Probing Dark Energy with high-intensity lasers

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Special thanks to

T. Tajima, D. Habs, G. Mourou

1. Today's version of cosmological constant problem
2. Scalar-Tensor Theory with Λ
3. *New proposal with high-intensity laser fields*

Accelerating Universe

Discovered in 1998

⇨ Cosmological constant

$$\Lambda_{\rm obs} \approx 10^{-120} \lll \Lambda_{\rm th} \sim \mathcal{O}(1)$$

Fine tuning?

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

$$t_0 \sim 1.4 \times 10^{10}{\rm y} \sim 10^{60}$$

⇨ $\Lambda_{\rm obs} \sim t_0^{-2}$ Decaying? Dynamical?

$\Lambda_{\rm obs}$ is this small today because we are old,

not because we fine-tuned parameters

Rediscover Jordan’s scalar-tensor theory

P. Jordan, Schwerkraft und Weltall, (1955)

Massless (gravitational) scalar field ϕ

Coupled to other fields gravitationally, unlike Higgs

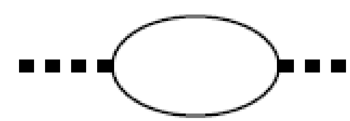
We had derived $\Lambda_{\rm obs} \sim t_0^{-2}$

Y.F. PRD26 (1982)2580. O.Bertolami, NC B93(1986)36. Y.F. & K. Maeda, *The scalar-tensor theory of gravitation*, Cambridege U Press, 2003

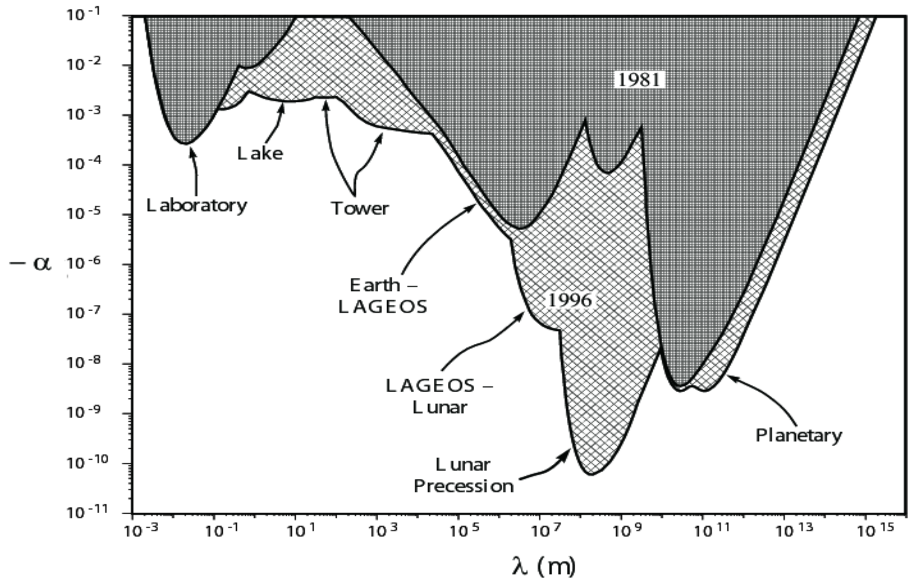
Two faces of the scalar field

- Cosmological behavior; Dark Energy, negative pressure: nearly classical
- Force between local objects; quantum effects, no immunity from acquiring self-energy, unlike genuine gauge fields

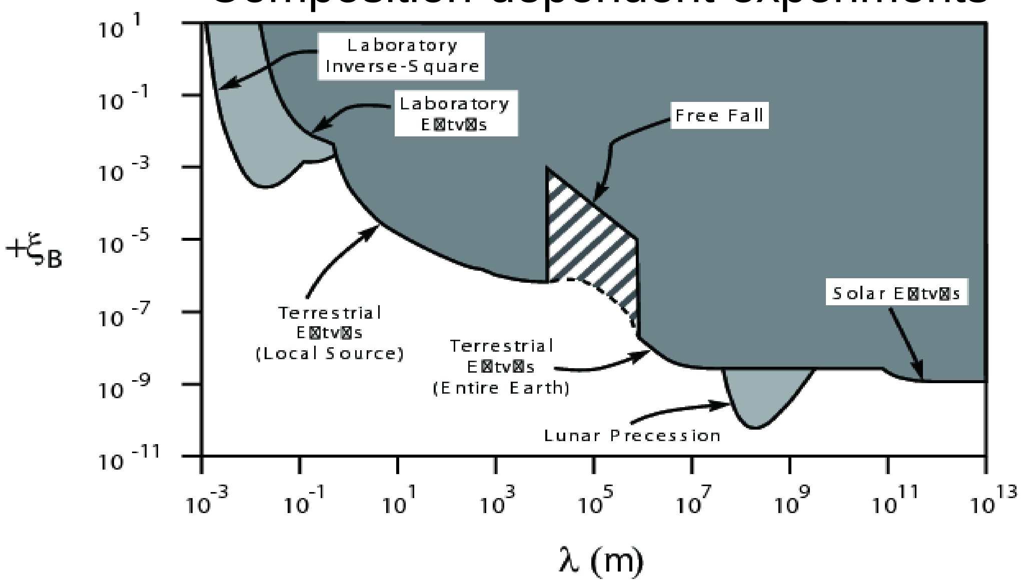
$$m_\phi{}^2 \sim \frac{m_{\rm q}^2 M_{\rm ssb}^2}{M_{\rm P}^2} \sim \left(10^{-9}{\rm eV}\right)^2, \quad \lambda = m_\phi^{-1} \sim 100{\rm m}$$



Composition-independent experiments



Composition-dependent experiments



Past experiments in 70s and 80s

To overcome weakness of gravity, huge, heavy objects used even natural environments

Only upper-bounds with limited accuracies

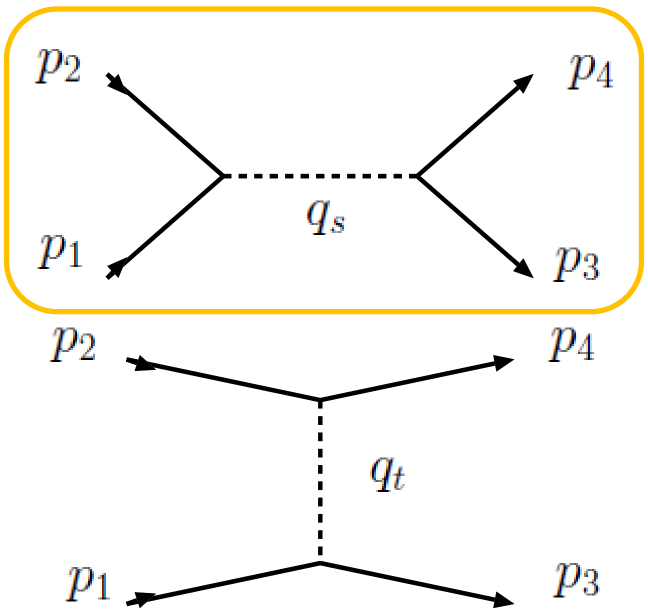
E.Fischbach & C.Talmadge, *The search for non-Newtonian gravity*, AIP/Springer, 1999

Scalar field production by photon-photon scattering with resonance enhancement

Building blocks

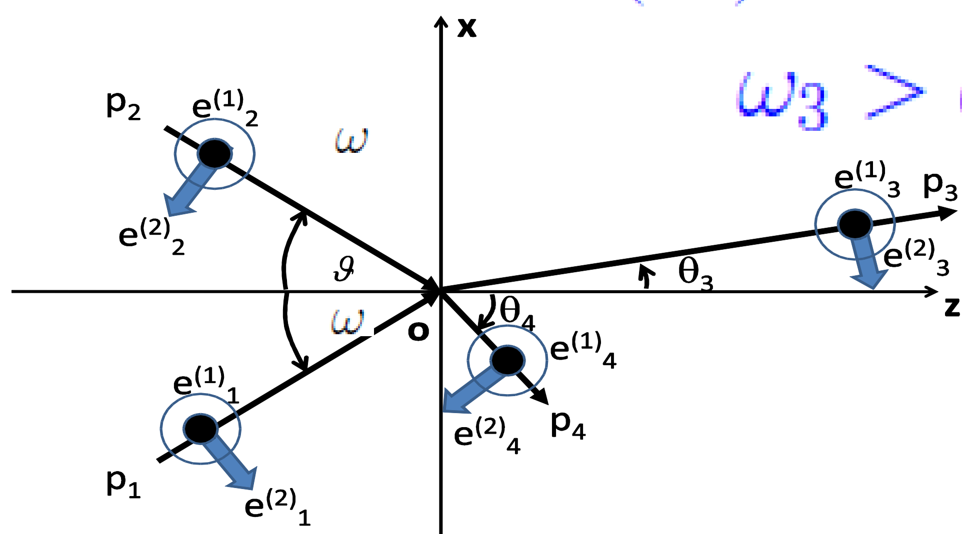
$$-L_{\mathrm{mx}\phi} = \frac{1}{4} B M_{\mathrm{P}}^{-1} F_{\mu\nu} F^{\mu\nu} \phi, \qquad B = (2\alpha/3\pi) \mathcal{Z} \zeta$$

$$\vartheta \sim \frac{m_\phi}{2\omega} \sim \frac{10^{-9}\mathrm{eV}}{\mathcal{O}(\mathrm{eV})} \sim 10^{-9}$$



Resonance-dominated only in the s channel

$$\omega_3 > \omega_4$$



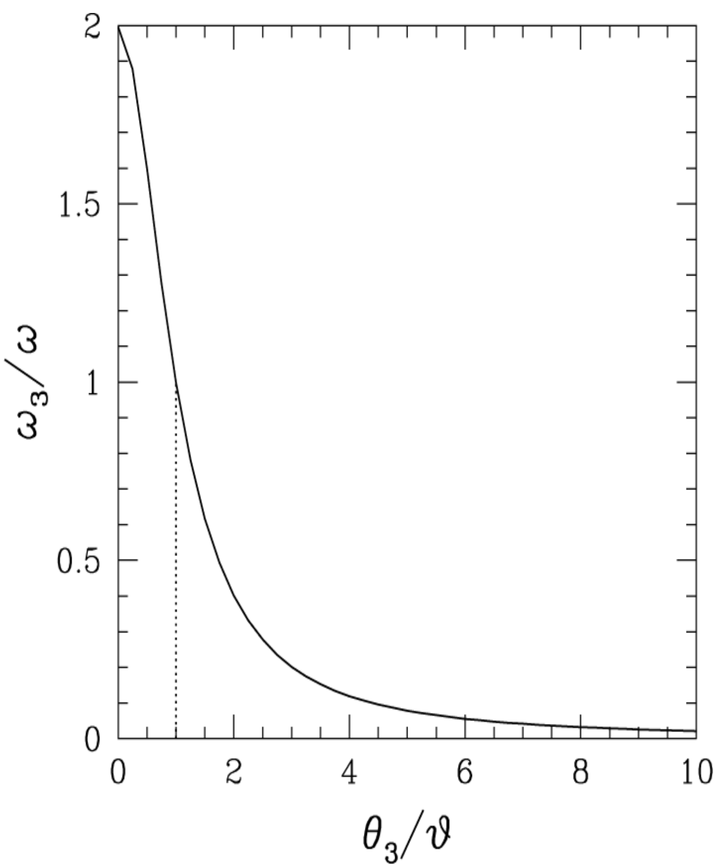
Quasi-parallel frame

$$\frac{d\sigma}{d\Omega_3} = \left(\frac{1}{8\pi\omega}\right)^2 \sin^{-4}\vartheta \left(\frac{\omega_3}{2\omega}\right)^2 |\mathcal{M}|^2, \qquad \frac{\omega_3}{\omega} = \frac{\sin^2\vartheta}{1-\cos\vartheta\cos\theta_3}$$

Trove $\sin^{-4}\vartheta \approx \vartheta^{-4}:$ $\begin{cases} \vartheta^{-2} & \text{Phase-volume integral} \\ \vartheta^{-2} & \text{Normalized flux of photons} \end{cases}$

No infinity in cross section

Distribution of p_3 → **Observational signature**



- Extremely forward direction within the angle ϑ
- Nearly doubled frequency $\omega_3 \approx 2\omega$

But integrated yield $\sim \vartheta^2$ too small to be measured

Multiply by ϑ^{-2}, eating up trove

Then smaller trove ϑ^{-2}

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

$$m_\phi \to m_\phi - i\frac{1}{2}\Gamma_\phi, \quad \Gamma_\phi = (16\pi)^{-1}\left(BM_{\rm P}^{-1}\right)^2 m_\phi^3 \quad \textbf{for } \phi \to 2\gamma$$

$$\omega_r^2 \equiv \frac{m_\phi^2/2}{1-\cos 2\vartheta} \approx \frac{m_\phi^2}{4\vartheta^2}, \qquad a = \frac{1}{2}\frac{m_\phi \Gamma_\phi}{1-\cos 2\vartheta}$$

$\chi = \omega^2 - \omega_r^2, \qquad \chi = 0$ at the resonance

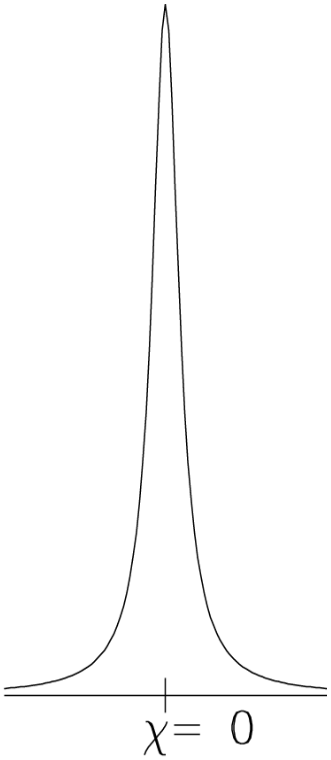
$$\mathcal{M}_{1111s} \overset{\chi\sim 0}{\approx} 4\pi \frac{a}{\chi + ia}, \qquad |\mathcal{M}_{1111s}|^2 \sim (4\pi)^2 \frac{a^2}{\chi^2+a^2}$$

BW formula

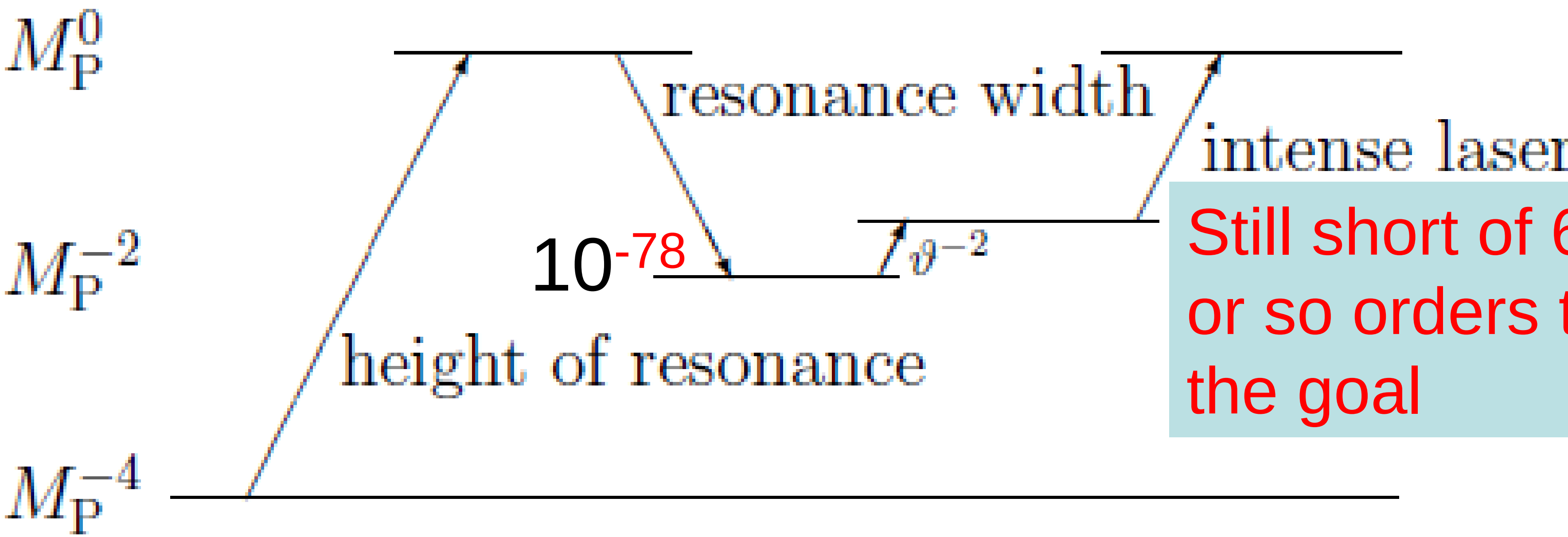
Peak-value independent of strength of the force

$$|\mathcal{M}_s|^2 \sim M_{\rm P}^{-4} \sim G^2 \ll 1, \ \textbf{but} \ |\mathcal{M}_s|^2_{\rm res} \approx (4\pi)^2 \sim M_{\rm P}^0$$

First step toward enhancement



Extremely narrow width squared



Still short of 60 or so orders to the goal

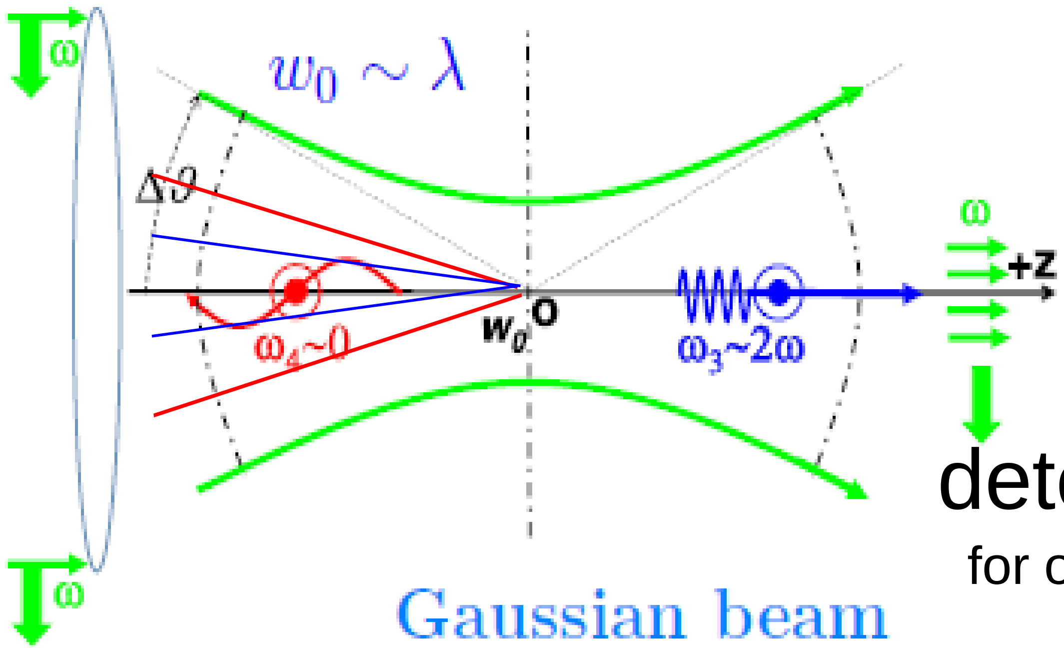
$$\frac{a}{\omega_0^2} \approx \frac{B^2}{64\pi}\left(\frac{m_\phi}{M_P}\right)^2\left(\frac{m_\phi}{\omega_0\vartheta}\right)^2 \sim 10^{-6}\times 10^{-72}\times 10^{0} \sim 10^{-78} \ll 1, \qquad (\omega_0 \equiv 1\mathrm{eV})$$

Averaging over range $\tilde{a} \sim \omega^2{}_0$

$$\overline{|\mathcal{M}_{1111s}|^2} = \frac{1}{2\tilde{a}}\int_{-\tilde{a}}^{\tilde{a}} |\mathcal{M}_{1111s}|^2 d\chi = 10^{-78}$$

Experimental setup

- Fixed ω_0
- varied ϑ



$$\vartheta_r = \frac{m_\phi}{2\omega_0}$$

detector

for observational signature

$$\left\{ \begin{array}{l} \omega_3 \sim 2\omega \\ \textbf{Extremely forward direction} \end{array} \right.$$

$$yield \propto N^2 \sigma$$

Second step toward enhancement

Intense laser beam described by coherent state

Averaged photon number

R.J. Glauber. PR 131(63)2766

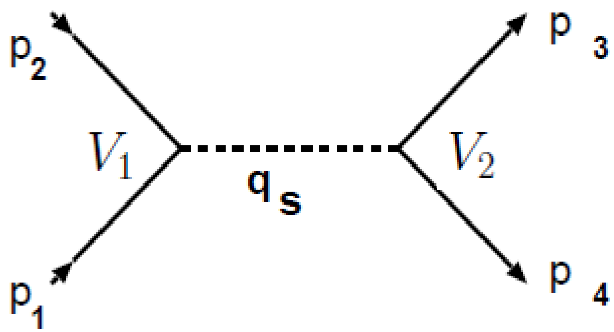
$$|p, N\gg \equiv e^{-N/2} \sum_{n=0}^{\infty} \frac{N^{n/2}}{\sqrt{n!}} |n>, \quad |n>= \frac{1}{\sqrt{n!}} \left(a^{\dagger}(p)\right)^{n} |0>$$

$$\ll p, N|a^{\dagger}a|p, N\gg = N, \qquad \ll p, N|a|p, N\gg = \sqrt{N}$$

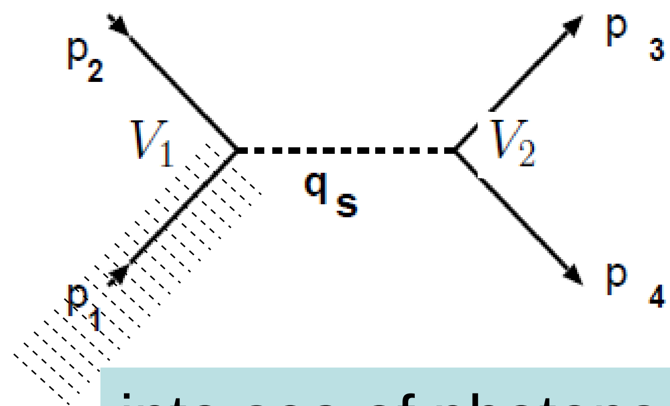
Single mode
approximation

Second step toward enhancement

$$V_2\left((p_1+p_2)^2+m_\phi^2\right)^{-1}V_1$$



into vacuum



into sea of photons

$$<0|F_{\mu\nu}|p_1>\rightarrow<0|a|p_1>=1$$

$$\ll p_1,N|a|p_1,N\gg=\sqrt{N}$$

Enhancement by $\sqrt{N}$ The same for p_2 but not for p_3,p_4

Total rate by $\left(\left(\sqrt{N}\right)^2\right)^2=N^2$

Yield per pulse of observational signature

$$\frac{d\mathcal{Y}}{d\Omega_3} = \frac{N^2}{\pi w_0^2}\frac{d\overline{\sigma}}{d\Omega_3} \approx \frac{u}{64\pi}\vartheta_r^2 10^{-78} N^2 \quad u \sim 0.1, \quad w_0 \sim \omega^{-1}$$

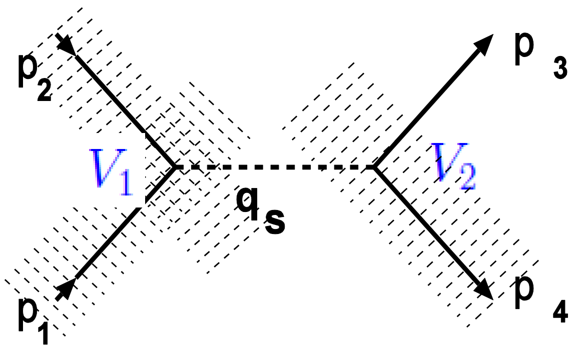
$N^2 =$ Enhancement factor of coupling strength

Requiring $d\mathcal{Y}/d\Omega_3 \sim 1$ $\Longrightarrow$ 1 event for p_3 per pulse

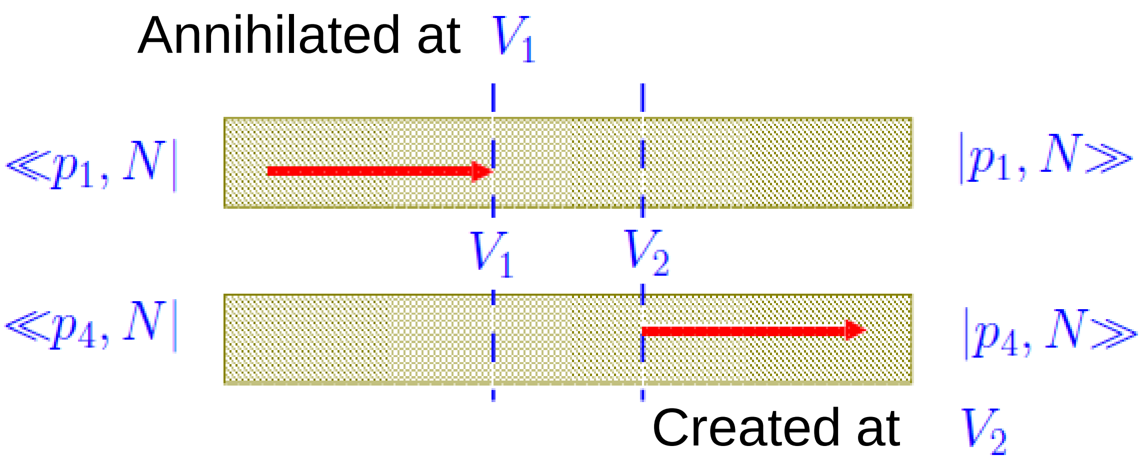
$\overline{N} \sim 10^{31}$ optical photons $\sim 10^{10}\mathrm{kJ} \gg \mathcal{O}(\mathrm{kJ})$

Too much, unrealistic

Adding Inducing beam $|p_4, N\gg$



Creating p_4 at V_2 from sea of photons enhanced by $\sqrt{N}$



Rate of producing p_3 enhanced by N

$\overline{N} \sim (\cdots)^{1/3} \sim 10^{21} = 1\mathrm{kJ},$ detectable, fortunately

Summary

Enhancement machanisms due to resonance nature and the triple product of coherent photons enable the detection of the scalar field as a candidate of Dark Energy in laboratory.