θ -term and strong CP problem

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \bar{q}(i\not{D} - M)q$$
$$+ \ \theta \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \cdots$$

θ-term is CP-violating

Physical effects depend on the combination

$\bar{\theta} = \theta + \text{Arg Det } M$

$$d_n \sim \frac{e}{m_n} \bar{\theta} \frac{m_u m_d}{m_u + m_d} \frac{1}{\Lambda_{\text{QCD}}}$$

$d_n < 0.63 \times 10^{-25} \ e \, \text{cm}$ ⇒ $\bar{\theta} < 10^{-9}$

The CP problem:

why $\bar{\theta}$ so small ?

θ_{QCD} ← unrelated

$\text{Arg Det } M$ ←

makes the problem worse !

Peccei-Quinn solution and axions

Peccei, Quinn

Chiral symmetry $U(1)_{PQ}$ allows to rotate $\bar{\theta}$ away

Spontaneous breaking of anomalous global symmetry → Pseudo Goldstone Boson (PGB)

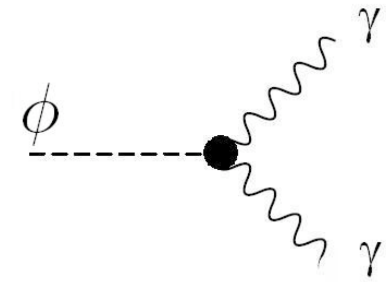
(QCD)- Axion model has large breaking scale f_a

- Interactions are weak $\propto f_a^{-1}$ Invisible axion
- Mass is small $m_a \propto f_a^{-1}$

Experiments looking for axions use coupling to two photons

$$c_\gamma \; \frac{\alpha}{\pi} \; \frac{1}{f_a} \; \epsilon^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta} \; a$$

Light bosons coupled to $\gamma\gamma$



- **Pseudoscalar coupled to $\gamma\gamma$**

$$\mathcal{L}_{\phi\gamma\gamma} = \frac{1}{8}\, g_{\phi\gamma\gamma}\ \phi\ \epsilon^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta}$$

two (independent) properties :

m mass

$g_{\phi\gamma\gamma} \equiv \frac{1}{M}$ coupling (notice dimensions)

- **Scalar coupled to $\gamma\gamma$**

$$\mathcal{L}_{\phi\gamma\gamma} = \frac{1}{8}\, g'_{\phi\gamma\gamma}\ \phi\ F_{\mu\nu} F^{\mu\nu}$$

- Similar except for $\mathrm{PS} \rightarrow \vec{E}\vec{B}$, $\mathrm{S} \rightarrow |E|^2 - |B|^2$

Call them AXION-LIKE PARTICLES (ALPs)

Light bosons coupled to $\gamma\gamma$

- (Current) axion experiments sensitive to $\gamma\gamma$ coupling

  Any light ALP could give a signal

- Other GB or PGB

  Family, Lepton num. sym. ⇒ familons, majorons

  MetaSM theories ⇒ $0^-, \ 0^+$

- Even for the axion, there might be extra contributions to mass, altering relation $m_a \sim f_a^{-1}$

- Interesting implications,

  cf. contribution to SN dimming, ...

Astrophysical constraints at the light of PVLAS experiment

Benasque 06

Eduard Massó
(UAB/IFAE, Barcelona)

with: Javier Redondo

and

Carla Biggio
Jörg Jäckel
Andreas Ringwald
Fuminobu Takahashi

OUTLINE OF THE TALK

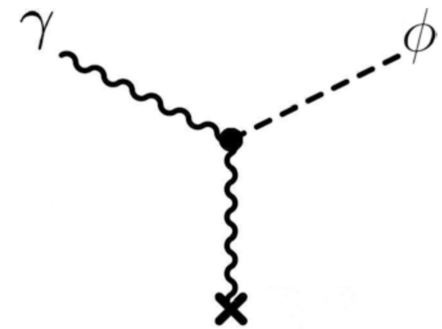
- ★ Strong CP, PQ, axions, light bosons with $\phi\gamma\gamma$
- ★ $\phi\gamma\gamma$ coupling: consequences / constraints
- ★ Recent results: CAST & PVLAS; the conflict
- ★ Ideas to evade astrophysical constraints

Consequences of $\phi\gamma\gamma$

- Primakoff-like processes

  allows $\gamma \rightarrow \phi$ and $\phi \rightarrow \gamma$

  (cf. Primakoff process for $\pi^0\gamma\gamma$)



- $\phi\gamma$ mixing in external B-field

$$\mathcal{L}_{\text{int}} = \mathcal{L}_{\phi\gamma\gamma} \Rightarrow g_{\phi\gamma\gamma}\ \phi\ \vec{\epsilon} \cdot \vec{B}$$

strength of interaction

photon polarization

Consequences of $\phi\gamma\gamma$

Interaction states $\neq$ Propagation states

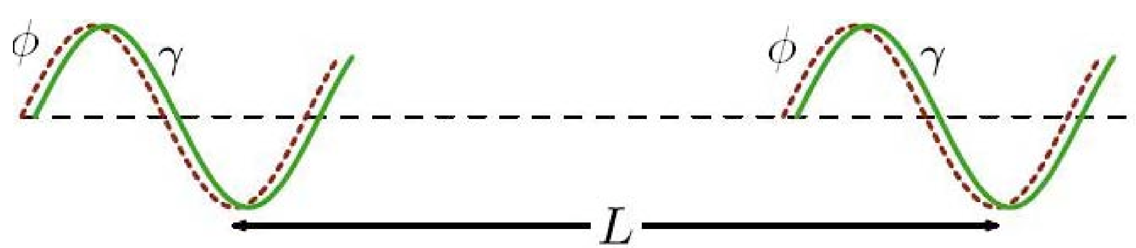
Sikivie
Raffelt, Stodolsky

$$|\phi'\rangle = \cos\theta\,|\phi\rangle - \sin\theta\,|\gamma\rangle$$
$$|\gamma'\rangle = \sin\theta\,|\phi\rangle + \cos\theta\,|\gamma\rangle$$

transition probability
after traveling a distance L

$$P(\gamma \to \phi) = \frac{1}{4}\, g_{a\gamma}^2\, B_T^2\, L^2$$

Coherent effect



Condition *

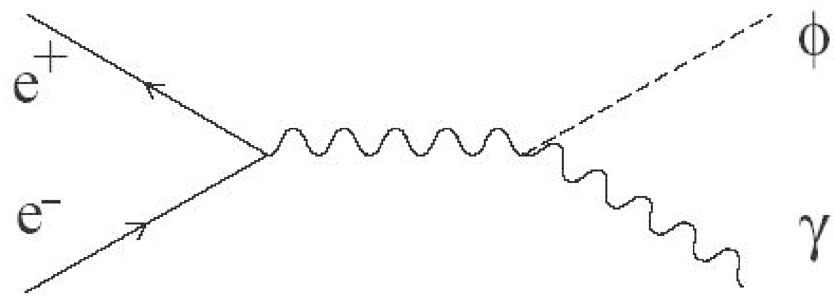
$$|k_\gamma - k_\phi|\, L \ll 2\pi \quad \Rightarrow \quad \frac{Lm^2}{E} < 1$$

$E =$ energy
(in vacuum)

* (Valid when $g_{\phi\gamma\gamma} B \ll L$ and $m_\phi^2/2E \ll E$)

Constraints on $\phi\gamma\gamma$

1. Particle physics (accelerator)



$$M = g_{\phi\gamma\gamma}^{-1} > 10^5 \text{ GeV}$$

EM, Toldrà

Klebart, Rabadan

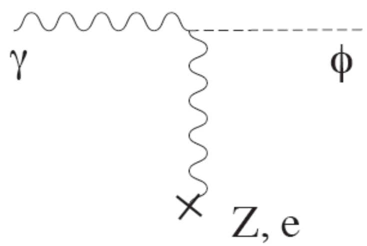
2. Astrophysical

3. Cosmological

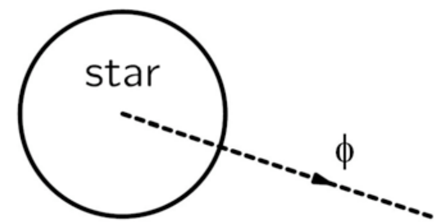
They push (very much) terrestrial limits

Astrophysical (Energy Loss Arguments)

Production Primakoff in the stellar plasma



Emission Weakly interacting particles leave the star



New energy loss channel accelerates star evolution

Time-scale observation constrains exotic energy drain from the star :

⇨ $M > 2 \times 10^{10}\ \text{GeV}\ (m < 10\ \text{keV})$

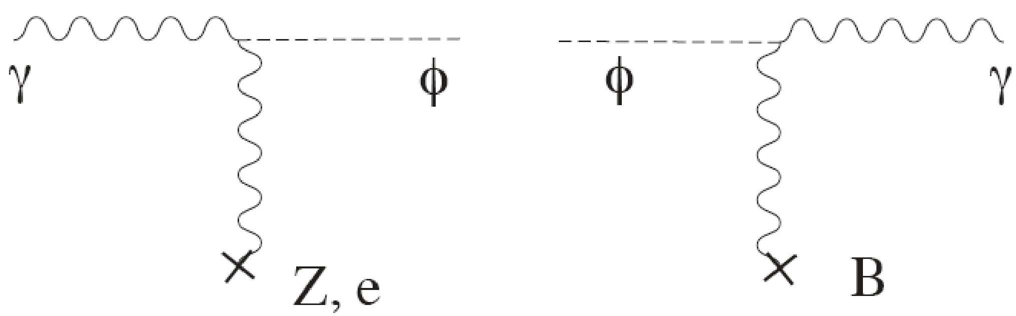
Raffelt → Horizontal Branch Stars

Also SN87 A $M > 10^{9}\ \text{GeV}\ (m < 50\ \text{MeV})$

Gamma-rays from SN

Grifols, EM, Toldrà
Brockway, Carlson, Raffelt

Part of the ϕ-flux produced in the SN core can be (partially) converted back to photons in galactic B

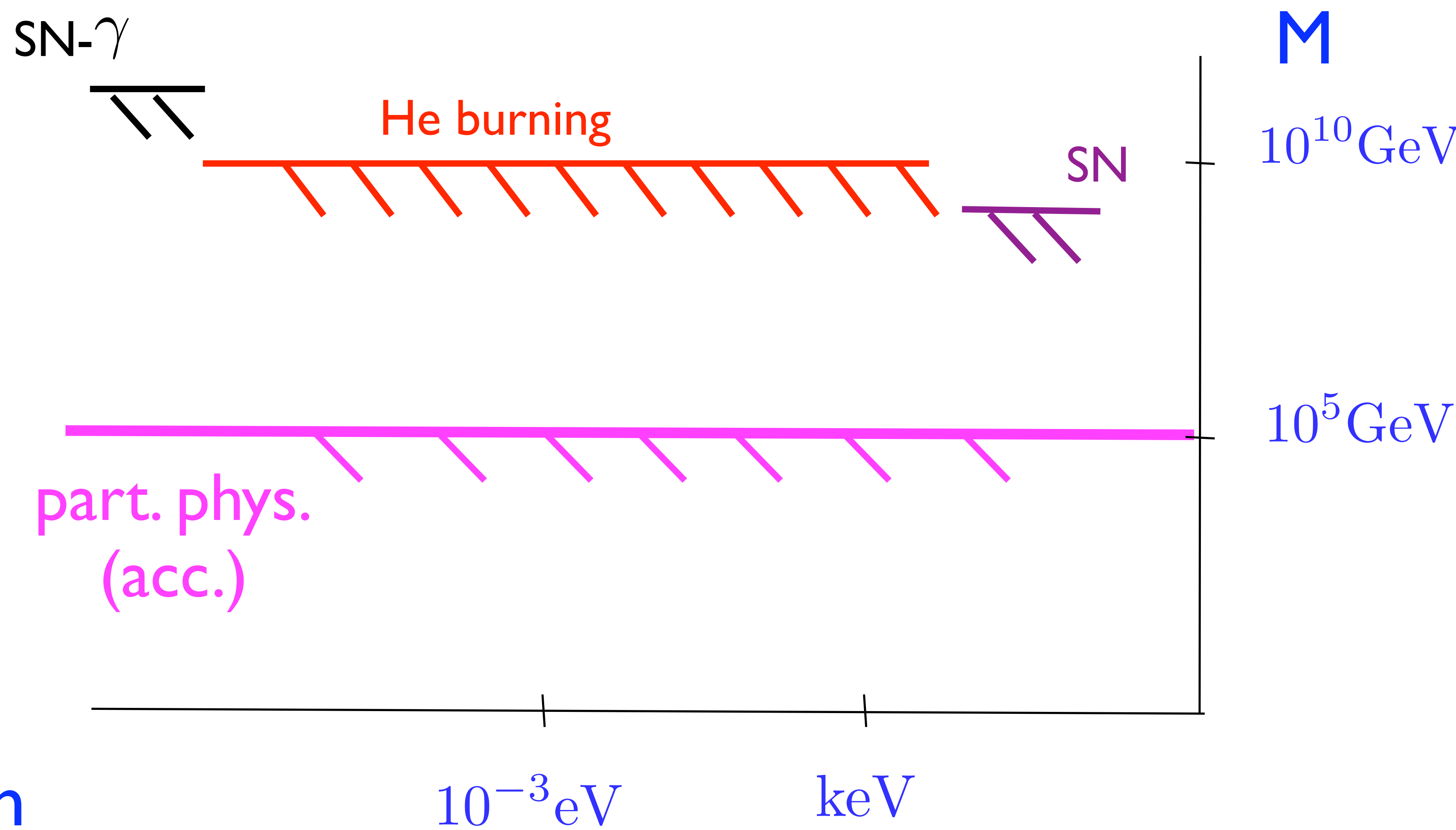


Limits on γ-flux by GRS at the time of observation of ν-flux in 02.1987

$$M > 10^{12}\ \text{GeV}$$
$$(m < 10^{-9}\ \text{eV})$$

In future galactic SN, we might get a signal since we have now more sensitive gamma-rays detectors in satellites

Constraints on $\phi\gamma\gamma$

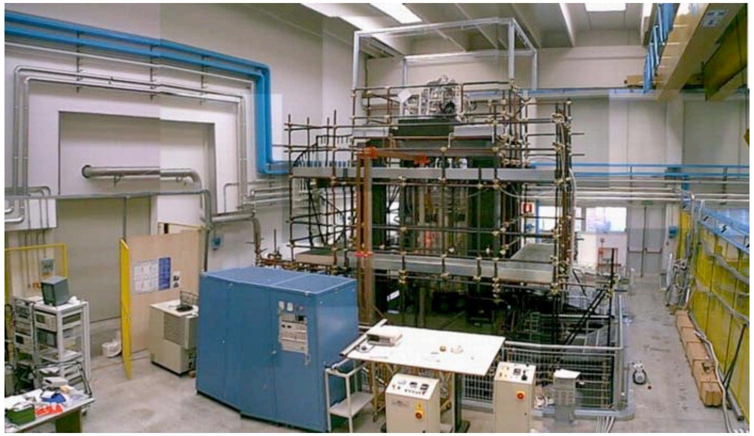


EM, Toldrà
Klebart, Rabadan

Recent experimental results (small masses)

CAST (CERN)

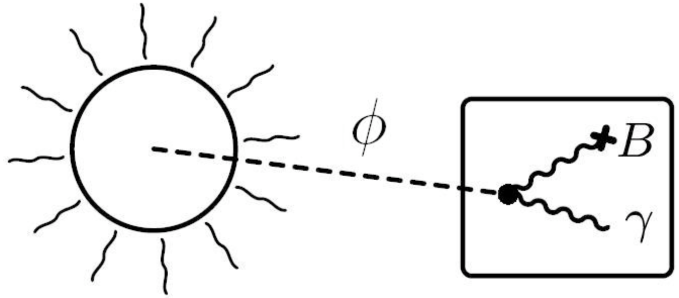
PVLAS (INFN)



CAST search

Helioscope

Sikivie



Idea: Sun is source of ALPs.
Use B to convert them back to photons
(of few keV , X-rays)

Comparable to stellar bounds

NO signal
(at the moment)

$$M > 0.9 \times 10^{10} \text{ GeV}$$
$$(m < 0.02 \text{ eV})$$

K. Zioutas et al. PRL 94 (2005)

Comments: Past helioscopes; Crystal search (Bragg-Primakoff)

PVLAS search

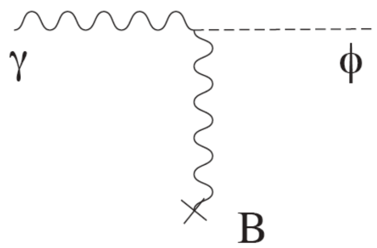
E. Zavattini et al.
PRL 96 (2006)

ROTATION of polarization plane of laser in B field

$B \simeq 5T, \;\; L \simeq 1m, N \simeq 4.4 \;\; 10^5$

$$\alpha = (3.9 \pm 0.5) \;\; 10^{-12} \text{ rad/pass}$$

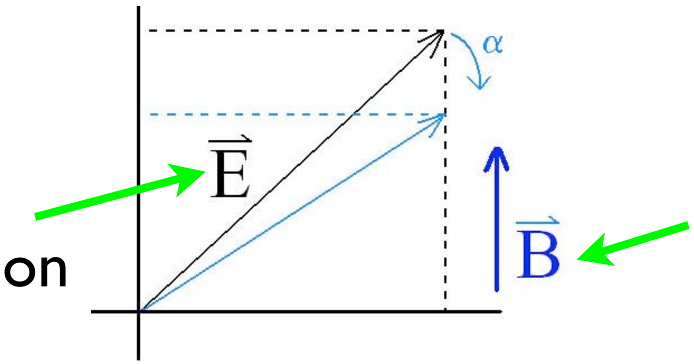
A possible interpretation :



$$\vec{\epsilon} \cdot \vec{B} = \epsilon_{\parallel} \, B$$

Selective absorption
(dichroism)

Light polarization



External field

Scale: $1 \;\; 10^5 < M < 6 \;\; 10^5$ GeV $\qquad M = g_{\phi\gamma\gamma}^{-1}$

Mass: $0.7 < m < 2$ meV

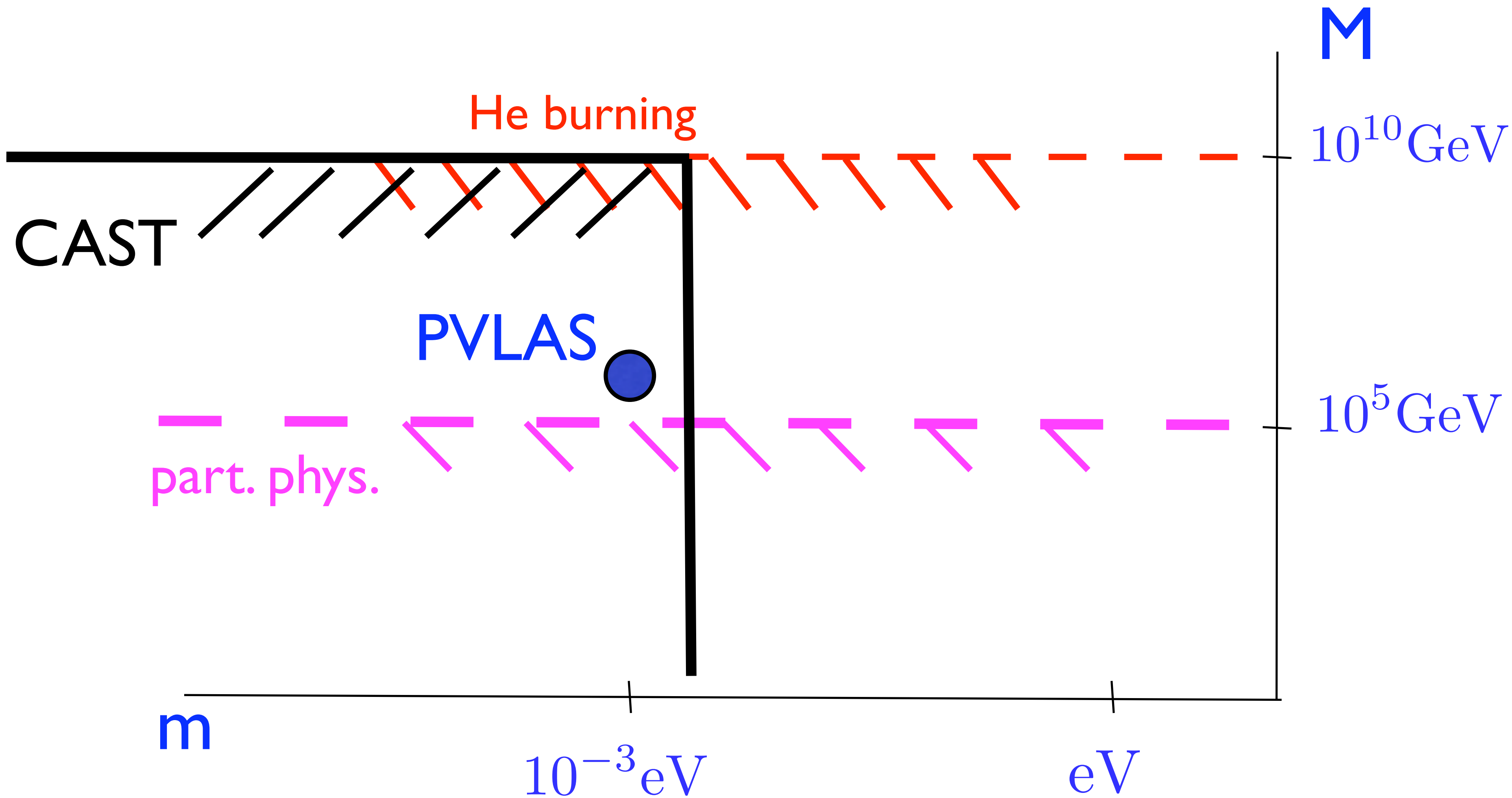
2 remarks, 2

- The particle that could explain the PVLAS results is NOT be the standard axion

- PVLAS and CAST results are inconsistent among them

PVLAS, CAST & the STARS

Obvious and dramatic conflict !



PVLAS strength of interaction leads to $\mathcal{L}_{exotic} \sim 10^{6}\ \mathcal{L}_{\odot}$

Future (experimental)

- CAST
  - → higher m (gas)
  - → Lower photon energy
- PVLAS
  - → higher m (gas)
  - → Search induced ellipticity

    ↑ Should be present if rotation signal is due to $\phi\gamma\gamma$
- New experiments welcome

Future (experimental)

<u>short term</u>: many projects (mainly photon regeneration)

CERN-SPSC-2005-034
SPSC--001
17 October 2005

Letter of Intent

QED Test and Axion Search by means of Optical Techniques

To the CERN SPSC

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[8] *Technical University of Liberec, Czech Republic*

Abstract

The re-use of recently decommissioned 15-meter long twin aperture LHC superconducting magnet prototypes, providing a transverse magnetic field $B \approx 9.5$ T offers a unique opportunity for the construction of a new powerful two-in-one experiment to investigate the properties of the vacuum by means of optical techniques. Linearly polarised laser light beams will be used as probes inside vacuum chambers housed inside superconducting magnet apertures. One of the apertures will be dedicated to the measurements of the Vacuum Magnetic Birefringence (VMB) and optical absorption anisotropy whereas the other one will be used to detect the photon regeneration from axions using "a shining light through the wall". The VMB predicted by the QED theory is expected to be measured for the first time and the CPT symmetry precisely tested. The values or the limiting values of mass and coupling constant to two photons of weakly interacting scalar or pseudo-scalar particles like axions are also aimed to be deduced from a sizeable deviation of the QED prediction. In case of null result for axion search and with the most conservative view concerning the detection technique, the limits of both parameters, i.e. mass and di-photon coupling constant, can be improved by at least 2 orders of magnitude with respect to present reference results obtained with a purely laboratory experiment. The interest in axion search, providing an answer to the strong-CP problem, lies beyond particle physics since such hypothetical neutral light spin zero particle is considered as one of the good dark matter candidates, and the only non-supersymmetric one.

* Contactperson

arXiv:hep-ph/0511103 v1

Photon Regeneration from Pseudoscalars at X-ray Laser Facilities

Raul Rabadan,[1,*] Andreas Ringwald,[2,†] and Kris Sigurdson[1,‡]
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Recently, the PVLAS collaboration has reported an anomalously large rotation of the polarization of light in the presence of a magnetic field. As a possible explanation they consider the existence of a light pseudoscalar particle coupled to two photons. In this note, we propose a method of independently testing this result by using a high-energy photon regeneration experiment (the X-ray analogue of "invisible light shining through walls") using the synchrotron X-rays from a free-electron laser (FEL). With such an experiment the region of parameter space implied by PVLAS could be probed in a matter of minutes.

Axion meetings:
1st (Dec. 05, CERN)
2nd (June 06, Univ. Patras)

PVLAS, CAST & the STARS

A way out of the puzzle is to have a model where the Sun emits much less ALPs than expected

There would be less energy loss and thus stellar limit are avoided

CAST limit not valid because it assumes "solar- standard" ϕ - flux

two possibilities

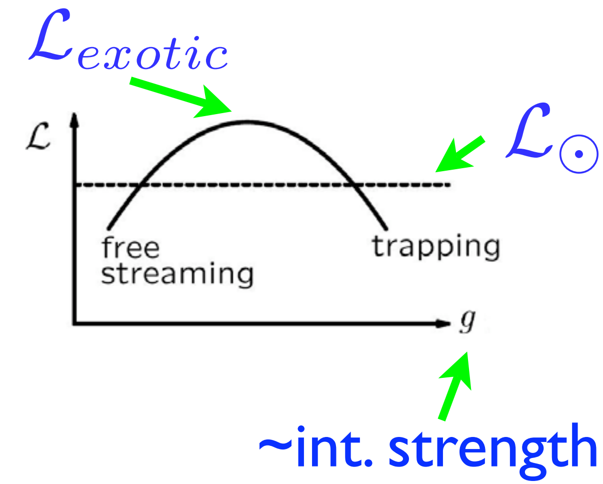
Trapping difficult to find a model

EM, Redondo
Jain, Mandal

Suppression of production at high energies

PVLAS & the STARS

Trapping



Strongly interacting ϕ

ϕ would follow a random walk on its way out of the Sun (like photons). When emitted would have much less energy than when produced in the core.

Problem: a strong interaction should have been seen elsewhere

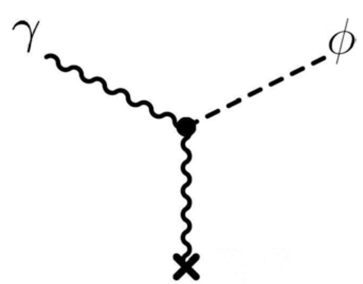
Interact through mediators ?

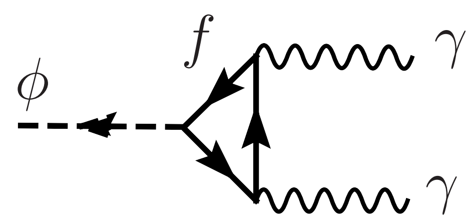
MODEL WANTED

PVLAS & the STARS

Suppression of production in the stars

★ Neutral particle coupled to 2 photons
Triangle diagram of charged particle





ϕ composite $\bar{f}f$

ϕ coupled to f

Amplitude $\sim 1/\Lambda$

Λ = mass scale

cf. pion

cf. Higgs, standard axion

★ Coupling is weak

- mass scale Λ is large — Problem: no running with energy
- q_f small ... models ?

Paraphoton model

Okun
Holdom

- QED $\mathcal{L} = -\frac{1}{4}F^2 + e\ j \cdot A$ Photons, charged particles
- Extend QED: $U(1) \times U(1)'$

Paraphotons,
Paracharged particles
\+ ultramassive fermions with charge and paracharge

$$\mathcal{L} = -\frac{1}{4}(1+\eta)F^2 - \frac{1}{4}(1+\eta')F'^2$$

$$+\ \frac{1}{2}\ \varepsilon\ F \cdot F' \ +\ \frac{1}{2}\mu^2\ A'^2$$

$$+\ e\ j \cdot A\ +\ e'\ j' \cdot A'$$

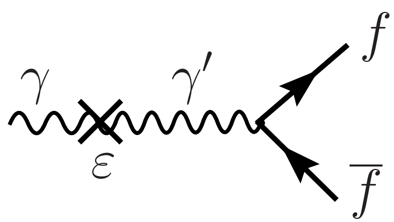
mixing (small) → $\frac{1}{2}\varepsilon F \cdot F'$

paraphoton mass → $\frac{1}{2}\mu^2 A'^2$

low energy fermions → $e'\ j' \cdot A'$

Paraphoton model

- A' (massive) paraphoton
- particles with paracharge e'
  adquire small electric charge



$\varepsilon\ e'$ charged particles

- others

Reconciling PVLAS with the stars

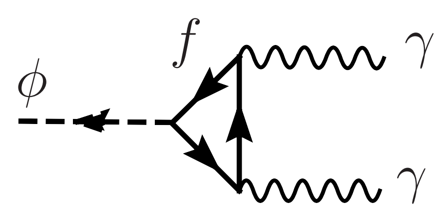
charge T-dependent q(T)

$$q(T_{\text{stellar}} \sim \text{keV}) \ll q(T_{\text{pvlas}} \sim 0)$$

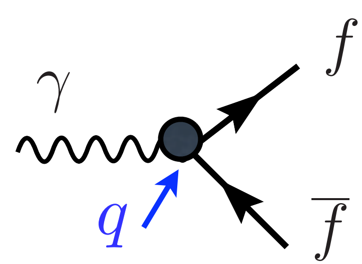
- PVLAS works at T=0

charge eq

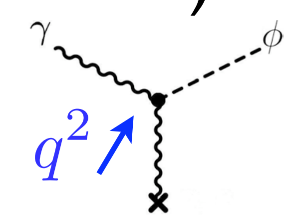
$$\frac{1}{\Lambda}\,\frac{\alpha_{\text{em}}}{\pi}\,q(0)^2 = \frac{1}{4\times10^5\ \text{GeV}}$$



- Stellar energy loss now dominated by



(No longer by Primakoff effect)



$q \leq 10^{-15}$ (RG)

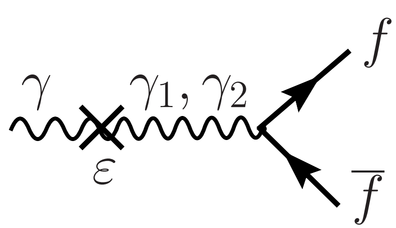
Davidson
Campbell, Bailey, Peskin
Hannestad, Raffelt

Two-Paraphoton model

Charge suppression at keV energies ?

May be obtained within a
two-paraphoton model with partial cancellation

Introduce γ_1, γ_2



$\varepsilon_1 = \varepsilon_2$ high-energy structure

$e'_1 = -e'_2$ (para)charge assignments

$\mu_1 \neq \mu_2$ scalar sector

$$q(T) \simeq \frac{\mu^2}{T^2}\, q(0)$$

$\mu \ll T$

To simplify

$e_1 = e, e_2 = -e$
$\mu_2 = 0, \;\; \mu_1 \equiv \mu \neq 0$

Low-energy scale

Cannot univocally determine parameters $\Lambda, \mu, q(0)$

$$q(T = 10\,\mathrm{keV}) \simeq \frac{\mu^2}{(10\,\mathrm{keV})^2}\, q(0) \;\; \leq 10^{-15}$$

$$\frac{1}{\Lambda}\,\frac{\alpha_{\mathrm{em}}}{\pi}\, q(0)^2 = \frac{1}{4\times 10^5\,\mathrm{GeV}}$$

$$\Rightarrow \quad \Lambda\,\mu^4 \;\leq\; 10^{-2}\ \mathrm{eV}^5$$

- If assume $\Lambda \sim \mu$
  - Bound on new scale

    $$\Lambda \sim \mu \leq 0.4\ \mathrm{eV}$$

  - Consistent with all masses of same order

    $$\Lambda \sim \mu \sim m_\phi \simeq 10^{-3}\ \mathrm{eV}$$

    (e-units)

    $$\Rightarrow \;\; q(0) = 10^{-7}$$

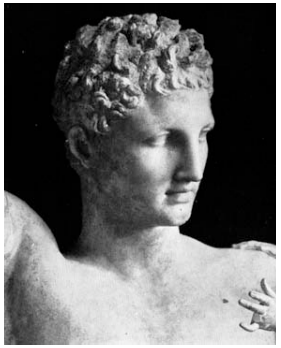
Looking for ALPS

Jäckel, EM, Redondo
Ringwald, Takahashi

- Axion Like Particles (ALPs)
  that explain PVLAS result
  and not contradict CAST
  neither astrophysical constraints

  perhaps indicate a dependence
  of ALPS properties
  on the environment (density, temperature, ...)

- (Low-energy) laboratory searches
  important



Hermes
(Messenger's God)
of Praxiteles

MESSAGE

Evasion of astrophysical bounds:
difficult = possible in sophisticated models

If PVLAS confirmed
not many new-physics models
do the job

CONCLUSIONS

If PVLAS signal confirmed, and it is due a new particle coupled to photons, we need a model to explain why astrophysical bound are not valid.

+ PVLAS + Astrophysical constraints

NEW LOW ENERGY SCALE

Thanks to

The organizers of the workshop

The persons behind the existence of the Benasque Center:
M. Asorey, J. I. Latorre

and specially the director
<u>Pedro Pascual</u>