Laser Searches for New Particles at Fermilab

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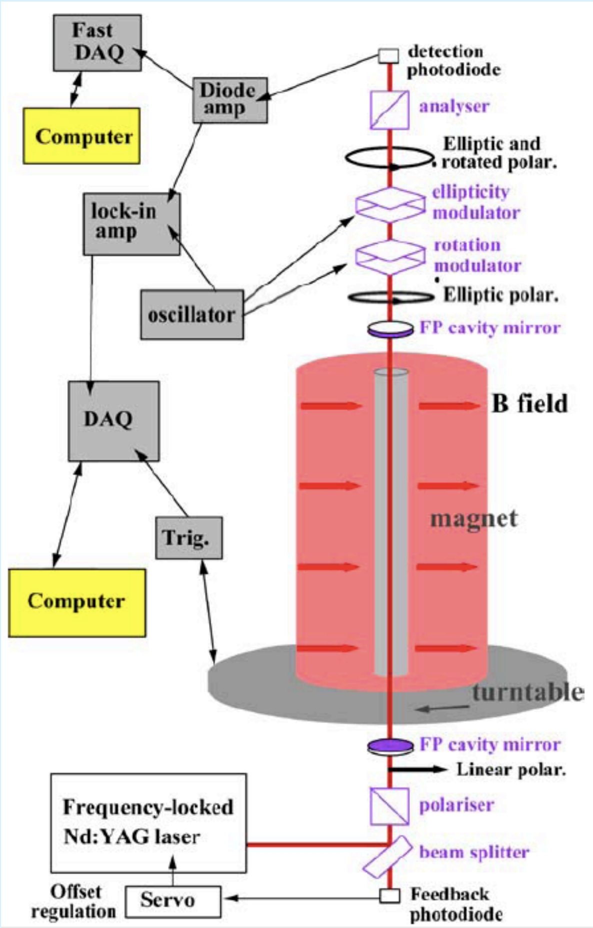
Outline

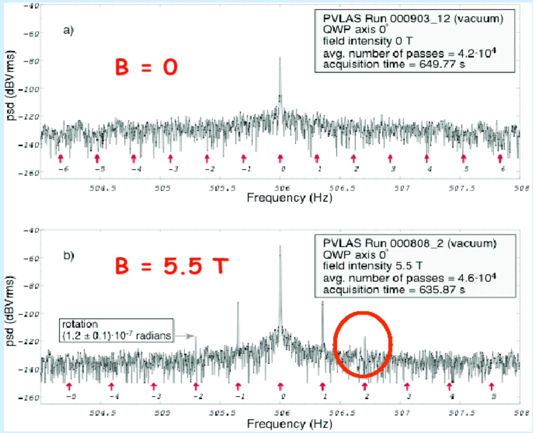
- Motivation
  - Experimental evidence
  - Theoretical interest
- Experimental Implementation
  - GammeV and GammeV-CHASE
- Results

Outline x 2: Once for the experiments and once for lessons learned.

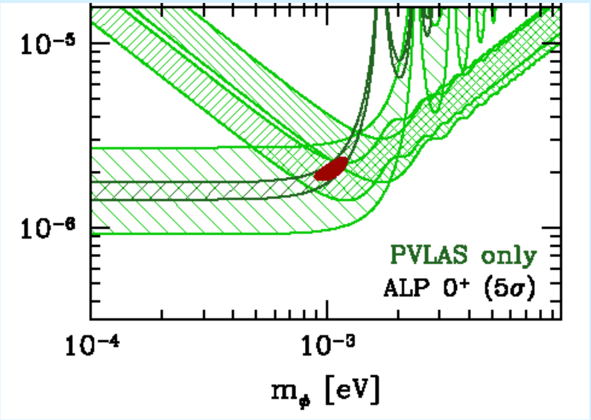
A strong hint in 2006

PVLAS: designed to study the vacuum by optical means: birefringence (generated ellipticity) and dichroism (rotated polarization). Reported results in 2006 interpreted as evidence for a new scalar “ALP” particle.



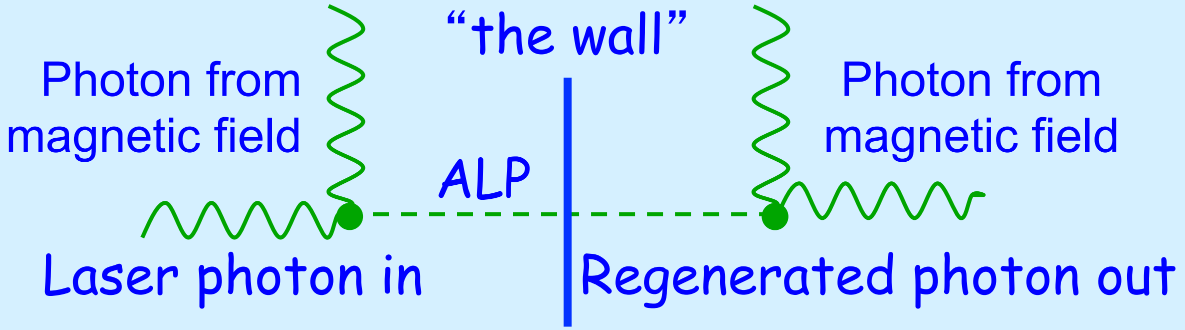


PRL **96**, 110406, (2006)



PRD **77**, 032006 (2008)

A light shining through a wall (LSW) experiment could test the milli-eV axion-like particle (ALP) interpretation.

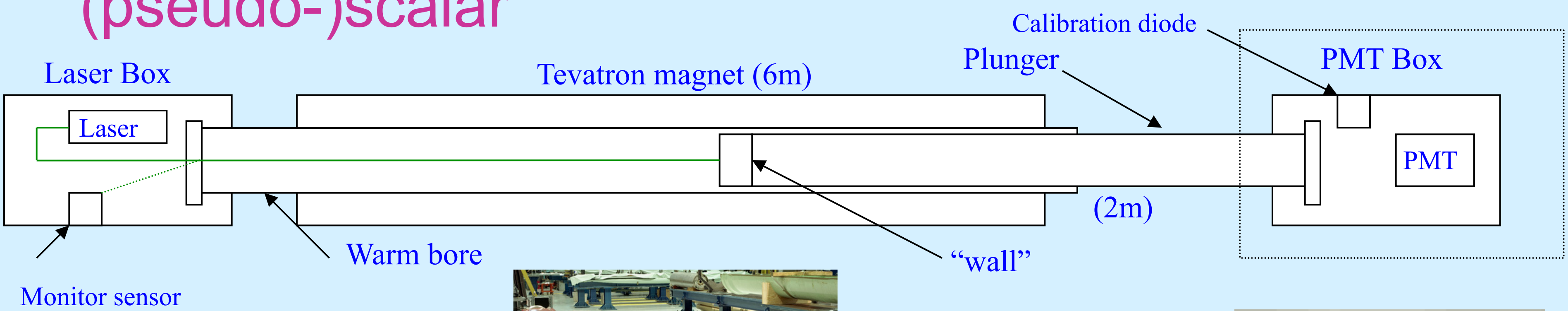


Theoretical motivation

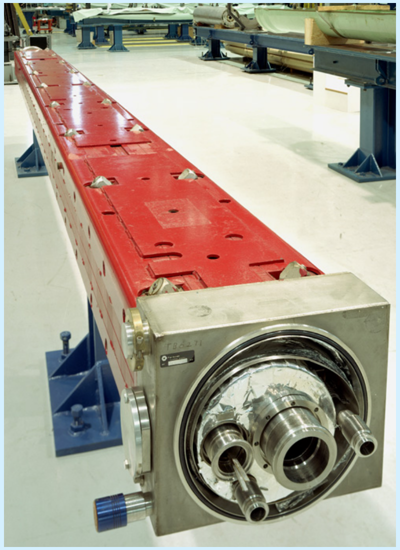
- milli-eV (10^{-3}) eV mass scale arises in various areas in modern particle physics.
  - Dark Energy density
    - $\Lambda^4 = 7 \times 10^{-30}$ g/cm^3 ~ $(2\times10^{-3}\text{ eV})^4$
  - Neutrinos
    - $(Dm_{21})^2 = (9\times10^{-3}\text{ eV})^2$
    - $(Dm_{32})^2 = (50\times10^{-3}\text{ eV})^2$
  - See-saw with the TeV scale:
    - meV ~ TeV^2/M_{planck}
  - Dark Matter Candidates
    - Certain SUSY sparticles (low mass gravitino)
    - Axions and axion-like particles

GammeV Experiment

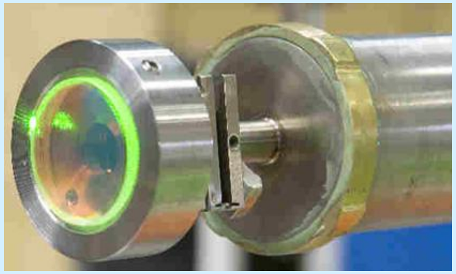
Search for evidence of a milli-eV particle in a light shining through a wall experiment to unambiguously test the PVLAS interpretation of an axion-like (pseudo-)scalar



Existing laser in Acc. Div. nearly identical with a similar spare available



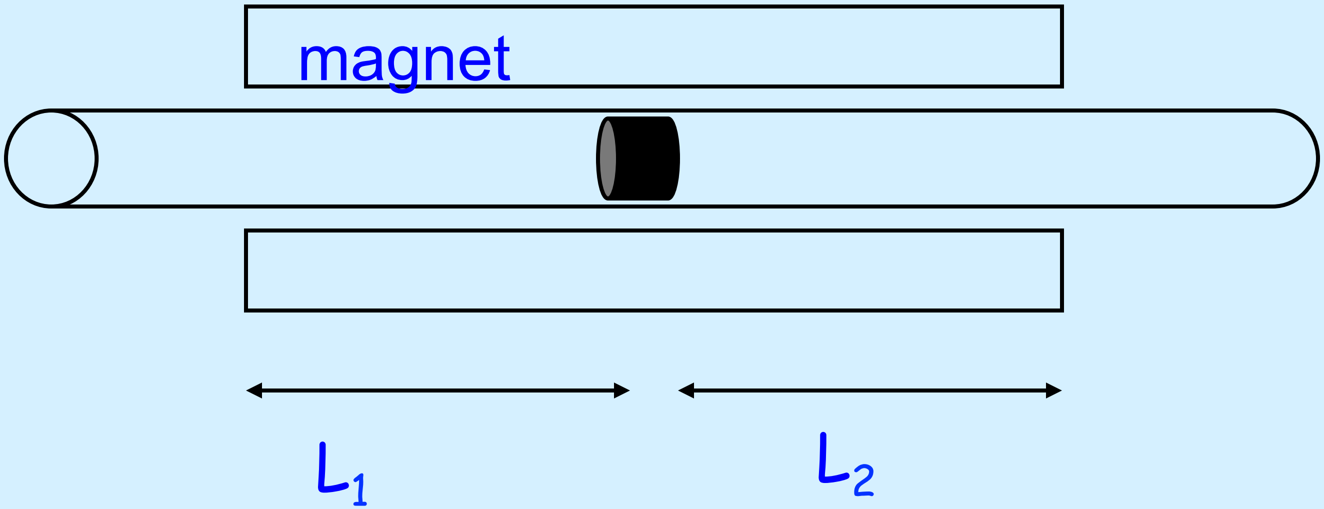
The "wall" is a welded steel cap on a steel tube in addition to a reflective mirror.



High-QE, low noise, fast PMT module (purchased)

Vary wall position to change baseline: Tune to the correct oscillation length

A <u>unique feature</u> of our proposal to cover larger m_f range

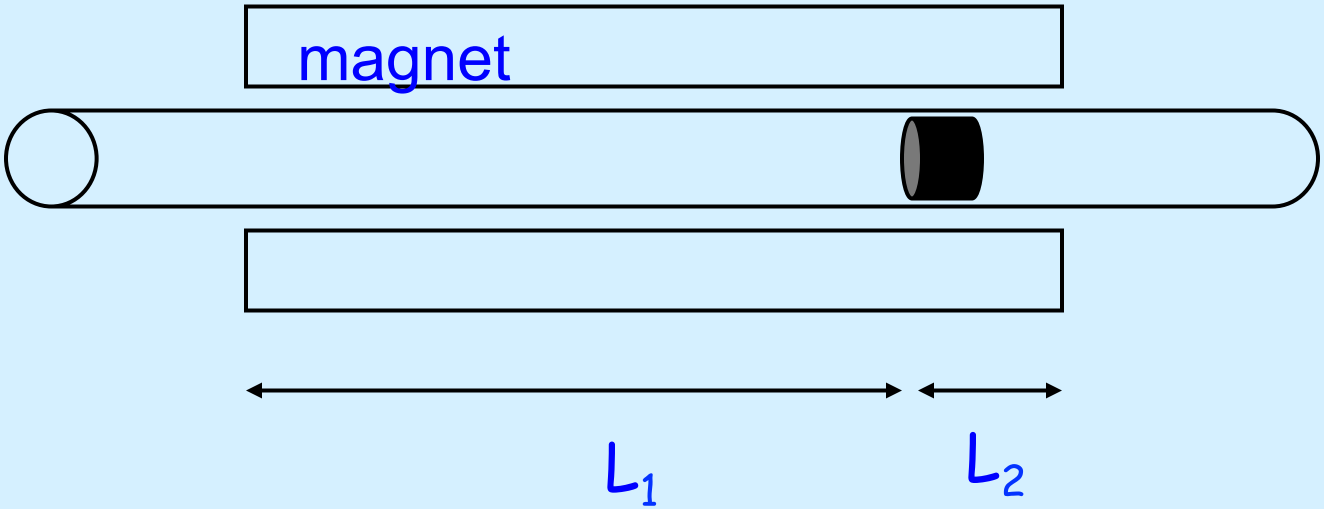


$$P_{regen} = \left(\frac{4B^2\omega^2}{M^2(\Delta m^2)^2} \right)^2 \left(\sin \frac{\Delta m^2 L_1}{4\omega} \right)^2 \left(\sin \frac{\Delta m^2 L_2}{4\omega} \right)^2$$

Scalar interactions: Polarization aligned with B field
Pseudoscalar interaction: Polarization anti-aligned with B field

Vary wall position to change baseline: Tune to the correct oscillation length

A unique feature of our proposal to cover larger m_f range



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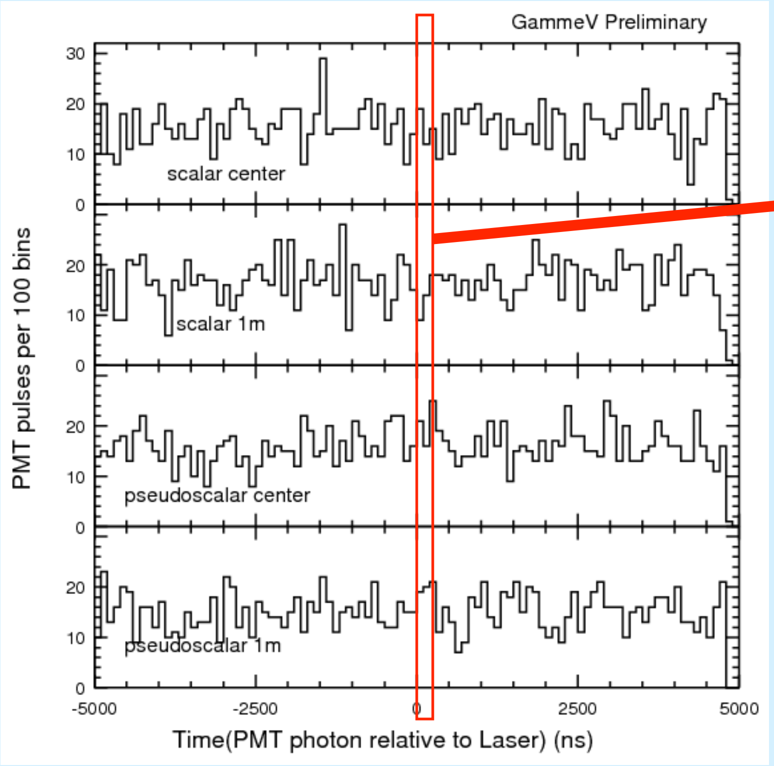
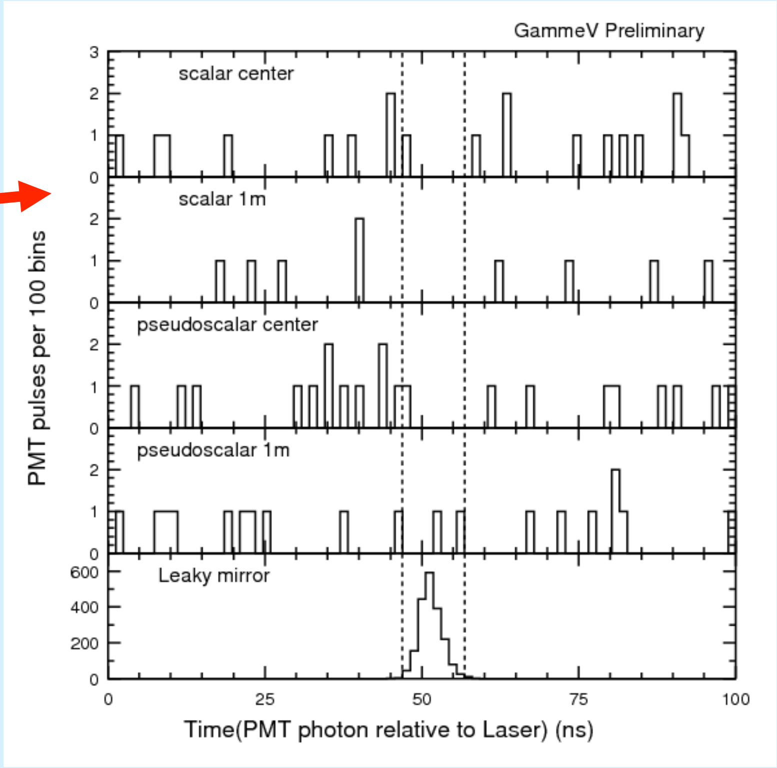
Scalar interactions: Polarization aligned with B field

Pseudoscalar interaction: Polarization anti-aligned with B field

Time correlate laser pulses with phototube hits

Spin	Position	# Laser pulse	# photon / pulse	Expected Background	Signal Candidates
Scalar	Center	1.34 M	0.41e18	1.56±0.04	1
Scalar	1 m	1.47M	0.38e18	1.67±0.04	0
Pseudo	Center	1.43M	0.41e18	1.59±0.04	1
Pseudo	1m	1.47M	0.42e18	1.50±0.04	2

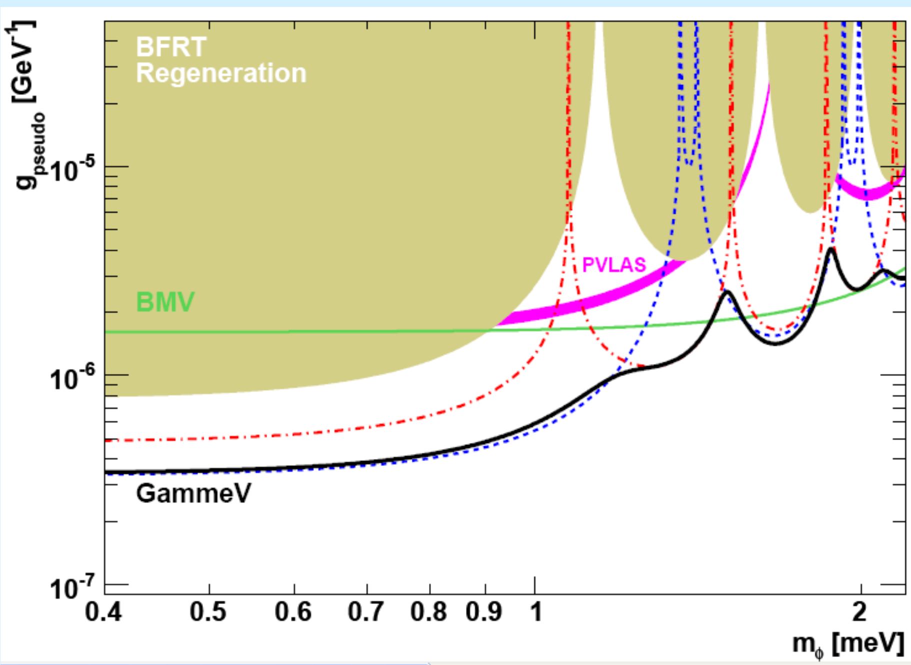




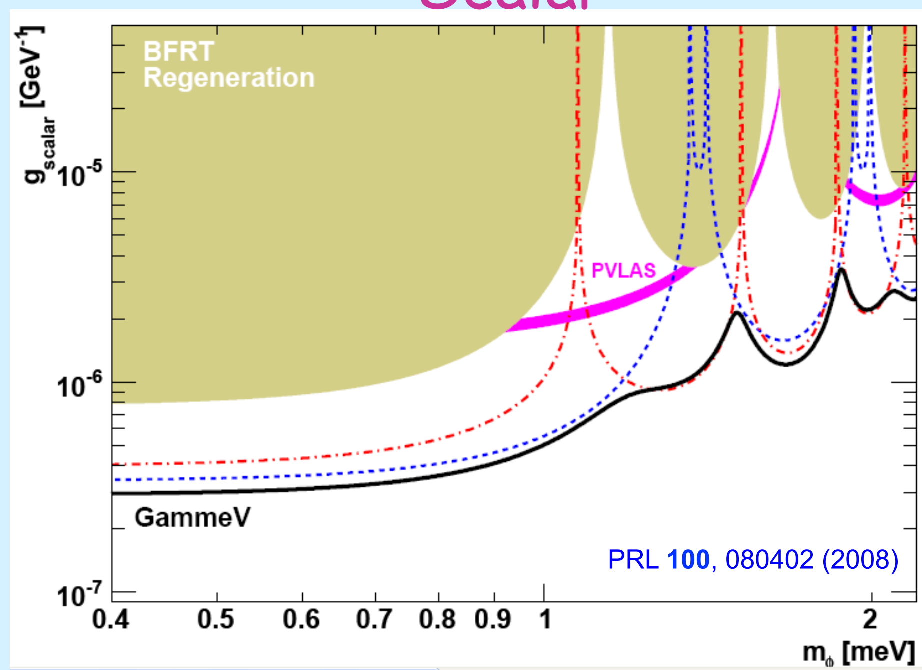
Gamme**V** Limits

- Results are derived. We show 3**s** exclusion regions and completely rule out the PVLAS axion-like particle interpretation by more than 5**s**.

Pseudoscalar



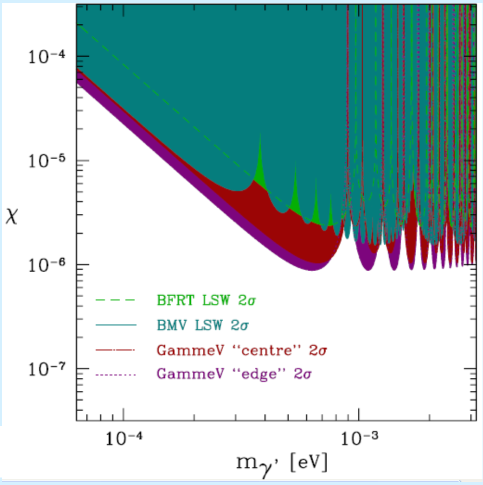
Scalar



- Job is done. Limit generally improves slowly (8^{th} root) vs. longer running time, or increased laser power, etc.

Other new particles

A dark photon could also cause light to shine through a wall even without an external magnetic field. The GammeV null result can also be interpreted as sensitivity for a new U(1) dark photon.



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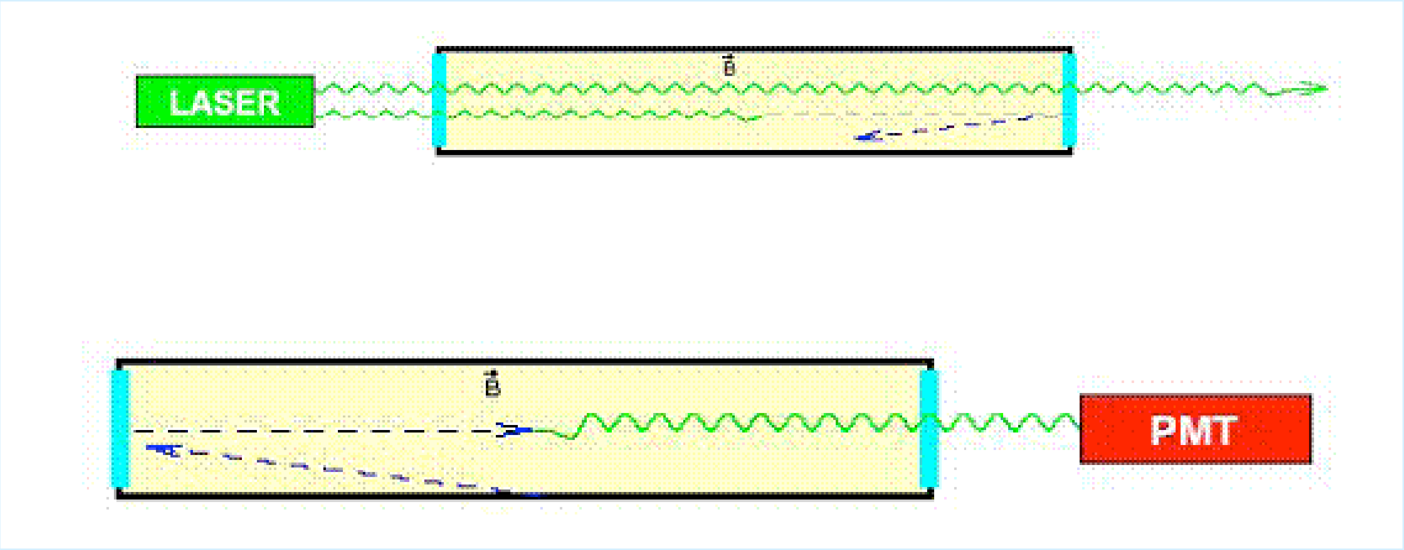
- An exotic type of new particle called a chameleon – a scalar – Tensor interaction results in a particle whose properties depend on it's environment.

$$\mathcal{L}_{\text{int}} = -V(\phi) + \exp\left(\frac{\phi}{M_D}\right) g_{\mu\nu} T^{\mu\nu} - \frac{1}{4}\frac{\phi}{M} F_{\mu\nu} F^{\mu\nu}$$

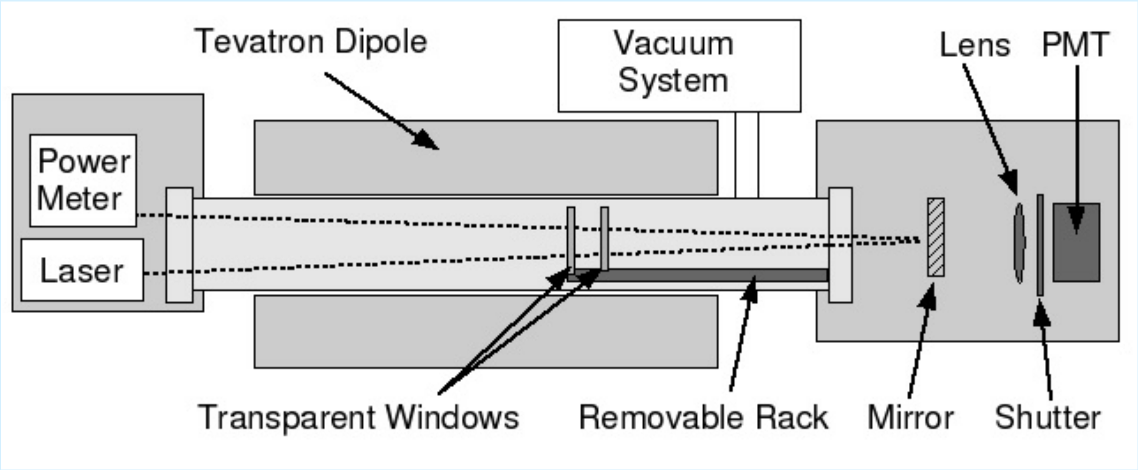
- The chameleon mechanism (Khoury and Weltman) was originally postulated as a mechanism to account for the cosmic expansion – i.e. "a dark energy particle".

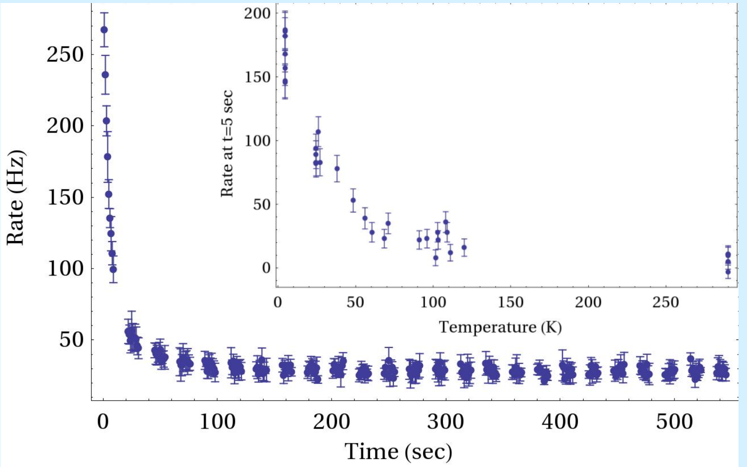
"Particle in a Jar" / Afterglow

- Chameleon properties depend on their environment – effective mass increases when encountering matter.
  - A laser in a magnetic field might have photons that convert into chameleons which reflect off of the optical windows. A gas of chameleons are trapped in a jar.
  - Turn off the laser and look for an afterglow as some of the chameleons convert back into detectable photons.

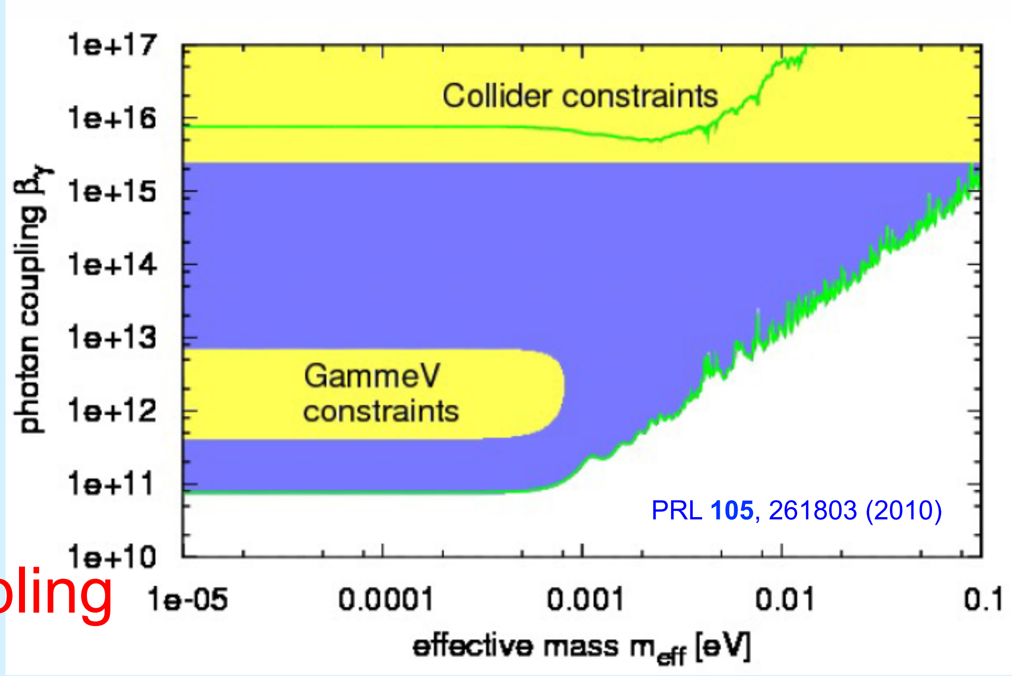


CHASE: Chameleon Afterglow Search





When we started to take data, we observed an afterglow that did not depend on B field (so, no evidence for chameleons). The afterglow rate did depend on temperature in a manner similar to vacuum grease.



First limits for chameleons coupling to photons.

Lessons Learned - Motivation

- Motivation
  - Experimental evidence
    - Right before we started taking data in earnest, PVLAS reported no anomaly when the apparatus was slightly reconfigured.
      - Did not provide an explanation of the original result
      - A chameleon possibility remained consistent with all obs.
  - Theoretical interest
    - milli-eV as a mass scale is suggestive, but not uniquely so.
    - Is the effort worth covering the yet-to-be-explored parameter space?

Lessons Learned - Experiment

- Experimental Implementation
  - GammeV
    - Some cleverness can go a long way … the plunger, using time correlation to reduce bkgd.
    - We had a target goal in mind. We were probing a region where CAST and star-cooling limits were several orders of magnitude more stringent.
  - CHASE
    - We spent a year working with a theorist to make sure we understood the theoretical implications of the experiment (self-interactions, residual gas).
  - Benefits from calibration signals – good to see something when looking for nothing.

Lessons Learned - Results

- Results
  - These are exciting times to use reasonable resources to probe new possible portals into the dark sector.
  - The presence of background limits extending sensitivity. Many experiments are designed around high rate when the focus should be on low background.
  - Next target is to improve to $g \sim 10^{-11}$ (IAXO, ALPS). Suggest work continue to make “hints” become either not-so-strong or more robust.
- There is Discovery potential!