“New solar axion search using the CERN Axion Solar Telescope with ^{4}He filling”

M. Arik, *et al.* (CAST Collaboration), PRD 92, 021101(R) (2015)

Contents

- Motivation -- brief introduction of axion
- CAST experiment
- Detector -- mainly MICROMEGAS detector
- Observation & Results
- future project ?

QCD Lagrangian

$$L_{QCD} = \bar{\varphi}\left(i\gamma_{\mu}D^{\mu} - m\right)\varphi - 1/4 \cdot F^{i}{}_{\mu\nu}F^{i\mu\nu}$$

$$\varphi = {}^{T}\left(\varphi_{red}, \varphi_{green}, \varphi_{blue}\right)$$

$$D^{\mu} = \partial_{\mu} - ig_{s}A^{i}{}_{\mu}\frac{\sigma^{i}}{2}$$

$$F^{a}{}_{\mu\nu} = \partial_{\mu}A^{a}{}_{\nu} - \partial_{\nu}A^{a}{}_{\mu} + g_{s}f^{abc}A^{b}{}_{\mu}A^{c}{}_{\nu}$$

Yang-Mills gauge theory based on the SU(3) color symmetry

Anomaly

Here, the case of QED with simple equations are shown as a model

Lagrangian (classical) level

$J_\mu = (e)\bar{\varphi}\gamma_\mu\varphi$: polar vector

$\partial^\mu J_\mu = (\partial^\mu\bar{\varphi})\gamma_\mu\varphi + \bar{\varphi}\gamma_\mu\partial^\mu\varphi = 0$

Using dirac equation $(i\gamma_\mu\partial^\mu - m)\varphi = 0$

$J_\mu{}^A = (e)\bar{\varphi}\gamma_\mu\gamma_5\varphi$: axial vector

$\partial^\mu J_\mu{}^A = 2im\bar{\varphi}\gamma_5\varphi = 0\,(if\ m = 0)$ → "chiral symmetry"

However, if the calculation is done with quantum level, such as using path integral,

$$\partial^\mu J_\mu{}^A = 2im\bar{\varphi}\gamma_5\varphi - \frac{e^2}{16\pi^2}\varepsilon^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta} \quad \neq 0\,(\text{evenif } m = 0)$$

Modification of QCD lagrangian

- θ vacuum and "instanton" ← my understand is not enough , , ,

  -- theoretical discussion arising at pure Yang-Mils gage theory

- Anomaly term from chiral transformation

  -- one of the supporting pieces regarding the θ vacuum

$$L_{eff} = L_{QCD} + \underline{L_{\theta}}$$

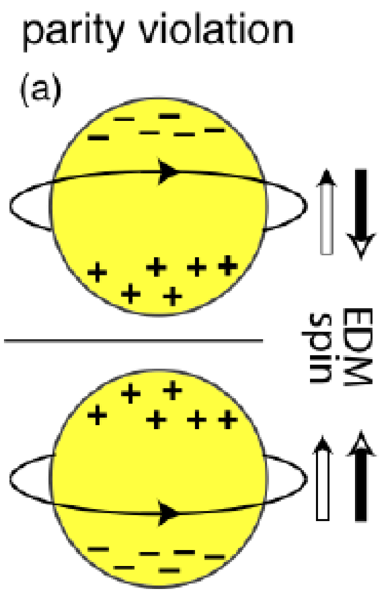
$$L_{QCD} = \bar{\varphi}\left(i\gamma_{\mu}D^{\mu} - m\right)\varphi - 1/4 \cdot F^{i}{}_{\mu\nu}F^{i\mu\nu}$$

$$L_{\theta} = \theta \frac{g^2}{32\pi^2} \varepsilon^{\mu\nu\alpha\beta} F^{i}{}_{\mu\nu} F^{i}{}_{\alpha\beta}$$

From "The Strong CP Problem and Axions" R.D. Peccei and elsewhere

The term q is unknown parameter, and L_{θ} breaks CP symmetry .

Neutron EDM (electrical dipole moment)



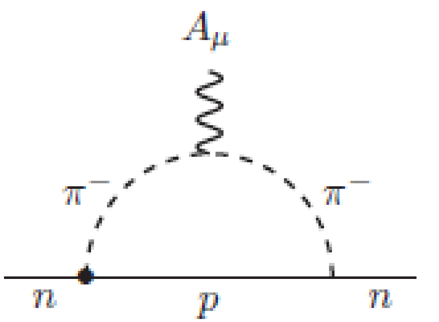


Fig 5(a) from Jihn.E. Kim and G. Carosi, Review of Modern Phys., Vol.82 (2010)

$$|d_N^{\mathrm{exp}}| < 2.9 \times 10^{-26}\,\mathrm{e}\cdot\mathrm{cm}$$

Baker, et al., PRL 97, 131801 (2006)

$$d_N^{\mathrm{model}} \simeq \bar{\theta}\cdot(6\times 10^{-17})\,\mathrm{e}\cdot\mathrm{cm} \;\Rightarrow\; \bar{\theta} < 10^{-9}$$

If there is CP-violating term, NEDM can be accompanied. But **NOT** observed so far.

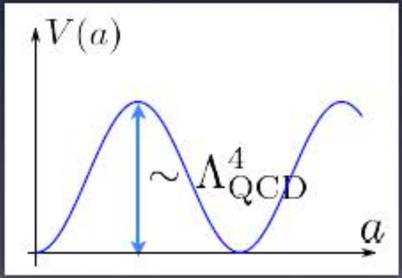
Axion

QCD axion as dark matter candidate

- Motivated by Pecccei-Quinn mechanism Peccei and Quinn (1977)
  as a solution of the strong CP problem
- Spontaneous breaking of global U(1) Peccei-Quinn (PQ) symmetry
  at a scale $F_a \simeq 10^{8-11}\,\mathrm{GeV}$ "axion decay constant"
  - Nambu-Goldstone theorem
    → emergence of the (massless) particle ≡ axion
    Weinberg (1978), Wilczek (1978)
- Axion has a small mass (QCD effect)
  → pseudo-Nambu-Golstone boson

$$m_a \sim \frac{\Lambda_{\rm QCD}^2}{F_a} \sim 6\times 10^{-5}\,\mathrm{eV}\left(\frac{10^{11}\mathrm{GeV}}{F_a}\right)$$

$\Lambda_{\rm QCD} \simeq \mathcal{O}(100)\mathrm{MeV}$

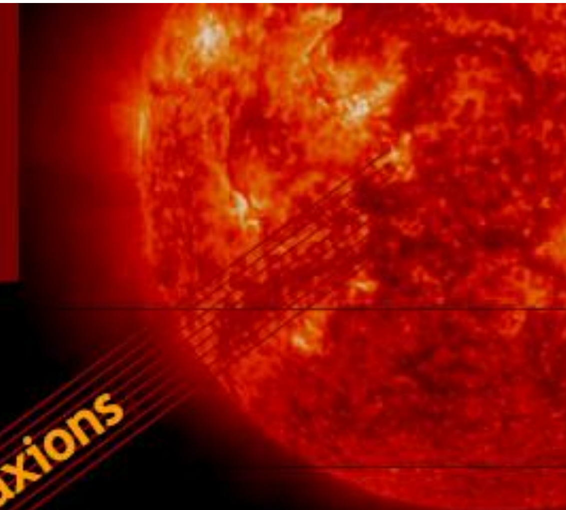


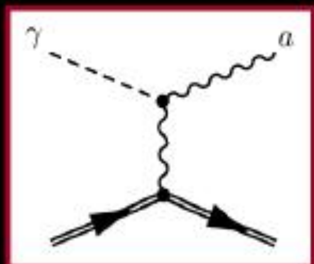
- Tiny coupling with matter + non-thermal production
  → good candidate of cold dark matter

$$L_{eff} = L_{QCD} + L_{\theta} + L_{axion} \sim L_{QCD}$$

Solar Axions

- Solar axions produced by photon-to-axion conversion of the solar plasma photons in the solar core

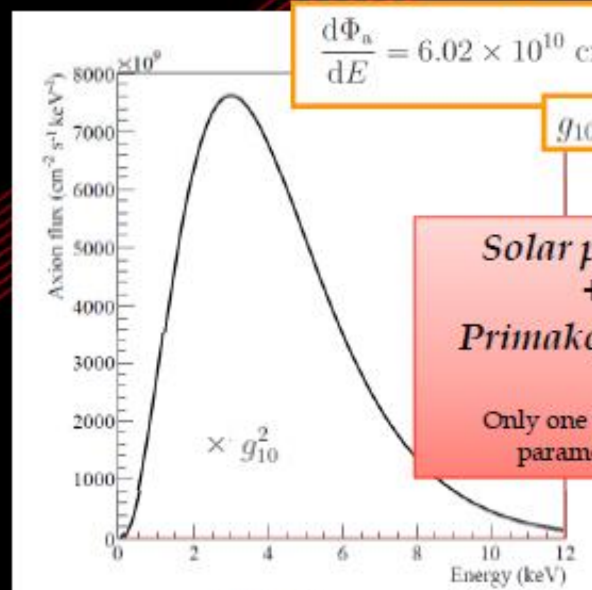




➢ ***Solar axion flux*** *[van Bibber PRD 39 (89)]* *[CAST JCAP 04(2007)010]*

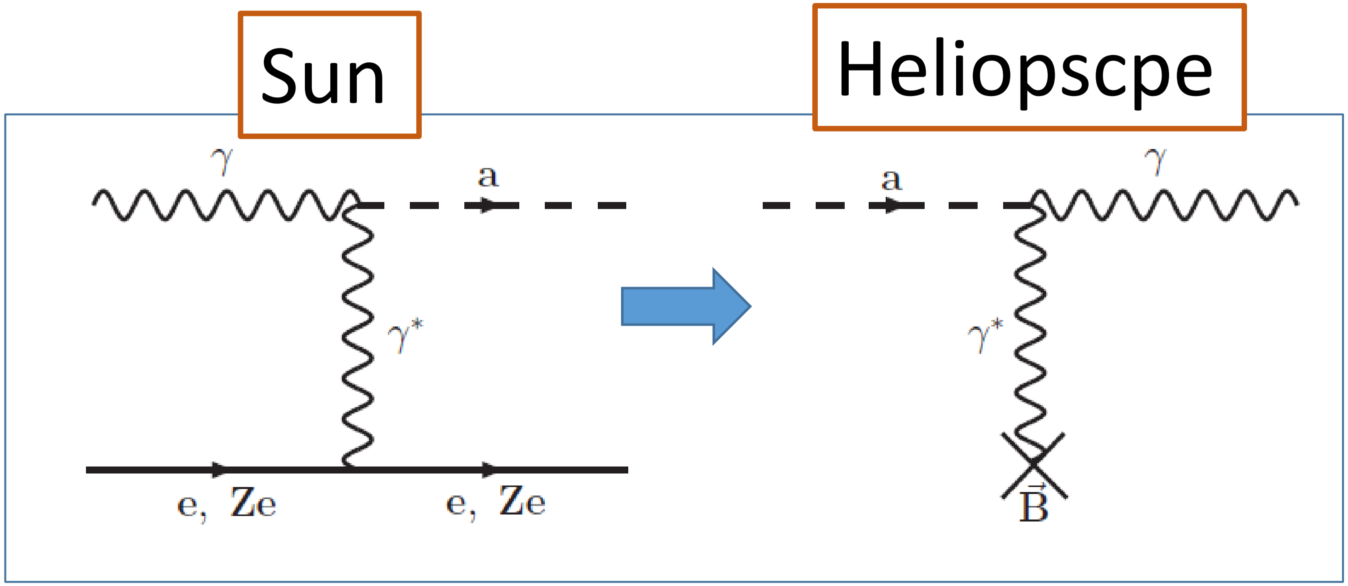
$$\frac{d\Phi_a}{dE} = 6.02 \times 10^{10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{keV}^{-1}\ g_{10}^2\ E^{2.481} e^{-E/1.205}.$$

$$g_{10} = g_{a\gamma}/10^{-10}\ \mathrm{GeV}^{-1}$$



Solar physics
+
Primakoff effect

Only one unknown parameter $g_{a\gamma}$



- Since the interaction of axion-photon is predicted as

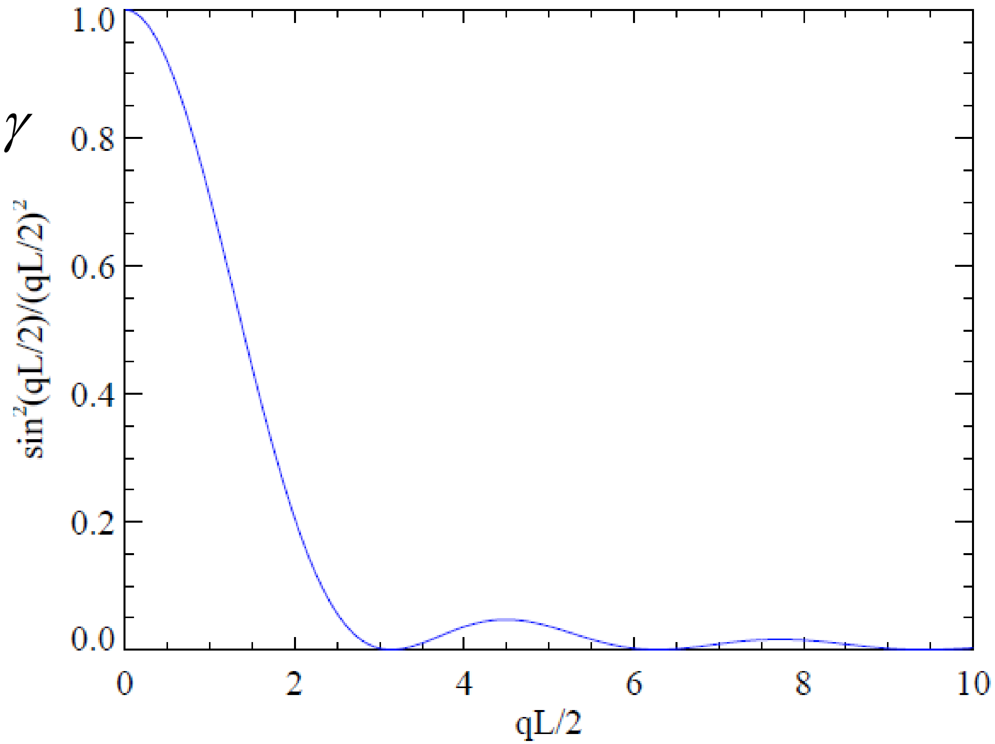
$$L_{a\gamma\gamma} \propto g_{a\gamma\gamma} a \cdot \varepsilon^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta} = g_{a\gamma\gamma} a \cdot \underline{\vec{E} \cdot \vec{B}}$$

the magnetic field is set perpendicular toward Sun

- X-ray photon (mean energy is ~ 4keV) can be observed

-- Flux @ the earth ~ 10^{11} $cm^{-2}s^{-1}keV^{-1}$ or ~ 10^{12} $cm^{-2}s^{-1}$

$P_{a\to\gamma}$



- Conversion probability of axions into photons at a length L

$$P_{a\to\gamma} = |\langle A_{\parallel}(z)|a(0)\rangle|^2 = \left(\frac{Bg_{a\gamma}}{2}\right)^2 \frac{1}{q^2+\Gamma^2/4}\left[1+\mathrm{e}^{-\Gamma L}-2\mathrm{e}^{-\Gamma L/2}\cos(qL)\right]$$

$$= \left(\frac{BLg_{a\gamma}}{2}\right)^2 \left(\frac{\sin\left(\frac{qL}{2}\right)}{\left(\frac{qL}{2}\right)}\right)^2 .$$

where, $q = |p_a - p_\gamma| \sim \left|\frac{m_\gamma^2 - m_a^2}{2E_a}\right|$

If photon goes through dielectric substance (gas), ***v < c***

➔ $"m_\gamma" > 0$ and higher m_a can be searched

CAST experiment and recent result

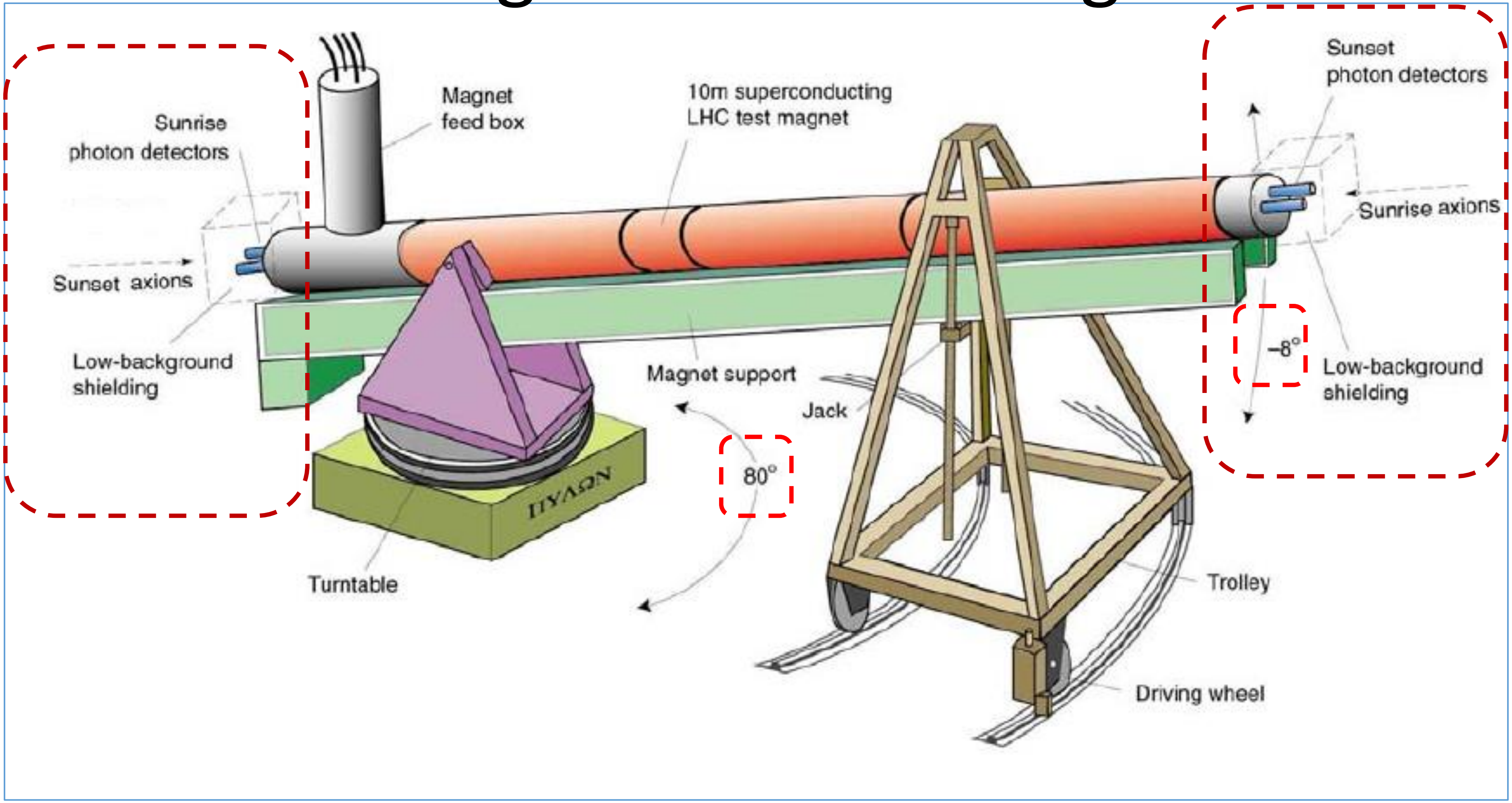
CERN Axion Solar Telescope (CAST)

Helioscope : tracking the Sun (solar core)

Long LHC prototype superconducting magnet :
(length = 9.26m, B field up to 9 T)

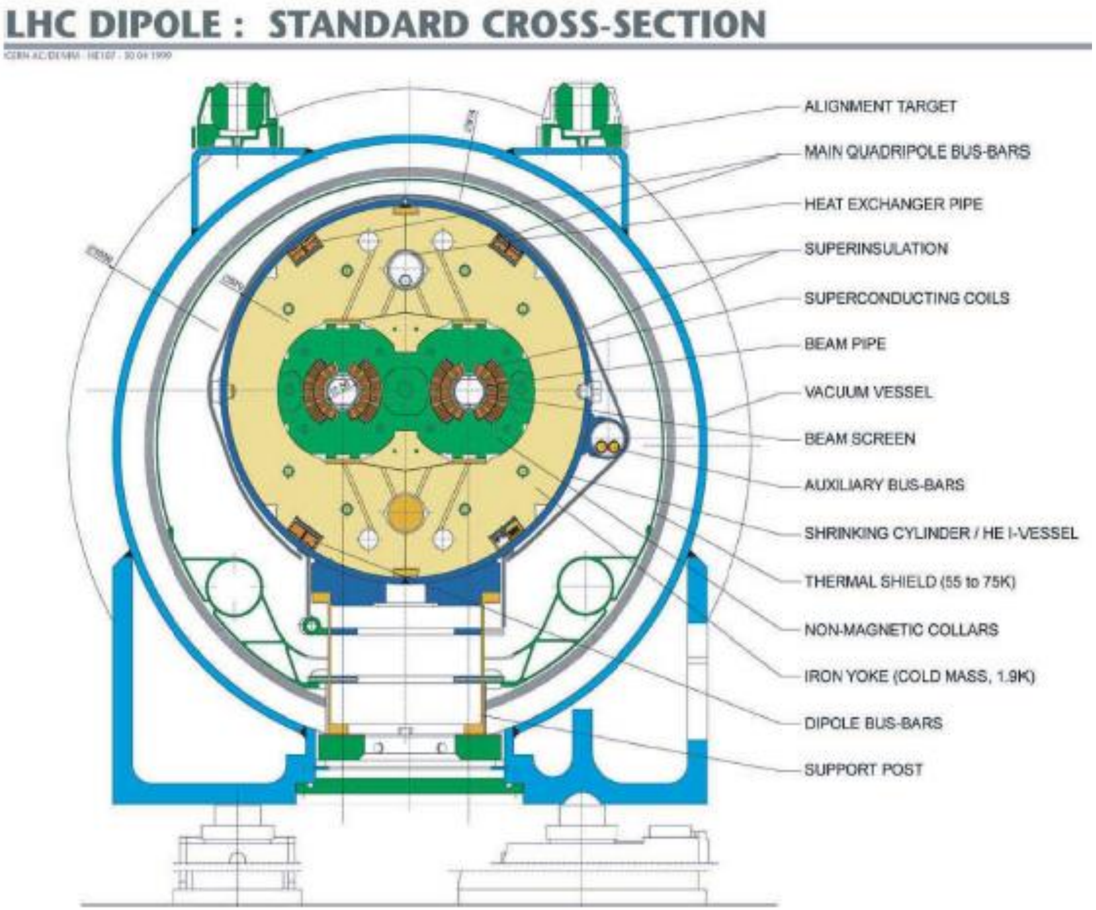
Location : above ground at Point 8 of LHC -- near LHCb

Drawing of the CAST magnet

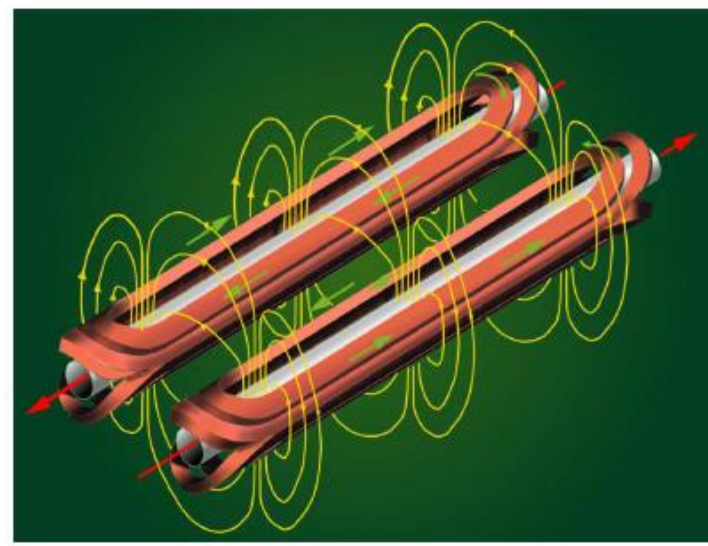


Rotation range is ±8 deg. (vertical) & ±40 deg. (horizontal),
It can point the Sun in the morning & evening ➔ both side equip detector, "Sunset photon detectors" & "Sunrise photon detectors"

LHC dipole magnet



Current [A]	Magnetic field [T]
0	0
4988	3.40
8981	6.12
10977	7.46
12000	8.13
12808	8.66
13330	9.00

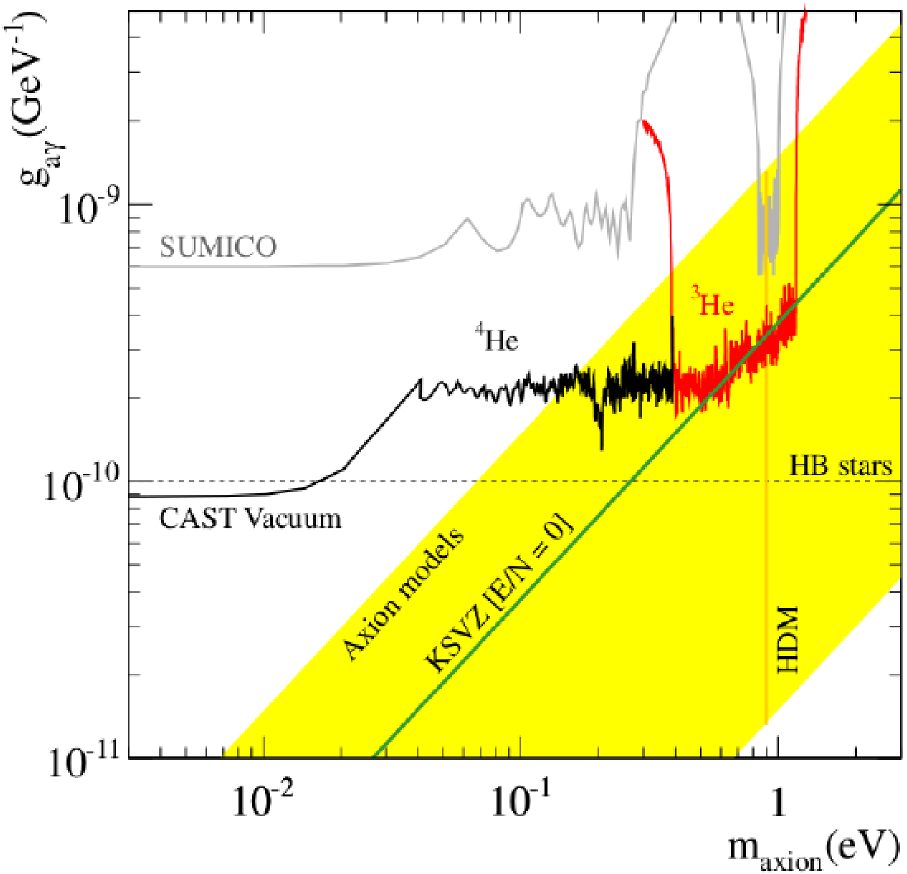


Orientation of the magnetic field

CAST Observation Mode (history)

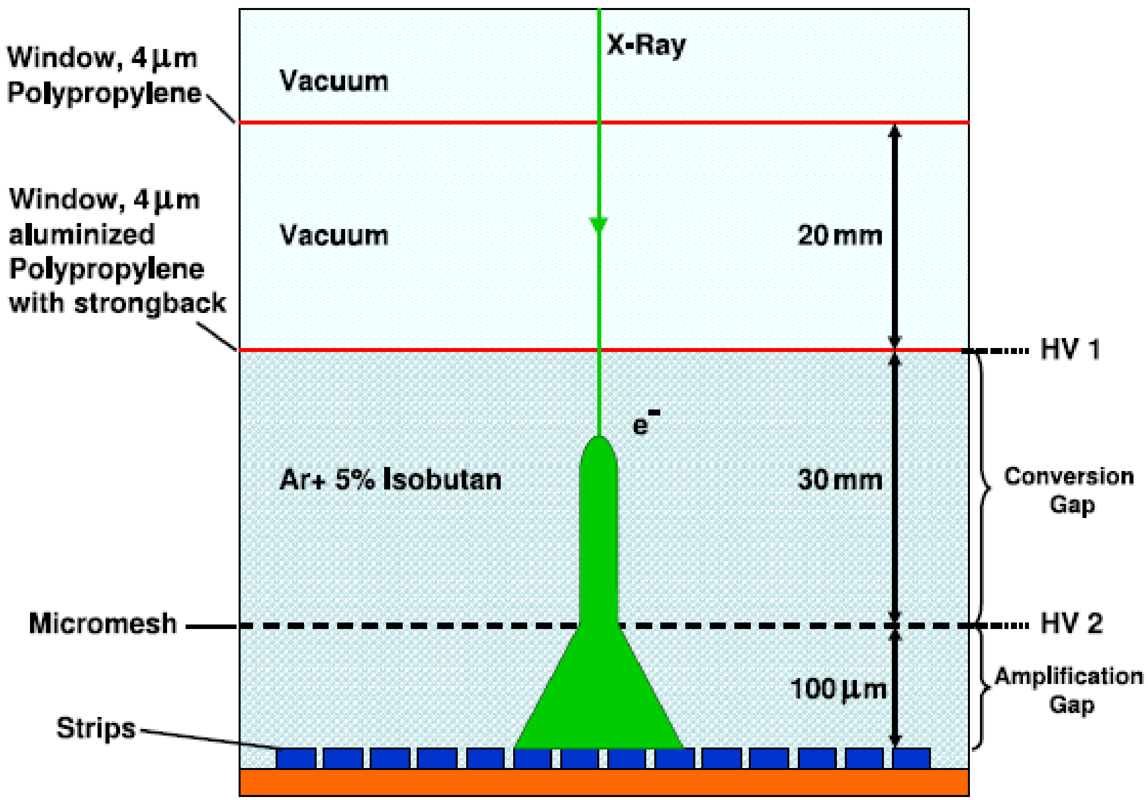
Table 4.1. The Run History of CAST.

Year	Phase	Sensitivity Range
2000-2003	Commissioning	
2003-2004	Phase I(Vacuum)	<0.02eV
2006-2007	Phase II(^{4}He)	0.02eV - 0.4eV
2008-2011	Phase II(^{3}He)	0.4eV - 1.15 eV
2012	Phase II(^{4}He)-Revisit	0.02eV - 0.4eV



Inside of the two cold bores (diameter of 43 mm) was vacuum in Phase I. or ^{4}He/^{3}He in Phase II.

MICROMEsh **GA**seous **S**tructure (MICROMEGAS)



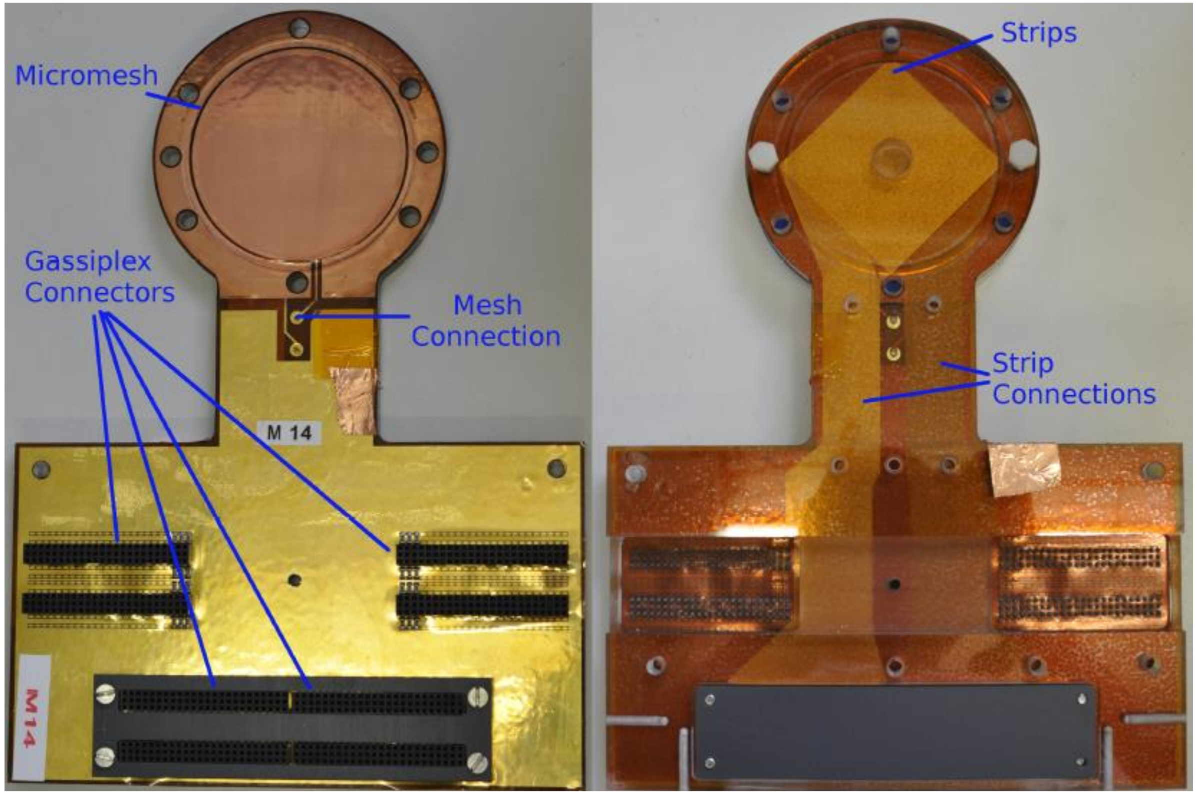
E ~ 60V/cm

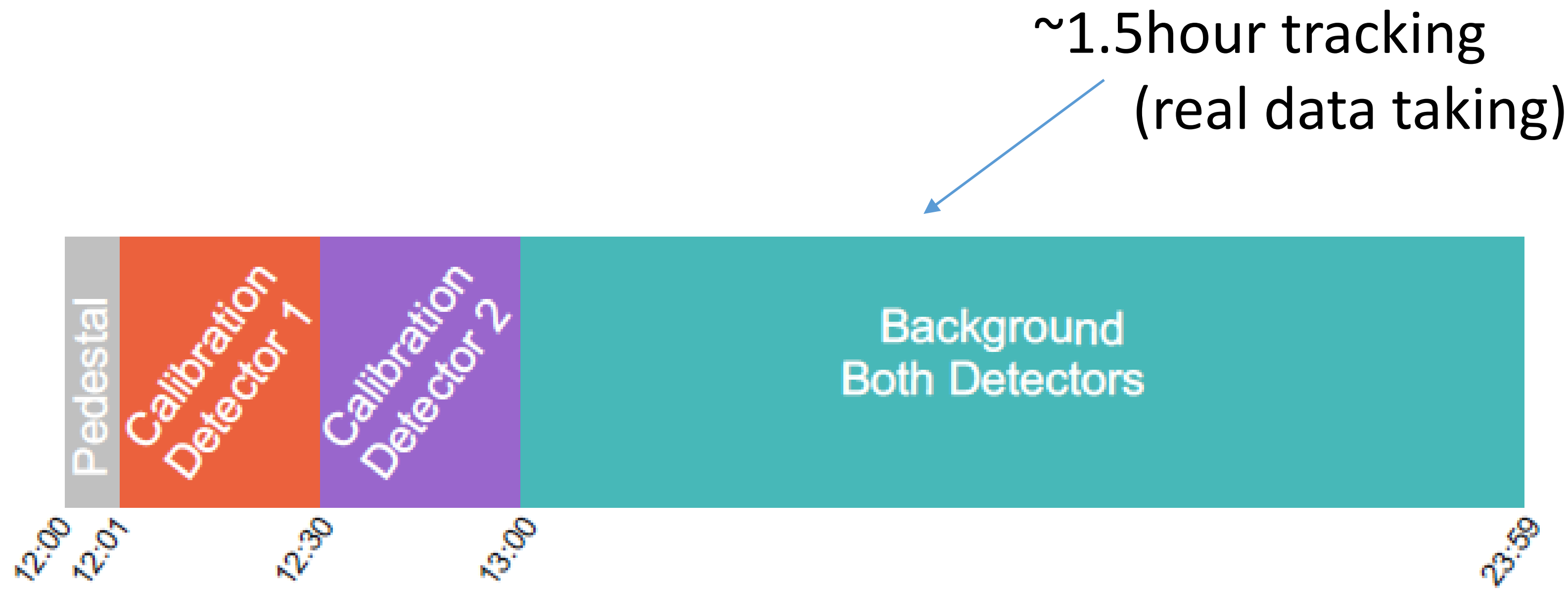
E ~ 3kV/cm

Ions move to the mesh → the signal is used for the estimation of the energy of the incoming particle, and generates a trigger

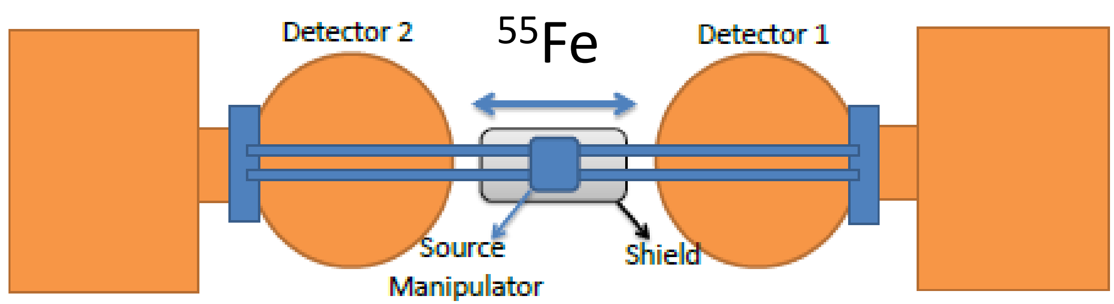
electrons create signals on the strips → the signal is used for the estimation of the position & energy of the incoming particle

Photograph of MICROMEGAS for CAST



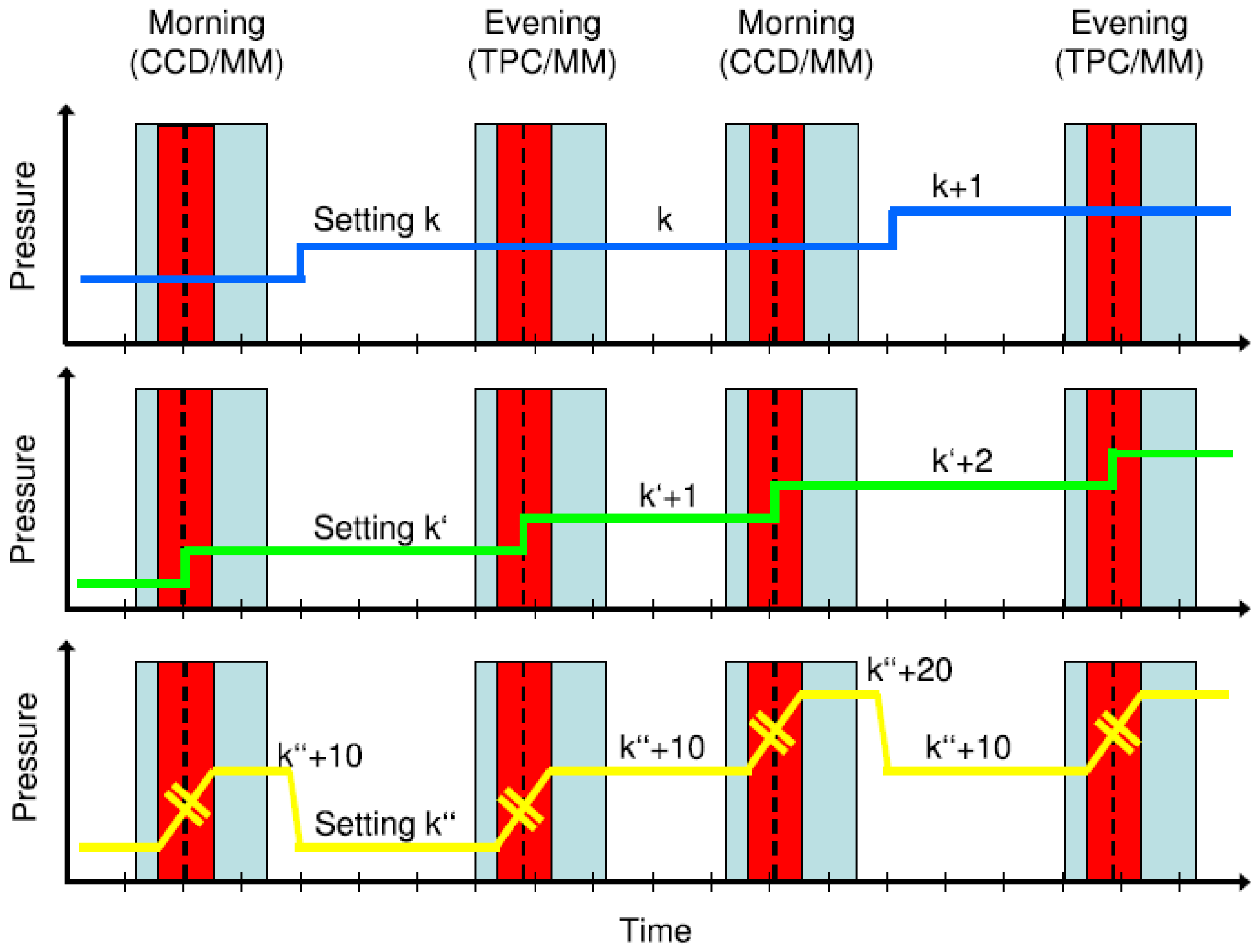


An example of 12 hours run schedule for Sunset Micromegas



Schematic drawing of the calibration system, viewed from backside of the detector

Reference : observation mode



Result I. Comparison of the number events between the background run and tracking run

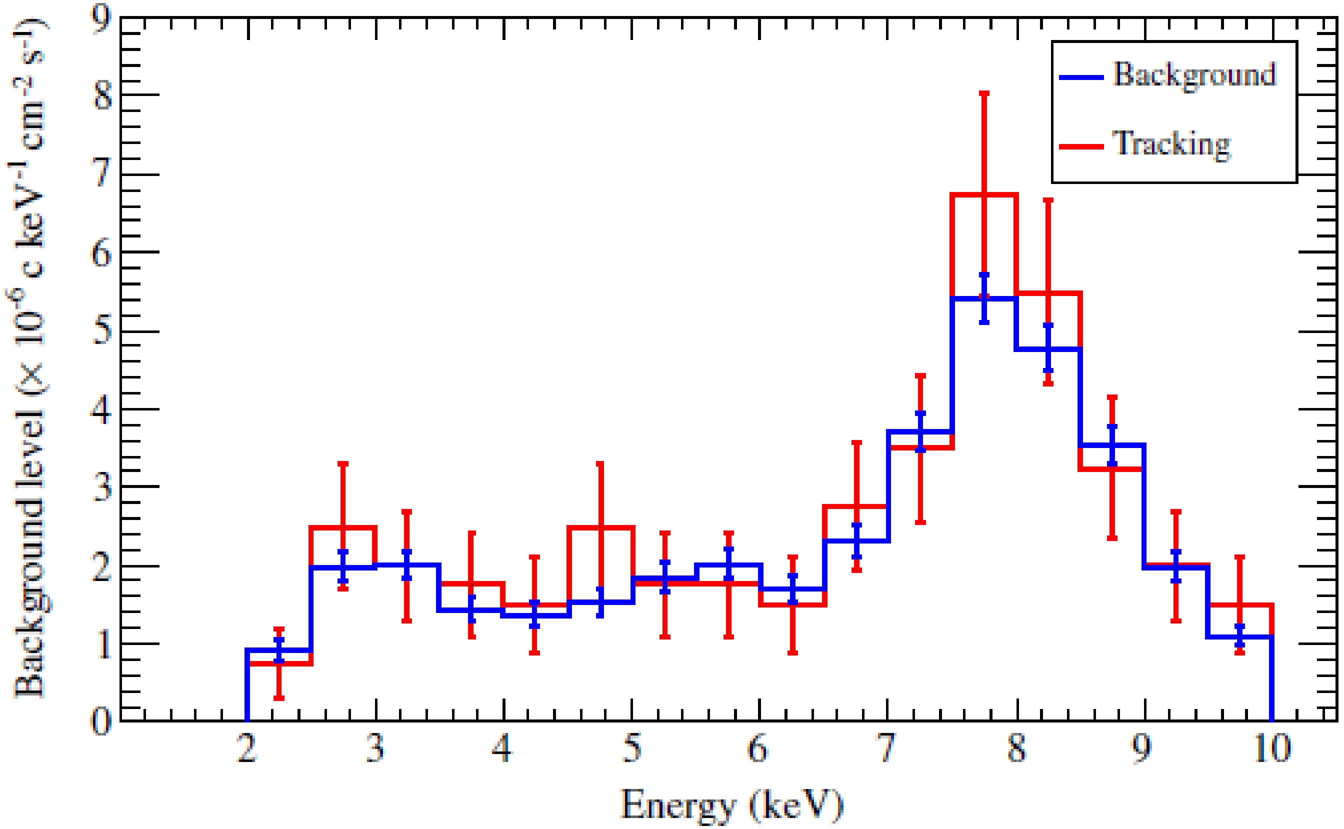


FIG. 2 (color online). Comparison between background (blue bars) and tracking (red bars) spectra of one Micromegas detectors installed in the sunset side.

Background spectrum taken by CCD

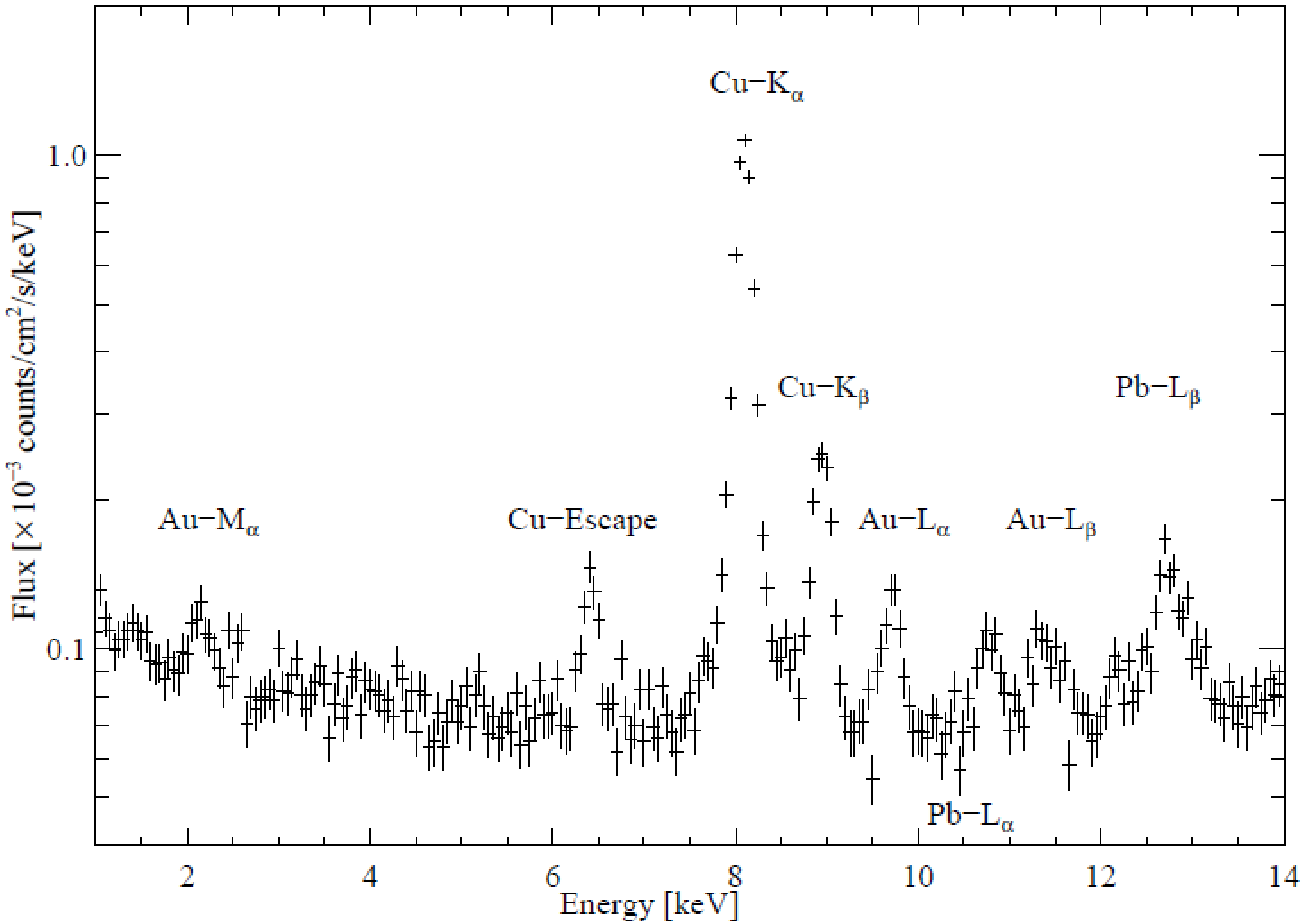
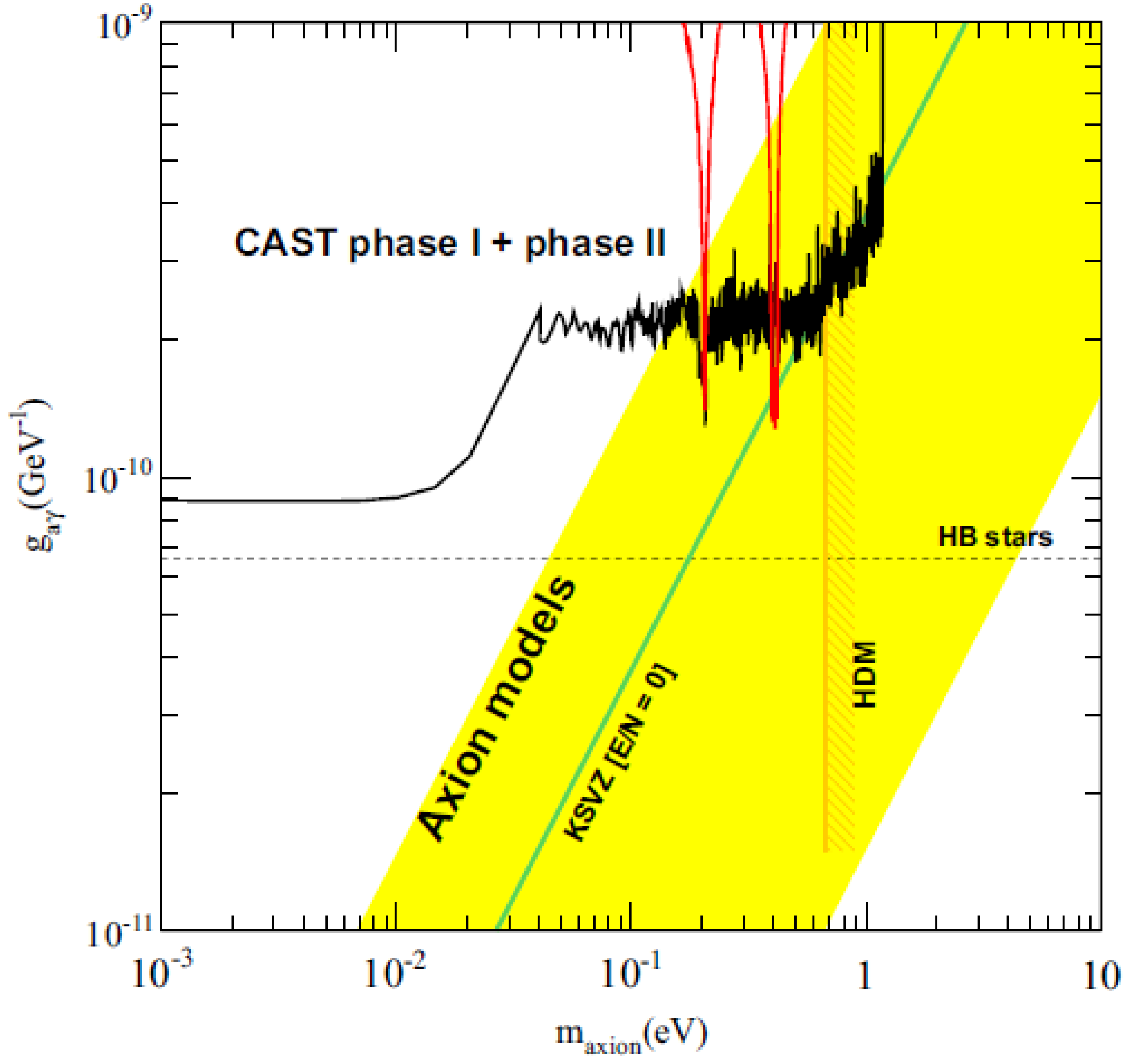


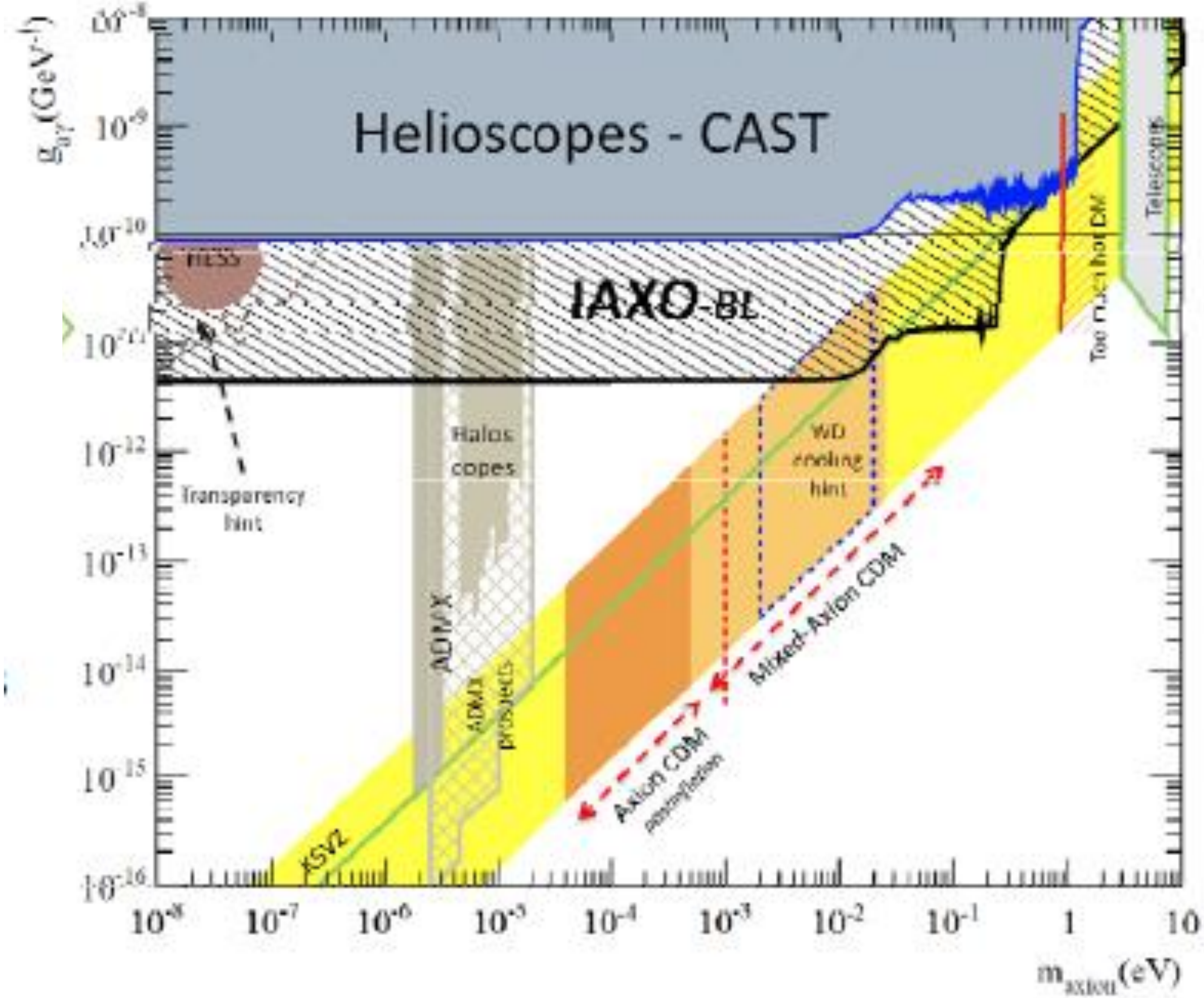
Figure 6.33: In the background spectrum for the data obtained with the CCD detector during Phase II of CAST, characteristic photon lines originating from the materials of the detector and its close surroundings can be observed.

Result II. Exclusion regions in the $m_a - g_{a\gamma}$ plane



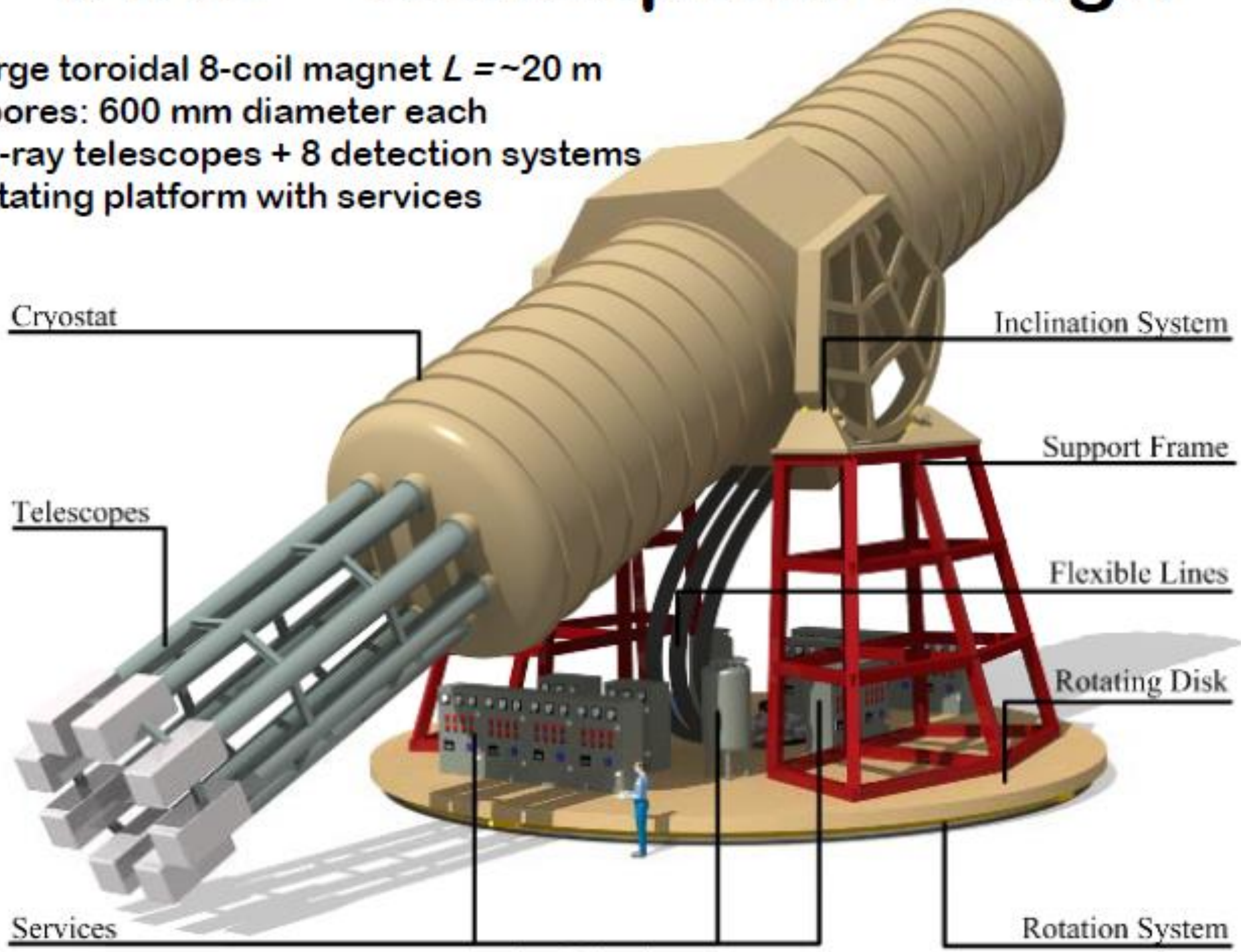
Next generation axion helioscope @ CERN ?

IAXO (International Axion Observatory)



IAXO – Conceptual Design

- Large toroidal 8-coil magnet L = ~20 m
- 8 bores: 600 mm diameter each
- 8 x-ray telescopes + 8 detection systems
- Rotating platform with services



~ 250 tons ! ⟷ ~40tons(CAST)