Laser-Based Search for Dark Matter Particles

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Hampton University/Jefferson Lab

Jlab Accelerator Division Seminar
February 5, 2009

Plan of Talk

- Motivation for Dark Matter Search
  - Evidence for Dark Matter
- Axion Hypothesis
- Status of axion searches
- LIPSS experiment at JLAB

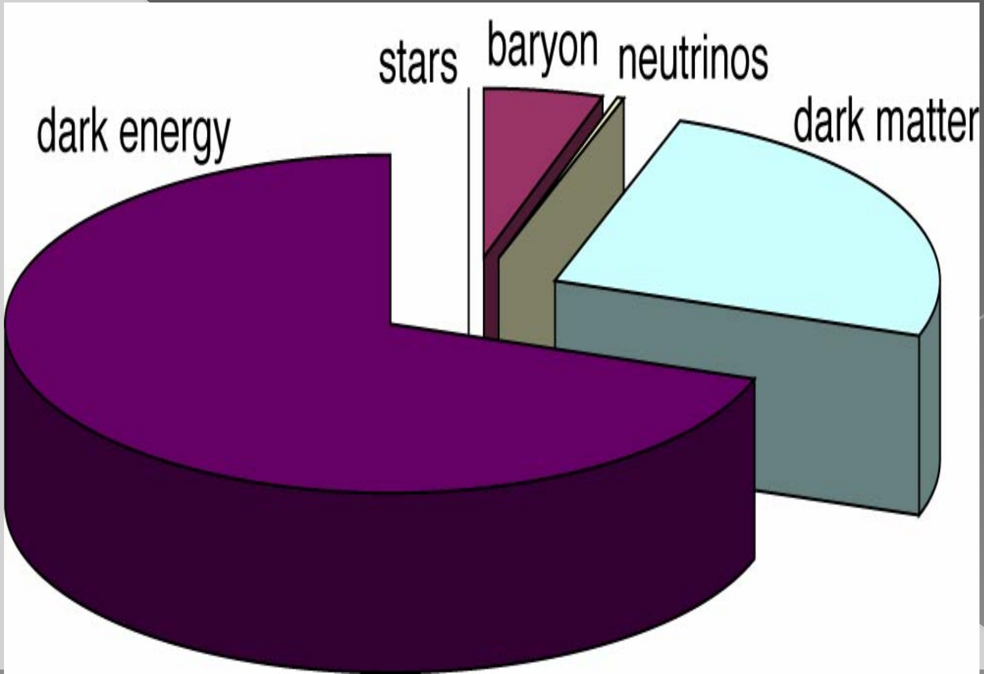
Motivation

- Unsolved Problems in Physics
  - Dark Matter problem
  - Strong CP problem
  - ....
- Can be addressed with a new elementary particle, an axion

Matter/Energy Budget of Universe

- Stars and galaxies are only ~0.5%
- Neutrinos are ~0.3–10%
- Rest of ordinary matter (electrons and protons) are ~5%
- Dark Matter ~30%
- Dark Energy ~65%
- Anti-Matter 0%

axion is a dark matter candidate

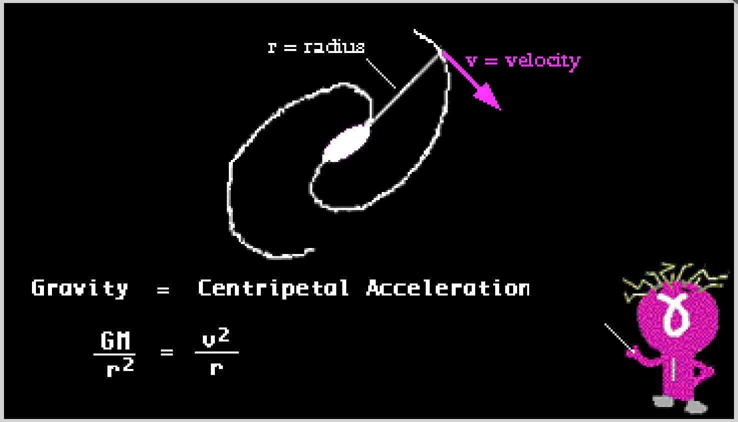


Dark Matter: Observational Evidence

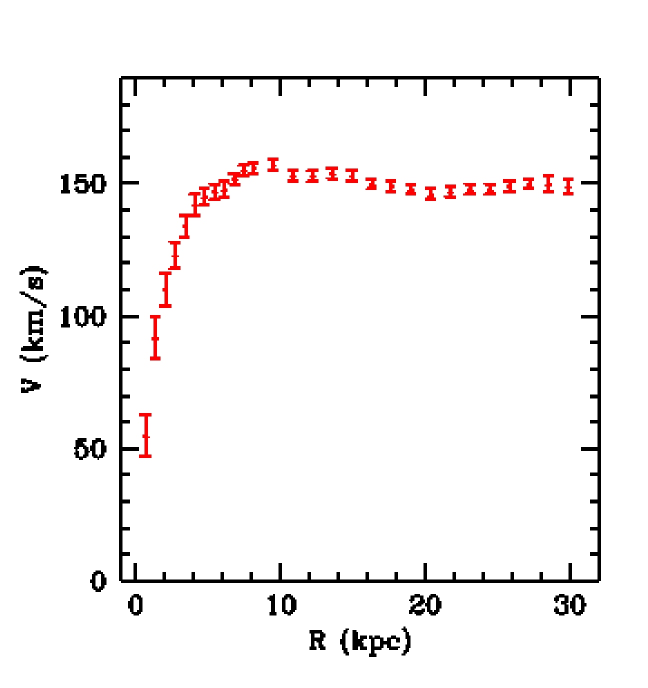
- Fritz Zwicky (1933): Dispersion speed of galaxies in a Coma Cluster too high => `dynamic mass' is ~400 times larger than `luminous mass'
- S. Smith (1936): similar observation in Virgo Cluster; x200 excess in mass, can be explained by presence of additional matter between the galaxies

Galactic rotation

- Vera Rubin (1970): Measured rotation of spiral galaxies, discovered stars on the periphery revolve too fast around the galaxy center=> an invisible halo carries ~90% of galaxy mass



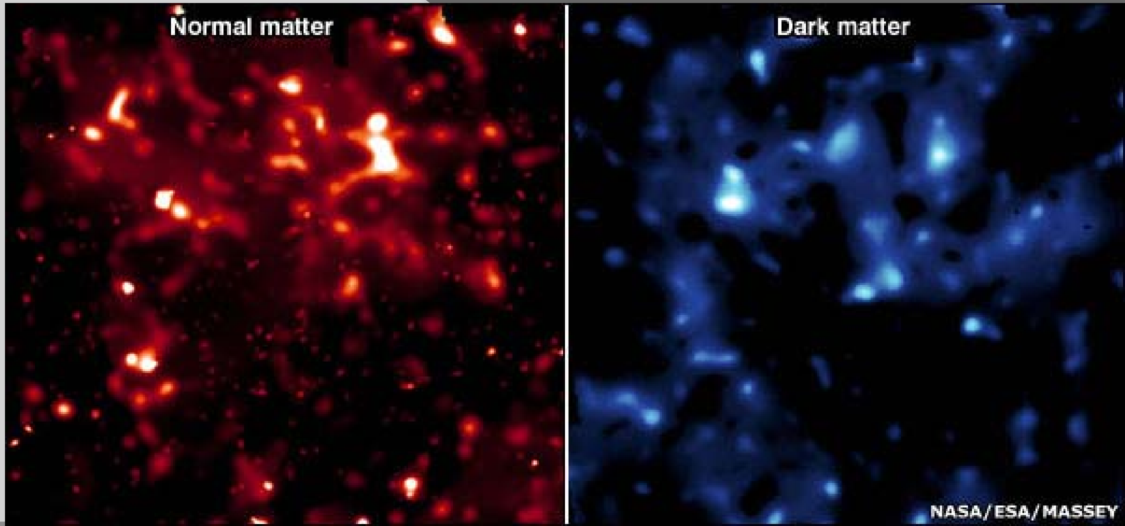
$v \sim R^{-1/2}$?



Gravitational lensing: 3D map of observable Universe from Hubble telescope

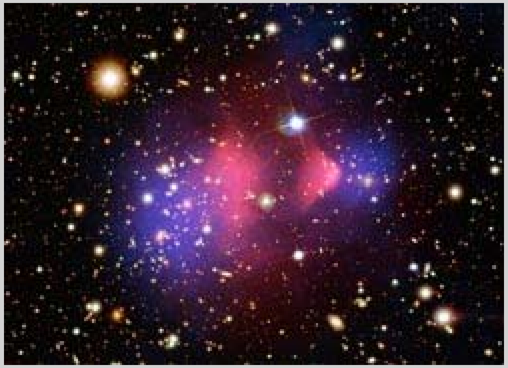
R. Massey et al, Nature 445, 286 (2007):
Dark Matter Maps Reveal Cosmic Scaffolding

- Area of 1.6 deg^2
- ~1/2 million galaxies

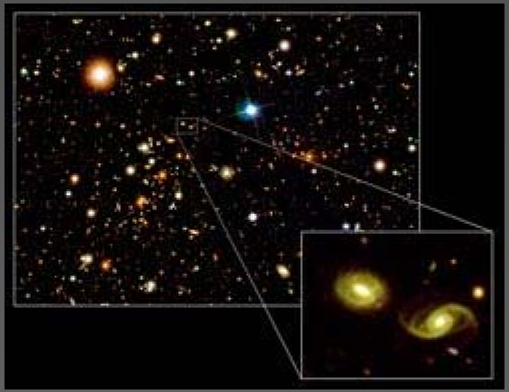


Dark Matter vs Ordinary Matter at Galactic Scale

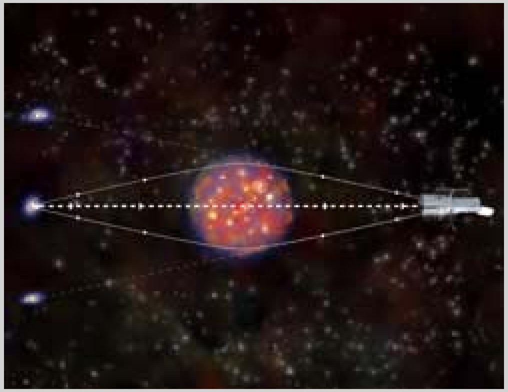
- Observed by combining data on gravitation lensing from Hubble and X-rays from Chandra space telescopes



Blue haze shows dark matter flanking the "Bullet Cluster". Purple haze shows X-rays from hot intergalactic gas



The Bullet Cluster is made of two colliding groups of galaxies



The Hubble Space Telescope was used to observe how the Bullet Cluster bent light coming from background stars

What is Dark Matter?

- An unknown elementary particle that only weakly interacts with ordinary matter
  - May be light (~10^{-3} eV) "axion"
    - See the rest of this talk
  - May be heavy (~10^{6} eV) "WIMP"
    - Evidence reported April'08 by DAMA Collab., observed semi-annual variations of electromagnetic background in NaI detector, published in Eur. Phys. J. C 56, 333 (2008)
  - Further evidence for Dark Matter: Excess of positrons
    - From e+e- annihilation, SPI/Integral, arXiv:astro-ph/0601673
    - Positron in cosmic rays, PAMELA, arxiv:0810.4995[astro-ph]
    - **News** PAMELA result: antiproton flux is probably not due to dark matter, Phys. Rev. Lett. 102, 051101 (2009)

Original papers proposing a new pseudoscalar boson

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.

Axion hypothesis

θ -term and strong CP problem

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + \bar{q}(i\not{D} - M)q + \theta\frac{\alpha_s}{8\pi}G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \cdots$$

θ-term is CP-violating

Physical effects depend on the combination
$\bar{\theta} = \theta + \mathrm{Arg\ Det}\ M$

$$d_n \sim \frac{e}{m_n}\,\bar{\theta}\,\frac{m_u m_d}{m_u + m_d}\,\frac{1}{\Lambda_{\rm QCD}}$$

$$d_n < 0.63 \times 10^{-25}\ e\,\mathrm{cm} \Rightarrow \theta < 10^{-9}$$

The CP problem:
why $\bar{\theta}$ so small ?

$\theta_{\rm QCD}$
$\mathrm{Arg\ Det}\ M$
unrelated

makes the problem worse !

Axion: Nambu-Goldstone boson of spontaneously broken $U(1)_{PQ}$ symmetry (Weinberg'78, Wilczek'78)

Peccei-Quinn solution and axions

Peccei, Quinn

Chiral symmetry $U(1)_{PQ}$ allows to rotate $\overline{\theta}$ away

Spontaneous breaking of anomalous global symmetry → Pseudo Goldstone Boson (PGB)

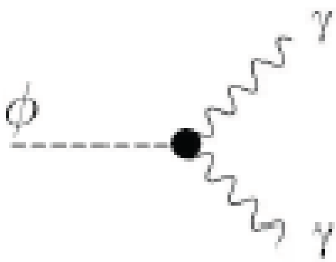
(QCD)- Axion model has large breaking scale f_a

- Interactions are weak $\propto f_a^{-1}$ Invisible axion
- Mass is small $m_a \propto f_a^{-1}$

Experiments looking for axions use coupling to two photons

$$c_\gamma \frac{\alpha}{\pi} \frac{1}{f_a} \epsilon^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta}\, a$$

Light bosons coupled to $\gamma\gamma$



- **Pseudoscalar coupled to $\gamma\gamma$**

$$\mathcal{L}_{\phi\gamma\gamma} = \frac{1}{8}\, g_{\phi\gamma\gamma}\, \phi\, \epsilon^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta}$$

two (independent) properties :

m mass

$g_{\phi\gamma\gamma} \equiv \frac{1}{M}$ coupling (notice dimensions)

- **Scalar coupled to $\gamma\gamma$**

$$\mathcal{L}_{\phi\gamma\gamma} = \frac{1}{8}\, g'_{\phi\gamma\gamma}\, \phi\, F_{\mu\nu} F^{\mu\nu}$$

- Similar except for $\mathrm{PS} \rightarrow \vec{E}\vec{B}$, $\mathrm{S} \rightarrow |E|^2 - |B|^2$

Call them AXION-LIKE PARTICLES (ALPs)

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)

[1]*Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Trieste and Università di Trieste, Trieste, Italy*
[2]*Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Ferrara and Università di Ferrara, Ferrara, Italy*
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[5]*Istituto Nazionale di Fisica Nucleare (INFN), Sezione Trieste and Università di Udine, Udine, Italy*
[6]*Istituto Nazionale di Fisica Nucleare (INFN), Laboratori Nazionali di Frascati, Frascati, Italy*
(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

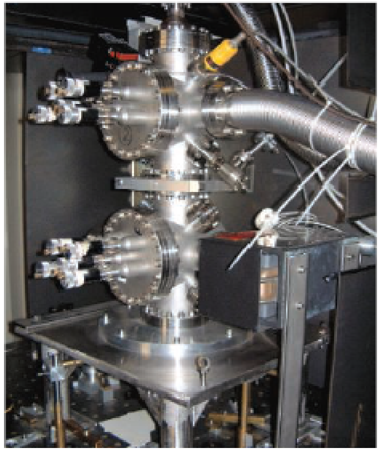
Science, 17 March 2006

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.

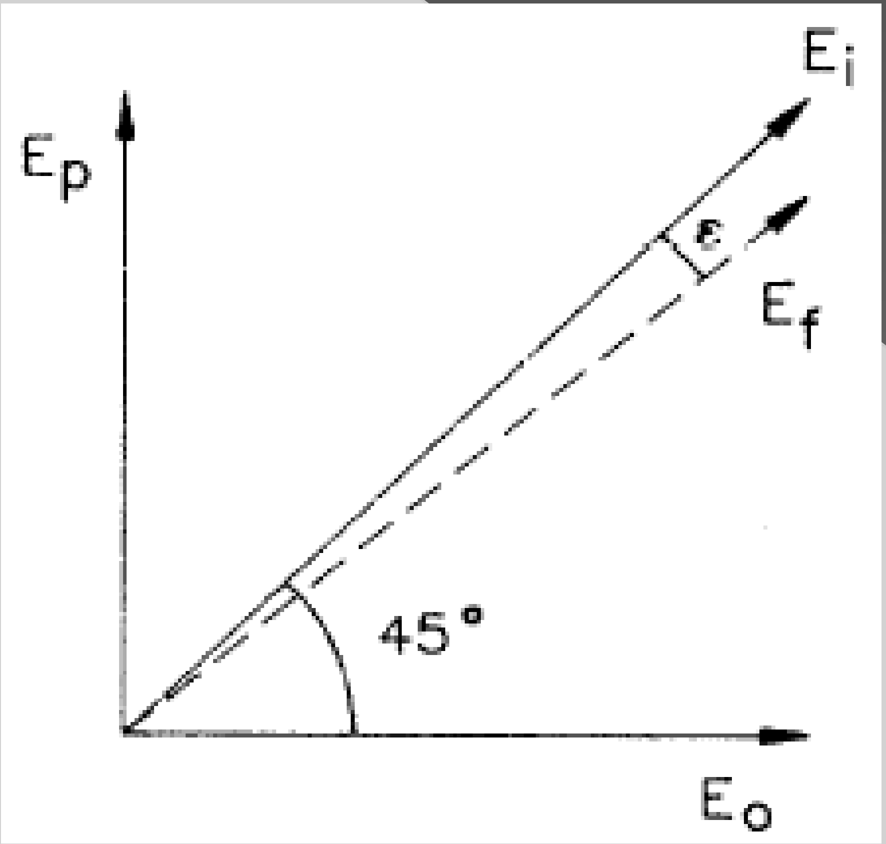


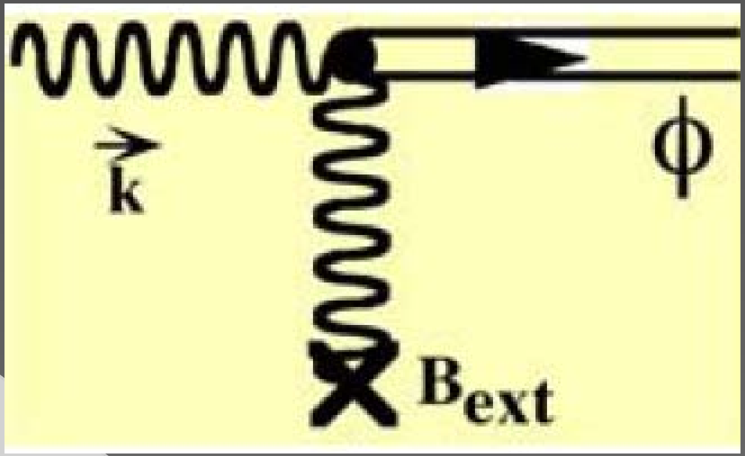
A twist in the tale. By rotating a laser beam with magnets, this experiment may have found never-before-seen particles.

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)



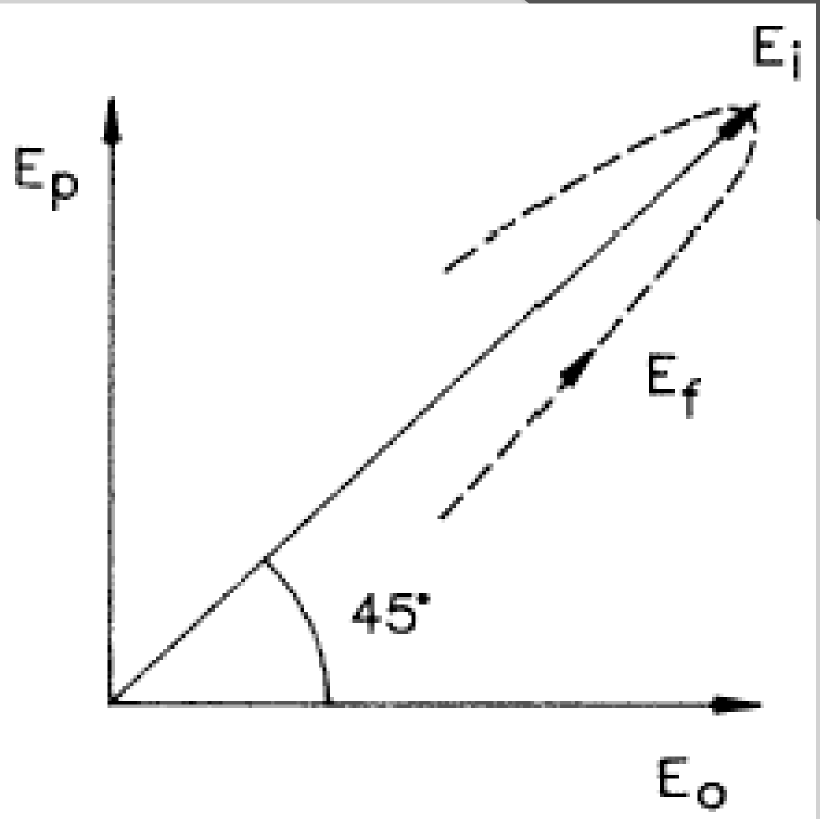


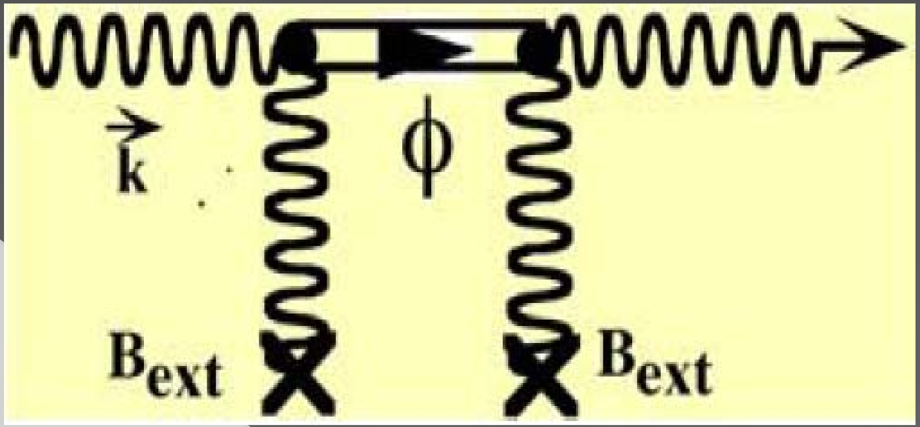
Dichroism caused by production of particle φ in photon-photon collision

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

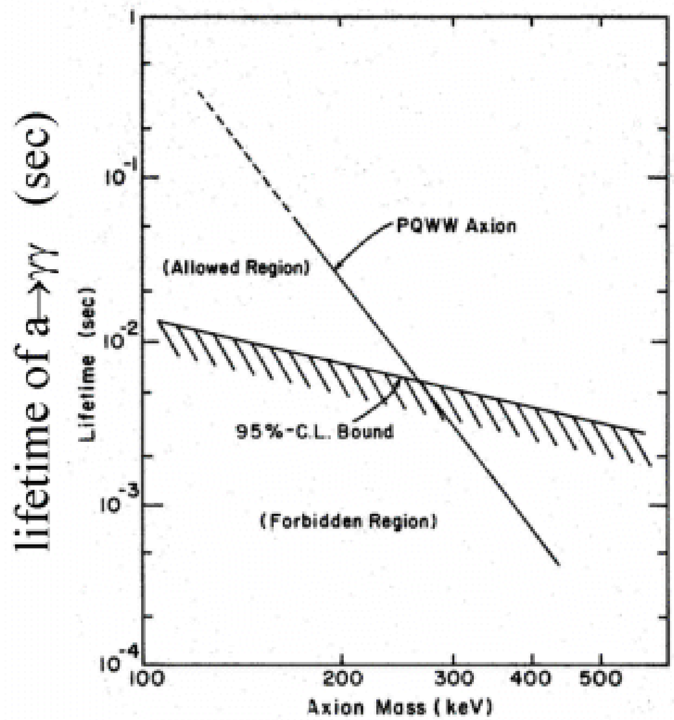
Previous Searches: Electron Beam Dump Experiments

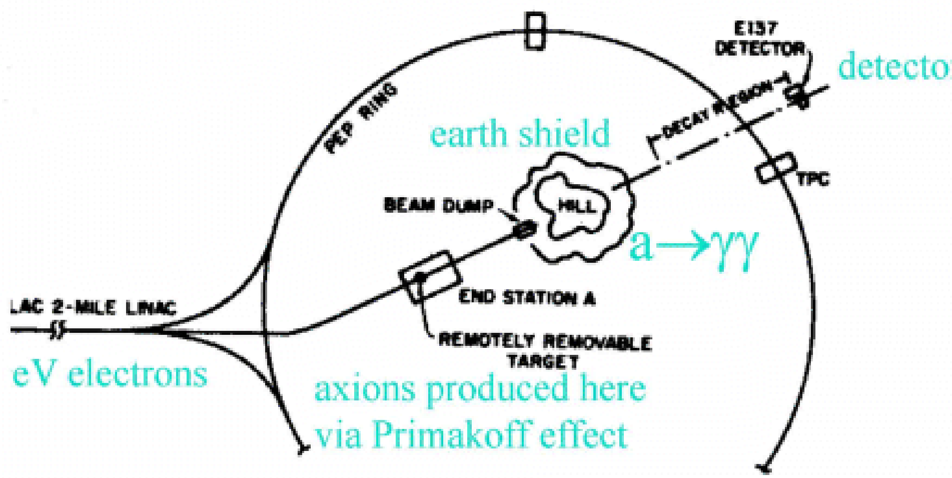
Summary of laboratory searches:
A heavy axion is excluded

AXION

For example: SLAC E137 (Bjorken et al.)

Bjorken et al, PRD **38**, 3375 (1988)

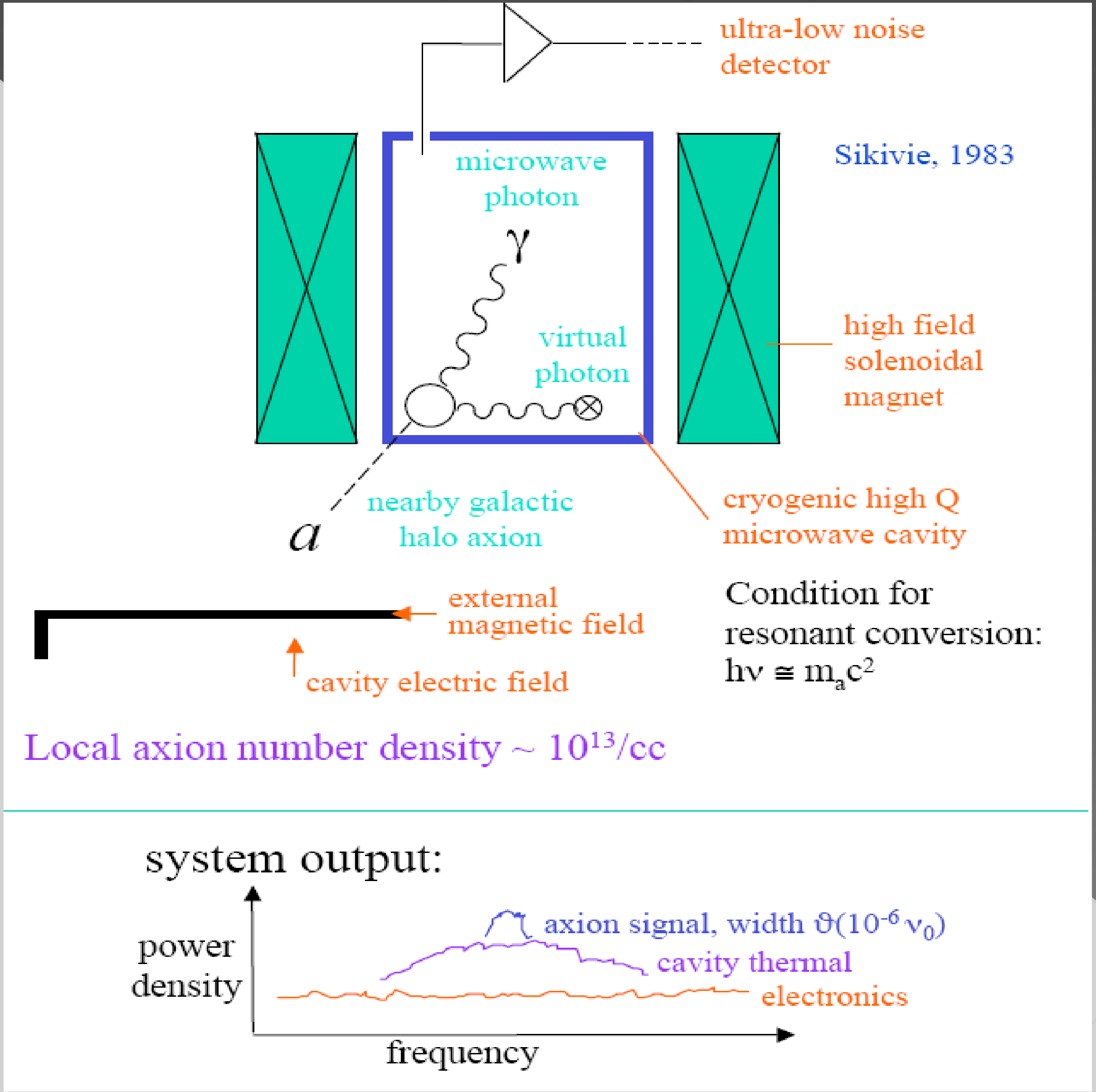




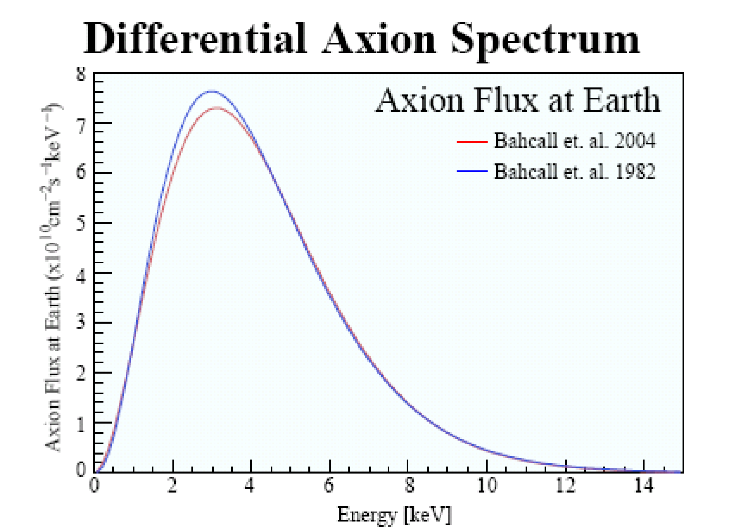
f_{PQ} **must be considerably greater than the weak scale**

Microwave cavity technique

R. Bradley et al, Rev. Mod. Phys. 75, 777(2003)



CAST experiment



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

Axion Luminosity:

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

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

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)

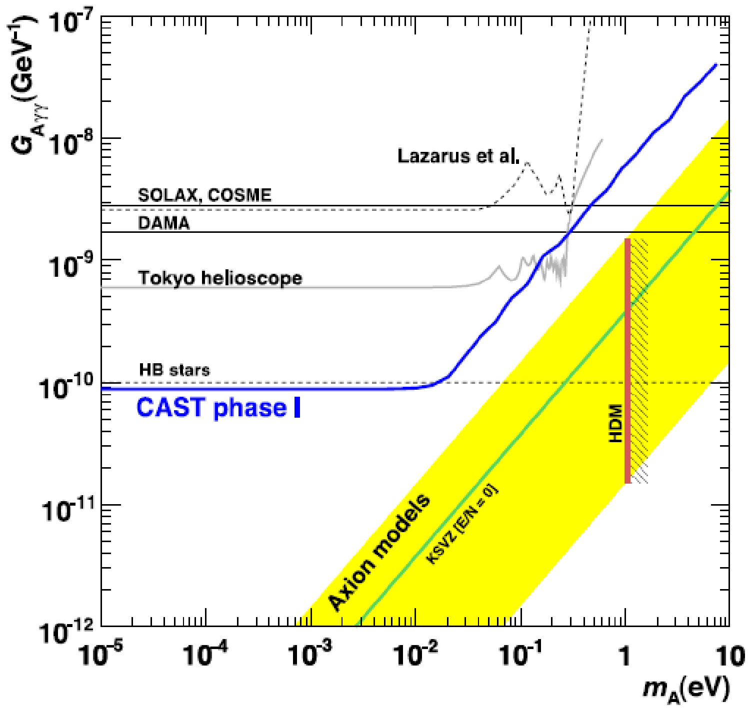
Have seen no effect

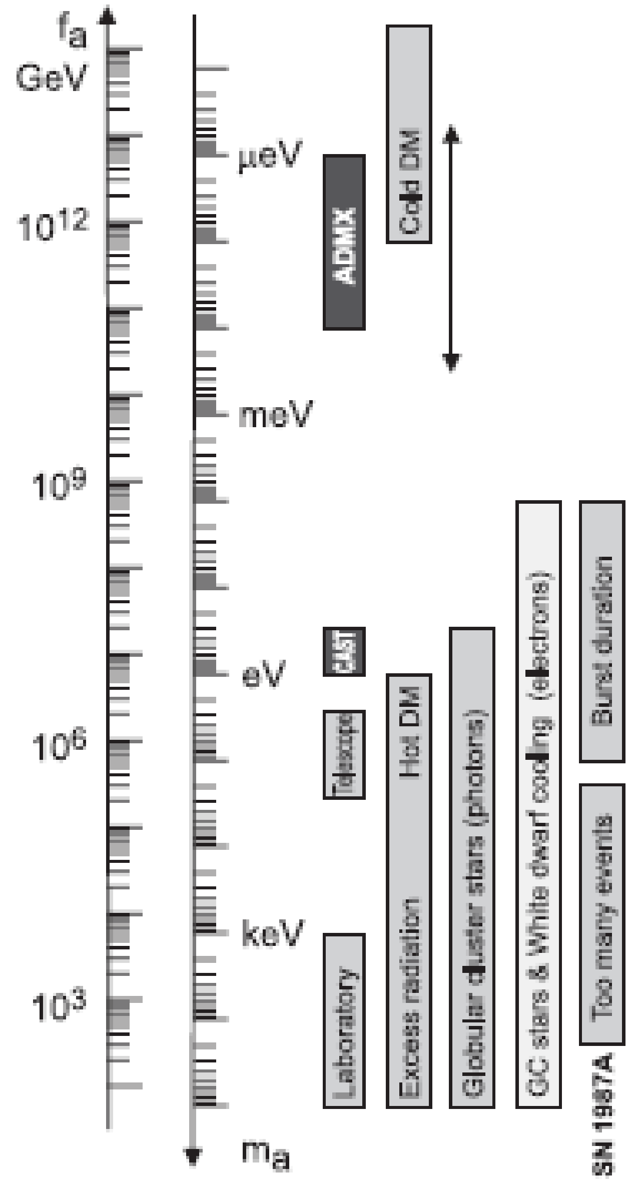
Open mass range for axions

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

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

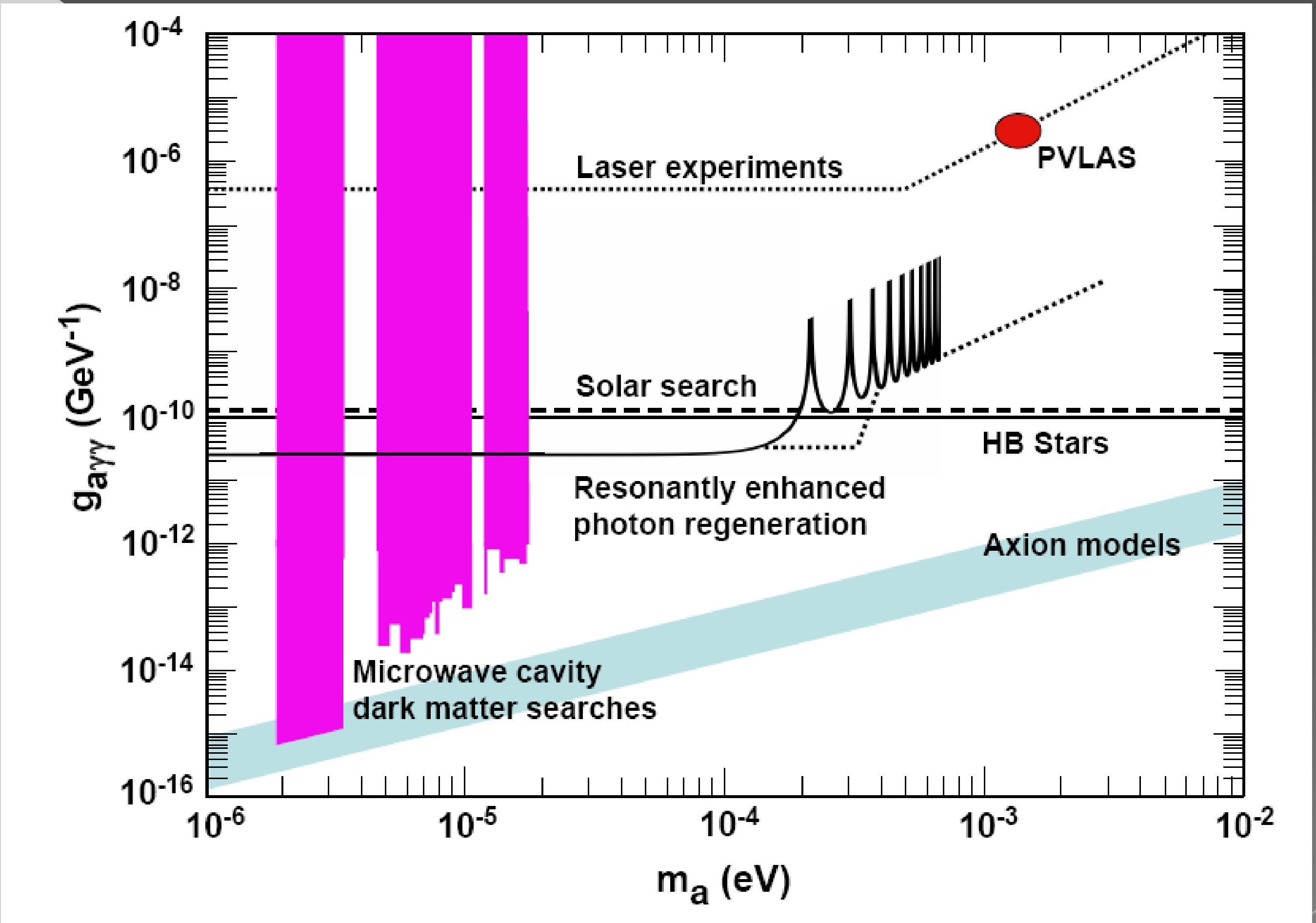
from PDG'08





Axion Search Summary

From P. Sikivie, talk at 4th Patras Worshop, DESY, June 2008



See also a review by G. Raffelt, Lecture Notes in Physics, 741 (2008)

LIPSS collaboration

O.K. Baker (*), M. Minarni, P. Slocum

Yale University

A. Afanasev(**), R. Ramdon

Hampton University

K. Beard, G. Biallas, J. Boyce, M. Shinn

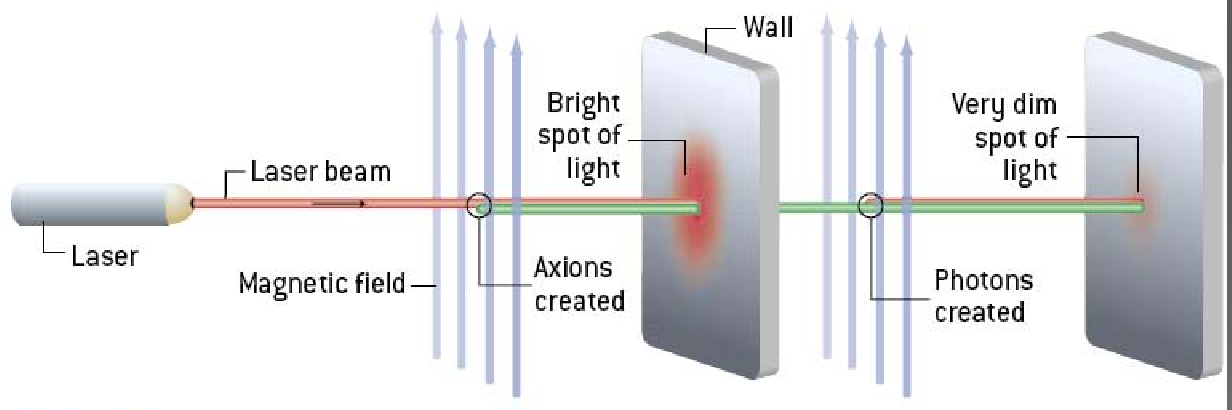
Jefferson Lab

(*) *Spokesman*

(**)*Co-Spokesman*

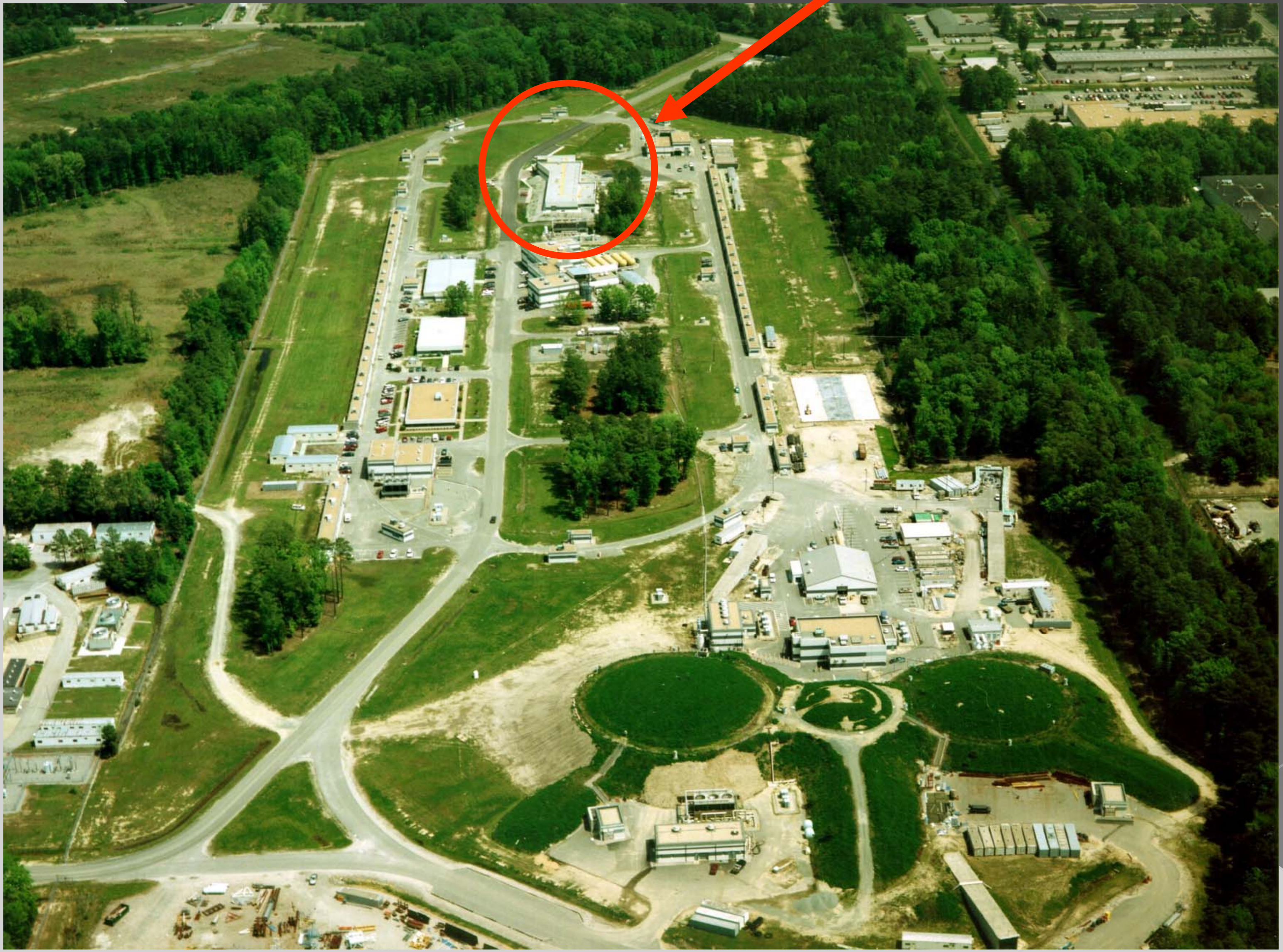
`Light Shining Through a Wall’

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

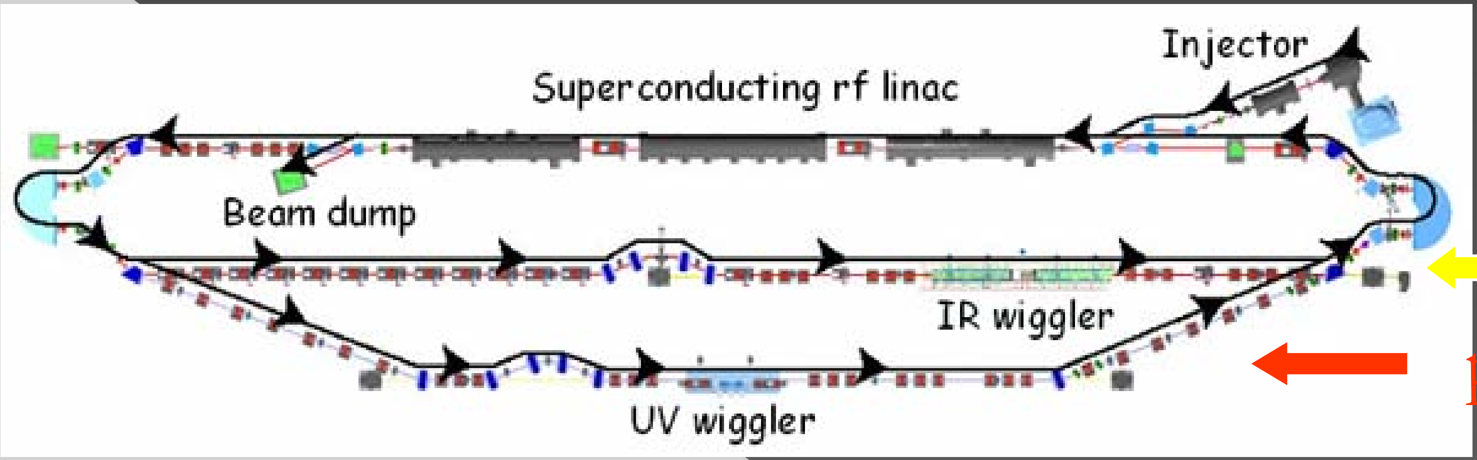


LIGHT BEAM experiment that would confirm the existence of axions passes a laser beam through a strong magnetic field, converting some photons to axions (*green beam*). The axions penetrate a wall before passing through another magnetic field that converts some of the particles back to photons, which form an extremely faint spot on the far wall.

Jefferson Lab’s Free Electron Laser



JLAB FEL: used for LIPSS experiment



current

planned

`Light-Shining-Through-The-Wall' Experiments to detect Axion-Like Particles

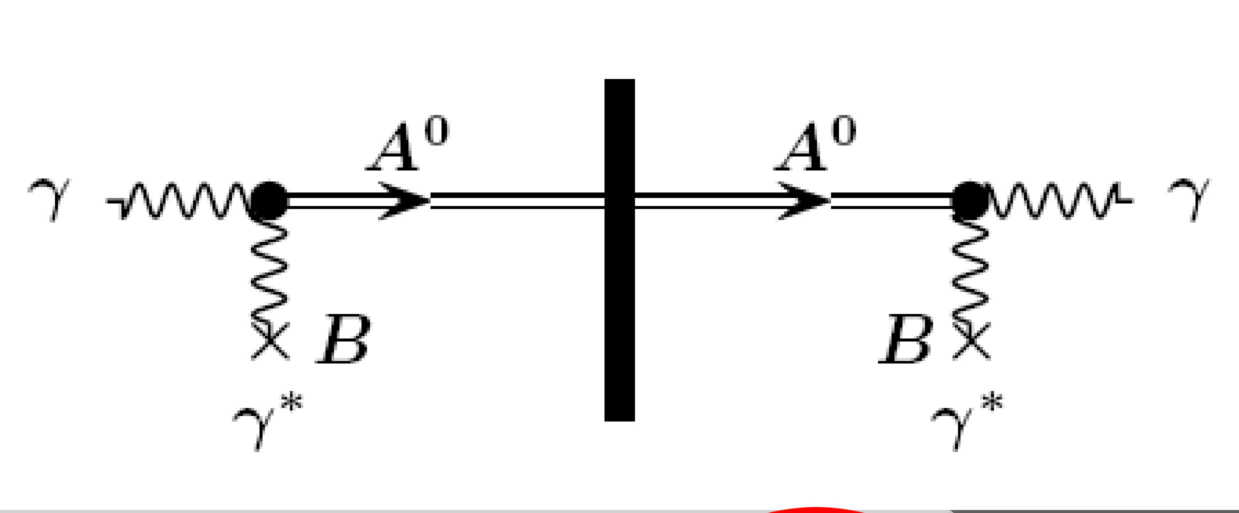
(from CERN Courier, Mar 2, 2007)

Table 1

name	place	magnet (field length)	laser wavelength power	P_{PVLAS}	photon flux at detector
ALPS	DESY	5 T 4.21 m	1064 nm 200 W cw	$\approx 10^{-19}$	10/s
BMV	LULI	11 T 0.25 m	1053 nm 500 W 4 pulses/day	$\approx 10^{-21}$	10/pulse
LIPSS	Jefferson Laboratory	1.7 T 1.0 m	900 nm 10 kW cw	$\approx 10^{-23.5}$	0.1/s
OSQAR (preliminary phase)	CERN	9.5 T 1.0 m 9.5 T 3.3 m	540 nm 1 kW cw	$\approx 10^{-20}$	10/s
PVLAS (regeneration)	INFN Legnaro	5 T 1 m 2.2 T 0.5 m	1064 nm 0.8 W cw Npass $= 5 \times 10^5$	$\approx 10^{-23}$	10/s

also GammeV at Fermilab (2007)

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

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

Axion-Like Particle Coupling to Photons

pseudoscalar particle or

pseudoscalar interaction

- Light, neutral boson coupling to photons

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

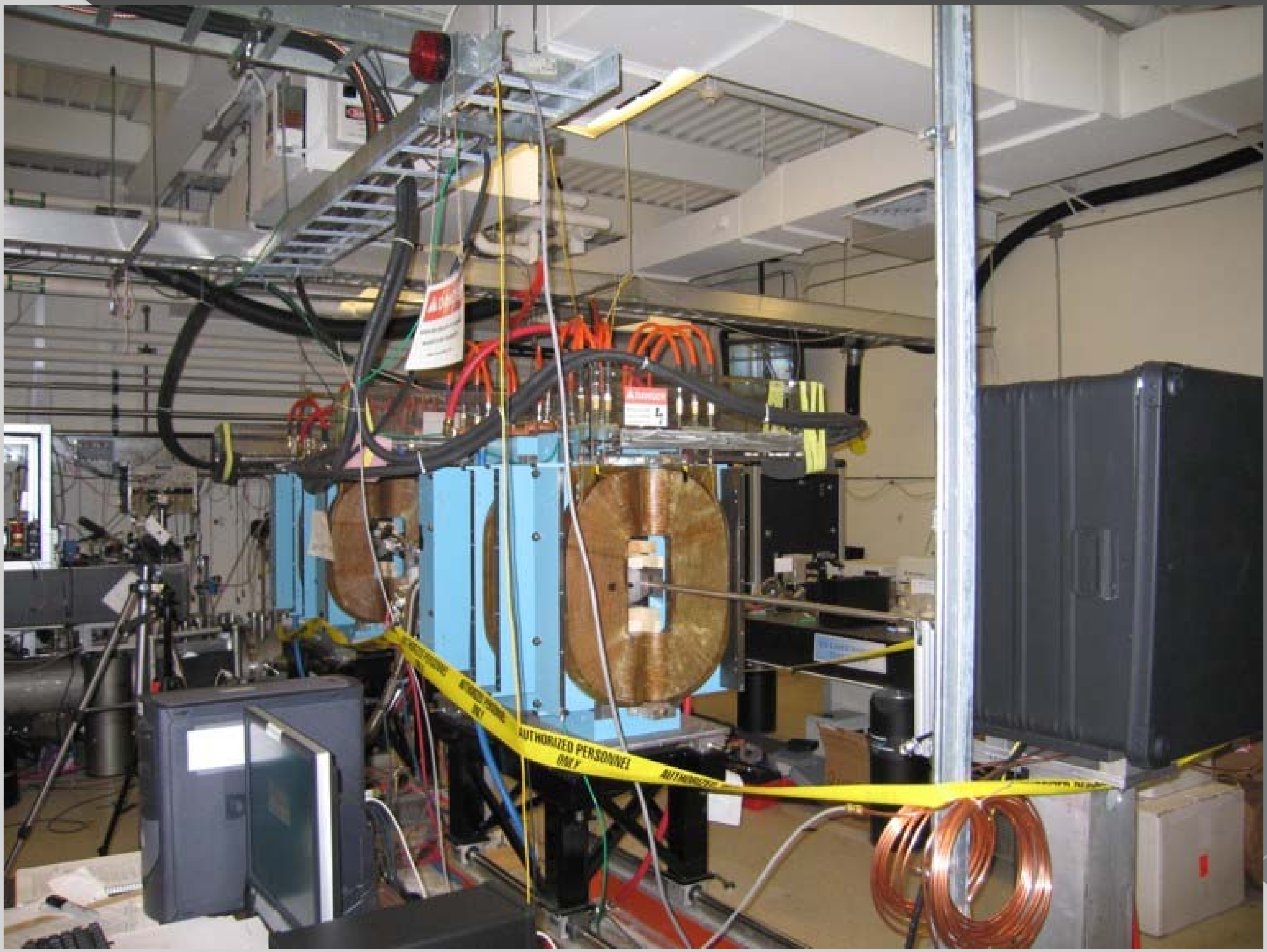
- in present case, use FEL laser light and magnetic field
- light polarization in direction of magnetic field
- we want to test PVLAS in a completely independent way

Parameters for initial LIPSS run (2007)

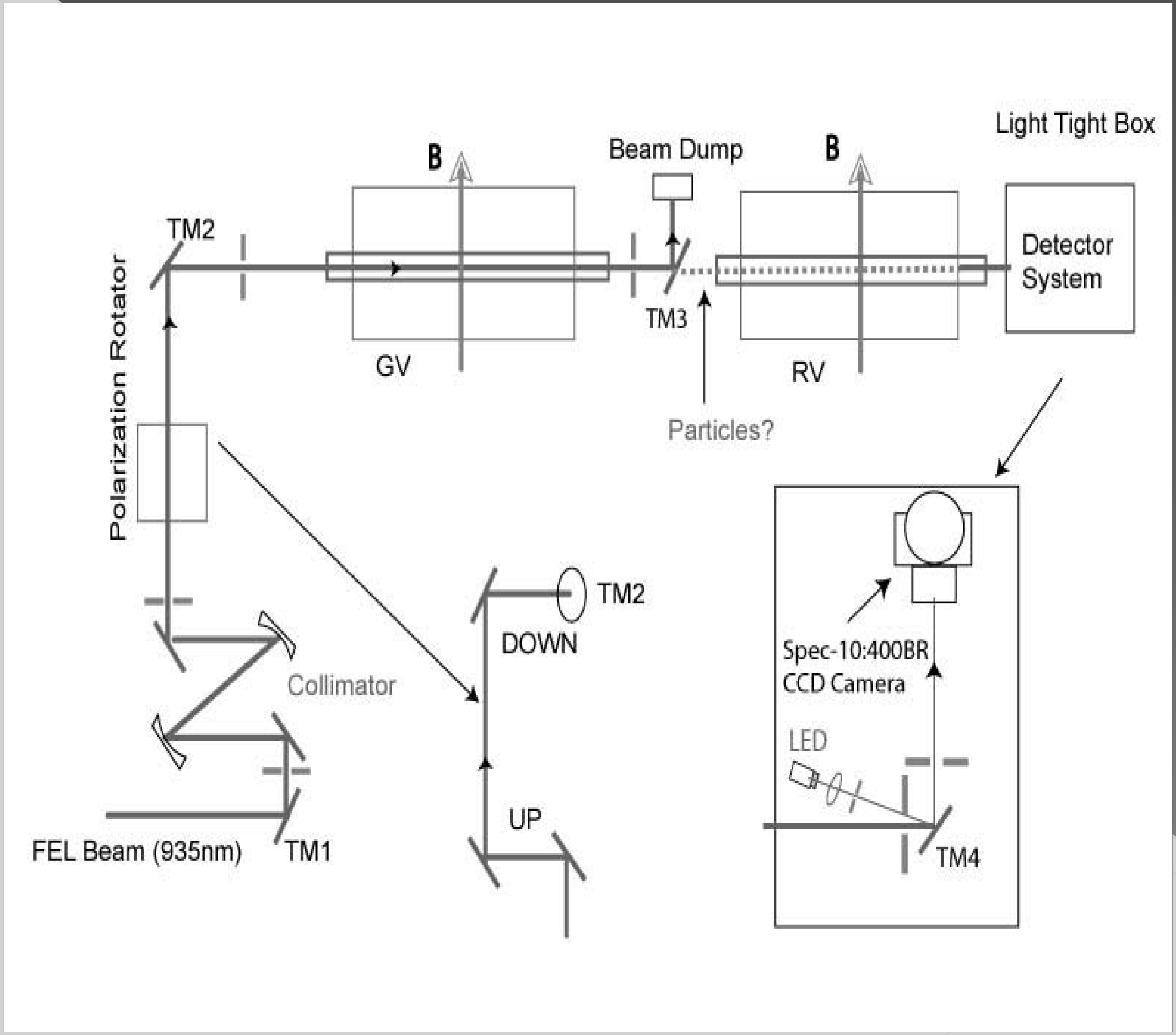
- B-field: 1.7 T
- magnet length: 1.0 m
- IR FEL power 0.2 kW
- IR FEL wavelength 935 nm (1.3 eV)
- quantum efficiency 0.4
- linear polarization 100%
- acceptance 100%
- experimental efficiency ~ 90%

Expect signal rate > 0.01 Hz for
$g_{a\gamma\gamma} = 1.7 \times 10^{-6}\ \mathrm{GeV}^{-1}$

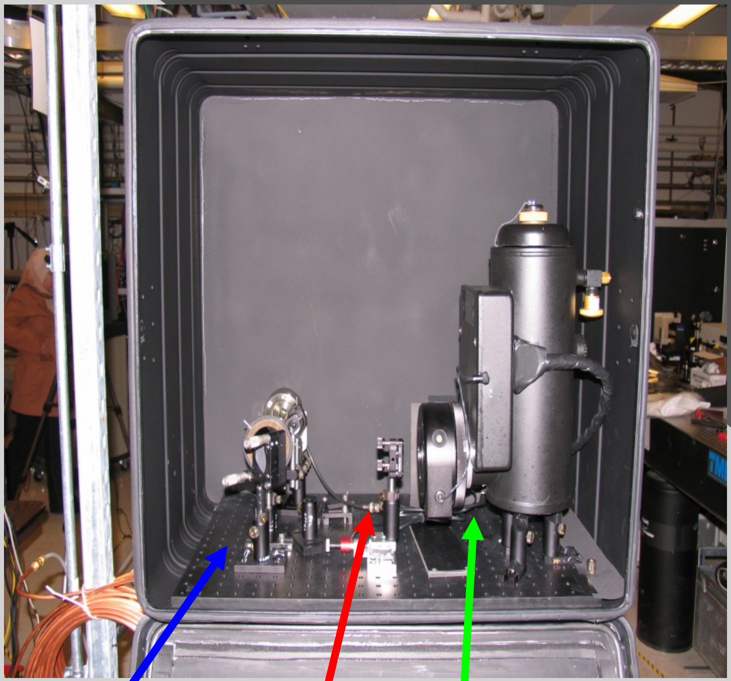
LIPSS apparatus



LIPSS Experiment Layout



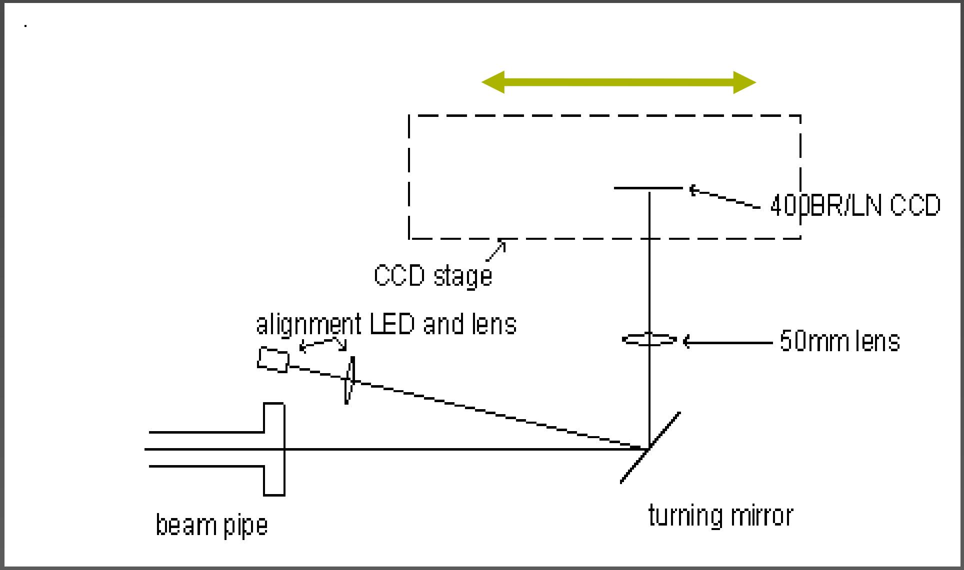
Detector optics

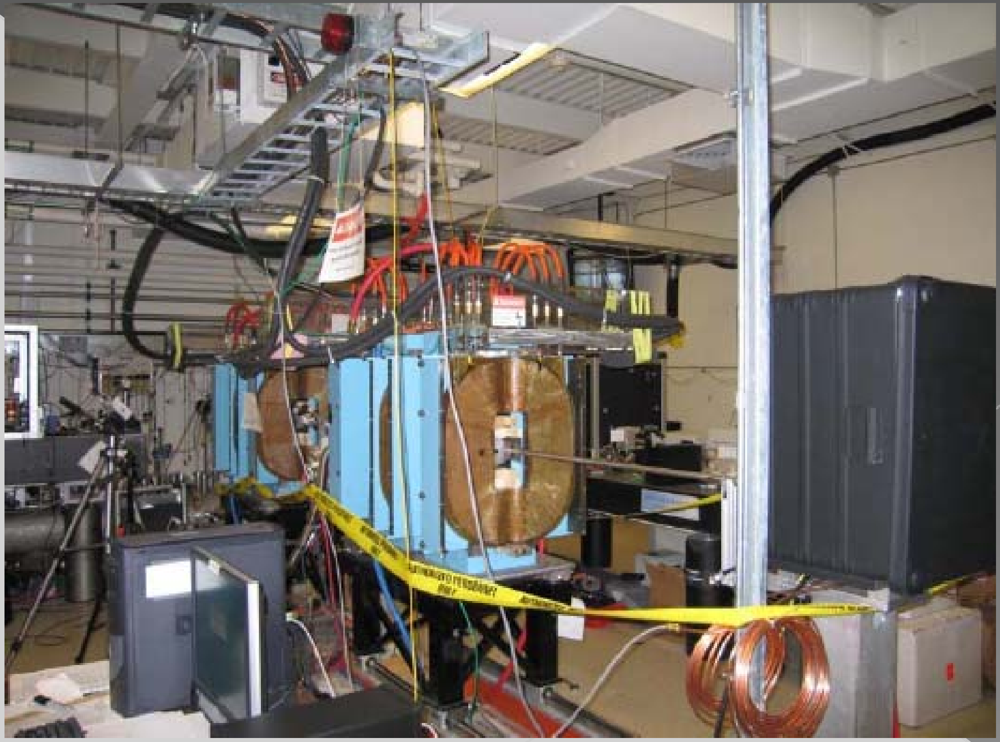


mirror

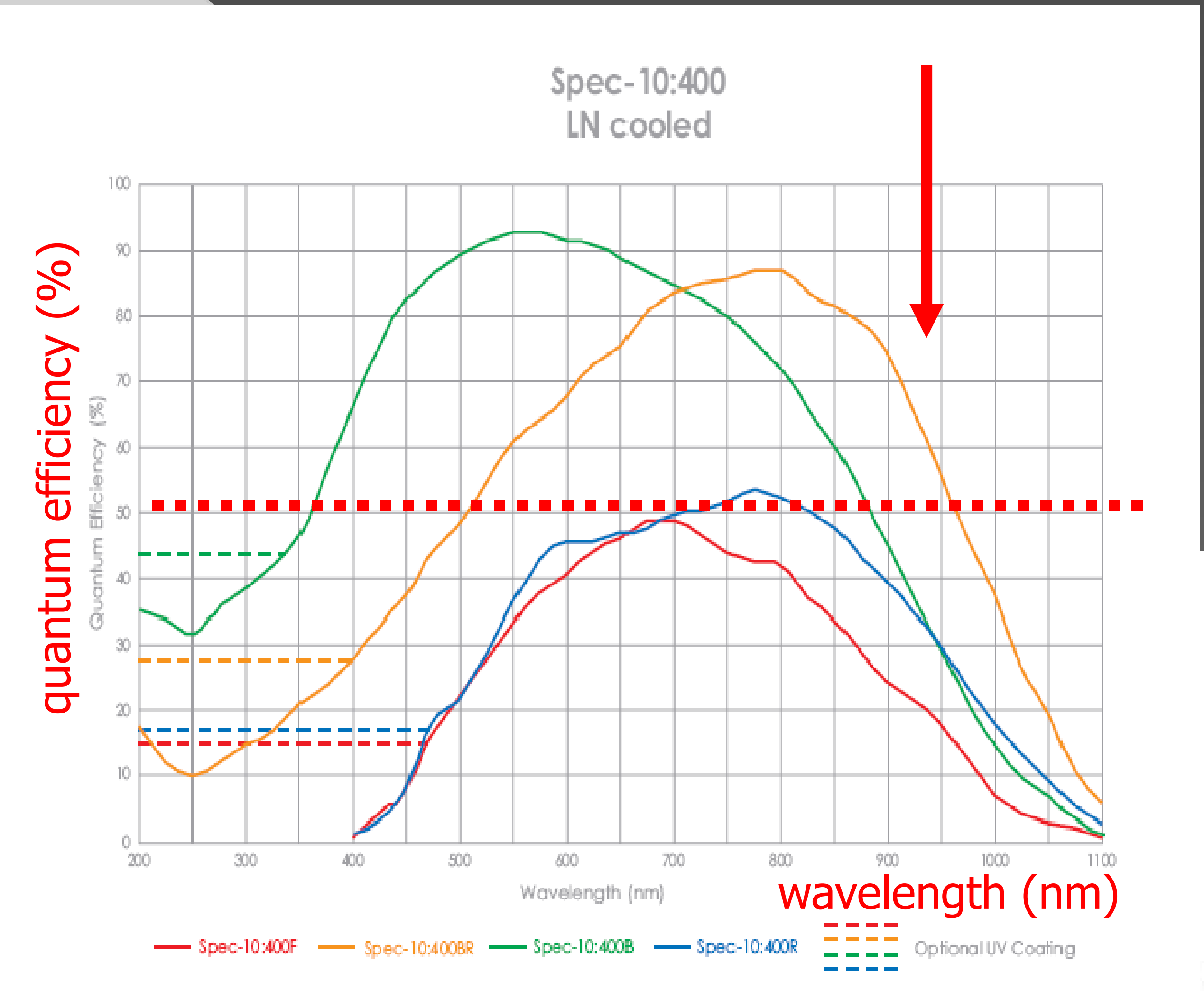
lens

Spec10:400BR-LN camera





Princeton Instruments ACTON 10:400BR-LN

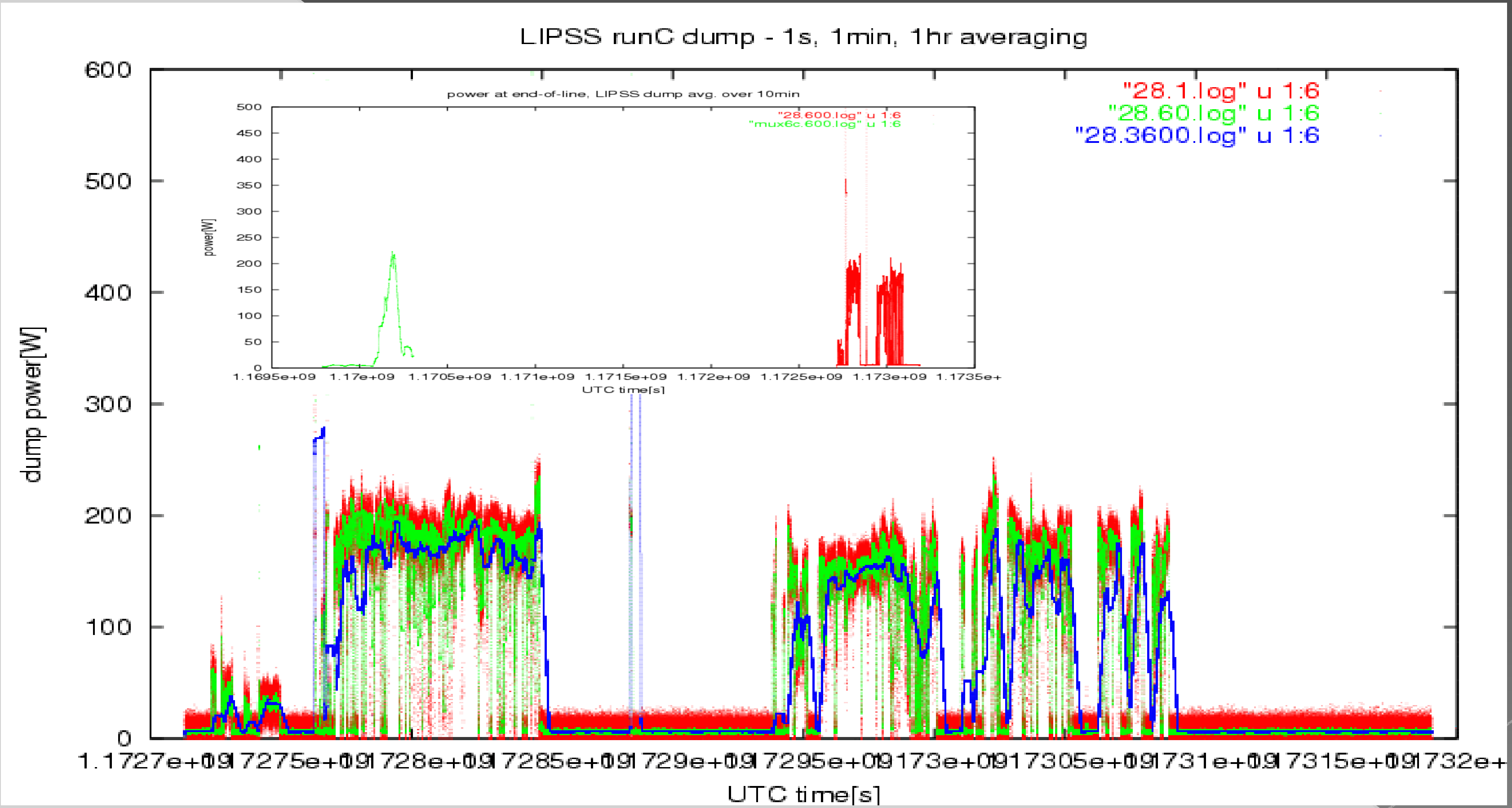


q.e. high at 935 nm

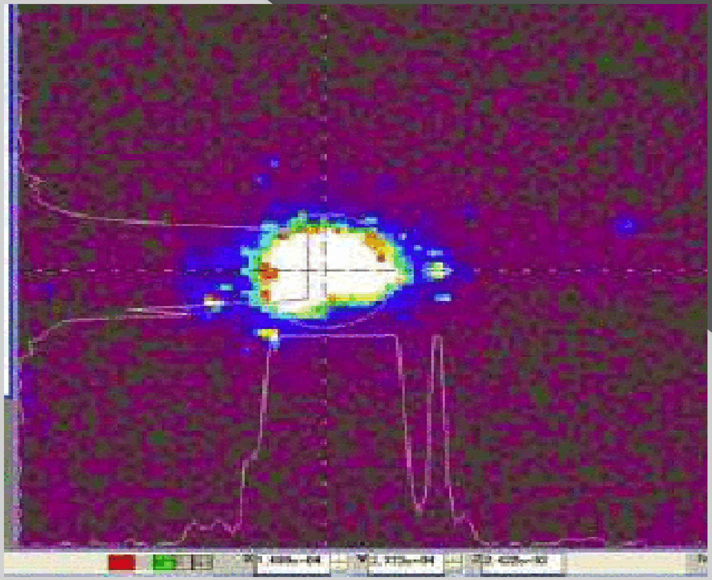
50%

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

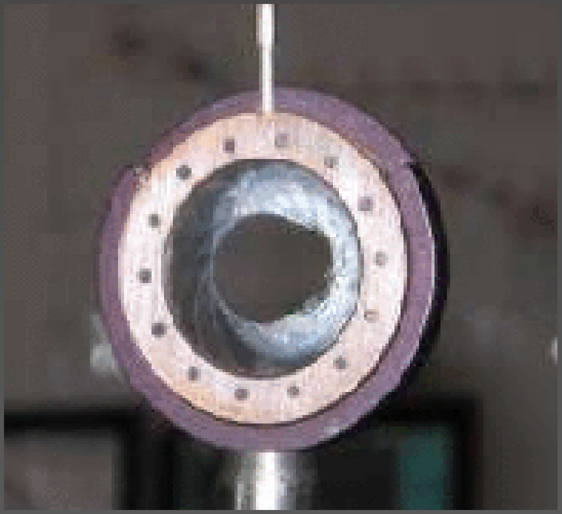
Actual power delivered to the LIPSS beam dump over 5 days



laser beam alignment



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

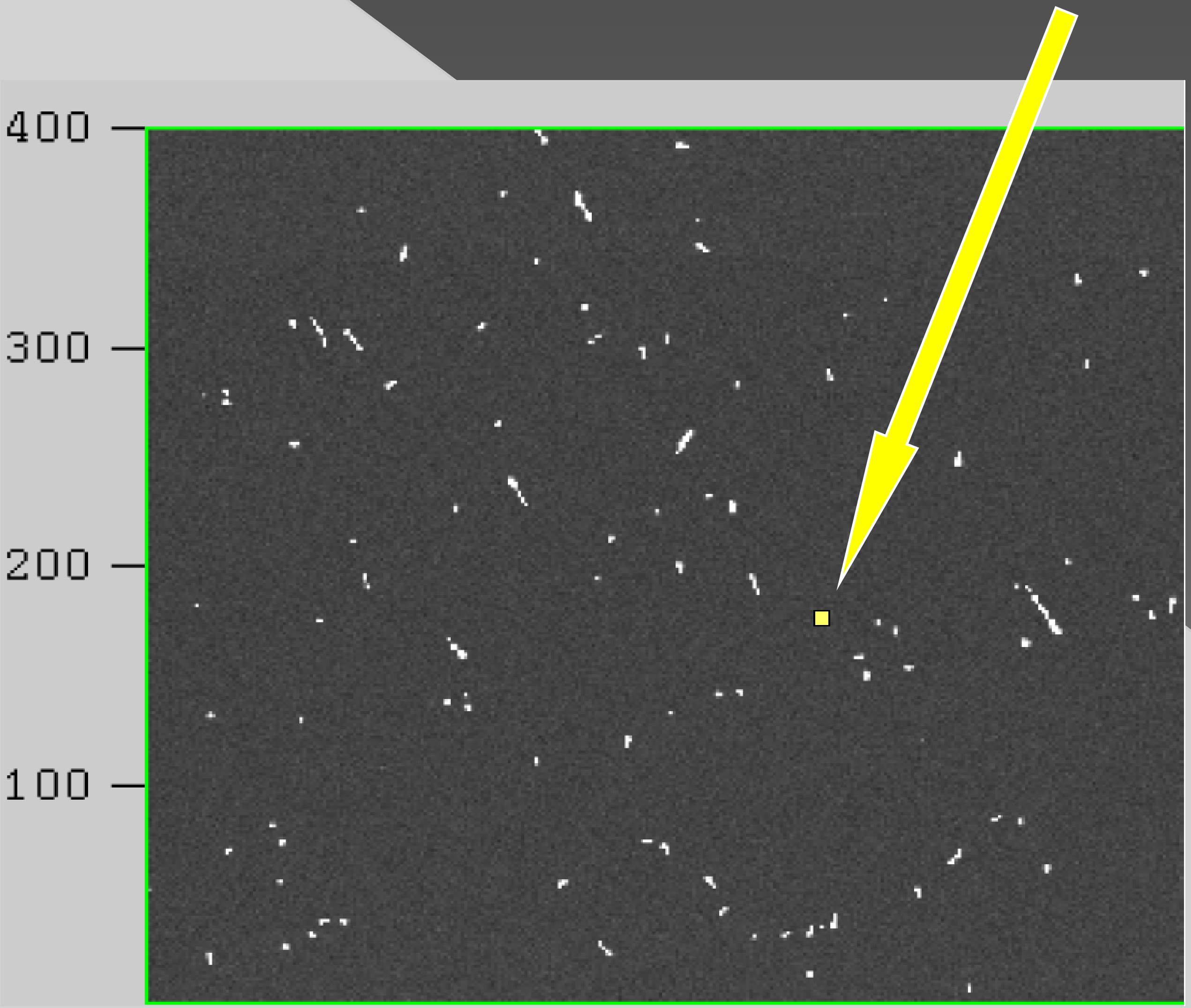


high power laser can cause damage to equipment if not monitored and held stable!!

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

1 pixel is 20x20 μm^2

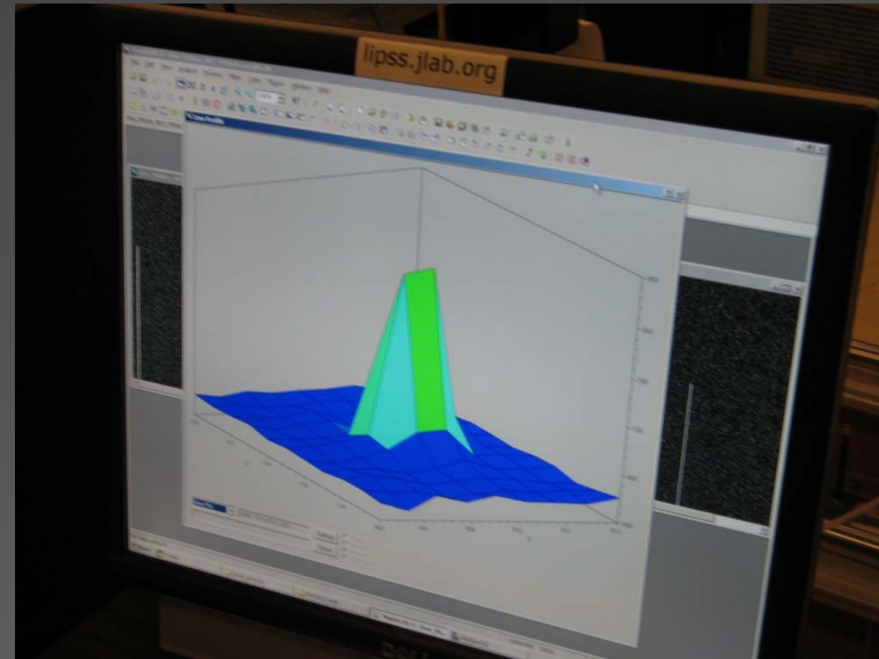
2 hour exposure; cosmic ray hits obvious exclude all regions where there were CR hits 5x5 pix array area shown in yellow

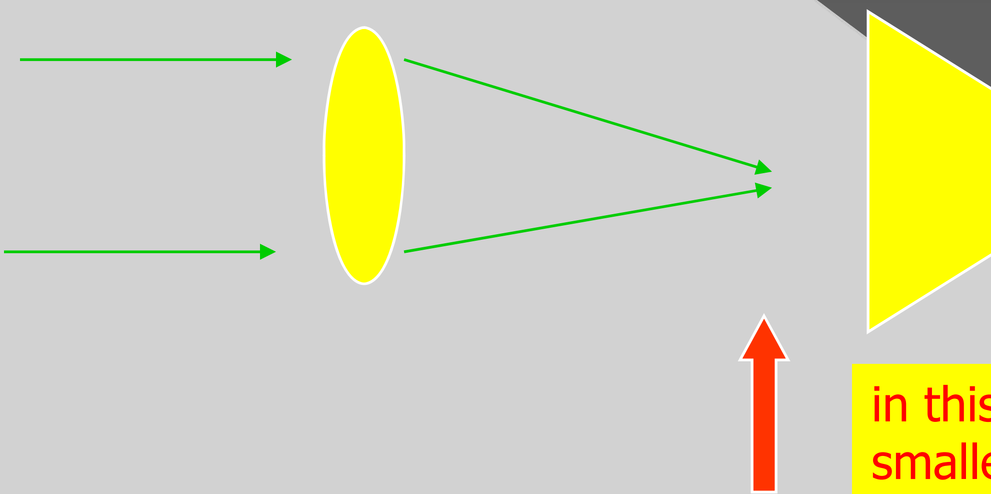


run procedure:

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

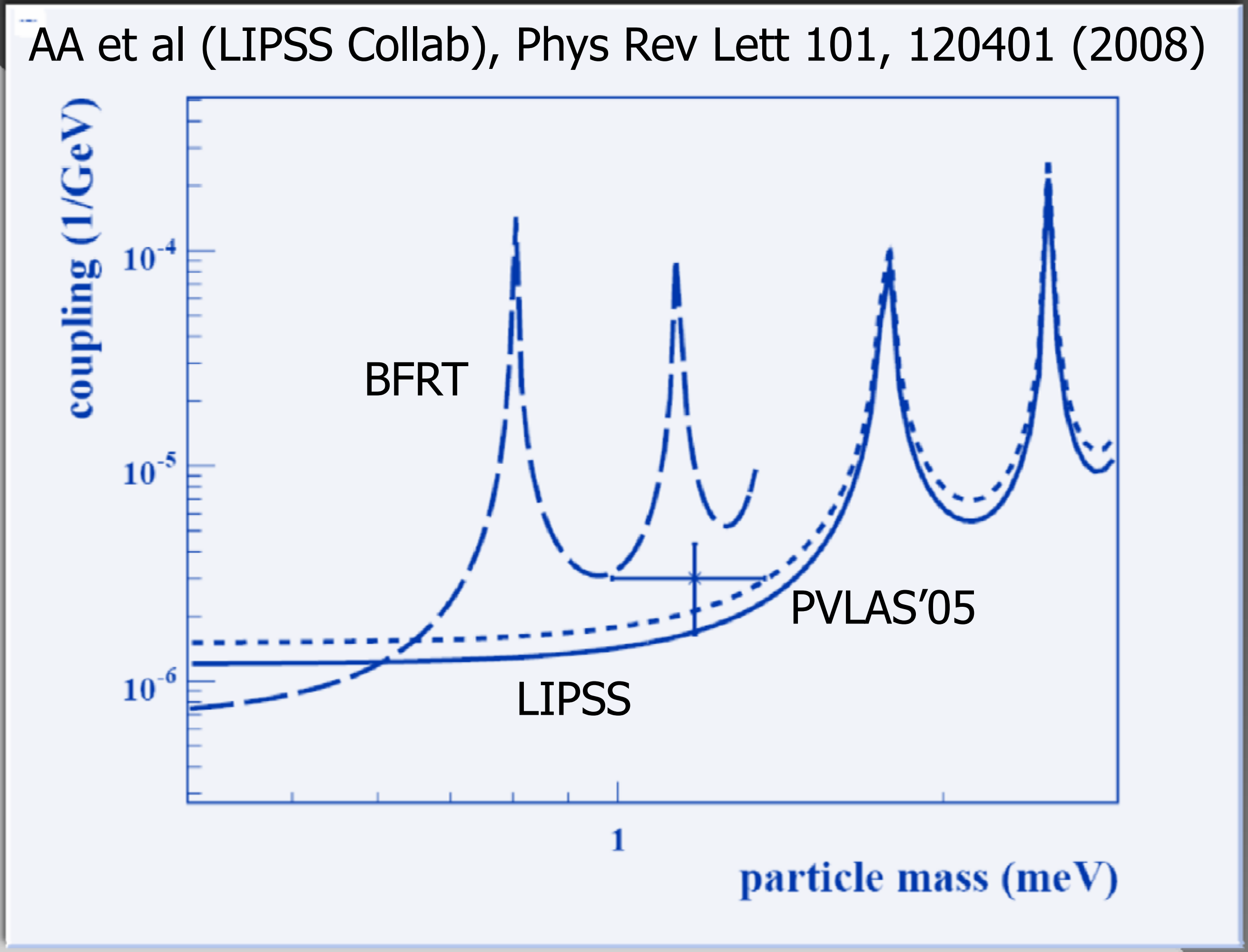
increase S/N: focusing light





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

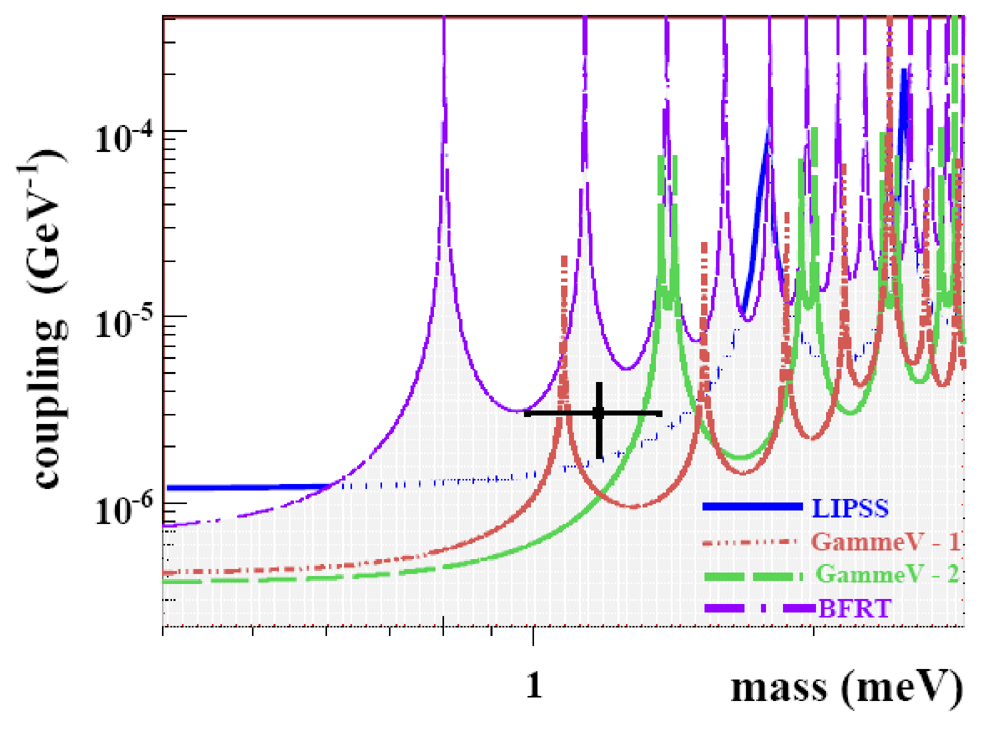
LIPSS Result

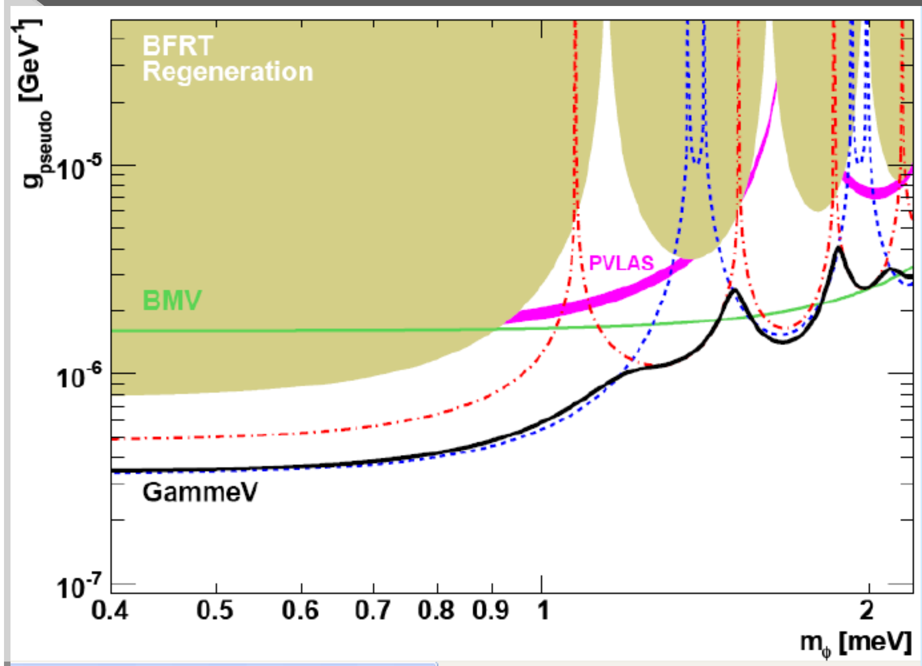


- No signal observed, regions above the curves are excluded by the experiment(s); data point is from PVLAS (2005)
- LIPSS reached the sensitive region for scalar coupling

Agreement with other experiments `light shining through a wall'

- BFRT, Cameron et al, PRD 47, 3707 (1993)
- BMV, Robilliard et al, PRL 99, 190403 (2007)
- GammeV, Chou et al, PRL 100, 080402 (2008)

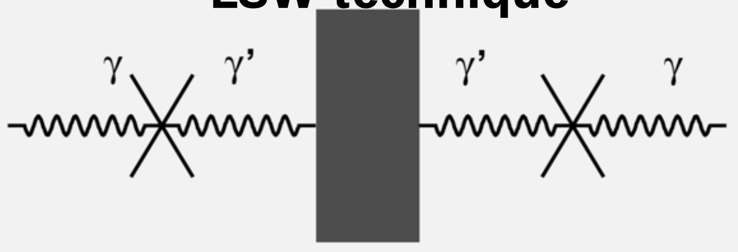




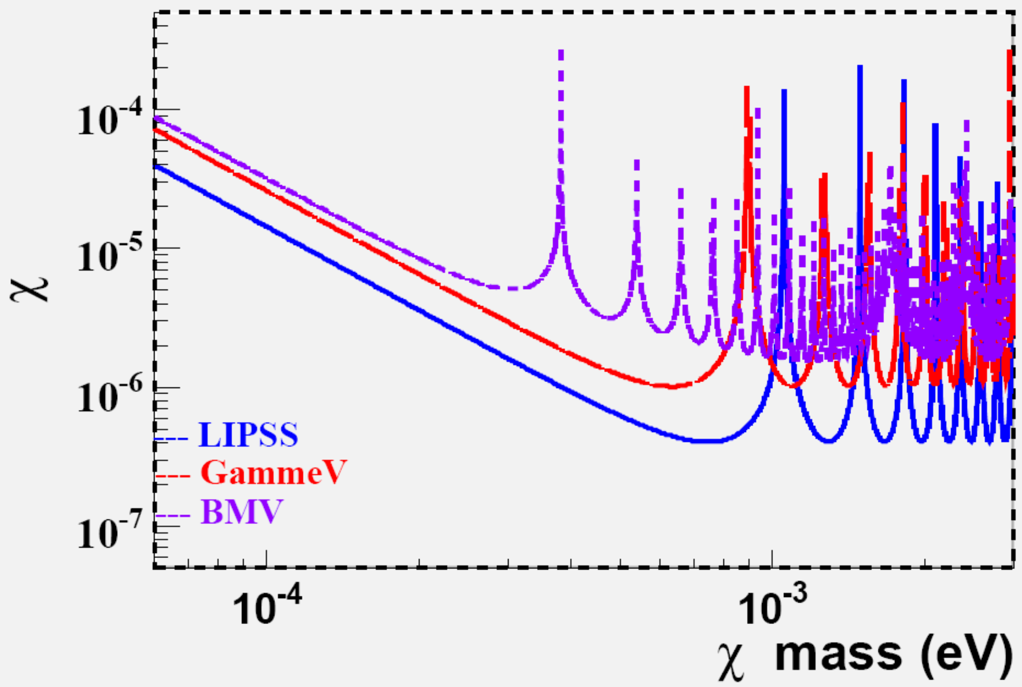
Another test of physics beyond the Standard Model

- Hidden-sector U(1) 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



- AA et al, arXiv:0810.4189 [hep-ex]
- LIPSS observed no oscillations
- Best LSW constraints due to high initial photon flux
- Region above the curves excluded at 95% CL



LIPSS Status Summary

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

(20h in `scalar boson’ configuration)

  - Quoted in `Axion Searches’ by PDG’08
  - Published in PRL 101, 120401 (2008)
- Equipment ready, awaiting FEL beam
- Further improvements planned

Acknowledgement

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