INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

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SCHOOL ON
NON-ACCELERATOR PHYSICS
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AXION ↔ PHOTON MIXING IN A MAGNETIC FIELD

by

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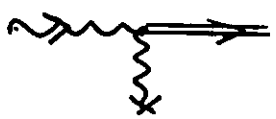
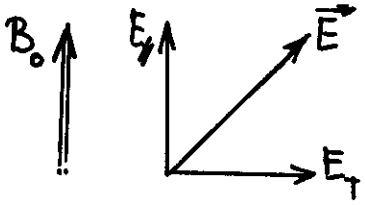
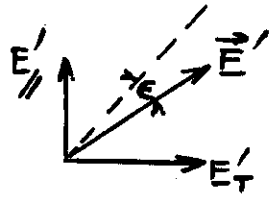
AXION ↔ PHOTON MIXING IN A MAGNETIC FIELD

1. ATTENUATION

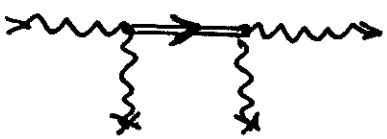


$\vec{E} \parallel \vec{B}$

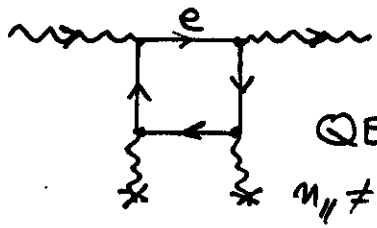




2. RETARDATION

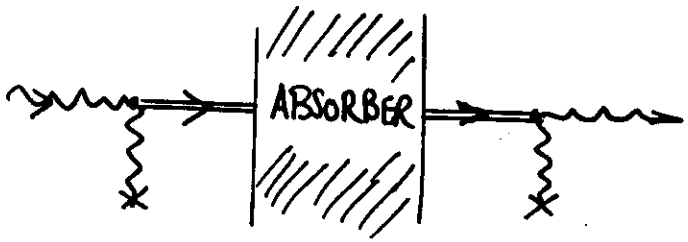


$n_\parallel = 1+\delta$, $n_\perp = 1$



$n_\parallel \neq n_\perp \neq 1$

3. REGENERATION



FORMALISM

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2}\left(\partial_\mu \phi_a \partial^\mu \phi_a - m_a^2 \phi_a\right)$$

$$+ \frac{1}{4M} F_{\mu\nu} \tilde{F}_{\mu\nu} \phi_a + \frac{\alpha^2}{90\, m_e^2}\left[\left(F_{\mu\nu} F^{\mu\nu}\right)^2 + \frac{7}{4}\left(F_{\mu\nu} \tilde{F}_{\mu\nu}\right)^2\right]$$

$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

m_a = axion mass

$M = 1/g_{a\gamma\gamma}$ (GeV)

In presence of $\vec{B}_0$ field, the photon acquires a refractive index

$n_\perp = 1 + 4\xi$

$n_\parallel = 1 + 7\xi$

$\xi = \frac{\alpha^2}{90\pi} \frac{B_0^2}{m_e^4}$

$A_\parallel$ produce, axions

$A_\perp$ does <u>not</u> produce axions

EVOLUTION IN TIME & SPACE

$A_\perp$, $A_\parallel$, ϕ_a HAVE THE SAME ENERGY ω

WAVE VECTORS k ARE DIFFERENT

$A_\perp$	$k_\perp = n_\perp \omega$	$k_T - \omega \equiv \Delta_T = 4\omega\xi$
$A_\parallel$	$k_\parallel = n_\parallel \omega$	$k_\parallel - \omega \equiv \Delta_\parallel = 7\omega\xi$
ϕ_a	$k_a = (\omega^2 - m_a^2)^{1/2}$	$k_a - \omega \equiv \Delta_a = -m_a^2/2\omega$

THE EQ. OF MOTION IS

$$\left[\omega - i\frac{\partial}{\partial z} + \begin{pmatrix} \Delta_T & 0 & 0 \\ 0 & \Delta_\parallel & \Delta_M \\ 0 & \Delta_M & \Delta_a \end{pmatrix}\right]\begin{bmatrix} A_\perp \\ A_\parallel \\ \phi_a \end{bmatrix} = 0$$

$$\Delta_M \equiv \frac{B_0}{2M}$$ MIXES ϕ_a , $A_\parallel$

We diagonalize the matrix by imposing a rotation on the fields,

$$U = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \qquad \frac{1}{2}\tan 2\theta = \frac{\Delta_M}{\Delta_\parallel - \Delta_a}$$

θ is mixing angle $\sim \frac{B_0}{M}\frac{\omega}{m_a^2} \ll 1$

PHASE SHIFT AFTER DISTANCE ℓ, [BETWEEN ϕ_a, $A_\parallel$]

$$\phi = (\Delta_\parallel - \Delta_a)\ell \leftarrow$$

IF $\phi \ll 2\pi$ THE TWO FIELDS ϕ_a , $A_\parallel$ REMAIN COHERENT

— FIND THE EVOLUTION OF THE FIELDS BY EXPANDING IN SMALL ANGLE θ

EXAMPLE : $A_\parallel$ TO ORDER θ^2

$$A_\parallel(\ell) - A_\parallel(0) = -\theta^2\left(1 + i\phi - e^{-i\phi}\right)$$

IF ALSO ϕ SMALL $\phi \ll 1$

$$A_\parallel(\ell) - A_\parallel(0) = -\frac{\phi^2\theta^2}{2} - i\frac{\phi^3}{6}\theta^2$$

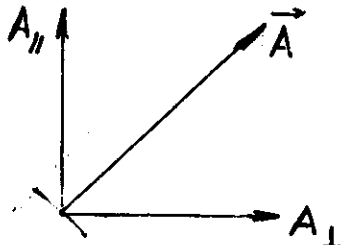
$\frac{\phi^2\theta^2}{2}$ ← ATTENUATION

$i\frac{\phi^3}{6}\theta^2$ ← RETARDATION

HOWEVER $A_\perp$ IS NOT AFFECTED BY θ

∴ RELATIVE AMPLITUDE & PHASE BETWEEN $A_\parallel$, $A_\perp$ CHANGES WITH DISTANCE

OBSERVABLE EFFECTS



At $t=0$

$|A_\perp| = |A_{//}|$ and in phase

$\therefore \vec{A}$ LINEARLY POLARIZED AT 45° TO $\vec{B}_0$

AFTER PATH LENGTH $L = N\ell$ IN B_0

ANGLE OF ROTATION $\gamma = N \frac{\ell^2}{16}\left(\frac{B_0}{M}\right)^2 \frac{1}{4\pi}$

ELLIPTICITY (MINOR/MAJOR AXIS) $\eta = N \frac{\ell^3}{96} \frac{m^2}{\omega}\left(\frac{B_0}{M}\right)^2 \frac{1}{4\pi}$

ASSUMED $\mu \ll 1$

FROM Q.E.D. ONLY PHASE SHIFT

$\mu' = (\Delta_{//} - \Delta_T)\ell$

ELLIPTICITY $\eta_{QED} = \frac{3}{2} N\ell\omega \left\{ = \frac{\alpha^2}{m_e^4} \frac{L}{60\pi} (B_0)^2 \right.$

NUMERICAL VALUES

$B_0 = 5.2\,T$

$\ell = 9\,m$ (2 MAGNETS)

$N = 600$ REFLECTIONS IN OPTICAL CAVITY

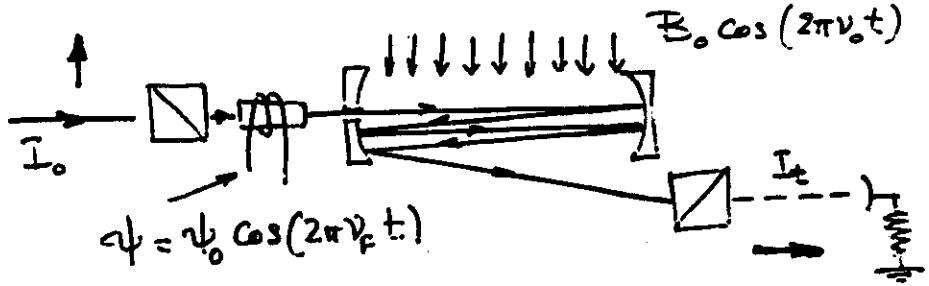
$\omega = 2\,eV$ VISIBLE (ARGON ION LASER)

FIND $\eta_{QED} = 3.5 \times 10^{-12}$ $I = |E|^2$

FOR $M = 10^8$ GeV, $m_a \lesssim 10^{-3}$ eV

ROTATION (AXIONS) $\gamma \approx 4 \times 10^{-12}$ rad

ELLIPTICITY (AXIONS) $\eta \approx 4 \times 10^{-12} \left[\frac{m_a\,(eV)}{10^{-5}}\right]$



$I_T = I_0 \left[\rho^2 + 2\psi(t)\eta(t) + \psi^2(t) + \eta^2(t)\right]$

FREQUENCIES DC $\quad \nu_F \pm 2\nu_0 \quad 2\nu_F \quad 4\nu_0$

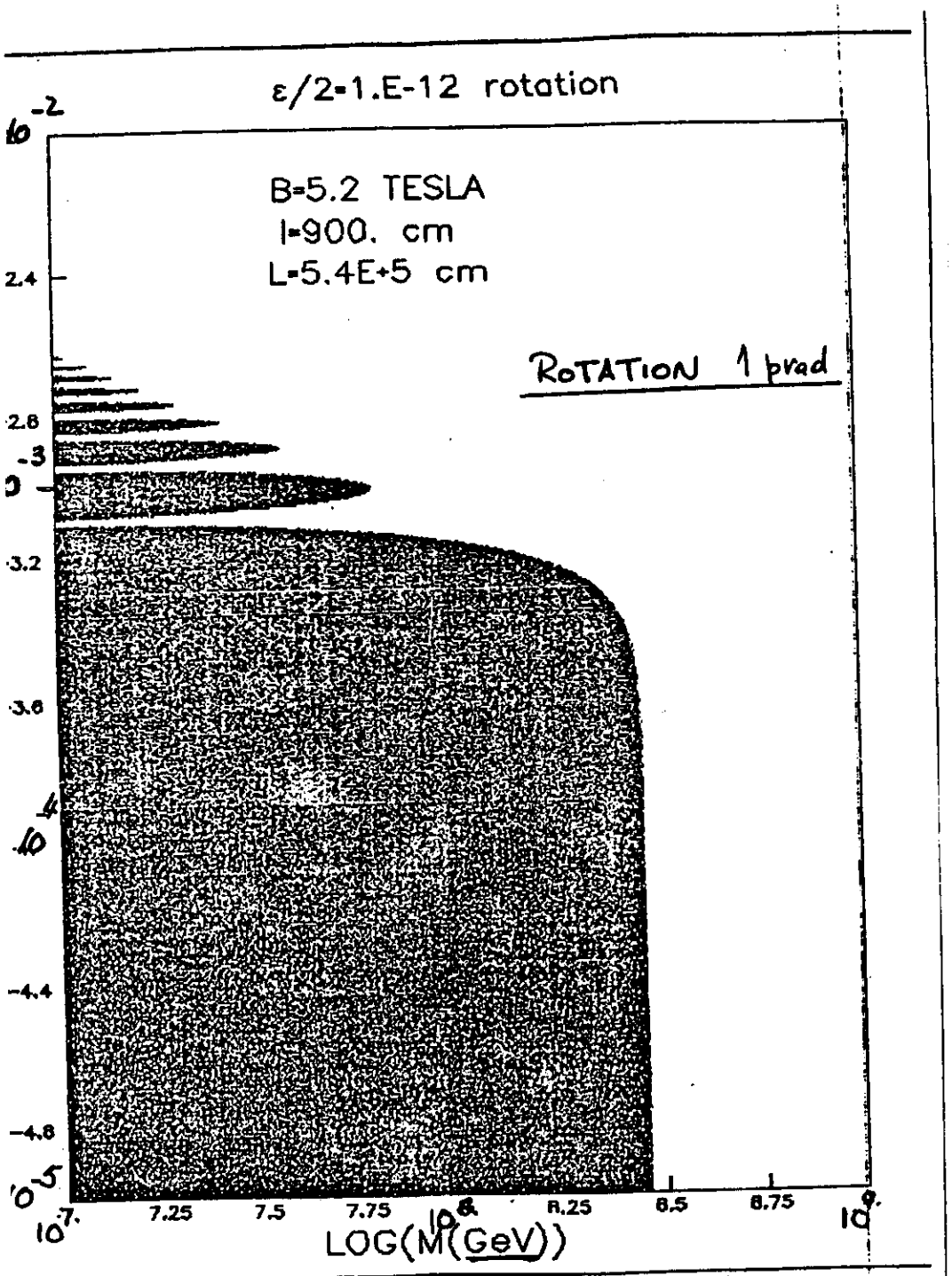
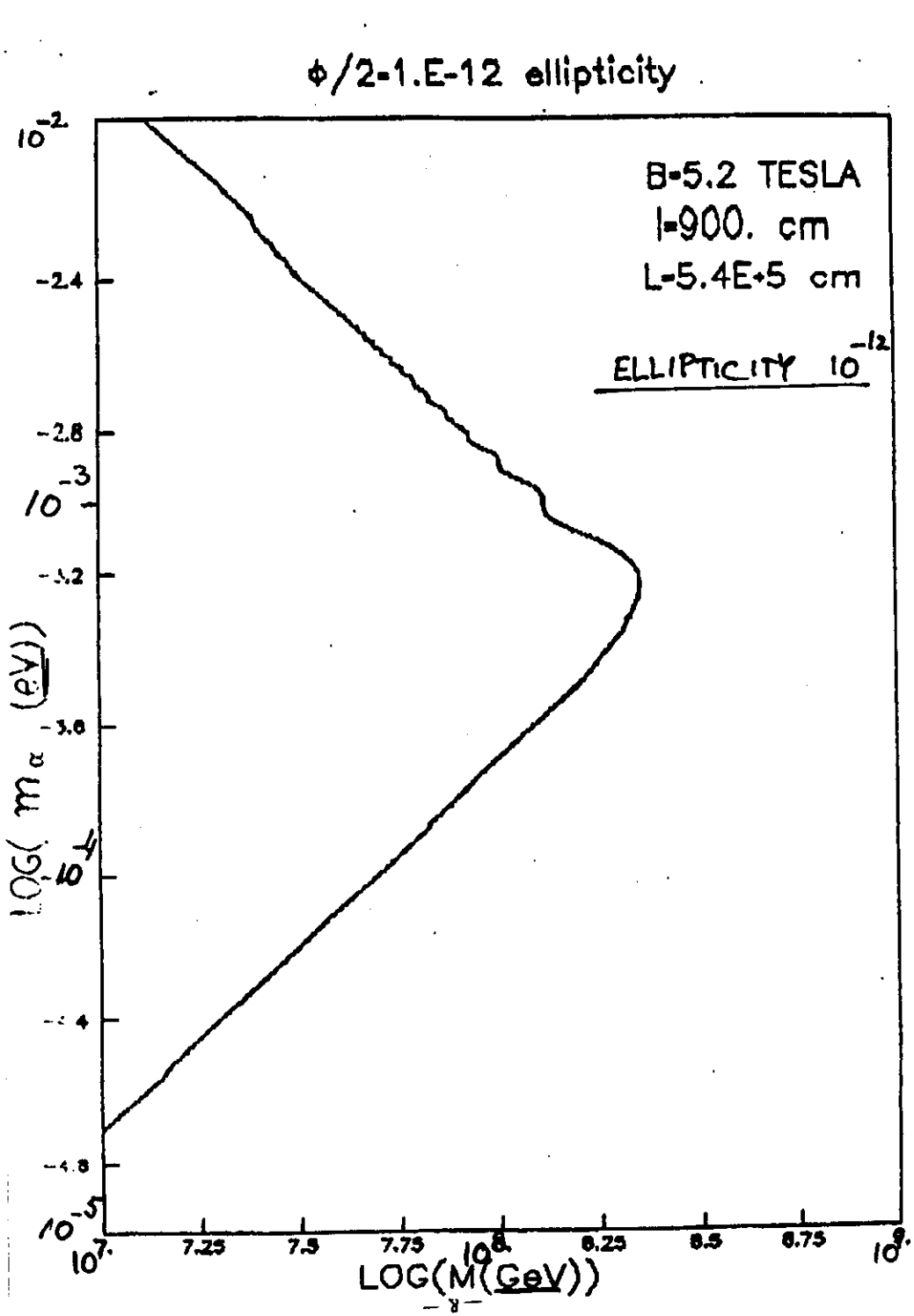
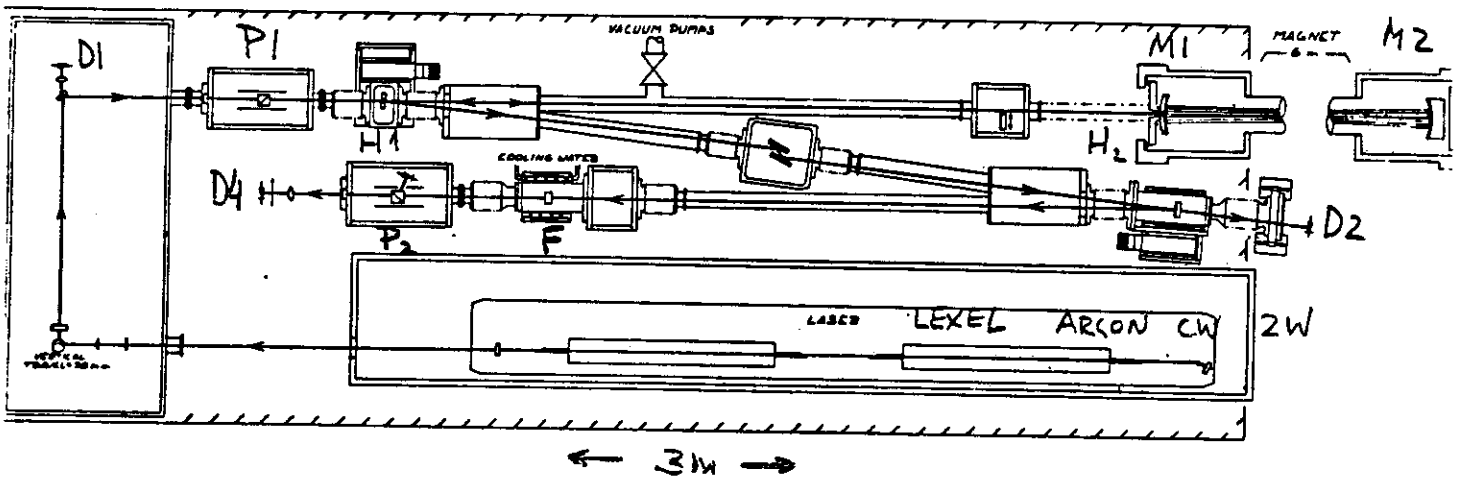

ε/2-1.E-12 rotation
B=5.2 TESLA
l=900. cm
L=5.4E+5 cm
ROTATION 1 prad
LOG(M(GeV))

FIG. 2A


ϕ/2-1.E-12 ellipticity
B=5.2 TESLA
l=900. cm
L=5.4E+5 cm
ELLIPTICITY 10^-12
LOG(m_α (eV))
LOG(M(GeV))



$$\delta \sim (1-2) \times \frac{10^{-8}\ \text{rad}}{\sqrt{T\ \text{sec}}}$$

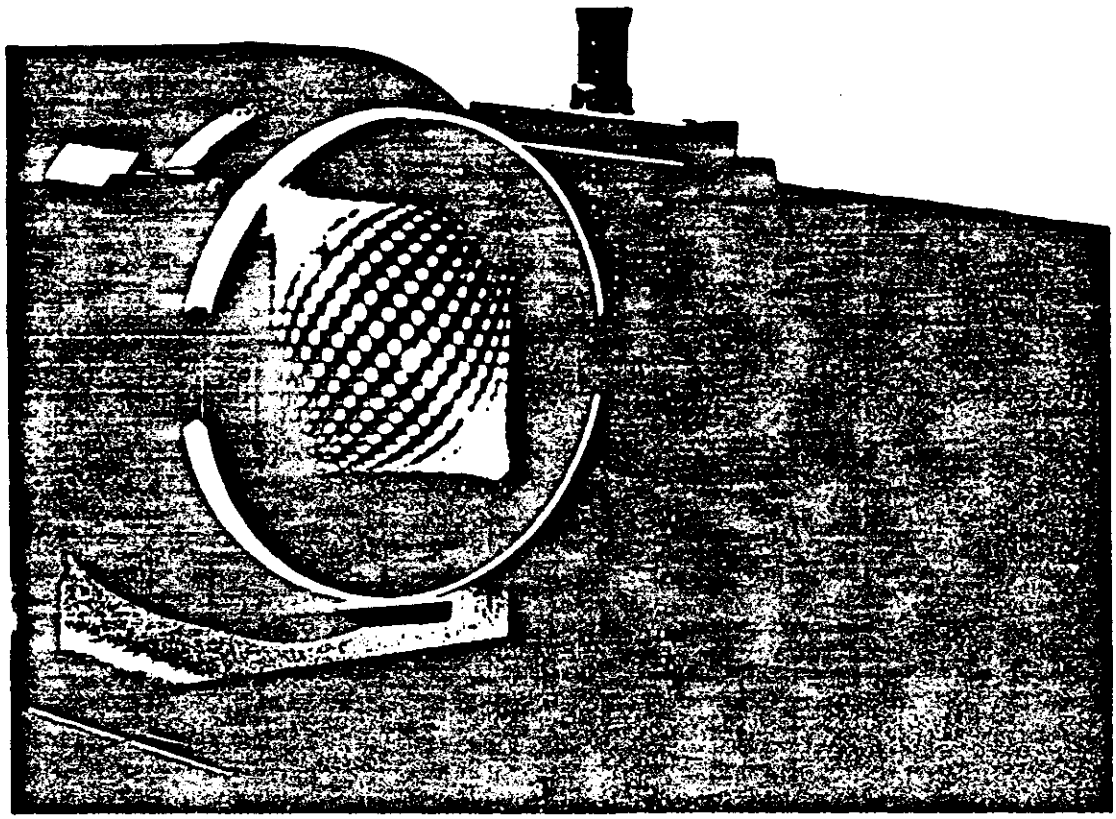


Fig. 4

400 REFLECTIONS
6cm MIRROR

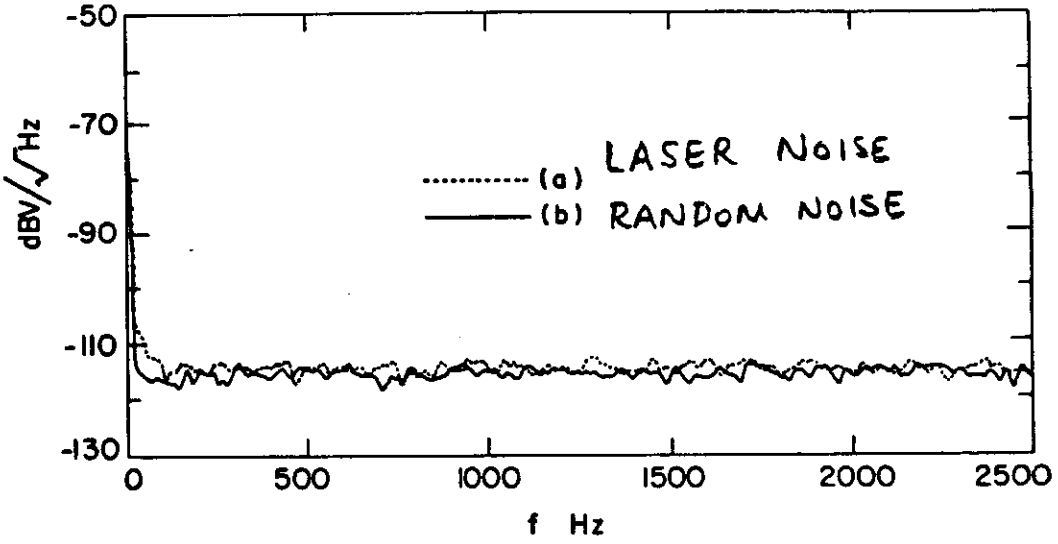


Fig. 9

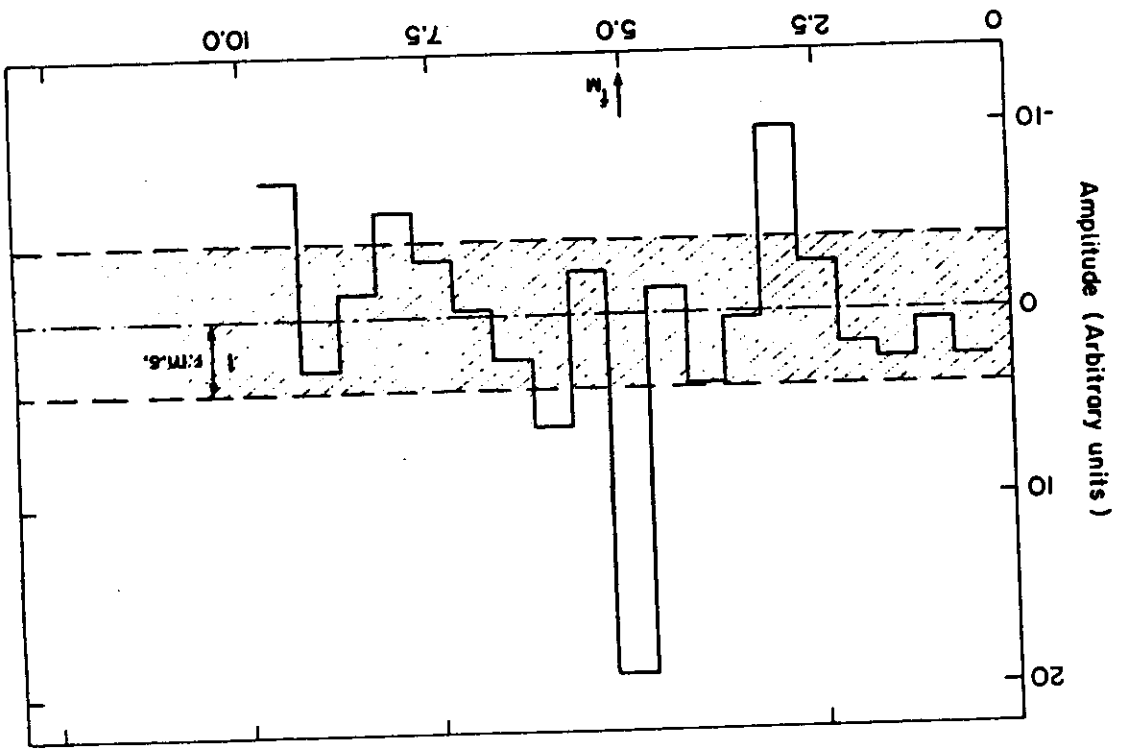


Fig. 11 — MONTE CARLO — 300 hours

EXPERIMENTAL CONSIDERATIONS

- MIRROR BIREFRINGENCE
  [NORMAL INCIDENCE, ROTATE TO PRINCIPAL AXIS]

- COTTON-MOUTON EFFECT
  [SOLVED (≡ MEASURED) BY CERN GROUP]
  VACUUM 10^{-7} TORR SUFFICIENT

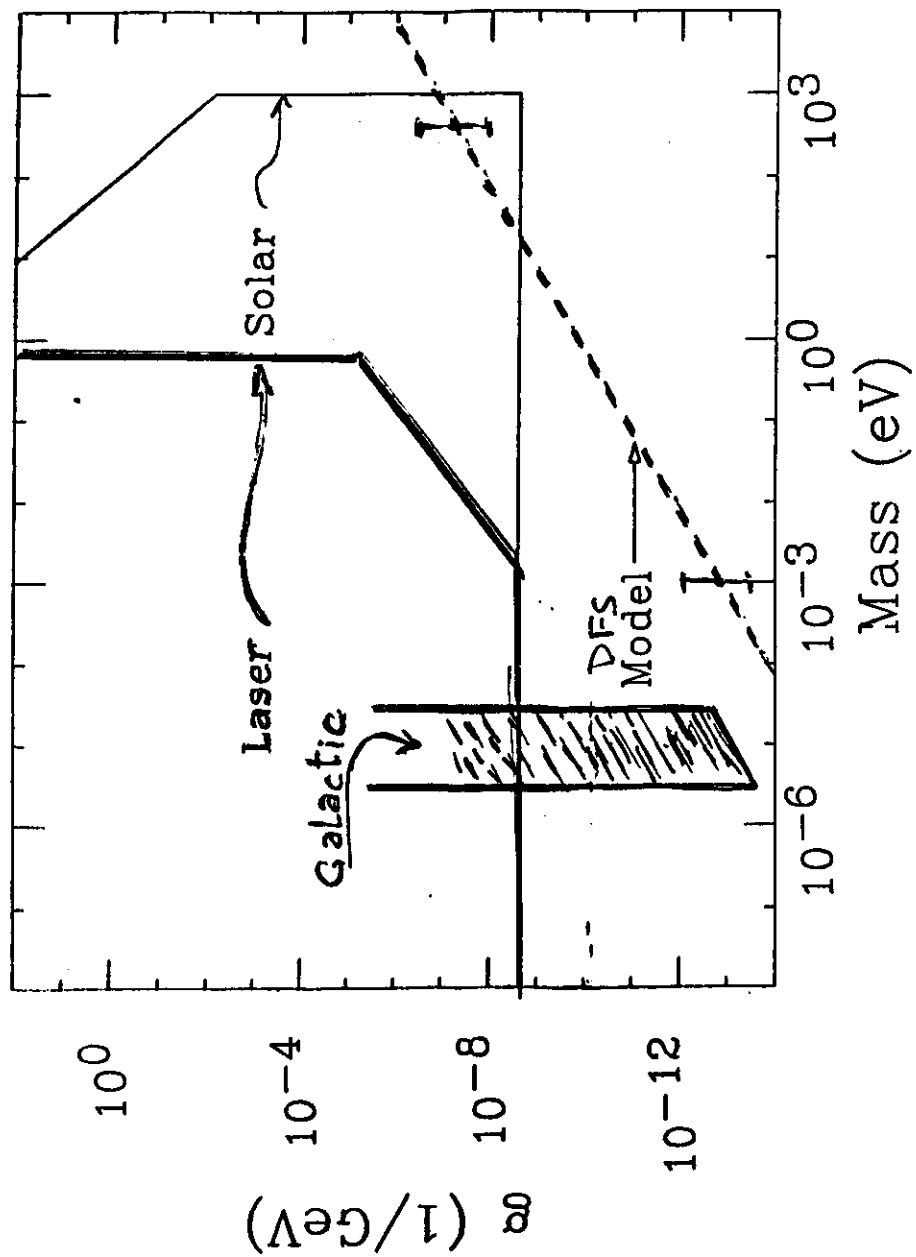
- SHIELDING OF MAGNETIC FIELD
  [NEED $< 10\mu$GAUSS AT OPTICS]

- MAGNET MODULATION
  [5 mHz OR BETTER — 4000 A]

- ENVIRONMENTAL STABILITY
  [TAKE DATA AT NIGHT etc]

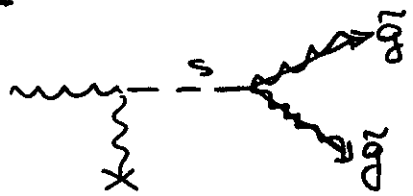
- SIGNAL TO NOISE
  PREDICT $S/N \sim 4$ $\eta \sim 10^{-12}$ $t = 100$ hrs

  ACHIEVED $\eta = 10^{-8}/\sqrt{\Delta t(\text{sec.})}$



OTHER COUPLINGS — SCALARS

— SUPERLIGHT GRAVITINO [PRL 59, 1517, (1987)]



s chiral scalar s-partner to goldstino

$m_s \ll 1\,eV$

$m_{3/2} = 10^{-6}\,eV$ gravitino

$m_{\tilde{\gamma}} = 10\,GeV$ photino

$$g_{s\tilde{\gamma}\tilde{\gamma}} = \frac{\sqrt{3}}{4}\sqrt{8\pi G_N}\,\frac{m_{\tilde{\gamma}}}{m_{3/2}} = 10^{-3}\,GeV^{-1}\;!!$$

— ANOMALOUS γee COUPLINGS
(i.e 1.8 MeV GSI peak)

— ? $^3S_1$ POSITRONIUM LIFETIME
[0.2% SHORTER THAN QED]

COMMENTS ON SEARCHES FOR "SOLAR AXIONS"

— PRODUCED BY INTERACTION OF EM-RADIATION IN CORE WITH NUCLEONS (ELECTRONS)

$\therefore \quad E_a \sim 1\,keV$

— TO HAVE OBSERVABLE RATE $f_a \sim 10^7\,GeV$

$\therefore \quad m_a \sim 1\,eV$

— THIS REGION EXCLUDED BY RED GIANT DATA

— TO OBTAIN COHERENT MIXING, MUST "SLOW DOWN" THE X-RAYS

USE HIGH PRESSURE GAS (AS IN γ COUNTERS)

— POINT TO THE SUN (ON/OFF)

— MASSIVE DETECTOR $\sim$100 TONS

— GO UNDERGROUND (TO REDUCE NOISE)

— HAVE $\sim 2\times10^3$ X-RAY DETECTORS