Searches for Axion-Like Particles and Paraphotons with JLAB FEL

Andrei Afanasev (for LIPSS Collaboration)
Hampton University/Jefferson Lab
USA

Dark Forces Workshop, SLAC
September 24-26, 2009

LIPSS collaboration

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(2) Presently at Muons, Inc (Batavia, IL)

What is Dark Matter? Particle interpretation:
(Still unknown) elementary particles that interact only weakly with `normal' matter

One of the candidates: **Axion** - also addresses a *strong CP problem* in QCD

VOLUME 40, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JANUARY 1978

A New Light Boson?

Steven Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 6 December 1977)

It is pointed out that a global U(1) symmetry, that has been introduced in order to preserve the parity and time-reversal invariance of strong interactions despite the effects of instantons, would lead to a neutral pseudoscalar boson, the "axion," with mass roughly of order 100 keV to 1 MeV. Experimental implications are discussed.

VOLUME 40, NUMBER 5 PHYSICAL REVIEW LETTERS 30 JANUARY 1978

Problem of Strong P and T Invariance in the Presence of Instantons

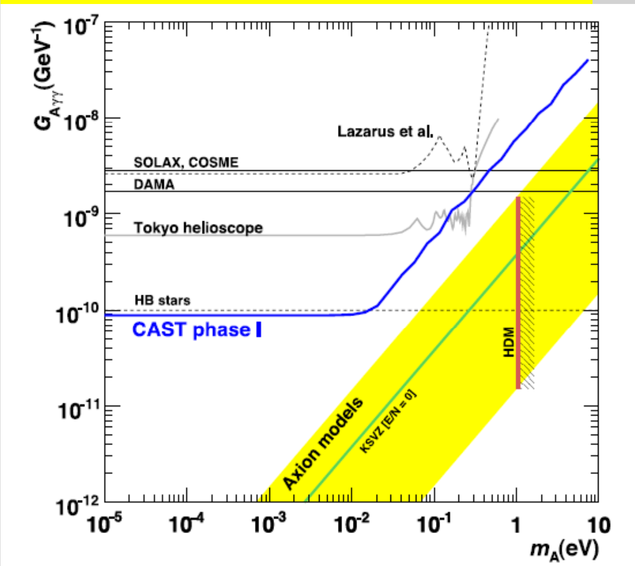
F. Wilczek[a]
Columbia University, New York, New York 10027, and The Institute for Advanced Studies, Princeton, New Jersey 08540[b]
(Received 29 November 1977)

The requirement that P and T be approximately conserved in the color gauge theory of strong interactions without arbitrary adjustment of parameters is analyzed. Several possibilities are identified, including one which would give a remarkable new kind of very light, long-lived pseudoscalar boson.

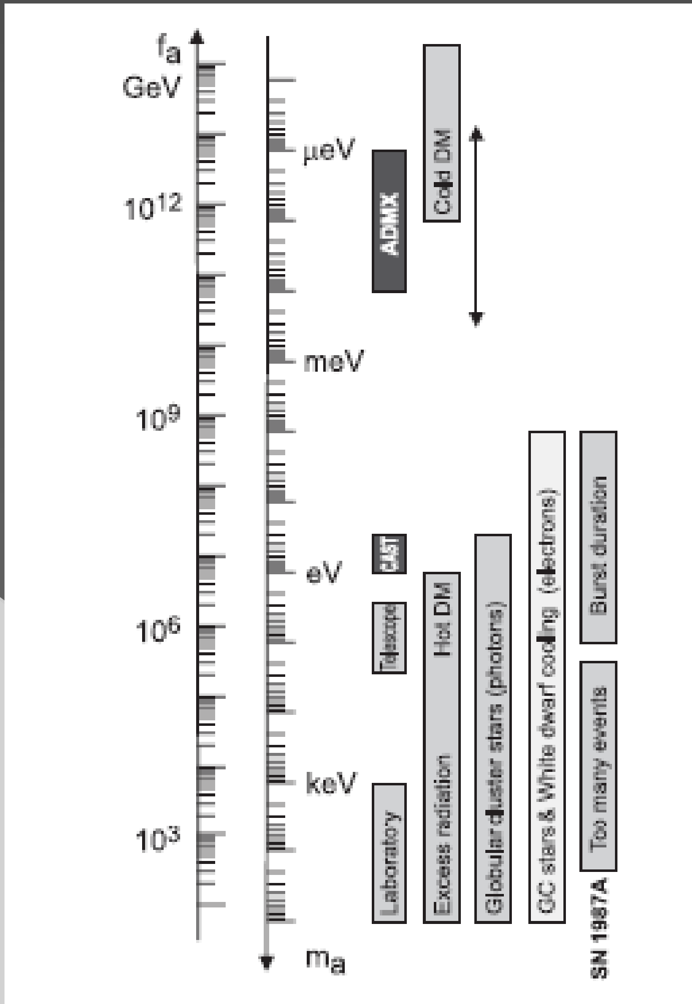
Open mass range for axions

The combination of accelerator searches, astrophysical, and cosmological arguments leaves open a search window

$10^{-6} < m_a < 10^{-3}$ eV



from PDG'08



LIPSS is a laser-based laboratory experiment that searches for axion-like particles with masses in the range of milli-eV

PVLAS results (2006)

PRL 96, 110406 (2006) PHYSICAL REVIEW LETTERS week ending 24 MARCH 2006

Experimental Observation of Optical Rotation Generated in Vacuum by a Magnetic Field

E. Zavattini,[1] G. Zavattini,[2] G. Ruoso,[3] E. Polacco,[4] E. Milotti,[5] M. Karuza,[1] U. Gastaldi,[3] G. Di Domenico,[2] F. Della Valle,[1] R. Cimino,[6] S. Carusotto,[4] G. Cantatore,[1,*] and M. Bregant[1]

(PVLAS Collaboration)

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(Received 29 July 2005; revised manuscript received 8 February 2006; published 24 March 2006)

We report the experimental observation of a light polarization rotation in vacuum in the presence of a transverse magnetic field. Assuming that data distribution is Gaussian, the average measured rotation is $(3.9 \pm 0.5) \times 10^{-12}$ rad/pass, at 5 T with 44 000 passes through a 1 m long magnet, with $\lambda = 1064$ nm. The relevance of this result in terms of the existence of a light, neutral, spin-zero particle is discussed.

DOI: 10.1103/PhysRevLett.96.110406 PACS numbers: 12.20.Fv, 07.60.Fs, 14.80.Mz

Based upon experimental idea of
L. Maiani, R. Petronzio, and
E. Zavattini,
Phys. Lett. B 175, 359 (1986)

Can be understood in terms of a new elementary particle about 500million times lighter than an electron

COSMOLOGY

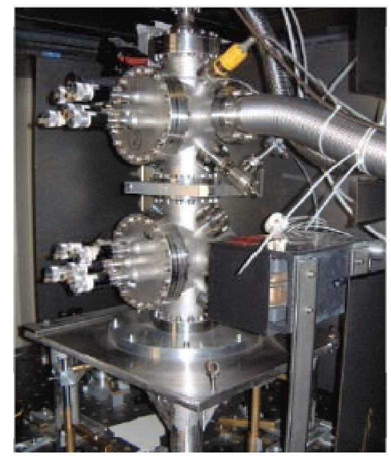
Science, 17 March 2006

Magnet Experiment Appears to Drain Life From Stars

It's an unassuming experiment: to see how a magnetic field affects polarized laser light. And the rotation the researchers saw was tiny, a mere 100,000th of a degree. If the result is true, however, the implications are huge. According to researchers in Italy who conducted the experiment, this slight twist in the beam—the result of disappearing photons—suggests the existence of a small, never-before-seen neutral particle, which, if made in stars, would siphon off all their energy.

Even theorists who find that scenario far-fetched are struggling to explain the disappearance of the photons. "I'm skeptical of the particle interpretation," says theoretical physicist Georg Raffelt of the Max Planck Institute for Physics in Munich, Germany. "But there are no other obvious explanations."

Standard physics predicts a very small rotation in a beam's polarization in a magnetic field due to ordinary particles popping in and out of the vacuum. But when researchers at the PVLAS experiment at Legnaro National Laboratory of Italy's National Institute for Nuclear Physics turned on their 5-tesla magnet in 2000, they immediately saw a rotation 10,000 times larger than expected, says PVLAS member Giovanni Cantatore of the University of Trieste.

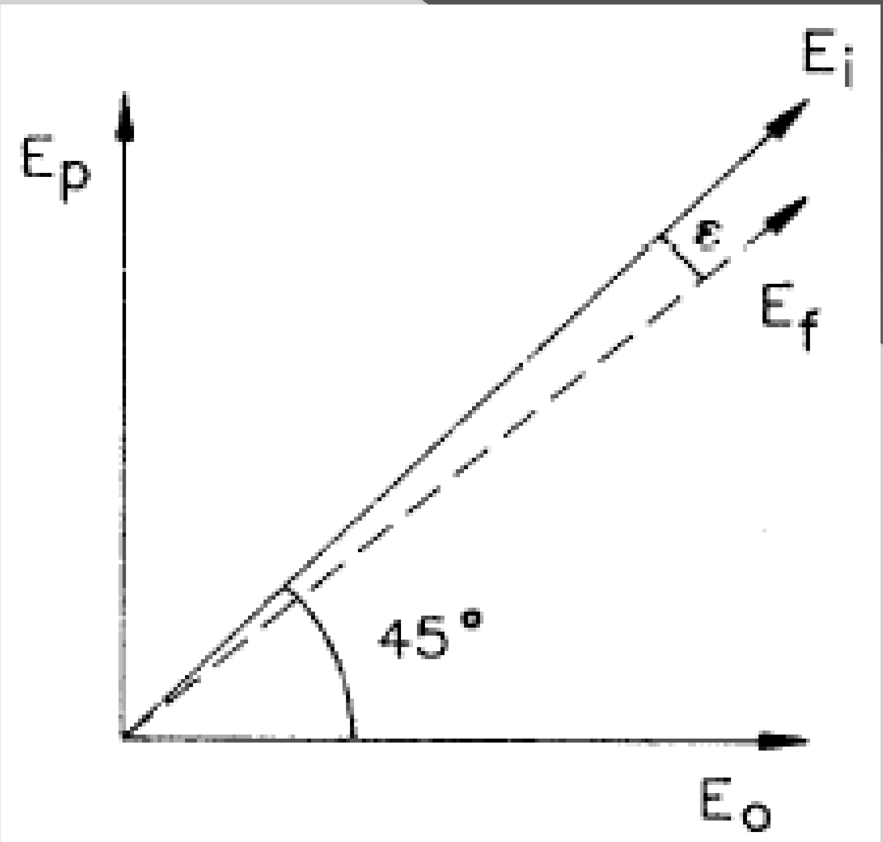


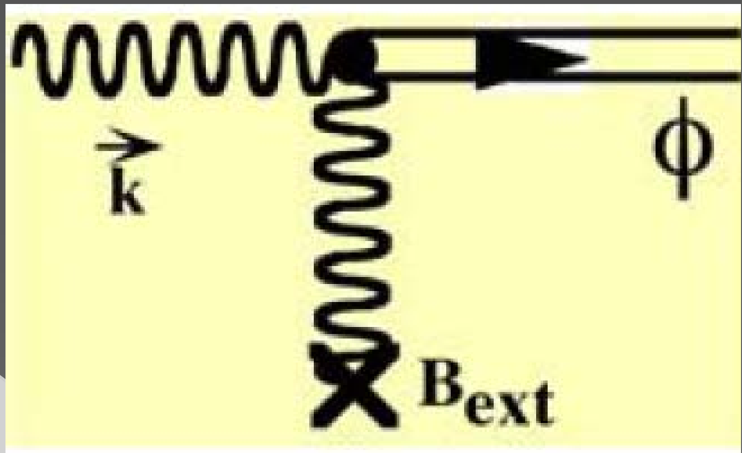
A twist in the tale. By rotating a laser beam with magnets, this experiment may have found never-before-seen particles.

some cosmologists propose is the invisible missing dark matter that makes up a large chunk of the mass of the universe. However, the particle suggested by the PVLAS experiment is not what

Dichroism

rotation of polarization plane
[PVLAS Collab] Phys.Rev.Lett. 96, 110406 (2006);
[BFRT Collab] Phys Rev D47, 3707 (1993)



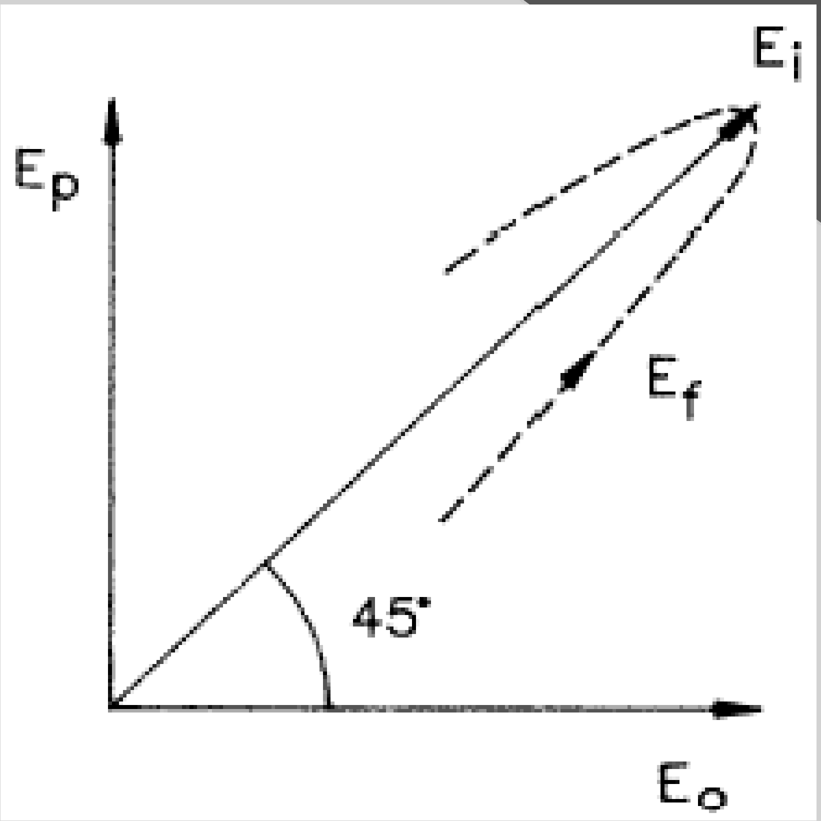


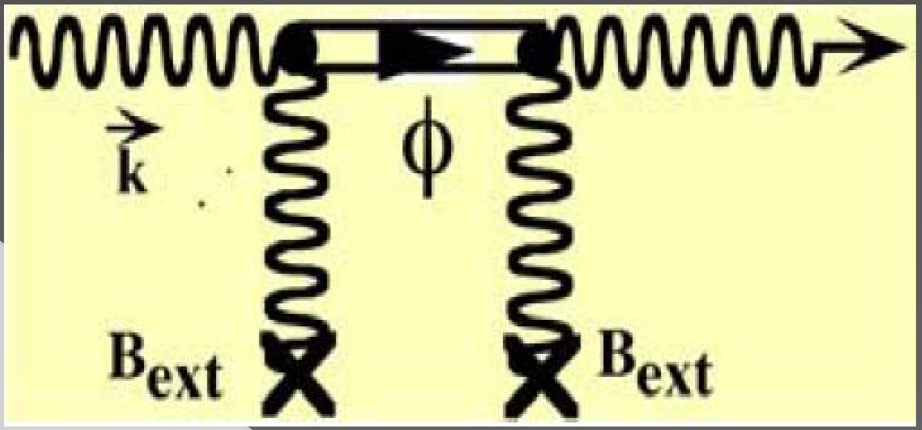
Dichroism caused by production of particle φ in photon-photon collision

Ellipticity

dispersion: photon-axion mixing

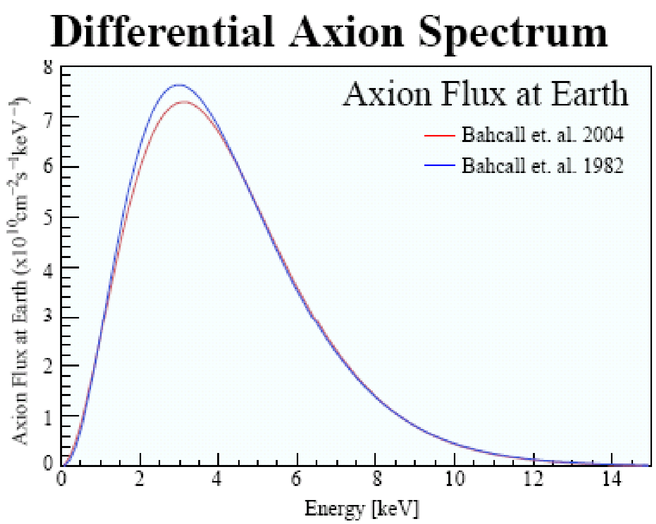
hep-ex/0507061 (2005); Phys Rev D47, 3707 (1993)





Ellipticity caused by a virtual particle φ mediating elastic photon-photon scattering

CAST experiment



Mean energy: $< E >= 4.2\,\mathrm{keV}$

Axion Luminosity:

$$L_a = 1.9 \times 10^{-3} L_\odot$$

Axion flux: $\Phi_a = 3.8 \times 10^{11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

Uses LHC prototype dipole, looks for axions from the sun regenerating photons in the x-ray region. K. Zioutas *et al.*, PRL 94, 121301 (2005)

Have seen no effect

PVLAS: No signal from the upgraded apparatus (2007)

PHYSICAL REVIEW D **77**, 032006 (2008)

New PVLAS results and limits on magnetically induced optical rotation and ellipticity in vacuum

E. Zavattini,[1,*] G. Zavattini,[2] G. Ruoso,[3] G. Raiteri,[1] E. Polacco,[4] E. Milotti,[1] V. Lozza,[1] M. Karuza,[1] U. Gastaldi,[3] G. Di Domenico,[2] F. Della Valle,[1] R. Cimino,[5] S. Carusotto,[4] G. Cantatore,[1] and M. Bregant[1]

(PVLAS Collaboration))

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[2]*INFN, Sezione di Ferrara and Dipartimento di Fisica, Università di Ferrara, Ferrara, Italy*
[3]*INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy*
[4]*INFN, Sezione di Pisa and Dipartimento di Fisica, Università di Pisa, Pisa, Italy*
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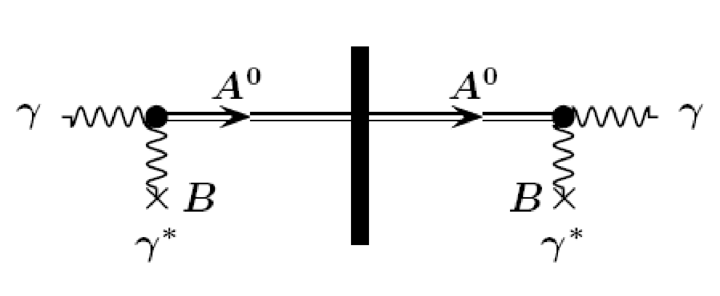
(Received 5 November 2007; published 29 February 2008)

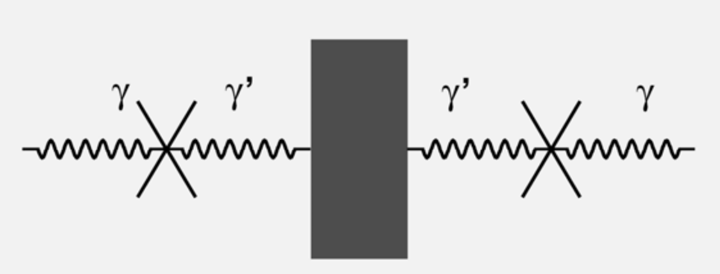
In 2006 the PVLAS collaboration reported the observation of an optical rotation generated in vacuum by a magnetic field. To further check against possible instrumental artifacts, several upgrades to the PVLAS apparatus have been made during the past year. Two data taking runs, at the wavelength of 1064 nm, have been performed in the new configuration with magnetic field strengths of 2.3 and 5 T. The 2.3 T field value was chosen in order to avoid stray fields. The new observations do not show the presence of a rotation signal down to the levels of 1.2×10^{-8} rad at 5 T and 1.0×10^{-8} rad at 2.3 T (at 95% C.L.) with 45 000 passes in the magnetic field zone. In the same conditions no ellipticity signal was detected down to 1.4×10^{-8} at 2.3 T (at 95% C.L.), whereas at 5 T a signal is still present. The physical nature of this ellipticity as due to an effect depending on B^2 can be excluded by the measurement at 2.3 T. These new results completely exclude the previously published magnetically induced vacuum dichroism results, indicating that they were instrumental artifacts. These new results therefore also exclude the particle interpretation of the previous PVLAS results as due to a spin-zero boson. The background ellipticity at 2.3 T can be used to determine a new limit on the total photon-photon scattering cross section of $\sigma_{\gamma\gamma} < 4.5 \times 10^{-34}$ barn at 95% C.L.

Photon Regeneration in `Light Shining through a Wall' (LSW)

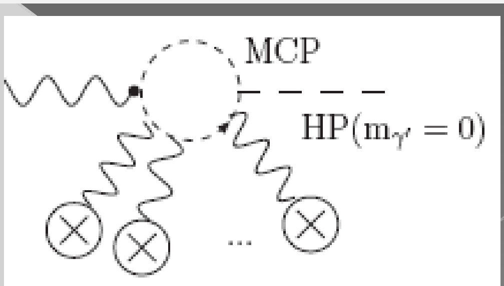
- Photon-axion conversion in presence of magnetic field



- Photon-(massive) paraphoton oscillation (no magnetic field)

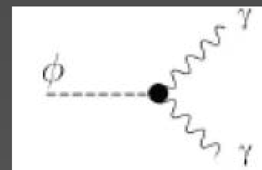


- Photon-(massless) paraphoton conversion in magnetic field via quantum loop of mini-charged particles (MCP)



Experimental that use LSW: LIPSS(Jlab, this talk) , BFRT (BNL), BMV(LULI), GammeV (Fermilab), ALPS(DESY), OSCAR (CERN), PVLAS (INFN)

Axion-Like Particle Coupling to Photons



- Light, neutral boson coupling to photons

pseudoscalar particle and pseudoscalar interaction

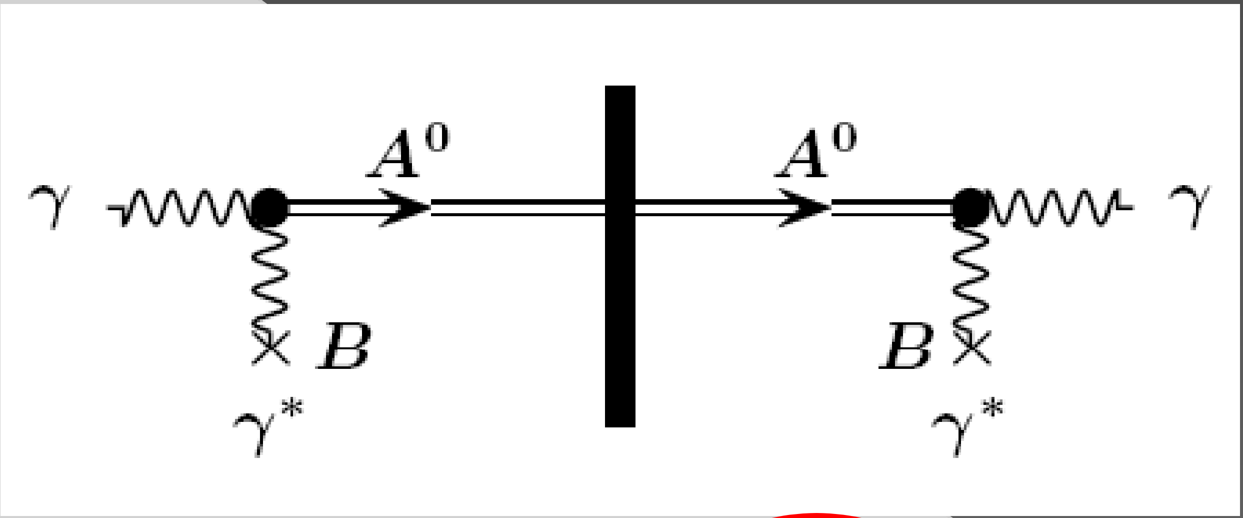
$$L_{\varphi\gamma\gamma} = -\frac{1}{4M}\varphi F_{\mu\nu}\tilde{F}^{\mu\nu} = \frac{g\varphi}{4}\vec{E}\cdot\vec{B},\ g \equiv \frac{1}{M}$$

$$L_{\varphi\gamma\gamma} = -\frac{1}{4M}\varphi F_{\mu\nu}F^{\mu\nu} = \frac{g'\varphi}{4}(\vec{E}^2 - \vec{B}^2)$$

scalar particle and scalar interaction

- in present case, use FEL laser light and magnetic field from a permanent magnet
- light polarization in direction of magnetic field (pseudoscalar $J^P=0^-$ particle) or perpendicular to magnetic field (scalar $J^P=0^+$ particle)

Photon Regeneration
‘light shining through a wall’



couple polarized laser light with magnetic field

Sikivie (1983); Ansel’m (1985); Van Bibber et al (1987)

$$P_{\gamma\to\varphi} \approx \frac{1}{4}(gBL)^2 \left\{ \frac{\sin\left(\frac{m_\varphi{}^2 L}{4\omega}\right)}{\frac{m_\varphi{}^2 L}{4\omega}} \right\}^2$$

axion – photon (or photon-axion) conversion probability

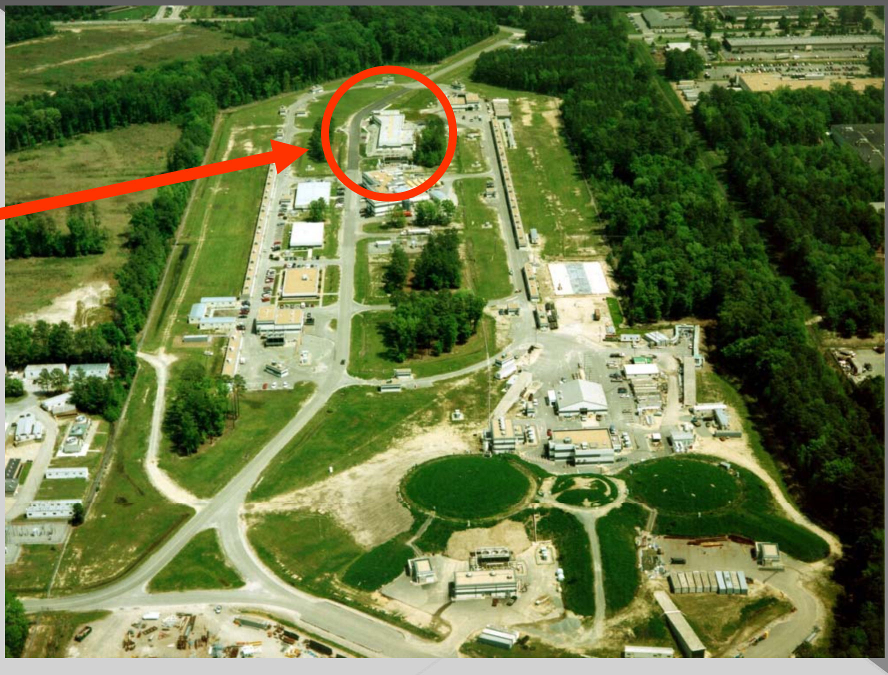
photon-ps coherence; {} ~ 1

$m_\phi^2 < 4\omega/L$

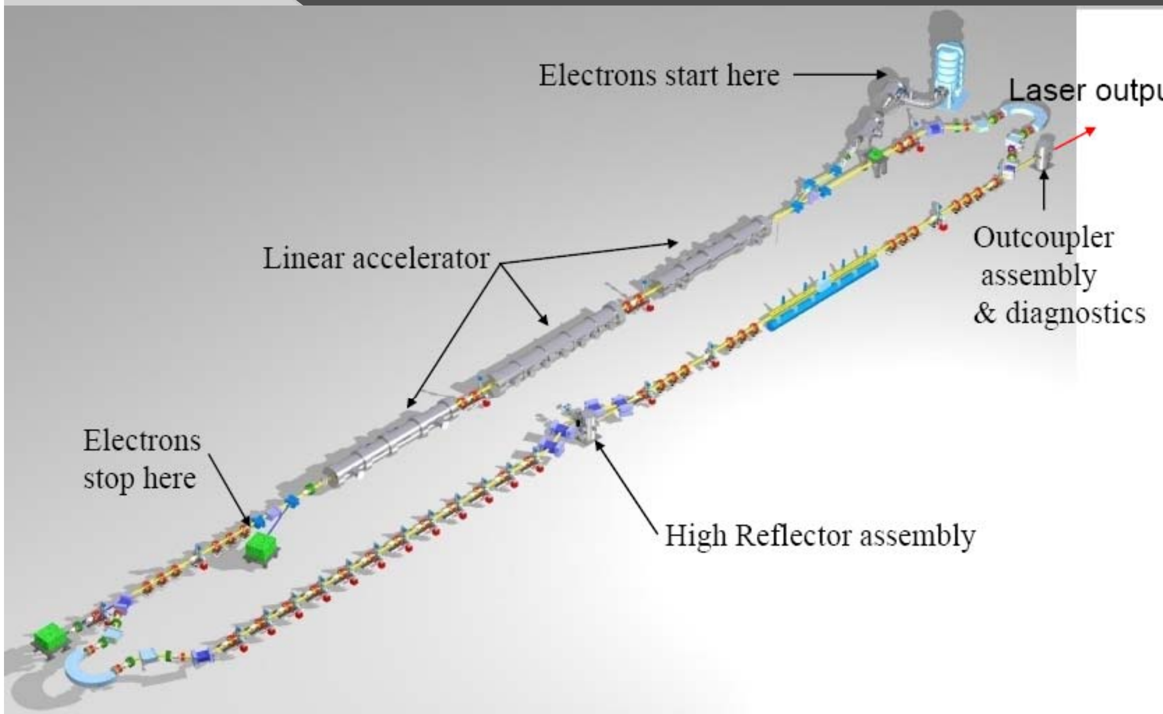
Jefferson Lab is Located in Newport News, Virginia

JLAB's Free Electron Laser

Produced up to 14kW of continuous light at 1.6 micron wavelength

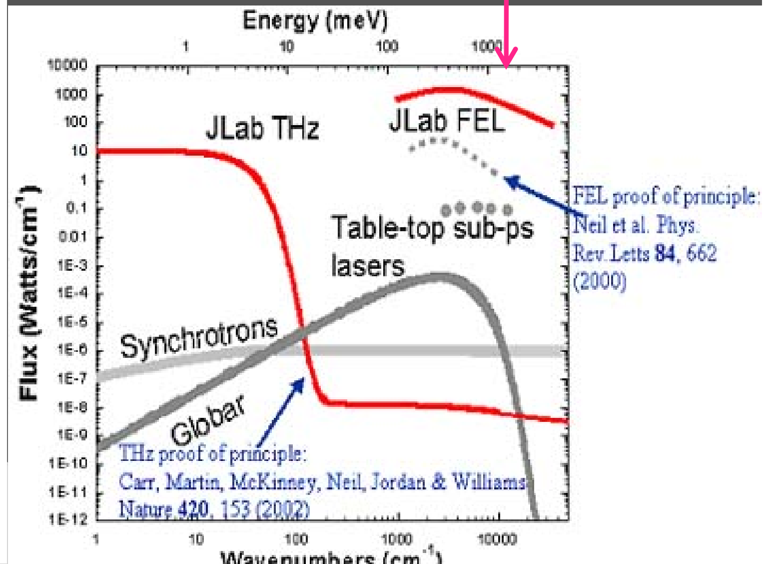


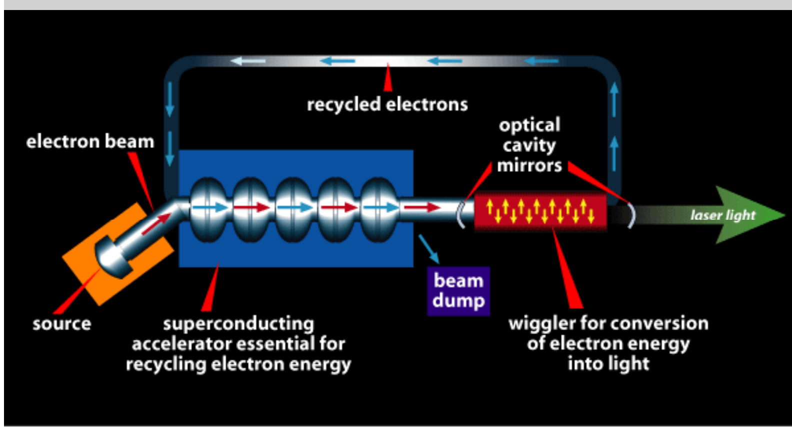
JLAB FEL: Used for LIPSS experiment



Accelerator is over 200 ft long

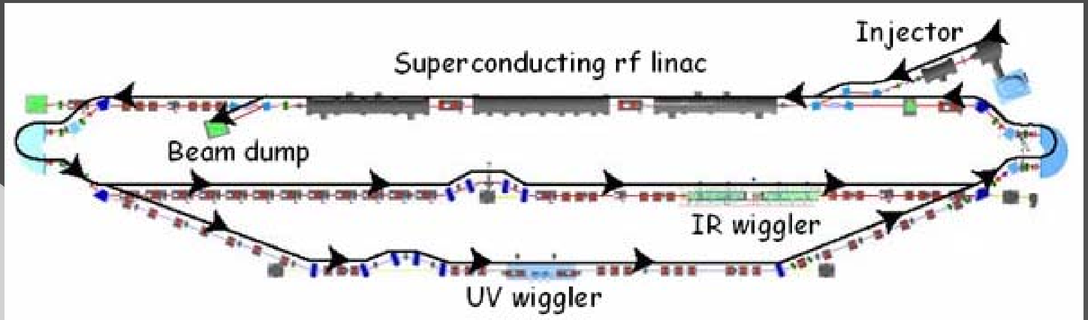
LIPSS IR run at 0.935 micron





- 150 fs wide pulses
- 75 MHz rep rate
- 100 % df
- 935. +/- 005 nm
- 200 watts avg power
- >99% linearly polarized

More info on JLAB FEL



Jefferson Lab FEL Output Light Parameters

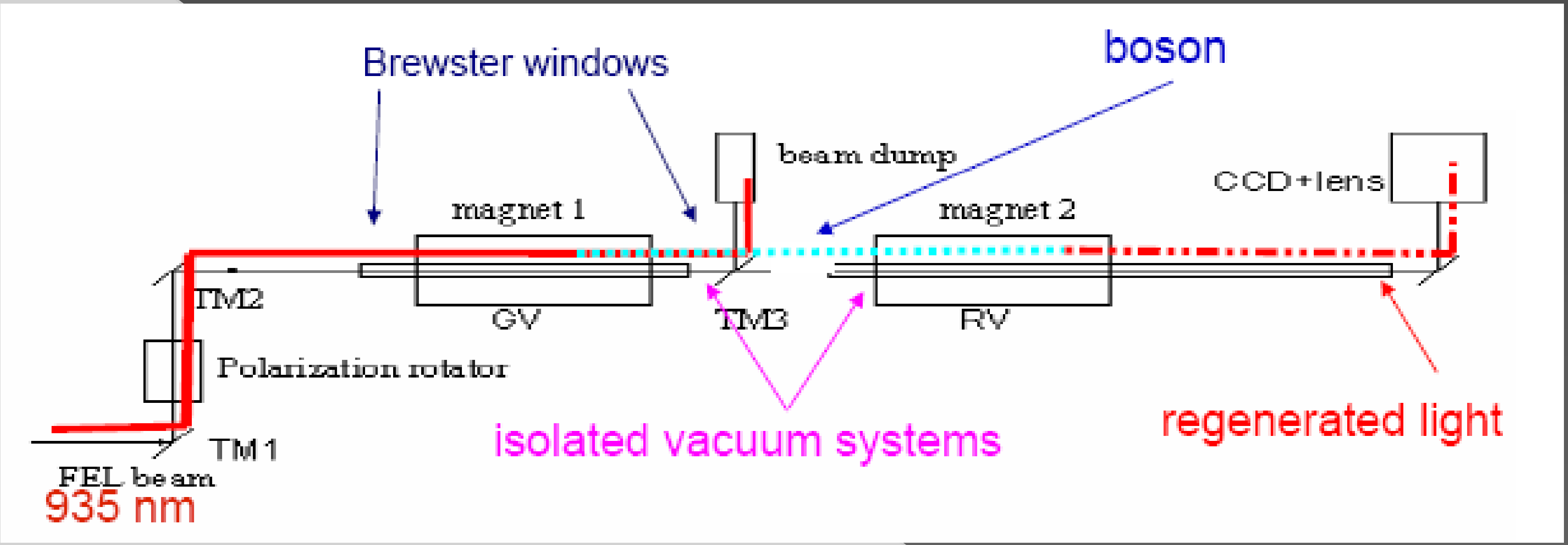
	IR Branch	UV Branch
Wavelength range (microns)	1.5 - 14	0.25 - 1
Bunch Length (FWHM psec)	0.2 - 2	0.2 - 2
Laser energy / pulse (microJoulesJ)	100 - 300	25
Laser power (kW)	> 10	> 1
Repetition Rate (cw operation, MHz)	4.7 - 75	4.7 - 75

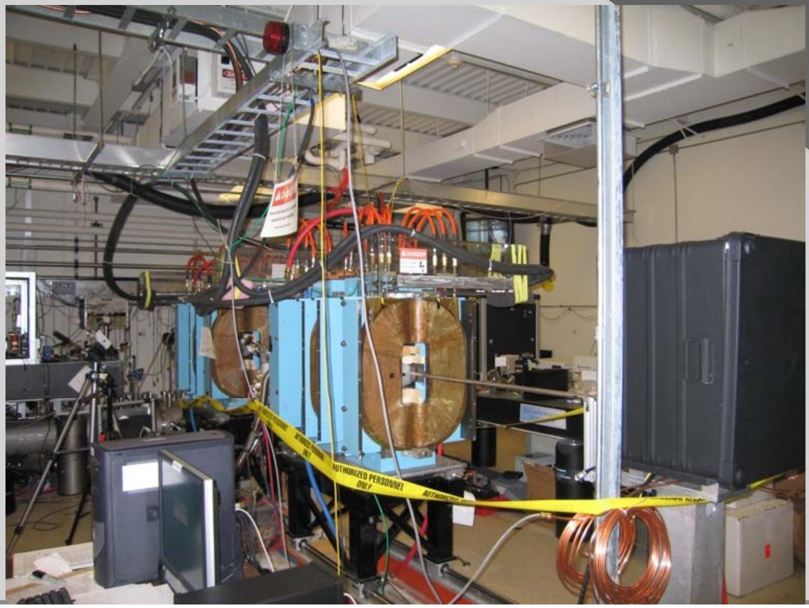
Jefferson Lab FEL Electron Beam Parameters

Energy (MeV)	80-200	200
Charge per bunch (pC)	135	135
Average current (mA)	10	5
Peak Current (A)	270	270
Beam Power (kW)	2000	1000
Energy Spread (%)	0.50%	0.13%
Normalized emittance (mm-mrad)	<30	<11
Induced energy spread (full)	10%	5%

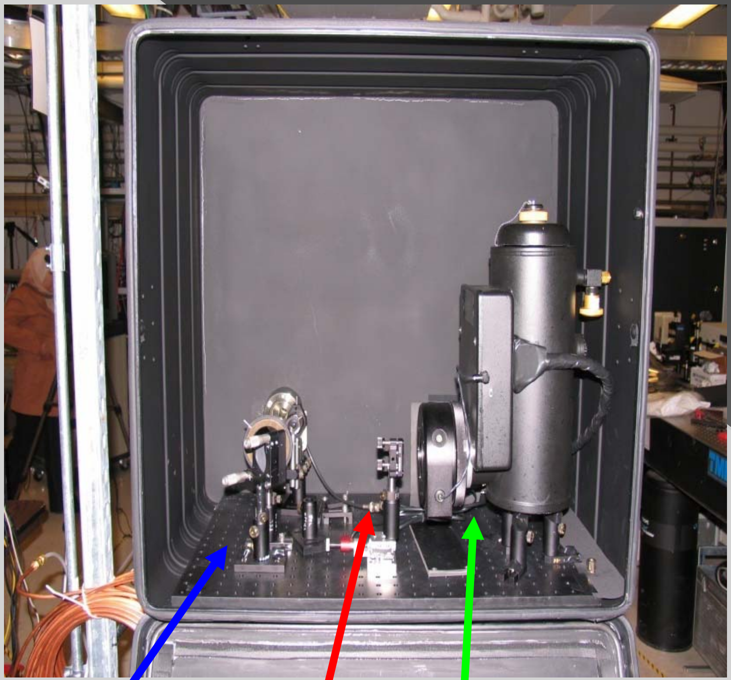
See G. Neil et al., NIM A 557, 9 (2006); www.jlab.org/FEL

LIPSS experiment schematic





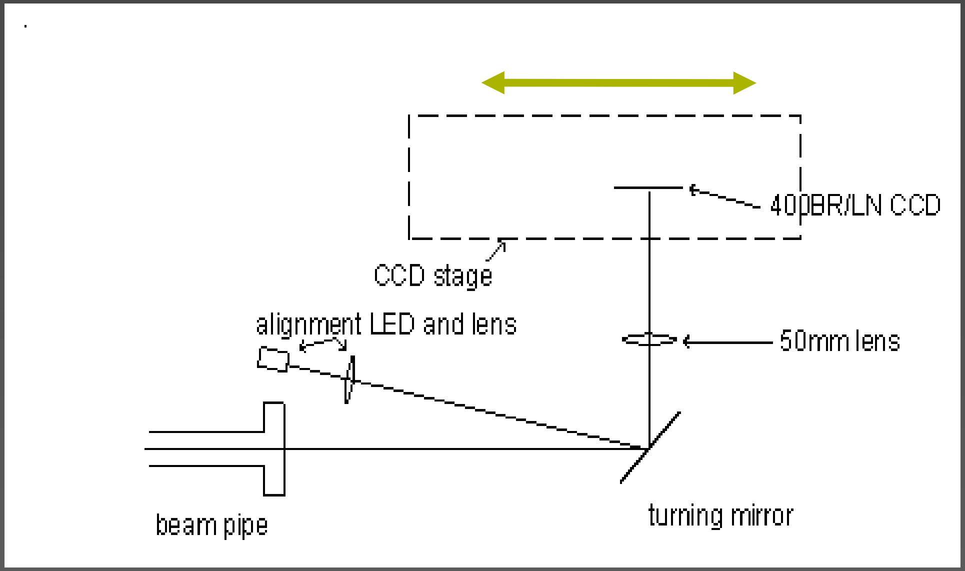
Detector optics

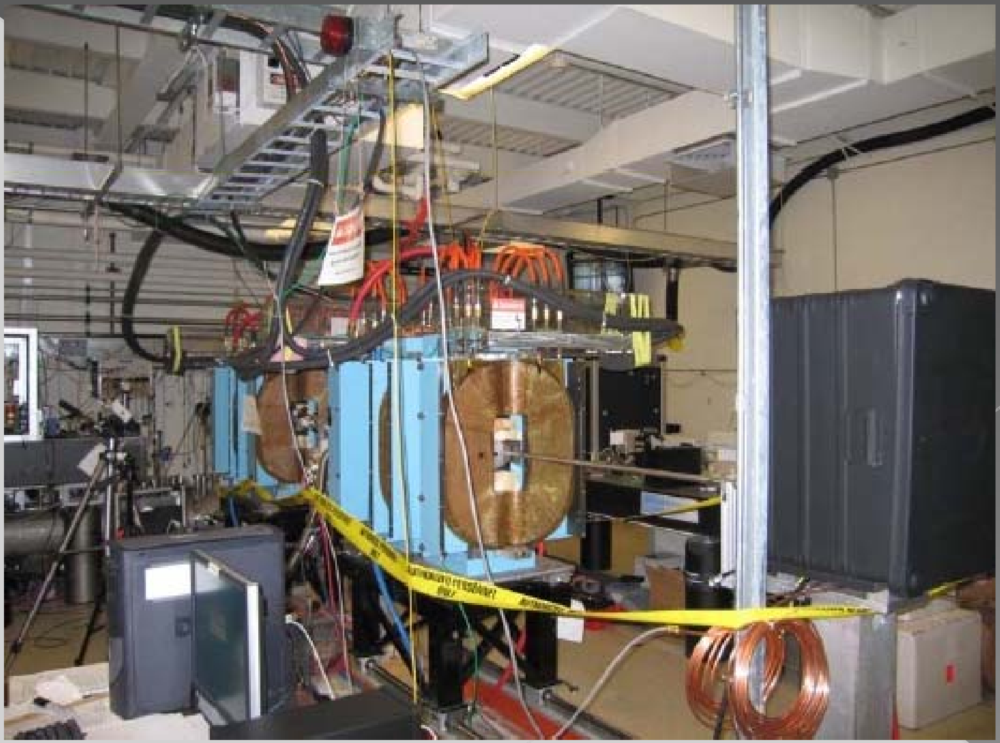


mirror

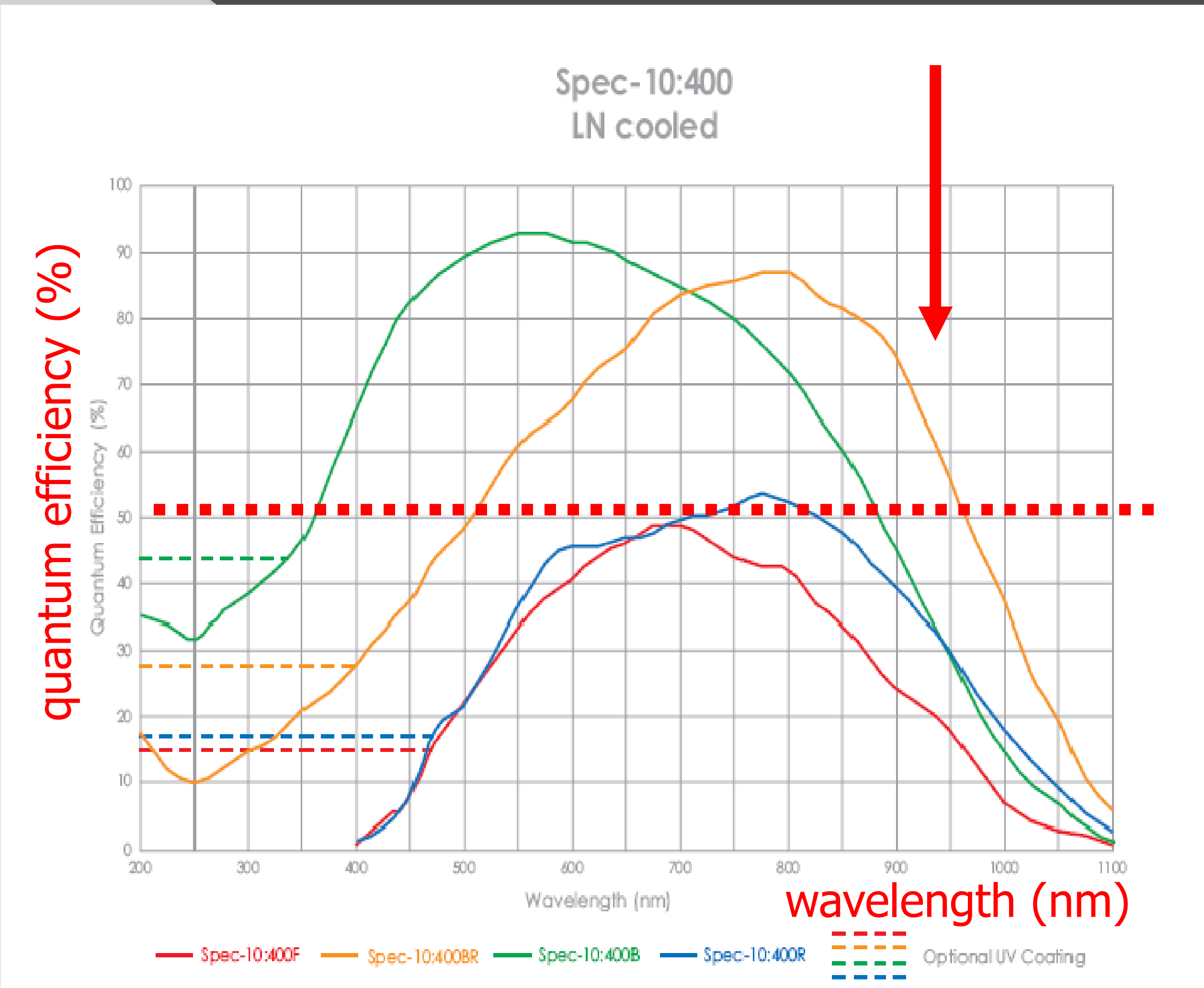
lens

Spec10:400BR-LN camera





Princeton Instruments ACTON 10:400BR-LN



q.e. high at 935 nm

50%

LN2 cooled: 1.3 e/pix/hour dark noise !!!
used 100 kHZ readout rate

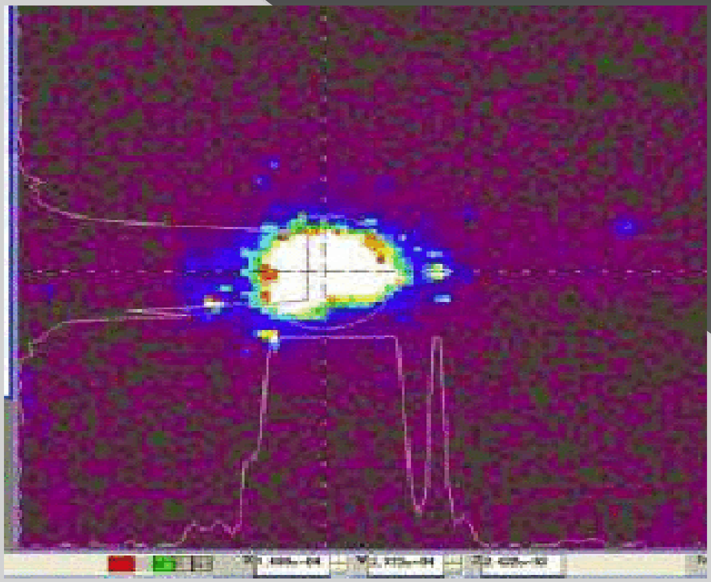
Parameters for initial LIPSS run (2007)

- B-field: 1.7 T
- Magnet length: 1.0 m
- IR FEL power: 0.2 kW (~1kW expected in 2009)
- IR FEL wavelength: 935 nm (1.3 eV)
- Detector quantum efficiency: 0.4
- Linear polarization: 100%
- Acceptance: 100%
- experimental efficiency: ~ 90%

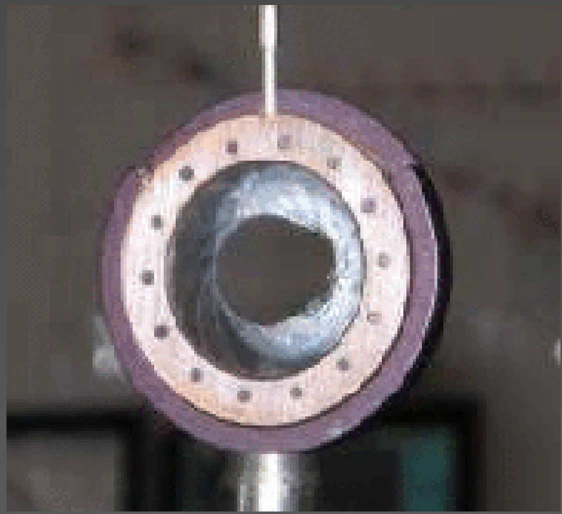
Expect signal rate > 0.01 Hz for

$g_{a\gamma\gamma}$ = 1.7 x 10^{-6} GeV^{-1}

laser beam alignment



beam spot occasionally drifted and had to be adjusted using picomotors; the spots were logged to VHS tape

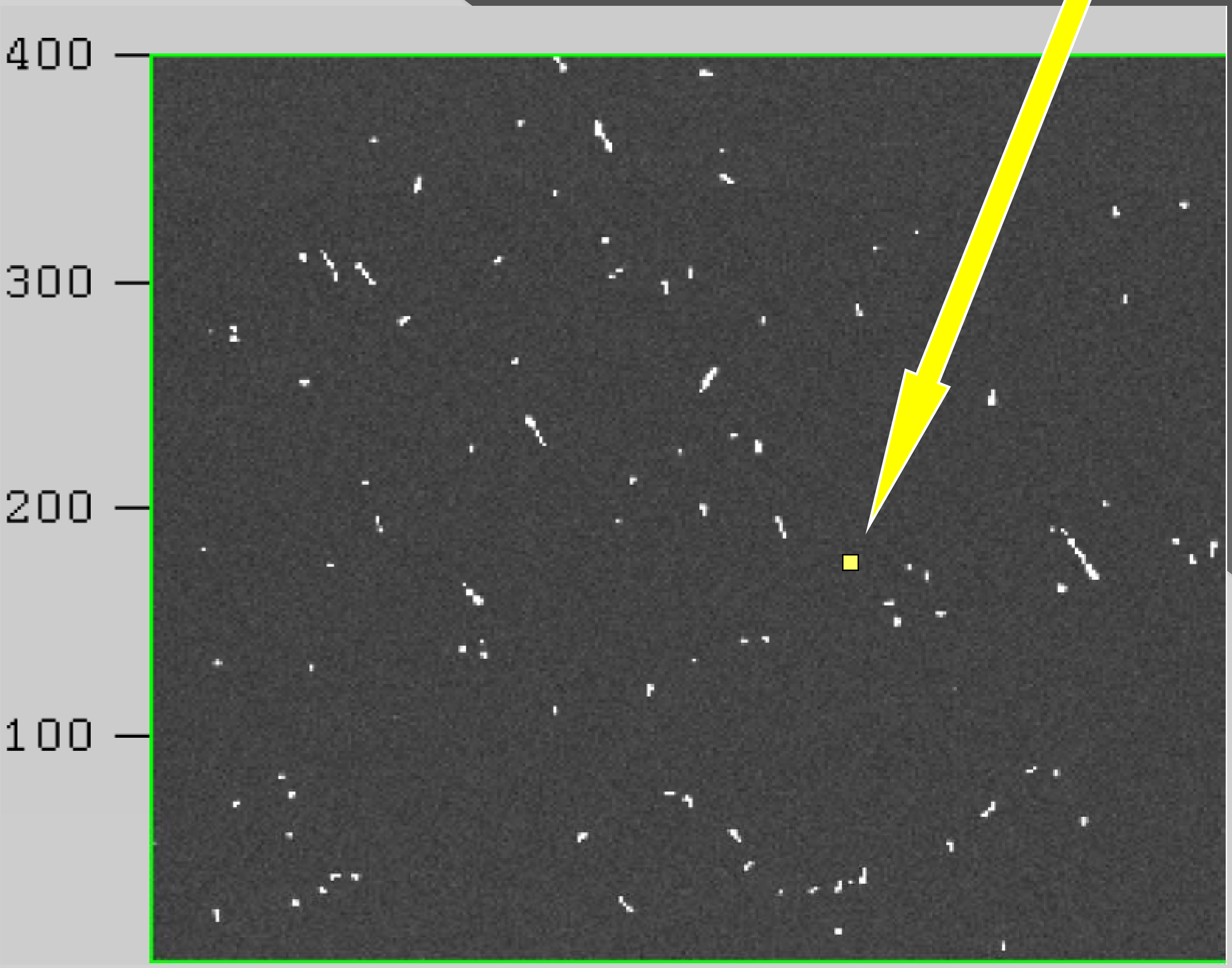


high power laser can cause damage to equipment if not monitored and held stable!!

Verified that the beam pointing motion was < 1 pixel on CCD

1 pixel is 20x20 μm^2

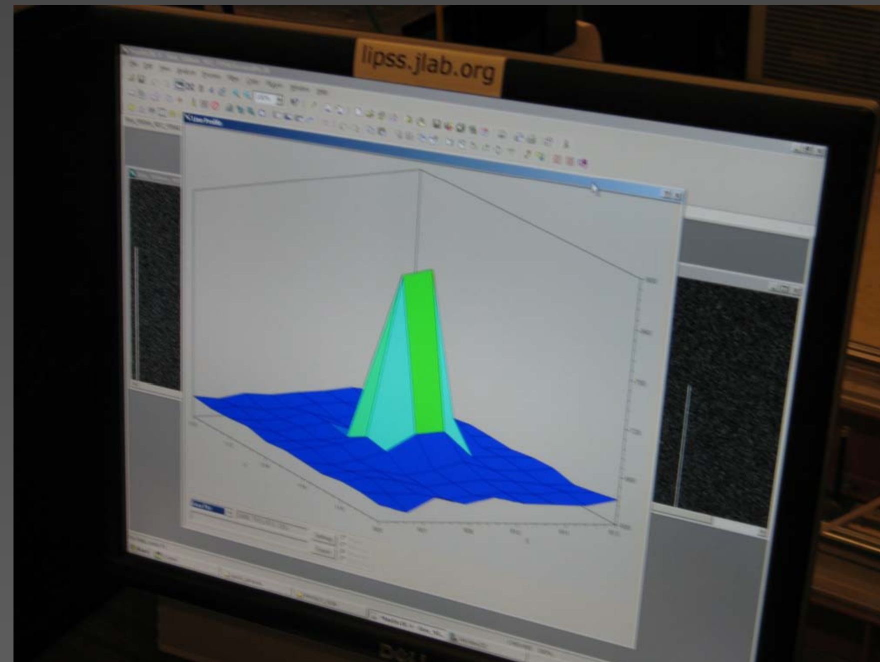
2 hour exposure; cosmic ray hits obvious
exclude all regions where there were cosmic ray hits
5x5 pix array area shown in yellow

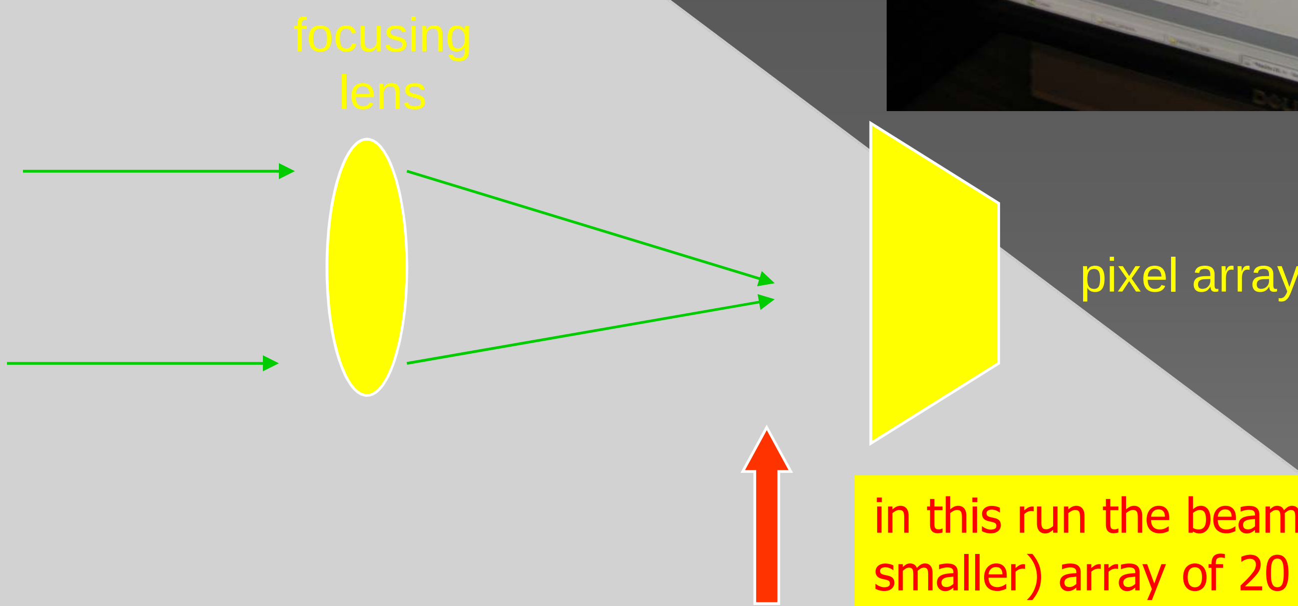


run procedure:

1. take short (bias) exposure
2. take LED exposure
3. take long (physics) exposure (2 hours)
4. if CR hit 'near' signal region, discard run

increase S/N: focusing light



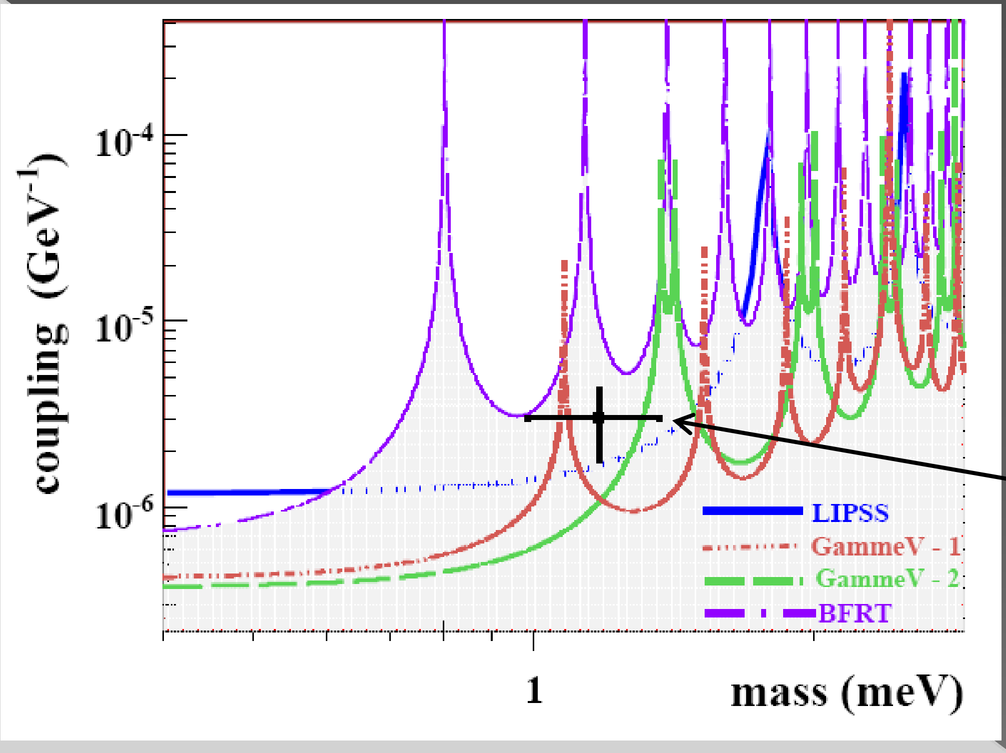


< 10 μm spot size

in this run the beam illuminated a 3x3 (or smaller) array of 20 micron x 20 micron pixels

LIPSS Result on Axion-Like Particle

AA et al (LIPSS Collab), Phys Rev Lett 101, 120401 (2008)



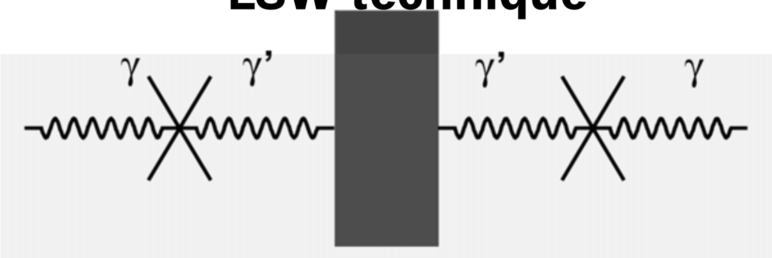
PVLAS'05 (now disclaimed)

- No signal observed, regions above the curves are excluded by the experiment(s) at 95%CL
- Scalar coupling probed (`B^2' interaction)

New Constraint on Photon-Paraphoton Mixing

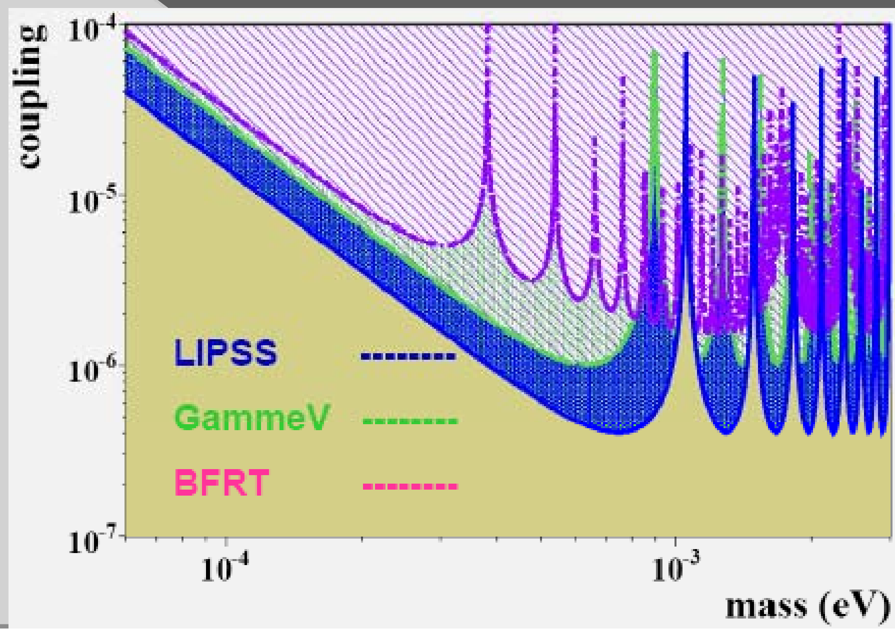
- Hidden-sector $U(1)_H$ symmetry: Paraphotons L.B. Okun, Sov Phys JETP 56, 502 (1982); B. Holdom, Phys Lett B 166, 196 (1986);
  - For the latest, see Ahlers et al, PRD 78, 075005 (2008) ; Abel et al, JHEP07, 124 (2008)

LSW technique



$$L_{mix} = -\frac{1}{2}\chi F^{\mu\nu} B_{\mu\nu}$$

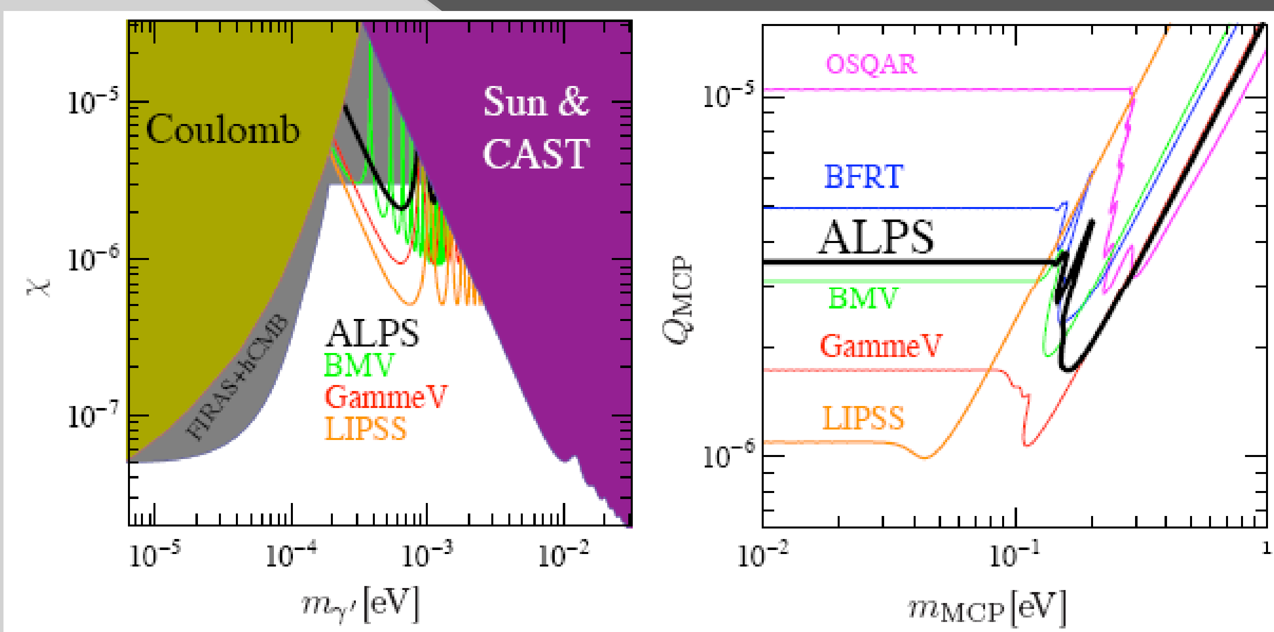
$$P = 16\chi^4 \left[\sin(\frac{\Delta k L_1}{2}) \sin(\frac{\Delta k L_2}{2}) \right]^2$$



•AA et al, Phys.Lett.B 679, 317 (2009) LIPSS observed no oscillations
•Best LSW constraints due to high initial photon flux
•Region above the curves excluded at 95% CL

Photon-Paraphoton Mixing

- LIPSS results Phys.Lett. B679, 317(2009) vs other constraints:
  - Achieved the highest sensitivity in milli-eV mass range (plot compiled in arXiv:0905.4159)



- Also results in a new constraint on mini-charged particle (MCP) mass and charge, see formalism in Ahlers et al, PRD 78, 075005 (2008)

LIPSS Status Summary

- Fall'06-Winter'07: Installation, calibration complete
- First data taken in March'07

(20h in `scalar boson' configuration)

  - Scalar boson result: Phys.Rev.Lett.101,120401 (2008)
  - Paraphoton result: Phys.Lett. B679, 317(2009)
- Spring 2009: Successful test run at ~1kW laser power
- July, August 2009: ran in `pseudoscalar boson' mode
- Will continue Fall 2009
- Further improvements planned
  - Chameleon search planned

Acknowledgement

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and National Science Foundation