Laser Driven Particle Physics

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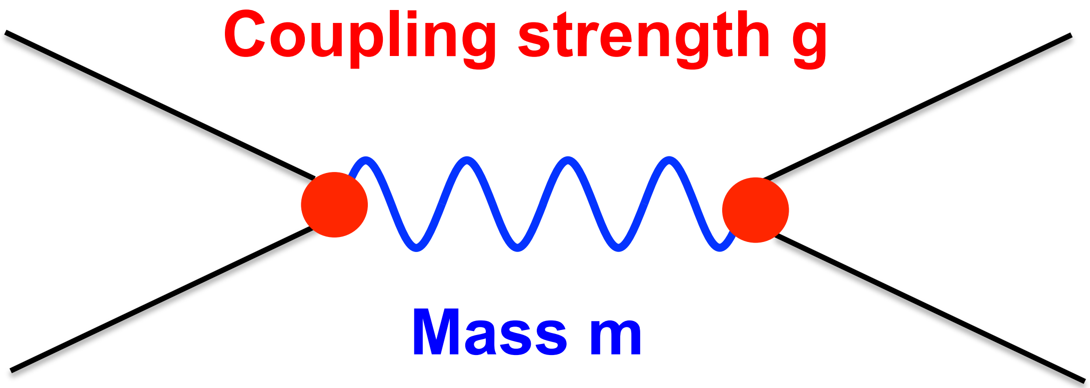
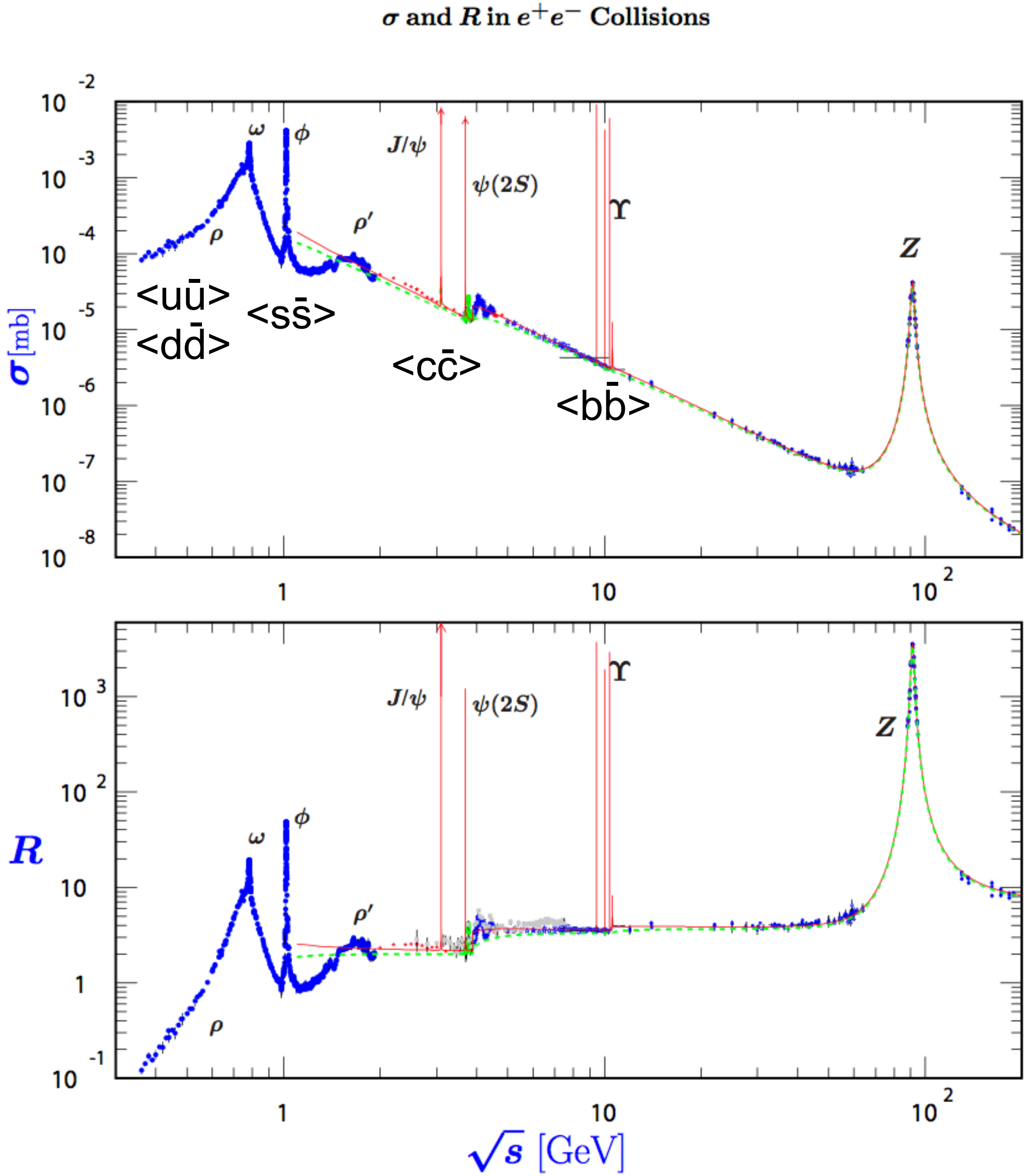
1. **Particle physic and dark components of the Universe**
2. **Photon-photon interactions: Higgs boson, pi0, nonlinear QED, Dark Fields in different energy scales**
3. **Laboratory searches for dark fields**
4. ***Four-Wave-Mixing to detect low-mass DM/DE***
5. **Future prospect on the sensitivity to dark fields**
6. **Summary**

Particle physics and gravity

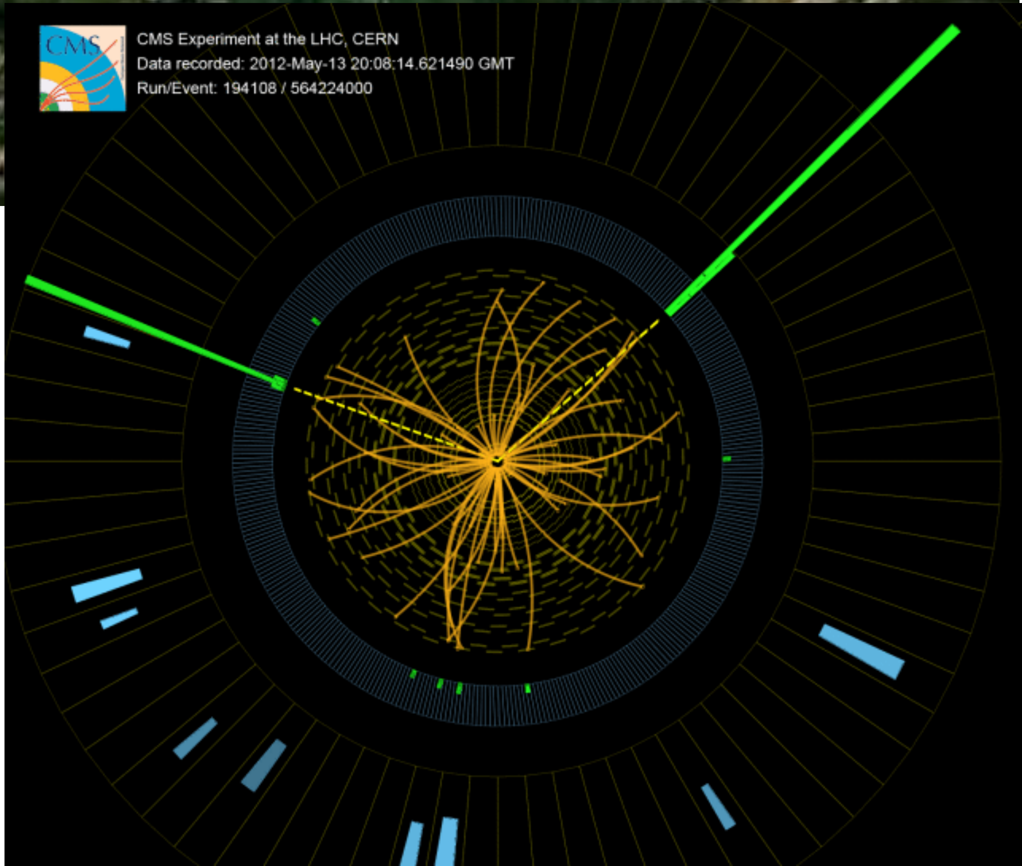


force	strong	nuclear	electromagnetic	weak	gravitational
strength	~0.1	10	1/137	10^{-5}	10^{-38}
distance (cm)	10^{-13}	10^{-13}	∞	10^{-16}	∞
potential	a / r + b r	exp(-mr) / r	1 / r	exp(-mr) / r	1 / r
gauge boson	gluon	pion	photon	W / Z	graviton
theory	QCD	Yukawa	QED	Electroweak	Relativity

Resonance states in nature above 0.1GeV



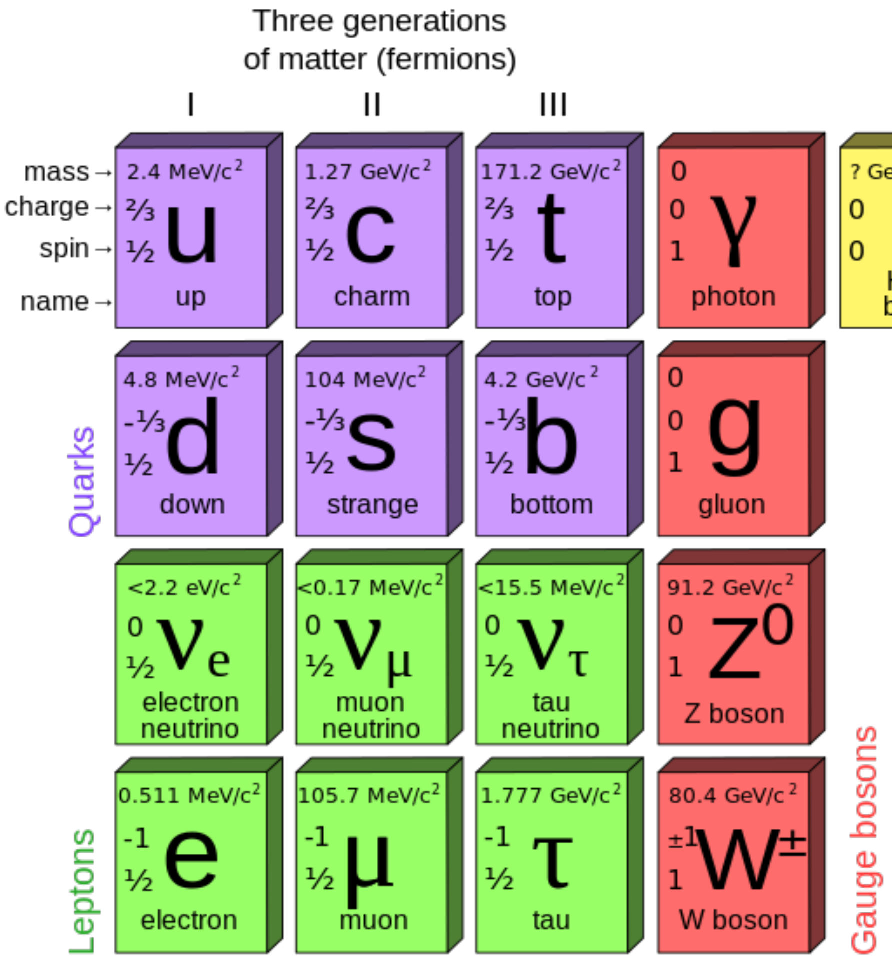
Higgs boson mass at 126 GeV



LHC-CMS Higgs candidate:

$$g + g \rightarrow h^0 \rightarrow \gamma + \gamma$$

The Standard Model



Three generations of matter (fermions)

		I	II	III		
Quarks	mass → charge → spin → name →	2.4 MeV/c^2 ⅔ ½ u up	1.27 GeV/c^2 ⅔ ½ c charm	171.2 GeV/c^2 ⅔ ½ t top	0 0 1 γ photon	? GeV/c^2 0 0 H Higgs boson
		4.8 MeV/c^2 -⅓ ½ d down	104 MeV/c^2 -⅓ ½ s strange	4.2 GeV/c^2 -⅓ ½ b bottom	0 0 1 g gluon	
Leptons		<2.2 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<15.5 MeV/c^2 0 ½ ν_τ tau neutrino	91.2 GeV/c^2 0 1 Z^0 Z boson	
		0.511 MeV/c^2 -1 ½ e electron	105.7 MeV/c^2 -1 ½ μ muon	1.777 GeV/c^2 -1 ½ τ tau	80.4 GeV/c^2 ±1 1 $W^\pm$ W boson	

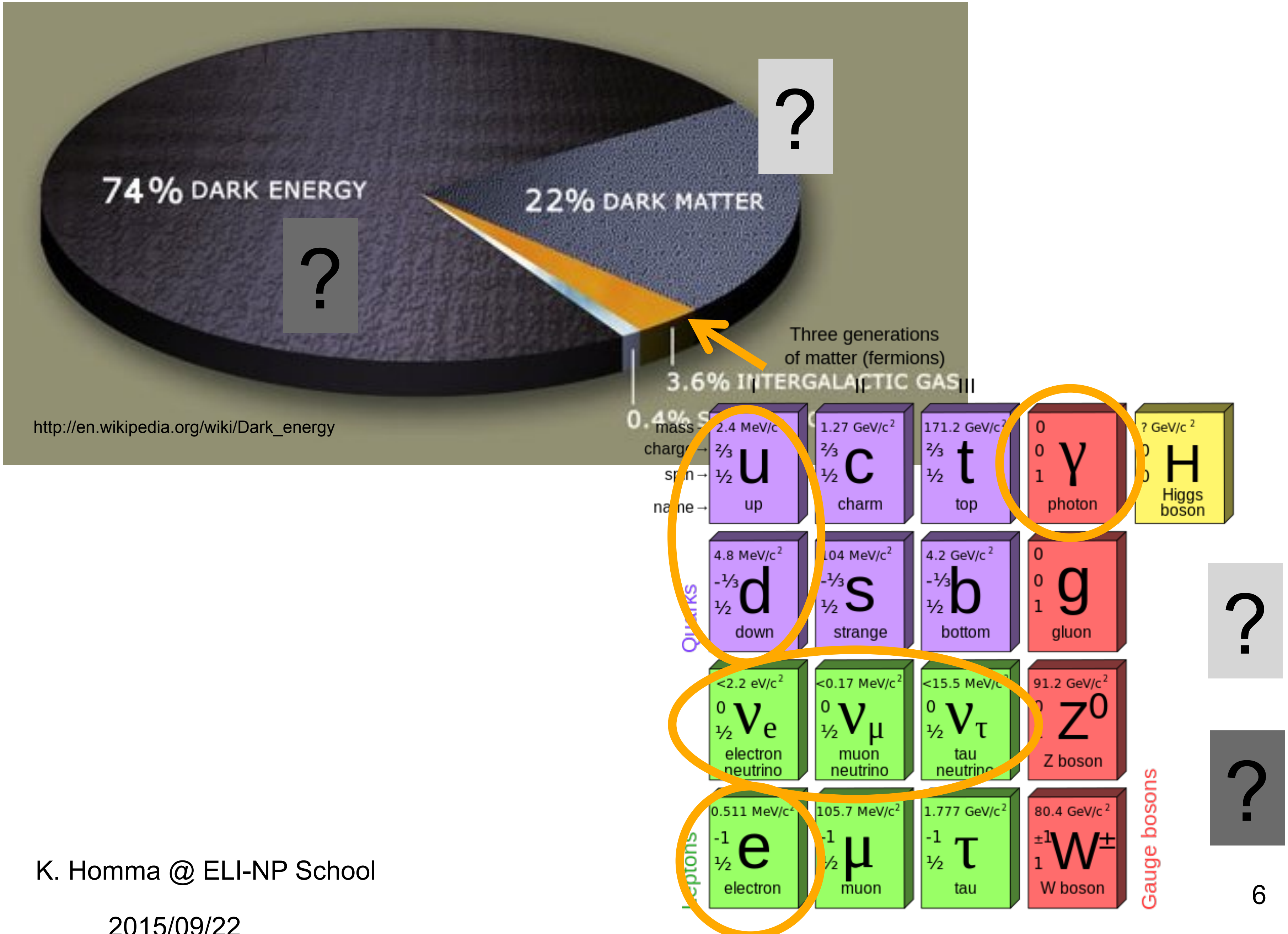
Gauge bosons

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

gives masses to W / Z and leptons

By requiring Gauge Invariance gauge bosons emerge

Dark Fields and the Standard Model



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

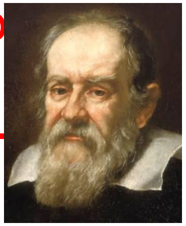
http://en.wikipedia.org/wiki/Standard_Model

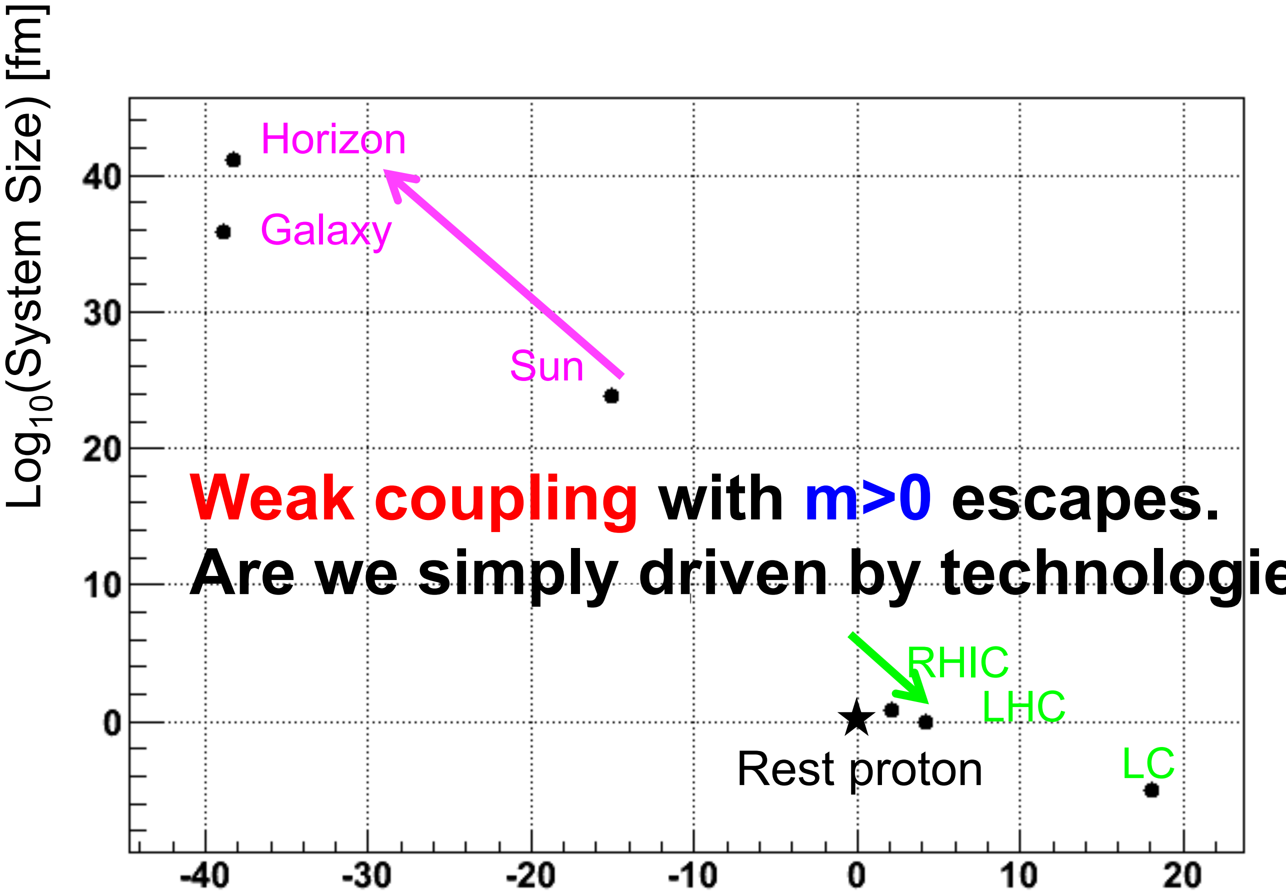
Domains of manifestation of physical laws

Astronomical observation

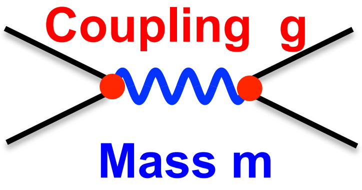
Weak coupling

$m=0$





Weak coupling with $m>0$ escapes.
Are we simply driven by technologies ?



Strong coupling
Heavy m

High energy collider

Laboratory searches for dark fields

- **Weakly Interacting Massive Particles (WIMPS)** such as super symmetric particles:

- Direct production by particle colliders
- Direct detection of dark matter in the universe

- **Weakly Interacting Sub-eV Particles (WISPS)** such as QCD axions and non-Newtonian gravity:

- Light Shining through a Wall (LSW)
- Solar axion search
- Measure deviations from Newtonian potential as a function of distance between bulk massive objects

Photon-Photon interactions in different energy scales

Laser-Laser quantum interaction

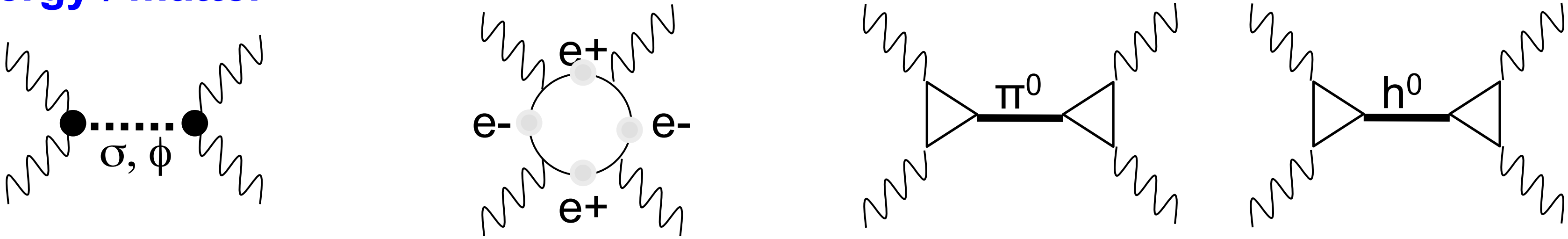
High-energy particle interactions

Very light field in the context of dark energy / matter

Interactions via QED (+QCD)

Chiral symmetry QCD int.

Gauge symmetry Electroweak int.



Undiscovered ! Below 1eV

Not verified ! Below 1 MeV

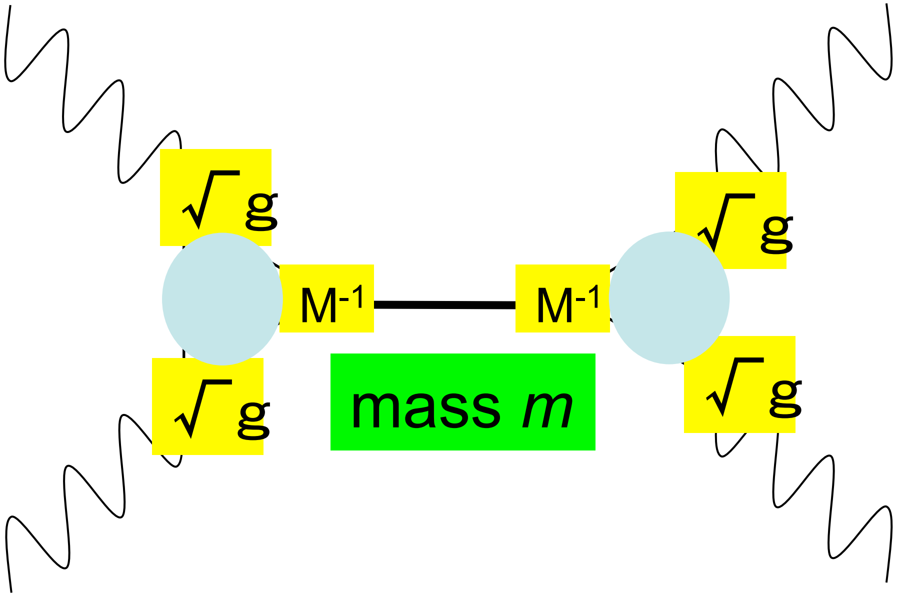
pseudoscalar 135 MeV

scalar 126 GeV

Photon-photon center of mass energy

Production of low-mass bosons by colliding laser photons

In the case of Higgs boson $\sim g(246\ GeV)^{-1} F^{\mu\nu} F_{\mu\nu} h$



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)

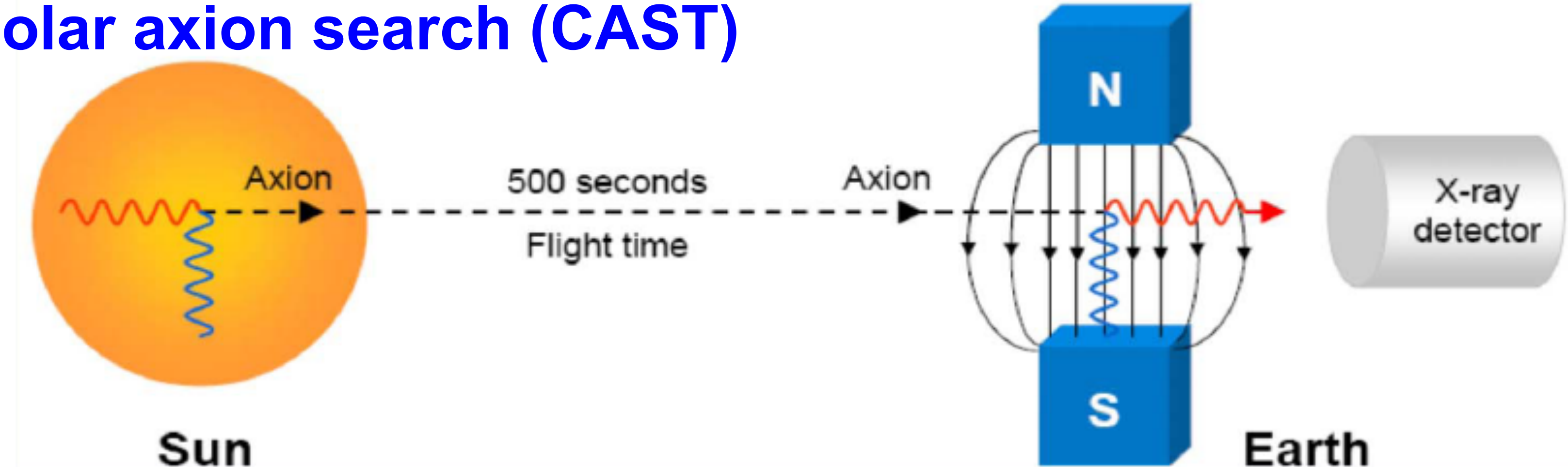
$$gM^{-1} F^{\mu\nu} F_{\mu\nu} \phi$$

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

mass>10^{-9} eV

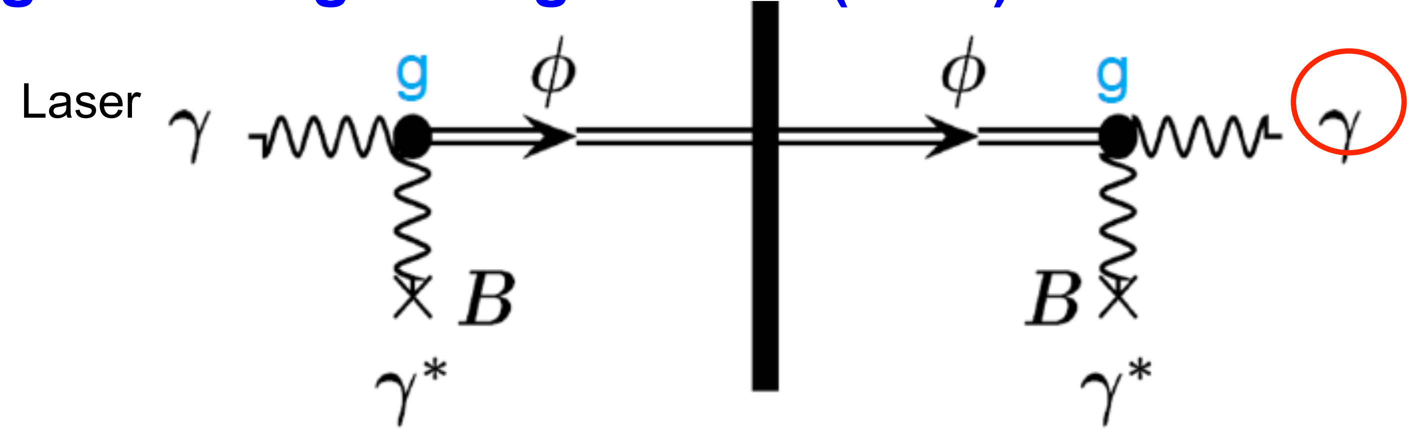
Conventional Axion seach

Solar axion search (CAST)



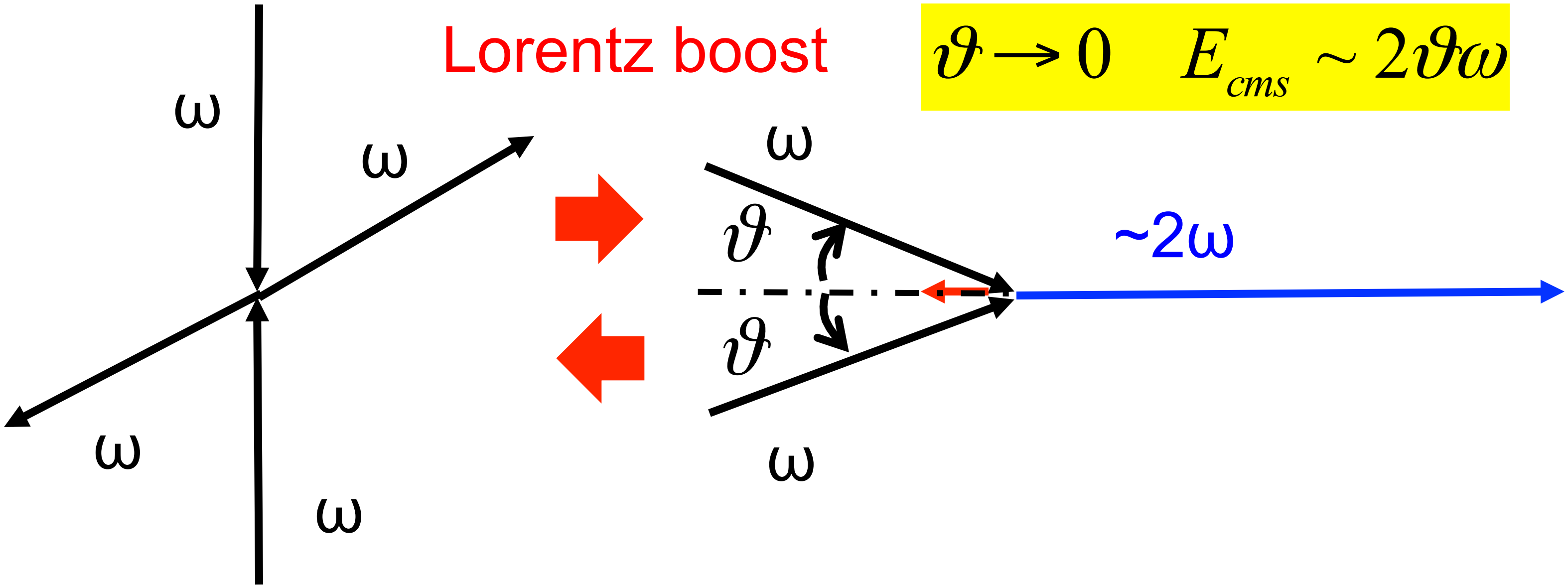
CAST, Theopisti Dafni, 7th Patras Workshop, Mykonos 2011

Light Shining through a Wall (LSW)



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

Hit resonance by lowering C.M.S. energy



$$\vartheta \to 0 \quad E_{cms} \sim 2\vartheta\omega$$

Center of Mass System

Quasi Parallel System

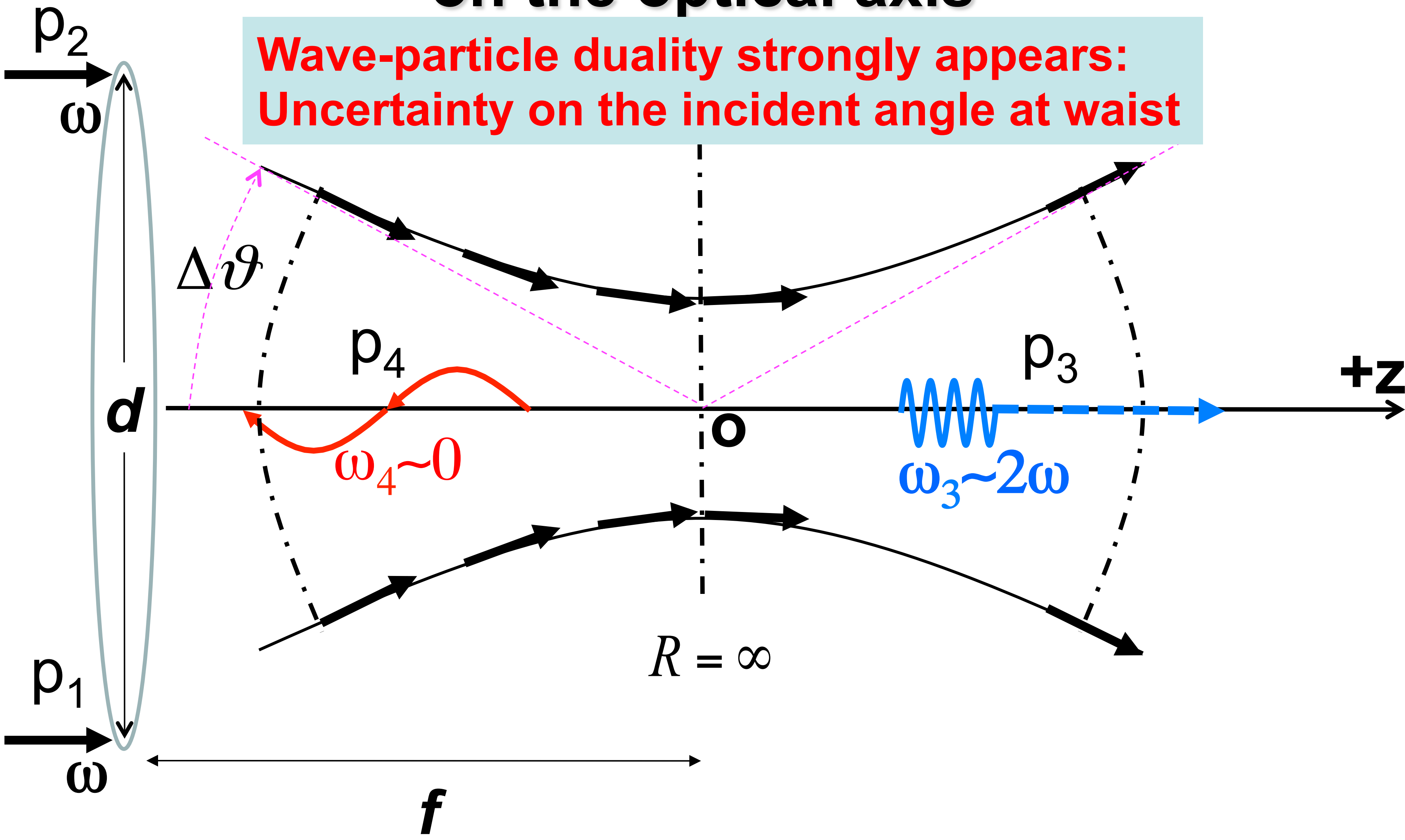
No frequency shift

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

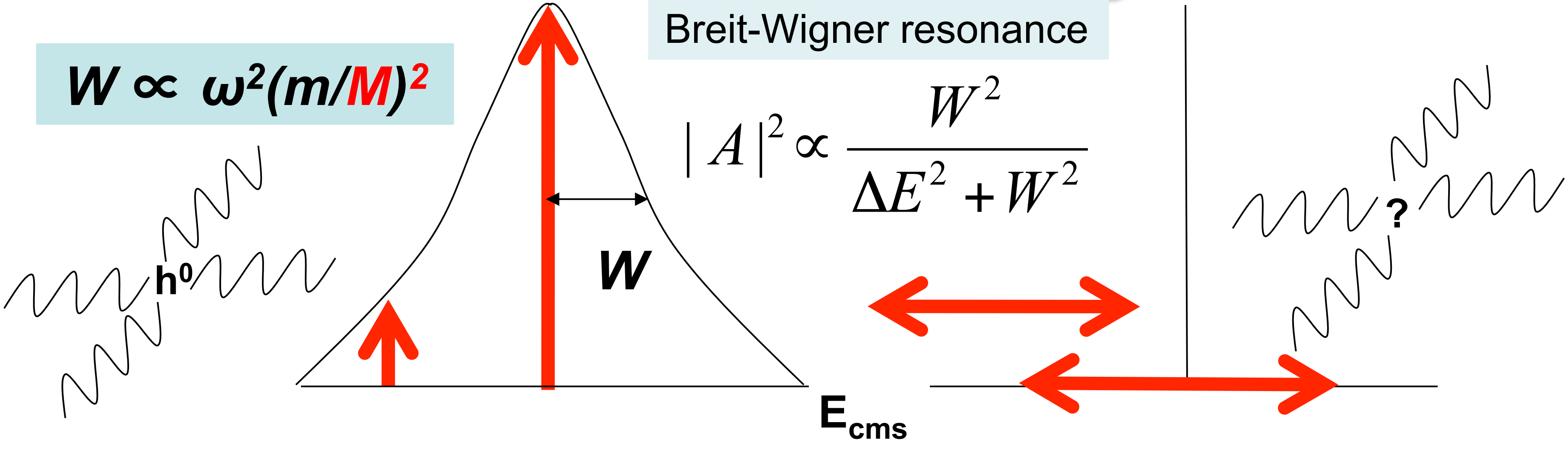
Low frequency photon in QPS is an ideal system !

Single laser focusing and second harmonic on the optical axis

Wave-particle duality strongly appears:
Uncertainty on the incident angle at waist



Enhancement by containing resonance



$W \propto \omega^2(m/M)^2$

Breit-Wigner resonance

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

e.g. γ−γ Higgs factory

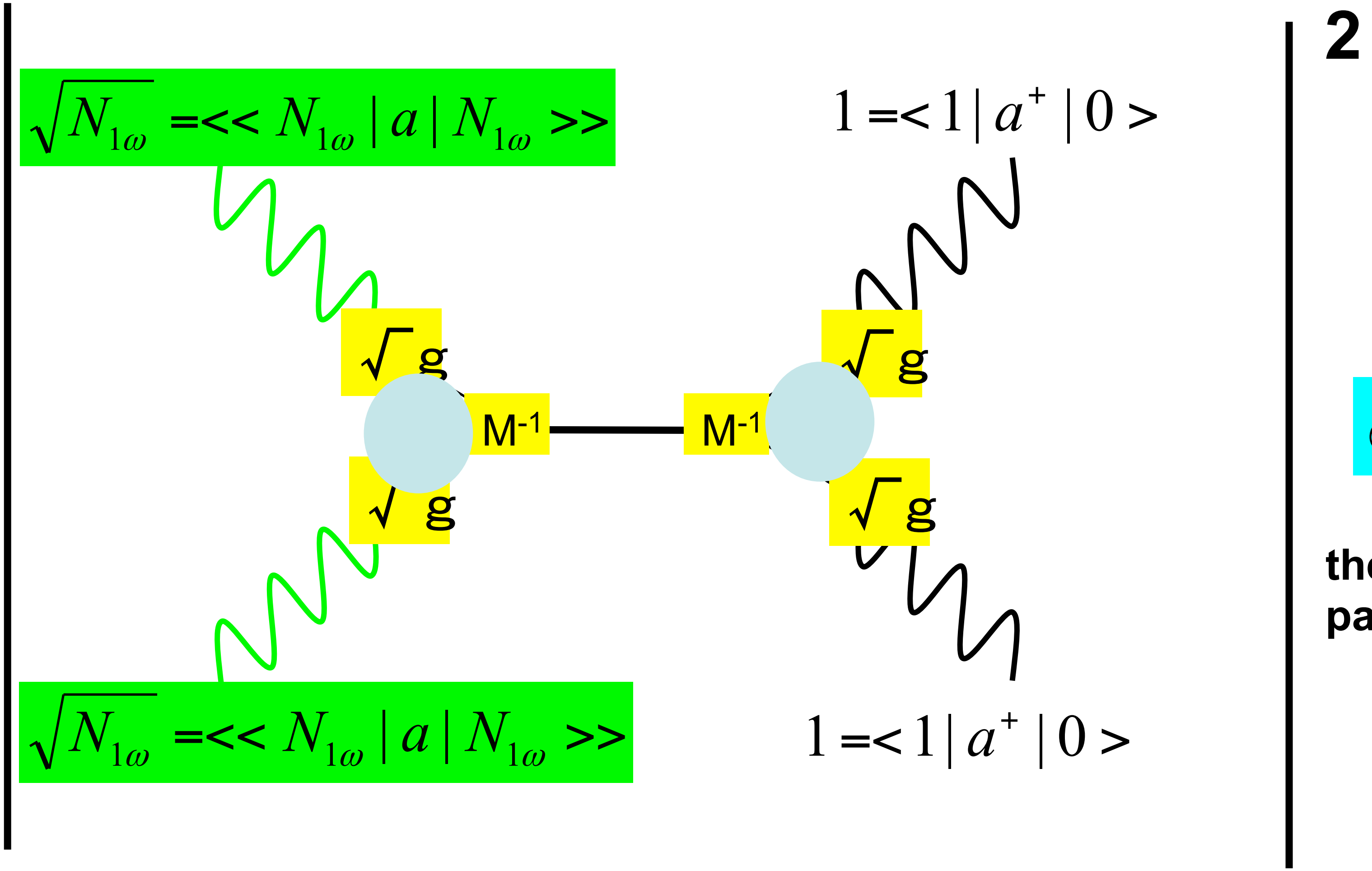
Collider in diffraction limit of QPS

We must integrate square of invariant amplitude in QPS

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

Gain by M^2

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



$$\sqrt{N_{1\omega}} = \langle\langle N_{1\omega} | a | N_{1\omega} \rangle\rangle$$

$$1 = \langle 1 | a^{+} | 0 \rangle$$

$$\sqrt{N_{1\omega}} = \langle\langle N_{1\omega} | a | N_{1\omega} \rangle\rangle$$

$$1 = \langle 1 | a^{+} | 0 \rangle$$

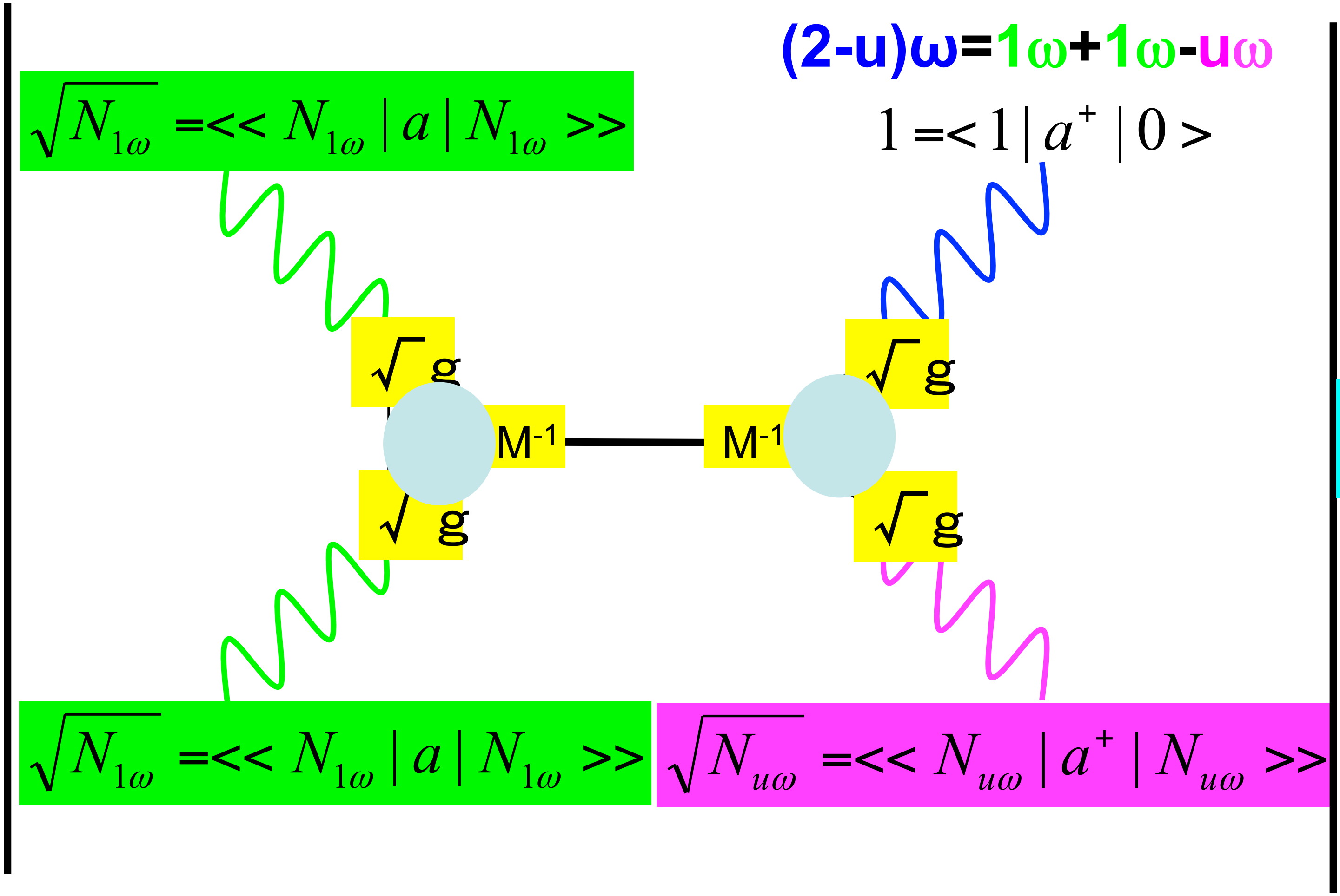
$$\propto N^{2}{}_{1\omega}$$

the same rate as particle colliders

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

Enhancement by inducing laser field

- decay in the sea of photons-



(2-u)ω=1ω+1ω-uω

$1 =< 1 | a^{+} | 0 >$

$\sqrt{N_{1\omega}} =<< N_{1\omega} | a | N_{1\omega} >>$

$\sqrt{N_{1\omega}} =<< N_{1\omega} | a | N_{1\omega} >>$

$\sqrt{N_{u\omega}} =<< N_{u\omega} | a^{+} | N_{u\omega} >>$

2

N~10²³ = 200kJ

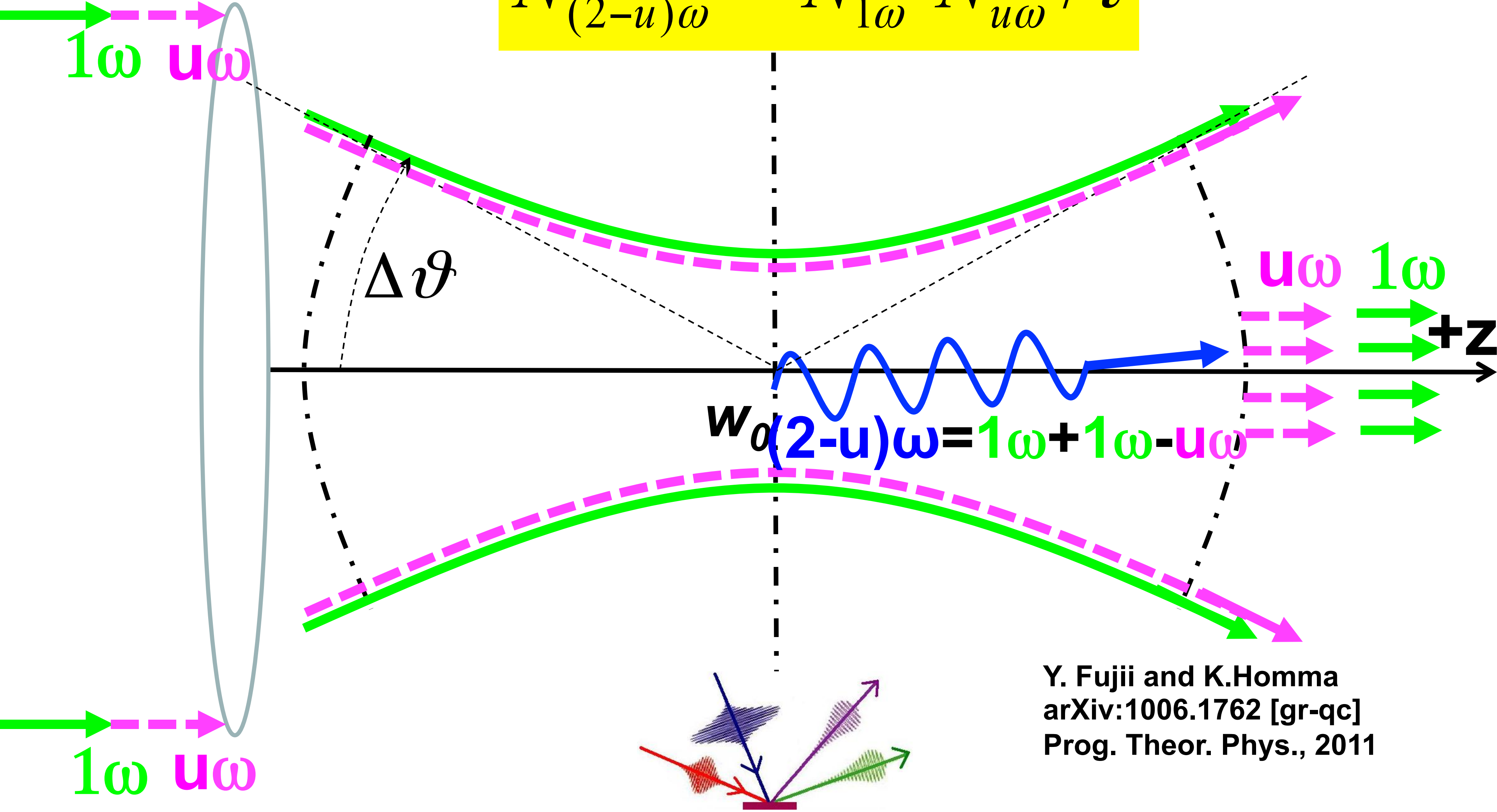
$\propto N^{2}_{1\omega} N_{u\omega}$

Cubic dependence

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

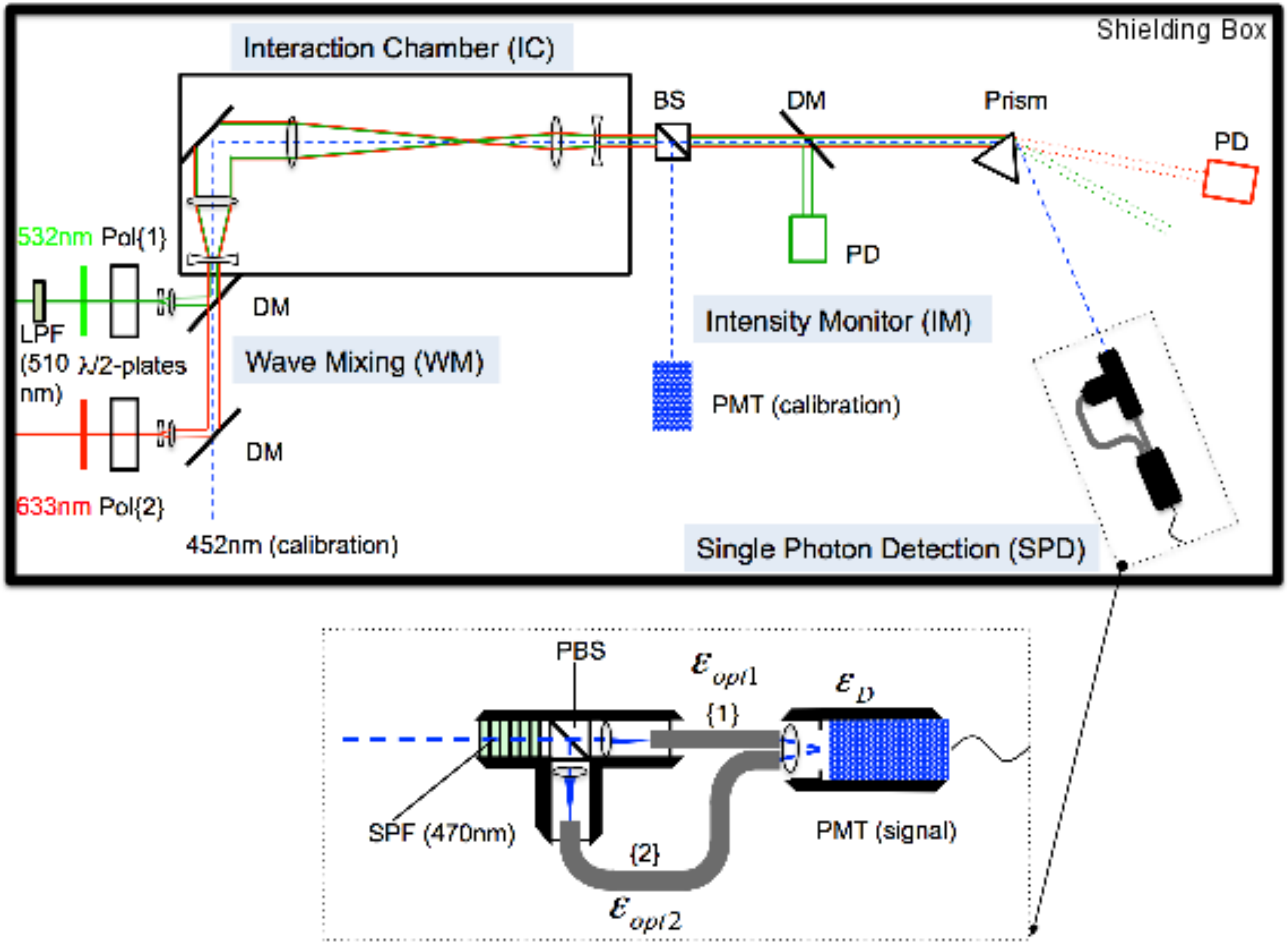
Four-Wave Mixing in Vacuum

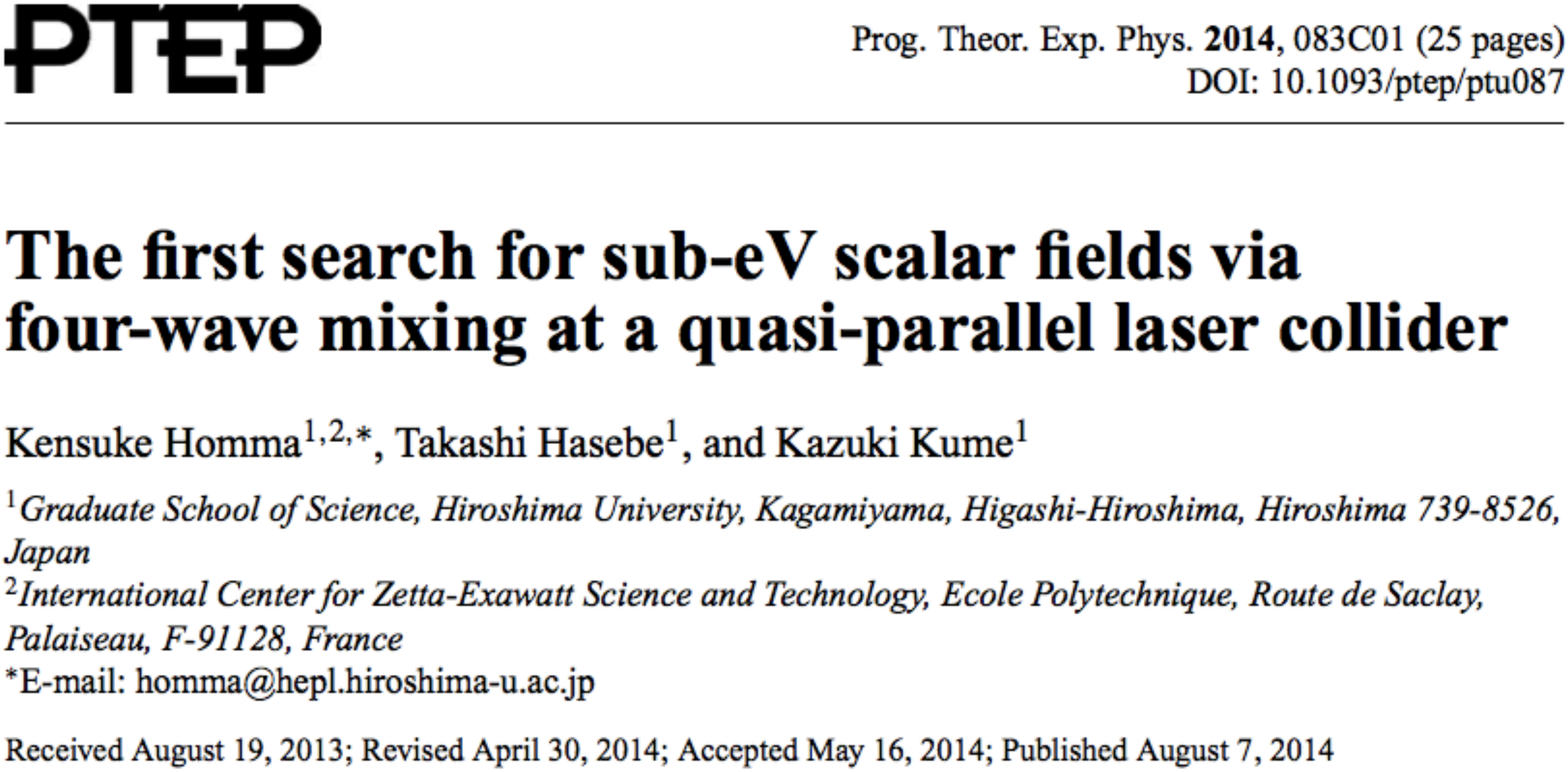
$$N_{(2-u)\omega} \propto N_{1\omega}{}^{2} N_{u\omega} / \tau$$



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

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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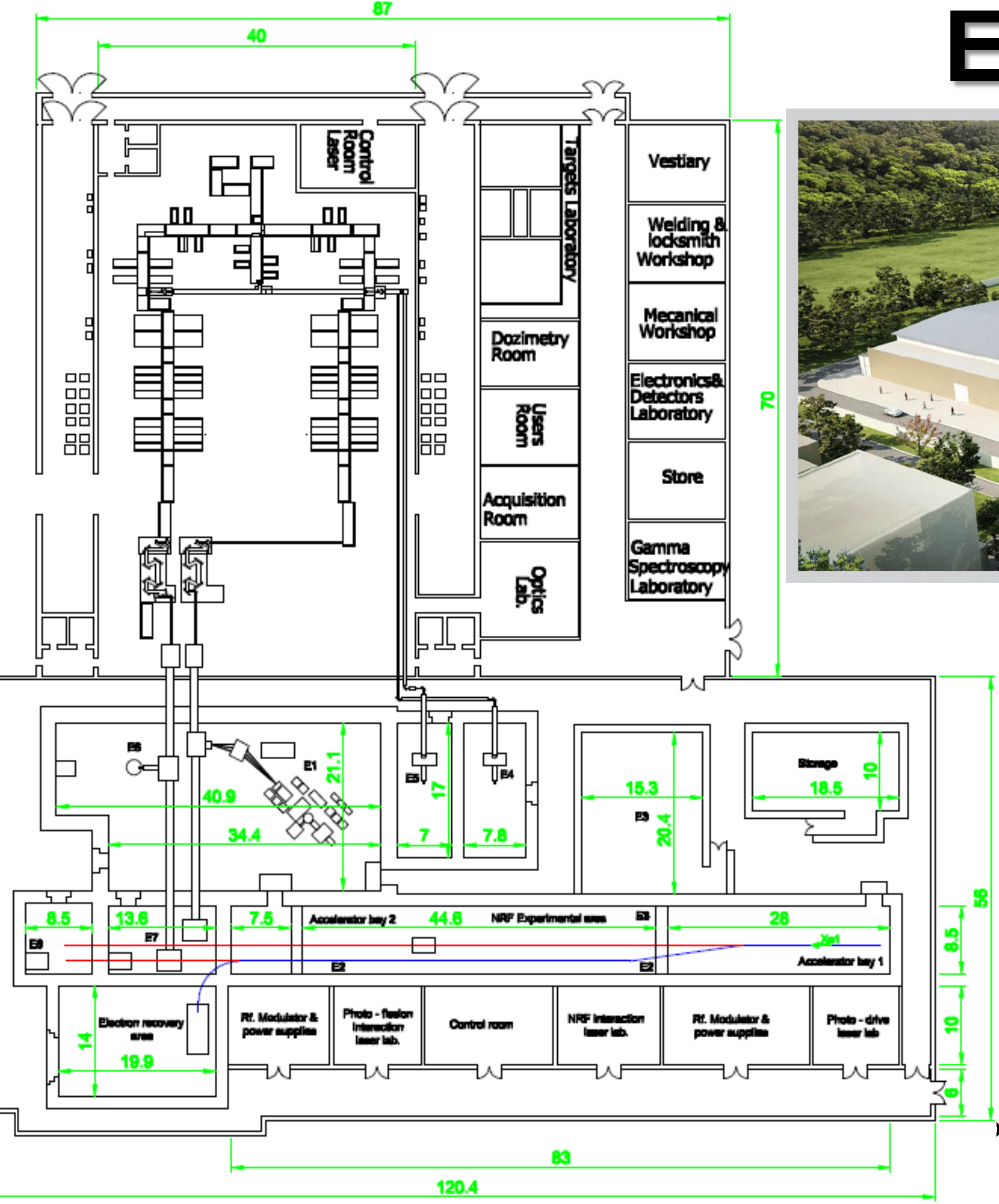
ELI project



ELI-NP facility (280M€)

2 x 10PW lasers

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

ICAN : 50J/100fs@10kHz

commentary

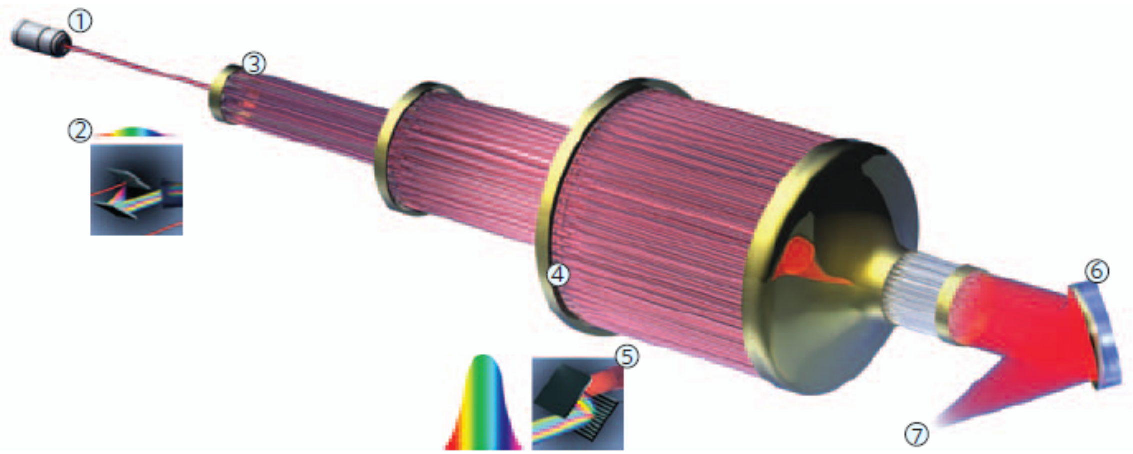
Nature Photonics 2013

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



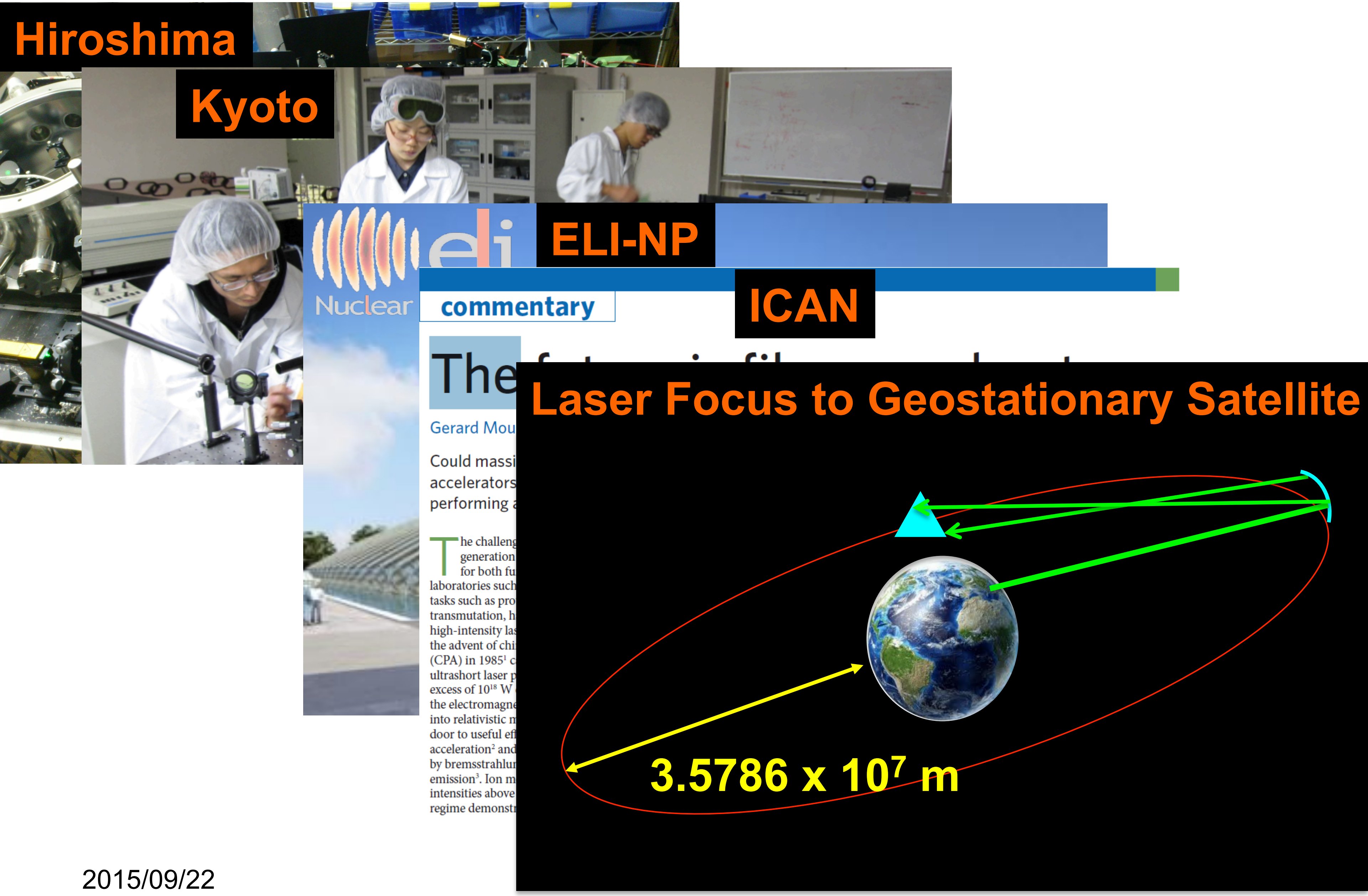
PHIL SAUNDERS

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).

Head-on Particle Collider vs. Degenerate Quasi-Parallel Particle Collider

Parameters	Head-on Particle Collider	Degenerate Quasi-parallel Particle 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	$(10^{11})^{2} \times 10^{8} = 10^{30}$	$(10^{20})^{3} \times 10^{4} = 10^{64}$

Strategy of searching for dark fields



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commentary

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emission[3]. Ion m
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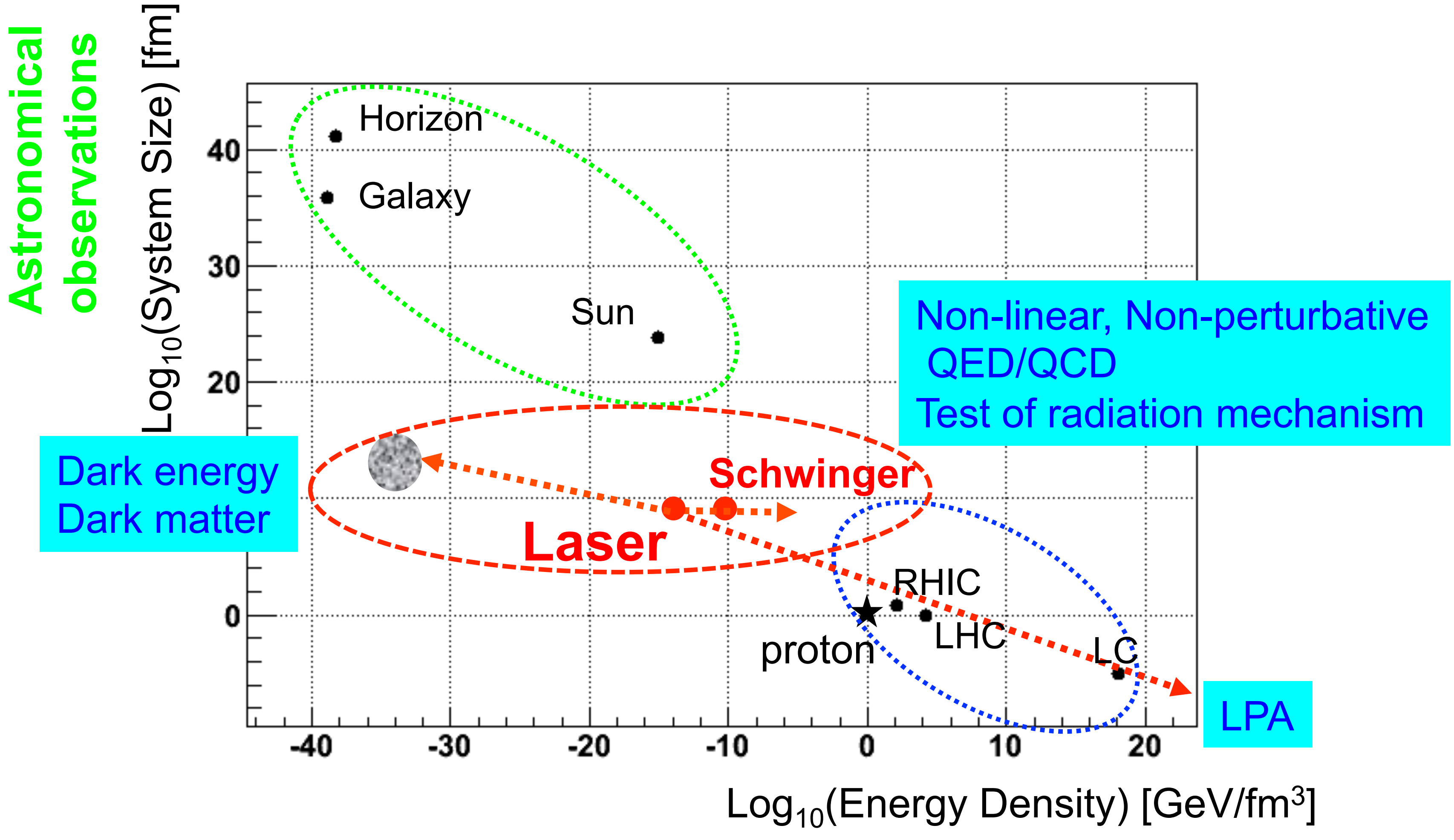
Laser Focus to Geostationary Satellite

Explorable three major directions by high-intensity lasers



Non-linear, Non-perturbative QED/QCD
Test of radiation mechanism

Dark energy
Dark matter

LPA

High energy colliders