Beyond the Standard Model: Physics of Axions

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HUGS 2007

Outline

- Dark Matter problem
- Strong CP problem
  - Axion hypothesis
- Axion searches

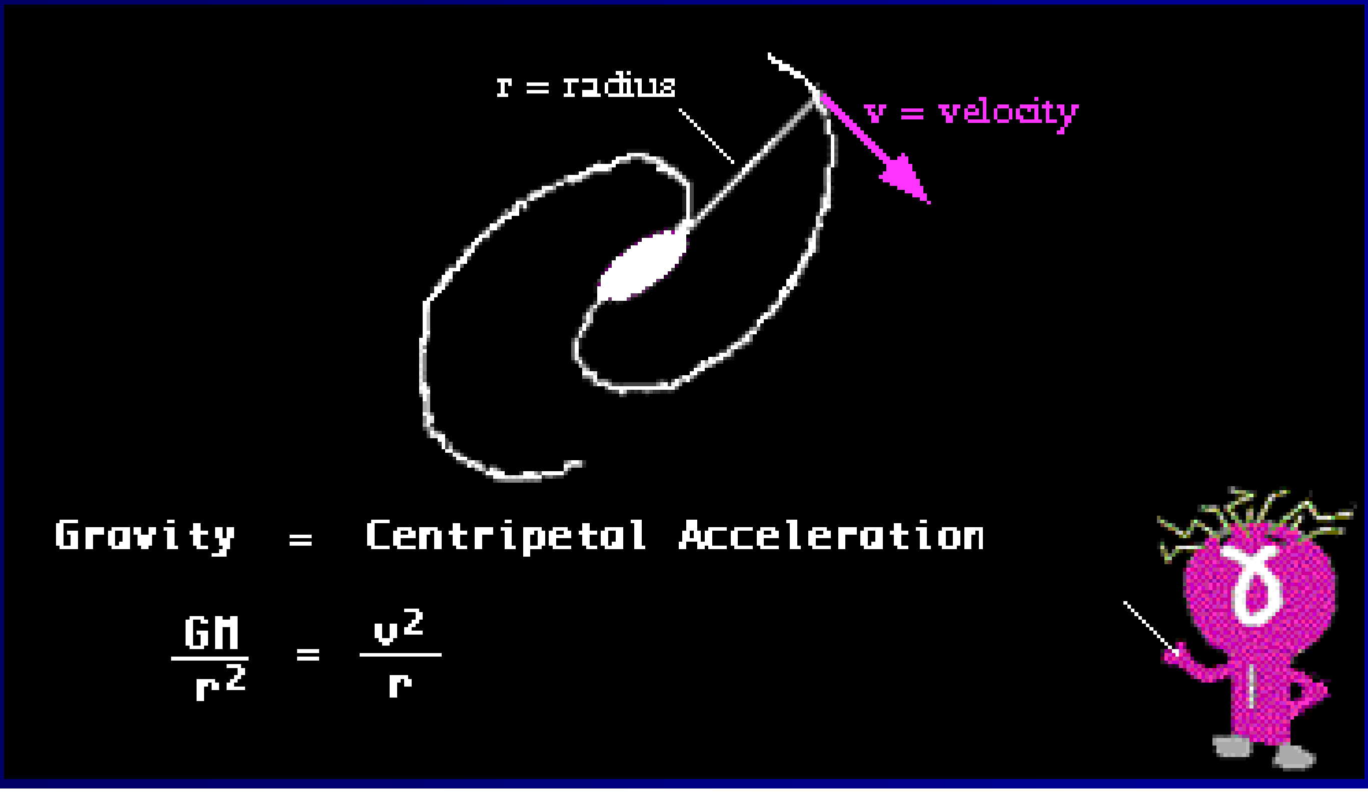
Dark Matter Problem

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

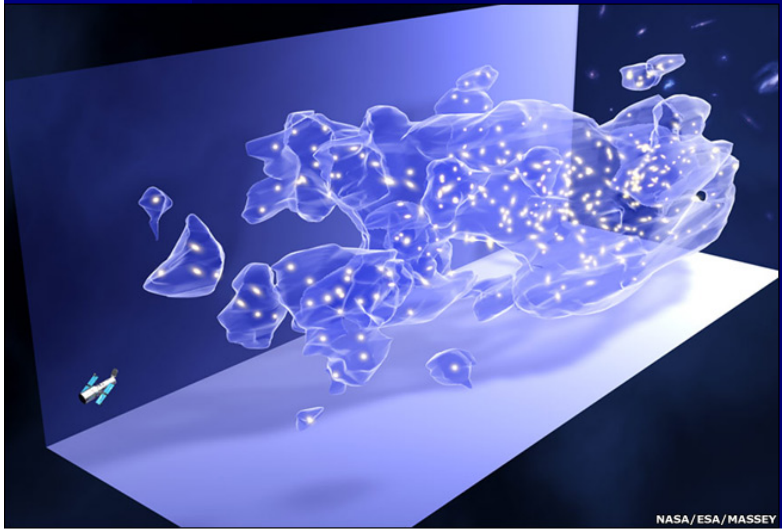


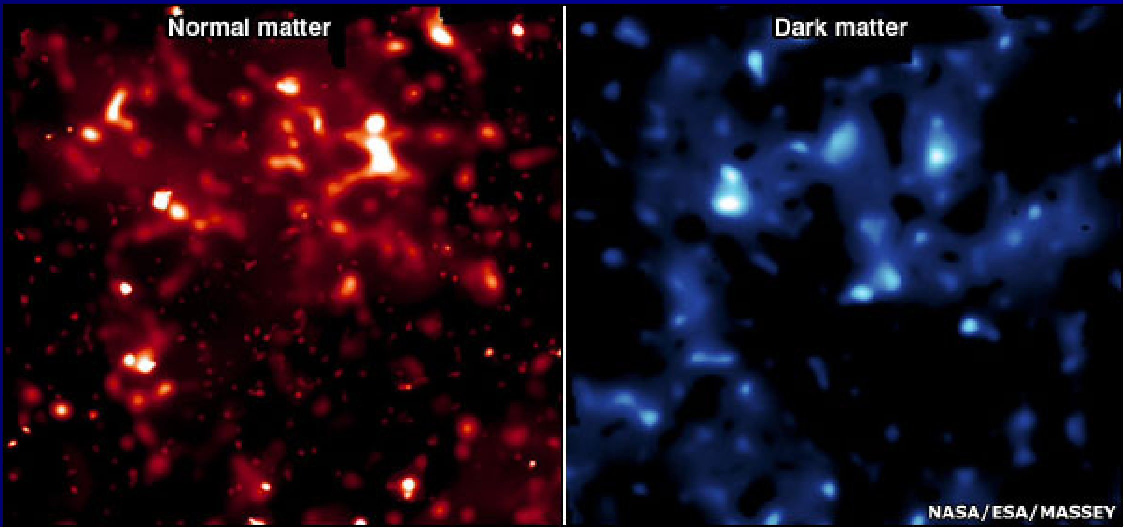
$v^2 \sim 1/r$?

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

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

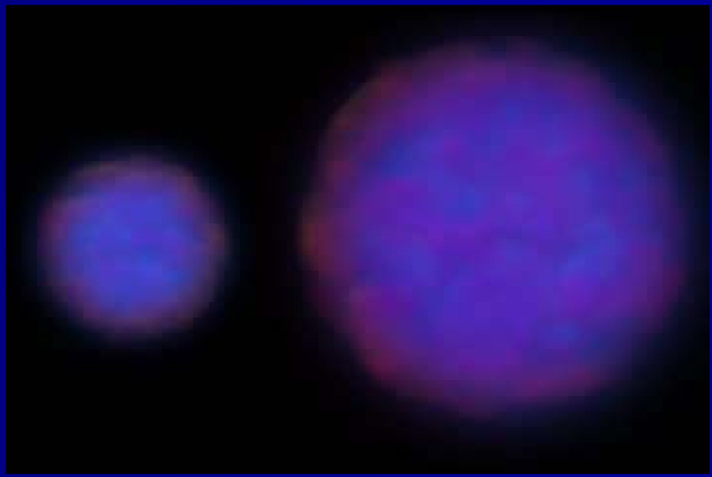
- Area of 1.6 deg^2
- ~1/2 million galaxies





Chandra X-ray observatory data'06 (see chandra.harward.edu)

- Galaxy cluster 1E 0657-56 (`bullet cluster')
- Dark matter (blue) not slowed by the impact; while hot gas (red) is slowed/distorted by drag force
- Separation during collision



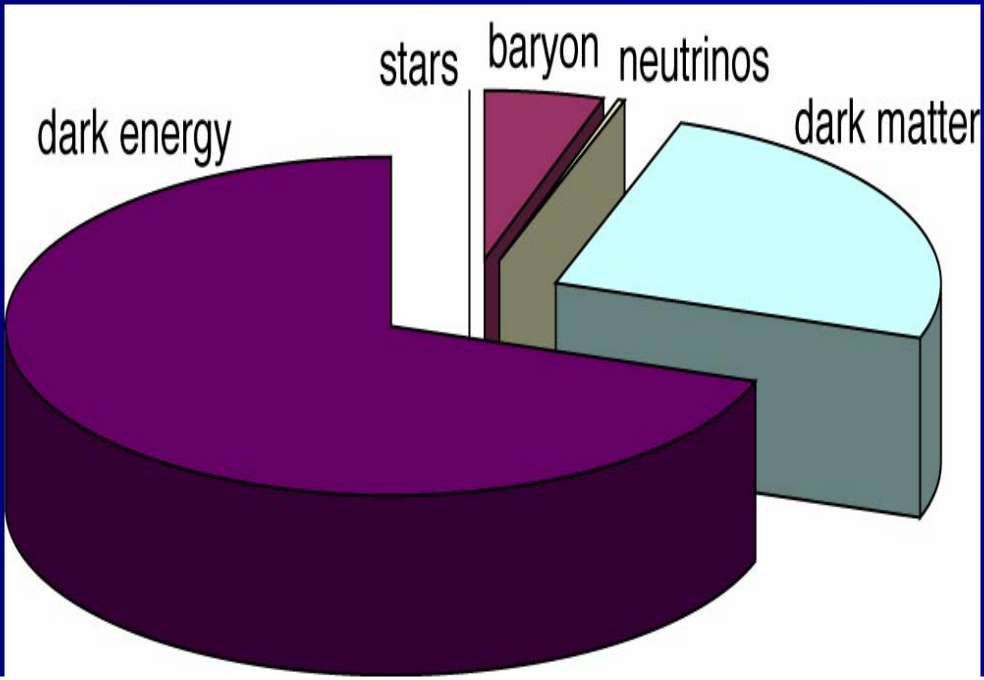
More dark matter evidence (2007)

- Ring of dark matter formed in collision of two galaxy clusters

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



Possible solution

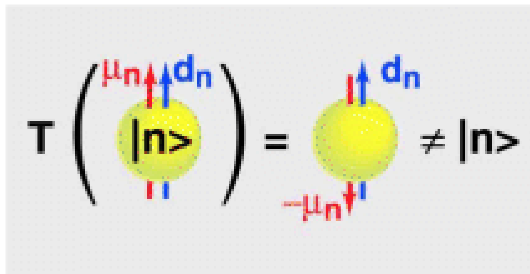
- There is a new elementary particle that escaped observation so far

Strong CP Problem

Axion Hypothesis

Peccei and Quinn:
CP conserved through a hidden symmetry

This CP violation should, e.g., give a large neutron electric dipole moment ($\cancel{T}$ + CPT = $\cancel{CP}$); 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.

θ -term and strong CP problem

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

θ-term is CP-violating

Physical effects depend on the combination

$\bar{\theta} = \theta + \mathrm{Arg\ Det}\ M$

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

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

The CP problem:

why $\bar{\theta}$ so small ?

θ_{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

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

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.

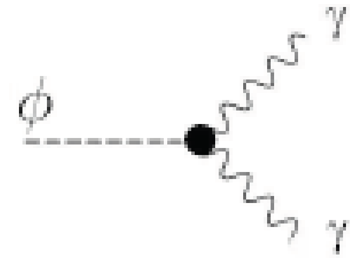
VOLUME 40, NUMBER 5 PHYSICAL REVIEW LETTERS 30 JANUARY 1978

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.

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 $\mathrm{PS} \rightarrow \vec{E}\vec{B}$, $S \rightarrow |E|^2 - |B|^2$
  Call them AXION-LIKE PARTICLES (ALPs)

Axion Searches

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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[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

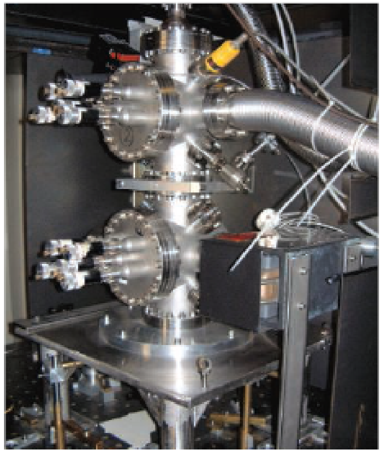
Science, 17 March 2006

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

Economist.com

Science & Technology

Dark matter

Accidence and substance

Apr 6th 2006

From *The Economist* print edition

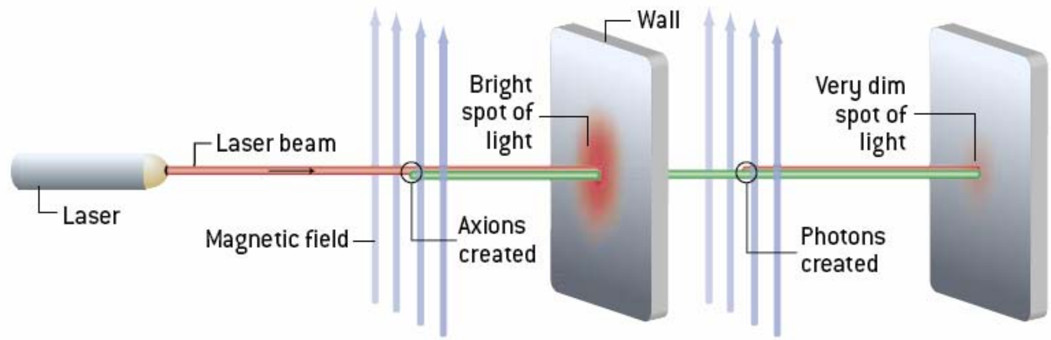
Two possible explanations for the b of reality

SCIENTIFIC AMERICAN

July 2006

PHYSICS

A Hint of Axions



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.

INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSIC

CERN COURIER

VOLUME 46 | NUMBER 6 |

AXIONS

Let there be axions

Konstantin Zioutas reports on the first Joint ILIAS–CAST–CERN Axion Training workshops, which covered a wide range of studies, from experiments at nuclear reactors to investigations of the roles of axions in solar physics and cosmology.

Optics.org

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NEWS

Laser experiment to explain dark-matter mysteries

31 July 2006

A dark matter particle known as the axion, formed by the interaction of a laser and a magnetic field in high vacuum, could be the key to a better understanding of dark matter, dark energy and why matter exists at all.

The Magneto-Optical Properties of the Quantum Vacuum

QED prediction: The Vacuum Magnetic Birefringence

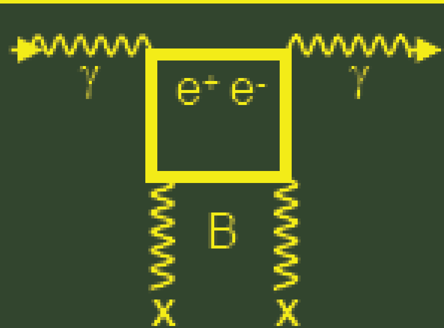
- VMB from the QED Theory: Euler-Heisenberg Lagrangian, *i.e.* *Taylor expansion of gauge and Lorentz invariants*

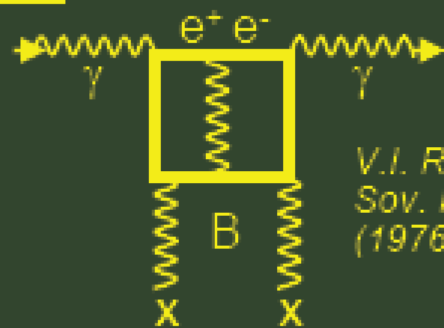
$$L=\frac{\varepsilon_0}{2}\left(E^2-c^2B^2\right)+\frac{2\alpha^2\hbar^3\varepsilon_0^2}{45\,m^4c^5}\left[\left(E^2-c^2B^2\right)^2+7c^2\left(EB\right)^2\right]+\ldots$$

Heisenberg & Euler, Z. Physik 38 (1936) 314

Weisskopf, K. Danske Vidensk. Selk. Mat.-fys. Medd. 14 n° 6 (1936)

Schwinger, Phys. Rev. 82 (1951) 664





V.I. Ritus, Sov. Phys. JETP 42 (1976) 774

- Tensors of permittivity and permeability of the vacuum:

$$\varepsilon_{ik}=\delta_{ik}+\frac{e_G^4\,\hbar}{45\,\pi\,m^4c^7}\left[2\left(E^2-c^2B^2\right)\delta_{ik}+7c^2B_iB_k\right]+\ldots.$$

$$\mu_{ik}=\delta_{ik}+\frac{e_G^4\,\hbar}{45\,\pi\,m^4c^7}\left[2\left(c^2B^2-E^2\right)\delta_{ik}+7E_iE_k\right]+\ldots.$$

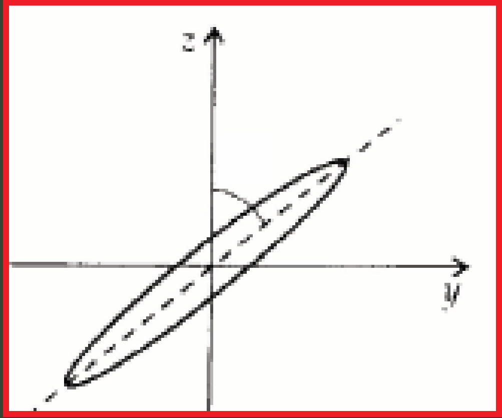
The change of the light velocity in a background magnetic field – "Pure" QED prediction

$$\frac{1}{n}=\frac{v}{c}=1-a\frac{\alpha^2\hbar^3\varepsilon_0}{45\,m^4c^3}B^2\sin^2\phi=1-a\left(1.3\times10^{-24}\right)B^2\sin^2\phi$$

S. L. Adler Ann. Phys. 67 (1971) 599

$$n_\perp=1+7\,A_e\,B_0^2\,\sin^2\phi \qquad n_{II}=1+4\,A_e\,B_0^2\,\sin^2\phi$$

As a consequence, a linear polarized light becomes "slightly" elliptical



$$\varepsilon=\pi\frac{l}{\lambda}\Delta n\;\sin 2\phi=\pi\cdot l\cdot C\cdot B^2\sin 2\phi$$

Analogue to the Cotton-Mouton effect

NA: $\Delta n \approx 3.6\ 10^{-22}$ in 9.5 T field & $\varepsilon \approx 2.10^{-10}$ for l = 250 km and λ =1.55 μm

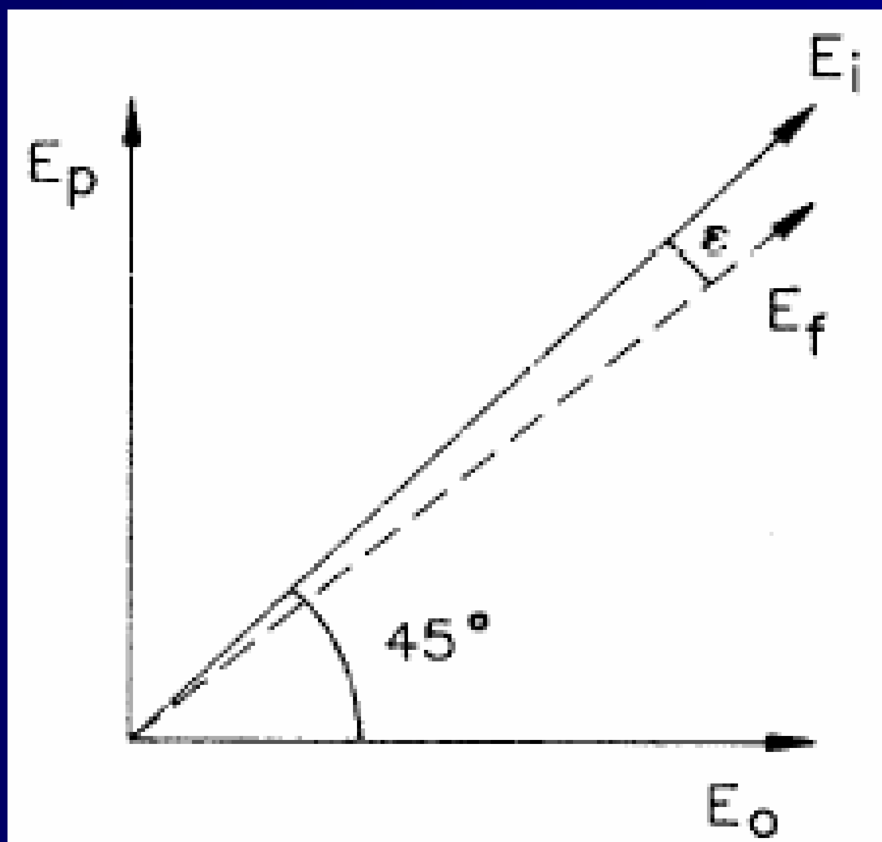
The second order correction to the Lagrangian gives a Δn correction of 1.45% with respect to the dominant term, *i.e.* a measurement of the QED birefringence at the level of few ‰ will provide a test for this term…

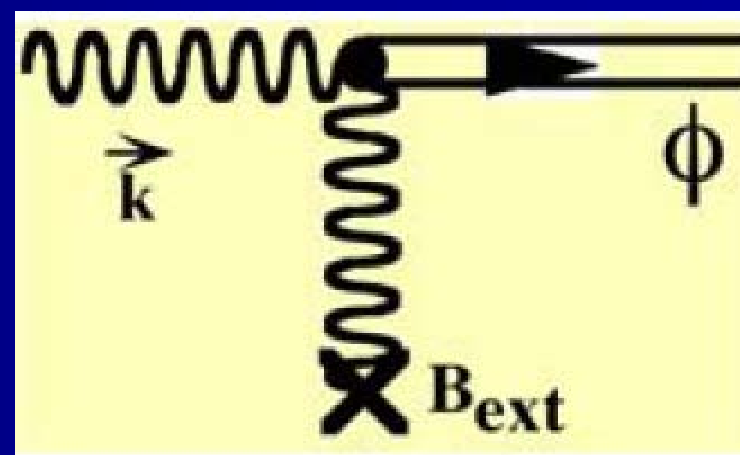
A technical challenge from the point of view of optical metrology; High-field magnet & optical cavity are required.

Dichroism

rotation of polarization plane

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

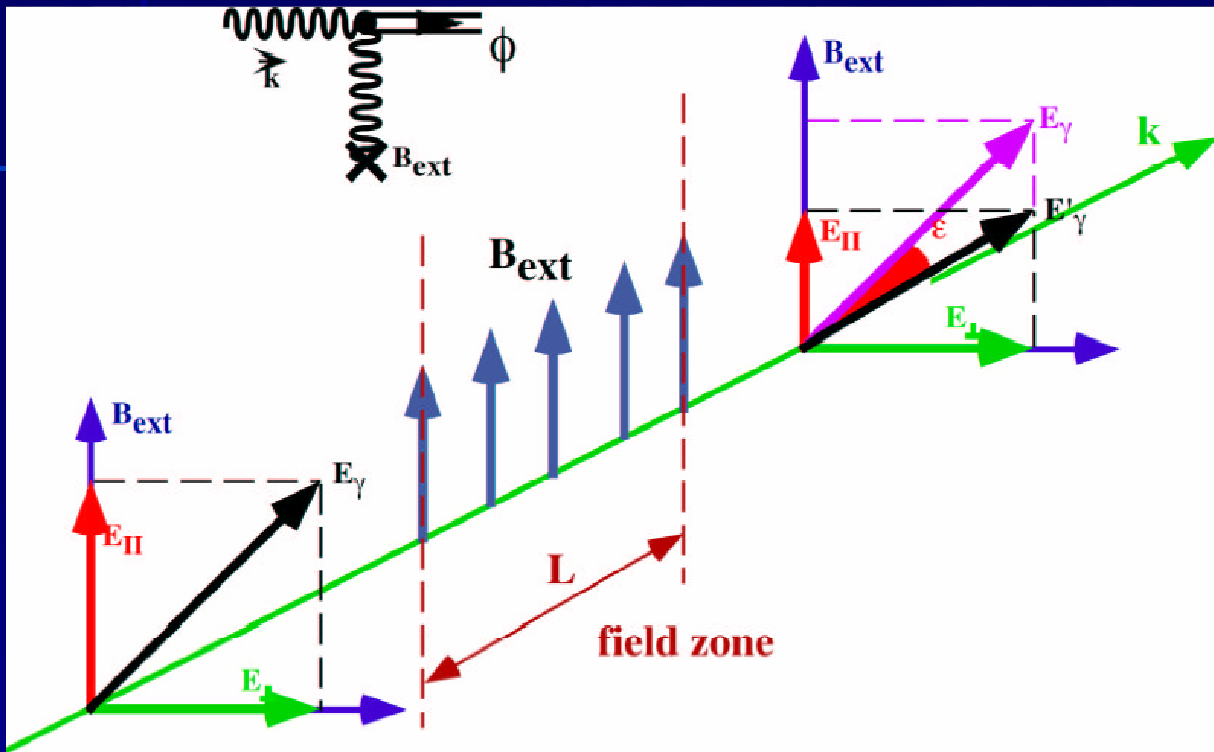




Dichroism

rotation of polarization plane

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



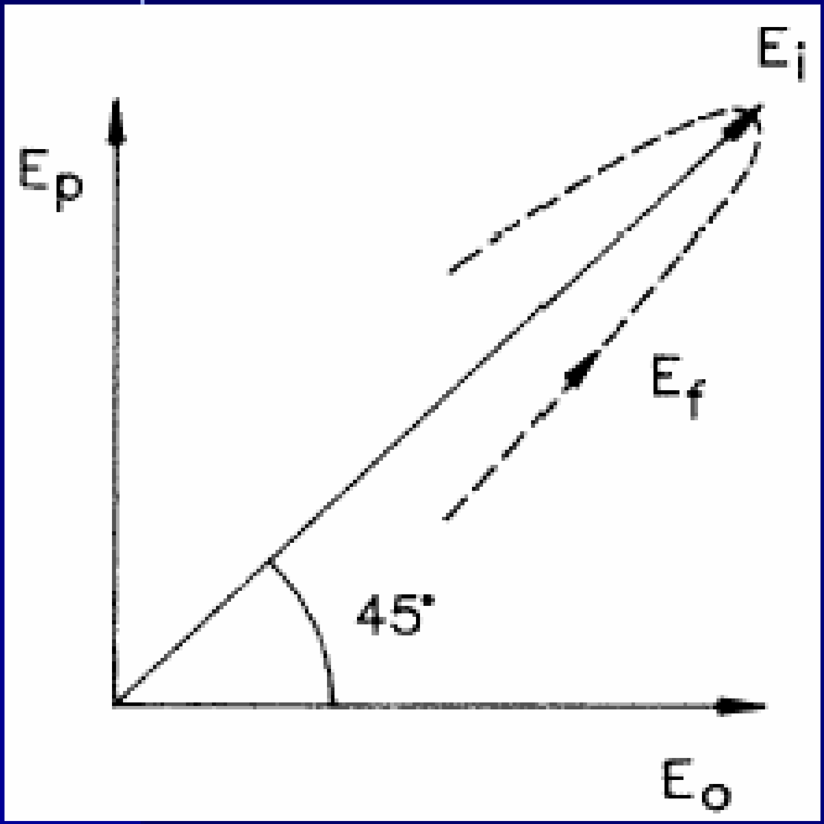
$$\varepsilon = -\left(\frac{B_{ext}L}{4M}\right)^2 \left\{ \sin\left[\frac{kL}{2}\left(1-\sqrt{1-\left(\frac{k}{K_m}\right)^2}\right)\right]\right\}^2 \frac{N}{\left[\frac{LK_m{}^2}{4k}\right]^2}$$

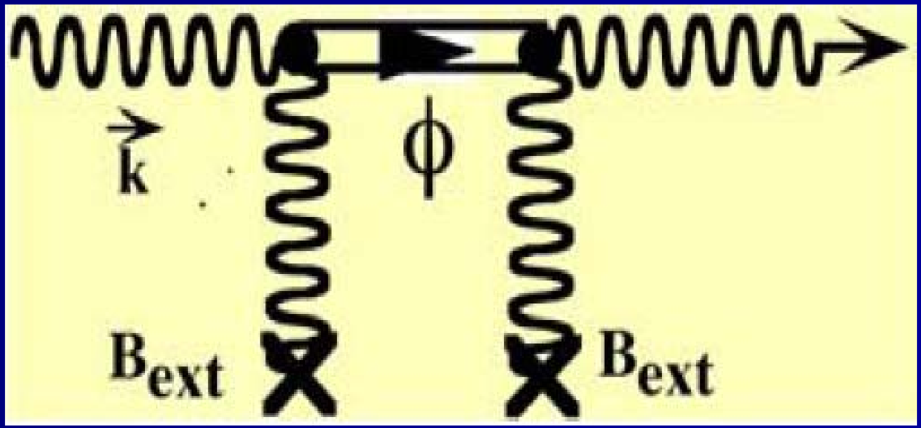
- M: inverse coupling
- K_m :inverse compton wavelength
- k: light wavenumber
- L: magnetic field region length
- N: number of traversals

Ellipticity

dispersion: photon-axion mixing

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

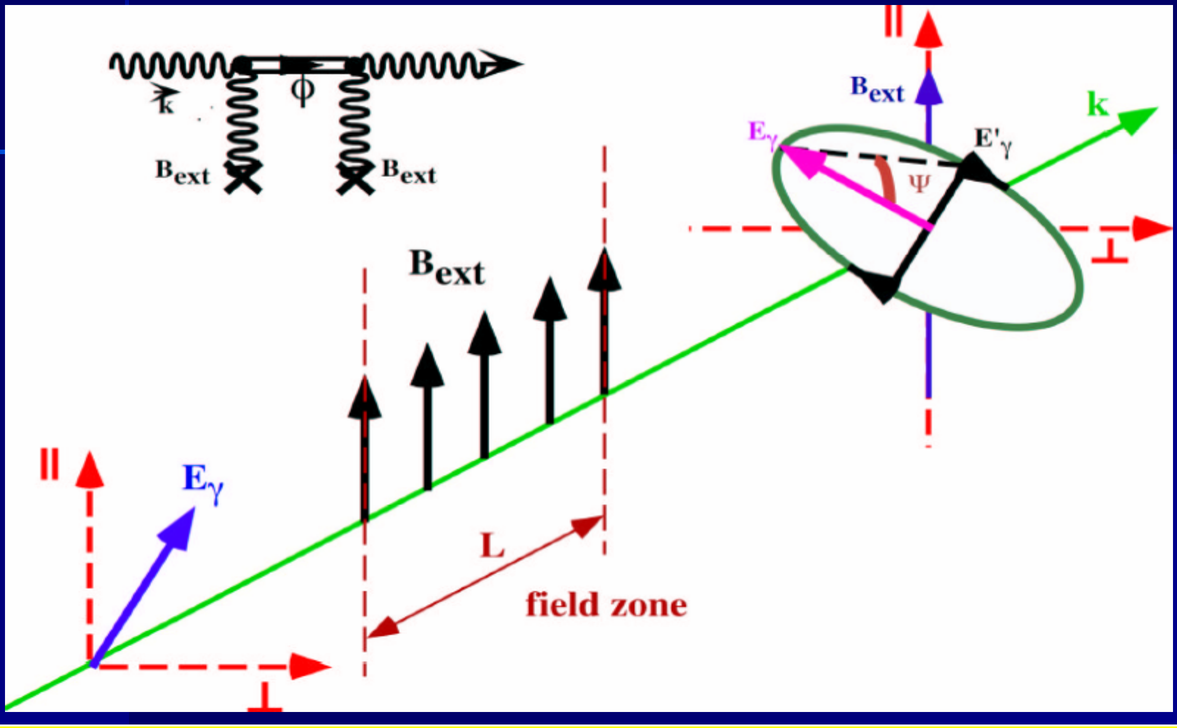




ellipticity

dispersion; photon-axion mixing

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



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

- M: inverse coupling
- K_m :inverse compton wavelength
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- L: magnetic field region length
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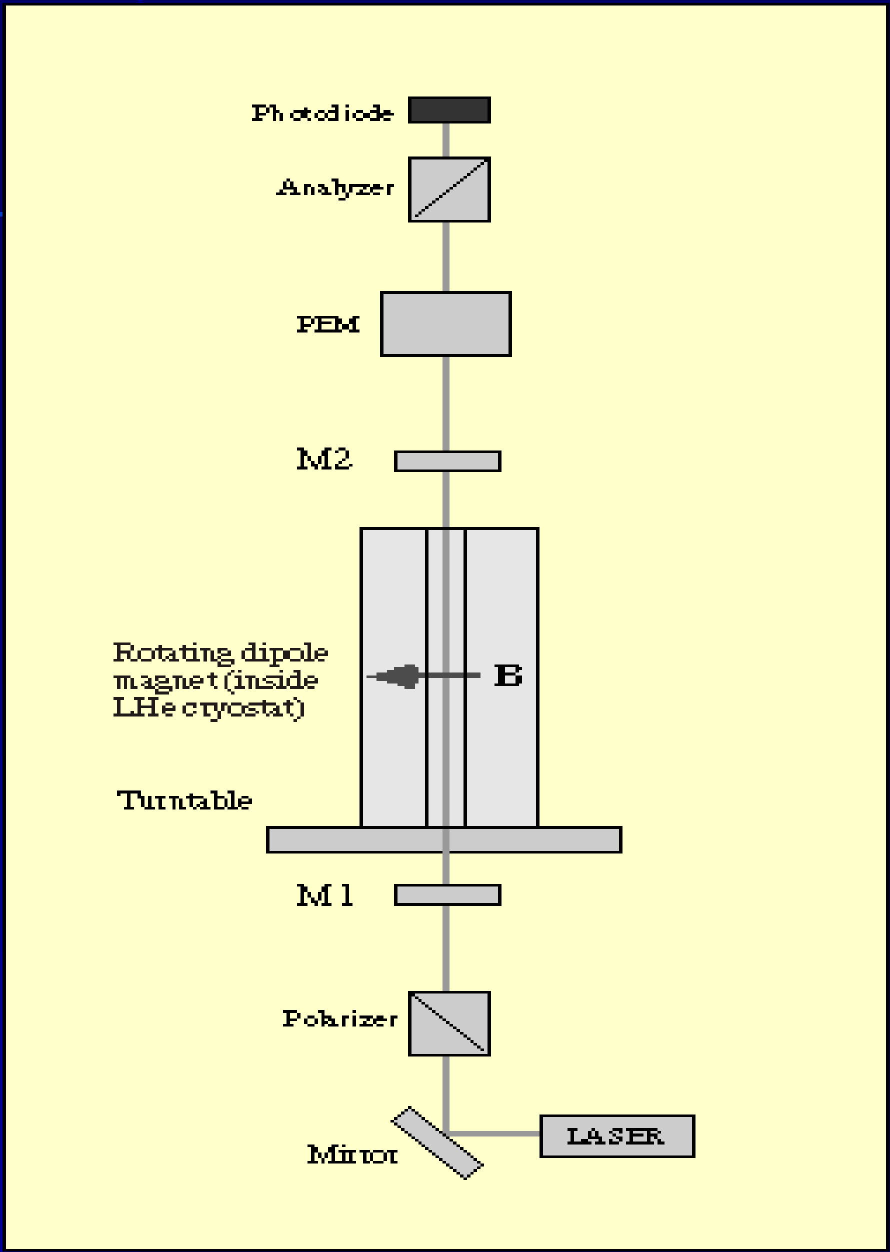
PVLAS setup



6 T ; 1 meter long dipole magnet

1064 nm ; 0.1 W laser

60 km path length in magnet

using 6 meters long optical cavity

cryostat rotation 0.3 Hz

PVLAS search

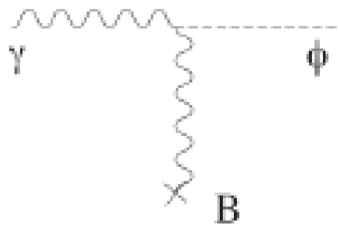
E. Zavattini et al.
PRL 96 (2006)

ROTATION of polarization plane of laser in B field

$B \simeq 5T, \ L \simeq 1m, N \simeq 4.4 \ 10^5$

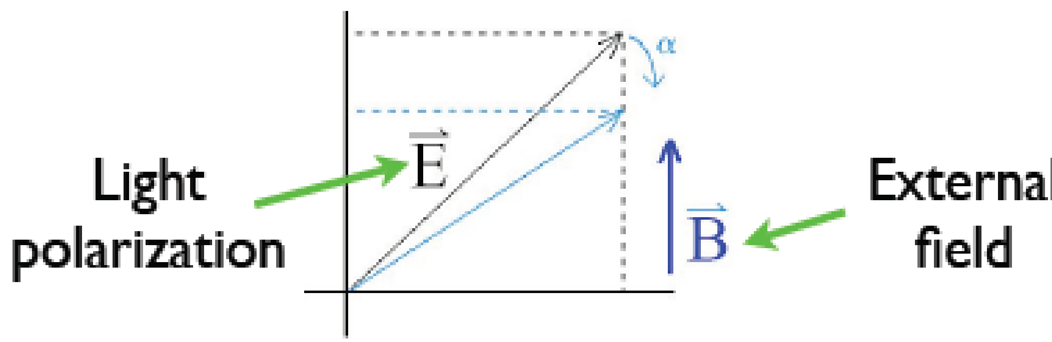
$$\alpha = (3.9 \pm 0.5) \ 10^{-12} \ \text{rad/pass}$$

A possible interpretation :



$$\vec{\epsilon} \cdot \vec{B} = \epsilon_{||} \ B$$

Selective absorption
(dichroism)



Scale: $1 \ 10^5 < M < 6 \ 10^5 \ \text{GeV} \qquad M = g_{\phi\gamma\gamma}^{-1}$

Mass: $0.7 < m < 2 \ \text{meV}$

Axion interpretation of PVLAS?
(from Ringwald'05)

- PVLAS ALP hardly compatible with standard QCD axion:

[Weinberg '78; Bardeen, Tye '78; . . .]

$$m_A = [z^{1/2}/(1+z)]\, m_\pi f_\pi / f_A = 0.6\,\mathrm{meV} \times (10^{10}\,\mathrm{GeV}/f_A)$$

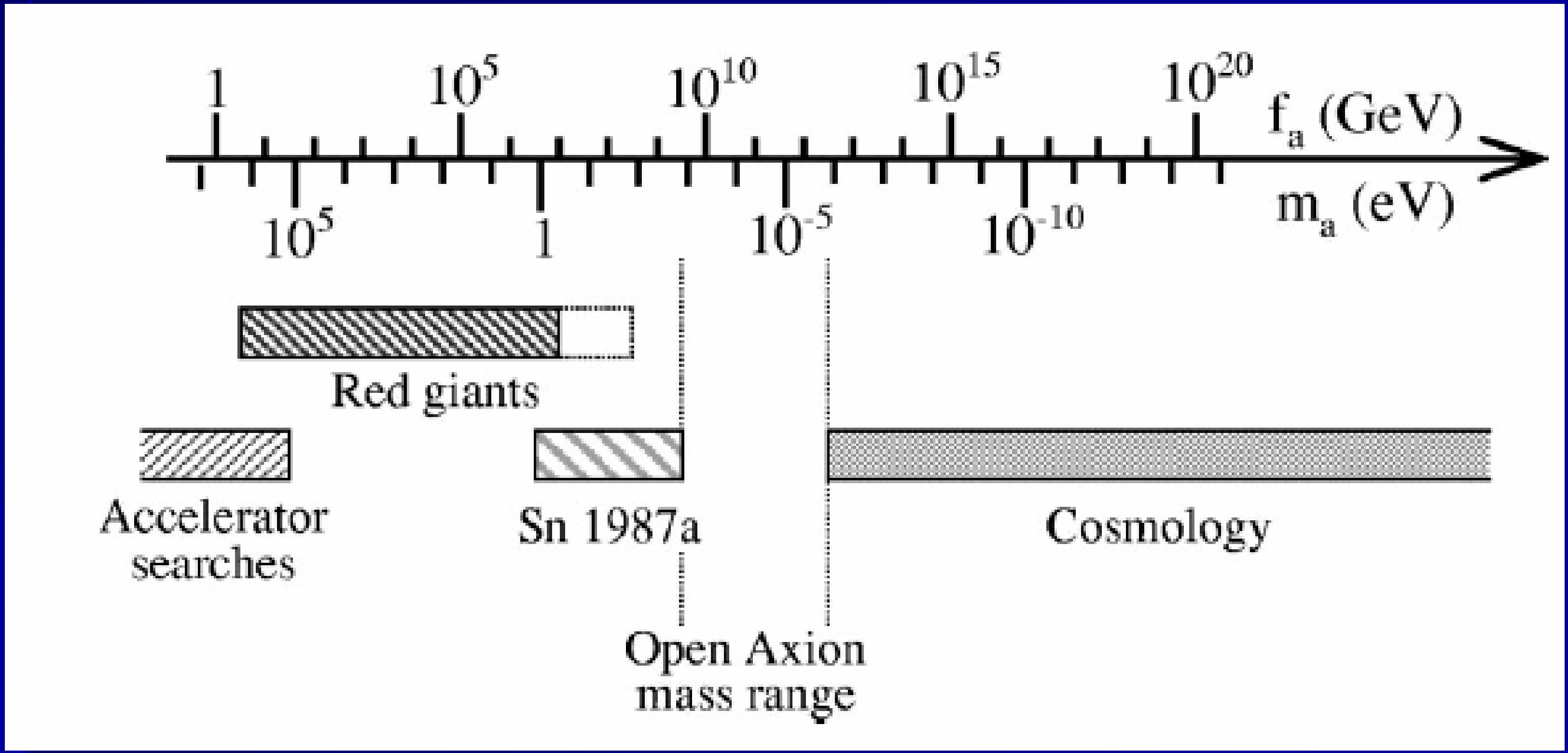
$$g_{A\gamma} = -\frac{\alpha}{2\pi f_A}\left(\frac{E}{N} - \frac{2}{3}\frac{4+z}{1+z}\right); \qquad z = m_u/m_d = 0.56$$

  - $m_A \sim 1\,\mathrm{meV}$ implies a symmetry breaking scale $f_A \sim 6 \times 10^9\,\mathrm{GeV}$
  - Need extremely large ratio $|E/N| \sim 3 \times 10^7$ of electromagnetic and color anomalies in order to arrive at $g_{A\gamma} \sim 5 \times 10^{-6}\,\mathrm{GeV}^{-1}$
  - All models conceived so far have $|E/N| = \mathcal{O}(1)$

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

Axions at the Institute for Advanced Study (Princeton, NJ, Oct.'06)

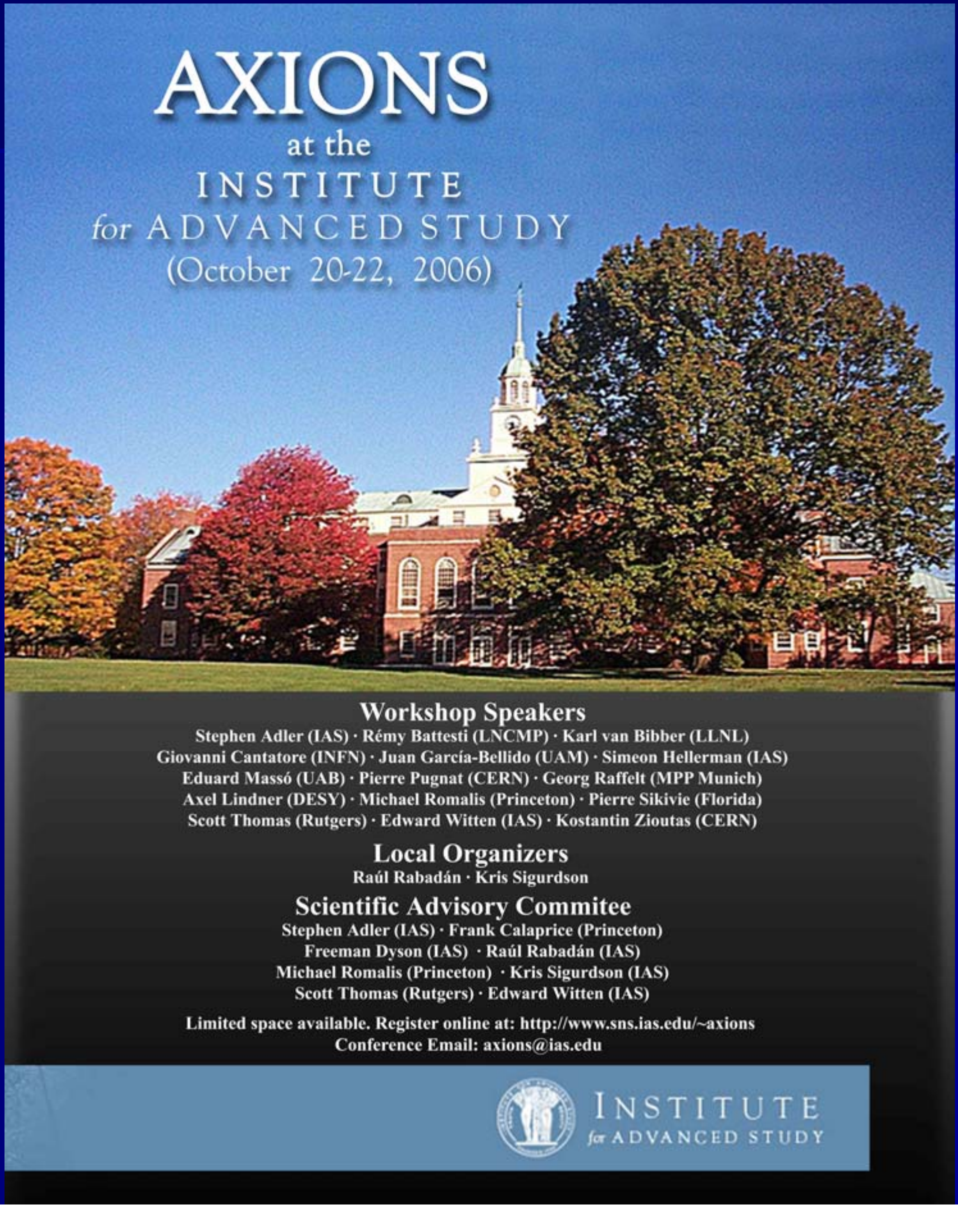
Planned `Light-Shining-Through-The-Wall' Experiments to detect Axion-Like Particles

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	$\approx 10^{-19}$	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

LIPSS is presently in the leadership position

Axion-Like Particle search status discussed at the IAS workshop Oct'06. Conclusion: LIPSS is ahead of other labs worldwide to test existence of axion-like particle claimed by PVLAS



LIPSS collaboration

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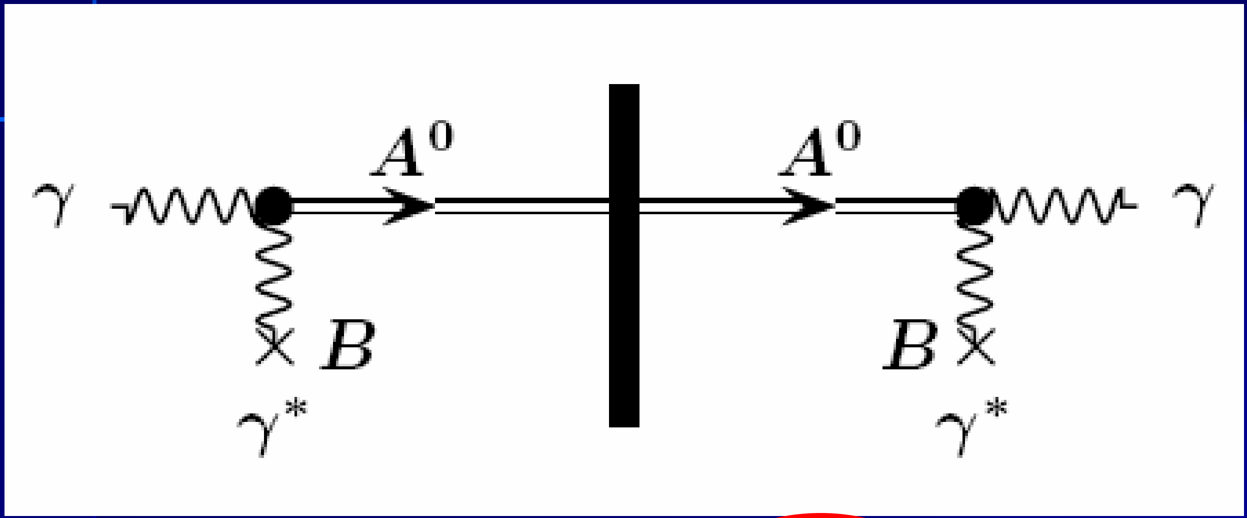
(*) *Spokesman*

(**) *Co-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

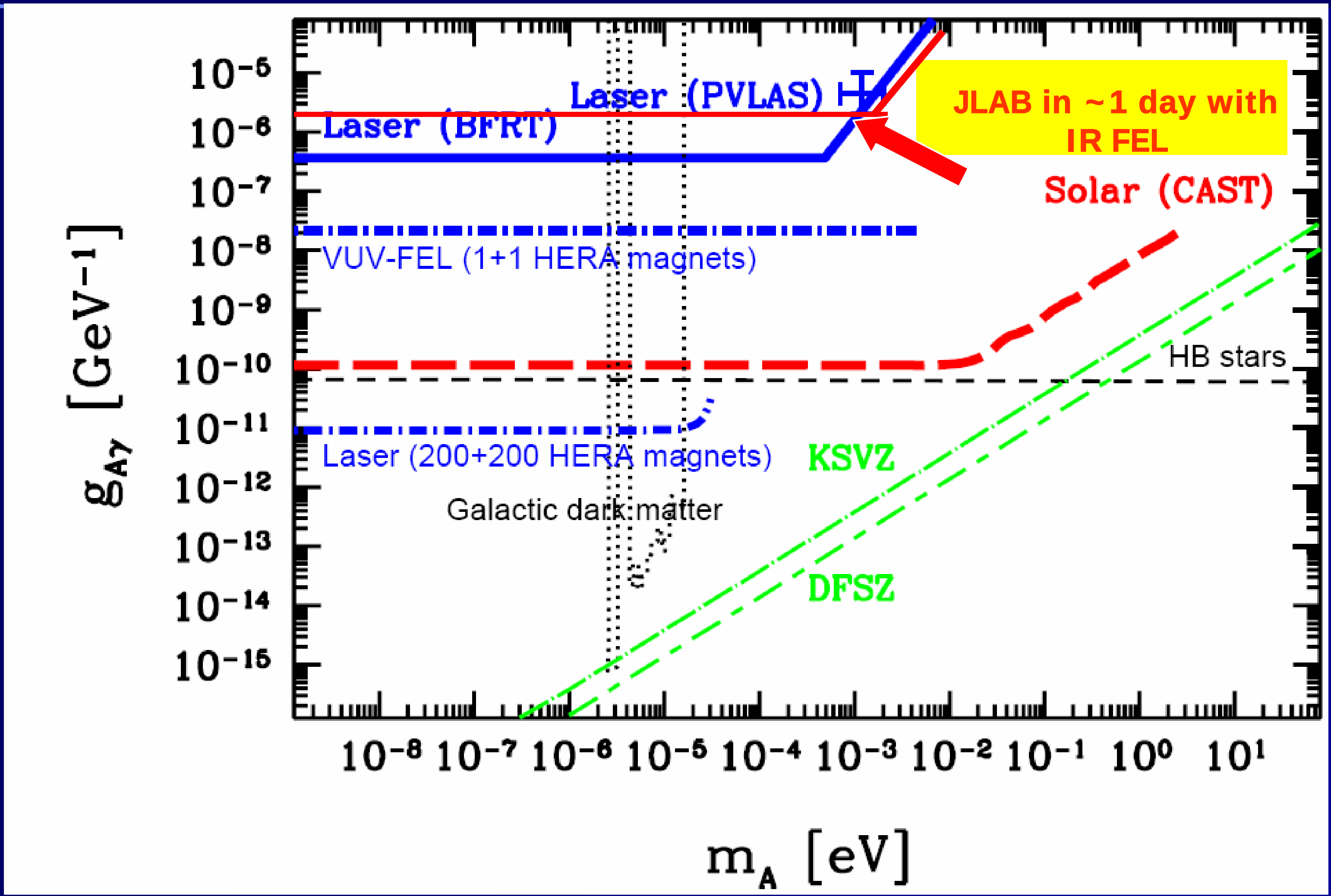
$$L_{\varphi\gamma\gamma} = -\frac{1}{4M}\varphi F_{\mu\nu}\widehat{F}^{\mu\nu} = \frac{g\varphi}{4}\vec{E}\cdot\vec{B}$$

- 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

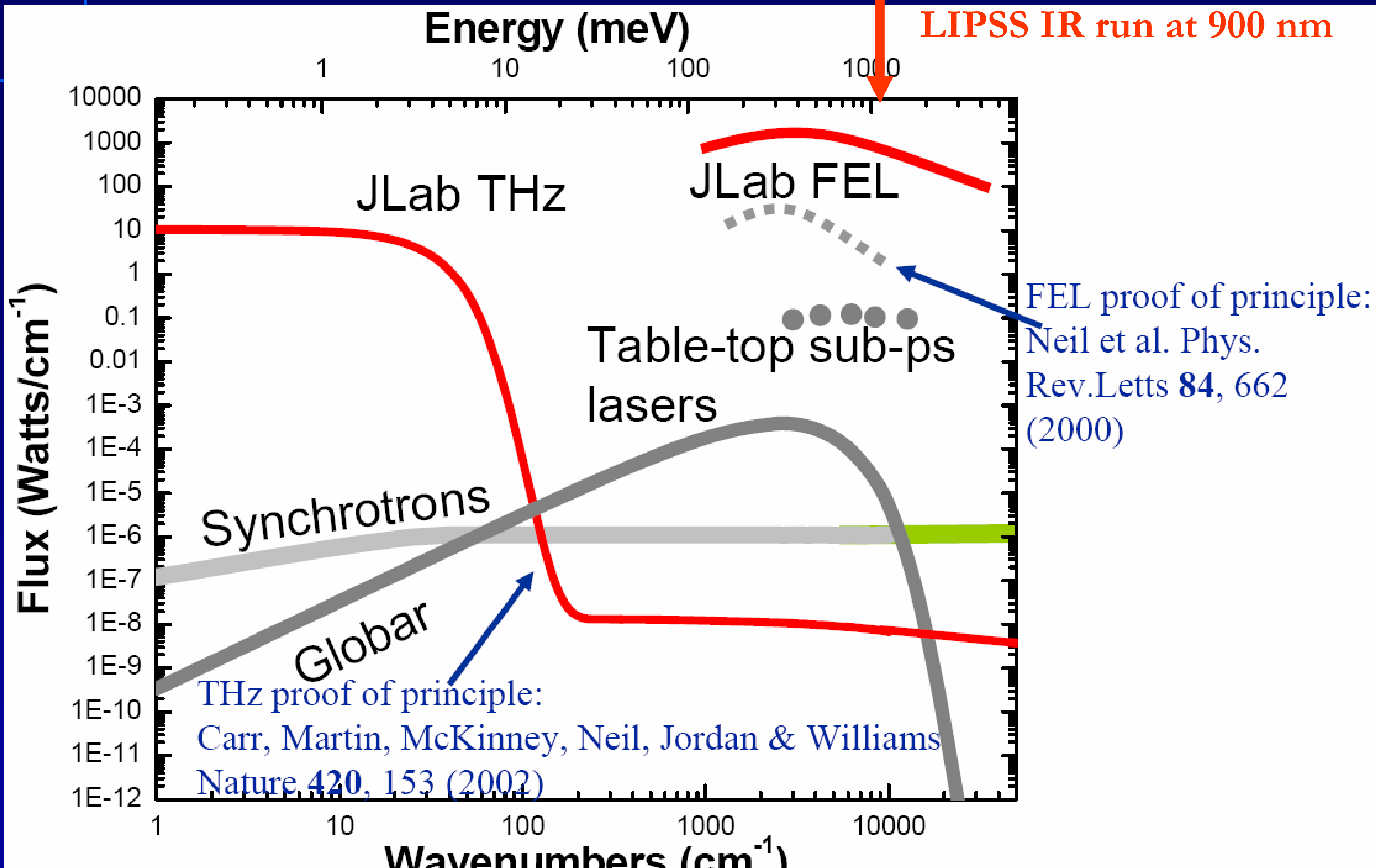
- $P = g^2 B^2 L^2 \sin^2(m^2 L/\omega)/(4m^2 L/\omega)^2$ γ-a prod prob
  - g = coupling constant (1/M)
  - B = magnetic field
  - L = magnet length
  - ω = light wavelength
- $Y = n\ P_1\ P_2\ \varepsilon\ (\Delta\Omega/\Omega)\ (N_r+2)/2$ yield (#/s)
  - n = photon flux (#/s)
  - P1 (P2) = production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

LIPSS sensitivity range



Jefferson Lab and the Free Electron Laser

JLAB facility spectroscopic range

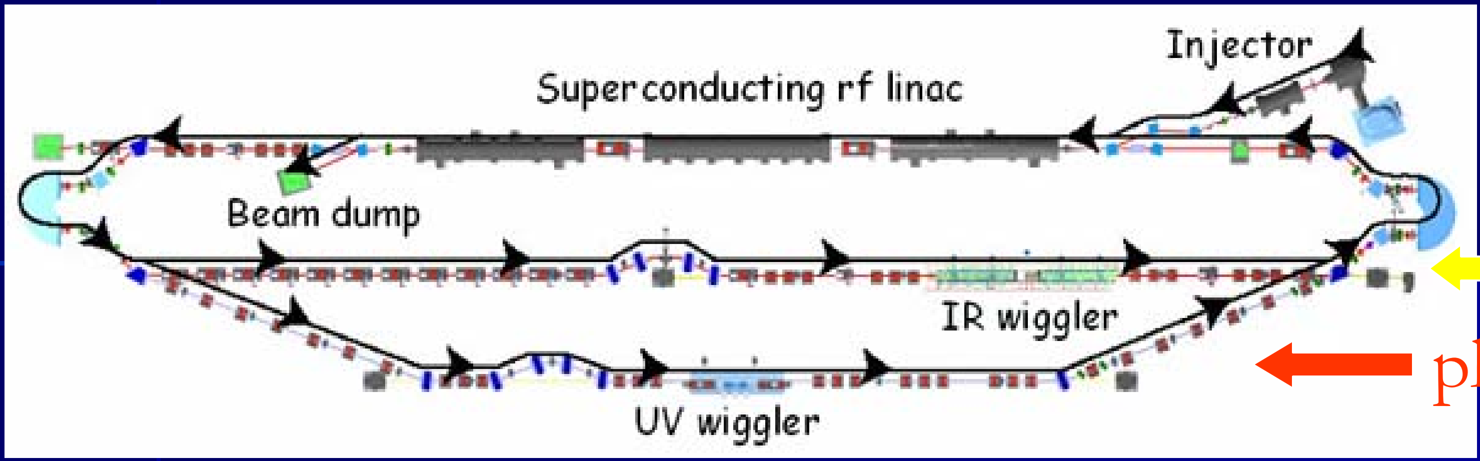


Anticipated parameters for LIPSS run

- B-field: 1.7 T
- magnet length: 1.0 m
- IR FEL power 3 kW
- IR FEL wavelength 900 nm (1.38 eV)
- quantum efficiency 0.4
- linear polarization 100%
- acceptance 100%
- expt'l efficiency ~ 80% (to be determined)

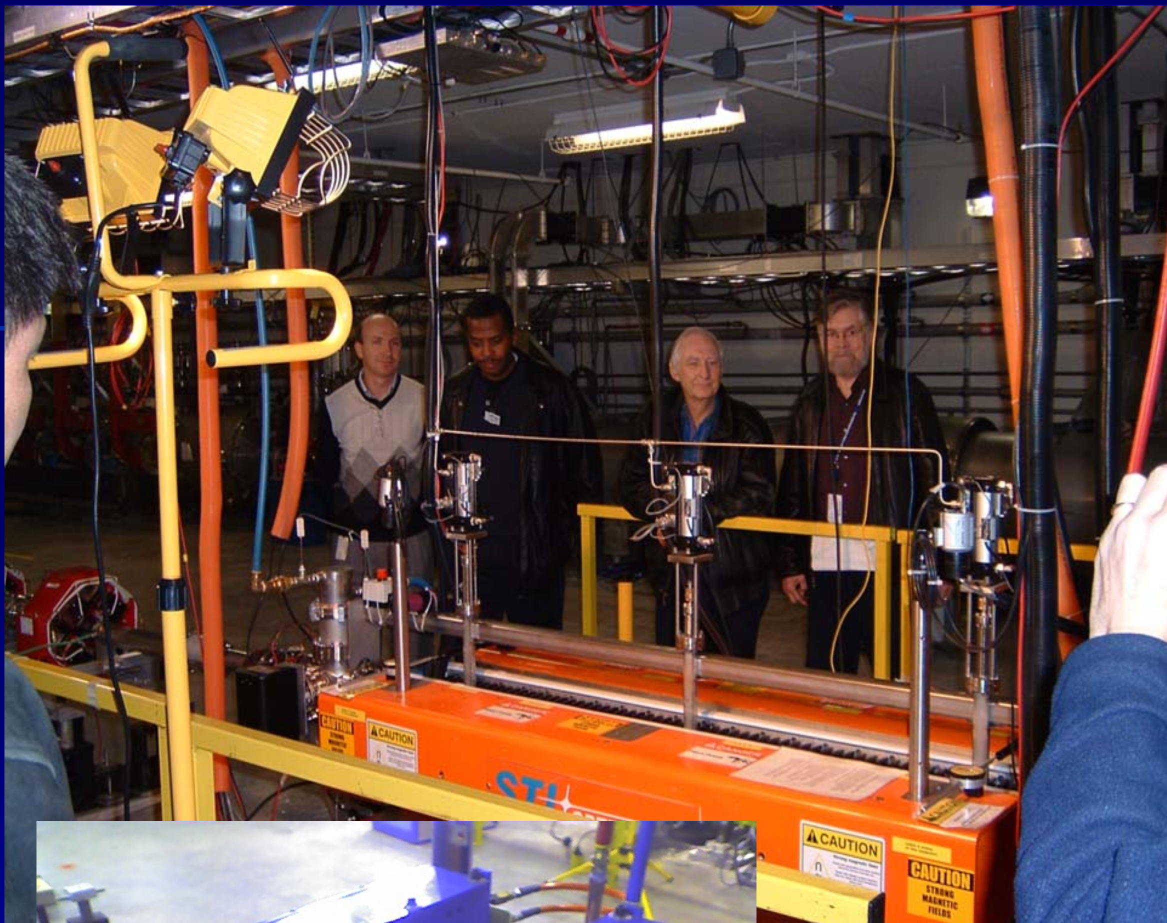
signal rate > 0.02 Hz; $g_{a\gamma\gamma}$ = 1.6 x 10^{-6} GeV^{-1}

JLAB FEL: regeneration experiment



current

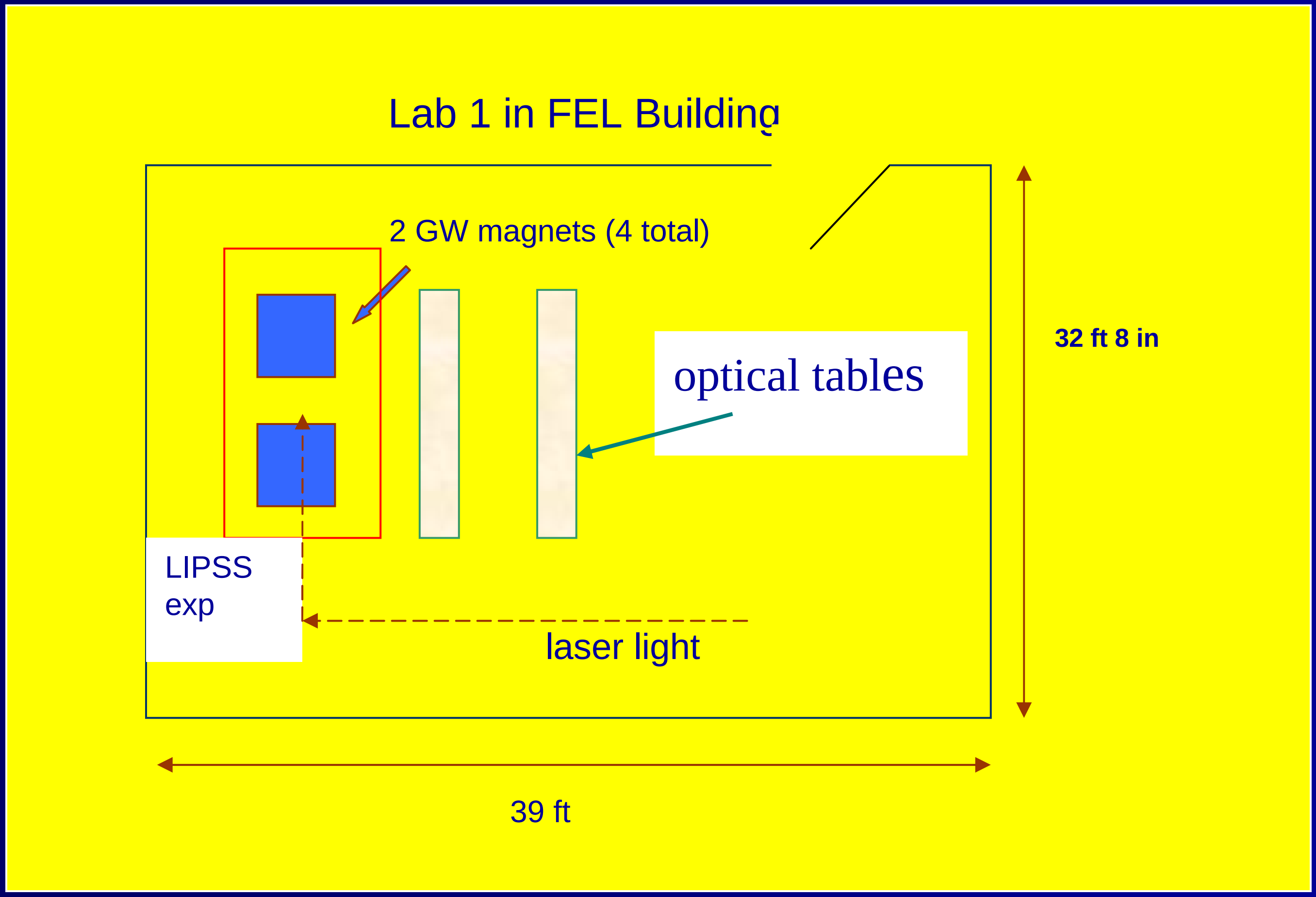
planned; 2007



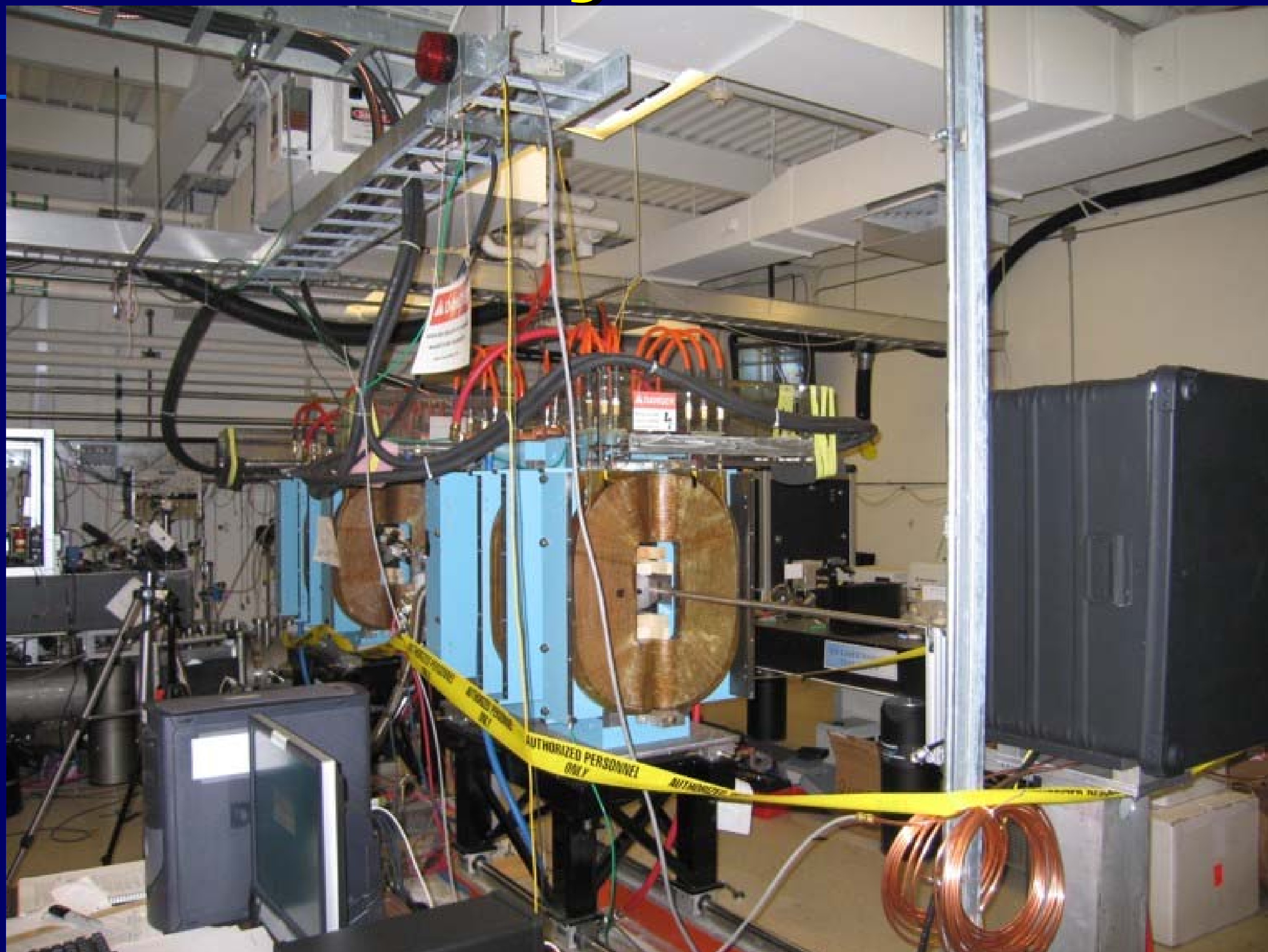
infrared FEL operational at 10 kW extracted power

- 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)



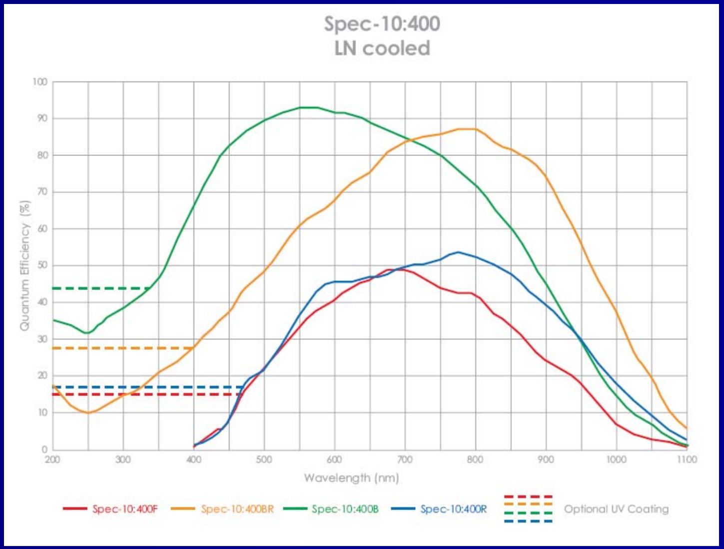
LIPSS today



LIPSS detector

Detector

Liquid nitrogen cooled CCD
Very low noise, <2 e/h per pixel,
20μm pixels



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 et al, hep-ph/0605250

  -Requires magnet length ~ m in IR;

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

LIPSS Status Summary

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

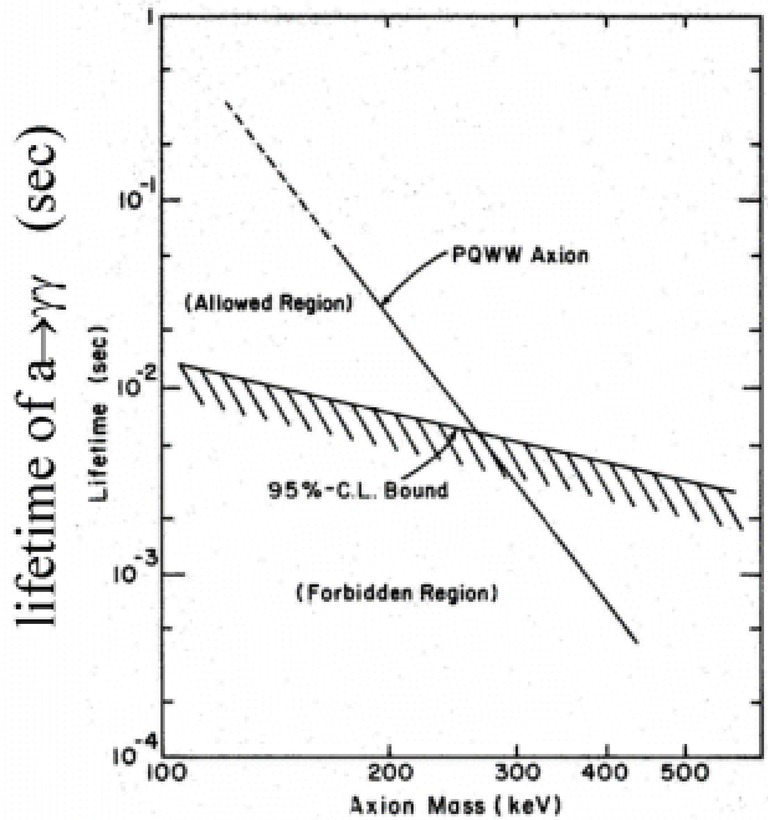
(20h in `scalar boson’ configuration)

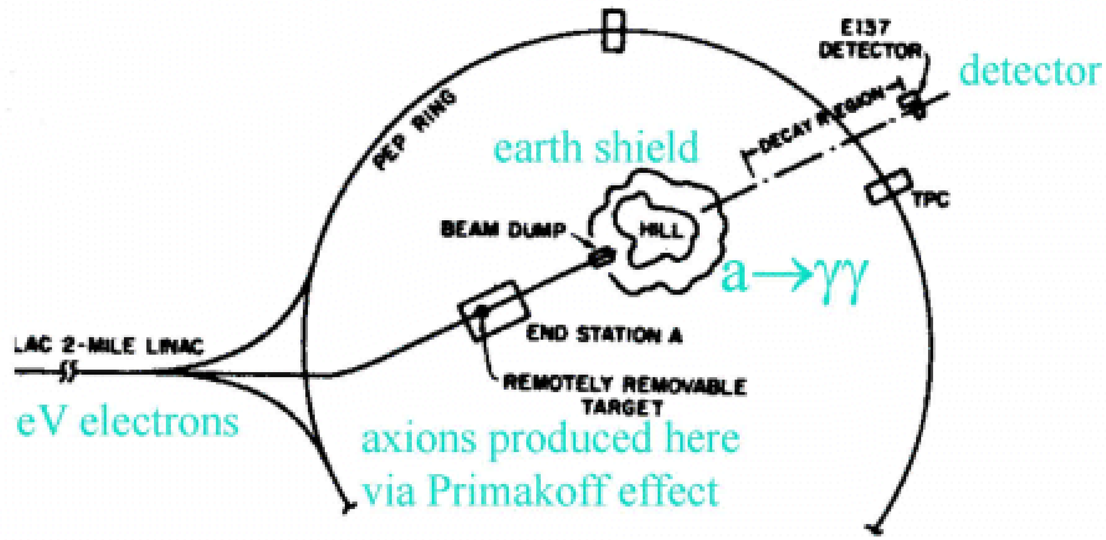
  – Analysis underway

- Will be taking `pseudoscalar’ data this Fall
- Further improvements possible – under discussion

Summary of laboratory searches: A heavy axion is excluded

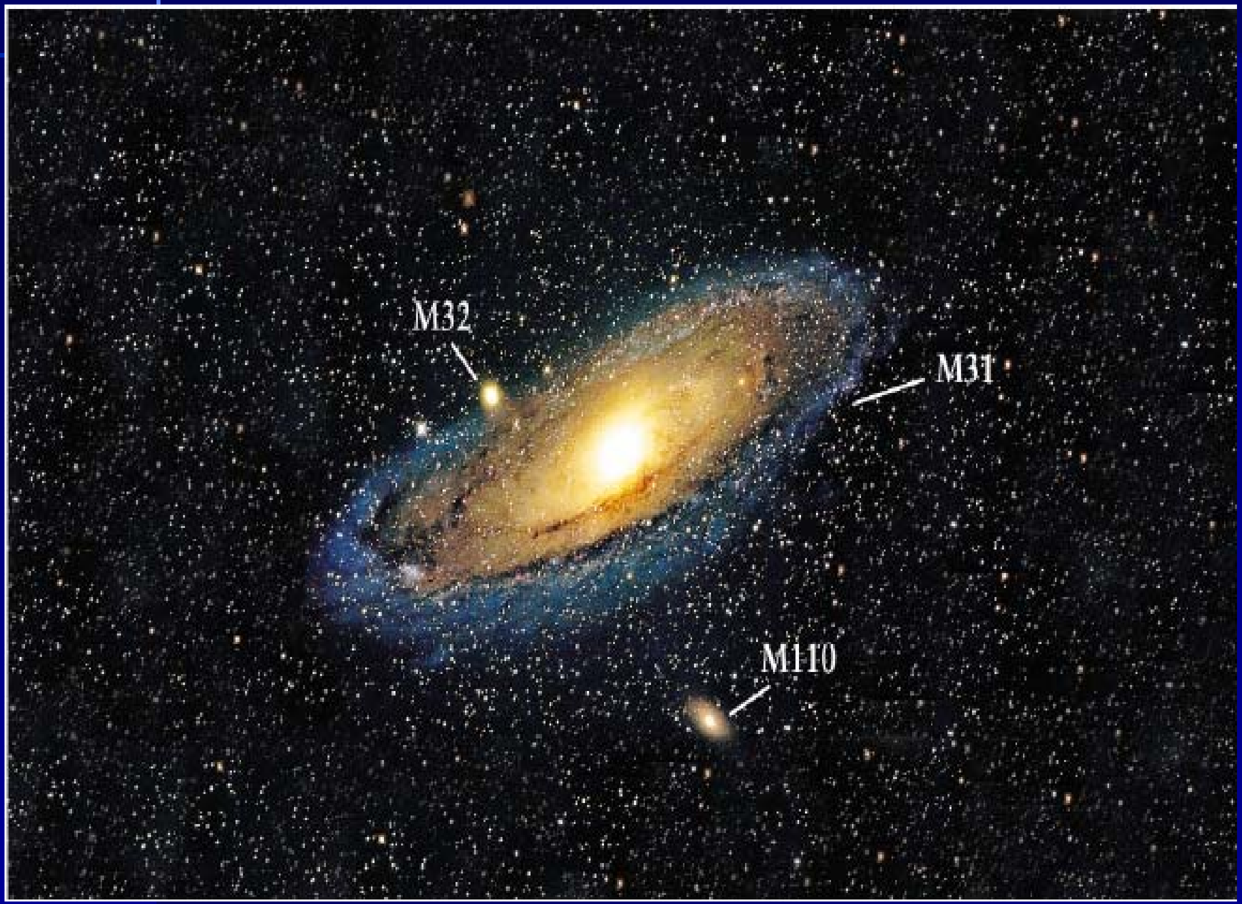
For example: SLAC E137 (Bjorken et al.)





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

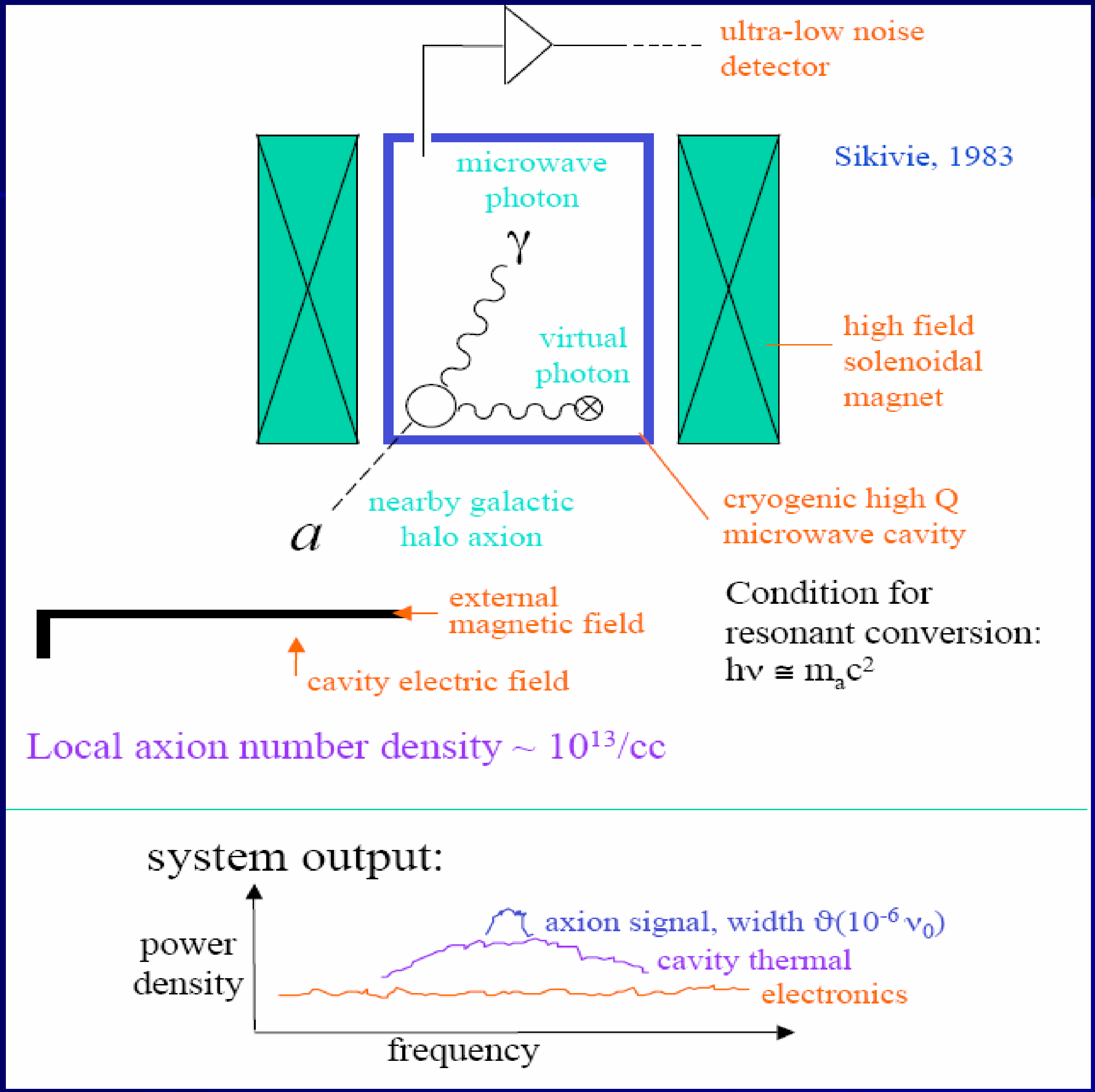
relic axions



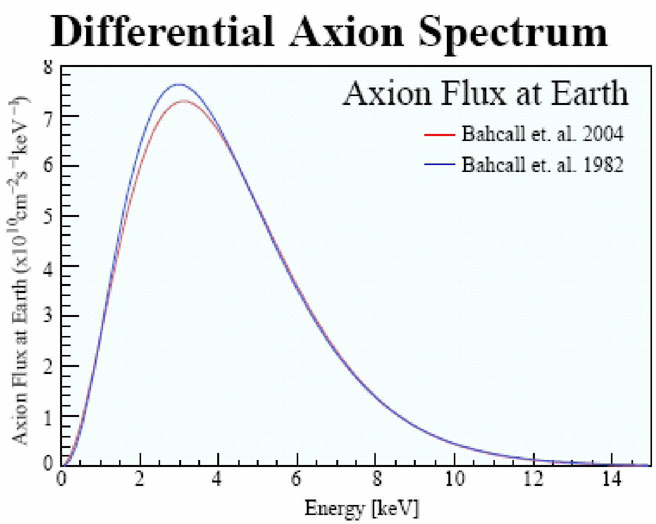
- axions created moments after the big bang.
- thermalized over time
- mass range must be consistent with astrophysical observables

microwave cavity technique

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



CAST experiment



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

Axion Luminosity:

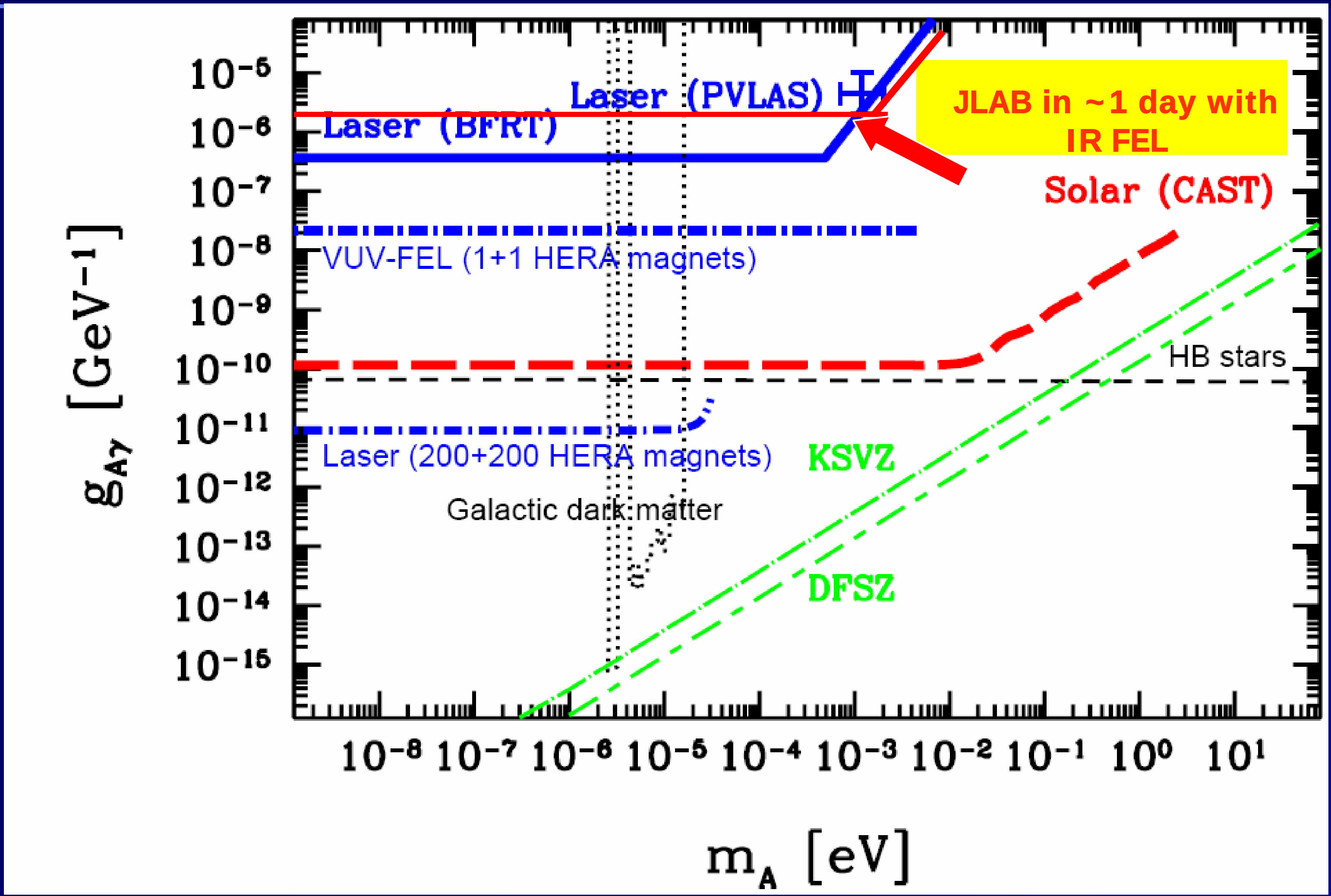
$$L_\mathrm{a} = 1.9 \times 10^{-3} L_\odot$$

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)

Has seen no effect

Axion Search Summary



Theory challenge:
Testing Deviations from QED in Precision Atomic Measurements

- Elastic Light-by-Light scattering in QED proceeds through creation/annihilation of virtual e^+e^- pairs [Heisenberg-Euler '36; Weisskopf '36]
- No experimental observation so far: effect too weak; negligible compared to PVLAS effect
- E^4-term of Heisenberg-Euler Lagrangian constrained by atomic physics: deviation from QED excluded at 20-50% level (Wichman-Kroll'56, 1/r4 correction to Coulomb potential). Cannot rule out PVLAS-strength pseudoscalar (E·B) effect; but large scalar E^2 interaction is likely constrained (AA, Flambaum, Karshenboim, in progress)

Acknowledgements

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