POLAR

A WIDE FIELD COMPACT DETECTOR FOR POLARIZATION MEASUREMENTS OF HARD X-RAYS FROM GRB

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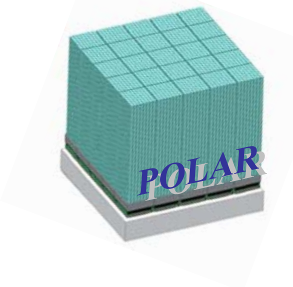
Preface



science goal:

are most of the Gamma Ray Bursts strongly polarized?
in attempt to solve the mystery of the GRB true nature

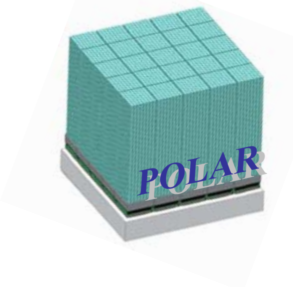
Experimental goal:

Perform first ever successful polarization measurement
of hard photons in space
with high statistical significance and controlled systematic effects.

Approach of the project:

Answer a very important scientific question
Do it as simple as possible
Use proven technologies
Do it fast

OUTLINE



- **Introduction:**

  GRB Polarization and the International context

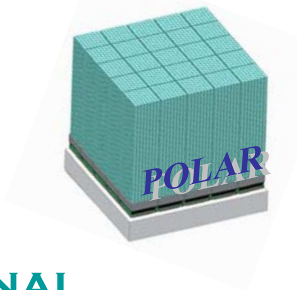
- **A possible approach:**

  The COMPTON effect for the polarization measurement

- **The POLAR Project:**

  - The international Collaboration
  - Working principles and Performance
  - Sub-systems
  - Milestones

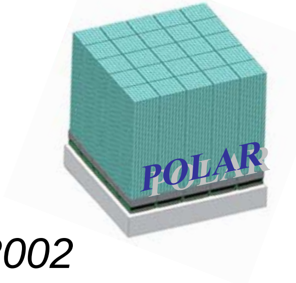
GRB Polarization



- The real exciting physics take place in the prompt signal, but there is not much we can observe.

- we can observe:
  - sky position (but this is done better with the afterglow)
  - light curve
  - spectrum
  - polarization
    - Difficult to impossible to do with actual detectors
    - Wrong measurements published in the best journals (claim 80%+- 20%)
    - A lot of theoretical interests

Current GRB polarization measurements

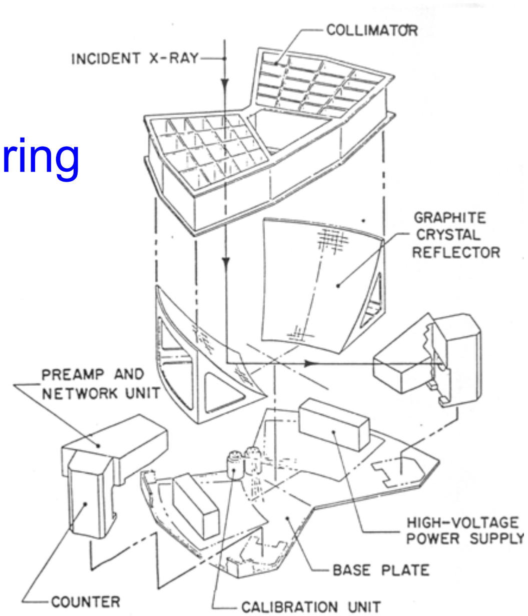


- *Polarization of the prompt γ-ray emission from the γ-ray burst of 6 December 2002 (RHESSI)*, Coburn, W; Boggs, S. E., *Nature*, 2003, 423, 415 (122 citations): P_{lin} = 80 ± 20% (highly significant detection!)
  - *Re-analysis of polarization in the γ-ray flux of GRB 021206*, Rutledge, R. E.; Fox, D. B., *MNRAS*, 2004, 350, 1288
    - *Statistical Uncertainty in the Re-Analysis of Polarization in GRB021206*, Coburn, W; Boggs, S. E., *2003astro.ph.10515B*
  - *Gamma-Ray Burst Polarization: Limits from RHESSI Measurements*, Wiggler, C. et al, *ApJ*, 2004, 613, 1088
- *Evidence of polarisation in the prompt γ-ray emission from GRB 930131 and GRB 960924 (BATSE/GRO)*, Willis, D. R. et al, 2005, *A&A*, 439, 245
- *Polarization studies of the prompt γ-ray emission from GRB 041219a using the spectrometer aboard INTEGRAL*, McGlynn, S., 2007, *A&A*, 466, 895

Important, rare, large uncertainty & controversial!

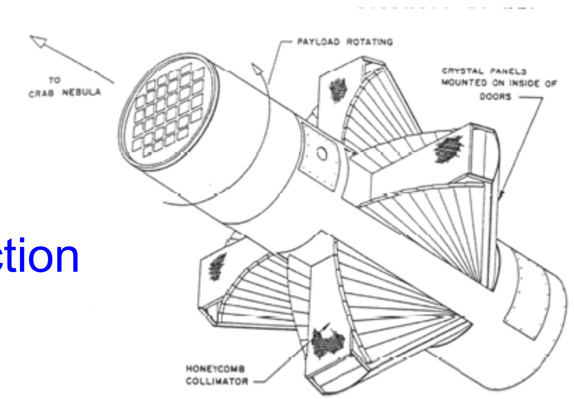
lapp

Thomson scattering polarimeter



OSO-8, 1975-1978 Columbia

Bragg reflection polarimeter



Rocket, 1972, Columbia

DETECTION OF X-RAY POLARIZATION OF THE CRAB NEBULA

R. NOVICK, M. C. WEISSKOPF, R. BERTHELSDORF, R. LINKE, AND R. S. WOLFF
Columbia Astrophysics Laboratory, Columbia University
Received 1972 February 28

ABSTRACT

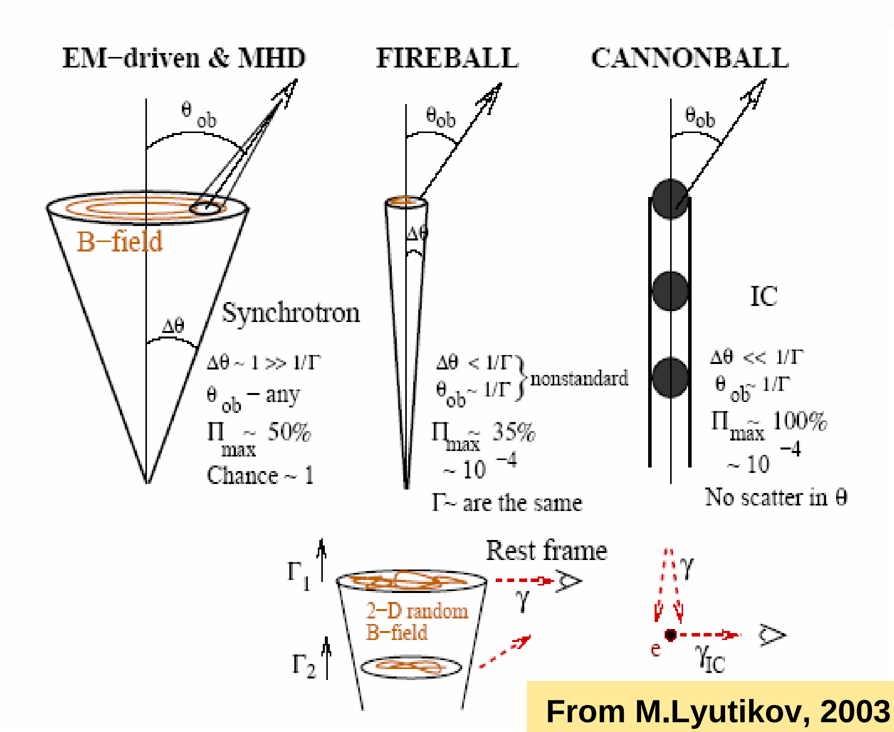
Two different types of X-ray polarimeters were used in a sounding rocket to search for X-ray polarization of the Crab Nebula. Polarization was detected at a statistical confidence level of 99.7 percent. If the X-ray polarization is assumed to be independent of energy, the results of this and a previous experiment lead to a polarization of (15.4 ± 5.2) percent at a position angle of 156° ± 10°. This result confirms the synchrotron model for X-ray emission from the Crab Nebula.

GRB Polarization

- **Fireball Model**
  high values excluded
  $P_{LIN} \sim 10\text{-}20\ \%$

- **Cannonball Model**
  full range possible
  $P_{LIN} = 0 - 100\%$
  (depends only on $\theta.\Gamma$)

- **Electromagnetic Model**
  well defined, moderate
  $P_{LIN} \sim 50\ \%$



From M.Lyutikov, 2003

See papers discussing various models:
T.Piran, A.Dar & A. De Rujula, M.Lyutikov, D.Eichler, G.Ghisellini, D.Lazzatti, M.Medvedev, E.Rossi etc.

POLARIMETER PROJECTS

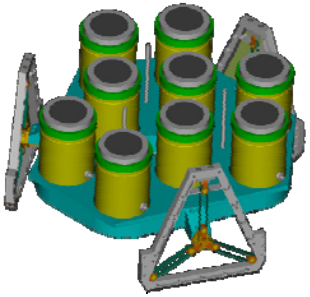
- **GRAPE** Gamma Ray Polarization Experiment: Low Z - high Z hybrid, 50-300 keV; *M.McConnell et al.*

- **PoGO** Polarized Gamma-ray Observer: phoswich of slow-fast units with AC, 30-100 keV; *T.Mizuno et al.*

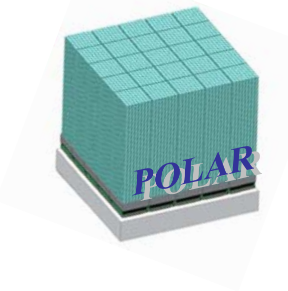
- **SGD** Soft Gamma-ray Detector: Compton telescope of Si-strips and CdTe pixels and AC, E<300 keV; *H.Tajima*

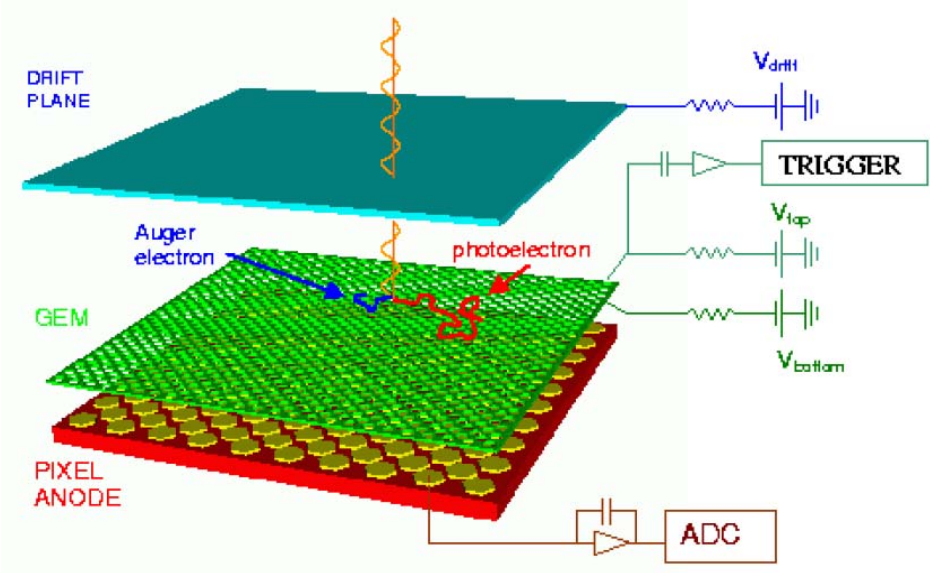
- **CIPHER** Coded Imager and Polarimeter for High Energy Radiation: CdTe array, E<1 MeV; *R.Curado da Silva*

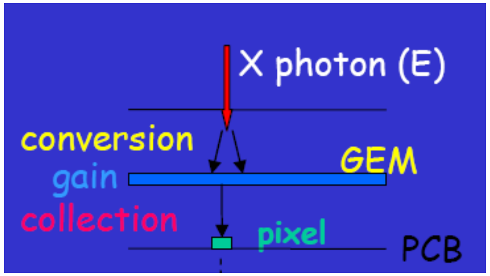
- **RHESSI** High Energy Solar Spectrometric Imager: 9 large Ge, active/passive modes, E>10 keV; *M.McConnell, C.Wigger*



GEM: a Photoelectric Polarimeter (<10 keV)





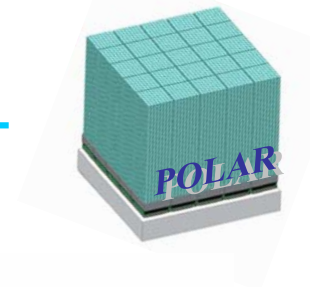


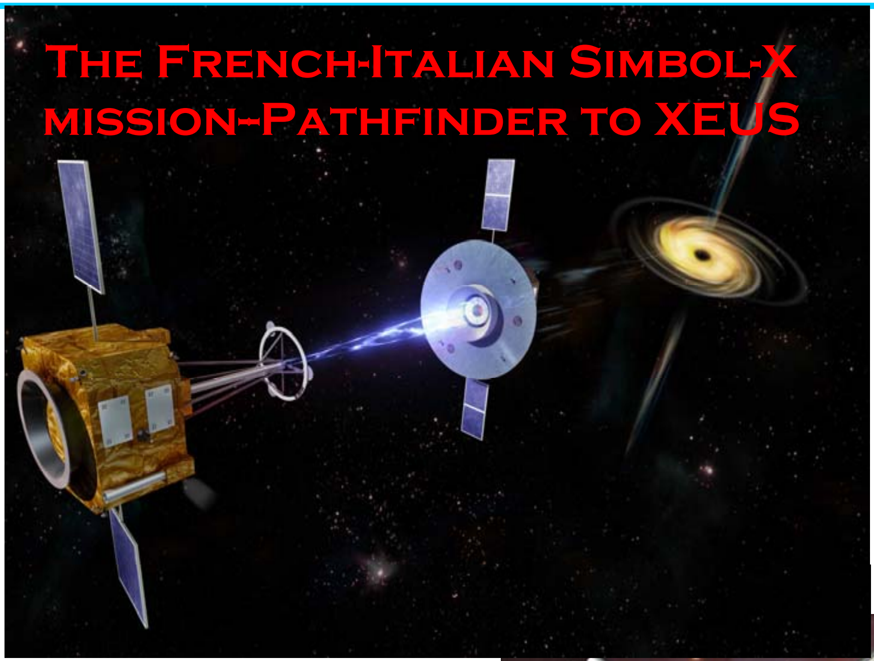
Polarization information is derived from the tracks of the photoelectron, imaged by a finely subdivided gas detector.

A new device: the Micro Pixel Detector developed at INFN-Pisa

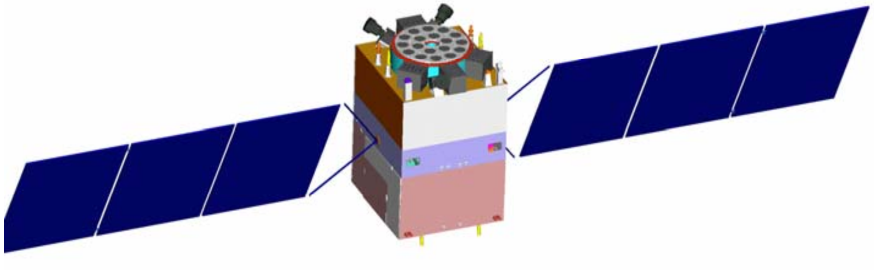
E.Costa & R.Bellazzini

GEM PROPOSED ON BOARD OF FUTURE X-RAY MISSIONS

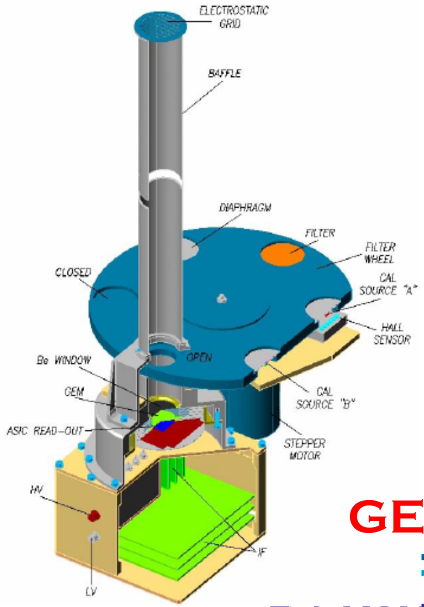


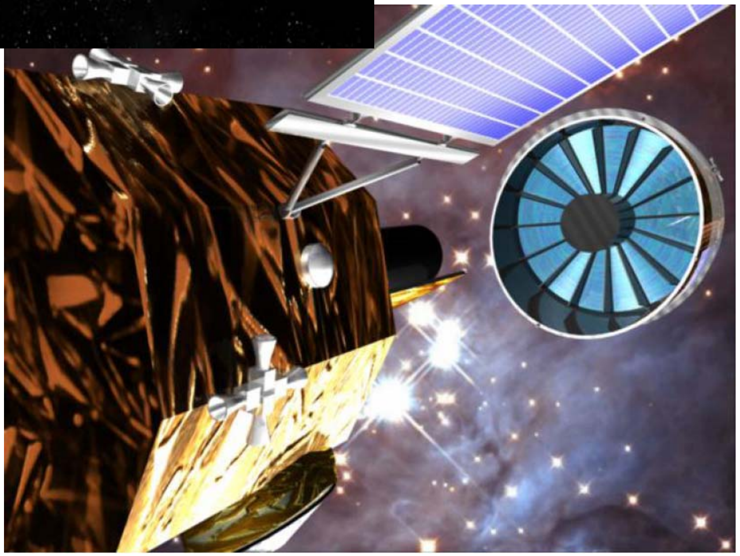


THE FRENCH-ITALIAN SIMBOL-X MISSION--PATHFINDER TO XEUS



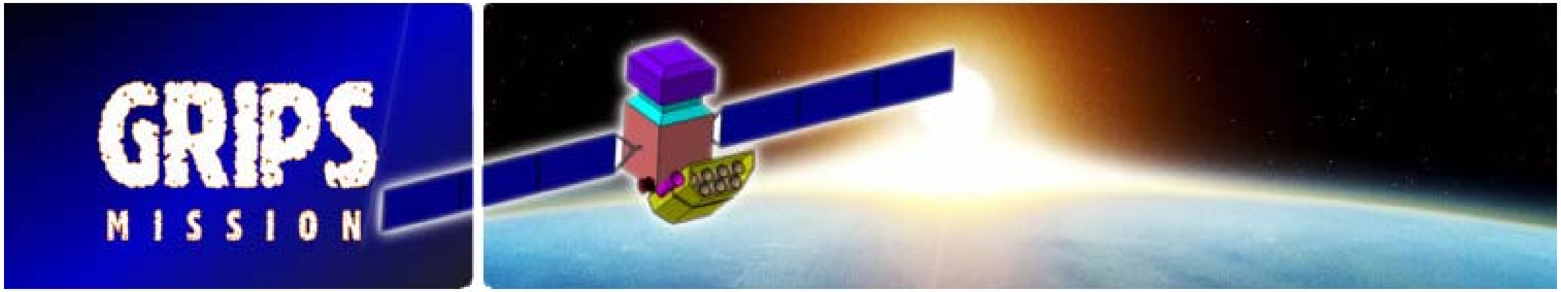
THE CHINESE HXMT

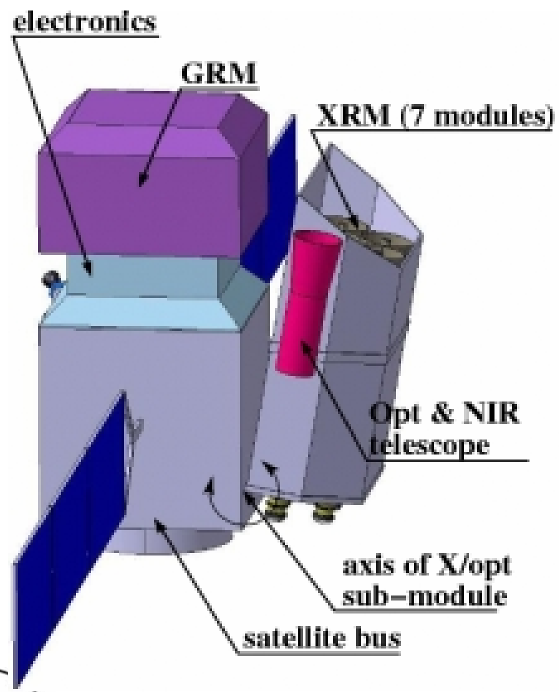




GEM DESIGN FOR XEUS

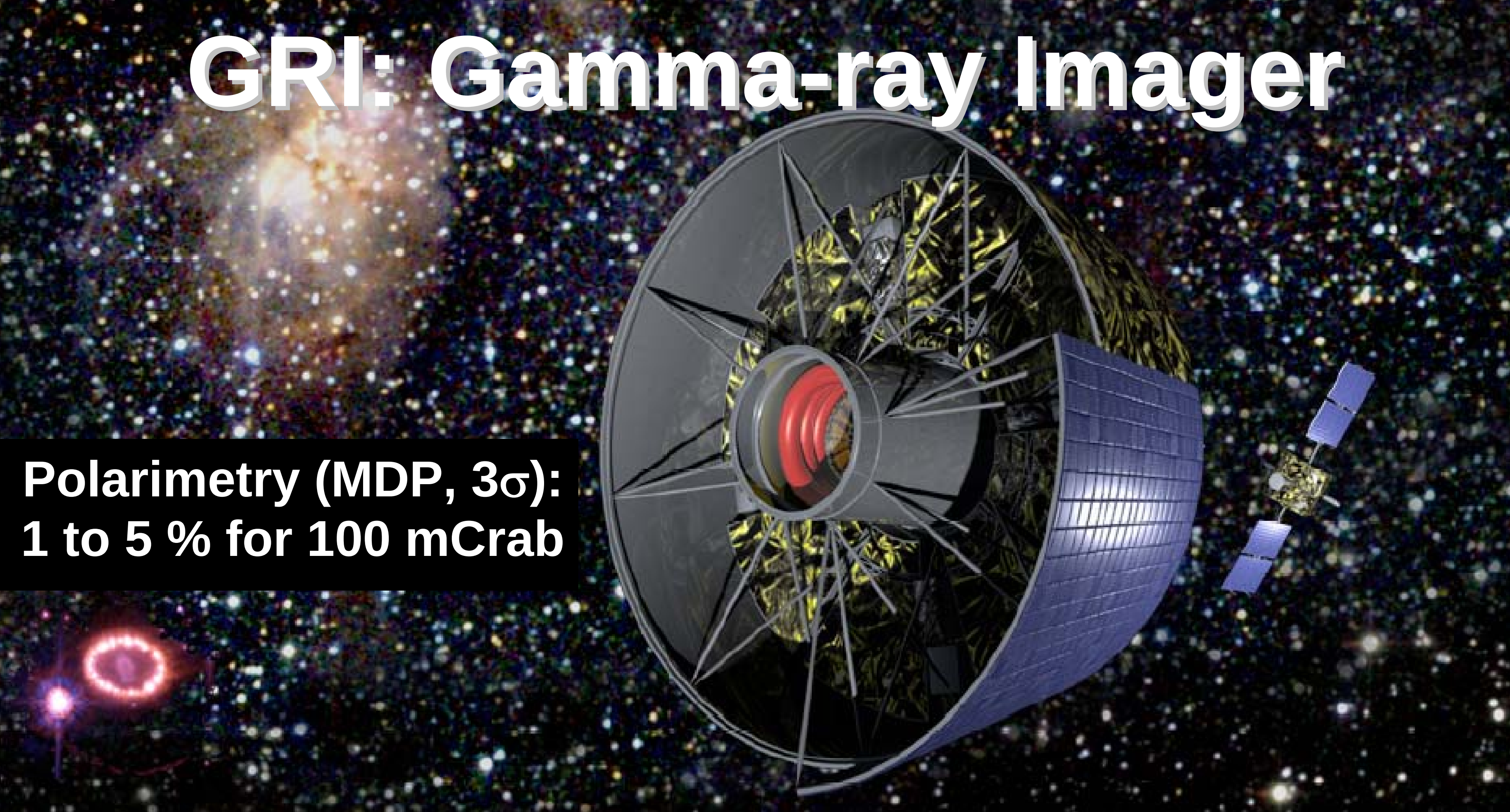
GRIPS A FUTURE PAYLOAD IN THE 2020 ESA COSMIC VISION…





GRIPS is a multi-instrument satellite mission. The prime instrument will use nearly 1000 kg of LaBr3 scintillator crystals for measuring spectra of GRBs, similar in measurement principle to BATSE on CGRO. Polarimetry will be performed via Compton scattering off a silicon strip tracker within the LaBr3 walls.

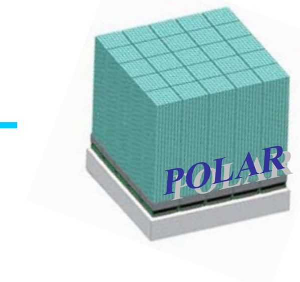
GRI: Gamma-ray Imager

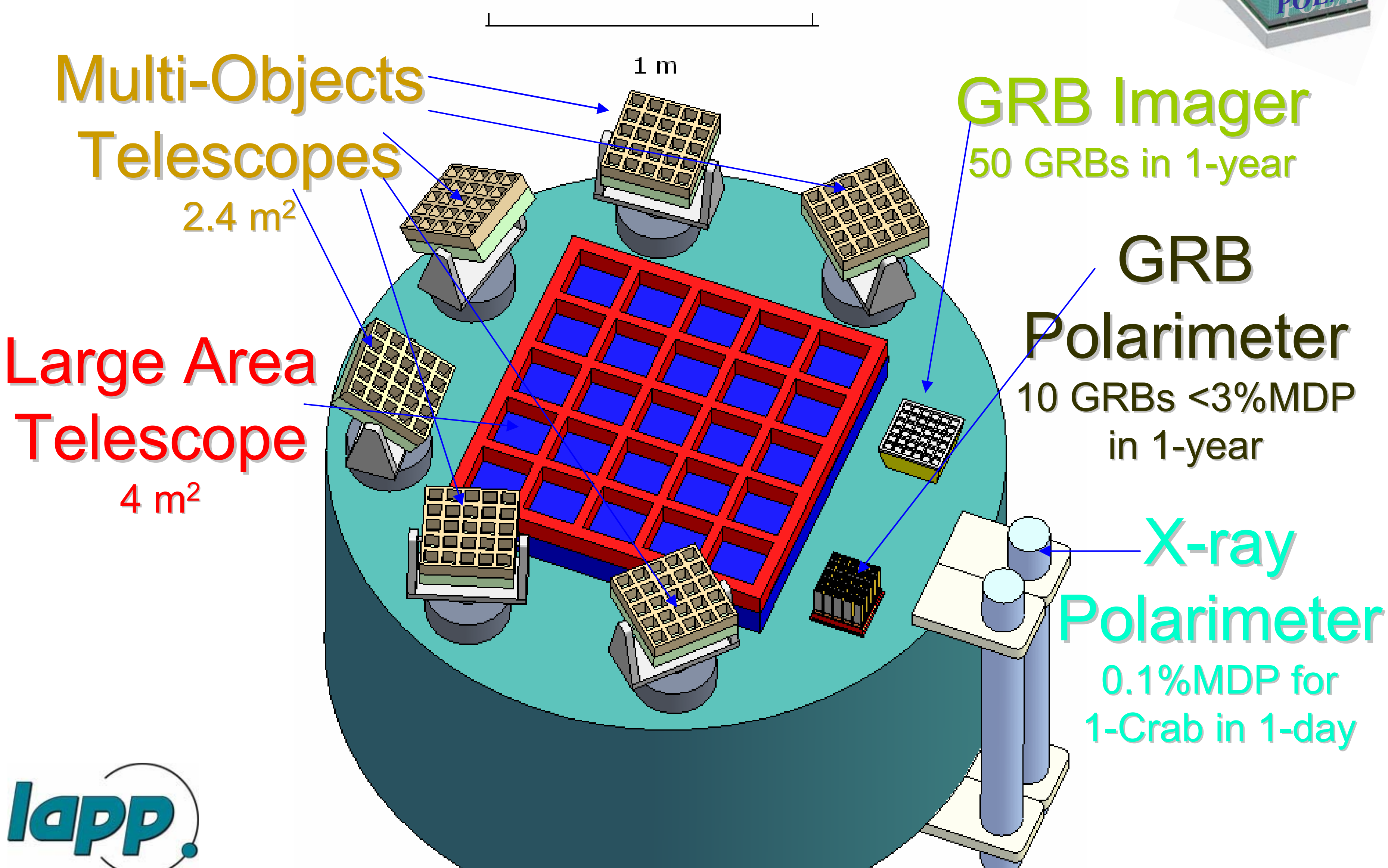


Polarimetry (MDP, 3σ):
1 to 5 % for 100 mCrab

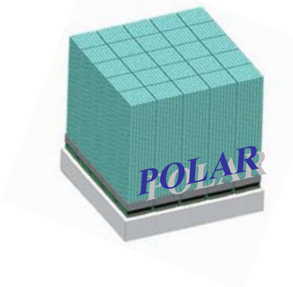
This proposal has been prepared by the GRI consortium, formed by about 100 scientists from the following countries (in alphabetical order): Belgium, China, Denmark, France, Germany, Ireland, Italy, Poland, Portugal, Russia, The Netherlands, Spain, Turkey, United Kingdom, and USA
A complete list of consortium members can be found at http://gri.iasf-roma.inaf.it/GRIMemberList.asp

X-ray Timing and Polarization mission: XTP (China)





POLAR International Collaboration



SWITZERLAND

ISDC - Geneva Observatory:

Dr. Nicolas Produit (PI)
Dr. Daniel Haas (POLAR PostDoc.)

PSI-Villigen:

Dr. Wojtek Hajdas
Dr. Aliko Mchedlishvili

University of Geneva:

Prof. Martin Pohl
Prof. Catherine Leluc
Prof. Divic Rapin
Dr. Silvio Orsi (POLAR PostDoc.)
Estela Suarez (POLAR PhD student)

POLAND

IPJ:

Dr. Michal Gierlik
Dr. Radoslaw Marcinkowski

FRANCE

LAPP – IN2P3-Annecy:

Dr. Giovanni Lamanna
Dr. Jean-Pierre Vialle
Dr. Richard Hermel (Engineer)

LAM-INSU-Marseille:

Dr. Stephane Basa
Dr. Alain Mazure

LAPTH – IN2P3-Annecy:

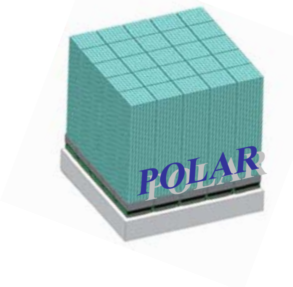
Prof. Paschal Chardonnet

CHINA

IHEP

Dr. Shuang-Nan Zhang (PI)
Dr. Bobin Wu
Xiong Shaolin (POLAR PhD student)

POLAR science



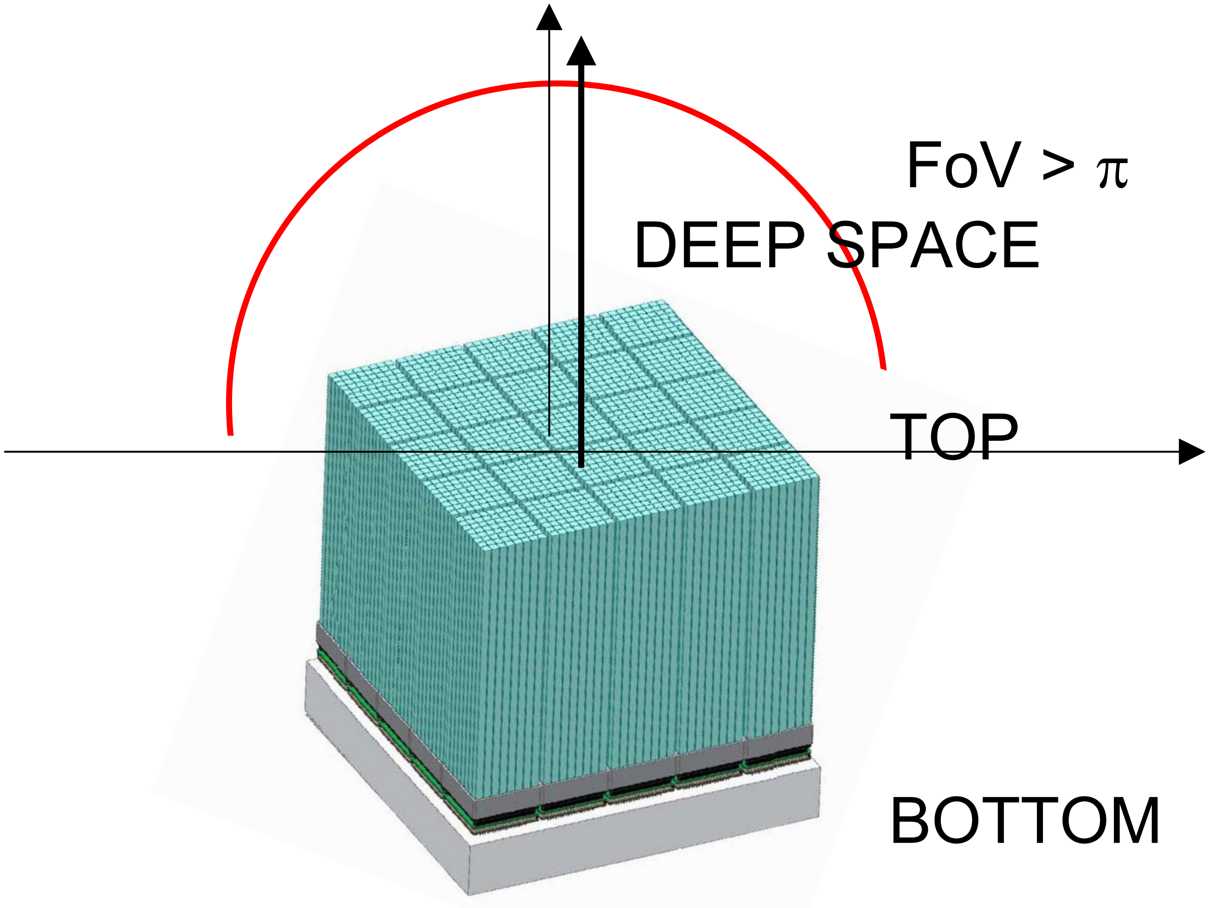
GRB-prompt signal polarization

POLAR is not tuned for analyzing point source but some more objectives cannot be excluded:

- point source (Crab, Cyg X-1)
- solar flares
- participate to IPN

Remind: POLAR needs other instruments to get GRB position observing simultaneously the same patch of sky.

The POLAR detector



Looking for large angle Compton scattering
inside the cubic (25 cm side) volume of the POLAR detector
uniform array of scintillator bars

COMPTON POLARIMETRY: BASIC PRINCIPLES

Klein-Nishina

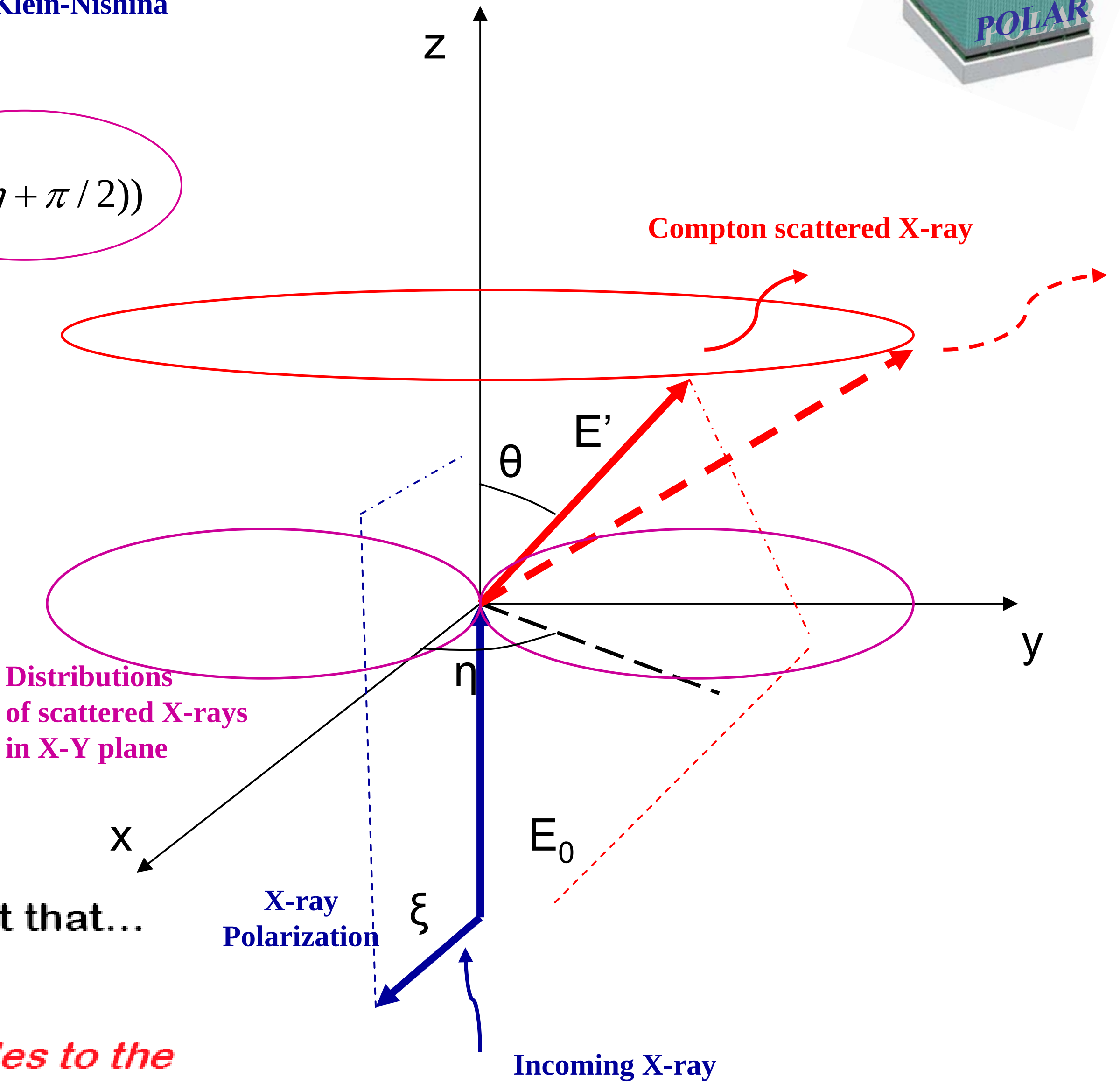
$$\frac{d\sigma}{d\Omega} = \frac{r_0^2\varepsilon^2}{2}\left(\frac{1}{\varepsilon} + \varepsilon - 2\sin^2\theta\cos^2\eta\right)$$

$$= \frac{r_0^2\varepsilon^2}{2}\left(\frac{1}{\varepsilon} + \varepsilon - \sin^2\theta + \sin^2\theta\cos(2(\eta+\pi/2))\right)$$

$$(\varepsilon = \frac{E'}{E_0})$$

θ is the Compton Scatter Angle

η is the Azimuthal Scatter Angle

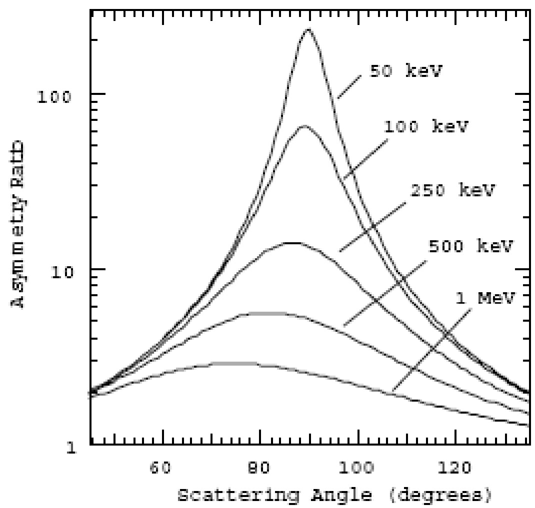


Polarimetry relies on the fact that…

photons tend to
Compton scatter at right angles to the
incident polarization vector

COMPTON POLARIMETRY: ASYMMETRY RATIO

Defines the quality of polarization signature.



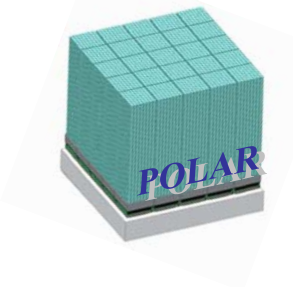
Ratio of max and min cross sections with respect to azimuthal scatter angle (η)

$$R = \frac{d\sigma(\eta = 90^\circ)}{d\sigma(\eta = 0^\circ)} = \frac{(E_o/E' + E'/E_o)}{(E_o/E' + E'/E_o - 2\sin^2\theta)}$$

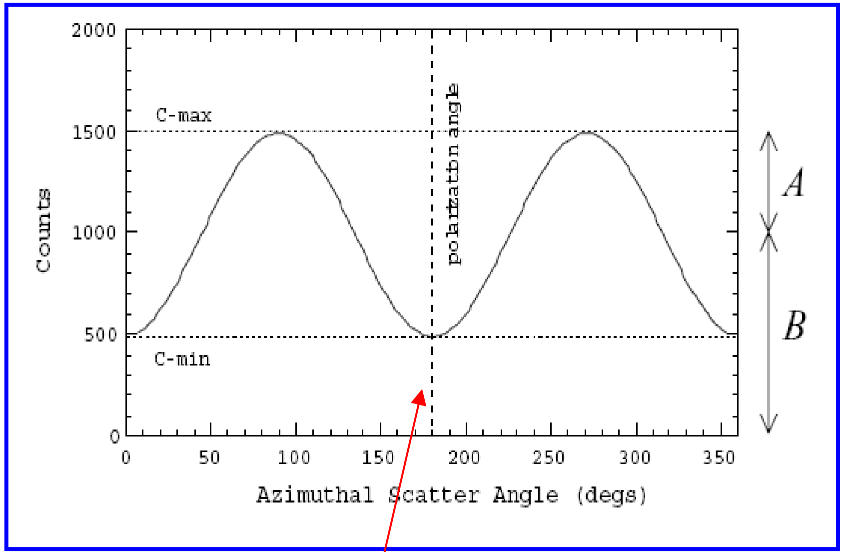
Important Features:

1. Ratio is very peaked wrt Compton scattering angle (θ)
2. At low-energies, ratio peaks near $\theta = 90°$
3. Peak moves to smaller θ at high energies ($\approx$ 45° at 10 MeV)

COMPTON POLARIMETRY: THE SIGNATURE



For a fixed Compton scatter angle (θ), the azimuthal distribution of scattered photons contains the polarization signature.



$$C(\eta) = A\cos(2(\eta - \varphi + \frac{\pi}{2})) + B$$

Modulation Factor for a 100% polarized beam is an important quality parameter for polarimeter's performance estimation:

$$\mu = \frac{C_{max} - C_{min}}{C_{max} + C_{min}} = \frac{A}{B}$$

Polarization angle: Corresponds to the minimum of the scatter angle distribution (ϕ) versus a predefined direction

The *amplitude* of the modulation defines the *level of polarization*.

The *minimum* of the distribution defines the *plane of polarization*.

The Polarization Measurement

LEVEL of Polarization

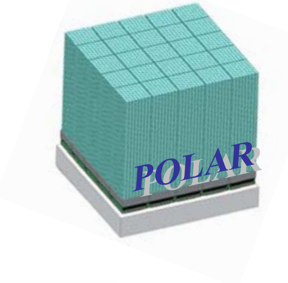
$$P = \frac{\mu_P}{\mu_{100}} = \frac{1}{\mu_{100}}\left(\frac{C_{max}(P) - C_{min}(P)}{C_{max}(P) + C_{min}(P)}\right)$$

μ_{100} = the modulation factor for 100% polarized flux

μ_P = the measured modulation factor

P = the level of polarization

The Polarization Measurement



MDP: Minimum Detectable Polarization

$$MDP = \frac{n_\sigma}{\mu_{100}\, S}\sqrt{\frac{2(S+B)}{T}}$$

S =	source counting rate
B =	background counting rate
T =	observation time
μ_{100} =	modulation factor for 100% polarization

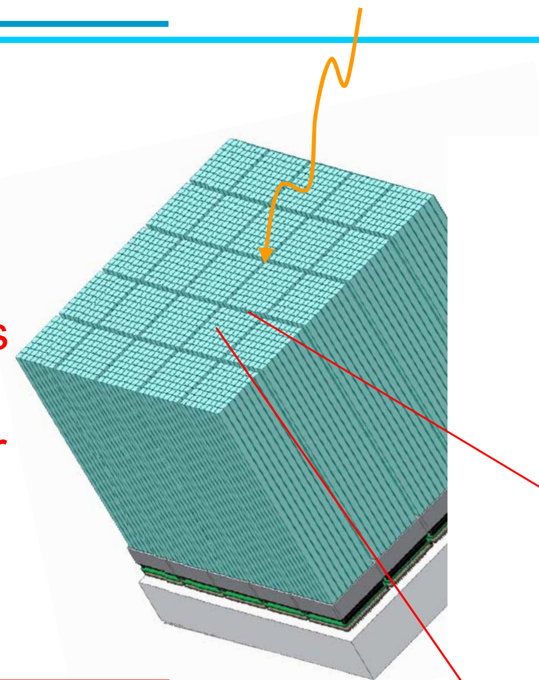
Sensitivity can be improved by :

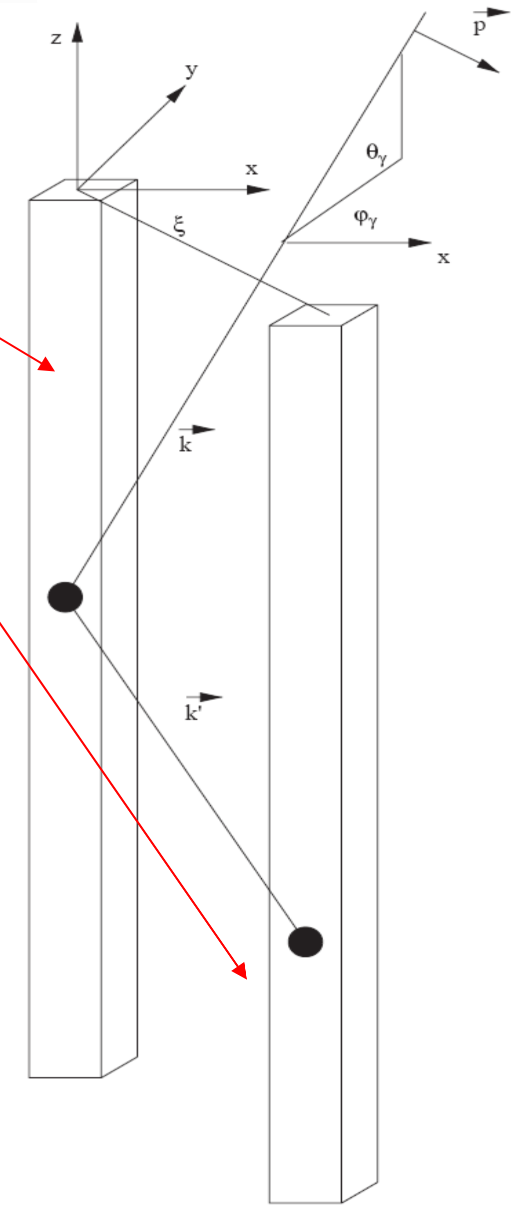
1) Increasing S (efficiency or geometric area)
2) Decreasing B
3) Increasing T
4) Increasing μ_{100} (optimize geometry)

THE POLAR DETECTOR

Geometry of the large angle Compton scattering.

The strategy is to look for the two bars where interactions occur: first Compton and second Compton or Photoelectric.



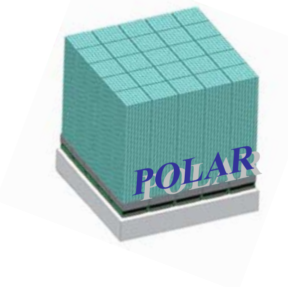


θ_γ and ϕ_γ are the entrance angles of the photon relative to a detector fixed coordinate system.

ξ is the measured azimuthal direction that correlate with polarization direction *p*

One does not need to know in which order the interactions occur, thanks to π symmetry of azimuthal distribution

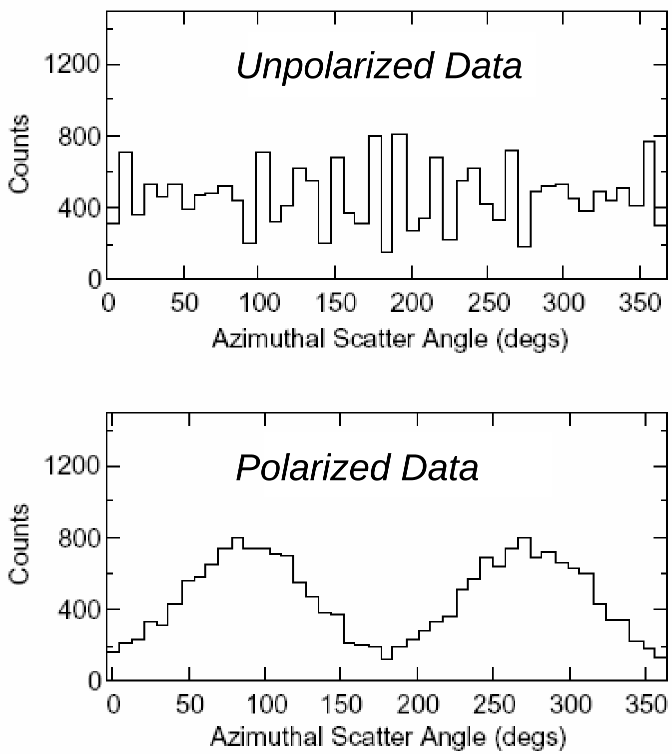
The Polarization Measurement



The ultimate goal is :

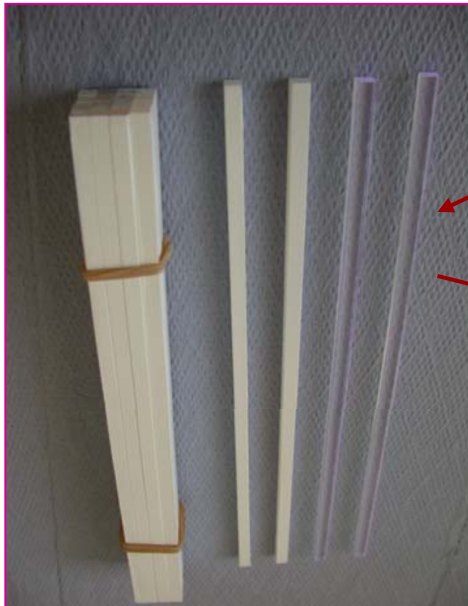
to measure GRB polarization with POLAR detector based on analysis of the reconstructed modulation curve:

Extraction of Compton scattered events (large angle) and building histograms with modulation pattern using the azimuth angle around the photon incoming direction

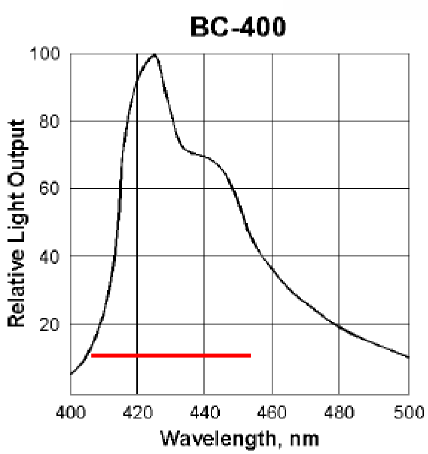


In practice, a measured distribution must also be corrected for geometrical effects based on the corresponding distribution for an unpolarized beam.

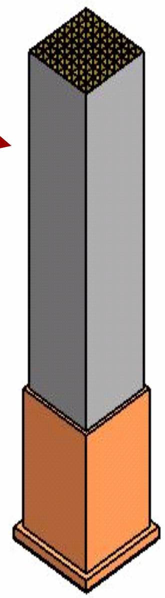
The POLAR detector

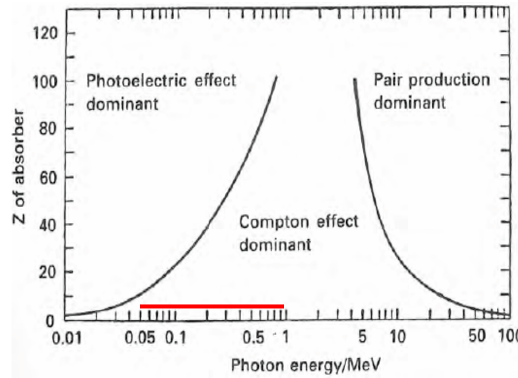


BC400: rad-hard and chemically stable

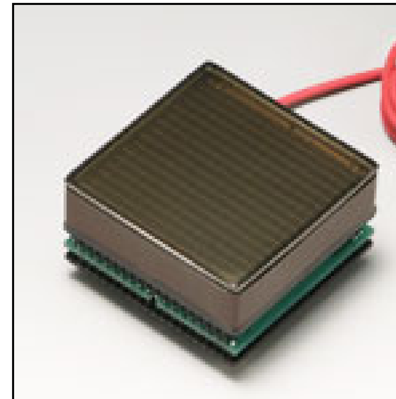


PS bars: 8x8*6mm*6mm*20cm





Light, fast and low Z plastic (in favor of Compton effect)



MAPM H8500 (8*8 anode pixel)

Wavelength (Peak)	420 nm
Uniformity	2-3

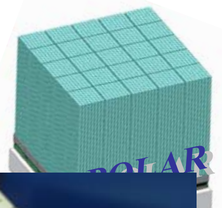
PS Bars	PMT (mm)	Weight (kg)	Dimension (cm)
40*40	5*5	20	30*30

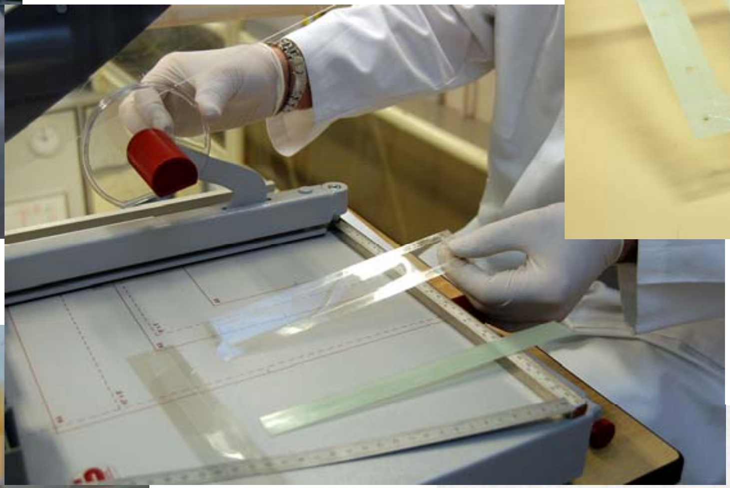
Light Collection Study

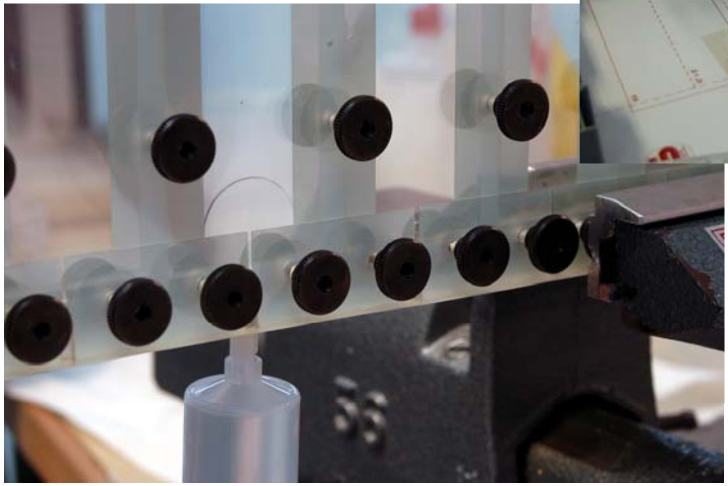
- Light collection goals:
  - Reasons of lower collection than theoretically expected
  - Maximizing Light Output and optimizing signal uniformity

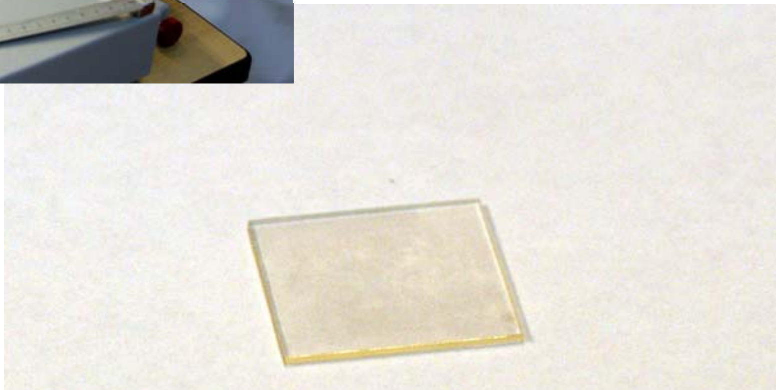
- Phenomena affecting light collection:
  - Scintillator attenuation length and surface roughness
  - Scintillator and wrapping refractive indexes
  - Reflective index of wrapping
  - PM Glass thickness & optical grease
  - Photomultiplier (PM) surface

The POLAR detector: Space know-how



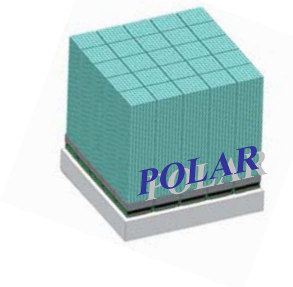






AMS-ECAL @ LAPP: Optical coupling

The POLAR detector

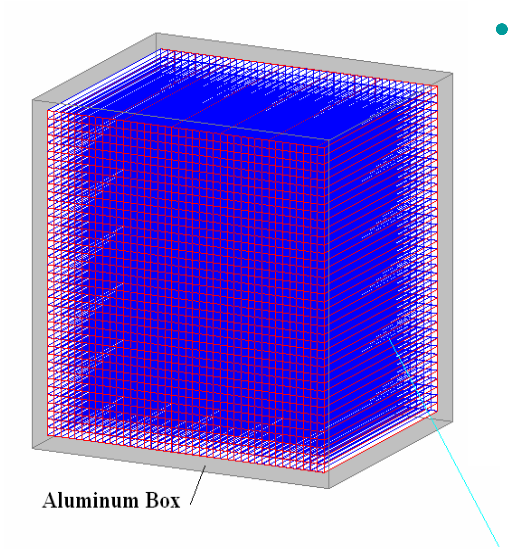


- Plastic optical coupling (space qualified)

- Carbon-fiber frame for mechanical target assembling

- Optical insulation and thin (≈ 1 mm) carbon fiber outside shielding (stopping electrons with E< 500 keV or protons E< 13 MeV)

- No active shielding; but outer layers can be used if needed for a ("topological") trigger



- Working principles validated by Monte Cralo simulation with GEANT4 package (CERN)

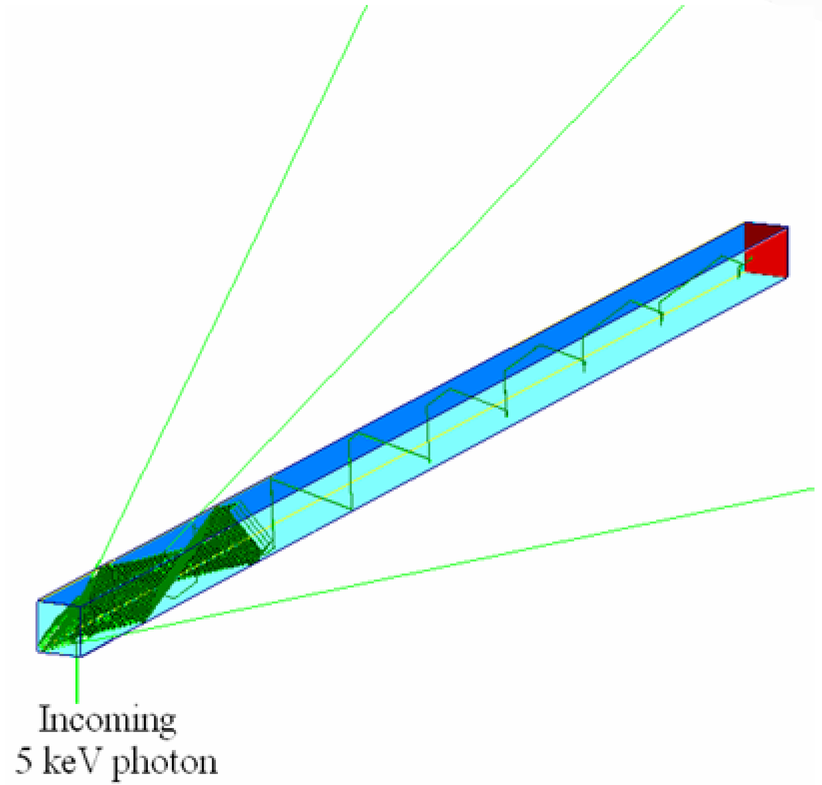
LIGHT COLLECTION STUDIES

- SIMULATIONS PREDICT:

  1. AROUND 45% OF THE OPTICAL PHOTONS REACH PM (THE REST IS ABSORBED OR ESCAPES)

  2. DIFFERENCES FOR INCOMING GAMMAS AT TOP OR BOTTOM: 10-20 %

  3. POLISHING OF THE SCINTILLATOR SURFACE IS VERY IMPORTANT



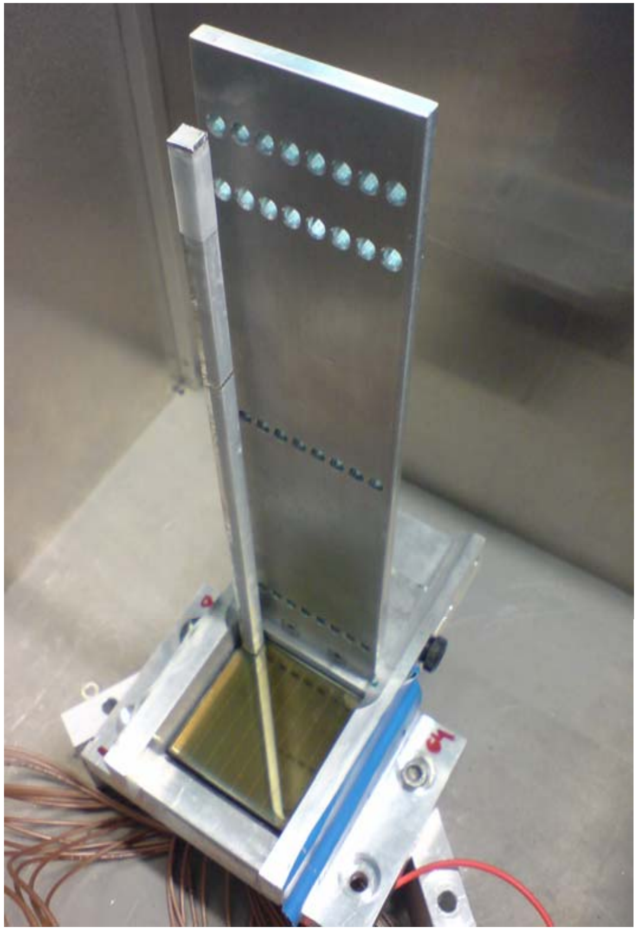
- EXPERIMENTAL MEASUREMENTS ARE FINISHED FOR 2 AND 3 AND THEY AGREE WITH THE SIMULATIONS.

LIGHT COLLECTION MEASURMENTS

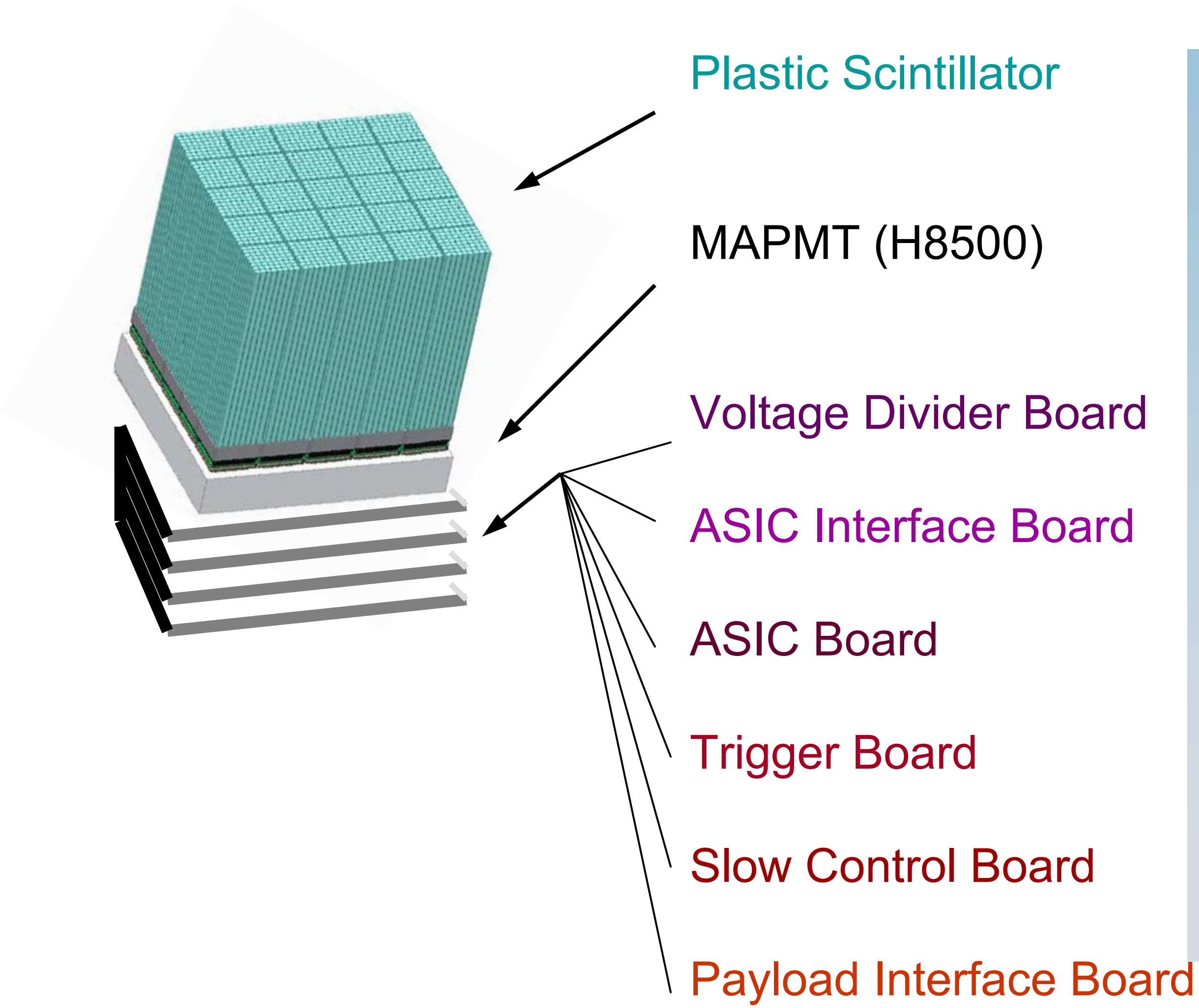
- Goal: optimize light output linearity
- Sources: ^{241}Am, ^{137}Cs, ^{90}Sr
- Wrapping: No coating, Al, Teflon, M3 Foil

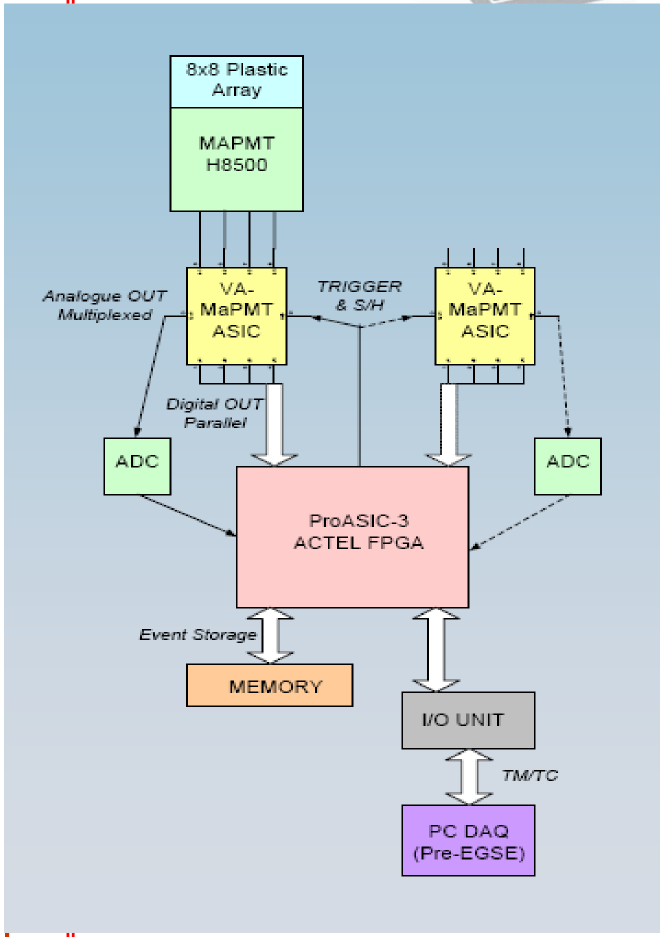
- Results:
  - Less than 10%-15% amplitude change between ends
  - M3 wrapping clearly makes light output highest and should be used

- Results are consistent with MC simulations



The POLAR detector: Electronics

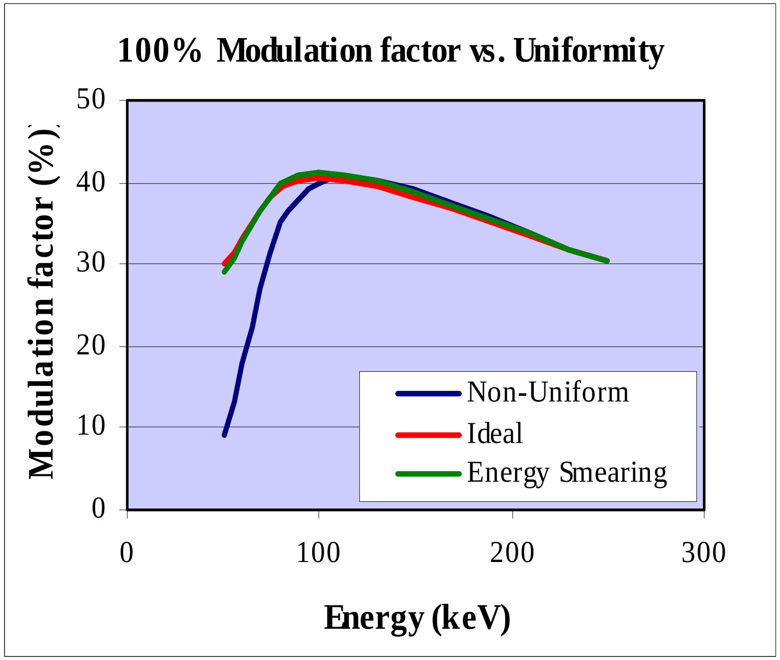




BLOCK FUNCTIONALITY

MAPMT UNIFORMITY STUDIES

- Lack of uniformity affects the modulation factor
- MC for 100% polarized photons coming from above to a central bar
- Conclusions:
  - Non-Uniformity of PM has a strong influence
  - Poor energy resolution from scintillators does not influence so strongly
- Effect should be measured in lab and corrected for



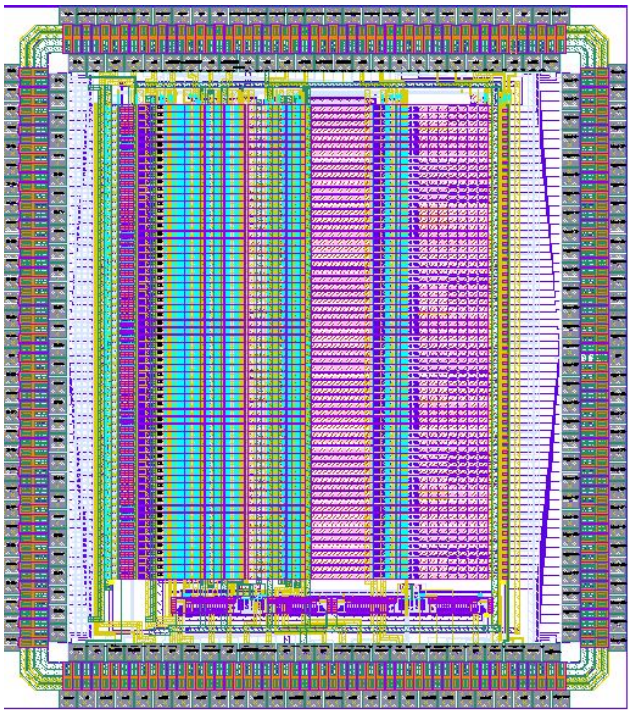
MAROC ASIC

MAROC (LAL-IN2P3) : 64 channels ASIC for ATLAS (CERN) luminometer

- Characteristics
  - 64 PMT channels input
  - Variable gain
  - 64 GTL outputs
  - Multiplexed direct signal output
  - Multiplexed charge output with variable shaping 20-200ns and Track&Hold. Dynamic range 100 photoelectrons
  - Fast unipolar shaping : 0.25-5 ns, dynamic range 10 photoelectrons
  - 3 thresholds loaded by 10bit DAC

- Technology : AMS SiGe 0.35µm
  - Area 12 mm^2
  - Dissipation O(100 mW)

Layout of PMT64_lumi



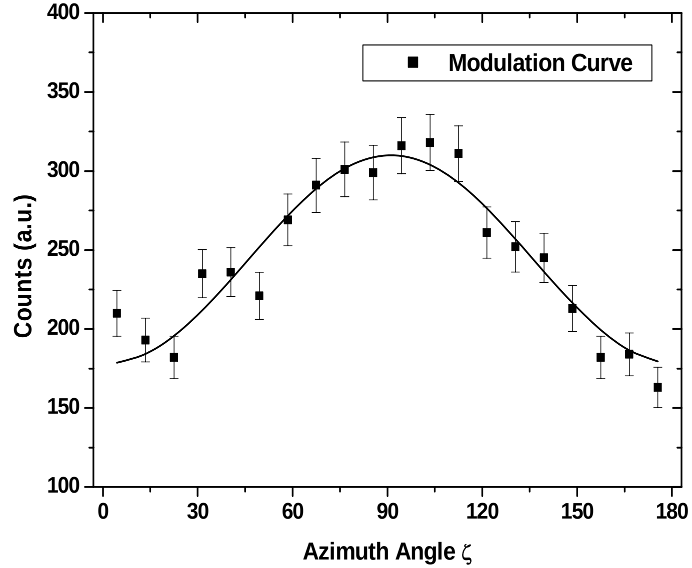
Monte Carlo Results

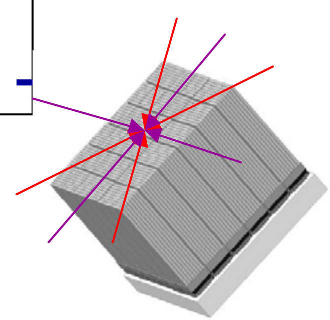
- Analysis uses two largest energy deposits with E_{THR} = 5 keV
  (corresponding to electron recoil energy from 50 keV photon scattered at 90°)
- GRB position is known (e.g. GCN)
- Fit function:

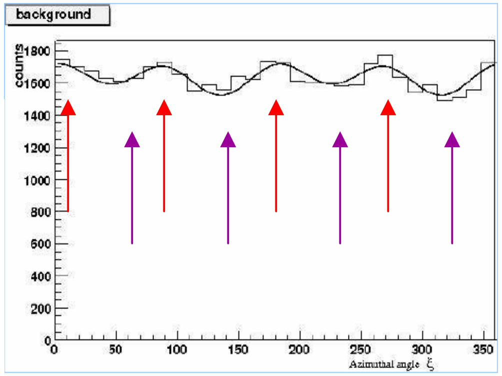
  $$N = A \cdot \cos(2(\eta - \phi) + \tfrac{1}{2}\pi) + B$$

  ϕ – polarization direction
- MC predicts clear modulation signal with period π
- Unpolarized photons create pattern with period $\pi/2$

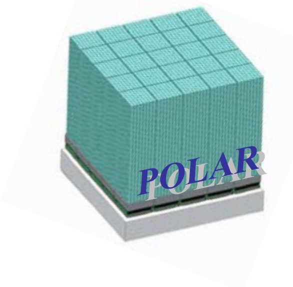
Direction and Spectrum known
Implies less systematic, less MC simulated cases for cross-checks…





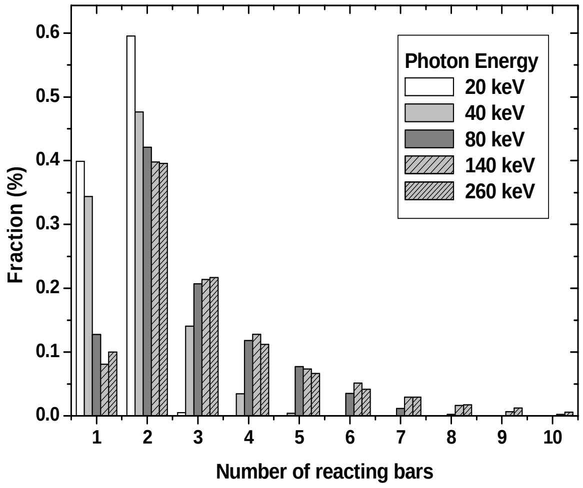


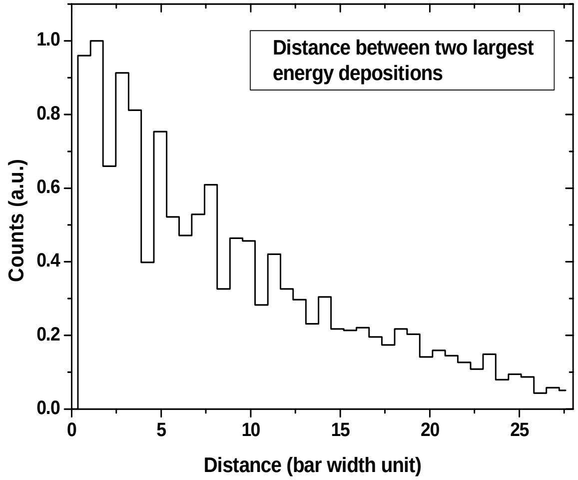
MULTIPLICITY AND TRIGGER CONCEPT (MC RESULTS)



- Most photons deposit energy in several bars
- Threshold set at E_{MIN}= 5 keV
- Upper threshold E_{SUM}< 300+ keV (total sum) (TBC)
- Trigger activation: at least 2 channels

- Selection of two highest E deposits
- Reacting pixels define geometry
- Further (on/off-line) cuts possible





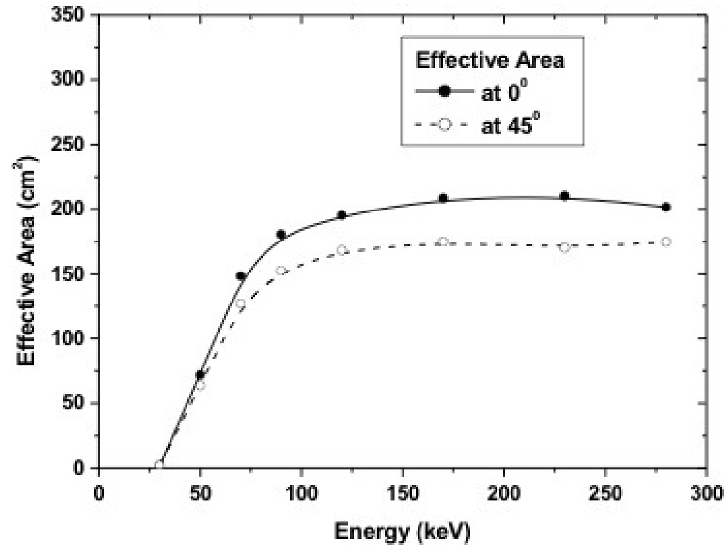
Performance (MC results)

- Maximum effective area for monochromatic photons

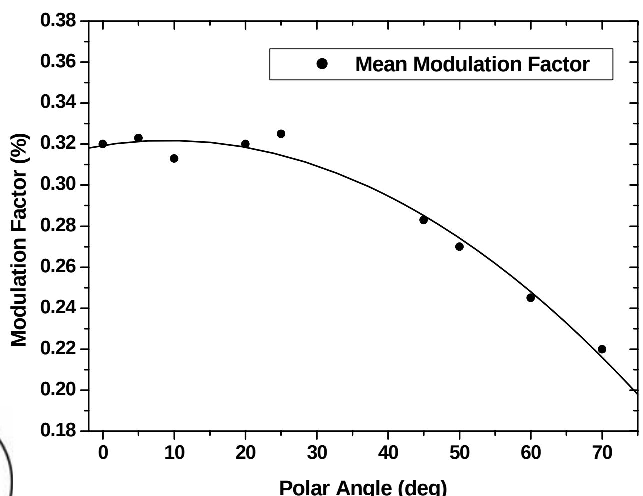
  $\varepsilon \cdot A = A_{EFF} \approx 200\ cm^2$ *(32x32 bars)*

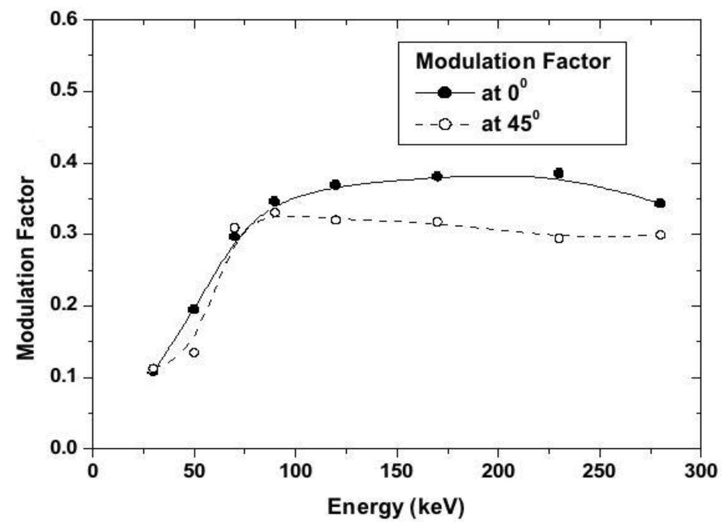
  ($A_{EFF} \approx 350\ cm^2$ with the new geometry)

- Polar angular dependence varies within 15% only
- Maximum Modulation Factor is 30% - 40%



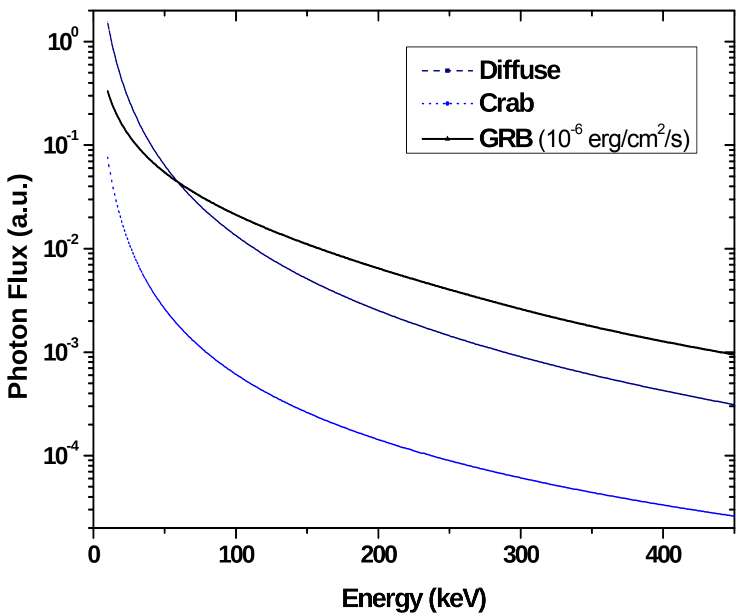
- Constant values kept up to $\theta_\gamma = 30°$ for off-axis GRB



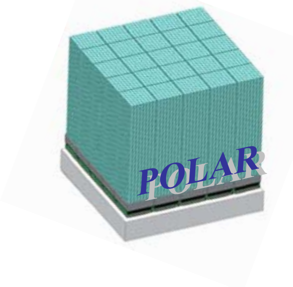


BACKGROUND SOURCES

- Cosmic rays removed by upper energy threshold
- Diffuse background $E_{\gamma,bg}$>10 keV
  F_{dif}=2.46 /cm²/sr/s – 430 coinc./s
- Non-GRB γ sources – e.g. Crab
  F_{Crab}=0.7 /cm²/s
- S/C induced γ's – ISGRI estimated
  F_{ind}=0.02 /cm²/sr/s
- Weaker GRBs at lower energies require careful background subtraction



MINIMUM DETECTABLE POLARIZATION



- MDP = $n_\sigma / \mu_{100} S \cdot \sqrt{(S+B)/T}$

B - background rates from S/C induced and diffuse ≈ 500 s^{-1}

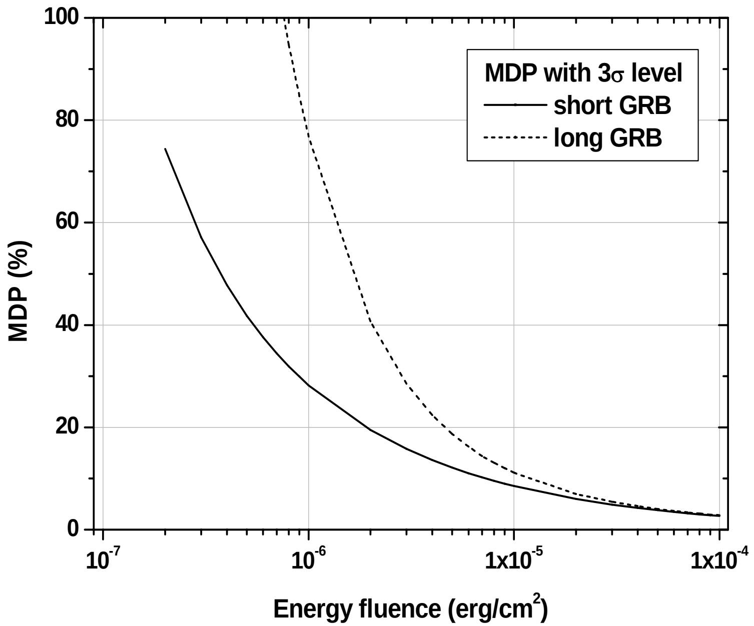
n_σ = 3, A_{eff} = 100 cm^2, μ_{100} = 30%,
T = 0.3, 20 s (short/long GRB)

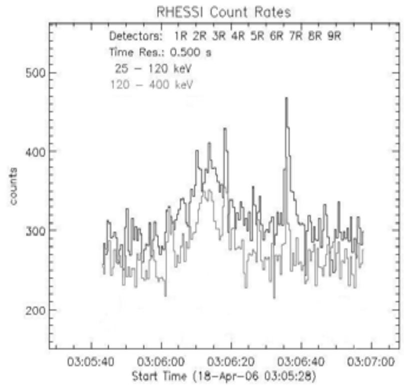
S – signal rate from Band spectrum
E_{Peak} = 320 keV, α = -1.6, β = -2.5

- E=10^{-5} erg/cm^2 → $MDP_{3\sigma}$ ≈ 10%

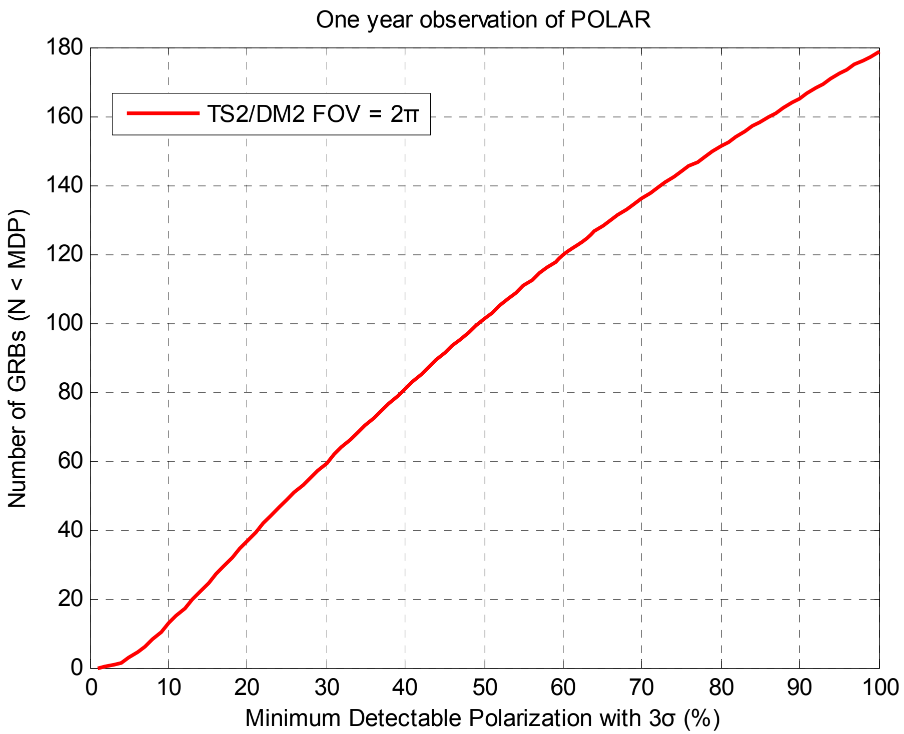
example LTC GRB060418 by RHESSI

- Several measurements per year !





Analysis Cut Optimization



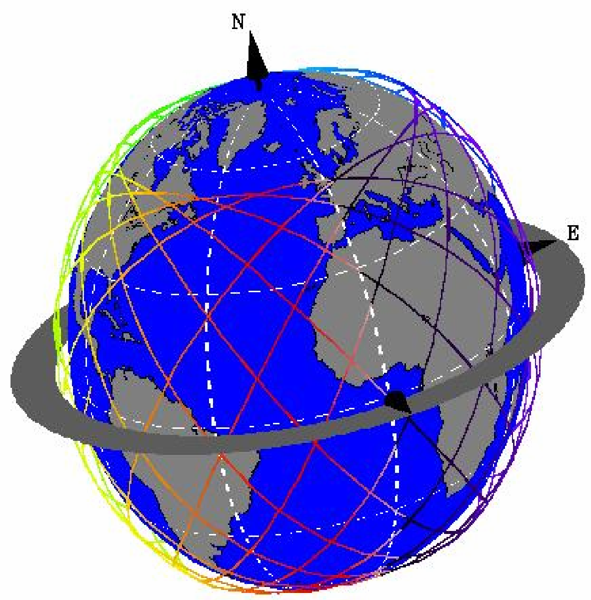
DM2 / TS2 / FOV = 2π

DM2: 40*40 bars, 28*28cm, 20kg
TS2: Edsec >= 5 keV &
the total Ed < 400 keV &
exclude the adjacent case

MDP	5%	10%	15%	20%	25%	30%
Number of GRB in 1 year	2.9	12.7	24.4	36.8	48.6	59.4

- GEO orbit: very high background during all orbit
- LEO orbit: good one.
  - Low background except for the SAA.

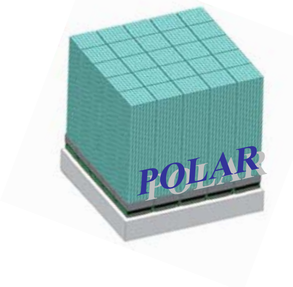
- Electrons and Protons at LEO from NASA models
- Spectra taken in the middle of South Atlantic Anomaly SAA
- Flux – counting rate studies across the SAA passage



BACKGROUND SUMMARY

Source	Flux (detections s^{-1} bar^{-1})	Accidental coincidences (s^{-1}) in POLAR	Edep Mean	Edep Max	Maximum of the Spectrum at:
GEO Electrons	53516	230000	280 keV	2200 keV	115 keV
SAA Electrons	700	100	108 keV	1600 keV	5 keV
SAA Protons	50	-	5 MeV	20 MeV	3 MeV
Cosmic Ray Protons	0.8	-	1600 keV	10 MeV	1200 keV

Project Milestones



DEMONSTRATOR 2x64 channels

Validation for beginning of 2008

- MC studies
- Electronic (ASIC, Trigger, Firmware – FPGA) and Scintillator testing
- Radioactive sources tests
- Polarized source final tests

POLAR Engineering Qualification Model

June 2007- June 2010

- Requirements definition
- Subsystems R&D
- Read-out and software project development
- Space qualification of the elements and global tests of the EM
- Payload specification

POLAR Flight Model

June 2009 – June 2011

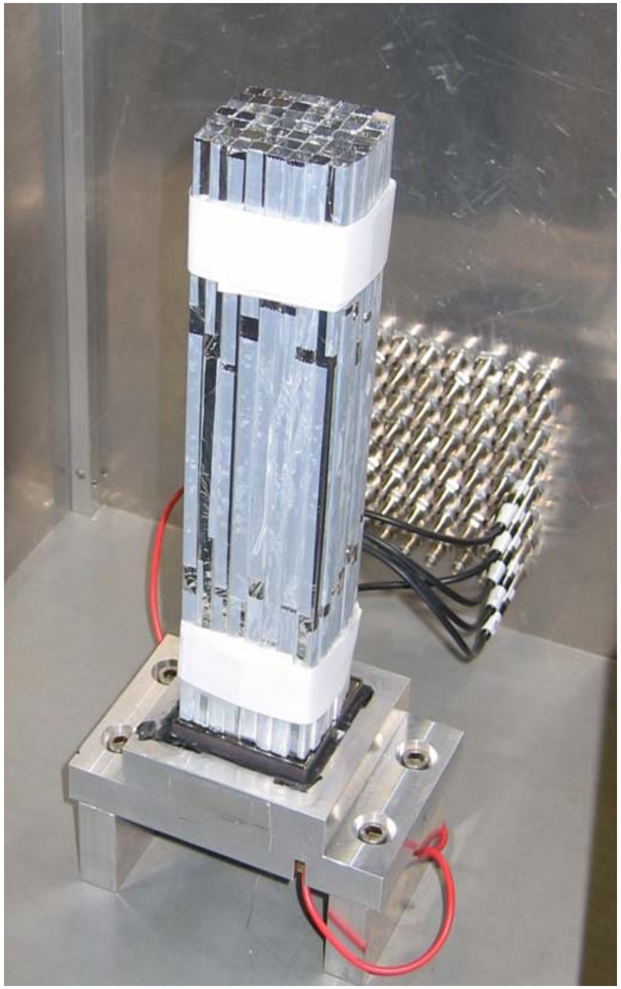
- Commissioning
- Ground segment definition
- Ready for launch

IN PREPARATION: DEMO MODEL TESTS

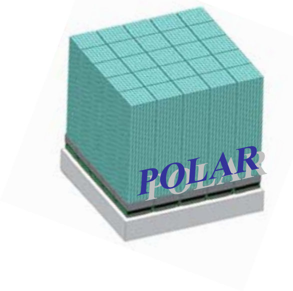
- 64 HIGHLY POLISHED SCINTILLATING BARS

- DEMO = 2 OUT OF 25 MODULES:
  - 2 x (8x8) SCINTILLATOR ARRAY
  - 2 x 64 BC400 BARS (6x6x200 MM^3 EACH)
  - 2 x H8500 MAPM

- SPECIALLY DESIGNED ELECTRONIC BOARD
- DAQ: LABWINDOWS ROUTINES
- TEST WITH POLARIZED γ-RAYS FROM SOURCE
- PSI SLS SYNCHROTRON POLARIZED γ-RAYS
  - VARIOUS ENERGIES UP TO MANY TENS KEV



Near-Term Goals



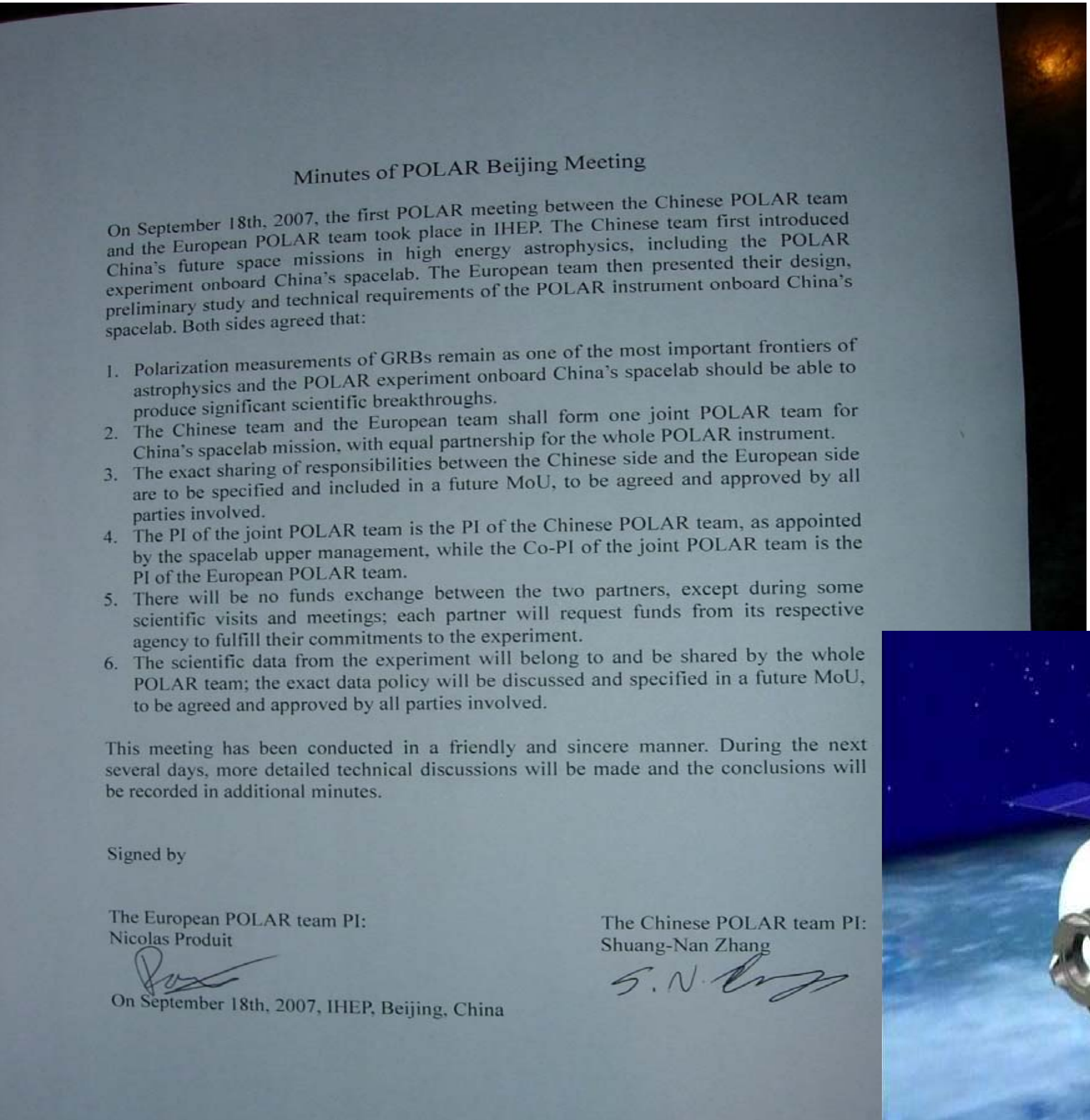
DEMONSTRATOR

- Final results report and publication
- Involvement of IHEP/TSING HUA (Review in China)

POLAR Engineering Qualification Model

- Requirements definition
  - Towards : MoU and Technical Report
- Subsystems R&D
  - Scintillator production definition
  - Mechanics
  - ASIC definition
- Read-out and software project development
  - MC and event reconstruction
- Space qualification of the elements and global tests of the EM
  - Sites and laboratories definition

Europe-China Agreement



Minutes of POLAR Beijing Meeting

On September 18th, 2007, the first POLAR meeting between the Chinese POLAR team and the European POLAR team took place in IHEP. The Chinese team first introduced China's future space missions in high energy astrophysics, including the POLAR experiment onboard China's spacelab. The European team then presented their design, preliminary study and technical requirements of the POLAR instrument onboard China's spacelab. Both sides agreed that:

1. Polarization measurements of GRBs remain as one of the most important frontiers of astrophysics and the POLAR experiment onboard China's spacelab should be able to produce significant scientific breakthroughs.
2. The Chinese team and the European team shall form one joint POLAR team for China's spacelab mission, with equal partnership for the whole POLAR instrument.
3. The exact sharing of responsibilities between the Chinese side and the European side are to be specified and included in a future MoU, to be agreed and approved by all parties involved.
4. The PI of the joint POLAR team is the PI of the Chinese POLAR team, as appointed by the spacelab upper management, while the Co-PI of the joint POLAR team is the PI of the European POLAR team.
5. There will be no funds exchange between the two partners, except during some scientific visits and meetings; each partner will request funds from its respective agency to fulfill their commitments to the experiment.
6. The scientific data from the experiment will belong to and be shared by the whole POLAR team; the exact data policy will be discussed and specified in a future MoU, to be agreed and approved by all parties involved.

This meeting has been conducted in a friendly and sincere manner. During the next several days, more detailed technical discussions will be made and the conclusions will be recorded in additional minutes.

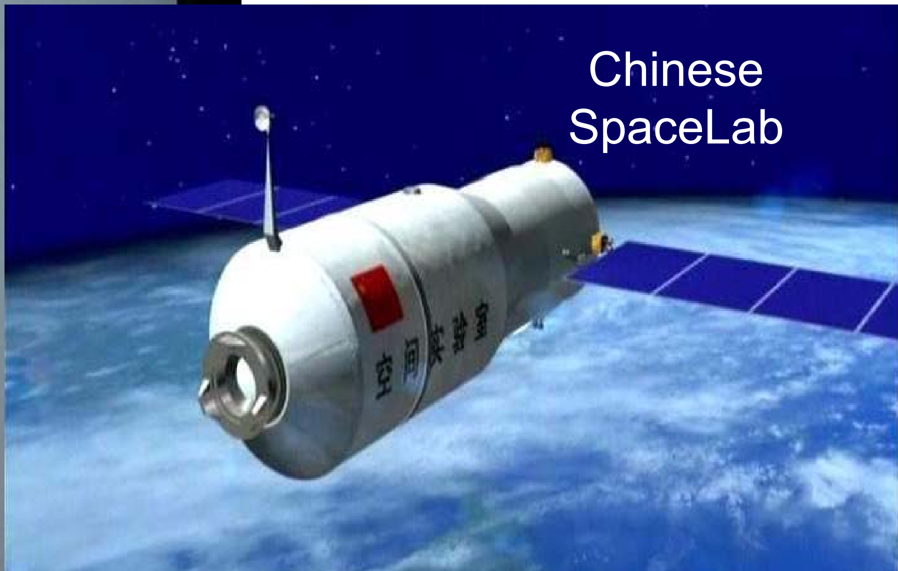
Signed by

The European POLAR team PI:
Nicolas Produit

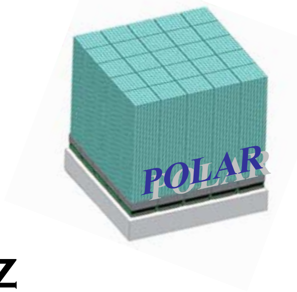
The Chinese POLAR team PI:
Shuang-Nan Zhang

S. N. Zhang

On September 18th, 2007, IHEP, Beijing, China



SUMMARY



- POLAR – Compton hard X-ray GRB polarimeter using low Z scintillators
- 40x40 homogeneous array of 6x6x200 mm^3 plastic bars

- FoV ≈ ⅓ of the sky and low γ energy threshold $E_{MIN} < 50$ keV
- $A_{EFF} \approx 400$ cm^2 and $\mu_{100} \approx 40\%$ at 200 keV
- $MDP_{3\sigma} \approx 10\%$ for GRB total energy of 10^{-5} erg/cm^2; tens of detections/year

- First asymmetry results obtained demonstrating polarimetric capability

- Engineering Qualification Model under development

- Collaboration with IHEP to include POLAR in forthcoming satellite experiments

Conclusions

- We try to solve an important scientific problem
- The detector is small and use proven techniques that where flown already in space
- First international scientific collaboration in the Chinese space manned program.
- We expect science results published in 2013