PoGOLite: opening a new window on the Universe with polarised gamma-rays

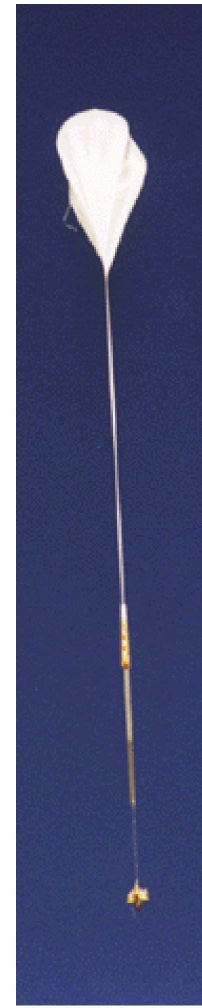
Mark Pearce

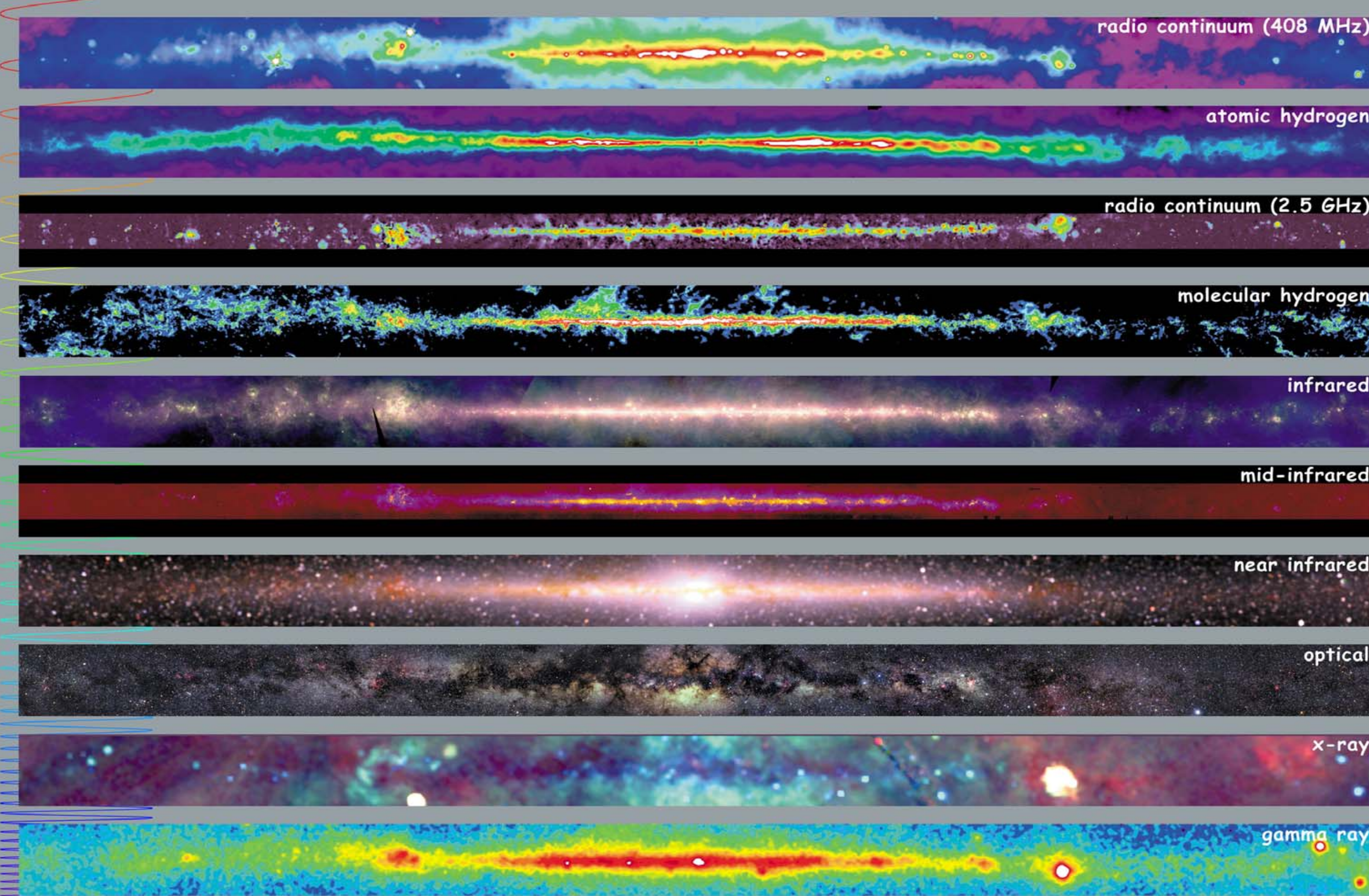
KTH Particle and Astrophysics Group

Instrumentation Seminar / AlbaNova / 2006-04-20

Overview of presentation

- **Scientific goals** of the PoGOLite experiment
- The PoGOLite **instrument design**
- **Performance studies**
  - Simulations of Crab pulsar observations
  - Tests at a polarised photon beam
- Scientific **ballooning**
- The Swedish PoGOLite consortium

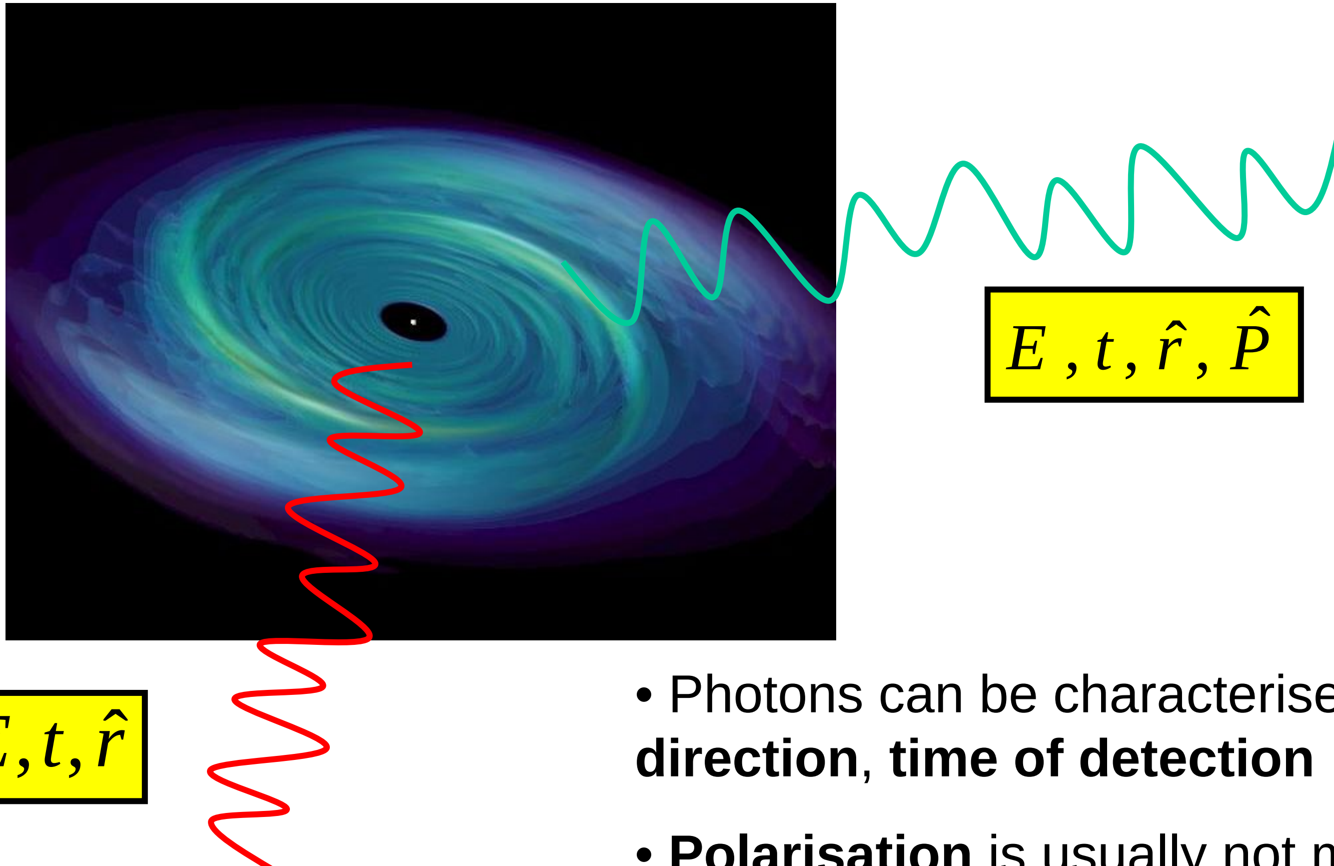




http://adc.gsfc.nasa.gov/mw

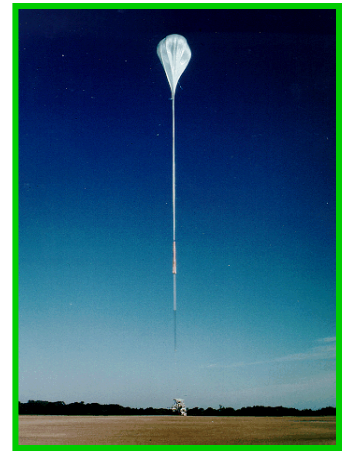
Multiwavelength Milky Way

A New View of the Universe



$$E\,,t\,,\hat{r}\,,\hat{P}$$

P o G OLite



[25 – 100 keV]

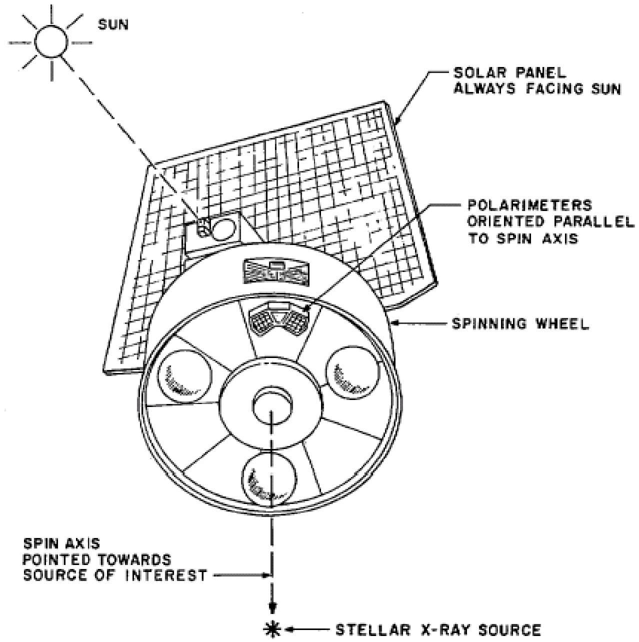
$$E,t,\hat{r}$$

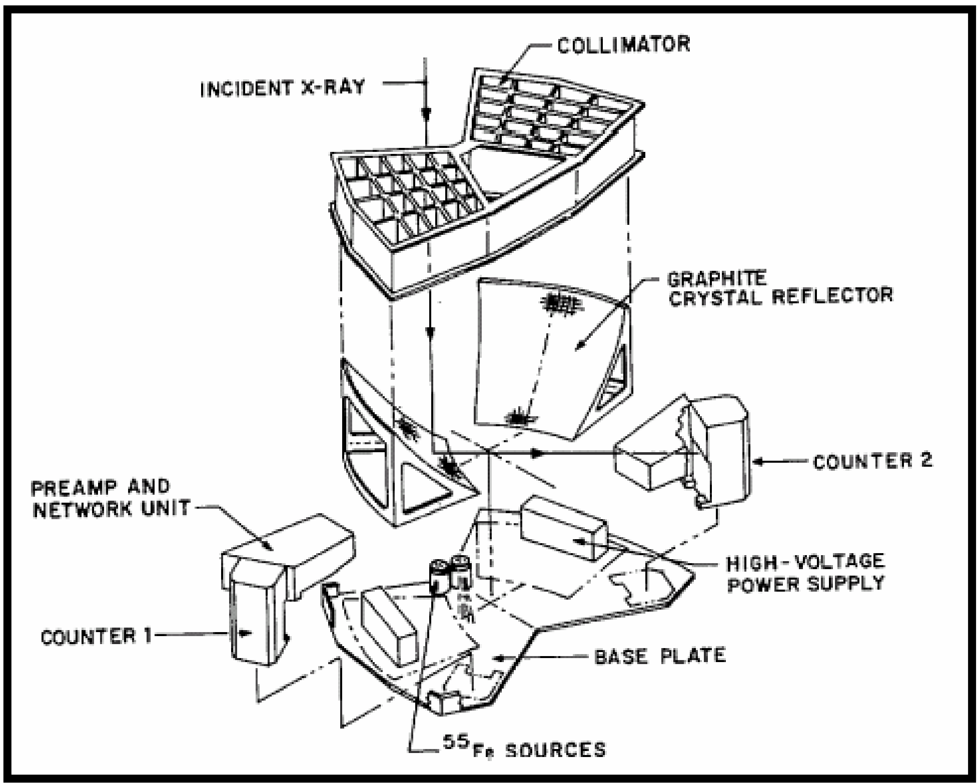
G L A S T

[10 keV – 300 GeV]

- Photons can be characterised by their **energy**, **direction**, **time of detection**
- **Polarisation** is usually not measured (once in 1976…)
- Measuring the polarisation of gamma-ray provides a powerful diagnostic for sources
- Polarisation can occur through scattering / synchrotron processes, interactions with a strong magnetic field
    - Sensitive to the history of the photon

OSO-8 (1976)

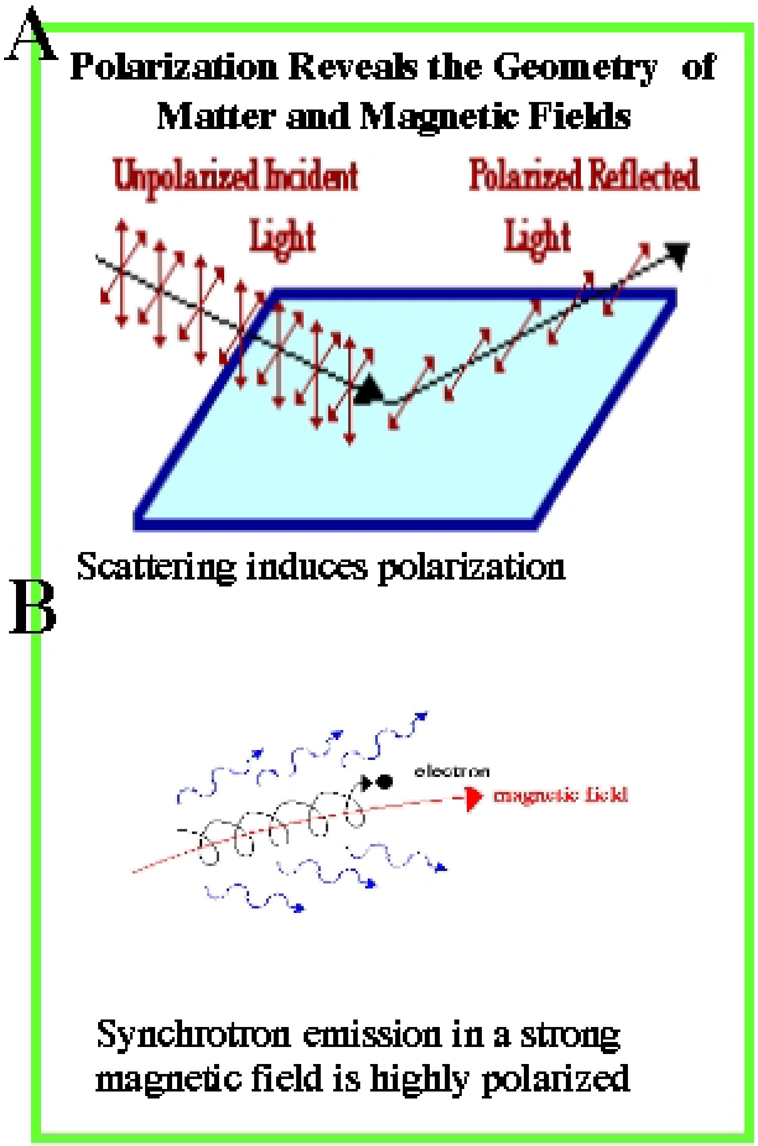




- Crab Nebula viewed at 2.6 keV, 5.2 keV
- Polarisation measured using Bragg diffraction: (16.1±1.4)%
- No measurements since then!
- At higher (soft γ-ray) energies, non-thermal processes are expected to increase polarisation

[M. Weisskopf et al, ApJ 208 L125 (1976), ApJ 220 L117 (1978)]

Polarisation as a probe



Re-scattered via Compton scattering

- Electric vector is perpendicular to the plane of scattering
- **A polarization measurement determines the geometrical relation between the photon source and the scatterer.**

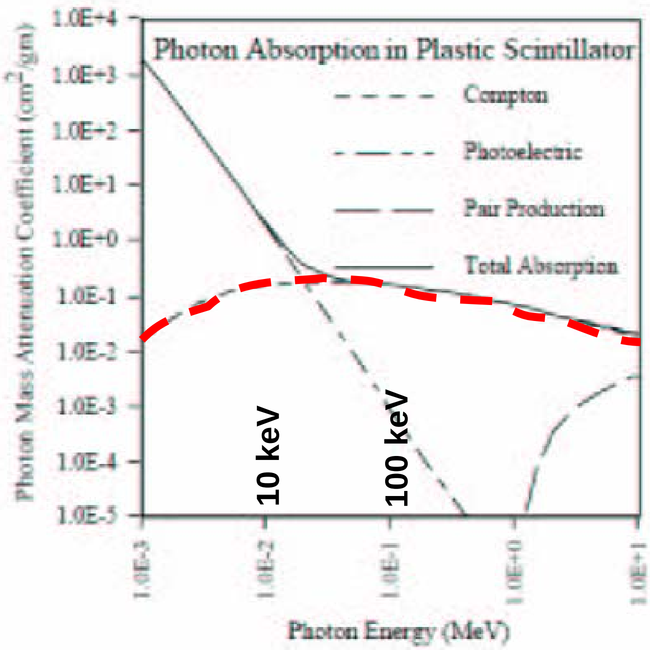
Synchrotron processes

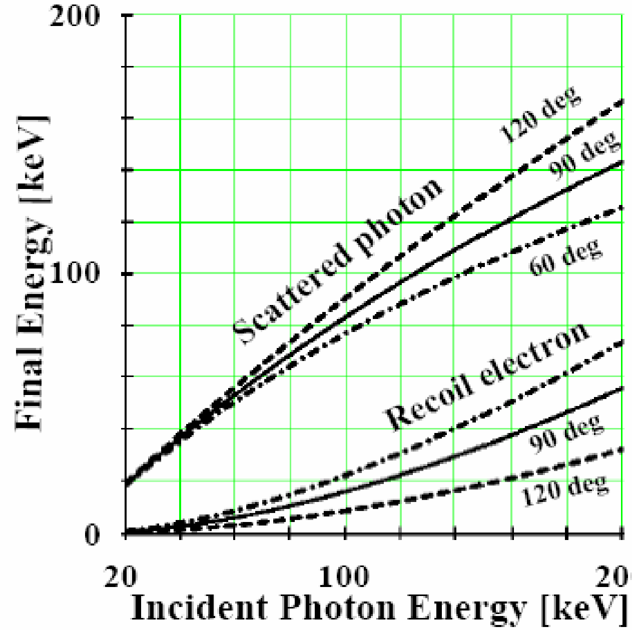
- Electrical vector is perpendicular to the magnetic field.
- **A polarization measurement determines the direction of magnetic field.**

Potential targets

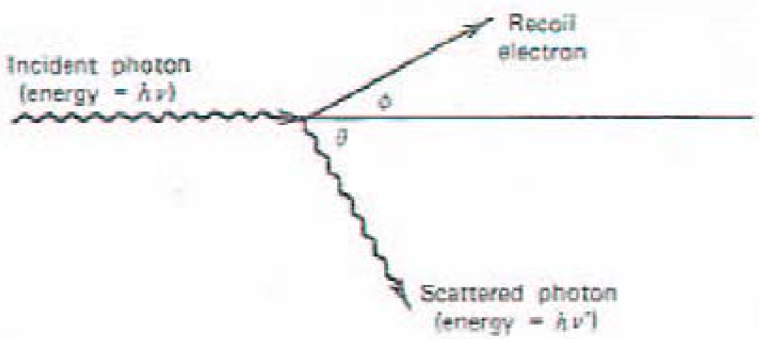
- **Super-massive black holes** where matter accretion powers relativistic jets, accelerates particles, and emits photons via **synchrotron** and **inverse-Compton** mechanisms;
- **Galactic X-ray binaries** where matter accretes onto a black hole or a neutron star and emits hard X-rays. **Inverse-Compton** reflection off the accretion disk polarizes hard X-rays. **Micro-quasars** belong to this category, where the accretion is likely to be powering stellar-scale relativistic jets;
- **Active galaxies** where isotropic emission is scattered toward the Earth by **inverse-Compton** scattering;
- **Accreting neutron stars** with strong **cyclotron line features**;
- Hard X-ray emission from **Soft Gamma-ray Repeaters** with super-critical magnetic fields;
- **Isolated pulsars** with **strong magnetic field**; Crab pulsar – a primary target
- **Ordinary galaxies** (including our own) with extended **inverse Compton** halo;
- **Solar flares and coronae**
- **Gamma-ray bursts (with luck…)**

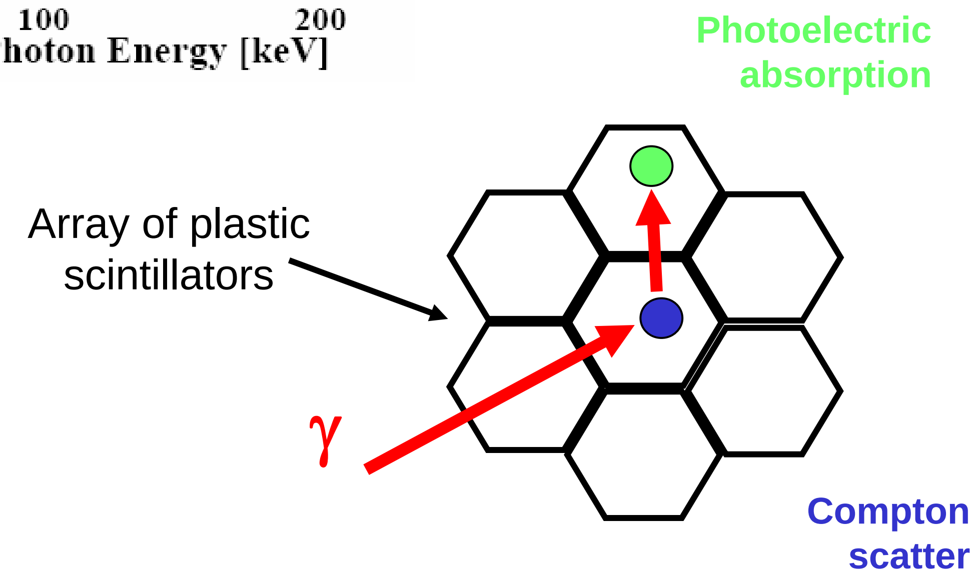
Compton scattering





- Incident γ deposits little energy at Compton site
- Most deposited at photoelectric absorption site
- Large energy difference
- Can be distinguished by simple plastic scintillators (despite intrinsic poor energy resolution)





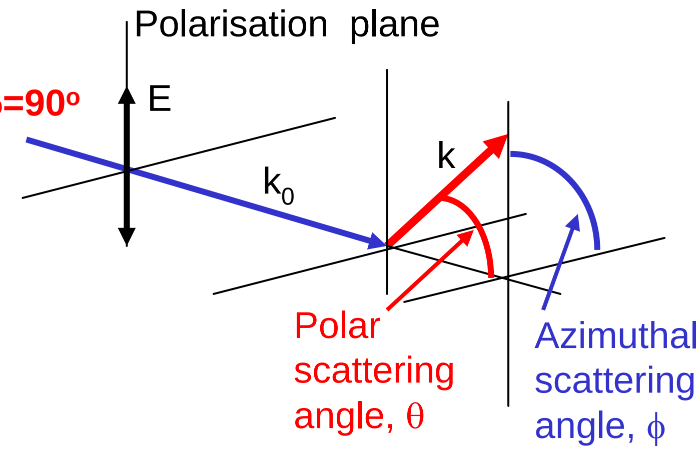
Measuring Polarisation

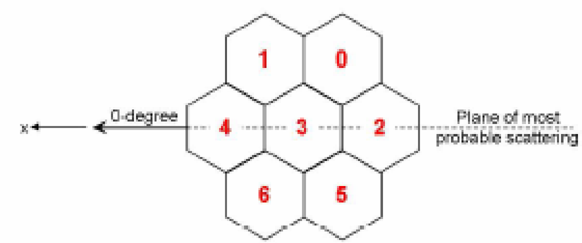
<u>Compton scattering</u>: Klein-Nishina formula

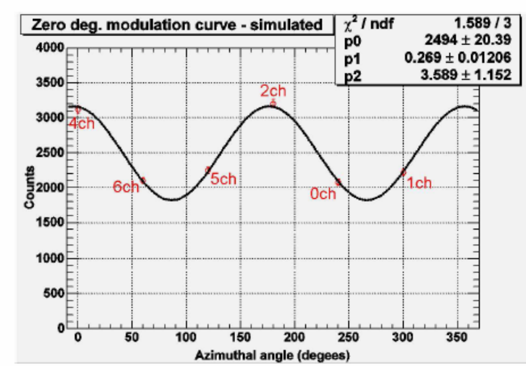
0 when ϕ=90º

$$\boxed{\frac{d\sigma}{d\Omega} = \frac{1}{2} r_e^2 \frac{k^2}{k_0^2}\left[\frac{k}{k_0}+\frac{k_0}{k} - 2\sin^2\theta\cos^2\phi\right]}$$

Max when ϕ=90º





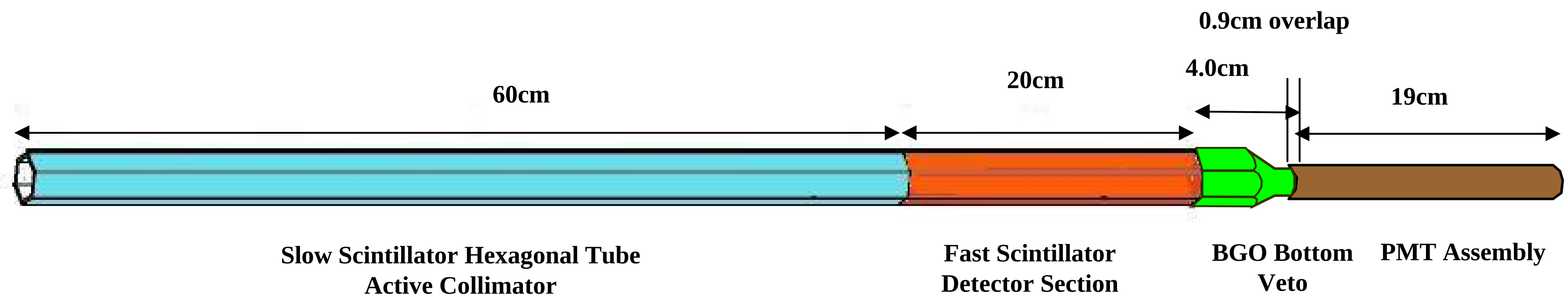


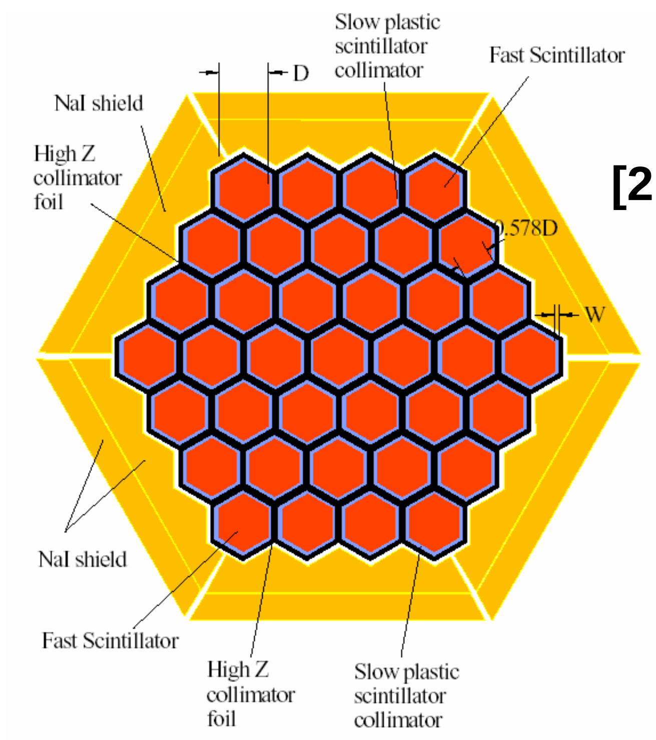
• γ from a **polarised** source undergo Compton scattering in suitable detector material

• Higher probability of being scattered perpendicular to the electric field vector (polarisation direction)

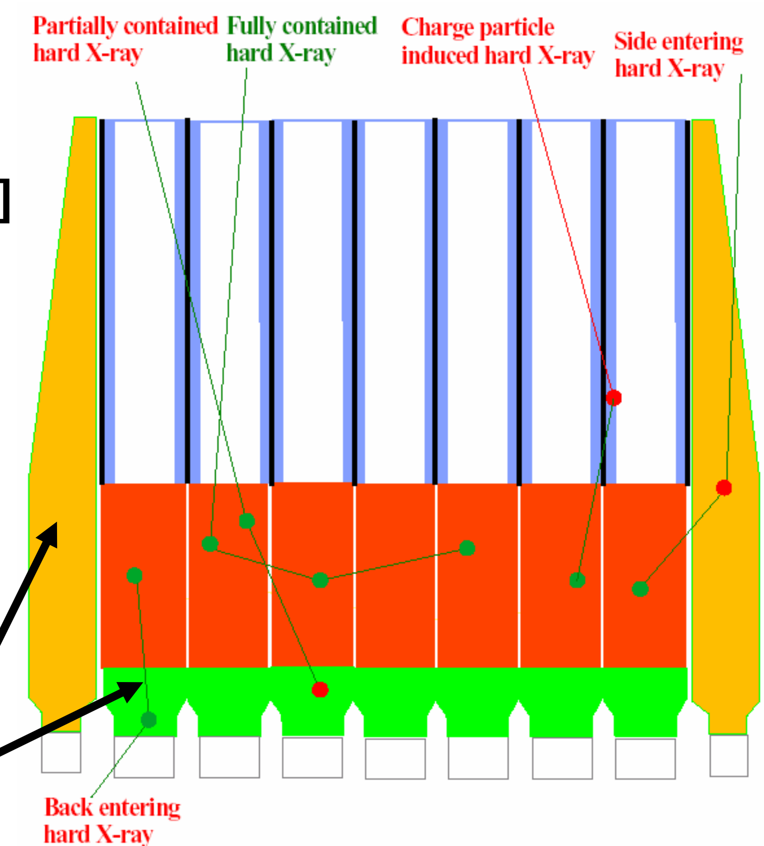
• Observed **azimuthal scattering angles** are therefore **modulated by polarisation**

PoGOLite instrument schematic





[217 wells in reality]

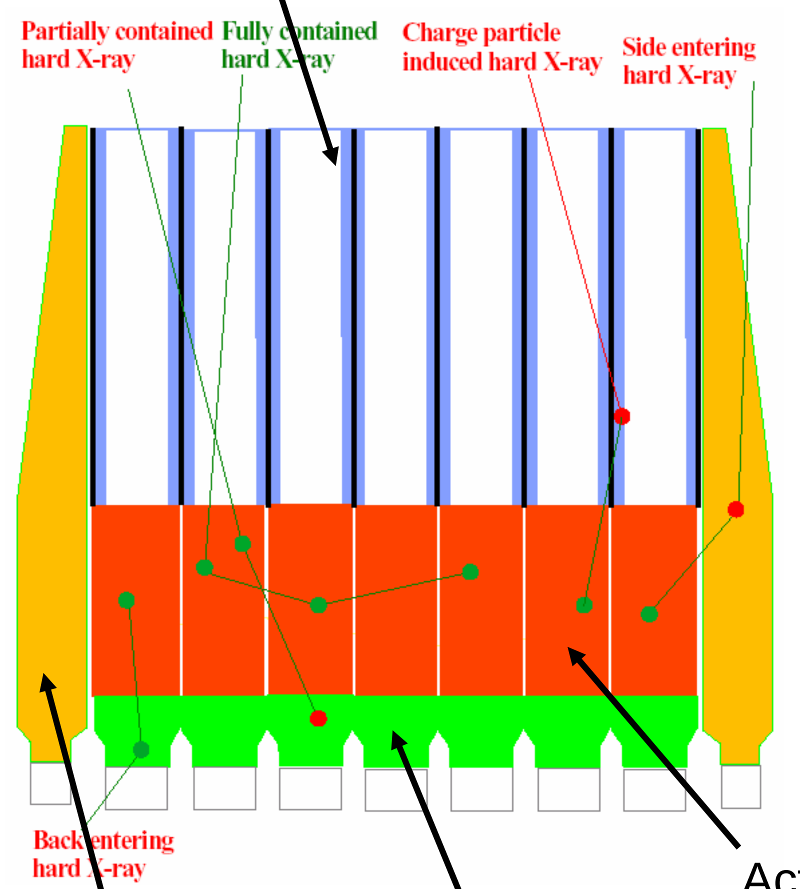


BGO
anticoincidence

Mark Pearce - KTH Stockholm -

Key design features

Charged particle anticoincidence.
Active γ collimation



Active γ detector

Lower anticoincidence

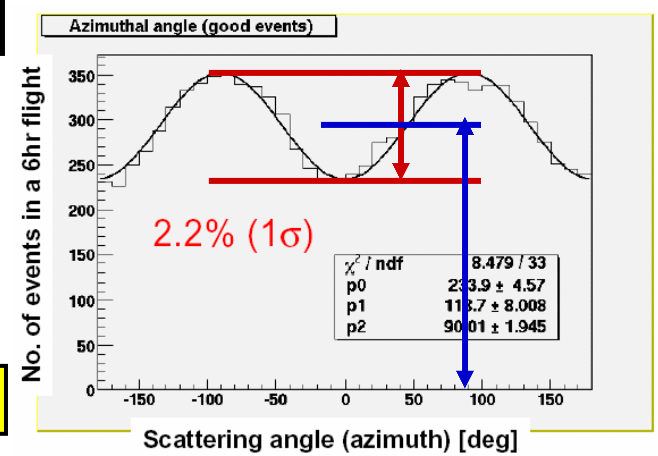
Side anticoincidence

CS S/N

- Energy range (25 keV – 100 keV)
- Sources: $dN/dE \sim E^{-(2\text{-}3)}$
  - @ 25 keV only 1-3 keV Compton deposited $\Rightarrow$ single p.e. detection (PMT has 0.05 p.e. ripple @ 10^6 gain)
- Phoswich design $\Rightarrow$ narrow F.o.V $\Rightarrow$ low backgrounds

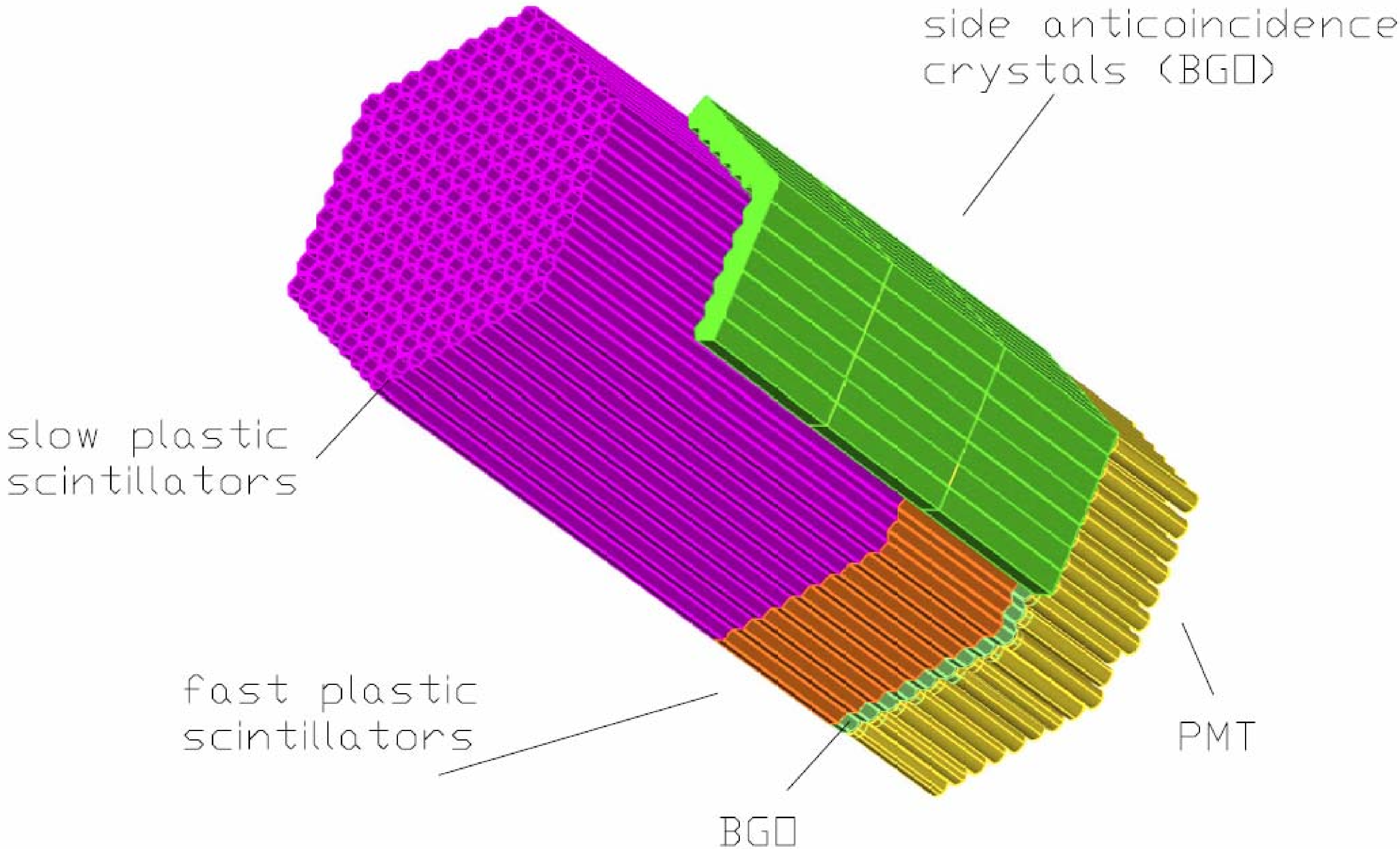
$$\boxed{P_{source} = \frac{M_{obs}}{M_{100}}}$$

Modulation factor
=difference/average

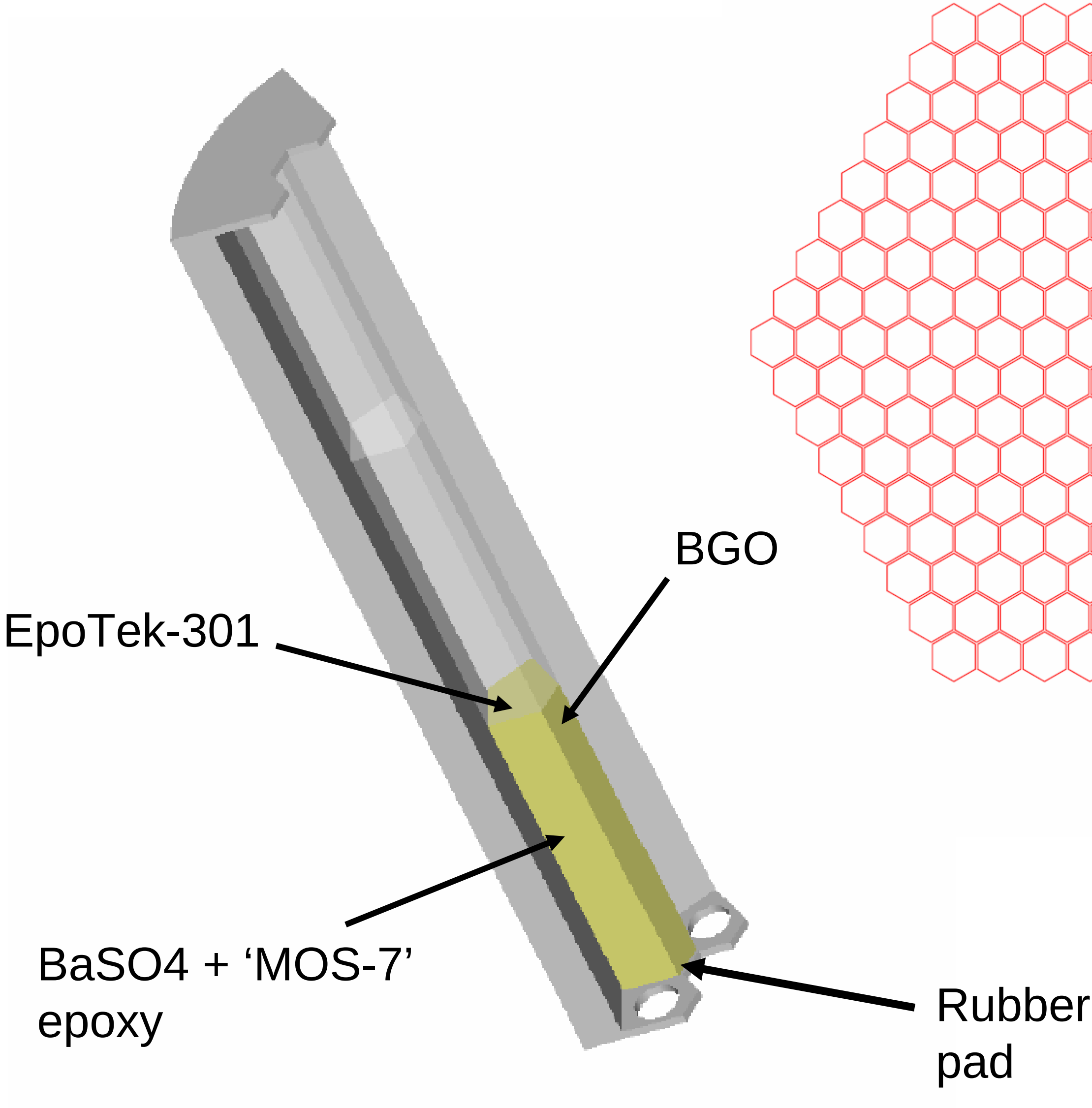


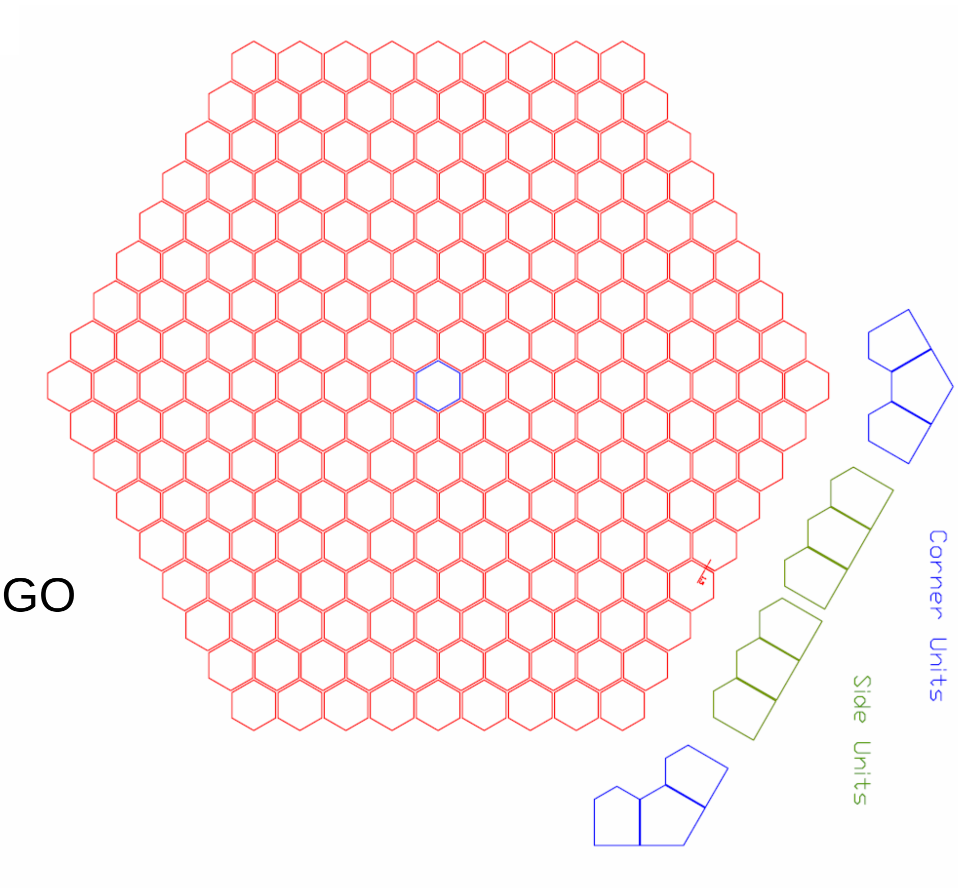
MDP (6 h) ~ 10% @ 100 mCrab

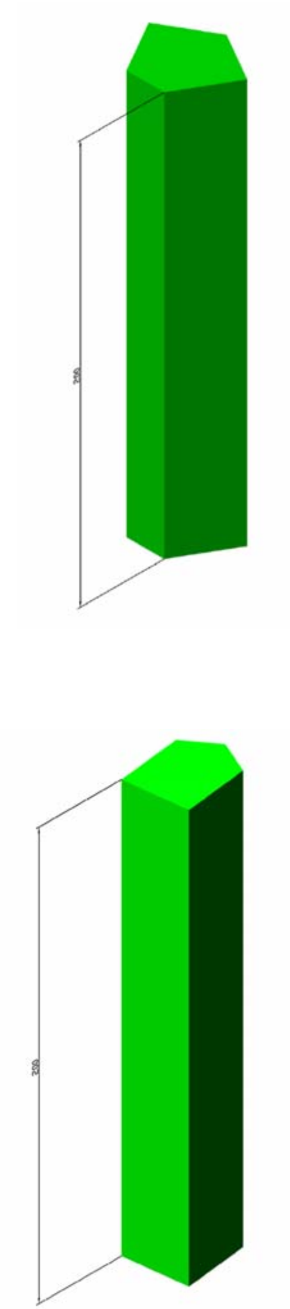
The complete PoGOLite instrument



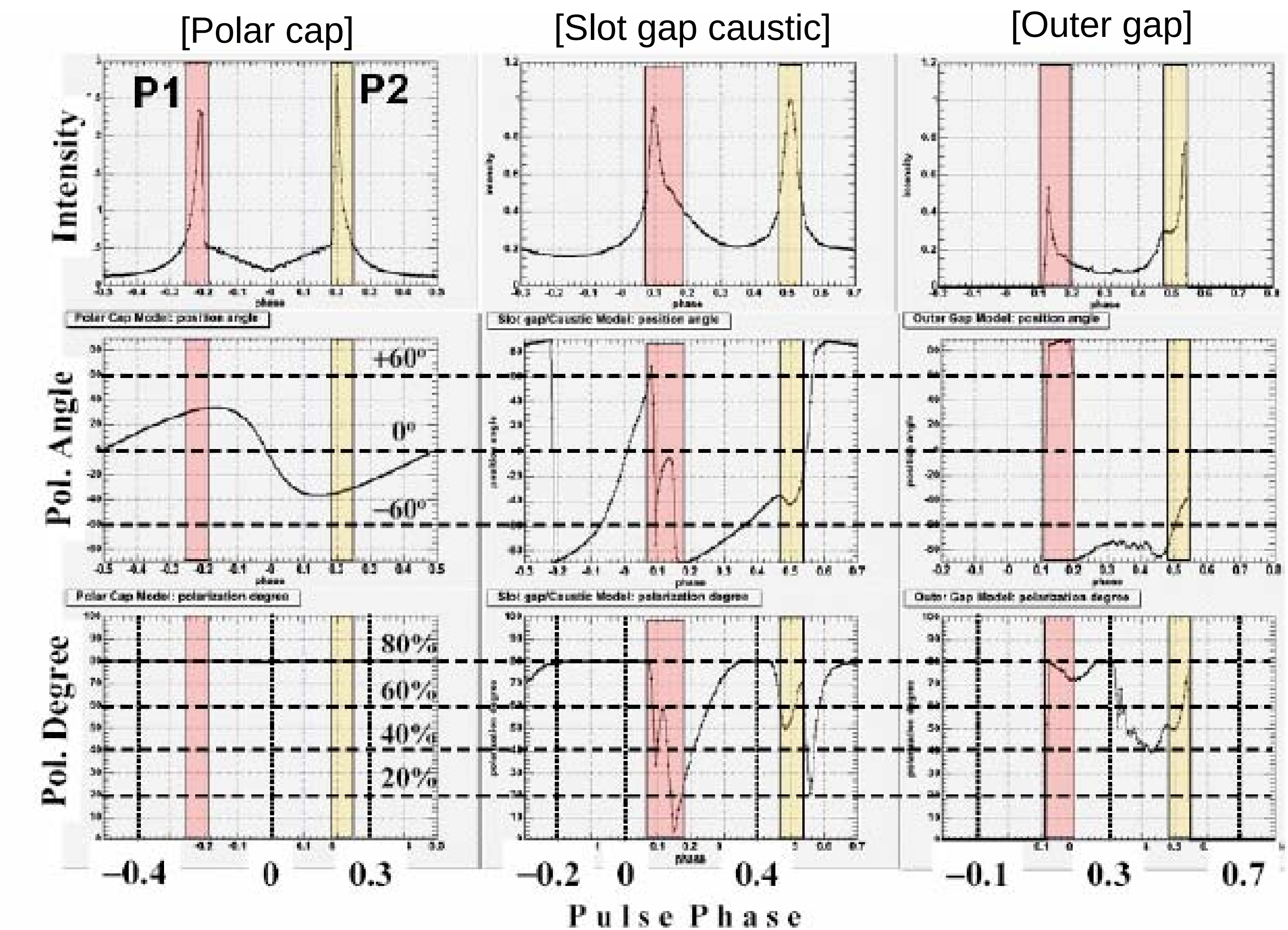
Lateral Anticoincidence







Distinguishing Crab Pulsar models



Crab Pulsar emission mechanism

(OSO-8 assumed)

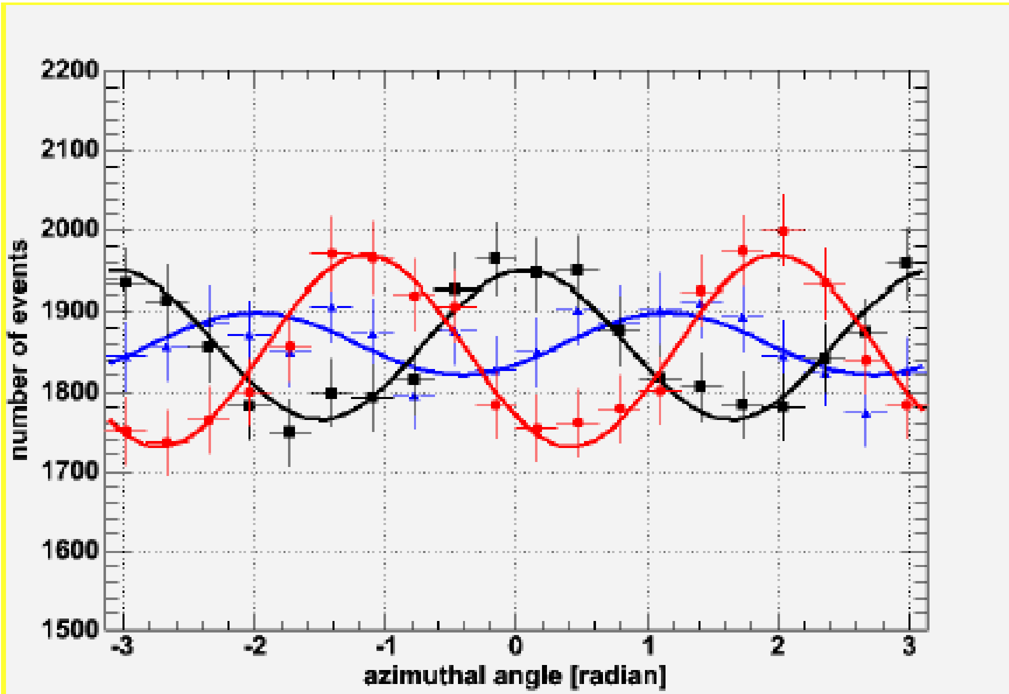
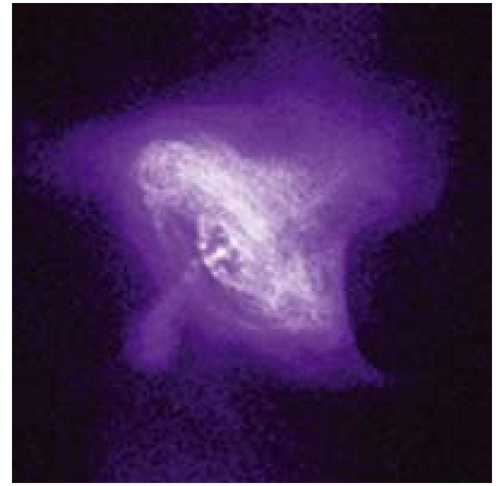
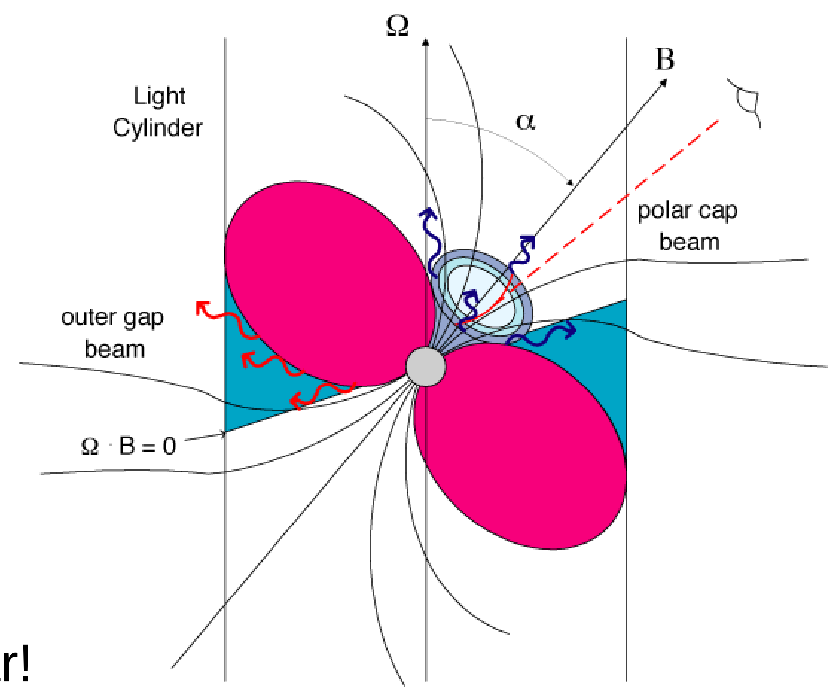


Figure 3.2: The polarization signal that PoGOLite will measure in 6 hrs for P1 of Crab Pulsar (defined in Figure 3.1) for the polar cap (red), slot gap/caustic (blue) and outer gap (black) models.





- Pulsars discovered in 1967
- Gamma-ray emission mechanism still unclear!

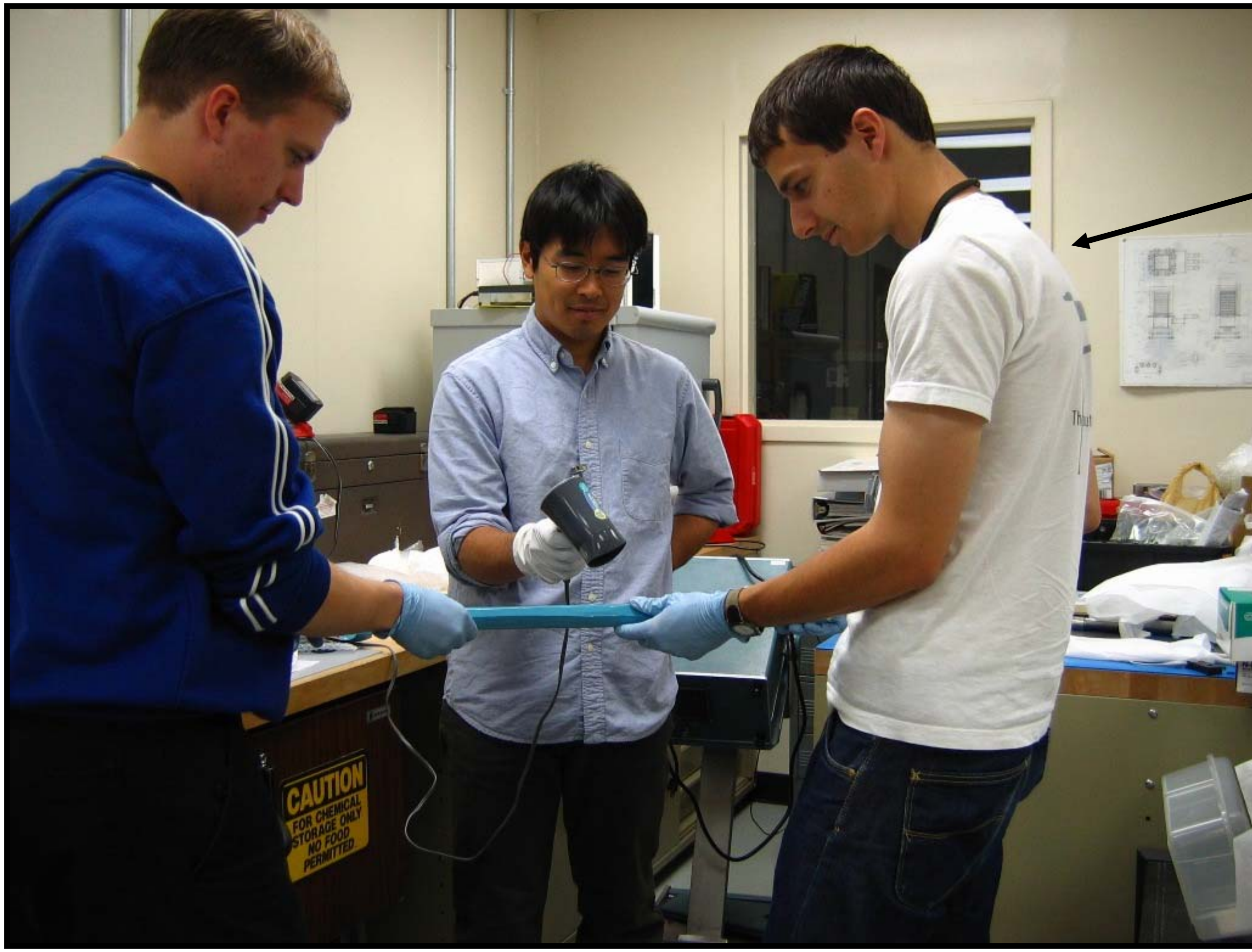
Instrument characteristics

Total weight without ballast=1000kg; Total power=200W; Envelope=3m×2m×2.5m					
	25 keV	30 keV	50 keV	100 keV	Total
Min Detectable Polarization for 100mCrab in 6 hours	10%				
Field of view	1.2msr（2.4 arcmin ×2.4 arcmin）				
Timing resolution	1.0 μs				
Geometric area	934 cm^2				
Effective area for polarization measurements at 4 g/cm^2 overburden	112 cm^2	185 cm^2	244 cm^2	143 cm^2	
Signal rate for a 100mCrab source at 4 g/cm^2 overburden	0.023/s/keV	0.037/s/keV	0.025s/keV	0.0044/s/keV	1.4/s
Background rate at 4 g/cm^2 overburden	0.0038/s/keV	0.0044/s/keV	0.0054/s/keV	0.0081/s/keV	0.36/s
Modulation for 100% polarized beam with Crab spectrum	25.7%.	24.8%	22.3%	40.2%	27.3%

PoGOLite prototype production

Tomi Ylinen

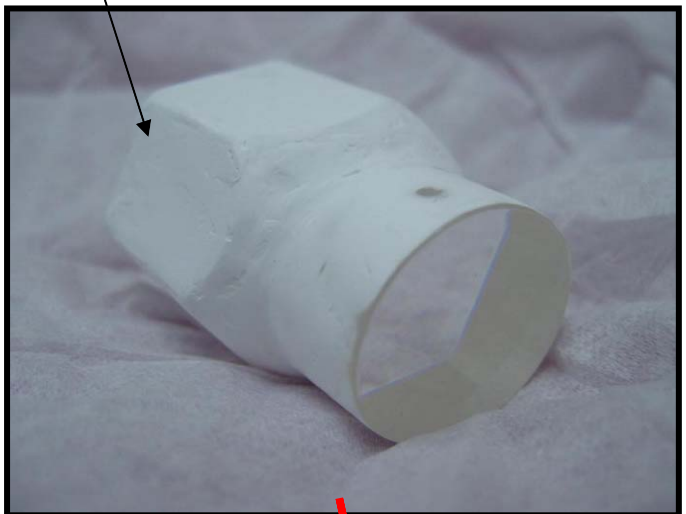
Mószi Kiss

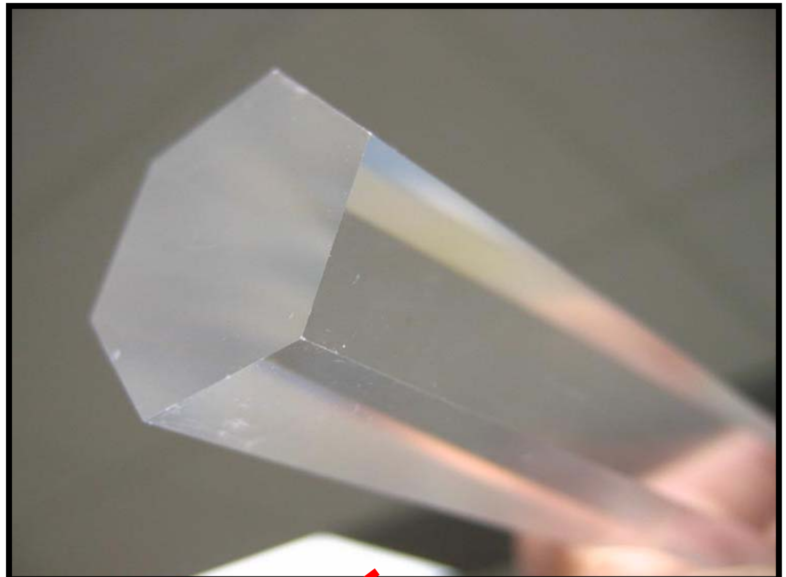


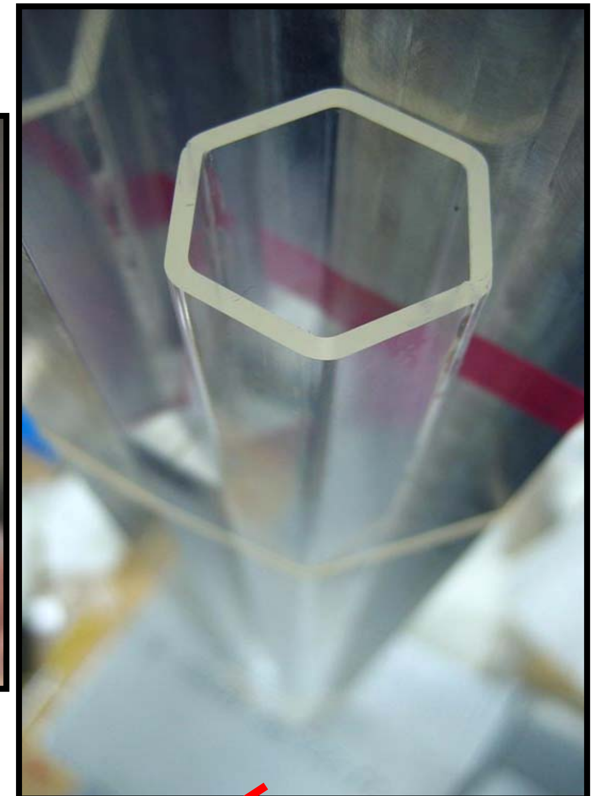
Diploma workers at SLAC (September 2005 – March 2006)

Phoswich detector cell components

BaSO$_4$



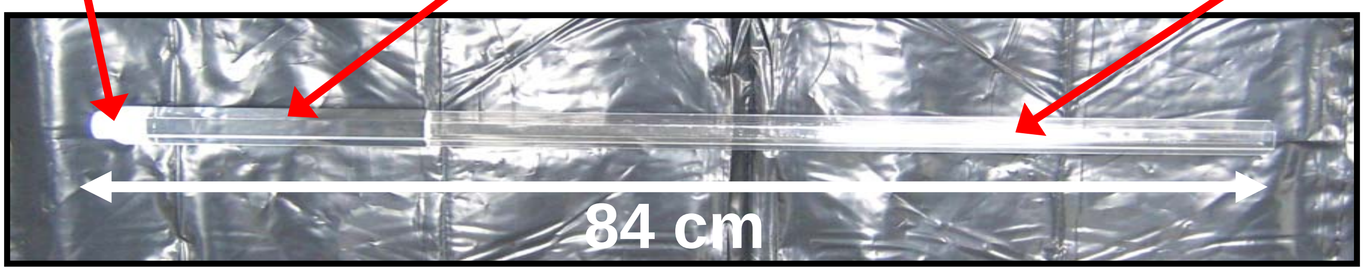




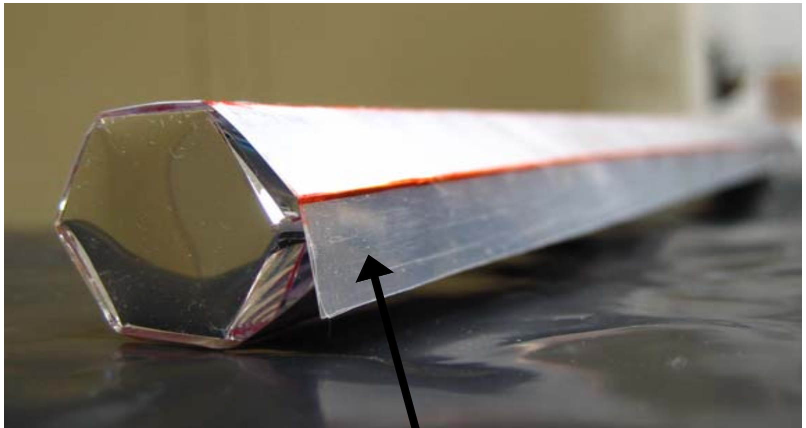
BGO crystal
(4 cm)

Solid “fast” plastic
scintillator (20 cm)

Hollow “slow”
plastic scintillator
(60 cm)



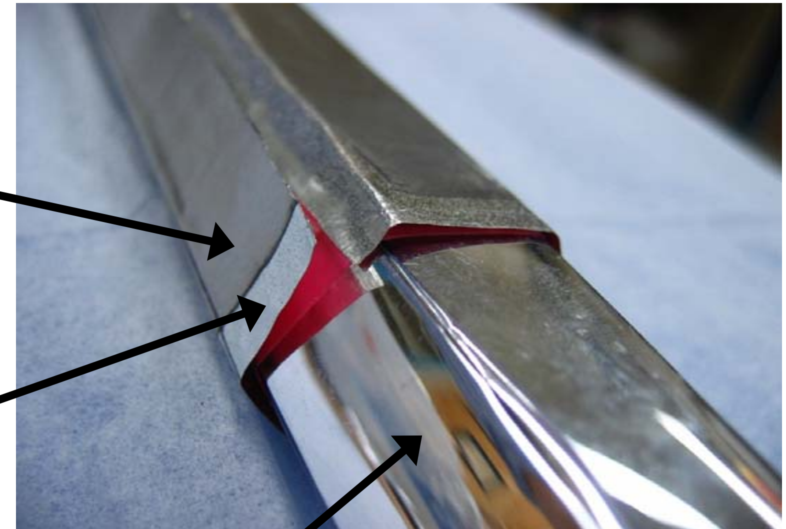
Phoswich detector cell wrapping



VM2000: multilayer birefringent polymer reflector film

Lead foil

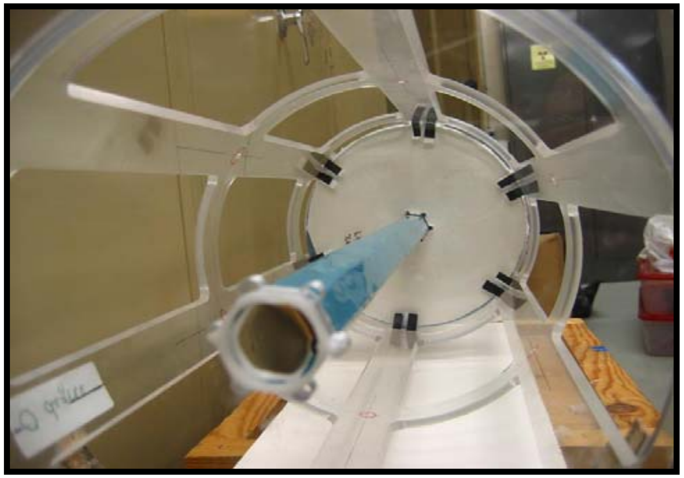
Tin foil



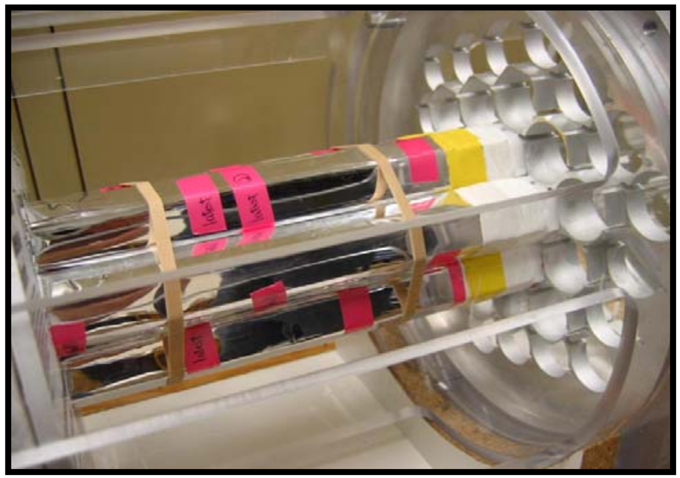
VM2000

Heat shrink tube

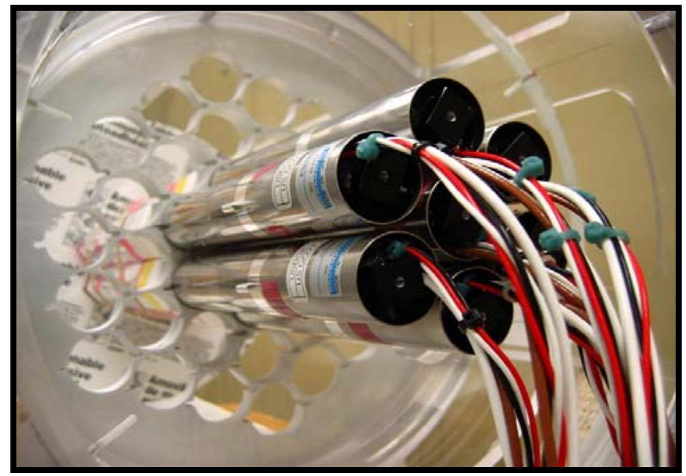
Phoswich detector cell assembly



Central unit (full PDC)

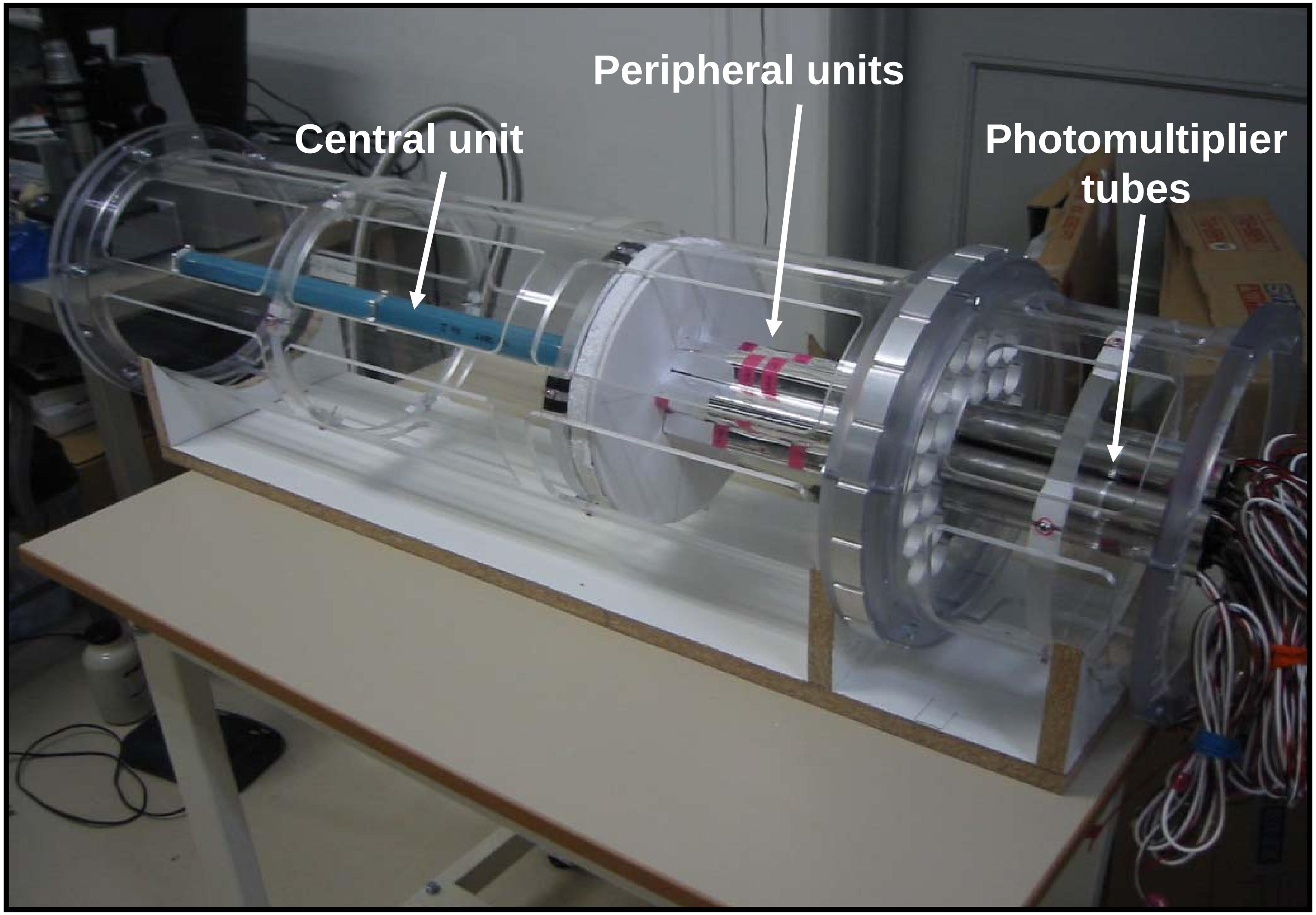


Peripheral units (fast scintillator only)

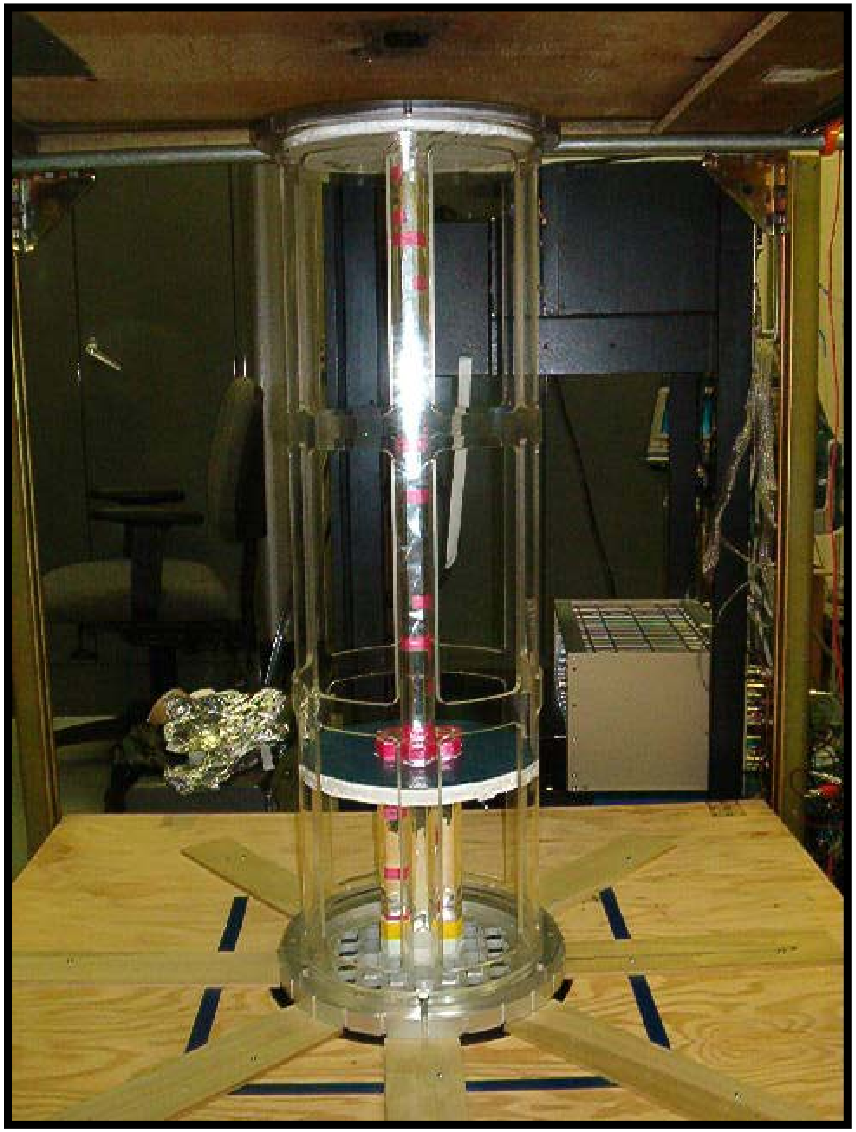


PMT read out

PoGO-Lite prototype completed



PoGOLite prototype completed



Tests of PoGOLite prototype

- Polarised photon beam at KEK ‘photon factory’, Japan

- Polarised photons from ^{241}Am with simultaneous particle (β–ray) background from ^{90}Sr

KEK experimental set-up

• Vertically plane-polarized beam from two monochromator crystals of Si(533)

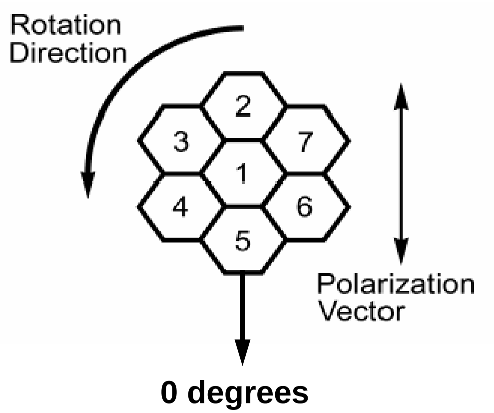
• Intensity adjusted with metal attenuator

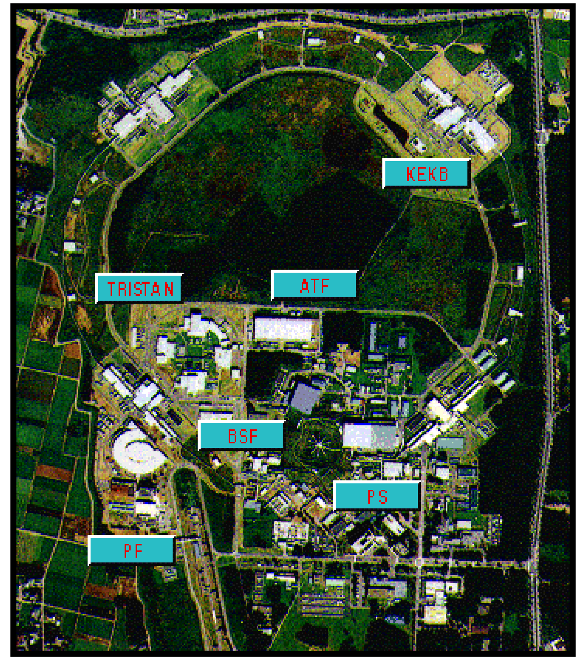
  • Trigger rate: ~1 kHz

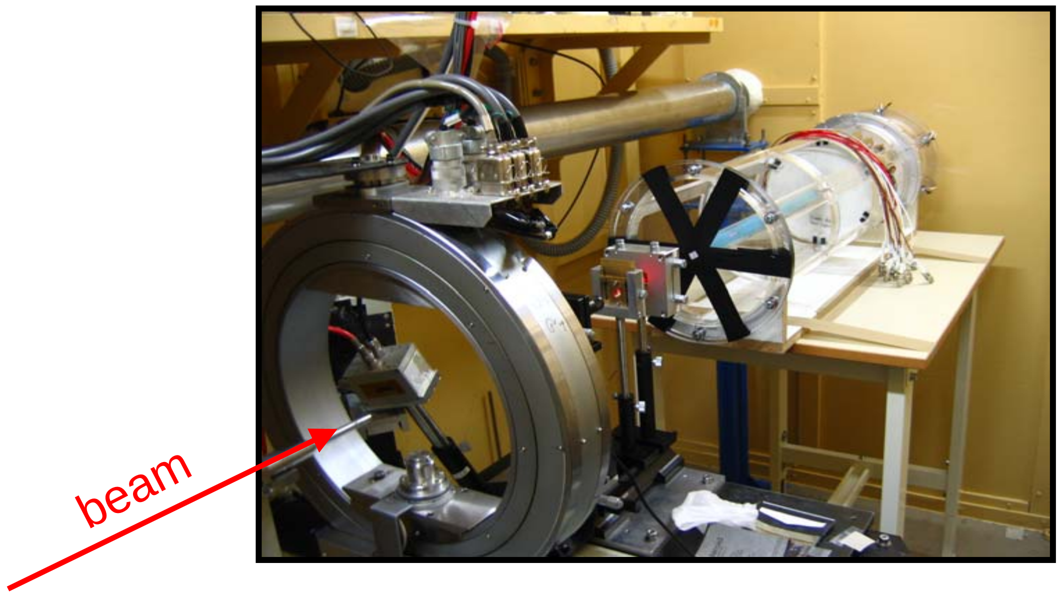
•Beam collimated with tantalum plates

  • Beam size: ~1 mm^2

• Data was taken at 25 keV, 30 keV, 50 keV and 70 keV. 15^o rotation between runs.





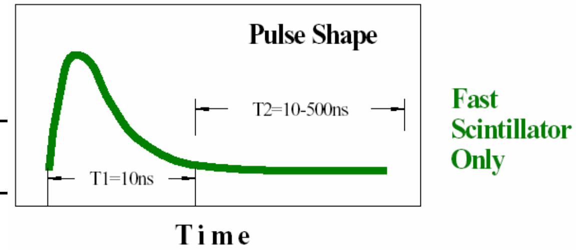


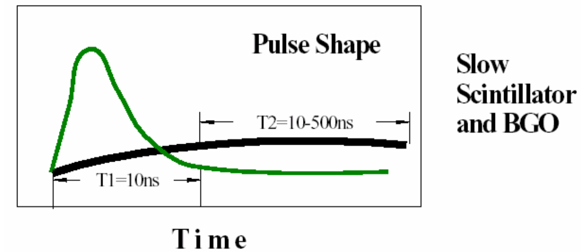
Pulse shape discrimination

• Single PMT reads out entire phoswich sandwich – use pulse shape discrimination to separate signals

Decay times	
Fast scintillator	1.8 ns
Slow scintillator	230 ns
BGO	~300 ns

Time constants of shaping amplifiers	
Fast	50 ns
Slow	1 µs





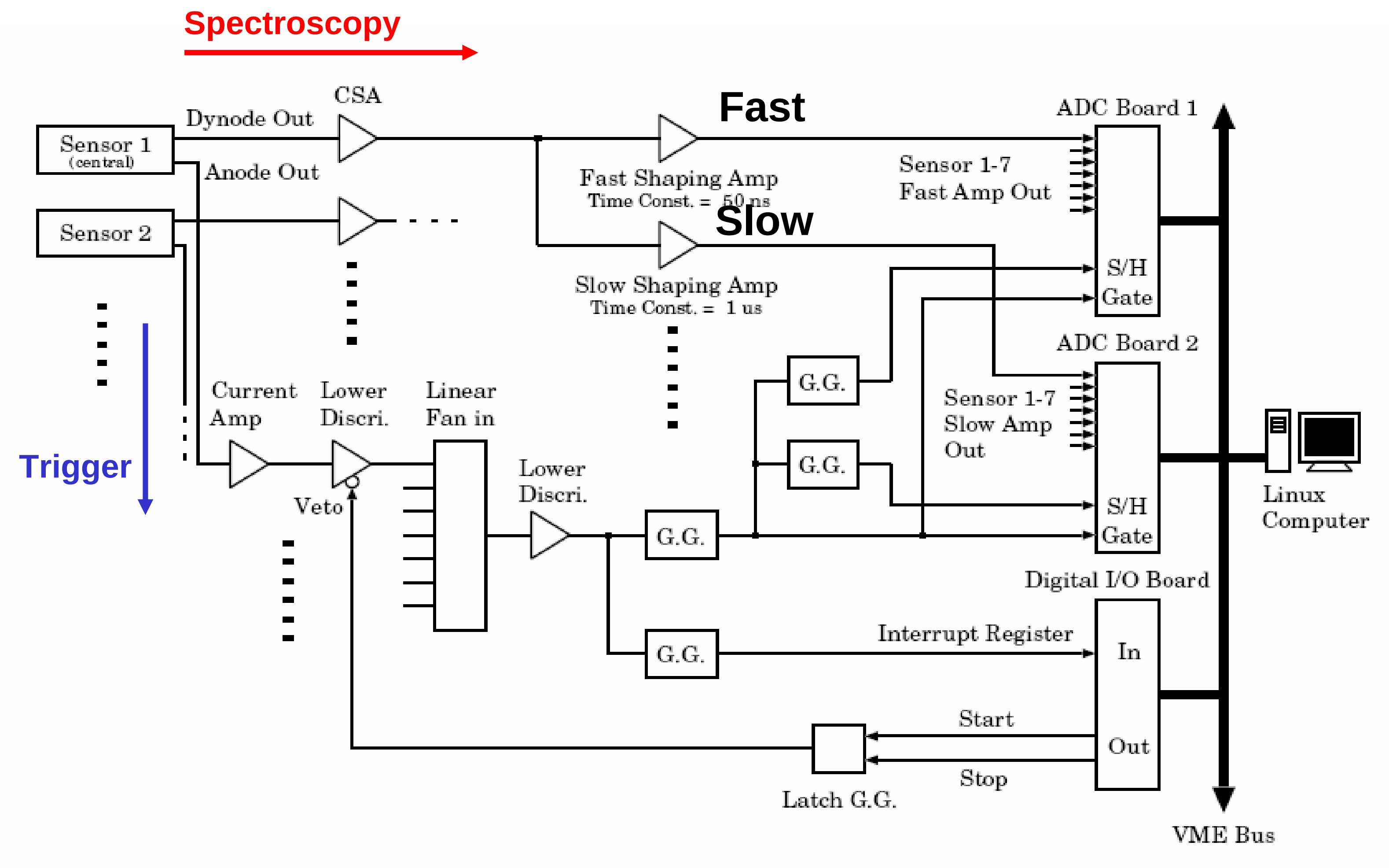
Fast shaping amplifier

- Entire signal from fast scintillator is integrated.
- Small part of the signal from BGO and slow scintillator are integrated

Slow shaping amplifier

- Entire signal from all scintillators integrated
- Signals from slow scintillator and BGO dominate

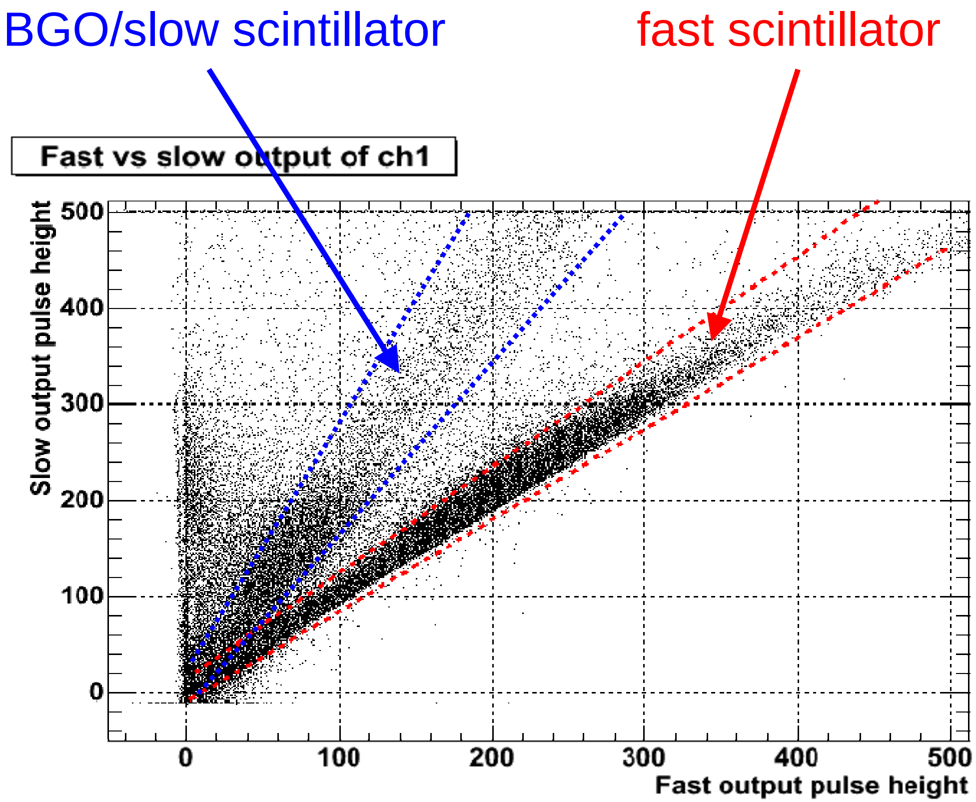
Data acquisition electronics



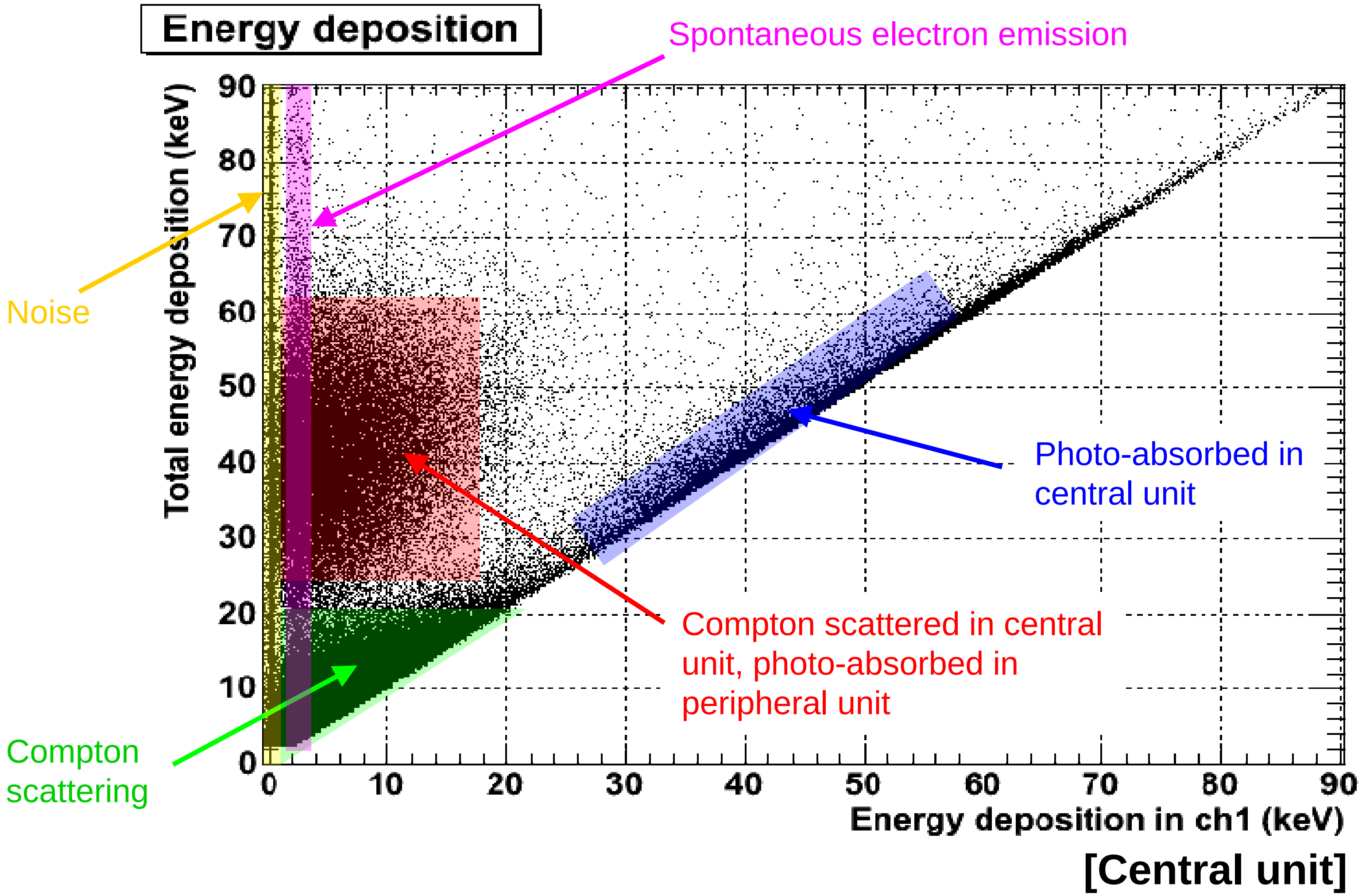
Selecting fast scintillator events

- Clear separation between signals from fast scintillator and BGO/slow scintillator

- Fast scintillator branch is chosen for analysis



Selecting Compton scatter events

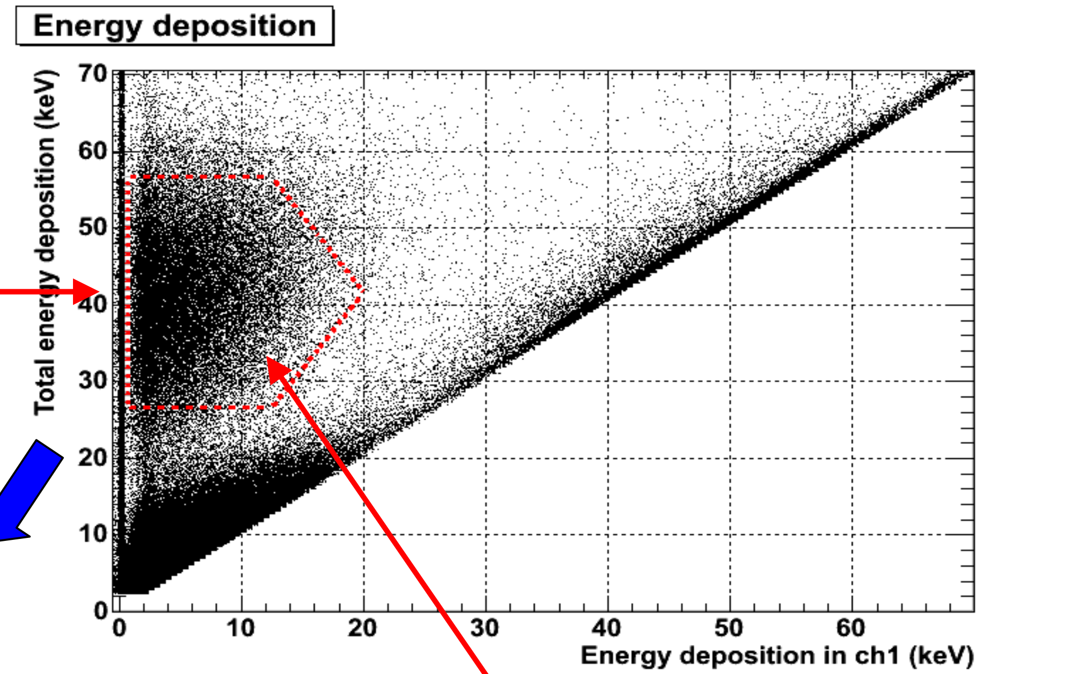


(Events where one peripheral scintillator is hit are plotted)

Selection of Compton scattering events

- Events which correspond to Compton scattering in the central unit and photo-electric absorption in a peripheral unit are selected

photo-electric absorption peak



Compton scattered in central unit and photo-absorbed in a peripheral unit

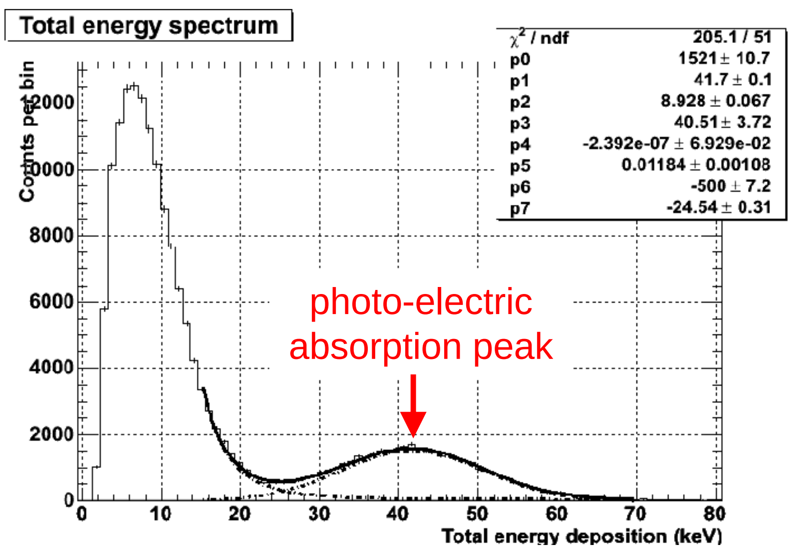
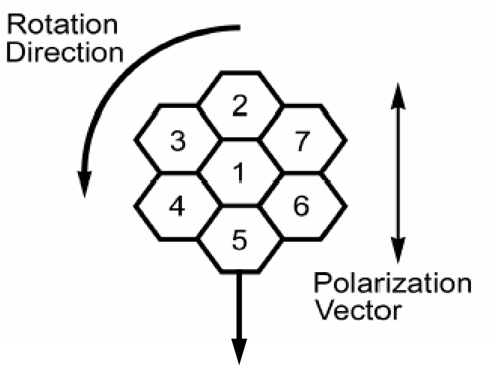


photo-electric absorption peak

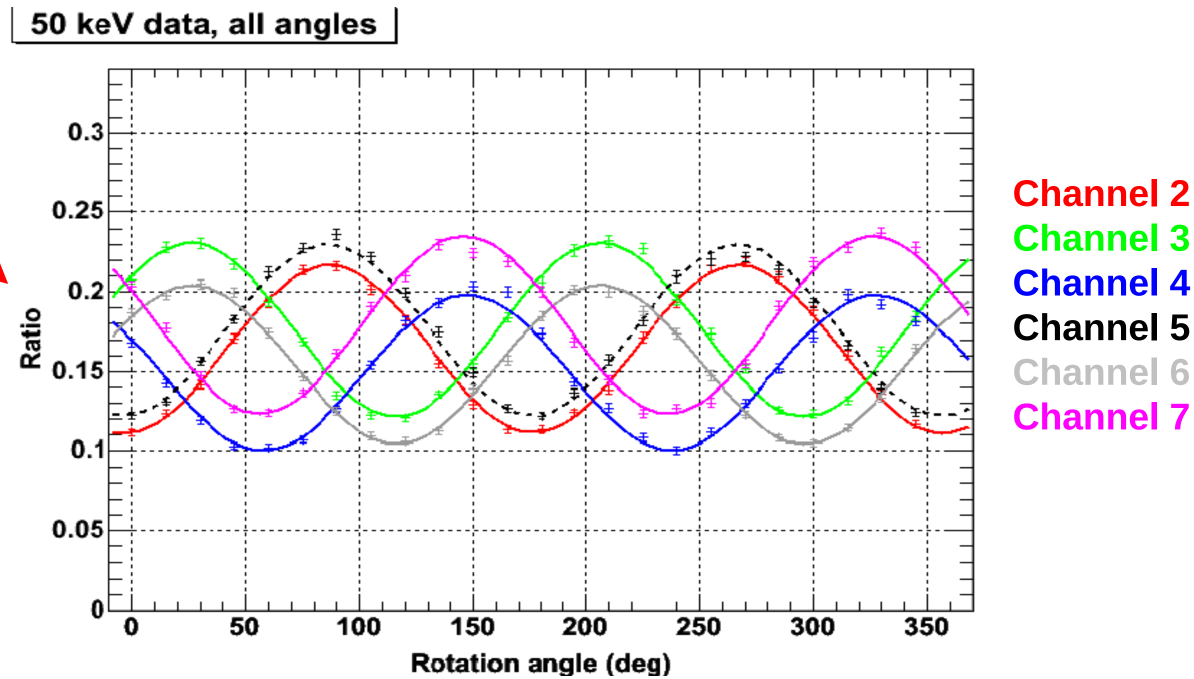
Modulation curves

- The relative number of events in each scintillator plotted as a function of rotational angle

Number of events in each scintillator divided by the sum of the events in all peripheral scintillators

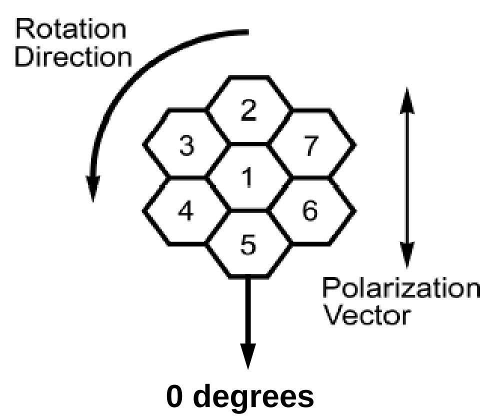


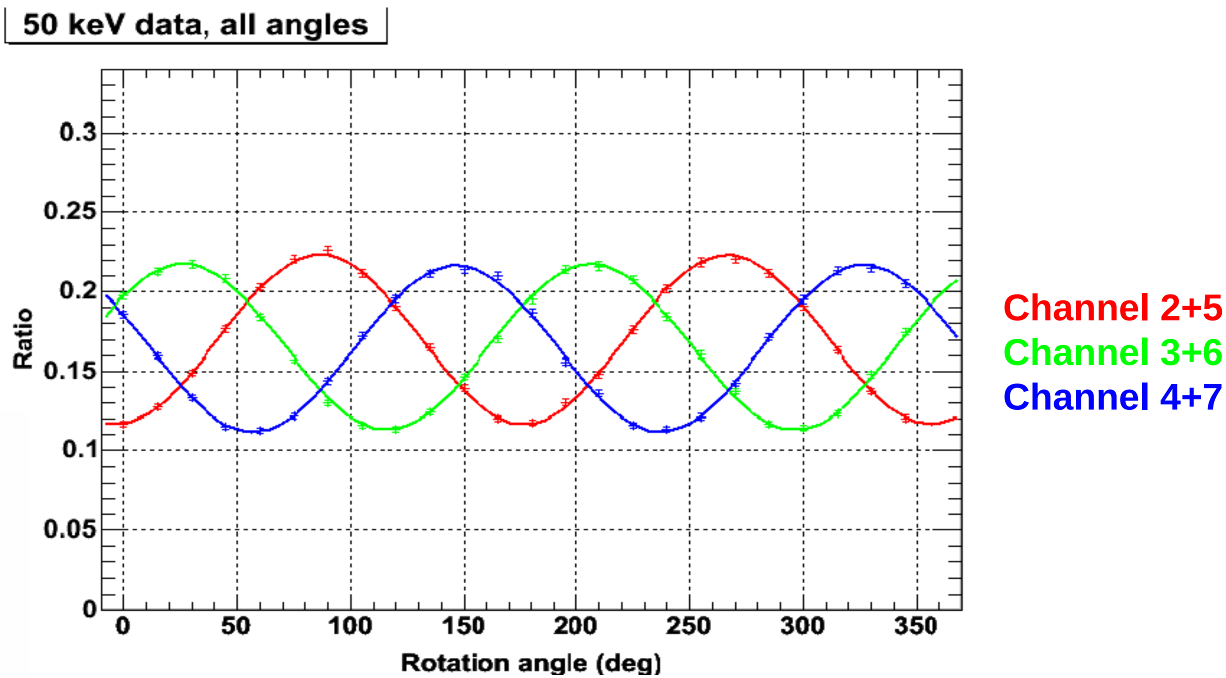
0 degrees



Modulation curves

- Average events in two opposing scintillators
- Effects of misalignment are avoided





Preliminary results

- Data taken at 25 keV, 30 keV, 50 keV and 70 keV
- The modulation factors are corrected for background and dead time
- The modulation factor for 100% polarized beam of photons, M_{100}, can be calculated by dividing with the degree of polarization of the beam:

$$P_{source} = \frac{M}{M_{100}} \Rightarrow M_{100} = \frac{M}{P_{source}}$$

- Simulation was made with Geant4 using a modified code for polarization

Energy	Degree of polarization	M	M_{100}	Simulated values of M_{100}
25 keV	not measured	0.287 ± 0.003	n/a	0.393 ± 0.002*
30 keV	0.88 ± 0.01	0.305 ± 0.002	0.346 ± 0.010	0.376 ± 0.001*
50 keV	0.91 ± 0.01	0.322 ± 0.002	0.354 ± 0.010	0.394 ± 0.002*
70 keV	0.91 ± 0.01	0.362 ± 0.005	0.397 ± 0.011	0.414 ± 0.003*

- **In progress:** non-linearlity of fast scintillator, variations in calibration.

Background rejection

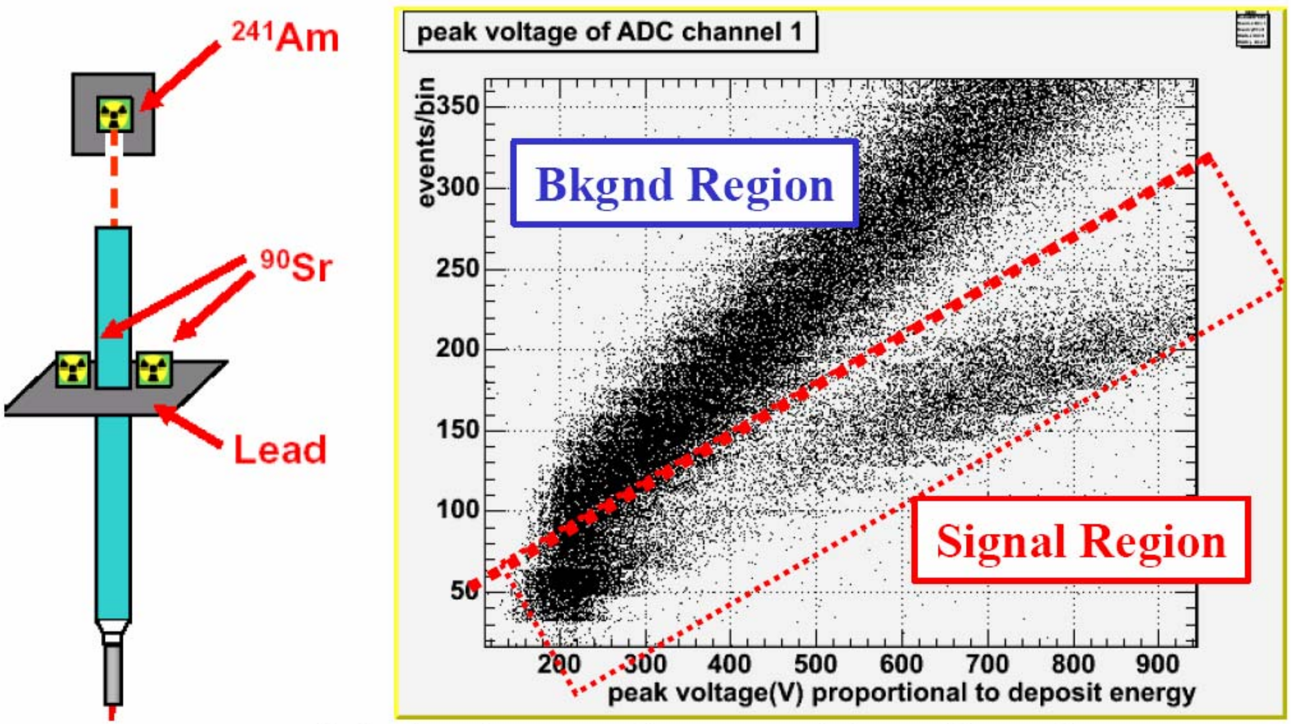
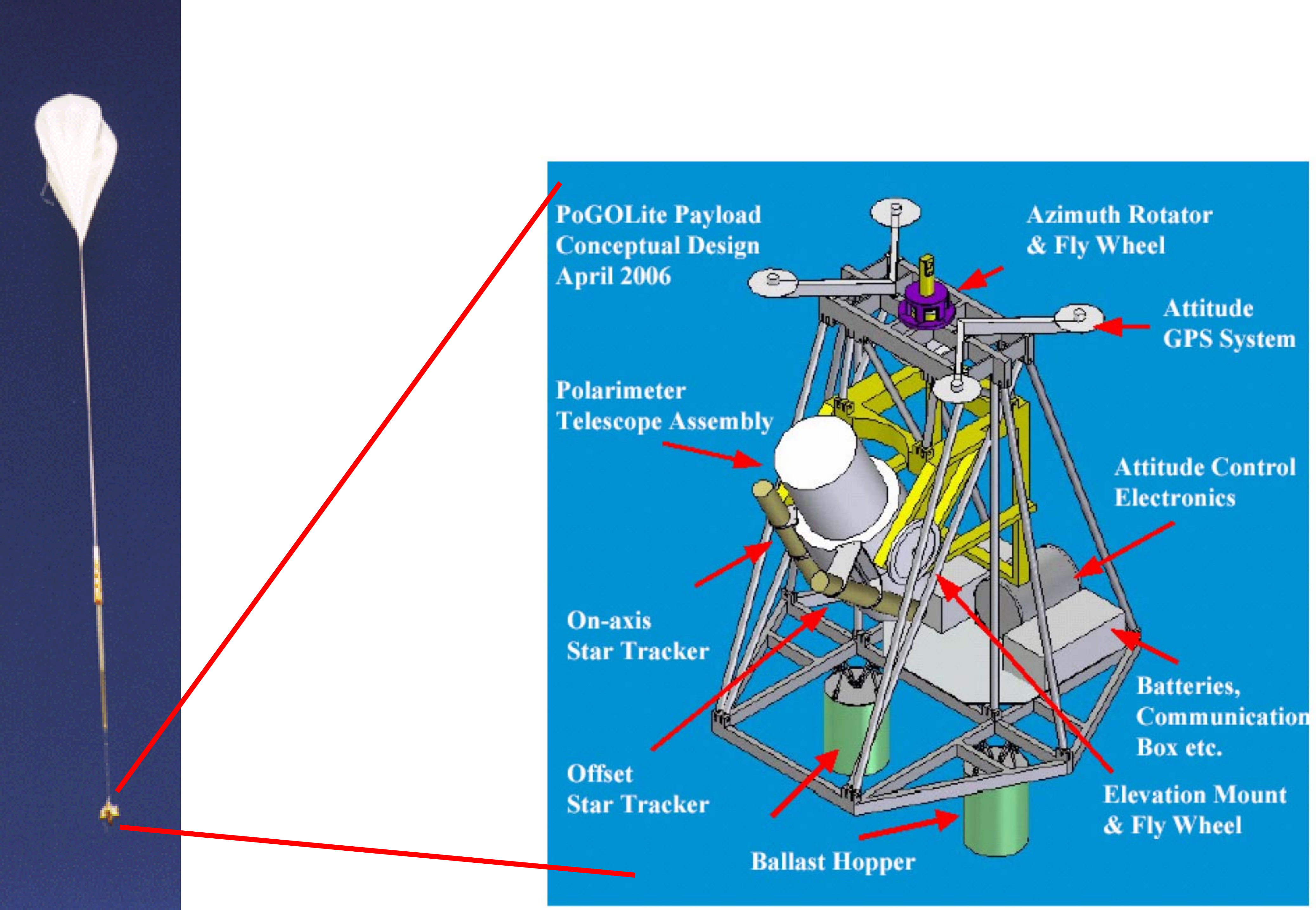


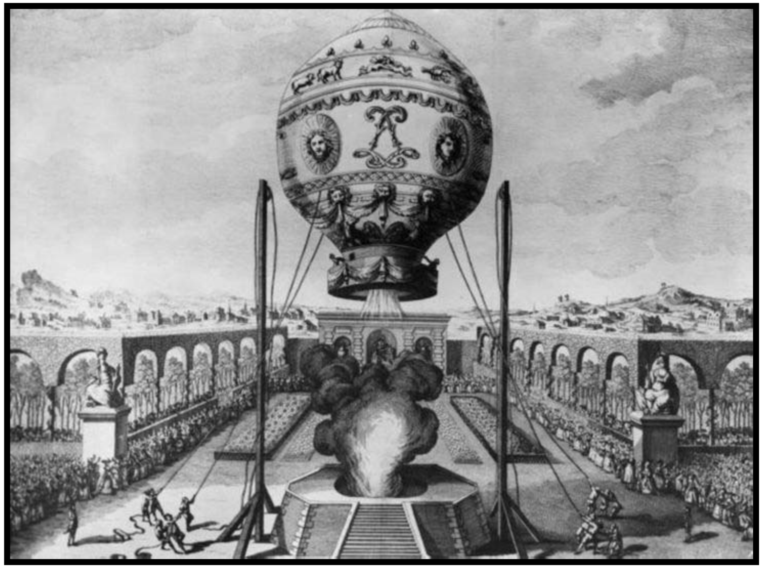
Figure 5.5: High-background tests with radioactive sources: (left) The source arrangement around one PDC; (right) The correlation between the fast and slow shaping output of the amplifier connected to the PDC PMT. The signal region is clearly visible even in the presence of 10 kHz electrons. The waveform has been recorded at 5MHz sampling for pulse-shape discrimination.

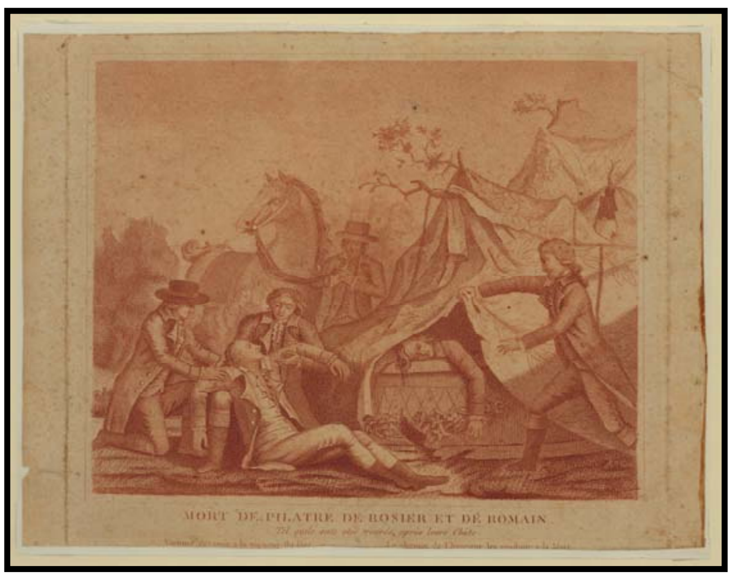
x10 expected rate

BGO not used


PoGOLite Payload
Conceptual Design
April 2006
Azimuth Rotator
& Fly Wheel
Attitude
GPS System
Polarimeter
Telescope Assembly
Attitude Control
Electronics
On-axis
Star Tracker
Batteries,
Communication
Box etc.
Offset
Star Tracker
Elevation Mount
& Fly Wheel
Ballast Hopper

Ballooning history





• December 1782 **Montgolfier brothers** experimented with silk/paper spheres (18 m^3). Rose to ~250 m powered by a bonfire.

• Believed that smoke contained an unknown element that had lifting power

• Thought that the **worst smelling smoke** had the best lifting power

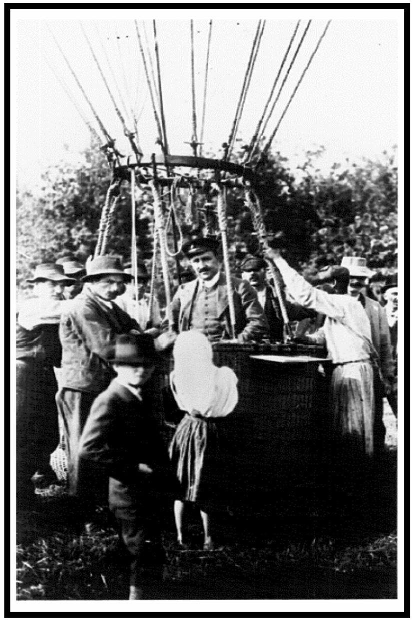
• Tried burning **old shoes, wet hay and rotting meat**.

• Tests with a **sheep, duck and cockerel** at Versailles before Louis XVI ⇒ permission for first human flight.

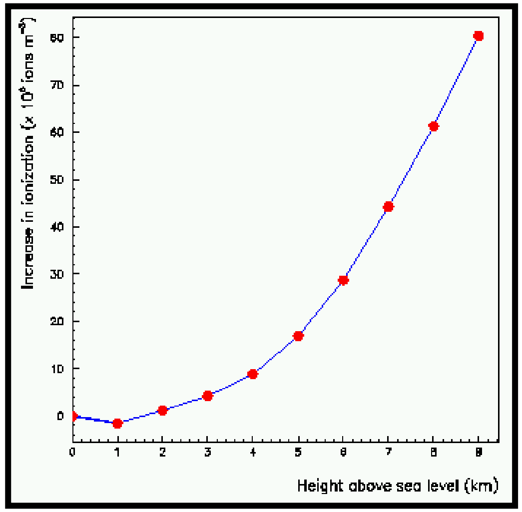
• First manned flight (Marquis de Rozier). November 1783. 100 m over Paris (9 km).

• Rozier became the first aviation fatality in 1785 …

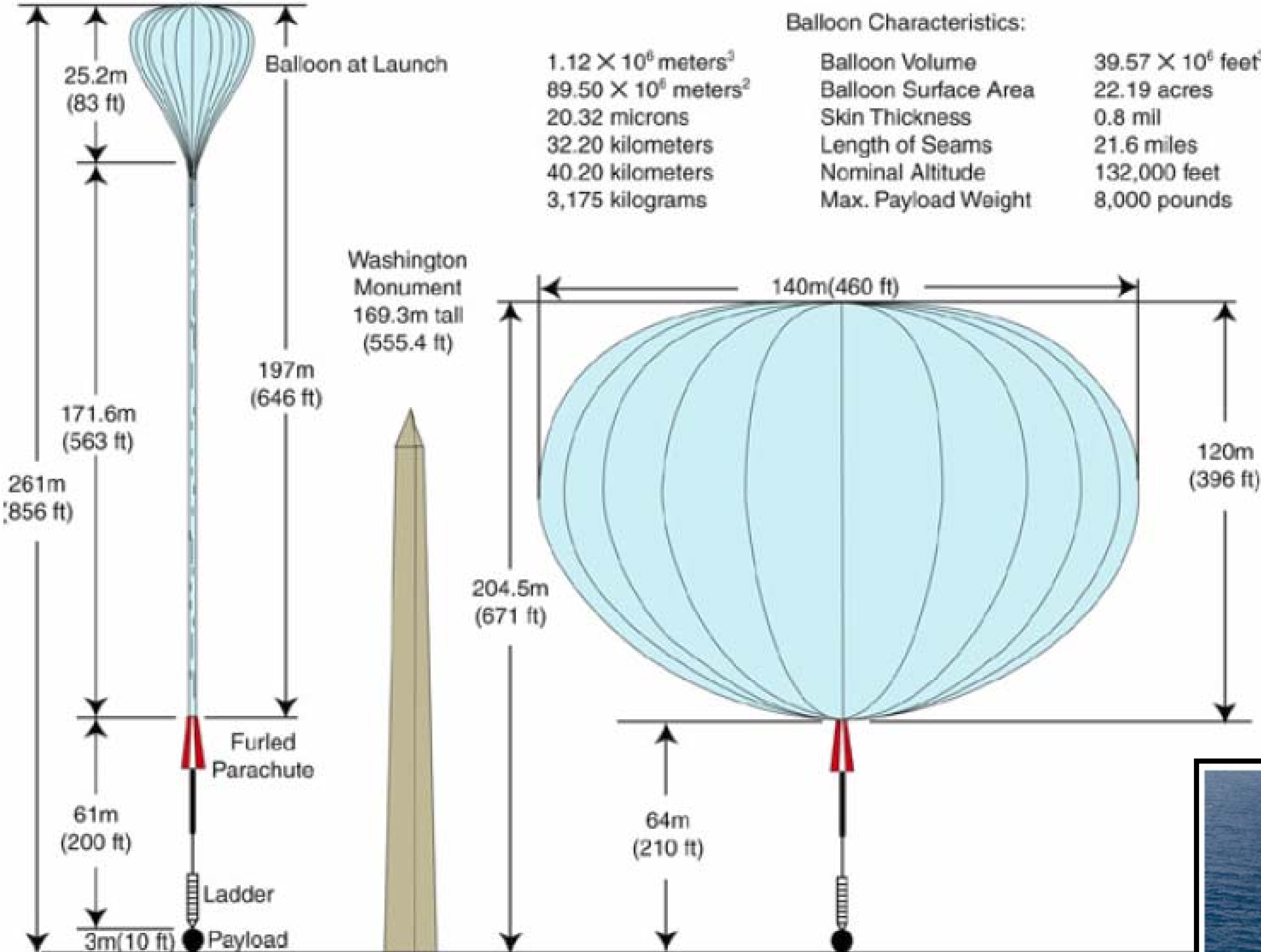
Balloons for research



- Viktor Hess **discovers cosmic rays** during his balloon ascent in 1912.
- Used an electroscope to measure ionisation
- Hydrogen-filled coated fabric balloon



- High-altitude balloon missions by USAF in 1950’s paved the way for manned space flight
- August 16th 1960, Capt. Joseph Kittenger, jumped from an open gondola at 31.3 km
- First person to break the sound barrier without a vehicle…

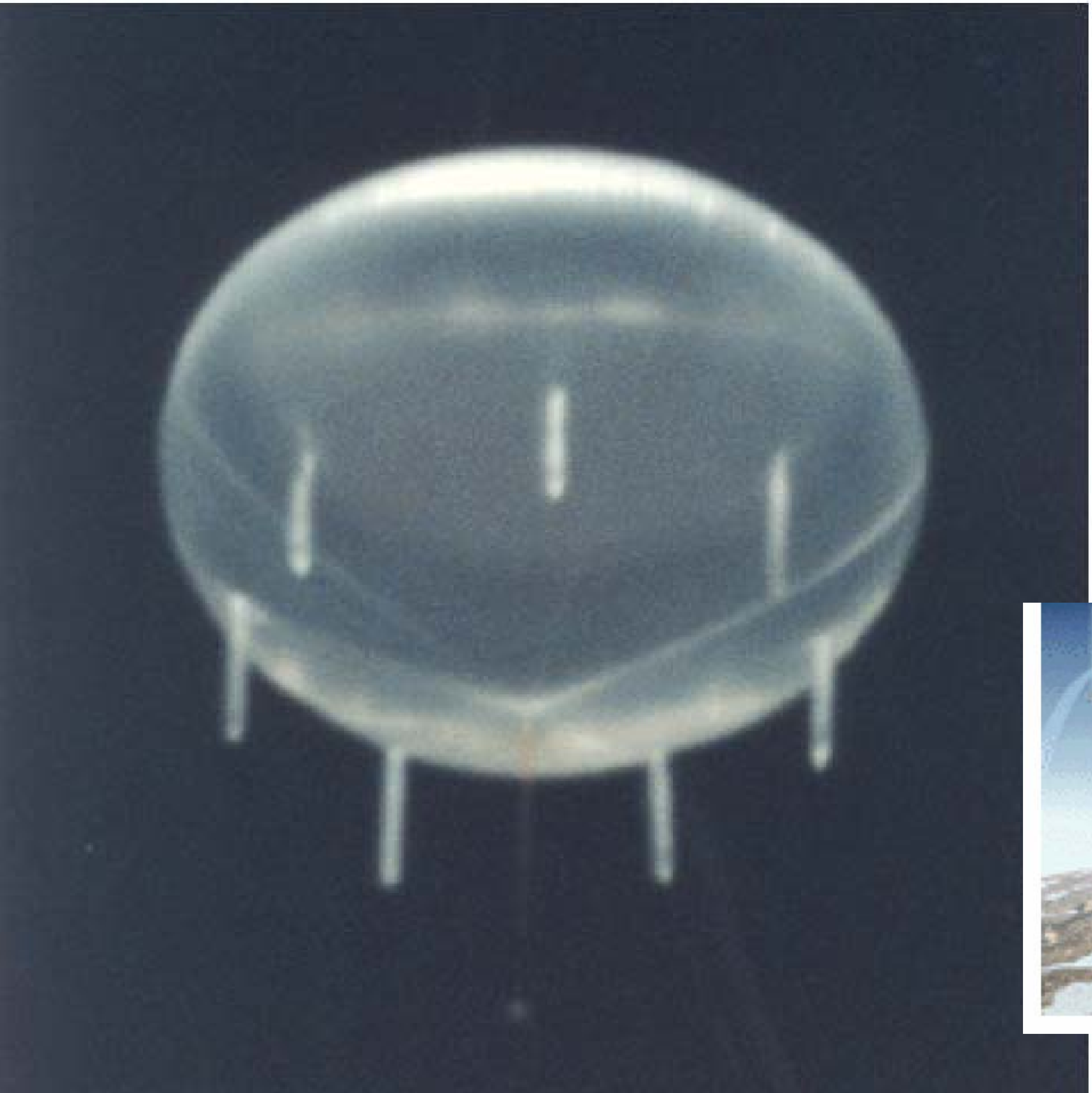

Balloon Characteristics:
1.12 X 10⁶ meters³ Balloon Volume 39.57 X 10⁶ feet³
89.50 X 10⁶ meters² Balloon Surface Area 22.19 acres
20.32 microns Skin Thickness 0.8 mil
32.20 kilometers Length of Seams 21.6 miles
40.20 kilometers Nominal Altitude 132,000 feet
3,175 kilograms Max. Payload Weight 8,000 pounds
25.2m (83 ft)
Balloon at Launch
171.6m (563 ft)
197m (646 ft)
261m (856 ft)
Washington Monument 169.3m tall (555.4 ft)
140m(460 ft)
120m (396 ft)
204.5m (671 ft)
Furled Parachute
61m (200 ft)
64m (210 ft)
Ladder
3m(10 ft)
Payload

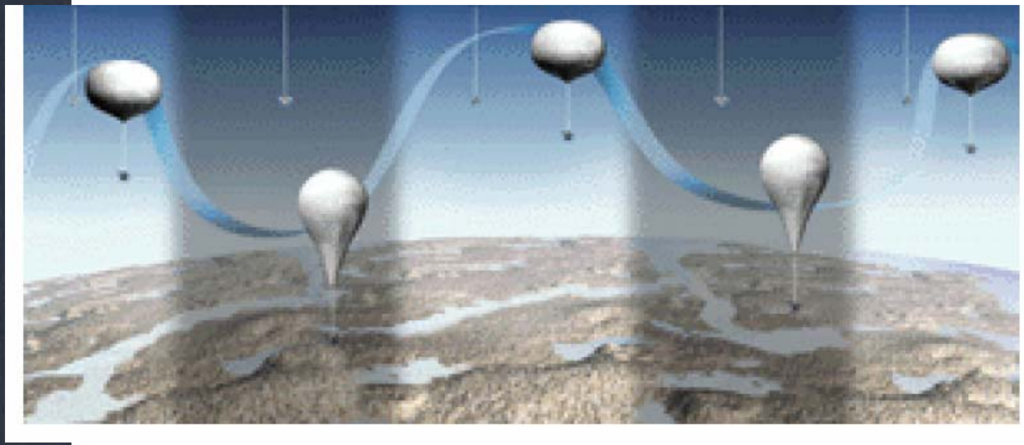
Launch sequence

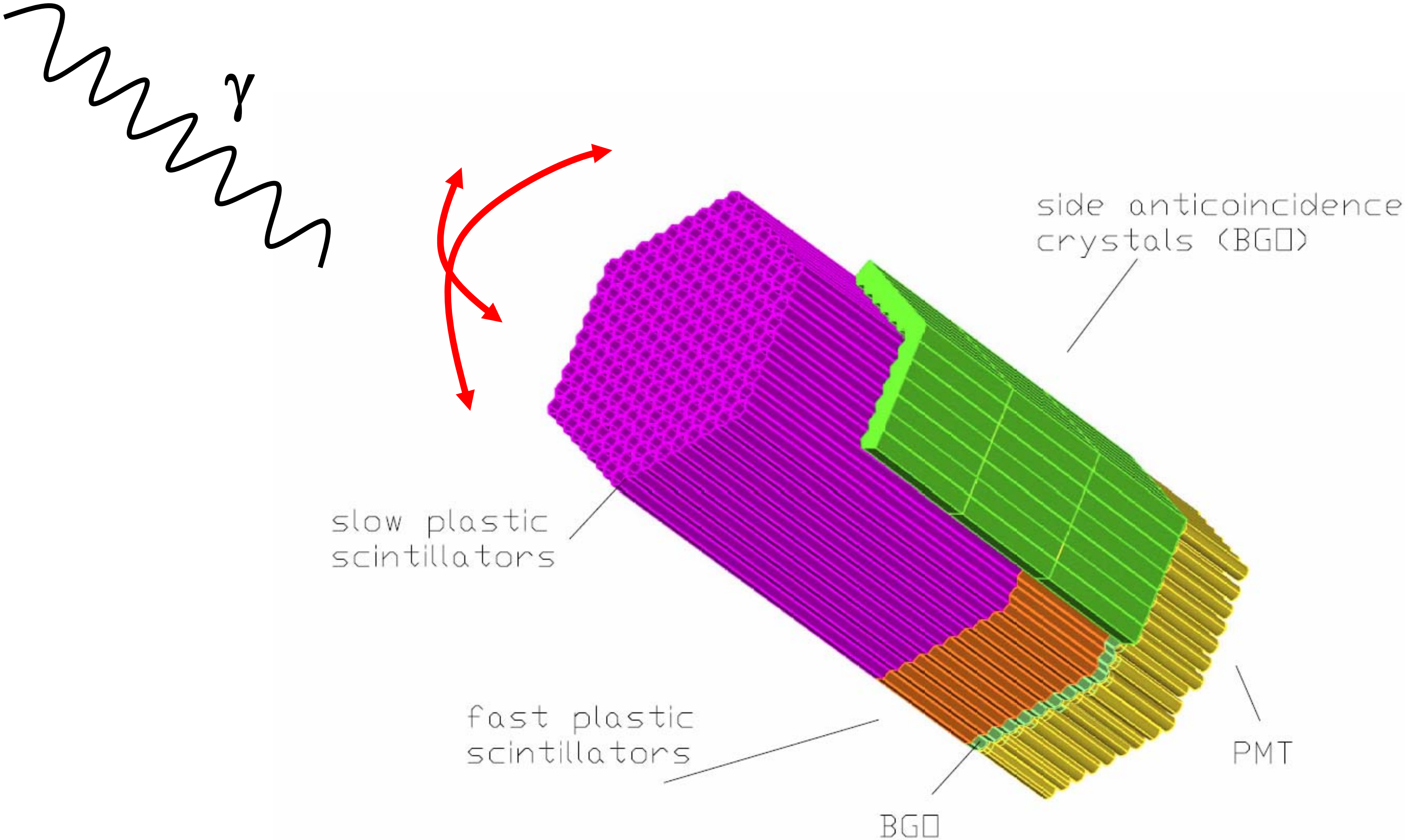
Esrange. 2005-06-12 / 0310

Balloon-borne Large Aperture Sub-millimeter Telescope (BLAST)

At ‘float’ (~40 km)






γ
side anticoincidence crystals (BGO)
slow plastic scintillators
fast plastic scintillators
BGO
PMT

HEFT: High Energy Focusing Telescope

[May 2005]

Performance of HEFT pointing system

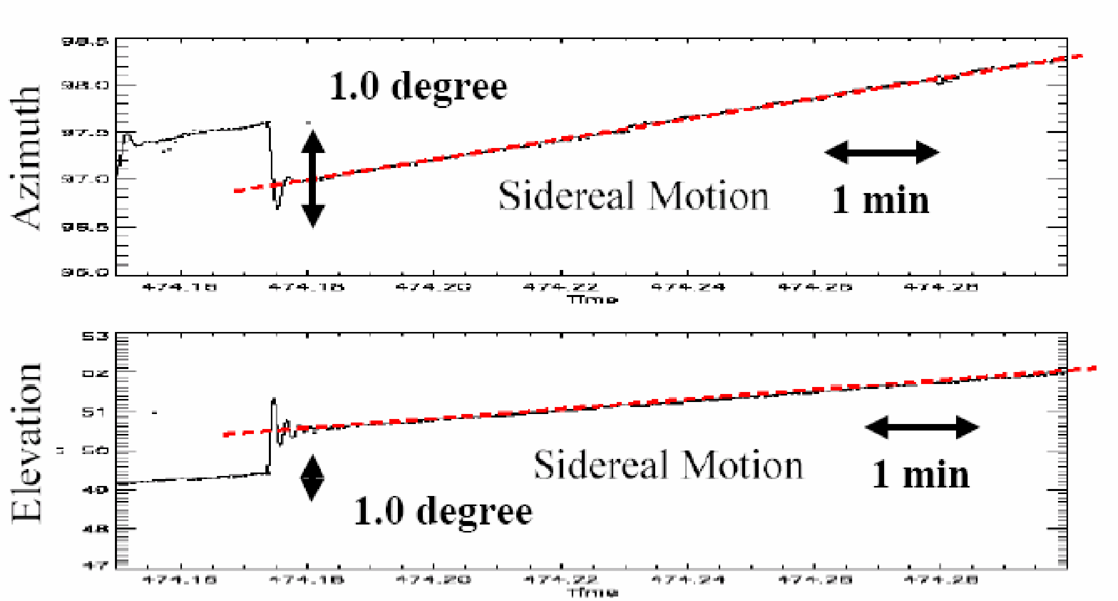
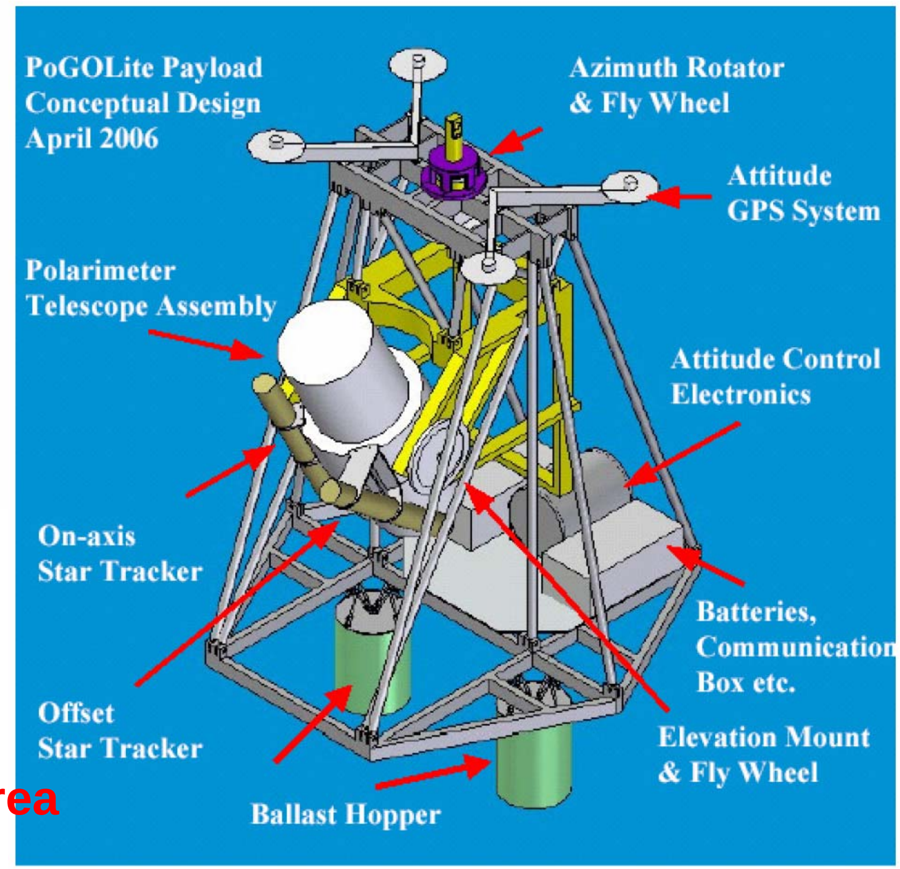


Figure 4.11: The intended pointing following the sidereal motion (red dashed) and the measured direction (black) for a 6 hour period during the 2005 HEFT flight.

- Day-time star trackers (8th mag)
- Differential GPS
- Gyroscopes, accelerometers, magnetometers



< 3 arcminute (3/60)º absolute pointing

< 0.2 arcminute in attitude

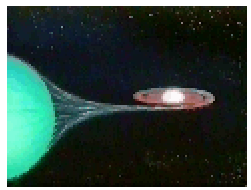
<5% of total field-of-view ⇒ maximises effective area

Maiden Flight – 2009

Primary Northern-sky targets

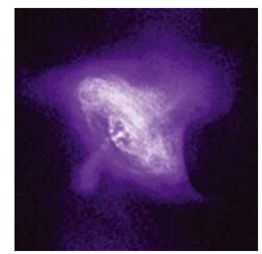
Object	Counting Rate	MDP (3σ)
Crab (total)	13.7/s	3%
Cyg X-1	Hard 13.3/s, Soft 4.6/s	Hard :3%, Soft: 5%
Her X-1	2.5/s	8%
Mkn 501 (Flare)	0.65/s	14%
V0332+53 (burst)	~4/s	5%
4U0115+63 (burst)	~4/s	5%
GRS 1915 (burst)	~4/s	5%

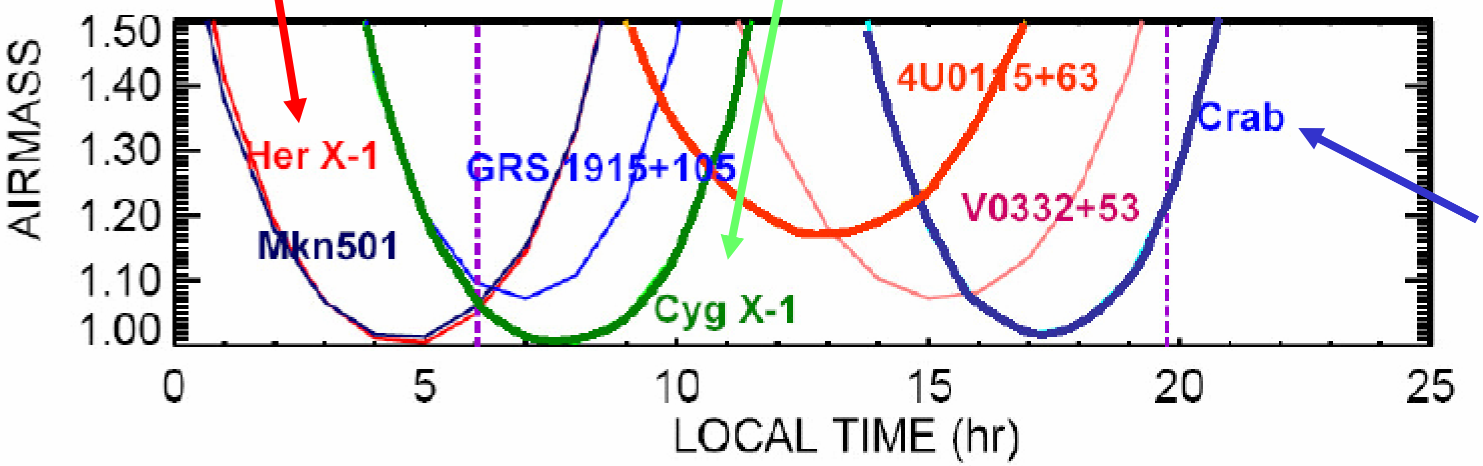
- Possible locations: **NASA Columbia Scientific Balloon Facility**, Palestine, Texas or **Esrange**, Sweden
- Nominal ~6 hour long maiden flight
- Total payload weight ~1000 kg
- 1.11×10^6 m^3 balloon
- Target altitude ~40 km



Accreting X-ray pulsar

High-mass X-ray binary





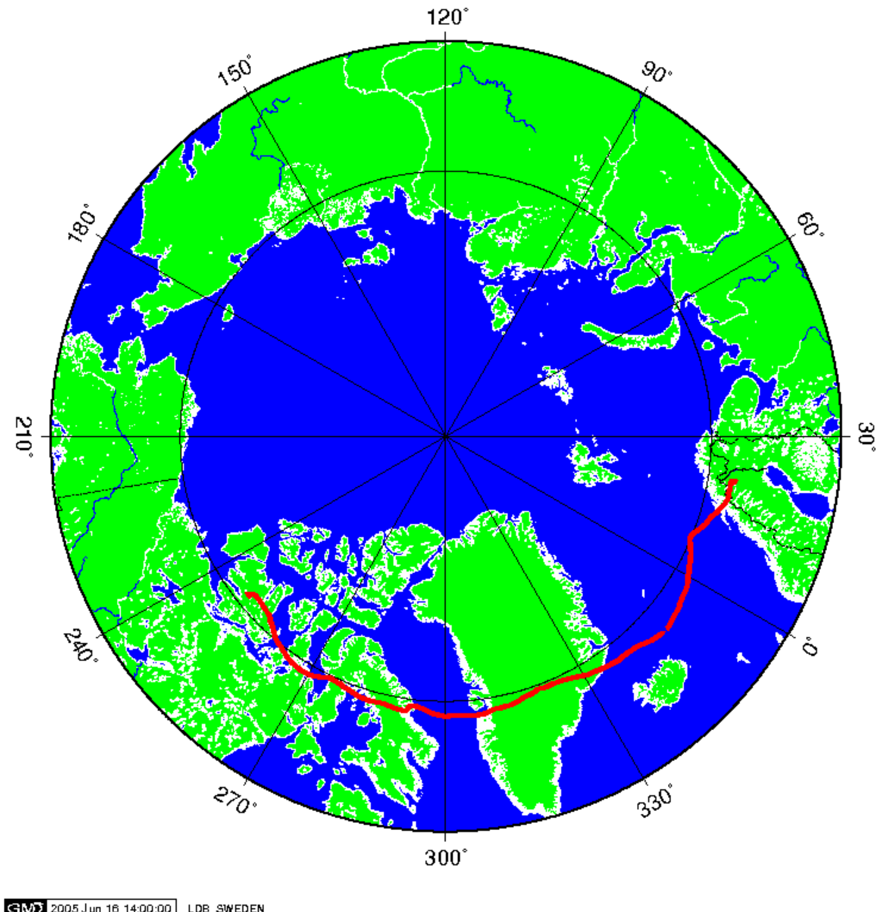
Pulsar / SNR

A PoGOLite campaign at Esrange?

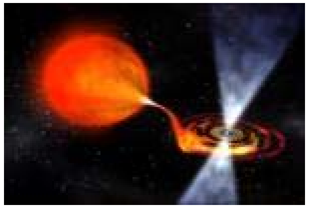
- **'Standard' flights (6 - 8 hours)**
  - Proof-of-principle. Observe Crab pulsar.

- **Long duration (~5 days) flight from Esrange to Western Canada**
  - High statistics studies. Time variation.
  - Acquire multiple targets. Crab, Cyg X-1, Her X-1

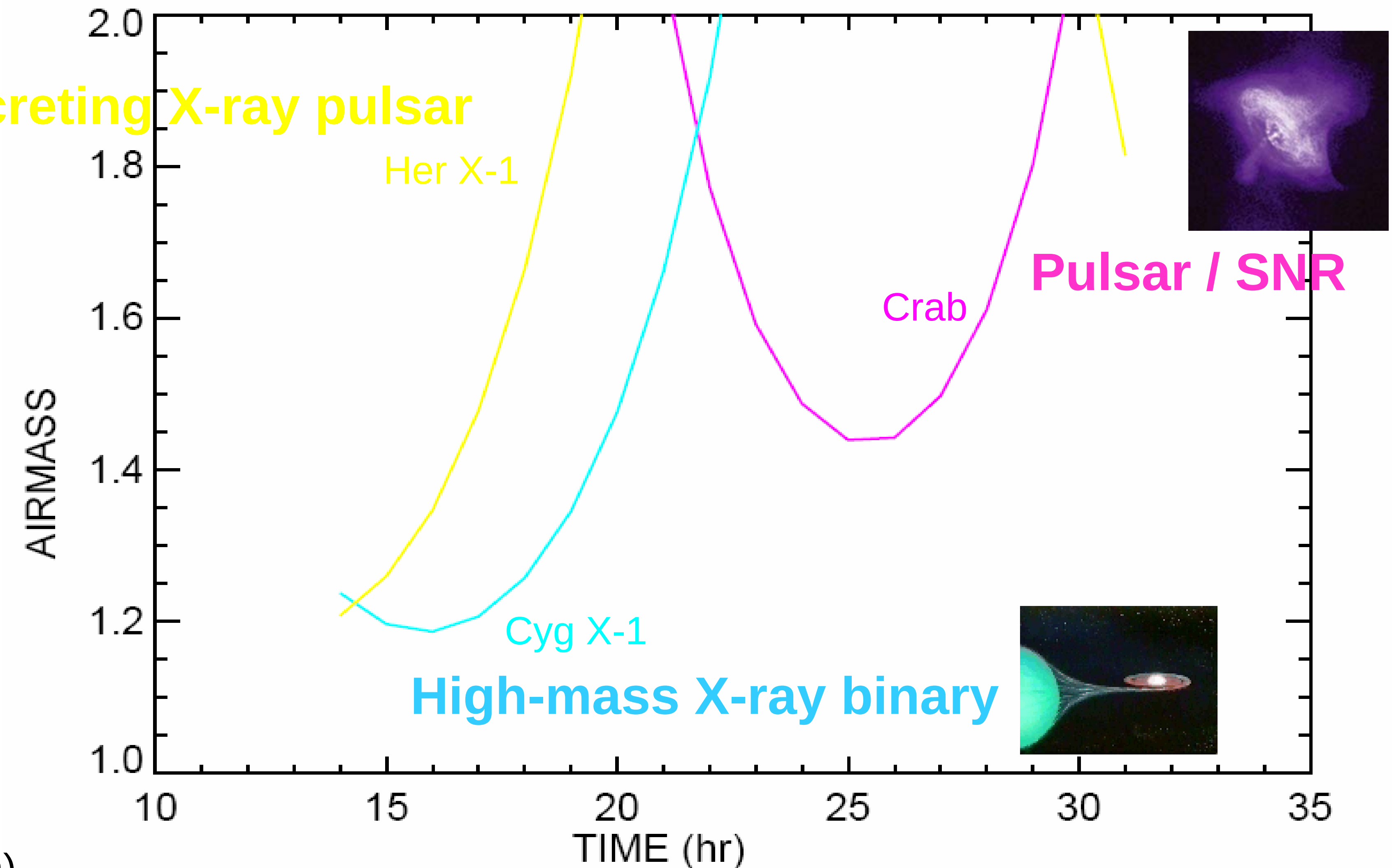
- **Flights of opportunity**
  - Launch upon notification of flaring states from GLAST / SWIFT. No consumables!



Observations from Esrange



Accreting X-ray pulsar

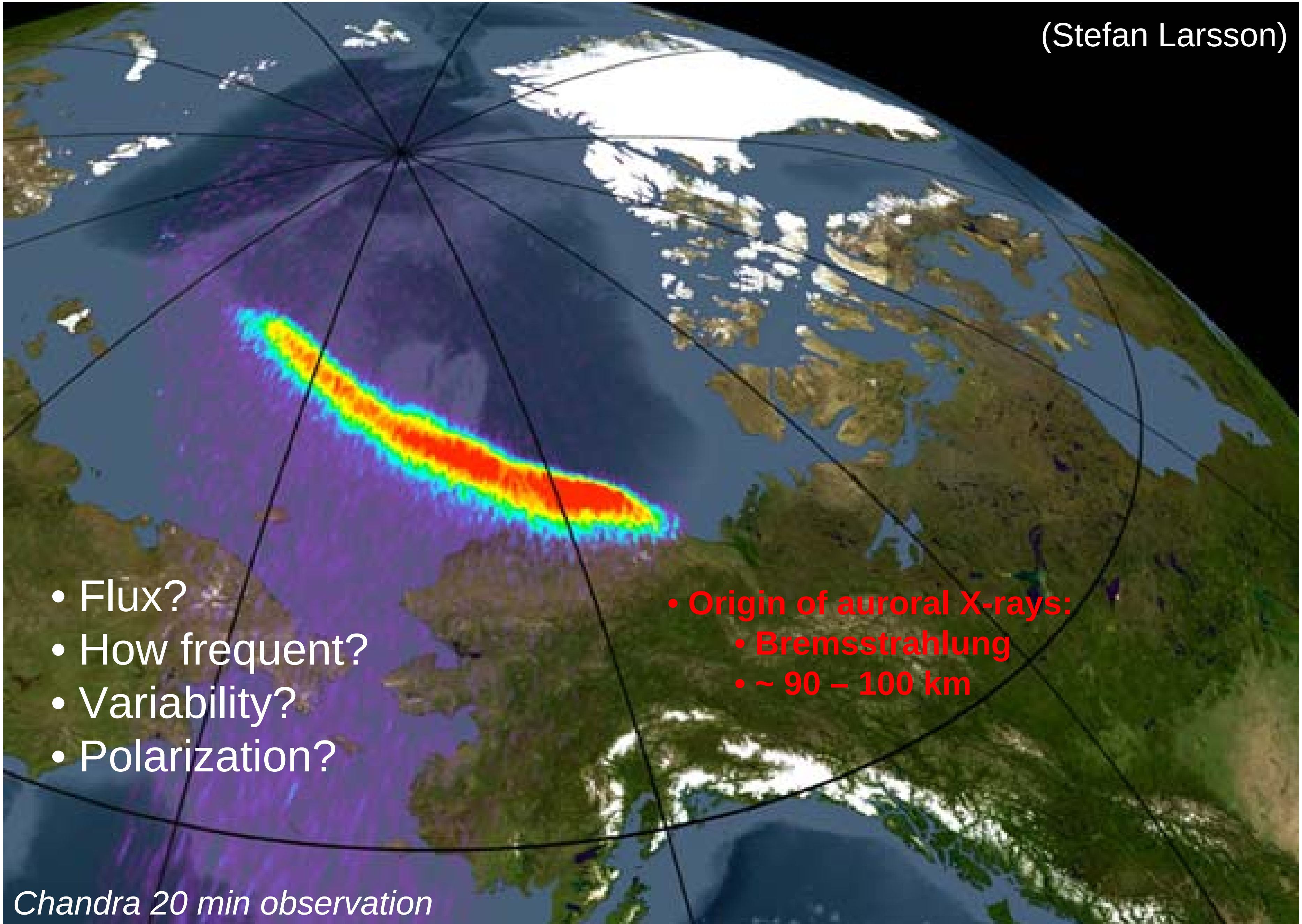


Pulsar / SNR

High-mass X-ray binary

(Stefan Larsson)

Study auroral X-rays during Esrange flights?



PoGOLite collaboration

SLAC / KiPAC

HEAC The AlbaNova High Energy Astrophysics and Cosmology Centre

Tokyo Institute of Technology, Hiroshima University, Institute of Space and Astronautical Science

KTH Vetenskap och Konst

Per Carlson
Tomas Ekeberg (Exjobbare - SLAC)
Bianca Iwan (Exjobbare - SLAC)
Mózsi Kiss (PhD student)
Wlodek Klamra
Cecilia Marini Bettolo (PhD student)
Mark Pearce

Stockholms Universitet

Magnus Axelsson (PhD student)
Claes-Ingvar Björnsson
Olle Engdegård (exjobbare)
Stefan Larsson
Felix Ryde

Knut och Alice Wallenbergs Stiftelse

Rymdstyrelsen Swedish National Space Board

Swedish responsibilities:

- BGO anticoincidence systems
- Gondola construction, pointing system (TBC)
- Observation planning