GammeV

Gamma to milli-eV particle search

Overview and past results

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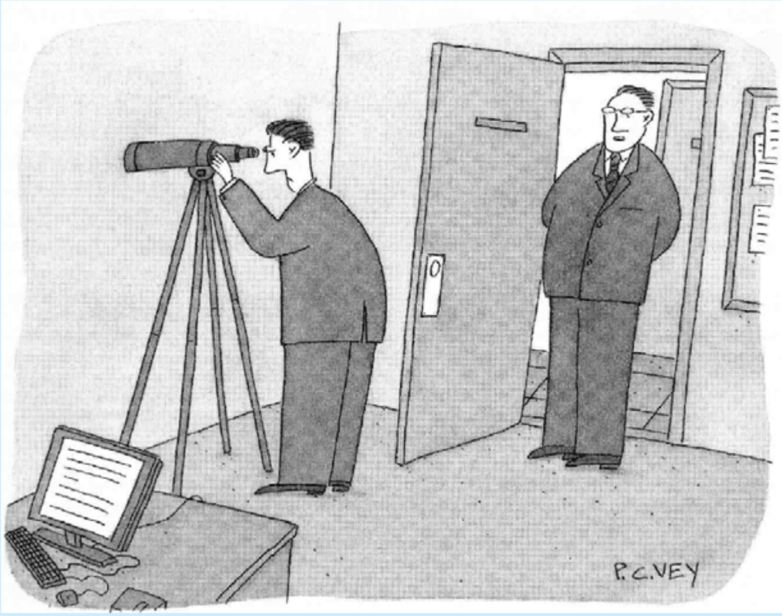
Fermilab

H Murayama

Outline

- Intro to Axions and Axion-like particles
- Physics motivation for our experiment
  - milli-eV mass scale
  - PVLAS anomaly
- "Light shining through a wall"
  - Past Experiments
  - **G**amme**V**
  - Other current experiments
- Results: **G**amme**V** Phase I
- Future Prospects
  - Chameleons Phase I and II (Jason)
  - Resonant Regeneration (Aaron)



New Yorker

GammeV

Axions

- Postulated in the late 1970s as a consequence of not observing CP violation in the strong interaction.

$$L_{CP} = -\frac{\alpha_s}{8\pi}\underbrace{(\Theta - \arg\det M_q)}_{0\leq\bar{\Theta}\leq 2\pi}\mathrm{Tr}\,\tilde{G}_{\mu\nu}G^{\mu\nu}$$

Raffelt

- The measurement of the electric dipole of the neutron implies $\Theta < \sim 10^{-10}$. => Strong CP Problem of QCD
  - This is very much on the same order of an issue with the Standard Model as the hierarchy problem that motivates supersymmetry.

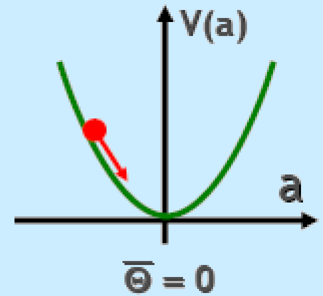
Bjorken "Axions are just as viable a candidate for dark matter as sparticles"
Wilczek "If not axions, please tell me how to solve the Strong-CP problem"
Witten "Axions may be intrinsic to the structure of string theory"

WW+K van Bibber

Axions

- Peccei-Quinn (1977) and Wilczek (1978) and Weinberg (1978) provided a solution: $\overline{\Theta}$ represents a dynamical pseudoscalar field, $a = \phi$, with a potential that conserves CP.

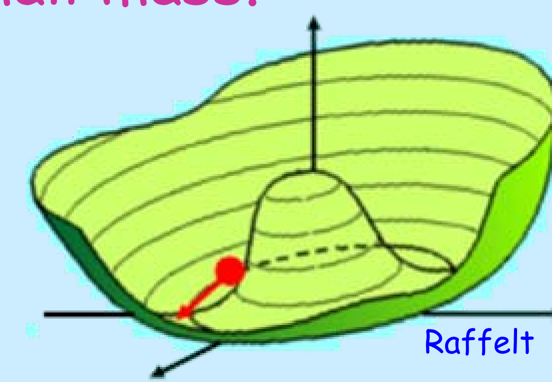
$$\overline{\Theta} = \frac{a(x)}{f_a}$$



- The Peccei-Quinn mechanism implies a new symmetry that gets spontaneously broken and the axion emerges as a pseudo Nambu-Goldstone boson with small mass.

- Mass and couplings related to the pion

$$m_a = m_\pi \frac{f_\pi}{f_a} = \frac{0.6\ \mathrm{meV}}{f_a/10^{10}\ \mathrm{GeV}}$$



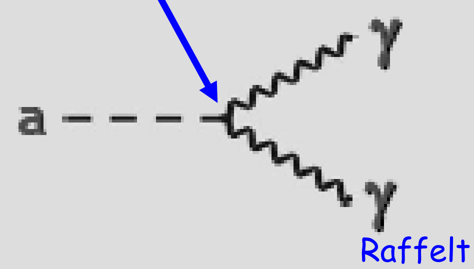
Axions

- Axions couple to photons

Photon coupling

$$L_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F} a = g_{a\gamma} \vec{E} \cdot \vec{B}\, a$$

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$$



- An *axion-like-particle* (ALP) is a more general particle that can arise from either a pseudoscalar or scalar field, ϕ, and no longer has the connection to the pion.

pseudoscalar

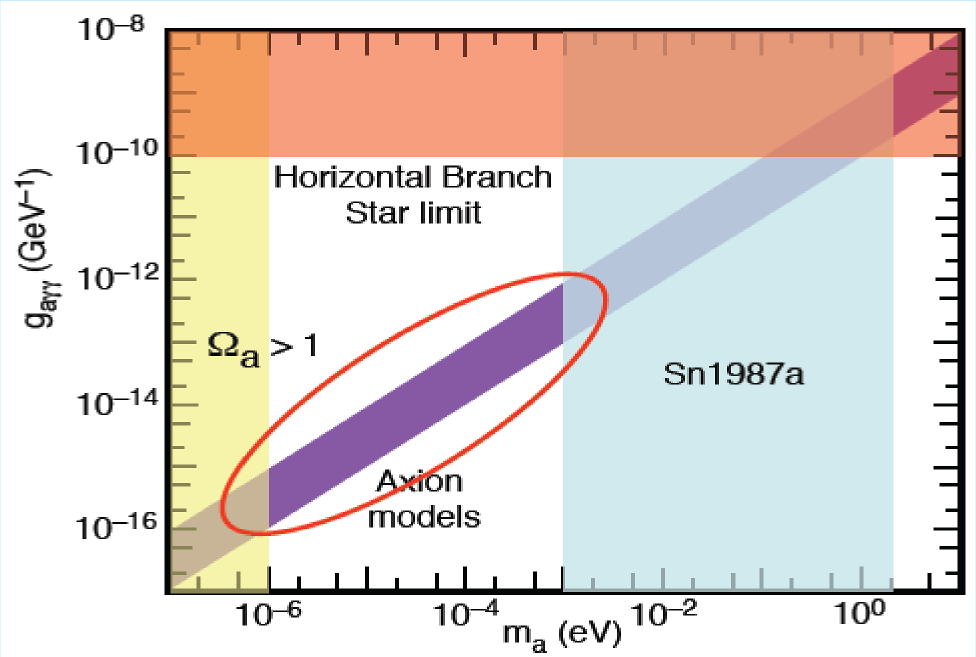
$$\mathcal{L}_{\rm int} = -\frac{1}{4}\frac{\phi}{M} F_{\mu\nu}\widetilde{F}^{\mu\nu} = \frac{\phi}{M}(\vec{E}\cdot\vec{B})$$

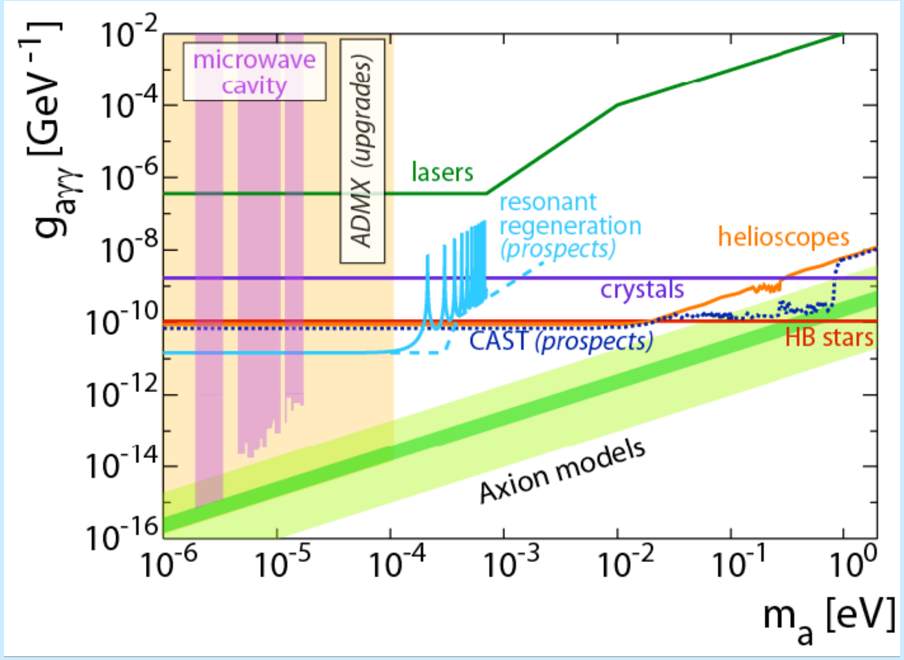
scalar

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

Searches for Axions

- Axion parameters are constrained by cosmological and experimental measurements
  - Stars don't burn out, SN1987A events+energy are OK, and axions aren't all the mass of the universe.
  - Low mass limits set by microwave cavities and higher mass axions are excluded by solar telescopes





K van Bibber

PDG

GammeV Motivation

- In the context of searching for axions, **G**amme**V** is looking for an axion-like particle with a mass in the milli-eV region.
- In particular, **G**amme**V** exploits the photon couplings and looks for the oscillation of photons into milli-eV particles and then back into photons (with a strong coupling that would otherwise be excluded by the CAST experiment).
- The motivation for **G**amme**V** to search in the milli-eV region follows …

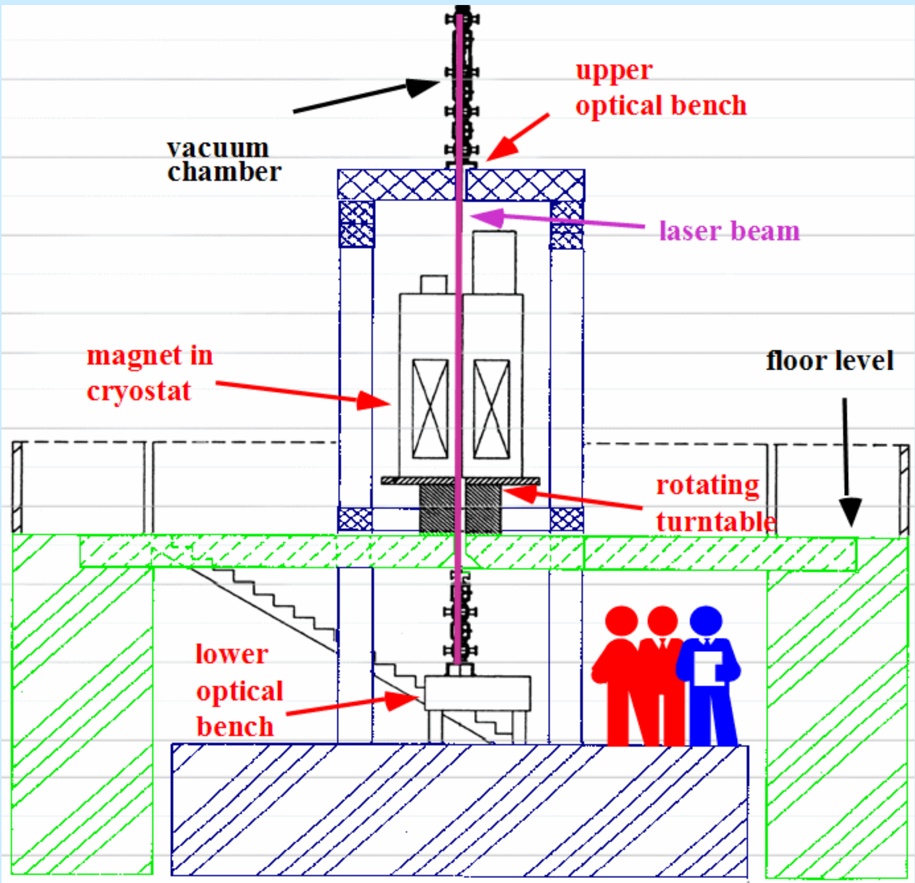
milli-eV Mass Scale

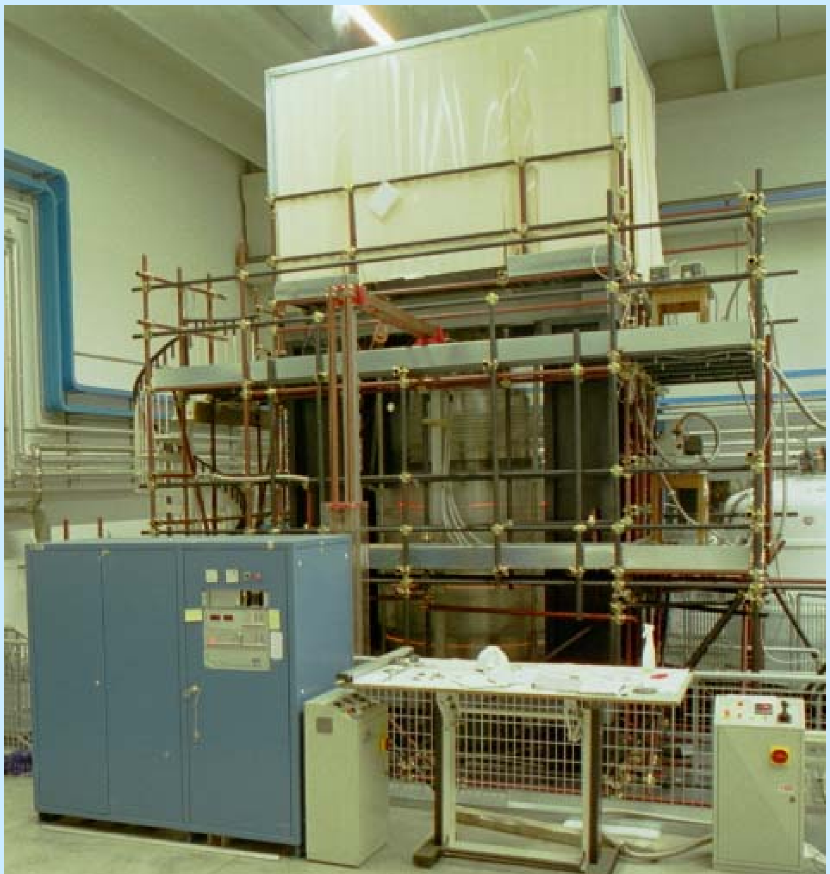
- milli-eV (10^{-3}) eV mass scale arises in various areas in modern particle physics.
  - Dark Energy density
    - $\Lambda^4 = 7 \times 10^{-30}$ g/cm^3 ~ $(2\times10^{-3}\text{ eV})^4$
  - Neutrinos
    - $(\Delta m_{21})^2 = (9\times10^{-3}\text{ eV})^2$
    - $(\Delta m_{32})^2 = (50\times10^{-3}\text{ eV})^2$
  - 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

Energy frontier
Neutrinos
Astrophysics
all in one!

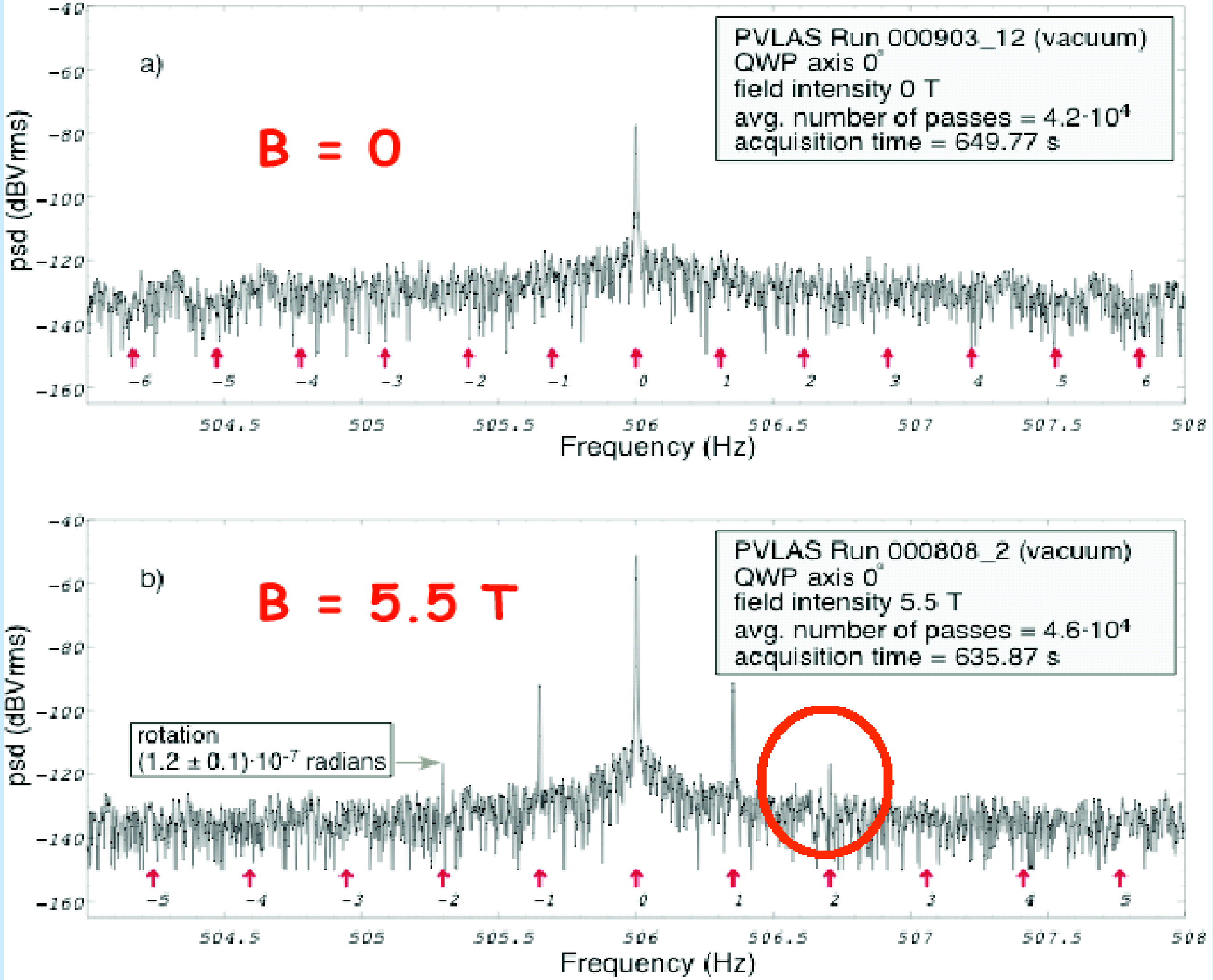
PVLAS Experiment

- Designed to study the vacuum by optical means: birefringence (generated ellipticity) and dichroism (rotated polarization)



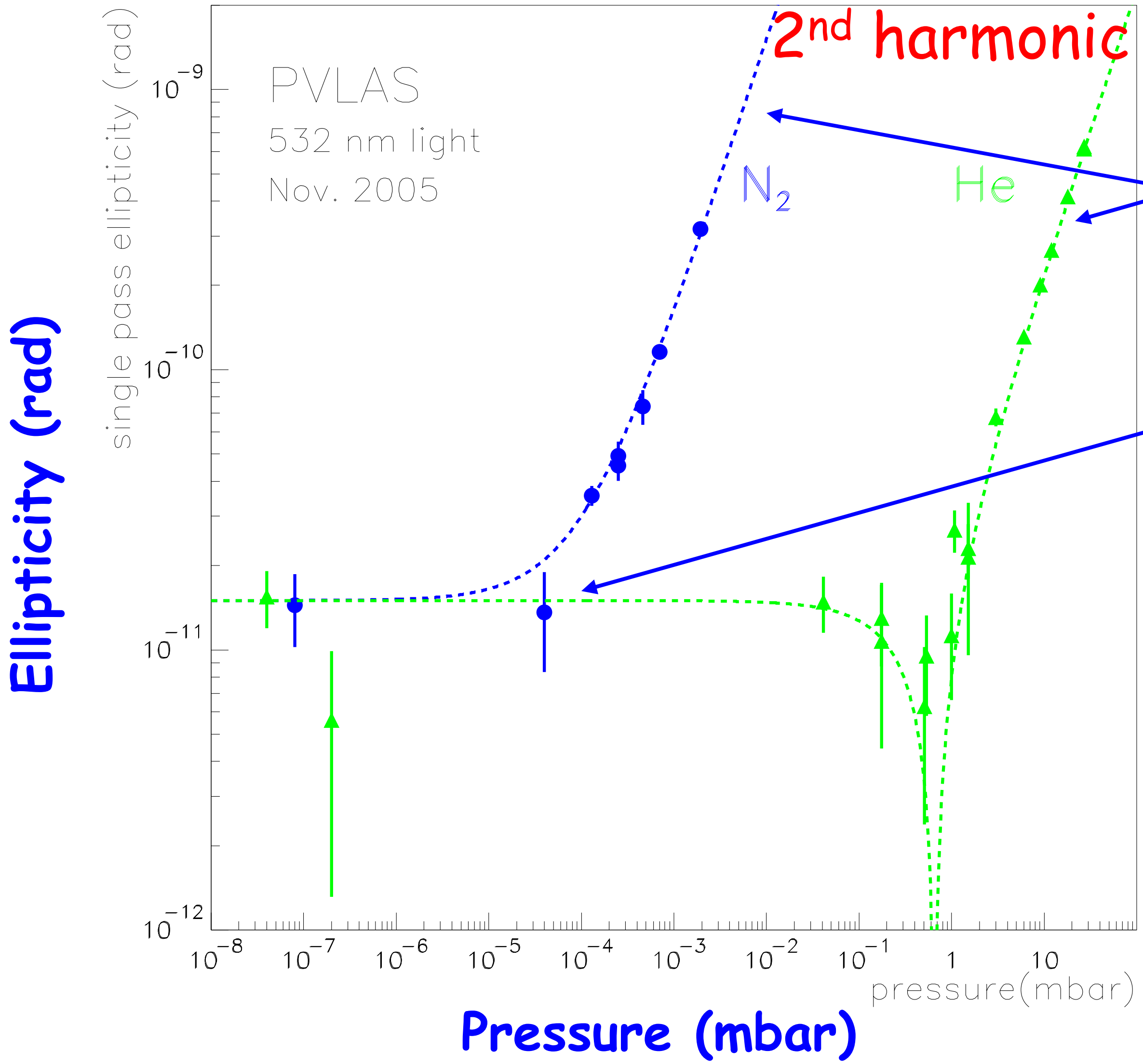


PVLAS Rotation Results



PRL 96, 110406, (2006)

PVLAS Ellipticity Results



Cotton-Mouton effect vs gas pressure

Amplitude is non-zero for 2nd harmonic

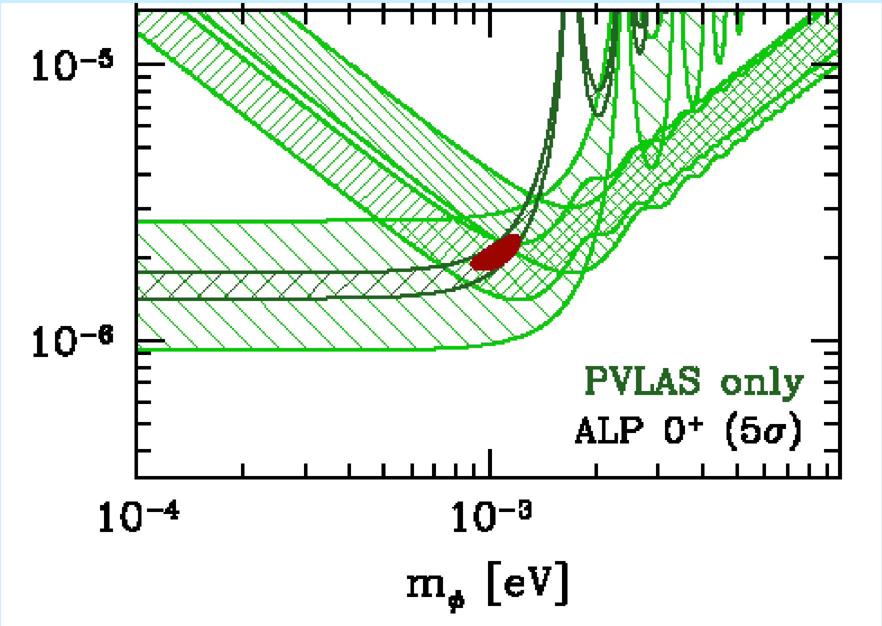
Non-zero amplitude is also seen at 1064nm

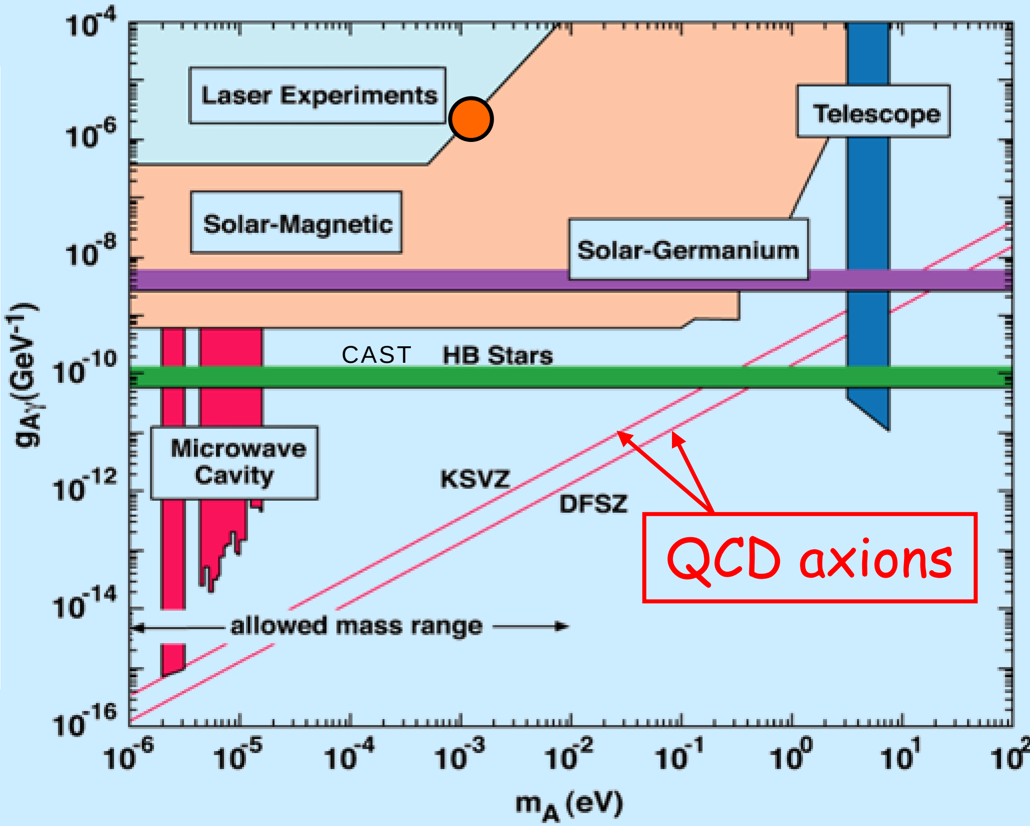
Conference Proceedings

GamмeV

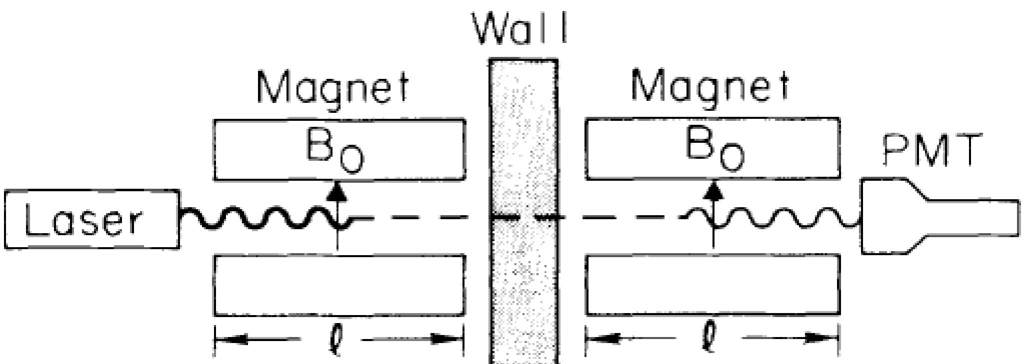
PVLAS ALP Interpretation

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

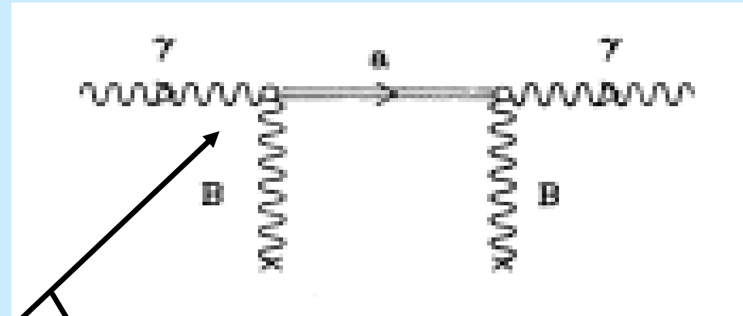




Light Shining Through a Wall Experiment



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



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

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

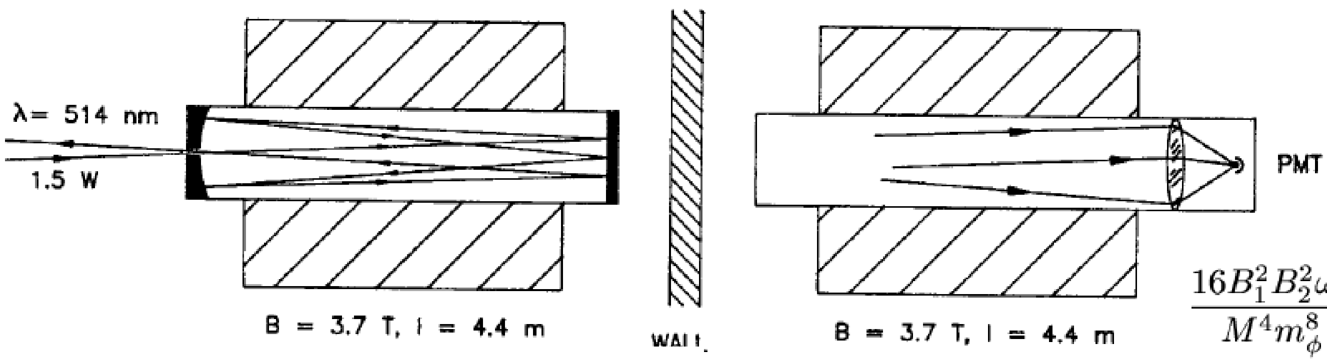
$$P_{regen} = \frac{16 B_1^2 B_2^2 \omega^4}{M^4 m_\phi^8} \sin^2\left(\frac{m_\phi^2 L_1}{4\omega}\right) \cdot \sin^2\left(\frac{m_\phi^2 L_2}{4\omega}\right)$$

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

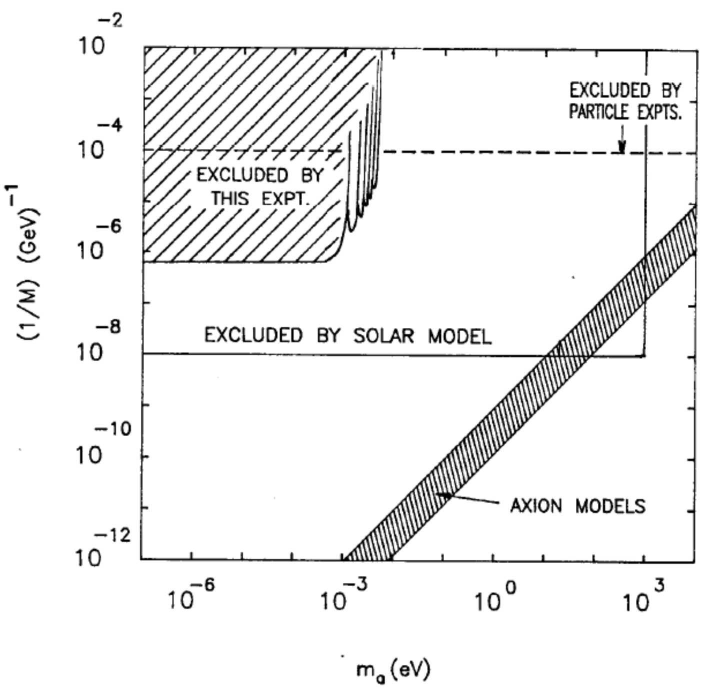
$$P_{regen}^{GammeV} = (3.9\times 10^{-21}) \times \frac{(B_1/5\ \text{T})^2 (B_2/5\ \text{T})^2 (\omega/2.33\ \text{eV})^4}{(M/4\times 10^5\ \text{GeV})^4 (m_\phi/1.2\times 10^{-3}\ \text{eV})^8}$$
$$\times \sin^2\left(\frac{\pi}{2}\frac{(m_\phi/1.2\times 10^{-3}\ \text{eV})^2 (L_1/2.0\ \text{m})}{(\omega/2.33\ \text{eV})}\right) \sin^2\left(\frac{\pi}{2}\frac{(m_\phi/1.2\times 10^{-3}\ \text{eV})^2 (L_2/2.0\ \text{m})}{(\omega/2.33\ \text{eV})}\right)$$

BFRT Experiment

- Brookhaven, Fermilab, Rochester, Trieste (1992)

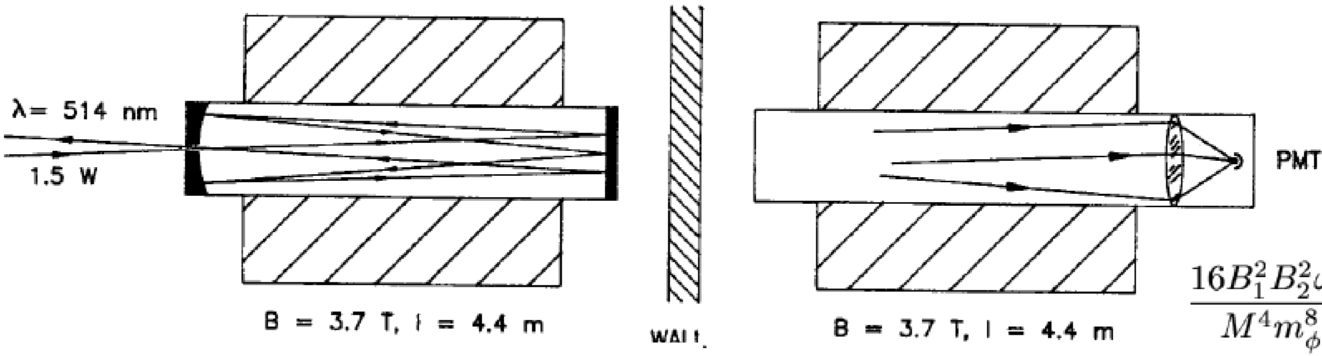


$$\frac{16 B_1^2 B_2^2 \omega^4}{M^4 m_\phi^8} \sin^2\left(\frac{m_\phi^2 L_1}{4\omega}\right) \cdot \sin^2\left(\frac{m_\phi^2 L_2}{4\omega}\right)$$

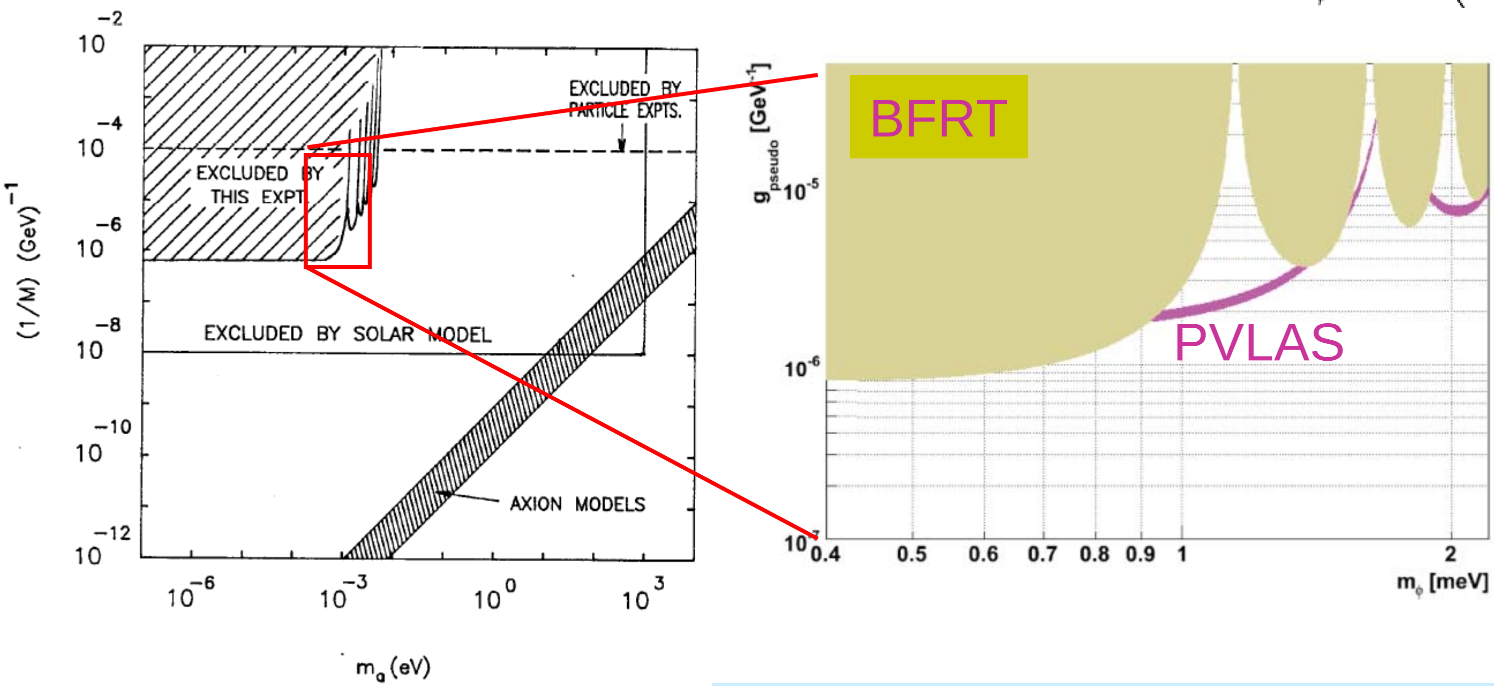


BFRT Experiment

- 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.

GammeV Collaboration

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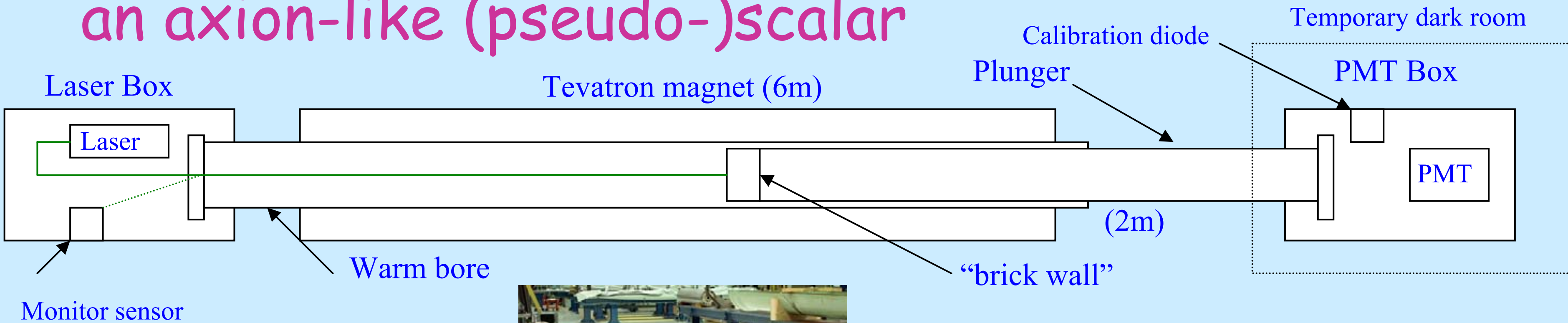
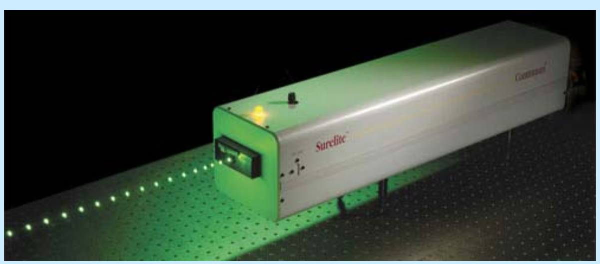
Ten person team including a summer student, 3 postdocs, 2 accelerator / laser experts, 4 experimentalists (nearly everyone had a day job) PLUS technical support at FNAL

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 Accepted (results reported here)

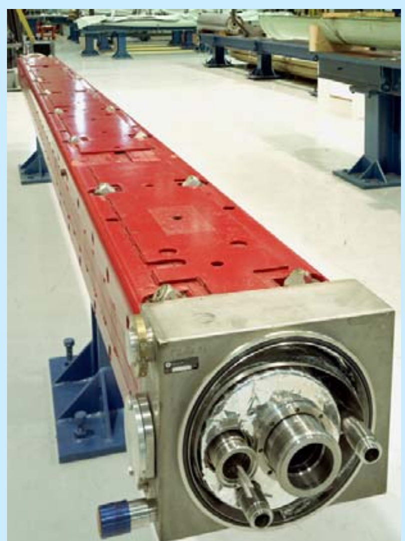
GammeV Proposal

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

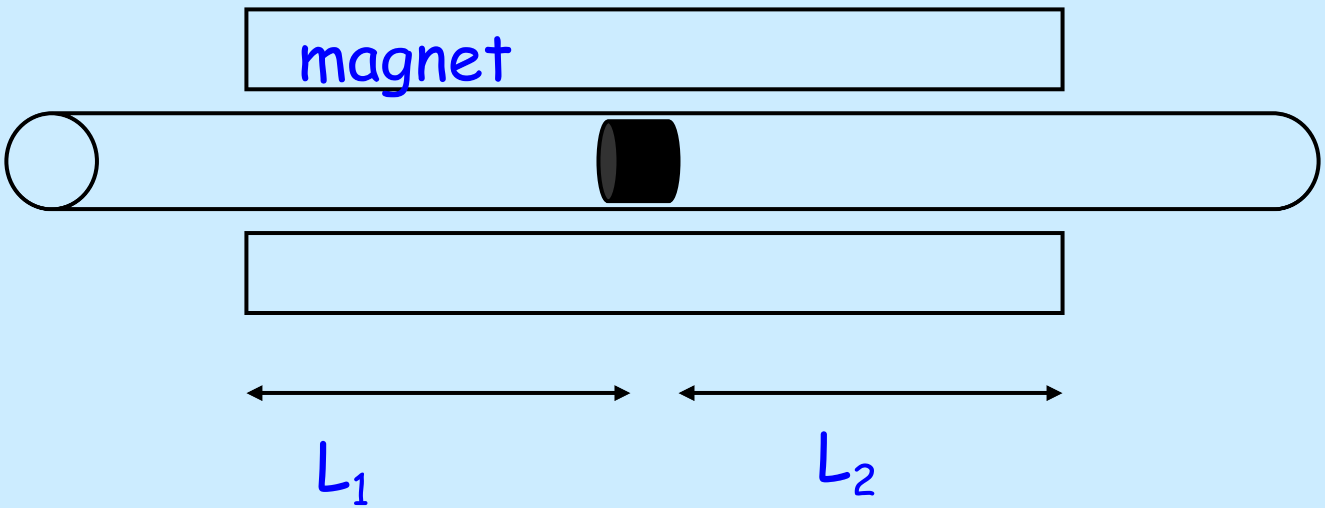


The “wall” is a welded steel cap on a steel tube in addition to a reflective mirror.

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

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

A unique feature 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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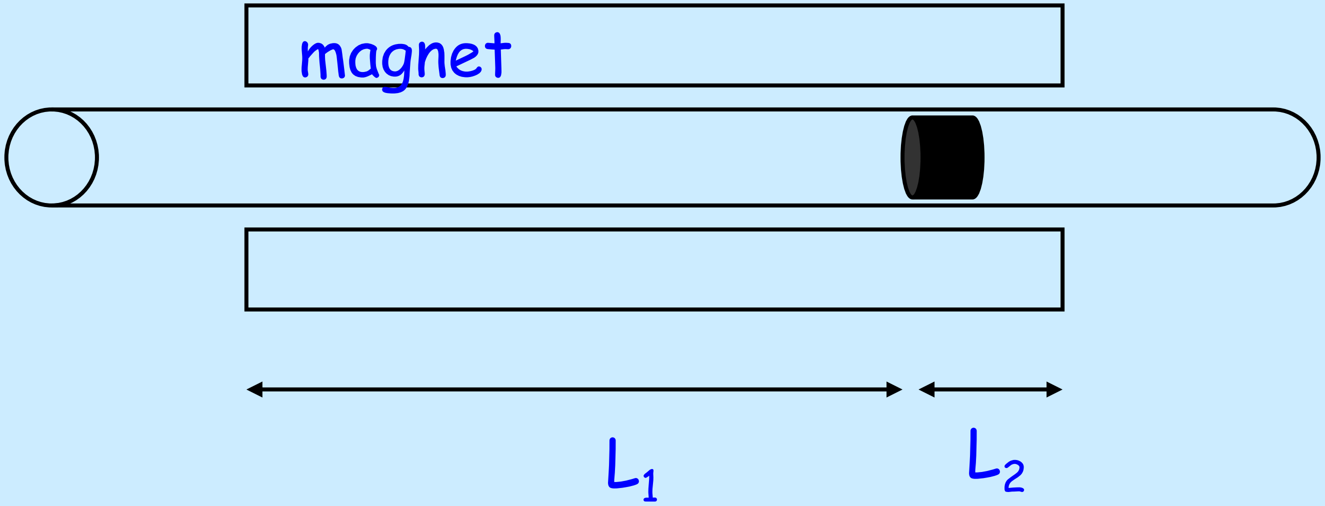

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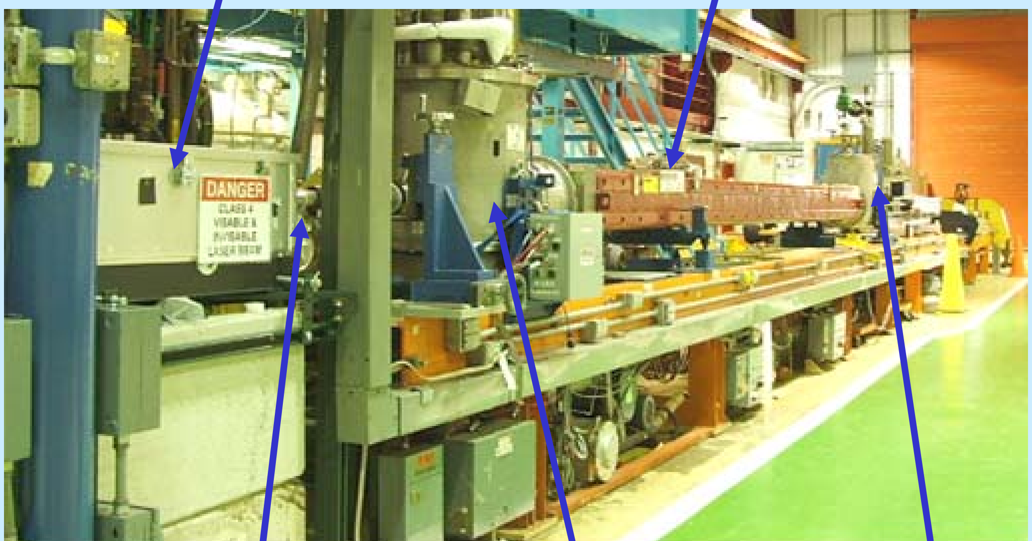
Apparatus

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

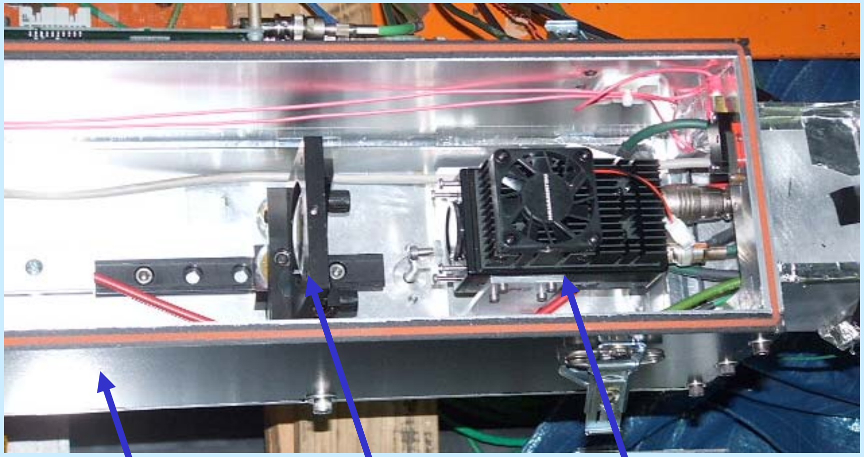
Cryogenic magnet feed can

Cryogenic magnet return can

Cryogenic magnet return can

Vacuum tube connected to plunger

PMT box



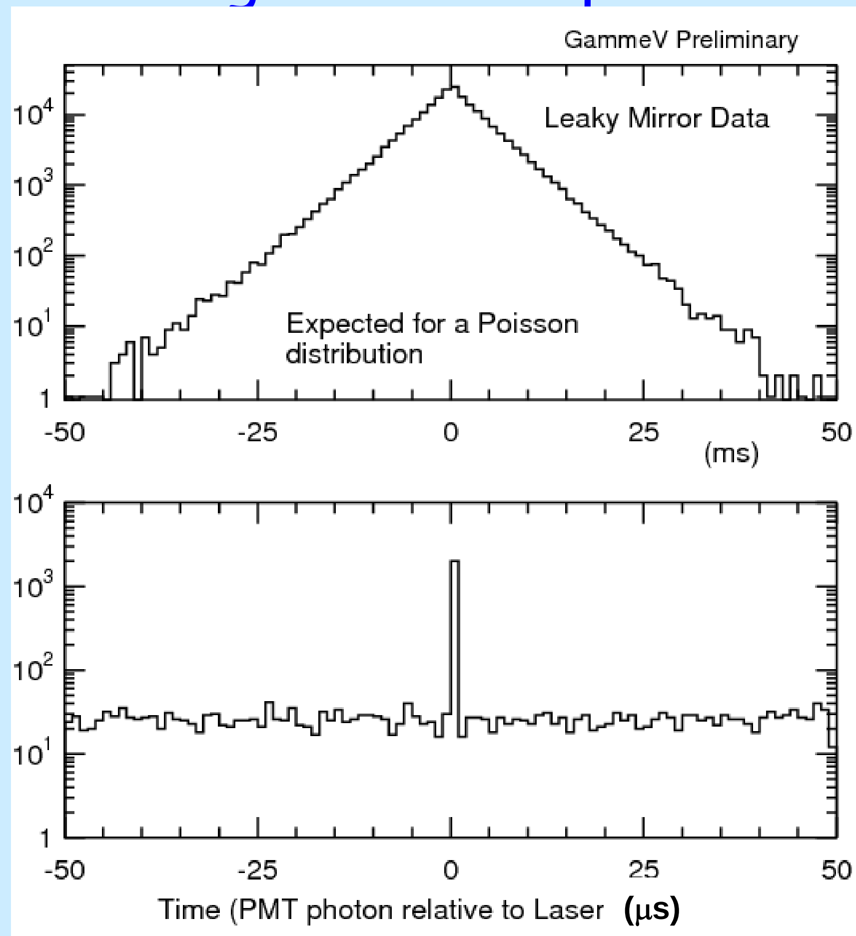
PMT box

Lens

PMT

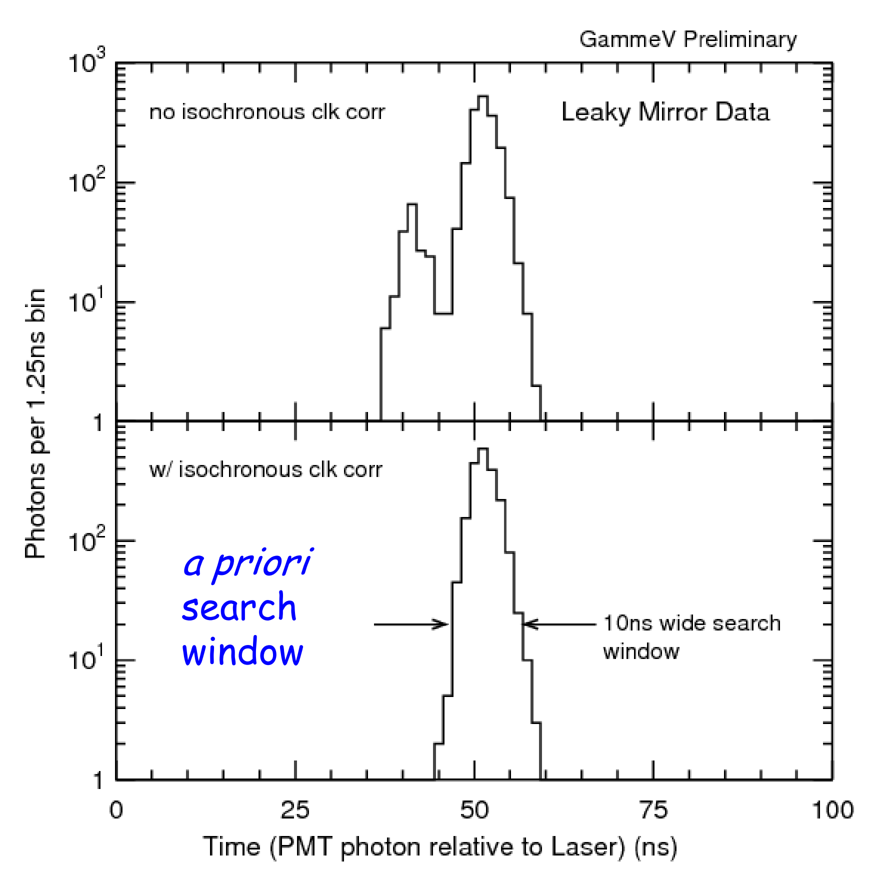
GammeV Results

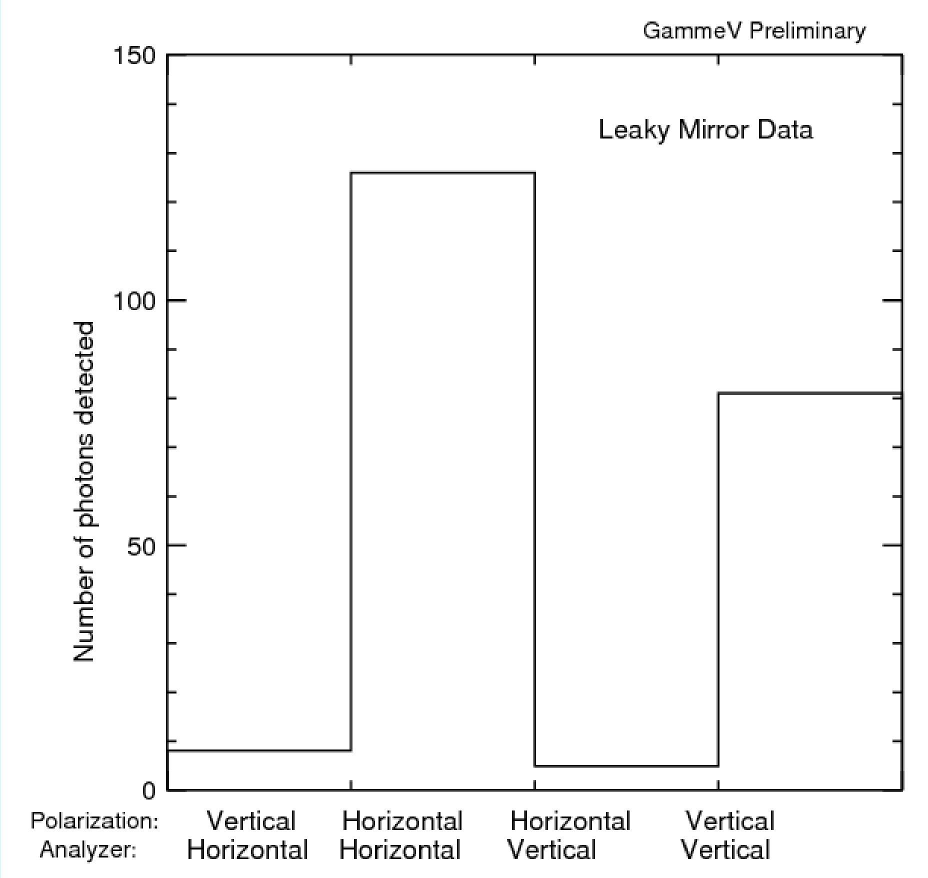
- "Leaky mirror" data involves sending the laser directly into our PMT after attenuation so that we get about 1 photon per 100 pulses.
  - Two mirrors leak ~10^{-6} through
  - 10 micron pin hole captures ~10^{-6}
  - Neutral density filters give ~10^{-7}
- Look at the PMT pulse closest to a laser pulse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



GammeV Results

- 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.



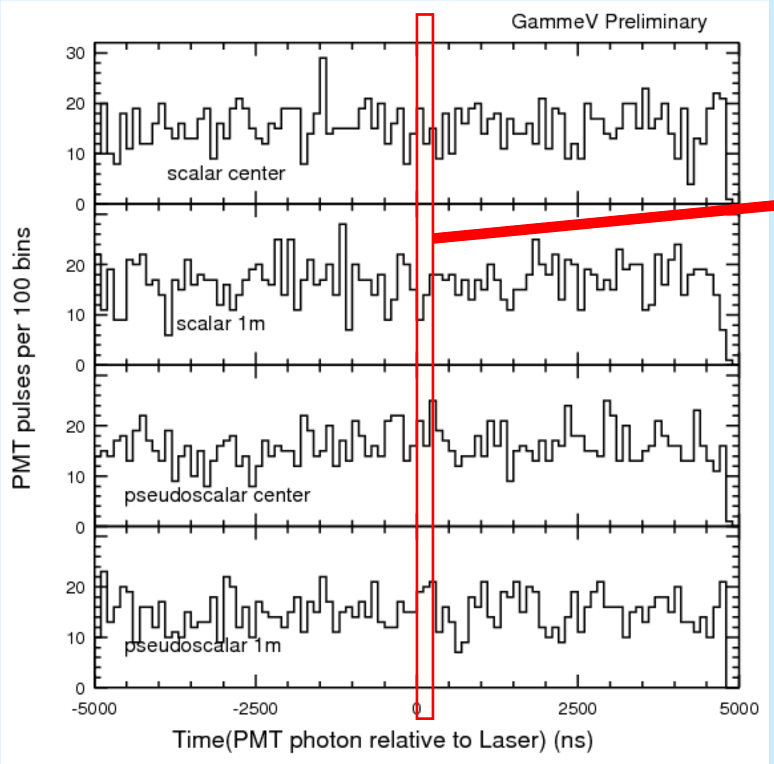


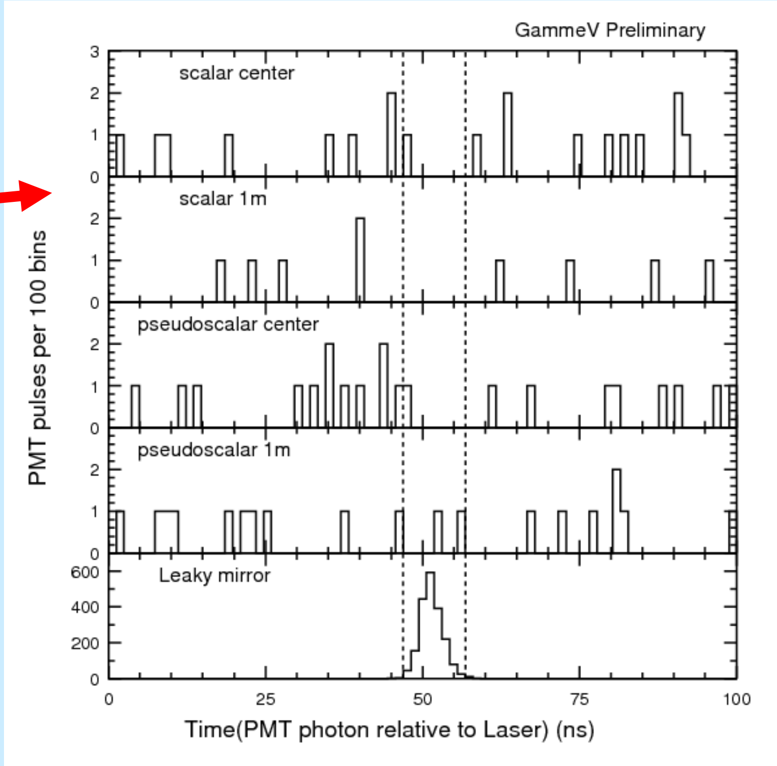
GammeV Results

- 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 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

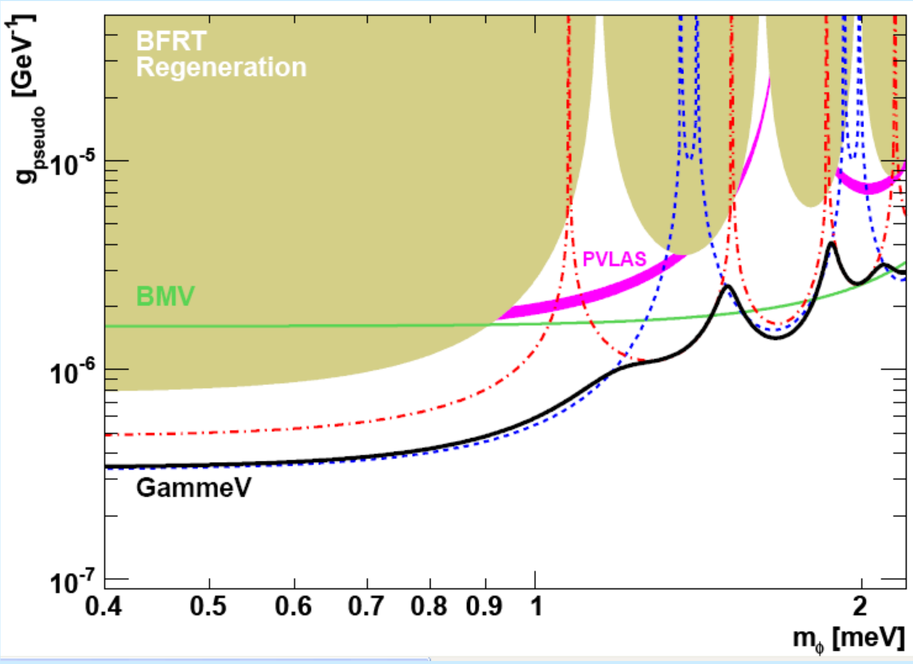




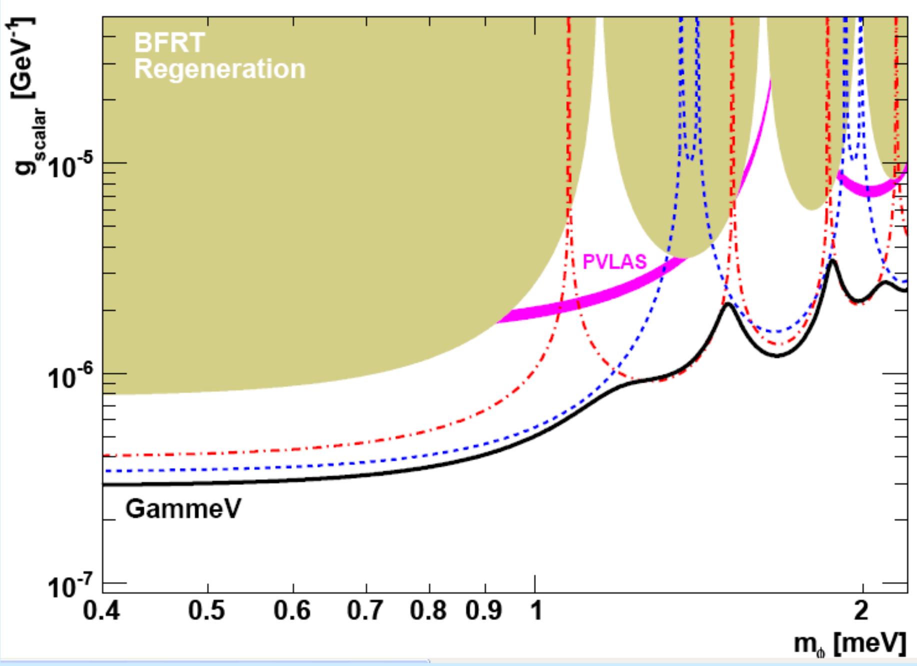
GammeV Results

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

Pseudoscalar



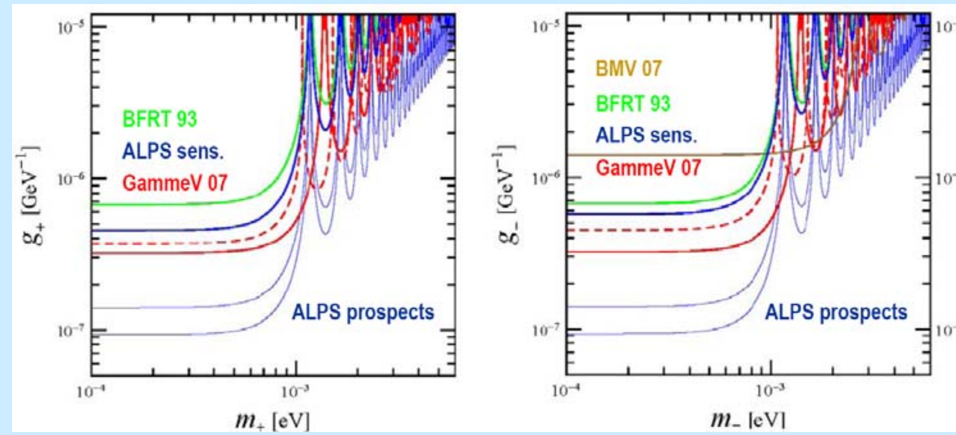
Scalar



PRL **100**, 080402 (2008)

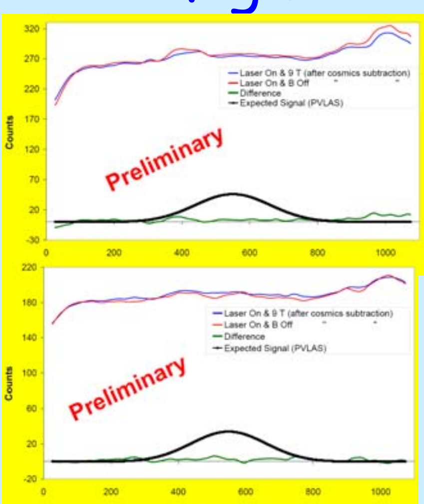
Other experiments

- 4th Patras Workshop on Axions, WIMPs, and WISPs
  - DESY, June 2008
  - web: axion-wimp.desy.de
- No evidence of axion-like particles using different configurations of LSW technique.



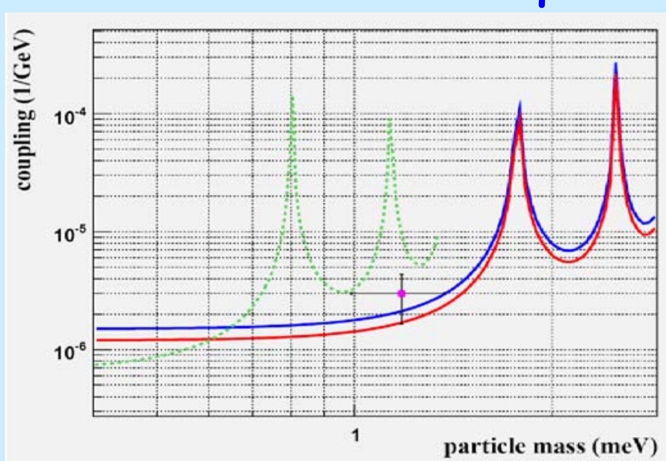
ALPS

conferences



OSQAR hep-ex/0712.3362

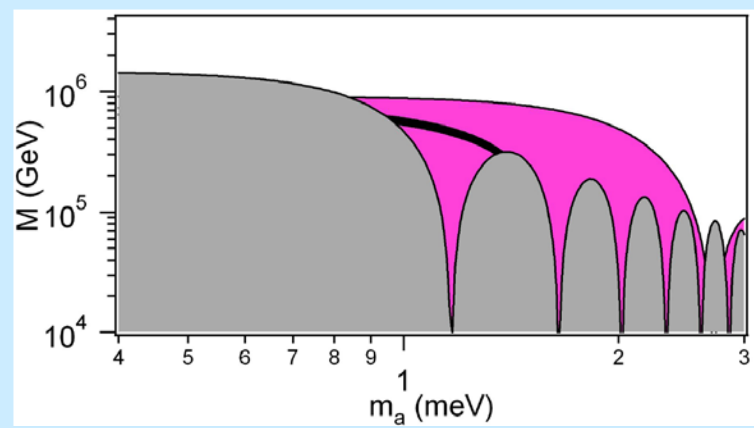
Note: with N_2 gas



LIPSS

scalar only

arXiv:0806:2631



BMV

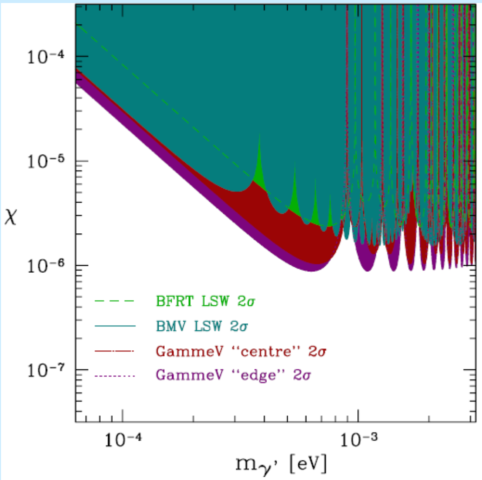
pseudoscalar only

1st results: PRL **99**, 190403 (2007)

Final results: PRD **78**, 032013 (2008)

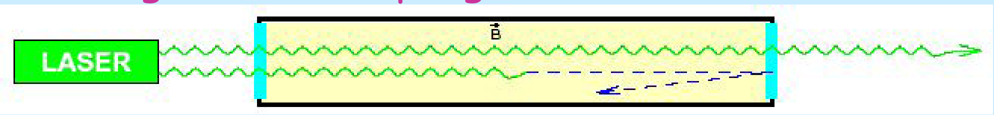
Other GammeV results

- **G**amme**V** results set limits on the mixing parameter for photons to oscillate into massive paraphotons that might arise from a new U(1) symmetry.
- **G**amme**V** took data in a "particle in a jar" configuration to set first ever limits on *chameleon* particles.

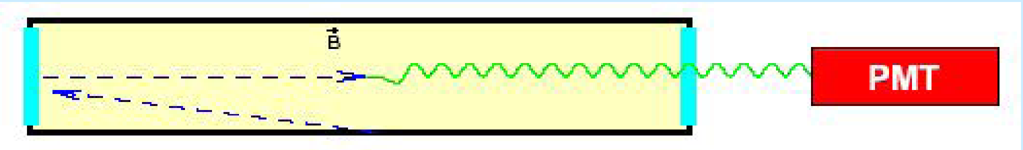


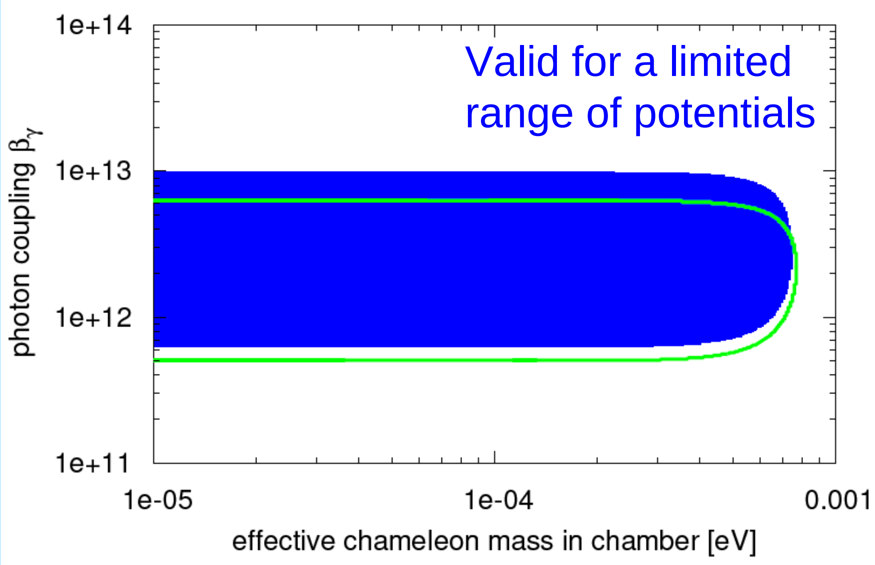
Phys. Rev. **D77**, 095001 (2008)

Generate 100% reflective chameleons due to strong matter coupling.



Turn off laser and look for a regenerated photon afterglow.





arXiv:0806.2438

Conclusion

- At FNAL, a small group of us had fun this past summer. 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.

- Axions are a real possible dark matter candidate. My opinion is that more effort should go into looking for them.
- 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 or something even stranger will be the next New Physics.

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

H Murayama

Conclusion

Publications

A.S. Chou, *et al.* [GammeV collaboration], "Search for axionlike particles using a variable-baseline photon-regeneration technique," Phys. Rev. Lett. 100, 080402, 2008. (link). Also, arXiv:0710.3783 [hep-ex].

A. S. Chou, *et al.* [GammeV collaboration], "A search for chameleon particles using a photon regeneration technique," arXiv:0806.2438 [hep-ex].

Conference Proceedings

J. Steffen for the collaboration, "Constraints on chameleons and axion-like particles with the GammeV experiment," Presented at the 34th Identification of Dark Matter 2008, Stockholm, Sweden, Aug. 18-22, 2008, arXiv:0810.5070 [hep-ex]. (link).

W. Wester for the collaboration, "GammeV: a milli-eV particle search at Fermilab," Presented at the 34th International Conference on High Energy Physics, Philadelphia, PA, July 29 – Aug. 5 2008, FERMILAB-CONF-08-454-A-E and arXiv:0810.4510 [hep-ex]. (link).

W. Wester for the collaboration, "GammeV: Fermilab axion-like particle photon regeneration results," Presented at the 4th Patras Workshop on Axions, WIMPs and WISPS – Training Workshop, Hamburg Germany, 18-21 Jun 2008, FERMILAB-CONF-08-340-A-E, Sep 2008. (link).

A. Chou for the collaboration, "Search for chameleon particles visa photon regeneration results," Presented at the 4th Patras Workshop on Axions, WIMPs and WISPs – Training Workshop, Hamburg Germany, 18-21 Jun 2008, FERMILAB-CONF-08-332-AD-CD-E-TD, Sep 2008. (link).

News Stories

Softpedia, "Axion Particles Constituents of Dark Matter?" March 4 2008, (pdf).
(some errors exist in the story – for example, there is no indication of chameleons in our data).

PhysOrg, "Is Dark Matter Made of Axions," March 3 2008, (pdf).

Fermilab Today, Result of the Week, "Axion result all washed up," February 21 2008, (pdf).

CERN Courier, "Fundamental Physics re-explored at Patras," CERN Courier, Vol. 47, No. 10, p. 43 (Nov 2007).

NZZ Online, "Vergebliche Suche nach Axion-artigen Teilchen," Nov 28 2007. (link) (German).

Physics World, "Results question merit of axion experiments," Nov 21, 2007. (link) (Spanish) (Russian). (registration required)

Symmetry Magazine, "Particle Search on a shoestring," Vol. 4, No. 6, Aug. 2007, (pdf).

DOE Pulse, "Spare parts turn into potential discovery tools," Num. 242, August 27, 2007, (pdf).

Fermilab Today, "GammeV turns spare parts into potential discovery tools," August 2 2007, (pdf).

Science Magazine, "A Spare Magnet, a Borrowed Laser, and One Quick Shot at Glory," Science Vol. 316, No. 5833, p. 1838 (29 June 2007).

Conference presentations, seminars, colloquia

J. Steffen, "Constraints on chameleons and axion-like particles from the GammeV Experiment," Identification of Dark Matter 2008, IDM2008, Stockholm, Sweden (Aug 22, 2008). (link)

W. Wester, "GammeV, A gamma to milli-eV particle search," 34th International Conference on High Energy Physics, Philadelphia, PA (Aug. 1, 2008). (link)

A. Chou, "GammeV: Fermilab chameleon search and future ideas," 4th Patras Workshop on Axions, WIMPs, and WISPs, DESY, Hamburg, Germany (June 20, 2008). (link)

W. Wester, "GammeV: Fermilab axionlike particle photon regeneration results," 4th Patras Workshop on Axions, WIMPs, and WISPs, DESY, Hamburg, Germany (June 20, 2008). (link)

J. Steffen, "Results of the GammeV Axion-like Particle Search," Lab for Particle Physics and Cosmology Seminar, Harvard, MA (Feb. 27, 2008). (link). Particle Theory Seminar, Johns Hopkins Univ., Baltimore (March 5, 2008). (link).

J. Yoo, "The First Results from GammeV: Varying Baseline Axion Like Particle Search at Fermilab," Eighth UCLA Symposium: Sources and Detection of Dark Matter and Dark Energy in the Universe, UCLA (Feb 21, 2008). (link)

W. Wester, "GammeV, A gamma to milli-eV particle search," High Energy and Astro-Particle Seminar, UCLA, (Jan 23, 2008). (link). Enrico Fermi High Energy Physics Lunch Seminar, Univ of Chicago (Feb 4, 2008). (link). High Energy Physics Division Seminar, Argonne National Laboratory (Feb 6, 2008). (link). High Energy Physics Seminar, Northwestern University (Feb 11, 2008). (link). High Energy Physics Seminar, Michigan State University, East Lansing (Mar 11, 2008). (link). High Energy Physics Seminar, University of Wisconsin, Madison (Mar 25, 2008). (link). High Energy Seminar, University of Notre Dame (Sept. 9, 2008). (link). High Energy Physics Seminar, University of Illinois (Sept. 15, 2008). (link).

A. Chou, "The GammeV Experiment: A search for oscillations of photons into milli-eV mass particles," Experimental Physics Seminar, Stanford Linear Accelerator Center, (Jan 14, 2008). (link). "The GammeV Experiment: A search for oscillations of photons into milli-eV mass particles," Particle Physics Seminar, Columbia University, (Feb 6, 2008). (link)

A. Upadye, "Chameleon scalar fields and the GammeV Experiment," Particle Astrophysics Seminar, (Dec 10, 2007), Fermilab (link)

A Chou, "GammeV: Search for oscillations from photons to milli-eV mass particles," Particle Physics Seminar, Brookhaven National Laboratory, (Oct 18, 2007). (link)

Jonghee Yoo, "Results from GammeV," Dark Matter 2007, (Sept 27, 2007, Sidney Australia). (link)

W. Wester, "GammeV, A gamma to milli-eV particle search," Colloquium, Kavli Institute for Cosmological Physics, Univ. of Chicago, (Sept 26, 2007). (link)

J. Steffen, "GammeV Status Report," Special report, Fermilab All-Experimenter's Meeting, (Oct 1, 2007, Fermilab). (link)

J. Steffen for the GammeV collaboration, "The GammeV Particle Search Experiment," 3rd Joint ILIAS-CAST-CERN-DESY Axion-WIMPs Training Workshop (19 June – 25 June 2007, Patras, Greece). (link)

W. Wester, "GammeV, A gamma to milli-eV particle search, T-969, Installation and Commissioning," Special report, Fermilab All-Experimenter's Meeting, (June 4, 2007, Fermilab). (link)

Posters

J. Steffen for the GammeV collaboration, "Results from the GammeV Axion-like Particle Search," Fermilab annual User's Meeting, (June 4-6, 2008, Fermilab). (link)

J. Steffen for the GammeV collaboration, "Results from the GammeV Axion-like Particle Search," 211th Meeting of the American Astronomical Society, Austin TX, January 2008).

The GammeV collaboration, "GammeV, a gamma to milli-eV particle search," Fermilab DOE Annual Review, (Sept 25, 2007, Fermilab) [first time results were presented]

The GammeV collaboration, "The GammeV Experiment," Fermilab annual User's Meeting, (June 6-7, 2007, Fermilab). (link)

+ 35 citations to our work
+ 1 Wilson Fellow
+ 1 WF candidate
+ 1 Post doc on job market
+ 1 GEM summer student

Back-up slides

Critique of PVLAS interpretation

Postives for a new particle interpretation

- -Effect seen in both ellipticity and rotation at 532 and 1064nm
- -Scalar interpretation points to a small region in M vs m
- -Cotton Mouton effect is observed as expected
- -No rotation effect with no B field
- -Copious theoretical ideas to evade astrophysical and other bounds

Concerns for a new particle interpretation

- -Systematics from rotation magnet (eddy currents) understood?
- -Extra 1st harmonic signal not explained
- -Some cross checks are done w/large signals
- -**New data does not observe the effect and concludes there is likely an instrumental artifact (hep-ex/0706.3419) [after we started]**

GammeV motivation is to test the axion-like particle interpretation of the PVLAS anomaly in a direct manner

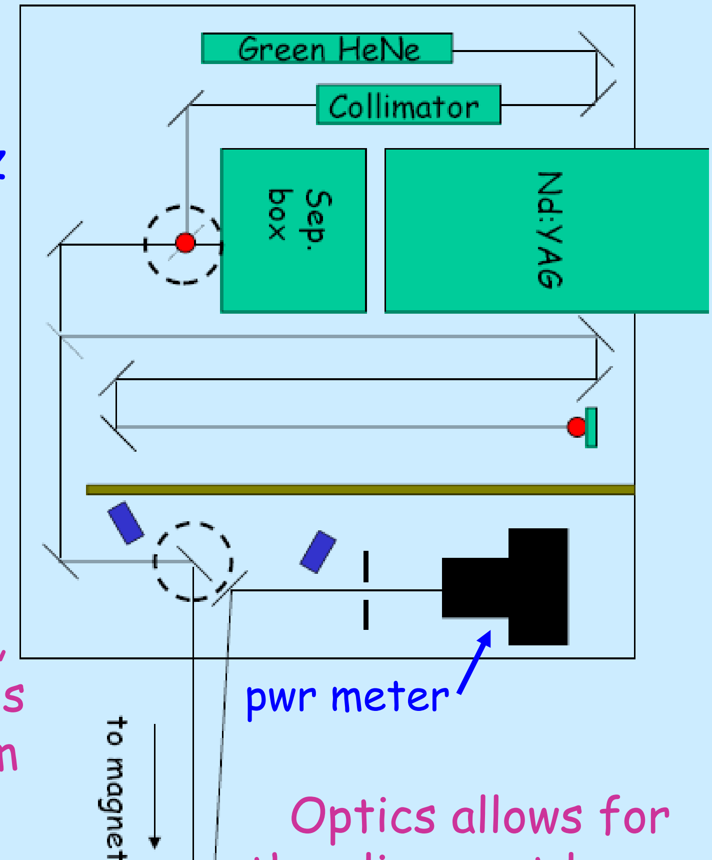
Laser box

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 laser
10ns wide
pulses@20Hz

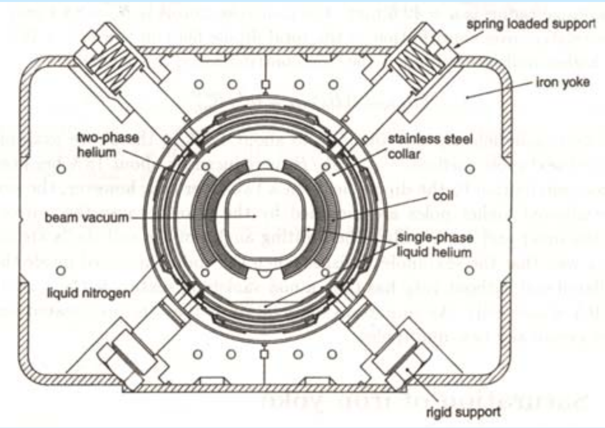
Laser box is safety interlocked, mounted on cement blocks, holds optics, and interfaces to vacuum inside the magnet.

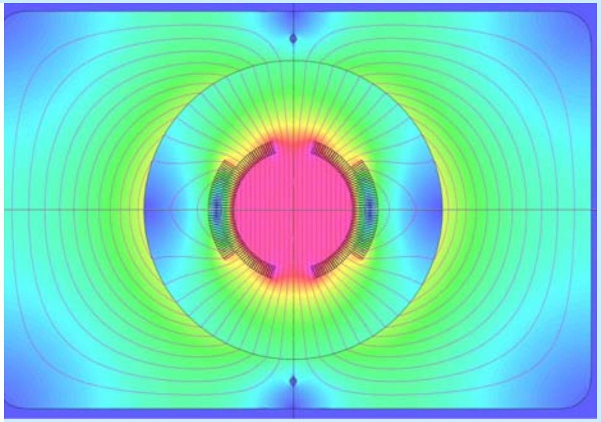
Video image of reflected laser spot is monitored during data taking.

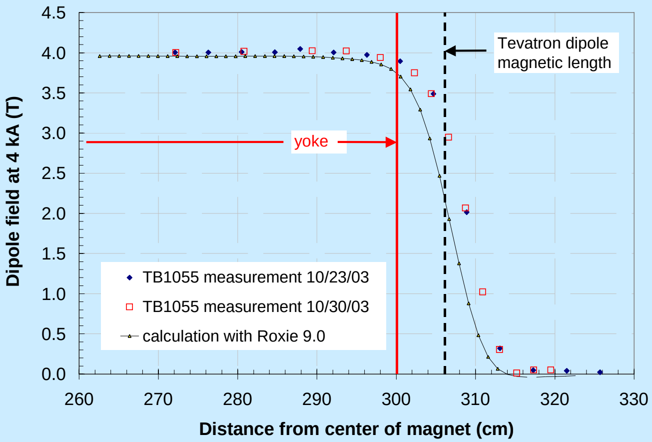


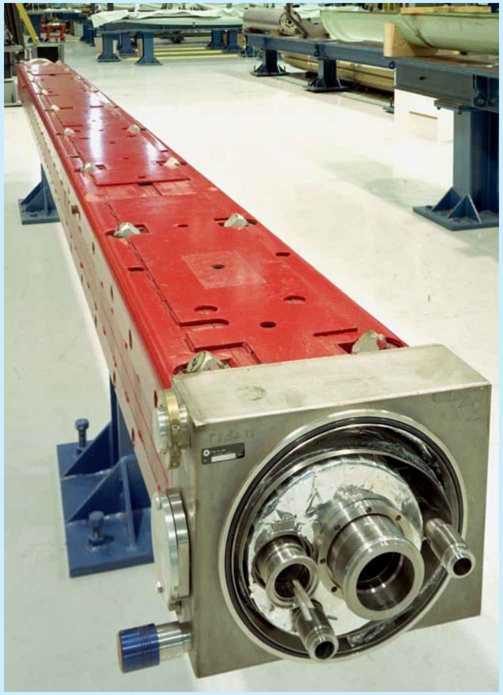
Optics allows for the alignment laser and Nd:YAG to be aligned using ~3m path in the box so the low power laser can be steered through the apparatus.

Tevatron Magnet



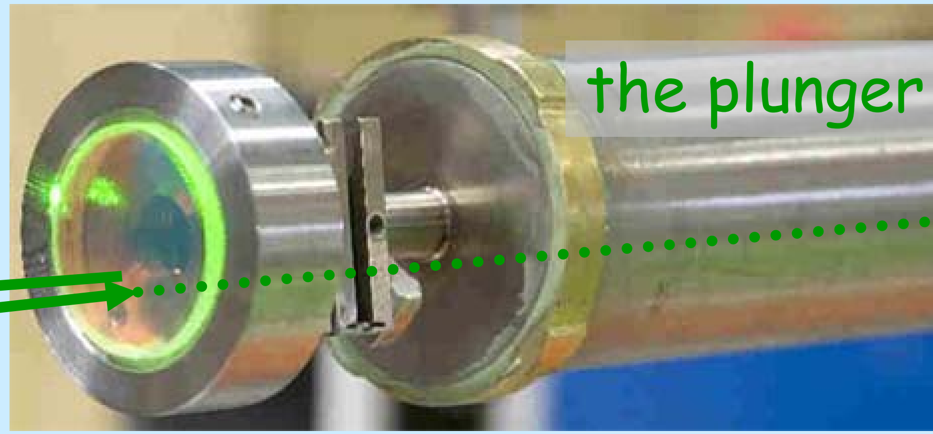


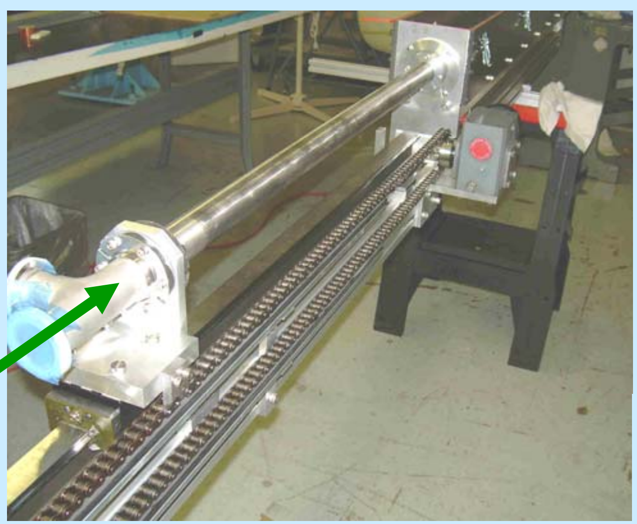




- Our magnet: TC1206 one of the best spare Tevatron dipole magnets. It was selected because it was previously run at high current
- Operating current was 5040A to have 5T over the entire 6m length. Measured with NMR probes.
- Terrific support from the magnet test facility that gave us space and infrastructure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

The "Wall" and plumbing



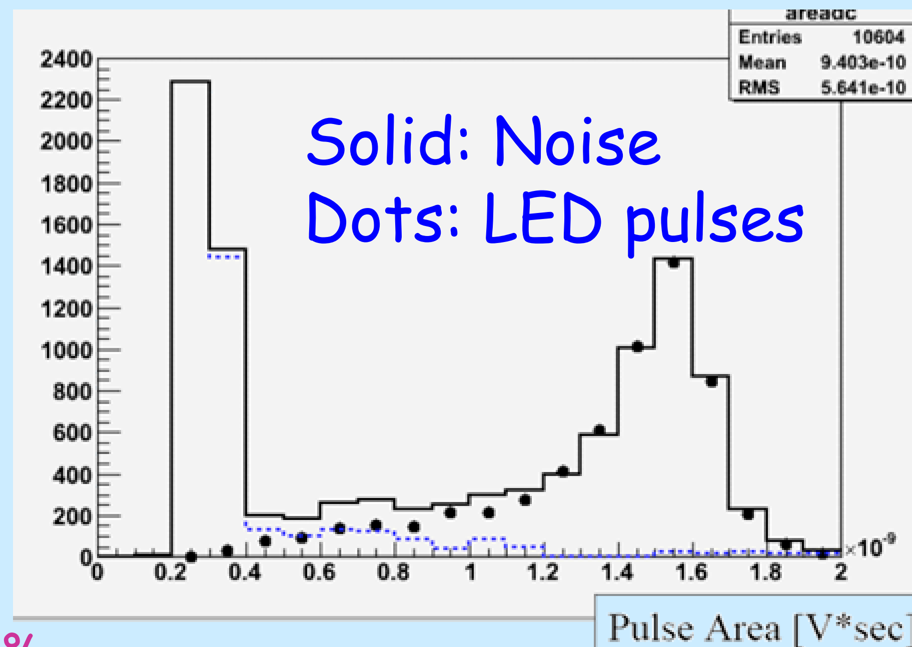


The plunger can be adjusted by 2 meters so that the wall can either be placed in the center of the magnet or at a position 1m from the end of the magnet. This unique feature allows us to be sensitive to other masses.

Single photon detector

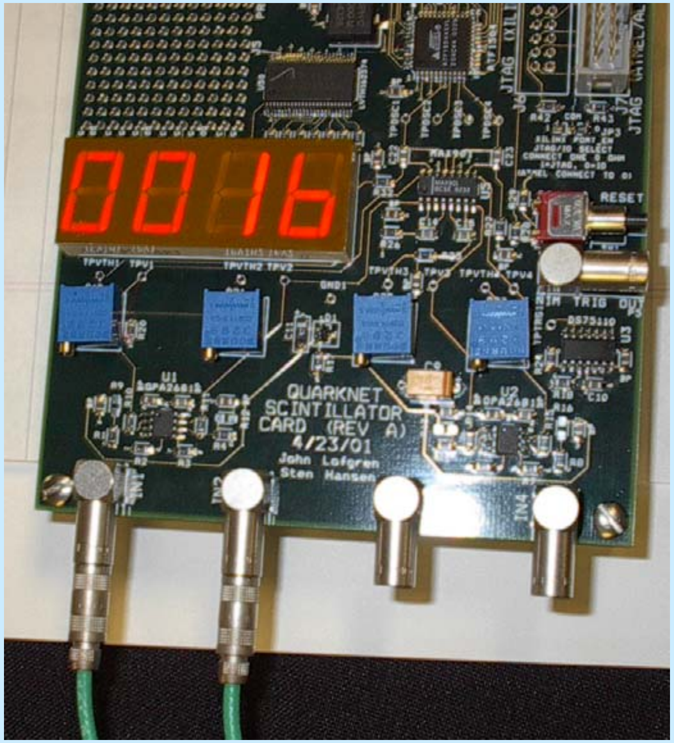
- Hamamatsu H7422P-40 PMT
- GaAsP photocathode, QE=40%
- Dark Count rate ~ 100 Hz with built-in thermoelectric cooler

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)%

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.

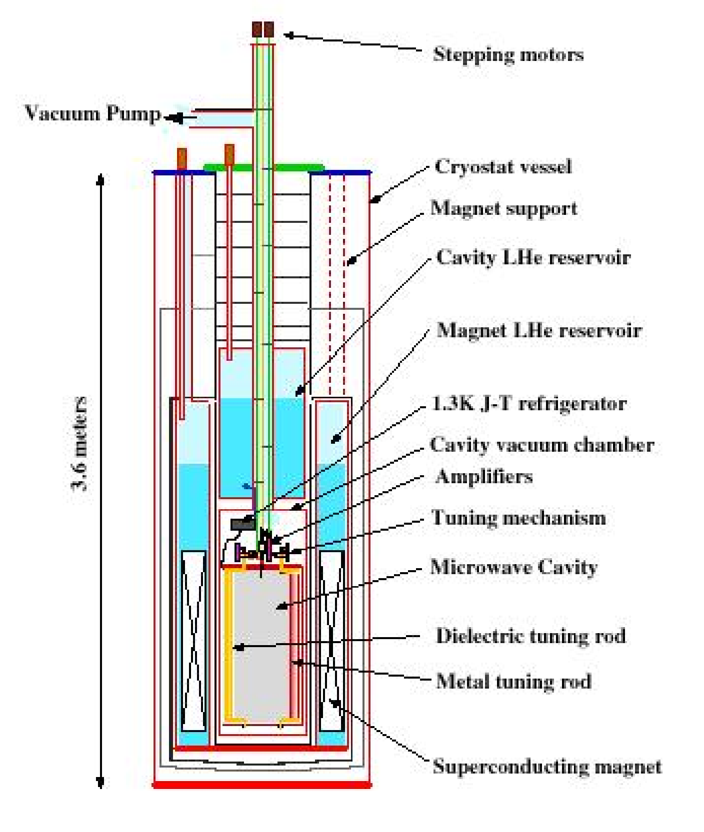
Time the laser pulses (20Hz) and time the PMT pulses (120Hz). Look for time correlated single photons. All pulses are ~10ns wide.

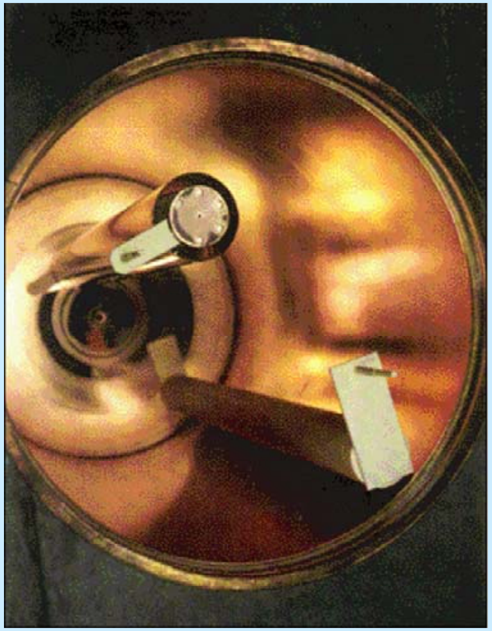
	Ch0	Ch1	Ch2	Ch3
PMT Quark Net	PMT pulse	LED pulse	Scope trigger	Isochro nous CLK
Laser Quark Net	Laser Photo diode	Laser Splash	Laser Synch pulse	Isochro nous CLK

GammeV

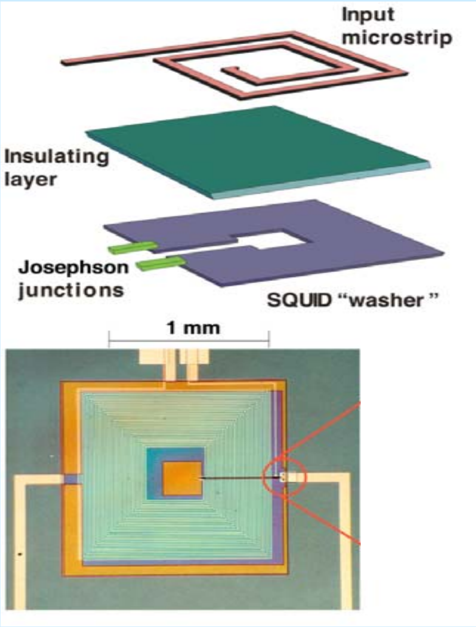
ADMX Experiment

- Axion Dark Matter Experiment
  - Tunable microwave cavity in B field looking for dark matter axions converting into a detectable photons.





High Q cavity



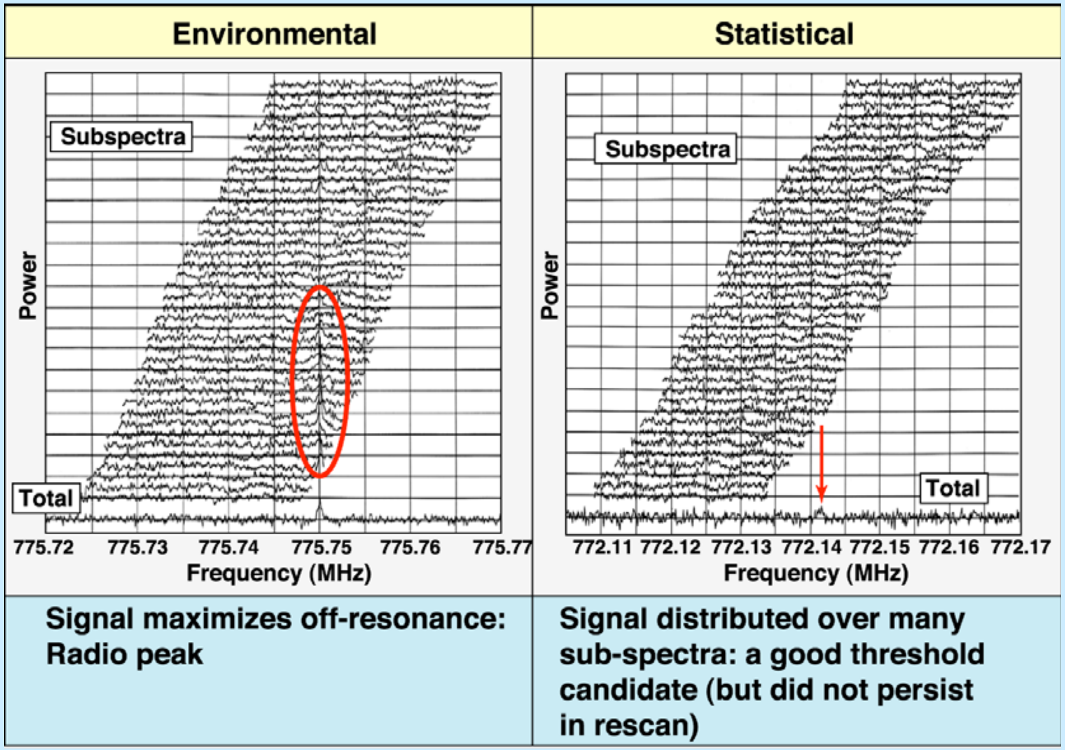
SQUID upgrade for receiver

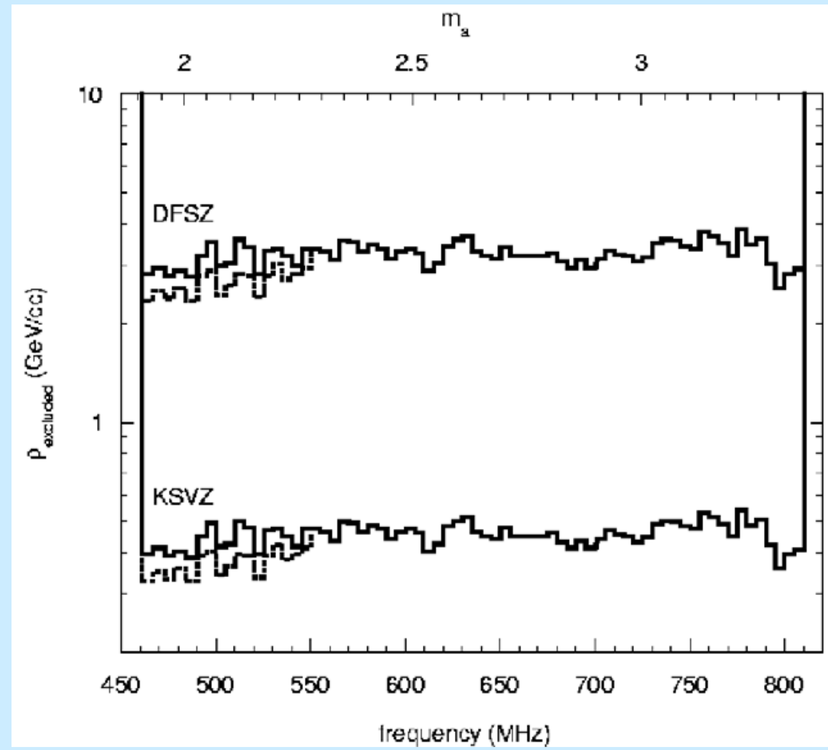
ADMX

GammeV

ADMX Results

- Scan narrow frequency bands. World's quietest spectral receiver.
- Observations consistent with known radio sources or statistics.



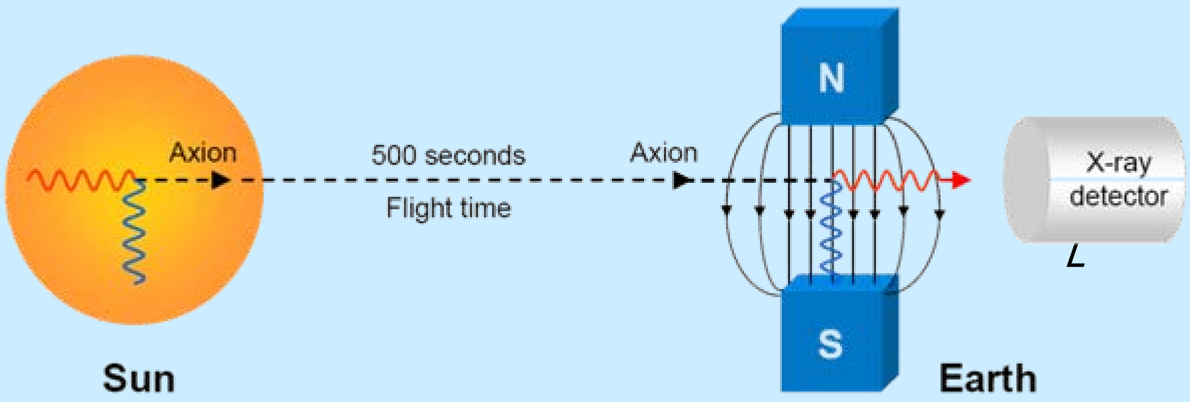


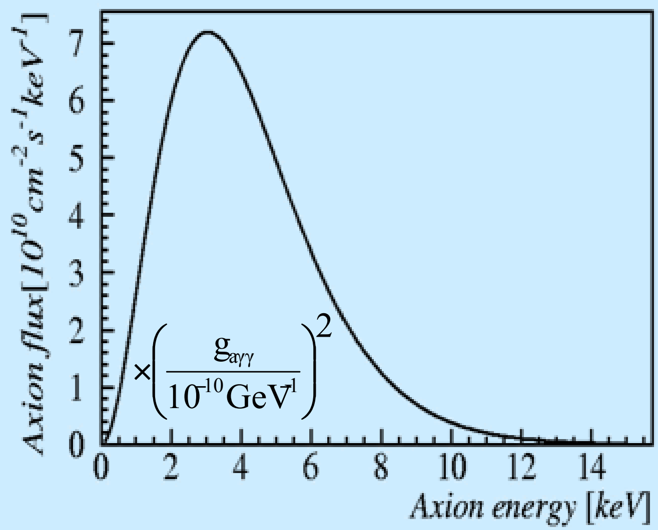
K van Bibber

- Upgrades should allow sensitivity into the QCD axion / dark matter candidate region of interest.

CAST Experiment

- CERN Axion Solar Telescope





Point LHC dipole toward the sun.

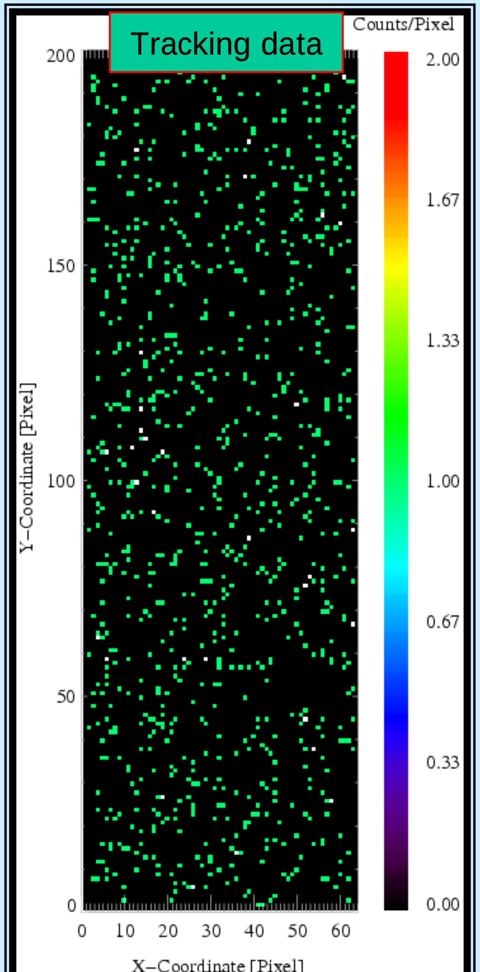
Detect possible X-rays from axion reconversion.

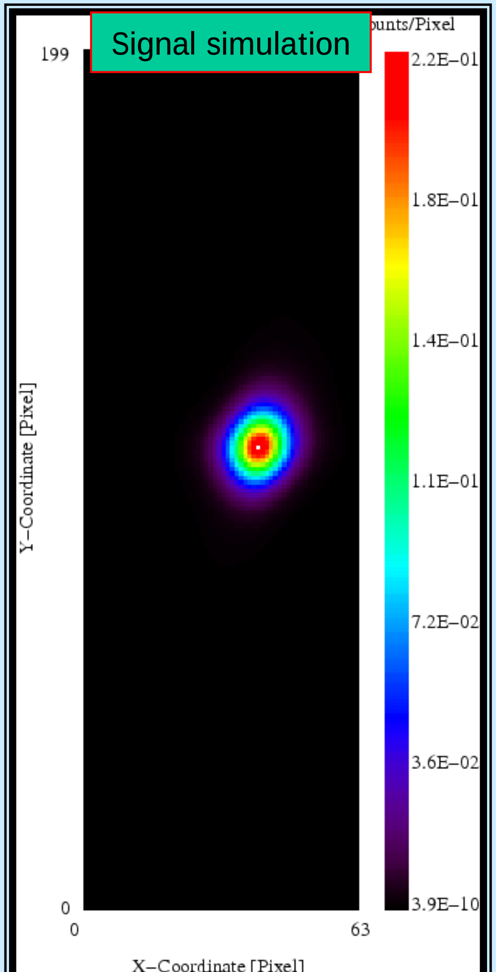
CAST

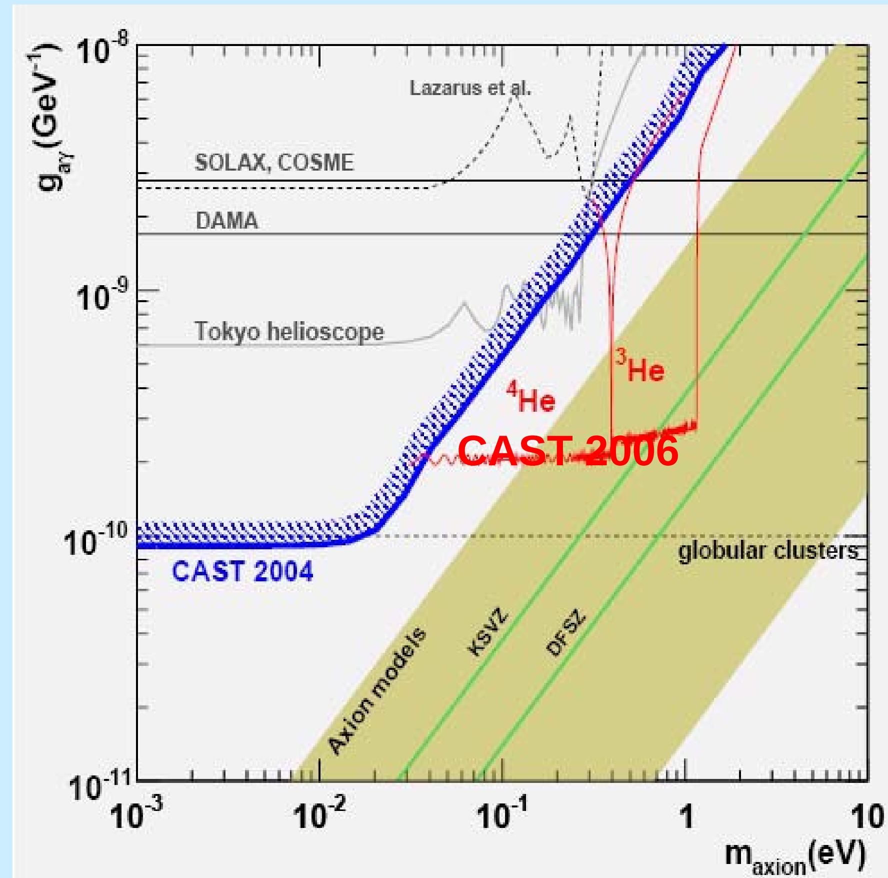
GammeV

CAST Results

- 2004 results hep-ex/0411033 and new results with small gas pressures hep-ex/0702006 to probe QCD axion.





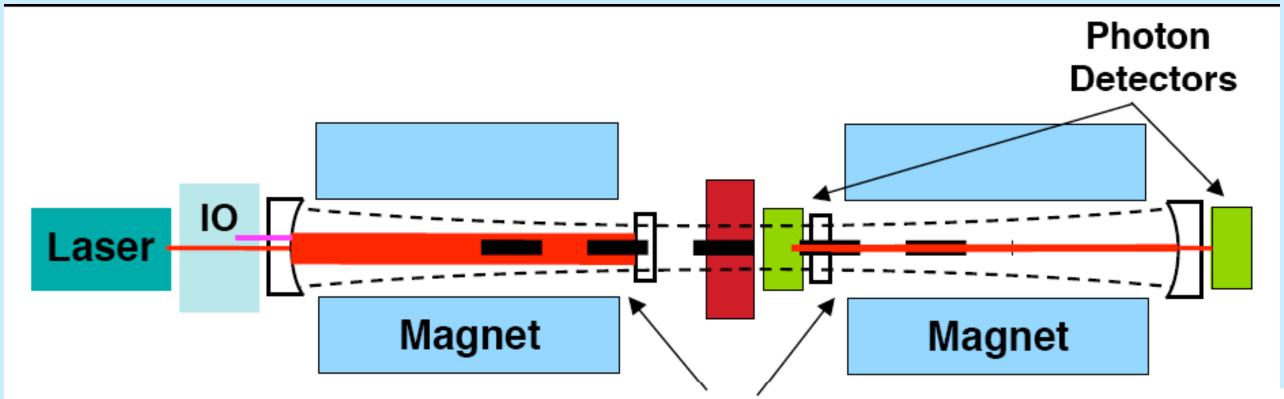


$g_{a\gamma\gamma}$ (95% C.L.) < 1.16×10^{-10} GeV^{-1}

CAST

Next future steps?

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 cooling and CAST limits.

Note that microwave cavity experiments (ADMX) are now probing the QCD axion.