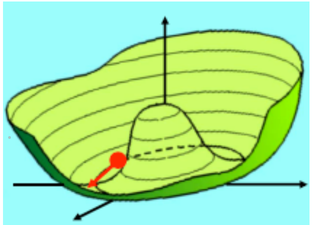
Particle (Astro)Physics with Lasers

Aaron Chou

FCPA retreat

April 18, 2009



Axions, Strong CP and Dark Matter

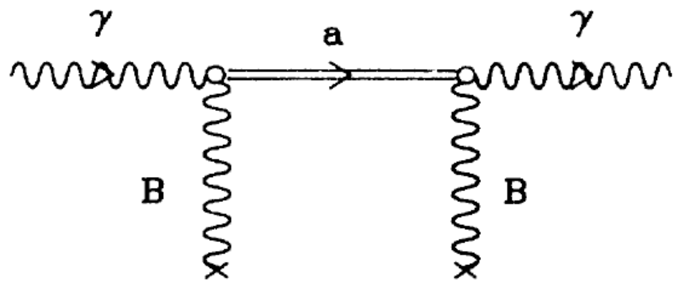
- The neutron electric dipole moment is measured to be $<10^{-10}$ of what is naïvely expected based on the neutron size and quark charges.
  - Total EDM = quark EDM (TeV EW scale) + orbital EDM (GeV QCD scale).
  - How can these two cancel to such precision without fine-tuning? Why is the strong force CP-conserving?

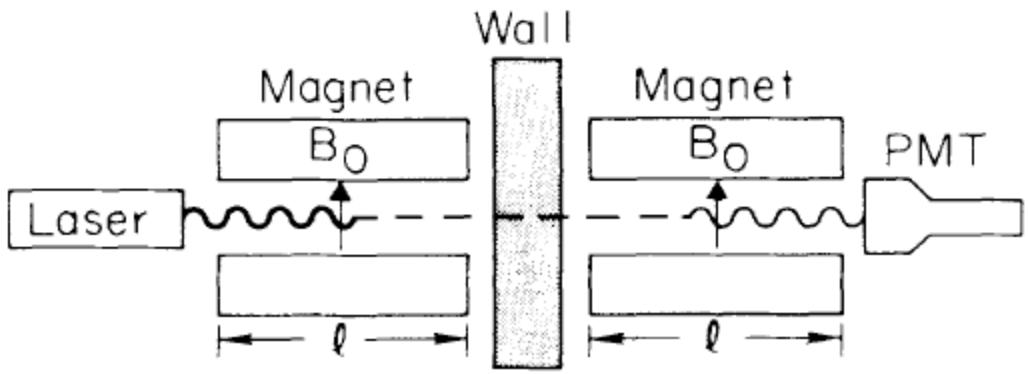
- Peccei-Quinn axion model gives a dynamical solution to the strong CP problem by introducing a new scalar field whose vacuum state after the QCD phase transition is CP-conserving.

- Latent axionic vacuum energy is released shortly after the phase transition in the form of cold axions, which can compose all or part of the inferred dark matter density.

- Axion dark matter fluctuations scale as $(H_I/f_A)^2$, and induce isocurvature temperature fluctuations on the CMB. Measuring f_A or isocurvature/adiabatic ratio can constrain H_I independently of B-mode polarizations.

Shining Light Through a Wall





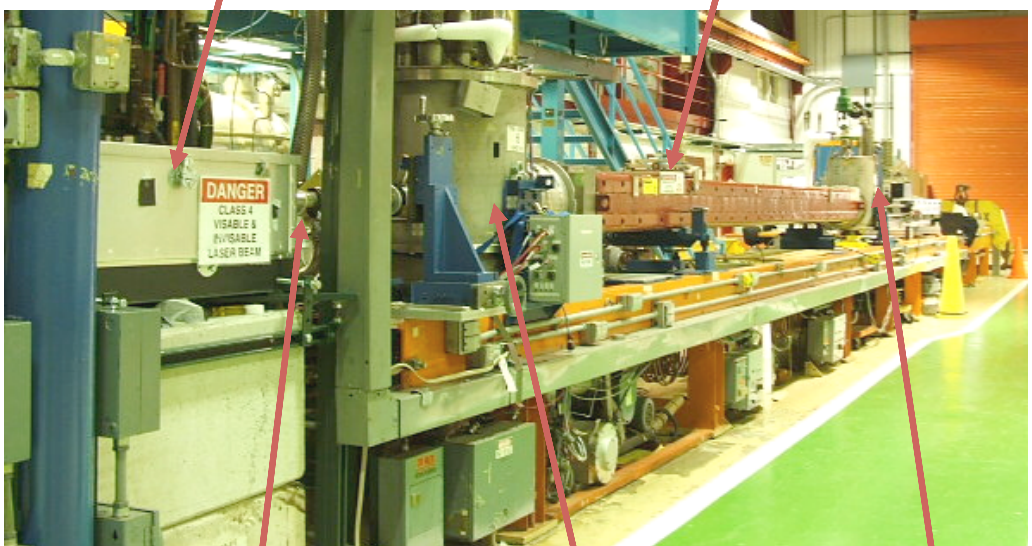
K. Van Bibber, et. al., PRL 59, 759 (1987)

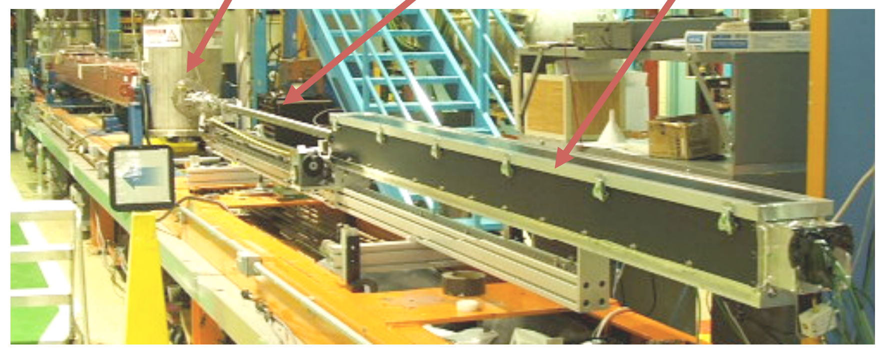
Prob(ϒ→a) ≈ $(gBL/2)^2$
Prob(ϒ→a→ϒ) ≈ $(gBL/2)^4$

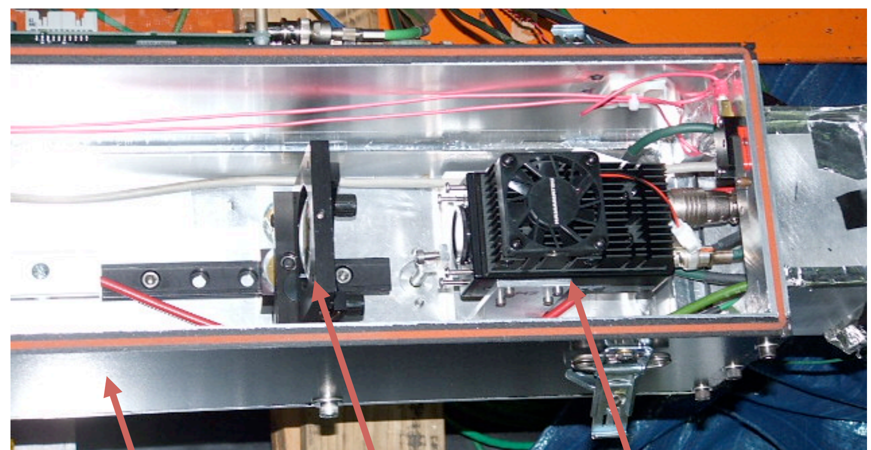
Tabletop appearance experiment:
Photons oscillate into axions, go through the wall, and oscillate back into photons.

GammeV Photon Regeneration Apparatus

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



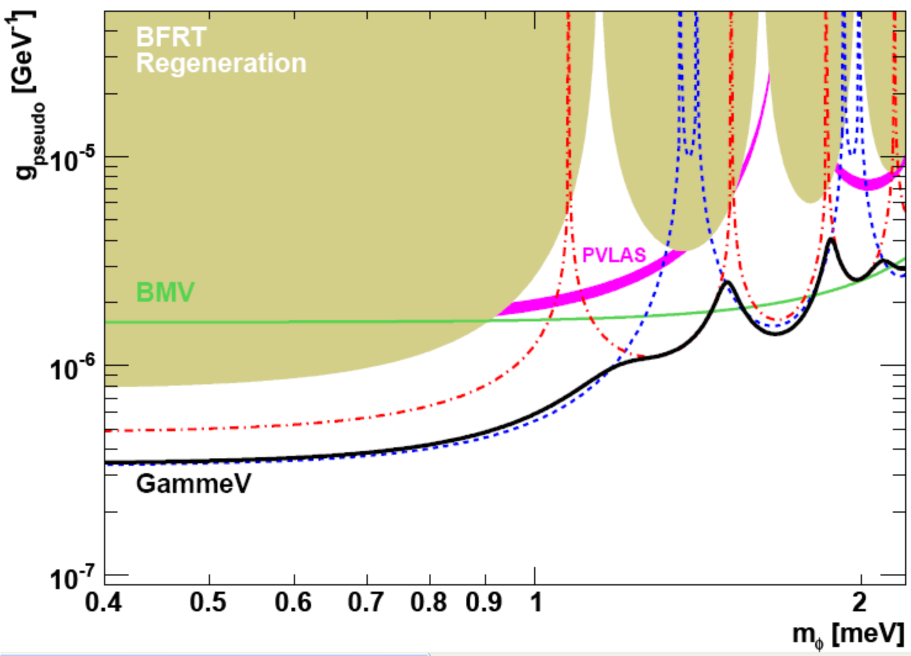




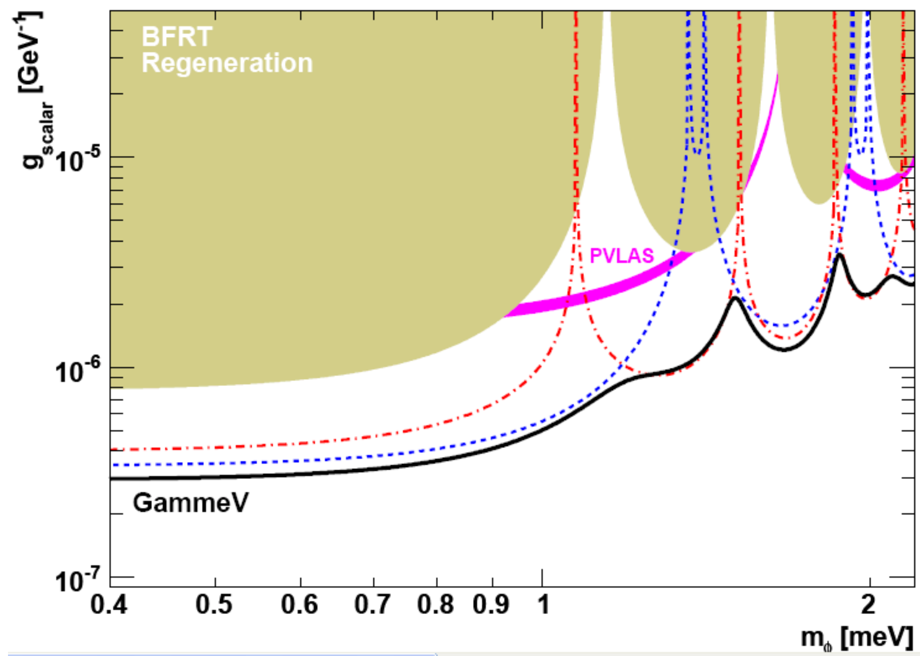
GammeV limits on axion-like particles

- From lack of excess above background, we derive **3**σ exclusion regions and completely rule out the PVLAS axion-like particle interpretation by more than **5**σ.

Pseudoscalar



Scalar



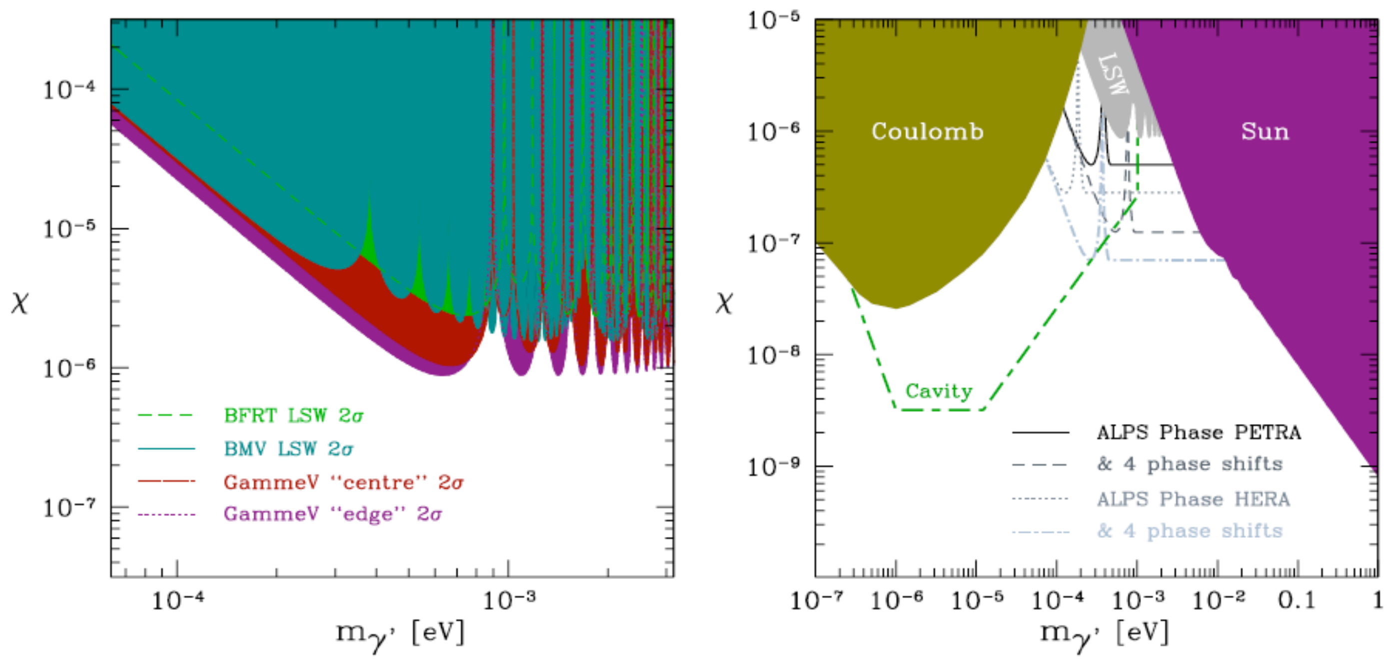
PRL **100**, 080402 (2008)

Search for dark U(1) paraphotons

- New low mass dark photons can mix with visible photons in our apparatus, without the need for a magnetic field. These dark gauge bosons are predicted generically in BSM theories and are perhaps implied by PAMELA/ATIC

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{2}\chi\, F^{\mu\nu}B_{\mu\nu} + \frac{1}{2}m_{\gamma'}^2 B_\mu B^\mu$$

GammeV has the best limits for masses in the milli-eV "dark energy scale"

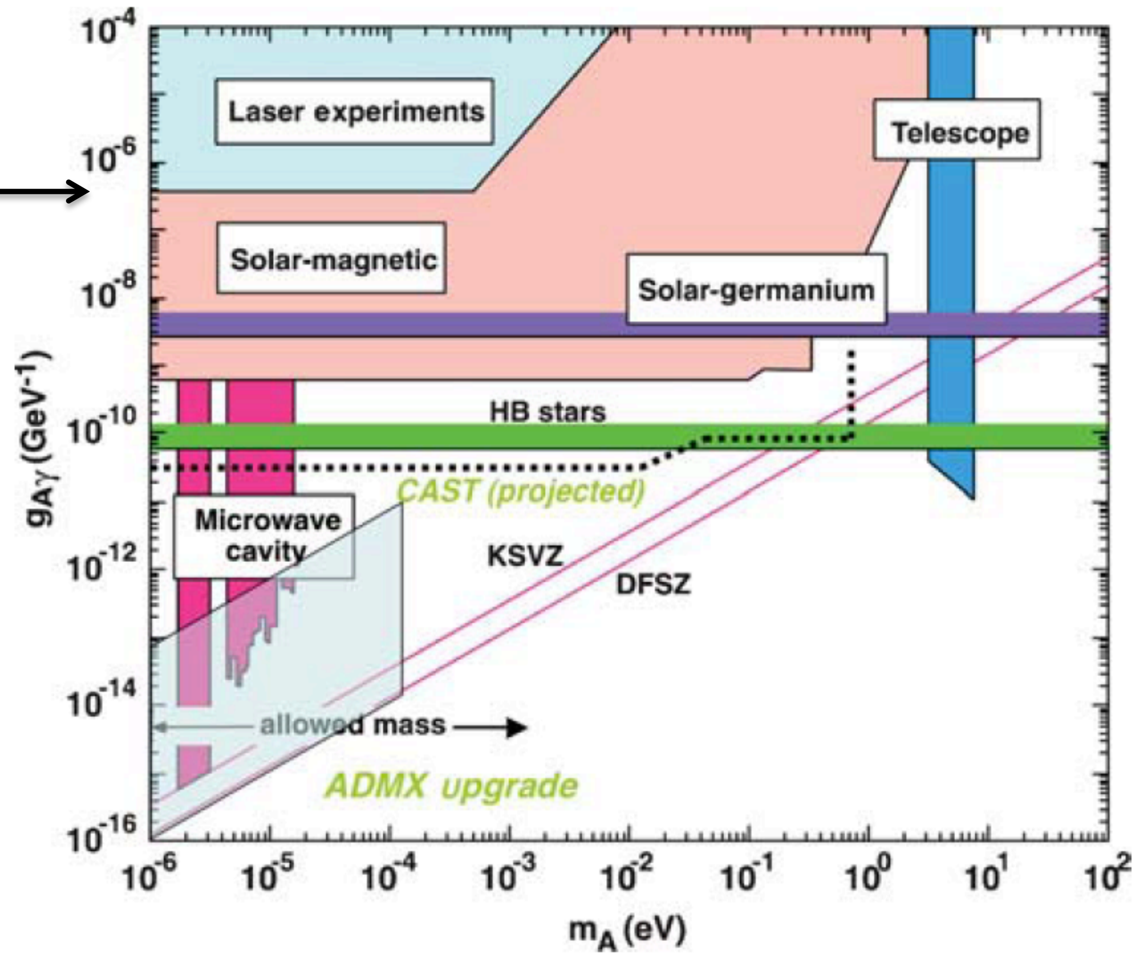


M. Ahlers[1], H. Gies[2], J. Jaeckel[2,3], J. Redondo[4] and A. Ringwald[4]

Axion limits

GammeV has world's best laboratory limit on the axion-photon coupling, but is not competitive with astrophysical limits.
How can we do better?

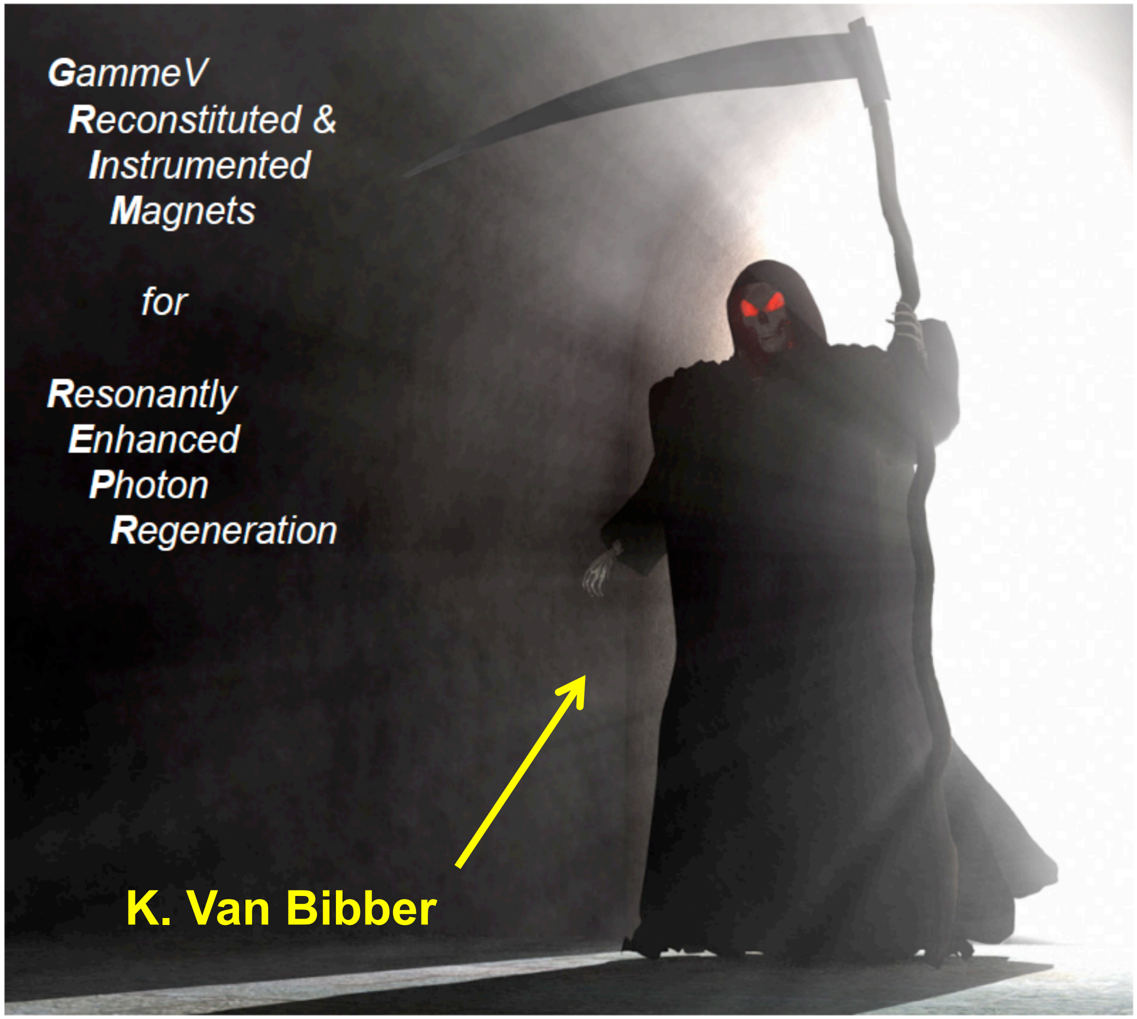
GammeV →



$$\mathcal{L}_{A\gamma\gamma} = -g_\gamma \frac{\alpha}{\pi} \frac{A(x)}{f_A} \vec{E} \cdot \vec{B}$$

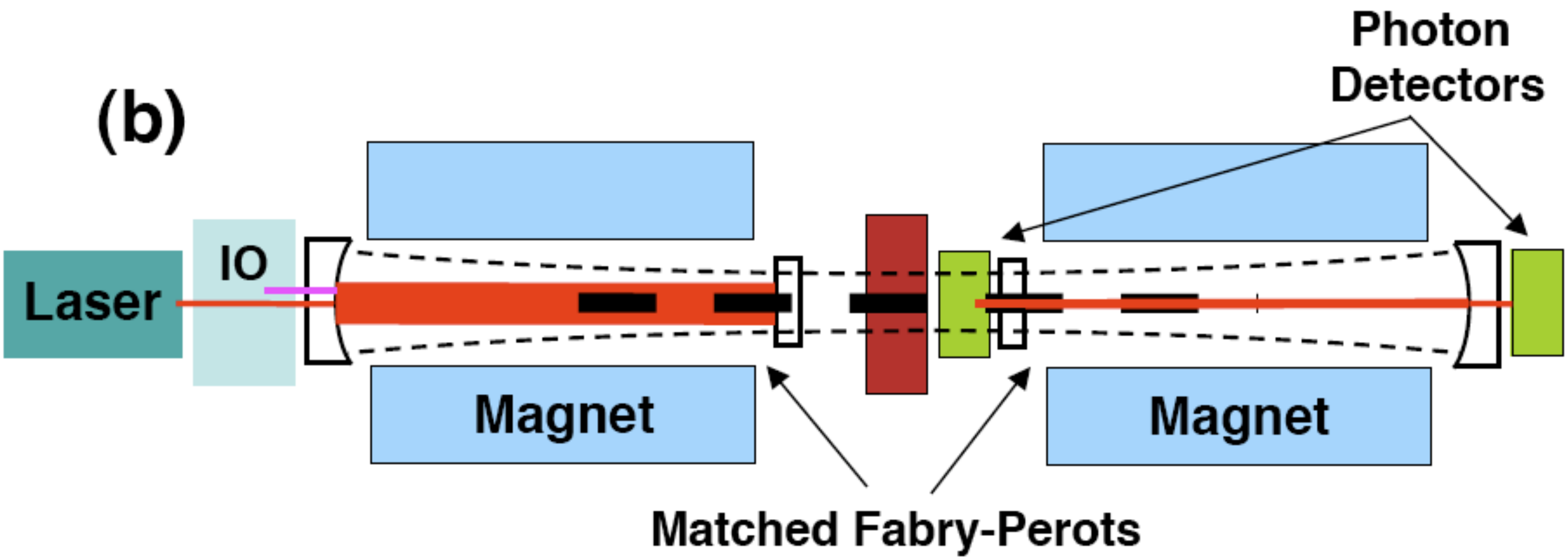
Search for axions via resonant photon regeneration

"This time we mow the axion down for good"



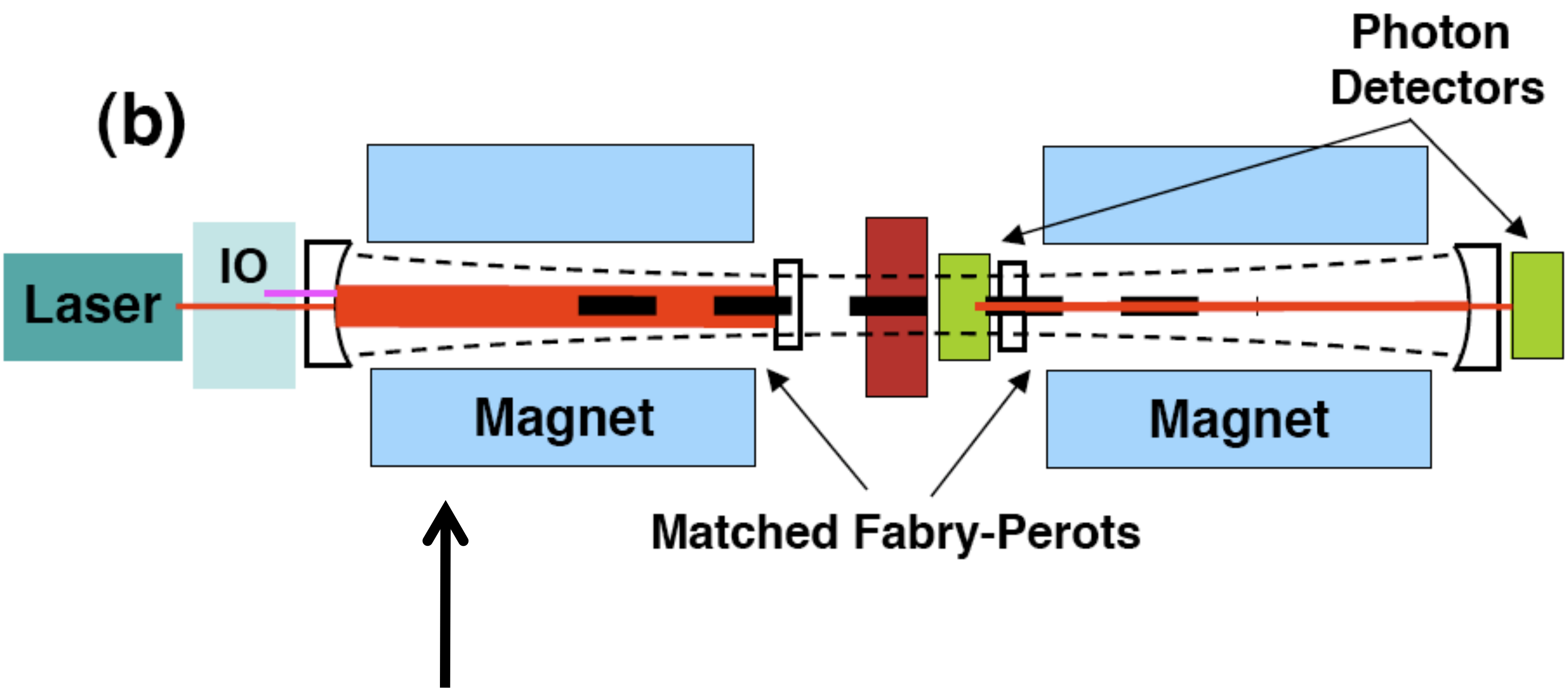
New FNAL experiment to probe the 10^{-11} GeV^{-1} coupling scale

- Sikivie/Tanner/van Bibber: resonantly-enhanced photon regeneration (PRL 98:172002,2007), hep-ph/0701198



Rate of photon-axion transitions is enhanced by a factor of the cavity finesse ($F= \sim 10^5$) on each side (resonant reconversion in the 2nd cavity)

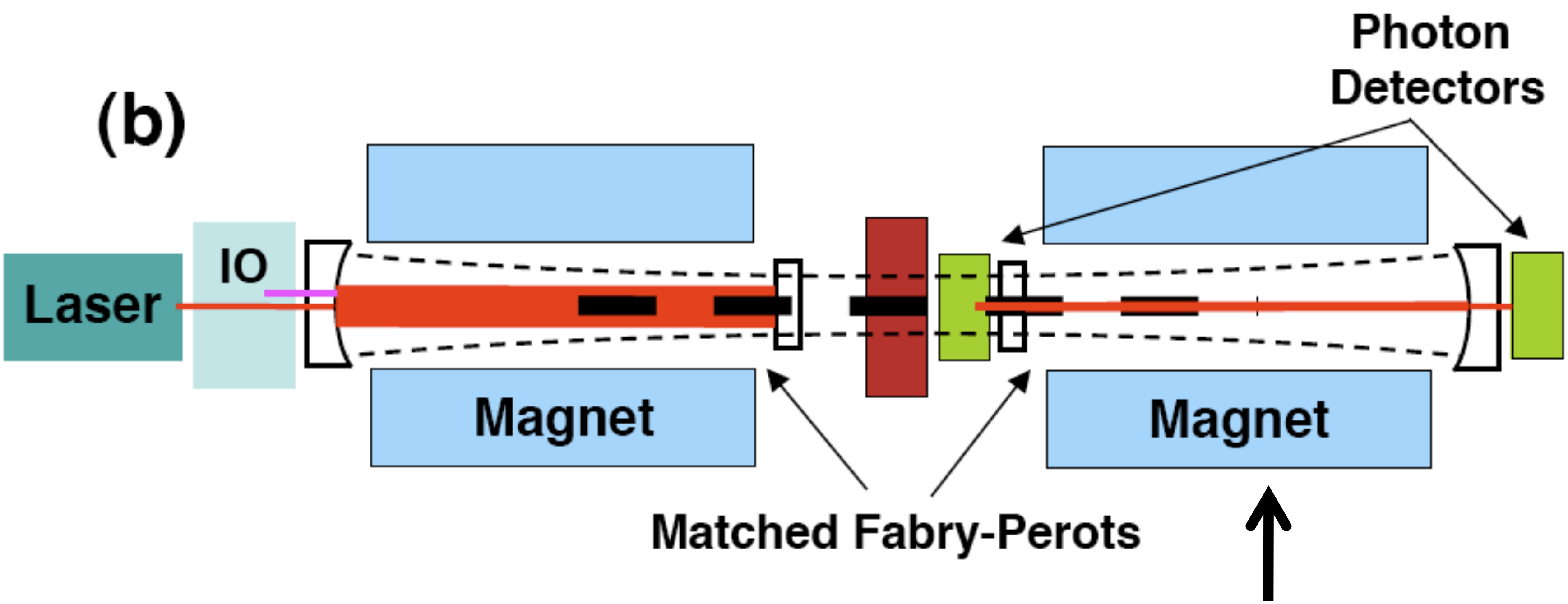
Resonant Regeneration



Cavity 1 recycles the laser beam. If the power transmission of the injection mirror is η, then the beam makes 1/η roundtrips on average.

The instantaneous power passing through the magnetic field is amplified by a factor of 1/η.

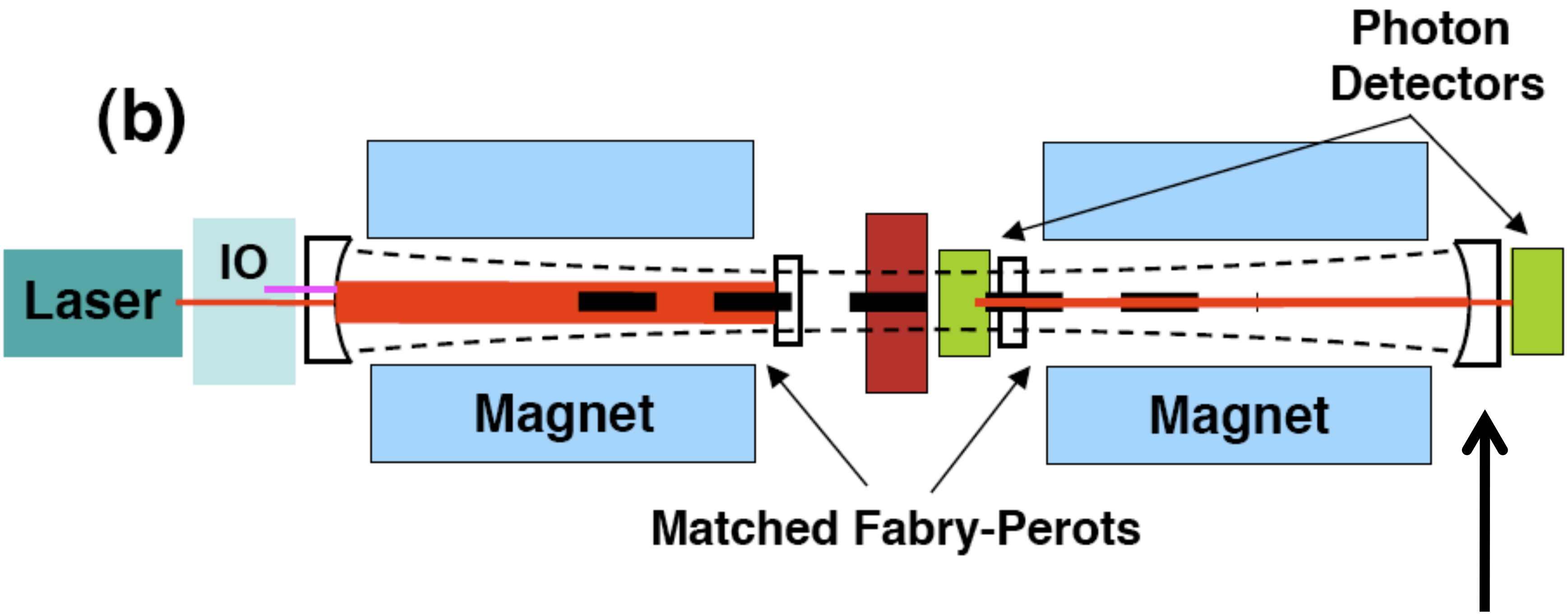
Resonant Regeneration



Cavity 2 captures the regenerated photon beam as a standing wave for 1/η roundtrips. If the two cavities are phase-locked, then the electric field of the standing wave builds up coherently over the cavity lifetime. The electric field is therefore enhanced by a factor of 1/η relative to that of a no-cavity configuration.

This coherent build-up gives a factor of $(1/\eta)^2$ in the regenerated photon population since $N \approx E^2$.

Resonant Regeneration

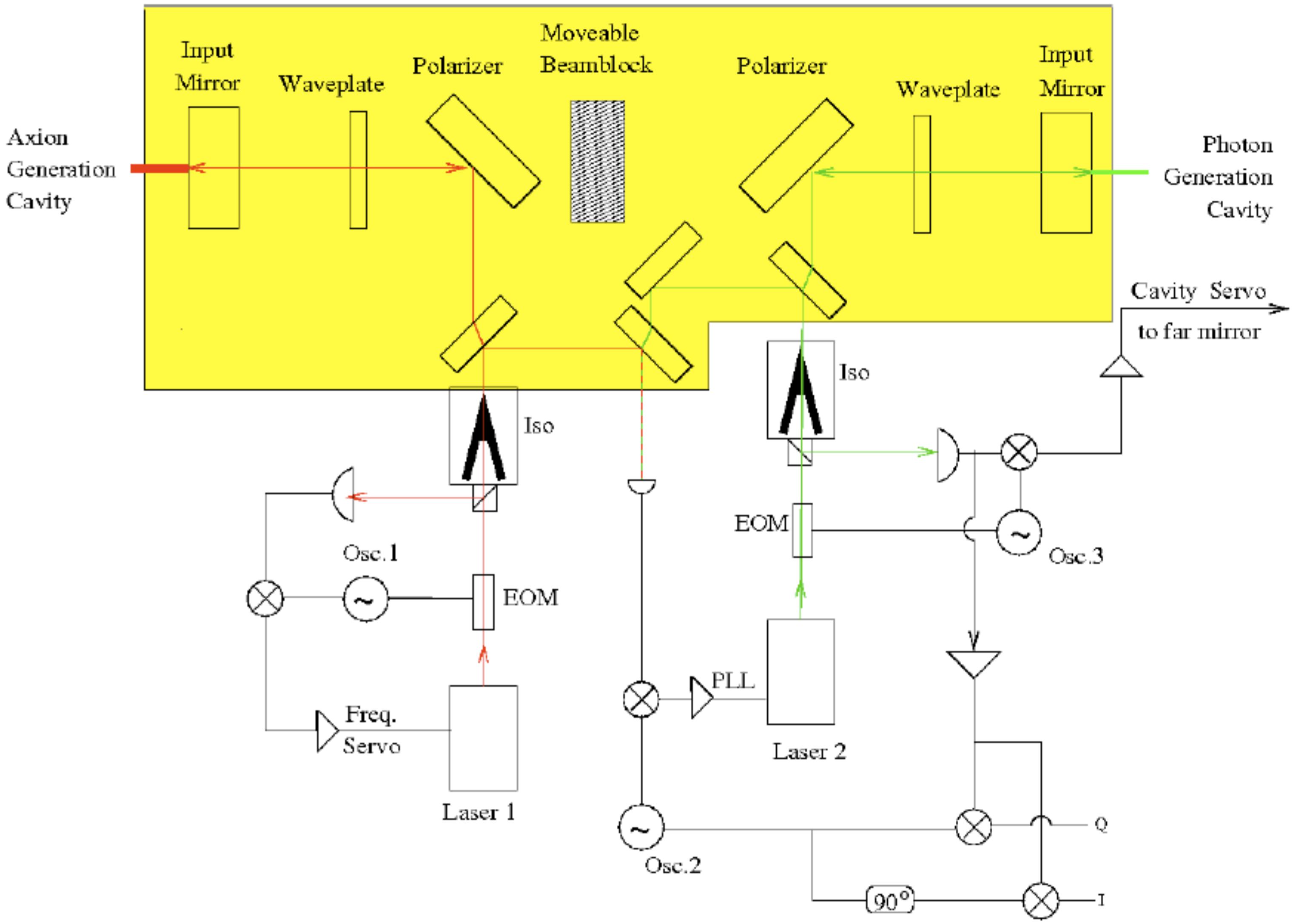


The regenerated standing wave is detected as it escapes the cavity through the far mirror. This escaping beam is attenuated by a factor of η relative to the photon flux bouncing around in the cavity.

The total enhancement in the event rate is:

$$(1/\eta)\times(1/\eta)^2\times\eta = (1/\eta)^2 = (F/\pi)^2$$

Phase-locking and heterodyne detection gives single-photon sensitivity



Resonant Regeneration baseline design

Regeneration rate:

$$\frac{dN_{\rm regen}}{dt} = \frac{dN_{\rm laser}}{dt} P^2_{\gamma\to\phi} \left(\frac{\mathcal{F}}{\pi}\right)^2 = \frac{dN_{\rm laser}}{dt} \left(\frac{gBL}{4}\right)^4 \left(\frac{\mathcal{F}}{\pi}\right)^2$$

$$\frac{dN_{\rm regen}}{dt} \approx (10^{-3}\ {\rm Hz}) \times g_{10}^4 B_4^4 L_{54}^4 F_5^2 P_{10}$$

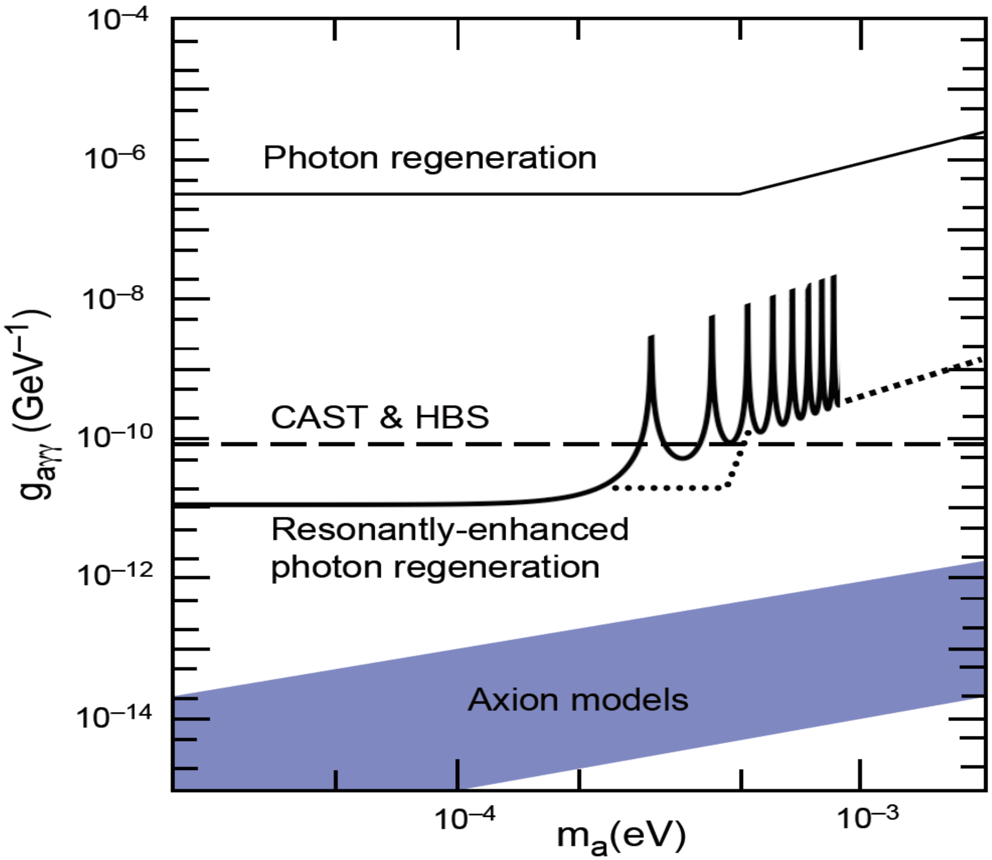
$g_{10} = g/(10^{-10}\ \mathrm{GeV}^{-1})$, $B_4 = B/(4\ \mathrm{T})$, $L_{54} = L/(54\ \mathrm{m})$ (9 magnets),
$F_5 = F/10^5$, $P_{10} = P/(10\ \mathrm{W})$

100% CL discovery at g_{10}=0.2 (3 events) in 30 days of continuous integration time if limited only by quantum zero-point background.

Sensitivity scaling:

$$g_{\rm limit} \propto \left(\frac{dN_{\rm laser}}{dt} \cdot T_{\rm integration}\right)^{-1/4} (BL)^{-1} \mathcal{F}^{-1/2}$$

Potential sensitivity to photon coupling g



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

Sensitivity g~10^{-11} GeV^{-1} or better with improved finesse.

Is the g=10^{-11} GeV^{-1} coupling scale interesting?

Yes! Axions are part of the hidden sector, which might be much richer than usually imagined (single WIMP + single QCD axion + nothing else).

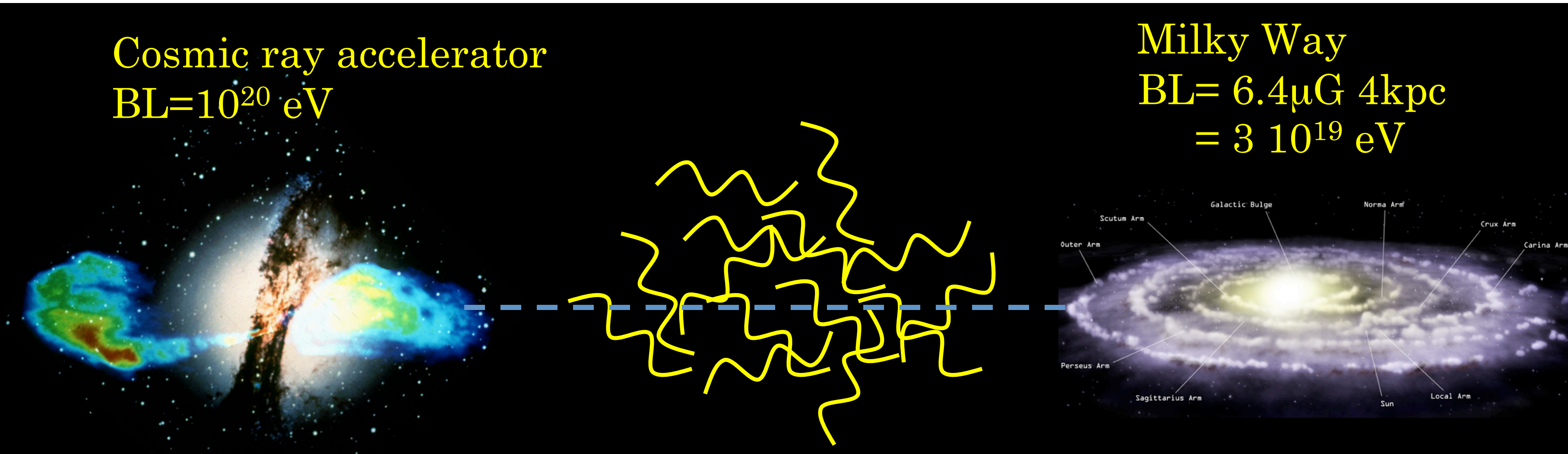
Nobody has ever looked in this coupling regime with a sensitive microscope before, and that alone is enough reason to build the experiment.

Another hint: Light shining through the universe

Anomalous transparency of the universe to VHE and UHE gamma rays observed by HESS, VERITAS, MAGIC, Whipple, HiRes, can be explained by mixing of photons with axion-like particles

Hooper, Serpico, 2007
De Angelis, Mansutti, Roncadelli, 2007
Simet, Hooper, Serpico, 2008
Fairbairn, Rashba, Troitsky, 2009

$\mathrm{Prob}(\gamma \leftrightarrow \phi) \approx (gBL/2)^2$



- If $g \approx 1/(BL) = 10^{-11}\ \mathrm{GeV}^{-1}$, then high energy gamma rays can penetrate the opaque wall of background photons by efficiently converting into axions at the source, and then efficiently reconverting into photons in the galaxy.

Who would do this experiment?

- External community:
  - The experimental/theoretical axion community is enthusiastic about this technique: van Bibber, Sikivie, Tanner, etc.
  - The gravity wave interferometer community is enthusiastic about another tricky application of the techniques which they have developed: Mueller, Gustafson, Waldman, Hild, etc.

- Internal community:
  - GammeV V1 collaborators
  - Various others have voiced interest, and/or are already participating.
  - Local holographic noise collaborators.

Why do this experiment at FNAL?

- Again, use/re-use items already available at the laboratory
  - Accelerator laboratories are unique in having access and capability of operating long superconducting magnets.
    - Tevatron spare pool has ~28 good quality magnets
    - Spool pieces, feed cans for cryogenic plumbing
    - Central helium liquifier, satellite refrigerator
  - 400 mW CW Nd:YAG laser left-over from Nesrick axion experiment
  - 2 good optical tables
- Existence of large experimental halls, lab space.

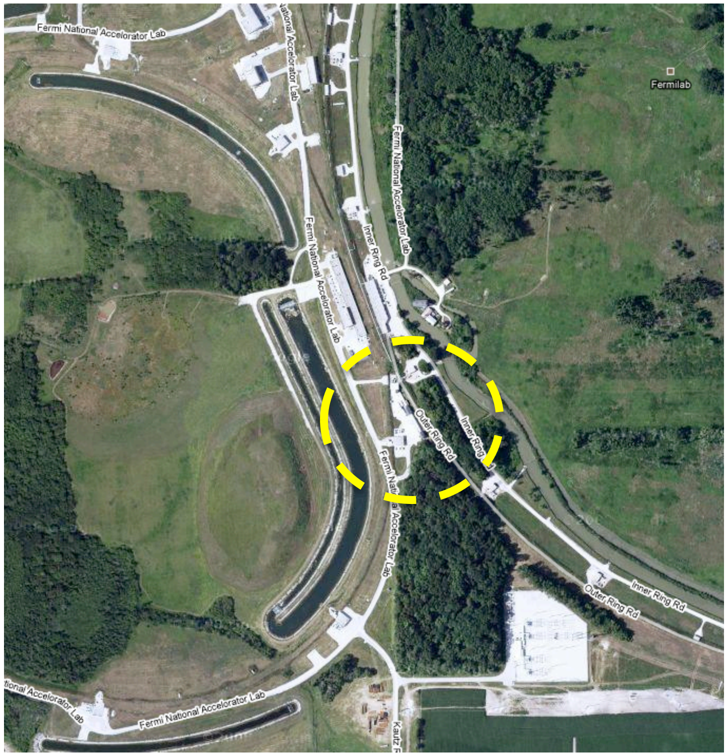
- Expertise in operating superconducting magnets, cryogenics, vacuum systems, RF electronics, ground motion studies

- **Complementarity with holographic noise interferometer proposal**. Common optics design, data acquisition.

Many $100K parts just sitting around the lab!

The spool piece provides the cryo and power connection between the 2 strings of magnets while providing an open drift space in between. One of several existing optical tables can be placed here.

The E4R Lab



This was the test area for SSC magnets. A satellite refrigerator + helium transfer lines already exist at one end of a 120m long tunnel.

A large "clean," climate-controlled room in the central area was constructed for a previous light-on-light scattering experiment. This is connected to office space in a neighboring trailer.

The climate-controlled area will need to be extended to the ends of the tunnel in order to avoid day-night thermal contractions of the apparatus.

Safety issues:

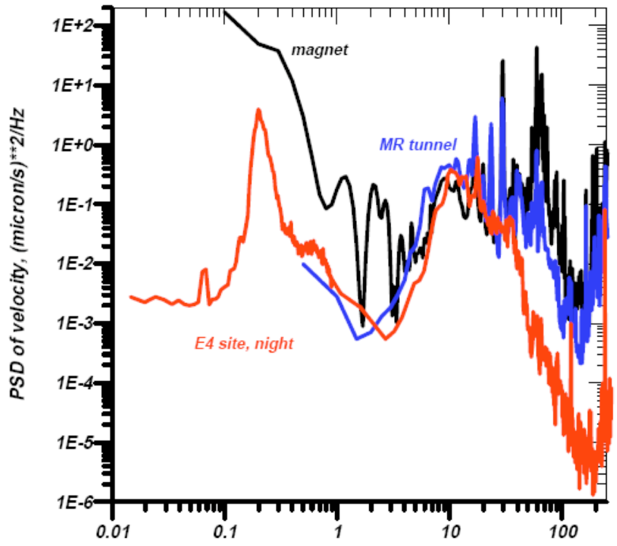
The entire lab space will need to have a safety evaluation, including high voltage, cryogenic safety, and laser safety-interlocked entrances.

100m long facility with 3 experimental halls

Cast concrete tunnel,
11’ wide,
9’ high,
140’ (?) long

14’ wide x 14’ high x 20’ long
clean rooms

Ground motion at E4R

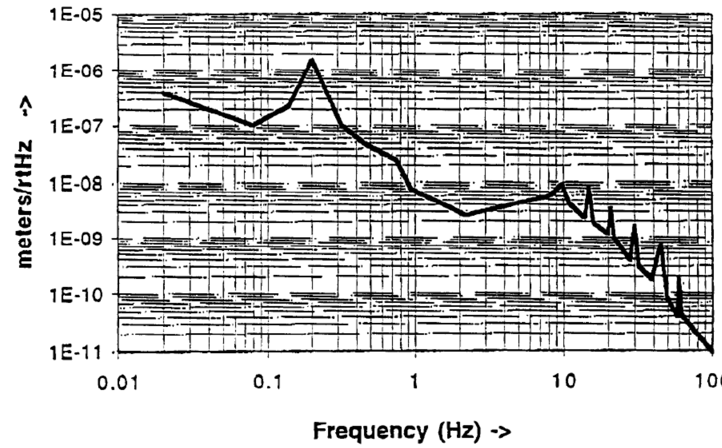


Baklakov, et.al

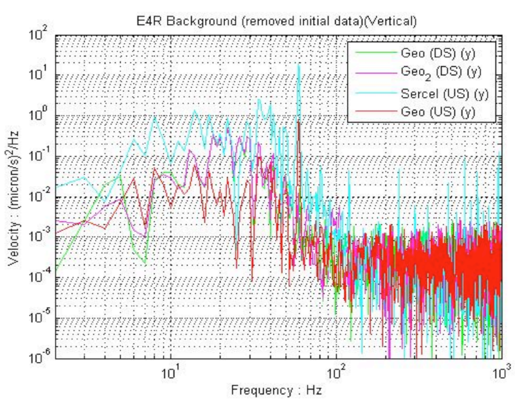
FIG. 7. (Color) Power spectral densities of vertical vibrations of the Tevatron quadrupole magnet (upper curve), the main ring tunnel floor, and on the surface at E4 (lower curve).

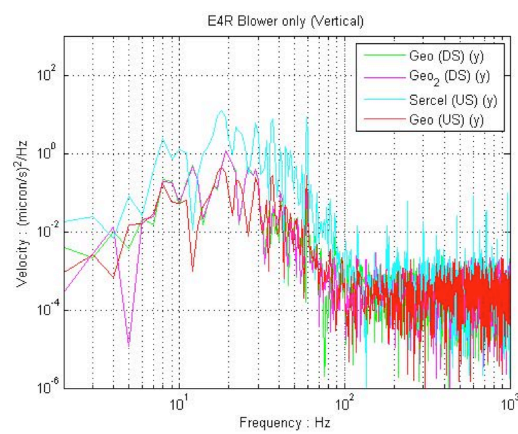
Amplitude = velocity/ (2π f)

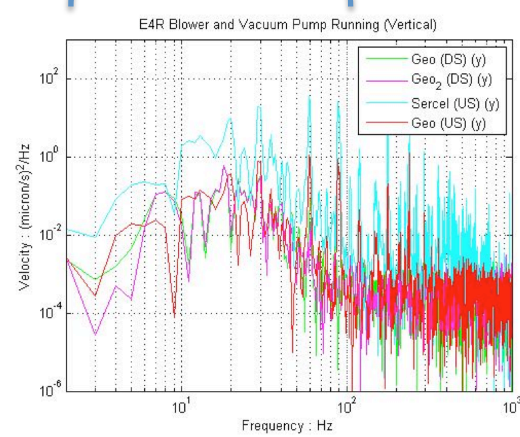
Fig 7.2, proposal for Nesrick cavity experiment



McGee, Volk, 2009







What are the risks?

- The sensitivity depends critically on cavity finesse $F^{1/2}$.
  - The highest finesse on a large cavity ever achieved was $F=3\ 10^5$, obtained routinely by PVLAS on a 1 meter cavity. (However, people in LIGO now talk about $F=10^7$)
  - We want to do $F=10^5$ on a 40 meter cavity where the spot sizes on the mirrors are much larger, and so we are more sensitive to local imperfections.
  - If we cannot achieve this finesse, then our sensitivity degrades to be comparable to that of the CERN Axion Solar Telescope.
    - However we would still have a comparable laboratory limit which does not rely on modeling of possible axion emission/reabsorption in the sun.

- There is NO risk to the Tevatron magnets. We ramp them slowly and leave them at DC for long periods of running.

- Collaboration with outside universities on LIGO may involve some NSF funding.

Timeline

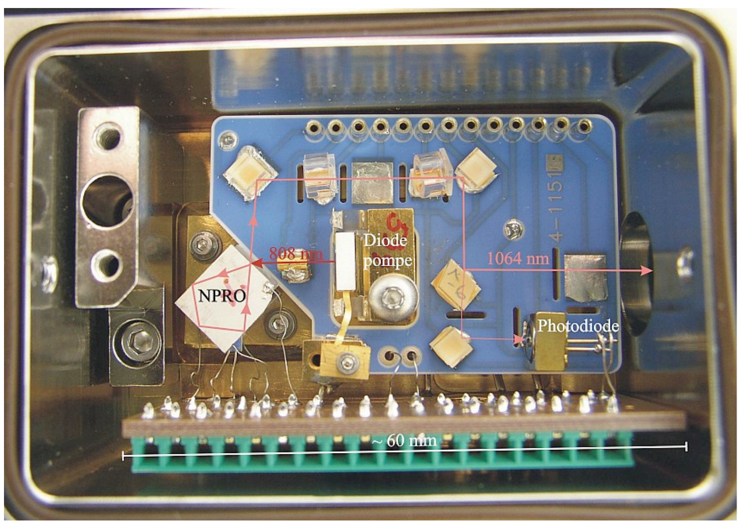
- December, 2008: Design meeting at University of Florida
  - Optical cavity parameters, heterodyne detection scheme

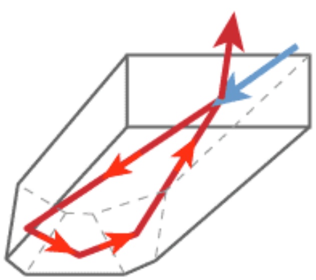
- Early 2009: we are making making measurements to qualify our laser and detectors. We have also obtained ground motion data as input into design of passive and active damping systems.

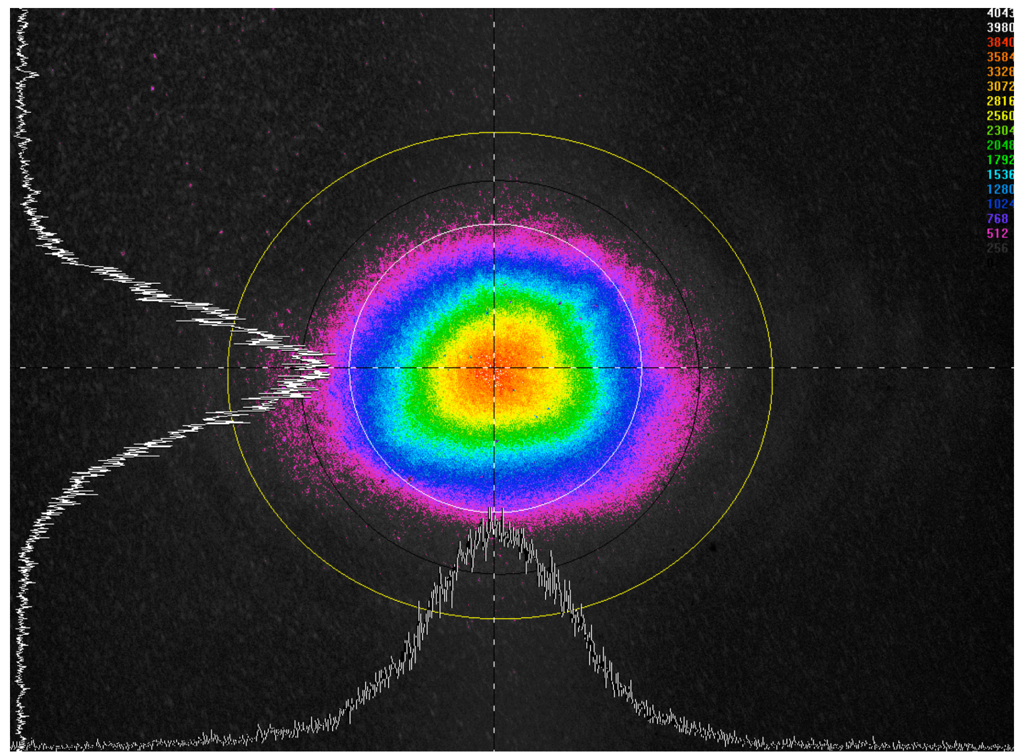
- Over the summer:
  - We are building a miniature, tabletop LIGO optical interferometer including all feedback systems to phase-lock the lasers to the cavities, and vice-versa
  - Collaborators at U.Florida will expand these locking systems to larger cavities using techniques developed for LISA.
  - The optical heterodyne detection scheme will be validated on a testbench.

- Over 1-year:
  - Develop holographic noise interferometer with 40 meter arm cavities with "easy" $F=10^3$, and use these long vacuum chambers to work towards $F=10^5$.
  - Once achieved, make proposal to the laboratory to borrow and operate a string of magnets at E4R.
    - All necessary parts for magnet operation are already available.

Laser profile measurements with CCD to aid in design of Gaussian optics transport system







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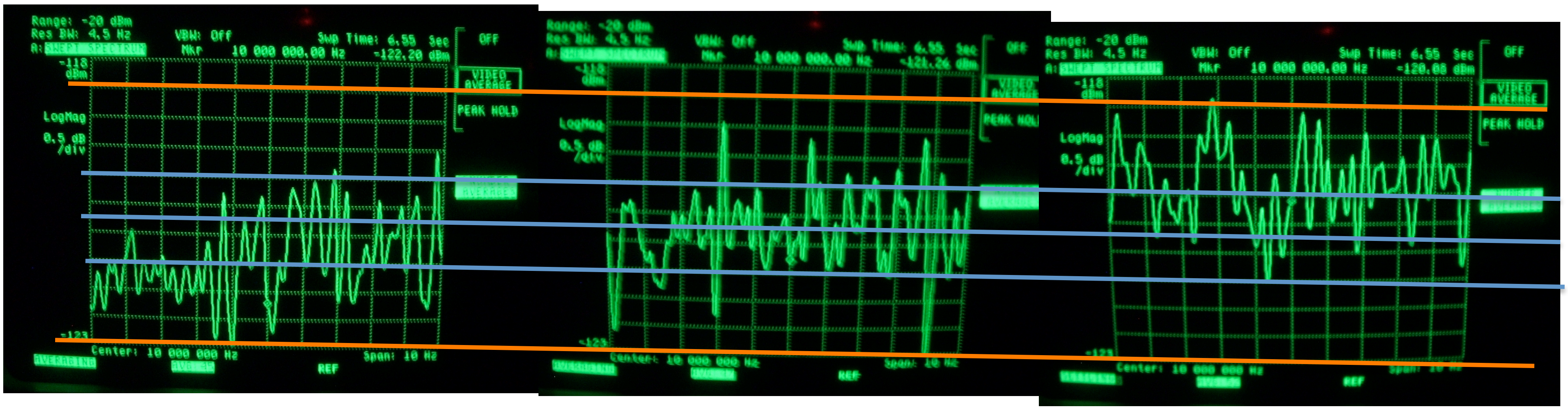
Laser Relative Intensity Noise measured with RF photodiode at 10 MHz, 40 sweep average

Laser OFF | Laser DC=43 mV (57 uW) | Laser DC=80 mV (107 uW)



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- Scaling of excess noise variance pA^2/Hz with laser power is ~linear.
- Axion measurement should be shot-noise-limited in our detection band of ~10 MHz.

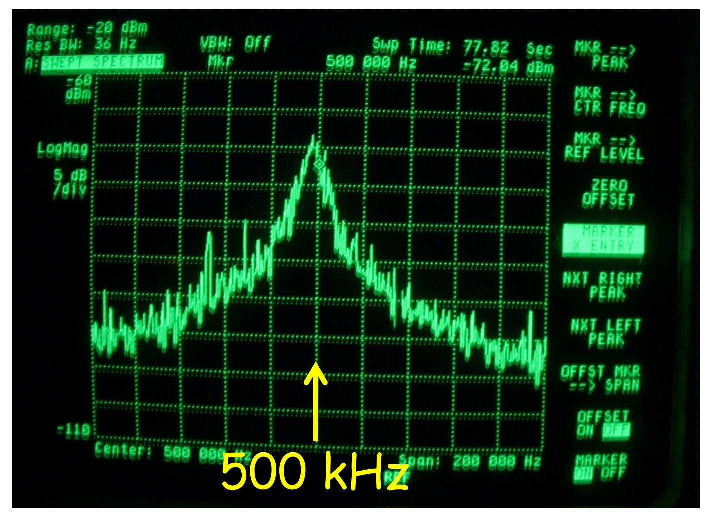
A last thought: Direct detection of axion dark matter (Optically-amplified ADMX)

- Melissinos, 2008: a monochromatic standing wave trapped in a cavity will develop sidebands due to non-linear interactions with the background axion field. $\vec{\nabla} \cdot \vec{E} = g\vec{B} \cdot \vec{\nabla}\phi$

Modified Maxwell's equations $\vec{\nabla} \times \vec{B} - \frac{\partial \vec{E}}{\partial t} = g\left[\vec{E} \times \vec{\nabla}\phi - \vec{B}\frac{\partial \phi}{\partial t}\right]$

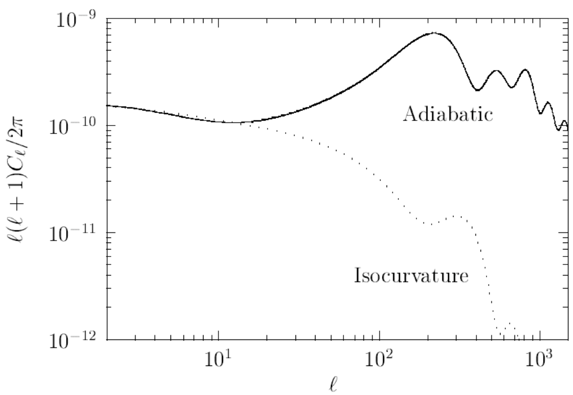
- Use optical homodyne detection to amplify and detect the sidebands. Example: measurement of 500 kHz laser cavity noise obtained by mixing (280 THz) with (280 THz+-500 kHz) output light into a 125 MHz detector.

QUIET HEMT detectors can act as IR photodiodes with >300 GHz bandwidth. This gives sensitivity to dark matter axion masses all the way up to 10^{-3} eV. (ADMX stuck at 10^{-5} eV)

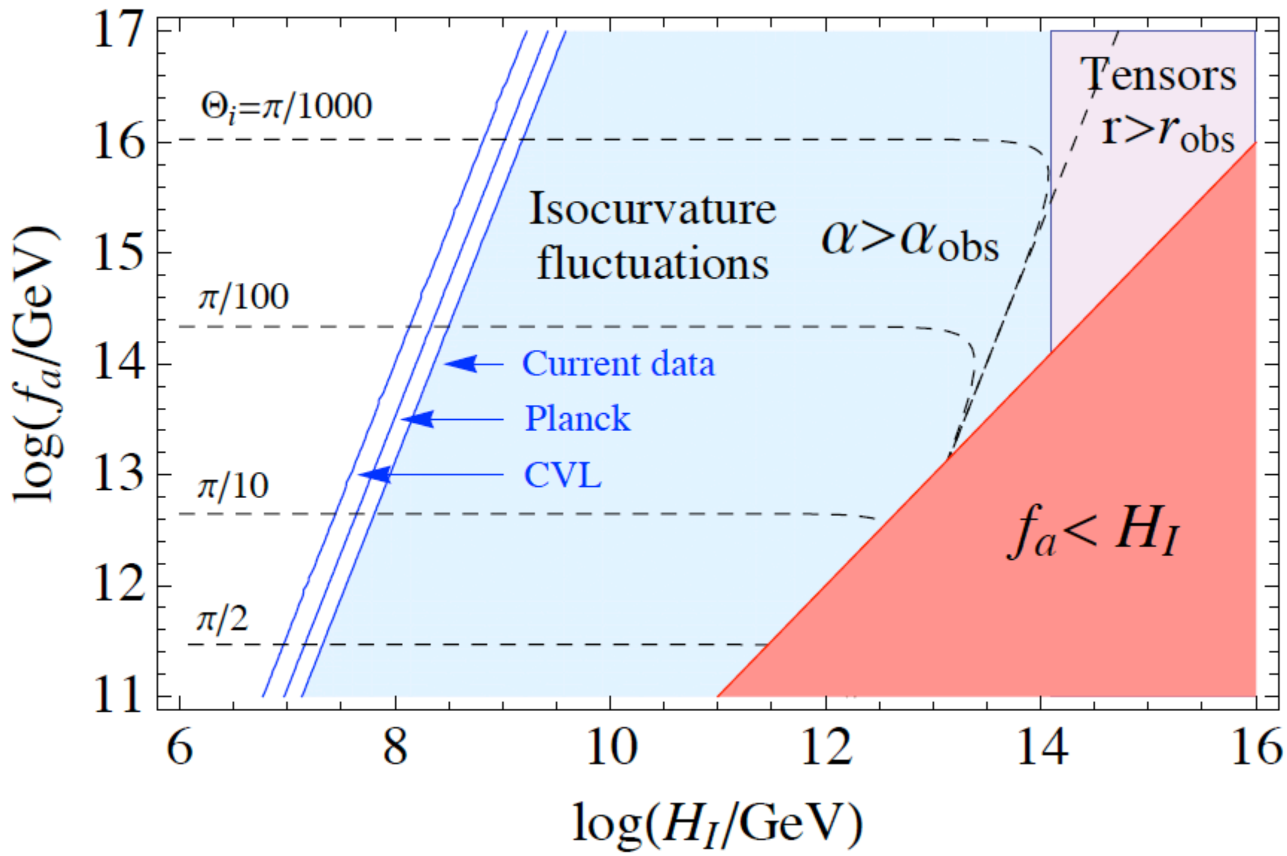


- **Unlike other direct detection experiments, the optically amplified signal is independent of target volume!**

Axions and CMB measurements are complementary probes of the scale of inflation



J. Hamann[1], S. Hannestad[2], G. G. Raffelt[3] and Y. Y. Y. Wong[4]

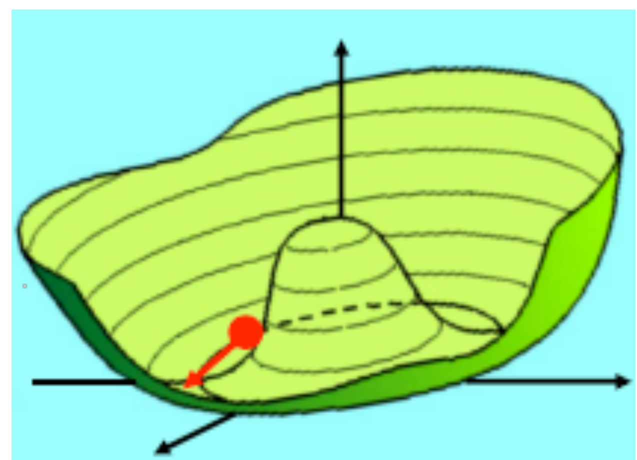


- *Axion dark matter searches measure mass, rate, and can determine the* coupling ~1/f assuming $m=\Lambda_{qcd}^2/f$. If $f>10^{14}$ GeV, then the inflation scale is low. Focus then on measuring H_I via isocurvature.
- Alternatively if B-mode polarization is discovered, then f is low.

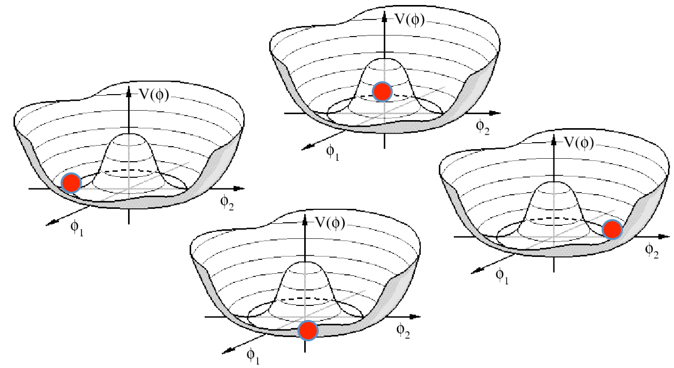
Backup slides

Dynamical solution: Peccei-Quinn axions

- Total EDM parameterized by the $\theta G\tilde{G}$ term in the QCD action.
- Promote θ to a dynamical field. $\frac{\theta g^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu} \rightarrow \frac{1}{2}\partial_\mu A \partial^\mu A + \frac{g^2}{32\pi^2}\frac{A(x)}{f_A} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$
- Spontaneous symmetry breaking of a new symmetry at some high mass scale f_A produces a Mexican hat potential for A.
  - Due to $AG\tilde{G}$ coupling this potential gets tilted by instanton effects (non-zero expectation value for $\langle G\tilde{G}\rangle$) during the QCD phase transition as the quark-gluon plasma condenses into protons/ neutrons
  - The action is minimized when $(\arg(\langle A\rangle) + \theta_{orbital} + \theta_{quark}) \langle G\tilde{G}\rangle = 0$ so the neutron EDM is dynamically set to zero.
  - The quantized fluctuation ϕ gets a mass:
    $V(\phi) \sim \Lambda_{QCD}^4 \cos(\phi/f_A) \dashrightarrow m_\phi \sim \Lambda_{QCD}^2/f_A$
  - The axion ϕ couples to two-photons via a quark loop.



Axion Dark Matter



- After the PQ phase transition, θ is an angular variable taking random values from 0-2π since all values of θ have equal potential energy.
- Furthermore, spatial fluctuations in this angular field are seeded by inflation $d\theta^2 \sim (H_I/f_{PQ})^2$.
- During the QCD phase transition, the vacuum degeneracy is broken, and locally, while $H>m_\phi$ the classical axion field gets frozen at a non-zero value with potential energy $\sim \theta^2\Lambda_{QCD}^4$

  – θ determines how much of the plasma energy goes into protons/neutrons and how much is stored as vacuum energy
  – A short period later, when $H<m_\phi$, the vacuum energy density is released as cold axions with momentum $\sim H = 3\ 10^{-9}$ eV
  – The axion contribution to Ω_m is determined by θ and m_ϕ, i.e. the total vacuum energy density, and how long it is preserved as dust/radiation get redshifted away.
  – Dark matter over/underdensities due to $d\theta^2$ induce isocurvature fluctuations in the CMB temperature via Sachs-Wolf.