Photon Regeneration at Optical Frequencies

Andrei Afanasev
Hampton University/Jefferson Lab

3rd Joint ILIAS-CERN-WIMPs
Training workshop
Patras, Greece, June 22, 2007

Motivation for Axion Search

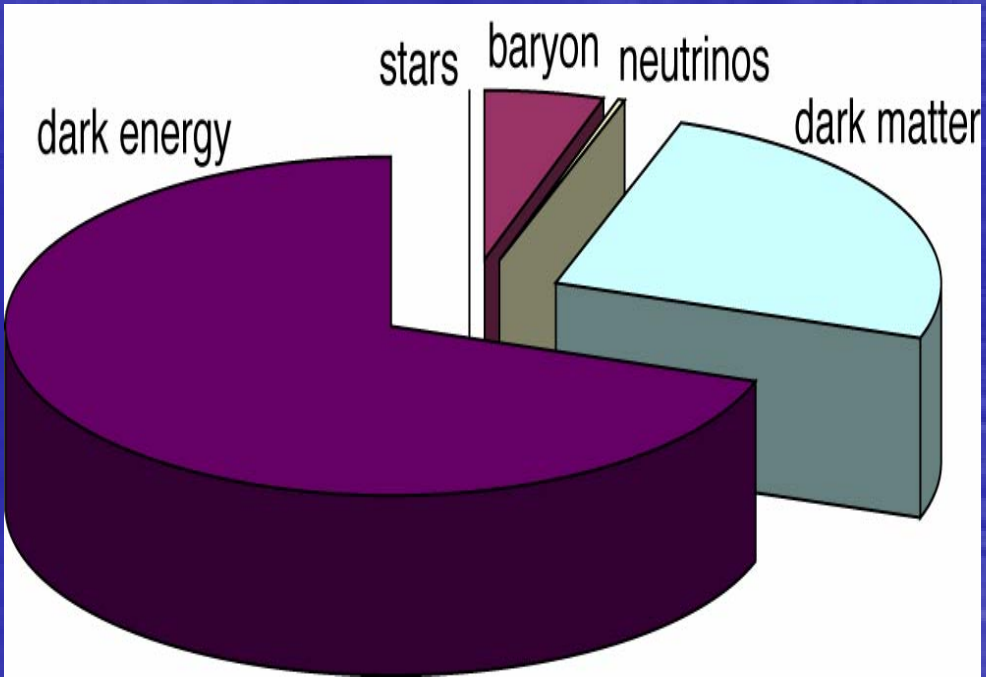
- Dark Matter problem
- Strong CP problem
  - Axion hypothesis
- Low-energy physics Beyond Standard model
  - PVLAS effect

Motivation for low energy studies

- Unsolved problem of mass hierarchy
  - What is behind the mass values of leptons and quarks?
  - Neutrino masses at sub-eV scale
- Strategy
  - Increase energy (new accelerators)
  - Explore low energies at sub-eV scales with high precision and sensitivity

matter/energy budget of universe

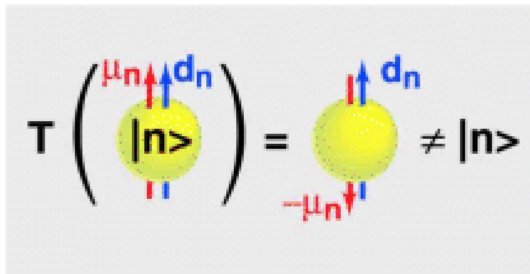
- Stars and galaxies are only ~0.5%
- Neutrinos are ~0.3–10%
- Rest of ordinary matter (electrons and protons) are ~5%
- Dark Matter ~30%
- Dark Energy ~65%
- Anti-Matter 0%



axion a dark matter candidate

Peccei and Quinn:
CP conserved through a hidden symmetry

This CP violation should, e.g., give a large neutron electric dipole moment $(\not{T} + CPT = \not{C}P)$; none is unobserved.
(9 orders-of-magnitude discrepancy.)



Why doesn't the neutron have an electric dipole moment?

This leads to the "Strong CP Problem": Where did QCD CP violation go?

1977: Peccei and Quinn: Posit a hidden broken U(1) symmetry ⇒
1) A new Goldstone boson (the axion);
2) Remnant axion VEV nulls QCD CP violation.

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.

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*
[3]*Istituto Nazionale di Fisica Nucleare (INFN), Laboratori Nazionali di Legnaro, Legnaro, Italy*
[4]*Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Pisa and Università di Pisa, Pisa, Italy*
[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

PVLAS results

based upon experimental idea of
L. Maiani, R. Petronzio, and
E. Zavattini, PLB 175, 359 (1986)

COSMOLOGY

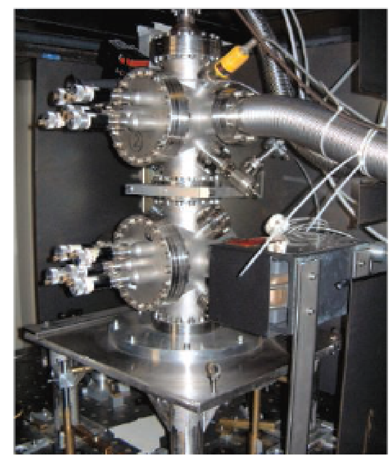
Science, 17 March 2006

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.



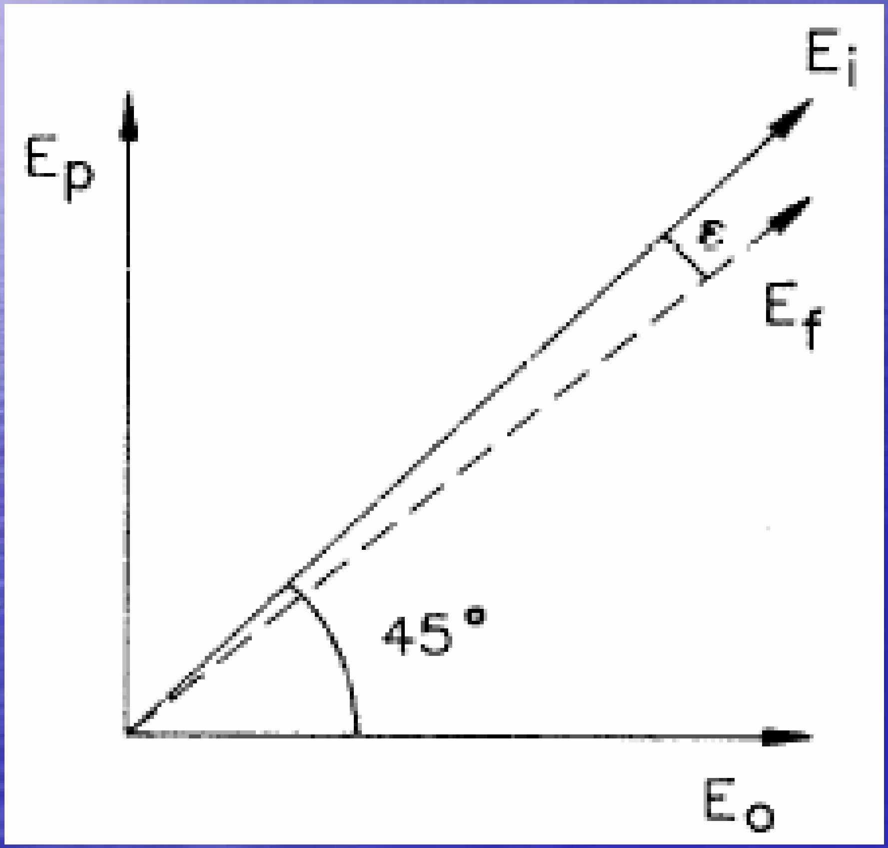
A twist in the tale. By rotating a laser beam with magnets, this experiment may have found never-before-seen particles.

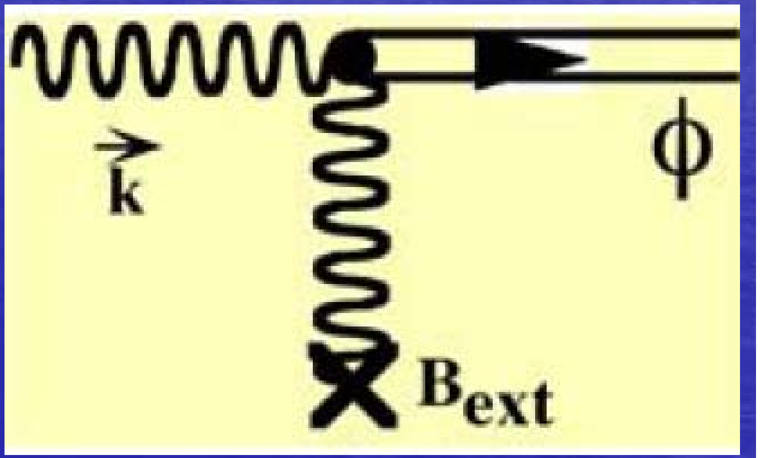
some cosmologists propose is the invisible missing dark matter that makes up a large chunk of the mass of the universe. However, the particle suggested by the PVLAS experiment is not what

Dichroism

rotation of polarization plane

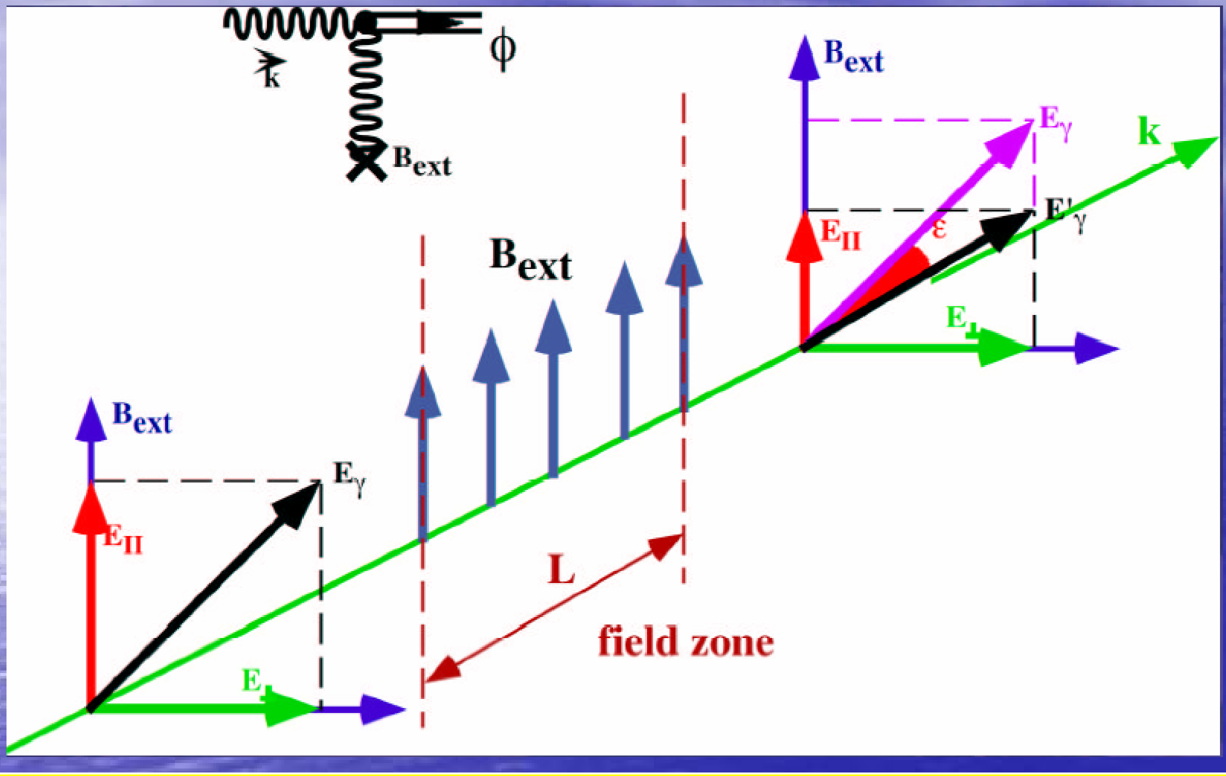
PVLAS Collab, PRL 96, 110406 (2006) [hep-ex/0507061]; CAST Collab, Phys Rev D47, 3707 (1993)





Dichroism
rotation of polarization plane

Maiani et.al., Phy. Lett. B175 (1986); www.ts.infn.it/experiments/pvlas



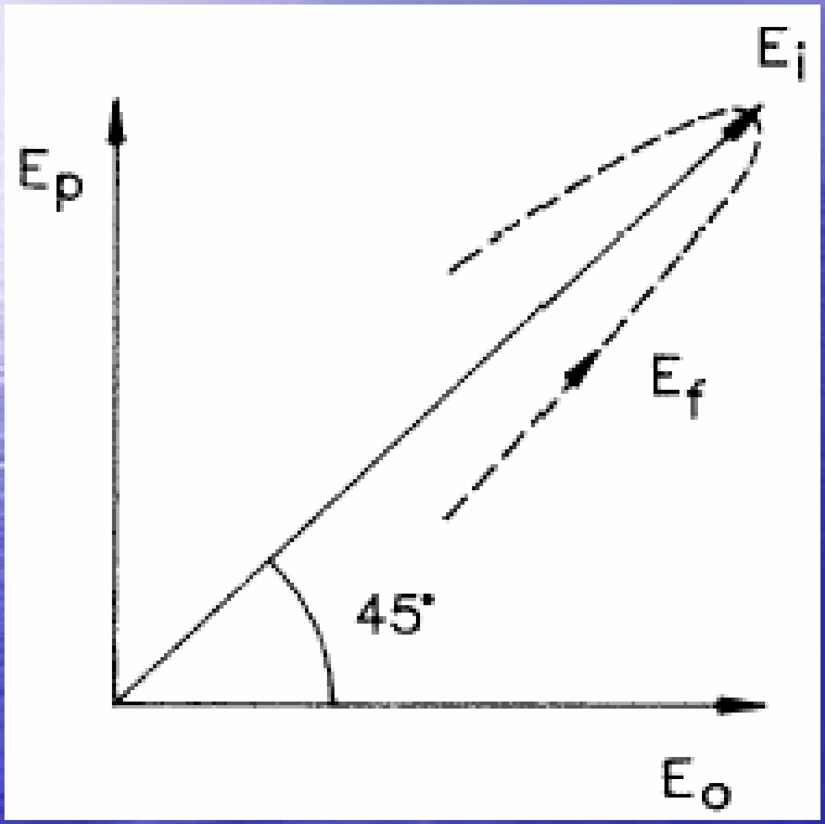
$$\varepsilon = -\left(\frac{B_{ext}L}{4M}\right)^2 \left\{ \sin\left[\frac{kL}{2}\left(1-\sqrt{1-\left(\frac{k}{K_m}\right)^2}\right)\right]\right\}^2 \frac{N}{\left[\frac{LK_m^{\,2}}{4k}\right]^2}$$

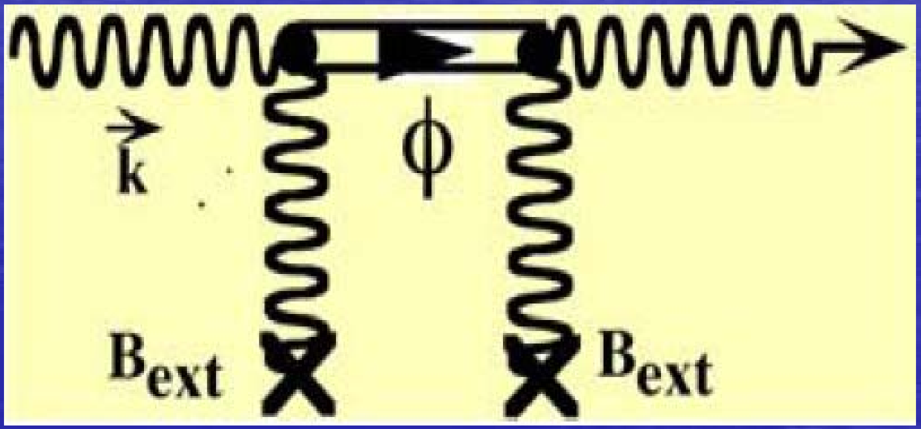
- M: inverse coupling
- K_m :inverse compton wavelength
- k: light wavenumber
- L: magnetic field region length
- N: number of traversals

Ellipticity

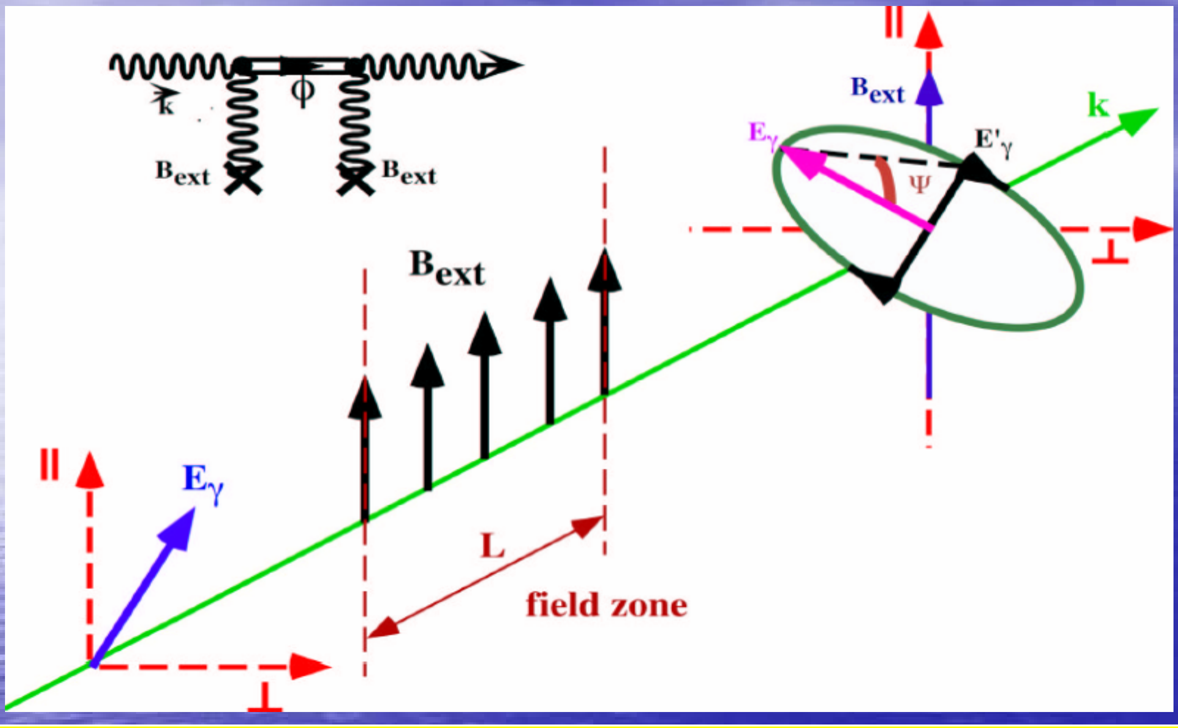
dispersion: photon-axion mixing

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





ellipticity
dispersion; photon-axion mixing



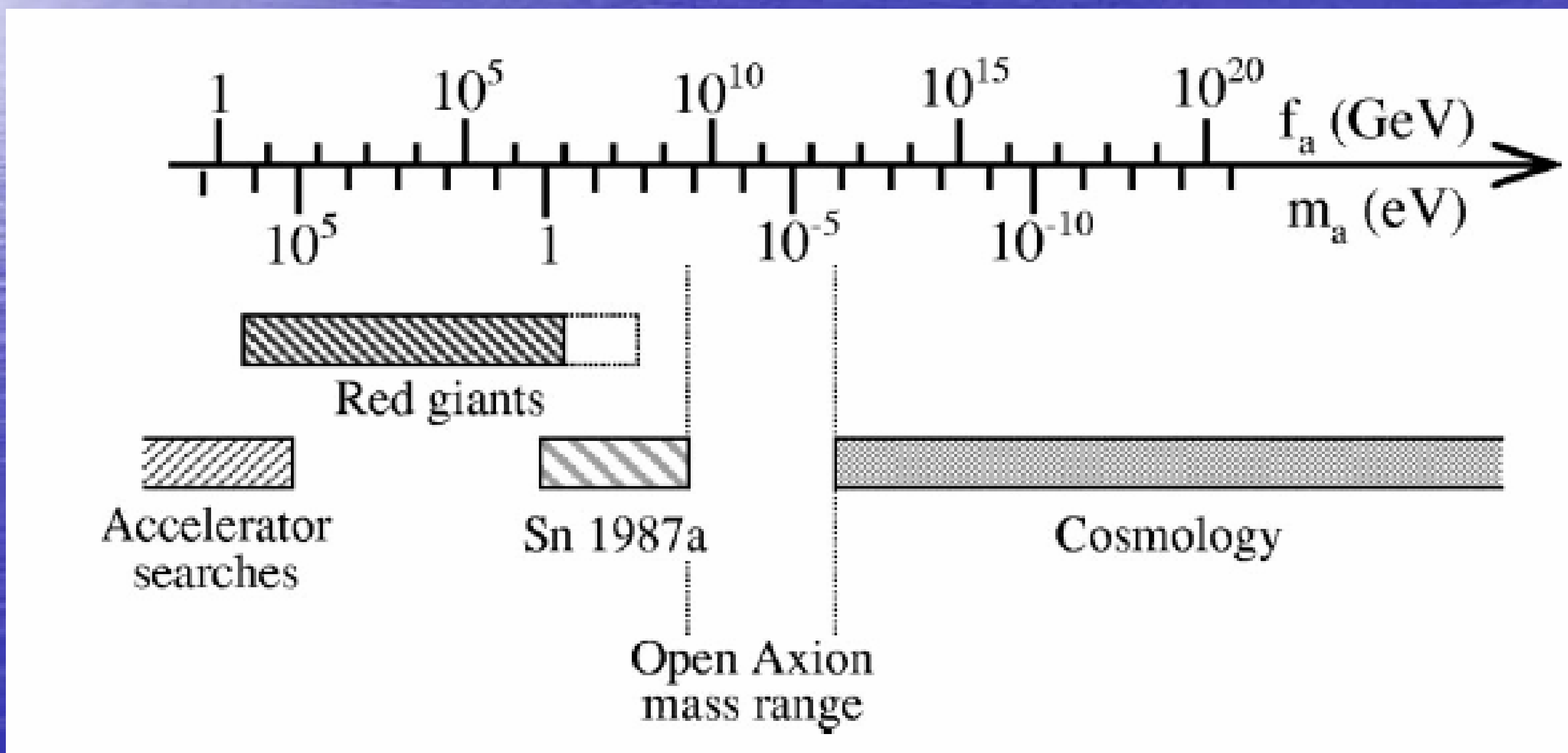
$$\psi = \left(\frac{B_{ext}{}^2 kL}{4M^2 K_m{}^2}\right)\left\{1 - \frac{\sin\left[kL\left(1-\sqrt{1-\left(\frac{k}{K_m}\right)^2}\right)\right]}{\frac{LK_m{}^2}{2k}}\right\}$$

- M: inverse coupling
- K_m :inverse compton wavelength
- k: light wavenumber
- L: magnetic field region length
- N: number of traversals

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



CERN COURIER
Volume 47, Number 2 (March 2007)

A workshop at the Institute for Advanced Study paid much attention to a small-scale experiment that might have found the first direct indication of a new particle

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

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	$= 10^{-19}$	10/s
BMV	LULI	11 T 0.25 m	1053 nm 500 W 4 pulses/day	$= 10^{-21}$	10/pulse
LIPSS	Jefferson Laboratory	1.7 T 1.0 m	900 nm 10 kW CW	$= 10^{-23.5}$	0.1/s
OSQAR (preliminary phase)	CERN	9.5 T 1.0 m 9.5 T 3.3 m	540 nm 1 kW CW	$= 10^{-20}$	10/s
PVLAS (regeneration)	INFN Legnaro	5 T 1 m 2.2 T 0.5 m	1064 nm 0.8W CW Npass $= 5 \times 10^5$	$= 10^{-23}$	10/s

LIPSS collaboration

A. Afanasev, K. McFarlane , R.Ramdon, H.Brown, C. Long

Hampton University

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

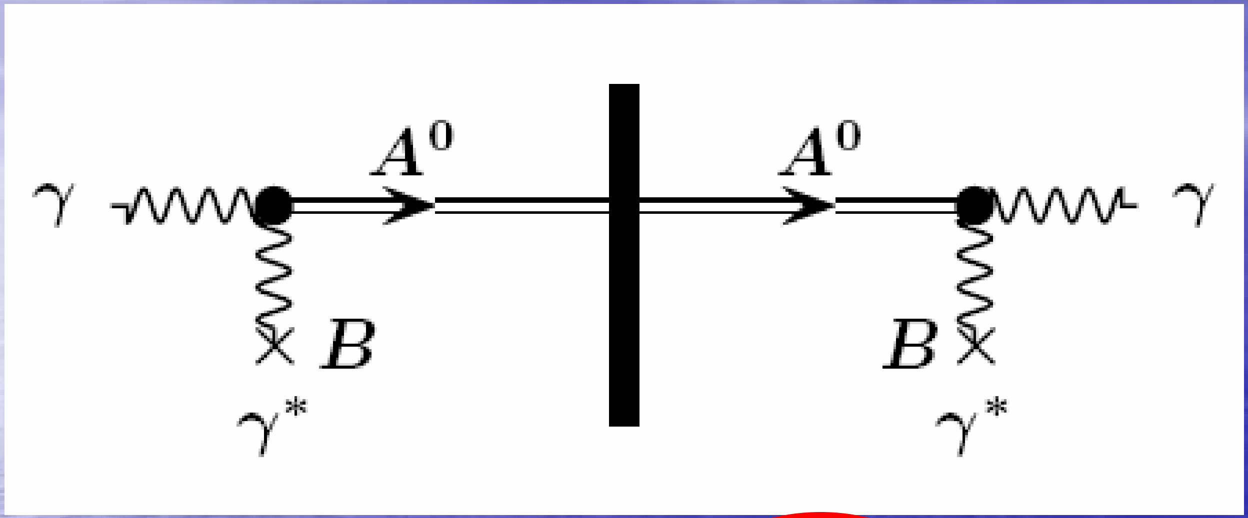
Jefferson Lab

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

Yale University

(*) *Spokesman*

Photon Regeneration
‘light shining through a wall’



couple polarized laser light with magnetic field

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

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

lnb – photon (or photon-lnb) conversion probability

photon-ps coherence; {} ~ 1

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

boson 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

Rate estimates

- $P = g^2 B^2 L^2 \sin^2(m^2 L/\omega)/(4m^2 L/\omega)^2$ γ-a prod prob
  - g = coupling constant (1/M)
  - B = magnetic field
  - L = magnet length
  - ω = light wavelength
- $Y = n\, P_1\, P_2\, \varepsilon\, (\Delta\Omega/\Omega)\, (N_r+2)/2$ yield (#/s)
  - n = photon flux (#/s)
  - P1 (P2) = production (regeneration) probability
  - ε = detection efficiency
  - ΔΩ/Ω = solid angle
  - N_r = number of reflections

parameters: initial run

- 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 90%
- expt'l efficiency ~ 90%
- **expected signal rate > 0.01 Hz at $g_{a\gamma\gamma}$ = 1.7 x 10^{-6} GeV^{-1}**

rate estimate, as example . . .

$$P = \frac{g^2 B^2 L^2}{4} \;; \quad (B = 1.7 \text{ Tesla} \;; \quad L = 1.0 \text{ meters})$$

$$= 6.2 \times 10^{-12}$$

axion-photon conversion probability, *P*

$$n_i = 200 \; watts \; (935 \text{ nm})$$

$$= 1.0 \times 10^{21} \; \gamma\text{'s} / s$$

photon rate, *n (200 W)*

$$r_s = n_i \bullet P^2 \bullet \frac{\Delta\Omega}{\Omega} \bullet \varepsilon_q \quad (\frac{\Delta\Omega}{\Omega} = 0.9 \;; \quad \varepsilon_q = 0.4)$$

$$= 0.012 \text{ Hz}$$

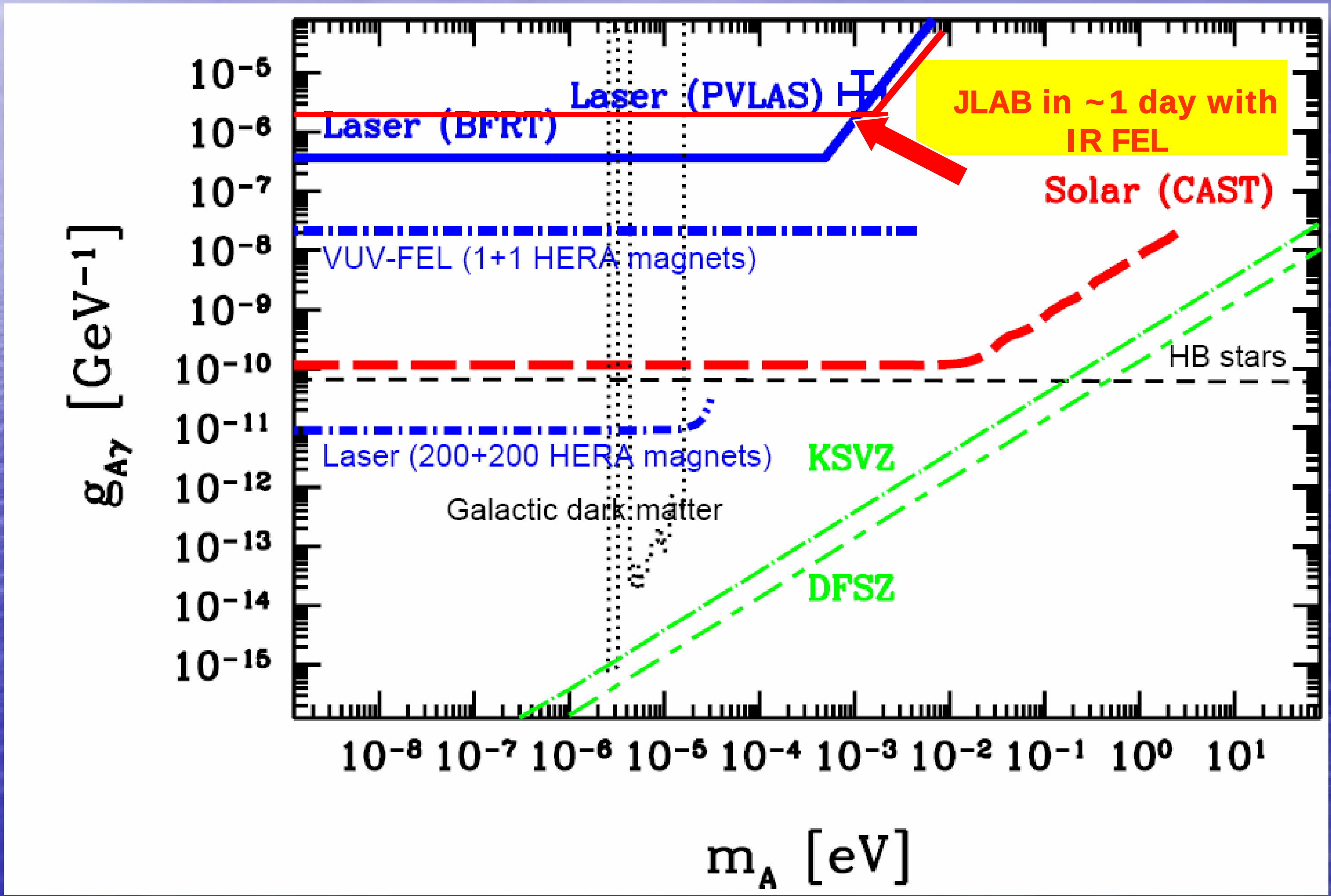
photon regeneration rate , *r*

1.7 T; 1 m magnet

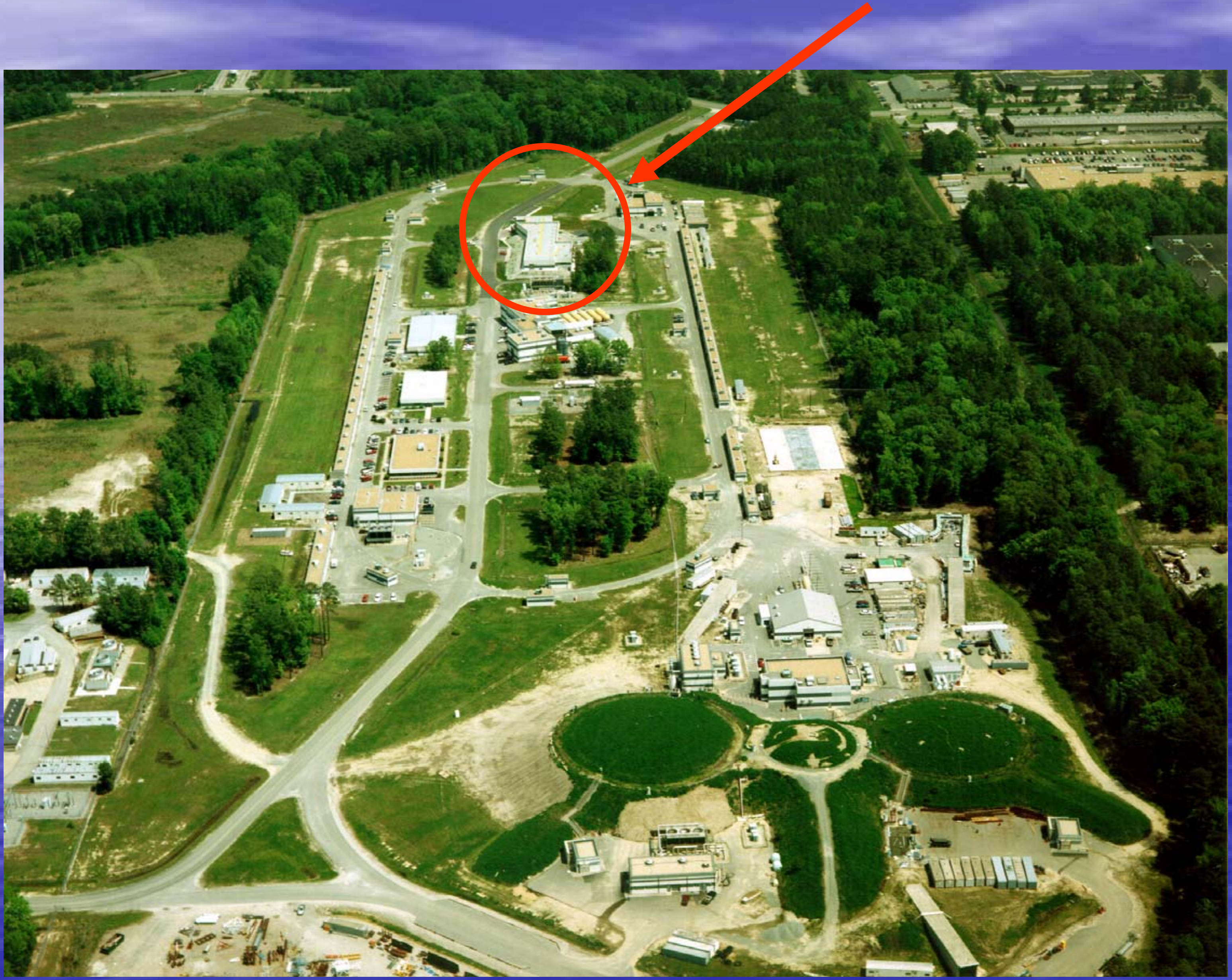
ε~ 0.4;

ΔΩ/Ω ~ 0.9

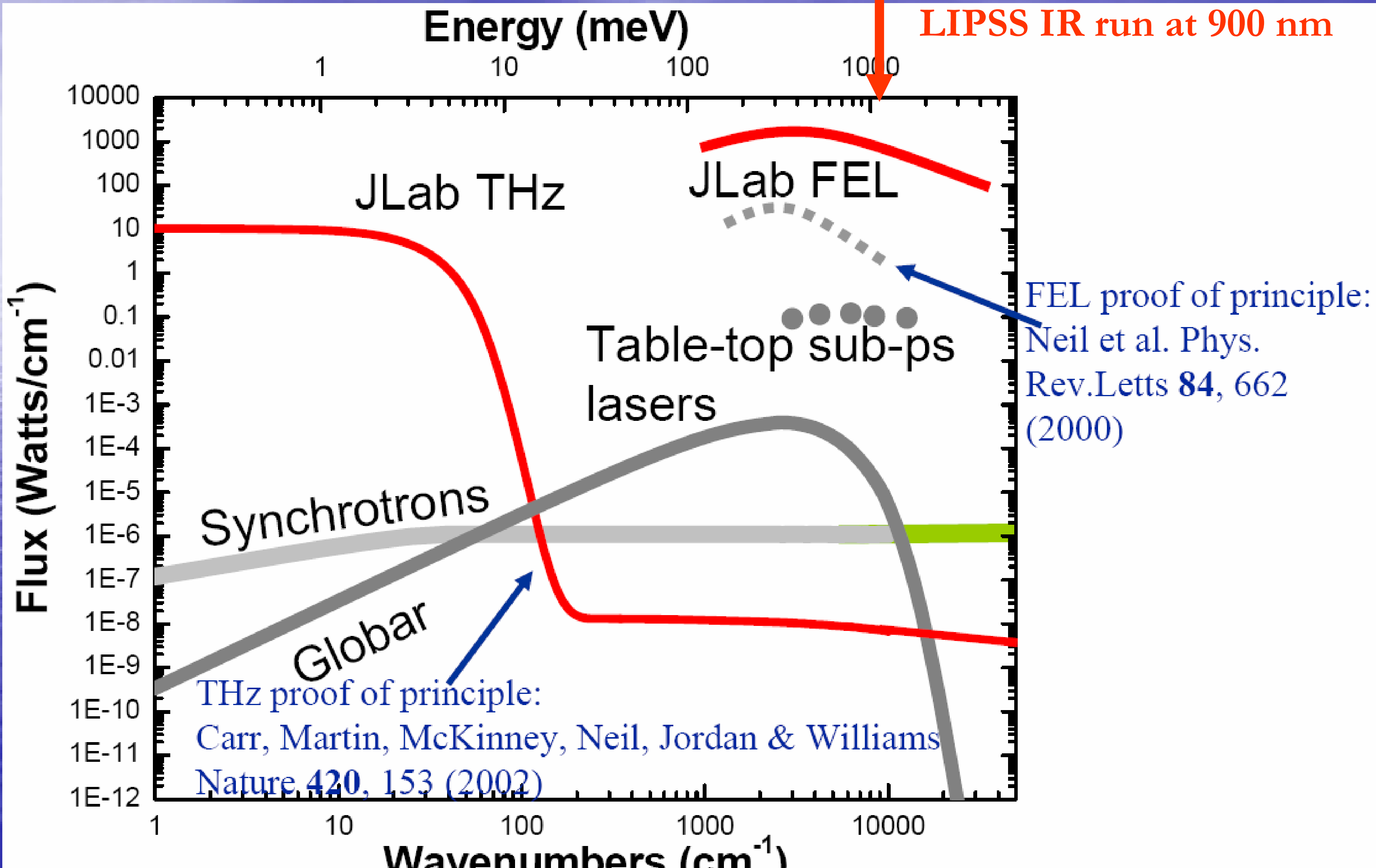
LIPSS sensitivity range



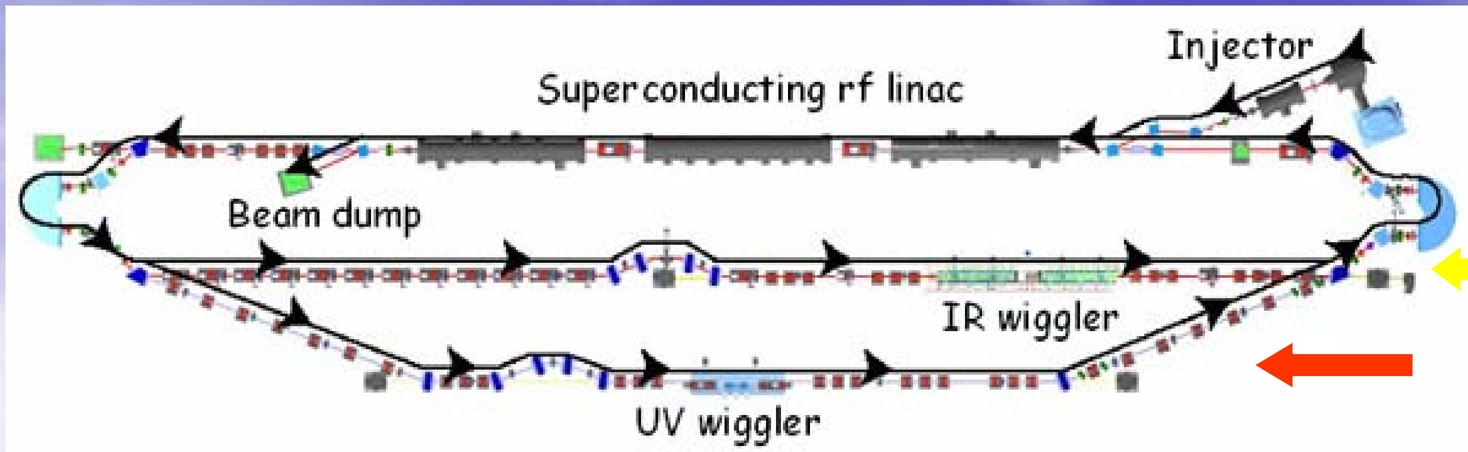
Jefferson Lab and the Free Electron Laser



JLAB facility spectroscopic range



JLAB FEL: regeneration experiment

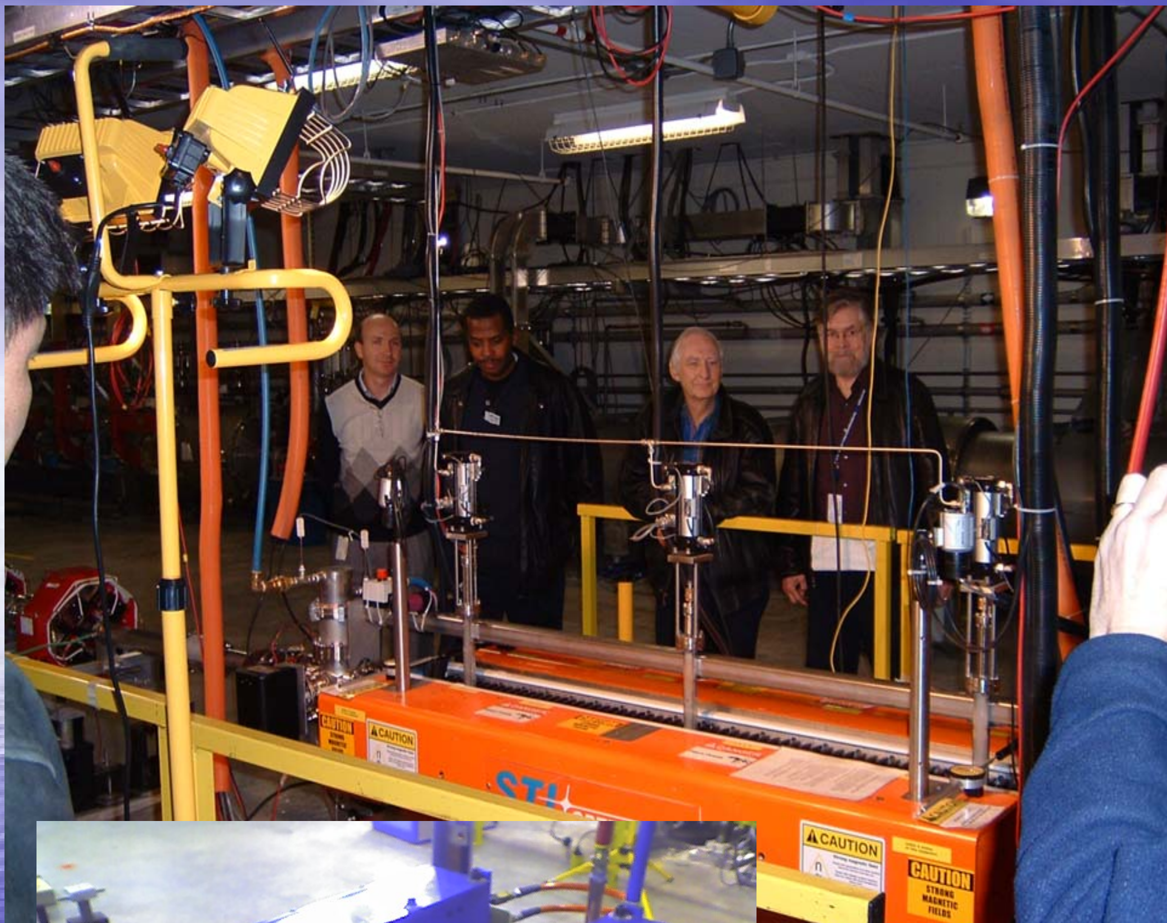


current

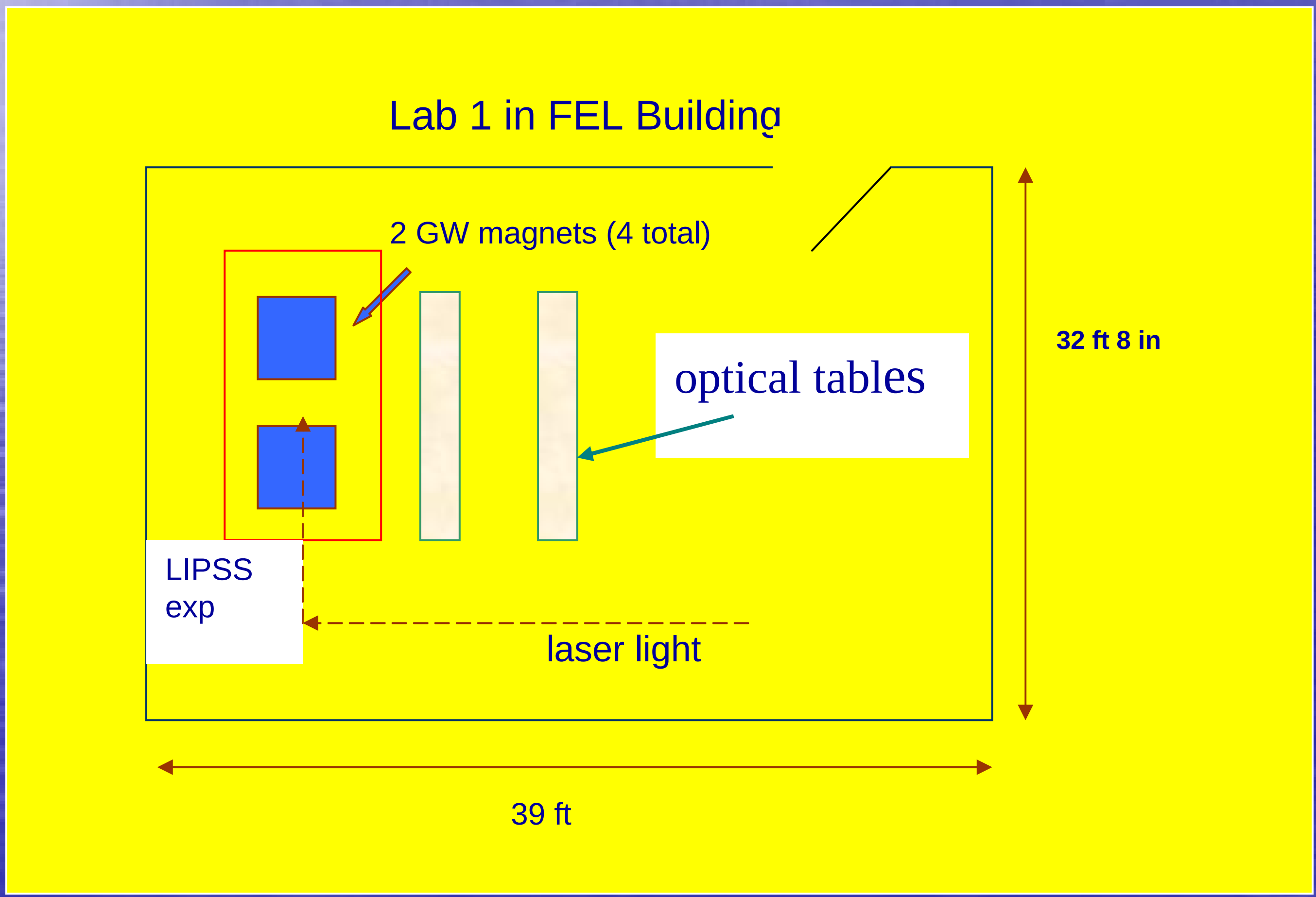
planned

infrared FEL operational at 10 kW extracted power

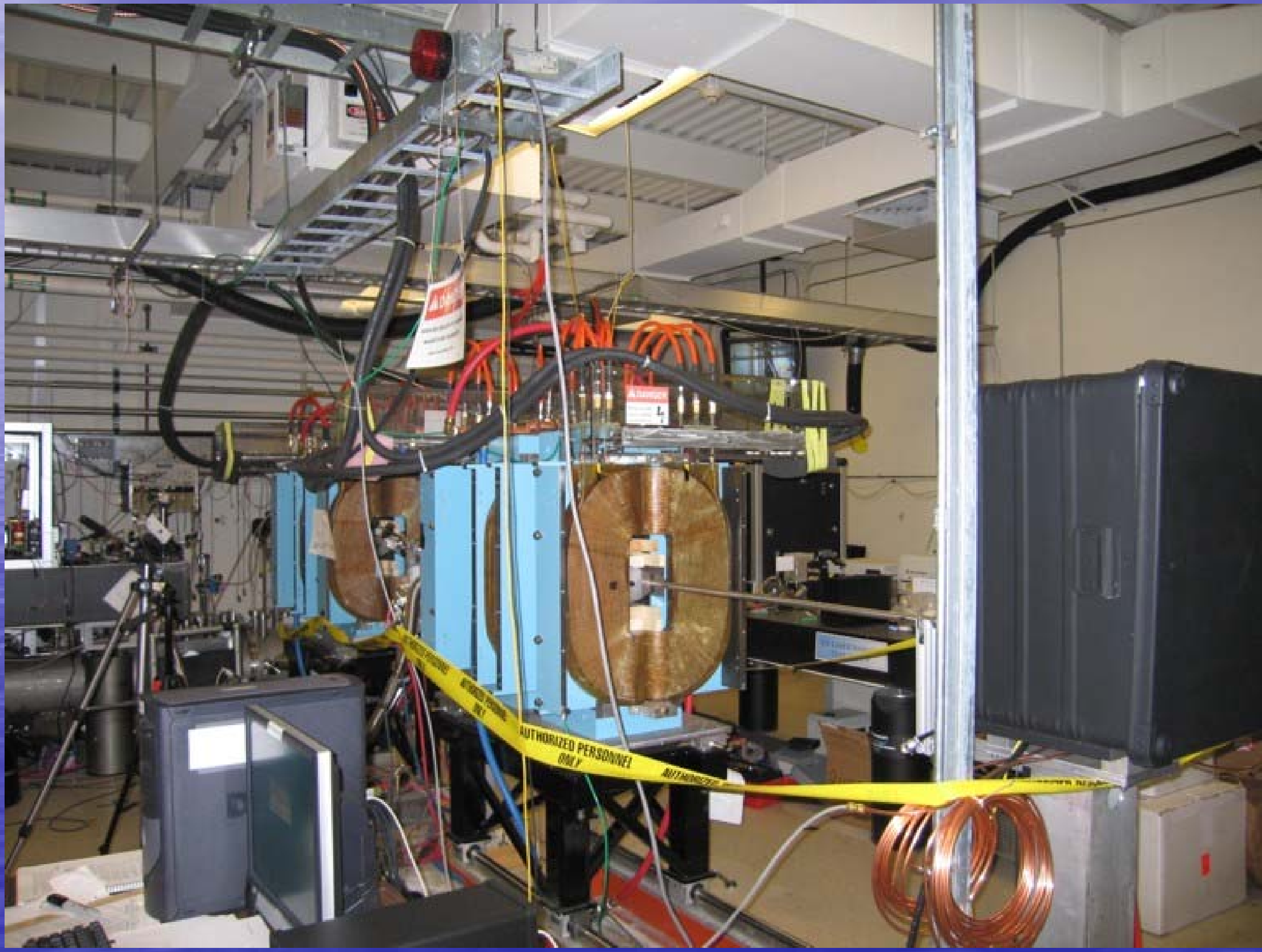
- 800 nm; tuneable
- up to 75 MHz rep rate



The experiment is mounted in Laboratory 1 in the FEL Building. There are two GW magnets used for PS generation, and two for photon regeneration. (0.5 m long; 1.8 T each)

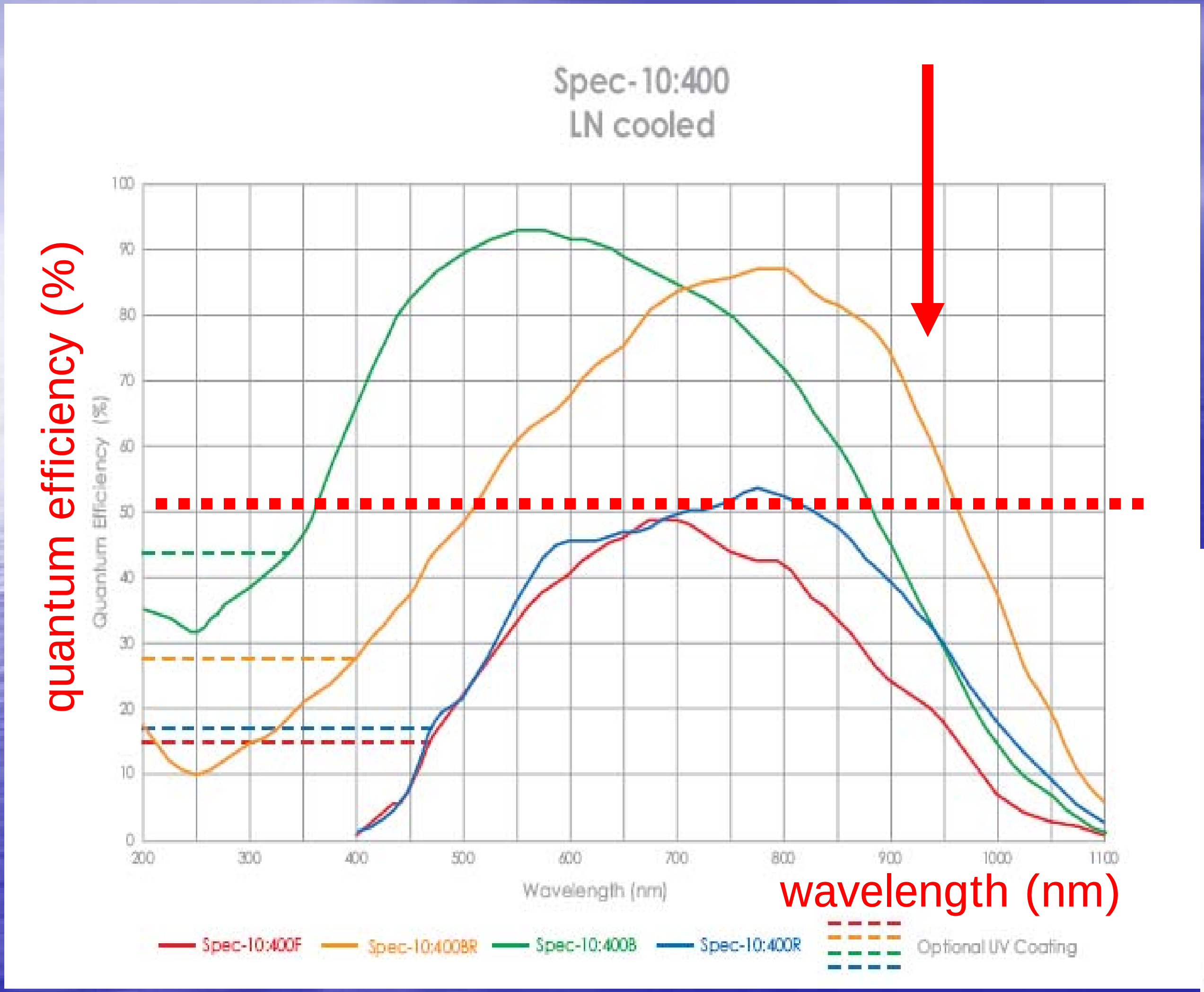


LIPSS today



LIPSS detector

Princeton Instruments ACTON 10:400BR-LN



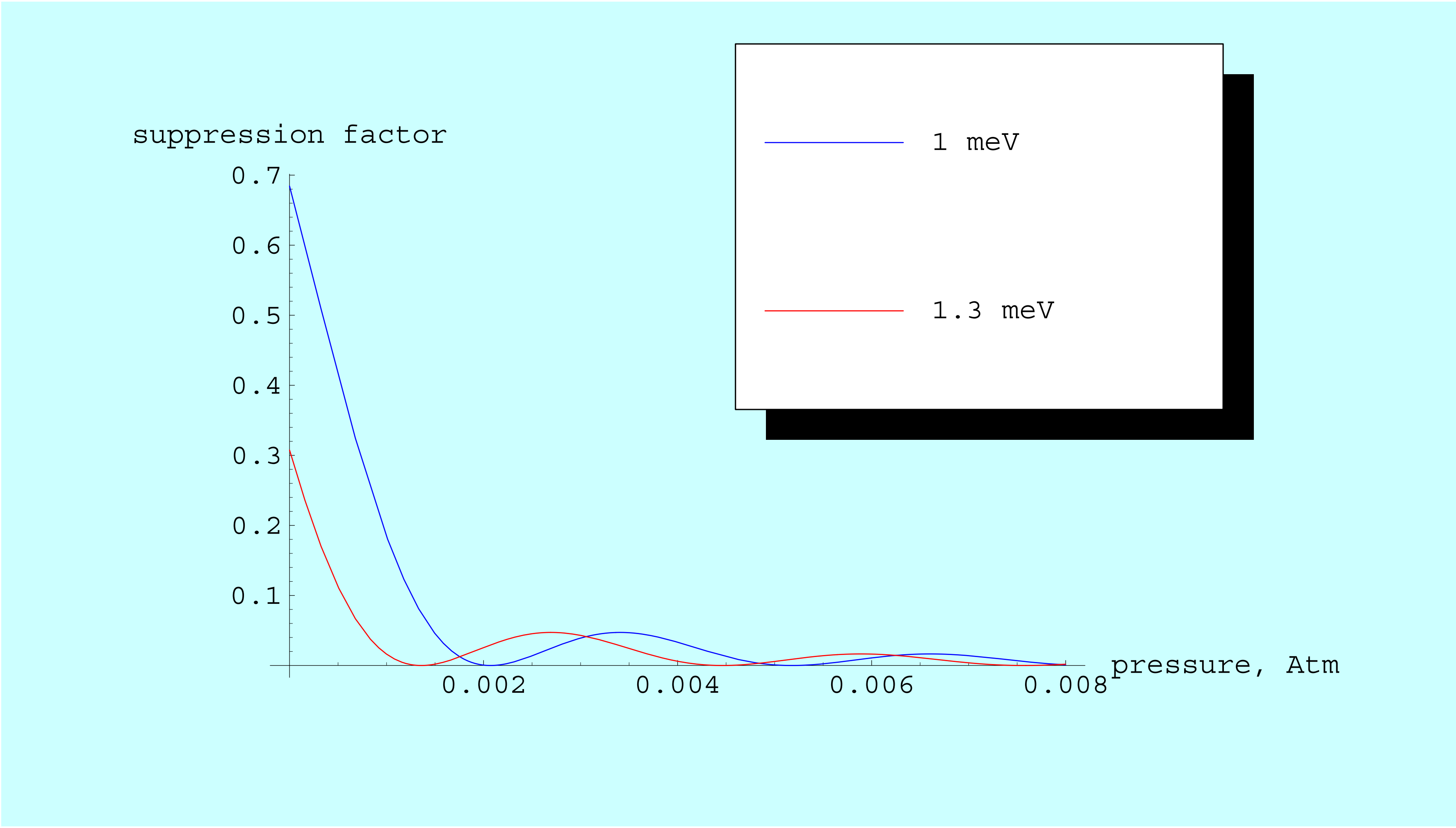
q.e. high at 935 nm

50%

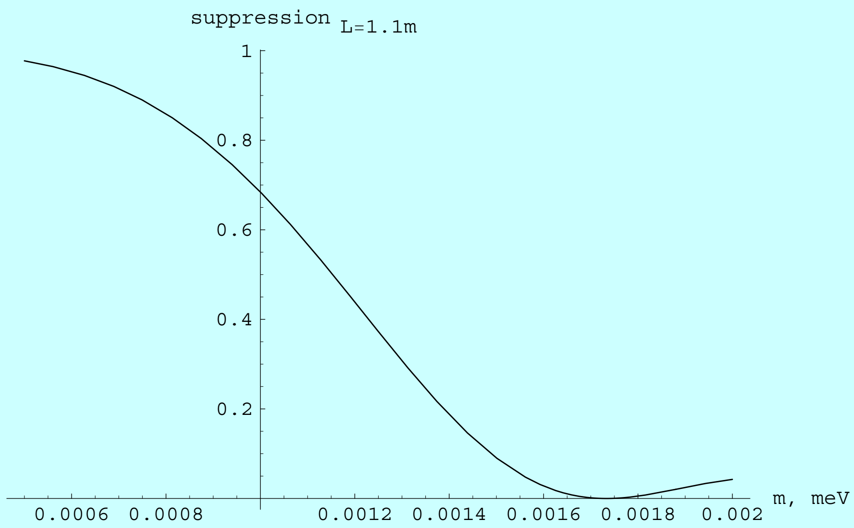
LN2 cooled: 1.3 e / pix / hour dark noise !!!
used 100 kHZ readout rate

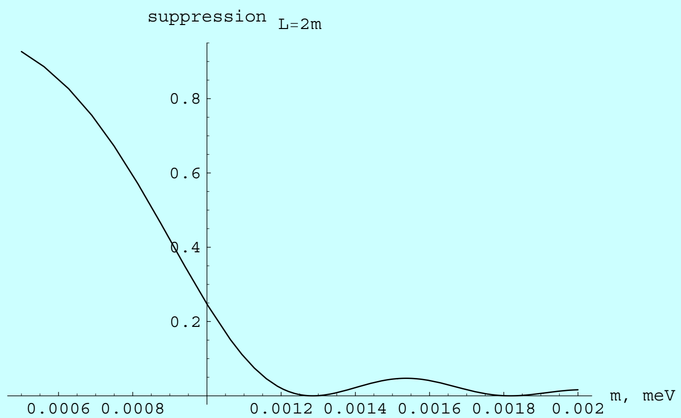
Importance of vacuum

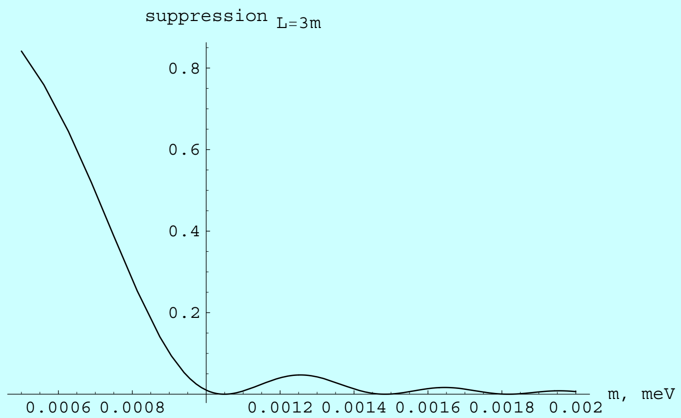
Signal suppressed for air present in gen/regen magnets



Destructive interference in photon regeneration vs magnet length



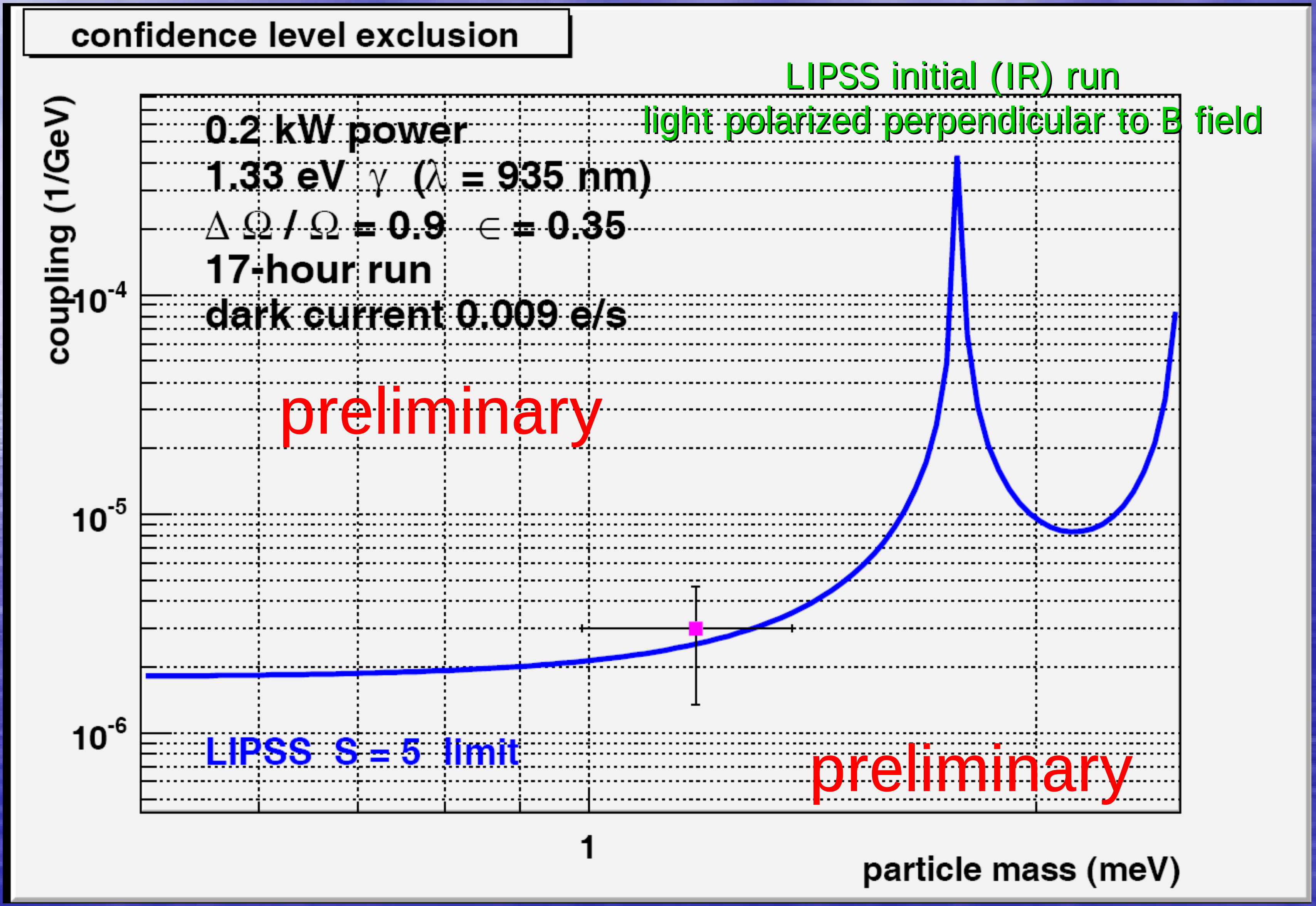




LIPSS Present Configuration

Longer magnets: less sensitivity in PVLAS region

not sensitive enough yet to cover full parameter space of PVLAS result, however did reach the sensitive region for scalar coupling



Periodic Magnetic Field: Opportunity at Optical Frequencies

- Removes $q \cdot l << 1$ constraint

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

- Can be used to measure mass m_b

  AA, Baker, McFarlane et al, hep-ph/0605250

  -Requires magnet length ~ m in IR;

  -Not practical for X-rays: need ~ km-long magnets

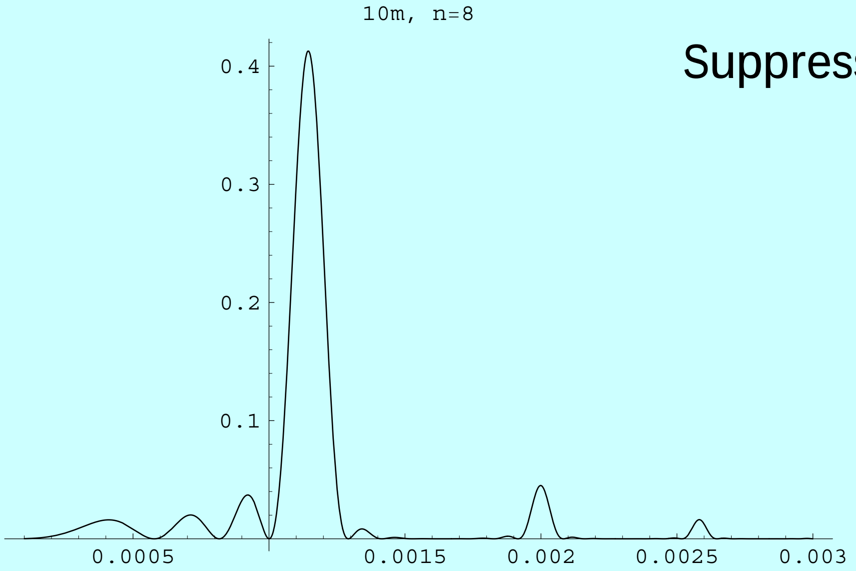
- Similar effect from `phase shift plates'

  Jaekel&Ringwald, hep-ph/0706.0693

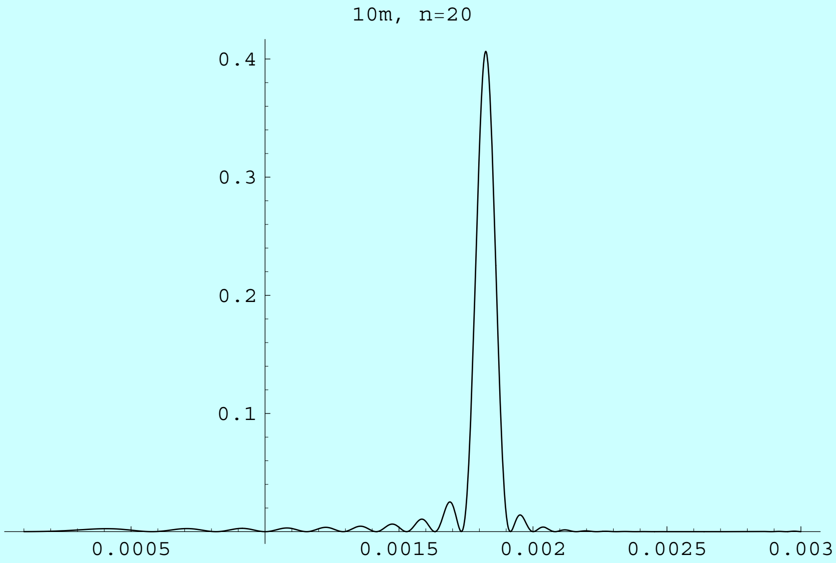
Periodic magnetic field effect

$$P_{\gamma\to\phi} = \frac{1}{4} g^2 B^2 L^2 \ \ for\ m_\phi = 0$$

$$P_{\gamma\to\phi} = \frac{1}{q^2} g^2 B^2 \tan^2(\frac{qL}{2N})[1-(-1)^n \cos(qL)]/2$$



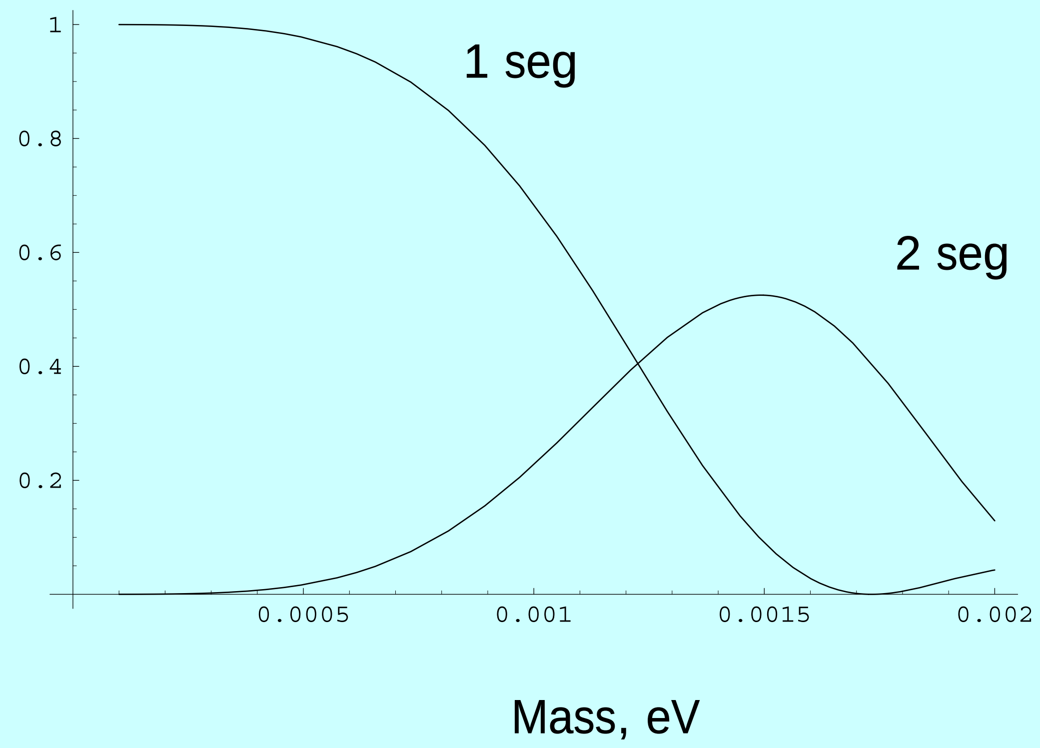
Suppression



Mass, eV

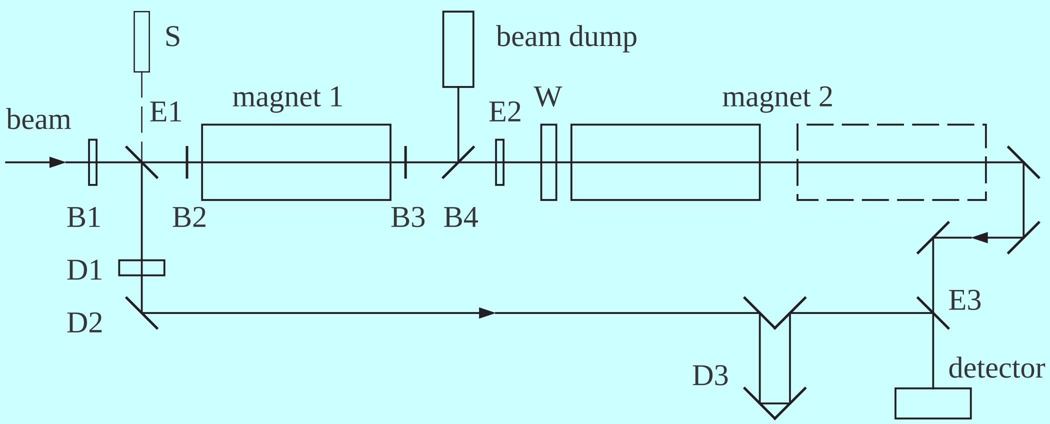
Periodic field for LIPSS in present configuration

- Each 1.1m magnet consists of 2 segments
  - Polarity of the segments can be flipped



Enhancement by Interference with reference beam (PSE)

- Van Bibber'87;AA, Baker, McFarlane et al. '06



summary

- LIPSS has begun to test axion interpretation of PVLAS result
  – data in scalar configuration
- uses JLAB FEL and its facilities
    - use dipole magnets that are on-hand (~1.8 T)
    - used ultra-low noise CCD array
    - 200 watts average power; light polarized perpendicular to B
- ran in Spring 2007 24 hours, 935 nm
  – some reach into sensitive region of parameter space
- **continue experiment in ~winter 2008**
  – **upgrade optics to get higher power**
  – **additional diagnostic monitoring equipment**
  – **get pseudoscalar data**


Thank you!