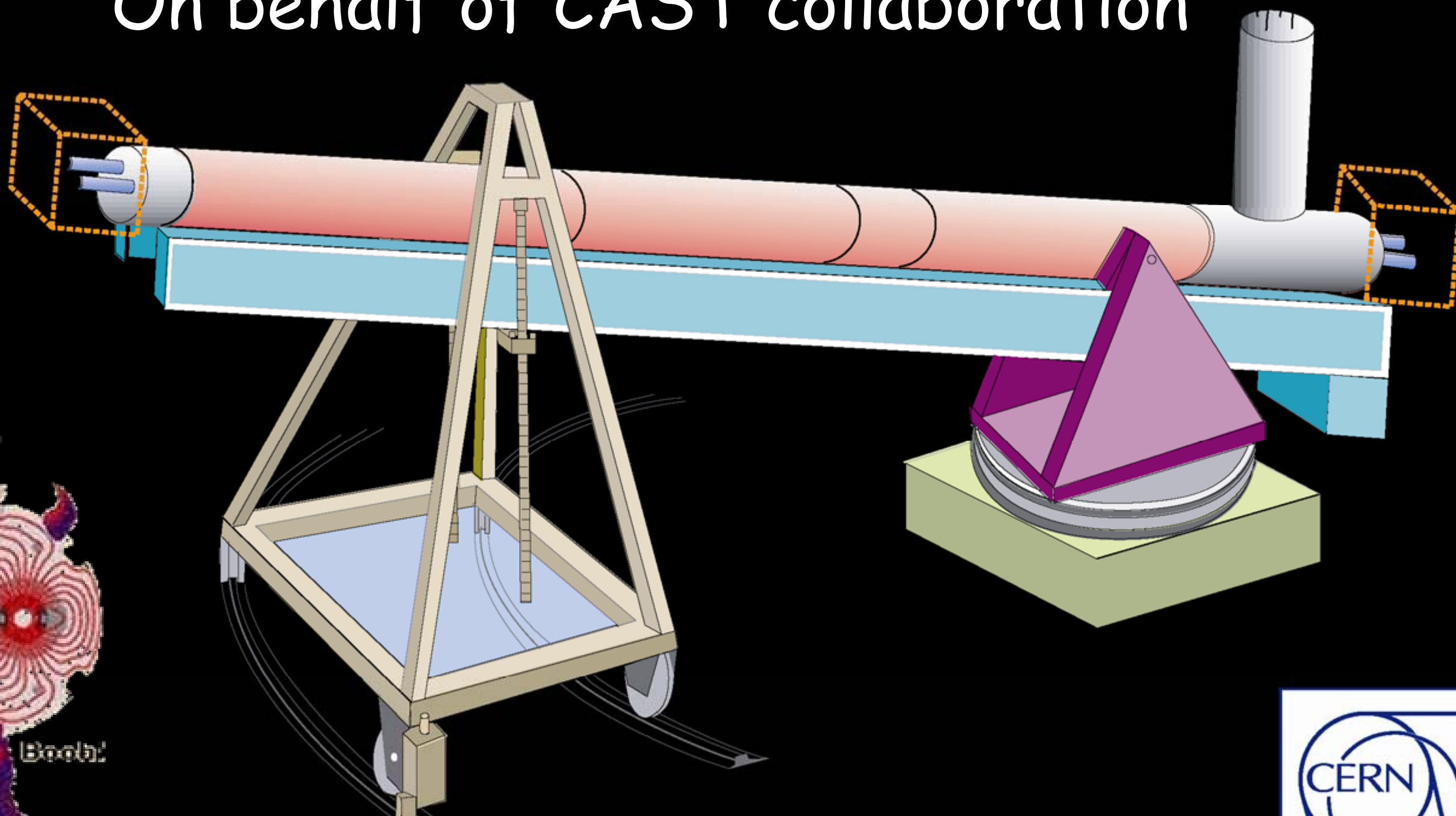
Solar axion search with the CAST experiment

Silvia Borghi –CERN
On behalf of CAST collaboration



Axion theory

QCD predicts that CP (and T) symmetry is broken in strong interaction

CP Violating Parameter in QCD Lagrangian:

$$\mathcal{L}_{CP} = \theta \frac{\alpha_s}{8\pi} G\tilde{G} \qquad 0 \le \theta \le 2\pi$$

Neutron electric dipole momentum

$$d_n \approx \theta \frac{e}{m_n} \frac{m^*}{\Lambda_{QCD}}$$

Λ_{QCD} QCD energy scale ≈ 1 GeV

$m^* = \frac{m_u m_d}{(m_u + m_d)}$ reduced mass of up and down quark

Prediction by Theory *M. Pospelow and A. Ritz Phys. 318 119 (2005)*

$$d_n \propto \theta \cdot 3.6 \cdot 10^{-16}\, e\,\mathrm{cm}$$

Experimental limit *C. A. Baker et al. 2006 (hex-exp/060220)*

$$d_n < 3.0 \cdot 10^{-26}\, e\,\mathrm{cm}\ (90\%\ \mathrm{CL})$$

Difference of a factor of $\theta = 10^{-10}$ between theory and experiment!

Strong CP problem: why is CP not badly broken in QCD?

Axion theory

Strong CP problem: why is CP not badly broken in QCD?

➲ **One solution was proposed by Peccei Quinn in 1977:**
the extension of the Standard Model with a new global chiral U(1) symmetry spontaneously broken at scale f_a

$$\mathcal{L}_a = \frac{\alpha_s}{8\pi \; f_a} \, a \, G\widetilde{G} \qquad\qquad f_a \propto \frac{1}{g_{a\gamma\gamma}}$$

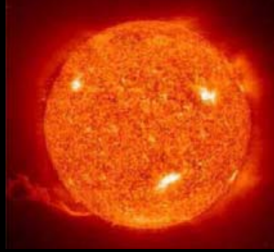
As a result, new pseudoscalar, neutral and very light particle is predicted, the axion

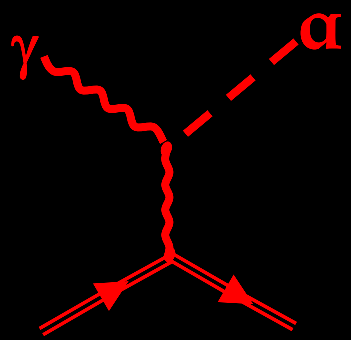
Some Basic Properties

- Pseudoscalar particle similar to π^0
- Light neutral Goldstone boson that couples to two photons
- Very weak interaction probability with matter
- Viable dark matter candidate for

$$m_a \approx 6\, eV \frac{10^6 \, GeV}{f_a}$$

Solar Axions





Stellar plasmas may be a powerful source of axions

Solar axions produced by photon-to-axion conversion of the solar plasma photons: the Primakoff Effect [1951]

Solar axion flux

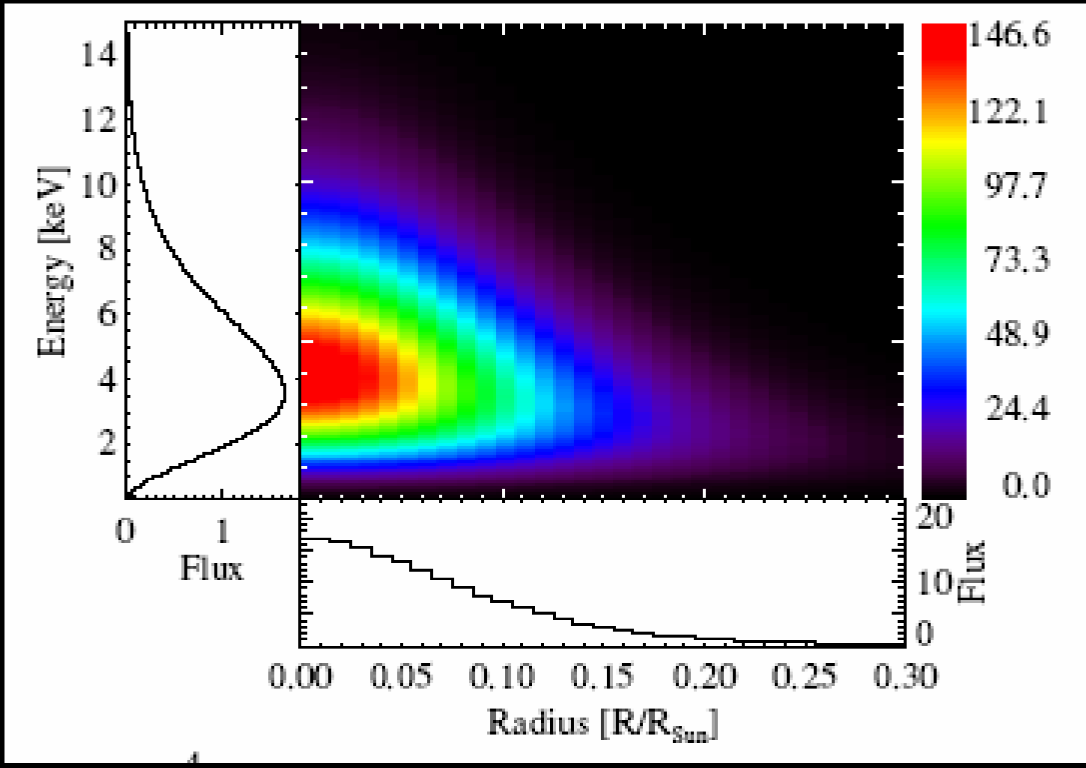
$$\frac{d\Phi}{dE_a} = \left(\frac{g_{a\gamma\gamma}}{10^{-10}\,GeV^{-1}} \right)^2 \frac{\Phi_0}{E_0} \frac{(E_a/E_0)^{2.481}}{e^{E_a/(1.205 E_0)}}$$

$$\Phi_0 = 6.020 \cdot 10^{10}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Mean energy = 4.2 keV

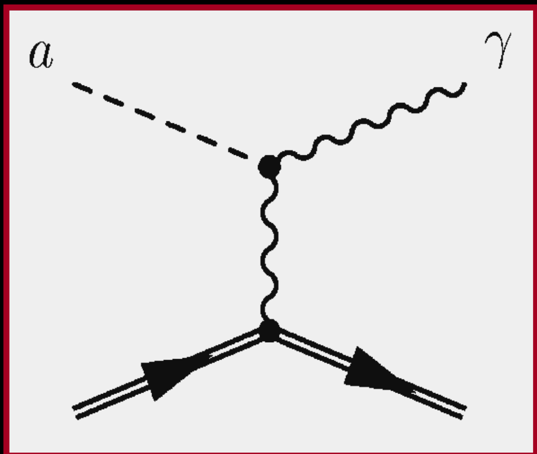
Axion Luminosity =1.9 x 10^{-3} $L_\odot$

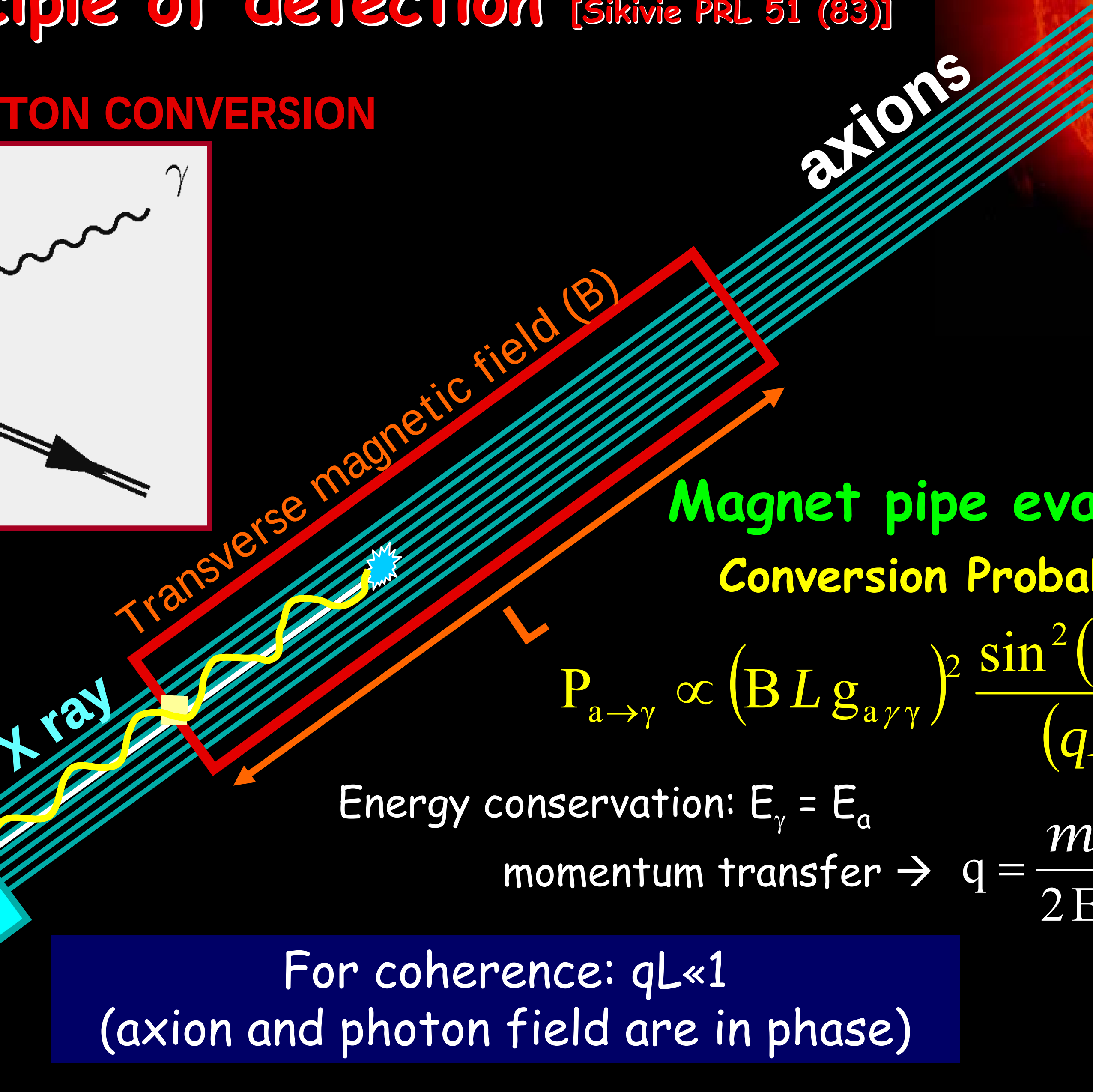
Axion flux = 3.8x10^{11} cm^{-2} s^{-1}



Principle of detection [Sikivie PRL 51 (83)]

AXION PHOTON CONVERSION





Magnet pipe evacuated

Conversion Probability

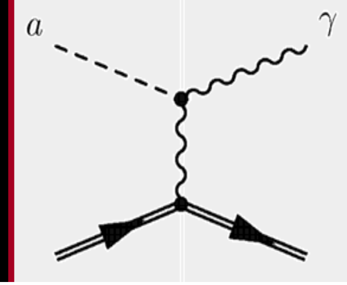
$$P_{a\to\gamma} \propto \left(B\,L\,g_{a\gamma\gamma}\right)^2 \frac{\sin^2(qL/2)}{(qL)^2}$$

Energy conservation: $E_\gamma = E_a$

momentum transfer → $q = \dfrac{m_a^2}{2E_\gamma}$

For coherence: qL«1
(axion and photon field are in phase)

Principle of detection



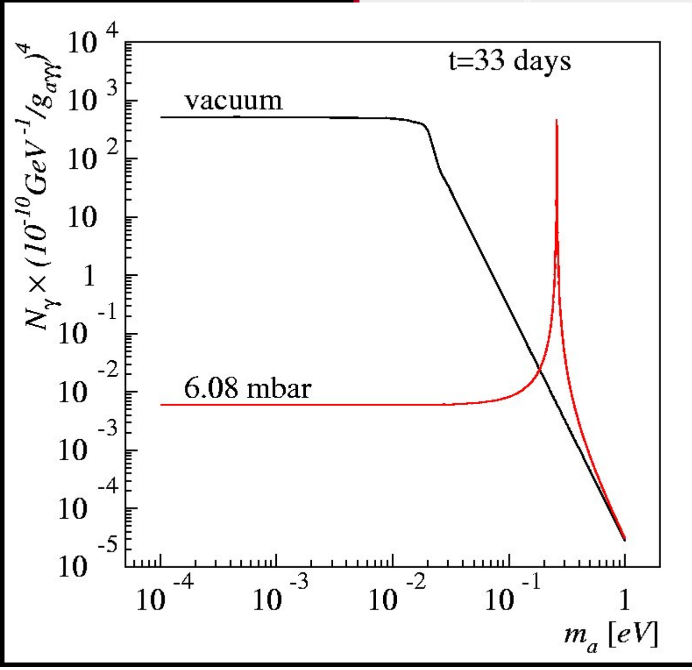
Magnet pipes filled with buffer gas

Conversion Probability

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

$$q=\left|\frac{m_\gamma^2-m_a^2}{2E_a}\right| ; \quad m_\gamma \approx \sqrt{\frac{4\pi\alpha N_e}{m_e}}=\sqrt{\frac{Z}{A}\rho}$$

Γ: absorption coef.
N_e: number of e⁻/cm³
ρ: gas density (g/cm³)

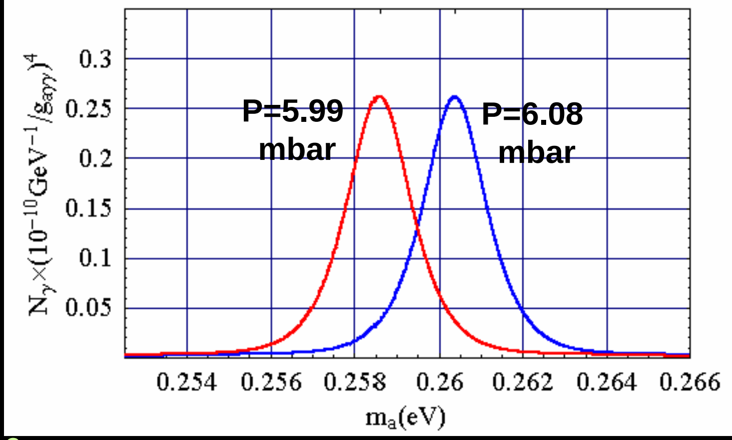


Coherence condition:

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

⇒Every specific pressure of the gas allows the test of a specific axion mass.

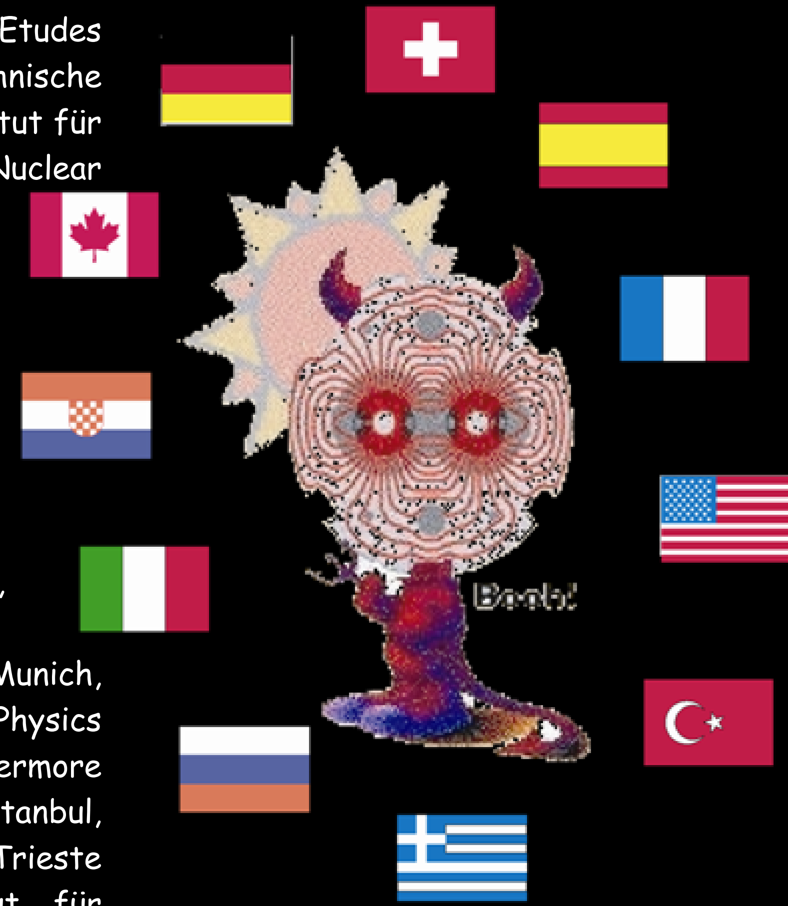
$$m_\gamma \approx \sqrt{0.02\frac{P(mbar)}{T(K)}}$$



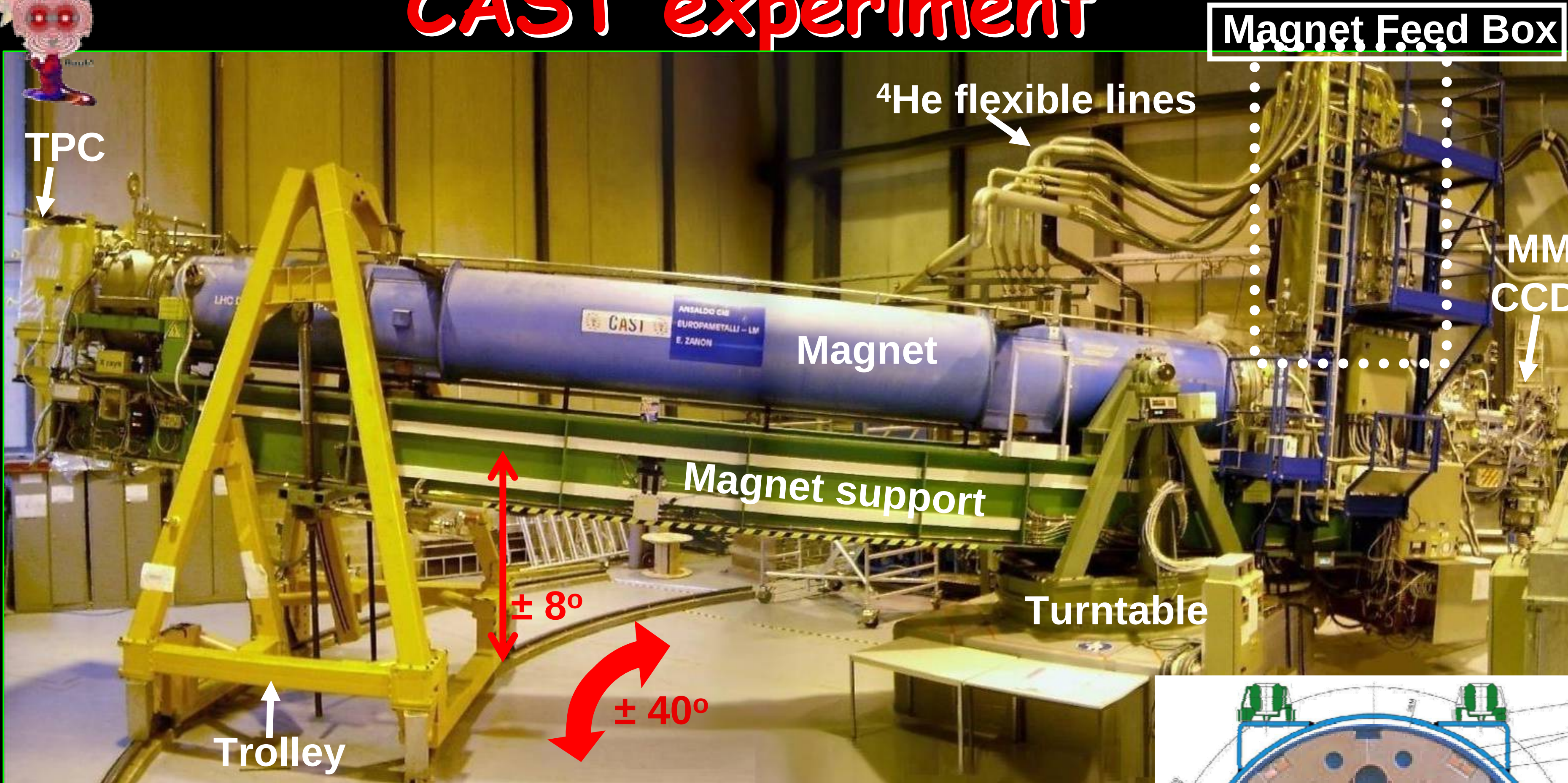
The CAST Collaboration

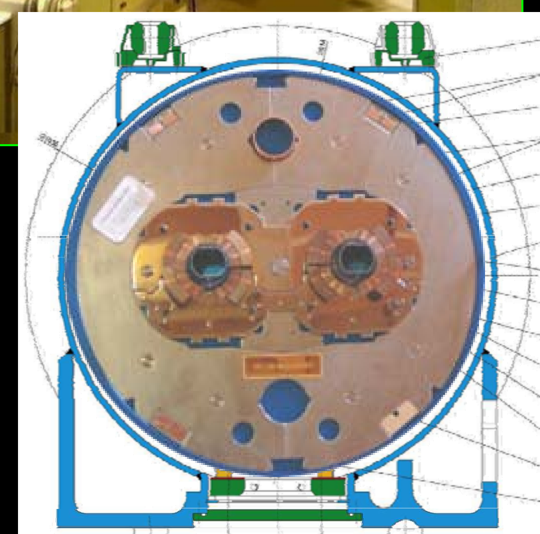
21 Institutes, ~80 scientists

European Organization for Nuclear Research (CERN), Genève, Switzerland – Universität Zurich, Zurich, Switzerland - DAPNIA, Centre d´Etudes Nucléaires de Saclay (CEA-Saclay), Gif-sur-Yvette, France - Technische Universität Darmstadt, IKP, Darmstadt, Germany - Max-Planck-Institut für extraterrestrische Physik, Garching, Germany - Instituto de Física Nuclear y Altas Energías, Universidad de Zaragoza, Zaragoza, Spain – Enrico Fermi Institute and KICP, University of Chicago, Chicago, IL, USA - Aristotle University of Thessaloniki, Thessaloniki, Greece – National Center for Scientific Research "Demokritos", Athens, Greece - Albert-Ludwigs-Universität Freiburg, Freiburg, Germany - Institute for Nuclear Research (INR), Russian Academy of Sciences, Moscow, Russia - Department of Physics and Astronomy, University of British Columbia, Department of Physics, Vancouver, Canada - Johann Wolfgang Goethe-Universität, Institut für Angewandte Physik, Frankfurt am Main, Germany – Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Munich, Germany - Rudjer Boskovíc Institute, Zagreb, Croatia - Physics Department, University of Patras, Patras, Greece- Lawrence Livermore National Laboratory, Livermore, CA, USA- Dogus University, Istanbul, Turkey - Instituto Nazionale di Fisica Nucleare (INFN), Sezione di Trieste and Universià di Trieste, Trieste, Italy- Max-Planck-Institut für Aeronomie, Katlenburg-Lindau - Germany -National Technical University of Athens, Athens, Greece



CAST experiment





- Decommissioned LHC test magnet (L=10m, B=9 T)
- Moving platform ±8°V ±40°H (potential to follow the sun for equivalent to 50 days / year)
- 4 magnet bores to look for X rays
- 3 X ray detector prototypes being used.
- X ray Focusing System to increase signal/bgrd ratio.

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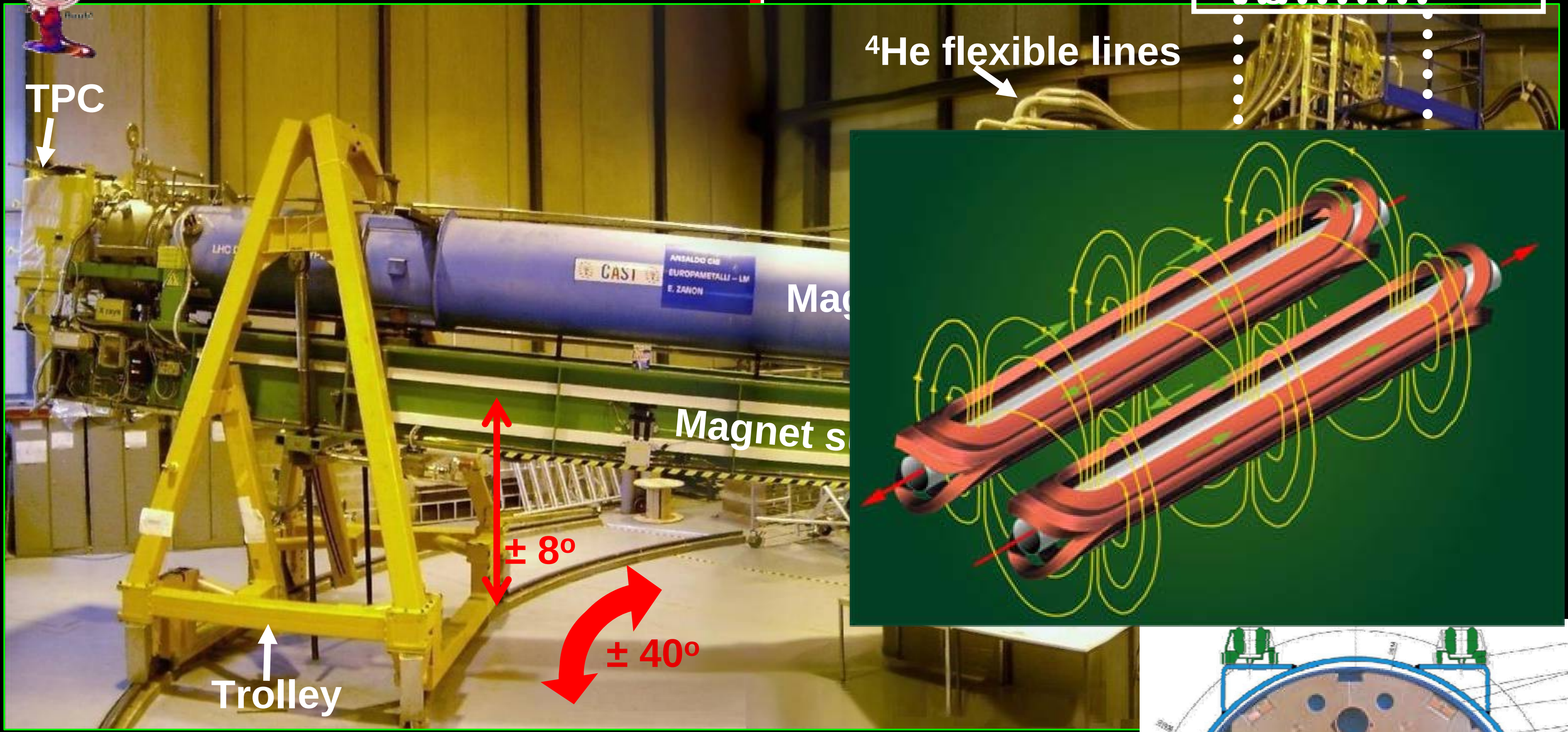

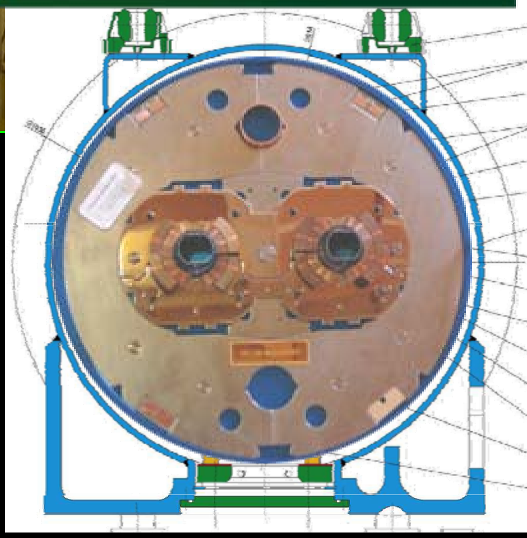

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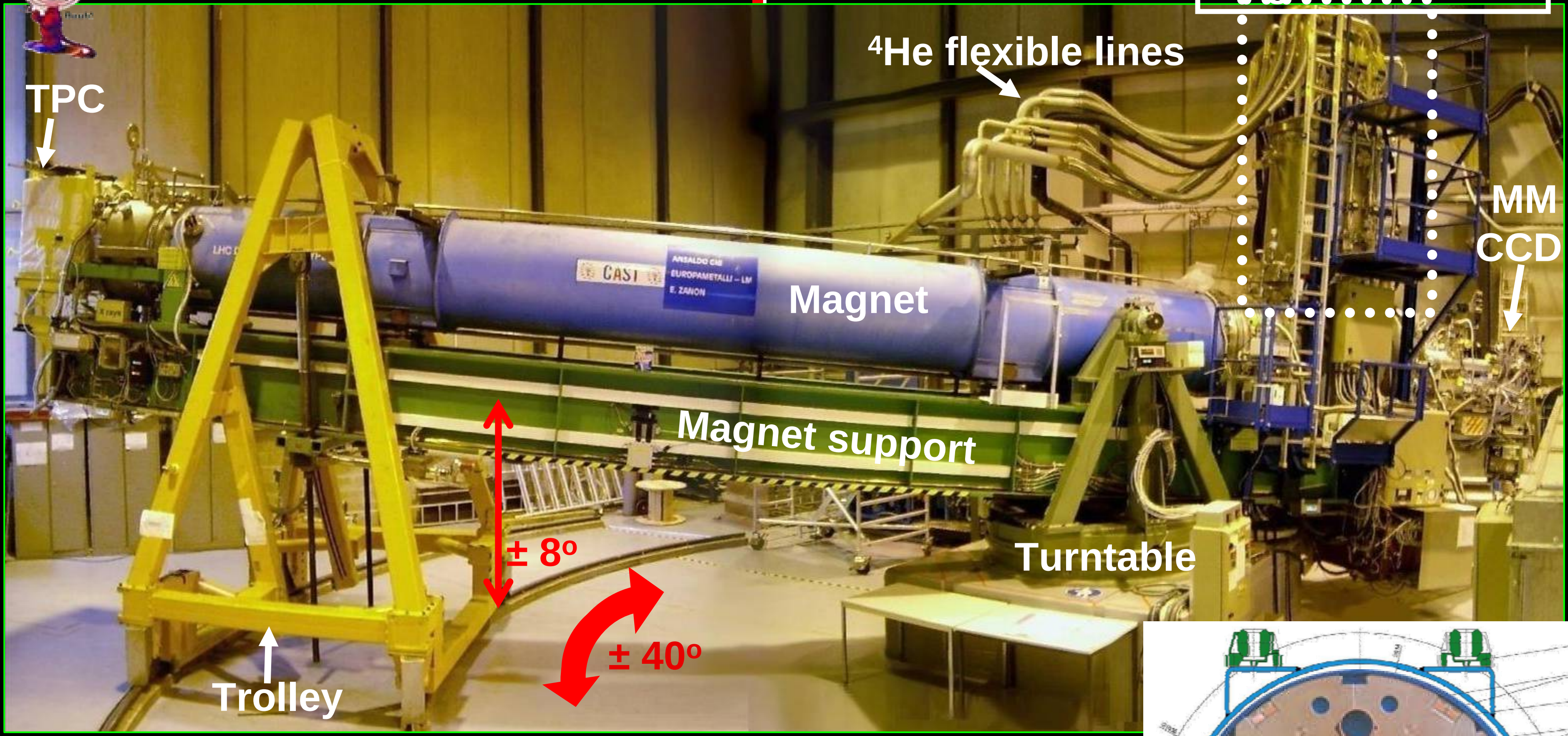

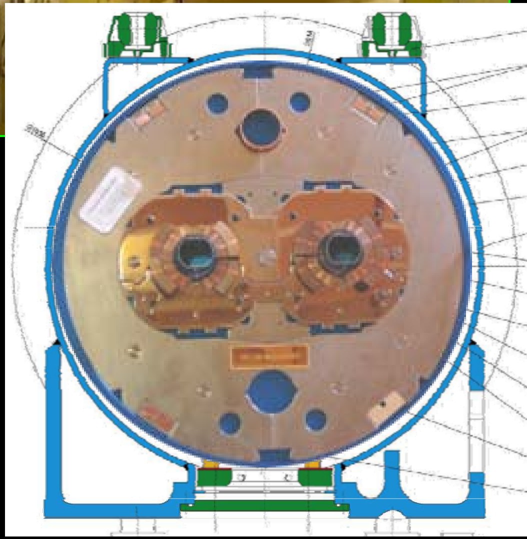

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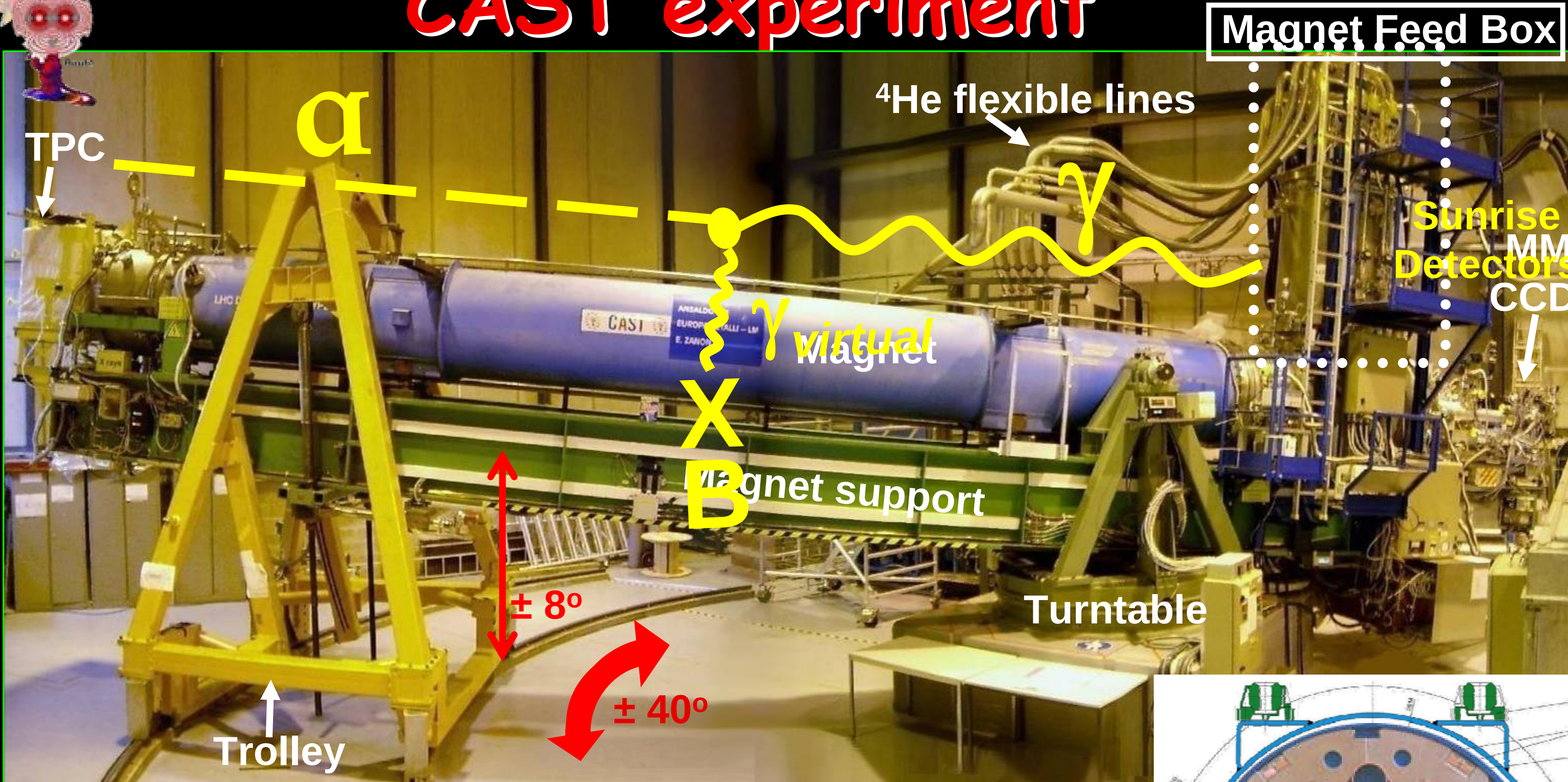

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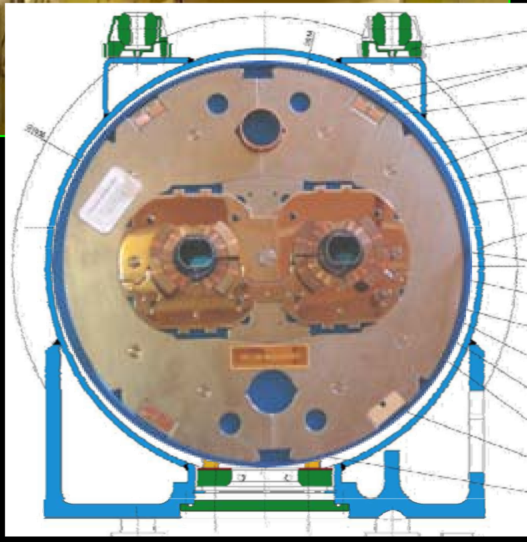

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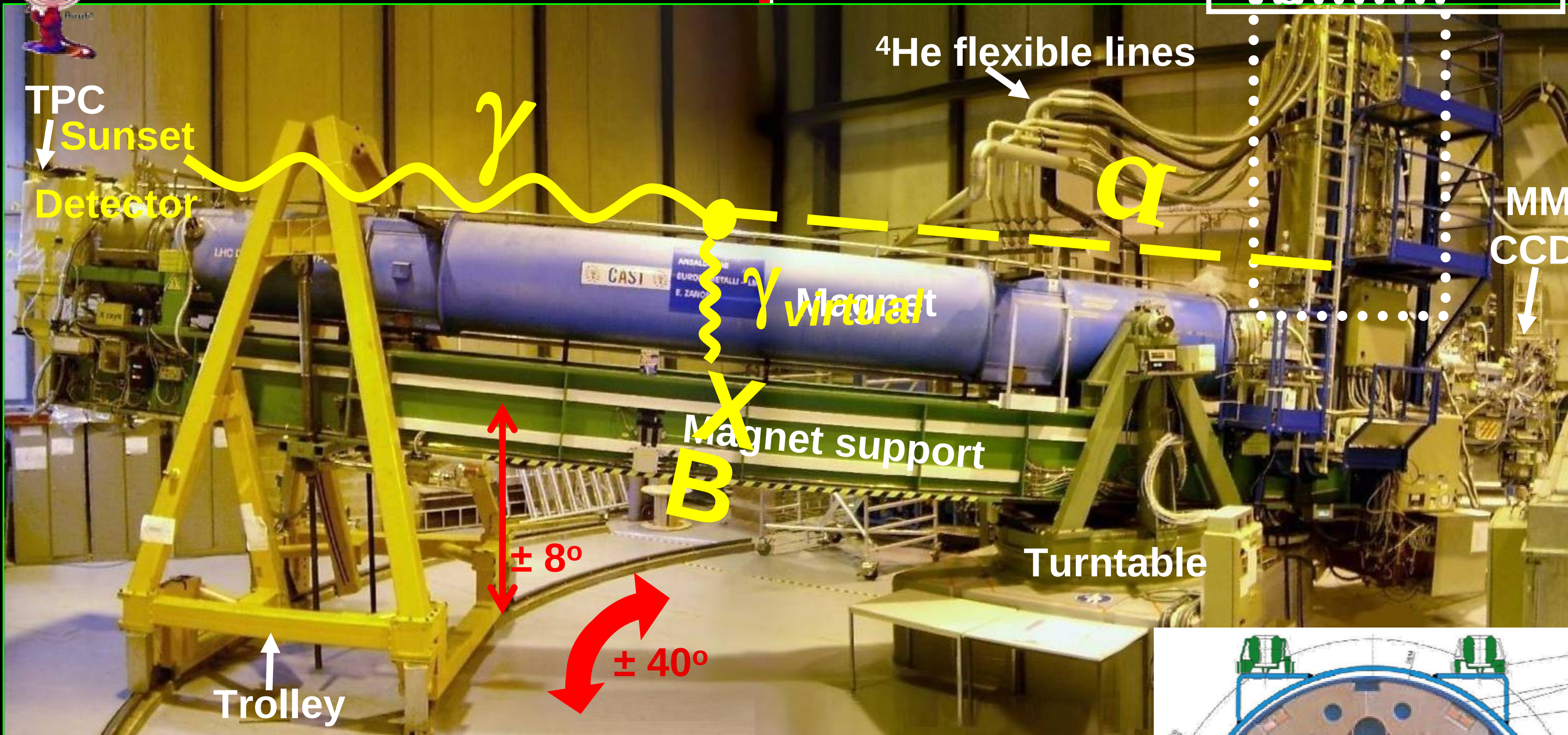

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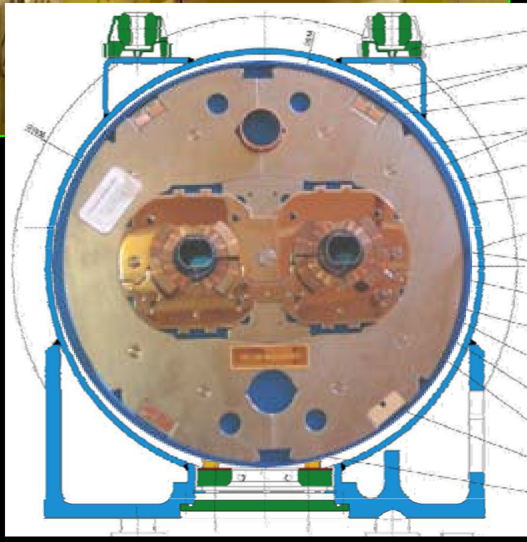
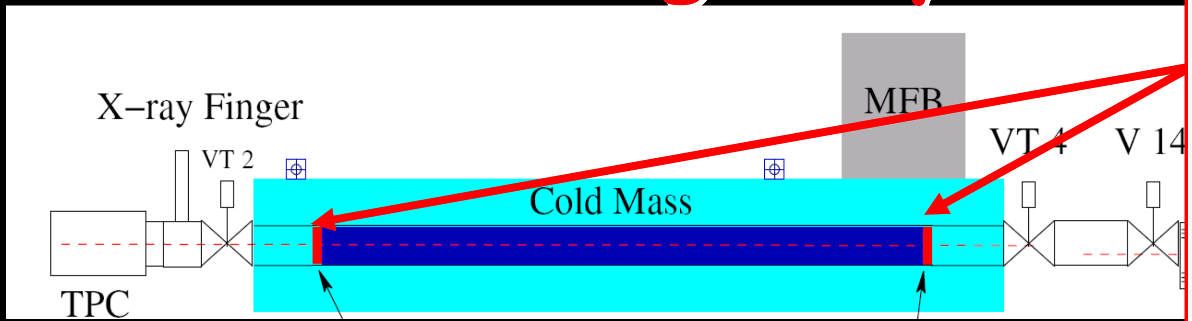
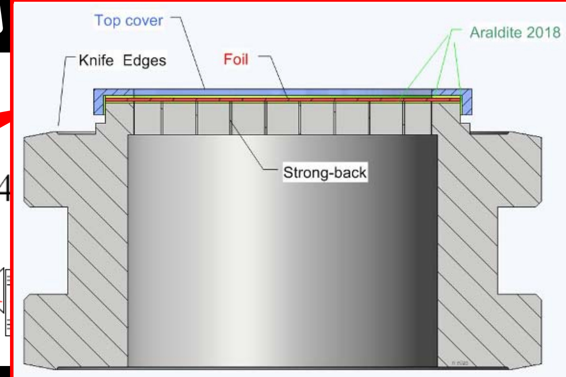



CAST

Phase II ^{4}He gas system



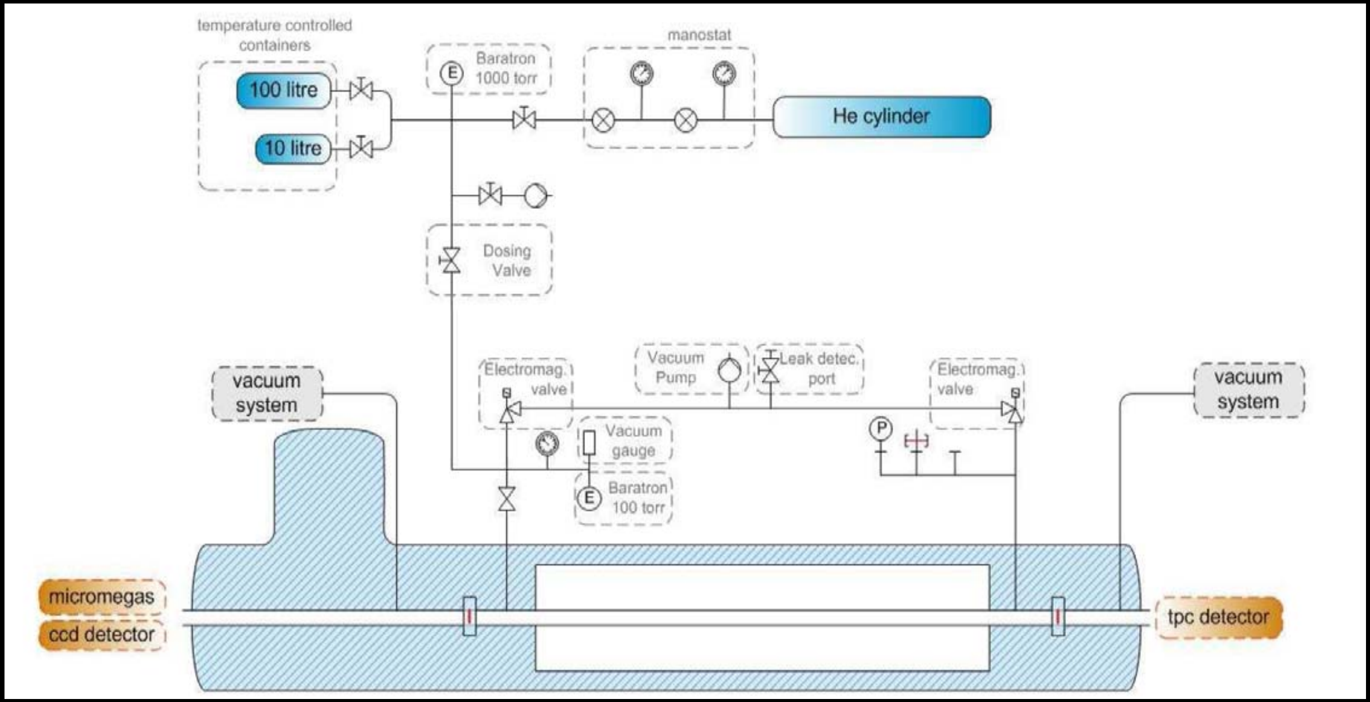


- Thin Cryogenic X-ray windows
  - High transmissivity at 1-7 keV
  - Minimum He leak rate
  - $q^4He < 10^{-8}$ mbar l/s @ 1.8K
  - Transparent in the optical of alignment of the telescope
  - Survive to a magnet transition from super conductive to normal conductive state ("Quench" pressure ≈ 1 bar)
- ^{4}He gas system was well understood:
  - Accuracy in measuring the quantity of gas introduced in the cold bore (100 ppm):
    - Density stability
    - Accurate steps 0.1 mbar
    - Reproducibility 0.01 mbar
  - Spontaneous thermo-acoustic oscillations eliminated
  - Window flanges heated to 120 K to avoid that cryopumped gases accumulate onto the window film

Design

- 15 μm polypropylene
- Strong-back mesh: 5.2mm, |0.3mm, ↓5mm
- Leak tested: < 1x10^{-7} mbar.l.s^{-1}
- Pressure Tested: Holds 3.5 ba
- Transmission tested: ~88%, PP15 >80% (>2keV), 95% @ 4.2keV

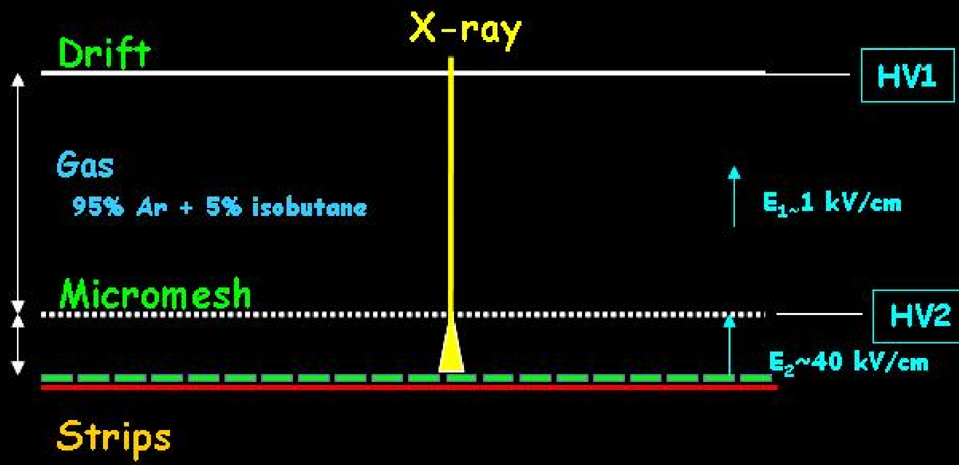
Phase II ^{4}He gas system



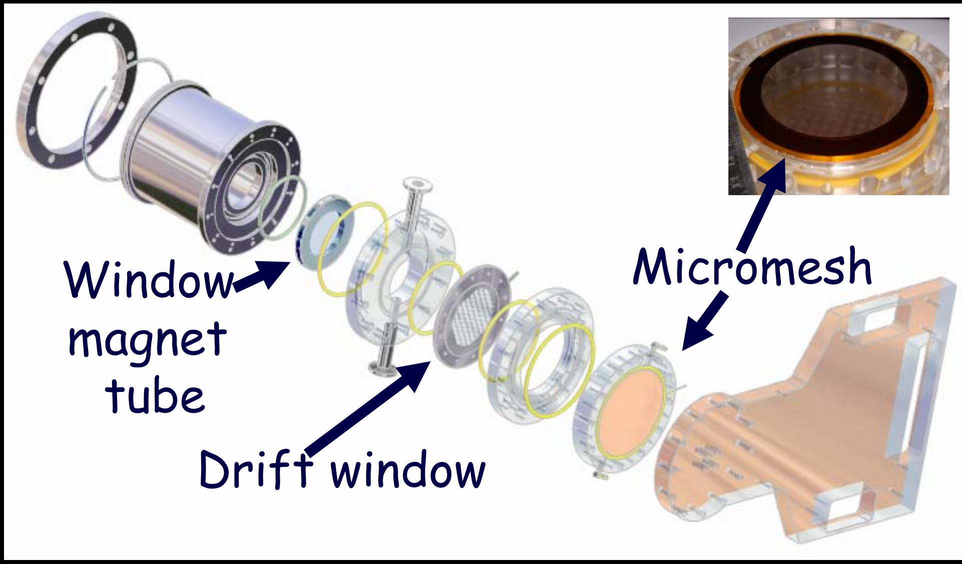
- ^{4}He data taking
  - between November 2005 and December 2006
  - ^{4}He density increased every day by an amount ≈0.083 mbar @1.8 K
  - 160 density steps measured, up to 13.4 mbar @ 1.8 K (m_a=0.39 eV)

Phase II ^4He: Micromegas

- Low background
- Efficient in detecting x-rays with a low threshold: ~0.6keV (95%Ar+5%Isobutane)
- Background rate: ~5×10^{-5} counts $keV^{-1}s^{-1}cm^{-2}$
- Position sensitivity ~100 μm



159 density steps completed (~340 h of tracking and ~3110 h of background data)



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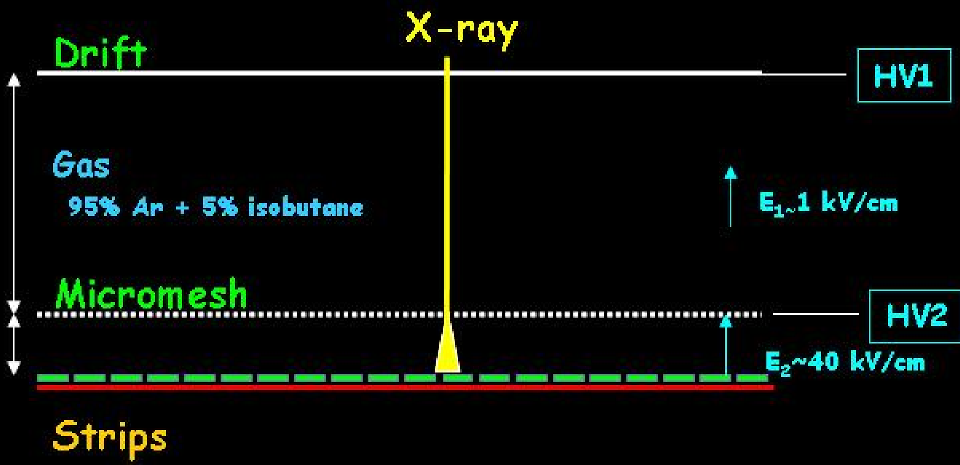

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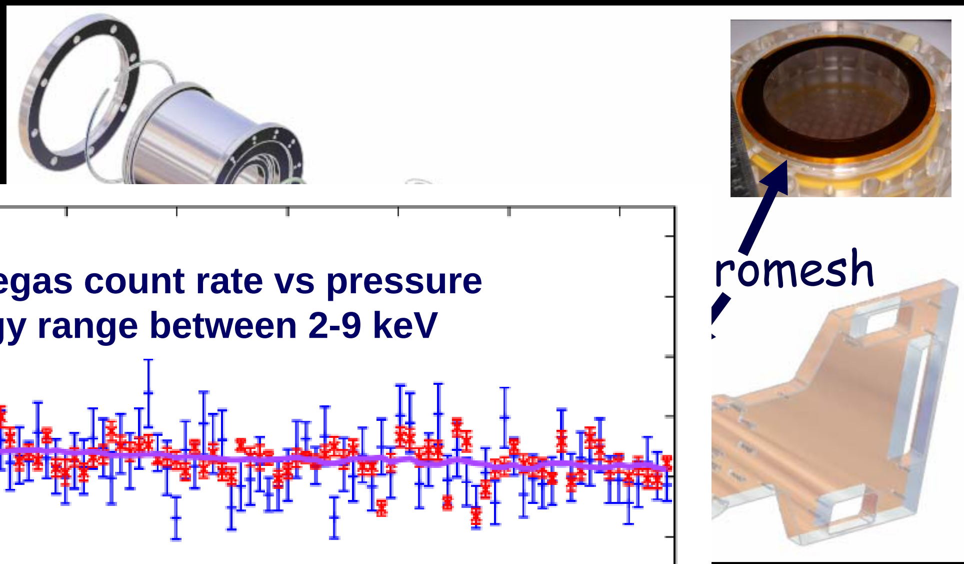
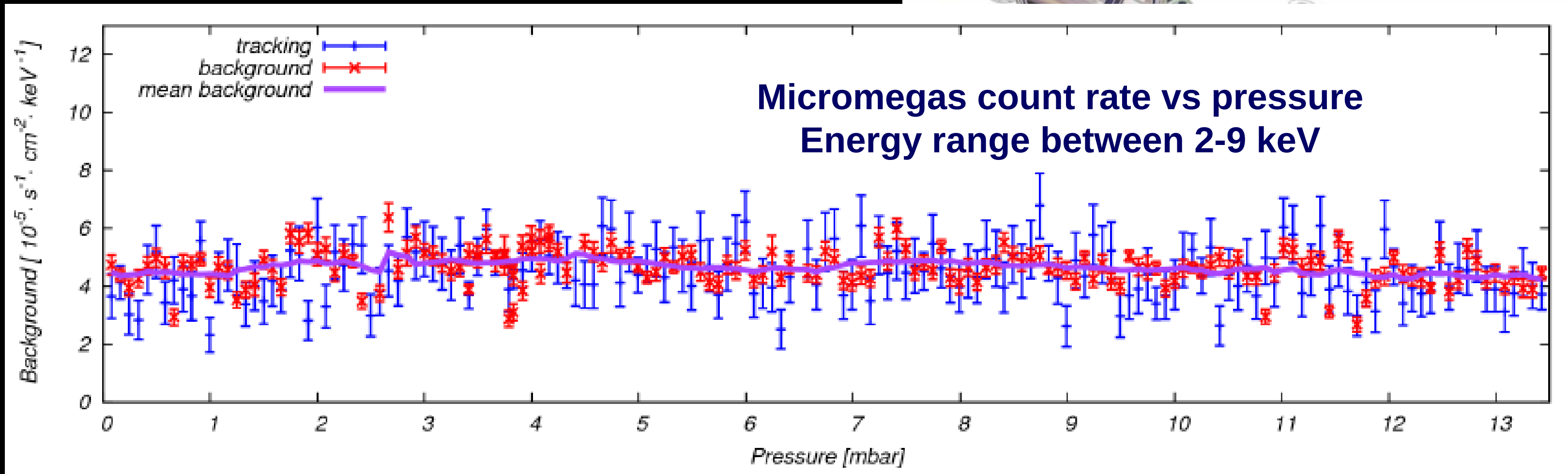
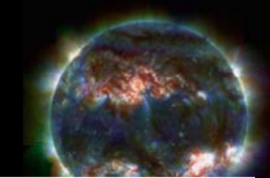
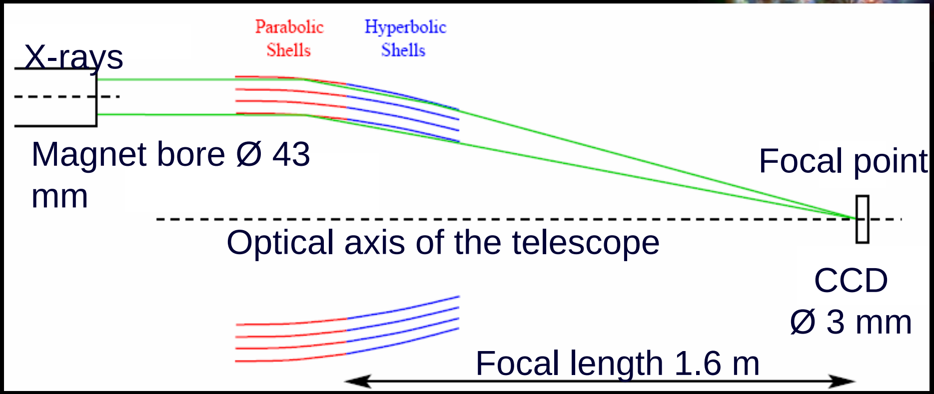




Phase II ^{4}He: CCD



- X-ray telescope is focusing photons from the magnet bore area to a ≈ 9 mm^2 spot on the CCD
- Background rate for full chip:
  $8.66 \pm 0.06 \cdot 10^{-5}$ counts cm^{-2} s^{-1} keV^{-1}
  0.24 ± 0.04 counts per tracking in the signal spot ⇒ 1 event in 4 tracking (in the spot)



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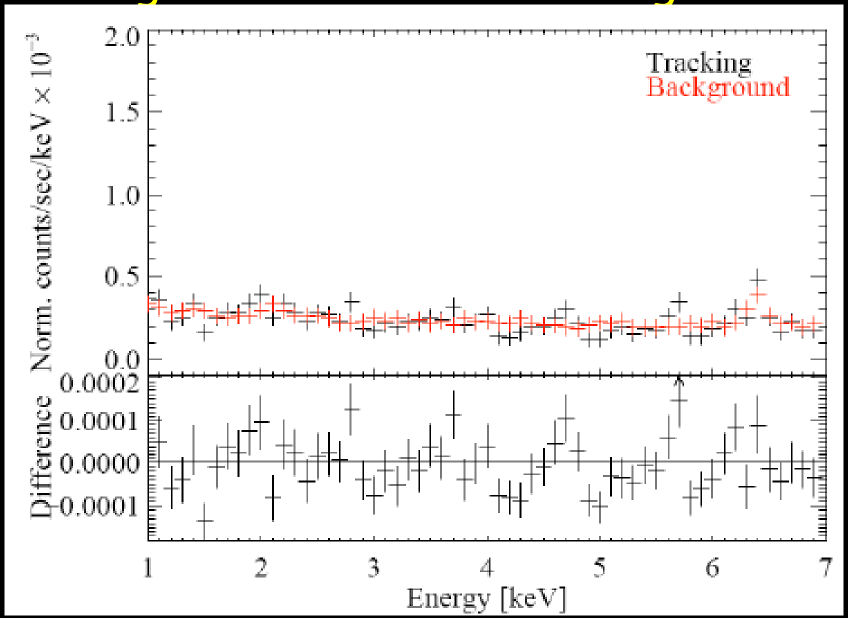

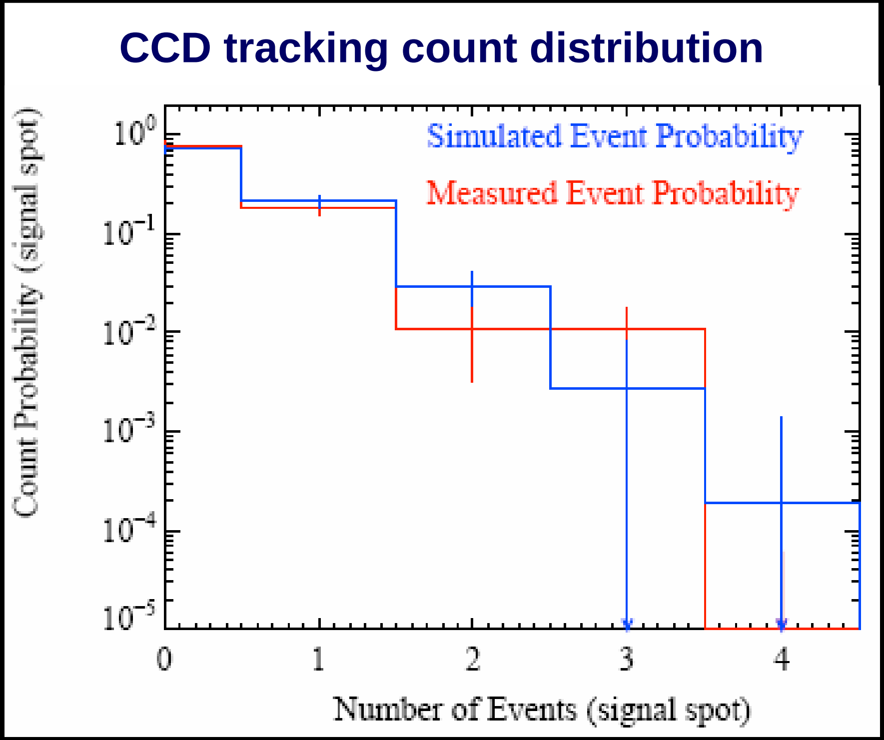

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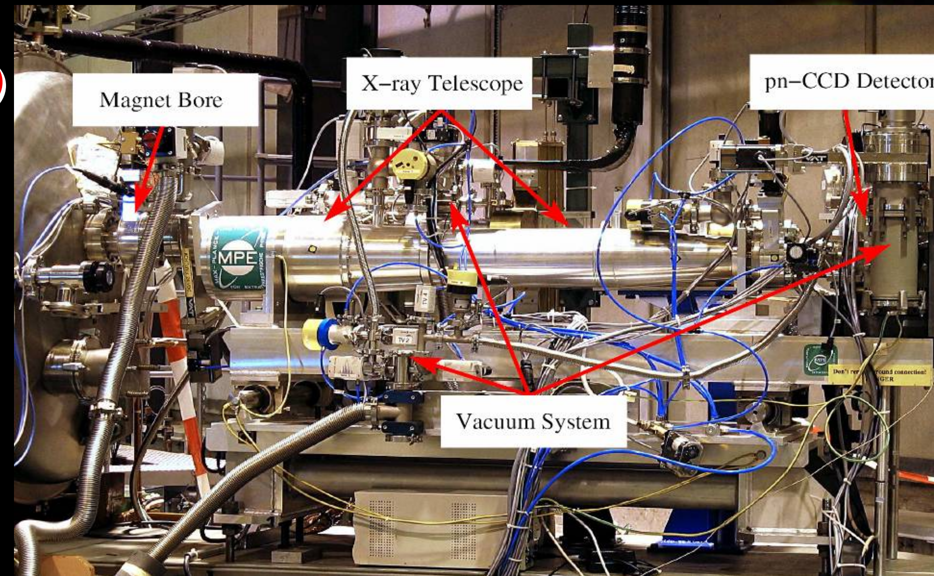

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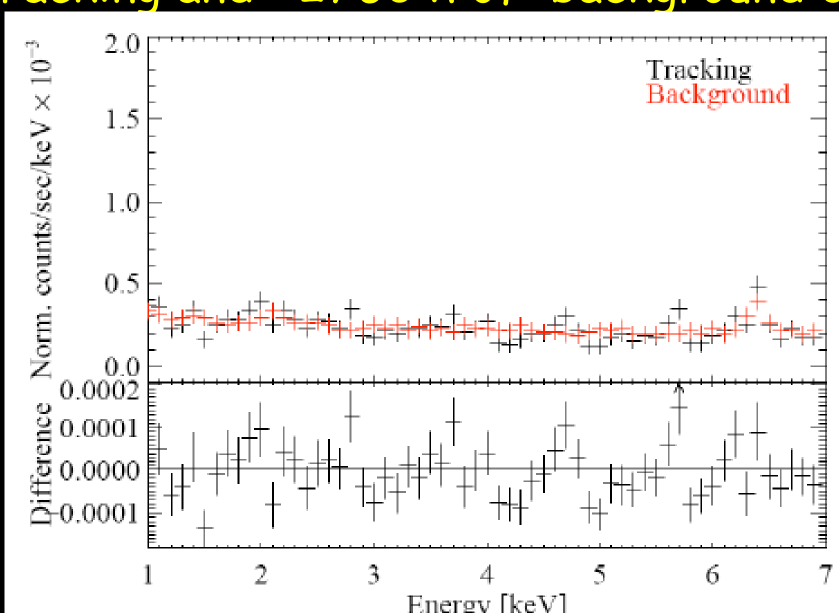
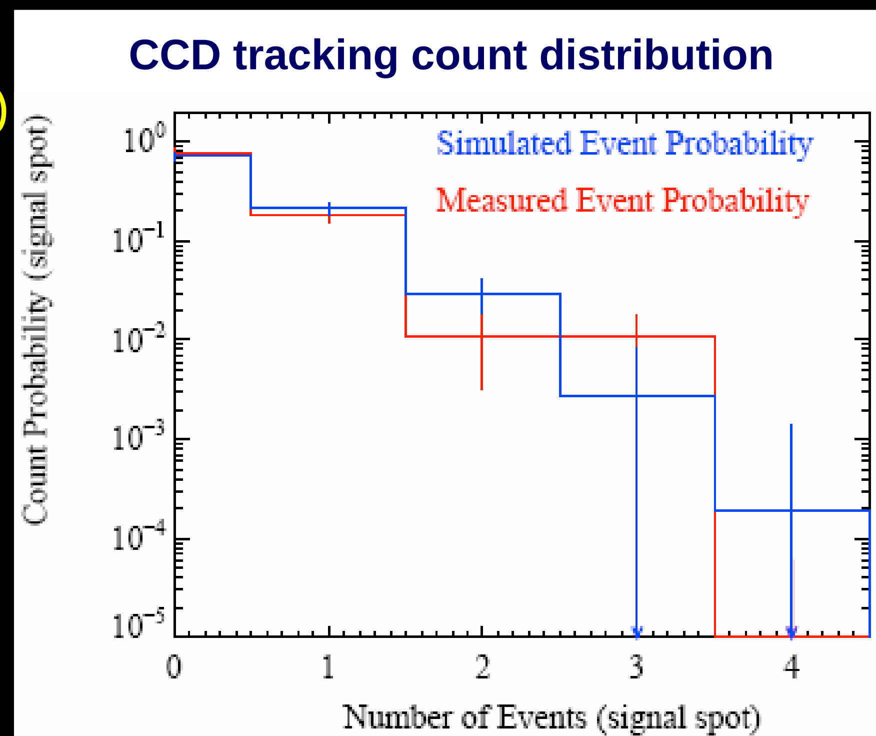
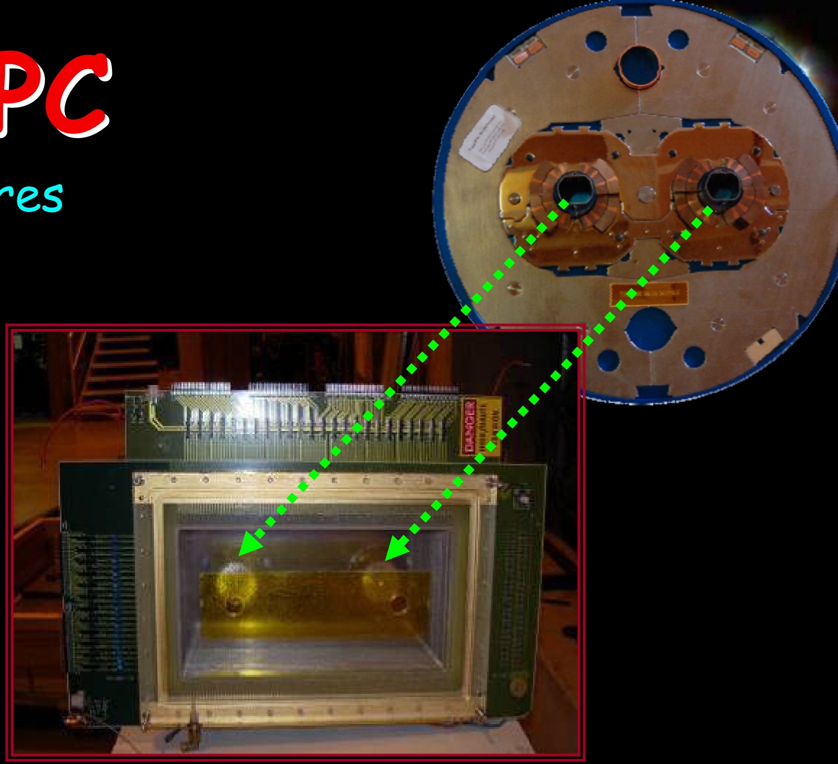




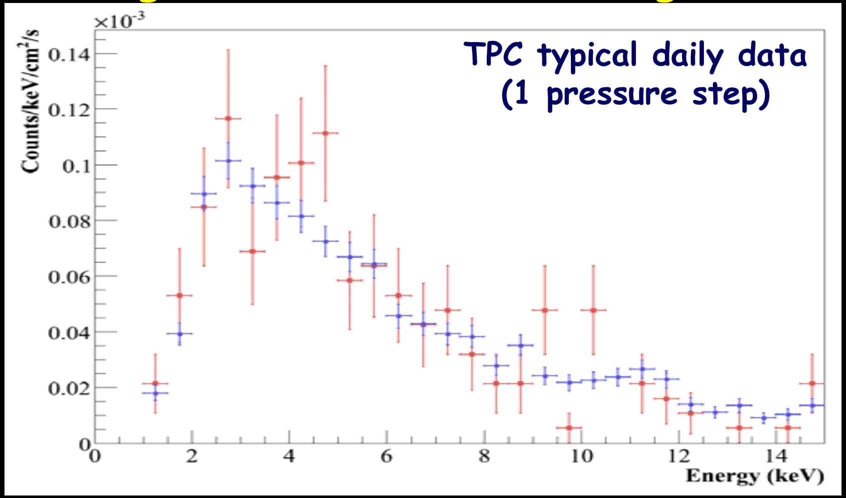
Phase II ^{4}He: TPC

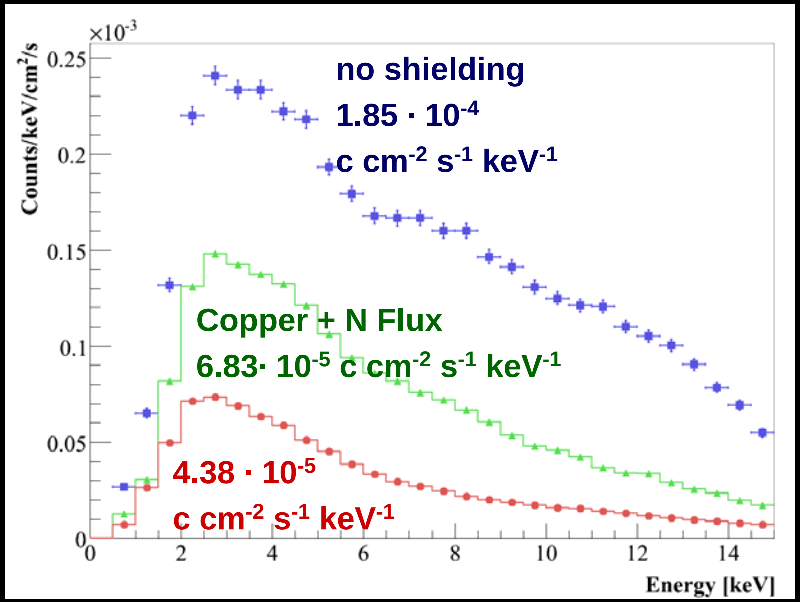
The detector covers both magnet bores



- a conventional Time Projection Chamber
  - drift space 10 cm
  - 48 anode wires, 96 cathode wires
  - signal measurement by 10 MHz Flash-ADC's
  - Shielding (polyethylene, copper, lead)
- Stable detector operation due to the shielding: average background
  4.38 10^{-5} counts cm^{-2} s^{-1} keV^{-1}

154 density steps completed (~300 h of tracking and ~4300 h of background data)





CAST results: ^{4}He phase II

- Improvement by a factor of 7 wrt previous experimental searches.
- It goes beyond astrophysical limit of globular clusters for coherence masses

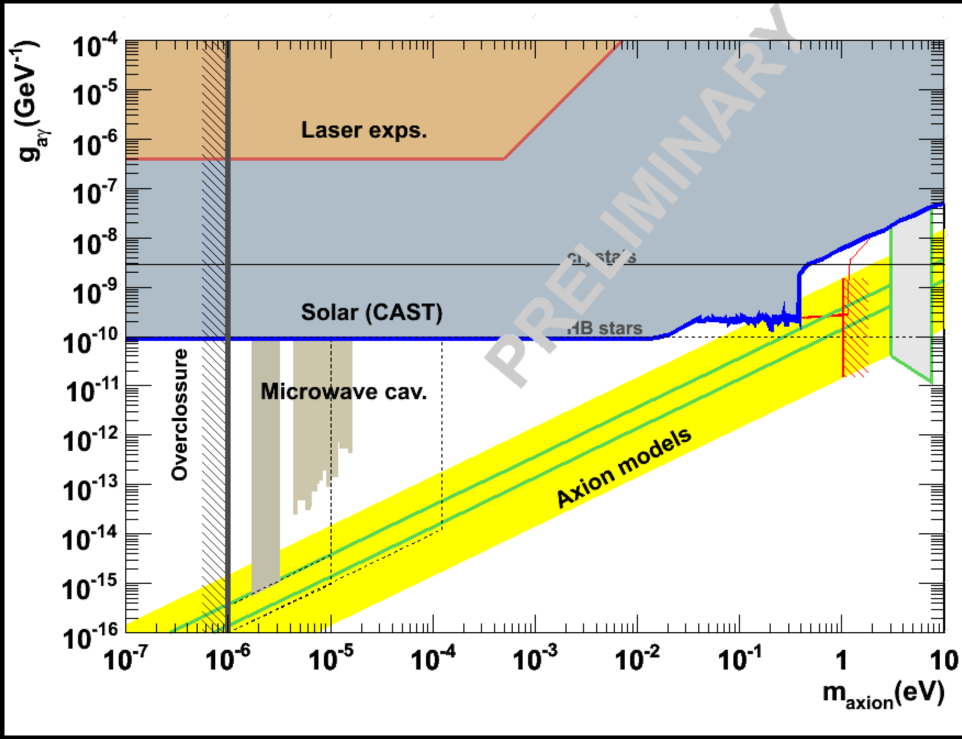
Phase I vacuum: $m_a \lesssim 0.02$ eV

Phase II ^{4}He: $0.02 \text{ eV} \lesssim m_a \lesssim 0.4$ eV

Phase II ^{3}He: $0.4 \text{ eV} \lesssim m_a \lesssim 1.15$ eV

Article published: JCAP04(2007)010

- Data taking with ^{4}He performed all along 2006
- ~160 density steps performed, reaching ~13 mbar (~0.4 eV)
- QCD theoretically axion models region is entered!!.
- **Finalizing Analysis. Publication under preparation**



- ^{3}He phase will start in few weeks entering deeper into the QCD theoretically axion models region

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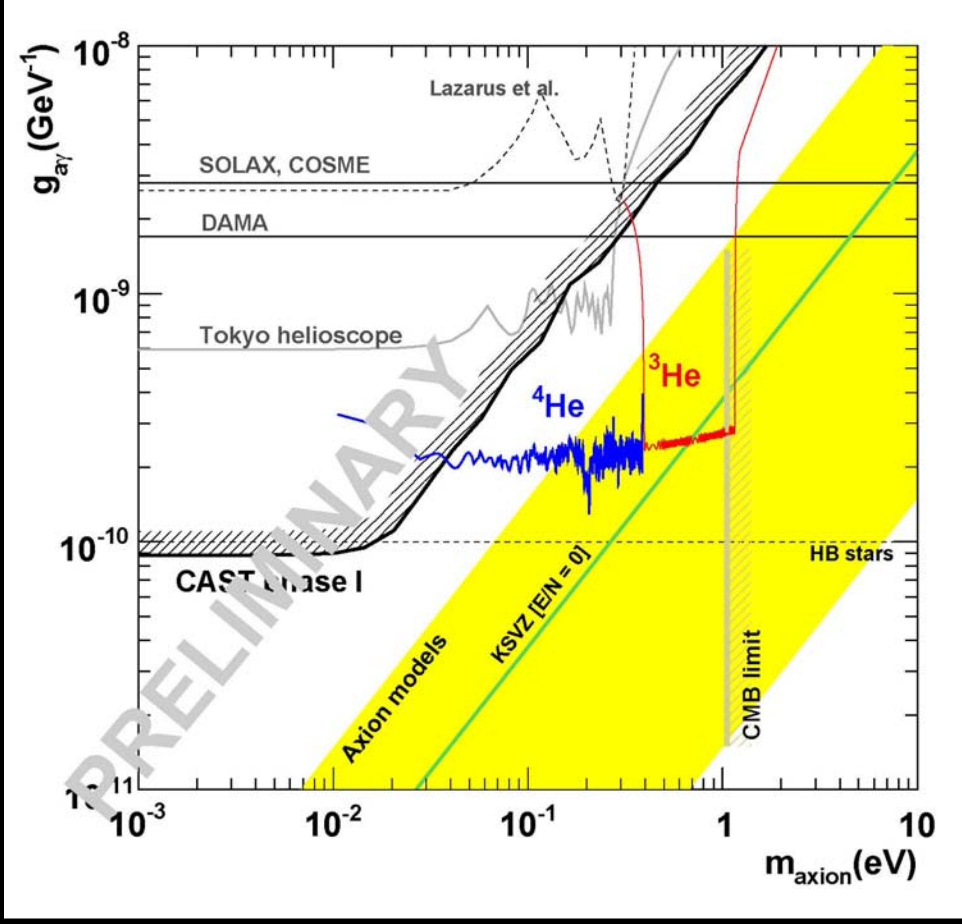
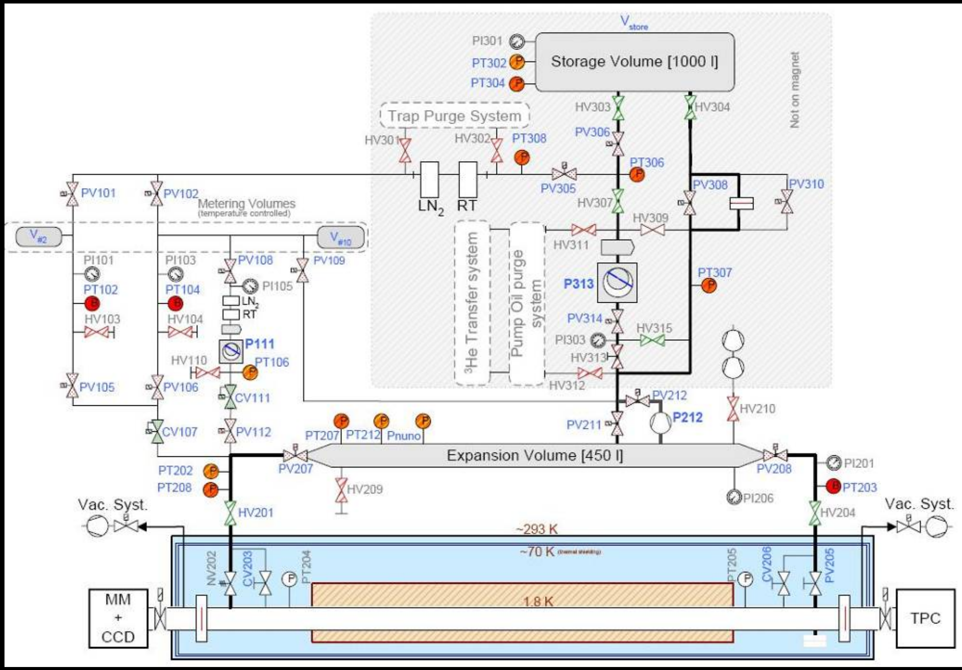


^{3}He II Phase: Gas System

^{4}He gas condensates at ~16 mbar @ 1.8 K
For higher pressures ^{3}He gas is used in CAST
Pressure: 13-120 mbar @ 1.8 K & 0.4 eV ≤ m_a ≤ 1.15 eV

Requirements

- Accuracy in measuring the quantity of gas introduced in the cold bore (100 ppm)
  - Density stability
  - Accurate steps 0.1 mbar
  - Reproducibility 0.01 mbar
- Safety against ^{3}He gas loss:
  - Hermetic closed system
  - Robust for high pressures
  - Rescue of Gas (MAGNET QUENCH)
  - High X-ray transmission windows



Change the ^{3}He pressure in the magnet bores

- Increasing of one step during the solar tracking
- Smoothly scan on a pressure range by a continuous ramping during the solar tracking

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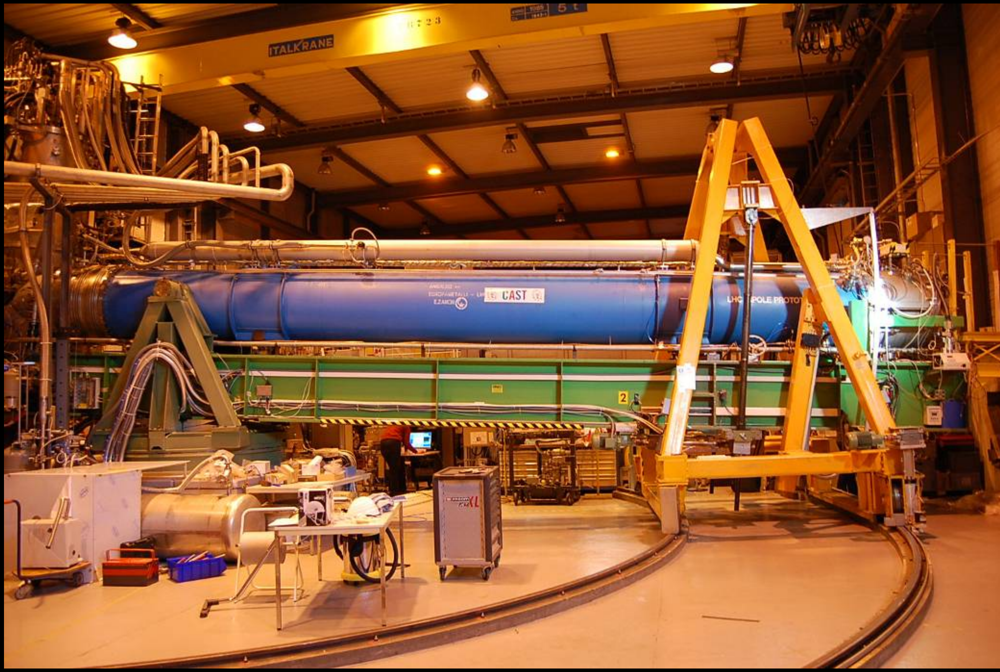
  - Rescue of Gas (MAGNET QUENCH)
  - High X-ray transmission windows



Change the ^3He pressure in the magnet bores

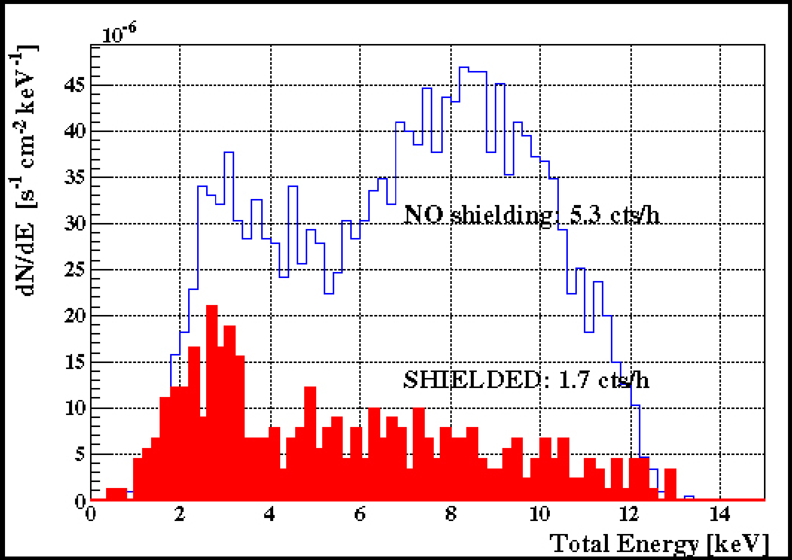
- Increasing of one step during the solar tracking
- Smoothly scan on a pressure range by a continuous ramping during the solar tracking

^{3}He II Phase: Detectors

Sunrise side

A new line was designed and installed replacing the old micromegas

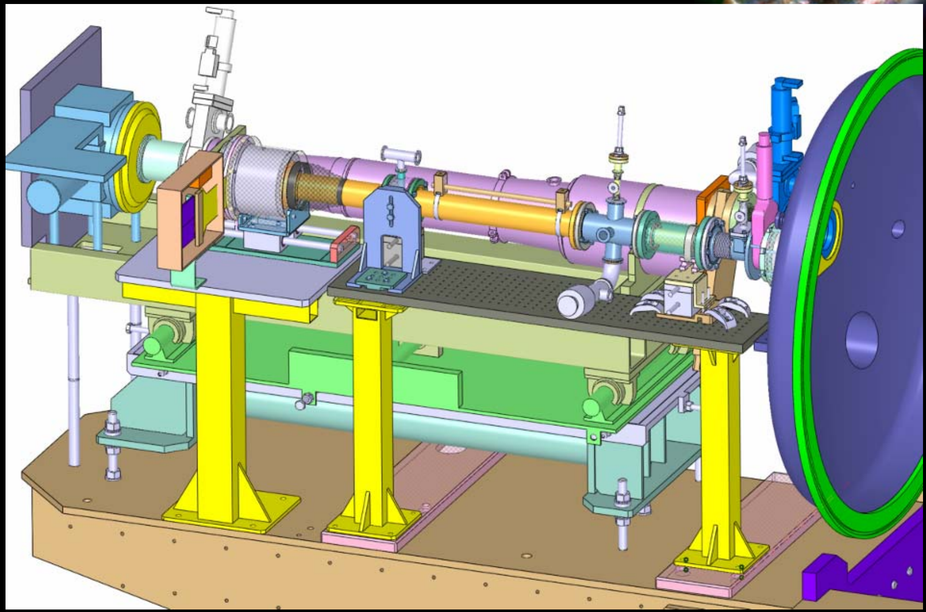
- possibility to use an X-Ray focusing device
- Shielding

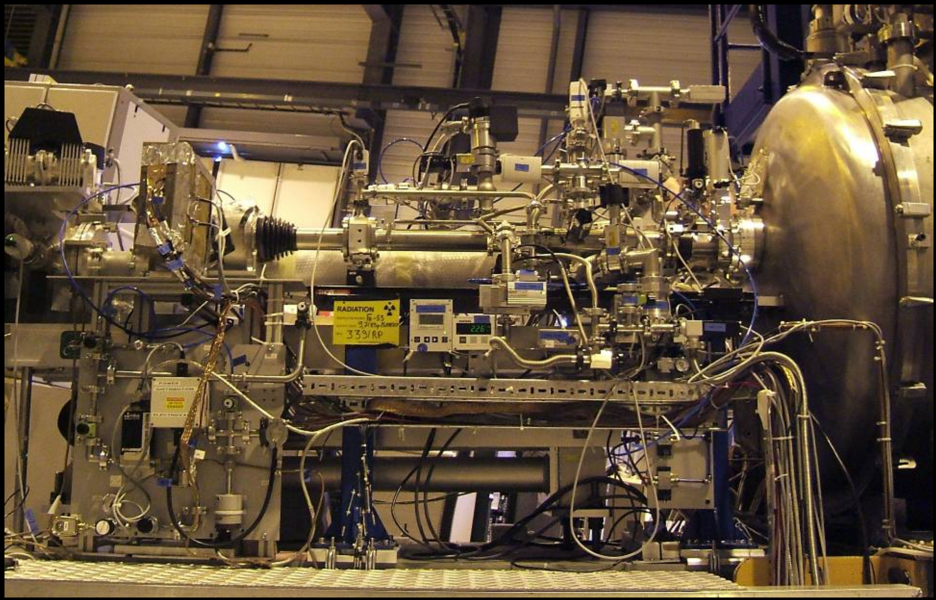


Measured background reduction by partial shielding by factor 3

Expected count rate

~7×10^{-6} sec^{-1} cm^{-2} keV^{-1}





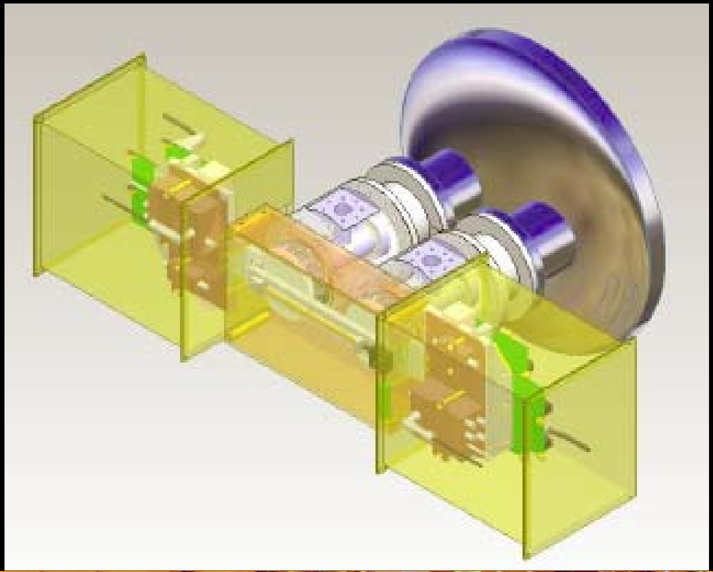
^{3}He II Phase: Detectors

Sunset side

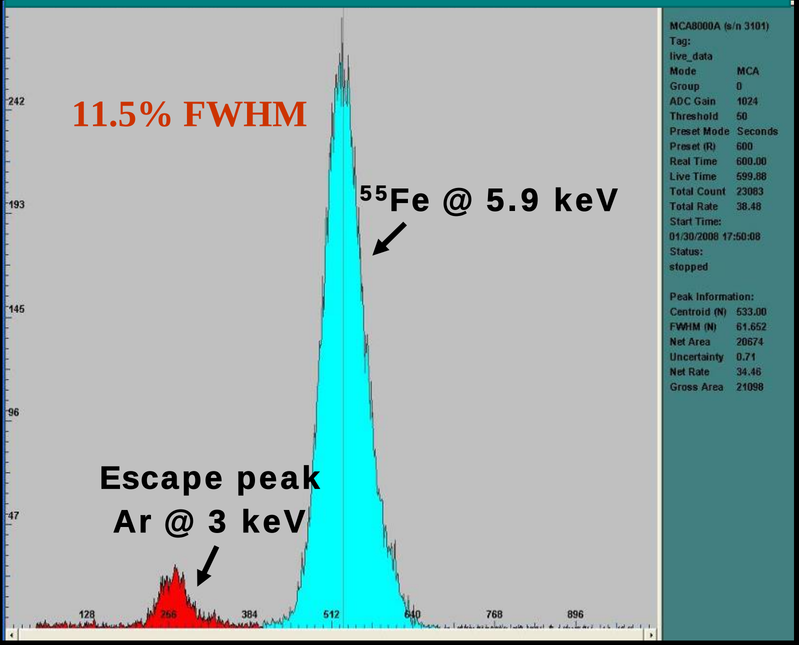
The TPC is being replaced by two new micromegas detectors

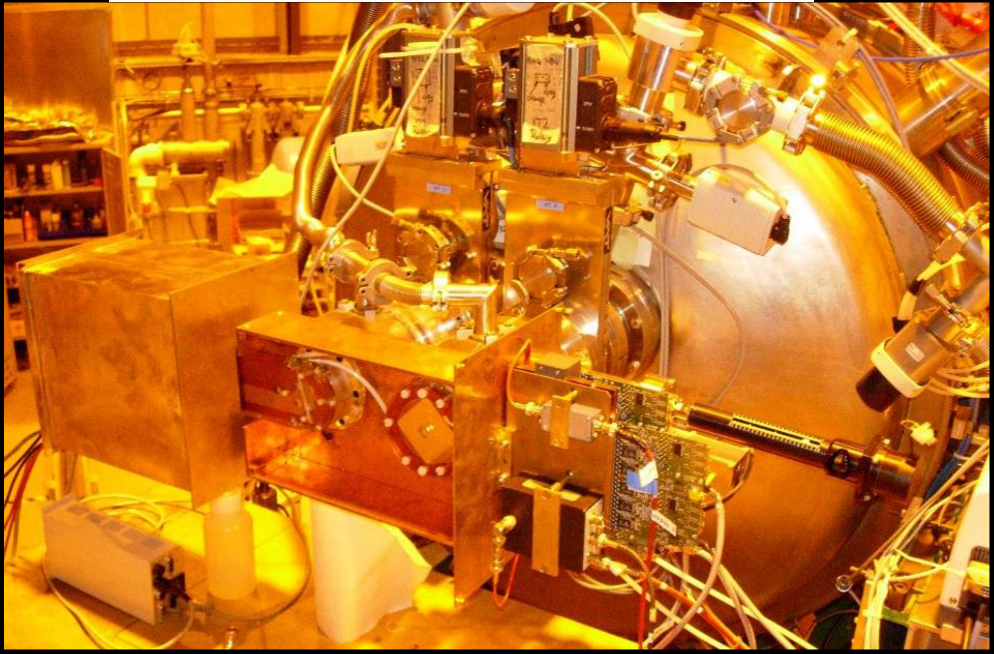
- better background rejection
- better energy resolution
- Shielding

New technology (microbulk/bulk)



Calibration source: ^{55}Fe





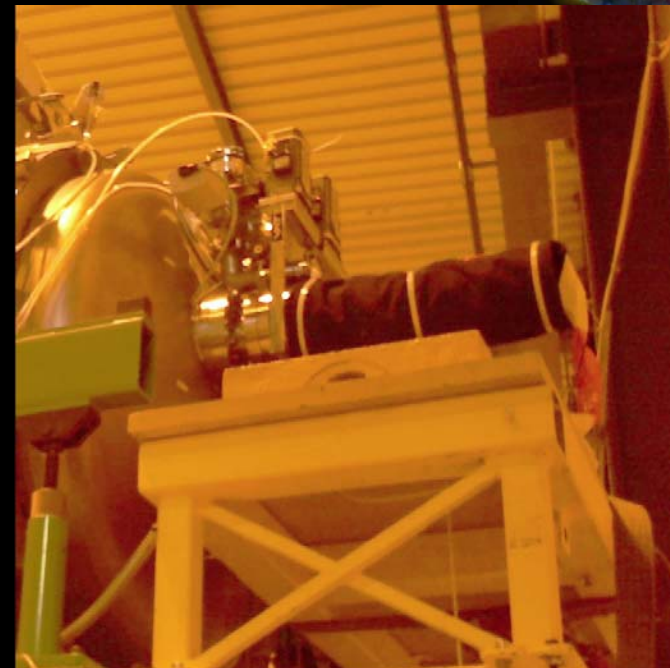
CAST Prospects: low energy axions

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

CAST has already performed a run during Nov 2007 in the visible region using 2 different PMT detector setups

- Ongoing data analysis
- Next run beginning of March 2008
- Possibility to create a 5th line by using an X-Ray transparent mirror



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

Axion Searches

Axions are searched in three different contexts (different sources of axions):

- Axions produced in the Sun:
  - Axion Helioscopes: CAST@CERN Tokyo@UniversityTokyo,
  - Crystal detectors: SOLAX, COSME@Canfranc , DAMA@GranSasso
  - Geomagnetic Conversion by satellites: SUZAKU satellite
- Dark matter axions (as relics of Big Bang):
  - Microwave cavities ADMX@LLNlab, CARRACK@Kyoto
- Axions produced in the laboratory
  - “Light shinning through wall” experiments
  - Vacuum birefringence experiments PVLAS@Legnaro, OSQAR@CERN, ALPS@DESY, BMV@LULI, LIPSS@Jlab