Probing nonlinearity of semi-macroscopic vacuum by second harmonic generation with intense laser fields

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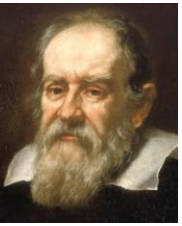
Special Thanks to
T. Tajima, D.Habs, and Y.Fujii

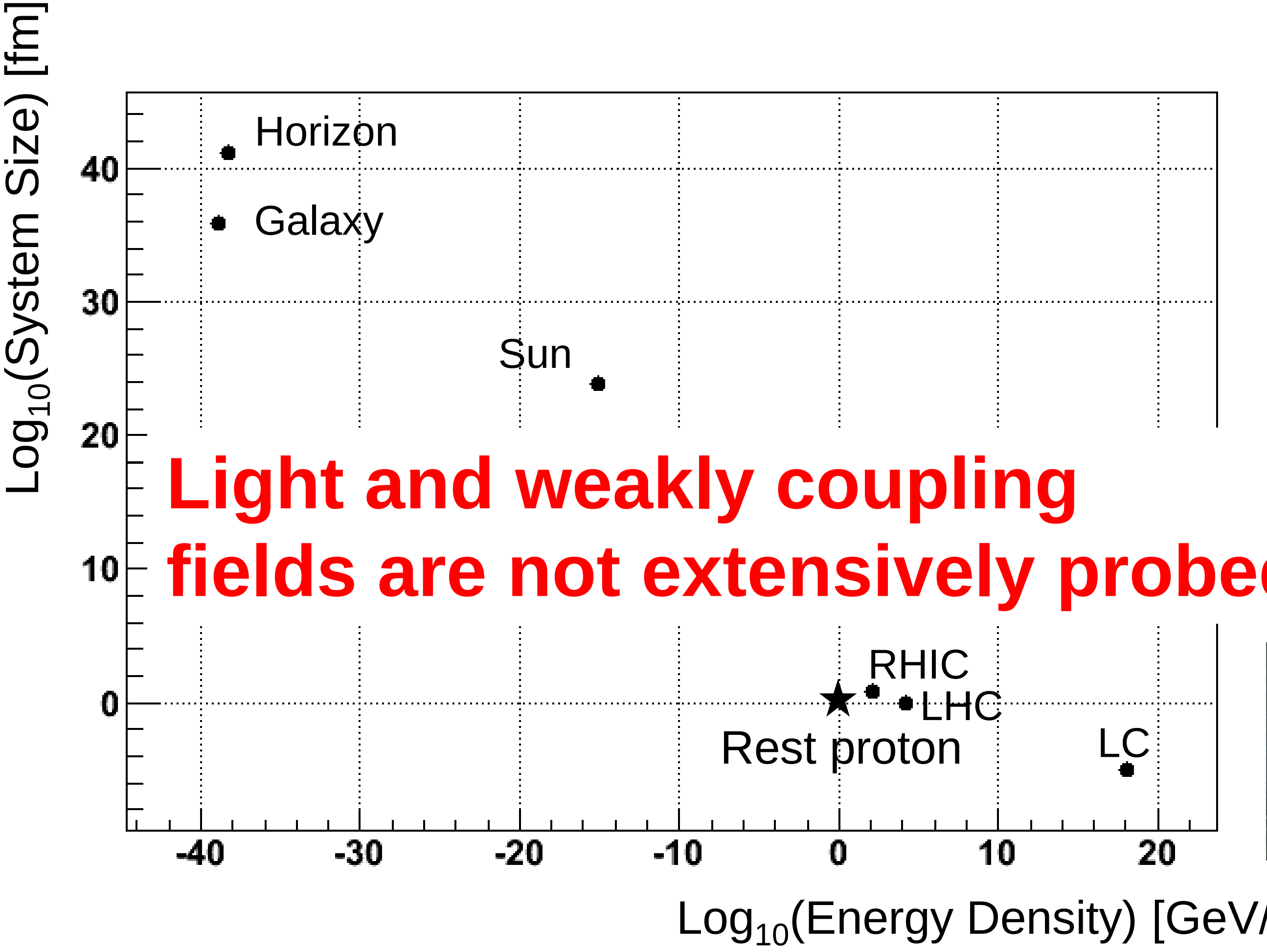
1. How little we have probed vacuum
2. Quasi parallel system
3. Dynamics of resonance production
4. Summary

How little we have probed vacuum

Cosmological observation

Weak coupling m=0



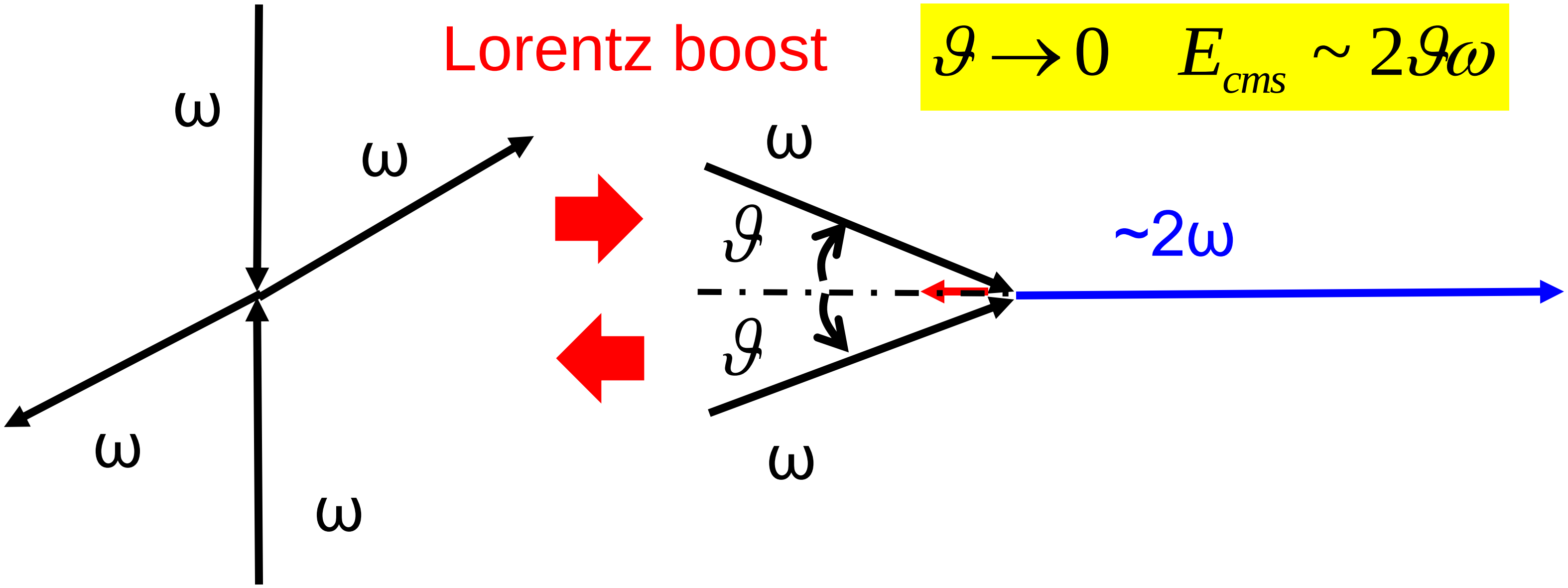


Light and weakly coupling fields are not extensively probed

Strong coupling
Heavy m

High energy collider

How to reduce center of mass energy



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

Center of Mass System

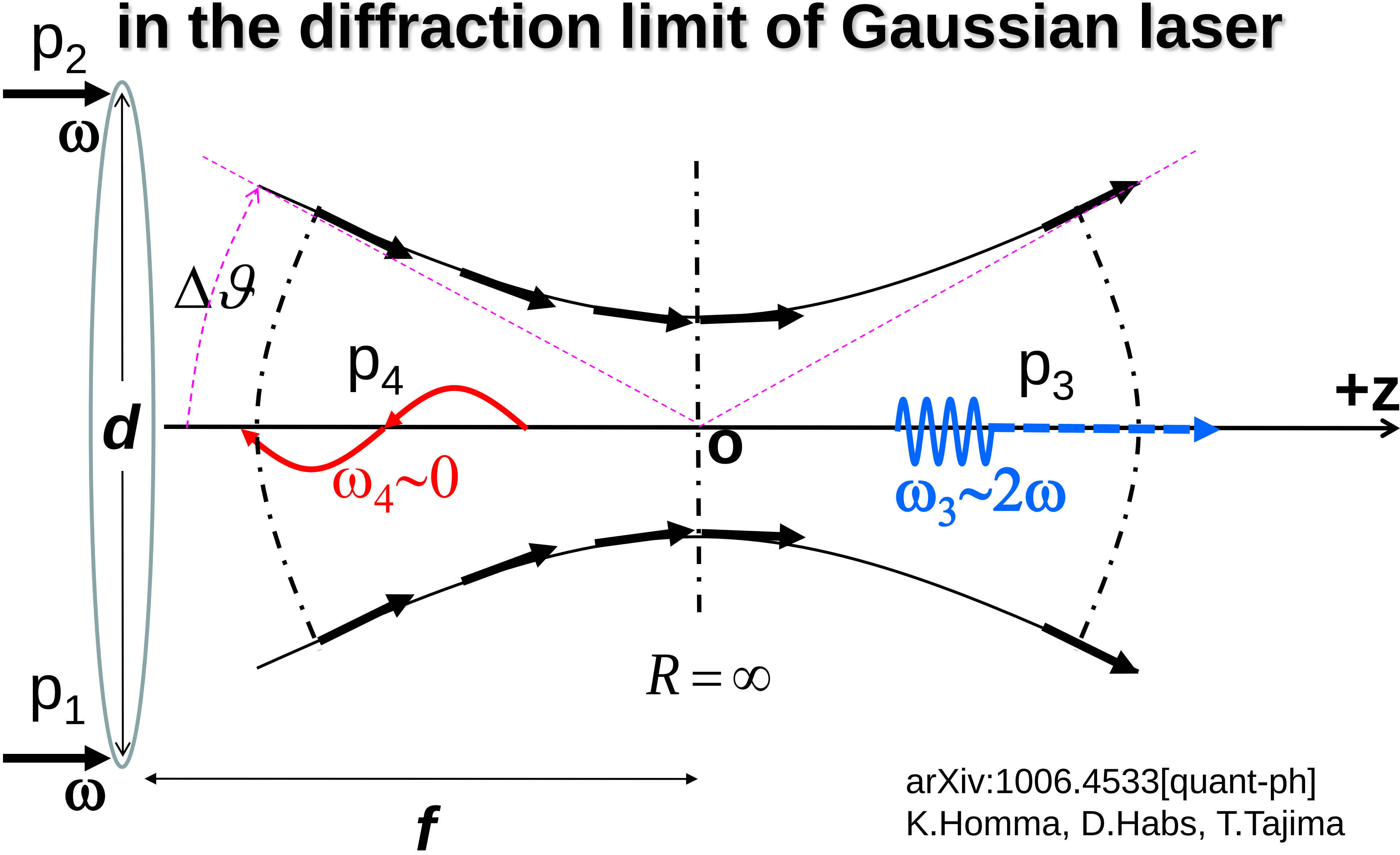
Quasi Parallel System

No frequency shift

- Lower E_{cms} without changing incident ω
- Frequency shift occurs on the boost axis

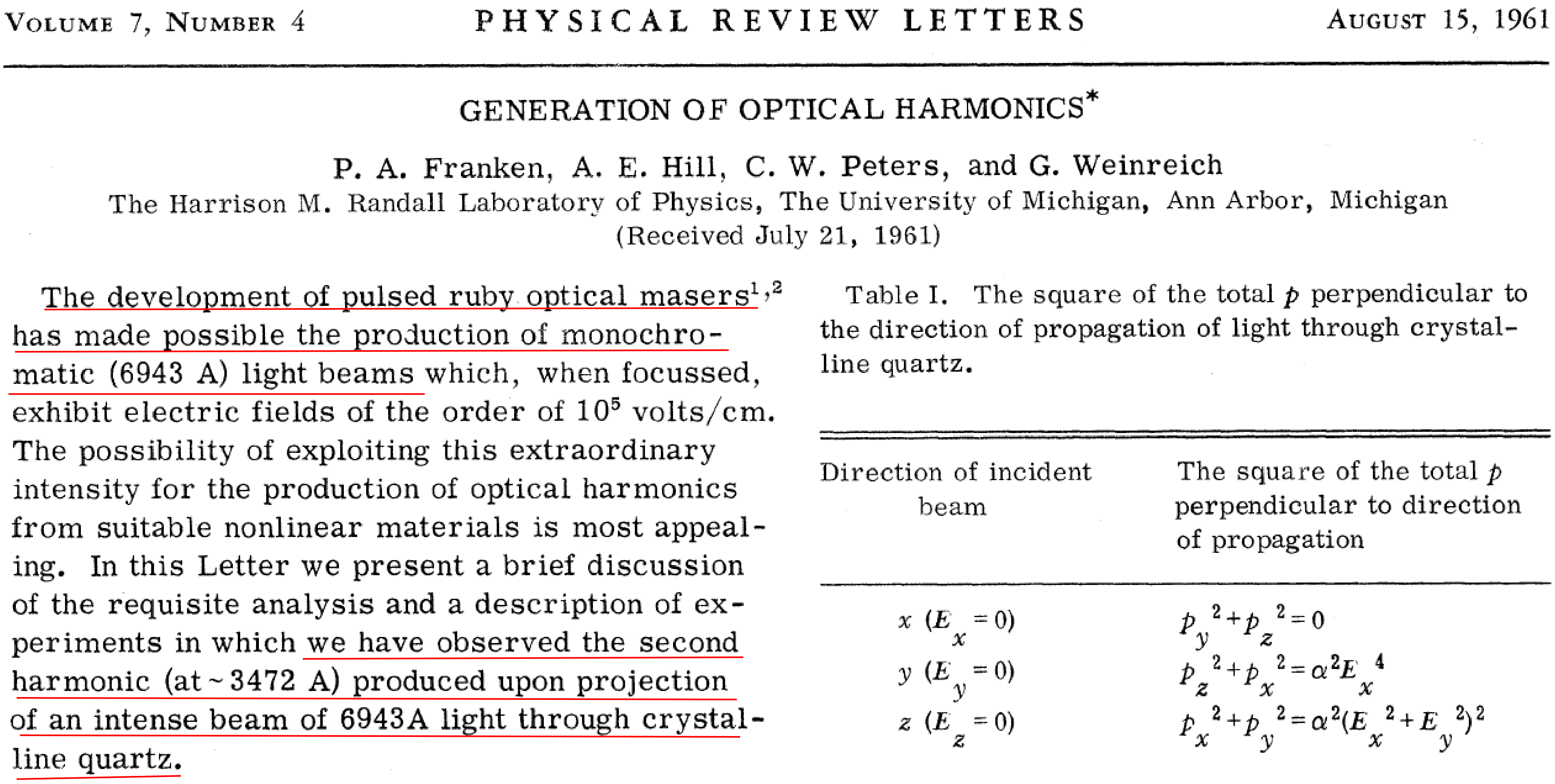
Low frequency photon in QPS is the best probe.

Uncertainty on the incident angle in the diffraction limit of Gaussian laser



arXiv:1006.4533[quant-ph]
K.Homma, D.Habs, T.Tajima

The technique is applicable even to vacuum



VOLUME 7, NUMBER 4 PHYSICAL REVIEW LETTERS AUGUST 15, 1961

GENERATION OF OPTICAL HARMONICS*

P. A. Franken, A. E. Hill, C. W. Peters, and G. Weinreich
The Harrison M. Randall Laboratory of Physics, The University of Michigan, Ann Arbor, Michigan

(Received July 21, 1961)

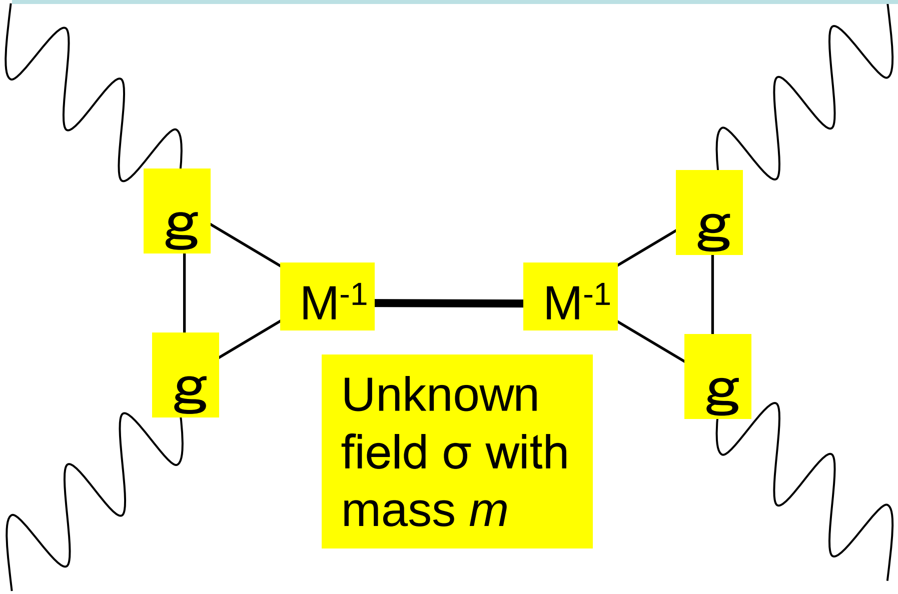
The development of pulsed ruby optical masers[1,2] has made possible the production of monochromatic (6943 A) light beams which, when focussed, exhibit electric fields of the order of 10^5 volts/cm. The possibility of exploiting this extraordinary intensity for the production of optical harmonics from suitable nonlinear materials is most appealing. In this Letter we present a brief discussion of the requisite analysis and a description of experiments in which we have observed the second harmonic (at ~3472 A) produced upon projection of an intense beam of 6943A light through crystalline quartz.

Table I. The square of the total p perpendicular to the direction of propagation of light through crystalline quartz.

Direction of incident beam	The square of the total p perpendicular to direction of propagation
$x\ (E_x = 0)$	$p_y^2 + p_z^2 = 0$
$y\ (E_y = 0)$	$p_z^2 + p_x^2 = \alpha^2 E_x^4$
$z\ (E_z = 0)$	$p_x^2 + p_y^2 = \alpha^2 (E_x^2 + E_y^2)^2$

Dynamics: Resonance production

Focus on the resonances in s-channel



Unknown field σ with mass *m*

Scalar type coupling

$$g^2 M^{-1} F^{\mu\nu} F_{\mu\nu} \sigma$$

Pseudoscalar type coupling

$$g^2 M^{-1} F^{\mu\nu} \tilde{F}_{\mu\nu} \sigma$$

Possible combinations of linear polarizations

Scalar type

$$M_{1111s} = M_{2222s} = -M_{1122s} = -M_{2211s}$$

Pseudoscalar type

$$M_{1212s} = M_{1221s} = -M_{2112s} = -M_{2121s}$$

How to overcome the narrow width

Resonance condition

$$m = E_{cms} \sim 2\vartheta_r \omega_r$$

Square of invariant amplitude

$$|A|^2 = (4\pi)^2 \frac{a^2}{\chi^2 + a^2}$$

$$\omega^2{}_r = \frac{m^2}{1 - \cos 2\vartheta_r} \qquad \chi(\vartheta) = \omega^2 - \omega_r{}^2(\vartheta) \qquad a = \frac{m\Gamma/2}{1 - \cos 2\vartheta} \propto \left(\frac{gm}{M}\right)^{2}$$

$$\Gamma = \frac{1}{16\pi}\left(\frac{g}{M}\right)^2 m^3$$

If *M* is e.g. Planckian mass scale, impossible to hit the top of resonance

We need to integrate square of invariant amplitude

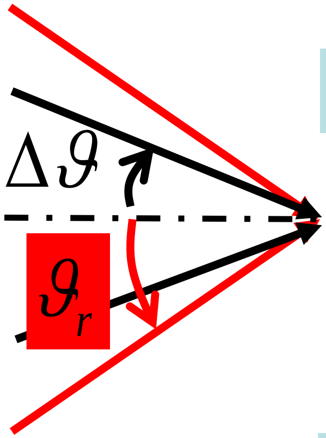
$$|\bar{A}|^2 \propto \int_{-\infty}^{+\infty} \frac{a^2}{\chi^2 + a^2} d\chi = \pi a \quad \leftrightarrow \quad |\bar{A}|^2 \propto \int_{-a}^{+a} \frac{a^2}{\chi^2 + a^2} d\chi = \frac{\pi}{2} a$$

If peak is contained in an integral range, average is proportional to *a*.

Enhancement by *M*² and definition of sensitive mass range

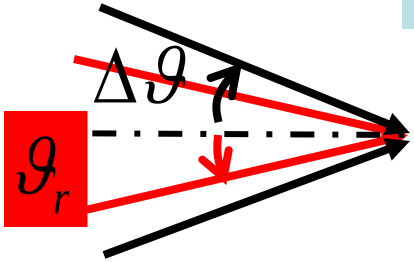
$$|\bar{A}|^2 \propto \int_{-\infty}^{+\infty} \boxed{\rho(\vartheta)} \frac{a^2}{\chi^2(\vartheta)+a^2}\, d\chi$$

Introduce experimental incident angle distribution



If resonance angle is out of experimental angle range

$$\vartheta_r > \Delta\vartheta \rightarrow |A|^2 \propto a^2 \propto \left(\frac{m}{M}\right)^{\textcircled{4}}$$



If resonance angle is within experimental angle range

$$\vartheta_r < \Delta\vartheta \rightarrow |A|^2 \propto a \propto \left(\frac{m}{M}\right)^{\textcircled{2}}$$

Focusing parameter can introduce a sharp cutoff in mass range.

Other enhancement factors

Extremely forward emission

$$\overline{\left(\frac{d\sigma}{d\Omega_3}\right)} \propto \sin^{-4}\vartheta \left(\frac{m}{M}\right)^2$$

Luminosity factor

Average number of optical photons N per 1J laser is N~O(10^{18}) photons.
${}_nC_2 \sim N^2$ produces a huge factor.

Induced absorption

Picture of induced absorption and spontaneous emission of resonances in laser field rather than in vacuum leads us to expect another power of N.

Challenge to gravitational coupling

Observation

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

constant fermion mass

$t=10^{60}$ in Planckian unit

$\Lambda = O(10^{-120})$

An example of scalar field

The Scalar-Tensor Theory of Gravitation
(Cambridge 2003) Y.Fujii arXiv:0908.4324
Y. Fujii and K. Homma arXiv:1006.1762 [gr-qc]

Decaying $\Lambda \propto t^{-2}$

$m_\sigma \sim 10^{-9}$eV ($\lambda \sim 100$m)in the context of Dark Energy

$$m_\sigma^{\ 2} \sim \frac{m_q^{\ 2} M^{\ 2}_{\ ssb}}{M_P^{\ 2}}$$

$$\left(\frac{m \sim 10^{-9} eV}{M \sim 10^{18} GeV}\right) \sim 10^{-36}$$

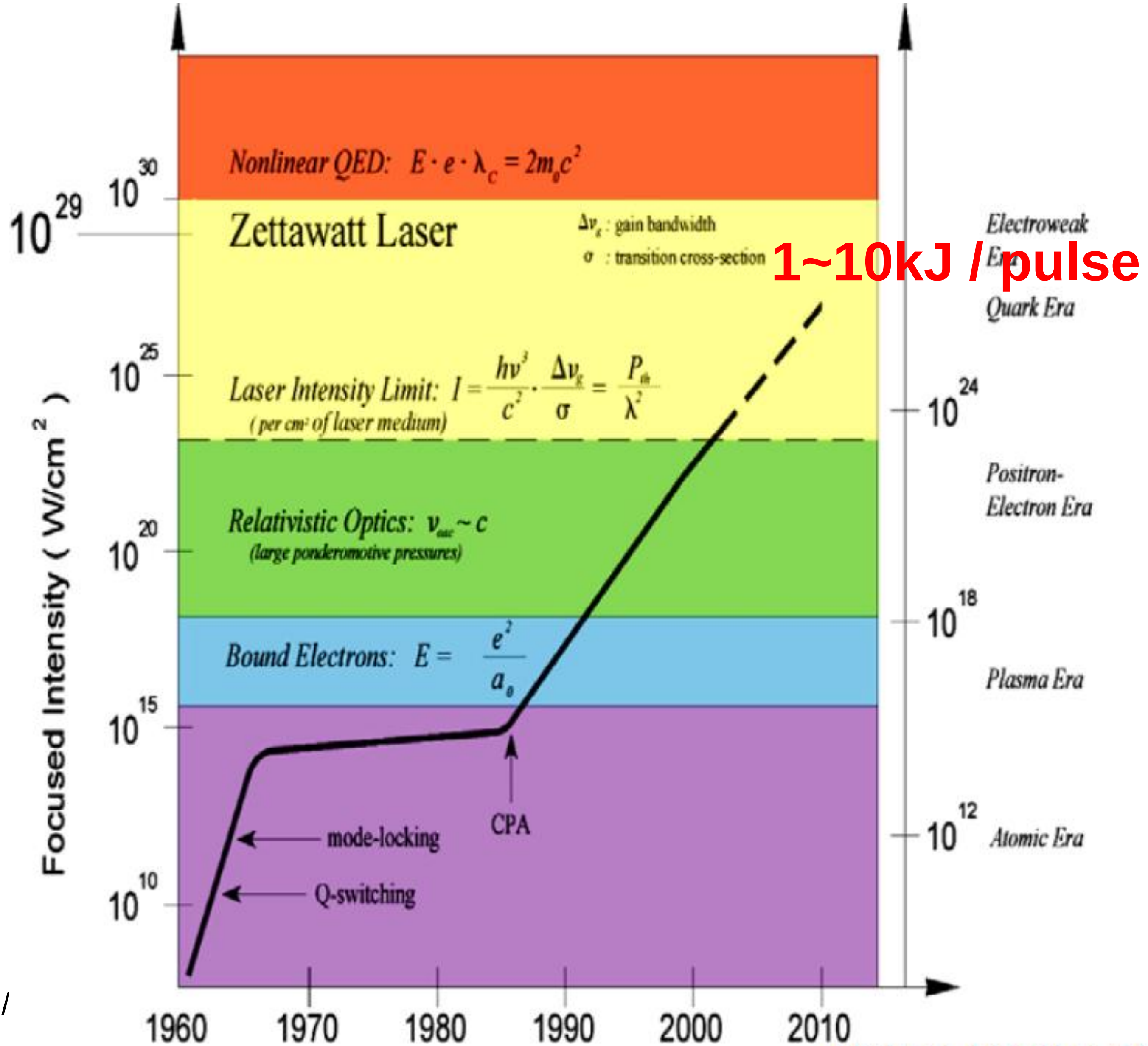
If ~1GJ laser

$$Lumi \times \overline{\left(\frac{d\sigma}{d\Omega_3}\right)} \times d\Omega_3 \propto N^2 \times \vartheta^{-4} \left(\frac{m_\sigma}{M_p}\right)^2 \times \vartheta^2 \sim (10^{27})^2 \times (10^{-9})^{-2} \times (10^{-36})^2$$

--------------- O(1) -------------

Coherent nature like induced absorption may relax the necessary intensity

Extreme Light Infrastructure is ahead



1~10kJ / pulse

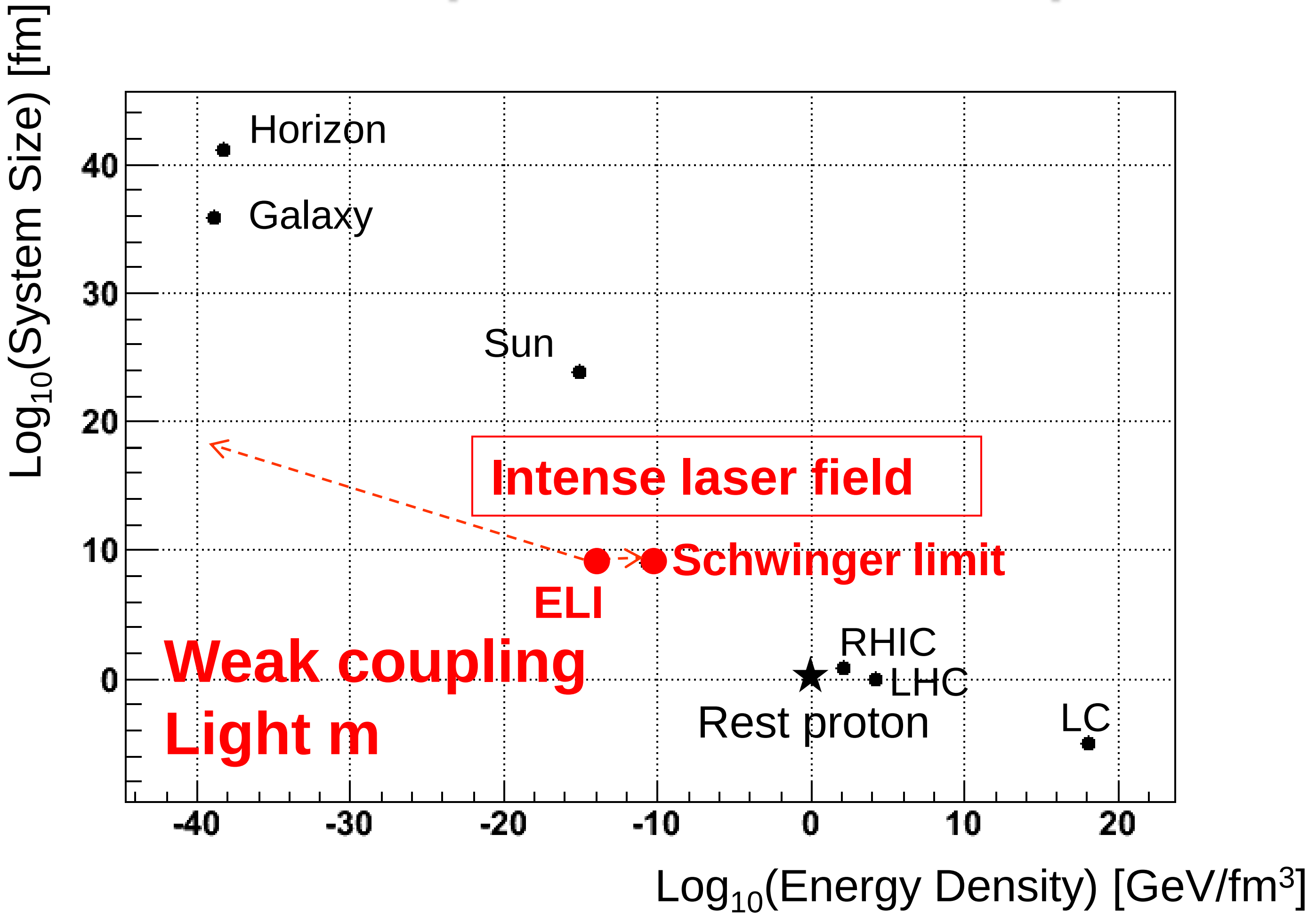
(Tajima,Mourou,2002)

Summary

A novel scope to semi-macroscopic vacuum

Cosmological observation

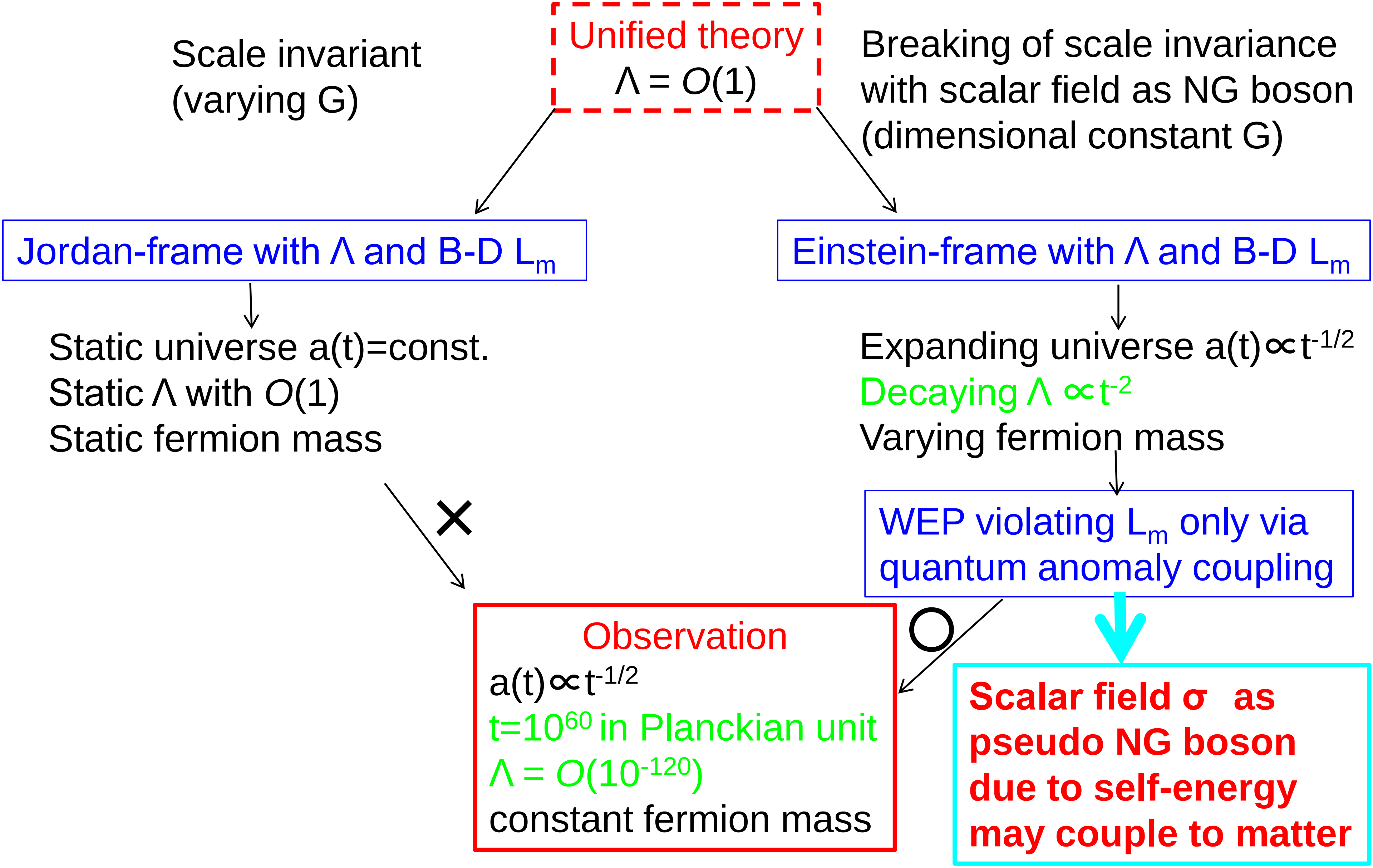
Weak coupling
m=0



Strong coupling
Heavy m

High energy collider

Scalar-Tensor-Theory with Λ (STTΛ)



Unified theory
$\Lambda = O(1)$

Scale invariant
(varying G)

Breaking of scale invariance
with scalar field as NG boson
(dimensional constant G)

Jordan-frame with Λ and B-D L_m

Static universe $a(t)$=const.
Static Λ with $O(1)$
Static fermion mass

×

Einstein-frame with Λ and B-D L_m

Expanding universe $a(t) \propto t^{-1/2}$
Decaying $\Lambda \propto t^{-2}$
Varying fermion mass

WEP violating L_m only via quantum anomaly coupling

○

Observation
$a(t) \propto t^{-1/2}$
$t = 10^{60}$ in Planckian unit
$\Lambda = O(10^{-120})$
constant fermion mass

Scalar field σ as pseudo NG boson due to self-energy may couple to matter

An approach toward laboratory search for the scalar field as a candidate of dark energy

Y. Fujii and K. Homma
arXiv:1006.1762 [gr-qc]

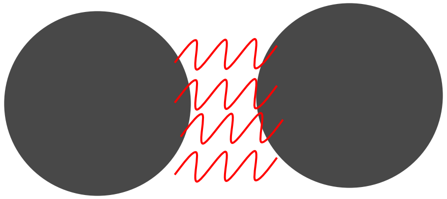
mσ~10^{-9}eV (Force range λ~100m)

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

Use massive bodies in a far distance.

Normal way

Use massive bodies in a short distance.



Coulomb force overwhelms
weak gravitational effects

$\sigma_{QED} \propto (\alpha / m^4{}_e)^2 \omega^6 \vartheta^4$ **is suppressed by ~49 orders of magnitude.**

Massless photon is the best probe to see very light fields, despite of the weak gravitational coupling !!!