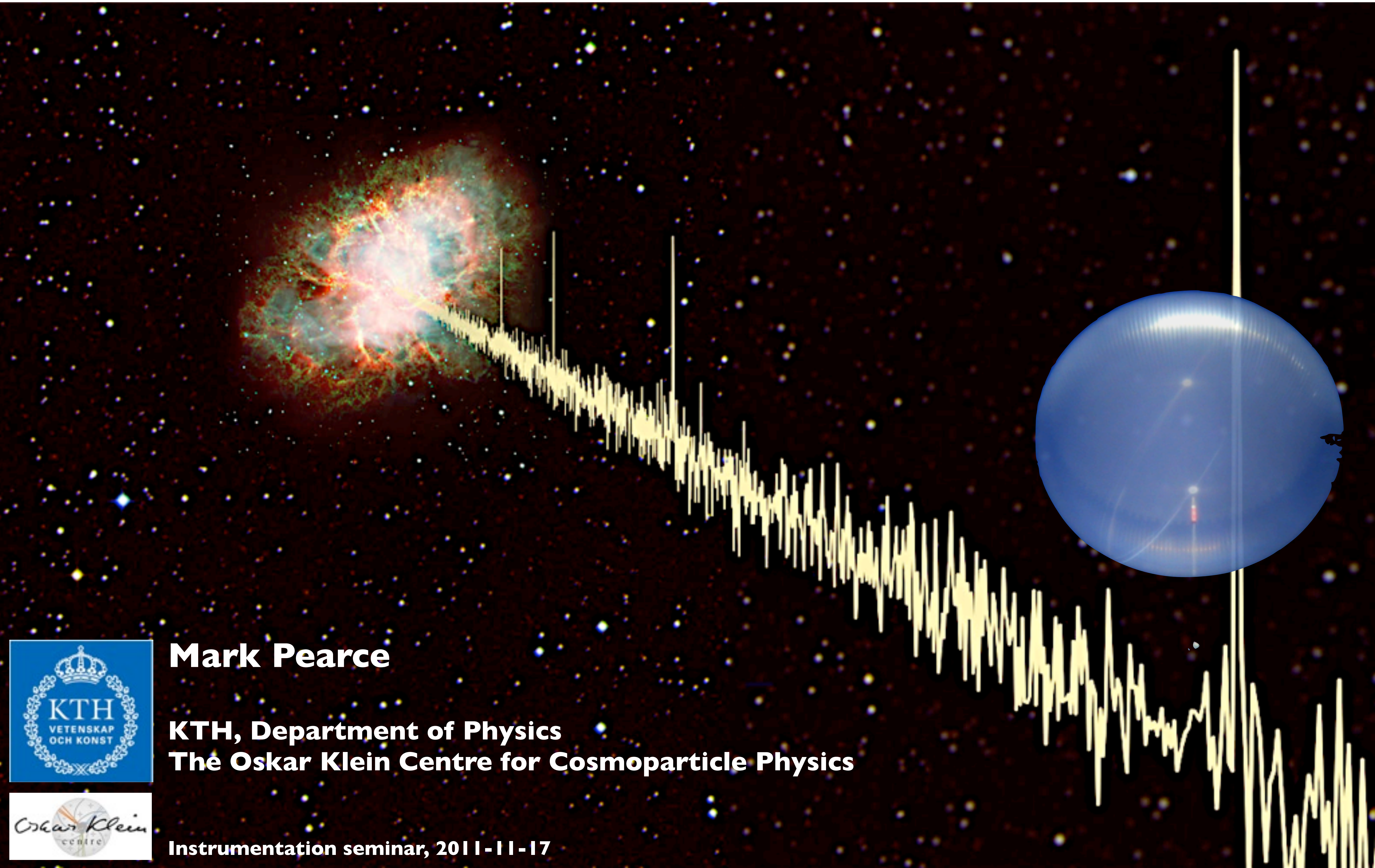
Floating at the edge of space

...balloon-borne soft gamma-ray polarimetry



Mark Pearce

KTH, Department of Physics
The Oskar Klein Centre for Cosmoparticle Physics

Instrumentation seminar, 2011-11-17

Overview

- Science case
- Measuring X-/gamma-ray polarisation
- The PoGOLite instrument
- Maiden flight: 'PoGOLite pathfinder'
  - Payload design
  - Flight plans
  - Results
- Outlook

Scientific motivation

• **X-ray astronomy born in 1962**. Sounding rocket observations of Scorpious X-1 (accreting neutron star).

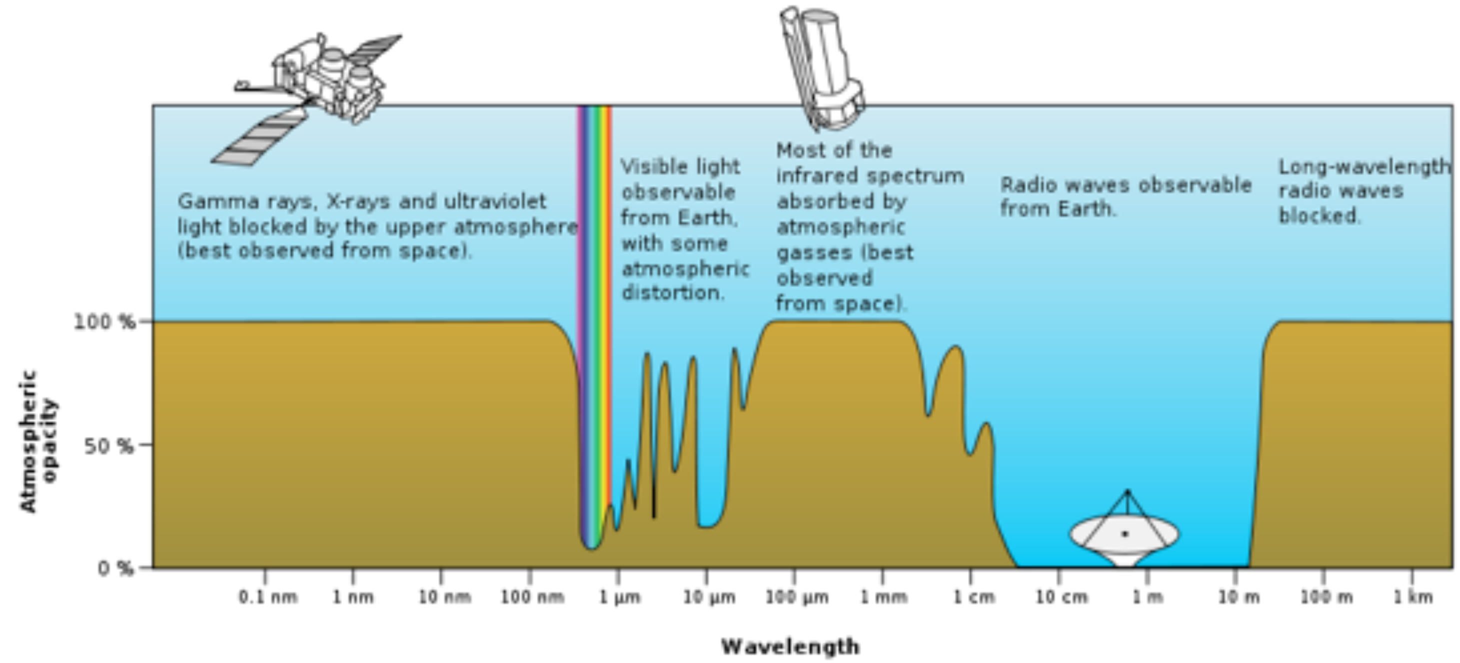
• Many sounding rocket, balloon, satellite X-ray missions since...

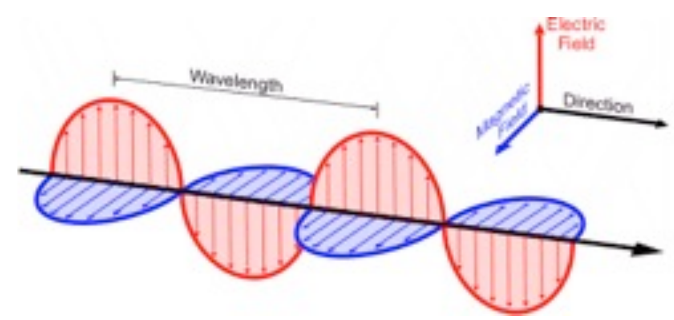
• Photons are characterised by their energy, arrival time and arrival direction. **Polarisation is neglected.**

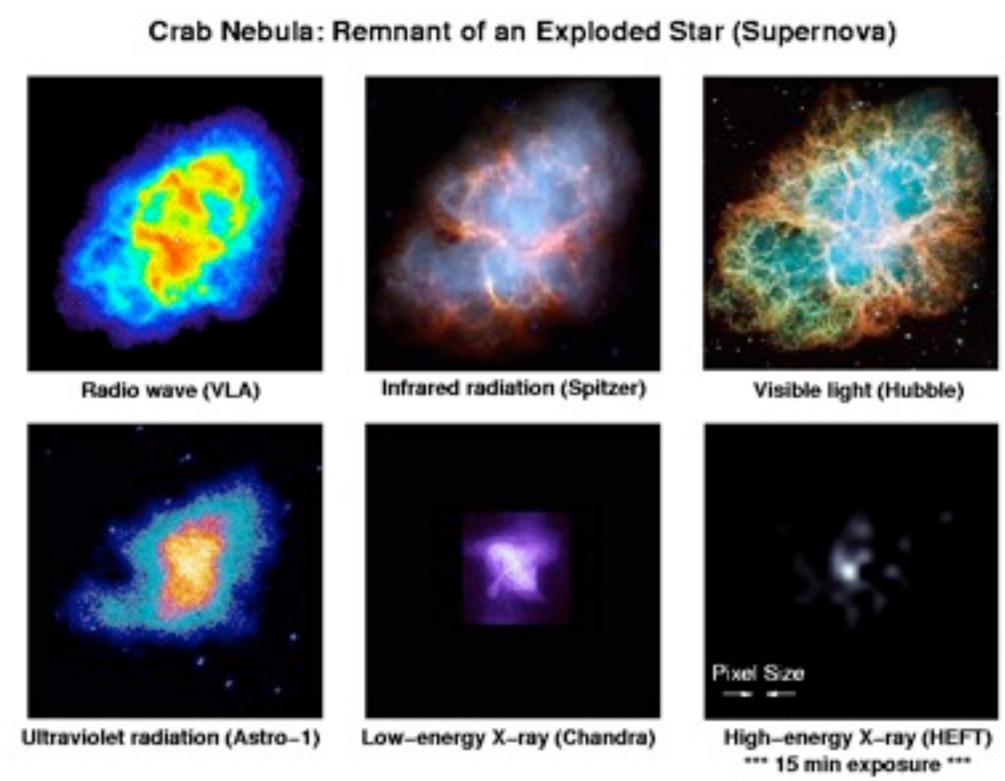
• Measuring the **polarisation** of gamma (X)-rays is a **powerful diagnostic** of source emission mechanisms

• **Only one dedicated mission to date**: 1976, OSO-8 satellite, Bragg reflectometer (2.6/5.2 keV). Crab nebula.

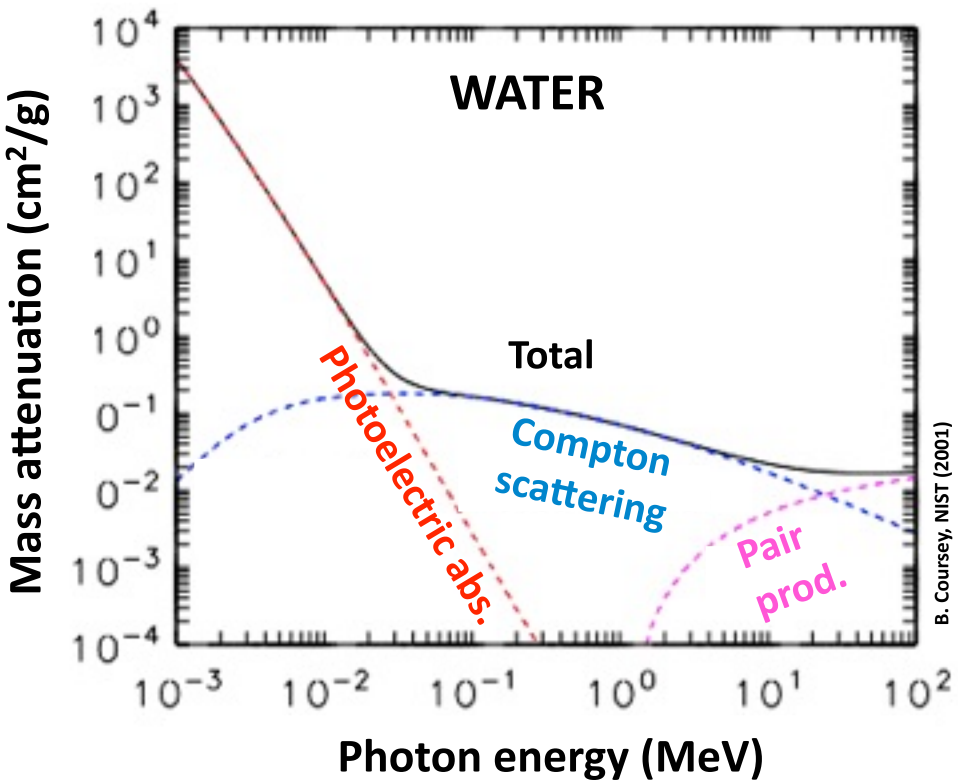
• **Field reinvigorated** of late by inventive use of Integral satellite instruments, IBIS + SPI. Several missions under development. **Stop press: GAP!**





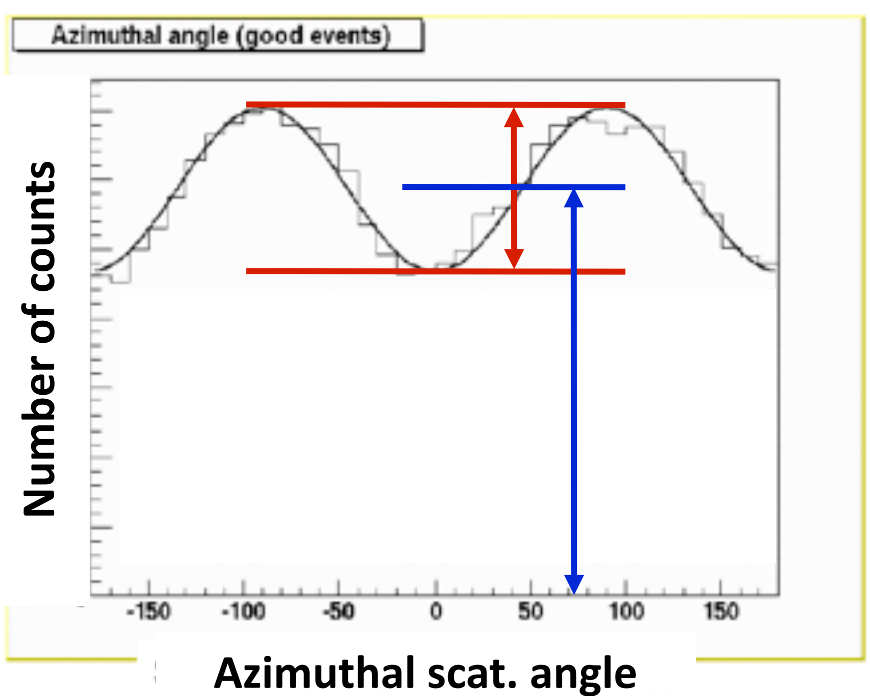


Measuring polarisation



- A characteristic angle in these photon interactions is modulated by polarization. Quantified through the **modulation factor.**
  - **Photoelectric effect:** azimuthal emission angle of the photoelectron
  - **Compton scattering:** azimuthal scattering angle of the photon
  - **Pair production:** azimuthal angle of plane containing the e^+e^- pair

Modulation factor = difference / average



- The polarization degree (Π) and angle can both be determined from modulation curve
- Polarization degree: $P_{source} = M / M_{100}$ (M: modulation factor, M_{100}: modulation factor for 100% polarized source)
- Polarization angle: phase of fitted modulation curve

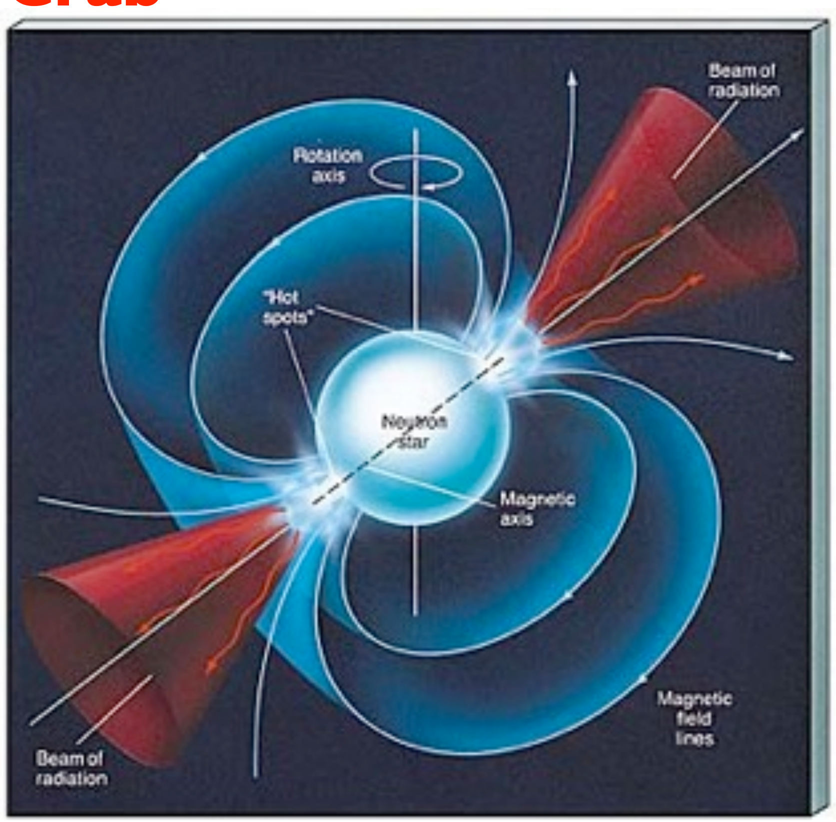
Polarisation targets

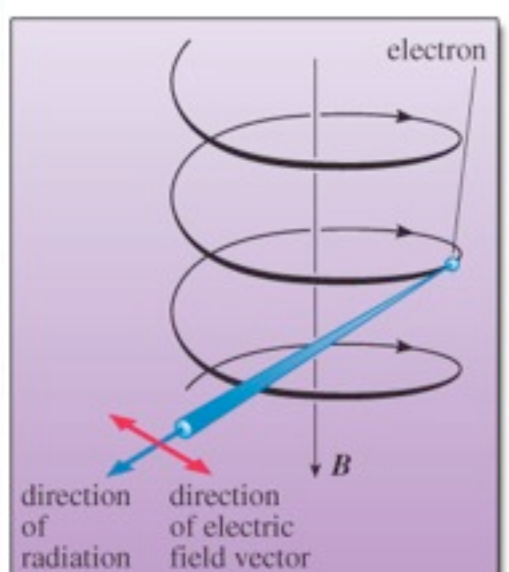
- **Synchrotron emission**:
  - **Rotation-powered neutron stars** (e.g. the Crab pulsar)
  - **Pulsar wind nebulae** (e.g. the Crab nebula)
  - **Jets in active galactic nuclei**

- **Compton scattering**:
  - **Accretion disk around black holes** (e.g. Cygnus X-1)

- **Propagation in strong magnetic field:**
  - **Highly magnetised neutron stars** (e.g. Hercules X-1)

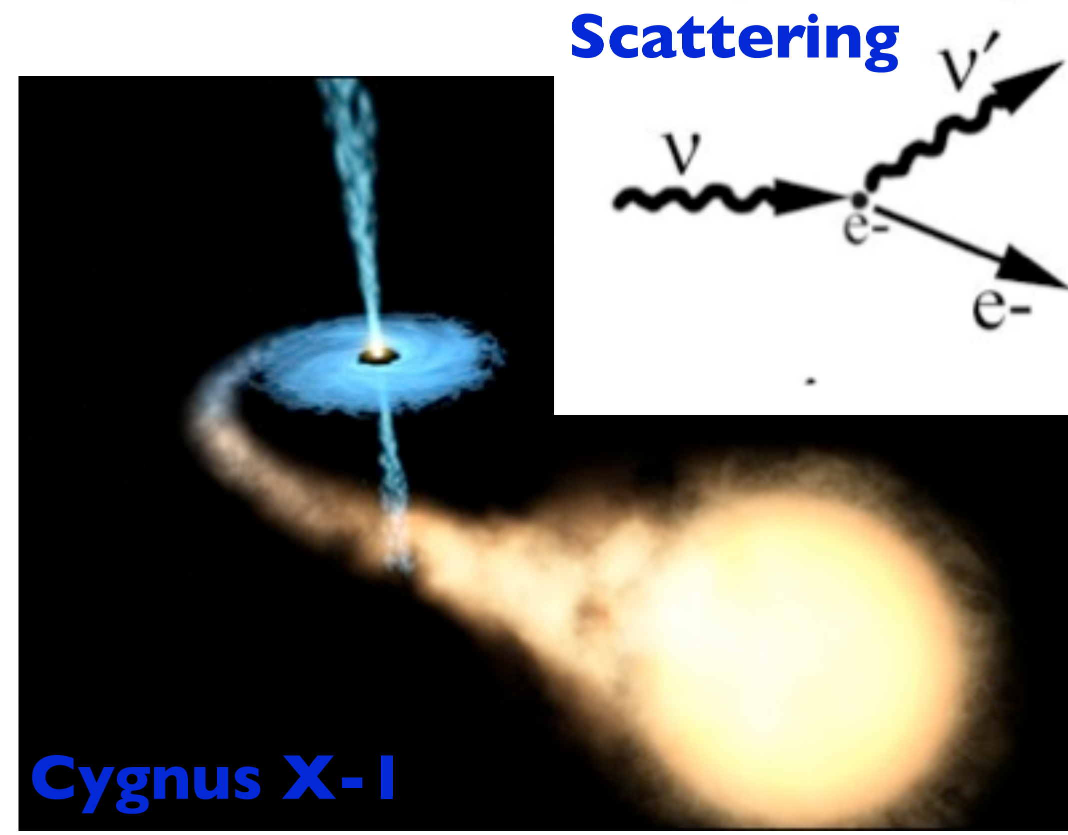
Crab





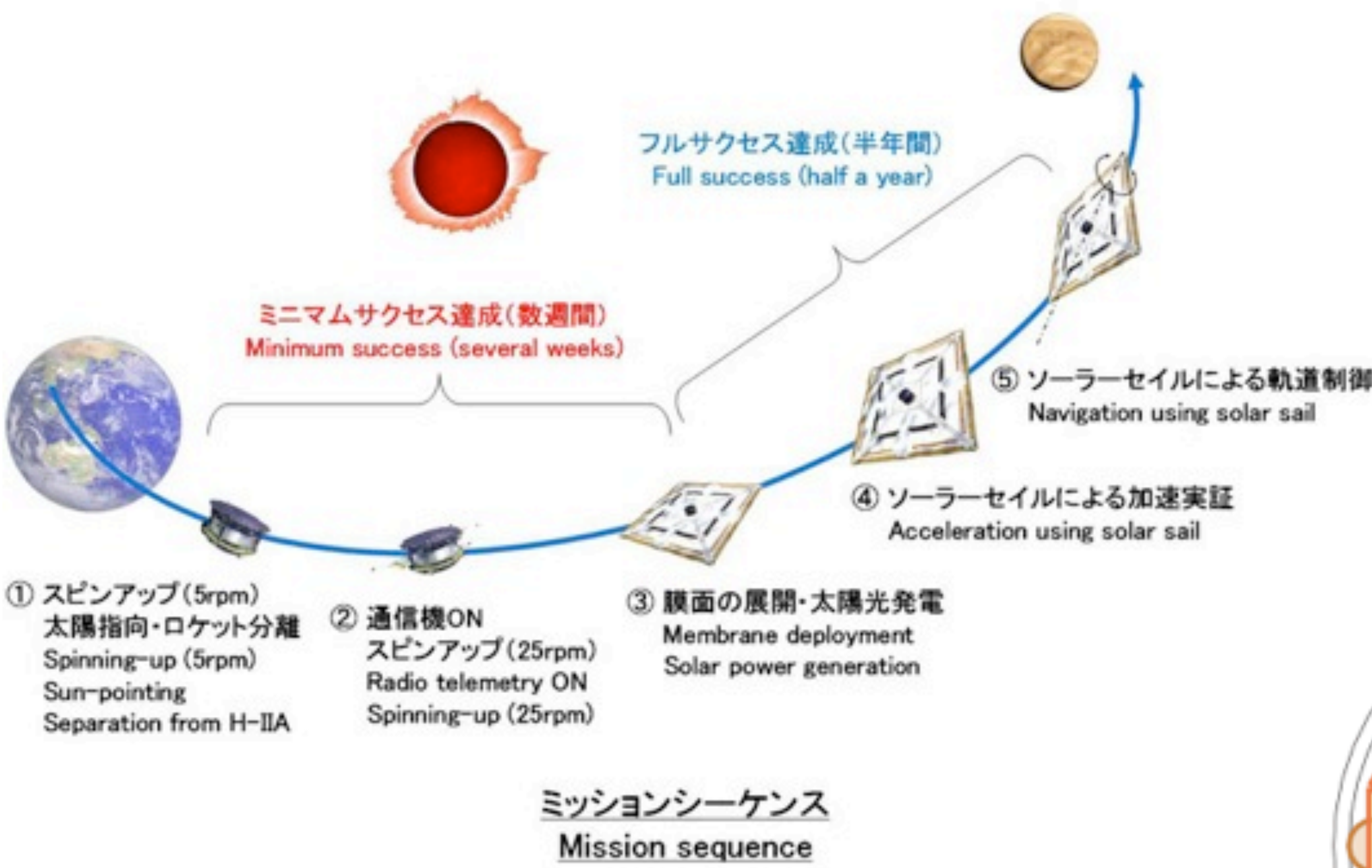
Synchrotron emission

Scattering

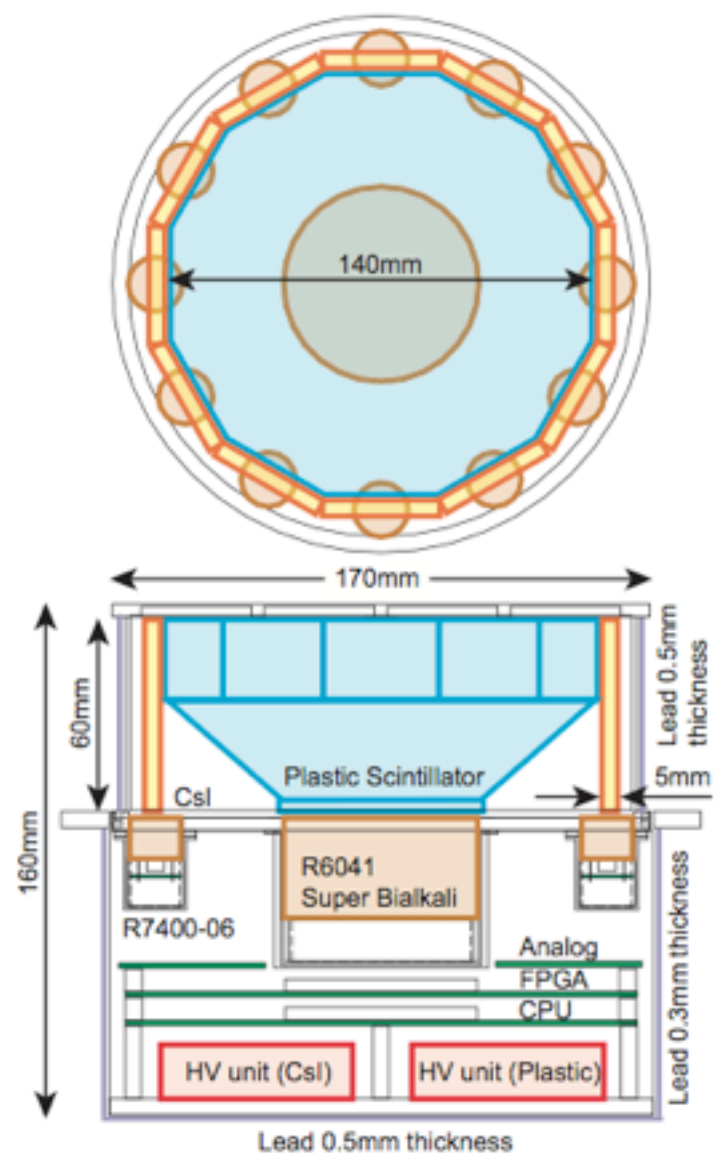


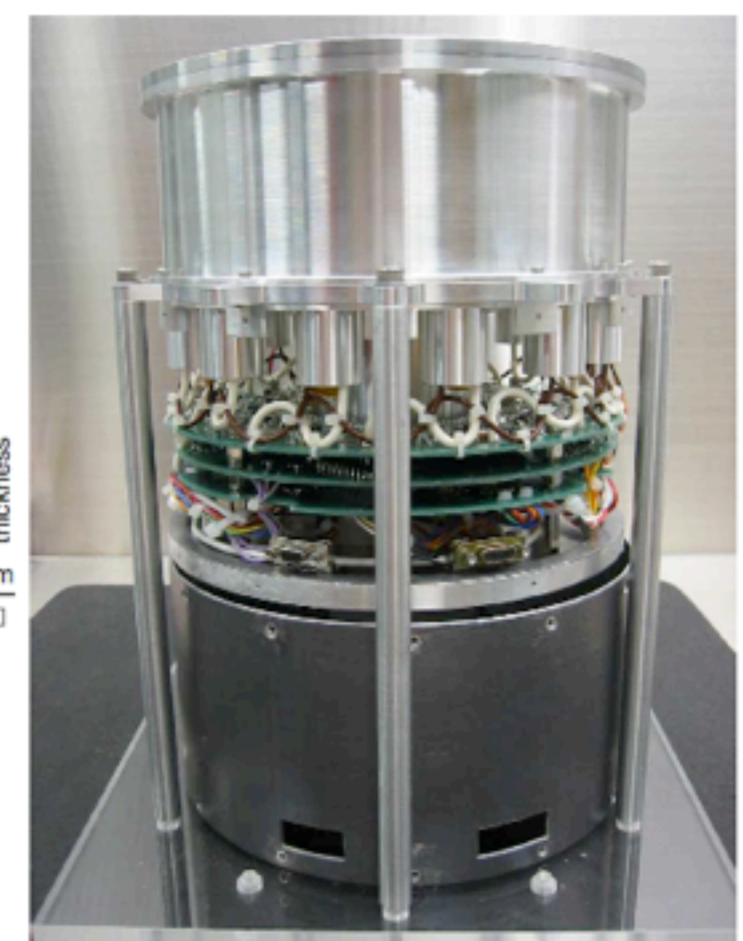
Cygnus X-1

A short diversion: GAP



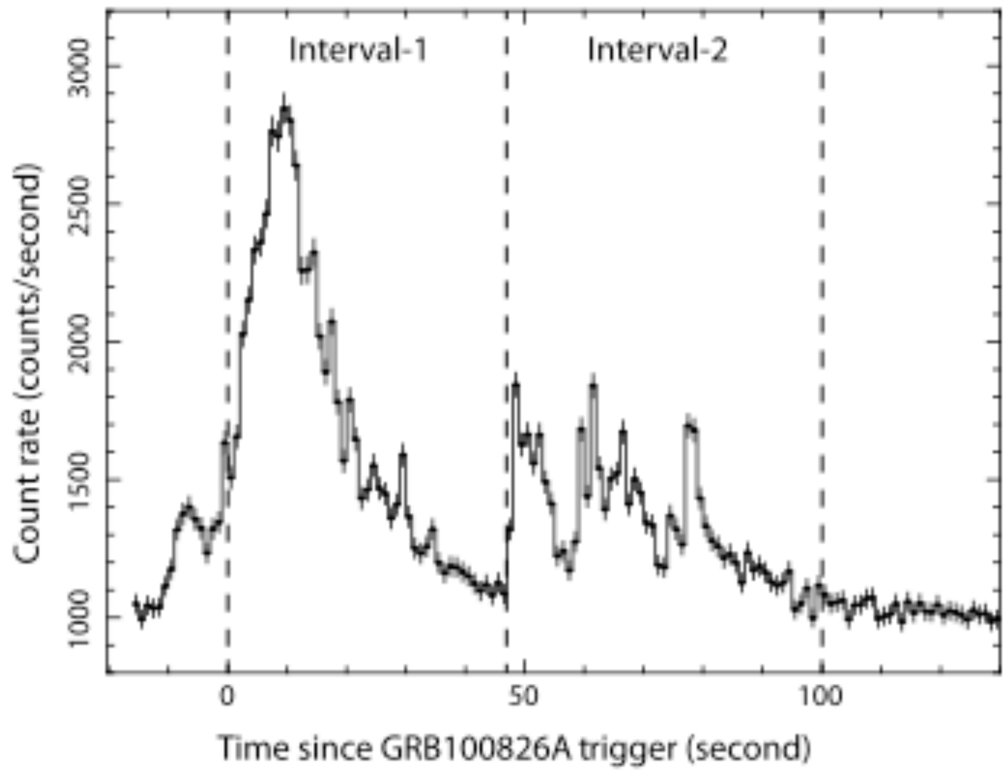
- Gamma-ray burst polarimeter, GAP
- 3.8 kg, 50-300 keV
- Compton scattering from central plastic counter to peripheral CsI units.
- **Designed** for polarimetry

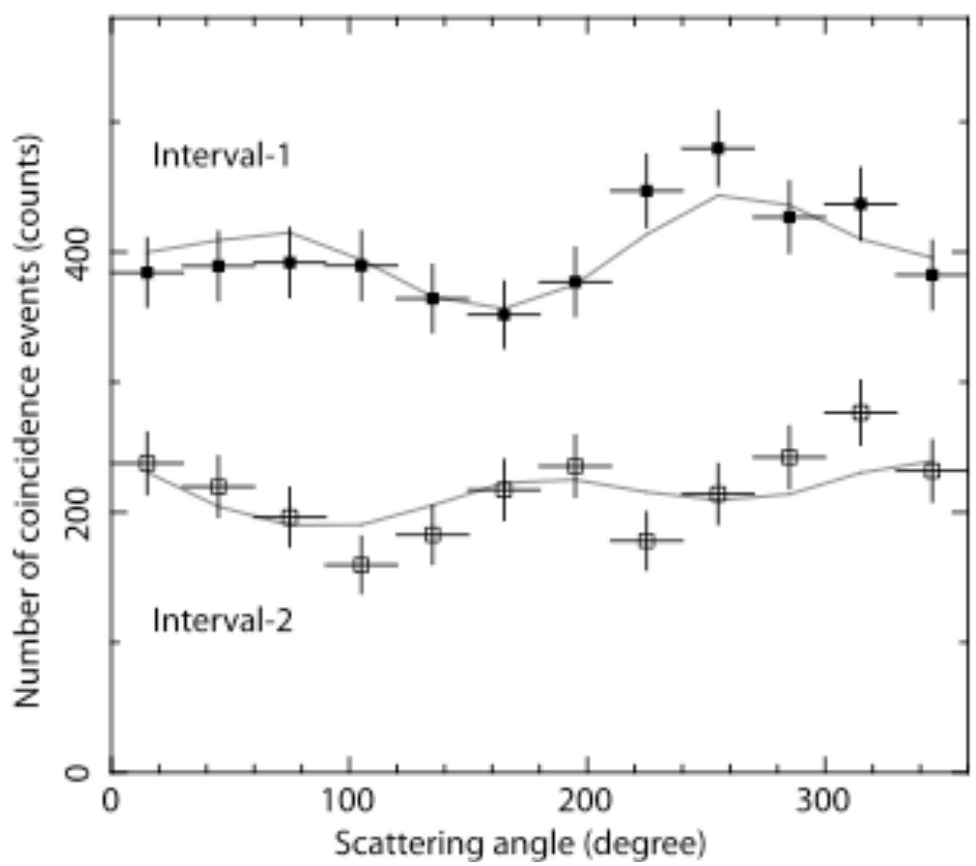




- IKAROS: solar sail demonstrator
- Launched: May 21st 2010. Aim to reach 2 AU.
- Propulsion: ion engine powered by thin film solar cells mounted on a ∅20m 7.5 μm polyamide sail **and** solar radiation pressure.

arXiv:1111.1779v1





- **Gamma-ray burst, GRB**
  - Most luminous electromagnetic events known in Universe
  - Serendipitous discovery in 1967
  - “long” (> 2 seconds): supernova-related
  - “short” (< 2 seconds): merger of neutron star binary
- **Emission mechanism much debated**

- GAP observed **GRB100826A**
- Extremely bright (top 1% BATSE catalogue), 20 keV-10 MeV (KONUS)
- Position localised using InterPlanetary Network (20°off-axis)
- Π=(27±11)% (2.9σ); PA varies significantly interval 1→2. 70-300 keV
- Low significance and dubious systematics, but will no doubt trigger discussions regarding interpretation.

- **OBS!** Pre-/post- null☺; BUT: off-axis, very slow satellite spin (1-2 rpm), systematics from non-polarised calibration (at lower energy).

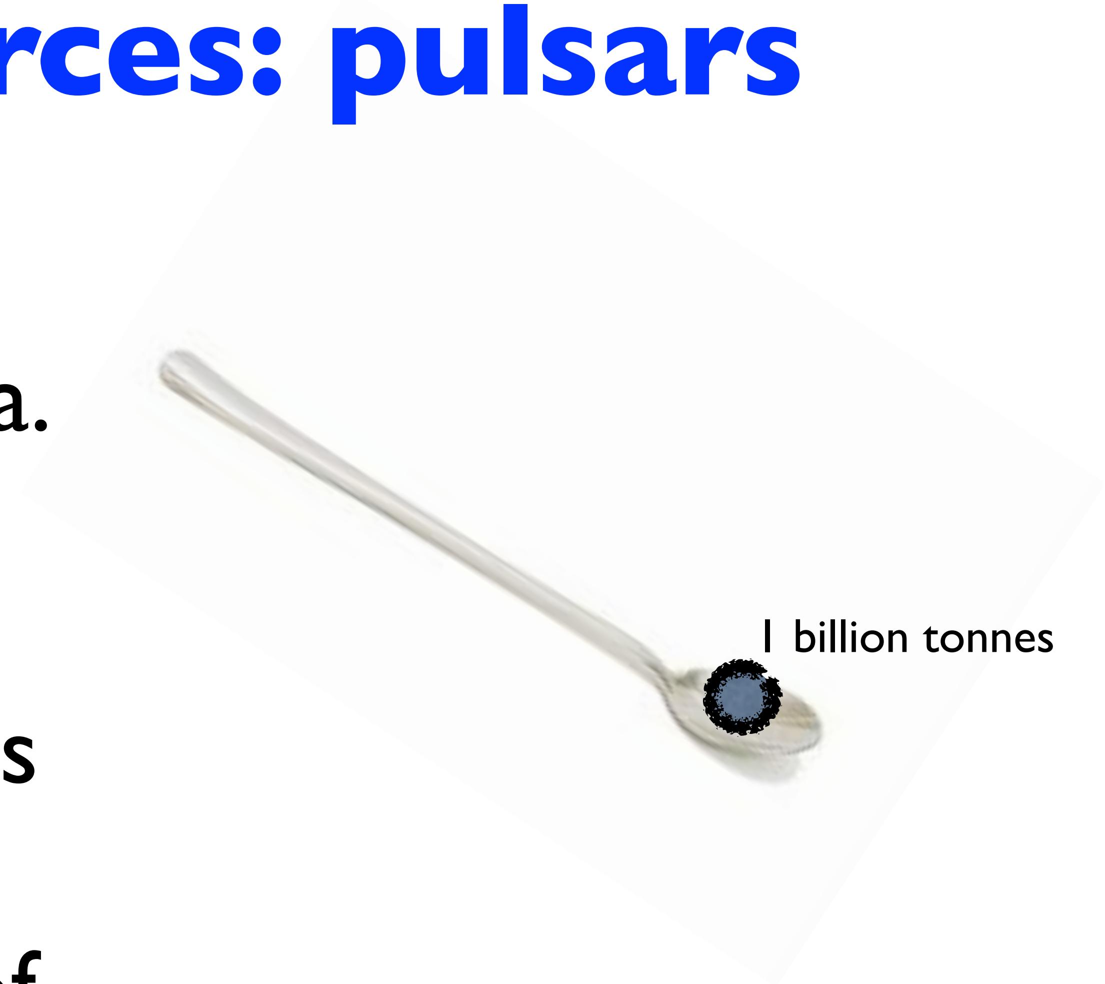
Back to point-sources: pulsars

• Pulsar = rapidly rotating neutron star, formed as a result of a supernova.

• **Diameter** ~20 km, but 1.4 times the mass of the Sun.

• **Surface gravitation** ~10^{11} times that at Earth.

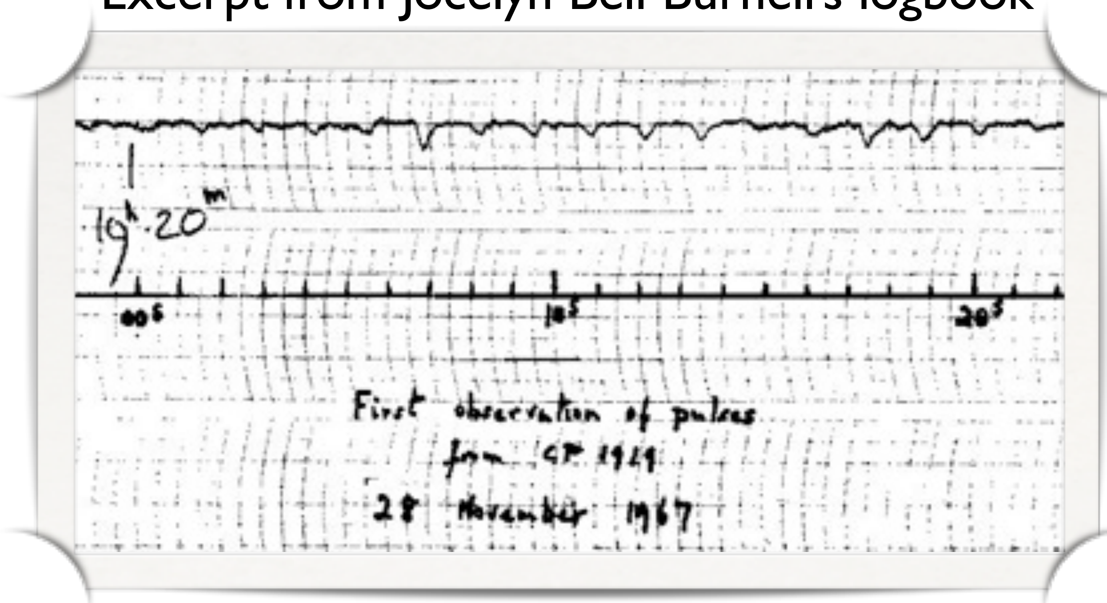
• **Magnetic field** ~10^6 times that of Earth.



• A laboratory for extreme physics.

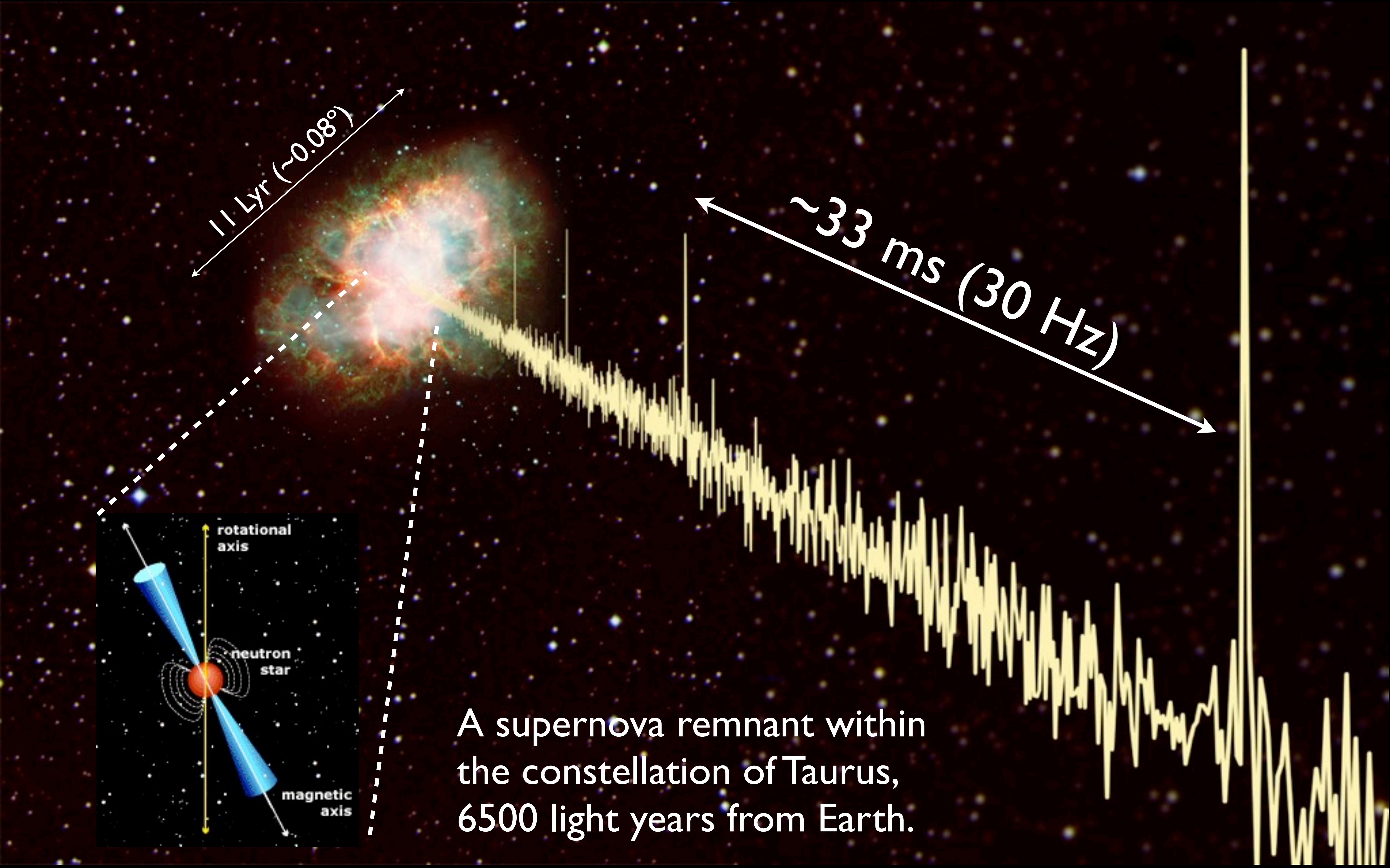
• Discovered in 1967. Mechanism responsible for emission of high energy radiation still not understood.

Excerpt from Jocelyn Bell Burnell's logbook

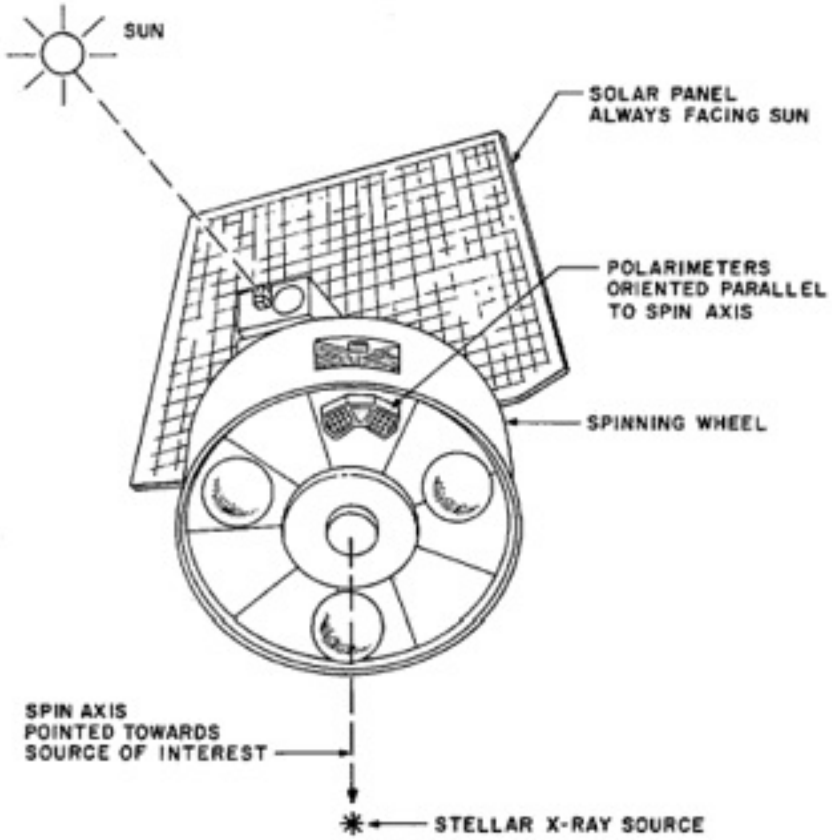


The signal from LGM 1

The Crab


11 Lyr (~0.08°)
~33 ms (30 Hz)
rotational axis
neutron star
magnetic axis
A supernova remnant within the constellation of Taurus, 6500 light years from Earth.

OSO-8 (1976)



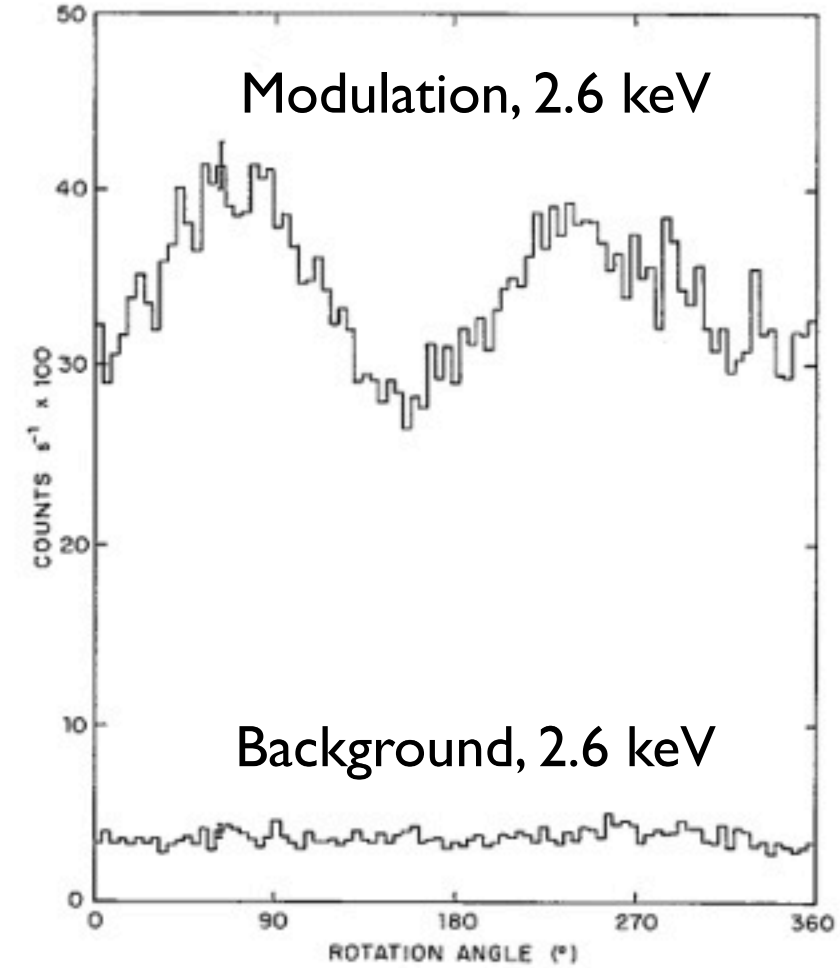
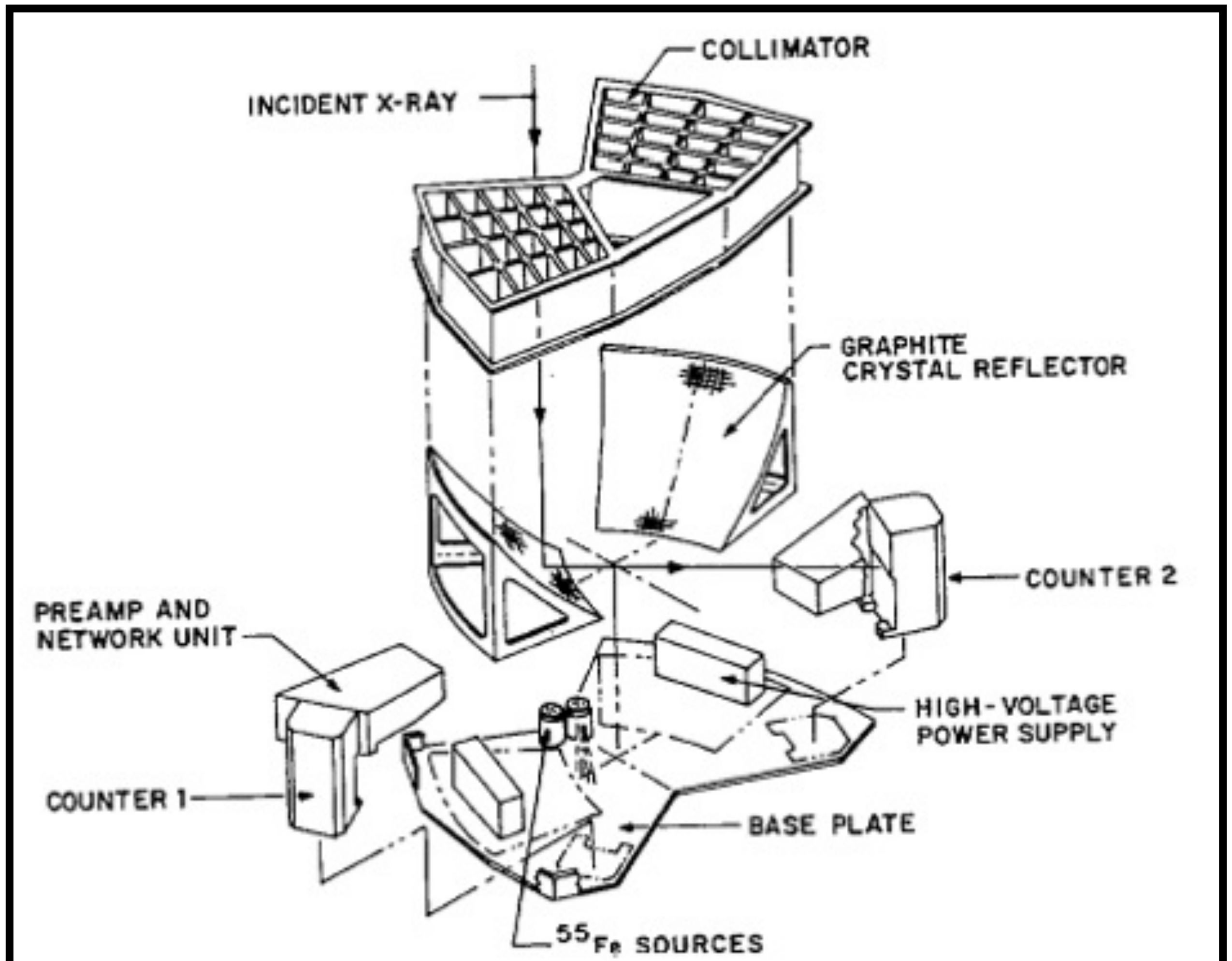


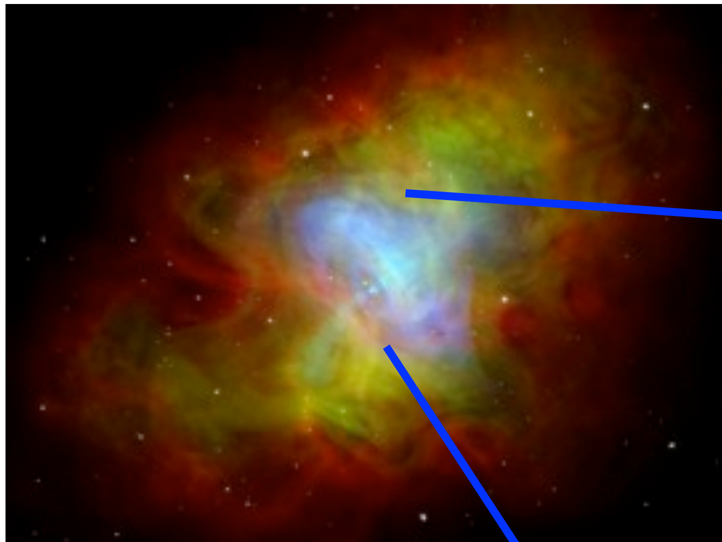
FIG. 2.—Average modulation curves obtained with both detectors at 2.6 keV during (*upper curve*) observations of the Crab Nebula and during (*lower curve*) observations of the Earth-occulted instrumental background.



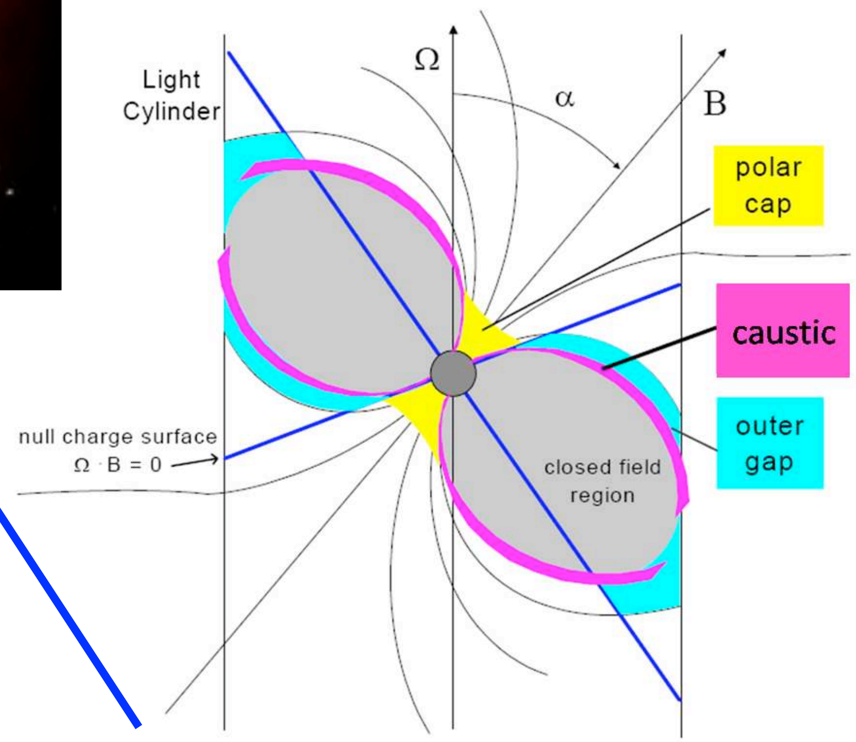
M. Weisskopf et al, ApJ 208 L125 (1976), ApJ 220 L117 (1978)

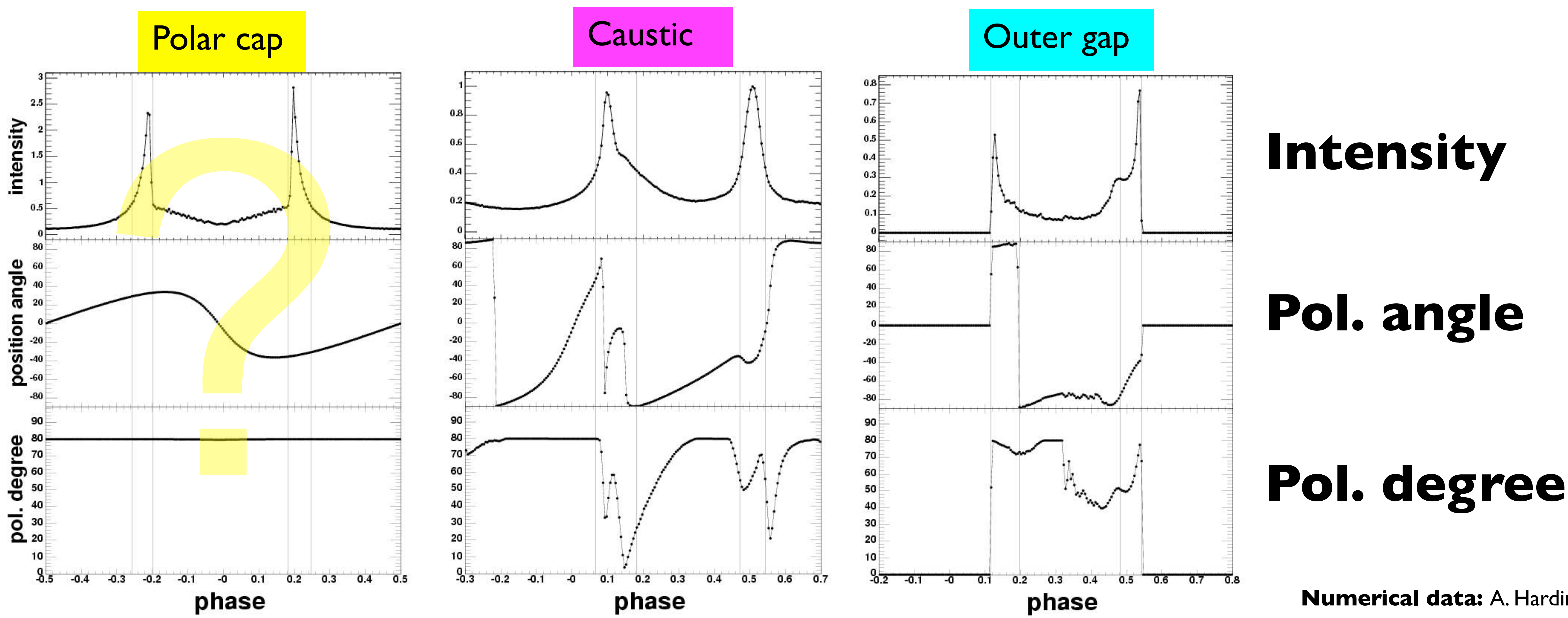
- **Crab nebula** viewed at 2.6 keV, 5.2 keV.
- Polarisation measured using Bragg diffraction: (19.2±1.0)% at angle (156.4±1.4)° (2.6 keV).
- No **dedicated** measurements since then.
- At higher (soft γ-ray) energies, non-thermal processes are expected to increase polarisation.

Crab pulsar emission models



X-rays (Chandra),
optical (HST),
radio (VLA)





Numerical data: A. Harding

X-rays (Chandra),
optical (HST),
radio (VLA)

KTH
Stockholm University
DST Control
SSC Esrange

Hiroshima University,
Tokyo Inst. of Tech,
ISAS/JAXA, Waseda Uni.

SLAC - KIPAC
Uni. of Hawaii

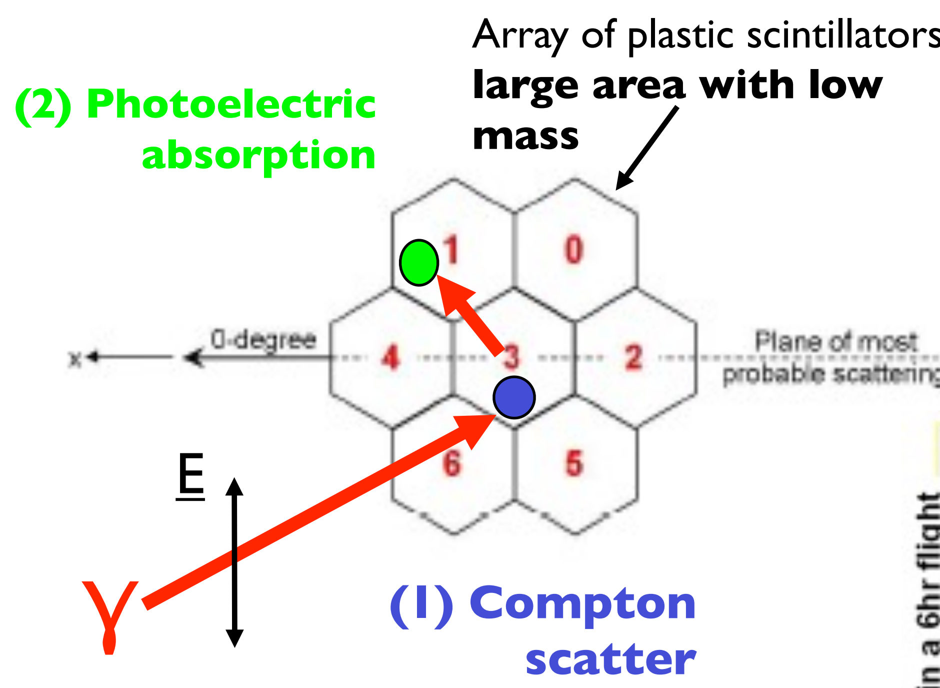
γ

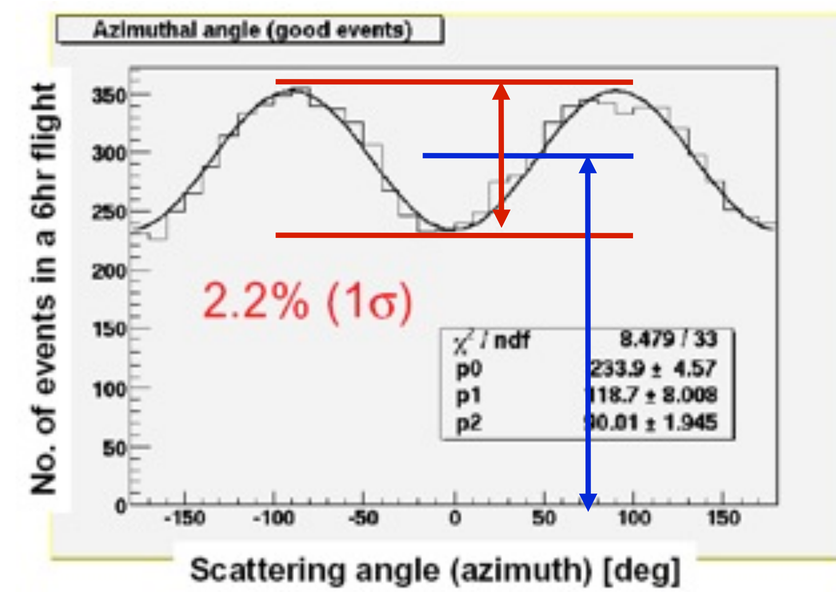
25 – ~100 keV

- **PoGOLite** is optimised for **point sources** (e.g. Crab pulsar, Cygnus X-1).
- Measures **10% polarisation** in **200 mCrab sources** in a **6 hour** balloon observation.
- **Maiden flight** of scaled down (less effective area) **‘pathfinder’** took place in **July 2011** from Esrange Space Centre, Sweden.

PoGOLite principle

- γ from a **polarised** source undergo **Compton scattering** in segmented detector material
- Higher probability of being **scattered perpendicular** to the **electric field vector**
- Observed **azimuthal scattering angles** are **modulated by polarisation**





MF=difference/average

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

- 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)

minimum detectable polarisation

signal rate

$$MDP_{99\%} = \frac{4.29}{M_{100} R_S} \sqrt{\frac{R_S + R_B}{T}}$$

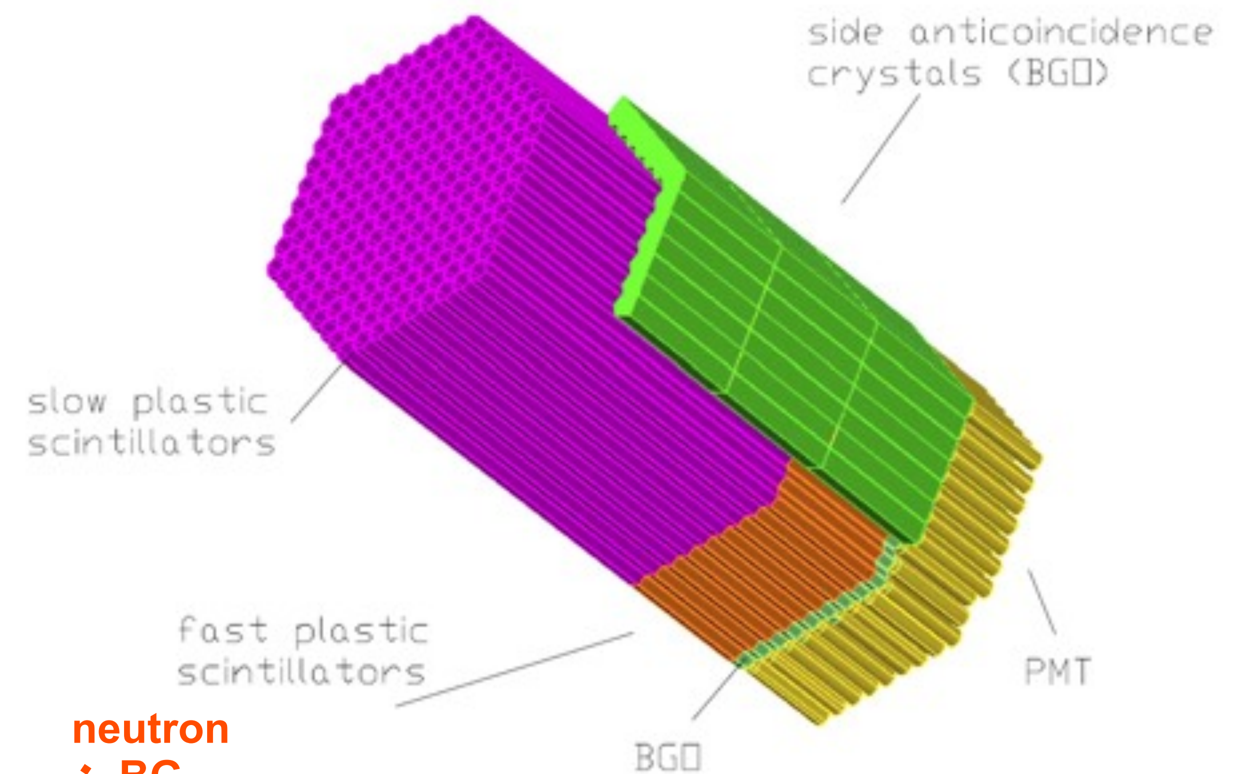
background rate

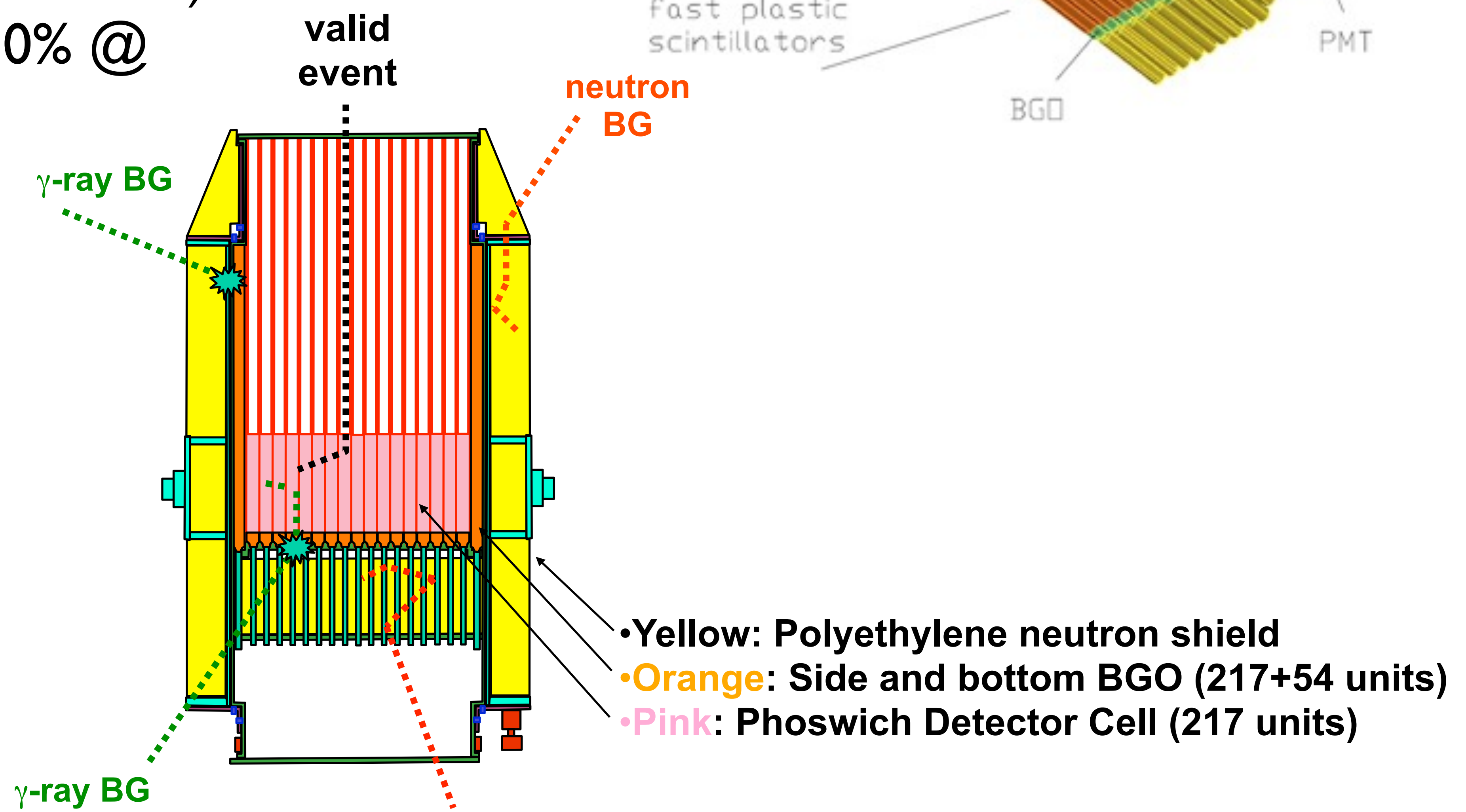
modulation for 100% polarised source

observation time

Implementation

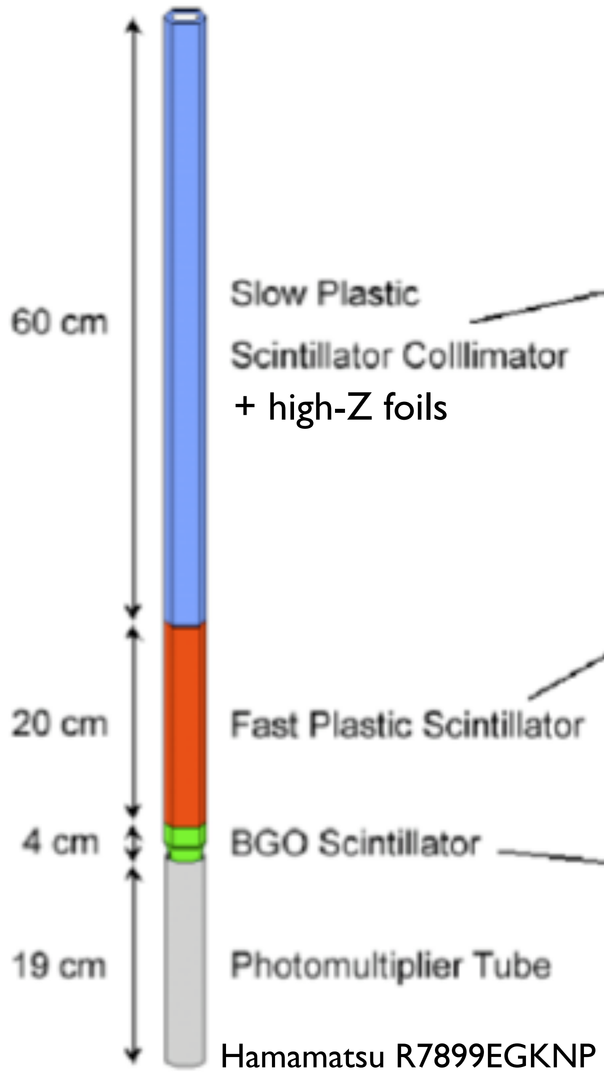
- Slow plastic collimators: **narrow field-of-view** (5 deg^2): **low aperture background**
- Poly-shield + BGO: **low γ + particle backgrounds**
- Plastic scattering scintillators: **large area** (~200 cm^2 @ 50 keV) and **reasonable MF** (~30% @ 50 keV)



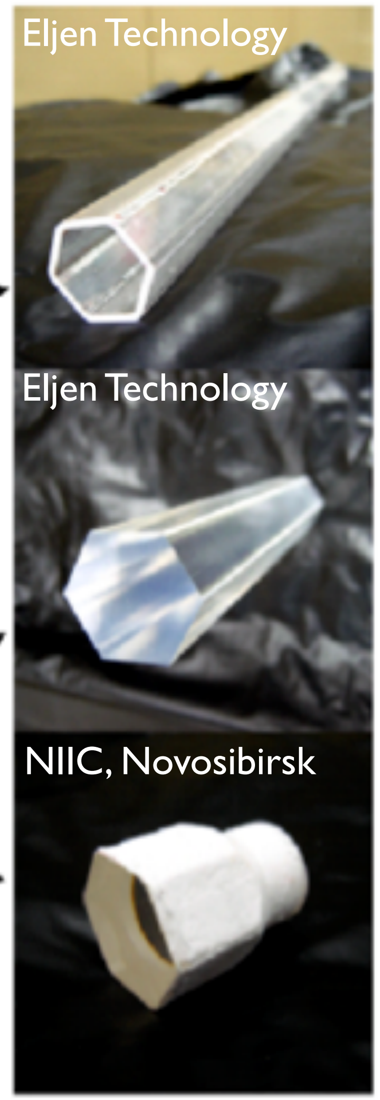


Scintillator array

Reflective wrappings:
VM2000 (plastic) / $BaSO_4$ (BGO)



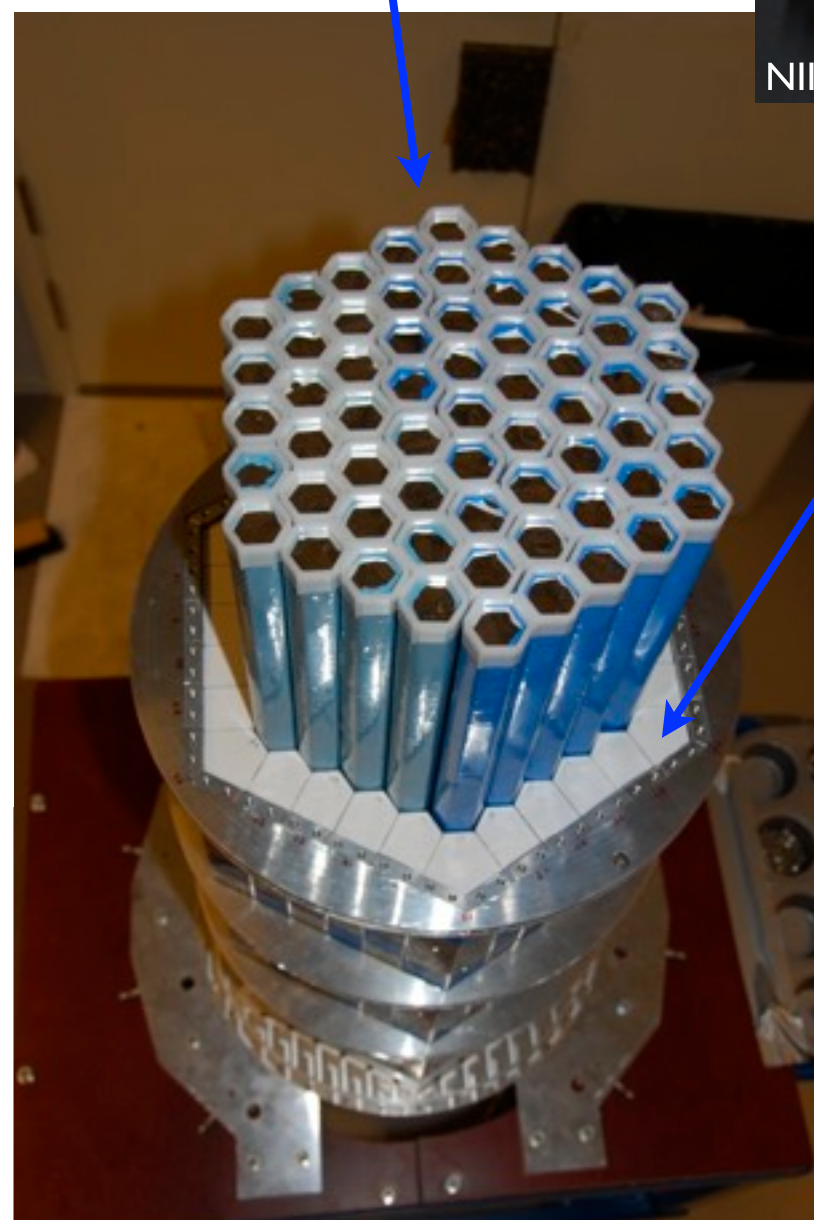
Hamamatsu R7899EGKNP



@ 25 keV only 1-3 keV Compton deposited - single p.e. detection (PMT has 0.05 p.e. ripple @ 10^6 gain)

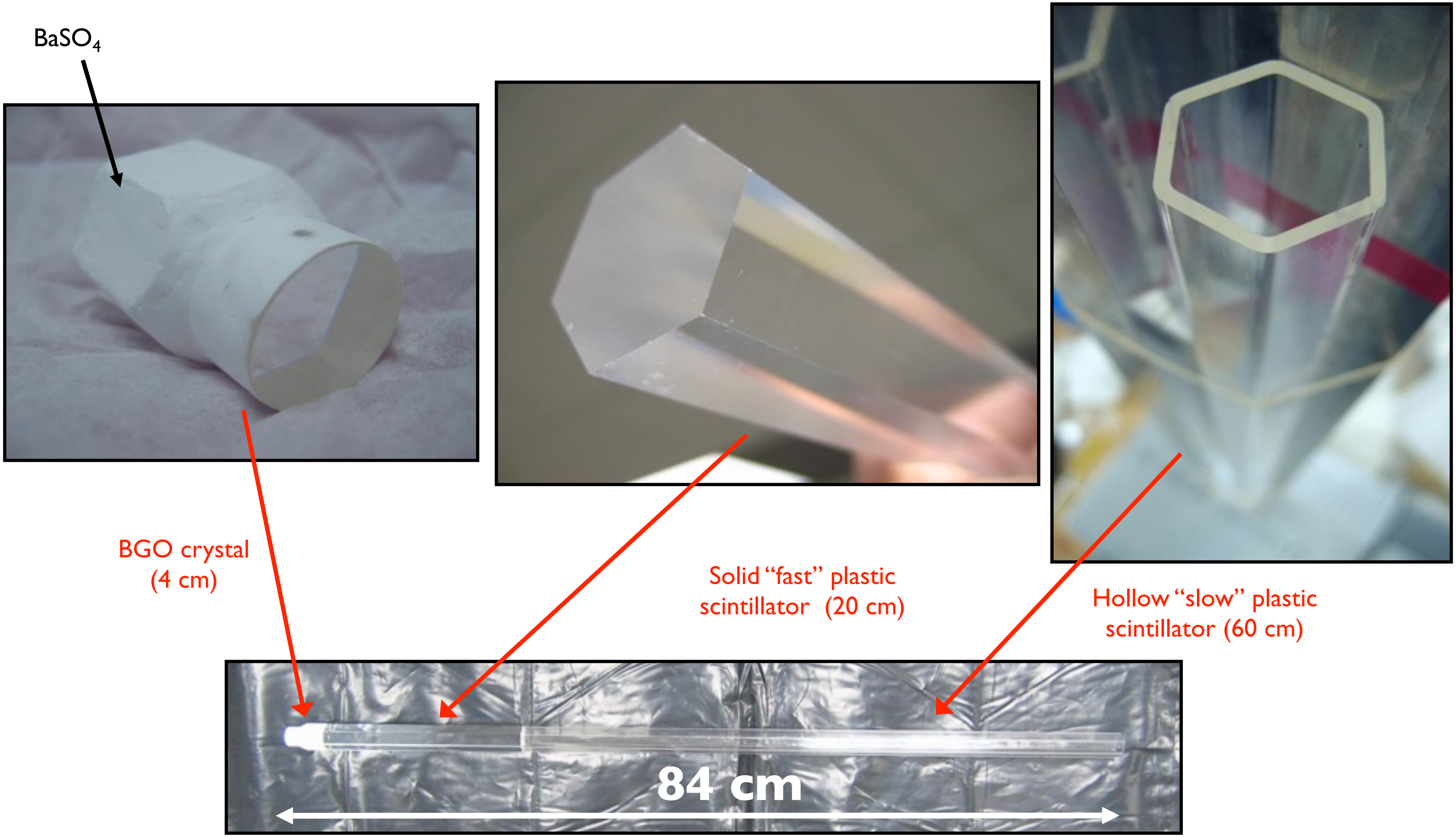
Phoswich Detector Cells (~30 kg)

Side anticoincidence, BGO ~150 kg

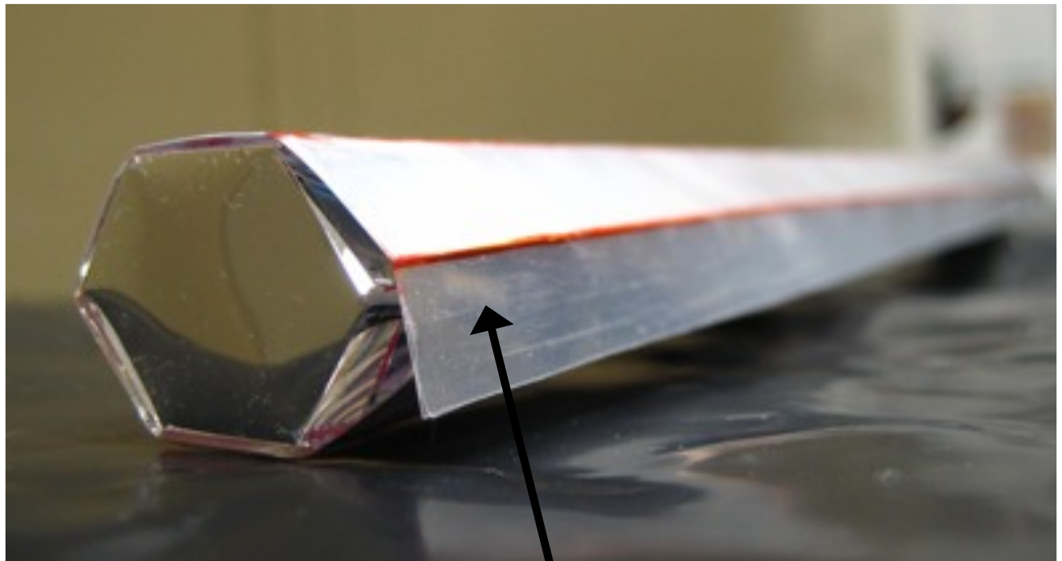


Pathfinder instrument
(61 units)

Phoswich detector cell components

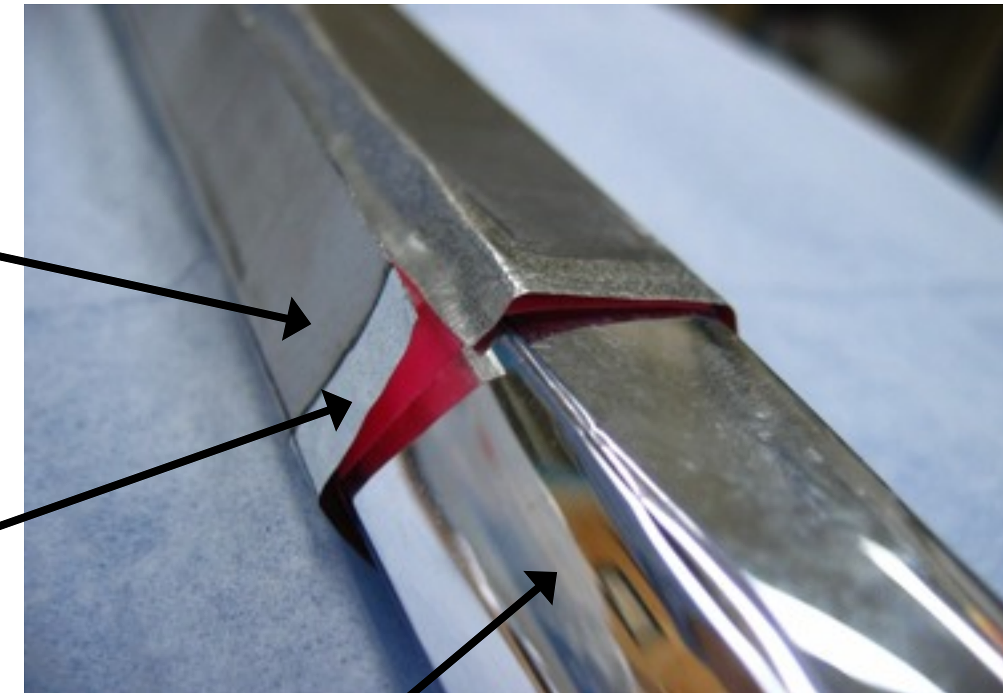


Phoswich detector cell wrapping



VM2000: multilayer birefringent polymer reflector film

Lead foil



Tin foil

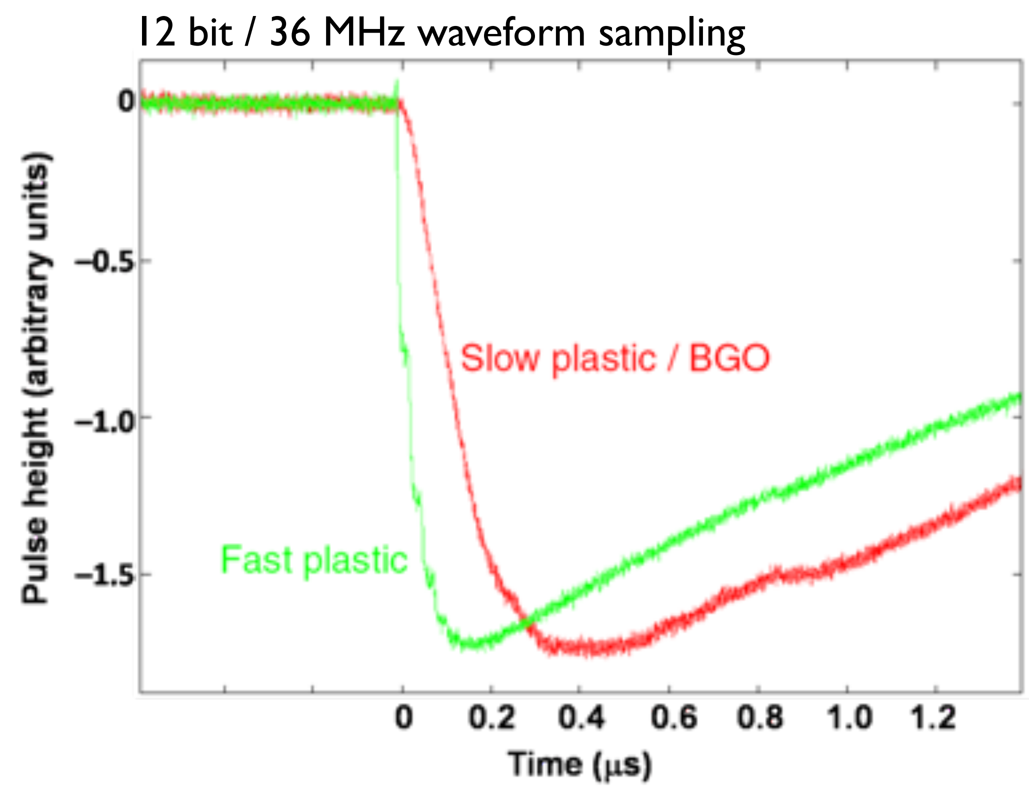
VM2000

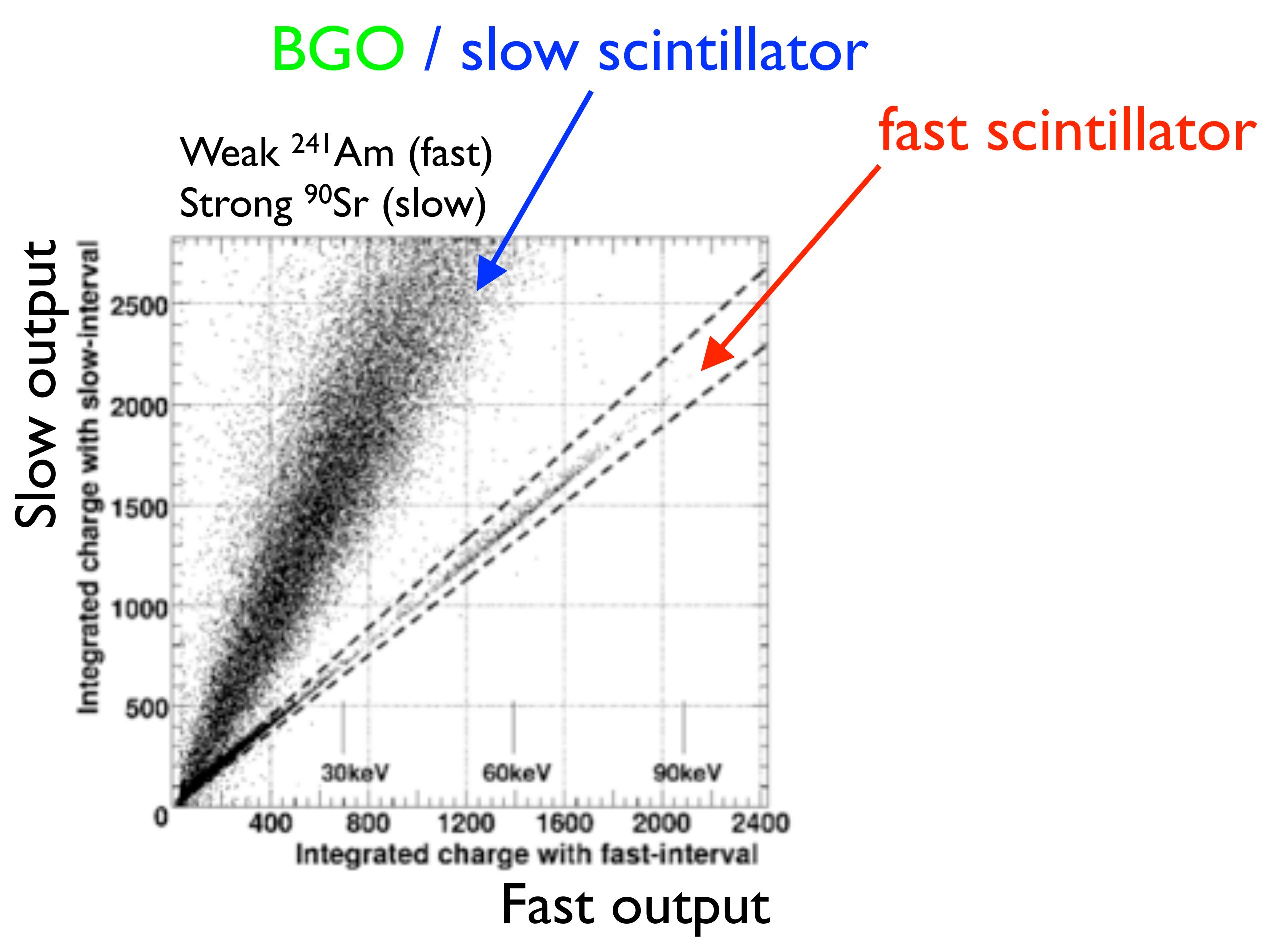
Heat shrink tube

Event selection

- Pulse shape discrimination

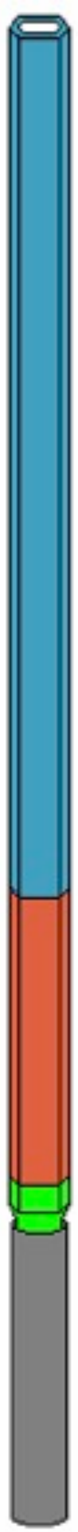
Decay times	
Fast scintillator	1.8 ns
Slow scintillator	285 ns
BGO	~300 ns





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

- Fast scintillator branch is chosen for analysis

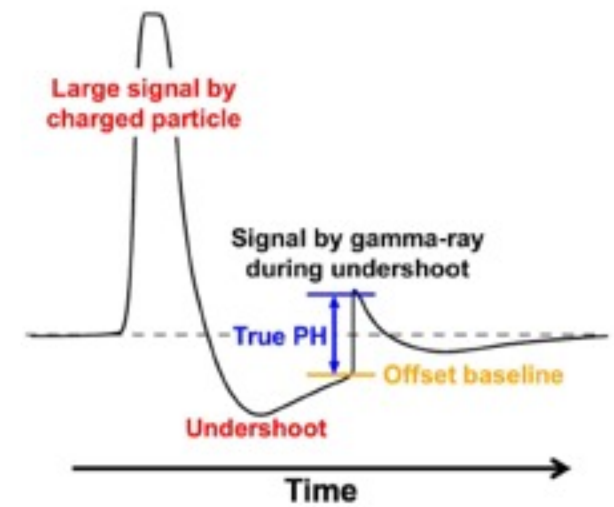


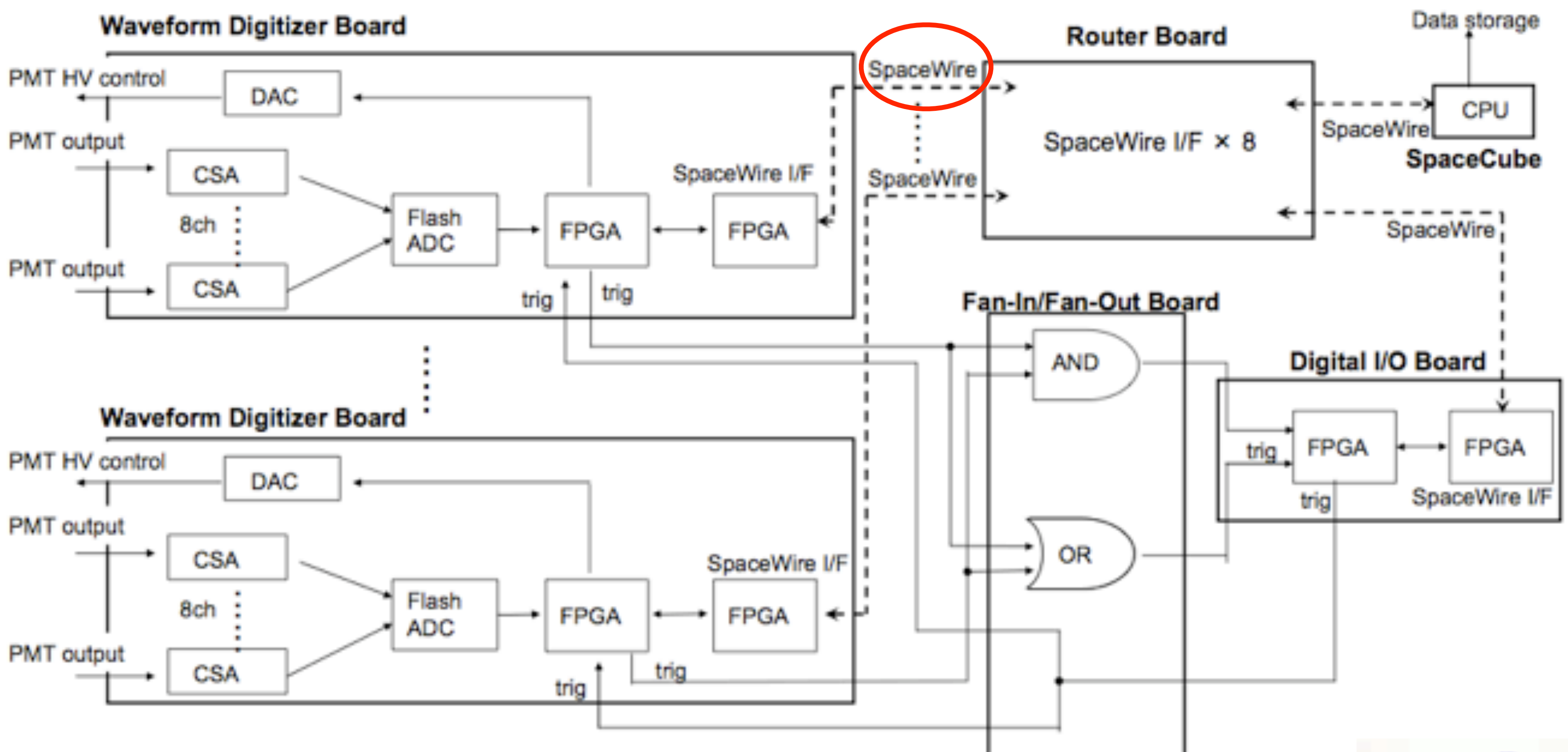
Data acquisition

Waveform digitiser board

- Front-end electronics
- 12 bit / 36 MHz waveform sampling
- Trigger logic:
  - Level-0 issued for fast hit > lower discriminator level (~15 keV)
  - Veto issued if signal > upper discriminator level or slow component

CPU and storage (now replaced by SpaceWire to Gb ethernet converter)





Global event logic

- Processes L0 and veto signals
- If no UD/PSD veto, **15 pre- and 25 post-trigger samples** from FADC moved to FIFO

Waveform digitizer board

Digital I/O board

SpW to GbE

Router board

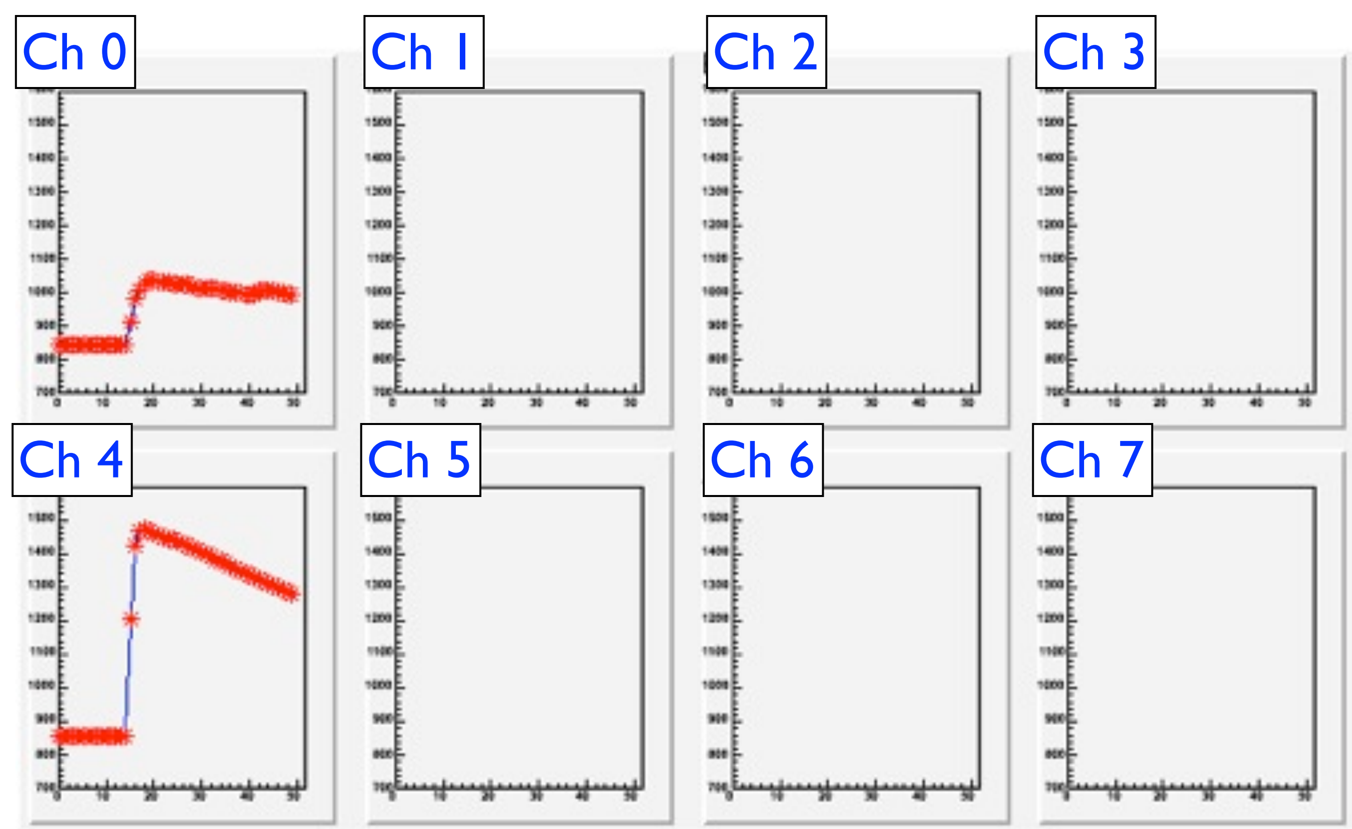
Collaboration between NEC/Shimafuji and JAXA

Example waveforms

- A photon has Compton scattered in channel 0 and subsequently been photoabsorbed in channel 4 of the same waveform digitizer board.
    - Such events are used to determine the azimuthal scattering anisotropy for polarisation events
- In this example, Ch 1-3, 5-7 are zero suppressed.

Compton

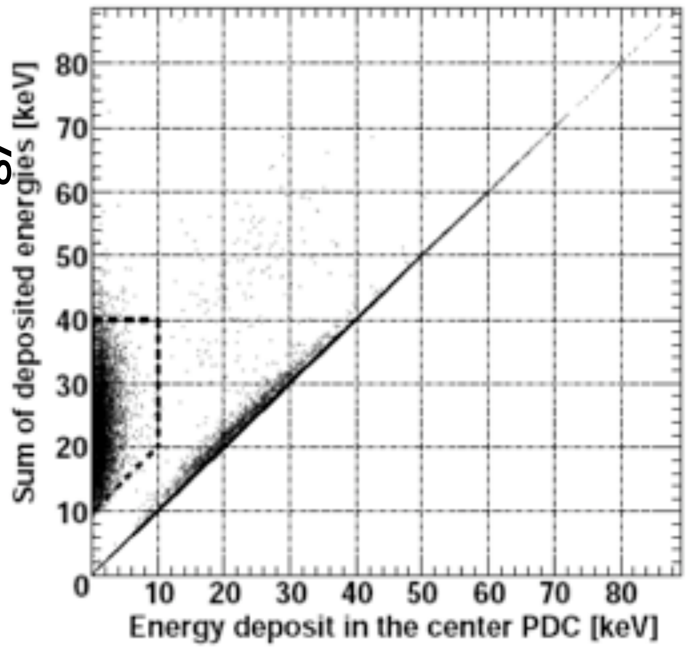
Photoabsorption



Tests of PoGOLite prototype

Fast / 25 keV / KEK

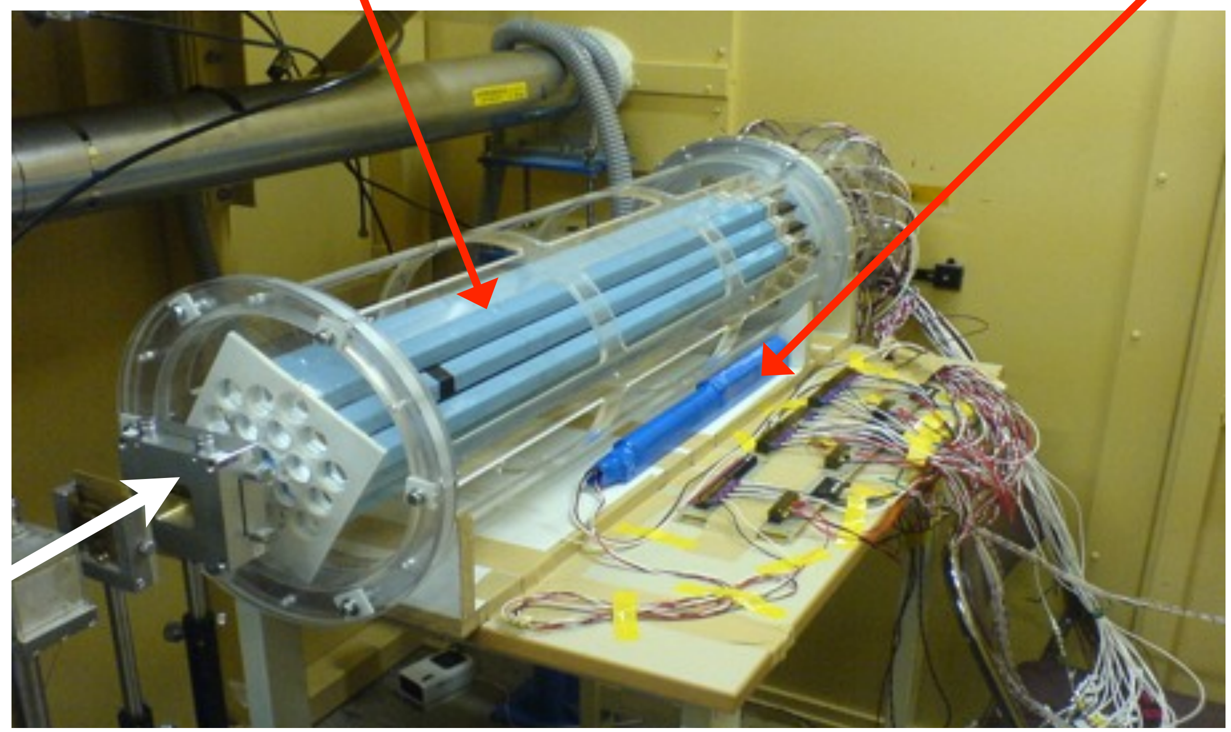
Energy sum



Centre energy

19 phoswich detector cells

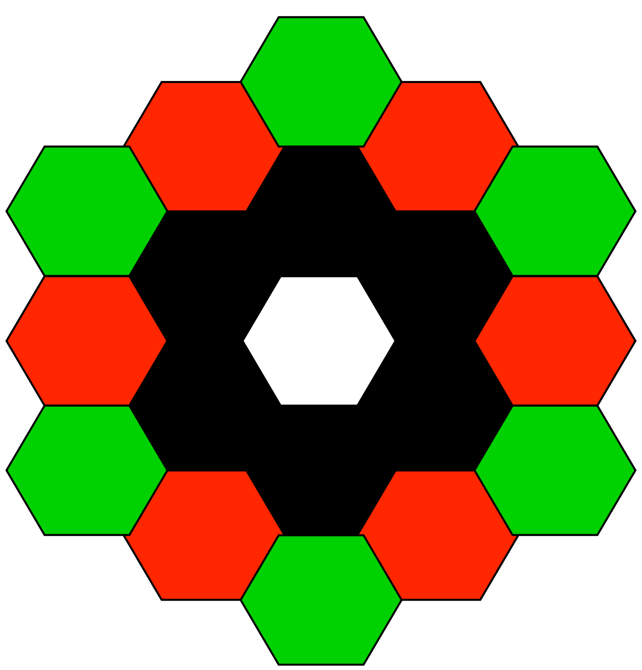
1 segment of the side anticoincidence shield



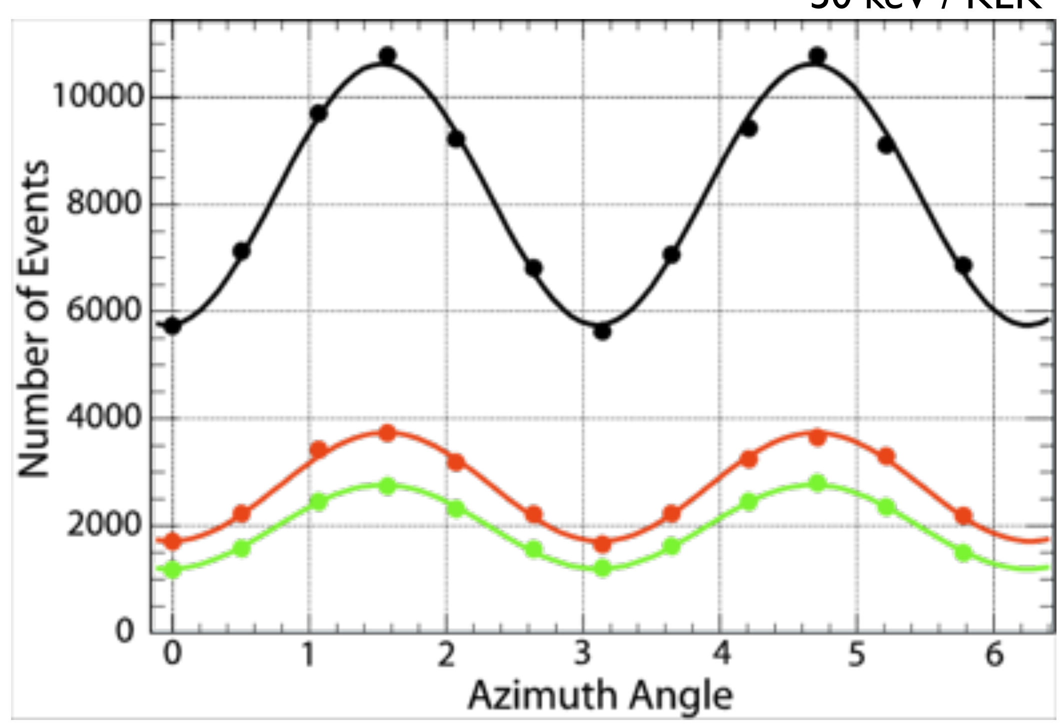
γ

(90 ± 1)%

19 units



50 keV / KEK



MF

Inner 6 units

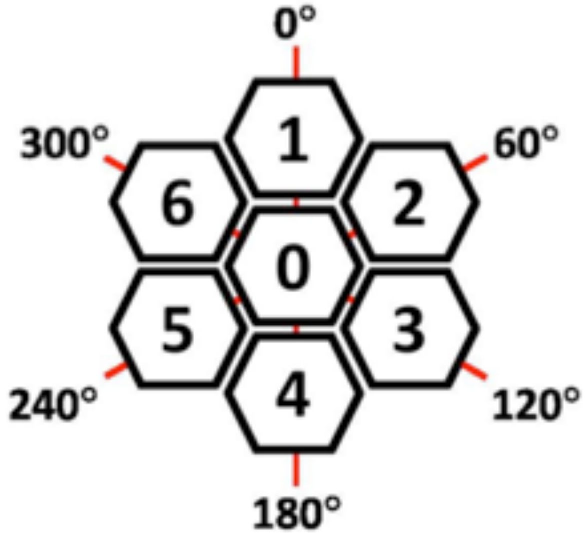
(31.3±0.4)%

Outer 12 units

(37.9±0.7)%

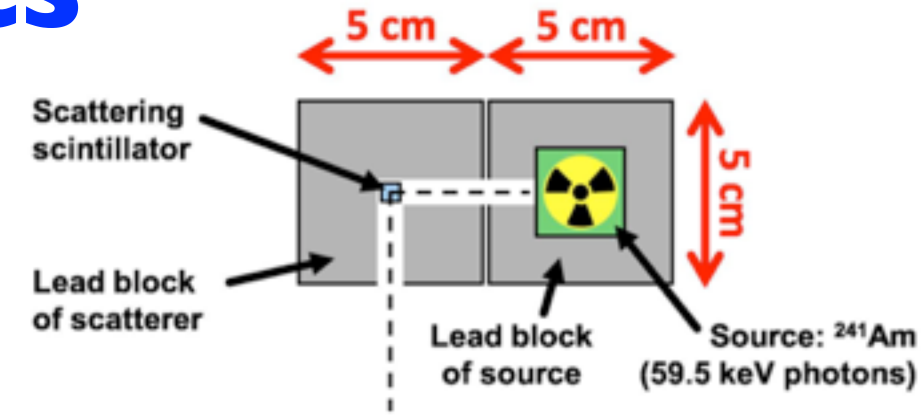
(40.2±0.8)%

Consistent with Geant-4

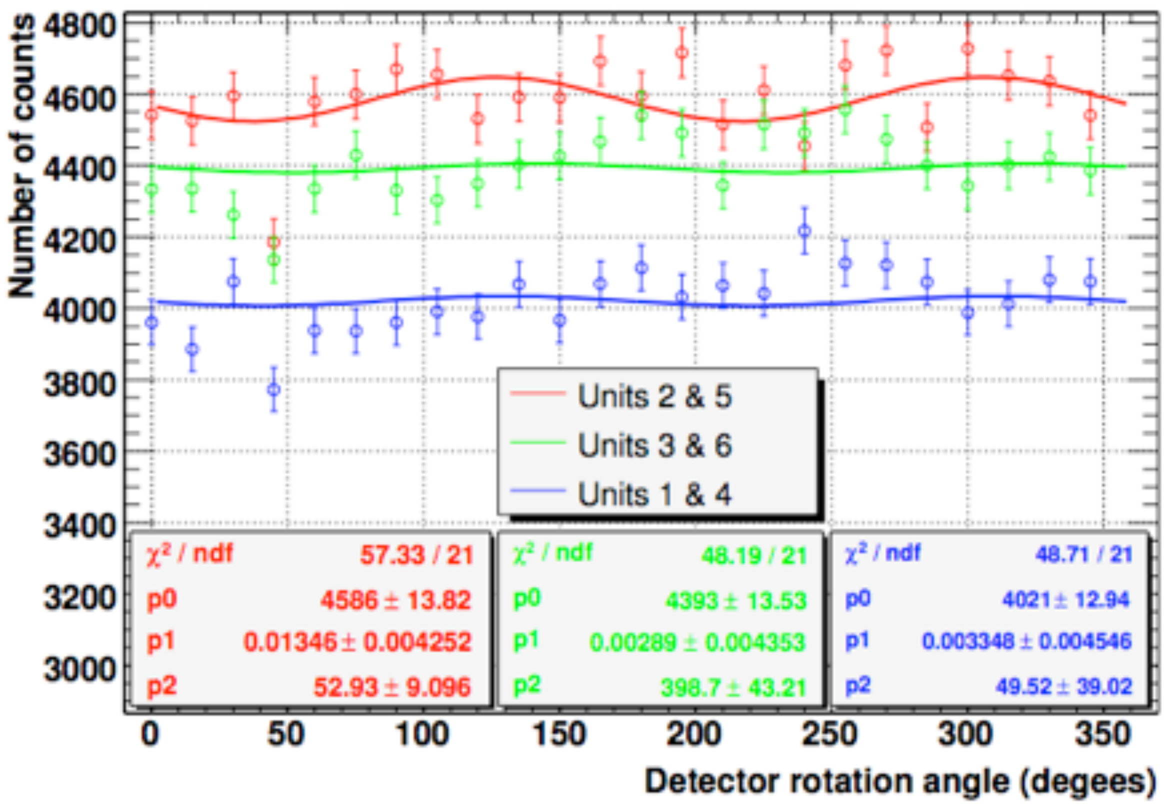


Laboratory tests

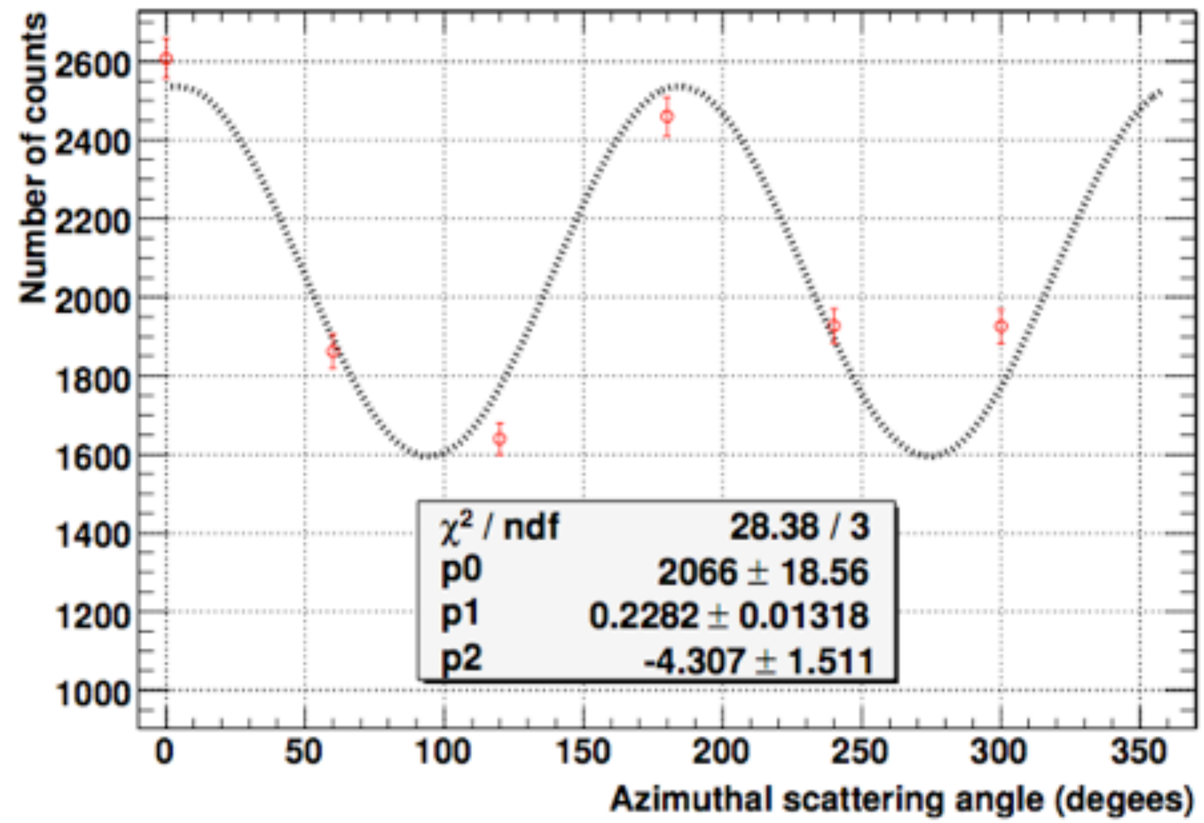
OBS!
Polarisation is a positive definite quantity



Unpolarised beam (^{241}Am, 60 keV)



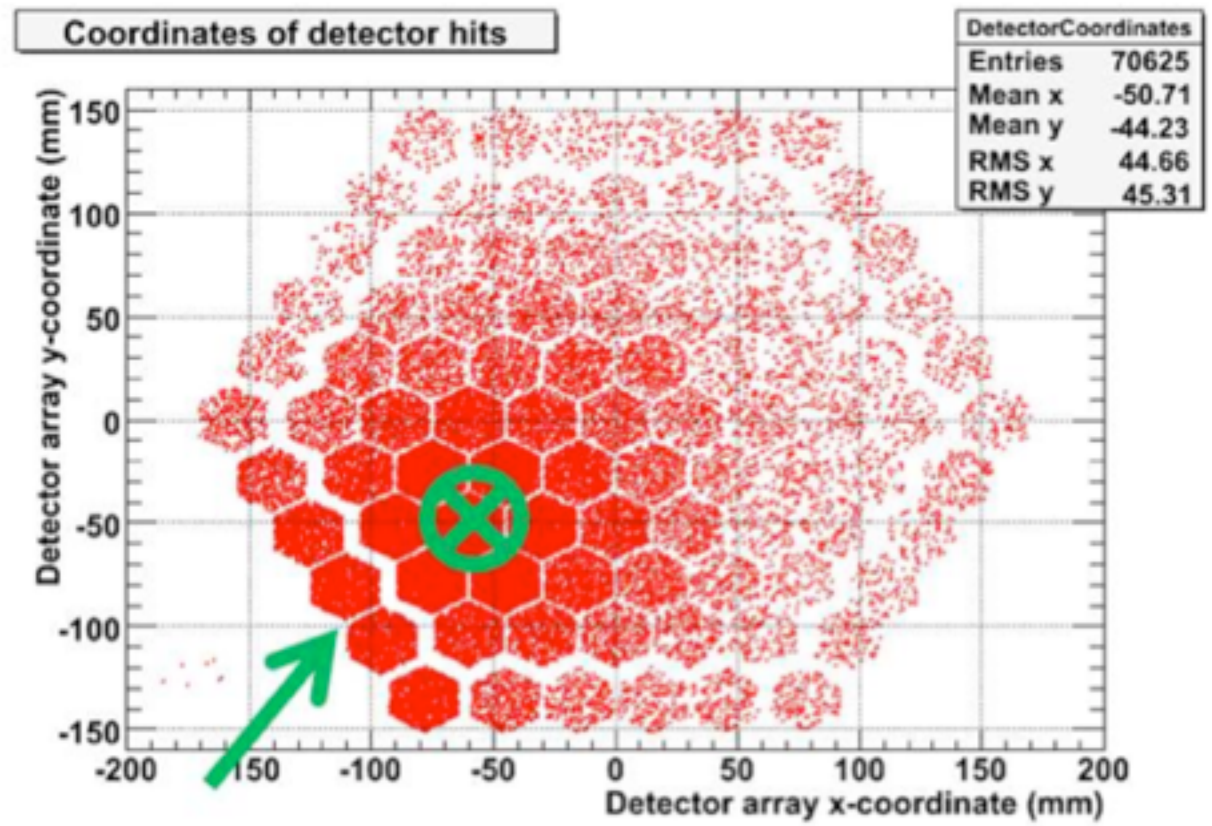
~100% polarised beam (scattered ^{241}Am, 53 keV)



- **Unpolarised** 60 keV beam, ^{241} Am
- Systematics reduced with a pairwise average
- Average MF = (0.6±0.3)%

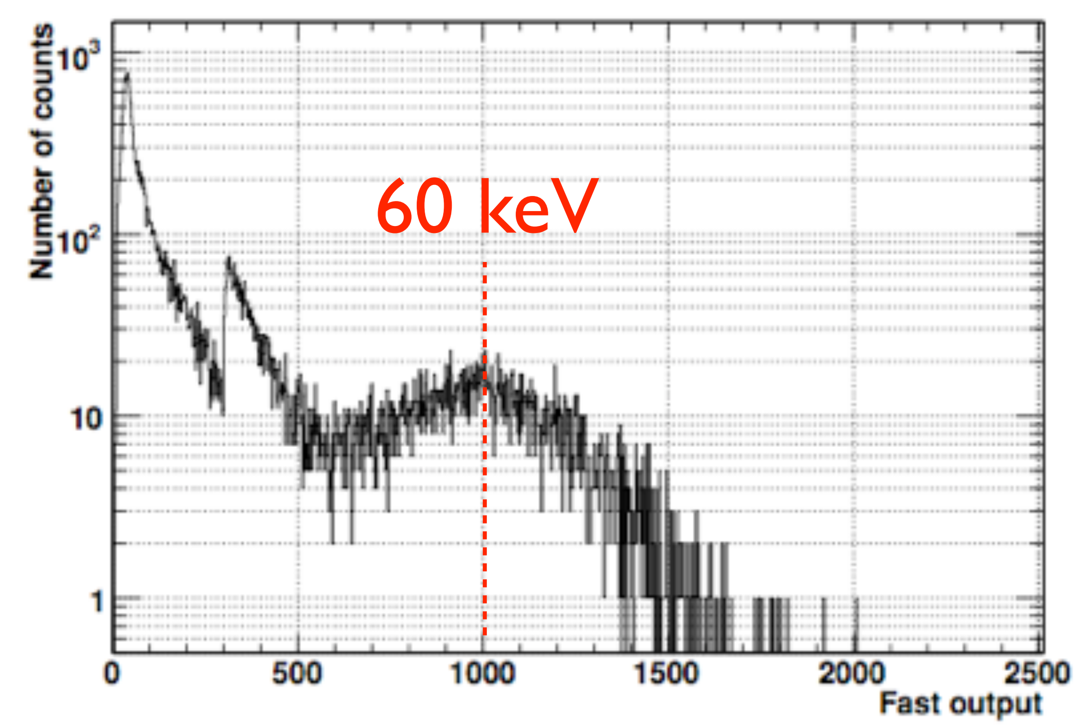
- **Polarised** 53 keV beam, scattered ^{241} Am
- MF compatible with Geant4 simulations

Photon background suppression

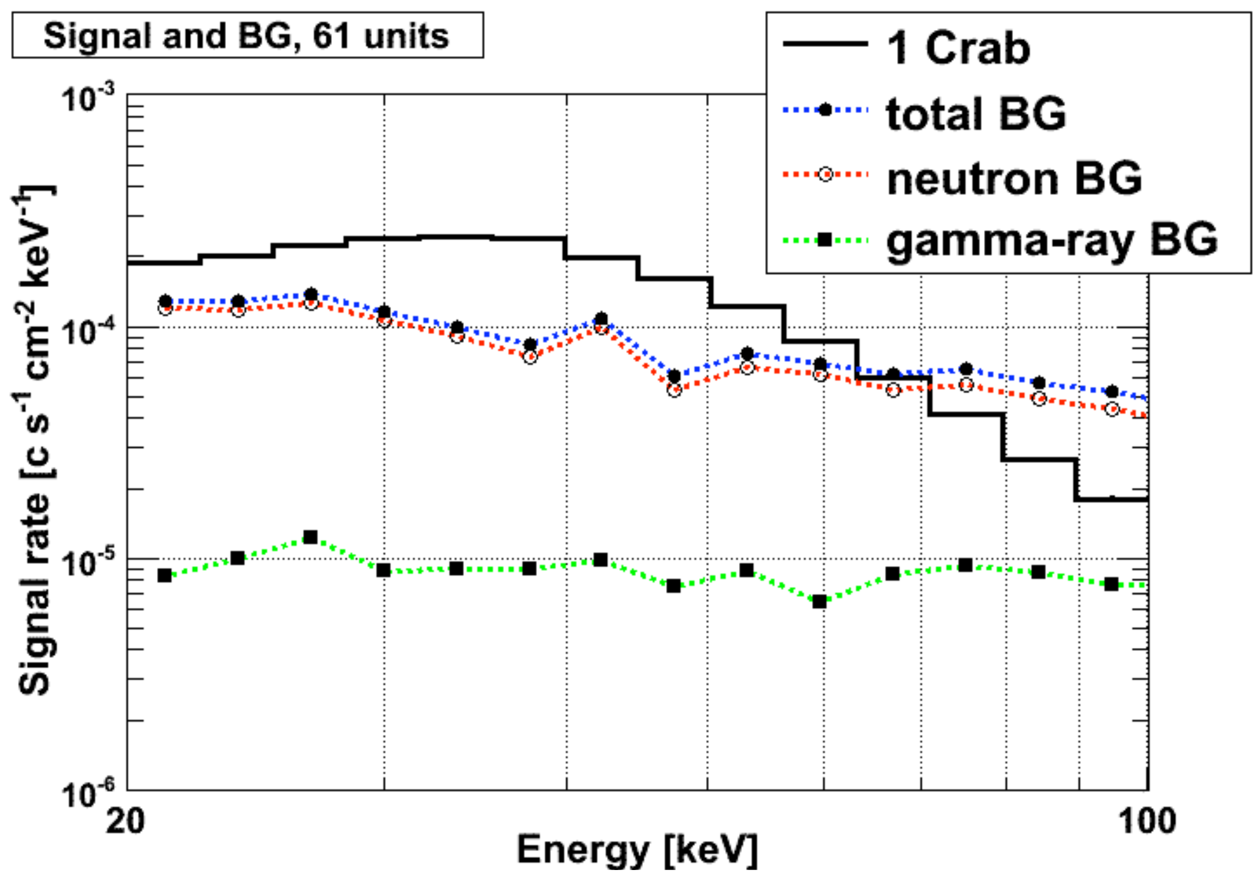


- Photon rates are comparable to Crab signal and background
- Background managed by Phoswich design, anticoincidence and kinematic selections

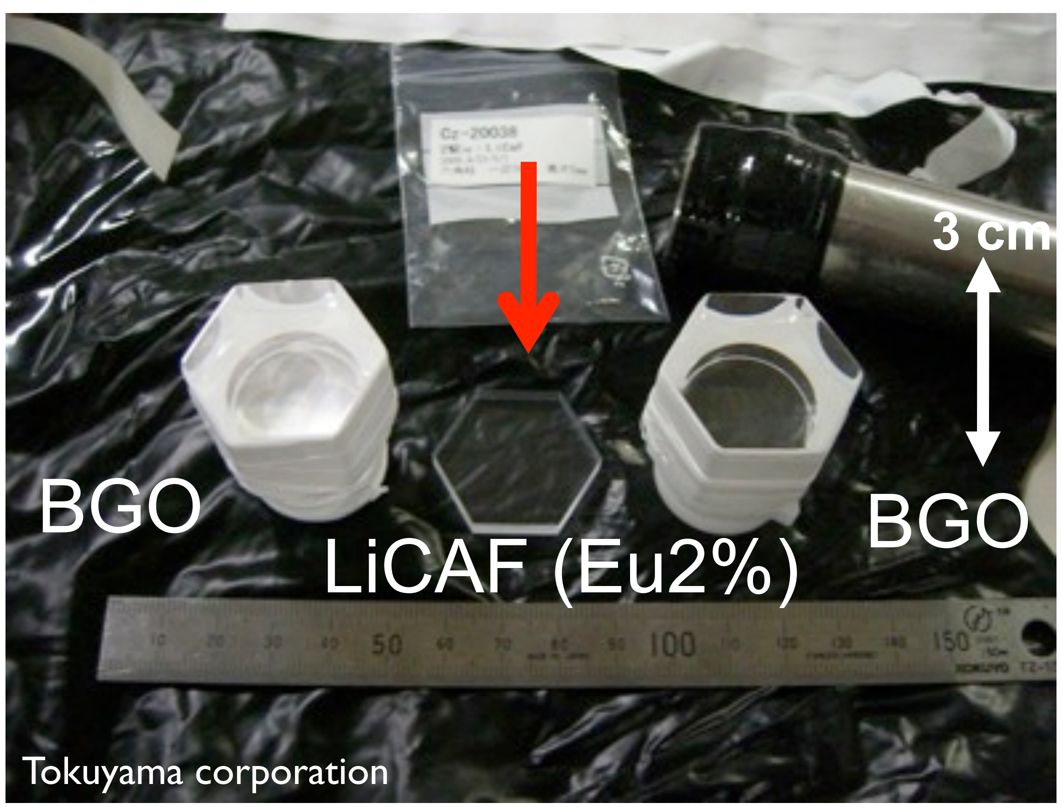
- Even in the presence of strong background the 60 keV photopeak is clearly visible (fast branch).

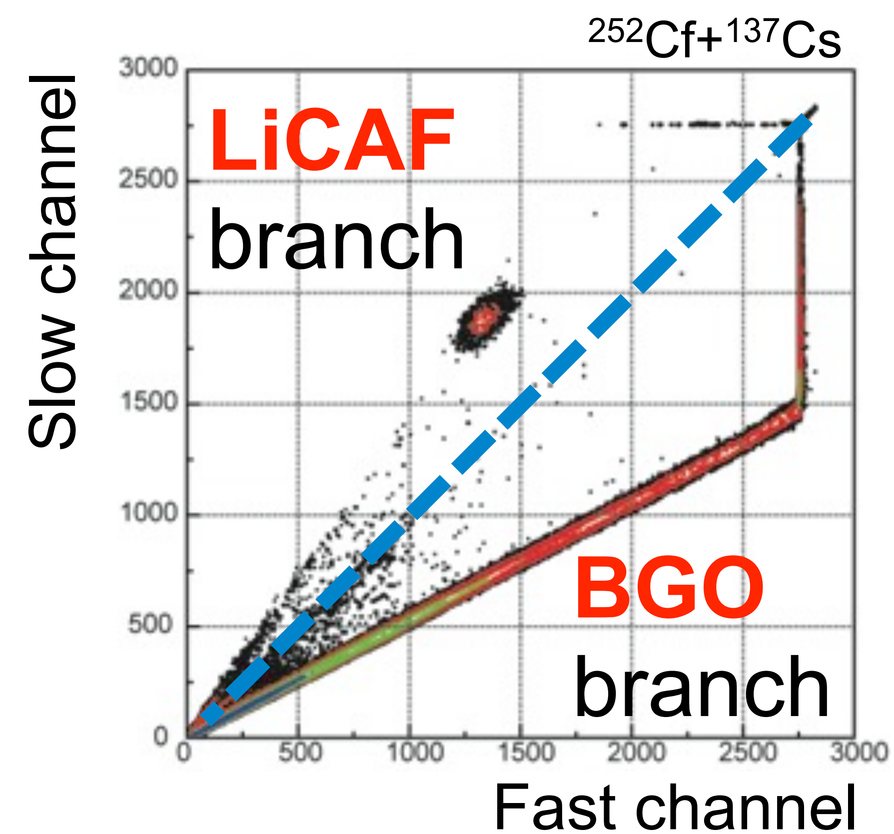


Neutron background



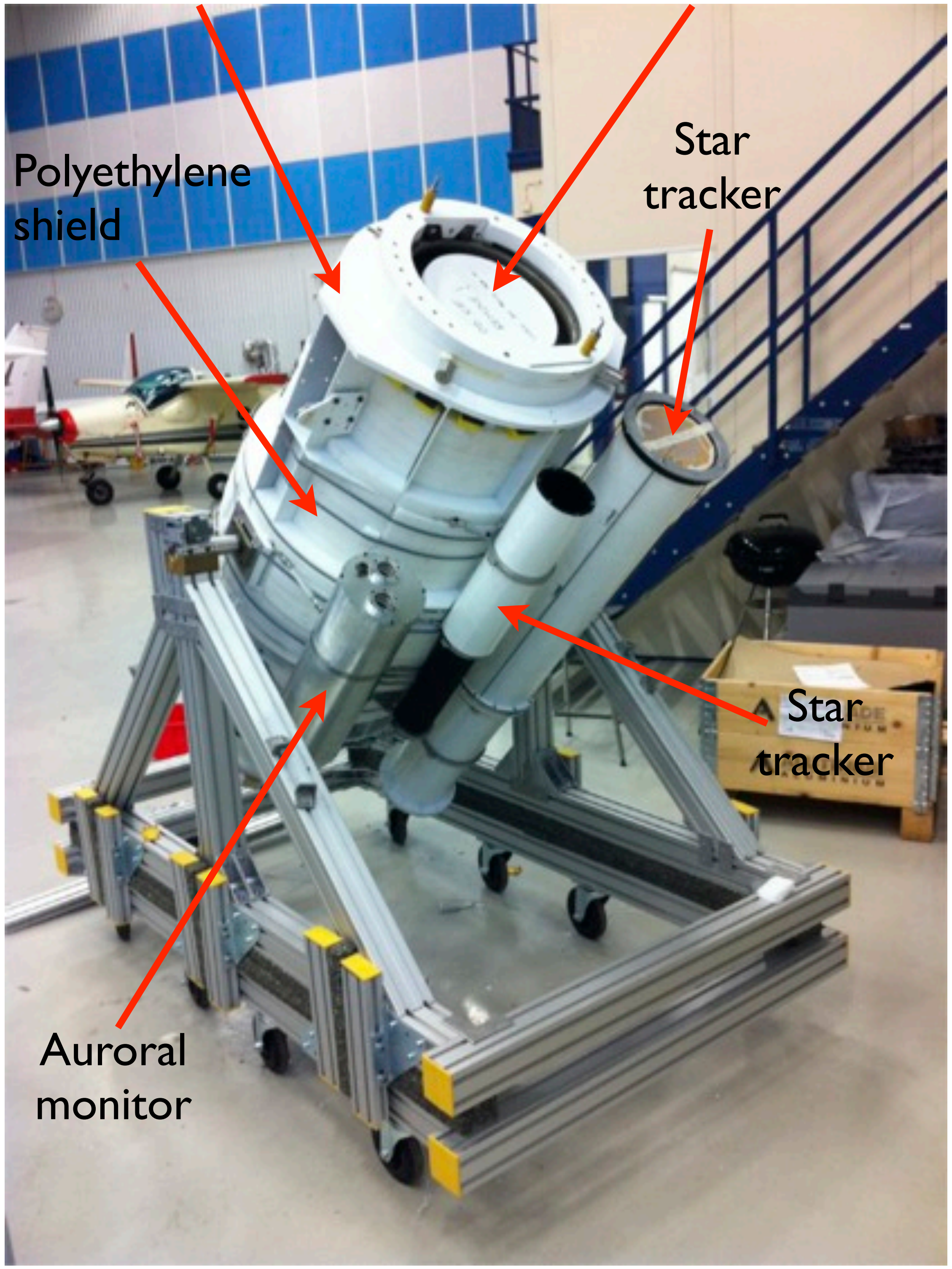
- Neutron background is found to dominate (Geant4 simulations)
- Neutrons are absorbed and thermalised by a thick polyethylene shield
- Neutrons monitored during flight by a novel LiCaAlF6 ('LiCAF') detector in a Phoswich arrangement with BGO
- $n+{}^6Li$ (low Z!)$\rightarrow T+\alpha$ (MeV line), 9000 γ/n, $\tau\sim1.5\mu s$ (BGO $\sim0.3\mu s$) .



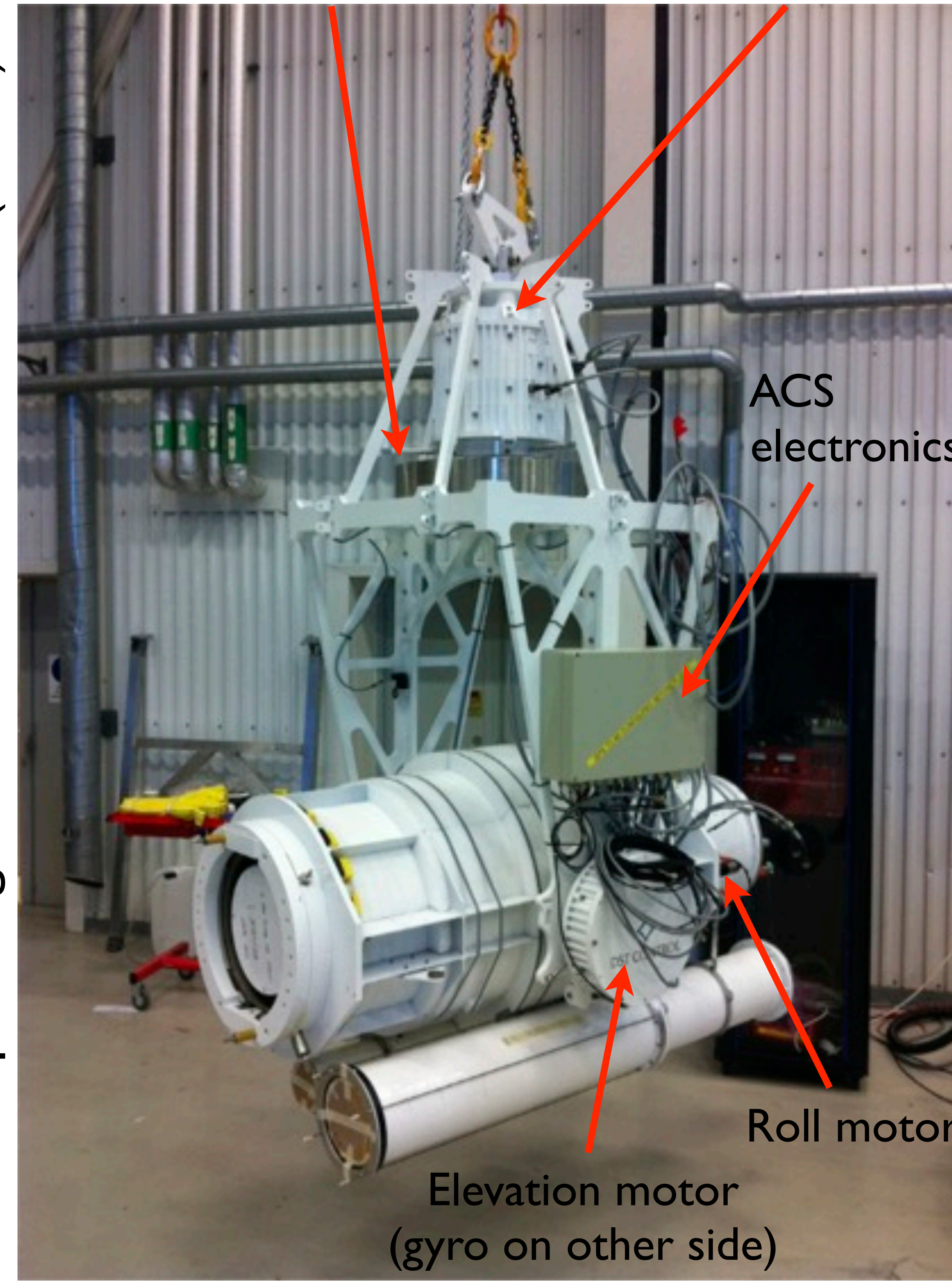


Thin PEEK window
~1.8 m, ∅ 45 cm
Detector PV
Photomultiplier (PMT)
PV
Electronics PV
~ 1.3 m

Polarimeter + ACS



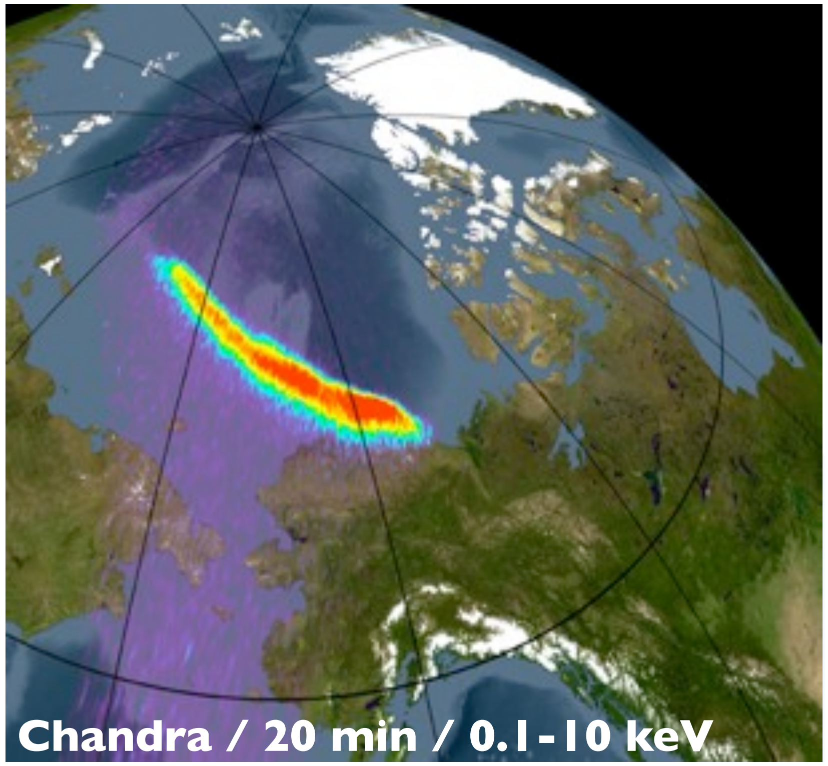
Aim: pointing to better than 5% of FOV (~0.1°)

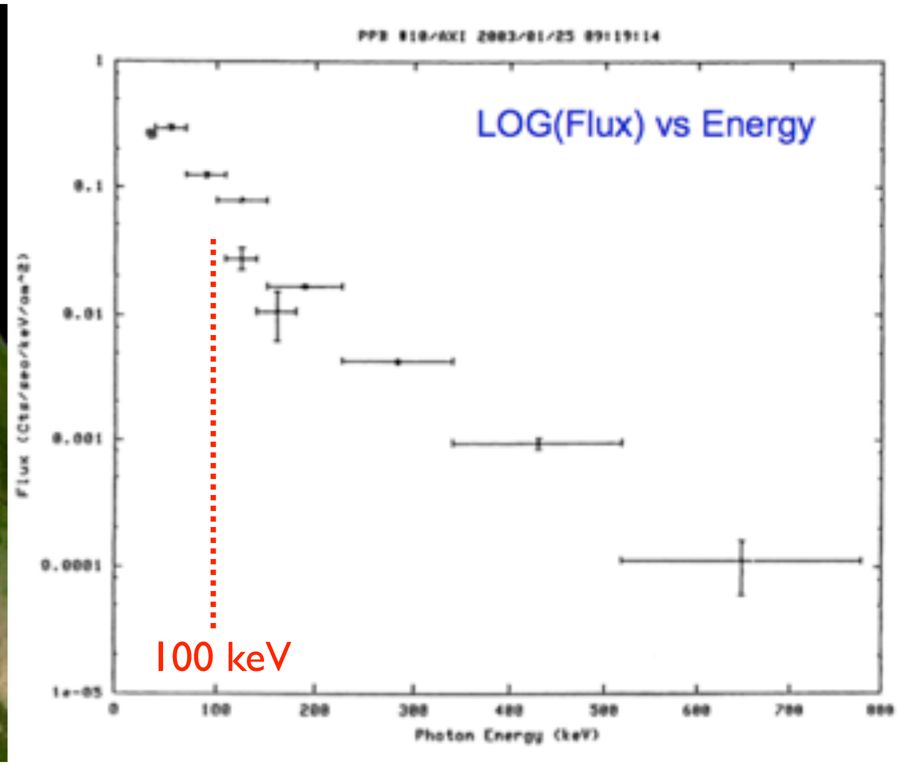


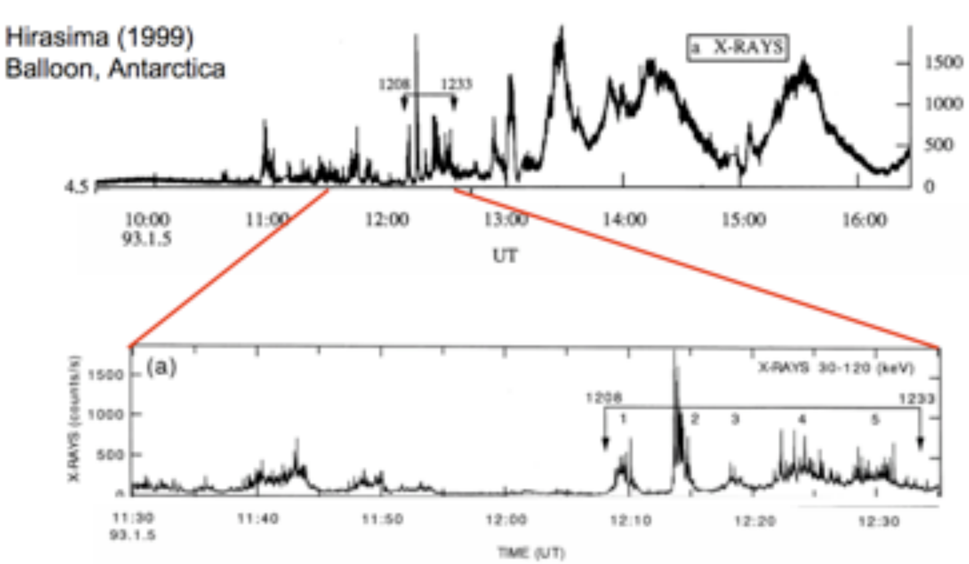
DST CONTROL

Auroral X-ray background

- PoGOLite pathfinder - relatively high latitude (67°N)
- Auroral X-rays produced due to Bremsstrahlung at ~90 – 100 km, and expected to be linearly polarised
- Instantaneous background estimated at ~10-50 mCrab
- ... and is highly variable
- Monitor using photometers, magnetometers (KTH Alfvén Lab), and instrument background rates
- **Our background is a signal for the aurora community!**

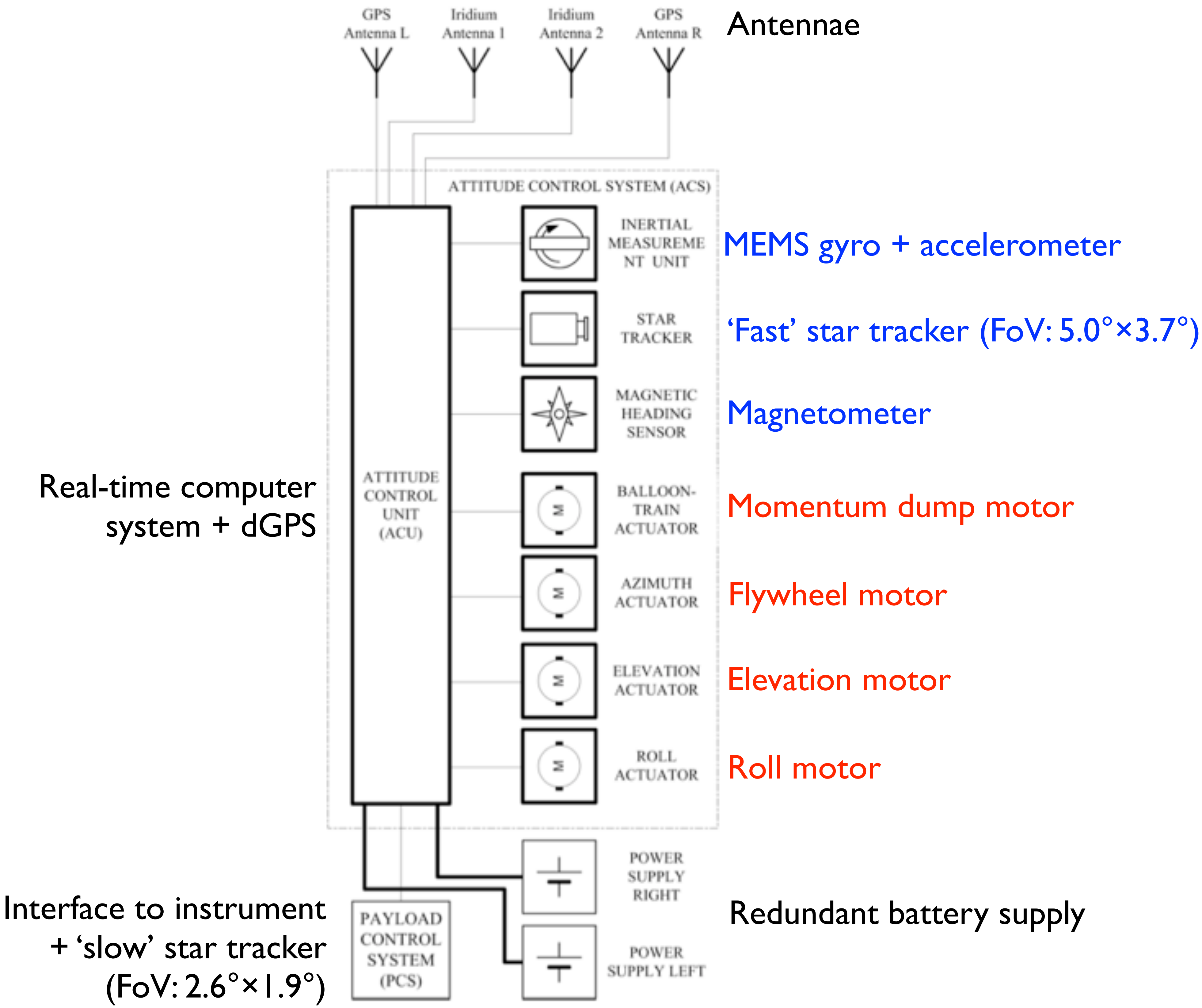






Nakamura et al. (2004). Polar patrol balloons 8 + 10.

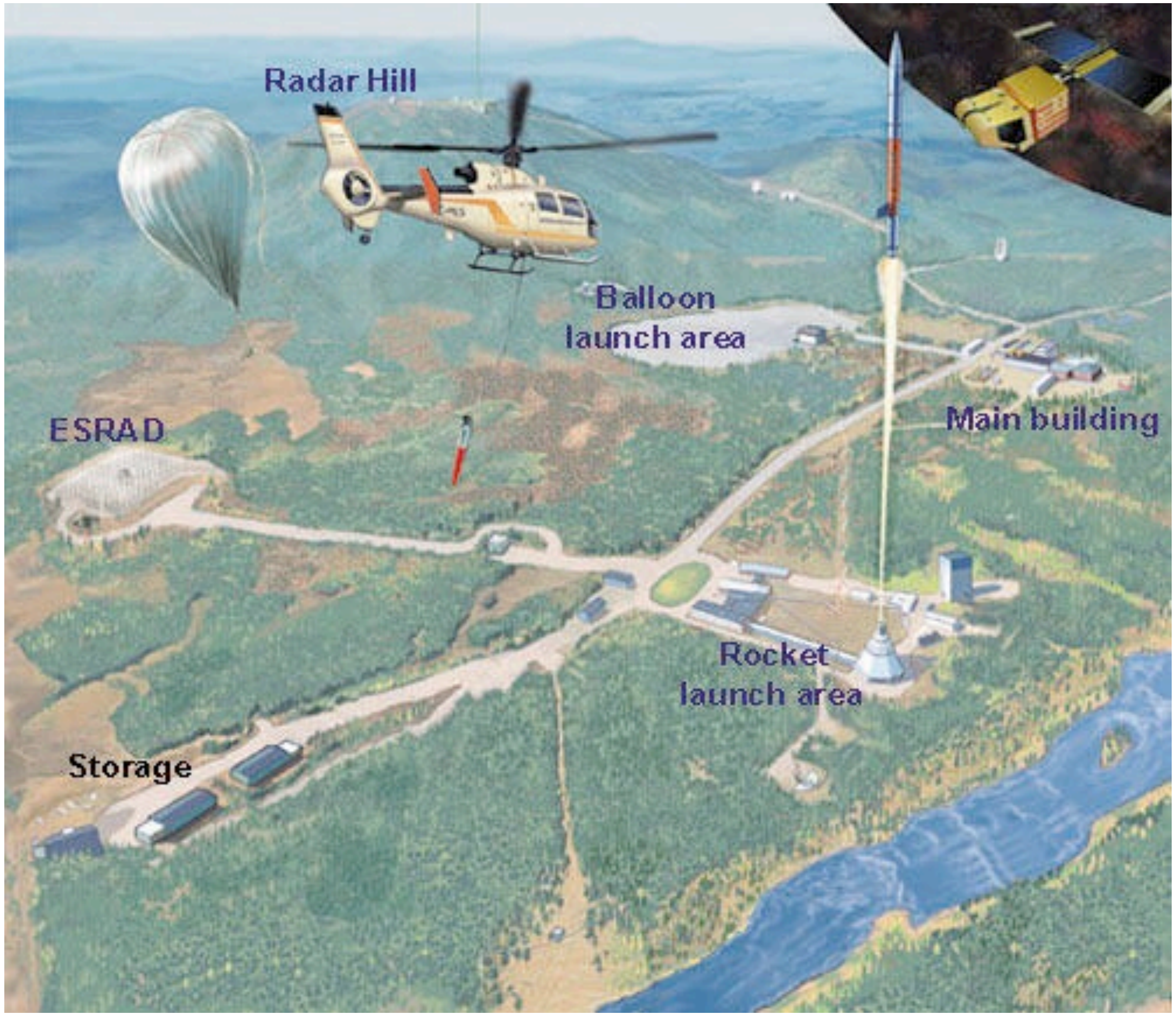
Attitude control system, ACS

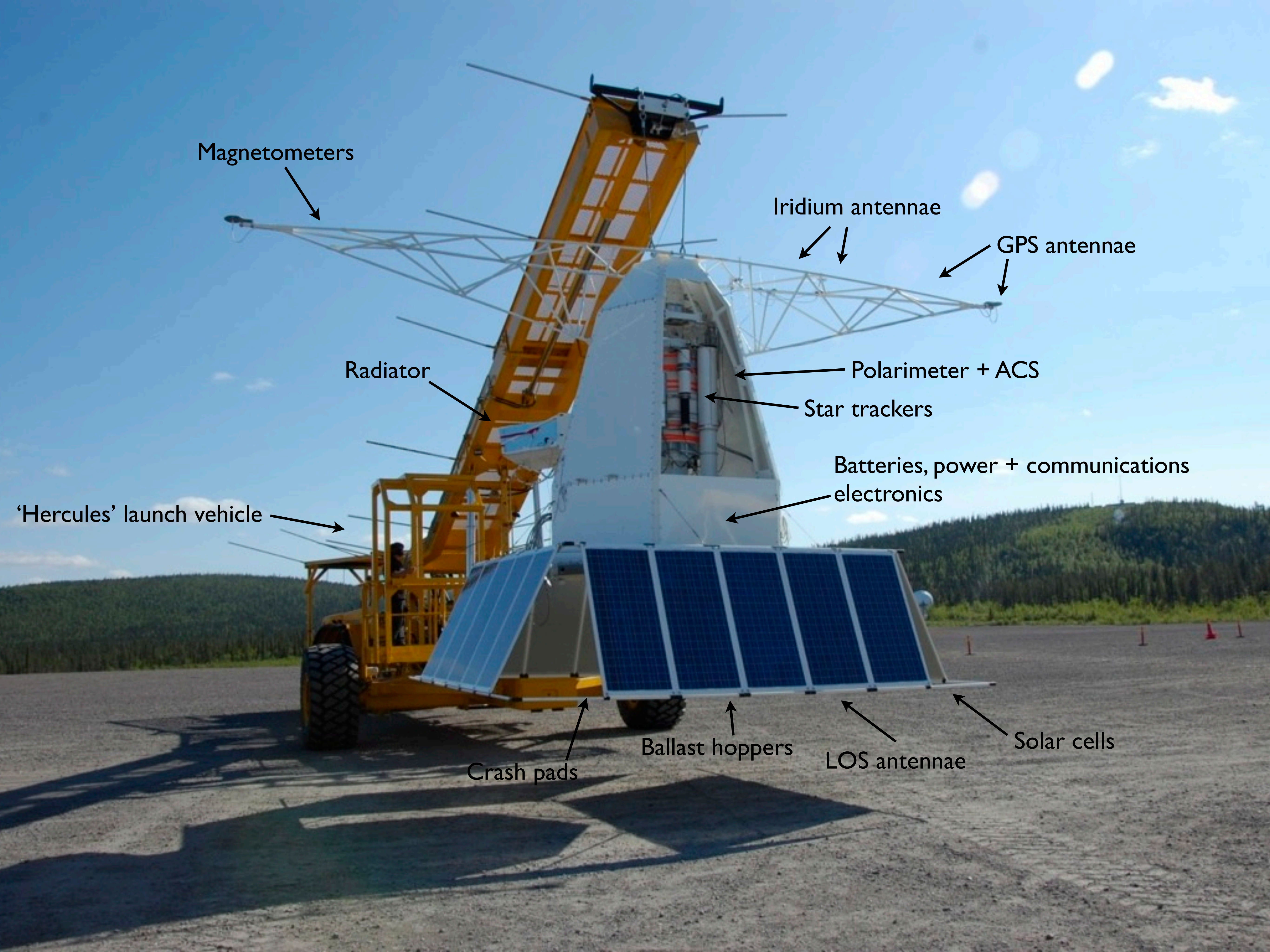


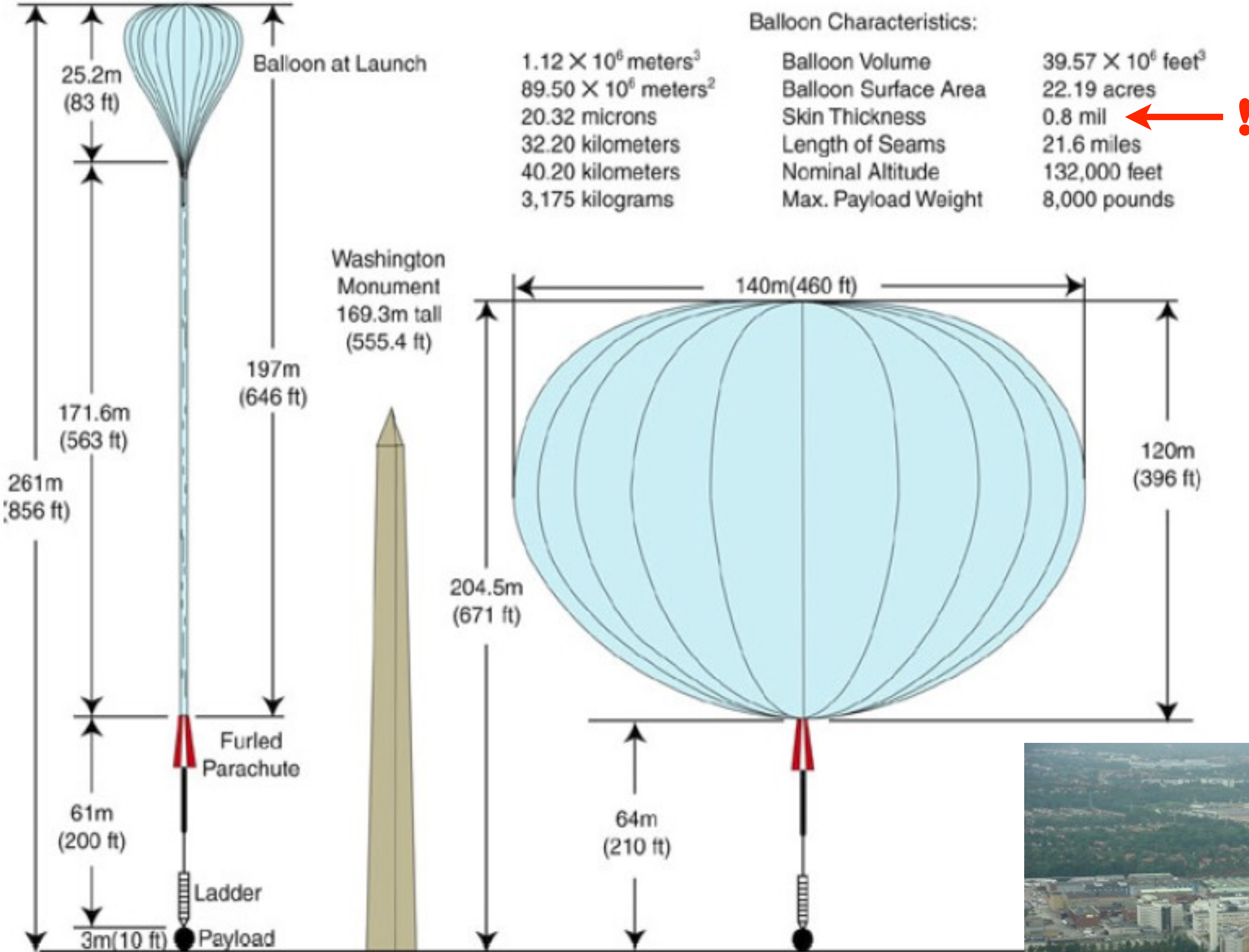
Tests of ACS at Linköping airport

Esrange


Esrange :
European Space Range
KIRUNA
Arctic Circle
SWEDEN
FINLAND
NORWAY
RUSSIA


Radar Hill
Balloon
launch area
ESRAD
Main building
Rocket
launch area
Storage


Magnetometers
Iridium antennae
GPS antennae
Radiator
Polarimeter + ACS
Star trackers
Batteries, power + communications
electronics
'Hercules' launch vehicle
Ballast hoppers
LOS antennae
Solar cells
Crash pads



The 'Globen' arena - a convenient yardstick...

Launch!

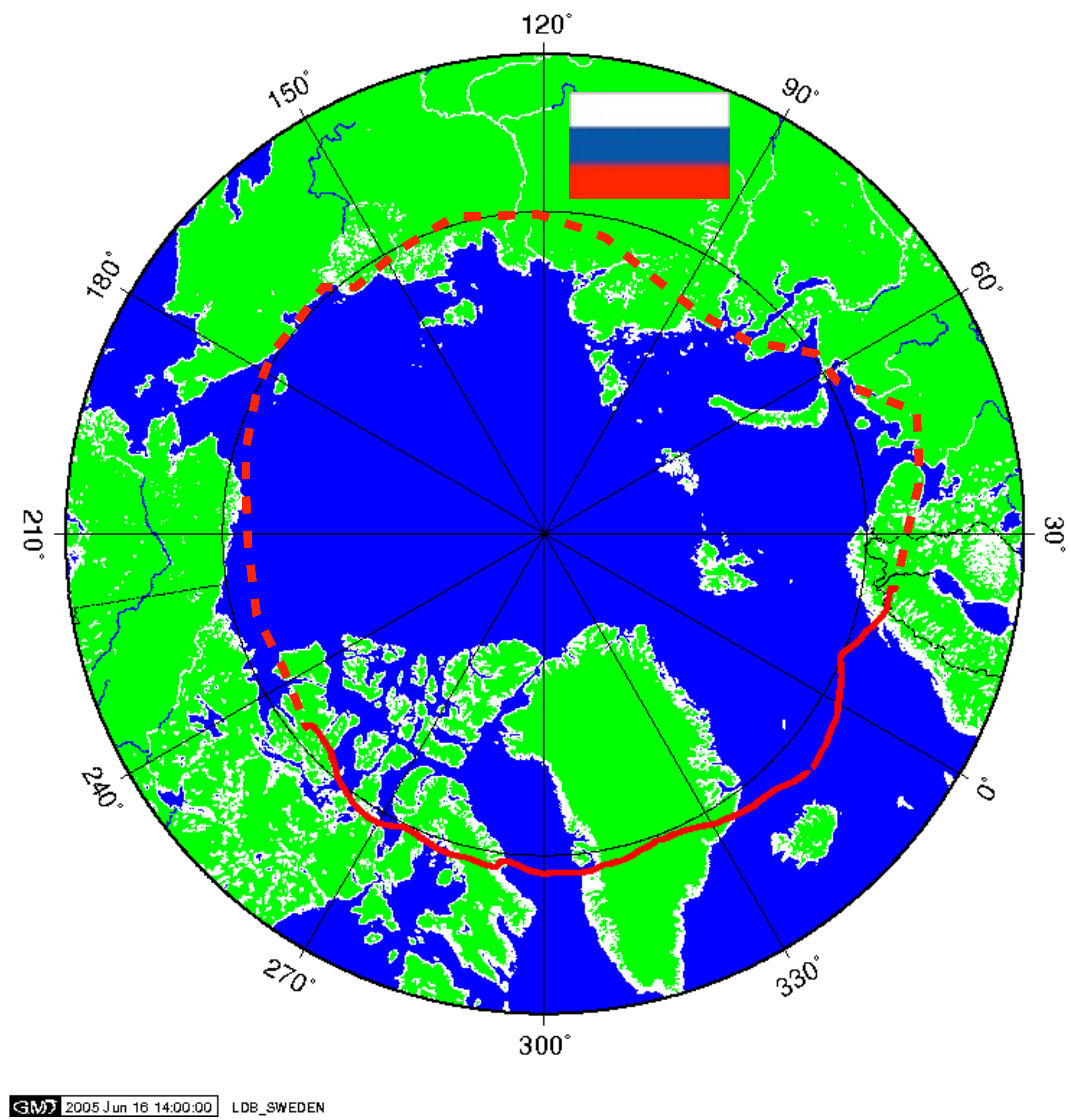
Pathfinder flight plan

Flight plan

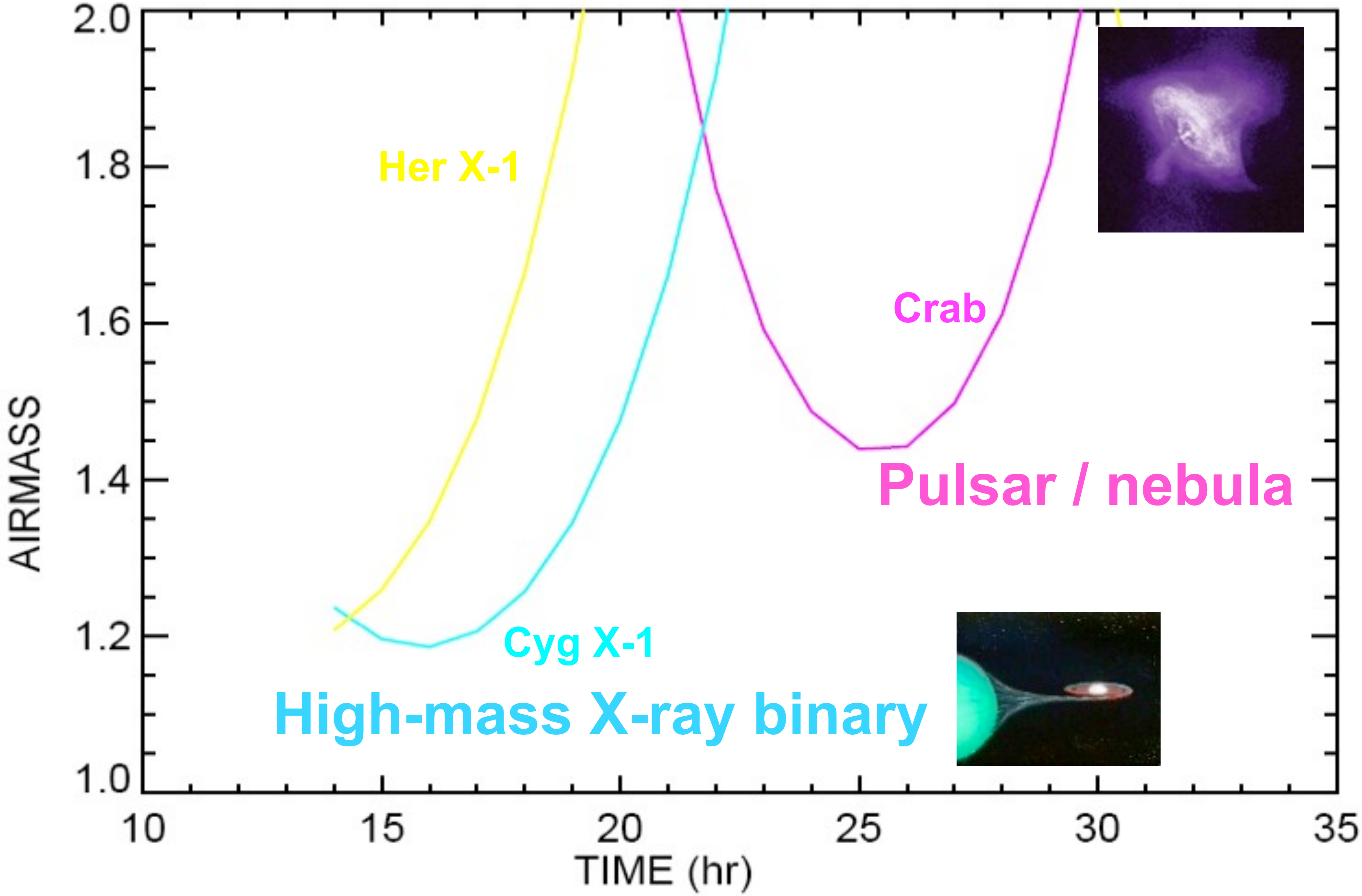
- **2010:** 'turn-around' flight in August (~1 day). Cancelled.
- **2011:** circumpolar flight (~15 days) proposed
  - Russia did not grant overfly permission in the end...
- ~5 day flight to Canada adopted instead

Challenges

- No line-of-sight communications (E-Link). Use Iridium over-the-horizon (Rudics + dial-up).
  - Robust data storage
  - Focus on autonomy
- Reliance on solar cells



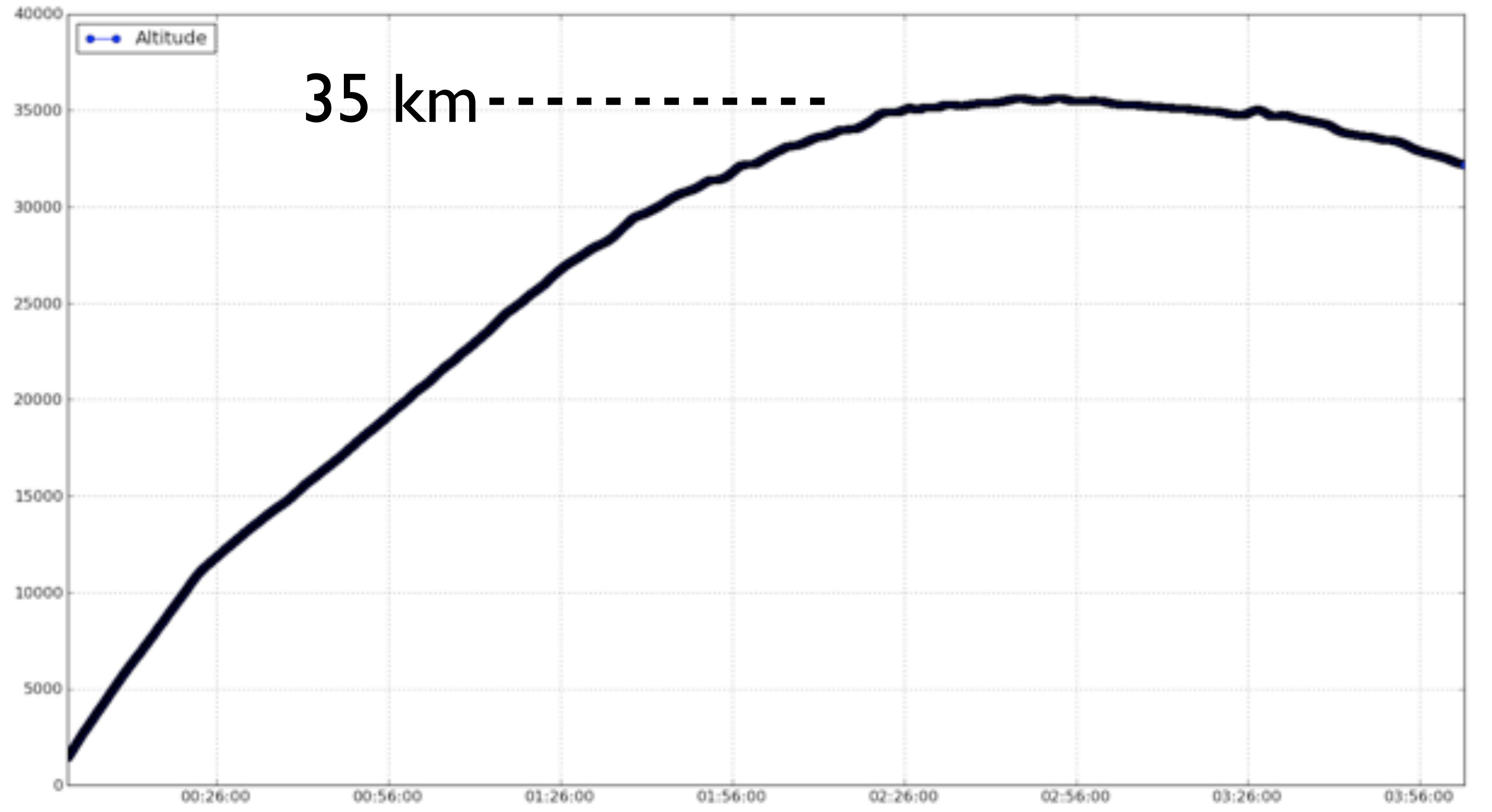
Observation plan



Flight timeline

- **July 7th 2011 (local times)**
  - ~0200: Launch
  - ~0430: altitude levels out at 35km
  - ~0520: altitude starts to decrease; decision to terminate
  - ~0600: PoGOLite is turned off
  - ~0720: balloon cut
  - ~0801: gondola touch-down

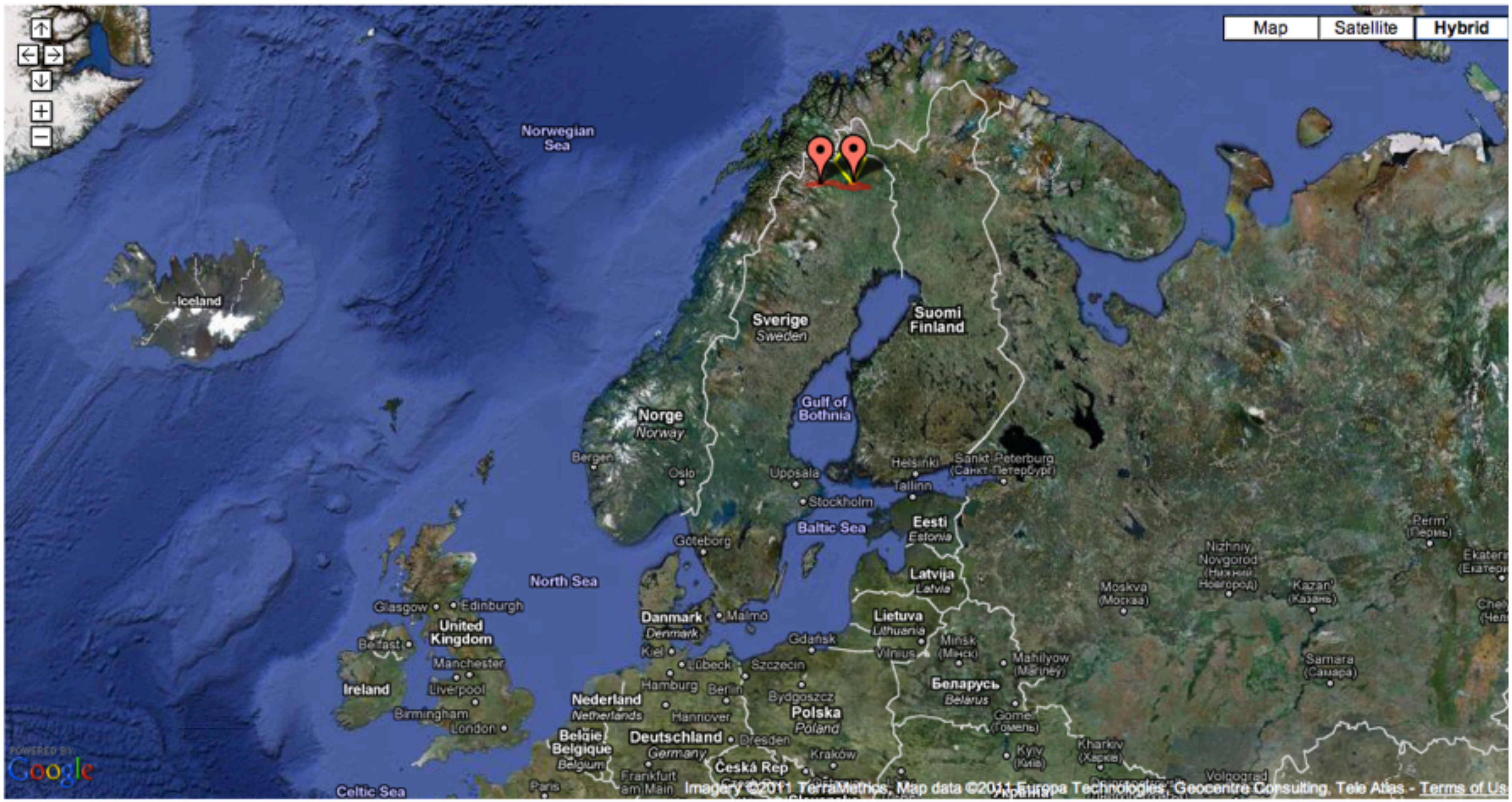
Happy faces: (short-lived...) first data downlink



Flight: SSC PoGOLite
Date: 2011-07-07
Time (UT): 06:04:05

Lat: N 67.85000000
Long: E 19.06666667
Altitude: 534 Meter

Range 85 Km



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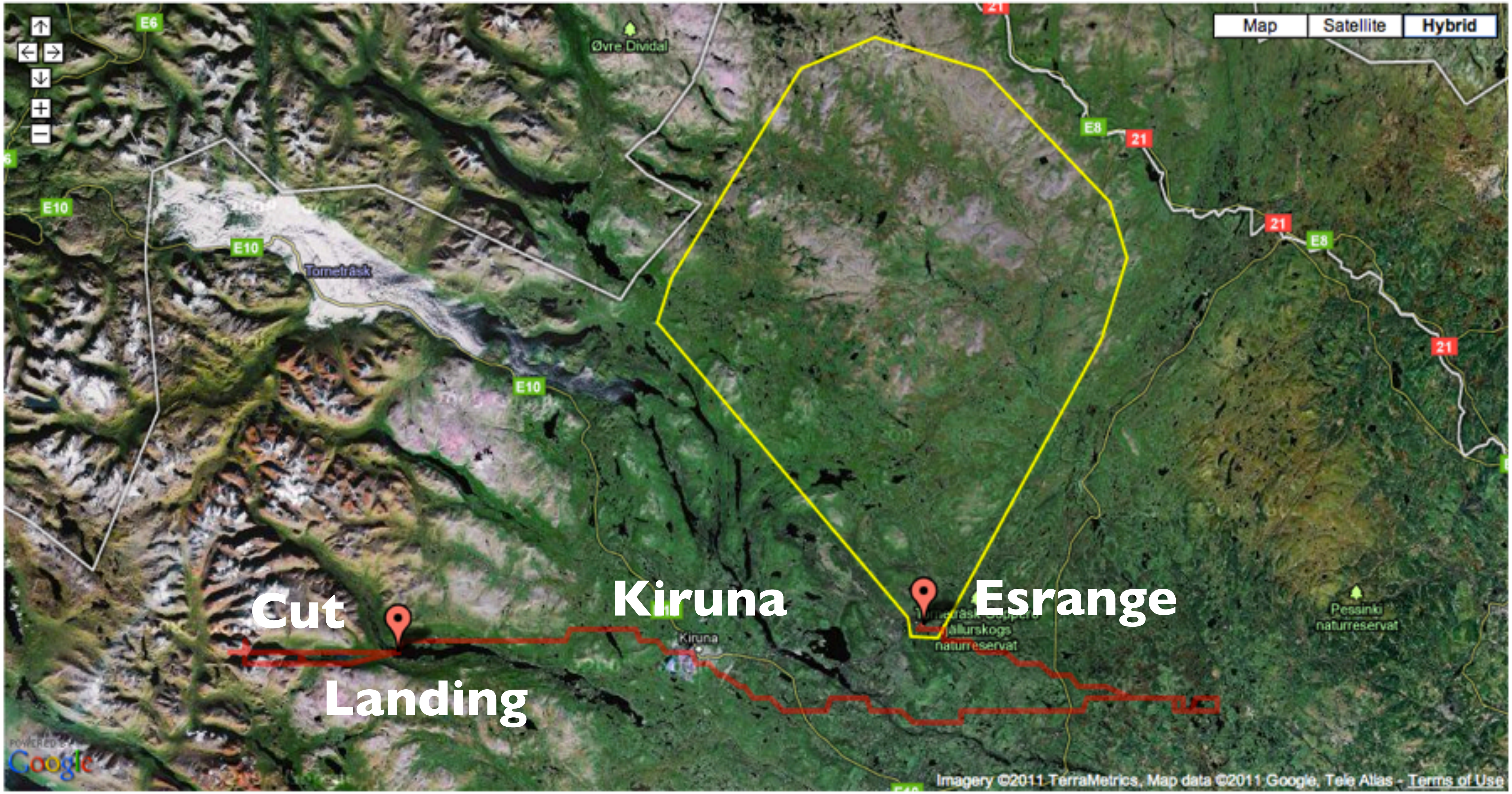

Flight: SSC PoGOLite
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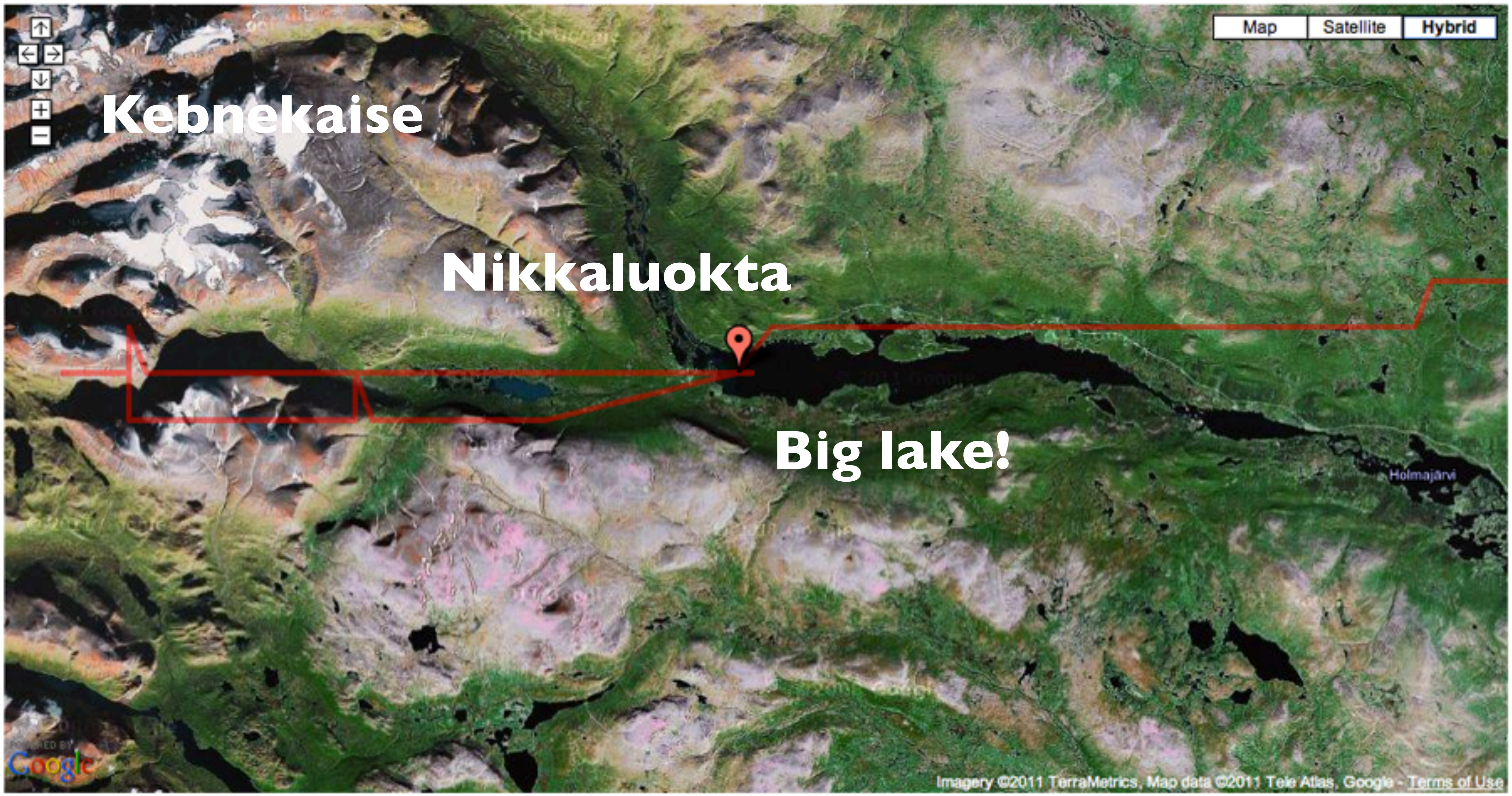
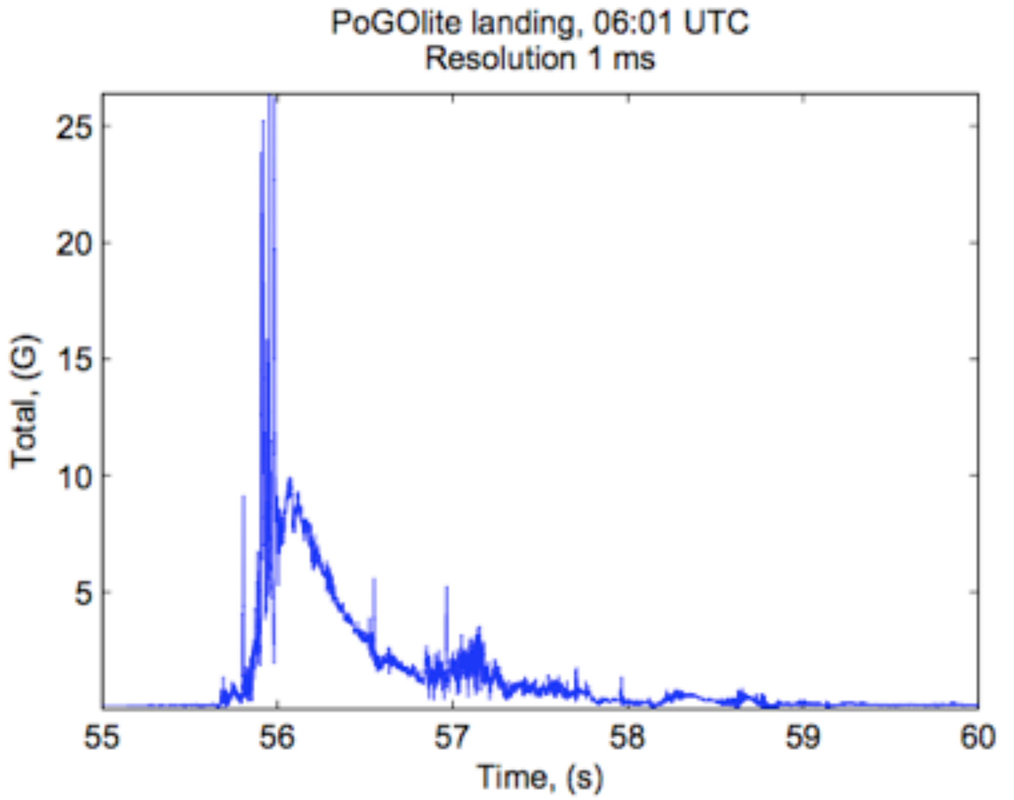


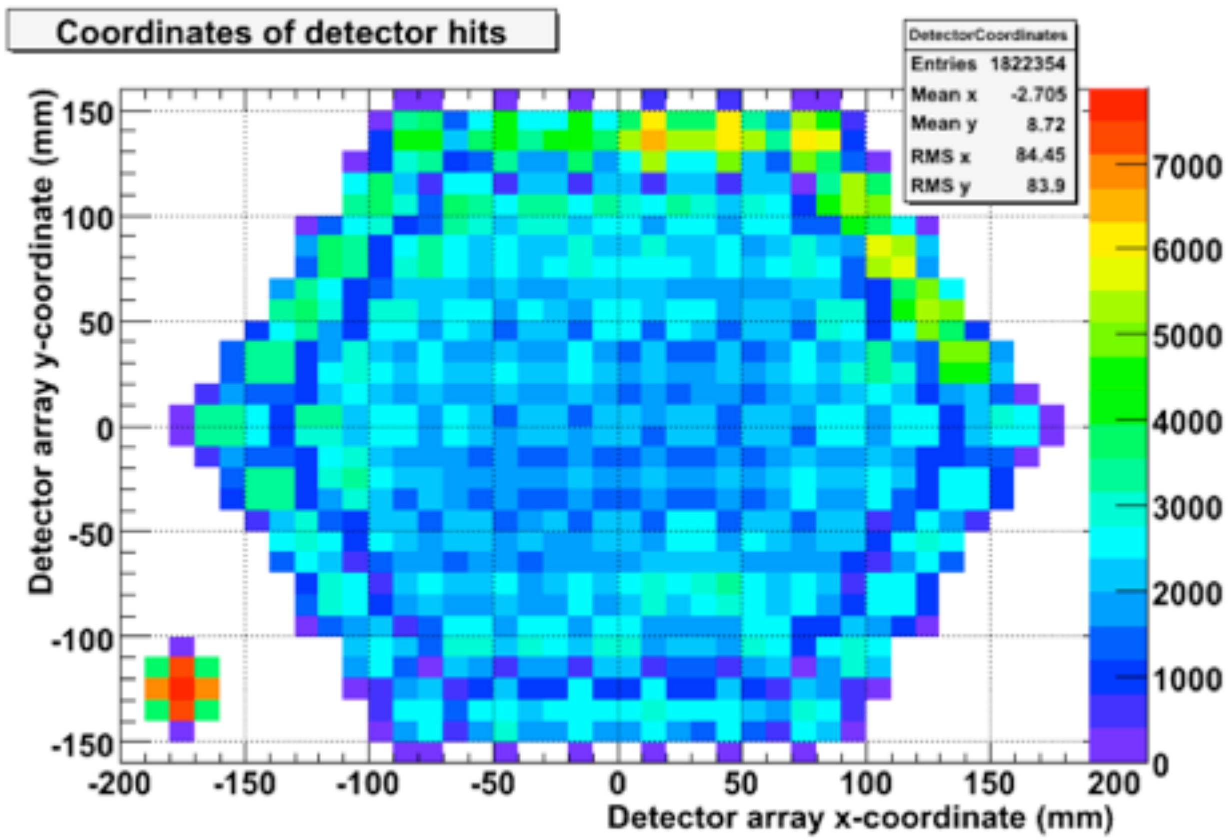
A hard, but dry, landing

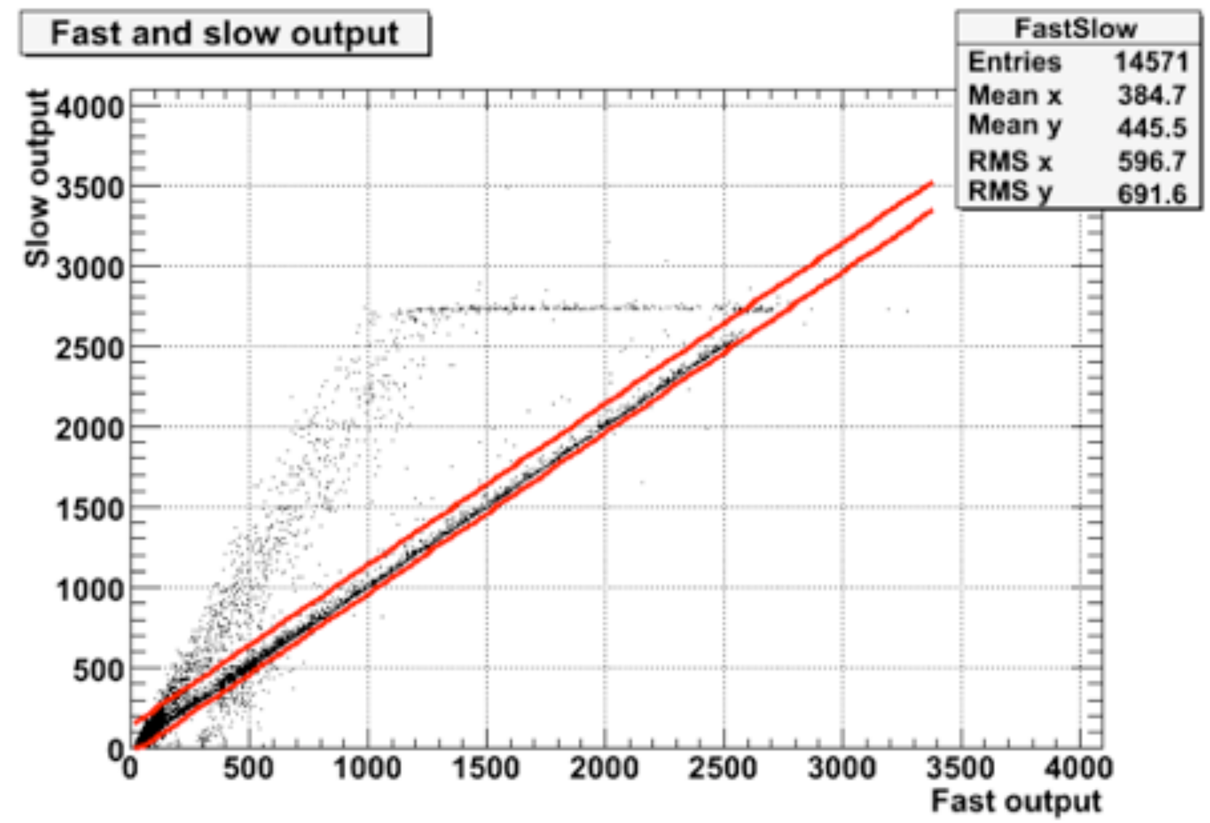


- The gondola was successfully recovered and the polarimeter found to be intact.

- No major damage... repair/rebuild of polarimeter is underway.
- No impediment to reflight in 2012.

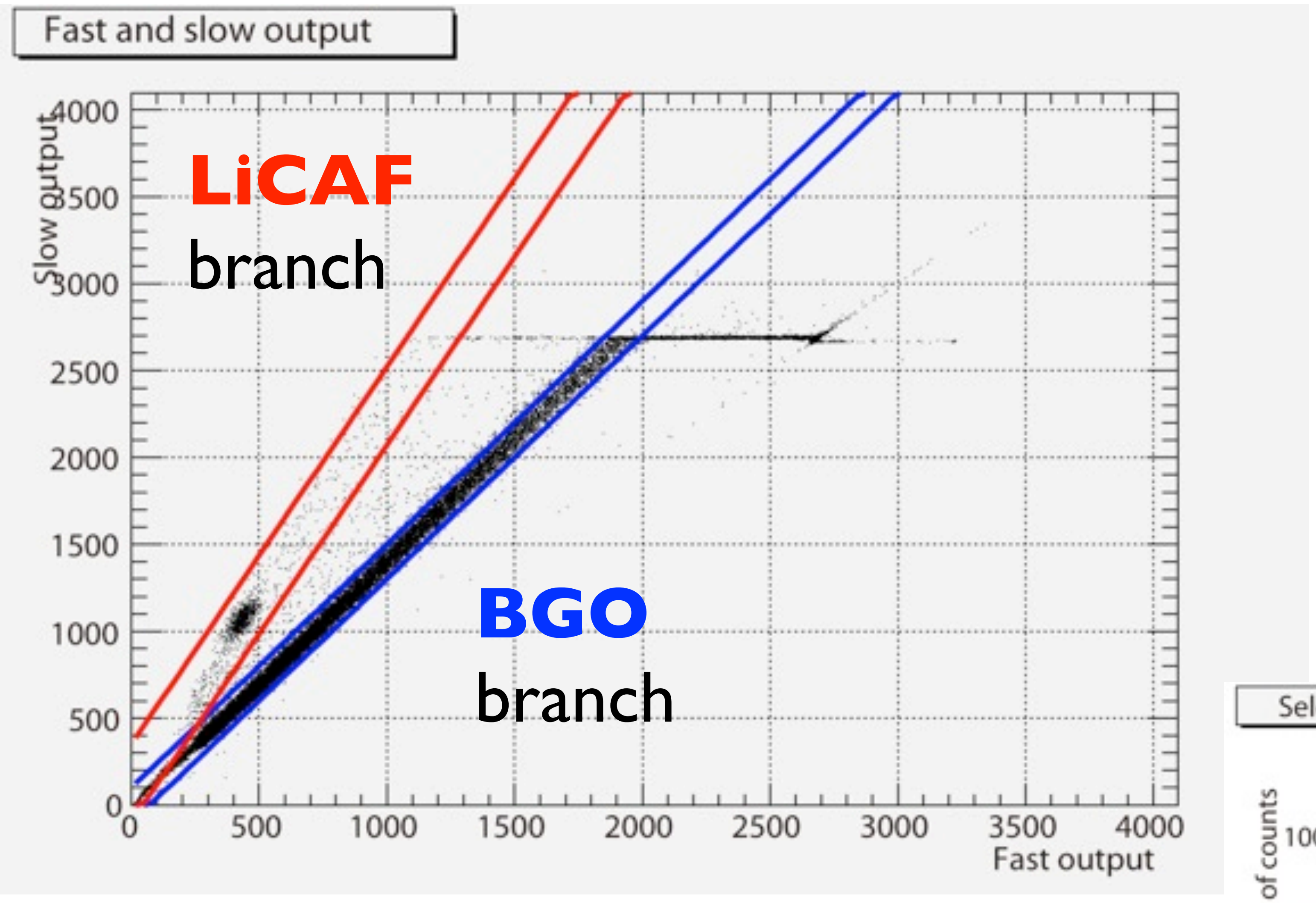
Polarimeter performance

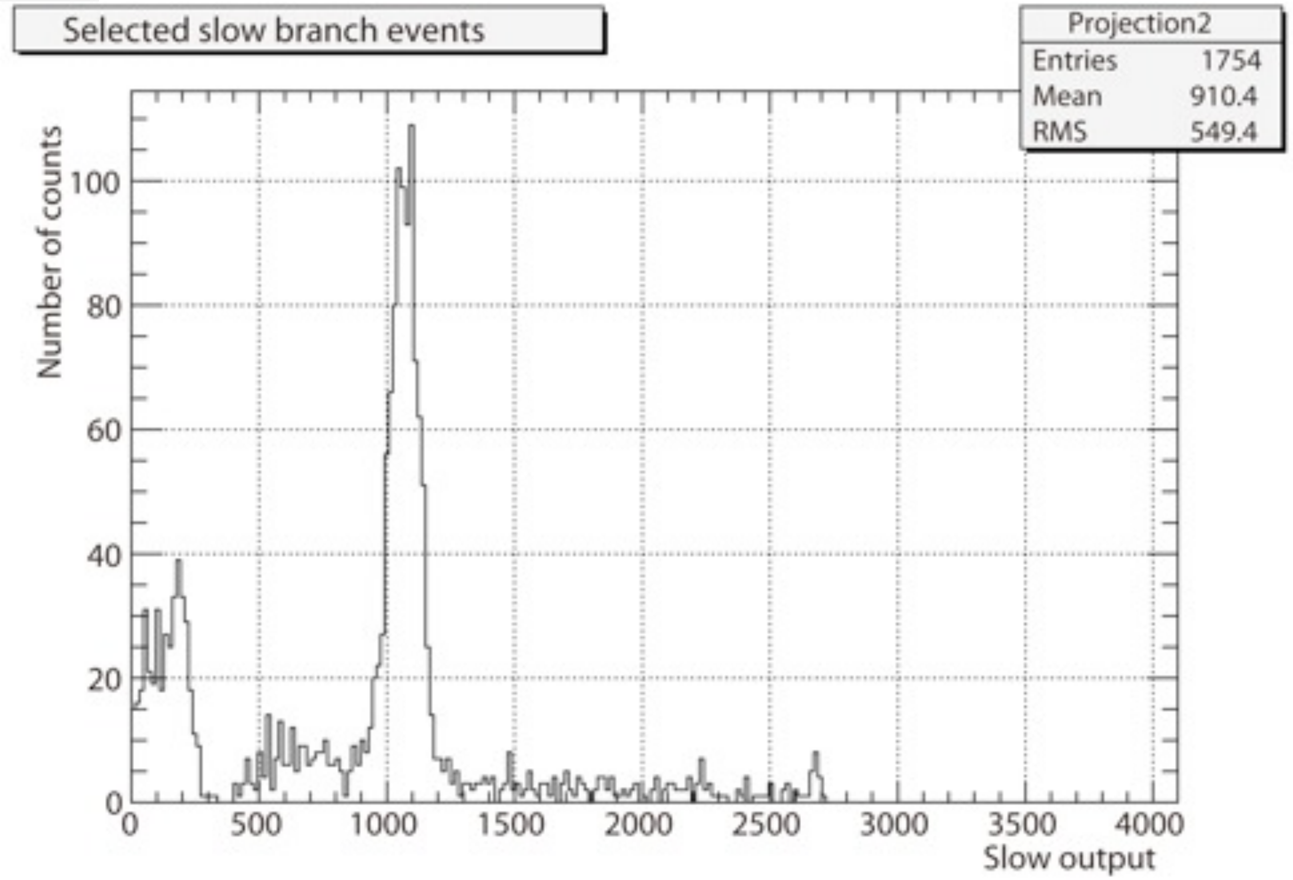




- **Entire instrument operated as foreseen during ascent and the short time 'at float'.**
- We could identify photons scattering in the fast scintillator.
- Before securing the instrument and cutting the power, we managed to downlink all data (precaution). Analysis on-going. Science not possible, but instrument performance and backgrounds can be studied.

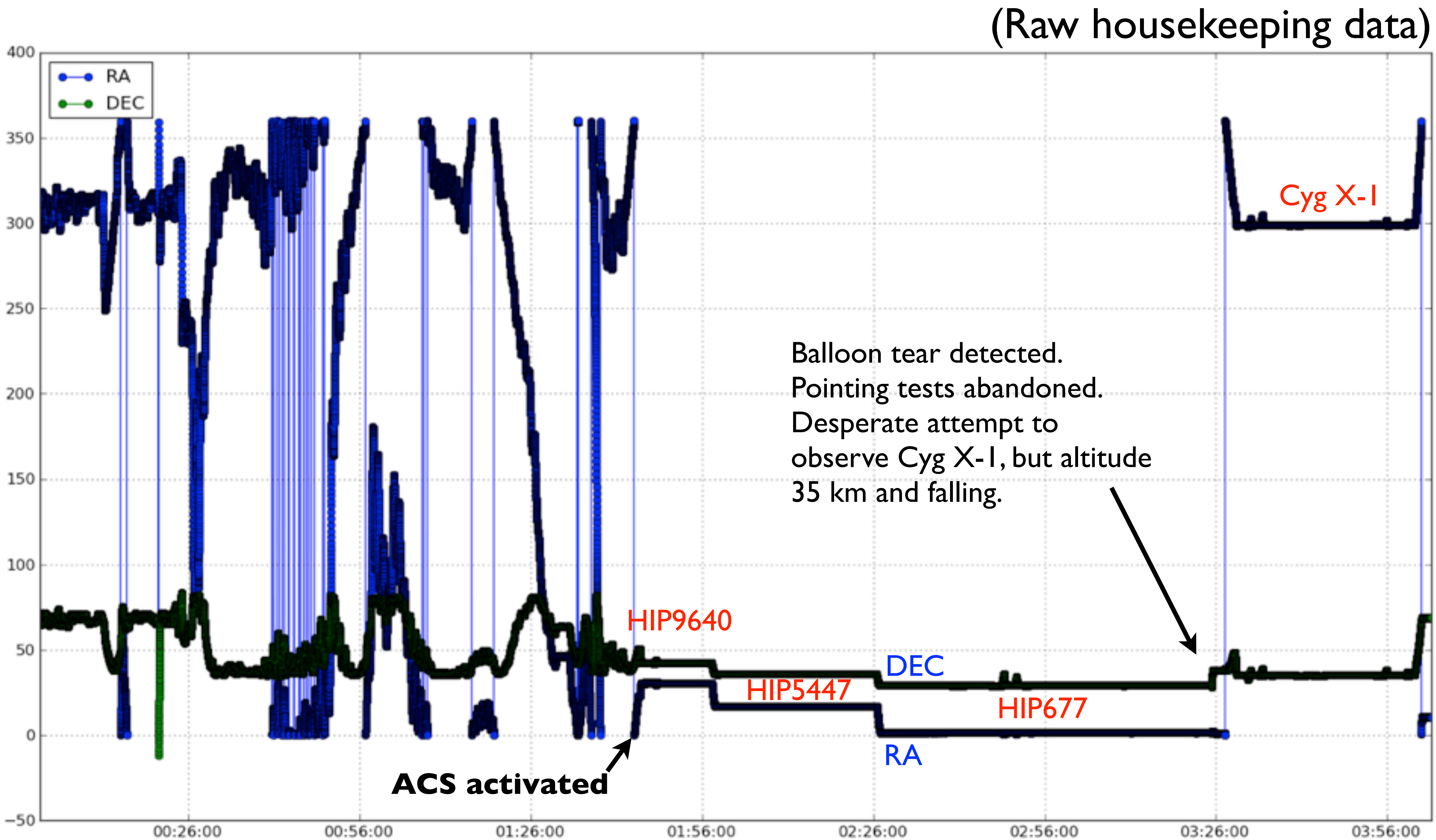
Neutron detector flight data





- Neutron detector mounted in the vicinity of the PMT array
- Detects neutrons thermalised in the polyethylene shielding
- **Neutrons can be cleanly identified!**

Pointing performance



Summary

• It is high-time for dedicated instruments for polarised X-ray astrophysics. Several groups are pursuing balloon-borne instruments and satellite missions are also under development.

• The PoGOLite soft gamma-ray polarimeter was launched from the Esrange Space Centre on July 7th.

• The 'pathfinder' instrument is designed to detect **10% polarisaton from 1 Crab point-like sources (25 - 80 keV) during a 6 hour observation**.

• Aim: **qualify design concept, study backgrounds, observe Crab, Cygnus-X1.**

• **Outcome:** a leaking balloon cut the flight short at ~35 km altitude. The payload was recovered mostly intact.

• We are now repairing the payload and will try again next year.

Thanks to the campaign team →

Campaign team:

KTH
Miranda Jackson, Mózsi Kiss, Merlin Kole, Victor Mikhalev, Elena Moretti, MP, Stefan Rydström, Nicola Schlatter

DST Control AB
Jonas Lind, David Steen, Jan-Erik Strömberg, Olle Wellin

Stockholm University
H-G. Florén, Göran Olofsson

Hiroshima University
Hiromitsu Takahashi

SLAC-KiPAC
Tune Kamae

SSC Esrange
Many people. Not shown.