GammeV

Gamma to milli-eV particle search

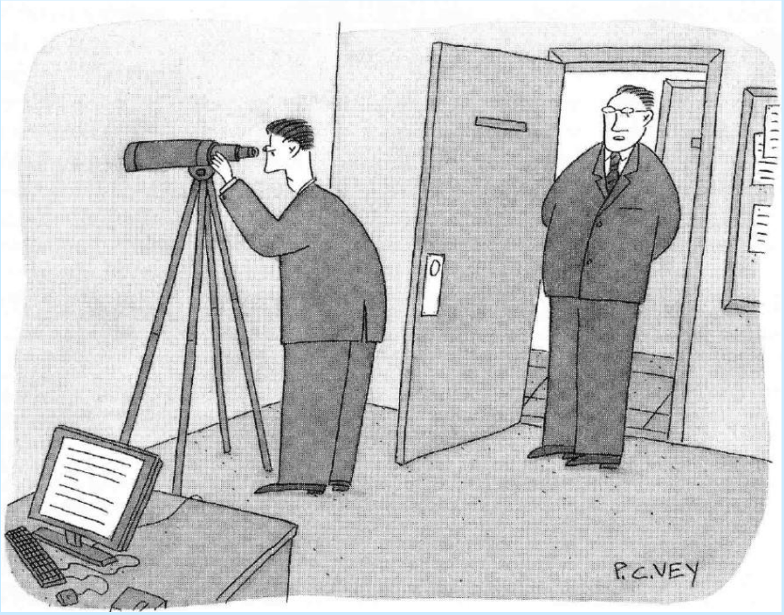
Laser experiments at Fermilab to search for new physics

William Wester
Fermilab

H Murayama

Outline

- Intro to Axions and “WISPs” particles
- Physics motivation for our experiment
  - milli-eV mass scale
  - PVLAS anomaly
- “Light shining through a wall”
  - **G**amme**V**
  - Other experiments
- “Particles in a Jar”
  - Chameleons
- “Holographic Noise”
  - Something completely new
- Future Prospects and Conclusions



New Yorker

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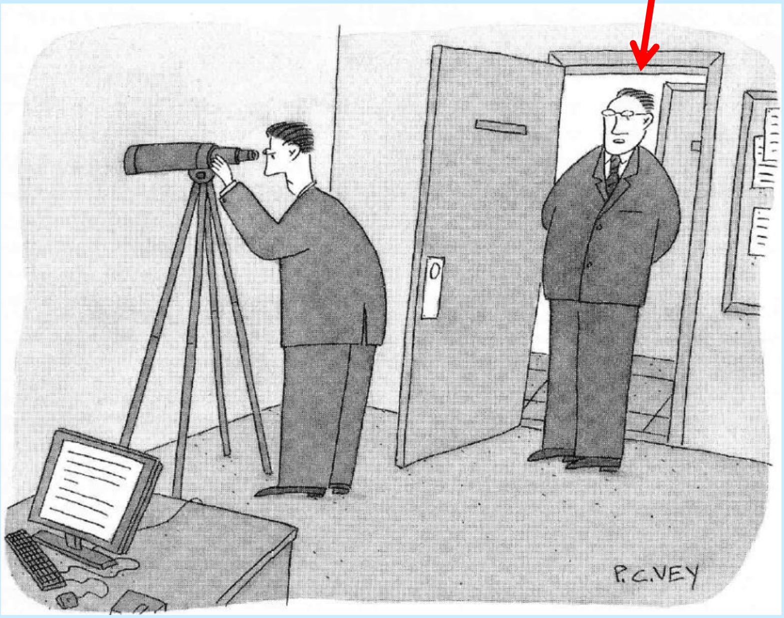
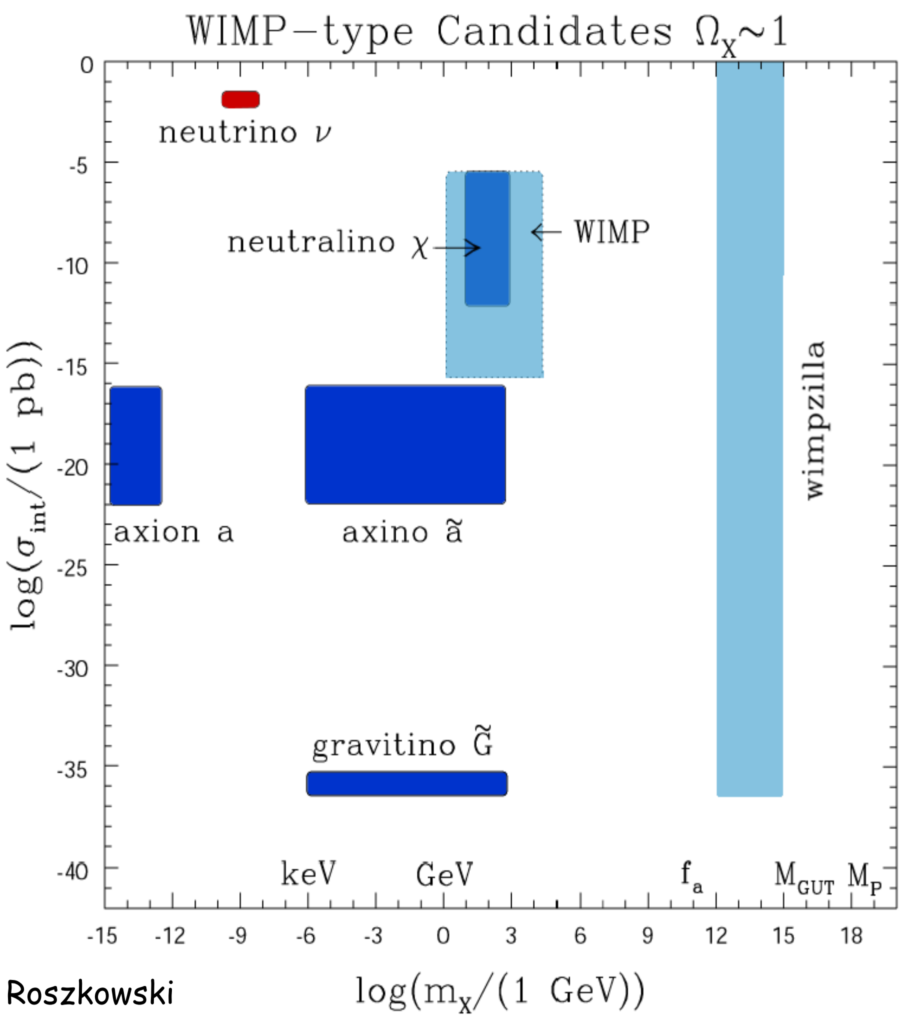
My boss on CDF!



New Yorker

Dark Matter

- What is the dark matter of the universe?



L. Roszkowski

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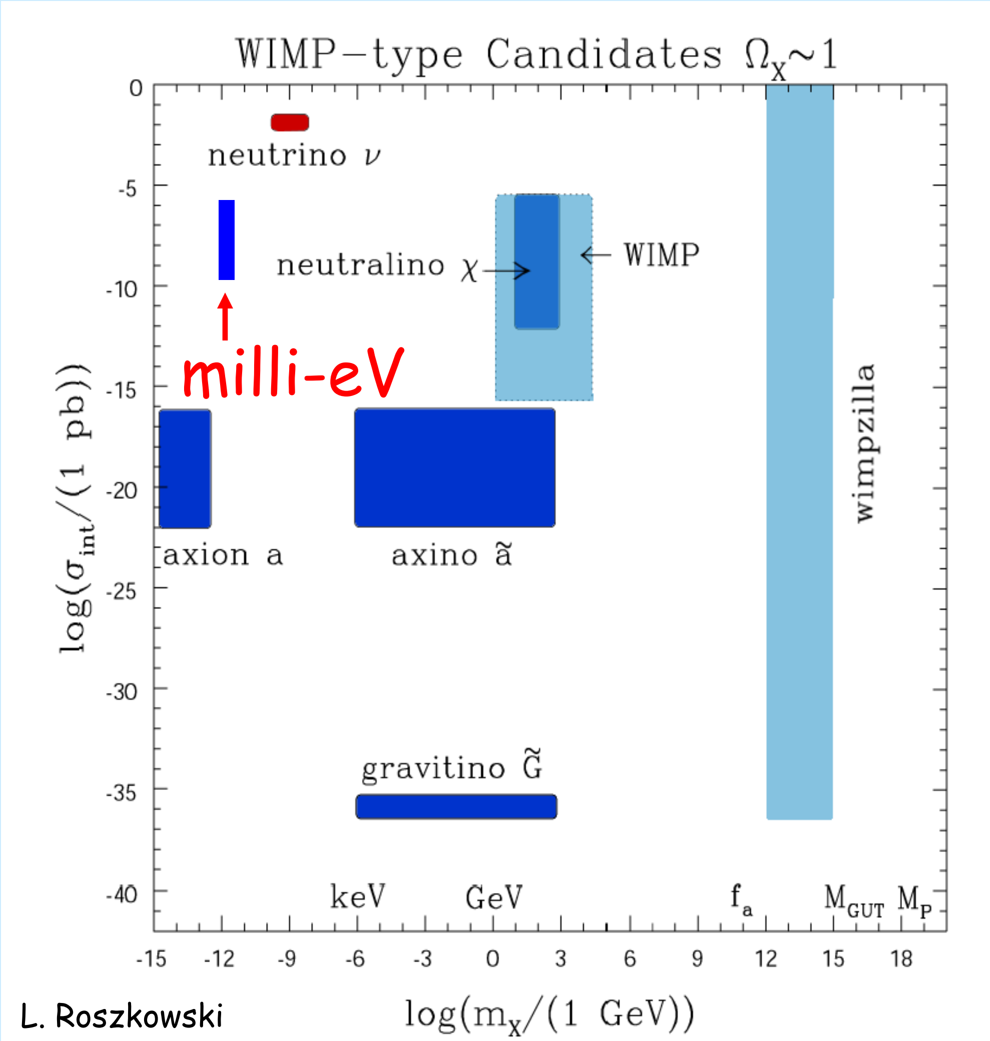


Axions

- 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 measurements of the electric dipole of the neutron imply $\bar{\Theta} < \sim 10^{-10}$. => 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.

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"

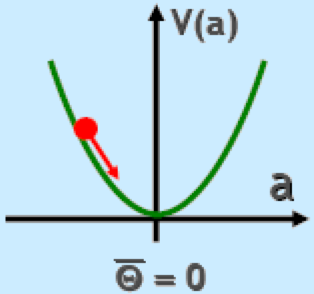
Witten • "Axions may be intrinsic to the structure of string theory"

WW+K van Bibber

Axions

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

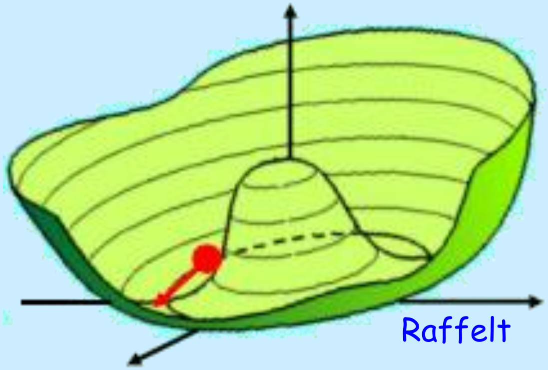
$$\bar{\Theta} = \frac{a(x)}{f_a}$$



- 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

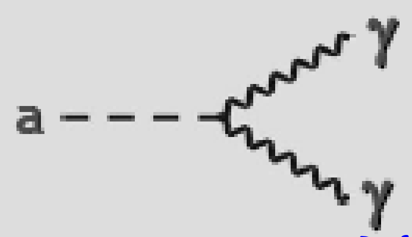
$$m_a = m_\pi \frac{f_\pi}{f_a} = \frac{0.6\ \text{meV}}{f_a/10^{10}\ \text{GeV}}$$



Axions and WISPs

- Axions couple to photons

Photon coupling	$L_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F}a = g_{a\gamma}\vec{E}\cdot\vec{B}\,a$ $g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$



Raffelt

- A WISP is a "*weakly interacting slim particle*" and includes *axion-like-particles* (ALPs) and other low mass particles that might have connections to ultra high energy scales.

pseudoscalar

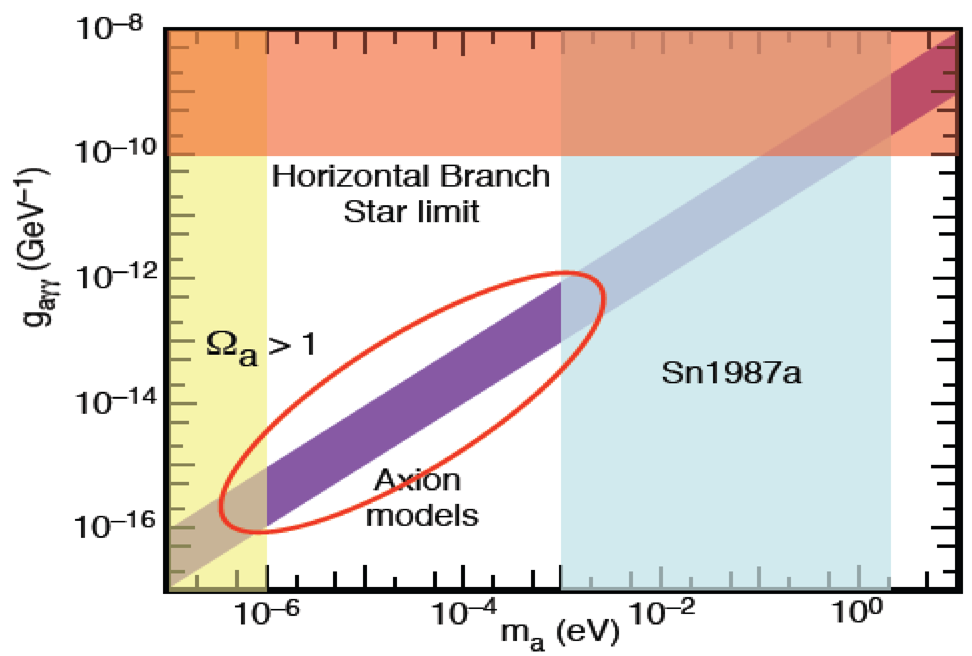
$$\mathcal{L}_{\rm int} = -\frac{1}{4}\frac{\phi}{M}F_{\mu\nu}\widetilde{F}^{\mu\nu} = \frac{\phi}{M}(\vec{E}\cdot\vec{B})$$

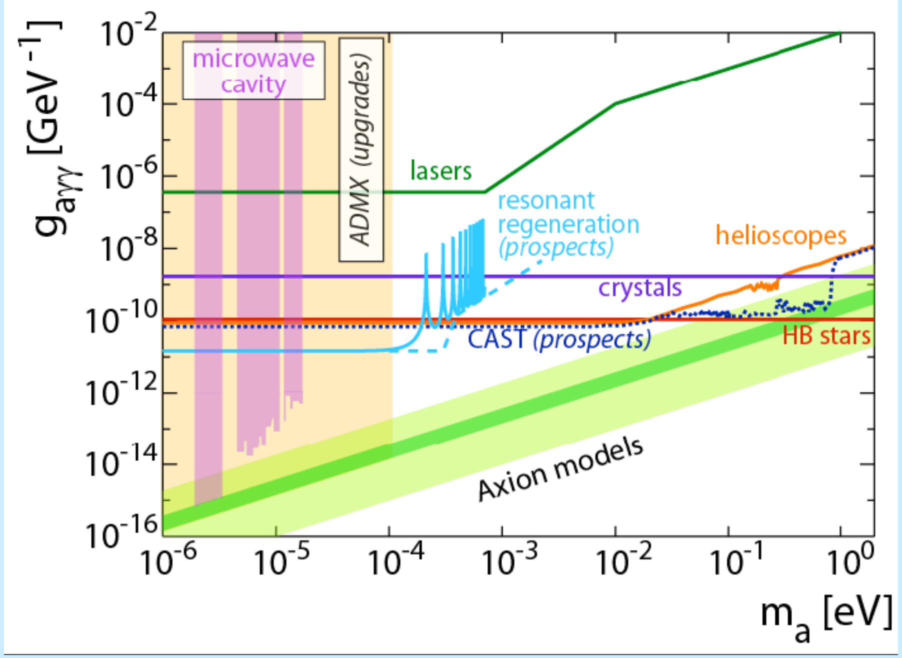
scalar

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

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



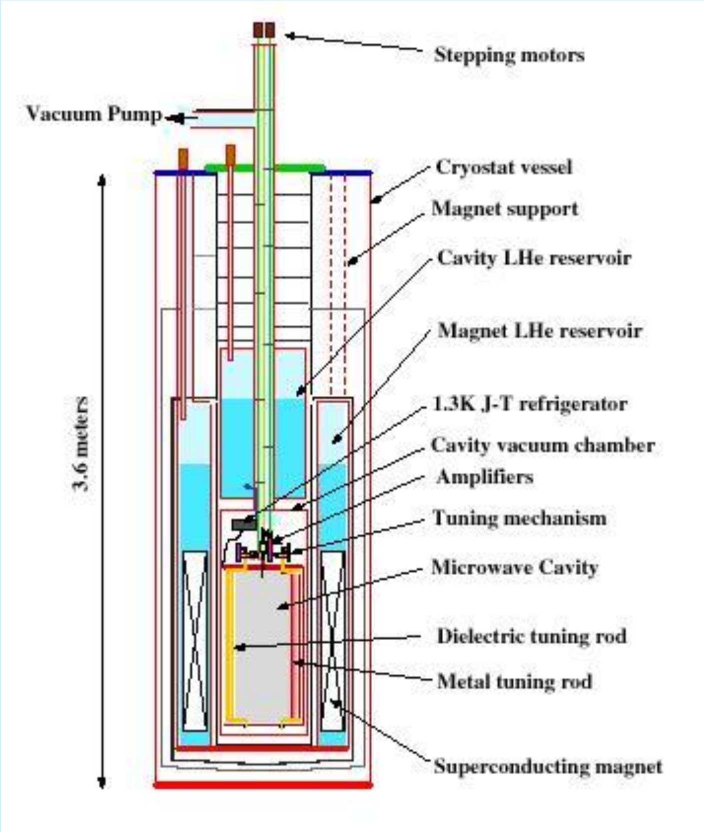


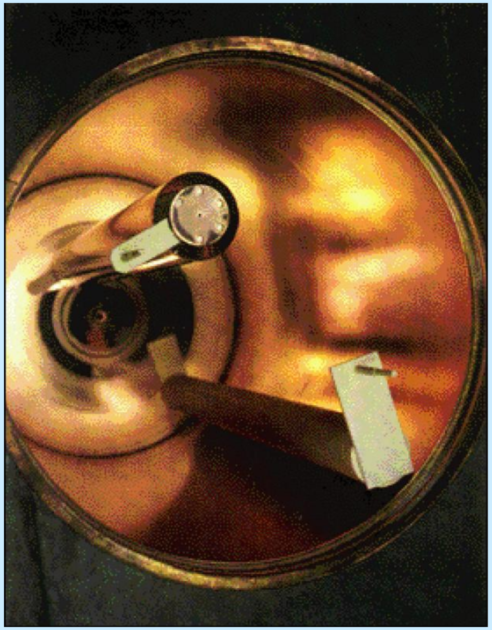
K van Bibber

PDG

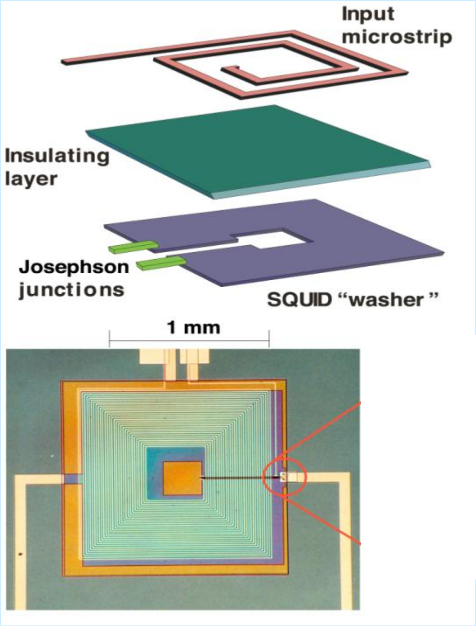
ADMX Experiment

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





High Q cavity

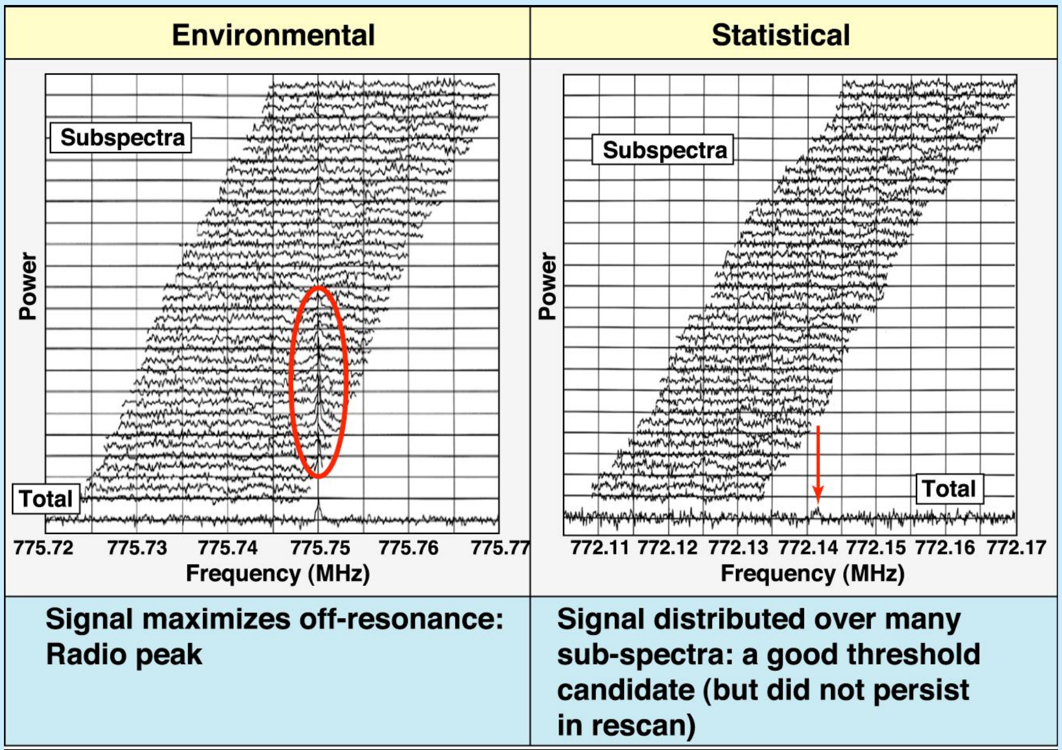


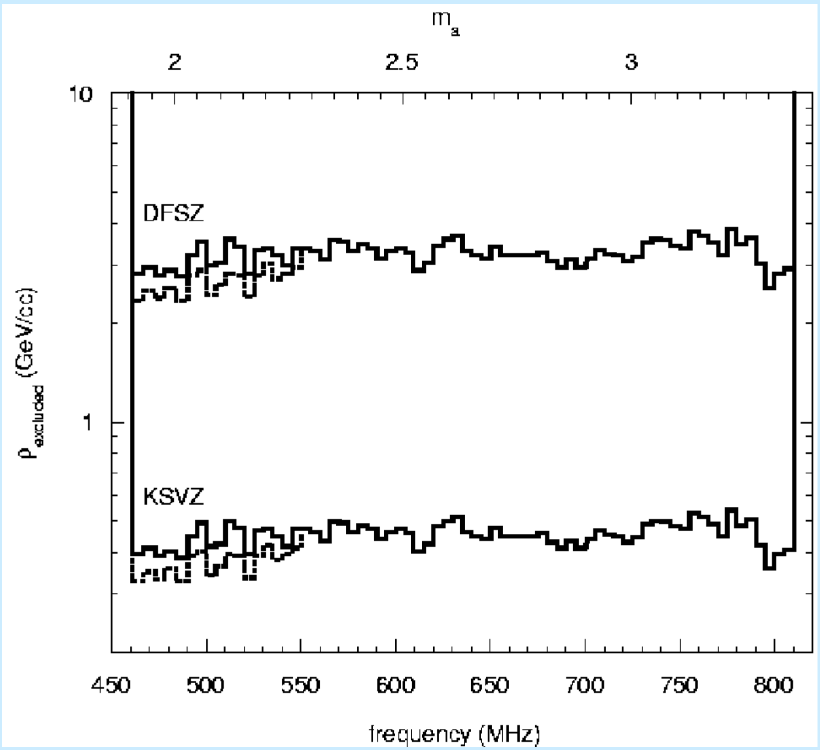
SQUID upgrade for receiver

ADMX

ADMX Results

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



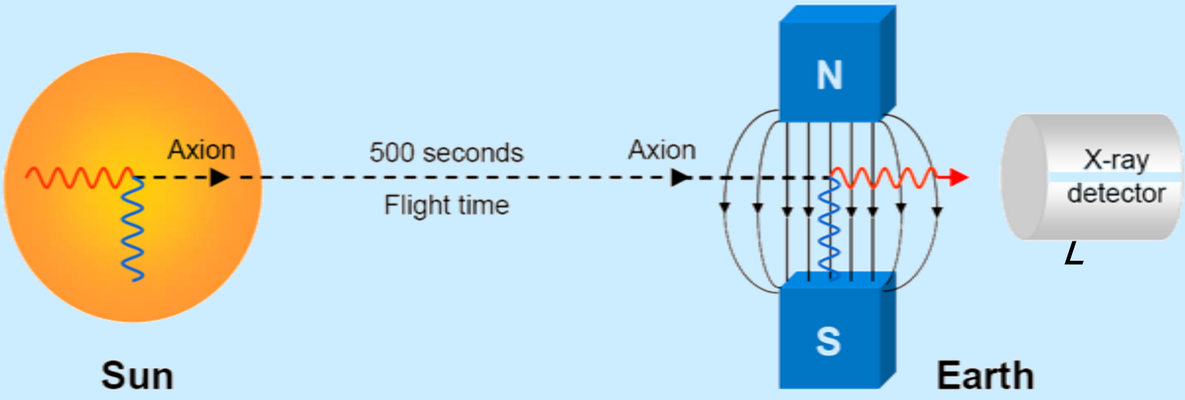


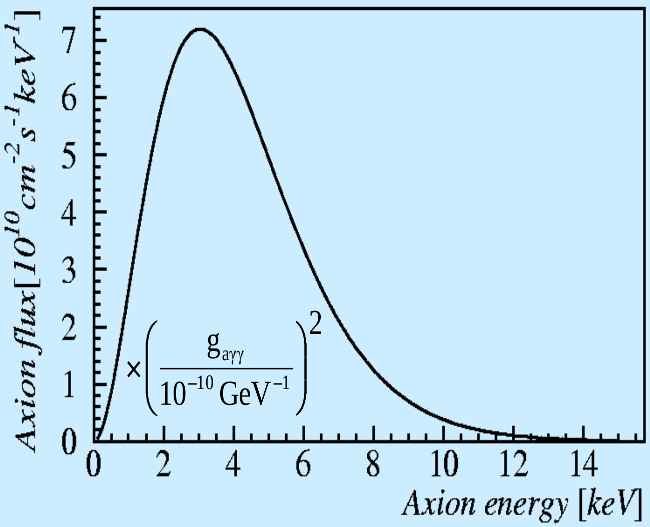
K van Bibber

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

CAST Experiment

- CERN Axion Solar Telescope





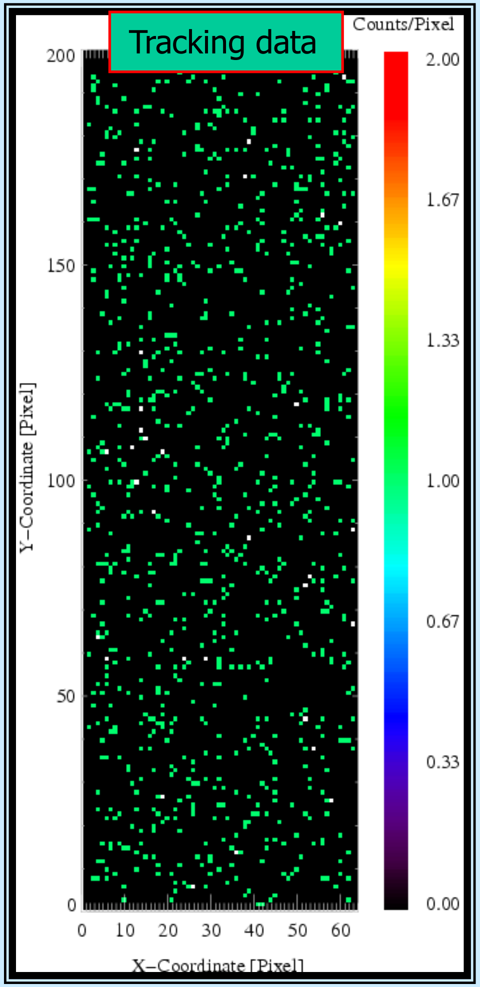
Point LHC dipole toward the sun.

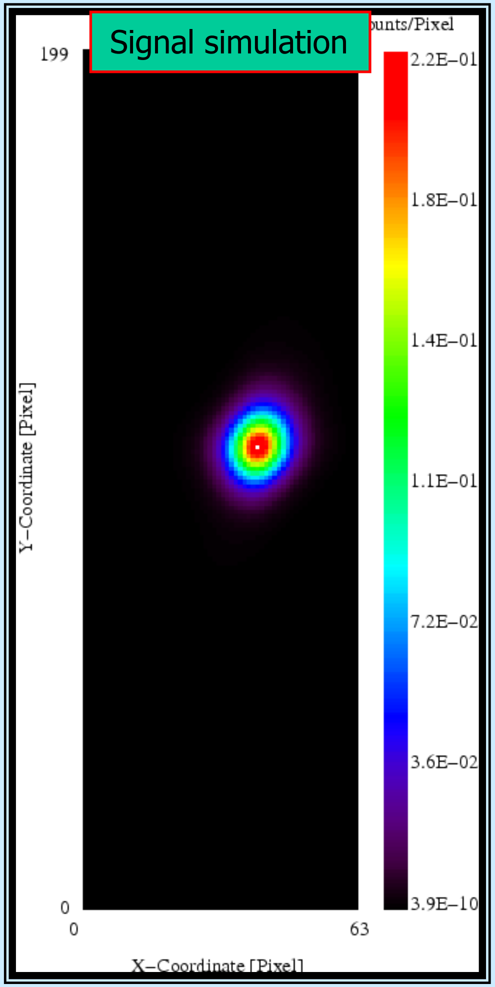
Detect possible X-rays from axion reconversion.

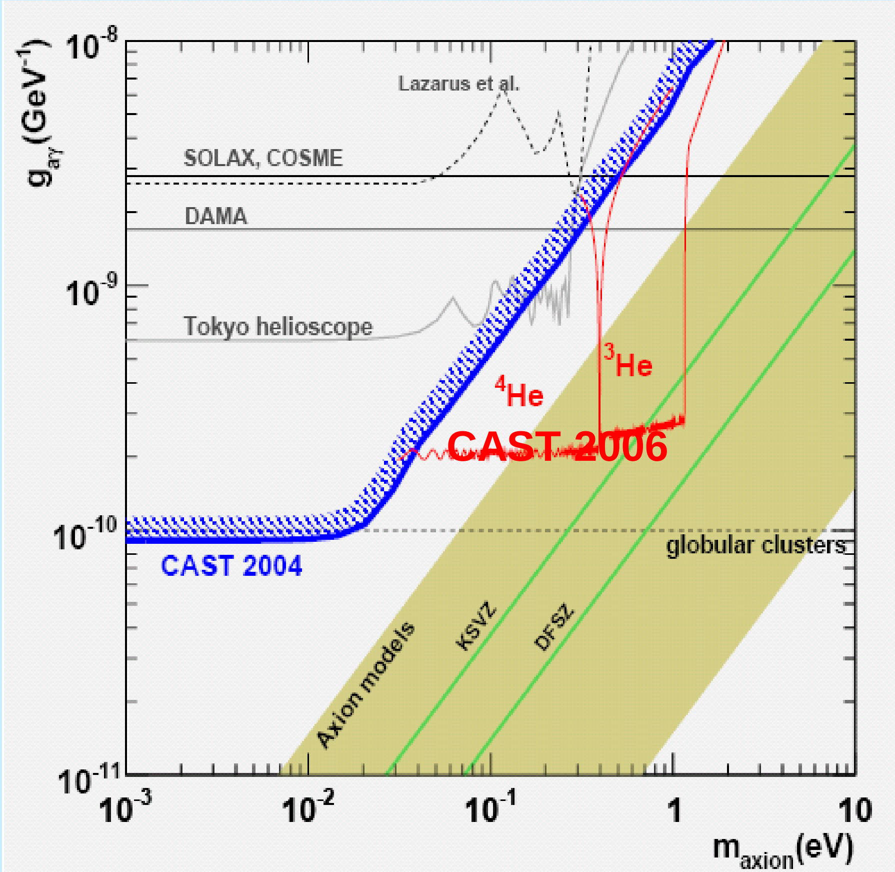
CAST

CAST Results

- Now a 10+ year program. Phase I results in 2004 and 2006 results with ^{4}He. On-going results with ^{3}He.







$$g_{a\gamma\gamma} < 0.88 \times 10^{-10}\ \mathrm{GeV}^{-1} \quad (m_a < 0.02\mathrm{eV})$$

JCAP 04(2007)010
JCAP 0902:008,2009

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 …

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

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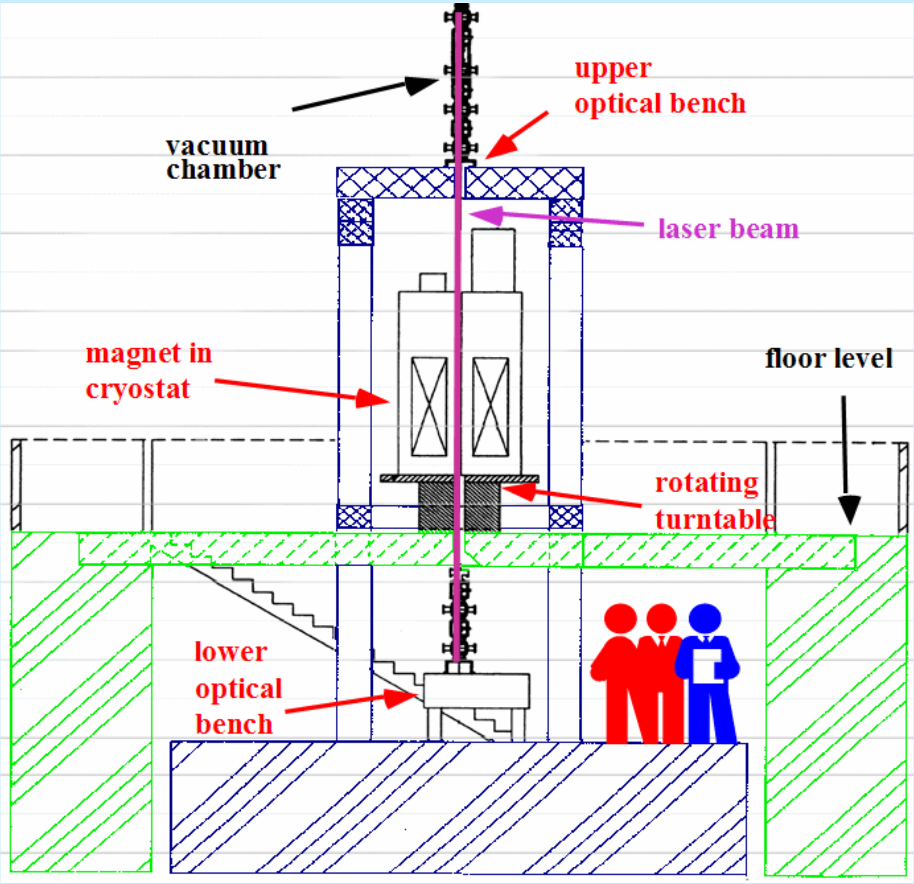
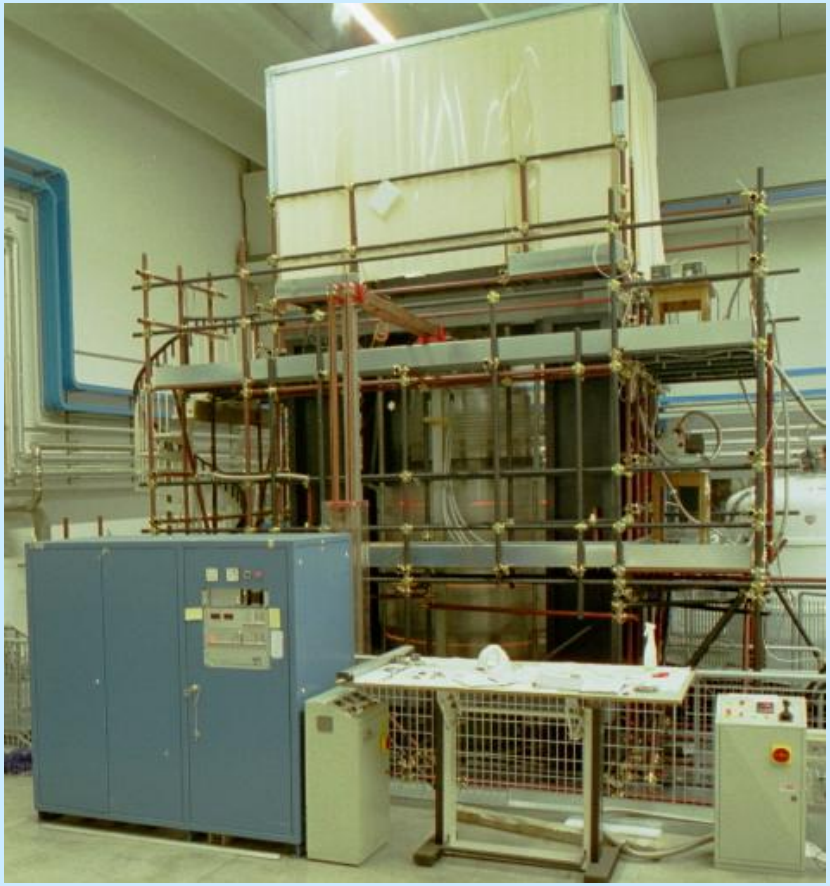
Energy frontier
Neutrinos
Astrophysics
all in one!

PVLAS Experiment

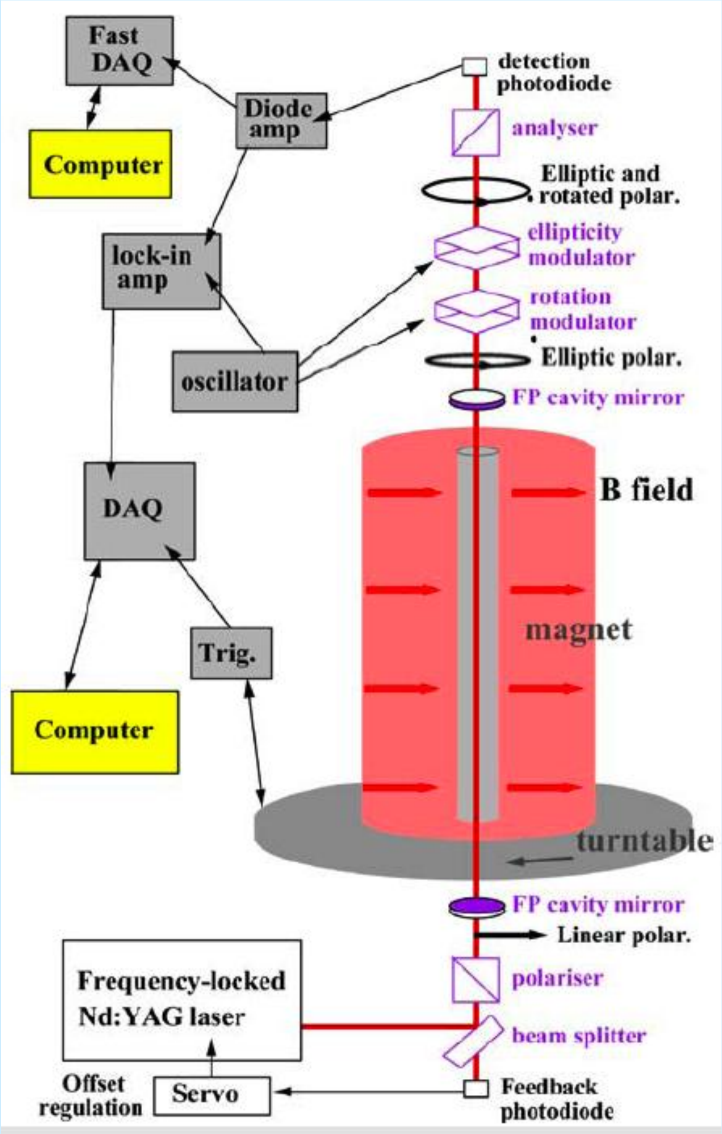
- Designed to study the vacuum by optical means: birefringence (generated ellipticity) and dichroism (rotated polarization)





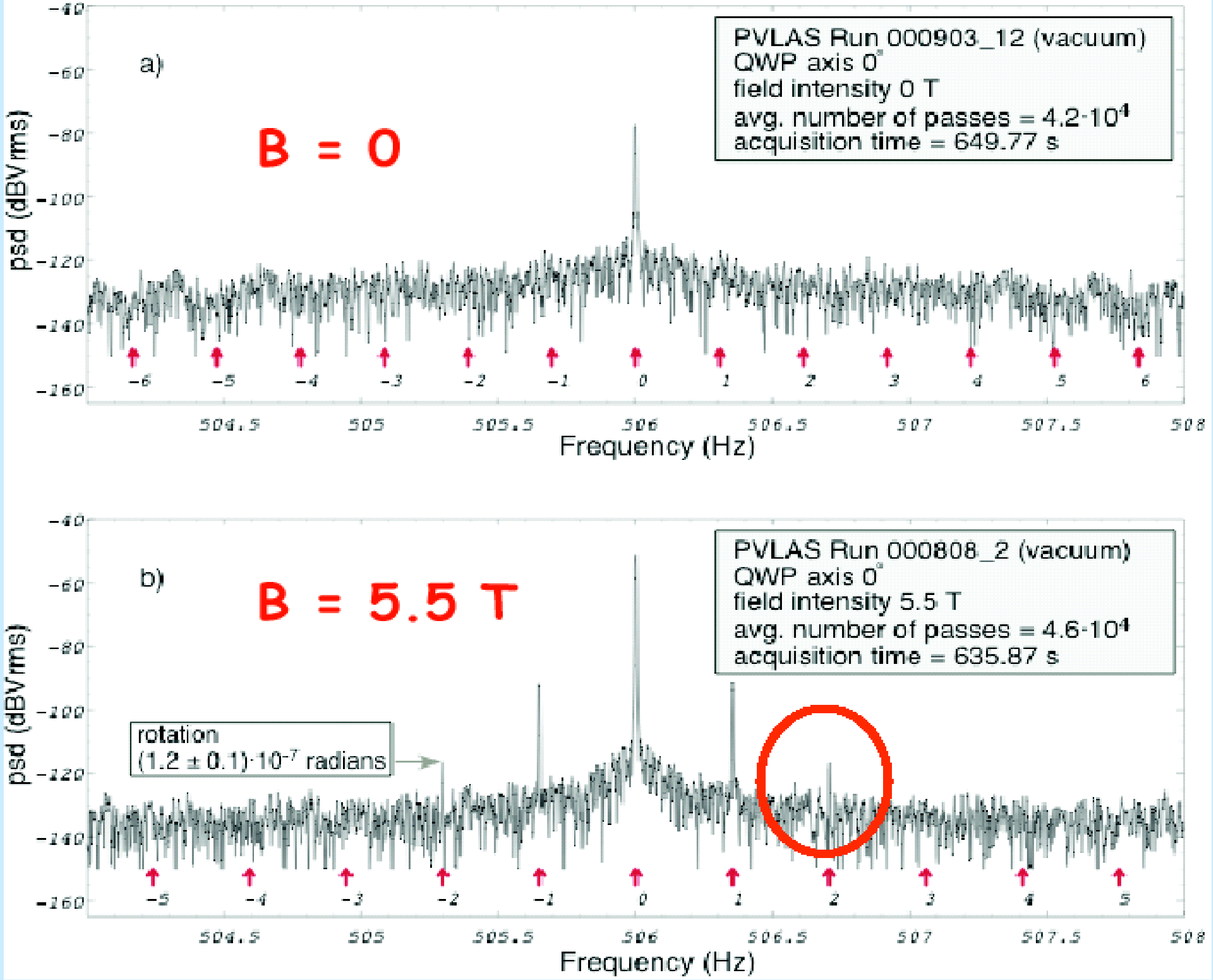
PVLAS Experiment

- Rotating SC magnet (½ Hz)
- Modulators (500 Hz)
- ¼ wave plate to switch between ellipticity and rotation
- Optical cavity to amplify path length in B field
- Expect signals in 2nd harmonic only when B_{ext} field is aligned with either E or B of the γ
- Cross-checks including with birefringent gasses



GamameV

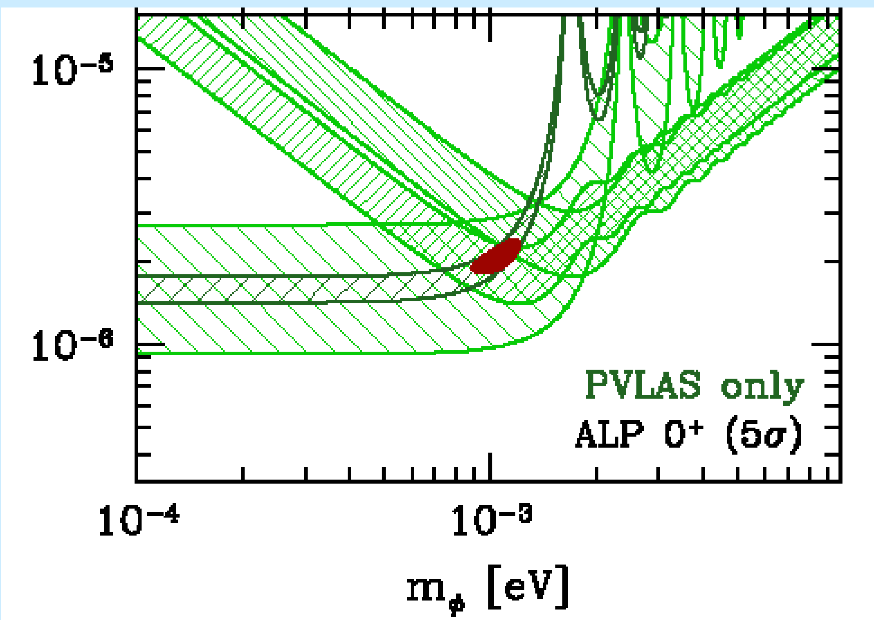
PVLAS Rotation Results

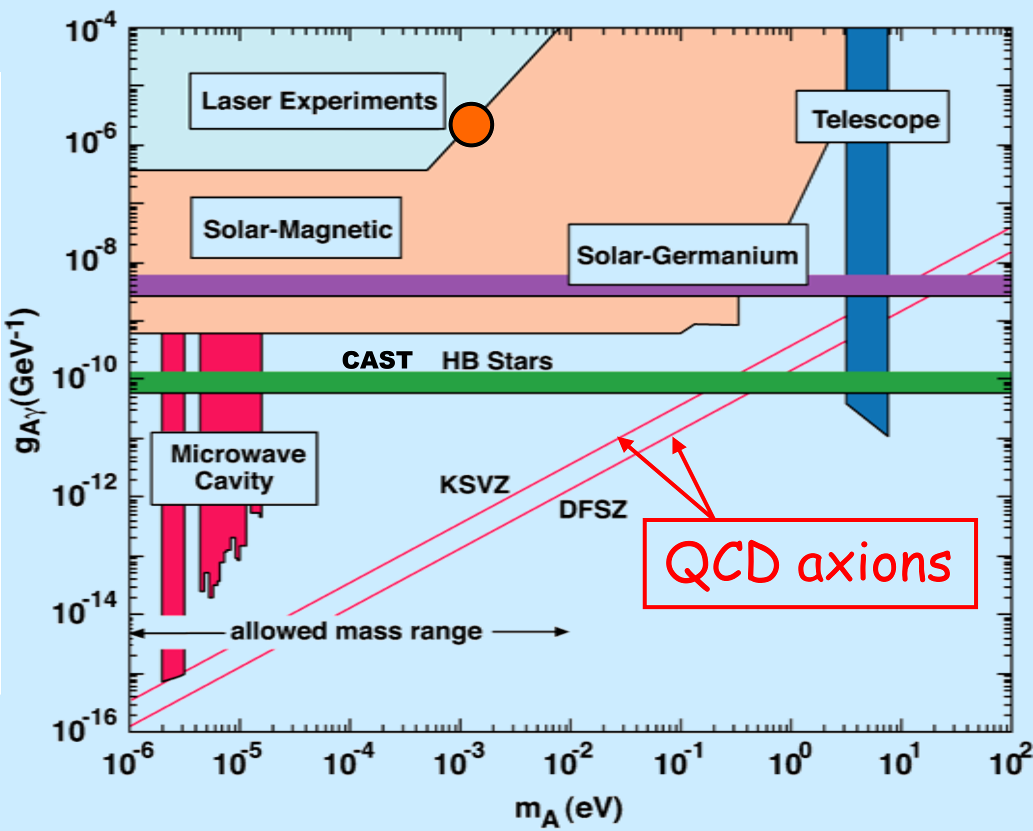


PRL 96, 110406, (2006)

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.





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

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

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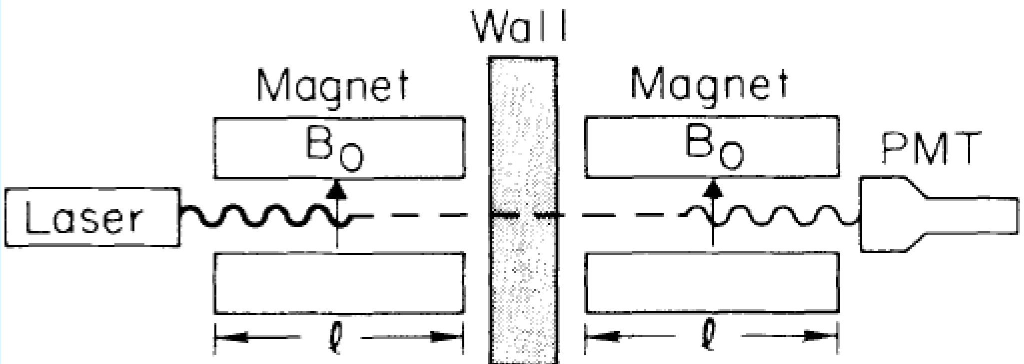
Concerns for a new particle interpretation

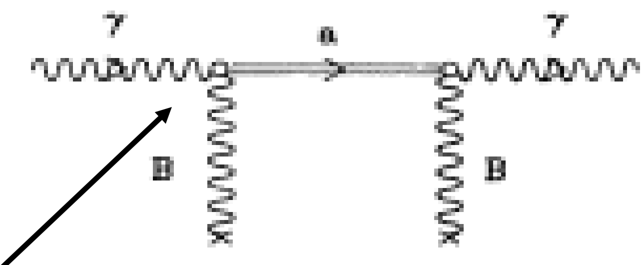
-Systematics from rotation magnet (eddy currents) understood?
-Extra 1st harmonic signal not explained
-Some cross checks are done w/large signals
-**New data does not observe the effect and concludes there is likely an instrumental artifact (Phys. Rev. D 77, 032006 (2008)) [after we started]**

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

Light Shining Through a Wall Experiment



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



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

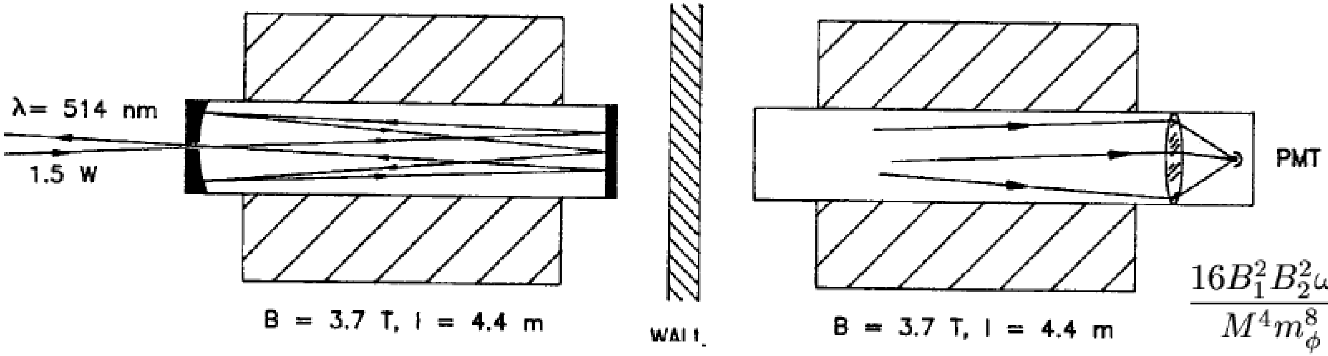
$$P_{regen} = \frac{16B_1^2B_2^2\omega^4}{M^4m_\phi^8}\sin^2\left(\frac{m_\phi^2L_1}{4\omega}\right)\cdot\sin^2\left(\frac{m_\phi^2L_2}{4\omega}\right)$$

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

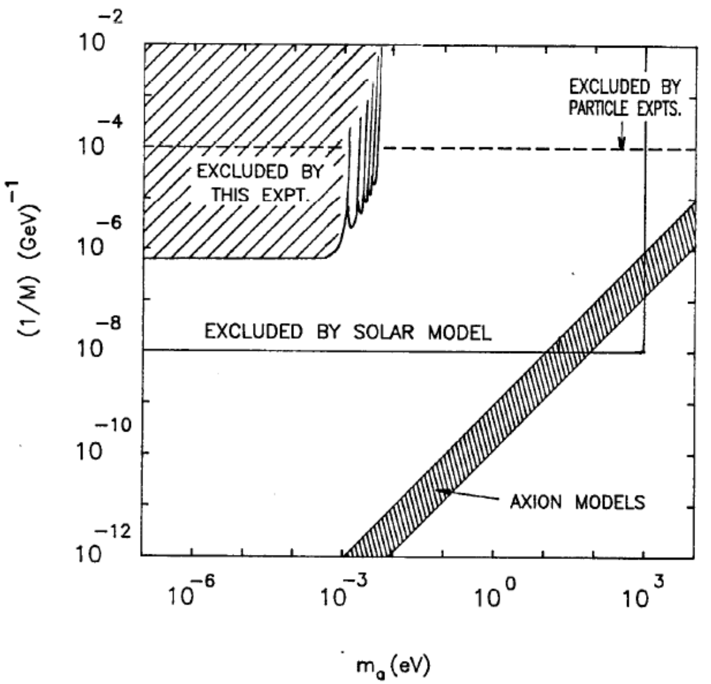
$$P_{regen}^{GammeV} = (3.9\times10^{-21})\times\frac{(B_1/5\text{ T})^2(B_2/5\text{ T})^2(\omega/2.33\text{ eV})^4}{(M/4\times10^5\text{ GeV})^4(m_\phi/1.2\times10^{-3}\text{ eV})^8}$$
$$\times\sin^2\left(\frac{\pi}{2}\frac{(m_\phi/1.2\times10^{-3}\text{ eV})^2(L_1/2.0\text{ m})}{(\omega/2.33\text{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

BFRT Experiment

- Brookhaven, Fermilab, Rochester, Trieste (1992)



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



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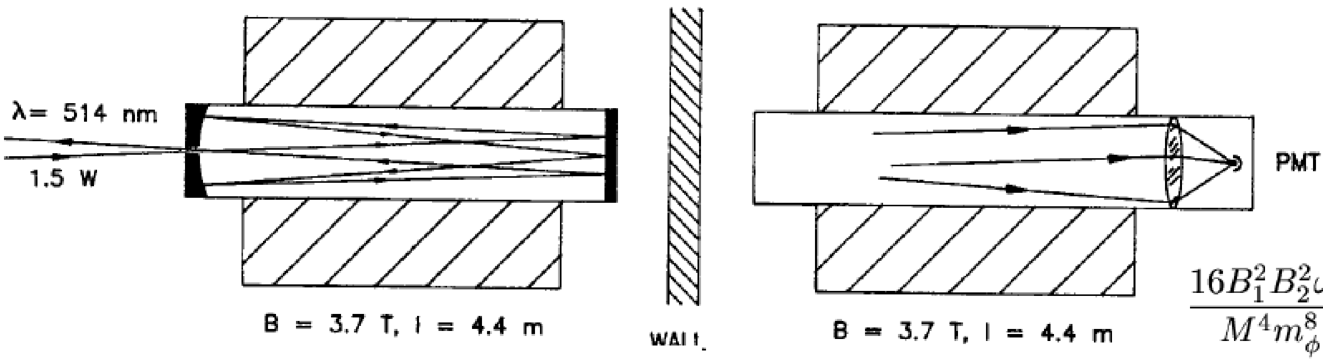

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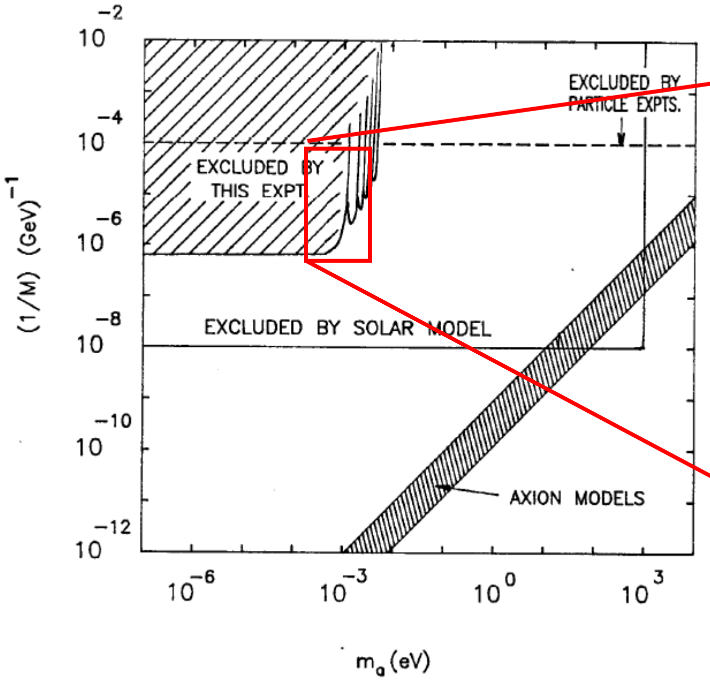
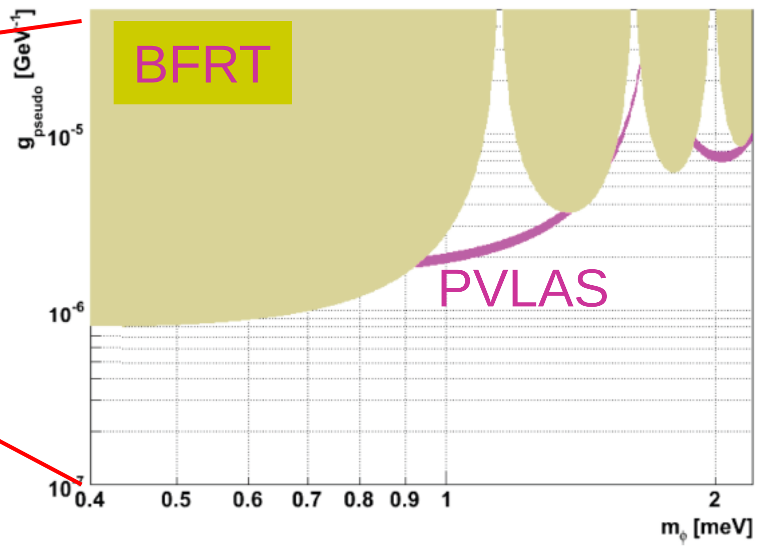




BFRT is not sensitive in the PVLAS region of interest.

GammeV Collaboration

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

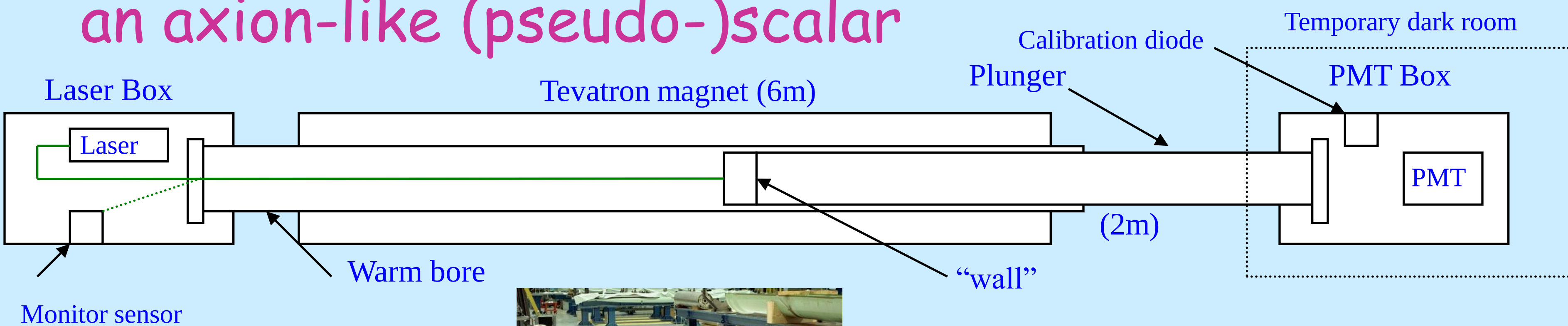
D. Gustafson
University of Michigan
Ann Arbor, MI 48109

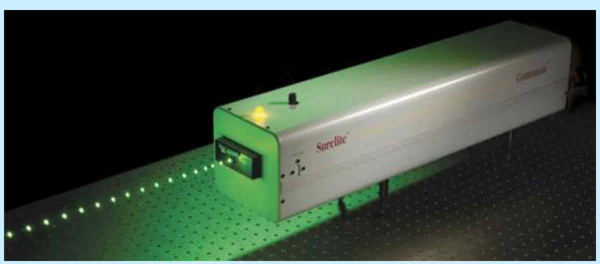
Ten person team including a summer student, 3 postdocs, 2 accelerator / laser experts, 4 experimentalists (nearly everyone had a day job) PLUS technical support at FNAL

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

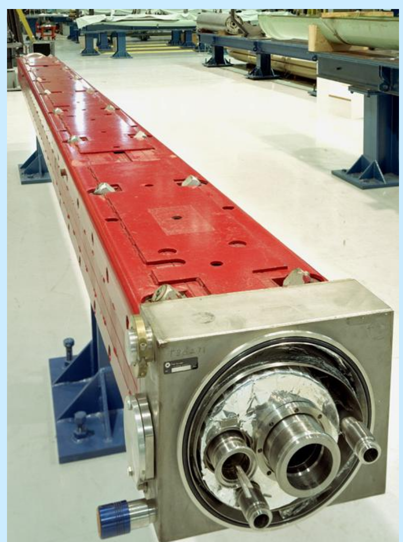
GammeV Proposal

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

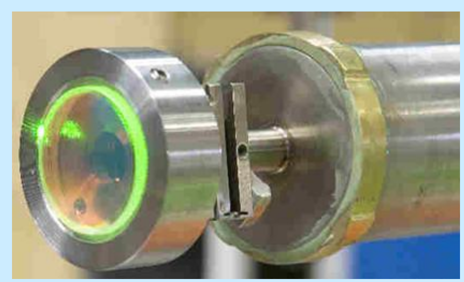




Existing laser in Acc. Div. nearly identical with a similar spare available



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

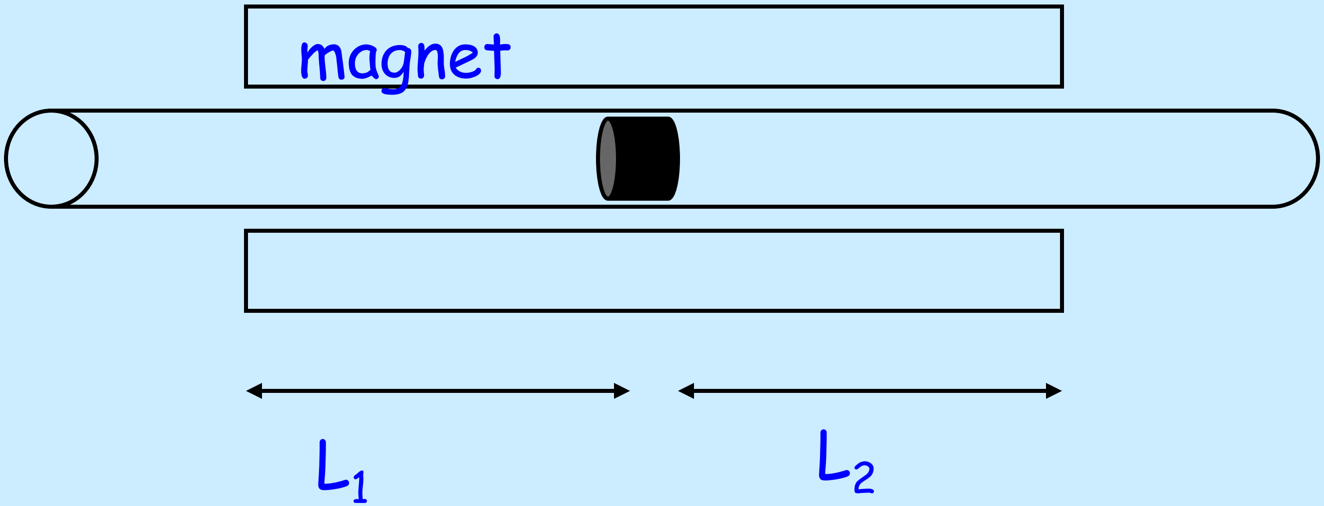


High-QE, low noise, fast PMT module (purchaced)

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

GammeV

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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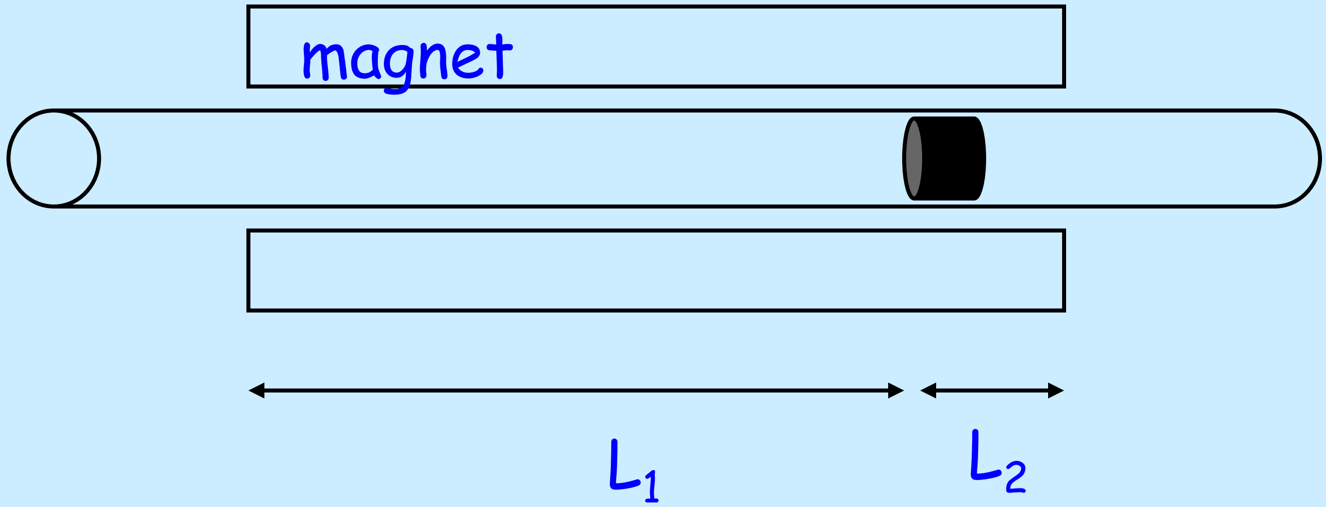

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Apparatus

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

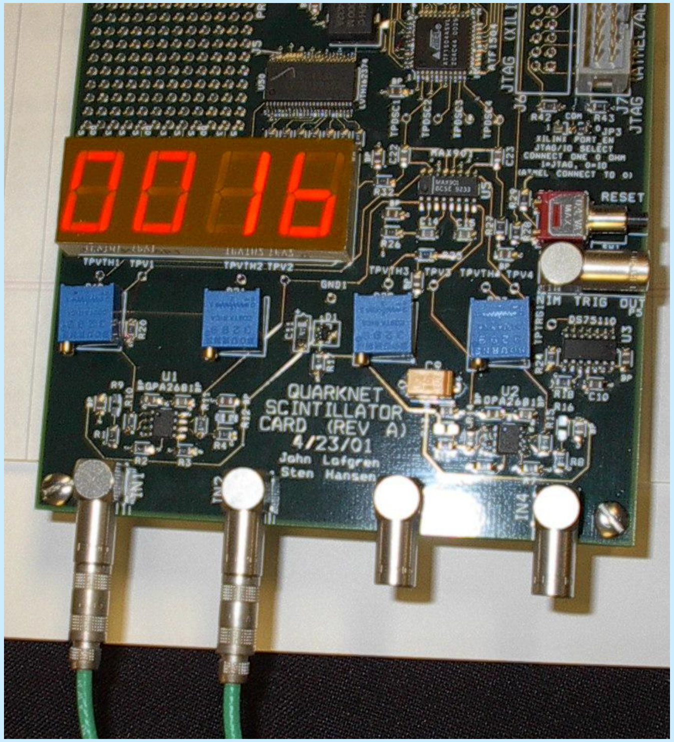
PMT box

Lens

PMT

GammeV

Data acquisition



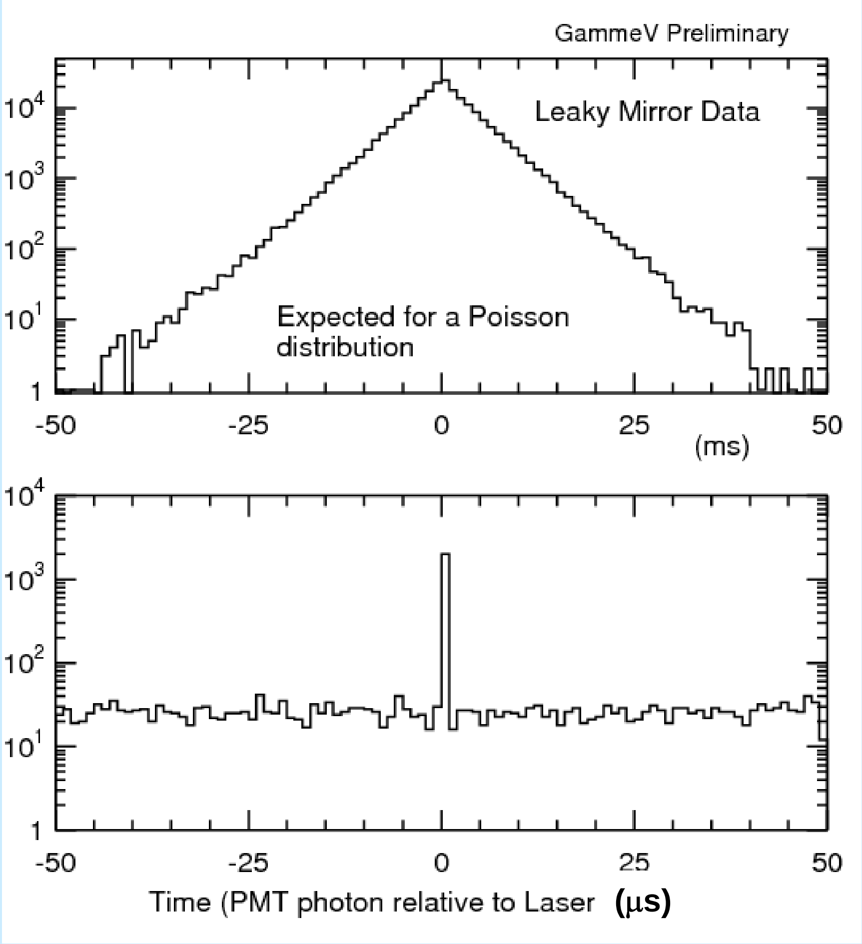
- QuarkNet timing cards
  - Built by Fermilab for Education Outreach (High School cosmic ray exp'ts.)
  - Interfaces to computer via USB (Visual Basic software for our DAQ)
- Four inputs, phase locked to a GPS 1pps using a 100MHz clock that is divided by eight for 1.25ns timing.
- Boards also send firing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

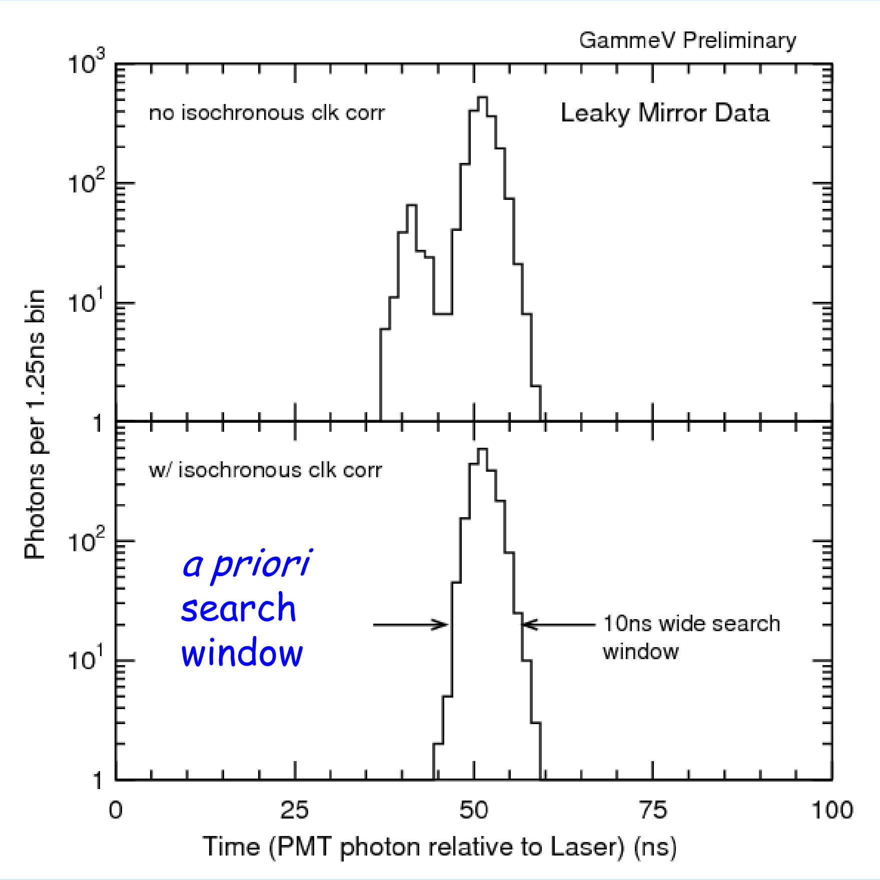
Calibration

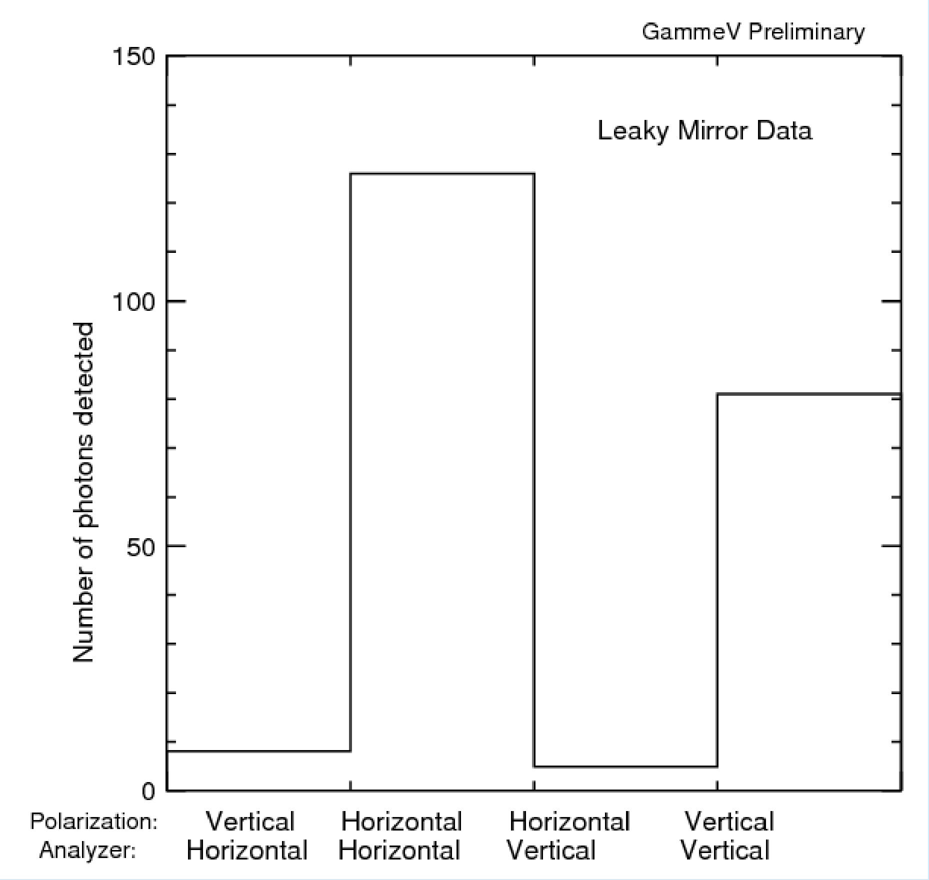
- "Leaky mirror" data involves sending the laser directly into our PMT after attenuation so that we get about 1 photon per 100 pulses.
  - Two mirrors leak ~10^{-6} through
  - 10 micron pin hole captures ~10^{-6}
  - Neutral density filters give ~10^{-7}
- Look at the PMT pulse closest to a laser pulse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



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.



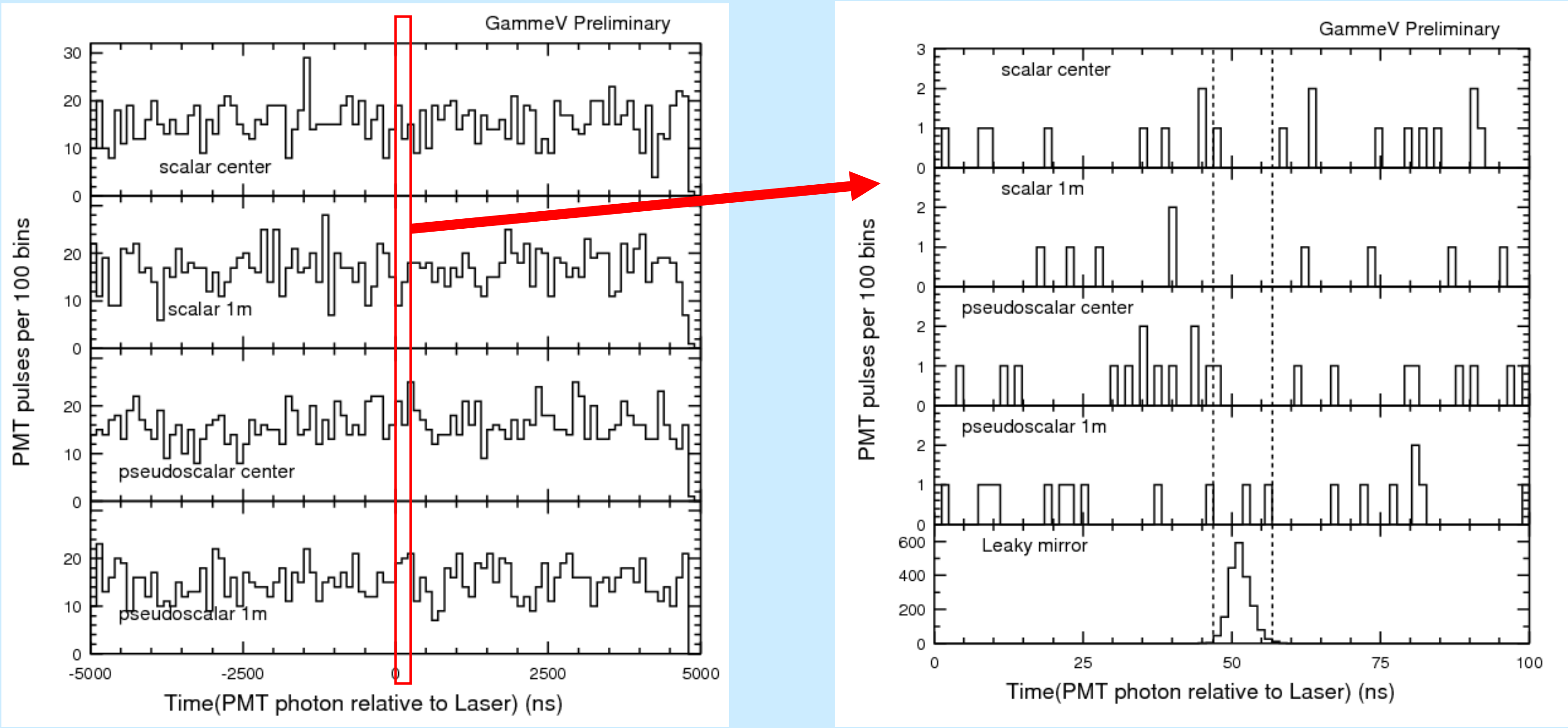


GammeV Procedure

- 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

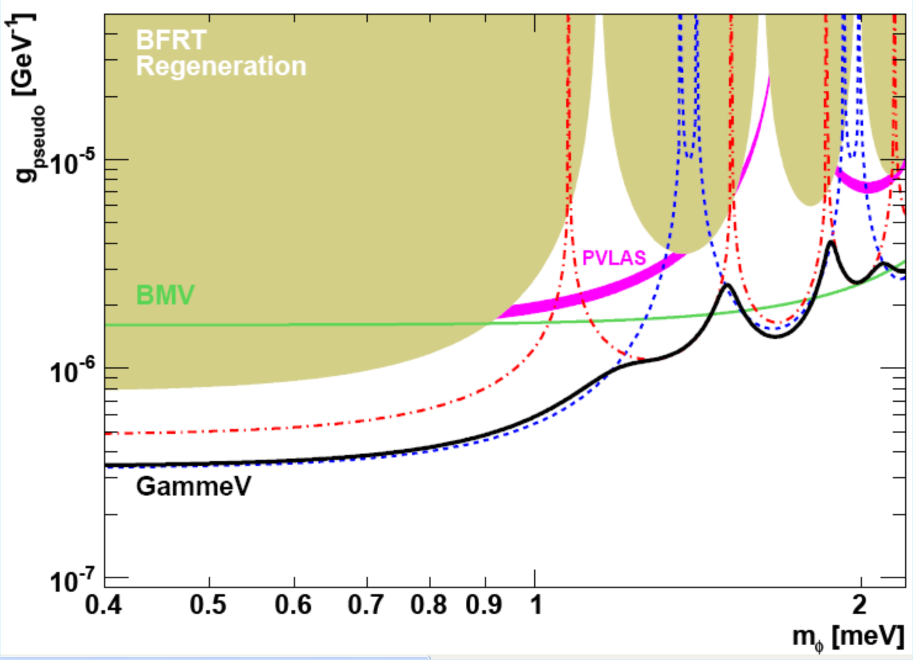
Spin	Position	# Laser pulse	# photon / pulse	Expected Background	Signal Candidates
Scalar	Center	1.34 M	0.41e18	1.56±0.04	1
Scalar	1 m	1.47M	0.38e18	1.67±0.04	0
Pseudo	Center	1.43M	0.41e18	1.59±0.04	1
Pseudo	1m	1.47M	0.42e18	1.50±0.04	2



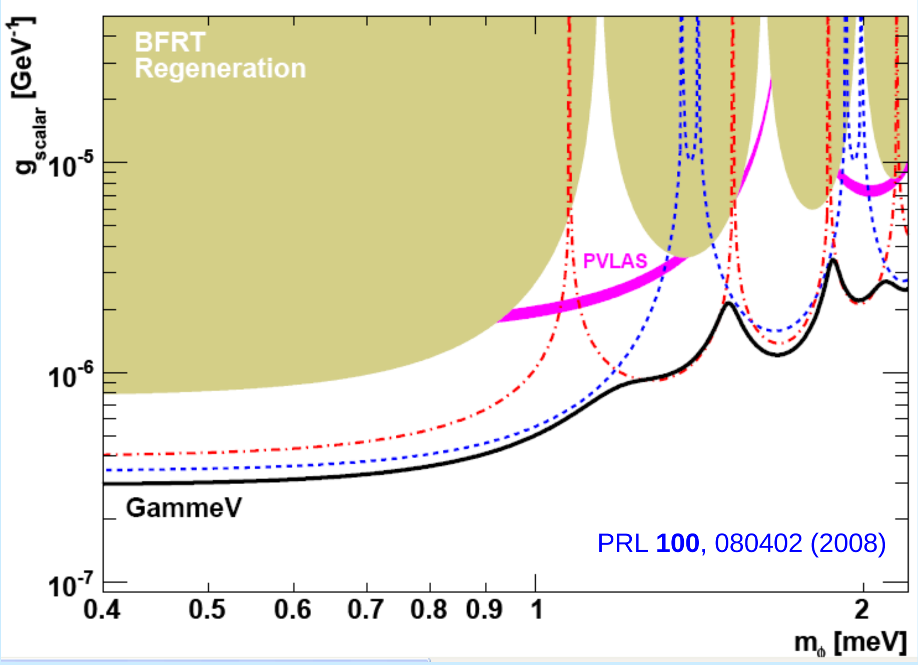
GammeV Limits

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

Pseudoscalar



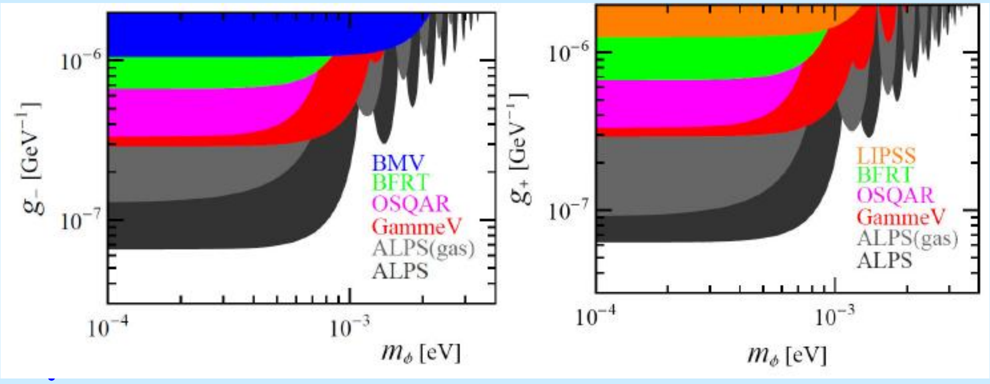
Scalar



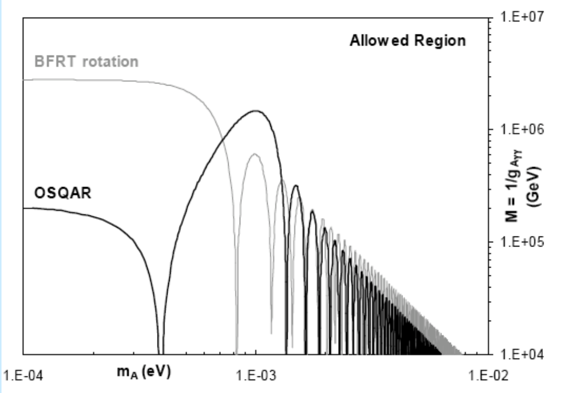
- Job is done. Limit generally improves slowly (4th root) vs. longer running time, or increased laser power, etc.

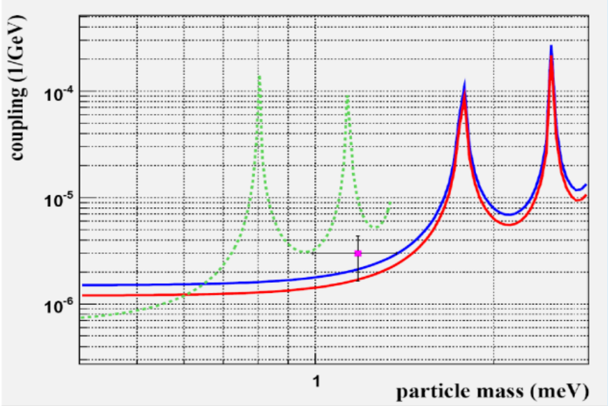
Other experiments

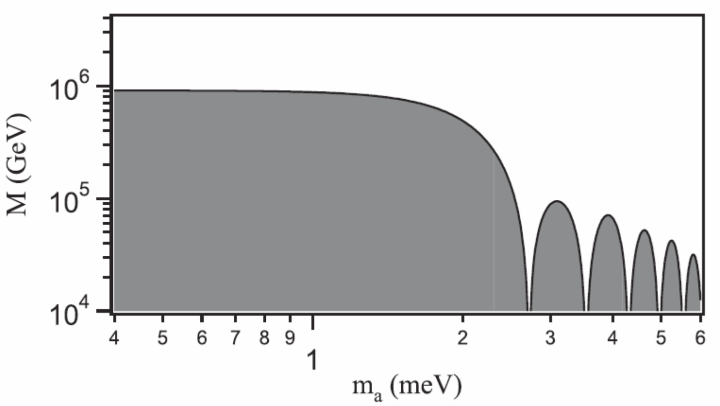
- 6th Patras Workshop on Axions, WIMPs, and WISPs
  - Zurich, July 2010
  - See axion-wimp.desy.de
- No evidence of axion-like particles using different configurations of LSW technique.



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







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

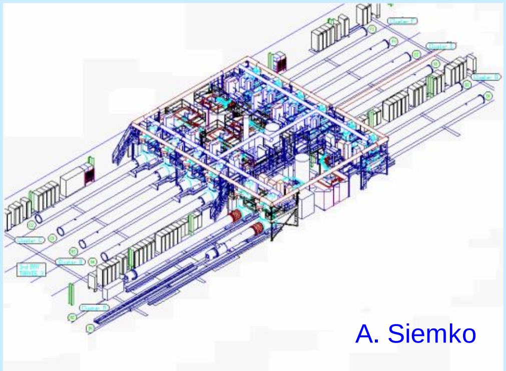
LIPSS scalar only
PRL **101**, 120401(2008)

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

GammeV

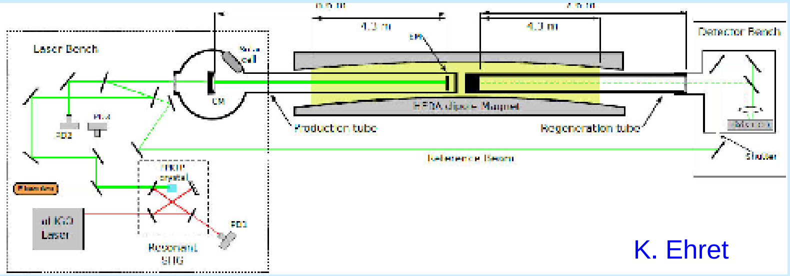
Other experiments

- OSQAR (CERN)
  - QED birefringence
  - LSW with two LHC magnets and future improvements with lasers and optical cavities
- ALPS (DESY)
  - Improvements using optical cavities
  - Limits derived for other WISPS (weakly interacting sub-ev) particles
- LIPSS
  - μ-wave cavity (Yale)
  - Beam dump (JLAB)

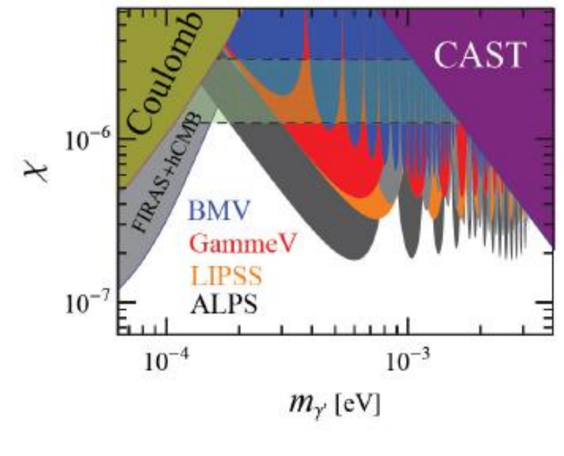


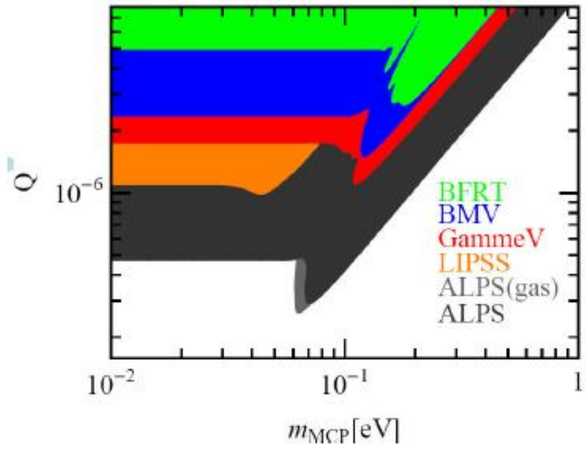
A. Siemko

Eventually with more Magnetic field length than two LHC magnets and employing optical cavities in a resonnant regeneration scheme, Sensitivity beyond CAST limits is posslible.



K. Ehret

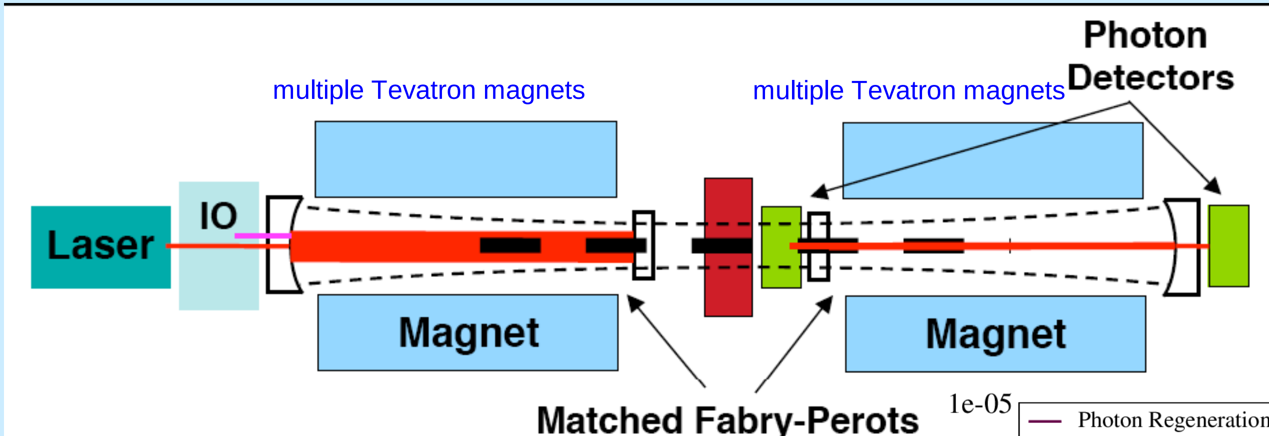




GammeV

Enhanced LSW

Resonantly enhanced axion-photon regeneration

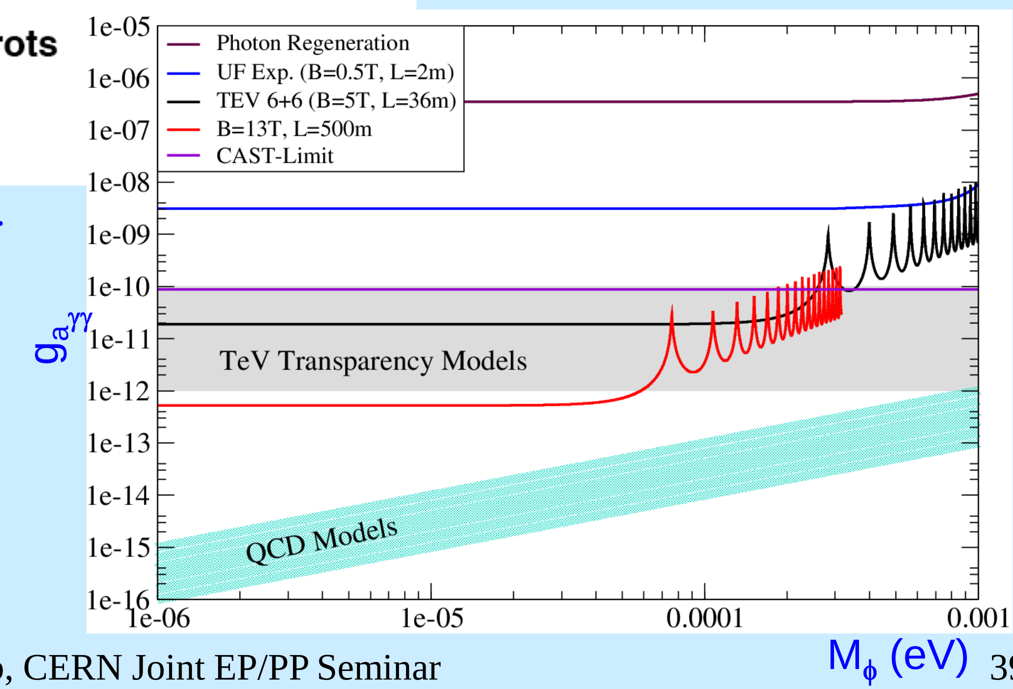


F. Hoogeveen and T. Ziegenhagen, Nucl. Phys. B **358**, 3 (1991)
Mueller, Sikivie, Tanner, van Bibber, Phys. Rev. D **80**, 072004 (2009)
Phys. Rev. Lett. **98**, 172002 (2007)

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

Possibility that this technique might exceed star / CAST limits.

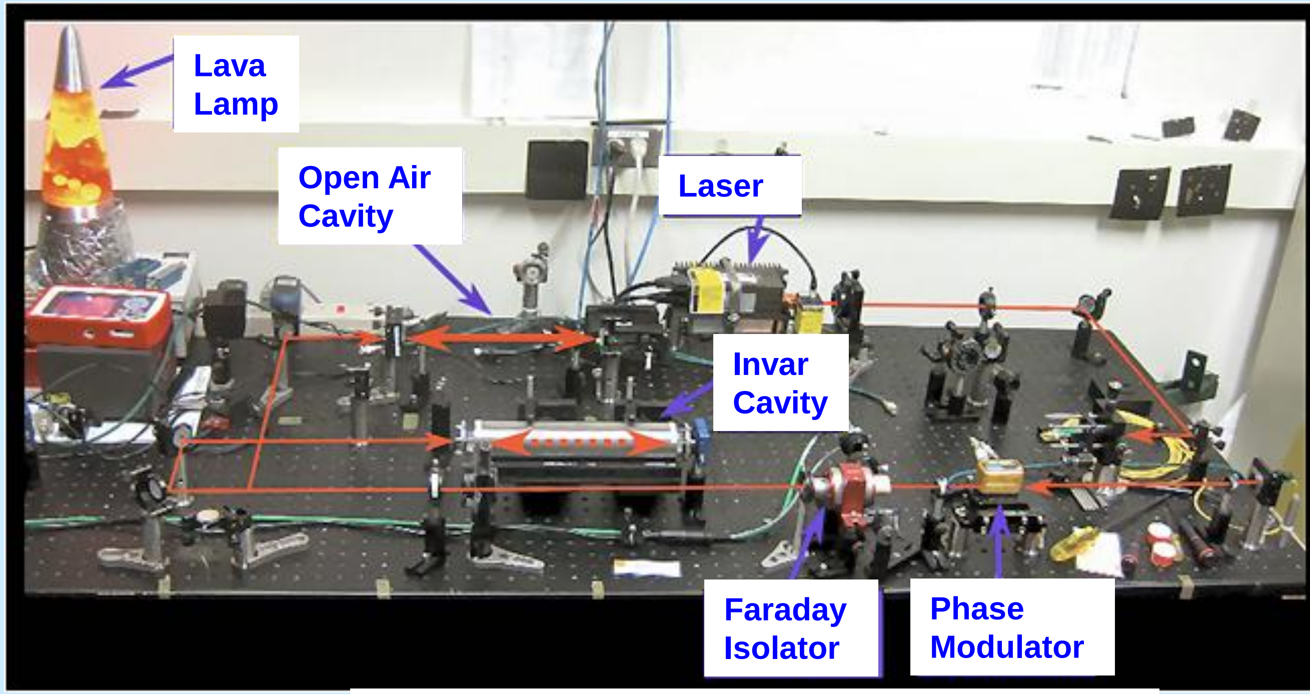
Hints that a coupling of 10^{-11} might be interesting from observations of unexpected high energy gamma rays that somehow propagate despite background IR photons.

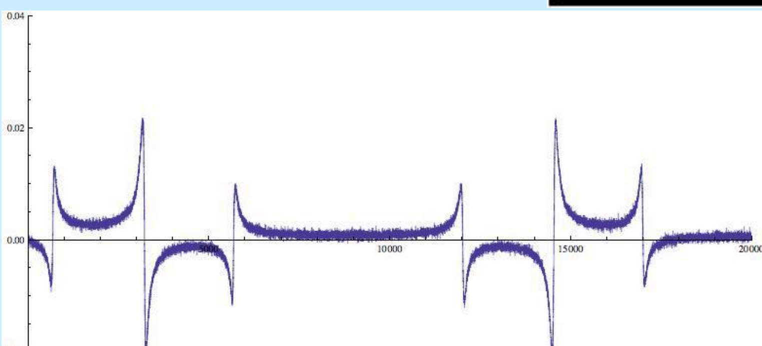


Bench top preparations

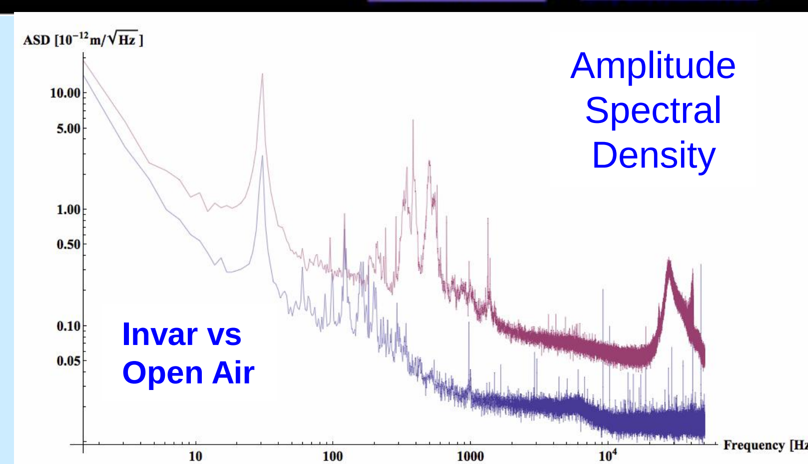
Study by Bobby Lanza,
grad student Univ. of Chicago

Invar optical cavity
(commercial mirrors)





PDH error signal used
to lock onto TEM_{00} mode



Amplitude
Spectral
Density

Chameleons

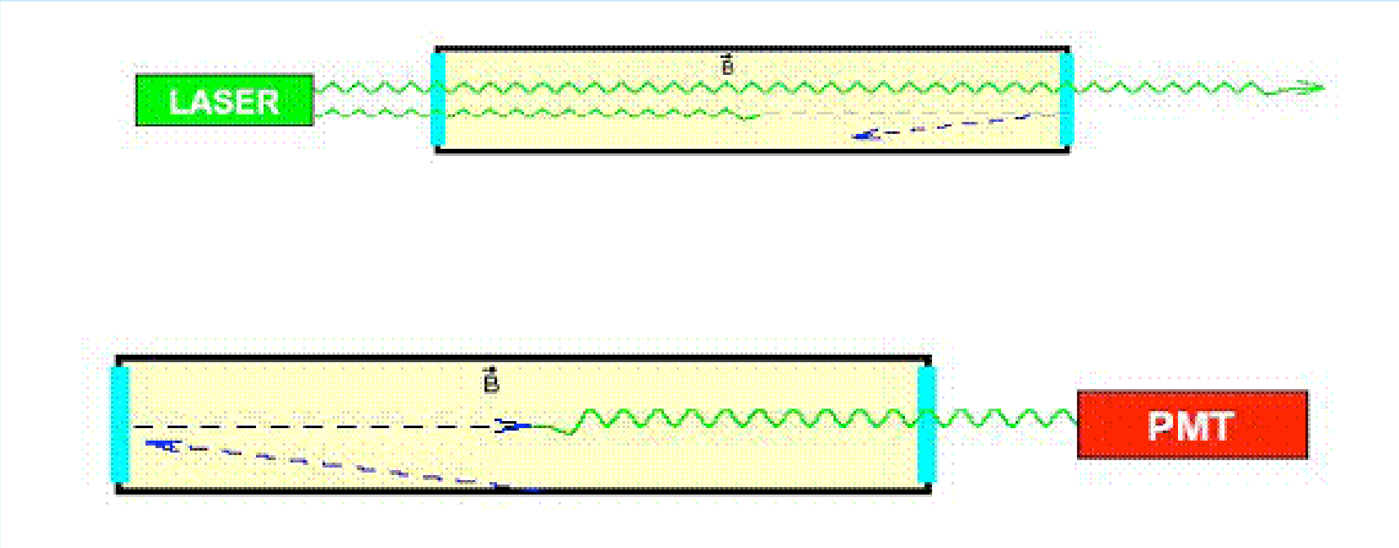
- A WISP with the property that its properties depend on its environment. In particular, a coupling to the stress energy tensor and a non-trivial potential result in unique properties such as a mass that depends on the ambient matter density: $m_{eff} \sim \rho^{\alpha}$.

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

- 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.

"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.

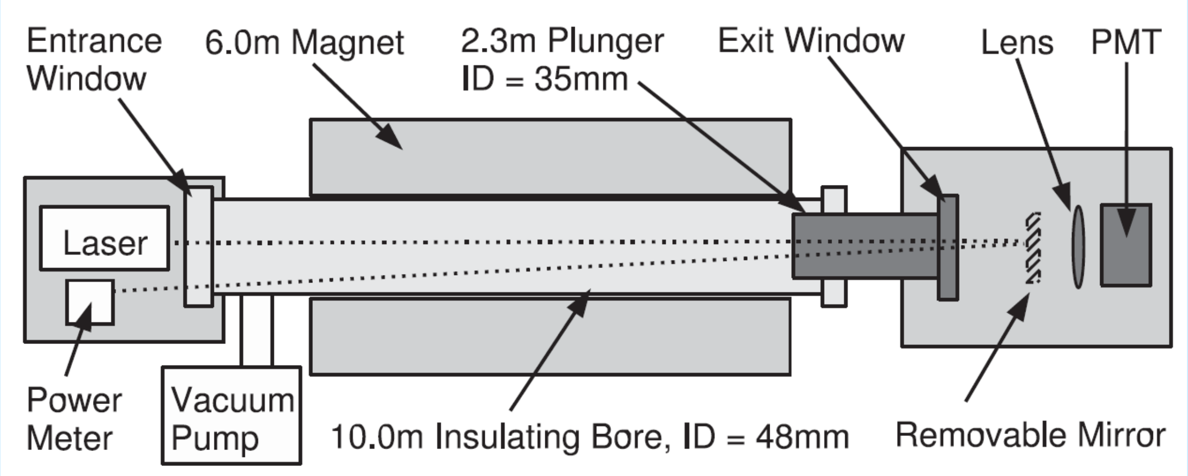


Chameleon Search

- **GammeV**

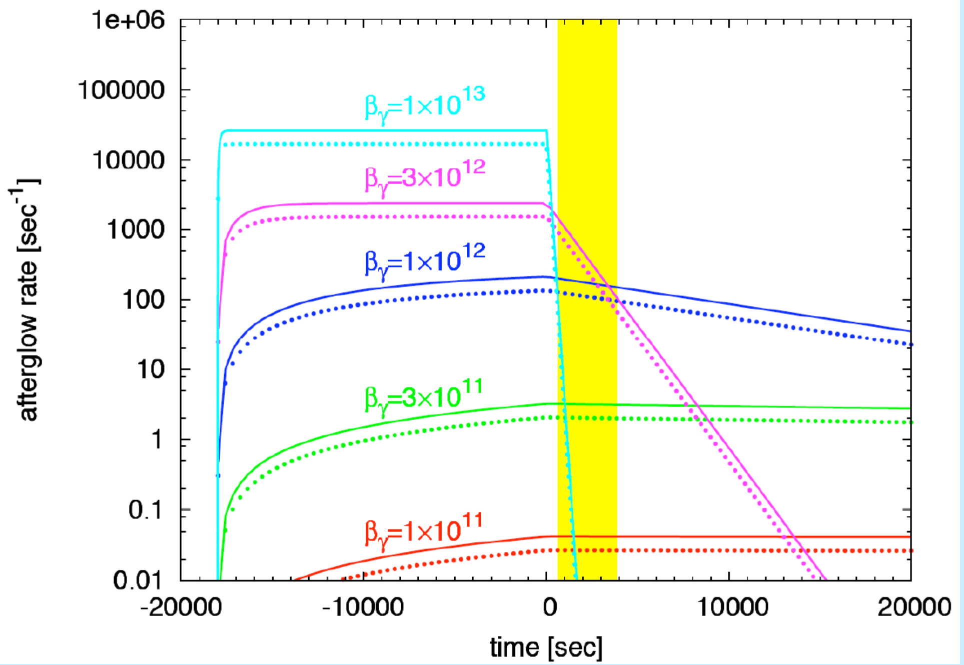
  ## Apparatus

  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.

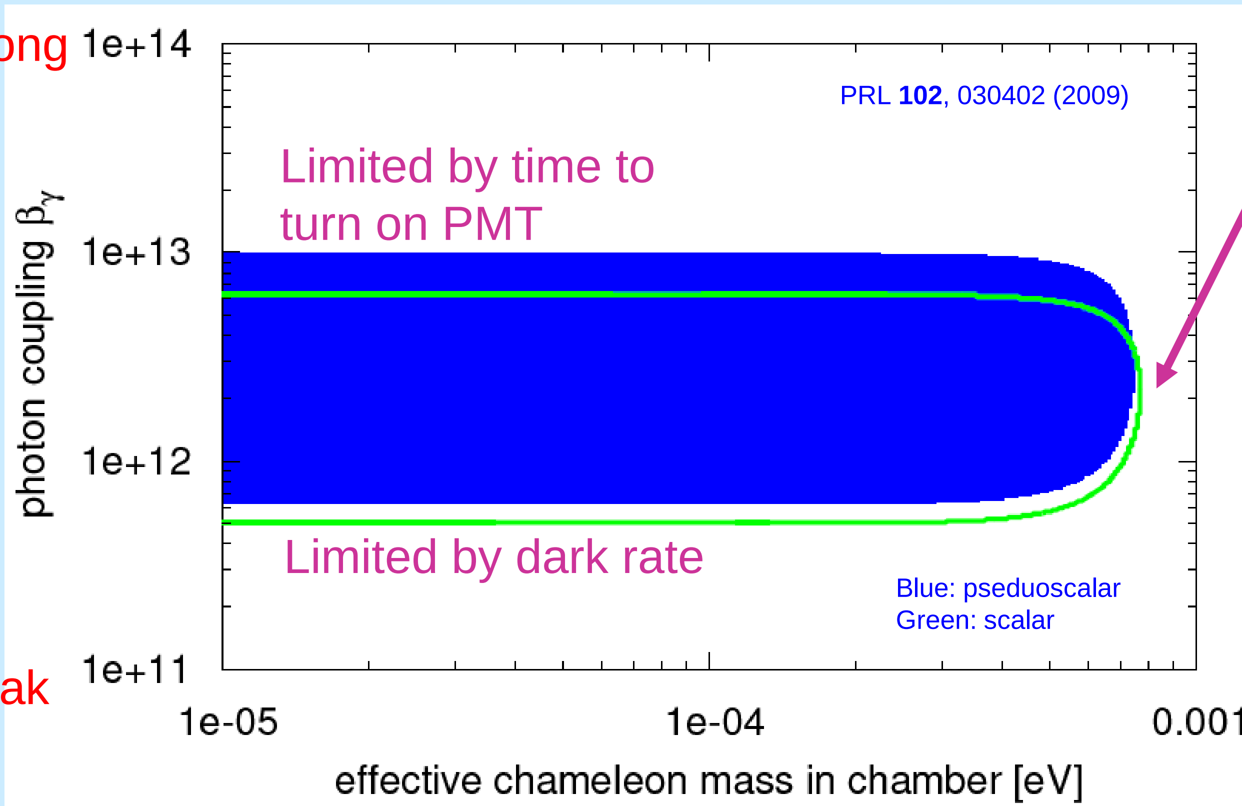


Chameleon Results

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

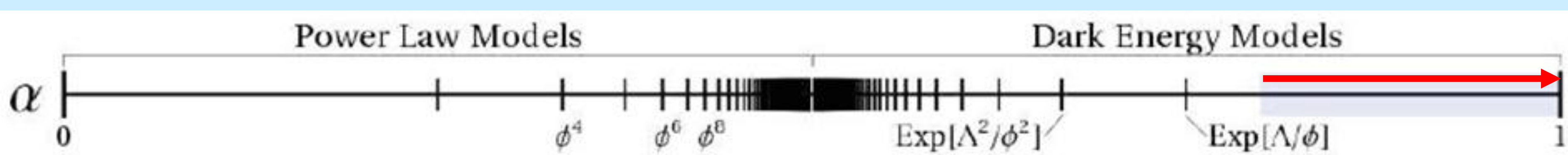
Strong

Weak



Reduced sensitivity at higher masses due to experimental configuration

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



New effort (2010)

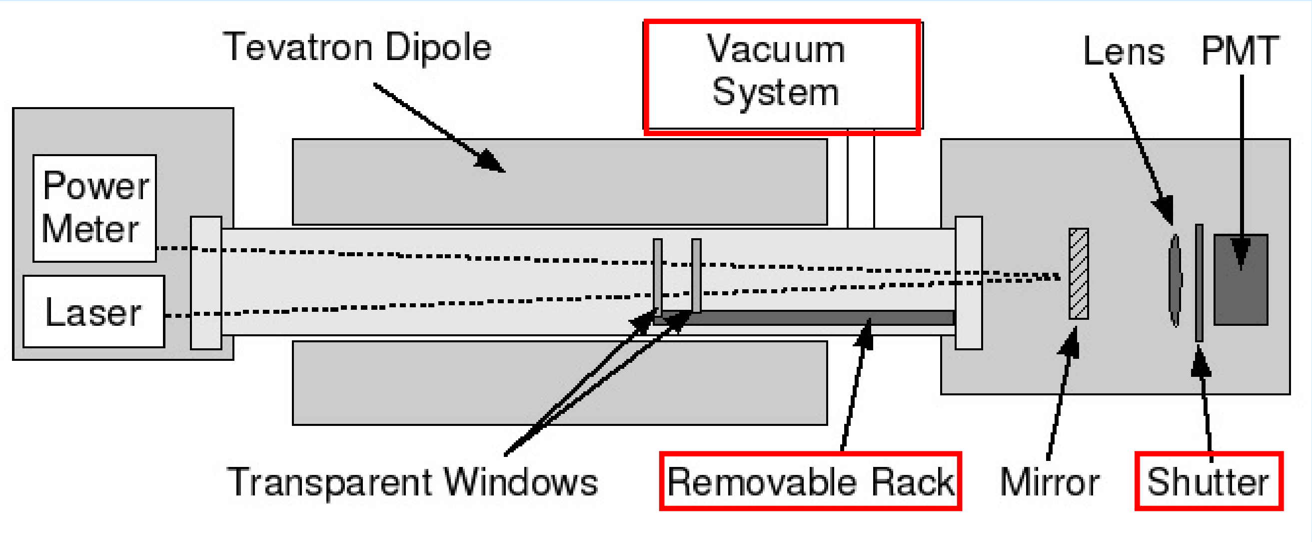
- GammeV – CHASE: Chameleon Afterglow Search

Improve vacuum (cryo pump) and monitoring.

Use a shutter to switch to PMT readout quickly.

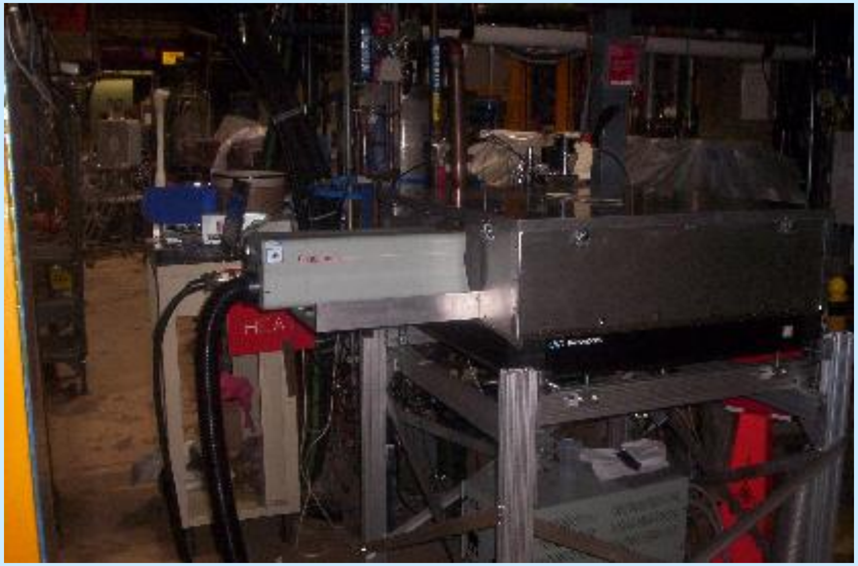
Use a run plan that with lower B fields in case the coupling is strong.

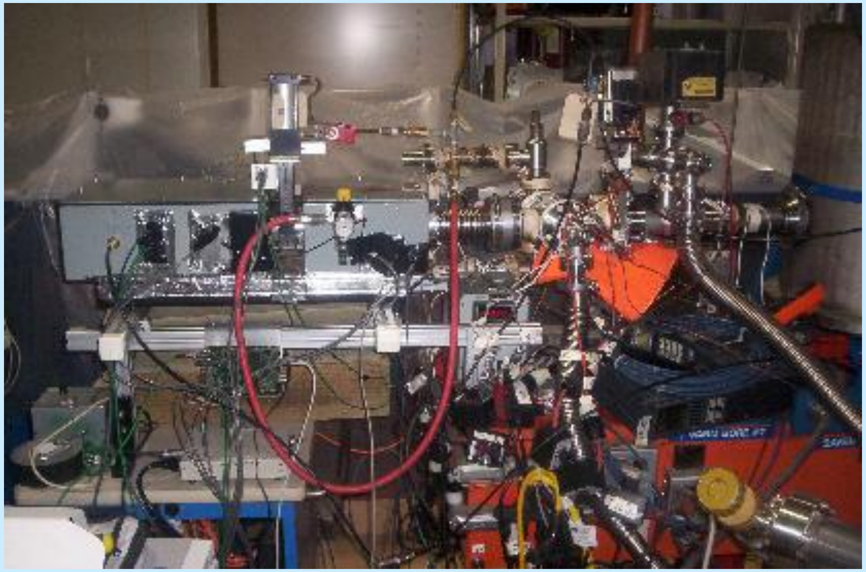
Use a lower noise PMT.



Employ the “dish rack” to effectively have 4.7m, 1m, 30cm magnetic field regions
-a bit of cleverness similar to the plunger idea to be initially sensitive to a wider range of chameleon masses.

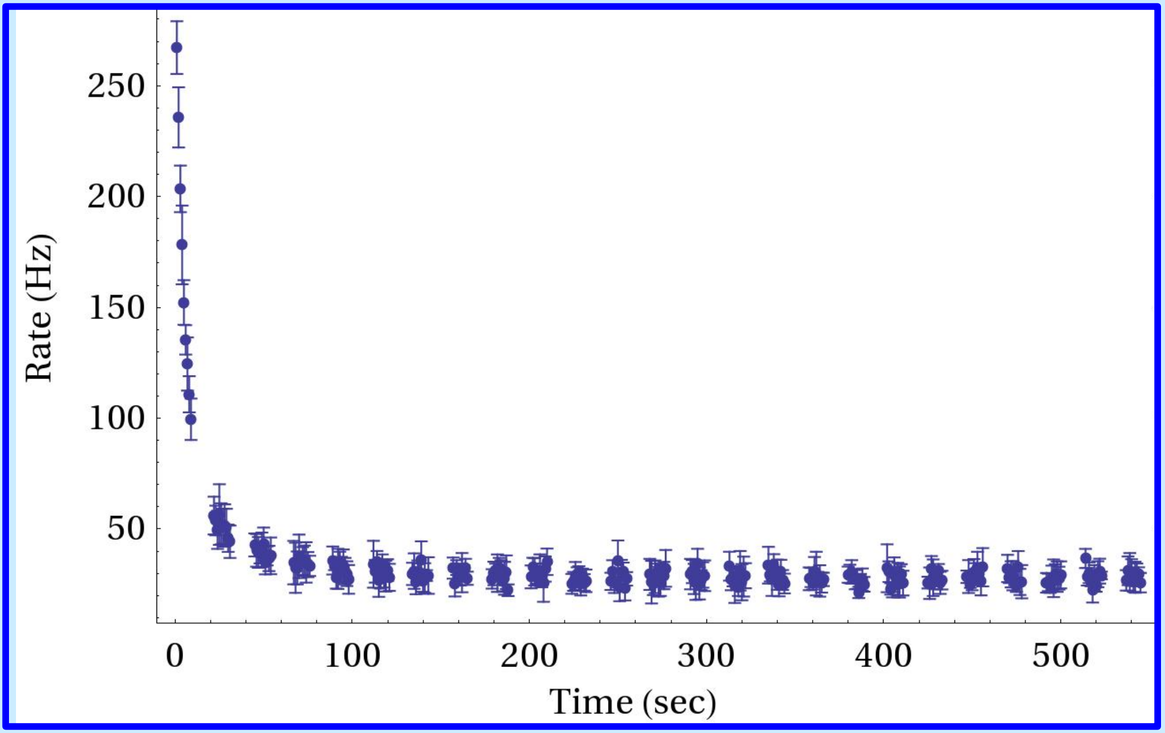
GammeV-CHASE

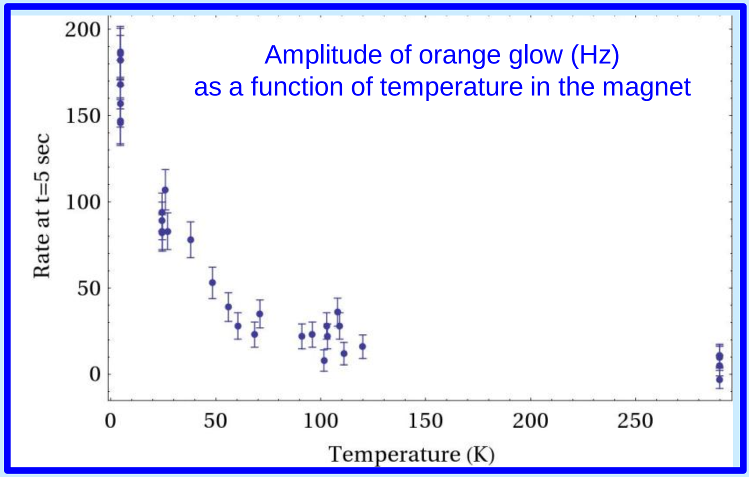




Two unexpected systematics

- About 1-2 Hz of photons from the ion pump
- An orange glow … a background (no B field dependence)

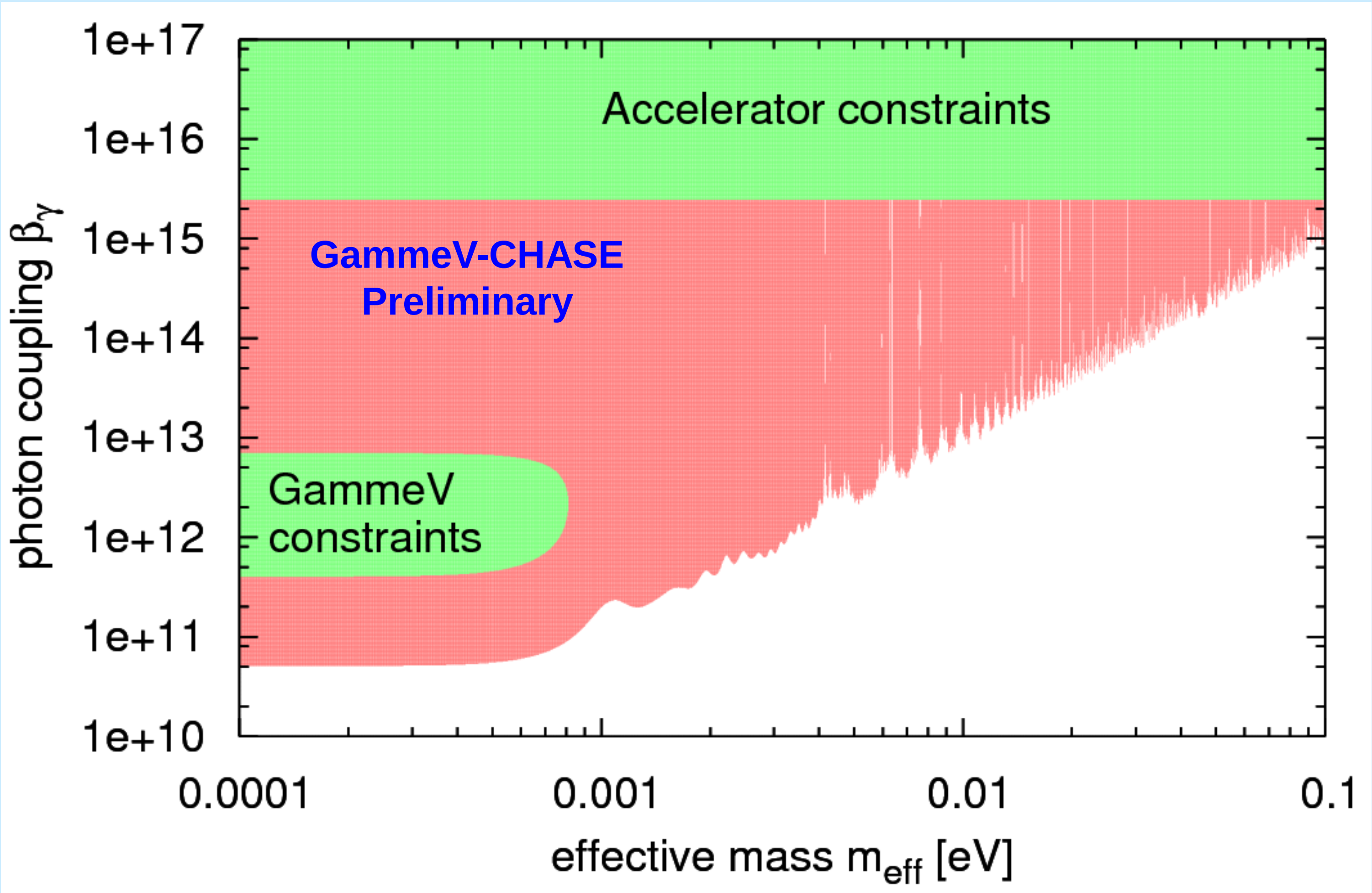




Afterglow rate has a strong temperature dependence

- Current hypothesis is that material freezes to internal windows or defects in the window phosphoresce – investigations continue

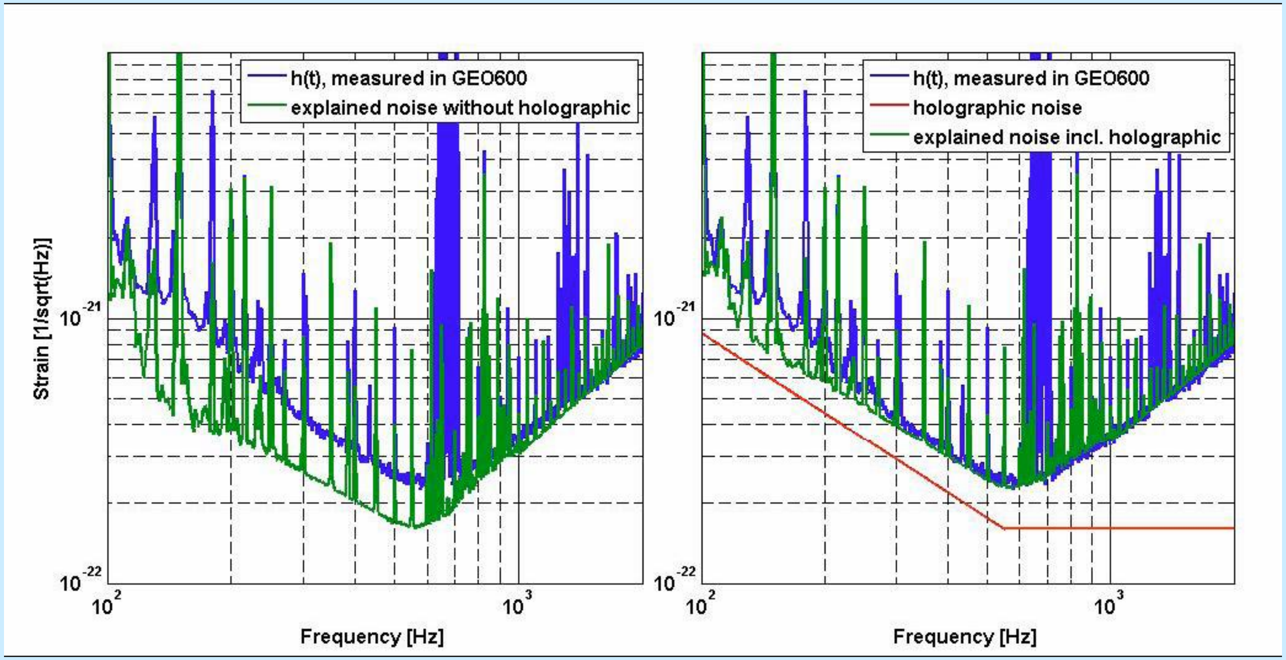
GammeV CHASE
Preliminary results



Preliminary results agree with design expectations:
A. Upadhye, J. Steffen, A. Weltman, Phys. Rev. D **81**, 015013 (2010)

And now for something completely different …

- Plans for R&D towards high finesse long optical cavity overlap with a theoretical idea from Craig Hogan …
  - Holographic noise: a new jitter of space time due to Planck scale effects
- A possible hint from GEO600 Gravity wave experiment

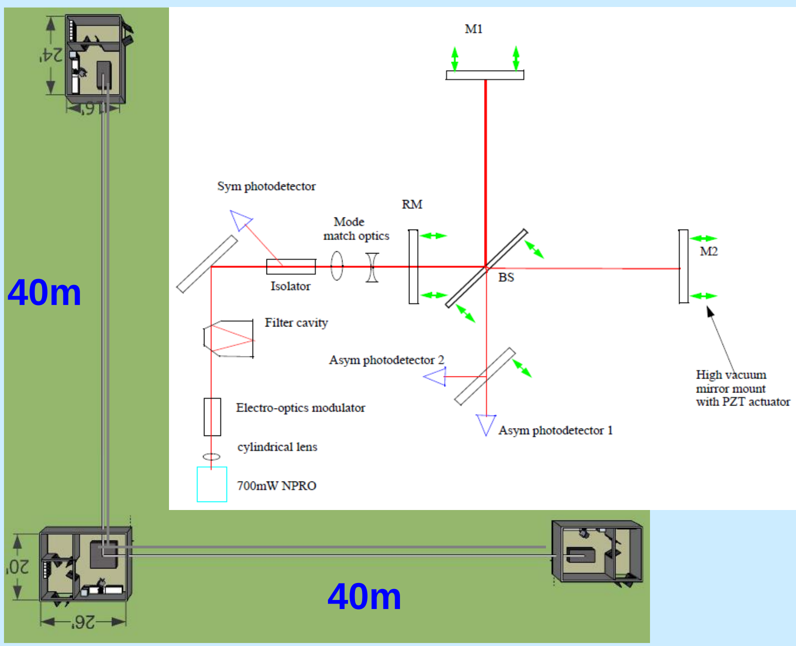


At f>600 Hz, a 0-parameter prediction invoking the expected holographic noise, explains nearly all of the “mystery noise.”

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.*



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

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

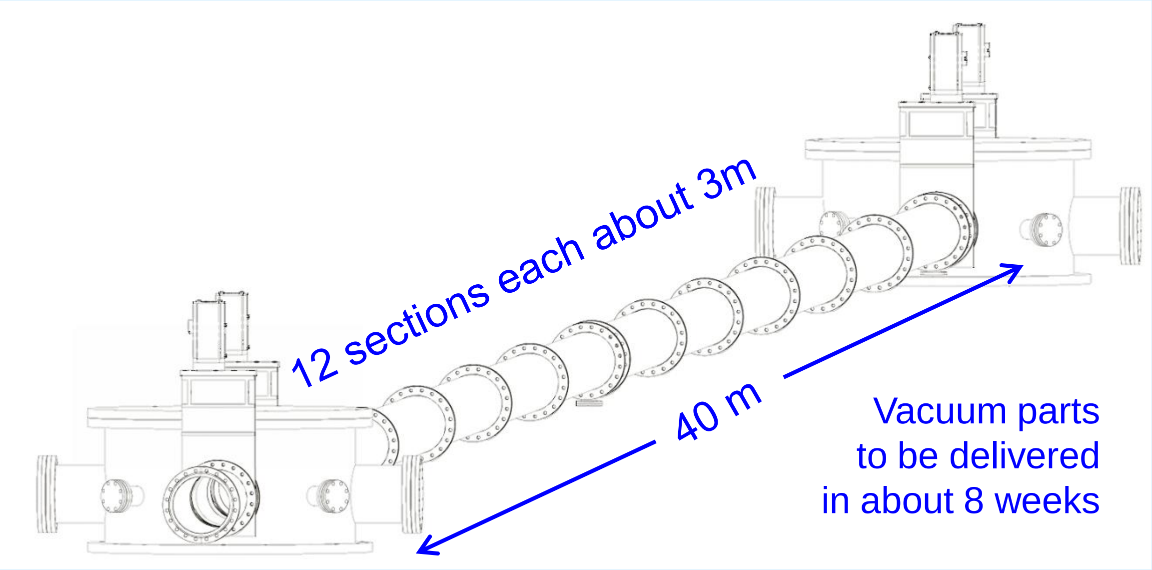
C. Hogan, "Holographic Noise in Interferometers"
http://arxiv.org/abs/0905.4803
C. Hogan, "Interferometers as Holographic Clocks"
http://arxiv.org/abs/1002.4480

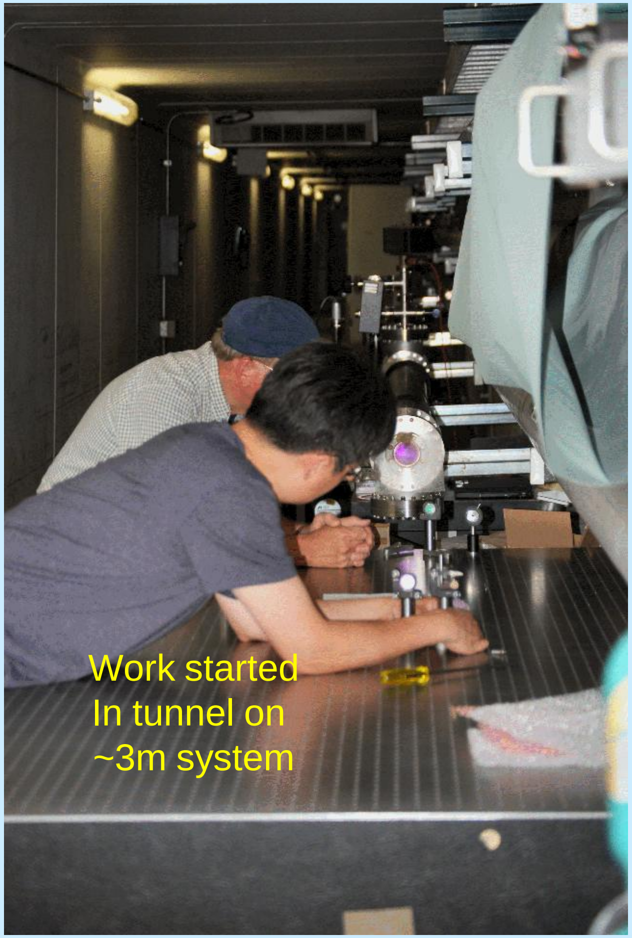
- *A new team including LIGO experts at MIT and Caltech are collaborating. Initial reviews at FNAL are positive.*

40m optical cavity R&D

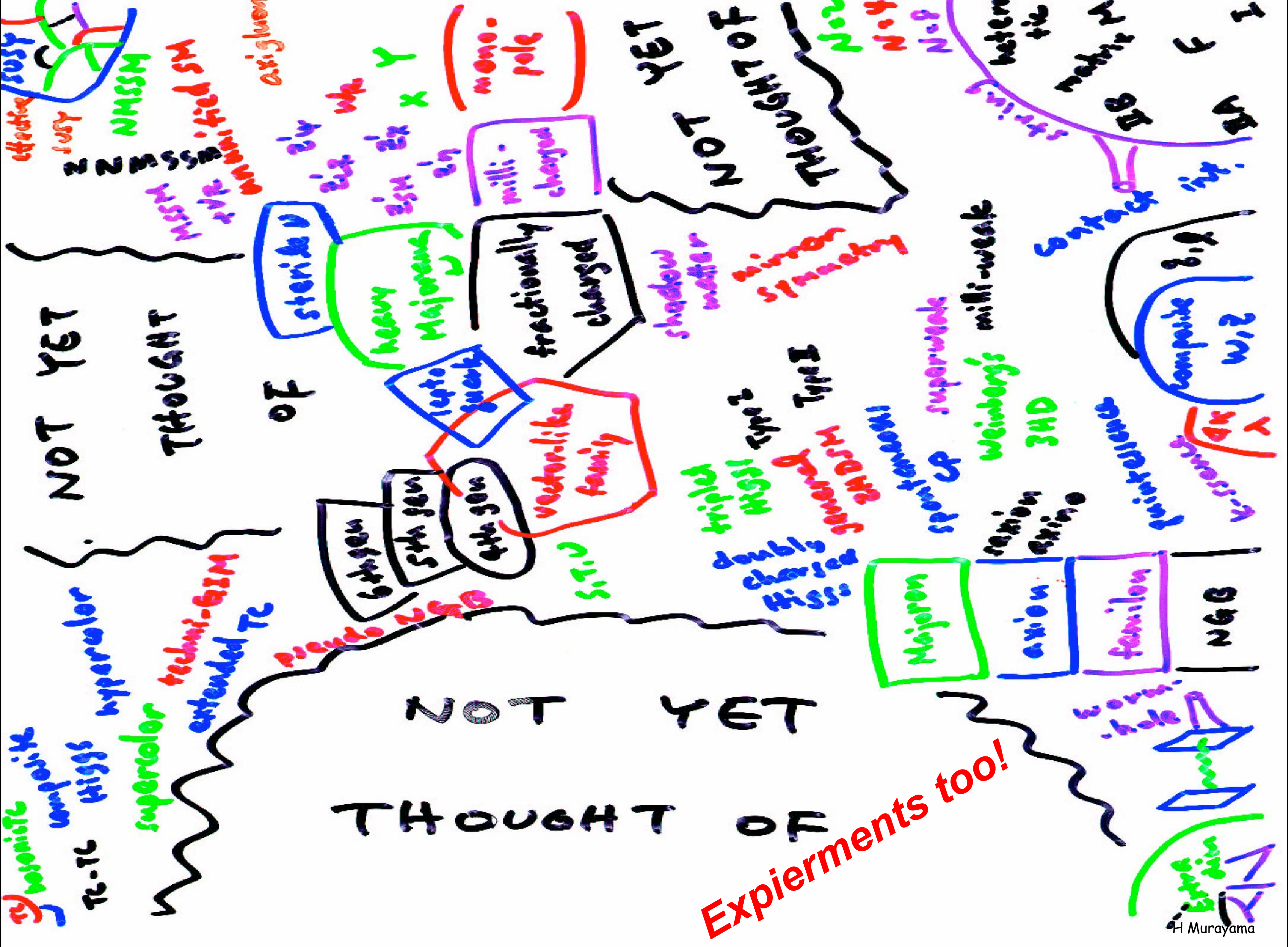
- Overlaps with holometer proposal and resonant axion-photon regeneration R&D

Holometer proposal presented Nov 2009 to Fermilab's Physics Advisory Committee
Positive response. Waiting for formal approval, grants or other funding to materialize.





- Fermilab has published results on axion-like particles and chameleons. New results on chameleons are presented.
- Next experiments are much more ambitious and we are starting to get experience with optical cavities and interferometers. New collaborators from gravitational wave experiments.
- 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.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effective SUSY
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MSSM
R-P
minimal unified SM
mono-pole
milli-charged
sterile ν
heavy Majorana ν
fractionally charged
shadow matter
mirror symmetry
milli-weak
contact int.
composite W,Z
leptoquark
vector-like family
4th gen
5th gen
6th gen
pseudo NGB
STU
triplet Higgs
doubly charged Higgs
type I
type II
generalized SUSY
spontaneous CP
superweak
Weinberg's 3HD
Majoron
axion
familon
NGB
axion
saxion
axino
worm-hole
brane
extra dim.
composite Higgs
TC-TC
supercolor
hypercolor
techni-GIM
extended TC
Expierments too!
H Murayama