Using LIGO to search for high frequency coherent fields that couple to two photons

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CLASSICAL "PICTURE" of LIGO

1. GRAVITATIONAL FIELD

   CONSIDER: SINGLE ARM, OPTIMAL INCIDENCE , $\Omega L/c << 1$

   FIELD IMPOSES SIDEBANDS

   $$E_{\pm} = (2kL)hE_c\, e^{i(\omega \pm \Omega)t}$$

   IF THE FIELD (ENERGY) DENSITY IS ρ_g

   $$h_g^{\,2} = \rho_g (32\, G_N / c^2)/\Omega^2$$

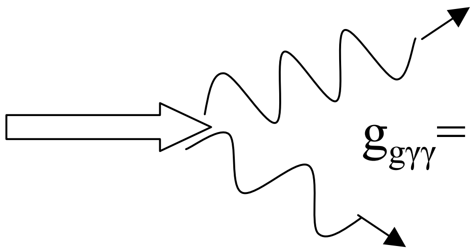
2. A SCALAR FIELD THAT COUPLES TO 2-PHOTONS

   WITH (INVERSE ENERGY) STRENGTH $1/\Lambda$

   IMPOSES SIDEBANDS AS WELL

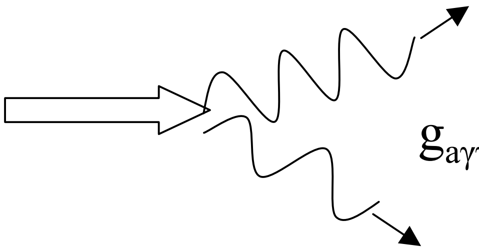
   $$h_a^{\,2} = \rho_a\, (2/\Lambda)^2 \hbar c^3/\omega_a^{\,2}$$

g



$g_{g\gamma\gamma} = (\sqrt{8\pi})/M_p c^2$

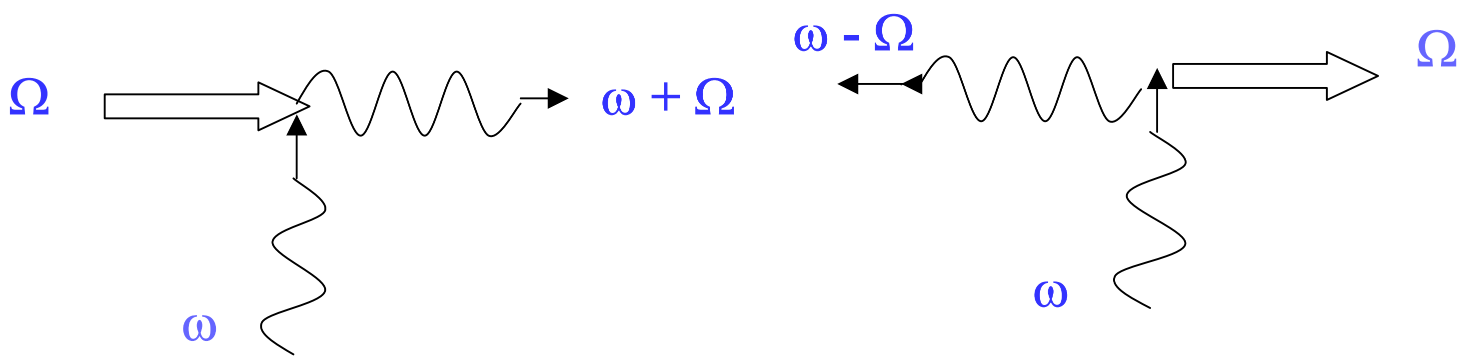
a



$g_{a\gamma\gamma} = 1/\Lambda$

QUANTUM "PICTURE" of LIGO

SIDEBANDS AT ±Ω ARE DUE TO ABSORPTION **AND**
STIMULATED EMISSION OF A GRAVITON FROM/INTO THE FIELD



- ENERGY CONSERVATION IS SATISFIED
- LINEAR AND ANGULAR MOMENTUM IS BALANCED
  BY THE RIGID MIRRORS
- LORENTZ INVARIANCE IS SATISFIED BY
  DIRECTION/POLARIZATION OF THE SIDEBANDS
- IF THE FIELD IS COHERENT AND IF ω+Ω AND/OR ω-Ω IS RESONANT
  THE SIDEBAND AMPLITUDE WILL GROW IN TIME:
  WE SPEAK OF **PARAMETRIC CONVERSION**

PARAMETRIC CONVERSION

1. THE LIGO IFO ADMITS A SPECTRUM OF DISCRETE FREQUENCIES ν_n

THE FREQUENCIES ARE EQUALLY SPACED

$$\Delta\nu \equiv \nu_0 = 2L/c$$

ν_0 IS THE FREE SPECTRAL RANGE (fsr)

$$\nu_0 = 37.52 \text{ kHz}$$

n+1

n

n-1

WHEN THE IFO IS LOCKED ONLY ONE MODE IS OCCUPIED $n = \nu_n / \nu_0 \approx 10^{10}$

THE WIDTH OF THE MODES IS

$$\delta = \nu / Q \qquad Q = F\,(2L / \lambda) \approx 10^{12}$$

IN THE PRESENCE OF A PERTURBATION AT FREQUENCY

$$\Omega / 2\pi \approx \Delta\nu = \nu_0$$

THE (n+1) AND (n-1) MODES BECOME POPULATED

2. EXPECTED SIGNAL

E_n	FIELD IN MODE n
$E_{n\pm1}$	FIELD IN MODE $n\pm1$
η or h	DIMENSIONLESS PERTURBATION

FOR $E_{n\pm1} << E_n$ AND $t >> Q / \omega$

$$E_{n\pm1} = \tfrac{1}{2} Q \, \eta \, E_n$$

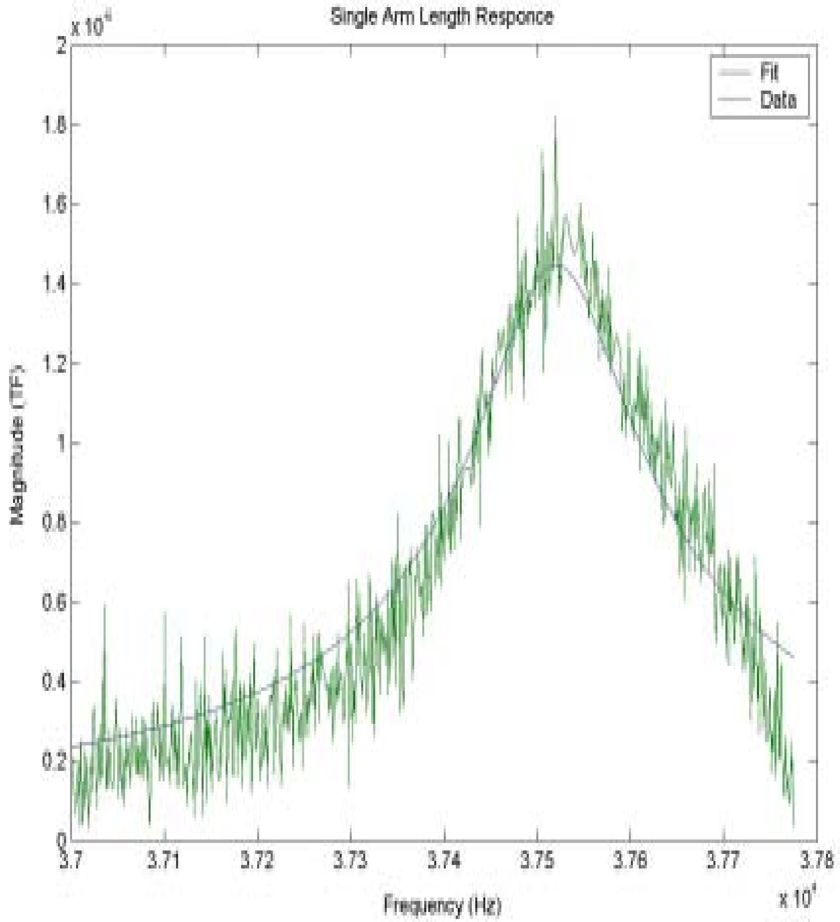
3. EXAMPLE: END MIRROR (ETM) MOTION

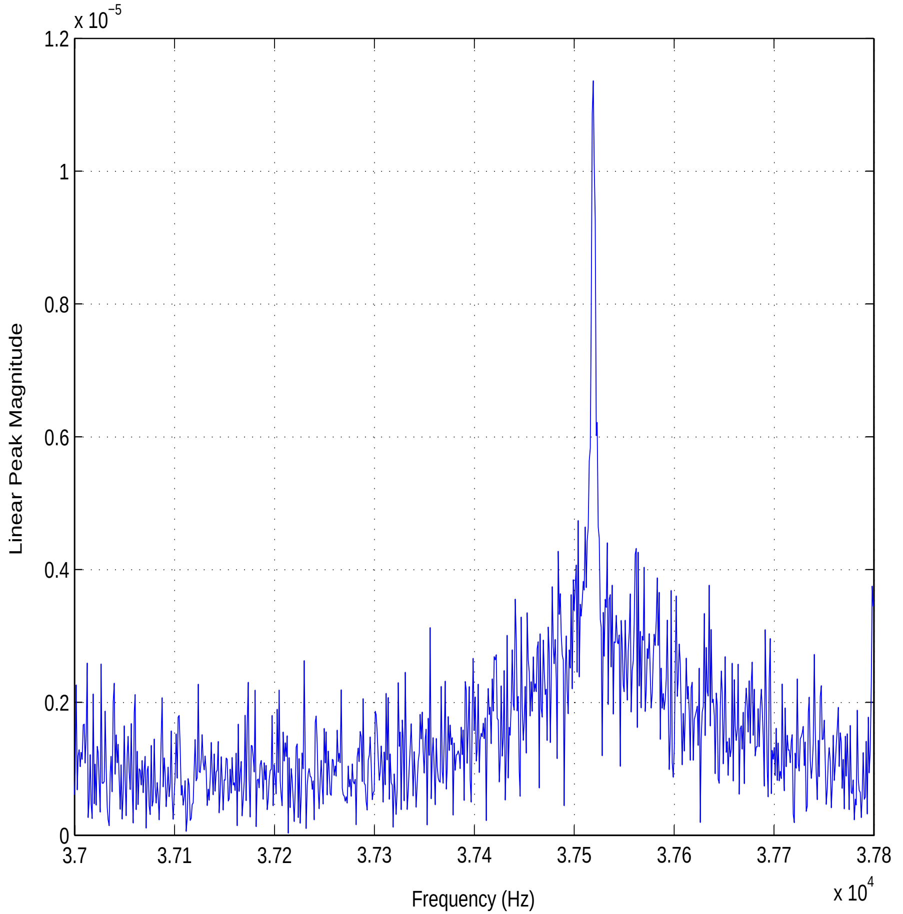
$x = x_0 \cos \Omega t$ $\quad\quad$ $\eta = x_0 / L$ $\quad\quad$ $\omega_\tau = \nu_0 (\pi / F)$

$$E_{n\pm1} = E_n \, \eta (L / \lambda_0) \, F / [1 + (\Omega_{\text{mod } 2\pi\nu o} / \omega_\tau)^2]^{1/2}$$

On resonance $\quad E_{n\pm1} = \tfrac{1}{2} Q \, \eta \, E_n \sim 10^{12} \, \eta \, E_n$

PARAMETRIC SIGNALS AT 37.52 kHz





SINGLE ARM

FULL IFO Narrow peak: Common mode
Broad peak: Differential mode

ARBITRARY INCIDENCE

For $\theta = 0$ $\quad H_1(\Omega=2\pi\nu_0) = 0$

For $\theta \neq 0$ $\quad H_1(\Omega=2\pi\nu_0) \neq 0$

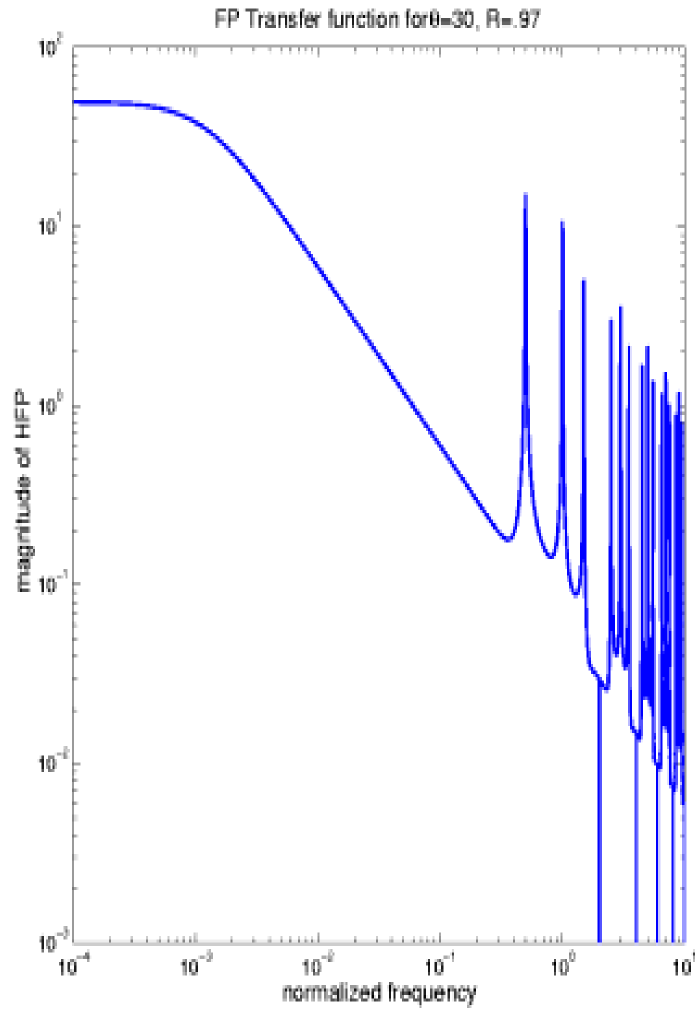
and the signal is enhanced at

$\Omega = n(2\pi\nu_0) \quad n = 1,2\ldots.$

HIGH FREQUENCY, $\Omega L/c >> 1$

For free test masses the response decreases as $(2\pi\nu_0)/\Omega$

For fixed test masses the response is constant at the dc value.



Normalized frequency = $\Omega/4\pi\nu_0$

DETECTION OF AXION FLOW

ASSUME **STATIONARY** AXION FIELD

$a(r,t) = |a| e^{i\Omega t}$ $\Omega = m_a$ $E_c = E_0 e^{i\omega t} (e^{ikz} + e^{-ikz})$

$L = (E_c \cdot B_s)a$ E_s perpendicular to E_c

SIDEBAND FIELD $E_s = | E_s e^{i(\omega+\Omega)t} (e^{ikz} + e^{-ikz})$

E_s beats with E_c with wavelength $\lambda = 1/m_a$

Consider only frequencies $\Omega = n (2\pi\nu_0)$

Sidebands will resonate and maintain their phase along z
Thus they stimulate further transitions. In the steady state

$$E_s = ½ (h_a Q) E_c$$

Detect sidebands as usual by beating against the rf sidebands

SENSITIVITY

$\rho_a \sim 1.7\times10^{-24}$ g/cm^3 $= 10^3$ MeV/cm^3 $\sim 10^5 \rho_c$

$m_a \sim 10^{-5}$ eV $\rightarrow$ $\Omega = 1.5\times10^{10}$ r/s ; $\Lambda = 10^{14}$ GeV

Find

$$h_a = (2/\Lambda)(c/\Omega)\sqrt{(\rho\hbar c)} = 6\times10^{-19}$$

EXPECTED LINE WIDTH

$$\Delta f_a \sim 10^{-6} f_a \sim 2.5 \text{ kHz}$$

COMPARE TO CAVITY WIDTH $\sim$ 250 Hz

For $T_{INTEGRATION} = 10^5$ S/N $= 10^4$

If $m_a \neq \Omega_n$ SCAN CAVITY ARM LENGTH $\sim$ 3 cm

RELATIVISTIC FIELDS

EXAMPLES: QUINTESSENCE, DILATON

NOW PROPAGATION DIRECTION AFFECTS THE PHASE AT THE DETECTOR

COLLINEAR PROPAGATION IS OPTIMAL

USE OPTICAL TECHNIQUES TO ISOLATE SIDEBANDS

FABRY-PEROT ETALON

$L = 1.5$ cm , $F \sim 10^5$

fsr = 10 GHz

Resolution = 100 kHz

IF THE LINE IS BROAD

"COMB OF SIDEBANDS"