GammeV

Gamma to milli-eV particle search

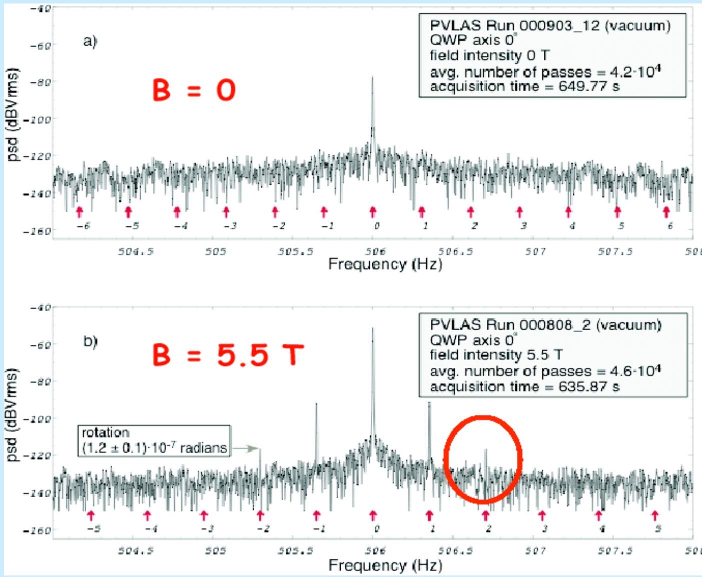
Results and Future Plans at Fermilab

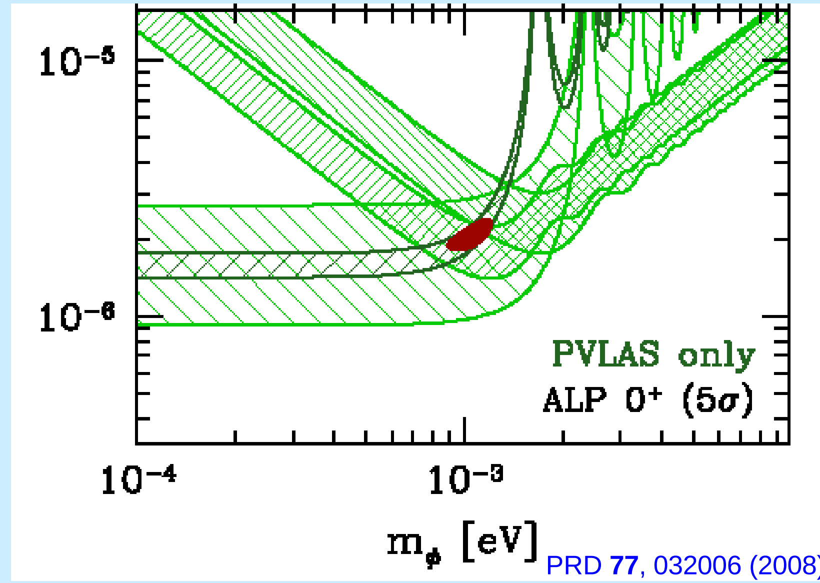
William Wester and Aaron Chou
Fermilab

H Murayama

Motivation

- PVLAS anomalous result in 2006 and axion like particle interpretation

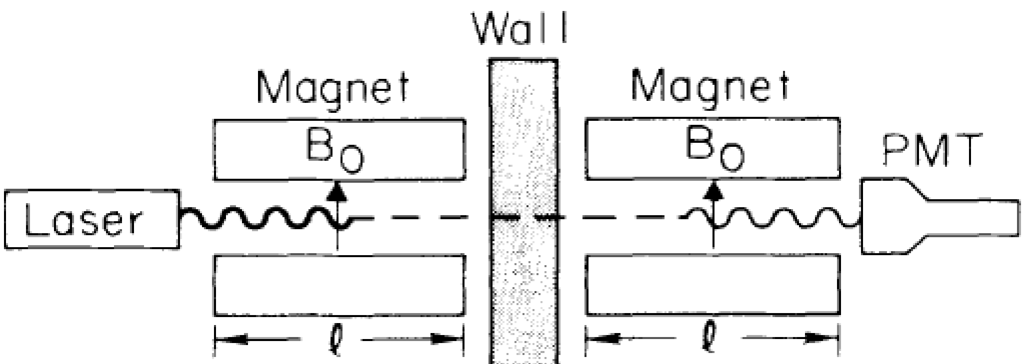




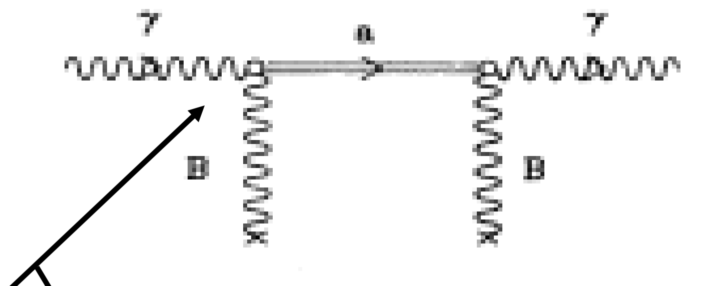
PRD **77**, 032006 (2008)

- sub-eV or milli-eV (10^{-3} eV) mass scale in modern particle physics
  - Dark Energy density: $\Lambda^4 = 7 \times 10^{-30}$ g/cm^3 ~ $(2\text{x}10^{-3}\ \text{eV})^4$
  - Neutrino mass differences:
    - $(\Delta m_{21})^2 = (9\text{x}10^{-3}\ \text{eV})^2$ and $(\Delta m_{32})^2 = (50\text{x}10^{-3}\ \text{eV})^2$
  - See-saw with the TeV scale: meV ~ TeV^2/M$_{planck}$
  - Dark Matter Candidates: gravitinos/axions/ALPs/other WISPs

Light Shining Through a Wall Experiment



K. Van Bibber, et. al., PRL 59, 759 (1987)



$$\mathcal{L}_{\text{int}} = -\frac{1}{4}\frac{\phi}{M}F_{\mu\nu}F^{\mu\nu} = \frac{\phi}{M}(\vec{E}\cdot\vec{E} - \vec{B}\cdot\vec{B})$$

$$\mathcal{L}_{\text{int}} = -\frac{1}{4}\frac{\phi}{M}F_{\mu\nu}\widetilde{F}^{\mu\nu} = \frac{\phi}{M}(\vec{E}\cdot\vec{B})$$

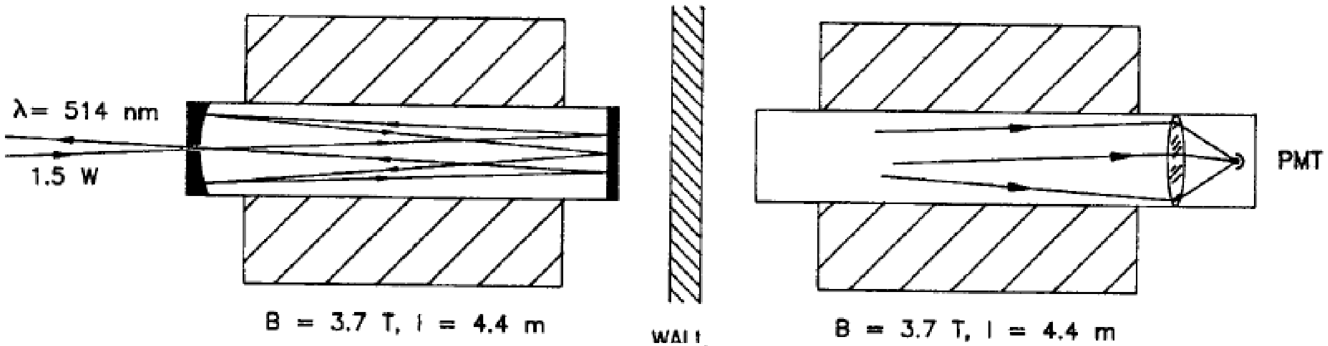
$$P_{regen} = \frac{16 B_1^2 B_2^2 \omega^4}{M^4 m_\phi^8}\sin^2\left(\frac{m_\phi^2 L_1}{4\omega}\right)\cdot\sin^2\left(\frac{m_\phi^2 L_2}{4\omega}\right)$$

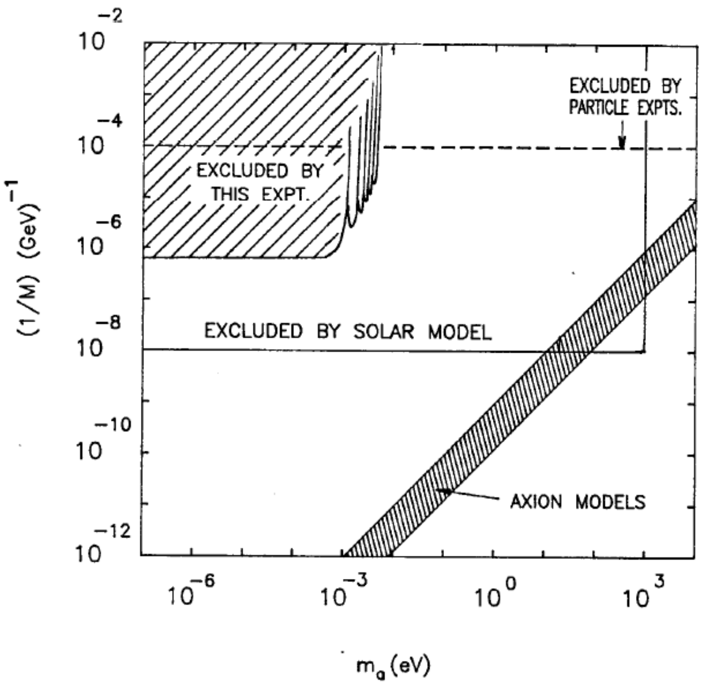
Assuming 5T magnet, the PVLAS “signal”, and 532nm laser light

$$P_{regen}^{GammeV} = (3.9\times10^{-21})\times\frac{(B_1/5\ \mathrm{T})^2(B_2/5\ \mathrm{T})^2(\omega/2.33\ \mathrm{eV})^4}{(M/4\times10^5\ \mathrm{GeV})^4(m_\phi/1.2\times10^{-3}\ \mathrm{eV})^8}$$
$$\times\sin^2\left(\frac{\pi}{2}\frac{(m_\phi/1.2\times10^{-3}\ \mathrm{eV})^2(L_1/2.0\ \mathrm{m})}{(\omega/2.33\ \mathrm{eV})}\right)\sin^2\left(\frac{\pi}{2}\frac{(m_\phi/1.2\times10^{-3}\ \mathrm{eV})^2(L_2/2.0\ \mathrm{m})}{(\omega/2.33\ \mathrm{eV})}\right)$$

BFRT Experiment

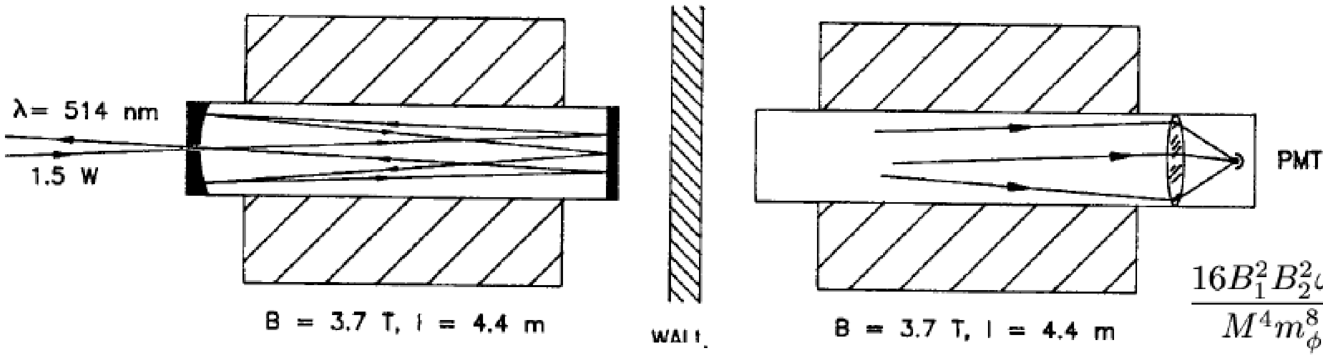
- Brookhaven, Fermilab, Rochester, Trieste (1992)



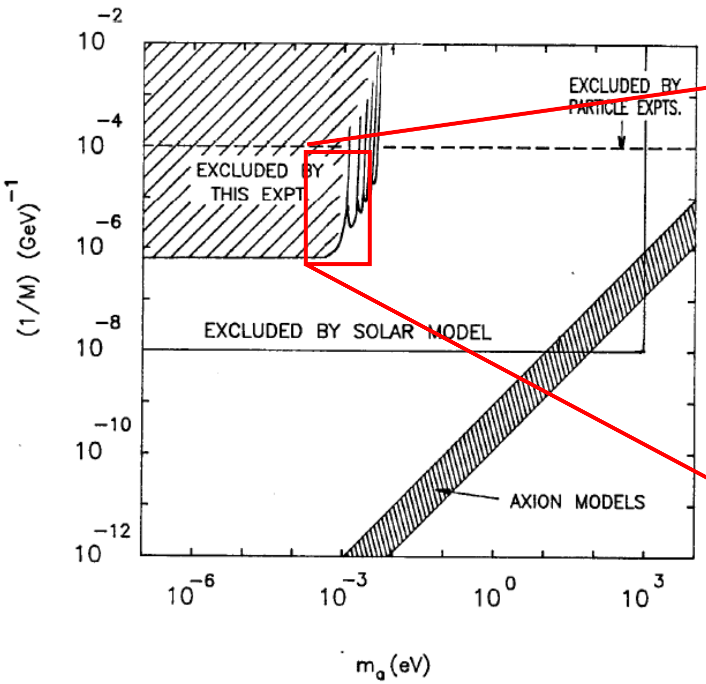


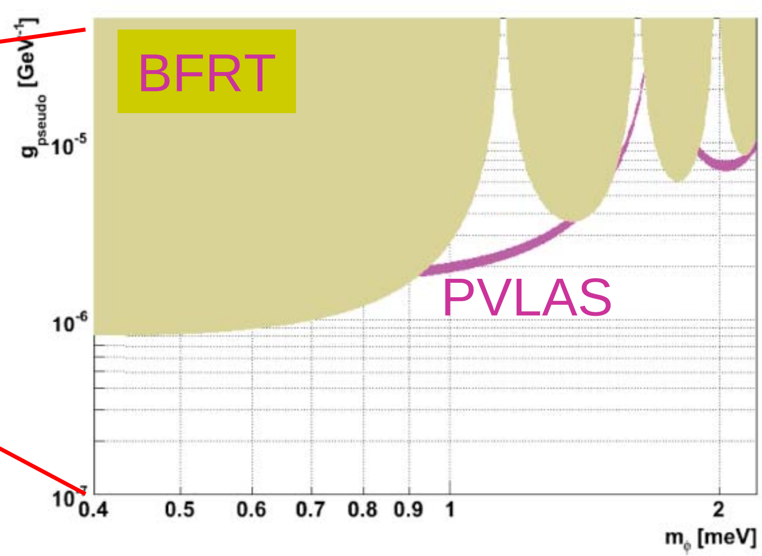
BFRT Experiment

- Brookhaven, Fermilab, Rochester, Trieste (1992)



$$\frac{16B_1^2B_2^2\omega^4}{M^4m_\phi^8}\sin^2\left(\frac{m_\phi^2L_1}{4\omega}\right)\cdot\sin^2\left(\frac{m_\phi^2L_2}{4\omega}\right)$$





BFRT is not sensitive in the PVLAS region of interest. Our goal is to cover the PVLAS region.

GammeV Collaboration

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Batavia, IL 60510

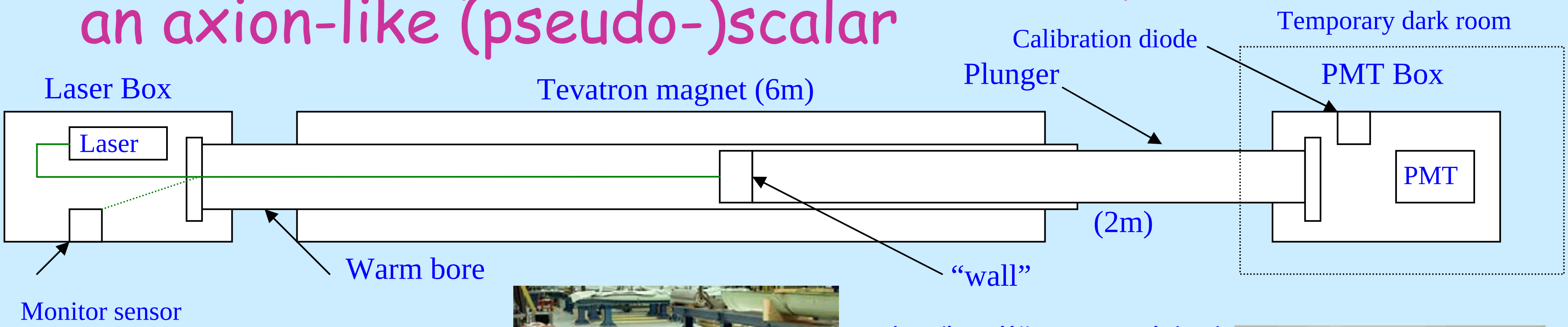
D. Gustafson
University of Michigan
Ann Arbor, MI 48109

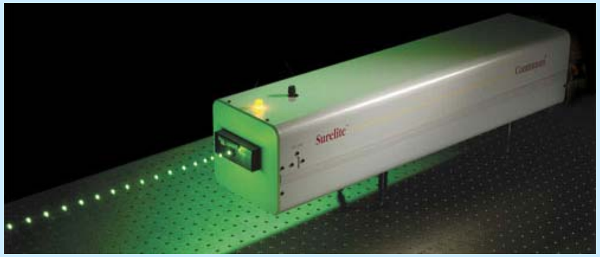
Ten person team including a summer student, 3 postdocs, 2 accelerator / laser experts, 4 experimentalists (nearly everyone had a day job) PLUS technical support at FNAL

Nov 2006 : Initial discussion and design (Aaron Chou, WW leaders)
Apr 2007 : Review and approval from Fermilab ($30K M&S budget!)
May 2007 : Acquire and machine parts
Jun 2007 : Assemble parts, test electronics and PMT calibration
Jul 2007 : First data but magnet and laser problems
Aug 2007 : Start data taking in earnest
Sep 2007 : Complete data taking and analysis
Jan 2008 : PRL with photon regeneration limits
Jan 2009 : PRL with chameleon limits

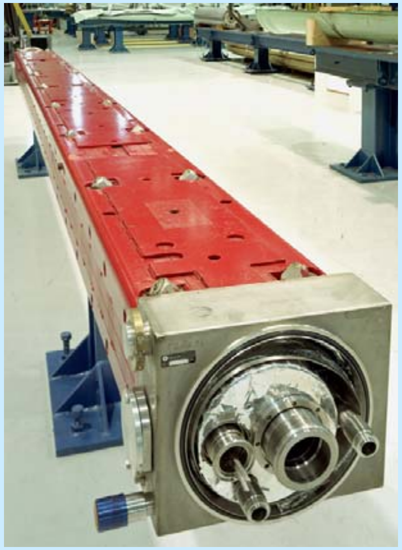
GammeV Design

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

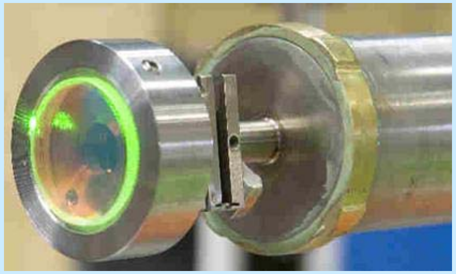




Existing laser in Acc. Div. nearly identical with a similar spare available



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

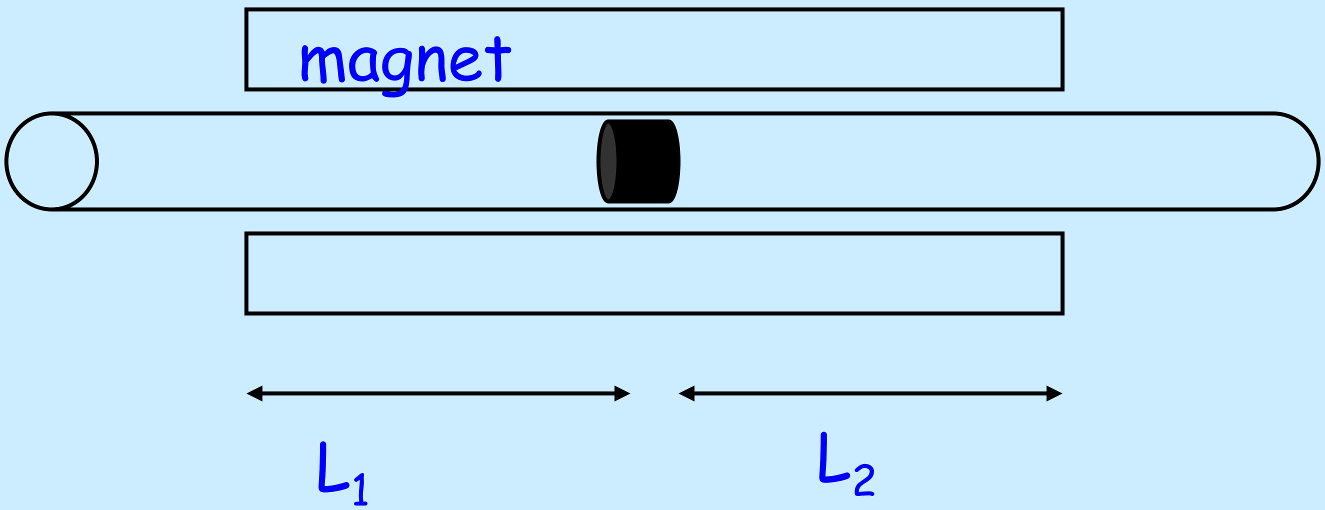


High-QE, low noise, fast PMT module (purchased)

GammeV

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

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



$$P_{\gamma\to\phi} = \frac{4B^2\omega^2}{M^2(\Delta m^2)^2}\left(\sin\frac{\Delta m^2 L}{4\omega}\right)^2$$

L = distance traversed in B field

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

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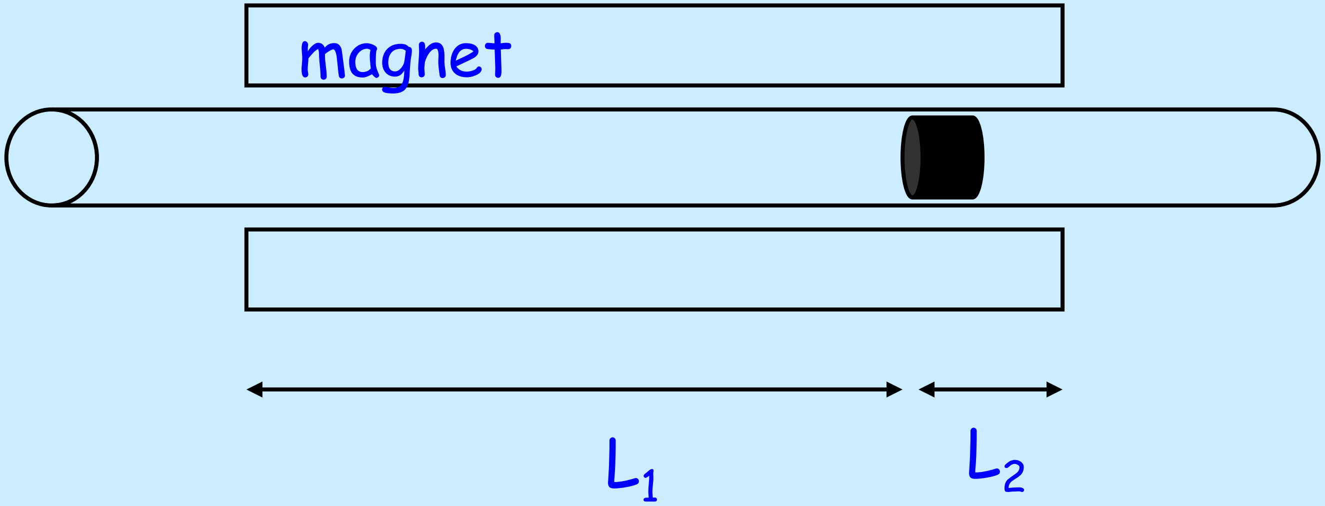

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Apparatus

Gamme**V** was located on a test stand at Fermilab’s Maget Test Facility. Two shifts/day of cryogenic operations were supported.

Laser box

Tevatron magnet

Vacuum port

Cryogenic magnet feed can

Cryogenic magnet return can

Cryogenic magnet return can

Vacuum tube connected to plunger

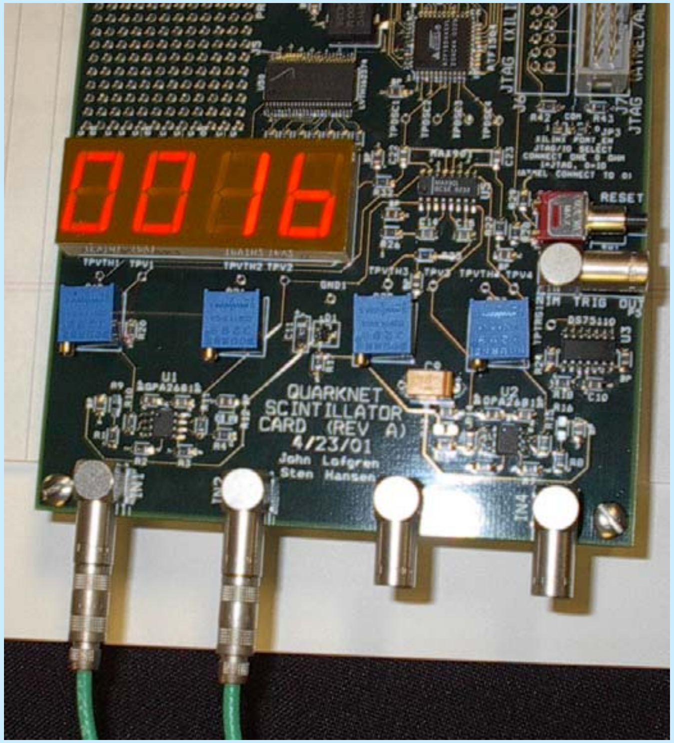
PMT box

PMT box

Lens

PMT

Data acquisition



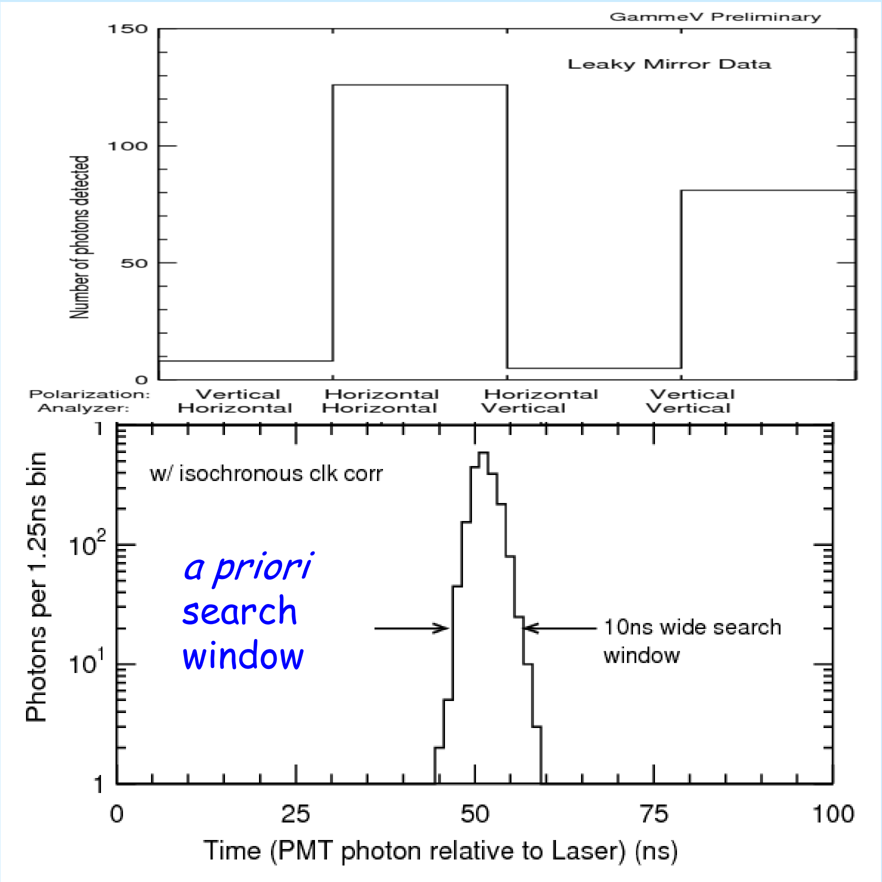
- QuarkNet timing cards
  - Built by Fermilab for Education Outreach (High School cosmic ray exp'ts.)
  - Interfaces to computer via USB (Visual Basic software for our DAQ)
- Four inputs, phase locked to a GPS 1pps using a 100MHz clock that is divided by eight for 1.25ns timing.
- Boards also send firing commands to the laser and LED pulser system
- Digital oscilloscope recorded PMT signals for LED photons and for rare coincidences.

Time the laser pulses (20Hz) and time the PMT pulses (120Hz). Look for time correlated single photons. All pulses are ~10ns wide.

	Ch0	Ch1	Ch2	Ch3
PMT Quark Net	PMT pulse	LED pulse	Scope trigger	Isochro nous CLK
Laser Quark Net	Laser Photo diode	Laser Splash	Laser Synch pulse	Isochro nous CLK

GammeV Calibration and Procedure

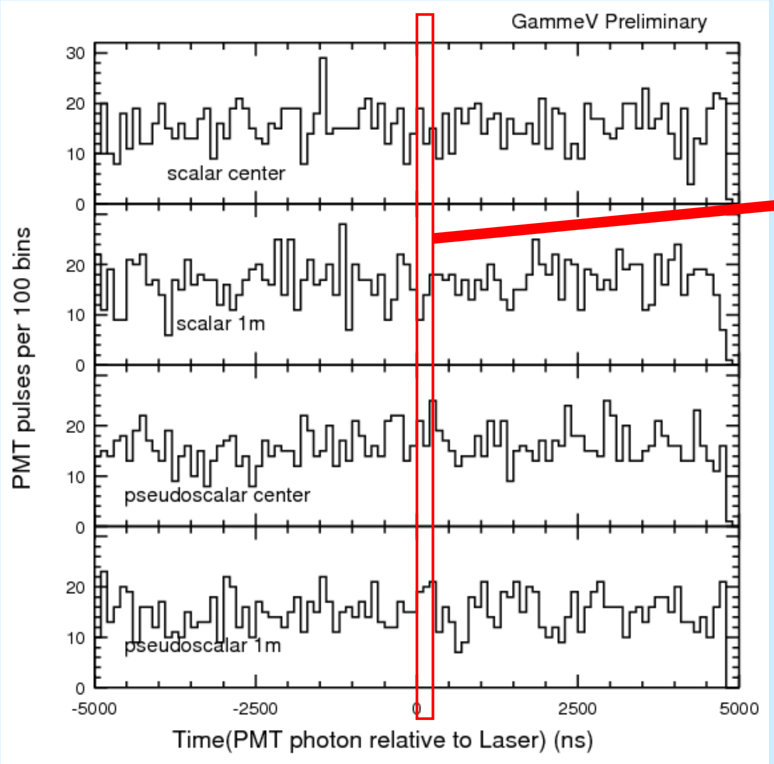
- *Leaky Mirror* data (~10^{19} attenuation to single γ's) verifies both the absolute timing and the sensitivity to polarization.
- An *a priori* search window is defined by this data

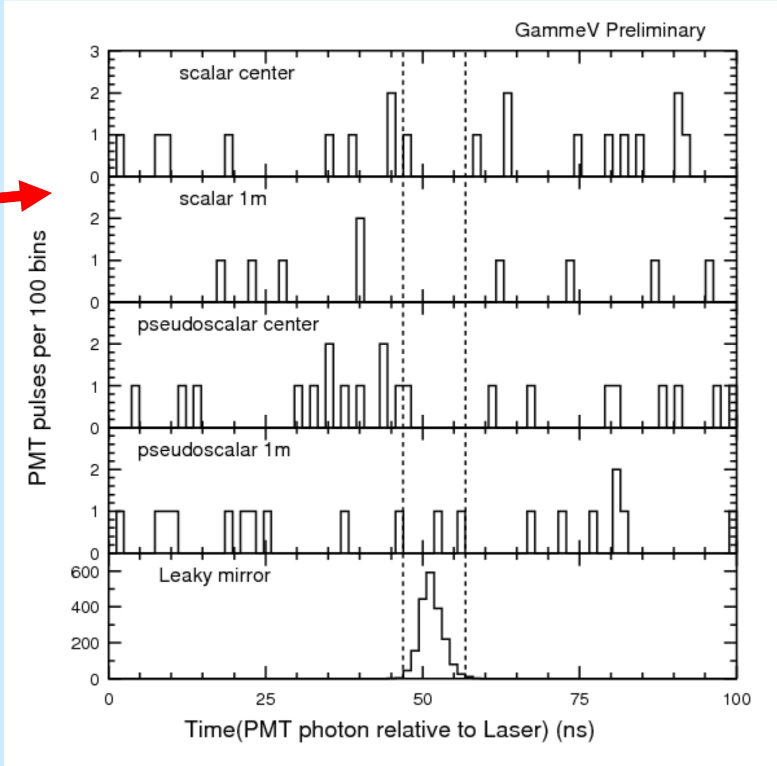


- Take data in 4 configurations
  - Scalar (with ½-wave plate) with the plunger in the center and at 1m
  - Pseudoscalar also with the plunger in the center and 1m positions
- ~20 hrs of magnet time x 4 or ~1.5M laser pulses at 20Hz.
  - Monitor laser power to +/-3%
- Total efficiency (25 +/- 3)%
  - PMT efficiencies and measured attenuation in glass and lens
- Background from a 10,000ns around the laser pulses.

GammeV Results

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

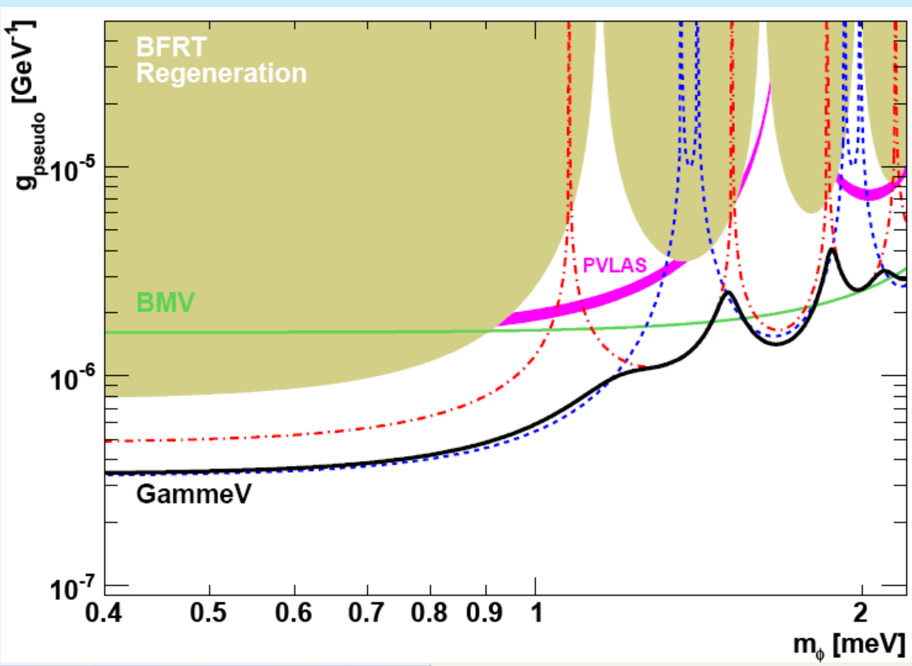




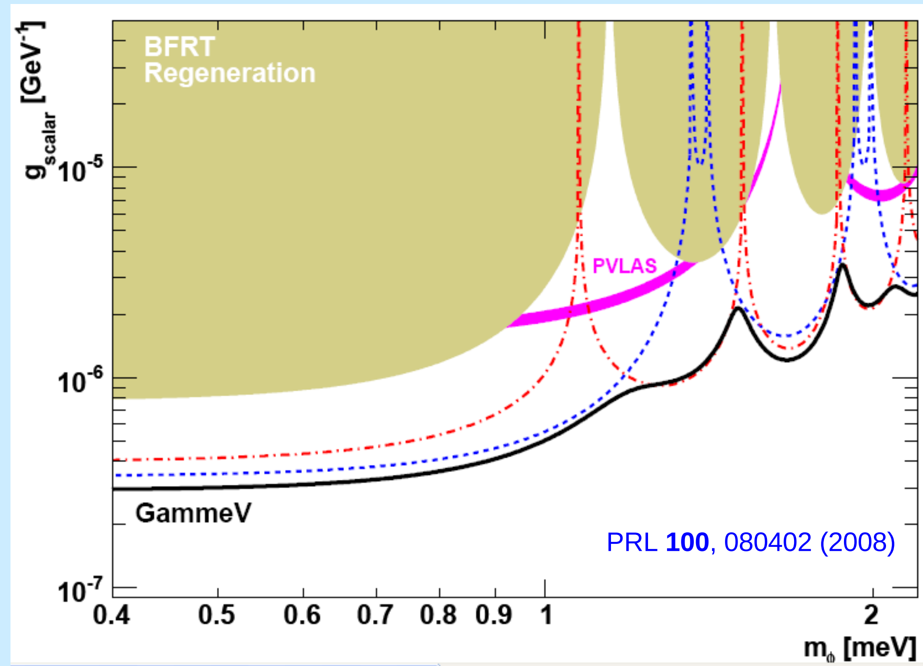
GammeV Limits

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

Pseudoscalar



Scalar



- Job is done. Limit would generally improve as the 4th root of longer running time, or increased laser power, etc.

Chameleons

- An axion-like particle with the property that its properties depend on its environment. In particular, a coupling to the stress energy tensor and a non-trivial potential result in unique properties such as a mass that depends on the ambient matter density: $m_{eff} \sim \rho^{\alpha}$.

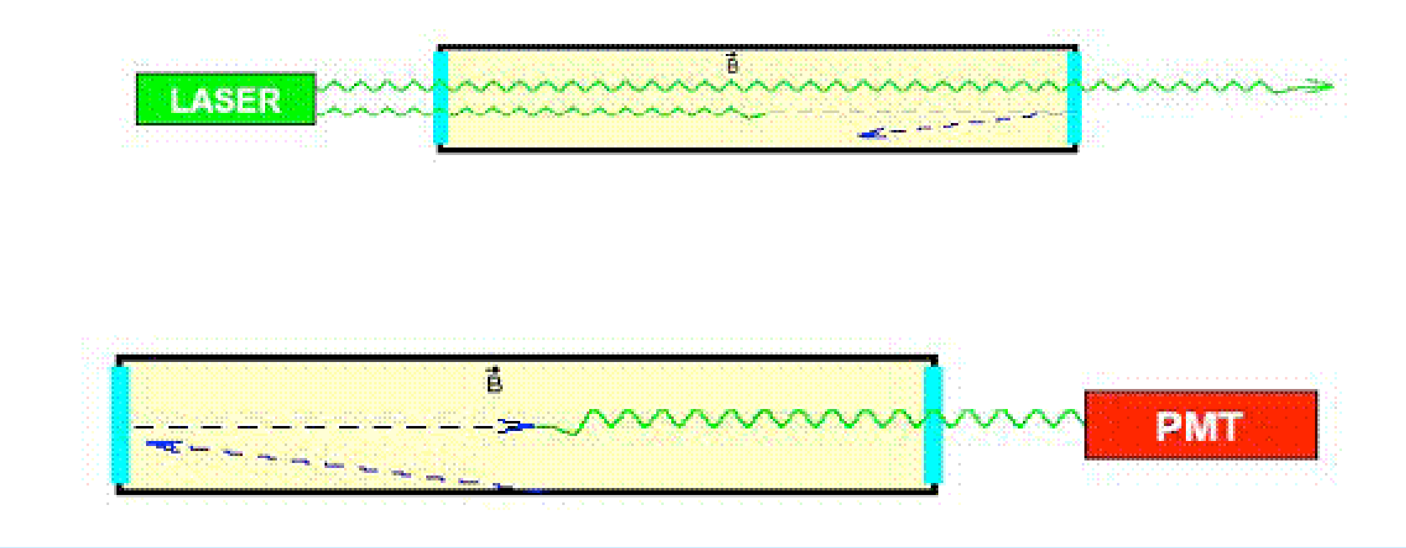
$$\mathcal{L}_{\mathrm{int}} = -V(\phi) + \exp\left(\frac{\phi}{M_D}\right) g_{\mu\nu} T^{\mu\nu} - \frac{1}{4}\frac{\phi}{M} F_{\mu\nu} F^{\mu\nu}$$

- Such a field might evade fifth force measurements and could explain how there could be an axion-like particle with a strong photon coupling which evades other bounds.

- The chameleon mechanism (Khoury and Weltman) was originally postulated as a mechanism to account for the cosmic expansion. [More theory in theory talk by P. Brax].

"Particle in a Jar"

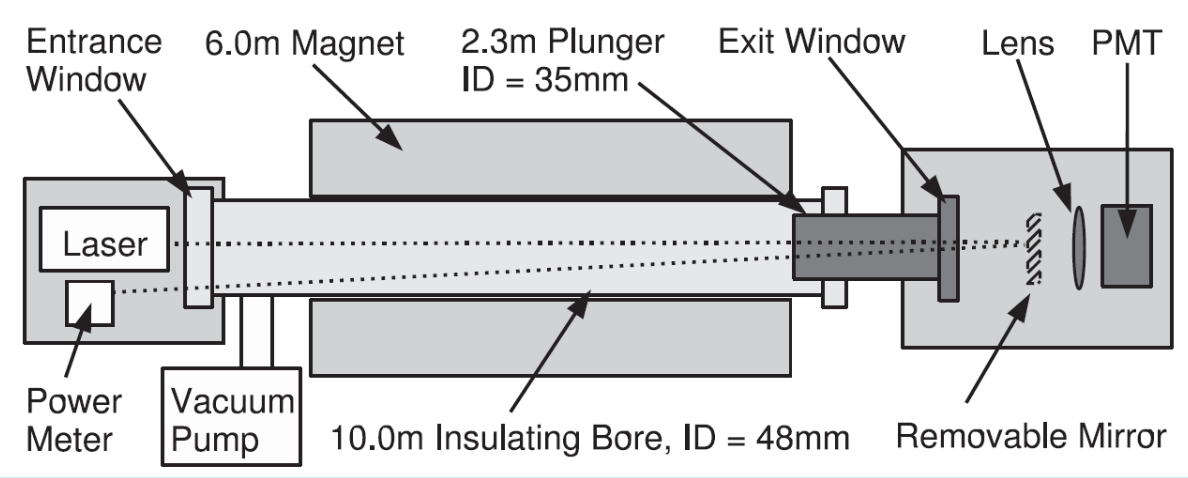
- Chameleon properties depend on their environment – effective mass increases when encountering matter.
  - A laser in a magnetic field might have photons that convert into chameleons which reflect off of the optical windows. A gas of chameleons are trapped in a jar.
  - Turn off the laser and look for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



Chameleon Search

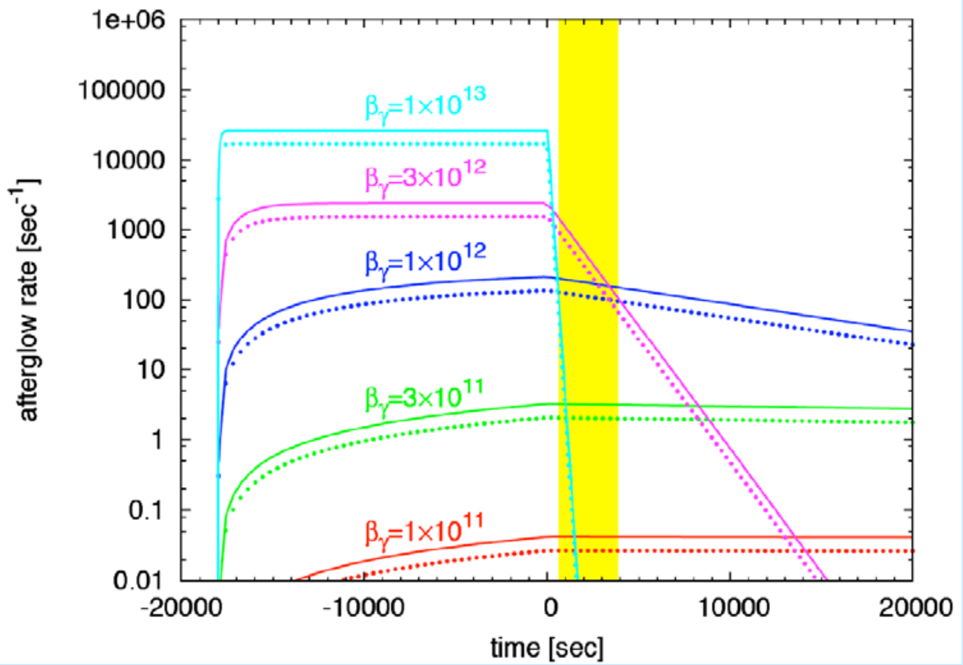
- **Apparatus**

  Replace the wall with a straight-through tube with an exit window



- **Procedure**

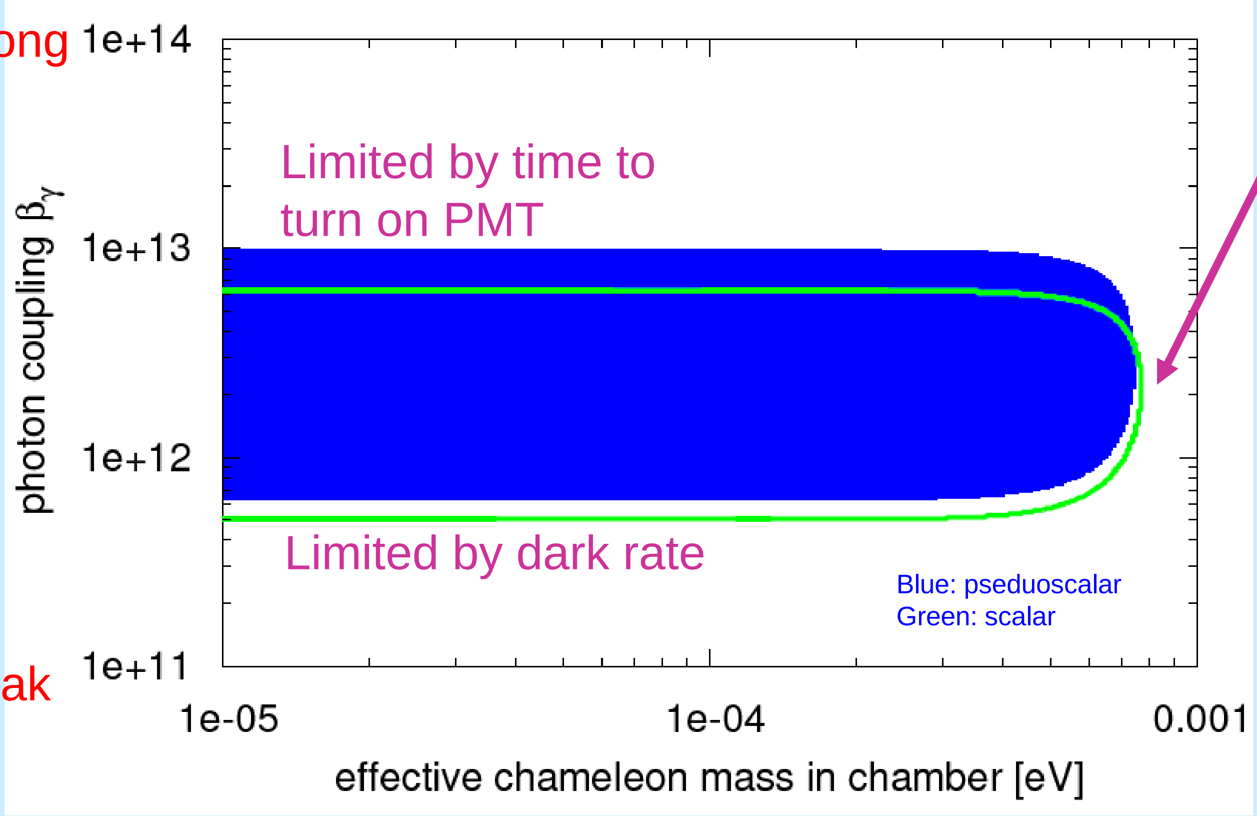
  Turn on pulsed laser for 5hrs using both polarizations. Turn off laser and look for an afterglow above PMT dark rate, either constant or exponentially decaying depending on the photon coupling.



Chameleon Results

- Coupling of photons vs m_{eff} in a region of validity

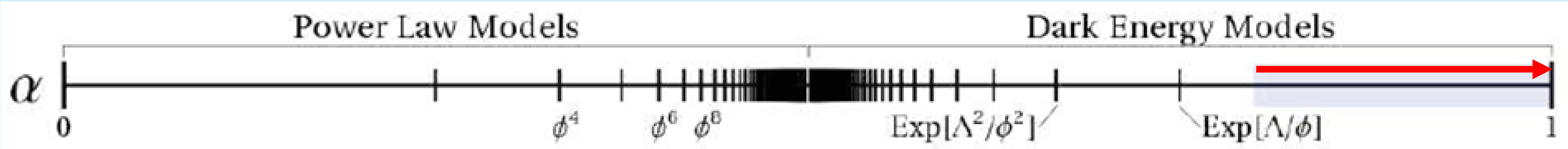
Strong



Weak

Reduced sensitivity at higher masses due to experimental configuration

Also, uncertainties in the vacuum levels limit sensitivity of possible potentials, with $m_{eff} \sim \rho^\alpha$, $\alpha > 0.8$.



New proposal (Fall 2009)

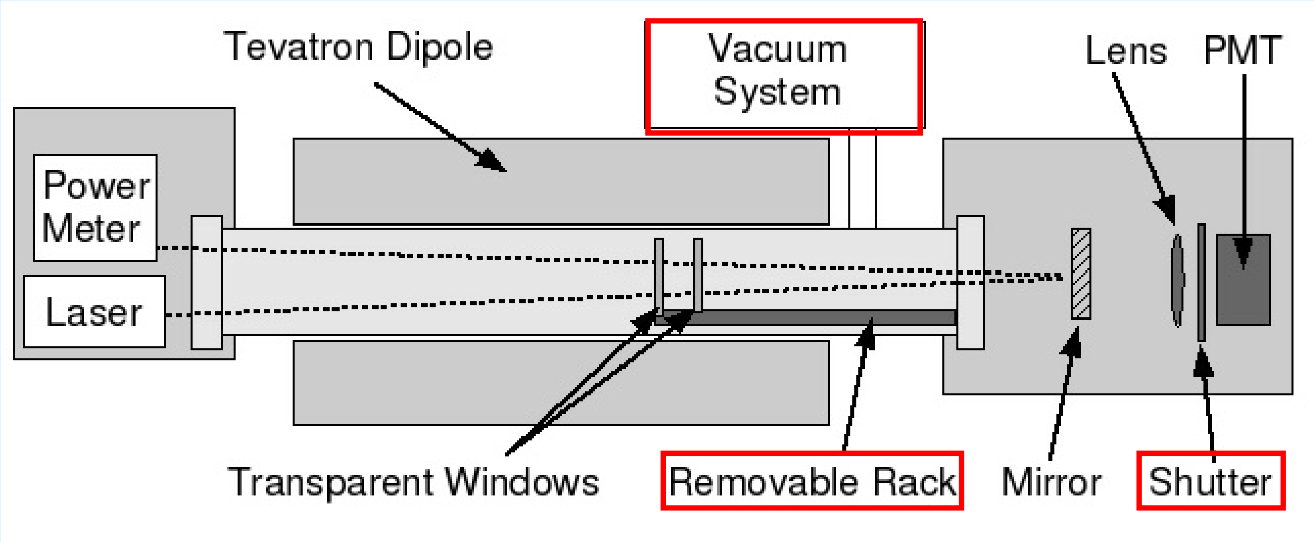
- GammeV – CHASE: Chameleon Afterglow Search

Improve vacuum (cryo pump) and monitoring.

Use a shutter to switch to PMT readout quickly.

Use a run plan that with lower B fields in case the coupling is strong.

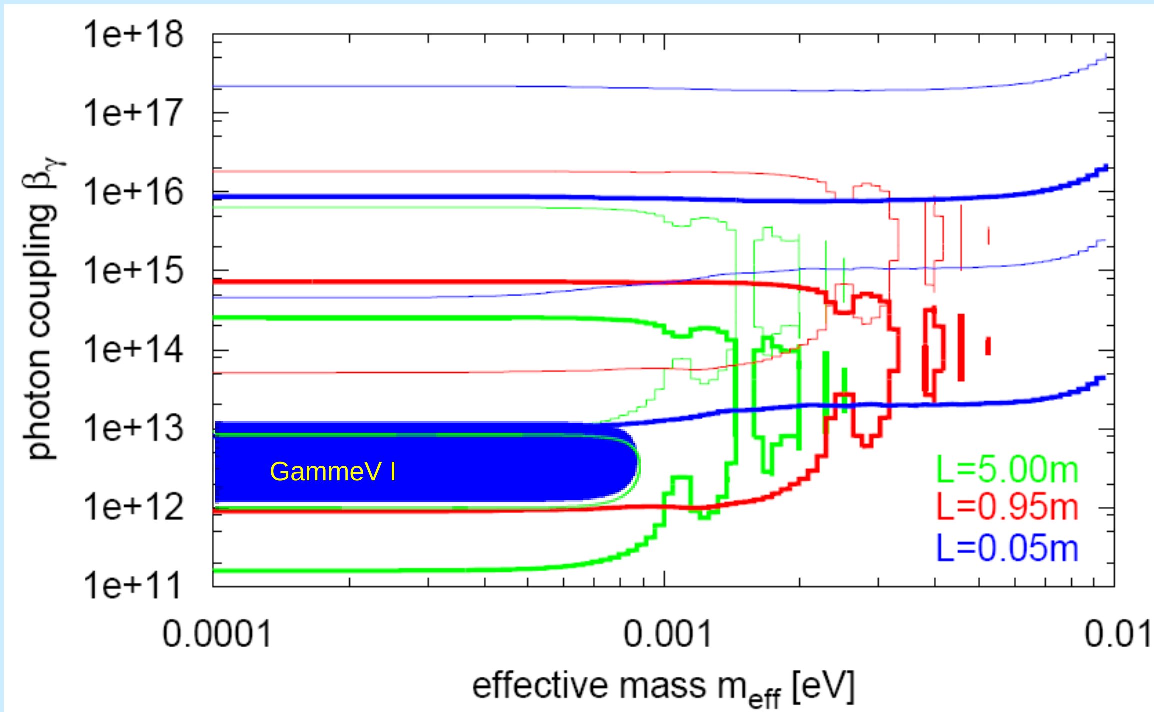
Use a lower noise PMT.



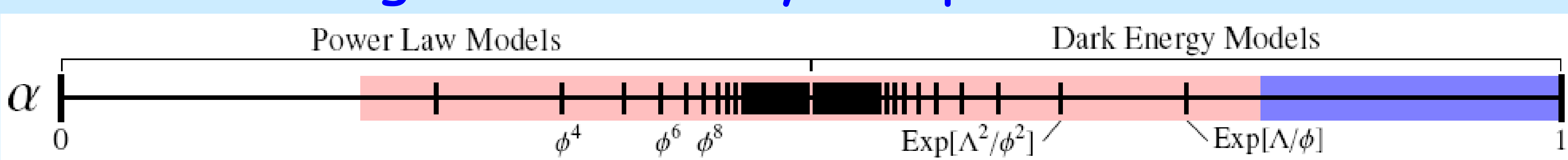
Employ the “dish rack” to effectively have 5m, 95cm, 5cm magnetic field regions -a bit of cleverness similar to the plunger idea to be initially sensitive to a wider range of chameleon masses.

Goal: Extend the Chameleon Limits

- Extend the sensitivity in coupling vs mass.



- Extend region of validity for potential models.



GammeV

Future initiatives

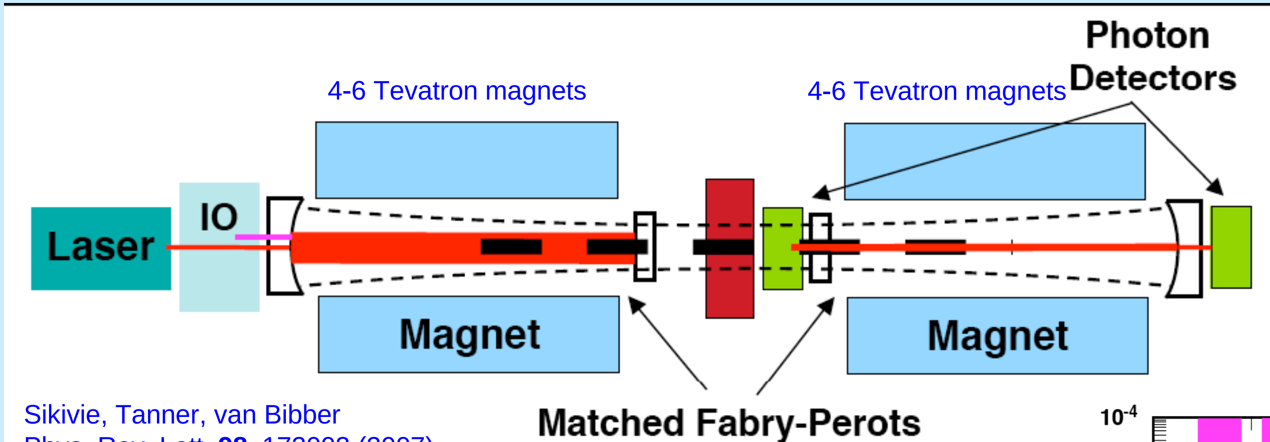
- Small scale experiments exploring a new region of parameter space have great potential especially when motivated by other observations.

- For ALPs, $g_{a\gamma\gamma}$~10^{-11} is potentially motivated by astrophysical observations that the universe is more transparent than expected and is a factor of several below CAST bounds at low m_a. Talks on Friday

- Leveraging our success with GammeV, we are beginning to pursue more ambitious endeavors and have received some funding and support.

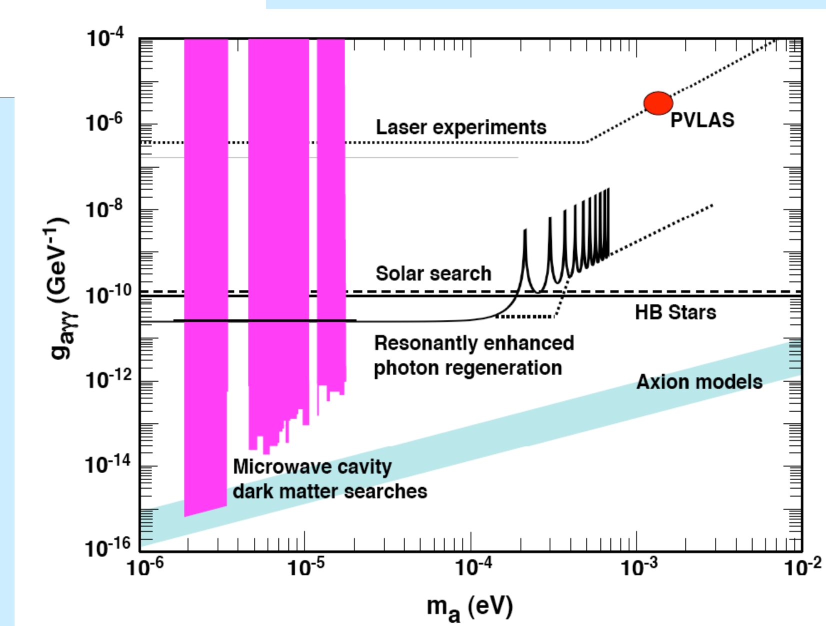
Next ALP search

Resonantly enhanced axion-photon regeneration



Sikivie, Tanner, van Bibber
Phys. Rev. Lett. **98**, 172002 (2007)

Probability of regeneration goes as the product of finesse's: $\mathcal{F}\mathcal{F}$



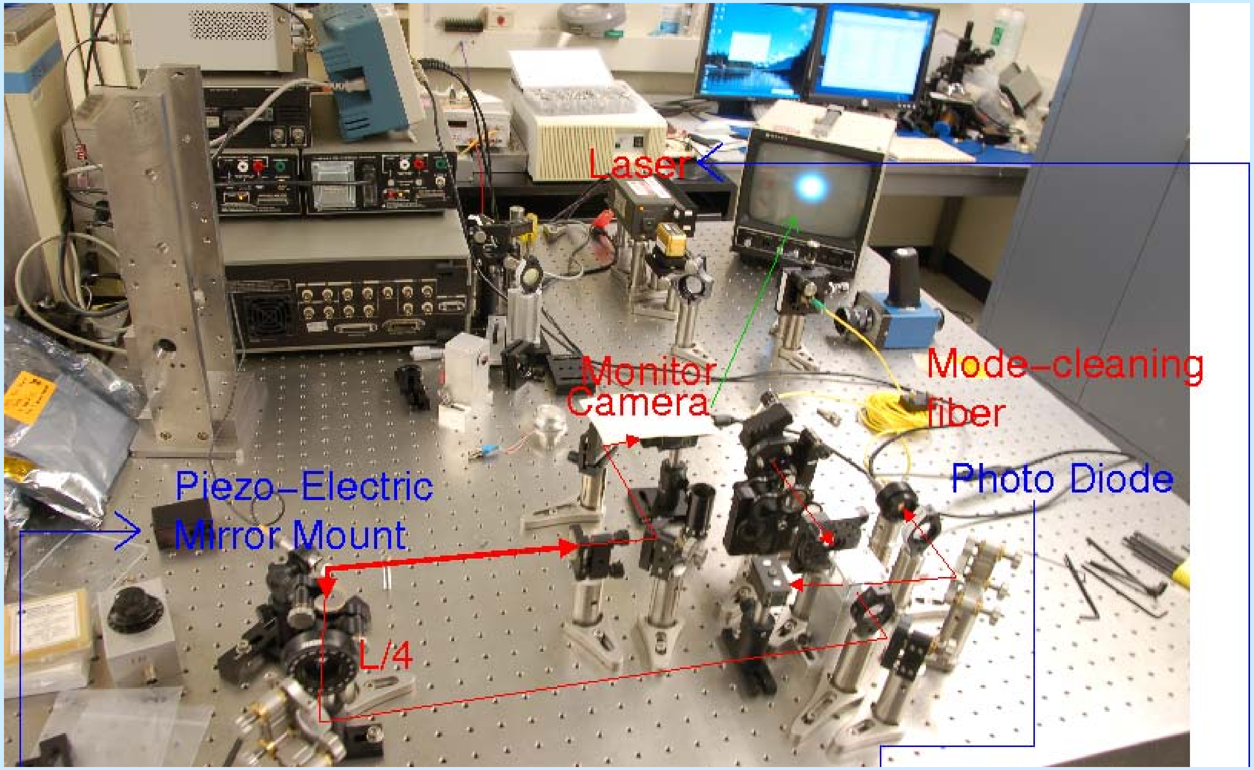
Possibility that this technique might exceed star / CAST limits.

More details in Dave Tanner's talk.

We are thinking about a new idea that dark matter ALPs could induce sidebands in an optical cavity.
A. Melissinos, PRL **102**, 202001 (2009)

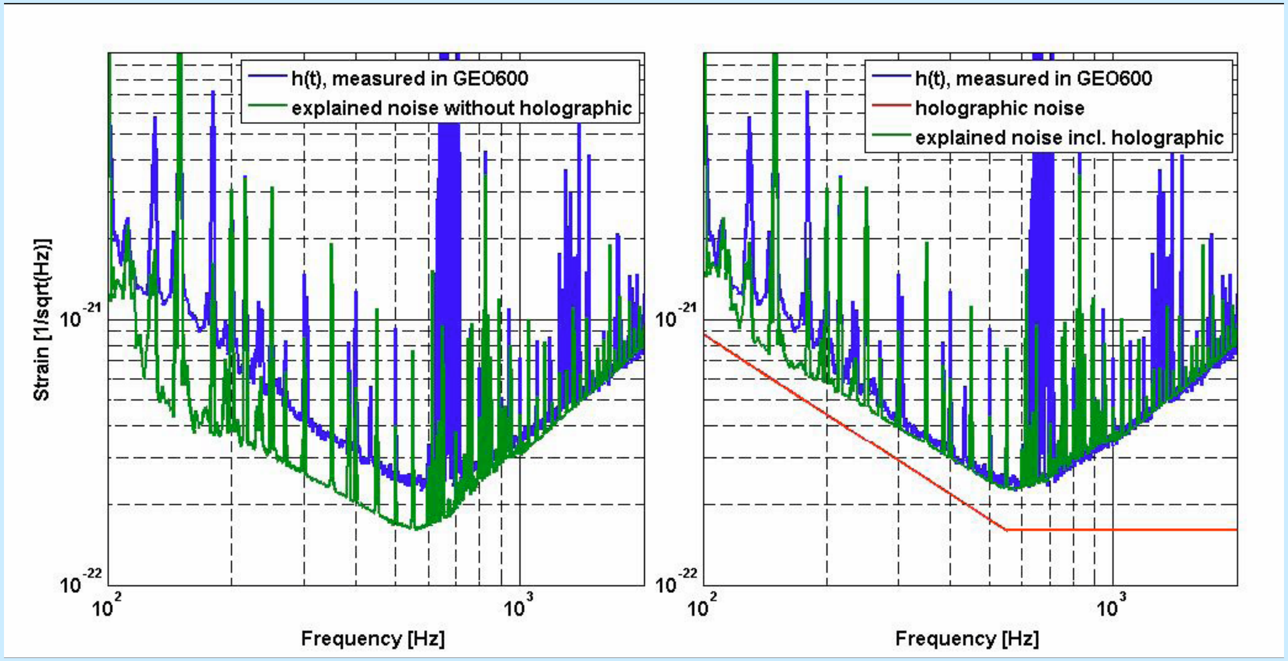
Preparations

- Work with interferometers, optical cavities, locking schemes and other optical techniques.
  - Enhanced team with new interested scientists and collaborators – some from the gravity wave community.



Holographic Noise

- A new indeterminacy due to Planck scale effects would cause a correlated noise in two close-by interferometers.
- Theory is based upon the holographic principle as invoked in black hole physics and the information paradox.
- Possible hint of this effect in GEO600 data.

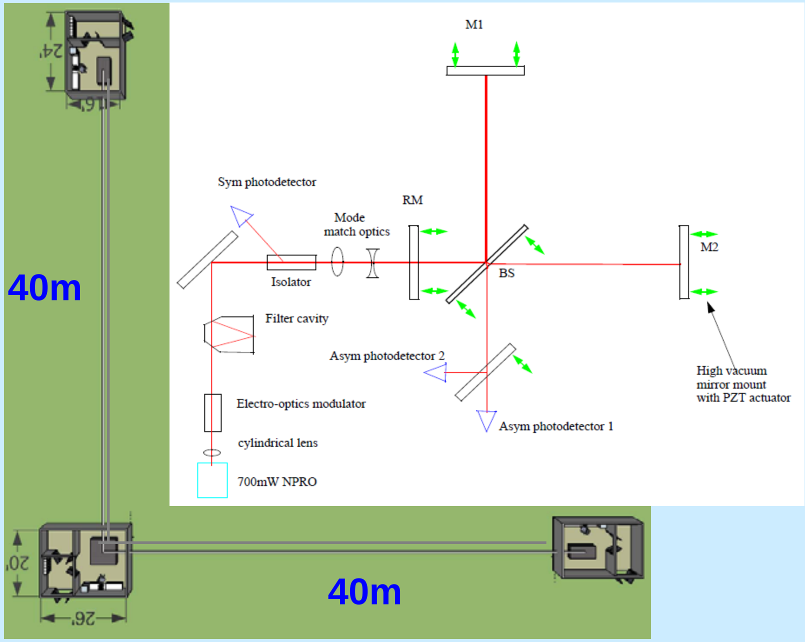


At f>600 Hz, a 0-parameter prediction invoking the expected holographic noise, explains nearly all of the "mystery noise."

A detailed analysis is in progress.

A Quantum Holometer

- A proposed experiment is to build two interferometers with ~40m arms to search for the correlated holographic noise and to observe its predictable decorrelation when the geometry of the interferometer is re-arranged.



$$l_P = \sqrt{\hbar G_N / c^3} = 1.616 \times 10^{-33}\mathrm{cm}$$

$$\Delta x_\perp^2 > l_P L$$

C. Hogan, "Holographic Noise in Interferometers"
http://arxiv.org/abs/0905.4803

- A new team including LIGO experts at MIT and Caltech are collaborating. Initial reviews at FNAL are positive.

Summary

PRL 100, 080402 (2008) PHYSICAL REVIEW LETTERS week ending 29 FEBRUARY 2008

Search for Axionlike Particles Using a Variable-Baseline Photon-Regeneration Technique

A. S. Chou,[1,2] W. Wester,[1] A. Baumbaugh,[1] H. R. Gustafson,[3] Y. Irizarry-Valle,[1] P. O. Mazur,[1] J. H. Steffen,[1] R. Tomlin,[1] X. Yang,[1] and J. Yoo[1]

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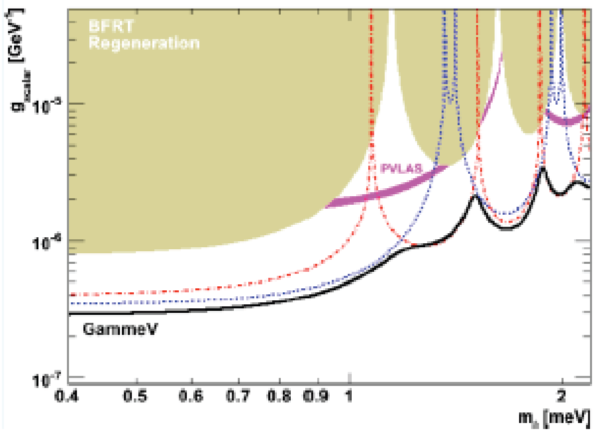
(Received 24 December 2007; published 25 February 2008)



Rules out anomalous PVLAS signal.
Limits also set on photon-paraphoton coupling.

PRL 102, 030402 (2009) PHYSICAL REVIEW LETTERS week ending 23 JANUARY 2009

Search for Chameleon Particles Using a Photon-Regeneration Technique

A. S. Chou,[1] W. Wester,[2] A. Baumbaugh,[2] H. R. Gustafson,[3] Y. Irizarry-Valle,[2] P. O. Mazur,[2] J. H. Steffen,[2] R. Tomlin,[2] A. Upadhye,[4] A. Weltman,[5,6] X. Yang,[2] and J. Yoo[2]

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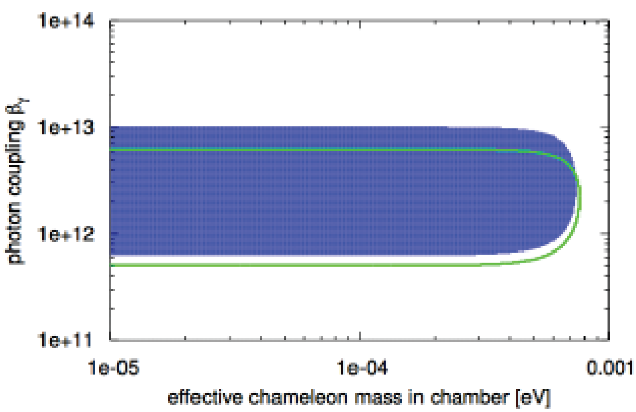
(Received 1 August 2008; published 22 January 2009)



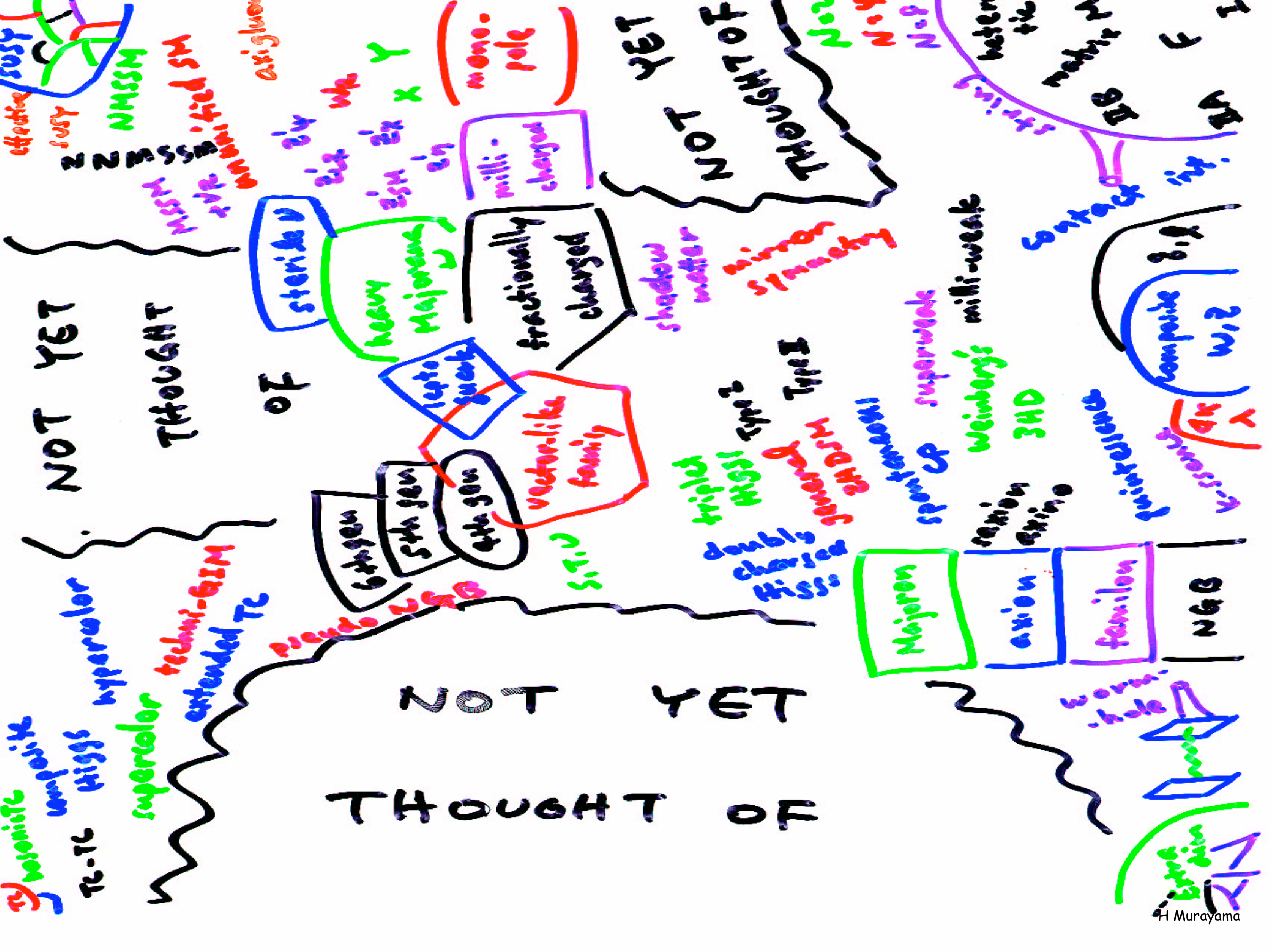
First-ever laser search for chameleons.
Upgrade with improved vacuum is planned.

Conclusions

- At FNAL, a small group of us had fun a couple summers ago. There were days I went into work thinking today *might* be the day that a new revolutionary particle might appear.
- We achieved the goal of excluding a region of interest for an axion-like particle with a high confidence level.
- We made a first search for chameleon particles.
- A new search for chameleons will employ lessons learned from our first project. Expect to start this Fall.
- Next experiments are much more ambitious and we are starting to get experience with optical cavities and interferometers. New lab support and new collaborators.
- Finally, just as theories abound for what the new physics might be, there are an abundance of experiments that can explore untested regions of parameter space.

gammev.fnal.gov

H Murayama


NOT YET THOUGHT OF
sterile ν
heavy Majorana ν
fractionally charged
milli-charged
mono-pole
vector-like family
4th gen
5th gen
6th gen
Majoron
axion
familon
NGB
doubly charged Higgs
triplet Higgs
spontaneous CP
Weinberg's 3HD
superweak
milli-weak
shadow matter
mirror symmetry
contact int.
hypercolor
supercolor
extended TC
techni-GIM
composite Higgs
TC-TC
worm-hole
Extra dim
NMSSM
NNMSSM
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