Axion Astronomy: Prospects of Searching for Axions by Astronomical and Experimental Methods.

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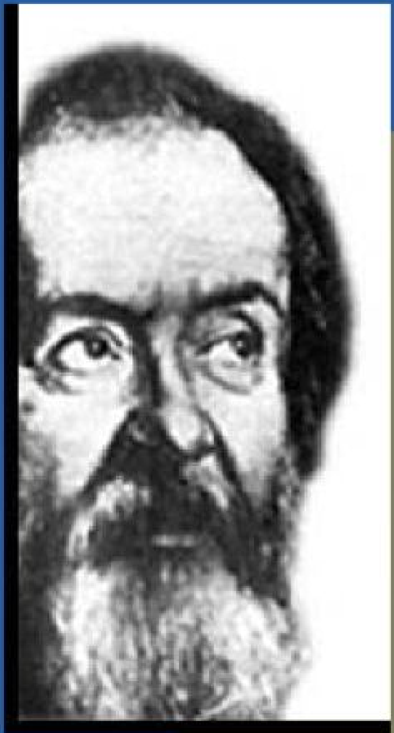
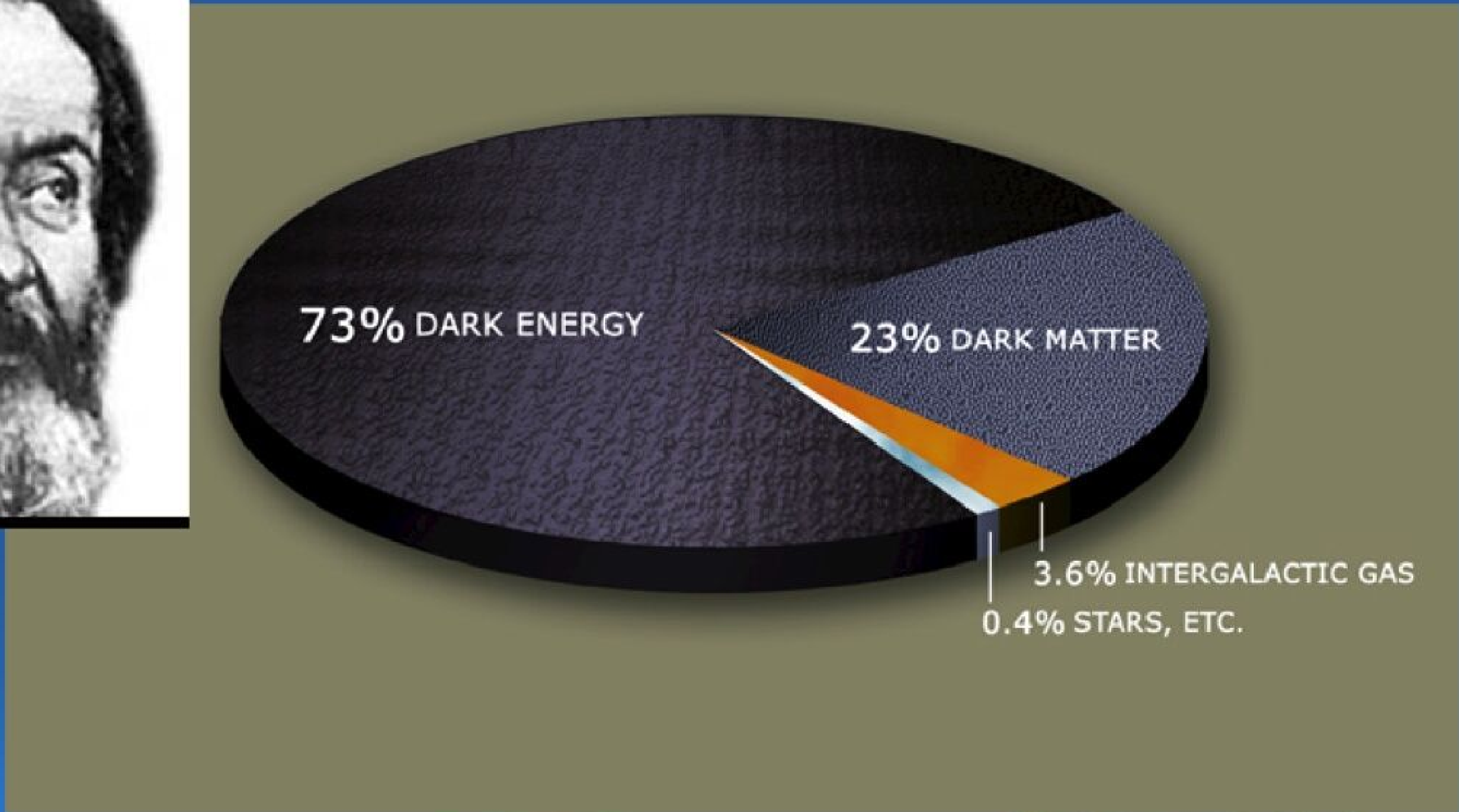
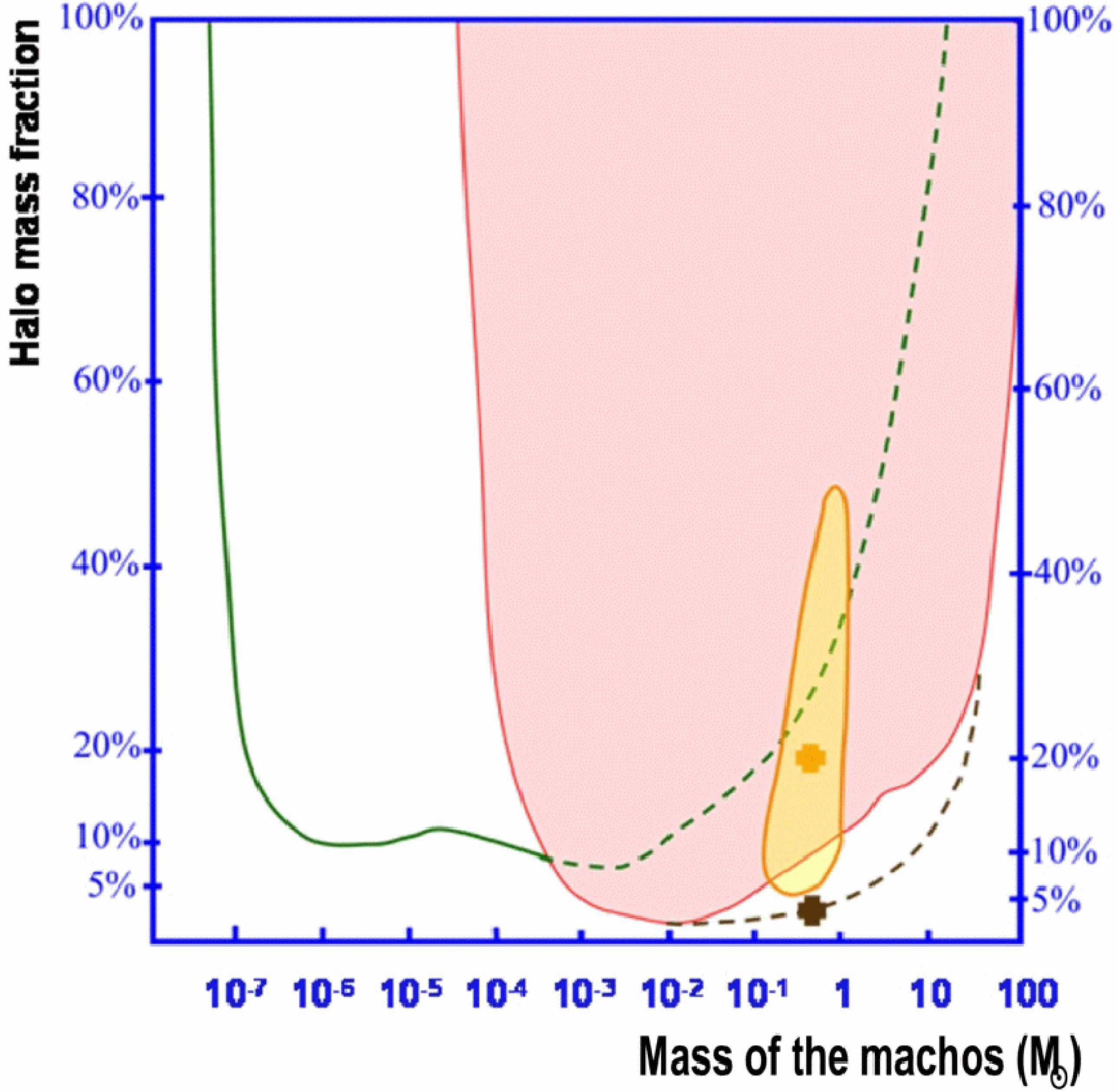
The Cosmic Mystery-Pie





'The constitution of the universe may be set in first place among all natural things that can be known'
Galileo Galilei, *Dialogue*



Halo mass fraction
100%
80%
60%
40%
20%
10%
5%
100%
80%
60%
40%
20%
10%
5%
10-7 10-6 10-5 10-4 10-3 10-2 10-1 1 10 100
Mass of the machos (M☉)

Axion Properties

The Peccei-Quinn (1977) solution to the **strong CP problem** gives us the **axion** (Weinberg, 1978; Wilczek, 1978).

New parameter: f_a, the Peccei-Quinn (PQ) symmetry breaking scale.

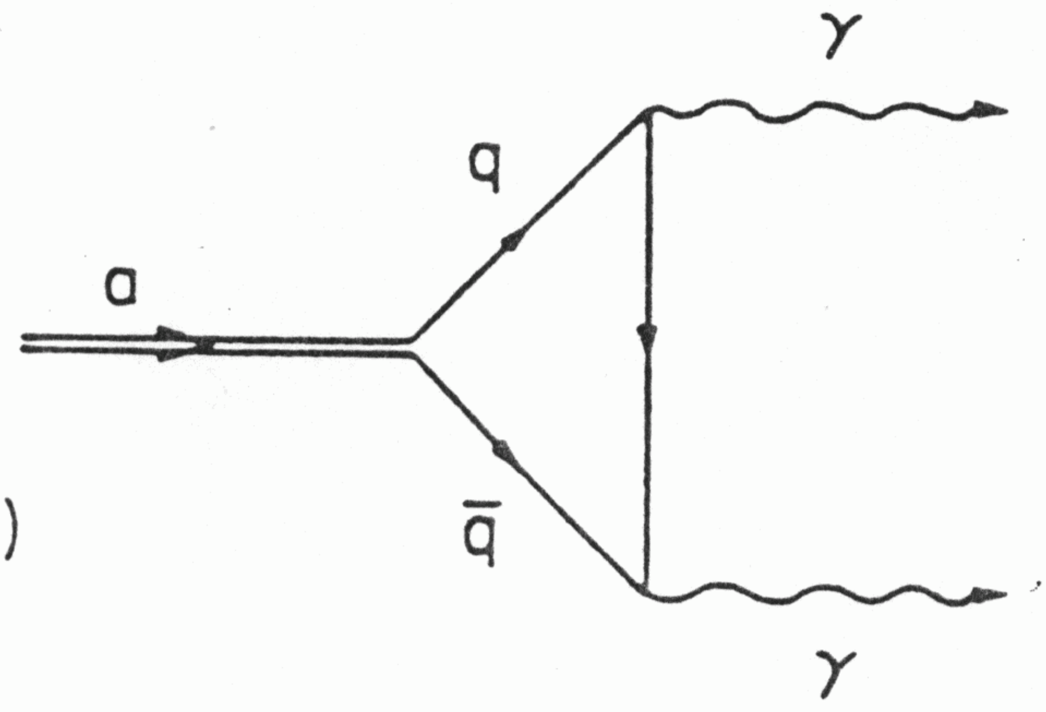
Small mass

$$m_a = 6\,\mu\mathrm{eV}\left(\frac{10^{12}\,\mathrm{GeV}}{f_a}\right) \quad (1)$$

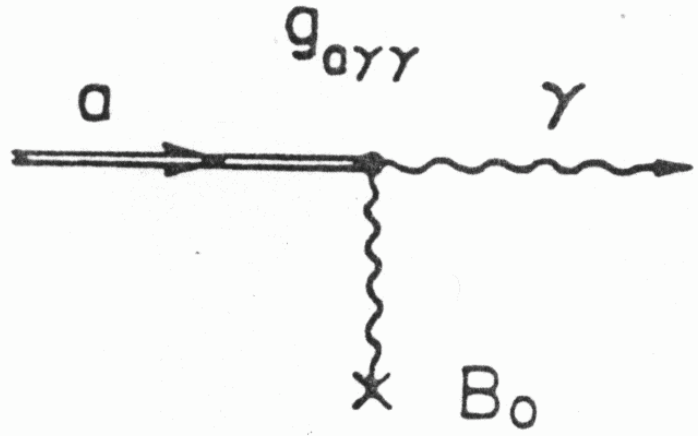
$$m_a \sim 10^{-6} - 10^{-2}\ \text{eV}$$

$$\implies f_a \sim 10^{9} - 10^{13}\ \text{GeV}$$

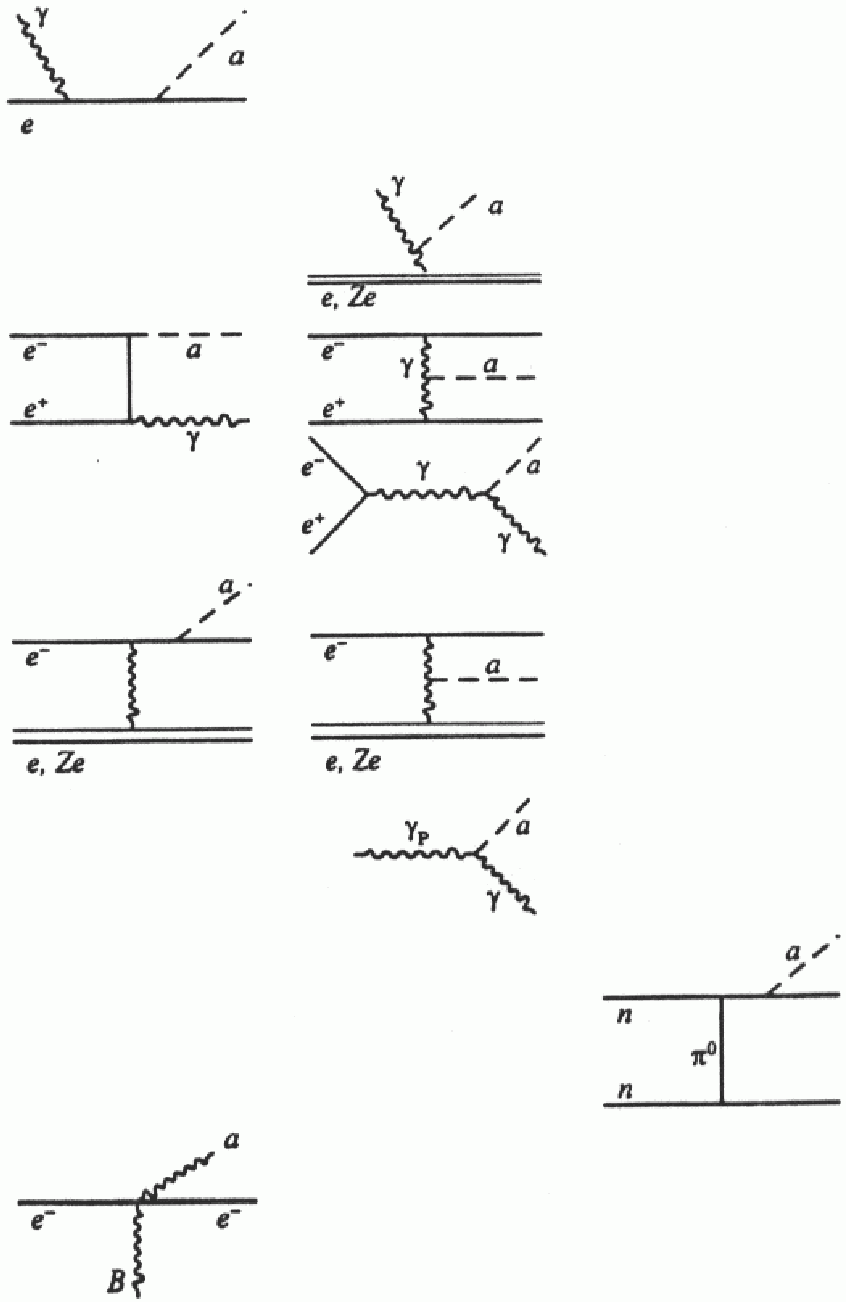
The parameter space is bounded - we know where to look!



(a)

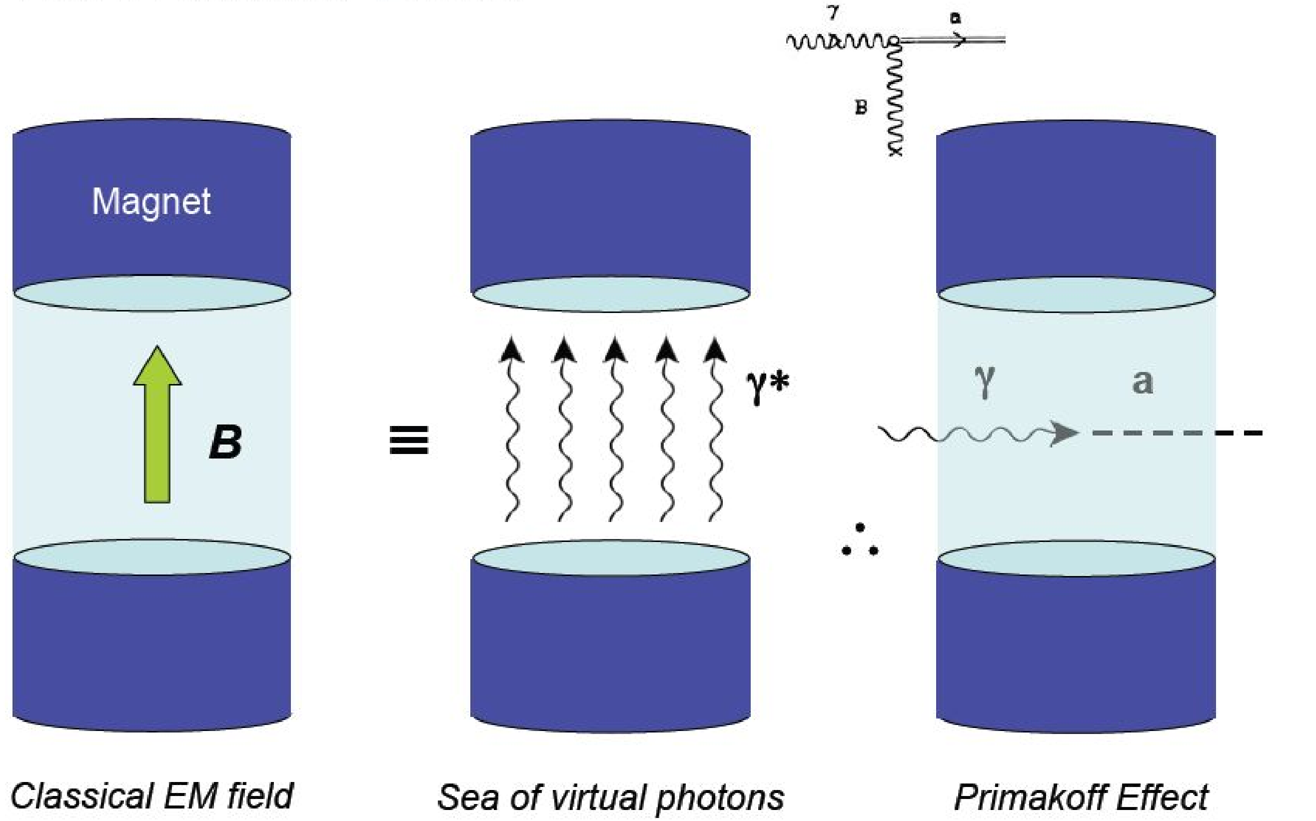


(b)



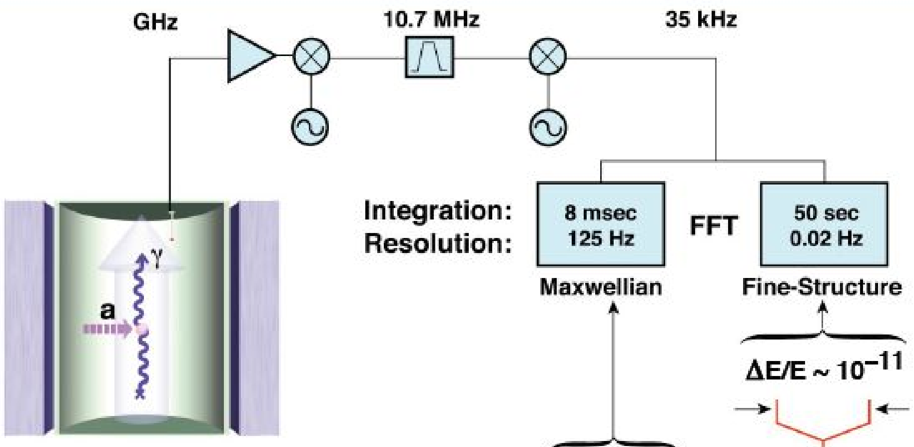
γ
a
e
γ
a
e, Ze
e⁻
a
e⁺
γ
e⁻
γ
a
e⁺
e⁻
γ
a
e⁺
γ
a
e⁻
e, Ze
e⁻
a
e, Ze
γP
a
γ
a
n
π0
n
a
e⁻
e⁻
B

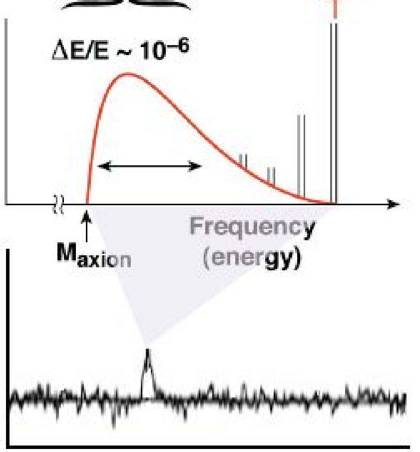
The Primakoff Effect



AXION

Nature of axionic dark matter, and principle of the microwave cavity experiment *[Pierre Sikivie, PRL 51, 1415 (1983)]*





Resonance condition:

$h\nu = m_a c^2 [\, 1 + O(\beta^2 \sim 10^{-6})\,]$

Signal power:

$P \propto (B^2 V Q_{cav})(g^2 m_a \rho_a)$

$\sim 10^{-23} W$

Local Milky Way density:

$\rho_{halo} \sim 450\ MeV/cm^3$

Thus for $m_a \sim 10\ \mu eV$:

$\rho_{halo} \sim 10^{14}\ cm^{-3}$

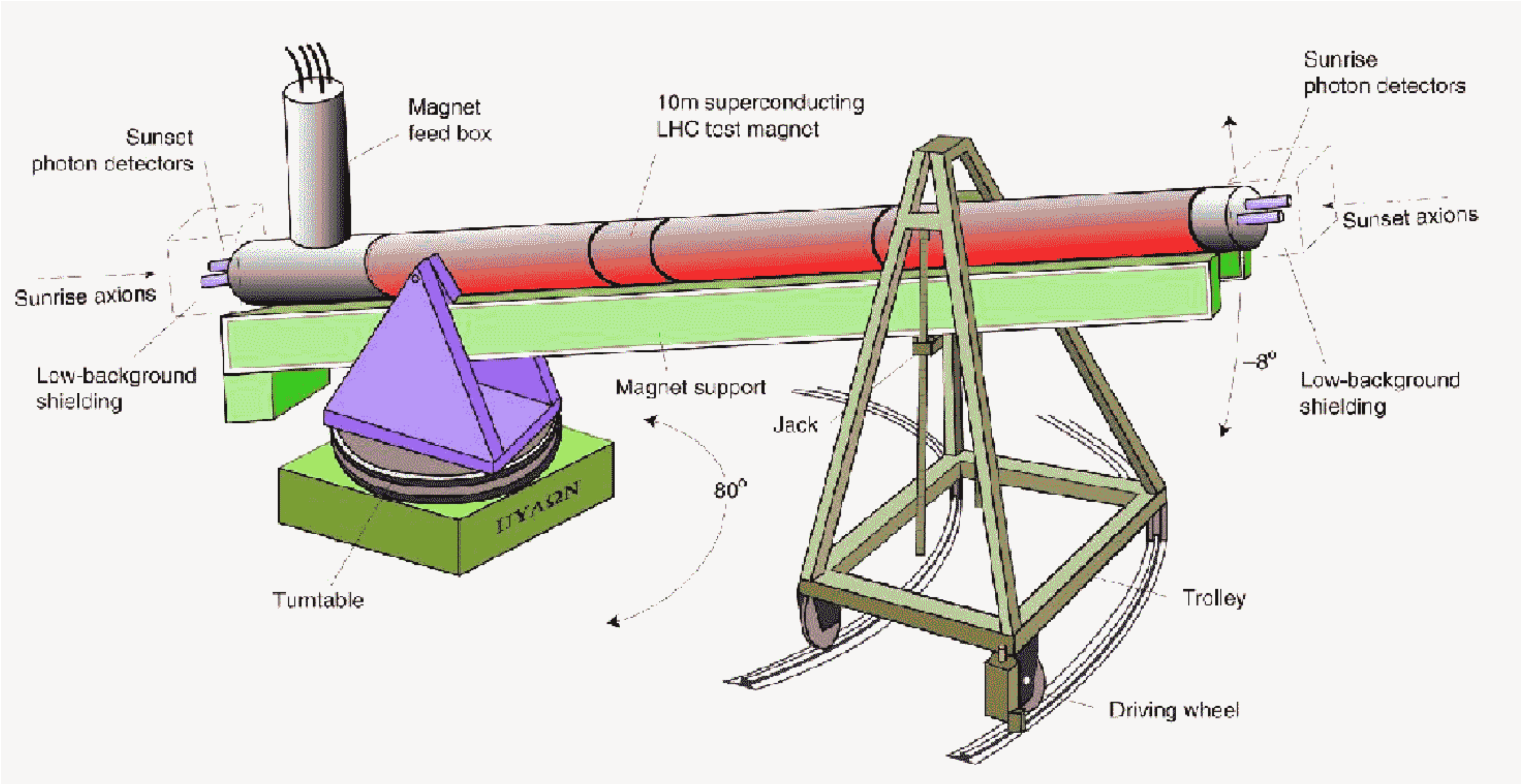
$\beta_{virial} \sim 10^{-3}$:

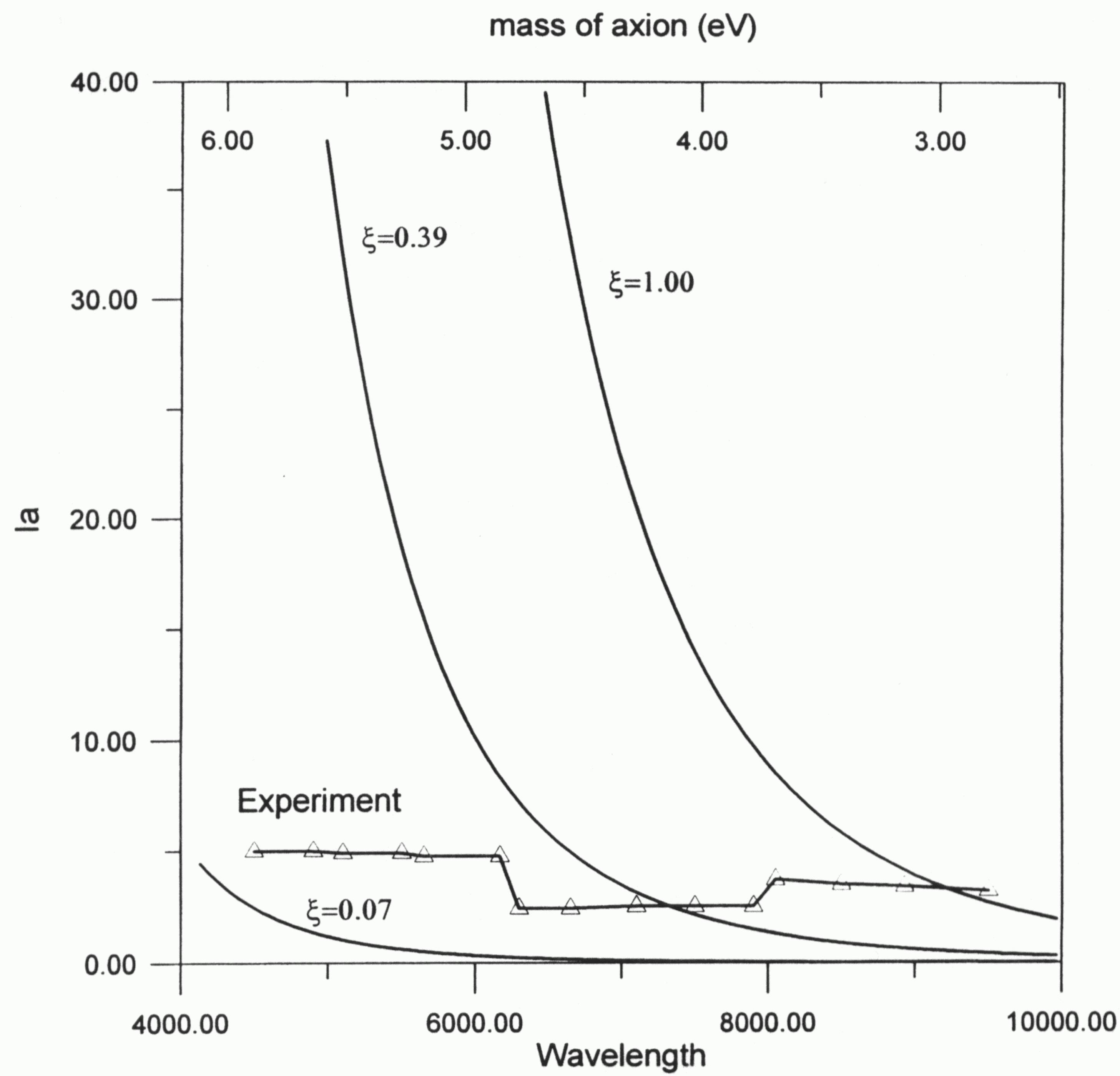
$\lambda_{De\ Broglie} \sim 100\ m$

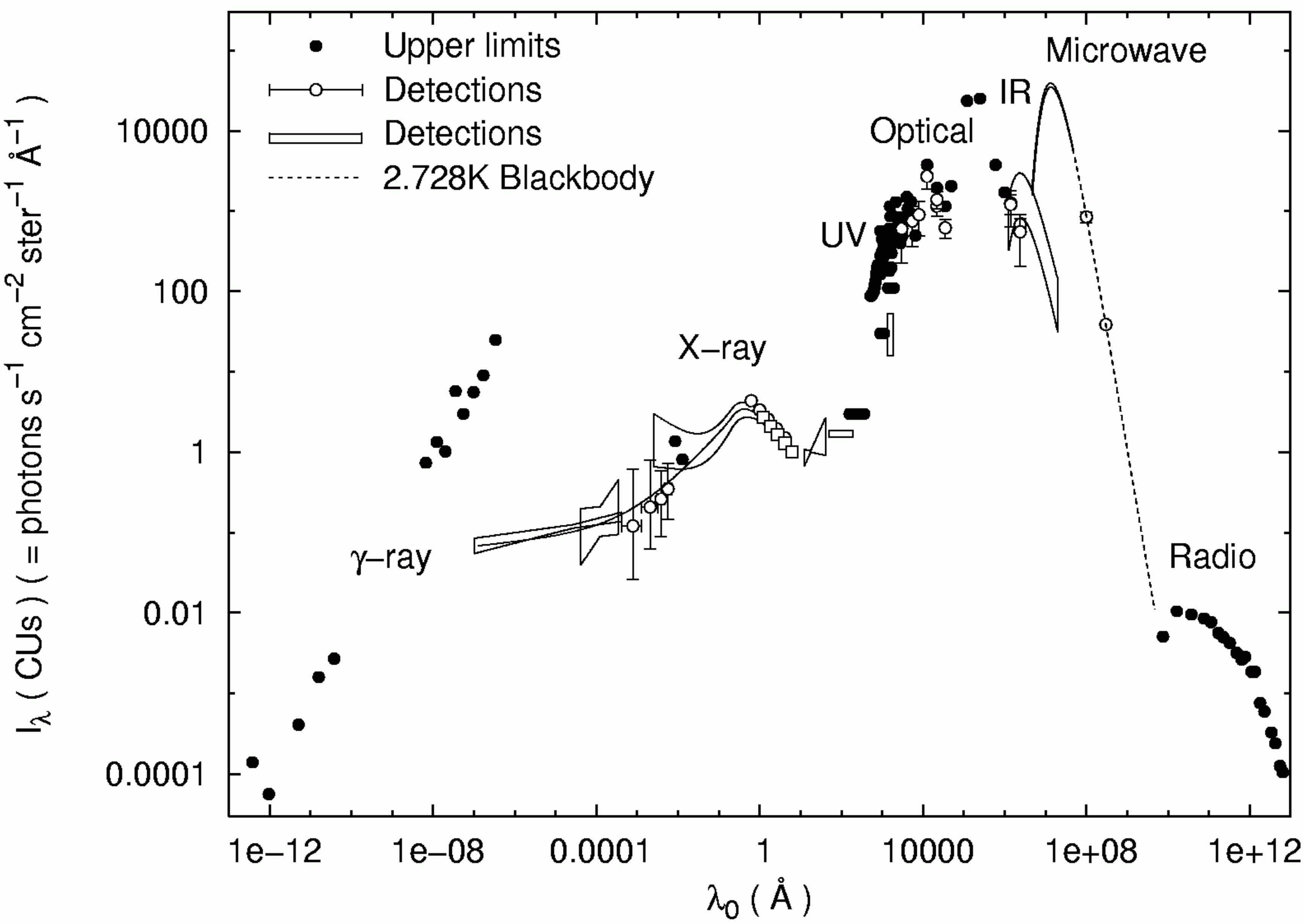
$\Delta\beta_{flow} \sim 10^{-3}$:

$\lambda_{Coherence} \sim 1000\ km$

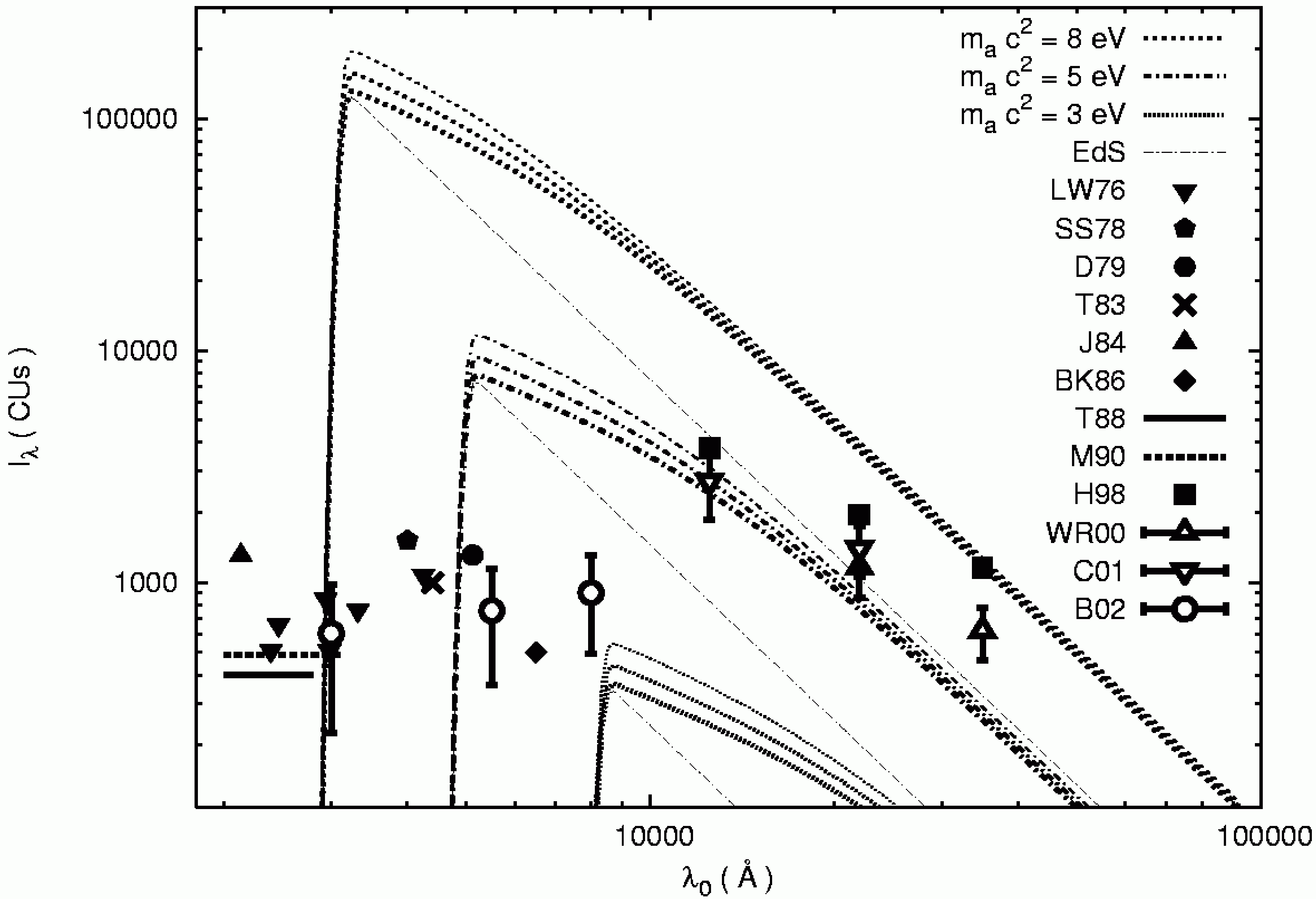
Key point !
The signal is the
Total Energy
(= Mass + Kinetic)
of the axion


Sunrise
photon detectors
Magnet
feed box
10m superconducting
LHC test magnet
Sunset
photon detectors
Sunset axions
Sunrise axions
Low-background
shielding
Magnet support
Jack
–8°
Low-background
shielding
80°
Turntable
Trolley
Driving wheel

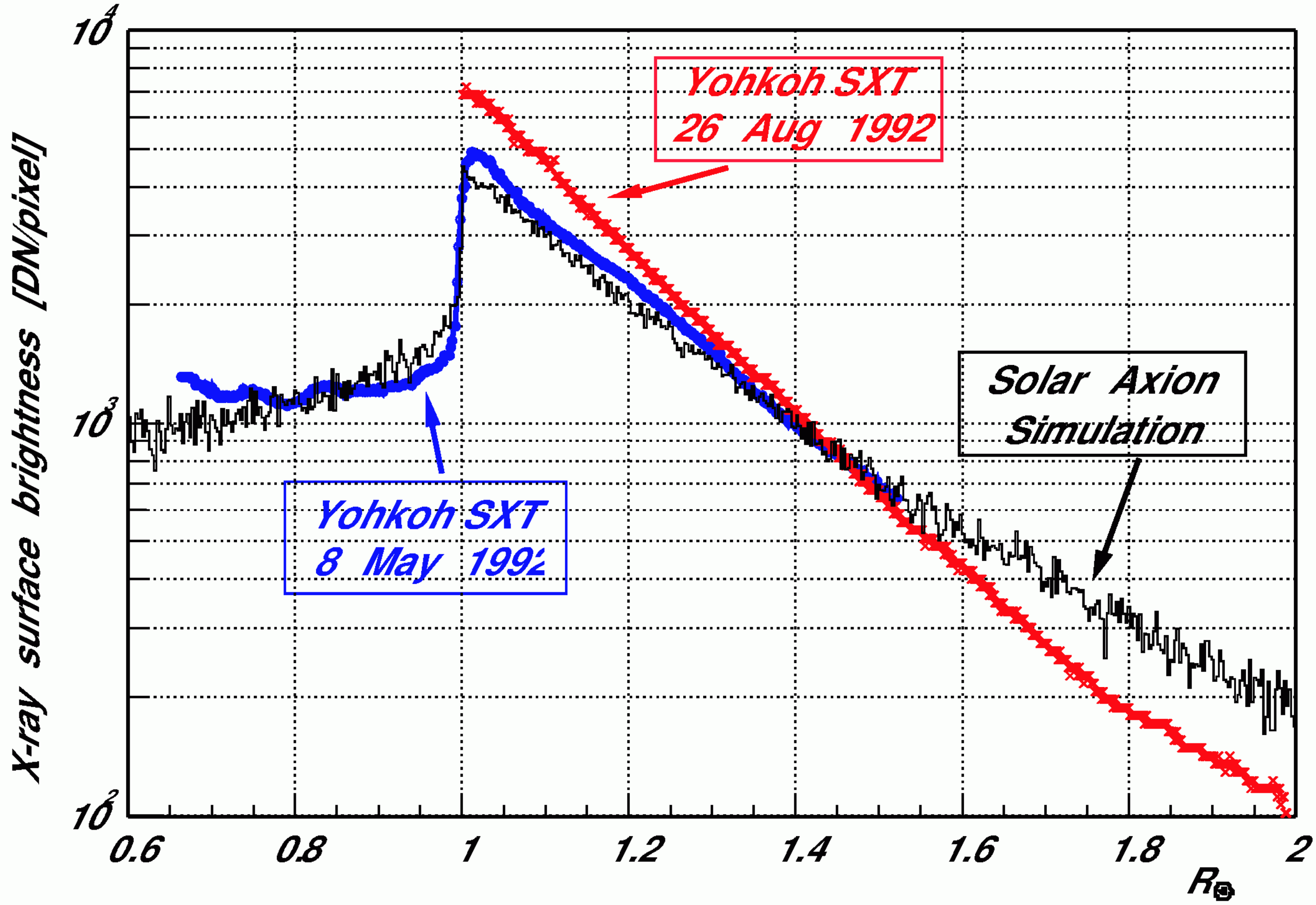

mass of axion (eV)
40.00
30.00
20.00
10.00
0.00
6.00
5.00
4.00
3.00
ξ=0.39
ξ=1.00
ξ=0.07
Experiment
Ia
4000.00
6000.00
8000.00
10000.00
Wavelength



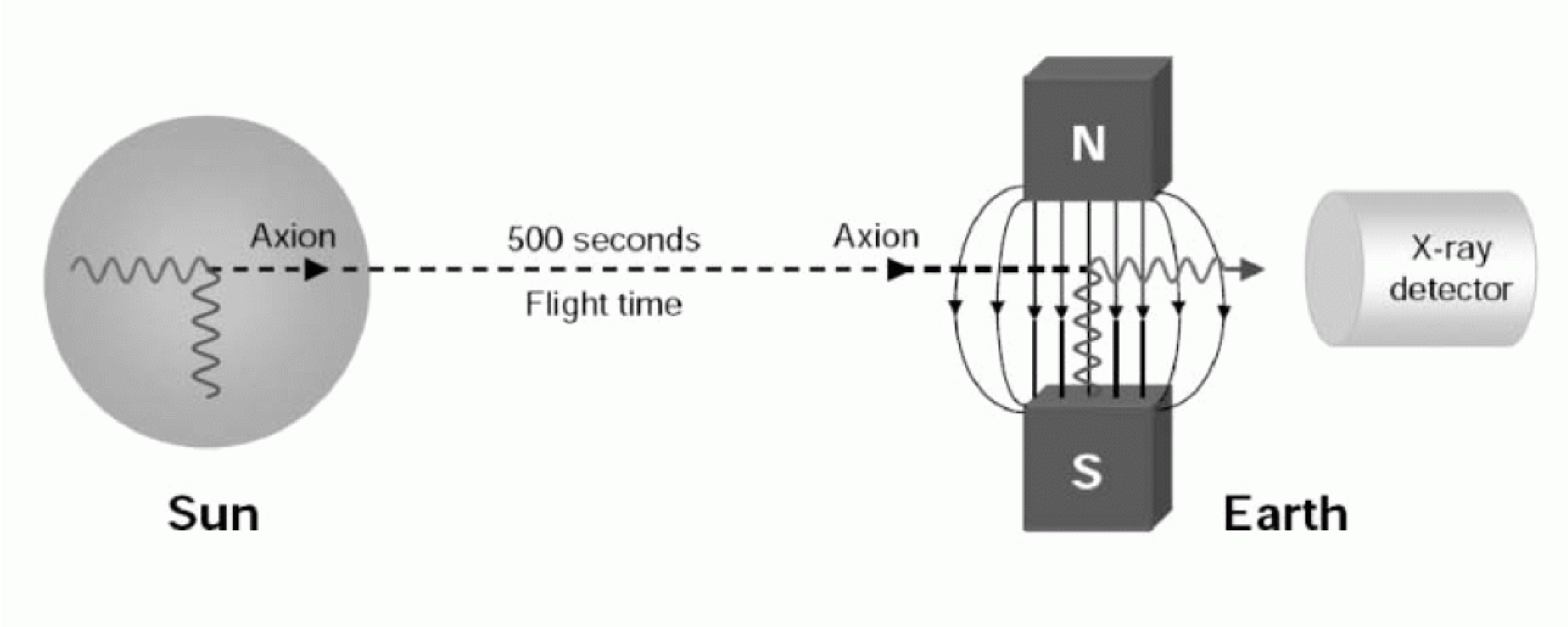
Upper limits
Detections
Detections
2.728K Blackbody
Microwave
IR
Optical
UV
X−ray
γ−ray
Radio
10000
100
1
0.01
0.0001
1e−12
1e−08
0.0001
1
10000
1e+08
1e+12
I_λ (CUs) (= photons s^{-1} cm^{-2} ster^{-1} Å^{-1})
λ_0 (Å)

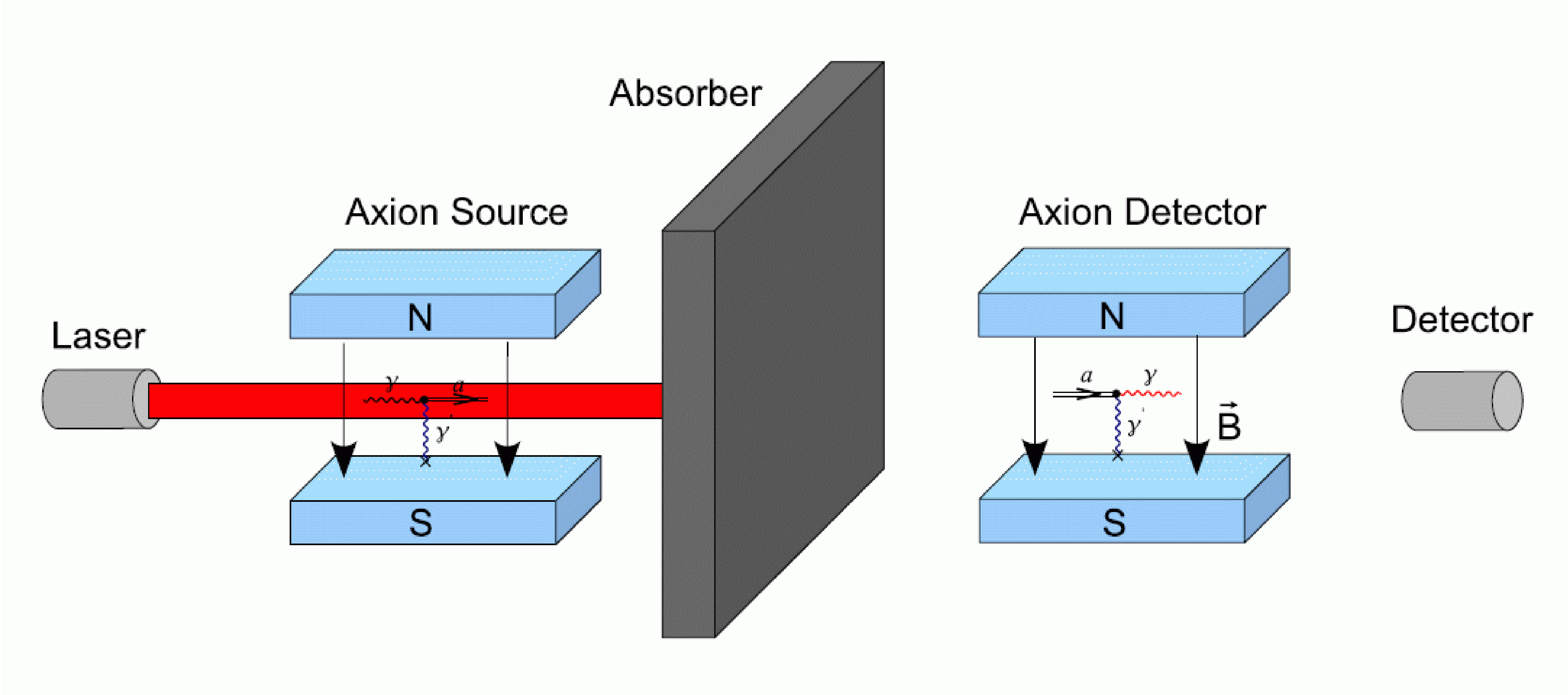


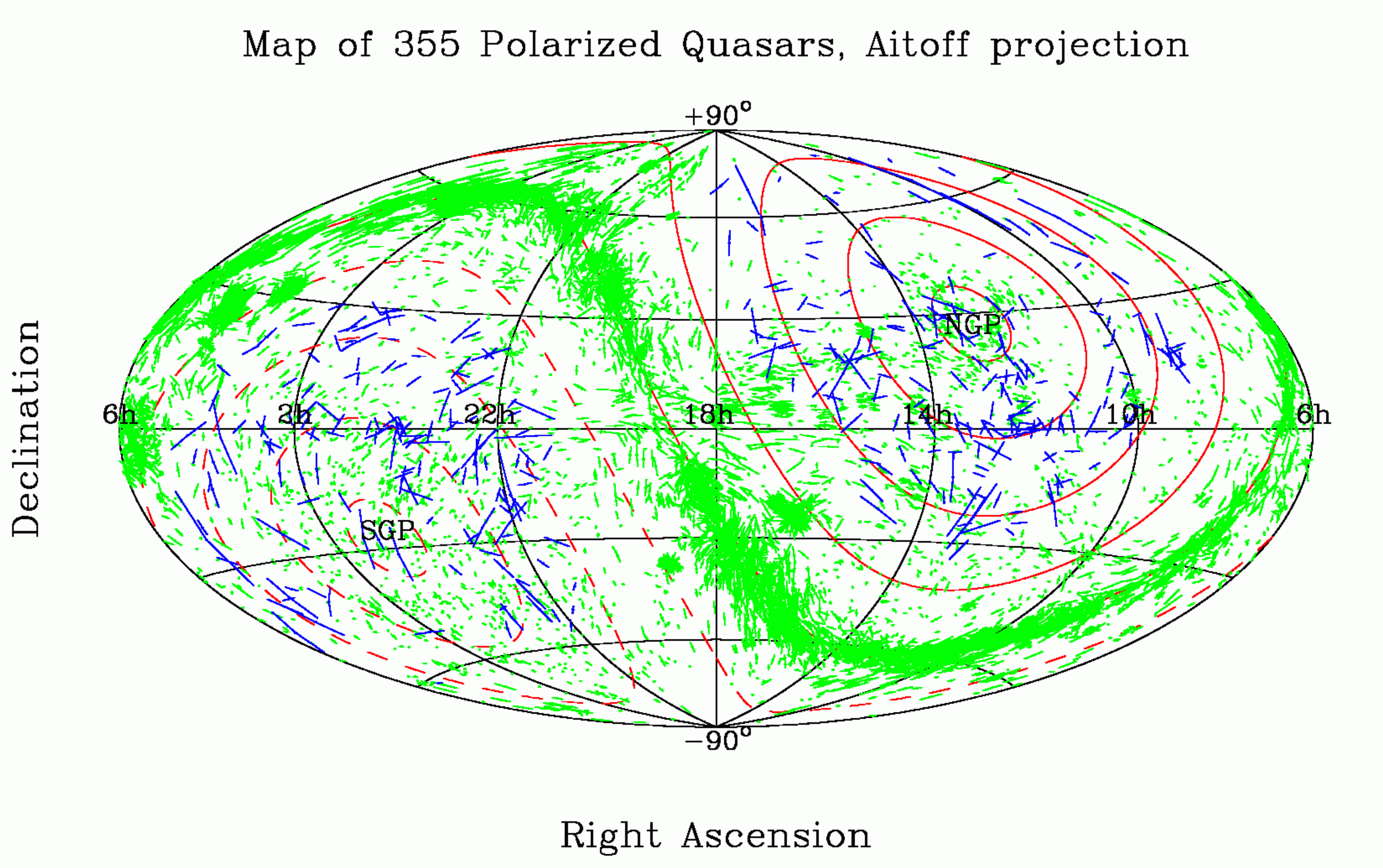
$m_a c^2$ = 8 eV
$m_a c^2$ = 5 eV
$m_a c^2$ = 3 eV
EdS
LW76
SS78
D79
T83
J84
BK86
T88
M90
H98
WR00
C01
B02
100000
10000
1000
I_λ (CUs)
10000
100000
λ_0 (Å)



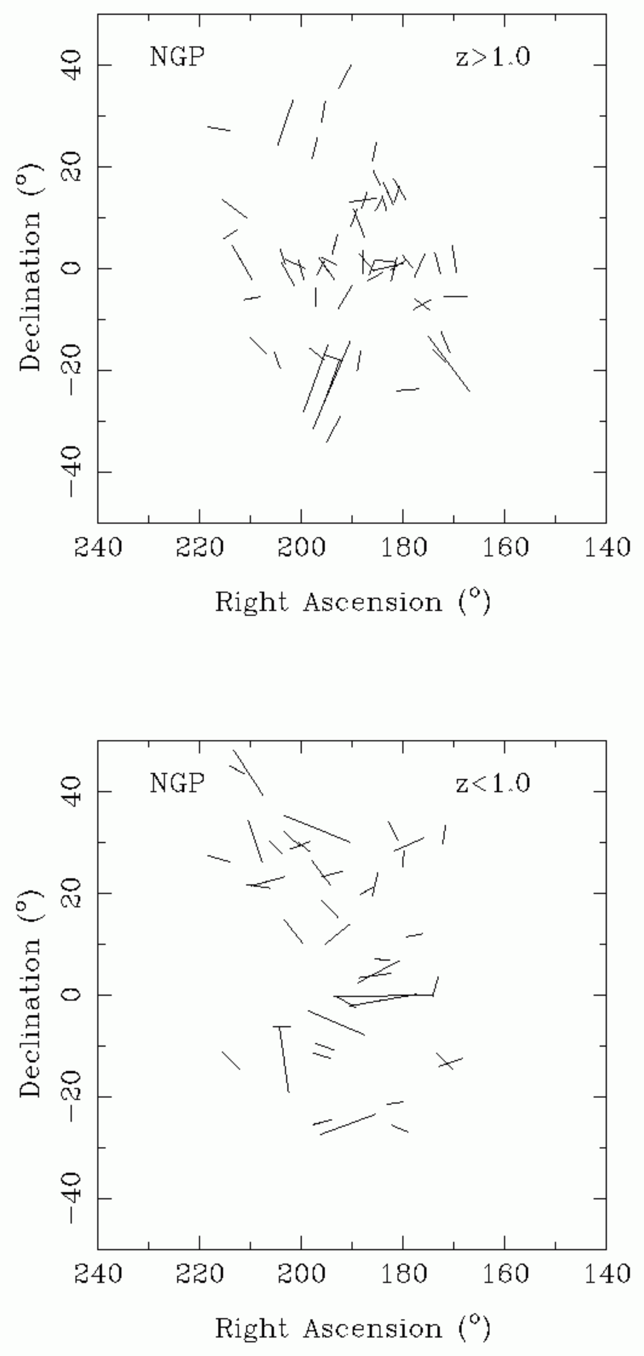
X-ray surface brightness [DN/pixel]
10^4
10^3
10^2
0.6
0.8
1
1.2
1.4
1.6
1.8
2
R⊙
Yohkoh SXT
26 Aug 1992
Yohkoh SXT
8 May 1992
Solar Axion
Simulation

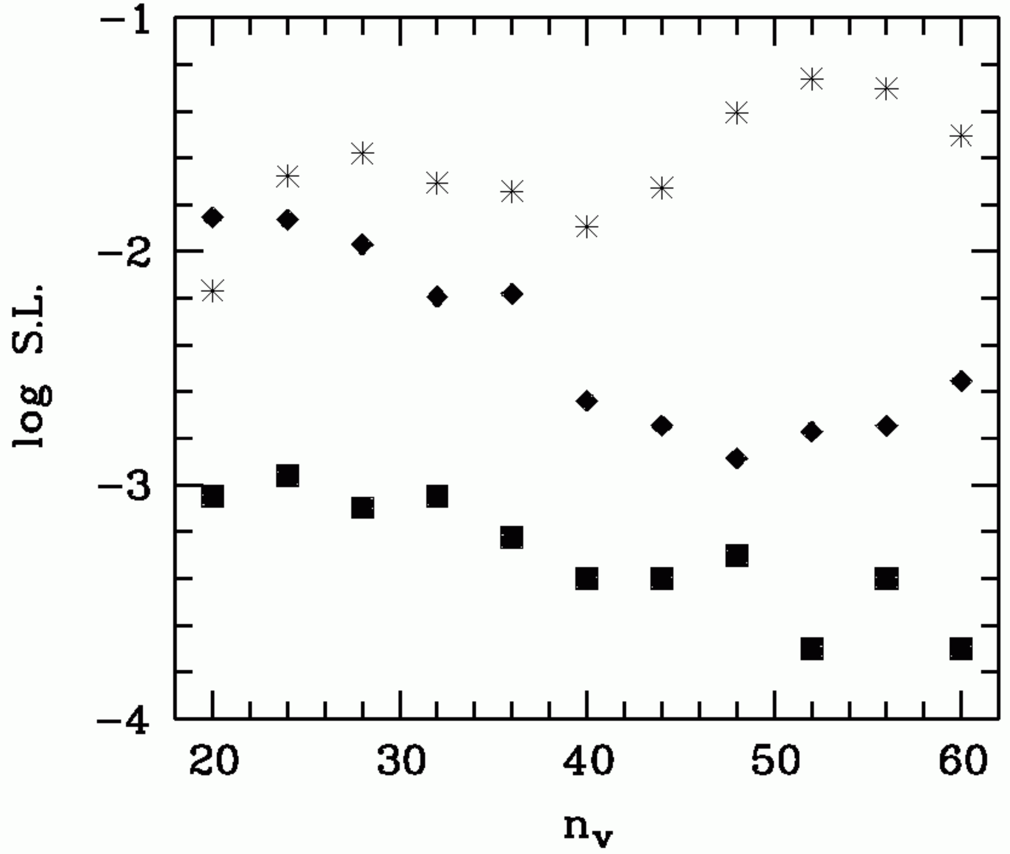

Axion
500 seconds
Flight time
Axion
N
S
X-ray
detector
Sun
Earth

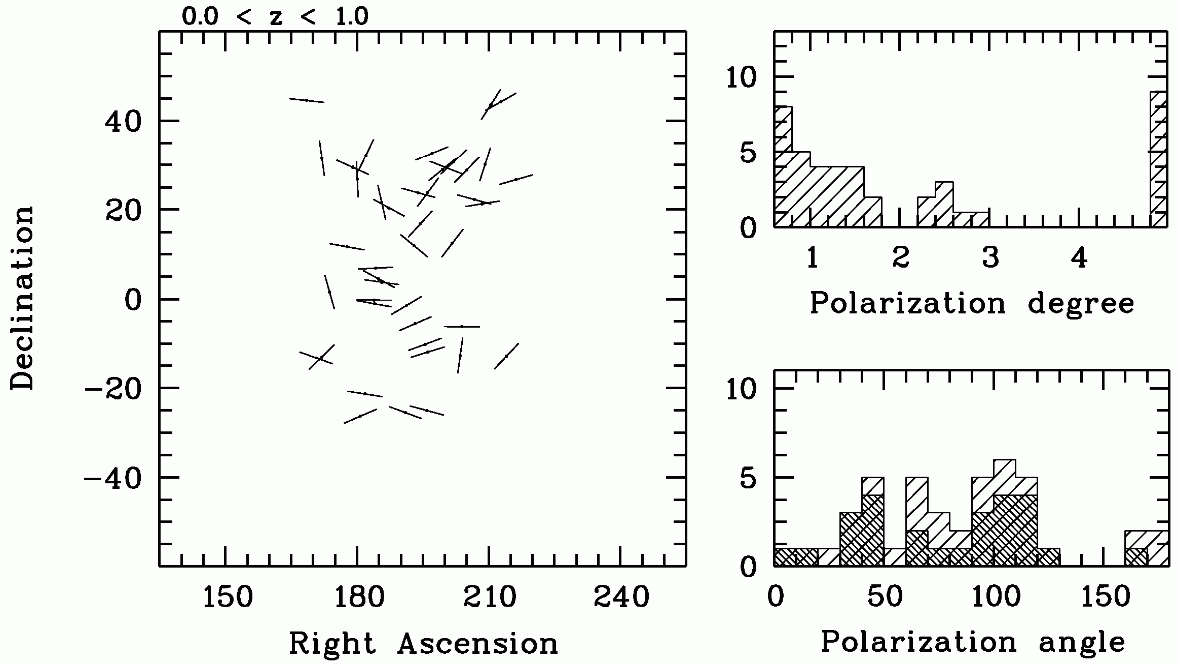

Absorber
Axion Source
Axion Detector
Laser
N
S
N
S
Detector
γ
a
γ'
a
γ
γ'
$\vec{B}$

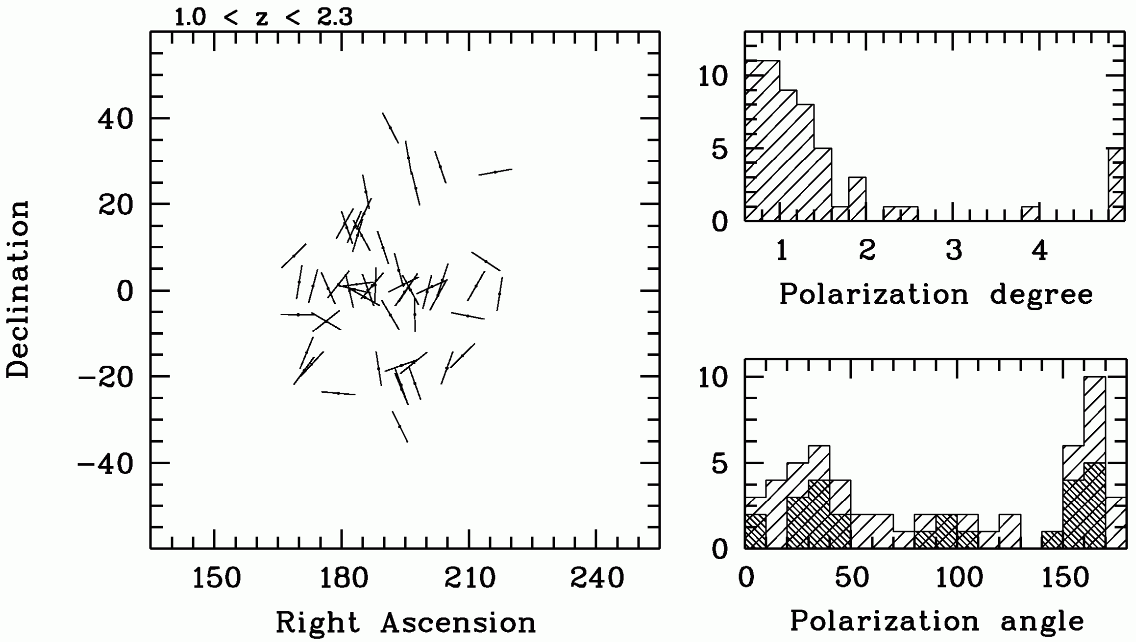


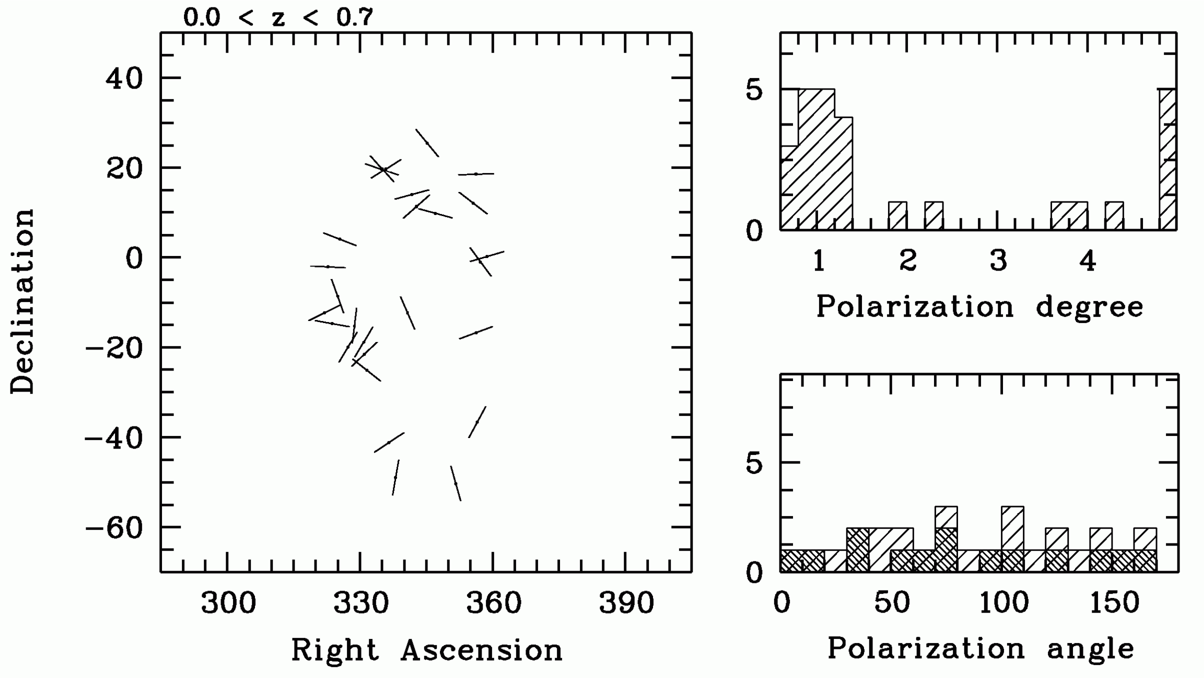
Map of 355 Polarized Quasars, Aitoff projection
+90°
−90°
6h
2h
22h
18h
14h
10h
6h
NGP
SGP
Declination
Right Ascension

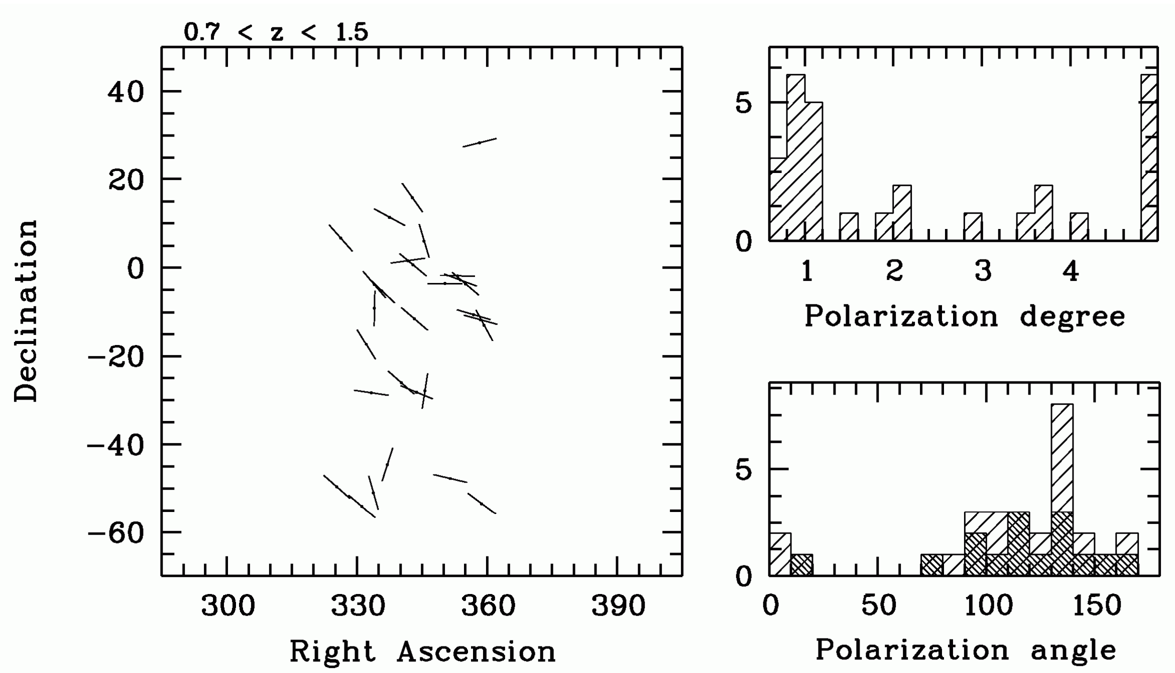

NGP
z>1.0
Declination (°)
40
20
0
−20
−40
240
220
200
180
160
140
Right Ascension (°)
NGP
z<1.0
Declination (°)
40
20
0
−20
−40
240
220
200
180
160
140
Right Ascension (°)

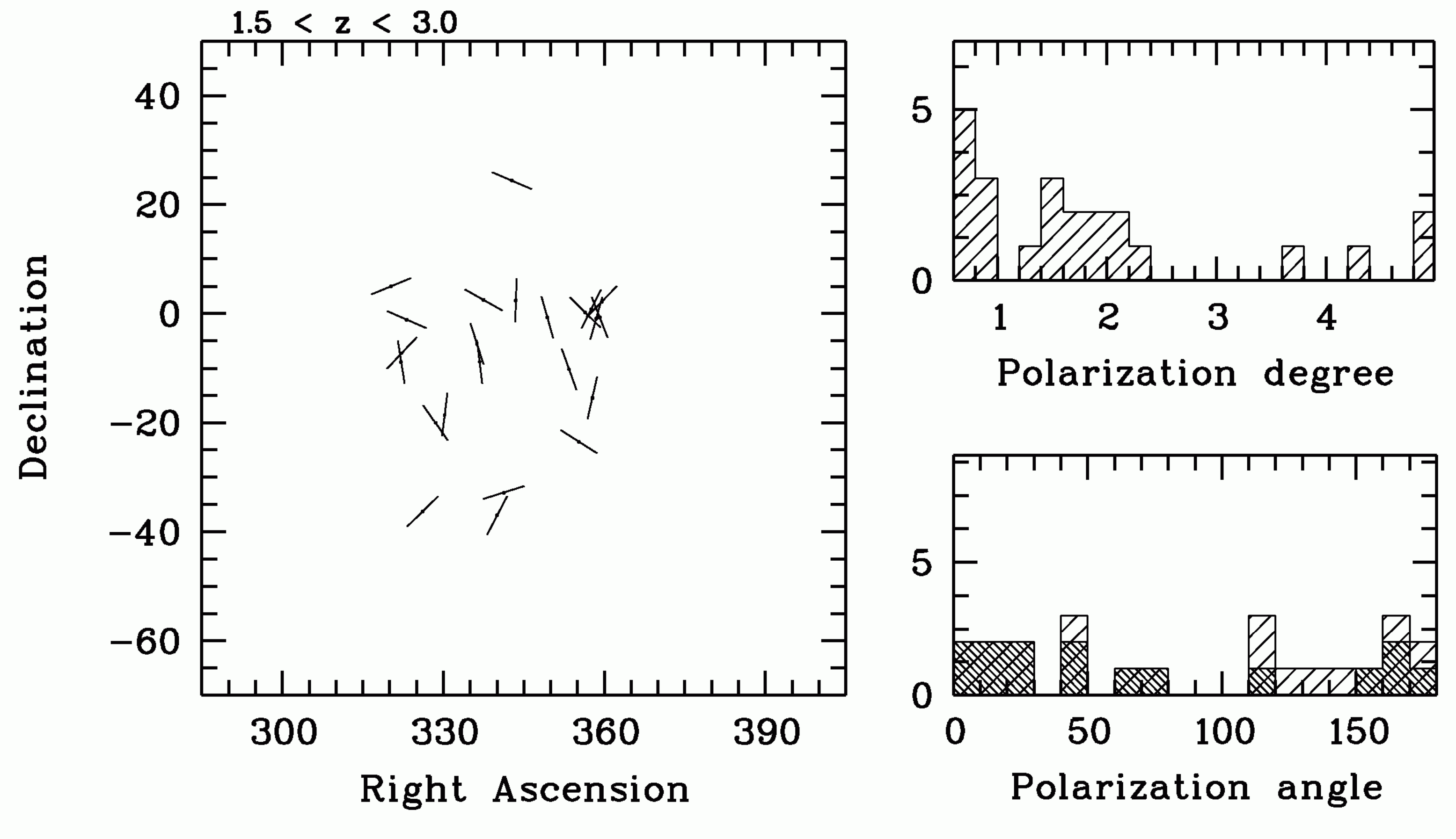

log S.L.
−1
−2
−3
−4
20
30
40
50
60
n_v


0.0 < z < 1.0
Declination
Right Ascension
Polarization degree
Polarization angle


1.0 < z < 2.3
Declination
Right Ascension
Polarization degree
Polarization angle


0.0 < z < 0.7
Declination
40
20
0
−20
−40
−60
300
330
360
390
Right Ascension
5
0
1
2
3
4
Polarization degree
5
0
0
50
100
150
Polarization angle


0.7 < z < 1.5
Declination
40
20
0
−20
−40
−60
300
330
360
390
Right Ascension
5
0
1
2
3
4
Polarization degree
5
0
0
50
100
150
Polarization angle



1.5 < z < 3.0
Declination
Right Ascension
40
20
0
−20
−40
−60
300
330
360
390
5
0
1
2
3
4
Polarization degree
5
0
0
50
100
150
Polarization angle

Magnetic Conversion of Photons into Fundamental Particles

Grand Unification theory (GUT) requires the existence of coupling between photons and fundamental particles. This coupling is determined by Lagrangian term (for scalars):

$$-\frac{1}{M_s}\phi F^{\mu\nu} F_{\mu\nu},$$

where F is the tensor of electromagnetic field and ϕ is a scalar field.
The theory gives the following expression for probability of conversion of definitely polarized photons $W_{\parallel}$ into scalar particles (Raffelt and Stodolsky (1988), Gnedin (1994)):

$$W_{\parallel} = \frac{L_p^2}{L_B^2 + L_p^2} \sin^2 \left(\frac{1}{2} \frac{B L_{coh}}{M_s} \sqrt{1 + L_B^2 / L_p^2} \right), \qquad \text{(a)}$$

where B is the magnetic field strength, L_{coh} is the coherence length of magnetic field, $L_B = 2\pi M_s / B$ and $L_p = 2\pi\omega / \omega_p^2$ are the oscillation lengths of magnetic conversion into vacuum magnetic field and into plasma, respectively. Only one polarization state for which the electric vector lies into the plane containing the magnetic field and line of sight directions is transformed. Here and below the symbol B means really the projection of the vector B on this plane.

The Eq.(a) is valid only if the condition $L_B, L_p < 2\pi\omega/m_\phi$ takes place, where m_ϕ is the mass of a scalar. Therefore, our consideration is restricted only by low mass and massless scalars or gravitons.

For the case of vacuum, i.e. when $L_p \gg L_B$ Eq.(3) is very simplified and takes a form:

$$W_{||} = \sin^2\left(\frac{1}{2}\frac{BL_{coh}}{M_s}\right) \approx \frac{B^2 L_{coh}^2}{4M_s^2}$$

if the condition takes $BL_{coh} \ll M_s$.

The degree of linear polarization p_l can be easily found by

$$P_l = \frac{I_\perp - I_{||}(1-W_{||})}{I_\perp + I_{||}(1-W_{||})} \approx W_{||}/2$$

if one has deal with non-polarized light, i.e. $I_{||} = I_\perp = I_0/2$ and $W_{||} \ll 1$.

Now the main problem consists in the estimation of the magnitudes of B and L_{coh} for real astrophysical conditions.

Magnetic Photon Conversion in the IGM

We shall make our estimations using approximation by Furlanetto and Loeb (2001) accepting the dependence of IGM magnetic field strength on coherence length in a form

$$B \equiv B_{ICM} = 10^{-9}\left(L_{coh}/1Mpc\right)^{-1/2}G.$$

The IGM electron density is

$$n_e = \Omega_b h^2 \times 10^{-5}(1+z)^3 cm^{-3} \approx 2\times 10^{-7}(1+z)^3 cm^{-3}.$$

The the oscillations lengths are:

$$L_p = \frac{2\pi\omega(1+z)}{\omega_p^2} \approx 2\times 10^{29}\left(\frac{\omega}{3eV}\right)\frac{1}{(1+z)^2}eV^{-1},$$

$$L_B = \frac{2\pi M_s}{B} = 10^{23}\left(\frac{10^{-9}G}{B}\right)\left(\frac{M_s}{1TeV}\right)eV^{-1},$$

where ω_p is the plasma frequency.

Получены наиболее сильные ограничения константы фотон-аксионной связи:

$$g_{a\gamma} \leq 4.6 \times 10^{-12} \left(\frac{B}{10^{-9} G} \right)^{-1} \left(\frac{H_0}{75 km/s\, Mpc} \right)^{1/2} \left(GeV \right)^{-1}$$

$$m_a \leq 1.8 \times 10^{-13} eV$$

Характерная длина однородности межгалактического магнитного поля:

$$l \sim 1 Мпк$$

Axion Birefrigence

$$\theta = \frac{1}{8} g_{a\gamma}^{2} B_{\perp}^{2} L^{2}$$

$$\varepsilon = \frac{\left(g_{a\gamma} B_{\perp} m_{a}\right)^{2}}{48\omega} L^{3}$$

Некоторые дополнительные следствия

1. E. Zavattini et al., hep-ex/0507107

$$\theta = \frac{1}{8} g_{a\gamma}^2 B_\perp^2 L^2 \rightarrow \left(3.9 \pm 0.5\right) \times 10^{-12} \frac{rad}{pass} \quad g_{a\gamma} \sim 4 \times 10^{-6} \, 1/GeV$$

Hutsemekers et al: $\theta \approx 30^\circ / Gpc \quad B_{IGM} \approx 10^{-15} G$

2. Local Bubble: intrinsic polarization of stars.
Intrinsic linear polarization of stars does not correspond their spectral types.

Leroy: 1000 stars ~ 50пс $B = 3 \times 10^{-6} G, L_B \sim L_P, P_l \sim P_{ISM}$

3. The circular polarization of radiation of AGN и QSOs.

$$P_V = \frac{\left(B_\perp m_a\right)^2}{48\omega} g_{a\gamma}^2 L^3, \quad L \sim 1 Gpc, B_\perp \sim 10^{-16} G, g_{a\gamma} = 4 \times 10^{-6} \, 1/GeV, m_a \approx 10^{-26} eV$$

Motivation from Particle Physics

Standard Model extremely successful … but incomplete!

Neutrinos oscillate -> are massive!
Hierarchy problem: 10^3 GeV << 10^{19} GeV

Popular extensions:

Supersymmetry (bosons - fermions)
LSP (neutralino)

Extra dimensions (3 + +1)
LKP (first KK excitation of the photon)

Generic: WIMPs, M ~ 10 GeV - 1 TeV

Axion Dark Matter eXperiment (ADMX)

AXION

University of California, Berkeley
John Clarke

University of Florida
Pierre Sikivie, Neil Sullivan, David Tanner

Lawrence Livermore National Laboratory
Stephen Asztalos, Gianpaolo Carosi, Christian Hagmann, Darin Kinion, Karl van Bibber

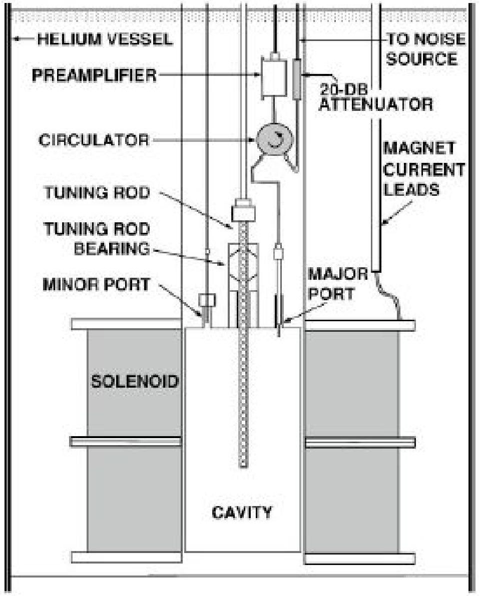
National Radio Astronomical Observatory
Richard Bradley

University of Washington
Michael Hotz, Leslie Rosenberg, Gray Rybka

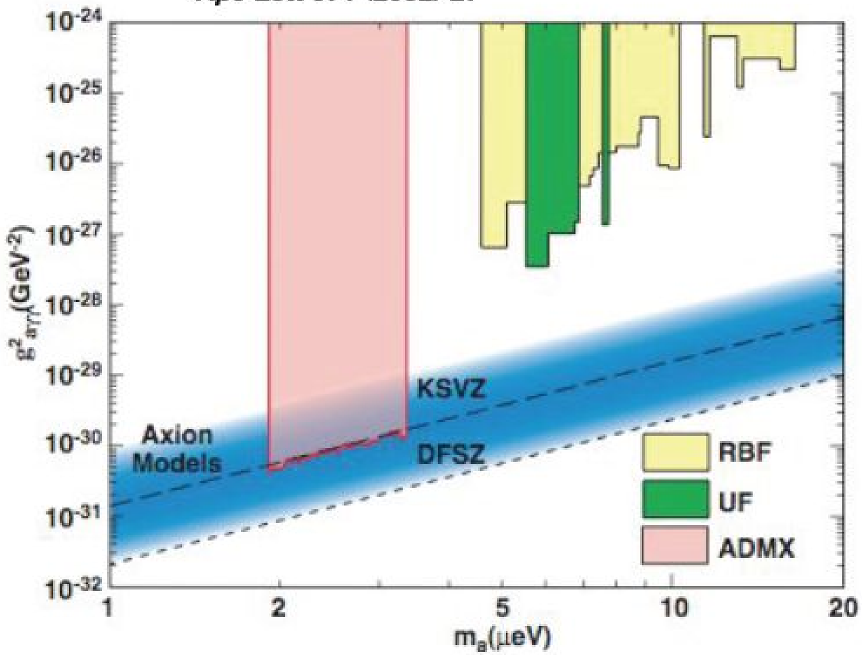
ADMX performed as designed – scanned in the model band

AXION

From W. Wuensch *et al.*, Phys. Rev. D40 (1989) 3153



PRL 80 (1998) 2043
PRD 64 (2001) 092003
PRD 69 (2004) 011101(R)
ApJ Lett 571 (2002) 27



We learned much from the first-generation exp'ts (~ liter volume)
Already came within a factor of 100-1000 of the desired sensitivity