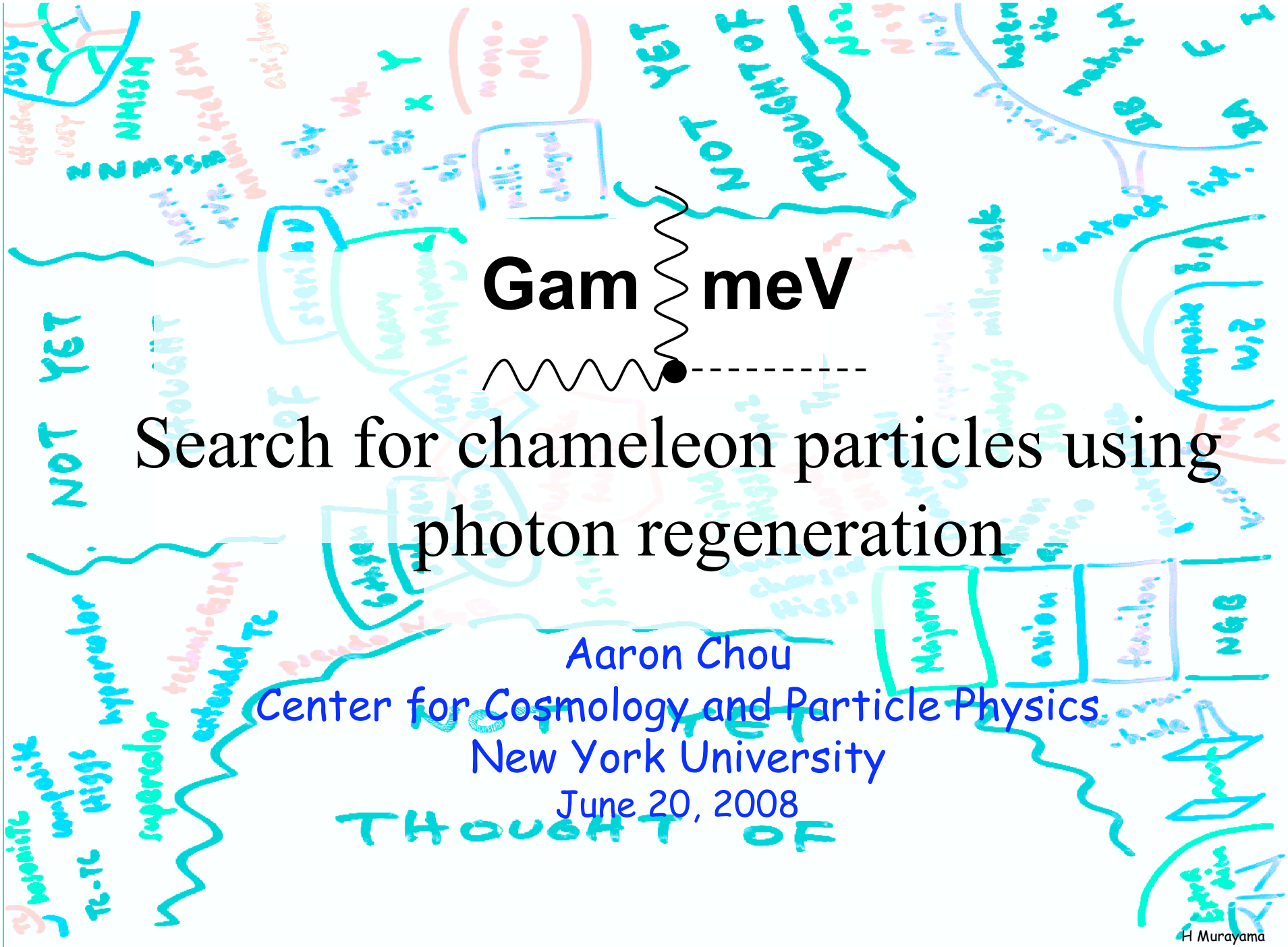


Search for chameleon particles using photon regeneration

Aaron Chou
Center for Cosmology and Particle Physics
New York University

June 20, 2008

H Murayama

GammeV

A search for chameleon particles using a photon regeneration technique

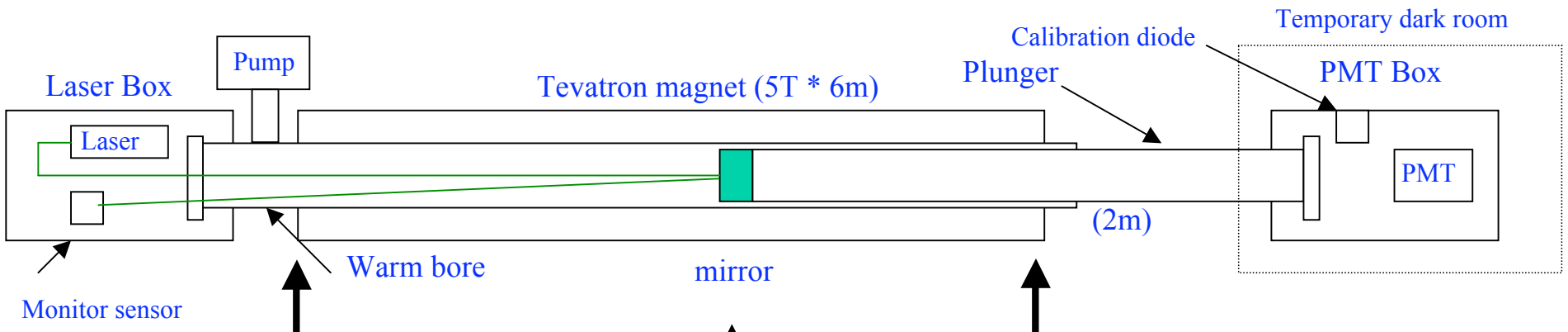
A. S. Chou[1], W. Wester[2], A. Baumbaugh[2], H. R. Gustafson[3], Y. Irizarry-Valle[2], P. O. Mazur[2], J. H. Steffen[2], R. Tomlin[2], A. Upadhye[4], A. Weltman[5], X. Yang[2], and J. Yoo[2]
[1]*Center for Cosmology and Particle Physics, New York University, 4 Washington Place, New York, NY 10003*
[2]*Fermi National Accelerator Laboratory, PO Box 500, Batavia, IL 60510*
[3]*Department of Physics, University of Michigan, 450 Church St, Ann Arbor, MI 48109*
[4]*Kavli Institute for Cosmological Physics, University of Chicago, IL 60637*
[5]*Department of Applied Mathematics and Theoretical Physics, Centre for Mathematical Sciences, Cambridge CB2 0WA, United Kingdon*

arXiv:0806.2423 [hep-ex]

12 person team including 1 summer student,
5 postdocs, 2 accelerator / laser experts,
4 experimentalists
PLUS technical support at FNAL

Nov 2006 : Initial discussion and design (Aaron Chou, William Wester)
Apr 2007 : Review and approval from Fermilab ($30K budget!)
May 2007 : Discussion with chameleon experts A.Upadhye, A.Weltman
Jun-July 2007 : Commissioning
Aug-Sept 2007 : Axion data-taking/analysis
Oct 2007 : Chameleon data-taking
Nov-present : Chameleon analysis

GammeV axion search experiment:
Designed to test the apparent signal seen by PVLAS



Non-adiabatic entry into the B-field projects the photon flavor state into a superposition of mass eigenstates which begin flavor oscillations

Non-adiabatic exit from the B-field projects instantaneous superposition back into flavor states. Regenerated photons are detected by the PMT.

A mirror projects the transmitted wave into pure axion flavor. This transmitted superposition of mass eigenstates again begins oscillations in the region beyond the mirror.

How can WISPS evade the GammeV axion search?

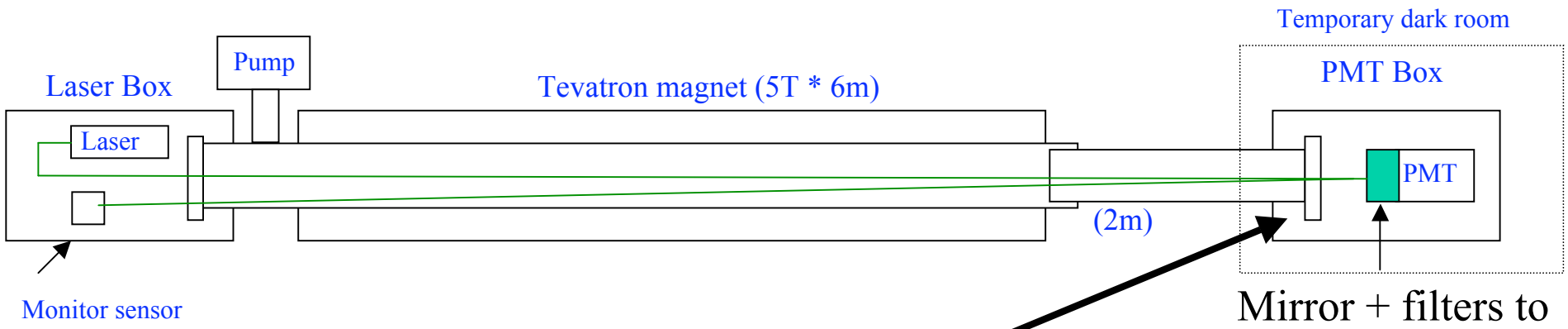
- "Shining light through a wall" only works if the intermediate particles are weakly-interacting so that ***they pass through the wall***.
  - The plunger mirror then projects the reflected wave into a photon state and the transmitted wave into an scalar state.

- If the new scalars have strong matter effects such that the effective mass in the 1 g/cm^3 material of the mirror is greater than the total particle energy, then ***they reflect just like photons***.
  - The plunger mirror makes no wavefunction reduction, and both components of the wave are reflected --> **No signal in GammeV!**

  - **Instead, vacuum windows may be used as quantum measurement devices which project the reflected wave into scalars and the transmitted wave into photons.**
  - **Reflective particles can be "trapped in a jar."**

(GammeV, M.Ahlers et.al, H.Gies, et.al)

GammeV chameleon search configuration: Use window as QMD.



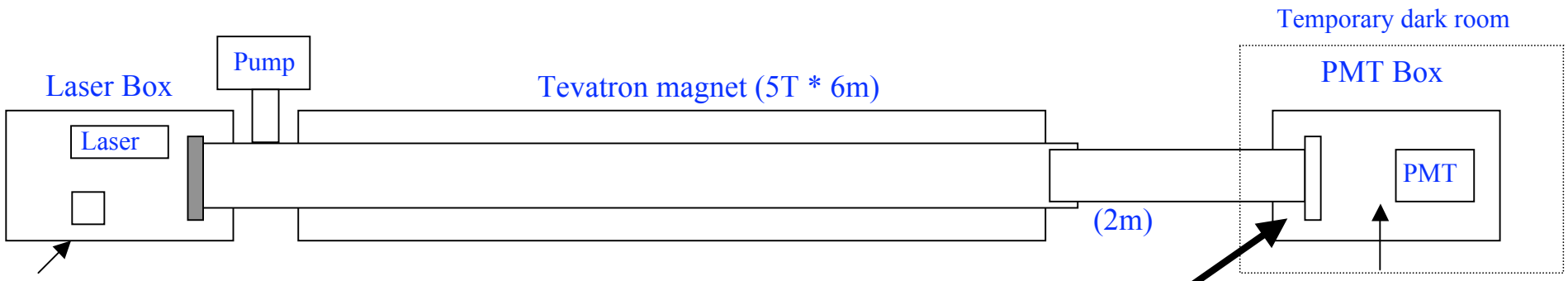
Mirror + filters to protect PMT. Reflected beam generates more chameleons on its 2nd pass through the magnet.

A vacuum window (outside of the magnetic field) projects the transmitted wave into pure photon flavor and the reflected wave into pure chameleon flavor.

A relativistic gas of chameleons builds up in the chamber after integrating for ~5h.

The direction vectors are isotropized by many bounces. Energy loss due to bounces is negligible
--> gas is monochromatic with energy ω.

GammeV chameleon search configuration: Use window as QMD.



Turn off laser and block entry window with foil.

Remove mirror + Turn on PMT

View the monochromatic afterglow light as the isotropized chameleon gas converts back into photons.
Many assumptions involved.

GammeV

Assumptions:

- Chameleon self-scattering is negligible
  - Elastic 2->2 scattering gives a thermal distribution with T~ ω.
  - Inelastic 2->3, 2->4, etc, converts kinetic energy into mass, resulting in a thermal distribution with T~m_{eff}.
    - This microwave light is not detectable with a PMT.
  - This assumption is non-trivial: V= Λ^{4+n}/ϕ^n potentials do not give perturbative results if $\langle\phi\rangle \sim \Lambda$.

- Chameleons do not decay to lighter particles on the time scales of interest.

- Chameleons do not "stick" to the inner surfaces of the chamber.
  - In principle, could have new short range attractive forces.

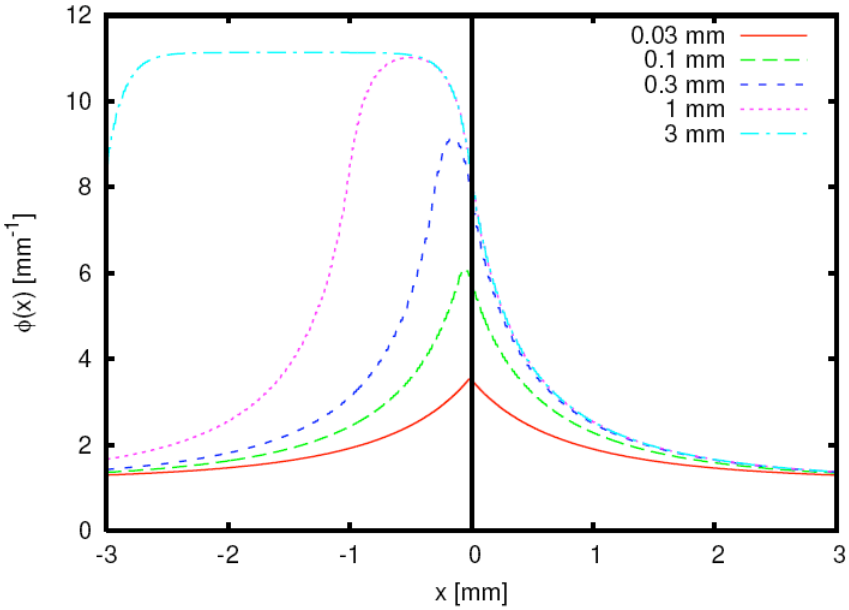
GammeV

Goals:

- Generic action: $$S = \int d^4x \Big(-\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - \frac{e^{\phi/M_\gamma}}{4}F^{\mu\nu}F_{\mu\nu} + \mathcal{L}_{\rm m}(e^{2\phi/M_{\rm m}}g_{\mu\nu}, \psi^i_{\rm m})\Big)$$
- Model is specified by $$V_{\rm eff}(\phi,\vec{x}) = V(\phi) + e^{\beta_{\rm m}\phi/M_{\rm Pl}}\rho_{\rm m}(\vec{x}) + e^{\beta_\gamma\phi/M_{\rm Pl}}\rho_\gamma(\vec{x})$$
- In the simplest models, this predicts: $m_{\rm eff}(\rho) \sim \rho^\alpha$
- The physical parameters of the apparatus define a region of validity in α, m_0 (defined at an arbitrary density).
  - Chameleons are confined --> lower bound on m_0.
  - Chameleon-photon oscillations must be coherent
    - --> upper bound on m_0 depends on assumed α.
- For this region of validity, measure β_γ

Chameleon "matter effects"

- By considering classical solution $\langle\phi\rangle(x)$, of the Klein-Gordon equation $+V(\langle\phi\rangle)$ with boundary condition $\langle\phi\rangle$=const deep inside a region of higher density, one obtains $m^2(x)=\mathrm{sqrt}(d^2V/d\phi^2)|_{\phi=\langle\phi\rangle(x)}$.



$\langle\phi\rangle(x)$, x=direction transverse to an infinite plane.

A.Upadhye, S.Gubser, J.Khoury, 2006

- The resulting mass as a function of distance r is generically:
- $m = m_0/(1+a*m_0*(r-r_0))$ where a is O(1).

- Far from the interface, the mass becomes m~1/r. This makes a local potential well inside the chamber which **traps chameleons in a jar**!

The location of the window matters!

- If the windows are placed inside the magnetic field region, then as the waves approach the window, the chameleon mass increases and the mixing angle decreases: $\theta_{eff} \sim \beta_\gamma B/(M_{pl}\, m_{eff}^2)$

- The quantum measurement takes place near the end of this Landau-Zener transition when the chameleons stop, and the photons pass through the window.
  - The measurement is made at very small θ_{eff}!

- GammeV windows are therefore placed safely outside of the B field region to measure the full θ_{eff} (in the vacuum, well away from the walls) as it is projected out during the non-adiabatic exit from the B field.
  - **Magnetic baseline is therefore fixed to the magnet length.**
  - Small regions of inefficiency occur when a trajectory goes near a side wall just as it exits the B field, resulting in a small projected θ_{eff}.

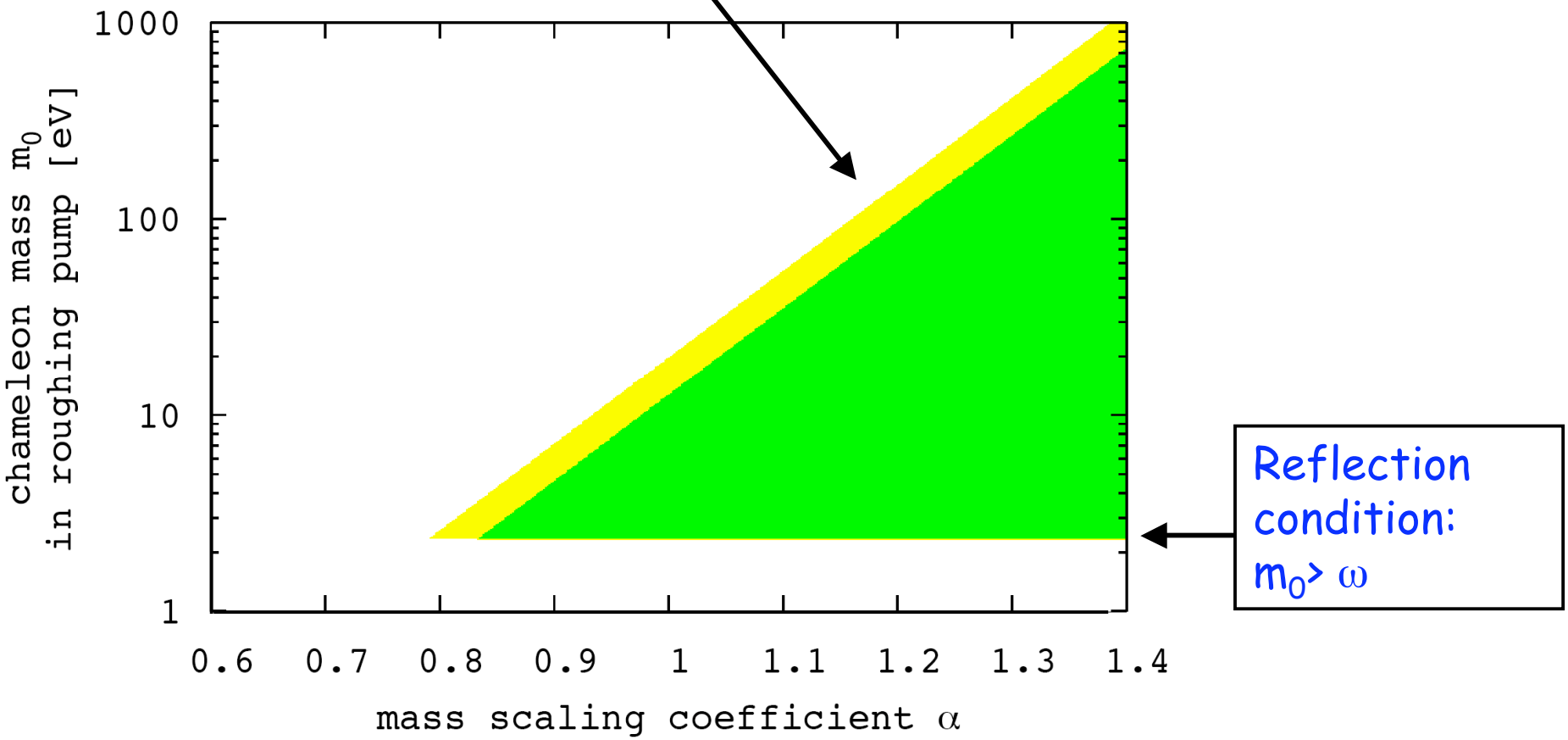
What models can we test?

- Chameleons must bounce on all solid surfaces (ρ ~ 1g/cm3).
- Need a good vacuum to maximize the photon phase velocity, and minimize the chameleon phase velocity (by minimizing m_{eff}).
- We used a roughing pump to get to P=2e-3 Torr, followed by a turbomolecular pump to get to P=1e-7 Torr.
  - Unfortunately, we failed to recognize that the positive displacement forepump could also "scoop out" the chameleon gas, and eject it into the room air.
- The most restrictive reflection condition is therefore that the chameleons reflect from the poor vacuum region between the two pumps.

- Using: $m_{eff} = m_0(P/2e\text{-}3\ Torr)^{\alpha}$
  - Reflection condition: $m_0 = m_{eff}(P=2e\text{-}3) > \omega$.
  - Coherent oscillations: $m_{eff}(P=1e\text{-}7\ Torr) < sqrt(4\pi\ \omega/L)$
    - For any fixed alpha, this gives an upper bound on m_0.

Example of regime of validity

Coherent oscillation condition (assuming m_{eff} dominated by matter coupling): $m_0 < \sim \mathrm{sqrt}(4\pi\,\omega/L)(P_{rough}/P_{chamber})^a$



Reflection condition: $m_0 > \omega$

Brax,et.al, PVLAS dark energy model

Signals we can see

- Afterglow must be:
  - 1) Weak enough so that the entire chameleon population does not decay faster than the few minutes it takes to uncover the PMT and seal the laser box.
  - 2) Strong enough that we can distinguish it from PMT dark noise.

- However, the model-dependent phase shift prevents us from making model-independent computations of the afterglow rate.

Phase shifts on reflection

- Due to the increase in mass as the chameleon flavor wavepacket approaches the wall
  - The group velocity decreases (but the delay of order 1 wavelength is much smaller than the correlation length of the laser, pulse length 5ns)
  - The phase velocity increases to become even more superluminal.
- **Because the photon phase velocity remains constant, an O(1) phase develops between the chameleon and photon waves in the flavor basis.** (Brax, et.al, Phys.Rev.D76:085010,2007)

- This model-dependent phase can affect the coherence of the oscillation as it continues after the bounce.
  - If walls are perfectly reflective, and phase=0, then bouncing trajectories can coherently build up photon amplitude, just like non-bouncing trajectories. If phase !=0, then the afterglow from bouncing trajectories is weaker.

To set extremely conservative model-independent limits

- 1) Overpredict the afterglow rate when estimating how fast the signal decays.
  - At large coupling, if there is any possibility the signal could have decayed before unmasking the PMT, then set no limit.
    - Assume all bouncing trajectories are maximally effective at producing escaping photons.
  - **Gives upper boundary on excluded region.**

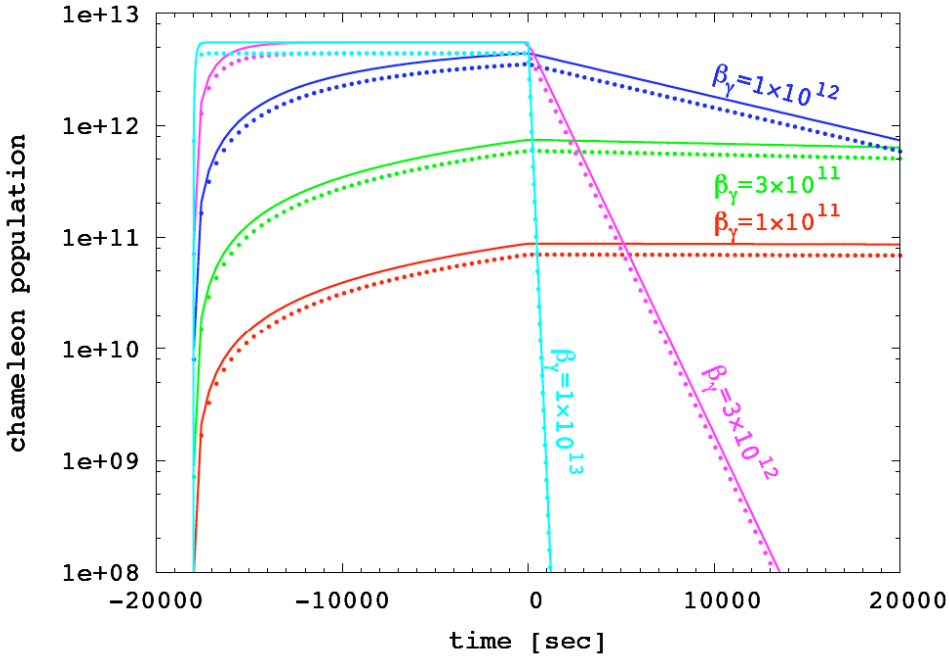
- 2) Underpredict the afterglow rate when estimating how strong an undecayed signal is when we are measuring it.
  - At small coupling, pretend that there is no contribution from bouncing trajectories, and predict the signal from only straight-through trajectories.
  - This is the minimum possible signal for a given coupling, so if we do not see it, then that coupling can be safely ruled out.
  - **Gives lower boundary on excluded region.**

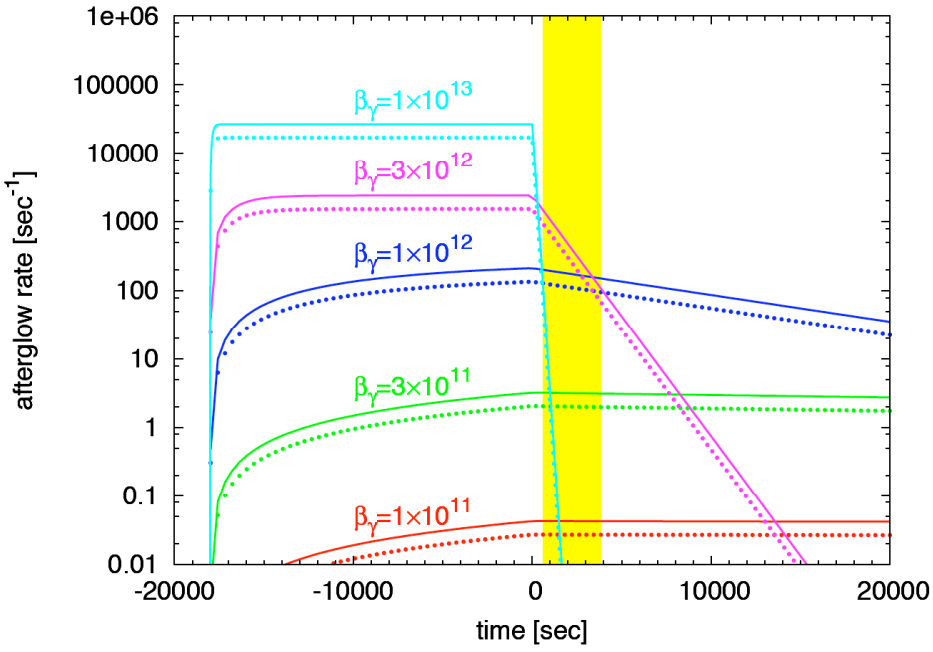
Predicted population and afterglow rates including all efficiencies

$$N_\phi^{(\max)} = F_\gamma \mathcal{P}_{\rm pr} \Gamma_{\rm dec}^{-1} (1 - e^{-\Gamma_{\rm dec}\tau_{\rm pr}})$$

saturates at 3.6×10^{12}

Solid: m_{eff}=1e-4 eV, Dotted: m_{eff}=5e-4 eV





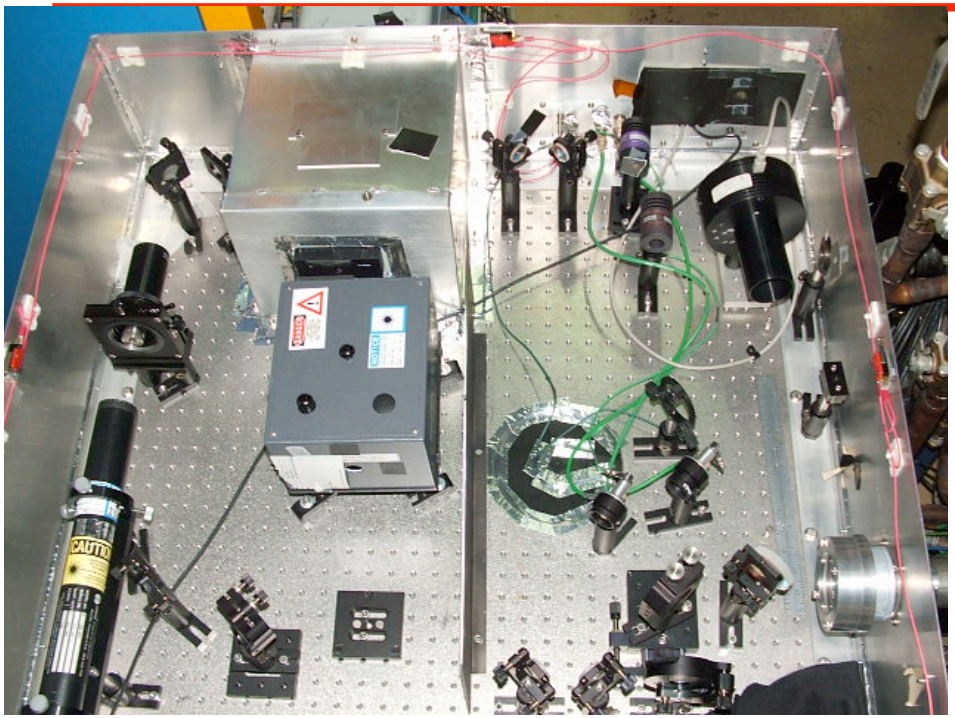
$\Gamma_{\rm dec} = 9.0 \times 10^{-5}$ Hz for $\beta_\gamma = 10^{12}$

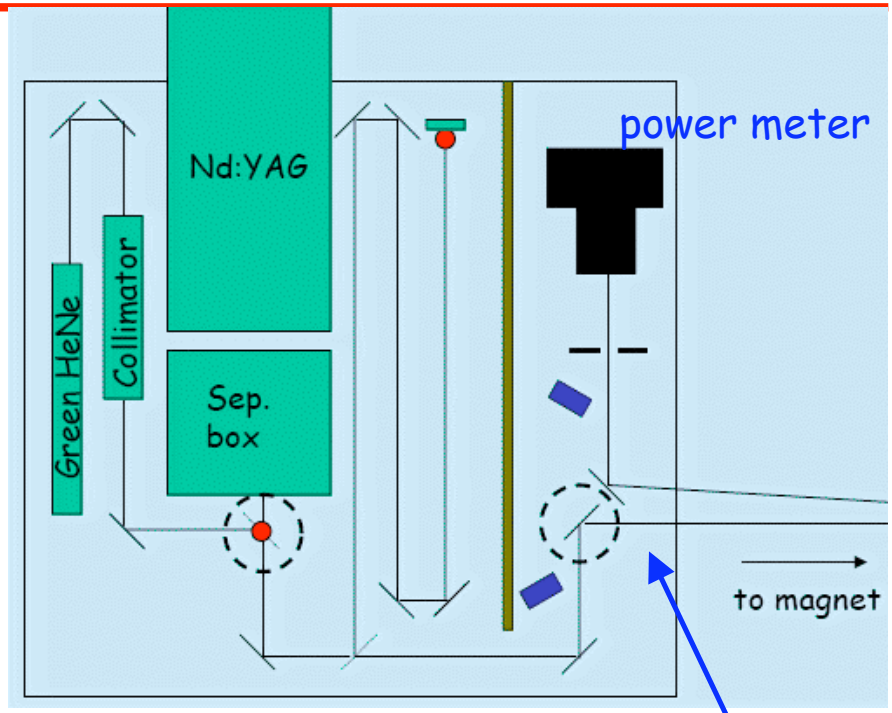
$\Gamma_{\rm dec} \propto \beta_\gamma^2$

0.049 m^3 jar is filled for 5 hours with a 3W, ω=2.33eV laser. Laser is turned off at t=0. **Yellow band=observation window.**

EMERGENCY
POWER OFF
DANGER
CLASS 4
VISABLE &
INVISABLE
LASER BEAM

Freq. doubled Nd:YAG laser, 3W avg power

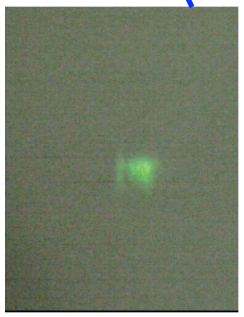




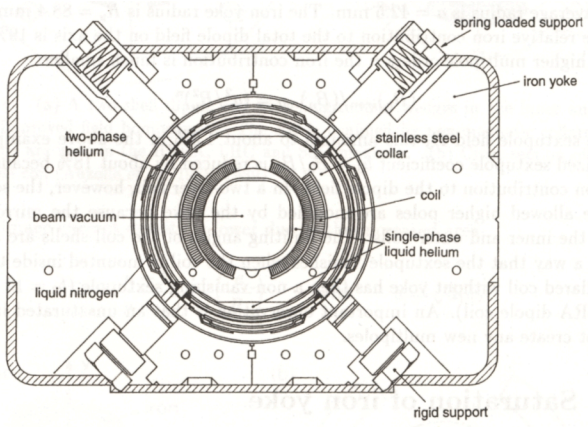
Laser box is safety interlocked, mounted on cement blocks, and interfaces to vacuum inside the magnet.

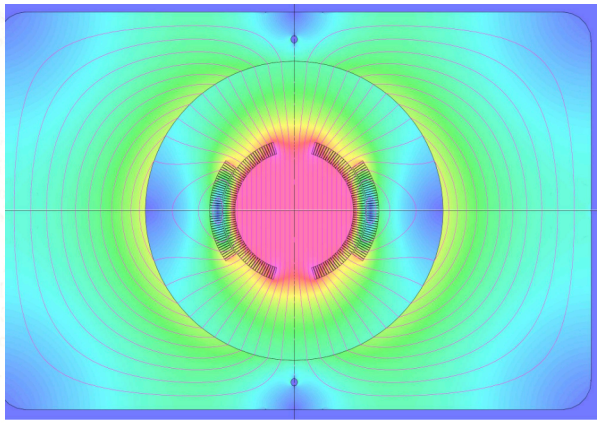
160mJ, 5ns pulses @20Hz of 532 nm light
~ 10^{19} (2.33 eV) γ/s

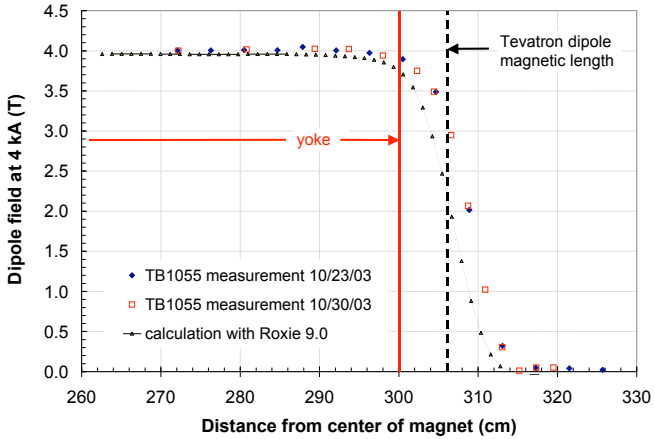
Reflected laser spot on mirror is monitored by video

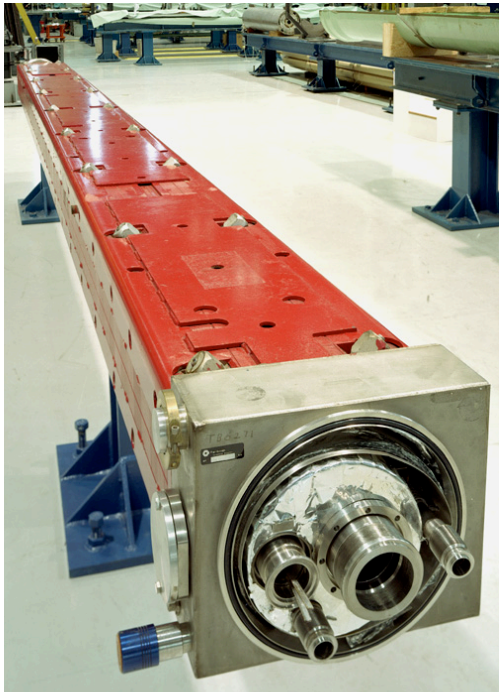


Tevatron Magnet





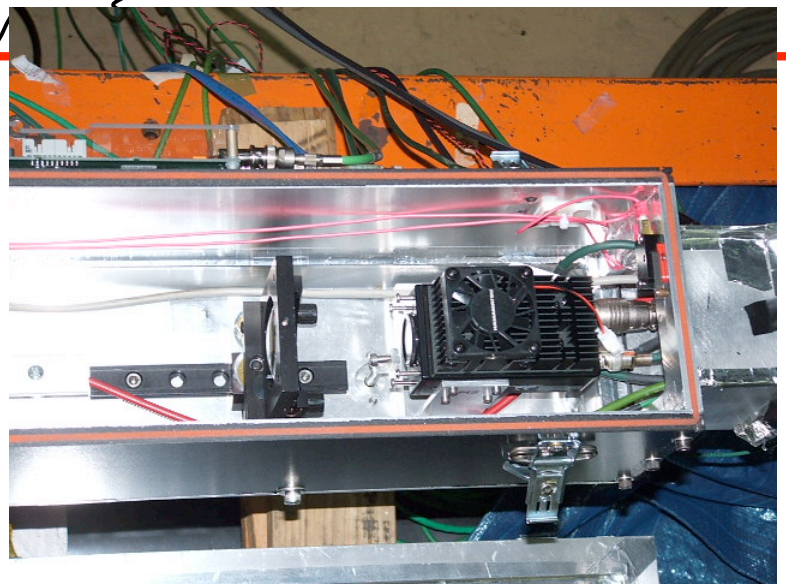




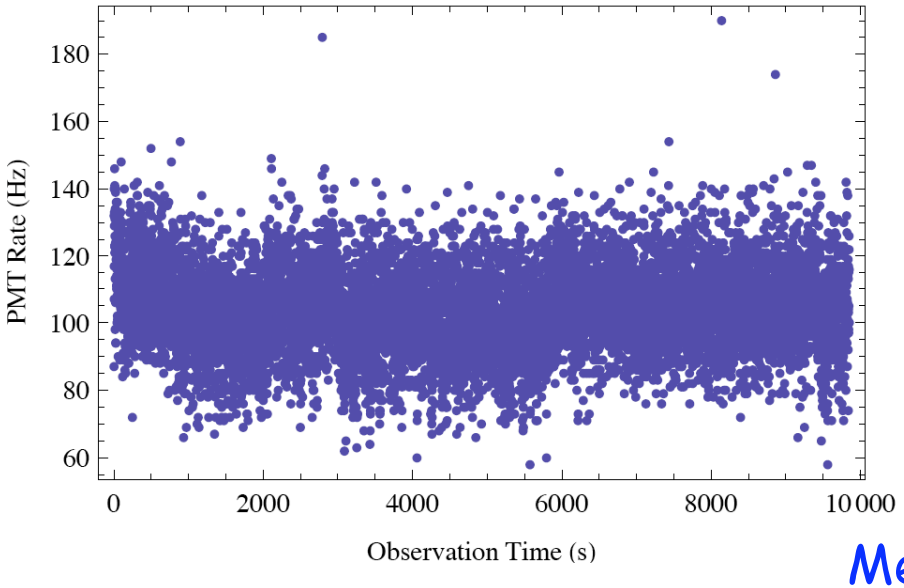
- Operating current was 5040A to have **5T over the entire 6m length.** Field cuts off abruptly at ends of magnet --> vacuum mass eigenstates (non-adiabatically) projected into flavor eigenstates as beam enters the magnet

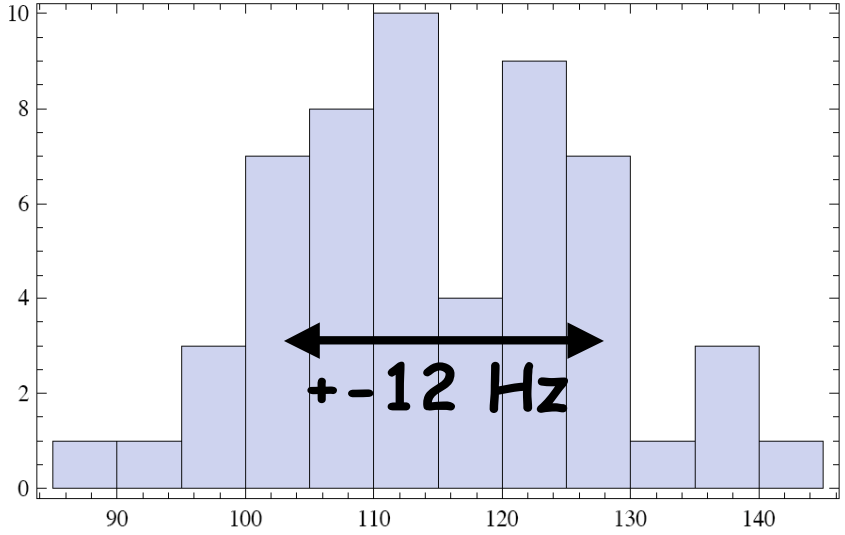
- Terrific support from the Fermilab Magnet Test Facility that gave us space and infrastructure on their test stand, and cryogenics support.

Single photon detector



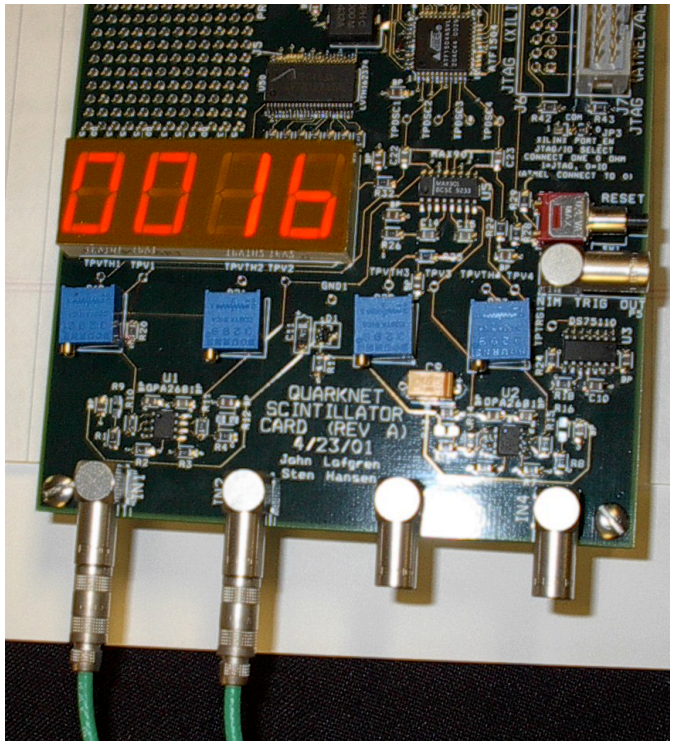
- Focussing lens subtends solid angle fraction of 5.3e-7.
- Total optical transport efficiency ~92%
- Hamamatsu H7422P-40 PMT module
- GaAsP, QE=39% at 532 nm, CE ~ 70%
- **Dark Count rate ~ 115 Hz**





Mean rate (Hz) in independent 1h samples

Data acquisition system



- QuarkNet timing cards
  - Built by Fermilab for Education Outreach (High school cosmic ray exp'ts.)
  - Maximum rate ~ 600 Hz
- Boards also send firing commands to the laser and LED pulser system

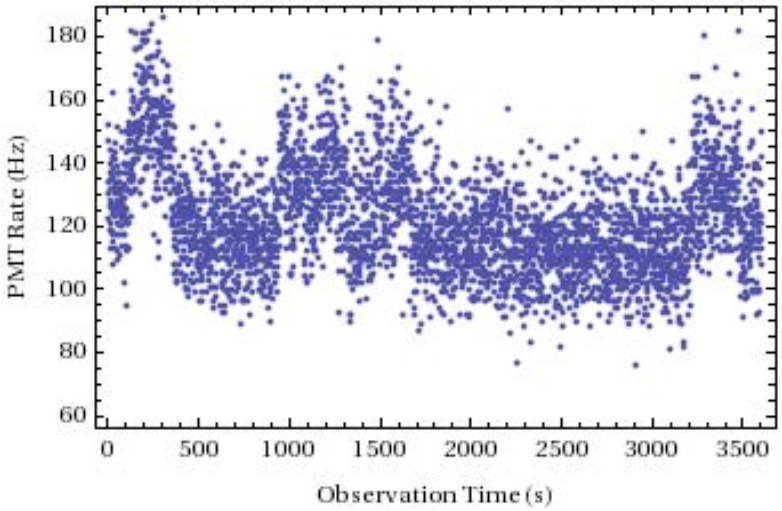
Data-taking procedure

- **Fill chamber for ~5h** while taking "Leaky mirror" data for axion timing calibration: Send the laser directly into our PMT after attenuation so that we get about 1 photon trigger per 100 laser pulses.
  - Two mirrors leak ~10^{-6} through
    - **Reflected light is used to monitor laser power.**
  - 10 micron pin hole captures ~10^{-6}
  - Neutral density filters pass ~10^{-7}

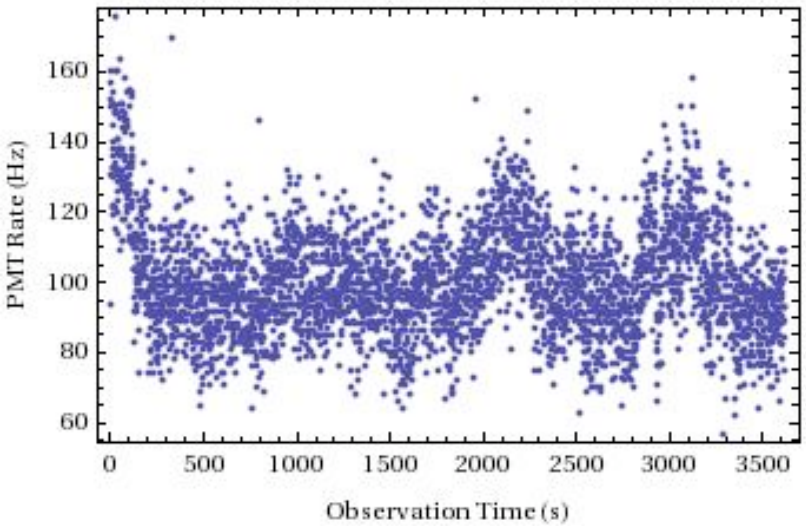
- Stop laser, turn off PMT, remove PMT protection, block laser port. Close/seal all boxes. Turn on PMT
  - **Takes ~15 minutes to prepare for afterglow data.**

- **Take 1 hour of afterglow data.**

Afterglow data



Pseudoscalar (vert pol),
After delay of 319s to set up PMT

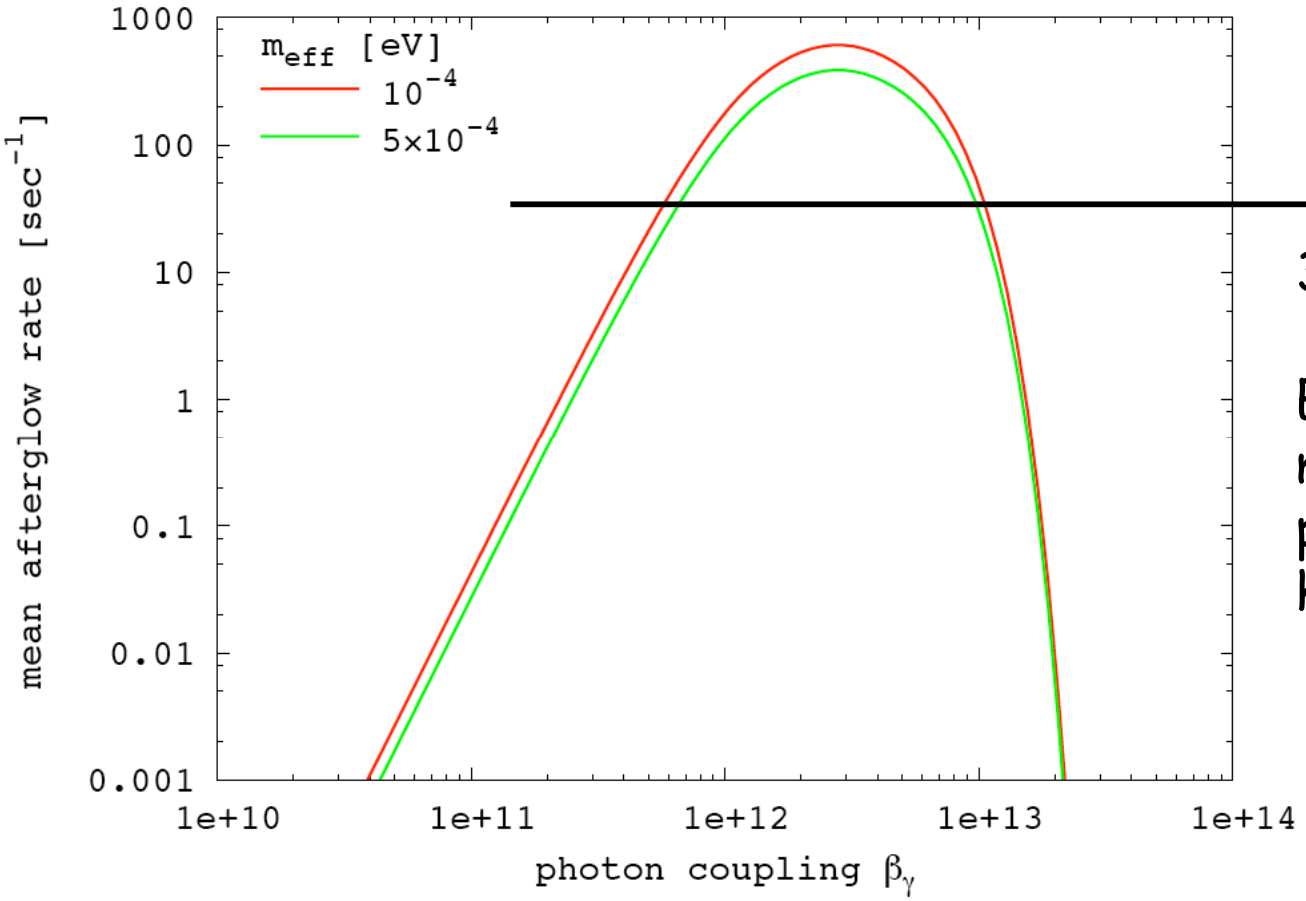


Scalar (horiz pol),
after delay of 1006s

Lots of time structure due to PMT instability.
To obtain an upper bound on the rate, measure average rate over 1h, and add 36 Hz (3-sigma in the mean rate distribution for 1h axion data samples).
Exclude models which predict a higher observable rate.

Predicted minimum avg. signal rate

Using only no-bounce trajectories for normalization, and overestimated Γ_{dec} for decay rate.

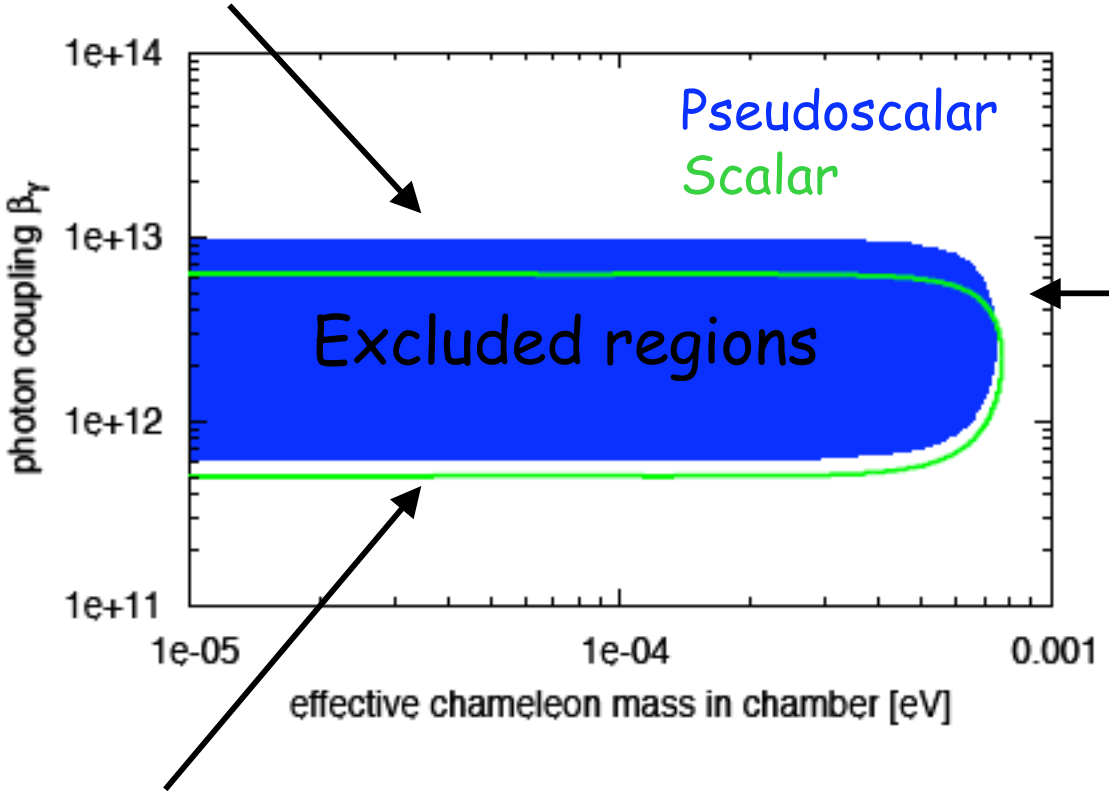


3σ threshold

Exclude models which predict a higher rate.

Photon coupling constraints

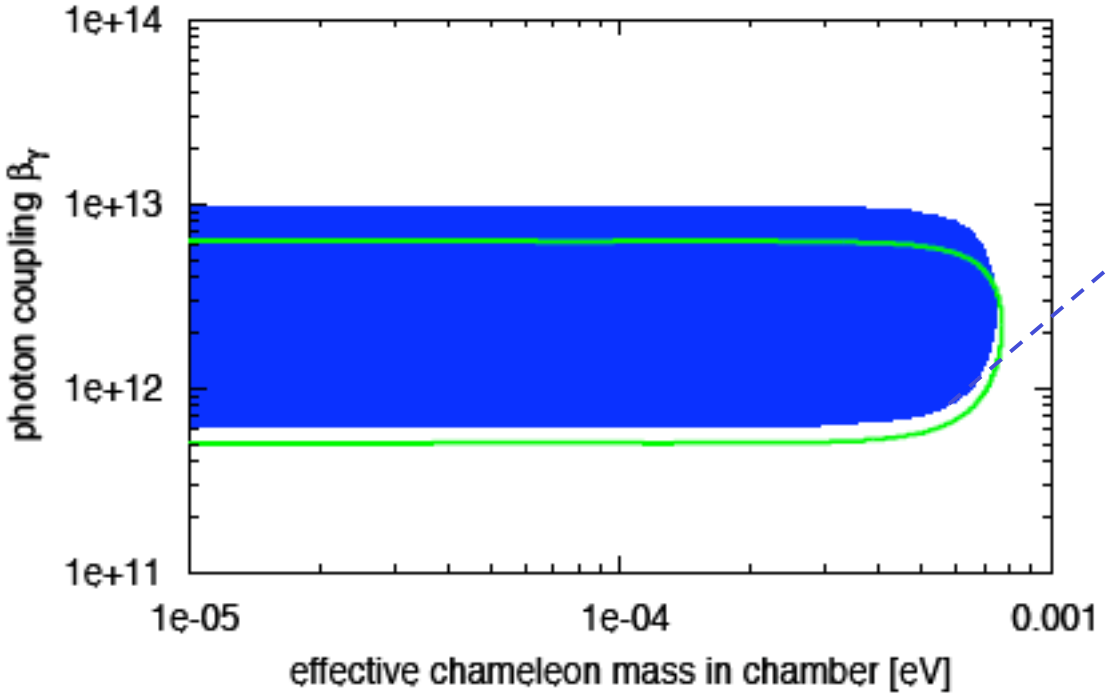
Fast afterglow decay rates prevent excluding large coupling

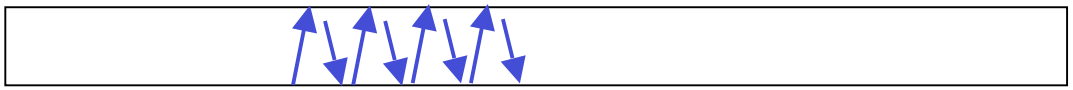


Scalar limit is lower because of the longer delay in setting up the PMT.

Using minimum afterglow predictions, the sensitivity at low coupling is determined as usual by the PMT noise rate.

Photon coupling constraints





Normal axion-like excluded regions at higher mass and larger β_γ can not be excluded here because there is a continuum of shorter baselines for bouncing trajectories.

Coherent oscillations, $P \sim M_{pl}^{-2}\ \beta_\gamma^{2}\ B^2\ R^2$ on horizontal trajectories followed by absorption on the walls.

Validity region in β_m

$N^* (\beta_\gamma * 7e\text{-}14\ g/cm^3 + \beta_m * 2.6e\text{-}13\ g/cm^3)^\alpha$

$< \sqrt{4\pi\ \omega/L}$ (coherent oscillations)

$< \omega$ (conservation of energy)

$< N^*(\beta_m * 2.6e\text{-}9\ g/cm^3)^\alpha$ (reflection)

(Using our estimates for energy densities from B^2, residual gas pressure, and forepump pressure.)

Solving gives:

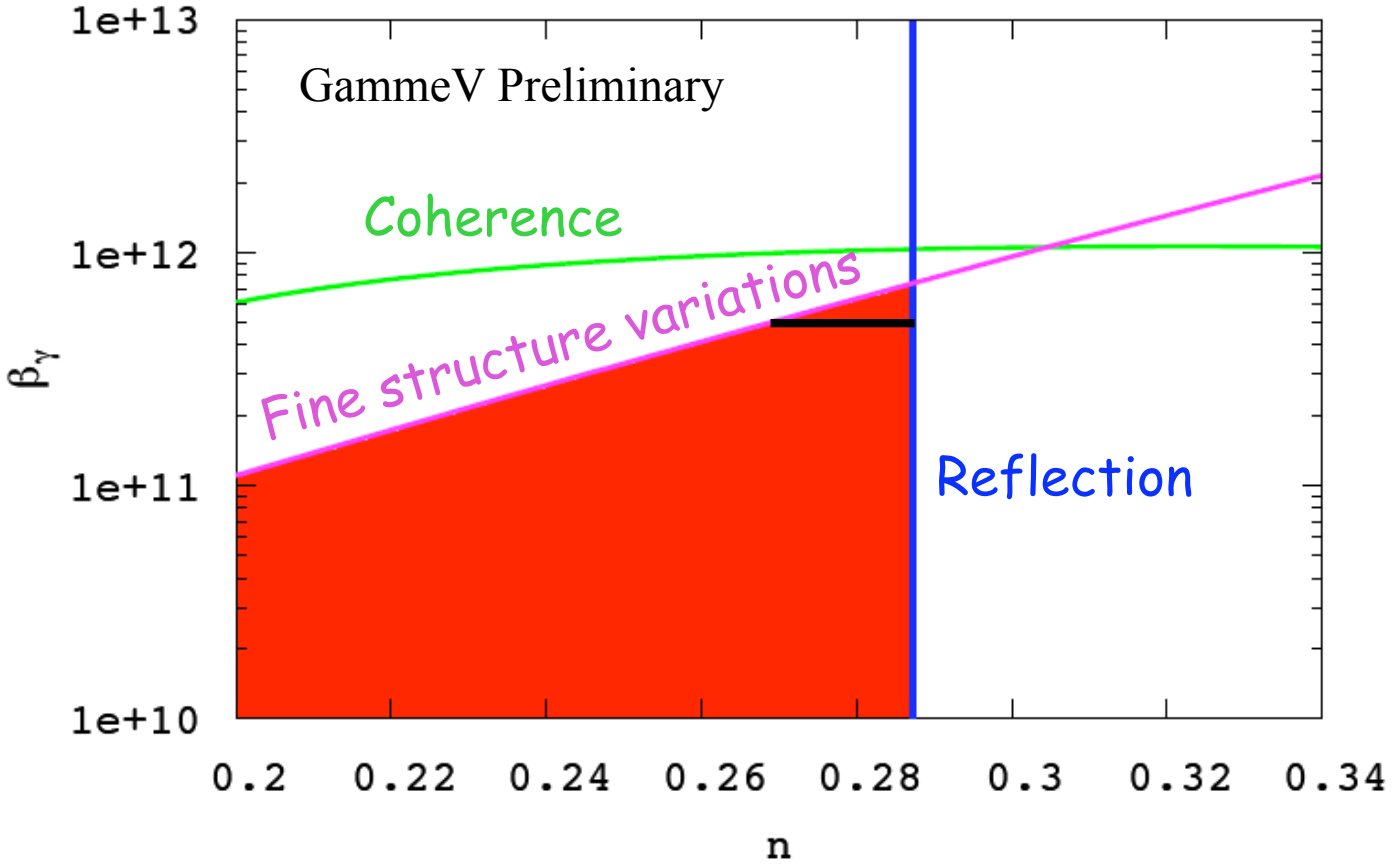
$\beta_m > 2.7e\text{-}5\ \beta_\gamma$.

When constraining specific models using our limit on β_γ, this requirement, and the more general requirements of coherent oscillations and reflections must first be applied to determine in which part of the model parameter space the limit β_γ on is valid.

Example: for a specific model, look at slices in the parameter space

$V(\phi) = \Lambda^4 \exp(\Lambda^n/\phi^n)$

Fixing Λ = 2.3e-3 eV,
β_m = 1e13

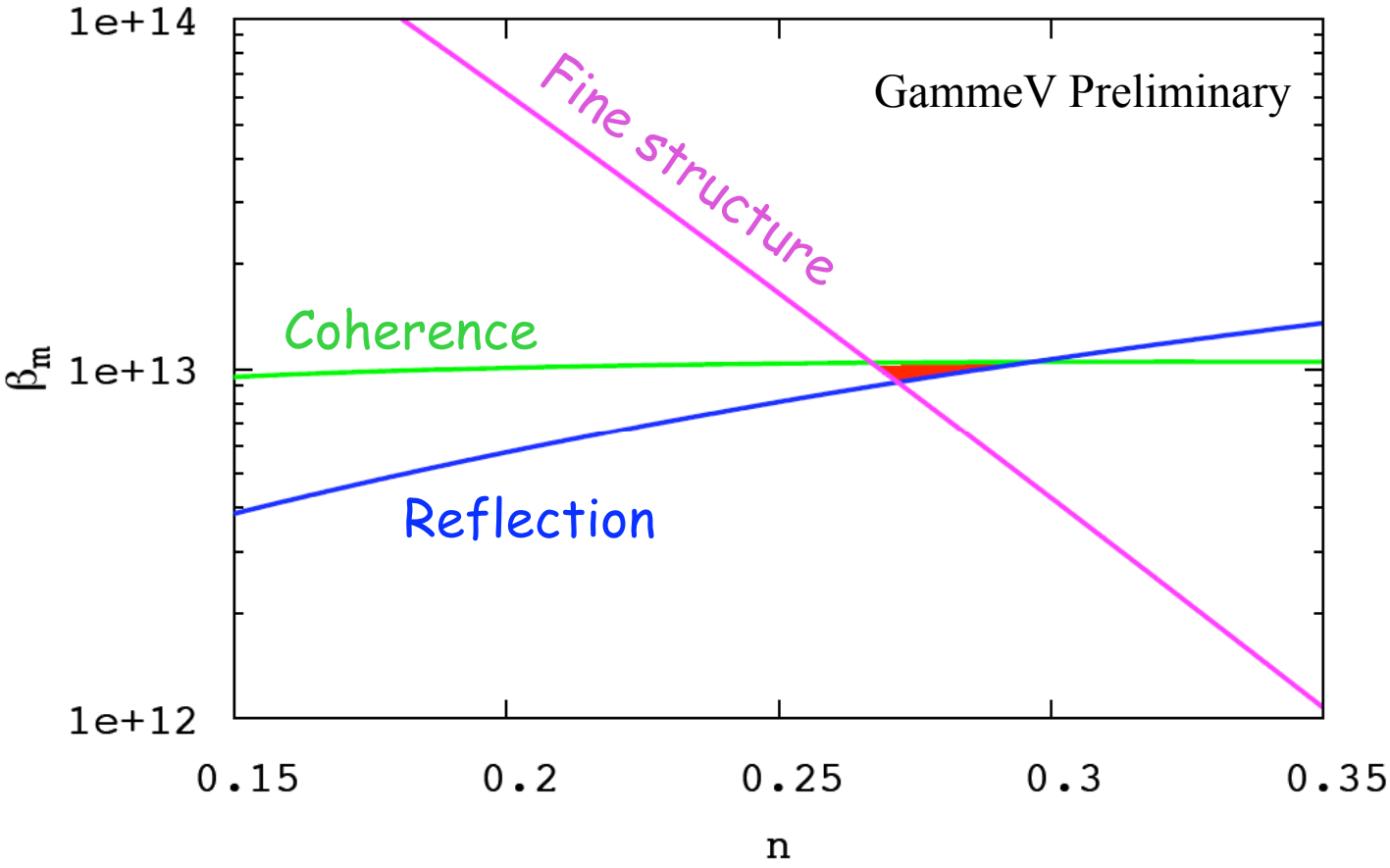


Red = allowed by fine structure constraints and also satisfying our conditions.

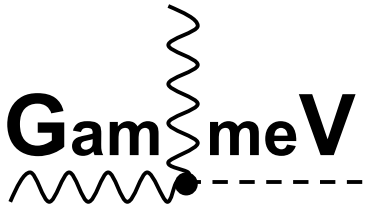
β_γ >5e11 now ruled out.

Similarly, for a slice in the β_m space

Fixing β_γ=5e11



β_m must be in this region for the β_γ constraint to be valid



Conclusions

- In the second stage of the experiment, we searched for reflective particles with strong matter effects with a novel new technique: **"Particles trapped in a Jar"**
  - Chameleons evade other experimental bounds

- **First demonstration of photon regeneration afterglow.**

- Difficult to present model-independent constraints.
  - Models have many parameters: Form of $V(\phi)$, including dimensionful constants, strengths of matter and photon couplings…

- Experimental issues limit the regime of sensitivity:
  - Large regions of parameter space yet to be tested

For future chameleon jars:
(Things we would do differently next time)

- Build a better vacuum, not requiring continous displacement pumping.
  - Immediate gain of 10^9 in (m_0,α) range of validity.

- To go to larger photon coupling,
  - paint the interior black to absorb photons produced on bouncing trajectories. Losses will scale as Sum(L_i^2) instead of (Sum(L_i))^2. This will preserve the straight-through afterglow rate while reducing the afterglow decay time by suppressing the afterglow from bouncing trajectories.
  - Reduce the PMT turn-on time in order to catch rapidly decaying signals.

- To go to smaller coupling, use better optics to capture more solid angle.

- To go to higher mass, use a shorter magnet (~1 m) to be sensitive to the milli-eV dark energy scale. (Recall that the windows cannot be placed inside the B field region, and so the baseline is fixed by the magnet.)