LOOKING FOR LIGHT PSEUDOSCALAR BOSONS IN BINARY PULSAR OBSERVATIONS

M. RONCADELLI

INFN - PAVIA - ITALY

New strategy to discover light spin 0 particles with a 2γ coupling via high-precision observations of certain binary pulsars.

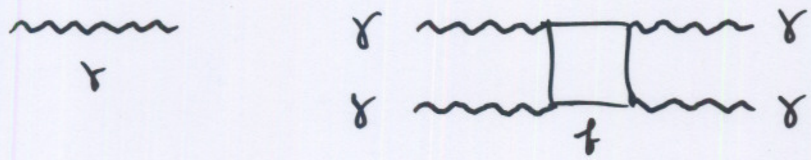
By product $\leadsto$ cross-check for PVLAS claim about existence of a new LPB.

QED EFFECTS

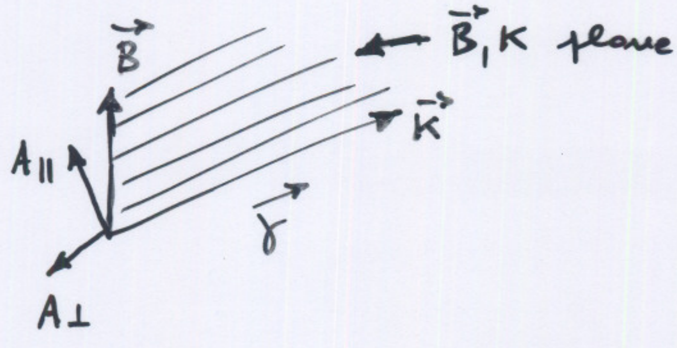
One-loop effects on photon propagation

Maxwell $\qquad\qquad\qquad$ Heisenberg - Euler

$$\mathcal{L}_{eff} = -\frac{1}{4} F_{\mu\nu}F^{\mu\nu} + \frac{\alpha^2}{90\, m_e^4}\left[\left(F_{\mu\nu}F^{\mu\nu}\right)^2 + \frac{7}{4}\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right)^2\right]$$



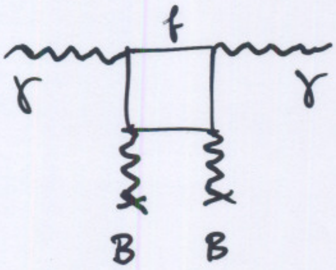
Suppose now that an EXTERNAL $\vec{B}$ = constant is present.



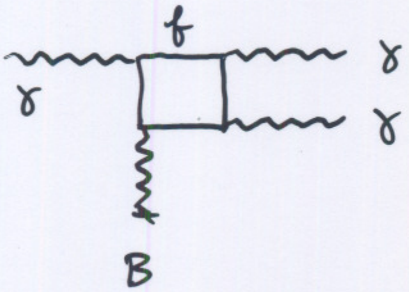
N.B. $\parallel$ and $\perp$ always refer to $\vec{B}, K$ plane

$\leadsto$ $\gamma_{\parallel}$ and $\gamma_{\perp}$.

Then vacuum dispersion effects arise from 2 different diagrams



$\rightsquigarrow$ nontrivial n $\rightsquigarrow$ quantum vacuum lensing + vacuum birefringence



$\rightsquigarrow$ photon splitting $\rightsquigarrow$ vacuum dichroism

Linearized Maxwell eqs. corresponding to $\mathcal{L}_{eff}$ yield 2 photon propagation eigenstates

$\gamma_\parallel$ $$n_\parallel^{QED} = 1 + \frac{7}{2}\left(\frac{\alpha}{45\pi}\right)\left(\frac{B_T}{B_{cr}}\right)^2$$

$\gamma_\perp$ $$n_\perp^{QED} = 1 + \frac{4}{2}\left(\frac{\alpha}{45\pi}\right)\left(\frac{B_T}{B_{cr}}\right)^2$$

$$B_{cr} \equiv m_e^2/e \simeq 4.41 \cdot 10^{13}\, G \, .$$

$\therefore$ For $\vec{B} \neq 0$ vacuum gives rise to 3 effects.

*) BIREFRINGENCE $\rightsquigarrow$ linearly polarized beam develops an ELLIPTICITY proportional to the phase difference between $\gamma_{\parallel}$ and $\gamma_{\perp}$

$$\Phi_{QED}(z) = \left(n_{\parallel}^{QED} - n_{\perp}^{QED}\right)\omega z = \frac{2\alpha^2 B_T^2}{15\, m_e^4}\,\omega z\,.$$

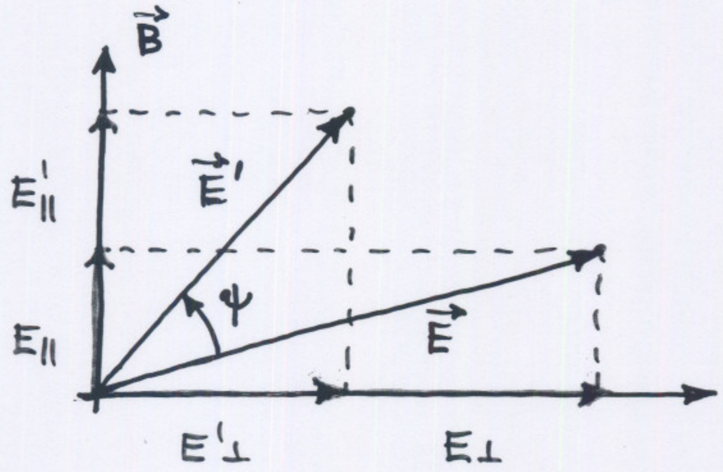
*) QUANTUM VACUUM LENSING $\rightsquigarrow$ analogous to optical and gravitational lensing. But achromatic and depends on photon polarization.

*) PHOTON SPLITTING $\rightsquigarrow$ $\gamma_{\perp}$ split predominantly into $\gamma_{\parallel}$ while $\gamma_{\parallel}$ do not split $\rightsquigarrow$ DICHROISM

selective γ absorption

$\rightsquigarrow$ ROTATION of the polarization plane of a linearly polarized beam.

Indeed



LIGHT PSEUDOSCALAR BOSONS (LPBs)

Several extensions of the SM contain LPBs

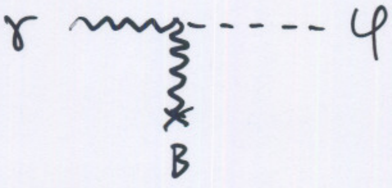
characterized by $m \lesssim 1\ \mathrm{eV}$ and 2γ coupling

$$\mathcal{L}_{int} = -\frac{1}{4M}\varphi F_{\mu\nu}\tilde{F}^{\mu\nu} = \frac{1}{M}\varphi\, \vec{E}\cdot\vec{B} .$$

N.B. 2 free parameters

When an EXTERNAL $\vec{B}$ is present $\mathcal{L}_{int}$ yields

a $\gamma\varphi$ mixing



2 main consequences are as follows.

A) Propagation eigenstates of $\gamma\varphi$ system $\neq$ interaction eigenstates $\rightsquigarrow$ $\gamma\varphi$ interconversion i.e. $\gamma\varphi$ OSCILLATIONS.

Analogy with ν OSCILLATIONS but $\vec{B} \neq 0$ needed, also to compensate spin mismatch.

short-wavelength approximation

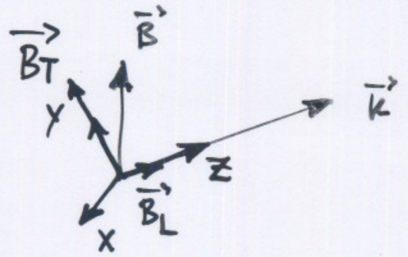
For $\omega \gg m$ and $\vec{B}$ arbitrary the propagation eq. for a light beam in the z-direction is

$$i \frac{\partial}{\partial z} |\psi(z)\rangle = \mathcal{M} \, |\psi(z)\rangle \,,$$

$$|\psi(z)\rangle = A_x(z) \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} + A_y(z) \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} + \varphi(z) \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

$$\mathcal{M} = \begin{pmatrix} \omega + \Delta_{xx} & \Delta_{xy} & B_x/2M \\ \Delta_{yx} & \omega + \Delta_{yy} & B_y/2M \\ B_x/2M & B_y/2M & \omega - m^2/2\omega \end{pmatrix} .$$

When $\vec{B}$ = constant we can take y-axis along $\vec{B}_T$ so now $B_x = 0$, $B_y = B_T$, $A_x = A_\perp$, $A_y = A_\parallel$



and

$$\mathcal{M} = \begin{pmatrix} \omega + \Delta_\perp & \Delta_R & 0 \\ \Delta_R & \omega + \Delta_\parallel & B_T/2M \\ 0 & B_T/2M & \omega - m^2/2\omega \end{pmatrix}.$$

Faraday rotation

N.B. Δ_R direct mixing between $\gamma_\parallel$ and $\gamma_\perp$
$\rightsquigarrow$ henceforth DISCARDED.

In general

$$\Delta = \Delta^{QED} + \Delta^{PL} + \Delta^{CM}$$

QED contribution — plasma contribution — Cotton - Mouton contribution where

$$\Delta_{\parallel}^{QED} = \left(n_{\parallel}^{QED} - 1\right)\omega = \frac{7}{2}\left(\frac{\alpha}{45\pi}\right)\left(\frac{B_T}{B_{cr}}\right)^2 \omega$$

$$\Delta_{\perp}^{QED} = \left(n_{\perp}^{QED} - 1\right)\omega = \frac{4}{2}\left(\frac{\alpha}{45\pi}\right)\left(\frac{B_T}{B_{cr}}\right)^2 \omega$$

$$\Delta^{PL} = -\frac{\omega_{PL}^2}{2\omega} = -\frac{2\pi\alpha\, n_e}{m_e\, \omega} \quad .$$

N.B. Also Δ^{CM} henceforth discarded.

In this case, B_L disappears from $\mathcal{L}$, $A_\perp$ decouples while $A_\parallel$ mixes with φ. We get

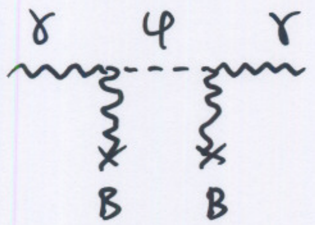
$$\text{prob}\left(\gamma_\parallel \leftrightarrow \varphi, s\right) = \sin^2 2\theta \, \sin^2\left(\frac{\Delta_{osc}\, s}{2}\right) ,$$

$$\theta \equiv \frac{1}{2}\, \text{arctg}\left(\frac{B_T/M}{\Delta_\parallel + m^2/2\omega}\right) ,$$

$$\Delta_{osc}^2 \equiv \left(\Delta_\parallel + \frac{m^2}{2\omega}\right)^2 + \left(\frac{B_T}{M}\right)^2$$

$\rightsquigarrow$ $l_{osc} \equiv 2\pi/\Delta_{osc}$ = OSCILLATION LENGTH .

B) Photon propagation affected by $\gamma\varphi$ mixing much in the same way as it happens in QED vacuum.



⇝ ADDITIONAL contribution to n

$$n'_{\parallel} = n_{\parallel} + \frac{1}{\omega}\left\{\left[\left(\frac{B_T}{M}\right)^2 + \left(\Delta_{\parallel} + \frac{m^2}{2\omega}\right)^2\right]^{1/2} - \left(\Delta_{\parallel} + \frac{m^2}{2\omega}\right)\right\},$$

QED + PLASMA contributions

refractive index for "propagating $\gamma_{\parallel}$"

N.B. ω-dependence

$$n'_{\perp} = n_{\perp} .$$

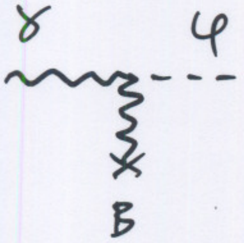
Hence we have

*) BIREFRINGENCE $\rightsquigarrow$ ADDITIONAL induced ELLIPTICITY for a light beam initially linearly polarized, proportional to the phase difference between φ and $\gamma_{\parallel}$

$$\Phi_{\varphi}(z) = \theta^2 \left(\Delta_{osc} z - \sin \Delta_{osc} z \right) .$$

valid for $\theta \ll 1$.

*) QUANTUM LENSING $\rightsquigarrow$ ADDITIONAL chromatic contribution.



$\rightsquigarrow$ ADDITIONAL contribution to DICHROISM

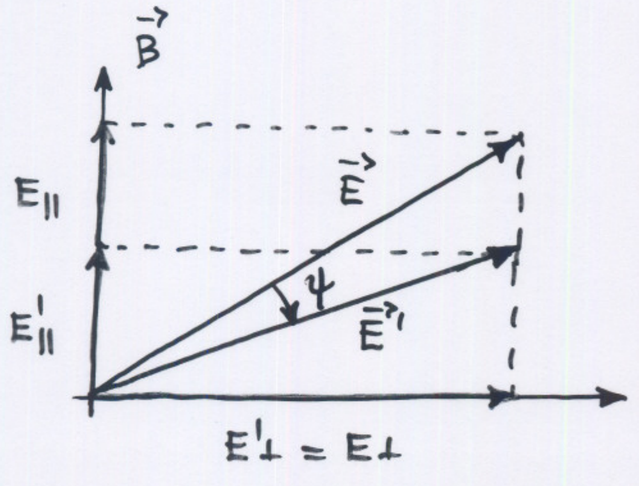
since ONLY $\gamma_{\parallel}$ mix with φ $\rightsquigarrow$ Just as before

ROTATION of the polarization plane of a beam initially linearly polarized

$$\psi(z) = 2\theta^2 \sin^2\left(\frac{\Delta\omega z}{2}\right) .$$

valid for $\theta \ll 1$.

Indeed



AXIONS

Axion = pseudo-Goldstone boson associated with $U(1)_{PQ}$ invented to solve the strong CP problem.

In terms of the scale f_a at which $U(1)_{PQ}$ is spontaneously broken, the axion mass and 2γ (inverse) coupling are

model - independent

$$m \simeq 6 \cdot \left(\frac{10^6 \, \mathrm{GeV}}{f_a} \right) \mathrm{eV} \, ,$$

model - dependent

$$M \simeq 1.2 \, K \, 10^3 f_a$$

N.B.

with $K = 1$ for DFSZ axion but in general $K = O(1)$.

$\therefore$

$$m \simeq 0.7 \, K \left(\frac{10^{10} \, \mathrm{GeV}}{M} \right) \mathrm{eV} .$$

N.B.

LABORATORY EXPERIMENTS

How to detect axions/LPBs ?

*) Resonant $\varphi\gamma$ conversion inside a tunable microwave cavity with $B \neq 0$ (Sikivie).

*) Measurement of induced ellipticity ϵ and rotation ψ of polarization plane of an initially linearly-polarized laser beam in vacuo with $B \neq 0$ (Maiani, Petronzio, Zavattini).

N.B. ϵ and ψ independent $\rightsquigarrow$ determination of m and M.

Second method implemented by PVLAS collaboration in LNL and reported positive evidence of a nontrivial signal. If interpreted in terms of a LPB

$$m \simeq 1 \cdot 10^{-3}\ \mathrm{eV},$$

$$M \simeq 3.8 \cdot 10^{5}\ \mathrm{GeV}.$$

What is going on?

It cannot be the axion, for the m-M relation would require $K \simeq 5.5 \cdot 10^{-8}$ instead of $O(1)$!

Unpredicted LPB discovered !?

ASTROPHYSICAL BOUNDS

Thermal photons in stellar cores converted into LPBs owing to fluctuating EM fields of stellar plasma. Stars should not loose too much energy via LPB emission $\rightsquigarrow$ UPPER bound on $\varphi\gamma$ coupling $\rightsquigarrow$ LOWER bound on M. Applying this argument to horizontal-branch stars in GCs

$$M > 10^{10}\ \text{GeV}$$

for $m \lesssim 1\,\text{eV}$.

N.B. SAME conclusion from CAST experiment.

⇝ If PVLAS has indeed detected a new LPB, it should not be emitted by stars.

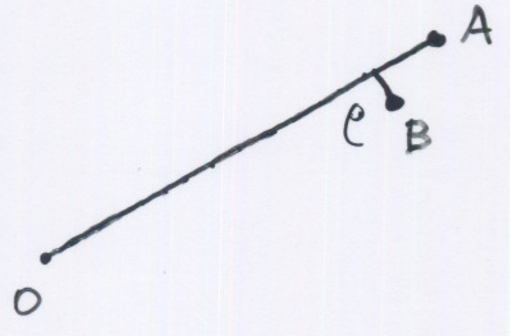
⇝ Either the LPB is not produced at all or is confined inside stars consistently with present knowledge.

⇝ Further new physics at low energy needed!

⇝ INDEPENDENT check of PVLAS compelling!

BINARY PULSAR

Consider a double pulsar seen almost edge-on like J0737-3039 and focus the attention on light beam from one star A. Let ρ be its impact parameter i.e. projected distance from B.



SMALL ρ $\rightsquigarrow$ beam crosses magnetosphere of B $\rightsquigarrow$ strong $\vec{B}$ $\rightsquigarrow$ $\varphi\gamma$ conversion $\rightsquigarrow$ beam attenuation.

LARGE ρ $\rightsquigarrow$ no effect.

$\rightsquigarrow$ observed luminosity of A undergoes periodic variation with a characteristic pattern.

N.B. Effect INDEPENDENT of fate of φ in stars.

We have applied above strategy to J0737-3039:

orbital inclination angle $i \simeq 87°$,

orbital period $T \simeq 2\,h + 2.77\,s$,

minimum value of $\rho \simeq 4 \cdot 10^3$ Km.

N.B $\vec{B} \neq$ constant

We model $\vec{B}$ of pulsar B as a dipolar field preceding along a random direction. Recall

$$\mathcal{M} = \begin{pmatrix} \omega + \Delta_{xx} & \Delta_{xy} & B_x/2\pi \\ \Delta_{yx} & \omega + \Delta_{yy} & B_y/2\pi \\ B_x/2\pi & B_y/2\pi & \omega - m^2/2\omega \end{pmatrix}.$$

N.B. Z-direction along line-of-sight.

We neglect beam polarization effects $\rightsquigarrow$

$$\Delta_{xx}^{QED} \simeq \Delta_{yy}^{QED} \simeq \left(\frac{\kappa}{45\pi}\right)\left(\frac{B}{B_{cr}}\right)^2 \omega \,,$$

$$\Delta_{xx}^{PL} \simeq \Delta_{yy}^{PL} \simeq -\frac{2\pi\alpha n_e}{m_e\,\omega} \,,$$

$$\Delta_{xy} = \Delta_{yx} = 0 \,.$$

Beam propagation described by

$$|\psi(z)\rangle = A_x(z)\begin{pmatrix}1\\0\\0\end{pmatrix} + A_y(z)\begin{pmatrix}0\\1\\0\end{pmatrix} + \varphi(z)\begin{pmatrix}0\\0\\1\end{pmatrix}$$

obeying

$$i\frac{\partial}{\partial z}|\psi(z)\rangle = \mathcal{M}\,|\psi(z)\rangle \,.$$

We solve numerically in small steps with initial condition $|\psi_1(0)\rangle = \begin{pmatrix}1\\0\\0\end{pmatrix}$ or $|\psi_2(0)\rangle = \begin{pmatrix}0\\1\\0\end{pmatrix}$. We compute

$$P(\gamma_i \to \varphi) = \left|\langle\varphi|\psi_i(z)\rangle\right|^2$$

$= 1,2$

$\rightsquigarrow$ transition probability for UNPOLARIZED beam

$$P(\gamma_{\parallel} \to \varphi) = \frac{1}{2} P(\gamma_1 \to \varphi) + \frac{1}{2} P(\gamma_2 \to \varphi) \; .$$

N.B. PVLAS

For $m = 1 \cdot 10^{-3}$ eV and $M = 3.8 \cdot 10^{5}$ GeV result shown in Figure.

F1

Effect SUBSTANTIAL for $\omega \gtrsim 10$ MeV, where pulsar typically emit!

N.B. OK with NO direct interaction in magnetosphere.

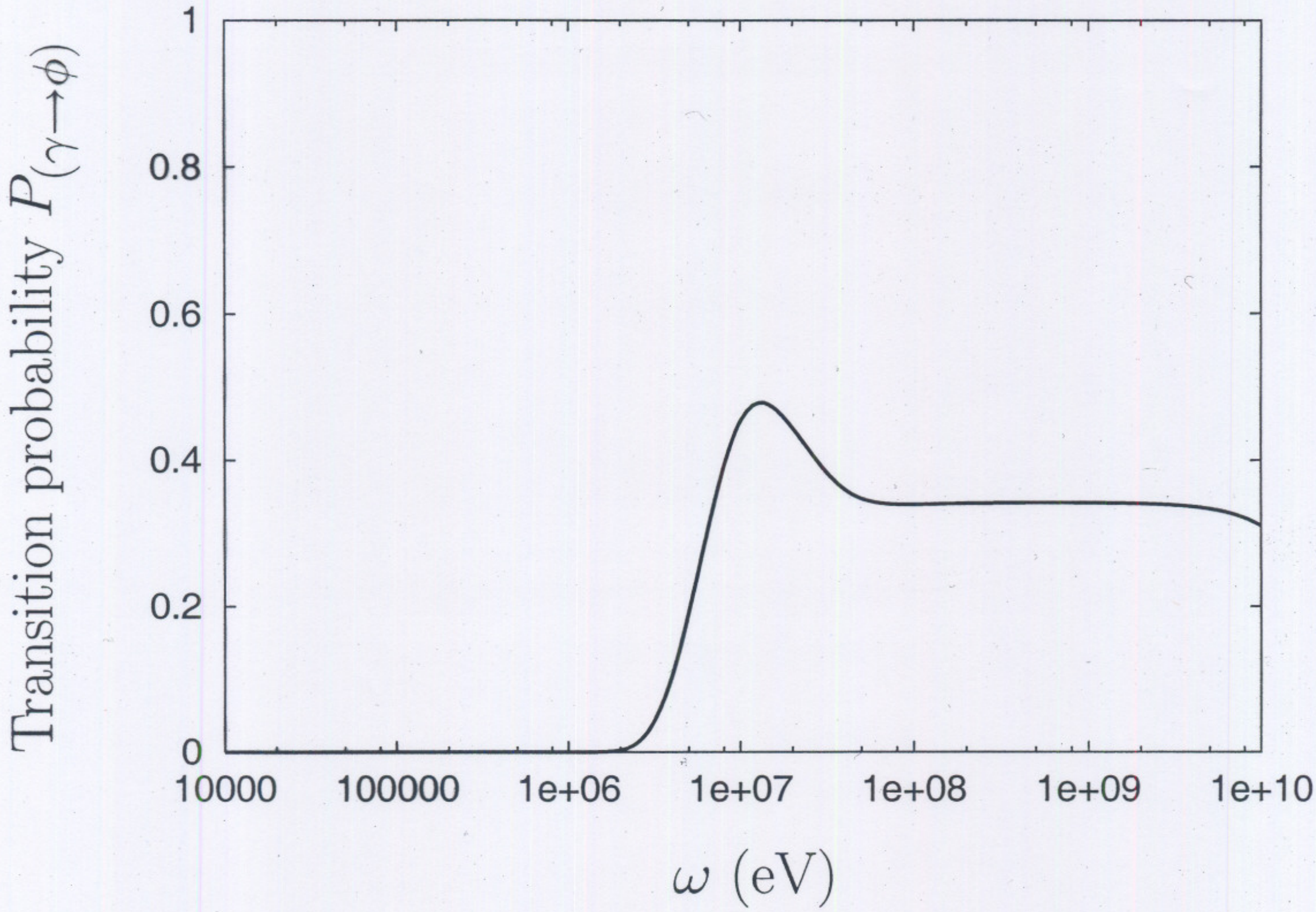
INTUITIVE UNDERSTANDING

$$B = \text{CONSTANT} \simeq 1.6 \cdot 10^4 \, G \quad \text{at} \quad \rho \simeq 4 \cdot 10^3 \, \text{km}$$

$\rightsquigarrow$

$$\Delta_{xx}^{QED} \simeq \Delta_{yy}^{QED} \simeq 6.3 \cdot 10^{-18} \left(\frac{\omega}{\text{MeV}}\right) \text{eV} \, ,$$

$$\frac{B_x}{2M} \simeq \frac{B_y}{2M} \simeq 0.4 \cdot 10^{-12} \; \text{eV}$$



Transition probability $P_{(\gamma \to \phi)}$
1
0.8
0.6
0.4
0.2
0
10000
100000
1e+06
1e+07
1e+08
1e+09
1e+10
ω (eV)

$$\frac{m^2}{2\omega} \simeq -0.5 \cdot 10^{-12} \left(\frac{\mathrm{MeV}}{\omega}\right) \mathrm{eV}$$

N.B. Δ^{PL} negligible

Mixing effect important $\rightsquigarrow$

$$\frac{B}{2M} \gtrsim \left| \Delta^{QED} + \frac{m^2}{2\omega} \right|$$

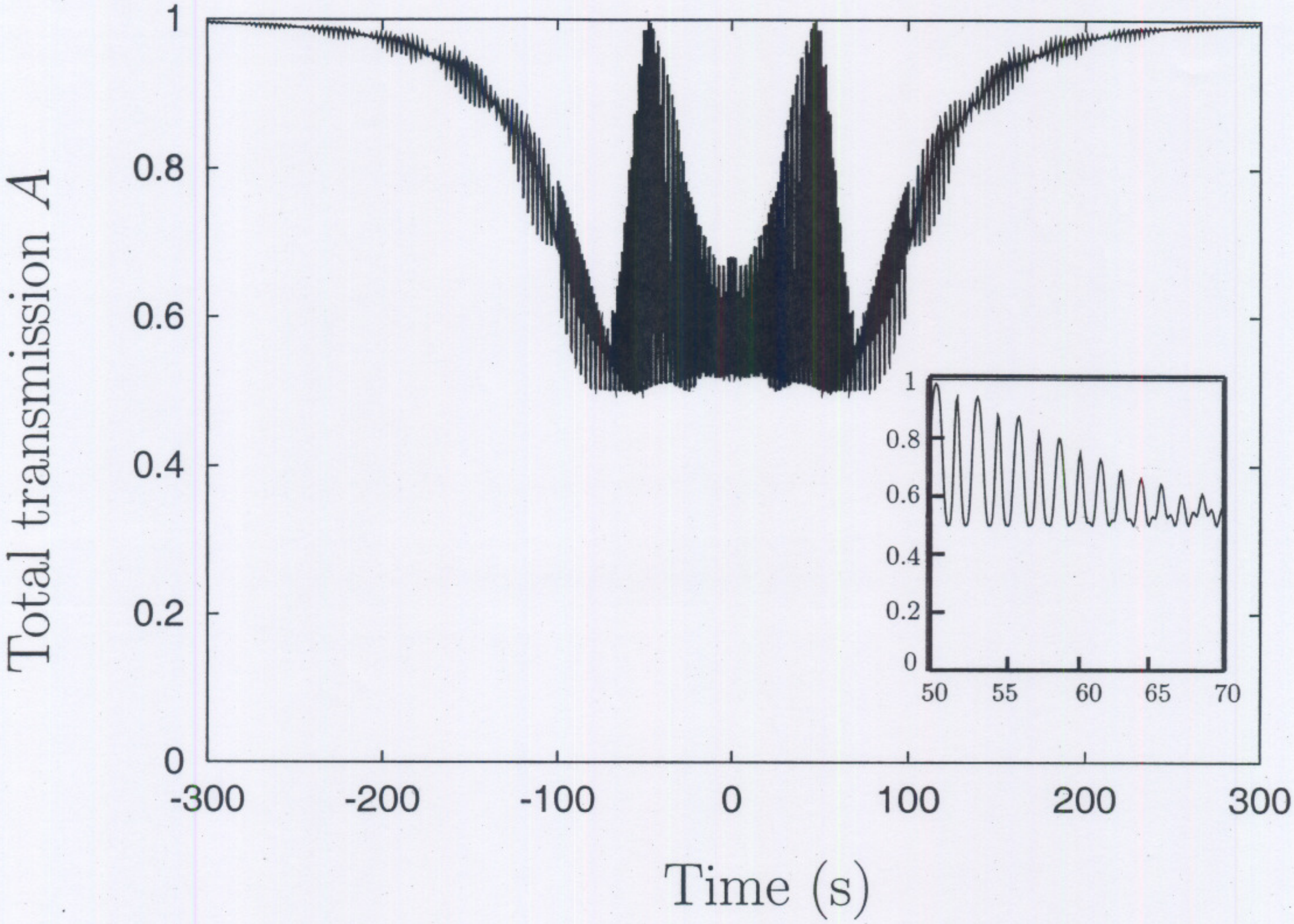
$\rightsquigarrow$ $\omega \gtrsim 1\ \mathrm{MeV}$.

TEMPORAL behaviour described by TRANSMISSION

$$A \equiv 1 - P(\gamma_{\parallel} \to \varphi) .$$

We find attenuation up to 50% with time duration $\sim 200\,\mathrm{s}$ and 3 temporal structures emerge.

F2



Total transmission A
Time (s)
0
0.2
0.4
0.6
0.8
1
-300
-200
-100
0
100
200
300
50
55
60
65
70

Finally NO detection of a 10% attenuation yields excluded region in

F3

Indeed a cross-check for PVLAS emerges!

Considered observations CAN be performed by GLAST (to be launched in 2007).

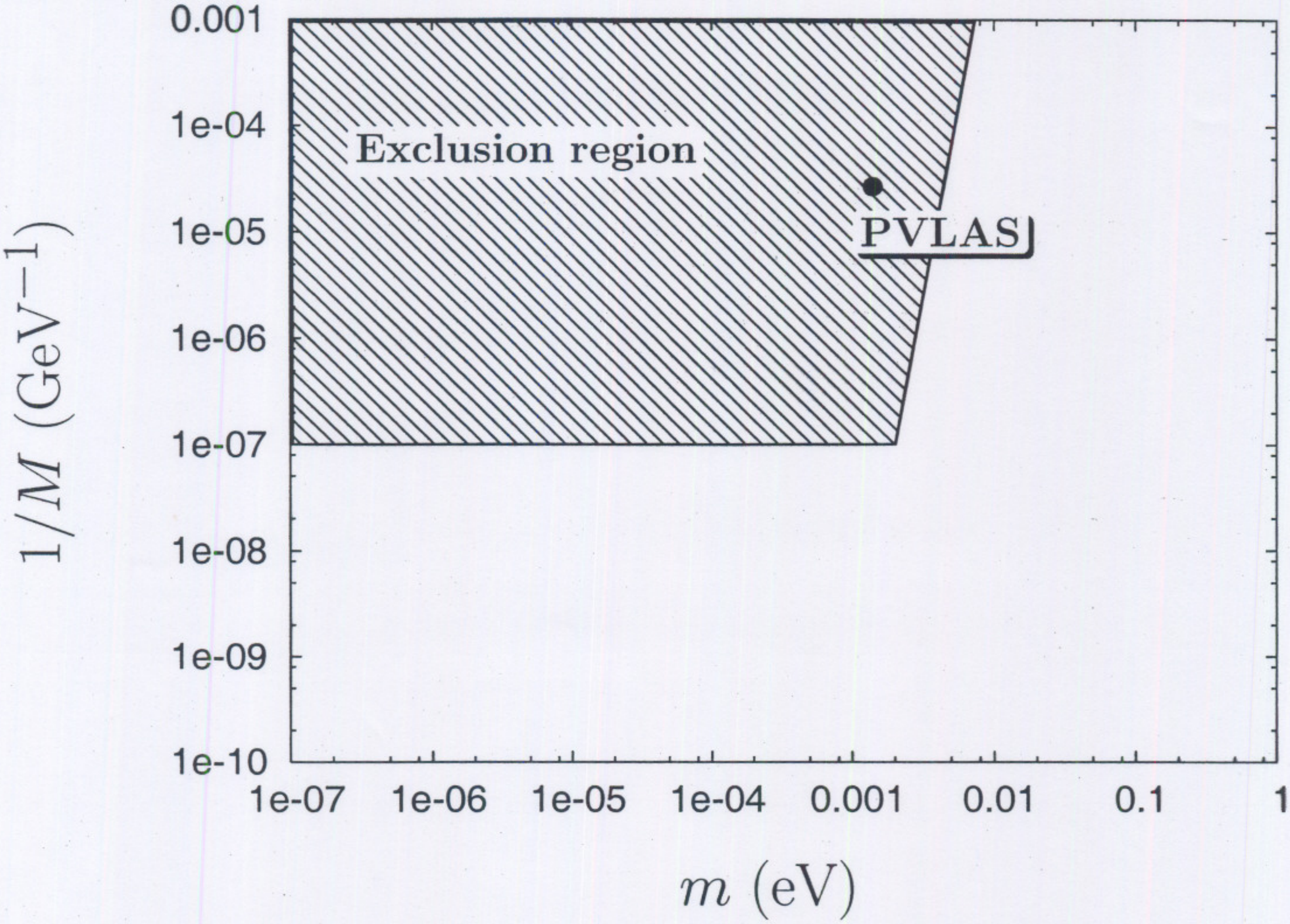
FURTHER WORK IN PROGRESS

*) Extension of above strategy to ARBITRARY m, M.

*) Study of QUANTUM VACUUM LENSING.

N.B. $\Delta n_{\parallel} \simeq 10^5 \, n_{\parallel}^{QED}$ at $\omega = 1$ KeV for PVLAS.

*) Study of periodic POLARIZATION effects.



0.001
1e-04
1e-05
1e-06
1e-07
1e-08
1e-09
1e-10
Exclusion region
PVLAS
1e-07
1e-06
1e-05
1e-04
0.001
0.01
0.1
1
$1/M$ (GeV-1)
m (eV)