REAPR
Resonantly Enhanced Axion Photon Regeneration

William Wester
Fermilab

Axions

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

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

Raffelt

- The measurement of the electric dipole of the neutron implies $\bar{\Theta} < \sim 10^{-10}$. => 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.
  - Axions originate from a new symmetry that explains small $\bar{\Theta}$

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

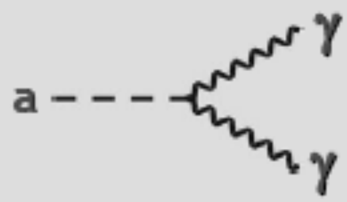
Axions

- Axion mass related to the pion mass: $m_a \sim m_\pi f_\pi / f_a$
- Axions couple to two photons

Photon coupling

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

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



Raffelt

- 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

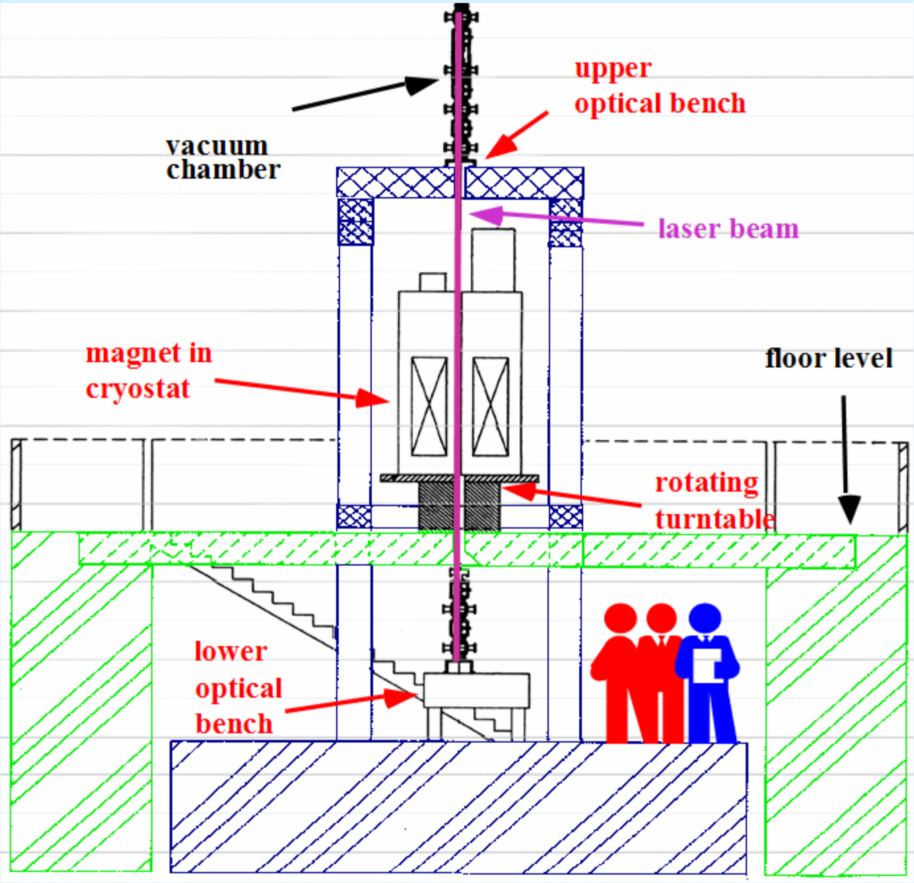
$$\mathcal{L}_{\rm int} = -\frac{1}{4}\frac{\phi}{M} F_{\mu\nu}\widetilde{F}^{\mu\nu} = \frac{\phi}{M}(\vec{E}\cdot\vec{B})$$

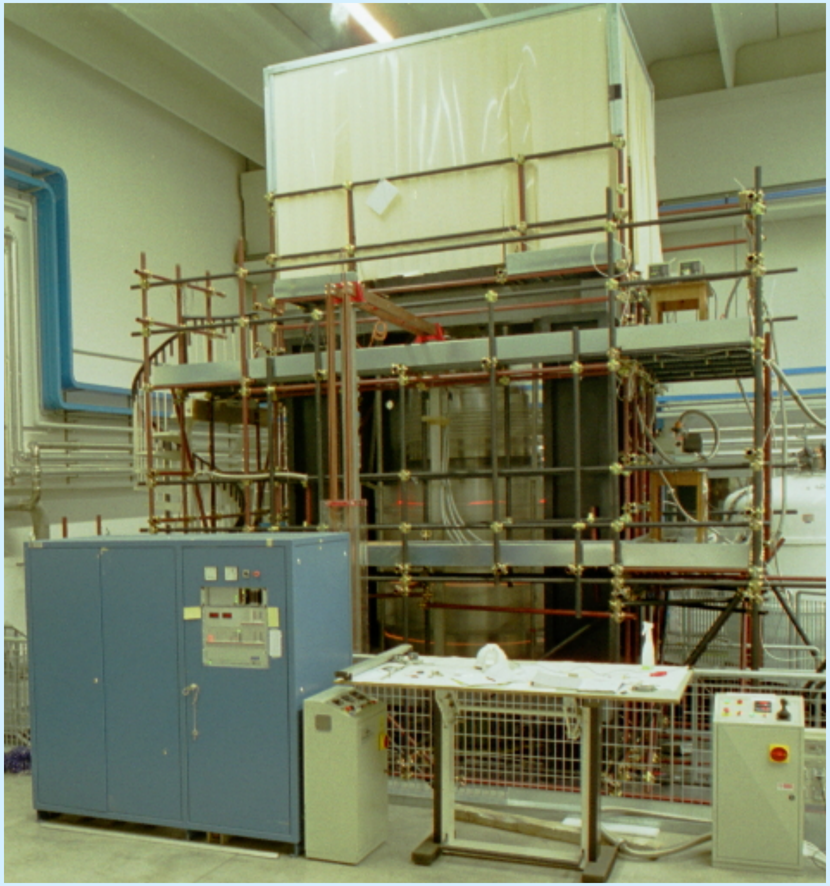
scalar

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

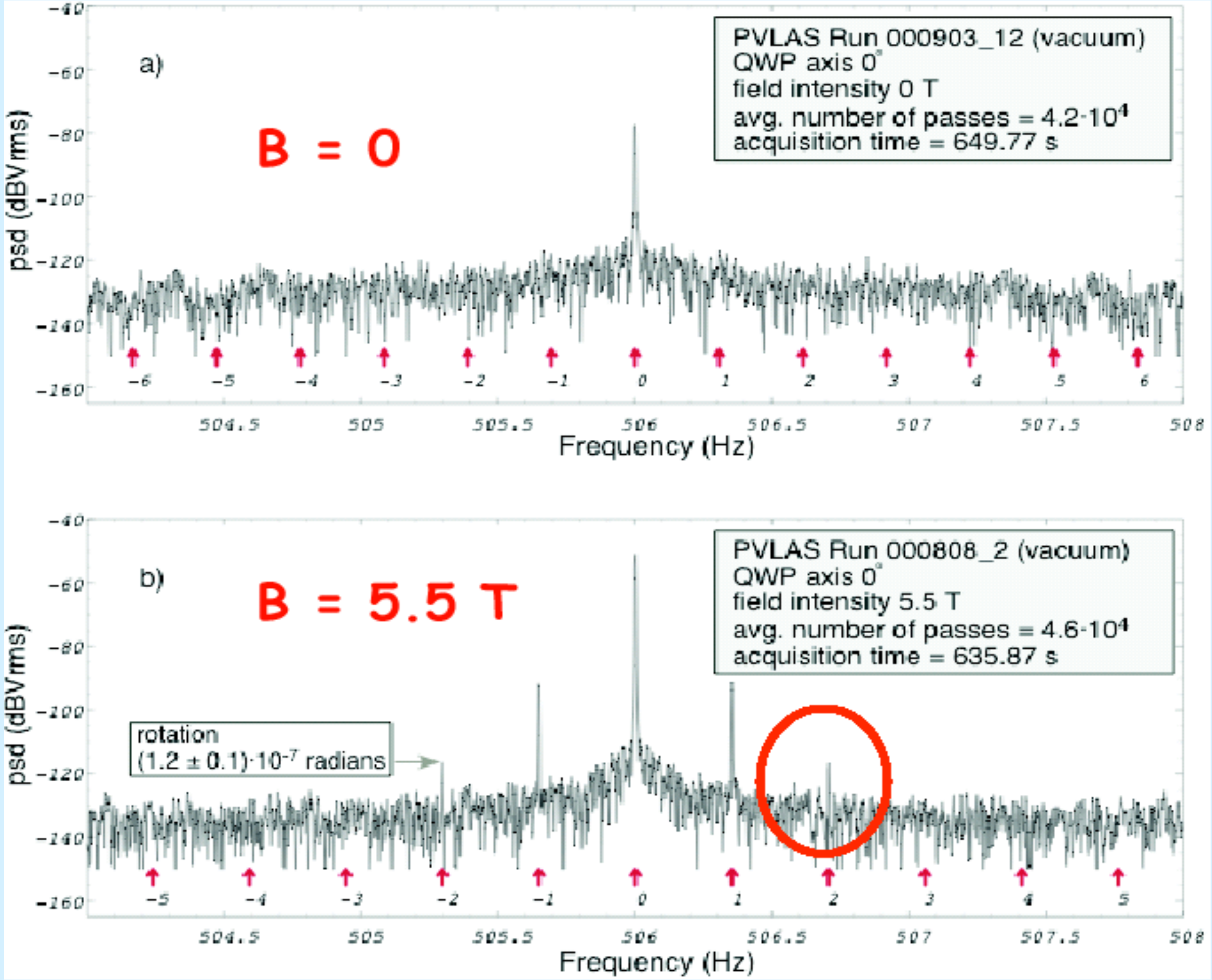
PVLAS Experiment (2006)

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





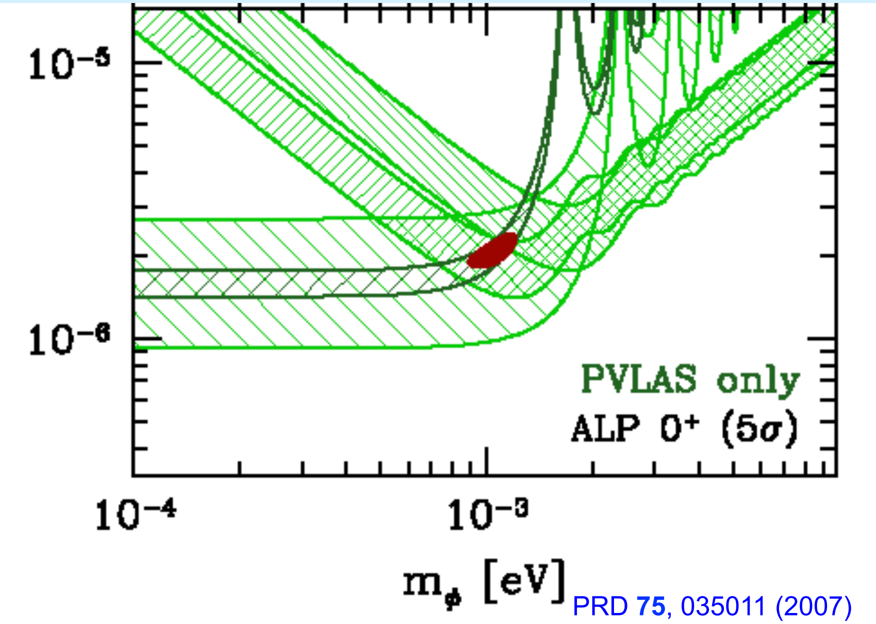
PVLAS Rotation Results



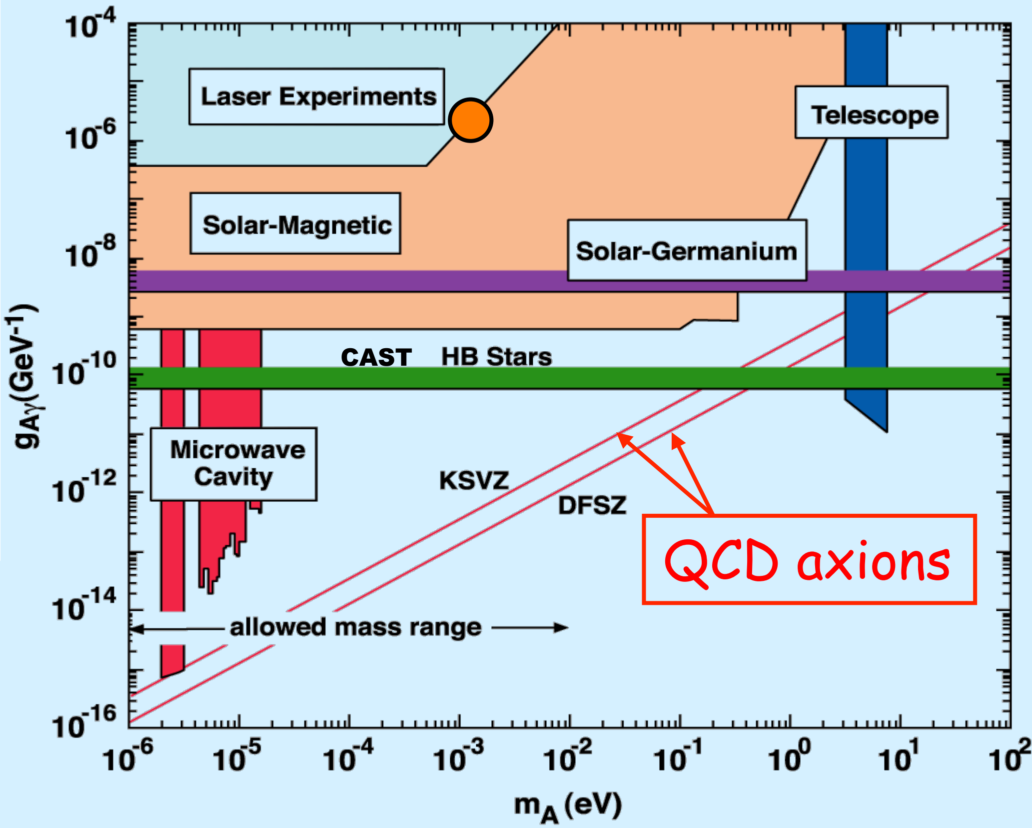
PRL 96, 110406, (2006)

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.



PRD **75**, 035011 (2007)



Additional data by PVLAS has since no longer seen the anomalous effects. However, the source of the anomaly has not been clarified.

PRD **77**, 032006 (2008)

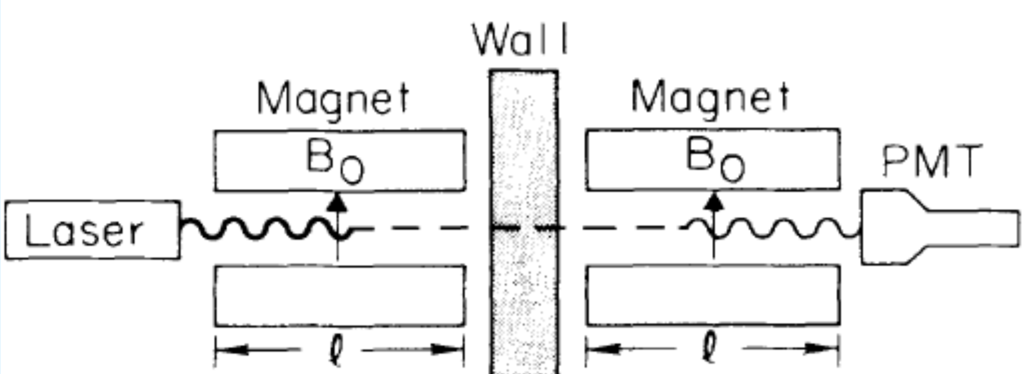
milli-eV Mass Scale

- 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}
  - Dark Matter Candidates
    - Certain SUSY sparticles (low mass gravitino)
    - Axions and axion-like particles

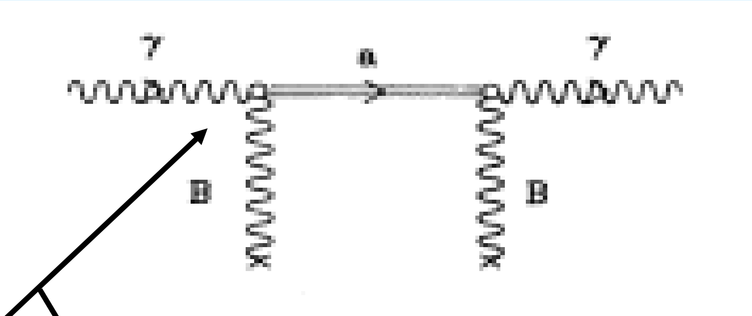
Motivation and target

- We had two points of motivation
  - PVLAS anomaly
  - milli-eV new particles that couple to photons
- Search for New Physics – on par with Dark Matter experimental efforts
- We also had a target with goals to unambiguously test the suggested PVLAS ALP interpretation
- Similar to DM efforts testing SUSY

Light Shining Through a Wall



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



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

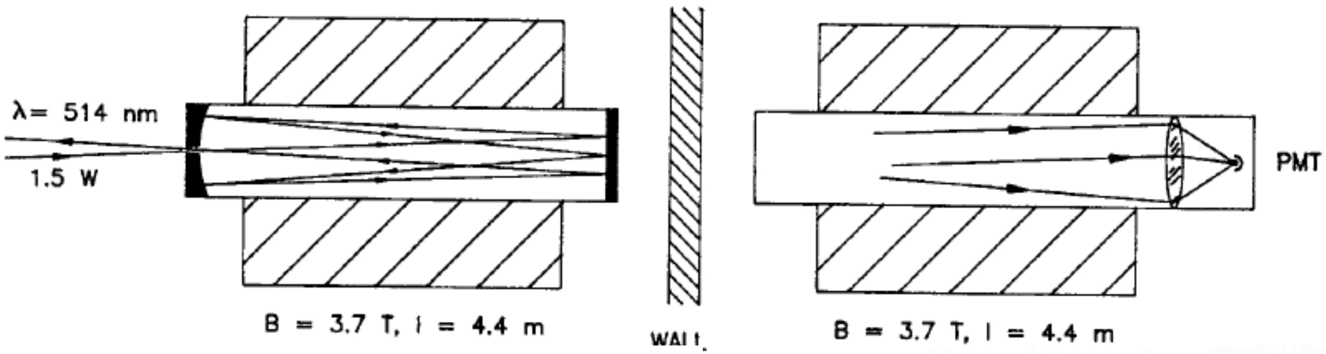
$$P_{regen} = \frac{16 B_1^2 B_2^2 \omega^4}{M^4 m_\phi^8}\sin^2\left(\frac{m_\phi^2 L_1}{4\omega}\right)\cdot\sin^2\left(\frac{m_\phi^2 L_2}{4\omega}\right)$$

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

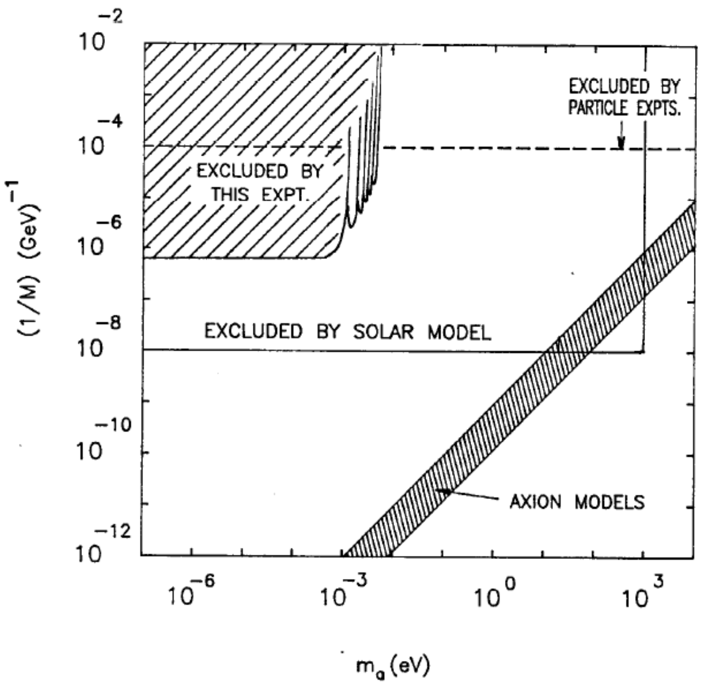
$$P_{regen}^{GammeV} = (3.9\times 10^{-21})\times\frac{(B_1/5\ \text{T})^2(B_2/5\ \text{T})^2(\omega/2.33\ \text{eV})^4}{(M/4\times 10^5\ \text{GeV})^4(m_\phi/1.2\times 10^{-3}\ \text{eV})^8}$$
$$\times\sin^2\left(\frac{\pi}{2}\frac{(m_\phi/1.2\times 10^{-3}\ \text{eV})^2(L_1/2.0\ \text{m})}{(\omega/2.33\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

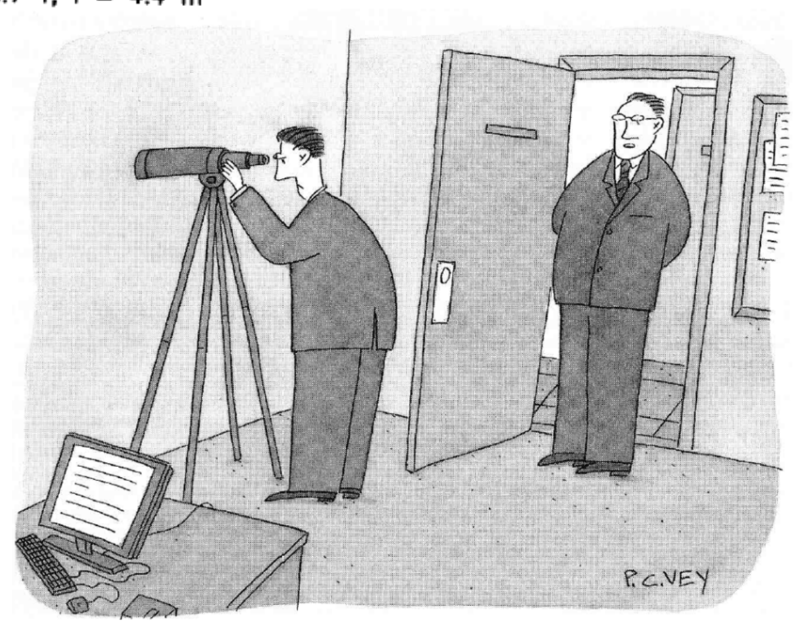
Light Shining Through a Wall

- Brookhaven, Fermilab, Rochester, Trieste (1992)



Light shining through a wall

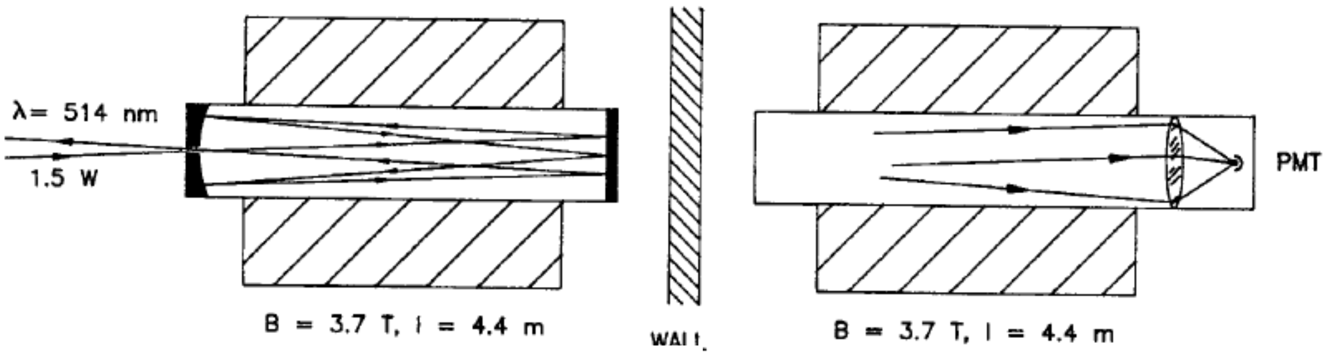




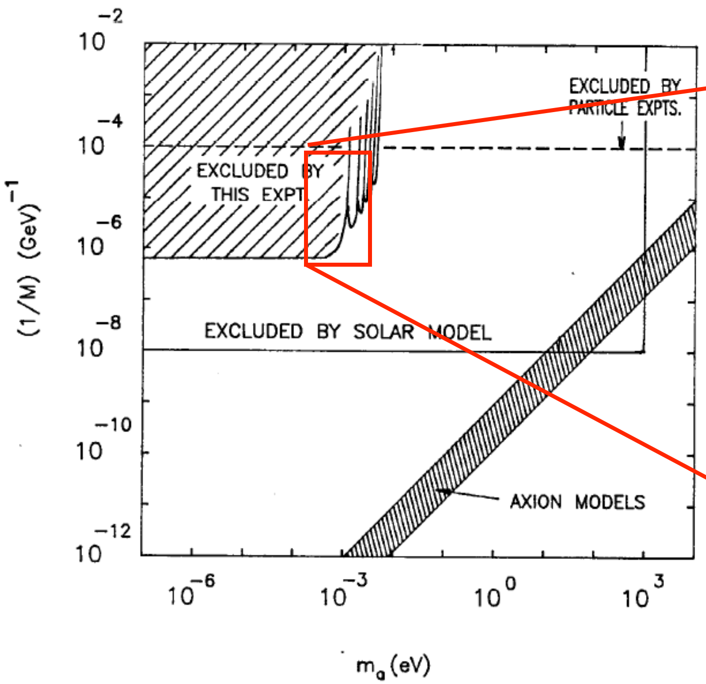
New Yorker

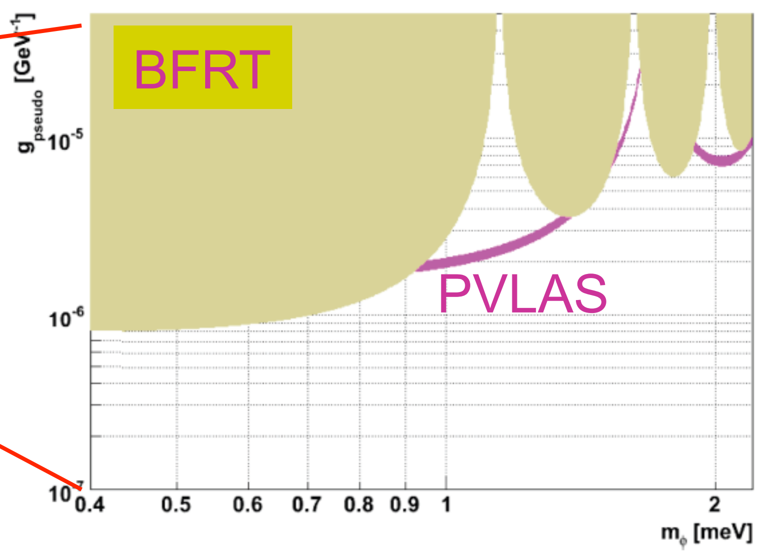
Light Shining Through a Wall

- Brookhaven, Fermilab, Rochester, Trieste (1992)



Light shining through a wall





BFRT is not sensitive in the PVLAS region of interest.

Nature picks it's own parameters

GammeV Collaboration

A. Baumbaugh, A. Chou*, Y. Irizarry-Valle†, P. Mazur, J. Steffen, R. Tomlin, W. Wester*, Y. Xi‡, J. Yoo
Fermi National Accelerator Laboratory
Batavia, IL 60510

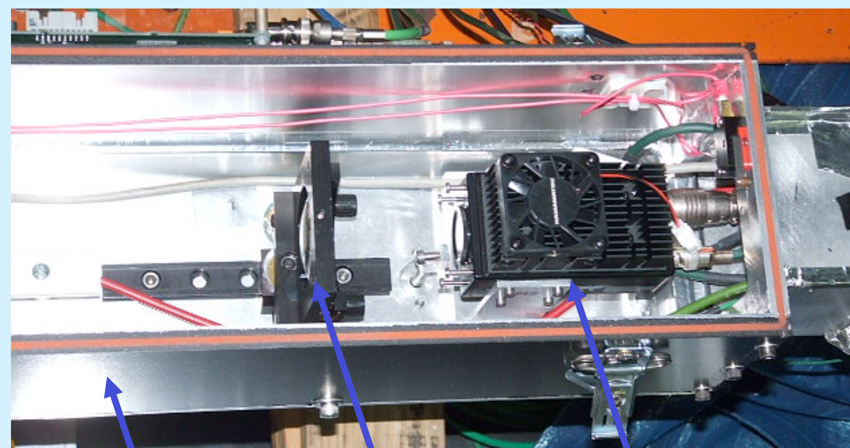
D. Gustafson
University of Michigan
Ann Arbor, MI 48109

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 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 Accepted

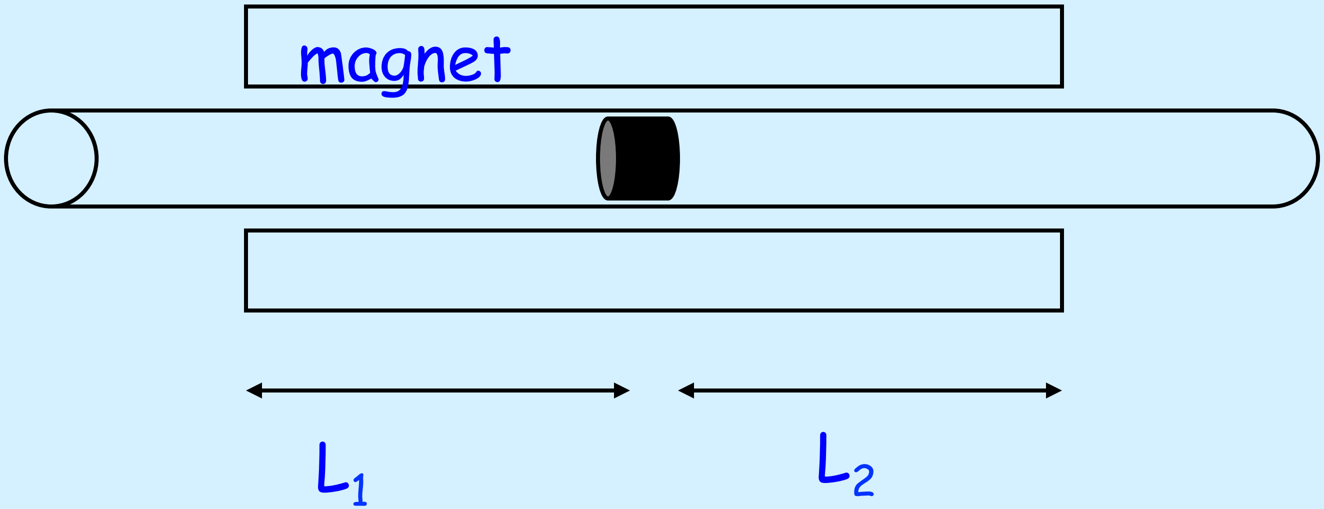
Apparatus

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



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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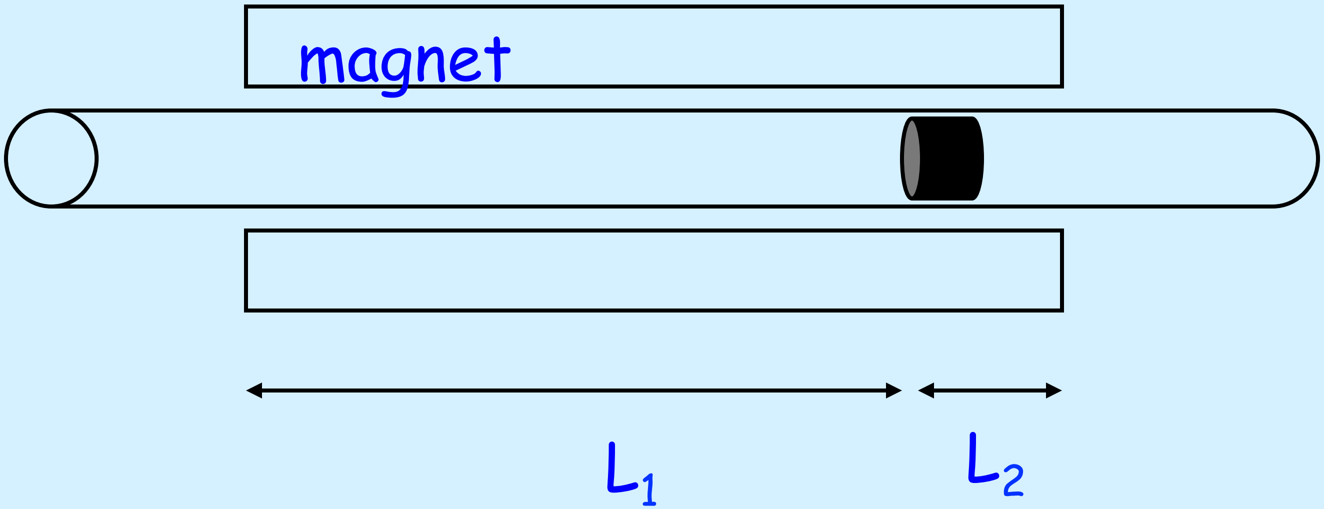

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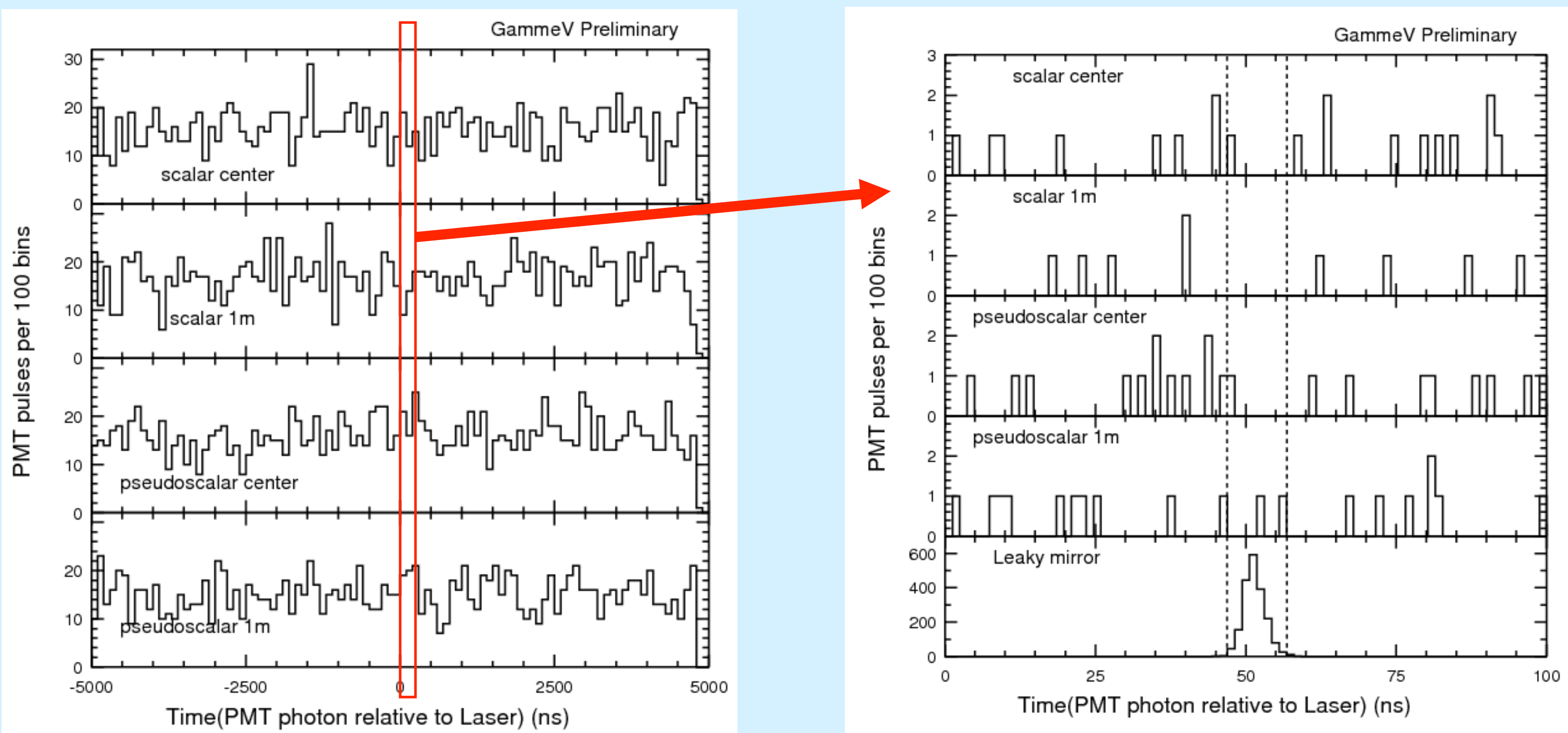
GammeV Results

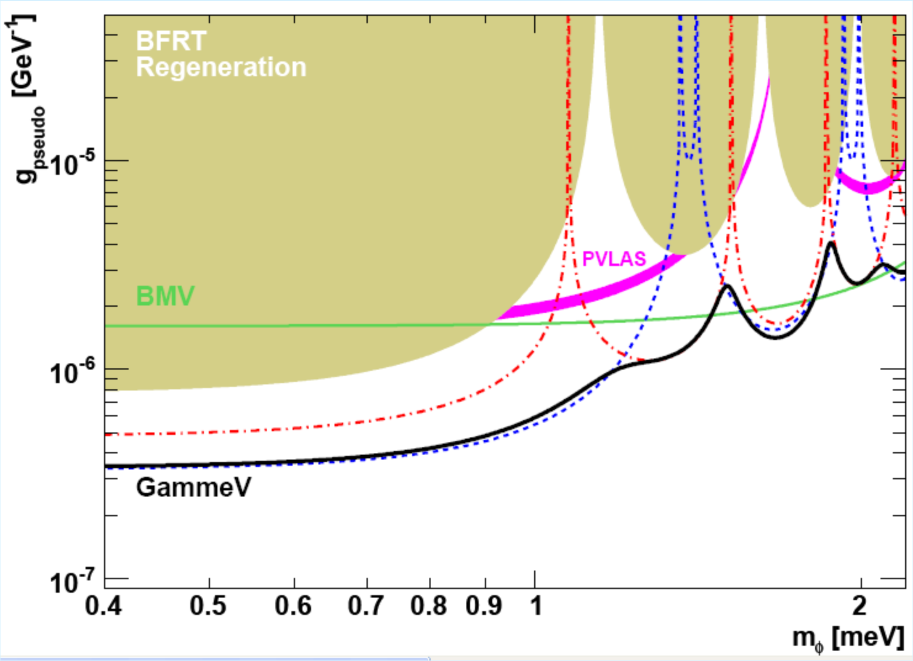
Spin	Position	# Laser pulse	# photon / pulse	Expected Background	Signal Candidates
Scalar	Center	1.34 M	0.41e18	1.56±0.04	1
Scalar	1 m	1.47M	0.38e18	1.67±0.04	0
Pseudo	Center	1.43M	0.41e18	1.59±0.04	1
Pseudo	1m	1.47M	0.42e18	1.50±0.04	2



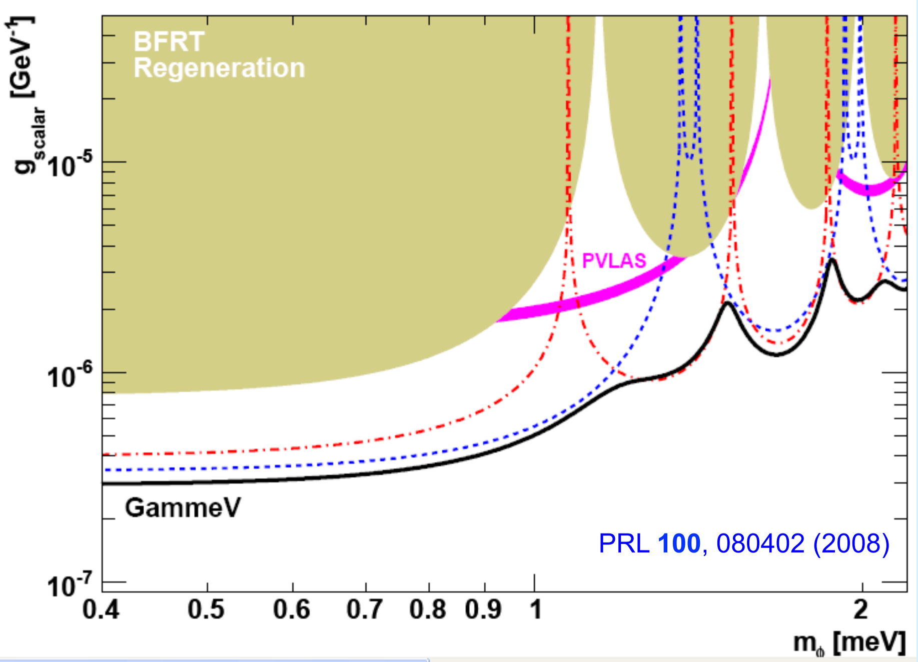
GammeV Limits

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

Pseudoscalar



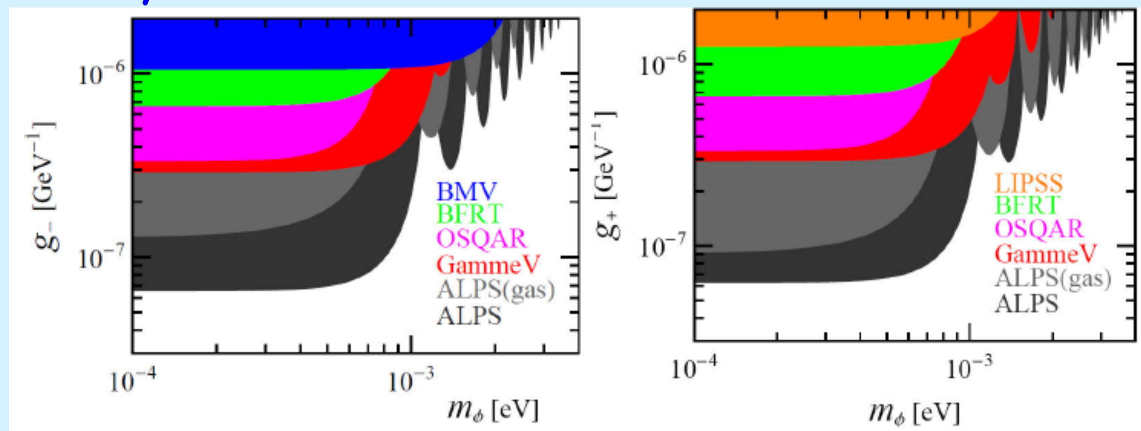
Scalar



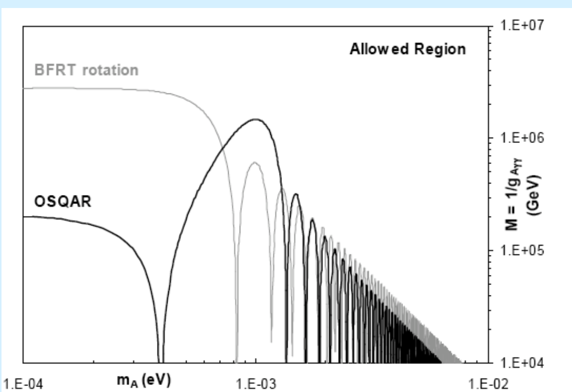
- Job is done. Limit generally improves slowly (4^{th} root) vs. longer running time, or increased laser power, etc.

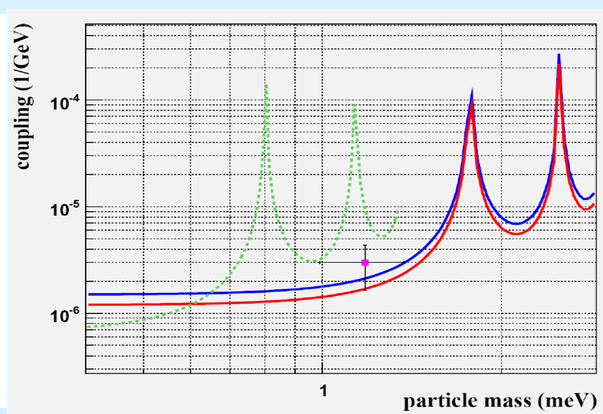
Other experiments worldwide

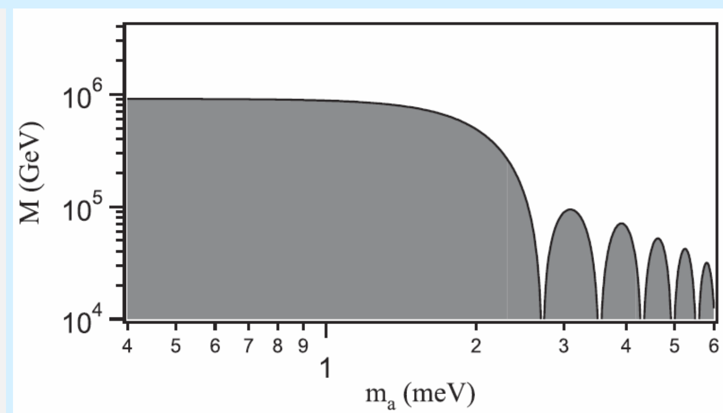
- Patras Workshop on Axions, WIMPs, and WISPs
  - 7th was in Mykonos
  - axion-wimp.desy.de
- No evidence of ALPs using different configurations of LSW technique.



ALPS PLB 689, **149** (2010)







OSQAR PRD **78**, 092003 (2008)
Note: with N_2 gas

LIPSS scalar only
PRL **101**, 120401(2008)

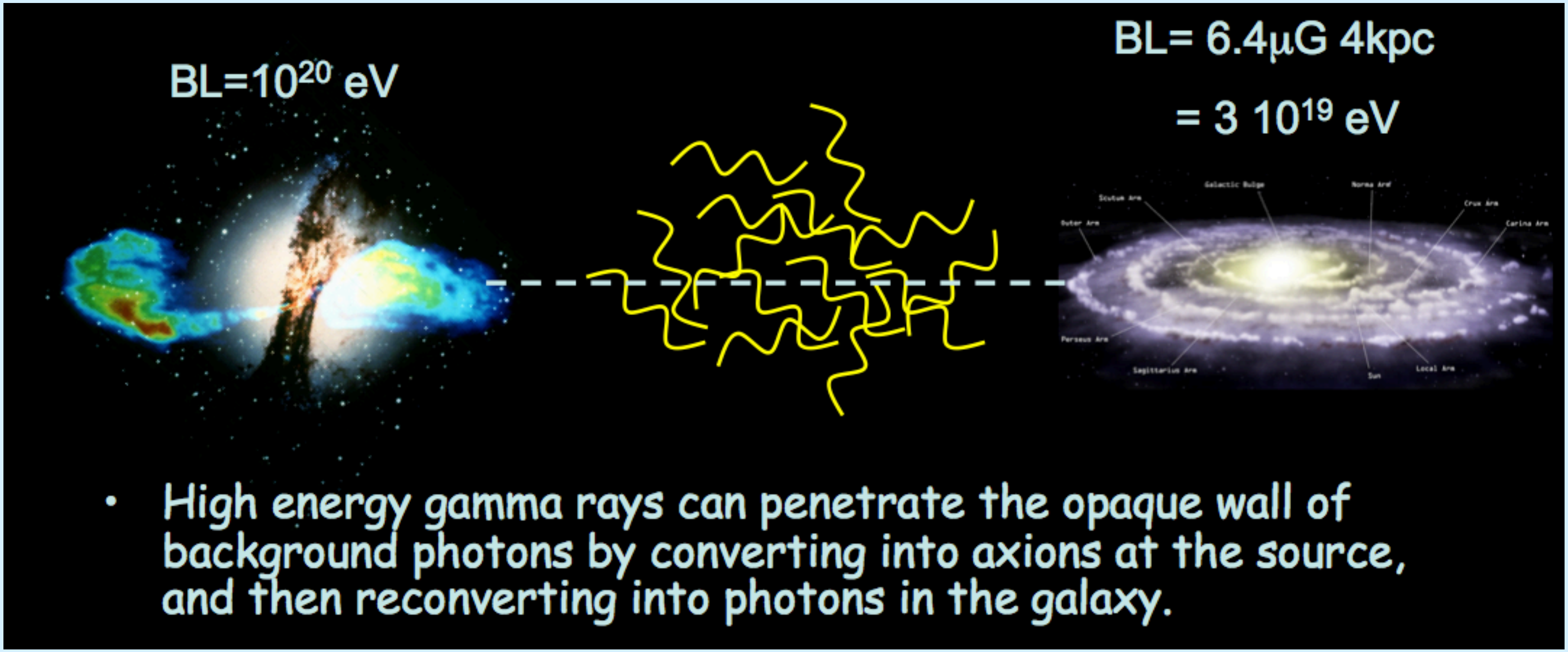
BMV pseudoscalar only
1st results: PRL **99**, 190403 (2007)
Final results: PRD **78**, 032013 (2008)

LSW as an intensity frontier experiment

- LSW uses
  - An intense beam of photons
  - New Physics weakly coupled to ordinary matter
  - Detection of a non-SM rare process = discovery
- LSW hindered by 4th root of the coupling constant due to production and regeneration but there are positives to purely lab exp't.
- Coupling to photons opens several experimental options using modern lasers and optical techniques

Motivation for $g_{\alpha\gamma\gamma} \sim 10^{-(11ish)}$

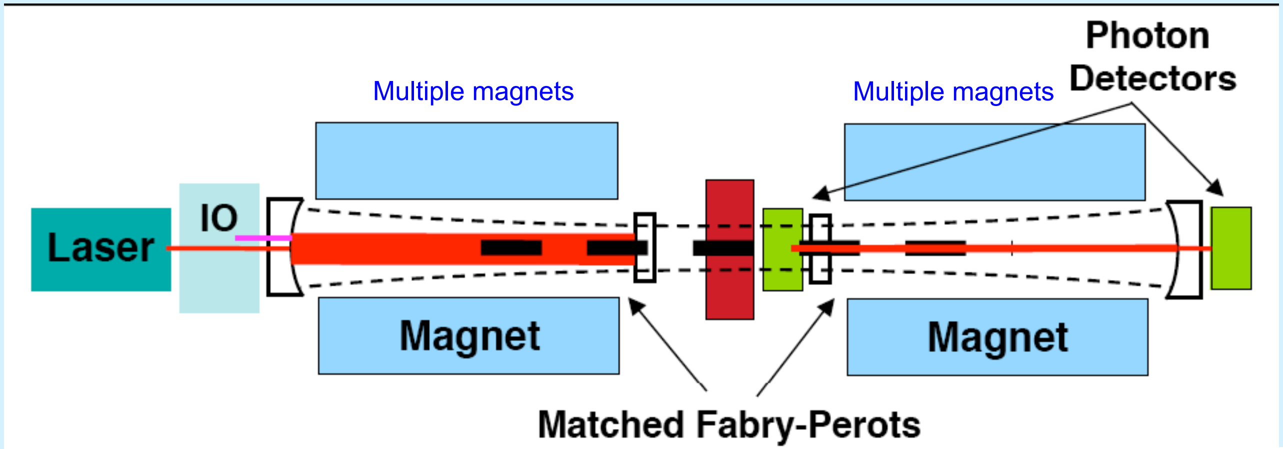
Anomalous observation of high energy gamma rays



Large uncertainties and so this is just a hint that there might be possible New Physics.

REAPR: Future LSW

Resonantly enhanced axion-photon regeneration



F. Hoogeveen and T. Ziegenhagen, Nucl. Phys. B **358**, 3 (1991)
Mueller, Sikivie, Tanner, van Bibber, Phys. Rev. D **80**, 072004 (2009)
Phys. Rev. Lett. **98**, 172002 (2007)

Prob(regeneration):

Linearly:
magnetic field length
30 -> 360 Tm (x12)

¼ - root:
0-bkgd int time (x3)
finesse factor: $\mathcal{F}\mathcal{F}$
(x300)

$\mathcal{F}$ factor of 10^5

Production cavity:
High finesse amplifies forward moving photons x $\mathcal{F}$

Regeneration cavity:
E field of regenerated photon amplified until quantum measurement -> E2 proportional to $\mathcal{F}\mathcal{F}$

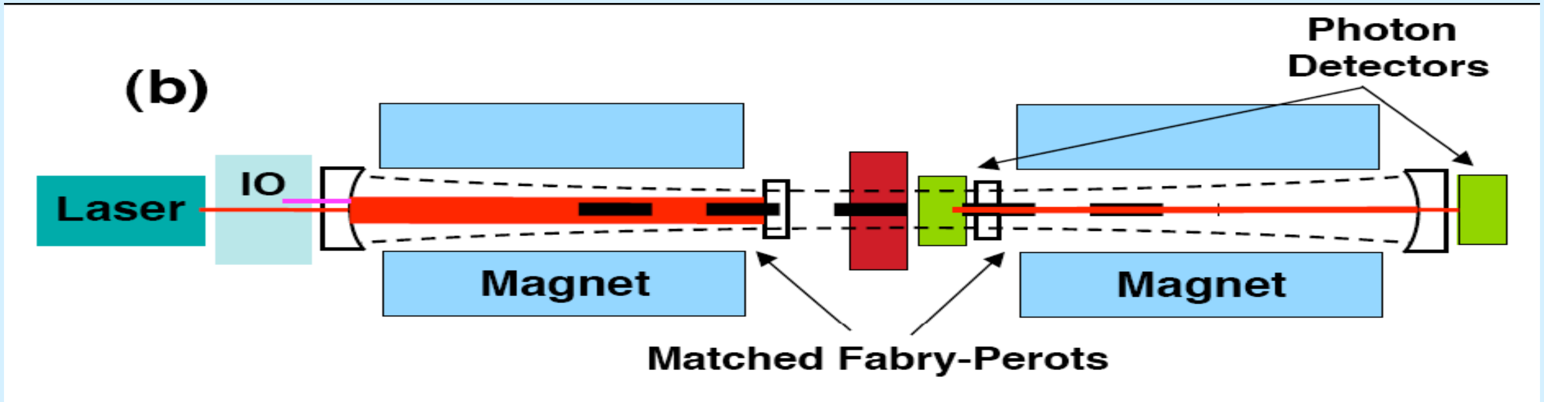
Measurement device:
loose a factor of $\mathcal{F}$ for regenerated photon to be detected

GRIM REAPR

Karl Van Bibber

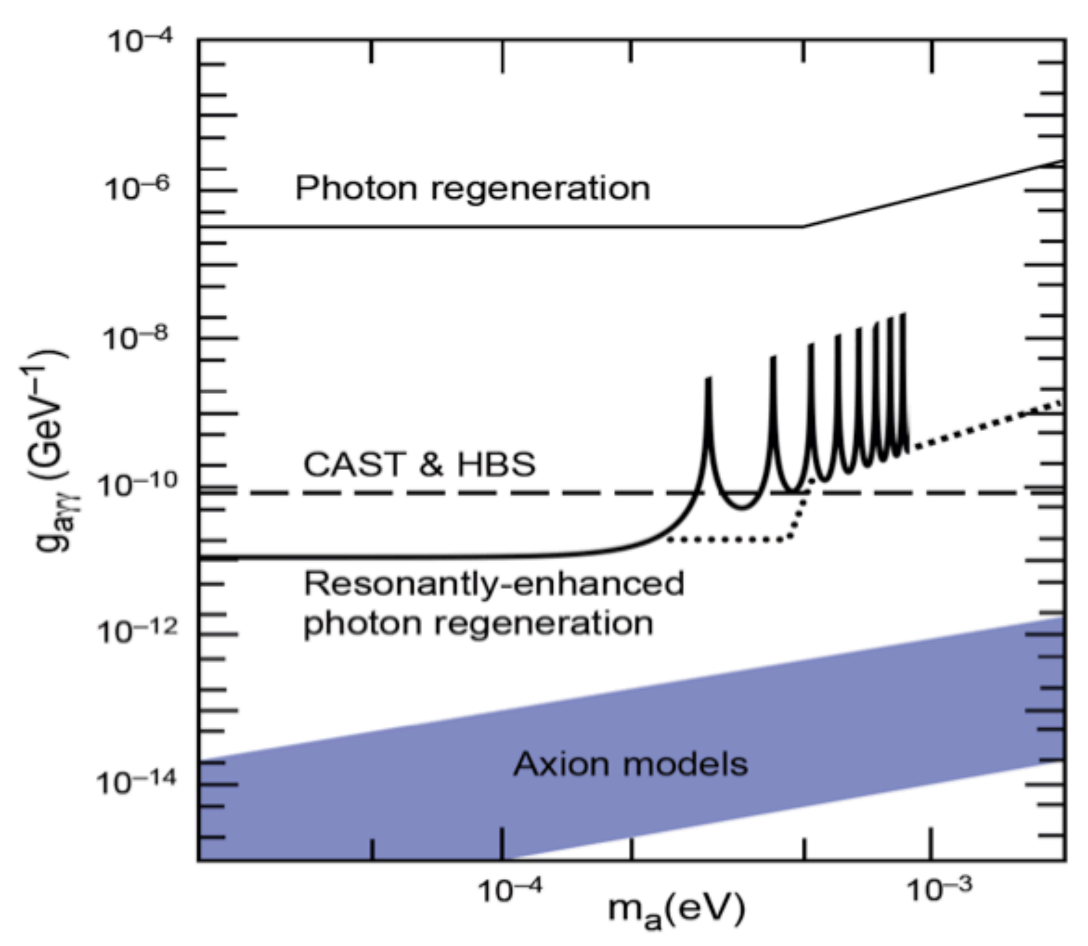
Effort at DESY
Talk by Axel Linder

REAPR Requirements



- Optimize magnetic field length — Talk by P. Mazur
- High finesse cavities — Talk by D. Tanner
- Cavities locked to each other with no leakage from the generation cavity
- Need sensitive photon detection

Possible reach



Baseline design with BL=180 Tesla-meters, with F=3 10^5 , P=10W, Integration time T=30 days.

R&D Phase

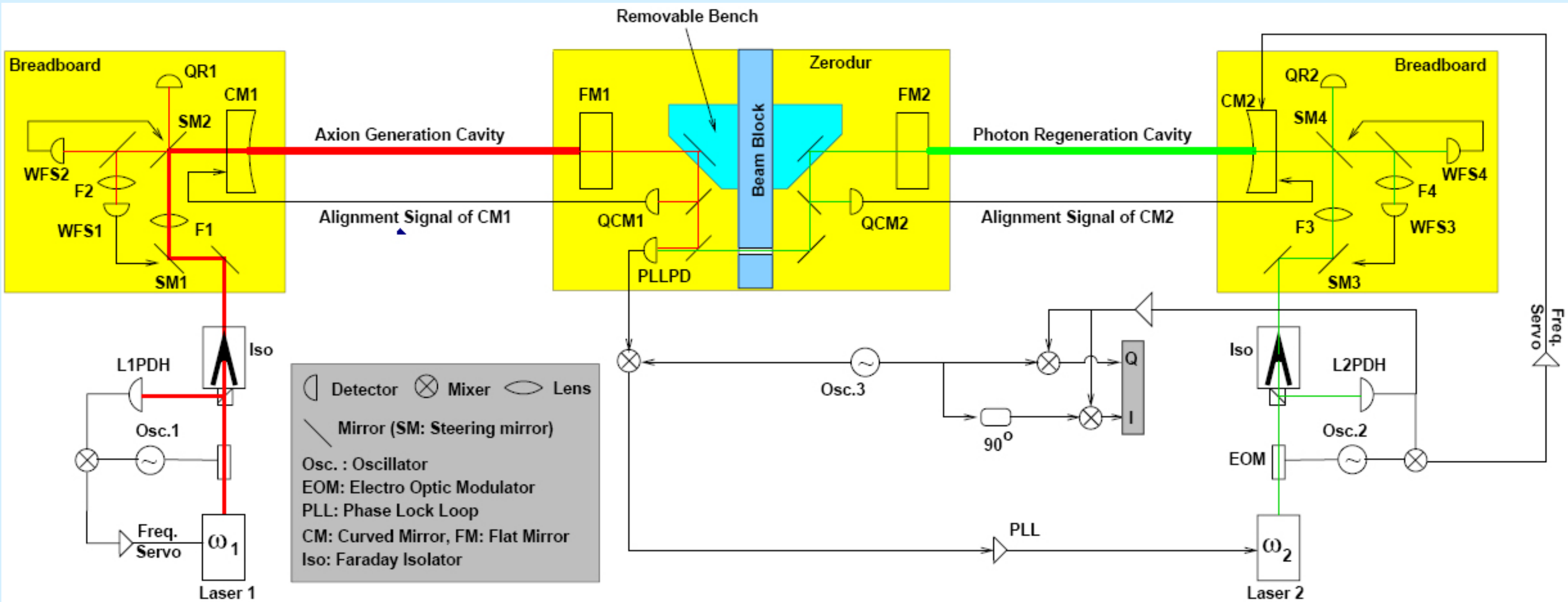
- Magnets
  - We are "on the list" for Tevatron magnets
  - Explore possible modifications to magnets
  - Preliminary discussions on the scope to operate a magnet string
- Optical cavities
  - Synergy with the Fermilab holometer project
- Optical bench and signal detection
  - Synergy with the Fermilab holometer project
  - To-be proposed demonstrator

Tevatron Magnets

- Besides those in the Tevatron, there are existing spares

- More important is magnet infrastructure at Fermilab
- Not excluded … new high field magnets

Strawperson optical design



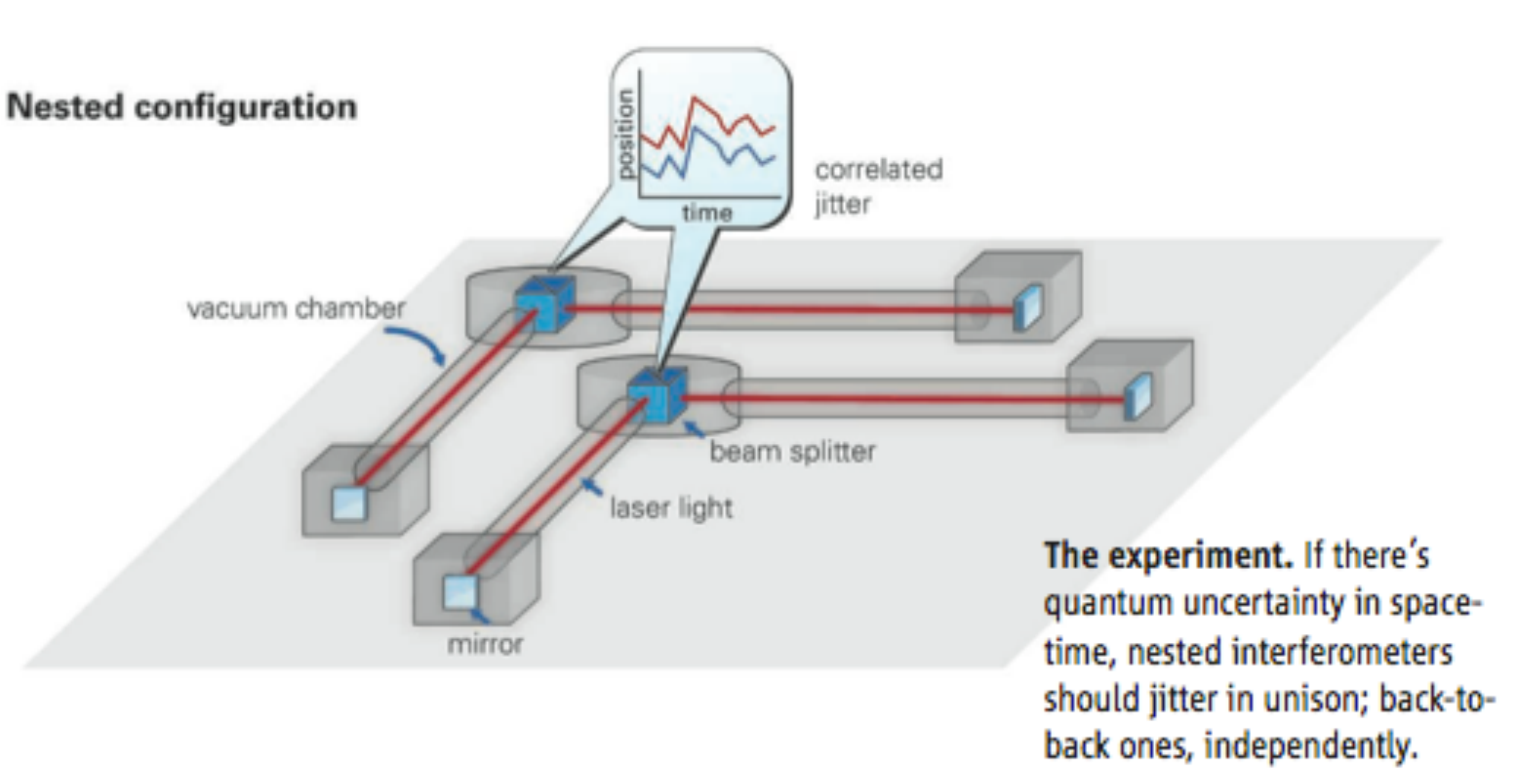
- Use two lasers.
- Laser 1 injects power into generation cavity
- Laser 2 is offset locked to Laser 1
- Offset frequency Ω = integer * FSR of the cavities
- Regeneration cavity is PDH locked to Laser 2
- Laser 2 used to for heterodyne readout of signal in regeneration cavity

G. Mueller (D. Tanner, Univ of FL, DOE Intensity Frontier Workshop)

Spin-off from GammeV

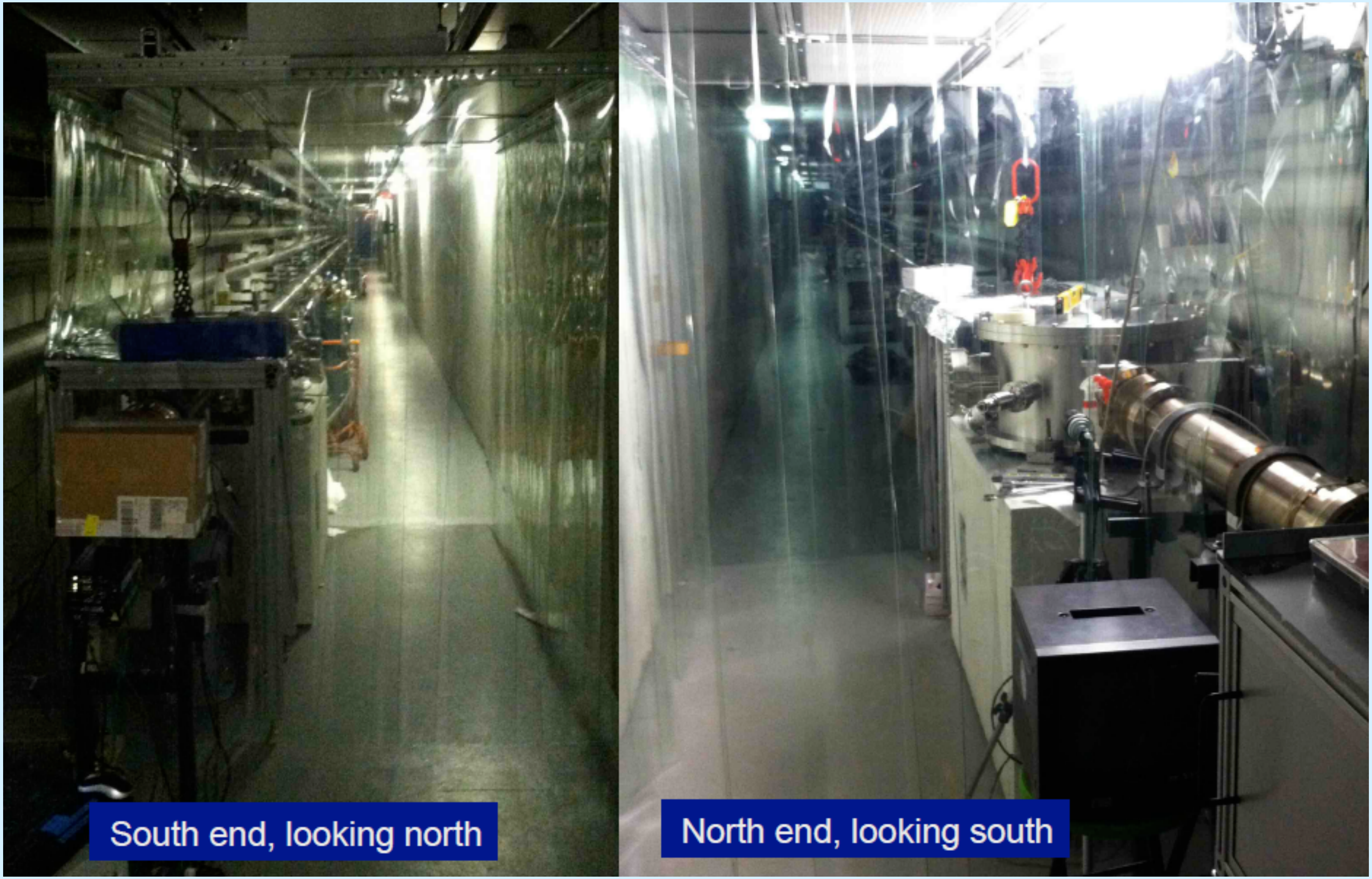
- The Fermilab Holometer.

  Two 40m long interferometers to test for a possible jitter in space-time.



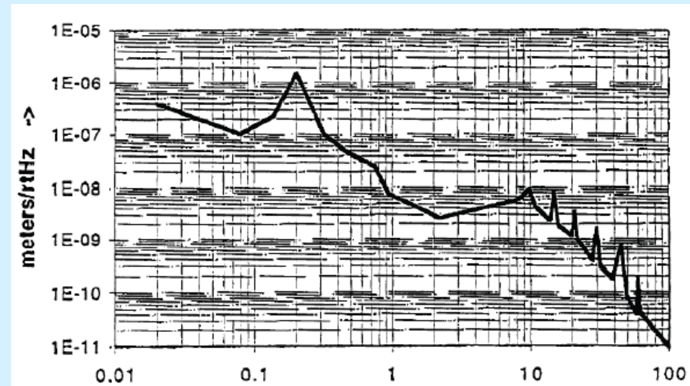
Science Magazine

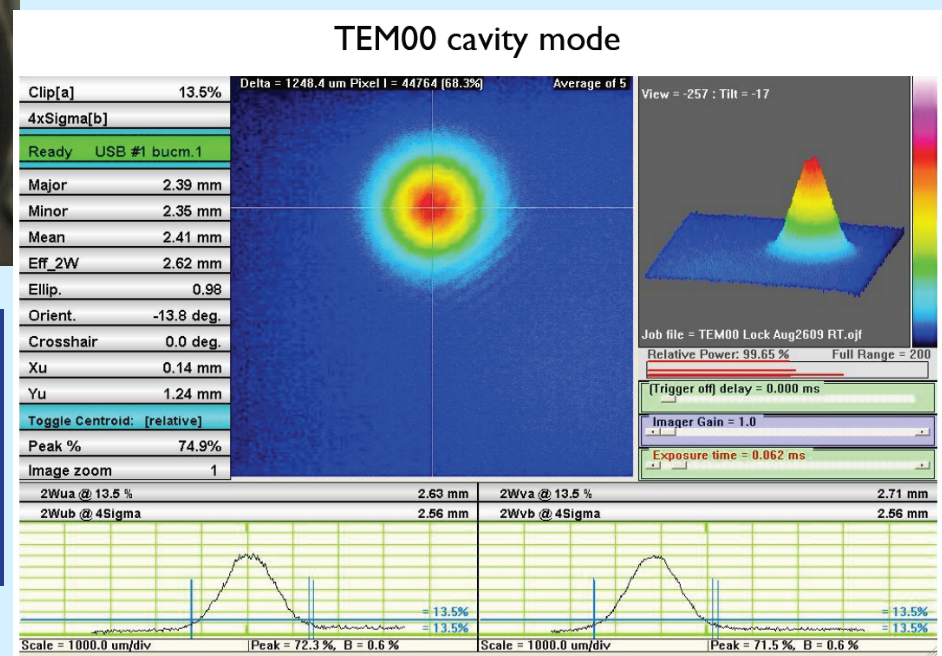
40 m cavity at FNAL



40 m cavity in lock

Seismic Noise



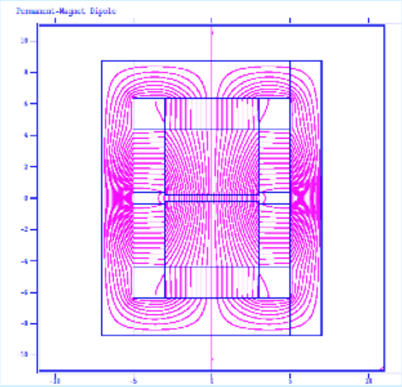


Have not fully studied 5ppm mirrors

Optical bench demonstrator

One possibility

- Univ of Florida to build optical bench to test/develop locking scheme and readout.
- FNAL supplies permanent magnets (0.5T 2m)
- Perform ALP search



J. Volk

- Possibility exists to bring optical bench to FNAL to first do a resonant regeneration hidden sector photon search (new phase space for lower mass HSPs).

Conclusions

- Fermilab has published results on axion-like particles and also chameleons.
- Next experiments such as REAPR are much more ambitious and we are starting to get experience with optical cavities and interferometers. We have a R&D path.
- New ideas are frequent and might lead to experiments not yet thought of such as holographic noise.
- **G**amme**V** has trained two postdocs (now Wilson fellows) and the third postdoc, Jason Steffen, lead the **G**amme**V**-CHASE experiment. In addition, we worked with two young theorists who now have permanent jobs!
- Nature picks its own parameters. Relatively low cost, high risk, but high payoff physics has an appropriate place.

Axion and WISP momentum

- Hidden sector photons, axions, and WISPs working group at the DOE Physics at the Intensity Frontier Workshop
- Vistas in Axions (April 2012, Seattle)
- 8th Patras Workshop (July 18-22, Chicago)

Registration now open
axion-wimp.desy.de