jgrg20, 22 Spt 10

An expected gravitational scalar field – Past and Future –

Yasunori Fujii

Past: How is the today's version of the cosmoloog-ical constant problem un-derstood in terms of the gravitational scalar field?

Y.F. & K.Maeda, *The scalar-tensor theory of gravitation*, Cambridge U Press, 03. Y.F. & M. Sasaki, PRD 75 (07), 064028. Y.F., PTP 118 (07), 983. Y.F., Proc XXVII IAU General Assembly, Rio de Janeiro, Aug. 09; Mem.S.S.It. Vol. 75, 282

Future: An attempt to probe the scalar field as light as $\sim 10^{-9}$eV by the laboratory experiment by means of laser physics

Y.F. & K. Homma, gr-qc 1006.1762

1.1 Scale invariance in particle phys broken spontaneously

Nambu-Goldstone boson – Massless scalar field "dilaton"

↘ massive? pseudo NGboson

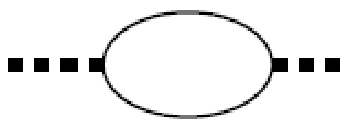
Tried to find it somewhere in particle physics

C.B. Chiu, Y.F., W.W.Wada, Scale invariance, Goldstone boson and f' trajectory, Lett Nuovo Cimento, 1 (71)110

1.2 But showing up in gravitation?

Scalar field; no immunity against acquiring self-energy $\neq 0$

$$m_\sigma^2 \sim \frac{m_{\rm q}^2 M_{\rm ssb}^2}{M_{\rm P}^2} \sim \left(10^{-9}{\rm eV}\right)^2, \quad \lambda = \mu^{-1} \sim 100{\rm m}$$



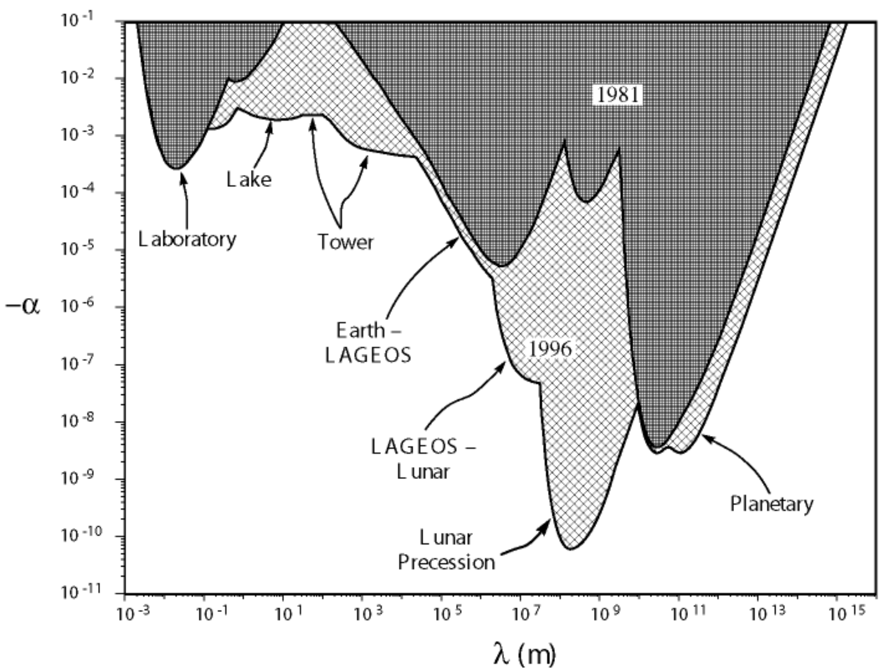
Non-Newtonian gravity

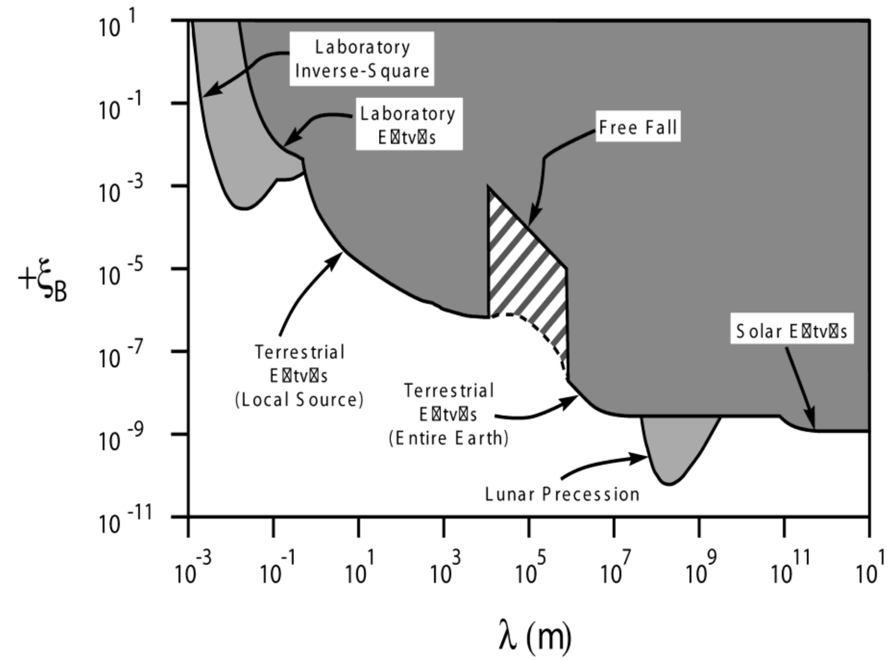
$$V_{ij} = -G_\infty \frac{m_i m_j}{r}\left(1 + \alpha_5\, ij\, e^{-r/\lambda}\right)$$

Weak Equivalence Principle (WEP) ↘ violated

Y.F., Dilaton and Possible Non-Newtonian gravity, Nature Phys.Sci. 234 (71)5

Extensive searches in precision measurements in phys, geology, earth sci, $\cdots$ but no solid evidence so far





Composition-independent exps   Composition-dependent exps

G.W. Gibbons and B.F. Whiting, Nat.291(81)636

E.Fishcback, C.Talmadge, The Search for Non-newtonian Gravity, Figs 2.13, 4.16-17; AIP/Springer (98): S. Schlamminger et al, PRL 100(08)041101

Allan Franklin, The rise and fall of the fifth force, AIP (93)

1.3 Scalar-tensor theory

P. Jordan, Schwerkraft und Weltalle (55)

Consistent with General Covariance? Yes, according to STT

J.O'Hanlon, Intermediate-range gravity: A generally covariant model, PRL 29(72)137

Nonminimal coupling term $= \frac{1}{2}\frac{1}{8\pi G_{\rm eff}(x)}R$

$$\mathcal{L} = \sqrt{-g}\left(\frac{1}{2}\overbrace{\xi\phi^2 R} - \epsilon\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + L_{\rm matter}\right)$$

P.A.M. Dirac, Nat 139(37)323

$\epsilon = {\rm Sgn}(\omega), \quad 4\xi = |\omega|^{-1}$ dimensionless

Reduced Planckian units $c = \hbar = M_{\rm P} (= (8\pi G)^{-1/2}) = 1$

$$t_0 = 13.7{\rm Gy} \approx 10^{60.2}$$

Conformal transformation/frame

$g_{\mu\nu} \to g_{*\mu\nu} = \Omega^2(x) g_{\mu\nu}$ Special choice $\Omega^2 = \xi\phi^2$

$$\mathcal{L} = \sqrt{-g_*}\left(\frac{1}{2}R_* - {\rm Sgn}(\zeta^2)\frac{1}{2}g_*^{\mu\nu}\partial_\mu\sigma\partial_\nu\sigma + L_{*\rm matter}\right)$$

$8\pi G_* = 1 = \text{const}$. Moved: Jordan frame $\Rightarrow$ Einstein frame

$$\phi = \xi^{-1/2}e^{\zeta\sigma}, \quad \zeta = \left(6 + \epsilon\xi^{-1}\right)^{-1/2}, \quad a_* = \Omega a, \ \ dt_* = \Omega dt$$

Dirac was right only in J frame.
The way of cosmic expansion differs from frame to frame.
Which is the physical frame?

1.4 Accererating universe – New life of the scalar field?

Today's version of cosmological const prob $\begin{cases} \text{fine-tuning prob} \\ \text{coincidence prob} \end{cases}$

$$\Omega_\Lambda = \frac{\Lambda}{\rho_{\rm cr}} \approx 0.7 \Rightarrow \Lambda_{\rm obs} \approx 10^{-120}, \quad \textbf{while} \quad \Lambda_{\rm th} \sim 1$$

The simplest idea (Jordan) comes to a unique finding for the most fundamental aspects

$$\mathcal{L} = \sqrt{-g}\left(\frac{1}{2}\xi\phi^2 R - \epsilon\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \Lambda + L_{\rm matter}\right) \quad \text{in J frame}$$

as suggested by closed string in higher dimensions? string frame?

$$\mathcal{L}_{\rm string} = \sqrt{-\bar{g}}e^{-2\Phi}\left(\tfrac{1}{2}\bar{R} + 2g^{\bar{\mu}\bar{\nu}}\partial_{\bar{\mu}}\Phi\partial_{\bar{\nu}}\Phi - \tfrac{1}{12}H_{\bar{\mu}\bar{\nu}\bar{\lambda}}H^{\bar{\mu}\bar{\nu}\bar{\lambda}}\right), \quad \phi = 2e^{-\Phi}, \epsilon = -1, \xi = 1/4$$

$$\mathcal{L} = \sqrt{-g_*}\left(\frac{1}{2}R_* - {\rm Sgn}(\zeta^2)\frac{1}{2}g_*^{\mu\nu}\partial_\mu\sigma\partial_\nu\sigma - \underbrace{\Lambda e^{-4\zeta\sigma}}_{V(\sigma)} + L_{*\rm matter}\right) \text{ in E frame}$$

$$\phi = \xi^{-1/2}e^{\zeta\sigma}, \quad \zeta = \left(6 + \epsilon\xi^{-1}\right)^{-1/2}$$

Lambda cosmology

Spataiilly flat FRW (spatially uniform), radiation-dominated

Asymptotic attractor solution

Y.F., PTP 118(07)983

K. Maeda and Y.F., Phys. Rev. D79(09)084026

J frame

$$a = \text{const}: \quad \text{Static univ} \Rightarrow \text{J frame} \neq \text{physical}$$

$$\phi = 2\zeta\sqrt{\Lambda\xi^{-1}}t, \quad \rho = -3\Lambda\zeta^2\left(2+\epsilon\xi^{-1}\right)$$

No smooth limit as $\Lambda \to 0$

BD model to save WEP by requiring

ϕ decoupled from $L_{\rm matter} \Rightarrow m = \text{const}$

C. Brans and R.H. Dicke, Phys. Rev. 124(61)925

Atomic clock, with $m_{\rm e}^{-1}$ as the unit (standard)

No way to detect possible time variation of the unit itself, unless other clock is used

Own Unit Insensitivity Principle (OUIP)

— unit is a constant in the current frame

E frame

$$a_* = t_*^{1/2} \sim t \quad \text{expansion} \Rightarrow \text{Physical frame?} \;-\; \text{Good news?}$$

$$\sigma(t_*) = \bar{\sigma} + (1/2)\zeta^{-1} \ln t_*$$

$$3H_*^2 = \rho_\sigma + \rho_*, \quad \text{where } \rho_\sigma = \frac{1}{2}\dot{\sigma}^2 + V(\sigma) = \Lambda_{\rm eff} \;-\; \text{Dark Energy}$$

$$\rho_\sigma = \frac{3}{16}\zeta^{-2} t_*^{-2}, \quad \rho_* = \frac{3}{4}\left(1 - \frac{1}{4}\zeta^{-2}\right) t_*^{-2}$$

But $m_* \sim t_*^{-1/2} \neq \text{const}$ – Bad news?

$$am \overset{\text{BD}}{=} \text{const} = a_* m_*$$

Univ expands in the same rate as microscopic size, $m_*^{-1} \sim t_*^{1/2}$,
against current view on the expansion of Univ.
– Univ expands in reference to microscopic size
Inter-galactic separations expand but smaller
distances, including microscopic size, held fixed.

Measuring redshits of atomic spectra, with their length units provided by m_{*e}^{-1}, unit = const (OUIP) $\Rightarrow m_* = \text{const}$

Can E frame be saved to be physical by $m_* = \text{const}$?
This requies leaving BD model, violating WEP.

BD $\searrow$ dimensionless $\rightarrow$ scale invariance $\uparrow$

$$L_{\text{matter}} = -\overline{\psi}\,(\partial\!\!\!/ + m)\,\psi \rightarrow -\overline{\psi}\,(\partial\!\!\!/ + f\phi)\,\psi \quad \text{Yukawa int with } \phi$$

$$L_{*\text{matter}} = -\overline{\psi}_*\,(\partial\!\!\!/ + m_*)\,\psi_*,\ m_* = \xi^{-1/2} f = \text{const}, \quad \psi_* = \Omega^{-3/2}\psi$$

Decoupled σ from $L_{*\text{matter}} \Rightarrow$ undetected WEP-violating effects if measured through ψ (ordinary matter)

Another way to save WEP but only classically

Quantum effects from Relativistic Quantum Field Theory allows them to re-emarge, computed by quantum anomalies, fortunately rather small.

$$\begin{cases} \text{Jordan frame} = \text{Theoretical, string} & \Lambda_{\rm th} \sim 1 \\ \text{Einstein frame} \approx \text{Physical, observational} & \Lambda_{\rm eff} \approx \rho_\sigma \sim t_*^{-2} \end{cases}$$

$$\Lambda_{\rm eff\,0} \sim t_{*0}^{-2} \sim \left(10^{60}\right)^{-2} = 10^{-120}$$ without fine-tuning

Observational agreement hardly dismissed as a coincidence!

Scenario of a decaying Λ nearly to entire history of Univ

Today's Λ is small simply because we are cosmologically old

Rediscovering Dirac(37) applied to Λ not to G!

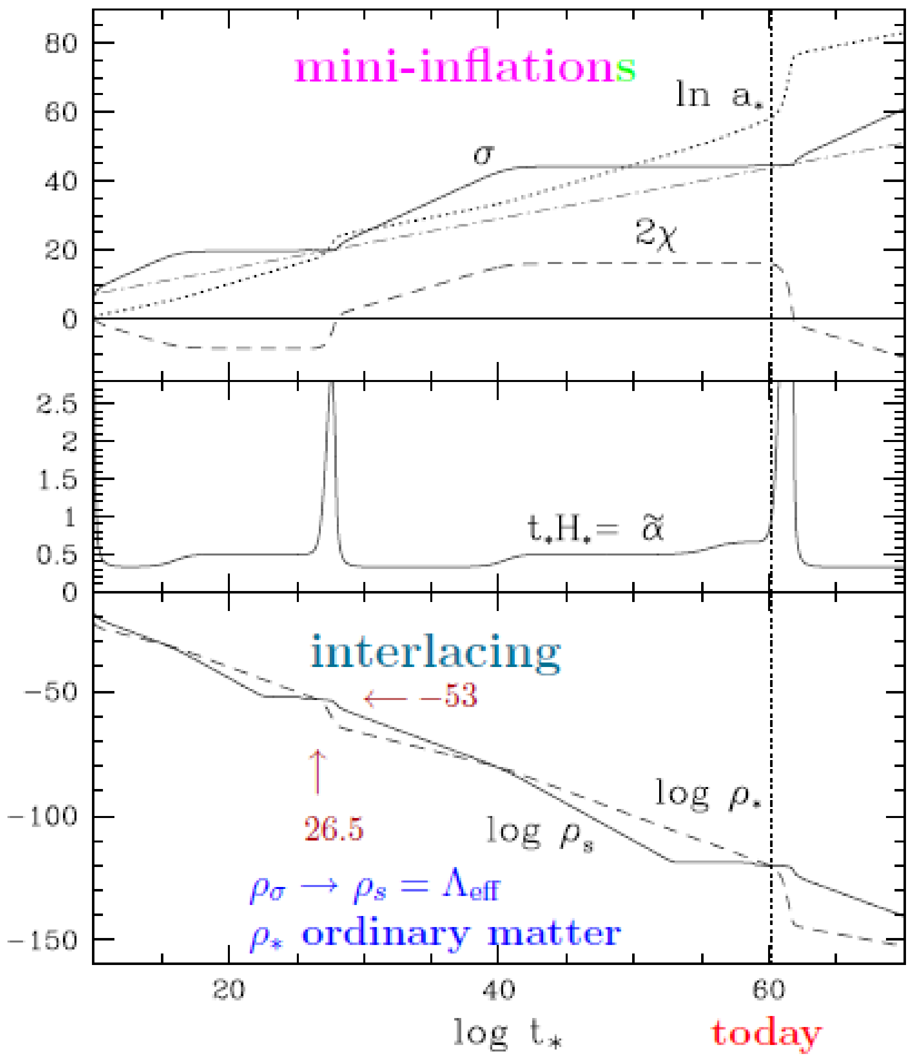
– Simplest approach has now reached Scenario by leaving BD model, at the risk of WEP violation, nontrivially selecting physical frame

A major success of Jordan's theory – like none of others

– Outgrowth of Y.F., PR D26(82),2580: O. Bertolami, NC B93(86),36

Other issues

- Scaling behavior *vs* tracking behavior?
- Locally massive *vs* globally massless?



Taken from Fig. 5.8 of Y.F. & K.Maeda, Cambridge book (03)

- $\rho_s, \rho_* \sim t_*^{-2}$ as overall behavior, inheriting Scenario $\Lambda_{\rm eff} \sim t_*^{-2}$
- Non-smooth behaviors; plateau, extra acceleration, interlacing

Underneath non-smooth aspects (of practical importance), we find an unmistakable sign of the persistent and dominant trend based on simple scalar-tensor theory

$$\begin{cases} \text{Locaaly massive} & - \text{ nonzero mass of } \sigma \\ \text{Globally massless} & - \text{ smooth potential } V(\sigma) = \Lambda e^{-4\zeta\sigma} \end{cases}$$

Apparently contradictory features are different ways in which the scalar field shows itself in different situations:

- $m_\sigma \neq 0$; Quantum effect in a force between local objects
- $\sigma(t_*) \sim \ln t_*$; Classical evolution of the entire Univ

2.1 Introduction

To probe experimentally the scalar field $m_\sigma \sim 10^{-9}\mathrm{eV}$

- Matter coupling as weak as gravitation

  How to overcome the weak signals by non-gravitational means
- By using large masses, as in the past searches for NonNewtonian gravity, fifth force, sometimes "natural" environments

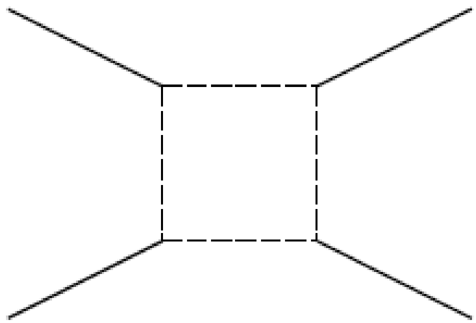
  – water reservoirs, boreholes, towers, cliffs, polar ice, $\cdots$ with unavoidable uncontrollable uncertainties –

- We aim laboratory exps by precision measurements on γ-γ scattering taking place in high-intensity lasers

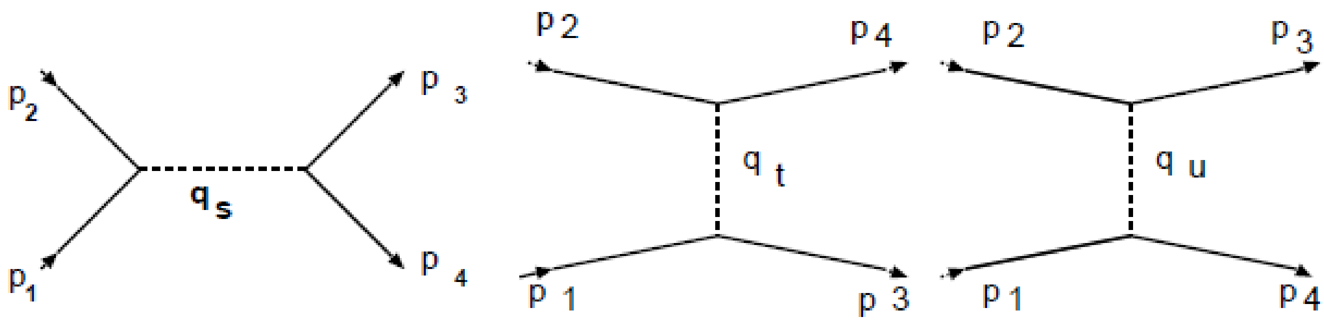
Assume the scalar-field-dominated diagrams

$\gamma - \gamma$ scattering

- QED box diagram still unobserved



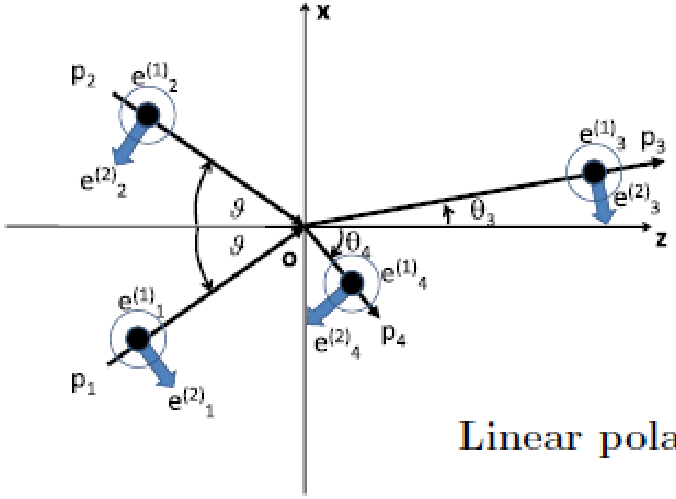
- Scalar-field (σ) dominance, assumed $m_\sigma \sim 10^{-9}$eV



Overwhelming contribution from the resonance in s-channel

2.2 Kinematics

Quasi-parallel incident beams — many advantages



Linear polarization, to be ignored

$$p_1 = (\omega \sin\vartheta, 0, \omega\cos\vartheta; \omega)\,, \qquad p_3 = (\omega_3 \sin\theta_3, 0, \omega_3\cos\theta_3; \omega_3)$$

$$p_2 = (-\omega \sin\vartheta, 0, \omega\cos\vartheta; \omega)\,, \qquad p_4 = (-\omega_4 \sin\theta_4, 0, \omega_4\cos\theta_4; \omega_4)$$

$$\vartheta \sim 10^{-9} \quad \Leftarrow \quad \vartheta \approx \frac{m_\sigma}{\omega_1}$$

$\omega_1 \equiv 1\text{eV} \sim \omega_{\text{opt}}$ – typical energy scale in our experiment

$$0 < \theta_3 < \vartheta < \theta_4 < \pi, \qquad 0 < \omega_4 < \omega_3 < 2\omega$$

Lorentz trsf from CM head-on collision in x, with $\beta_z = \cos\vartheta$

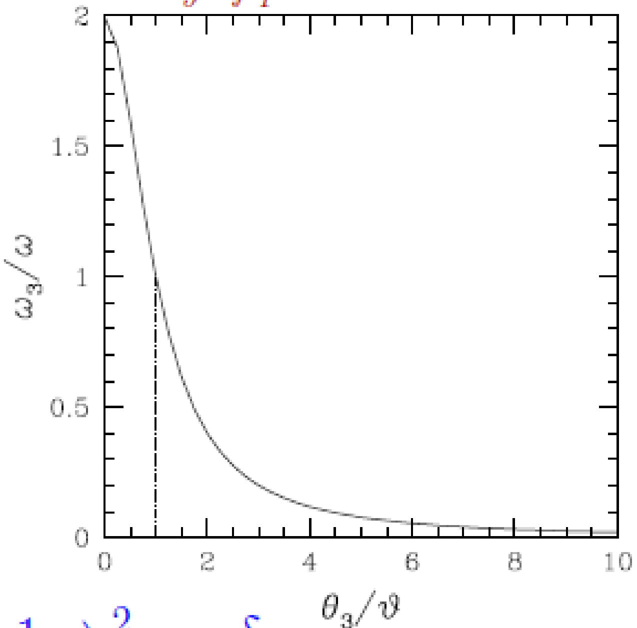
$$\frac{d\sigma}{d\Omega_3} = \left(\frac{1}{8\pi\omega}\right)^2 \sin^{-4}\vartheta \left(\frac{\omega_3}{2\omega}\right) |\mathcal{M}|^2$$

$$\sin^{-2}\vartheta \Leftarrow 1/\sqrt{(p_1 p_2)^2} \approx 1/\left(2\omega^2 \sin^2\vartheta\right)$$ **for $\gamma - \gamma$ flux**

Eq. (3.78) in J.M. Jauch and F. Rhorich, *The theory of photons and electrons*

$$\omega_3 = \frac{\omega \sin^2\vartheta}{1 - \cos\vartheta\cos\theta_3} \Rightarrow \omega_3 \approx 2\omega \quad (\theta_3 \to 0)$$

Nearly-doubled frequency



- **Sharp forward peak confined to $\vartheta \ll$ observational angular resolution**
- **Frequency threshold (given $\overline{\omega}_3$)**

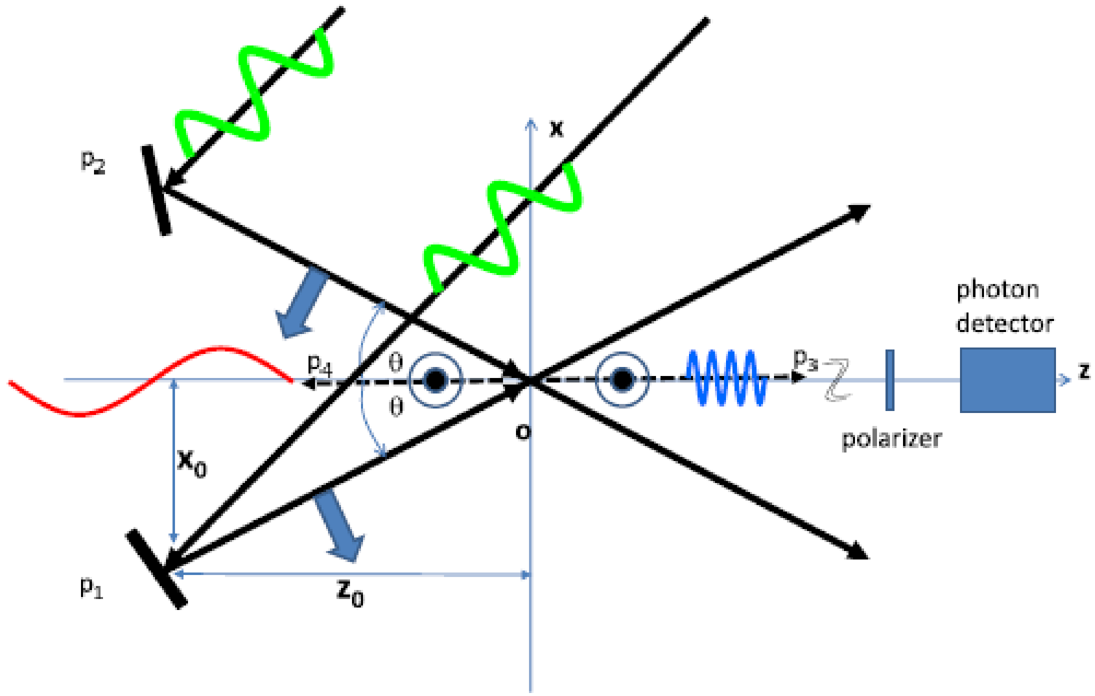
$$\omega_3 > \overline{\omega}_3 \Rightarrow \overline{\theta}_3/\vartheta < \sqrt{\delta/2} \quad (\delta = 2 - \overline{\omega}_3/\omega)$$

Partially integrated cross section

$$\Longrightarrow \Delta\sigma \equiv \int \frac{d\sigma}{d\Omega_3} d\Omega_3 \sim \frac{d\sigma}{d\Omega_3} \pi \vartheta^2 \frac{\delta}{2} = \pi \left(\frac{1}{8\pi\omega}\right)^2 \vartheta^{-2} \frac{\delta}{2} |\mathcal{M}|^2$$

Laser setups – preliminary – 2-beam focusing

Easy to understand in principle, but hard to be implemented in practice because of $\vartheta \sim 10^{-9} \ll 1$



2.3 Dynamics

shown explicitly

$$-L_{\mathrm{mx}\sigma} = \frac{1}{4} B M_{\mathrm{P}}^{-1} F_{\mu\nu} F^{\mu\nu}\sigma, \quad B = (1/3)(\alpha/\pi)\mathcal{Z}\zeta, \quad \zeta^{-1} = 6 + \epsilon\xi^{-1}$$

WEP violating, due to Quantum Anomaly, with $\mathcal{Z} = 5$

$$\Gamma_\sigma = (16\pi)^{-1}\left(BM_{\mathrm{P}}^{-1}\right)^2 m_\sigma^3, \quad \Gamma_\sigma^{-1} \sim 3\times 10^{54} t_0$$

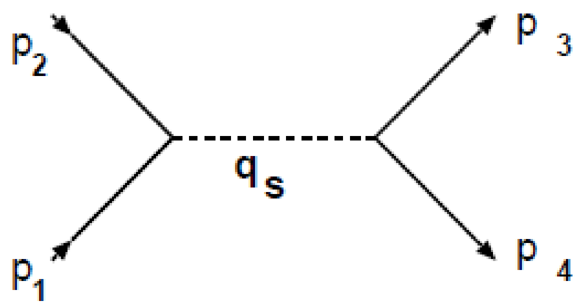
$$\mathcal{M}_{1111s} = -\left(BM_{\mathrm{P}}^{-1}\right)^2 \frac{\mathcal{N}}{(p_1+p_2)^2 + m_\sigma^2} = -\left(BM_{\mathrm{P}}^{-1}\right)^2 \frac{\omega^4(\cos 2\vartheta - 1)^2}{2\omega^2(\cos 2\vartheta - 1) + m_\sigma^2}$$

$$\mathcal{N} = \mathcal{N}_{12}\mathcal{N}_{34}, \quad \mathcal{N}_{ab} = (p_a p_b)(e_a e_b) - (p_a e_b)(p_b e_a), \quad m_\sigma \to m_\sigma - i\Gamma_\sigma/2$$

Breit-Wigner type near the resonance $\xi \sim 0$

$$\xi = \omega^2 - \omega_r^2, \;\; \omega_r^2 = \frac{m_\sigma^2/2}{1-\cos 2\vartheta}, \;\; a = \frac{m_\sigma \Gamma_\sigma/2}{1-\cos 2\vartheta}$$

$$\mathcal{M}_r \approx -4\pi\frac{a}{\xi + ia}, \quad |\mathcal{M}_r|^2 \approx (4\pi)^2 \frac{a^2}{\xi^2 + a^2}$$



$\mathcal{M}_r = 4\pi i, \quad |\mathcal{M}_r|^2 = (4\pi)^2$ at $\xi = 0$; **independent of strength**

But $\mathcal{M}_{\mathrm{whole}} \sim M_{\mathrm{P}}^{-2}, \;\; |\mathcal{M}_{\mathrm{whole}}|^2 \sim M_{\mathrm{P}}^{-4}$

Extremely narrow width $a \sim M_{\mathrm{P}}^{-2} \sim 10^{-77}(\mathrm{eV})^2 \ll \omega_1^2 = 1(\mathrm{eV})^2$

A needle-like pinnacle erected high up by M_{P}^4 on the surface of the vast (non-resonance) plane

ω_1 – typical energy scale of practical measurement

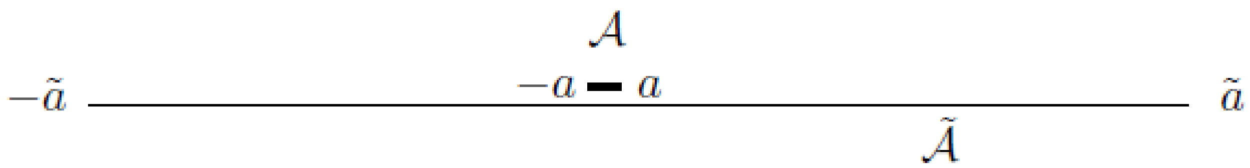
Too narrow to be measured directly in any practical way

Averaging over $\tilde{\mathcal{A}} = \{-\tilde{a}, \tilde{a}\}$ with $\tilde{a}(\sim \omega_1^2 \gg a)$

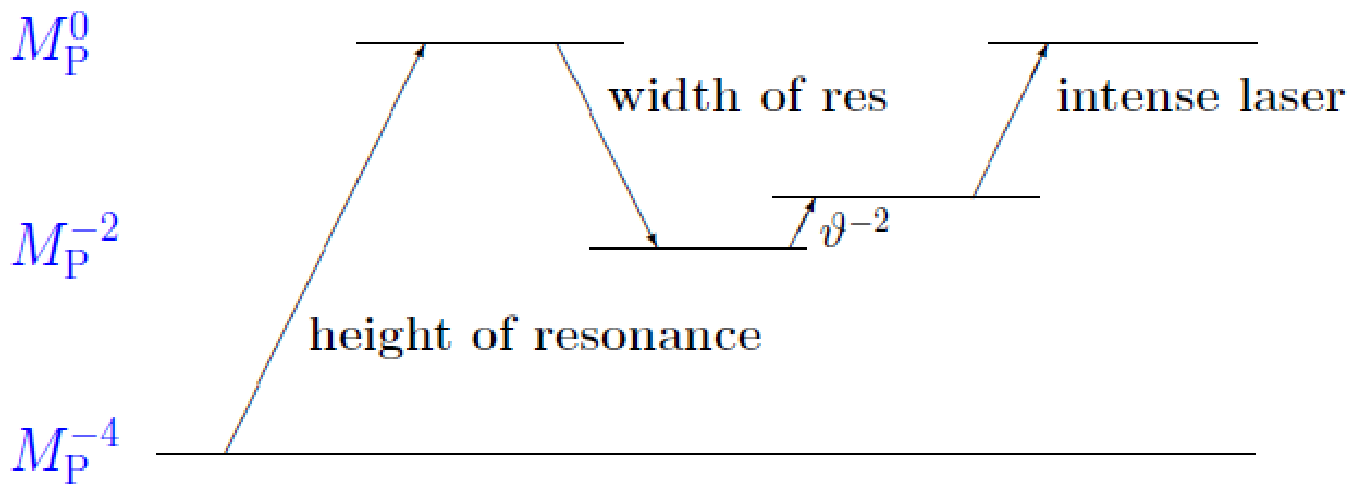
$$\overline{|\mathcal{M}_r|^2} \equiv \frac{1}{2\tilde{a}} \int_{-\tilde{a}}^{\tilde{a}} |\mathcal{M}_r(\xi)|^2 d\xi = (4\pi)^2 \eta^{-1} \frac{\pi}{2} \hat{\eta}, \quad \eta = \frac{\tilde{a}}{a} \gg 1$$

$$\int_{-\tilde{a}}^{\tilde{a}} \left(\xi^2 + a^2\right)^{-1} d\xi = 2\tfrac{1}{a} \tan^{-1}\left(\tfrac{\tilde{a}}{a}\right), \quad \hat{\eta} \equiv \tfrac{2}{\pi} \tan^{-1} \eta \to 1$$

Dilution?



$$\eta^{-1} \sim 10^{-77} \sim (m_\sigma / M_{\mathrm{P}})^{-2} \approx 10^{-72}$$



$\Delta\sigma \sim \vartheta^{-2}|\mathcal{M}|^2, \quad \overline{|M|^2} \sim \eta^{-1}$ $\quad \vartheta = 10^{-9}$

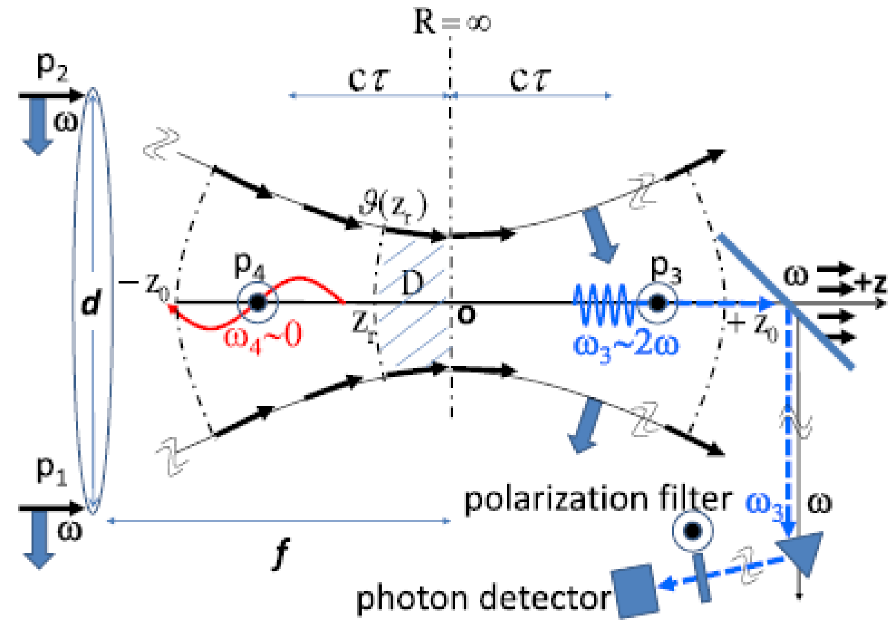
$\Rightarrow \overline{(\Delta\sigma)} \sim \dfrac{\pi^2}{4\omega^2}\vartheta^{-2}\eta^{-1} \Leftarrow \vartheta^{-2} \sim 10^{18} \sim (M_P/m_\sigma)^{1/2}$, another gain?

$\vartheta^{-4} \to \infty$ as $\vartheta \to 0$, but no physical infinities, because

$\mathcal{M} \sim \vartheta^4 \Rightarrow \dfrac{d\sigma}{d\Omega_3} \sim \vartheta^{-4}\times\left(\vartheta^4\right)^2 \sim \vartheta^4 \to 0,$ true in t, u channels, too

Justified no matter how small ϑ might be

A more realistic setup by one-beam focusing inside the beam itself



varying ω fixed ϑ	$\Longrightarrow$	varying ξ for averaging	$\Longleftarrow$	fixed ω varying ϑ

$$\xi = \omega^2 - \frac{m_\sigma^2/2}{1-\cos 2\vartheta} \approx \omega^2 - \frac{m_\sigma^2}{4\vartheta^2}$$

$$\vartheta_r = m_\sigma/(2\omega_1) \sim 10^{-9}$$

Yield and luminosity

$$\frac{d\mathcal{Y}}{d\Omega_3} = \mathcal{L}\overline{\left(\frac{d\sigma}{d\Omega_3}\right)}, \qquad \mathcal{L} \approx \frac{\bar{N}^2/2}{\pi\lambda^2}$$

$\bar{N}$: average number of photons per pulse

$$\mathcal{Y} \approx \int \frac{d\mathcal{Y}}{d\Omega_3} d\Omega_3 \sim \frac{d\mathcal{Y}}{d\Omega_3}\vartheta^2 \sim \frac{\bar{N}^2}{\lambda^2}\frac{1}{16\omega^2}\vartheta^{-2}\eta^{-1} \sim 10^{-62}\bar{N}^2$$

$\mathcal{Y} \sim 1$ for 1 event per pulse

$\Rightarrow \bar{N}_1^2 \sim 10^{62}$ **or** $\bar{N}_1 \sim 10^{31} \gg 10^{22} = 1\mathbf{kJ}$ **Too large!**

$1\mathrm{eV} \approx 1.602 \times 10^{-19}\mathrm{J}$ **hence** $1\mathrm{eV} \times 10^{22} = 1.602 \times 10^{3}\mathrm{J}$

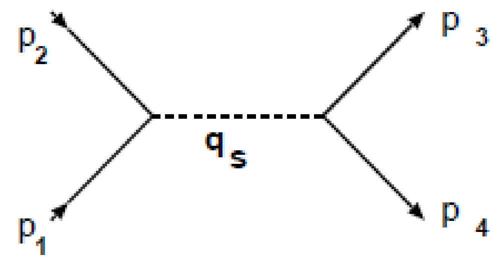
– **Strongest pulse beam available at the present time by a state-of-the-art technology**

With $\bar{N}_1 \sim 10^{22}$ **in 10 Hz, we find**

$\mathcal{Y} \sim 10^{-62+44} = 10^{-18}$ **per pulse**

$\Rightarrow$ **An event needs** $\sim 10^{18}$ pulses $\sim 10^{17}$sec $\sim 10^{10}$y

A possible way out?



Initial photon annihilates into sea of photons in the interaction volume, not into vacuum, some sharing the same state as p_1, suppose n of them

$< n|a|n+1 >= \sqrt{n+1}$, rather than $< 0|a|1 >= 1$

induced absorption (annihilation) spontaneous → Feynman-rule estimate

Feynman amplitude, $\mathcal{Y}_{\rm conv}$ } to be corrected by $\times \begin{cases} \sqrt{n+1} \\ n+1 \end{cases}$

$n+1 \sim n \to n(\vartheta)\bar{N}$ with $\int n(\vartheta)d\vartheta = 1$ $(\Leftarrow \sum n = \bar{N})$

Through the discussions on $\cdots$ $\cdots$ $\cdots$

$$\mathcal{Y}_{\rm conv} \to \mathcal{Y} = \mathcal{Y}_{\rm conv} \times n^2(\vartheta_r)\bar{N}^2 \approx 10^{-62} n^2(\vartheta_r)\bar{N}^4$$

with an obvious enhancement, though depending on $n(\vartheta_r)$

– Search encouraged for the gravitational scalar field as a constituent of DE?

- Ratio of QED box contribution to σ-exchange in the forward direction;

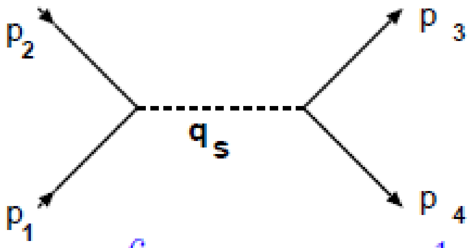
$$\frac{\vartheta^4\omega^6\left(\alpha^2/m_e^4\right)^2}{\left(\pi/8\omega^2\right)\vartheta^{-2}\eta^{-1}} \approx \vartheta^6\alpha^4\frac{4\pi}{B^2}\left(\frac{M_P}{m_\sigma}\right)^2\left(\frac{\omega}{m_e}\right)^8 \sim 10^{-30},$$

mainly due to the resonance enhancement

W. Dittrich and H. Gies, *Probing the quantum Vacuum* (Springer 1994)

- Axion search (ALP)

– Regeneration due to the shining-light-through-the-wall approach



$$m_{\text{axion}} \gtrsim 10^{-6}\text{eV}, \qquad \text{“}M_P^{-1}\text{”} \gtrsim 10^2$$

G. Mueller, P. Skivie, D.B. Tanner and Karl van Bibber, arXiv: 0907.5387.
A. Lindner, arXiv:0910.1686