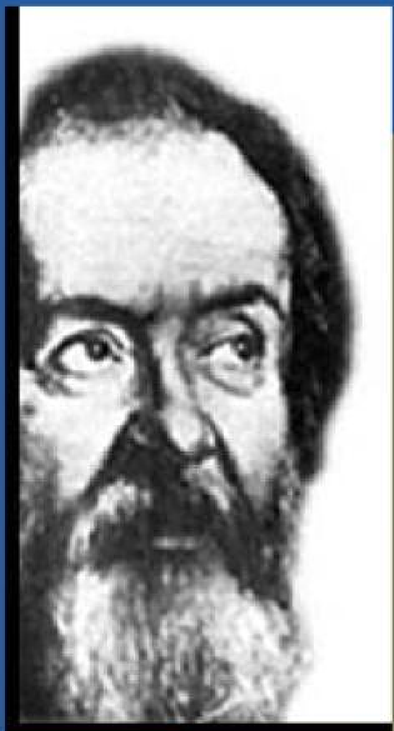
Astronomy and Particle Physics: New Results of Mutual Interaction.

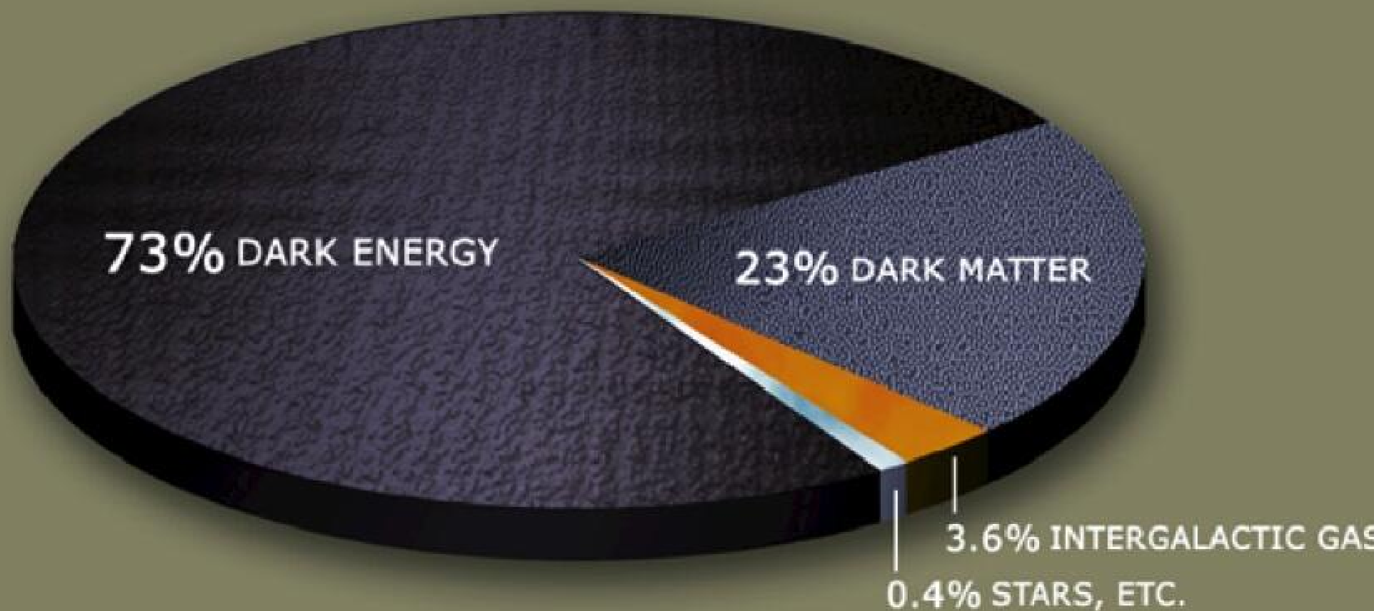
(Yu.N. Gnedin, Pulkovo Observatory)

Basic Topics

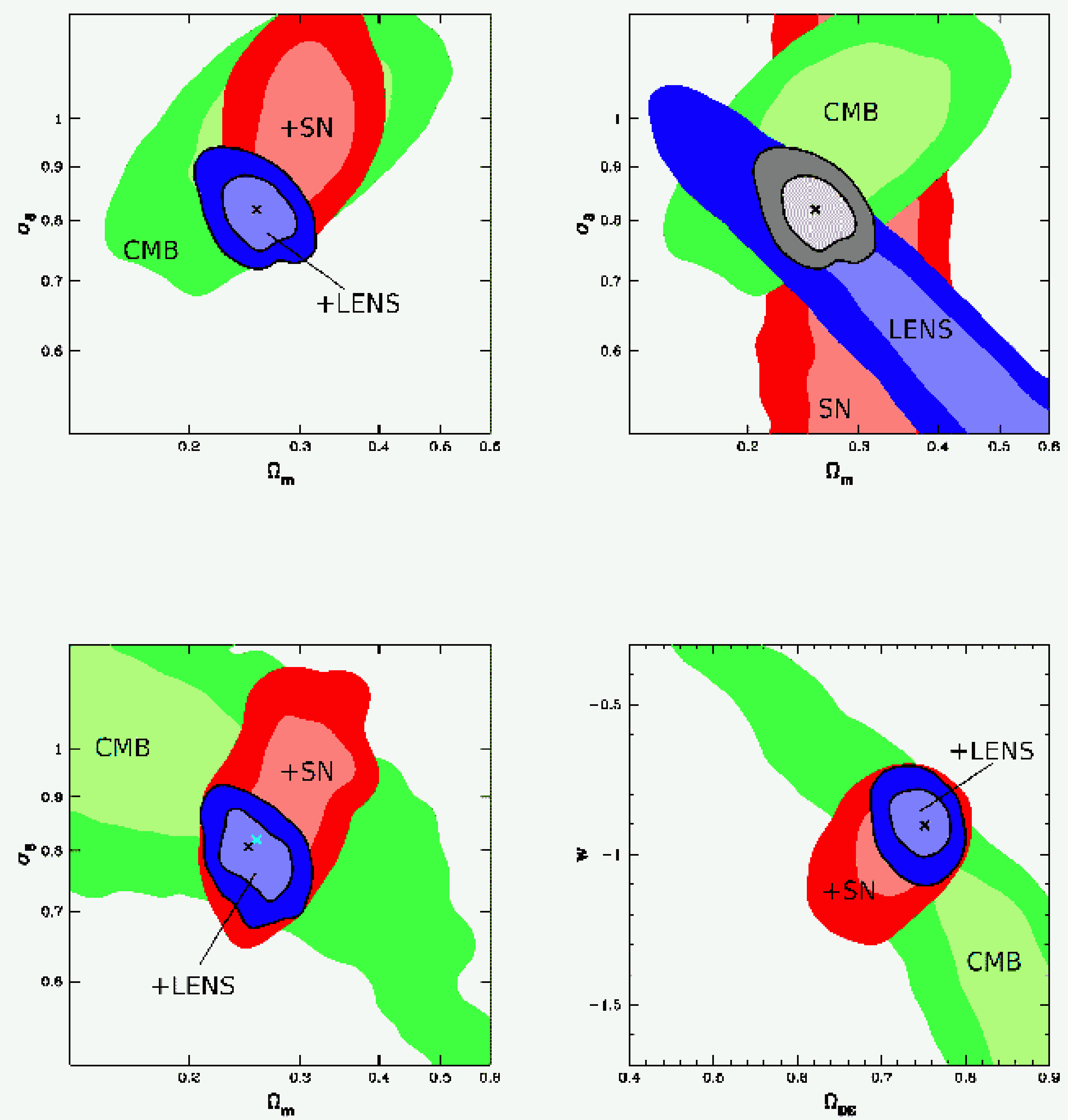
1. Axions (Arions): Marginal Evidence of Existence.
2. Weakly Interacting Massive Particles: Direct and Indirect Searches.
3. Vacuum Polarization Effect in Strong Magnetic Fields of Neutron Stars and White Dwarfs.

The Cosmic Mystery-Pie





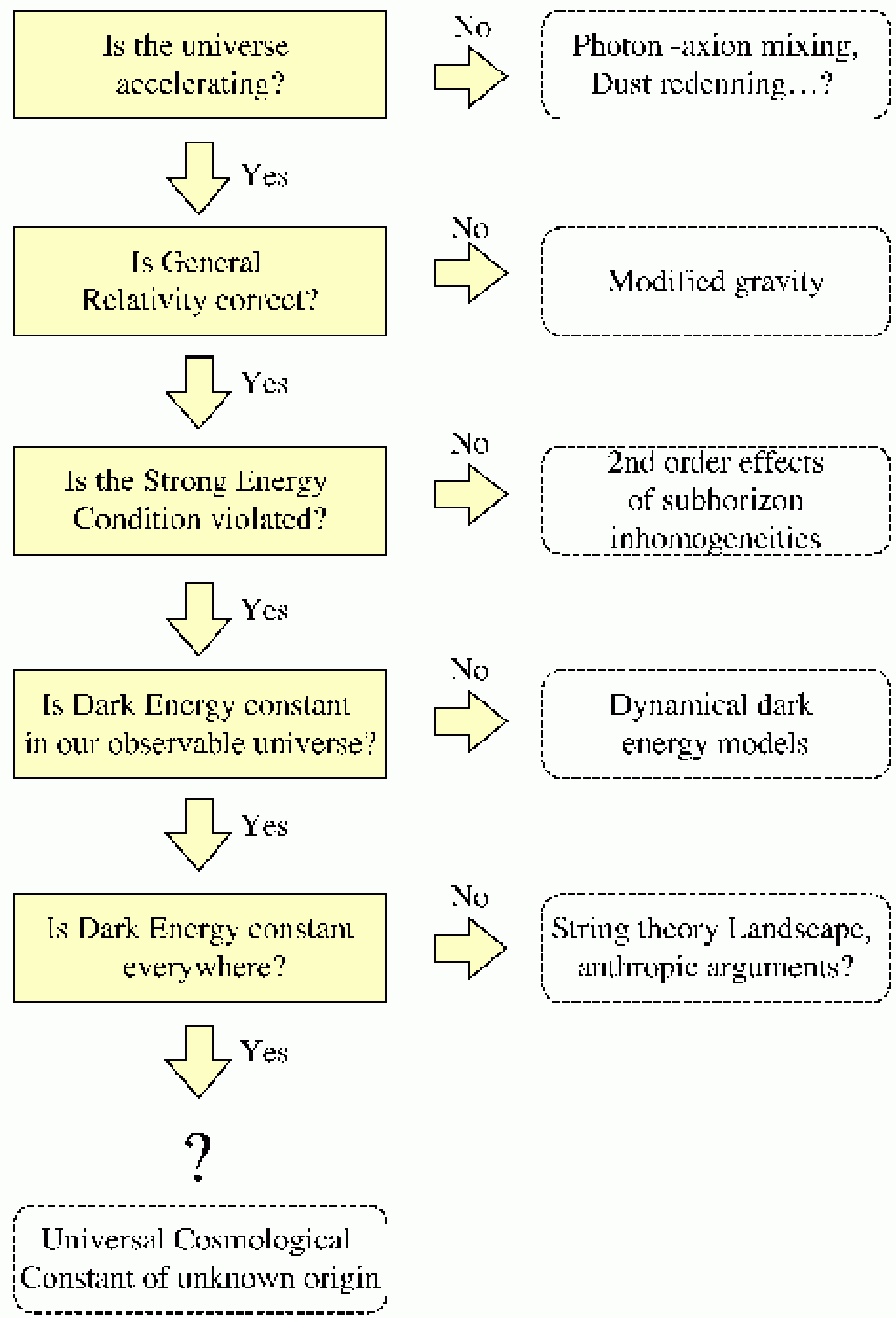
'The constitution of the universe may be set in first place among all natural things that can be known'
Galileo Galilei, *Dialogue*

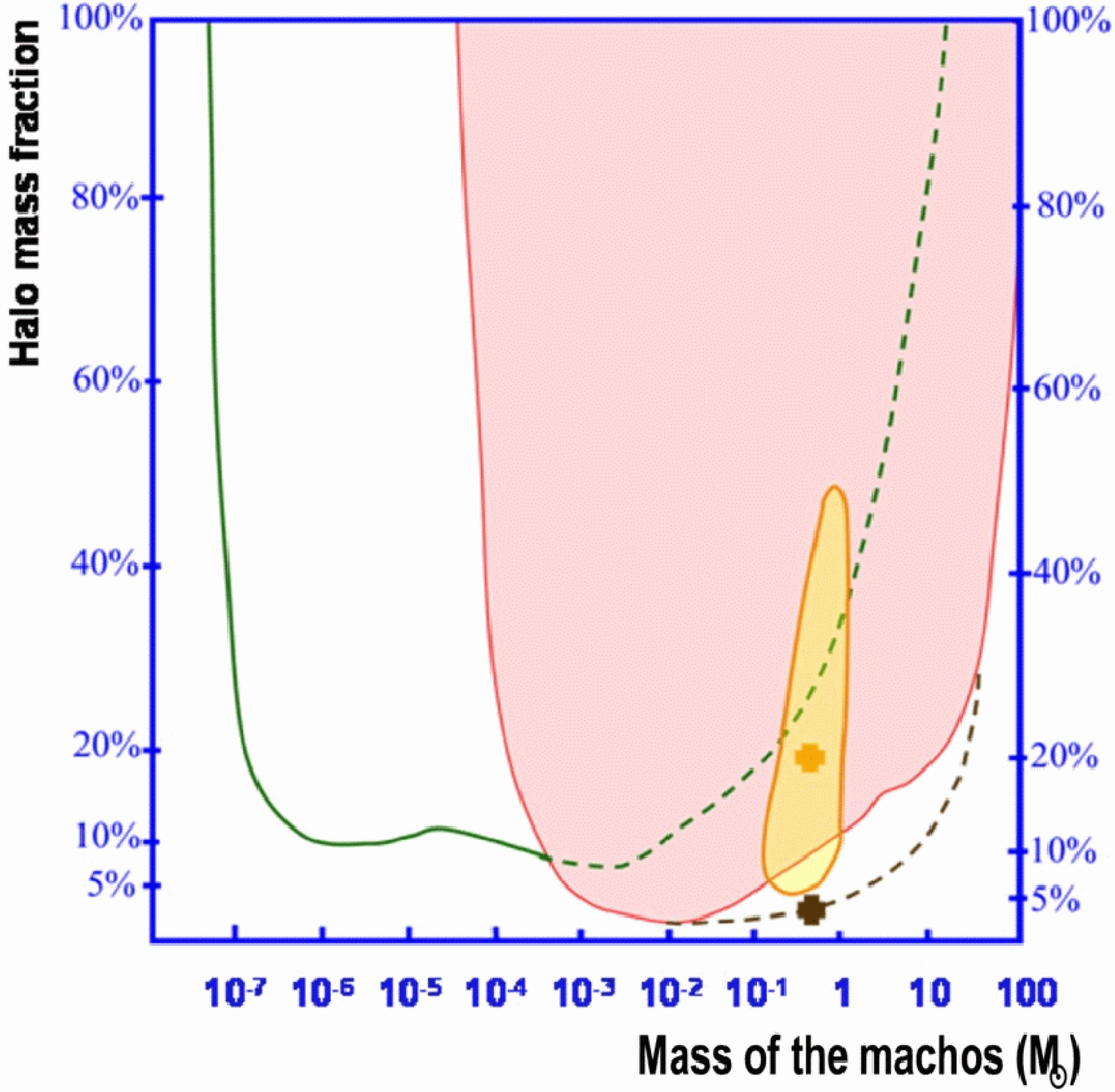


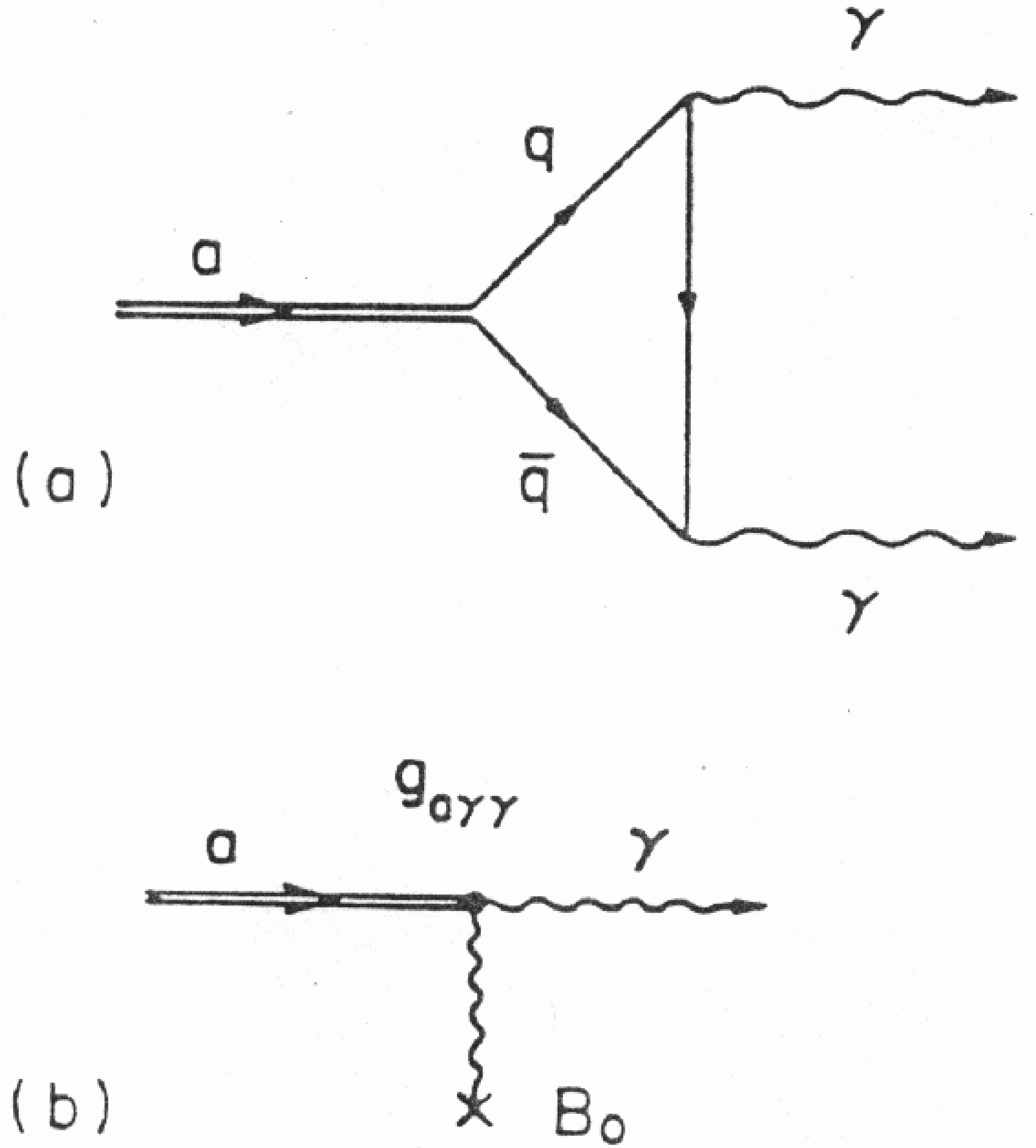
+SN
CMB
+LENS
σ_8
Ω_m
CMB
LENS
SN
+SN
+LENS
CMB
w
Ω_{DE}

ТАБЛ.1. КАНДИДАТЫ В ТЕМНУЮ МАТЕРИЮ

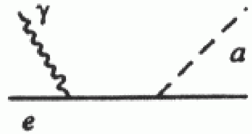
Барионная материя	**Небарионная материя (элементарные частицы)**
Нейтронные звезды	Нейтрино
Черные дыры	Аксионы
Коричневые карлики	Слабо взаимодействующие массивные частицы (WIMP)
Юпитеры	Нейтралино
Астероиды	Суперсимметричные (SUSY) частицы
Холодные белые карлики	

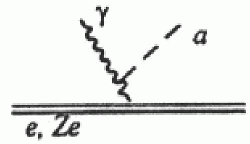

Is the universe accelerating?
No
Photon -axion mixing, Dust redenning…?
Yes
Is General Relativity correct?
No
Modified gravity
Yes
Is the Strong Energy Condition violated?
No
2nd order effects of subhorizon inhomogeneities
Yes
Is Dark Energy constant in our observable universe?
No
Dynamical dark energy models
Yes
Is Dark Energy constant everywhere?
No
String theory Landscape, anthropic arguments?
Yes
?
Universal Cosmological Constant of unknown origin

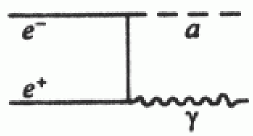

Halo mass fraction
100%
80%
60%
40%
20%
10%
5%
10-7
10-6
10-5
10-4
10-3
10-2
10-1
1
10
100
Mass of the machos (M☉)

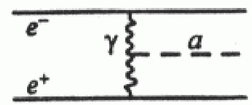


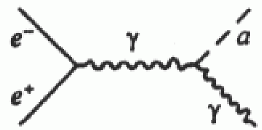
γ
q
a
(a)
q̄
γ
$g_{a\gamma\gamma}$
a
γ
(b)
B_0

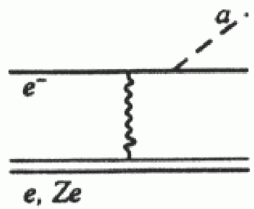

γ
a
e

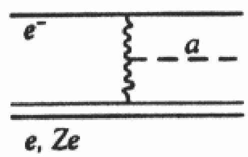

γ
a
e, Ze

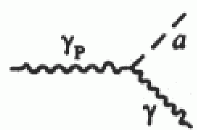

e⁻
a
e⁺
γ

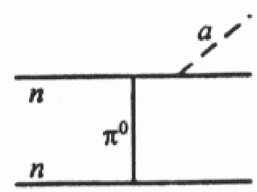

e⁻
γ
a
e⁺

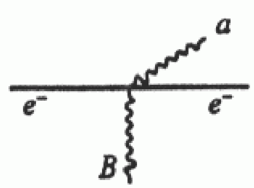

e⁻
γ
a
e⁺
γ

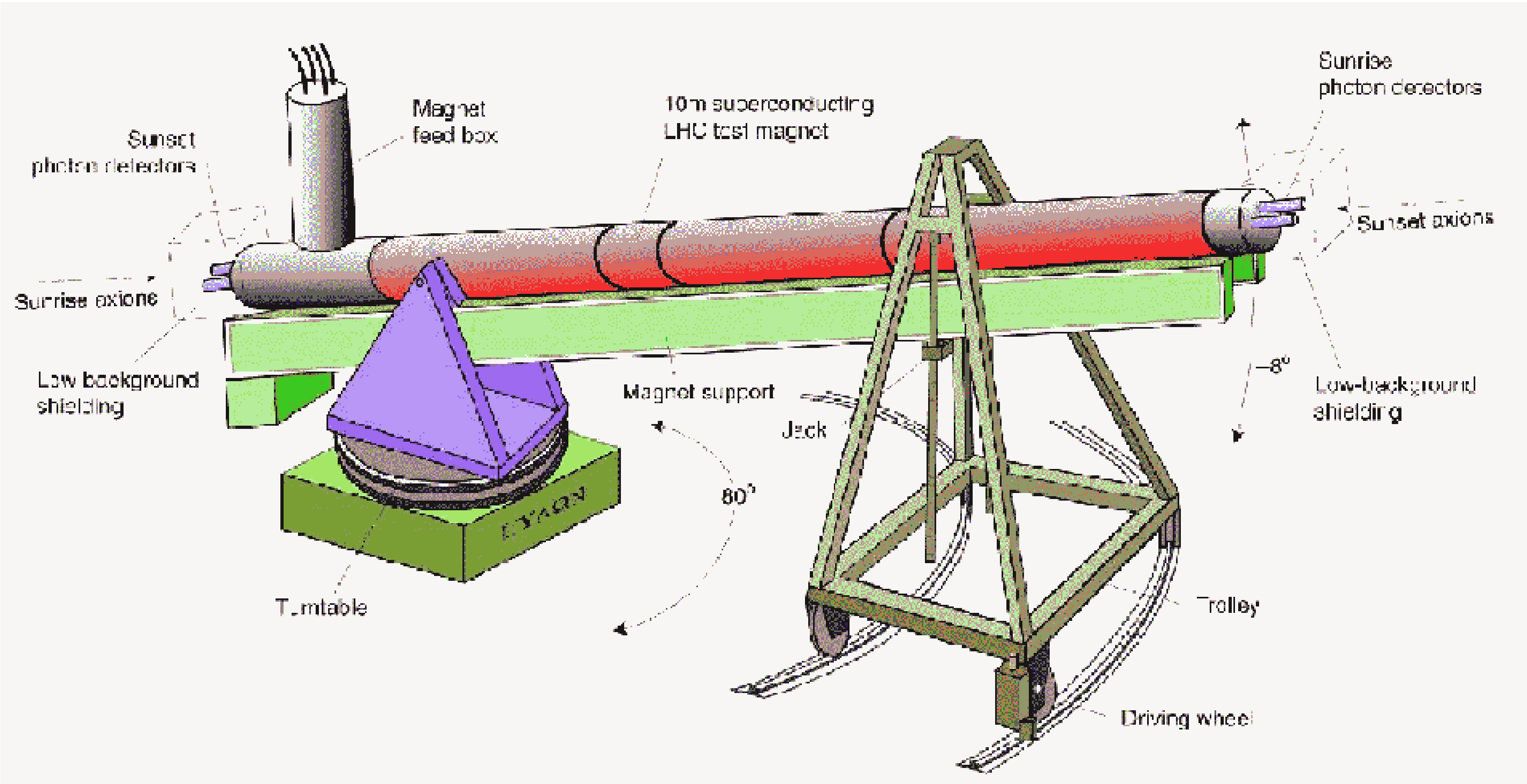

a
e⁻
e, Ze

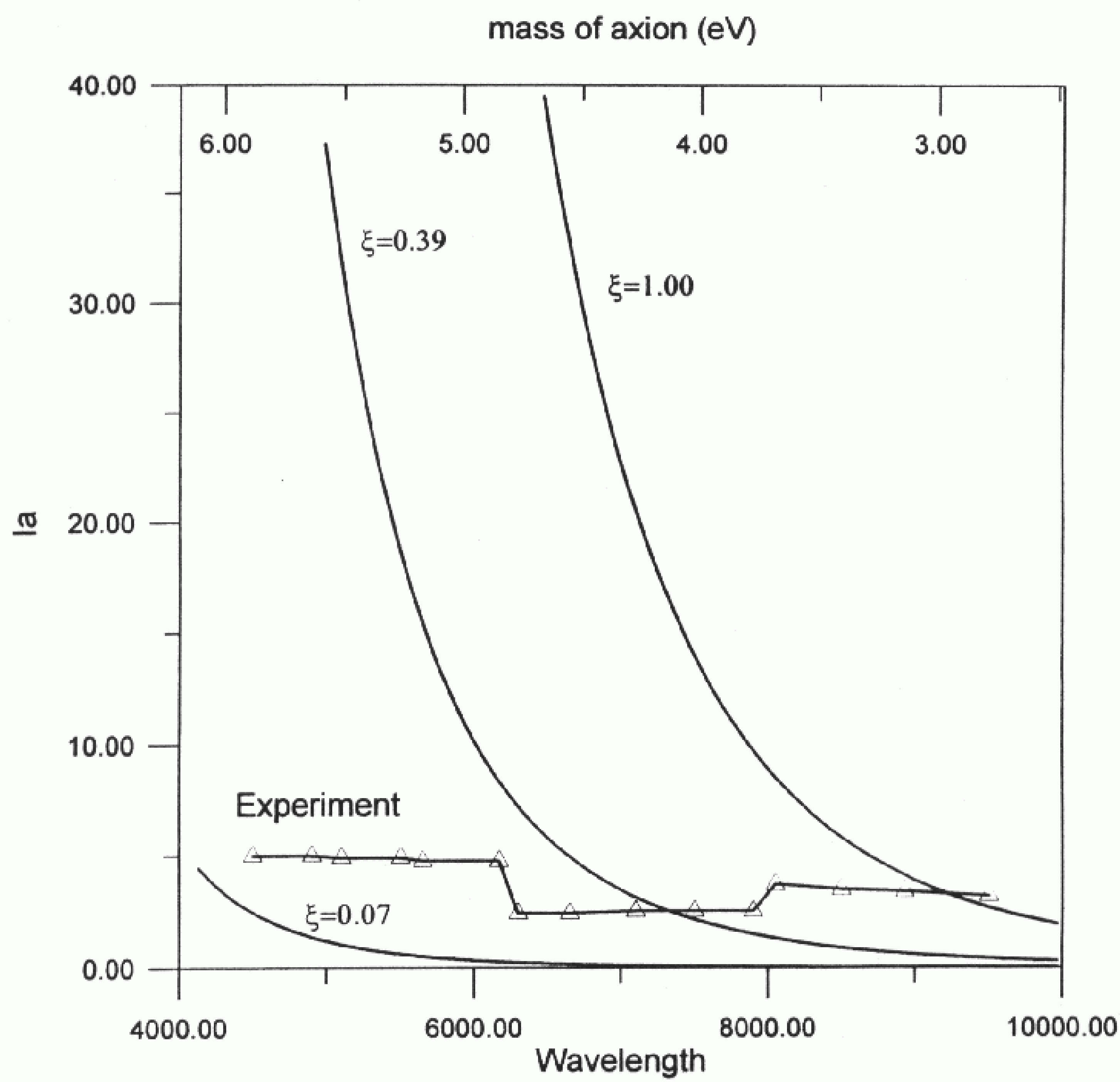

e⁻
a
e, Ze


γP
a
γ

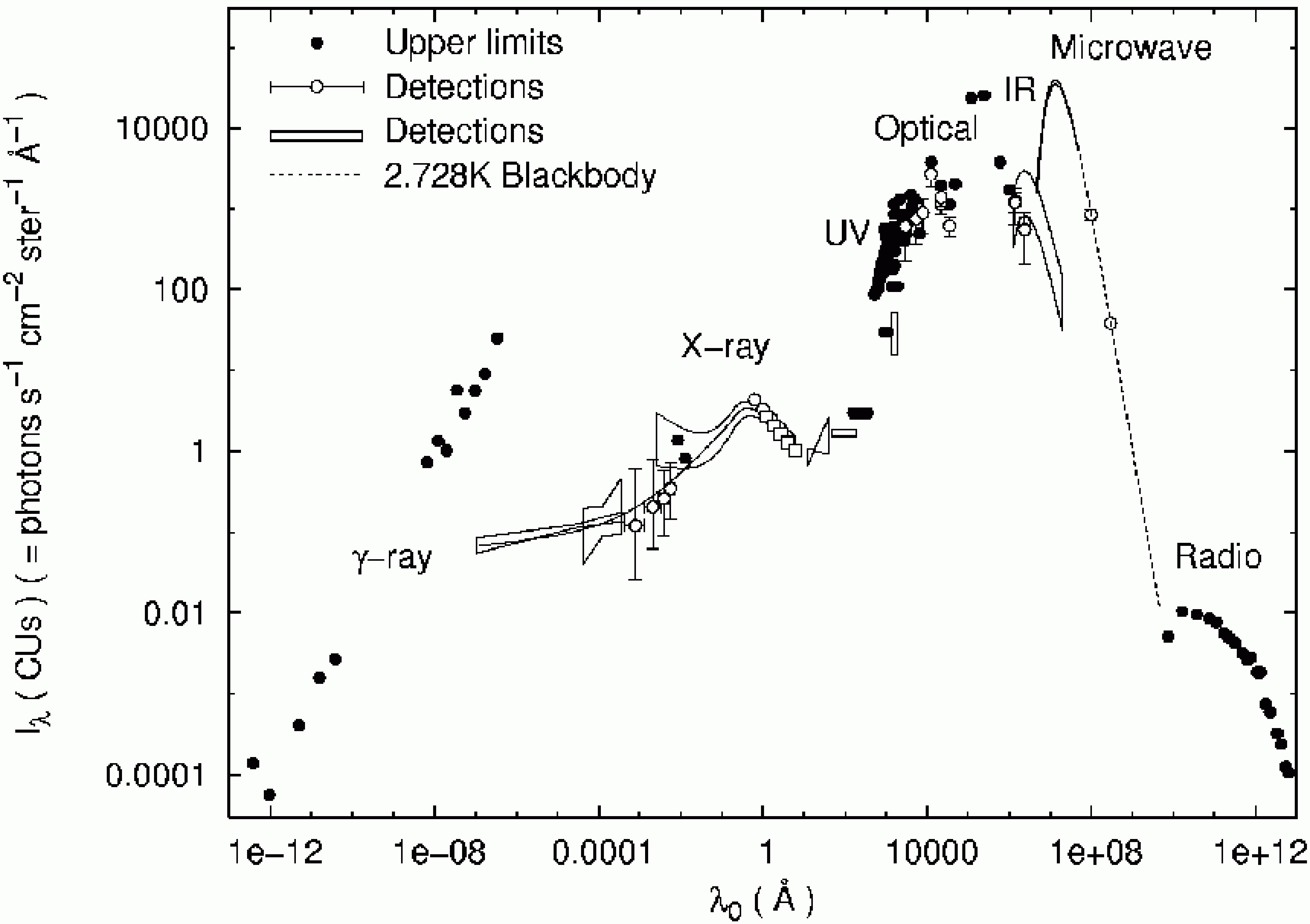

a
n
π0
n

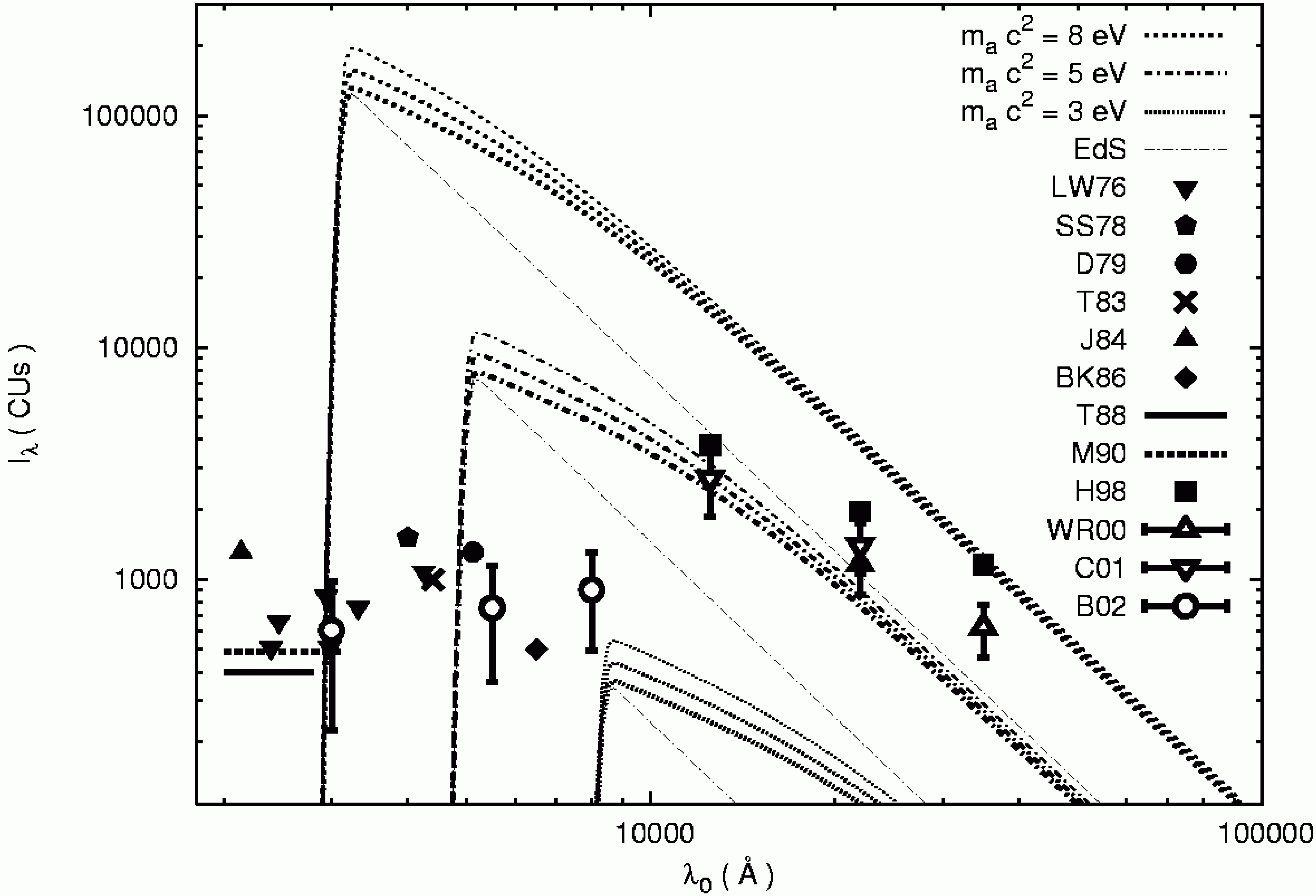

a
e⁻
e⁻
B


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

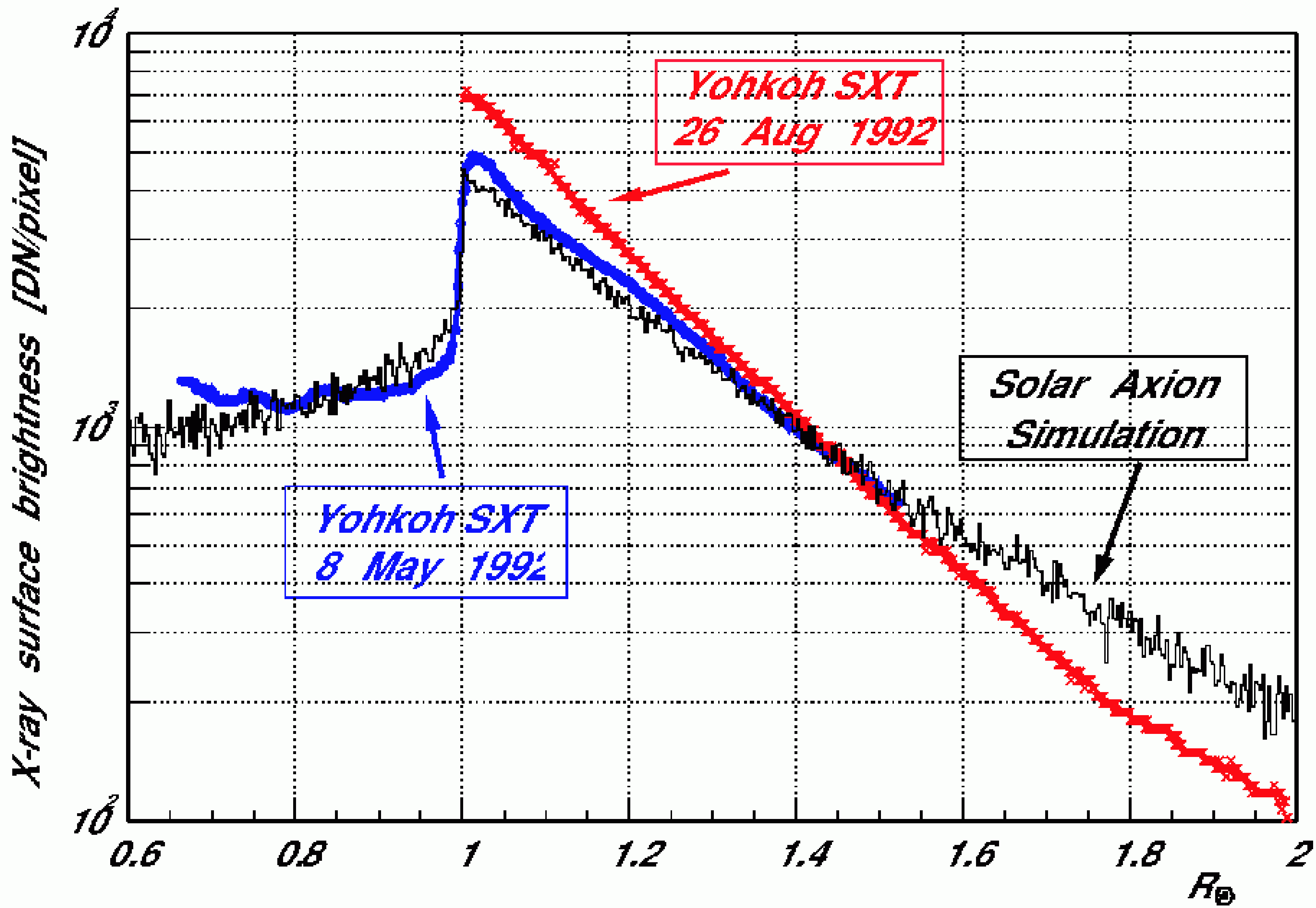


mass of axion (eV)
6.00
5.00
4.00
3.00
40.00
30.00
20.00
10.00
0.00
Ia
ξ=0.39
ξ=1.00
Experiment
ξ=0.07
4000.00
6000.00
8000.00
10000.00
Wavelength

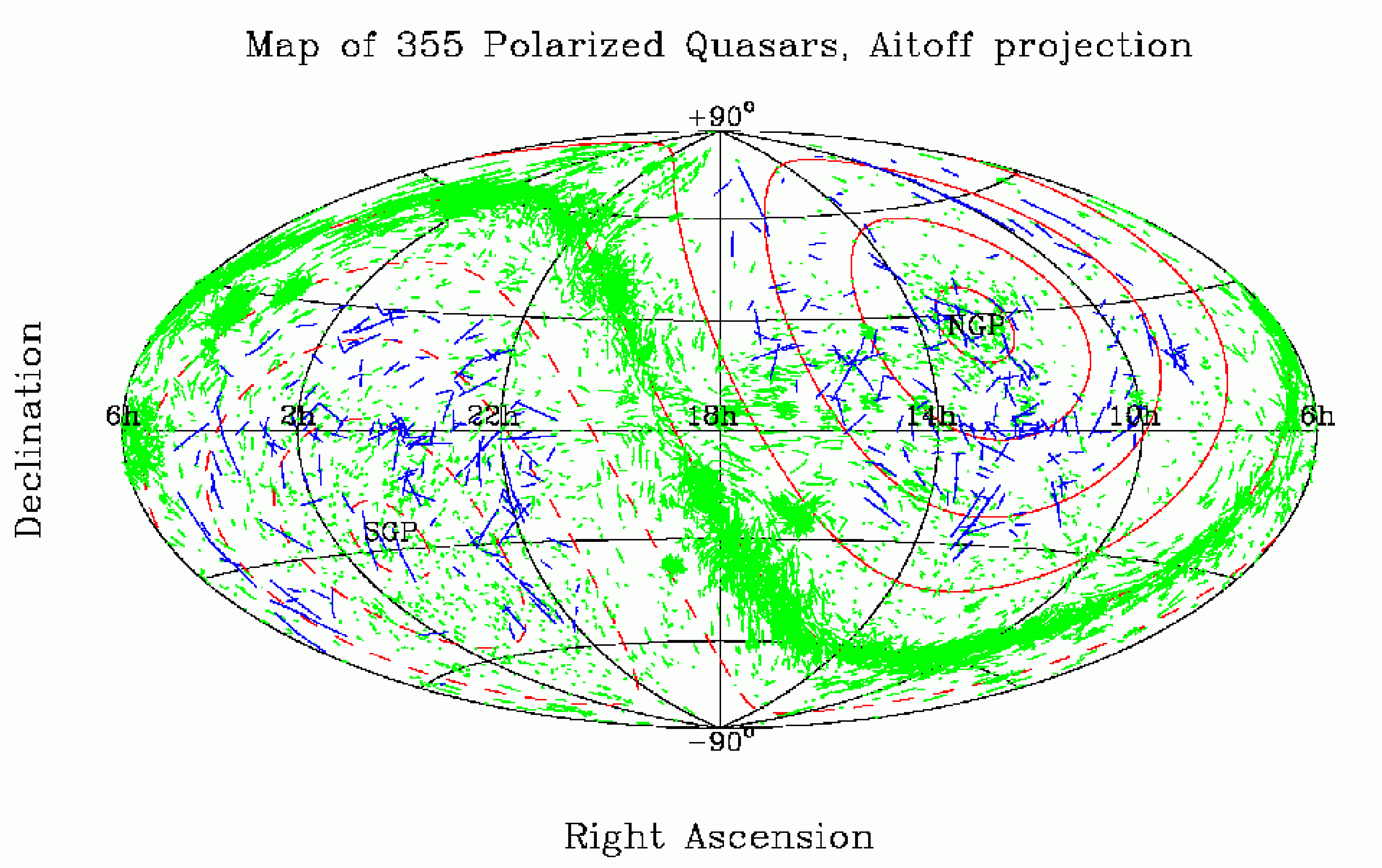

Upper limits
Detections
Detections
2.728K Blackbody
Microwave
IR
Optical
UV
X−ray
γ−ray
Radio
10000
100
1
0.01
0.0001
1e−12
1e−08
0.0001
1
10000
1e+08
1e+12
Iλ (CUs) (= photons s−1 cm−2 ster−1 Å−1)
λ0 (Å)

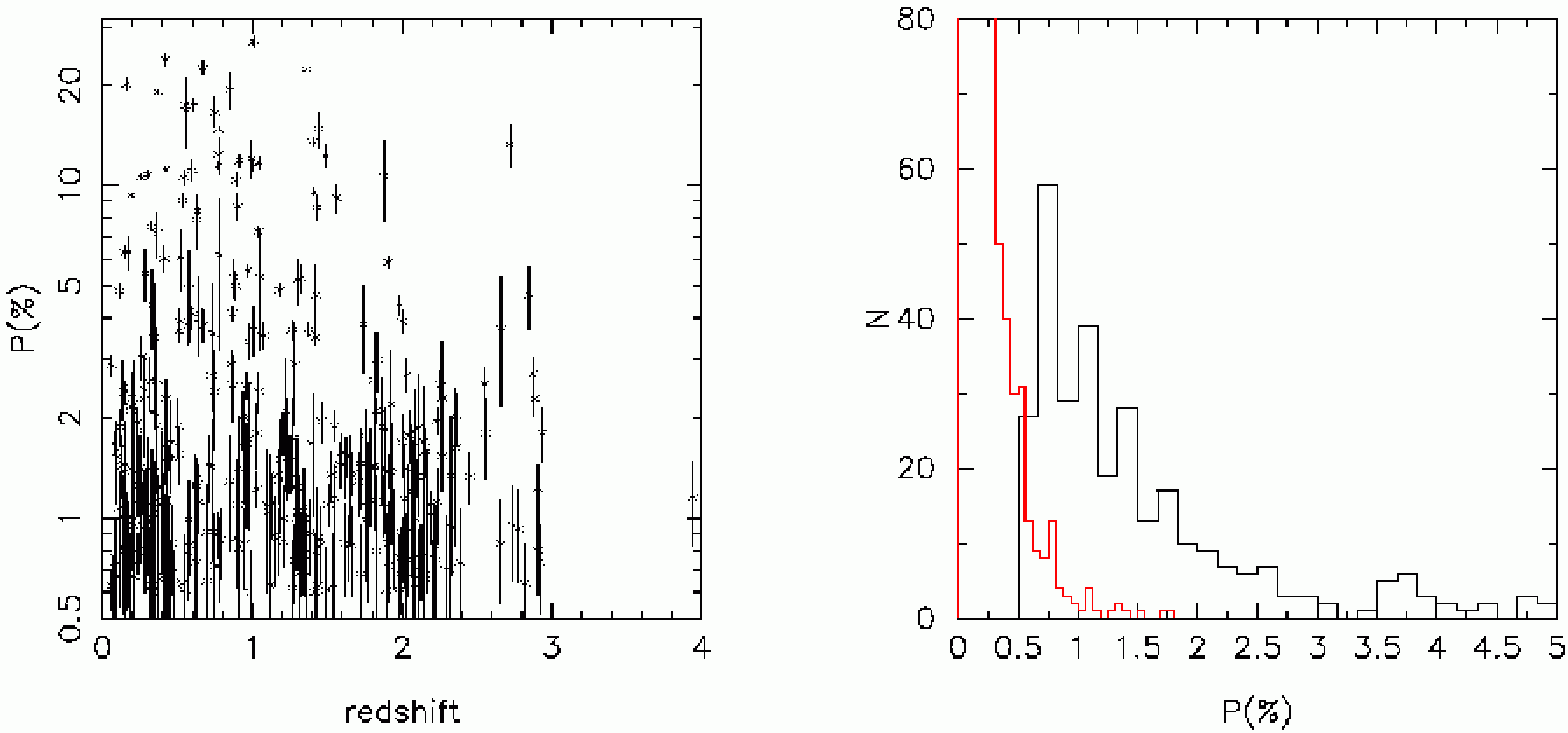


$m_a c^2$ = 8 eV
$m_a c^2$ = 5 eV
$m_a c^2$ = 3 eV
EdS
LW76
SS78
D79
T83
J84
BK86
T88
M90
H98
WR00
C01
B02
100000
10000
1000
I_λ (CUs)
10000
100000
λ_0 (Å)

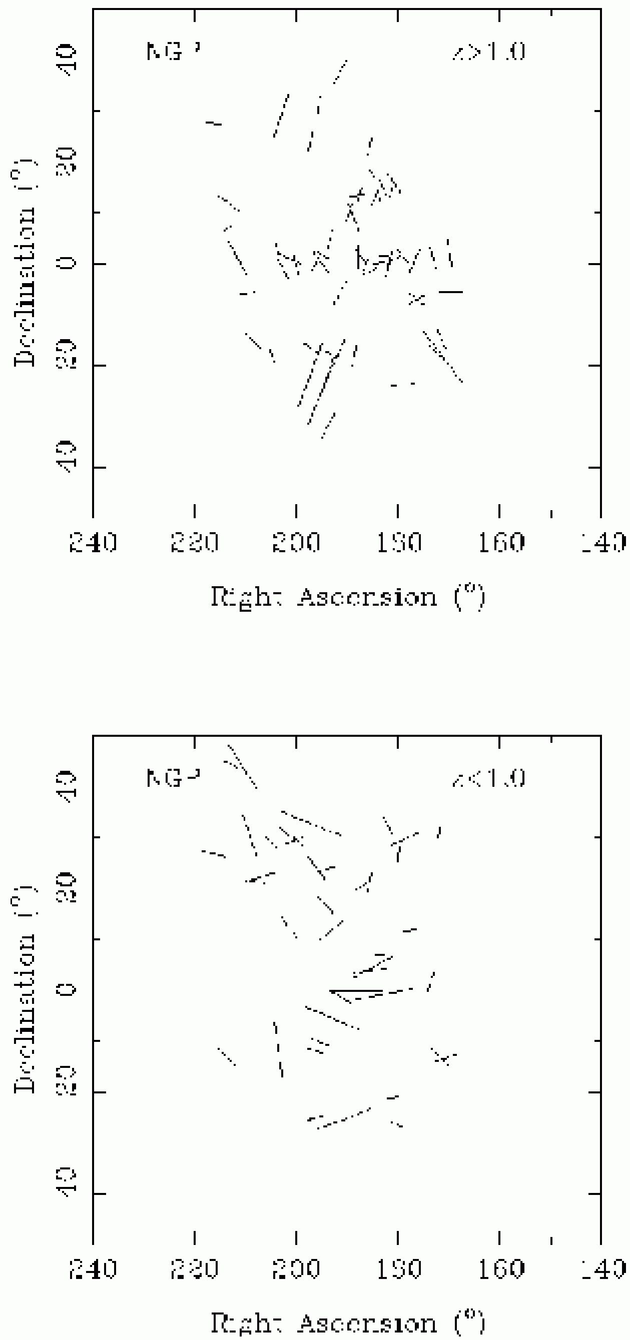


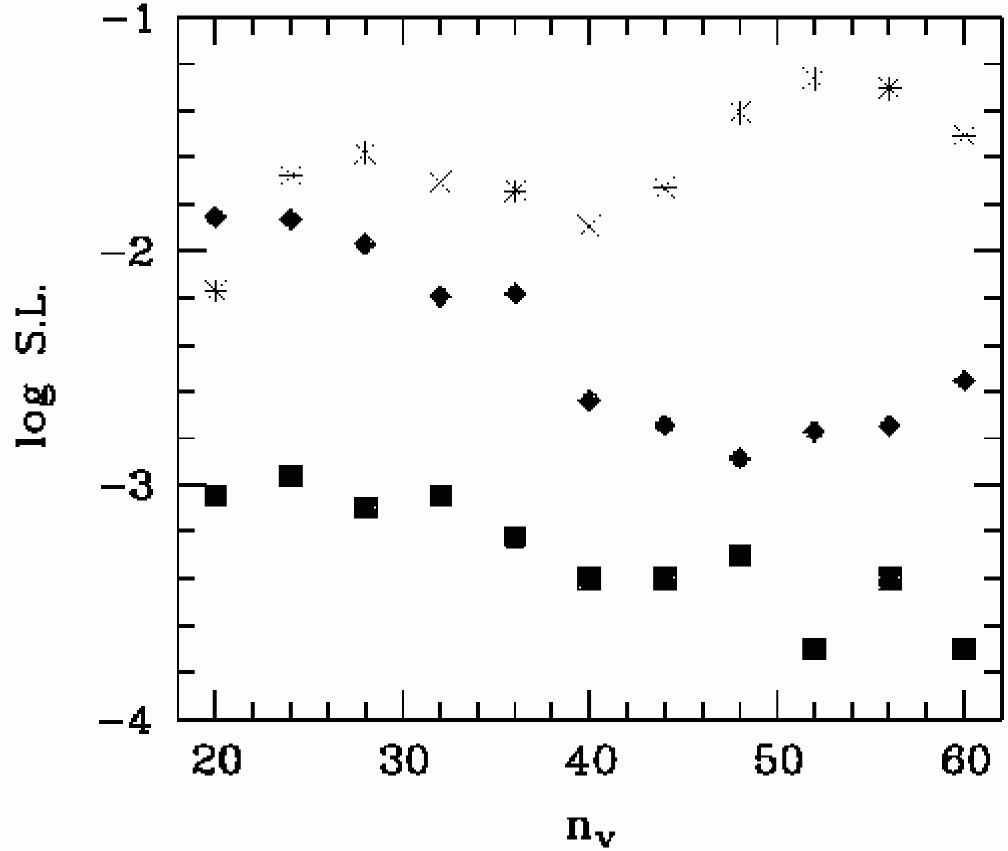
X-ray surface brightness [DN/pixel]
10^4
10^3
10^2
0.6
0.8
1
1.2
1.4
1.6
1.8
2
R⊙
Yohkoh SXT
26 Aug 1992
Yohkoh SXT
8 May 1992
Solar Axion
Simulation

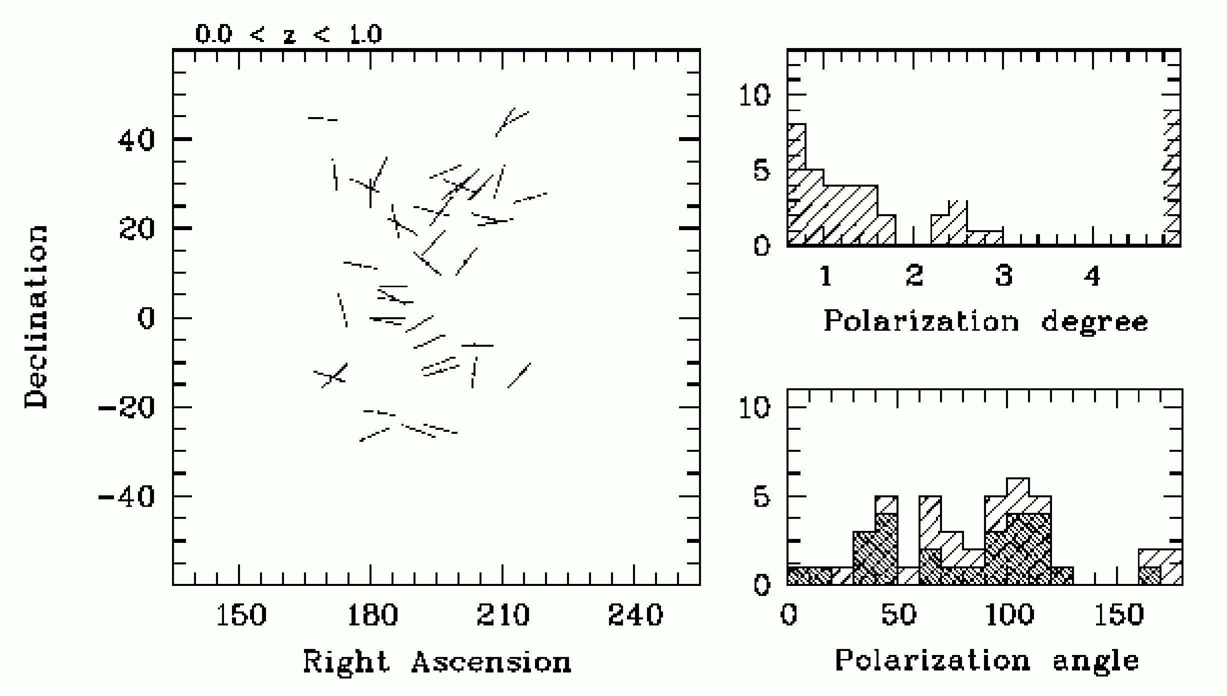

Map of 355 Polarized Quasars, Aitoff projection
+90°
-90°
6h
2h
22h
18h
14h
10h
6h
NGP
SGP
Declination
Right Ascension

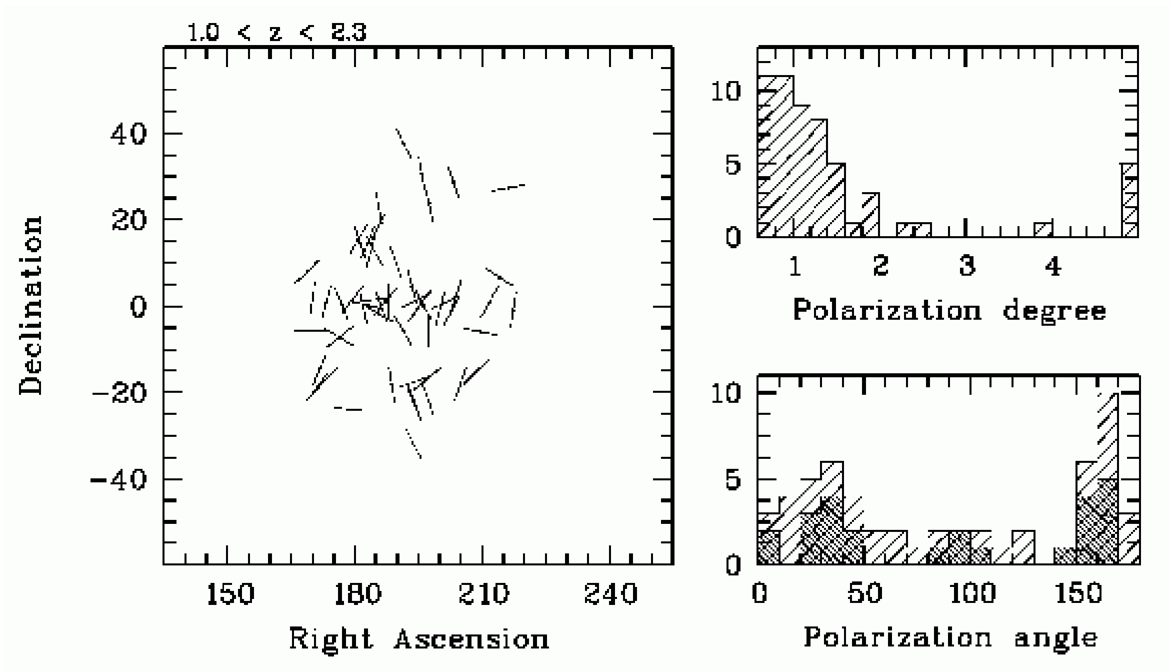


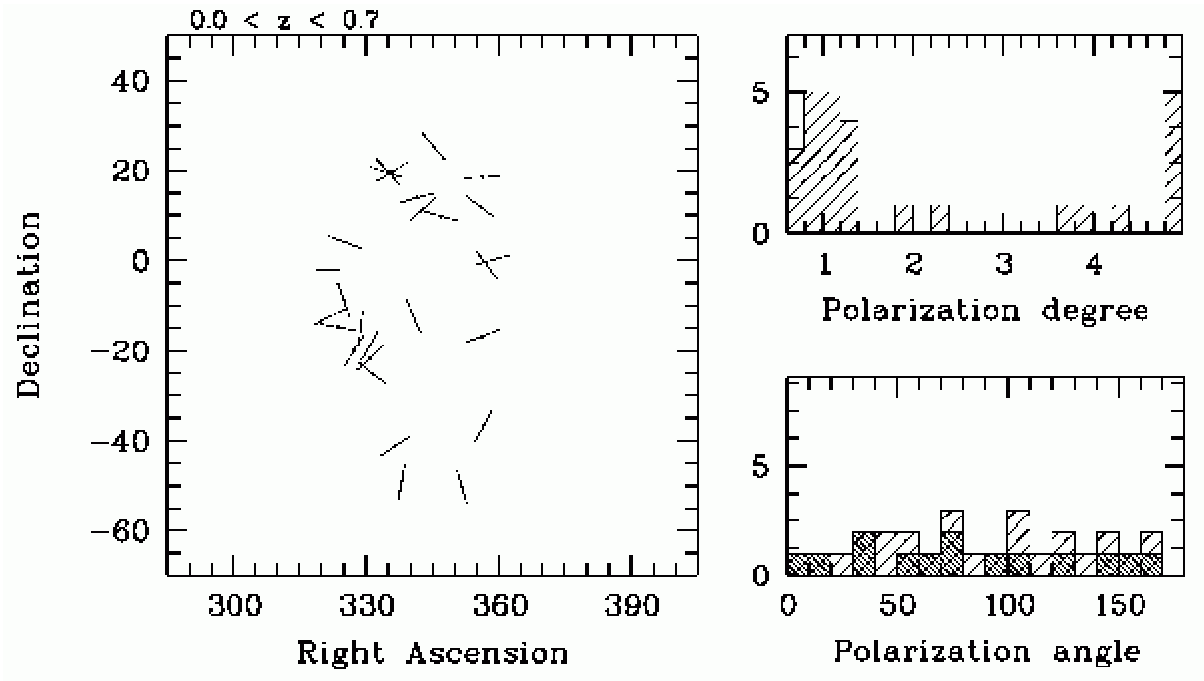
P(%)
0.5
1
2
5
10
20
0
1
2
3
4
redshift
N
0
20
40
60
80
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
P(%)

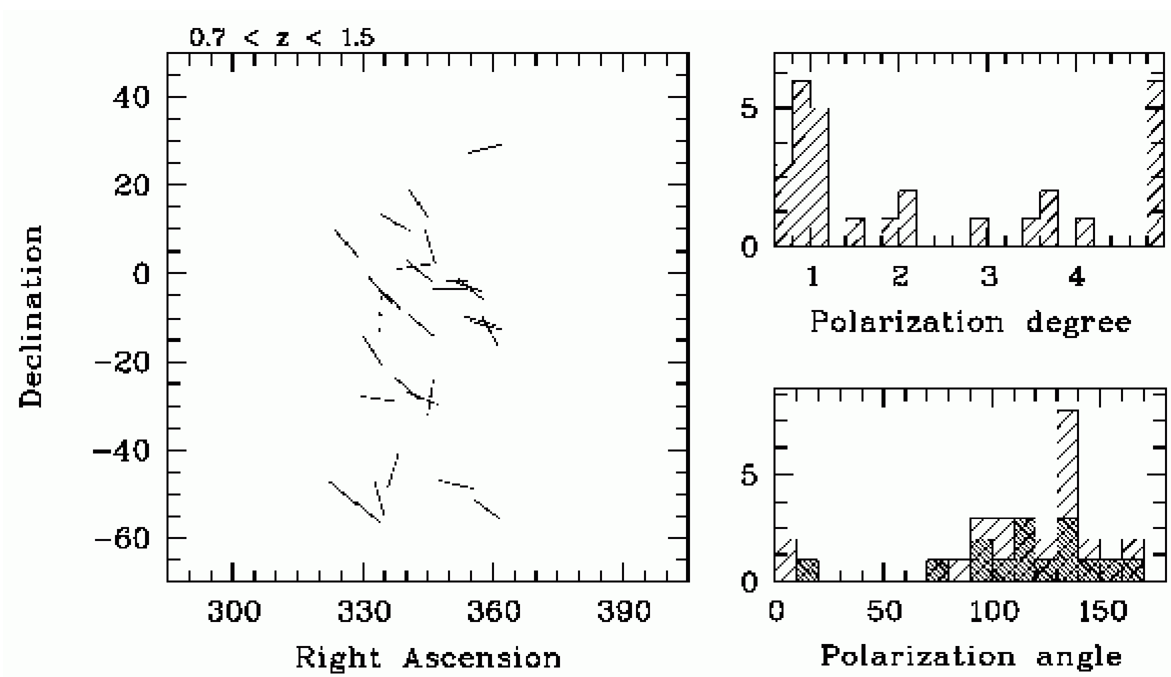

NGP
z>1.0
NGP
z<1.0
Declination (°)
Right Ascension (°)
40
20
0
20
40
240
220
200
180
160
140

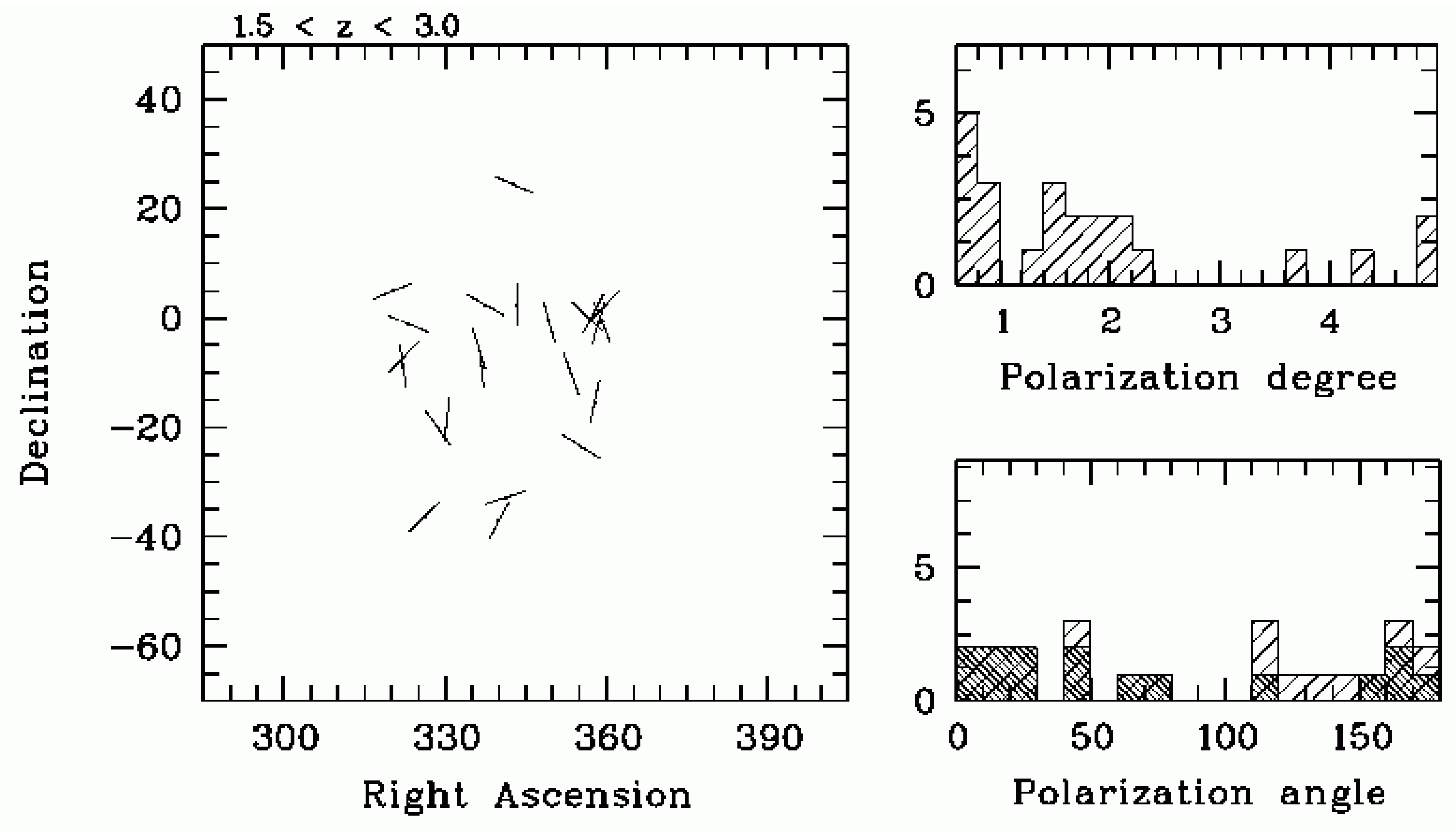

log S.L.
n_v
−1
−2
−3
−4
20
30
40
50
60


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

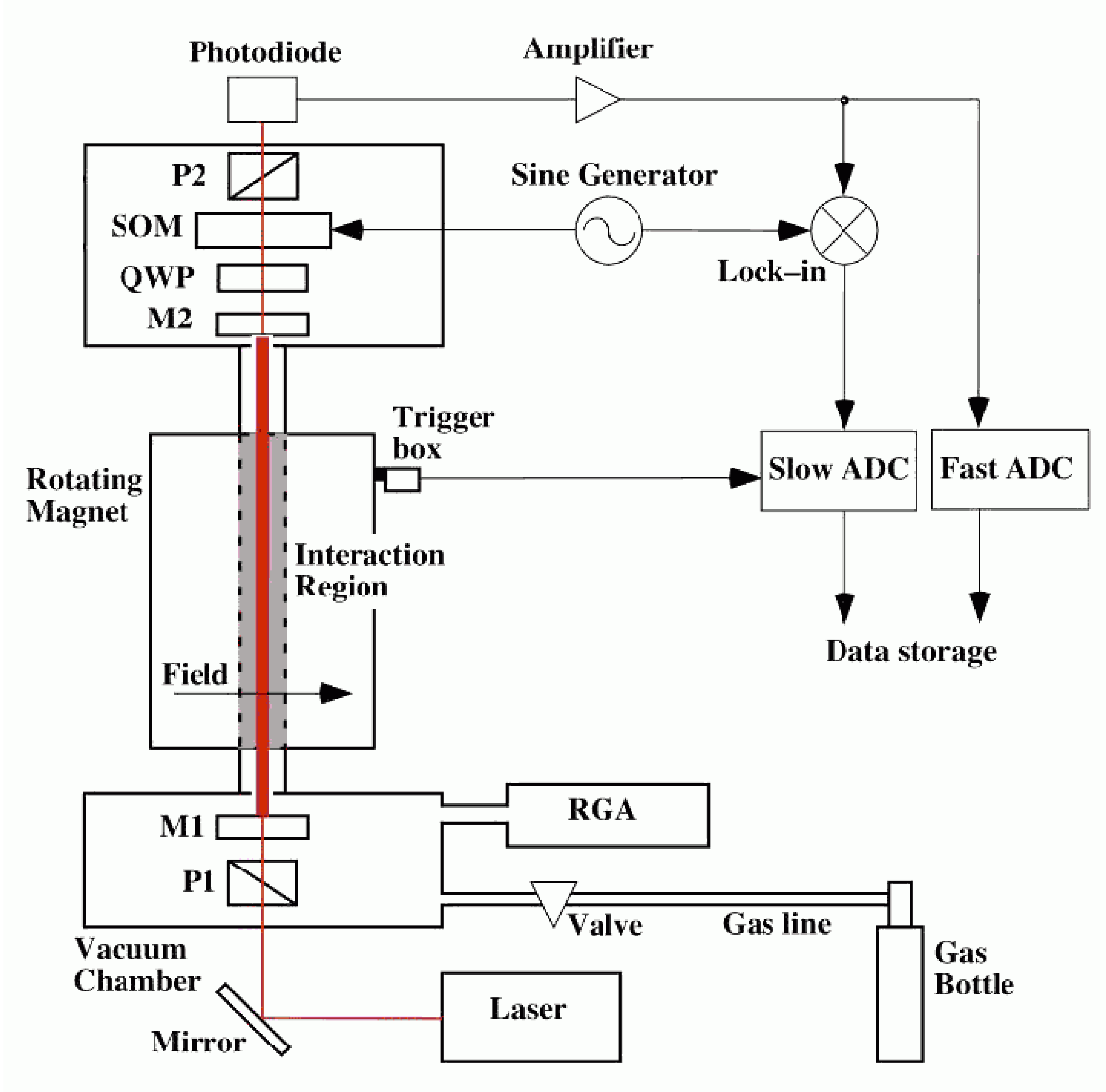

1.0 < z < 2.3
Declination
Right Ascension
Polarization degree
Polarization angle


0.0 < z < 0.7
Declination
Right Ascension
Polarization degree
Polarization angle


0.7 < z < 1.5
Declination
Right Ascension
Polarization degree
Polarization angle



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


Photodiode
Amplifier
P2
SOM
QWP
M2
Sine Generator
Lock–in
Trigger
box
Rotating
Magnet
Slow ADC
Fast ADC
Interaction
Region
Data storage
Field
RGA
M1
P1
Valve
Gas line
Vacuum
Chamber
Gas
Bottle
Laser
Mirror

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):

$$-\frac{1}{M_s} f F^{mn} F_{mn} ,$$

where F is the tensor of electromagnetic field and f is a scalar field.

The theory gives the following expression for probability of conversion of definitely polarized photons $W_{\|}$ into scalar particles (Raffelt and Stodolsky (1988), Gnedin (1994)):

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

where B is the magnetic field strength, L_{coh} is the coherence length of magnetic field, $L_B = 2p M_s / B$ and $L_p = 2pw / w_p^2$ 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 $L_B, L_p < 2pw/m_f$ takes place, where m_f 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:

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

if the condition takes $BL_{coh} \ll M_s$.
The degree of linear polarization p_l can be easily found by

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

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

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

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

where w_p is the plasma frequency.

Axion Birefrigence

$$q = \frac{1}{8} g_{ag}^{2} B_{\perp}^{2} L^{2}$$

$$e = \frac{\left(g_{ag} B_{\perp} m_{a}\right)^{2}}{48w} L^{3}$$

Weakly Interacting Massive Particles

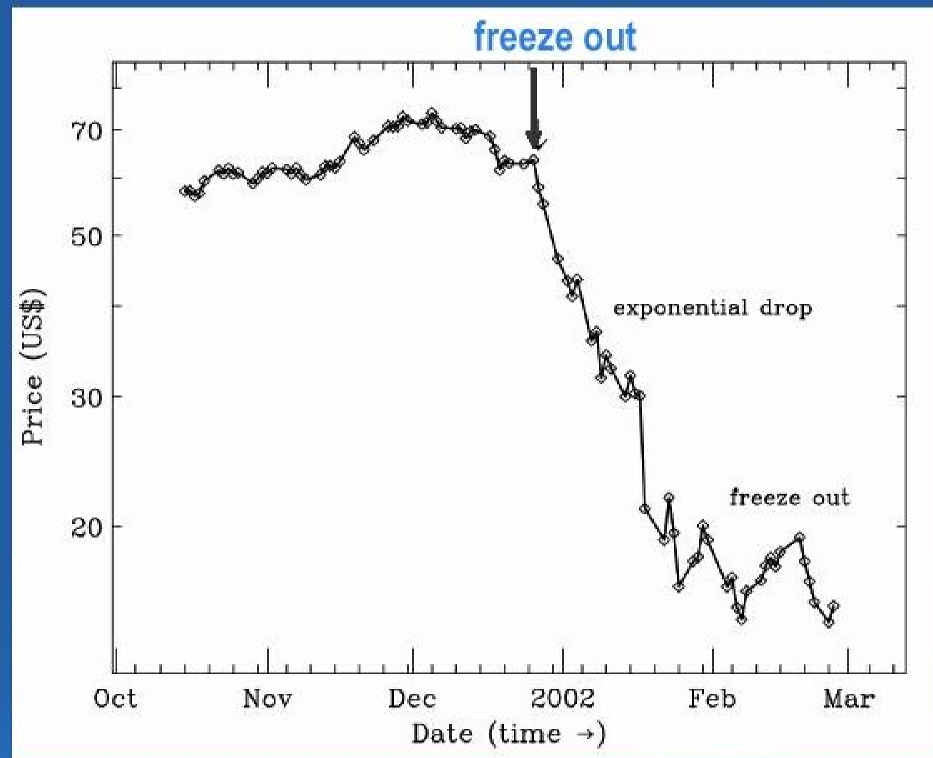
Particles in thermal equilibrium
Decoupling when non-relativistic

Freeze out when annihilation rate
≈ expansion rate

Relic abundance:
$\Omega_\chi h^2 \approx 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1} / \langle \sigma_{ann} v \rangle$

if m and $_{ann}$ determined by electroweak physics, then ~ 1

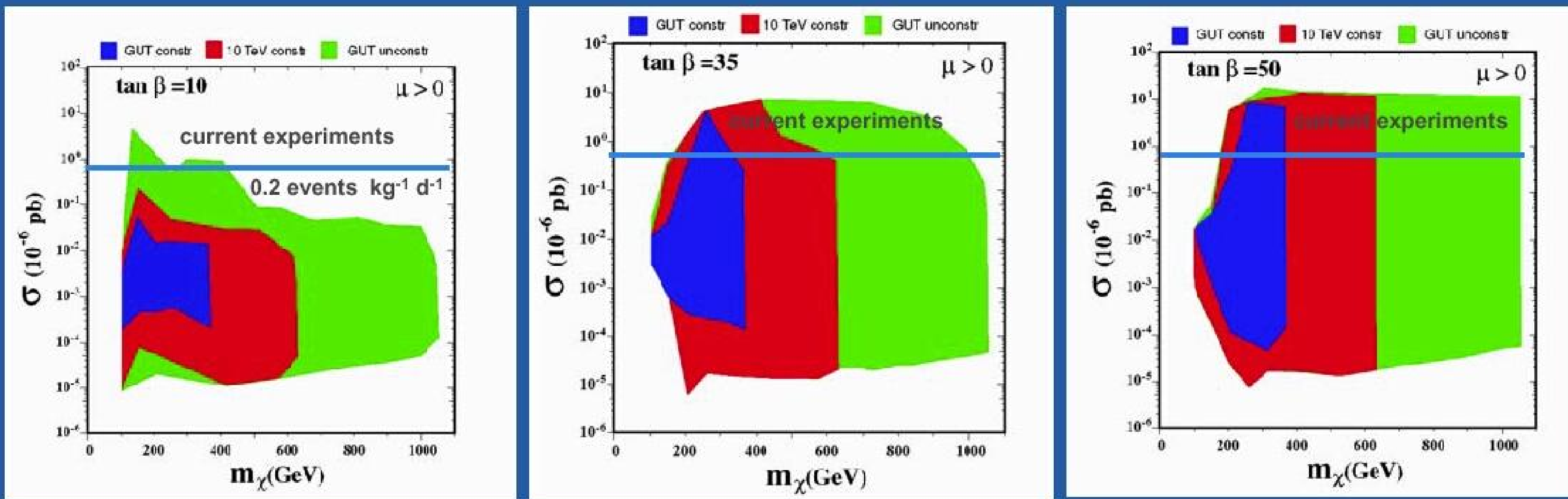
Martha Stewart sells ImClone stock



J.Feng astro-ph/0405479

WIMP nucleus cross section

In MSSM/CMSSM (neutralino):



Ellis, Olive, Santoso, Spanos: hep-ph/0308075

- No tachyons before GUT scale
- No tachyons before 10 TeV
- No constraints: low energy effective SUSY

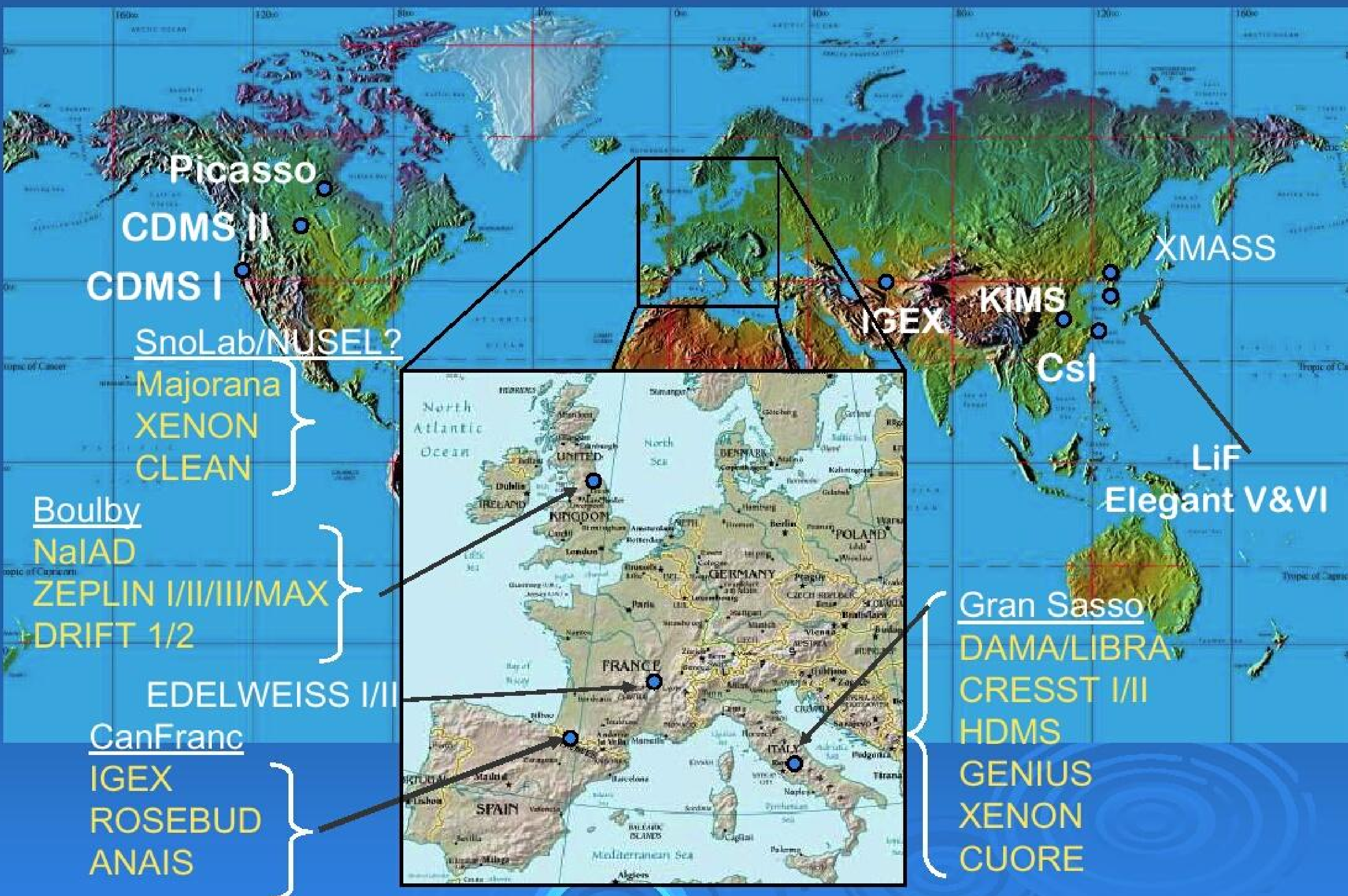
WIMPs:

10^6 per second through your thumb without being noticed!

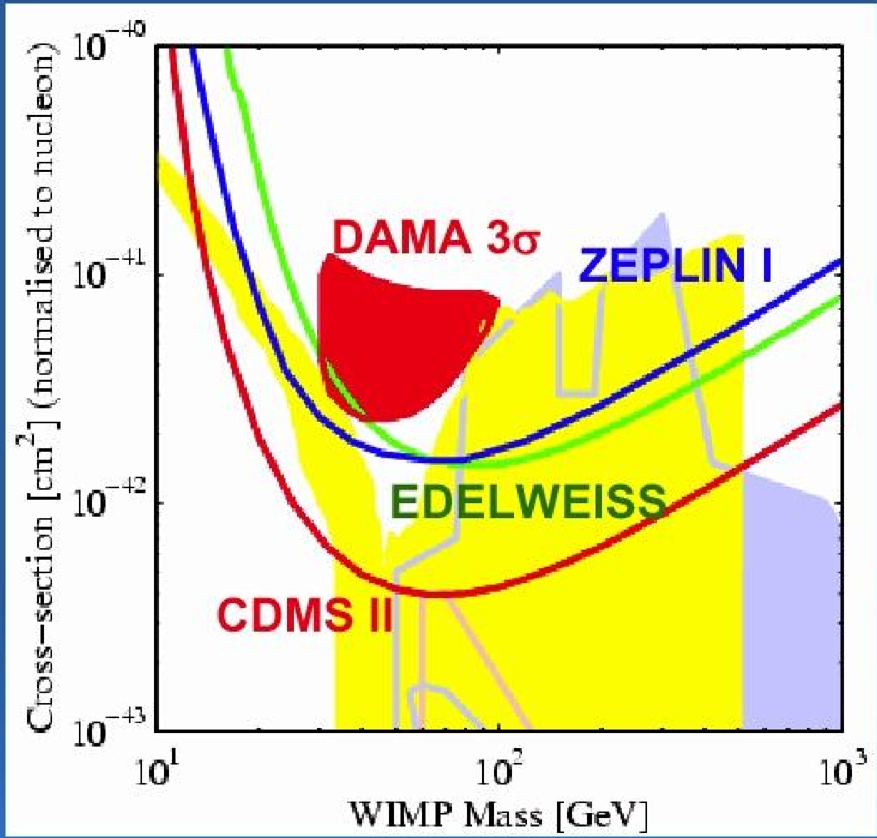
10^{15} through a human body each day: only < 10 will interact, the rest is passing through unaffected!

If their interaction is so weak, how can we detect them?

World Wide WIMP Search



Where do we stand?



~ 0.2 events/kg/day

Most advanced experiments start to test the predicted SUSY parameter space

One evidence for a positive WIMP signal (DAMA NaI)

Not confirmed by other experiments

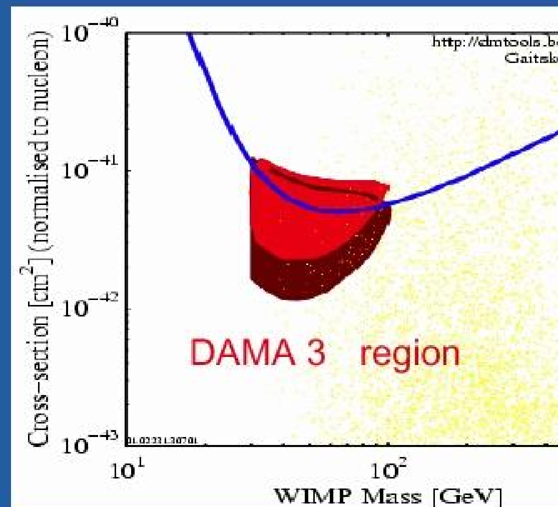
Predictions: Ellis & Olive, Baltz & Gondolo, Mandic & all

The DAMA experiment

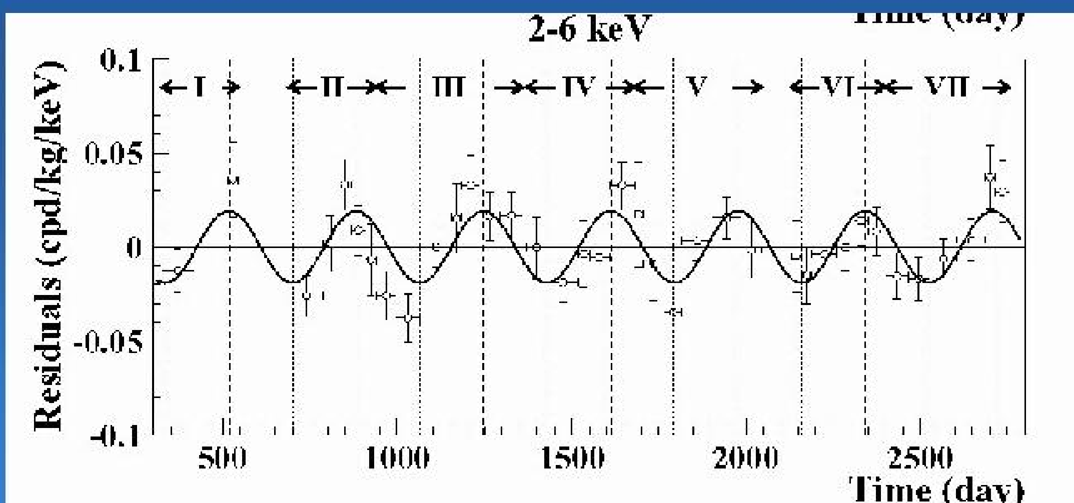
At Gran Sasso (3800 mwe)
9 x 9.7 kg low activity NaI crystals, each viewed by 2 PMs (5-7 pe/keV)

Annual modulation analysis:

7 annual cycles: 107731 kg x days
positive signal (6.3 CL)
(astro-ph/0307403, Riv. N. Cim. 26, 2003)



A cos [(t-t_0)]; t_0 = 152.5 d; T = 1yr A = 0.0195 +/- 0.031 dru



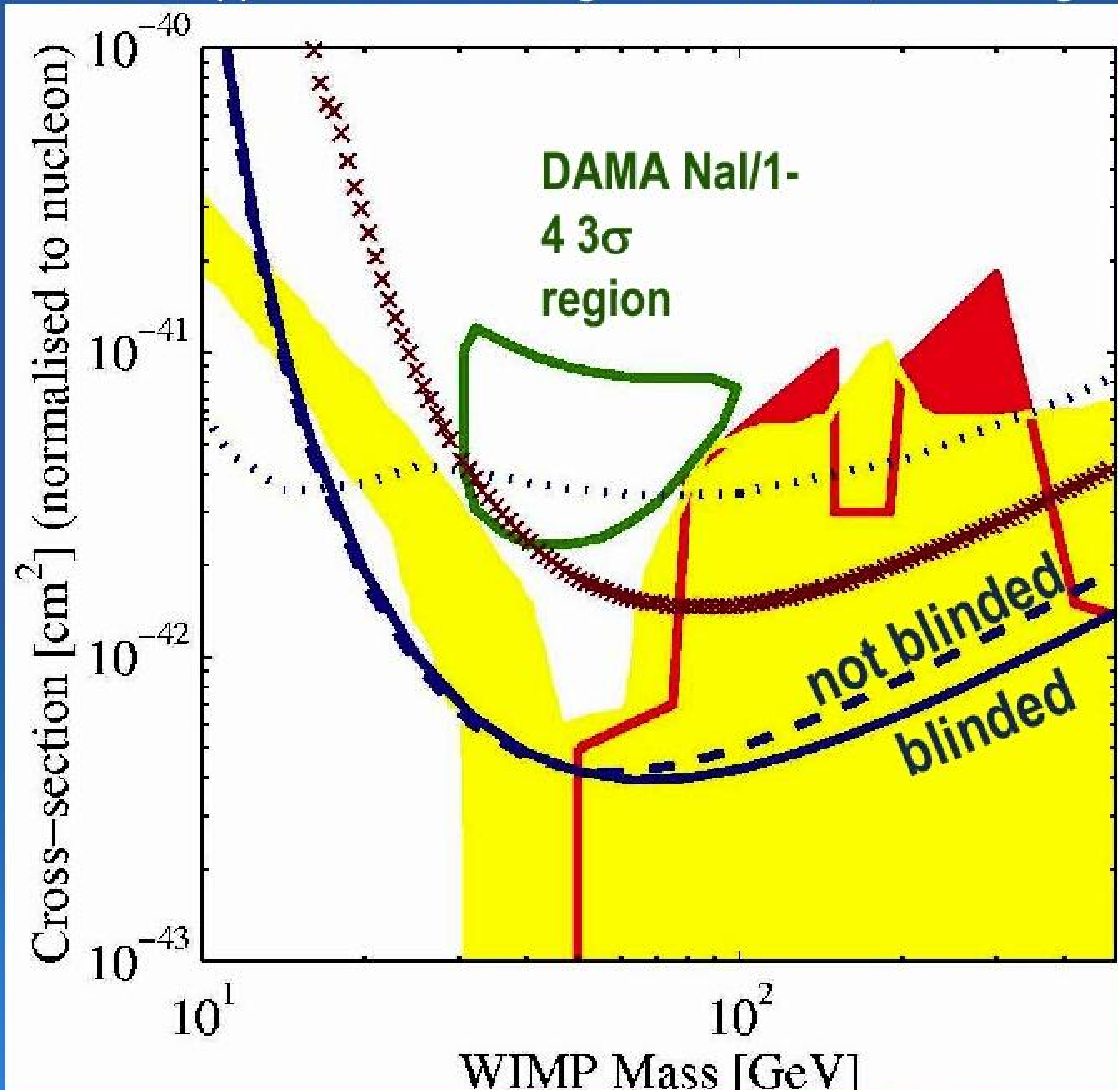
Studied variations of:
T, P(N_2), radon, noise,energy scale, n-background, -background

WIMPs? UNCLEAR!

Efficiency?
Shape of energy spectrum?
Stability?…

Resulting experimental upper limits

90% CL upper limits assuming standard halo, A^2 scaling



Upper limits on the WIMP-nucleon cross section are 4 10^{-43} cm^2 for WIMP mass of 60 GeV/c^2

Phys. Rev. Lett. 93, 211301, (2004)

Factor of 4 below best previous limits (EDELWEISS)

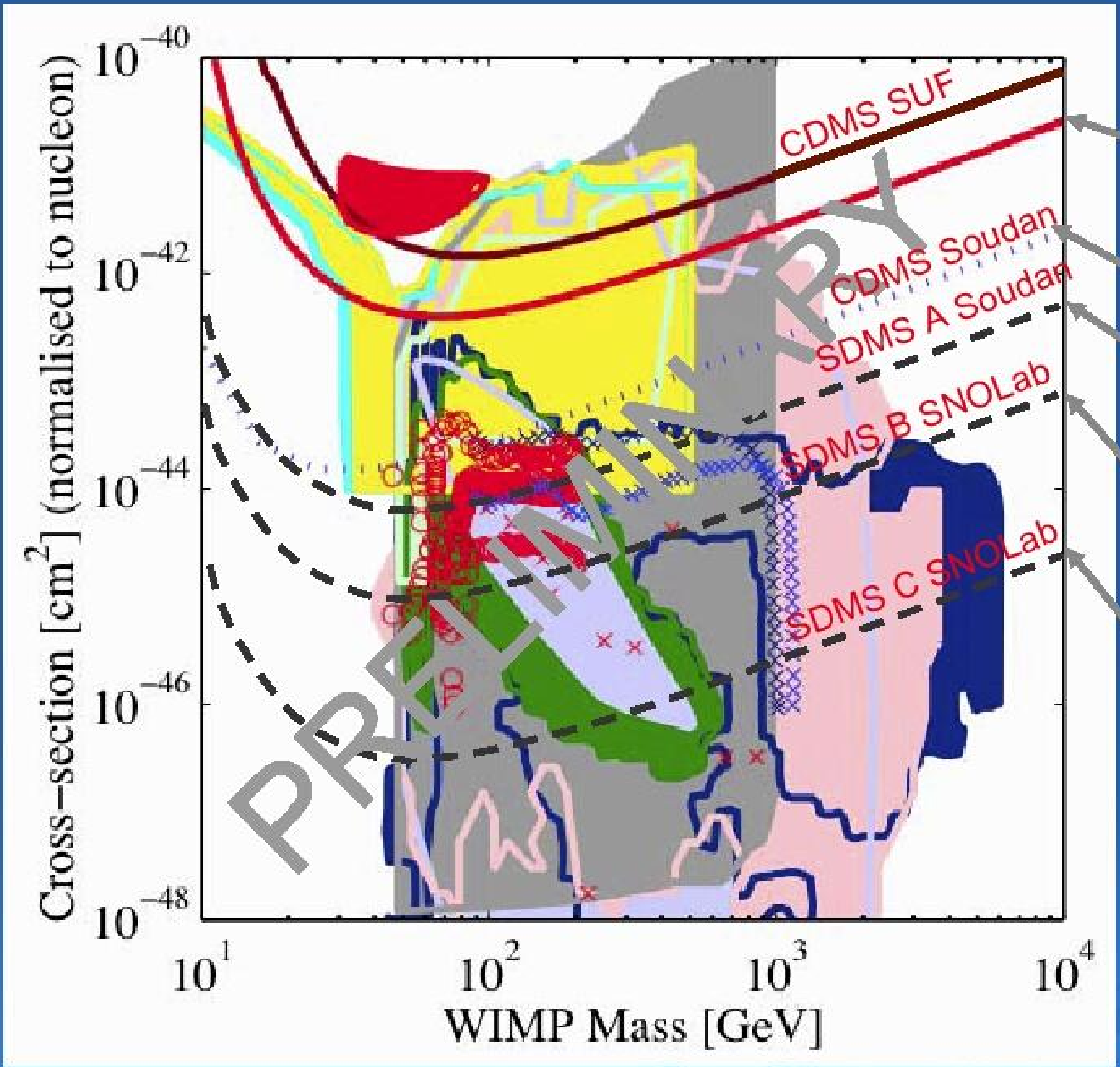
Factor of 8 below CDMS-SUF

Excludes large regions of SUSY parameter space and DAMA

Bottino et al. 2004 in yellow
Baltz&Gondolo 2003 in red

(poster 2531, J. Filippini, SD limits)

SuperCDMS Reach



CDMS II 2004

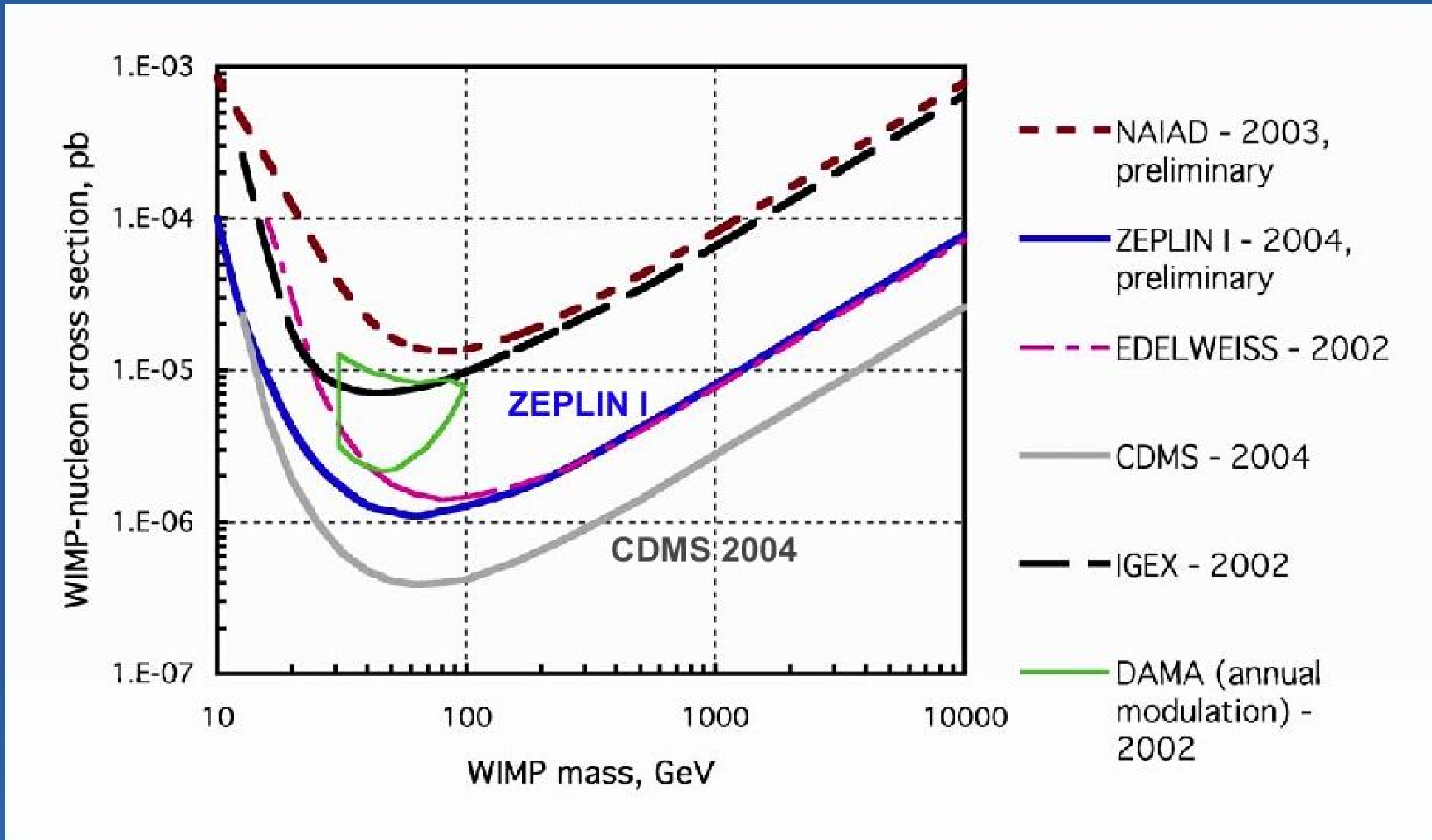
CDMS II goal 2006

SuperCDMS Phase A
25 kg of Ge 2008

SuperCDMS Phase B
150 kg of Ge 2011

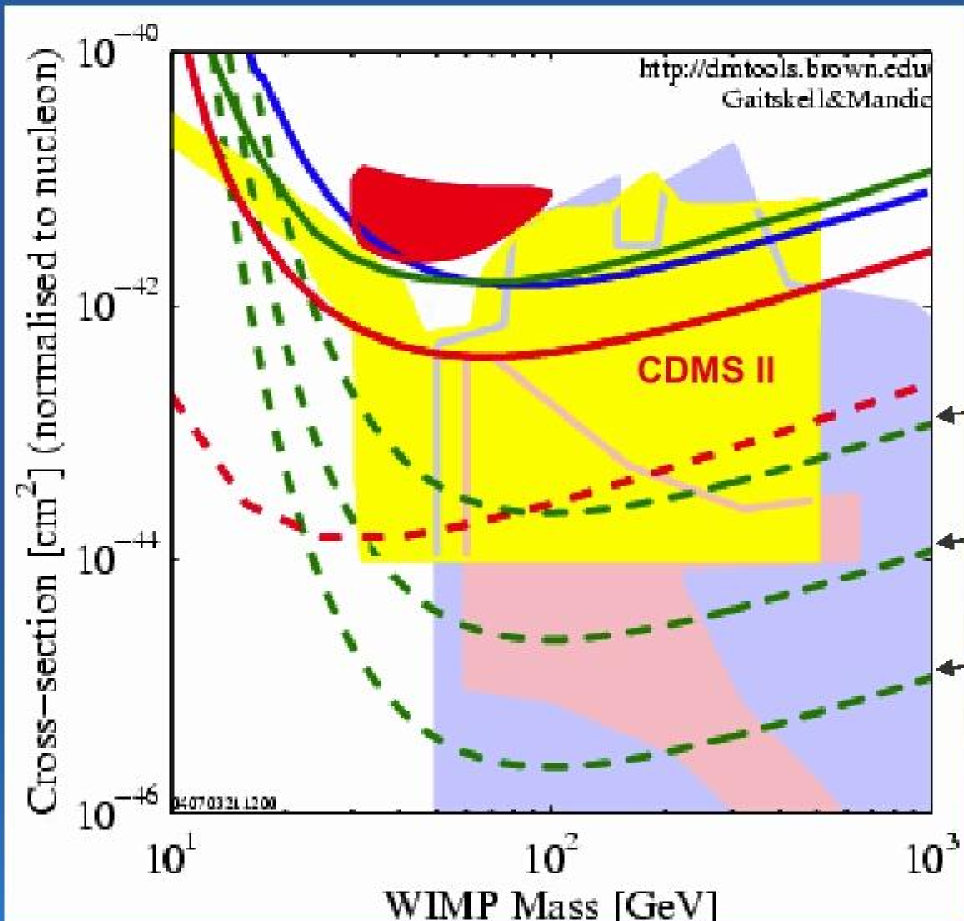
SuperCDMS Phase C
1000 kg of Ge 2018

ZEPLIN I limits (preliminary)



Spin-independent interactions

The XENON Project



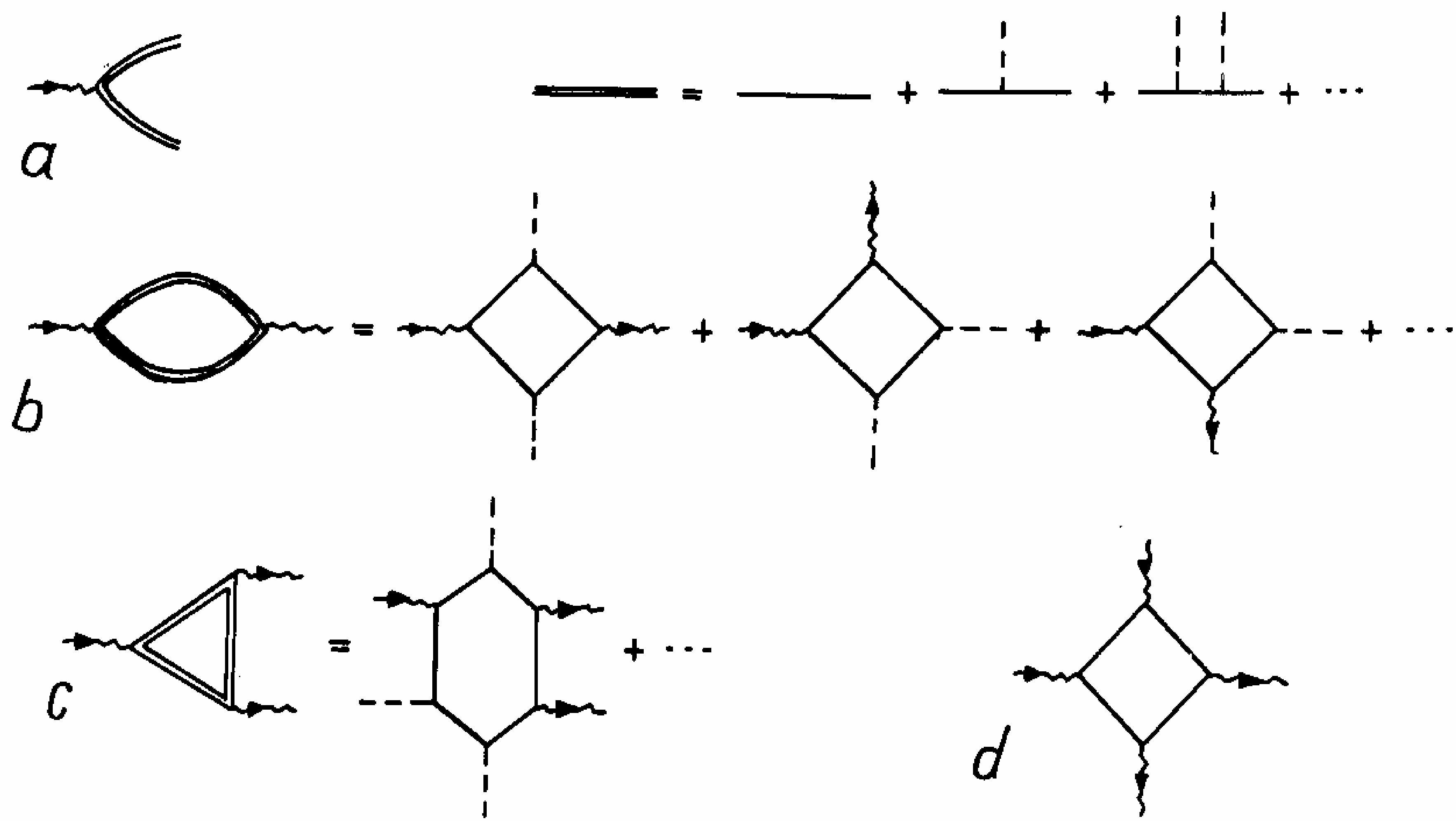
Modular design:

10 LXe modules: ~ 60cm ø, 60 cm h
each 100 kg active Xe mass

XENON: 10 kg

XENON: 100 kg

XENON: 1 ton, no backgrounds


a
b
c
d

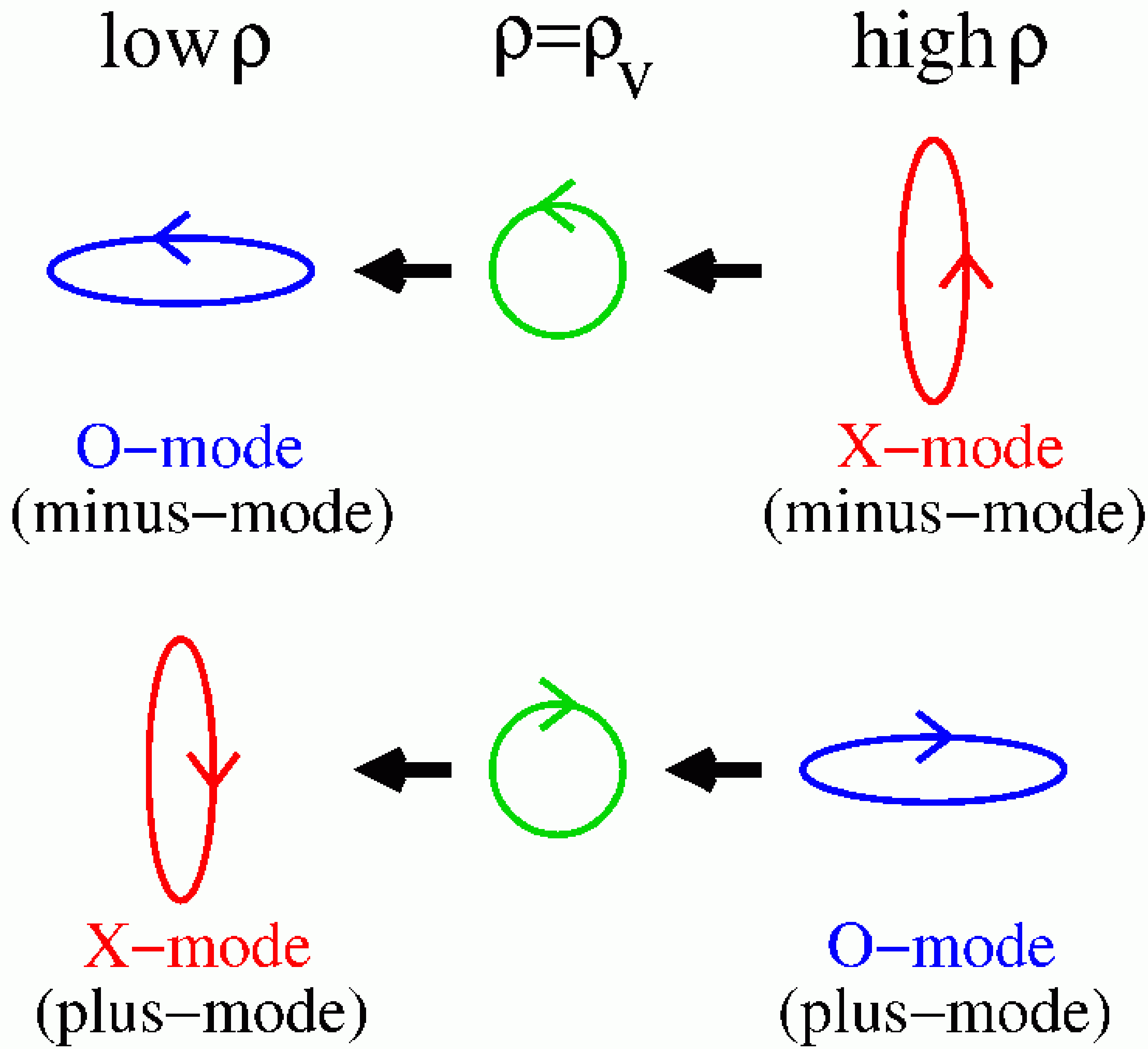
$$q = \frac{4GM}{r c^2} + \frac{5p\, a B_0^2 r_0^6}{r^6} \qquad B \geq B_C = \frac{m_e^2 c^3}{e\mathbf{h}} = 4.414 \times 10^{13} G$$

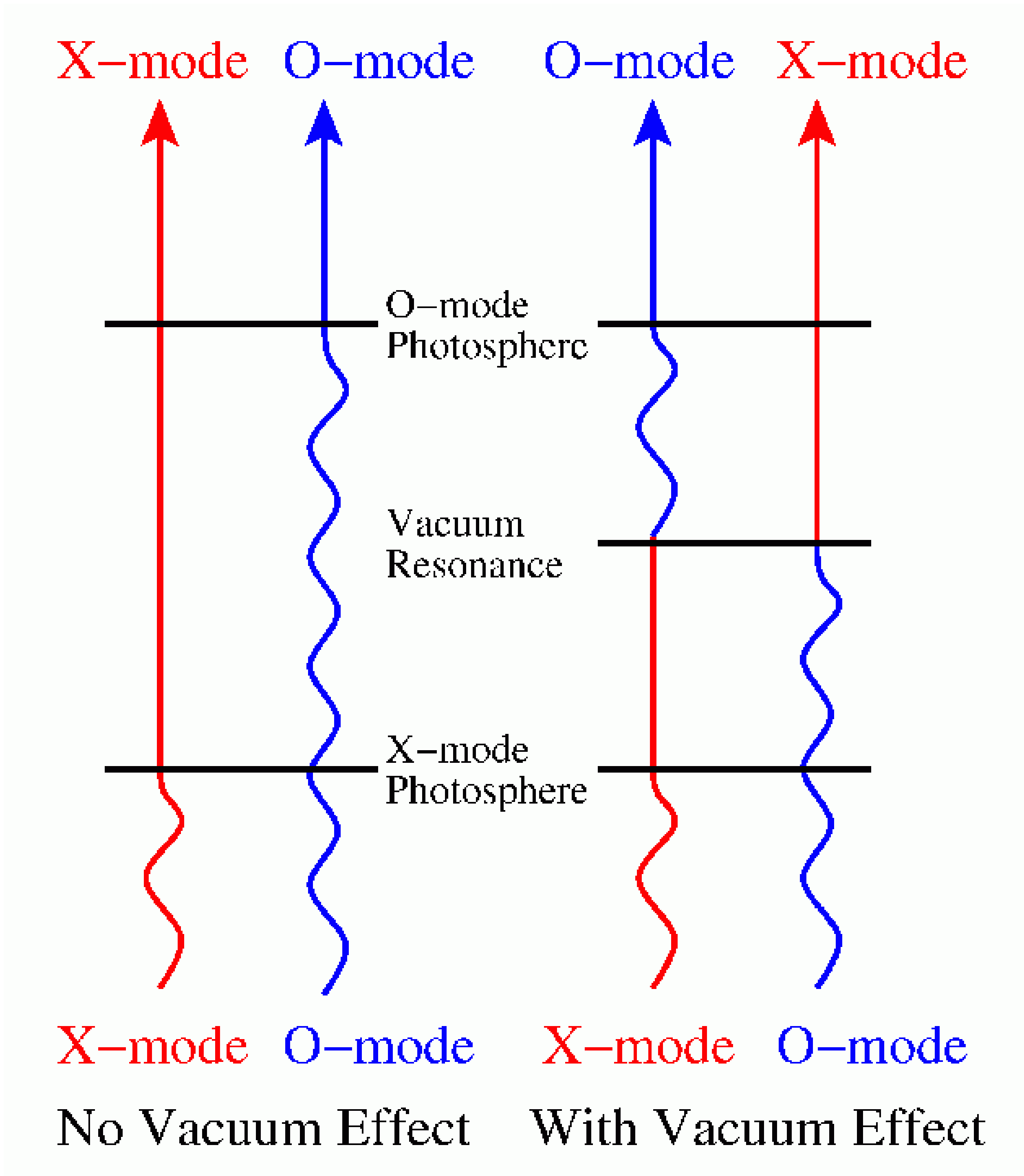
$$n_1 = 1 + \frac{7}{90p} \frac{e^2}{\mathbf{h}c} \left(\frac{B_\perp}{B_C} \right)^2 ; n_2 = 1 + \frac{2}{45p} \frac{e^2}{\mathbf{h}c} \left(\frac{B_\perp}{B_C} \right)^2$$

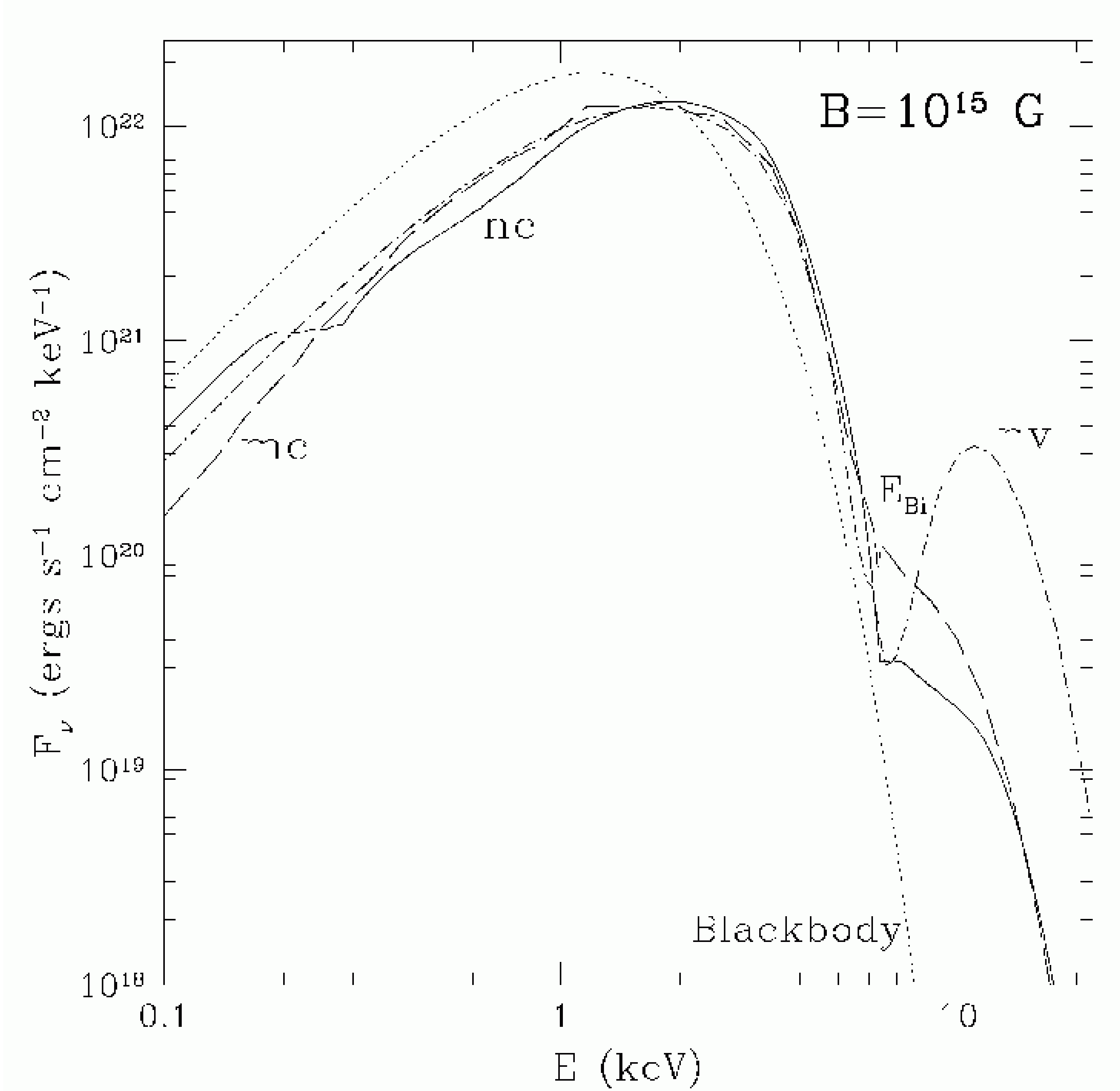
$$j = \frac{w}{c} \int |n_1 - n_2| dl = \frac{l}{5 \times 10^{-7} cm} \frac{\mathbf{h}w}{m_e c^2} \left(\frac{B_\perp}{B_C} \right)^2 \qquad j = 1.2 \left(\frac{\mathbf{h}w}{3eV} \right) \left(\frac{B_\perp}{4 \times 10^8 G} \right)^2 \left(\frac{R_{WD}}{10^9 cm} \right)$$

$$NS : E_V = 0.24 \left(\frac{Y_e N_V}{6 \times 10^{19}} \right)^{1/2} \left(\frac{10^{12}}{B} \right) KeV$$

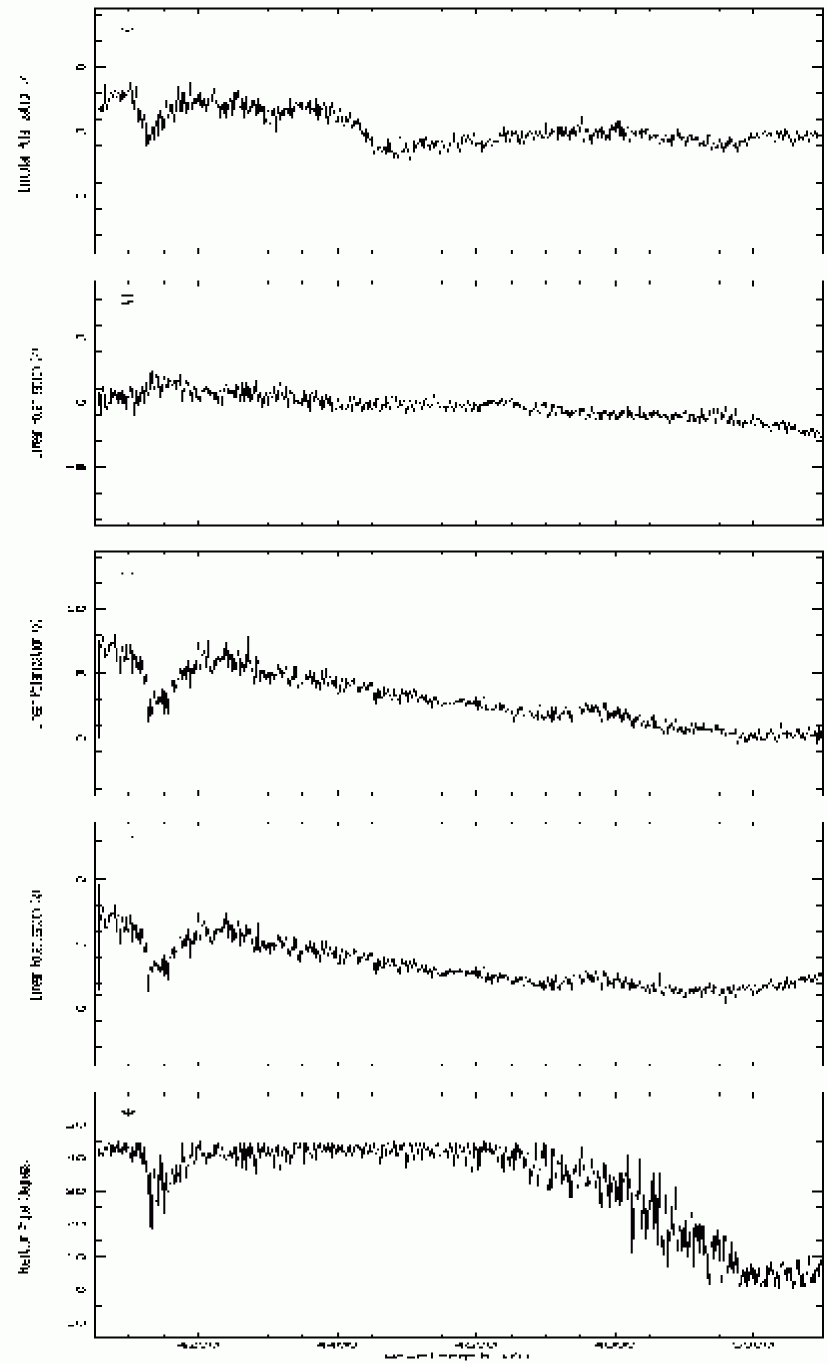
$$WD : l_V = 0.283 \left(\frac{10^8}{Y_e N_V} \right)^{1/2} \left(\frac{B}{3 \times 10^8} \right) mm$$

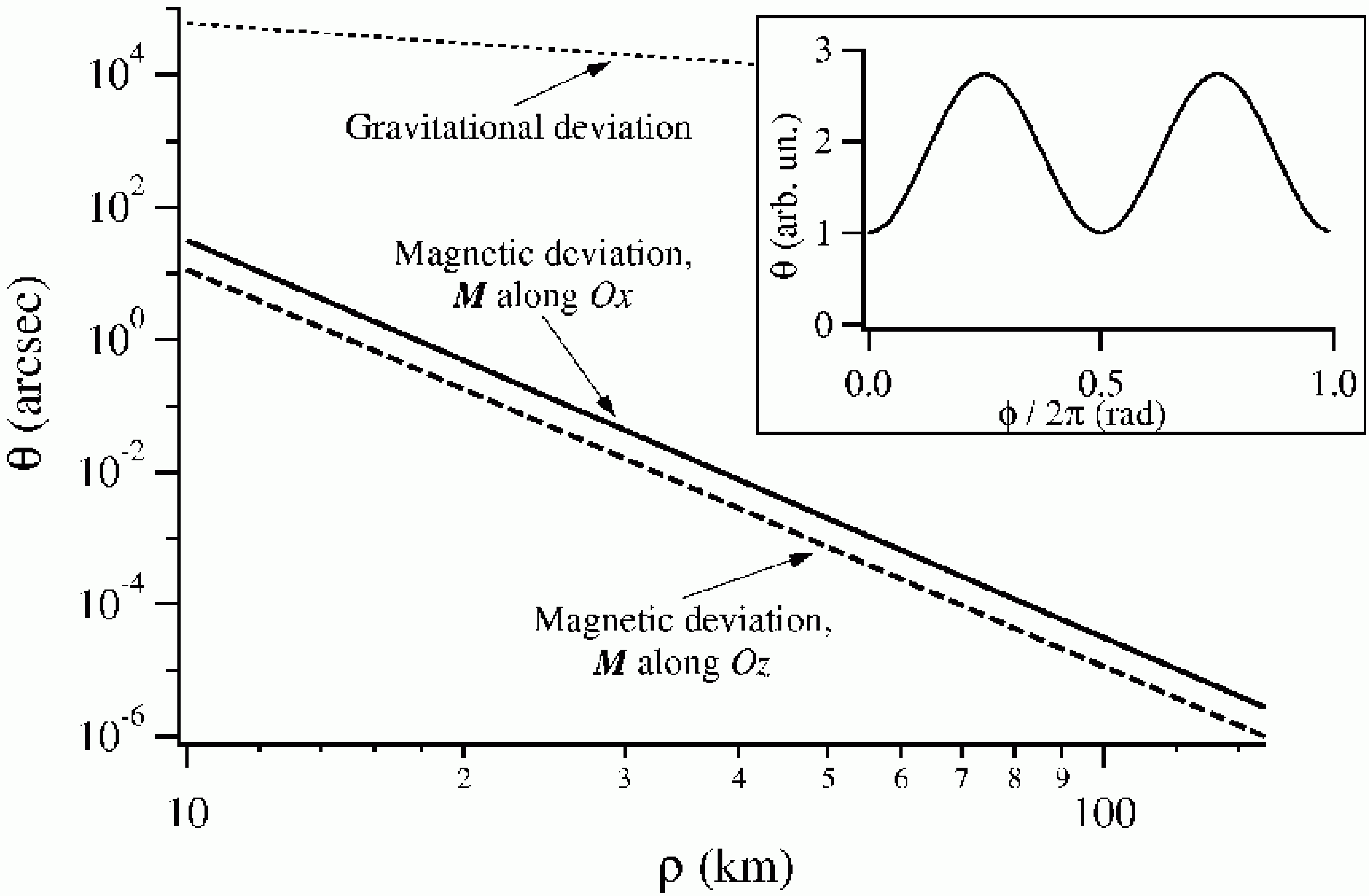

low ρ
ρ=ρ$_V$
high ρ
O−mode
(minus−mode)
X−mode
(minus−mode)
X−mode
(plus−mode)
O−mode
(plus−mode)


X−mode
O−mode
O−mode
X−mode
O−mode
Photosphere
Vacuum
Resonance
X−mode
Photosphere
X−mode
O−mode
X−mode
O−mode
No Vacuum Effect
With Vacuum Effect

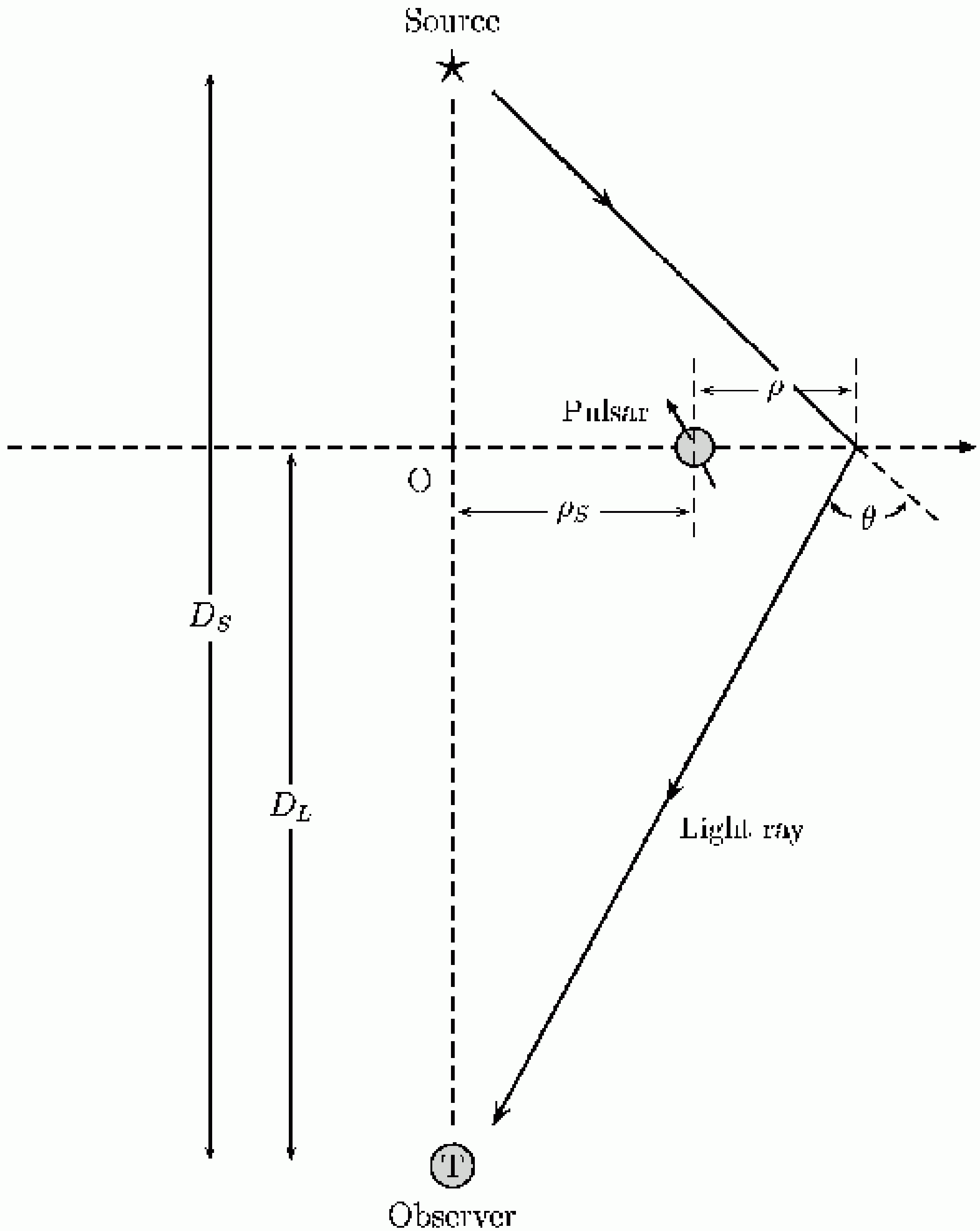


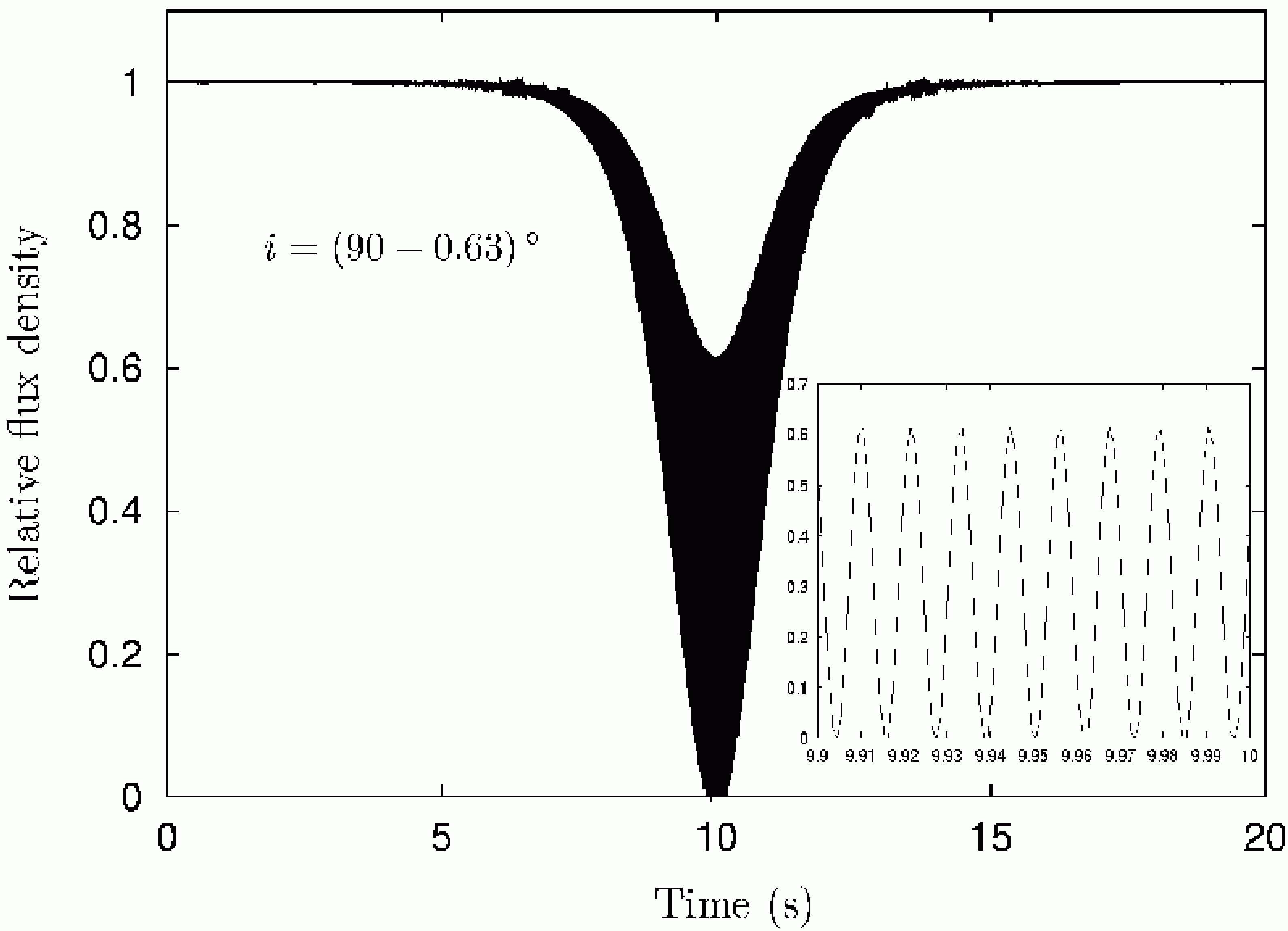
B=10^15 G
nc
mc
F_Bi
Blackbody
10^22
10^21
10^20
10^19
10^18
0.1
1
10
E (keV)
F_ν (ergs s^-1 cm^-2 keV^-1)





Gravitational deviation
Magnetic deviation,
M along Ox
Magnetic deviation,
M along Oz
θ (arcsec)
ρ (km)
10
100
θ (arb. un.)
φ / 2π (rad)


Source
Pulsar
ρ
ρ_S
O
θ
D_S
D_L
Light ray
Observer



Relative flux density
Time (s)
$i = (90 - 0.63)\,^\circ$
0
0.2
0.4
0.6
0.8
1
0
5
10
15
20
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
9.9
9.91
9.92
9.93
9.94
9.95
9.96
9.97
9.98
9.99
10