WIMPS and LIPSS

A. Afanasev, O.K. Baker (contact person), K. McFarlane
Hampton University
for the LIPSS collaboration

CASA seminar

Feb 2, 2006

outline

- PVLAS results and implications
  - – overview only
- previous experimental studies
  - – how did all previous searches miss it?
- LIPSS (light pseudoscalar particle search)
  - – plans and history
- summary

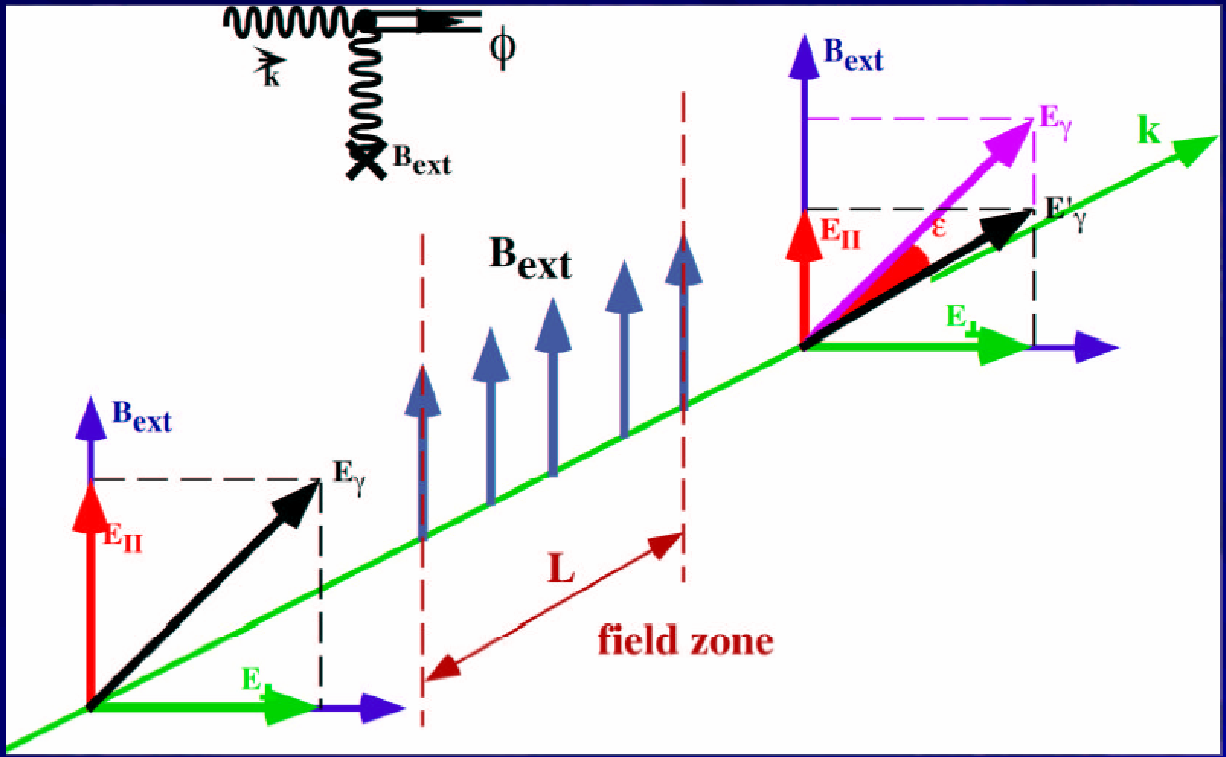
PVLAS results

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

Dichroism

rotation of polarization plane

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



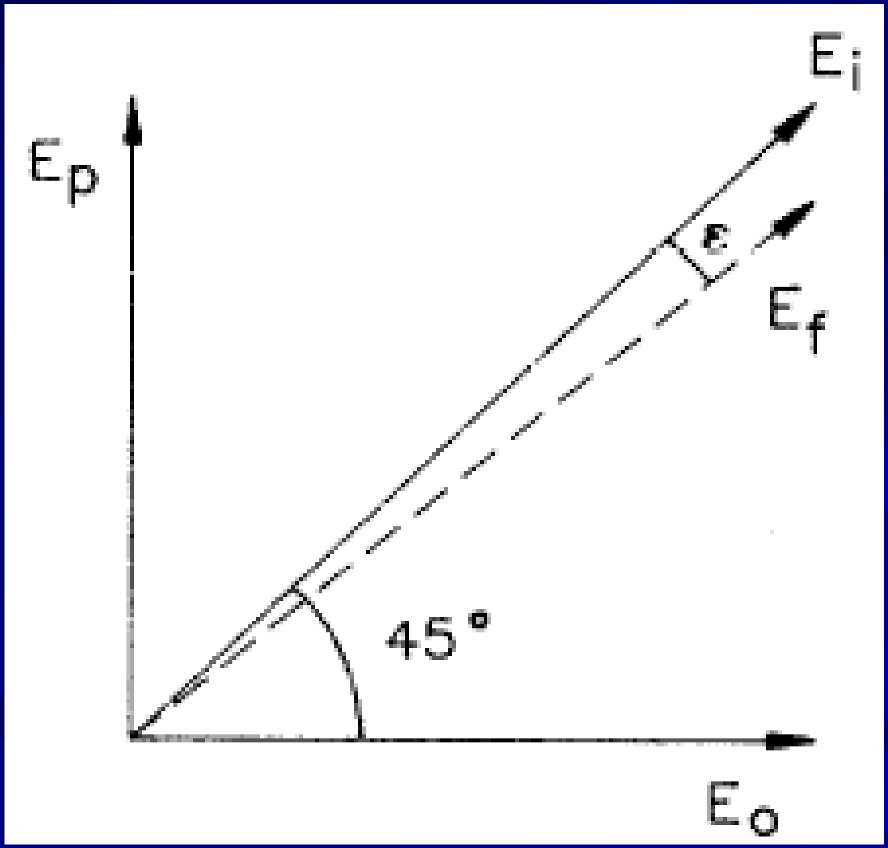
$$\varepsilon = -\left(\frac{B_{ext}L}{4M}\right)^2 \left\{ \sin\left[\frac{kL}{2}\left(1-\sqrt{1-\left(\frac{k}{K_m}\right)^2}\right)\right]\right\}^2 \frac{N}{\left[\frac{LK_m{}^2}{4k}\right]^2}$$

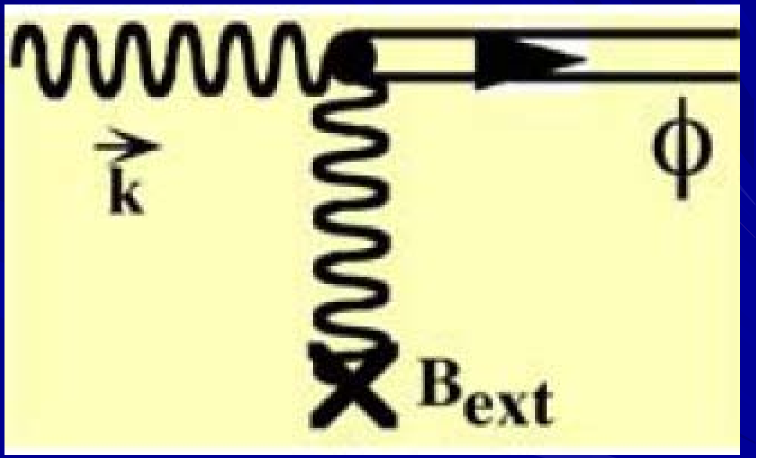
- M: inverse coupling
- K_m :inverse compton wavelength
- k: light wavenumber
- L: magnetic field region length
- N: number of traversals

Dichroism

rotation of polarization plane

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

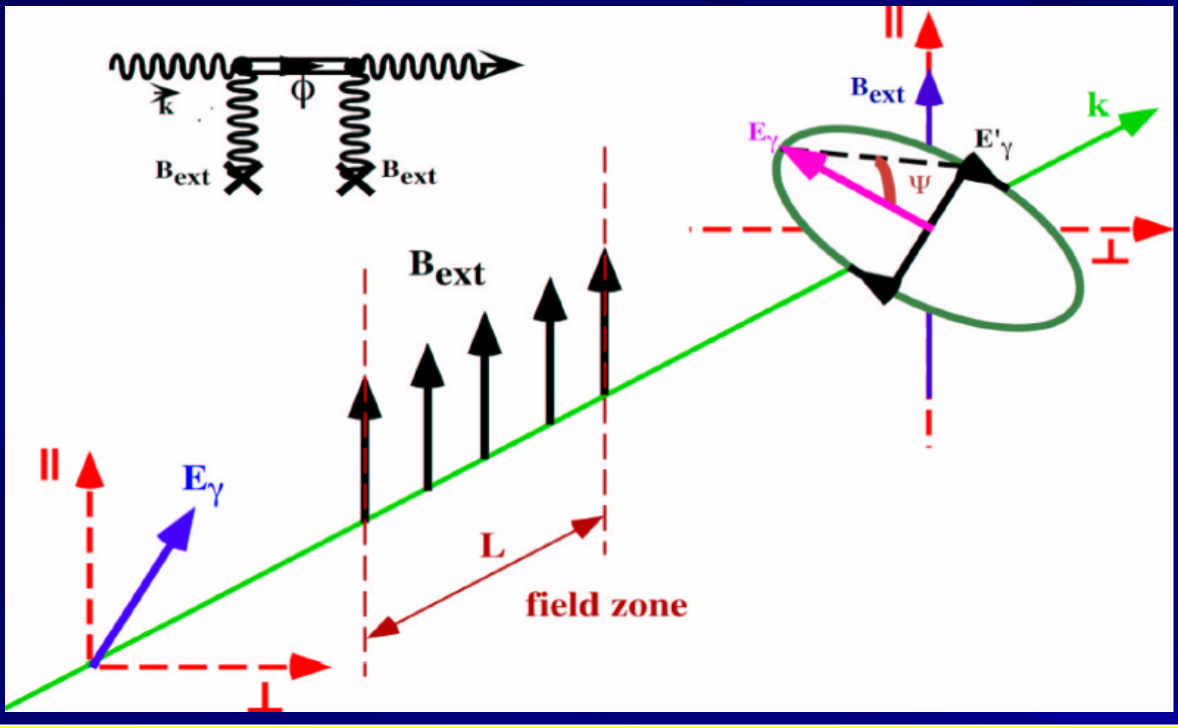




ellipticity

dispersion; photon-axion

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



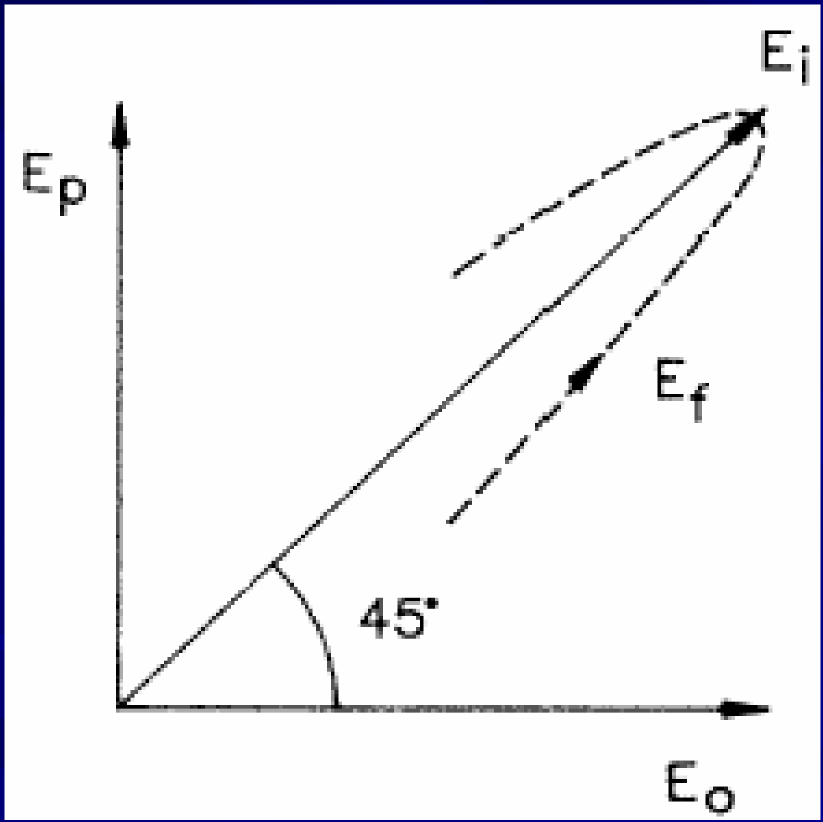
$$\psi = \left(\frac{B_{ext}^{2} kL}{4M^{2}K_{m}^{2}}\right)\left\{1 - \frac{\sin\left[kL\left(1-\sqrt{1-\left(\frac{k}{K_m}\right)^{2}}\right)\right]}{\frac{LK_m^{2}}{2k}}\right\}$$

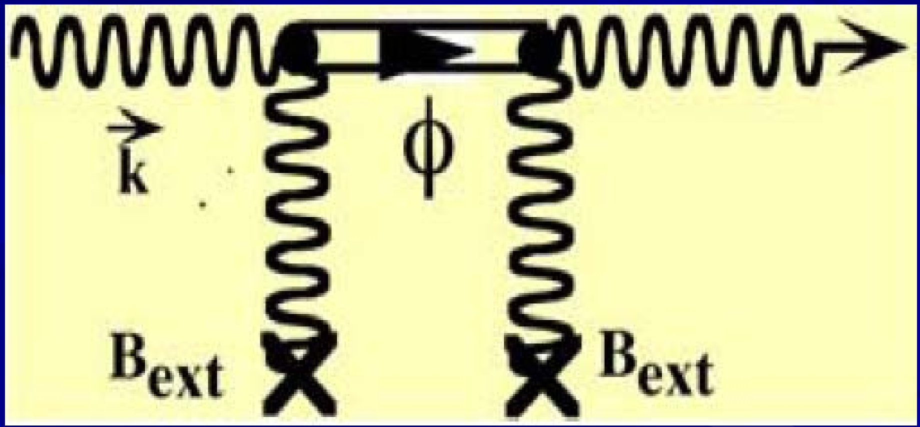
- M: inverse coupling
- K_m :inverse compton wavelength
- k: light wavenumber
- L: magnetic field region length
- N: number of traversals

ellipticity

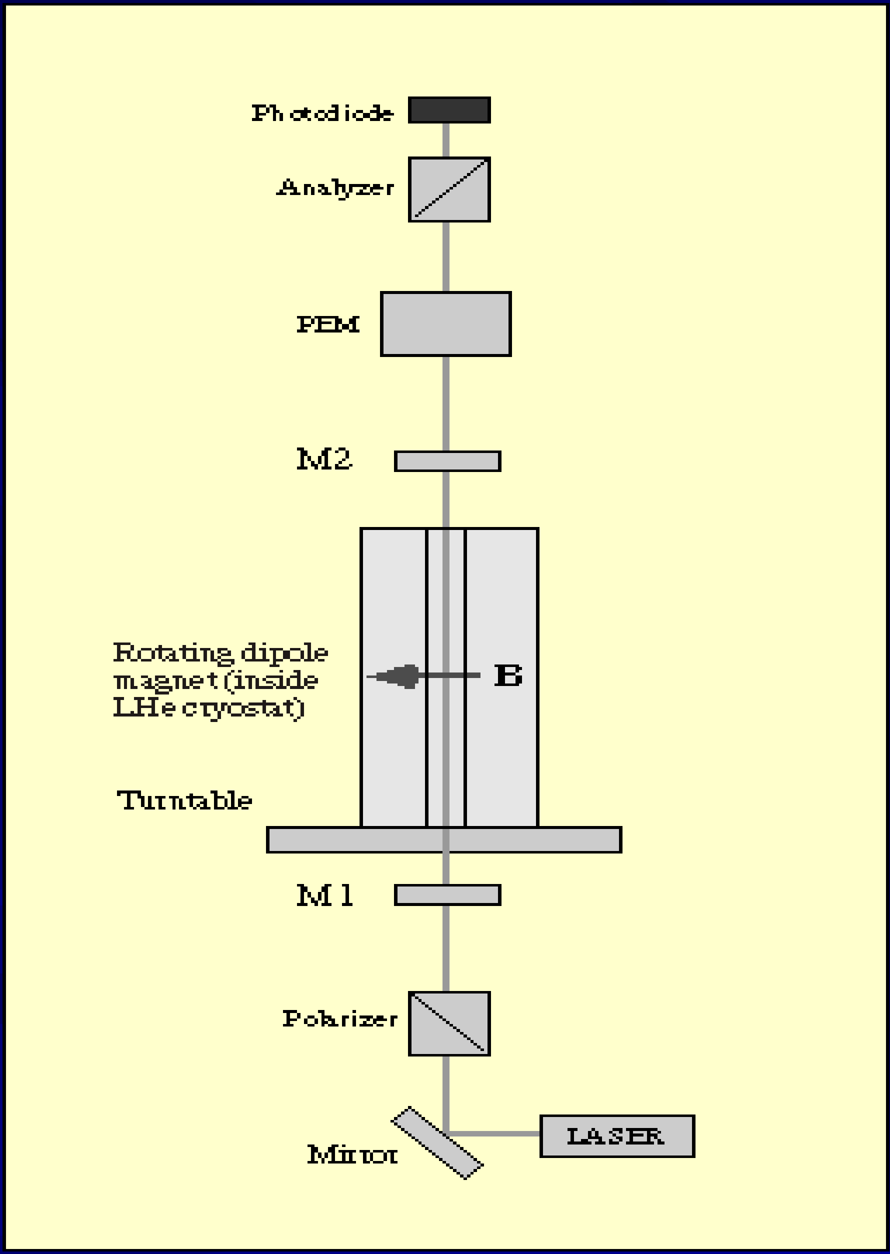
dispersion: photon-axion

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





PVLAS setup



6 T ; 1 meter long dipole magnet

1064 nm ; 0.1 W laser

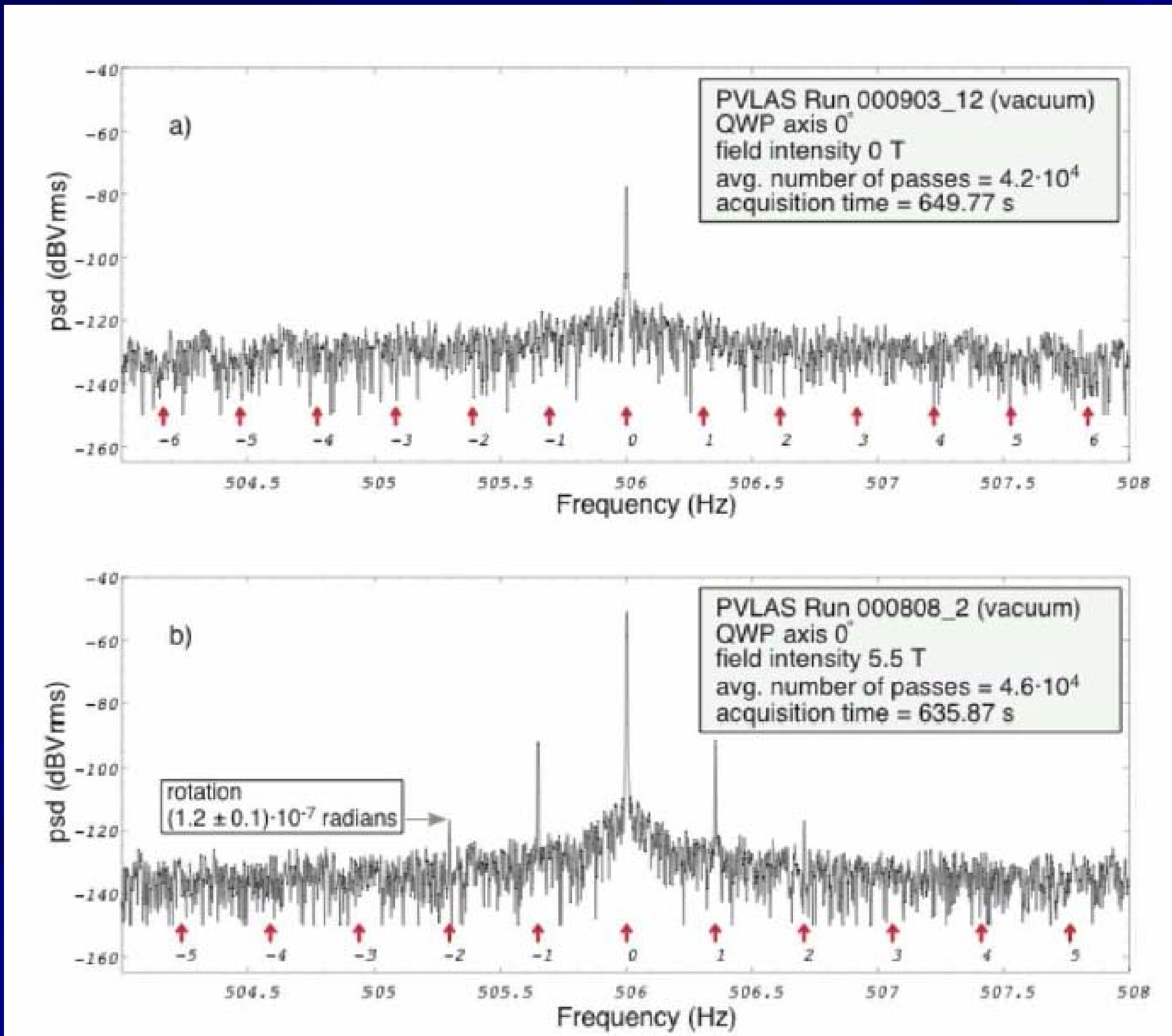
60 km path length in magnet

using 6 meters long
optical cavity

cryostat rotation 0.3 Hz

PVLAS results

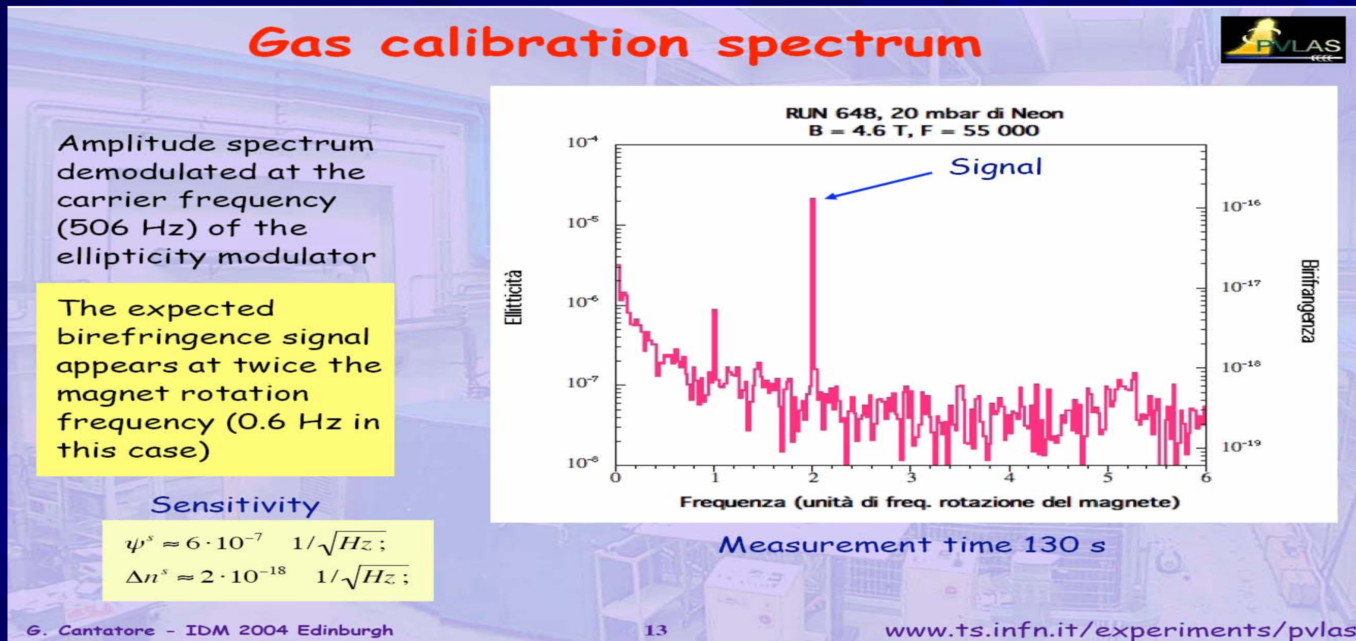
zavattini et al; see www.ts.infn.it/experiments/pvlas

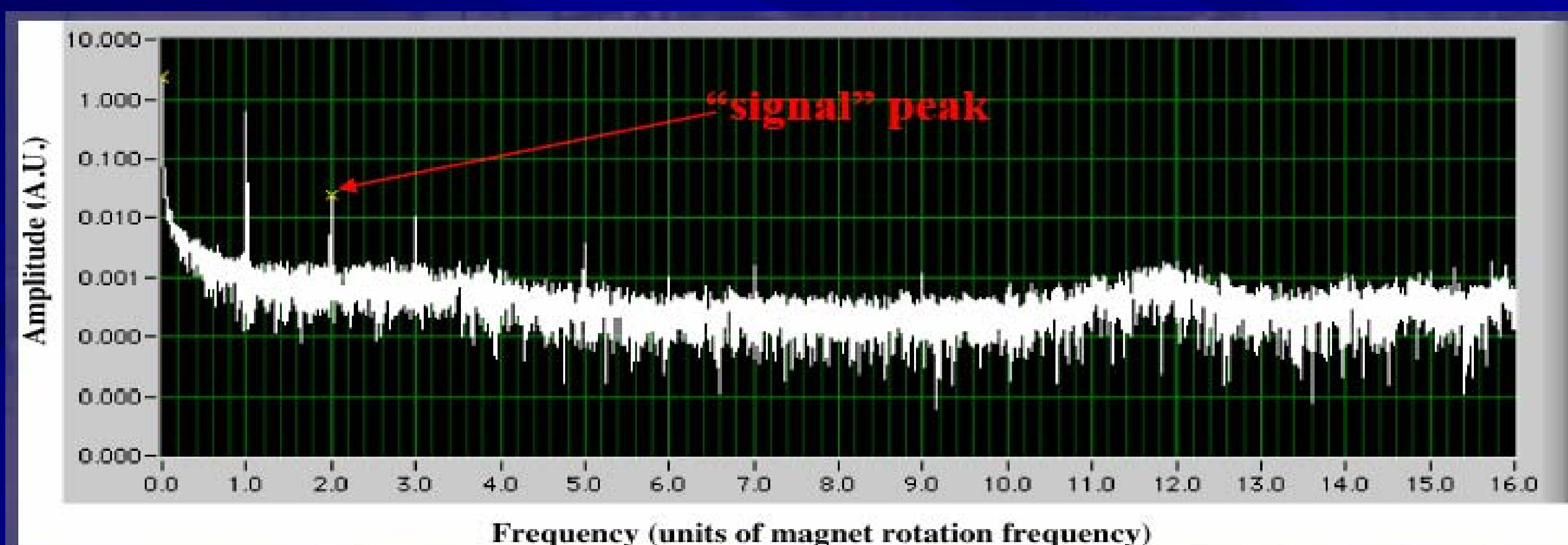


- B: 5 T
- L: 1 m
- ω: 1.2 eV (1.064 μ)
- OC: 6.3 m
- N: 44000

PVLAS example data

www.ts.infn.it/experiments/pvlas





PVLAS results may be explained by a region . . .

$$1.7 \times 10^{-6} < g < 1.0 \times 10^{-5}\ \mathrm{GeV}^{-1}$$

$$0.7 < m < 1.7\ \mathrm{meV}$$

PVLAS effect is 10^4 stronger than QED (Euler-Heisenberrg) prediction!

interpretation

light pseudoscalar particle

weakly interacting

(weakly interacting massive particle)

pseudoscalar coupling

- pseudoscalar particle coupling to photons

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

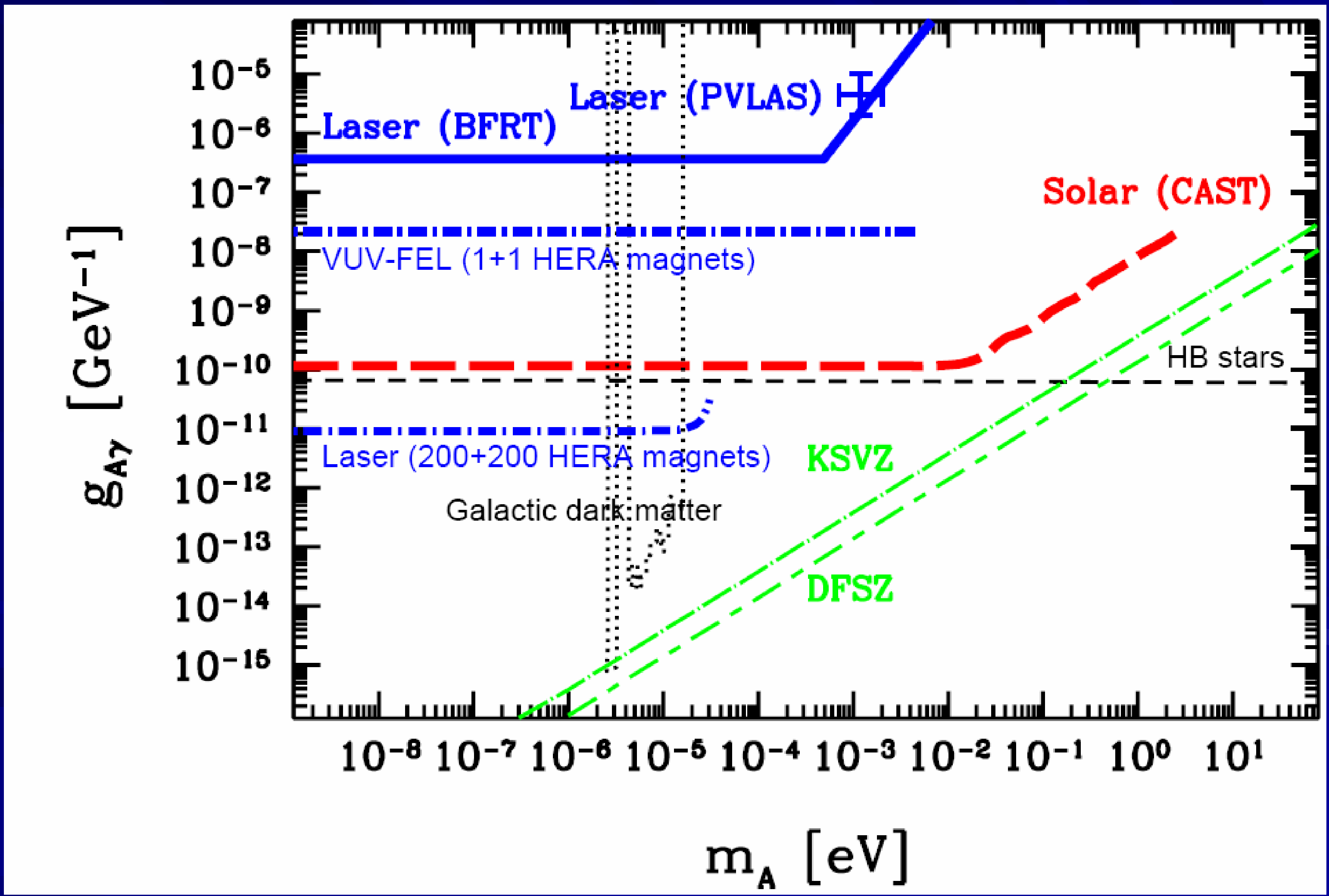
- in present case, use laser light and magnetic field
- light polarization in direction of magnetic field

- PVLAS claims to see effect in both dichroism and ellipticity (using same apparatus).
- we want to test this result in a completely independent way

Axion interpretation?

A. Ringwald; hep-ph/0511184

K. Zioutas et.al., PRL 94, 121301 (2005)



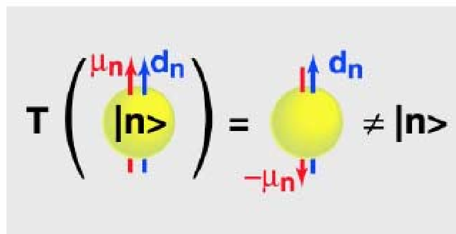
possibilities . . .

L. Rosenberg SLAC Summer Institute 2004

Peccei and Quinn:
CP conserved through a hidden symmetry

AXION

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?

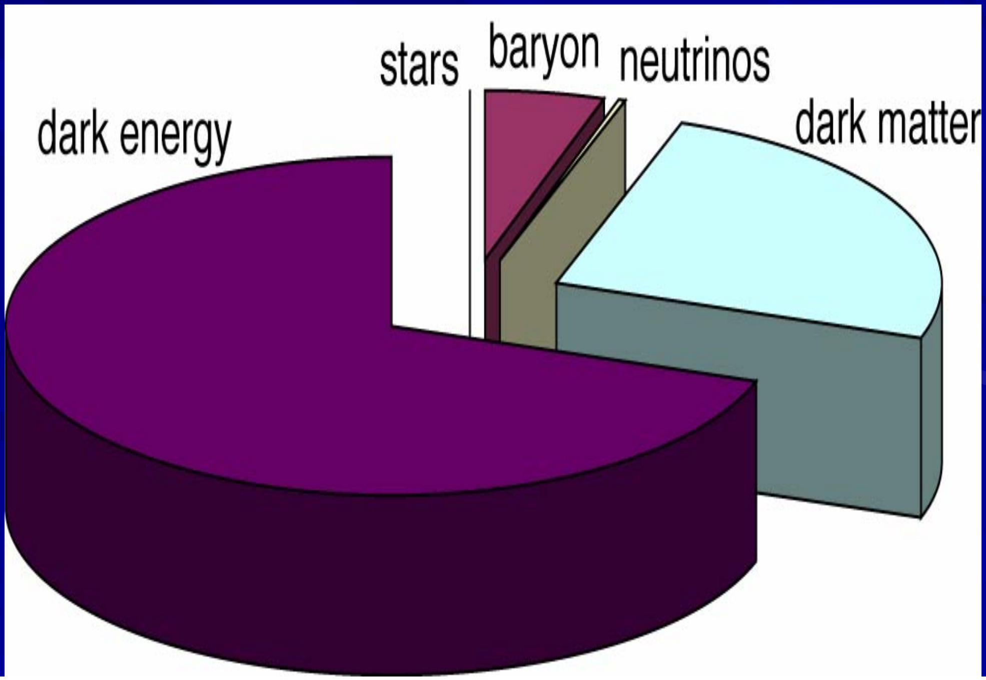
1977: Peccei and Quinn: Posit a hidden broken U(1) symmetry ⇒
1) A new Goldstone boson (the axion);
2) Remnant axion VEV nulls QCD CP violation.

Peccei, Quin (1977); S. Weinberg (1978); F. Wilczek (1978)

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



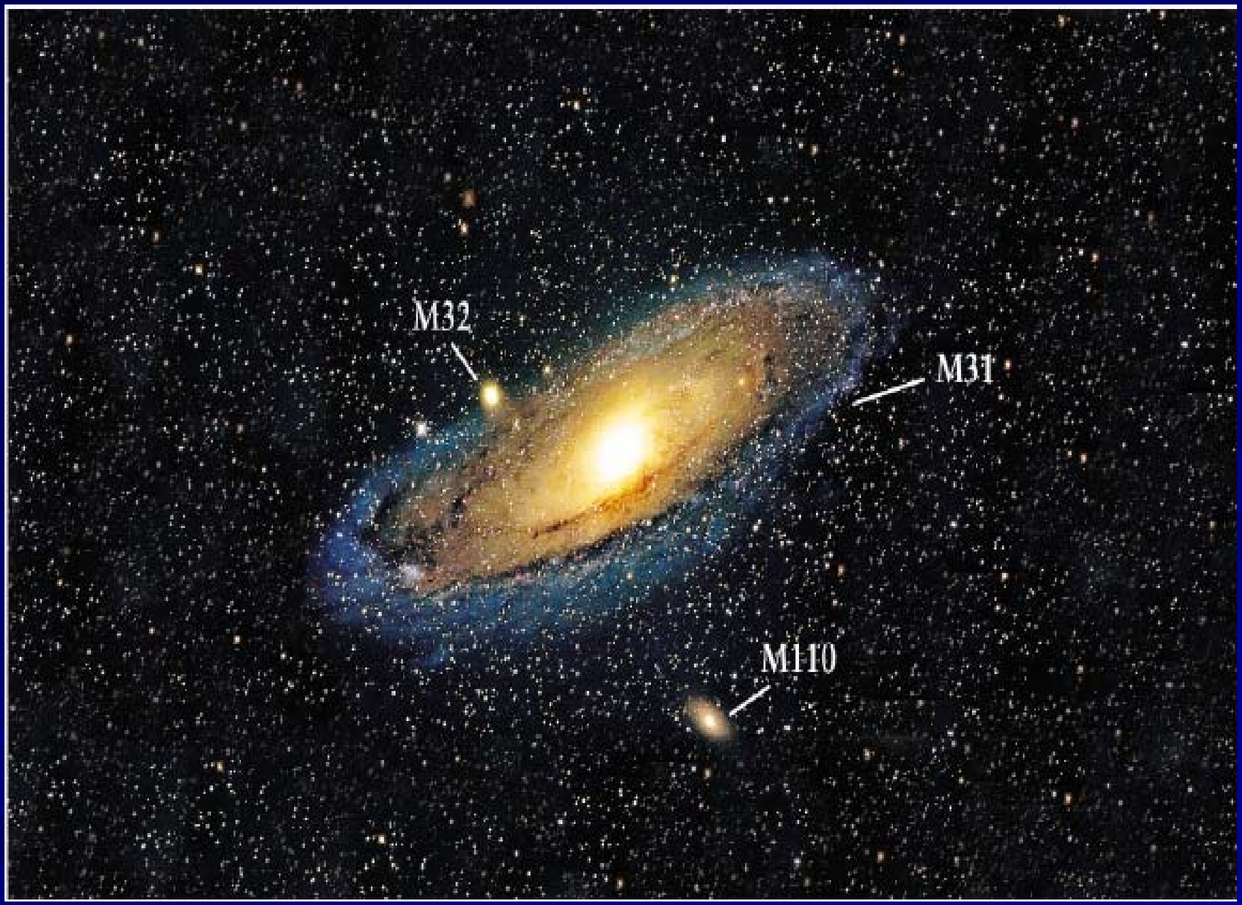
search strategies to date

- two broad classes of axion searches
  - detect relic (big-bang leftover), or solar, or stellar axions
  - produce and then detect axions in terrestrial expt
    - more difficult, in general, since there are two factors of small couplings
    - LIPSS uses this strategy
    - BFRT collaboration also used this strategy

relic axions

microwave cavities

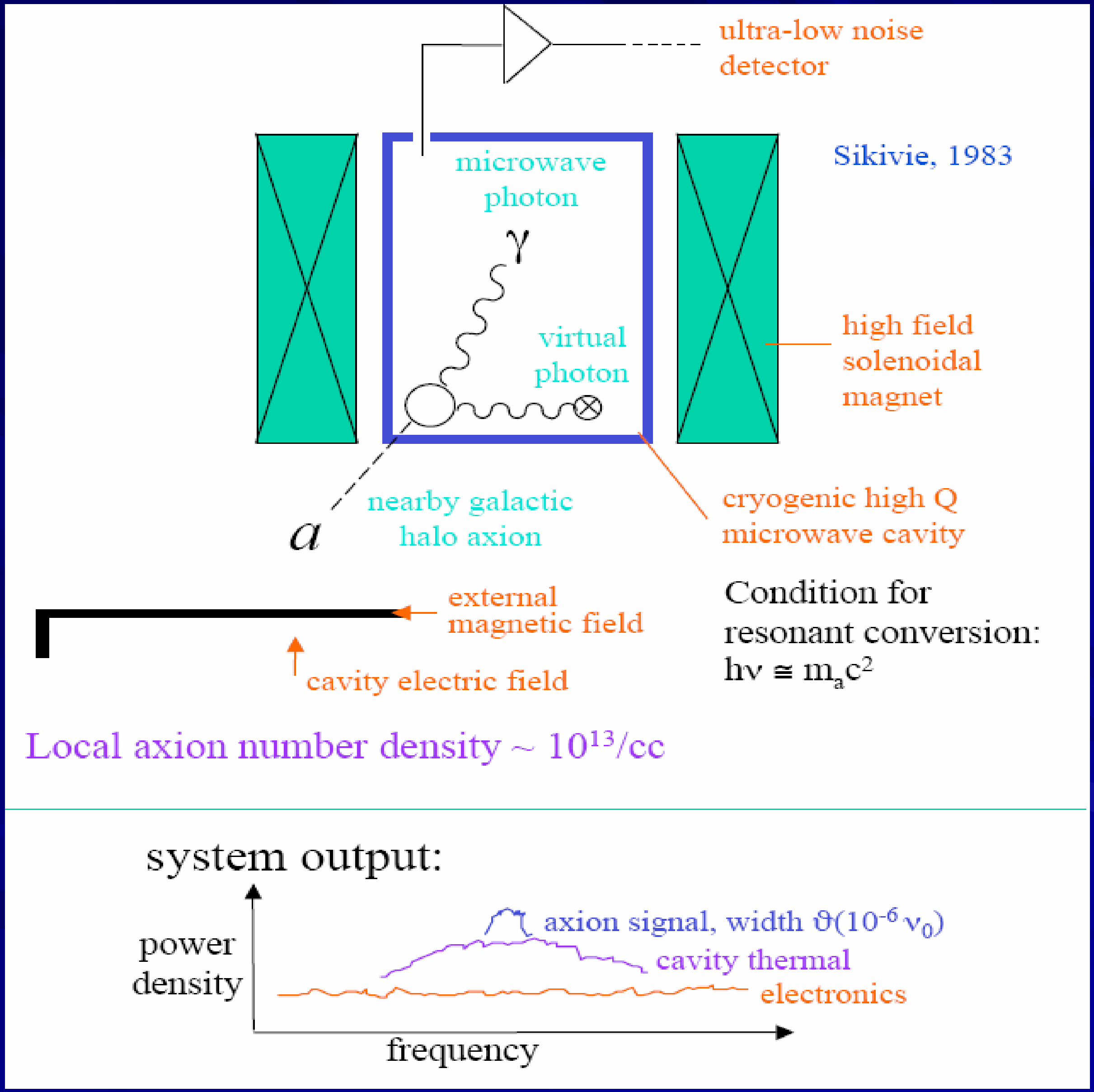
relic axions



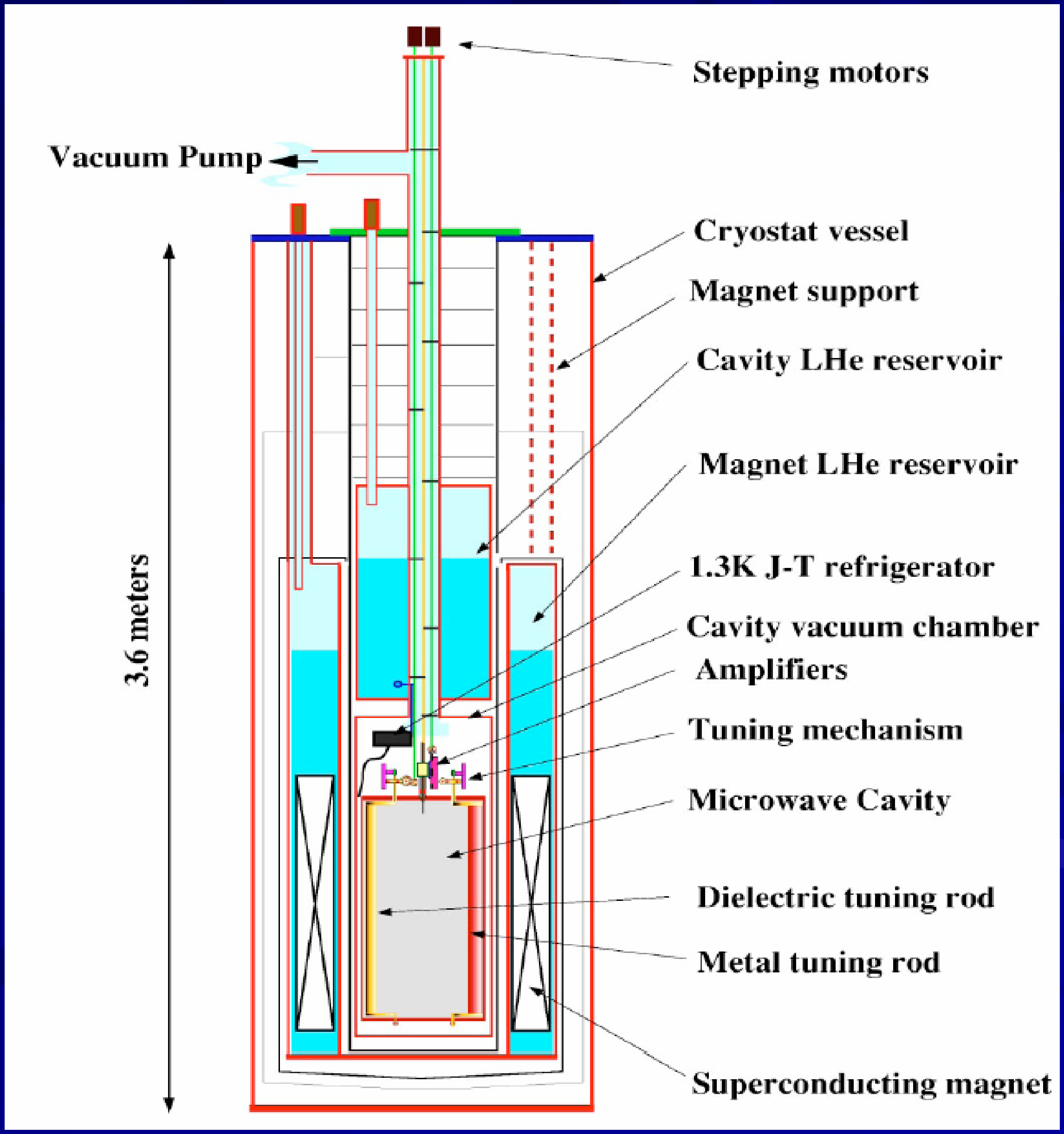
- axions created moments after the big bang.
- thermalized over time
- mass range must be consistent with astrophysical observables

microwave cavity technique

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

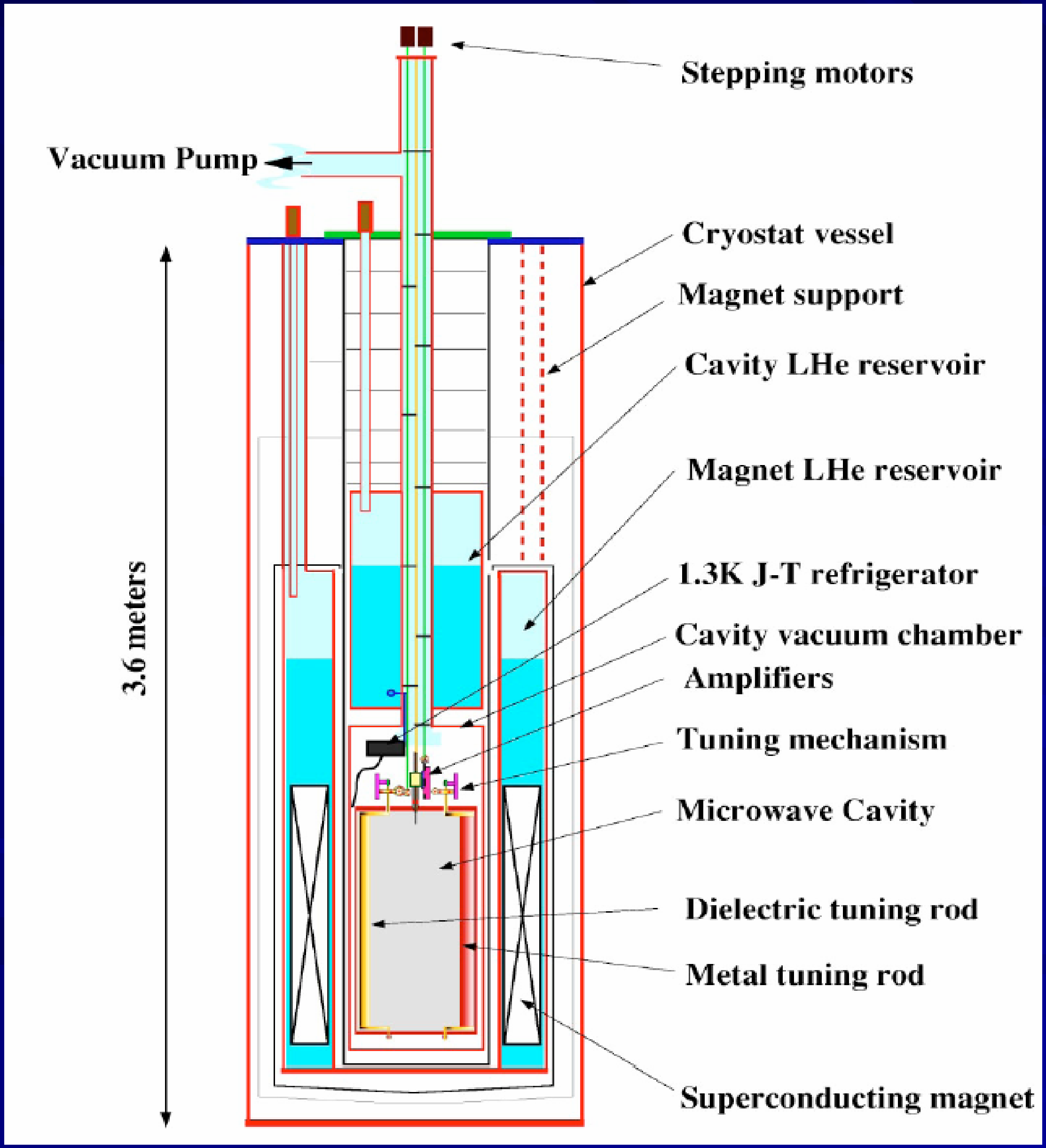


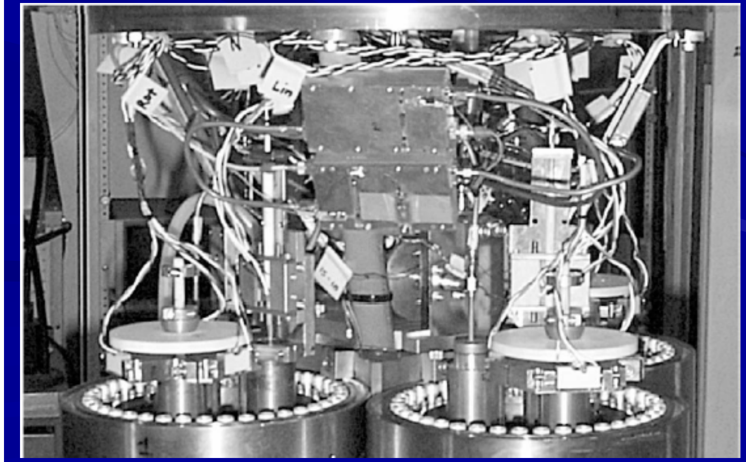
microwave cavity search: example



Sikivie (1983); Ansel'm (1985); van Bibber et al (1987)

microwave cavity search: example





microwave cavities

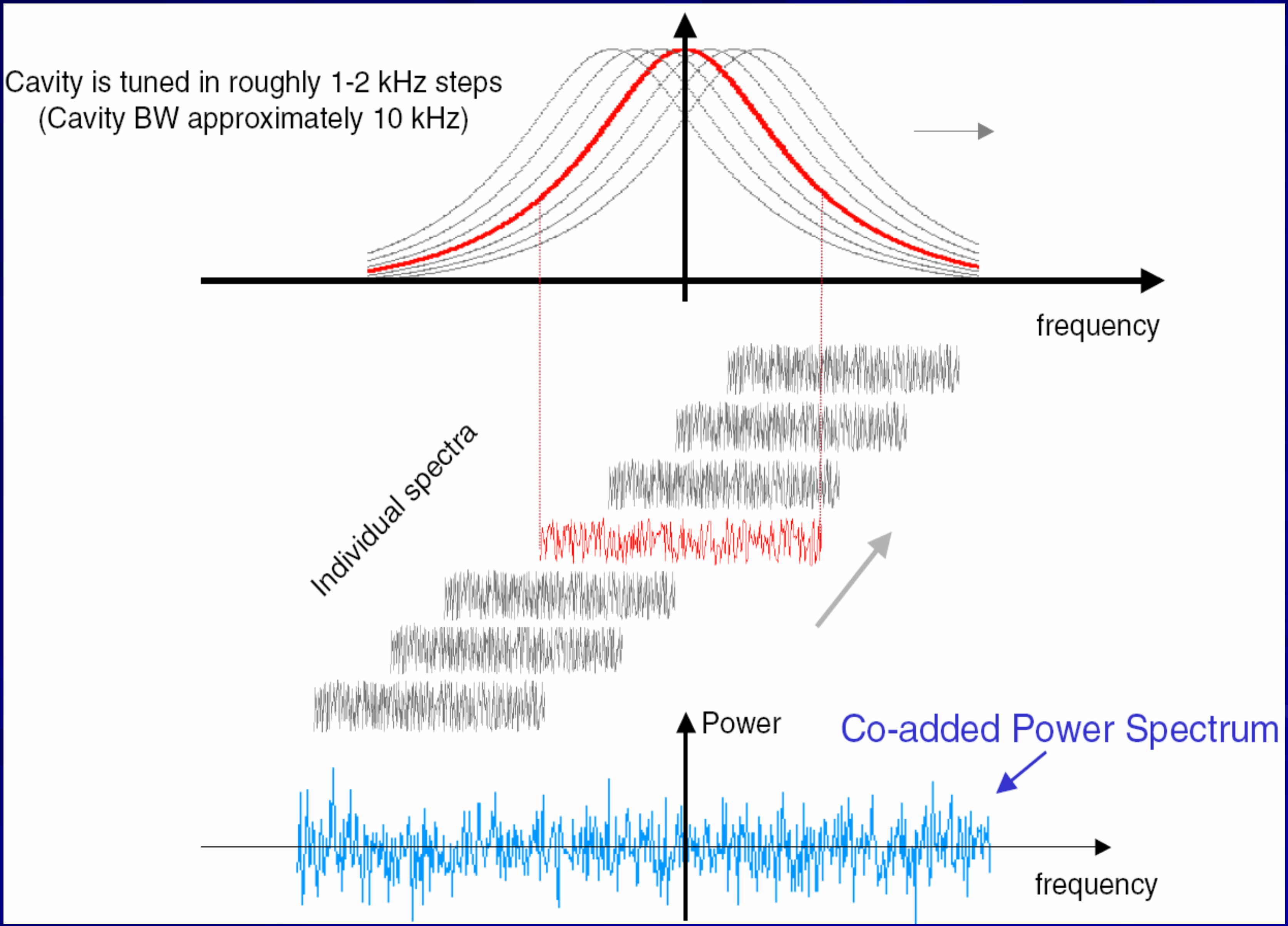
$$P_a = \left(\frac{\alpha}{\pi}\frac{g_\gamma}{f_a}\right)^2 V B_0^2 \rho_a C \frac{1}{m_a} \mathrm{Min}(Q_L, Q_a)$$

- V: cavity volume
- m (f) mass (coupling)
- B: magnetic field
- R: galactic halo axion density on Earth
- C: mode dependent constant (0.6)
- Q_L: cavity's loaded quality factor
- Q_a: galactic halo axion quality factor (10^6)

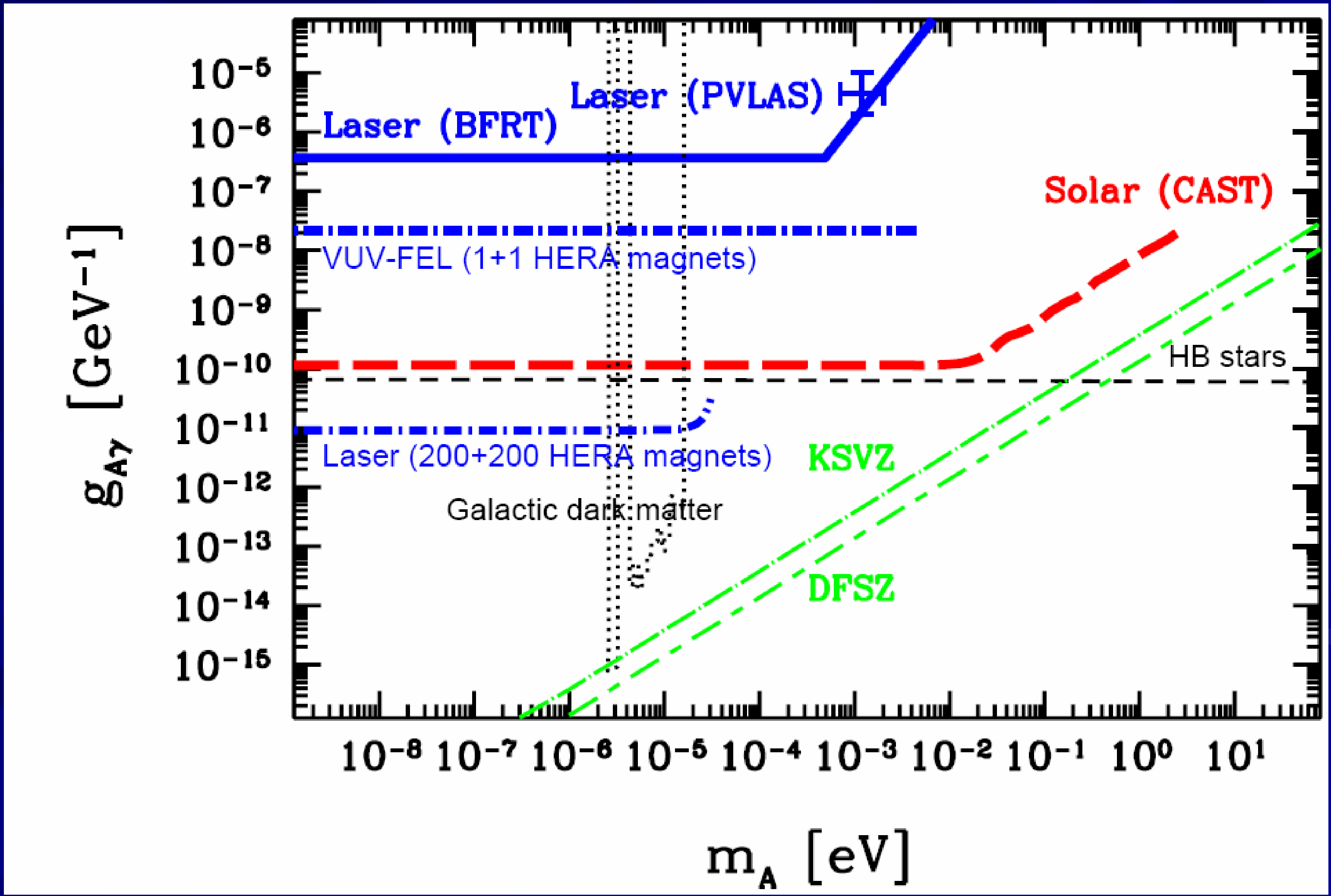
$$\mathrm{SNR} = \frac{P_a}{\overline{P}_N}\sqrt{Bt} = \frac{P_a}{k_B T_S}\sqrt{\frac{t}{B}}$$

- P_N: average thermal noise power
- T_s cavity temperature plus noise 'temperature'

data taking – microwave cavities



microwave cavity experiments find no evidence for relic axions in parameter space indicated

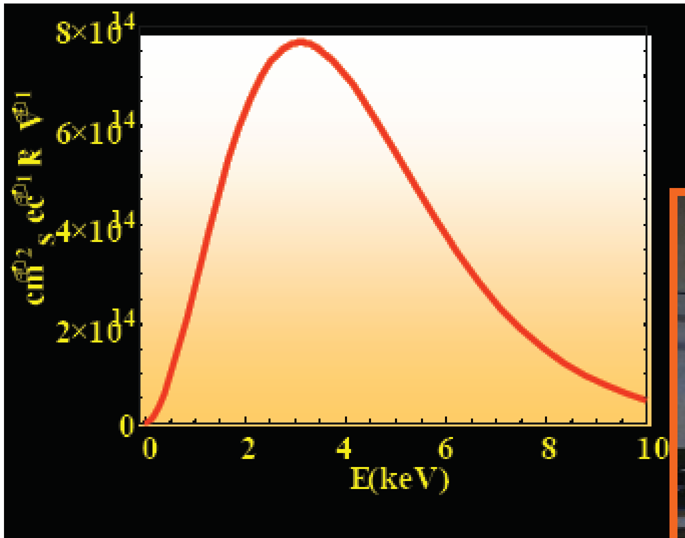


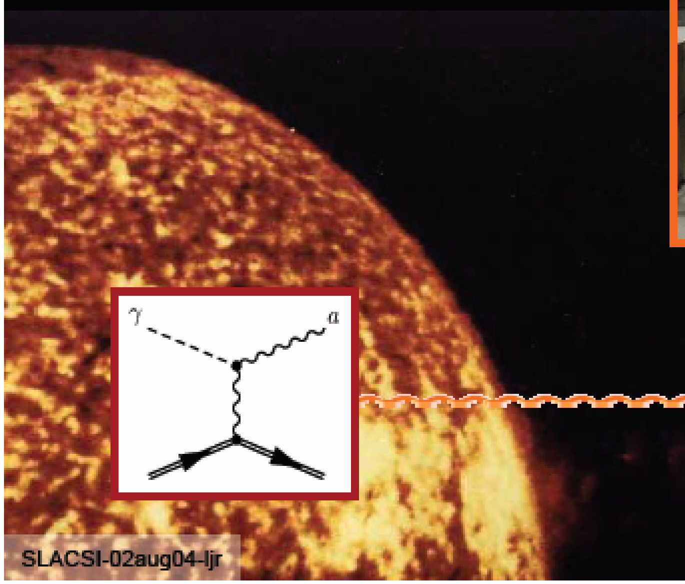
solar and stellar axions

helioscope search

supernova explosions

CAST – axions from the sun

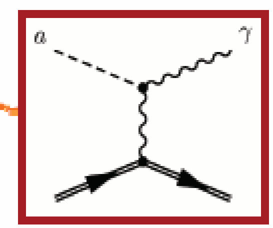




CERN Axion Solar Telescope

Axions from the sun…

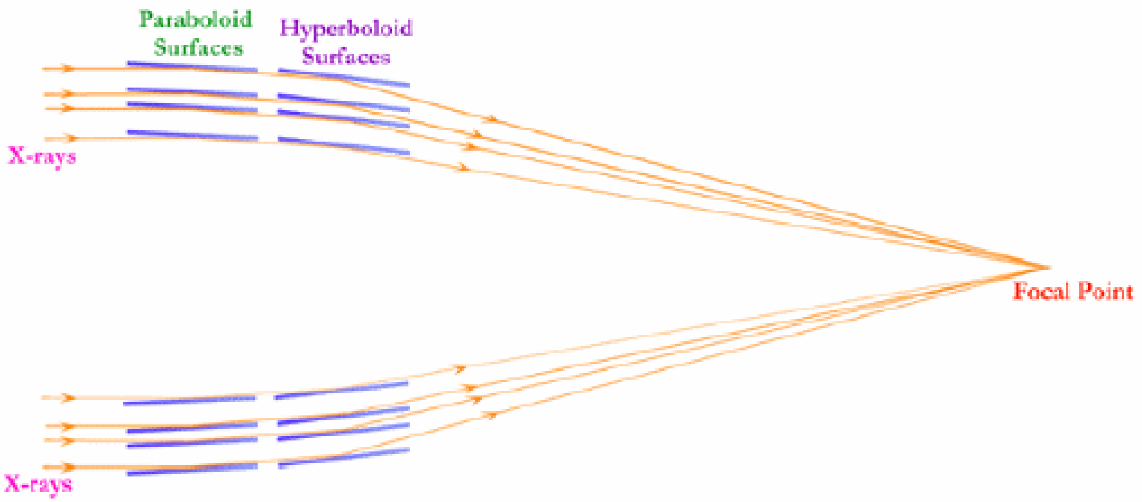
…become x-rays inside an LHC dipole magnet



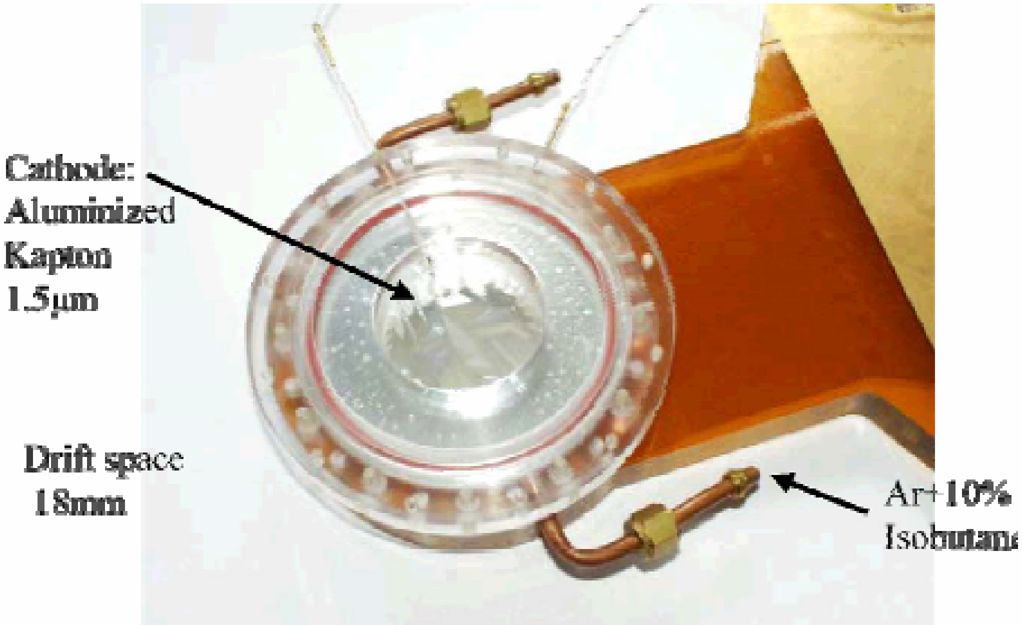
CAST experiment

- decommissioned LHC test magnet
  - L = 10 m ; B = 9 T
- moving platform
  - up to 50 days/year of alignment
- 4 magnet bores, for x-ray detection
  - solar temperature → keV axions → keV x-rays
- 3 x ray detectors
- x ray focussing system to increase S/N ratio

CAST technology

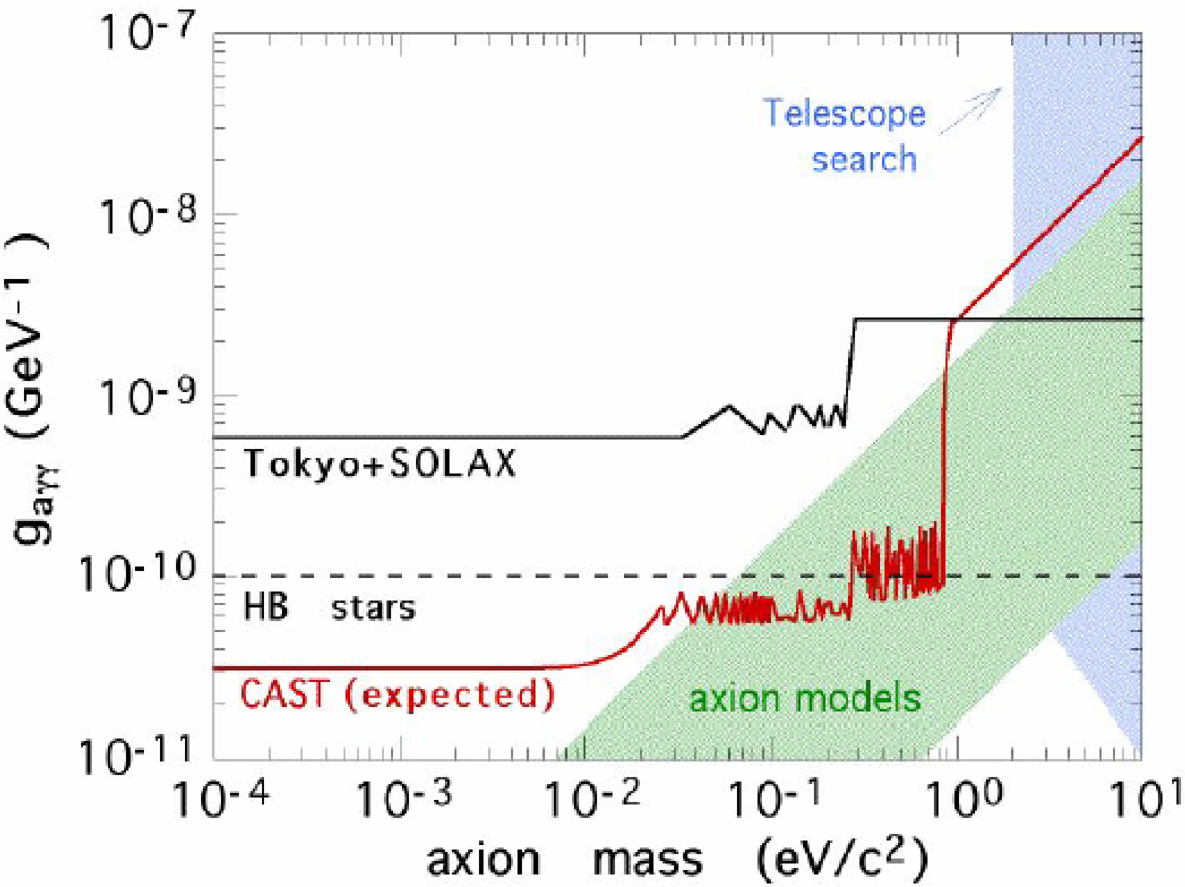


Grazing-incidence x-ray optics



Micromegas x-ray camera

CAST finds no evidence to date for solar axions in parameter space indicated



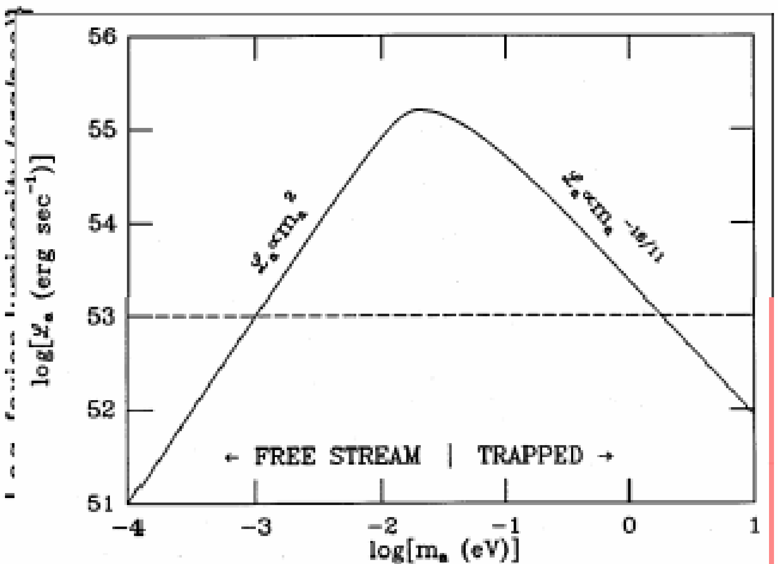
Current the best astrophysical bounds

vary He gas pressure to match dispersion relation

astrophysical bounds

L. Rosenberg, SLAC Summer Institute 2004

Example:neutrinos from SN1987A



Ellis and Olive, 1987; Raffelt and Seckel, 1988; Turner, 1988, etc

Supernova in the LMC.
Neutrinos are trapped and diffuse out over timescales of around 10 seconds.

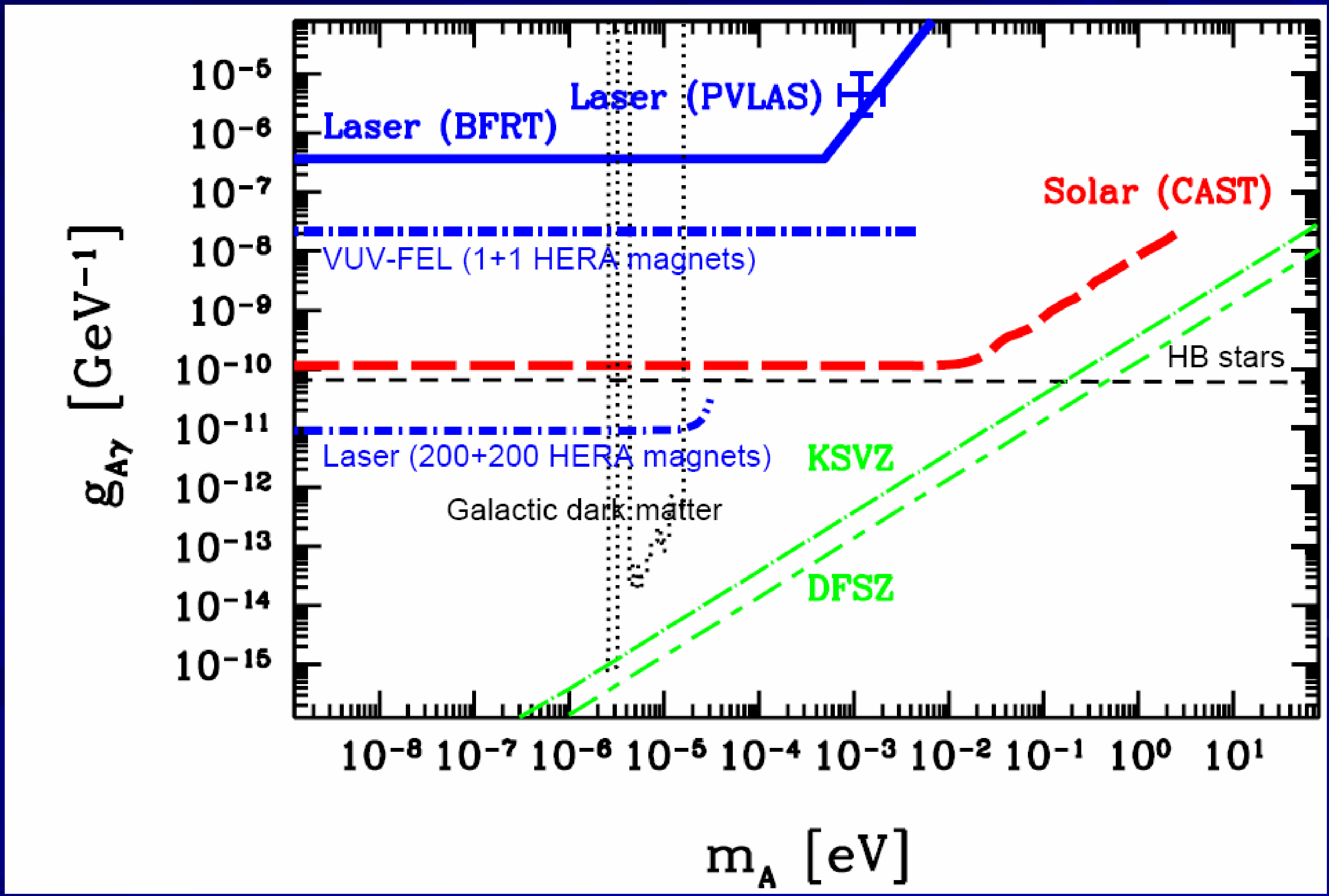
Kamiokande and IMB together recorded 19 neutrinos from SN1987A.

An axion of mass between 10^{-3} and 2 eV would take so much energy out that... the length of the explosion would be observably forshortened.

Overall summary: Astrophysics (stellar evolution and SN1987A), cosmology, and laboratory experiments leave the invisible CDM axion window $10^{-6} < m_a < 10^{-3}$ eV (with large uncertainties)

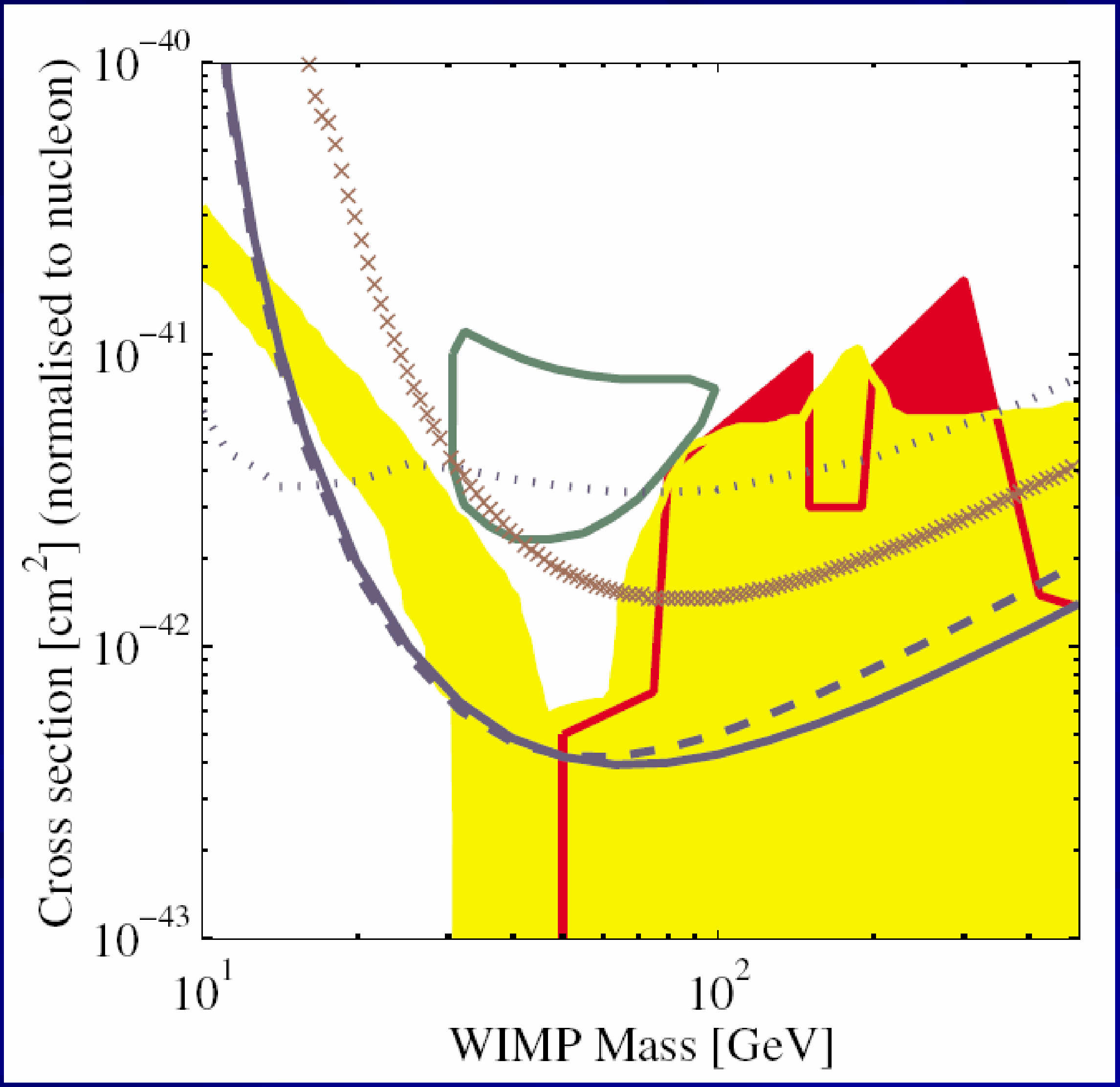
CAST finds no evidence to date for solar axions in parameter space indicated

SN1987A does not rule out PVLAS result



cryogenic dark matter search in Soudan underground laboratory

D.S. Akerib et al, Phys. Rev. Lett 93, 211301-1 (2004)

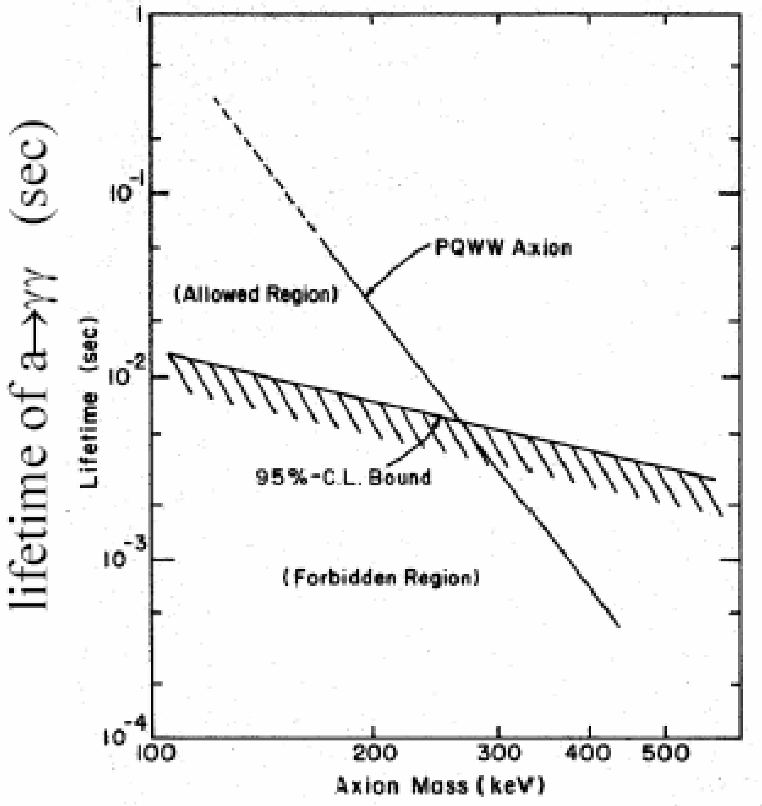


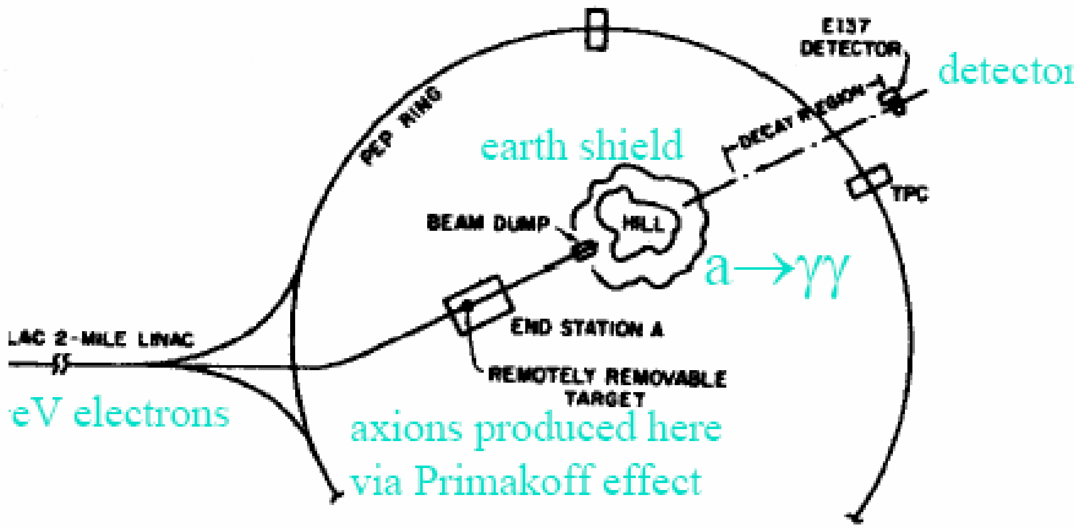
new limits in large mass range; no evidence for WIMPs

production and detection

accelerator/laser experiments

SLAC Experiment E137



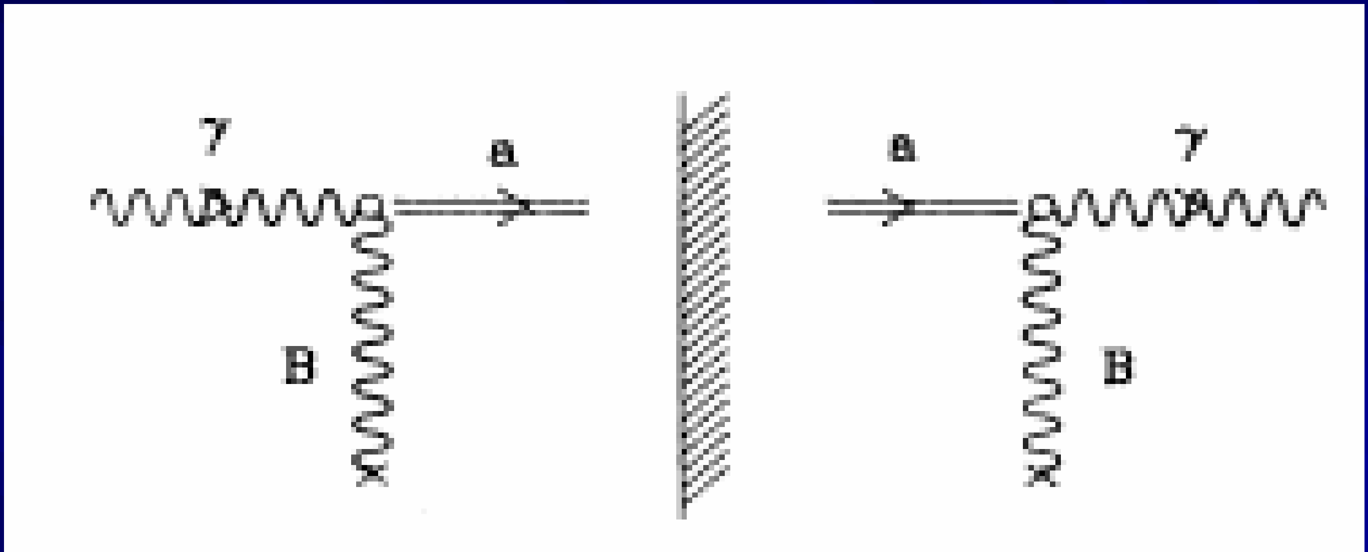


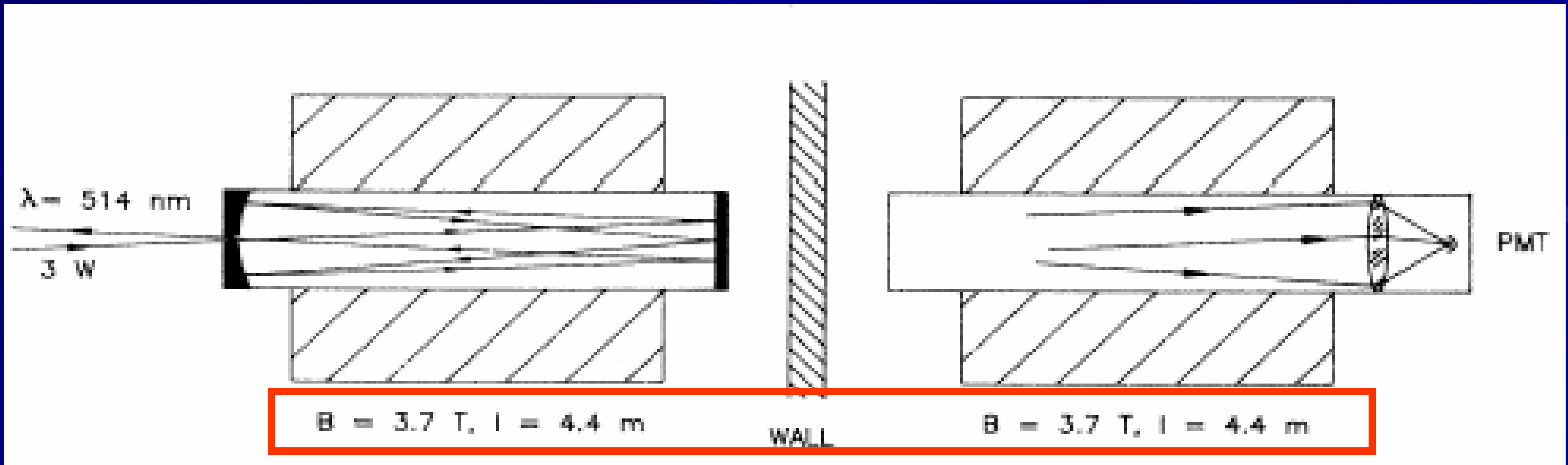
f_{PQ} **must be considerably greater than the weak scale**

sensitive to massive (> eV) axions; none seen

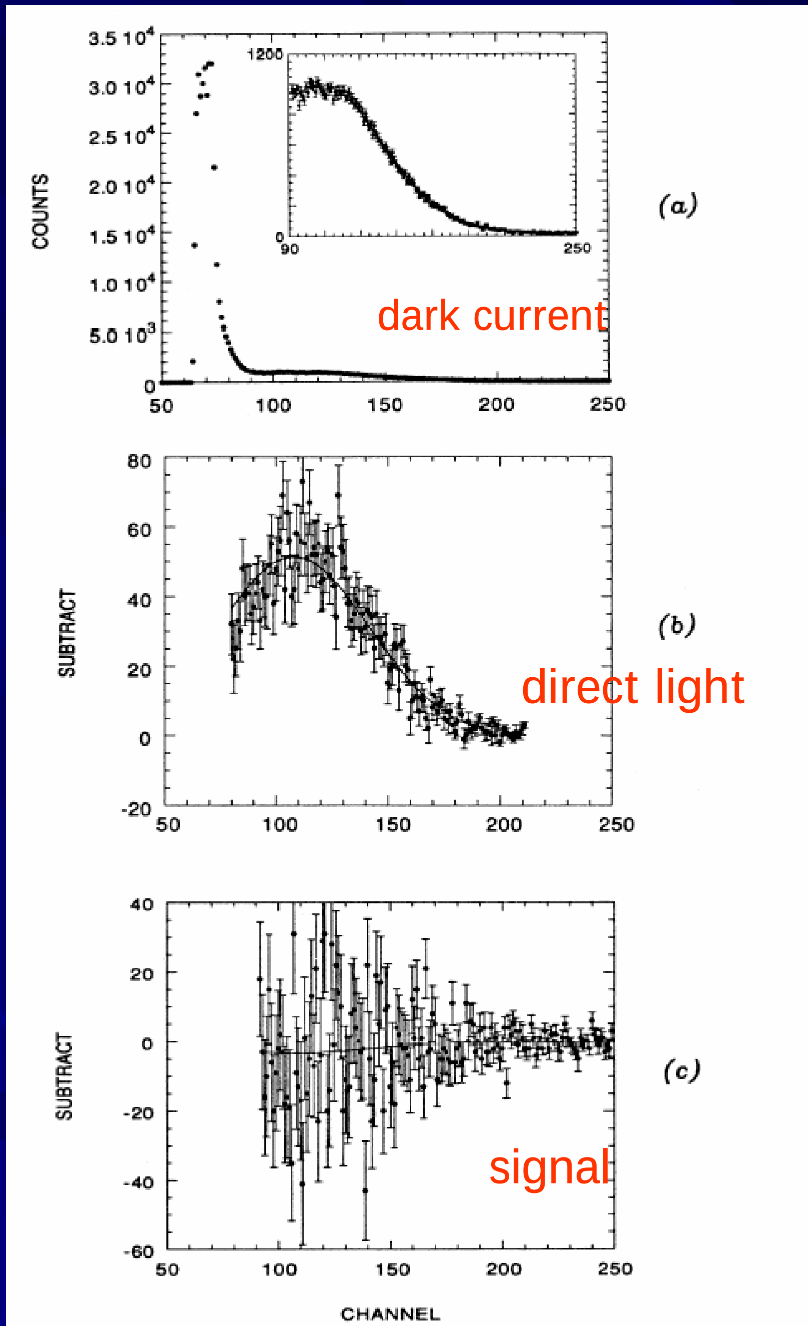
Photon regeneration

(Phys. Rev. D47 3707 (1993 BFRT collaboration)





Phys. Rev. D47 3707 (1993)



BFRT results:
regeneration expt

no ps signal seen

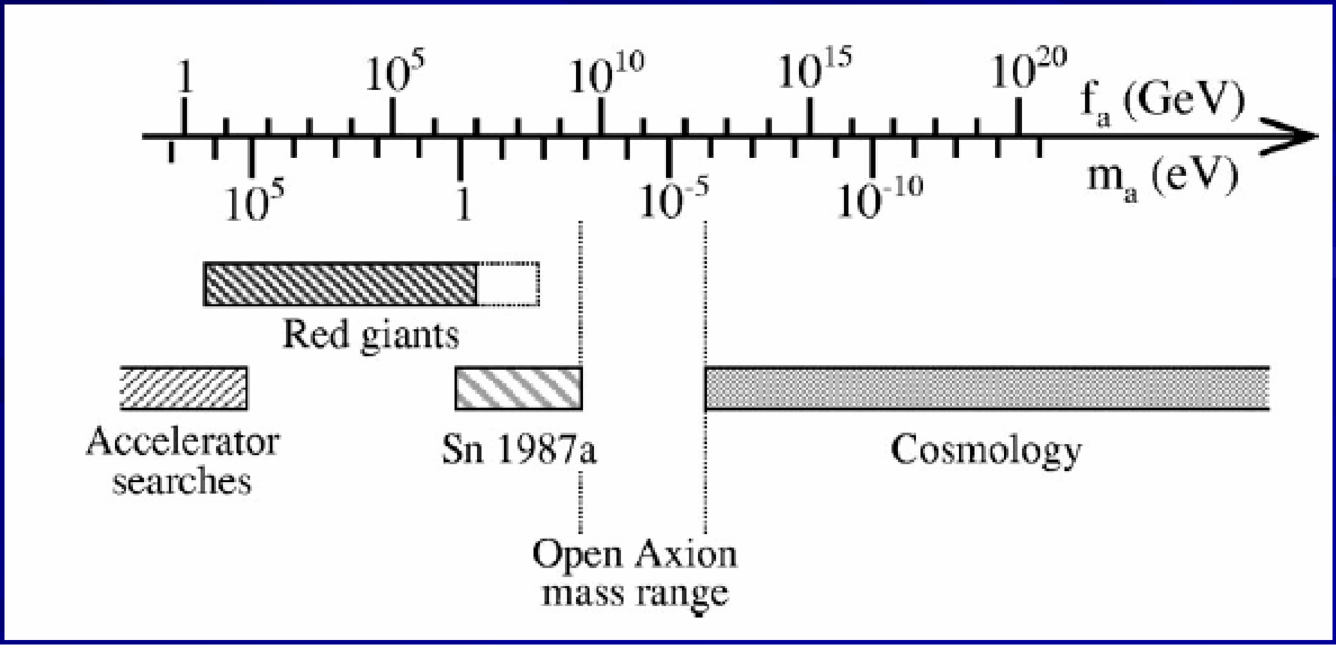
FIG. 18. Integrated charge spectrum. The pedestal is at channel 63 and the single photoelectron peak [see inset in (a)] is fitted by a truncated Gaussian centered at channel 108, with standard deviation of 34 channels. The sensitivity is 0.25 pC/channel. (a) Dark current spectrum including the electronic noise. (b) Subtracted spectrum when light was admitted from the first magnet; used for calibration. (c) Subtracted spectrum when no light was allowed into the second magnet.

searches to date: summary

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

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

- massive axion discovery still solves the strong CP problem, but not the dark matter problem. → search for light axions (< eV)

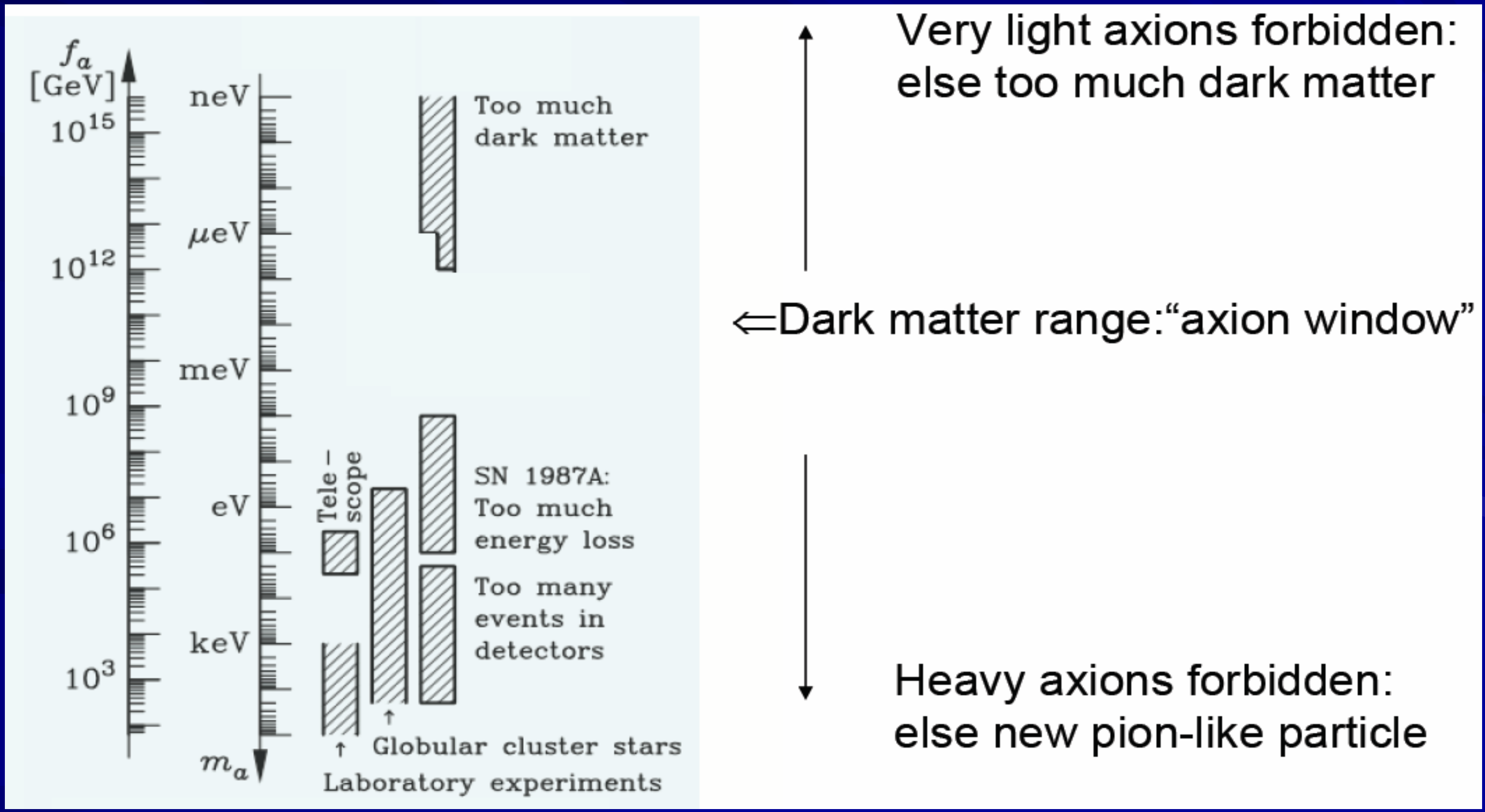


searches to date: summary

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

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

- massive axion discovery still solves the strong CP problem, but not the dark matter problem. → search for light axions (< eV)



searches to date: theoretical issues

- neutron and electron edm conflict?
- no conflict with atomic contribution (E^2).
- higher order (nonlinear) qed effect?
- noncommutative field theory?
- . . .

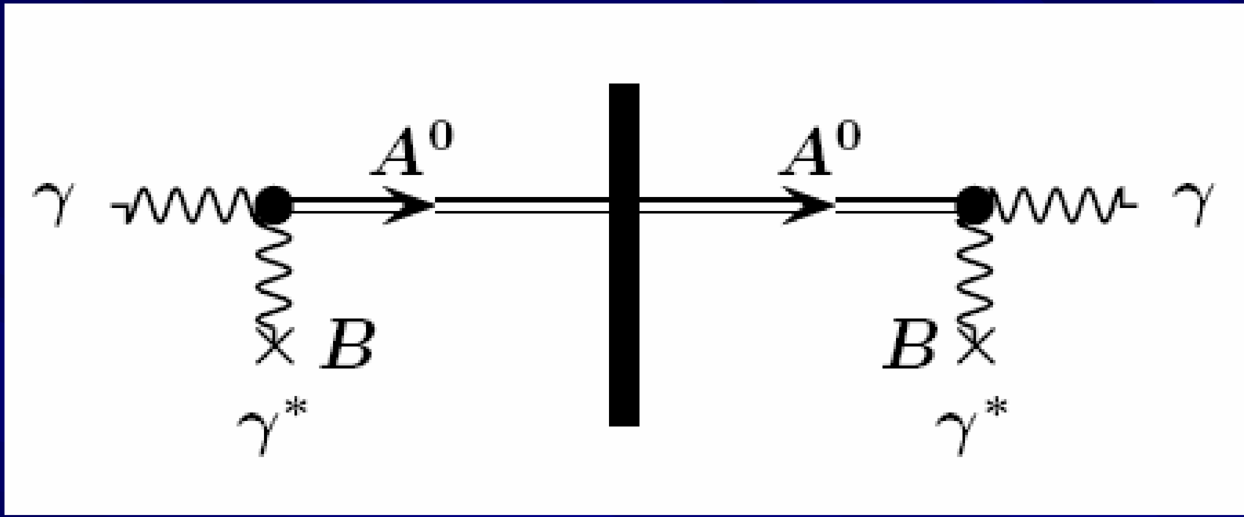
possibilities at JLAB

Light PseudoScalar Particle Search (LIPSS)

possibilities at JLAB FEL

- polarization plane rotation, ellipticity
  - reproduce PVLAS with different apparatus
- regeneration
  - FEL photons regeneration
  - Primakoff photons regeneration
- photon collisions
  - wide angle axion production at wiggler center
  - polarization plane rotation
  - four wave mixing in vacuum
    - $2 \rightarrow 2$ or $3 \rightarrow 1$
- microwave cavity
  - primordial axions
  - solar production and lab regeneration (a la CAST)

‘light shining through a wall’

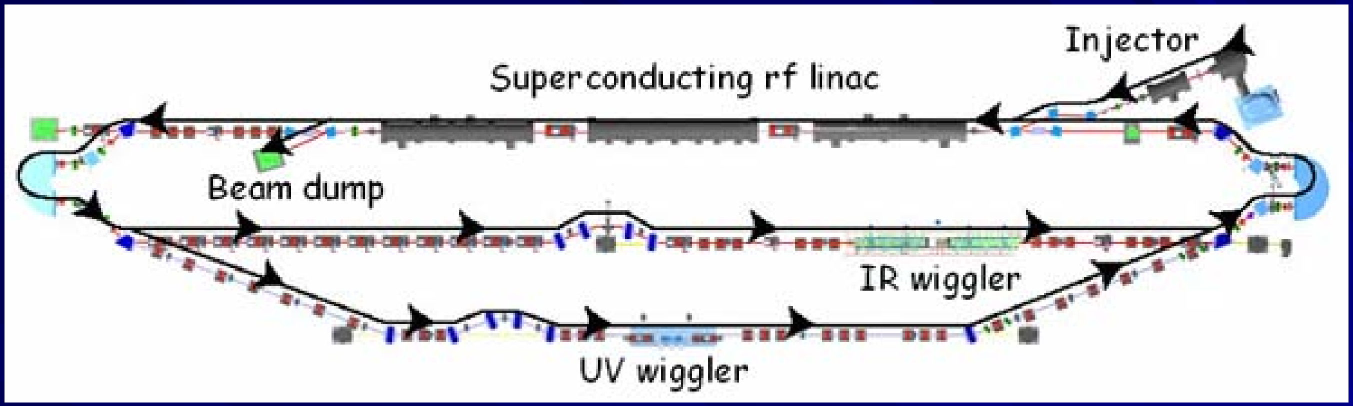


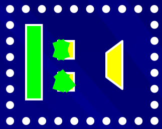
- couple polarized laser light with magnetic field
- Sikivie (1983); Ansel’m (1985); Van Bibber et al (1987)

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

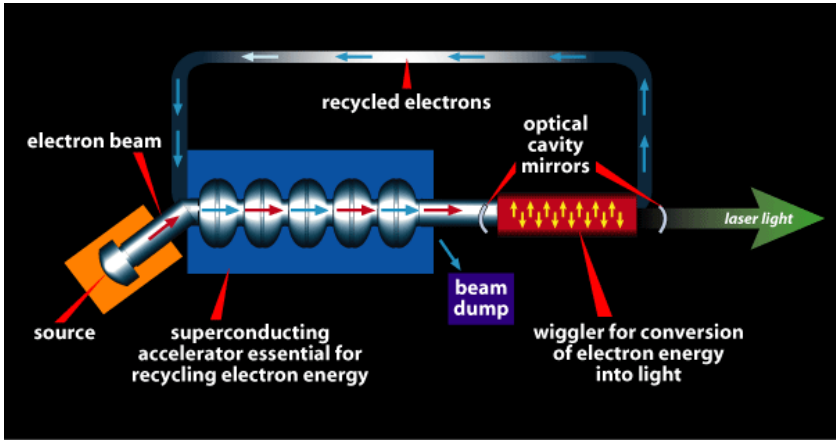
ps – photon (or photon-ps) conversion probability

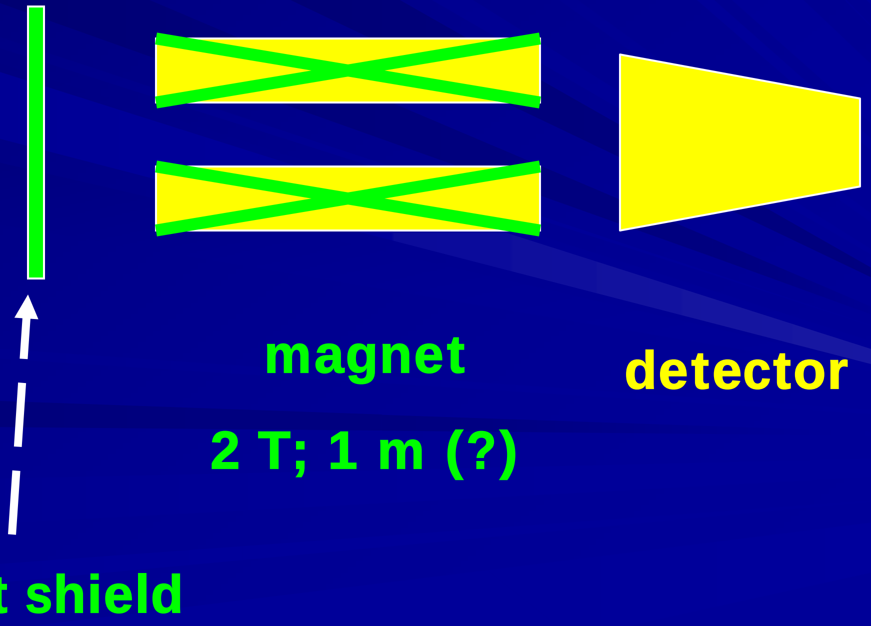
JLAB FEL setup I: regeneration experiment





"parasitic "





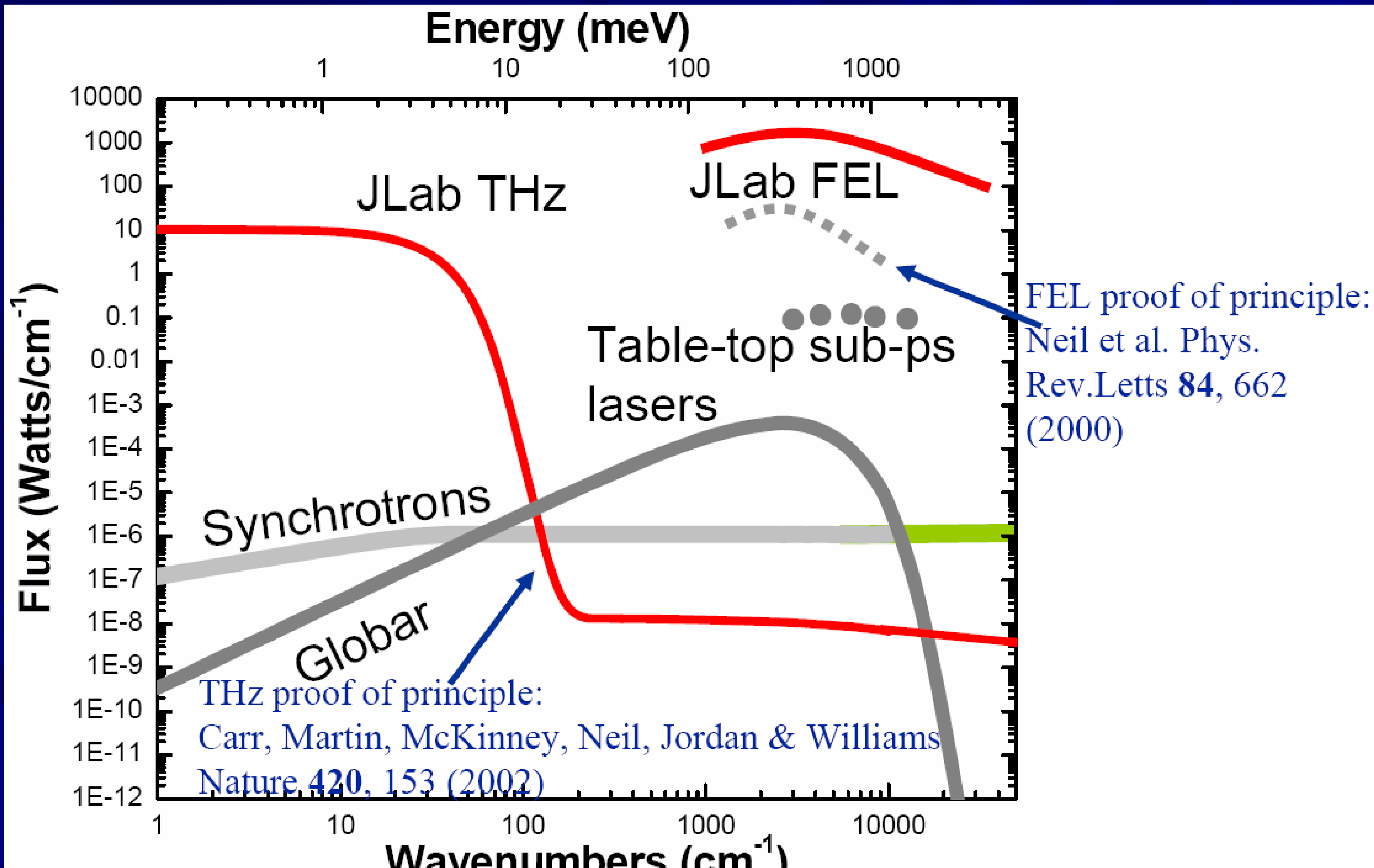
ϕ's produced at JLAB FEL

LIPSS plans

back-of-the-envelope

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

JLAB facility spectroscopic range



experimental requirements

- B-field parallel to photon polarization
- photon-axion coherence

$$m_a^{\ 2} < 4\pi\omega / L$$

- large magnetic field
- shield detector from field; vacuum vessel

rate estimate, as example . . .

$$P = \frac{g^2 B^2 L^2}{4}$$
$$= 10^{-11}$$

axion-photon conversion probability, *P*

$$N = 1.0\,\mathrm{mJ/pulse} \times 75\mathrm{MHz}$$
$$= 6 \times 10^{23}\ \gamma\text{'s}/s$$

JLAB FEL photon rate, *n*

$$Y \sim n \bullet P^2 \bullet \frac{\Delta\Omega}{\Omega} \bullet \varepsilon$$
$$\geq 1\,\mathrm{Hz}$$

photon regeneration rate estimate, *Y*

2 T; 1 m magnet

ε **~ 0.5;** $\Delta\Omega/\Omega$ **~ 0.5**

rates (using current FEL)

B_r (Tesla)	L_r (meters)	g (eV^{-1})	rate (Hz)
1.0	1.0	10^{-15}	.005
1.0	1.0	5×10^{-15}	3.0
1.5	0.8	10^{-15}	.01
1.5	0.8	5×10^{-15}	4.2

uses: dipole magnet at end of straight section: 1.0 m long and 0.31 Tesla

100 kW (1 eV) FEL laser light

q.e. ~ 0.3; detector accep ~ 0.9

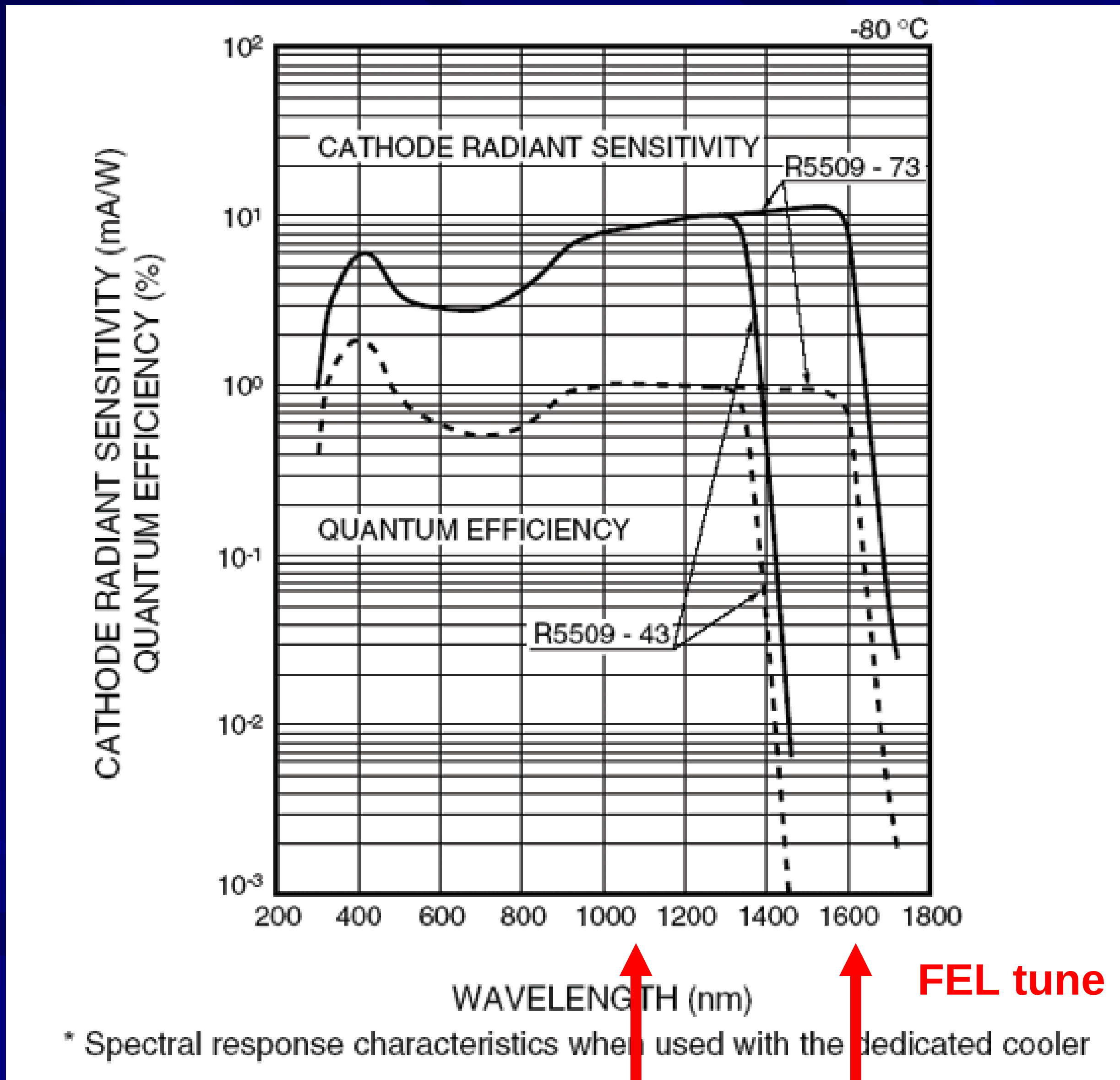
experimental issues

single photon counting in IR

axion-photon coherence

Hamamatsu
R5509 PMT

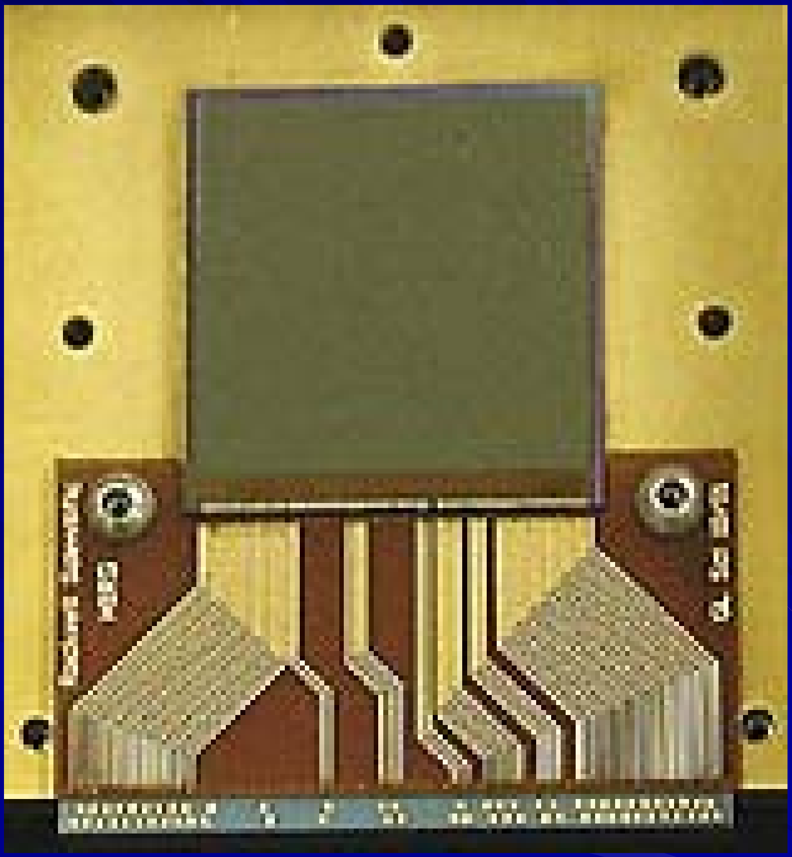
dark current > nA



FEL tune

Rockwell Scientific Hawaii 1RG – for example

FPA Parameter	Rockwell FPAs
Detector technology	MBE HgCdTe or Si PIN
Detector input circuit	SFD
Readout mode	Ripple
Pixel readout rate	100 kHz to 5 MHz (continuously adjustable)
Total pixels	1024 x 1024
Pixel Pitch	18 µm
Fill factor	≥ 98%
Output ports	Signal: 1, 4, 32 selectable Guide Window and Reference
Spectral range	0.3 - 5.3 µm
Operating temperature	≥ 30K
Quantum Efficiency (array mean)	≥ 65%
Charge storage capacity	≥ 100,000 e-
Pixel Operability	≥ 95%
Dark Current (array mean)	≤ 0.1 e-/sec (77K, 2.5 µm)
Read noise (array mean)	≤ 15 e- CDS @ 100 kHz
Power Dissipation	≤ 4 mW @ 100 kHz



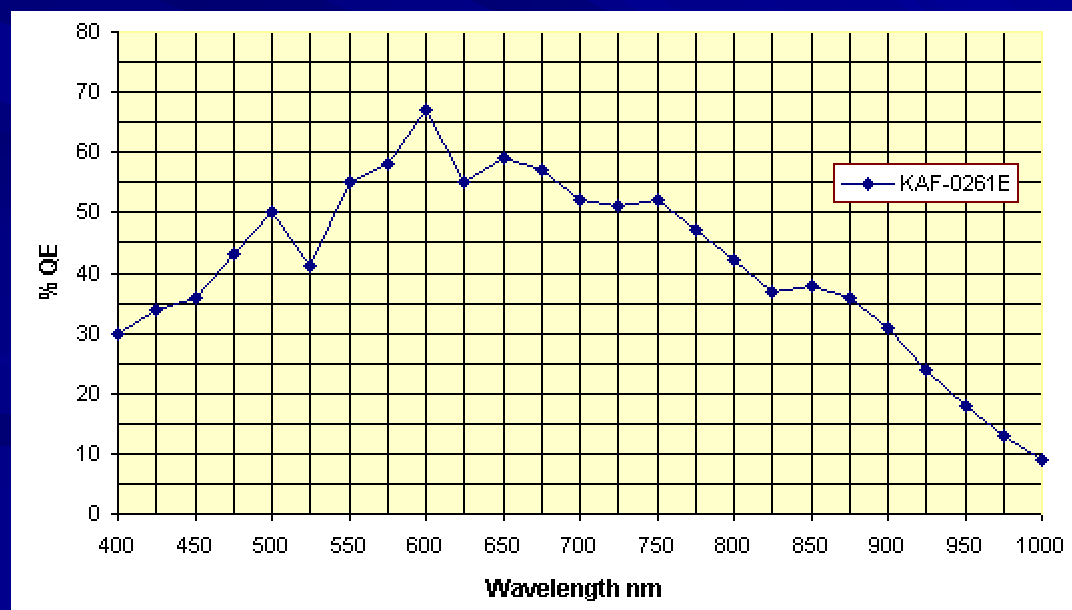
dark current and read noise

quantum efficiency

spectral range

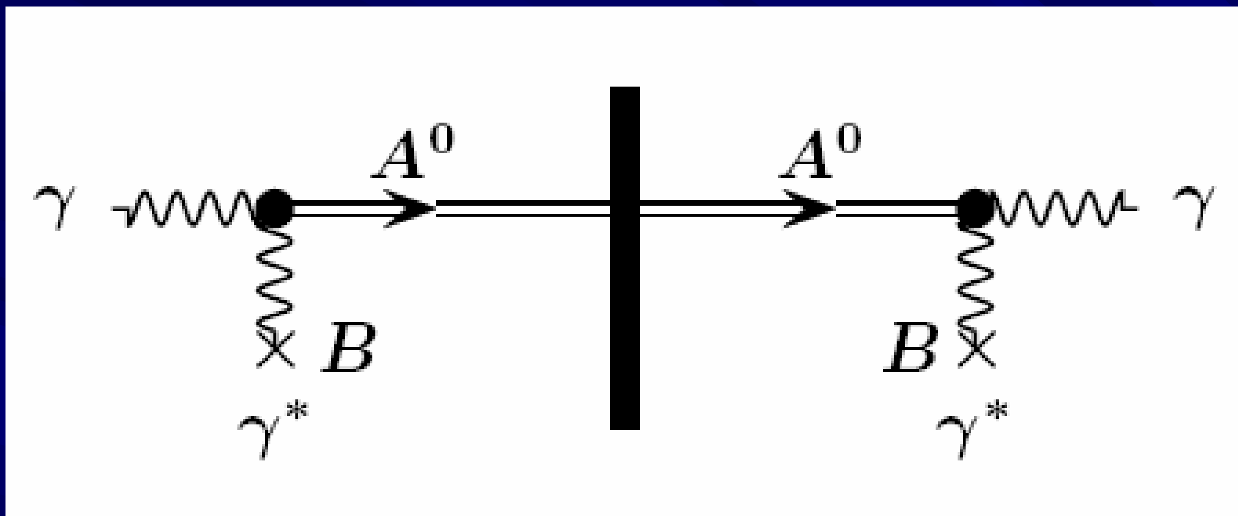
begin with this? (on hand)
SBIG ST-237A

Camera	Pixel Array	Number of Pixels	Pixe l Size	CCD Size mm	CCD Area mm2	Diag FOV 11" Fastar (544mm FL)	Dark Current at 0 C.	Read Noise	Full Well Capacity	Peak QE	Compute r Interface	Full Frame Transfer
ST-402ME	765 x 510	390,000	9u	4.6 x 6.9	32	52 arcmin	1e-/p/s	17e-	100,000 e-	83%	USB 2.0	0.8 sec
ST-237A	657 x 495	325,000	7.4u	3.7 x 4.9	18	38 arcmin	5e-/p/s	15e-	20,000e-	75%	Parallel	15 sec



‘light shining through a wall’

www.desy.de/~ringwald



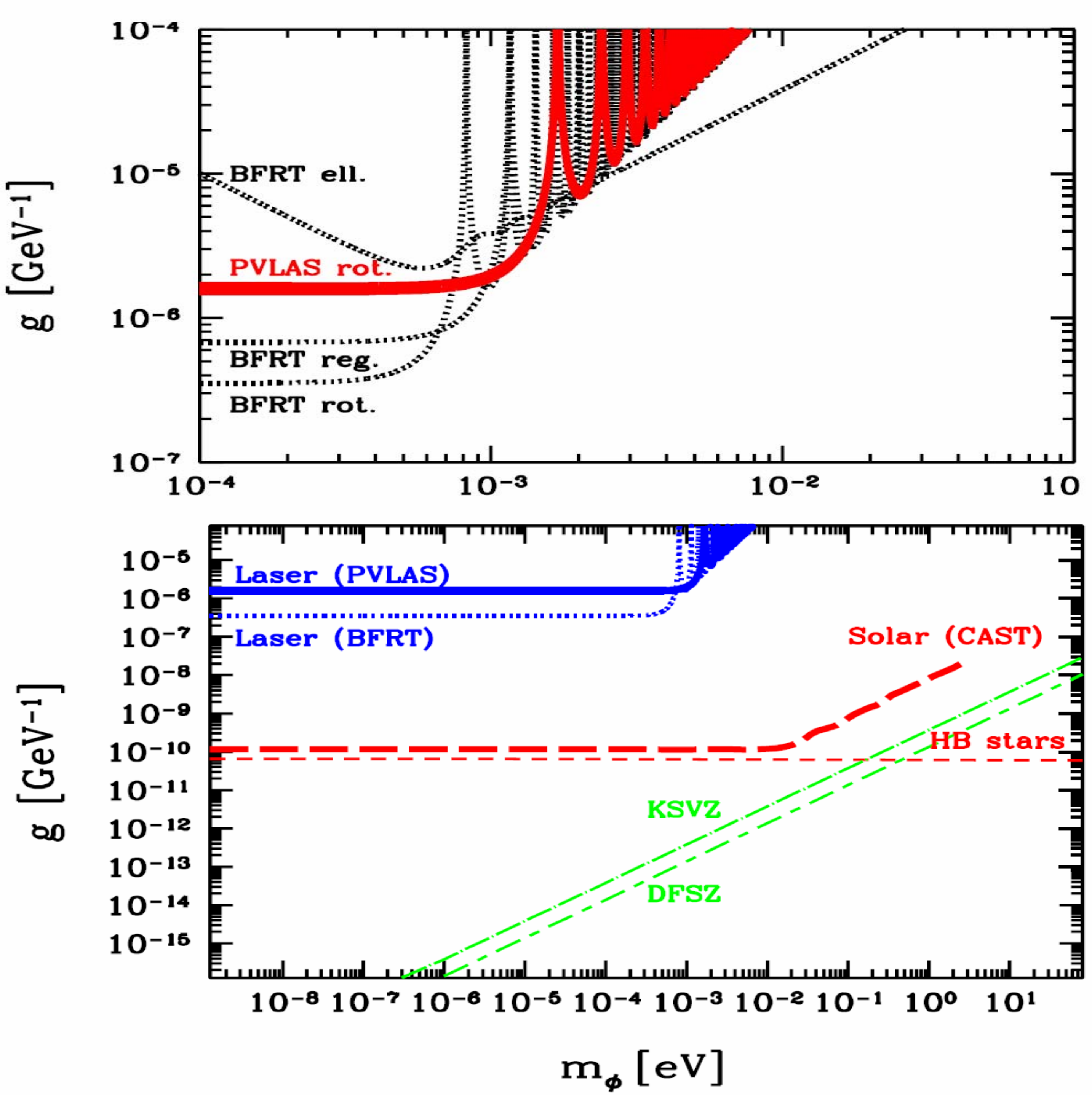
- couple polarized laser light with magnetic field
- Sikivia (1983); Ansel’m (1985); Van Bibber et al (1987)

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

ps – photon (or photon-ps) conversion probability

photon-ps coherence; {} ~ 1

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

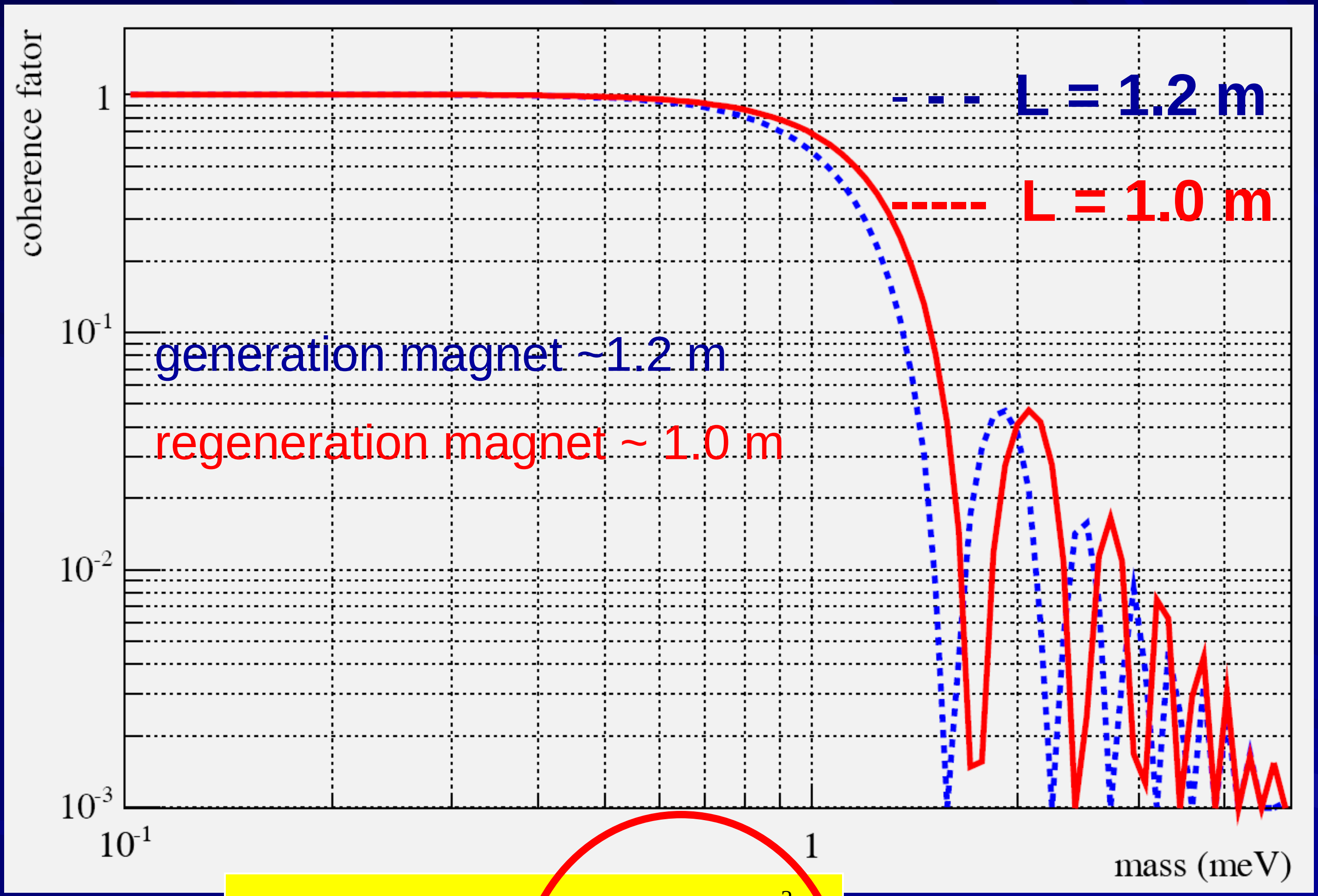


see web site:
www.desy.de/~ringwald

coherence

PVLAS ; BFRT

ps-photon coherence - LIPSS

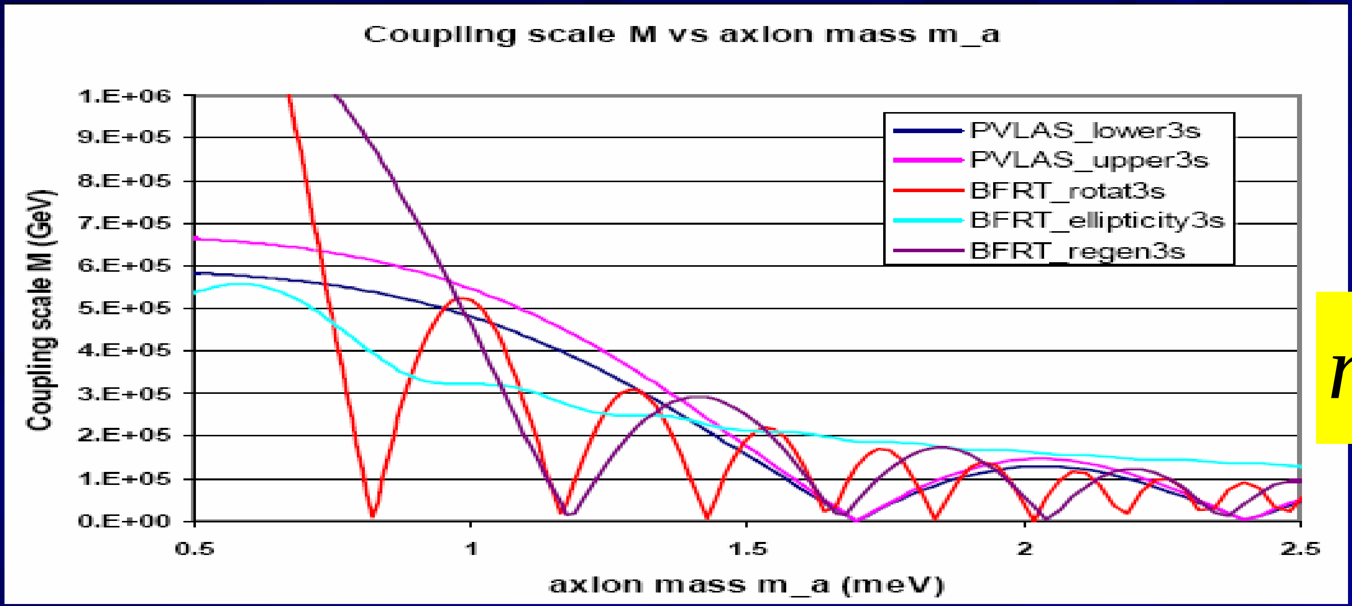


ω = 1.2 eV
(1064 μ)
(same as PVLAS)

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

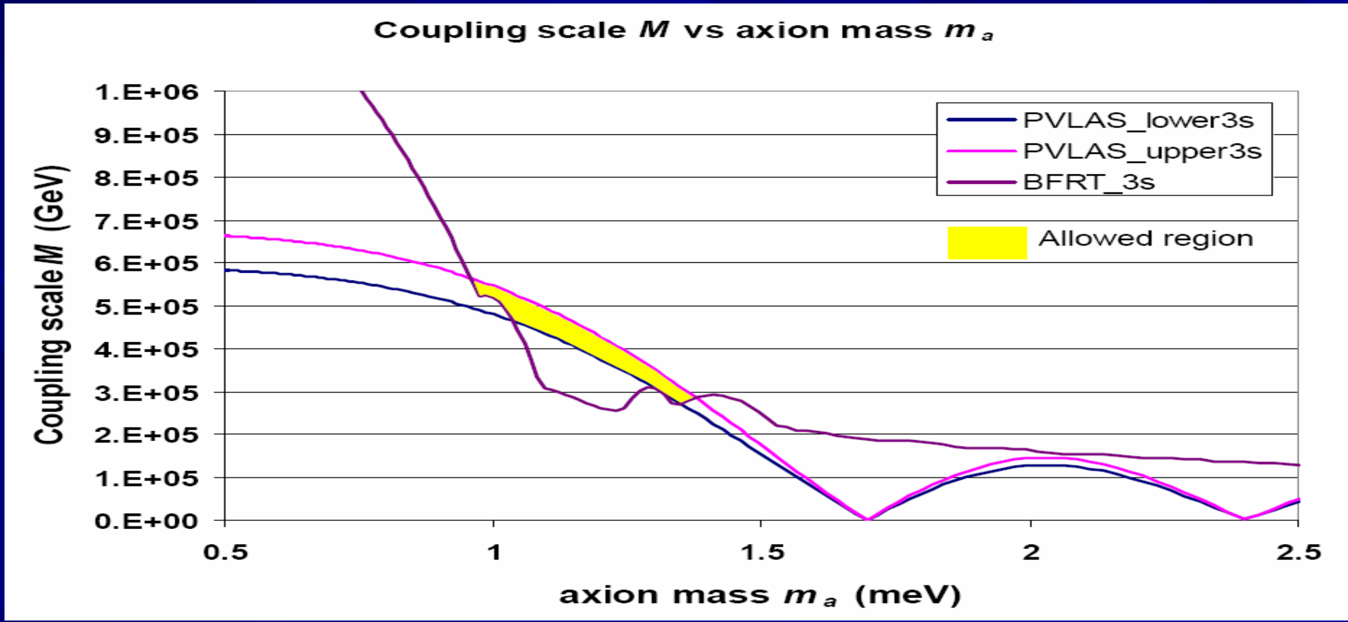
vertical - axis

PVLAS and BFRT: photon-axion coherence



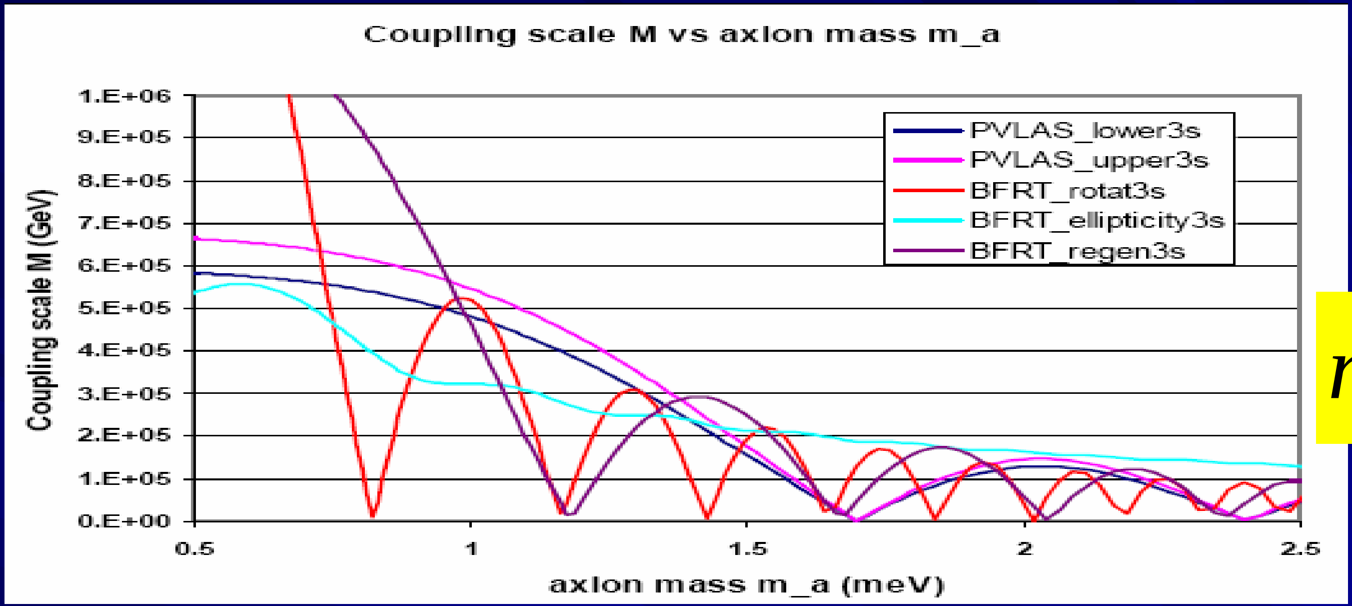
plots from K. McFarlane

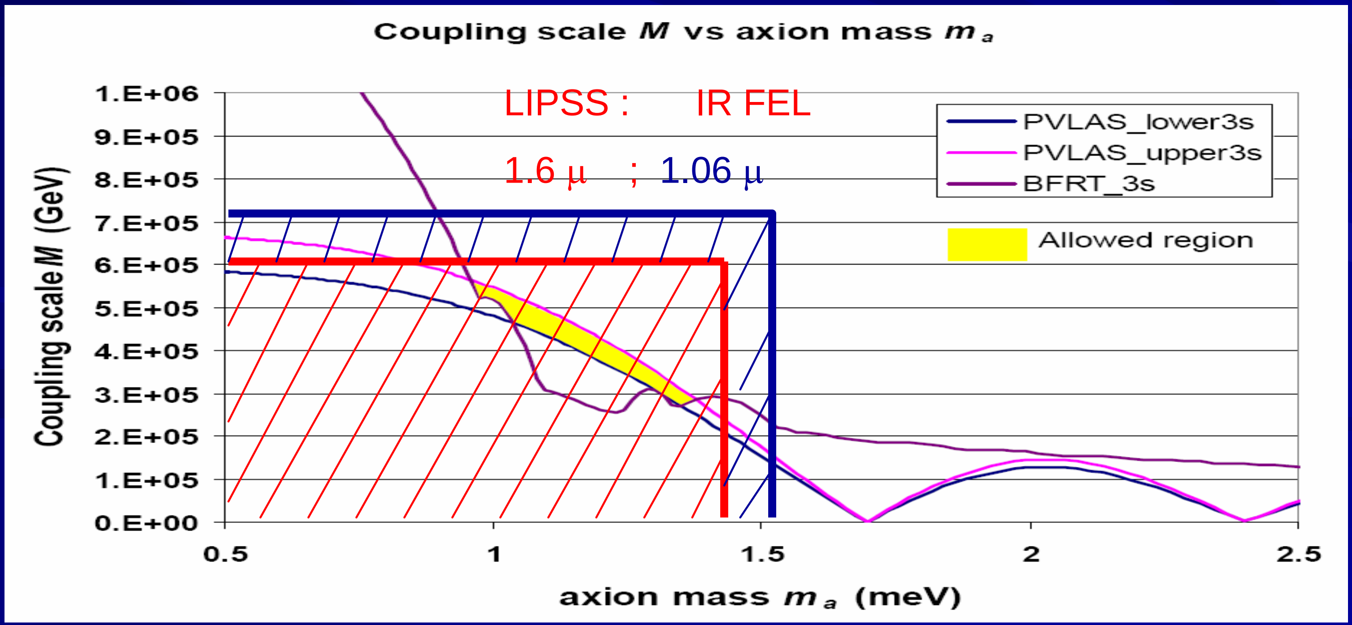
$$m_a^{\ 2} < 2\pi\omega / L$$



magnet length a limitation in BFRT

PVLAS and BFRT: photon-axion coherence





plots from K. McFarlane

$$m_a^{\ 2} < 4\pi\omega / L$$

magnet length a limitation in BFRT

uncertainty relation – ultralow count rates

Heitler (1954); Rev. Mod. Phys 75, 777 (2003)

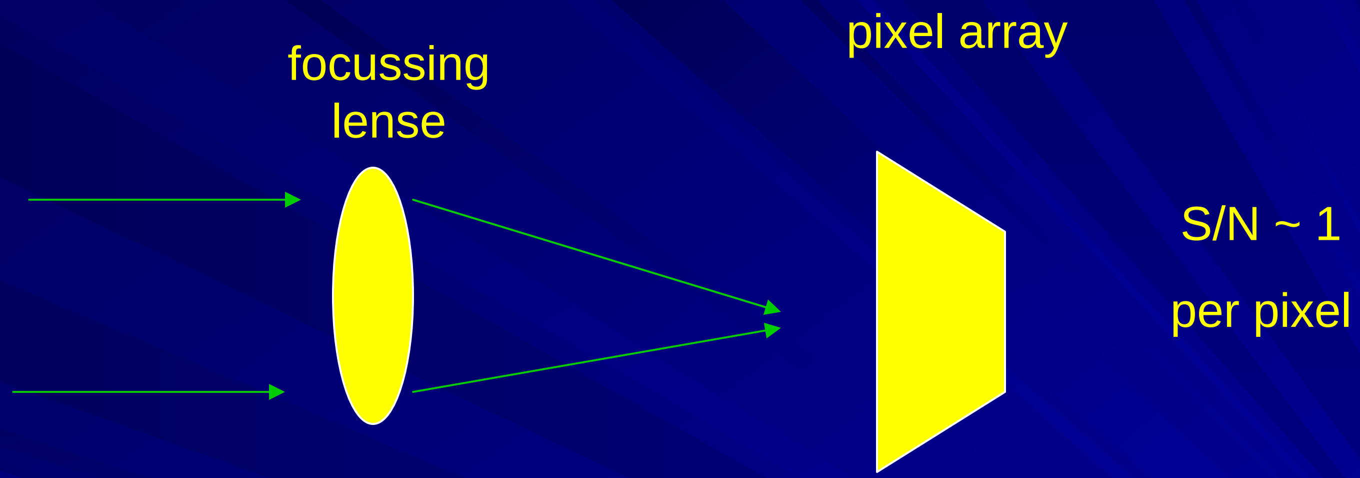
- QM uncertainty relation
  - $\Delta n \Delta \phi > 1$
    - n number of quanta detected
    - ϕ phase of detected radiation
- limit on the measurement precision of the number of quanta n in a wave, and the phase of the radiation ϕ.

ideas . . .

- use focussing lens at end of regeneration magnet
  - focus on small pixel area → better S/N
- use new rf structure in upstairs lab with two powerful magnets
  - purchase 2 ea ~ 0.5 m long, ~ 2 T magnets
- use B field of electron beam
  - can get ~100 T close to electron beam
  - probably too small an effect
- . . .

ideas

1



GW magnets

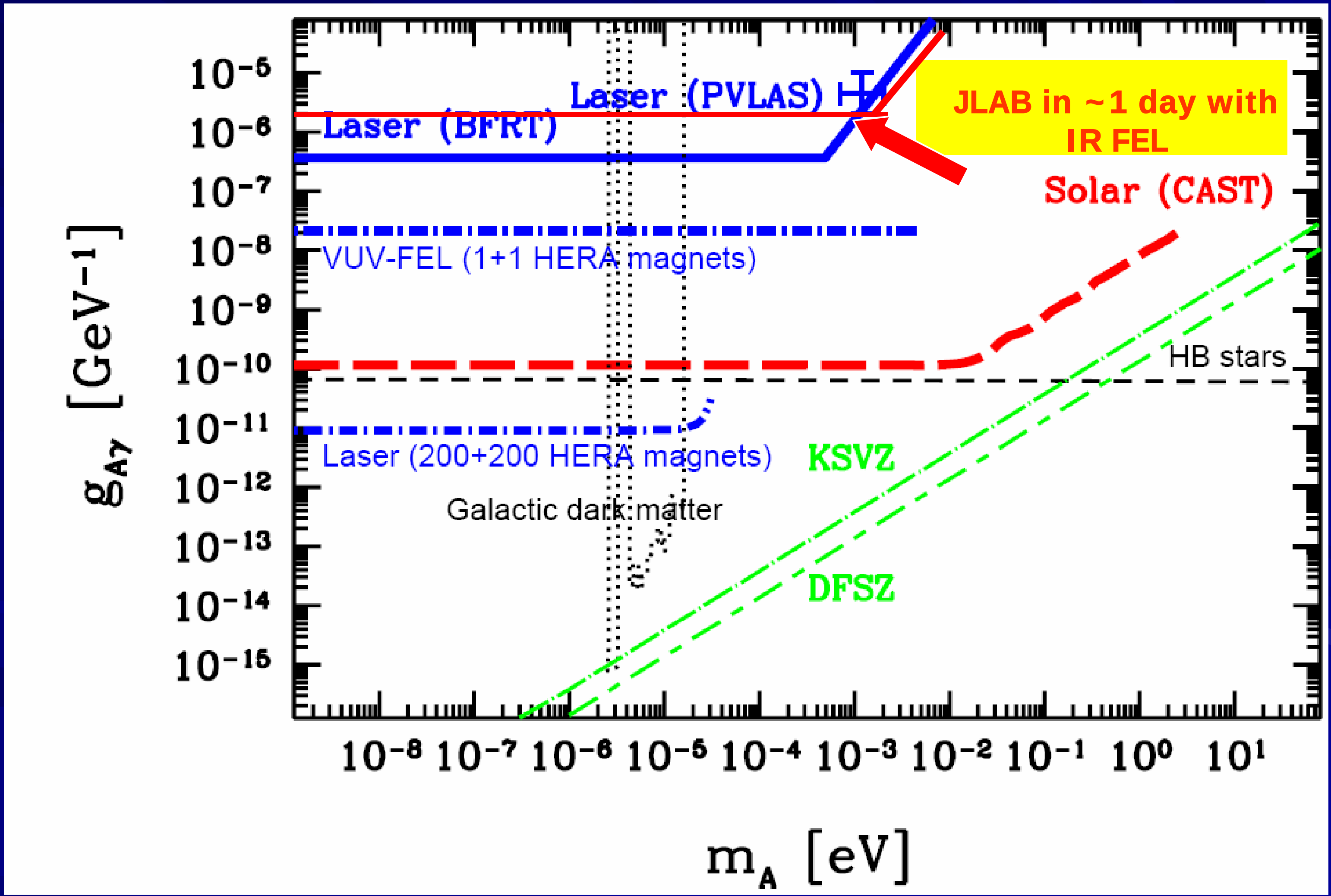
gap: 7.9 cm
magnetic length: 0.42 m
design field intergral: 5.92 KGauss.
current 223.24 A

have 4 extra magnets and their stands in Magnet Test and 2 mounted to stands in the FEL UV Line.

a rarely used power supply for the 2G dump spectrometer is available in the FEL for quick response at slightly lower max current. 220 A maximum.

max field at 0.8 Tesla → 1.5 Tesla with shims
the GWs are 0.6 or so meters long

with current setup, IR light . . .

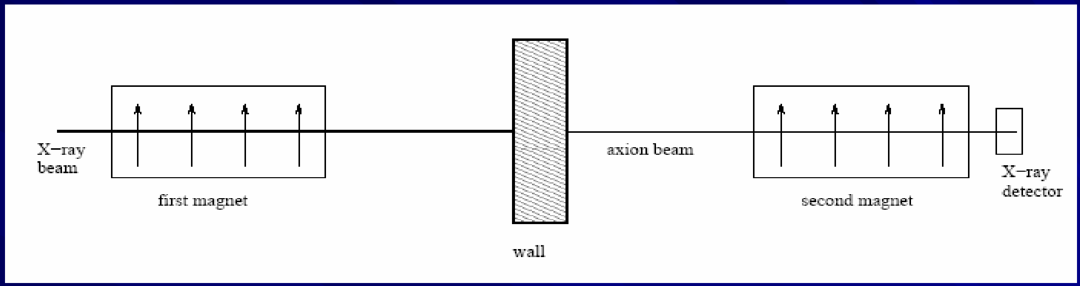


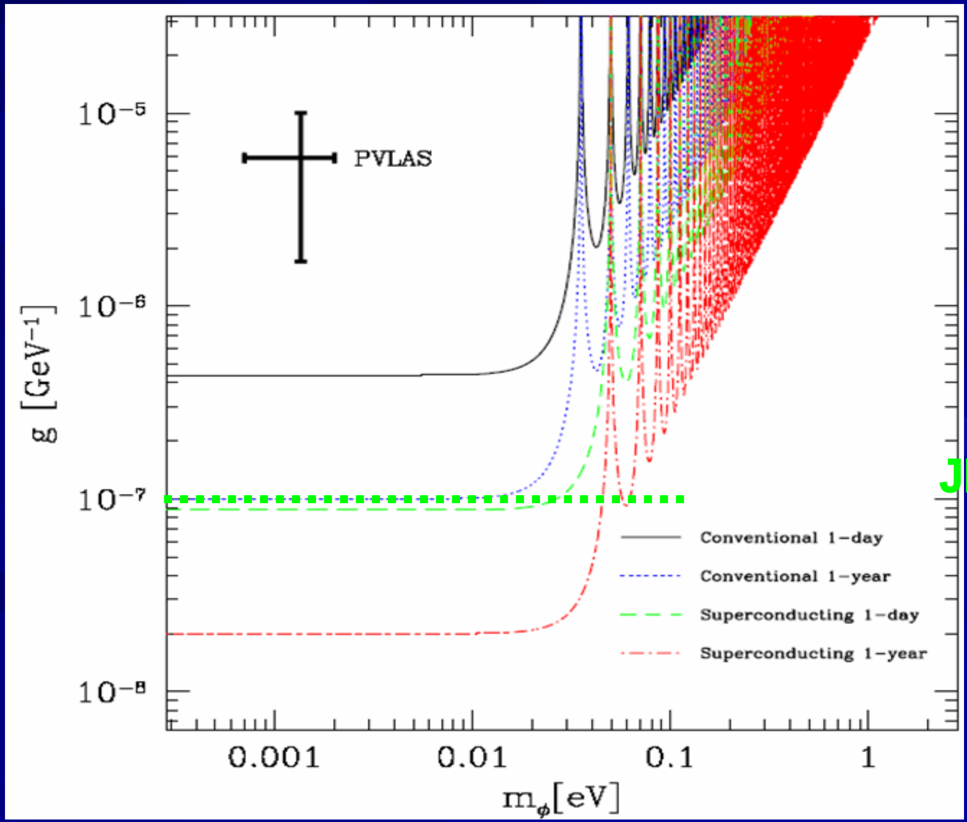
UV FEL – the way to go!!

- visible and UV light → use phototube
  - fast (can time relative to rf structure of beam)
    - reduce noise
  - good quantum efficiency
  - experience
- can use longer magnets
  - axion-photon coherence
  - probability ~ L^2
- more space on vault floor

photon regeneration from pseudoscalars at x-ray lasers

Rabadan, Ringwald, Sigurdson hep-ph/0511103



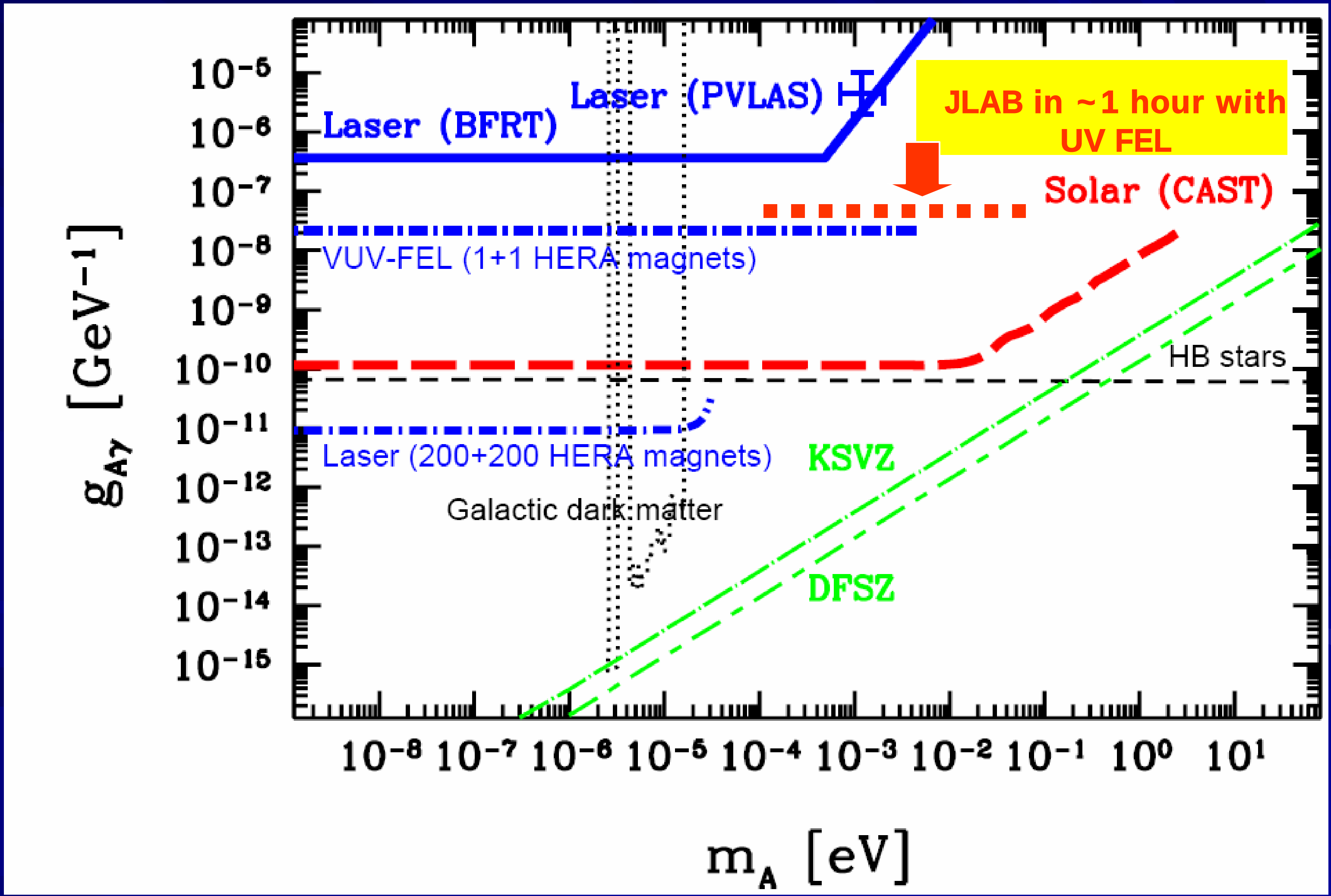


JLAB in ~1 hour with UV FEL

axion interpretation?

A. Ringwald; hep-ph/0511184

K. Zioutas et.al., PRL 94, 121301 (2005)



initial ‘engineering’ run

- 100 kW IR FEL
  - 1.06 μ and 1.64 μ IR light
- 2 GW magnets for regeneration
  - 1.5 T, 1.0 meter long, acceptance ~ 0.8
- SBIG Astronomical Instruments ST-237A CCD camera
  - ~10% q.e., low dark current (cps), on hand
- begin within next couple of months (?)

how we got to this point

- A. Afanasev alerted okb > 2 years ago of importance of measurement
- okb made initial approaches to FEL people (Boyce, Shinn, etc), axion experts (Rosenberg); very low level
- initial meetings began at Hampton ~ year ago; VFWM discussed; HU laser experiment discussed.
- PVLAS result: Afanasev again emphasized importance of measurement. K. McFarlane and other HU particle experimentalists joined discussions
- initial meeting of interested Hampton and JLAB scientists (Williams, Boyce, etc); more serious now
- series of meetings at JLAB; talks at TAWG and JLAB

initial meetings participants

- A. Afanasev – particle/nuclear theorist
- G. Biallas – FEL experimentalist
- J. Boyce – FEL experimentalist
- O.K. Baker – particle/nuclear experimentalist
- H. Brown – graduate student
- S. Ma – graduate student
- K. McFarlane – particle experimentalist
- J.T. Seo – optics experimentalist
- T. Shin – particle experimentalist
- S. Shukui – FEL experimentalist
- V. Vassilakopoulos – particle experimentalist
- G. Williams – optics experimentalist
- Q. Yiang – optics experimentalist

summary

- axion search not just a shot in the dark now!!
  - PVLAS result can be tested; new data point from LIPSS
- can perform regeneration experiment to test PVLAS result at JLAB FEL
  - can reach interesting region of parameter space with IR FEL
  - can perform definitive experiment with UV FEL
- this is particle physics at the FEL
  - constraints on a new mass scale in particle physics
    - PeV scale!!