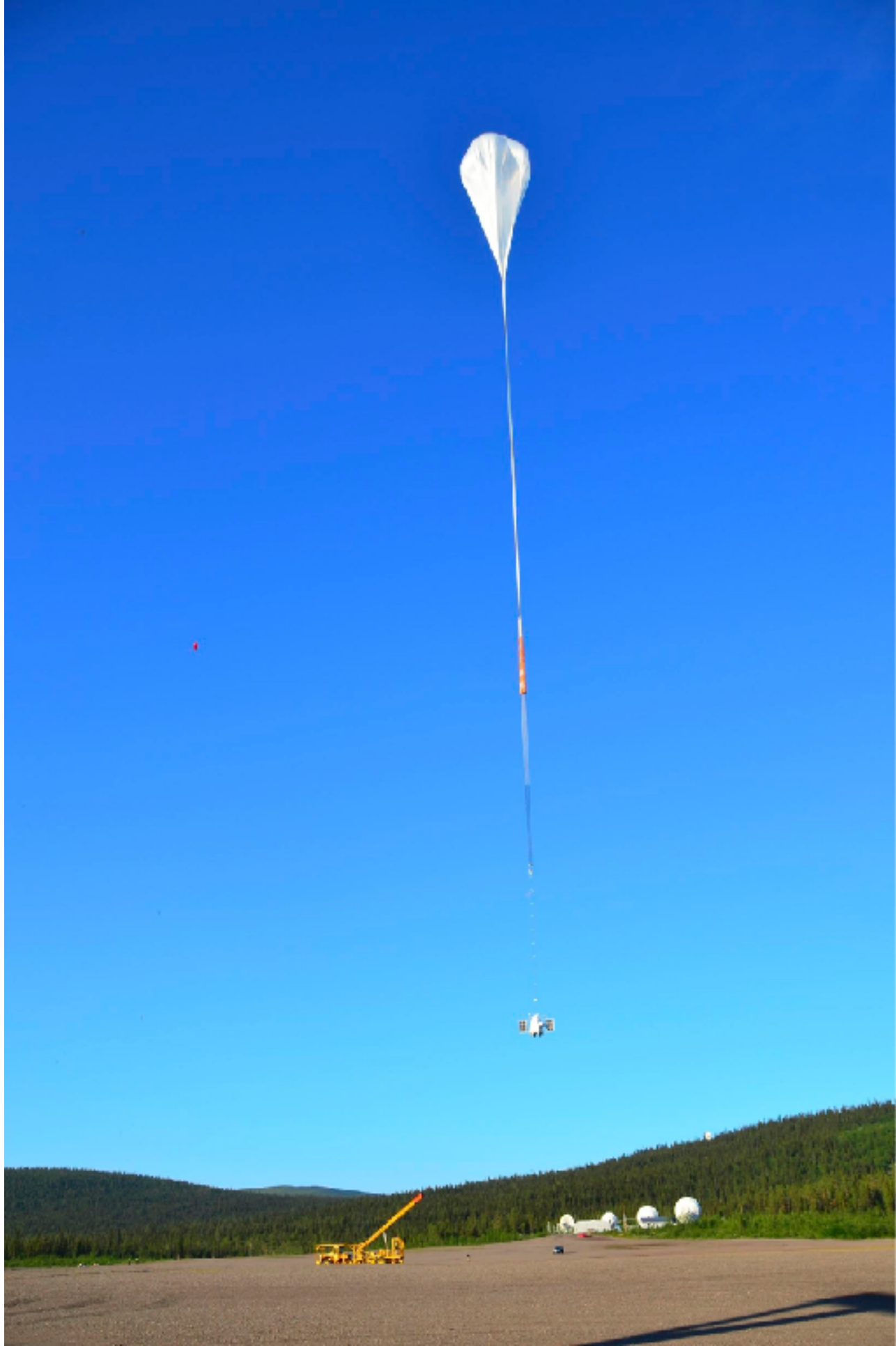
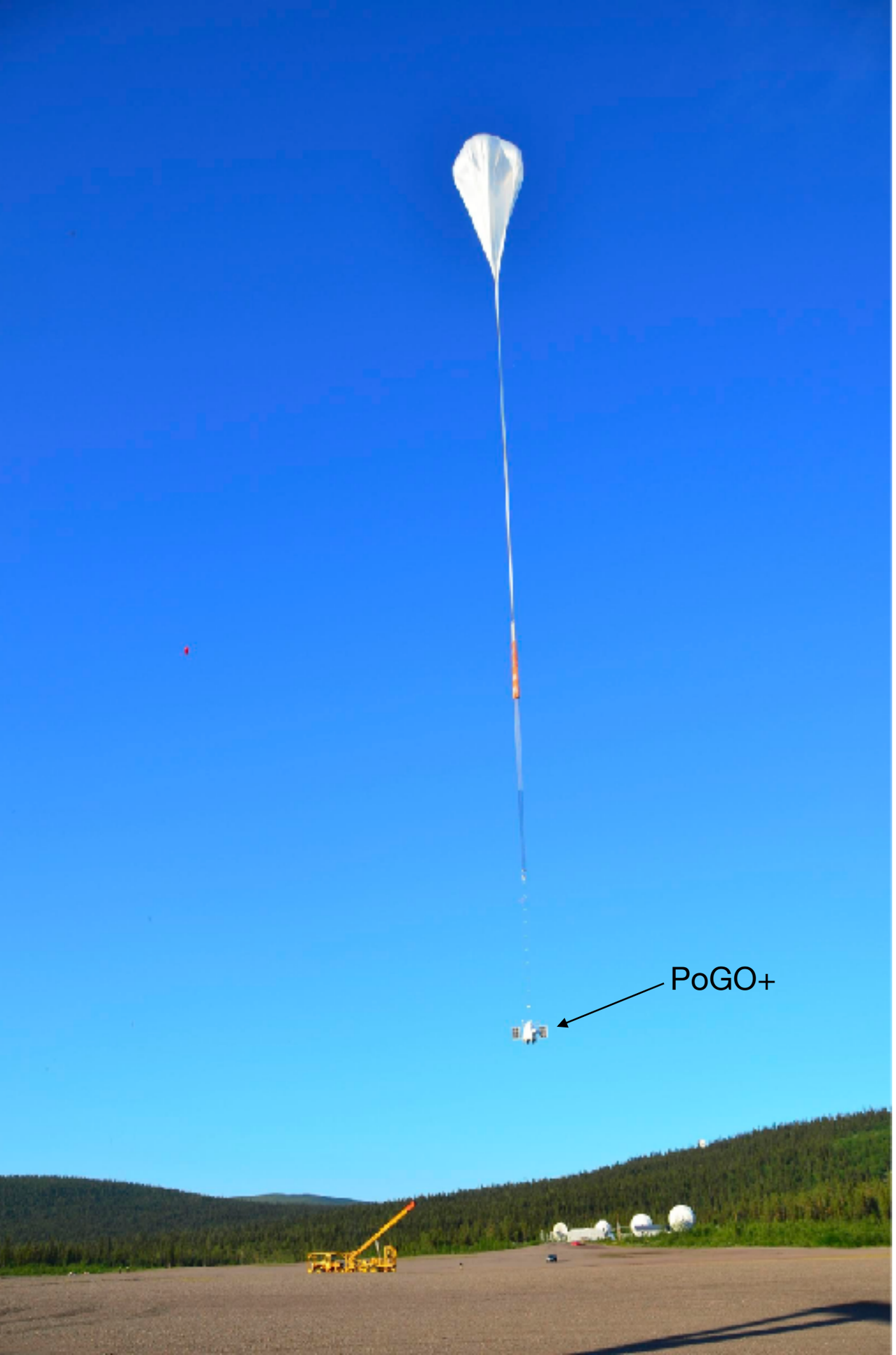
X-ray polarimetry from a stabilised balloon-borne platform

Mark Pearce

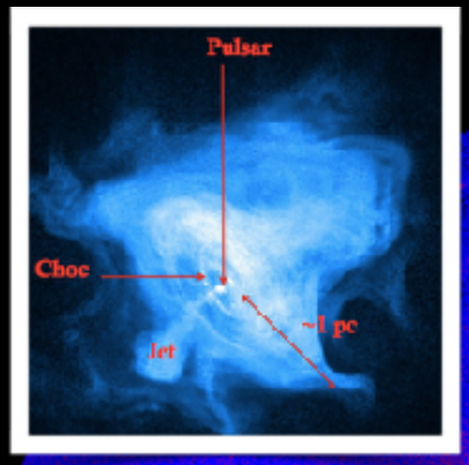
Annual meeting of the German Astronomical Society

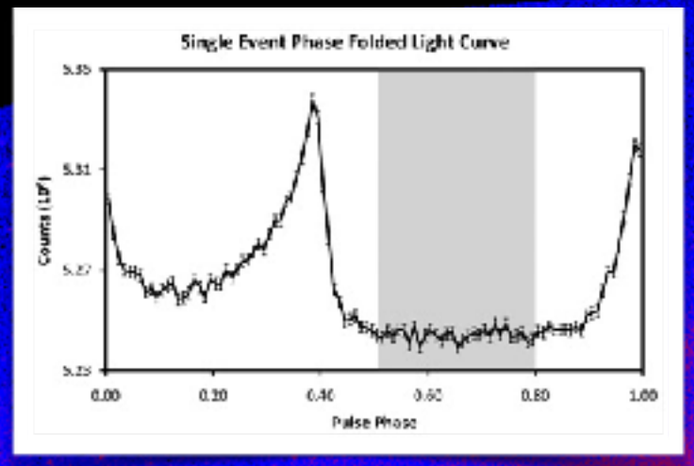
Via Zoom / 2019-09-19

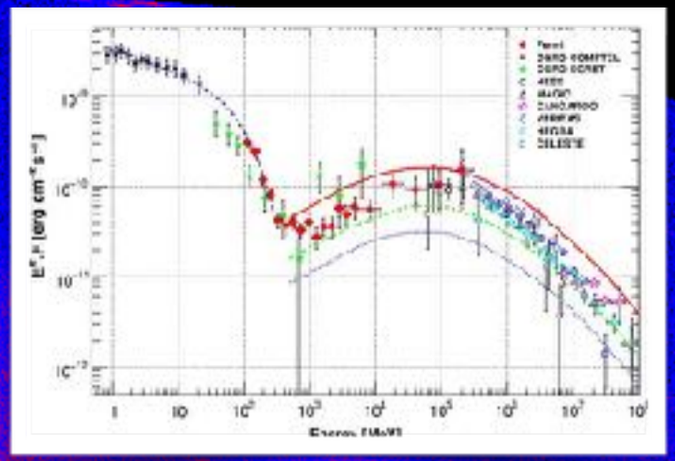




- X-ray polarimetry (very briefly)
- "PoGO+" mission design and performance **(my focus)**
- Results achieved (very briefly)
- What's next?





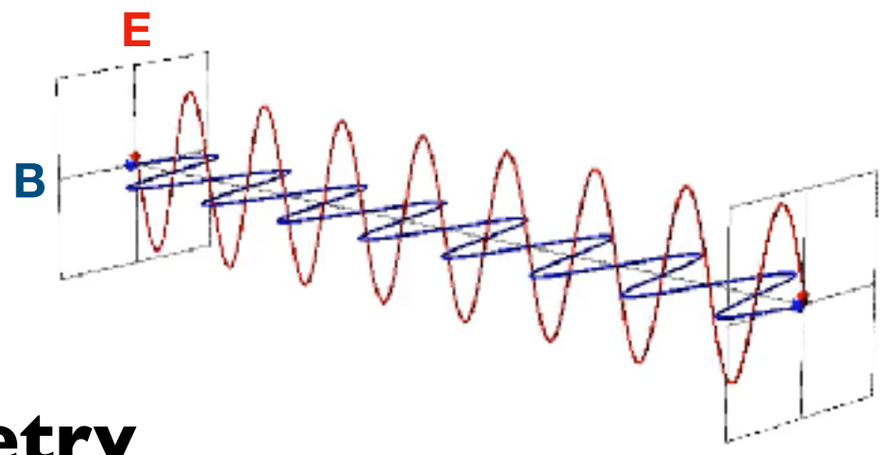


?

image **light curve** **energy spectrum** **polarisation**

- In X-ray astronomy, the **linear polarisation** of emissions (orientation of electric field vector) is not measured

  - **Polarisation Fraction** (PF) = 100%
  - **Polarisation Angle** (PA) = 0°

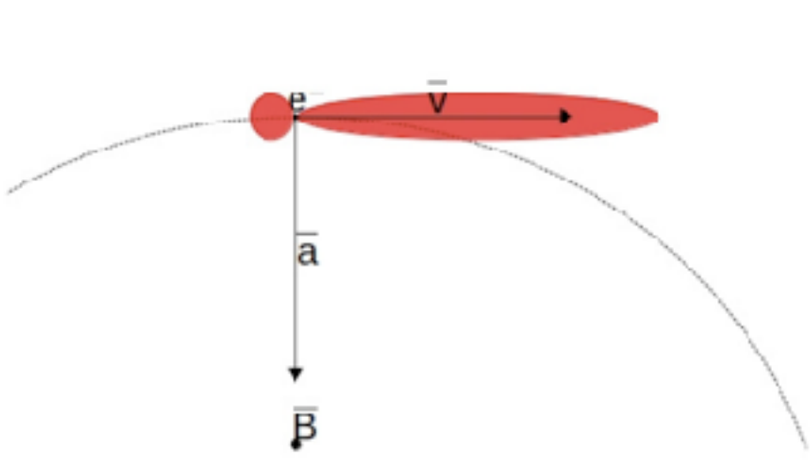


- Linear polarisation puts **constraints on geometry**

  - **PF** defines the level and kind of symmetry of the system
  - **PA** indicates its orientation

e.g. Crab

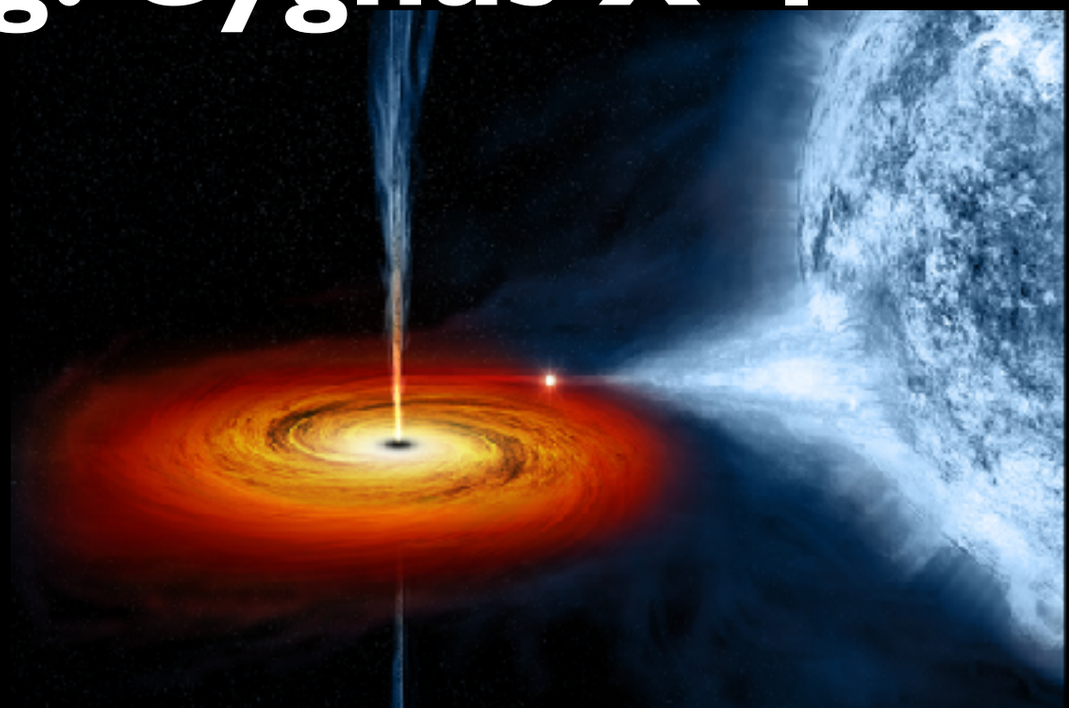
Synchrotron emission



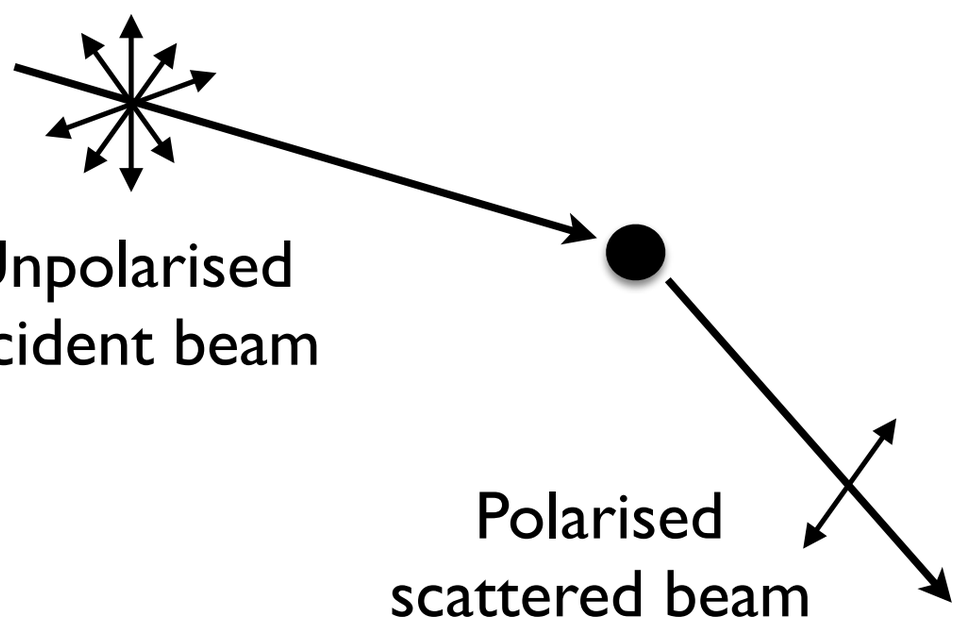
- Polarisation angle determines the magnetic field direction

- Maximum polarisation fraction for synchrotron emission ~75%. Will be reduced for a disordered magnetic field.

e.g. Cygnus X-1

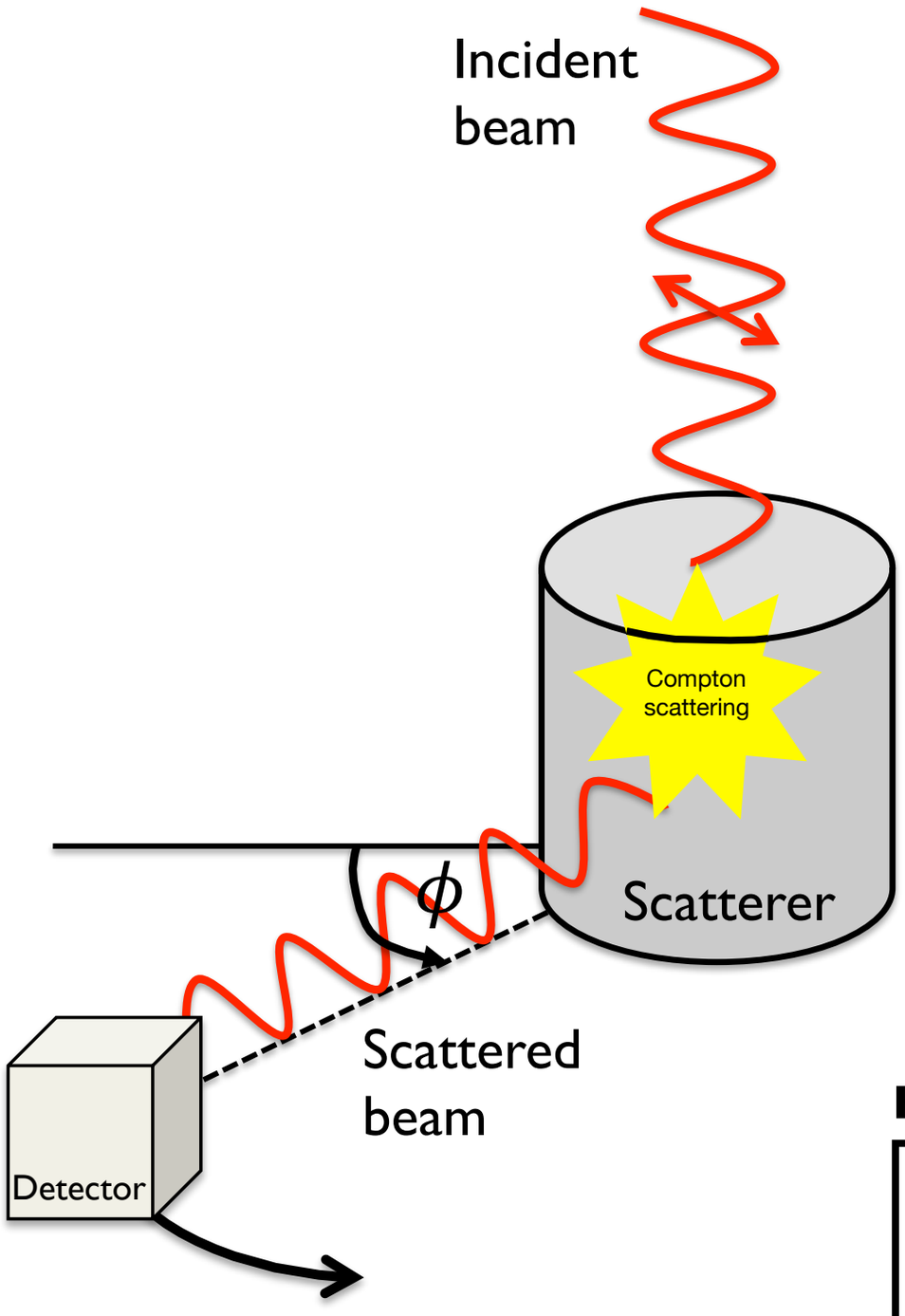


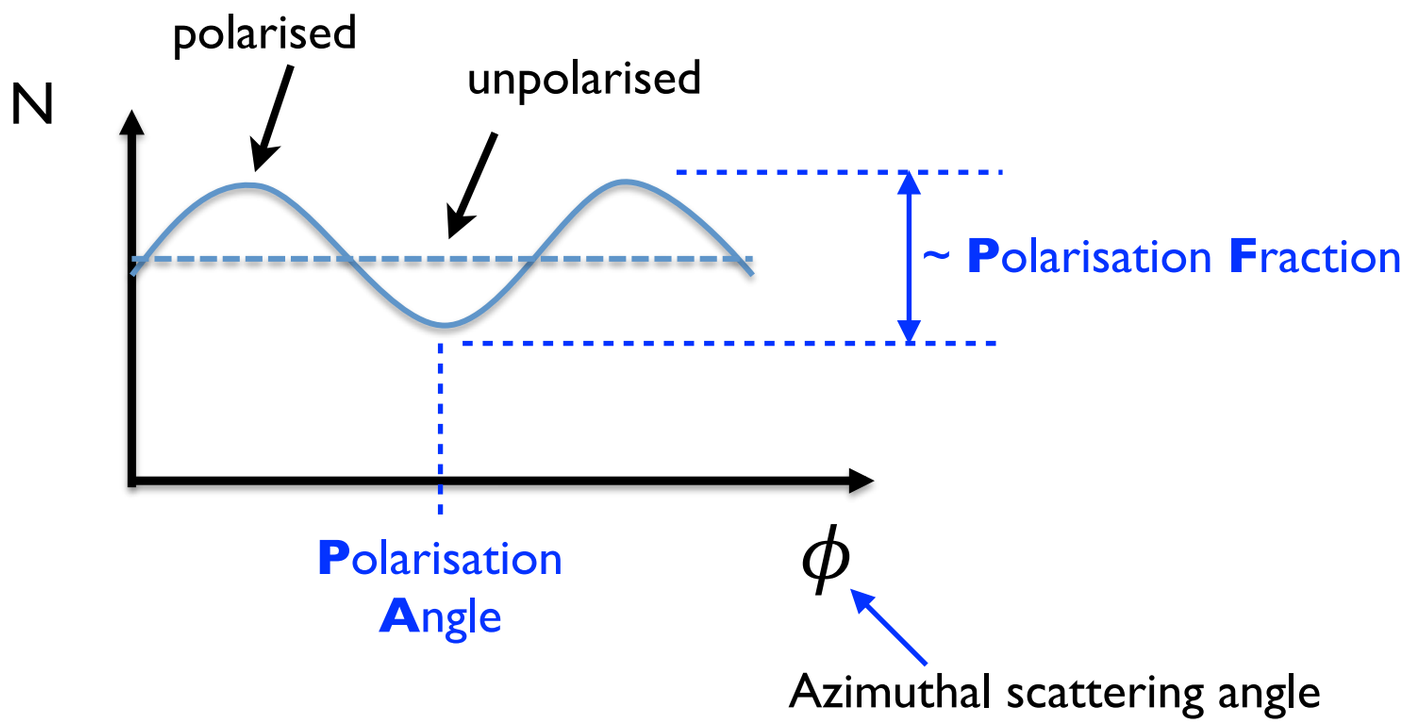
Reflection / scattering



- Polarisation probes coronal geometry close to the black hole

Measuring X-ray polarisation



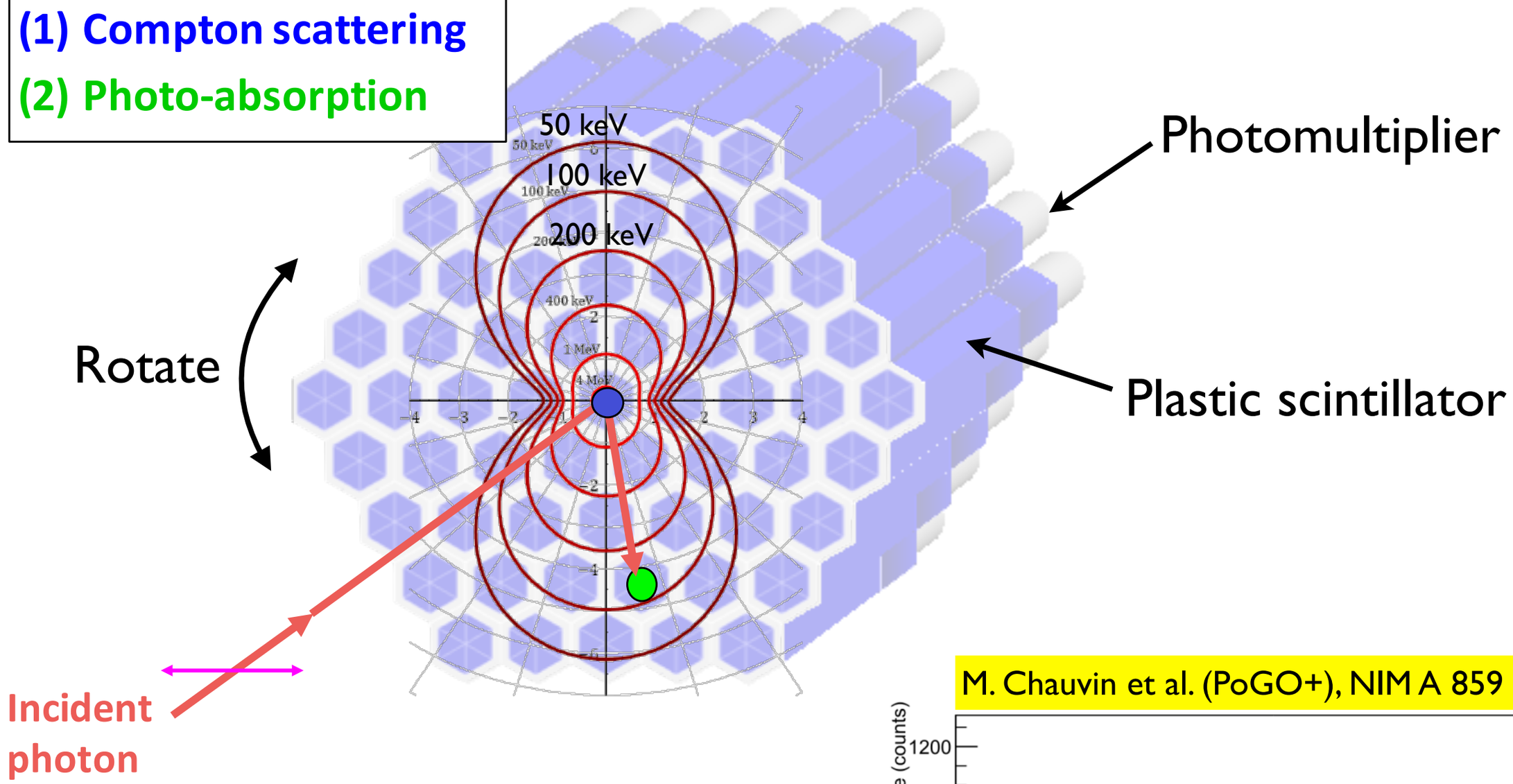


Klein Nishina relationship

$$\frac{d\sigma}{d\Omega} = \frac{r_o^2}{2}\frac{E'^2}{E^2}\left(\frac{E'}{E} + \frac{E}{E'} - 2\sin^2\theta\cos^2\phi\right)$$

(1) Compton scattering

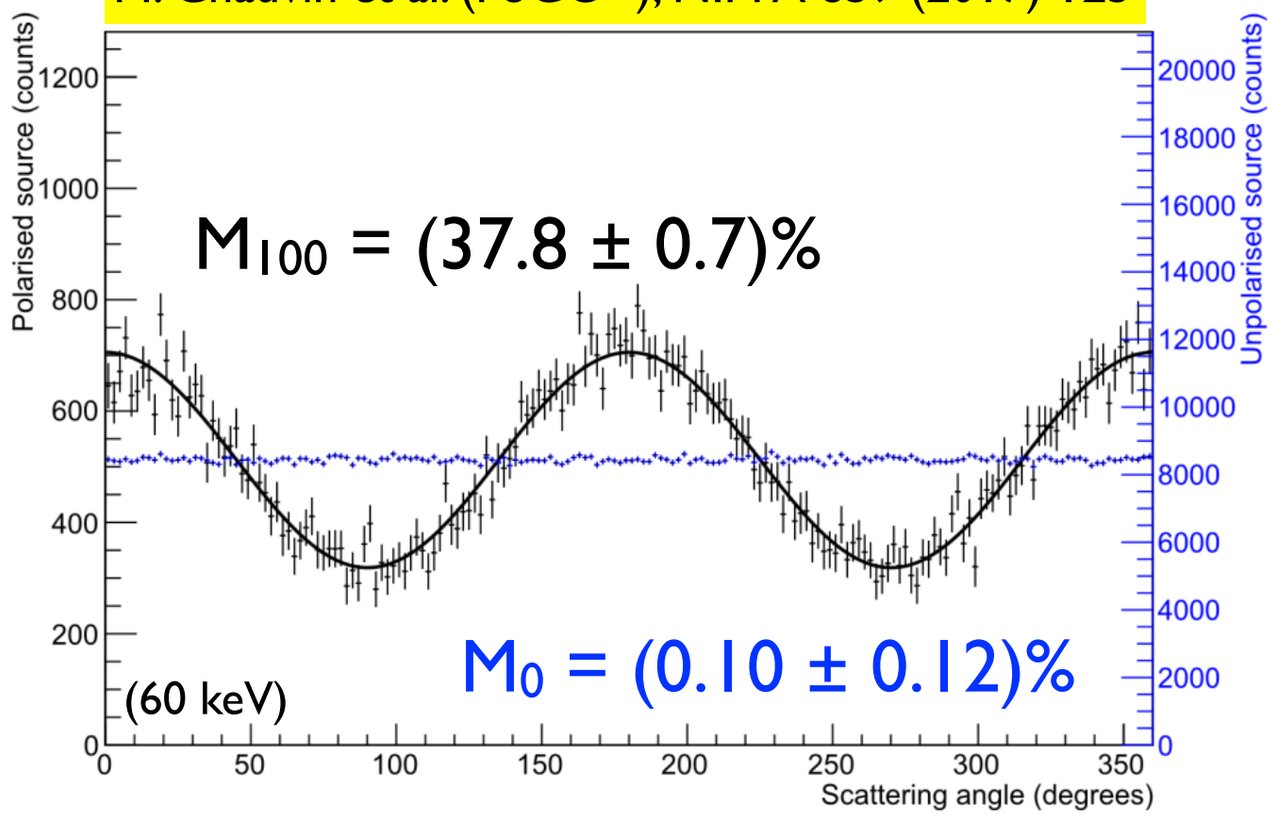
(2) Photo-absorption



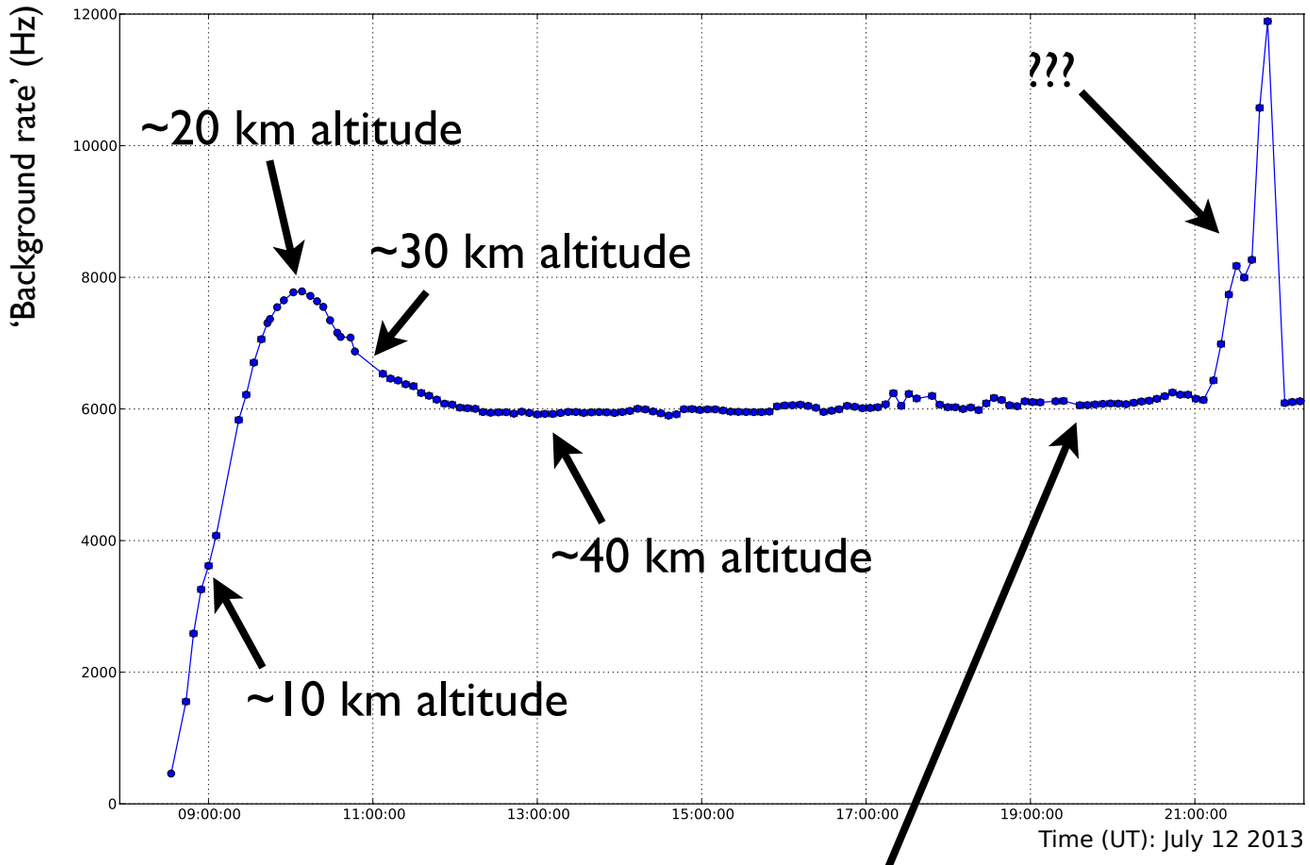
- The distribution of azimuthal scattering angles defines the polarisation of the incident beam

- **Positive definite measurement.**
Preflight calibration with (un-)polarised X-ray beams essential.

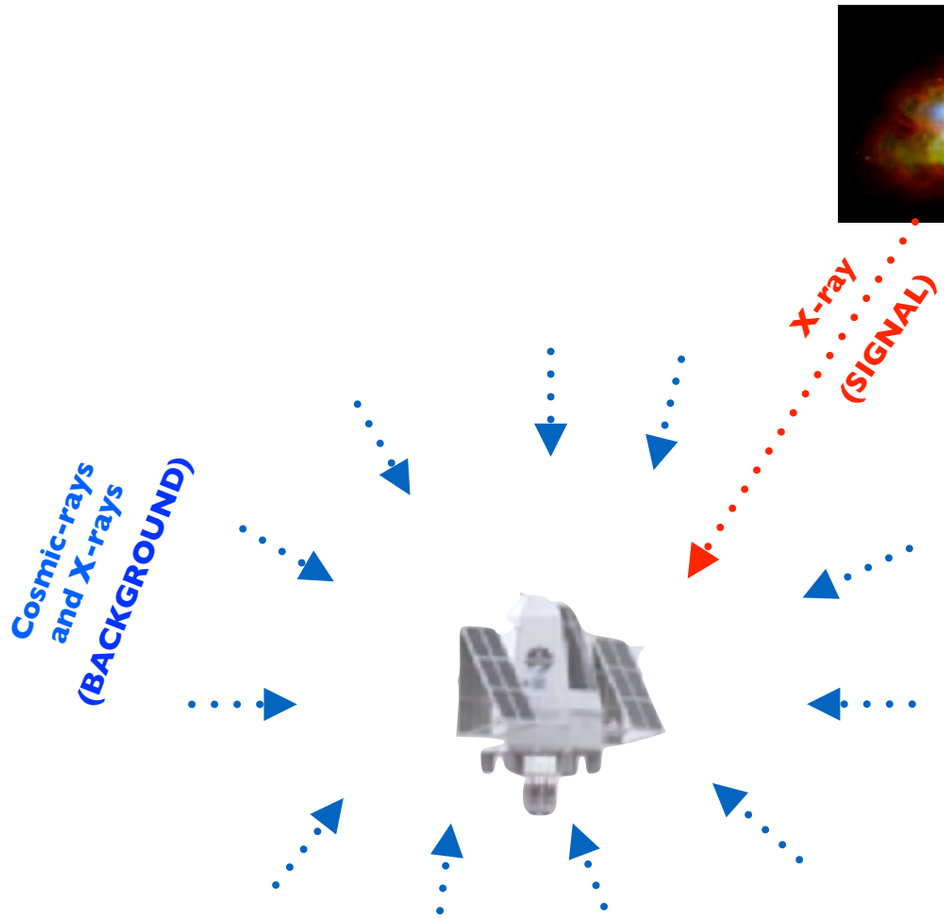
M. Chauvin et al. (PoGO+), NIM A 859 (2017) 125



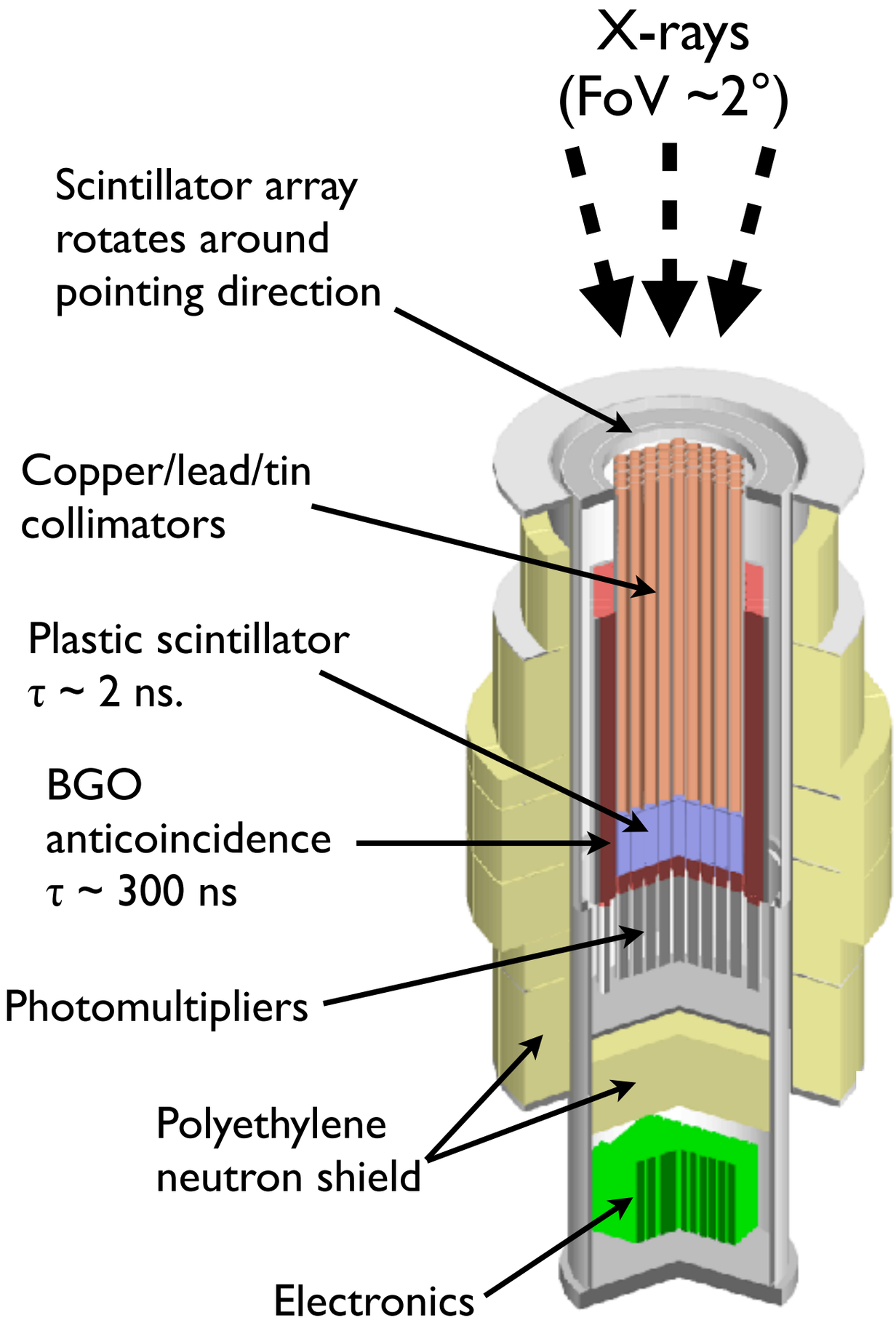
Radiation environment



Understanding the details of this 'background' rate is crucial to a convincing polarisation measurement!



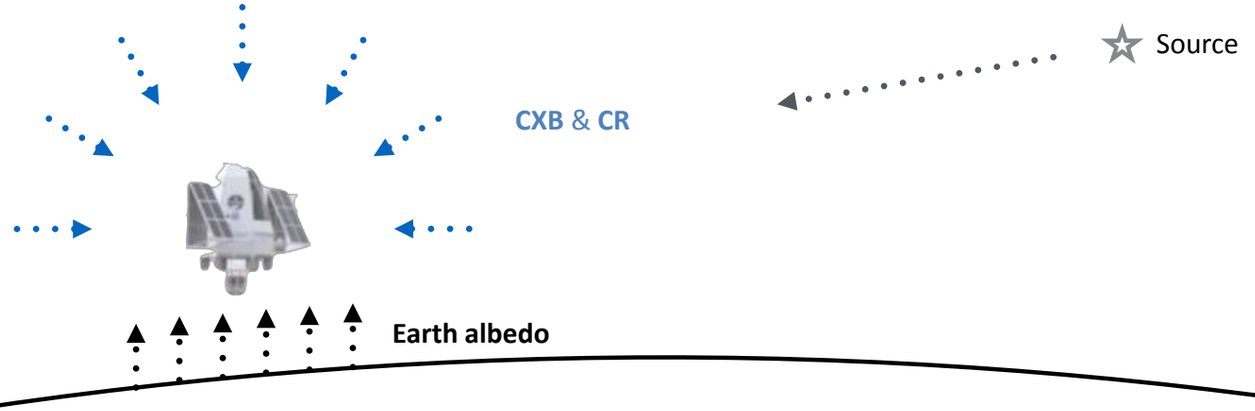
M. Chauvin et al. (PoGOLite), Exp. Astronomy 41 (2016) 17
M. Chauvin et al. (PoGO+), Astroparticle Physics 82 (2016) 99.



Robust measurement requires:

(1) purpose-built and calibrated instrument (positive definite measurement)

(2) Multiple background rejection methods



PCU_control

PCU_iridium

Pump

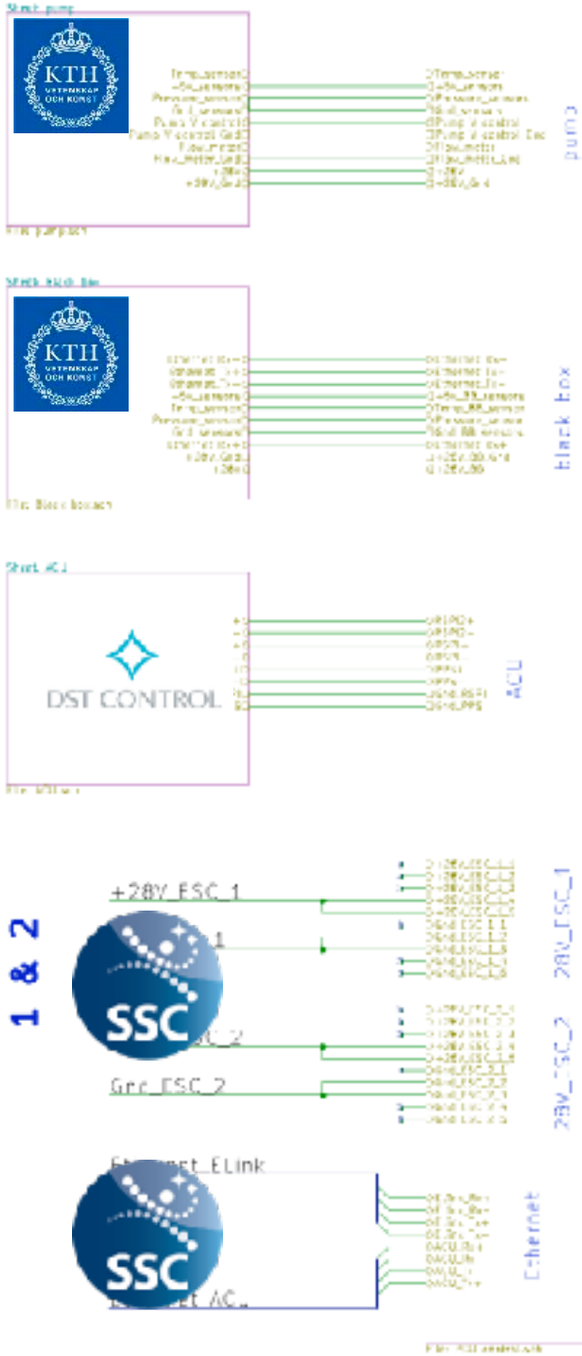
Black box

ACU

ESC 28V in 1 & 2

Ethernet

Polarimeter



PCU_control

PCU_iridium

Pump

Fluid based system

Power

Control

RS232

RS232

RS232

RS232_sensors

RS232_sensors

28V_ESC_1

Gnd ESC 1

28 V

28V_ESC_2

Gnd ESC 2

ESC 28V in 1 & 2

Antenna

Black box

Ethernet

- PC104 + SSD

Power

- DC/DC
- Iridium modems

Polarimeter

Sense

ACU

RS485

- RTC

PPS (RS422)

- 2 PC104 + SSD
- Real-time computer (RTC)
- Ethernet switches

Power

- FADC boards
- SpaceWire
- DAQ logic
- Power control

ESC 28V In 1 & 2

+28V_ESC_1

Grd_ESC_1

28 V

+28V_ESC_2

Grd_ESC_2

RS485

PPS (RS422)

Ethernet

Ethernet

Ethernet_ELink

To ACS

Ethernet_AC...

Esrange Ethernet (ELink + Pilot)

NB: *sensor connections (pressure, temp, etc.) not shown*

- Innovation: digital direct drive torque motors
- **Entire system is ITAR-free**

DST CONTROL

Flight train connection

Flight train motor and momentum dump system

Flywheel

Elevation encoder

Polarimeter assembly

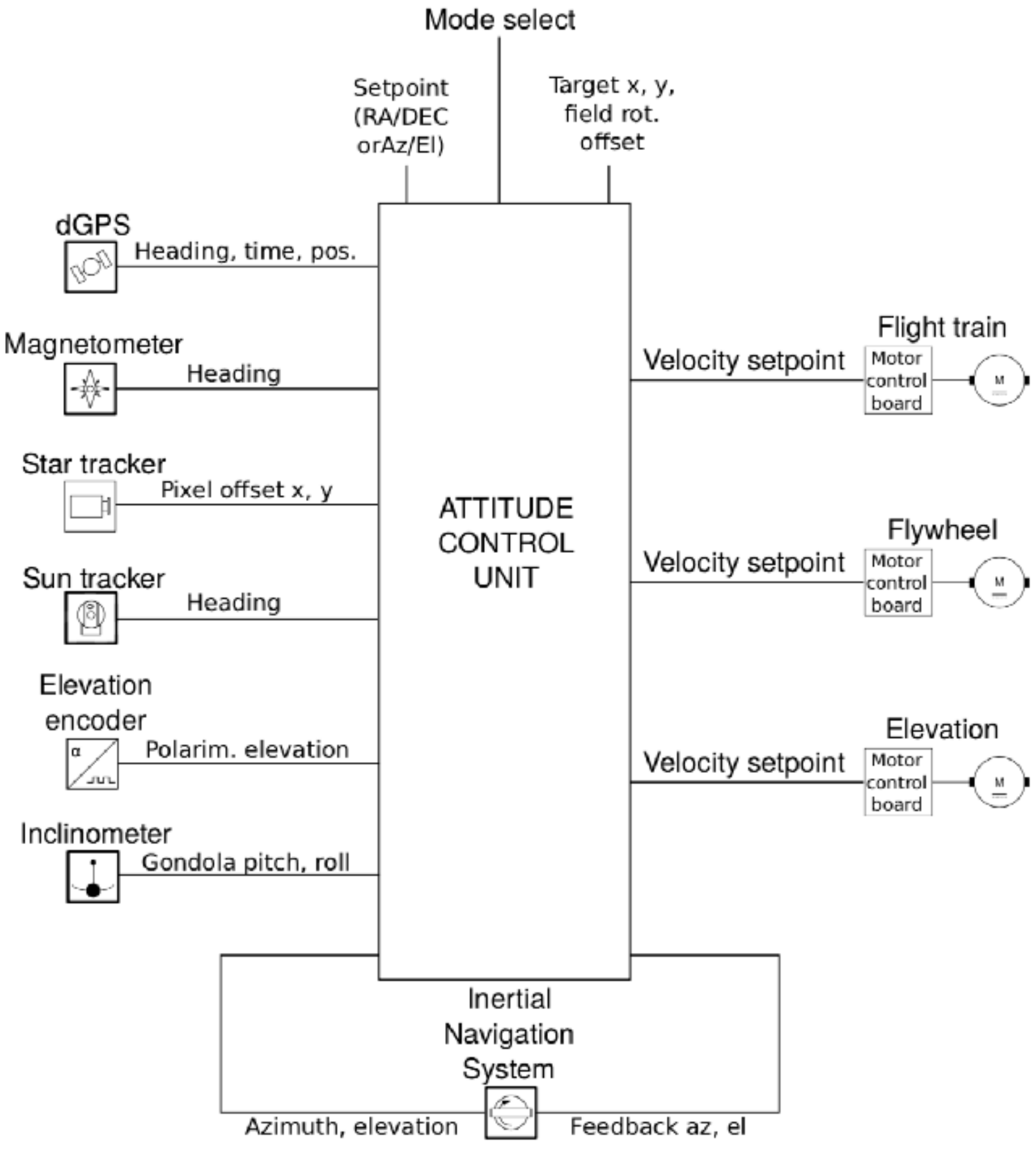
Field-of-view and roll axis

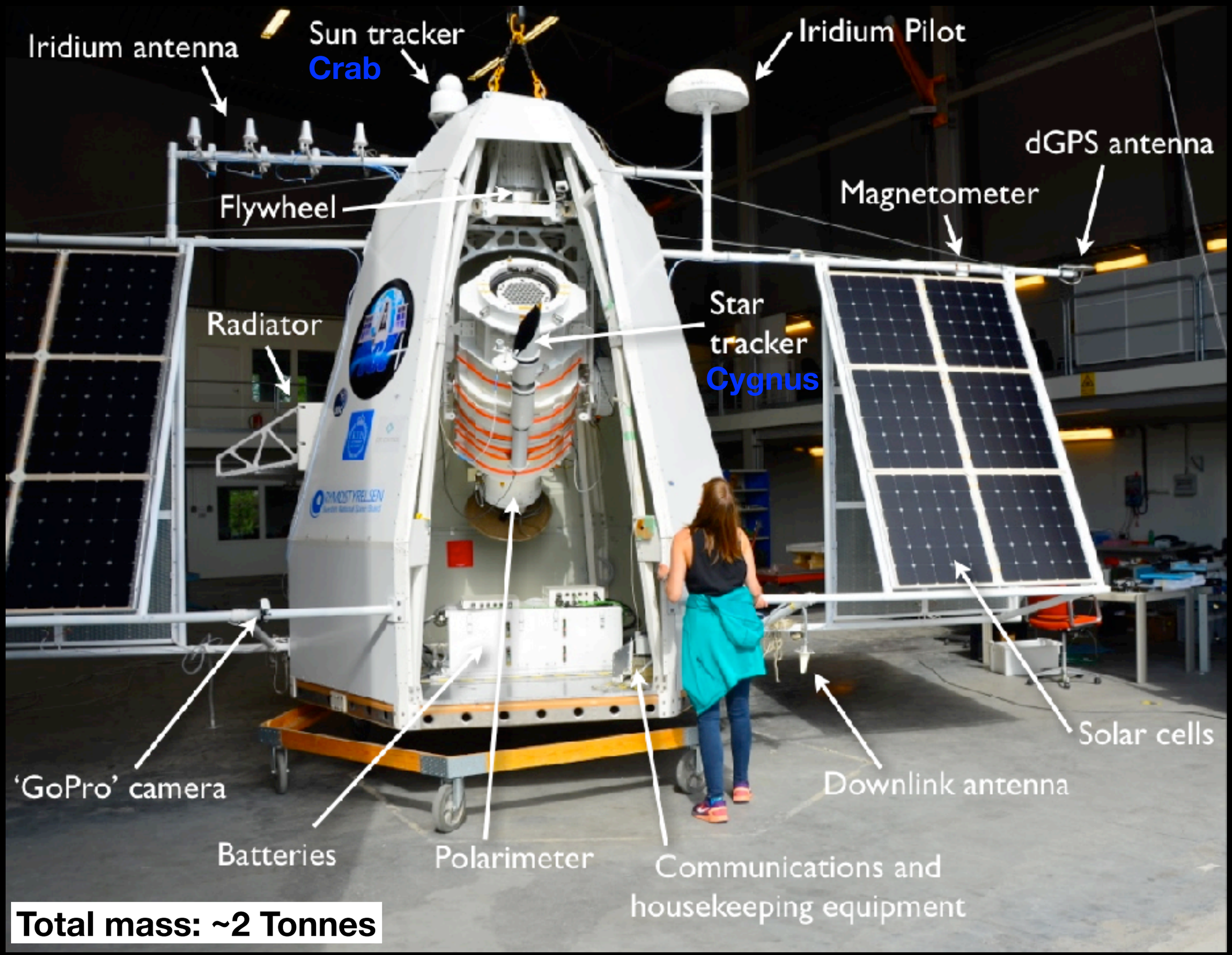
Roll motor

Elevation motor

Polarimeter ~1 Tonne

DST CONTROL


Mode select
Setpoint (RA/DEC orAz/El)
Target x, y, field rot. offset
dGPS
Heading, time, pos.
Magnetometer
Heading
Star tracker
Pixel offset x, y
Sun tracker
Heading
Elevation encoder
Polarim. elevation
Inclinometer
Gondola pitch, roll
ATTITUDE CONTROL UNIT
Flight train
Velocity setpoint
Motor control board
Flywheel
Velocity setpoint
Motor control board
Elevation
Velocity setpoint
Motor control board
Inertial Navigation System
Azimuth, elevation
Feedback az, el



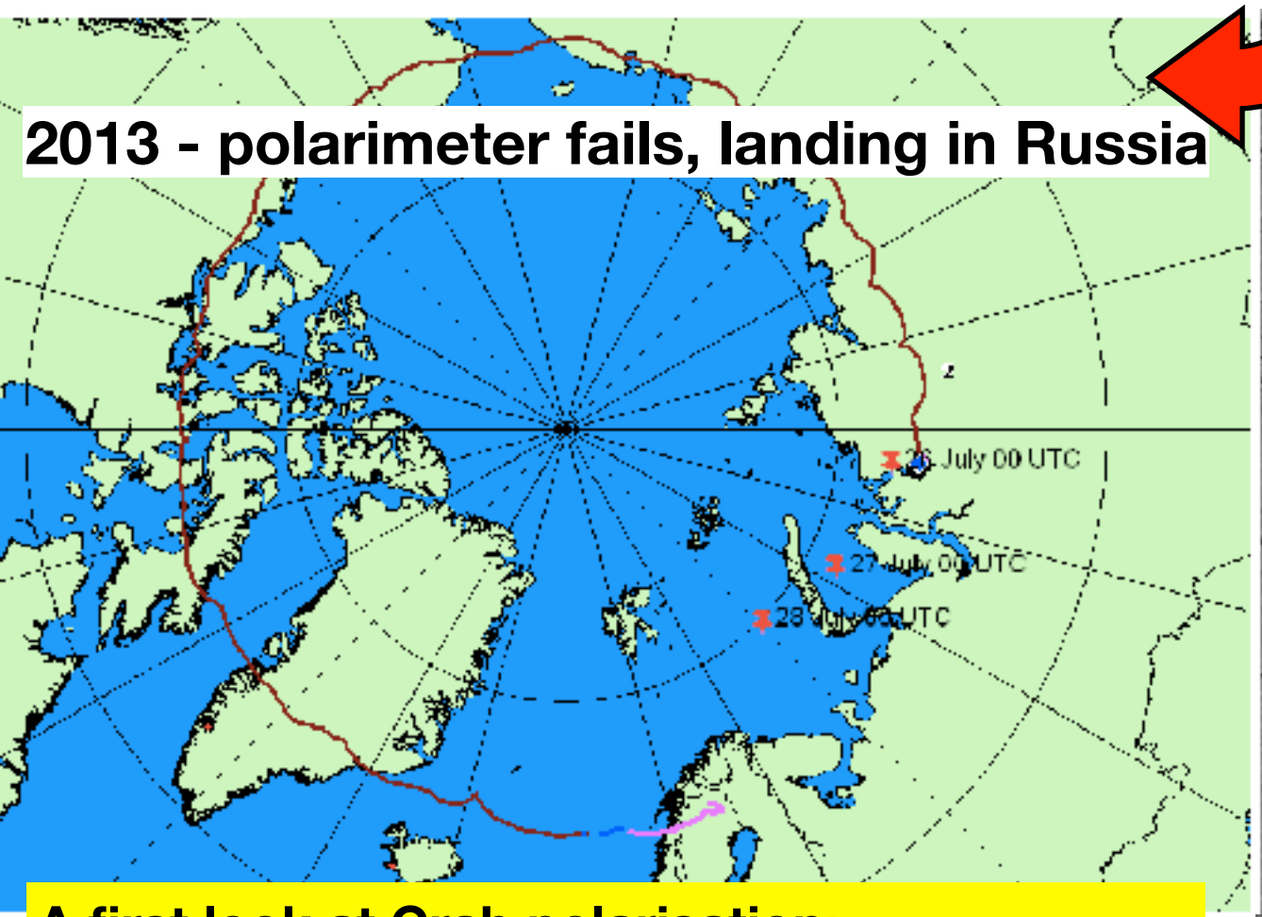
Total mass: ~2 Tonnes

2010 - NASA equipment grounded

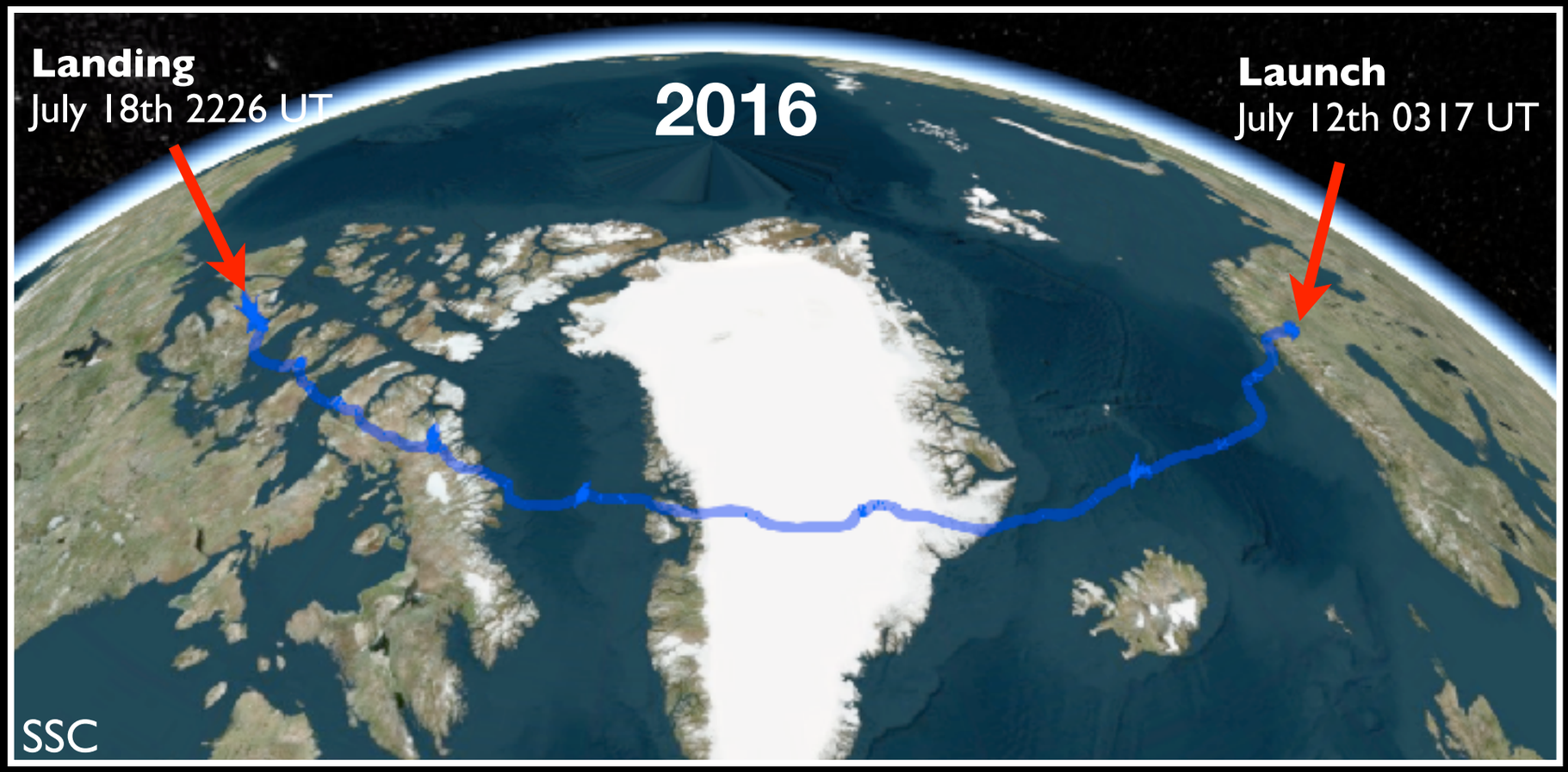
2011 - balloon damaged on launch

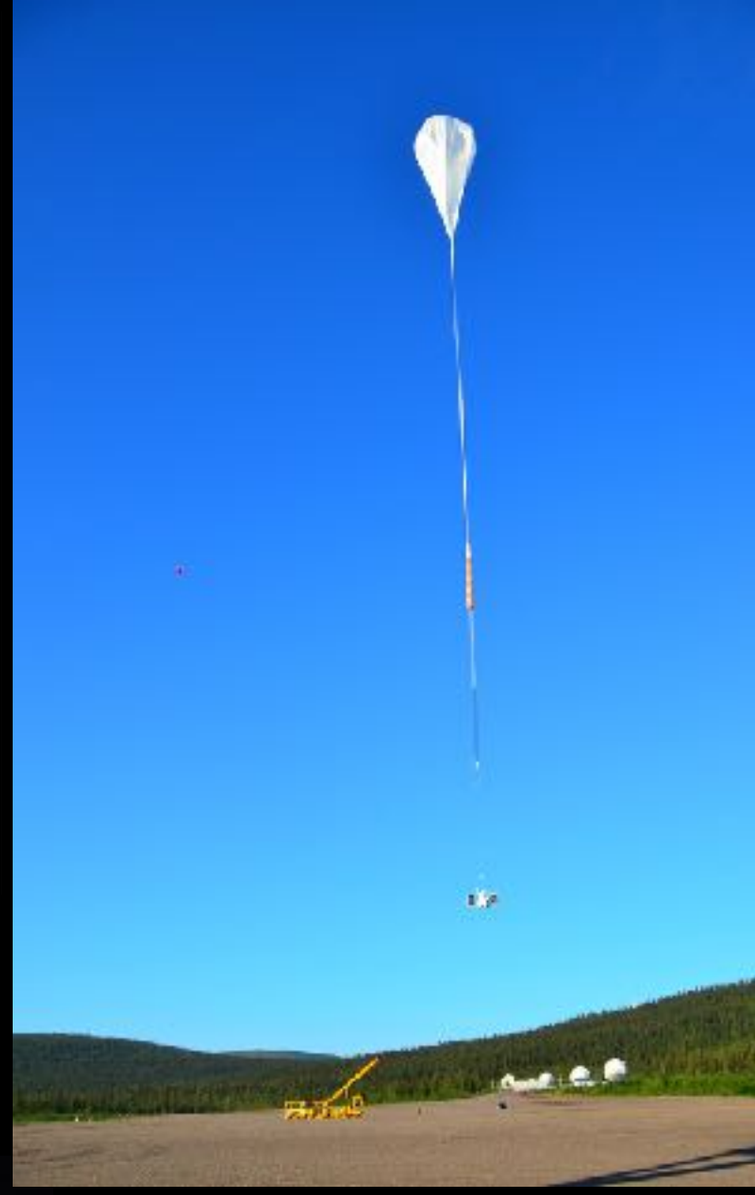
2012 - poor weather, no launch

2013 - polarimeter fails, landing in Russia

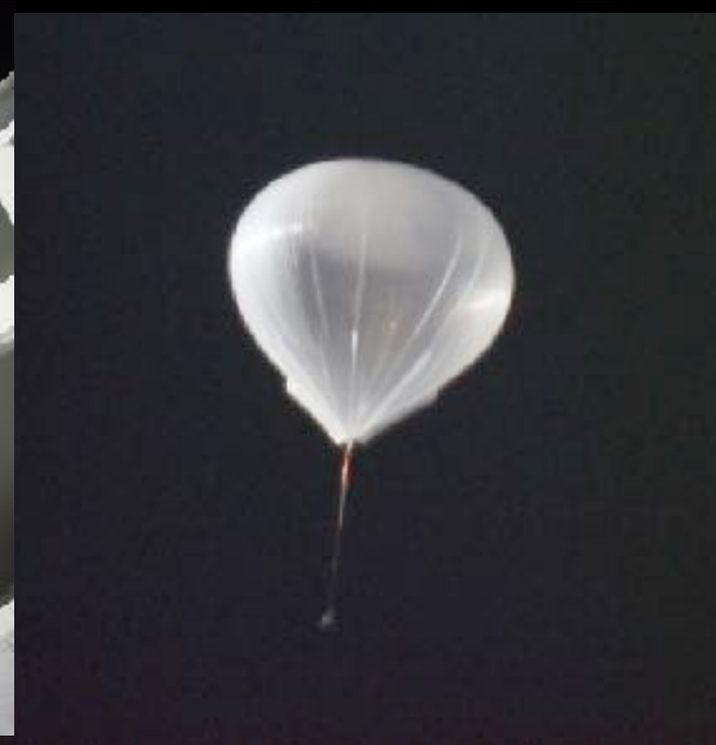


A first look at Crab polarisation:
M. Chauvin et al., MNRAS Letters 456 (2016) 84.

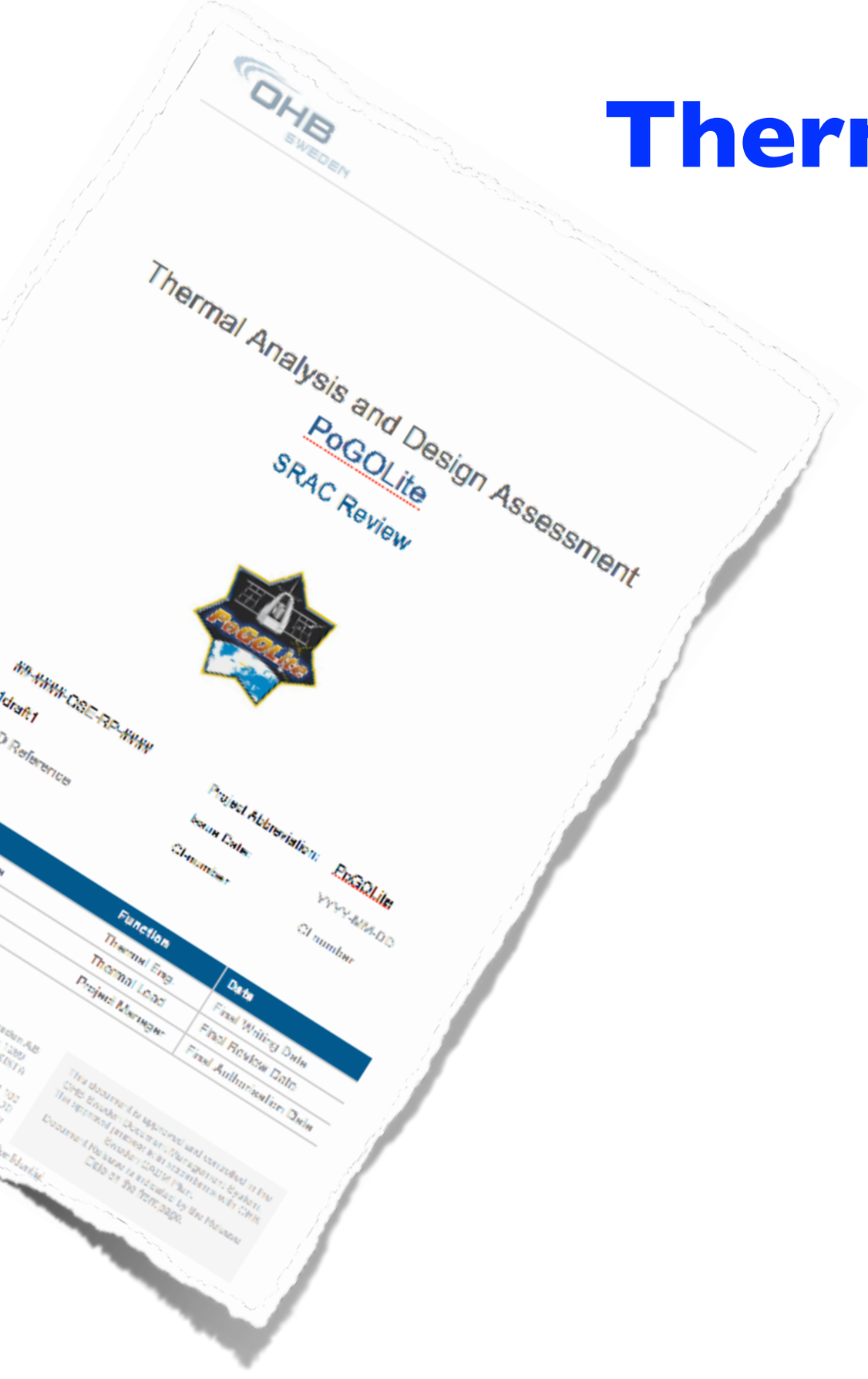

Landing
July 18th 2226 UT
2016
Launch
July 12th 0317 UT
SSC

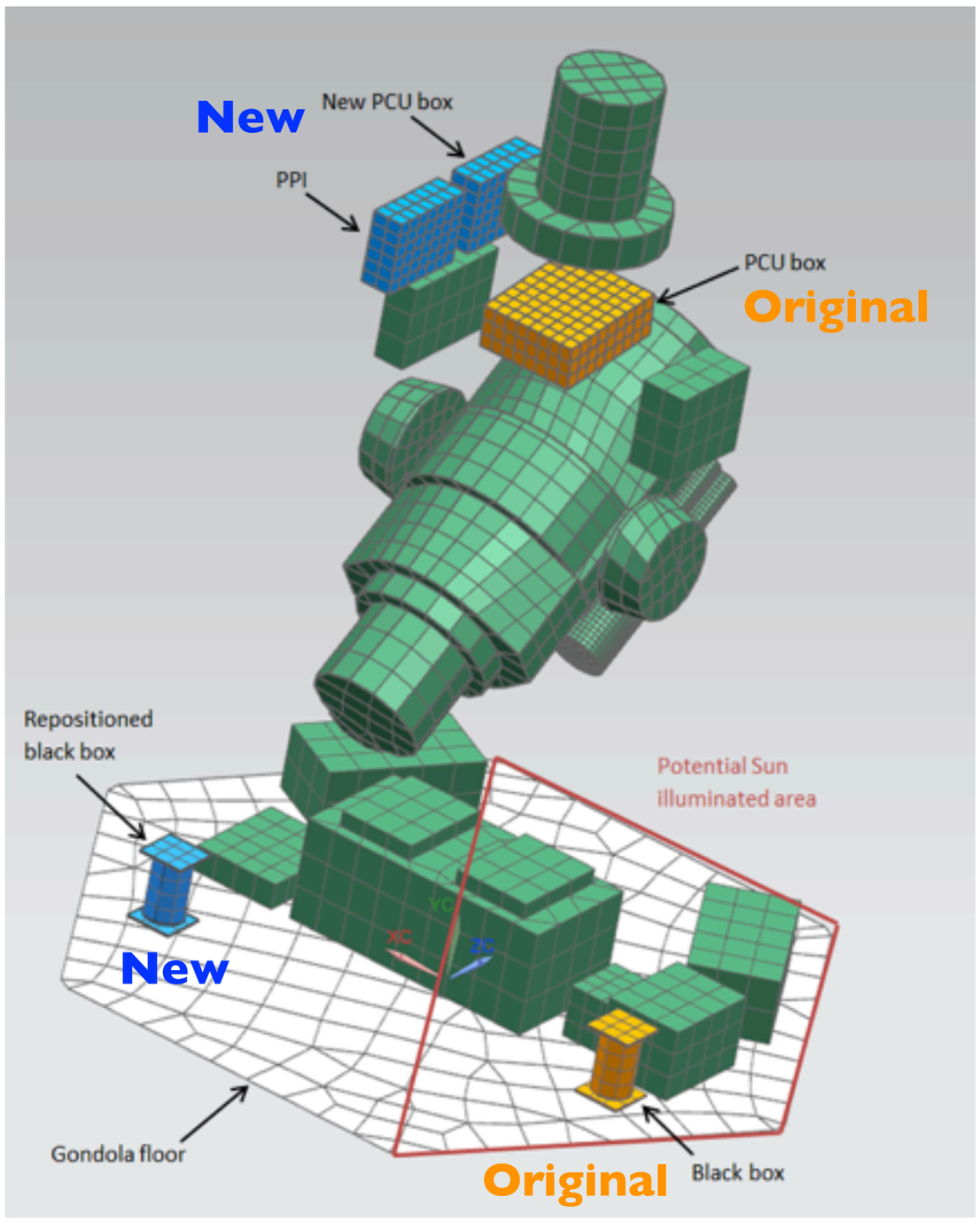


YouTube



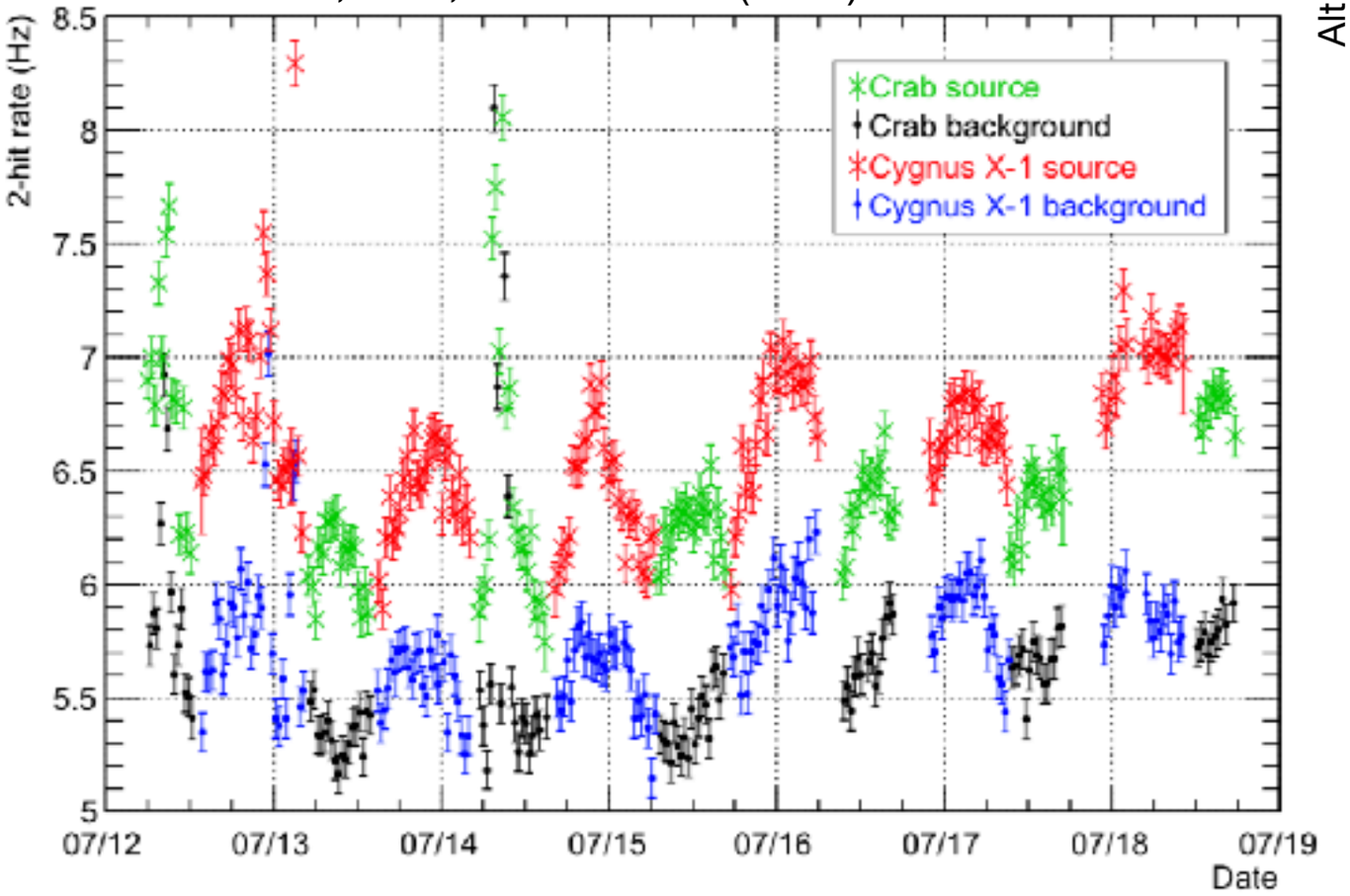
Thermal review



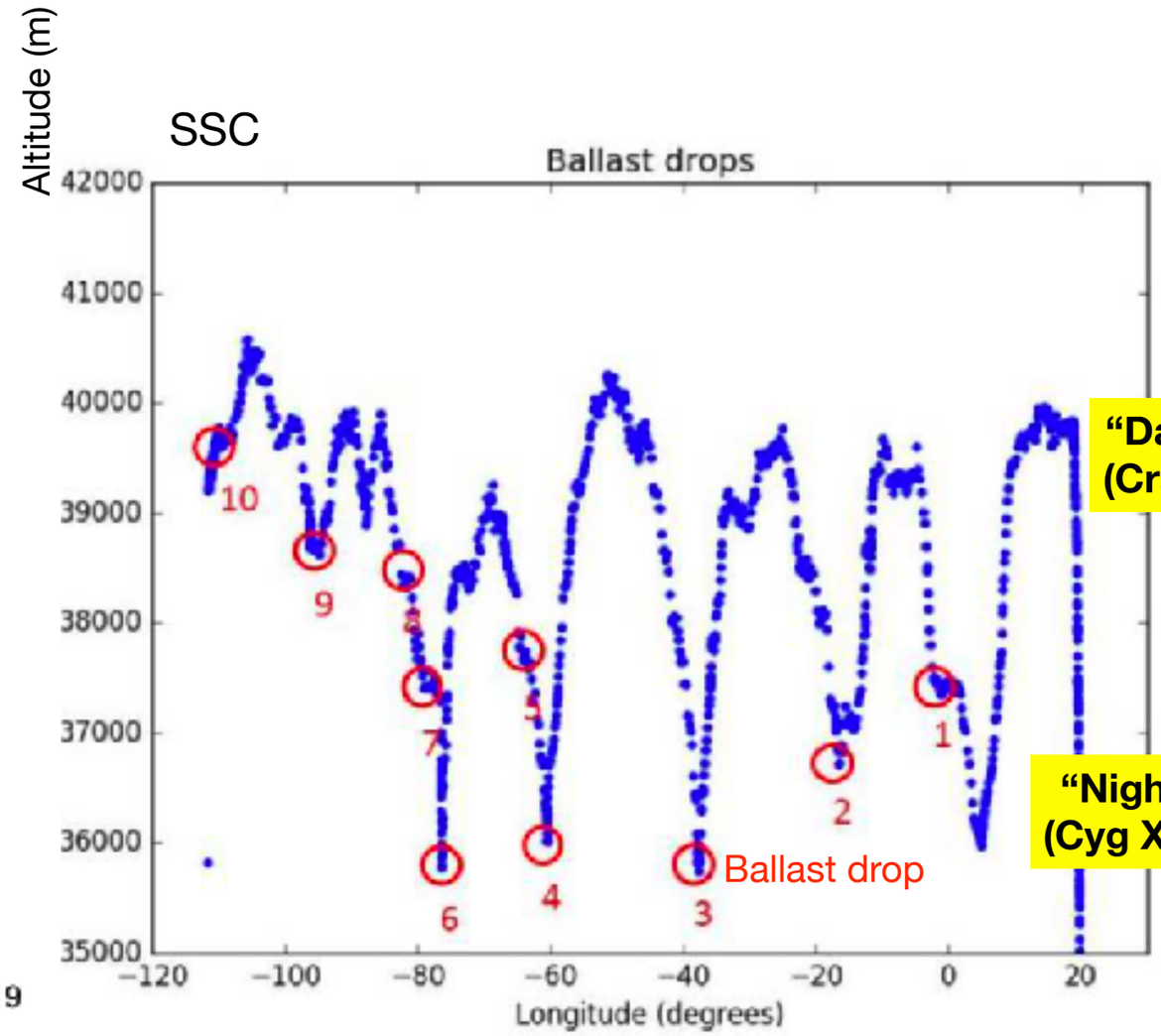


Extremely important!

V. Mikhalev, KTH, Ph.D. Thesis (2018)



SSC



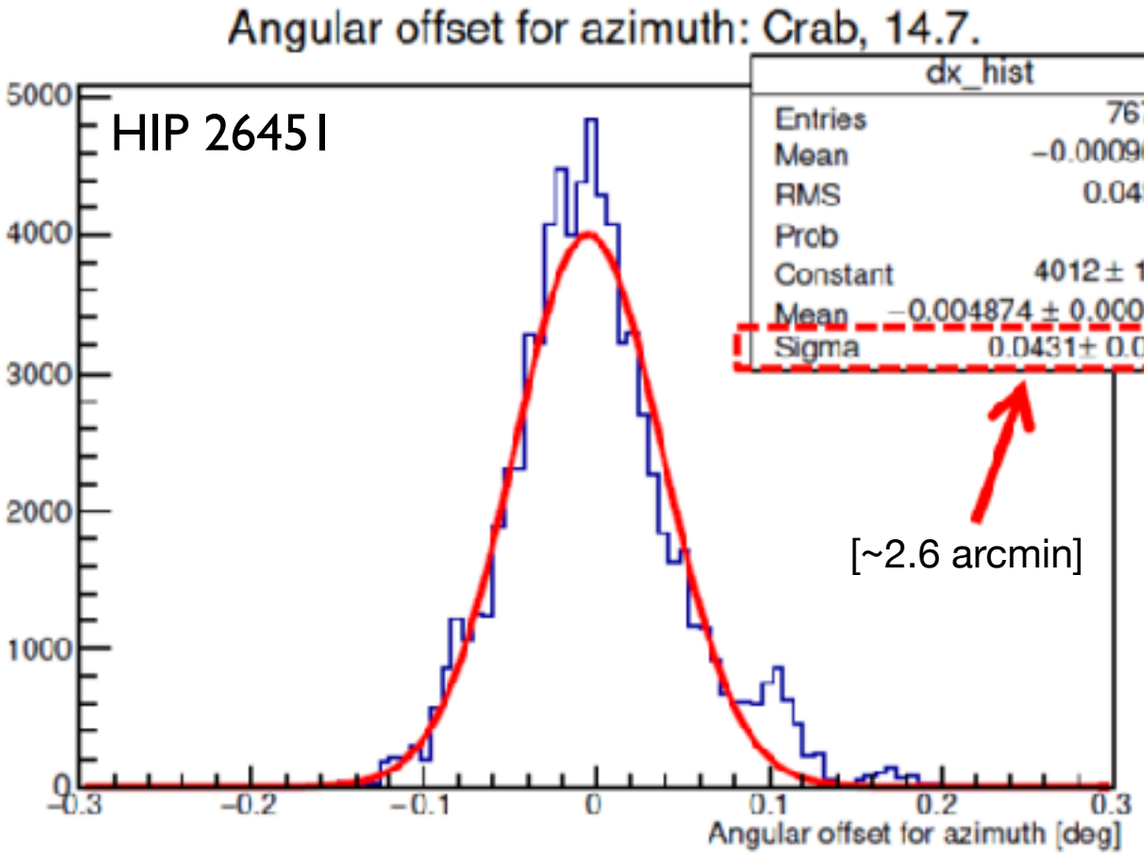
- Pointing strategy: "on-source/off-source", i.e. to measure background polarisation
- 5° East/West (azimuth) of source, 15 mins period.
- Signal / Background ~ 1 / 7
- MDP* ~10%

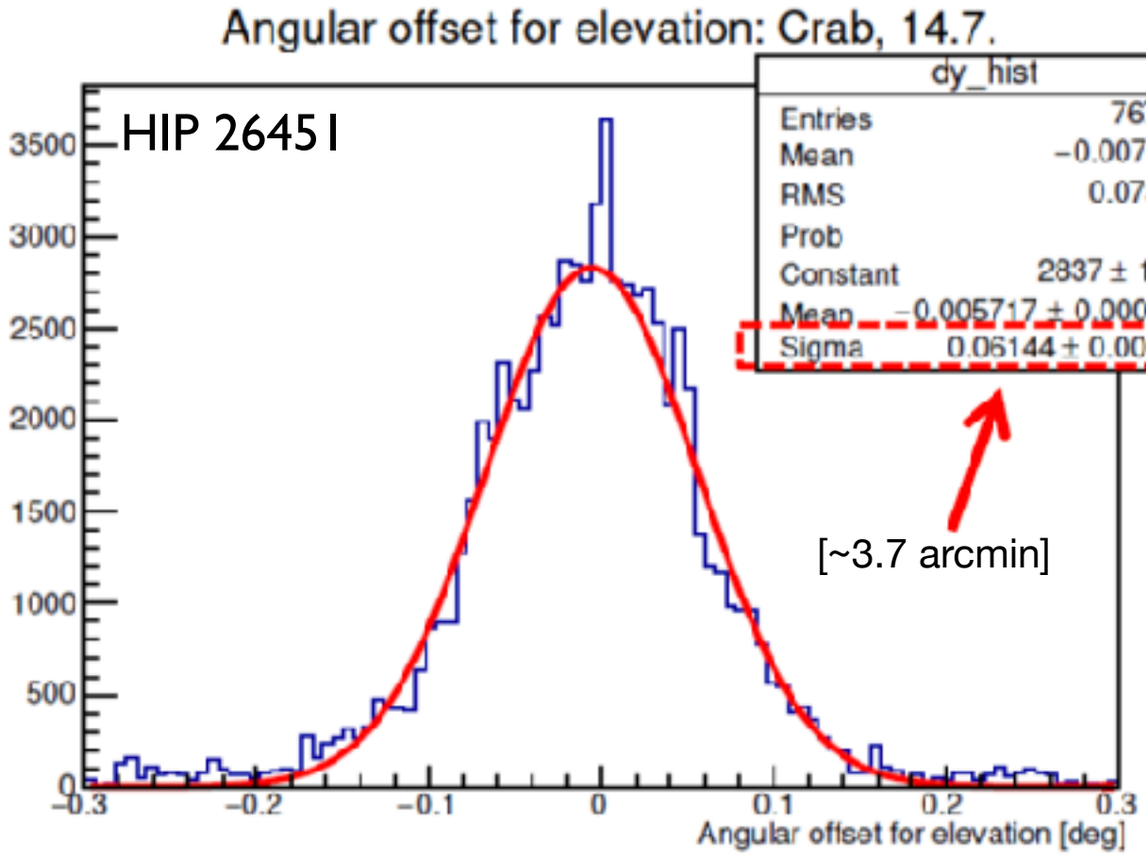
- Ballast drops were important!

** Unpolarised beam has 1% probability of yielding PF > MDP*

Polarimeter field-of-view: ~2°
Pointing requirement: < 0.1° (< 6 arcmin)

Sun tracker performance (Crab observations). Monitor with star camera.

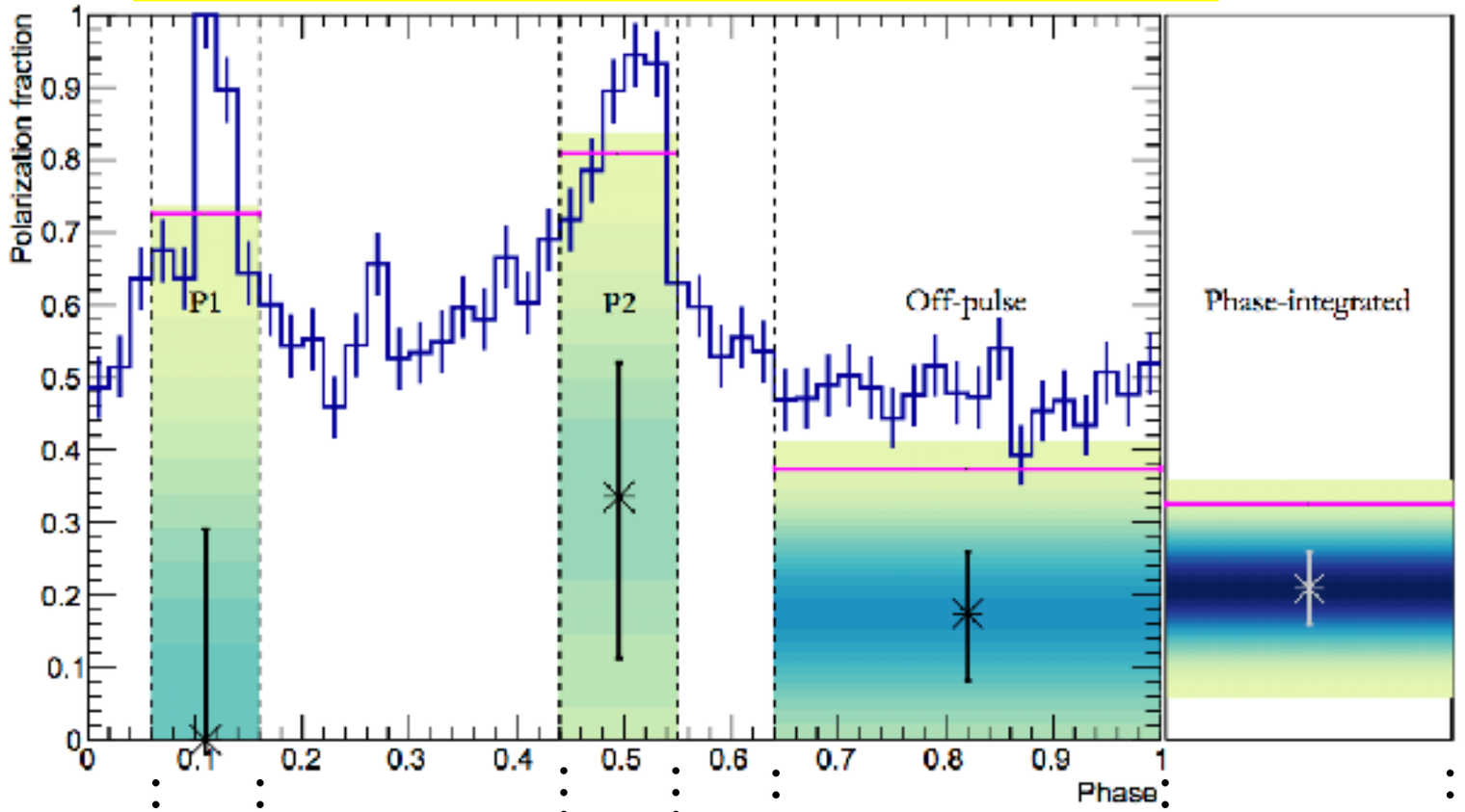


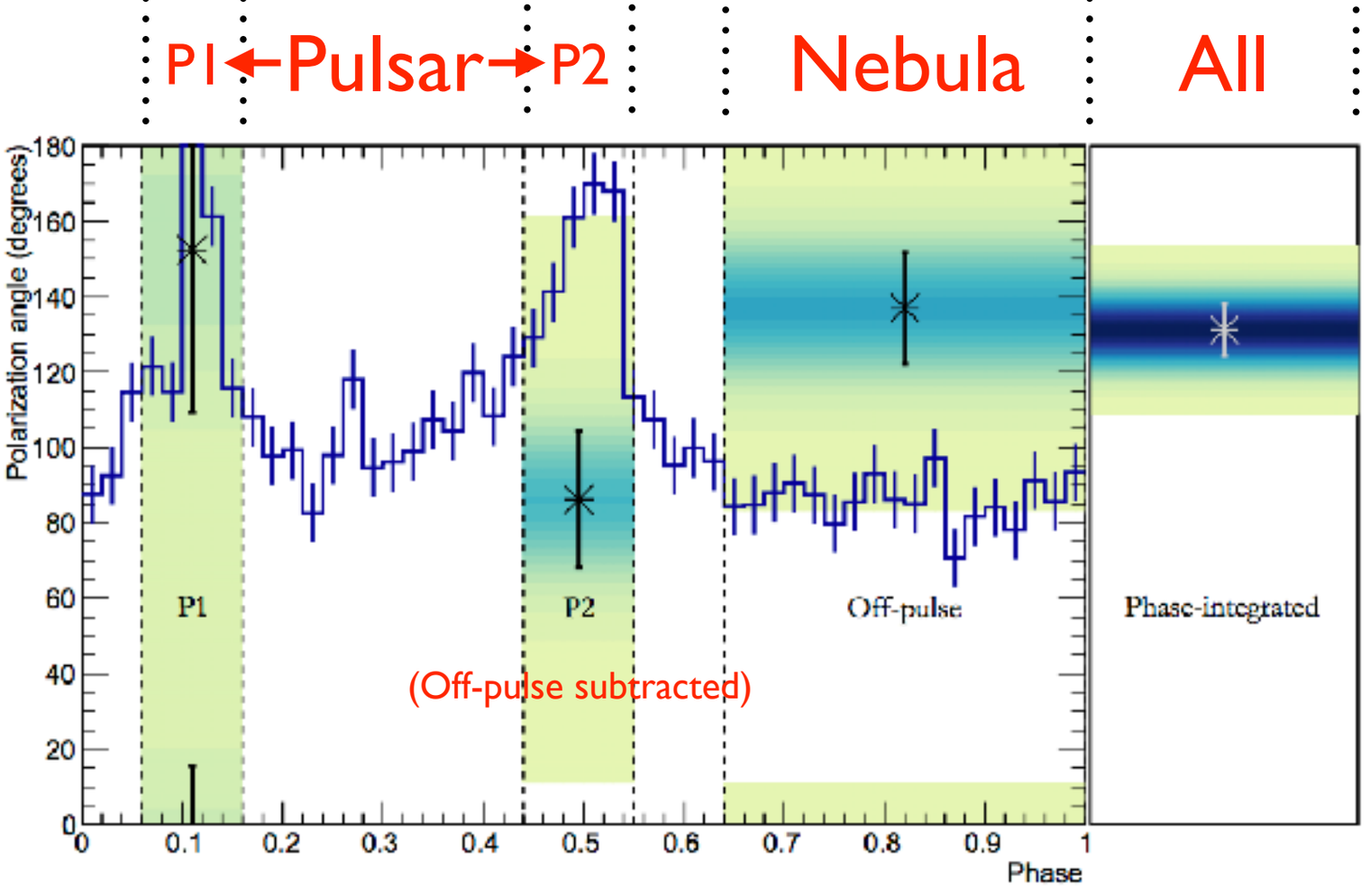


Star tracker performance (Cygnus X-1 observations).

$\sigma_{Az}=(0.013\pm0.002)^\circ$ [~0.8 arcmin]
$\sigma_{El}=(0.003\pm0.0003)^\circ$ [~0.2 arcmin]

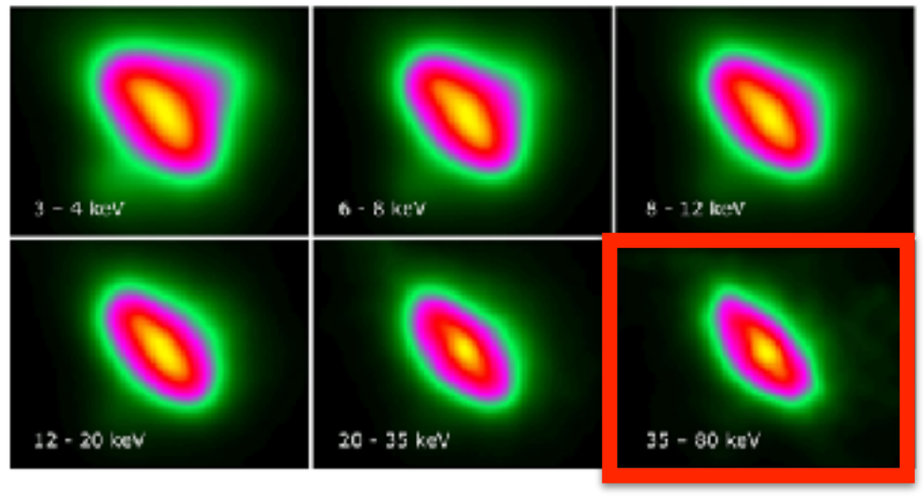
M. Chauvin et al. (PoGO+), Sci. Rep. 7 (2017) 7816.





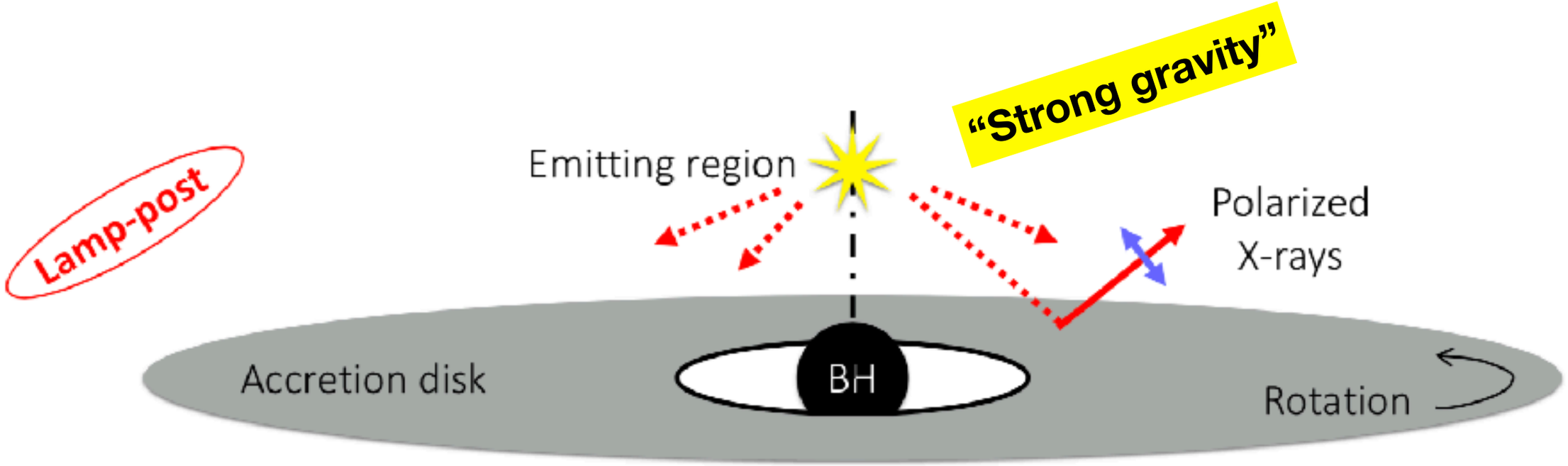
First measurement of polarised emissions from Crab in hard X-ray band (18-160 keV)

- Phase integrated PF ~ (21±5)%
  - Purely toroidal magnetic field with isotropic particle distribution ⇒ PF = 37%
  - Indicates degree of disorder in emission region
  - Explore further with MHD/ PIC simulations

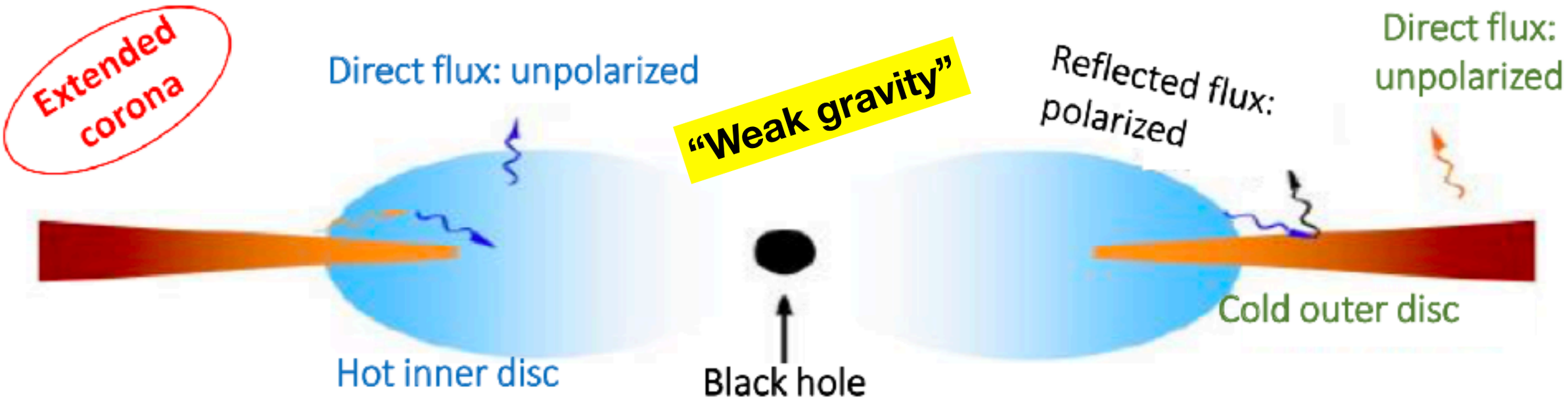


NuSTAR - Madsen et al. (2015)

PoGO+



Prediction ==> ✓ Polarization fraction: ~15% ✓ Polarization angle: || disk



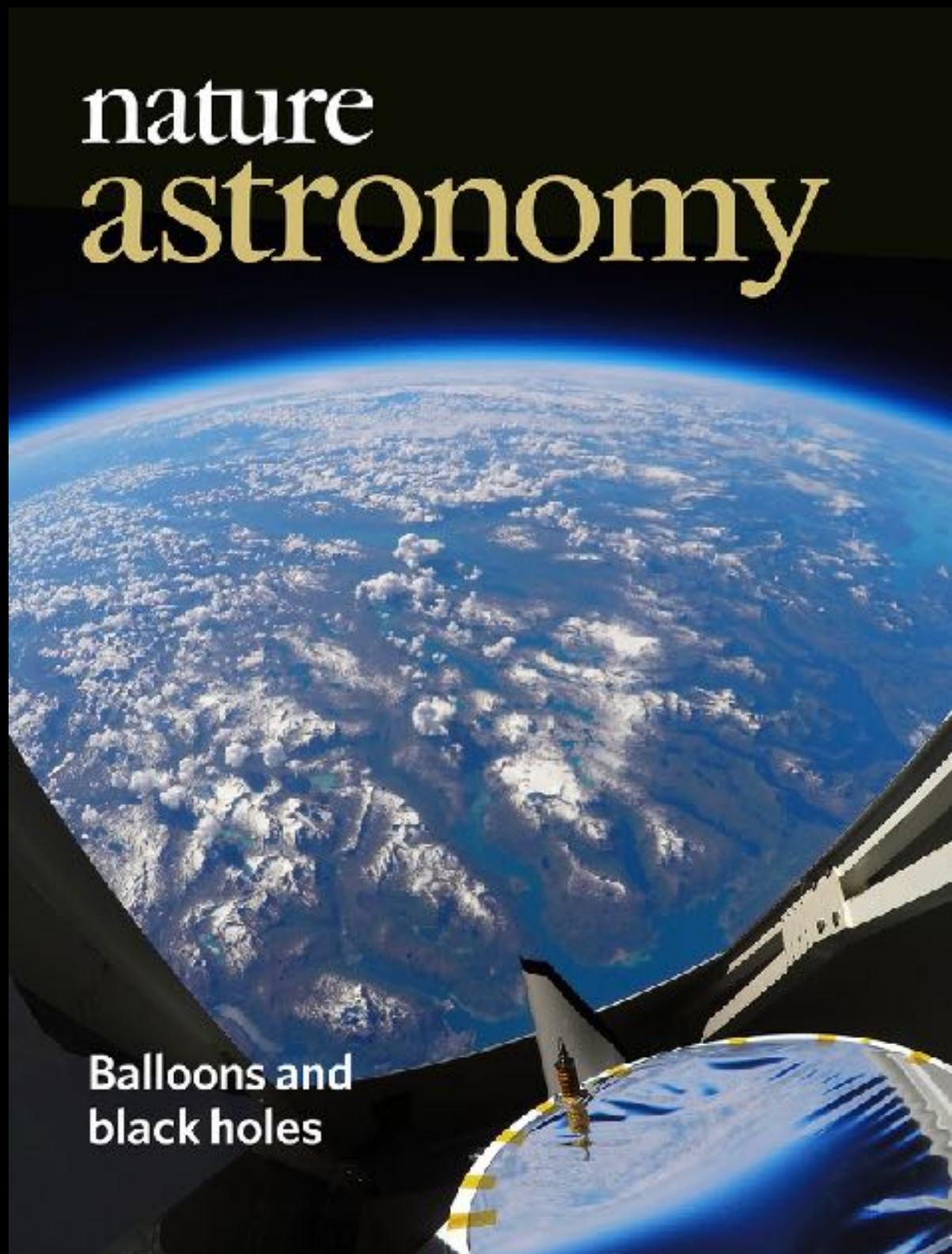
Prediction ==> ✓ Polarization fraction: few % ✓ Polarization angle: ⊥ disk

M. Chauvin et al. (PoGO+), Nature Astronomy 2 (2018) 652.

FAQ

Q: Will PoGO+ fly again?

A: No



Celestial X-ray source

X-rays

~2 m

X-ray detector

PoGO

Celestial X-ray source

X-rays

X-ray lens

~10 m

X-ray detector

X-Calibur

X(L)-Calibur

CZT-based X-ray polarimeter
~15-60 keV

X-ray focussing optics
HPD: 1 arcmin
FoV: 13 arcmin

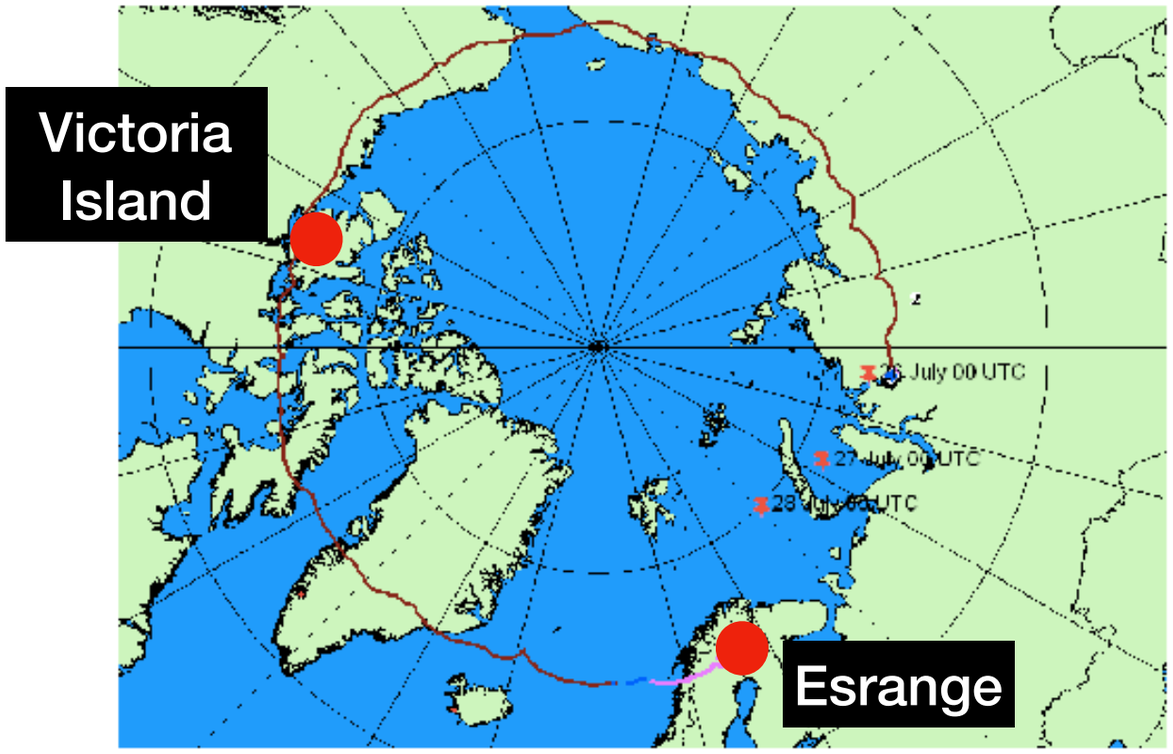
8m truss
(CFRP rods + aluminium joints)

WASP pointing system
Stability: 1 arcsec RMS
Knowledge: <15 arcsec (3σ)

Newsflash: funding approved under NASA-APRA programme! Flight locations TBD…

Observation plans

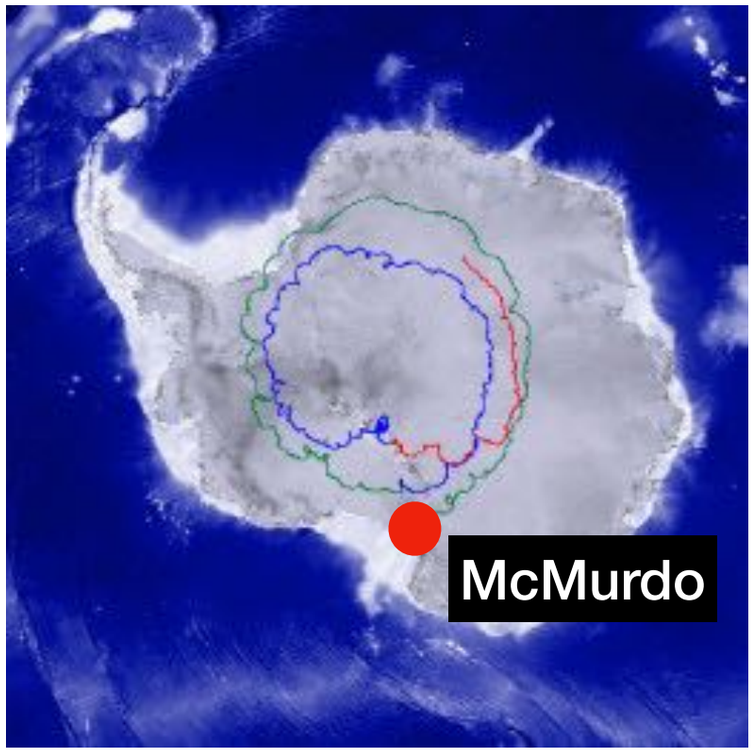
e.g. Crab pulsar, Cyg X-1, Her X-1, …



~5-7 days (to Victoria Island)
May/June/July

2021, 2022 (TBC)

e.g. GX301-2, Vela X-1, …

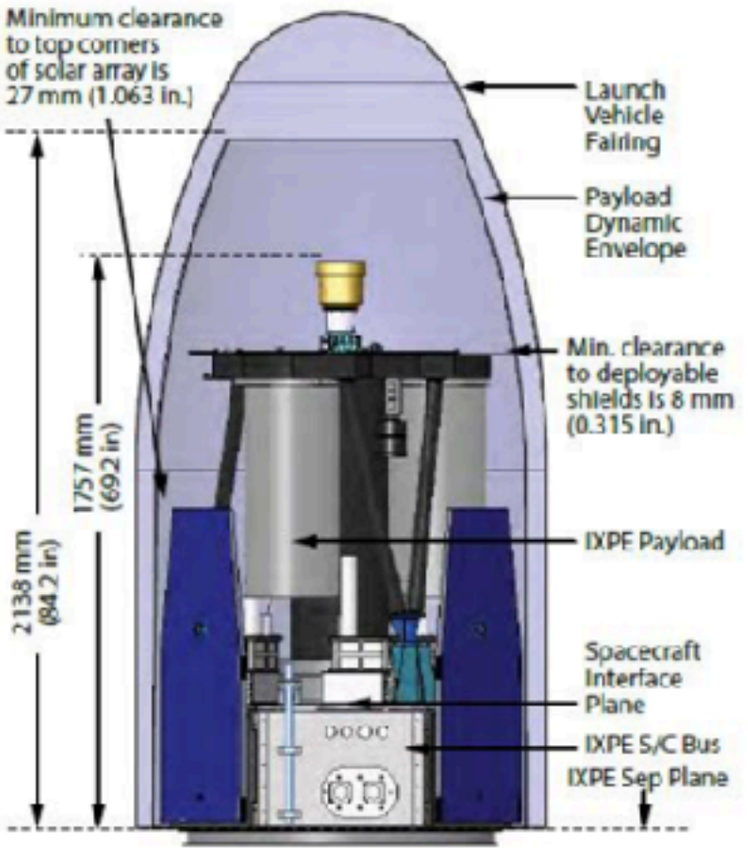


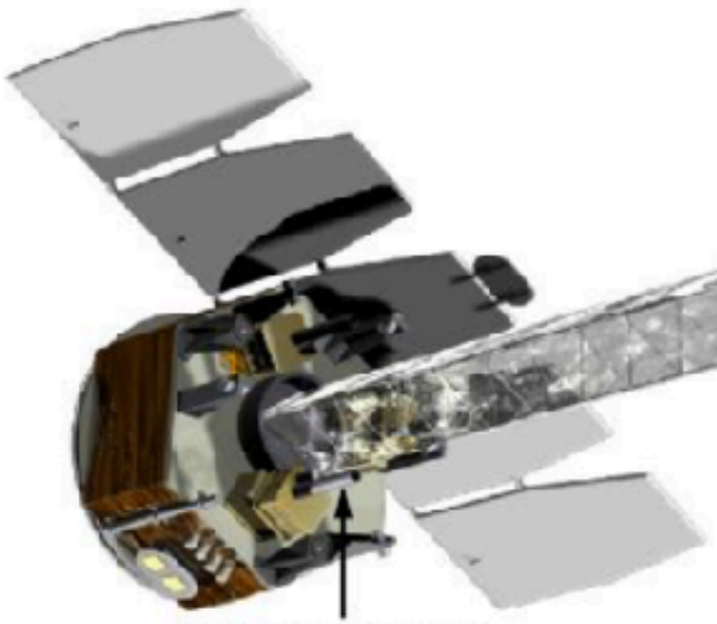
~8-55 days
December/January

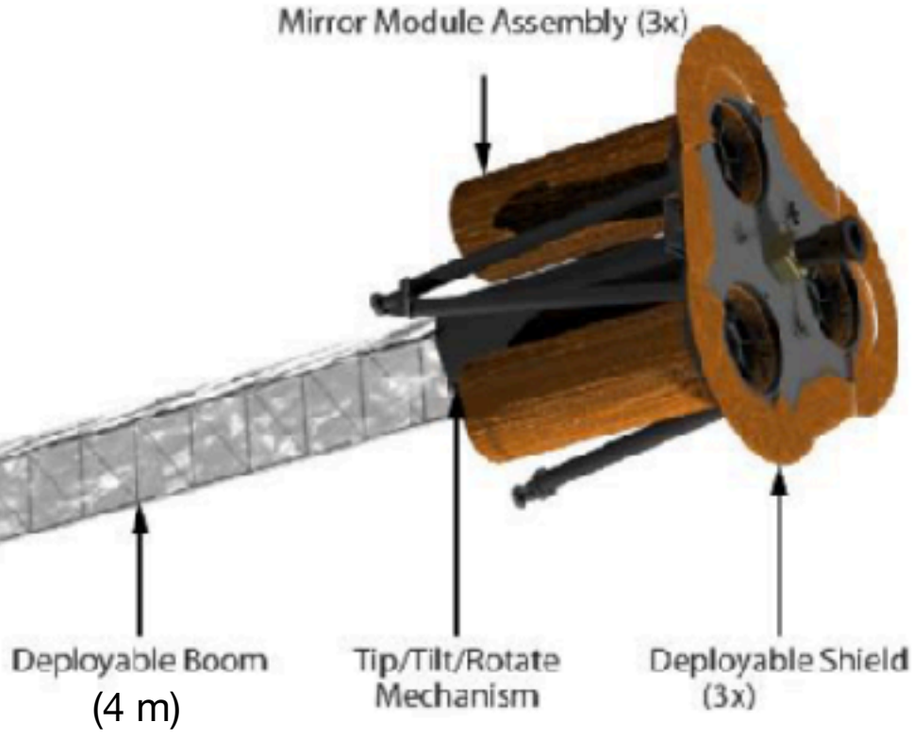
2023 (TBC)

MDP_{day} (0.5 Crab) ~1%

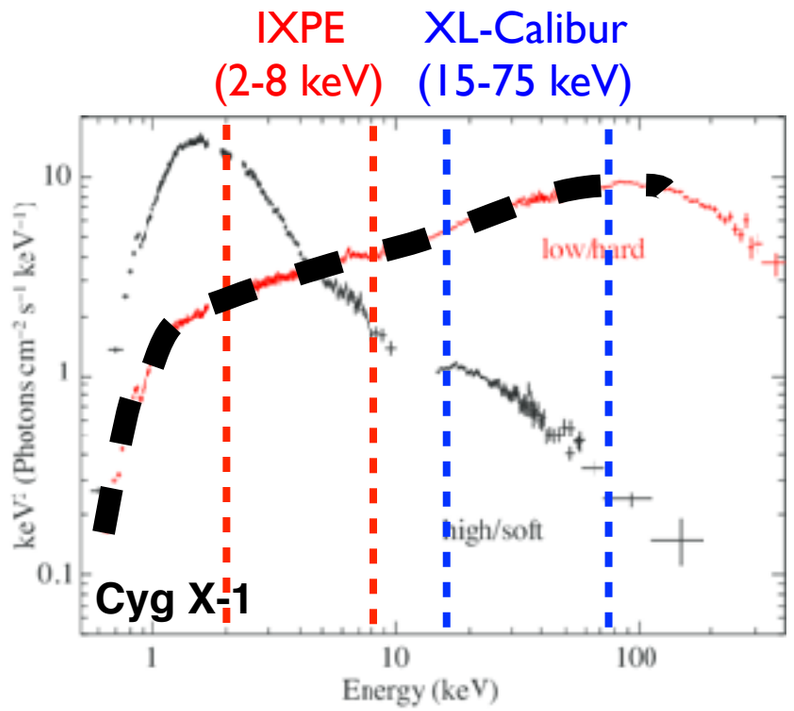
Balloon - satellite synergy







- NASA Small Explorer mission, *IXPE*
- 2-8 keV (photoelectric polarimeter)
- 30” imaging
- **Launch in 2021**



Stockholm University

HIROSHIMA

RYMDSTYRELSEN
Swedish National Space Board

SSC

DST CONTROL

OHB
SWEDEN

Knut och Alice Wallenbergs Stiftelse

Vetenskapsrådet

References

PoGO+

- M. Chauvin et al., 'PoGO+ polarimetric constraint on the synchrotron jet emission of **Cygnus X-1**', MNRAS 483 (2018) L138.
- M. Chauvin et al., 'Accretion geometry of the black-hole binary **Cygnus X-1** from X-ray polarimetry', Nature Astronomy 2 (2018) 652.
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