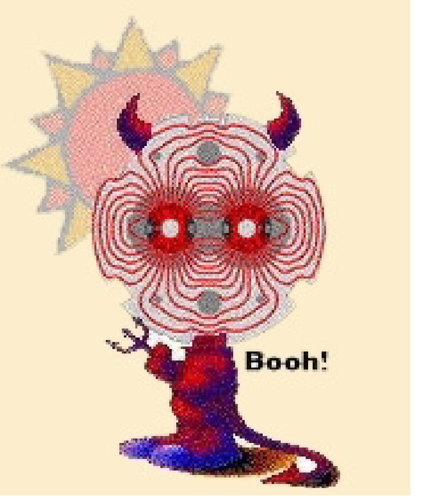
Search for Solar Axions: the CAST Experiment



Séminaire IRFU Saclay, 7 October 2008

Thomas Papaevangelou
CEA Saclay

The Strong CP Problem

Solution of the U(1)A problem from t'Hooft (θ-vacuum) resulted in a CP-violating term in QCD lagrangian:

$$\mathcal{L}_{CP} = \bar{\theta}\frac{a_s}{8\pi}G\widetilde{G} \qquad \left(\tilde{G}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}G^{\rho\sigma} \right)$$

***Experimental consequence:* prediction of electric dipole moment for the neutron:**

$$|d_n| = A|\bar{\theta}| \times 10^{-15}\ e \times cm \qquad (A = 0.04 - 2.0)$$

BUT experimental result... $|d_n| \leq 2.9 \times 10^{-26}\ e \times cm$ *(90% CL)*

So, $\boxed{|\bar{\theta}| < 10^{-9}}$

$$\bar{\theta} = \theta + \text{Arg}\det M$$

(QCD vacuum + EW quark mixing)

The strong CP violating term could be suppressed easily!
All needed is a massless quark! → …no quark is massless…

The Peccei – Quinn solution

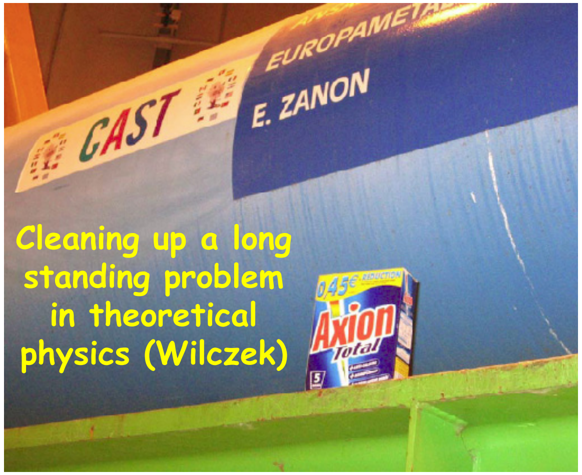
Peccei-Quinn (1977) proposed an elegant solution to this problem:

new global chiral U(1) symmetry (PQ) spontaneously broken at scale f_a

θ is not anymore a constant, but a field

→ *the axion a(x)*

$$\boxed{\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{\alpha_s}{8\pi f_a} a G\tilde{G}}$$



*The **AXION** appears as the Nambu-Goldstone boson of the spontaneous breaking of the PQ symmetry (Weinberg and Wilczek (1978)*

PQ symmetry is not perfect

➔ axions acquire mass

$$\boxed{m_a = 6\,\mathrm{eV}\,\frac{10^6\,\mathrm{GeV}}{f_a}}$$

- 1st scenario:

  $f_a \sim f_{EW} \rightarrow m_a \sim O(1MeV)$

  Visible axions, but… ruled out by experiments

- 2nd scenario:

  $f_a \gg f_{EW} \rightarrow m_a \ll O(1MeV)$

  Invisible axions, what CAST is looking for

Axion summary

Axion properties

- **Neutral pseudoscalar,**
- **practically stable,**
- **very low mass,**
- **spin-parity 0^-**
- **very low interaction cross-sections**

➔ Nearly invisible to ordinary matter

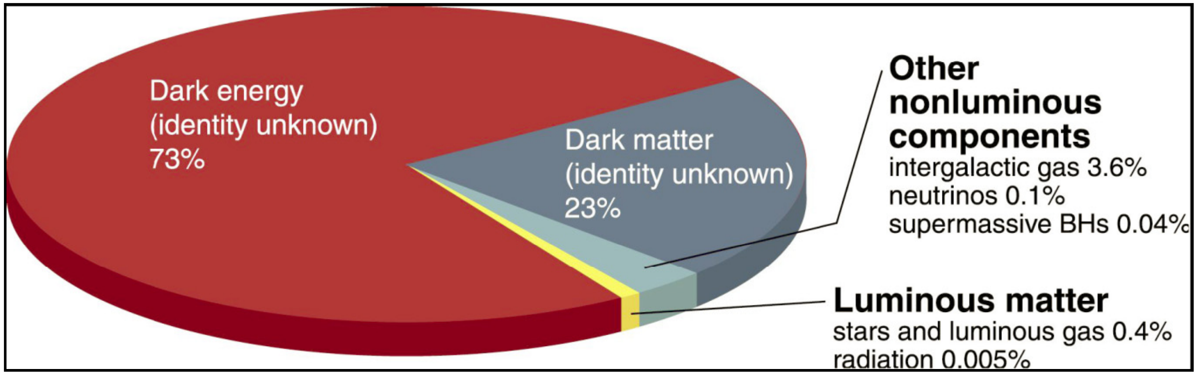
➔ excellent candidates for **dark matter** (together with WIMPS)

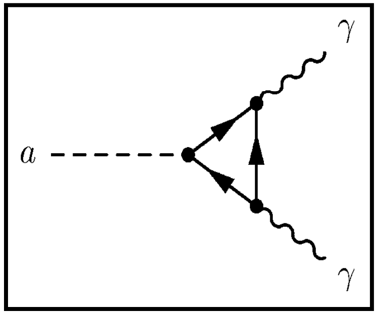
Axions couple to photons

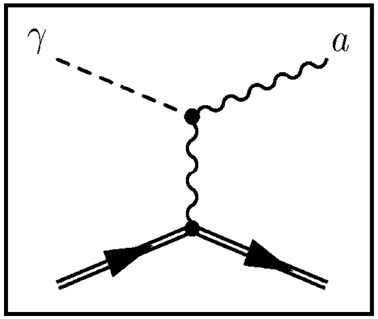
$$L_{a\gamma} = g_{a\gamma}(\mathbf{E}\bullet\mathbf{B})\, a$$

(PRIMAKOFF EFFECT)

$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi f_a}\left[\frac{E}{N} - 1.92 \pm 0.08\right]$$





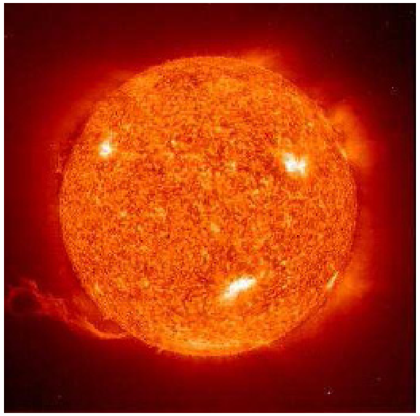


Astrophysical & **cosmological** contraints on m_a, f_a ⇨ *small window* in g_a – m_a *plane left*

Axions are viable candidates for Cold and Hot DarkMatter (10^{-6}eV ≤ m_a ≤ 1.05 eV)

Axion origin

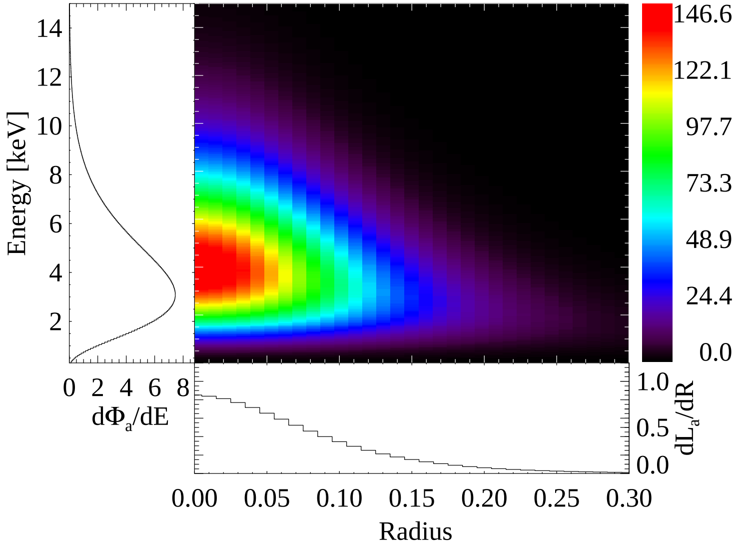
- Cosmological axions (cold dark matter)
- Solar axions



Stellar plasmas may be a powerful source of axions…

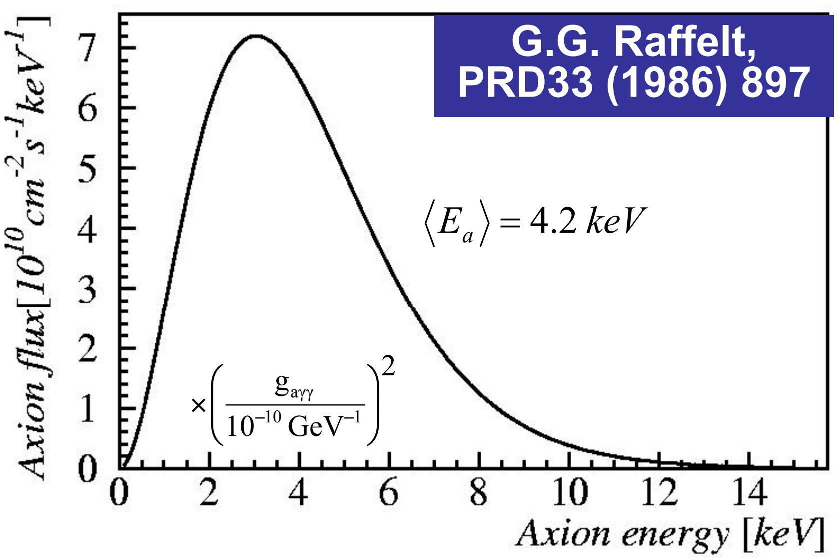
The closest stellar plasma available is: the Sun

Solar surface axion luminosity



$$L_a = g_{10}^2\, 1.85 \times 10^{-3}\, L_\odot$$

Axion flux on earth



Axion searches

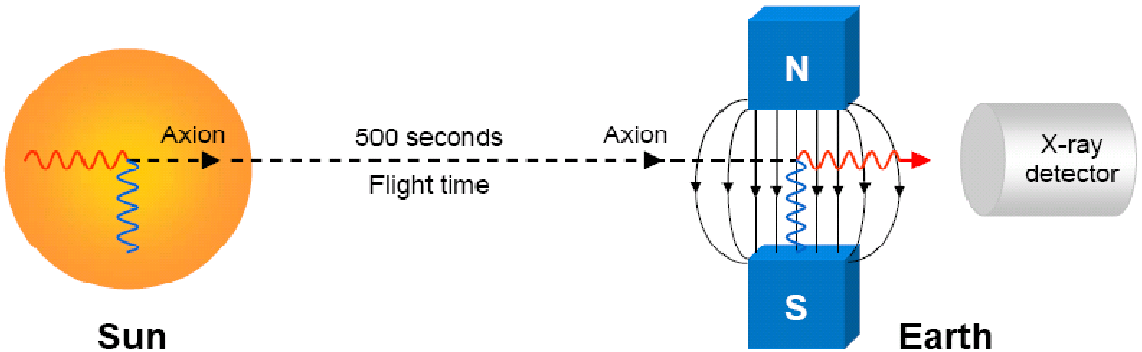
Cosmological implications (stellar energy loss, overclosure…)

Experimental

- Laboratory searches (*laser experiments, PVLAS, OSQAR, etc*)
- Dark matter axion searches (*microwave cavity experiments, ADMX*)
- **Solar axion searches** (*helioscopes Tokyo, **CAST***)

➔ search for axion – photon interaction (coupling constant $g_{a\gamma\gamma}$ & axion mass m_a)

The principle of axion detection with helioscopes (Sikivie 1983)



Signal: excess of x-rays during alignment over background

A thermal photon converts into an axion in the Coulomb fields of nuclei and electrons in the solar plasma

The axion converts into a photon under a strong **transverse magnetic field** in the laboratory (inverse process)

Axion to photon conversion

Axion to photon conversion probability:

$$\boxed{P_{a\to\gamma} = \left(\frac{Bg_{agg}}{2}\right)^2 \frac{1}{q^2+\Gamma^2/4}\left[1-e^{-\Gamma L/2}-2e^{-\Gamma L/2}\cos(qL)\right]}$$

Vacuum:
Γ=0, m_γ=0

Coherence condition: $qL < \pi$

L magnet's length, q the momentum transfer $\quad |q| = \dfrac{m_a^2}{2E}$

$$P_{\alpha\to\gamma} = 1.7\cdot10^{-17}\left(\frac{BL}{9T\cdot9.26m}\right)^2\left(\frac{g_{\alpha\gamma\gamma}}{10^{-10}GeV^{-1}}\right)^2\cdot|M|^2$$

CAST has ~100 times higher conversion probability than other helioscopes!

For CAST phase I conditions (vacuum), coherence is lost for m_a > 0.02 eV

In the presence of a buffer gas inside the magnet bores the photon acquires an **effective mass m_γ > 0**. The momentum transfer is now

$$|q| = \left|\frac{m_a^2 - m_\gamma^2}{2E}\right|$$

Coherence is restored for a narrow mass range:

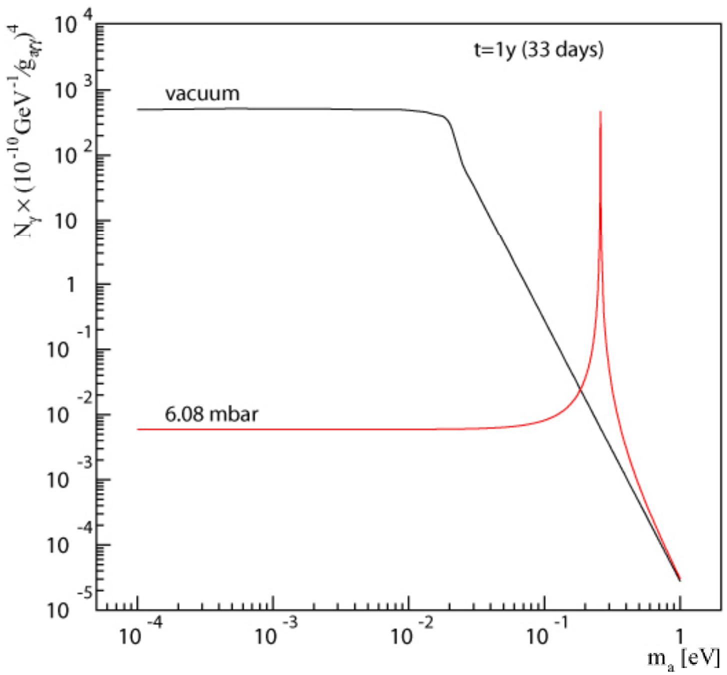
$$\boxed{qL < \pi \Rightarrow \sqrt{m_\gamma^2 - \frac{2\pi E_a}{L}} < m_a < \sqrt{m_\gamma^2 + \frac{2\pi E_a}{L}}}$$

Extending sensitivity to higher axion masses…

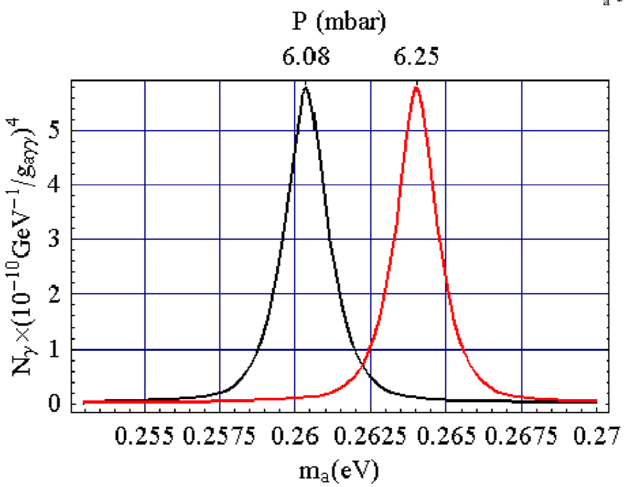
m_γ can be adjusted by changing the gas pressure:

$$m_\gamma = \sqrt{\frac{4\pi\alpha N_e}{m_e}} \approx 28.9\sqrt{\frac{Z}{A}\rho} \quad eV$$

or $$\boxed{m_\gamma(eV) \approx \sqrt{0.02\frac{P(mbar)}{T(K)}}} \qquad (T=1.8\ K)$$



- Every specific pressure of the gas allows the test of a specific axion mass.
- The higher the pressure, the higher the photon effective mass, the higher the axion mass tested.
- **For every pressure setting there is a *new discovery potential* !!!**



For P~50 mbar $\Delta m_a \sim 10^{-4}$ eV !!!

CAST, who we are

24 Institutes, ~80 scientists

The CAST Collaboration

CEA Saclay, France – CERN, Switzerland – Dogus University, Turkey – INFN University of Trieste, Italy – Lawrence Livermore National Laboratory, USA – Max-Planck-Institut für extraterrestrische Physik, Germany – Max-Planck-Institut für Physik, Germany – Max-Planck-Institut für Physik Werner-Heisenberg-Institut, Germany – Max-Planck-Institut für Solare Physik, Germany – National Center for Scientific Research Demokritos, Greece – National Technical University of Athens, Greece – Rudjer Boskovic Institute, Croatia – Institute for Nuclear Research (Moscow), Russia – TU Darmstadt, Germany – University of British Columbia, Canada – University of Chicago, USA – Universität Frankfurt, Germany – Universität Freiburg, Germany – Universität Zürich, Switzerland – University of Florida, USA – University of Patras, Greece – University of Thessaloniki, Greece – Universidad de Zaragoza, Spain

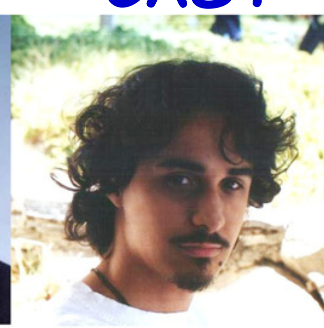
CAST

Prof. Dr.
Engin ARIK
(1948-2007)

CAST

Doç. Dr.
İskender HİKMET
(1964-2007)

CAST



Araş. Gör.
Özgen Berkol Doğan
(1980-2007)

Araş. Gör.
Mustafa FİDAN
(1978-2007)

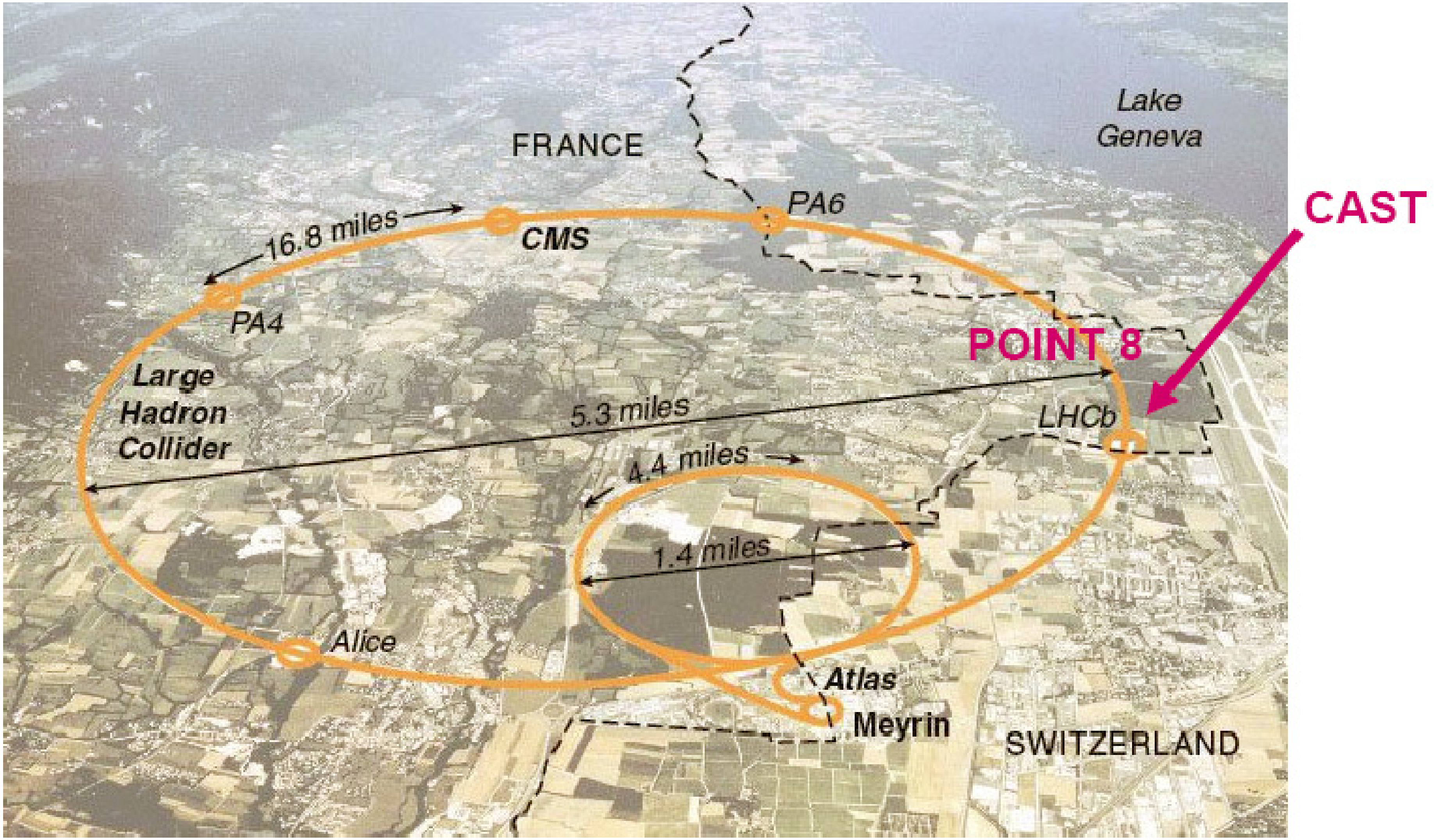
Engin ABAT
(1979 -2007)

CAST

Prof. Dr.
F. Şenel BOYDAĞ
(1947-2007)

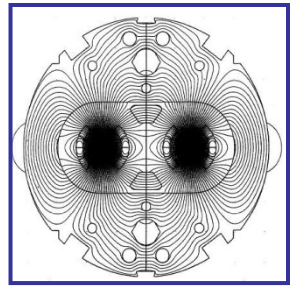
CAST, where we are

CERN



CAST, infrastructure

- Decommissioned prototype LHC dipole magnet.
- Superconducting, operation at T=1.8 K.
- Electric current 13,000 A.
- Magnetic field: **B=9T**
- Length: **L=9.26m**.

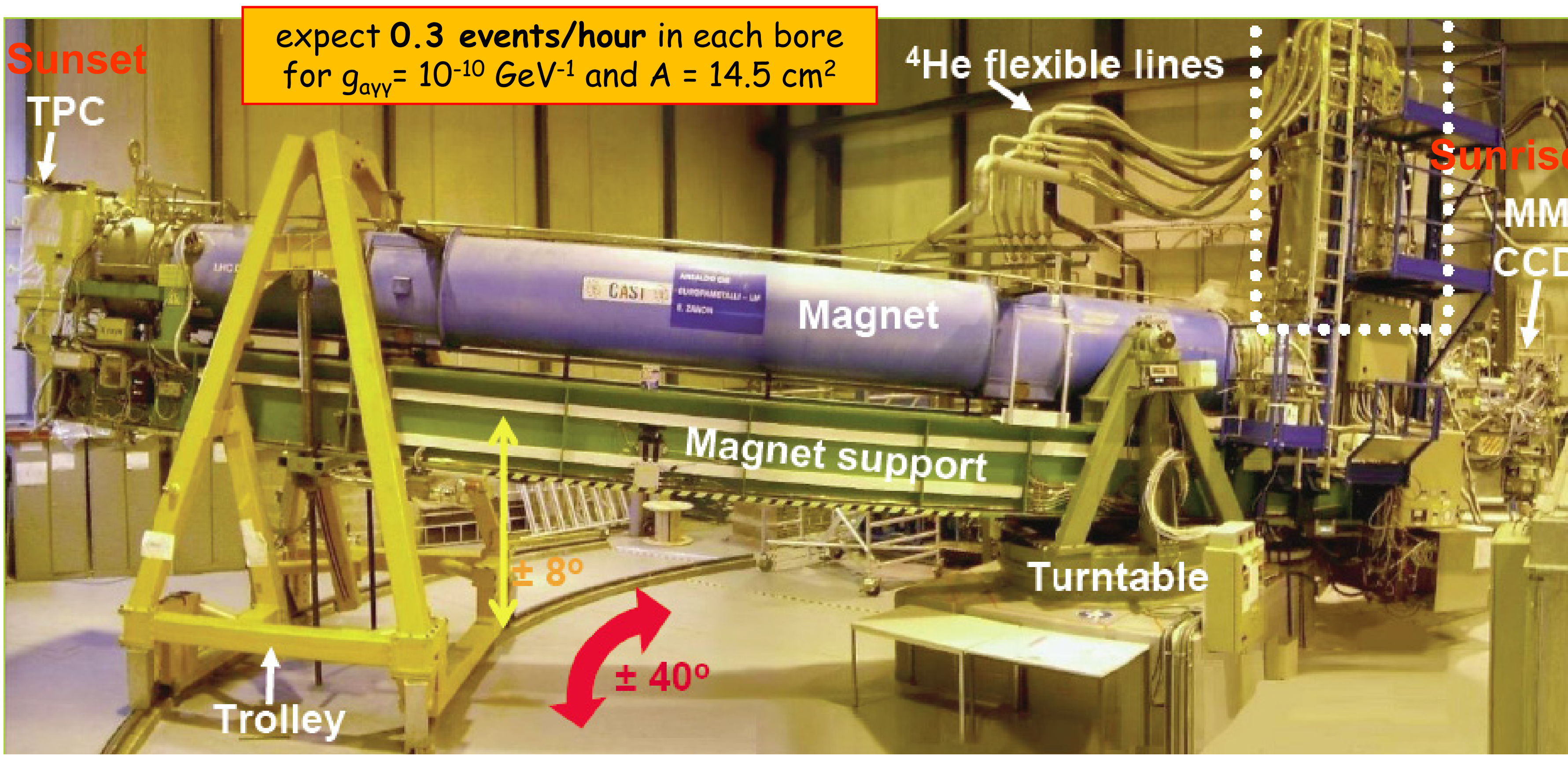


Rotating platform
(Vertical: ±8°, Horizontal: ±40°)

~90 min solar tracking during sunrise/sunset

3 X-ray detectors

X-ray Focusing Device



CAST, Physics program

1) ***CAST Phase I:*** **vacuum operation, *completed* (2003 - 2004)**

2) ***CAST Phase II:*** **^{4}He run, *completed* (2005 – 2006)**

^{4}He vapor pressure < 16.4 mbar

P<13.4 mbar, 160 steps,

0.02 eV < m_a < 0.39 eV

^{3}He run, commissioning in Nov. 2007

data taking started in Mar. 2008

^{3}He vapor pressure < 135.6 mbar

P~120 mbar, ~1000 steps,

0.39 eV <m_a<~1.20 eV

3) ***Low energy axions* (2007 – 2010)** **in parallel with the main program**

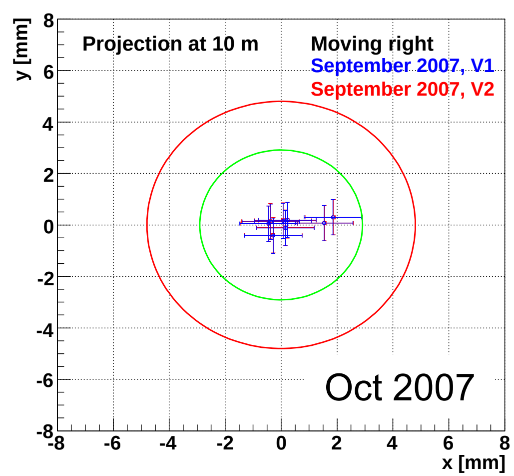
i.e. the X-ray range

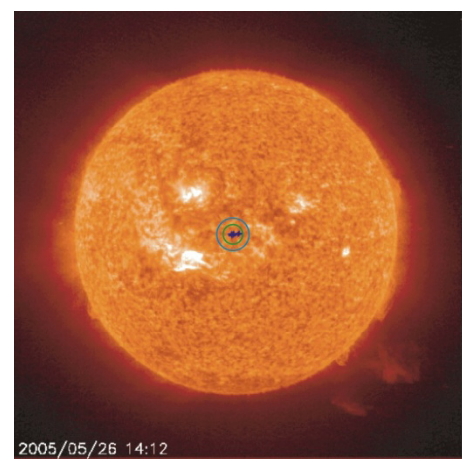
~ few eV range and 5 eV – 1 keV range

CAST, solar tracking

- The orientation of the magnet is determined with the use of **stepping encoders** (horizontal/vertical)
- **Correlation** between encoder value – magnet orientation has been established for a number of points **(GRID)**
- **Solar coordinates** are calculated **every minute**, and magnet is guided towards them by software
- The correlation is **checked periodically** for a number of points ("GRID measurements")

Comparison with 2002 GRID



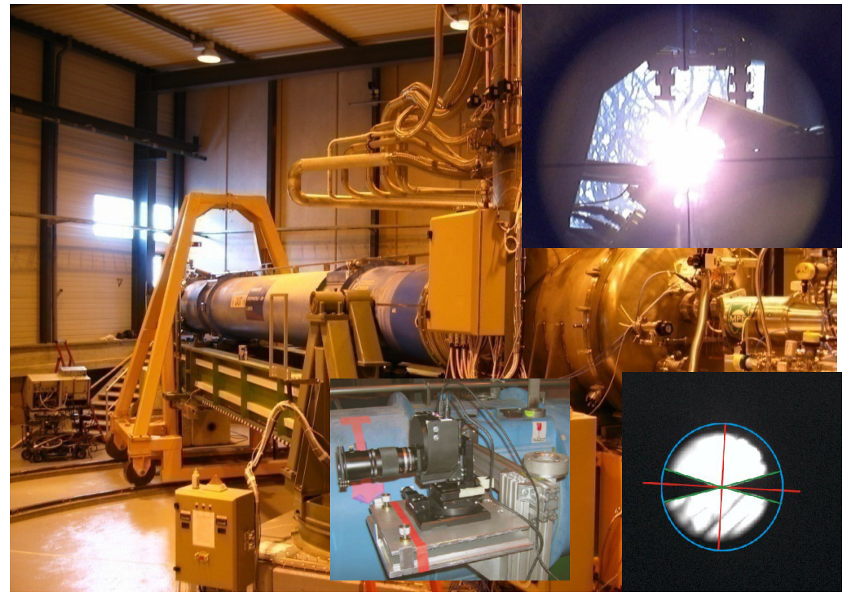


Thomas Papaevangelou, CEA Saclay

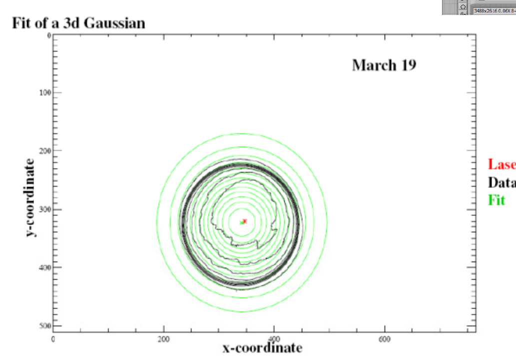
CAST, Verifying solar tracking

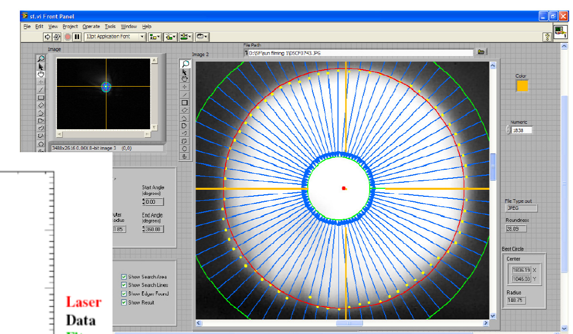
Sun filming

- Twice per year (September/March) tracking is passing trough a window
- A camera is placed on top of the magnet and is aligned with the bore axis (*parallel laser beam*)
- Corrections for visible light refraction are taken into account
- Since March 2008 **2 independent** systems are in use



Both systems verify that the Dynamic Magnet Pointing Precision (~ 1 arcmin) is within our acceptance

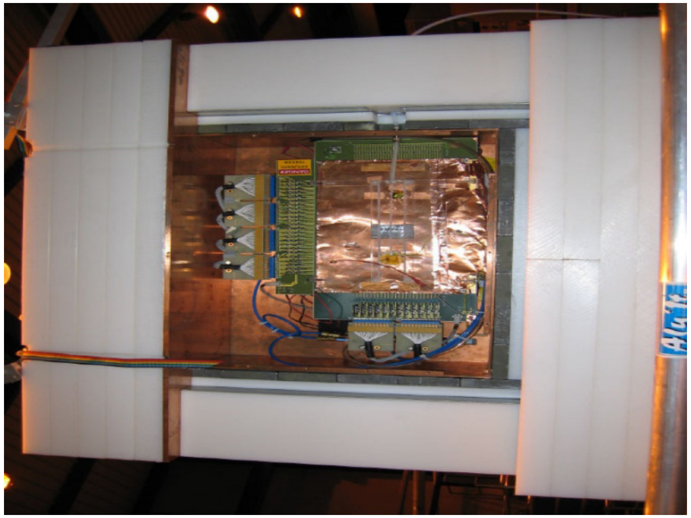




CAST detectors (phase I & phase II-^{4}He)

Sunset side

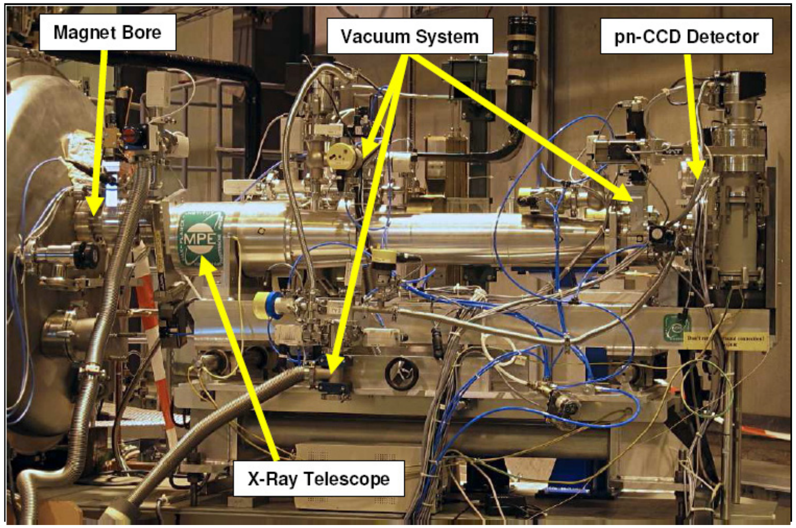
Shielded TPC, covering both magnet bores



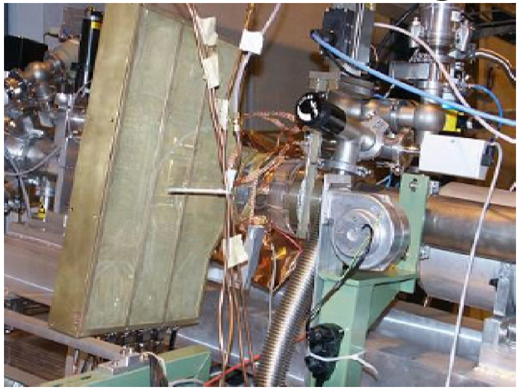
	Typical rates
TPC	85 counts/h (2-12 keV)
MM	25 counts/h (2-10 keV)
CCD	0.18 counts/h (1-7 keV)

Sunrise side

CCD + X-Ray Telescope (prototype for the ABRIXAS Space mission)



Unshielded Micromegas



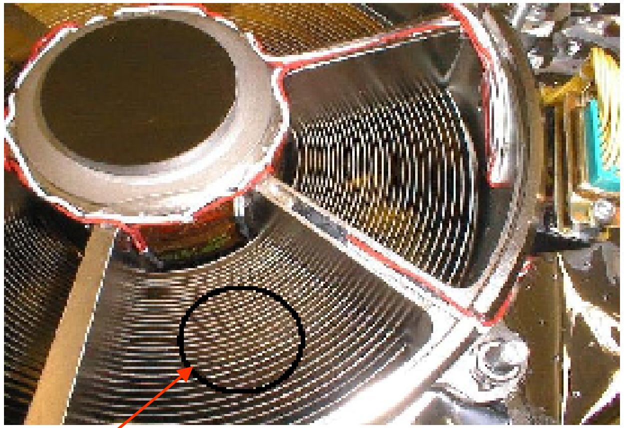
The X-Ray telescope

27 nested mirror shells (nickel foils, gold coated)

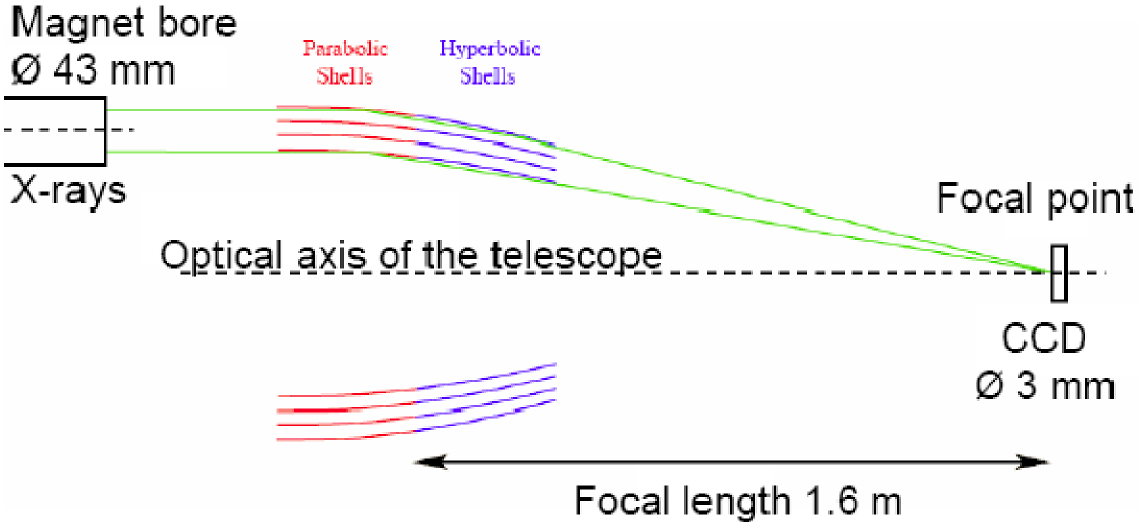
Focusing X-Rays from the ∅ 43mm magnet bore to ∅ 3mm on the CCD

Measure background and signal events simultaneously

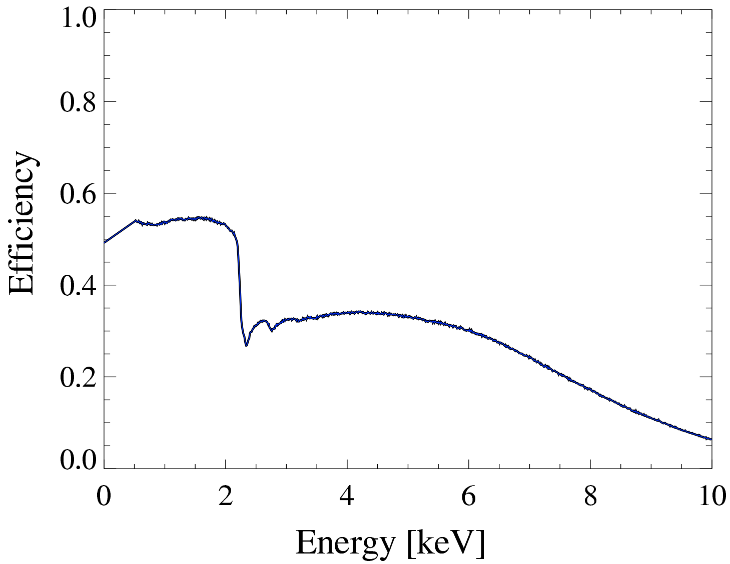
very strong signal-to-noise improvement!



Magnet bore size (43 mm)



Focusing efficiency



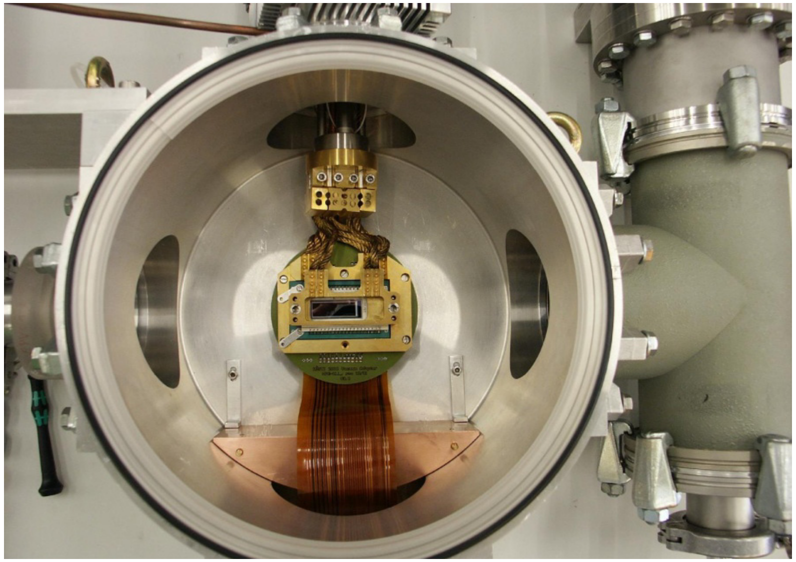
Sunrise detectors, CCD

280 μm thick, fully depleted pn-CCD, pixel-size: $(150 \times 150)\ \mu m^2$

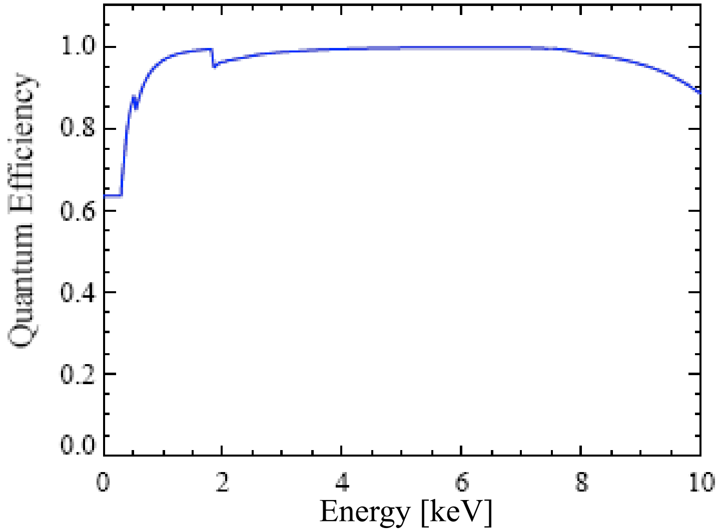
Excellent Energy Resolution

Excellent Space Resolution

After 2004: additional shielding plus X-ray finger source for continuous monitoring of the spot position



Chip dimensions: $3{\times}1\ cm^2$

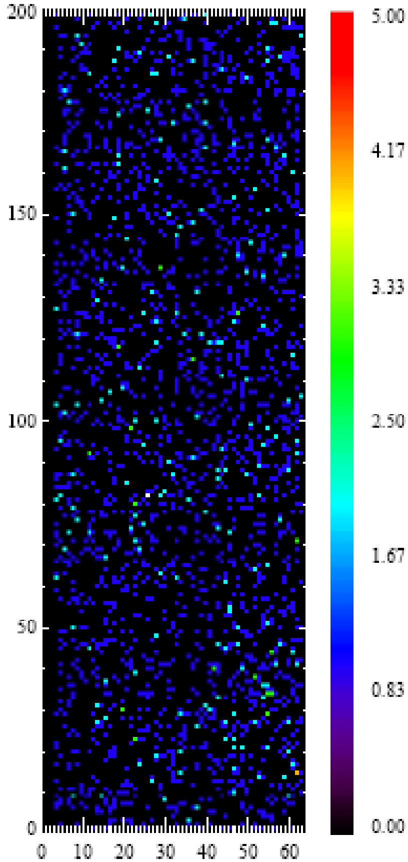


64 x 200 pixels

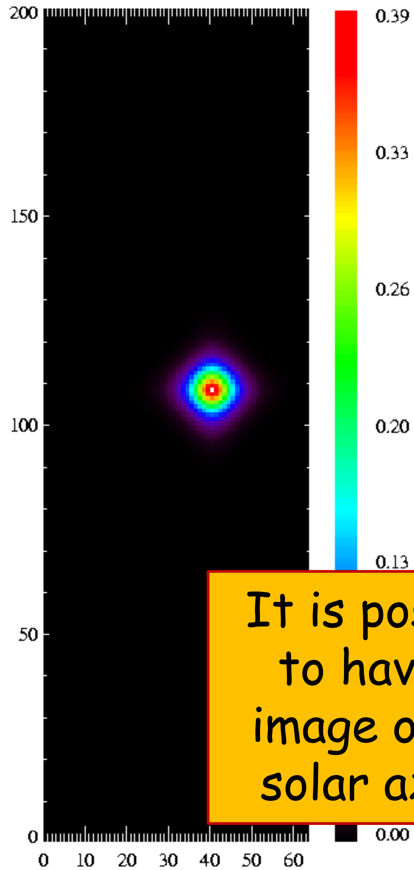
Readout: accumulated charge in the pixels (read in rows)

- Exposure time: 60 ms,
- Readout time: 6 ms

Sunrise detectors, CCD

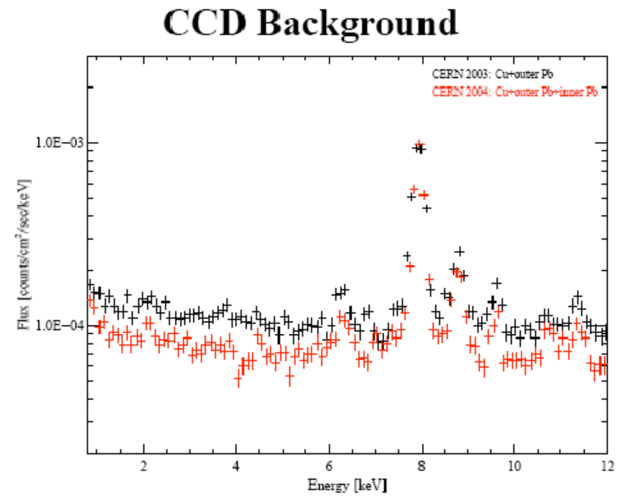


Background

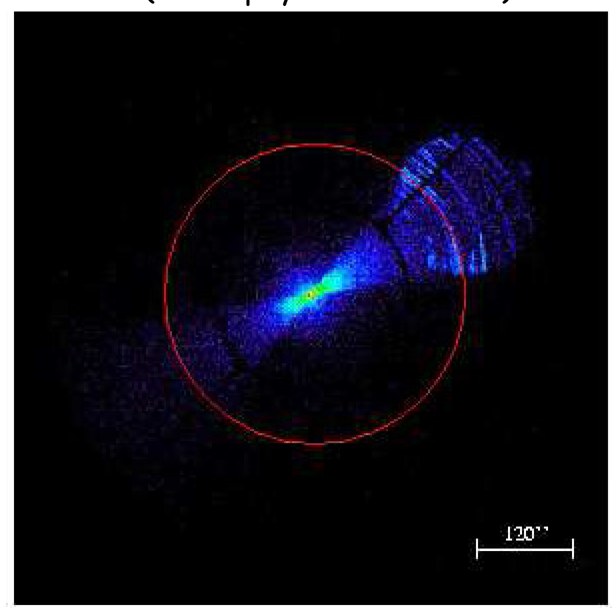


It is possible to have an image of the solar axions

Pattern recognition in hits topology



Logarithmic Intensity Image of the PSF (arXiv:physics/0702188)

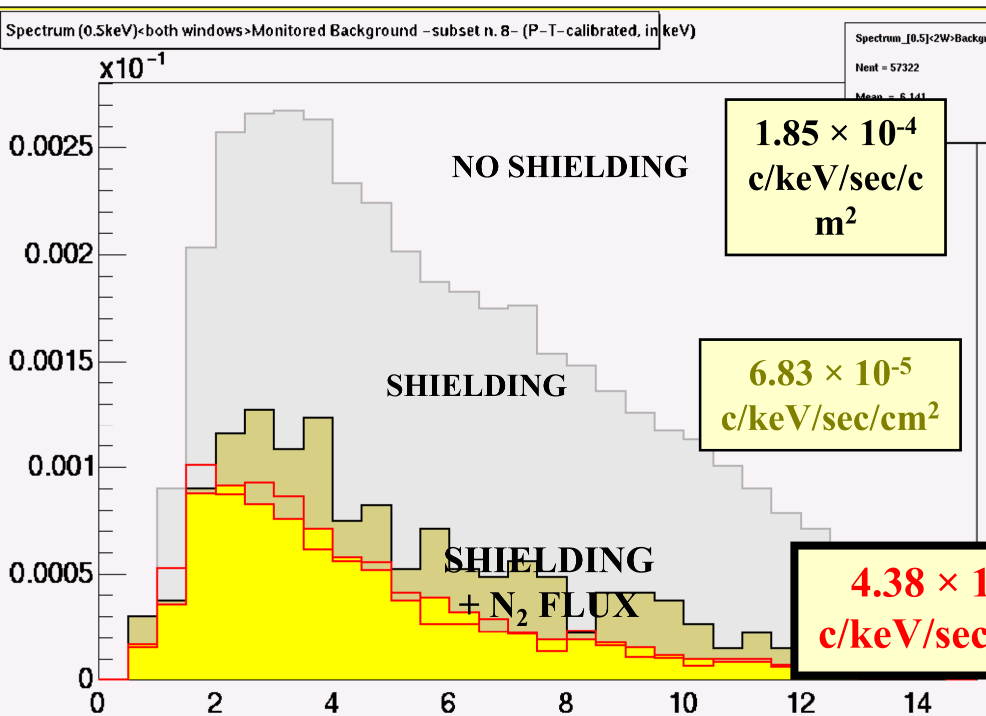


- Energy resolution: 160 eV at 6 keV
- Background rate: 7.69×10^{-5} cts keV^{-1}s^{-1}cm^{-2}
  - **0.15 cts/h in potential signal area**

Sunset detector, TPC

The detector covers both magnet bores

Clean materials + shielding
(polyethylene+copper+*ancient* lead)



Background is reduced by shielding (Cu + Pb +Cd + Polyethylene)

Position sensitive *(3mm spacing)*

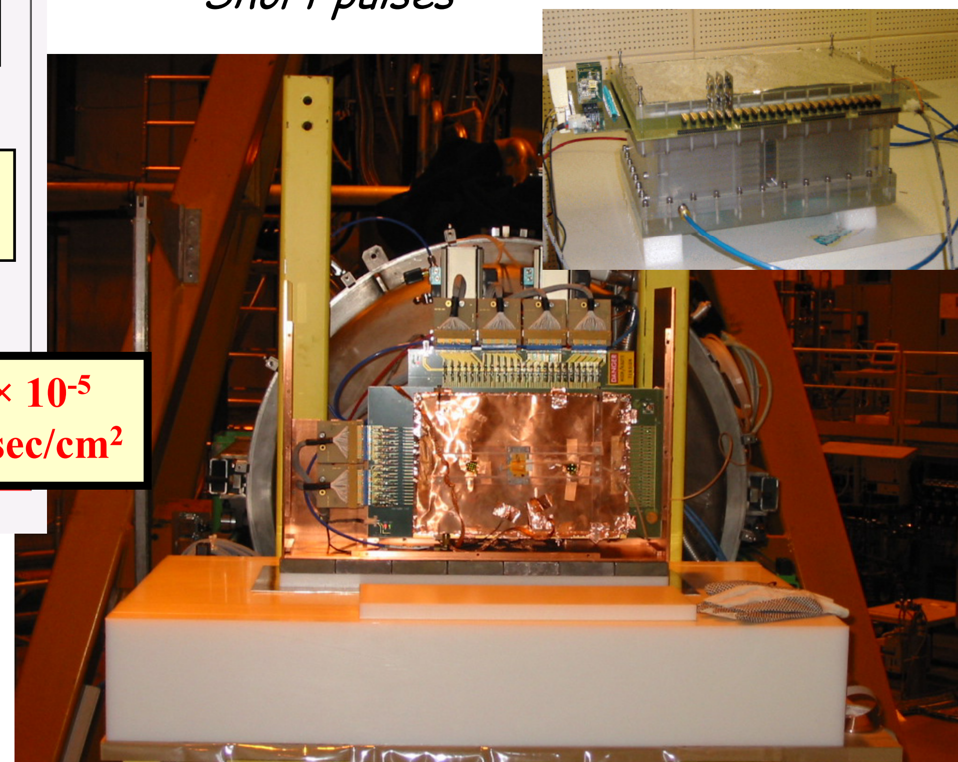
48 anode wires (x)

96 cathode wires (y)

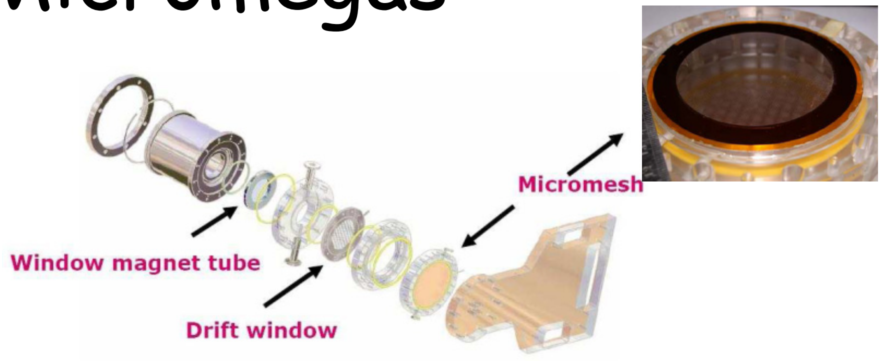
Readout: 10 MHz ADC's *in each wire*

Pattern recognition:

- *Clusters of few wires*
- *Short pulses*

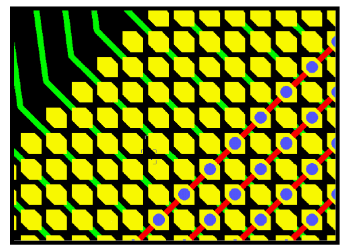


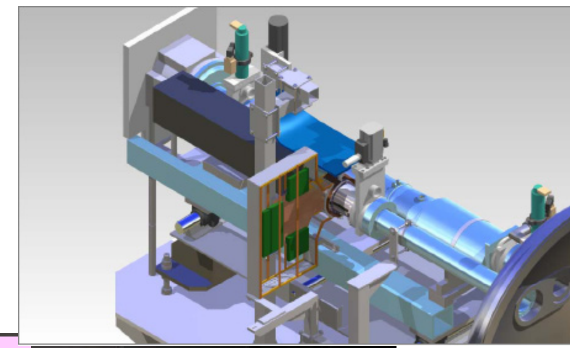
Sunrise detectors, Micromegas



Phase I (2003-2004) &
He-4 phase (2005-2006)
one conventional not shielded Micromegas was used (sunrise)

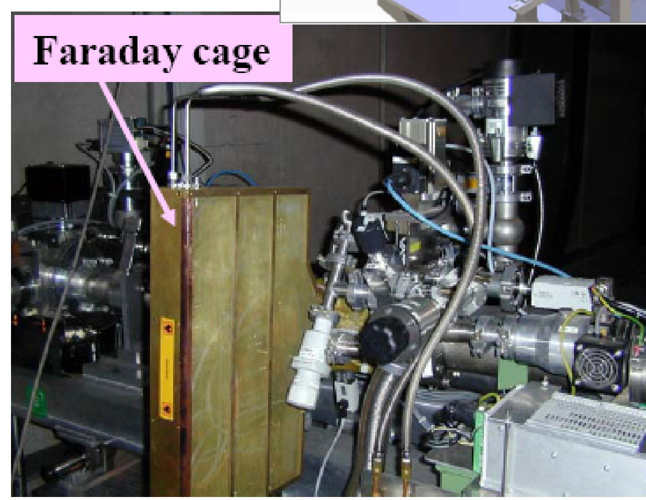
- Readout :192 x 192 strips, 350 μm pitch
- Gas mixture: 95% Ar, 5% Isobutane @ 1 bar (flamable)





X-Ray detection Threshold: ~0.6keV
Background ~5×10^{-5} events $keV^{-1}s^{-1}cm^{-2}$

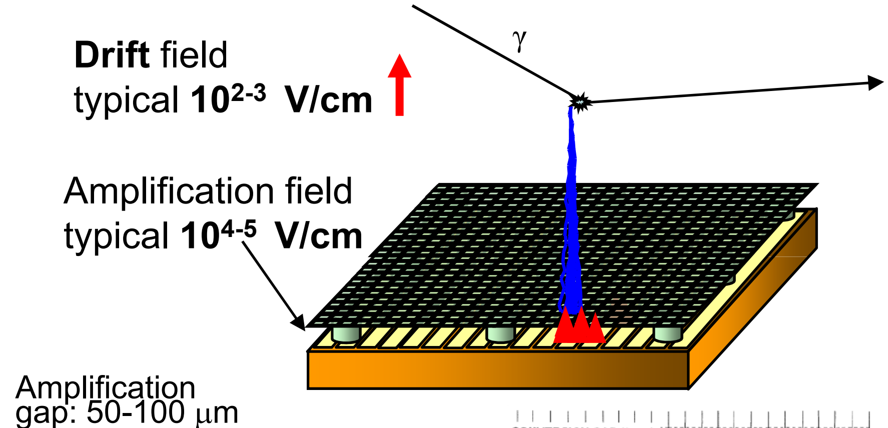
Position sensitivity ~100 μm



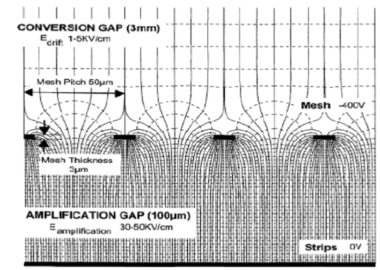
Micromegas Detector

Two-region gaseous detector:

- Conversion region
  - ➢ Primary ionization
  - ➢ Charge drift
- Amplification region
  - ➢ Charge multiplication
  - ➢ Readout layout
    - Strips (1/2 D)
    - Pixels

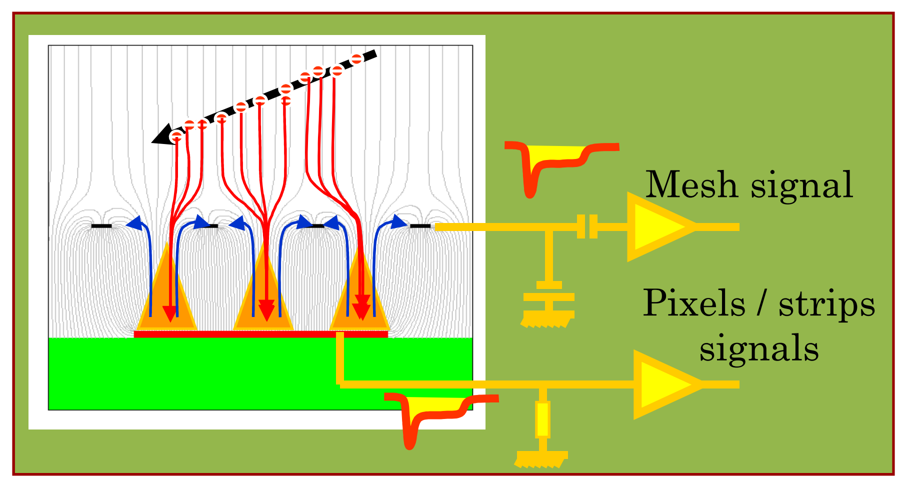


Giomataris, Charpak (1996)



Separated by a Micromesh

➔ Very strong and uniform electric field



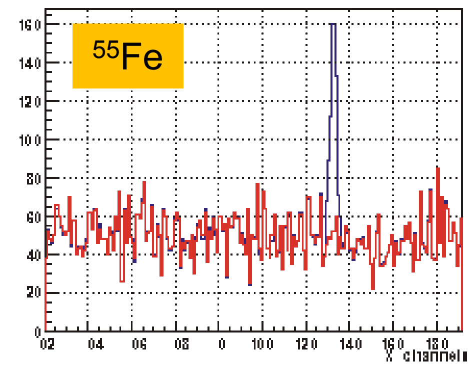
Micromegas readout

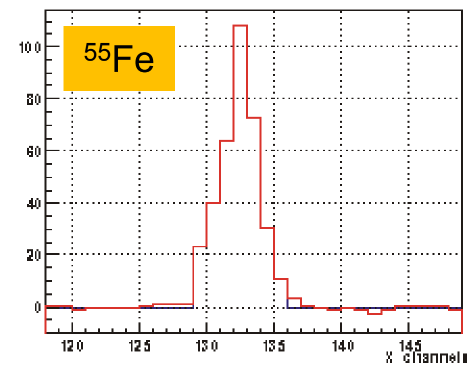
- Mesh: 1 GHz FADC, 2.5 μsec (MATACQ)
- Strips: Integrated charge at each strip in groups of 96 (Gasiplex)

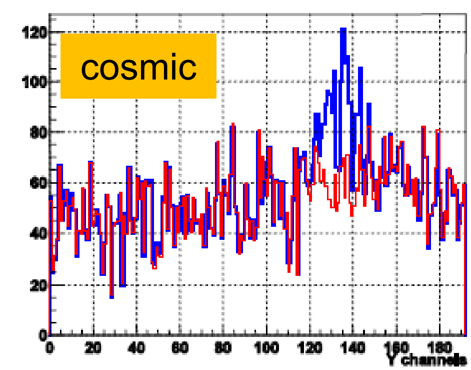
1 – 10 keV X-Rays: Localized energy deposition (<1 mm)

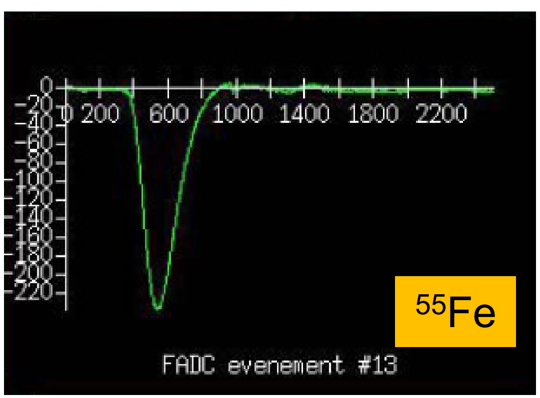
- ➢ Short risetime and pulse width for the analogue signal
- ➢ Charge in one cluster of few strips per axis

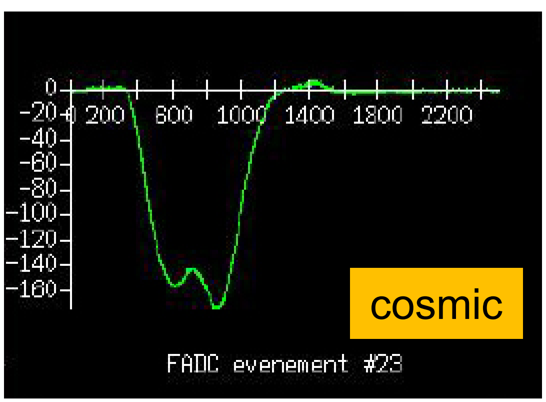
Pattern recognition algorithm can be applied to reduce background







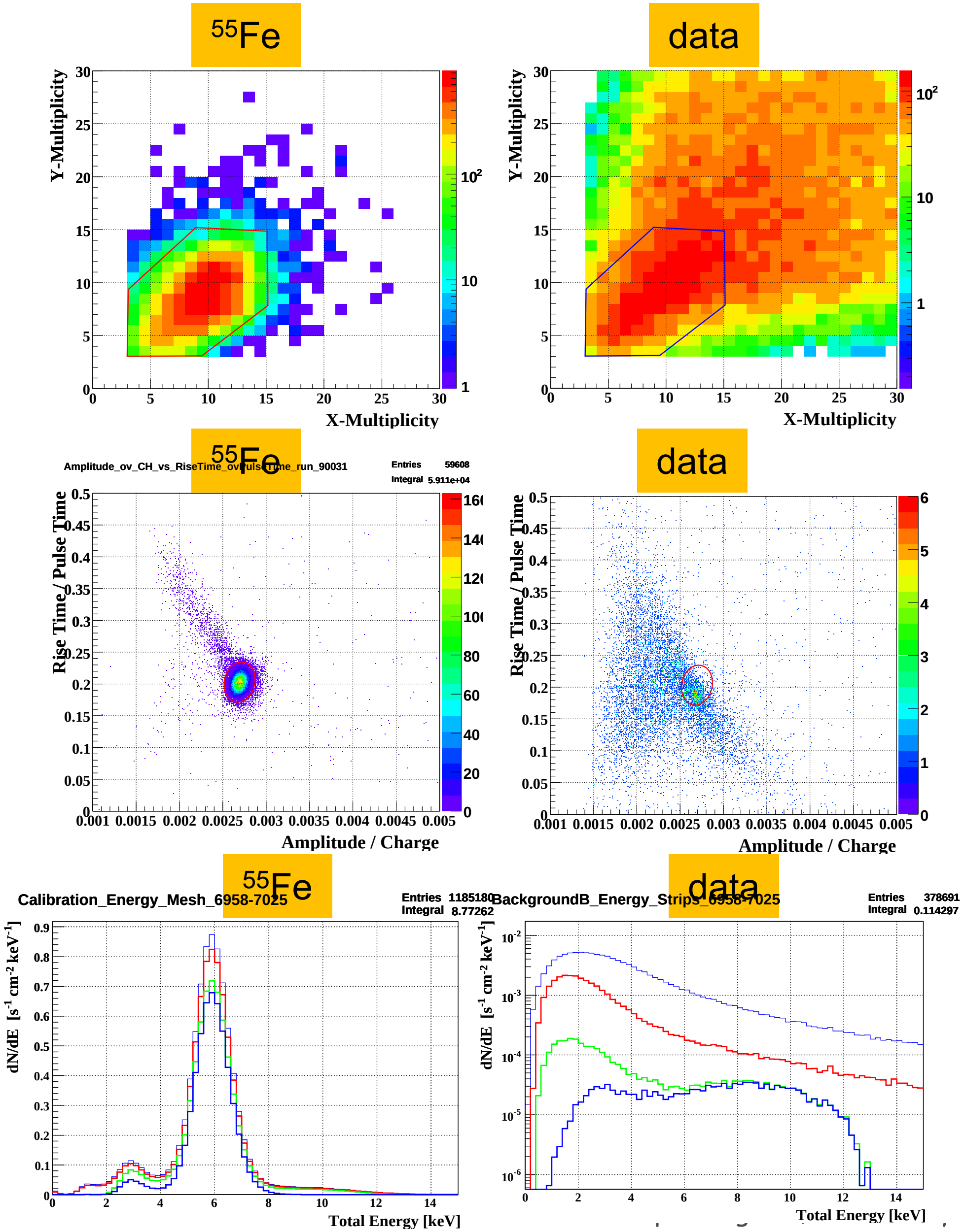




Pattern recognition

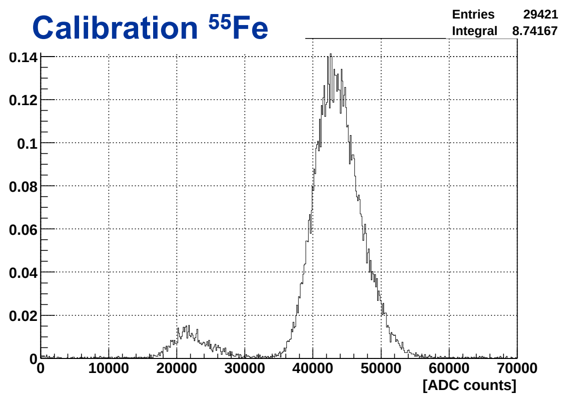
- Define signal characteristics for ^{55}Fe X-Rays (daily calibration runs)
  - Strips: multiplicity, width, topology of clusters
  - Mesh: risetime, width, amplitude, integral of signals
- Examine distributions
- Apply cuts in data runs
  - Sequential
  - Multivariate analysis
  - Neural networks
- Optimize between efficiency and rejection

Data reduction >10^3

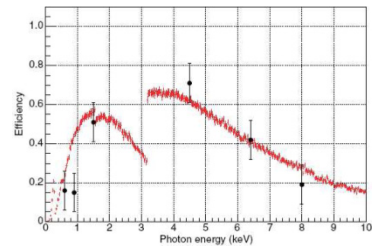


Detector Performance

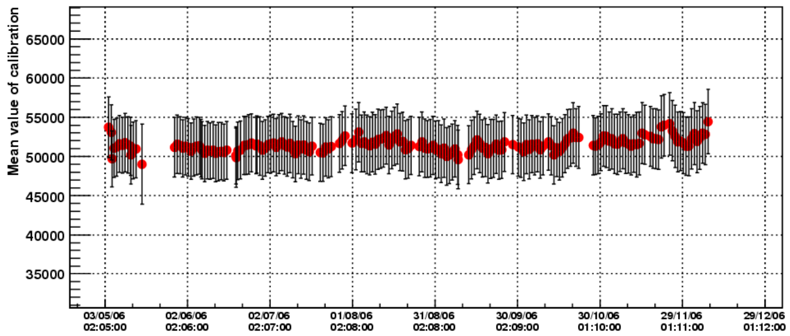
Energy resolution



Efficiency

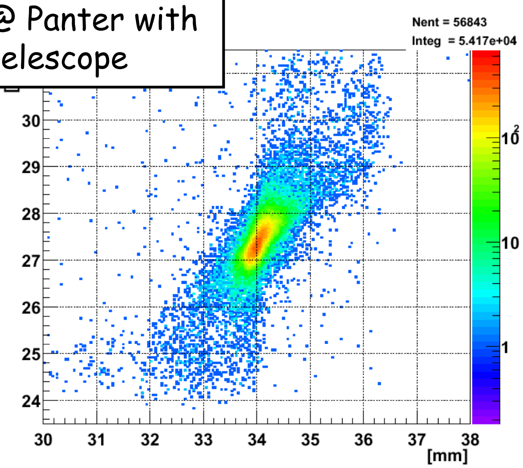


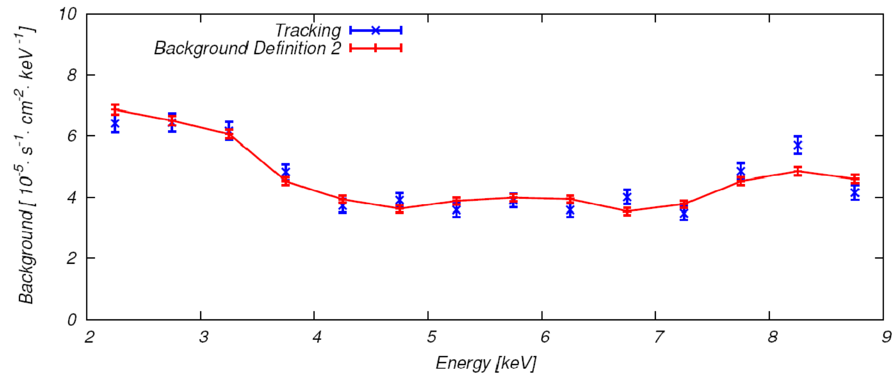
Gain Stability



Spatial resolution

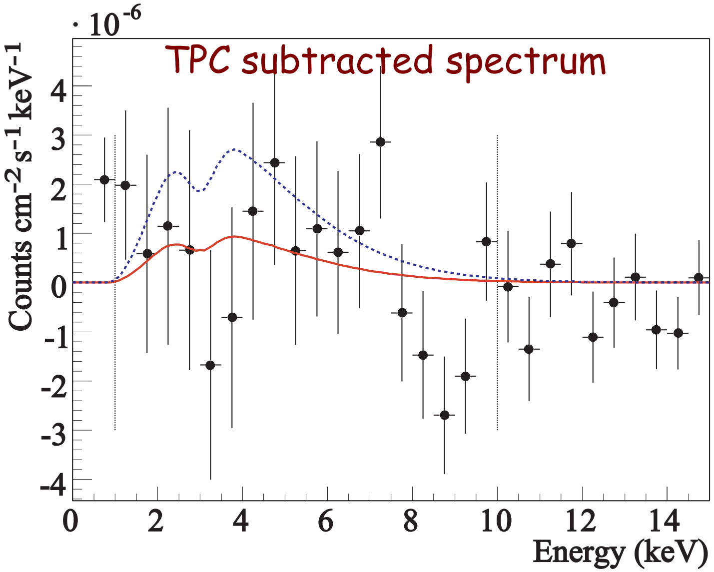
Calibration @ Panter with
X-Ray telescope

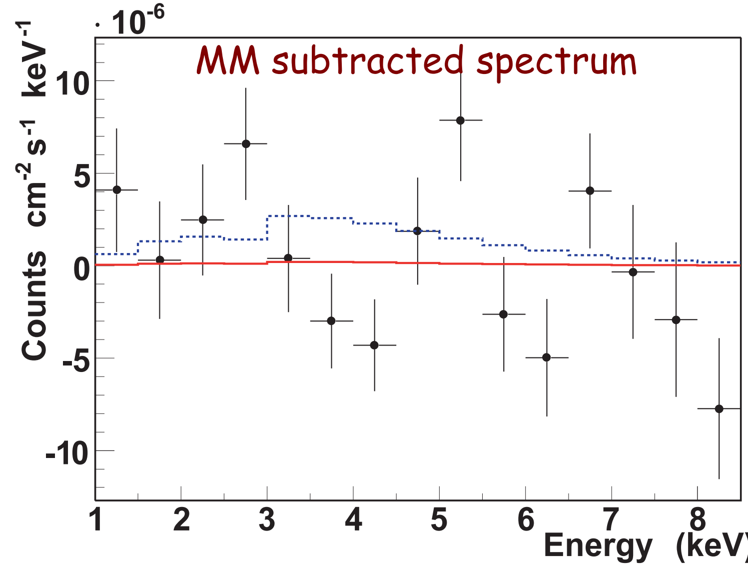


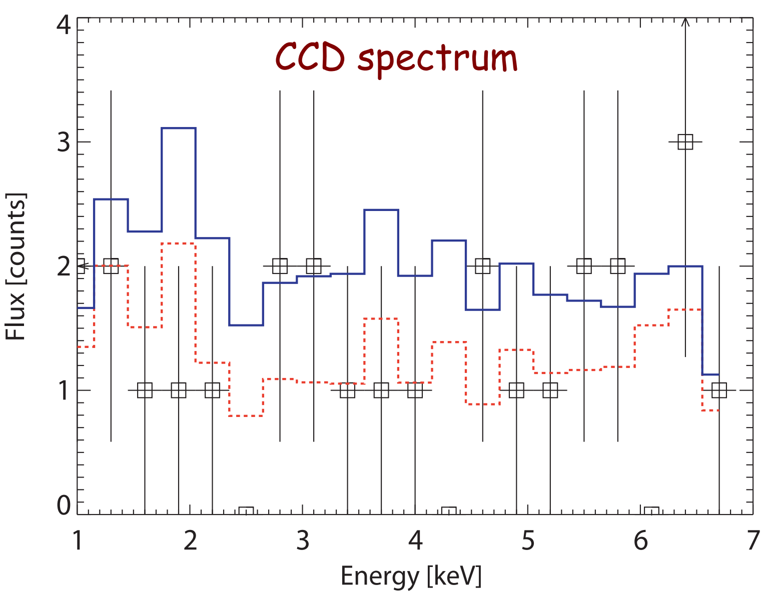


Background rate:
~4.7×10^{-5} cts keV^{-1}s^{-1}cm^{-2}

CAST Phase I result







Data taking during 2003 and 2004

(total 12 months)

Result from CAST phase I:

$$\boxed{g_{a\gamma\gamma} < 0.88\times10^{-10}\,GeV^{-1}}$$

(m_a < 0.02 eV)

JCAP04(2007)010, CAST Collaboration

PRL (2005) 94, 121301, CAST Collaboration

CAST Phase II (^{4}He)

^{4}He gas system – filling the magnet bores

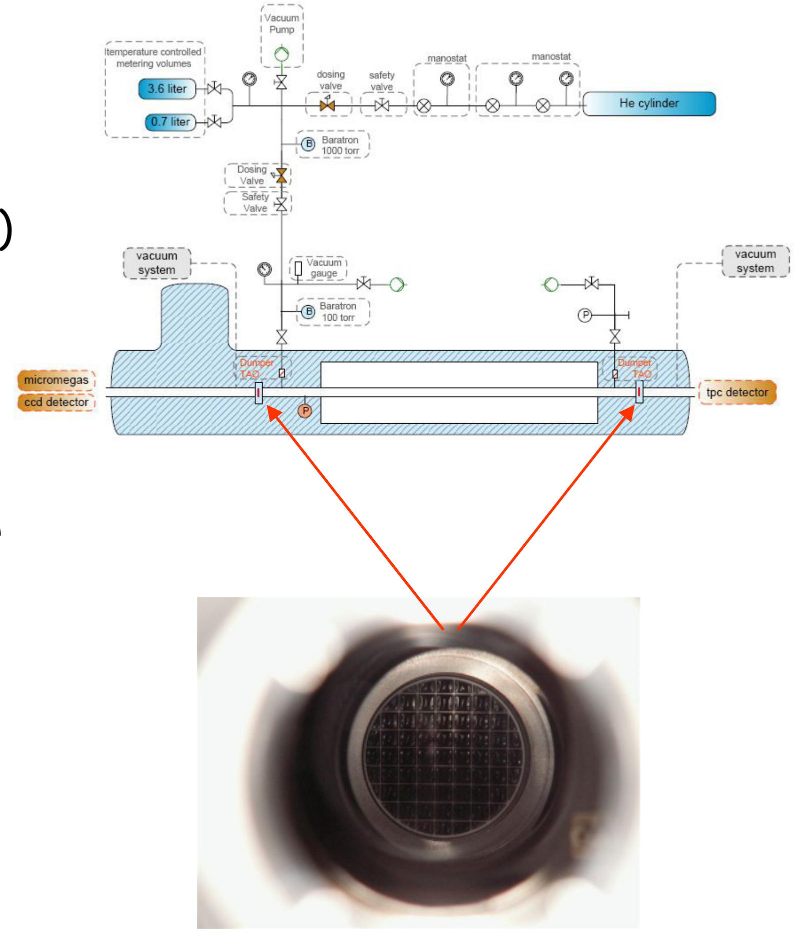
(in operation in 2005 and 2006)

- Controlled injection of ^{4}He in the bores
- Precise measurement of injected gas quantity (measuring volume in controlled P,T)
- Precise monitoring of gas P,T
- High reproducibility precision (< 0.01 mbar)
- No thermoacoustic oscillations

Cold Windows installed to contain the gas in the bores

- Transparent to X-rays and visible light
- Resistance to **magnet quenches**

Same detector setup



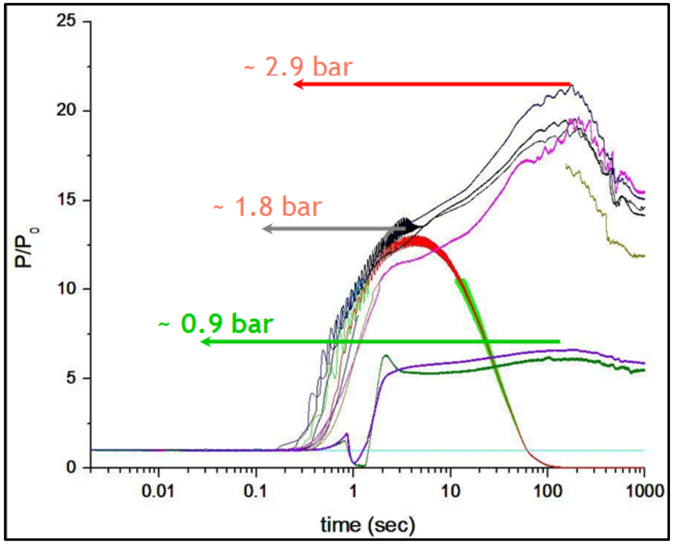
During 2005/2006 we covered 160 ^{4}He pressure steps, reaching P = 13.43 mbar $\Rightarrow$

$m_a \sim 0.39$ eV/c^2

Magnet quench

Superconducting magnet resistive transition

- Rapid temperature rise
  → Gas pressure increase
  (*x10 in ~1.5 sec*)
- Specially designed windows
  (*CERN, Saclay, Freiburg*)
- Fast gas recovery



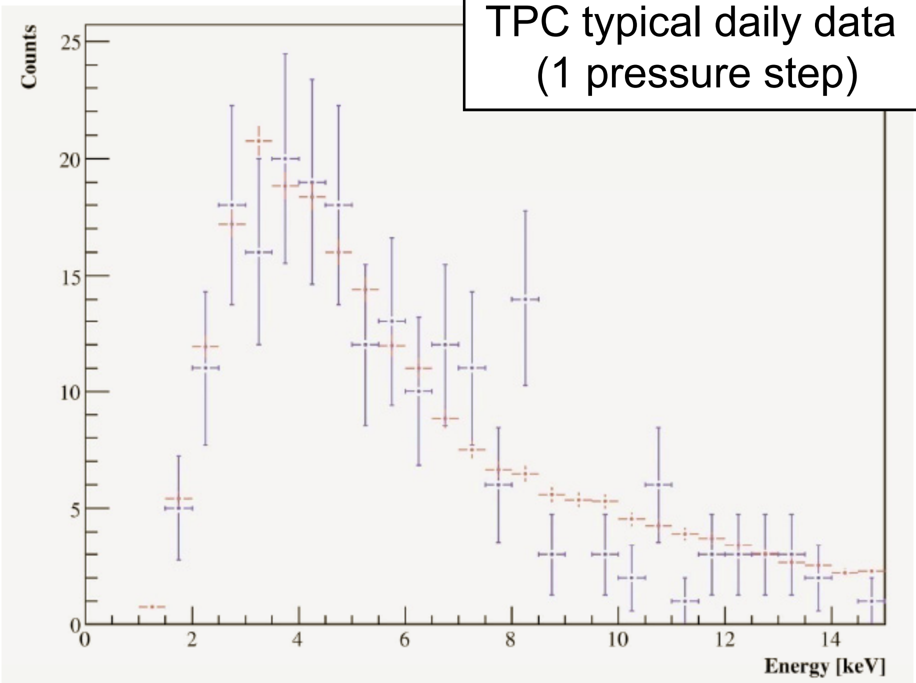
CAST Phase II-^{4}He result (to be published in JCAP)

- Spent at least one full tracking per pressure setting
- Measure / calculate corresponding backgrounds
- Compare with tracking rates
- During 2005/2006 we have covered 160 ^{4}He pressure settings, reaching

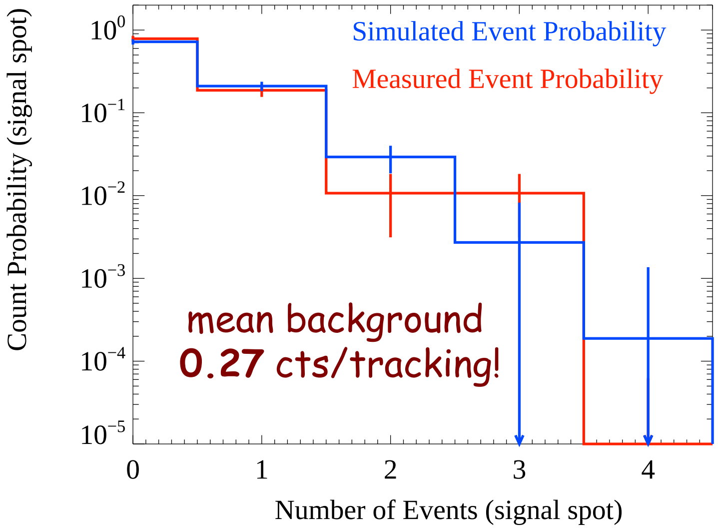
P = 13.43 mbar $\Rightarrow$ **m_a~ 0.39 eV/c^2**

Every day is a "new" experiment

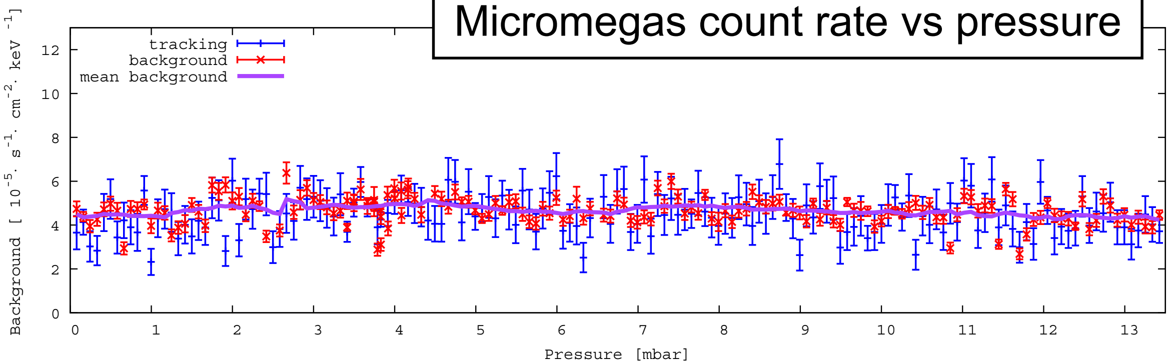
TPC typical daily data (1 pressure step)



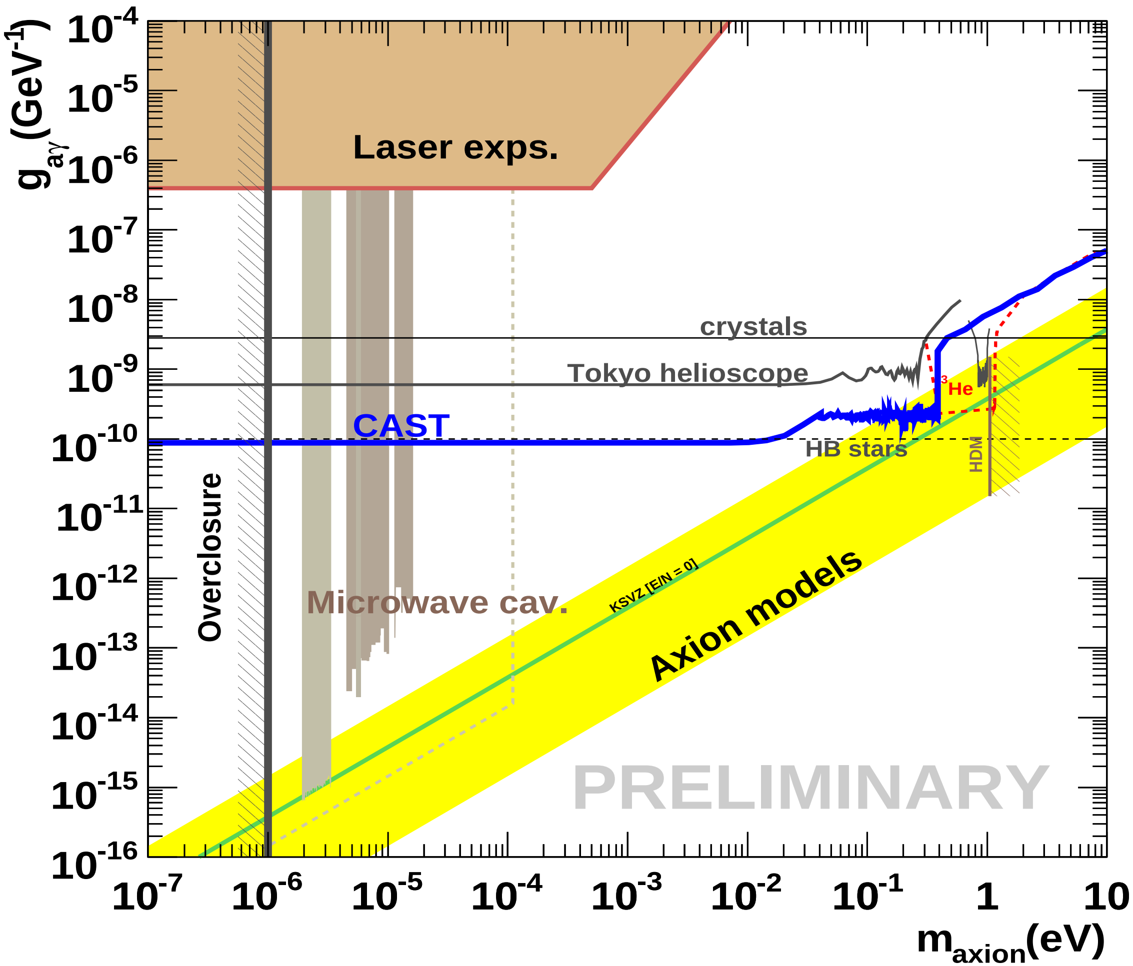
CCD tracking count distribution



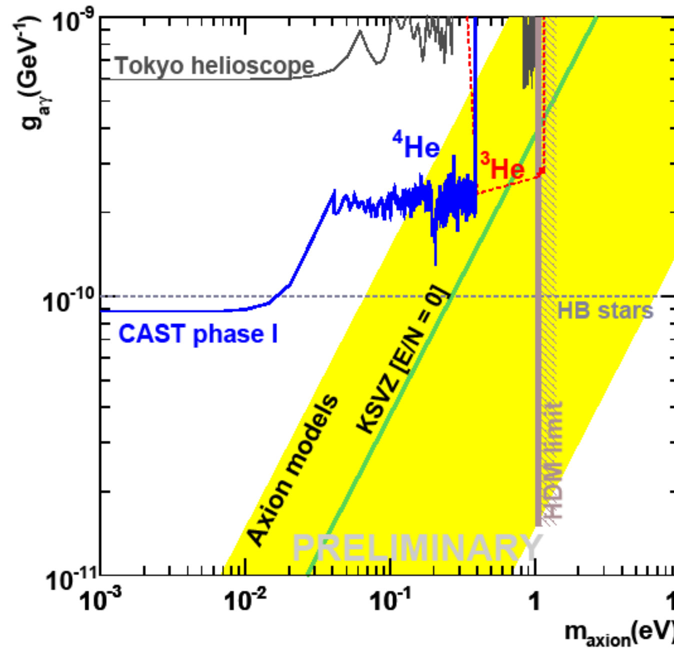
Micromegas count rate vs pressure



CAST Phase I & II-^{4}He result



to be published in JCAP



CAST has entered the theoretically favored axion model region!

CAST <u>experimental</u> limit dominates in the most of the favored (cosmology/astrophysics) parameter space

Cast Prospects: ^{3}He Phase

^{4}He gas saturates at ~16 mbar for T=1.8K

For higher pressures only ^{3}He remains gas

➔ Very expensive

During 2007 CAST has upgraded the gas system

- Controlled injection of ^{3}He in the bores with precise measurement of gas quantity
- High reproducibility precision (< 0.01 mbar)
- Extra safety for ^{3}He loss
  - Protection from magnet quenches
  - Protection from window failures
- Possibility to smoothly scan a pressure range

During ^{3}He phase (approved by CERN till 2010)

CAST will cover 1050 pressure steps, aiming to

P = 120 mbar $\Rightarrow$ **m_a~ 1.15 eV/c^2**

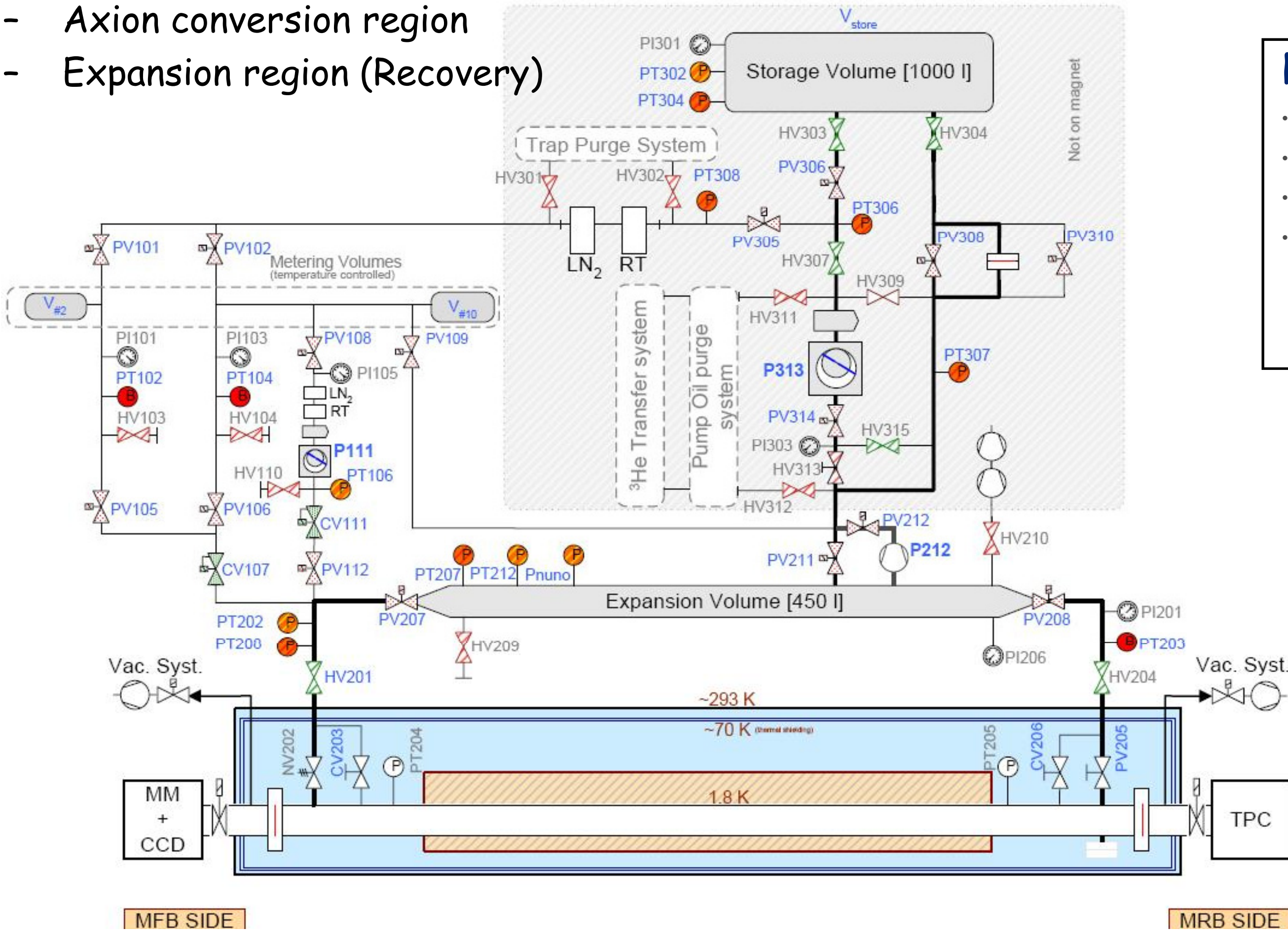
Data taking is going on since March 2008.

215 pressure settings covered up to now

^{3}He Phase gas system

- Storage region
- Metering region
- Axion conversion region
- Expansion region (Recovery)

Technical Design Report [CERN-SPSC-2006-029]



Requirements:
- Avoid loss of ^{3}He
- Absence of TAO's
- Precision/Reproducibility
- Multiple stepping / Ramping of density

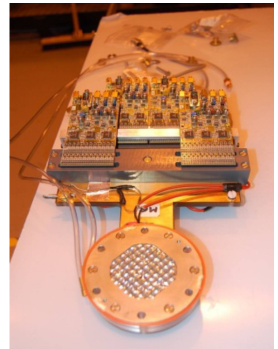
Constraints:
- Limited space
- Weight restrictions
- Custom components
- Magnet movement
- Instrumentation

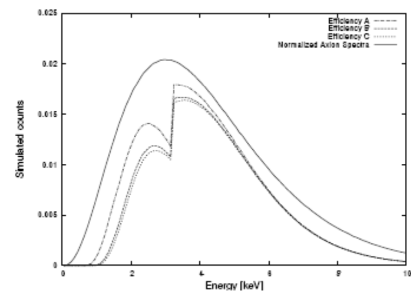
Detector upgrades

MM Sunrise line: it has been redesigned for

- ➢ Shielding
- ➢ X-Ray focusing optics

- A **Bulk** detector replaced the conventional one
- Readout :106 x 106 strips, 550 μm pitch
- Gas mixture: 97.7% Ar, 2.3% Isobutane @ **1.44 bar** (non flammable – increased efficiency)

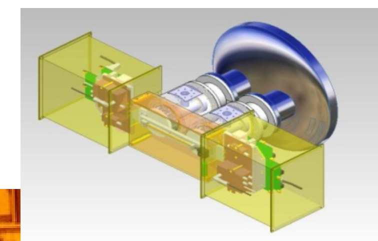


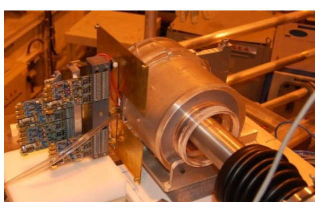


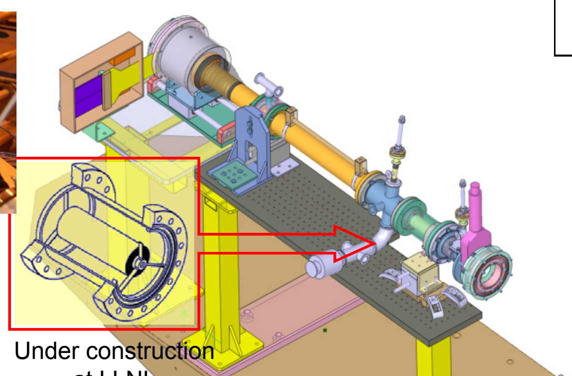
Overal efficiency (2-7 keV)		
A	mM detector	75.97 %
B	mM + CW	62.45 %
C	mM + CW + DW	61.49 %

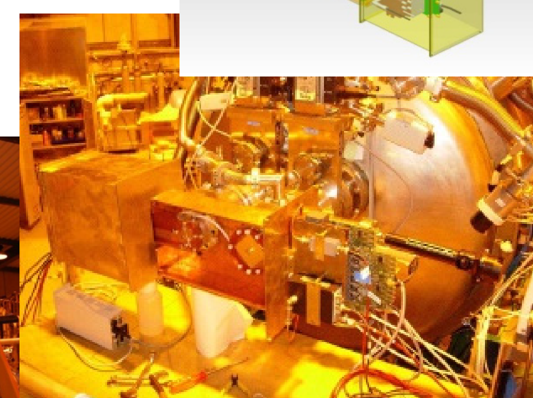
Sunset side:

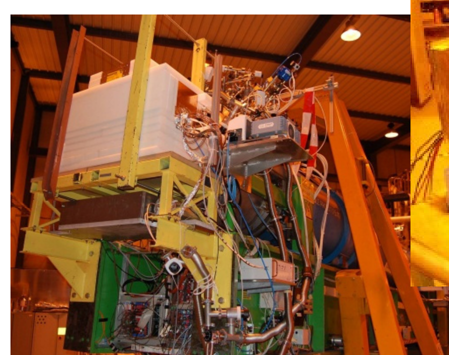
- the TPC was replaced by **one Bulk** and one **Microbulk** detector
- Readout :106 x 106 strips, 550 μm pitch
- Gas mixture: 97.7% Ar, 2.3% Isobutane @ **1.44 bar**









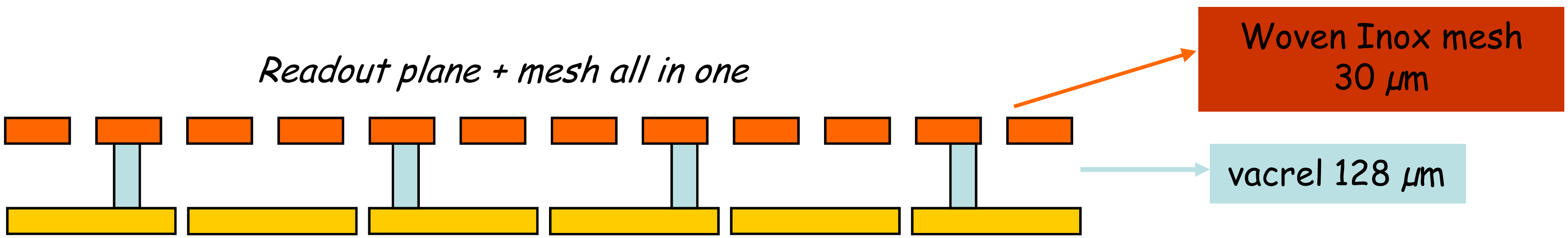


Bulk technology

__Bulk technology__
The pillars are attached to a **woven mesh** and to the readout plane, constructed with lamination

__Conventional technology__
The pillars are attached to the mesh. A supporting ring or frame is adjusting the mesh on top of the readout plane

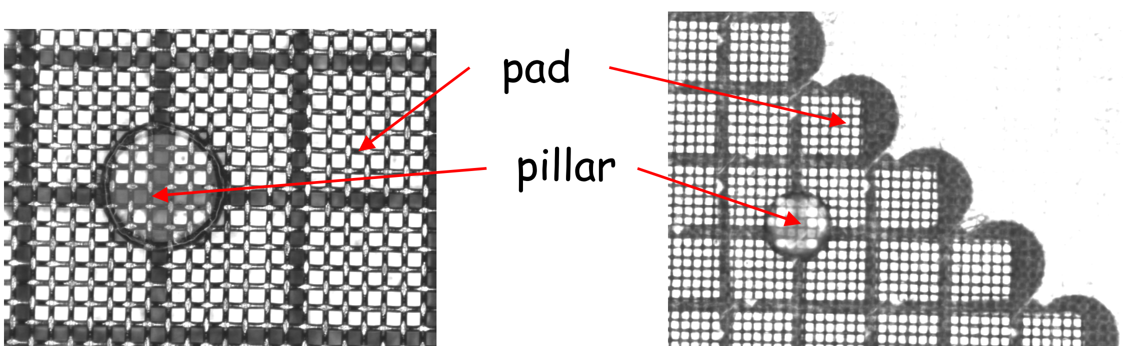
Readout plane + mesh all in one



Well established technique

Advantages: Uniformity, Reachable resolution (~18% @ FWHM, limited by the thickness of the mesh), very robust, low noise due to lower capacity, easy to construct

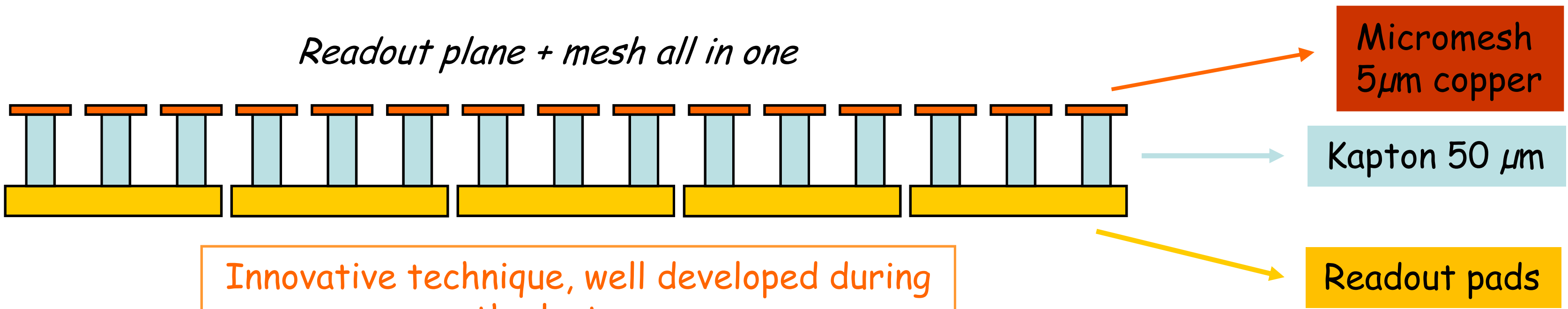
Disadvantages: higher risetime, sensitivity to pressure variations, stability



Microbulk technology

The pillars are constructed by chemical process of a kapton foil, that is attached to the mesh and to the readout plane

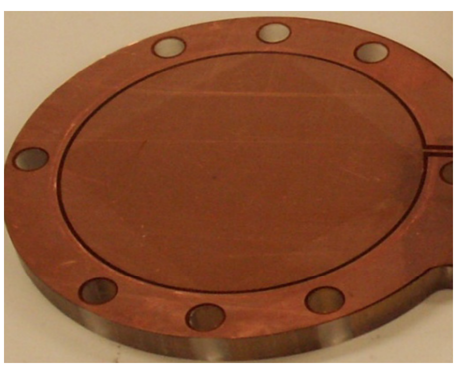
Readout plane + mesh all in one



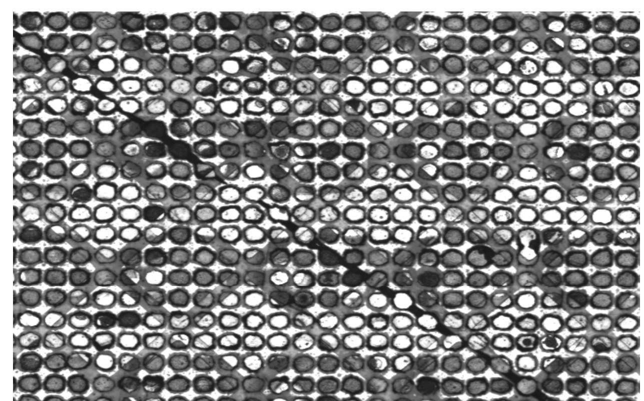
Innovative technique, well developed during the last year

Advantages: Uniformity, reachable resolution (better than 13% @ FWHM), stability at long term runs, less sensitivity to pressure variations, background rejection

Disadvantages: Higher electronic noise due to higher capacity, complexity of the manufacturing process, fragility

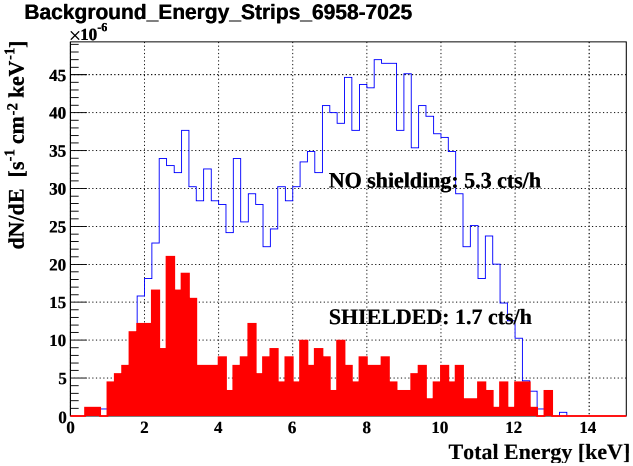


Mesh 5 μm of copper
Holes 30 μm diameter
Pitch 100 μm
Pads of 400 μm



New micromegas background in CAST

2007: Implementation of shielding
(Pb+ Cd + Cu + Polyethylene)



The background level (after cuts) is reduced by a factor 3 to 5

Background level	
Sunrise (B4)	$1.20 \cdot 10^{-5}$
Sunset (B3)	$1.42 \cdot 10^{-5}$
Sunset (M6)	$1.76 \cdot 10^{-5}$

The new background levels imply

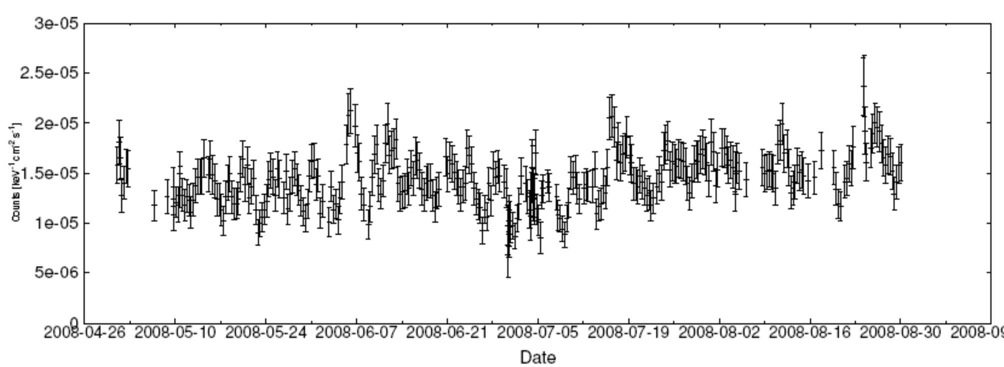
2-3 expected bkg counts per pressure setting

(~2800 sec solar tracking per setting) compared to

25 (Micromegas) and 80 (TPC)

from ^{4}He phase (~5700 sec)

The combined performance of the three detectors is comparable with the Telescope-CCD system concerning discovery potential

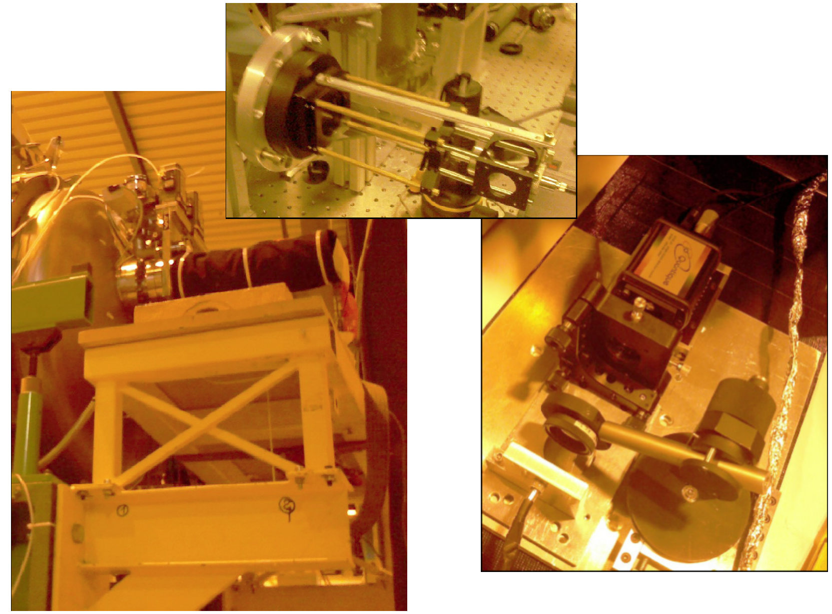


Implementation of a telescope in the sunrise side can decrease the background by a factor ~100

CAST Prospects: low energy axions

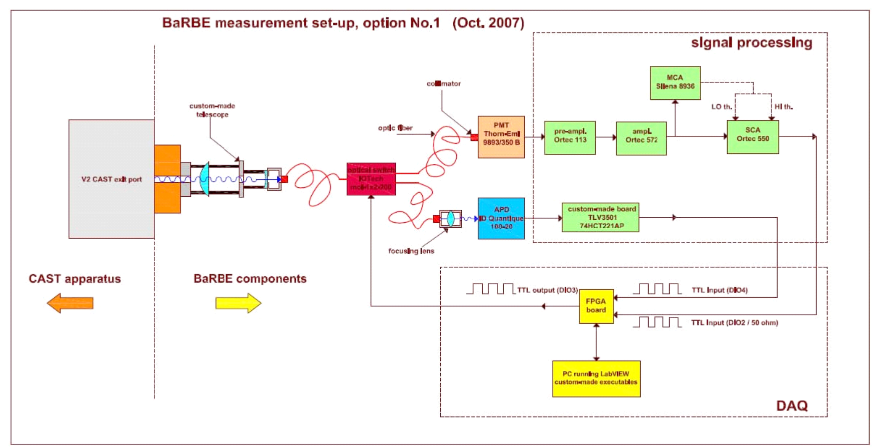
Motivation

- Several not understood solar phenomena (corona heating, huge variations in solar emission during 11 year cycle beyond the EUV, etc…)
- Solar models did not take into account magnetic fields
- PVLAS (initially…)



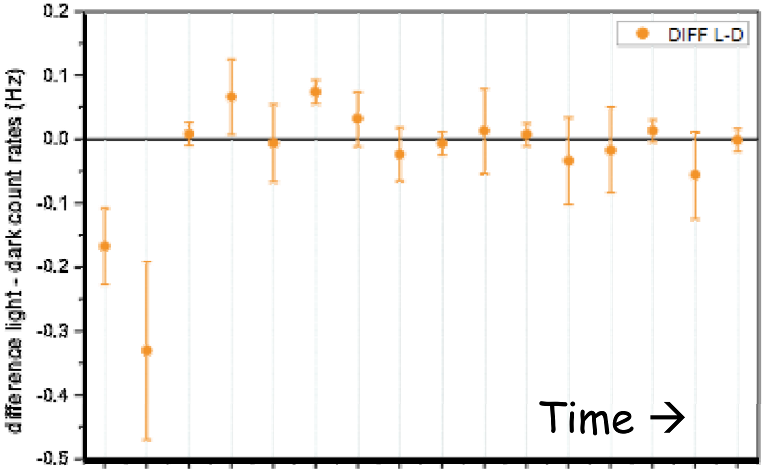
CAST has already performed two runs during 11/2007 & 03/2008 in the visible region (~5 eV) using 2 different PMT detector setups

- Ongoing data analysis
- Low dark current rate (0.35±0.02 Hz)
- Possibility to create a 5th line by using an X-Ray transparent mirror



In parallel with our main project we are examining the possibility to explore the ***whole sub-keV*** *region in a future run (low threshold detectors, ultra thin windows …)*

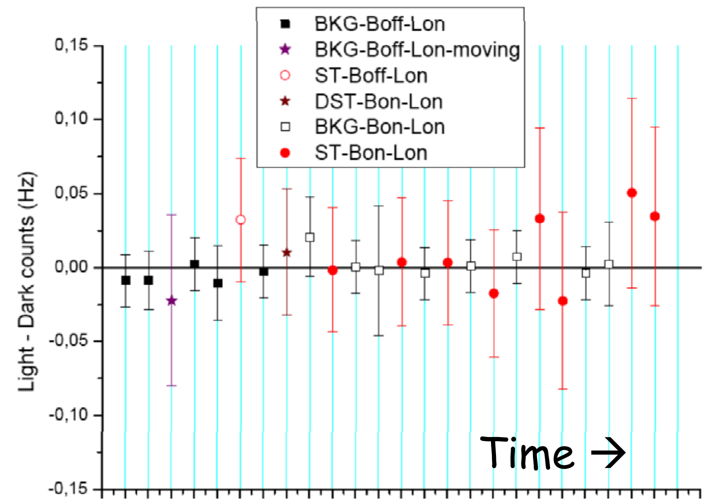
Visible measurements: first resuts



Background – Tracking

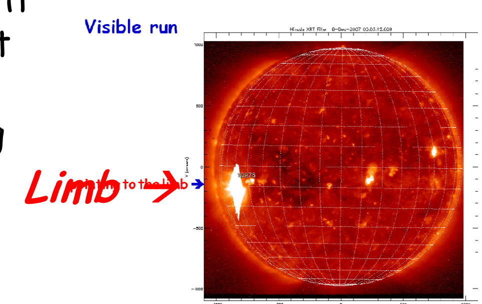
Measurements (Nov. 2007):
1) Background data
2) Dummy solar tracking
   (off pointing the Sun)
3) Solar Tracking data

Dark Count Rate = 0.35 Hz ± 0.02 Hz
NO signal excess over background.
The DESY theory group could use this number to obtain the best limit on paraphotons



Background – Tracking

Measurements (Feb.-Mar.2008):
1) Background data
2) Dummy solar tracking
   (off pointing the Sun)
3) Solar Tracking data: 50% center
   25% →0.25° to the right
   25% →0.25° to the left
   pointing to the limp
   (Sun very quite during these runs)



First results: 'Search for low Energysolar Axions with CAST'
(G. Cantatore for the CAST coll. arXiv:0809.4581v1)

The sub keV-region

Exploration in the energy range between 5 eV and 1keV:

Most solar puzzling phenomena like corona heating mystery etc occur predominantly in the sub-keV range.

- Will first require the development of suitable detectors in this technically - challenging energy range.
- Low energy axion running in this energy range will require dedicated vacuum-filled cold bores with the cold windows removed.
- This must await the end of the ^{3}He running or another possibility would be to transform the CAST setup into one cold bore for low energy work and the other to complete the ^{3}He high energy scan.
- This would could be envisaged since the performance of the X-ray detectors continue to improve and two such detectors could provide adequate sensitivity and redundancy.

CAST in the Sun?

The helioscope detection principle should work also in the Sun

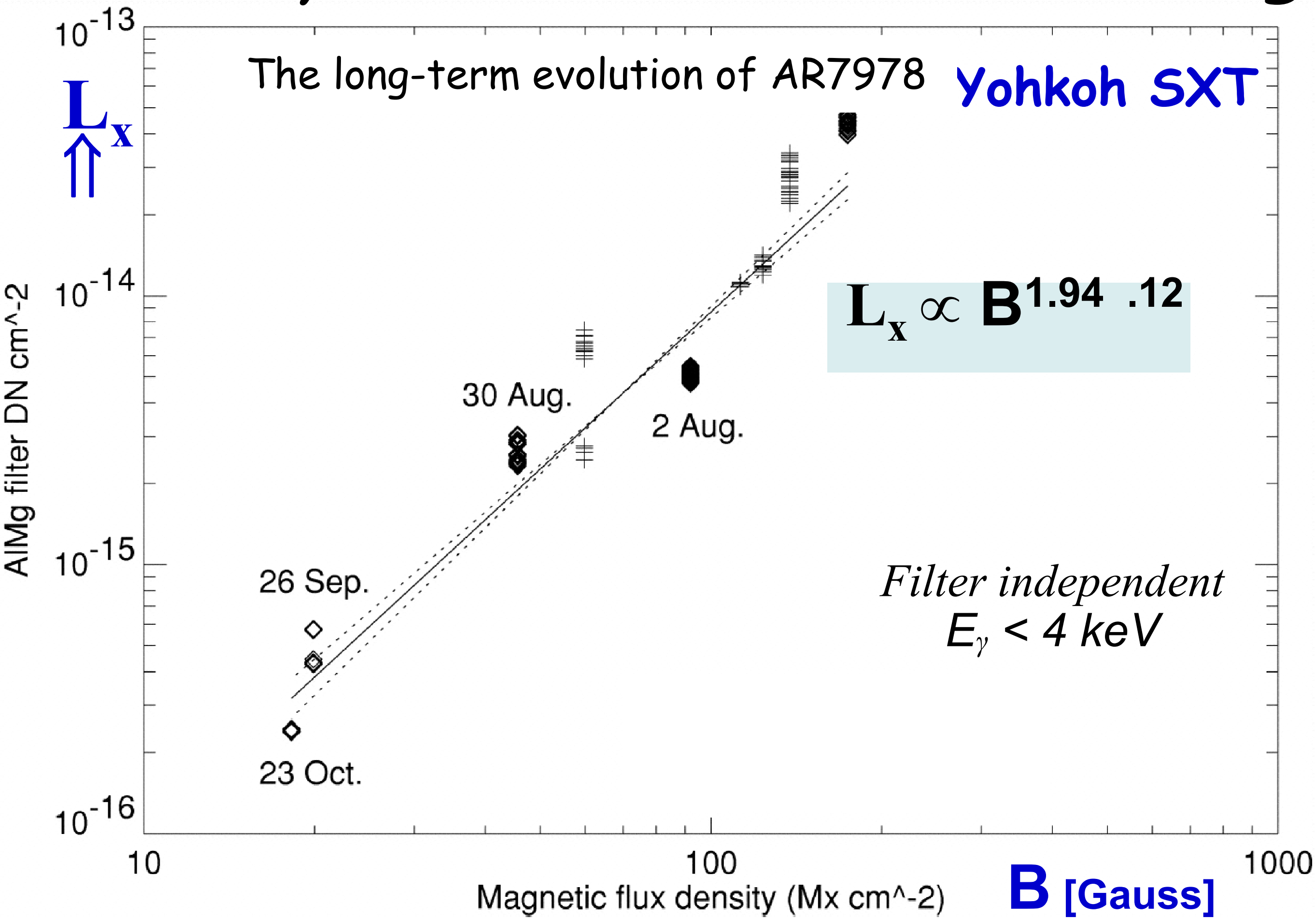
Magnetic field related observations:

➔ **charachteristic $\propto B^2$ behavior**

Axions (or APL's) could provide an explanation to several not understood solar phenomena:

- *Soft X-ray emission and Active regions*
- *Sunspots*
- *Flares*
- Corona heating problem
- *Oxygen abundance*

X-Ray emission from active regions



X-ray flux outside flaring times in AR7978

Steeply increased flux @emergence

decreased @ decay phase

Only the decaying phase (diamonds) is included in the fit

<B> = total mag flux / **AR**$_{\mathbf{surface}}$

July-Nov. 1996: *The only sizable and long-lived AR on the solar disk @ 5 solar rotations*

It produced 3 slow CMEs + 3 major flares

van Driel-Gesztelyi, Démoulin, Mandrini, Harra, Klimchuk, **ApJ.586 (2003) 579**

Zioutas, Dennerl, Grande, Hoffmann, Huovelin, Lakic, Orlando, Ortiz, Papaevangelou, Semertzidis, Tzamarias, Vilhu,**TAUP2005**, J. Phys. Conf. Ser. 39 (**2006**) 103

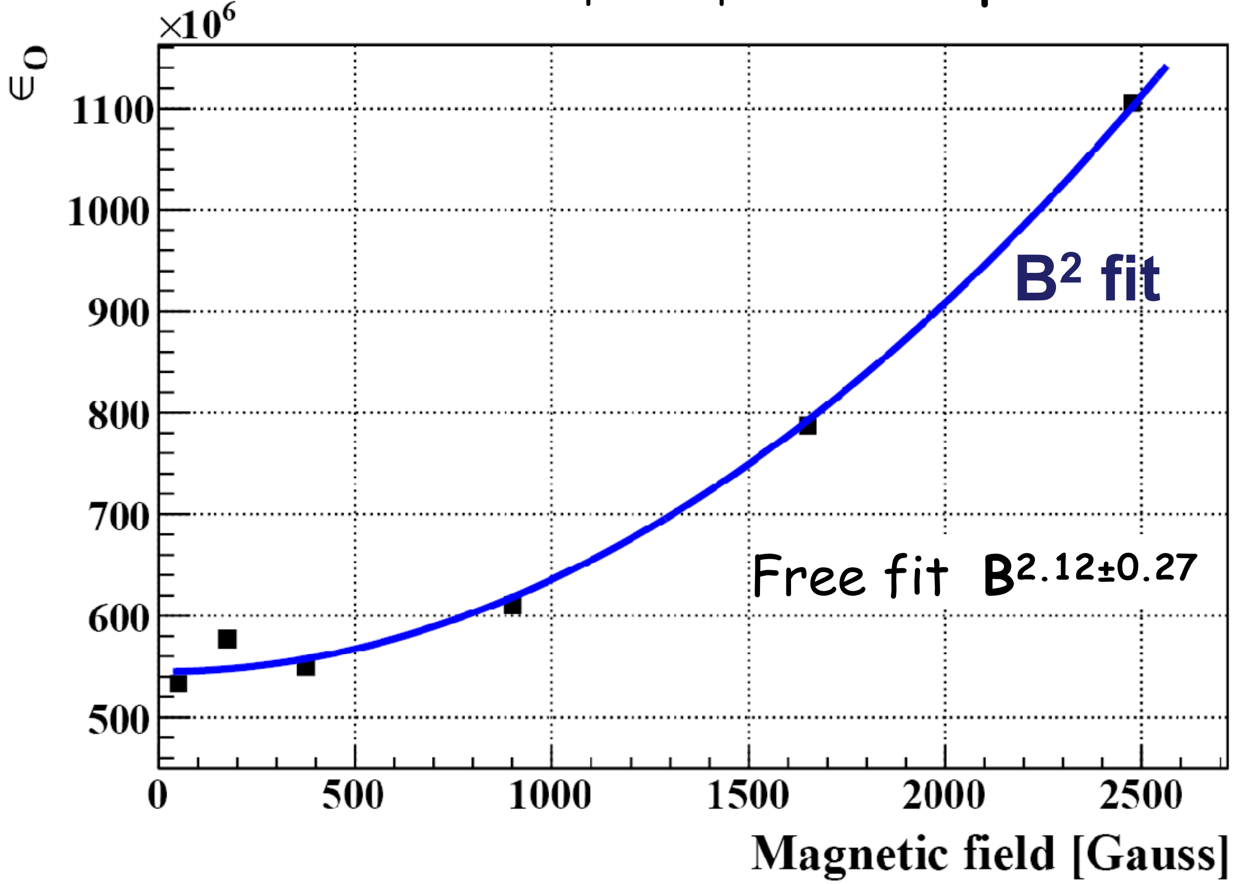
Oxygen Abundance

Oxygen abundance is enhanced in the region of a pore by factor up to 3

In an axion scenario:

- X-rays are produced by axion convertions in the magnetic field.
- The emerging photons create an outwards pointing radiation pressure
- Heavier elements (i.e. O) are affected more

Solar oxygen abundance vs magnetic field at the base of the photosphere near a **pore**.



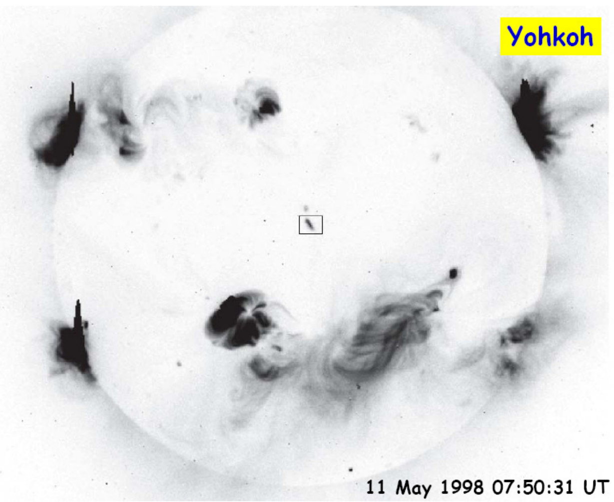
Private communication, H. Socas-Navarro.

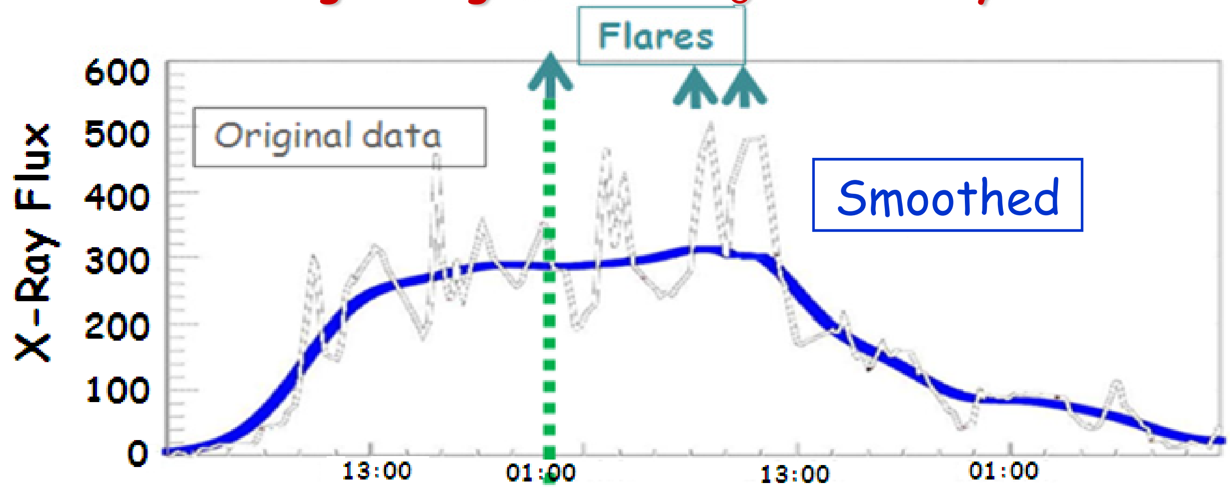
Zioutas, Tsagri, Semertzidis, Papaevangelou, Nordt, Anastassopoulos, astro-ph/0701627

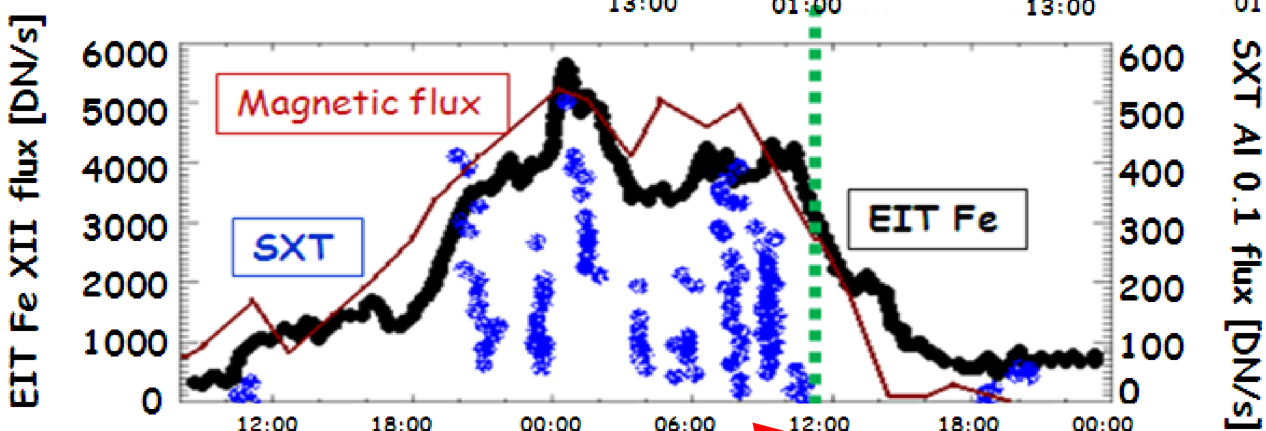
Small active region crossing solar disk center

the time evolution of X-ray emission from sunspots as they cross the disk centre of the Sun

→ a brightening @ ±10% $R_\odot$" → ~3 days!





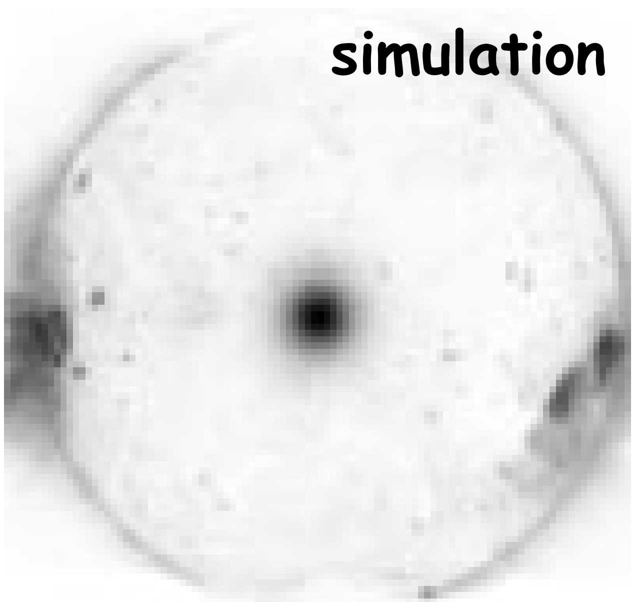


Crossing solar disk centre

A) CH Mandrini *et al.*, A&A 434 (2005) 725
B) P Preś, KJH Phillips, ApJL. 510 (1999) L73
Zioutas, Tsagri, Semertzidis,T.P.,Nordt, Anastasopoulos , astro-ph/0701627

Search for solar X-rays from axions

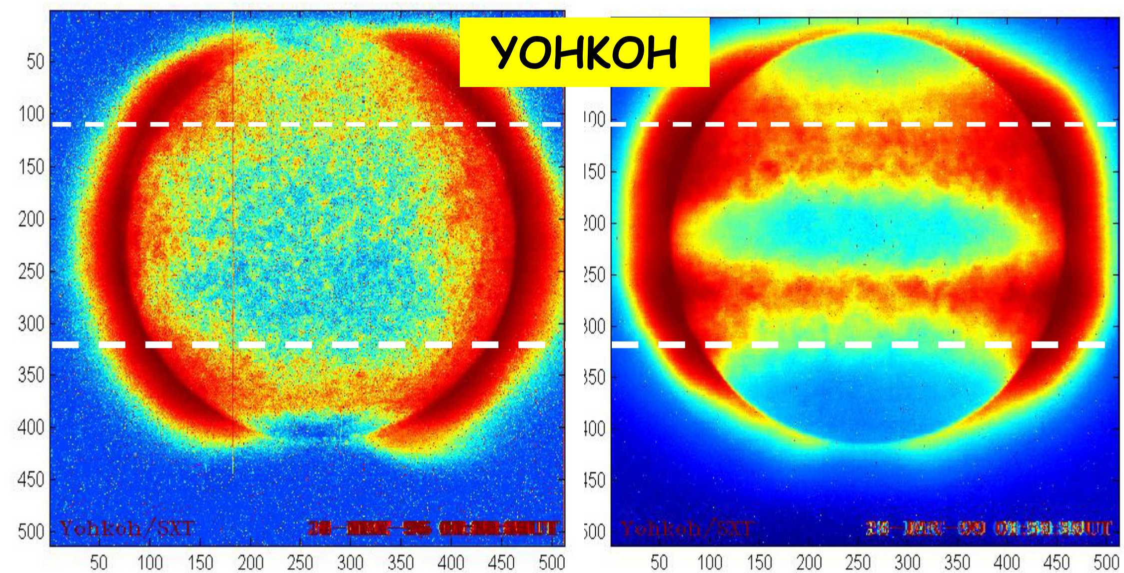
RHESSI science nugget
H. Hudson, 30.4.**2007**



Soft X-rays from **Hinode/Yohkoh** showing an axion signal. The axions, for a uniform coronal magnetic field, would give an **image of the solar core**.

However…
Overlaid soft X-ray images from 49 quite sun days, as well as from active sun, shows a different result…

Solar Minimum **Solar Maximum**



Solar Flares

The precise causes of solar flares & Coronal Mass Ejections (CMEs) remains one of the great solar *mysteries*

What ignites solar flares?

How do they unleash so much energy so quickly?

- storage and release of the energy that powers solar flares is generally *believed* to be in the coronal *magnetic field* …
- *magnetic reconnection* necessary for solar flares to occur.

Observations suggest:

magnetic energy = main energy source for solar active phenomena.

open question:

how magnetic energy is rapidly released in the solar corona so as to create solar explosions such catastrophic events as flares & CMEs.

Solar Flares: the axion scenario

The magnetic field is no more the energy reservoir for solar flare activity but the catalyst for axion to photon conversions transferring energy from the solar core!

- this scenario has been overlooked in the past because of energy and angular distribution of the flare associated x-rays…

However:

- under proper conditions (magnetic field, gas density…) a to γ conversions can start taking place near solar surface, irradiating overlaying layers to plasma
- the associated radiation pressure could be behind the CMEs and energetic X-ray emission at the early phase
- the created photo-electrons may solve the "number problem" in flare models
- their bremsstrahlung could explain the low energy X-ray spectrum

The flare region is heated up to 10-30 MK $\equiv$ core temperature!!!

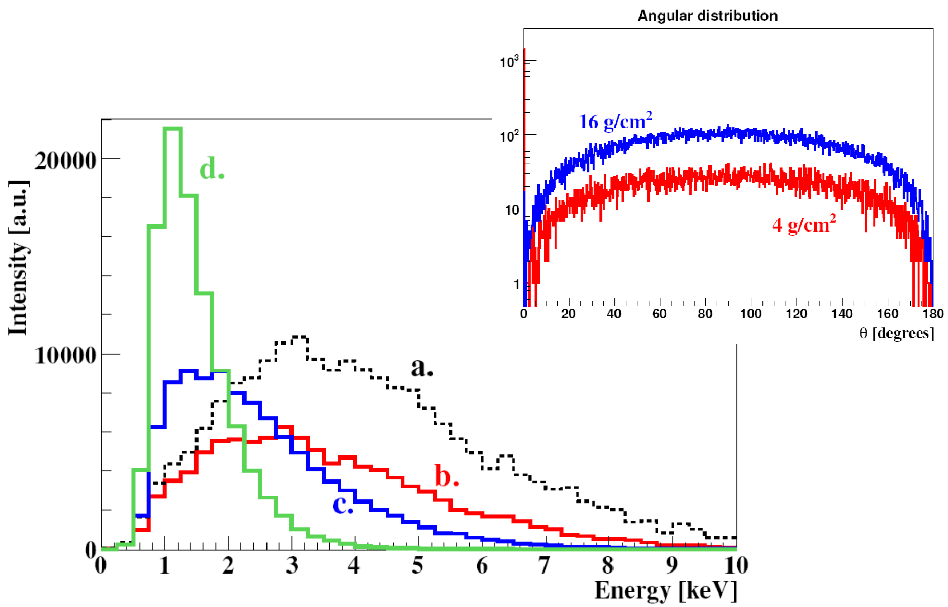
Such hot region remains a **fully ionized plasma** during flare activity

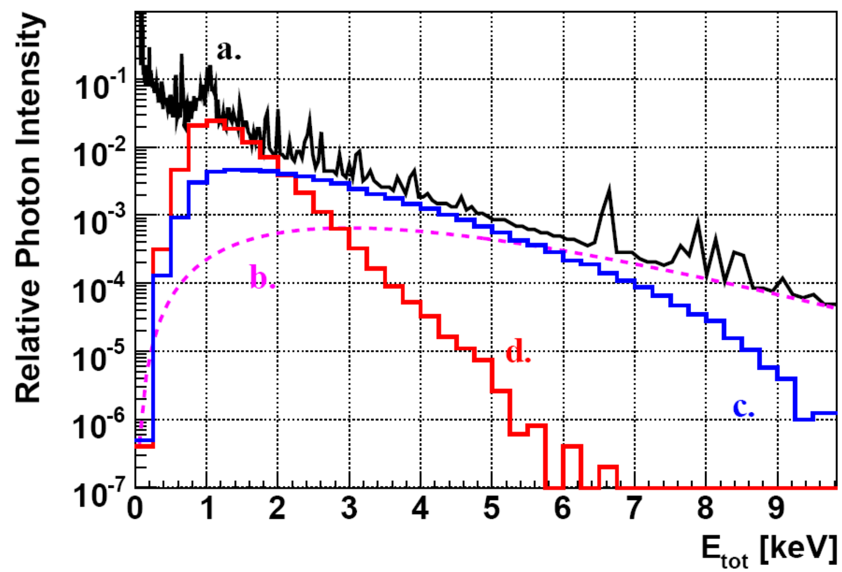
Zioutas, Tsagri, Semertzidis, Papaevangelou, astro-ph /0808.1545, submitted to PRL

Solar Flares: the axion scenario

In the plasma photon Compton scattering and photon Bremsstrahlung are the dominant effects

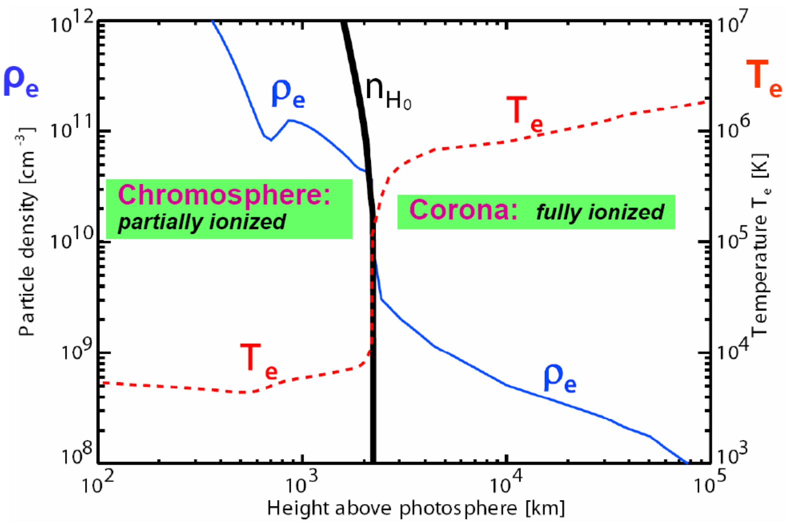
- Compton scattering is isotropic → the solar core do not appear any more as a preferred x-ray source
- The initial axion energy spectrum is shifted to lower energies

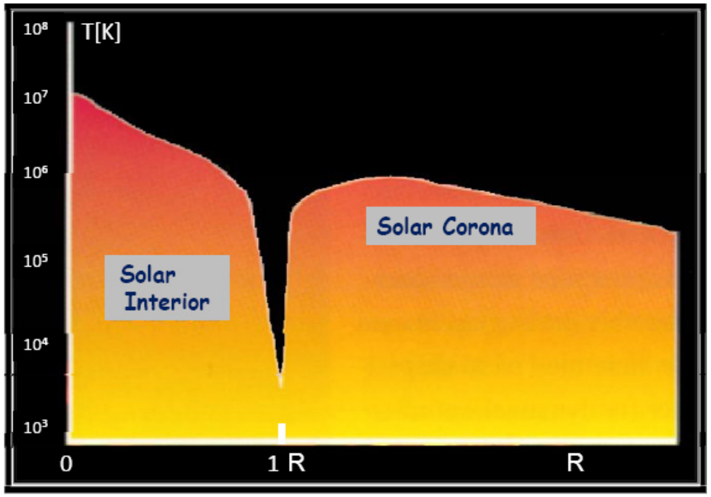




First simulations on the working principle

Solar Corona problem





One of the longest standing astrophysical problems (1939)

In conflict with 2nd law of thermodynamics !

Axions:

- Internal heating component (flares)
- External component: decaying gravitationally trapped KK axions!

DiLella, Zioutas Astrop. Phys 13(2003)145

CONCLUSIONS

There are some remaining open questions related to axions

1. Strong CP problem

2. Dark matter

3. Several Solar/Astrophysical observations (solar corona heating, unexplained X-Ray solar emissions…)

CAST has established the most stringent experimental limit on axion coupling constant over a wide range of masses, exceeding for the first time astrophysical constraints

CAST ^{3}He Phase (started 03/2008) is now probing the model region, aiming to cover axion masses up to 1.15 eV (…**and hopping for a discovery!!!**)

The number of solar "mysteries" that could be "easily" explained be an axion (~ALP) scenario is growing, motivating further efforts!!!