Looking for Evidence of Light Pseudoscalar Bosons (Axions) in Double Neutron Star Systems.

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Journal Club 7/2/07

Talk Outline

1. Background articles.

2. Optical properties of the magnetized vacuum.

3. Vacuum lensing in astrophysical systems.

4. PVLAS and the Axion.

5. Double Neutron Stars, Axion Factories?

1.Background Articles

"Cleaning up Dark Matter" - Physics World, November 2006, Vol 19, No 11

"The First Axion?" - Steve Lamoreaux, Nature, 441, 31-32

"Experimental Observation of Optical Rotation Generated in Vacuum by a Magnetic Field" - E Zavattini *et al*, 2006, Phys. Rev. Lett., 96, 110406

"Observing Quantum Vacuum Lensing in a Neutron Star Binary System" - A Dupays *et al*, 2005, Phys. Rev. Lett., 94, 161101

"Looking for Light Pseudoscalar Bosons in the Binary Pulsar System J0737-3039" - A Dupays *et al*, 2005, Phys. Rev. Lett., 95, 211302

2. Optical properties of the magnetized vacuum.

2.1 Classical optical phenomena.

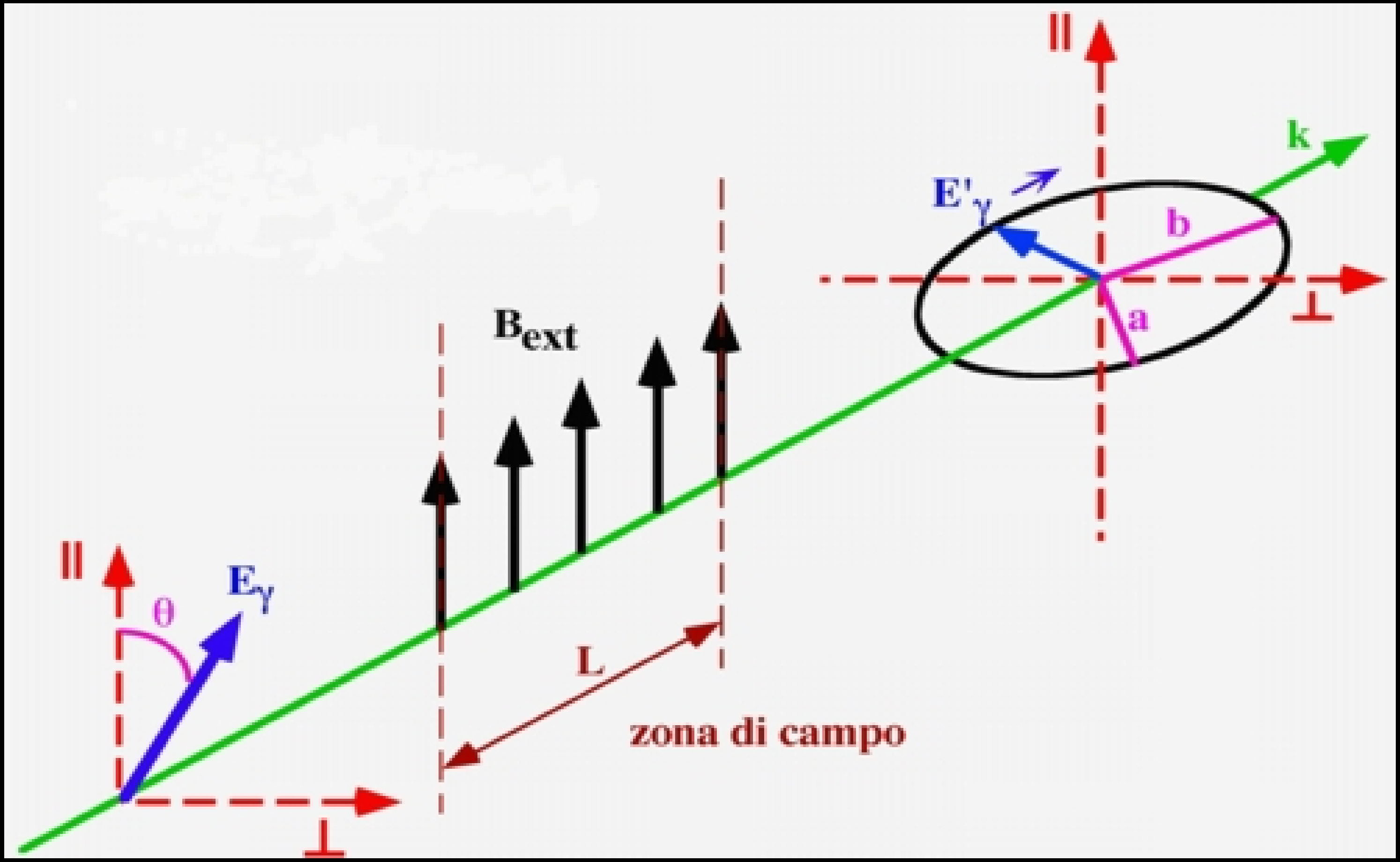
Birefringence - Different polarizations experience a different refractive index. Common example is a uniaxial crystal. Birefringence magnitude:

$$\Delta n = n_{parr} - n_{perp}$$

Cotton-Mouton Effect (liquid) or Voigt Effect (gases) - Transparent substance becomes birefringent in presence of external magnetic (or electric) field perpendicular to direction of propagation. Birefringence magnitude:

$$\Delta n \propto B^2$$

Linearly polarised light enters at 45° to axis (B-field). Parallel and perpendicular components travel at different velocities and become out of phase. Exits medium elliptically polarised.



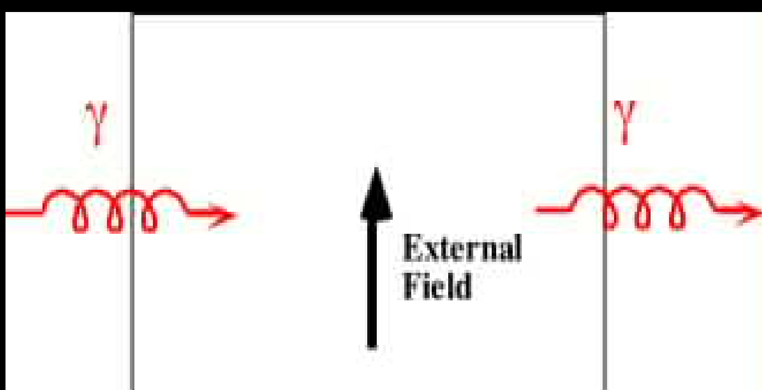
2.2 Quantum optical phenomena (from the advent of QED).

- From the uncertainty principle applied to energy and time, $\Delta E \Delta t = \frac{h}{2}$ it is possible to create virtual particle anti-particle pairs in small enough times.

- Vacuum consists of fleeting virtual particle anti particle pairs.

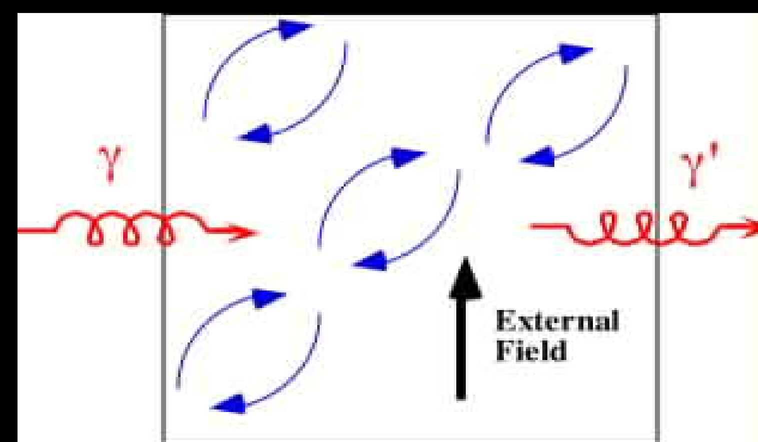
- Apply a magnetic field to the vacuum and send a light ray through it:

Classical Vacuum



No effect on the polarisation of the light ray.

Quantum Vacuum



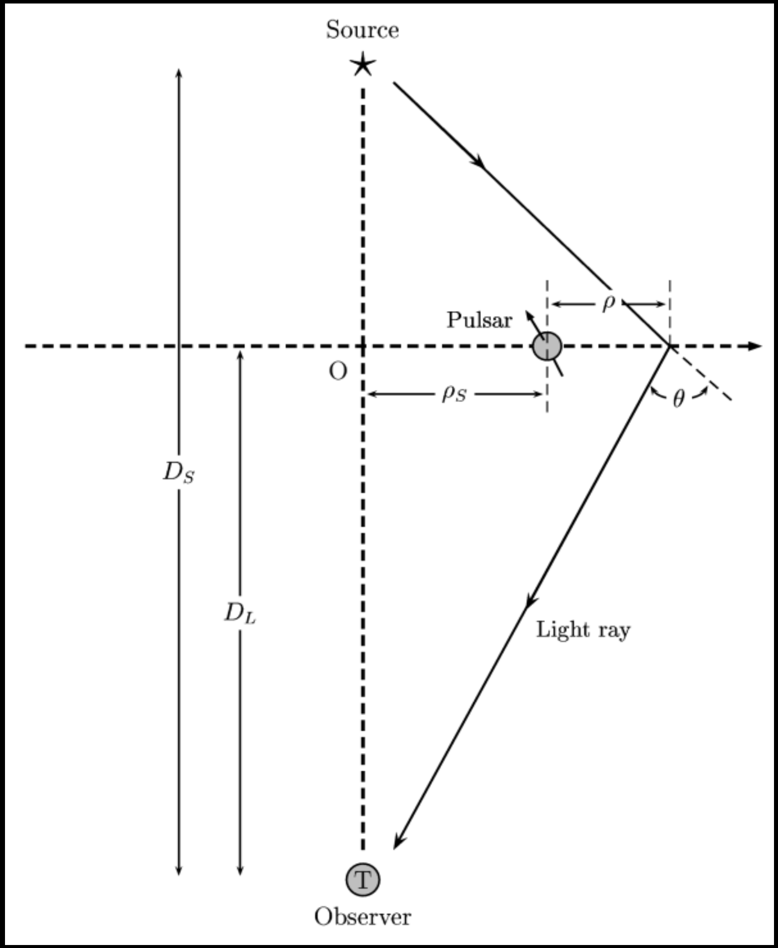
B-field creates uniaxial structure just like Cotton Mouton effect in a gas.

Birefringence invokes a change in polarisation of light ray.

3. Observing Quantum Vacuum Effects in Astrophysical Systems.

- In general light bends toward regions of higher refractive index.

- Because of refraction index variation in the magnetized vacuum, light passing close to a magnetized source will behave as though it is attracted to the source.



- Strong magnetic sources:
  neutron stars $B = 10^8 - 10^9$ T
  magnetars $B = 10^{11}$ T

- Static B-field: $n_{parr(perp)} = 1 + a_{parr(perp)} B^2$

$$a_{parr} = 9 \times 10^{-24} T^{-2}$$

$$a_{perp} = 5 \times 10^{-24} T^{-2}$$

for fields below ~5×10^9 T

A Dupays *et al*, 2005

Deflection angle, θ :

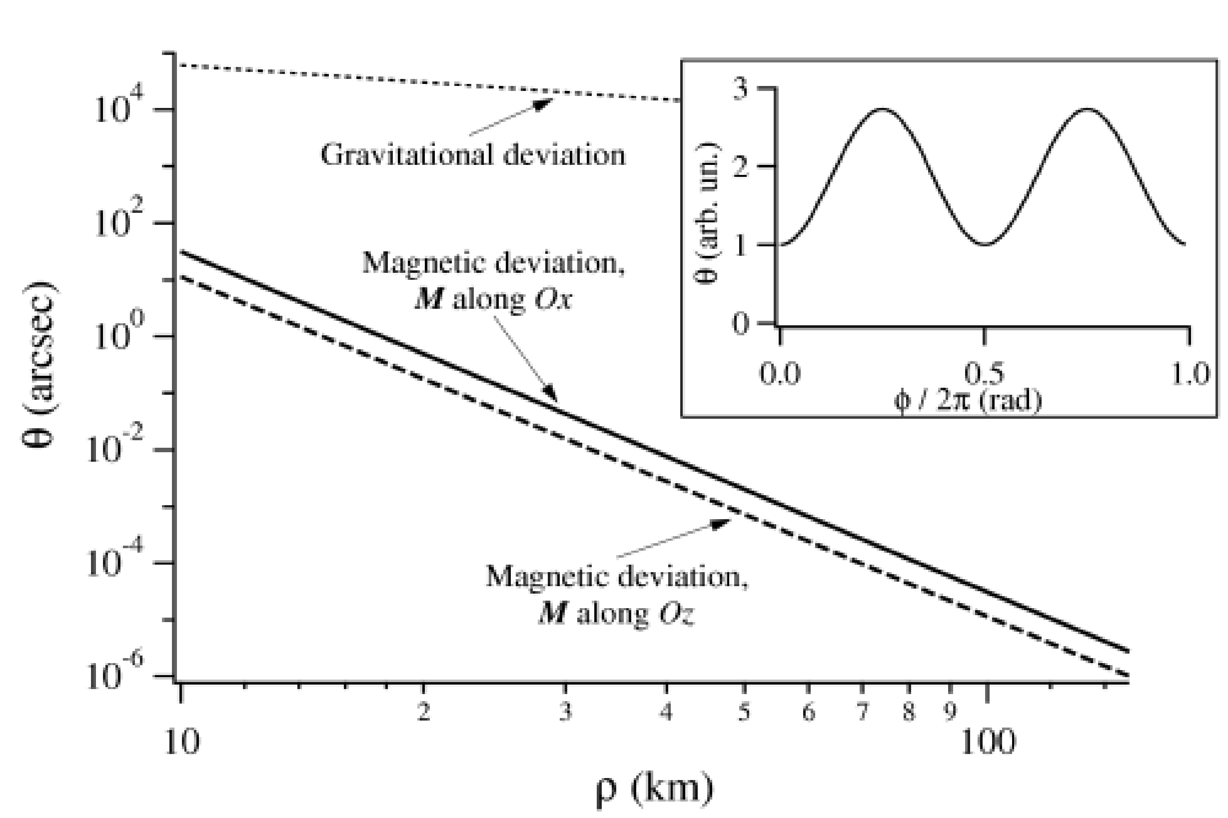
$$\theta = \frac{4GM}{\rho c} + \frac{5\pi a B_0^2 \rho_0^6}{\rho^6}$$

M and ρ_0 = pulsar mass (M_{solar}) and radius (10 km).

ρ = impact parameter

$B_0 = 10^8 - 10^9$ T

$a = a_{perp}$



- Deflection angle goes as $1/\rho^6$, modulation at half pulsar spin period c.f. McLaughlin & Graham Smith 2004.

- Gravitational deviations always larger for normal NS.

- At short distances (i.e. at R_E) magnetic deviations of same magnitude as gravitational but only for the magnetar.

- Cotton Mouton effect?

Neutron Star - Background Source

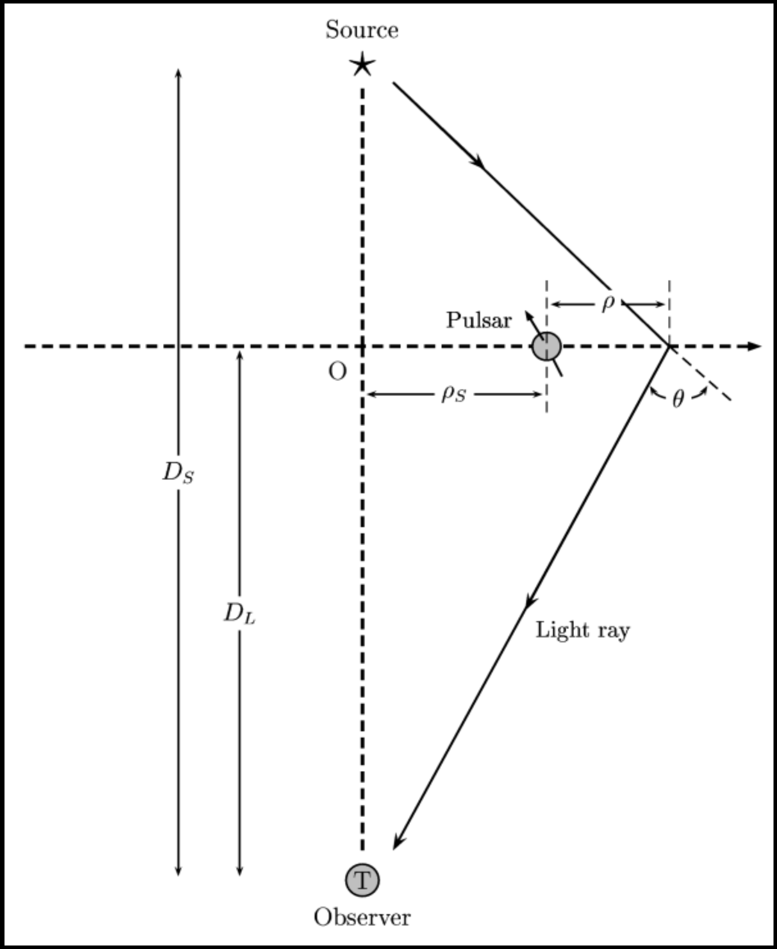
- Background source must be along line of sight within einstein ring radius.
- Generally $\rho_s \gg R_E$.

Neutron Star - Non Degenerate Companion

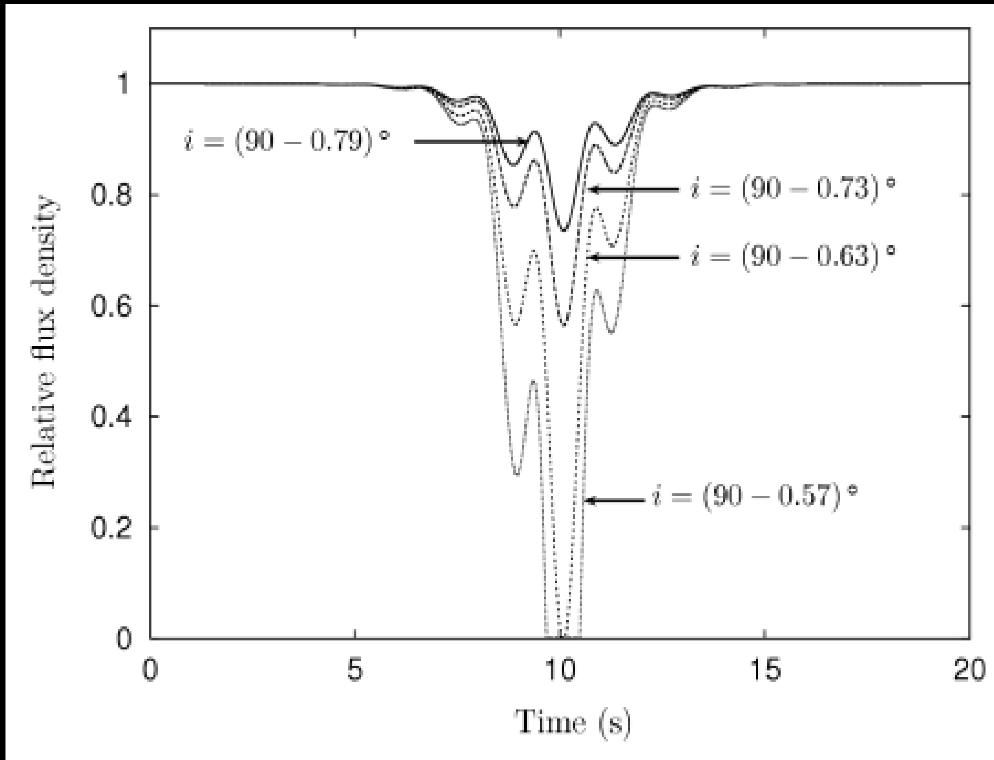
- Einstein ring radius is tiny for binary system.
- Deviations from gravitational lensing of order few % only occur at R_E. Require $B_0 \sim 10^{16}$ T !!!
- Accretion processes obliterate these subtle effects.

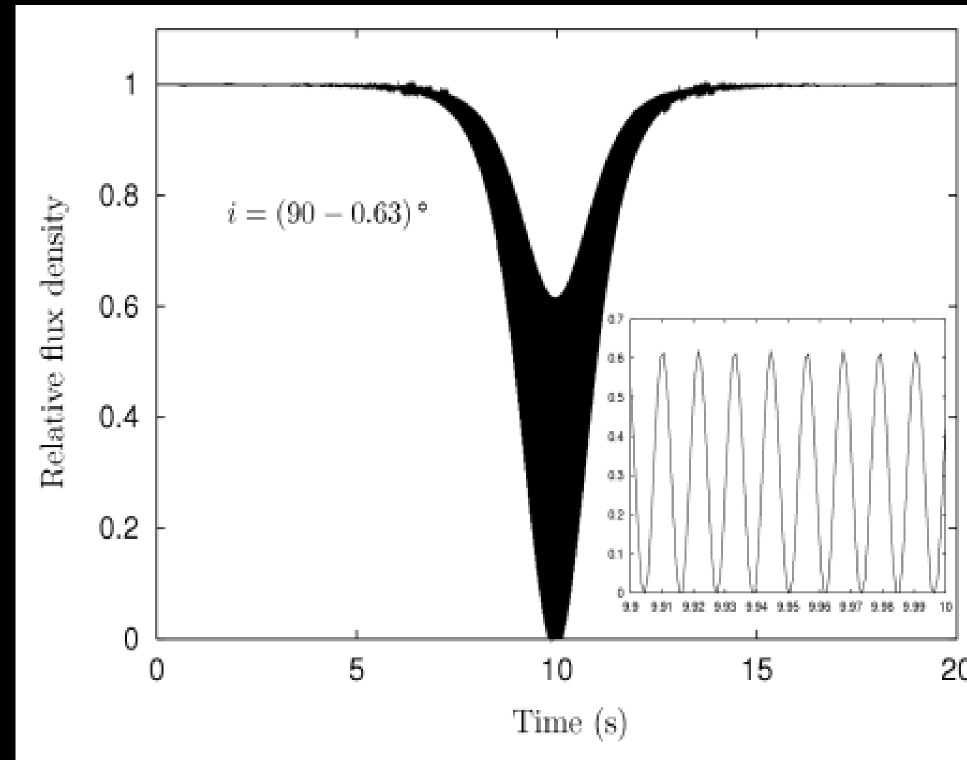
Neutron Star - Neutron Star Binary

- Double pulsar J0737-3039 at i ~89° perfect system.
- Single directional light ray passing close to NS surface.
- Precession of i means geometric eclipse predicted in 2020! Is this true?
- Radio eclipses already visible due to magnetosphere (absorption stops above 7.5 GHz).



B eclipsing A **A eclipsing B ???**





- Photons too energetic to interact with magnetoshpere.

- Quantum vacuum lensing will cause eclipses of photons at a slightly different orbital phase to the geometrically eclipsed photons.

- Rely on precise knowledge of epoch of geometric eclipse.

- Vacuum lensing achromatic (X-rays, γ-rays).

- Measure a_{perp} to test QED prediction.

Meanwhile on earth.....

NEWS & VIEWS

PARTICLE PHYSICS

The first axion?

Steve Lamoreaux

For almost 30 years, the hunt has been on for a ghostly particle proposed to plug a gap in the standard model of particle physics. The detection of a tiny optical effect might be the first positive sighting.

Writing in *Physical Review Letters*[1], Emilio Zavattini and colleagues of the Italian PVLAS collaboration report that a magnetic field can be used to rotate the polarization of a light wave in a vacuum. Although this is the first experimental evidence for such an effect, there is a well-rehearsed, but controversial, explanation for it: the existence of a never-before-seen, chargeless, spinless and near-massless particle — the axion. Has the elusive axion finally allowed itself to be glimpsed?

The idea that static electric and magnetic fields alter the optical properties of matter, whether solid, liquid or gas, is not new. In 1845, Michael Faraday showed that the direction of polarization of light changes in a medium permeated by a magnetic field. Similar demonstrations followed: of the Cotton–Mouton and Kerr effects, for instance, in which the propagation speed of a light wave can be made to vary according to the orientation of its polarization with respect to an applied magnetic or electric field, respectively.

That static electromagnetic fields can be used to alter the properties of empty space might seem surprising. The culprit is quantum electrodynamics (QED), the quantum field theory that expresses the electromagnetic interaction in terms of the exchange of quanta of energy — photons — between particles. It was recognized in the early 1930s that the rules of QED allowed the creation and annihilation in an electromagnetic field of short-lived 'virtual' charged-particle pairs consisting of an electron and its antiparticle, the positron. The resulting 'self-interaction' of the field introduces a nonlinearity in the governing equations of electromagnetism (Maxwell's equations) analogous to that induced by the presence of matter. The vacuum self-interaction is further complicated by the fact that, given the presence of sufficiently energetic photons, real (as opposed to virtual) electron–positron pairs can be created. Nevertheless, by 1936, vacuum analogues of various optical effects in matter had already been calculated[2,3].

So what other particles might the vacuum be hiding? In the late 1970s, a suitable candidate was postulated to solve the so-called strong CP problem. This problem pops up as a term in the field equations of quantum chromodynamics (QCD) — the equivalent of QED for the strong nuclear force, which binds together the innards of neutrons and protons. This term is not symmetric when, in a process involving the strong force, particles are replaced by antiparticles (charge conjugation; C) and the process is viewed in a mirror (parity inversion; P). The degree of this 'symmetry breaking' can be parametrized by an angle that, according to a limit obtained from measurements of the electric dipole moment of the neutron, is less than a billionth of a radian. Strong-force interactions covered by QCD thus hardly seem to break CP symmetry at all.

This is an odd fact, because interactions involving the weak nuclear force (which can be incorporated with the electromagnetic force in QED) observably break CP symmetry. As there is no a priori reason for the discrepancy between these forces, Roberto Peccei and Helen Quinn proposed[4] a mechanism implying the existence of another electrically neutral particle that would force the QCD symmetry-breaking angle — which could otherwise be as large as that in QED — to become zero. This particle cleaned up the strong CP problem, so Frank Wilczek dubbed it the 'axion', after a

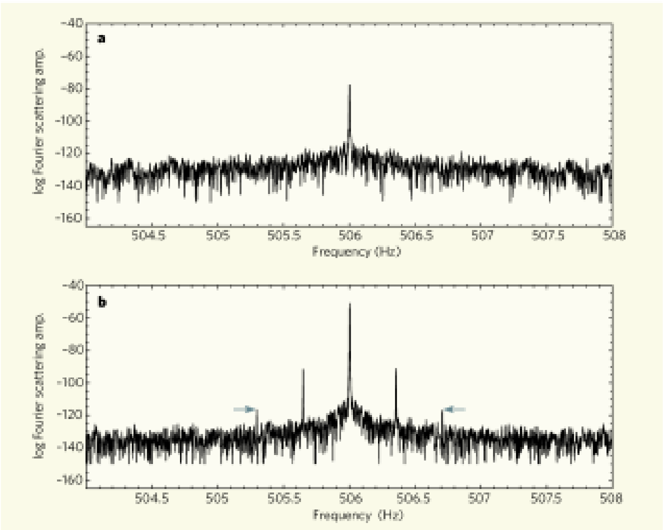


Figure 1 | Now you see it? Before (**a**) and after (**b**) Fourier amplitude spectra (logarithmic scale) of Zavattini and colleagues' vacuum polarization-rotation experiment[1]. A sine wave generated at 506 hertz is modulated by the frequency of rotation, $\nu \sim 0.3$ Hz, of the experimental apparatus, which consists of a 1-metre-long interaction region traversing the bore of a 5.5-tesla magnet cooled cryostatically to 4.2 kelvin. **a**, With the magnetic field off, a central peak is observed, corresponding to the generated sine frequency. **b**, With the magnet on, side peaks are observed at frequencies displaced from the central peak by $\pm\nu$, corresponding to the magnet's rotation. Crucially, a signal displaced by $\pm 2\nu$ is also observed (arrows). This unexpected additional rotation of the light polarization vector could be the signal of axion production.

4. PVLAS and the Axion.

4.1 Experiment

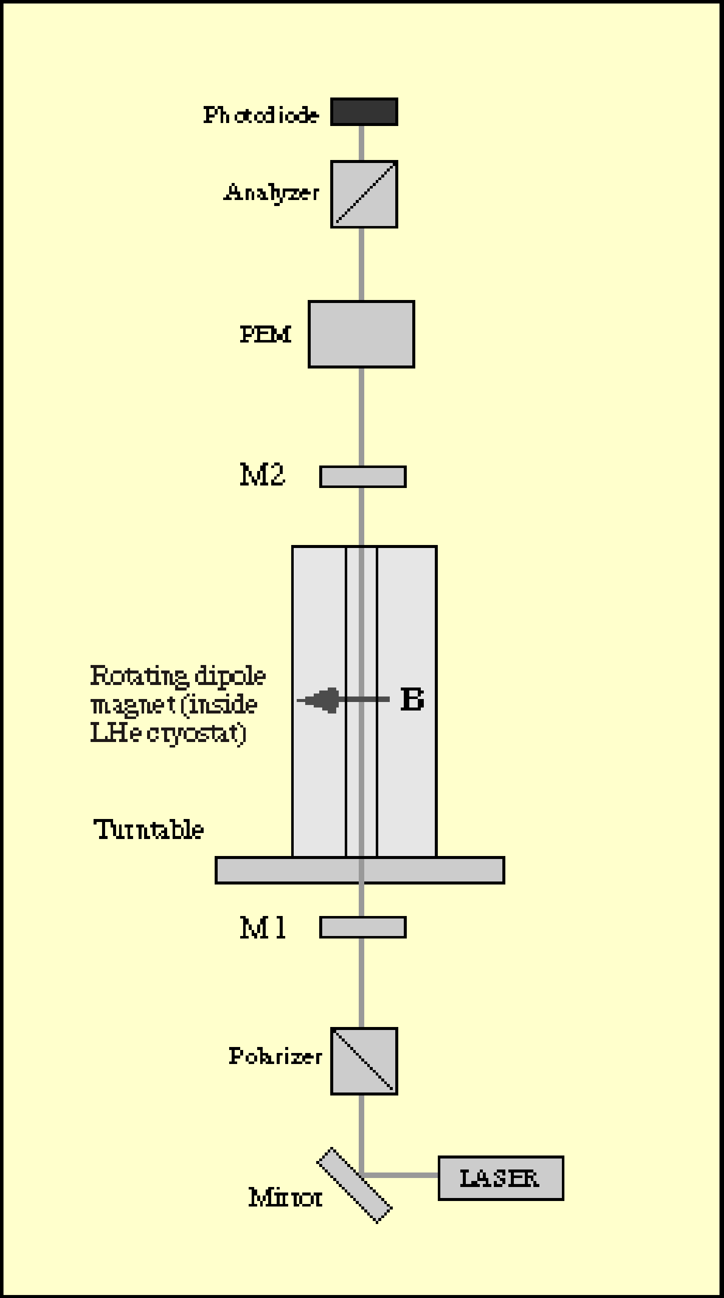
- E. Zavattini *et al* at University of Trieste.

- Designed to detect ellipticity induced in a linearly polarised laser beam by vacuum magnetic birefringence.

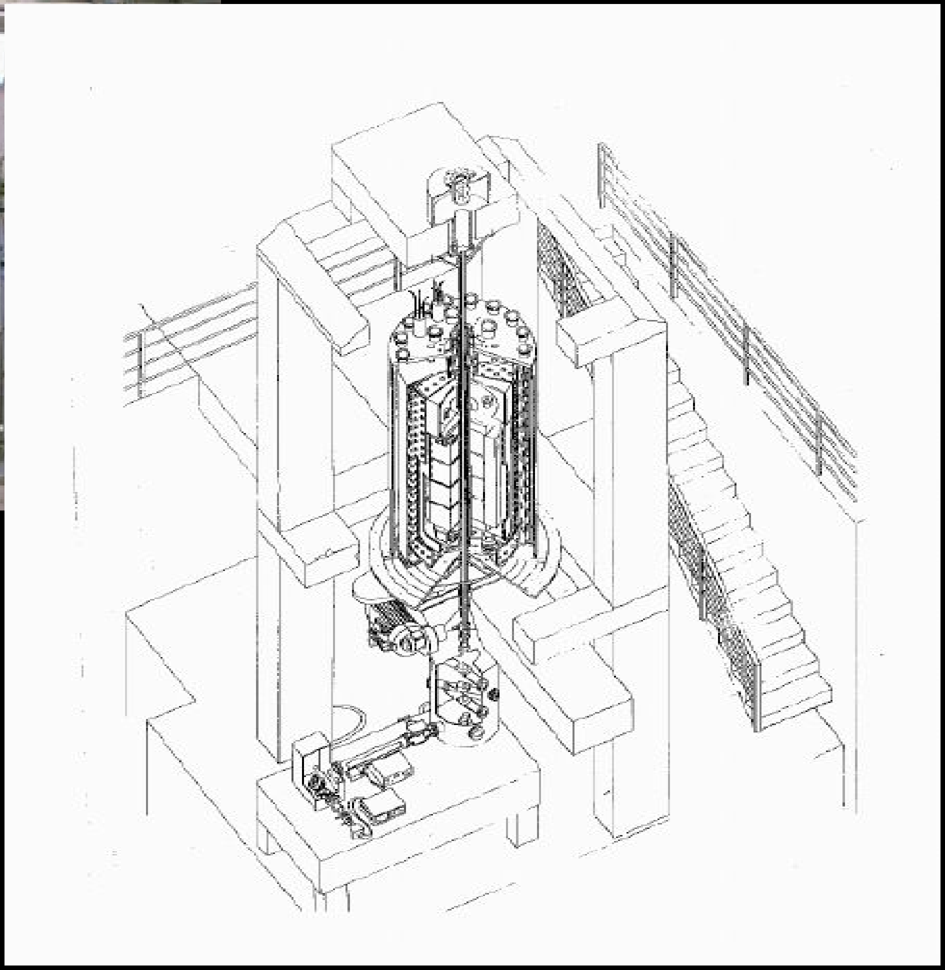
- Ellipticity so small, heterodyne detection used.

- Small rotation detected (E. Zavattini *et al* 2006).

- Subtle difference is rotation (dichroism) not ellipticity (birefringence).



PVLAS...

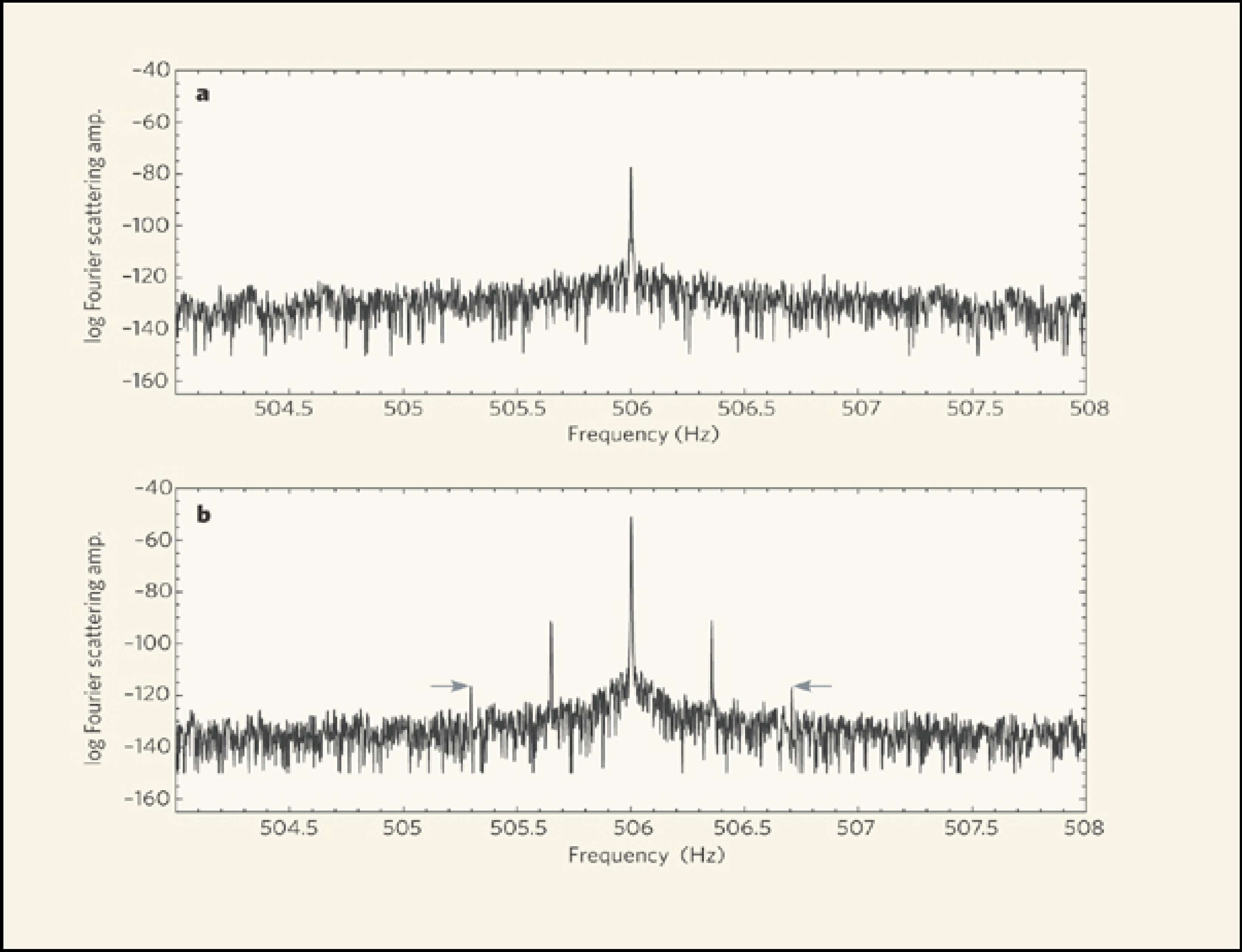


4.2 PVLAS Result

- Unexpected additional peaks at x2 freq of magnetic rotation.

OFF

ON

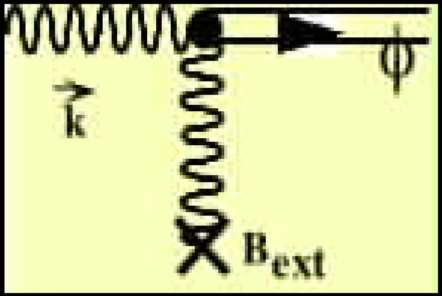


E Zavattini *et al* 2006

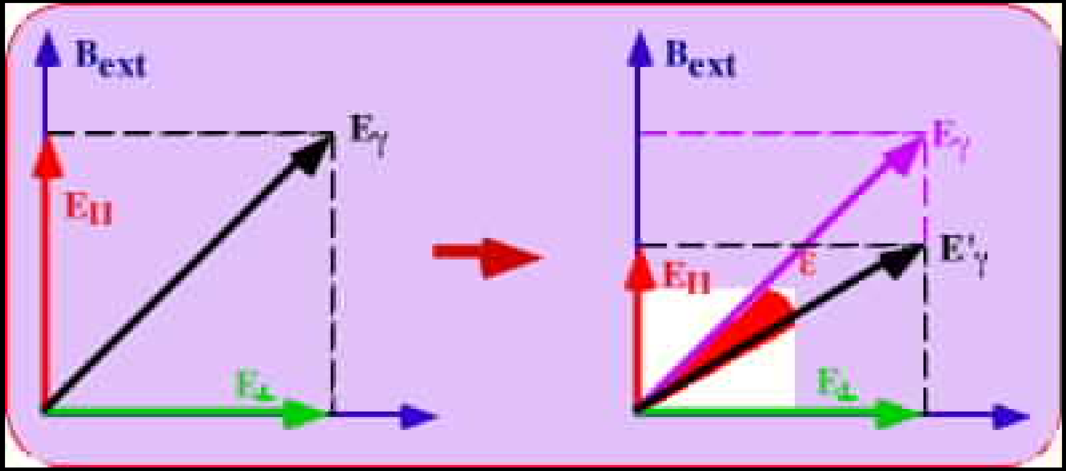
4.3 Explanation of PVLAS result

- Dichroism (rotation of polarisation vector)

- Primakoff effect. Photons parallel to the B-field interact with photons in the vacuum creating a light, weakly interacting, spinless, neutral particle (light psuedoscalar boson, LPB) Φ.

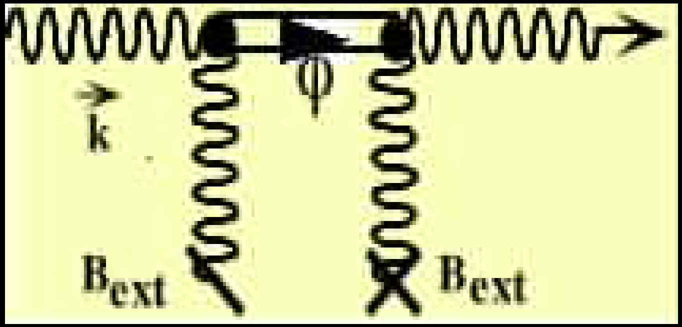


- Reduction of E_{parr} effectively rotates polarisation vector.



- Ellipticity (retardation of E_{parr})

- Virtual particle production. Two photons combine to produce LPB Φ, then quickly decay back into photons.



- Since the LPB has mass it travels at less than *c*. E_{parr} is delayed wrt to E_{perp}, mimics QED effect of ellipticity.

4.4 What are LPB?

- A particular case of LPB is the Axion.

- Axion first postulated 30 years ago to solve strong CP problem.

- Candidate for non baryonic dark matter.

- **Standard Axion**

  Mass: 1 μeV – 0.01 eV (50 million – 500 billion less massive than electron)

  Photon Axion Coupling Strength: 0.6×10^{-10} GeV^{-1}

- **PVLAS Axion**

  Mass: 1 meV

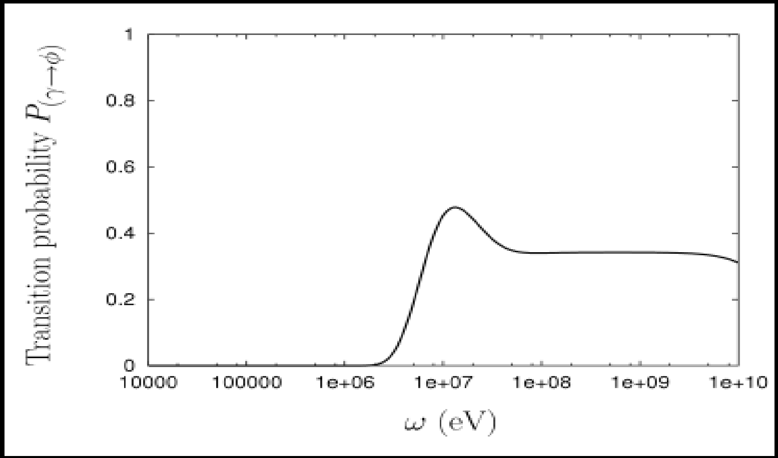
  Photon Axion Coupling Strength: 5×10^{-5} GeV^{-1}

4. Double Neutron Stars, Axion Factories?

- Photon to axion conversion probability proportional to B^2 and distance traversed through field.

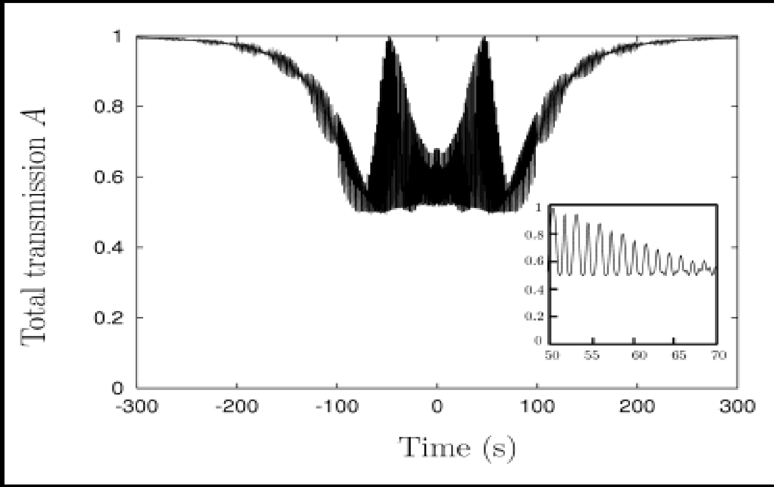
- NS magnetic field ~ billion times PVLAS field (6.6 T).

- Conversion probability increases for high energy photons:



- J0737-3039 edge on. Detect attenuation at gamma ray energies.

- NASA GLAST can observe attenuation (launch 2007), and test PVLAS axion.



A Dupays *et al* 2005

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2.2 Quantum optical phenomena.

- By the 1930s it was recognized that the rules of quantum electrodynamics (QED) allowed the creation and annihilation of virtual particle anti-particle pairs.

- From the uncertainty principle applied to energy and time, $\Delta E \Delta t = \frac{h}{2}$ it is possible to create particle anti-particle pairs in small enough times.

- Vacuum analogues to all the

- Calculations prompted by early speculation that NS could be intense sources of magnetic field.

- Birefringence of the vacuum can also be explained by physics beyond the standard model...see later.

Classical spin orbit coupling causes inclination of the double pulsar to move. Which direction is the double pulsar moving? Toward or away form 90 degress? How long will it take to get to 90 degrees? It is precisely because inclination is so close to 90 degrees that it is difficult to calculate the change of i.