The Compton Spectrometer and Imager

Andreas Zoglauer

for the COSI & COSI-X collaborations

UC Berkeley (SSL & BIDS)

COSI Overview

Instrument

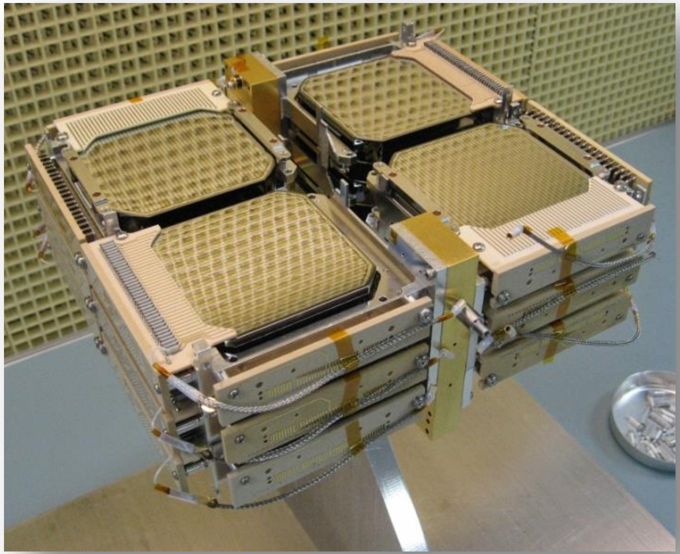
- Balloon-borne Compton telescope
- Energy range: 0.2 – 5.0 MeV
- 12 high-purity Ge double-sided strip detectors with 2 mm strip pitch
- Energy resolution: 1.5-3.0 keV FWHM
- Depth resolution: ~0.5 mm FWHM
- Angular resolution: up to ~4° FWHM
- Large field-of-view: almost 1/4 of full sky

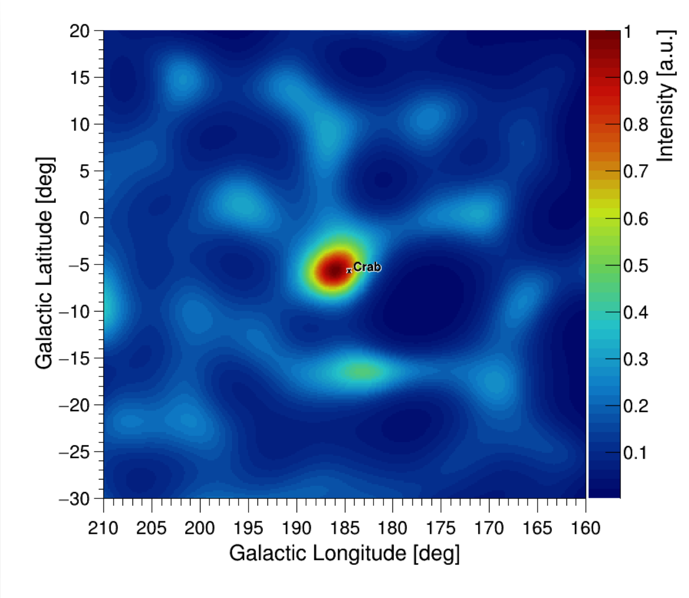
Science Objectives

- Life cycle of (anti-) matter in our Galaxy
- The most violent events and the most extreme environments in our Universe

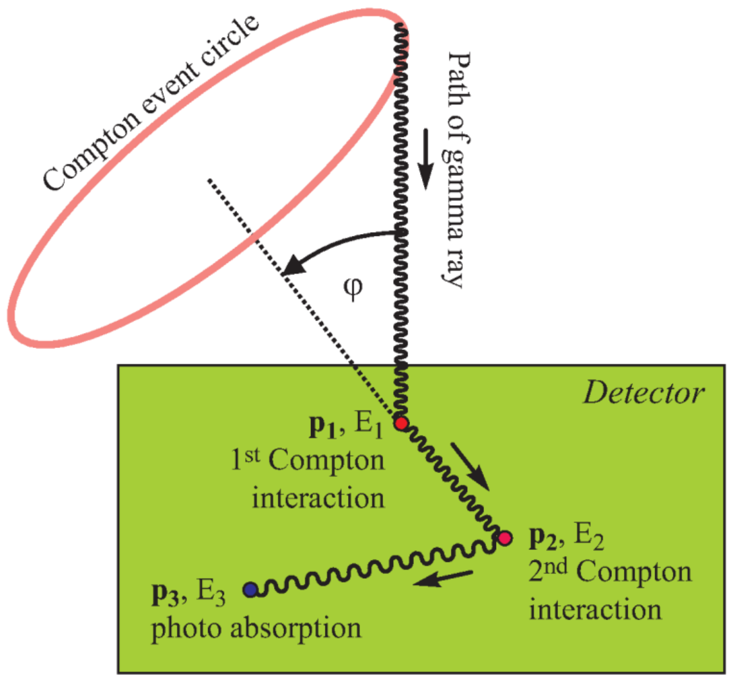
Balloon Campaigns: 5 in total

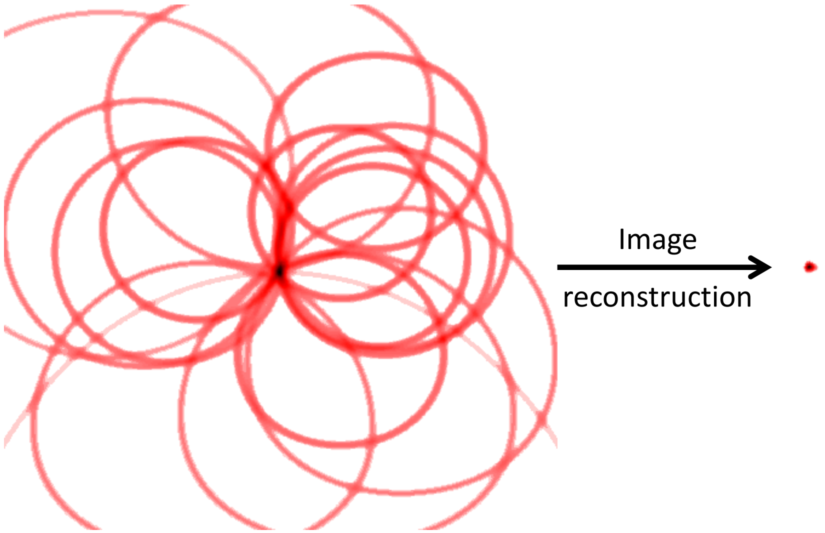
- Last: COSI: 46-day flight from Wanaka, New Zealand, 2016 – 1st science flight of NASA new super-pressure balloon platform
- Next: COSI-2 in 2020 or COSI-X1 in 2022





COSI Overview: Operating Principle





- Photons interact multiple times in active Germanium detectors via Compton scatters
- The interaction sequence has to be determined from information such as scatter angles, absorption probabilities, scatter probabilities
- The origin of a single not-tracked Compton event can be restricted to the so called Compton "event circle"
- The photons originate at the point of all overlap
- Deconvolution creates sky maps

Science with COSI & COSI-X

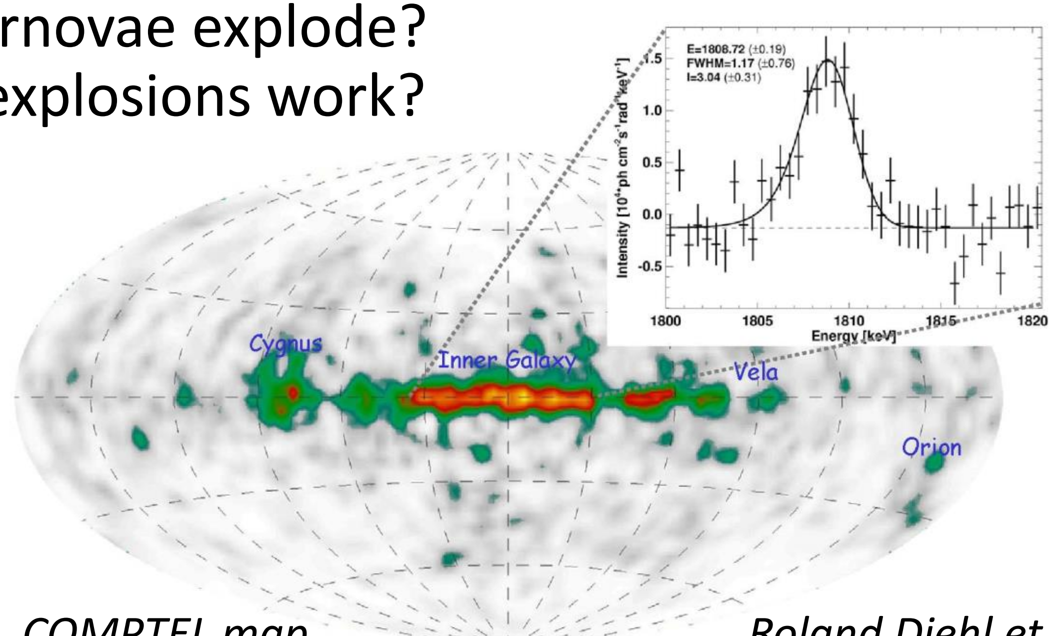
Nucleosynthesis

Creation and release of new elements:
Stars, supernovae, novae, and mergers

Each nuclear line tells a different story:
^{26}Al: History of star formation over last million years
^{60}Fe: History of core-collapse supernova
^{44}Ti: Young supernova remnants
^{56}Ni: How do type Ia supernovae explode?
^{22}Na & ^{7}Be: How do nova explosions work?

Observe:
- Location
- Fluxes
- Line width & shift
- Temporal evolution

SPI spectrum

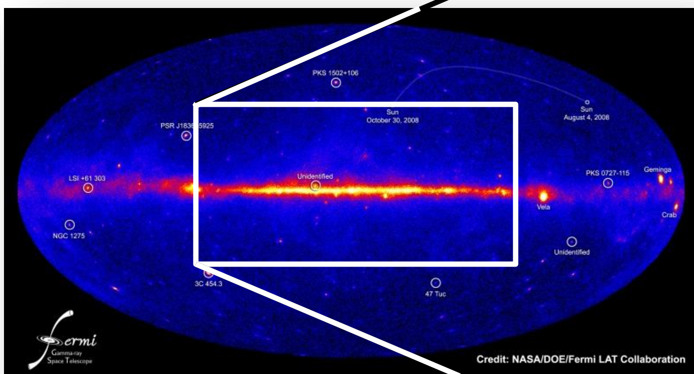


COMPTEL map

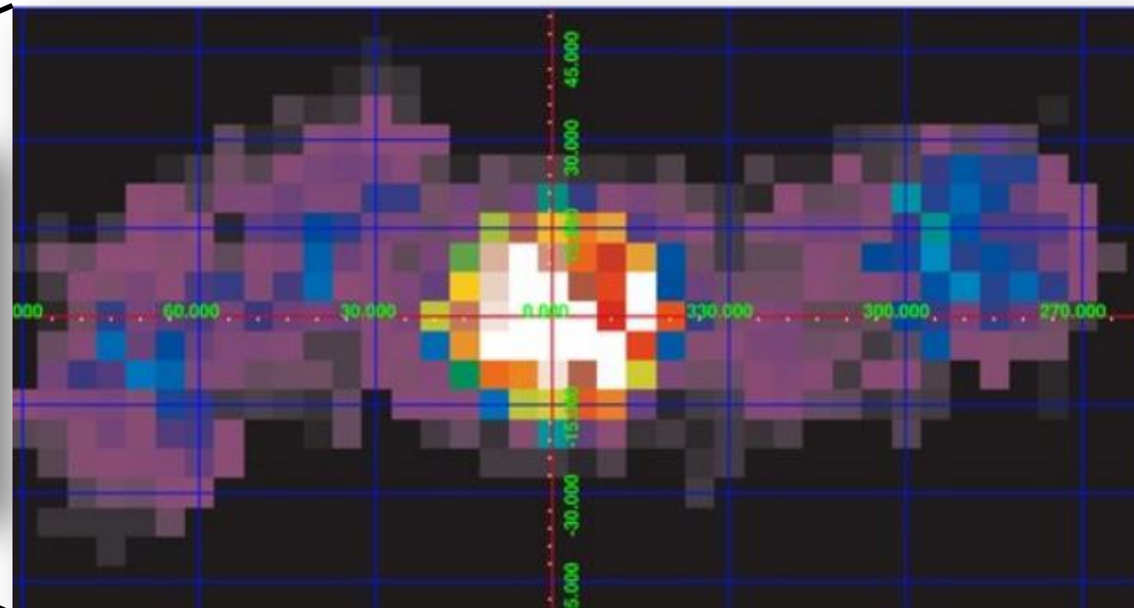
Roland Diehl et al.

Understand the Origin of the 511-keV Emission

Sky > 100 MeV (FERMI telescope)



511-keV map (SPI telescope) *Bouchet et al. 2010*



SPI observations (2002 - present):

Very extended 511-keV emission from positron annihilation centered around galactic center/bulge and around the galactic disk

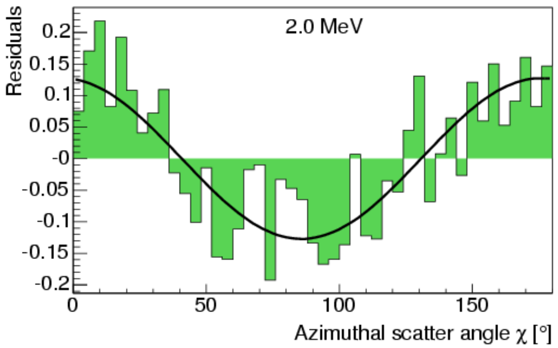
Contributors (how much TBD):

Nuclear decays, novae, supernovae, X-ray binaries, dark matter?

Open a New Dimension: Polarization

Klein-Nishina cross-section: $$\left(\frac{d\sigma}{d\Omega}\right)_{C,unbound,pol} = \frac{r_e^2}{2}\left(\frac{E_g}{E_i}\right)^2\left(\frac{E_g}{E_i}+\frac{E_i}{E_g}-2\sin^2\varphi\cos^2\chi\right)$$

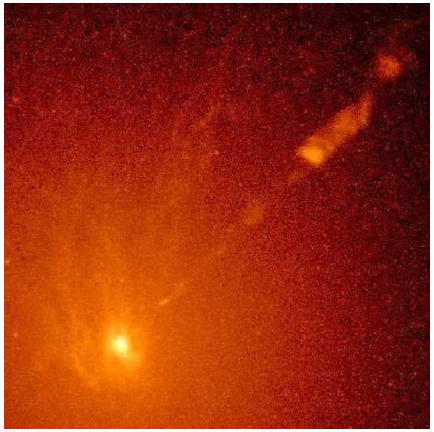
Compton scattering preserves information about the linear polarization of the gamma rays.



Polarization helps to better understand / constrain models about the geometry and emission processes with which the gamma rays are created, for example in

- Pulsars
- AGN (black-hole) jets
- Gamma-ray bursts

Crab pulsar (X-rays, Chandra)

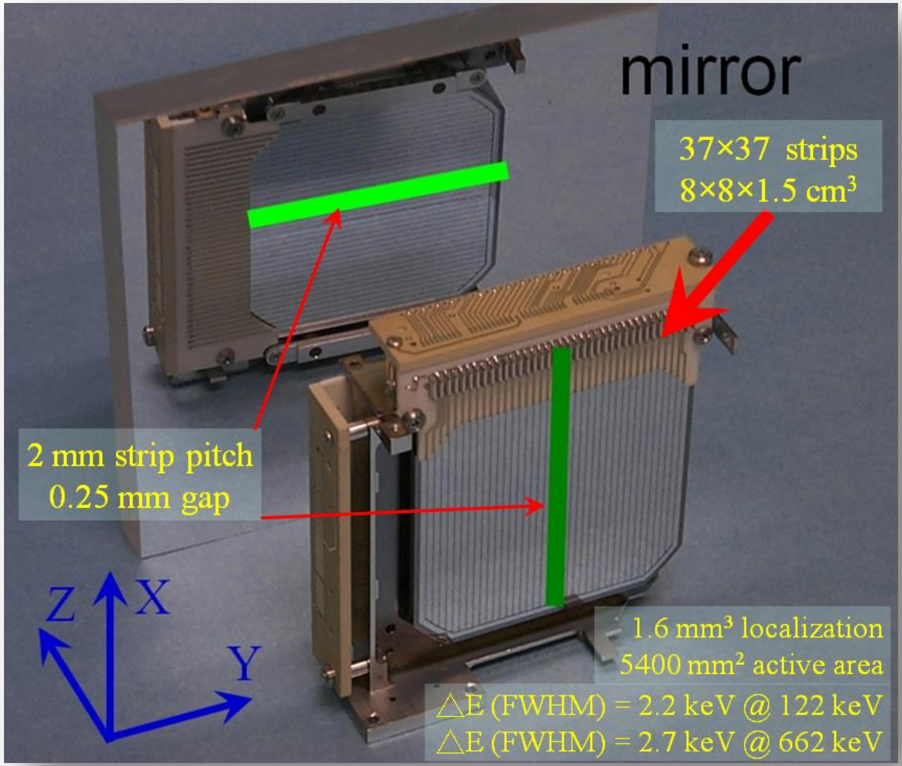


M87 (Hubble)

The Instrument and the 2016 Flight

The COSI Germanium Detectors

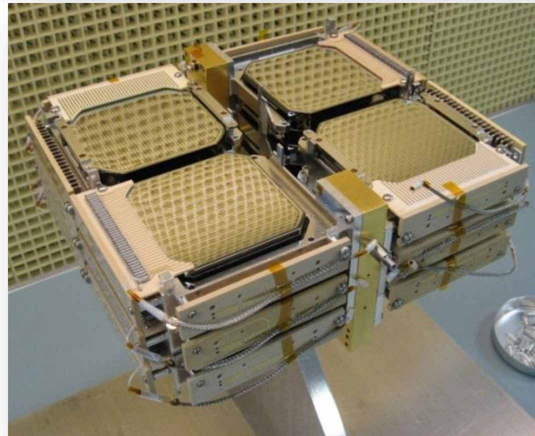
- Size: 8 x 8 x 1.5 cm^3
- Wafer: Ortec, Processing: LBNL
- 37 orthogonal strips per side
- 2 mm strip pitch
- Operated as fully-depleted p-i-n junctions
- Excellent spectral resolution: 1.5 – 3 keV FWHM
- Excellent depth resolution: 0.5 mm FWHM
- 12 are integrated in the COSI cryostat



The COSI Detector Head

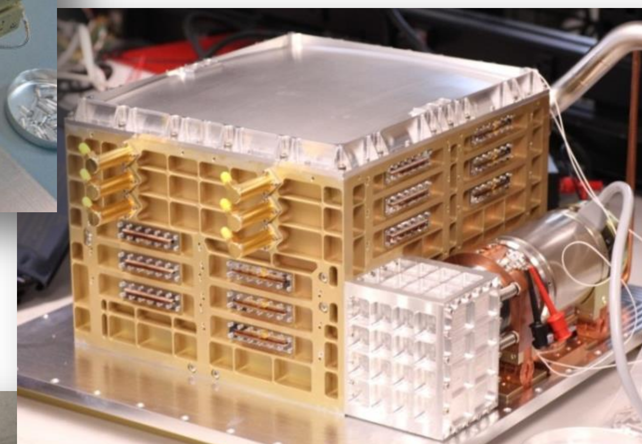
2x2x3 detector geometry

- Wide field-of-view,
- Good polarimetry



Cryostat & mechanical cooler

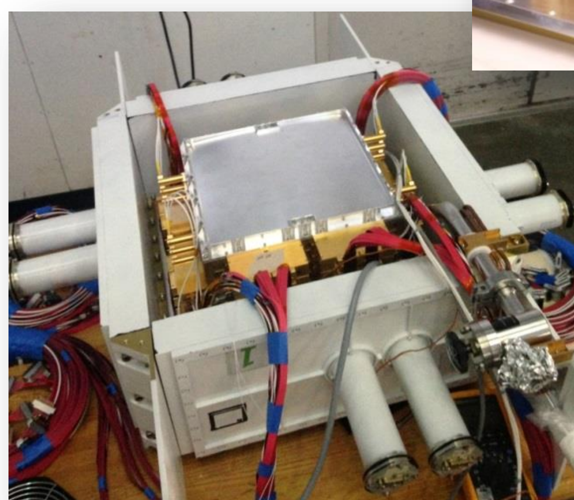
- Constant temperatures
- Enables ULDB flights



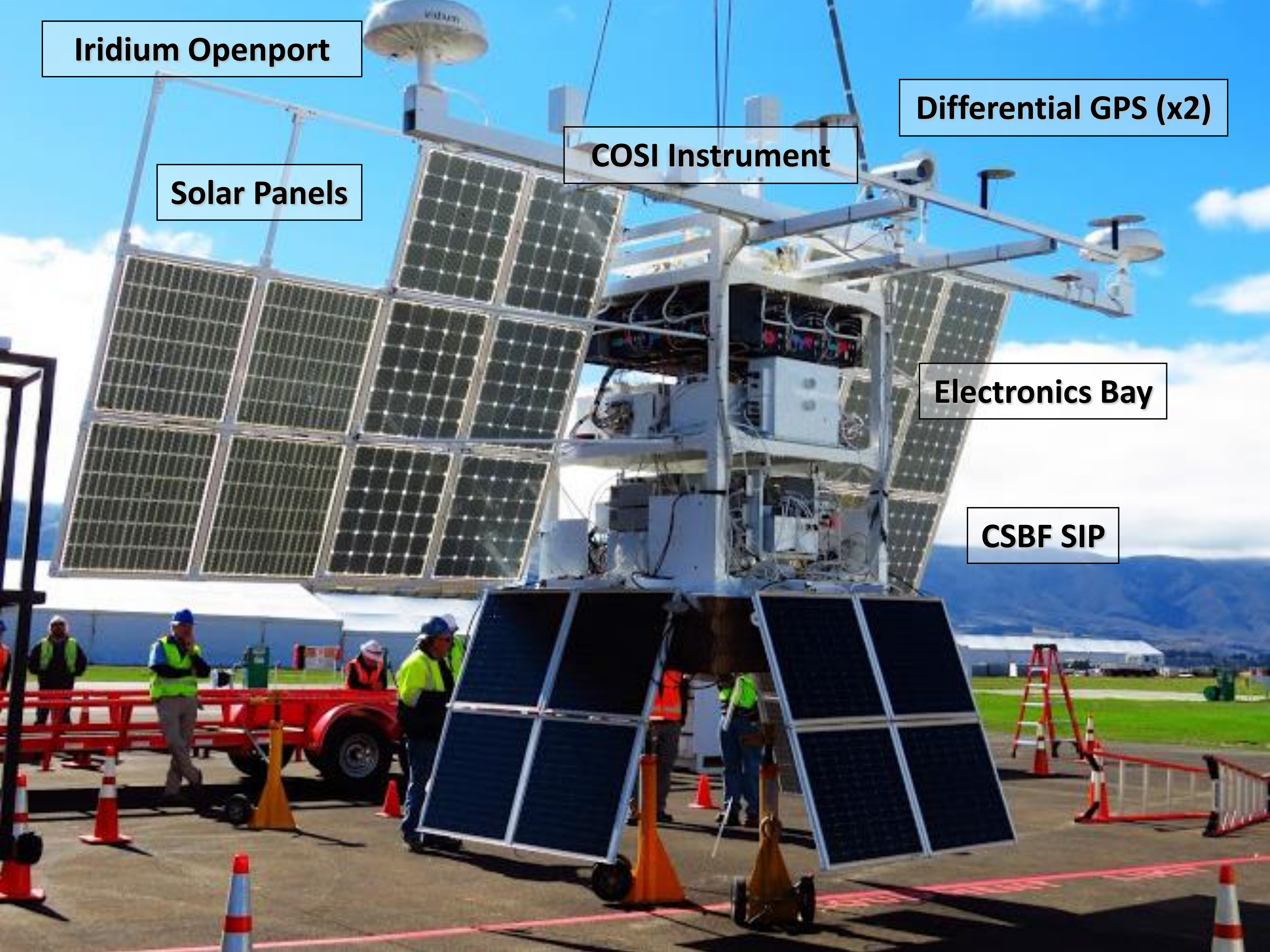
Sunpower CryoTel 10 W lift for 160 W input

CsI shielding

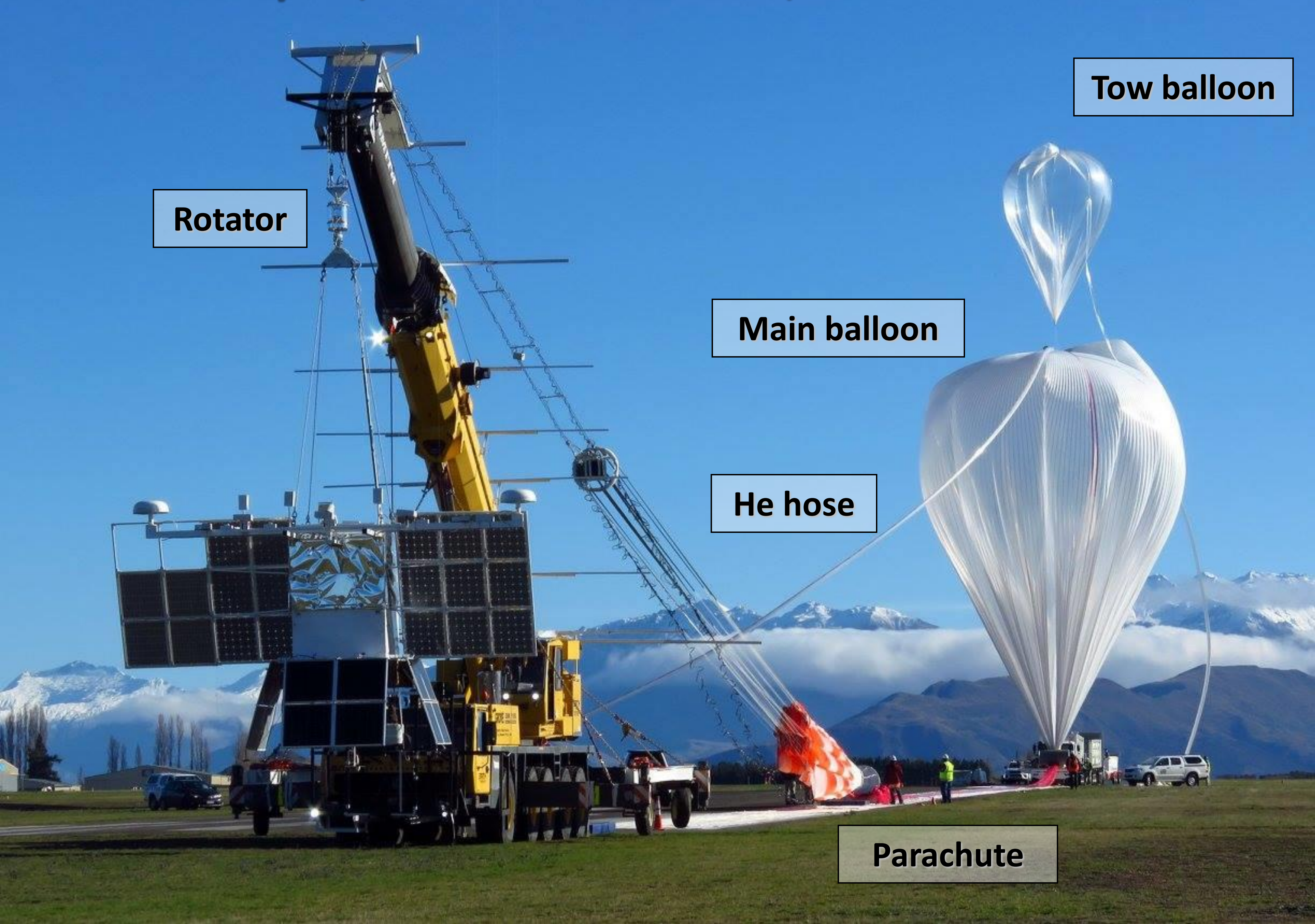
- Veto dominating atmospheric background components
- Read out by PMTs



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

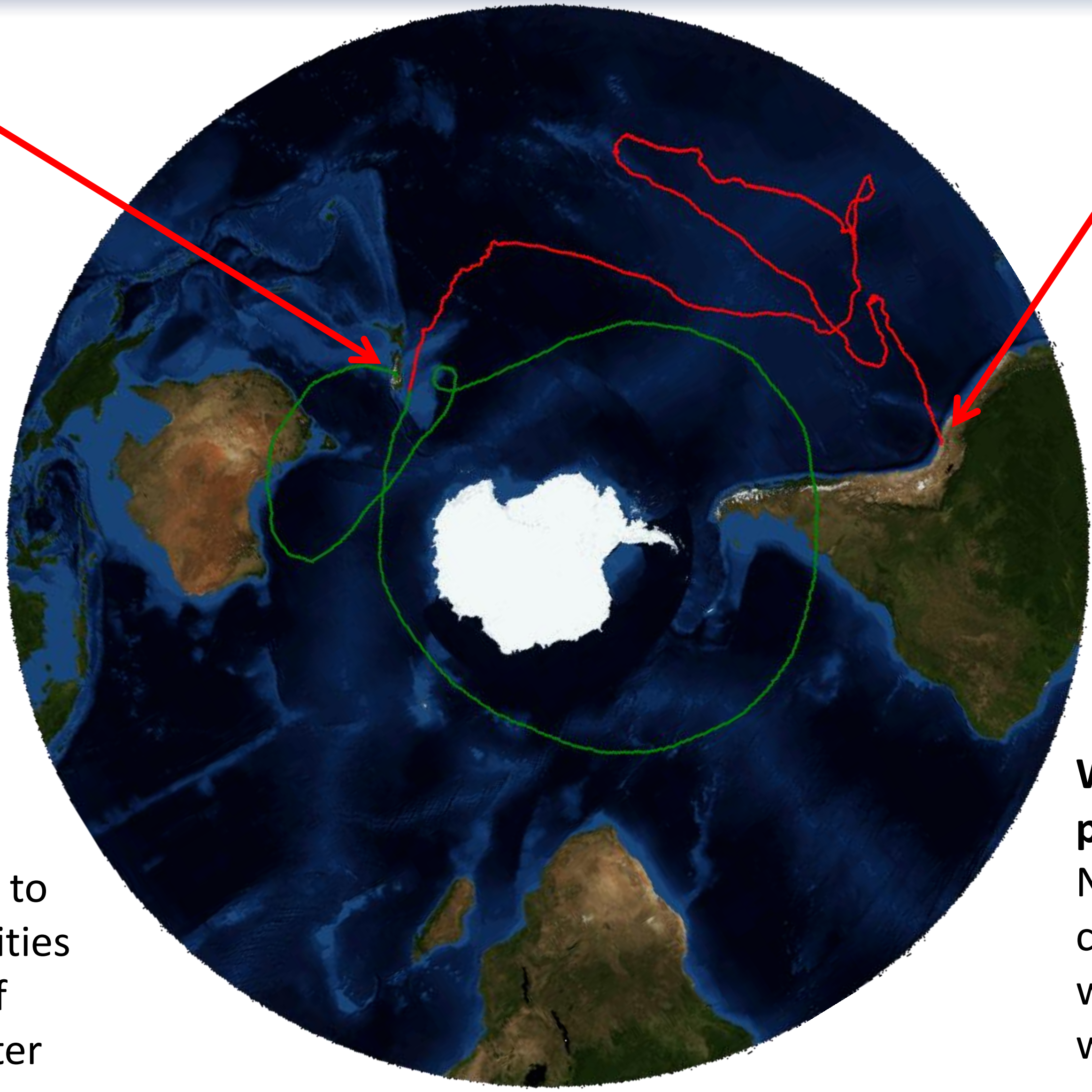
Launch: May 16, 2016 from Wanaka, New Zealand



Flight Path

Launch:
May 16, 2016,
Wanaka, NZ

1^{st} circum-navigation (green line) on May 31, 14 days after launch



Landing:
July 2, Atacama desert, Peru
(46 day flight)

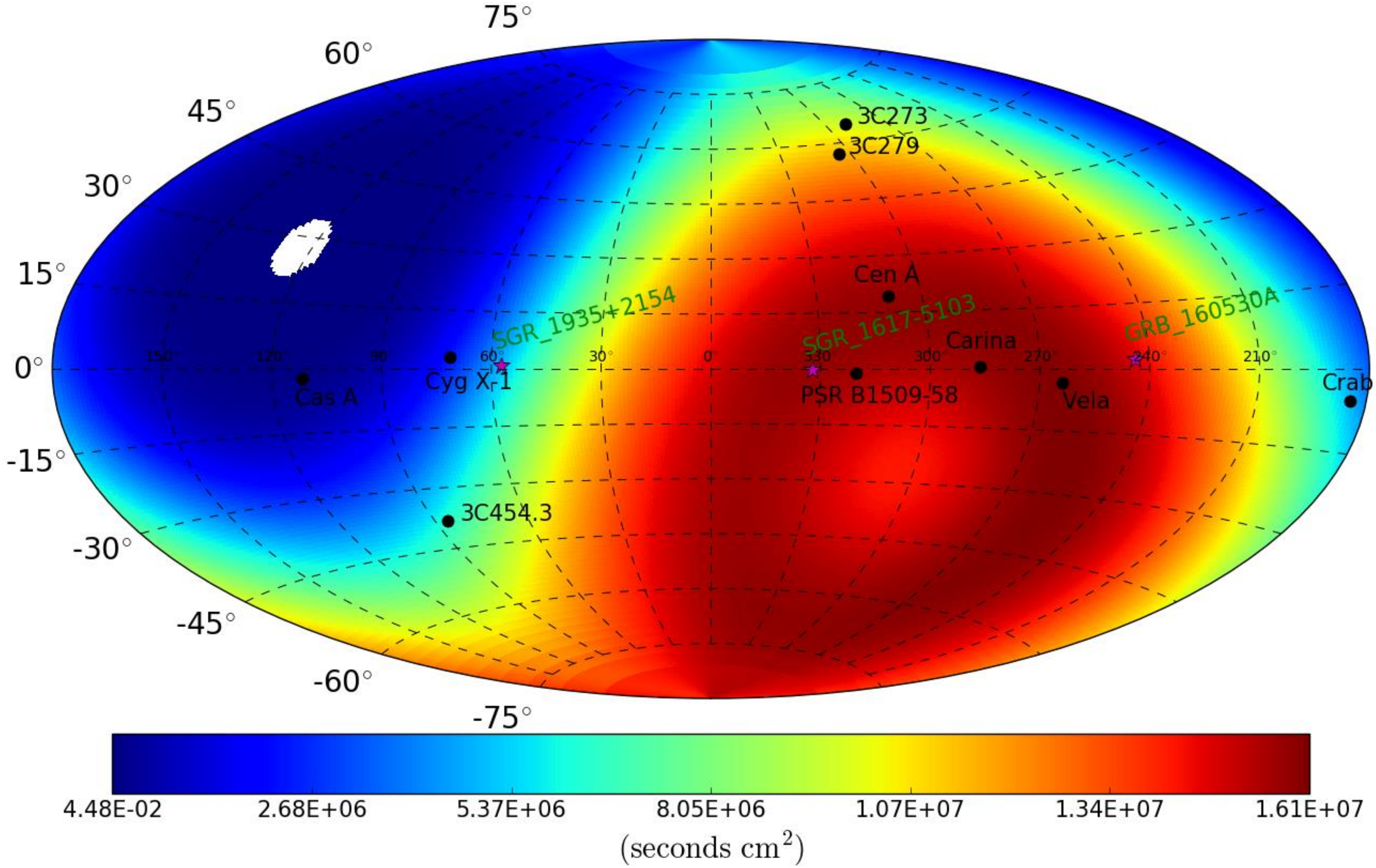
Why southern Hemisphere?

- Least chance to fly over big cities
- Good view of Galactic Center

Why this flight path?
No possibility to control flight – we go where the winds carry us…

Select COSI 2016 Science Results

Sky Exposure in Galactic Coordinates

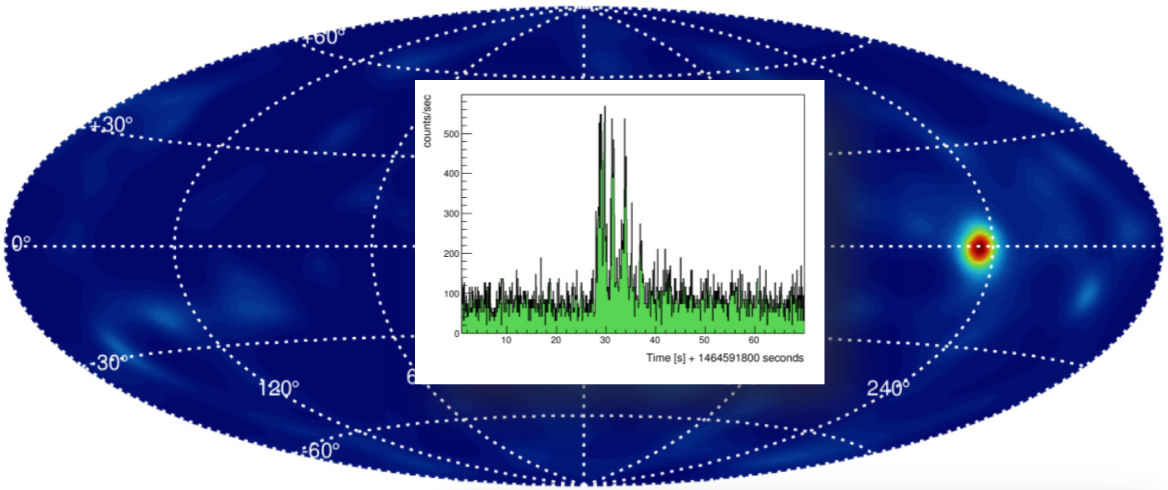


GRB 160530A – Polarization Analysis

PhD thesis Alex Lowell (2017)

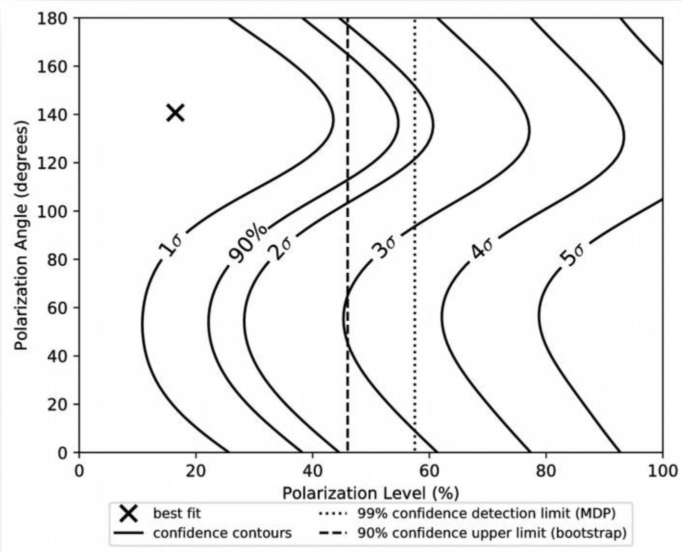
Real-time analysis:

COSI's real-time alert capabilities (a first for a balloon payload) enabled prompt notification to the observer community via GCN (GCN19473, Tomsick+)



Polarization analysis:

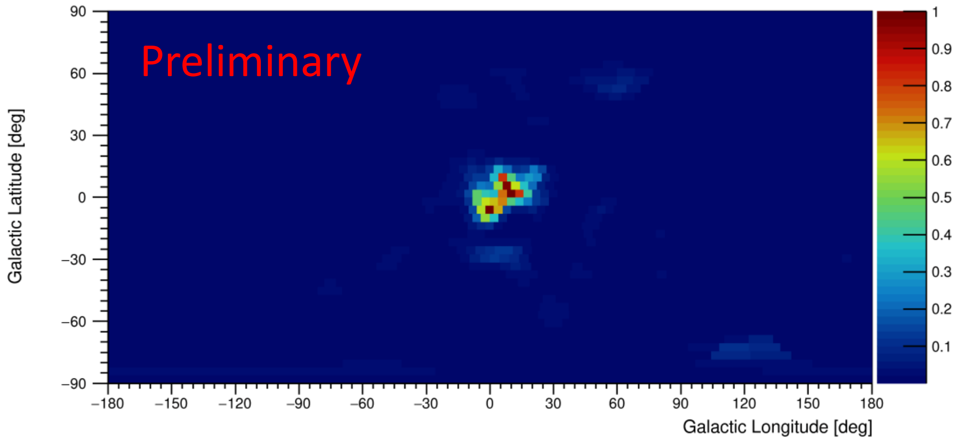
- New ML-approach (Krawczynski+ 2011)
- 90% confidence upper limit: 46%
- Best fit: 16% (+27%, -16%)

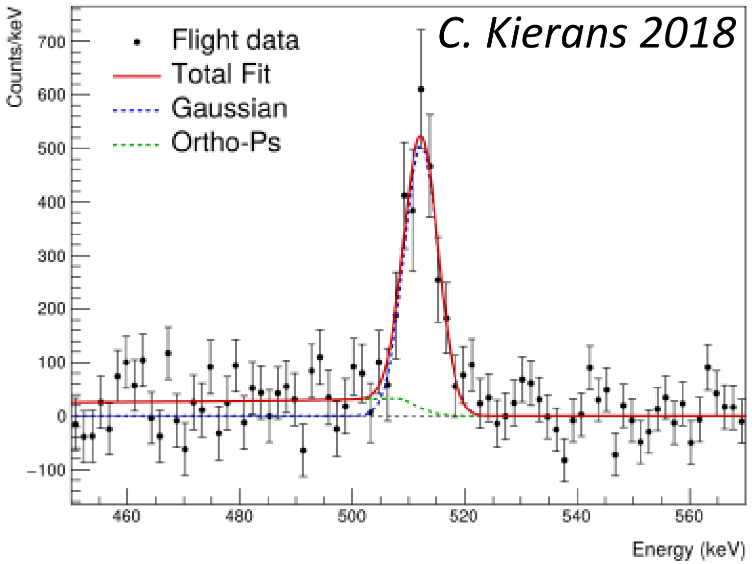


Lowell+ 2017: ApJ: 484, 119 & 484, 120

511-keV Emission from Galactic Center

PhD thesis Carolyn Kierans (2018) & Andreas Zoglauer



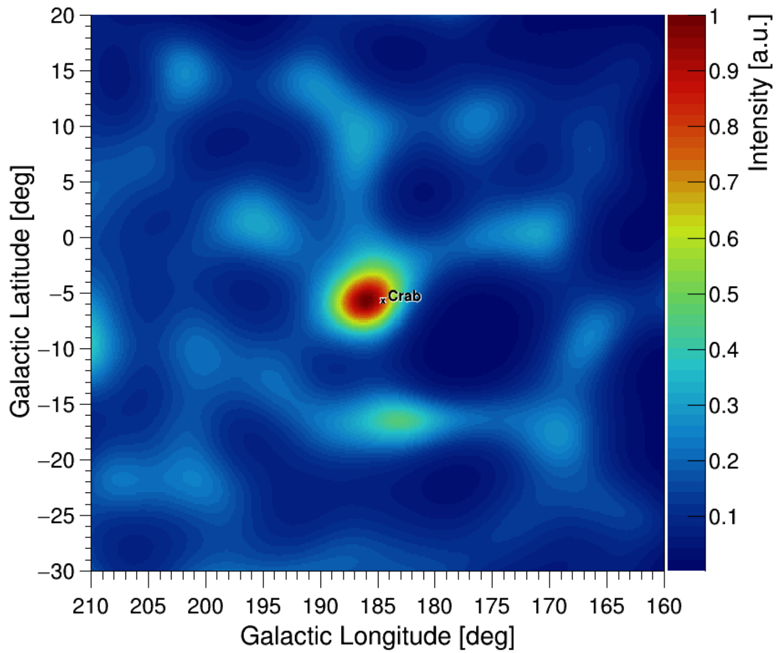


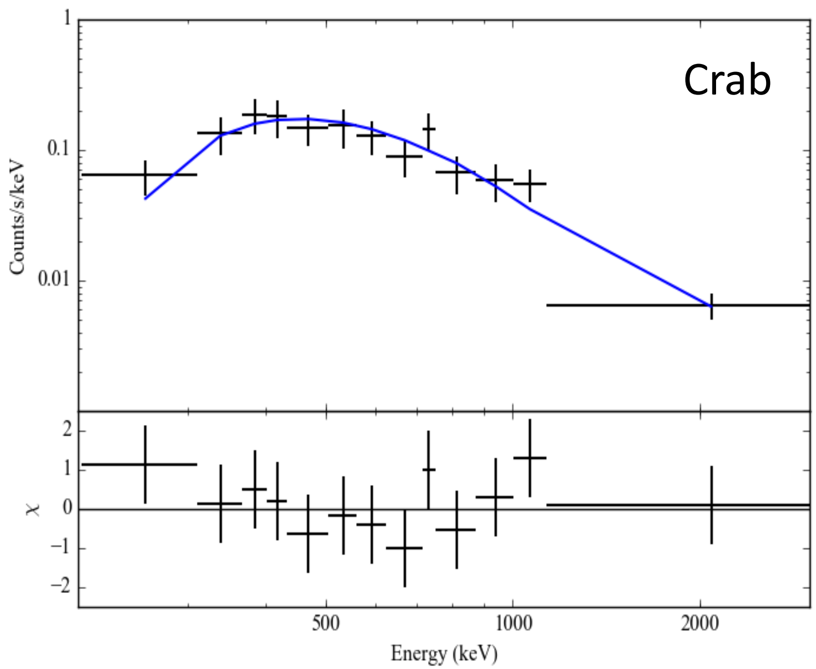
- First image of the Galactic center in 511-keV with a direct imaging telescope using Maximum-Entropy deconvolution fully corrected (background, exposure, atmosphere)
- **Don't over-interpret any structure in the image**, its just 10-days of data

Working on:
- Testing various imaging / model fitting approaches, significance maps
- Event reconstruction and 511-background detection with neural networks

Spectral Analysis Pipeline & Crab

PhD thesis Clio Sleator (soon)



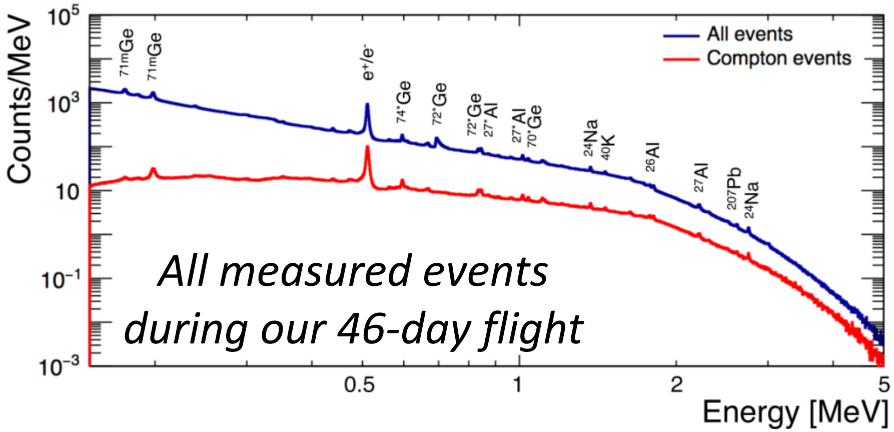


- Developed spectral fitting pipeline using xspec
- Test calibration, simulations, detector effects engine & analysis tools by reproducing Crab results
- Analyze detected point sources (polarization)

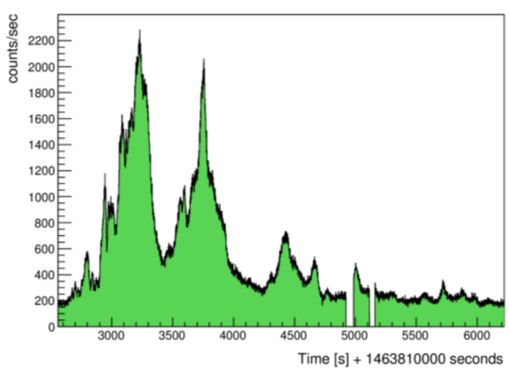
In Progress and Future Science Analysis Projects

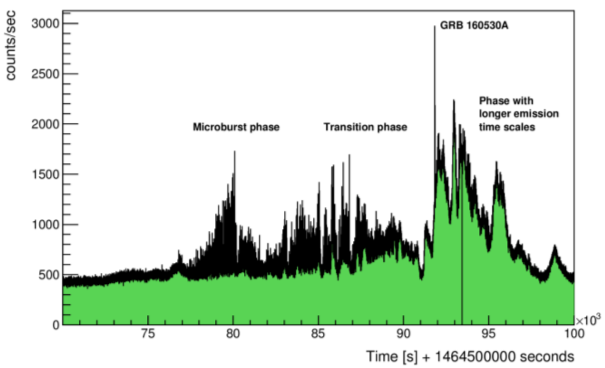
Hadar Lazar, Jacqueline Beechert (PhD students), Jarred Roberts, Thomas Siegert (Postdocs) & Andreas Zoglauer

- Other point sources: Cyg X-1, Cen A, etc.
- All-sky continuum images
- ^{26}Al imaging
- Better background modeling



- Relativistic Electron Precipitation (REP) events





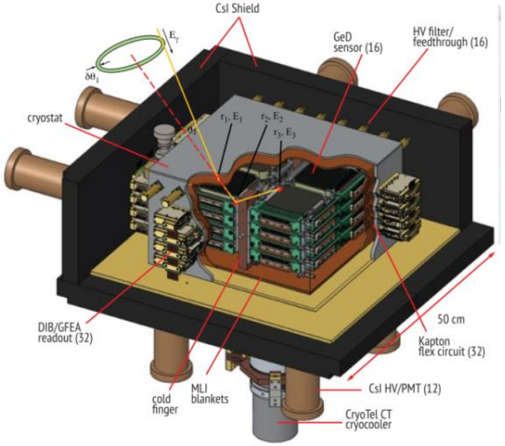
Hardware Preparations for the Next Balloon Flights

The Two Possible Futures

COSI-2 (APRA): Re-flight of COSI

COSI is fully assembled and ready for its next flight!

COSI-X (Explorer): Upgraded COSI



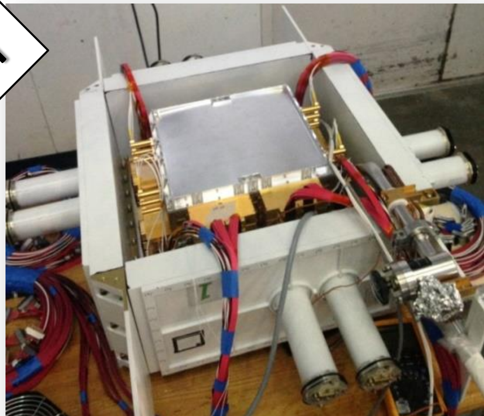
Goals:

- Build upgraded COSI-like instruments with improved performance
- Perform 3 100-day flights from Wanaka, NZ, starting 2022
- Science: Same as COSI, just with better sensitivity

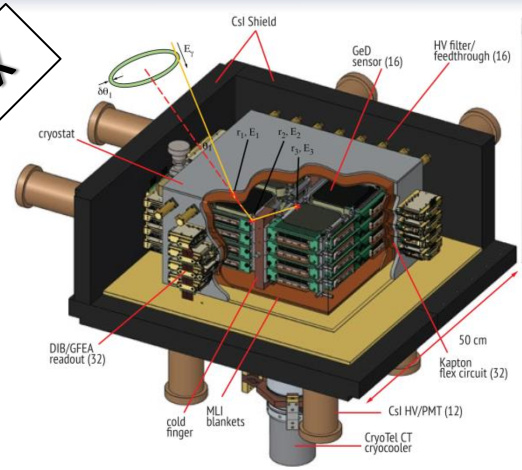
→ **Waiting for decision from NASA which path forward to take**

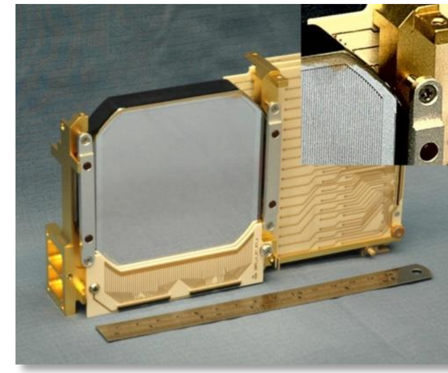
Technology Advances for COSI-X

COSI



COSI-X





Upgrade Goals:

- Improved angular resolution
- Increased effective area
- Stronger background rejection

Path forward:

- 3.4x smaller detector strip pitch (with M. Amman)
- ASICs (with E. Wulf, NRL)
- Cryo-cooler upgrades (with T. Brandt, GSFC)
- More detectors (16 vs. 12)
- Better shielding (no gaps)

Recent COSI-X Instrumentation Work

ASIC testing

- ASIC produced at NRL (Eric Wulf)
- Board designed by Jarred Roberts

Vibration damper

- Significant noise reduction
- Working with GSFC (Terri Brandt)

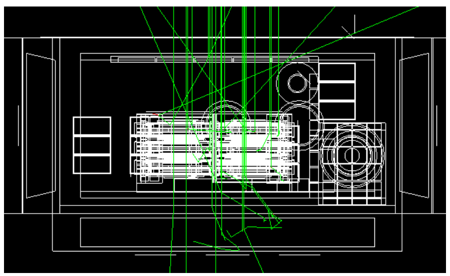
Commercially available from Sunpower

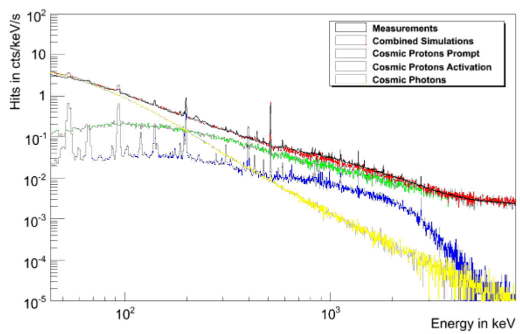
Improving the Data-Analysis Pipeline for COSI, COSI-X & AMEGO

(and thus ultimately for all future Compton telescope missions)

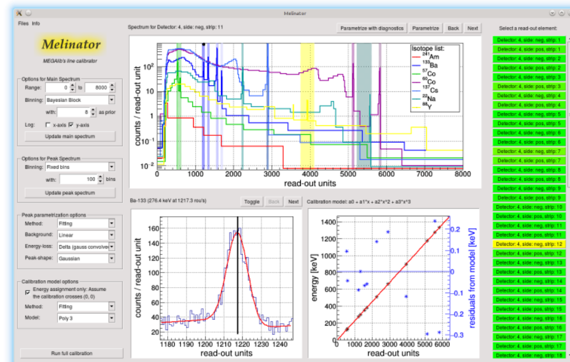
MEGAlib – Medium-Energy Gamma-ray Astronomy library

- Full data analysis chain for γ-ray instruments in space & on ground
- Generalized to be applied to arbitrary detector systems not only COSI
- Based on ROOT & Geant4, written in C++ with Python bindings
- Freely available from GitHub (just google "MEGAlib")

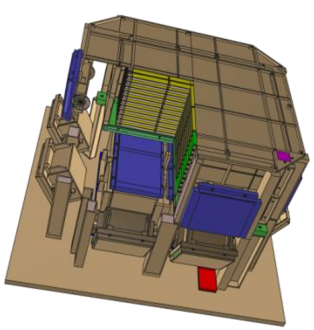




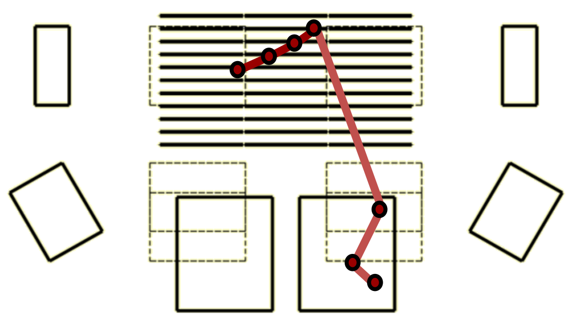
Monte-Carlo simulations



Detector calibra-tions



Geometry



Event pattern classification

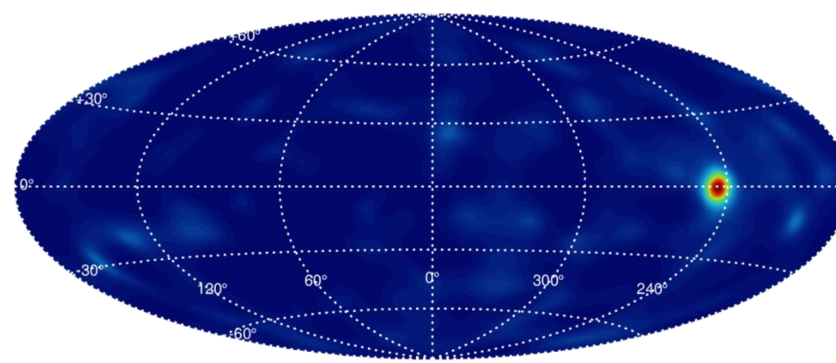


Image deconvolution

MEGAlib Overview

Generation

Measurements

Universal calibration: Fretalon framework

Universal simulator: Cosima (Geant4-based)

Data is assembled as times, positions & energies

Reconstruction

Event identification, quality assessment, background identification: Revan

Response generation / machine learning for data analysis: ResponseGenerator & Sivan

Data consists of Compton events, pair events, etc.

Science

Event selection optimization

Image Reconstruction

Spectral analysis

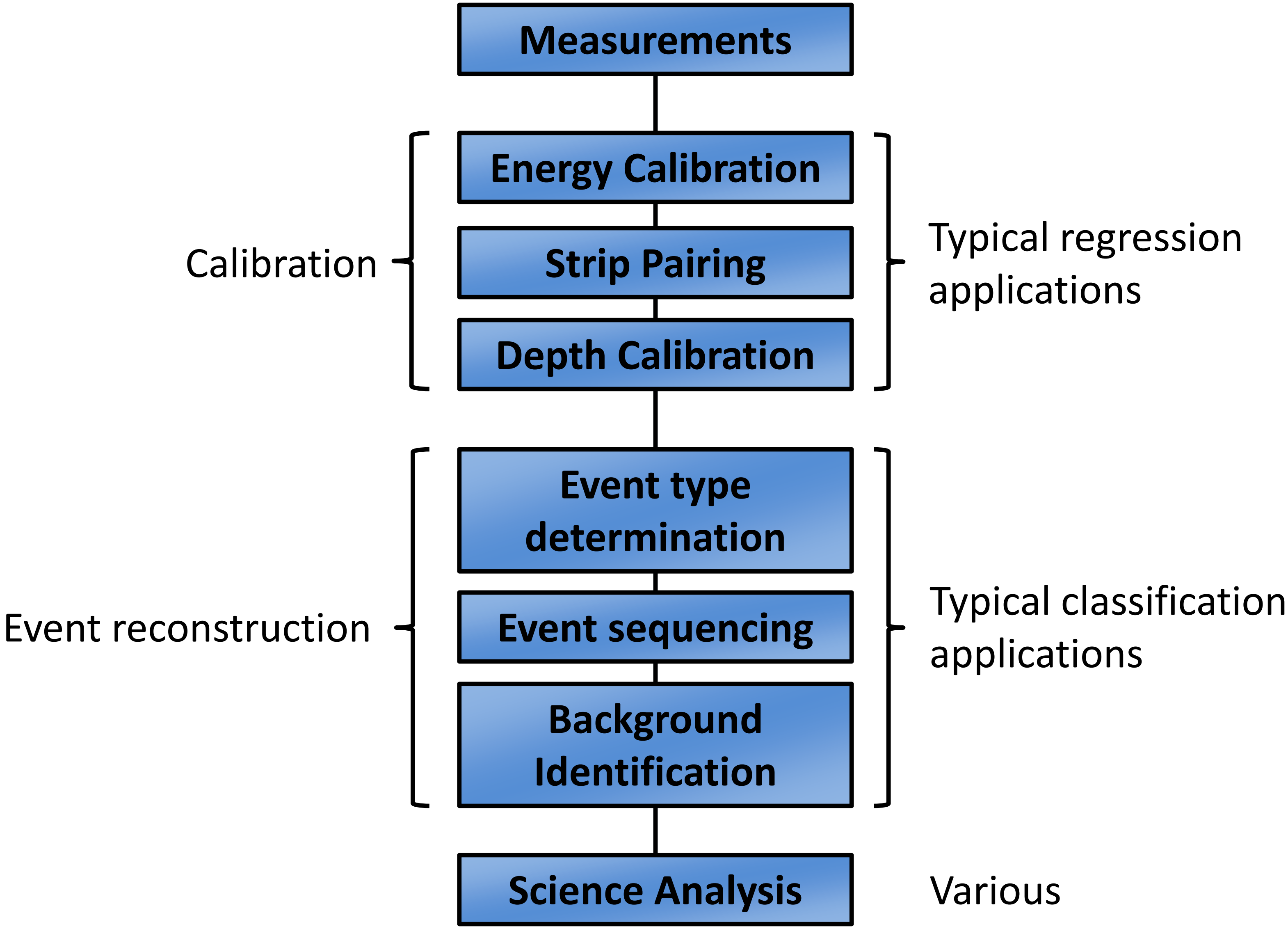
Performance analysis

and more…

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

Applying Machine Learning to the COSI Data Analysis Pipeline

Simplified COSI Analysis Pipeline



Software Tools

MEGAlib
Medium-Energy Gamma-ray Astronomy library

A. Zoglauer et al. 2006

ROOT
CERN's high-energy physics data analysis framework

R. Brun & F. Rademakers, 1997

TMVA
Toolkit for Multivariate Data Analysis

P. Speckmayer et al. 2010

TensorFlow
Google's machine-learning library

M. Abadi et al. 2016

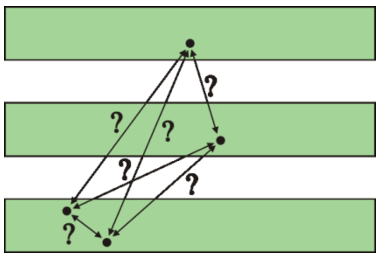
All are freely available, open source, and written in C++ with Python bindings

Format of the Project

Undergraduate Research Apprenticeship Program

- Undergraduates work during the semester on a research project with a faculty / researcher as mentor
- Currently managing 11 undergraduates

Example 1: Compton Event Reconstruction



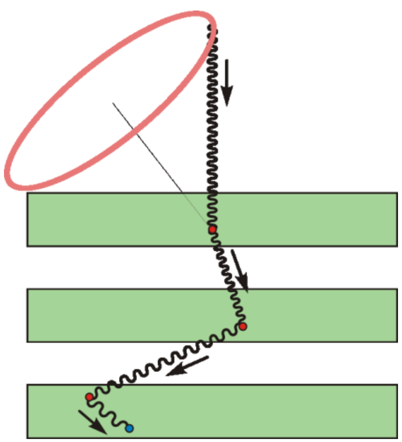
Problem:

- Detector only measures hits without time information

  → Path of photon is unknown!

Information available to determine path:

- The kinematics of the events, i.e. the redundant Compton scatter information (electron track and/or multiple Compton interactions)
- The known response of the detector to incident gamma-ray (absorption probabilities, scatter probabilities, etc.)



Techniques used:

- Classic Compton sequence reconstruction *(Boggs+ 2000)*
- Bayesian approach *(Zoglauer+, 2005 & 2007)*
- Random forest of boosted decision trees
- Neural network

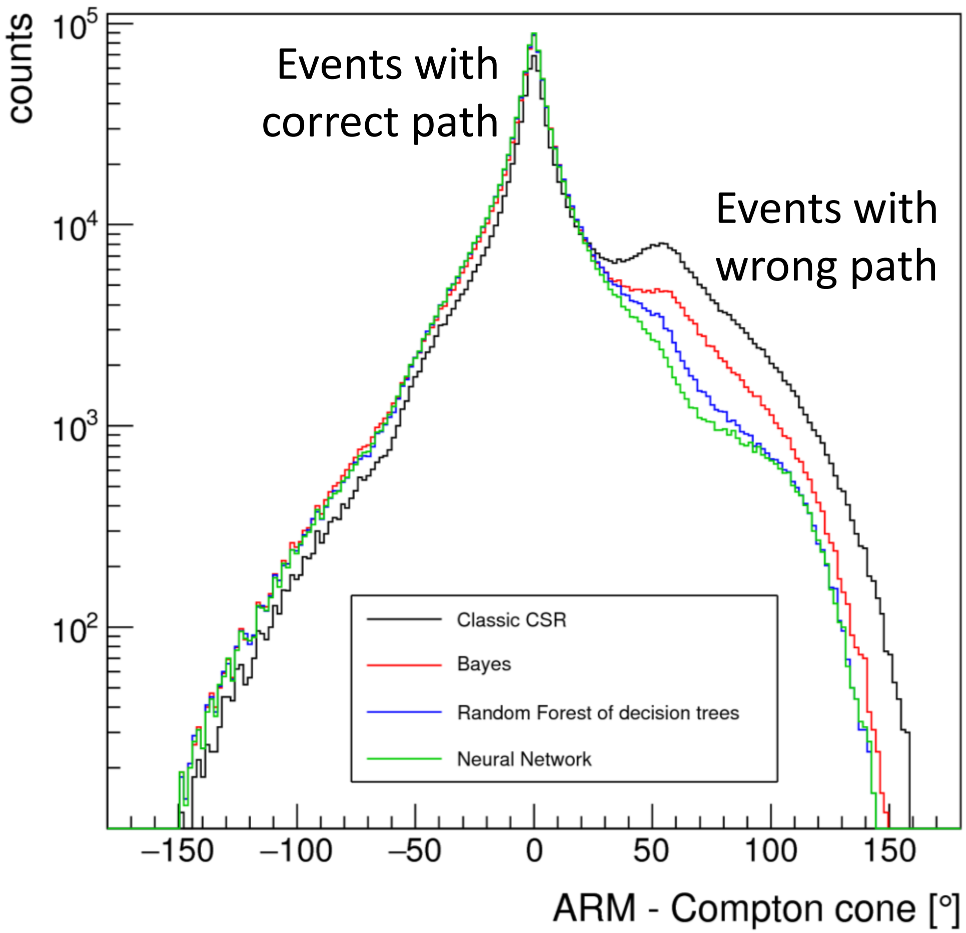
  (Zoglauer+ 2019, in prep) [random forest and neural network]

Output:

- Correct interaction sequence

Event Reconstruction Performance

Performance metric: ARM
The narrower, the better



Training:

- Isotropic 511-keV gamma rays
- 10,000,000 triggers

Testing:

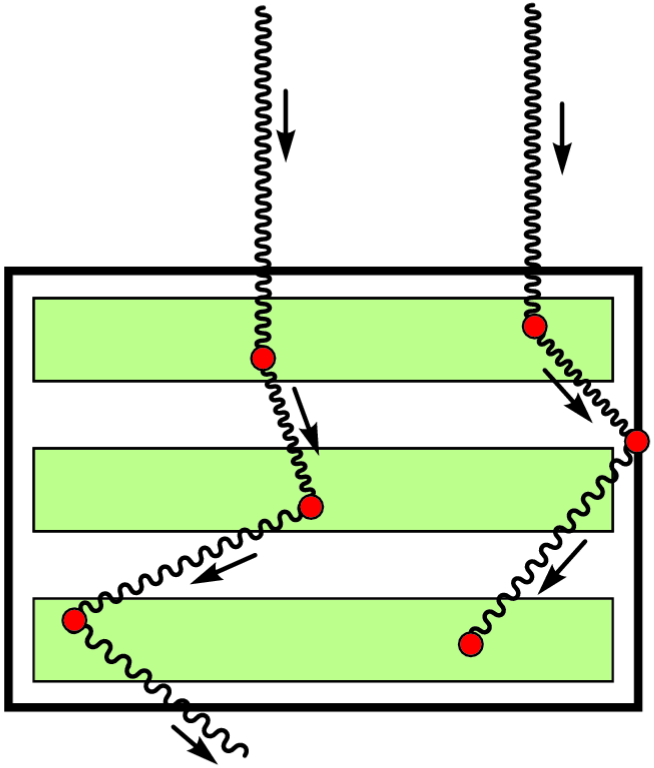
- 511-keV from ^{22}Na COSI calibration data
- Background from 1276-keV line

RMS improvement:

CSR: 0%
Bayes: 17.0%
RF-BDT: 24.9%
NN: 27.4%

Example 2: Identification of Not-contained Events

together with Winnie Lee (not contained event identification), Huy Hoang (Albedo gamma-ray identification) & Rebecca Abraham (internal decay identification)



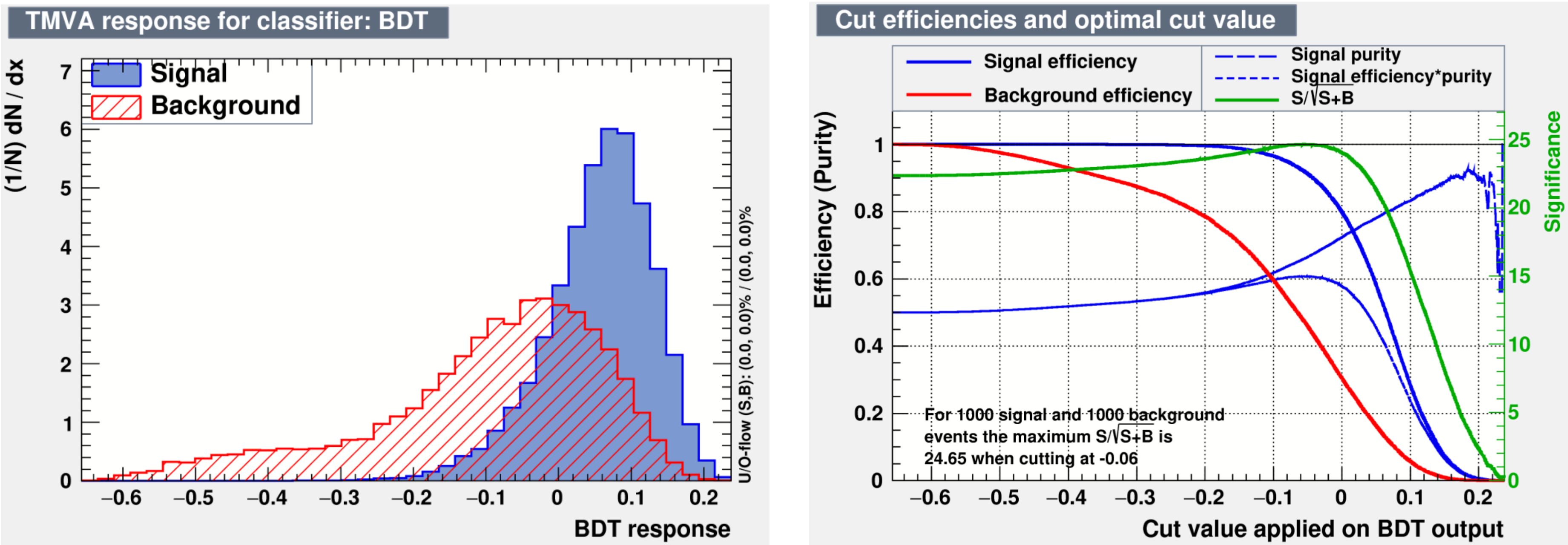
Task:

- Identify gamma rays which escape the detector or have interactions in passive material, i.e. all events which are not fully contained in our detector.

Challenge:

- Not done in current pipeline
- No reliable non-machine learning approach exist

Example 2: Identification of Not-contained Events



Current status:

- Keep 92% of the good events
- Throw away 51% of the incomplete absorbed ones

➢ Working on improving separation

Example 3: AMEGO Event Reconstruction

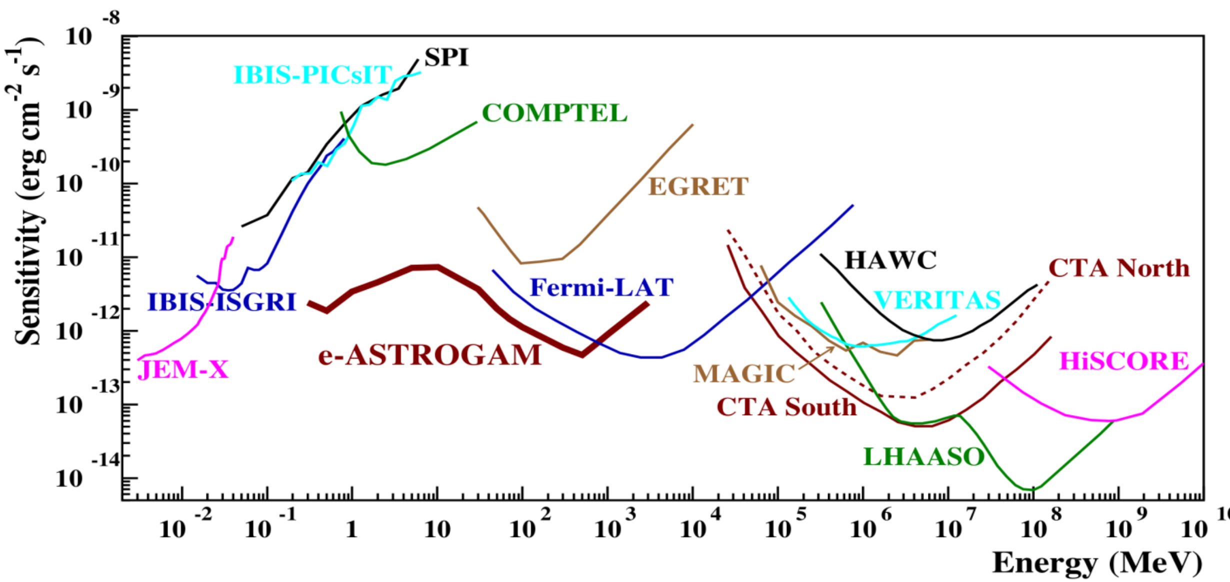
together with Caitlyn Chen, Anna Chen & Amal Mehta

NASA APRA funding:

- Title: "Applying supervised machine-learning approaches to the reconstruction of high-energy tracked Compton events and low-energy pair events"
- Official start: As soon as funding arrives
- Status: URAP team already in place and started working

Goal:

- Overcome the sensitivity bump around 10 MeV

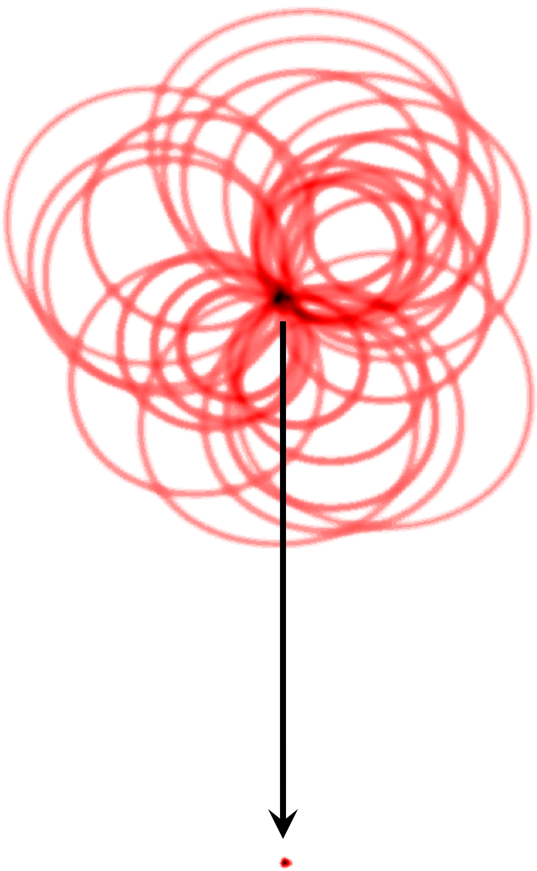


Towards Imaging with a 9-dimensional Detector Response

Compton Imaging

Measurement process: $D(d) = R(d; \chi, \psi, E) \times I(\chi, \psi, E) + B(d)$

measured data	detector response	sky distribution	detector background



Goal: Infer sky distribution from measured data

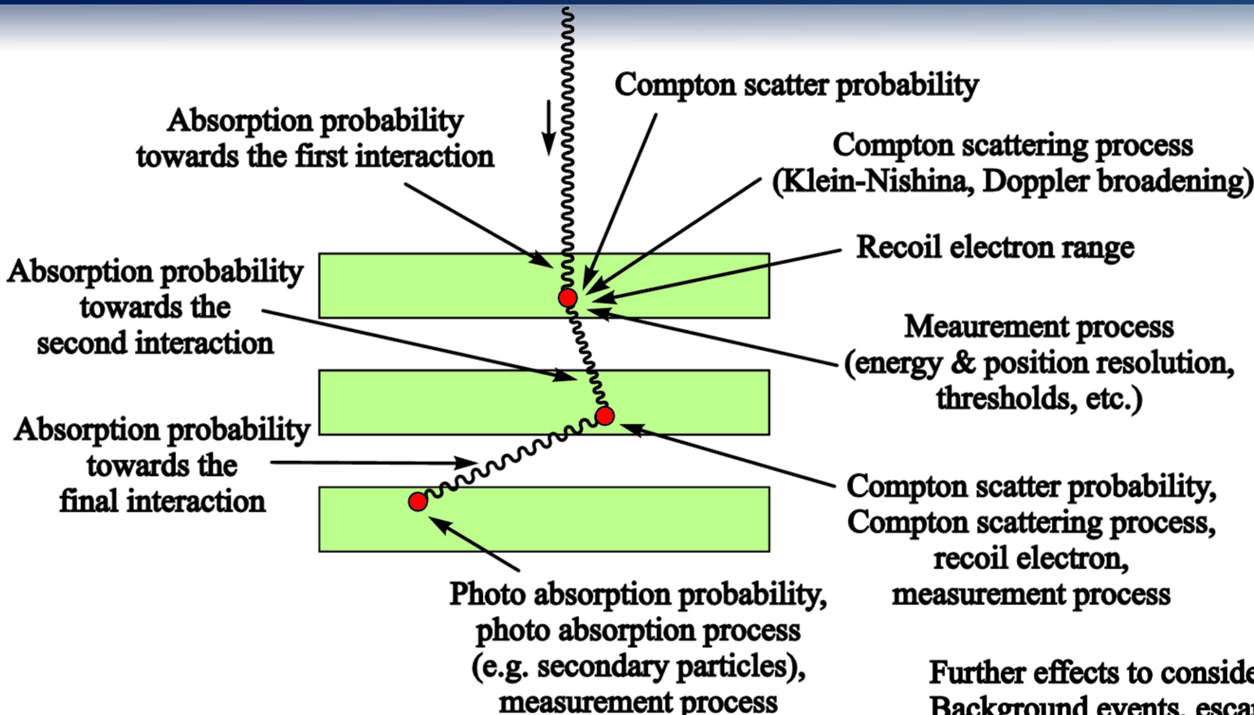
Inverse problem, but not invertible:

- Too few events
- Randomness of measurement process

Utilize iterative approaches:

- Maximum-likelihood expectation-maximization
- Maximum-entropy methods
- Stochastic origin ensembles
- Etc.

The Challenge: Accurate Response Required

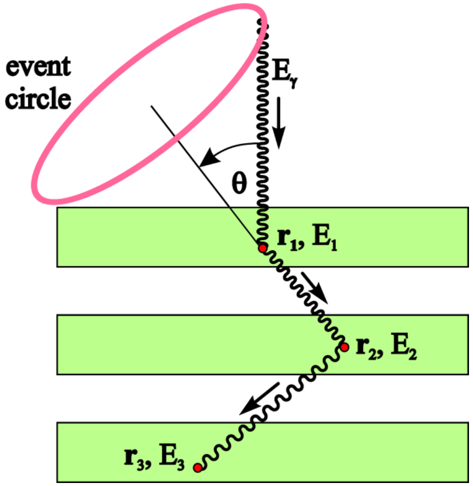


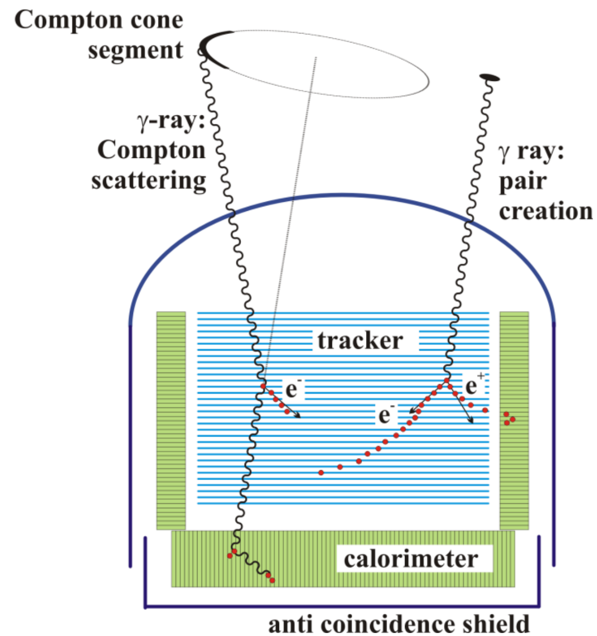
Further effects to consider:
Background events, escaping events, wrongly reconstructed events, defective strips / detectors, etc.

- To reach sensitivity limit, response needs to be determined with detailed, benchmarked Monte-Carlo simulations
- A (semi) analytical "list-mode" approach is not sufficient due to difficulties with background modeling, flux recovery & exposure correction
  - ➢ List-mode images will not be close to the sensitivity limit

The Data Space

NCT,
COSI,
COSI-X,
ASCOT,
etc.





MEGA,
ComPair,
AMEGO,
ASTROGAM
variants,
etc.

Raw data space: N hits of energy & position

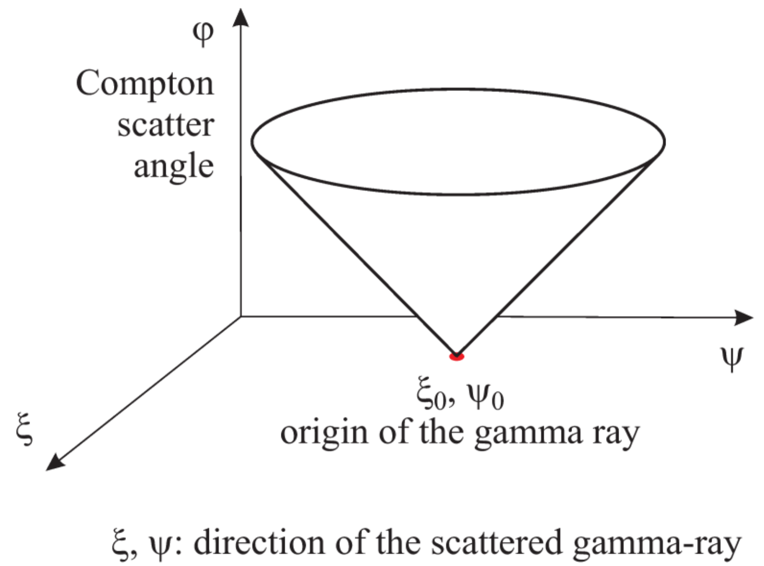
For example, COSI resolution elements:
Energy: ~1,000
Position: ~$(2*37)^2$ * 30 * 12 = 1,971,360

→ ~2 x 10^9 per hit!

→ Drastic simplifications required to determine detector response!

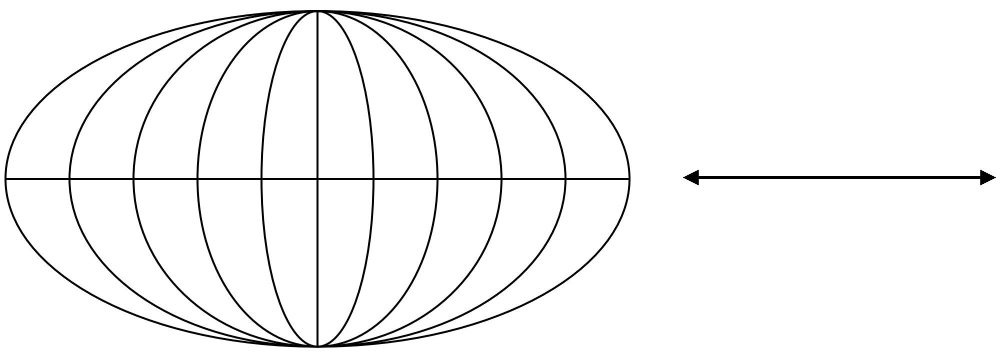
The Point Spread Function (PSF) in the Compton Data Space (CDS)

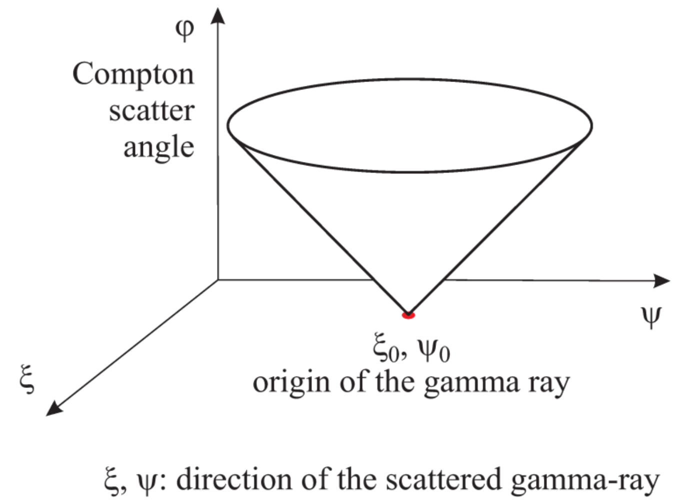
- As determined in the early days of COMPTEL, the best suited data space for Compton data analysis is the **Compton Data Space (CDS)**
- For imaging purposes, the raw data space can be reduced to 3 key dimensions, the CDS (ignoring electron tracks):
  1. Compton scatter angle φ
  2. Galactic longitude ξ,
  3. Galactic latitude ψ of the direction of the scattered gamma ray
- In this data space the PSF is a cone with 90-degree opening angle pointing at the origin of the gamma rays (ξ_0, ψ_0)

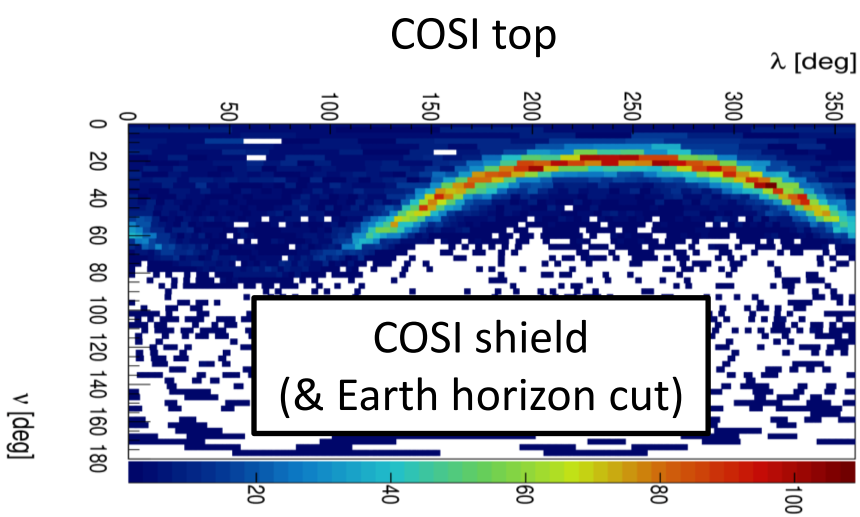


The Response

The instrument response connects image space and data space:

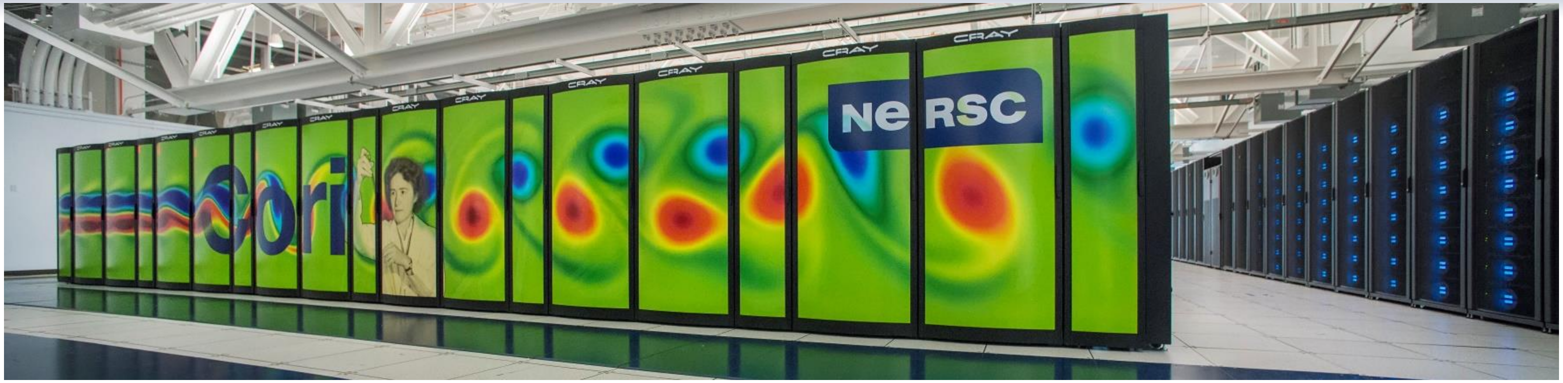






Origin of (fully absorbed) 511-keV gamma rays with measured at (φ, χ, ψ) = (50°, 30°, 60°), COSI

Simulating the Response for COSI



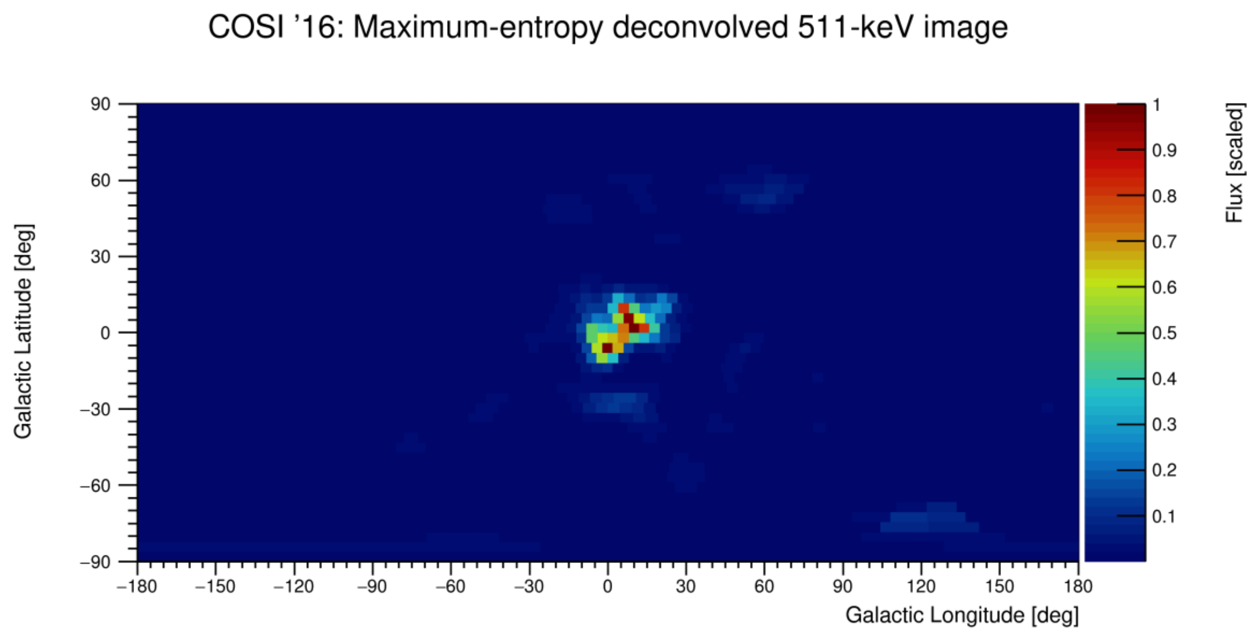
- Response simulations are the most computationally & storage-wise expensive task
- Applied for and awarded 6,550,000 core hours of computation time on NERSC's Cori supercomputer
  - PI: Andreas Zoglauer
  - Title: "Enhanced All-sky Gamma-ray Imaging in the MeV Domain with the COSI Compton Telescope").
- Used exclusively to simulate the 5D (511-keV) and 7D (continuum) COSI response for this project

Response: The Curse of Too Many Dimensions

5D nuclear-lines imaging (e.g. 511-keV, ^{26}Al):

2D image space → 3D Compton data space

Doable but needs supercomputer



10 best days of observation with COSI

Response: The Curse of Too Many Dimensions

5D nuclear-lines imaging (e.g. 511-keV, ^{26}Al):

2D image space → 3D Compton data space ✓

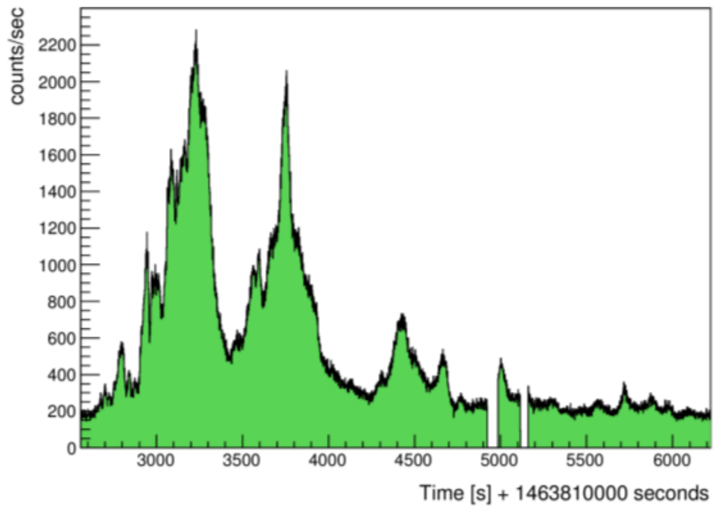
7D energy-resolved imaging (continuum sources: pulsars, AGN, etc.):

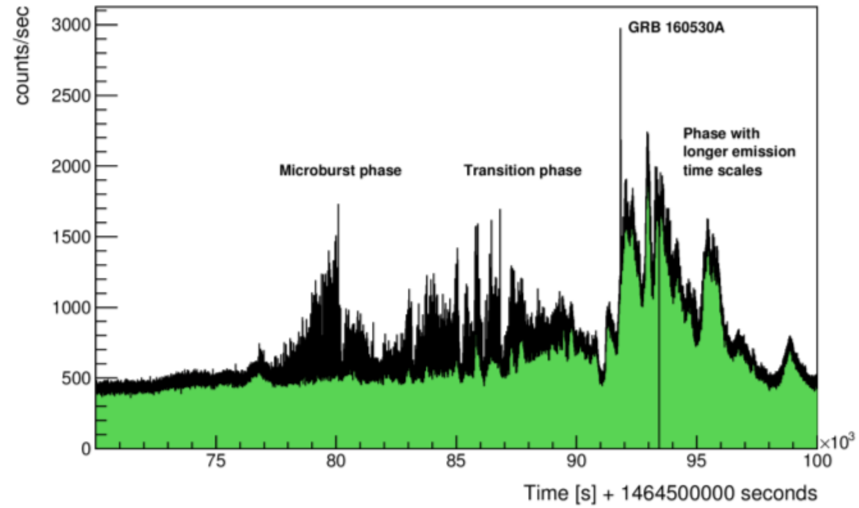
2D image space → 3D Compton data space +

1D energy 1D measured energy

Doable for COSI & COSI-X, but with *significant* supercomputer and storage requirements (PB's)

Spatial-Spectral-Polarization-resolved "Imaging"



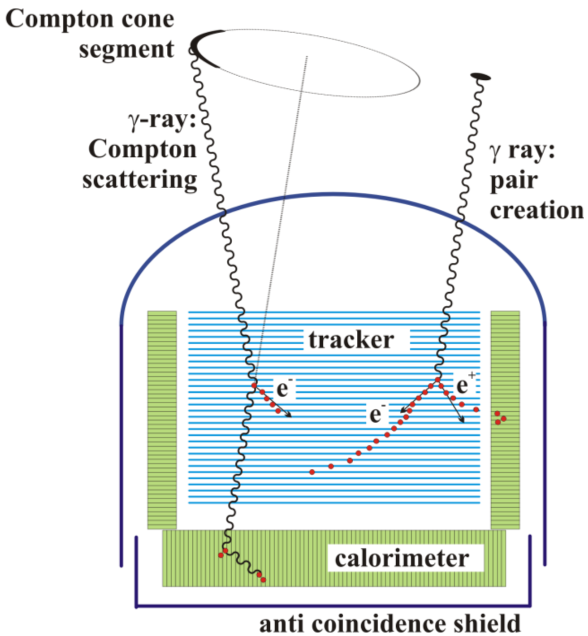


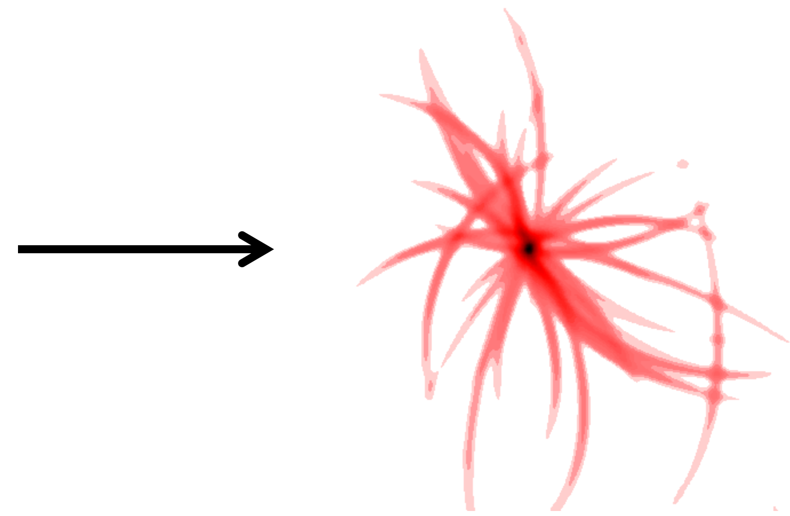
COSI-observed relativistic electron precipitation events

- First time these events where observed with an all-sky imaging polarimeter
- Measuring polarization could help reveal the electron scattering mechanisms for the first time
- Challenge: Emission is distributed over large part of sky and thus requires spatial-spectral-polarization deconvolution for analysis

➢ Extremely challenging with current approaches: Exa-Byte-scale problem

Electron-tracking Compton Telescopes





Recoil-electron-tracked Compton events

- Adds at least two more dimensions to response for recoil electron direction
- 100-1000 times more resolution elements in response

➢ Binned-mode imaging response creation (to reach the sensitivity limit) using current approach is “challenging” (O(Exa-Bytes))

Interpolating the Response with Deep Neural Networks

together with Shivani Kishnani & Jasper Gan

Idea:

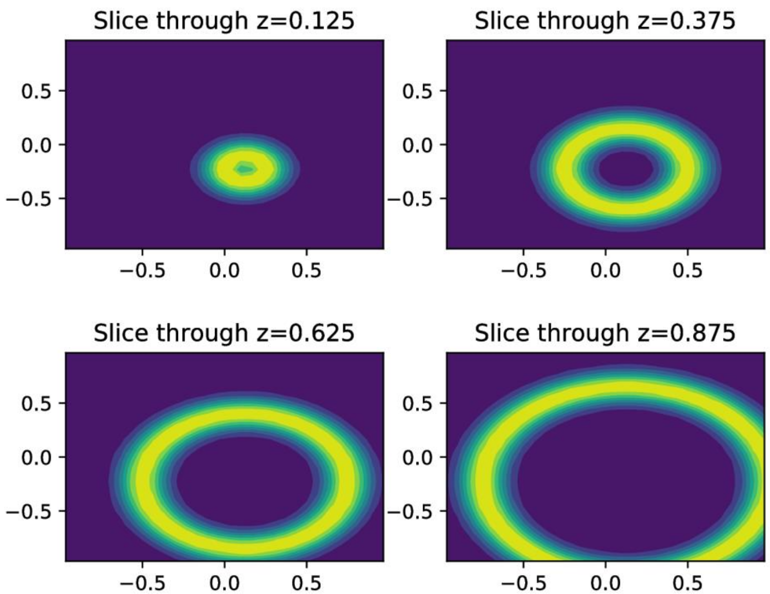
- Changes in response are smooth in field of and over energy, therefore..
- Simulate N response points in the field-of-view & interpolate the rest with a deep neural network

Status:

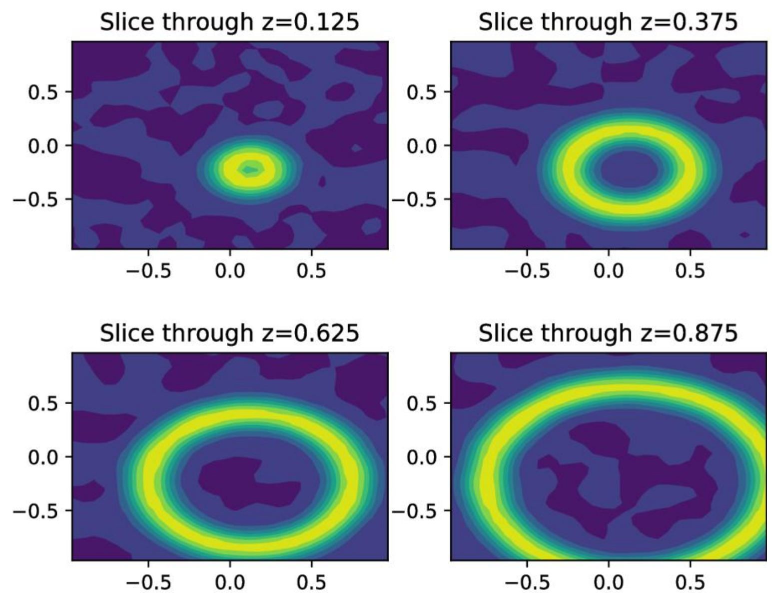
- Exploratory research exploring the problem with a simplified "toy model" Compton response

Proof of Concept

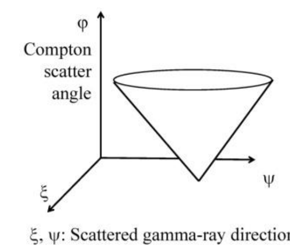
Simulated test cone



Reconstructed cone with NN



Slices through the Compton cone in data space:



✓ Proof-of-concept achieved!

Challenges:

- Best network architecture?
- How to minimize fluctuations
- High-dimensionality and thus high-complexity of neural network when considering AMEGO

Next steps:

- Optimization
- Reversal training: Data to image space
- Application to full COSI geometry
- Work-level: PhD thesis

Thank You!

COSI US is supported through NASA Grant NNX14AC81G

COSI-X Phase-A study is supported by NASA

Imaging developments are supported through NASA grant NXX17AC84G

Event reconstruction developments are supported through NASA grant 80NSSC19K0349

Applying machine learning approaches to COSI is supported by the Gordon and Betty Moore Foundation through Grant GBMF3834 and by the Alfred P. Sloan Foundation through Grant 2013-10-27 to the University of California,

This research used resources of the National Energy Research Scientific Computing Center (NERSC), a U.S. Department of Energy Office of Science User Facility operated under Contract No. DE-AC02-05CH11231.

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