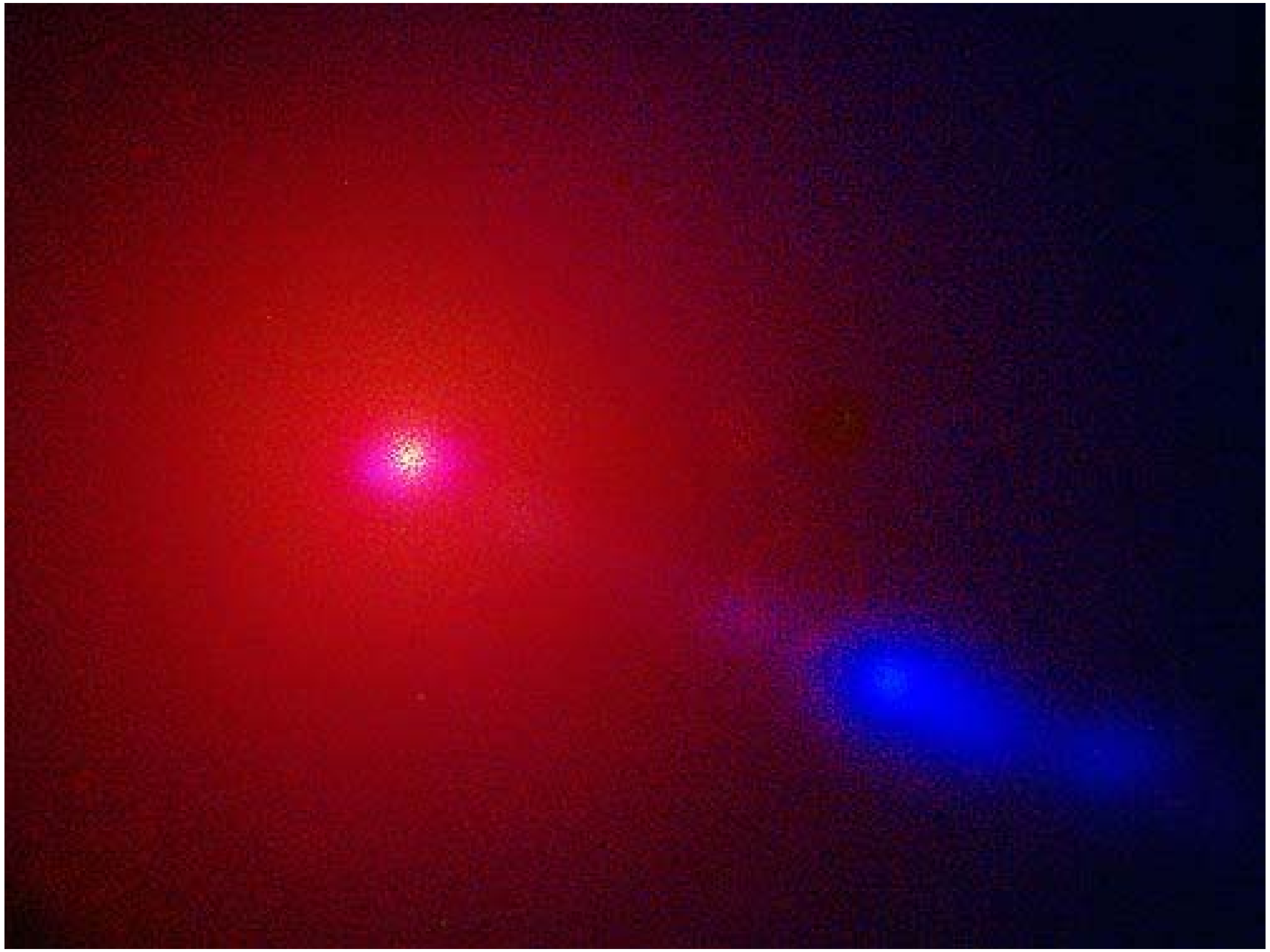
A Search for Axions from the Sky



Kay Königsmann Seminar at CERN 8 September 2004

Why do we need an axion ?

the QCD Lagrangian may contain a term

$$\mathcal{L} = \ldots + \theta \, \frac{\alpha_s}{8\pi} \, G^{\mu\nu} \, \tilde{G}_{\mu\nu}$$

with θ being an arbitrary parameter $O(1)$ and

$G^{\mu\nu}$ being the gluon field tensor (a la $F^{\mu\nu}$ in QED)

BUT: this term violates CP ! Why?

Lagrangian density

$$\mathcal{L} \;=\; \ldots + \theta \, \frac{\alpha_s}{8\pi} \, G^{\mu\nu} \, \tilde{G}_{\mu\nu}$$

with $\tilde{G}^{\mu\nu} = (1/2) \; \epsilon^{\mu\nu\alpha\beta} \; G_{\alpha\beta}$

CP-violation of this term

can only be seen by investigating the properties under Lorentz-transformations

with help from Andreas Schäfer (but too complicated for this talk)

CP-Violation

but easy to understand when calculating $G^{\mu\nu}\tilde{G}_{\mu\nu}$

whereas $G^{\mu\nu}G_{\mu\nu} \propto \vec{E}^2 + \vec{B}^2$ CP conserving !

is $G^{\mu\nu}\tilde{G}_{\mu\nu} \propto \vec{E} \cdot \vec{B}$ CP violating !

thus : $\mathcal{L} = \theta \frac{\alpha_s}{4\pi} \vec{E}_{color} \cdot \vec{B}_{color}$

But there is no P-violation in the strong interaction sector !

How do we know ?

the electric dipole moment of the neutron is measured to be $d_n < 10^{-25}$ e cm : the predicted value of

$d_n \simeq \theta \times 10^{-15}$ e cm implies a value of $\theta < 10^{-10}$

this means that θ would need to be fine tuned to such a small value: something physicists don't like

How to circumvent P-violation ?

The original proposal by Peccei & Quinn in 1974 : a U(1) symmetry

- existence of a new, massless pseudoscalar field a, the axion field $(J^{PC} = 0^{-+})$, interacting with the gluon field
- this adds two other terms to the Lagrangian :

$$\mathcal{L}_{\mathcal{PQ}} = \ldots + \frac{1}{2}(\partial_\mu a)^2 + (\theta - \frac{a}{f_a})\frac{\alpha_s}{8\pi} G^{\mu\nu}\tilde{G}_{\mu\nu}$$

Kinetic term

Peccei-Quinn scale

thus: if $\theta = \langle a \rangle / f_a$ no P-violating term remains !

The PQ - Axion

Solid predictions for

- its mass: $m_a = 75\ \mathrm{keV}\ (x + 1/x) > 150\ \mathrm{keV}$

  where x is the ratio of the two vacuum expectation values (giving mass to up and down quarks)

- **and for the branching ratios $J/\psi \to a\,\gamma$ and $\Upsilon \to a\,\gamma$**

- **this Axion was quickly ruled out (although some beam dump experiments kept on claiming a signal)**

Crystal Ball and the axion

$$
\begin{aligned}
B(\mathrm{J}/\psi \to \gamma a) &\propto x^2 \qquad \text{and} \\
B(\Upsilon \to \gamma a) &\propto 1/x^2 \qquad \text{gives}
\end{aligned}
$$

$$B(J/\psi \to \gamma a) \times B(\Upsilon \to \gamma a) = \frac{(G_F\, m_c\, m_b)^2}{2\pi^2\alpha^2} = (1.4 \pm 0.3) \times 10^{-8}$$

both measurements by a young post doc (Königsmann)

yielded the result

$$B(\mathrm{J}/\psi \to \gamma a) \times B(\Upsilon \to \gamma a) < 5.6 \times 10^{-10}$$

thus ruling out the standard PQ-axion

Therefore: the invisible axion

here the PQ-mechanism is decoupled from the electroweak scale:

the normal Higgs field and a new field a with a very(!) high VEV f_a

thus no dependence on the ratio of VEVs anymore, just on f_a , the axion decay const

(f_a in analogy to f_π)

Axion coupling to photons

Axions can decay to photons because of
$a \rightarrow q\bar{q}$ transitions $\rightarrow$ a-π^0 mixing (0^{-+})
albeit with a reduced coupling strength
w.r.t. the π^0 by $\simeq f_\pi / f_a$
its lifetime is given by

$$\tau_a \propto f_a^2 \, m_a^{-3} > 10^{17} \text{ y} \quad \text{for} \quad m_a = 1 \text{ eV}$$

exceeding the lifetime of the universe by 10^7 !

Axion coupling to photons

$$\mathcal{L}_{a\gamma} = g_{a\gamma\gamma}\ a\ \vec{E}_c \cdot \vec{B}_c$$

CP-conserving !

with $$g_{a\gamma\gamma} = \frac{\alpha}{2\pi f_a}\,(E/N - 1.9)$$

and $$E/N = \mathcal{O}(1) \text{ in GUT models}$$

Astrophysical constraints

Astrophysical arguments from energy loss of HB- stars in globular cluster, Raffelt 1996

$g_{a\gamma\gamma} < 10^{-10}$ **GeV^{-1}**

which implies

$$f_a \simeq \frac{\alpha}{2\pi\, g_{a\gamma\gamma}} > 10^7 \text{ GeV}$$

Other axion properties

$$m_a \simeq 0.5 \frac{f_\pi m_\pi}{f_a} \simeq 0.6\,\mathrm{eV}\ \frac{10^7\ \mathrm{GeV}}{f_a}$$

i.e. the range we are interested in is

$m_a < 1\mathrm{eV}$ (with $f_a > 10^7$ GeV)

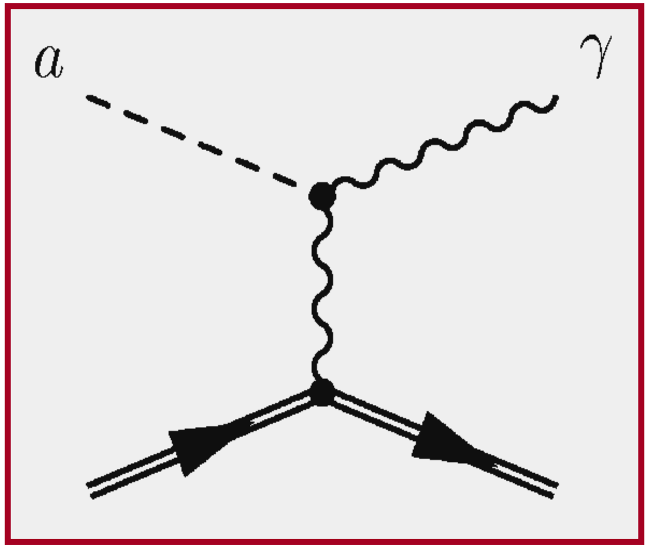
Note: generally, CAST is a search for any kind of light neutral bosons coupling to two photons, Axions being the most popular example

Axions as Cold Dark Matter

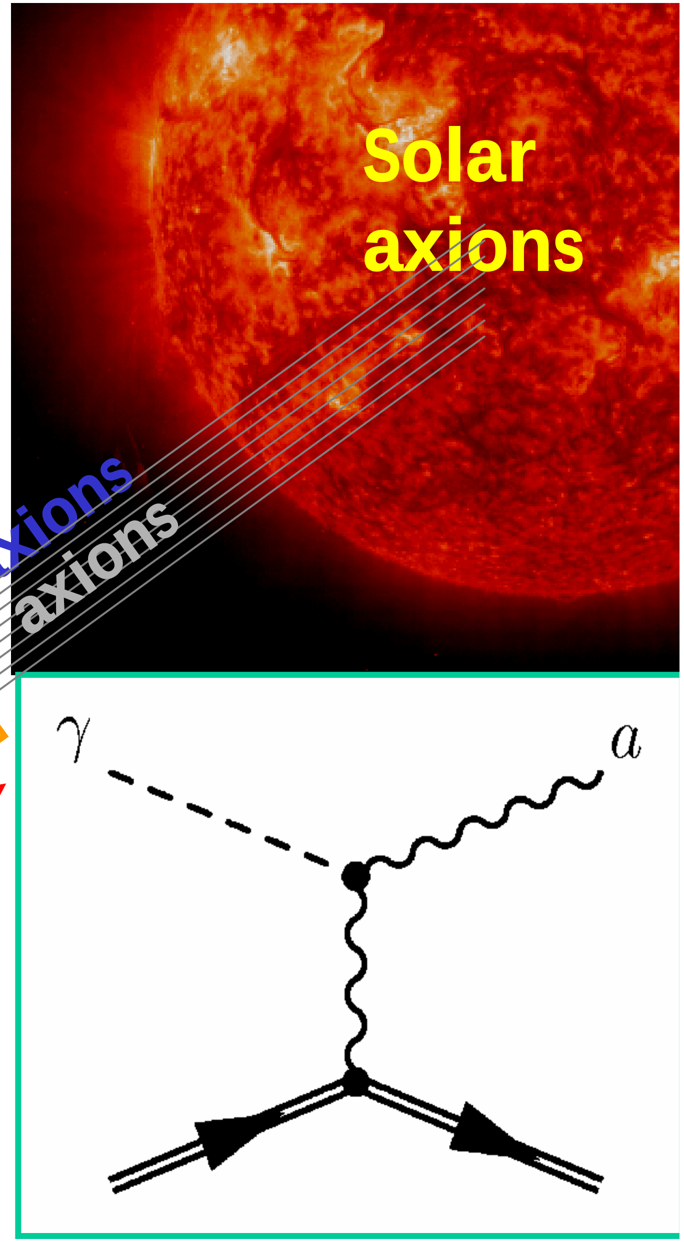
- an Axion with mass $10^{-5} < m_a < 10^{-1}$ eV is an excellent candidate for cold dark matter
- thus a proof of its existence would have major consequences for our understanding of the universe ! It's energy density would be about 0.5 GeV/cm^3 in our galaxy!

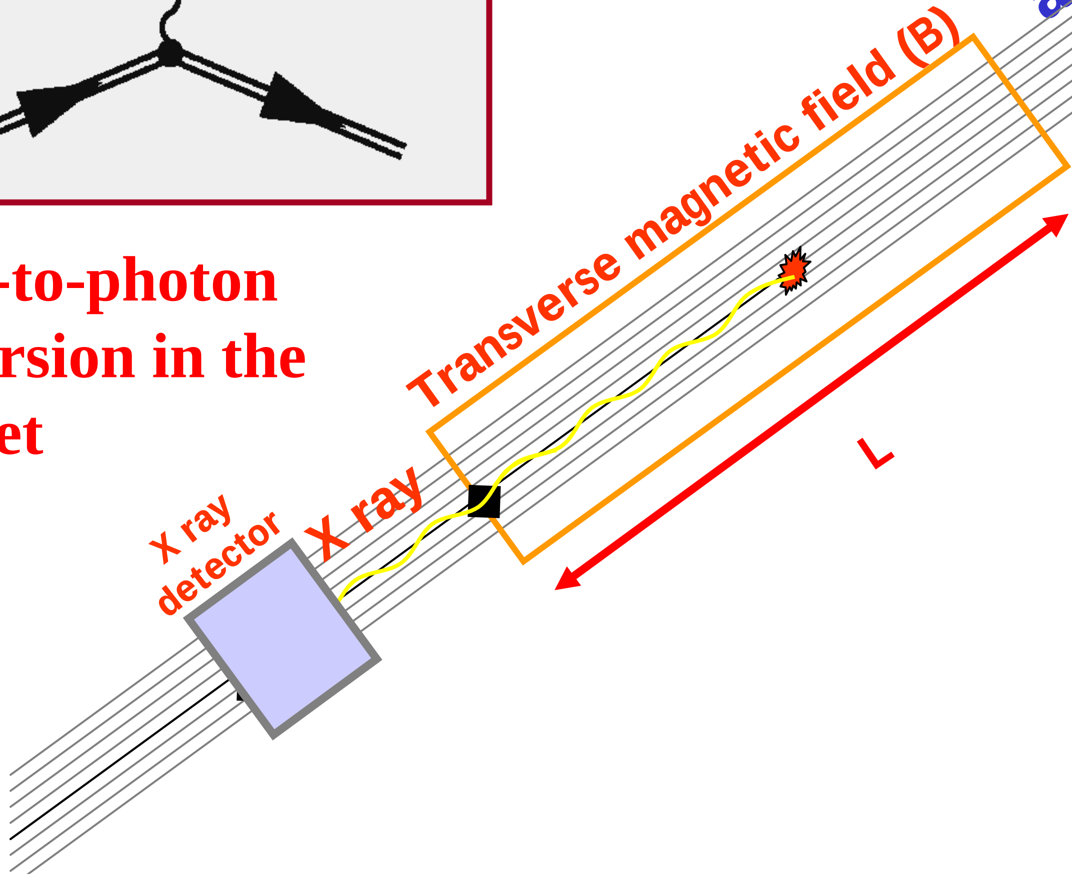
compare to $\rho_{crit} = 5*10^{-6}$ GeV/cm^3 for our universe

Principle of Detection



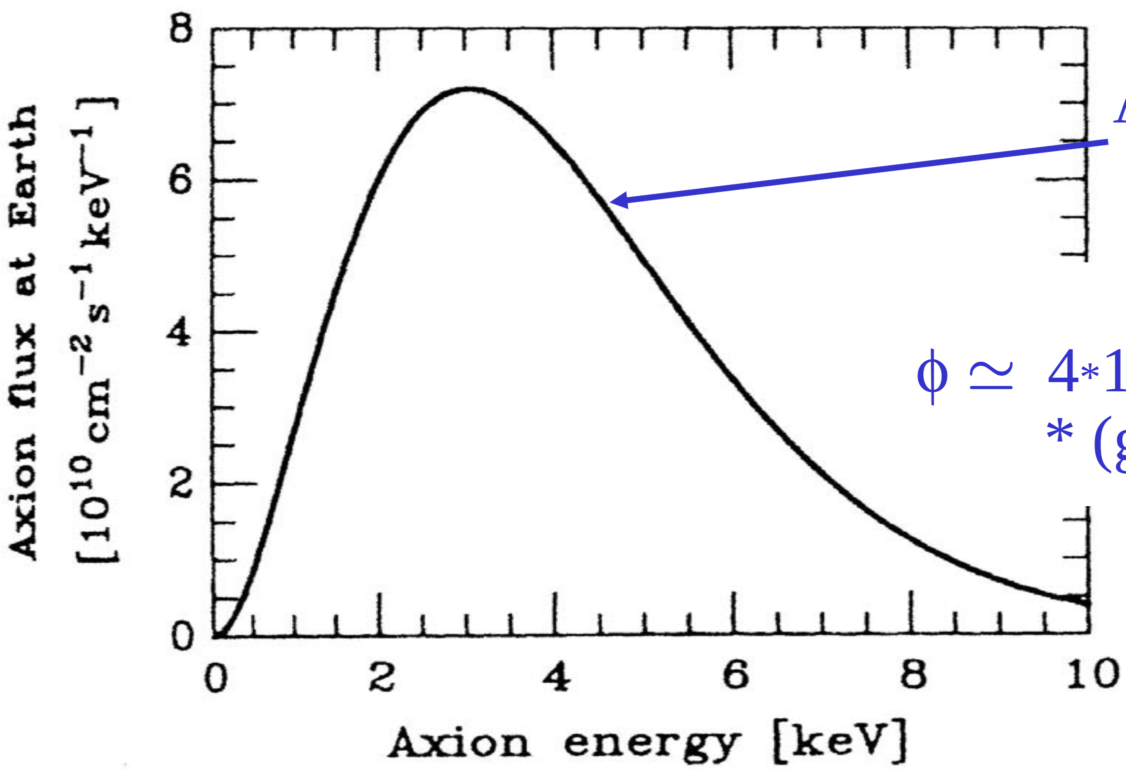
axion-to-photon conversion in the magnet





photon-to-axion Conversion in the sun

Energy spectrum of axion flux



Average energy

$\simeq$ 4.2 keV

$\phi \simeq 4{*}10^{12}$ axions/cm^2 s
$*\ (g_{a\gamma\gamma}/10^{-10}\ \text{GeV})^2$

$$\frac{\mathrm{d}\phi}{\mathrm{dE_a}} \propto g_{a\gamma\gamma}^2 \frac{E_a^3}{\exp(E_a/1\ \mathrm{keV}) - 1}$$

Planck's law

Conversion probability in the magnet

$$P_{a\gamma} \simeq \left(\frac{g_{a\gamma\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}}\right)^2 \left(\frac{B}{9.6\,\mathrm{T}}\ \frac{L}{9.3\,m}\right)^2 \ |M|^2$$

where $\boldsymbol{M} = 1$ for full coherence over magnet ($L\, m_a^2 / 2E_a < 1$)

this results in signal counts/day of

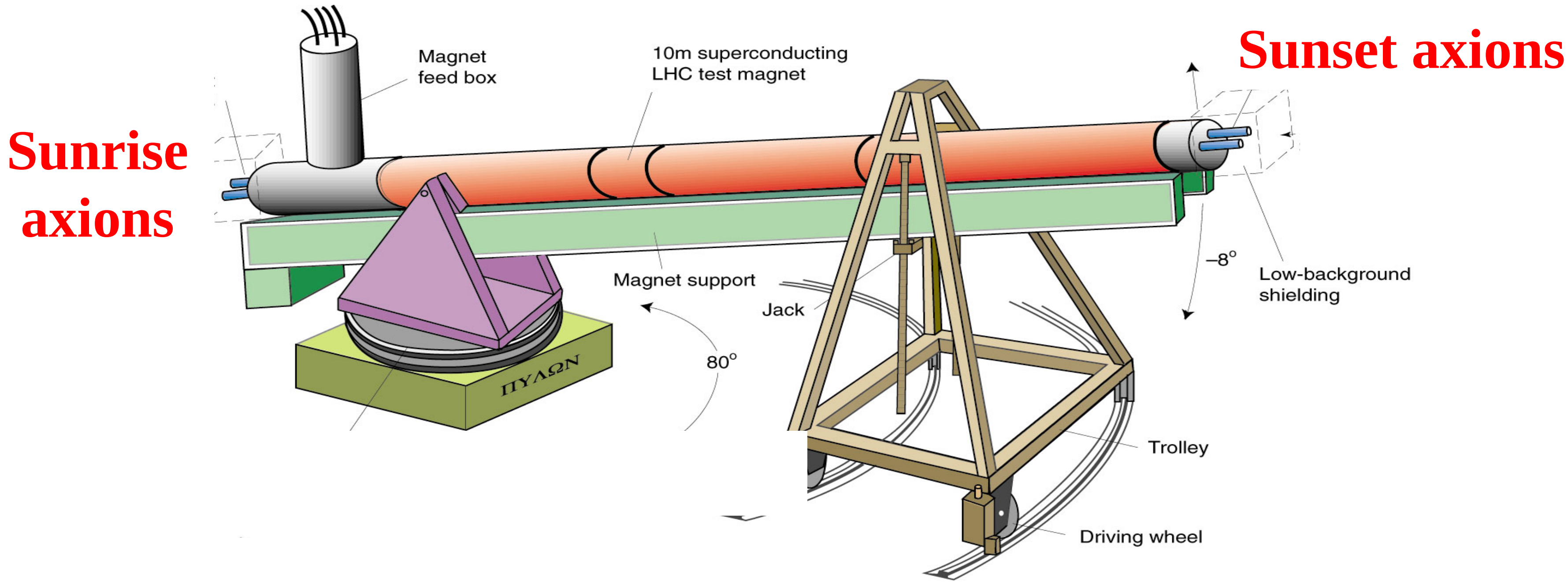
$N_a \sim 6$ Axions / day

with $g = 10^{-10}\ \mathrm{GeV}^{-1}$, $B = 9\mathrm{T}$, $L = 9.3\mathrm{m}$, $Area = 13\mathrm{cm}^2$

The CAST experiment: CERN Axion Solar Telescope

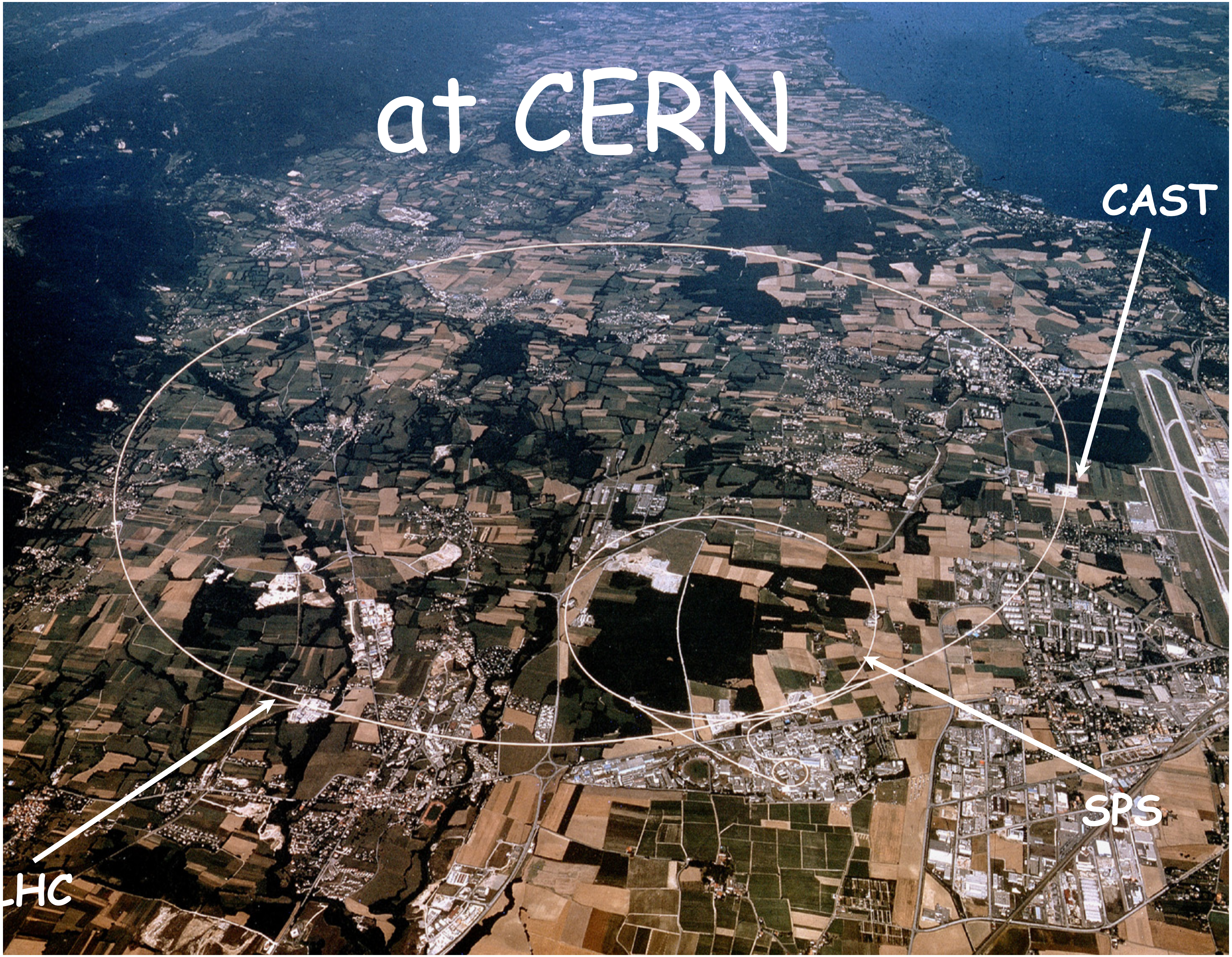
with L=9.3m and B=9T : 100*better sensitivity than previous expt^{s}

Using a decommissioned LHC magnet on a rotating platform



2 X-ray gas detectors + 1 CCD with a X-ray focussing device

The magnet at -8 degrees


at CERN
CAST
SPS
LHC

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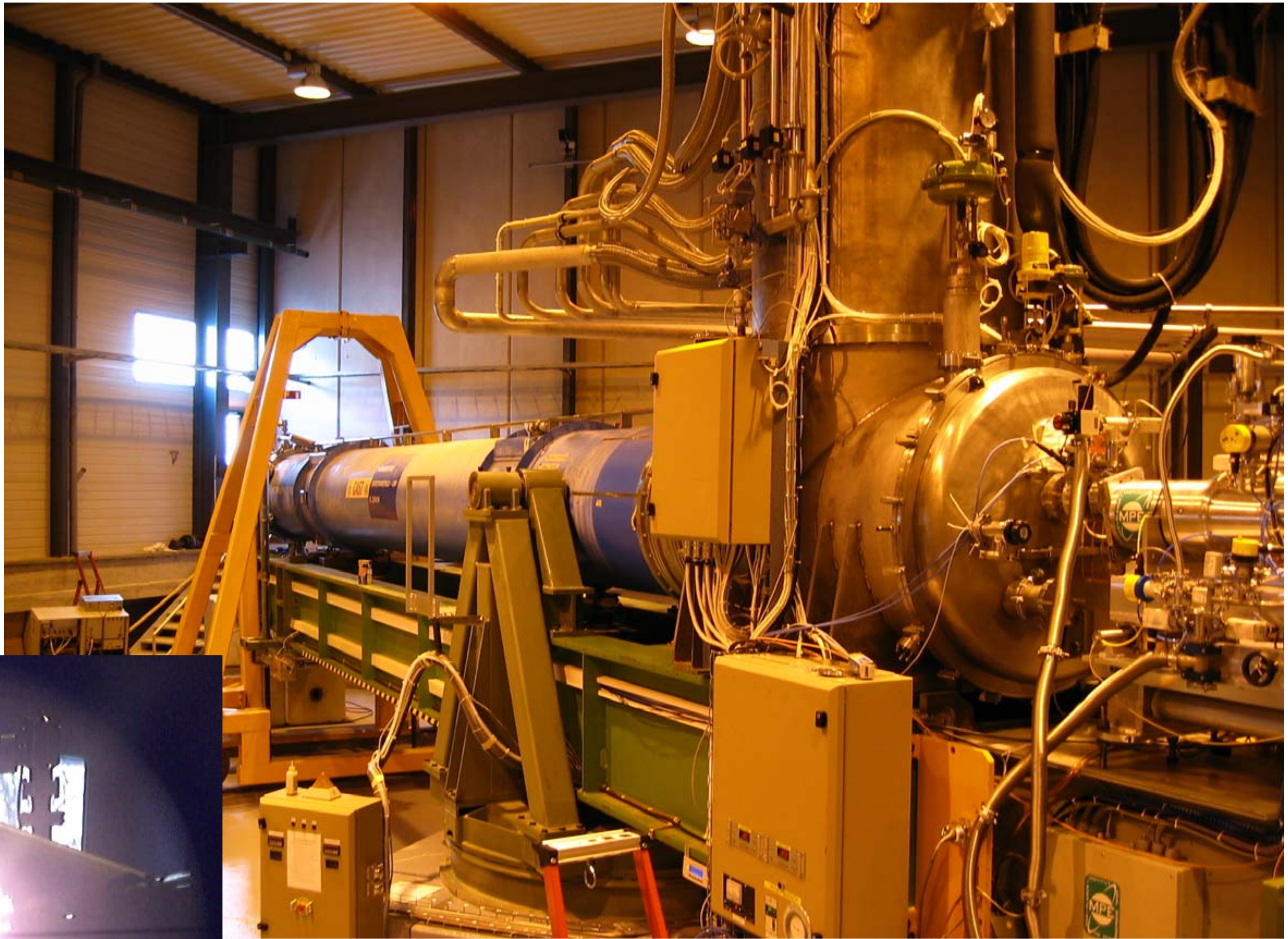
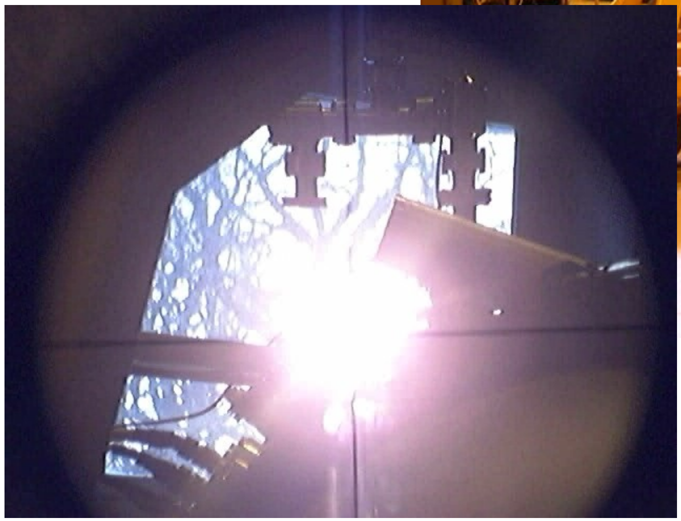
Magnet, sun tracking

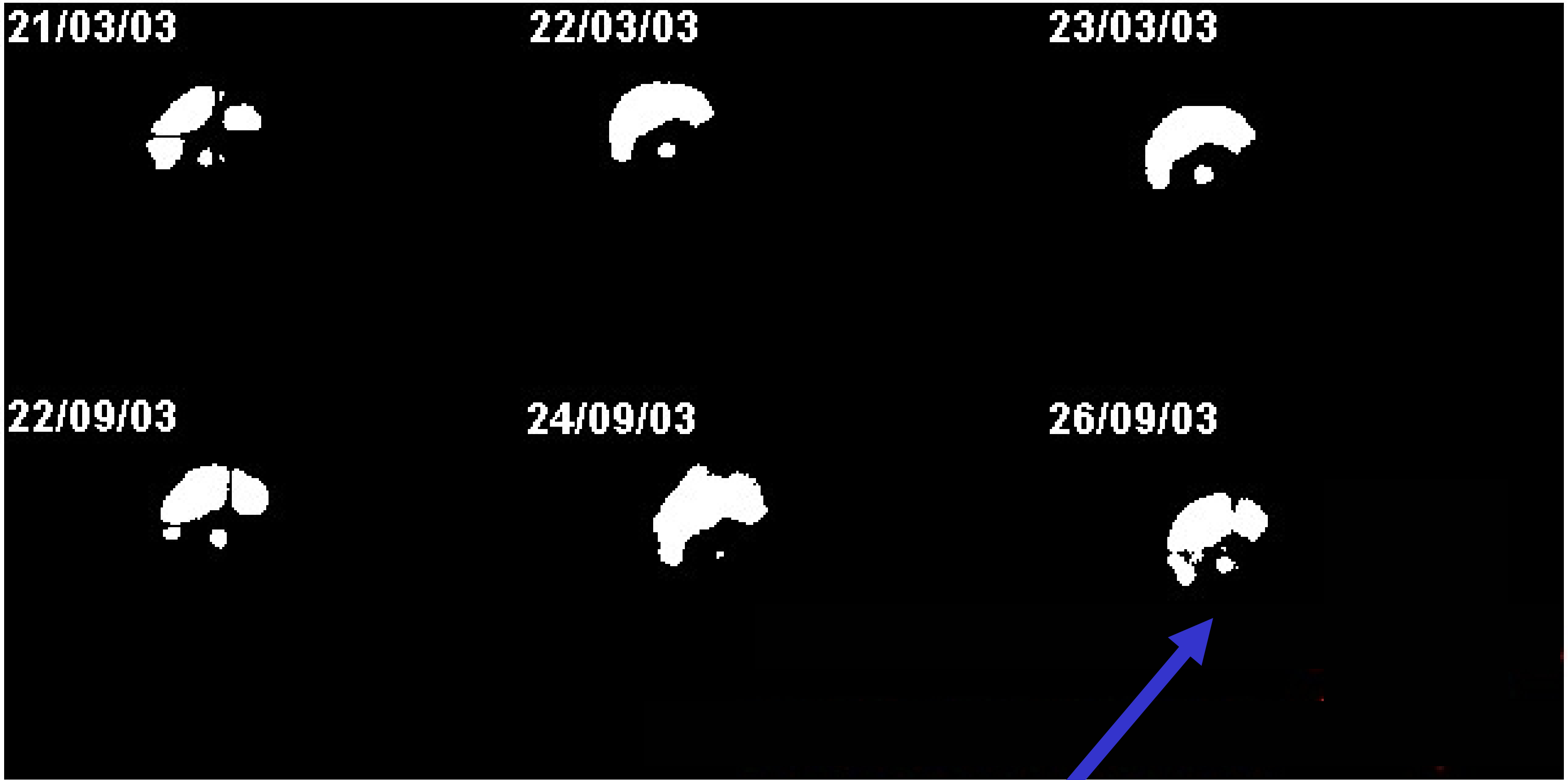
Looking at sunrise





twice a year (September & March)
we can film the sun through a window

Optical sun tracking



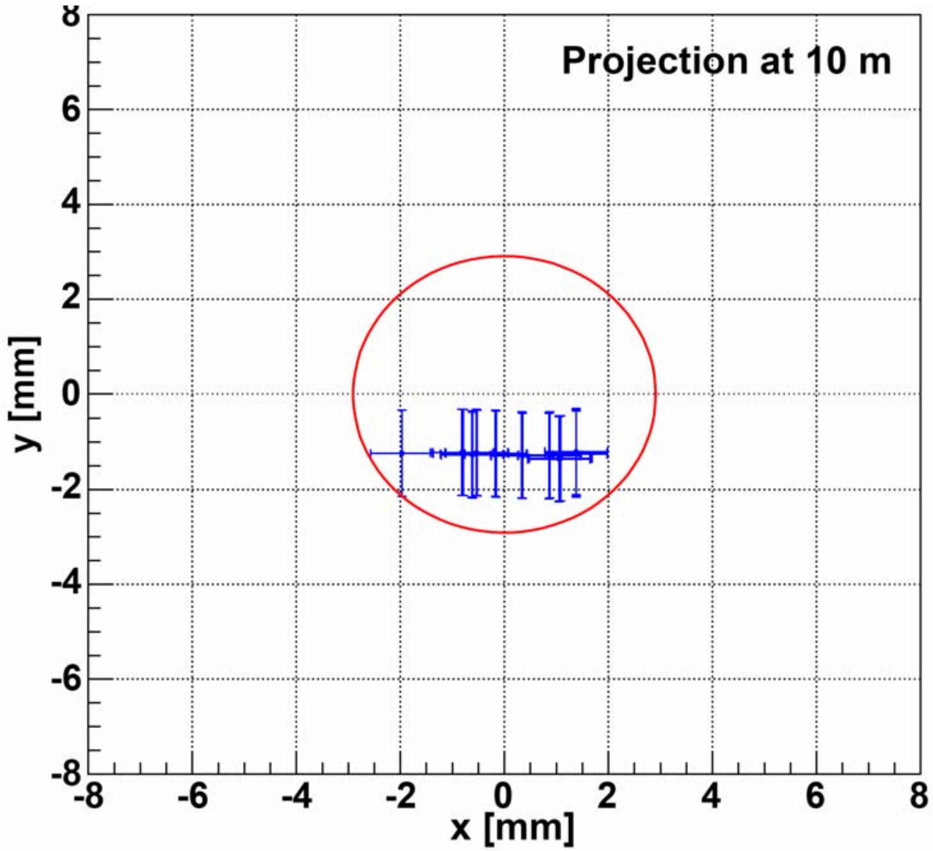
Sun partly hidden by trees and leaves

Tracking accuracy

- checked by geometers twice a year
- comparison of 2002 and 2004 tracking

  reproducibility better than 1 mm
- tracking system calibrated and correlated to celestial coordinates

Comparison between 2002 and 2004 grid



Magnet quenching

8 events
in 2003
6 events
in 2004

only one
real quench

With several innovative detectors

- TPC : time projection chamber
- Micromega : drift chamber with micro-strips
- CCD : charged coupled Si-detector attached to a focusing X-ray telescope (used on the ABRIXAS space mission)

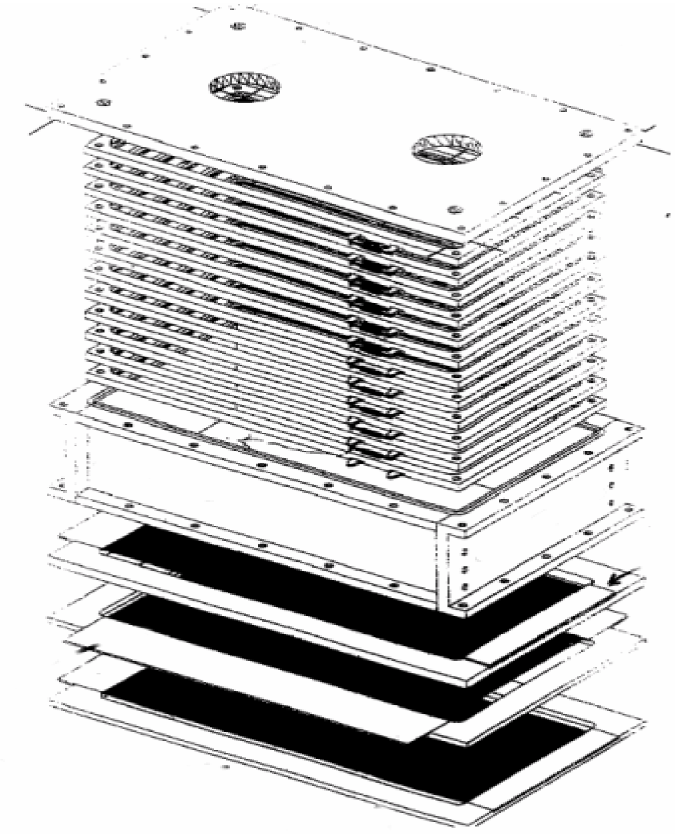
TPC

Sun tracking time: 63 h

Background time : 720 h

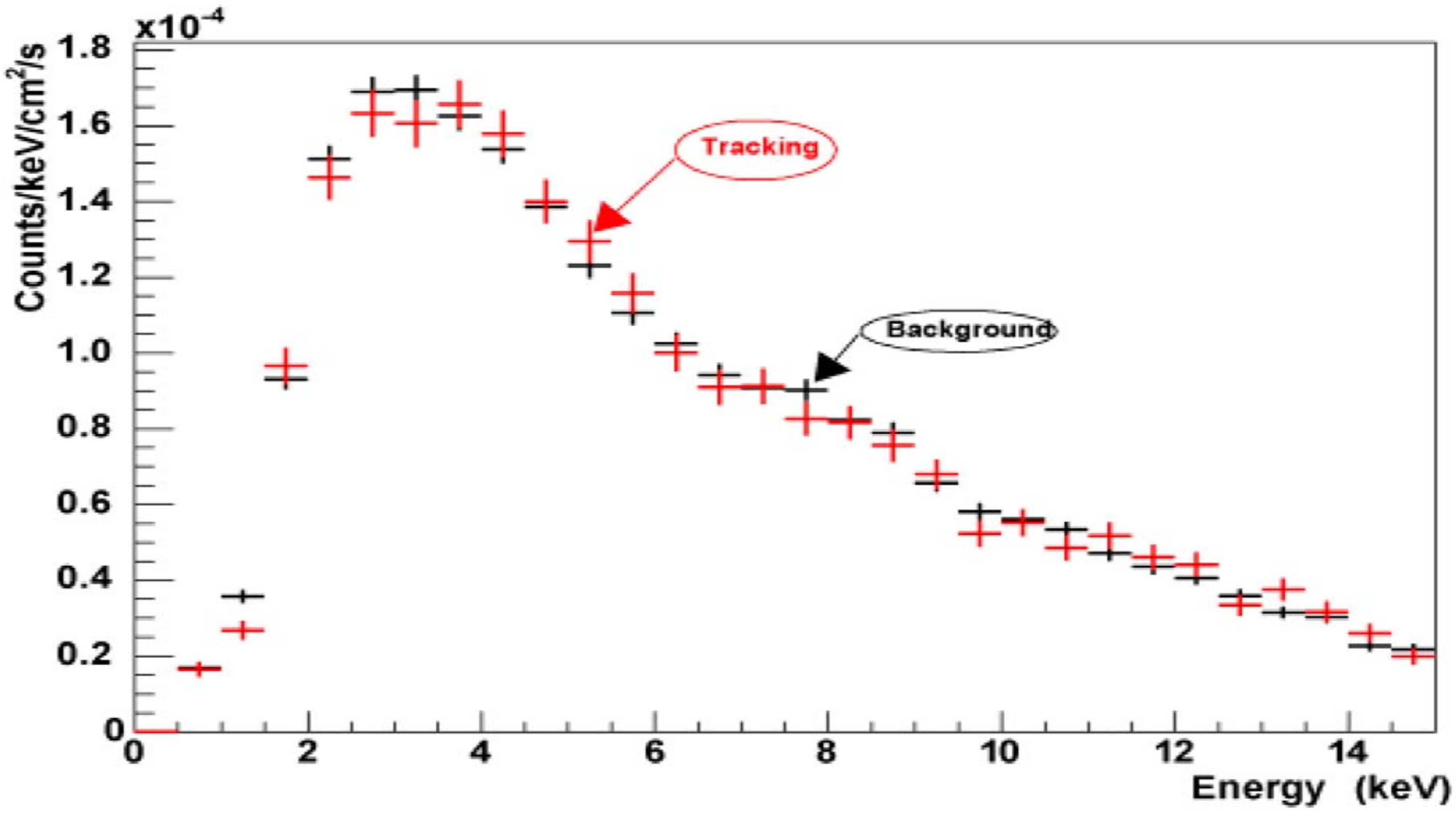
The TPC layout

- a conventional Time Projection Chamber (TPC) built with low radioactivity materials (mainly Plexiglas)
- drift space 10 cm
- charge collected by a MWPC at the end of the drift space:
- 48 anode wires, 96 cathode wires
- signal measurement by 10 MHz Flash-ADC's

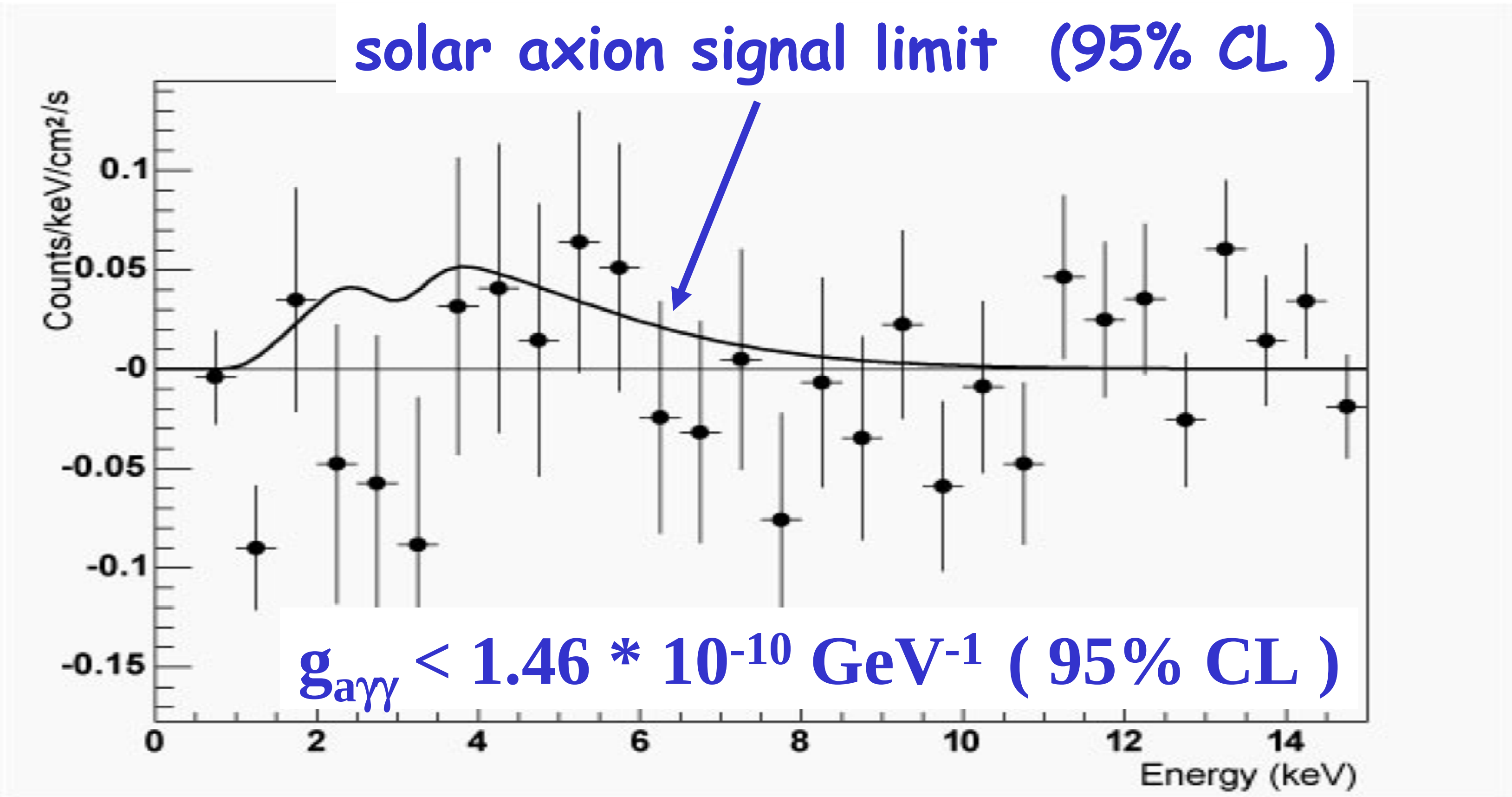


TPC Spectrum from 2003 Data

improvement in 2004: 3 times less background



Subtracted TPC spectrum with signal at 95% CL



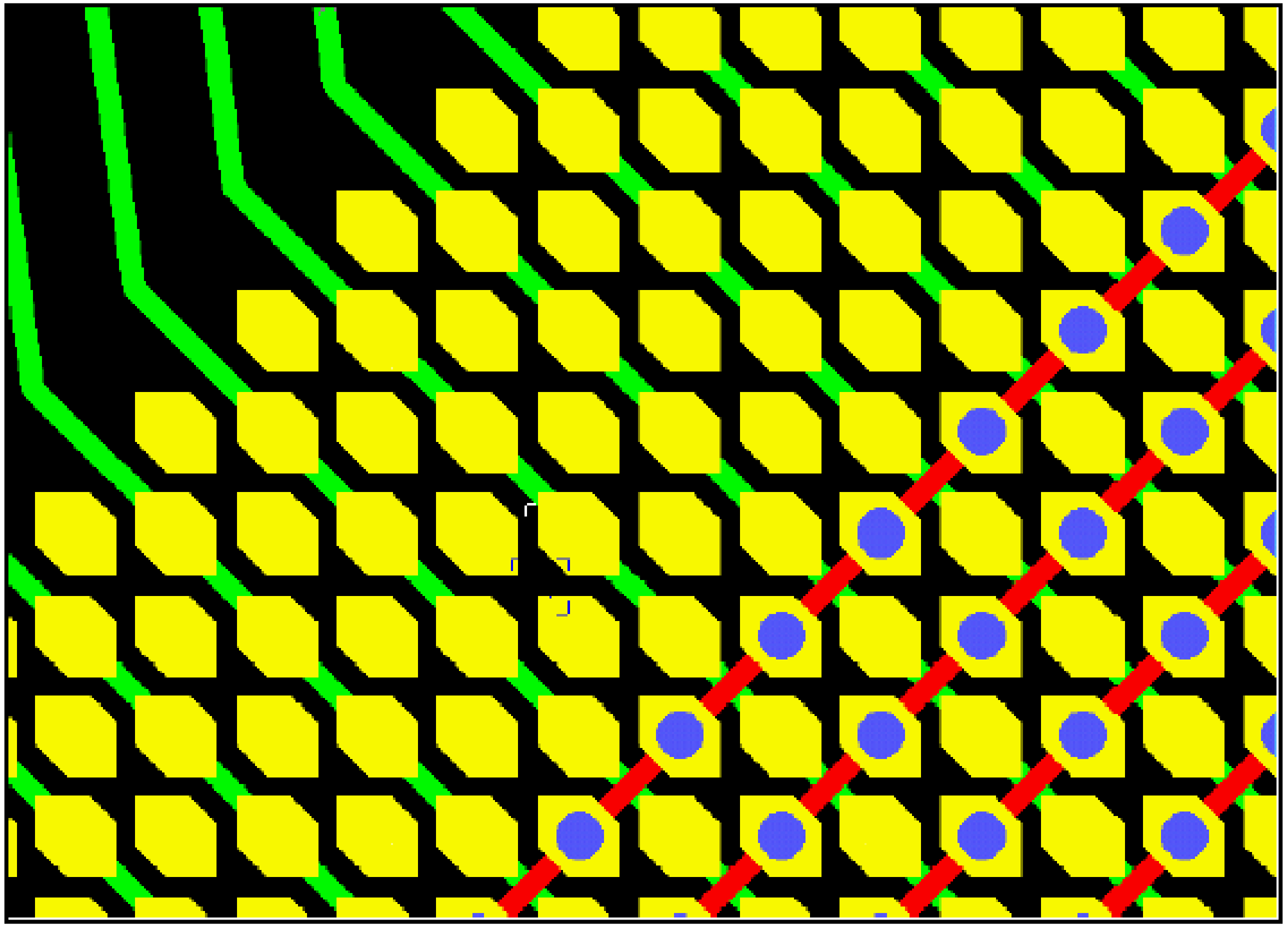
$g_{a\gamma\gamma} < 1.46 * 10^{-10}\ \mathrm{GeV}^{-1}$ (95% CL)

MicroMega

Sun tracking time: 77 h

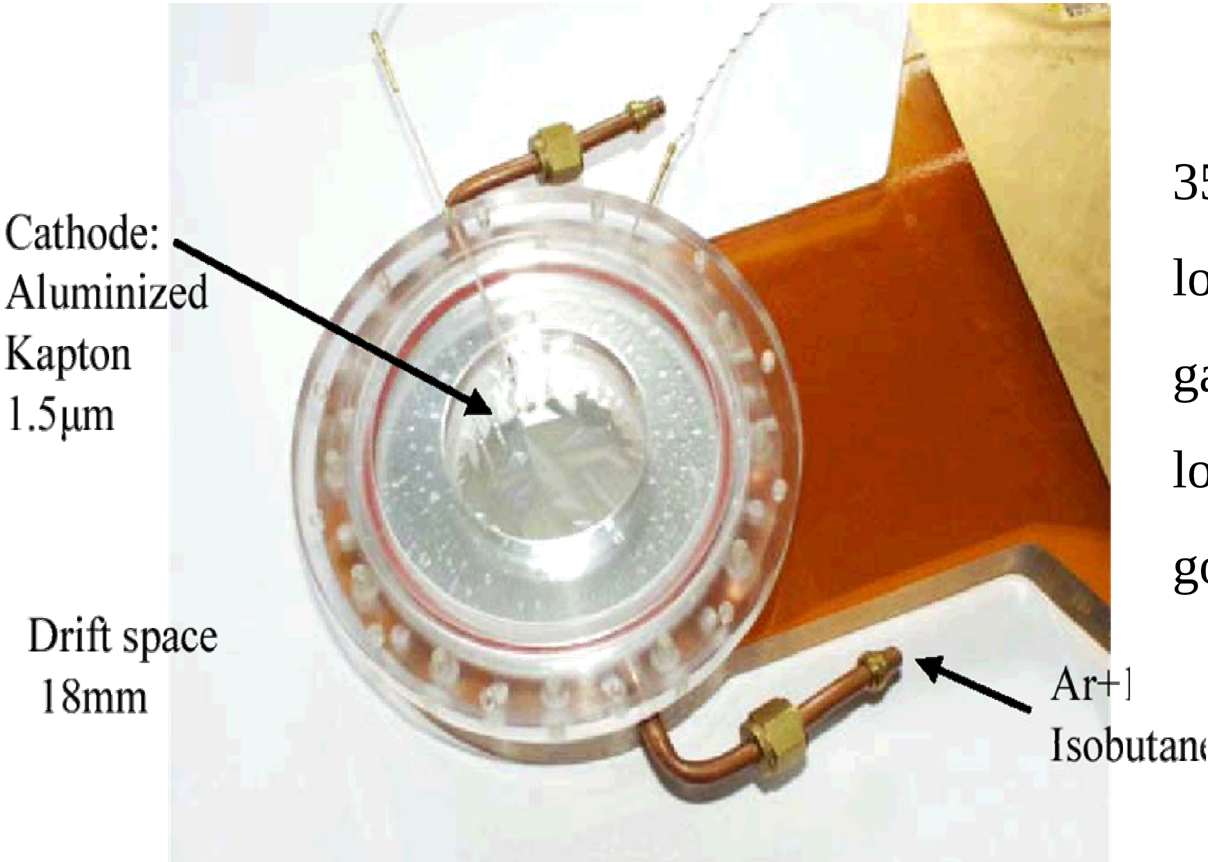
Background time : 809 h

The MicroMega detector



192 charge collection strips for x and for y

The MicroMega detector



350 µm X-Y strip pitch

low threshold ~ 0.6 keV

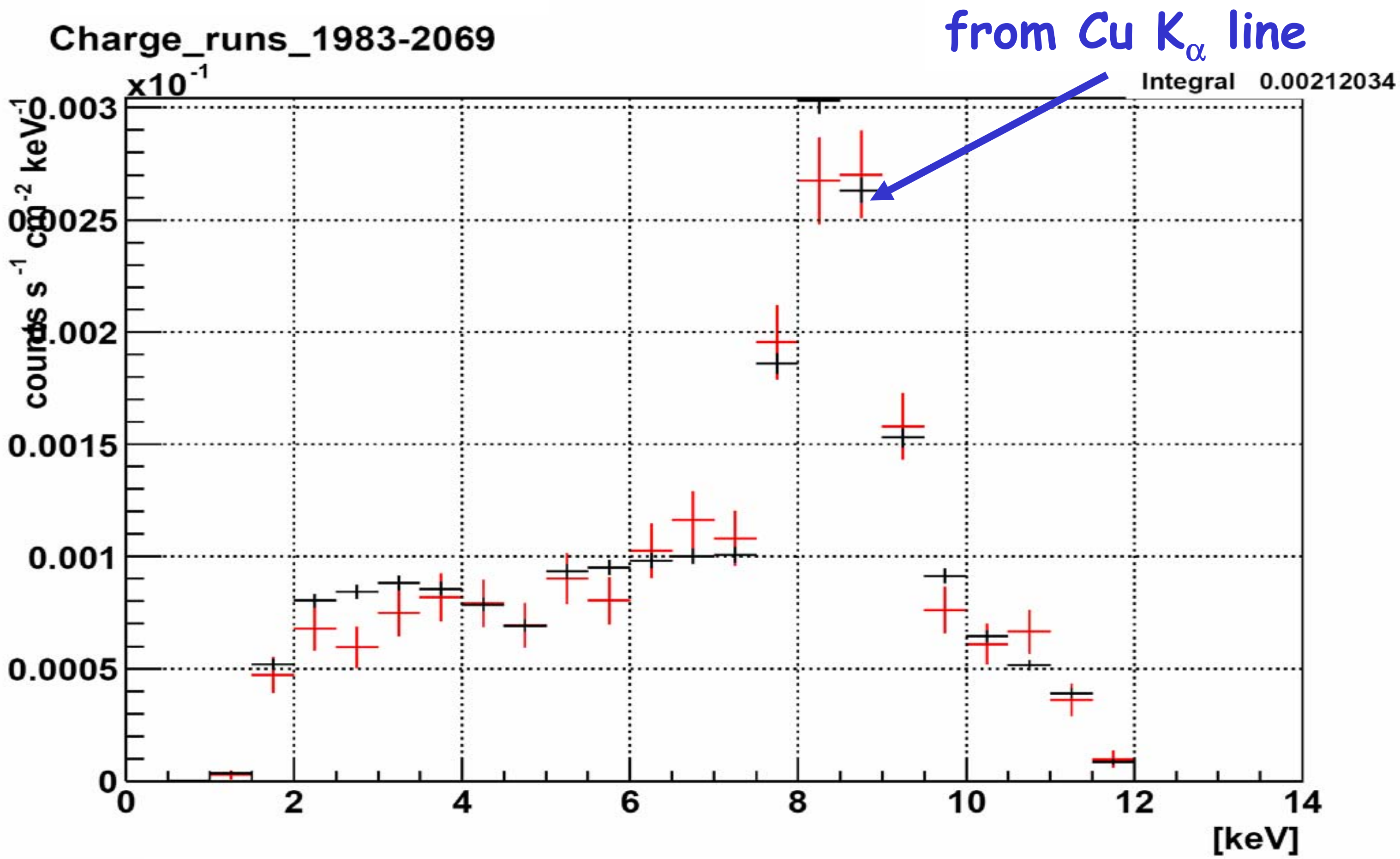
gas : 95%Ar + 5%Isobutan

low background

good spatial resolution

MicroMega Spectrum from 2003

improvement in 2004: 3 times less background



$g_{a\gamma\gamma} < 1.44 * 10^{-10}\ \mathrm{GeV}^{-1}$ (95% CL)

CCD +
X-ray telescope

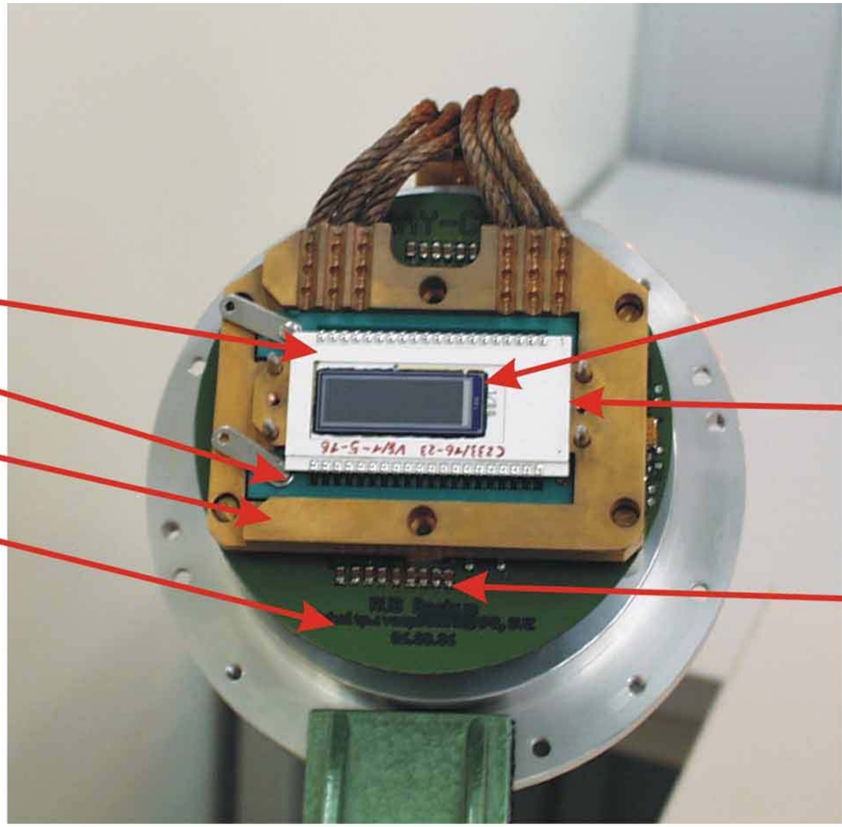
Sun tracking time: 121 h

Background time : 1233 h

CCD detector for the X-ray telescope:

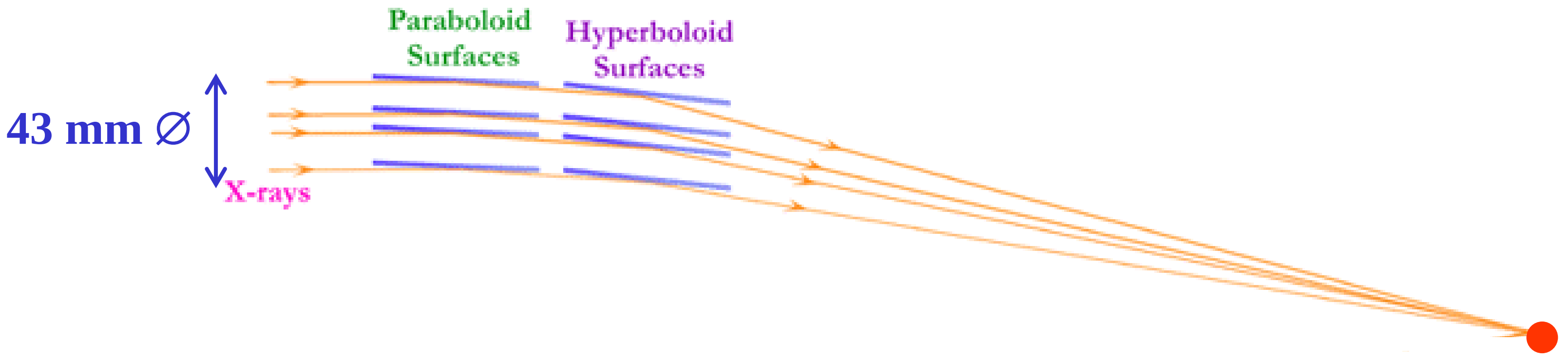
1 x 3 cm^2 CCD with energy resolution of < 500 eV

is used with in combination with a X-ray telescope



CCD can work in vacuum : no window needed

X-ray telescope



focal point

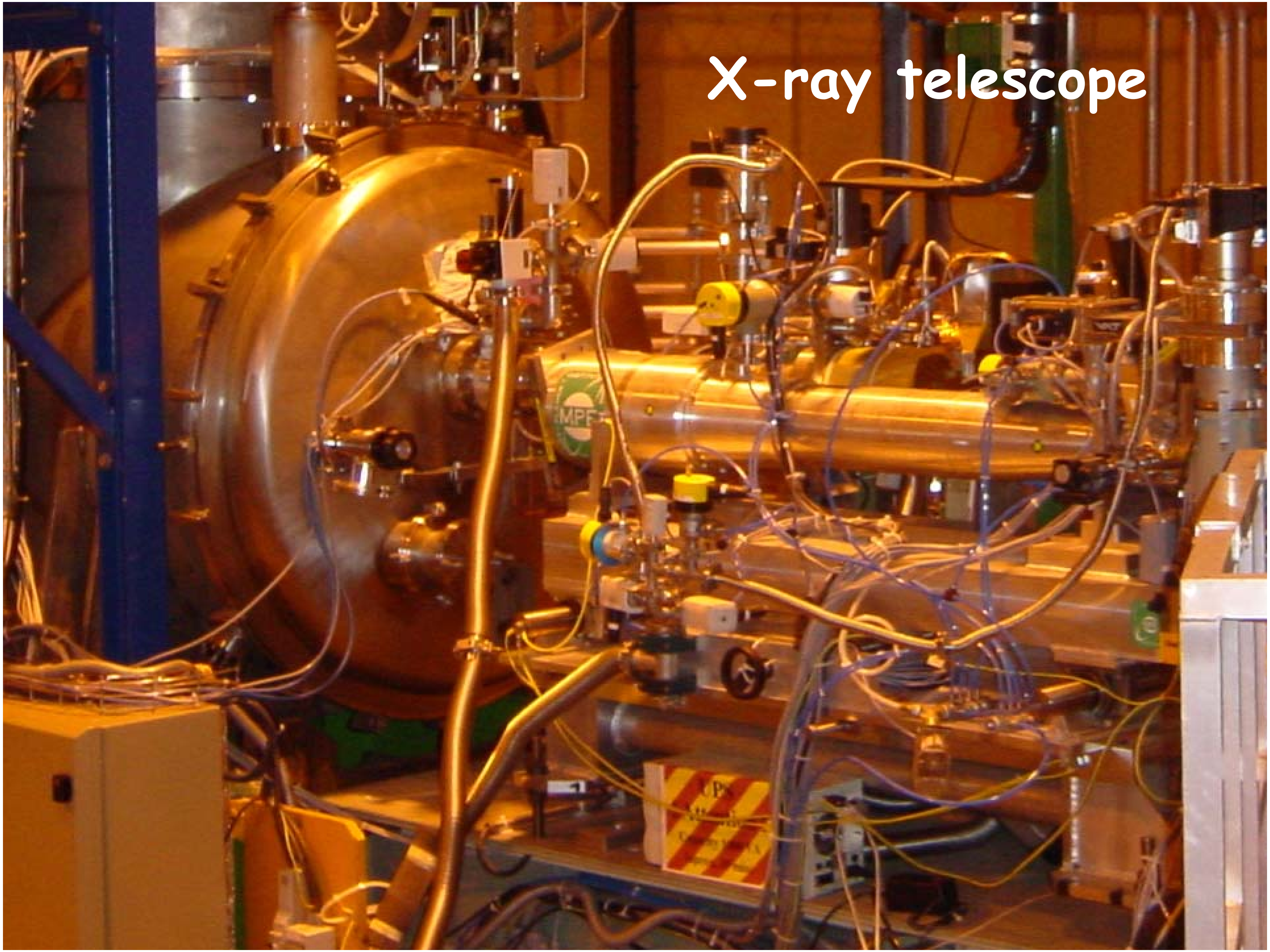
of $\simeq$ 7 mm^2

27 nested pairs of mirrors

from 43 mm ∅ LHC magnet aperture to < 3 mm ∅

i.e. measure signal and background simultaneously

signal-to-noise improvement

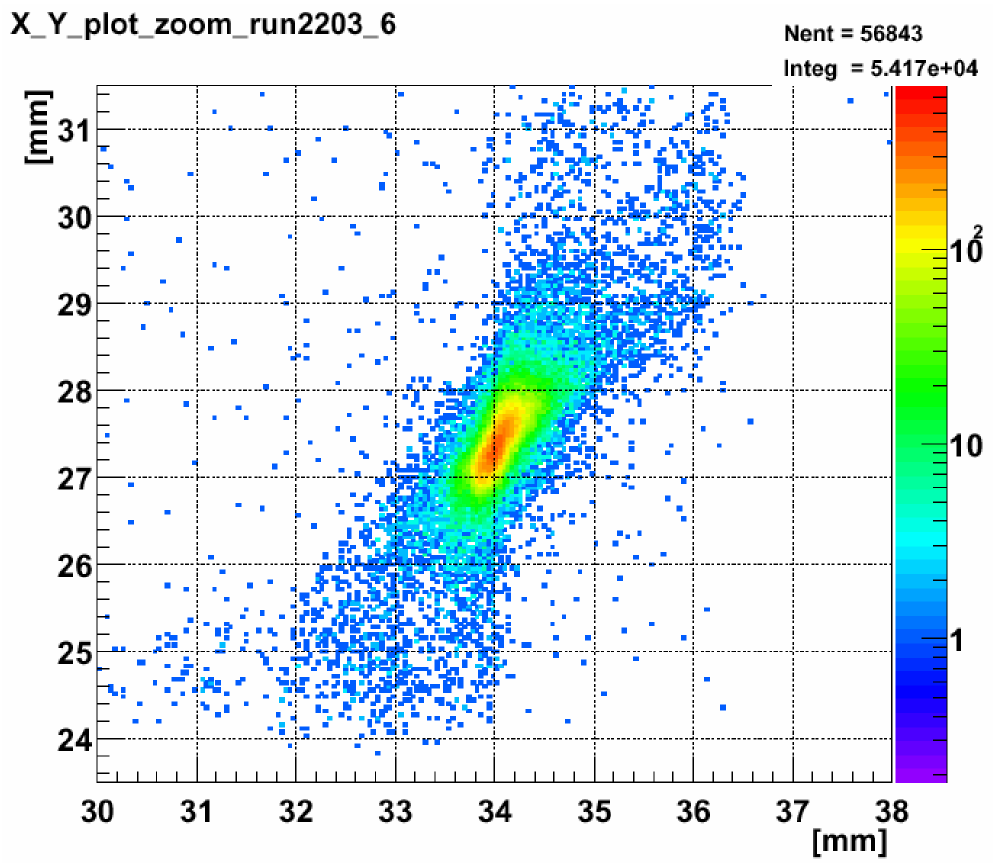

X-ray telescope
MPE

Focus of a X-ray source

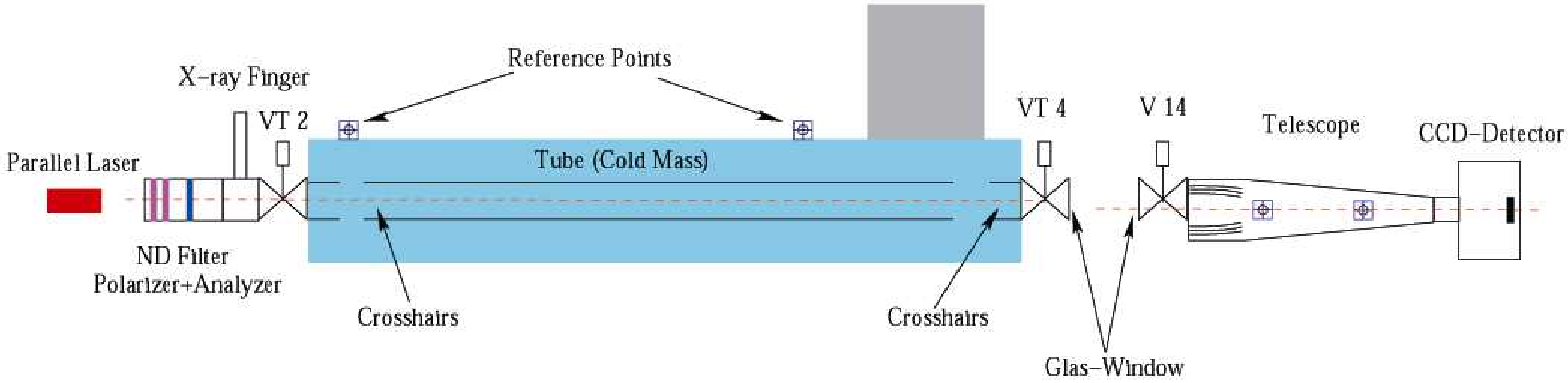
x-y image of a 6.4 keV X-ray beam in MicroMega chamber

(note: log scale for density)

the spot of $7mm^2$ will yield a much better signal to noise ratio



X-ray telescope alignment with Laser and ^{56}Fe source



Spot of a Laser Beam on the CCD

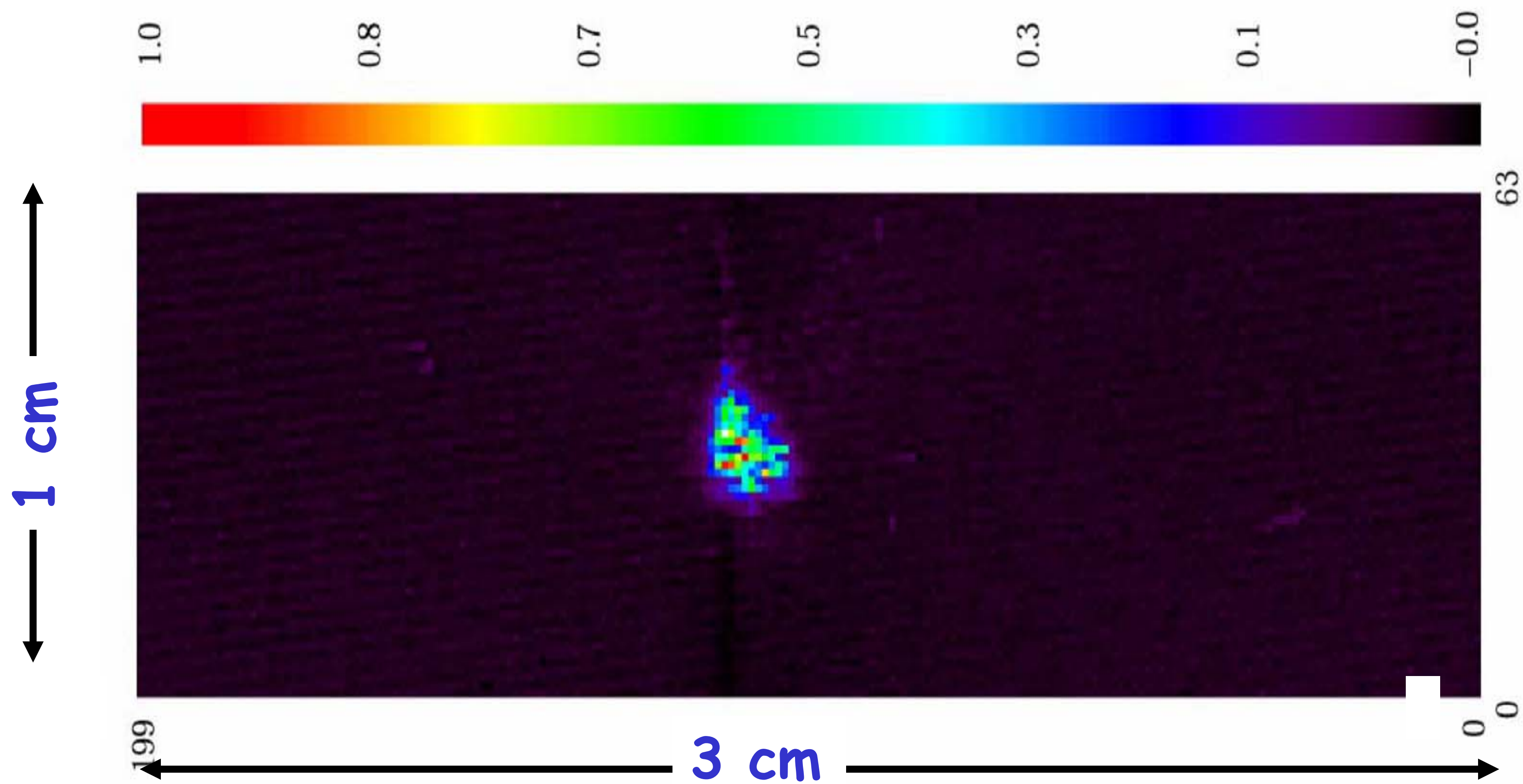
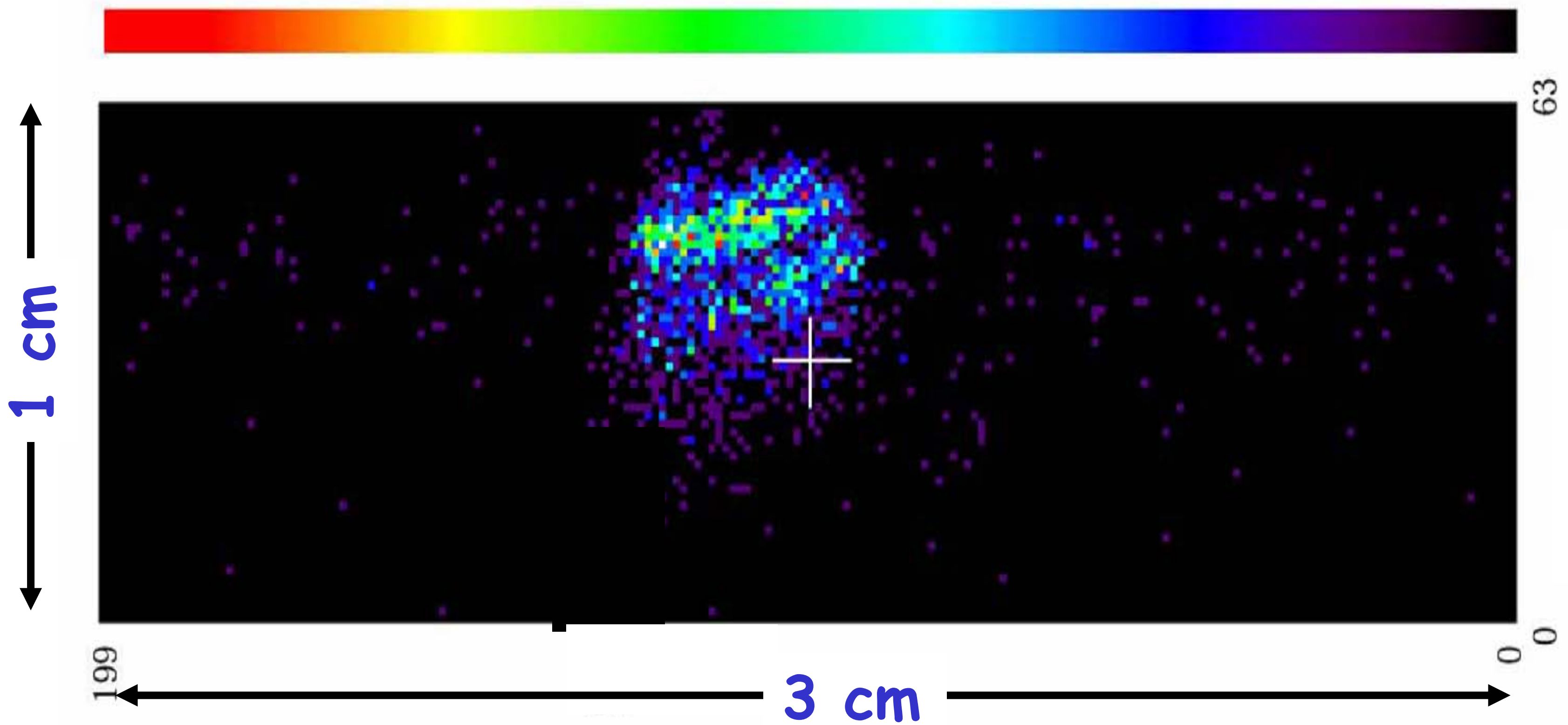
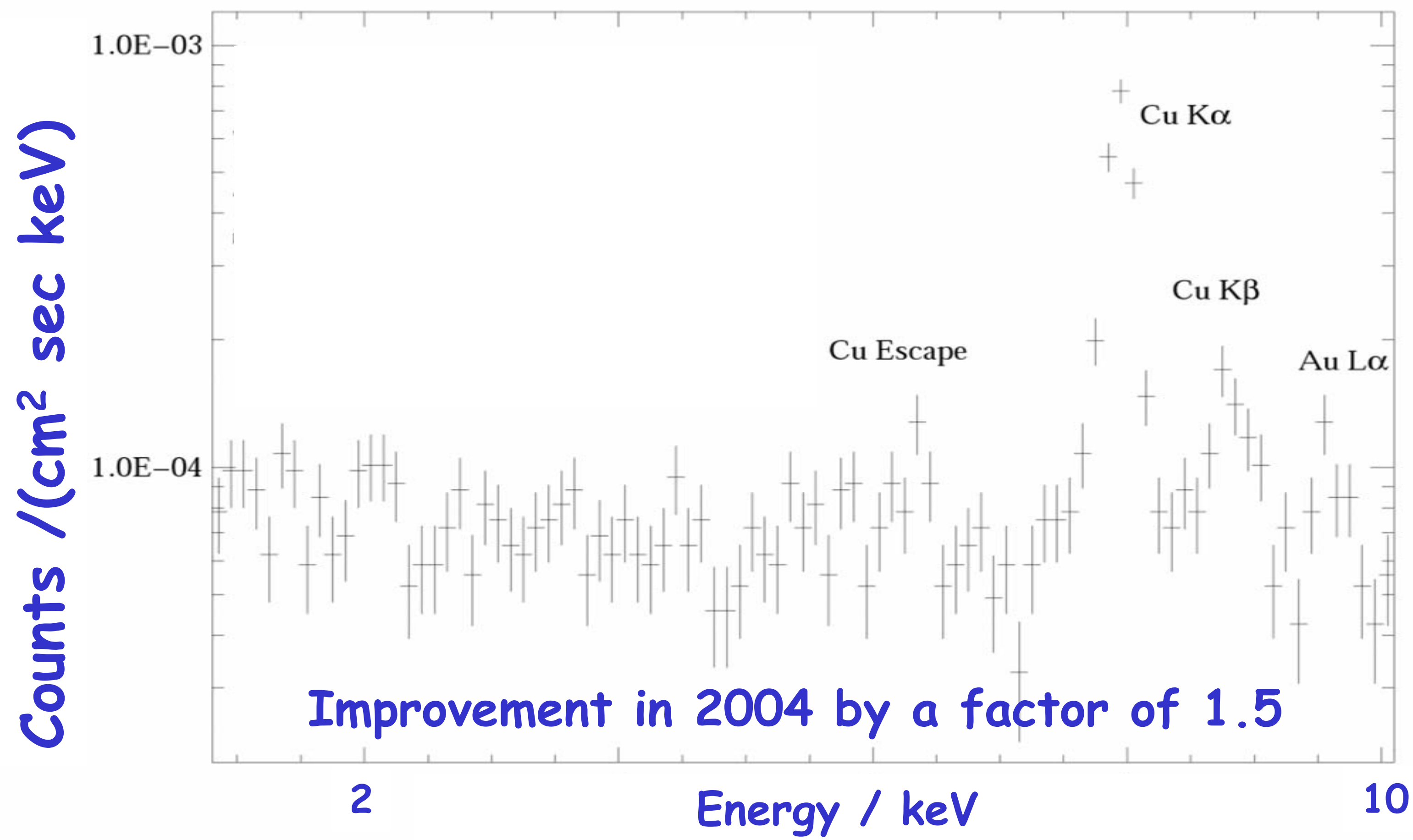


Image of a X-Ray Source through the CAST Magnet



Background spectrum of the CCD



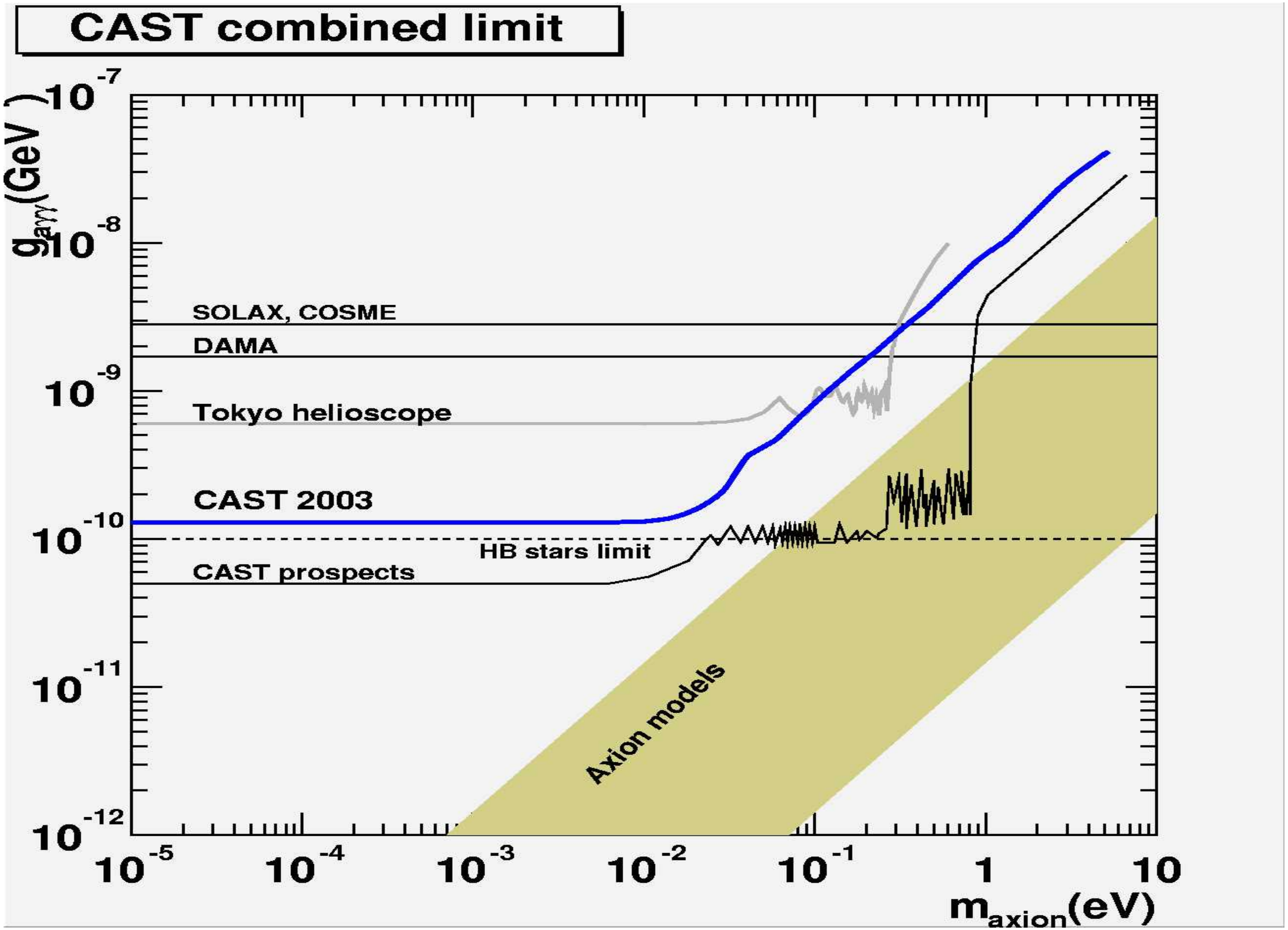
$g_{a\gamma\gamma} < 1.21 * 10^{-10}$ GeV^{-1} (95% CL)

Exclusion limits from all 3 Detectors

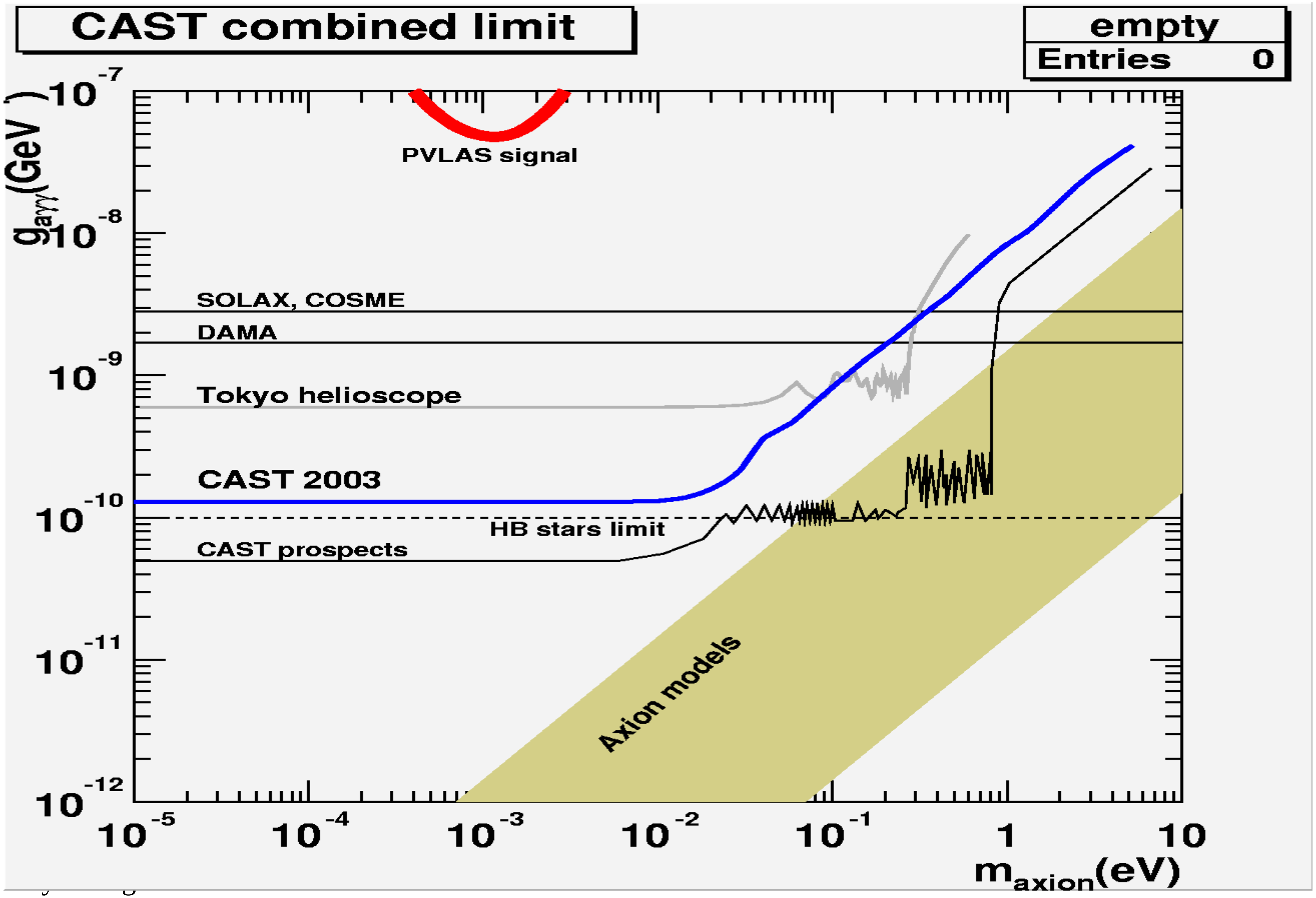
- **TPC:** $g_{a\gamma\gamma} < 1.46 \times 10^{-10}\ \mathrm{GeV}^{-1}$
- **MM:** $g_{a\gamma\gamma} < 1.44 \times 10^{-10}\ \mathrm{GeV}^{-1}$
- **CCD:** $g_{a\gamma\gamma} < 1.21 \times 10^{-10}\ \mathrm{GeV}^{-1}$

- **Combined :** $g_{a\gamma\gamma} < ? \times 10^{-10}\ \mathrm{GeV}^{-1}$

Combined exclusion Plot

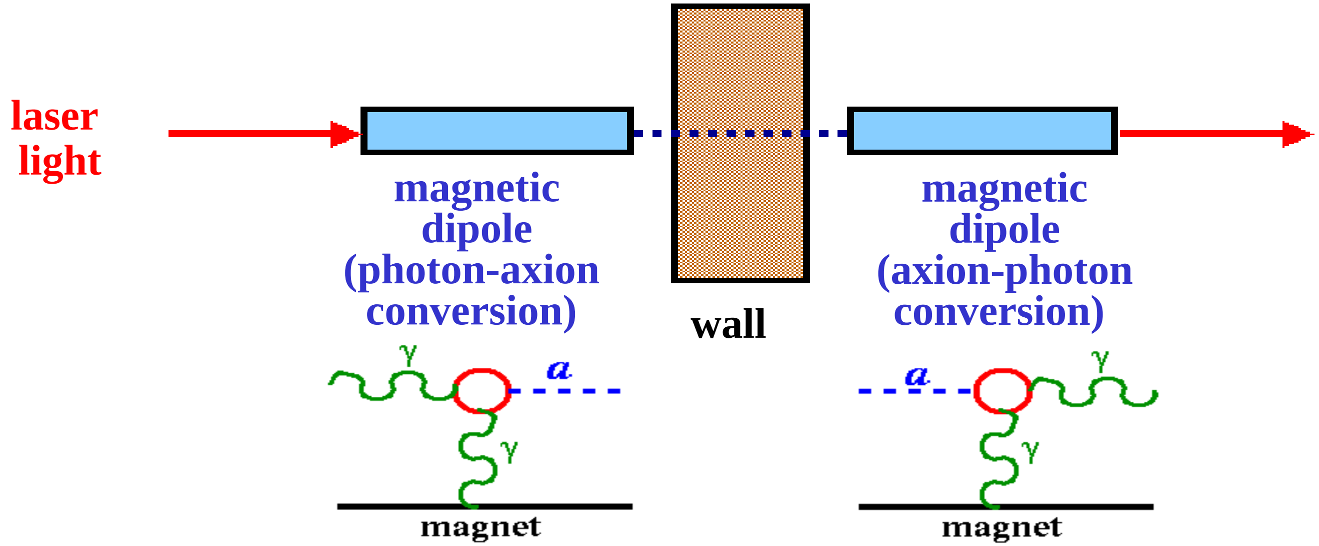


CAST vs. PVLAS



PVLAS is a LASER experiment

to search for the invisible axion



polarised LASER light propagating through a magnetic dipole magnet produces axions

(using mirrors at the end of each dipole for multiple traversals)

CAST: 2nd phase

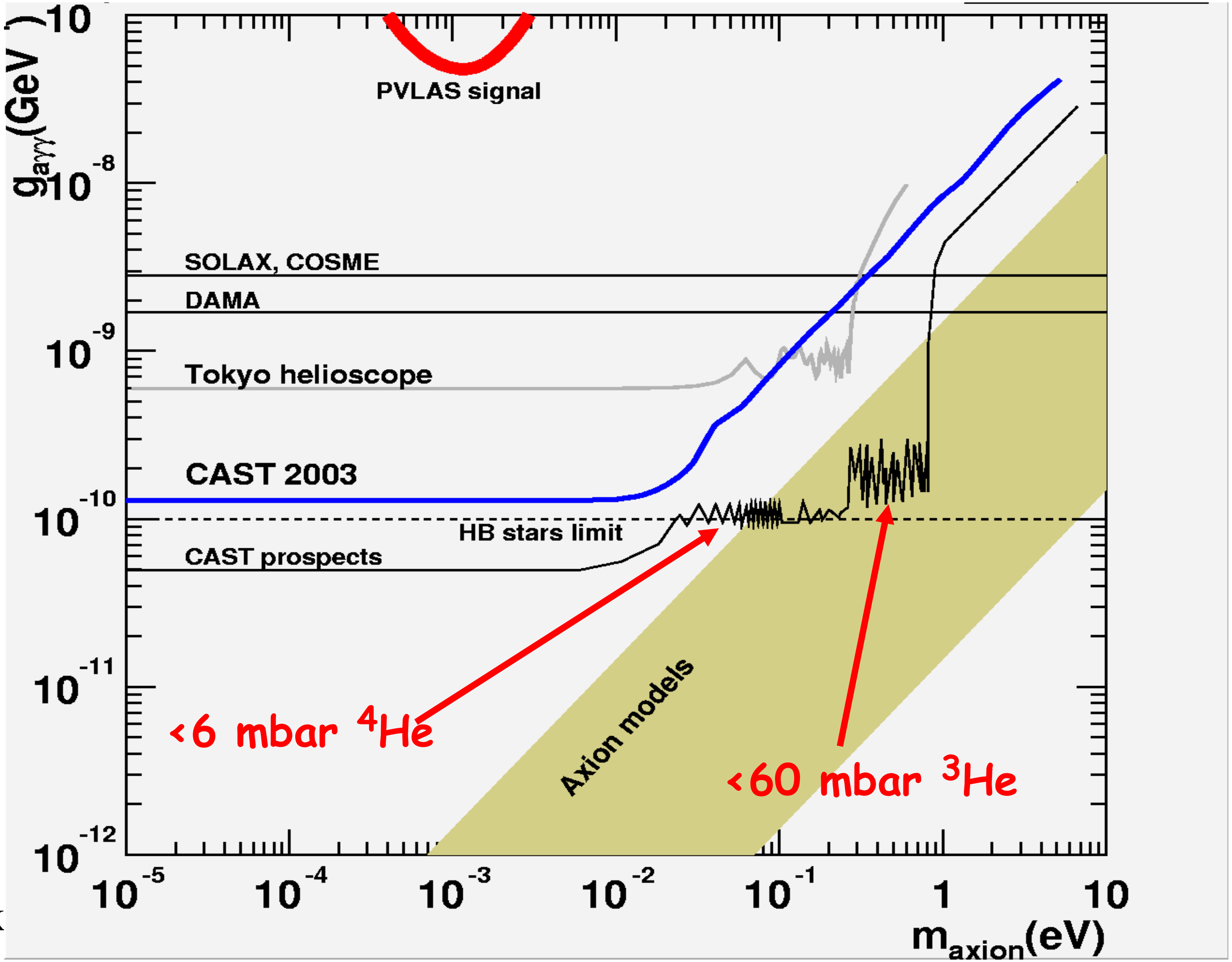
The coherence condition is : $L\, m_a^2 / E_a < 1$
which holds for $m_a < 0.02$ eV/c² for a photon energy of 4.2 keV in vacuum

Coherence can be restored for m_a by filling the magnetic conversion region with ^{4}He or ^{3}He gas to give photons an effective mass:

$$m_\gamma = \sqrt{4\pi\alpha N_e/m_e} \simeq 29\,\mathrm{eV}\sqrt{Z\rho/A}$$

then coherence for $L\,(m_a^2 - m_\gamma^2) / E_a < 1$ implies many steps in ρ necessary since $m_a^2 \simeq m_\gamma^2 \propto \rho$

CAST : 2nd phase



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Other axion searches

- Crystal experiments: solar axions convert coherently in a 100 kg NaJ crystal (DAMA experiment in Gran Sasso) or in a 1 kg Ge-crystal (SOLAX experiment in Sierra Grande)
- Cavity experiments: dark matter galactic axions convert in a μ-wave cavity, which is placed in a strong magnetic field, resonance when $m_a \sim h\nu$ with ν the frequency of the cavity:
  here the sensitivity is typically 2.8 to 3.3 μeV

The conclusions

- CAST has searched for the Axion
- no signal (yet)
- improvement over previous experiment by a factor of 6
- new upper limit on $g_{a\gamma\gamma}$ at the astrophysical limit from HB-stars
- improved limits at higher mass with He