GammeV

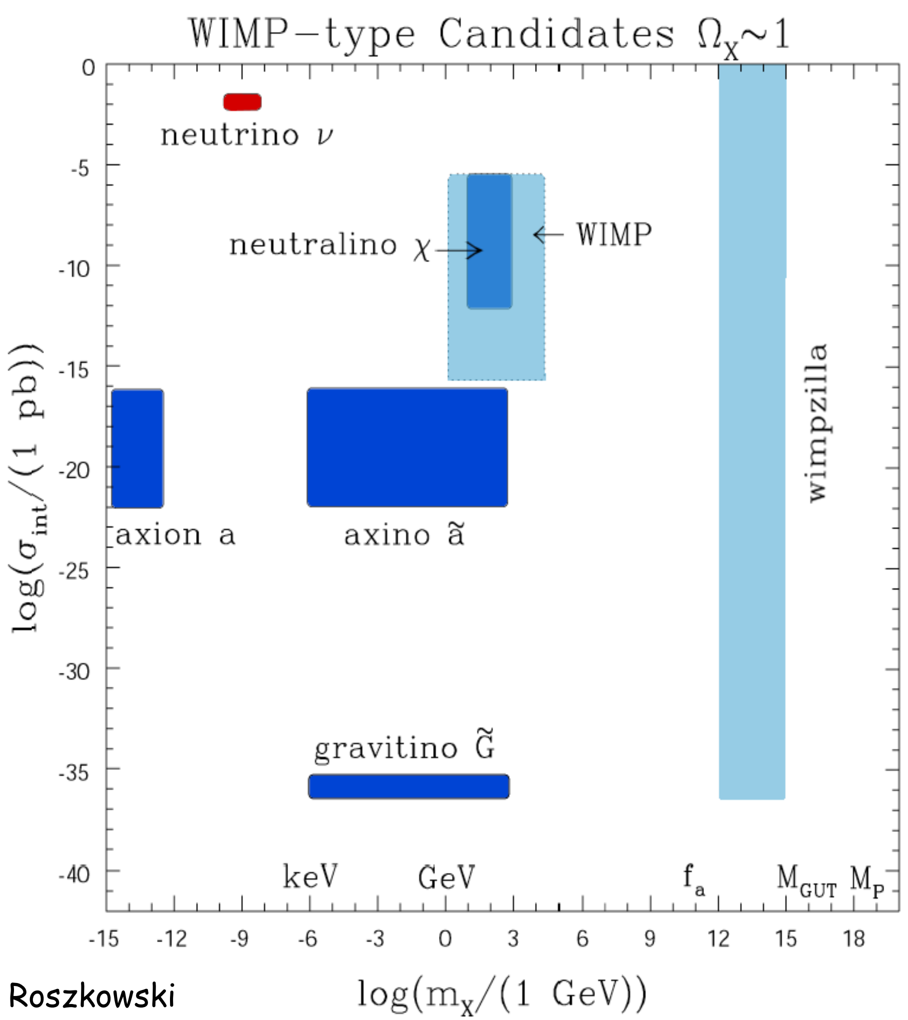
Gamma to milli-eV particle search
Photon regeneration results

William Wester
Fermilab

H Murayama

Dark Matter

- What is the dark matter of the universe?



L. Roszkowski

Dark Matter

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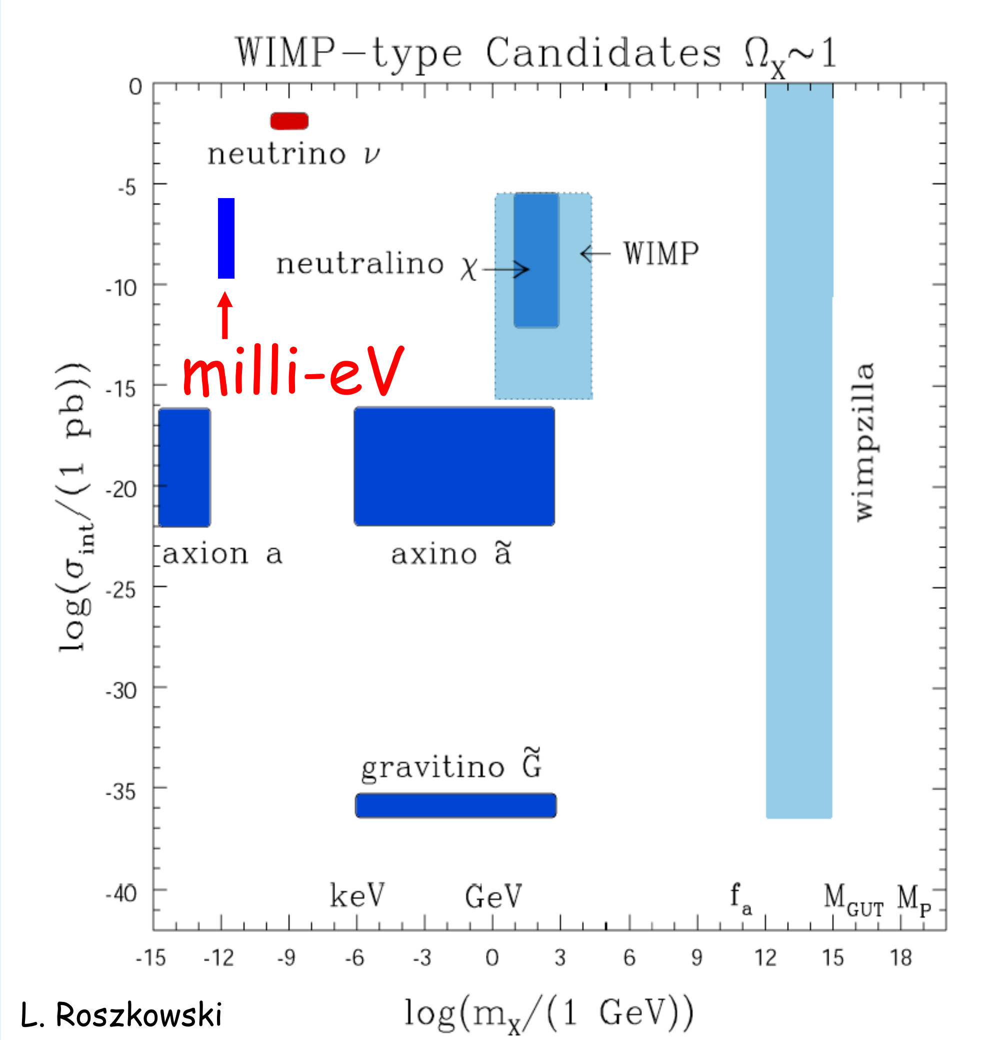
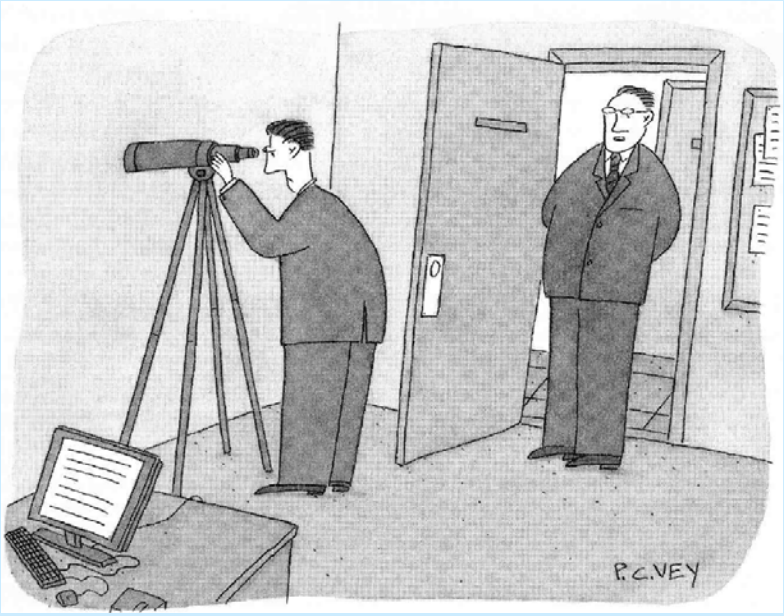


Outline

- Physics motivation for our experiment
  - milli-eV mass scale
  - PVLAS anomaly
- "Light shining through a wall"
  - Past Experiments
  - **G**amme**V**
- Results
  - Photon Regeneration
- Conclusions



New Yorker

GammeV

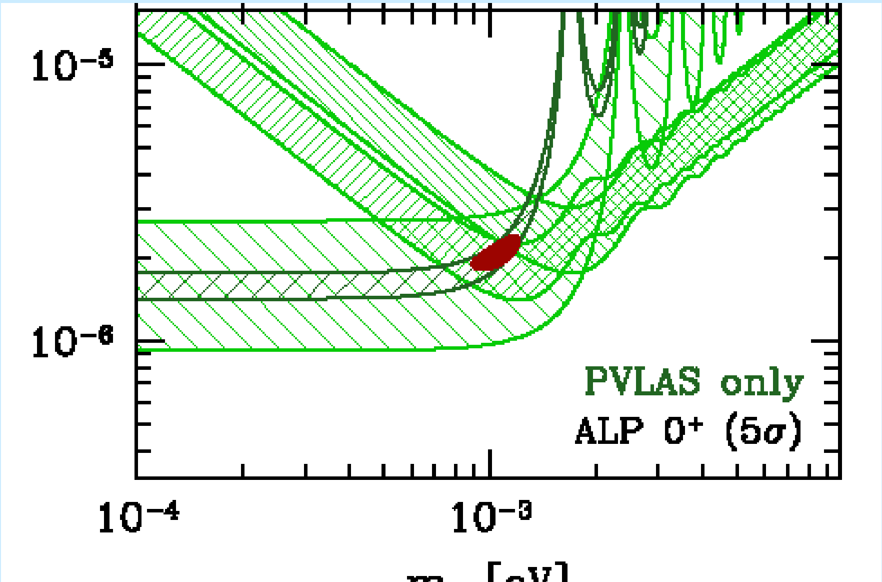
milli-eV Mass Scale

- 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 ~ $(2\times10^{-3}$ eV$)^4$
  - Neutrinos
    - $(\Delta m_{21})^2 = (9\times10^{-3}$ eV$)^2$
    - $(\Delta m_{32})^2 = (50\times10^{-3}$ eV$)^2$
  - See-saw with the TeV scale:
    - meV ~ TeV^2/M$_{planck}$ String theory
  - Dark Matter Candidates
    - Certain SUSY sparticles (low mass gravitino)
    - Axions and axion-like particles

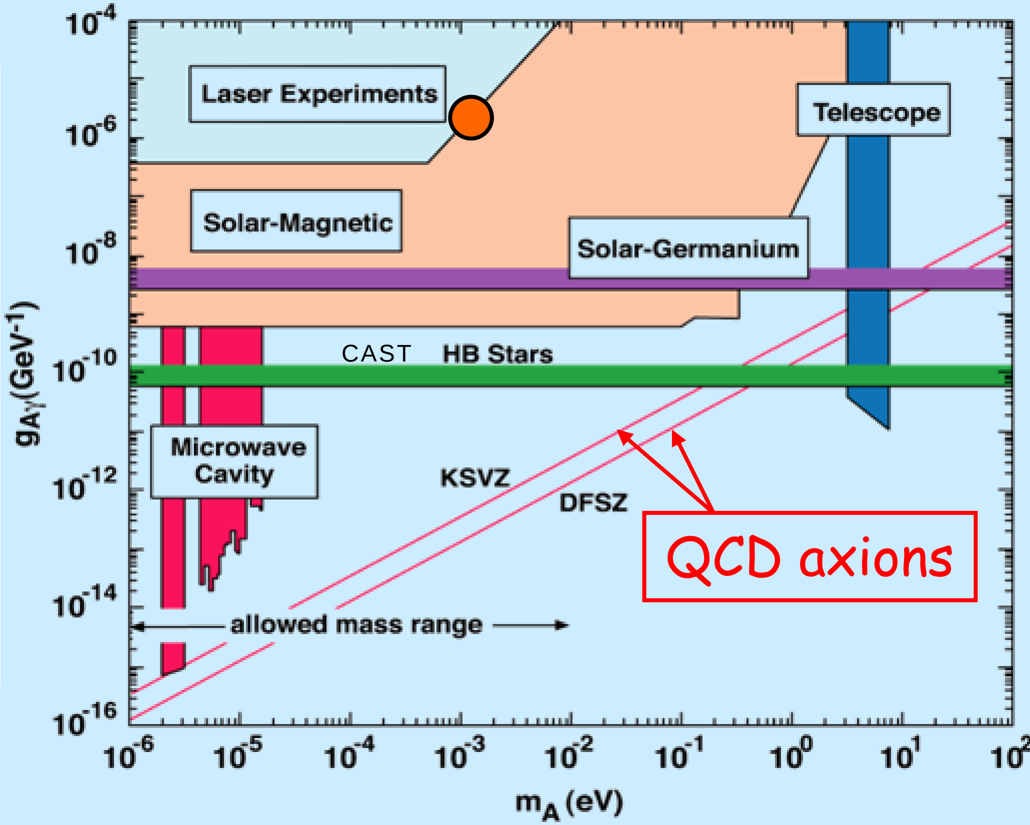
Energy frontier
Neutrinos
Astrophysics
all in one!

PVLAS ALP Interpretation

A new axion-like particle with mass at 1.2 meV and g~2x10^{-6} is consistent with 2006 reported PVLAS rotation and ellipticity measurements.

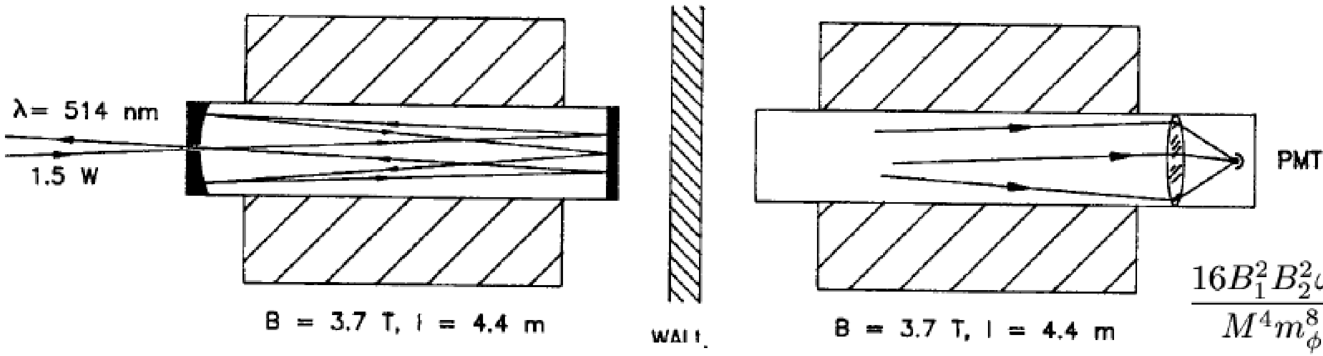


PRD **75**, 035011 (2007)

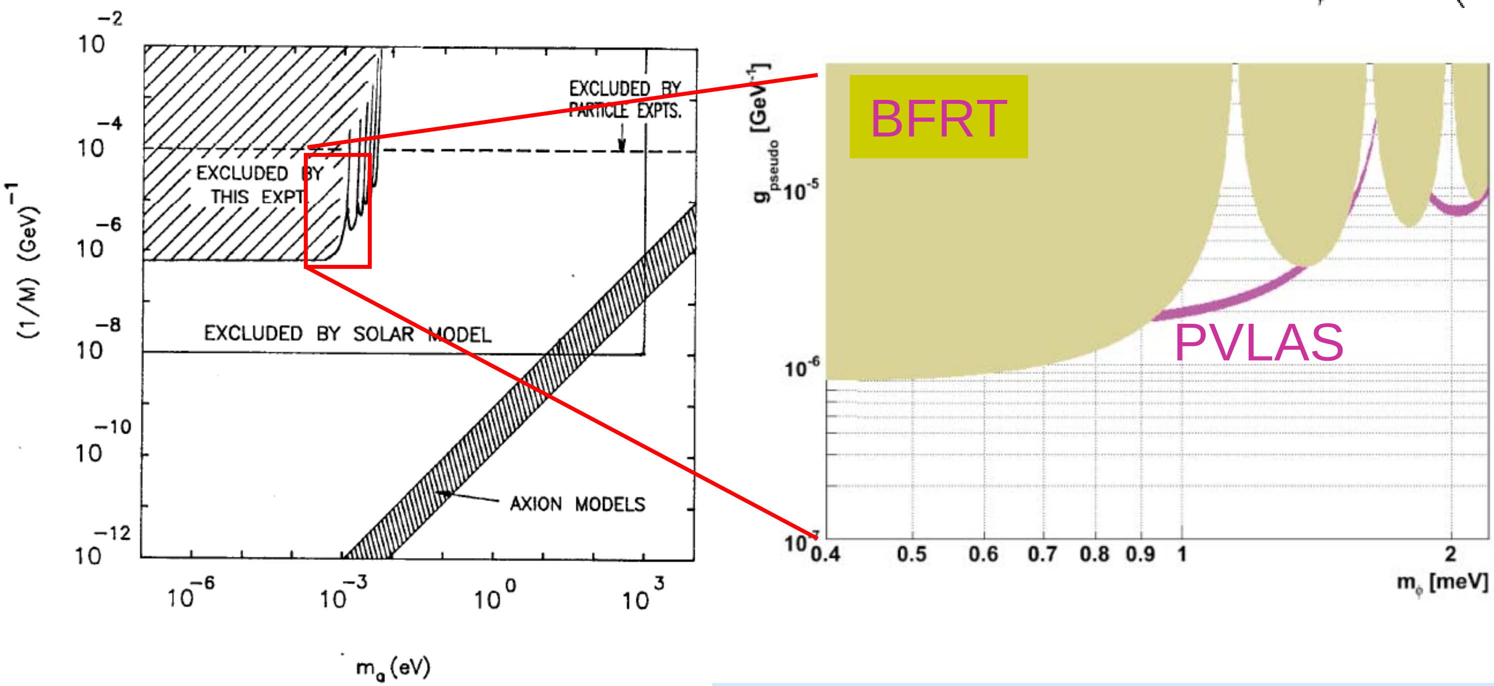


BFRT Experiment

- Brookhaven, Fermilab, Rochester, Trieste (1992)

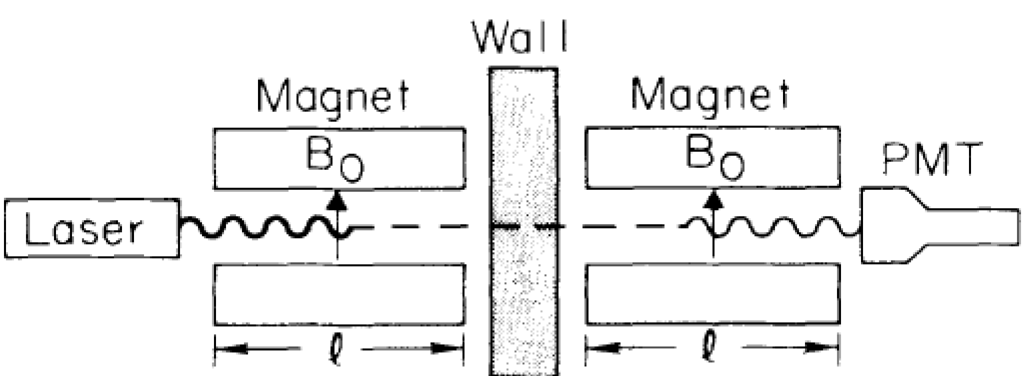


$$\frac{16 B_1^2 B_2^2 \omega^4}{M^4 m_\phi^8} \sin^2\left(\frac{m_\phi^2 L_1}{4\omega}\right) \cdot \sin^2\left(\frac{m_\phi^2 L_2}{4\omega}\right)$$

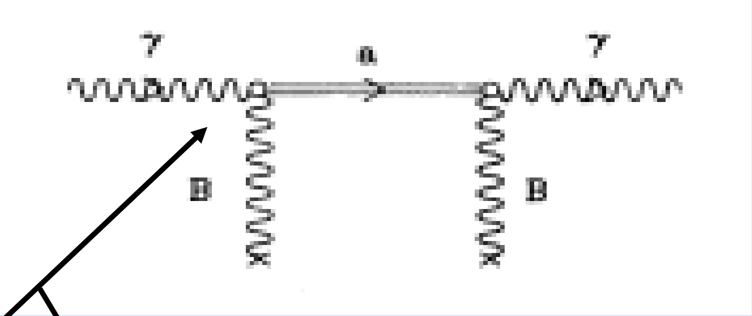


BFRT is not sensitive in the PVLAS region of interest.

Light Shining Through a Wall Experiment



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



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

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

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

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

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

GammeV Collaboration

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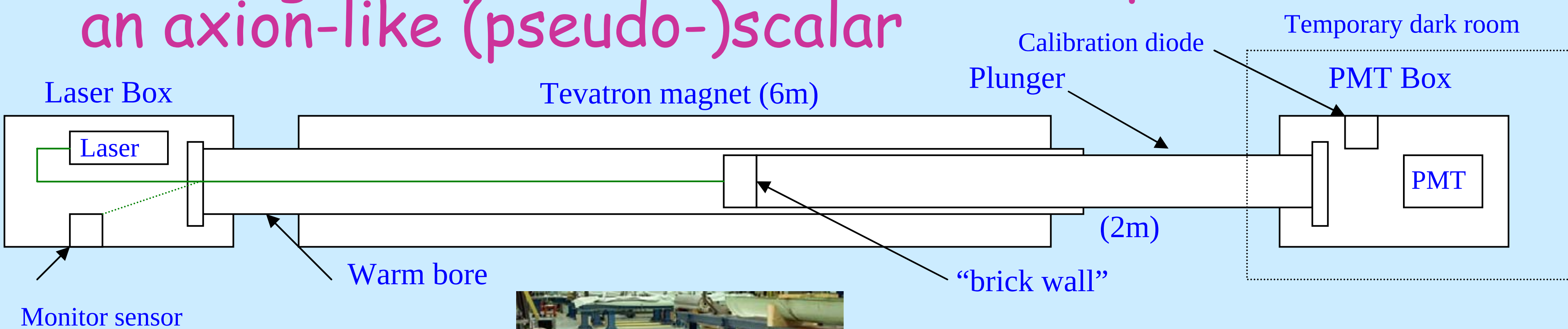
D. Gustafson
University of Michigan
Ann Arbor, MI 48109

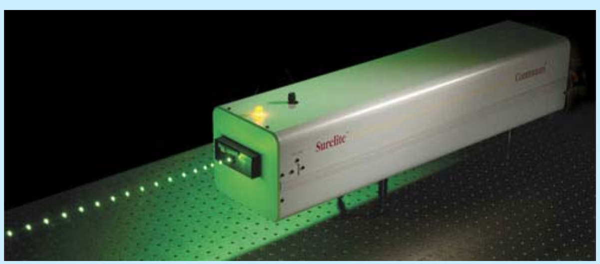
Ten person team including a summer student, 3 postdocs, 2 accelerator / laser experts, 4 experimentalists (nearly everyone had a day job) PLUS technical support at FNAL

Nov 2006 : Initial discussion and design (Aaron Chou, WW
Apr 2007 : Review and approval from Fermilab ($30K
May 2007 : Acquire and machine parts
Jun 2007 : Assemble parts, test electronics and PMT
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

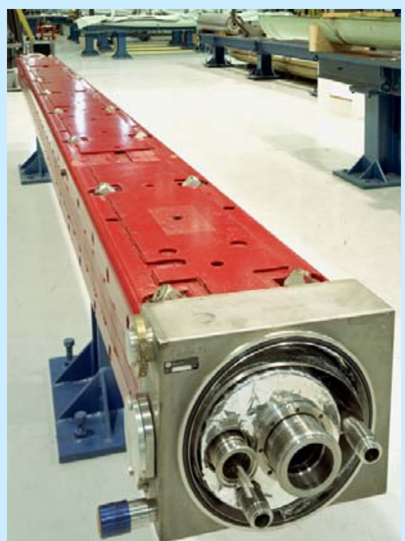
GammeV Proposal

Search for evidence of a milli-eV particle in a light shining through a brick 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)

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

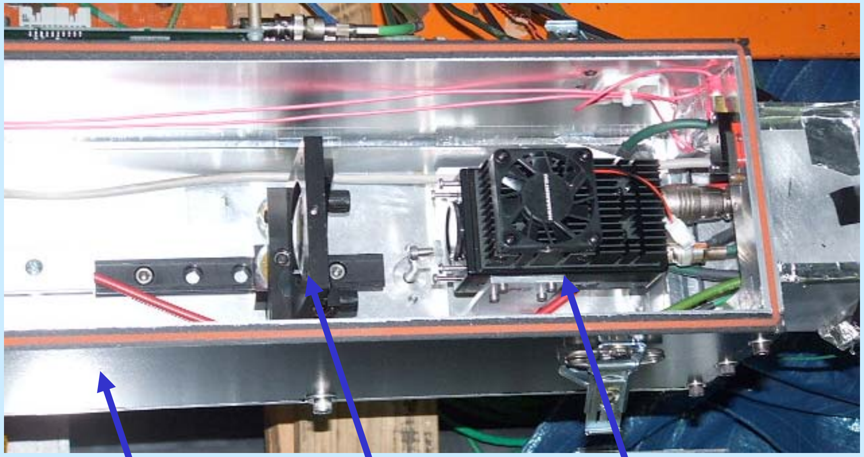
Cryogenic magnet feed can

Cryogenic magnet return can

Cryogenic magnet return can

Vacuum tube connected to plunger

PMT box



PMT box

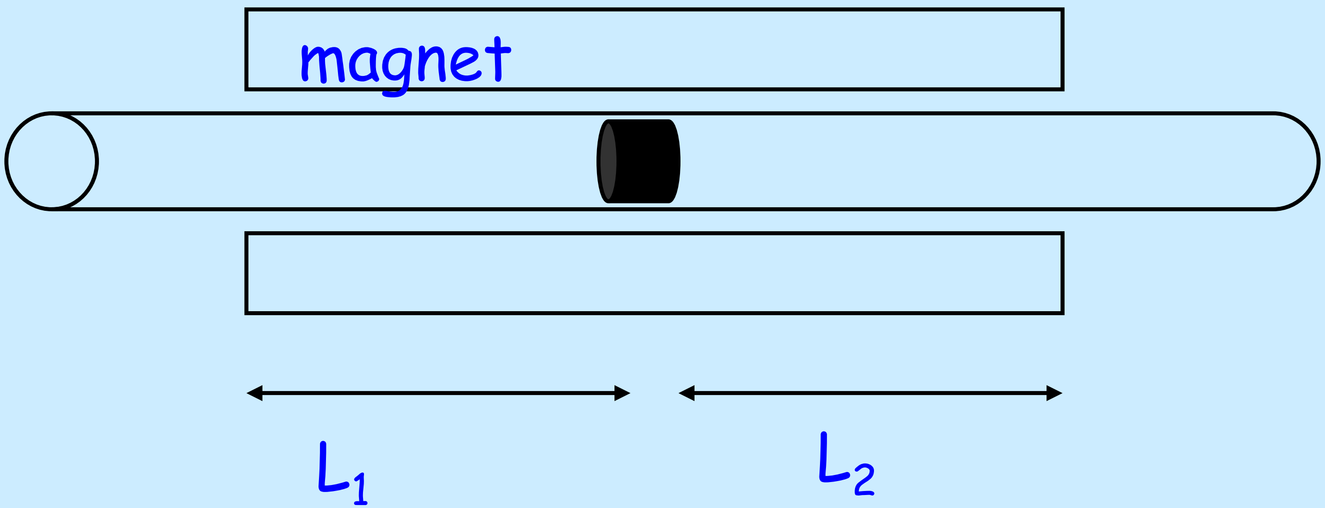
Lens

PMT

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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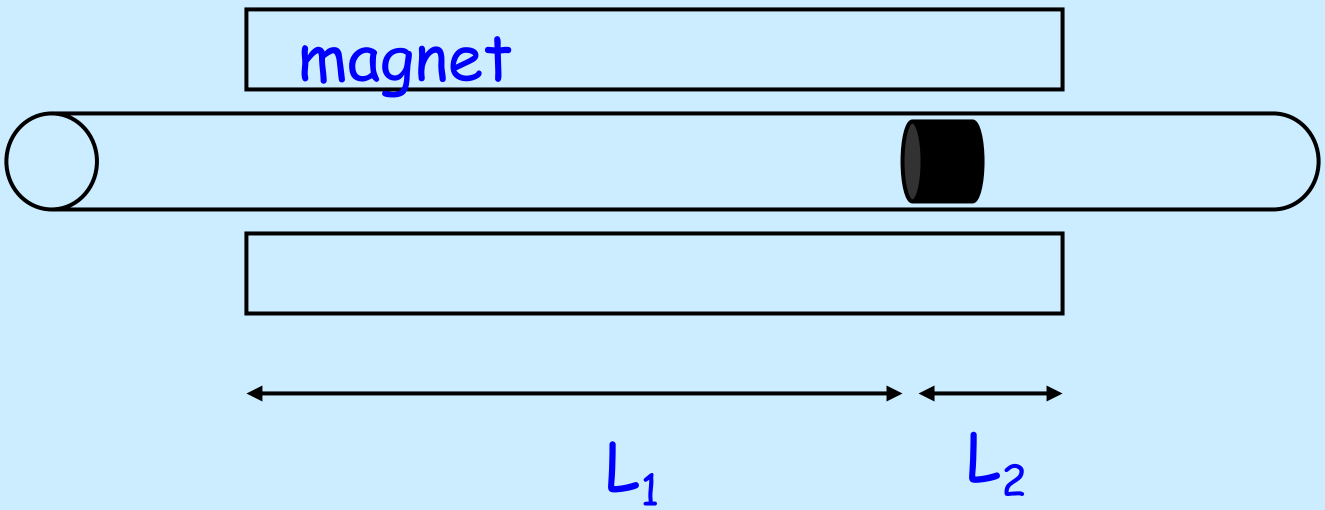

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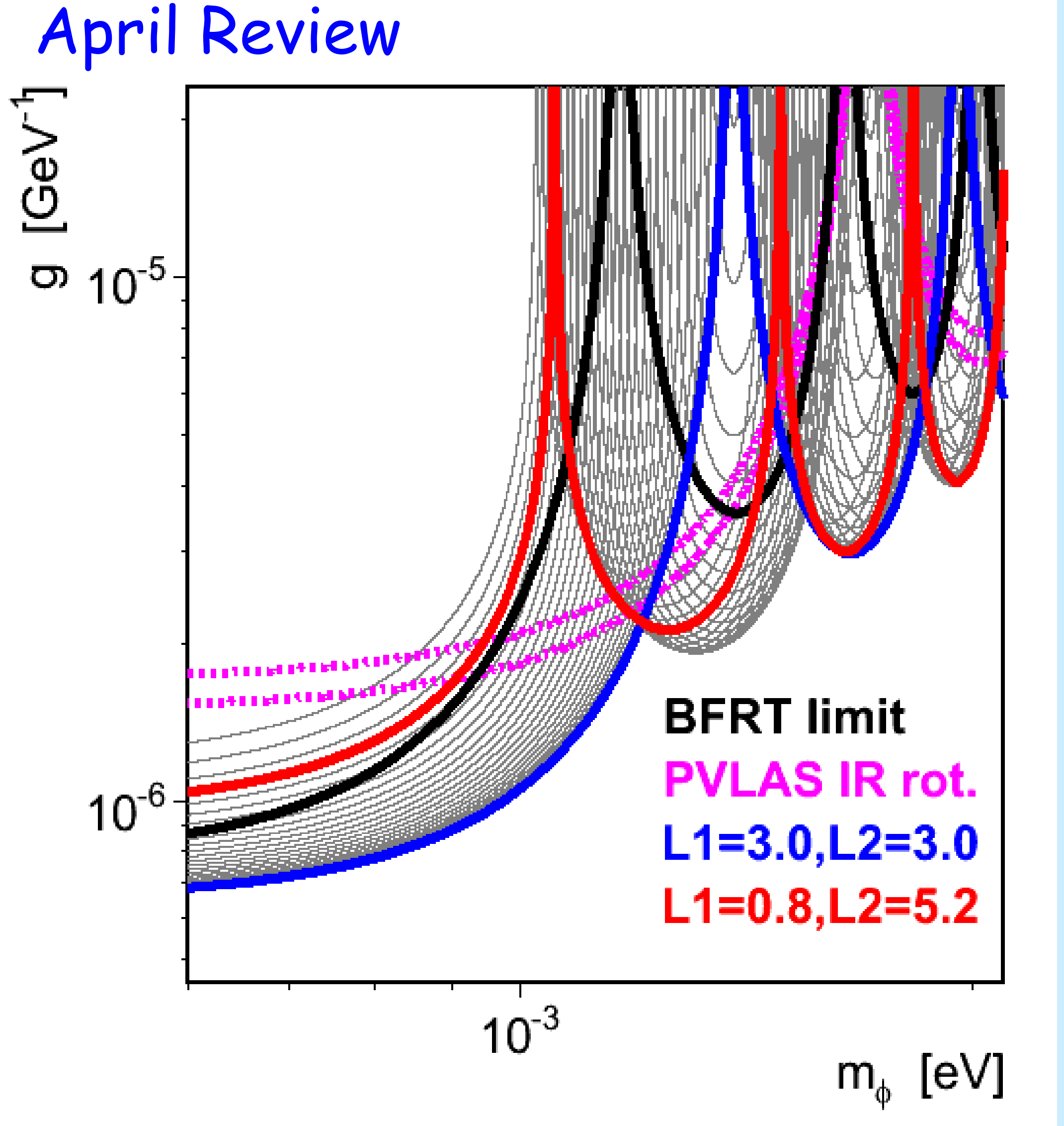
Expected Sensitivity

- Black = BFRT 3 sigma upper bound
- Pink = PVLAS 3 sigma signal region
- Grey = FNAL 3 sigma exclusion with 5 hours running at each beam dump position
  - Blue = center of magnet
  - Red = 0.8m from end
- **By changing the baseline, we cover the entire PVLAS signal region**



Laser box

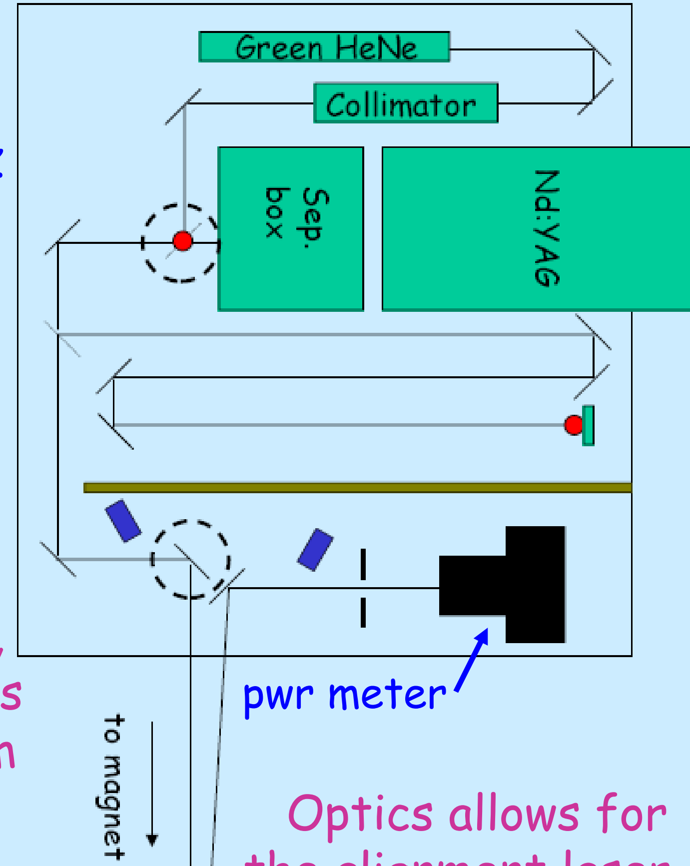
SURELITE™ SPECIFICATIONS

DESCRIPTION	I-10	I-20
Repetition Rate (Hz)	10	20
Energy (mJ)		
1064 nm	450	420
532[1] nm	200	160
355 nm	65/100[2]	60/100[2]
266 nm	60	45
Pulsewidth[3] (nsec)		
1064 nm	5-7	5-7
532 nm	4-6	4-6
355 nm	4-6	4-6
266 nm	4-6	4-6
Linewidth (cm^{-1})		
Standard	1	1
Injection Seeded[4]	0.005	0.005
Divergence[5] (mrads)	0.6	0.6
Rod Diameter (mm)	6	6
Pointing Stability (±µrads)	30	50
Jitter[6] (±ns)	0.5	0.5
Energy Stability[7] (±%)		
1064 nm	2.0; 0.7	2.0; 0.7
532 nm	3.5; 1.2	3.5; 1.2
355 nm	4.0; 1.3	4.0; 1.3
266 nm	7.0; 2.3	7.0; 2.3
Power Drift[8] (±%)		
1064 nm	3.0	3.0
532 nm	3.0	3.0
355 nm	3.0	3.0
266 nm	6.0	6.0
Beam Spatial Profile[9]		
Near Field (<1 m)	0.70	0.70
Far Field (∞)	0.95	0.95
Deviation from Gaussian[10]		
Near Field (<1 m)	30	30

3.2W, polor., 10ns wide pulses@20Hz

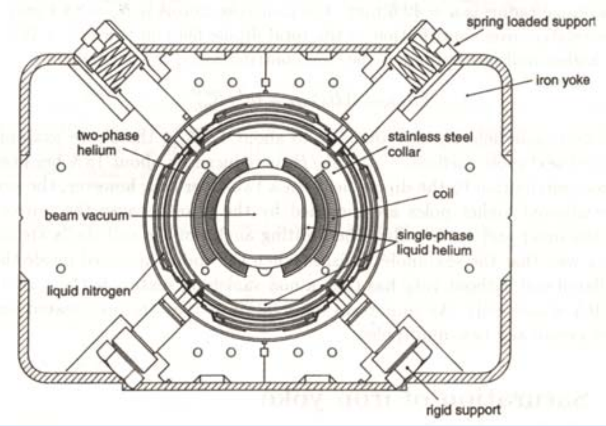
Laser box is safety interlocked, mounted on cement blocks, holds optics, and interfaces to vacuum inside the magnet.

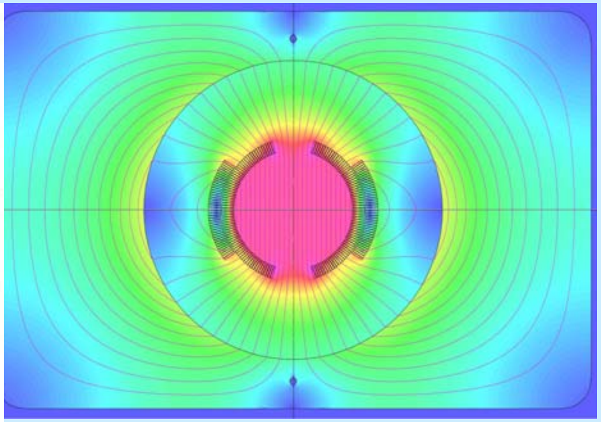
Video image of reflected laser spot is monitored during data taking.

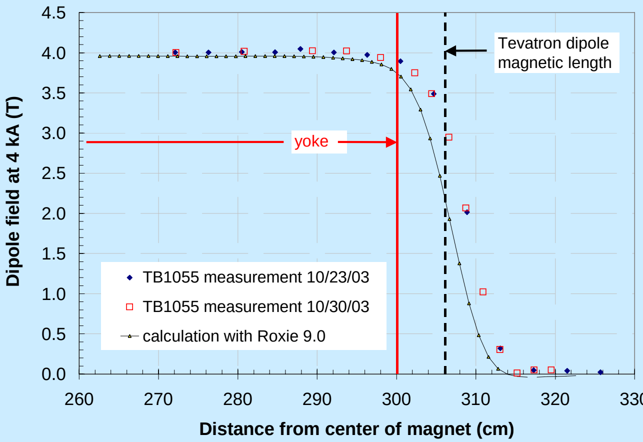


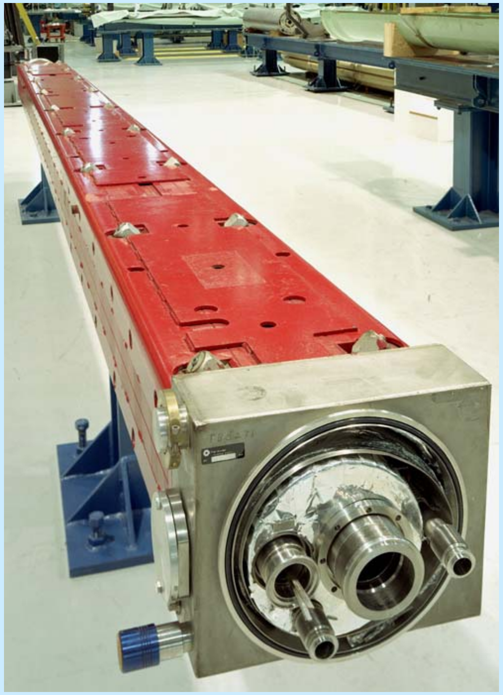
Optics allows for the alignment laser and Nd:YAG to be aligned using ~3m path in the box so the low power laser can be steered through the apparatus.

Tevatron Magnet







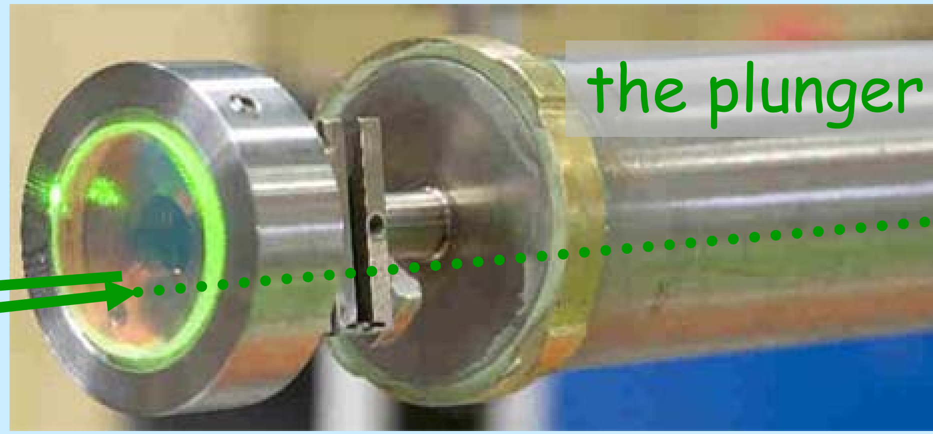


- Our magnet: TC1206 one of the best spare Tevatron dipole magnets. It was selected because it was previously run at high current
- Operating current was 5040A to have 5T over the entire 6m length. Measured with NMR probes.
- Terrific support from the magnet test facility that gave us space and infrastructure on their test stand.

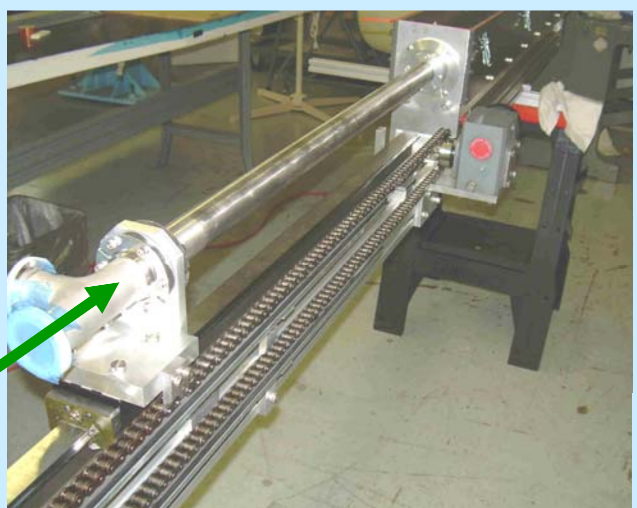
The "Wall" and plumbing

To PWR meter

From laser



ALP heading toward PMT

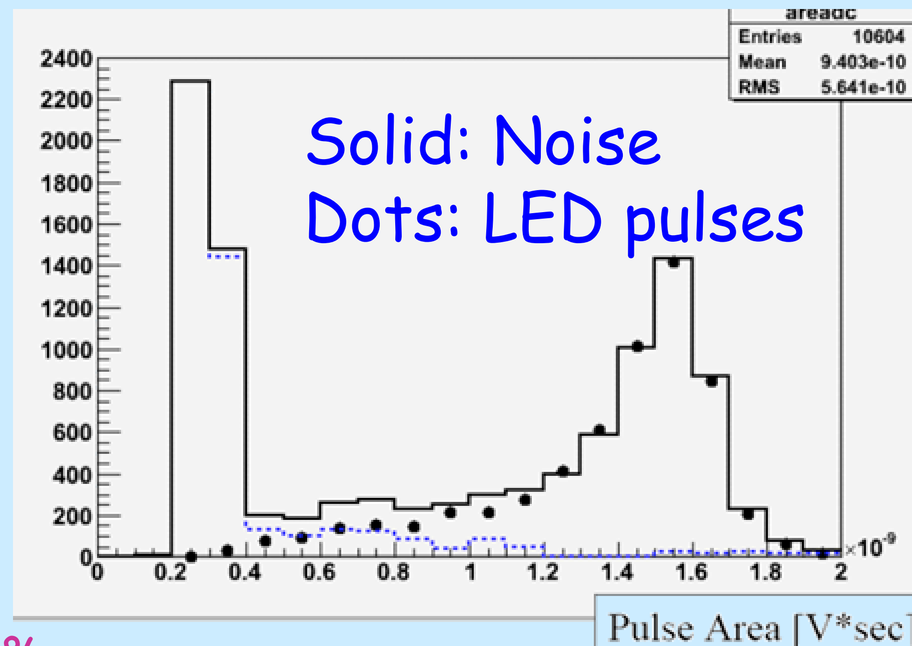


The plunger can be adjusted by 2 meters so that the wall can either be placed in the center of the magnet or at a position 1m from the end of the magnet. This unique feature allows us to be sensitive to other masses.

Single photon detector

- Hamamatsu H7422P-40 PMT
- GaAsP photocathode, QE=40%
- Dark Count rate ~ 100 Hz with built-in thermoelectric cooler

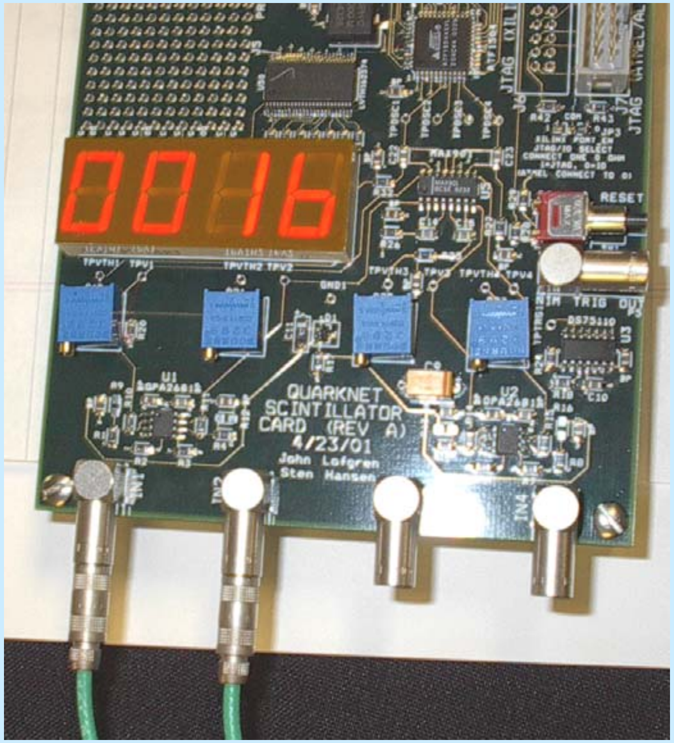
We studied the response of the PMT using a single photon LED flasher system. There is a clear separation between noise dominated by the power supply and the single photon peak. We flash the LED during data taking.



Discriminator inefficiency (0.6+/-0.1)%

GammeV

Data acquisition



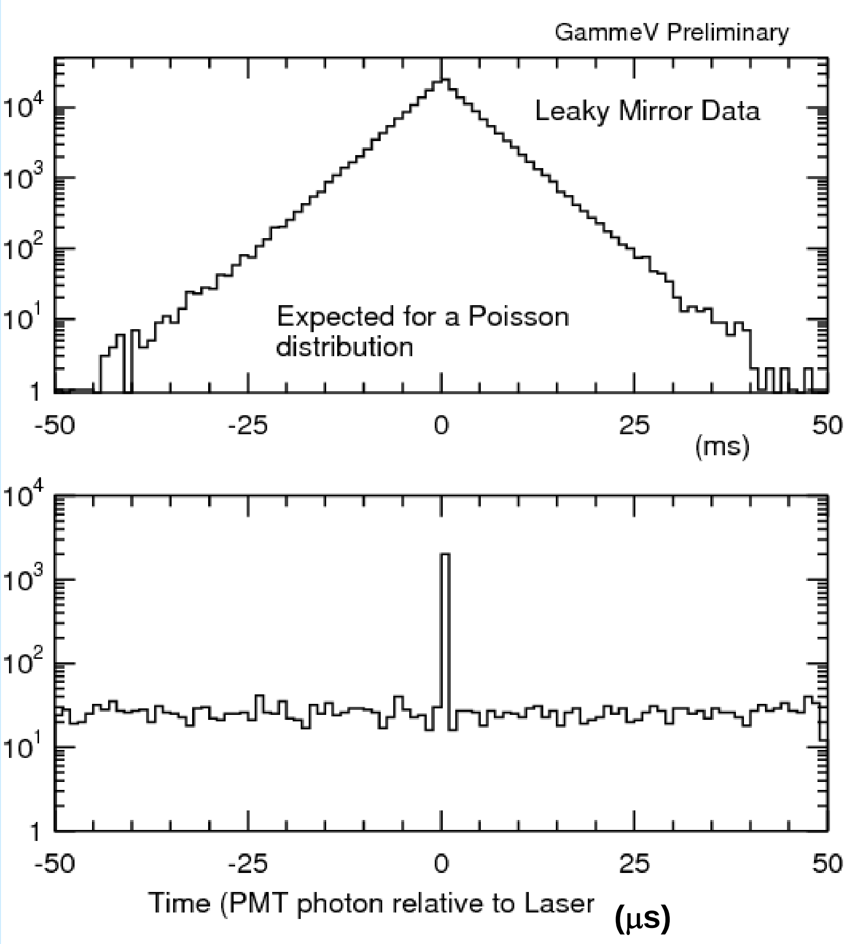
- QuarkNet timing cards
  - Built by Fermilab for Education Outreach (High School cosmic ray exp'ts.)
  - Interfaces to computer via USB (Visual Basic software for our DAQ)
- Four inputs, phase locked to a GPS 1pps using a 100MHz clock that is divided by eight for 1.25ns timing.
- Boards also send firing 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	Isochronous CLK
Laser Quark Net	Laser Photo diode	Laser Splash	Laser Synch pulse	Isochronous CLK

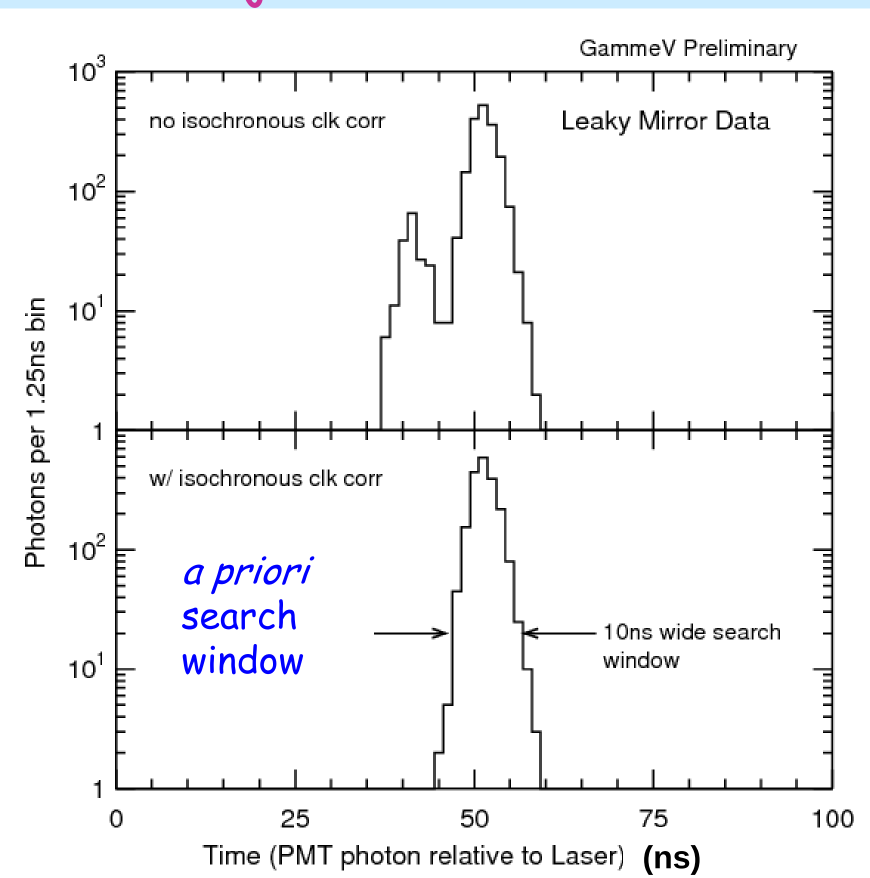
GammeV Calibration

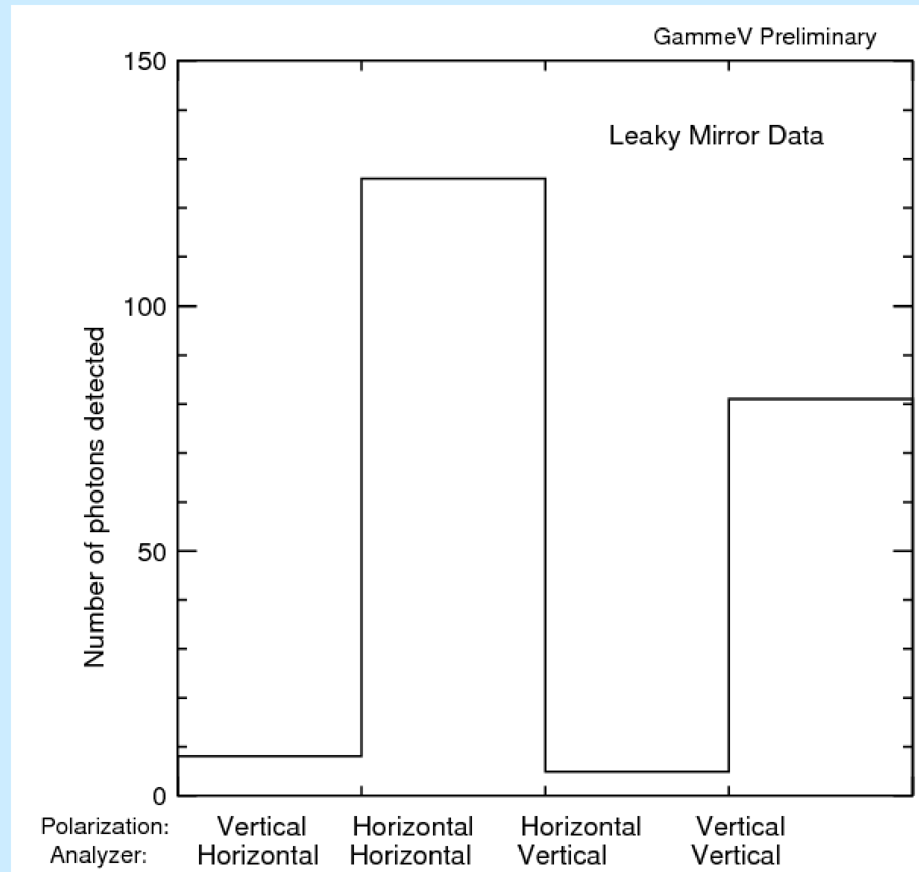
- "Leaky mirror" data involves sending the laser directly into our PMT after attenuation so that we get about 1 photon per 100 pulses.
  - Two mirrors leak ~10^{-6} through
  - 10 micron pin hole captures ~10^{-6}
  - Neutral density filters give ~10^{-7}
- Look at the PMT pulse closest to a laser pulse and plot the time difference.
  - Poisson distribution
  - Nearly flat over short times <<ms
- Real photons show up!



GammeV Calibration

- Use the "Leaky Mirror" data to verify both the absolute timing and the sensitivity to polarization.
- The isochronous pulse to both QuarkNet boards can be used to remove a 10ns jitter.



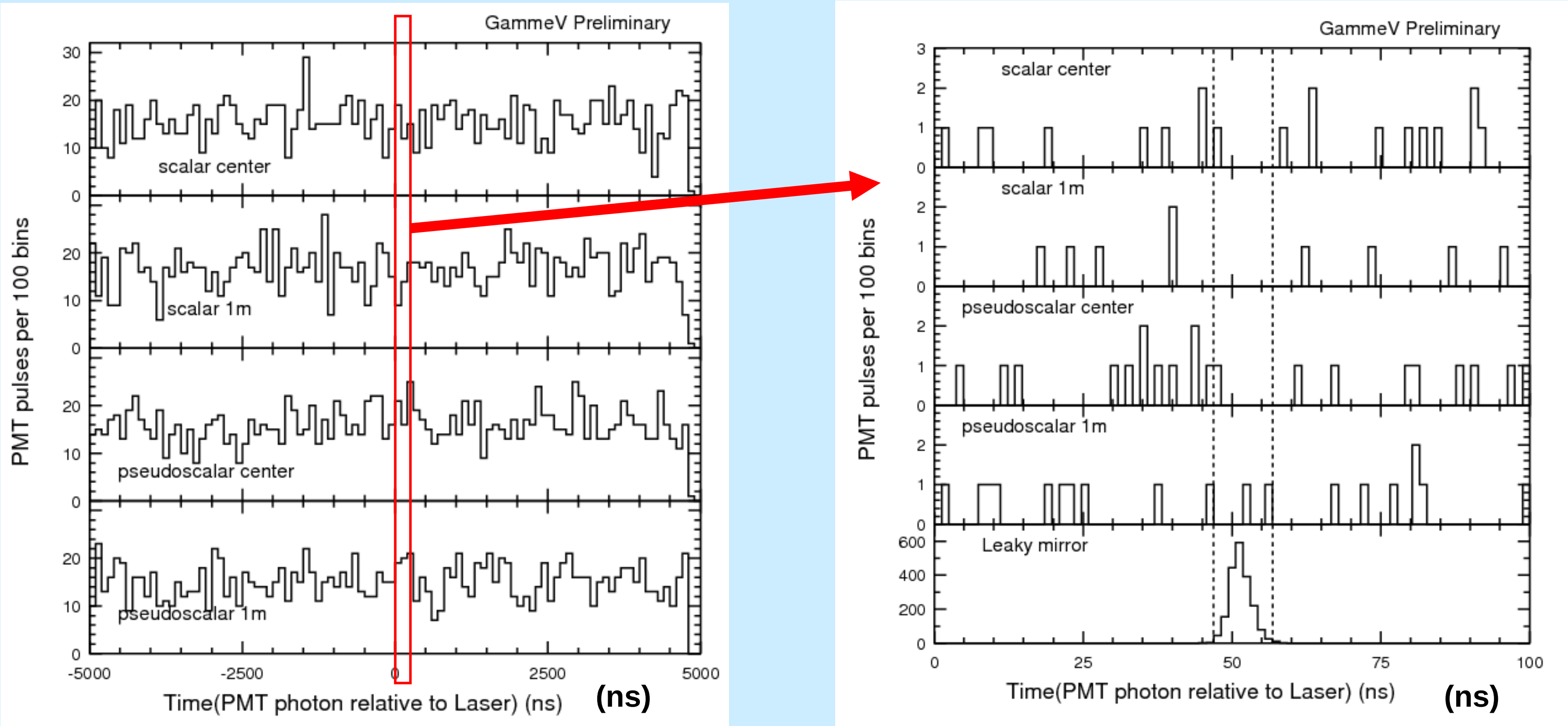


GammeV Method

- Take data in four 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
- In each configuration, acquire about 20 hours of magnet time or about 1.5M laser pulses at 20Hz.
  - Monitor the power of the laser using a power meter that absorbs the laser light reflected back into the laser box using NIST traceable calibration to +/-3%
- Total efficiency (25 +/- 3)%
  - PMT detection efficiencies from factory measurements QE x CE 39% x 70% = 27%
  - Measured attenuation in BK7 windows and lens: 92%
- Background in a 10ns wide search region is estimated by counting the events in a 10,000ns wide window around all the laser pulses and dividing by 1000.

GammeV Data

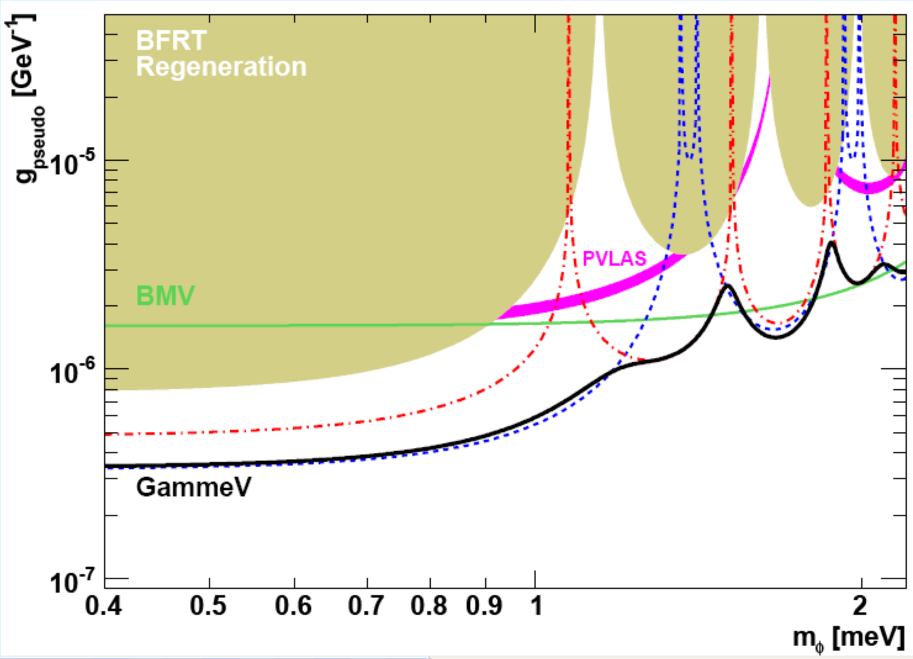
Spin	Position	# Laser pulse	# photon / pulse	Expected Background	Signal Candidates
Scalar	Center	1.34 M	0.41e18	1.56±0.04	1
Scalar	1 m	1.47M	0.38e18	1.67±0.04	0
Pseudo	Center	1.43M	0.41e18	1.59±0.04	1
Pseudo	1m	1.47M	0.42e18	1.50±0.04	2



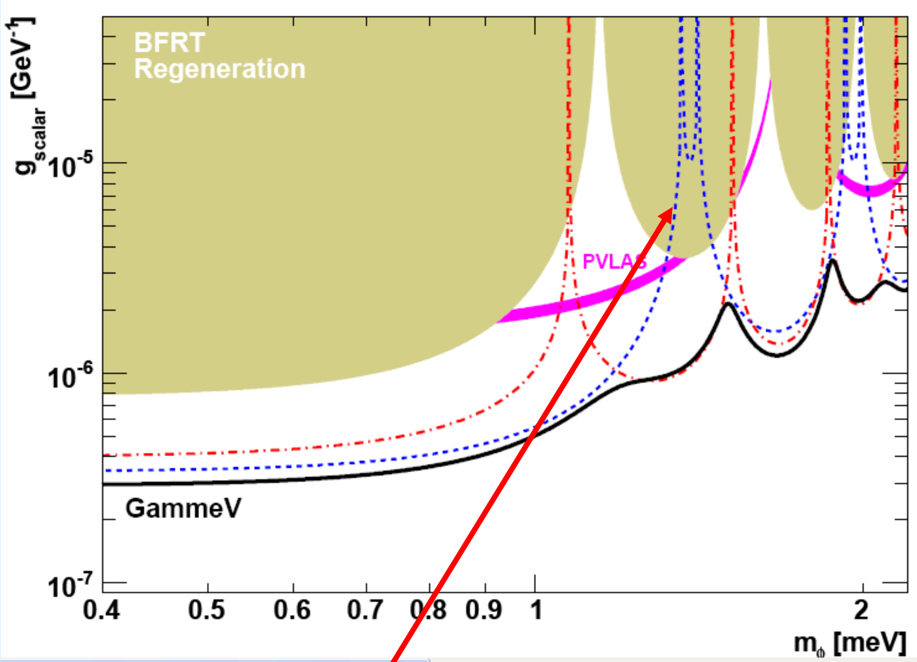
GammeV Results

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

Pseudoscalar



Scalar



Double spike because we were 10cm away from the center

PRL **100**, 080402 (2008)

Conclusion

- At FNAL, a small group of us had fun one summer ago. There were days going into work thinking today *might* be the day that a new revolutionary particle might appear.
- We achieved the goal of probing the milli-eV region of interest for axion-like particles with at high confidence level
- Some Lessons: simple design, some cleverness, low noise, specific goal to target, support from Fermilab's divisions.
- Finally, just like there are theories that are "Not Yet Thought Of", so there are also opportunities for such experiments. Maybe something like a chameleon (see Aaron Chou's talk) or something even stranger will be the next New Physics.