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LIPSS* and dark matter

*LIght PseudoScalar boson Search

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for the LIPSS collaboration

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Participants

Currently:

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Still developing.

Thanks to Mike Kelley, George Neil, Joe Gubeli, Gwyn Williams, Fred Dylla, and many others for useful discussions and help. The mistakes are my own.

Outline

- An experiment (PVLAS collaboration) has observed an unexpected effect
- Interpretation in terms of a new particle – a light pseudoscalar boson, axion-like.
- A candidate for dark matter
- Conflict (or not) with other experiments
- Testing this with the JLab FEL: the LIPSS collaboration's ideas.

The PVLAS experiment

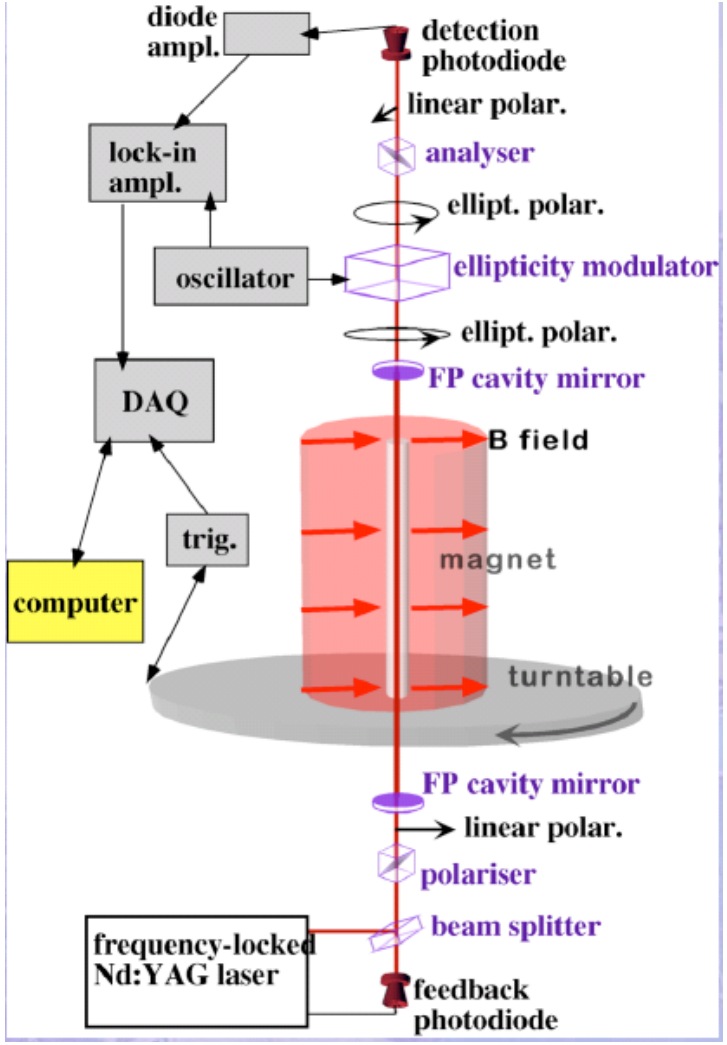
- This experiment (E. Zavattini *et al*., arXiv:hep-ex/0507107, 26-Oct-2005 and 0512022) measures, with a beam of linearly polarized laser light in a magnetic field in a vacuum:
  - Rotation of the plane of polarization, and
  - Production of ellipticity
- A positive effect is observed, greater by four orders of magnitude than expected from QED
- Other experiments bear on this question.

The PVLAS experiment

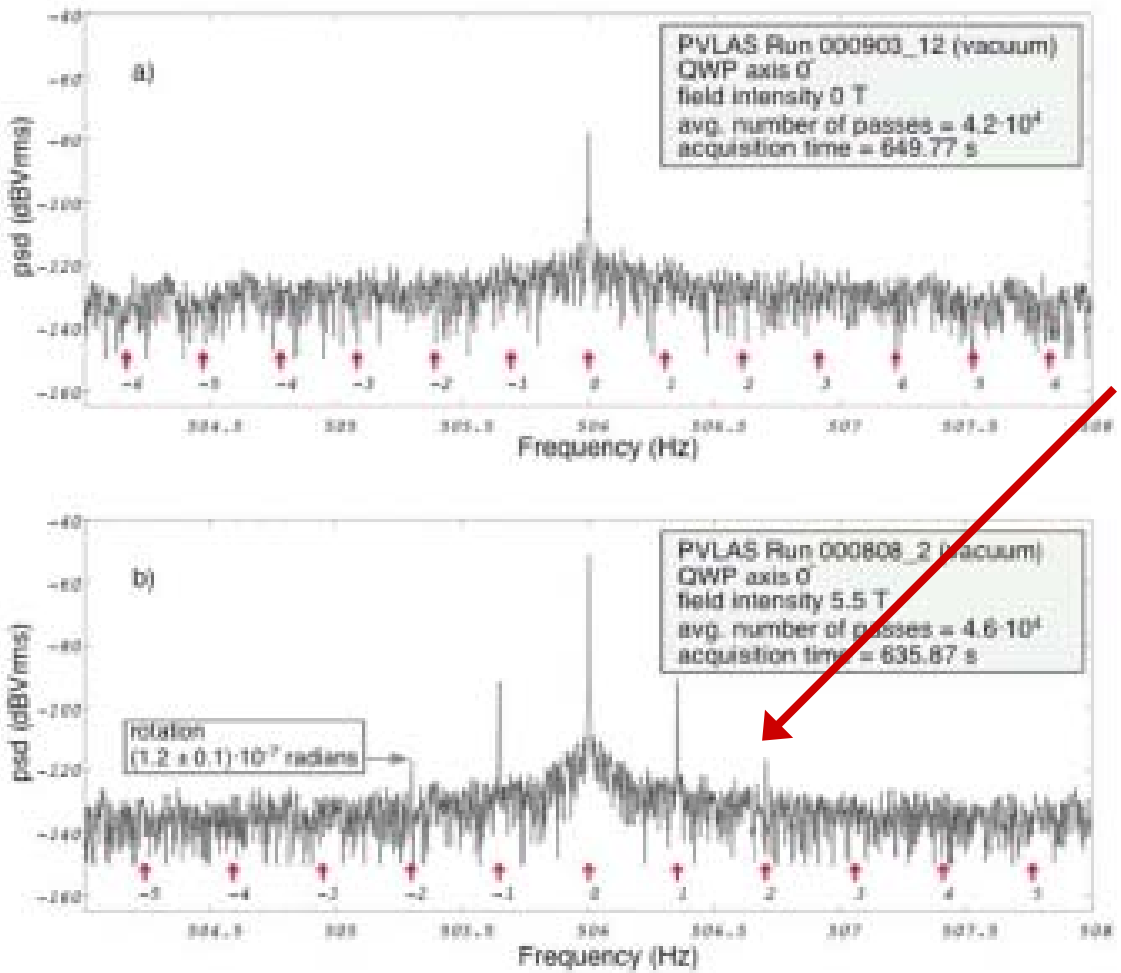
Magnet: 5T, 1m dipole
Crossed polarizers
FP cavity, finesse: ~ 60,000
Ellipticity modulator
1/4 – wave plate
Laser: 1064nm 0.1W Nd:YAG CW

The magnet is rotated at 0.3 rev/s, ellipticity modulated at 506 Hz.

The photodiode detects the polarization rotation signal which is Fourier analyzed for components at appropriate frequencies.



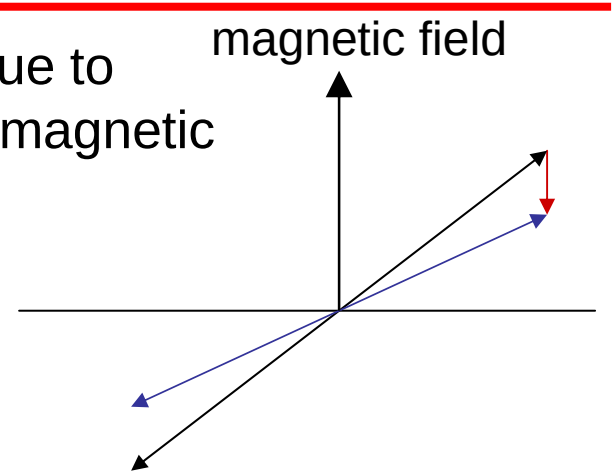
PVLAS result



A polarization rotation signal at twice the magnet rotation frequency is observed.
The phase of the polarization rotation is correct for it being produced by absorption of the component parallel to the magnetic field.

PVLAS interpretation

- The rotation of the plane of polarization is due to absorption of the component parallel to the magnetic field.



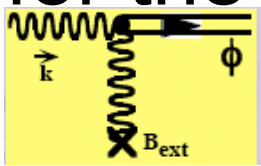
$$\varepsilon = -\sin 2\theta \left(\frac{BL}{4M_b}\right)^2 N \left[\frac{\sin\left(m_b^2 L/4\omega\right)}{m_b^2 L/4\omega}\right]^2$$

$$\alpha = \varepsilon_0 / N = (3.9 \pm 0.5)10^{-12} \quad \text{rad/pass}$$

- The absorption is attributed to the production of a light pseudoscalar boson (PSB) with a specific relation between the boson mass m_b and its coupling $g = 1/M_b$ to two photons. Pseudoscalar because effect is proportional to $\boldsymbol{E}\cdot\boldsymbol{B}$.

PVLAS interpretation (2)

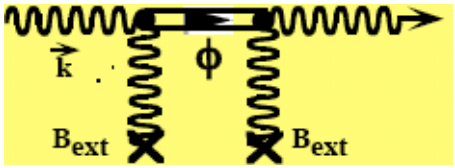
- The diagram for the absorption process is:

photon 

real PSB

- For the production of ellipticity:

virtual PSB

photon 

photon

- For regeneration:

real PSB

PVLAS result for boson properties

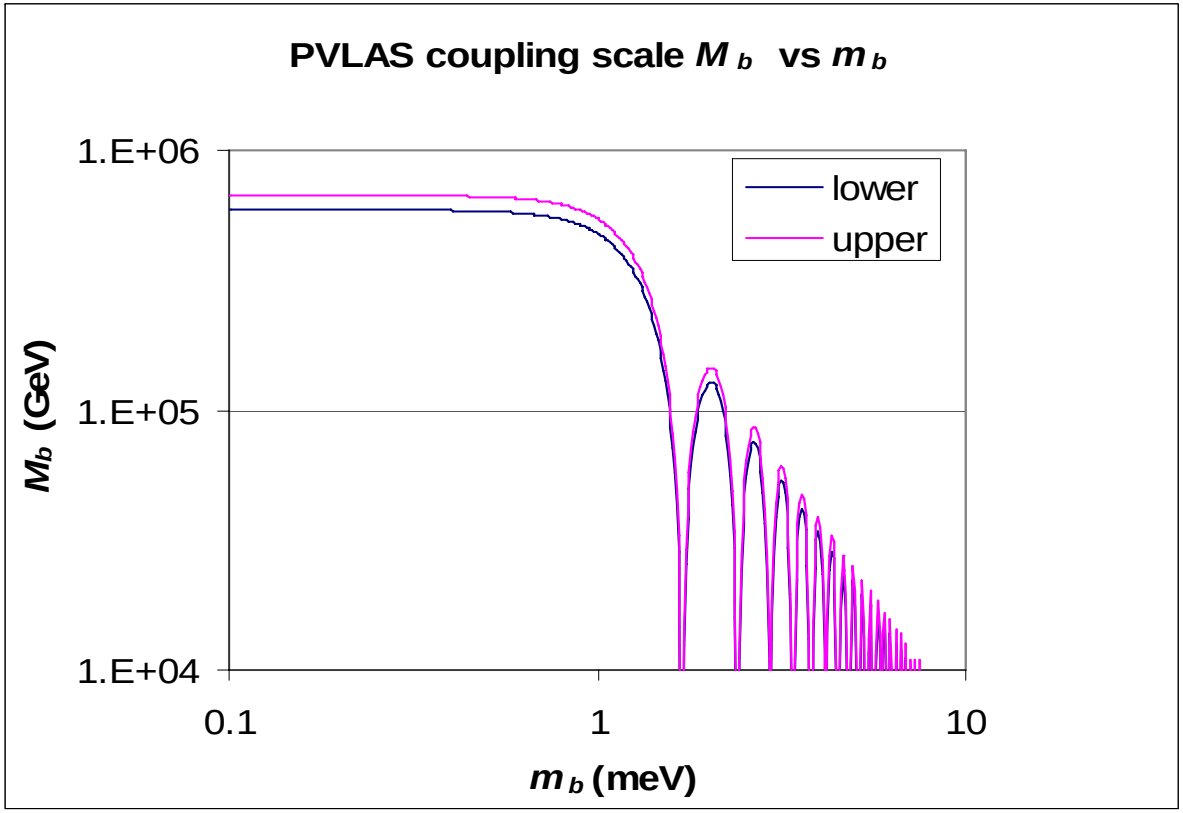


Figure 1 – Raw PVLAS result for M_b vs. m_b.

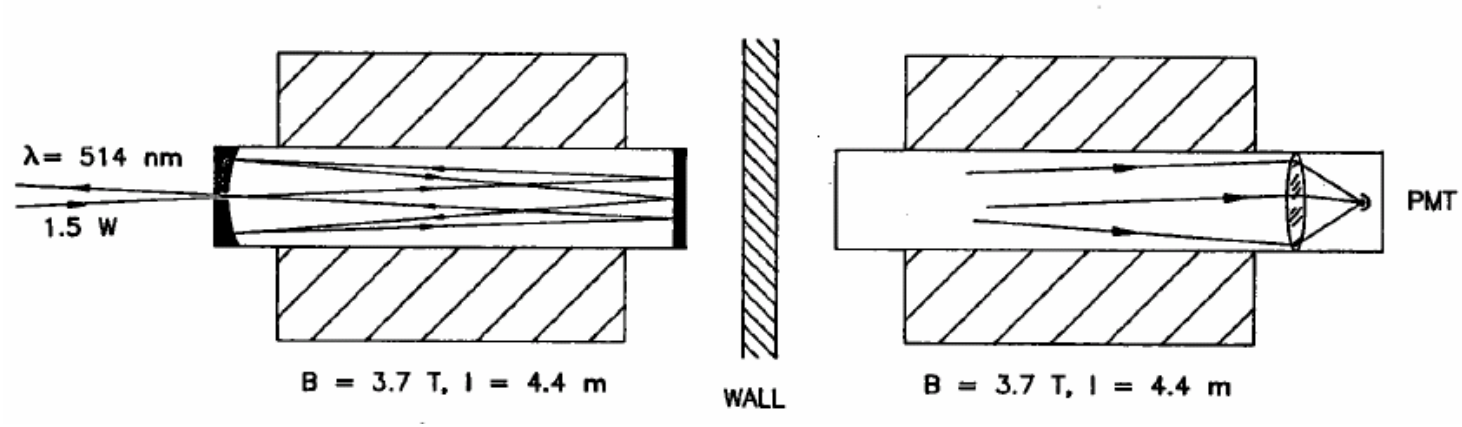
This result comes from the measured rotation of the polarization

The BFRT experiment

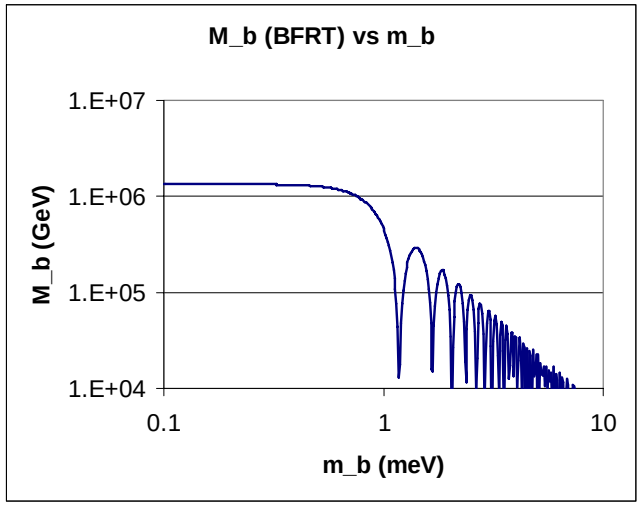
- The Brookhaven-Fermilab-Rochester-Trieste collaboration carried out all three searches:
- Rotation of polarization AND ellipticity (Cameron *et al.*, Phys.Rev.D 47, 3707 (1993))
- Regeneration of photons (G. Ruoso *et al.*, Z. Phys. C56, 505 (1992))

BFRT regeneration

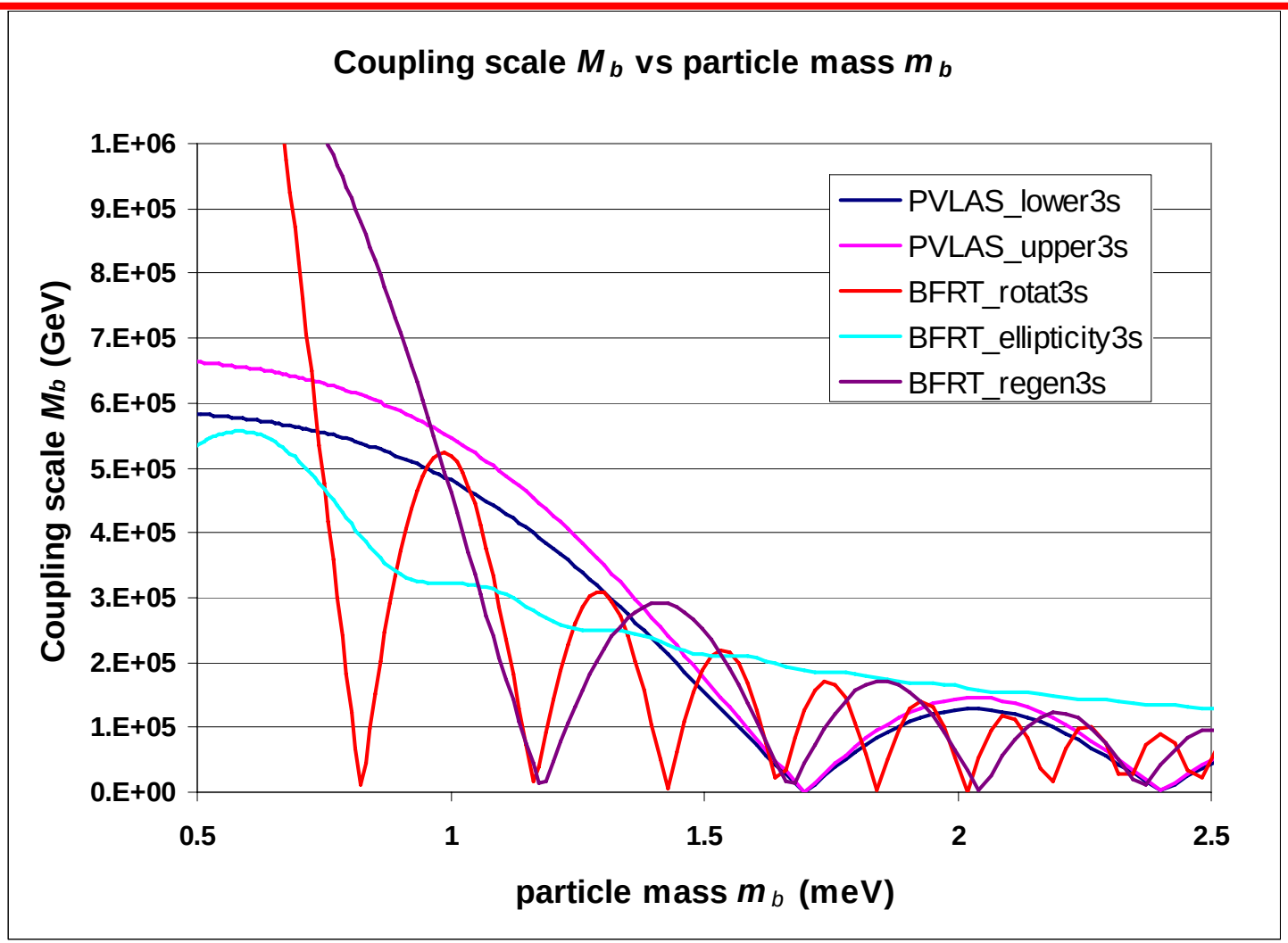
CBA magnets, ~200 reflections of 1.5W, 514nm laser.



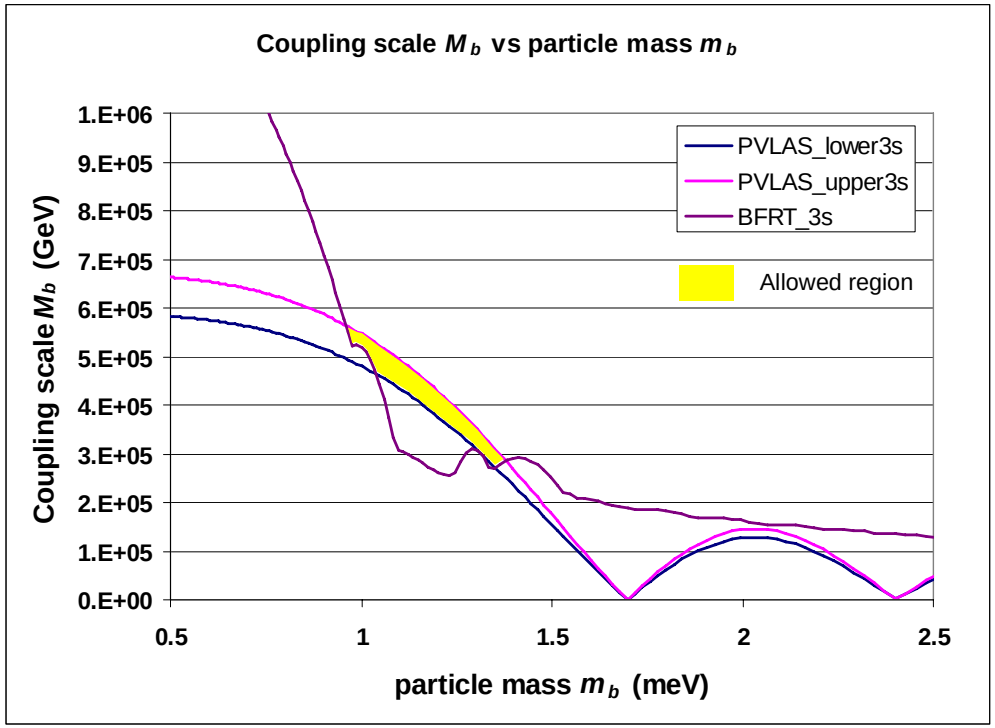
Lower limit of M_b is plotted vs. m_b



PVLAS & BFRT combined (1)



PVLAS & BFRT combined (2)



Result is a PSB with
$1 < m_b < 1.5$ meV,
and
$2\text{x}10^5$ GeV $< M_b < 6\text{x}10^5$

This is a new and unexpected combination not in the Standard Model and not predicted.

Why the interest?

- A particle with similar properties, the axion, was proposed by Weinberg and Wilczek from violation of PQ symmetry (R.D. Peccei and H.R. Quinn, Phys.Rev.Lett 38, 1440 (1977)) to solve the ‘strong CP’ problem.
- Non-perturbative effects related to the vacuum structure of QCD lead to a CP-violating term in L_{QCD} : $L_\theta = \alpha_s / 2\pi \, \theta G \Box \tilde{G}$
- This would give the neutron an observable electric dipole moment unless $\theta < 10^{-10}$.

The PQ & WW solution

- Add a new symmetry, $U(1)_{PQ}$ to the SM, that drives θ to near zero, resulting in a new particle, the axion, and a new mass scale F_{PQ}.
- The mass m_a is $\propto 1/F_{PQ}$
- Cosmological constraints give

$$10^{10} GeV < 1/F_{PQ} < 10^{12} GeV$$

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

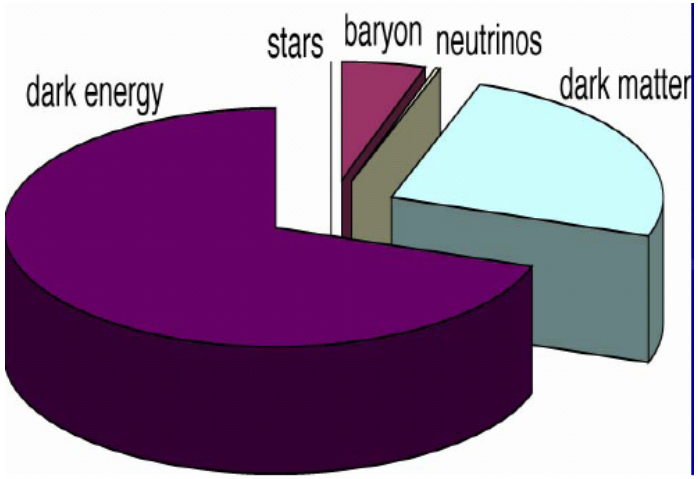
- $m_a F_{PQ} \sim 0.1$ GeV^2
- The mass range encompasses the PVLAS result, but the coupling scale does not: $m_b M_b \sim 10^{-7}$ GeV^2
- Other couplings are very small – the axion is neutrino-like in that regard.

More on axions

- The theory has developed (see, e.g., the PDG reviews, pdg.bnl.gov) and modifications have been proposed
- While other models have different couplings to other fields, they all have the two-photon coupling
- Axions could be produced during early part of the Big Bang – there are cosmological constraints – and could be part of the dark matter
- Axions affect stellar evolution, can be a significant contribution to stellar energy loss.

What is the impact?

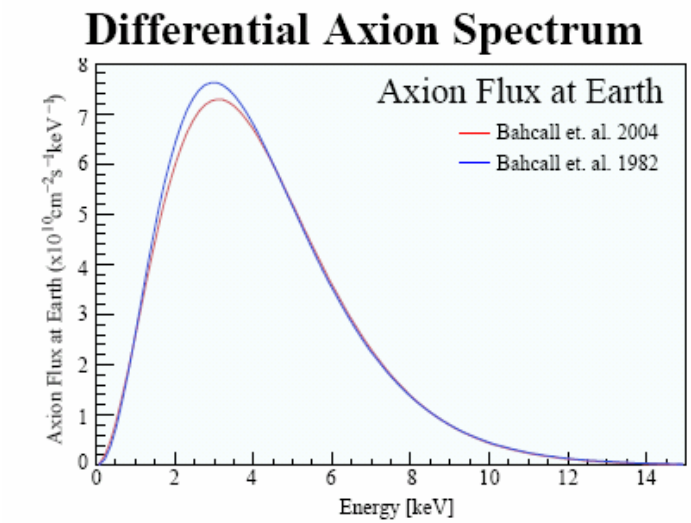
- Axions, or axion-like particles, could solve two important problems:
- The strong-CP problem
- The dark-matter problem
- High importance in particle physics and cosmology.



Many searches for axions

- The CAST collaboration (e.g., K. Zioutas *et al*.,PRL 94, 121301 (2005)) looked for axions from the sun and is upgrading
- The ADMX collaboration (Kinion, IDM2004) is upgrading its microwave experiment to search for relic axions
- PVLAS is upgrading, and running with new configurations (λ~500nm, etc.)
- Lab searches are proposed at HERA and with the under-construction VUV FEL at DESY (A. Ringwald, TAUP 2005).

CAST experiment



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

Axion Luminosity:

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

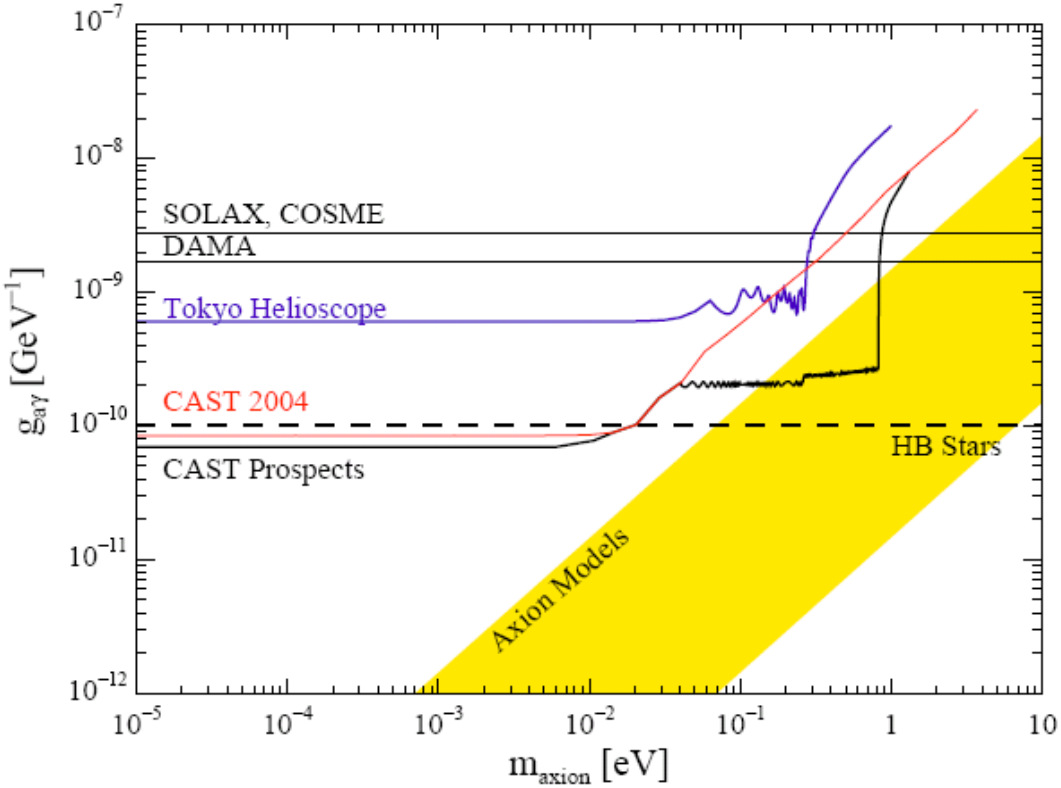
Axion flux: $\Phi_a = 3.8 \times 10^{11}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

Has seen no effect

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)

CAST 2004 preliminary

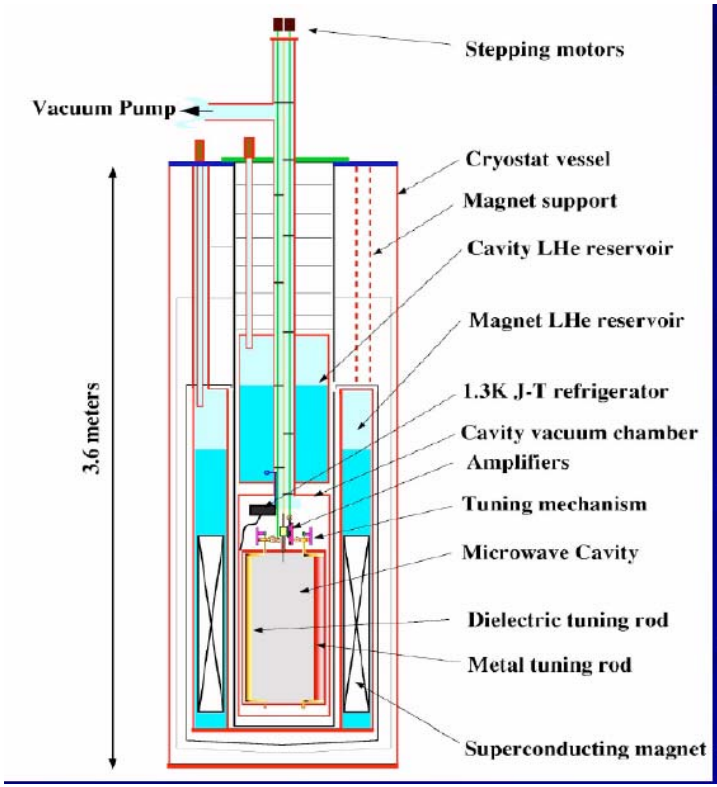
PVLAS
×

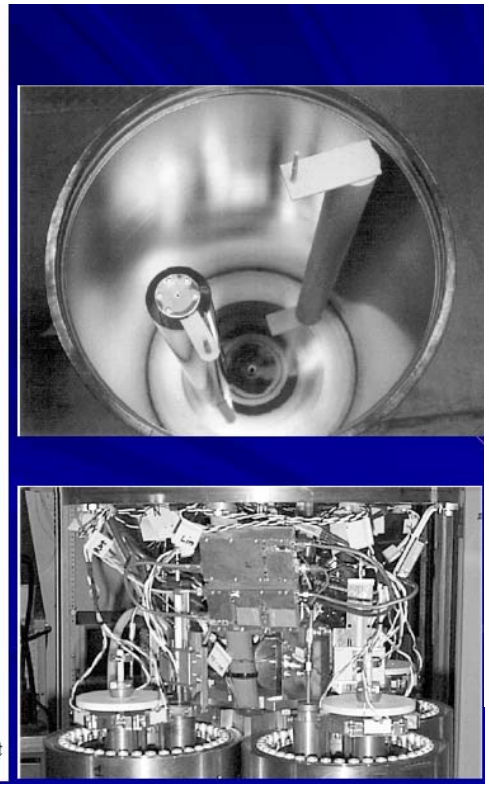


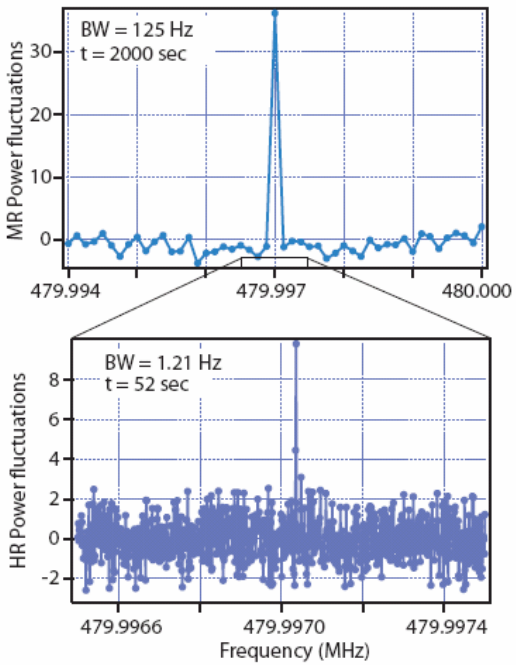
M. Kuster, 2005.
$g = 1/M$ is plotted to compare a wide of results.

The PVLAS result is not even in the range of the plot!

Microwave experiment







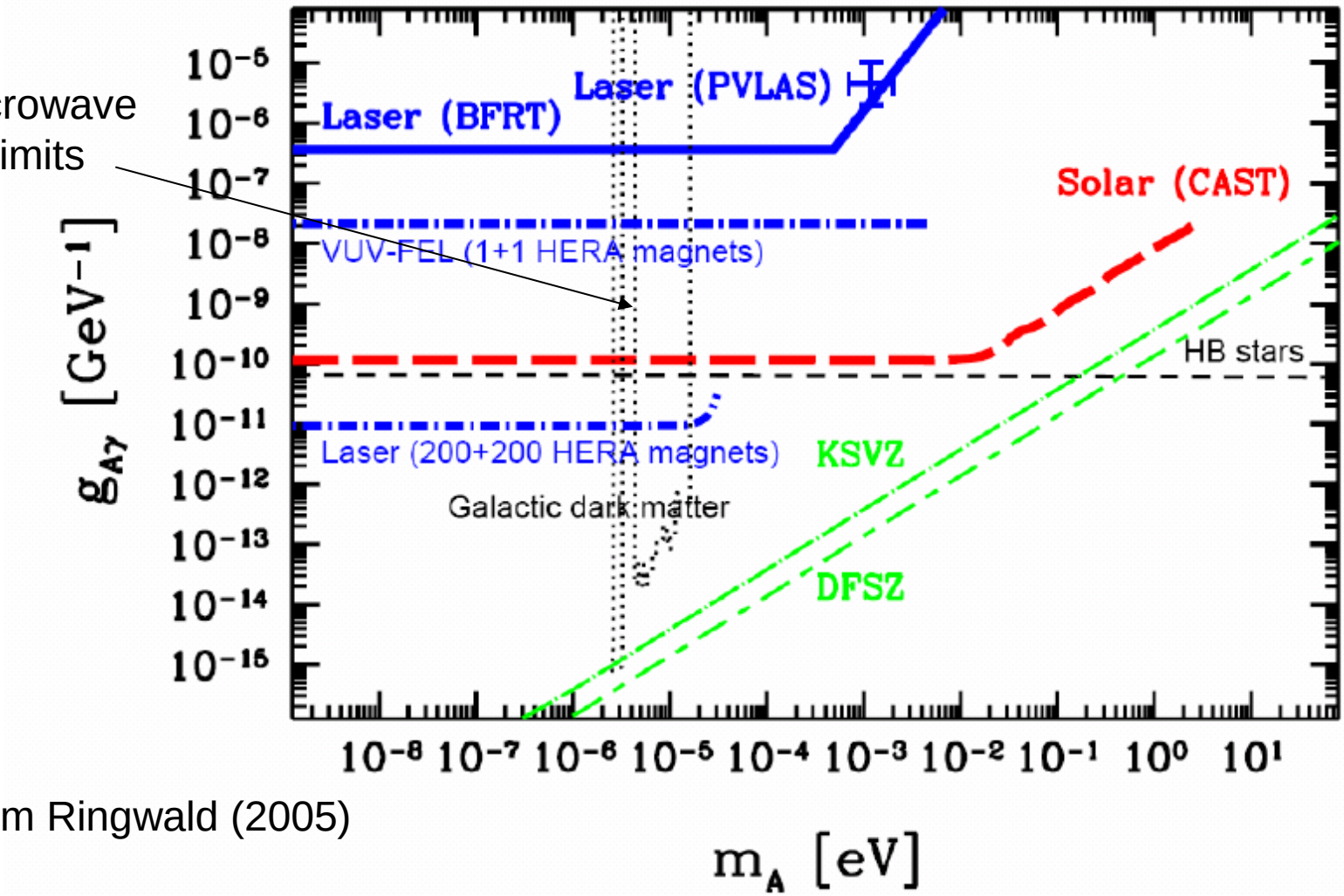
'Environmental' peak

Looks for conversion of remnant axions in resonant microwave cavity. Sikivie (1983), Ansel'm (1985), van Bibber *et al*. (1987), Duffy (2005), Kinion (2005)

Has seen no effect

A summary

Microwave limits

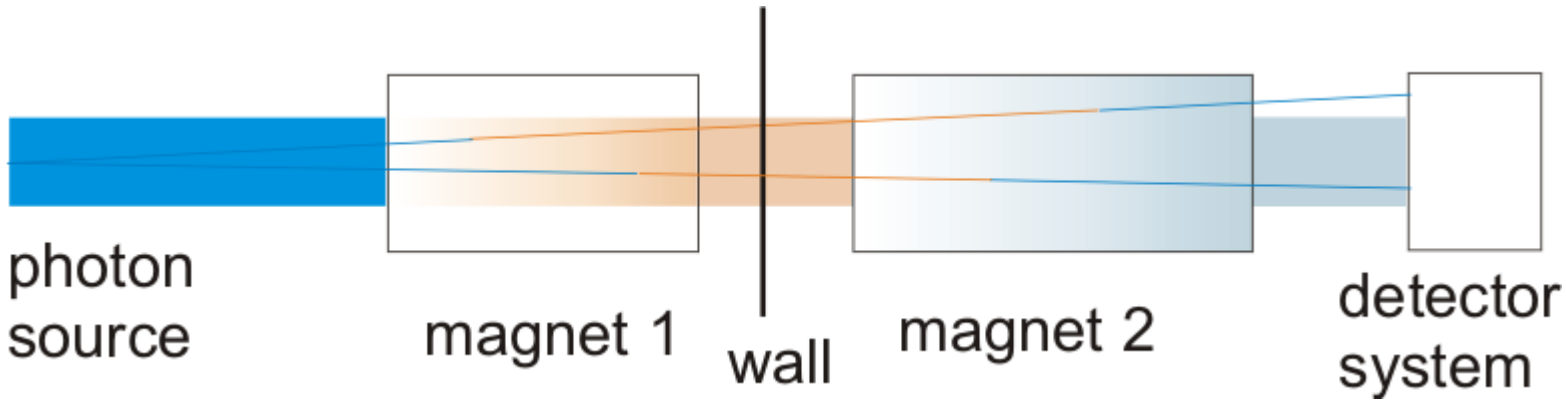


From Ringwald (2005)

Why the apparent disagreement?

- Note that only two experiments listed are pure laboratory experiments – BFRT and PVLAS
- The others all look for astrophysical effects
- Maybe axions, or light pseudoscalar bosons, have unexpected properties (remember the ‘solar neutrino problem’)
- Important to confirm or refute the PVLAS result.

Regeneration experiment



1. A photon beam passes into a magnetic field
2. Particle amplitude (orange) builds up
3. A wall stops photons, but the particle ‘beam’ passes into magnet 2
4. The particle amplitude creates increasing photon amplitude in the magnetic field
5. A detector measures the photon flux.

Regeneration coupling mass scale

$$M_b = \sqrt{(\frac{1}{2} B_1 l_1 \left|\sin(y_1)/y_1\right|)} \sqrt{(\frac{1}{2} B_2 l_2 \left|\sin(y_2)/y_2\right|)} \sqrt[4]{W\eta / R}$$

$B_1 l_1$ the magnetic field and length of PSB generation region;

$|\sin(y_1)/y_1|$, where $y_1 = m_b^2 l_1 / 4\omega$,

is the reinforcement, or diffraction-like, term;

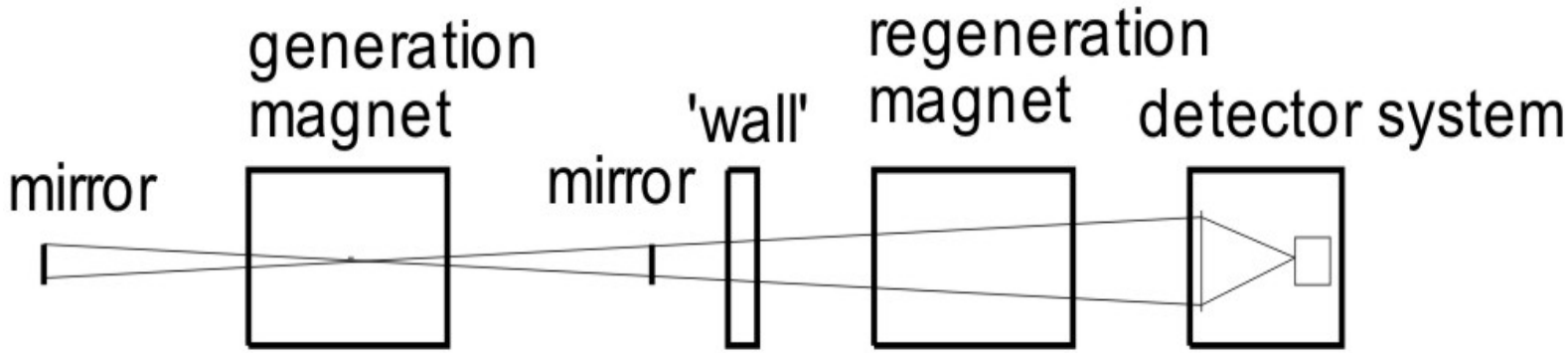
W is the photon rate, η the overall efficiency, and R the measured rate.

JLab FEL advantages

The Jefferson Lab FEL has many properties which make it unique as a source to probe this mass range, including:

- High average power, required to give the required signal rate
- Stable operation, allowing data collection over extended periods
- Low-emittance beam, useful to separate signal from background
- Bunched beam, also useful to reduce background
- Coherence between bunches, that may be useful to determine axion parameters
- High polarization, necessary to enhance the polarization-dependent production
- Tuneability, to explore effect of different photon energies
- Infrastructure, to support high-field magnets, and other experimental requirements.

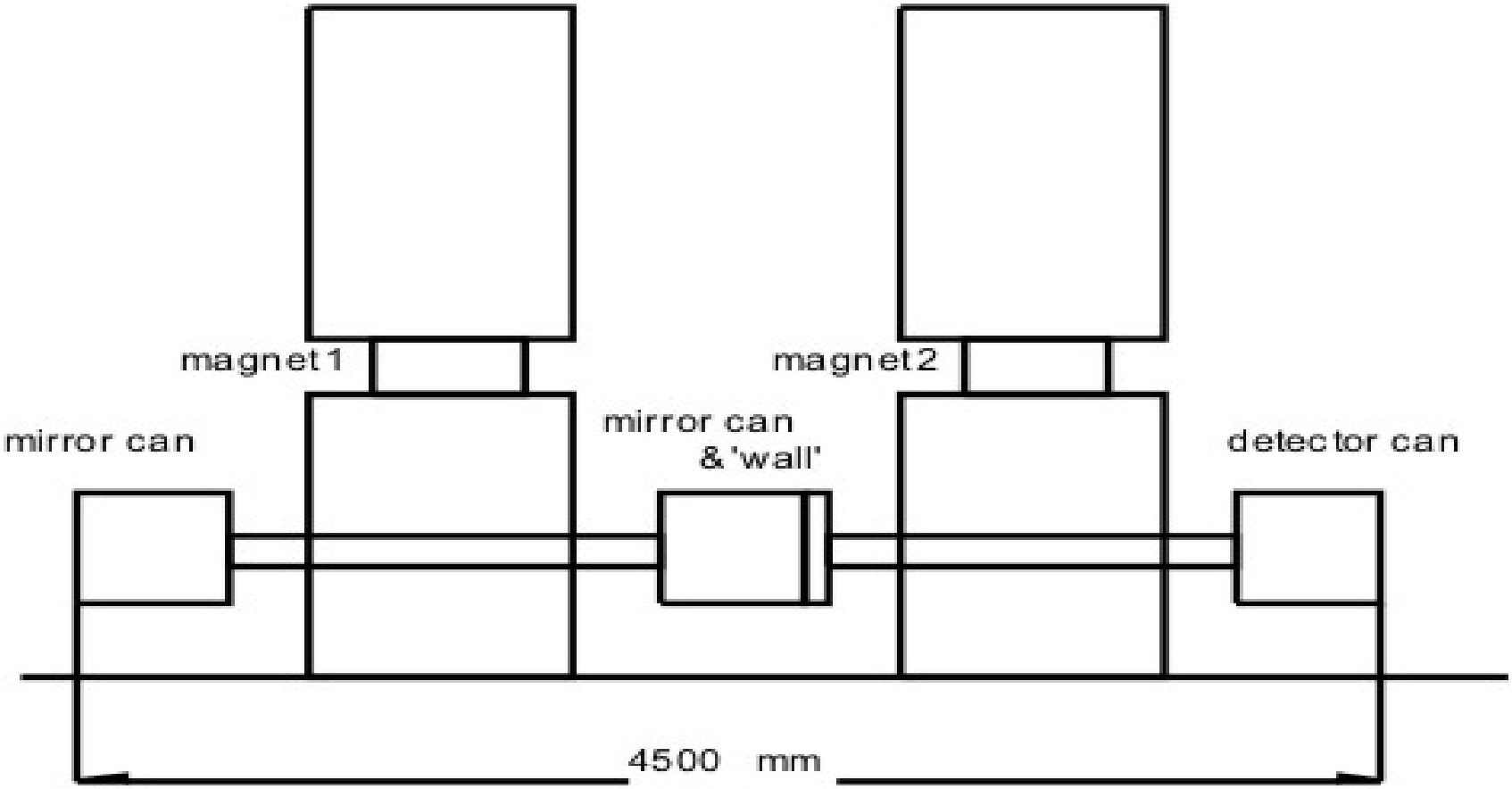
LIPSS at the JLab FEL



An optical cavity between the mirrors stacks pulses from the FEL. 'Axions' are produced in the generation magnet, travel through the mirror and wall and produce photons, in the regeneration magnet, that are focused on the detection system. Re-arranging the equation in slide 25:

$$R = \frac{1}{16M_b^4} B_1^2 l_1^2 \left[\sin(y_1)/y_1 \right]^2 \cdot B_2^2 l_2^2 \left[\sin(y_2)/y_2 \right]^2 \cdot W \cdot \eta \cdot Q$$

LIPSS tentative layout



Tentative parameters

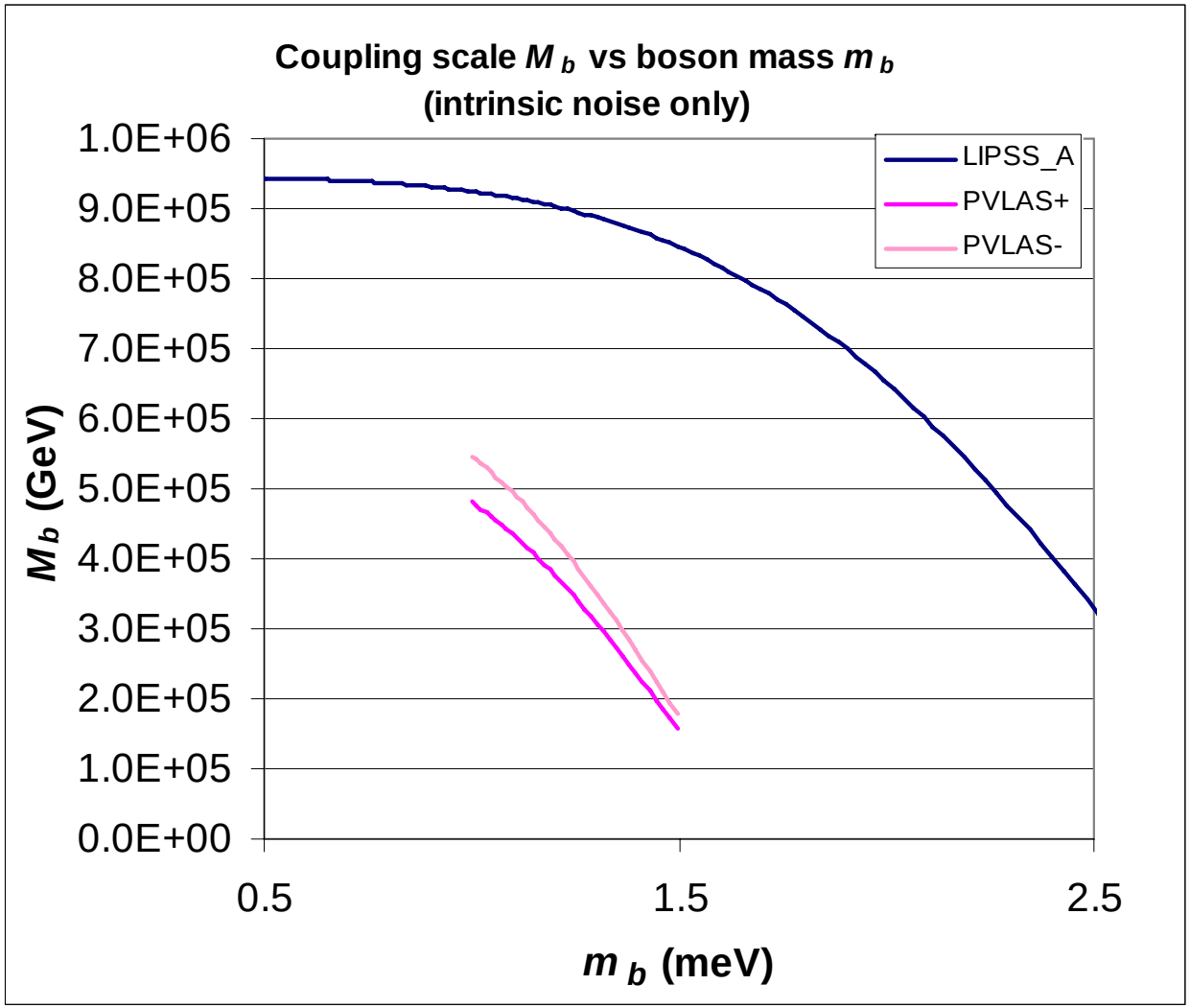
Parameters and rates

Wave-length	In-cavity power	Magnet 1 integrated field	Magnet 2 integrated field	Detector	Q.E.	Signal rate for $m_b = 1\,\text{meV}$, $M_b = 5\times10^5\,\text{GeV}$*	M_b reached in 4-hour run at 5σ
1064nm	100kW	2 T·m	2 T·m	CCD	0.1	0.3 s^{-1}	7×10^5 GeV
532nm	10kW	2 T·m	2 T·m	PMT-MCP	0.12	0.02 s^{-1}	9×10^5 GeV

Detectors

Detector	Pixel size or resolution	Timing resolution (FWHM)	Dark rate	Read noise
Hamamatsu CCD	24 × 24 μm	None	0.6 e^-/pixel/s	<12 e^-/pixel/s
Quantar PMT-MCP	~55 × 55 μm	100ps	<0.001 s^{-1}	0

Tentative performance



The LIPPS_A line is the upper limit for a 4-hour run with 10kW of 532nm light.

Backgrounds

- Intrinsic detector rate
  - Photocathode emission
  - Radioactive components
  - Leakage currents
- Thermal radiation (IR detector)
- Stray light
- Cosmic rays in detector and components
- Radiation from FEL in detector and components (lenses, mirrors, fibers)

Background reduction tools

- Optical characteristics of photons
  - Very small emittance – can be focused to a small spot (few μm)
  - Polarization parallel to magnetic field
  - Precise wavelength
  - Coherent with original and successive bunches
- Precise timing, ~150 fs
- Single photon events
- Signal proportional to magnetic field

Emittance

- This can be exploited in two ways:
  - Small detector or aperture to a larger detector
  - Use of an imaging device (a ‘picture’ of the PSB beam would be very convincing)
- First method does not affect intrinsic noise, only photon noise from outside detector.
- Regenerated light could be collected by a fiber.
- For imaging detector, assume that beam is focused to pixel size so that intrinsic noise from a limited number of pixels (1 or 4) is relevant

Polarization, wavelength

- A polarization filter could reduce external background light by 2, but would also reduce signal
- A rotating polarization filter could be used to modulate signal
- A bandpass filter would reduce external light by a large factor; would also reduce signal.

Timing

- The FEL beam runs at an integer fraction of 75MHz (t = 13.33 ns) bunch spacing
- A stacker can also run at 75MHz, or an integer fraction
- A detector with timing and appropriate DAQ can reduce background by a factor of $2.34*\sigma_t/t$ while retaining ~75% of signal.

Types of detectors

- Single photon counters
  - Photocathode+multiplier
    - K+ dynodes
    - K + MCP w/position sensing
  - Avalanche photodiode (APD)
- Integrating devices (also imaging)
  - Si CCD
  - HgCdTe (MCT) array

A figure of merit

s = signal rate

t = run time

$S = st$, signal counts

n = noise/background rate

t = run time

$N = nt$, background counts

Want $S/\sqrt{N} \geq 5$.

$s = 5\sqrt{(n/t)}$

With $\eta_D\,\eta_A$ = detector × analysis efficiency,

$R = s/(\eta_D\,\eta_A)$, FOM relative to PVLAS is

$$X = 2.5\times10^{-6}\,F_1F_2\,W^{1/4}\eta^{1/4}\eta_A^{1/4}\eta_D^{1/4}n^{-1/8}t^{1/8}$$

Remembering that the magnet factors F_1 and F_2 go as the square root of Bl, they are the most powerful tool.

What can give a null result?

- The PVLAS effect could be a systematic effect, although the collaboration has spent ~5 years understanding their systematics
- The PSBs or axions may have other properties – for example, there may be a family of such objects that oscillate like neutrinos and are undetectable in a regeneration experiment. This would be interesting!

Conclusion

- The JLab FEL and its unique characteristics open a window of opportunity to contribute to important problems in particle physics, astrophysics, and cosmology.
- Even if some calculations are optimistic (usually the case!), the LIPSS approach has the flexibility to succeed.

The End