Probing the quantum vacuum by high-intensity lasers

- toward search for dark fields -

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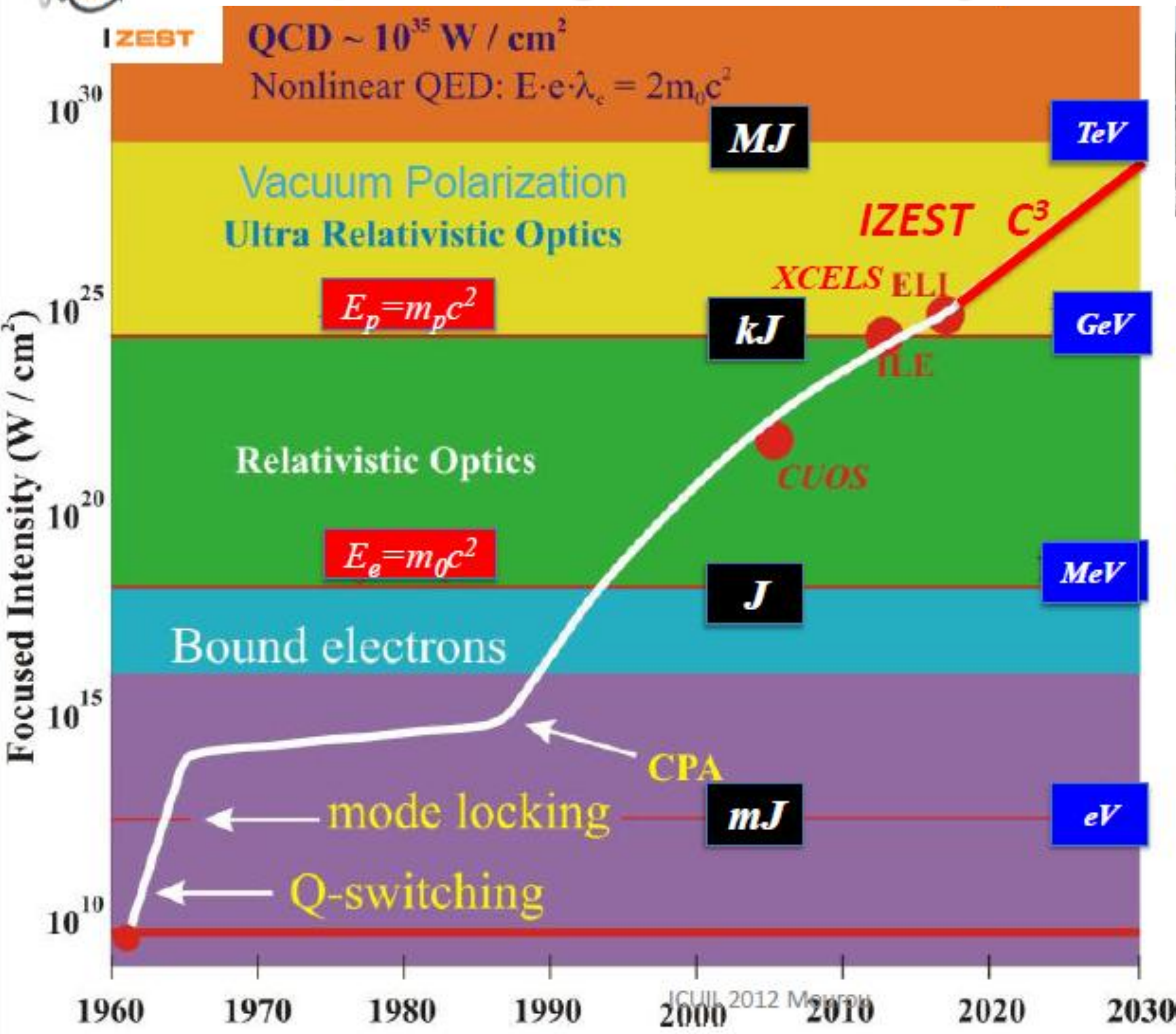
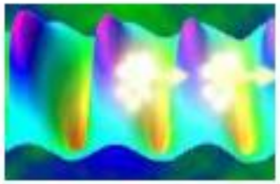
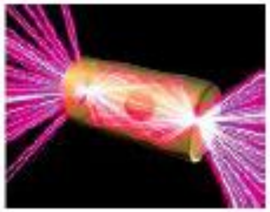
Acknowledgment :
G. Mourou, T. Tajima, Y. Fujii, D. Habs, K. Witte, V. Zamfier,
S. Sakabe, J.C. Kieffer, K. Otani, J. Fuchs, K. Nakajima

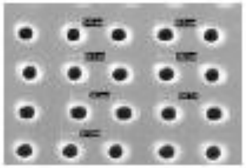
1. **Leap of high-intensity lasers**
2. **International center on Zetta-Exawatt Science and Technology (IZEST association)**
3. ***Four-Wave-Mixing to detect low-mass Dark Fields***
4. ***Particle Collider vs. Degenerate Particle Collider***
5. **Explorable three directions of fundamental physics by high-intensity laser technologies**

Leap of high-intensity lasers









IZEST Associate Laboratories

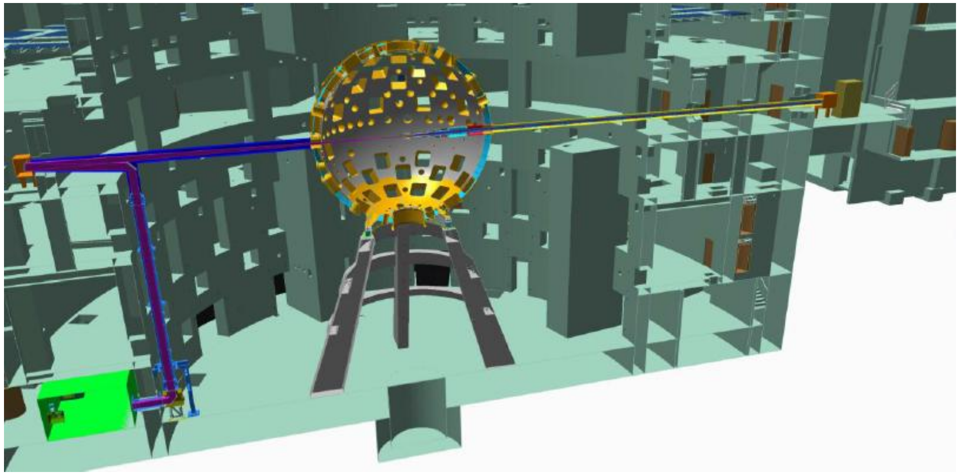
International center on Zetta-Exawatt Science & Technology
http://www.izest.polytechnique.edu

Ecole Polytechnique - Palaiseau, France
CEA - Commissariat à l'Energie Atomique et aux énergies alternatives, Bordeaux, France
PPPL - Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA
FERMILAB - Fermi National Accelerator Laboratory, Chicago, Illinois, USA
LLNL - Lawrence Livermore National Laboratory, Livermore, California, USA
CUOS - Center for Ultrafast Optical Science, Ann Arbor, Michigan, USA
ALLS - Advanced Laser Light Source, Montreal, Canada
JAI - John Adams Institute for accelerator science, Oxford, UK
TOPS - TeraHertz to Optical Pulse Source, Strathclyde, UK
HHU - Heinrich Heine Universität, Düsseldorf, Germany
MEPhI - Moscow Engineering Physics Institute, Moscow, Russia

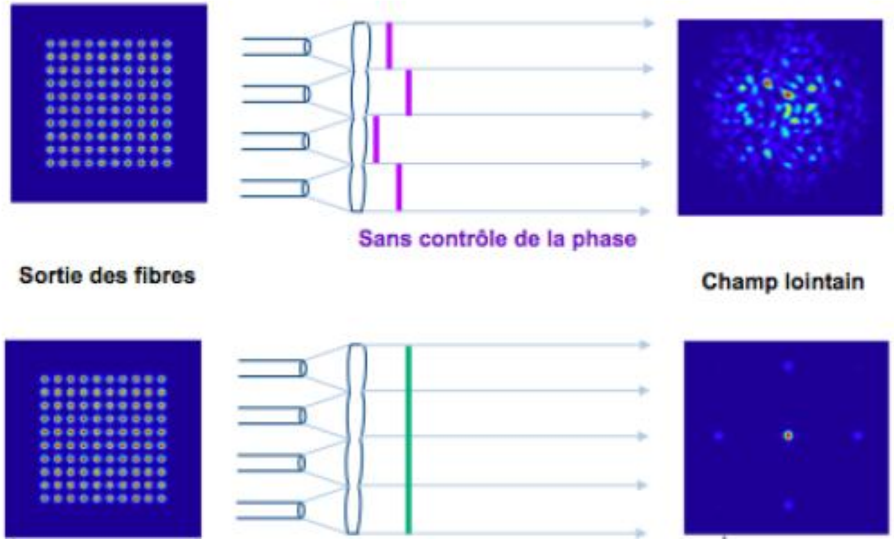
IAP - Institute of Advanced Physics, Nizhy Novgorod, Russia
GIST - Gwangju Institute of Science and Technology, Gwangju, Republic of Korea
KEK - High Energy Accelerator Research Organization, Tsukuba, Japan
KPSI - Kansai Photon Science Institute, Kansai, Japan
LeCosPa - Leung Center for Cosmology and Particle Astrophysics, Taipei, Taiwan
CLPU - Centro de Láseres Pulsados Ultracortos Ultraintensos, Salamanca, Spain
CERN - Organisation Européenne pour la Recherche Nucléaire, Genève, Switzerland
SIOM - Shanghai Institute of Optics and Fine Mechanics, Shanghai, China
Kyoto University - Kyoto, Japan
ELI-NP - Extreme Light Infrastructure - Nuclear Physics, Magurele, Romania
Beijing University - Beijing, China
TCHILS - Texas Center for High Intensity Laser Science, Austin, USA

IZEST pillars at present

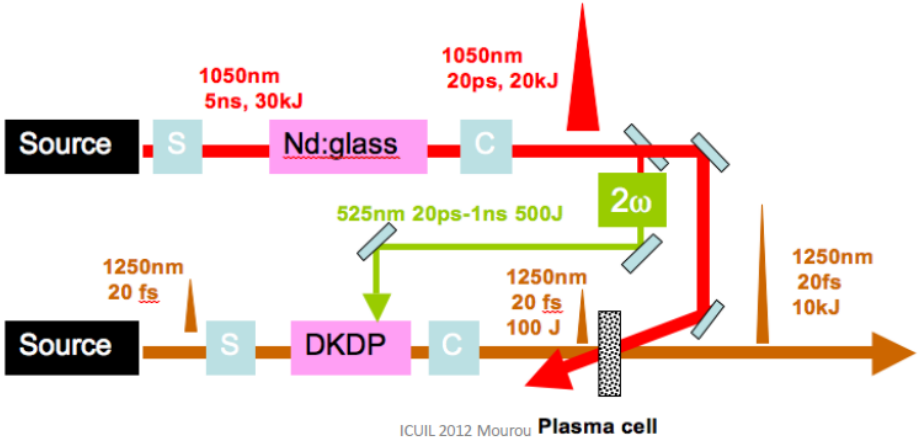
Laser plasma Wake Field Acceleration (100GeV ascent)



High repetition rate laser R&D (ICAN)



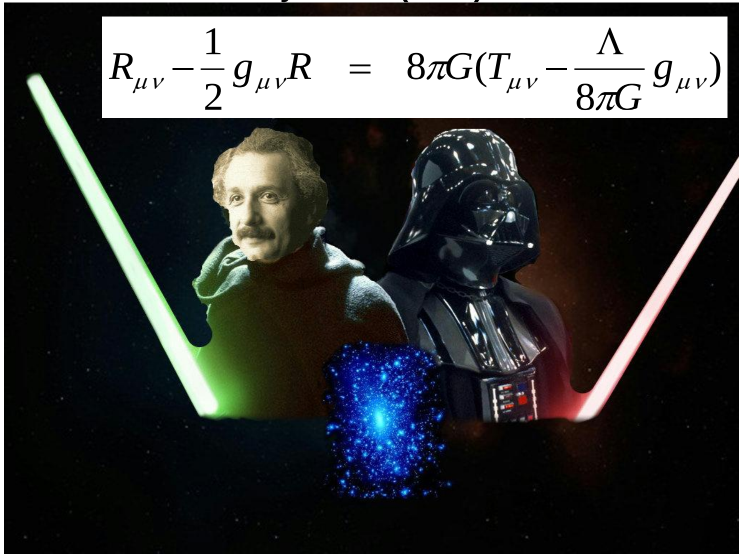
Pulse compression from ns to sub-ps (C3)



ICUIL 2012 Mourou

Fundamental Physics

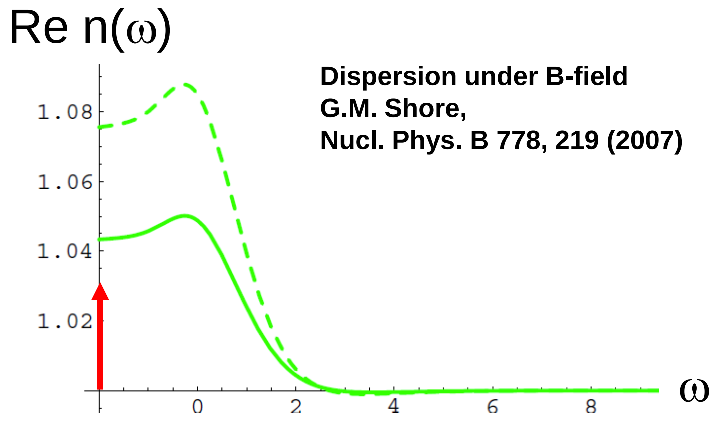
T. Tajima and K. Homma
Int. J. M. Phys. A 27 (2012) 1230027



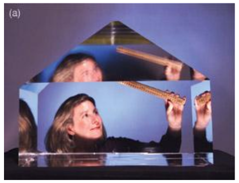
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G\left(T_{\mu\nu} - \frac{\Lambda}{8\pi G} g_{\mu\nu}\right)$$

Accessible subjects by high-intensity lasers

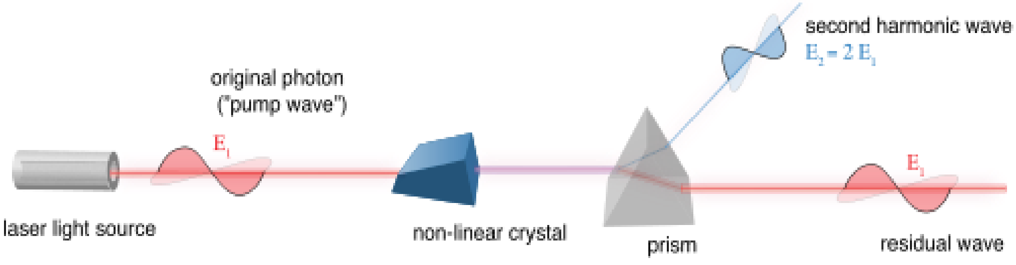
① Laser-laser collision: nonlinear QED and light DM/DE



Dispersion under B-field
G.M. Shore,
Nucl. Phys. B 778, 219 (2007)

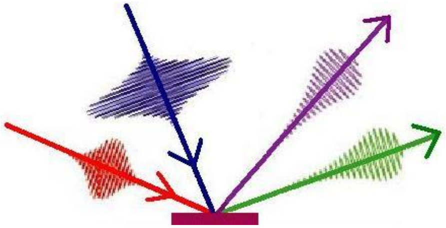


Vacuum Birefringence



Harmonic generation in vacuum

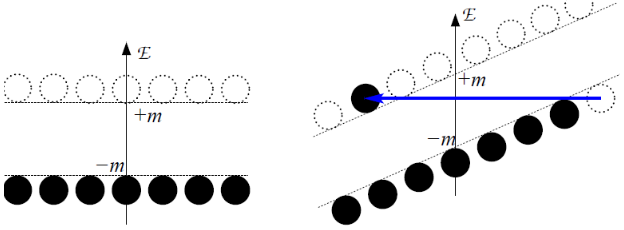
Optical Parametric Effect in vacuum

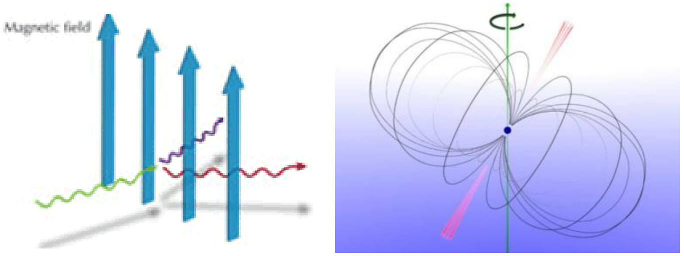


② Laser-γ collision:

non-perturbative aspect of QED/QCD vacuum structure

$$R \propto \exp\left(-\pi \frac{E_s}{E}\right) \longrightarrow R \propto \exp\left(-\frac{8}{3}\frac{E_S}{E}\boxed{\left(\frac{m_e}{E_\gamma}\right)}\right)$$



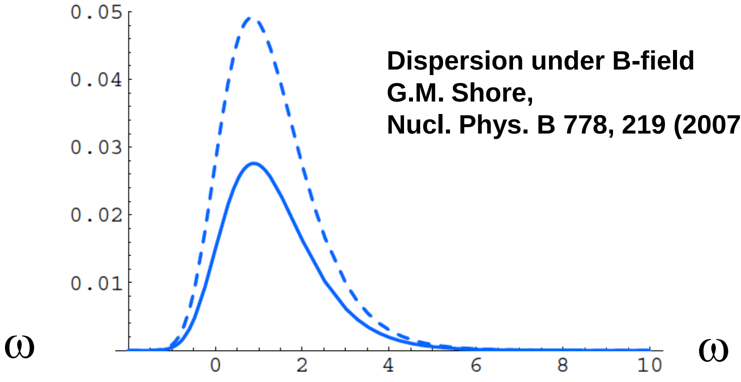


http://www.extreme-light-infrastructure.eu/

QED/QCD tunneling

Photon splitting (magnetor)

Im n(ω)



Dispersion under B-field
G.M. Shore,
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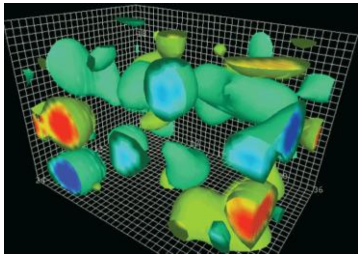
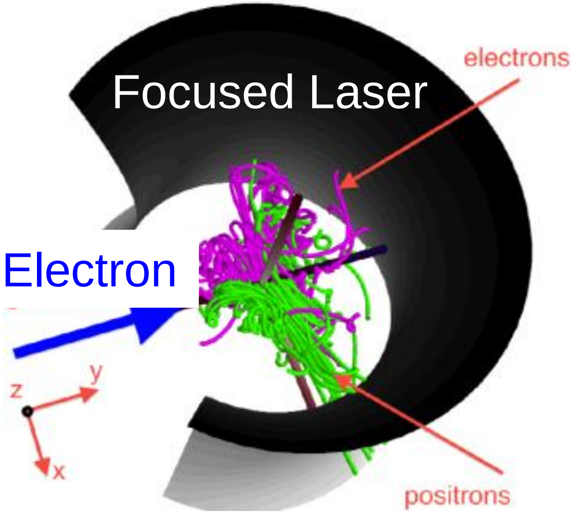


D. B. Leinweber

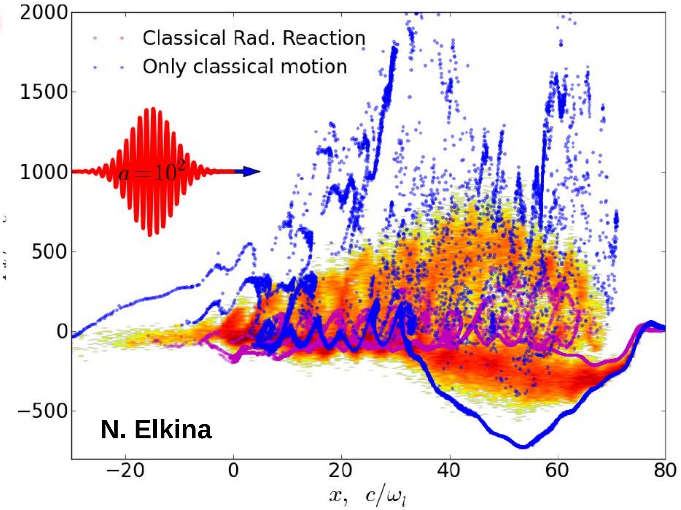
QCD vacuum

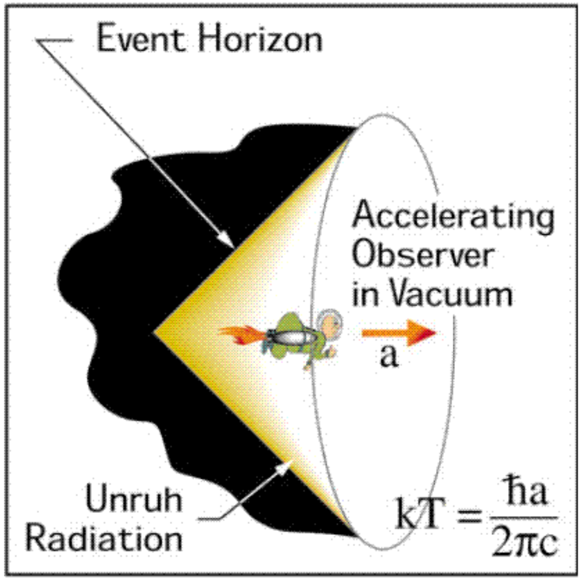
③ Laser-electron collision:

QED cascade and quantum radiations under high-acceleration field



N. Elkina and H. Ruhl





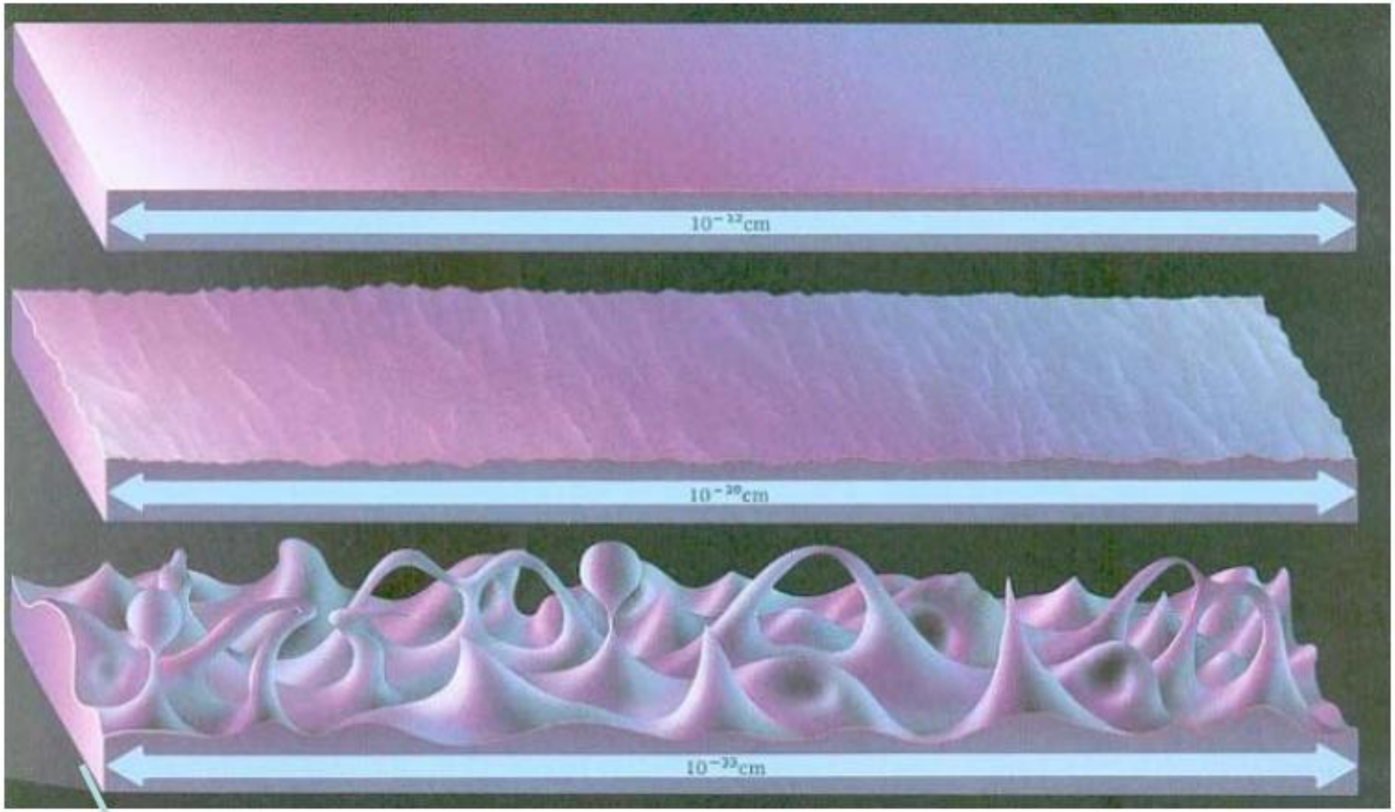
P.Chen, AAPPS Bulletin Vol.13, No.1, 3-10, (2003)

QED cascade

Mechanisms of radiations under acceleration

Feel vacuum texture: PeV energy γ

Laser acceleration → controlled laboratory test to see quantum gravity texture on photon propagation (Special Theory of Relativity: c_0)



Coarser, lower energy texture

Finer, higher energy texture

$c < c_0$

← (0.1PeV)

1km

←(1PeV : fs behind)

goalline

PeV γ (converted from e$^-$)

Shown at CEA by T. Tajima

Symmetry breaking accompanies (pseudo-) Nambu-Goldstone bosons

Chiral symmetry breaking @ sub-GeV ⇔ *π*-mesons mass~100MeV

Gauge symmetry breaking @ sub-TeV ⇔ Higgs scenario mass~100GeV

Other symmetry breakings also predict N.G. bosons

GUT scale

Cold Dark Matter

PQ symmetry breaking @ 10^{16} GeV ⇔ Axion mass~10^{-4}-10^{-6} eV

Planck scale

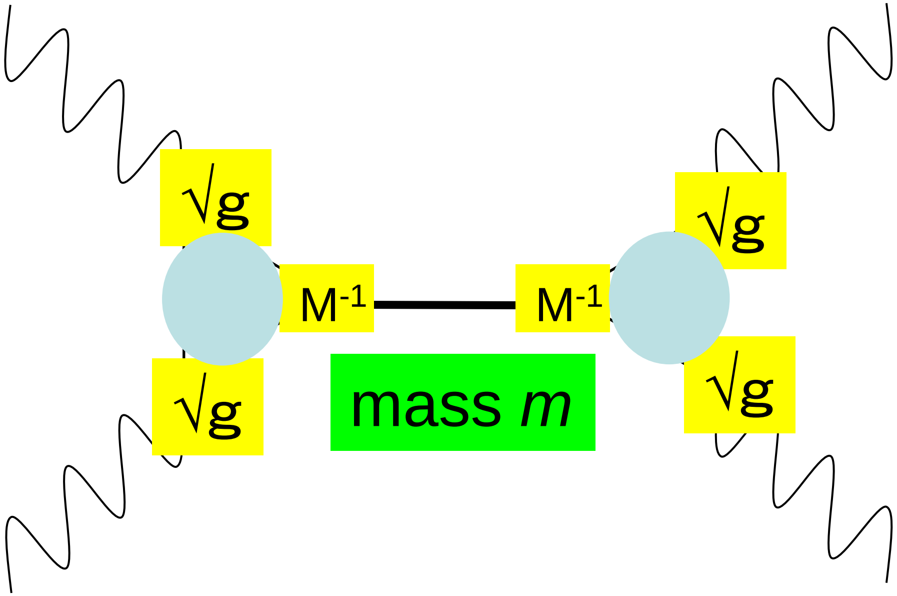
Dark Energy

Conformal symmetry breaking @ 10^{18} GeV ⇔ Dilaton mass~10^{-9} eV

Search for neutral spin-0 scalar / pseudo-scalar bosons !

Resonant production of low-mass N.G. bosons by laser-laser collision

Coupling to Higgs boson $\sim g(246\ GeV)^{-1}F^{\mu\nu}F_{\mu\nu}h$



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

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

arXiv:1103.1748 [hep-ph]
K.Homma, D.Habs, T.Tajima
Appl. Phys. B, 2011

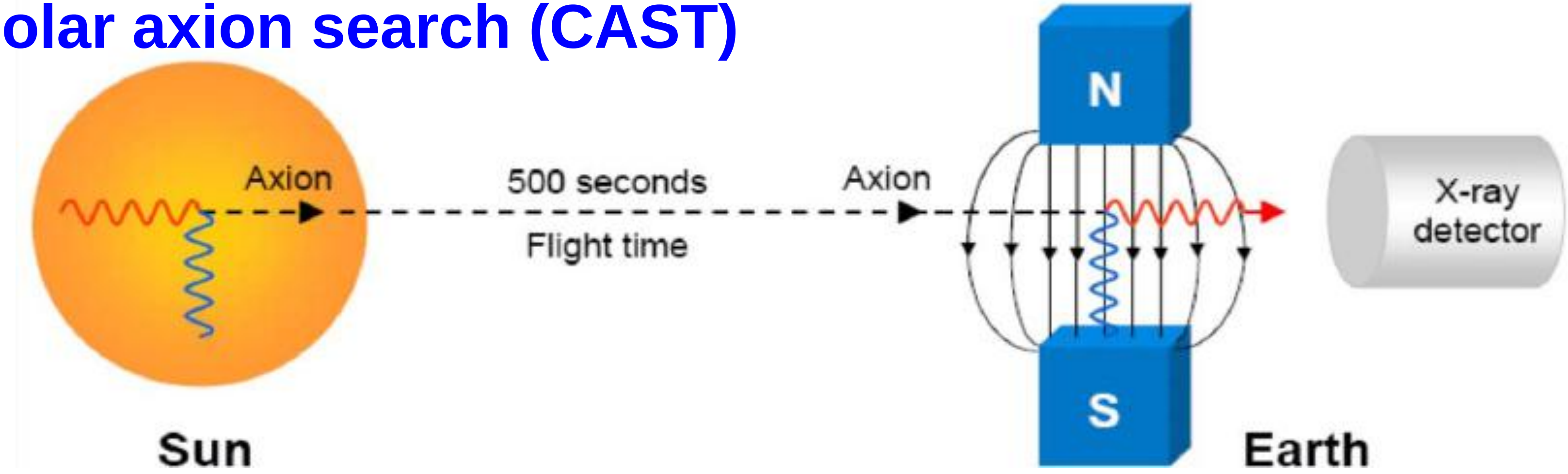
If M~M$_{Planck}$, Dark Energy

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

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

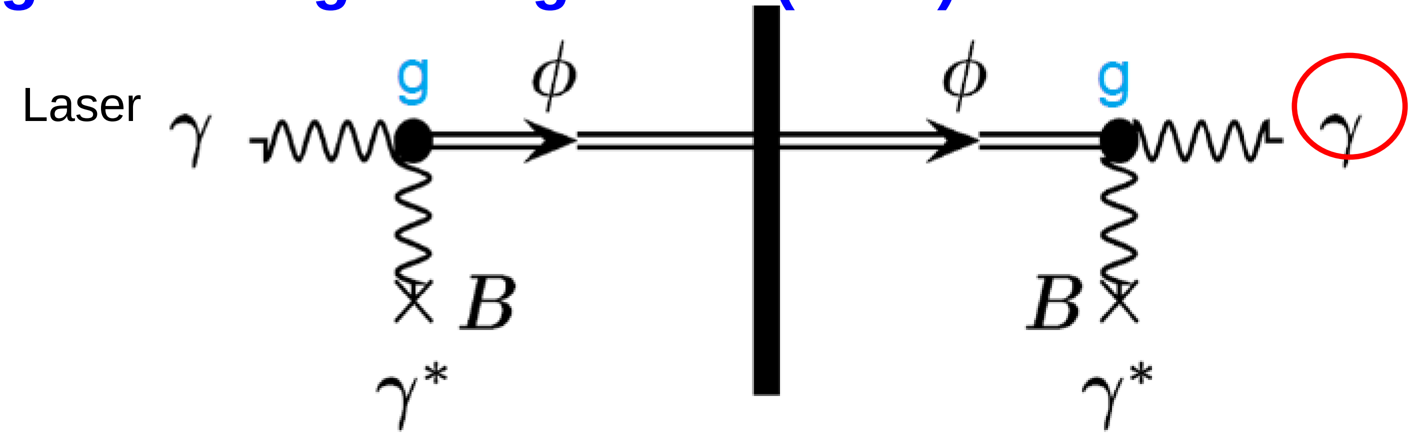
Conventional Axion seach

Solar axion search (CAST)



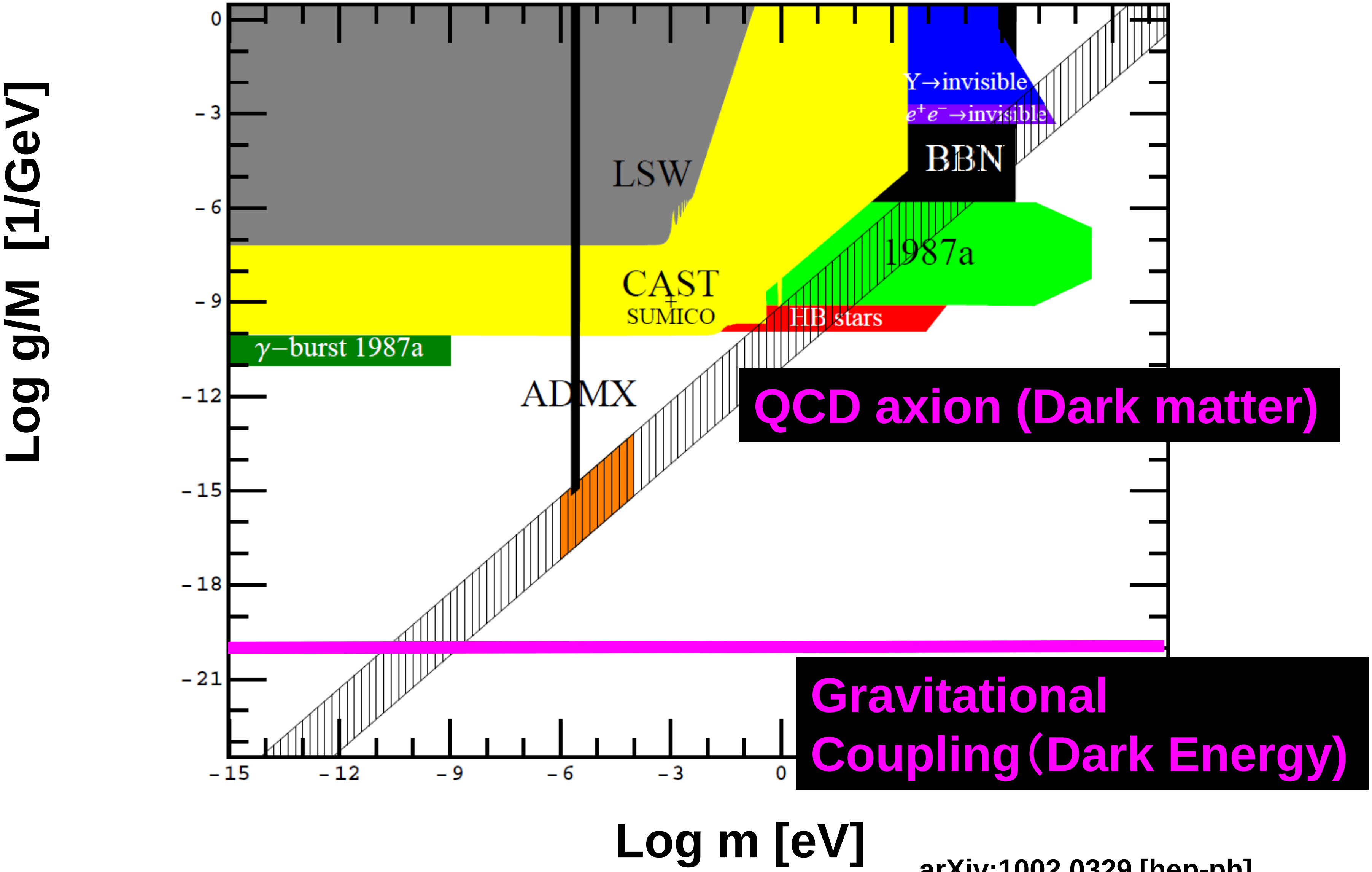
CAST, Theopisti Dafni, 7th Patras Workshop, Mykonos 2011

Light Shining through Wall (LSW)



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

Present limits on coupling vs. mass



arXiv:1002.0329 [hep-ph]
J. Jaeckel, A. Ringwald

Approach to dark energy in neV range

Observation

$a(t) \propto t^{1/2}$

constant particle mass

$t = 10^{60.2}$ in reduced Planckian units

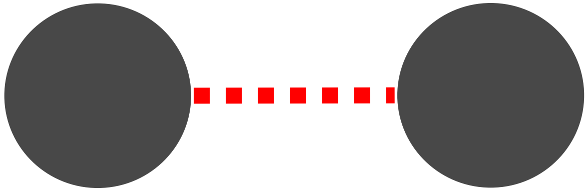
Cosmological constant $\Lambda = 10^{-120}$

The Scalar-Tensor Theory of Gravitation (Cambridge 2003) Y.Fujii arXiv:0908.4324

Why Λ is extremely small?
Because a scalar field (dilaton) causes **$\Lambda \propto t^{-2}$**

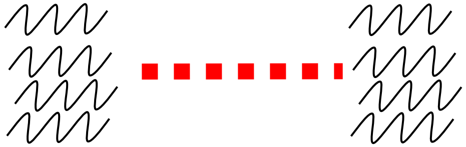
$m_\sigma > 10^{-9}$eV ($\lambda \sim 100$m) through gravitational coupling

$$m_\sigma^2 \sim \frac{m_q^2 M_{ssb}^2}{\boxed{M_P^2}}$$



Huge massive bodies

Large background from EM-force

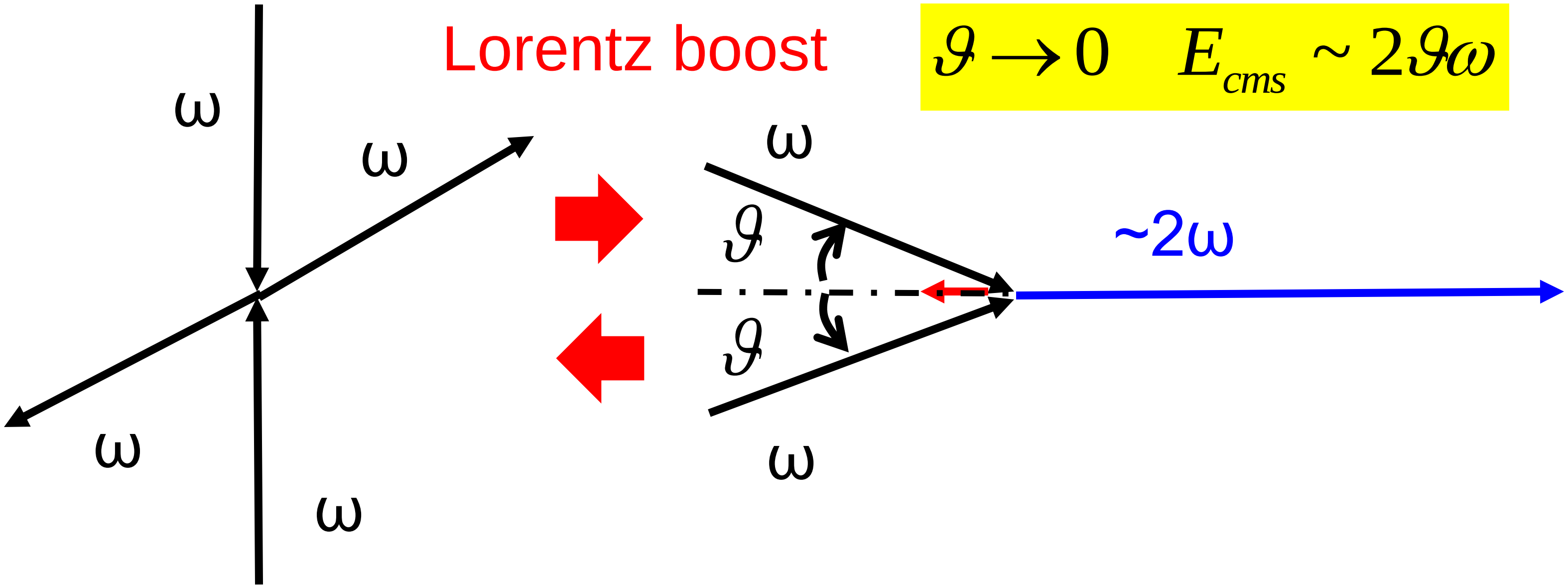


QED process is suppressed by in photon-photon

$$\sigma_{QED} @1eV << 10^{-42} b$$

How to overcome the weakness of coupling ?

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

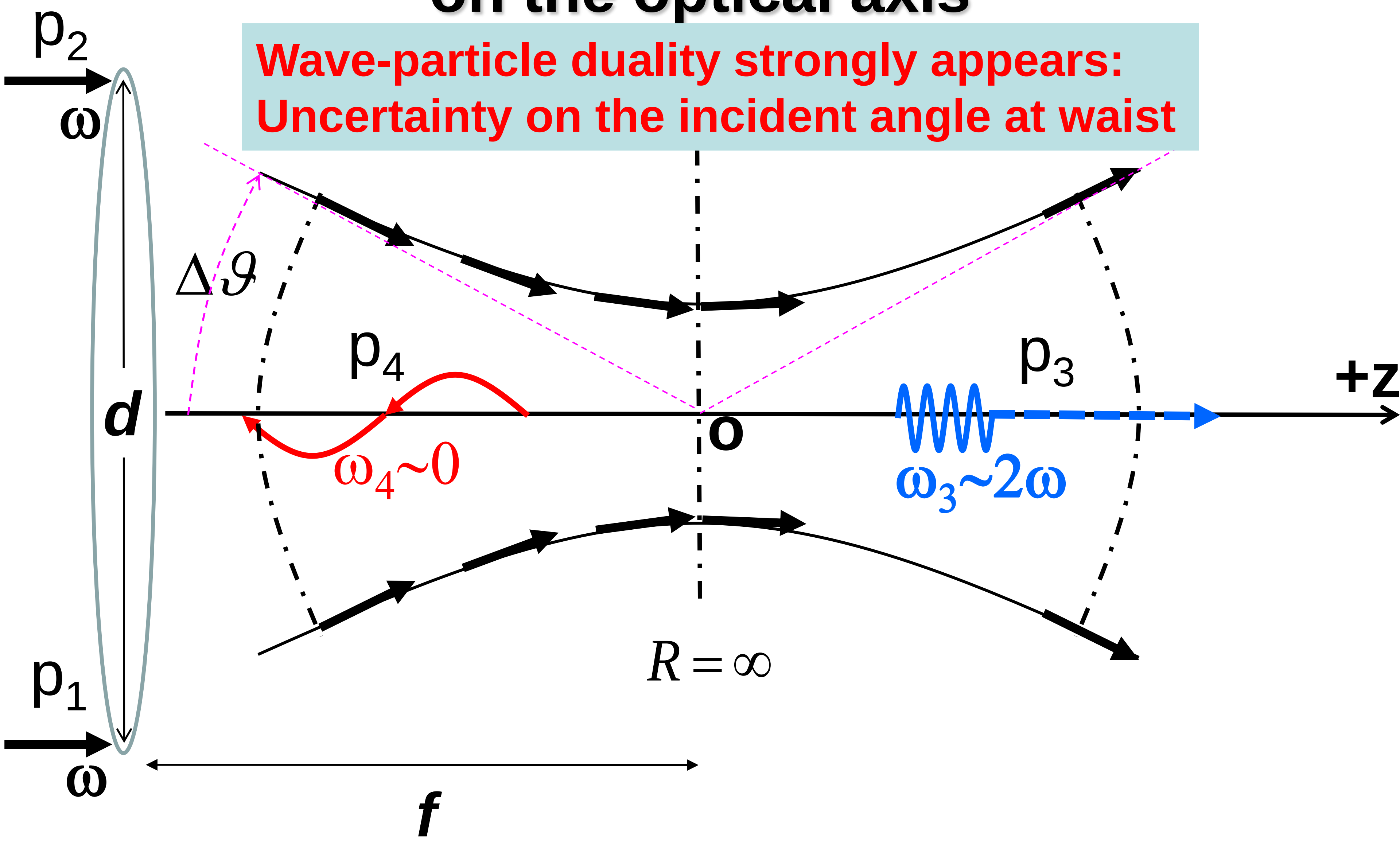
No frequency shift

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

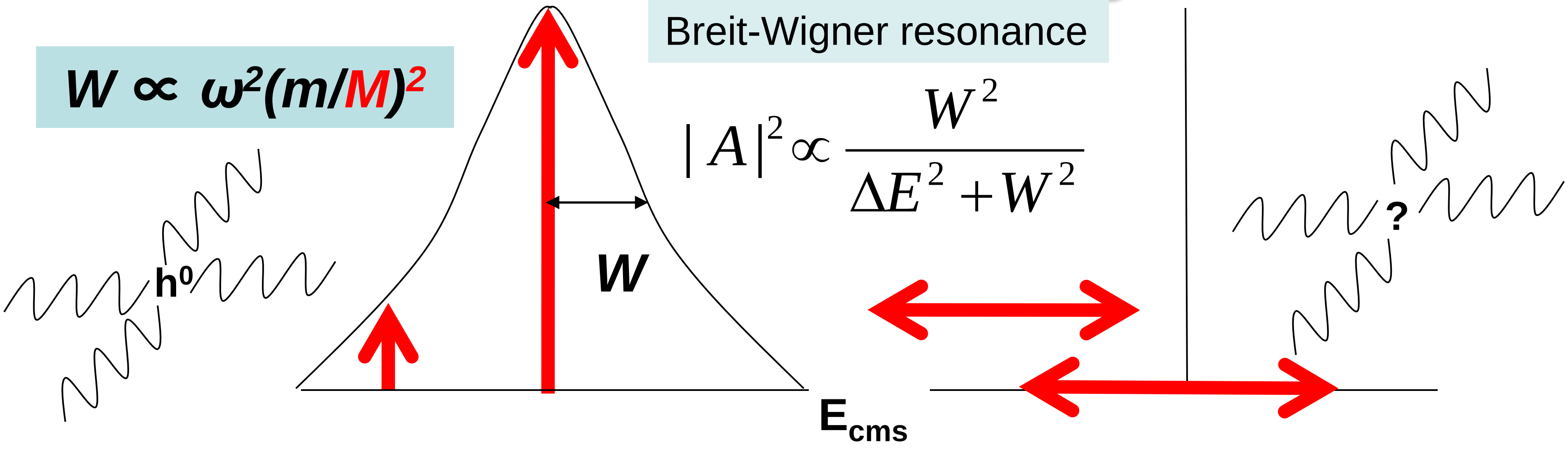
Low frequency photon in QPS is an ideal system !

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

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

High energy γ–γ collider
(e.g. Higgs factory)

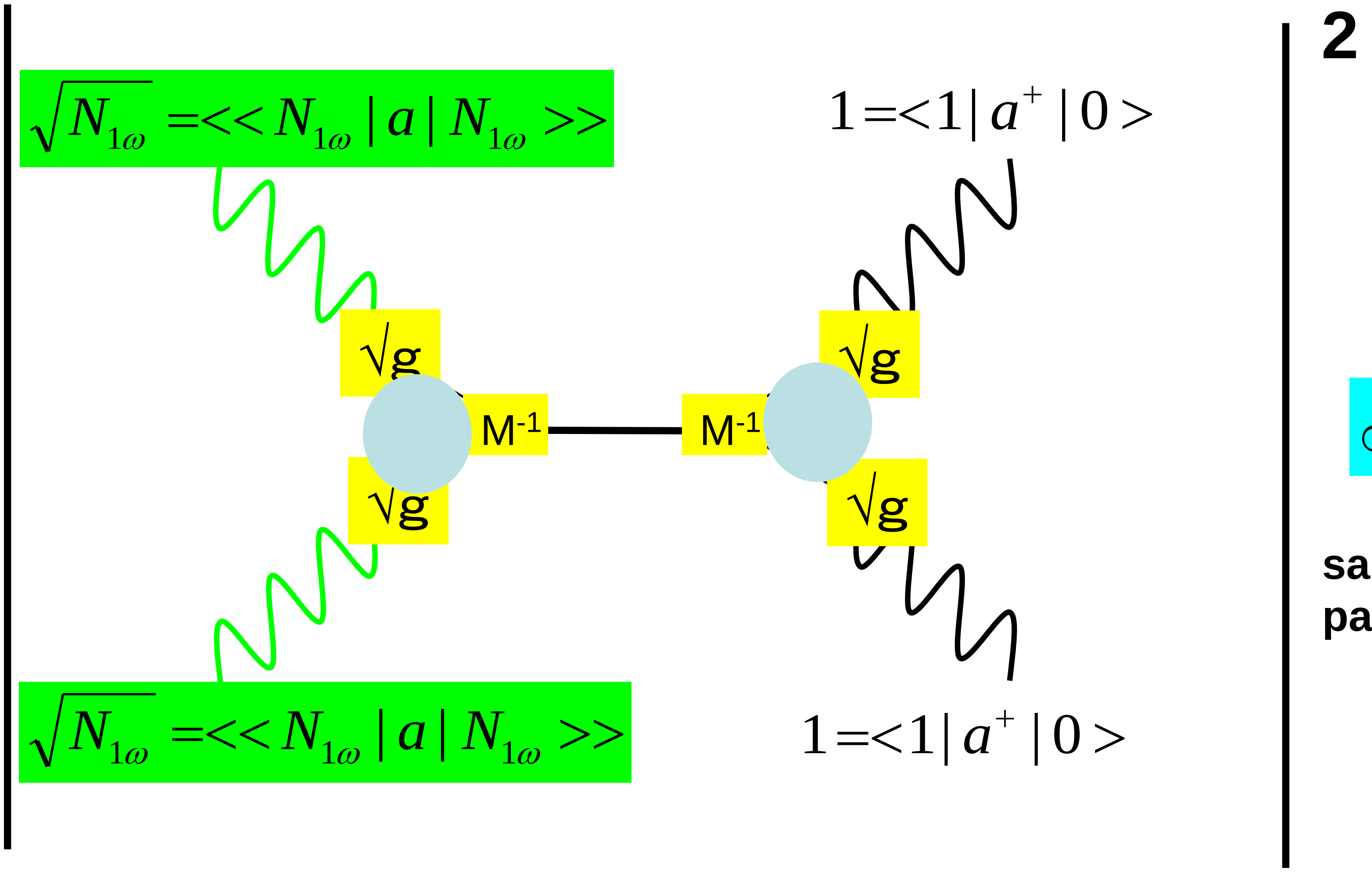
Collider in diffraction limit of QPS

We must integrate square of invariant amplitude in QPS

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

Gain by *M*²

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



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

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

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

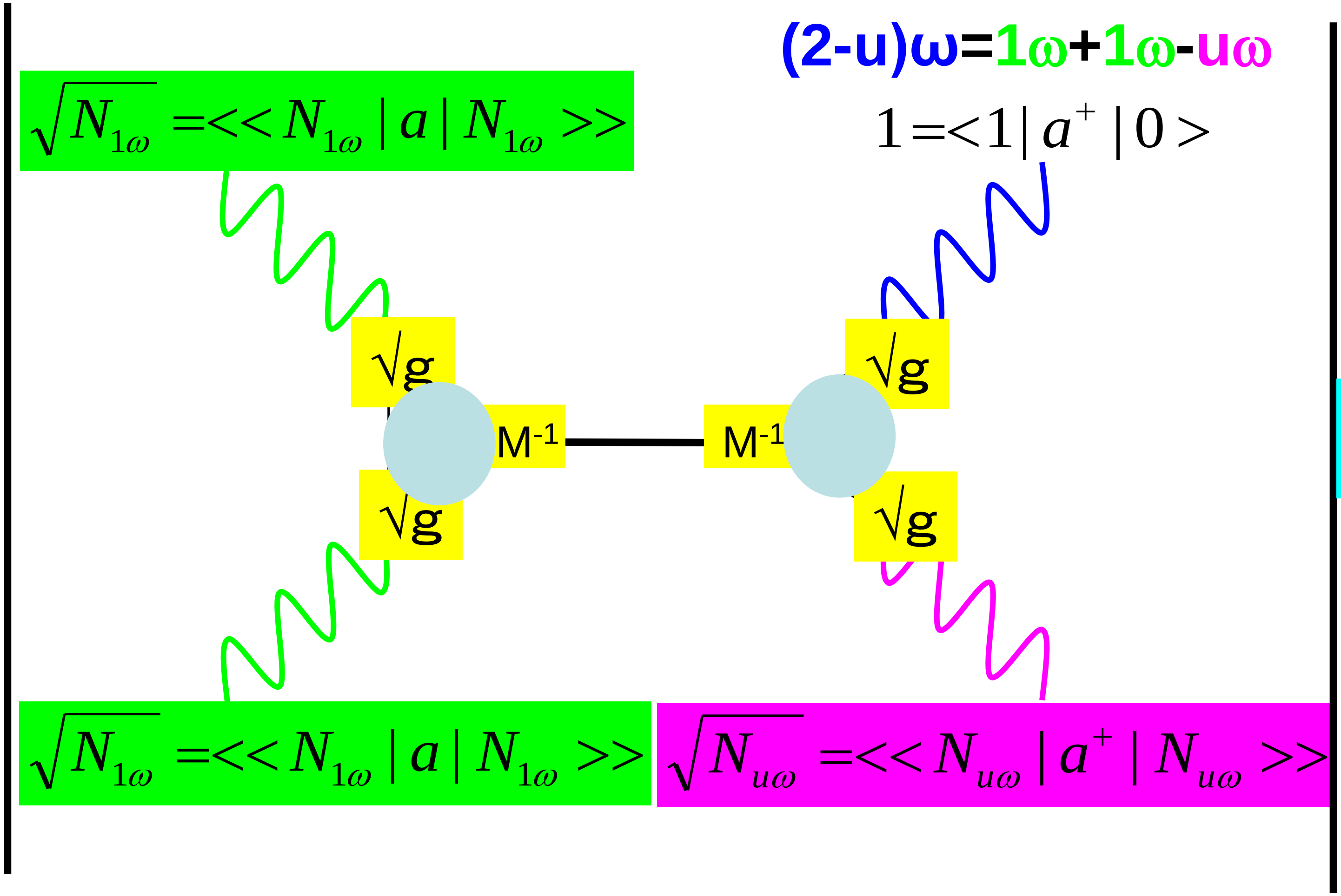
$1 = \langle 1 | a^{+} | 0 \rangle$

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

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 coherent photon medium-



(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

$N \sim 10^{23}$ = 200kJ

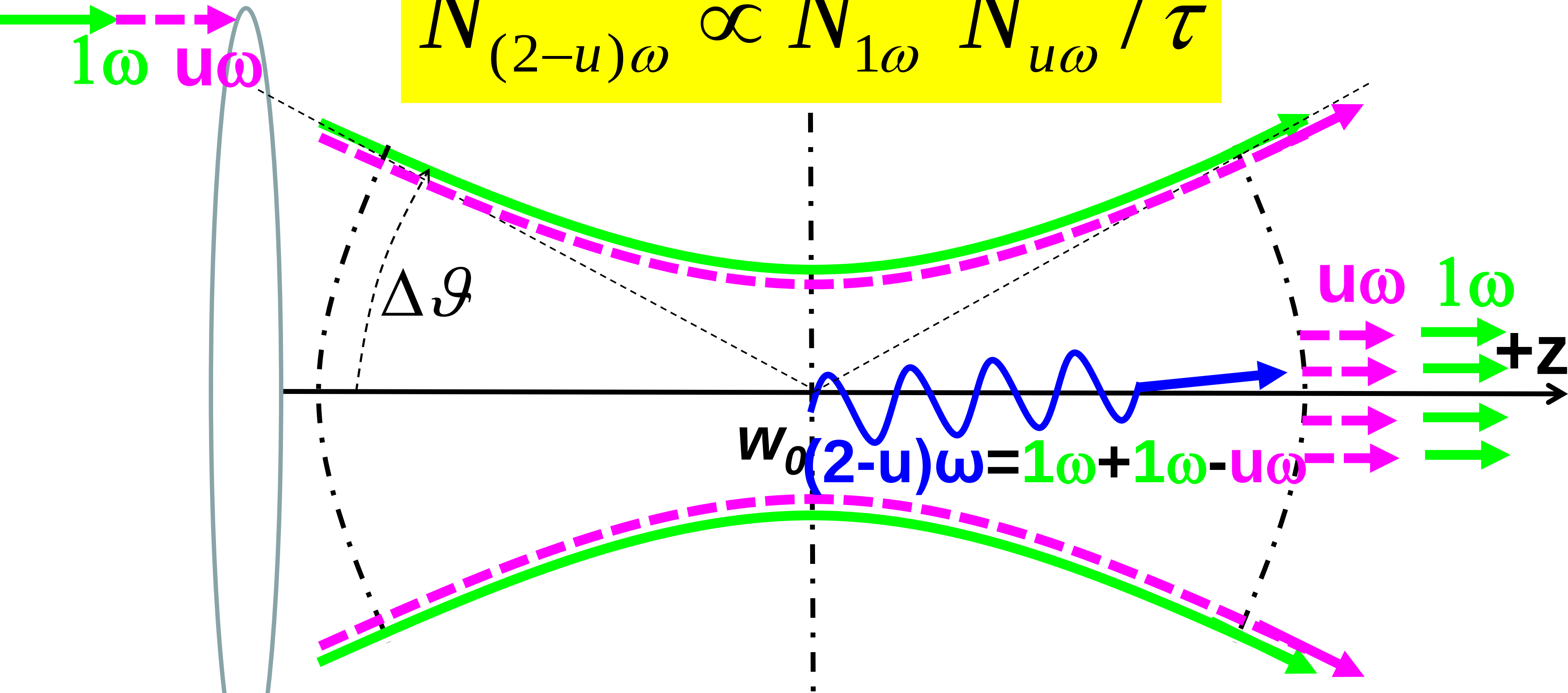
$$\propto N^{2}_{1\omega}N_{u\omega}$$

Cubic dependence

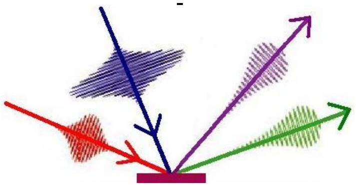
arXiv:1006.1762 [gr-qc]
Y. Fujii and K.Homma
Prog. Theor. Phys., 2011

Degenerate Four-Wave Mixing

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



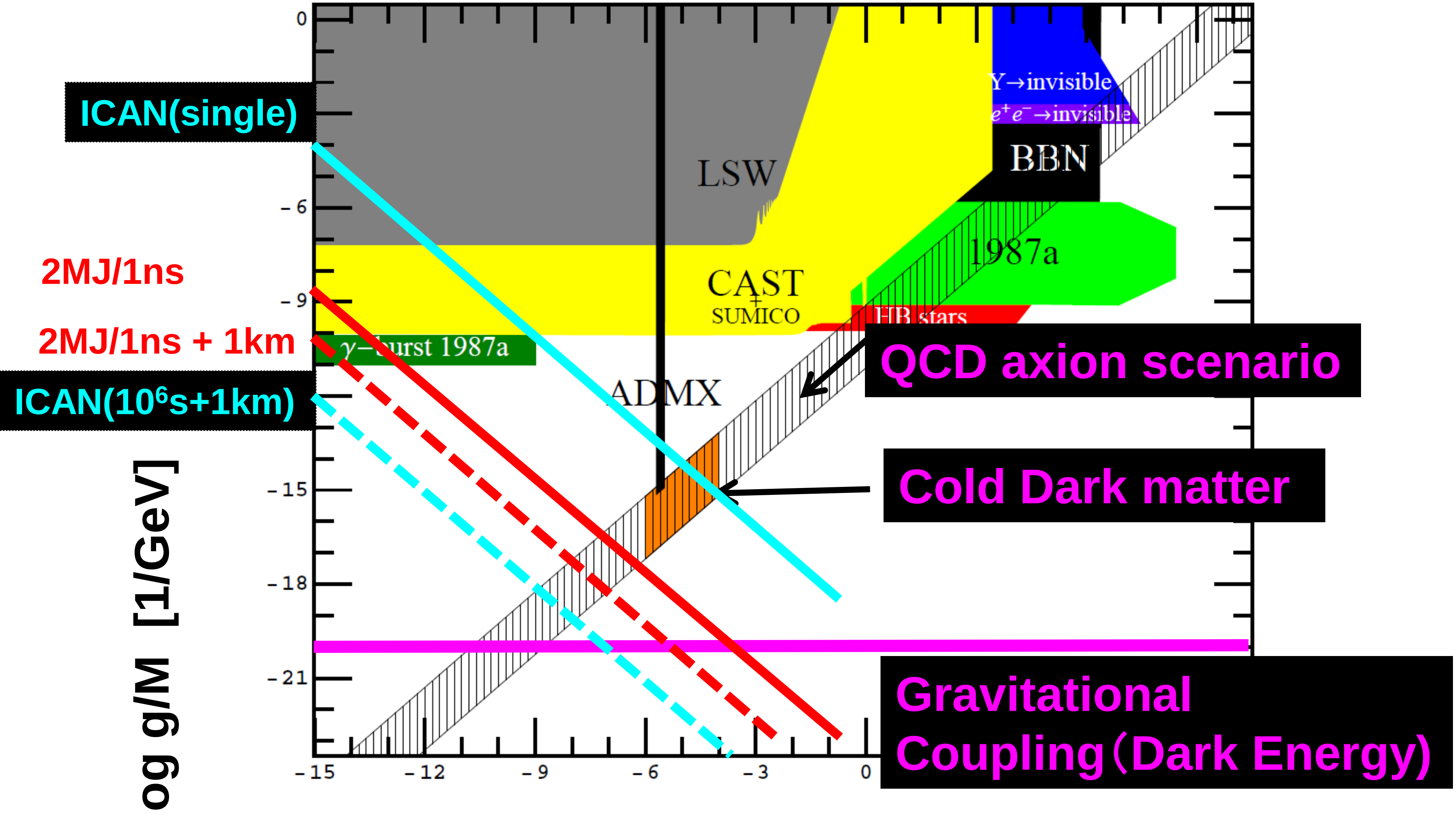
$(2-u)\omega = 1\omega + 1\omega - u\omega$



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

arXiv:1103.1748 [hep-ph]
K.Homma, D.Habs, T.Tajima
Appl. Phys. B, 2012

Single shot sensitivity on coupling vs. mass



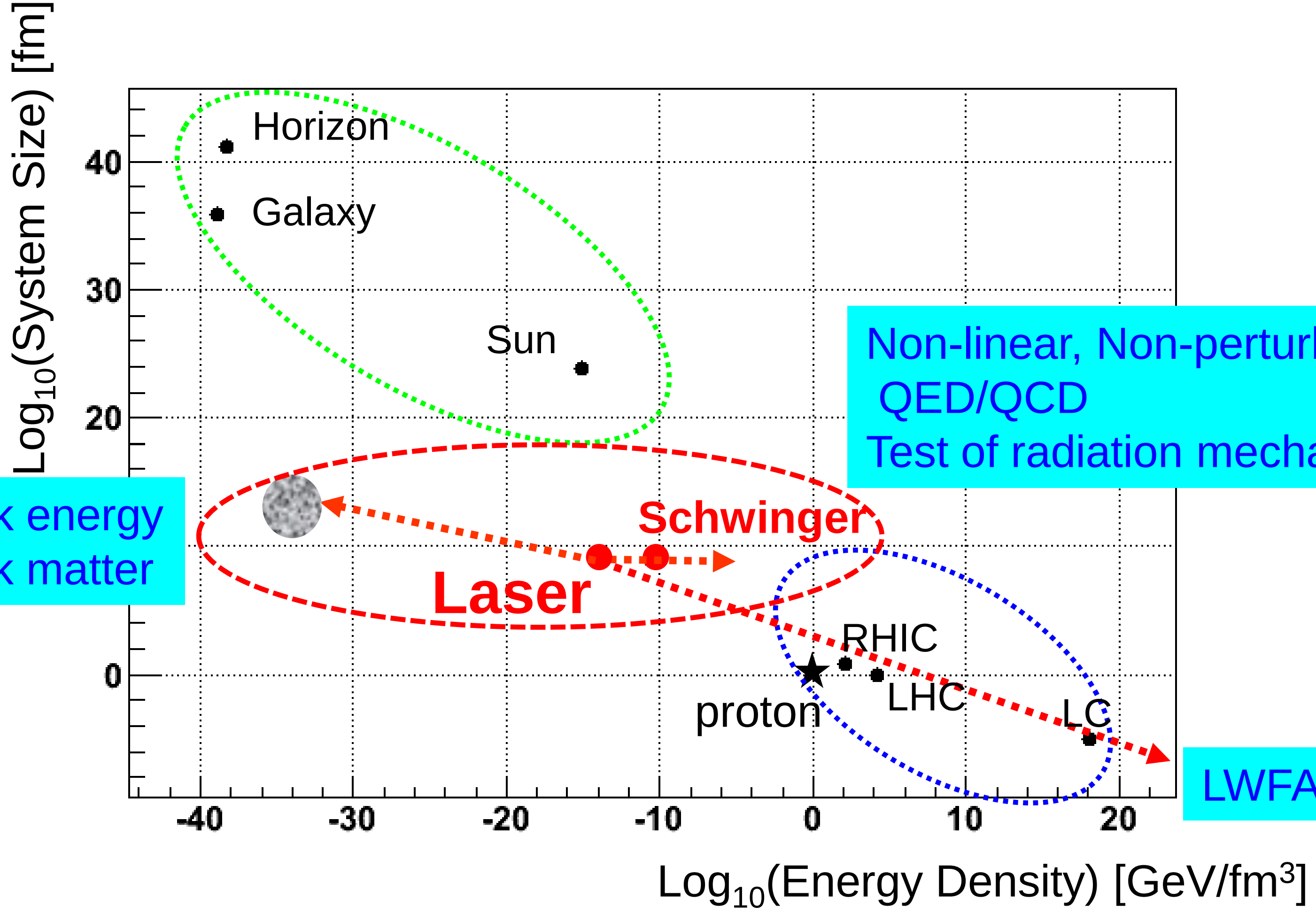
Derived from K.Homma, Prog. Thoer. Exp. Phys. (2012) , 04D004 arXiv:1211.2027

log m [eV]

Particle Collider vs. Degenerate Particle Collider

Parameters	Particle Collider	Degenerate 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	10^{22} (@10kJ/pulse) limited by technology
Single shot dimensionless intensity in luminosity	$(10^{11})^2 = 10^{22}$	$(10^{22})^3 = 10^{66}$
Collision rate	100MHz	ICAN provides 10kHz rep. rate
Overall dimensionless intensity in luminosity	$(10^{11})^2 \times 10^8 = 10^{30}$	$(10^{22})^3 \times 10^5 = 10^{71}$

Explorable three major directions by high-intensity lasers



Astronomical observations

Dark energy
Dark matter

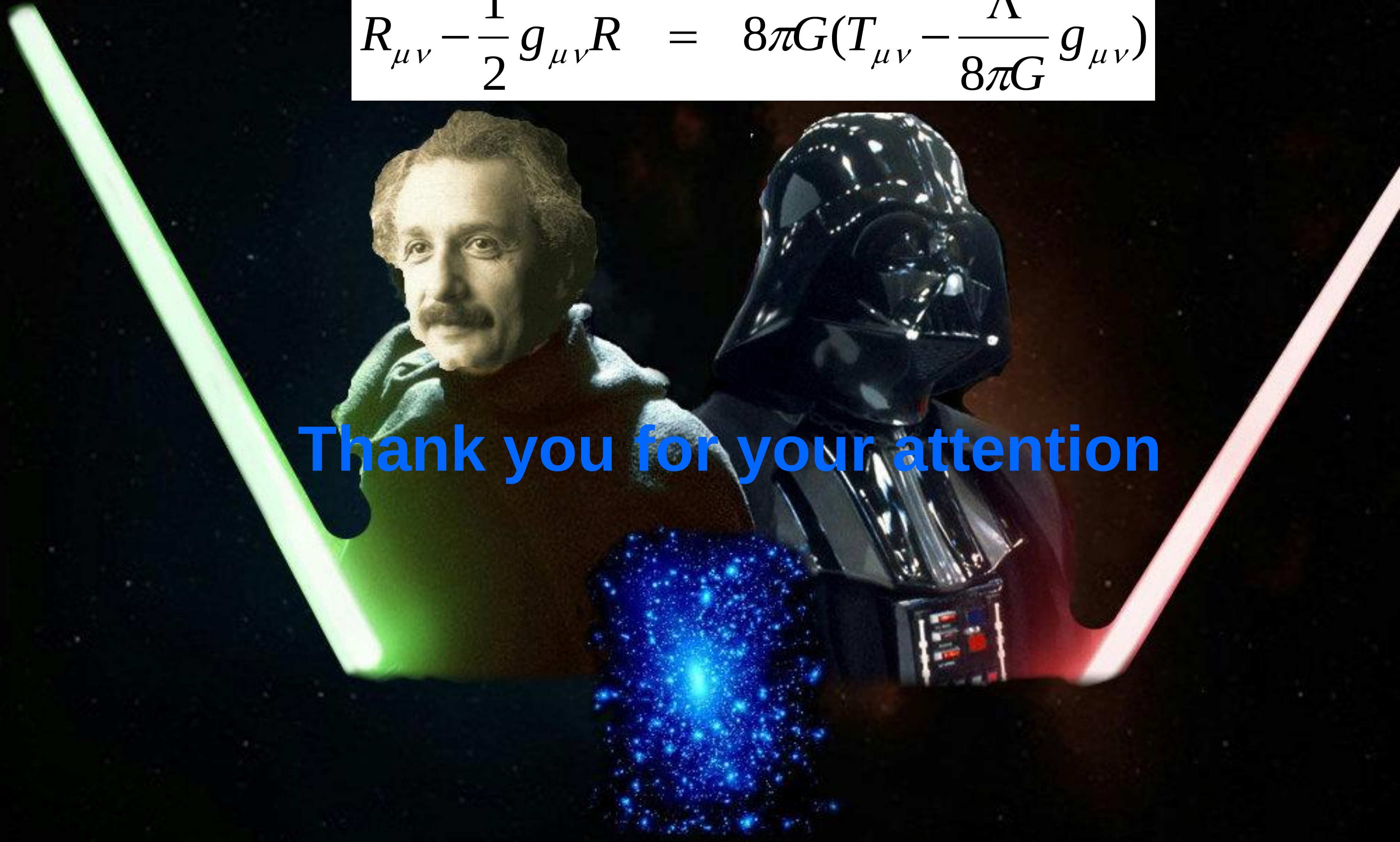
Non-linear, Non-perturbative
QED/QCD
Test of radiation mechanism

LWFA

High energy colliders

Einstein Gravity vs. Cosmological Constant(?)

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G \left(T_{\mu\nu} - \frac{\Lambda}{8\pi G} g_{\mu\nu}\right)$$



Thank you for your attention