Vacuum Polarization

Vistas in Axion Physics

April 25, 2012

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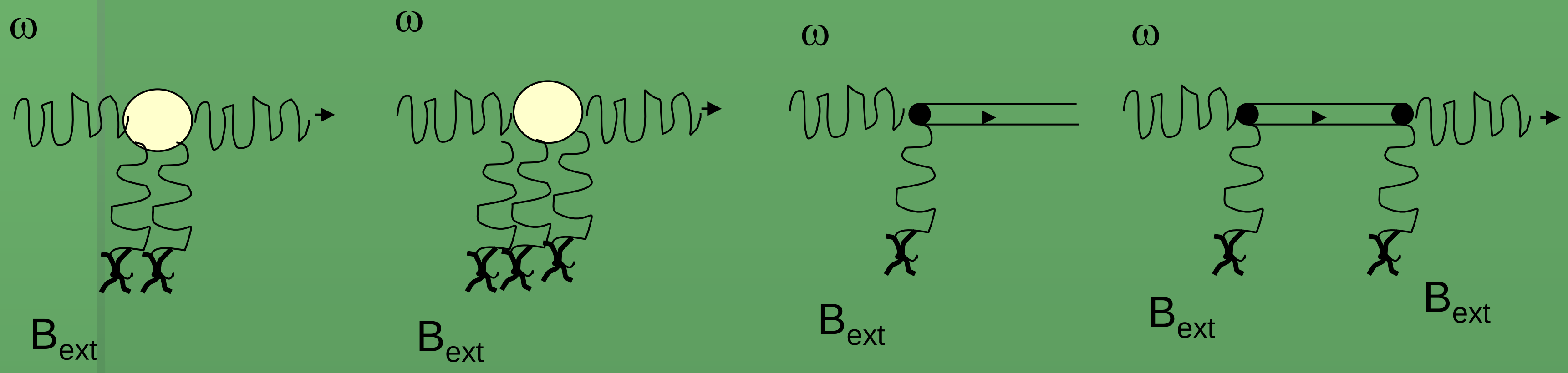
Experimental Searches

- Photon-Axion Coupling Diagrams
- BNL’s E840
- PVLAS
- BMV
- Beam Splitting
- Bifurcation

Photon Coupling to B_{ext}



- Diagrams: a.) QED vacuum polarization, b.) photon splitting, c.) axion real production and d.) axion virtual production

Index of Refraction

- Diagrams alter the index of refraction for photons polarized along direction of B_{ext}
- Lagrangian:

$$L = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(\partial_\mu a \partial^\mu a - {m_a}^2 a^2) + \frac{1}{4} g_a a F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{\alpha^2}{90{m_e}^4}\left[\left(F_{\mu\nu}F^{\mu\nu}\right)^2 + \frac{7}{4}\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right)^2\right], \qquad (1)$$

Photon-EM Coupling

- In the presence of an externally applied Magnetic field:

$$L = \frac{1}{8} (E^2+B^2) + \frac{A}{4\pi} [(E^2 - B^2)^2 + 7 (E \cdot B)^2]$$

- Vacuum becomes birefringent

Photon-EM Coupling

- A photon propagating through an external field will acquire an ellipticity:

$$n_{\parallel} = 1 + 7\,A\,B^2_{ext}\,\sin^2\theta$$

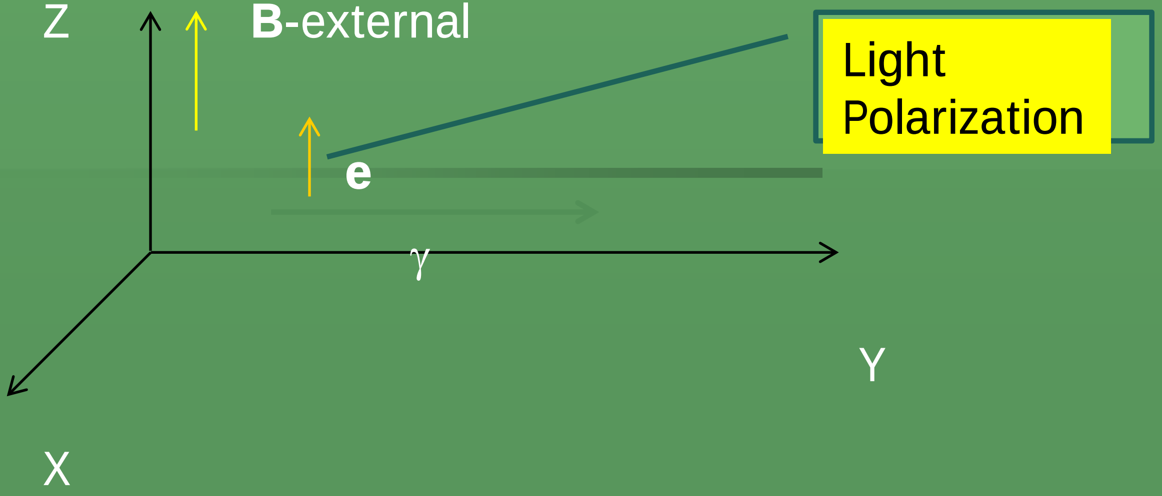
$$n_{\perp} = 1 + 4\,A\,B^2_{ext}\,\sin^2\theta$$

$$\psi = \pi\,\frac{L}{\lambda}\,(n_{\parallel} - n_{\perp}) = \frac{\pi\,L}{\lambda}\,3\,A\,B^2_{ext}$$

Axion Coupling Term

$$L_{int} = \frac{1}{4} g_a\, a F_{\mu\nu} \tilde{F}^{\mu\nu} = g_a\, a \left(\vec{B}^e \vec{E} \right).$$

Magnetic field geometry and coordinates



Z

B-external

Light Polarization

e

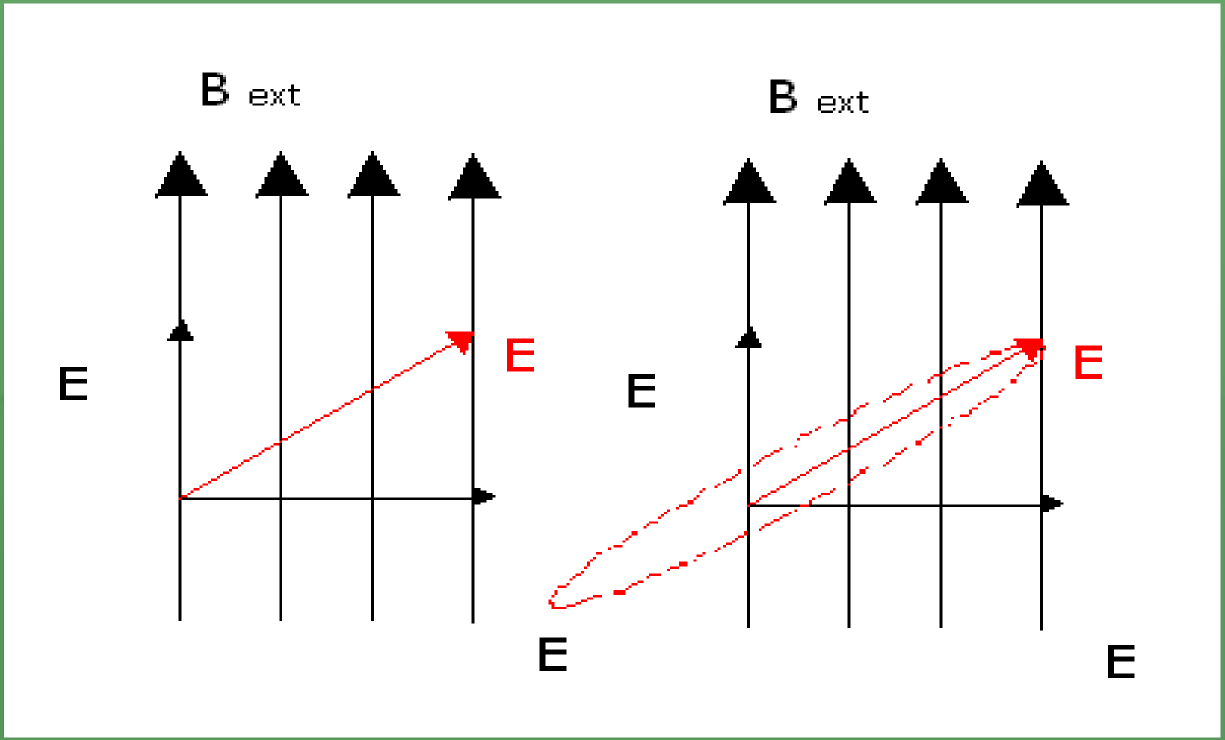
γ

Y

X

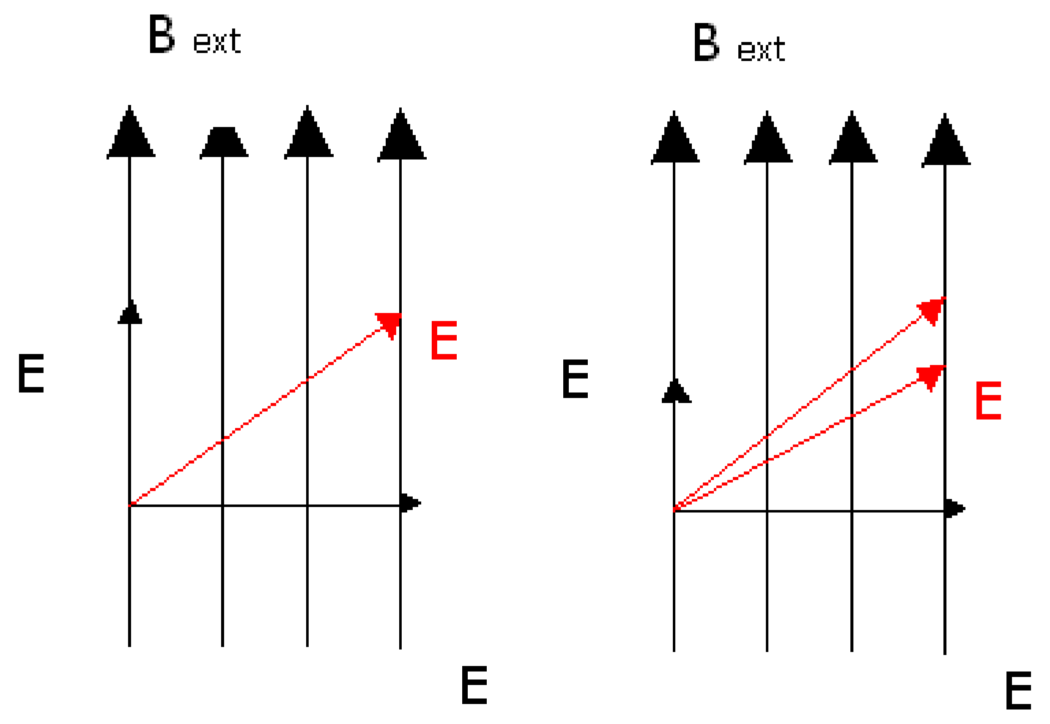
Measurable Effects

- Ellipticity:

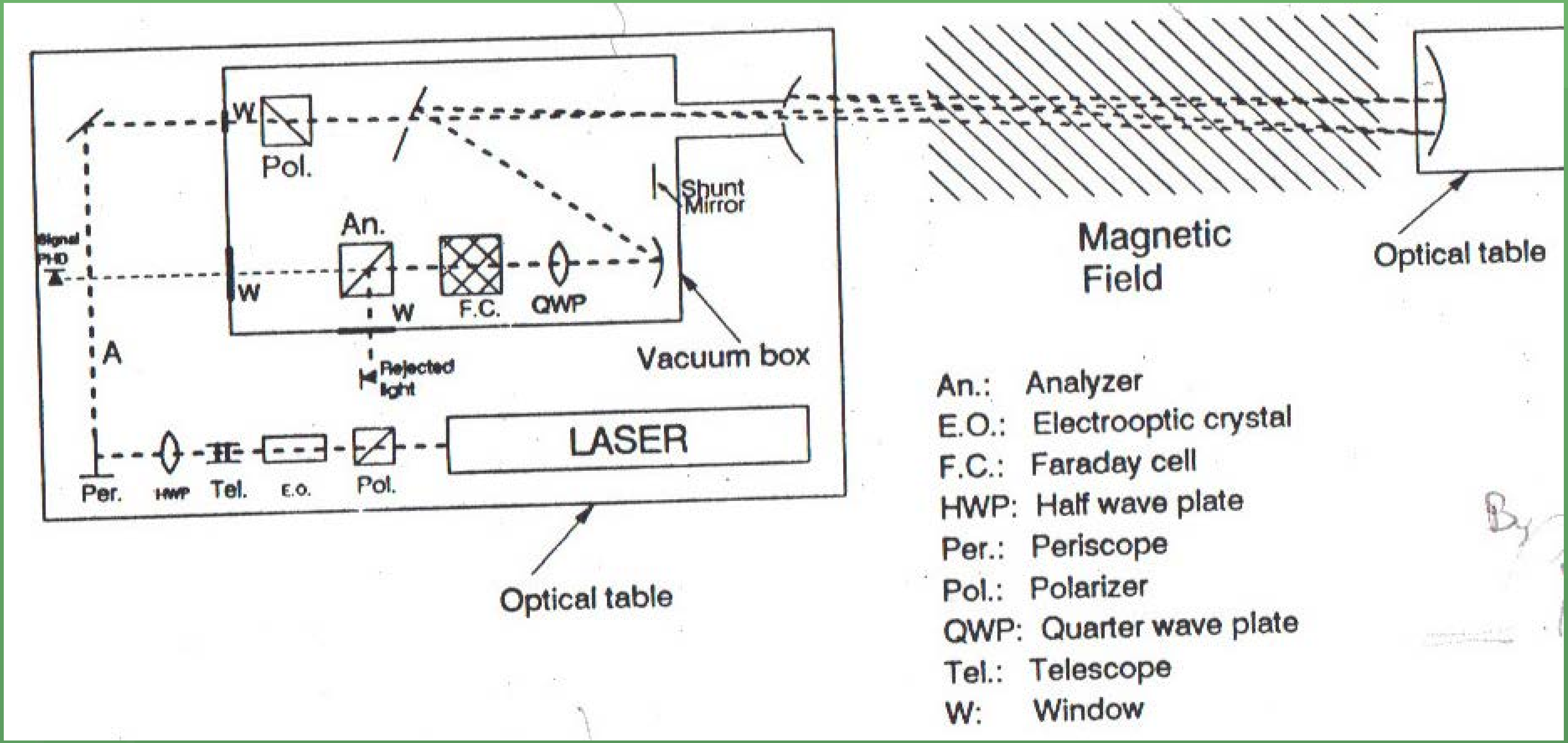


Measurable Effects

- Dichroism:



BFRT [BNL – E840]



- E840 looked for evidence of axions through measuring both induced ellipticity changes and selected absorption

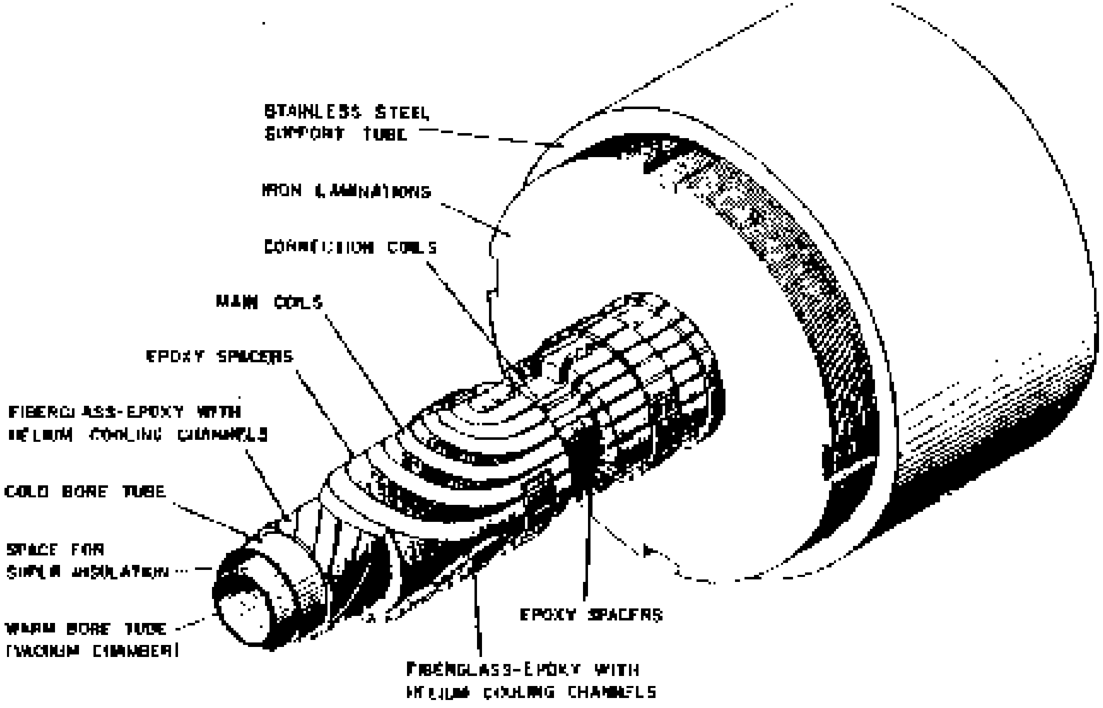
BNL – E840

- 2 CBA Superconducting magnets each 4.4m long
- Dipole Field of 2.2 T at full Strength
- Field is Vertical to direction of incoming beam
- Field extends some 10 m
- Modulated at ~ 16.5mHz with B field given by:

  $$B[\,T\,] = T_F \times I\,[\,\text{Amps}\,] \times 10^{-4}$$

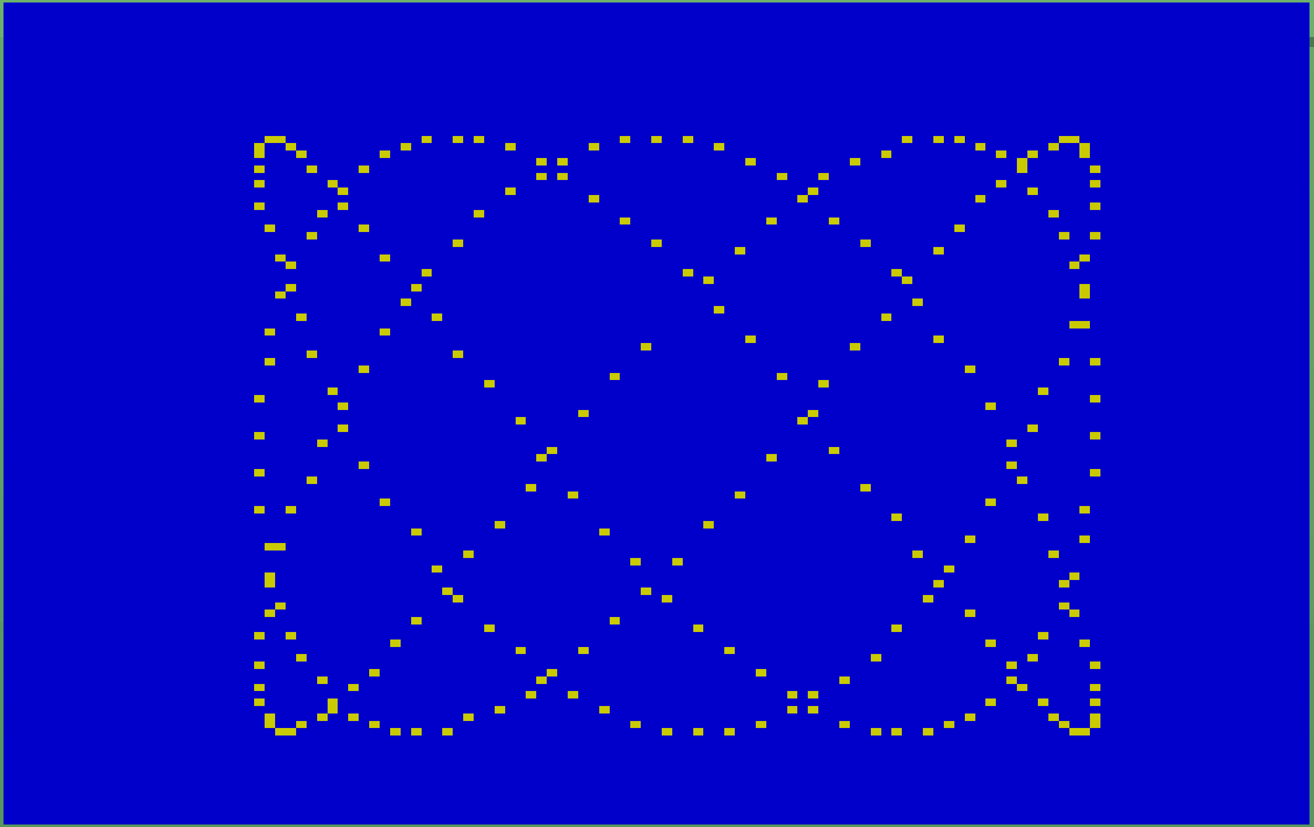
  where T_F refers to the transfer function
- Homogeneity of > 10^{-4}
- Laser 90_5 Argon Ion Laser delivered $\lambda = 514.5$nm with 2 watts
- Optics under vacuum produced by turbo pump
- Cavity composed of two mirrors with Diameter = 11.25 cm and Radius of curvature = 19.03 m (this is an optical delay line)
- Output fed to silicon photodiode
- Signal sought at magnet modulation frequency ω_m

Superconduction CBA



- End section for magnet used in E840 Setup
- Coil orientation shows that the field is aligned vertically relative to the direction of the incoming beam projected along the warm bore tube

Optical Delay Line



- Optical cavity consists of two mirrors one of which has an entrance hole
- One mirror deformed so that pattern closes but misses hole, tracing out more ellipses
- Lissajous pattern forms on the end mirrors similar to seen above

Sensitivity & Signals

- Ellipticity after analyzer using Jones Matrices

$$\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} \cos\eta & \sin\eta \\ -\sin\eta & \cos\eta \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & -i \end{bmatrix} \bullet$$

$$\begin{bmatrix} \cos^2\theta + \sin^2\theta e^{-i\vartheta} & \cos\theta\sin\theta(1-e^{-i\vartheta}) \\ \cos\theta\sin\theta(1-e^{-i\vartheta}) & \cos^2\theta e^{-i\vartheta} + \sin^2\theta \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} A_x e^{i\vartheta_x} \\ A_y e^{i\vartheta_y} \end{bmatrix}$$

here ϕ is the phase shift from the cavity due to the magnetic field

- This gives a current at the photodiode:

$$\begin{aligned} I_T &= I_0[\alpha^2 + \frac{\eta_0^2}{2} + \frac{\eta_0^2}{2}\cos 2\omega_F t + 2\alpha\eta_0 \cos\omega_F t \\ &-\psi_0\eta_0 \sin 2\theta\{\cos(\omega_F - \omega_M)t + \cos(\omega_F + \omega_M)t\}] \end{aligned}$$

here ψ = ϕ/2 represents the ellipticity induced by the field

Sensitivity & Signals

- A similar analysis reveals the expected photodiode current for the rotation setup:

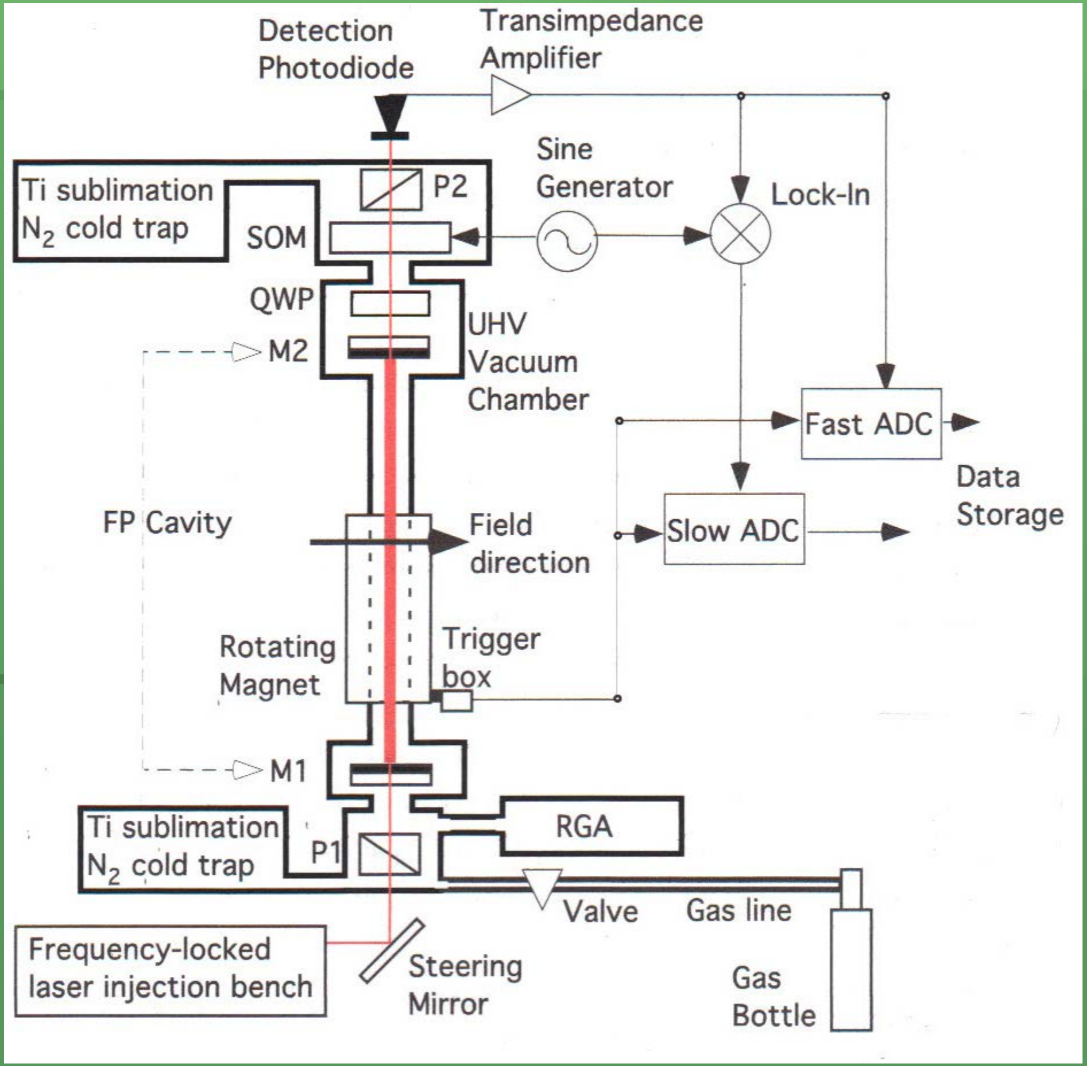
$$
\begin{aligned}
I_T = I_0[\alpha^2 + \frac{\eta_0^2}{2} + \frac{\eta_0^2}{2}\cos 2\omega_F t + 2\alpha\eta_0 \cos\omega_F t \\
+ \varepsilon_0\eta_0\{\cos(\omega_F - \omega_M)t + \cos(\omega_F + \omega_M)t\}]
\end{aligned}
$$

here the rotation parameter is ε_0. Note: there is actually an attenuation given as ε'

- In the final analysis, the signal to noise took into account shot noise (as a limit) along with electronic sources (e.g. laser amplitude)

PVLAS

- PVLAS looked for ellipticity and rotation as well
- Enhanced cavity compared to E840
- Magnet rotates in lieu of modulation

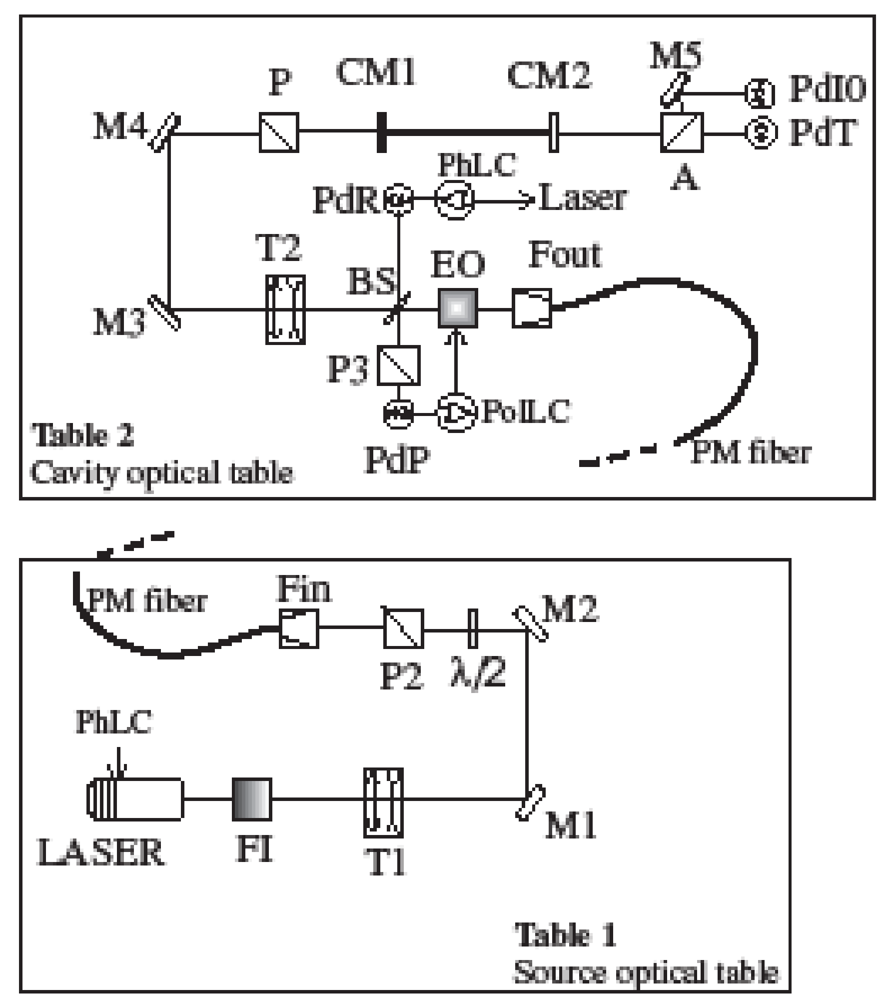


PVLAS

- Dipole Field of 2.5 T and 5 T achieved
- Magnet is positioned vertically and on rotating table
- Magnet length is 1 m long
- Modulated achieved through rotation of magnet $\Omega_{mag} \approx 0.3$ Hz
- Stray field reduced to $< 50 \cdot 10^{-3}$ gauss as part of 2007 upgrades… following which a previously observed signal disappeared
- Laser Source Nd: Yag emitts 800mW at 1064nm
- Optics cavity is a Fabry-Perot optical resonator
- Cavity mirrors are multilayer, highly reflective dielectrics with a Radius of curvature = 11 m and are 6.4 m apart
- Some $4.5 \cdot 10^{4}$ gauss traversals of the magnet are achieved
- Ellipticity Modulator used (heterodyne technique)
- Signal sought at magnet modulation frequency ω_m

BMV

- Ultra high finesse cavity achieving up to . 10^6 traversals
- Used 25.4 mm diameter mirrors
- Capable of using both hetero- and homo- dyne techniques
- Designed to look for regeneration of photons



Vacuum Experiments

Table 1:

	B Field	**Length**	**QED Effect**	**Sensitivity**
E840	5 T	~ 1 km	~ 10^{-12} rad	~ 10^{-8} rad/ √ Hz
PVLAS	5.5 T	~ 10 km	~ 10^{-11} rad	~ 10^{-9} rad/ √ Hz
BMV	25 T	~ 3×10^{3} km	~ 10^{-10} rad	~ 10^{-9} rad/ √ Hz

- Can anymore be gained from cavity experiments?

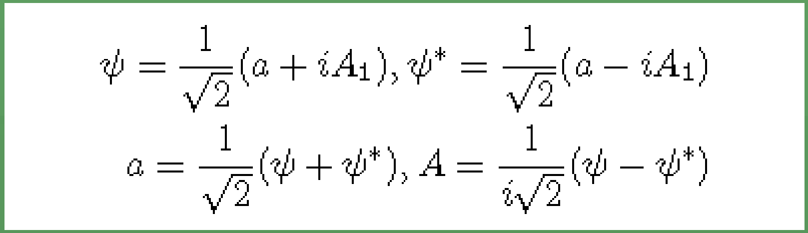
Mixing of Photon-Axion

- **George Raffelt and Leo Stodolsky : Mixing of photons with low-mass particles , Phys. Rev. D 37 (1988) 1237**
- **Eduardo Guendelman :**

Photon and axion splitting in an inhomogeneous magnetic field,

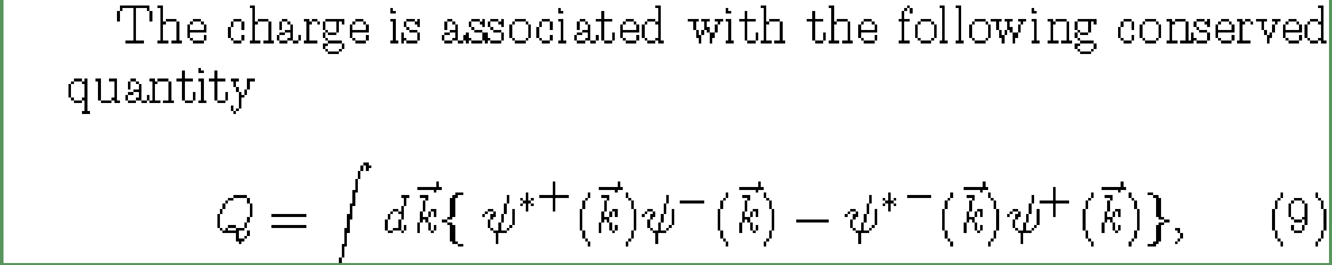
Phys. Lett. B 662(2008) 445 ;

Axions and photons in terms of “particles “ and “antiparticles”



$$\psi = \frac{1}{\sqrt{2}}(a + iA_1), \psi^* = \frac{1}{\sqrt{2}}(a - iA_1)$$

$$a = \frac{1}{\sqrt{2}}(\psi + \psi^*), A = \frac{1}{i\sqrt{2}}(\psi - \psi^*)$$



The charge is associated with the following conserved quantity

$$Q = \int d\vec{k}\{ \psi^{*+}(\vec{k})\psi^-(\vec{k}) - \psi^{*-}(\vec{k})\psi^+(\vec{k})\}, \qquad (9)$$

Beam Splitting

- The unit tangent vector

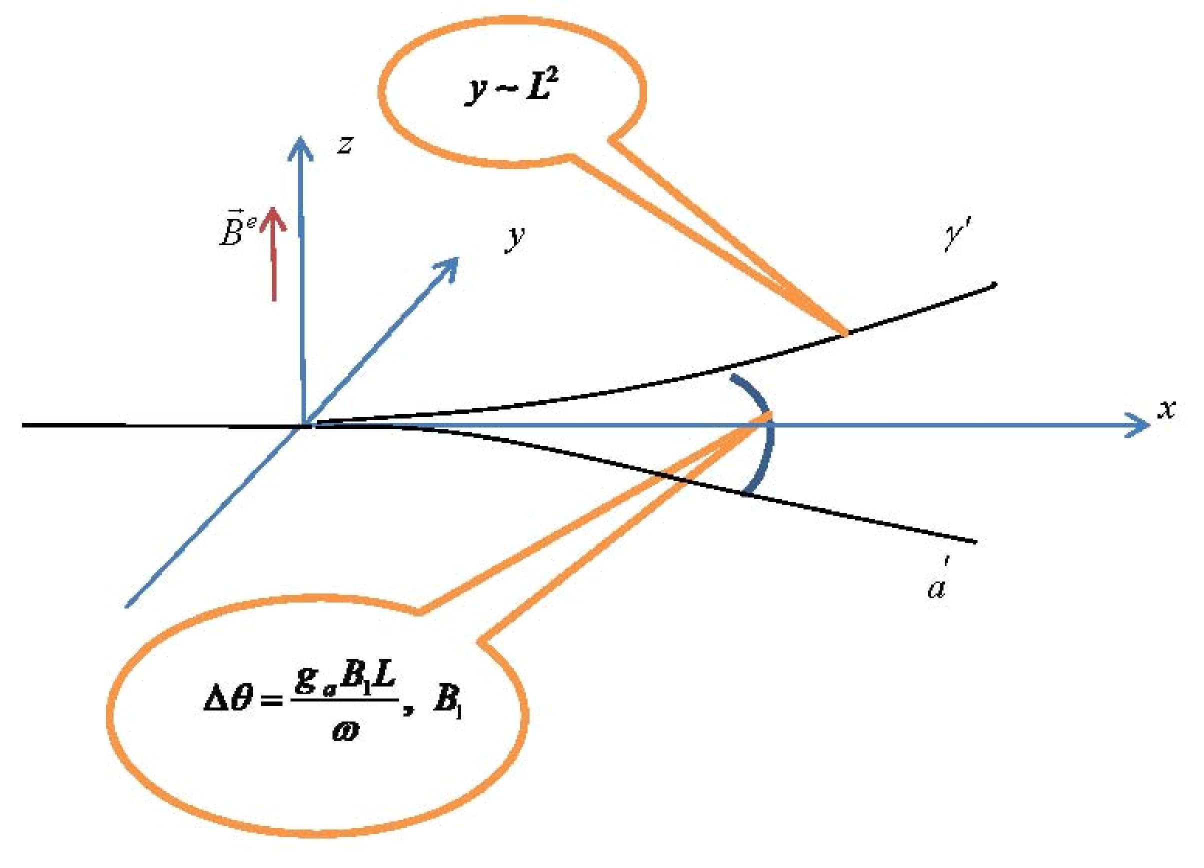
$$l_y\begin{cases}\sqrt{1-\dfrac{n_0^2}{n^2}} & n>n_0,\\ -\sqrt{1-\dfrac{n^2}{n_0^2}} & n<n_0,\end{cases}$$

- Beam trajectory:

$$z(y)=\int_{y_0}^{y}\frac{n_0dy}{\sqrt{n^2(y)-n_0^2}}+z_0,\qquad n>n_0;$$

$$z(y)=-\int_{y_0}^{y}\frac{n(y)dy}{\sqrt{n_0^2-n^2y}}+z_0,\qquad n<n_0;$$

Beam Splitting



Beam Splitting

Input Parameters

$B^e \sim 10^4 - 10^5\, G$

$L_0 \sim 1m$

$\frac{\partial B^e}{\partial y} \sim 10^6 G$ **(The magnetic field gradient)**

$\lambda \approx 10^{-5} m$ **(A photon's wave length)**

Beam splitting

- $L = 1m: \boxed{\Delta\theta \approx 10^{-5} g_a}$ **(The splitting angle as function of** g_a**)**

$\boxed{\Delta\theta \approx 10^{-15} rad}$ **for** $g_a = 10^{-10} Gev^{-1}$.

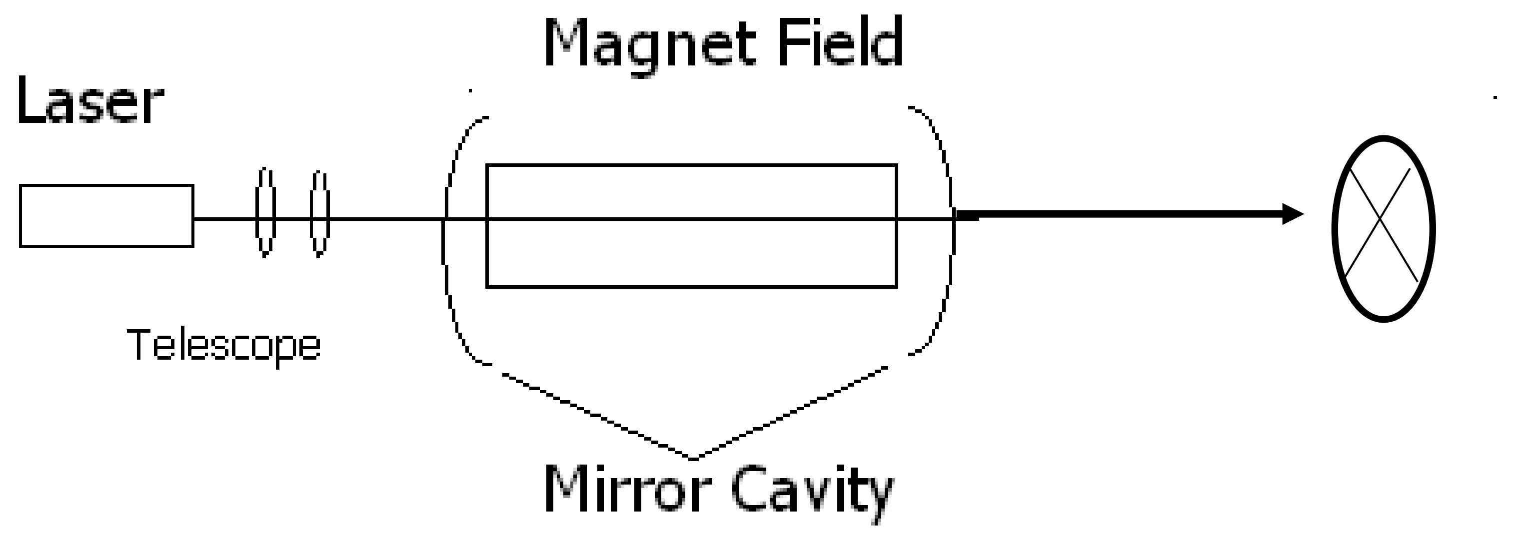
$\bullet\bullet$ $L = 10^5 m$ **(**10^5 **bounces!)**

$\boxed{\Delta\theta \approx 10^{-10} rad}$

Beam splitting $+$ **Bifurcation**

$\boxed{\Delta\theta \approx 10^{-9} rad}$ **and The FWHM drop of** $\sim 10^{-6} E_0$

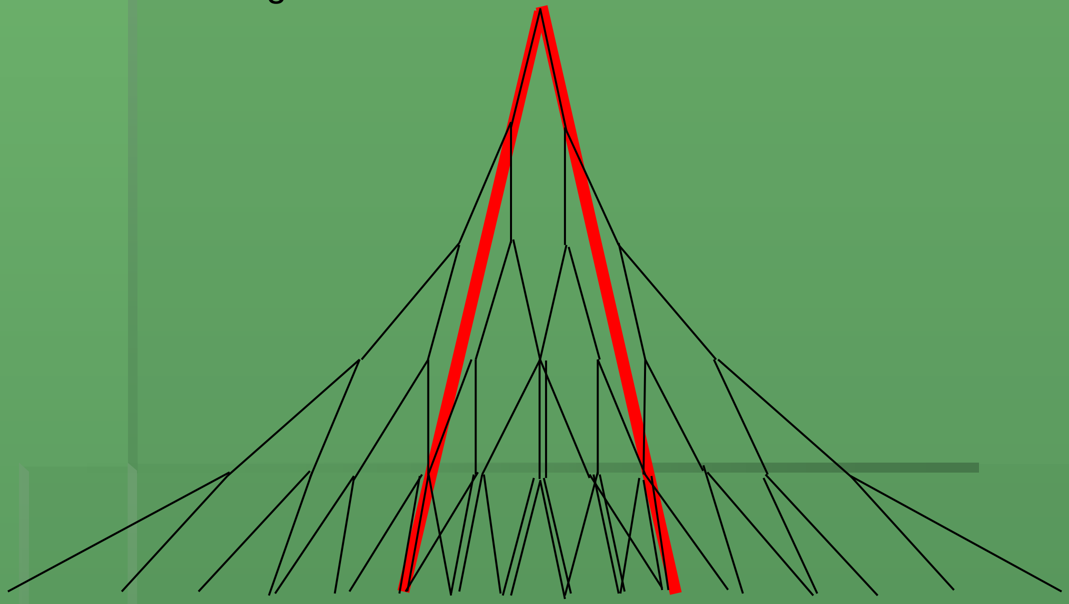
Splitting in a Cavity



- Consider a cavity such as the one used in PVLAS/E840 (optical delay line)

Bifurcation

Bifurcation Diagram

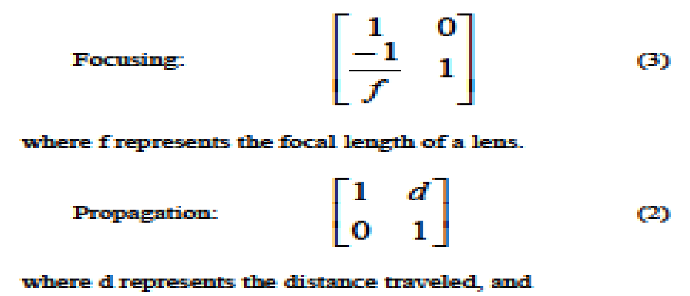


Linear Separation of two beams occurs along red line

- At the mirror, the photon-axion state dissolves
- The reflected light re-enters the cavity and divides again

Simulations

- Treat beam using Jones Matrices



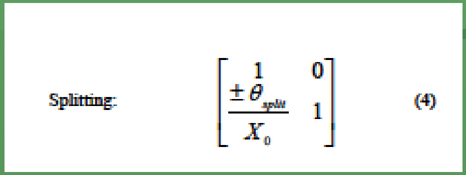
Focusing: $\begin{bmatrix} 1 & 0 \\ \frac{-1}{f} & 1 \end{bmatrix}$ (3)

where f represents the focal length of a lens.

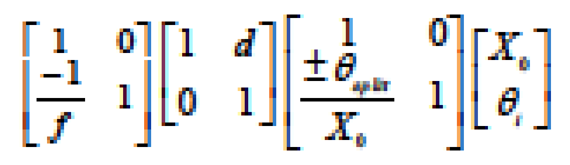
Propagation: $\begin{bmatrix} 1 & d \\ 0 & 1 \end{bmatrix}$ (2)

where d represents the distance traveled, and

- Introduce splitting matrix



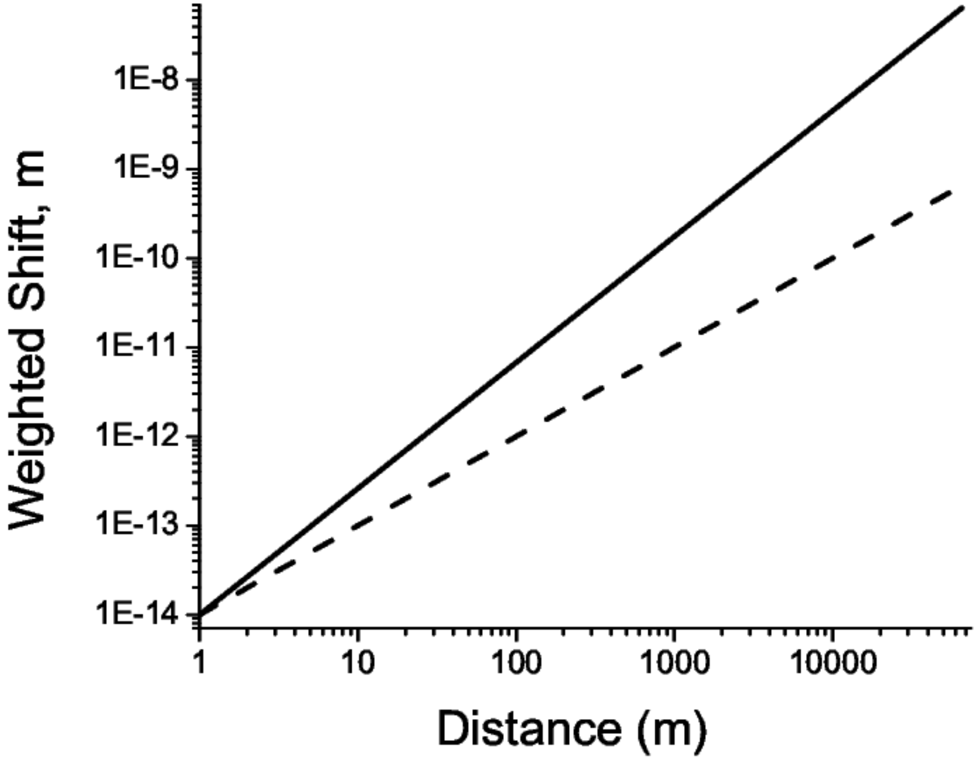
Splitting: $\begin{bmatrix} 1 & 0 \\ \frac{\pm\theta_{split}}{X_0} & 1 \end{bmatrix}$ (4)



$$\begin{bmatrix} 1 & 0 \\ \frac{-1}{f} & 1 \end{bmatrix} \begin{bmatrix} 1 & d \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{\pm\theta_{split}}{X_0} & 1 \end{bmatrix} \begin{bmatrix} X_0 \\ \theta_i \end{bmatrix}$$

Bifurcation vs Linear Spreading

- For a splitting of ~ 10^{-15} rad
- The position of the rays are weighted by their relative density and summed
- The solid line represents the bifurcated distribution and the dashed line represents a linear sepreading



Future Cavity Searches ?

- Future cavity searches could search for bifurcation in the form of energy loss
- Development of an interferometer to interfere a cavity beam with reference source