

New Physics below the Standard Model? – puzzles from the PVLAS experiment –

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Outline

1 The Quantum Vacuum

- A view on the quantum vacuum
- From QED to nonlinear ED

2 The PVLAS Experiment

- Experimental Setup & Results
- Standard(-Model) Explanations?
- ALP model

3 Implications of PVLAS.

- ALP bounds
- Options
- Future

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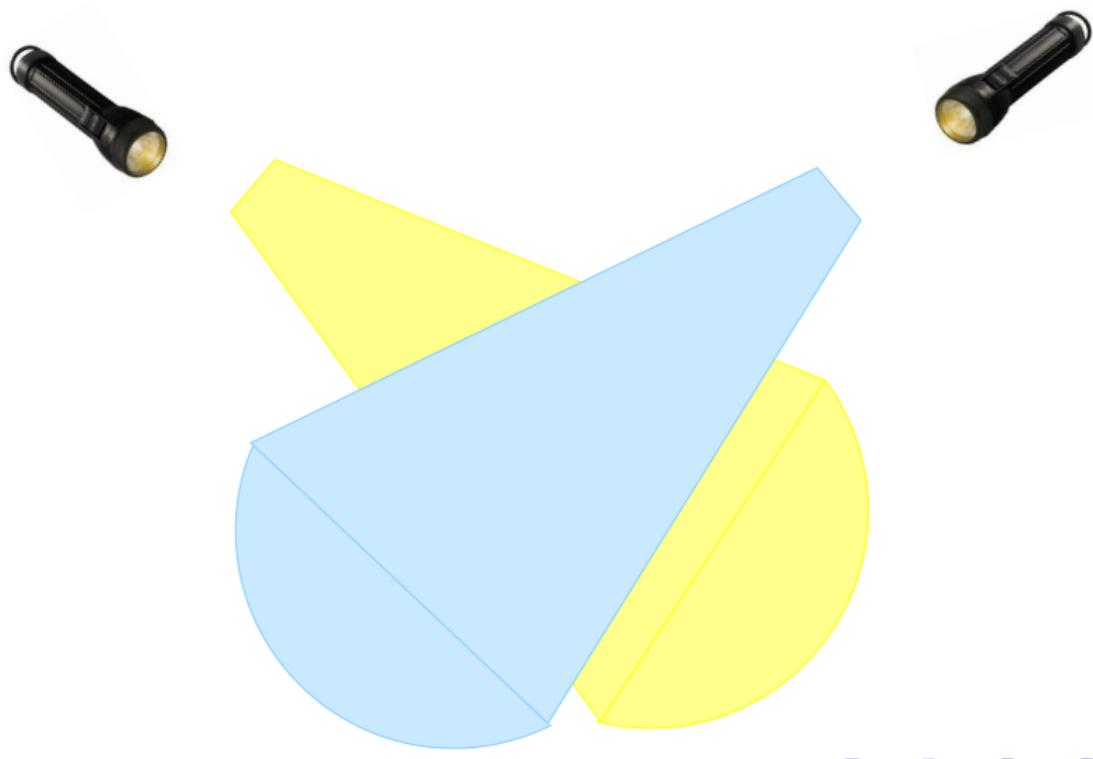
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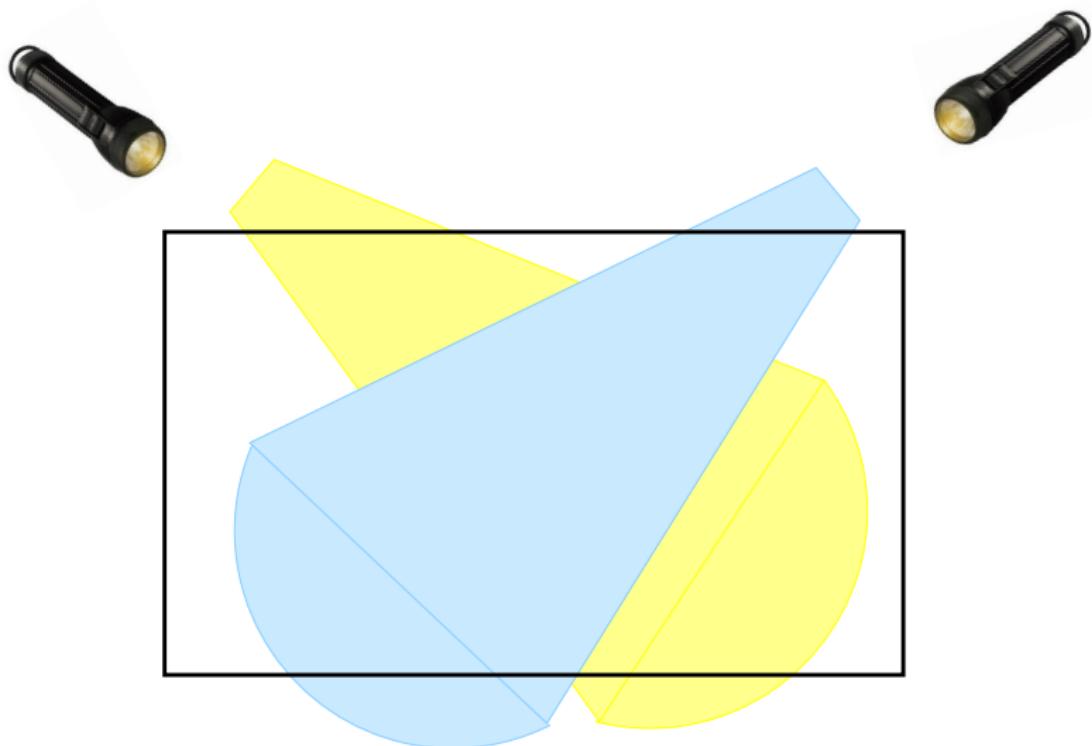
A view on the quantum vacuum.



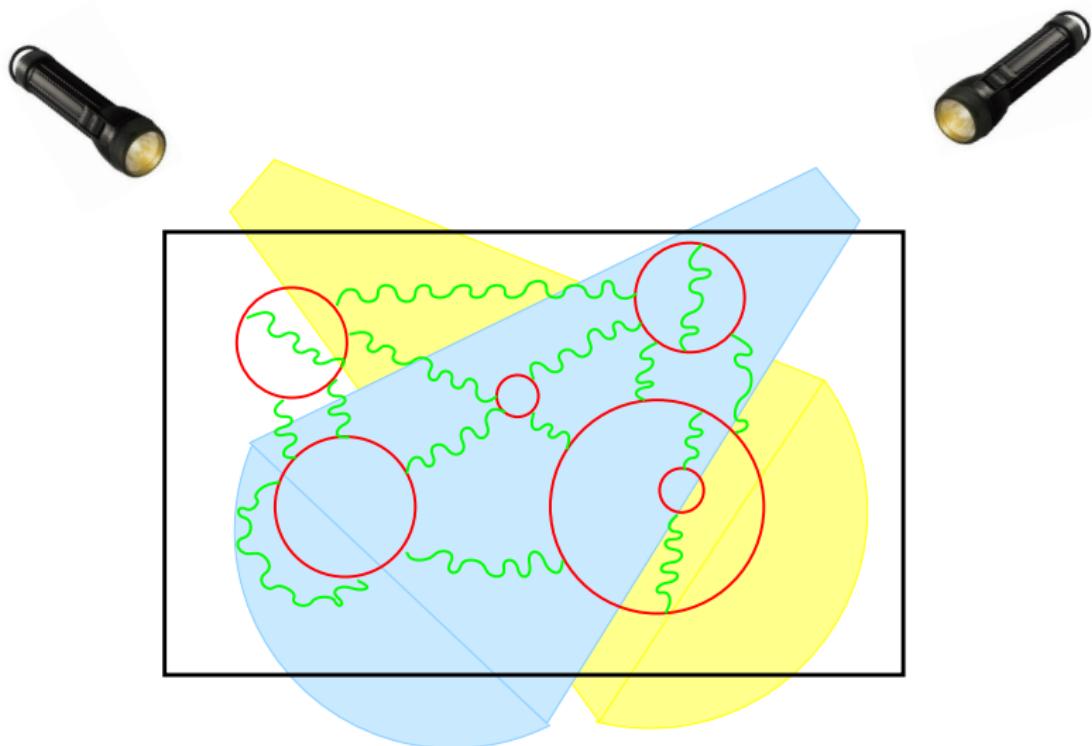
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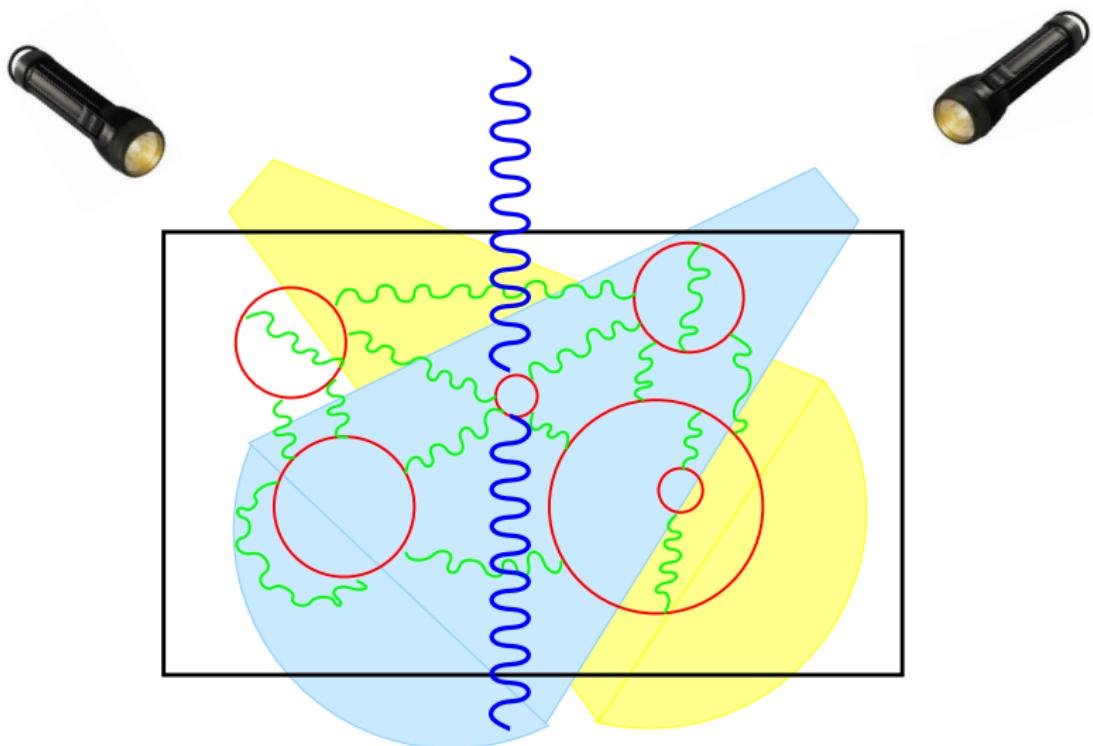
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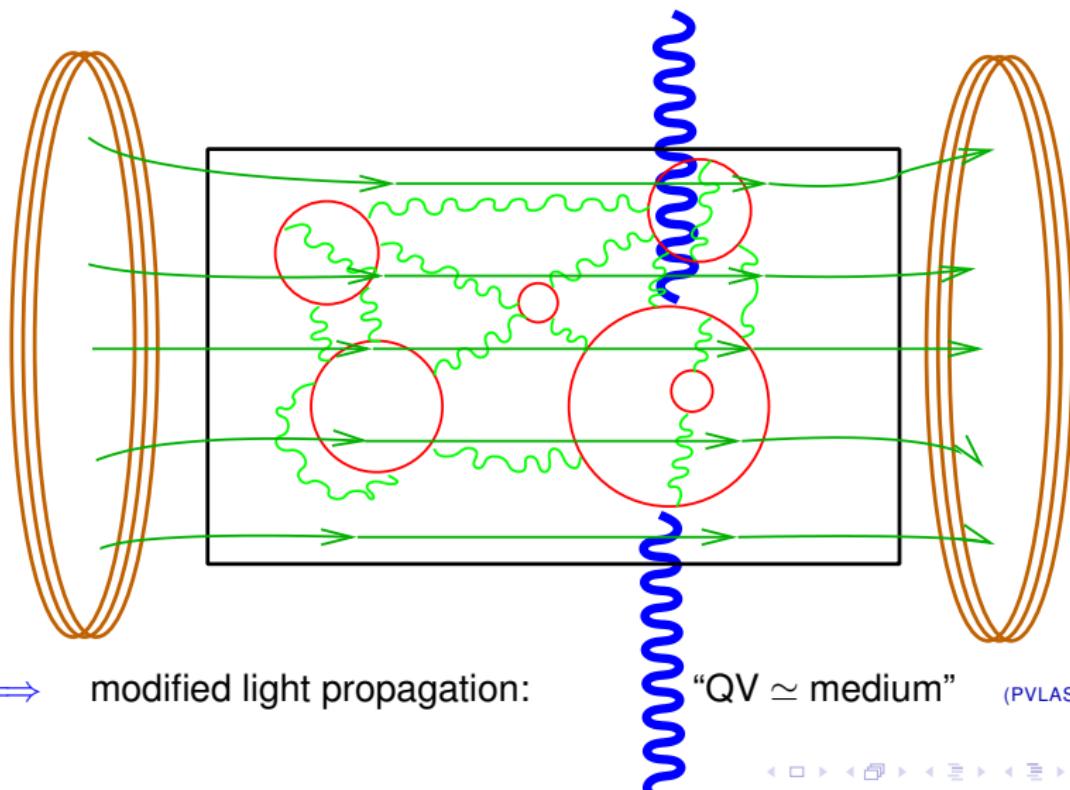
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From QED to nonlinear ED.

Observation: the electron is **very “heavy”**

- $m \simeq 511 \text{ keV} \simeq 9 \cdot 10^{-31} \text{ kg}$
- $m \simeq 7.6 \cdot 10^{11} \text{ GHz} \simeq 6 \cdot 10^9 \text{ Kelvin}$
- $m^2 \simeq 1.3 \cdot 10^9 \text{ Tesla} \simeq 4 \cdot 10^{17} \text{ Volt/m}$

Critical field strengths:

$$B_{\text{cr}} = \frac{m^2}{e} \simeq 4.3 \cdot 10^9 \text{ Tesla}, \quad E_{\text{cr}} = \frac{m^2}{e} \simeq 1.3 \cdot 10^{18} \text{ Volt/m}$$

From QED to nonlinear ED.

- ▶ mass scale m divides quantum fluctuations in

hard $|p^2| > m^2$

(photons and electrons)

soft $|p^2| < m^2$

(only photons = EM fields)

Physics of the soft fields:

average over \int integrate out hard modes

⇒ Heisenberg-Euler effective action Γ

Heisenberg-Euler effective action.

(EULER, KOCKEL'35; HEISENBERG, EULER'36; WEISSKOPF'36; SCHWINGER'51; RITUS'76)

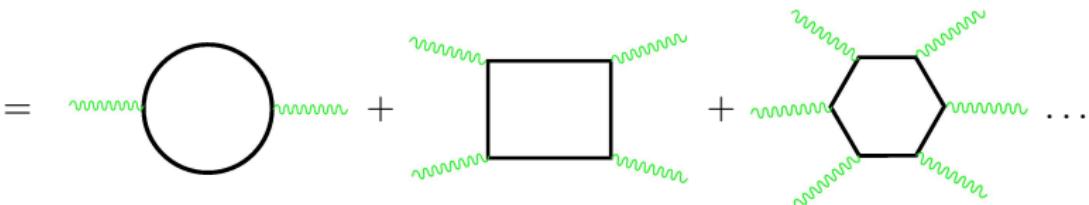
$$\begin{aligned}
 \Gamma &= \text{wavy line} + \text{loop diagram with green wavy lines} + 1\% \text{ loop diagram with blue wavy lines} + \dots \\
 &= - \int \mathcal{F} + \frac{1}{8\pi^2} \int_X \int \frac{ds}{s} e^{-im^2 s} \left[(es)^2 |\mathcal{G}| \cot(es \sqrt{\sqrt{\mathcal{F}^2 + \mathcal{G}^2} + \mathcal{F}}) \right. \\
 &\quad \left. \times \coth(es \sqrt{\sqrt{\mathcal{F}^2 + \mathcal{G}^2} - \mathcal{F}}) \right] \dots
 \end{aligned}$$

Conventions: $\mathcal{F} = \frac{1}{4} F_{\mu\nu} F^{\mu\nu} = \frac{1}{2}(B^2 - E^2)$, $\mathcal{G} = \frac{1}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} = -B \cdot E$

Heisenberg-Euler effective action.

(EULER, KOCKEL'35; HEISENBERG, EULER'36; WEISSKOPF'36; SCHWINGER'51; RITUS'76)

▷ weak-field expansion

$$\Gamma = \int \left\{ -\mathcal{F} + \frac{8}{45} \frac{\alpha^2}{m^4} \mathcal{F}^2 + \frac{14}{45} \frac{\alpha^2}{m^4} \mathcal{G}^2 + \mathcal{O}(\mathcal{F}^6) \right\}$$
$$= \text{circle diagram} + \text{square diagram} + \text{hexagon diagram} \dots$$


Conventions: $\mathcal{F} = \frac{1}{4} F_{\mu\nu} F^{\mu\nu} = \frac{1}{2} (B^2 - E^2)$, $\mathcal{G} = \frac{1}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} = -B \cdot E$

Why is it interesting . . . ?

“ . . . QED is the world’s best-tested theory !?”

(KINOSHITA’96; JENTSCHURA ET AL.’02-05)

- “ . . . exploring some issues of fundamental physics that have eluded man’s probing so far”
(TAJIMA’01)
- QFT: high energy (momentum) vs. high amplitude
- “new physics” discovery potential: hypothetical NG bosons
(axion, majoron, familon, etc.)

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Light Propagation in a B field.

- ▷ quantum Maxwell equation

$$0 = \partial_\mu \left(\mathcal{F}^{\mu\nu} - 2 \frac{8}{45} \frac{\alpha^2}{m^4} \mathcal{F} \mathcal{F}^{\mu\nu} - 2 \frac{14}{45} \frac{\alpha^2}{m^4} \mathcal{G} \tilde{\mathcal{F}}^{\mu\nu} \right)$$

Light Propagation in a B field.

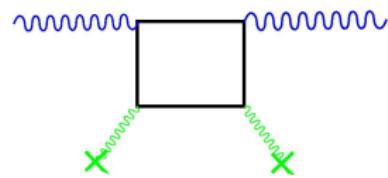
- ▷ quantum Maxwell equation for a “light probe” $f^{\mu\nu}$

$$0 = \partial_\mu f^{\mu\nu} - \frac{8}{45} \frac{\alpha^2}{m^4} F_{\alpha\beta} F^{\mu\nu} \partial_\mu f^{\alpha\beta} - \frac{14}{45} \frac{\alpha^2}{m^4} \tilde{F}_{\alpha\beta} \tilde{F}^{\mu\nu} \partial_\mu f^{\alpha\beta}$$

Phase and group velocity

$$v_{\parallel} \simeq 1 - \frac{14}{45} \frac{\alpha^2}{m^4} B^2 \sin^2 \theta_B$$

$$v_{\perp} \simeq 1 - \frac{8}{45} \frac{\alpha^2}{m^4} B^2 \sin^2 \theta_B$$



(TOLL'54)

(BAIER, BREITENLOHNER'67; NAROZHIY'69)

(BIALYNICKA-BIRULA, BIALYNICKI-BIRULA'70)

⇒ magnetized quantum vacuum induces birefringence

Light Propagation in a B field.

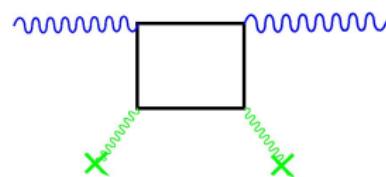
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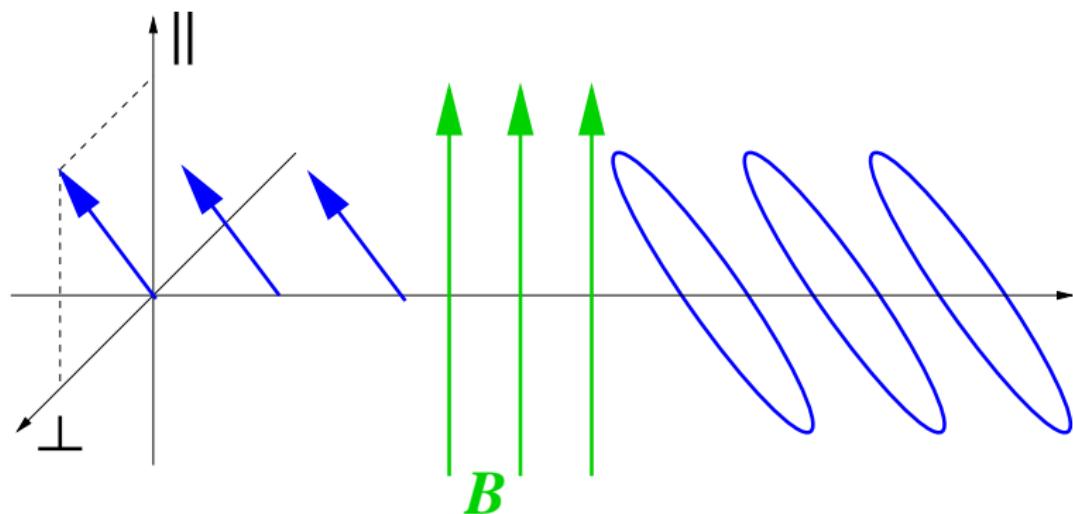
(BIALYNICKA-BIRULA, BIALYNICKI-BIRULA'70)

⇒ magnetized quantum vacuum induces birefringence

- ▷ detection schemes: (PVLAS, BMV, Q&A, HEINZL ET AL.'06, DiPIAZZA, HATSAGORTSYAN, KEITEL'06)

Light Propagation in a B field.

- ▷ observable: birefringence induces ellipticity

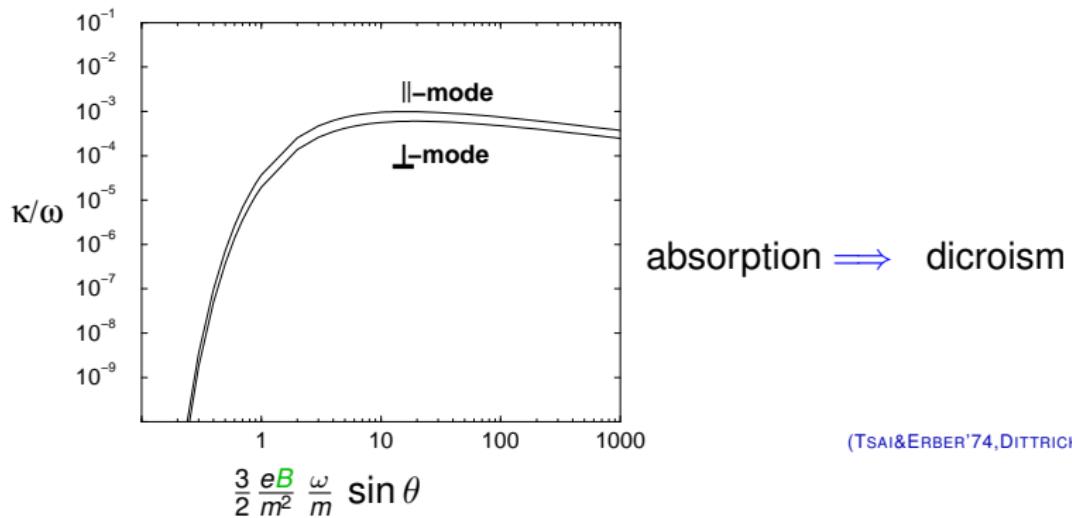


$$\text{ellipticity phase shift: } \Delta\phi = 2\pi \frac{L}{\lambda} \Delta v, \quad \Delta v(5.5\text{T}) \simeq 10^{-22}$$

Light Propagation in a B field.

- absorption: in QED only above threshold $\omega > 2m$

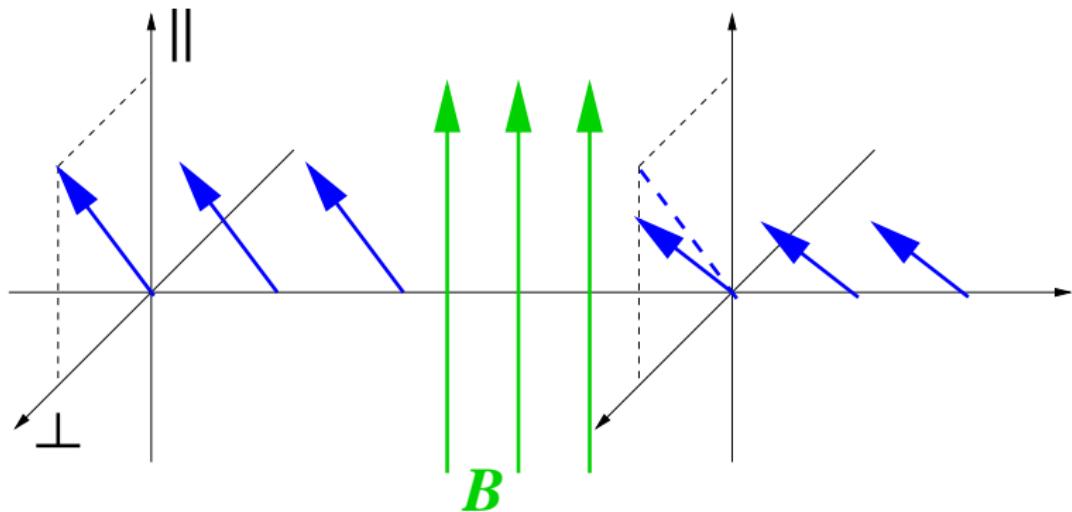
$$\kappa_{\parallel,\perp} = -\frac{1}{\omega} \operatorname{Im} \Pi_{\parallel,\perp}$$



(TSAI&ERBER'74, DITTRICH&HG'00)

Light Propagation in a B field.

- ▷ observable: dichroism induces rotation



rotation: $\epsilon \sim \Delta\kappa L$

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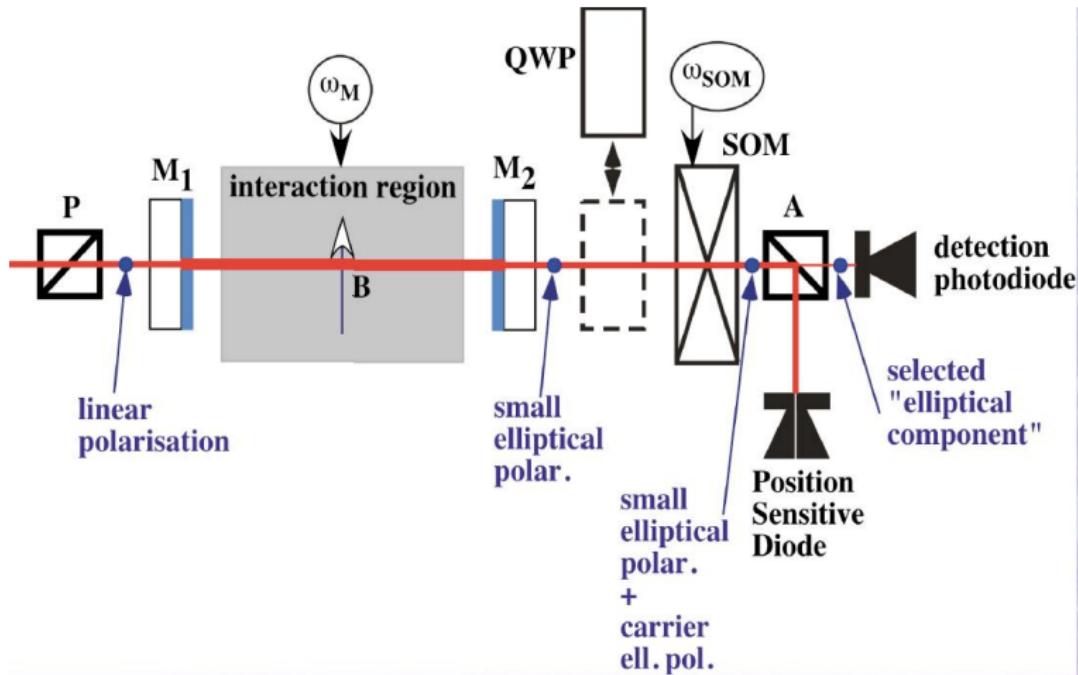
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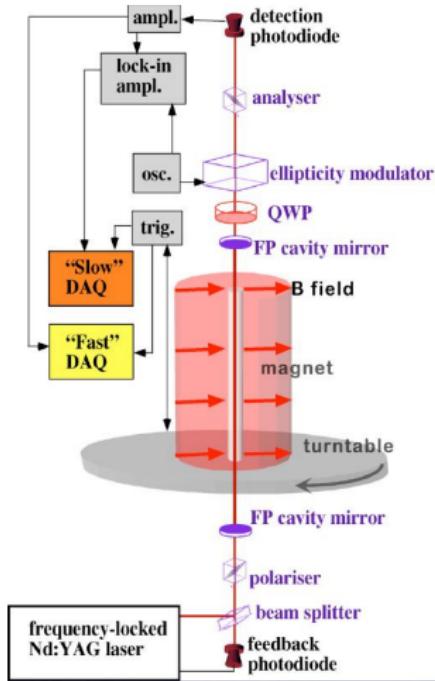
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PVLAS Detection Method.

(BAKALOV ET AL.'94, CANTATORE ET AL.'00, ZAVATTINI ET AL.'05)



PVLAS Design.



- magnet: 6T, 4.2K, 1m
- magnet rotation: $\simeq 0.3\text{Hz}$
- laser: $\lambda = 1064\text{nm}$
- cavity: high-finesse ($N \sim 10^5$)
Fabry-Perot, $\Rightarrow L \simeq 60\text{km}$

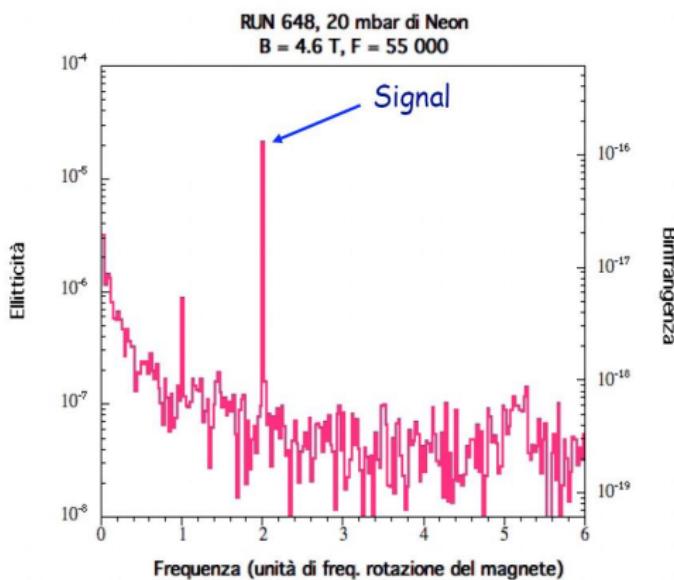
PVLAS @ LNL.



PVLAS Calibration.

- ▷ Cotton-Mouton effect with residual gas ("classical physics")
- ▷ Fourier analysis of signal
- ▷ physical signal at

$$\omega_{\text{signal}} = 2\omega_{\text{Magnet}}$$



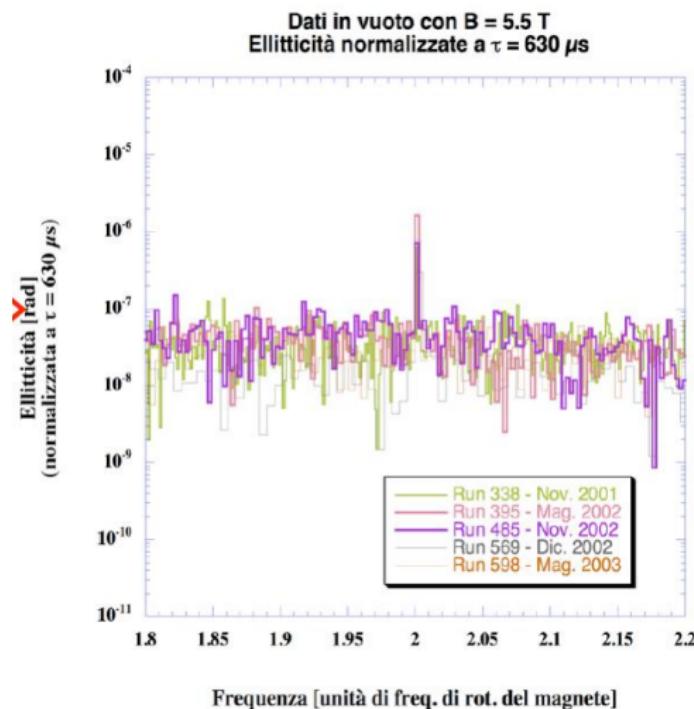
Vacuum Birefringence?

▷ observed signal

$$\Delta v_{\text{exp}} = 3.4 \cdot 10^{-18}$$

at $B = 5.5\text{T}$

$$\Rightarrow \frac{\Delta v_{\text{exp}}}{\Delta v_{\text{QED}}} \simeq 2.8 \cdot 10^4$$



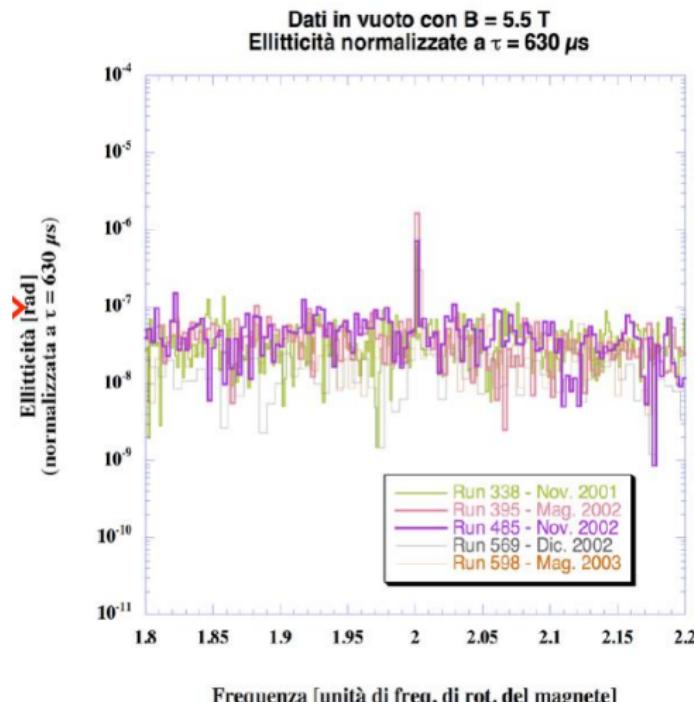
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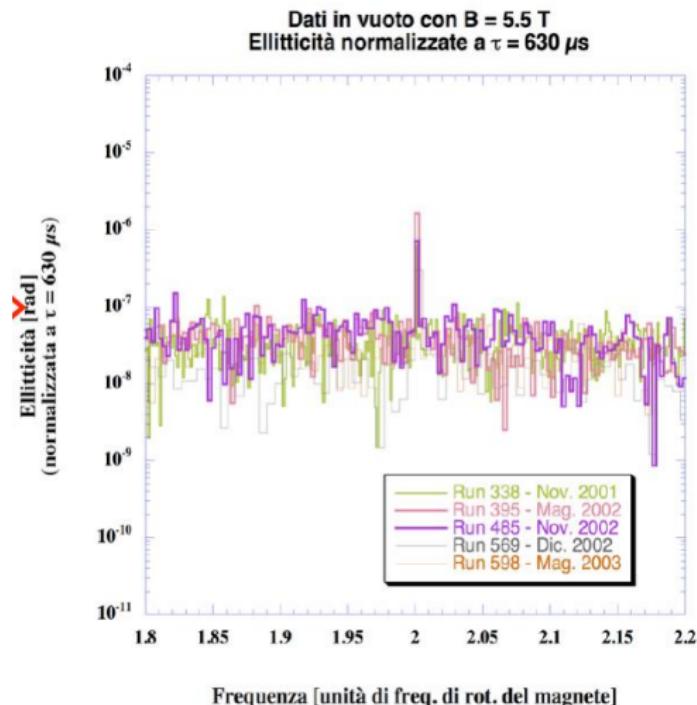
$$\xrightarrow{\quad} \frac{\Delta v_{\text{exp}}}{\Delta v_{\text{QED}}} \simeq 2.8 \cdot 10^4$$



Vacuum Birefringence?

BUT:

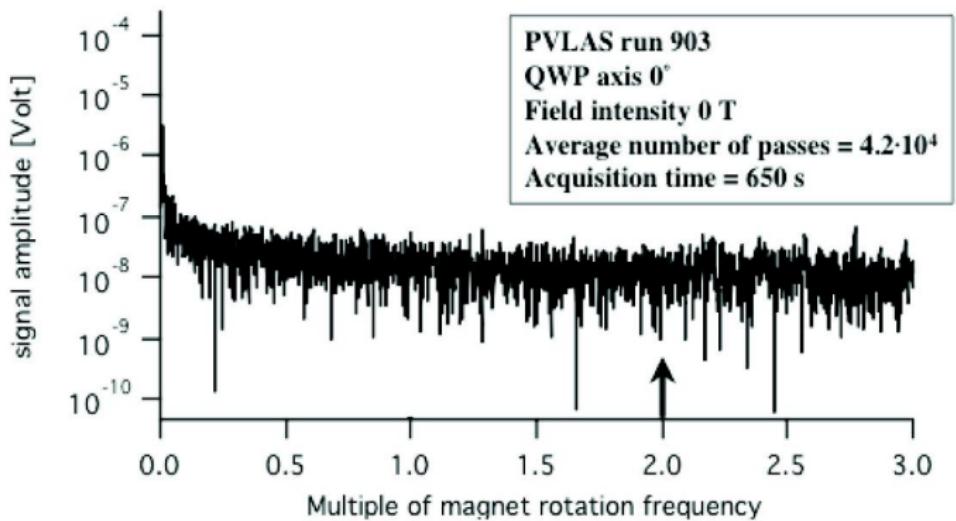
- almost everything is birefringent
- variable birefringence from small beam movements



(CANTATORE@IDM2004)

Vacuum Rotation.

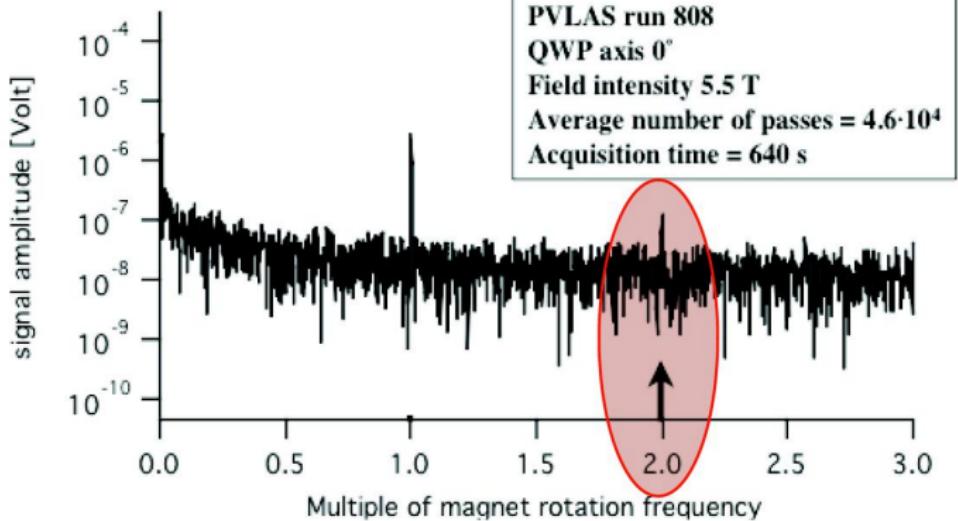
$B = 0\text{ T}$



(CANTATORE@CERN-AXION-TRAINING2005)

Vacuum Rotation.

$B = 5.5\text{ T}$

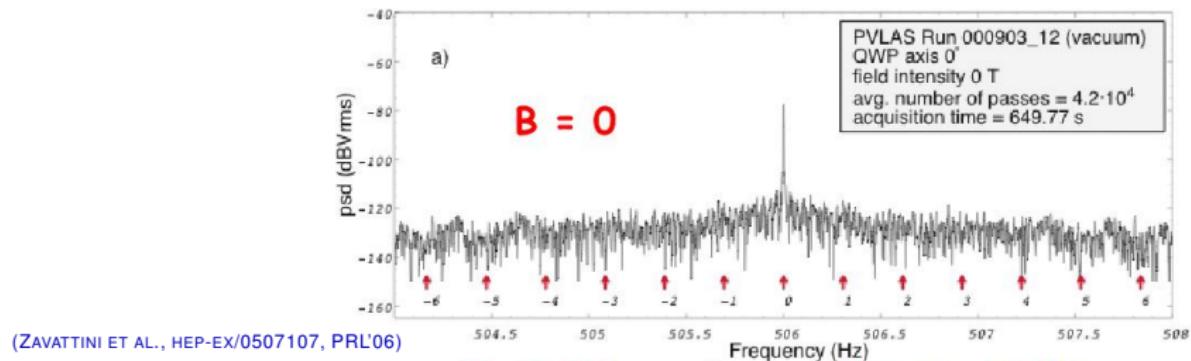


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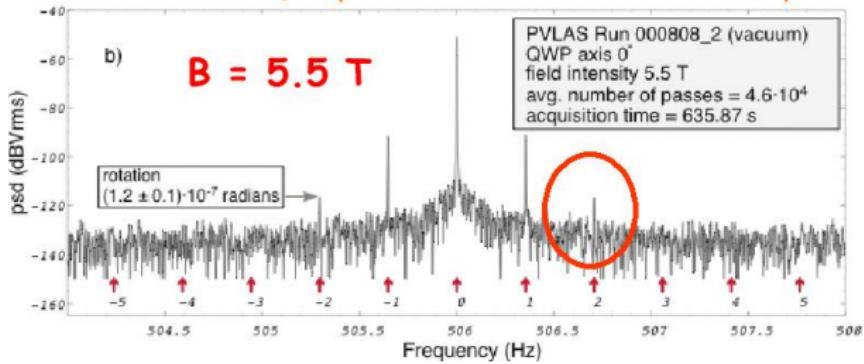
observed rotation $\sim 2.0 \pm 0.3 \cdot 10^{-7} \text{ rad}$

(ZAVATTINI ET AL., HEP-EX/0507107, PRL'06)

Vacuum Rotation.



"Fast" DAQ - spectra around 506 Hz = SOM freq.



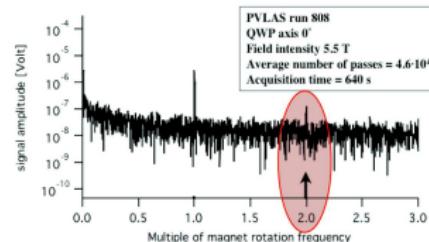
Vacuum Rotation.

► experimental facts:

- observed rotation $\sim 2.0 \pm 0.3 \cdot 10^{-7}$ rad
- selective absorption of photons with

$$\mathbf{e} \parallel \mathbf{B}$$

- SNR $\sim 5\text{-}10$ within seconds



(ZAVATTINI ET AL., HEP-EX/0507107, PRL'06)

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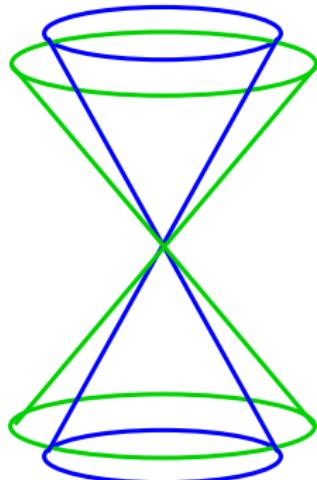
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Modified Light Propagation?

Light cone condition, polarization sum rule

$$k^2 = Q \langle T^{\mu\nu} \rangle k_\mu k_\nu$$



$$Q = \frac{22}{45} \frac{\alpha^2}{m^4}$$

$$\langle T^{00} \rangle_{\text{EM}} = \frac{1}{2} (\mathcal{E}^2 + \mathcal{B}^2)$$

$$\langle T^{00} \rangle_{\text{heat bath}} = \frac{\pi^2}{15} \mathcal{T}^4$$

$$\langle T^{00} \rangle_{\text{Casimir}} = -\frac{\pi^2}{720} \frac{1}{a^4}$$

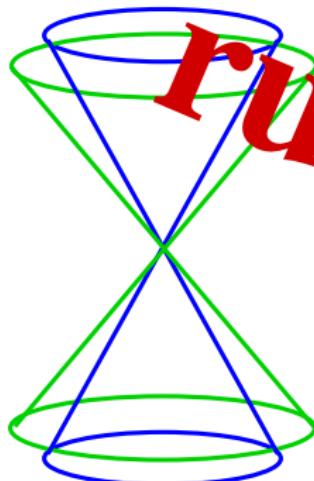
⋮

(LATORRE, PASCUAL, TARRACH'95; SHORE'96; DITTRICH, HG'98)

Modified Light Propagation?

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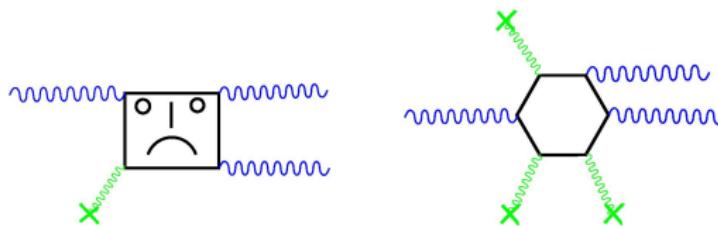
ruled out!

$$Q = \frac{22 \frac{\alpha^2}{\pi}}{45 m} \langle T^{\mu\nu} \rangle_{\text{Casimir}}$$
$$\langle T^{00} \rangle_{\text{EM}} = \frac{1}{2} (E^2 + B^2)$$
$$\langle T^{00} \rangle_{\text{heat bath}} = \frac{\pi^2}{15} T^4$$
$$\langle T^{00} \rangle_{\text{Casimir}} = -\frac{\pi^2}{720} \frac{1}{a^4}$$
$$\vdots$$

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Photon Splitting?

(ADLER'71)

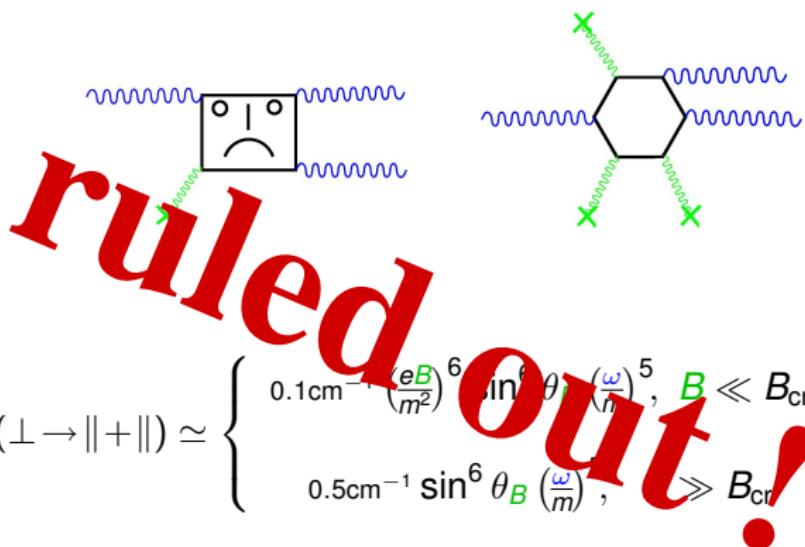


$$\kappa(\perp \rightarrow \parallel + \parallel) \simeq \begin{cases} 0.1 \text{cm}^{-1} \left(\frac{eB}{m^2} \right)^6 \sin^6 \theta_B \left(\frac{\omega}{m} \right)^5, & B \ll B_{\text{cr}} \\ 0.5 \text{cm}^{-1} \sin^6 \theta_B \left(\frac{\omega}{m} \right)^5, & B \gg B_{\text{cr}} \end{cases}$$

- ▷ PVLAS mean free path $1/\kappa \sim \simeq 3 \cdot 10^{57} \times \text{SoU}$

Photon Splitting?

(ADLER'71)

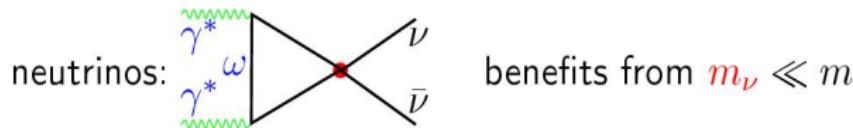
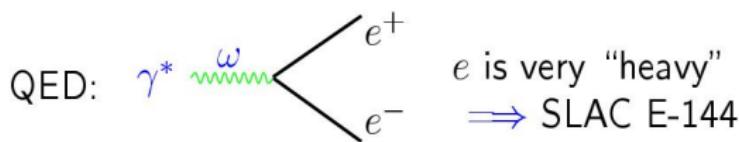
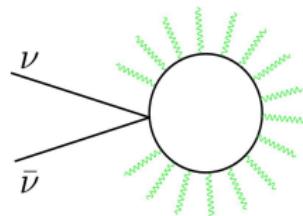


- ▷ PVLAS mean free path $1/\kappa \sim \simeq 3 \cdot 10^{57} \times \text{SoU}$

Neutrino Production?

- ▷ effective photon-neutrino interactions
- ▷ $\nu\bar{\nu}$ pair emission in EM fields:

(HG&SHAI SULTANOV'00)

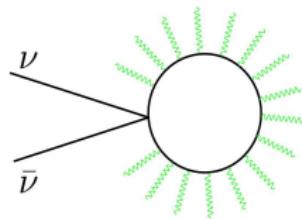


$$\#\nu\bar{\nu} \doteq 5.11 \left(\frac{m_\nu}{1\text{eV}}\right)^2 \left(\frac{\omega_0}{1\text{eV}}\right)^2 \frac{(\mathbf{E}_0 \cdot \mathbf{B}_0)^2}{B_{\text{cr}}^4} \left(1 - \frac{m_\nu^2}{\omega_0^2}\right)^{1/2} \theta(\omega_0 - m_\nu) \text{cm}^3\text{s}$$

Neutrino Production?

- ▷ effective photon-neutrino interactions
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(HG&SHAI SULTANOV'00)



ruled out!

neutrinos: γ^*, ω

e^+ e^-

e is very "heavy"
 \Rightarrow SLAC E-144

benefits from $m_\nu \ll m$

$$\#\nu\bar{\nu} \doteq 5.11 \left(\frac{m_\nu}{1\text{eV}}\right)^2 \left(\frac{\omega_0}{1\text{eV}}\right)^2 \frac{(\mathbf{E}_0 \cdot \mathbf{B}_0)^2}{B_{\text{cr}}^4} \left(1 - \frac{m_\nu^2}{\omega_0^2}\right)^{1/2} \theta(\omega_0 - m_\nu) \text{cm}^3\text{s}$$

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ALP model.

▷ selective absorption of photons with $e \parallel B$

⇒ effective interaction:

$$\mathcal{L}_{\text{ALP}} = \text{something} \times \mathbf{E} \cdot \mathbf{B}$$

ALP model.

▷ selective absorption of photons with $\mathbf{e} \parallel \mathbf{B}$

⇒ effective interaction:

$$\mathcal{L}_{\text{ALP}} = g \phi \mathbf{E} \cdot \mathbf{B} = -\frac{1}{4} g \phi F_{\mu\nu} \tilde{F}^{\mu\nu}$$

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$$\mathcal{L}_{\text{ALP}} = g \phi \mathbf{E} \cdot \mathbf{B} - \frac{1}{2} (\partial_\mu \phi)^2 - \frac{1}{2} m_\phi^2 \phi^2$$

⇒ 2 parameters: $m_\phi, g \equiv \frac{1}{M}$

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- pseudoscalar particle ϕ
- weakly coupled to matter
- can be light

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~ NG boson of “axial” SB?

- pseudoscalar particle ϕ
- weakly coupled to matter
- can be light

natural candidate: Axion

⇒ (breaking of $U(1)_{\text{PQ}}$, “strong-CP problem”, QCD axion: $g \sim \frac{1}{M}$)

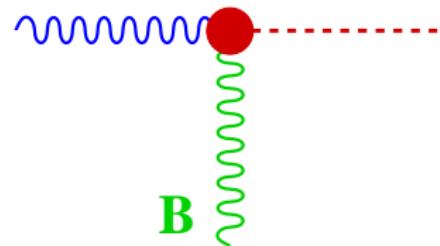
Axion-Like-Particle (RINGWALD'06)

ALP effects.

(MAIANI, PETRONZIO, ZAVATTINI'86; RAFFELT, STODOLSKY'88)

- ▷ dicroism / rotation:

$$\epsilon = -N \left(\frac{B L}{4M} \right)^2 \left[\frac{\sin \left(\frac{m_\phi^2 L}{4\omega} \right)}{\left(\frac{m_\phi^2 L}{4\omega} \right)} \right]^2$$

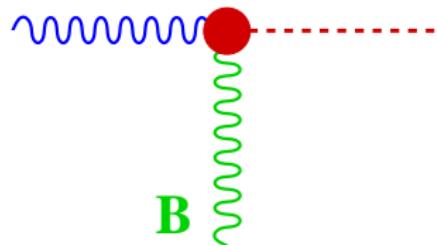


ALP effects.

(MAIANI, PETRONZIO, ZAVATTINI'86; RAFFELT, STODOLSKY'88)

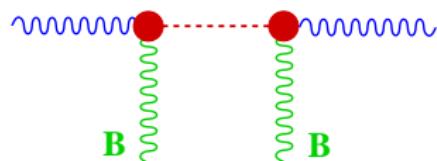
- ▷ dicroism / rotation:

$$\epsilon = -N \left(\frac{BL}{4M} \right)^2 \left[\frac{\sin \left(\frac{m_\phi^2 L}{4\omega} \right)}{\left(\frac{m_\phi^2 L}{4\omega} \right)} \right]^2$$



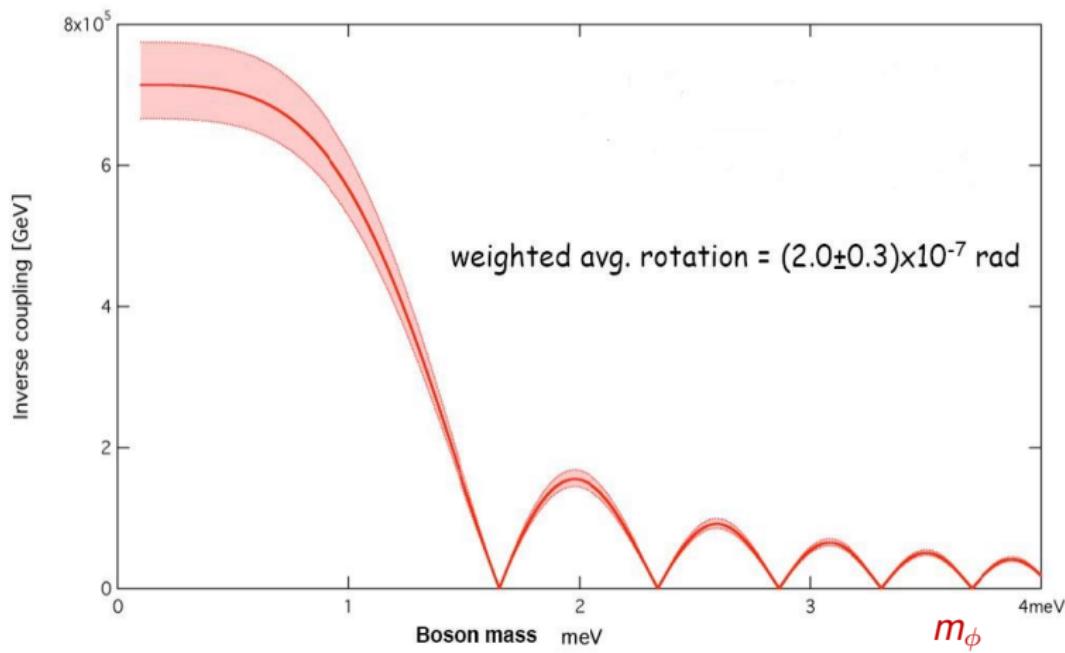
- ▷ birefringence / ellipticity:

$$\Delta\phi = -N \frac{B^2 \omega L}{2M^2 m_\phi^2} \left[1 - \frac{\sin \left(\frac{m_\phi^2 L}{4\omega} \right)}{\left(\frac{m_\phi^2 L}{4\omega} \right)} \right]$$



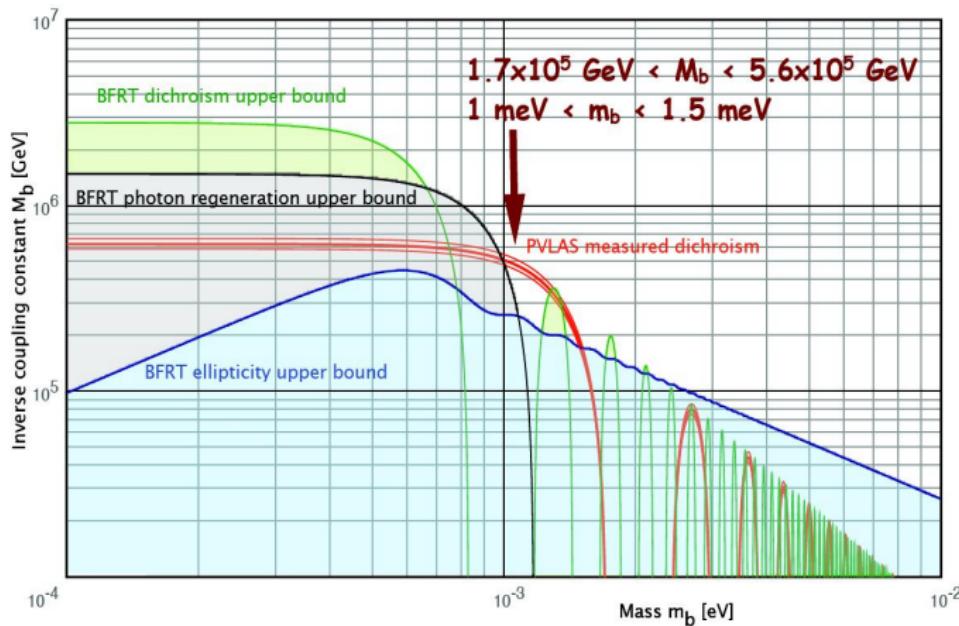
PVLAS Rotation from ALP?

M



PVLAS Rotation from ALP?

M



(BFRT: BROOKHAVEN, FERMILAB, ROCHESTER, TRIESTE; CAMERON ET AL '93)

m_ϕ

“Physical Test” of ALP signal.

▷ dicroism / rotation :

$$\epsilon = -N \left(\frac{BL}{4M} \right)^2 \left[\frac{\sin \left(\frac{m_\phi^2 L}{4\omega} \right)}{\left(\frac{m_\phi^2 L}{4\omega} \right)} \right]^2$$

“Physical Test” of ALP signal.

▷ dicroism / rotation with residual gas:

$$\epsilon = -N \left(\frac{B L}{4M} \right)^2 \left[\frac{\sin \left(\frac{(m_\phi^2 - 2\omega^2 \frac{p_{\text{gas}}}{p_{\text{atm}}} (n_{\text{gas}} - 1))L}{4\omega} \right)}{\left(\frac{(m_\phi^2 - 2\omega^2 \frac{p_{\text{gas}}}{p_{\text{atm}}} (n_{\text{gas}} - 1))L}{4\omega} \right)} \right]^2$$

"Physical Test" of ALP signal.

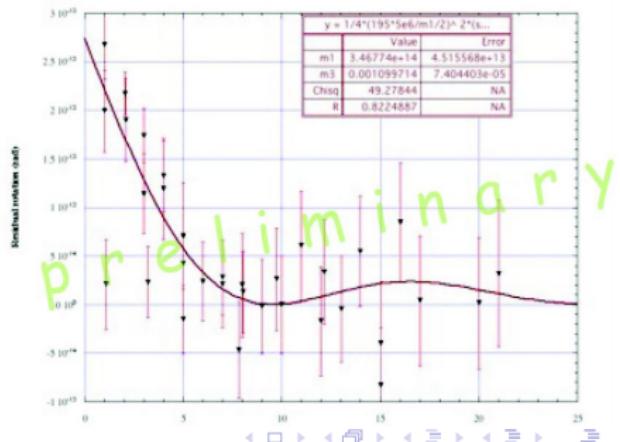
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$$m_\phi = 1.0 \pm 0.1 \text{ meV}$$

$$M = 3.8 \pm 0.35 \cdot 10^5 \text{ GeV}$$

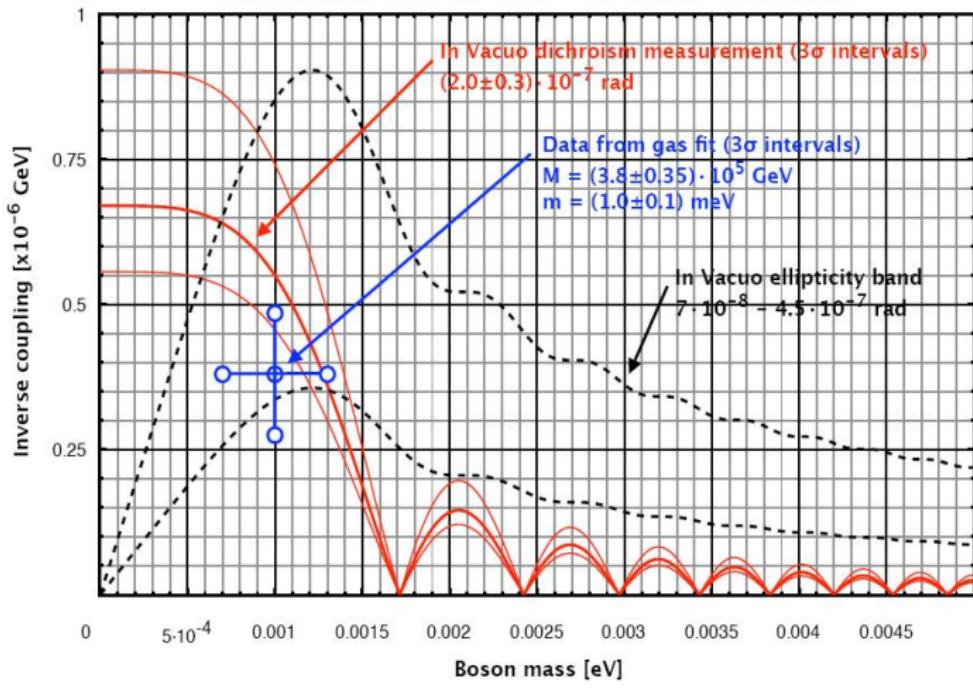
(CANTATORE@CERN-AXION-TRAINING2005)



"Physical Test" of ALP signal.

M

Summary plot @ 1064 nm, with $B = 5.5$ T and $N \sim 50000$ passes



Outline

1 The Quantum Vacuum

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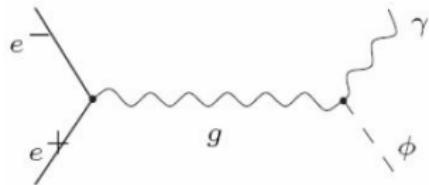
3 Implications of PVLAS.

- **ALP bounds**
- Options
- Future

Collider Bounds.

- ▷ scattering process

$$\mathcal{L}_{\text{int}} = -\frac{\textcolor{red}{g}}{4} \phi F_{\mu\nu} \tilde{F}^{\mu\nu}$$



(MASSO, TOLDRA'95)

- ▷ signature:

$$e^+ e^- \rightarrow \gamma + \cancel{E}_T, \quad E_\gamma \simeq E_{\text{CM}}/2$$

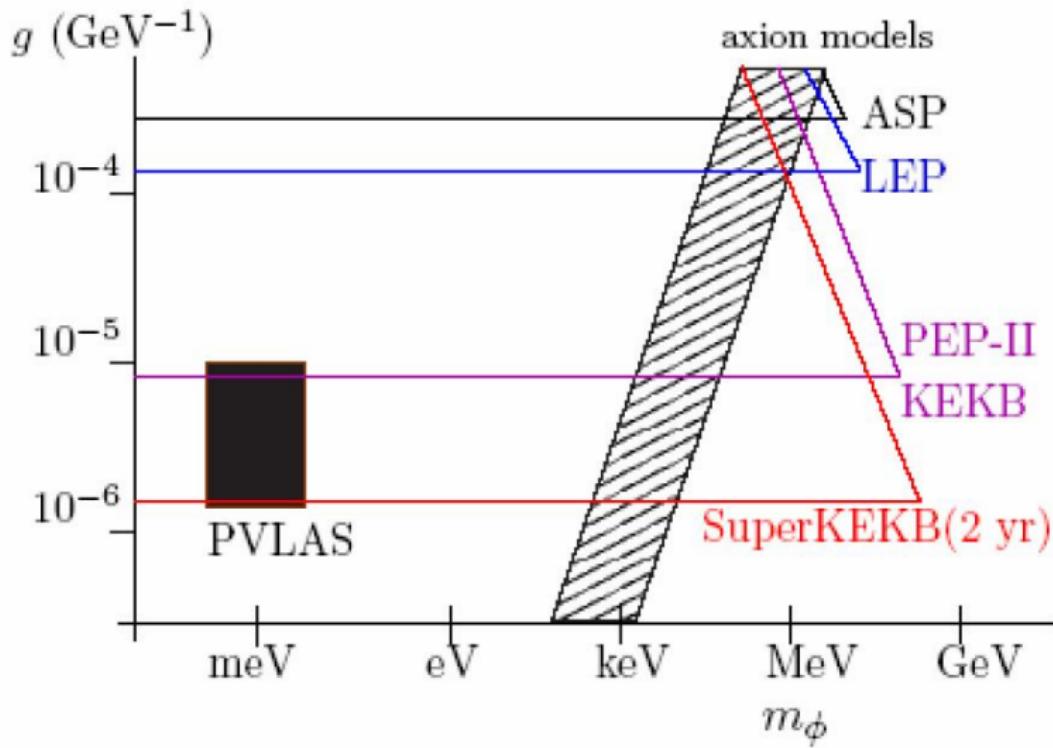
- ▷ cross section

(KLEBAN, RABADAN'05)

$$\sigma_{e\bar{e} \rightarrow \gamma\phi} = \left(\frac{\textcolor{red}{g}}{10^{-5} \text{GeV}^{-1}} \right) \times 1.2 \cdot 10^{-5} \text{ pb}$$

Collider Bounds.

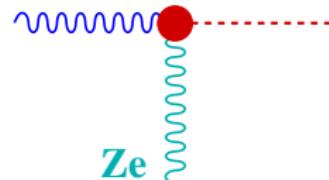
(KLEBAN, RABADAN'05)



Astrophysical Bounds.

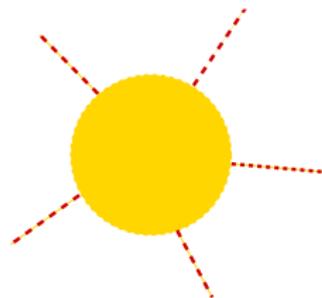
- ▷ Axion production:

Primakov process in stellar plasma



- ▷ Axion emission

weakly interacting particles leave the star



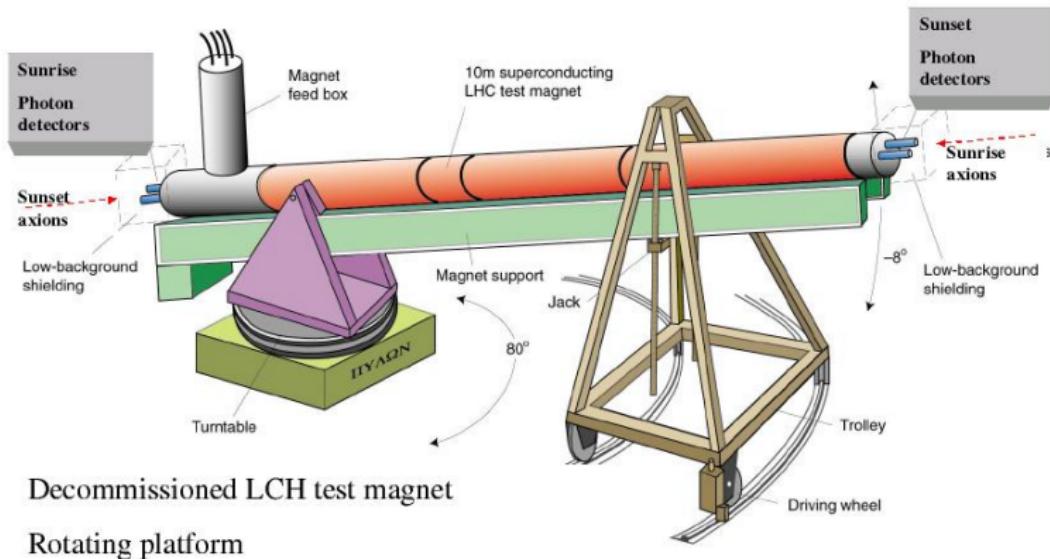
- ▷ Axion luminosity

$$\mathcal{L}_\phi \sim 10^{-3} \left(\frac{\textcolor{red}{g}}{10^{-10} \text{GeV}^{-1}} \right)^2 \mathcal{L}_\gamma \stackrel{\text{PVLAS}}{\simeq} 10^6 \mathcal{L}_\gamma$$

(VAN BIBBER ET AL.'89)

Astrophysical Bounds.

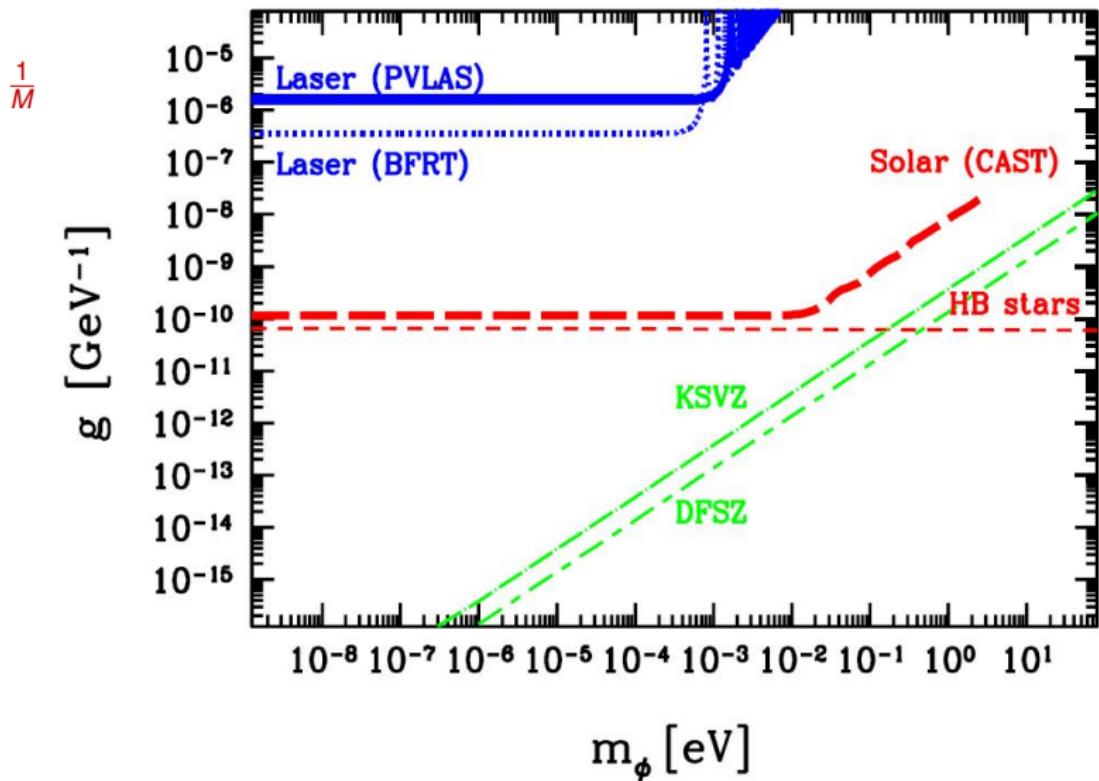
Cern Axion Solar Telescope



Astrophysical Bounds.



Astrophysical Bounds.



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Options.

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Options.

- ▷ PVLAS could be

wrong

Options.

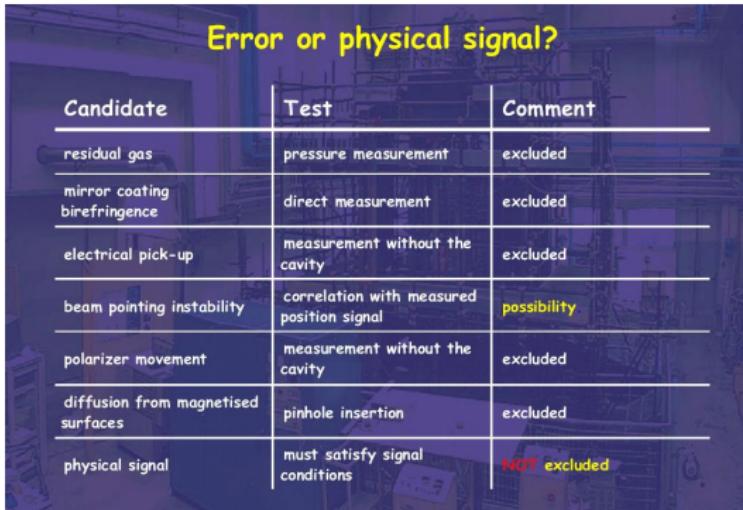


Options.

Error or physical signal?

Candidate	Test	Comment
residual gas	pressure measurement	excluded
mirror coating birefringence	direct measurement	excluded
electrical pick-up	measurement without the cavity	excluded
beam pointing instability	correlation with measured position signal	possibility
polarizer movement	measurement without the cavity	excluded
diffusion from magnetised surfaces	pinhole insertion	excluded
physical signal	must satisfy signal conditions	NOT excluded

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“The possibility that this effect is due to an unknown, albeit very subtle, instrumental artifact has been investigated at length without success.” [\(HEP-EX/0507107\)](#)

Options.

- ▷ PVLAS could be

Options.

► PVLAS could be

right

⇒ “CAST-PVLAS puzzle”

Options.

▷ ALP interpretation could be **wrong**.

(... rotation, ellipticity, res. gas effect ?)

▷ ALP interpretation could be **right**.

(... requires mechanism that avoids fast solar cooling)

- trap ALPs in the sun (MASSO, REDONDO'05; JAIN, MANDAL'05)

(CAVE: solar physics & other astrophysical/collider bounds)

- suppress solar ALP production

(MASSO, REDONDO'05; JÄCKEL, MASSO, REDONDO, RINGWALD, TAKAHASHI'06)

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Options.

▷ PVLAS vs. Sun:

- temperature T
-
- density n
-
- (electro-)magnetic fields E, B
-
- neutrino flux, ...

▷ solar ALP production could be suppressed by

$$m_\phi, g = f(T, n, B, \dots)$$

(JÄCKEL, MASSO, REDONDO, RINGWALD, TAKAHASHI'06)

Options.

- ▷ e.g., temperature suppression:

$$Q_{\text{Sun}}^2 \sim T^2 \sim \text{keV}^2 \quad Q_{\text{PVLAS}}^2 \sim 7 \cdot 10^{-13} \text{eV}^2$$

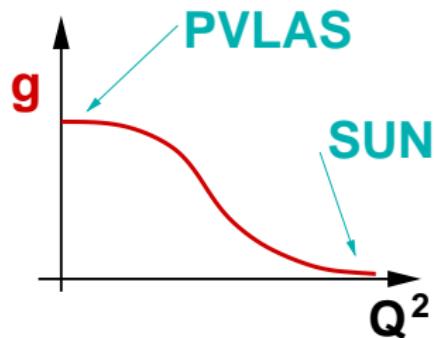
- ▷ assume: ALP is composite (e.g., $\sim \pi^0$ in QCD)

(MASSO,REDONDO'05)

- ▷ CAST-PVLAS puzzle resolved
if $g(Q^2 \gg Q_0^2) \rightarrow 0$ for

$$(8 \cdot 10^{-7} \text{ eV})^2 < Q_0^2 < (0.15 \text{ keV})^2$$

(JÄCKEL,MASSO,REDONDO,RINGWALD,TAKAHASHI'06)



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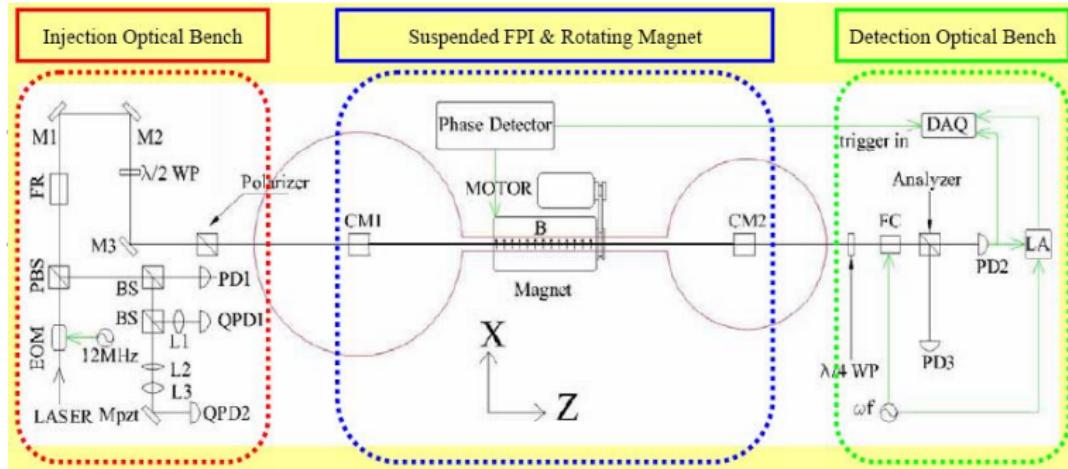
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Future Experiments.

► New laser polarization experiments:

- Q&A (Taiwan)
- BMV (Toulouse)

Future Experiments.



Future Experiments.

► New Experiments

- Gravity wave detector
- Beam splitter

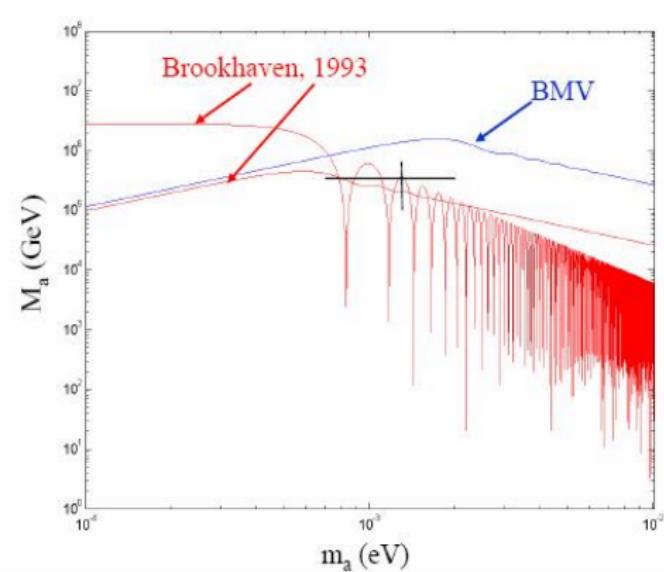


Future Experiments.

► New

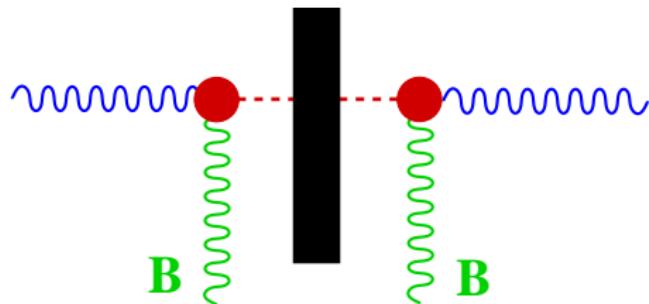
- G
- B

Goal for 2007 :



Future Experiments.

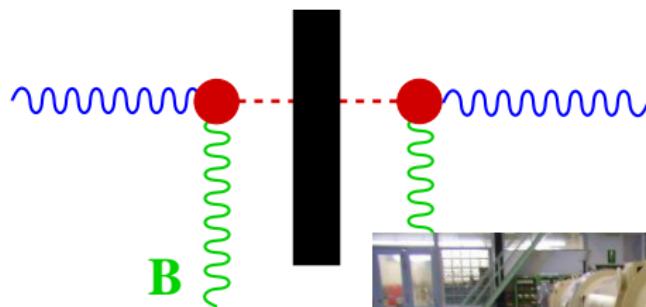
- ▷ “light-shining-through-walls” experiments:



- PVLAS upgrade
- APFEL (DESY) (VUV-FEL at TTF)

Future Experiments.

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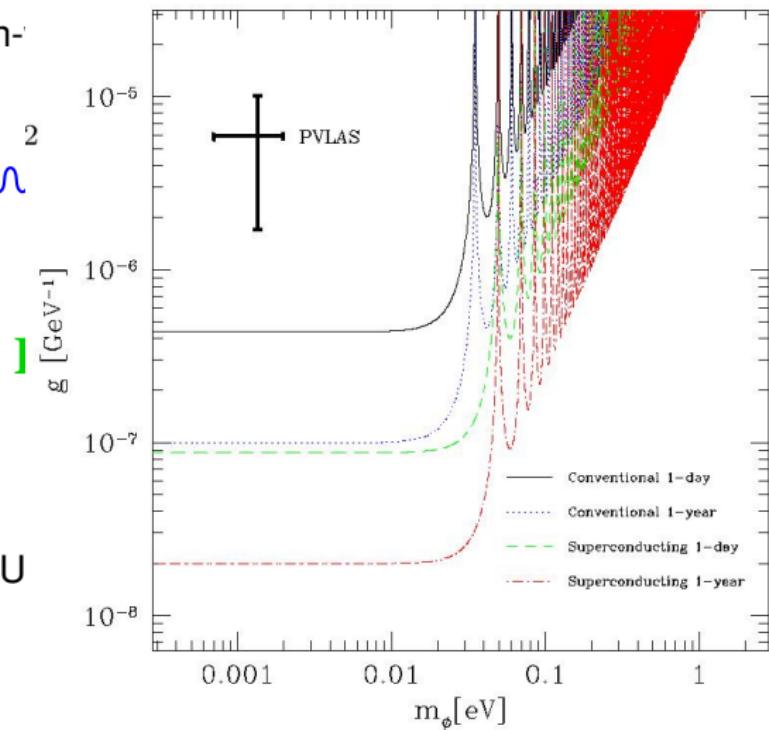


Future Experiments.

▷ “light-shining-through-



- PVLAS upgrade
- APFEL (DESY) (VU)



Conclusion.

Conclusion.

... yet another “Who-ordered-the-muon?” problem ...