GammeV

Using lasers and magnets to search for new physics

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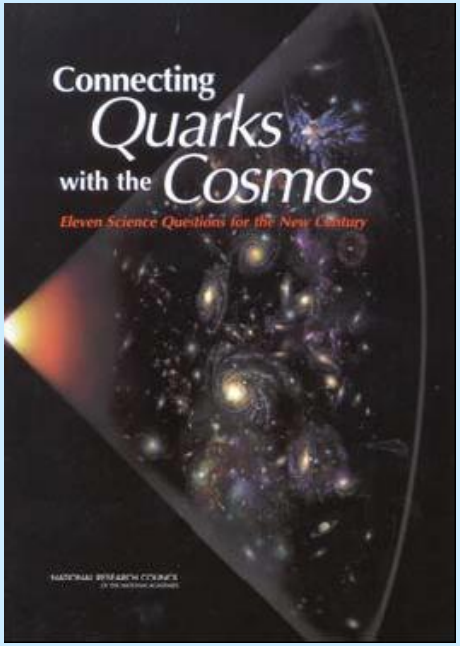
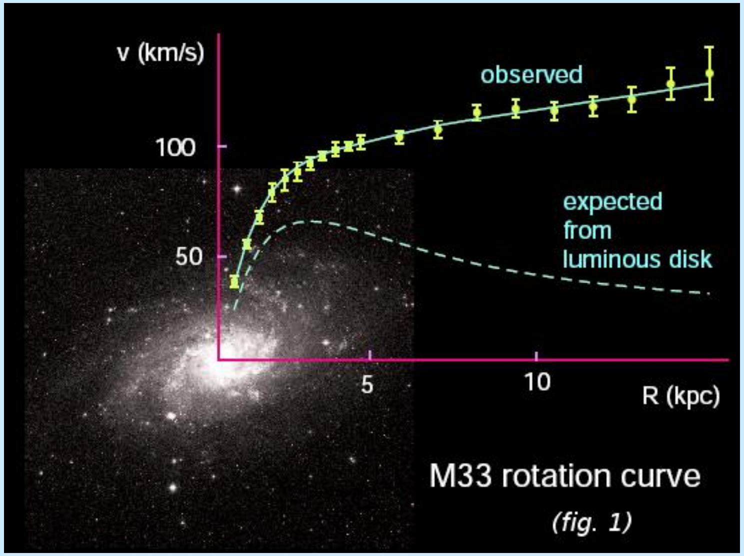
GammeV

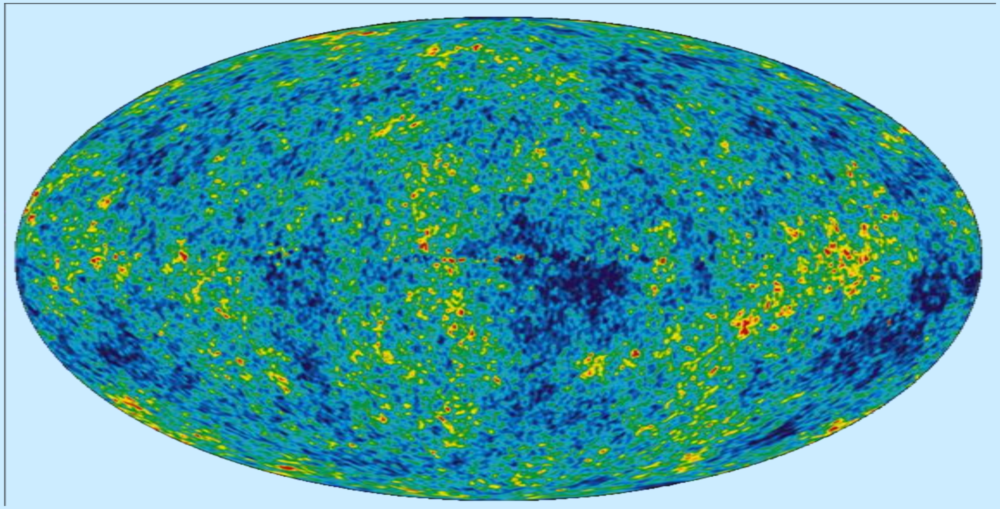
New Physics

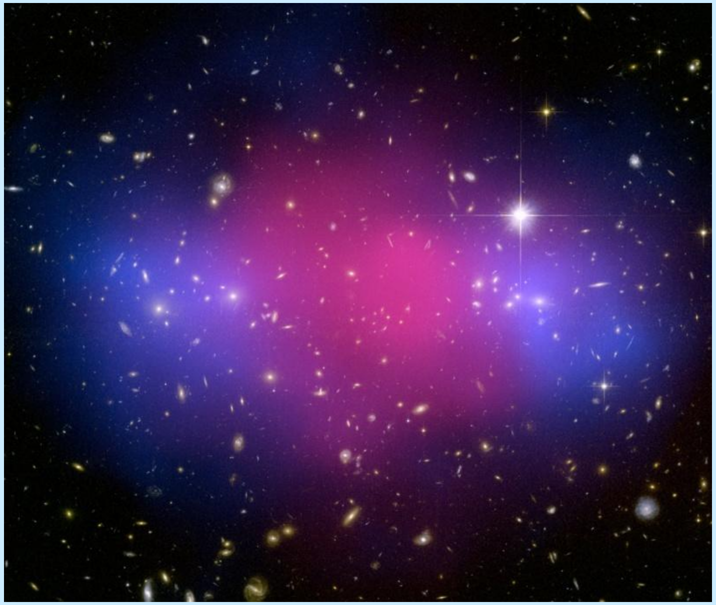
- The next layer of the "new physics" has already started to reveal itself.
  - Neutrinos have mass!
  - Dark Matter exists!
  - There is something called Dark Energy!
- "Quarks to the Cosmos" and "The Quantum Universe" ask current fundamental questions in particle physics, astroparticle physics, and related fields.

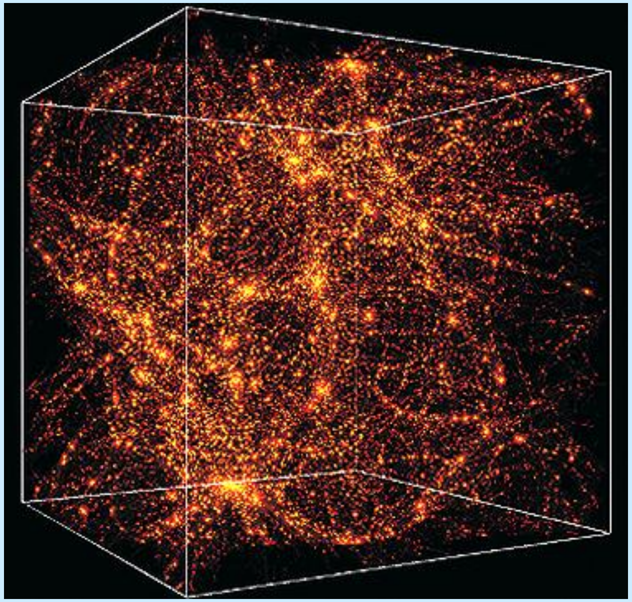


Dark Matter exists



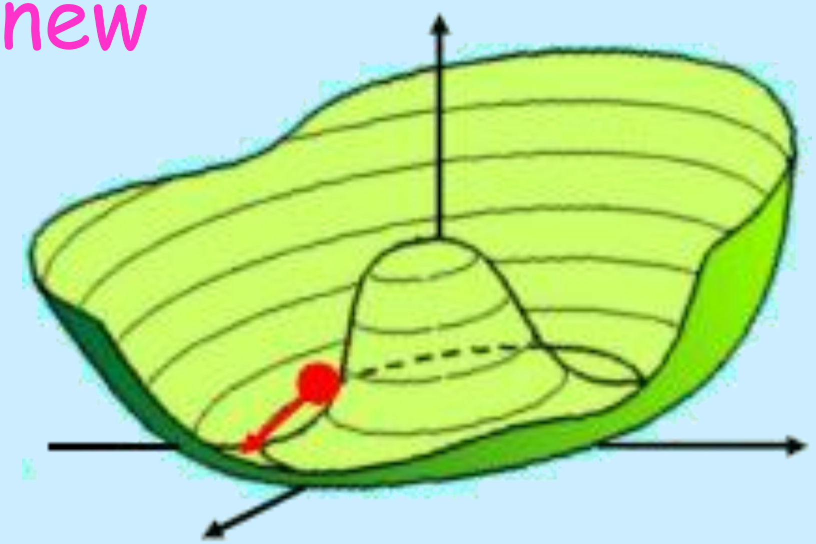






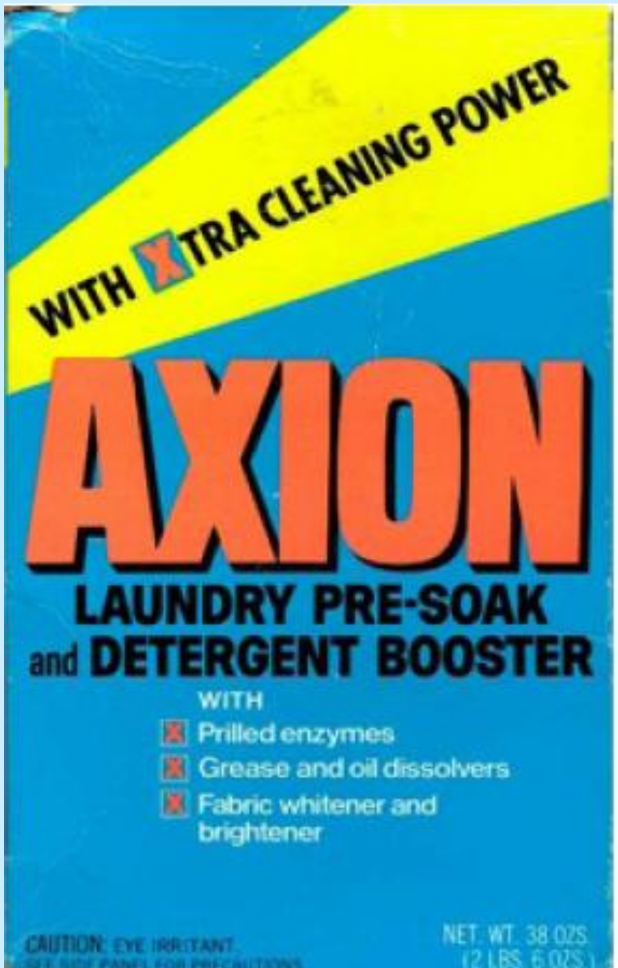
Strong CP problem

- The theory of the strong force predicts an electric dipole moment of the neutron.
- Precision measurements: $d_{EDM} < 10^{-28}$ e-cm
- Related to an angle parameter Θ which can be any number between 0 and 2π. Why ~0?
- Preferred solution is a new field with a new boson called the axion
- A real mystery in particle physics !!

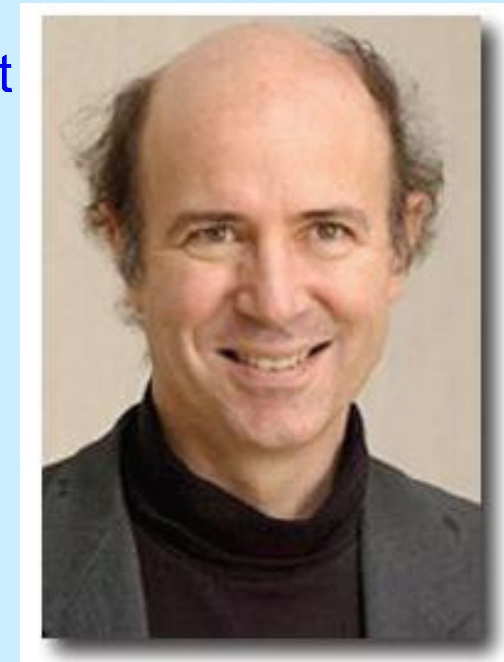


Axions

- Axions "clean-up" the strong-CP problem!



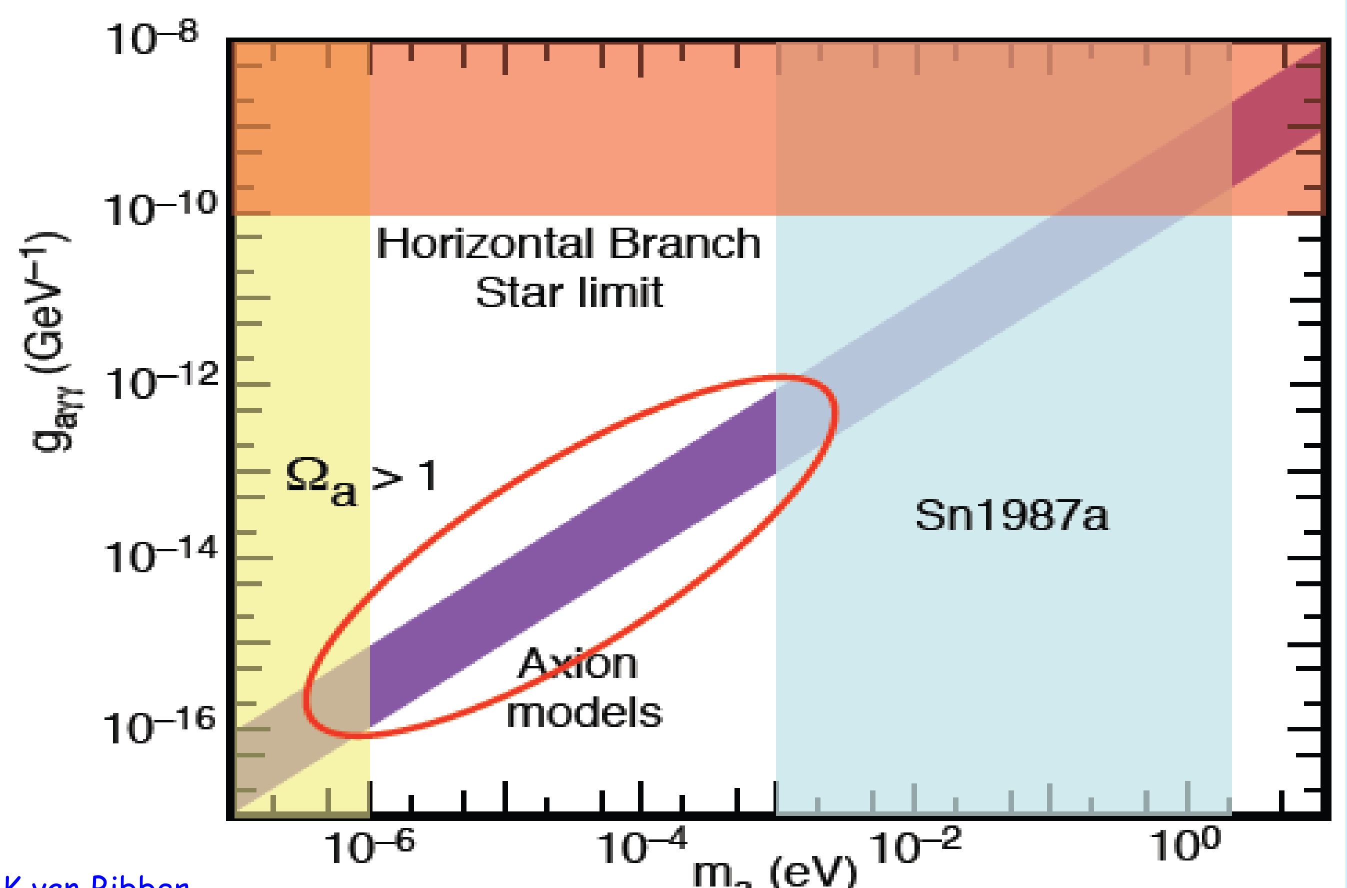
"If the axion does not exist, please tell me how to solve the strong CP problem." (Wilczek)



"Axions may be intrinsic to the structure of string theory." (Witten)

Axions as dark matter

- The axion is also a viable candidate for the dark matter of the universe!



K van Bibber

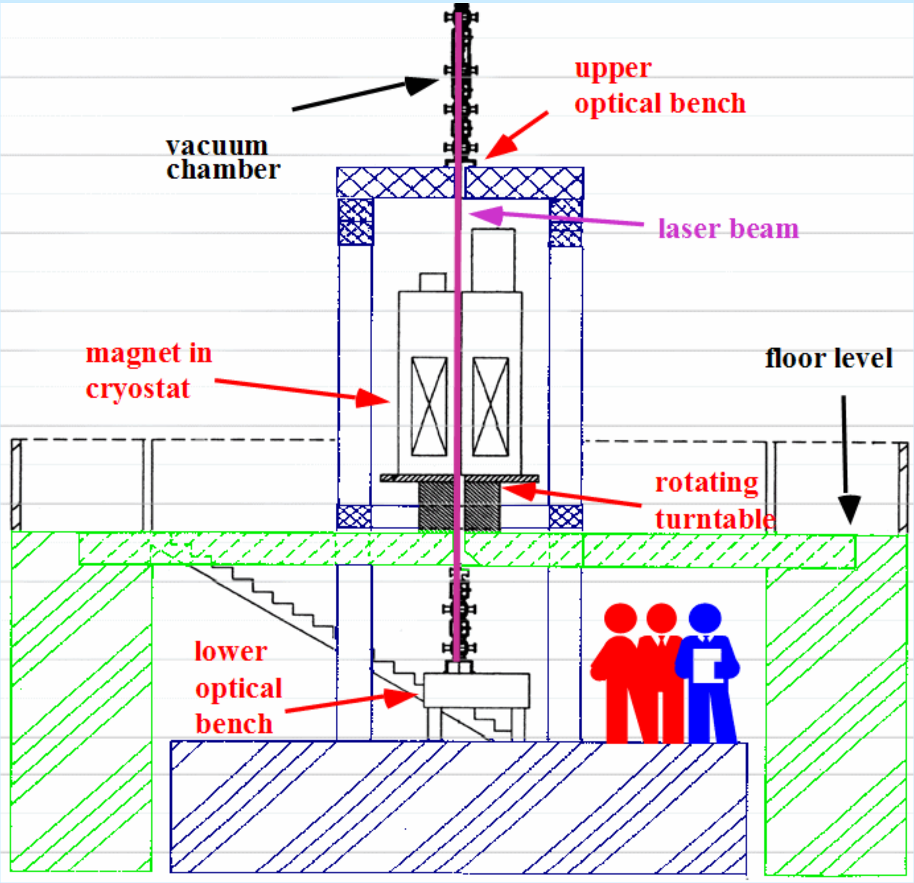
GammeV motivation

- sub-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

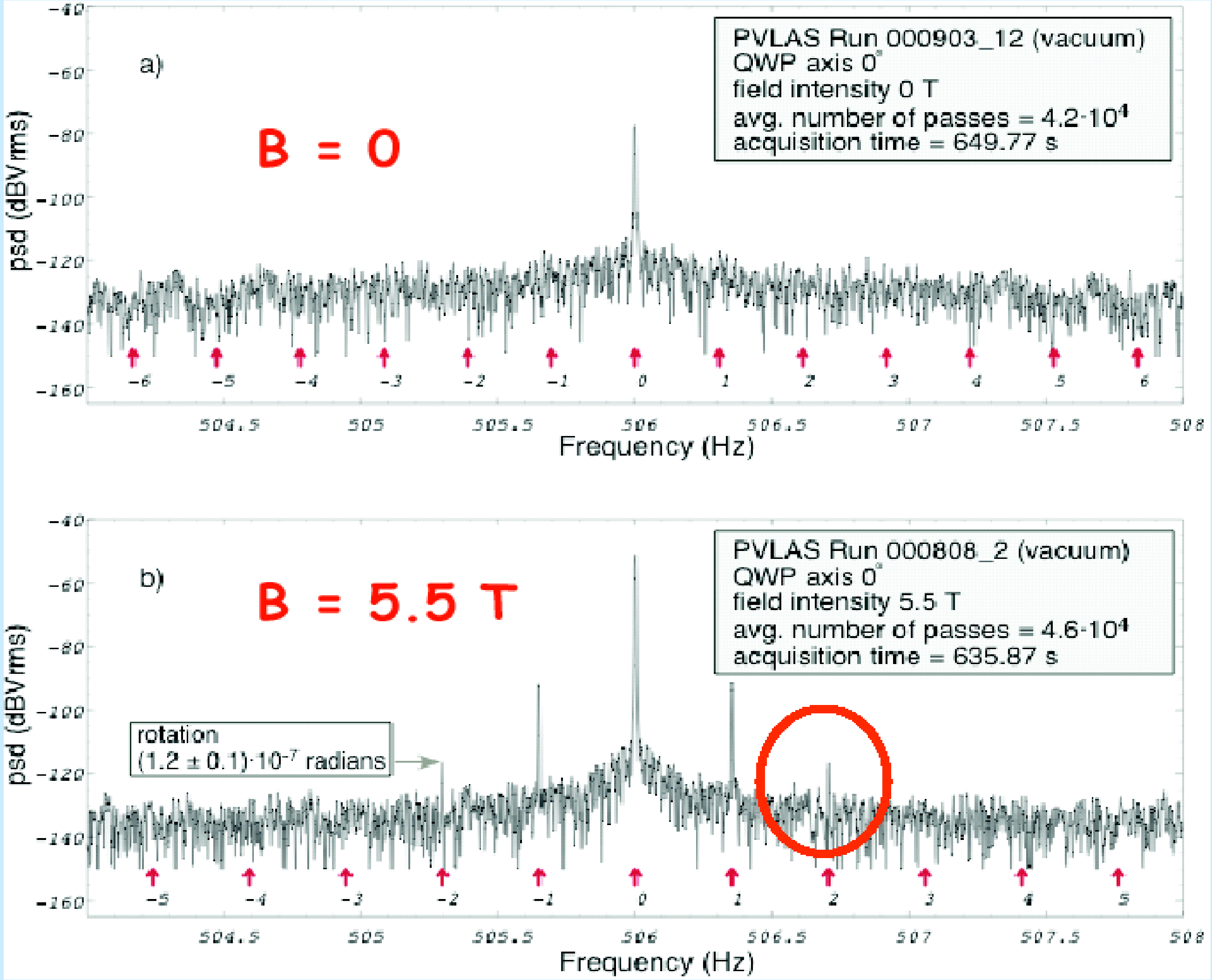
Energy frontier
Neutrinos
Astrophysics
all in one!

PVLAS Experiment

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



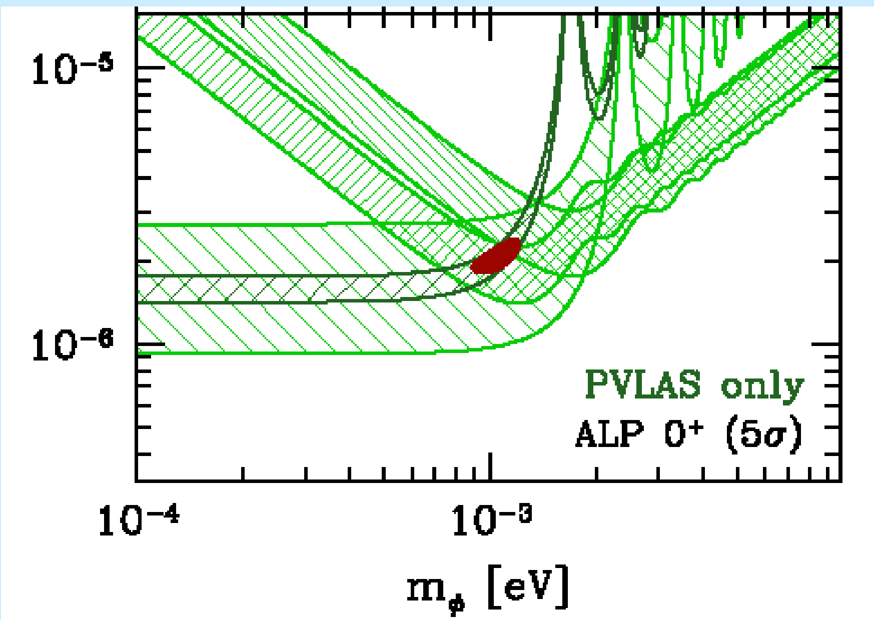
PVLAS Rotation Results

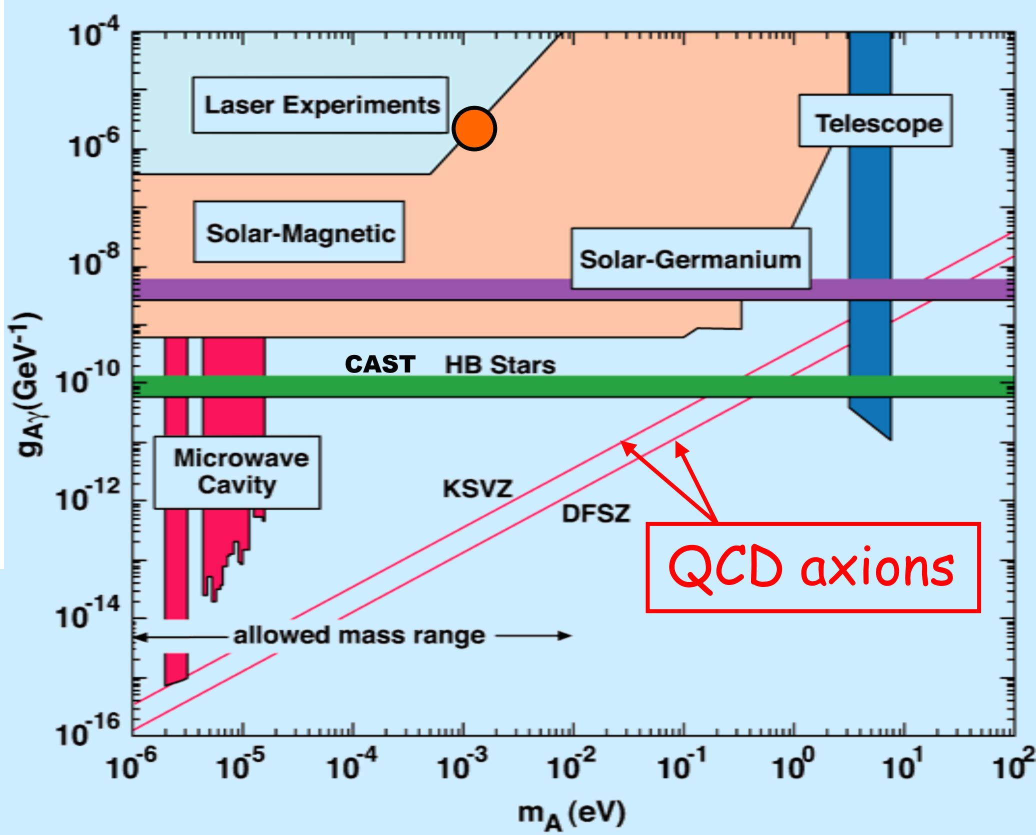


PRL 96, 110406, (2006)

PVLAS ALP Interpretation

A new axion-like particle with mass at 1.2 meV and $g \sim 2 \times 10^{-6}$ is consistent with rotation and ellipticity measurements.

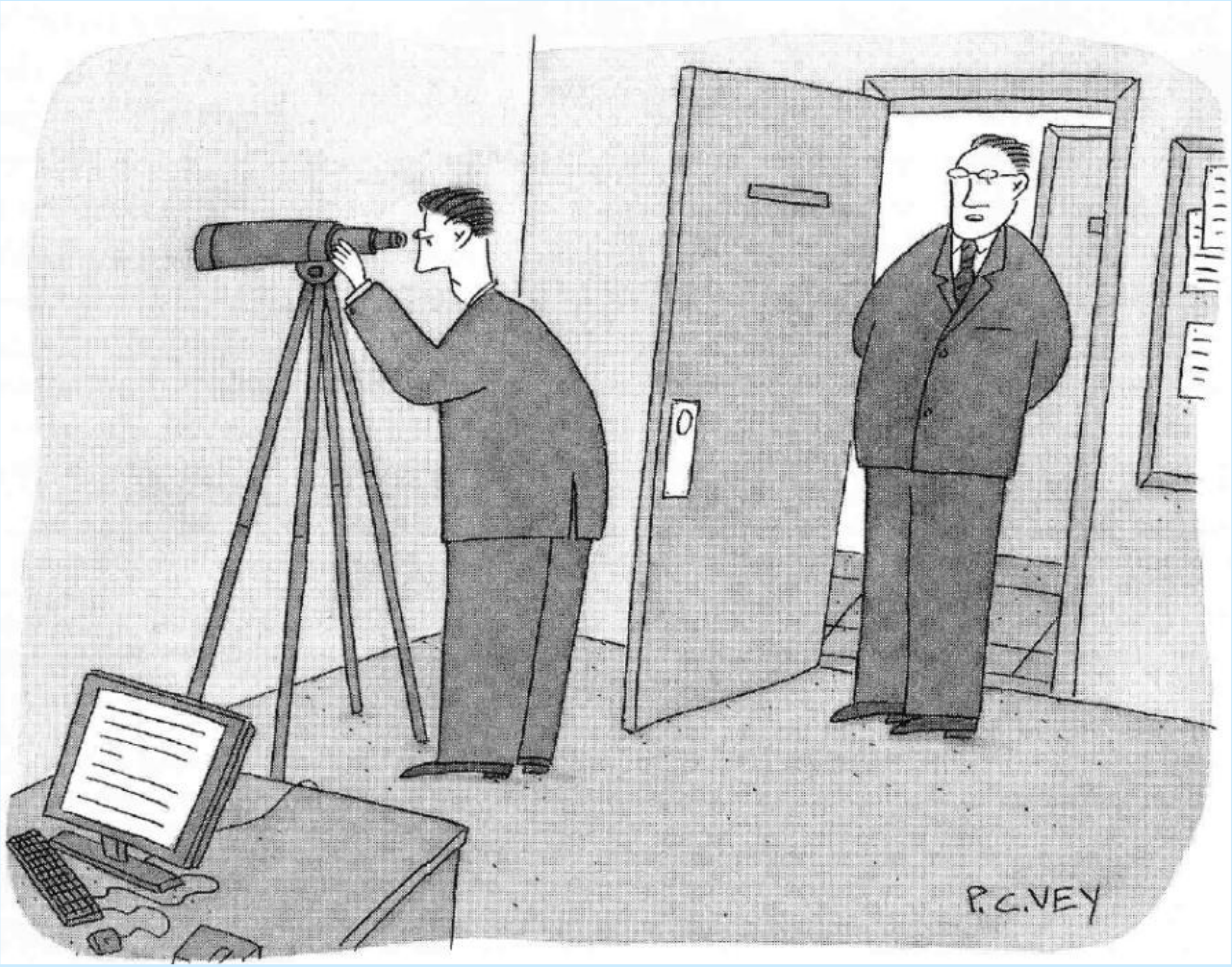




Additional data by PVLAS has since no longer seen the anomalous effects. However, the source of the anomaly has not been clarified.

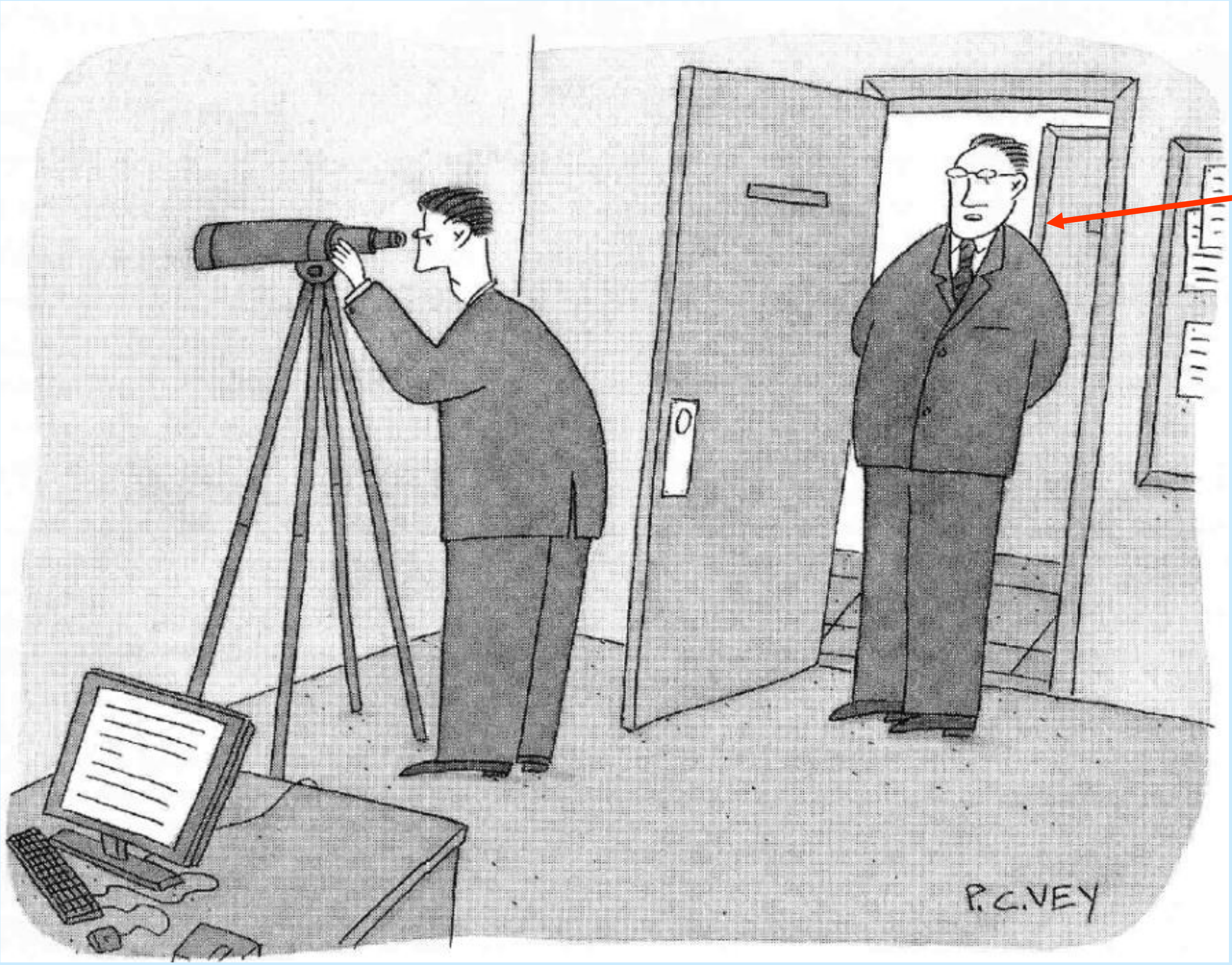
PRD **77**, 032006 (2008)

Light Shining Through a Wall Experiment



New Yorker

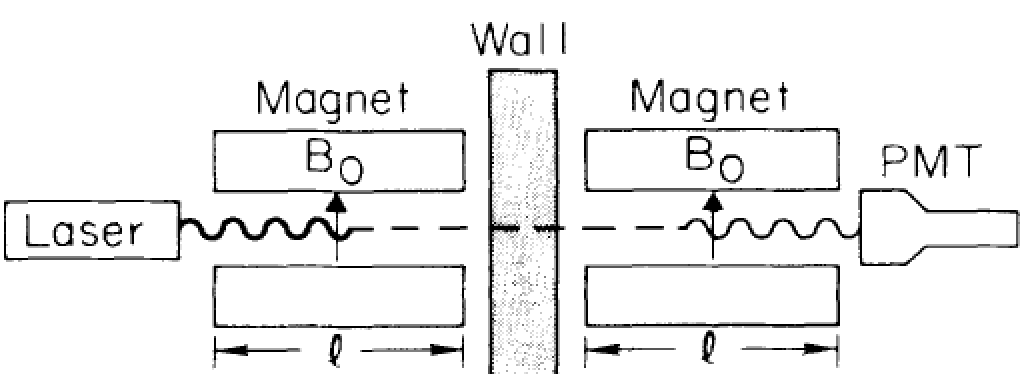
Light Shining Through a Wall Experiment



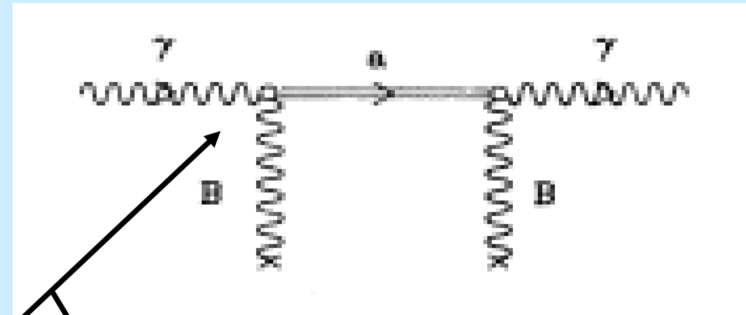
My boss

New Yorker

Light Shining Through a Wall Experiment



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



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

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

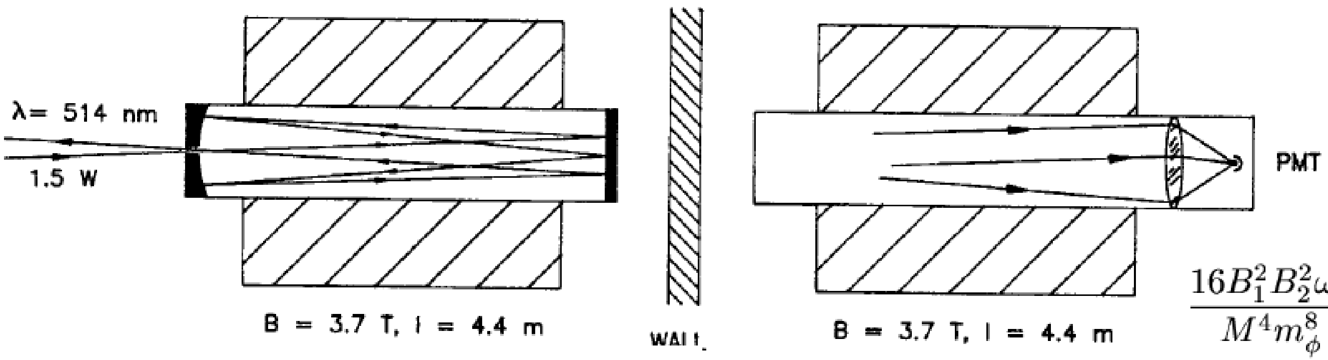
$$P_{regen} = \frac{16B_1^2B_2^2\omega^4}{M^4m_\phi^8}\sin^2\left(\frac{m_\phi^2L_1}{4\omega}\right)\cdot\sin^2\left(\frac{m_\phi^2L_2}{4\omega}\right)$$

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

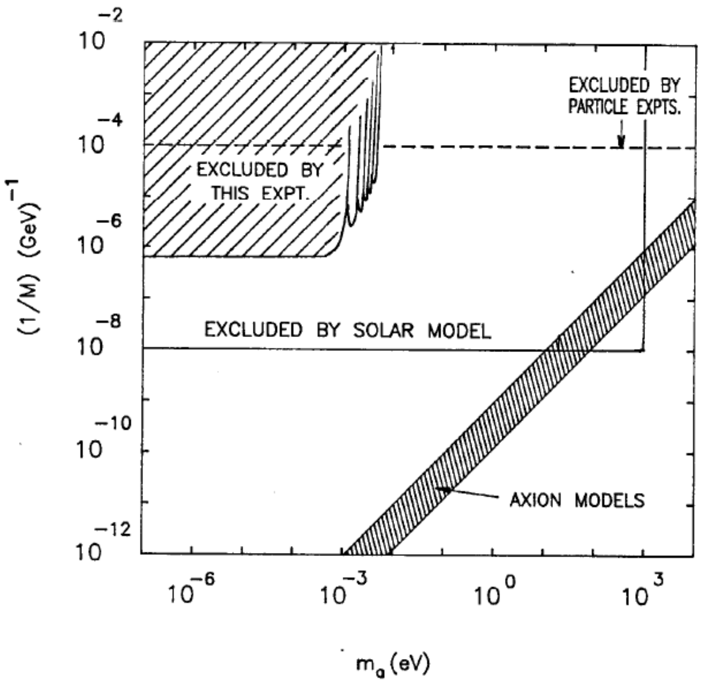
$$P_{regen}^{GammeV} = (3.9\times10^{-21})\times\frac{(B_1/5\ \mathrm{T})^2(B_2/5\ \mathrm{T})^2(\omega/2.33\ \mathrm{eV})^4}{(M/4\times10^5\ \mathrm{GeV})^4(m_\phi/1.2\times10^{-3}\ \mathrm{eV})^8}$$
$$\times\sin^2\left(\frac{\pi}{2}\frac{(m_\phi/1.2\times10^{-3}\ \mathrm{eV})^2(L_1/2.0\ \mathrm{m})}{(\omega/2.33\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

BFRT Experiment

- Brookhaven, Fermilab, Rochester, Trieste (1992)



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



BFRT Experiment

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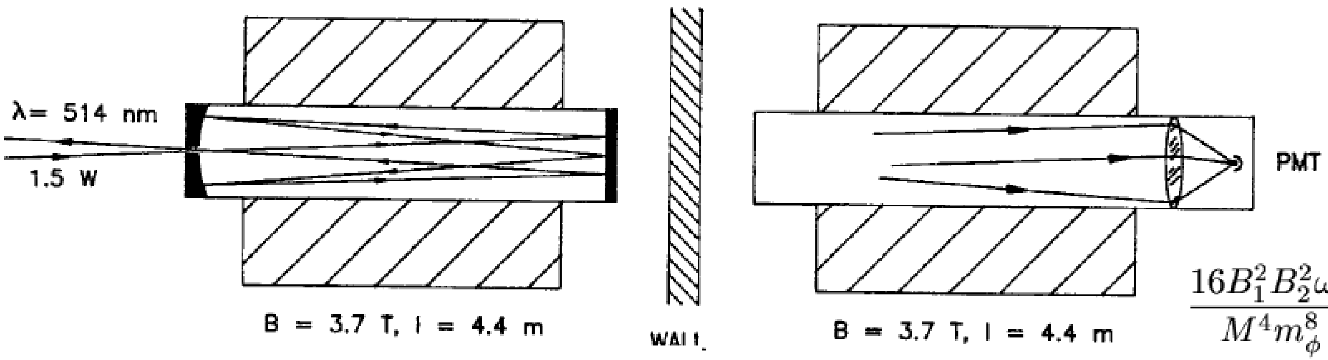
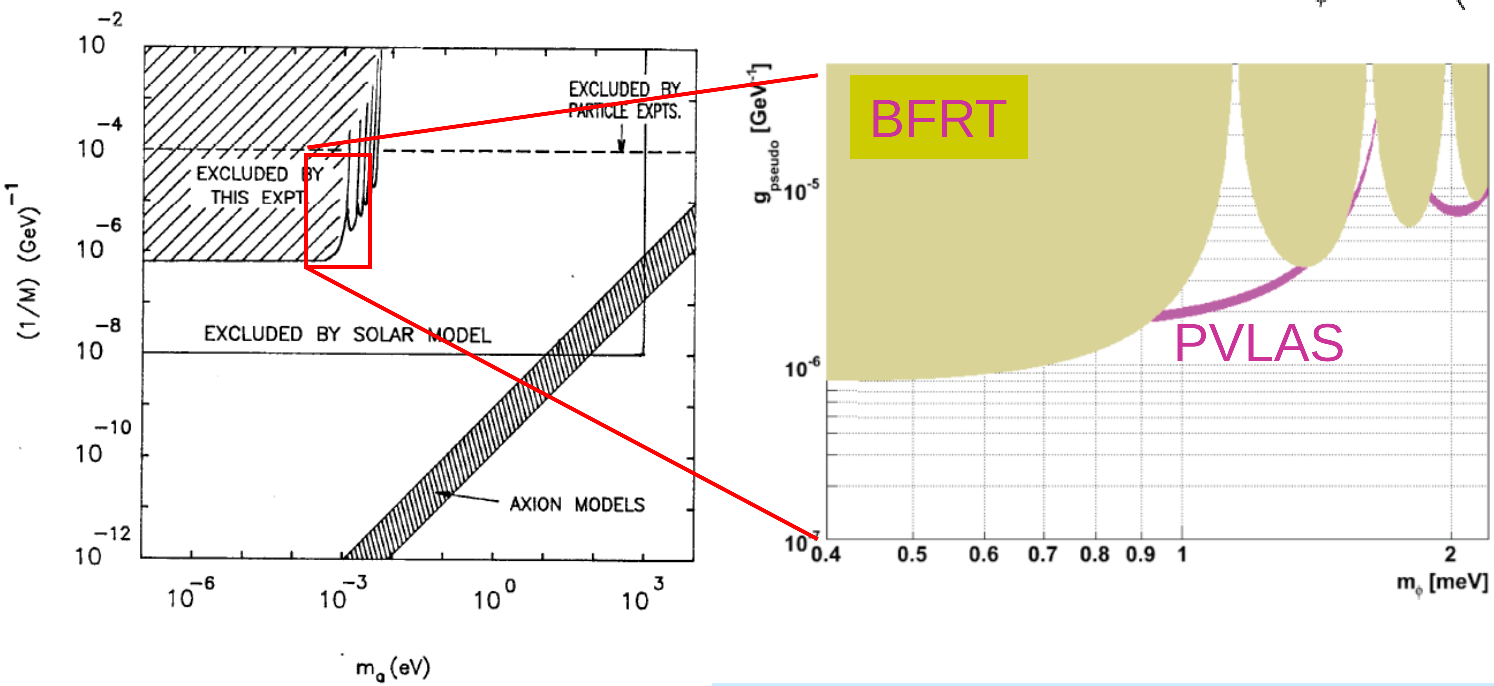


$$\frac{16B_1^2B_2^2\omega^4}{M^4 m_\phi^8}\sin^2\left(\frac{m_\phi^2 L_1}{4\omega}\right)\cdot\sin^2\left(\frac{m_\phi^2 L_2}{4\omega}\right)$$



BFRT is not sensitive in the PVLAS region of interest.

GammeV Collaboration

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

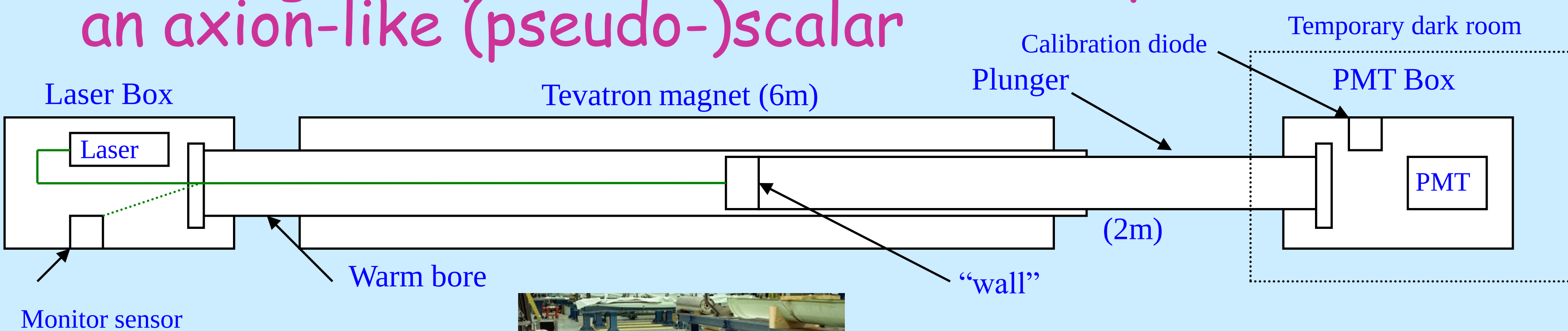
D. Gustafson
University of Michigan
Ann Arbor, MI 48109

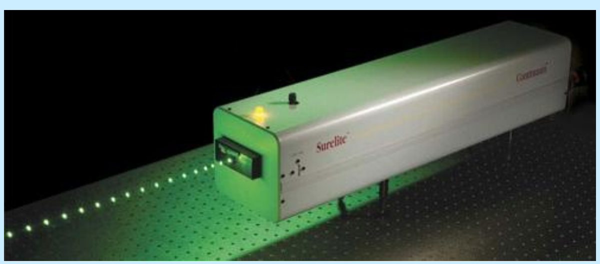
Ten person team including a summer student, 3 postdocs, 2 accelerator / laser experts, 4 experimentalists (nearly everyone had a day job) PLUS technical support at FNAL

Nov 2006 : Initial discussion and design (Aaron Chou, WW leaders)
Apr 2007 : Review and approval from Fermilab ($30K 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

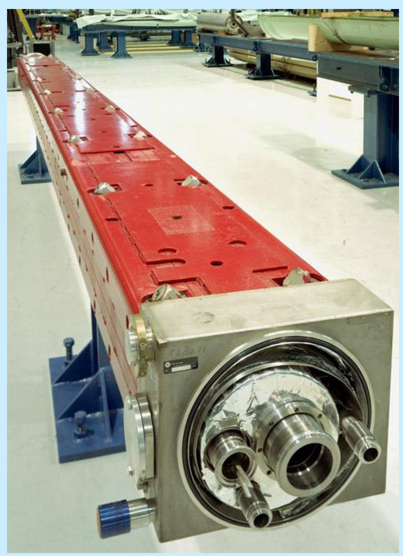
GammeV Proposal

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

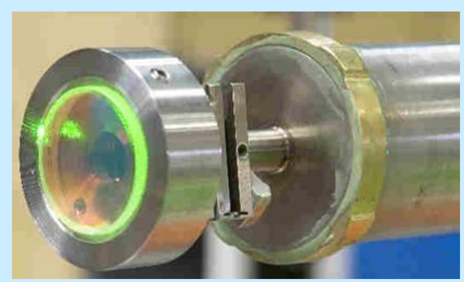




Existing laser in Acc. Div. nearly identical with a similar spare available



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

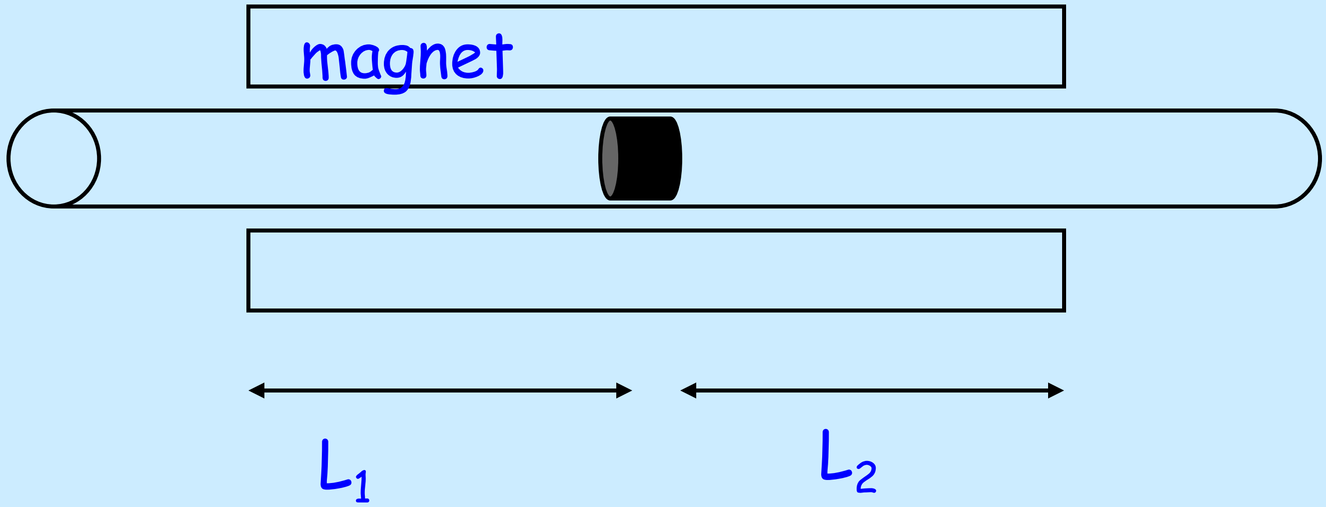


High-QE, low noise, fast PMT module (purchased)

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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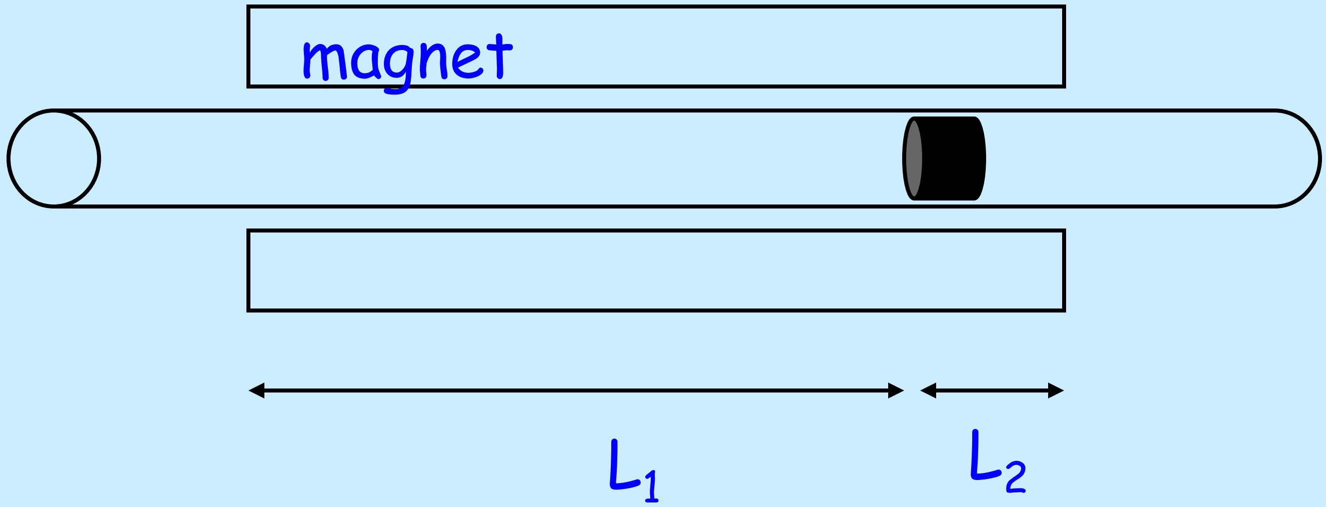

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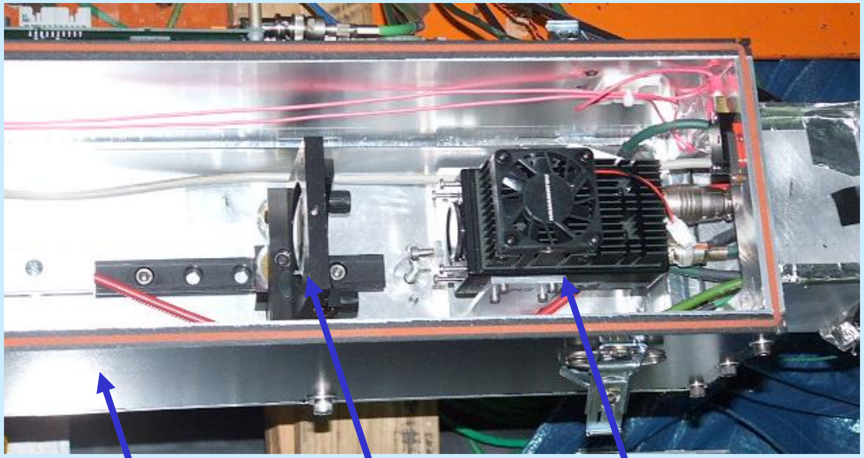
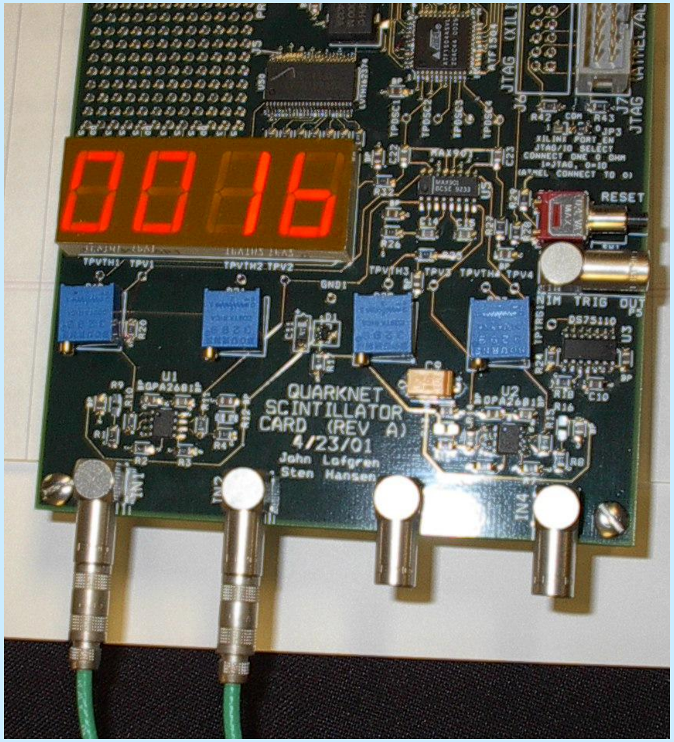
GammeV

Apparatus

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



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.

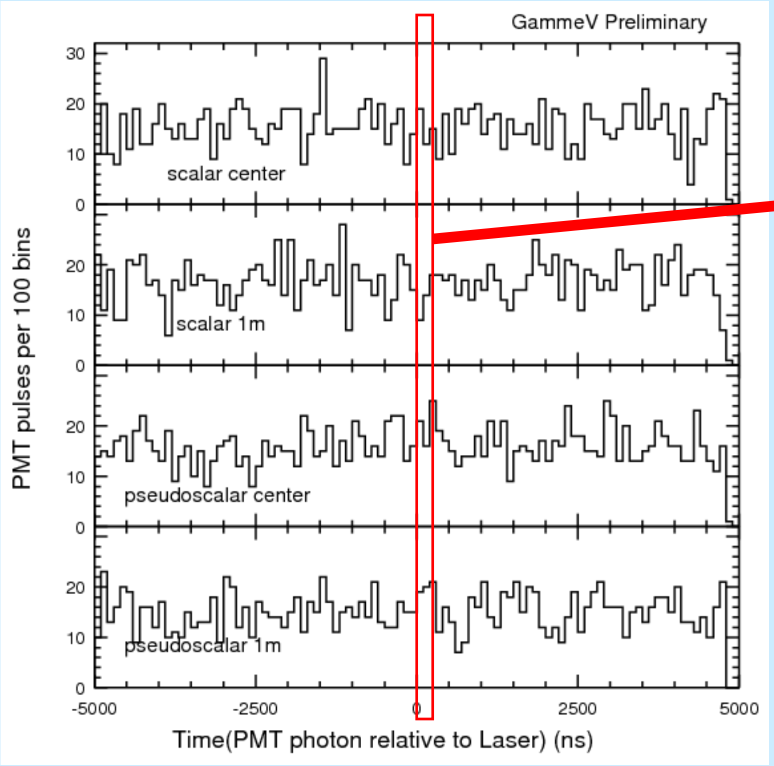
	Ch0	Ch1	Ch2	Ch3
PMT Quark Net	PMT pulse	LED pulse	Scope trigger	Isochro nous CLK
Laser Quark Net	Laser Photo diode	Laser Splash	Laser Synch pulse	Isochro nous CLK

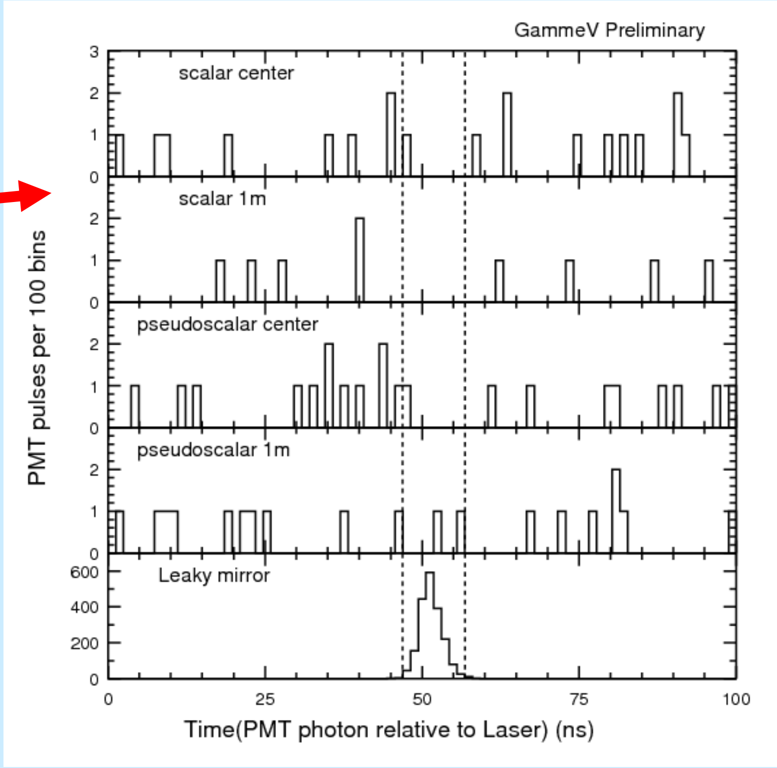
GammeV Procedure

- 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

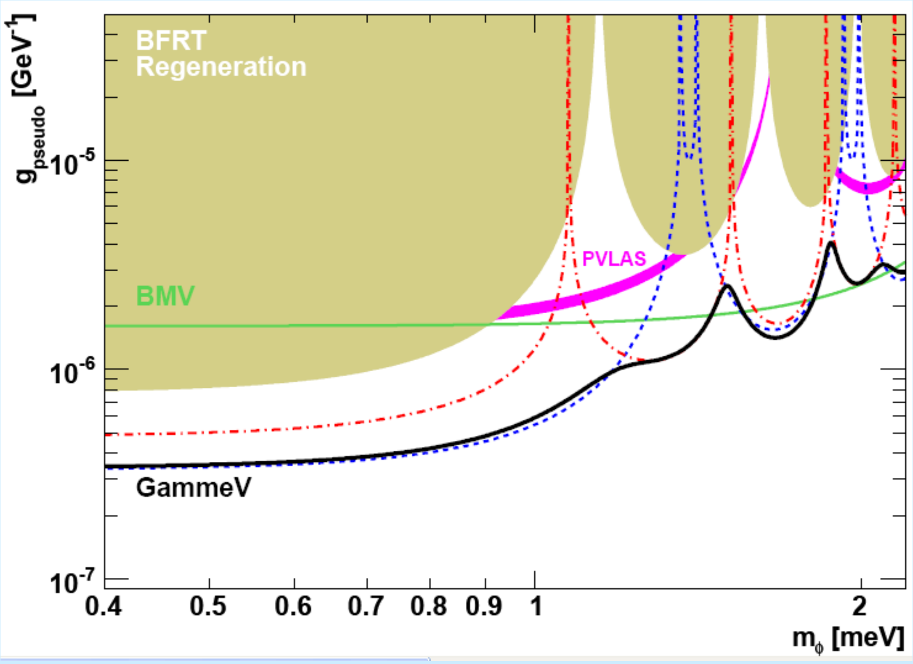




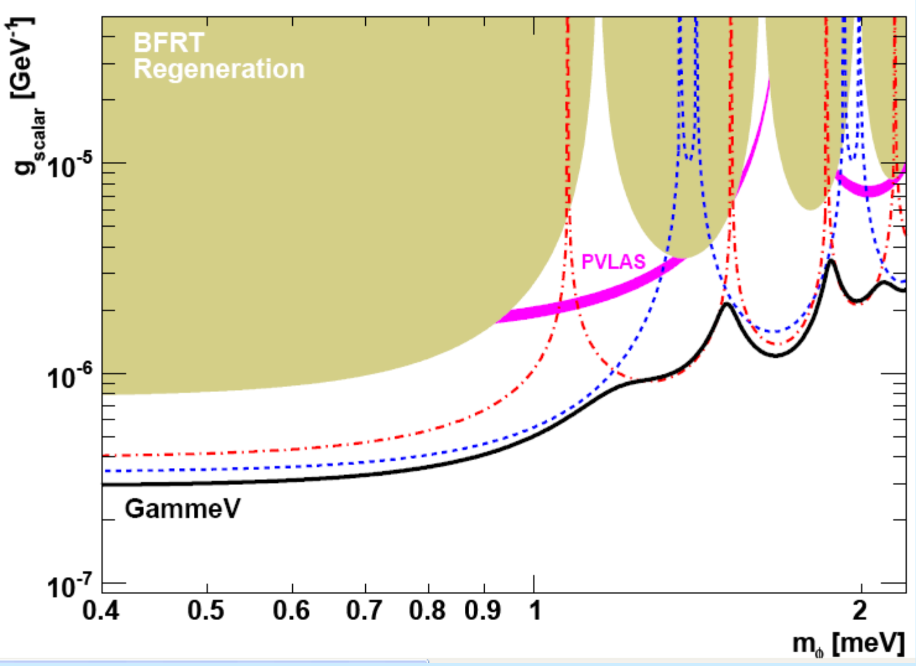
GammeV Results

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

Pseudoscalar



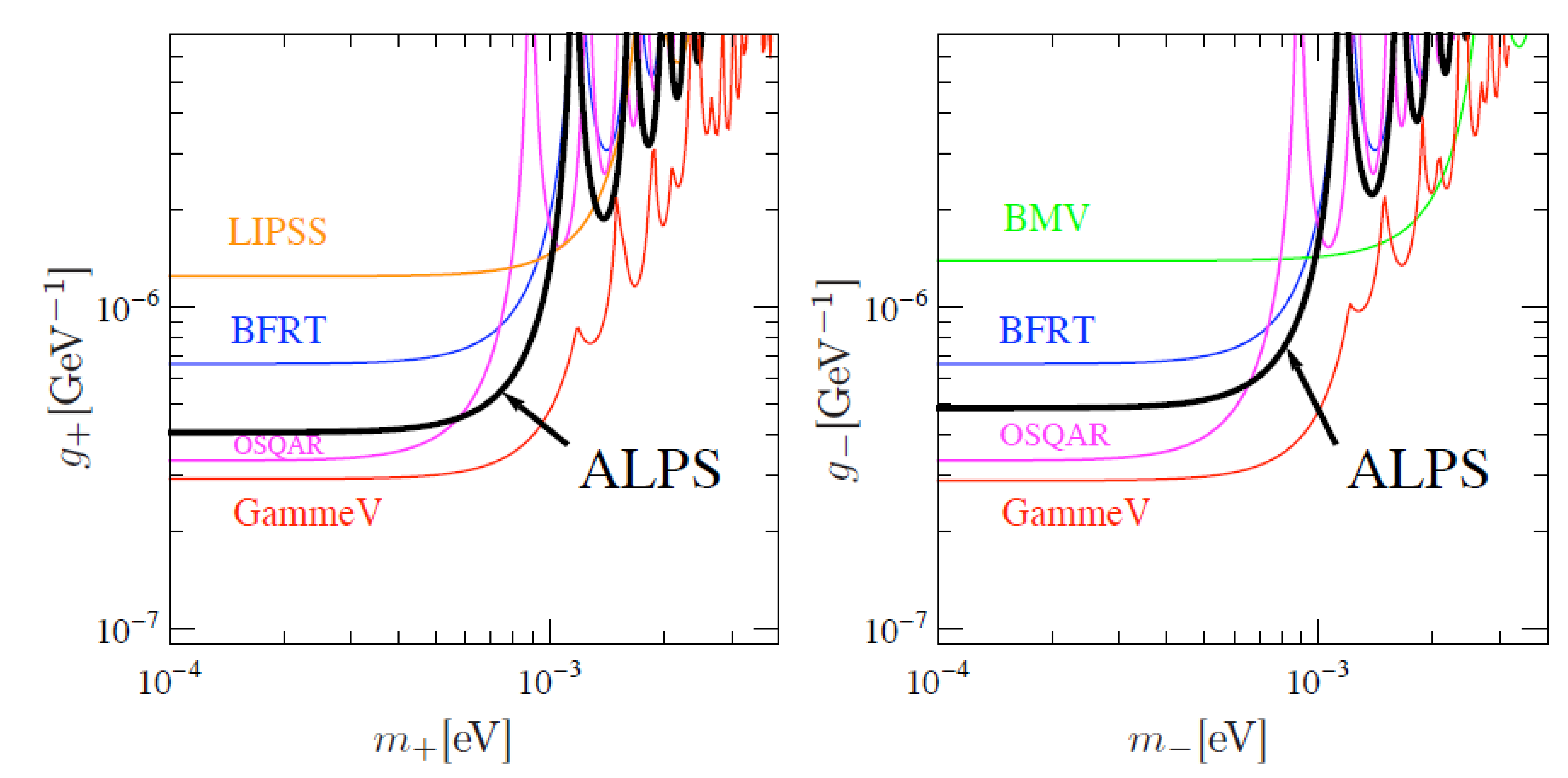
Scalar



PRL **100**, 080402 (2008)

Other experiments

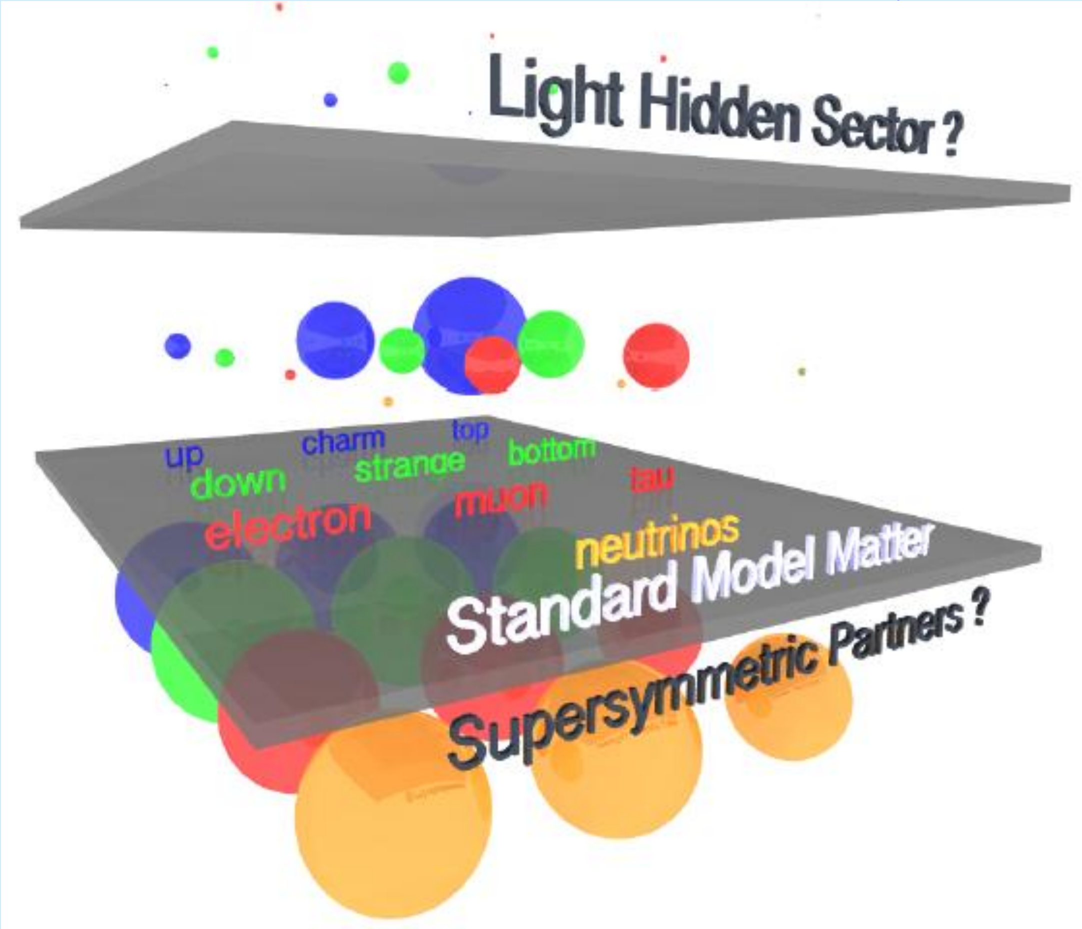
- We competed with a number of other efforts worldwide



ALPS arXiv:0905.4159

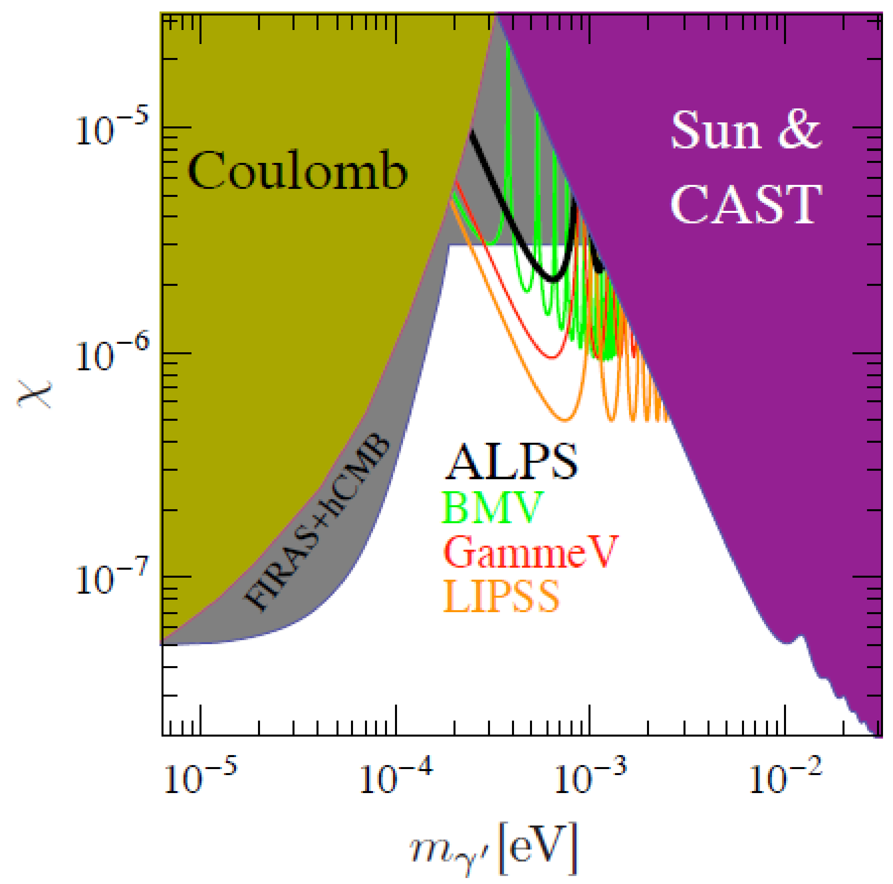
Other WISPs

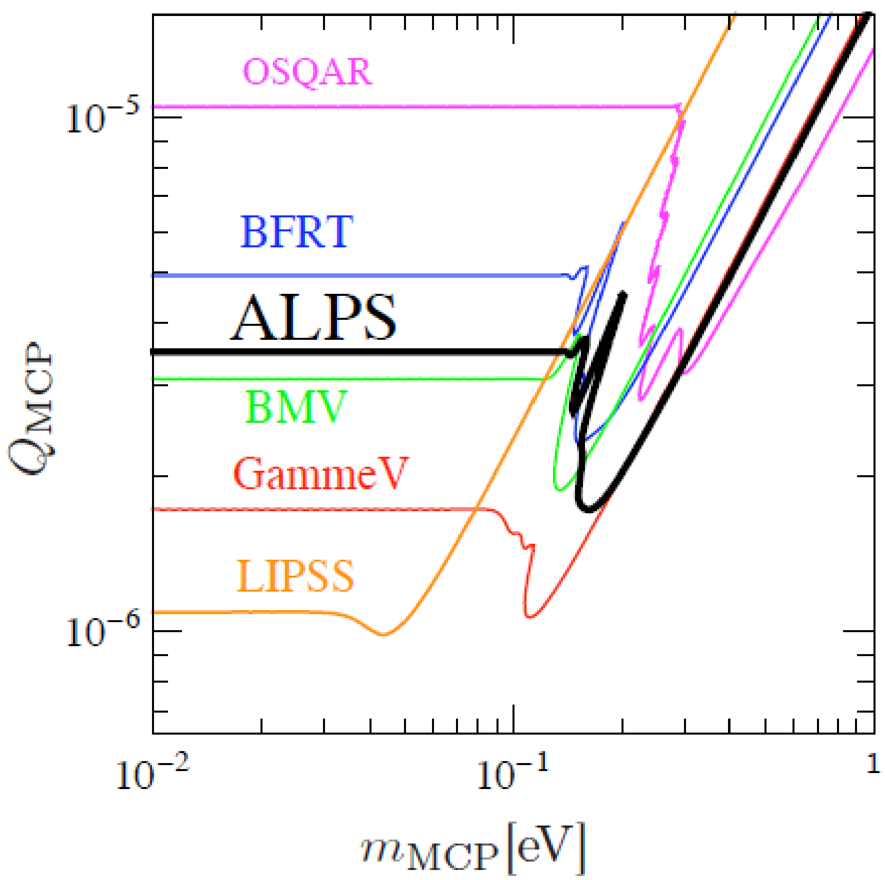
- New symmetries give weakly interacting sub-eV particles that interact with known particles



Other WISPs

- "paraphotons" and "mini-charged particles" are two examples. Constrained by LSW experiments.





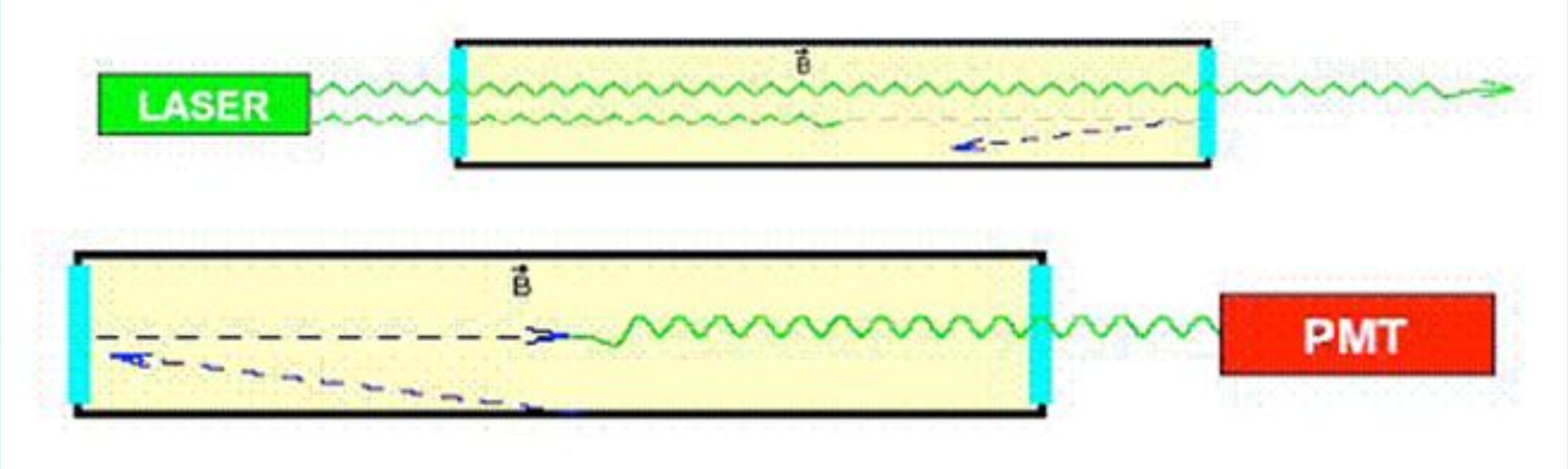
Chameleons

- A theory of dark energy exists that invokes an axion-like particle with the property that it changes its properties depending on it's environment!

- Vacuum environment, the chameleon is almost massless, Dense environment, the chameleon becomes massive

"Particle in a Jar"

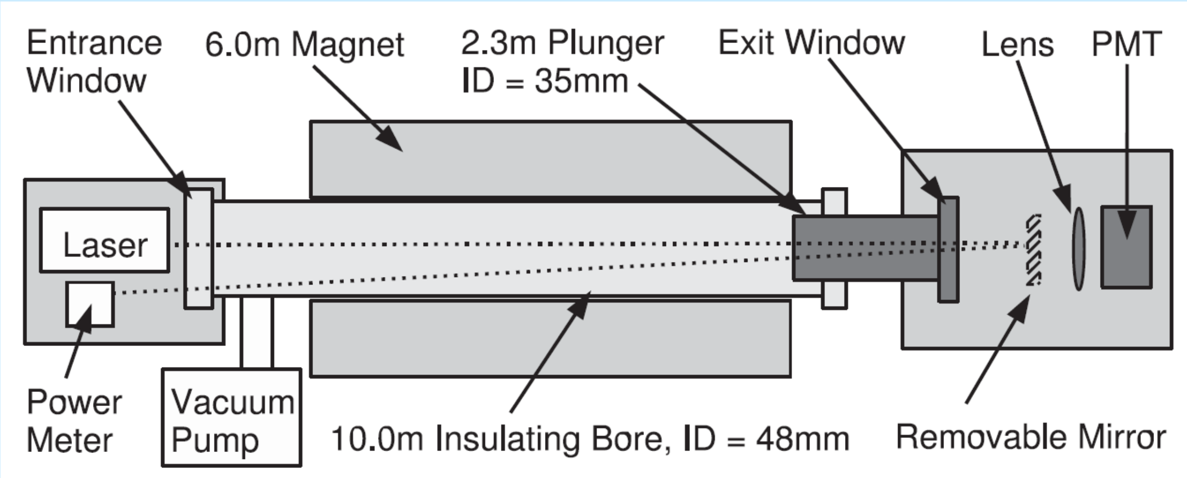
- Chameleon properties depend on their environment – effective mass increases when encountering matter.
  - A laser in a magnetic field might have photons that convert into chameleons which reflect off of the optical windows. A gas of chameleons are trapped in a jar.
  - Turn off the laser and look for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



Chameleon Search

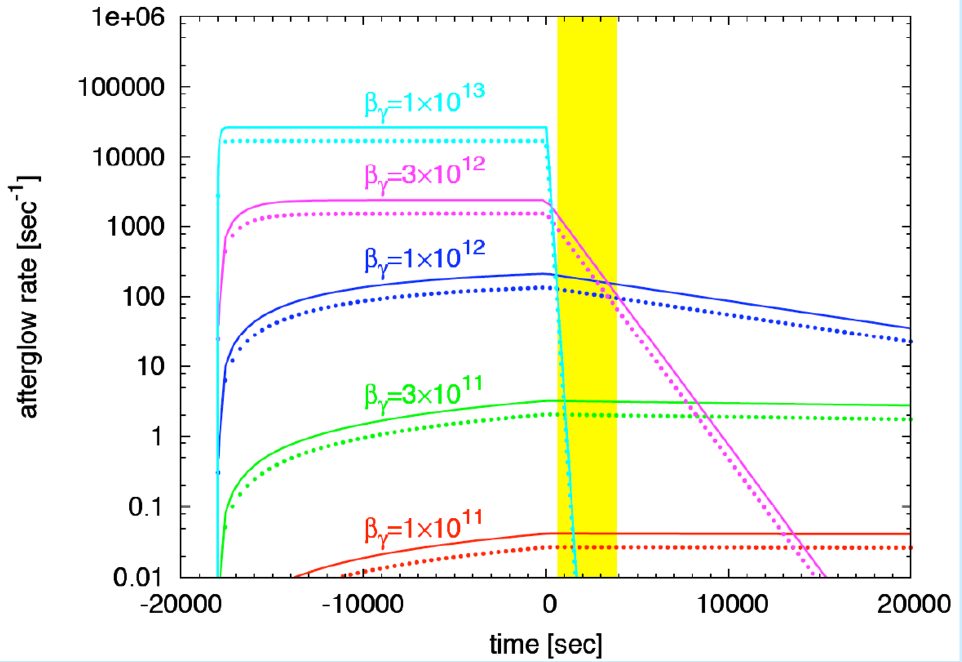
- **Apparatus**

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



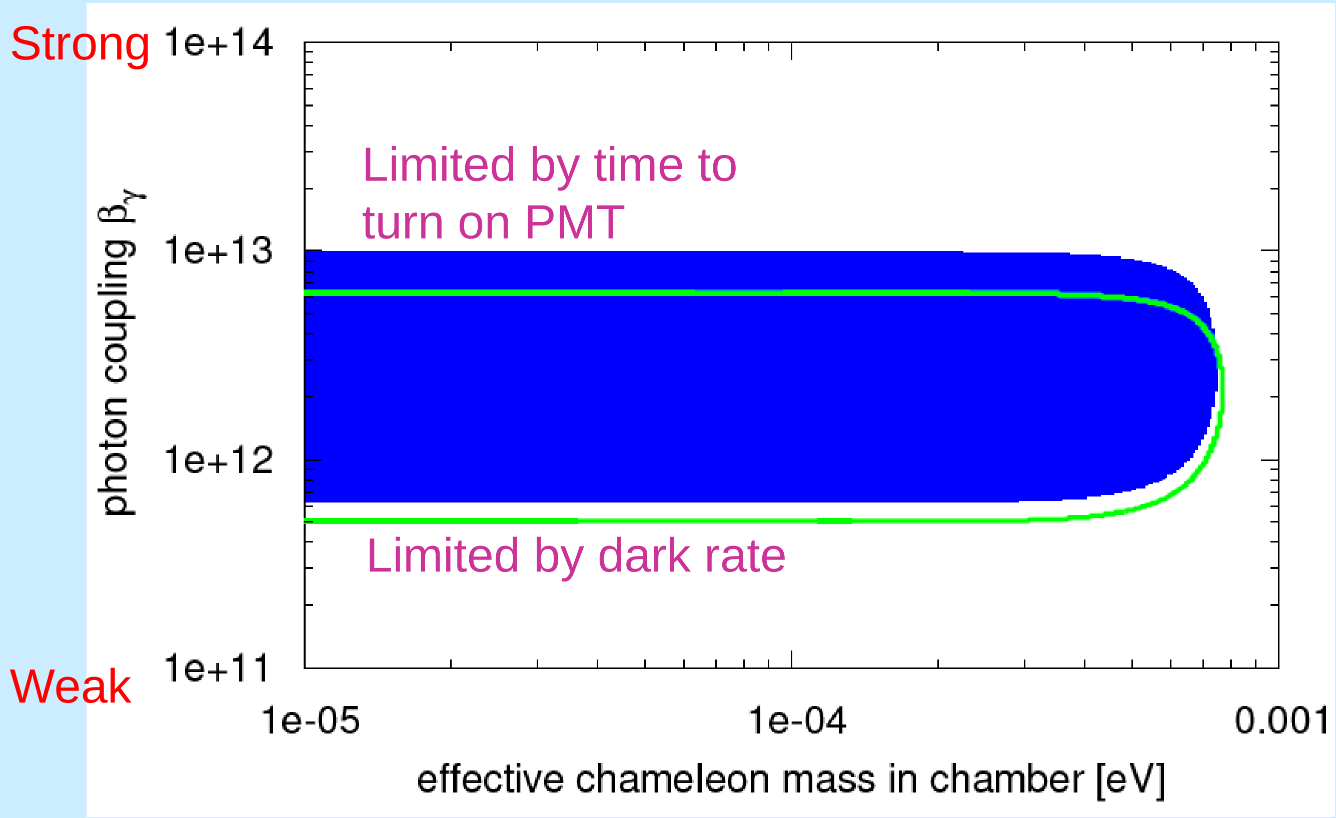
- **Procedure**

  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 to photons vs effective mass
  - Blue region is pseudoscalar, green line is scalar exclusion region

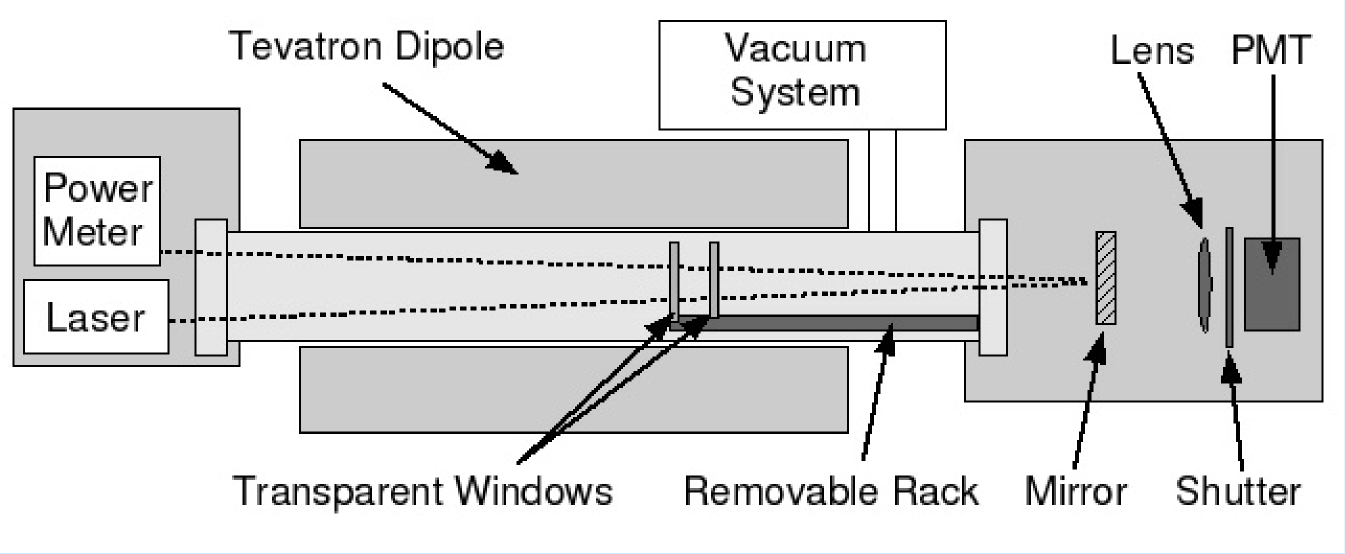


Reduced sensitivity at higher masses due to experimental configuration

Also, uncertainties in the vacuum levels limit sensitivity of possible potentials.

New experiment (next week)

- GammeV – Chase (chameleon afterglow search)



Improve vacuum (cryo pump) and monitoring.

Use a shutter to switch to PMT readout quickly.

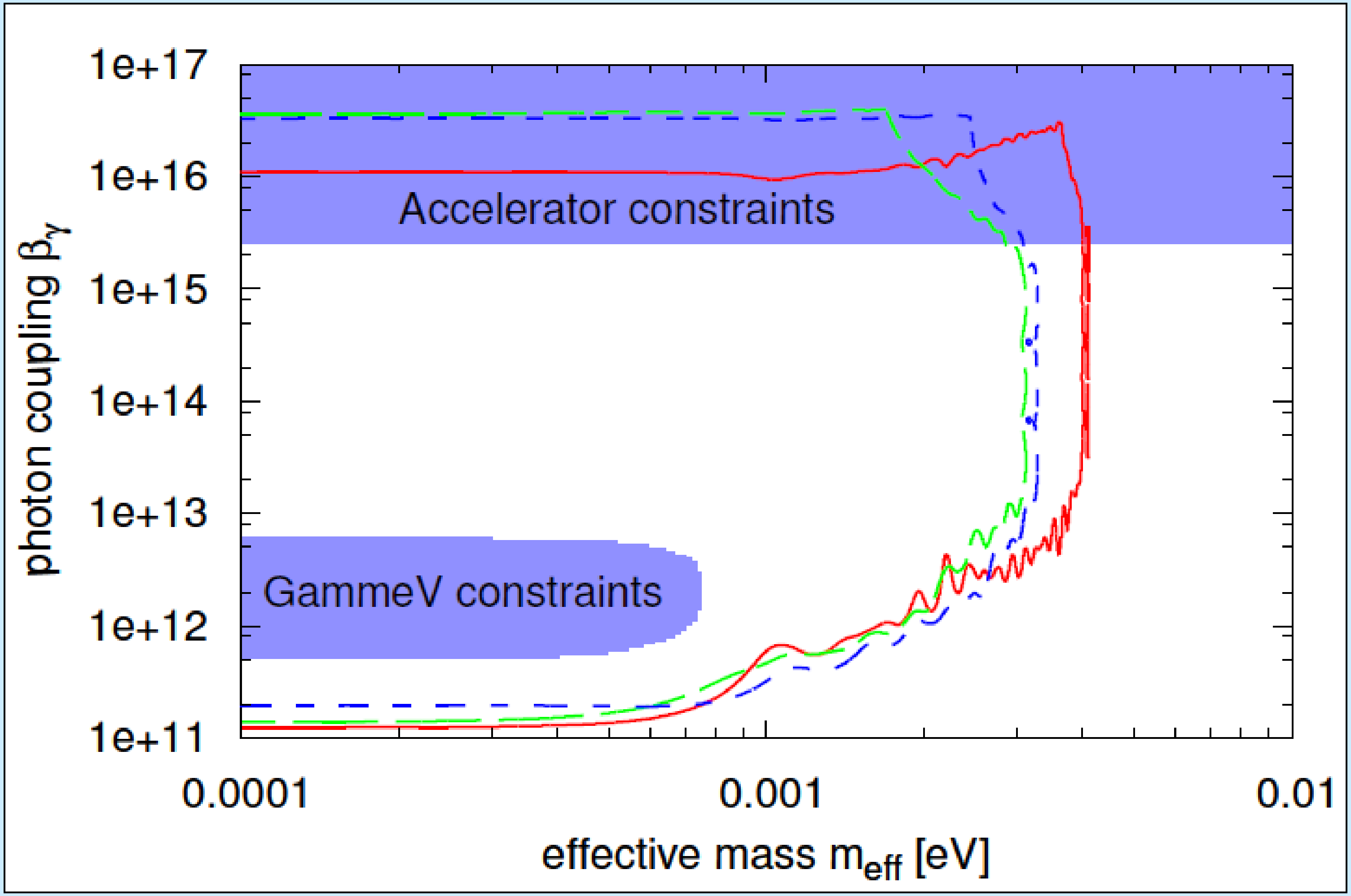
Use a run plan that with lower B fields in case the coupling is strong.

Use a lower noise PMT.

Employ the "dish rack" to effectively have 4.7m,1m, and 30cm magnetic field regions.

Goal: Extend the Chameleon Limits

Extend the sensitivity in coupling vs mass



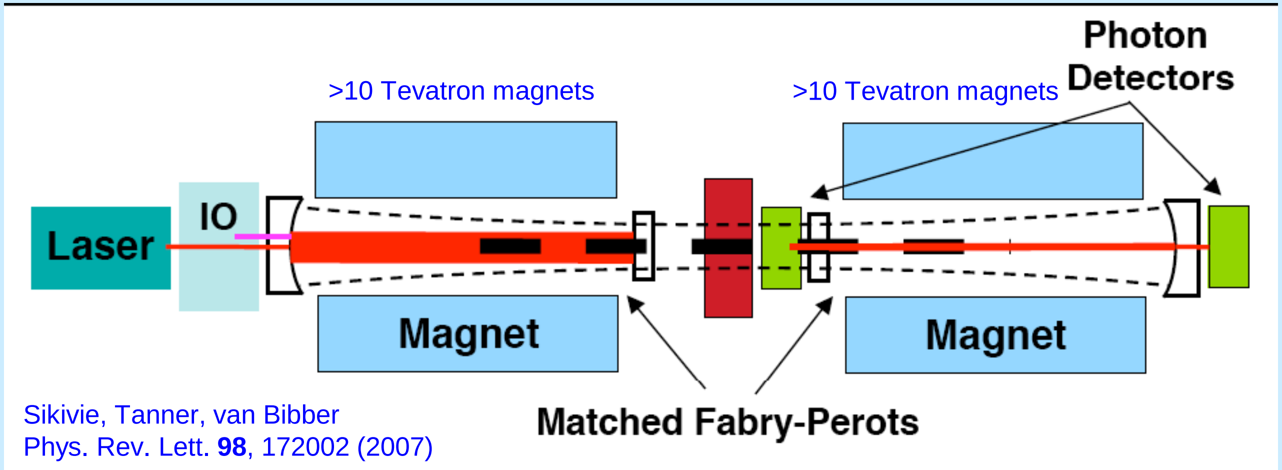
Next axion experiment

- World-wide renewed interest in axions and the possibility of new physics at the sub-eV mass scale
- Next experiments to probe new regions will still be small, but not negligible (~couple to few $M scale)
- Fermilab can play a large role in developing a program to probe new unexplored regions for new physics using lasers and magnets

Resonant regeneration

GammeV

Resonant regeneration

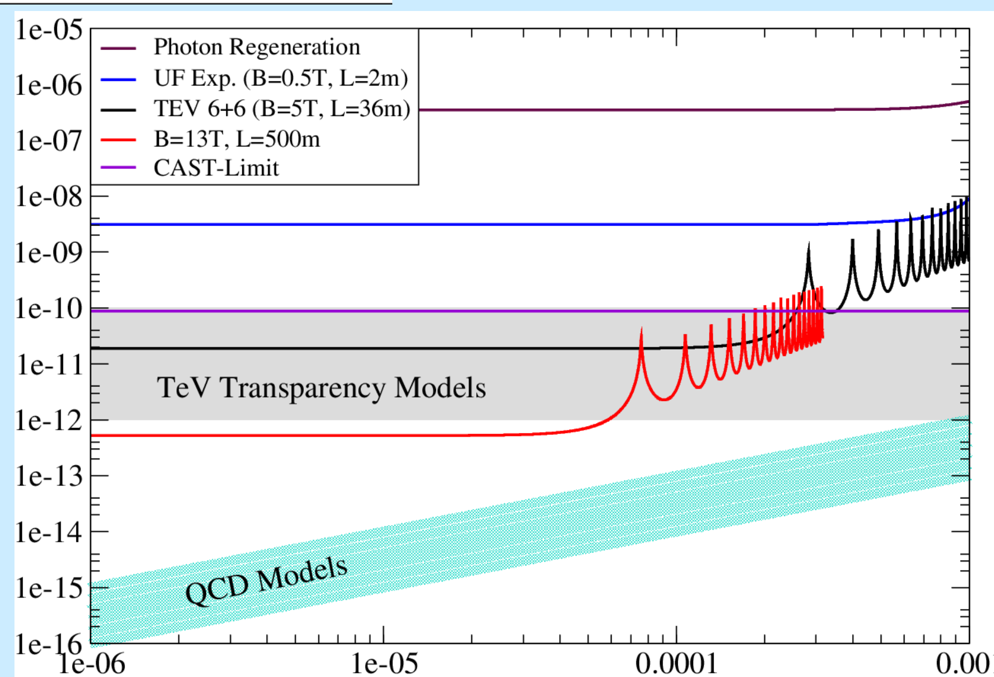


Probability of regeneration goes as the product of finesse's: $\mathcal{F}\mathcal{F}$

Collaboration with University of Florida and Naval Postgraduate School

R&D efforts are underway

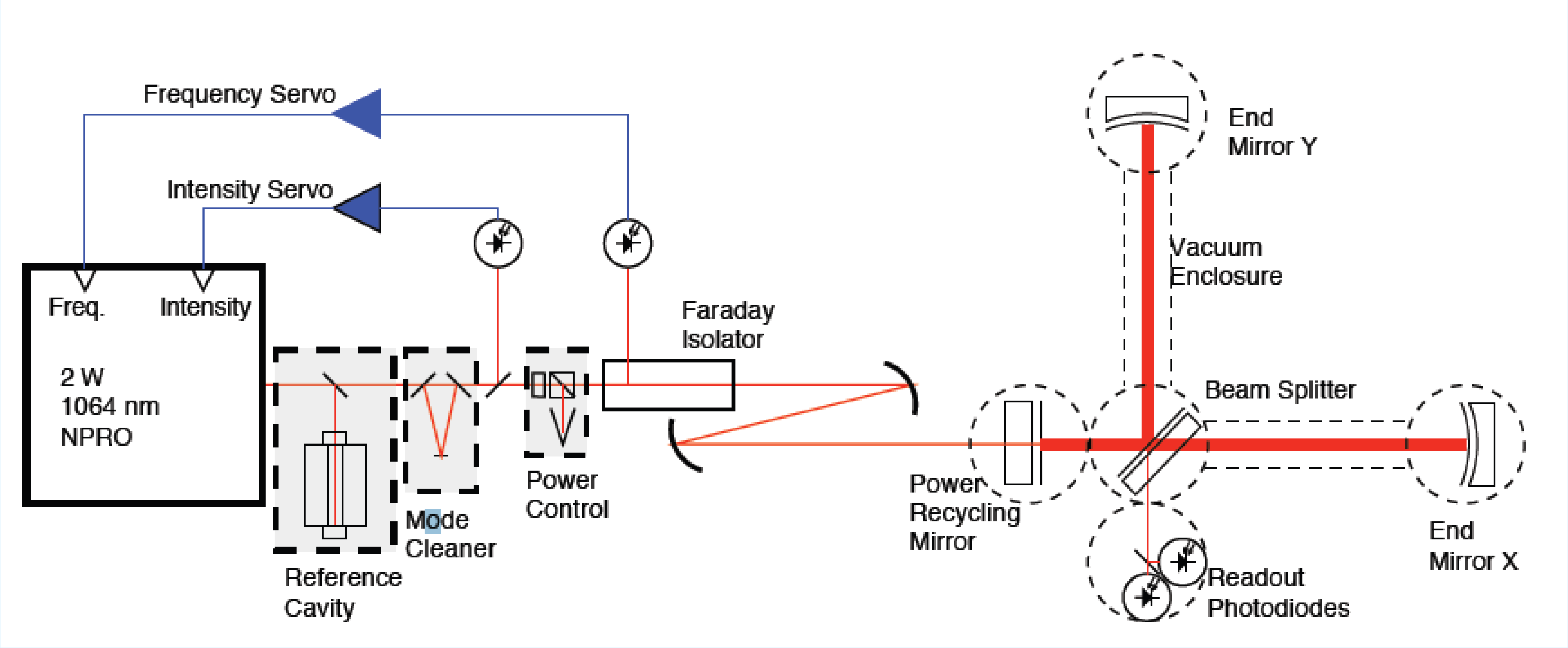
Plan on using TeV magnets; ultimately, long strings w/ high field + large aperature



GammeV And while we're doing R&D

- New idea (C. Hogan) related to black holes and a Planck scale cutoff predicts so-called Holographic noise – a jitter in space time.
- Build two laser interferometers and look for a correlated signal of this jitter.
- Collaboration with Fermilab, Univ. of Chicago, MIT, Univ. of Michigan, Cal Tech.
- Favorably reviewed by the PAC – some additional theory review also done. Director/DOE deciding how to proceed.

The holometer



- Two interferometers (one shown) with 40m arms
- LIGO-like technology (easier at 100 KHz-few MHz)
- Systems: vacuum/mechanical, optical, electronics/DAQ
- Considering warehouse rental for siting

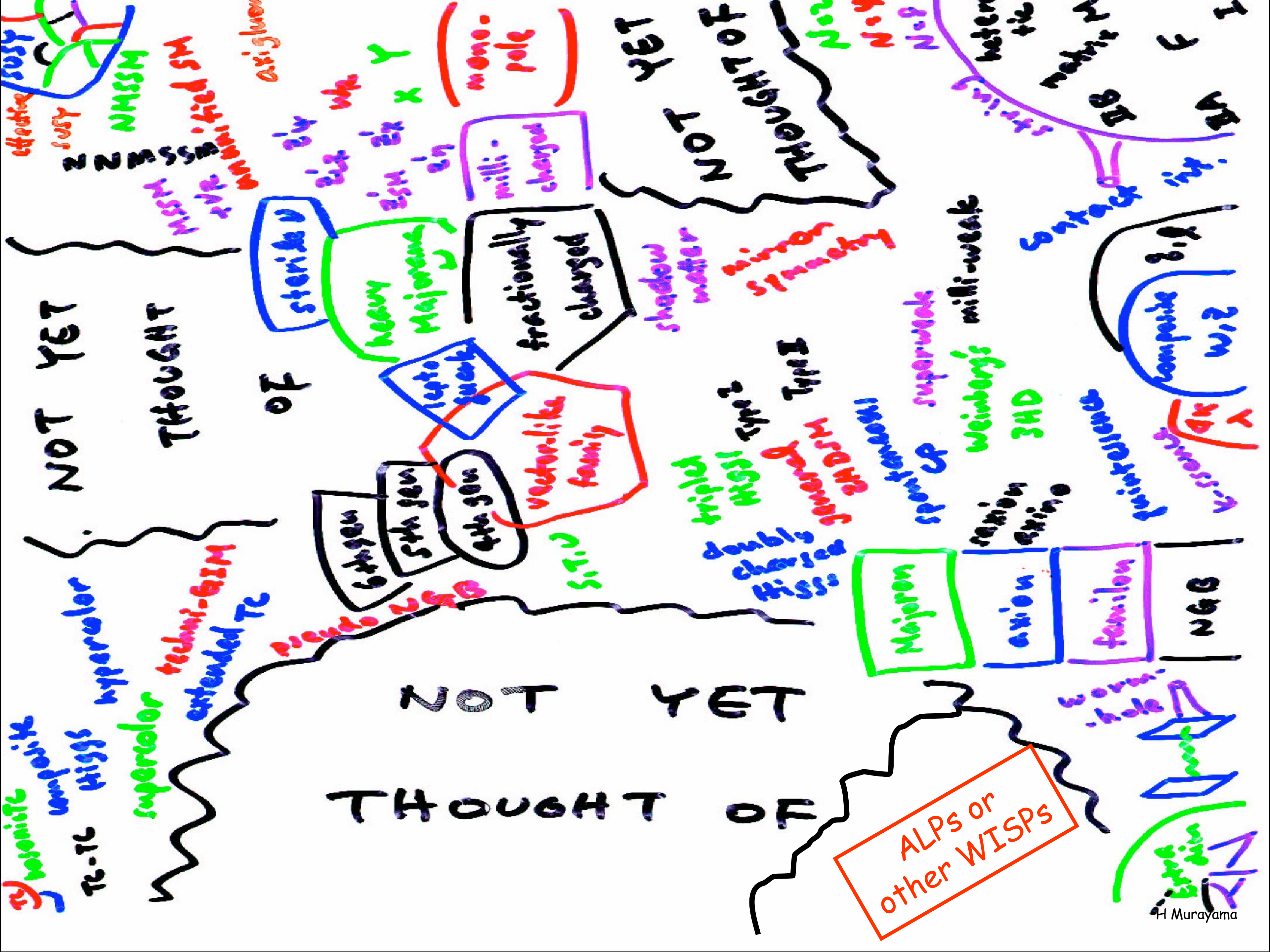
Conclusion

- At FNAL, a small group of us are having fun. There are days I've gone 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.
- R&D is beginning for a future axion project
- Along the way, an interesting proposal to test space-time
- 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.

gammev.fnal.gov

H Murayama


NOT YET THOUGHT OF
ALPs or other WISPs
H Murayama
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Majoron
axion
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NGB
sterile ν
heavy Majorana ν
fractionally charged
vector-like family
4th gen
5th gen
6th gen
mono-pole
milli-charged
milli-weak
shadow matter
mirror symmetry
doubly charged Higgs
triplet Higgs
superweak
Weinberg's 3HD
contact int.
strings
NMSSM
NNMSSM
MSSM
effective SUSY
axi-gluon
pseudo NGB
supercolor
hypercolor
extended TC
composite Higgs
TC-TC
worm-hole
extra dim