PVLAS Axion: Implications for astrophysics and cosmic rays

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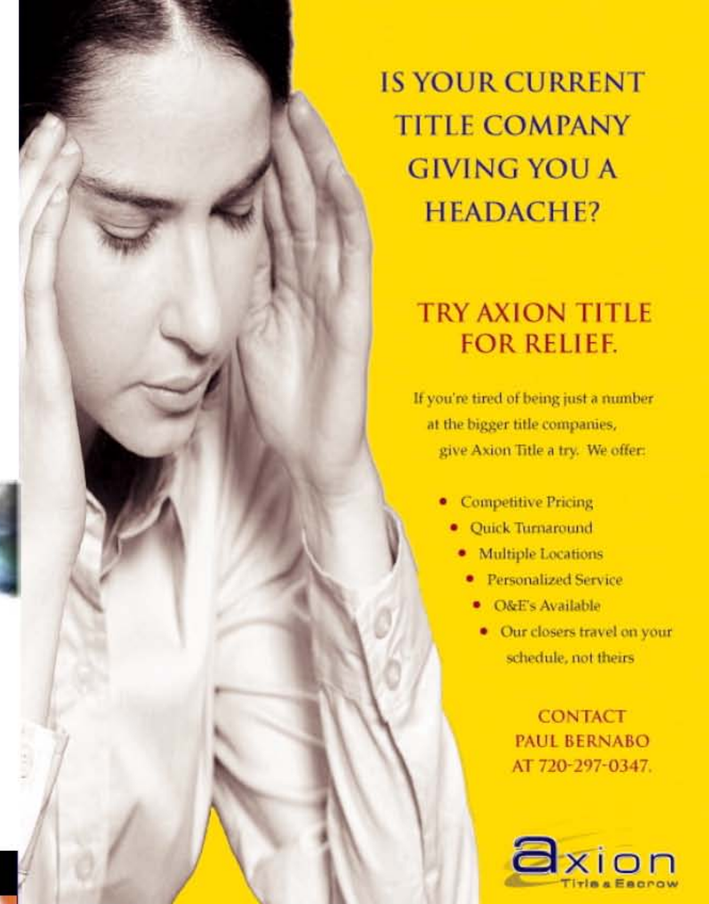
Chór PWr „AXION" wyśpiewał nagrody
Legnica Cantat
Chór Kameralny „Axion" Politechniki Wrocławskiej na przełomie maja i czerwca uczestn
konkursach chóralnych. Obie imprezy przyniosły mu laury.
Na Ogólnopolskim Turnieju Chórów „Legnica Cantat 35" zespół otrzymał III nagrodę
Powtórzył w ten sposób ubiegłoroczny sukces.
Natomiast na III Międzynarodowym Festiwalu Muzyki Chóralnej im. Feliksa Nowowiejsk
zdobył Złoty Dyplom (I nagroda w konkursie).


axion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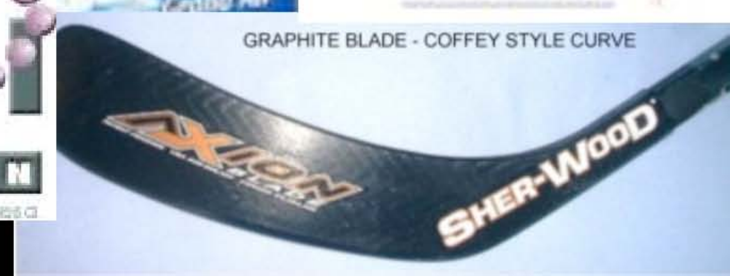

GRAPHITE BLADE - COFFEY STYLE CURVE
AXION
SHER-WOOD

Axions

Originally invoked to explain QCD CP problem, there are many theories with pseudo-scalar axions which couple to the electro magnetic field as:-

$$L = -\frac{1}{2}\left(\partial^{\mu} a \partial_{\mu} a + m^2 a^2\right) + \frac{a}{M} F_{\mu\upsilon} \tilde{F}^{\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

a is the axion field, m is the mass of the axion, and M is the inverse coupling of the axion to the gauge field. The mass m drives the coupling a/M to zero to avoid CP violating vertices.

For QCD axion m~ 10^{-3}-10 eV, M~10^{10} GeV

$$m_a M \sim m_a f_a \sim m_\pi f_\pi$$

Photon-Axion Mixing

In presence of non-zero B-field, axion can lead to photon axion mixing

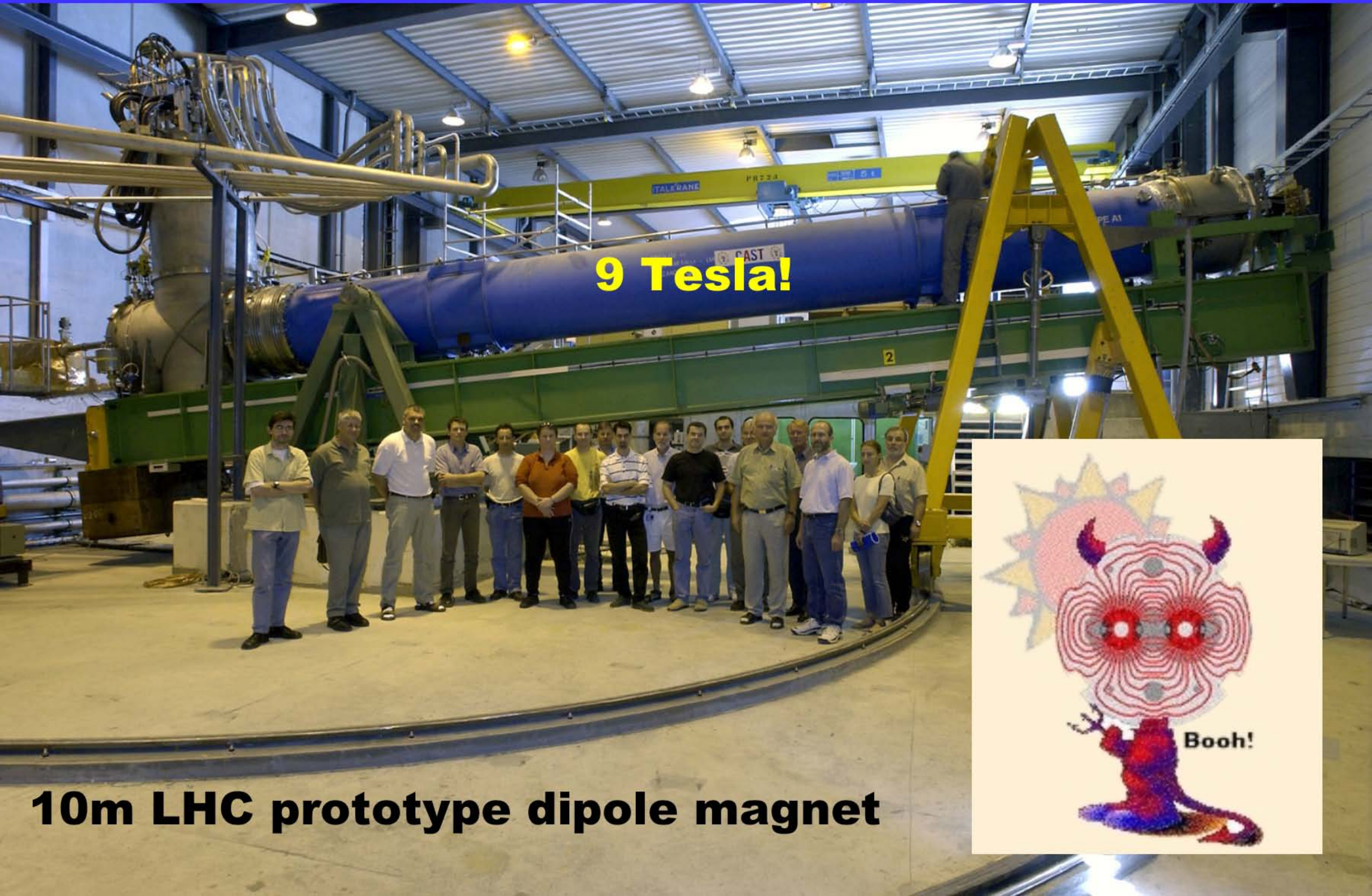
Probability of a photon remaining a photon after traveling a length L is given by

$$P_{\gamma\to\gamma} = 1 - \frac{B^2\omega^2}{m^4M^2 + B^2\omega^2}\sin^2\left[\frac{\sqrt{m^4M^2 + B^2\omega^2}}{\omega M}L\right]$$

Here ω is the energy of the photon, m is the axion mass, M is the inverse coupling of the axion to the photon, L is the distance traveled and B is the magnetic field perpendicular to the direction of propagation of the photon.

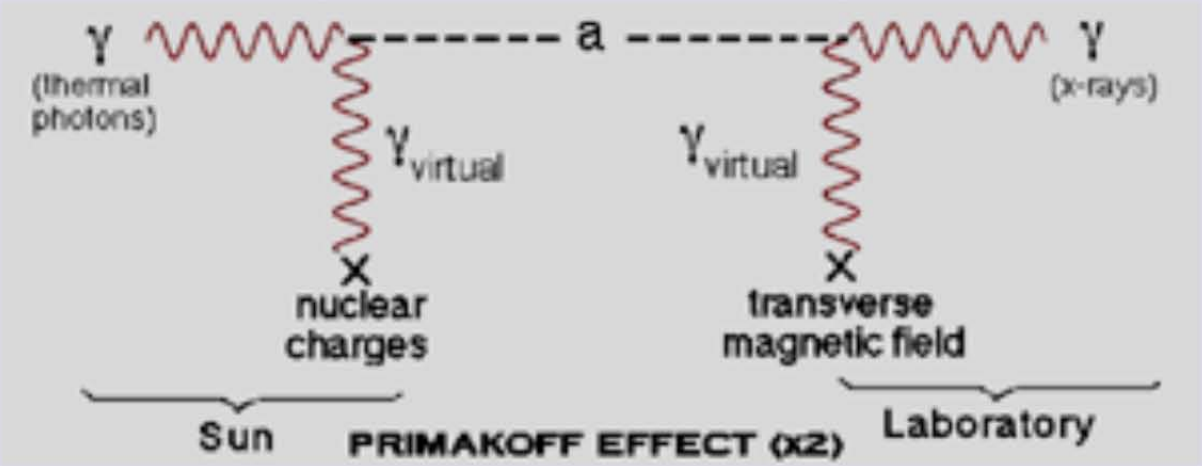
So some photons disappear...

and reappear ! C.A.S.T. Cern Axion Solar Telescope

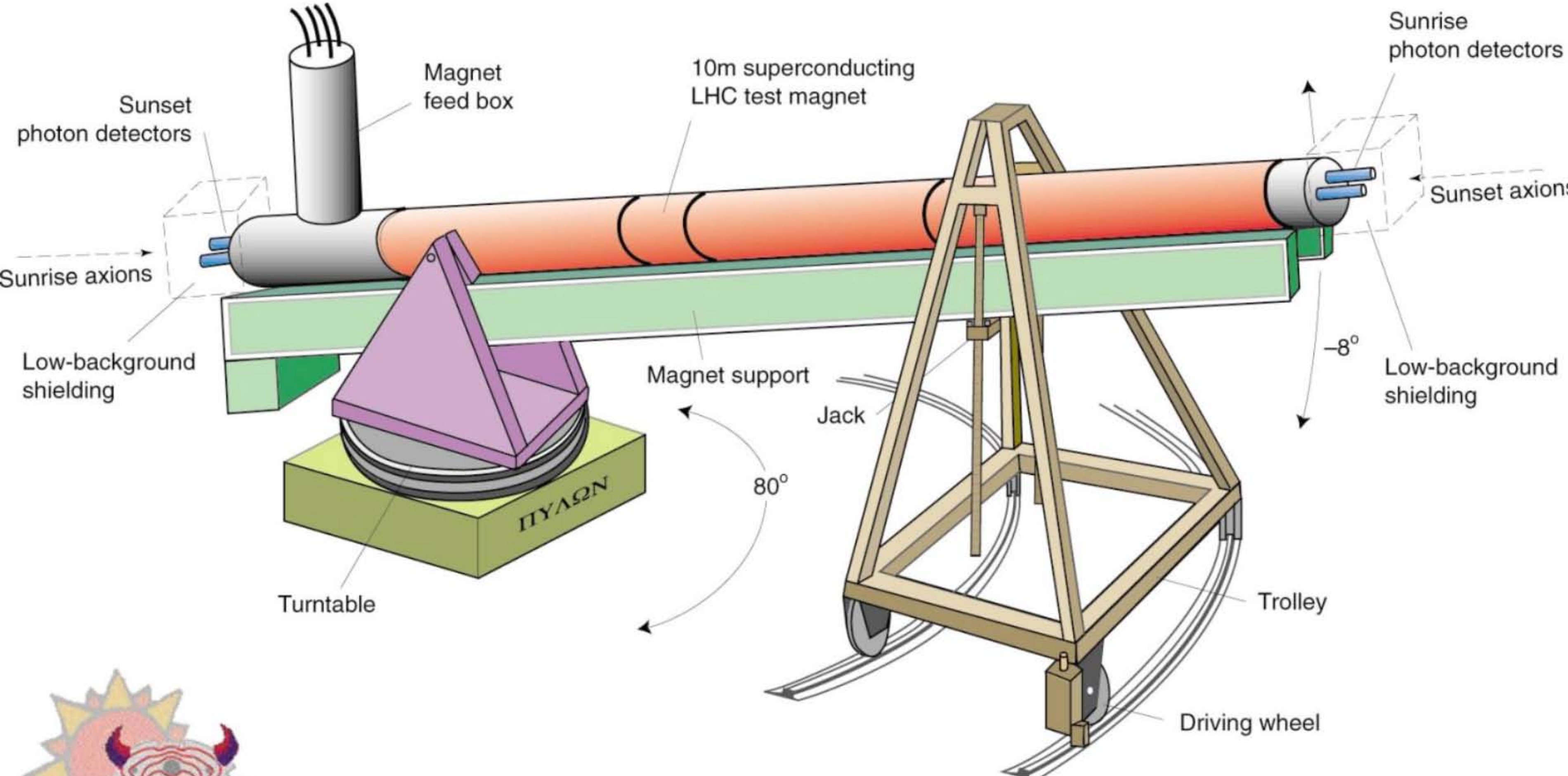


What does C.A.S.T. look for?

axions would be produced in the centre of the sun due to thermal x-ray photons converting in the magnetic field of nucleons

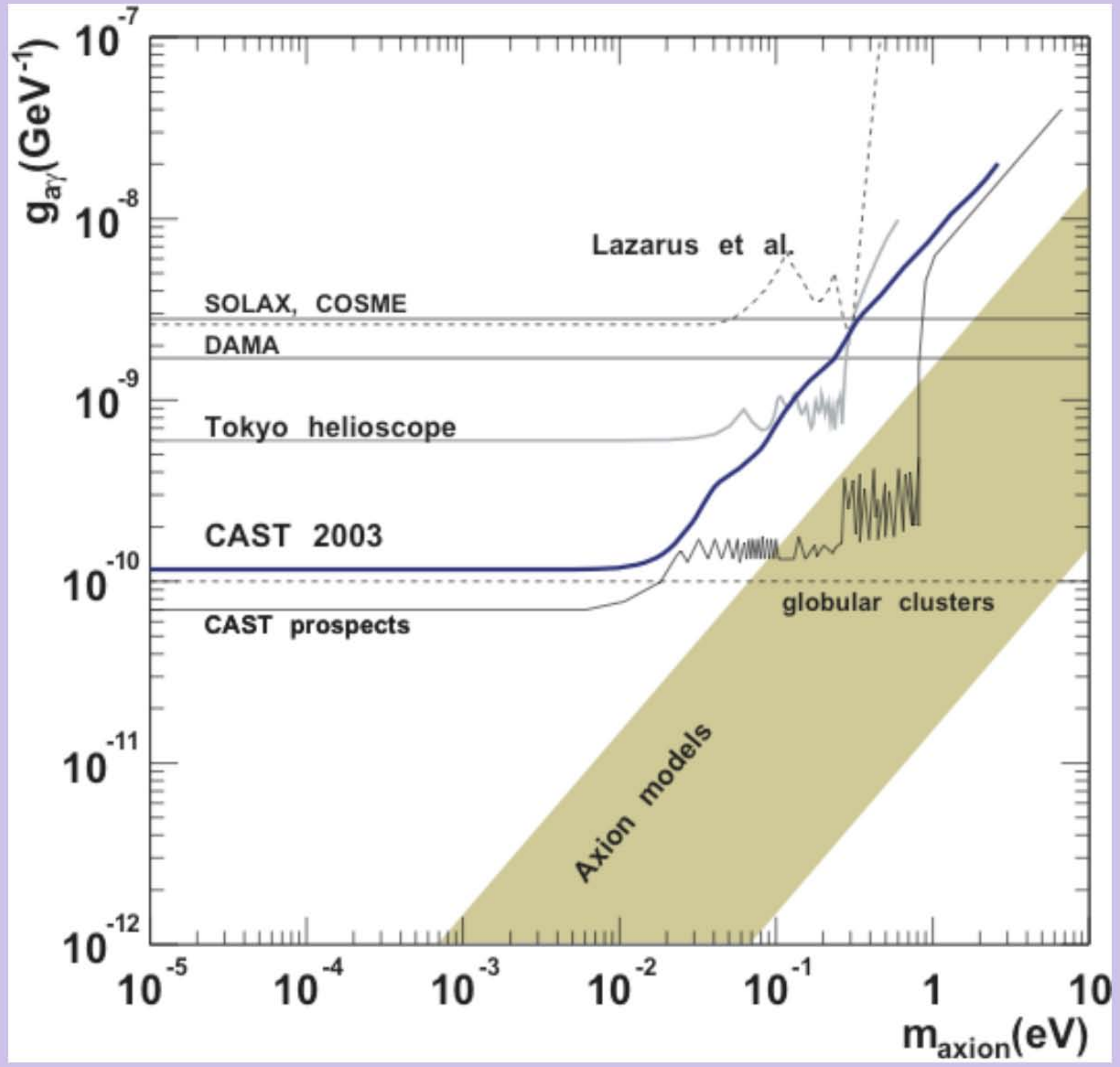


These axions can then convert back into photon in the magnetic field of the experiment.



Cern **A**xion **S**olar **T**elescope

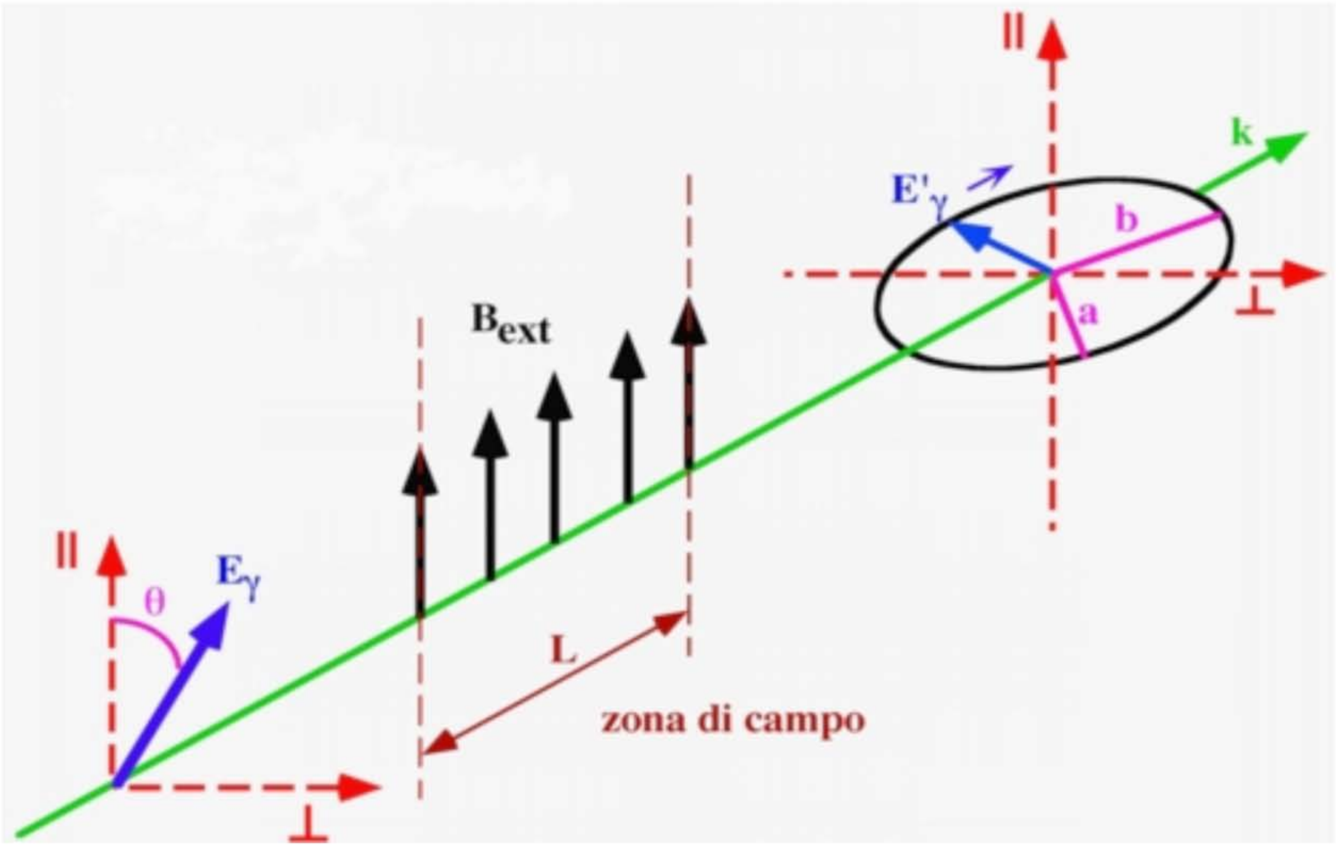
C.A.S.T. CONSTRAINTS hep-ex/0411033



So what is PVLAS?

Bi-refringence and Ellipticity

In a bi-refringent vacuum, different polarisations propagate at different velocities - induces an ellipticity.



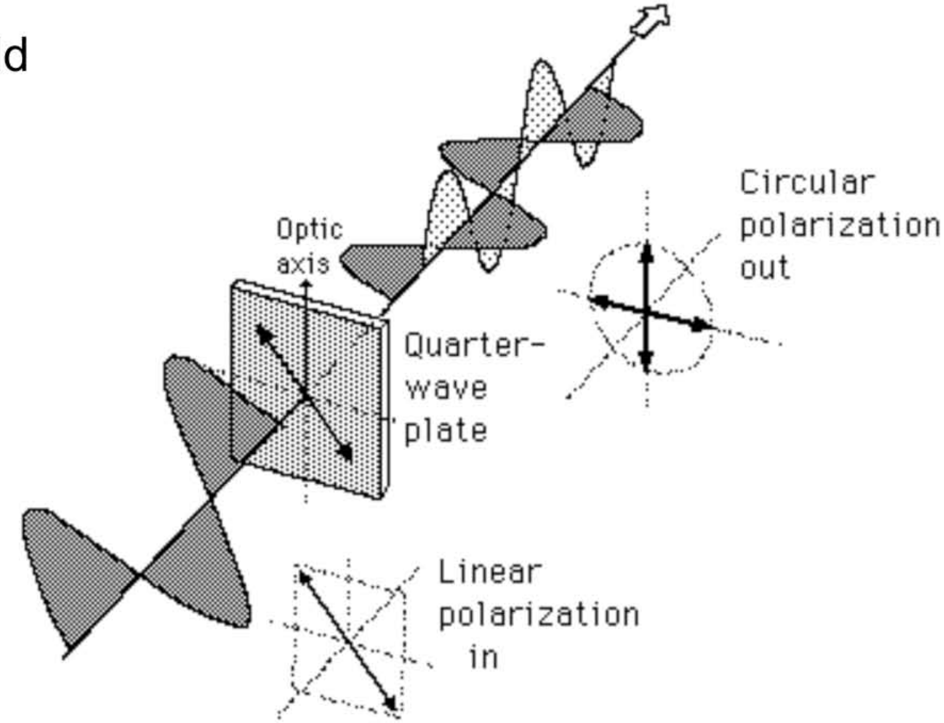
Example:- Cotton-Mouton effect due to fermion loops in presence of B-field

FROM DICHROISM TO ELLIPTICITY

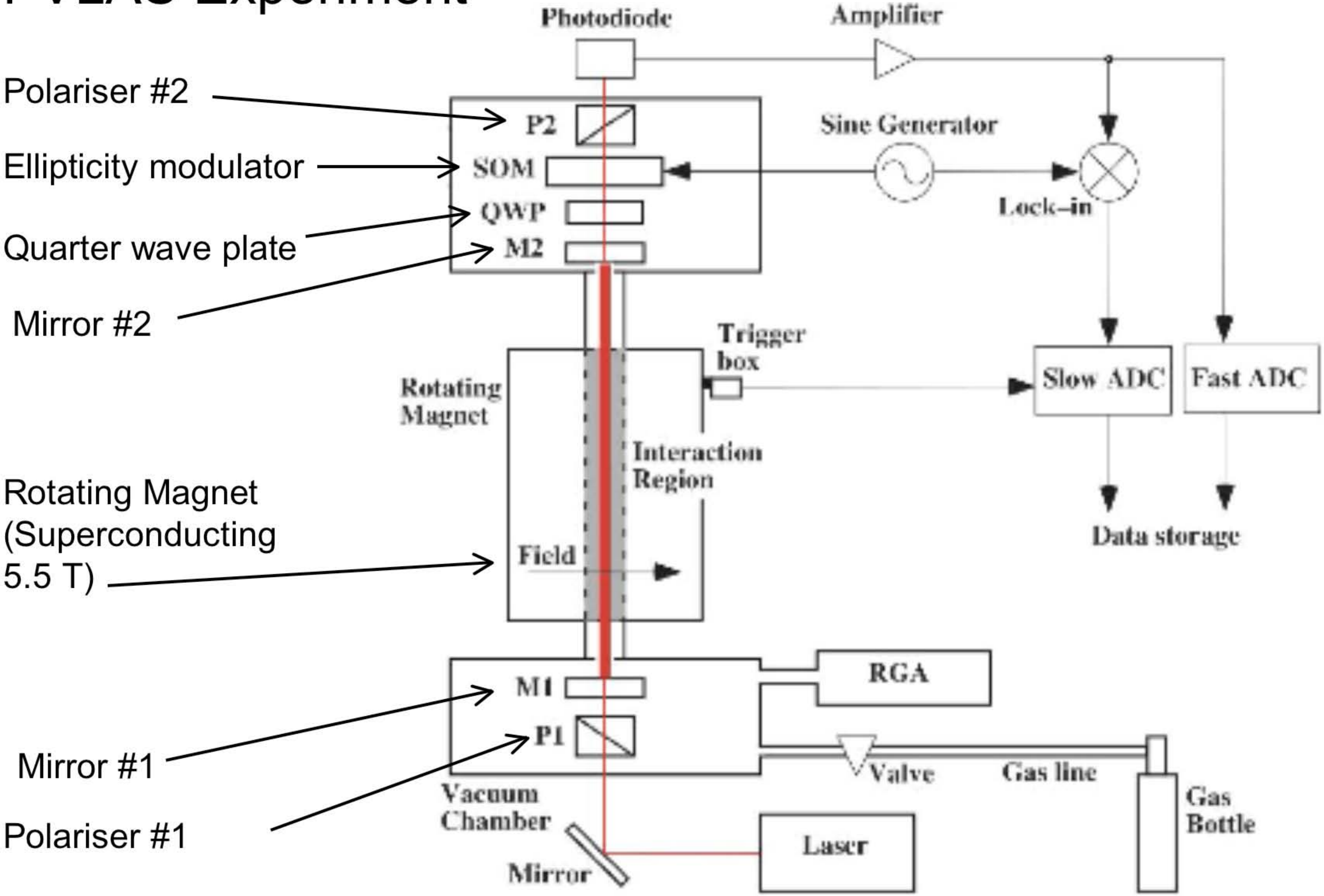
Dichroism - one polarisation dissapears c.f. photon turning into axion in B field

Linearly polarised light at 45^o to B-field polarisation axis will rotate

Send beam through quarter wave plate aligned with initial polarisation. Will induce ellipticity in beam.



PVLAS Experiment



PVLAS DETECTION PROCEDURE

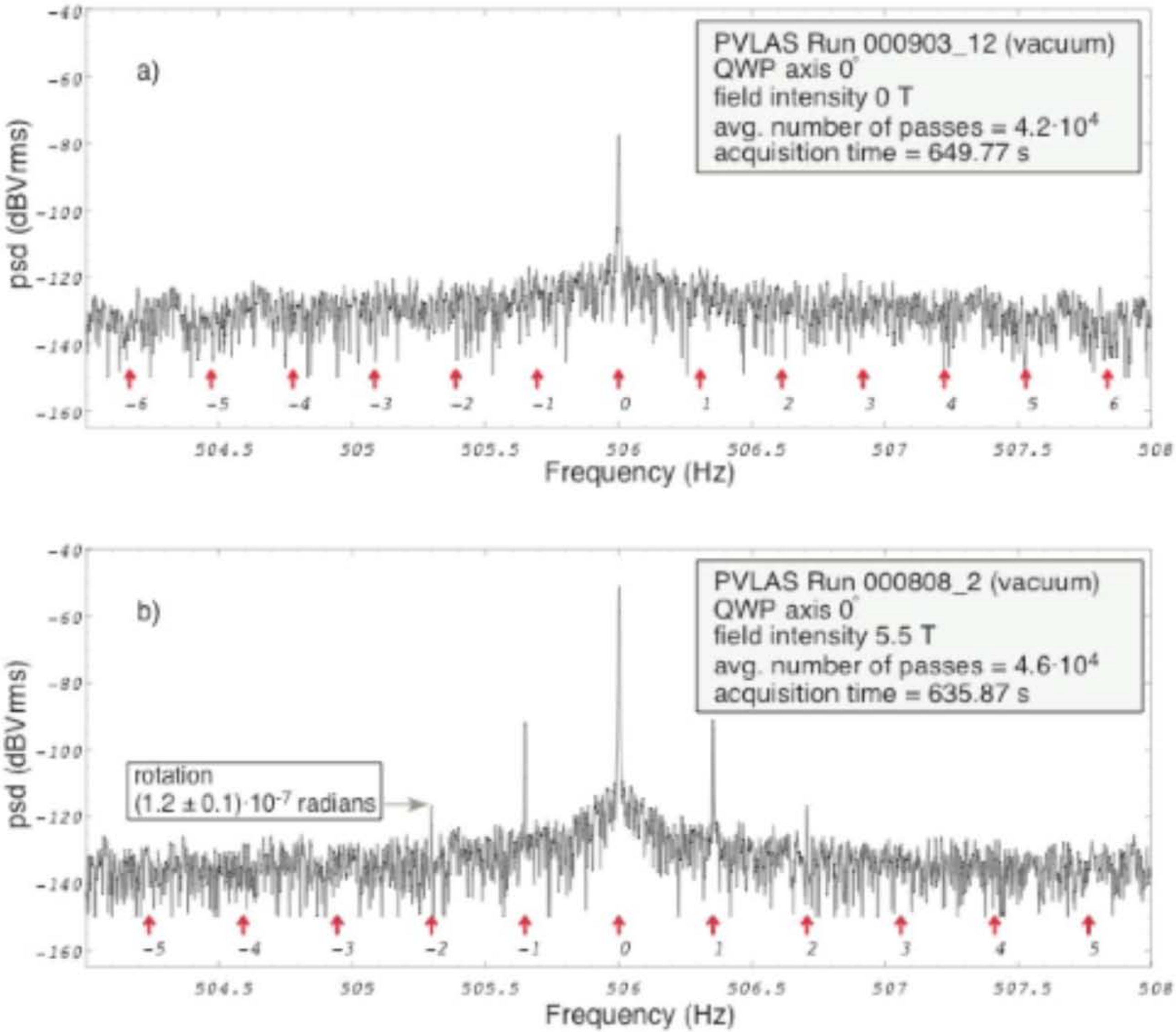
Magnetic field rotated at frequency ω_m

Ellipticity induced with frequency ω_{MOD}

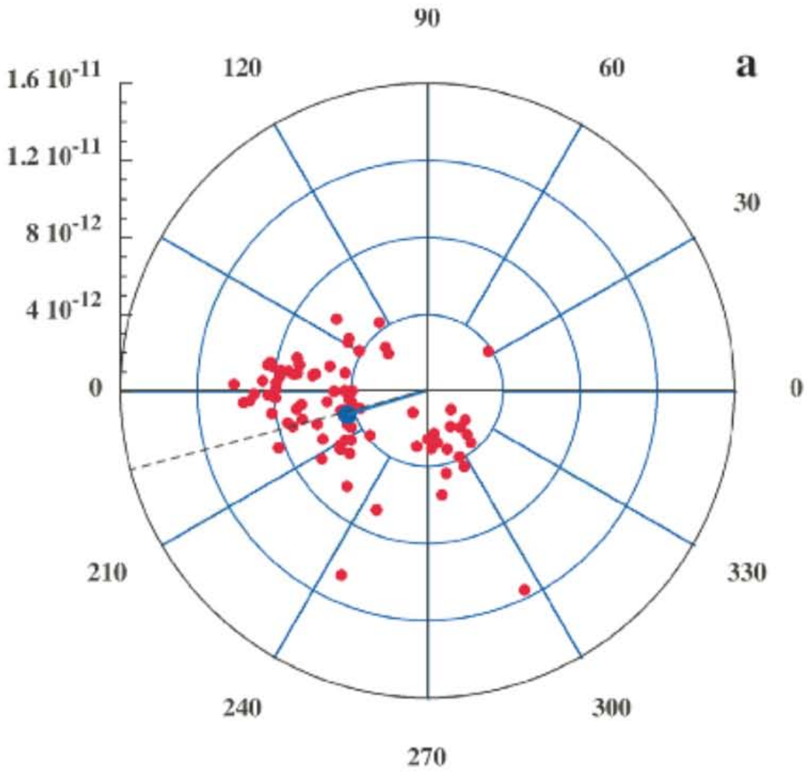
If there is an ellipticity induced by the rotating magnet, it will beat with that from them modulator, creating side bands.

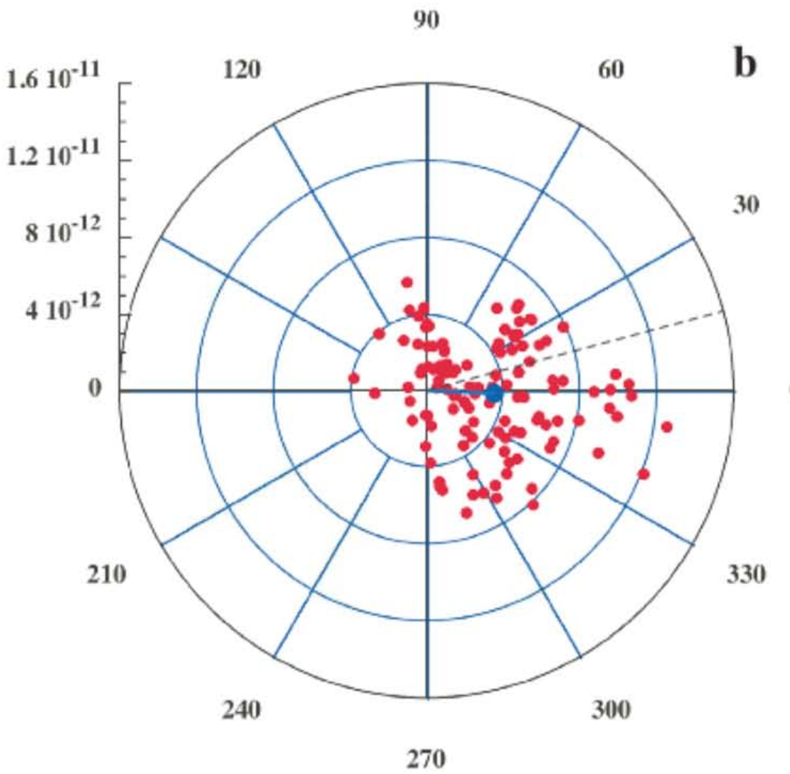
$$\omega = \omega_{MOD} \pm \omega_m$$

PVLAS beat frequency detected



PVLAS results - rotation/pass





Quarter wave plate at 90° to initial polarisation

Quarter wave plate at 0° to initial polarisation

Axion interpretation

Production of axions rotates the plane of polarisation by

$$\epsilon = N\frac{B^2\omega^2}{M^2m^4}\sin^2\left(\frac{m^2L}{4\omega}\right)\sin 2\theta \sim \frac{N}{16}(\frac{BL}{M})^2\sin 2\theta$$

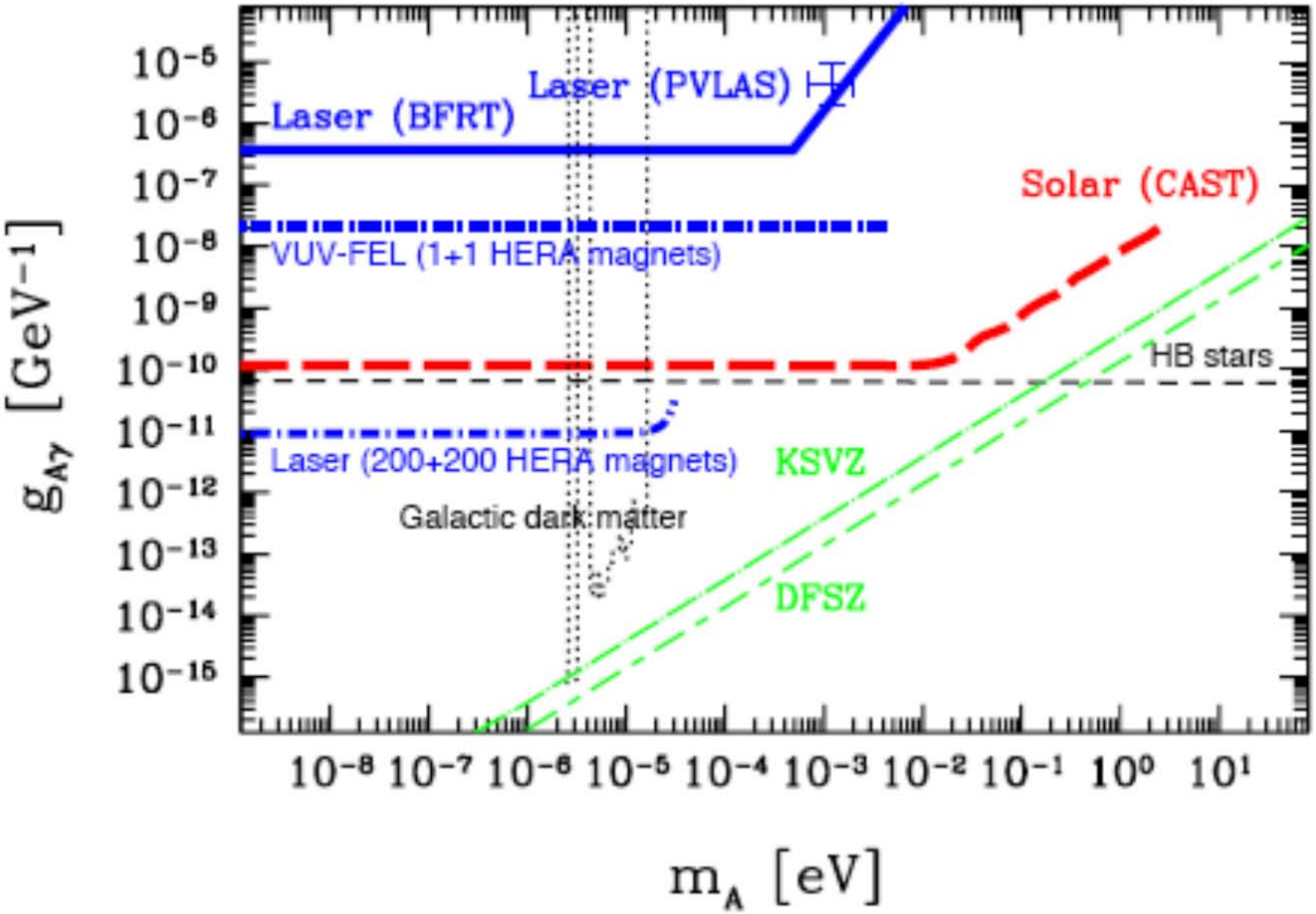
In particular, the PVLAS results are compatible with

$m = 10^{-3}\text{eV}$ $\quad$ $M = 10^6\text{GeV}$

Which is rather strongly coupled compared with existing bounds

EG, supernova explosions no longer a bound because of coupling

Comparison with other experiments



Ringwald 2005

Explaining the Discrepancy with C.A.S.T.

Composite model (Masso & Redondo 2005)

$\pi^0\gamma\gamma$ vertex described by quark triangle loop with off-shell photons leads to form factor and suppression

$$|F| \sim \frac{m_{u,d}^2}{q^2}$$

Can try to imagine that the PVLAS axion is made of partons and that

$$\left[|F|^2 \frac{1}{M_{pvlas}^2}\right] \frac{1}{M_{pvlas}^2} < \left[\frac{1}{M_{cast}^2}\right] \frac{1}{M_{cast}^2}$$

(photons exchanged with protons in sun off shell, with B-field in CAST not)

Explaining the Discrepancy with C.A.S.T.

Composite model (Masso & Redondo 2005)

Mass of partons

We require

$$|F| \sim 10^2 \frac{(2m_f^2)}{|s_{virt}|} < 2 \times 10^{-9}$$

Momentum exchanged with proton

Which leads to

$$m_f \leq 2 \times 10^{-2} eV$$

Explaining the Discrepancy with C.A.S.T.

Self interaction (Jain & Mandal 2006)

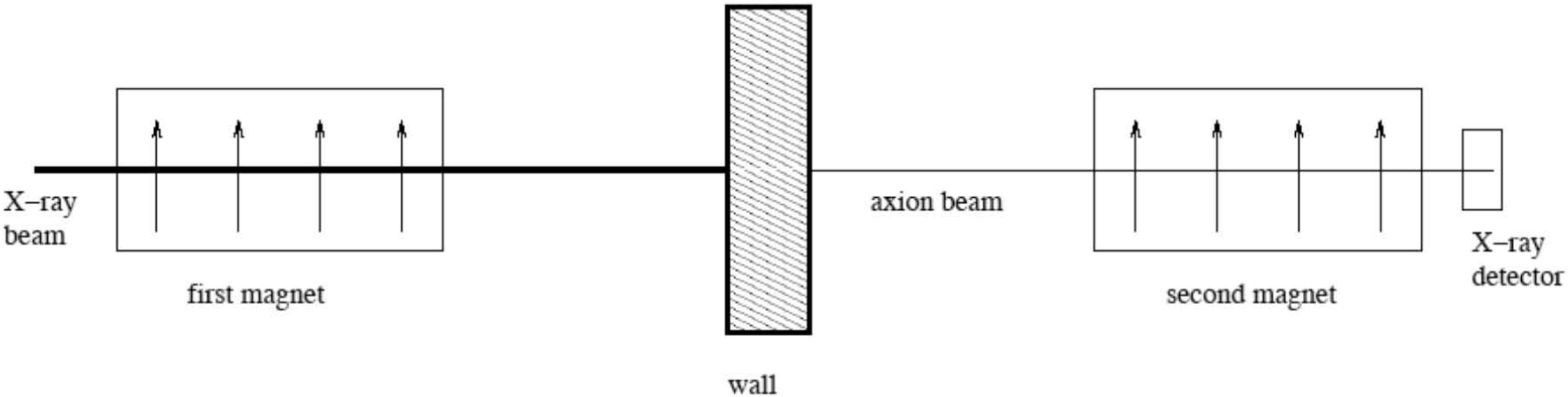
$$L_{\text{int}} = \frac{a}{M} F_{\mu\upsilon} \tilde{F}^{\mu\nu} + \frac{\lambda}{4!} a^4$$

1. MASSIVE production of pseudo-scalars in core of sun
2. Pseudo-scalars trap themselves in core via $\phi\phi \rightarrow \phi\phi$
3. also lose energy via loop diagram $\phi\phi \rightarrow \phi\phi\phi\phi$
4. Final mean free path 10^{-11} cm in core of sun
5. Come into equilibrium with photons via inverse Primakov effect

(probably 1001 ways to kill this model!)

How to test PVLAS : Shining Light Through Walls

Rabadan, Ringwald and Sigurdson 2005



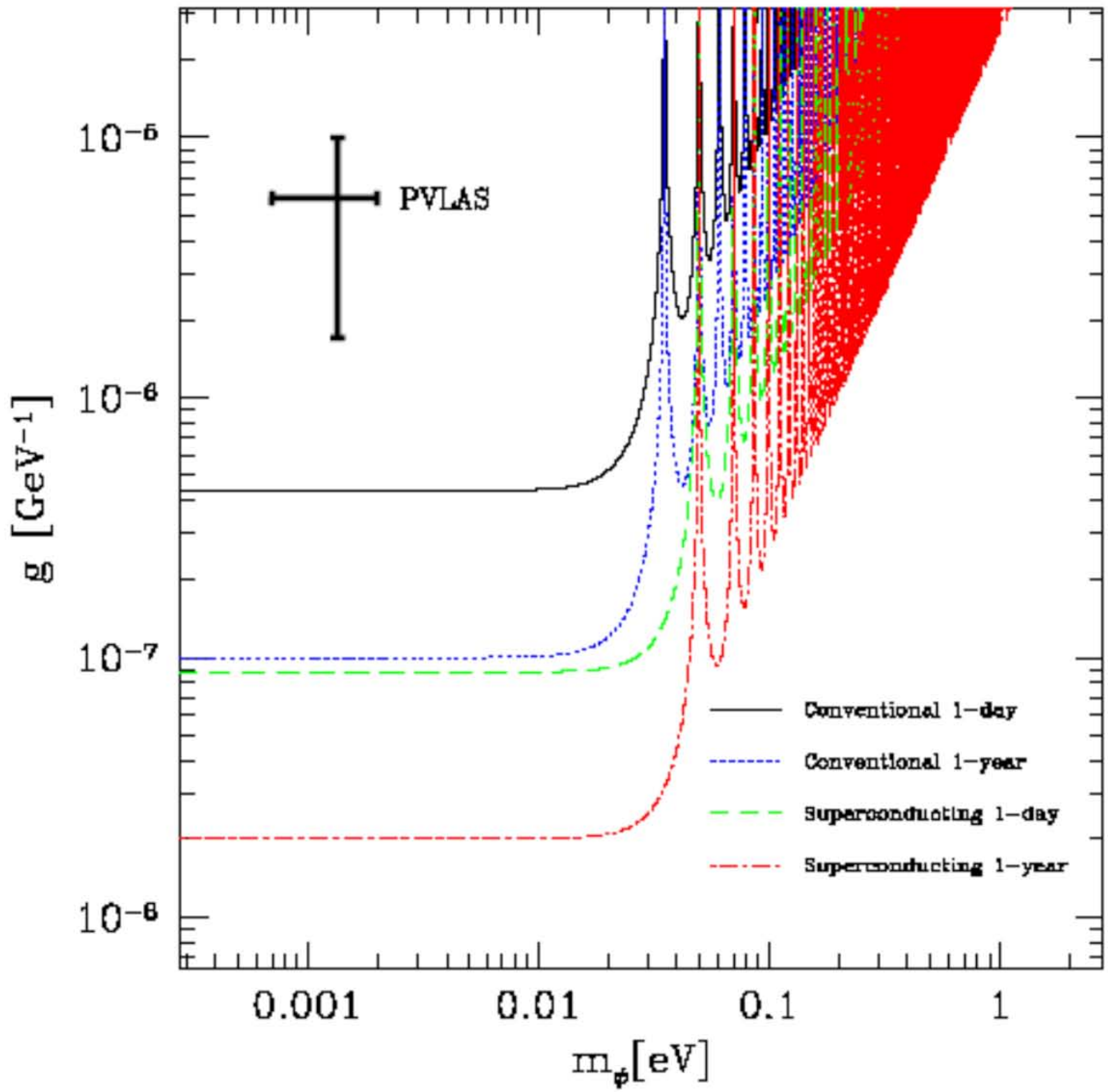
PROPOSAL: use free electron laser x-ray laser (SLAC-LCLS 2009 or DESY-XFEL 2012) generates $10^{17\text{-}19}$ keV photons per second

Also use conventional magnets (1T) or decommissioned HERA magnets (10 T)

How to test PVLAS : Shining Light Through Walls

Would be able to probe region of interest in days!

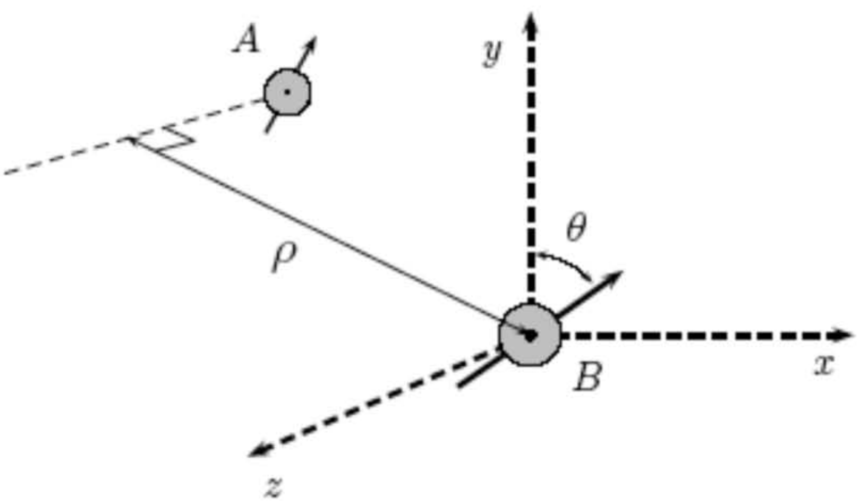
Rabadan, Ringwald and Sigurdson 2005

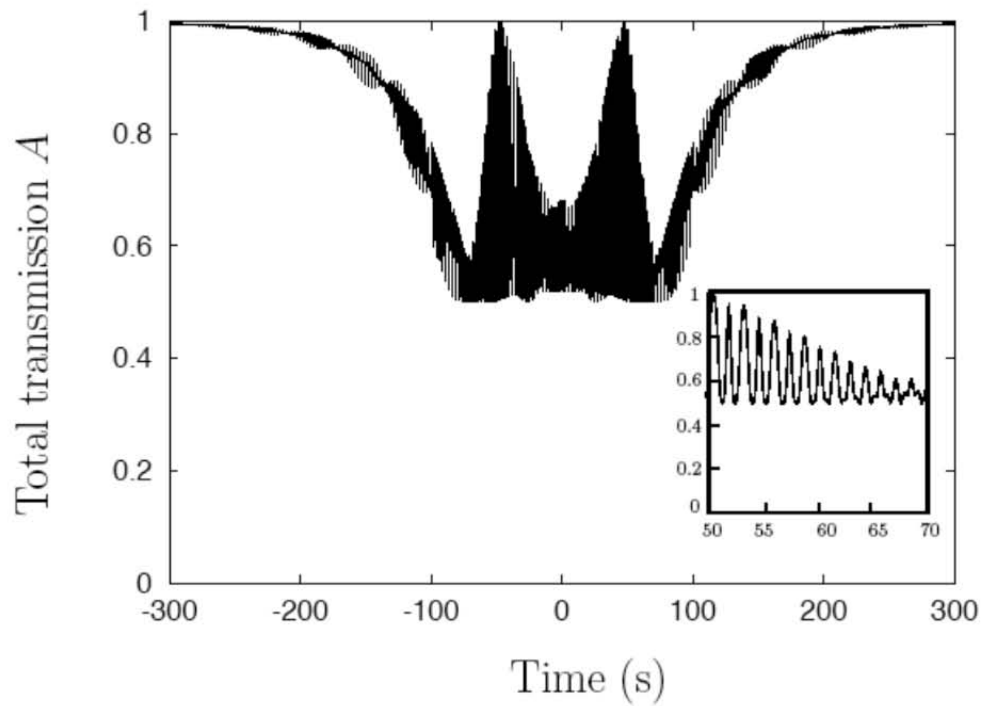


Dimming in Binary Pulsar systems

Photons from one pulsar pass through the magnetosphere of companion

Binary Pulsar System J0737-3039





May be detected by GLAST (Dupays et al 2005)

Resonant mixing in stellar atmospheres

Effect of refractive index for photons on mixing angle:-

$$\sin^2\theta = \frac{B^2\omega^2}{(m^2-\omega_p^2)^2M^2+B^2\omega^2}$$

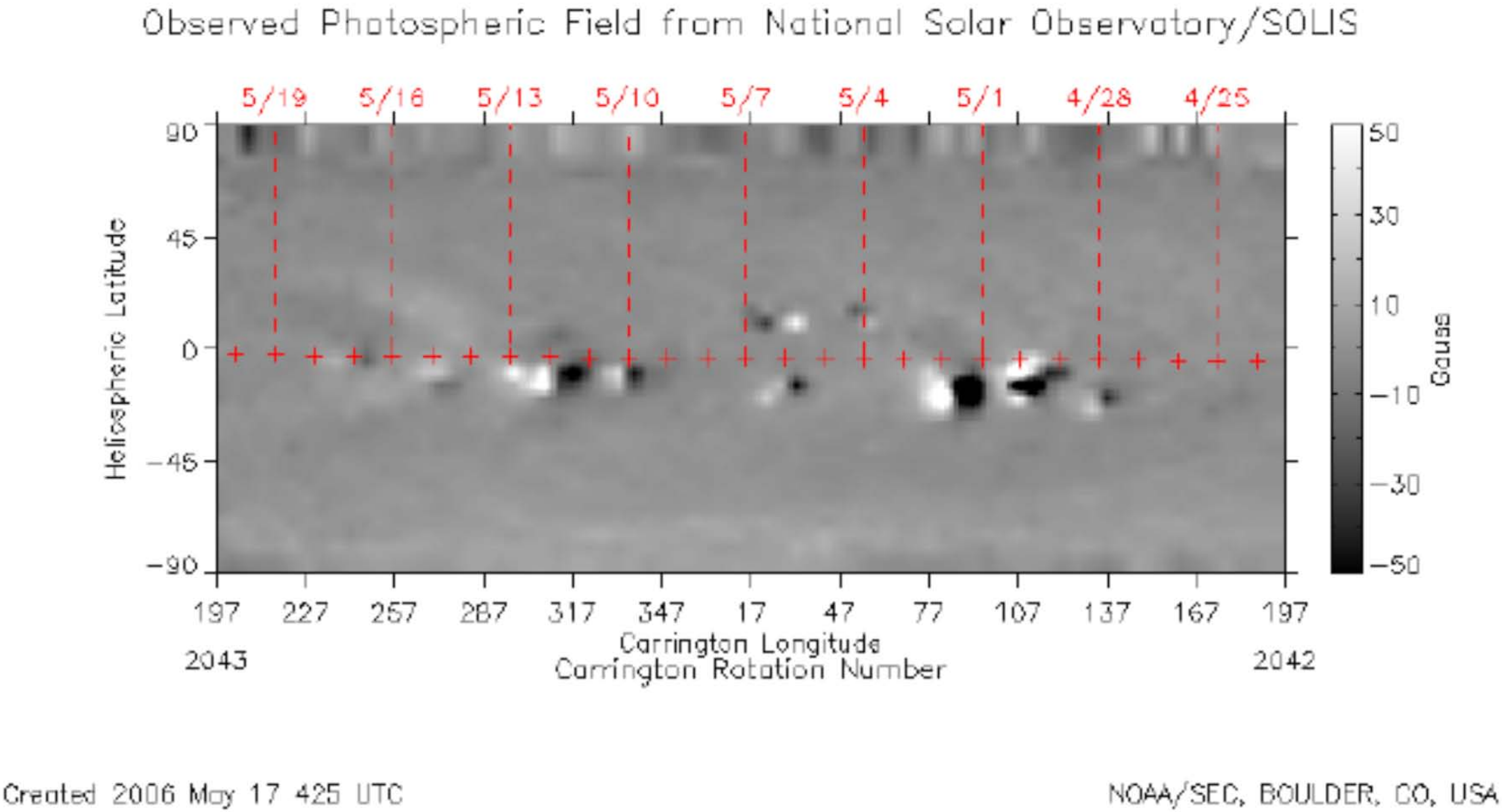
Where the plasma frequency is given by $\omega_p^2 = \frac{4\pi\alpha n_e}{m_e}$ ← number density of electrons in plasma

Resonant mixing:-

$$\omega_p^2 = \frac{4\pi\alpha n_e}{m_e} = m_a^2 \rightarrow n_e \sim 10^{14}\text{cm}^{-3}$$

Happens almost exactly at the surface of the sun.

The Magnetic field at the solar surface (yesterday)



$$l_{osc} = \frac{M}{B} \sim 10^6\text{km} \rightarrow P_{a\rightarrow\gamma} \sim 10^{-4}$$

So we may expect some anomalous events from the sun…

Cosmic Rays: QCD vs. PVLAS Axion

See Gorbunov, Raffelt and Semikoz (2001)

QCD axion

$$M \geq 10^{10}\,\mathrm{GeV}$$

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

PVLAS axion

$$M = 10^{6}\,\mathrm{GeV}$$

$$m = 10^{-3}\,\mathrm{eV}$$

Magnetic field required for maximal mixing for a high energy cosmic ray $(\omega = 10^{19}\,\mathrm{eV})$

$$B_{maxmix} \geq 10^{-4}\,\mathrm{G}$$

$$B_{maxmix} = 10^{-8}\,\mathrm{G}$$

Cosmic Rays: QCD vs. PVLAS Axion

QCD axion	PVLAS axion

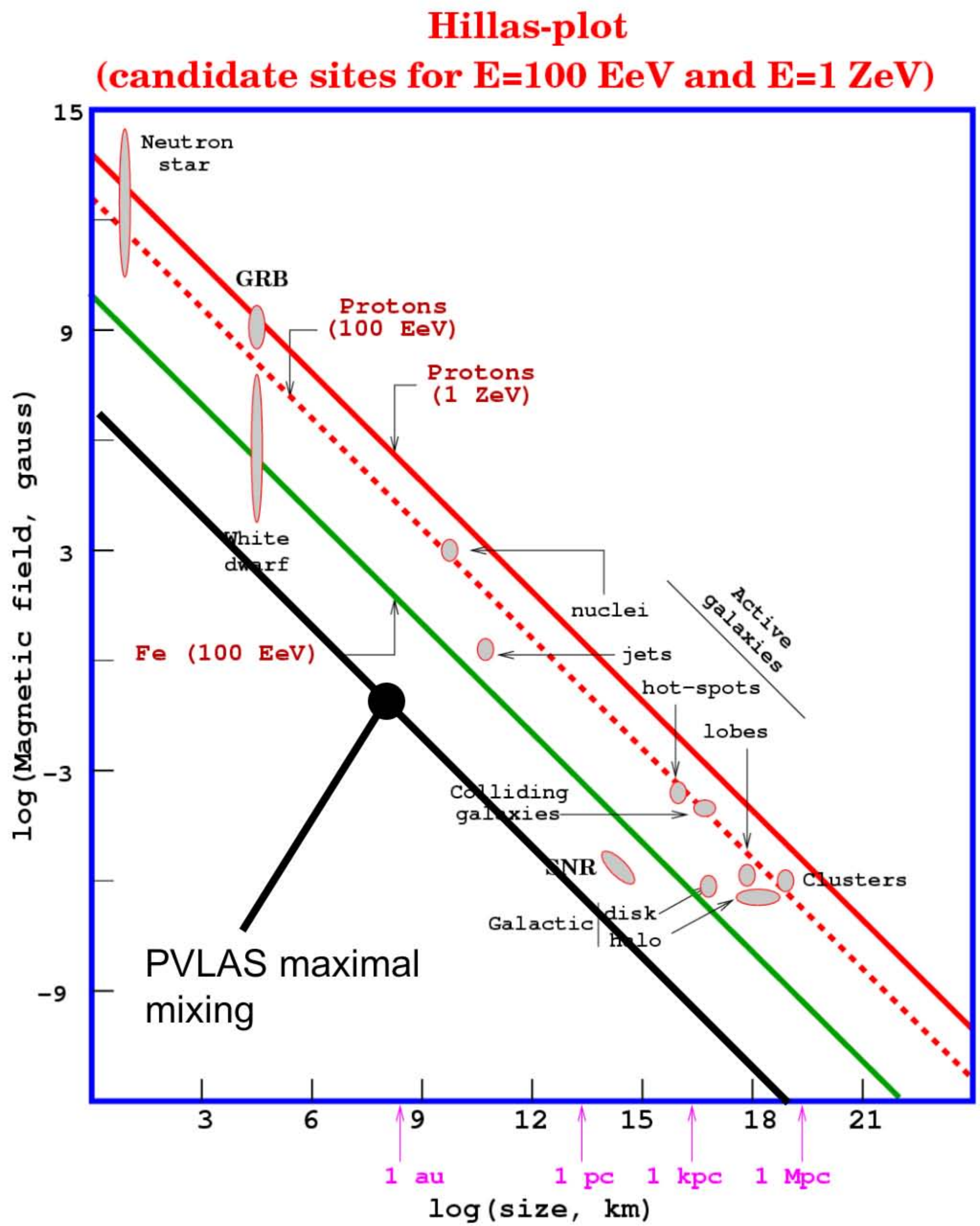
Mixing length in cluster/galaxy $(\omega = 10^{19}\mathrm{eV}, B = 10^{-6}G)$

$l_{osc} \geq 1\mathrm{kpc}$	$l_{osc} \sim 10\mathrm{pc}$

Photon energy required for maximal mixing in cluster/galaxy

$(B = 10^{-6}G)$

$\omega_{maxmix} \geq 10^{21}\mathrm{eV}$	$\omega_{maxmix} \sim 10^{17}eV$



maximal mixing:-

$$\omega \geq \frac{m^2 M}{B}$$

oscillation length when $\sin^2\theta$ maximal

$$l_{osc} = \frac{M}{B}$$

(Hillas plot by Alexander Kappes)

Conclusions

- PVLAS results predict rather strongly coupled axion
- Incompatibility with stellar axion production needs to be understood
- If particle exists, there may be interesting implications for cosmic ray physics