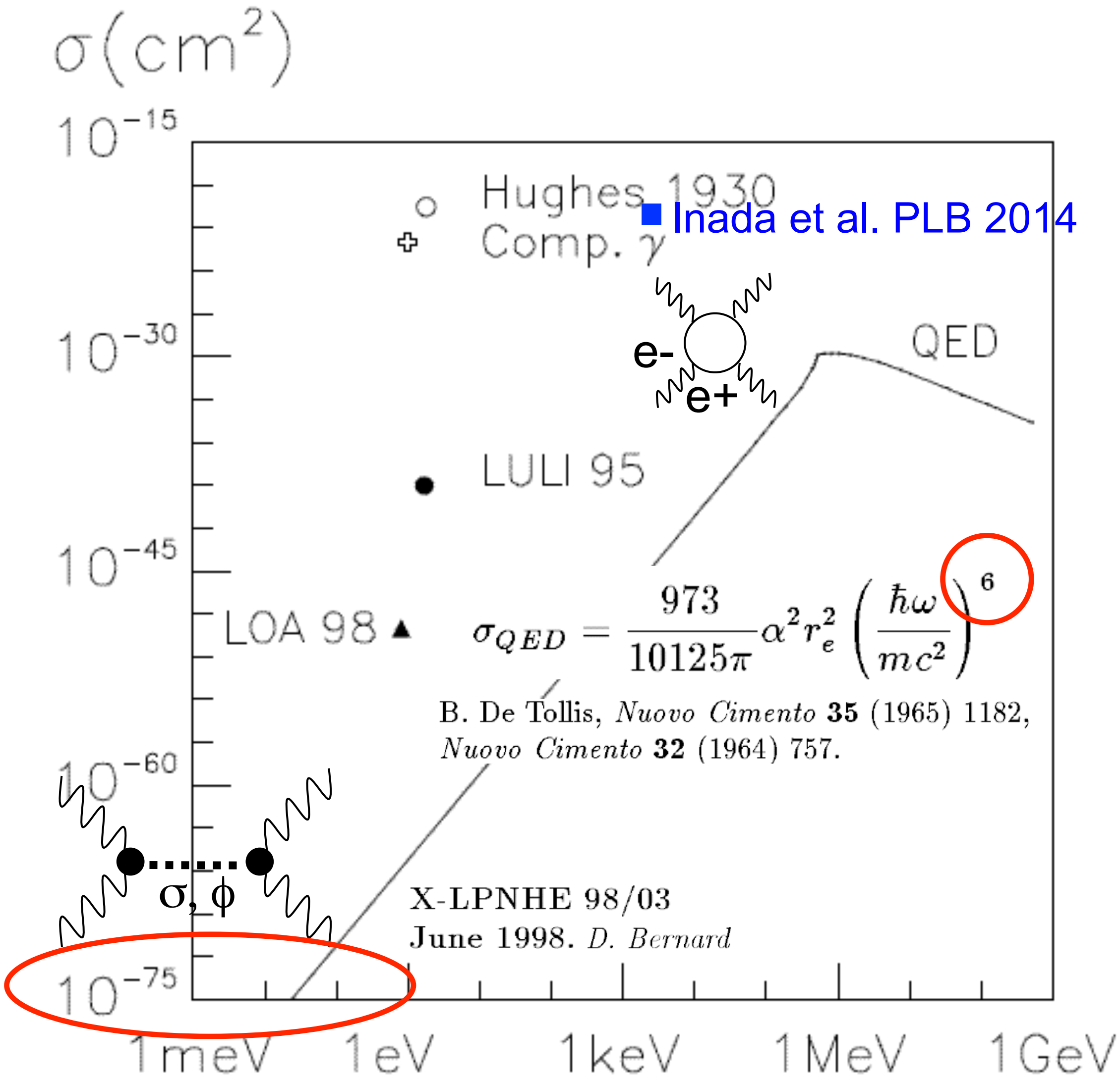


scalar

126 GeV

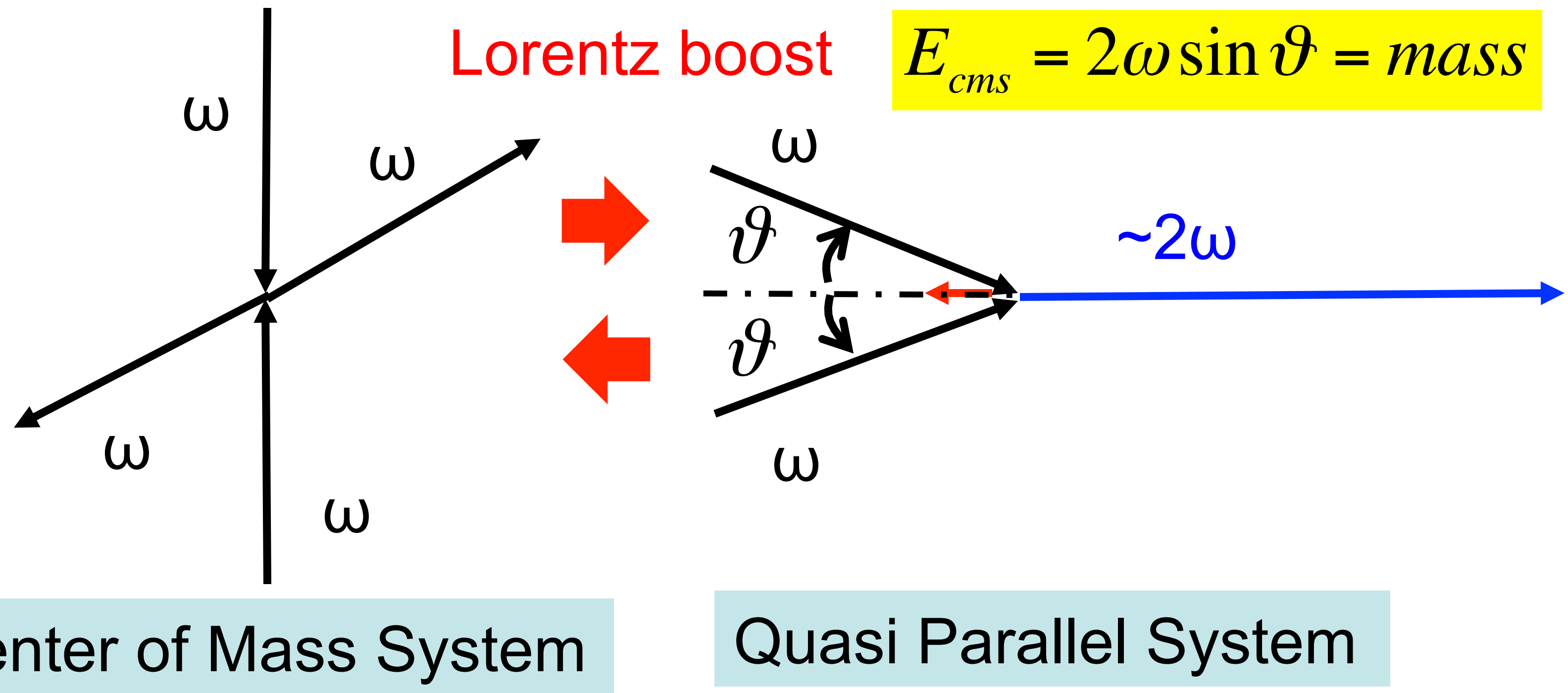
Photon-photon center of mass energy

Photon-photon interaction in sub-eV – MeV



$E_{cms}/2$

Hit resonance by lowering C.M.S. energy



$$E_{cms} = 2\omega \sin\vartheta = mass$$

No frequency shift

- **Frequency shift on the boost axis**
- **Lower Ecms by *θ* keeping ω constant**

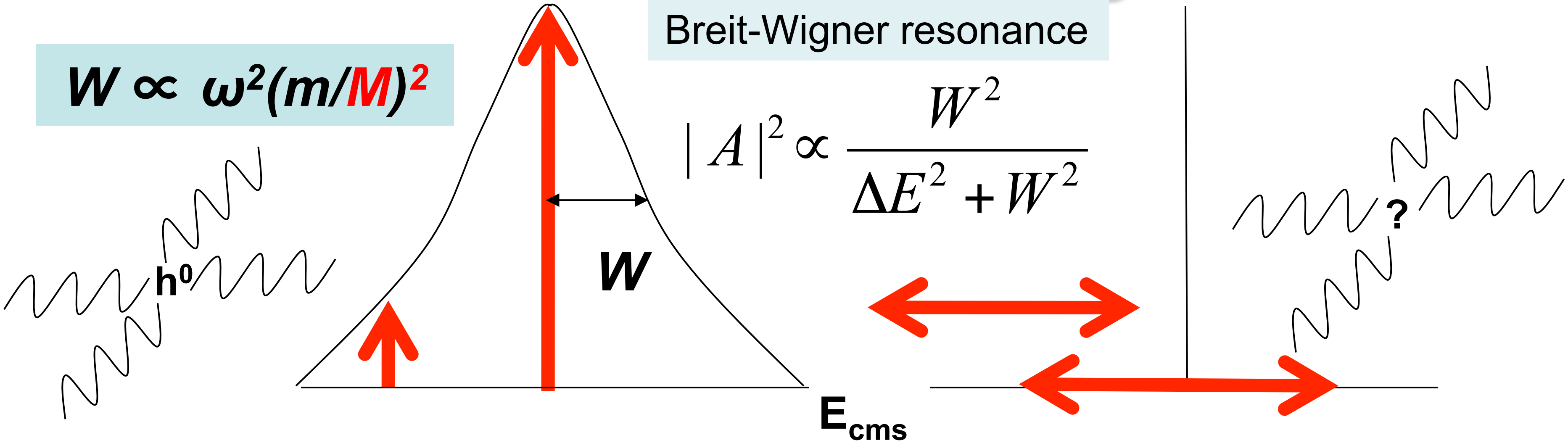
Low frequency photon in QPS is an ideal system !

Enhancement by containing resonance

***W* ∝ *ω*²(*m*/*M*)²**

Breit-Wigner resonance

$$|A|^2 \propto \frac{W^2}{\Delta E^2 + W^2}$$



e.g. γ−γ Higgs factory

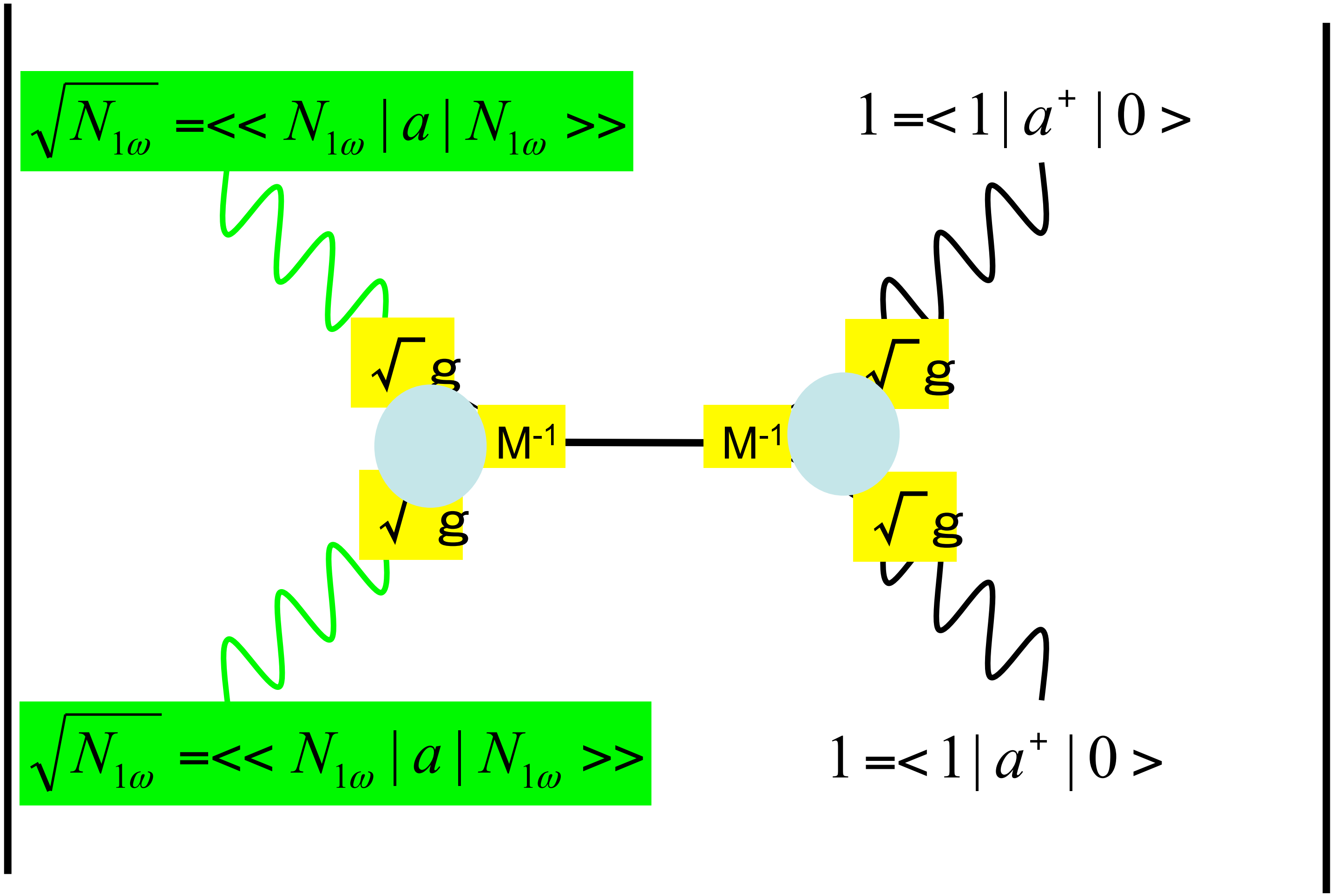
Collider in diffraction limit of QPS

We must integrate square of invariant amplitude in QPS

$$|A|^2 \propto W^2 \; if \; \Delta E >> W \;\Leftrightarrow\; |\overline{A}|^2 \propto \int_{-W}^{+W} \frac{W^2}{\Delta E^2 + W^2} dE = \frac{\pi}{2} W$$

Gain by *M*²

High-energy laser is required
- spontaneous scattering in vacuum -

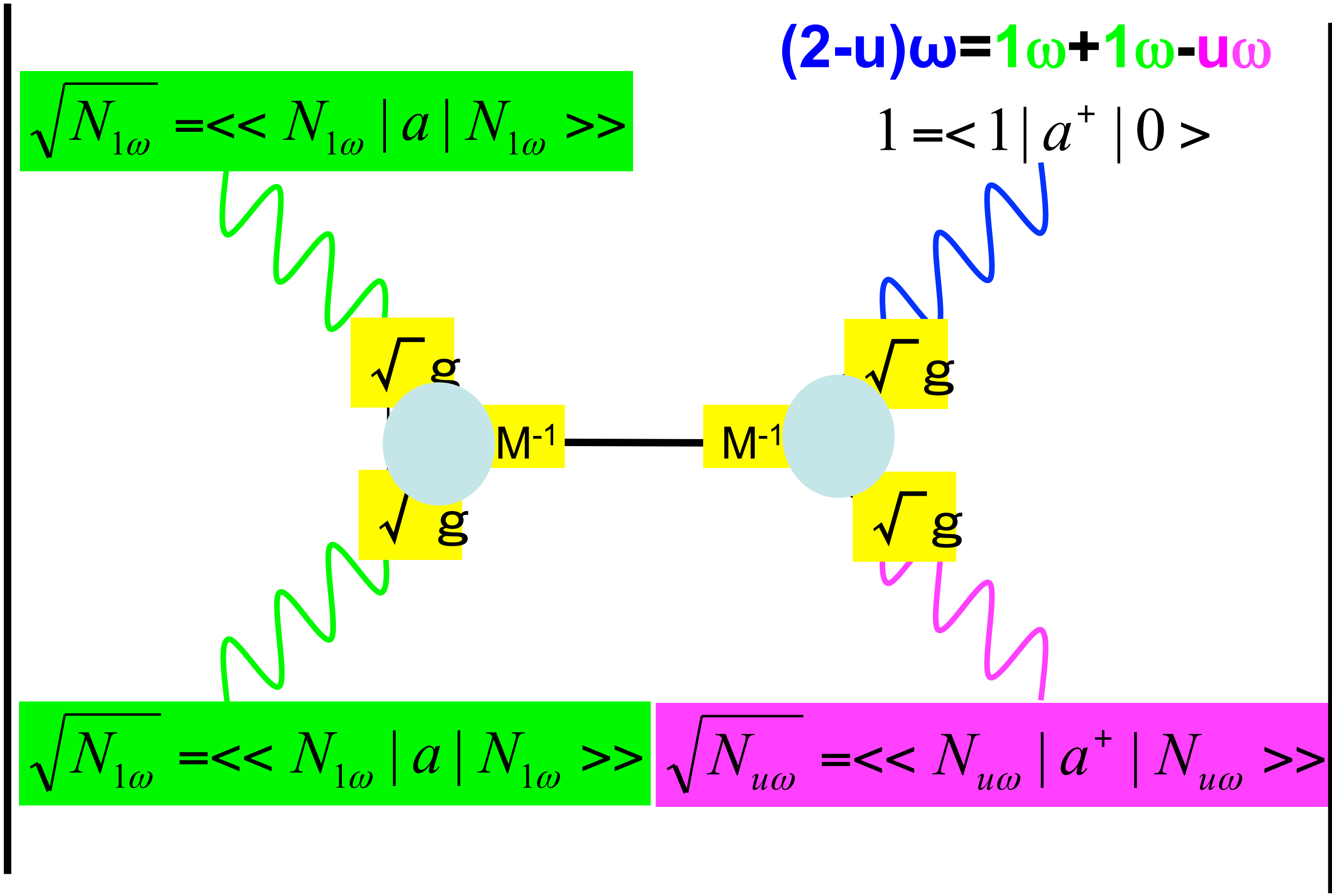


$\propto N^{2}_{1\omega}$

the same rate as particle colliders

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

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



2

N~10²³ = 200kJ

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

Cubic dependence

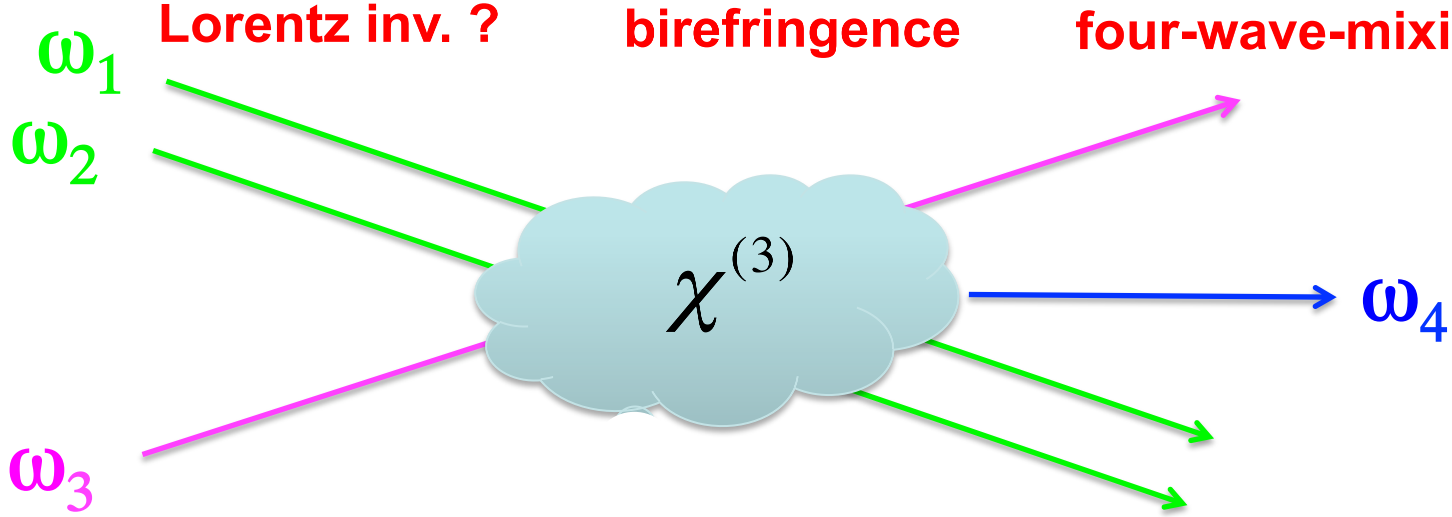
arXiv:1006.1762 [gr-qc]
Y. Fujii and K.Homma
Prog. Theor. Phys., 2011

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



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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[2] *International Center for Zetta-Exawatt Science and Technology, Ecole Polytechnique, Route de Saclay, Palaiseau, F-91128, France*
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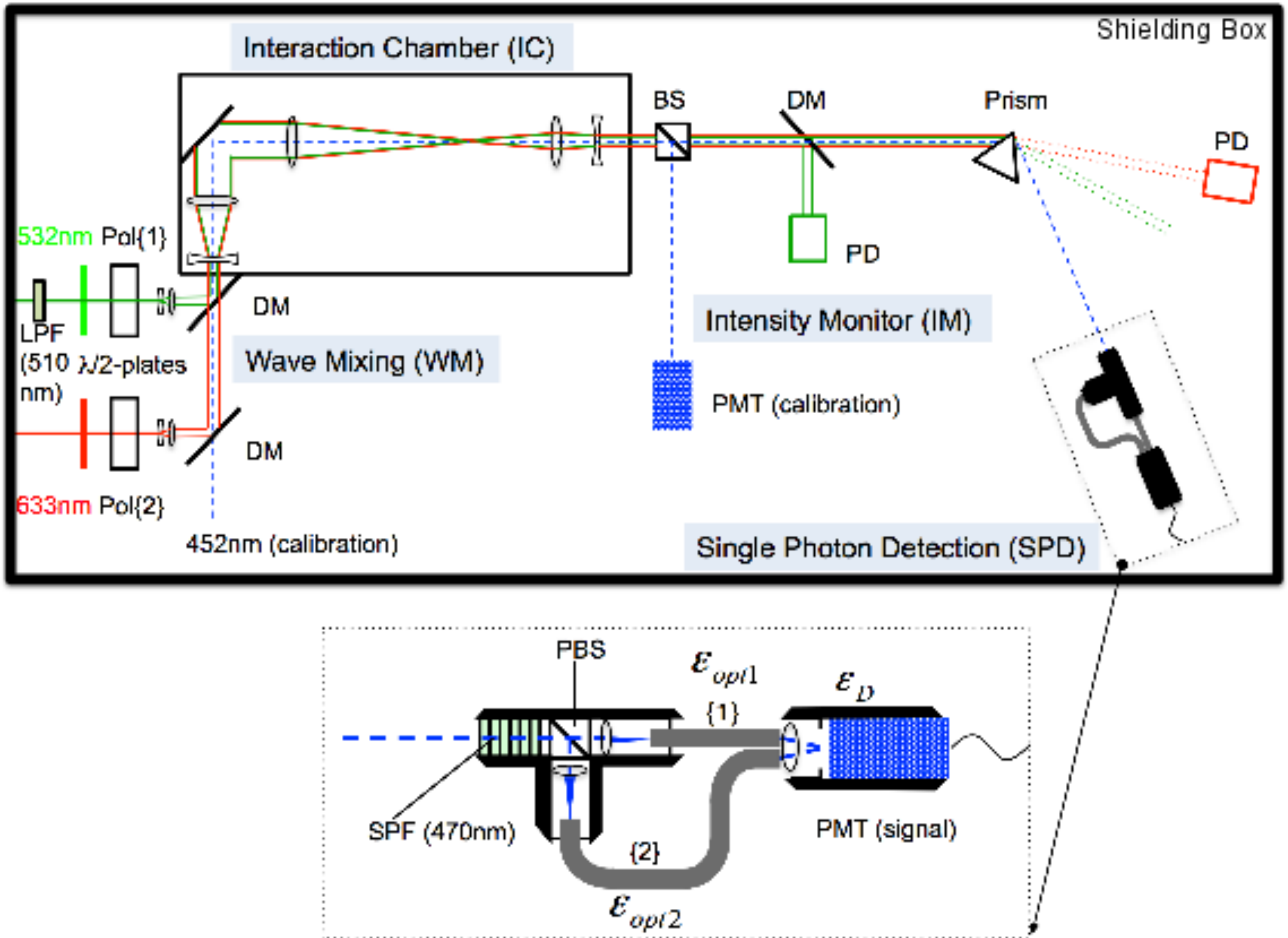
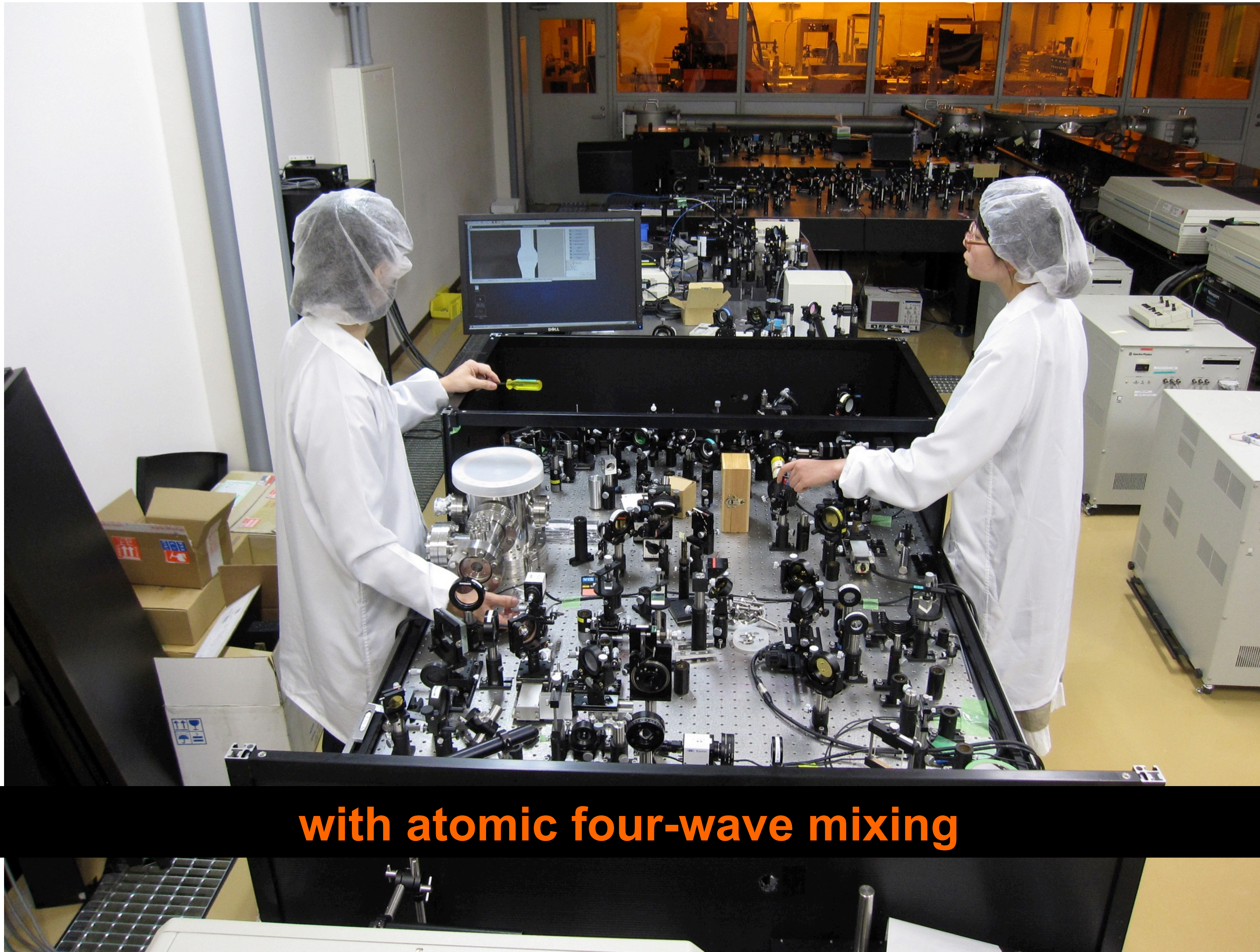
A search for sub-eV scalar fields coupling to two photons has been performed via four-wave mixing at a quasi-parallel laser collider for the first time. The experiment demonstrates the novel approach of searching for resonantly produced sub-eV scalar fields by combining two-color laser fields in the 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.

The first search for scalar field with FWM



Run I at Kyoto-ICR



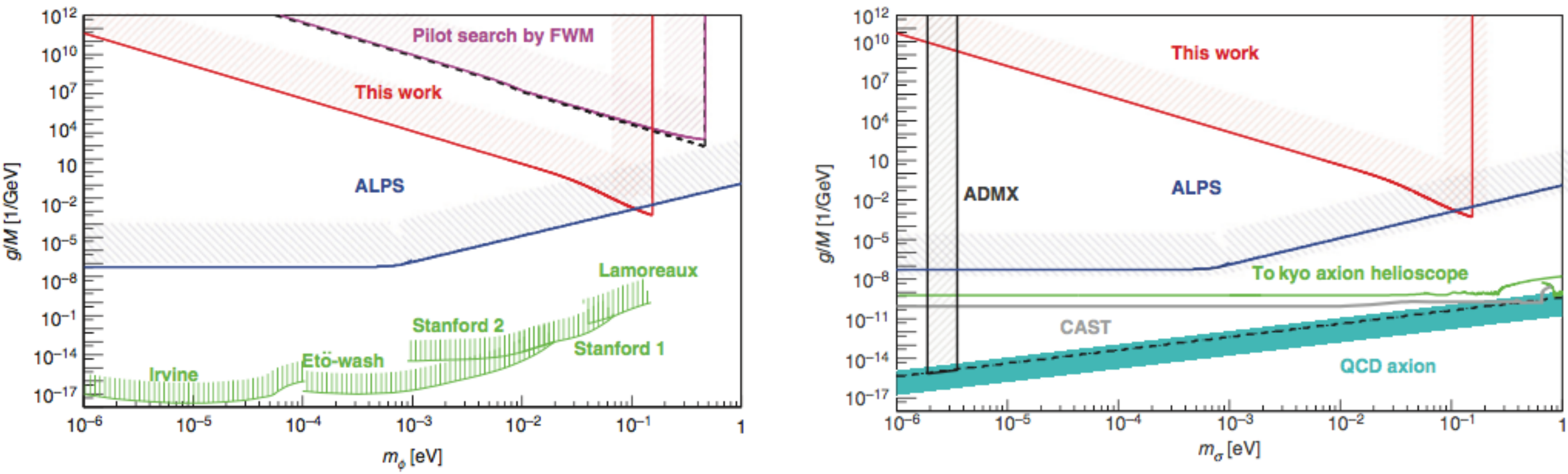
with atomic four-wave mixing

PTEP

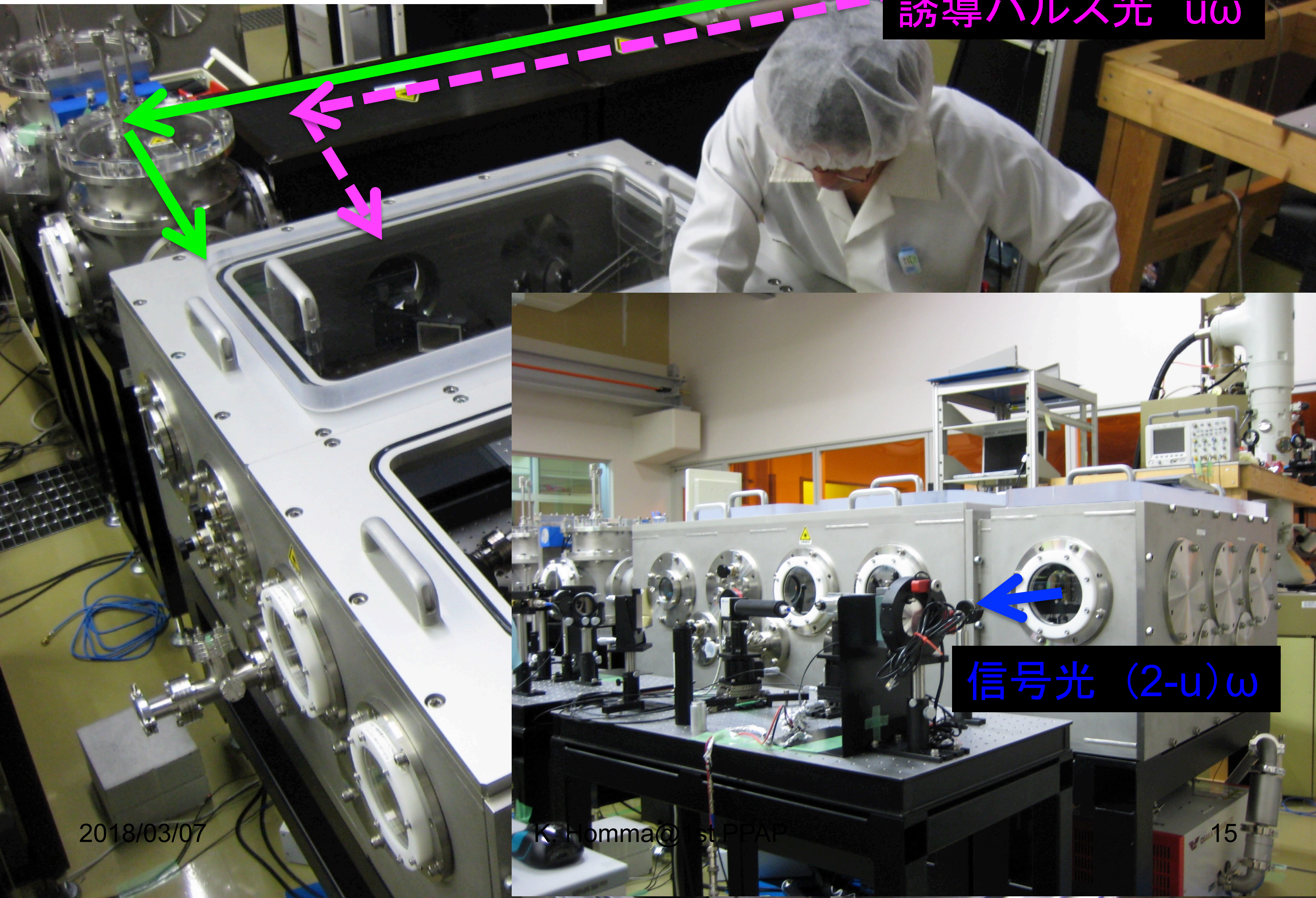
Prog. Theor. Exp. Phys. **2015**, 073C01 (19 pages)
DOI: 10.1093/ptep/ptv101

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

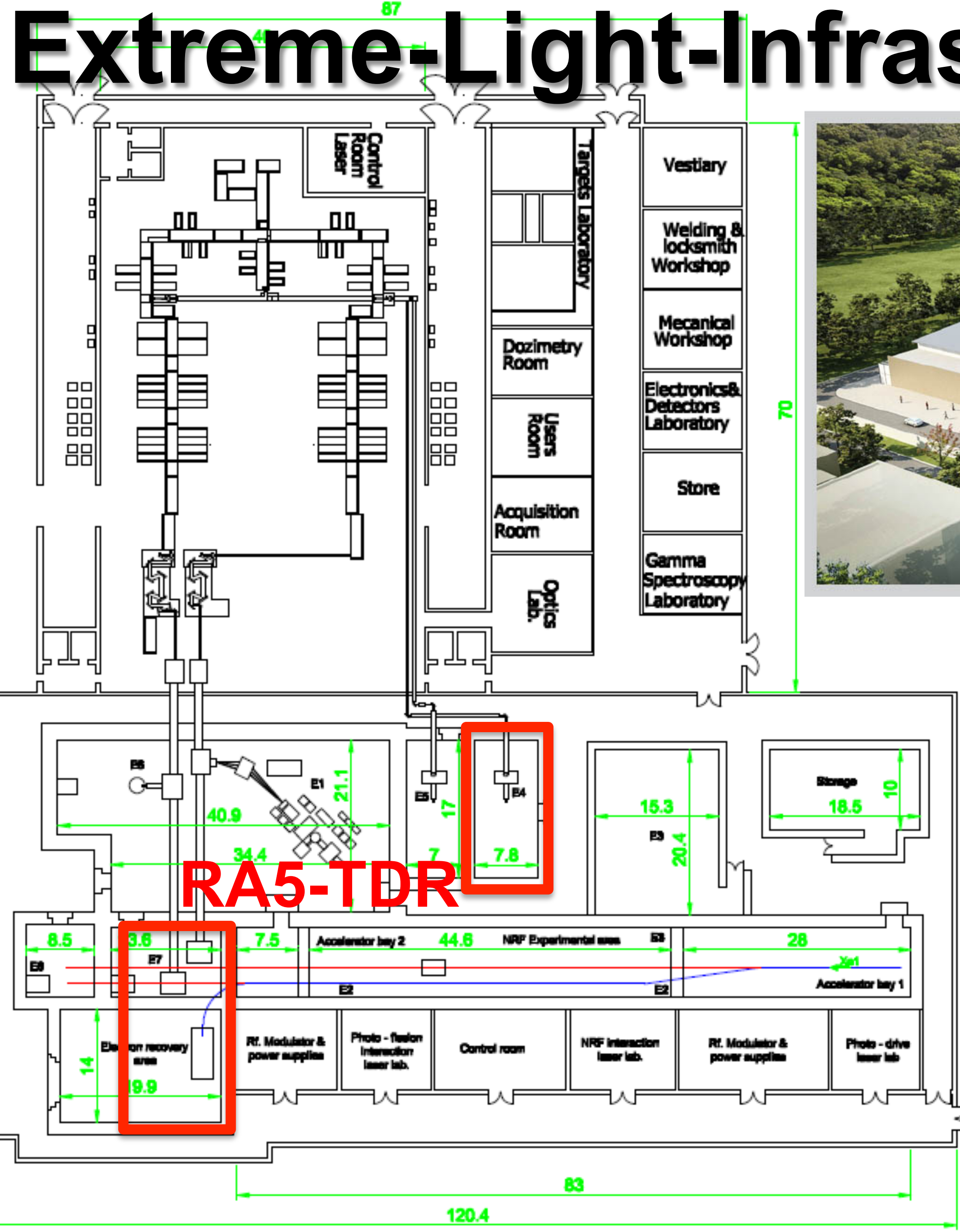
Takashi Hasebe[1], Kensuke Homma[1,2,*], Yoshihide Nakamiya[3], Kayo Matsuura[1], Kazuto Otani[4], Masaki Hashida[3,5], Shunsuke Inoue[3,5], and Shuji Sakabe[3,5]



Run II at Kyoto-ICR



Extreme-Light-Infrastructure (ELI)

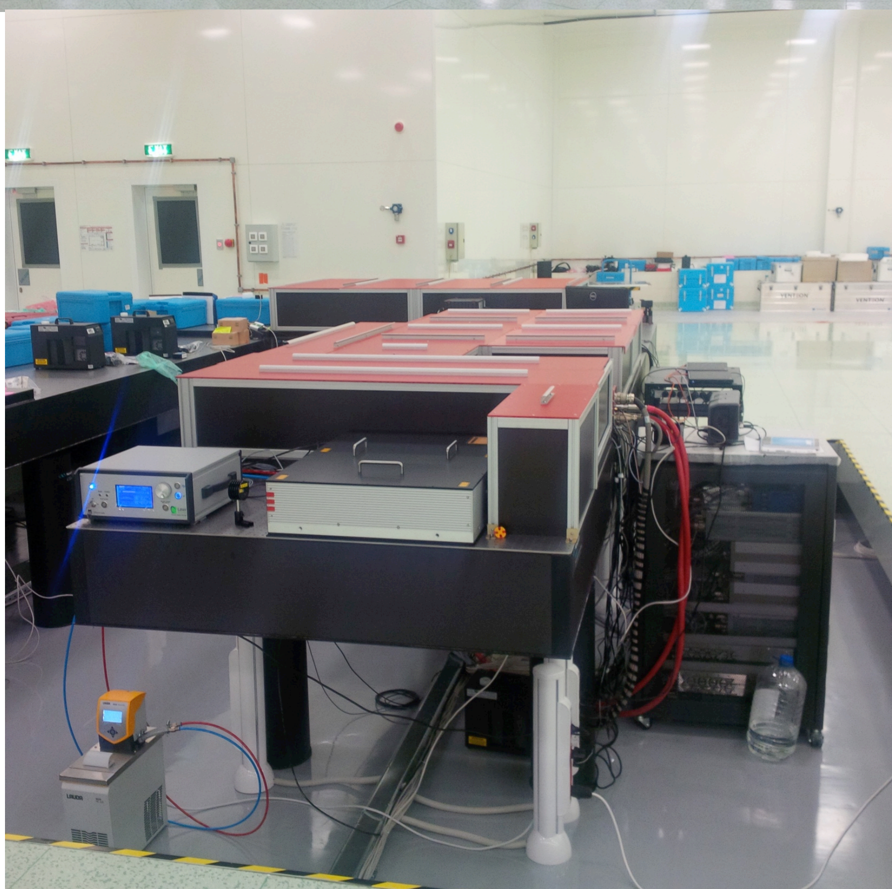


ELI-NP facility (280M€)
Comm. starts from 2019

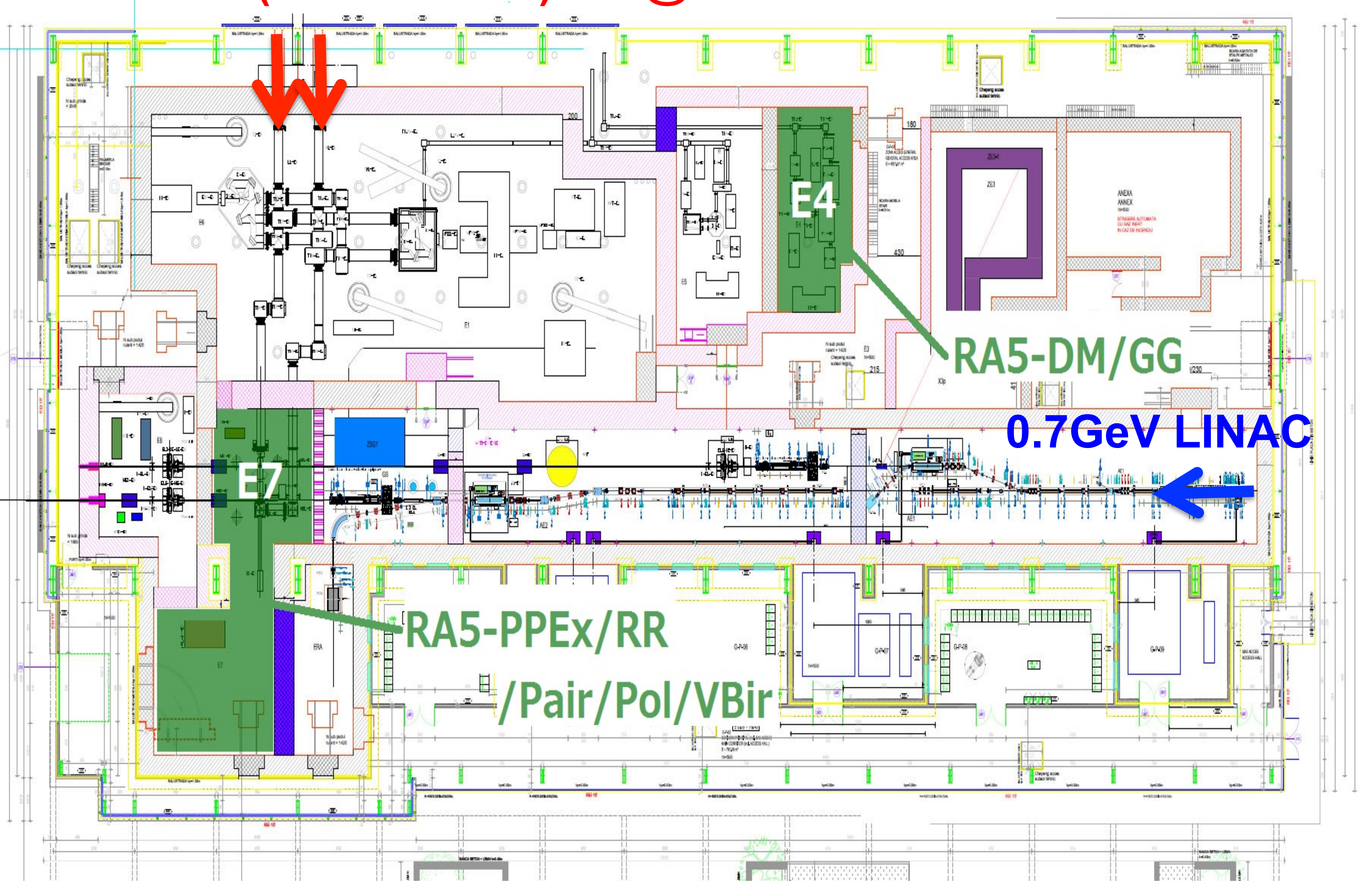
2 x 10PW
2 x 1 PW
2 x 0.1 PW

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

ELI-NP as of June, 2017



$10PW\ (10^{22\text{-}24} W/cm^2) \times 2$ @ 1 shot / min

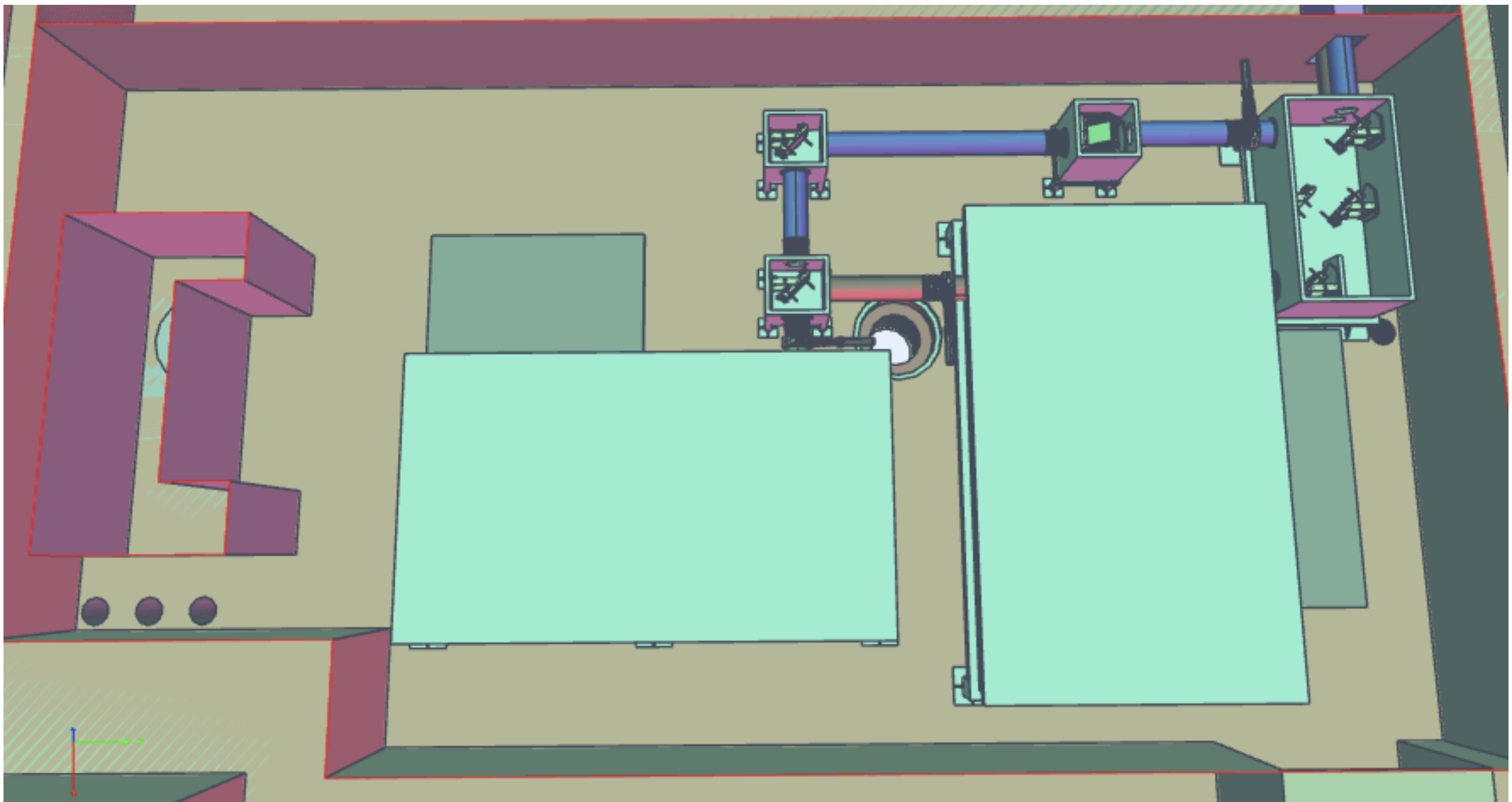


ELI-NP RA5 proposal for dark field search

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]



ICAN : 50J/100fs@10kHz

commentary

Nature Photonics 2013

The future is fibre accelerators

Gerard Mourou, Bill Brocklesby, Toshiki Tajima and Jens Limpert

Could massive arrays of thousands of fibre lasers be the driving force behind next-generation particle accelerators? The International Coherent Amplification Network project believes so and is currently performing a feasibility study.

The challenge of producing the next generation of particle accelerators, for both fundamental research at laboratories such as CERN and more applied tasks such as proton therapy and nuclear transmutation, has been taken up by the high-intensity laser community. With the advent of chirped pulse amplification (CPA) in 1985[1] came the ability to generate ultrashort laser pulses with intensities in excess of 10^{18} W cm^{-2}. At these intensities, the electromagnetic field drives electrons into relativistic motion, opening the door to useful effects like wakefield acceleration[2] and hard X-ray production by bremsstrahlung, Compton or betatron emission[3]. Ion motion becomes relativistic[4] at intensities above 10^{22} W cm^{-2} — an intensity regime demonstrated or anticipated with

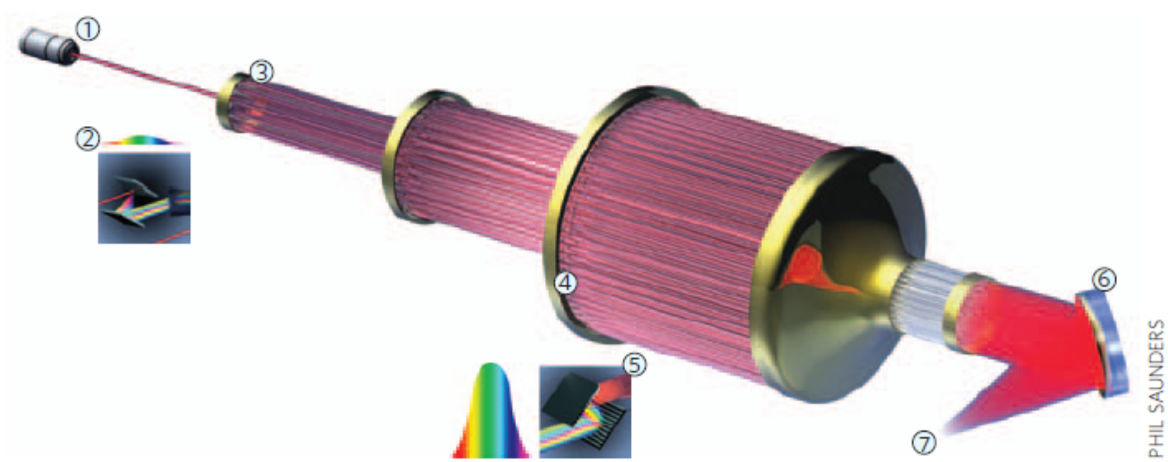
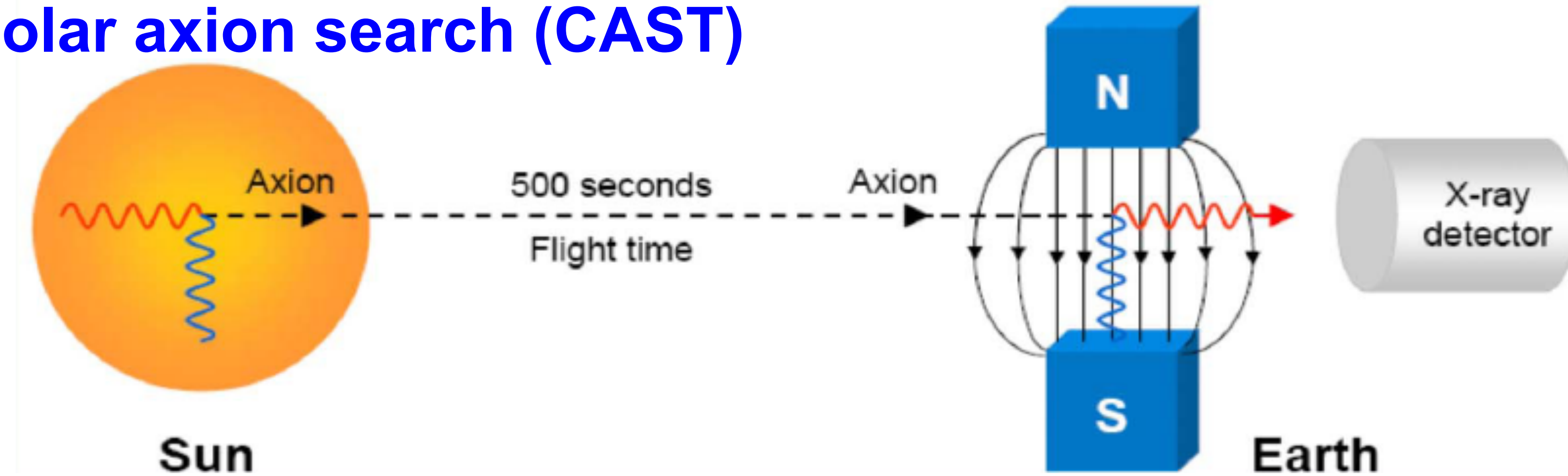


Figure 1 | Principle of a coherent amplifier network. An initial pulse from a seed laser (1) is stretched (2), and split into many fibre channels (3). Each channel is amplified in several stages, with the final stages producing pulses of ~1 mJ at a high repetition rate (4). All the channels are combined coherently, compressed (5) and focused (6) to produce a pulse with an energy of >10 J at a repetition rate of ~10 kHz (7).

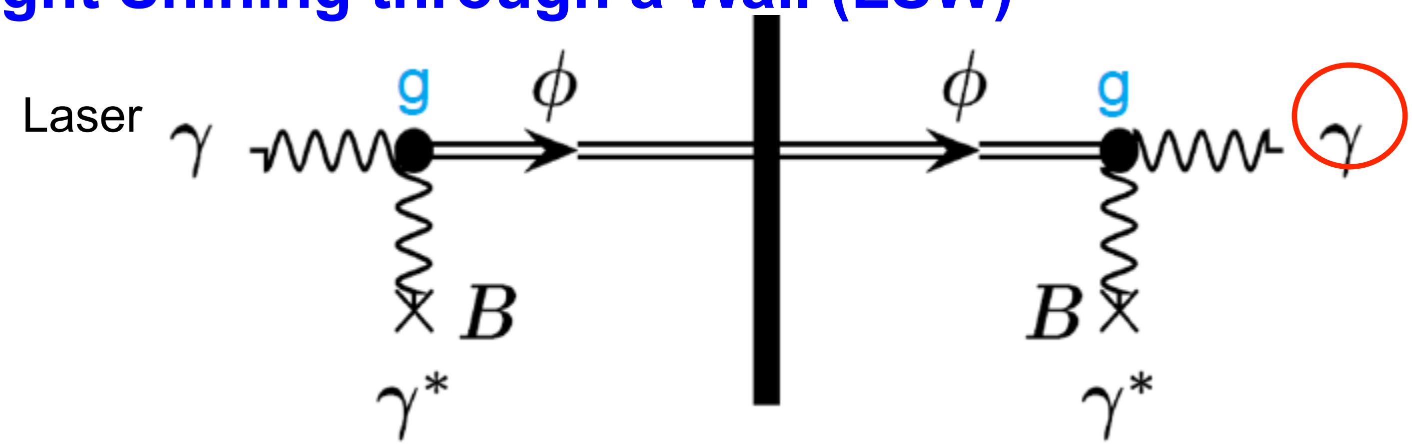
Conventional Axion seach

Solar axion search (CAST)



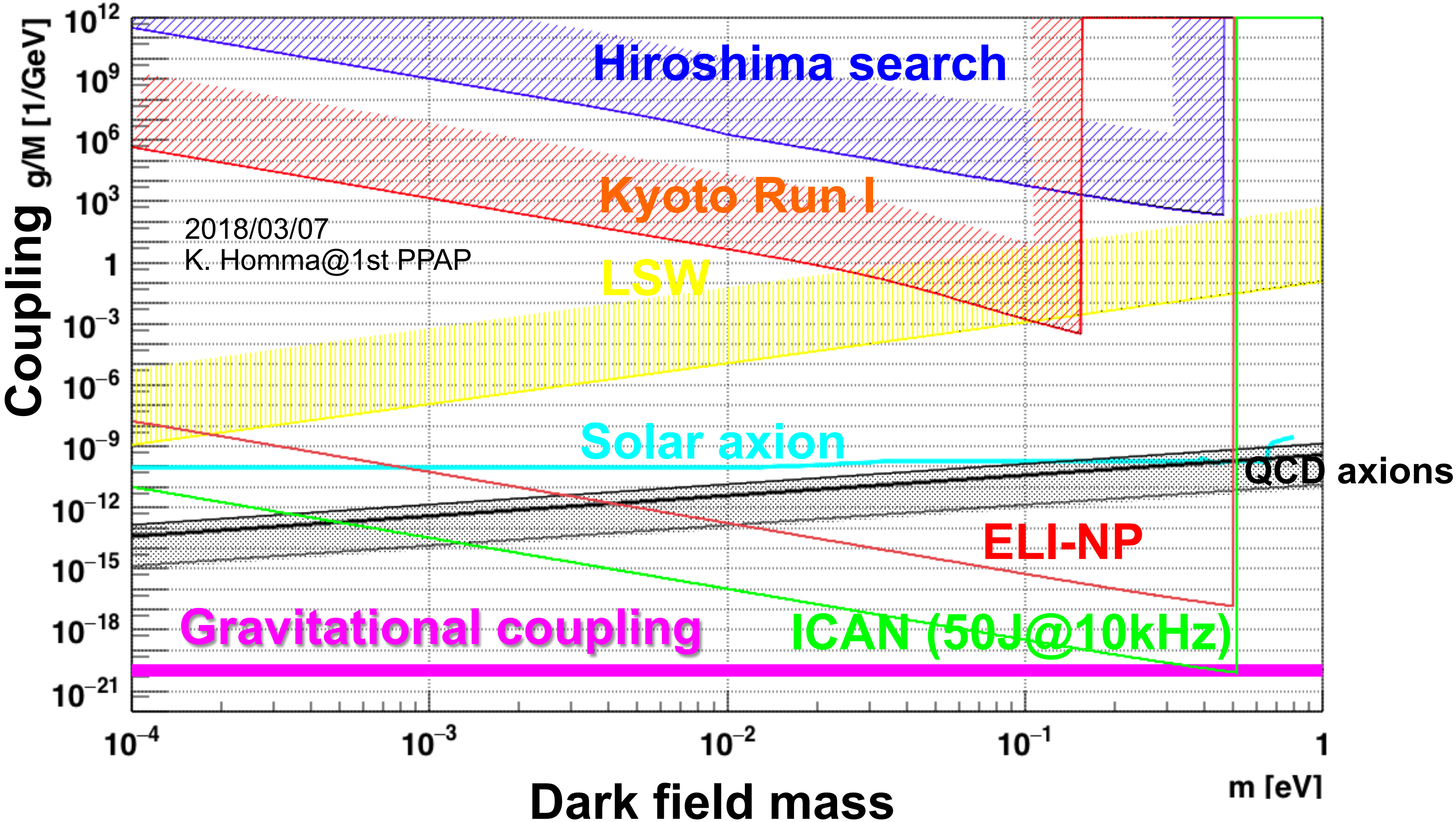
CAST, Theopisti Dafni, 7th Patras Workshop, Mykonos 2011

Light Shining through a Wall (LSW)



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

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



Possibility of 7keV Dark Matter ?

THE ASTROPHYSICAL JOURNAL, 789:13 (23pp), 2014 July 1
doi:10.1088/0004-637X/789/1/13

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

ESRA BULBUL[1,2], MAXIM MARKEVITCH[3], ADAM FOSTER[1], RANDALL K. SMITH[1], MICHAEL LOEWENSTEIN[2,4], AND SCOTT W. RANDALL[1]
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA; ebulbul@cfa.harvard.edu
[2] CRESST and X-ray Astrophysics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[3] NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
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Received 2014 February 10; accepted 2014 April 28; published 2014 June 10

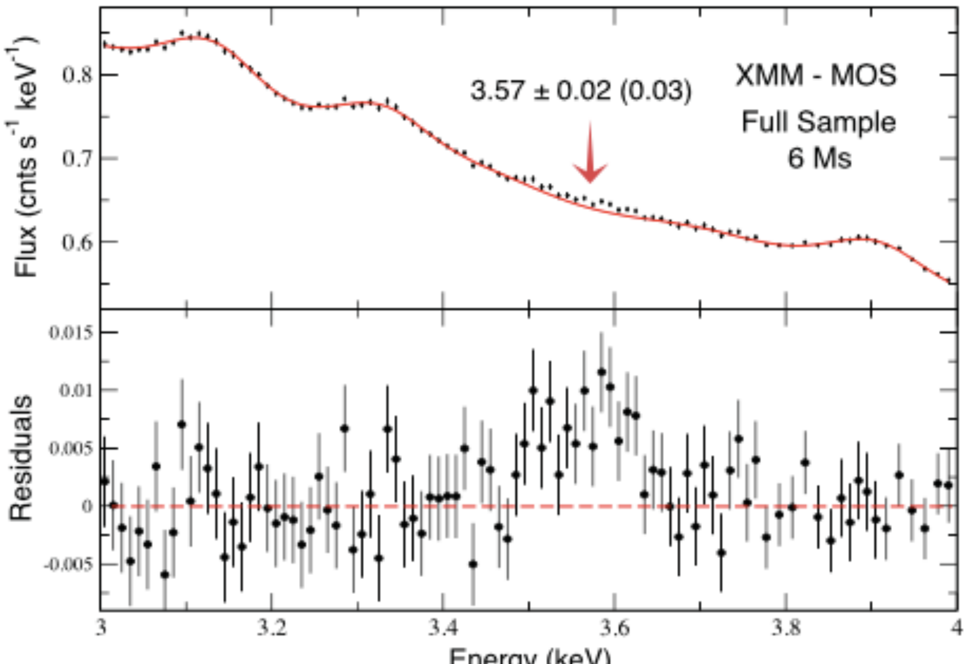


Figure 6. 3–4 keV band of the stacked *XMM-Newton* MOS spectrum of the full sample. The spectrum was rebinned to make the excess at ~3.57 keV more apparent.

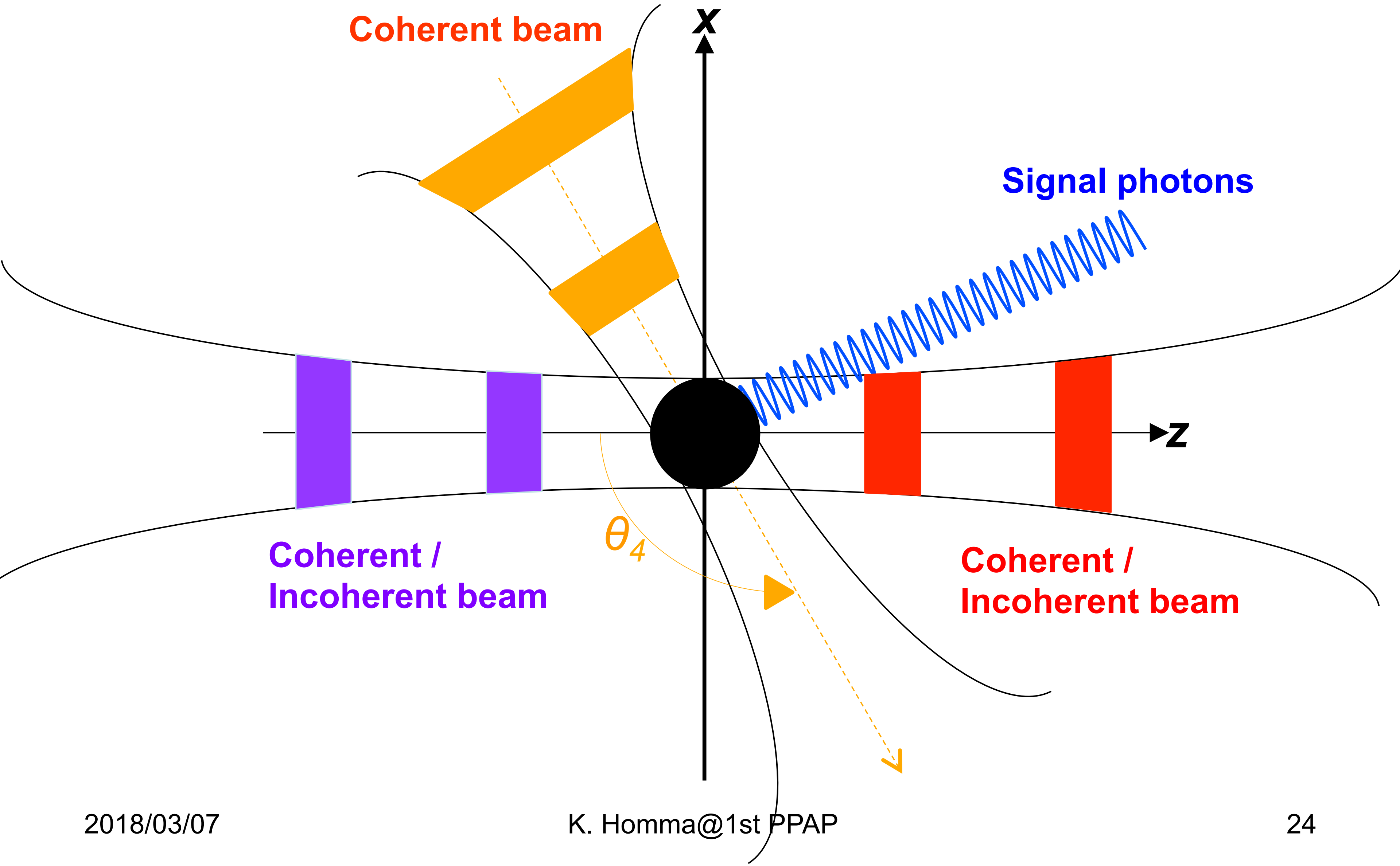
Possibility of ALP ?

$\phi \rightarrow \gamma + \gamma$

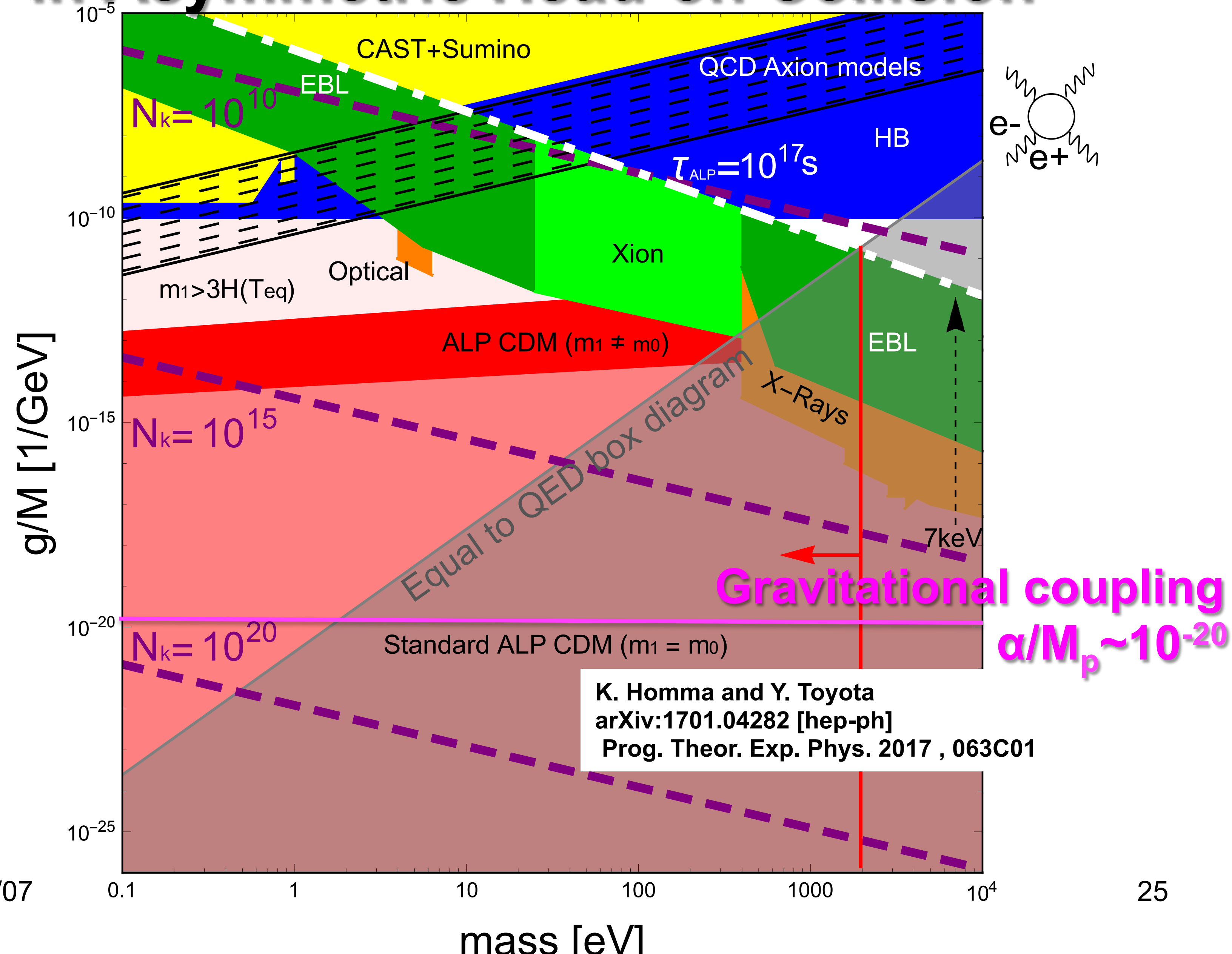
m_ϕ=7.1keV

$10^{-12} < g/M < 10^{-18}\,\mathrm{GeV}^{-1}$

Extension to higher mass domains

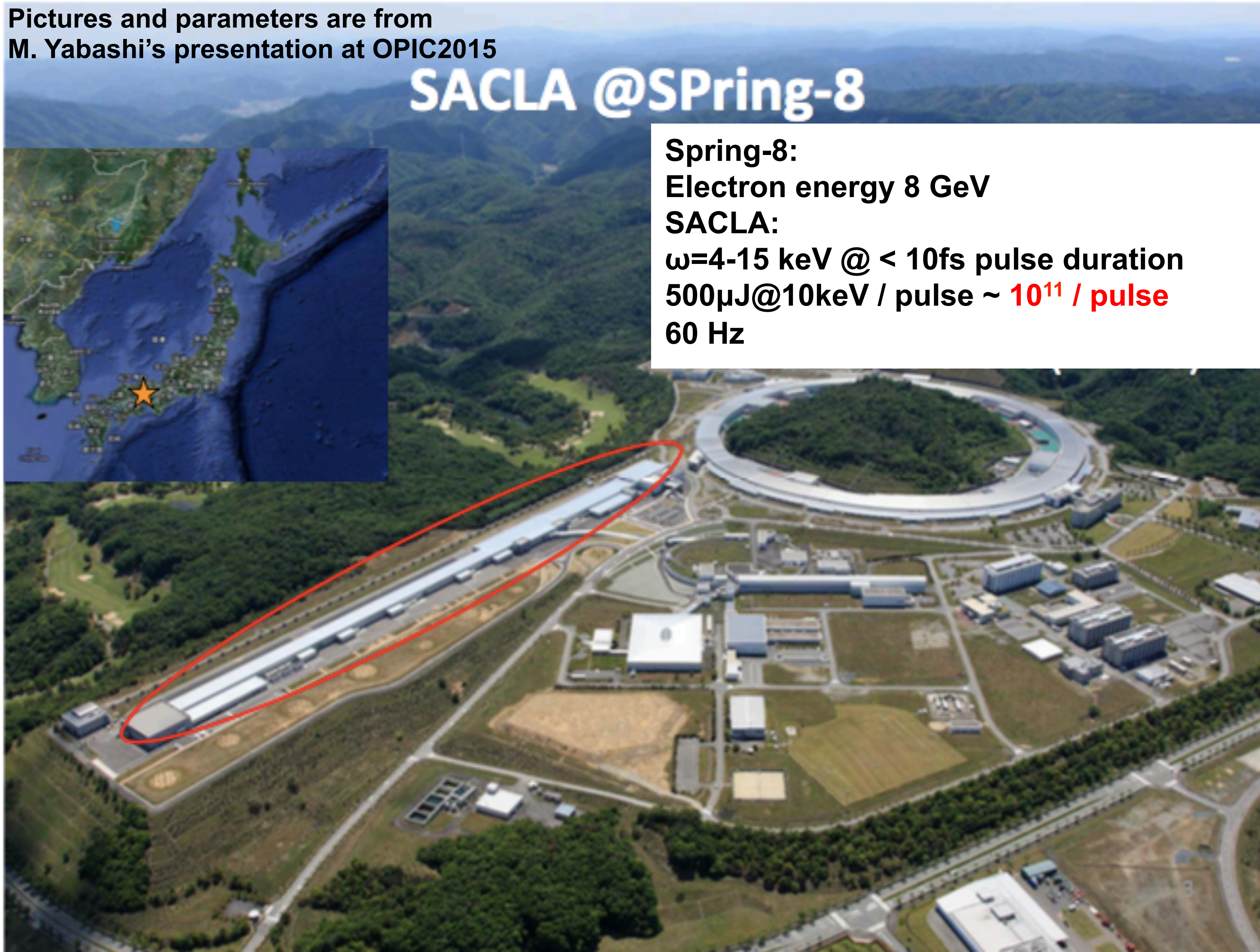


Sensitivity in sub-eV–10 keV mass domain in Asymmetric Head-on Collision



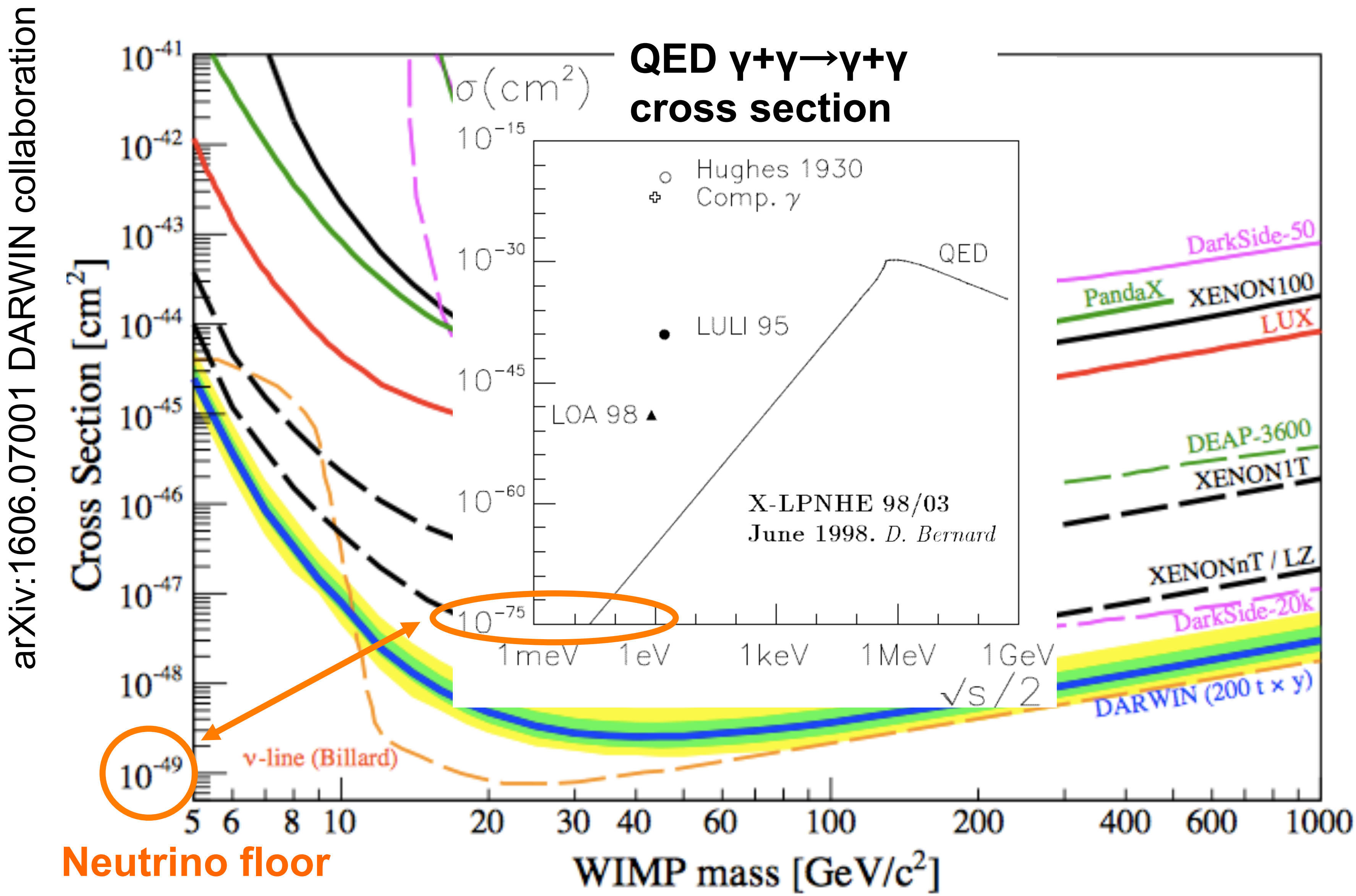
3-XFEL beams, too expensive ?

Pictures and parameters are from
M. Yabashi's presentation at OPIC2015



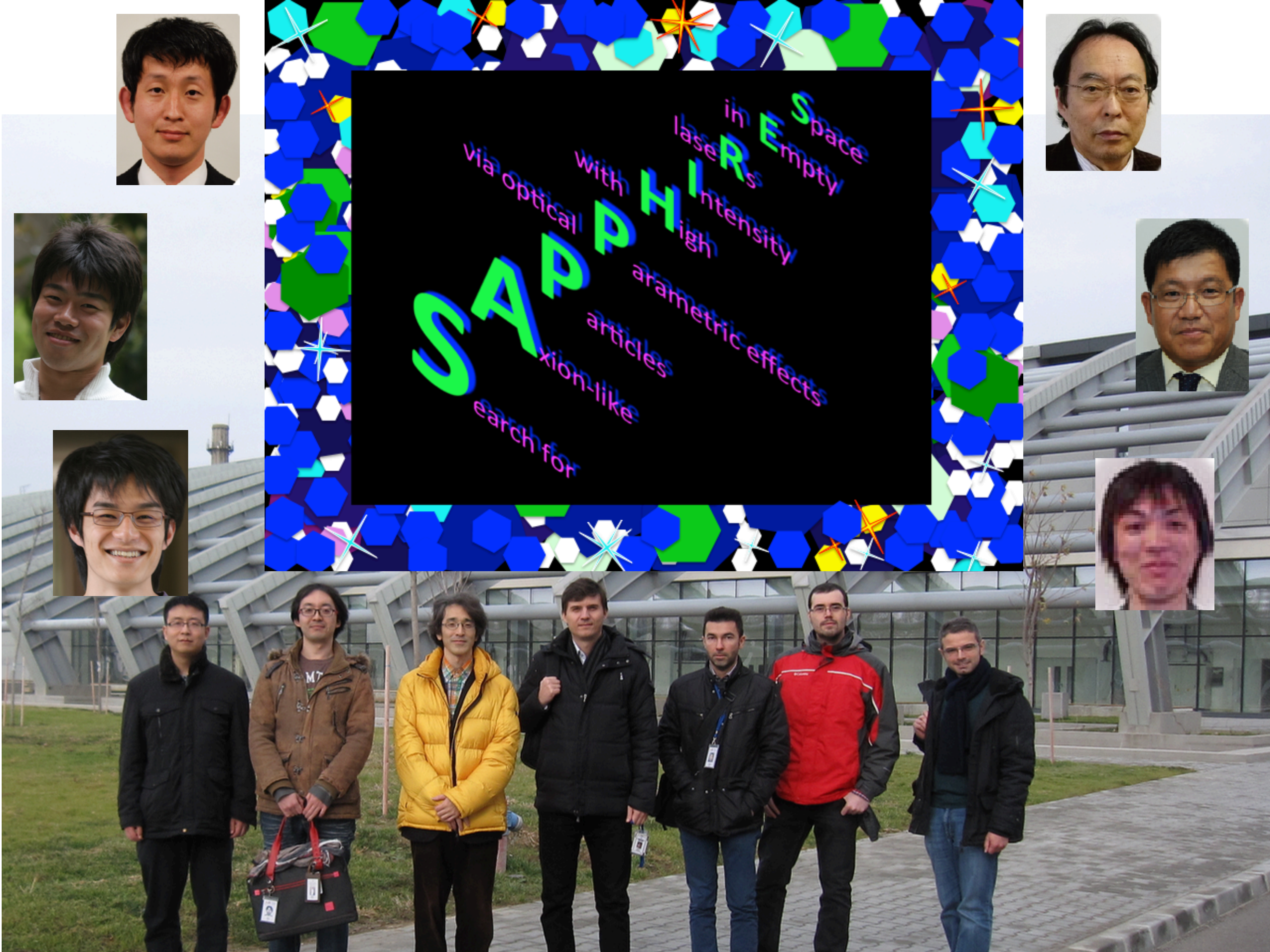
Spring-8:
Electron energy 8 GeV
SACLA:
ω=4-15 keV @ < 10fs pulse duration
500μJ@10keV / pulse ~ 10^{11} / pulse
60 Hz

Comparison with WIMP searches



Charged particle collider vs. Stimulated laser collider

Parameters	Head-on charged particle collider	Stimulated laser collider
c.m.s energy E_{cms}	E_{cms} > 100 GeV	E_{cms} < 1 eV
# of particles / bunch	10^{11} charged particles physically limited by space-charge effect	If ICAN, 10^{20} (@100J/pulse) limited by technology and budget
Single shot dimensionless intensity in luminosity	$(10^{11})^2 = 10^{22}$	$(10^{20})^3 = 10^{60}$
Collision rate	100MHz	If ICAN provides 10kHz
Overall dimensionless intensity in luminosity	$(10^{11})^2 \times 10^8 = 10^{30}$	$(10^{20})^3 \times 10^4 = 10^{64}$



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