The 2016 COSI Balloon Flight

Andreas Zoglauer, UC Berkeley
for the COSI collaboration

The COSI Collaboration:

S.E. Boggs (PI), J.-L. Chiu, C. Kierans, A. Lowell, C. Sleator, J.A. Tomsick, A. Zoglauer *(UCB/SSL)*

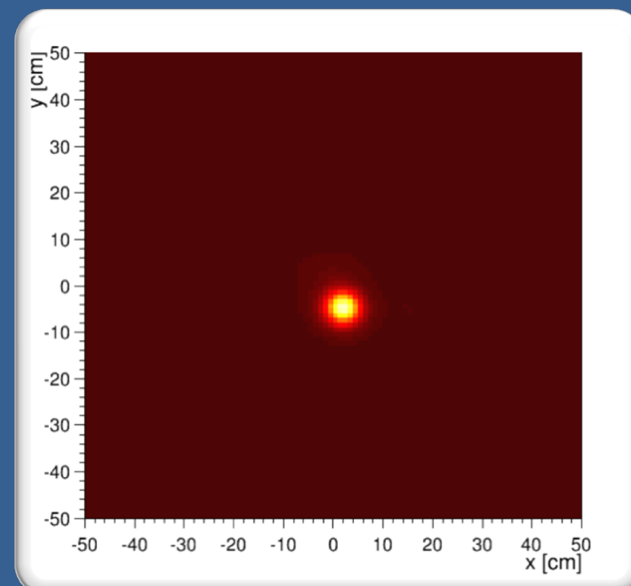
M. Amman *(LBNL)*

P. Jean, P. von Ballmoos *(IRAP, France)*

H.-K. Chang, C.-Y. Yang, J.-R. Shang, C.-H. Tseng *(NTHU, Taiwan)*,

C.-H. Lin *(AS, Taiwan)*, Y.-H. Chang , Y. Chou *(NCU, Taiwan)*

COSI US is supported through grants by NASA



COSI's "First Light":
Calibration image of a 662 keV ^{137}Cs source ~56 cm above the instrument.

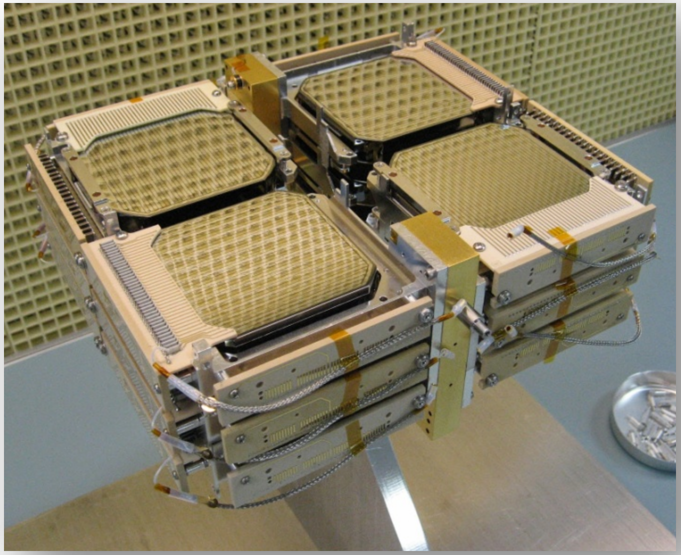
Overview: COSI Instrument & Campaigns

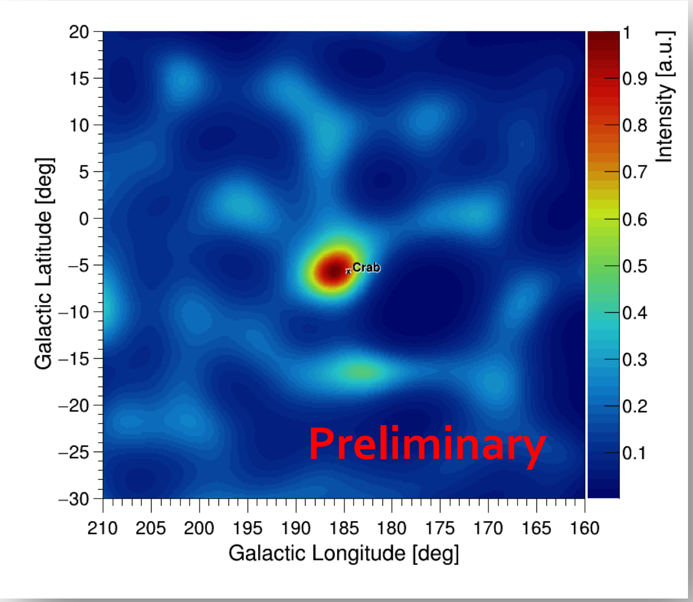
Instrument

- Balloon-borne Compton telescope
- Energy range: 0.2 – several MeV
- 12 high-purity Ge double-sided strip detectors, 2 mm strip pitch
- Energy resolution: 1.5-3.0 keV FWHM
- Depth resolution: ~0.5 mm FWHM
- Angular resolution: up to ~4° FWHM
- Large field-of-view: almost 1/4 of sky

Balloon campaigns

- NCT: 2 GeD prototype, Ft. Sumner, 2005
- NCT: 38-hour flight of 10 GeD instrument , Ft. Sumner, 2009
- NCT: Failed launch attempt from Alice Springs, Australia, 2010
- COSI: 1.5-day flight from McMurdo, 2014
- COSI: 46-day flight from Wanaka, New Zealand on super-pressure balloon, 2016

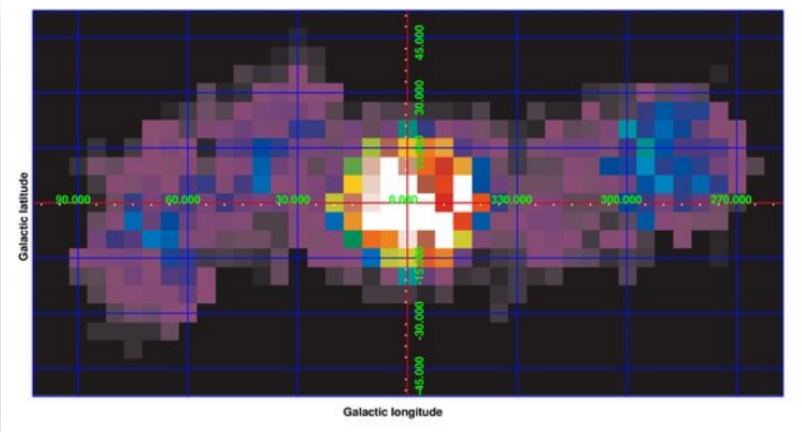




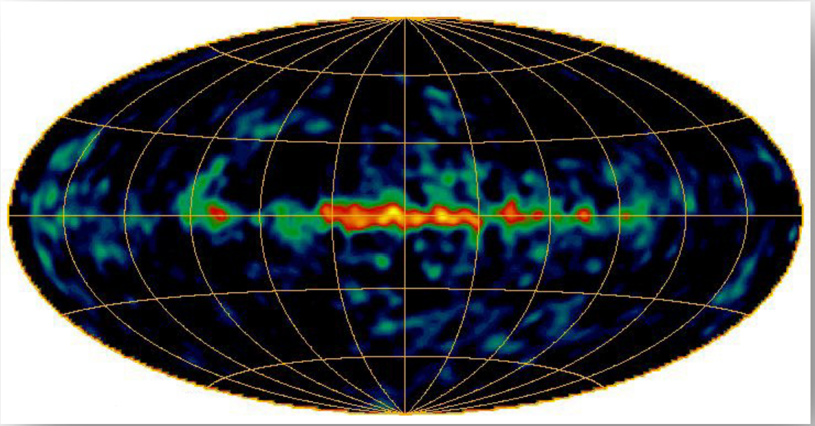
Overview: COSI Science Goals

Subset of all MeV goals is accessible via a small balloon:

- Polarimetry of Gamma-ray Bursts (GRBs), pulsars, X-ray binaries, and AGN
- Map 511-keV positron annihilation emission near the Galactic Center
- Studies of Galactic radioactivity: lines from stellar and supernova nucleosynthesis (^{26}Al, ^{60}Fe, ^{44}Ti)



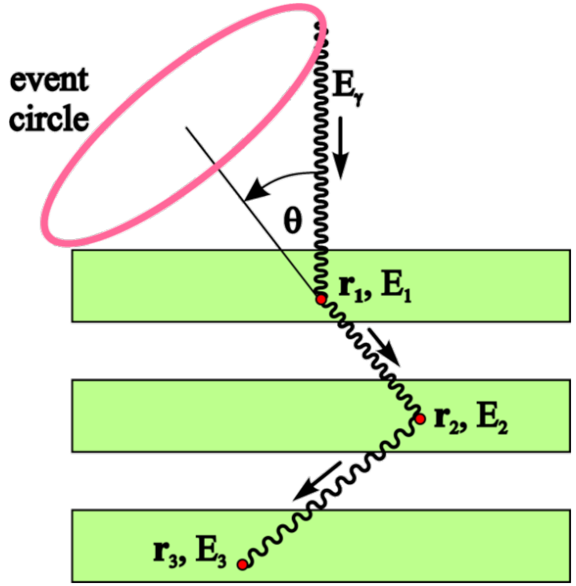
INTEGRAL/SPI Galactic center map of the positron annihilation radiation (0.511 MeV) *(Bouchet et al. 2010)*

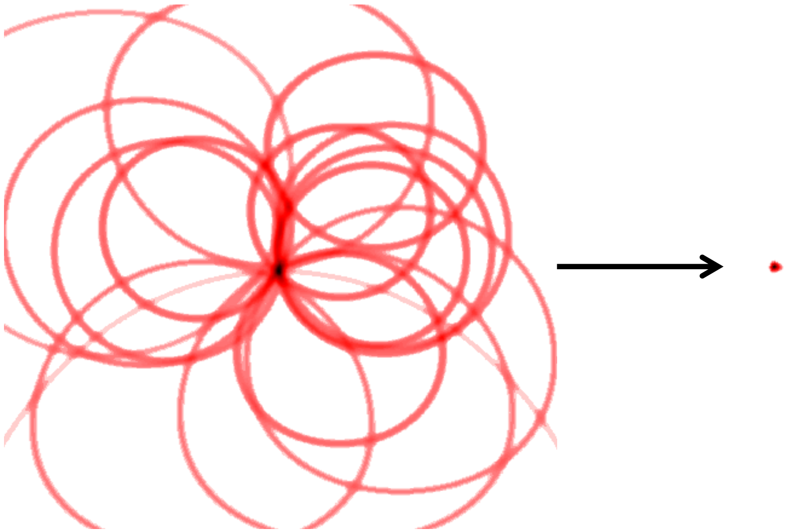


COMPTEL map of ^{26}Al emission (1.809 MeV) *(Oberlack et al. 1997)*

Operating Principle

of COSI-style Compton telescopes

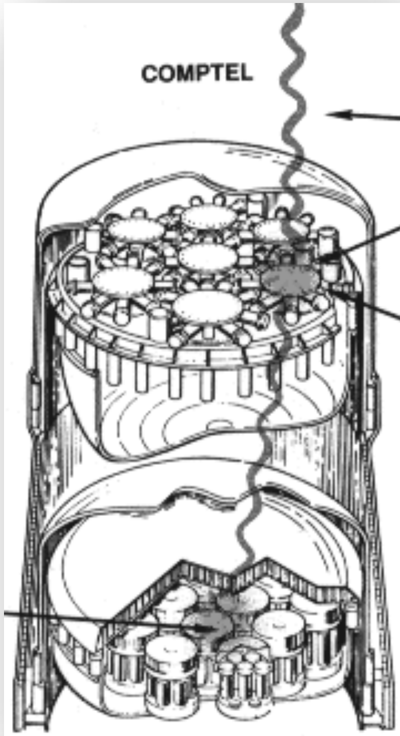




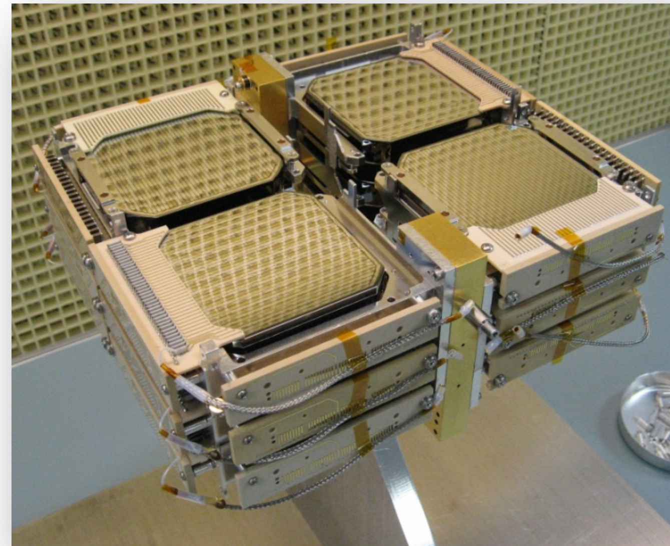
- Photons interact multiple times in active detector (here: Ge).
- The interaction sequence can be determined from information such as scatter angles, absorption probabilities, scatter probabilities.
- The origin of a single not-tracked event can be restricted to the so called “event circle”.
- The photon originated at the point of all overlap.
- Deconvolve to obtain skymaps.

Compton Telescopes: From COMPTEL to COSI

1.5 m



30+ years development



CGRO/COMPTEL:

- ~40 cm^3 resolution
- ΔE/E ~10%
- Up to 0.4% efficiency
- ToF background rejection

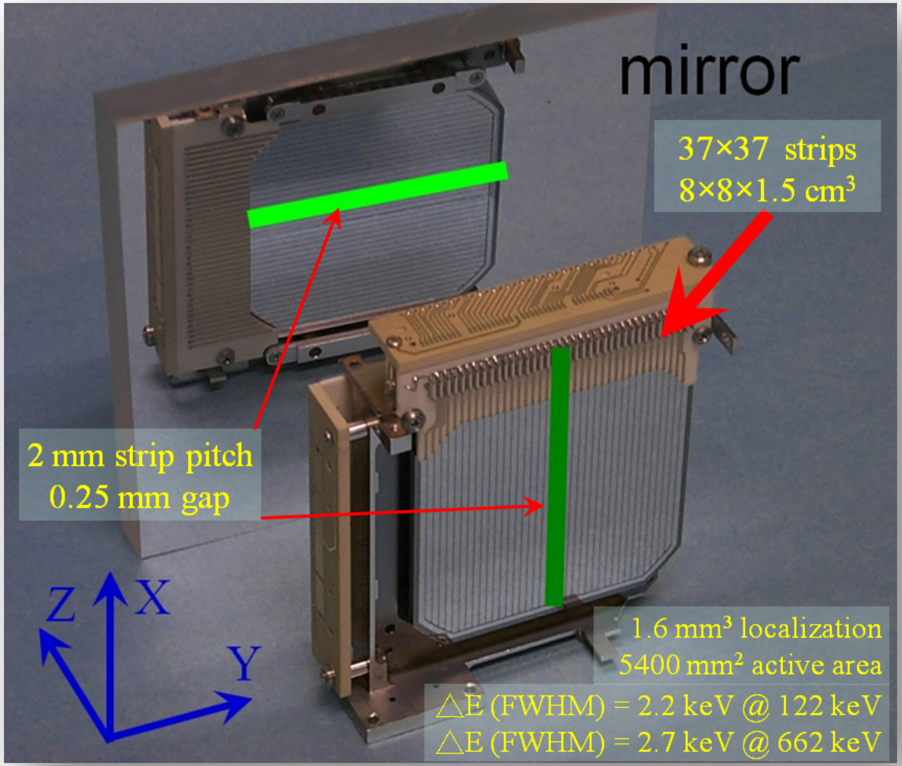
COSI:

- 2 mm^3 resolution
- ΔE/E ~0.2-1%
- Up to 16% efficiency
- Multi-mode background suppression & rejection
- polarization

➢ Improved performance with a fraction of the mass and volume

The Germanium Detectors

- Size: 8 x 8 x 1.5 cm^3
- 37 orthogonal strips per side
- 2 mm strip pitch
- Operated as fully-depleted p-i-n junctions
- a-Ge and a-Si surface layers
- Excellent spectral resolution: 1.5 – 3 keV FWHM
- Excellent depth resolution: 0.5 mm FWHM
- 12 are integrated in the COSI cryostat



The Detector Head

2x2x3 detector geometry

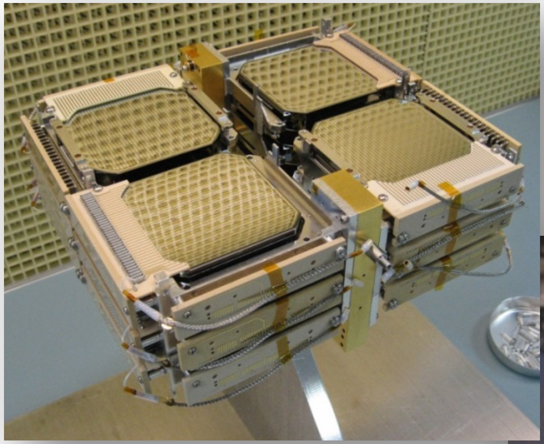
- Wide field-of-view,
- Good polarimetry

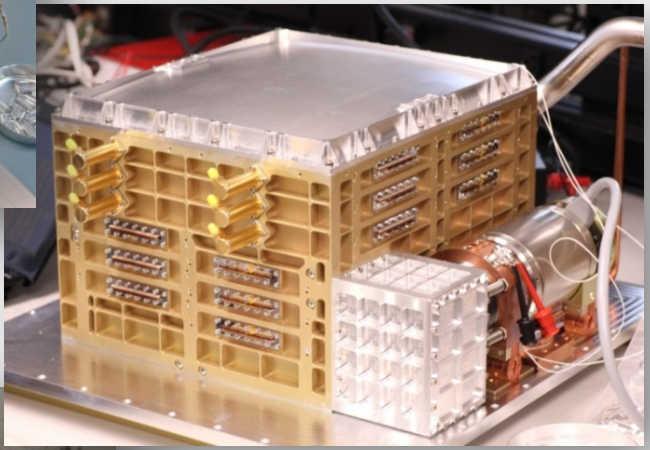
Cryostat & mechanical cooler

- Constant temperatures
- Enables ULDB flights

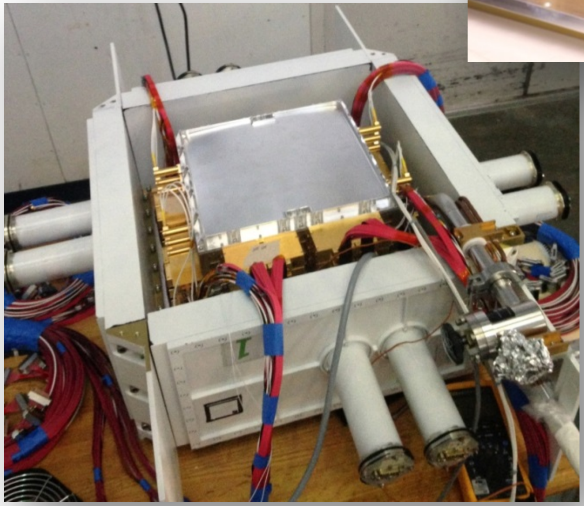
CsI shielding:

- Veto dominating atmospheric background components
- Read out by PMTs

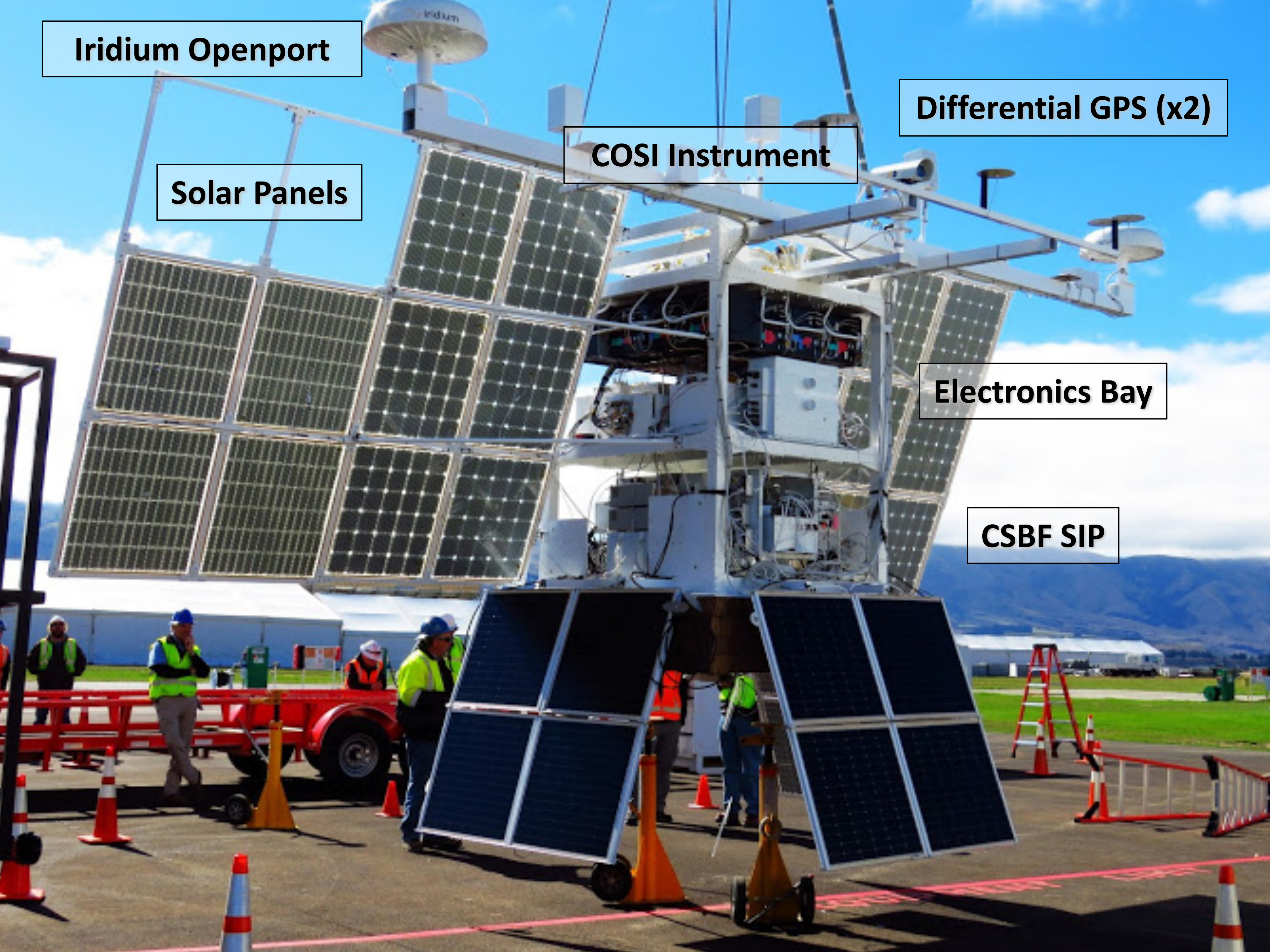




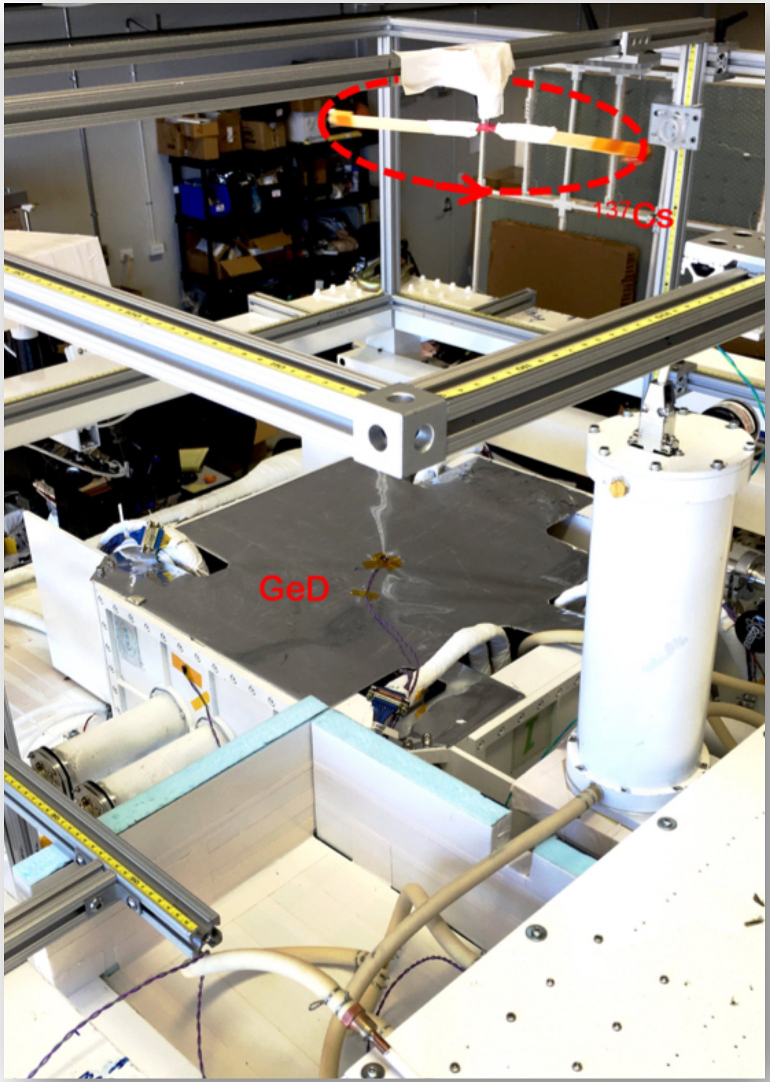
Sunpower CryoTel 10 W lift for 160 W input



Detector surrounded by (white) CsI shield read out by conventional photo multipliers


Iridium Openport
Differential GPS (x2)
COSI Instrument
Solar Panels
Electronics Bay
CSBF SIP

Calibration: Diffuse Imaging Test



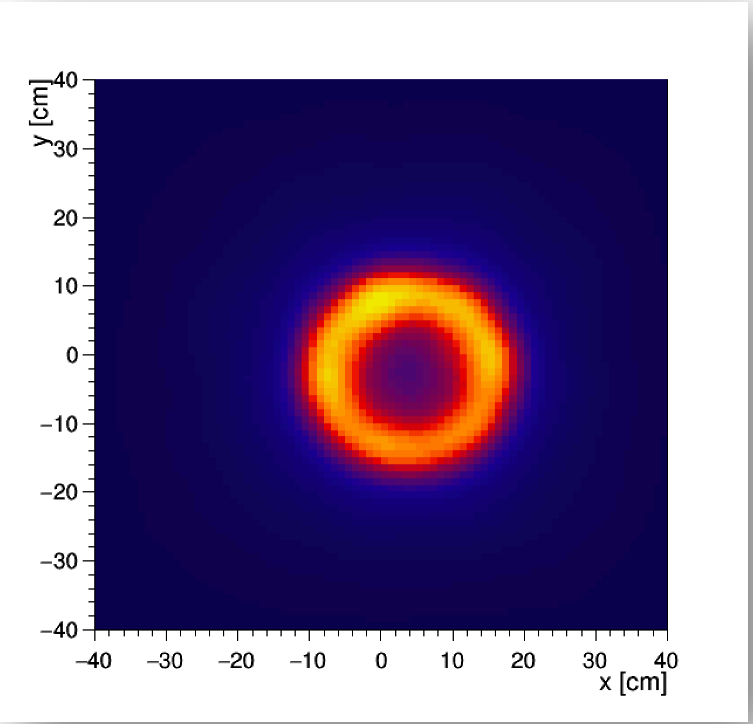
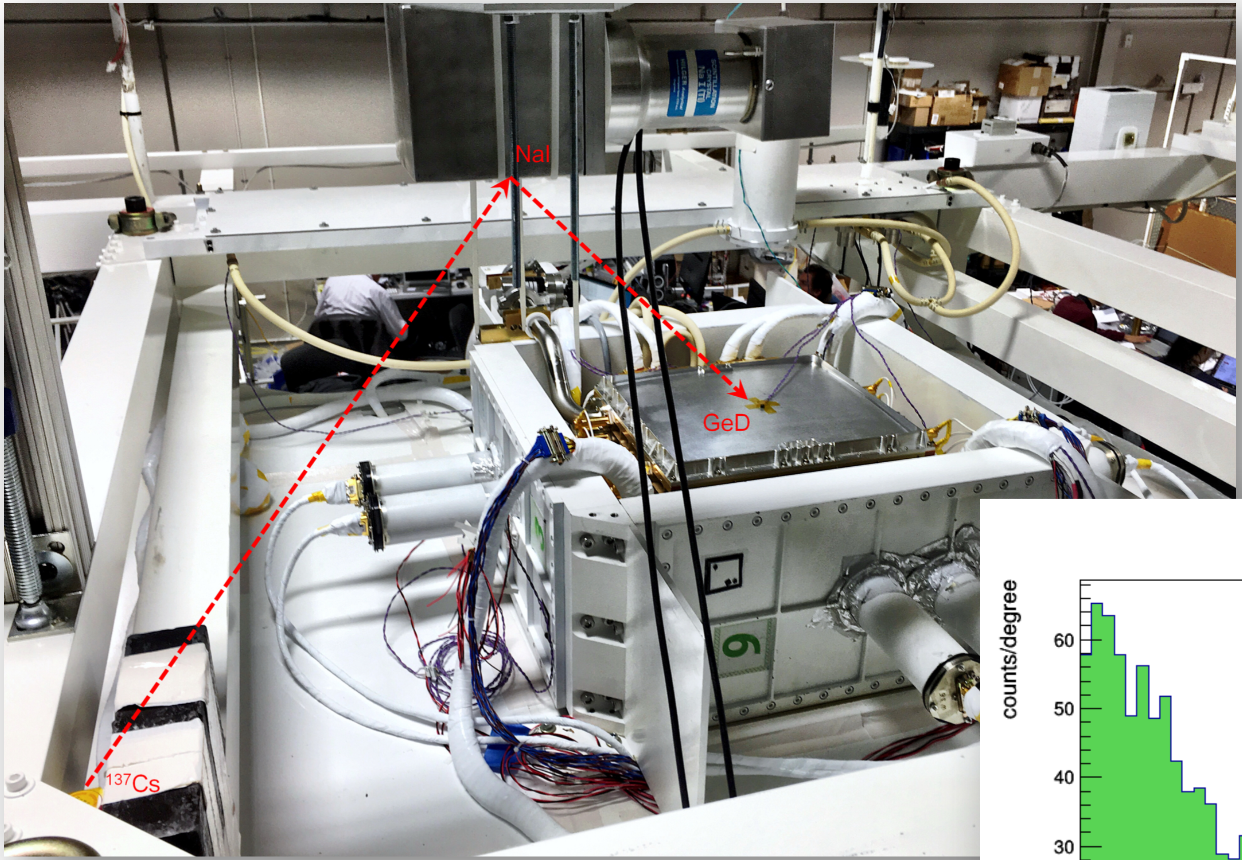


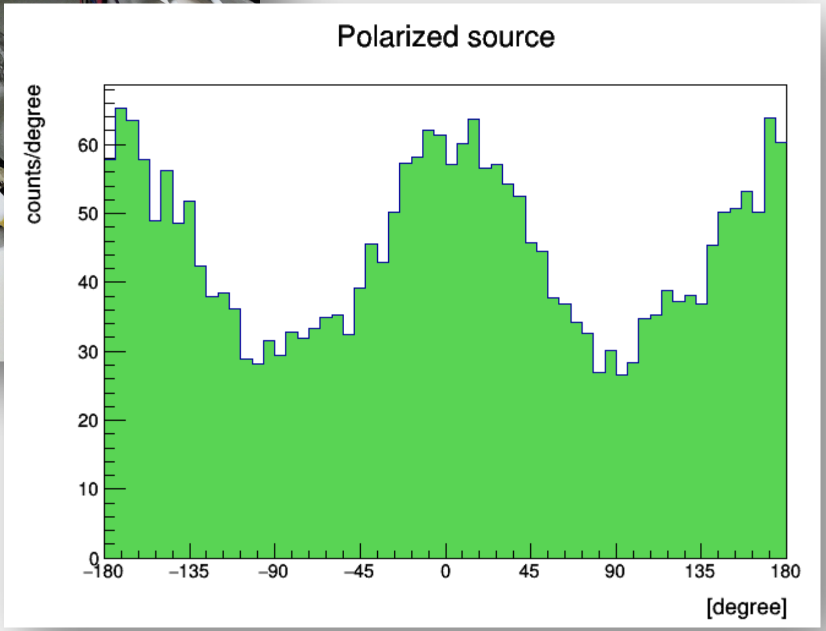
Image of a ^{137}Cs source on a rotor

Calibration: Polarization

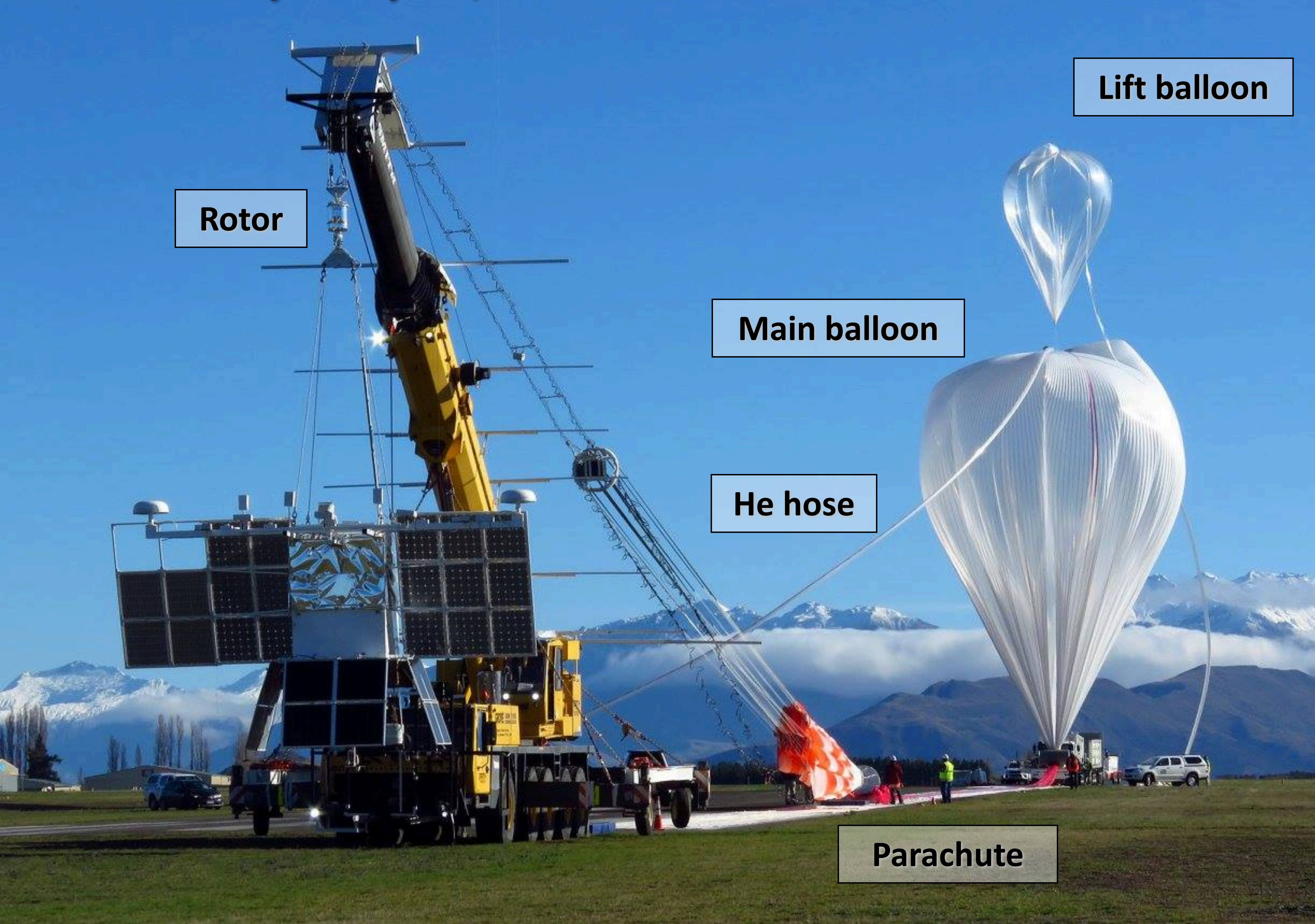


^{137}Cs gamma rays scatter off NaI detector (active detector for coincidence) as thus have preferred polarization angle.

The photons Compton scatter a second time in the Germanium detectors, and their polarization is detected as a sinusoidal modulation of the azimuthal scatter angle.

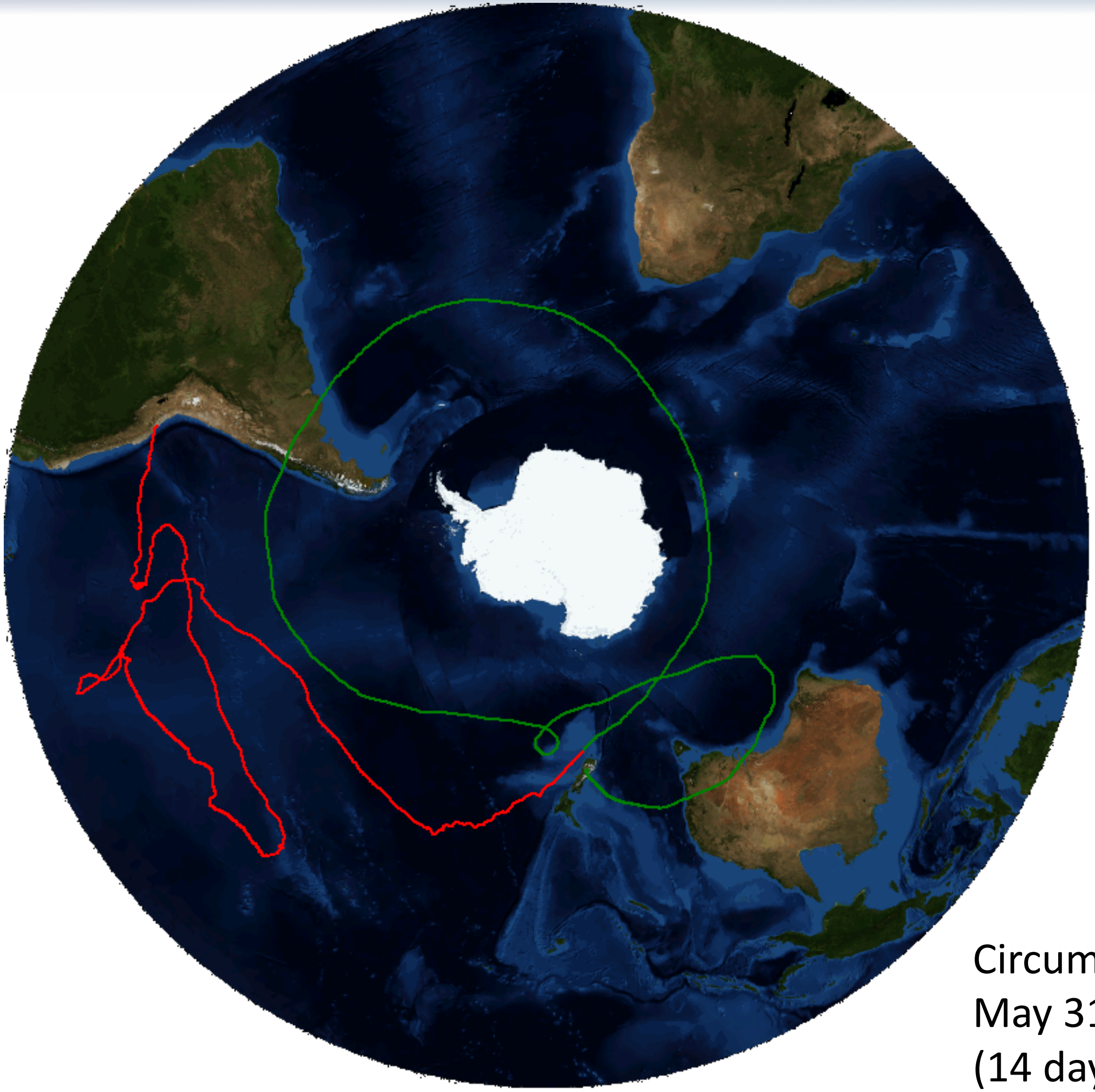


Launch Day: May 16, 2016



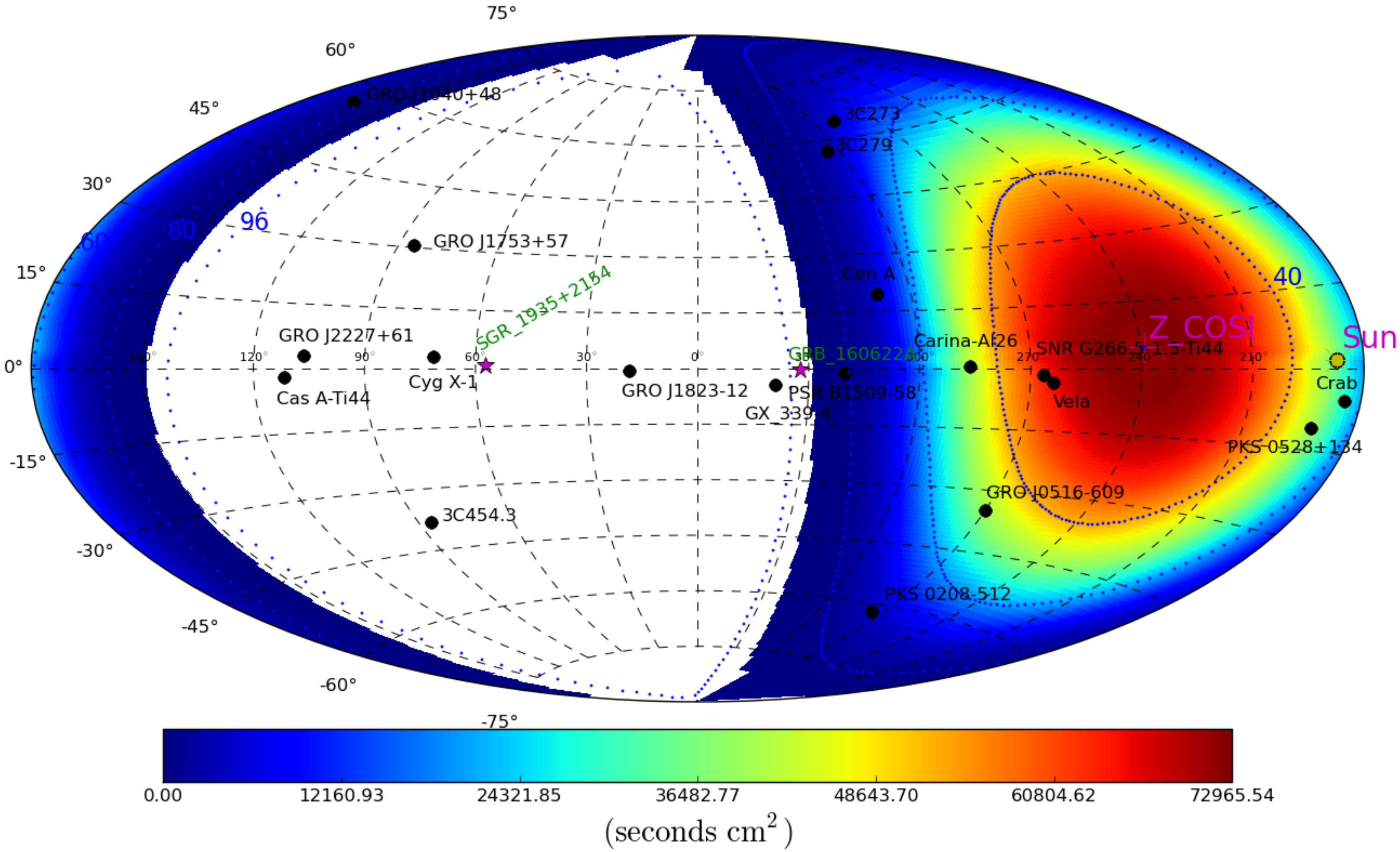
Flight Path

Landed in Atacama desert in Peru on July 2 (46 day flight)

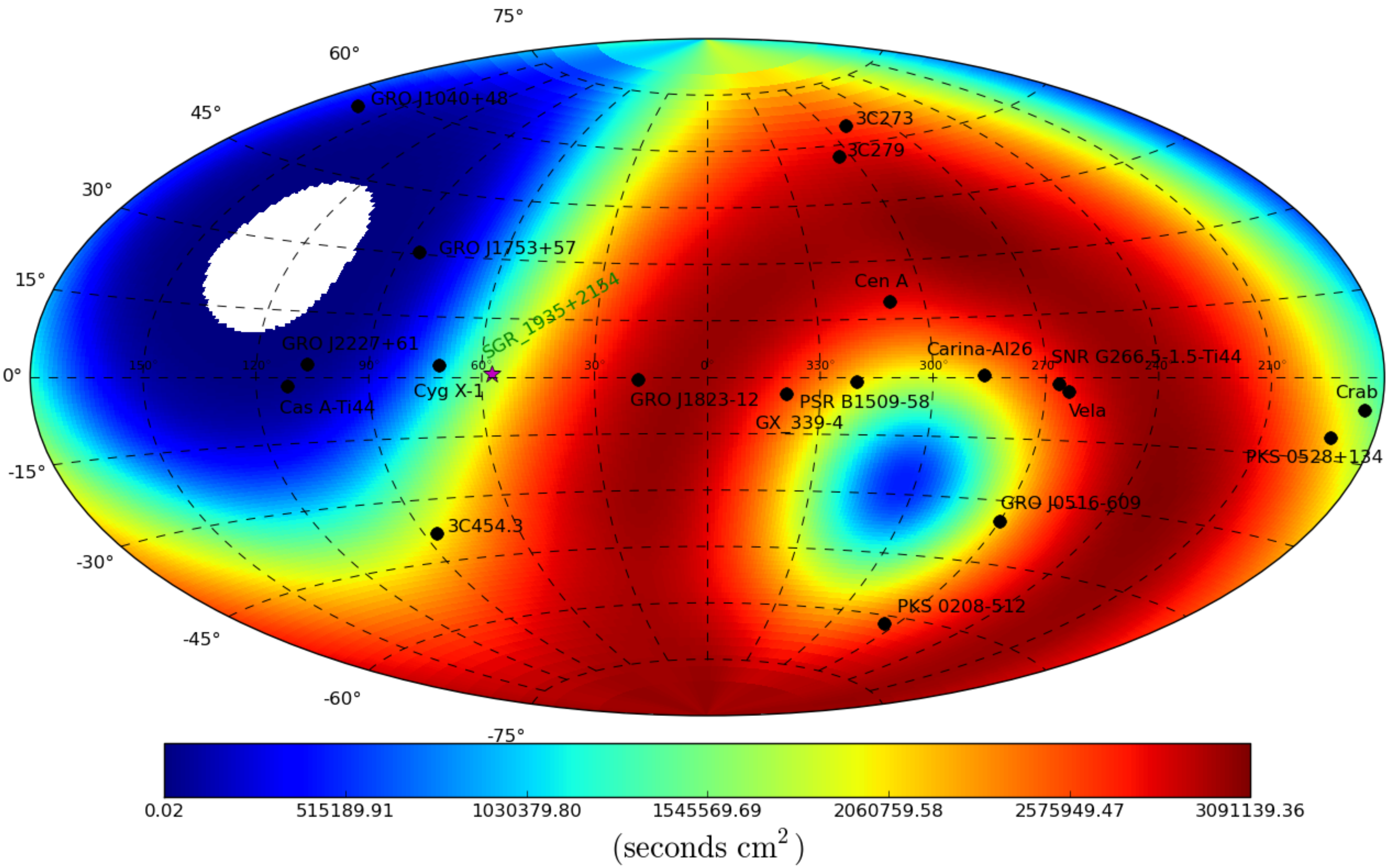


Circum-navigation on May 31 (14 days after launch)

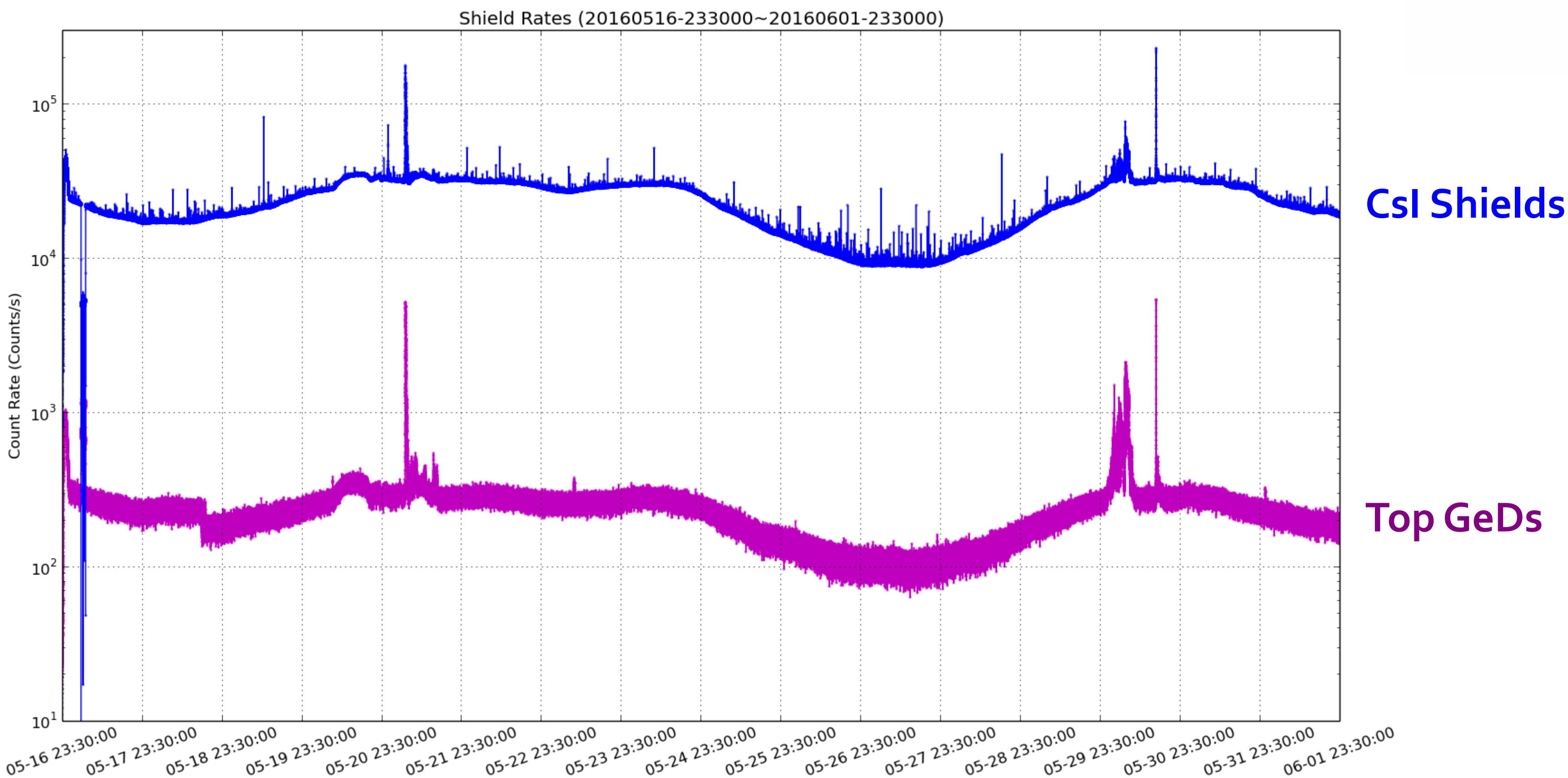
Field of View



Daily Exposure

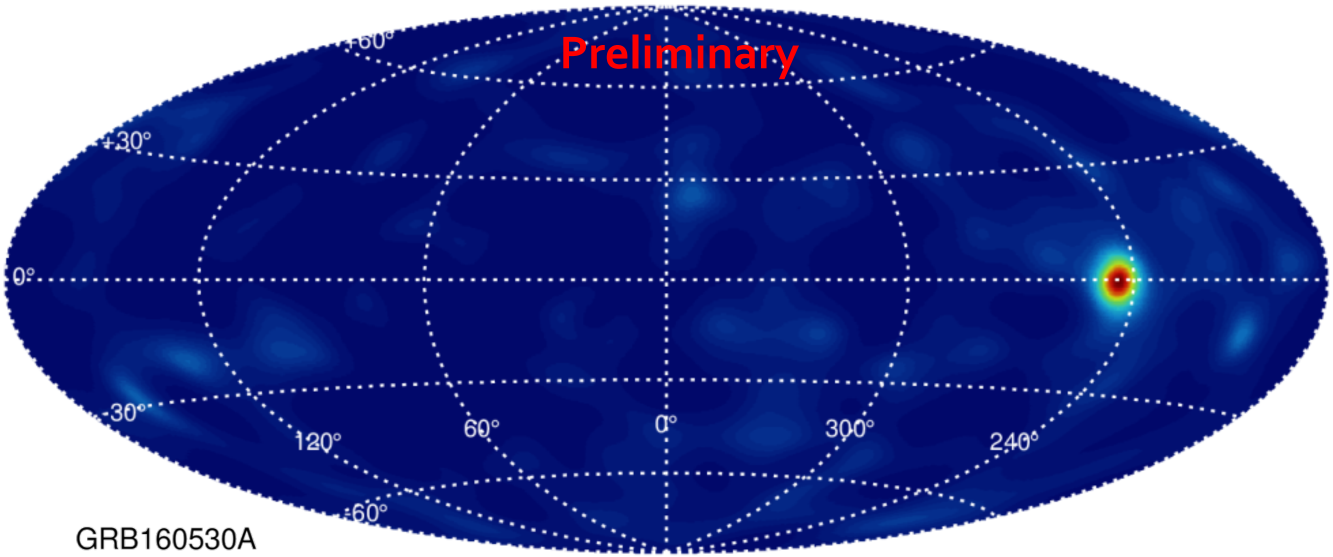


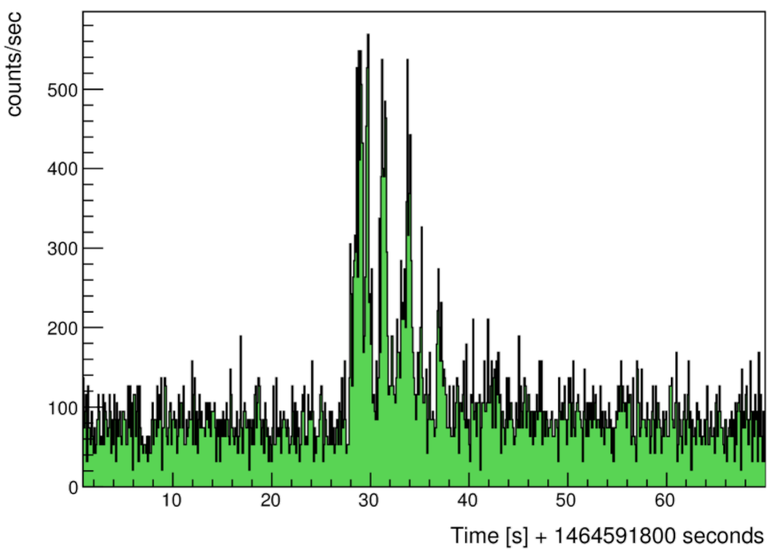
Shield and GeD Rates – 1st Two Weeks



- Long-term fluctuations due to distance from magnetic south pole
- Relativistic electron precipitation events on 5/21 and 5/30
- GRB 160530A during relatively high background

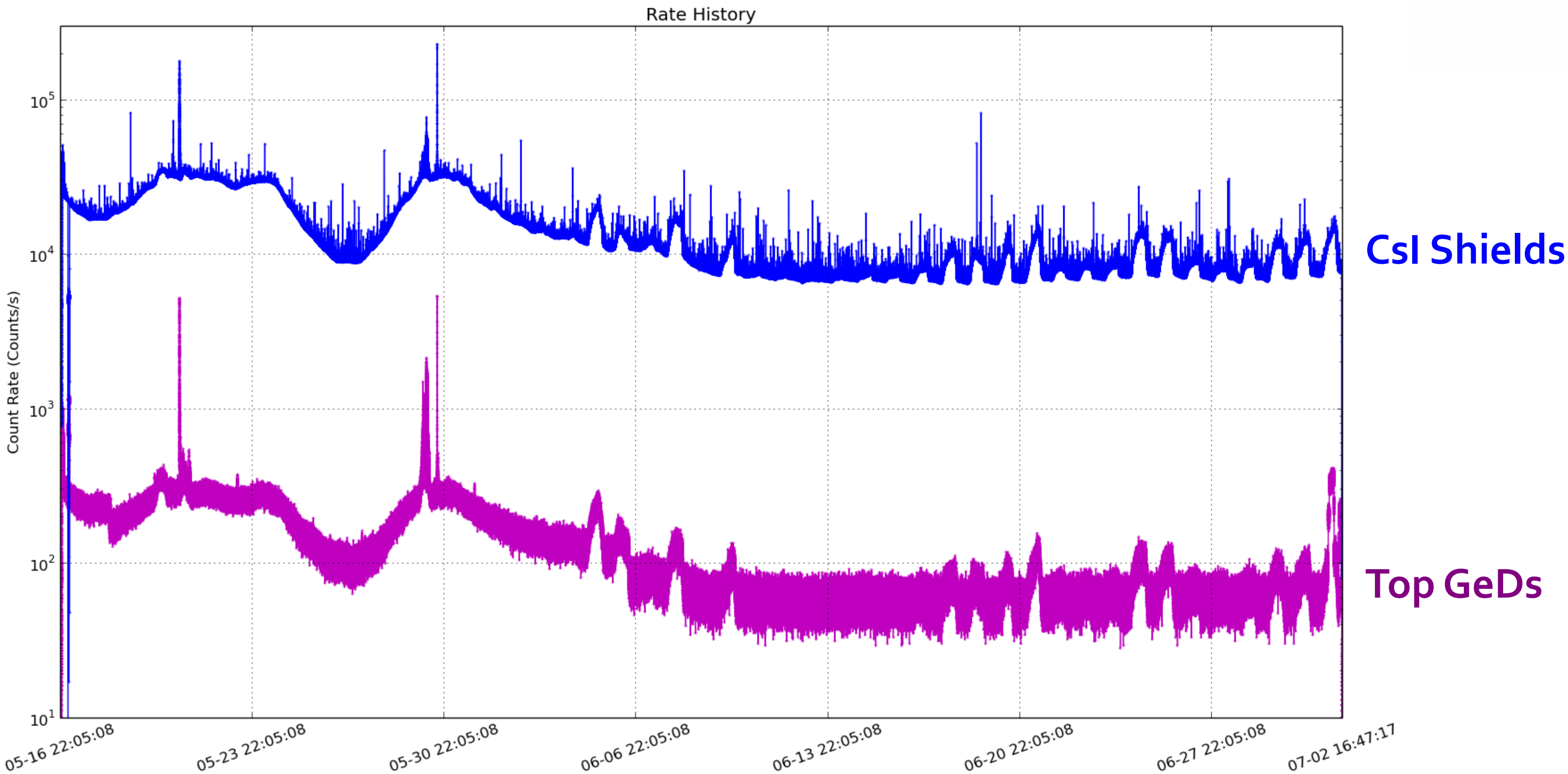
GRB 160530A





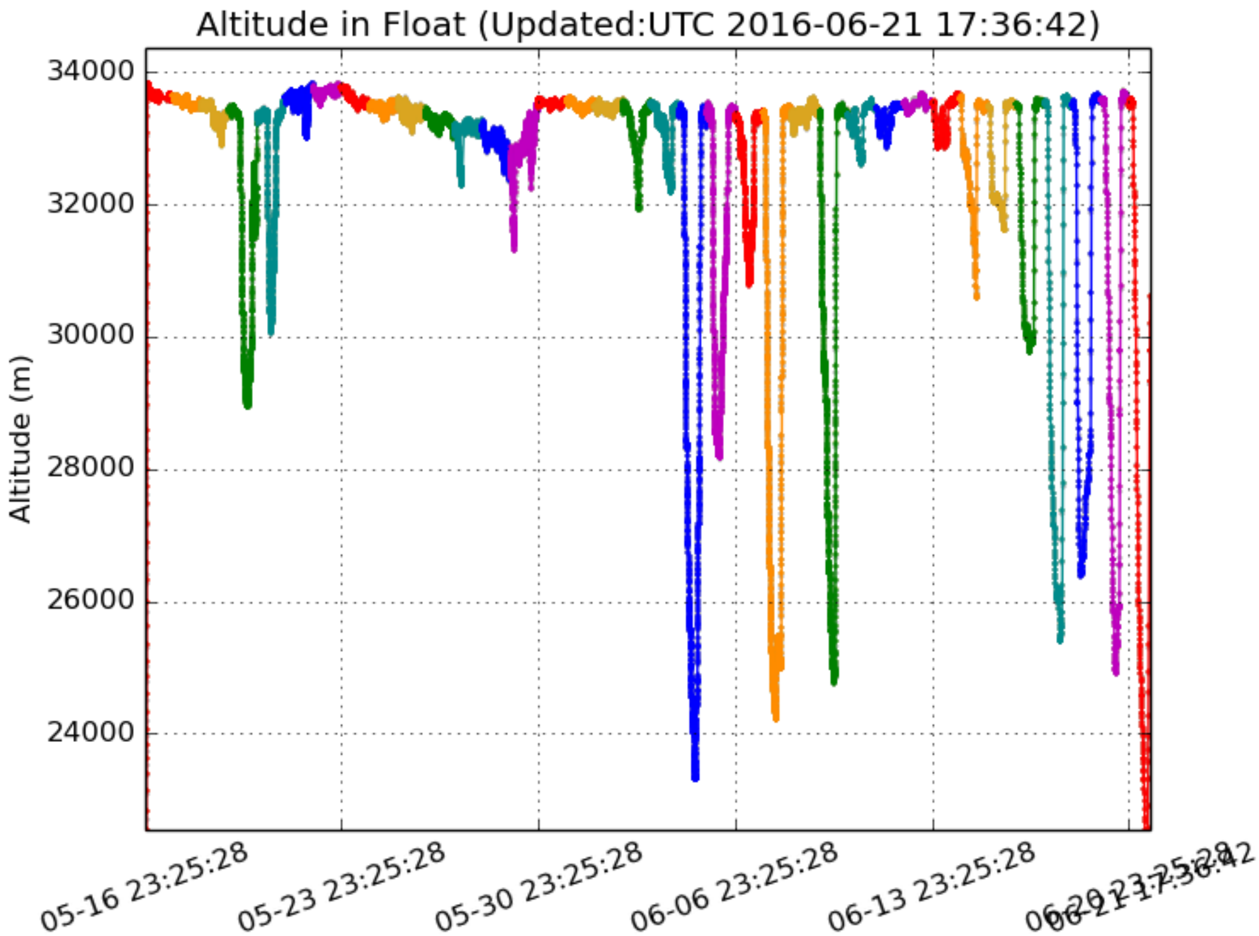
Polarization analysis happening now with new maximum-likelihood analysis technique (Alex Lowell et al., in prep.)

Shield and GeD Rates – Full 46 Days



- As we drifted North, the background dropped, and Crab and Cyg X-1 came into our field-of-view
- Day/night oscillations started around 6/4 (due to altitude variations)

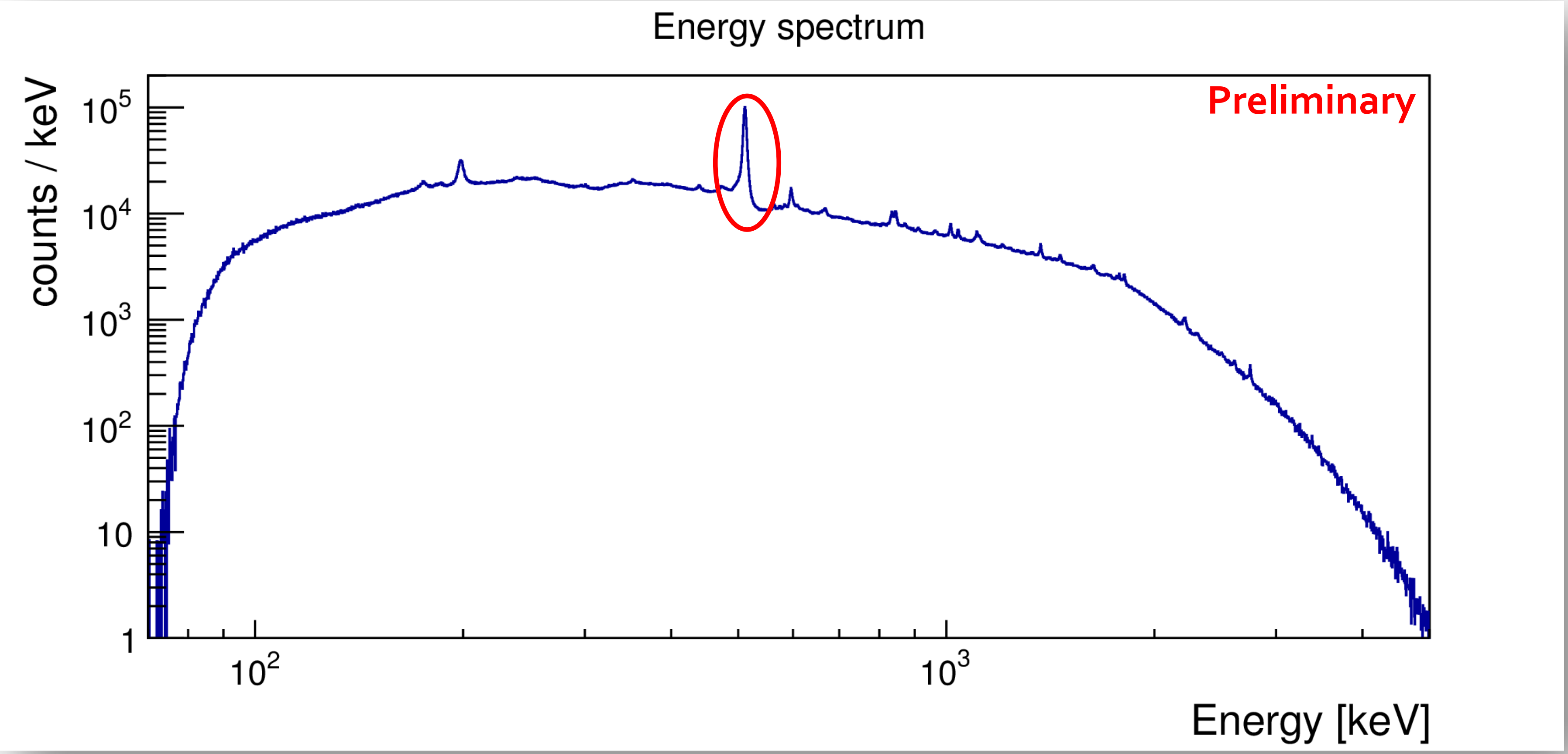
Altitude Profile



Night-time dips:

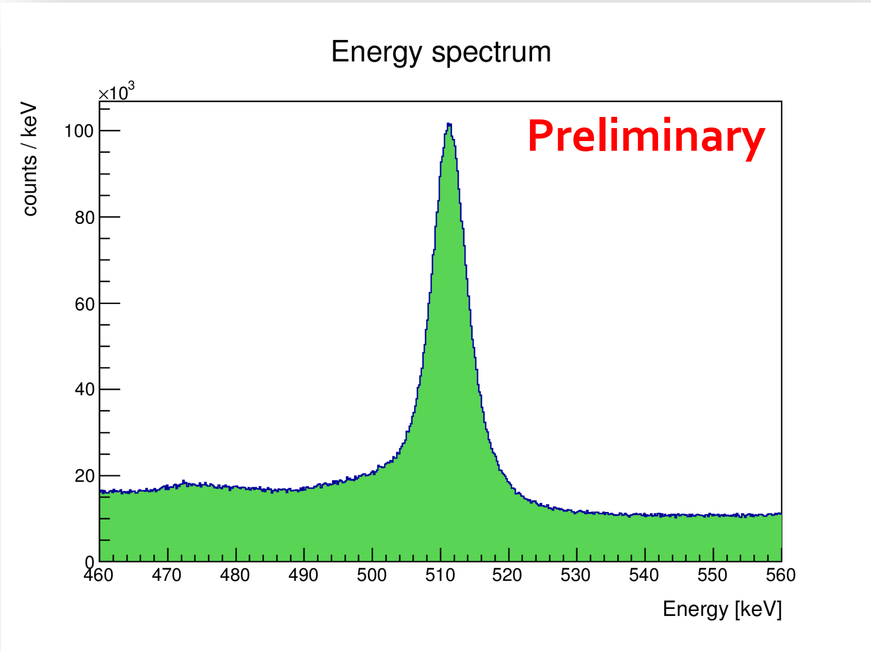
Unfortunately during the times when the Galactic Center was visible…

Measured Compton Spectrum

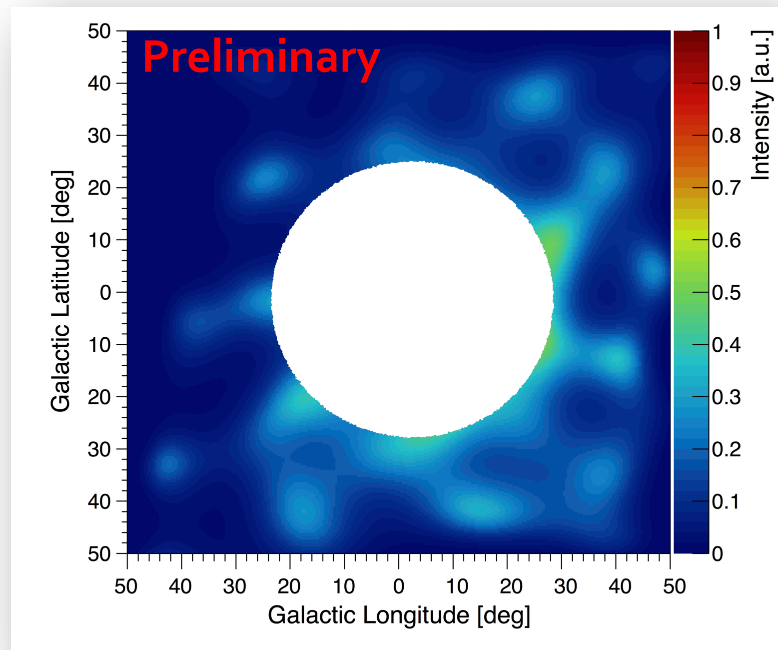


- Still working on temperature-depended energy calibration
- Strongest line is 511-kev line

511-keV Annihilation Line



- Analysis of 511-keV line is work in progress (PhD thesis of Carolyn Kierans)
- We do see clear 511-keV signature in spectrum and image
- Some differences to SPI in image…

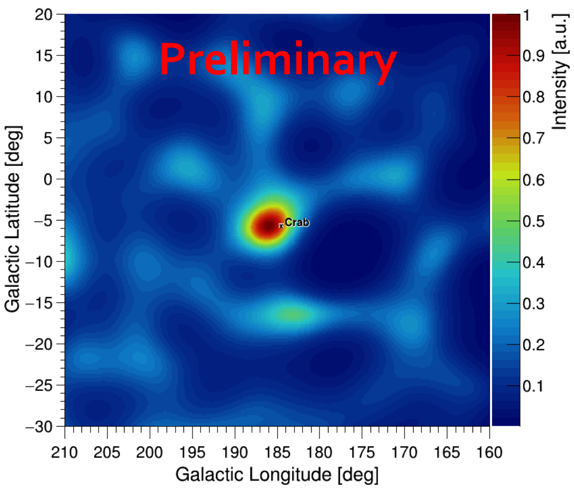


Contributions to annihilation peak:

- Atmospheric 511-keV photons
- Internal beta+-decays + annihilation
- Annihilation of atmospheric positrons
- A few Galactic 511-keV photons

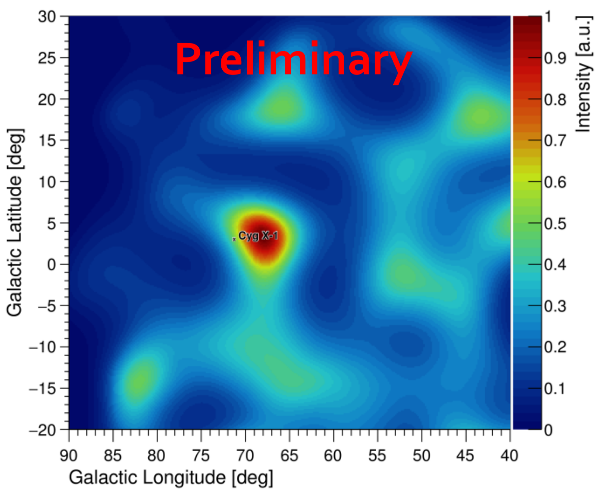
Obvious Point Sources

Crab
(pulsar wind nebula)



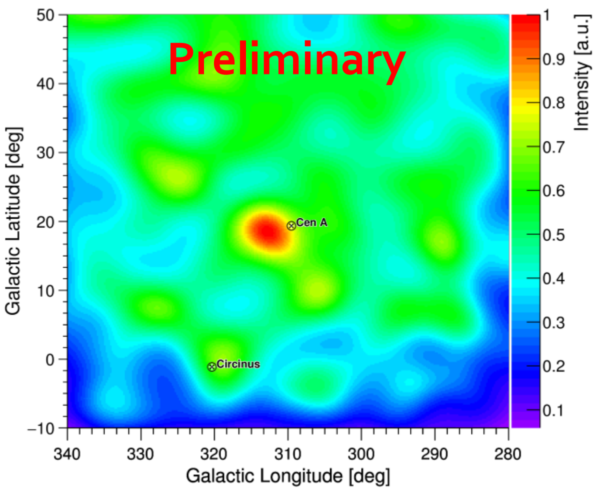
Best 2 days of data

Cyg X-1
(Galactic black hole)



~3 days within field-of-view

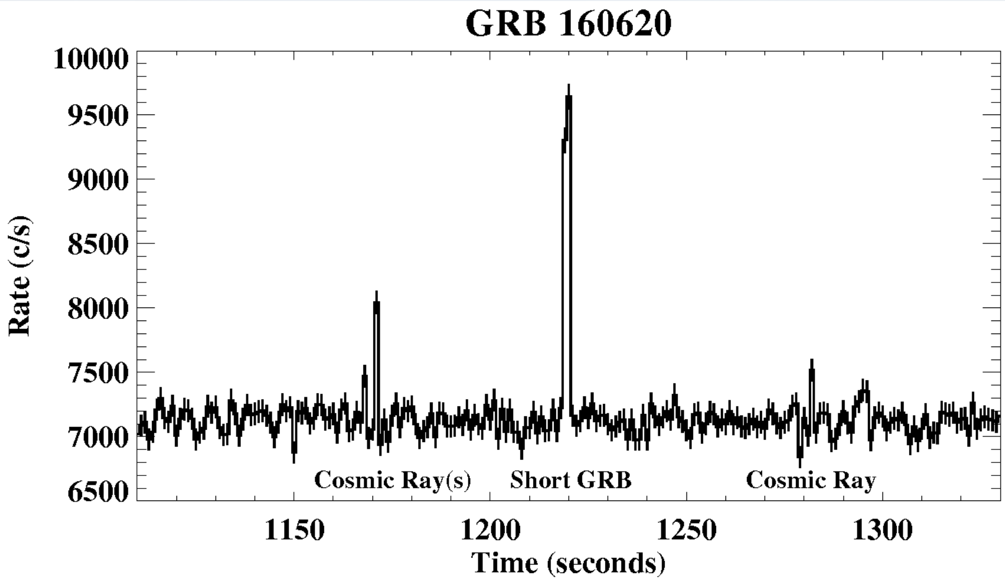
Cen A
(closest AGN)

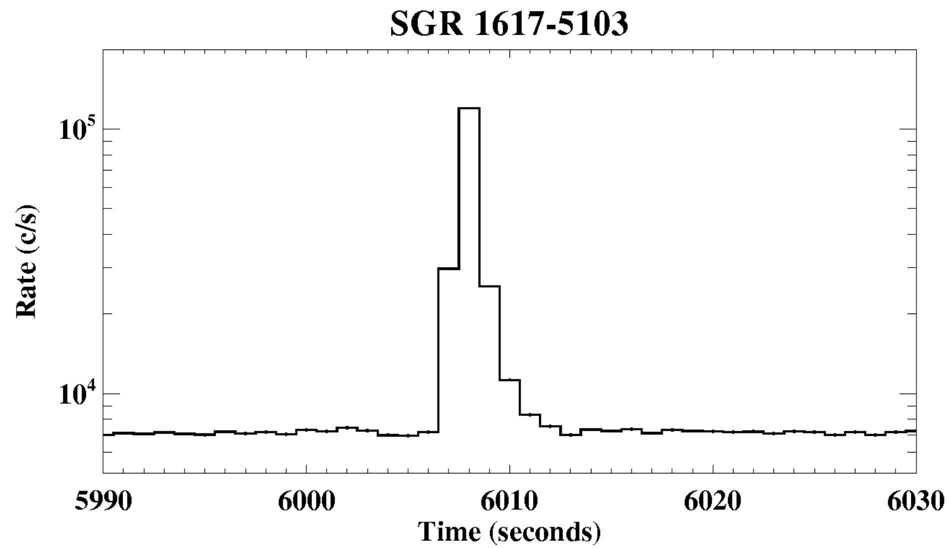


8 days of data

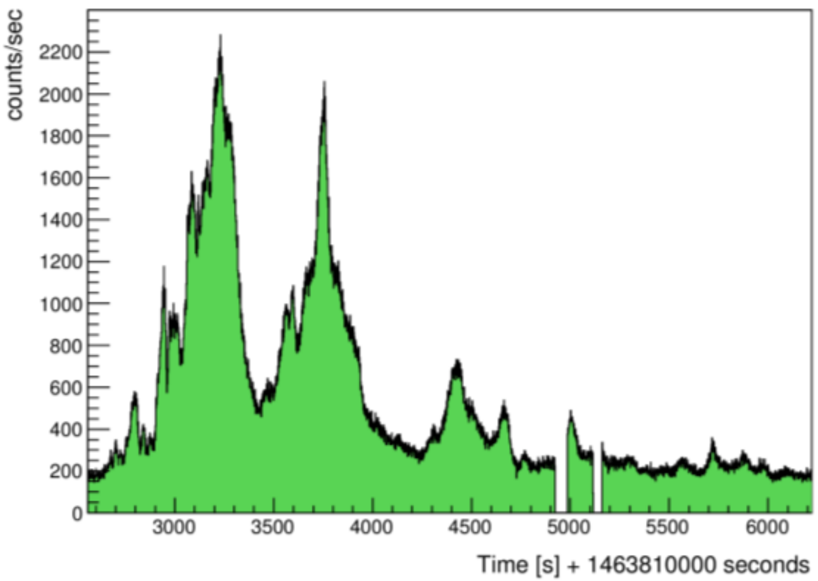
CsI Shields Events

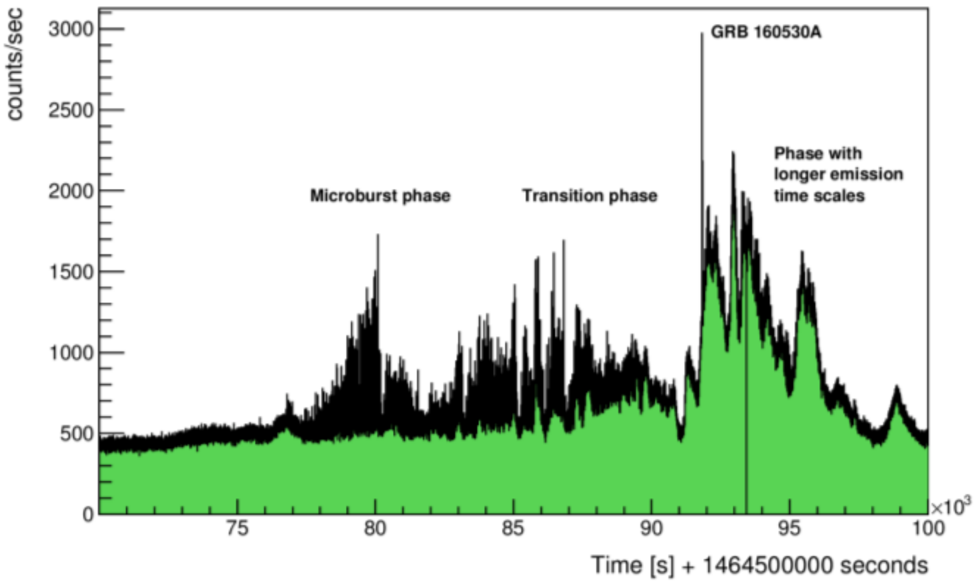
- Cosmic ray events
  - single (1 sec) time bin events
  - ~1 per minute
- Several confirmed GRBs
- Soft Gamma-ray Repeaters
  - SGR 1935+2154
  - SGR 1617-5103





Relativistic Electron Precipitation





- Relativistic electrons from the radiation belt hit the atmosphere and generate Bremsstrahlung emission
- COSI for the first time was able to image the gamma-ray emission

Payload Recovery

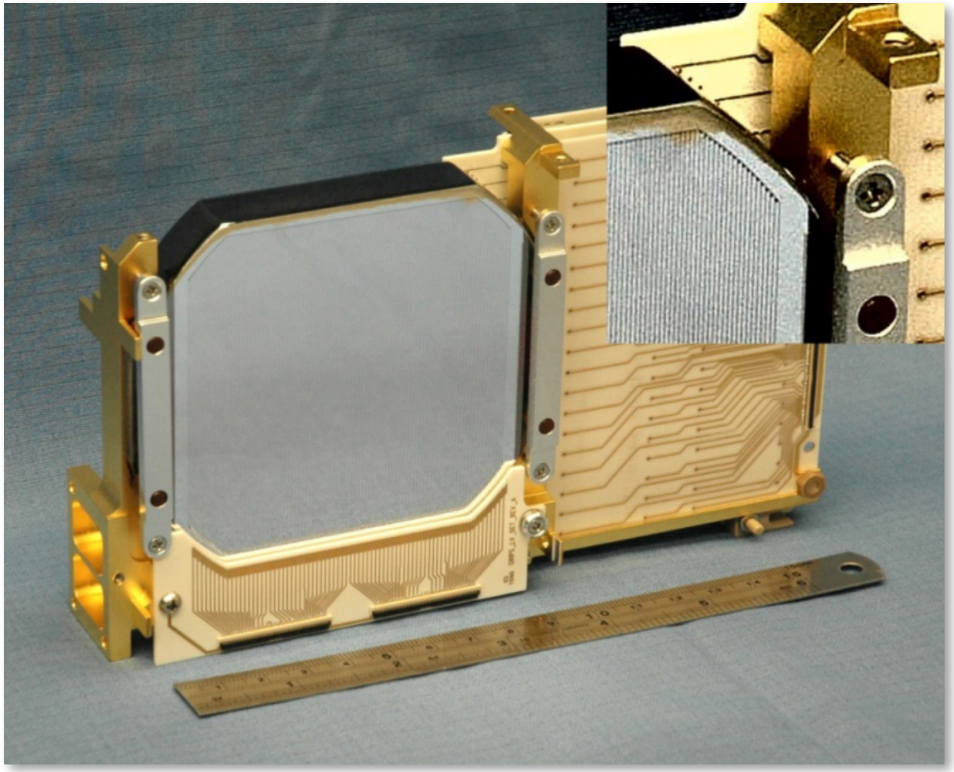
- Found in one piece in remote location in Atacama desert, Peru
- COSI detector back home and fully operational
- Gondola and electronics *still* waiting for customs clearance in Peru….

Work in Progress on the 2016 Data

- Working on data-analysis improvements, simulation-data-matching (required for final response), background rejection, etc.
- Crab & Cyg X1 analysis and thus detector-effects engine, response, and data analysis pipeline verification (Clio Sleator's PhD thesis)
- GRB 160530A polarization (Alex Lowell's PhD thesis)
- Spectrum & image of 511-keV emission from the Galactic Center region (Carolyn Kierans' PhD thesis)
- Other point sources (Alan Chiu)
- Galactic diffuse emission (Andreas)
- REP and microburst analysis (Andreas)

Wish List for Future Flights

- Finer strip pitch (0.5 mm): improve angular resolution (up to ~1.6 degrees) and overall sensitivity
- ASIC read-out: enable finer strip pitch, lower power, less weight (with E. Wulf, NRL)
- Cryocooler: active damping to lower noise
- Better shielding: No gaps on side and bottom, side walls higher up (i.e. really restrict FoV to 1π)



GRIPS Germanium detector

MEGAlib

„Medium-Energy Gamma-ray Astronomy library“

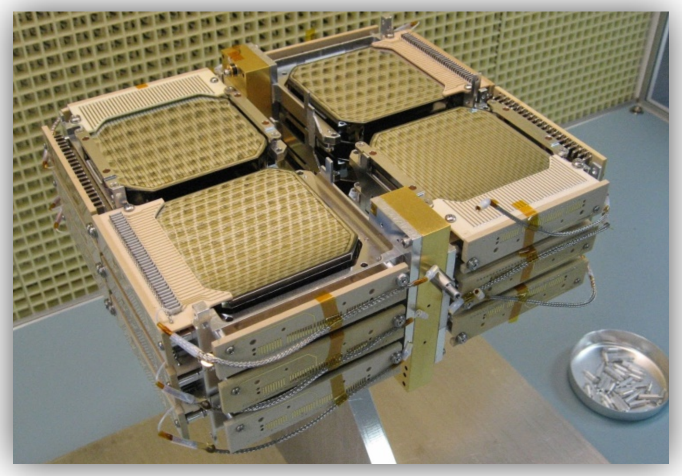
Provides calibration, simulation & data analysis tools for hard X-ray and soft-to-medium-energy gamma-ray detectors/cameras/telescopes

Its flexible design allows its easy application to different projects and missions, such as MEGA, ACT, NCT, COSI, COMPTEL, GRI, GRIPS, NuSTAR,Hitomi, (e)AstroGam, ComPair/AMEGO, hadron therapy monitoring, X-FEL detectors, HEMI, ARES, and many more!

MEGAlib is completely object-oriented, open-source, written in C++, and utilizes ROOT and Geant4

http://megalibtoolkit.com

MEGA prototype (Si-tracker & CsI Compton telescope)



COSI – balloone-borne Germanium Compton telescope

MEGAlib Overview

Generation

Measurements

Universal calibration framework: Fretalon

Universal simulator: Cosima (Geant4-based)

Data is assembled as times, positions & energies

Pre-Analysis

Event identification, quality assessment, background identification: Revan

Response generation for analysis: ResponseCreator & Sivan

Data consists of Compton events, pair events, etc.

Analysis

Image deconvolution

Event selection optimization

Spectral analysis

Automated performance analysis

and more…

Foundation: geometry tool, detector effects engine, response description, etc.

MEGAlib Updates for COSI / AMEGO

Special branches in repository: https://github.com/zoglauer/megalib

- megalib_v2.xy
  - Normal MEGAlib releases
- master
  - Default development branch
  - At the moment restricted to ROOT compatibility and bug fixes
- amego:
  - Same as master but with pair tracking improvements for AMEGO
- experimental:
  - All new developments for COSI 2016
  - Rapid changes thus might not always behave as expected
  - Only 99% backward compatible
  - Will end up as MEGAlib 3.0 when we are done with analysis of 2016 balloon flight

MEGAlib developments for COSI '16

(not everything checked in)

- ✓ Improved calibration framework
- ✓ Event reconstruction: Improved neural network pattern identification and background identification & Improved clustering
- ✓ Responses: improvements for basically all COSI relevant responses plus xspec compatibility for spectrum (by Clio), CASEBALL-binning for everything in spherical coordinates, etc.
- ✓ Imaging updates such as exposure, new 5D response, COMPTEL-data space, etc.
- ✓ Maximum-likelihood polarization analysis (by Alex)
- ✓ Overall much improved automation

Final words…

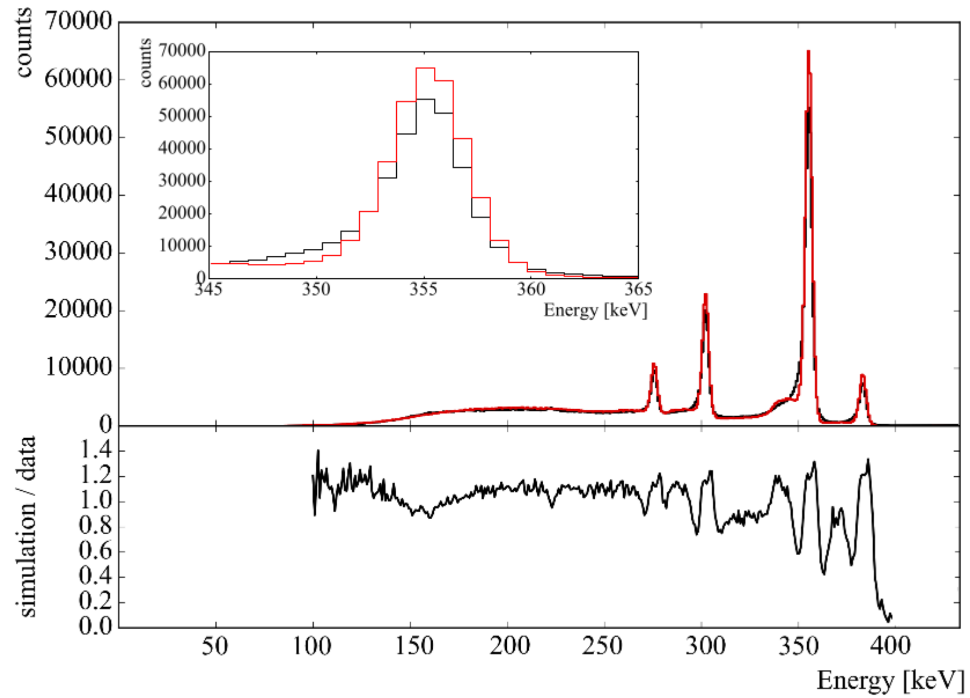
Perform balloon flight with a small proof-of-concept instrument!

You will learn so much more about your Compton detector and all its small and big quirks than with simulations alone. And you will have a large data set to play with afterwards.

Work on good Detector Effects Engine early

Simulations (and the performance estimates) will always be too good until really, really, really all detrimental detector effects are included:

- Perfect mass model
- Energy resolution
- Charge sharing
- Charge loss / Light loss
- Charge trapping
- Depth resolution
- Non working detectors
- Threshold variations
- etc.

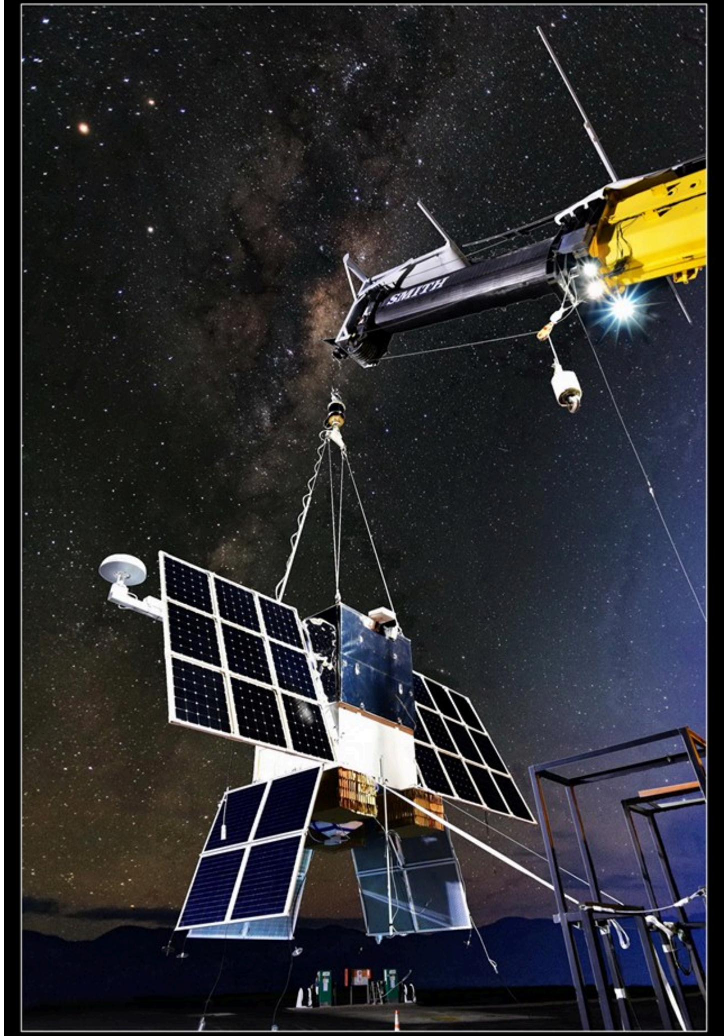


COSI DEE, Sleator+ 2016

It takes a <u>l o n g</u> time to get a good match…

Summary and Conclusions

- Very successful 46 day flight from New Zealand to Peru
- Clear detections of a GRB, Crab, Cyg X-1, Cen A, and Galactic Center
- Detector recovered and in good shape for future flights
- Working on improvements of data analysis tools and data analysis itself



Compton Spectrometer and Imager (COSI) @ Wanaka, New Zealand