Demokritos
National Centre for Scientific Research

Axions
In QCD and Cosmology

George K. Fanourakis
Institute of Nuclear Physics – NCSR 'Demokritos'

Outline

- **The $U(1)_A$ Problem of QCD**
- **The QCD Vacuum and the Strong CP Problem**
- **A solution: $U(1)_{PQ}$ and Axions**
- **Invisible Axion Models**
- **Cosmological implications**
- **Experimental techniques**
- **The CERN Axion Solar Telescope (CAST)**
- **Concluding Remarks**

The U(1)$_A$ Problem

In the 1970's the strong interactions had a puzzling problem, becoming more clear with the development of QCD.

The QCD Lagrangian density for N flavors:

$$L = \sum_{n=1}^{N} \overline{\psi}_n \left(i\gamma^\mu \partial_\mu - g\gamma^\mu A_\mu^a t^a - m_n \right) \psi_n - \frac{1}{4} G^{a\mu\nu} G_{\mu\nu}^a$$

Where: $G_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a - g f_{abc} A_\mu^b A_\nu^c$

are the field strength tensors of the gluon fields: A_μ^a **,α=1,2,…,8**

t^a **are the generators of the group of rotations of the quark fields in the color space**

$$\psi_n \rightarrow e^{i\alpha_a(x) t^a} \psi_n$$

Defining the covariant derivative: $D_\mu = \partial_\mu - ieA_\mu^a t^a = \partial_\mu - ieA_\mu$

The Lagrangian becomes: ⇨

$$L = \sum_{n=1}^{N} \overline{\psi}_n \left(i\gamma^{\mu} D_{\mu} - m_n \right) \psi_n - \frac{1}{4} G^{a\mu\nu} G^{a}_{\mu\nu}$$

The QCD Lagrangian is invariant under $SU(3)_c$, but it has also, in the limit of $m_n \to 0$, a global symmetry:

$U(N)_V x U(N)_A$

$$\psi_n \to e^{i\alpha_a \frac{t^a}{2}} \psi_n \qquad \psi_n \to e^{i\alpha_a \gamma_5 \frac{t^a}{2}} \psi_n$$

Vector **Axial Vector**

U(1) axial symmetry, because the associated Noether current:

$$j_A^{a,\mu}(x) \equiv \overline{\psi}(x) \gamma^{\mu} \gamma_5 t^a \psi(x)$$ **is an axial vector**

In reality only u and d quarks are approximately zero

We expect the strong interactions to be approximately $U(2)_V x U(2)_A$ invariant

Indeed: $U(2)_V = SU(2)_V x U(1)_V$ = Isospin x Baryon #

Baryon# is an exact symmetry and Isospin is a good approximate symmetry of nature

(p, n) and (π^+, π^-, π^o) multiplets in spectrum

However the corresponding axial symmetries are not seen in the spectrum !

Reason: the $SU(2)_A$ symmetry is not preserved by the vacuum and by spontaneous breaking we get NG bosons (the pions) BUT we have no pseudoscalar NG candidate for the spontaneous breaking of the global $U(1)_A$ symmetry

THE U(1) PROBLEM

The QCD Vacuum and the Strong CP problem

The resolution of the U(1) problem came with the deeper study of the QCD vacuum

Two CP violating terms enter the QCD Lagrangian

$$L_\theta = \frac{\alpha_s \theta}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \qquad L_m = \frac{\alpha_s Arg(\det M)}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

$$\bar{\theta} = \theta + Arg(\det M) \Rightarrow L_{\bar{\theta}} = \frac{\alpha_s \bar{\theta}}{8\pi} \vec{G}_{\mu\nu} \cdot \vec{\tilde{G}}^{\mu\nu}$$

$$\Rightarrow L = \sum_{n=1}^{N} \bar{\psi}_n \left(i\gamma^\mu D_\mu - m_n \right) \psi_n - \frac{1}{4} G^{a\mu\nu} G^a_{\mu\nu} + \frac{\alpha_s \bar{\theta}}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

We do not observe any CP violating effects in the strong interactions → the theta parameter must be very small

Indeed if we calculate the neutron electric dipole moment we get: $d_n \approx 10^{-16}\ \bar{\theta}$ e·cm

Given the experimental limit: $d_n < 0.63 \times 10^{-25}$ e·cm

→ $\bar{\theta} \approx 10^{-9}$

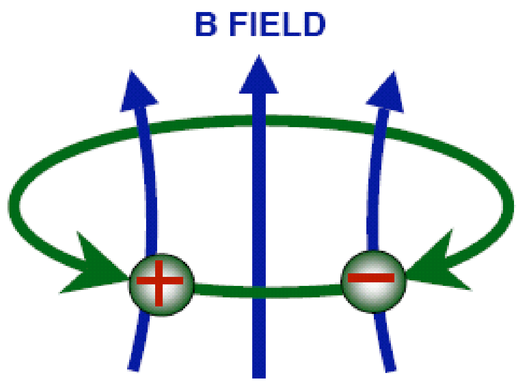
Why is theta so small ?

OR

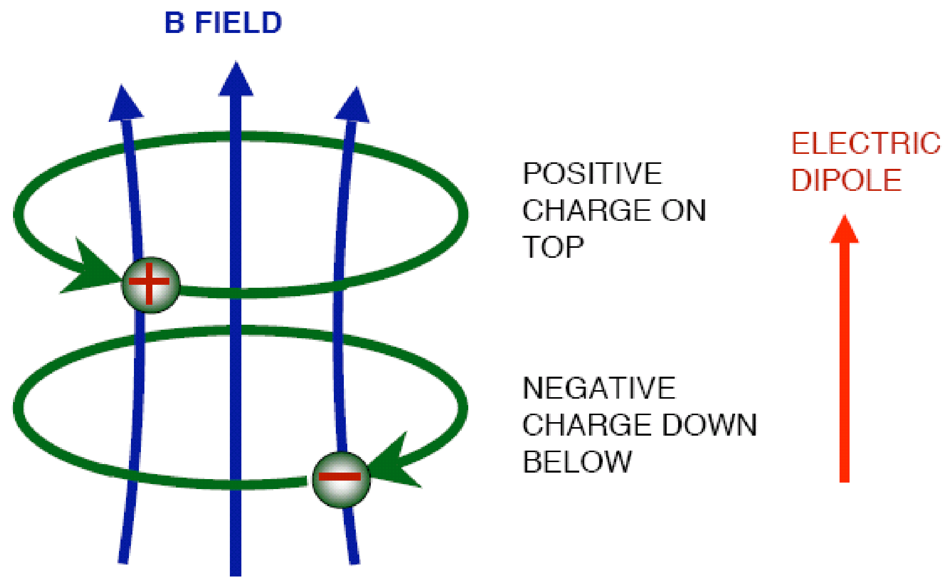
Why CP is conserved in Strong Interactions ?

The Strong CP PROBLEM

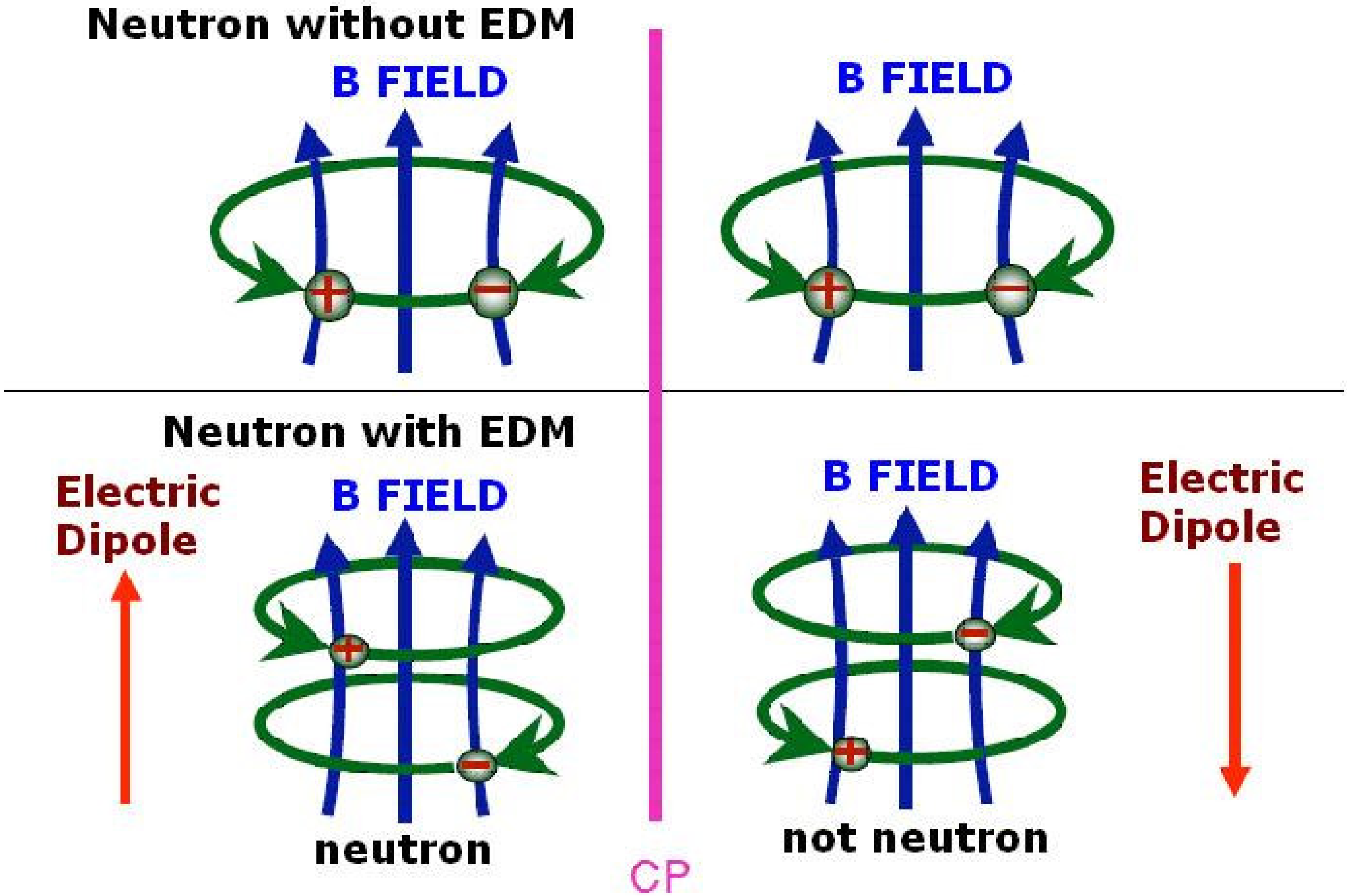
Let us have a look in the neutron



The neutron has magnetic moment



The neutron may have an electric dipole moment



Neutron without EDM
B FIELD
B FIELD
Neutron with EDM
Electric
Dipole
B FIELD
neutron
CP
B FIELD
Electric
Dipole
not neutron

A solution: $U(1)_{PQ}$ and Axions

Peccei and Quinn (1977) proposed the existence of a global chiral $U(1)_{PQ}$ quasi-symmetry, which:

- **Is a symmetry of the theory at the Lagrangian level.**
- **Is broken explicitly by the non-perturbative effects which introduce the parameter theta.**
- **It is spontaneously broken.**

- **A pseudo-NG boson particle appears: the axion**
- **The parameter theta is driven dynamically to zero.**

$$L_a = \xi \frac{\alpha_s}{8\pi f_a} a(x) \vec{G}_{\mu\nu} \cdot \tilde{\vec{G}}^{\mu\nu}$$

$\alpha(x)$ is the axion field

f_a is the axion decay constant

$$L_{SM}^{eff} = L_{SM} + \frac{\alpha_s \bar{\theta}}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} - \frac{1}{2} \partial_\mu \alpha \, \partial^\mu \alpha + L_{\text{int}} \left[\frac{\partial^\mu \alpha}{f} ; \psi \right] + \frac{a}{f} \xi \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

The last term in the Lagrangian provides an effective potential for the axion field

$$\xi \frac{\alpha_s}{8\pi f_a} a(x) \vec{G}_{\mu\nu} \cdot \tilde{\vec{G}}^{\mu\nu}$$

The minimum of the potential is the VEV of the axion field

$$\left\langle \frac{\partial Veff}{\partial \alpha} \right\rangle = -\xi \frac{\alpha_s}{8\pi f_a} \left\langle \vec{G}_{\mu\nu} \cdot \tilde{\vec{G}}^{\mu\nu} \right\rangle |_{\langle \alpha \rangle} = 0$$

which results in:

$$\langle \alpha \rangle = -f_\alpha \frac{\bar{\theta}}{\xi}$$

Then by defining the physical axion as $\alpha_{phys} = \alpha - \langle \alpha \rangle$

We get a Lagrangian with no CP violating theta parameter

The axion gets its mass via the instanton effects

expanding the V_{eff} around its minimum

$$m_\alpha^2 = \left\langle \frac{\partial^2 Veff}{\partial \alpha^2} \right\rangle = -\xi \frac{\alpha_s}{8\pi f_a} \frac{\partial}{\partial \alpha} \left\langle \vec{G}_{\mu\nu} \cdot \tilde{\vec{G}}^{\mu\nu} \right\rangle_{\langle \alpha \rangle}$$

The axion interacts with photons, electrons, hadrons with a strength ~ f_α^{-1}

$$m_\alpha \approx 0.6\, eV \frac{10^7\, GeV}{f_\alpha}$$

Invisible Axion models

Initially f_a was tied to the Electroweak scale and the CP breaking with the Electroweak breaking

The so-called PQWW (Peccei-Quinn-Weinberg-Wilzcek) axion was subsequently ruled out by the experiments

The realization that the axion scale can be very big (and its coupling very weak) initiated the 'invisible axion' models

The KSVZ (Kim-Shifman-Vainstein-Zacharov) and the DFSZ (Dine-Fischler-Srednicki-Zhitniski) models have viable possibilities

DFSZ

- $f_a >> f_{ew}$
- Two Higgs fields and
- one scalar field.
- Fermions: carry PQ charge.

KSVZ

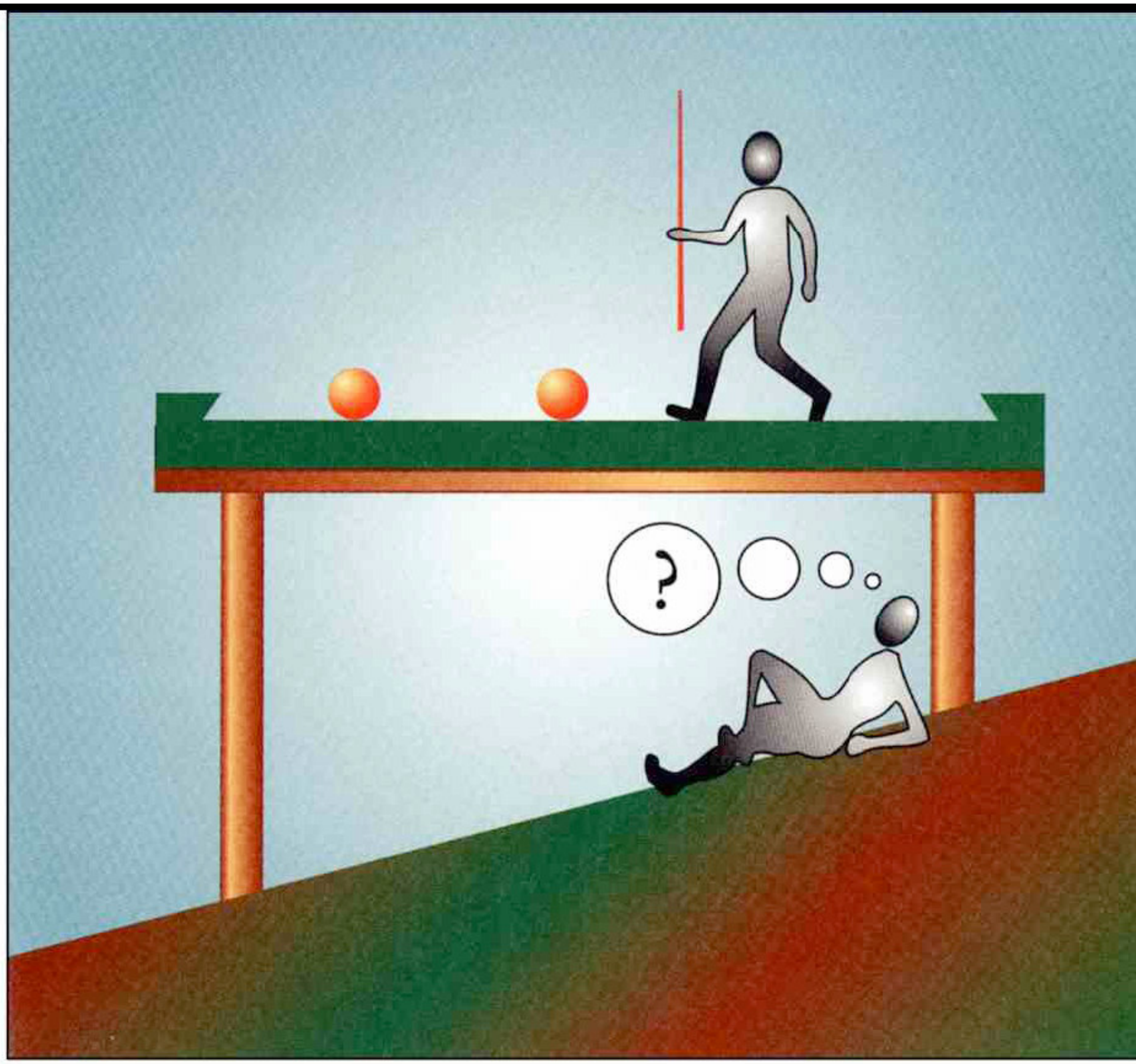
- $f_a >> f_{ew}$
- One Higgs field,
- one scalar field
- one exotic quark with PQ charge.

The axion always couples with the photons

$$L_{\alpha\gamma\gamma} = -0.36 \frac{\alpha_{fine} a(x) 10^7}{\pi f_\alpha} \vec{E} \cdot \vec{B}$$

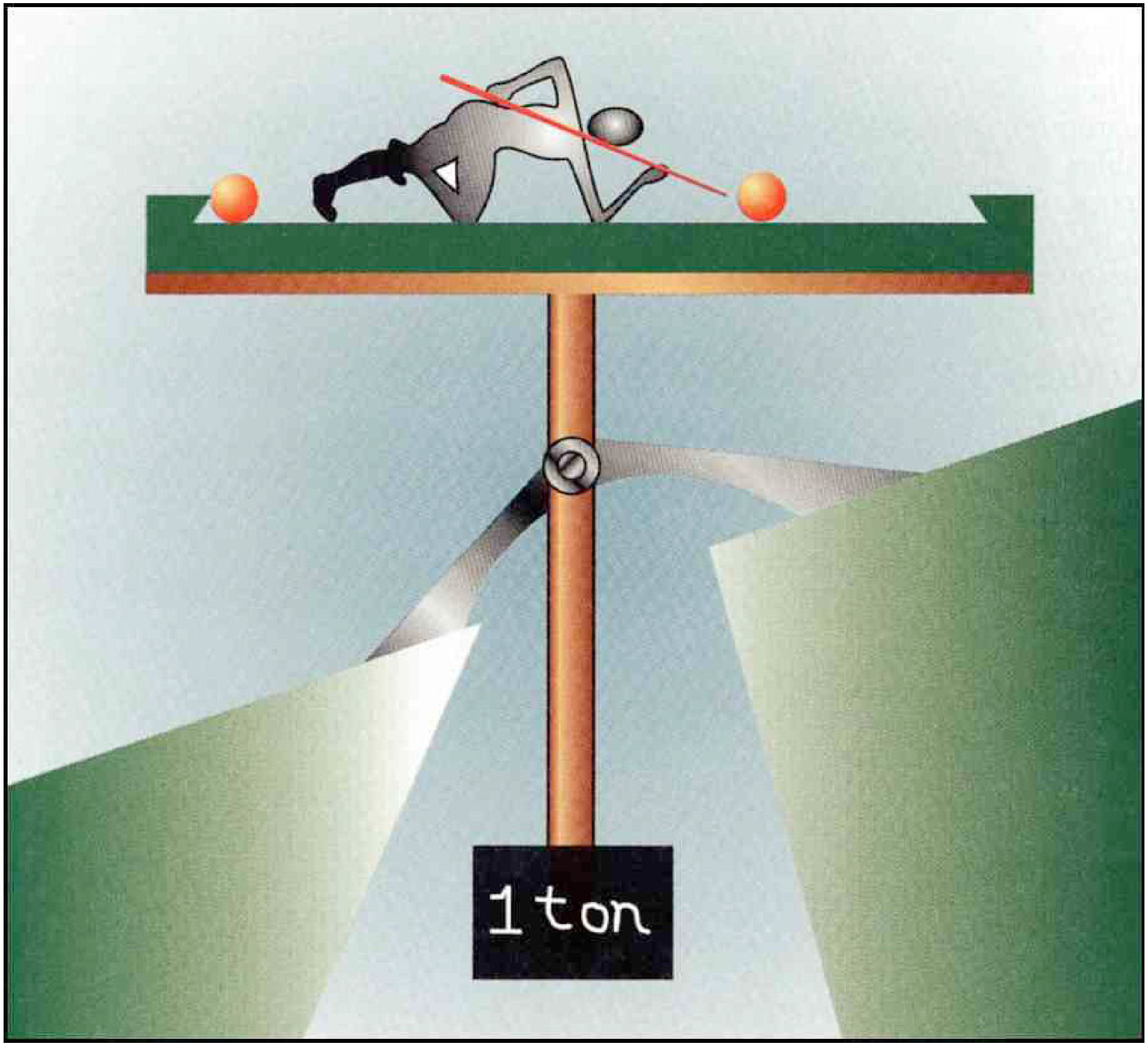
$$L_{\alpha\gamma\gamma} = 0.97 \frac{\alpha_{fine} a(x) 10^7}{\pi f_\alpha} \vec{E} \cdot \vec{B}$$

Flatness → CP invariance

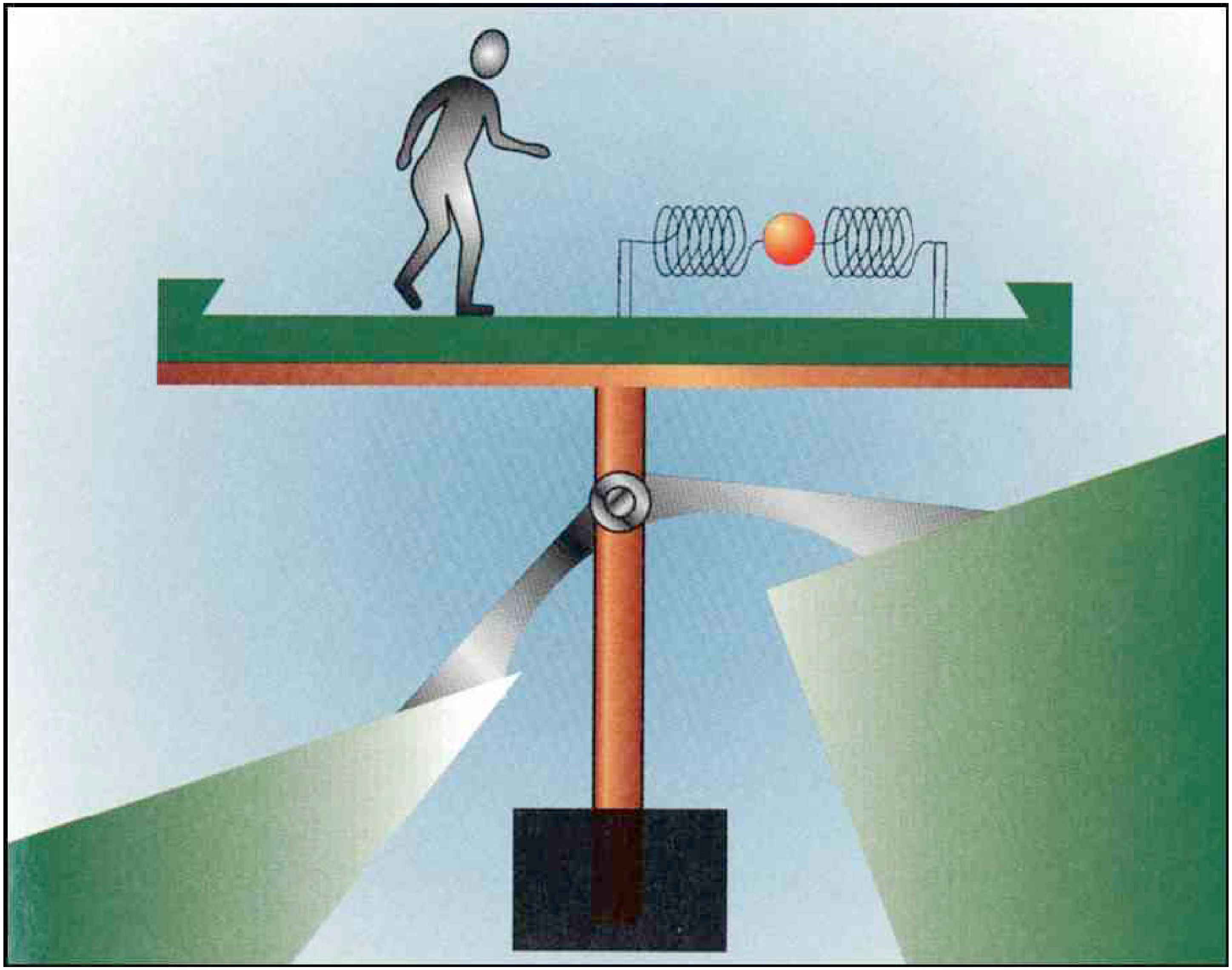


*Thinking Snookers Player (Pierre Sikivie, Physics Today 49 (1996)22)

Leveling mechanism → PQ mechanism



(Remnant) Oscillations → (Halo) axions



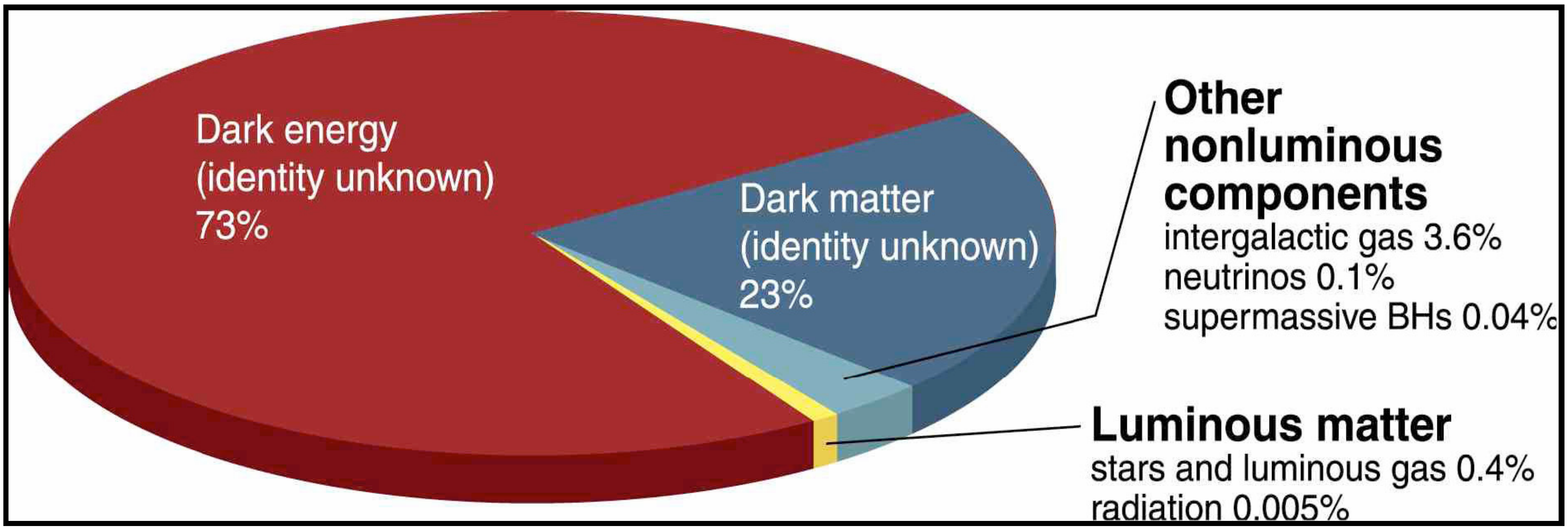
Cosmological Implications

The universe is composed of dark matter and dark energy

But we don't know what the dark energy or what the dark matter is

- **A particle relic from the Big Bang is strongly implied for DM**

—WIMPs ?
—Axions ?



Science (20 June 2003)

The axion dark matter scenario

Peccei-Quinn symmetry breaks at $T \sim f_a \leq 10^9$GeV

- The axion is created, but it is massless
- A network of axion strings is created, slowly decaying into cosmic background axions

The axions acquire mass at $T \sim \Lambda_{QCD}$

- Instanton effects 'switch on' and the axion gets a small mass
- Domain walls form between the strings and the complex hybrid network annihilates into axions

Present day cold axion abundance

the ratio of the axion energy density to the critical density for closing the universe:

$$\Omega_\alpha \approx \left(\frac{5\,\mu eV}{m_\alpha} \right)^{7/6}$$

axions in stellar evolution

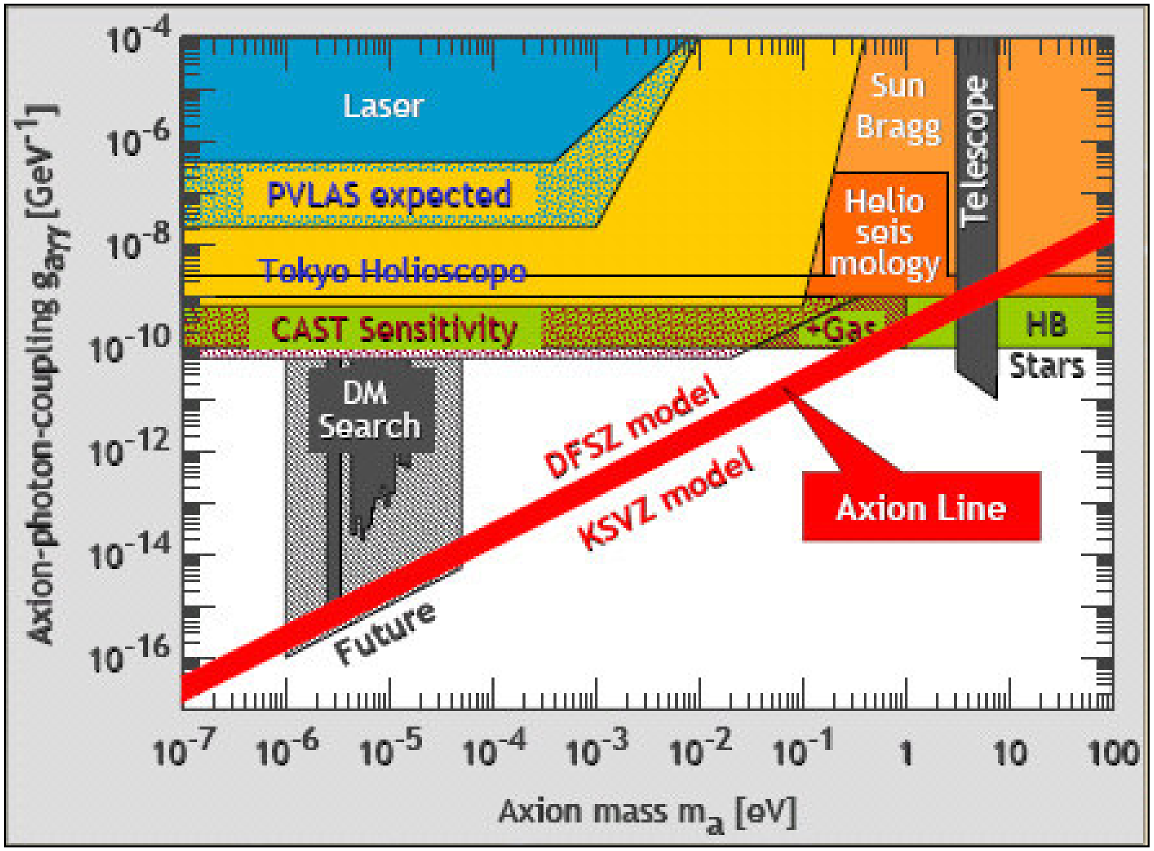
The evolution of any star is controlled by its thermal emission. Axions can easily transport energy since they are very weakly interacting.

New energy loss channel accelerates star evolution

Axion mass window

$10^{-(5 \text{ to } 6)}$ eV < m_a < $10^{-(2 \text{ to } 3)}$ eV

Overclosure SN1987a



Nucleon-Nucleon Bremsstrahlung

NN→ NNa

Experimental Techniques

RF cavity experiments

Examples: ADMX, CARRACK

Laser Experiments

Example: PVLAS

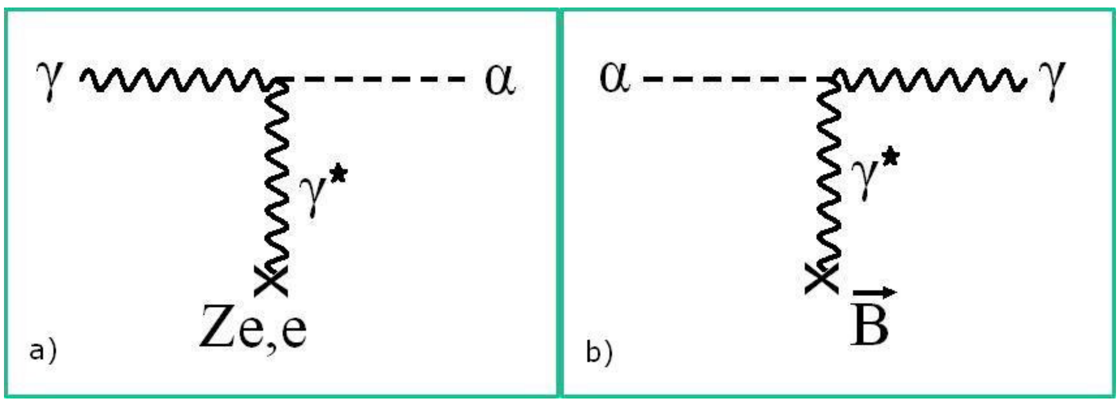
Helioscopes

Examples: Tokyo, CAST

(Direct) Axion production and detection

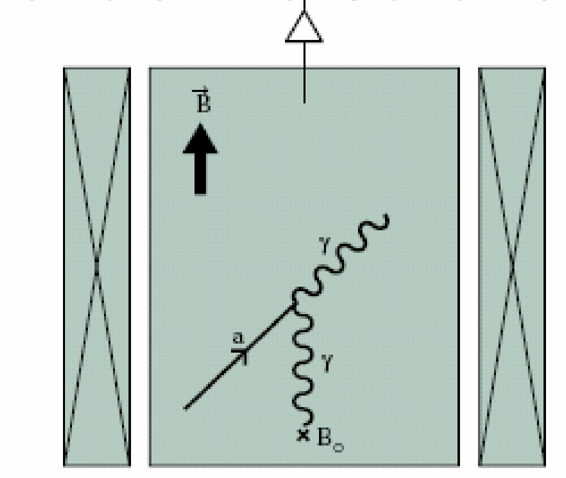
Via the Primakoff and inverse Primakoff effect

$$Z+\gamma(k)\rightarrow Z+a(k_a) \quad or \quad e(p_1)+\gamma(k)\rightarrow e(p_2)+a(k_a)$$



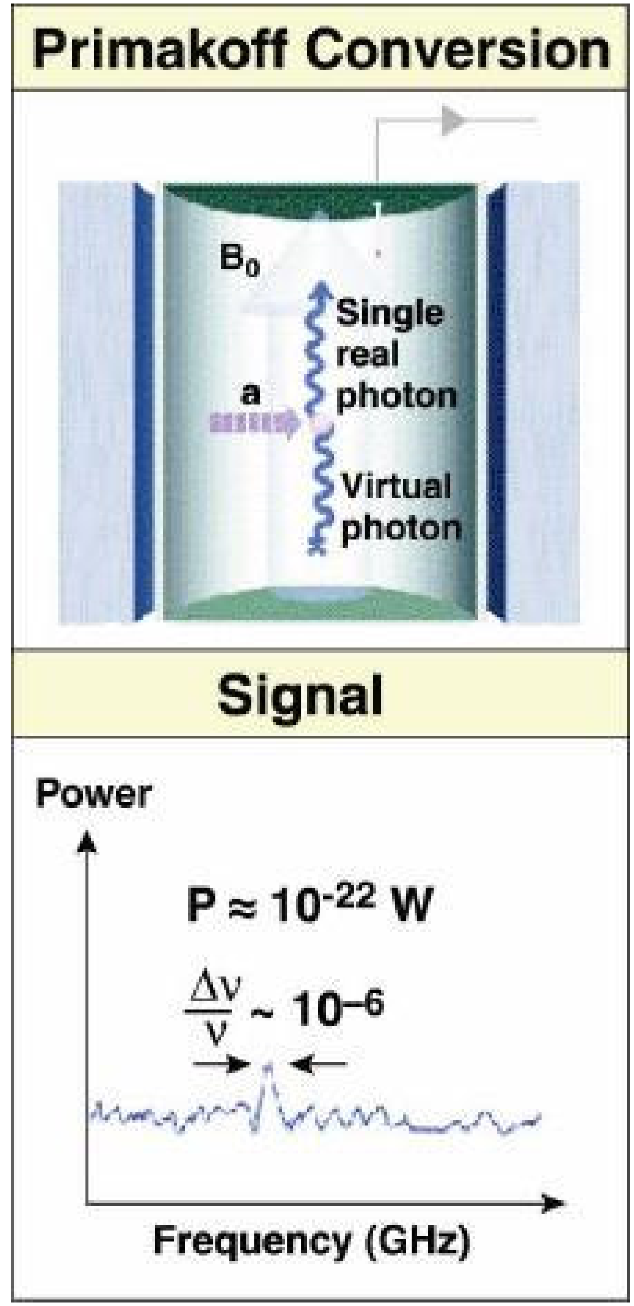
The principle of the RF cavity experiments

Energy exchange between
Galactic Halo Axions and E&M field



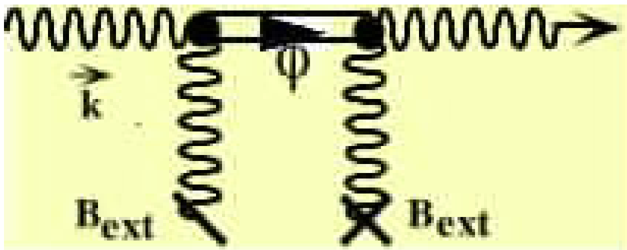
Galactic halo axions have speeds $\beta=10^{-3}$

When the frequency $\omega=2\pi f$ of a cavity mode equals m_a, galactic halo axions convert resonantly into quanta of excitation (photons) of that cavity mode (m_a=4.14 meV corresponds to f =1 GHz). Very sensitive amplifiers are used to monitor the microwave cavity power (HFET, HEMT, SQUID, Rydberg atoms)



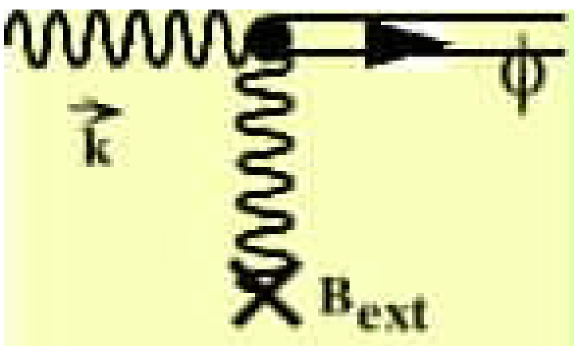
The principle of the laser experiment PVLAS

virtual production



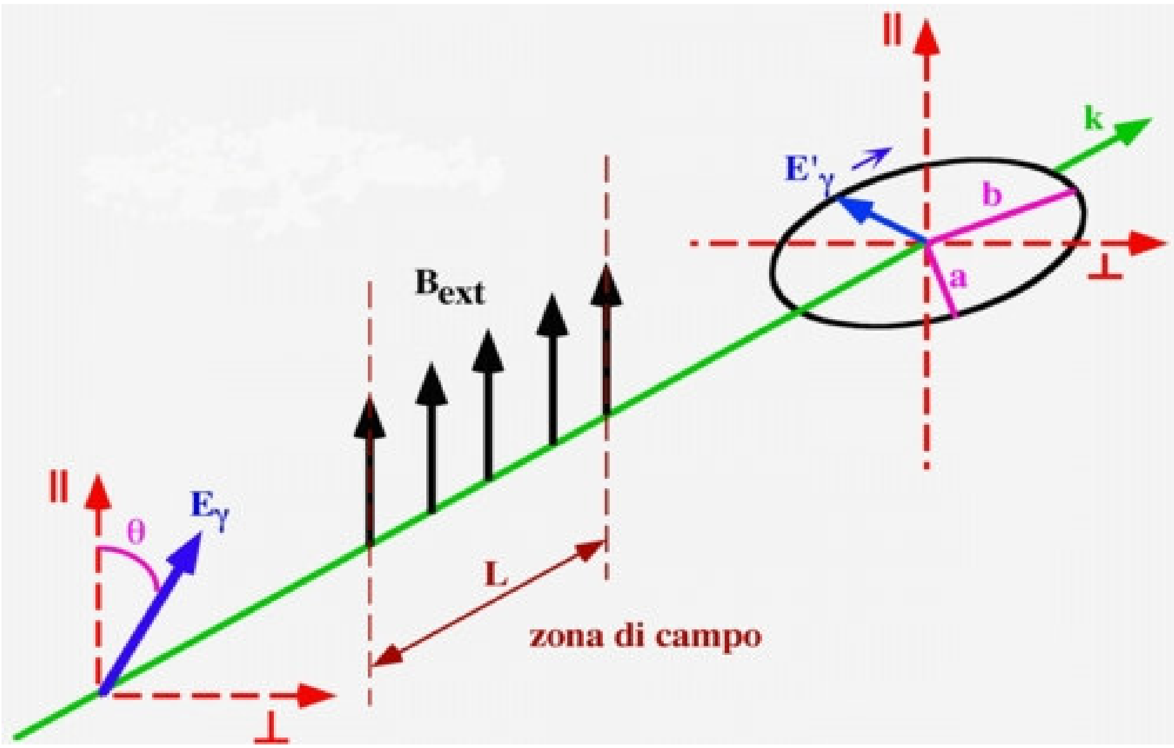
This causes retardation of the real photon → ellipticity.

real production

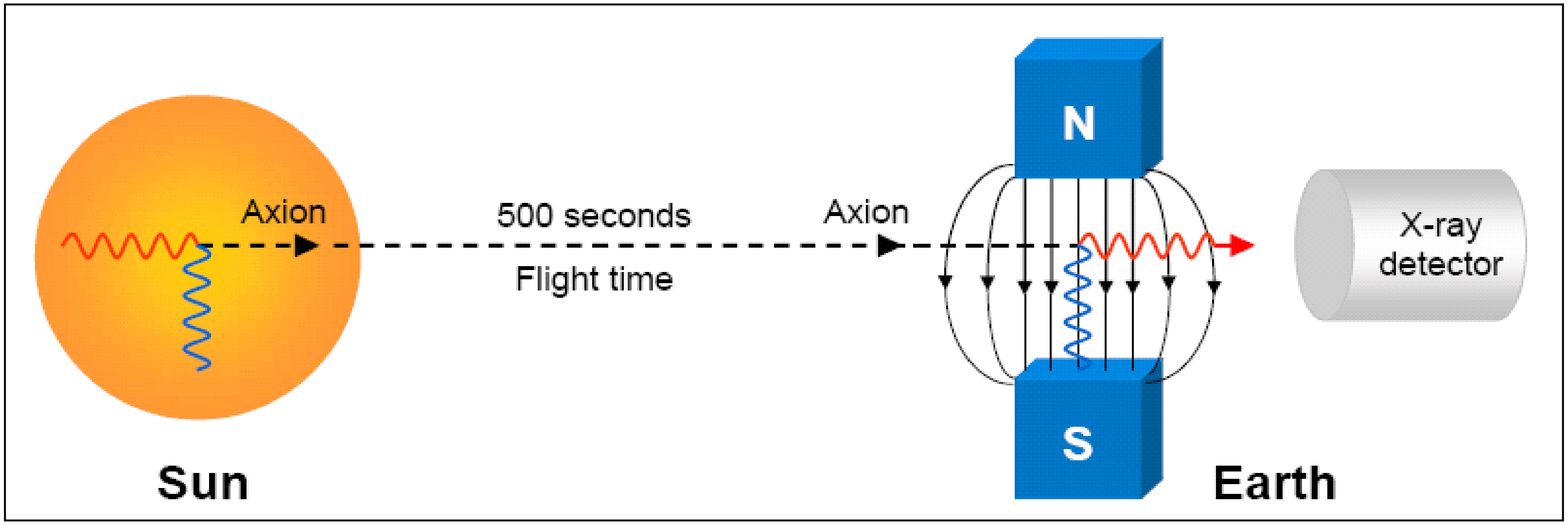


This causes loss of photons in the beam → dichroism.

If linearly polarised light enters a birefringent medium with its polarisation vector at 45 degrees to the axis (field) direction, the two components of this vector, parallel and normal to the axis, will propagate with different velocities and become out of phase. When exiting the medium the light polarisation state will have changed from linear to elliptical.

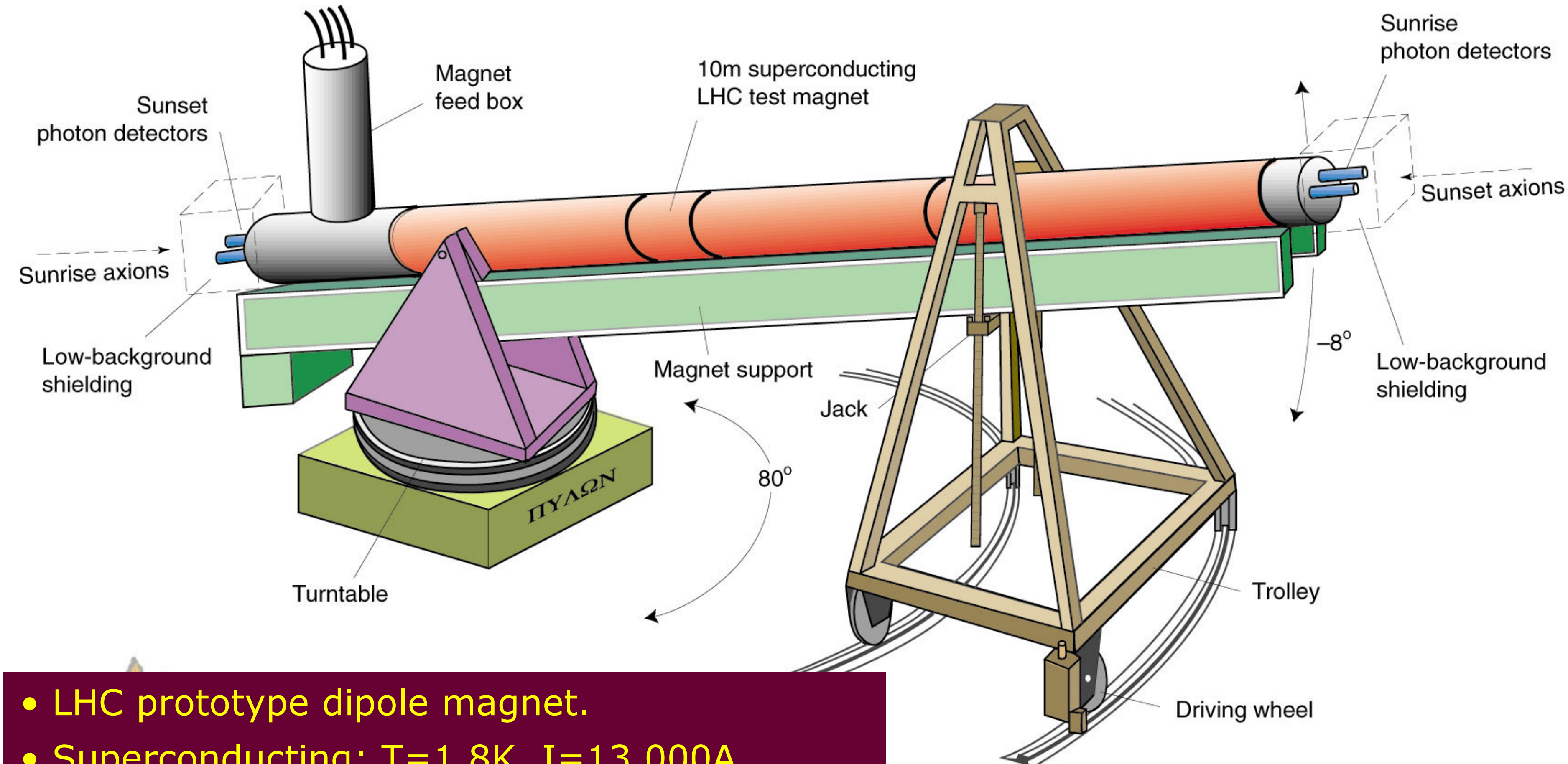


The principle of Axion Helioscopes



Axions are produced in the core of the sun via the Primakoff effect. Then, they travel to earth where by interacting with a transverse magnetic field they are converted into X-ray photons and detected by appropriate X-ray detectors.

The CERN Axion Solar Telescope (CAST)



- LHC prototype dipole magnet.
- Superconducting: T=1.8K, I=13,000A.
- B=9T, L=9.26m.
- ±8° vertical movement, 80° horizontal movement.
- 3h sun tracking daily.

Magnetic field: B = 9T
Length: L = 10m

X-ray detector requirements:

- ✓ Low background rate.
- ✓ Positional sensitivity.
- ✓ Fiducial area ~14cm^2.
- ✓ Good energy resolution.
- ✓ Excellent stability.

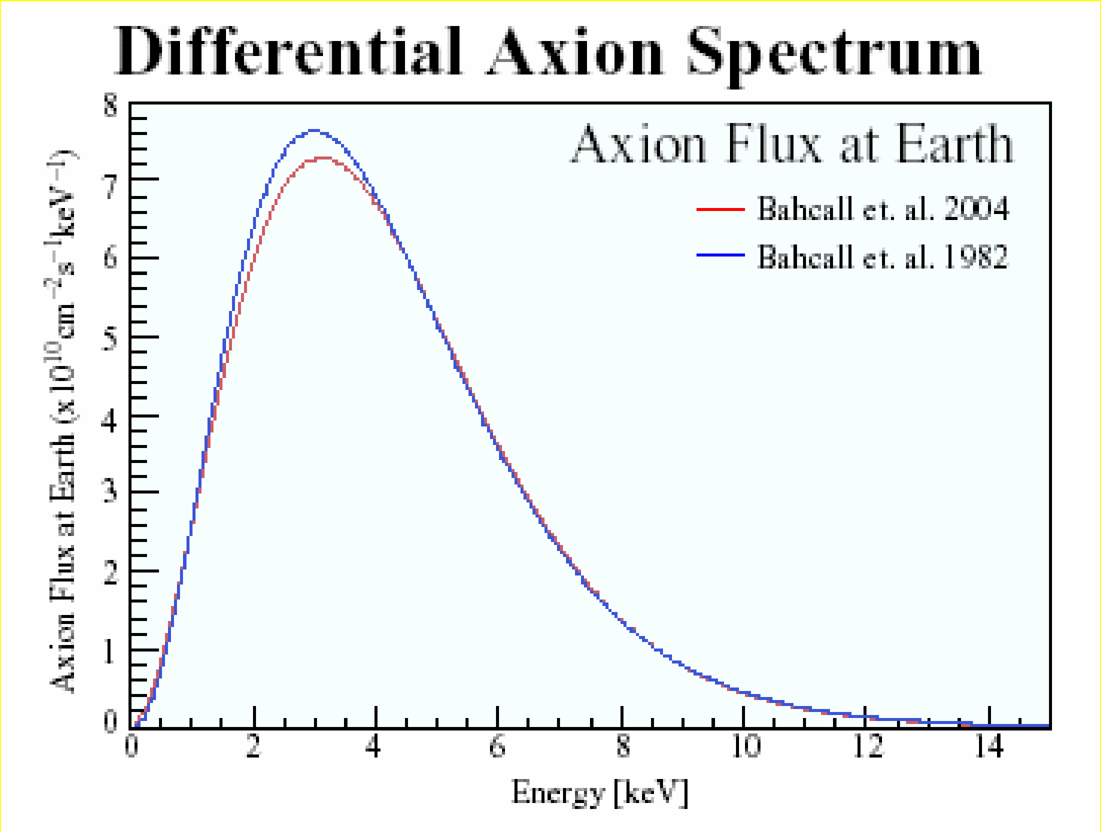
Sunrise detectors: Micromegas,
CCD with focusing telescope

Sunset detector: TPC

solar axions - detection plan

Axion flux on Earth

$$\frac{d\Phi_\alpha}{dE} = 6.02\times10^{10}\left(\frac{g_{\alpha\gamma\gamma}}{10^{-10}GeV^{-1}}\right)^2\left(\frac{E}{keV}\right)^{2.481} e^{\left(-\frac{E}{1.205keV}\right)} axions/cm^2/\sec/keV$$



$$g_{a\gamma\gamma} \equiv M^{-1} \approx 10^{-10}\left[\frac{m_a}{1\,\mathrm{eV}}\right]\mathrm{GeV}^{-1}$$

$$\Phi_a \approx 3.5\times10^{11}\left[\frac{10^{10}\,\mathrm{GeV}}{M}\right]^2/\mathrm{cm}^2\,\mathrm{s}$$

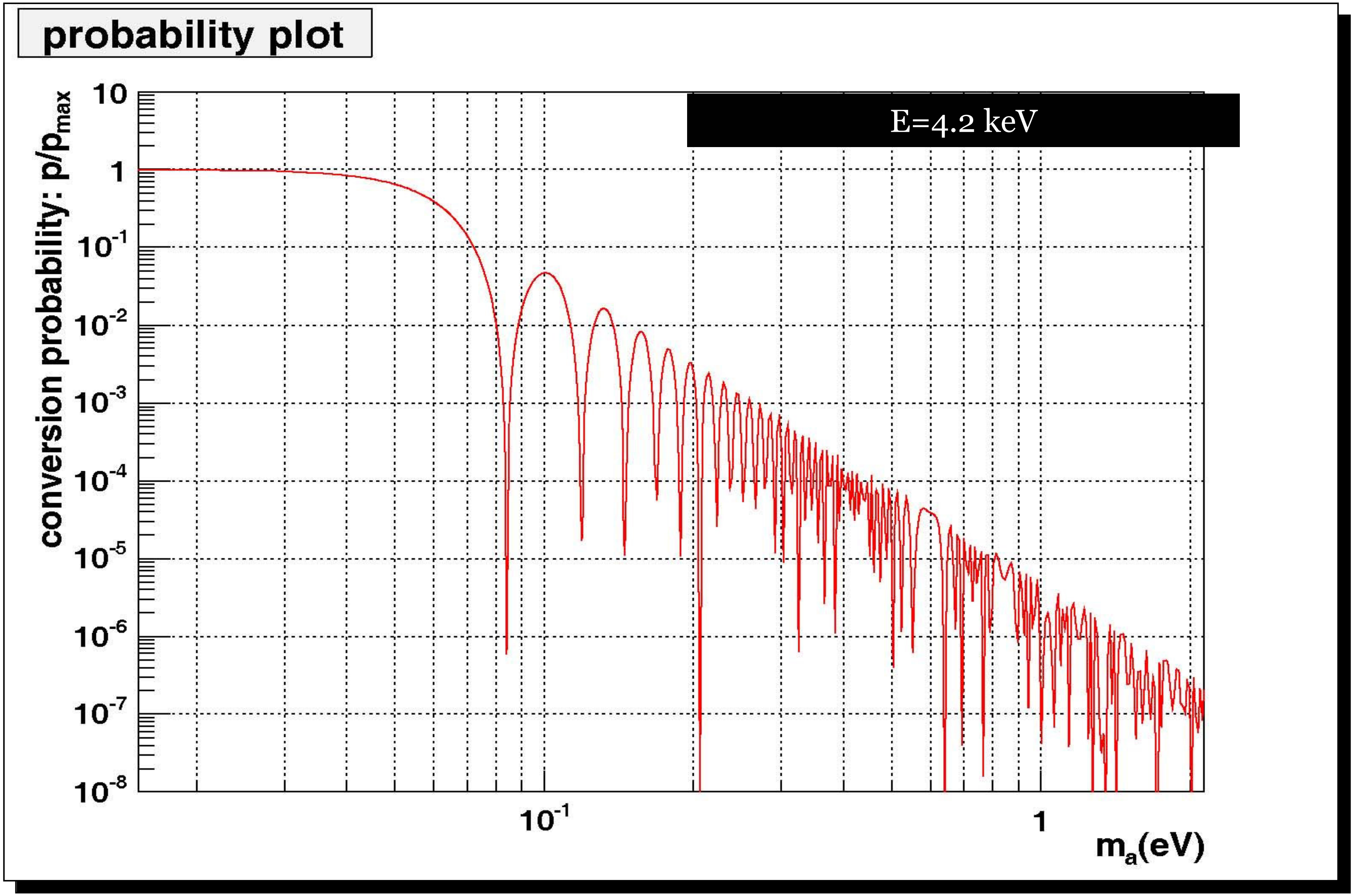
Conversion probability in transverse magnetic field

$$P_{a\to\gamma} = \left(\frac{Bg_{a\gamma\gamma}}{2}\right)^2 L^2 \frac{\sin^2(qL/2)}{(qL/2)^2}$$

X-ray flux expected in CAST (for low mass axions)

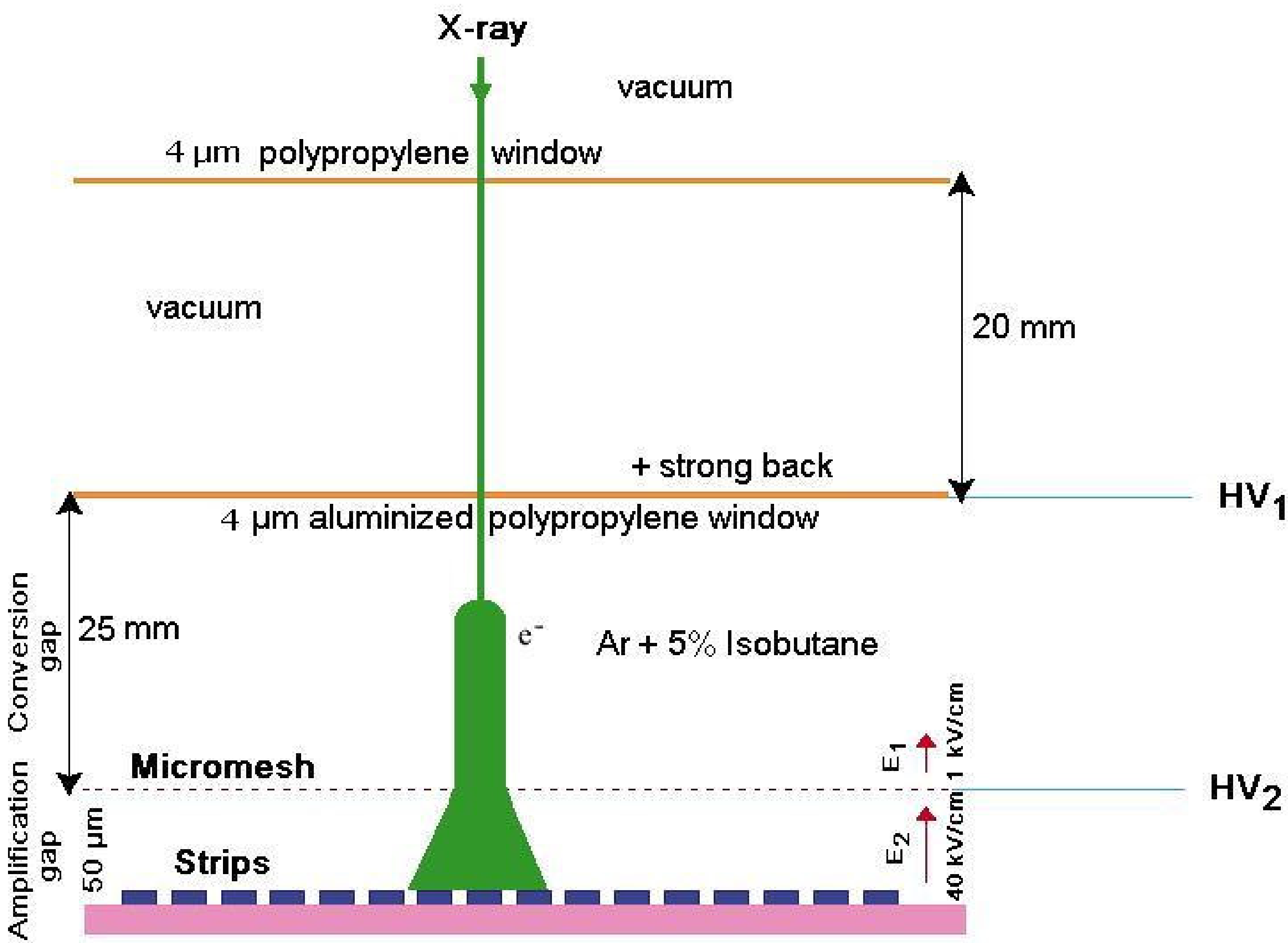
$$\Phi_\gamma = 0.51\,cm^{-2}day^{-1}\left(\frac{g_{\alpha\gamma}}{10^{-10}GeV^{-1}}\right)^4\left(\frac{L}{9.26m}\right)^2\left(\frac{B}{9.0\,T}\right)^2$$

To detect higher mass axions the effective photon mass needs adjustment to retain the coherence between the axion and photon amplitudes along the detection volume.



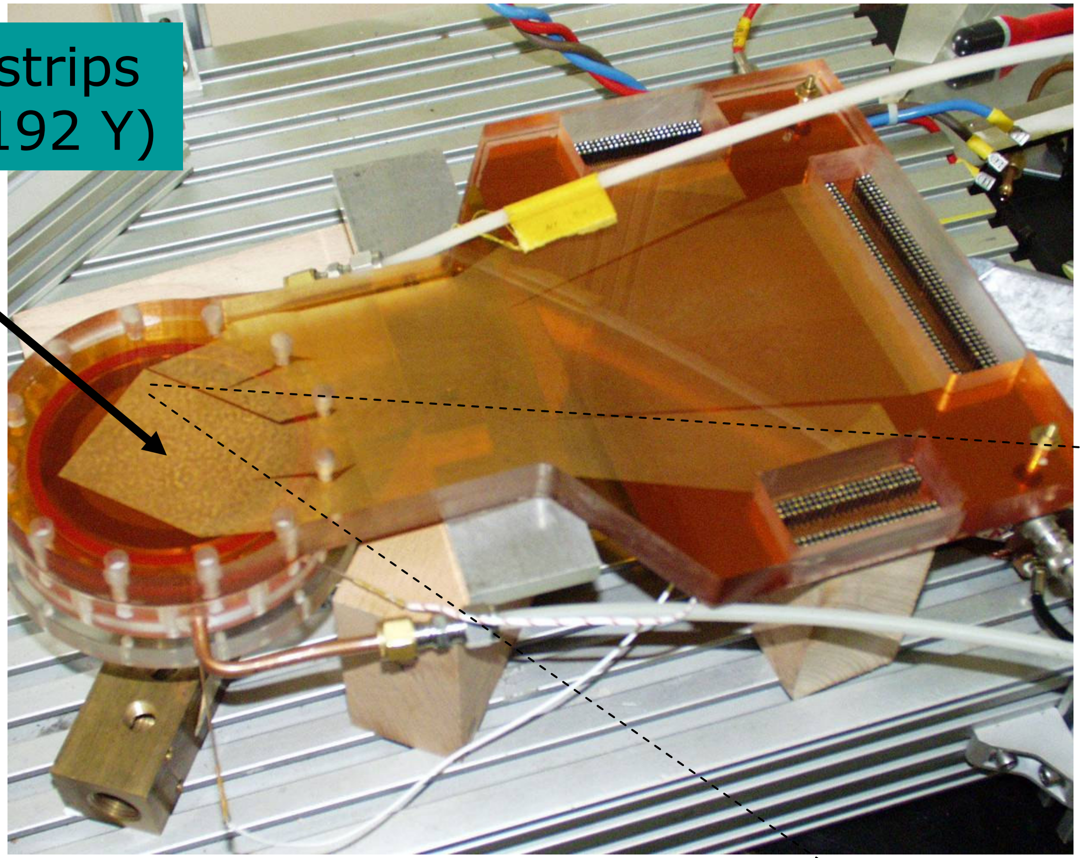
probability plot
E=4.2 keV
conversion probability: p/p_{max}
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-1}
1
m_a(eV)

The Micromegas principle as implemented at CAST

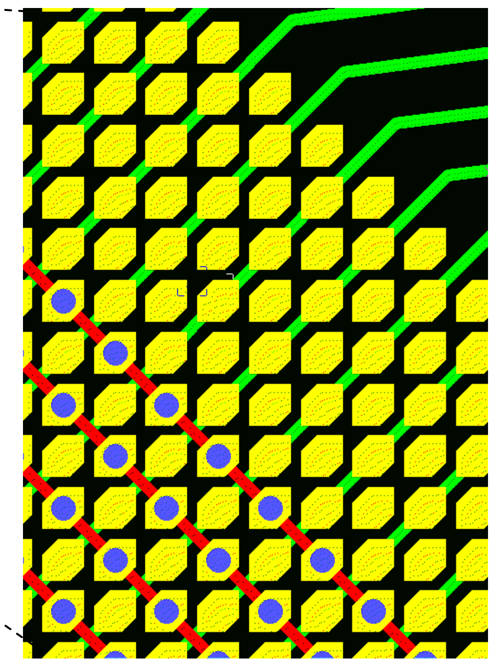


The very first Micromegas with X-Y readout

384 X-Y strips
(192 X, 192 Y)

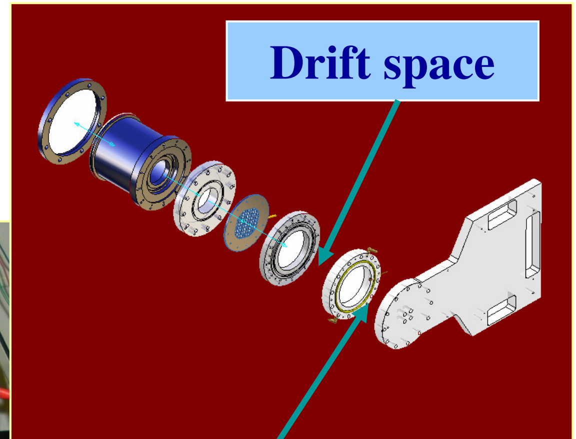


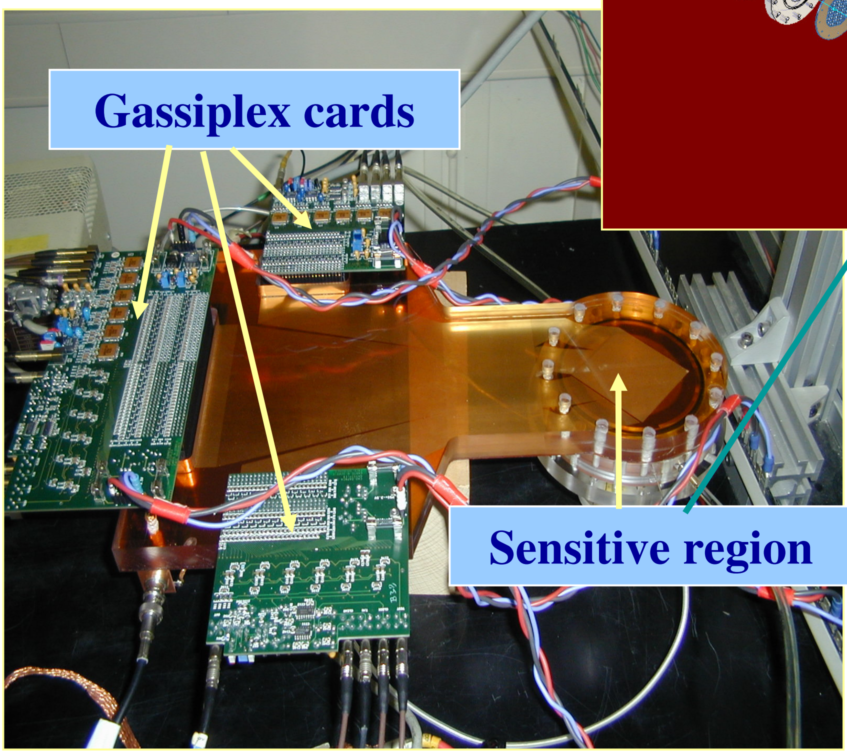
Readout plane and grid: made at CERN



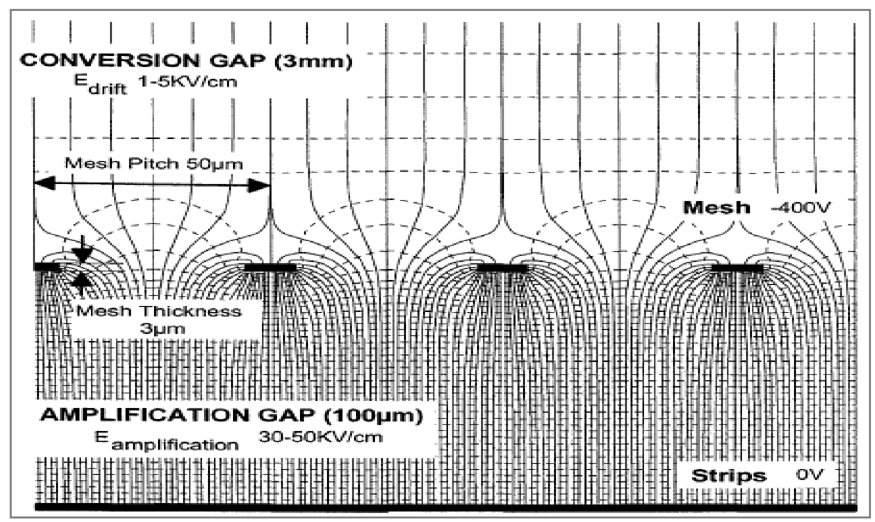
Strip width: 350μm

CAST Micromesh gaseous detector



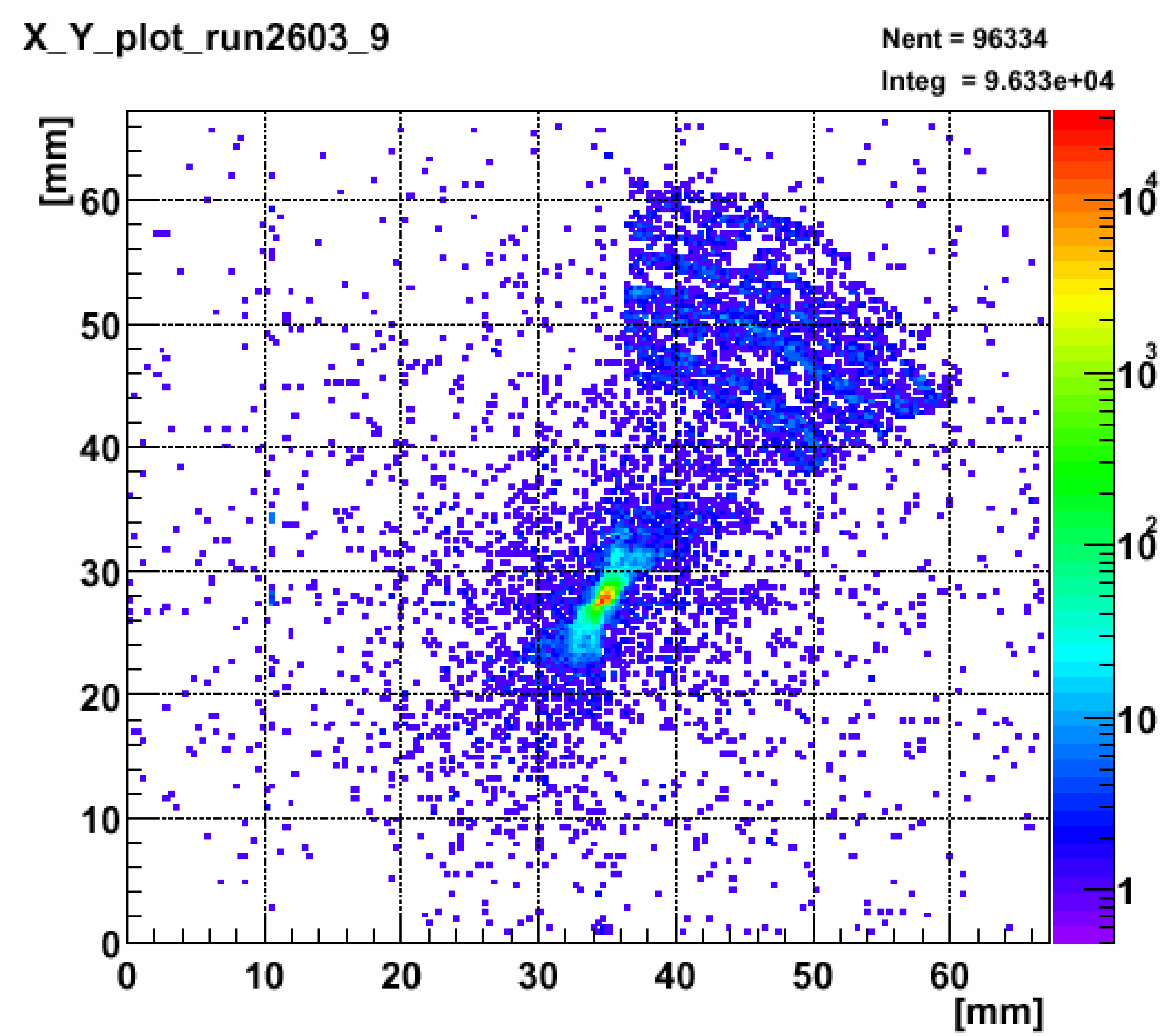


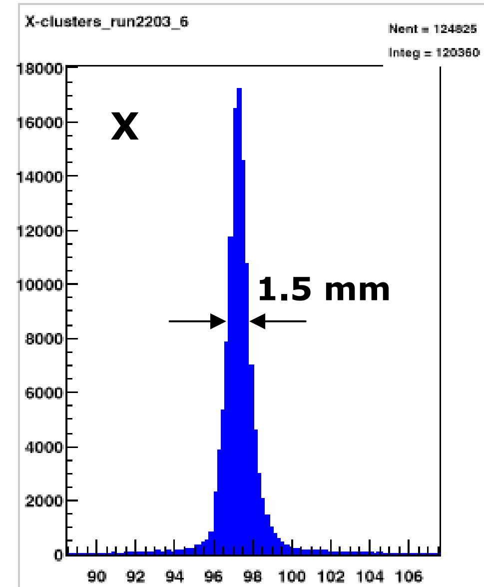
- ✓ Low background materials
- ✓ The operating gas is at atmospheric pressure.
- ✓ 10^4 amplification is easily achievable.
- ✓ High field ratio: 100% electron transparency.
- ✓ No space charge effects due to fast collection of positive ions.

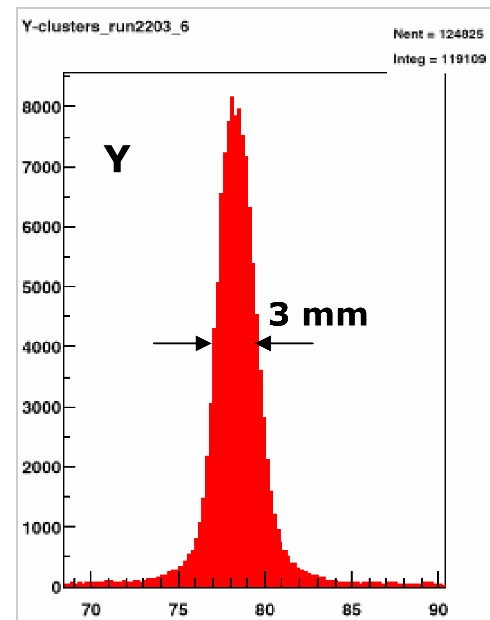


Development/construction/operation
Saclay-Demokritos-CERN

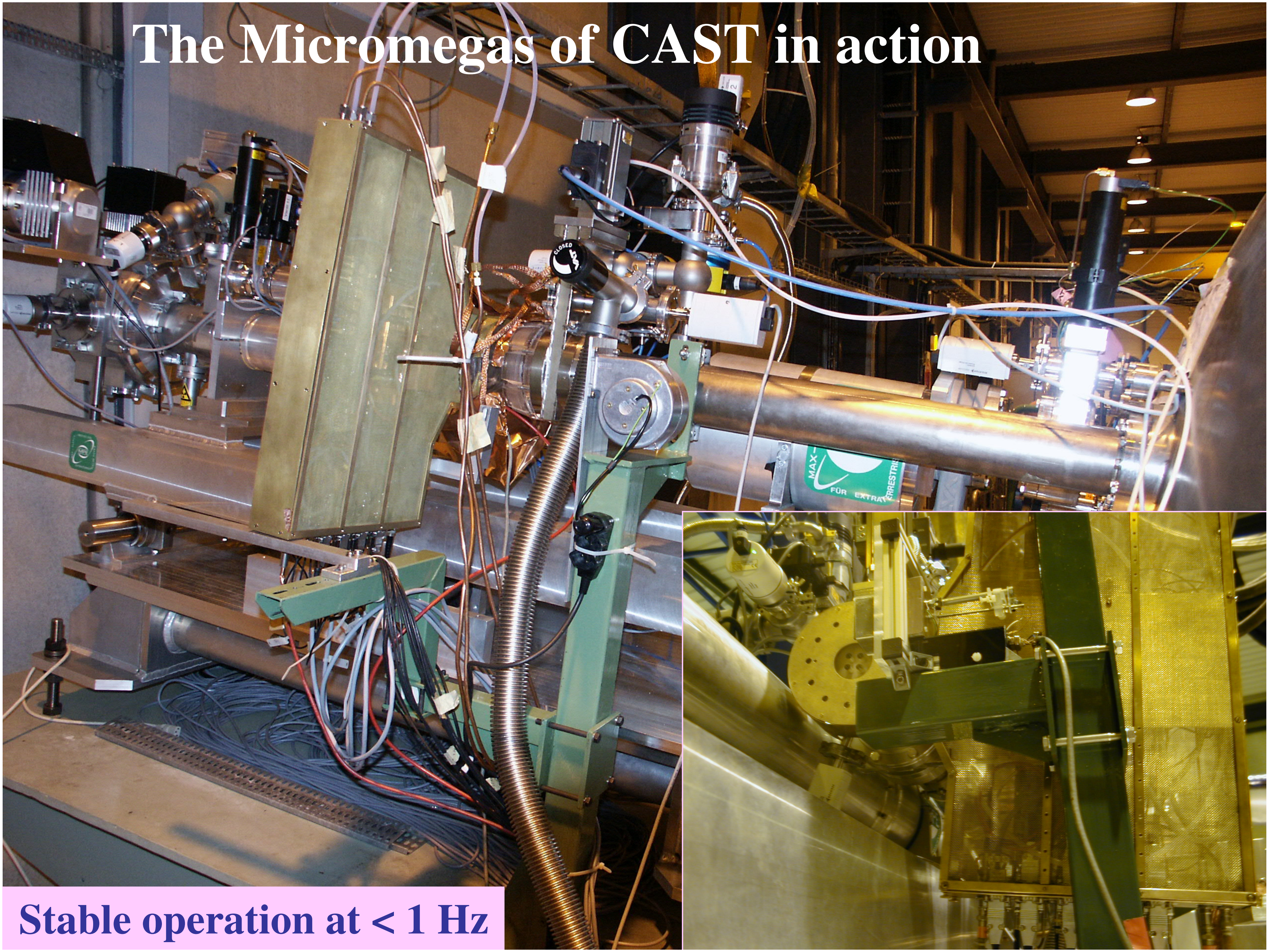
4.5 keV photons from PANTHER + focusing telescope







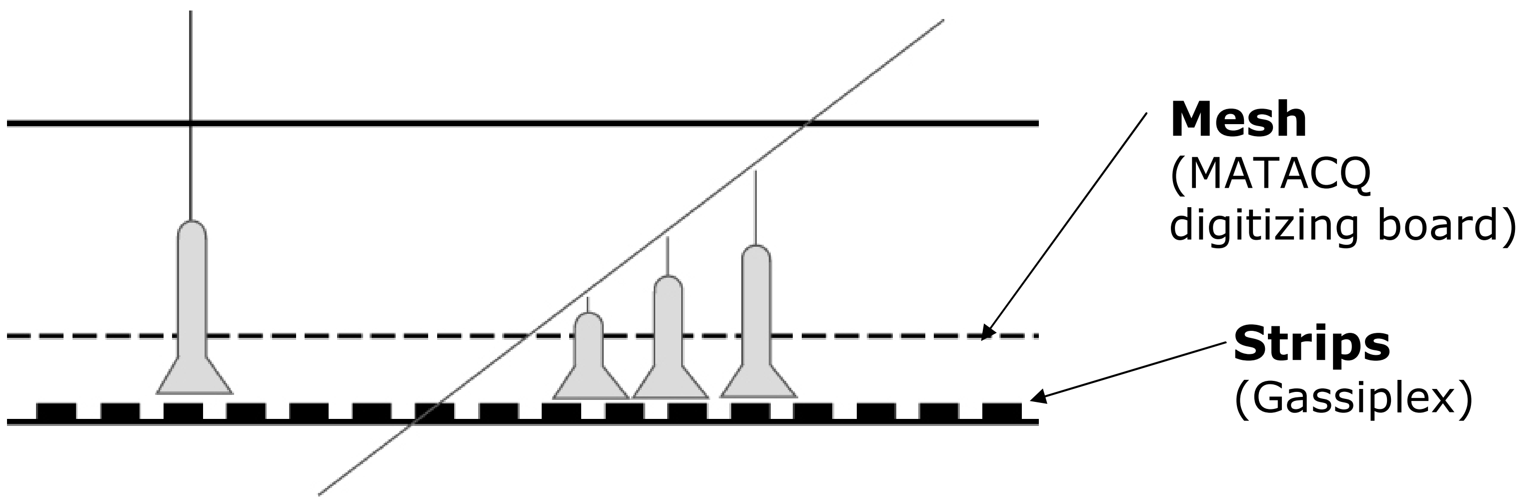
The Micromegas of CAST in action



Stable operation at < 1 Hz

Micromegas analysis

Tracking (1.5 h/day)
Background (the rest of the time)
Fe^{55} Calibration (once per day)



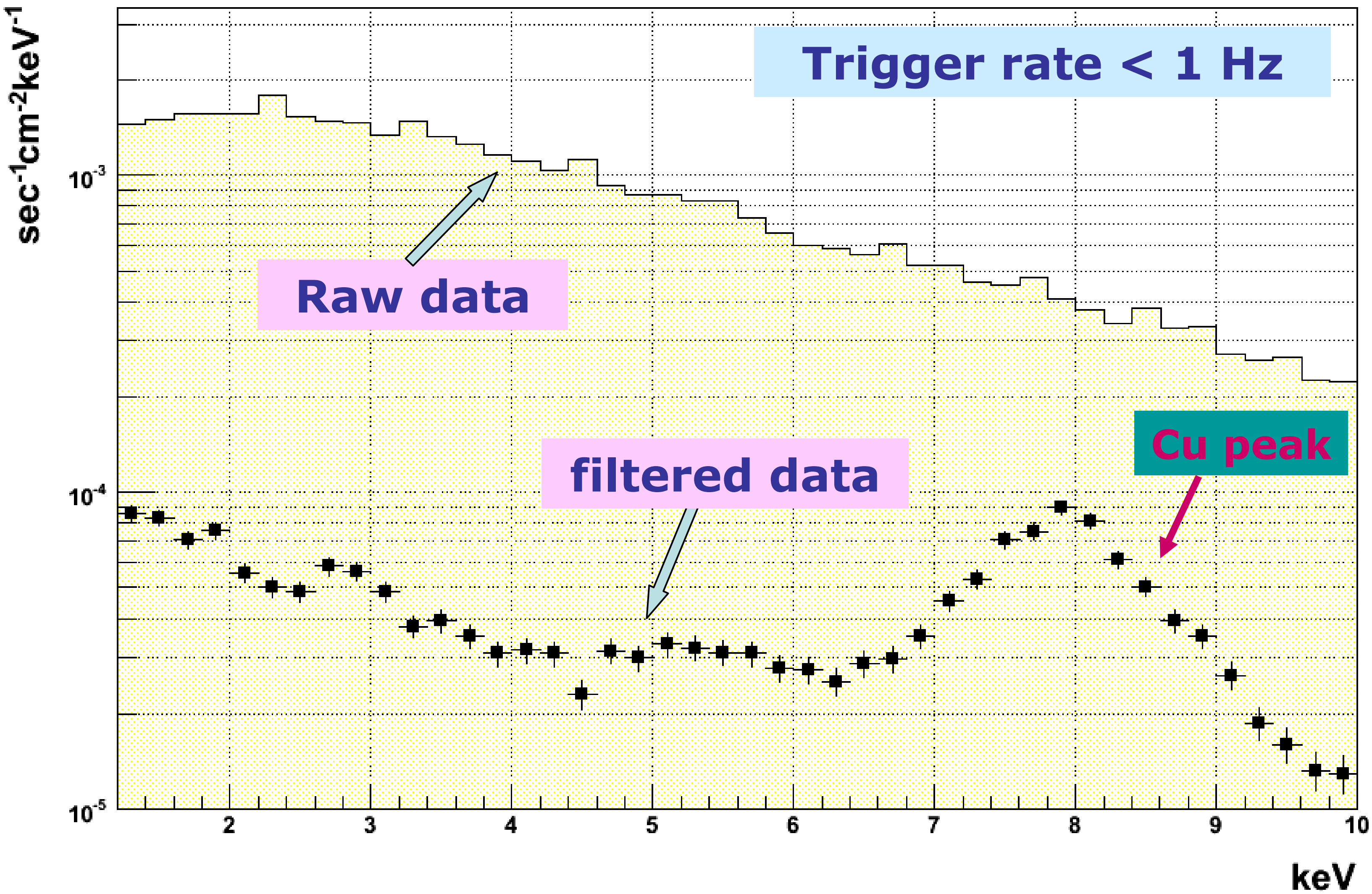
ANALYSIS STRATEGY

Main background:
- natural radioactivity
- cosmic rays

Rejection based on:
- micromesh pulse shape
- topology of strip cluster

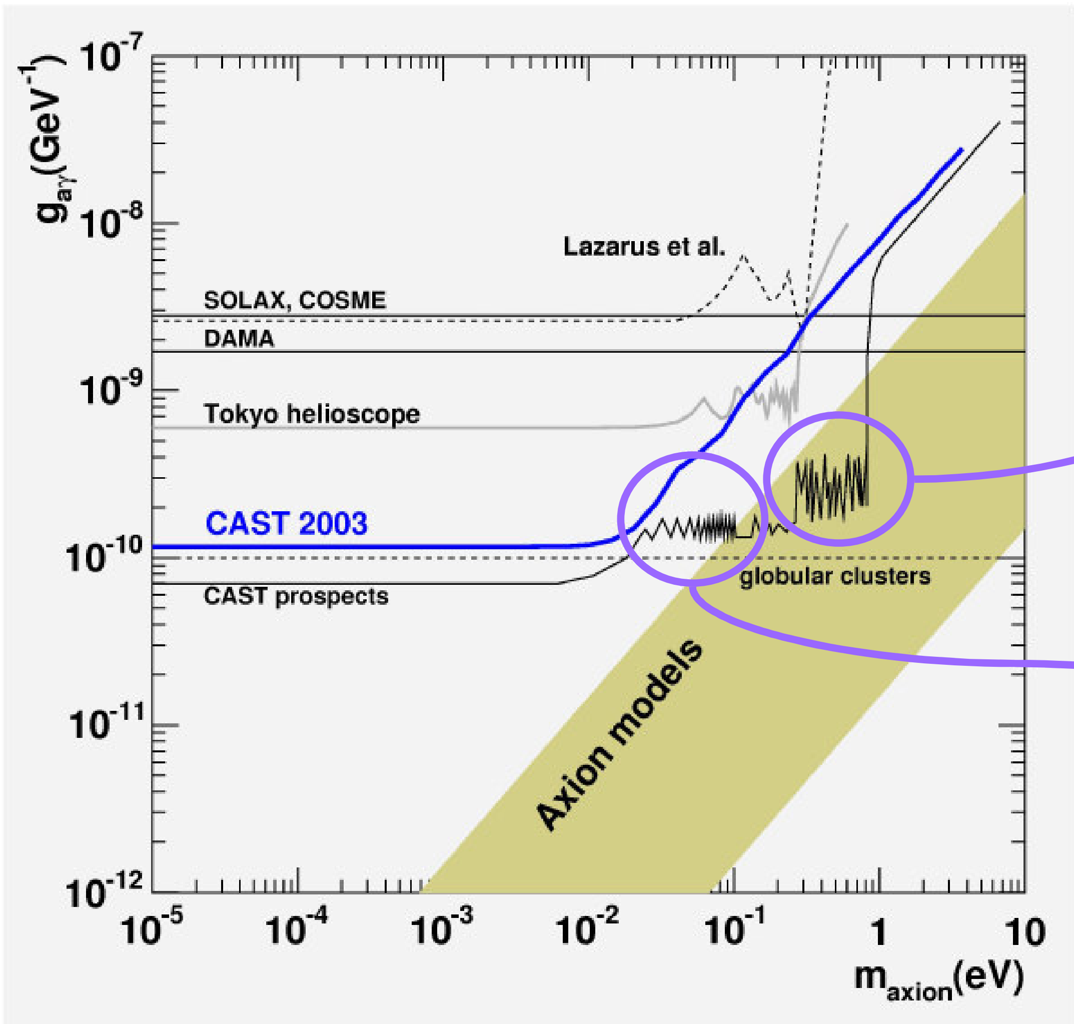
The power of the background rejection

Raw spectrum vs filtered



Phase II CAST started October 2005

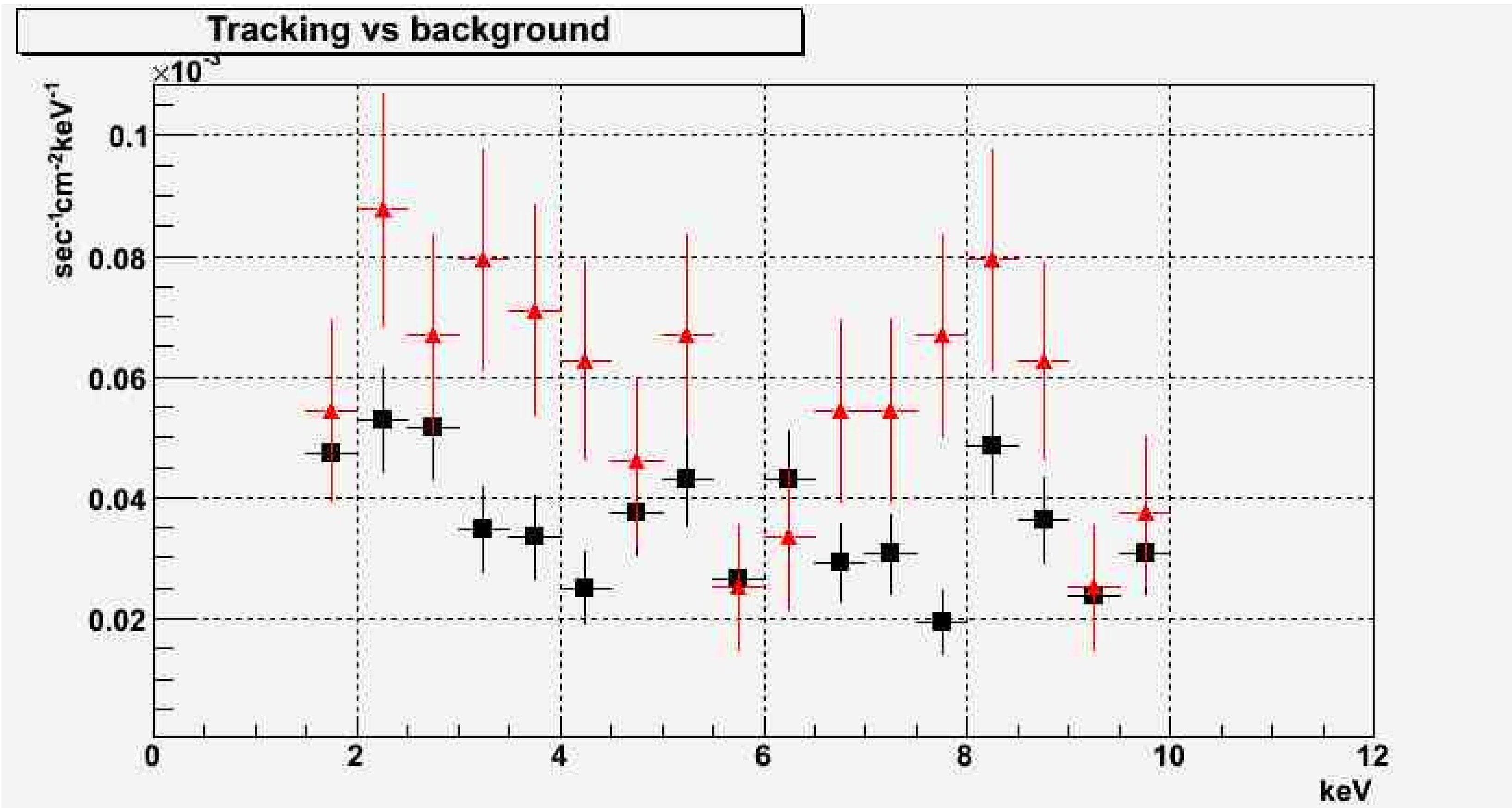
Zioutas et al., PRL 94 (2005) 121301



^{3}He
590 pressure steps
$m_a \leq 0.8$ eV/c^2

^{4}He
74 pressure steps
$m_a \leq 0.26$ eV/c^2

MC created fake axion signal



Concluding Remarks

- **The particle astrophysics approach complements accelerator-based research on the most fundamental problems in physics and cosmology.**

- **If the axions are discovered, a half-century long puzzle in the Standard Model will be finally put to rest.**

- **Axions could be the main component of the dark matter.**

Resources

1. ‘QCD, Strong CP and Axions’, R.D. Peccei in arXiv:hep-ph/9606475 v1 28 June 1996.
2. ‘Quantum Field Theory’, Mark Srednicki, U.C. Santa Barbara.
3. ‘Dark Matter Axions ’96’, Pierre Sikivie in arXiv:hep-ph/9611339 v1 15 November 1996.
4. ‘An Introduction to axions’, E. Daw, lecture slides, lecture 18, PHY-323.
5. ‘Searching for Dark Matter Axions’, L.J. Rosenberg & K.A. VanBibber, Beamline Magazine Fall 1997.
6. The ADMX (cavity axion search) experiment web page: http://www.phys.ufl.edu/~axion/Welcome.html
7. PVLAS experiment web page: http://www.ts.infn.it/experiments/pvlas/
8. CAST experiment web page: http://cast.web.cern.ch/CAST/