The Nuclear Compton Telescope

A balloon-borne gamma-ray spectrometer, polarimeter, and imager

Andreas Zoglauer

for the NCT collaboration

The NCT Collaboration:

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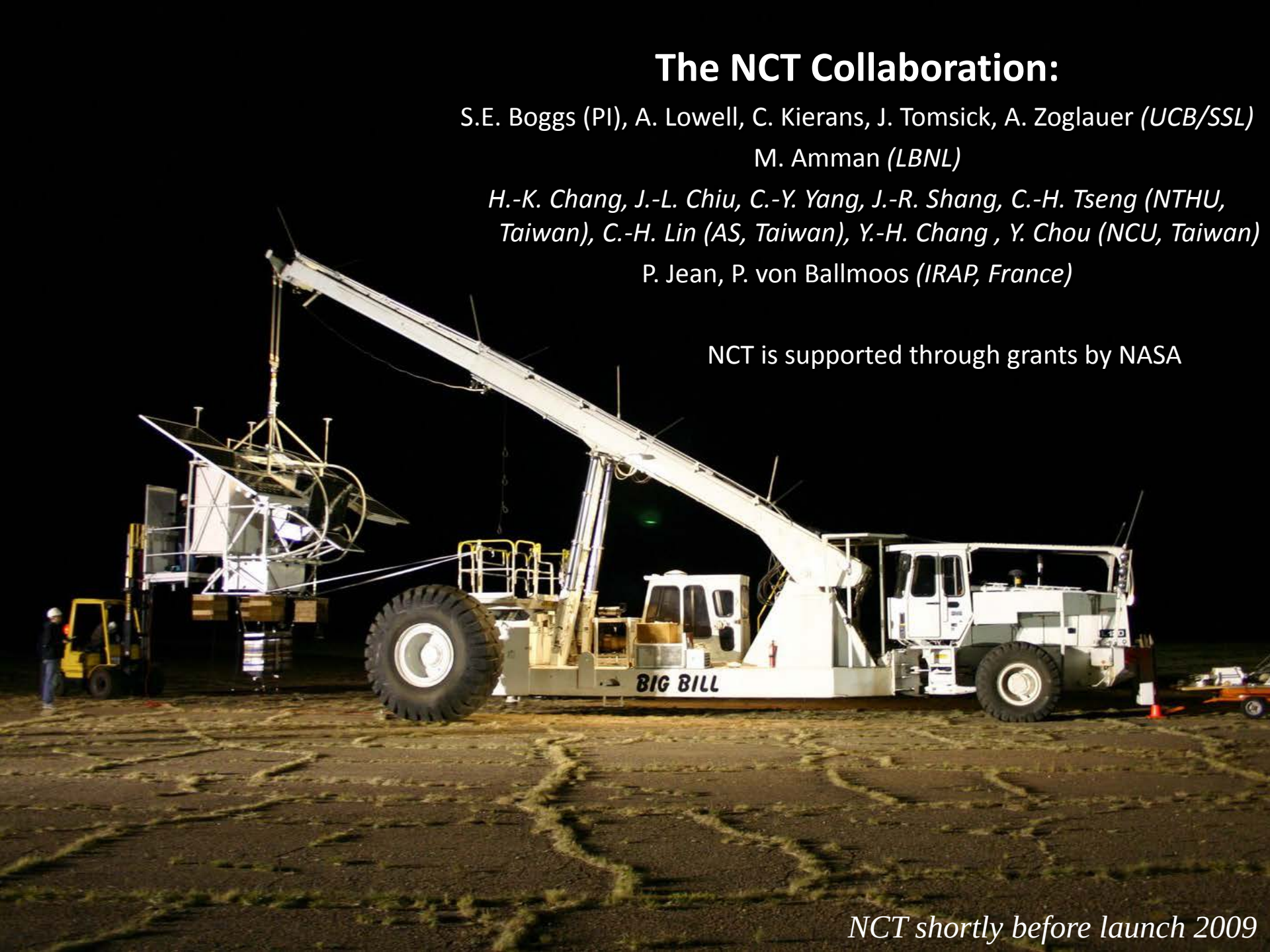
M. Amman *(LBNL)*

H.-K. Chang, J.-L. Chiu, C.-Y. Yang, J.-R. Shang, C.-H. Tseng (NTHU, Taiwan), C.-H. Lin (AS, Taiwan), Y.-H. Chang , Y. Chou (NCU, Taiwan)

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

NCT is supported through grants by NASA



NCT shortly before launch 2009

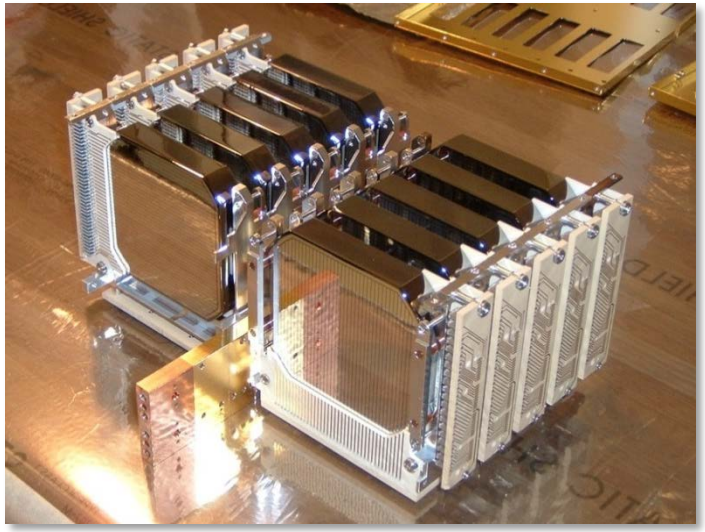
Overview: Instrument & Campaigns

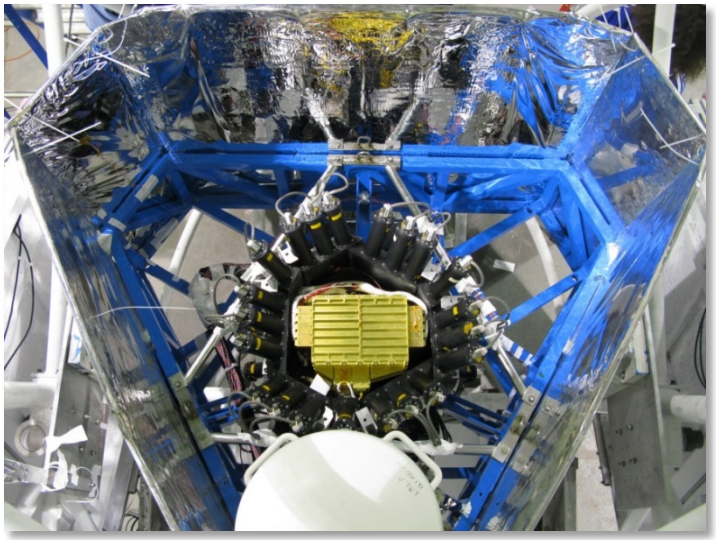
Instrument:

- 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:

- 2 GeD prototype flew from Ft. Sumner, NM on June 1st, 2005
- 10 GeD instrument flew from Ft. Sumner, NM on May 17th, 2009
- Failed launch from Alice Springs, Australia on April 29th, 2010
- Winter 2014/15: Antarctica campaign
- 2016 & 2018: New Zealand campaigns

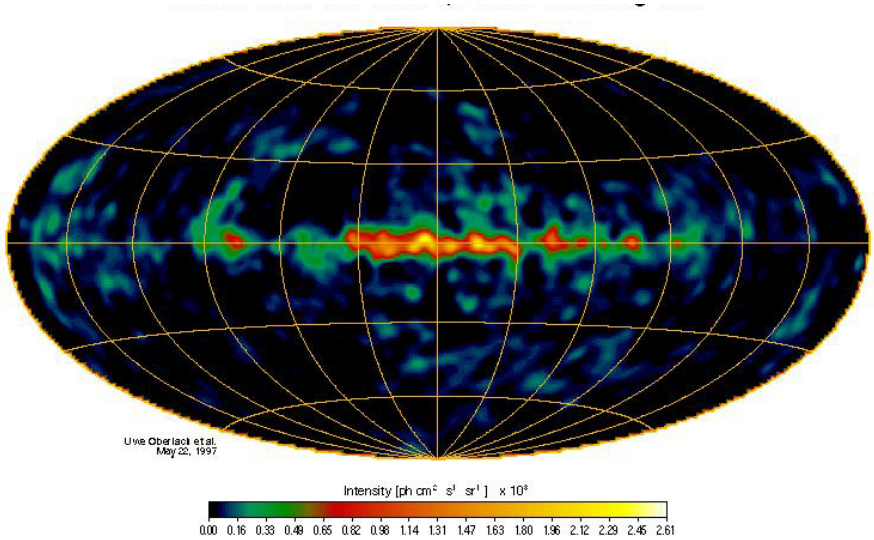




Overview: Science Goals

Unravel the mysteries of how the elements are created & understand the most energetic and violent explosions in our Universe

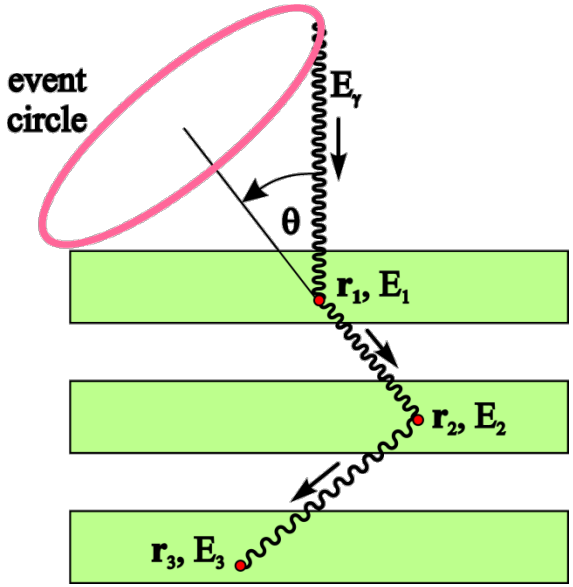
- Map Galactic nucleosynthesis
  - ^{26}Al (1.809 MeV), ^{60}Fe (1.173, 1.333 MeV), ^{44}Ti (1.157 MeV)
- Determine GRB polarization
- Map positron annihilation (511 keV) from the Galactic center and disc
- Observe compact objects and determine their polarization (if possible)
  - AGN
  - Black holes
  - Pulsars

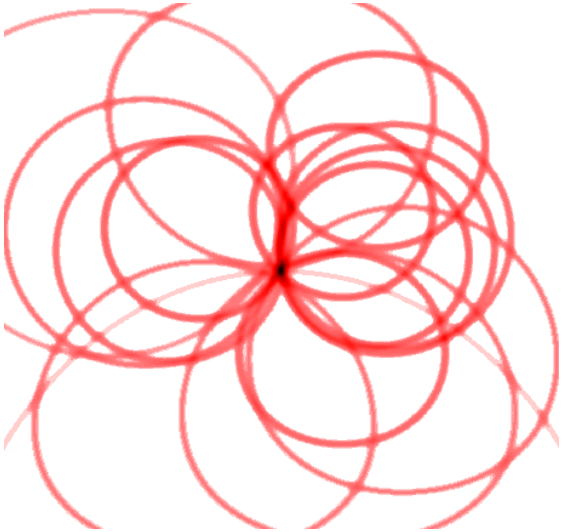


COMPTEL ^{26}Al all-sky map

Operating Principle

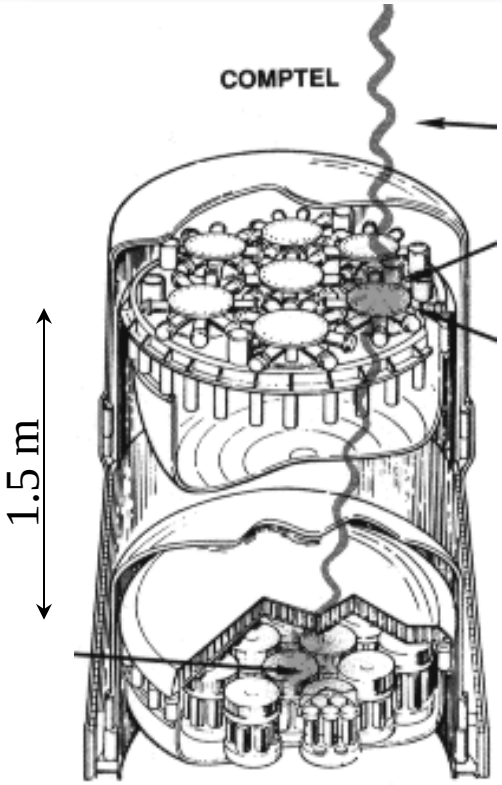
of NCT-style Compton telescopes



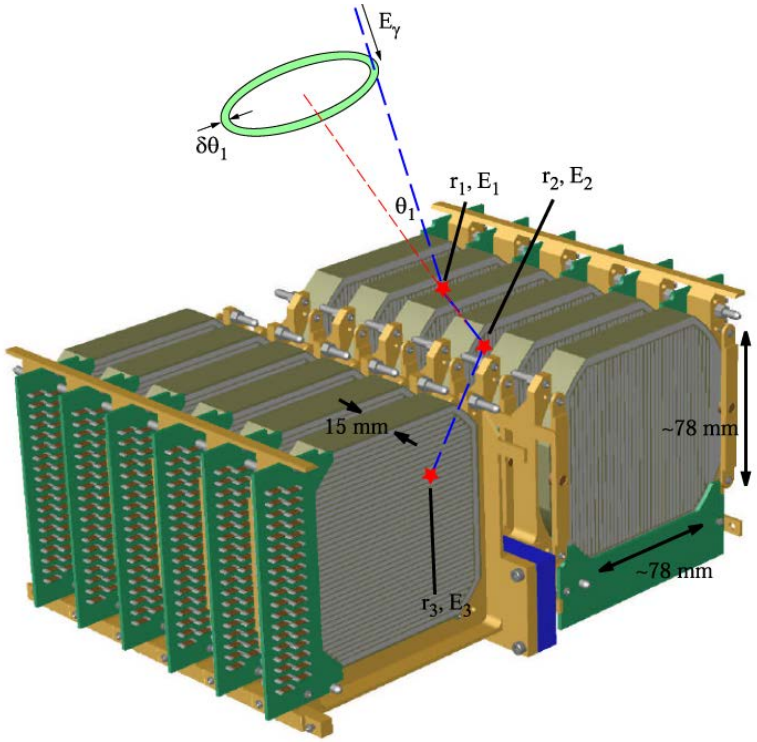


- Photons interact multiple times in active detector (here: Ge).
- The interaction sequence can be determined from information such as scatter angles, absorption probabilities, scatter probabilities
- The origin of a single not-tracked event can be restricted to the so called “event circle”.
- The photon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

Compton Telescopes: From COMPTEL to NCT



30+ years development



CGRO/COMPTEL:

- ~40 cm^3 resolution
- $\Delta E/E$ ~10%
- Up to 0.4% efficiency

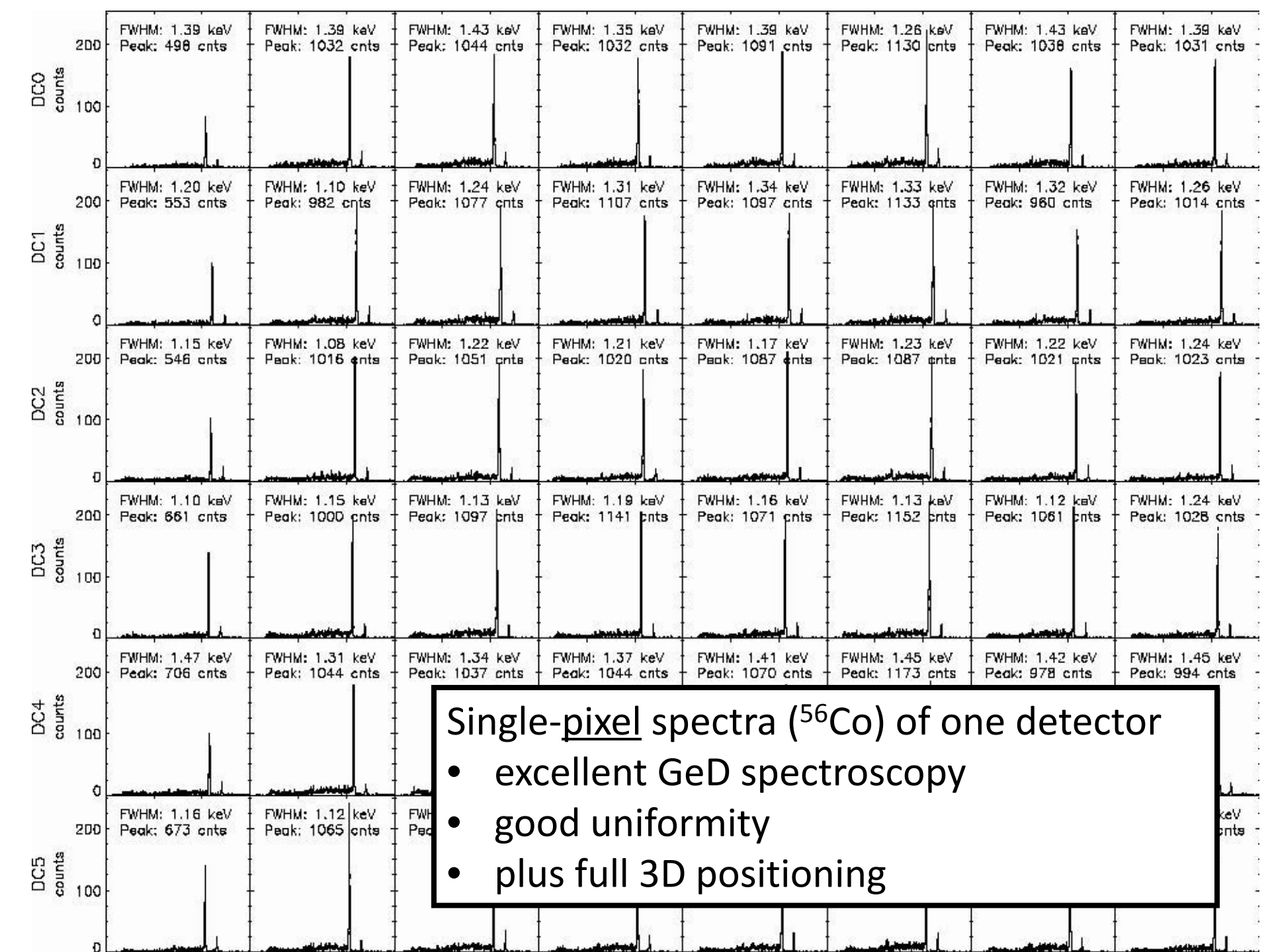
NCT:

- 1 mm^3 resolution
- $\Delta E/E$ ~0.2-1%
- Up to 16% efficiency
- background 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: 0.2-1% FWHM
- Excellent depth resolution: 0.5 mm FWHM
- 14 have been fabricated at LBNL
  - 10 have been used for the 2009 balloon flight, 12 will be used for the 2014 campaign

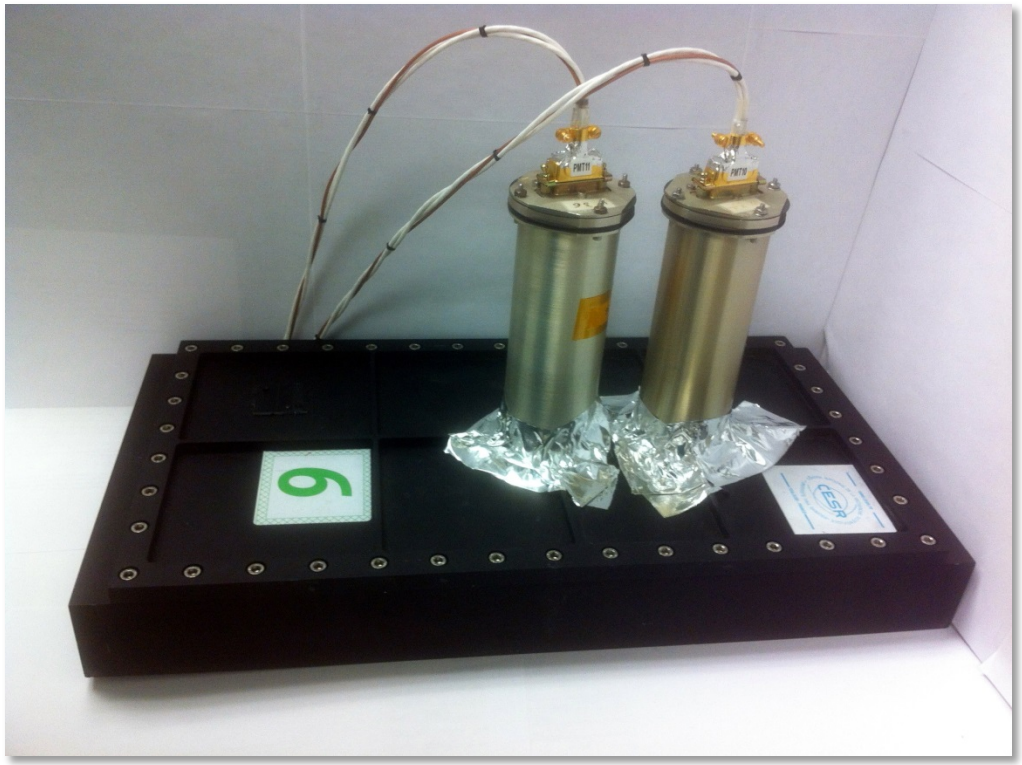


Single-<u>pixel</u> spectra (^{56}Co) of one detector

- excellent GeD spectroscopy
- good uniformity
- plus full 3D positioning

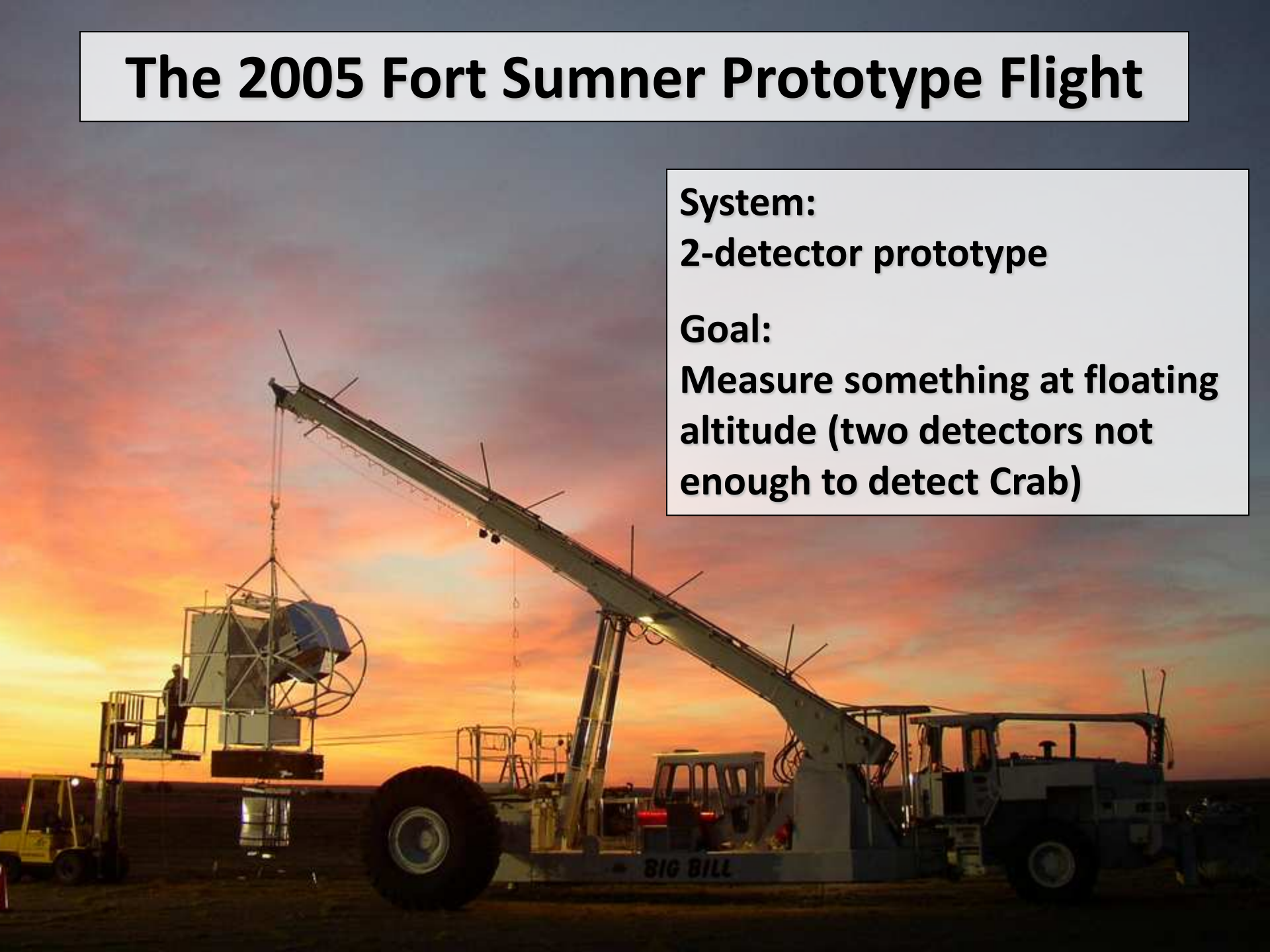
The Shield

- Goal: Veto dominating atmospheric background component
- Material: CsI (previous flights: BGO)
- Size: ~48 x 24 x 6 cm^3
- Weight: ~21 kg
- Veto threshold: ~80 keV
- 6 shields have been build by IRAP, France for 2014 and later balloon flights



One CsI shield module

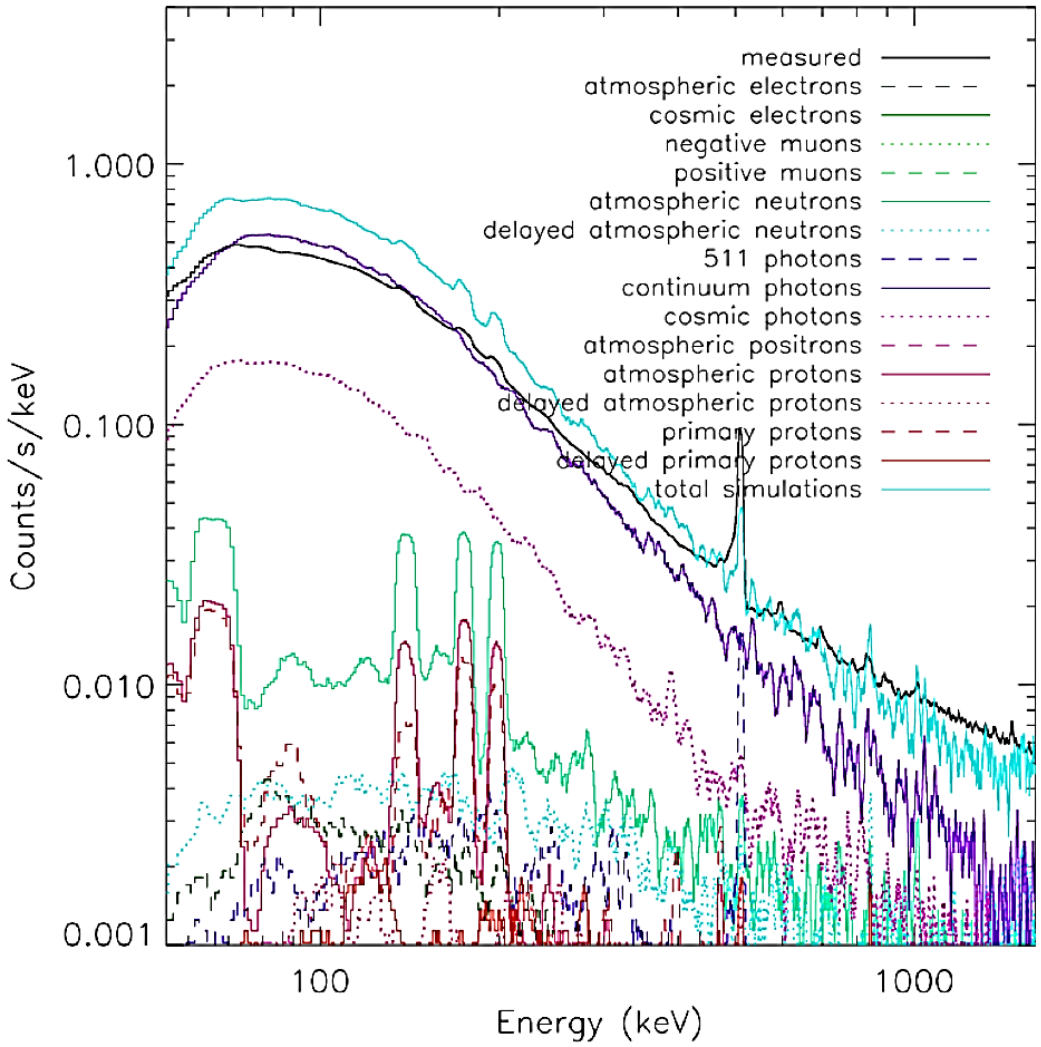
The 2005 Fort Sumner Prototype Flight



System:
2-detector prototype

Goal:
Measure something at floating altitude (two detectors not enough to detect Crab)

Key result: Background at Balloon Altitudes

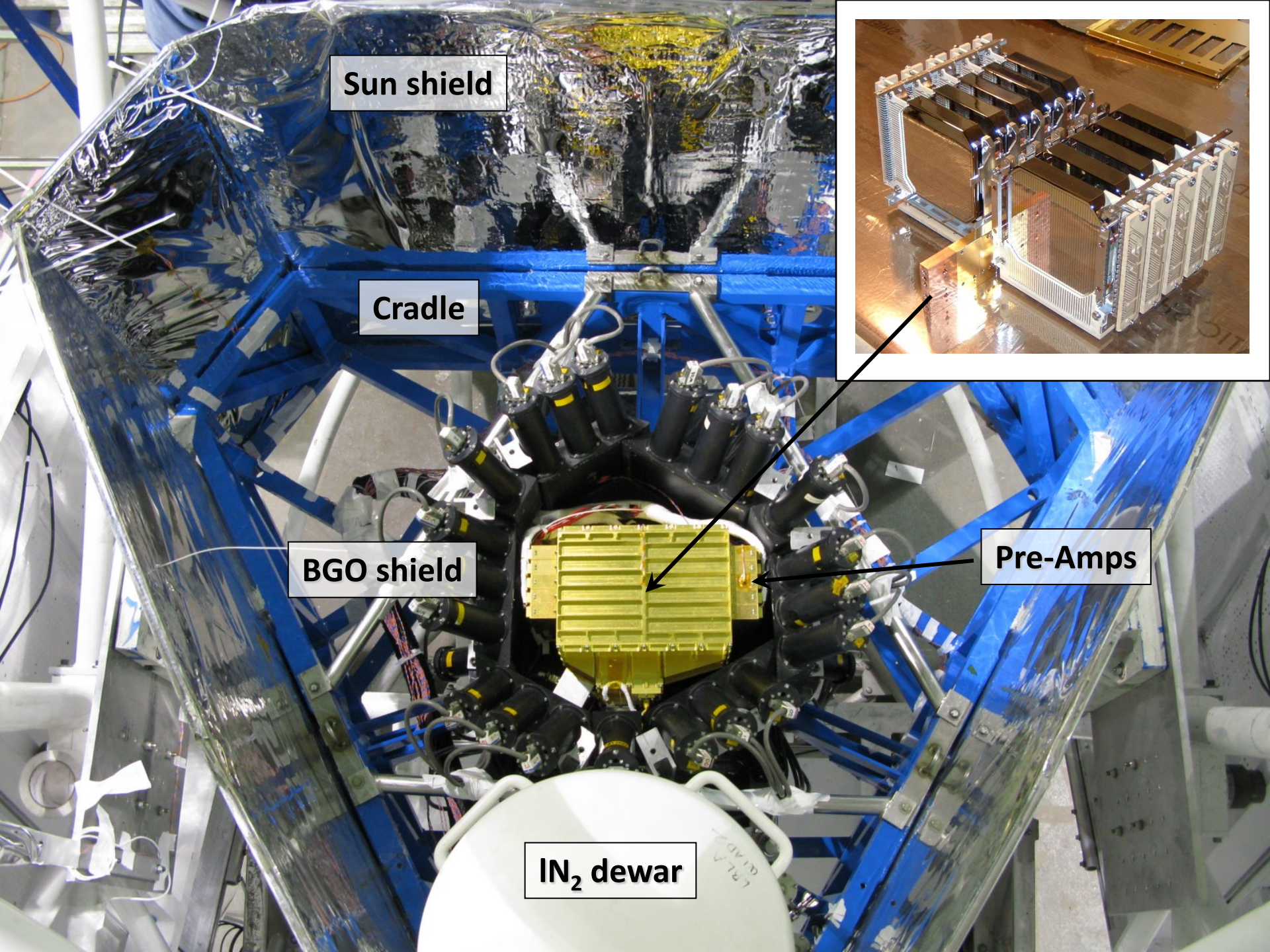


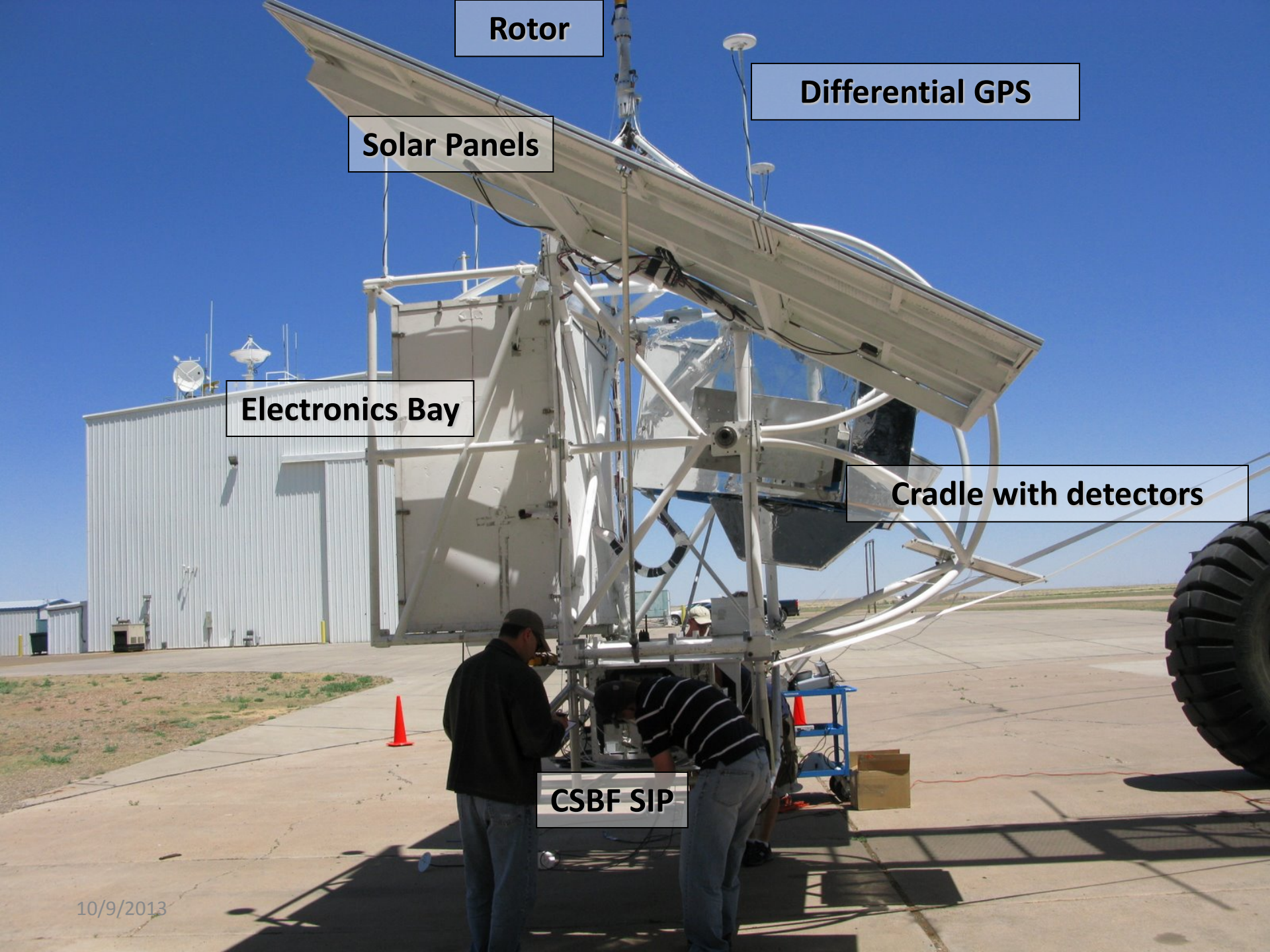
(J.D. Bowen et. al., IEEE, 2007)

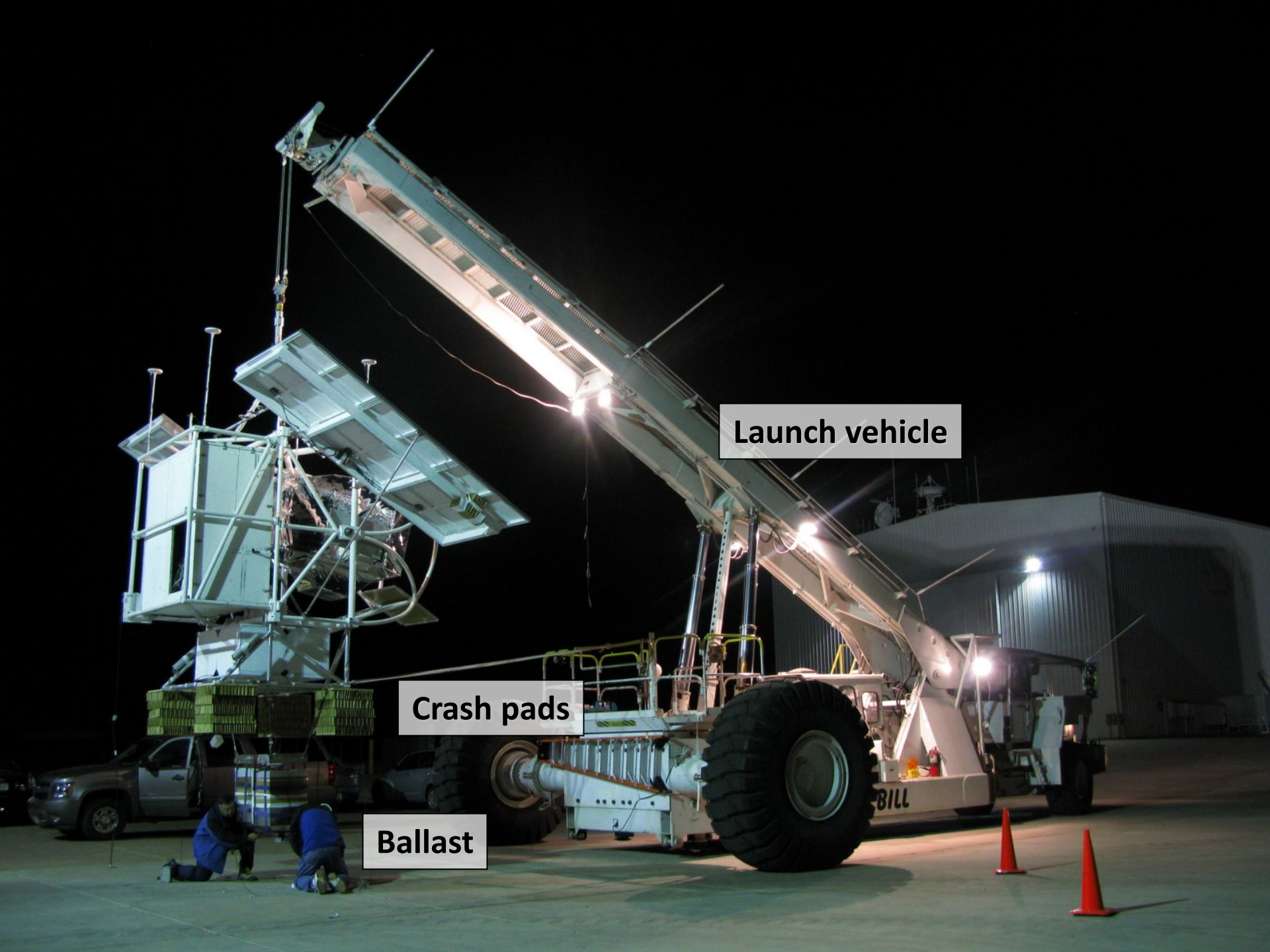
- 6 hour prototype flight from Ft. Sumner, New Mexico on June 1st, 2005.
- Measurement of gamma-ray background at balloon floating altitudes and comparison with simulations

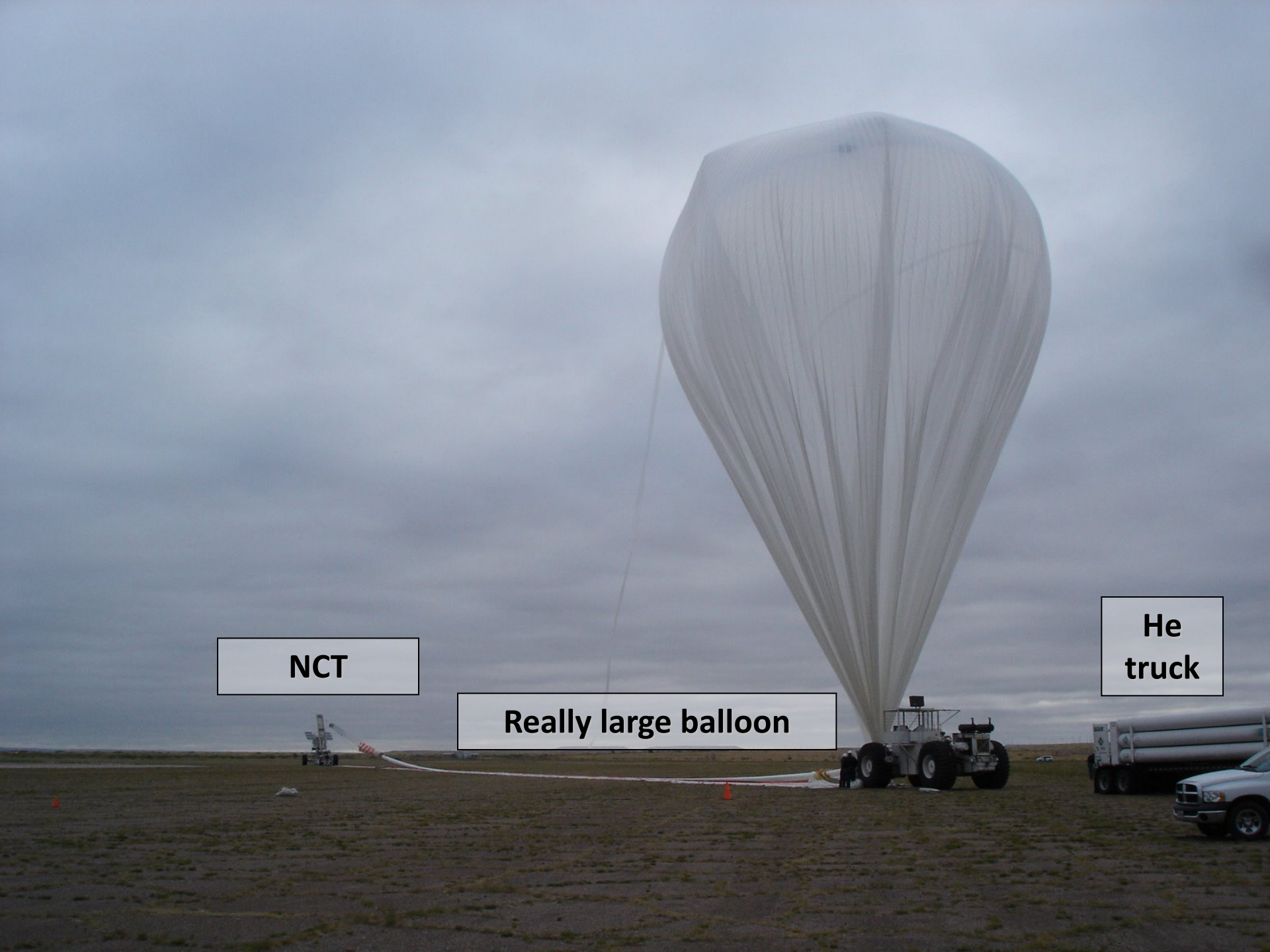
The 2009 Fort Sumner Campaign

Goal: Verify detection principle in a space radiation environment by detecting the Crab pulsar


Sun shield
Cradle
BGO shield
Pre-Amps
lN2 dewar


Rotor
Differential GPS
Solar Panels
Electronics Bay
Cradle with detectors
CSBF SIP


Launch vehicle
Crash pads
Ballast

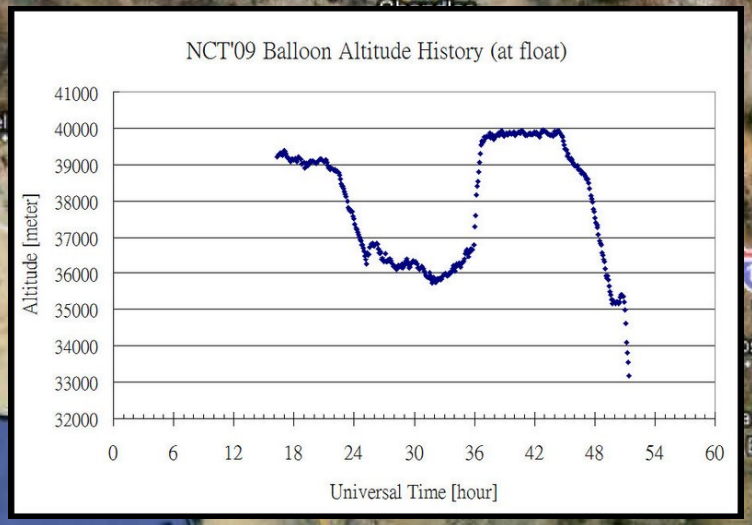

NCT
Really large balloon
He truck


Balloon will inflate to ~1 million m³ at floating altitude
Parachute


Tiny balloon illuminated by the sun

Roughly 38 hours flight!

Minor problems with rotor as well as the power supply during night and shortly before cut off



UFO sighted!

THE BUZZ

BACK TO THE BUZZ FEED

UFO Reported in Arizona and New Mexico!

05/19/09 by Kyle
KEYWORDS: Space, Science, Weird News

This week, many people in Arizona and New Mexico spotted a strange object in the sky. It seems that space aliens weren't flying this UFO, though. NASA claims that they had a research balloon flying over the area this week. The research balloon weighs 4,000 pounds and is used to measure gamma ray emissions.

Do you think the reported UFO was NASA's research balloon?

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Arizona UFO identified as NASA balloon

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Published: May 19, 2009 at 5:54 PM
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PALESTINE, Texas, May 19 (UPI) -- Experts said a UFO spotted over Arizona was a research balloon launched by the U.S. space agency to measure gamma ray emissions.

Bill Stepp of the Columbia Scientific Balloon Facility in Palestine, Texas, said the UFO reported Monday was a 4,000-pound balloon sent to measure the gamma ray emissions at high altitudes by the National Aeronautics and Space Administration, The Arizona Republic reported Tuesday.

Stepp said the balloon was sent out at about 7:30 a.m. Sunday from Fort Sumter in New

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Status after landing:

- Cryostat OK, detector remained cooled
- Damage to the gondola and to the solar cells
  - Easily repairable…

Summary:

- **~22 hour of good flight data**
- **Qualified for a long duration balloon flight**

Data Analysis Tool

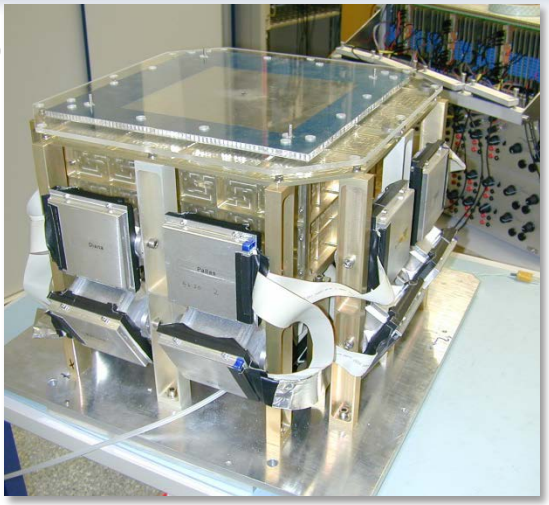
MEGAlib

The Medium-Energy Gamma-ray Astronomy library

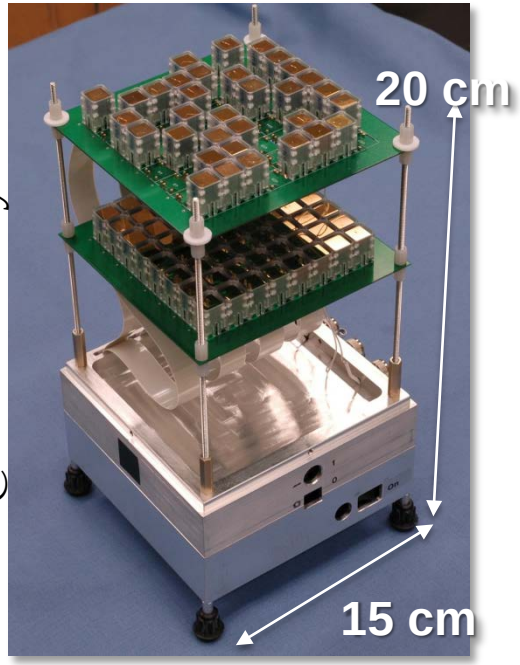
Provides simulation, calibration, and data analysis tools for hard X-ray and soft-to-medium-energy gamma-ray detectors/cameras/telescopes

Very flexible design allowing its easy application to different projects and missions, such as MEGA, ACT, NCT, COMPTEL, GRI, GRIPS, NuSTAR, ASTRO-H, HEMI, DUAL, hadron therapy simulations, X-FEL detectors, etc.

For more details see: http://megalibtoolkit.com



MEGA @ MPE/Garching



HEMI @ LBL/Berkeley

The NCT Data Analysis Pipeline

Data acquisition and storage

↓

Calibration including energy calibration with charge loss and charge sharing correction, strip pairing, depth/position calibration

↓

Event reconstruction (determining the sequence of the hits in the detector) of Compton events using a Bayesian model selection approach.

↓

Event selections by energy, scatter angle, interaction distances, Earth horizon distance, Bayesian quality factor, etc. to maximize sensitivity

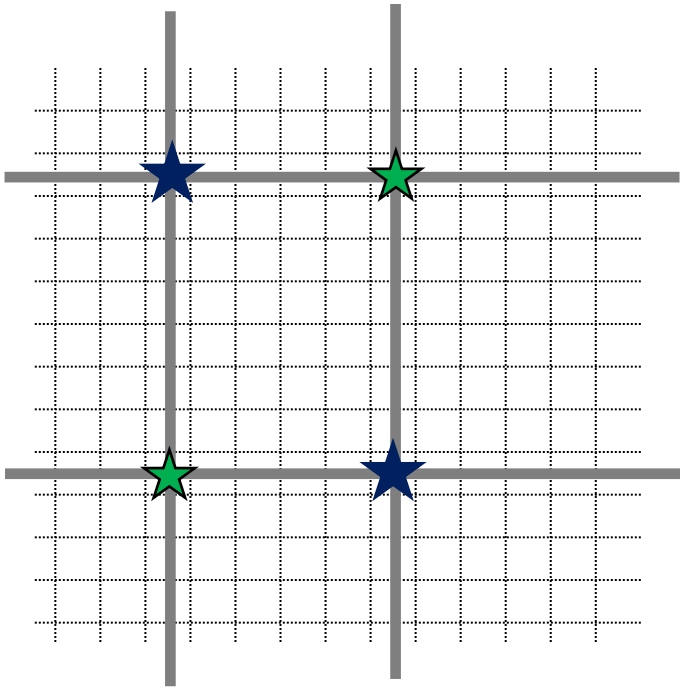
↓

List-mode **image reconstruction** taking into account the individual response of the detector and of each event

Analysis Challenge 1: Calibration

1. **Energy calibration** taking into account:
   - charge sharing between strips
   - charge loss between strips
   - cross-talk between strips

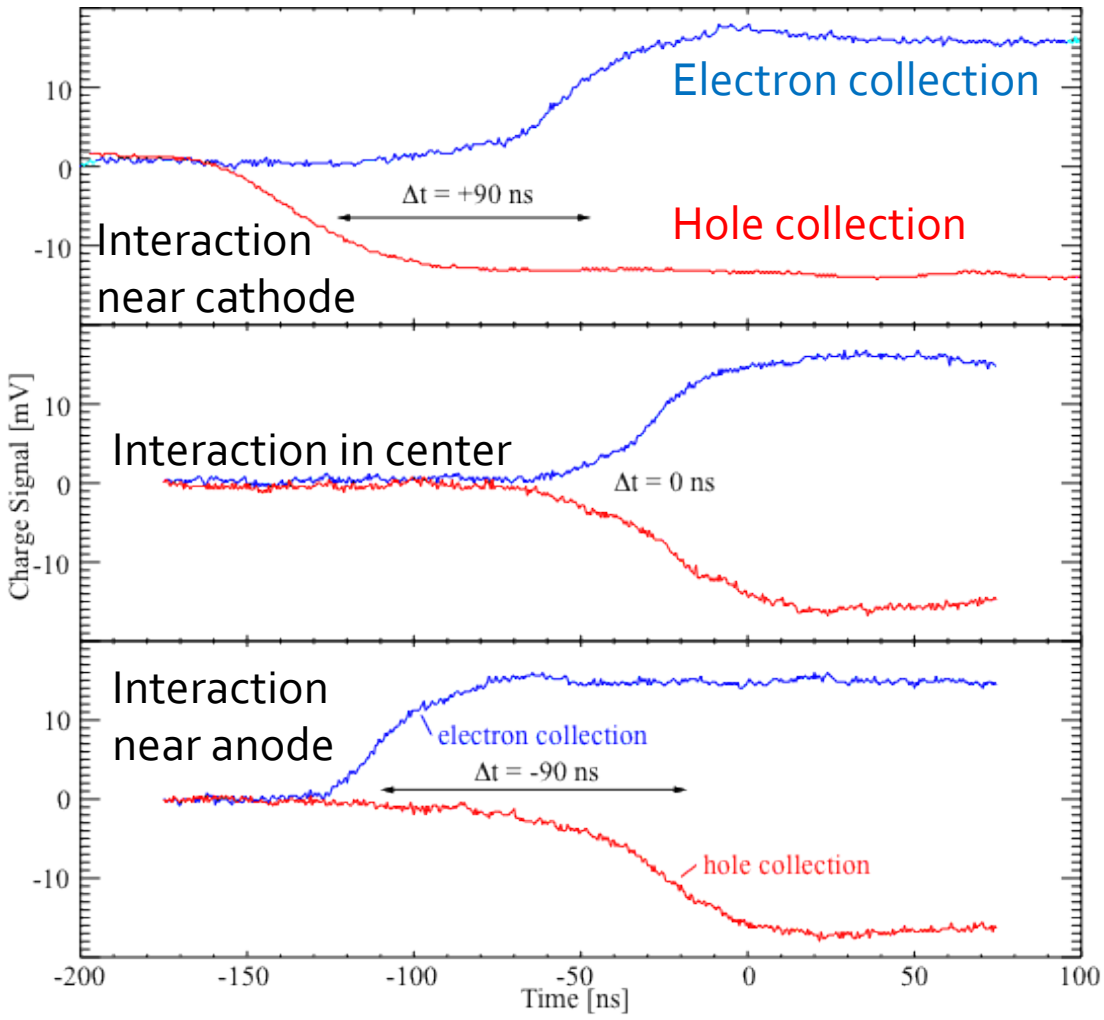
2. **Strip pairing** if more than one interaction happened in the detector



Is blue or green the right solution?

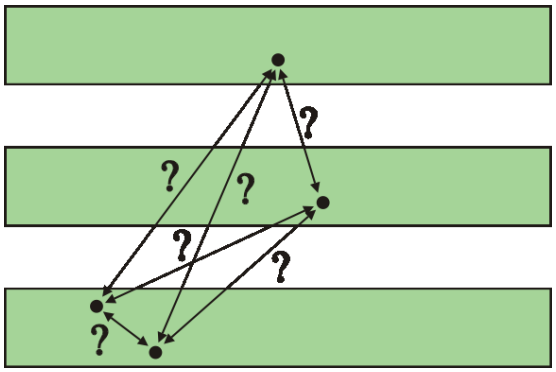
Analysis Challenge 1: Calibration

3. **Depth calibration** by considering the different charge collection times for electrons and holes as a function of interaction depth as well as the timing differences between strips

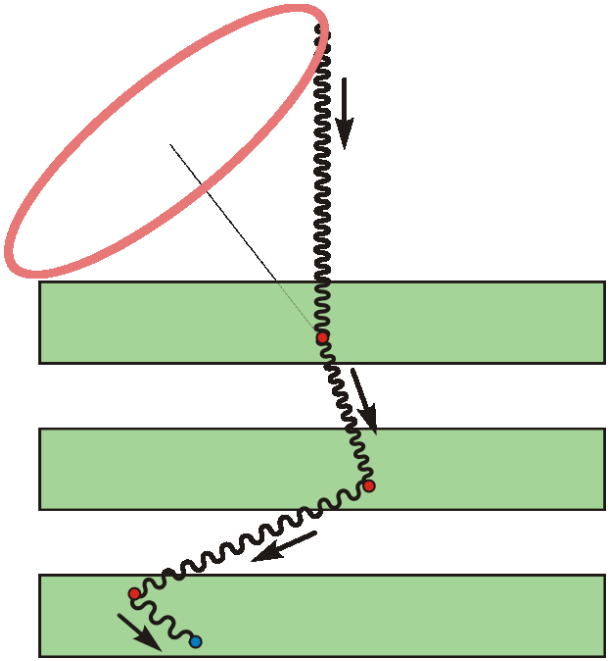


Analysis Challenge 2: Event reconstruction

Where did the photon come from?



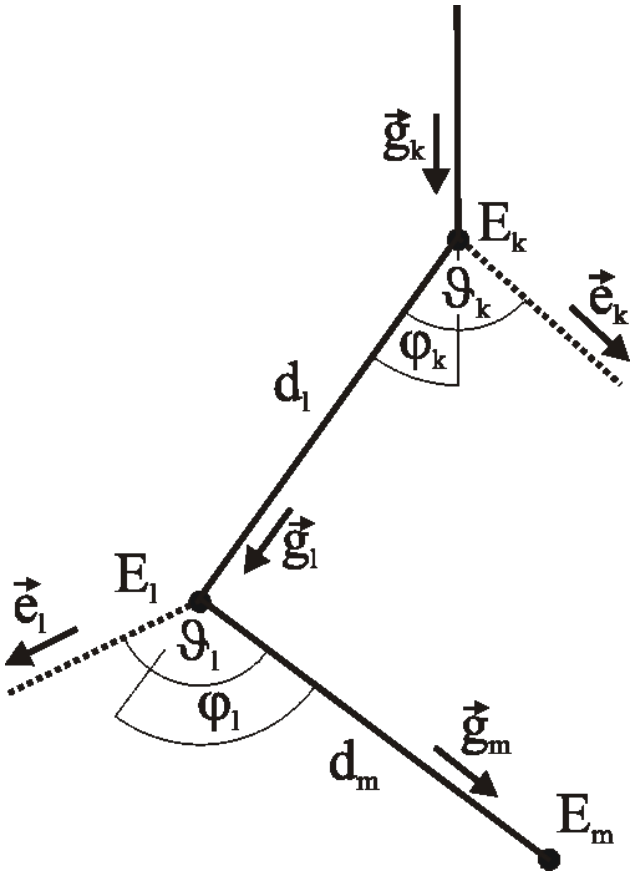
Compton event reconstruction



Main goals of event reconstruction:

- Reconstruct the path of the original photons
- Find the parameters of the original Compton interaction
- Determine if the event originated from a completely absorbed non-background photon

Analysis Challenge 2: Event reconstruction



Basic data:

- All measured information: N × (x,y,z,E)

Enhanced data:

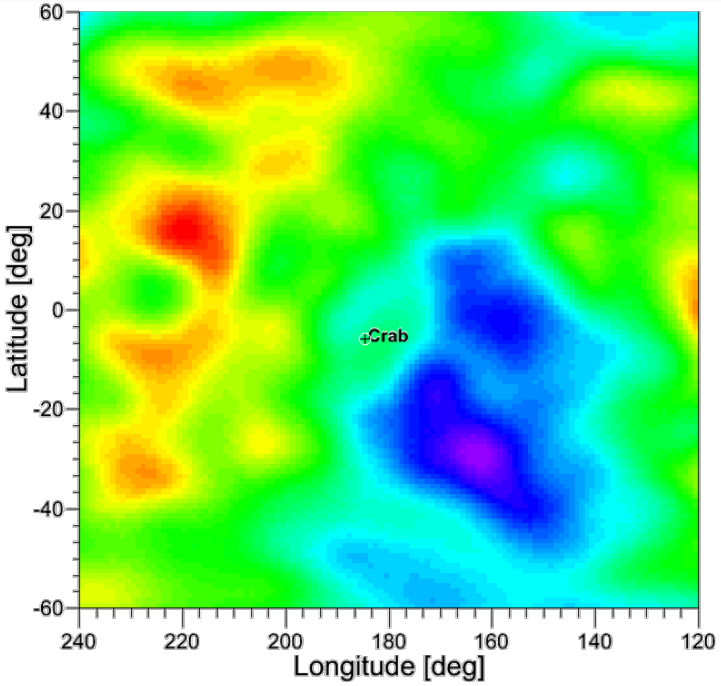
- Redundant scatter angles:

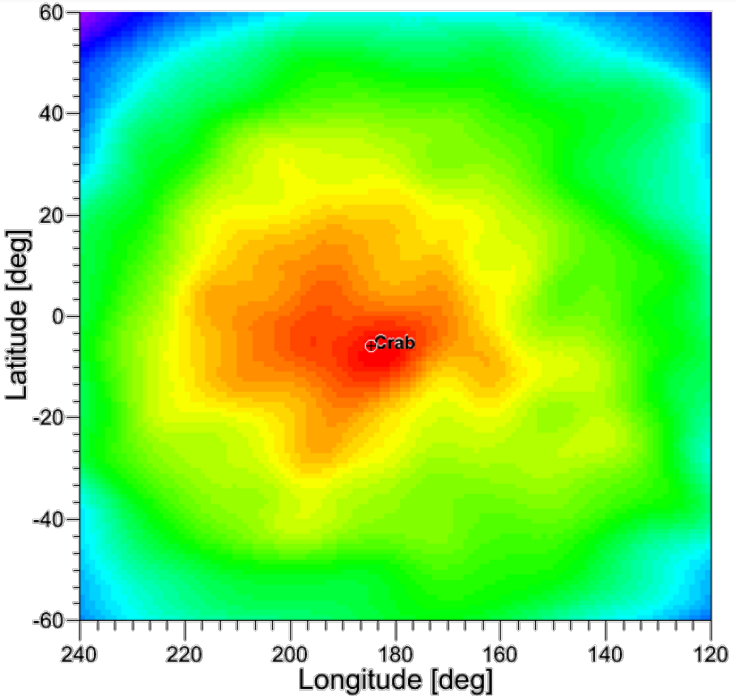
  Angles φ_l, ϑ_k, ϑ_l can be determined via geometry and via Compton kinematics ($d\varphi$, $d\vartheta$-criterion)!
- Absorption probabilities along d_l, d_m
- Klein-Nishina scatter probabilities
- Probabilities that the above are measured with the current geometry.

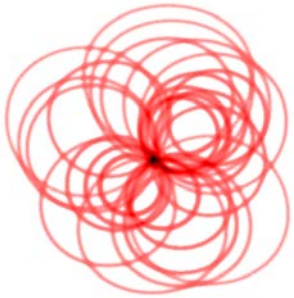
Approaches:

- Classic CSR based on χ^2 method
- Bayesian ← best background identification!
- Neural Network

Analysis Challenge 3: Event Selections







Images show backprojections only

Left: All data (with time cut) - no event selections

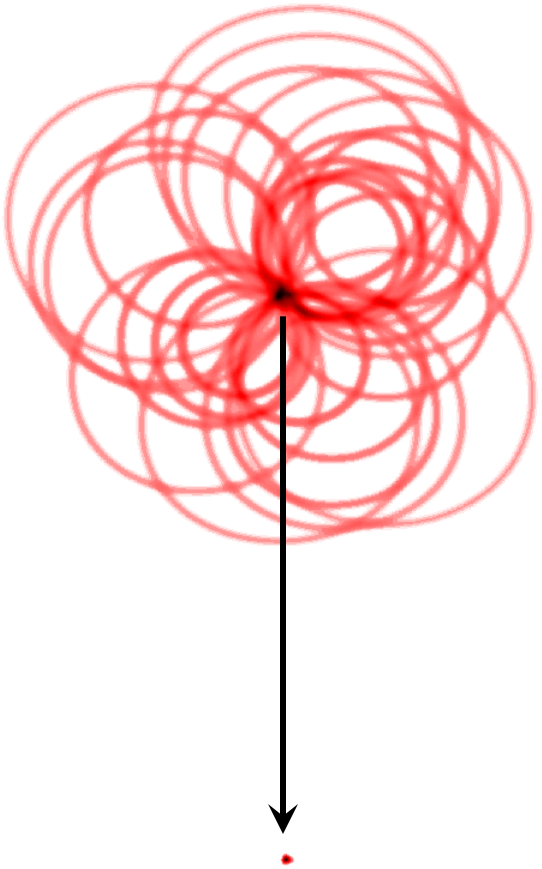
- Dominated by atmospheric background

Right: Optimized event selections

- Dominated by emission from "above"
- Cut on energy, earth horizon distance, event reconstruction quality factor, Compton scatter angle
  - ➢ But at the cost of a reduced effective area!

Challenge 4: Image Deconvolution

Deconvolution = Determine image by "undoing" the measurement process



$$D(\vec{d}) = T(\vec{d};\chi,\psi) \times I(\chi,\psi) + B(\vec{d})$$

measured data	detector response	sky distribution	detector background

Problem:

- No unique solution for recovering "I"

Some iterative approaches:

- Maximum-likelihood expectation-maximization
- Maximum-entropy methods
- Multi-resolution approaches
- Stochastic origin ensembles

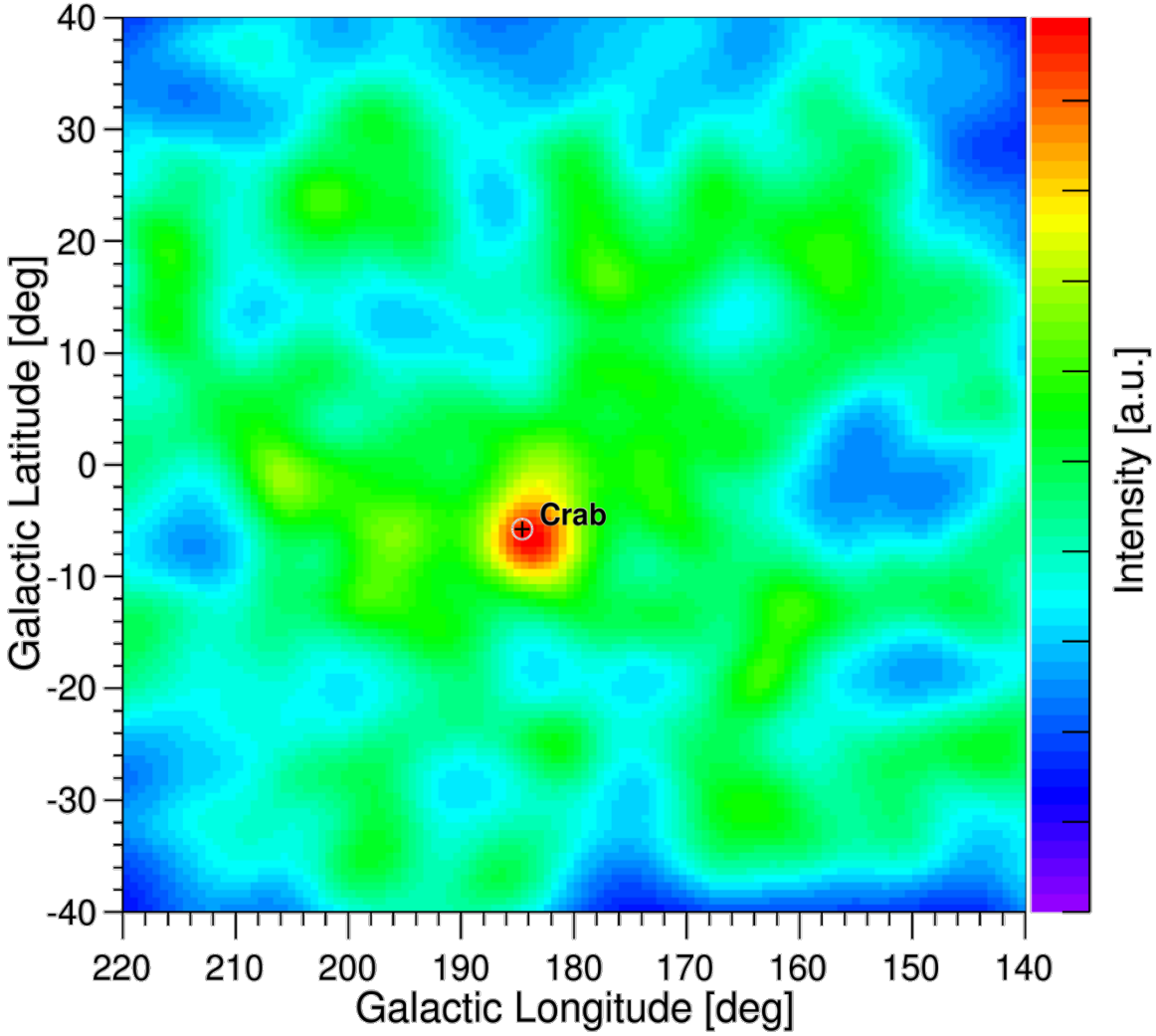
Crab Observation

Data:

- 7 hours at floating altitude of 40 km while Crab was in the field-of-view of NCT.
- Energy range: 0.25-1.5 MeV (excluding 511-keV background line)
- Event selections: Earth horizon cut, a Bayesian quality factor cut, and a cut on the Compton scatter angles ($\varphi < 90°$)

Interpretation:

- The **Crab** is clearly visible with a detection significance of ~6 sigma



Alice Springs Campaign – the "Mishap"

Location:

- Alice Spring, Australia – ideally suited to observe Galactic Center region

Primary science goals:

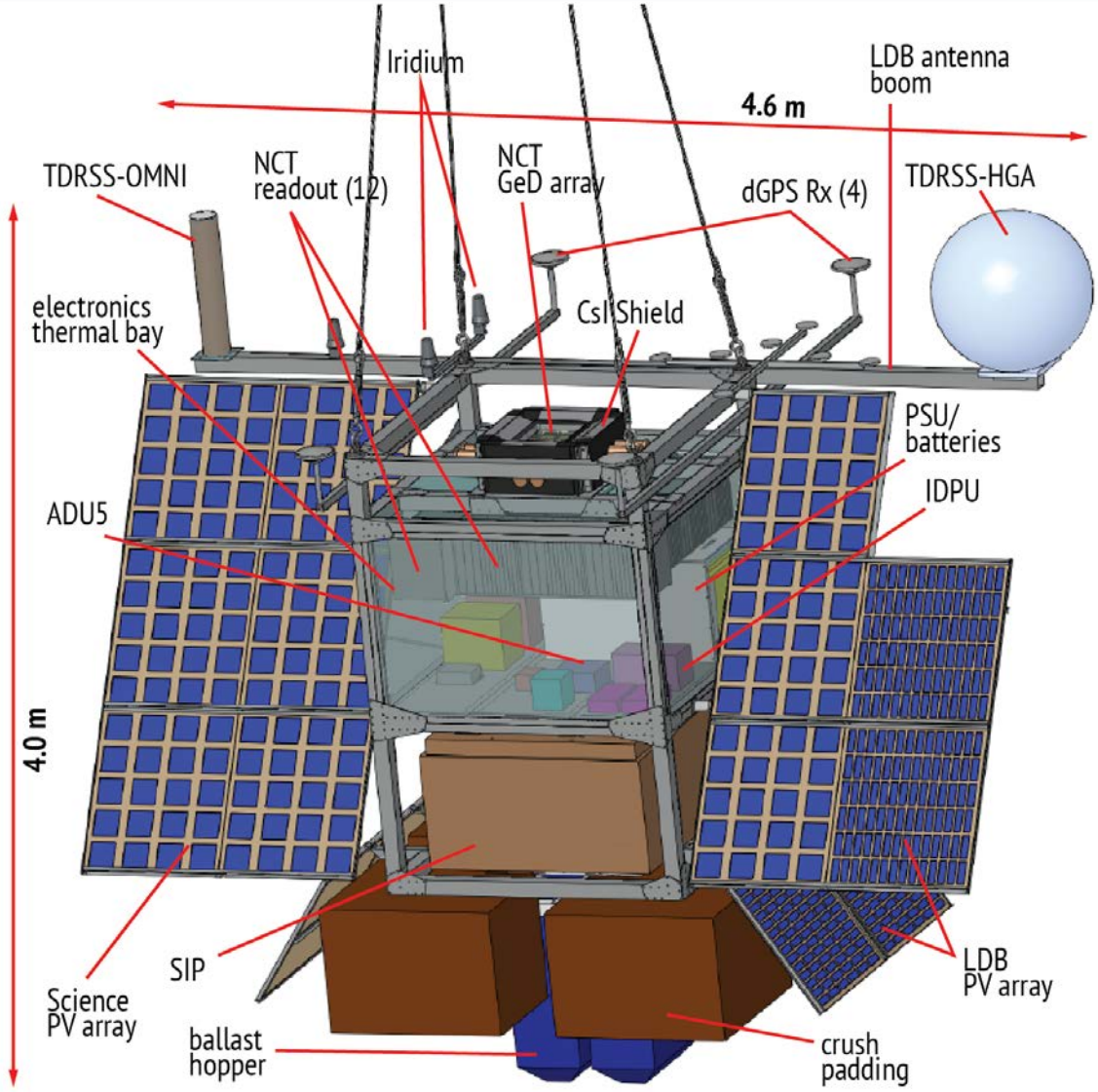
- Map galactic e^+-e^- annihilation as well as ^{26}Al emission

- Unfortunately NCT's launch attempt on April 29th, 2010 failed
- CSBF gondola release mechanism failed on launch resulting in a crash
- Fortunately, the detectors and electronics chains were relatively unharmed

NCT 2014 – the Upgrade

Key changes:

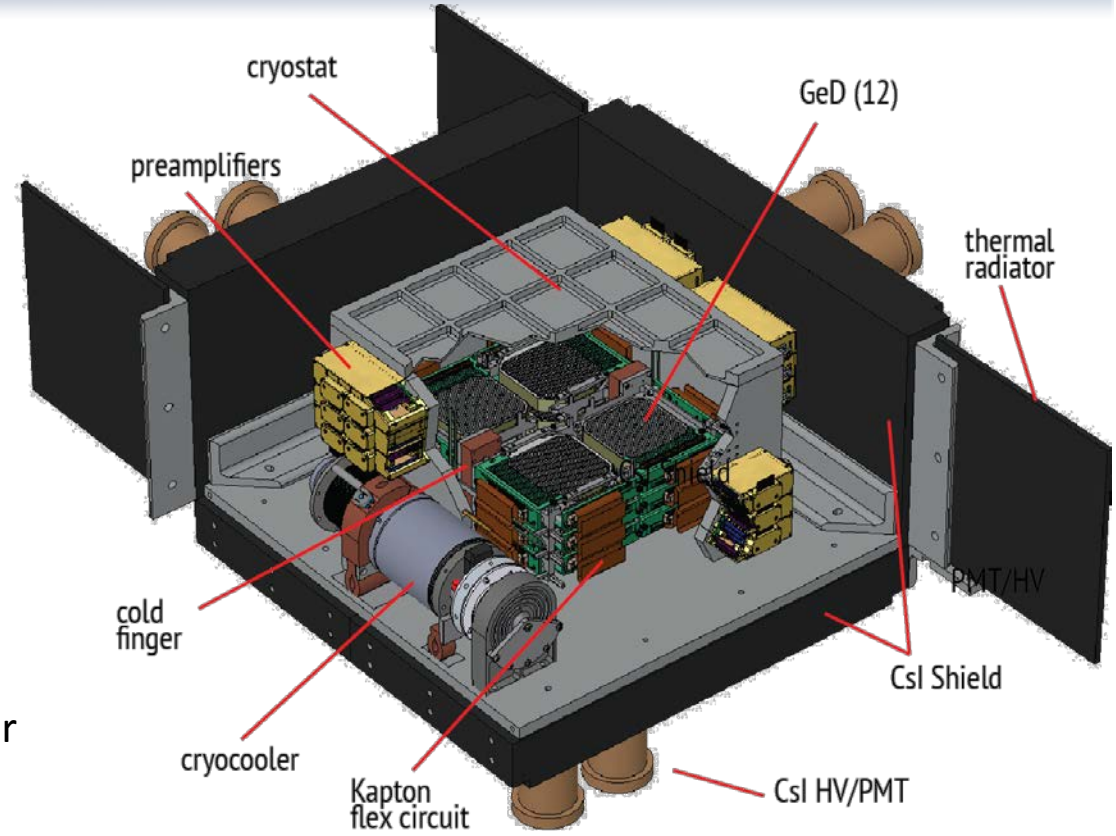
1. New lightweight gondola
   - Enables ULDBs (ultra-long duration balloon flights)



NCT 2014 – the Upgrade

Key changes:

1. New lightweight gondola
2. New shielding: CsI instead of BGO shields
   - More space available for detectors
3. Allows for: Improved detector geometry:
   - Improved field-of-view, better low-energy response, better polarimetry
4. Cryo-cooling instead of liquid Nitrogen cooling
   - Enables long and ultra-long duration balloon flights



The 2014/15 Antarctica Campaign

Flight type: LDB

Duration: up to 50 days
12/2014 → 1/2015

Main technical goal:

- Long duration test of upgraded system and real-time analysis (for GRBs)

Main science goals:

- Gamma-ray burst polarization
- Nuclear-line science in Carina region

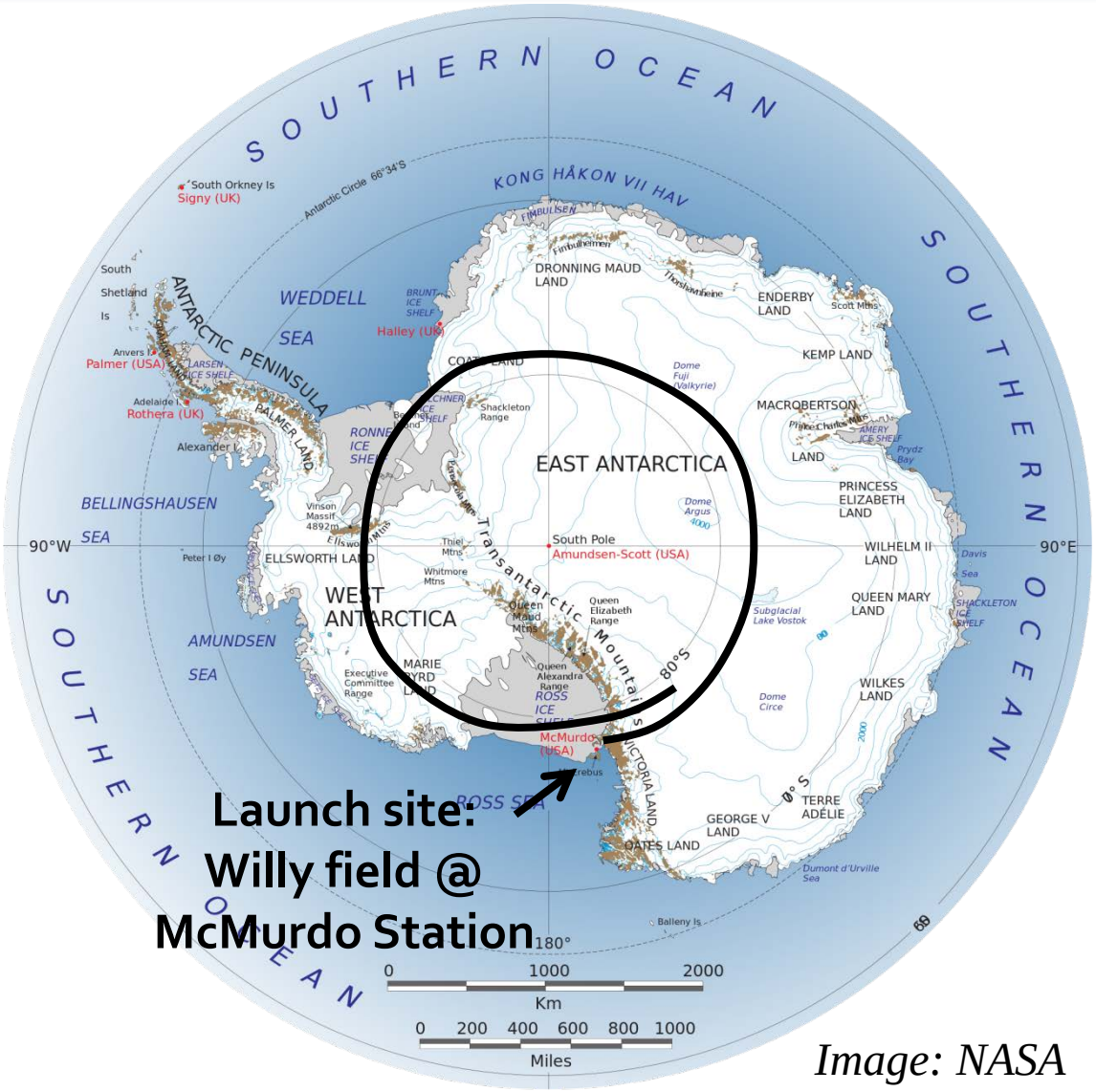
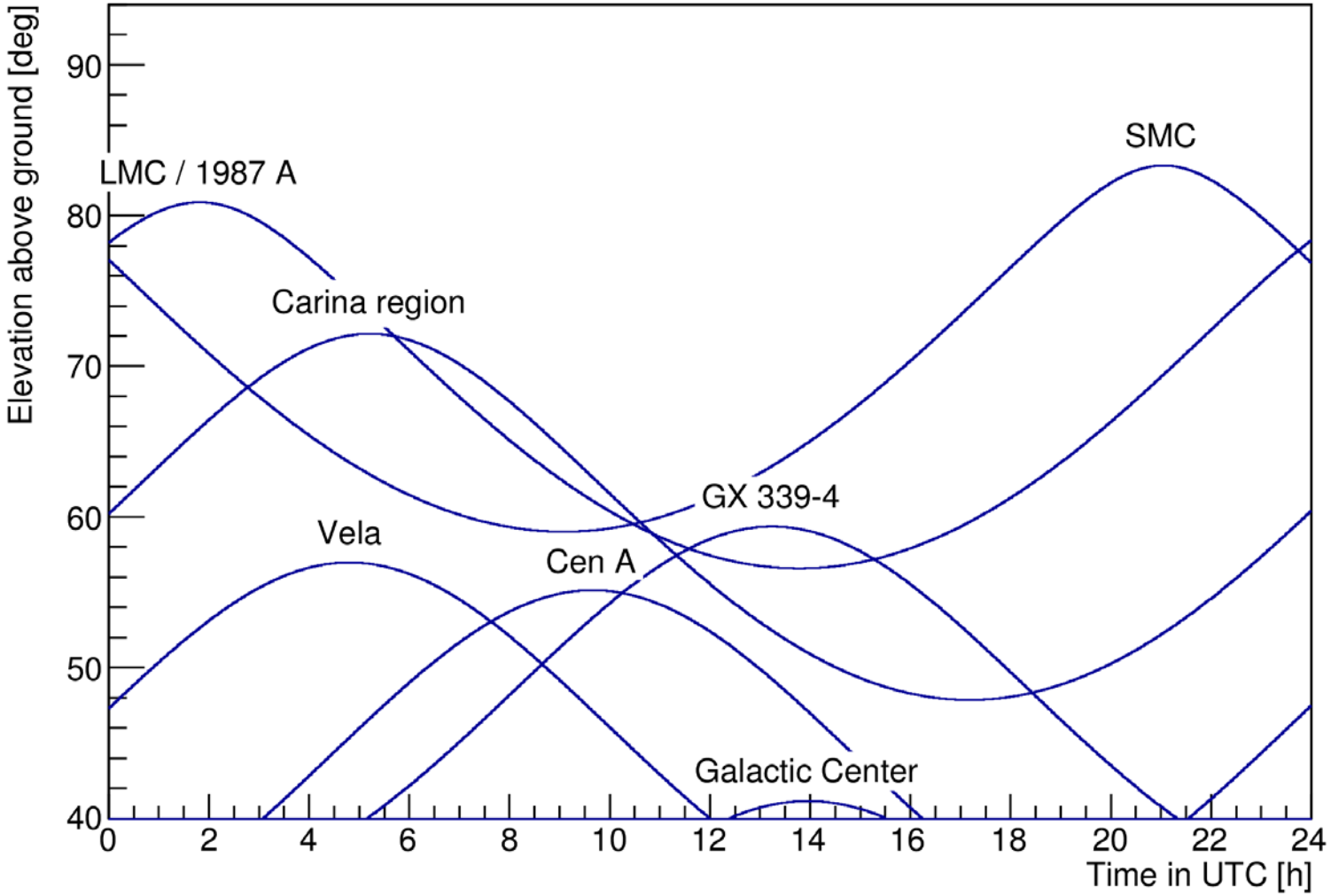


Image: NASA

Observable Sources Antarctica Campaign



The 2016 & 2018 New Zealand Campaigns

Flight type: Super-pressure ULDB

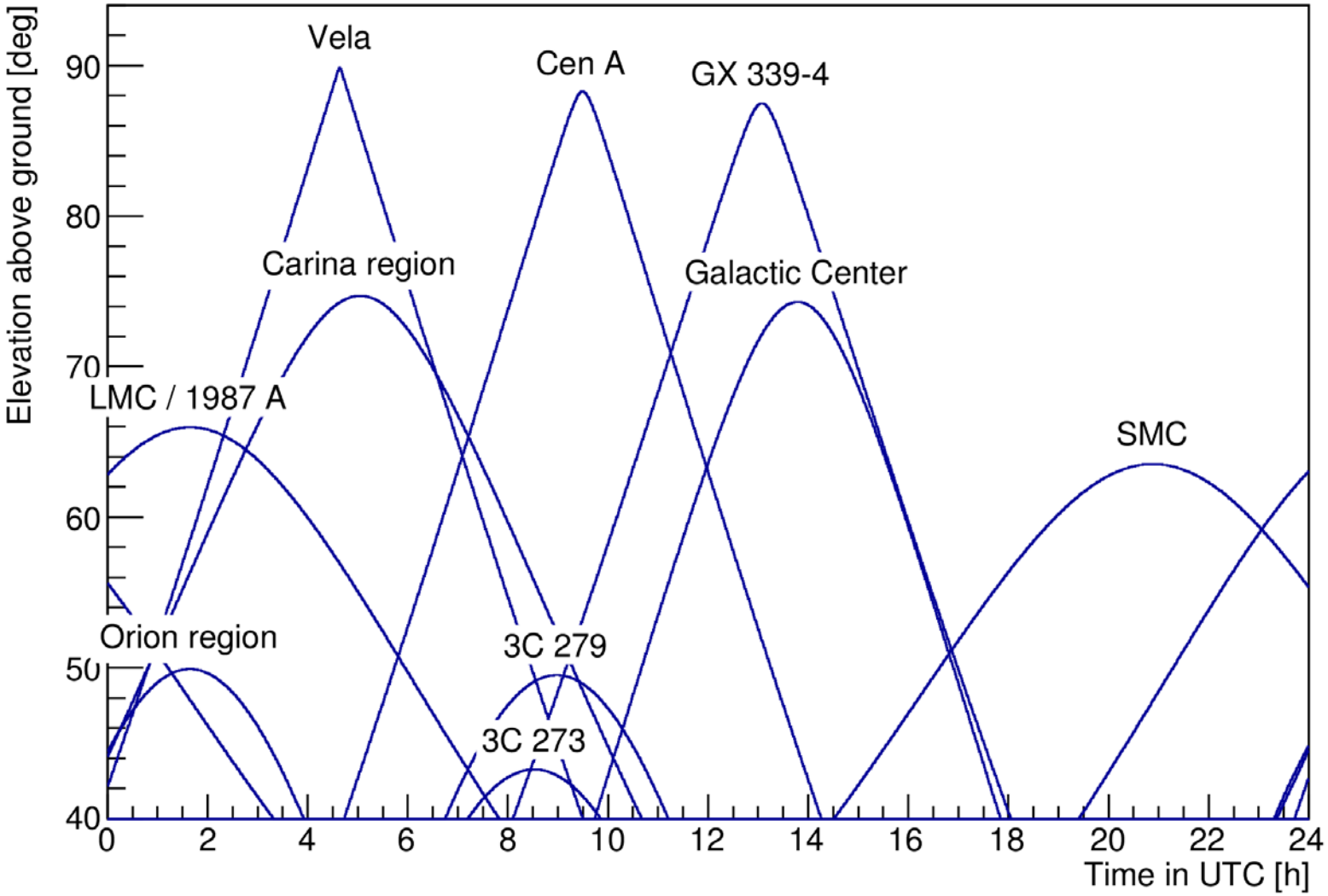
Anticipated launch dates: 2016 & 18

Duration: Up to 100 days – multiple times around the world

Main science goals:

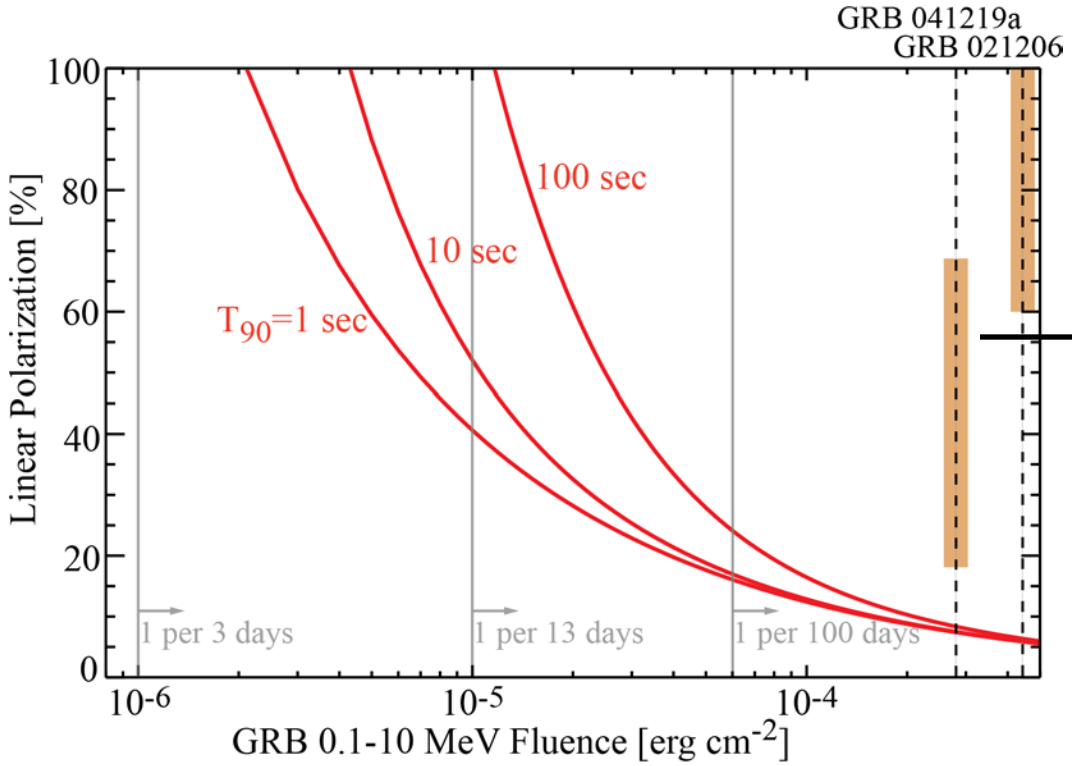
- Nuclear line science in Galactic Center region
- Gamma-ray burst polarization

Observable Sources New Zealand Campaign

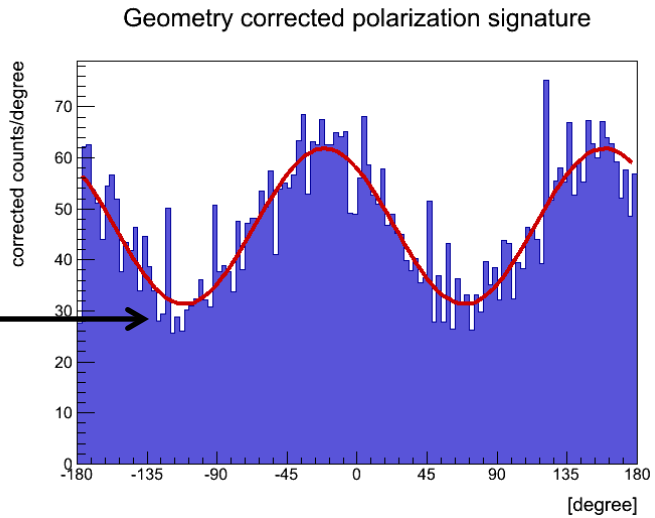


Gamma-ray Burst Science

3-sigma minimal detectable polarization as a function of fluence and burst duration



Simulation of GRB 041219a: (60% linear polarization)

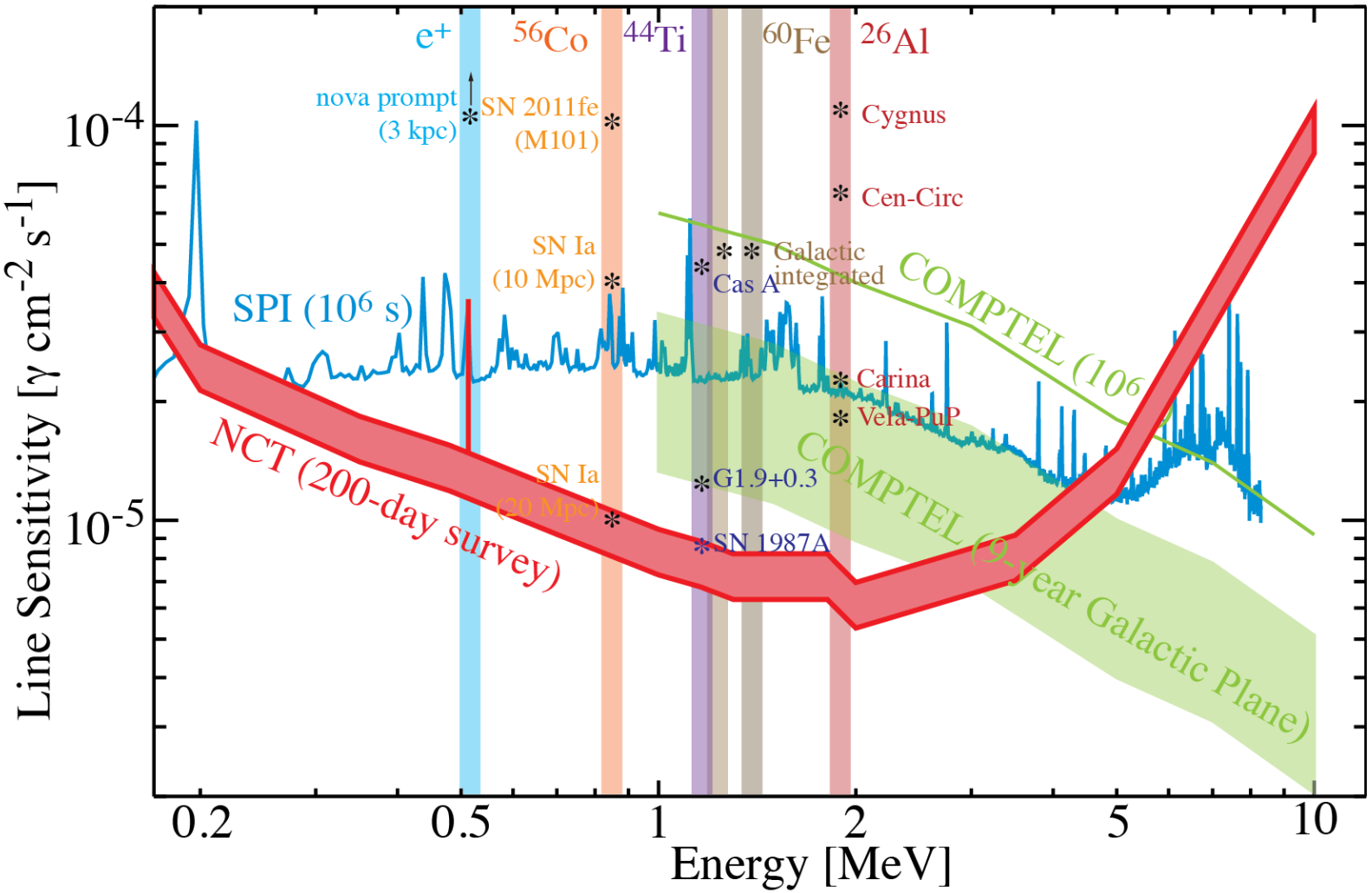


For bursts, we will downlink Compton and single-hit data, thus we will have spectra from ~30 keV to several MeV

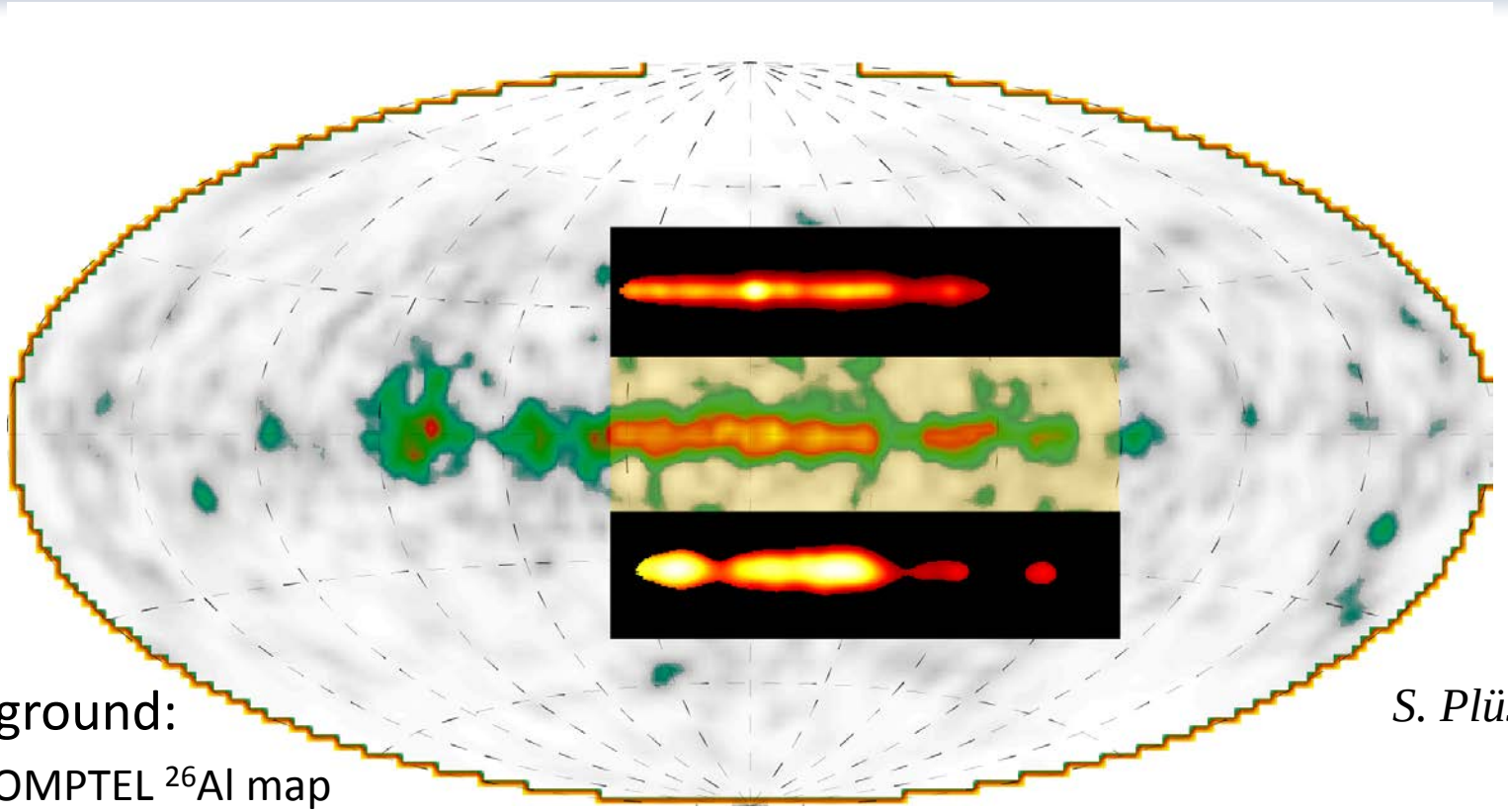
NCT should be able to get good polarization measurements of a few gamma-ray bursts!

Nuclear Line Science

in the Galactic Center region



Improve upon COMPTEL's ^{26}Al map



S. Plüschke

Background:

COMPTEL ^{26}Al map

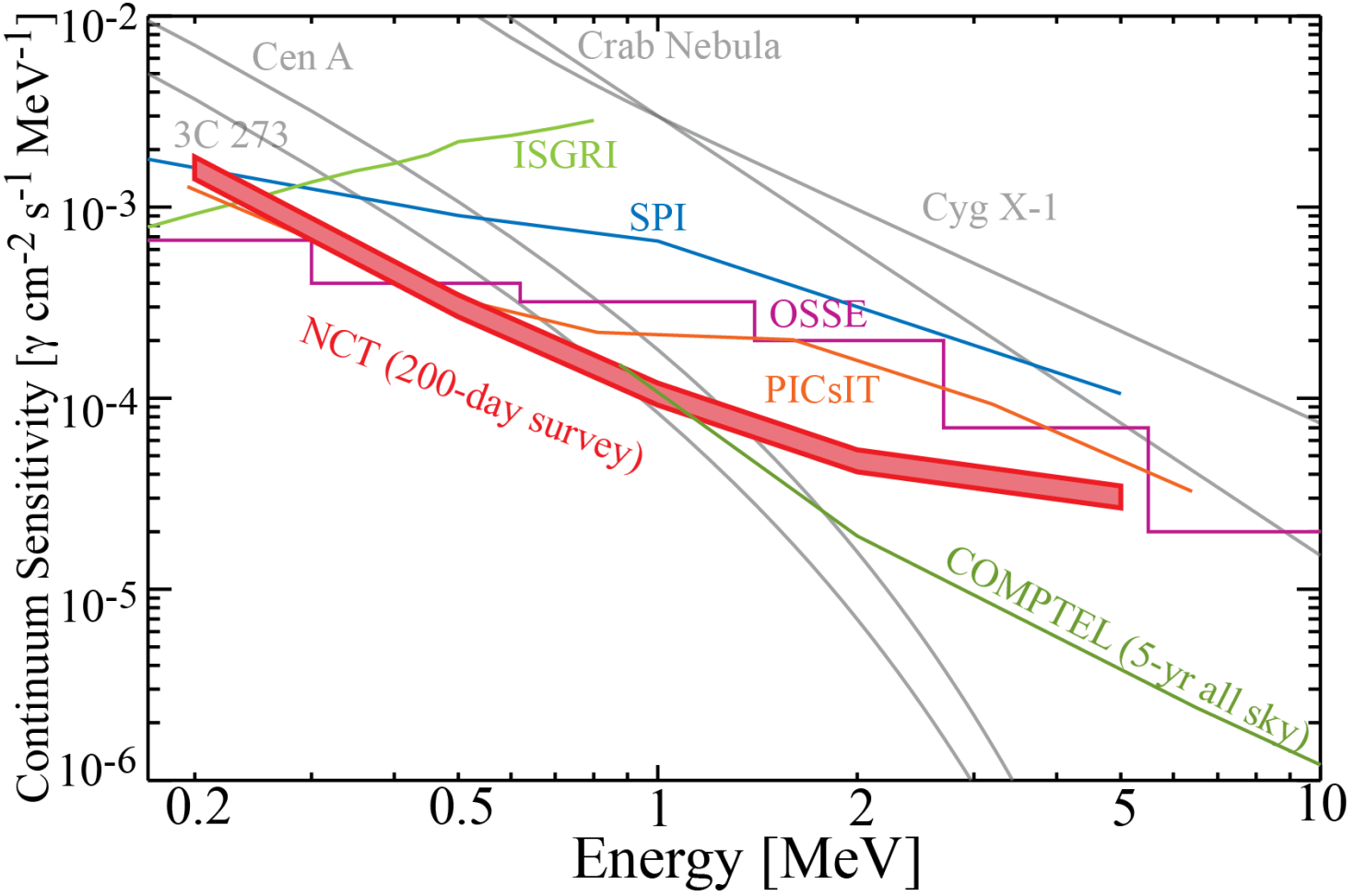
Foreground:

NCT simulations using different ^{26}Al tracer maps between which COMPTEL couldn't distinguish (top: DIRBE 240 um tracing dust – bottom: 53 GHz free-free emission tracing ionized matter)

Plus: Determine the origin of ^{60}Fe

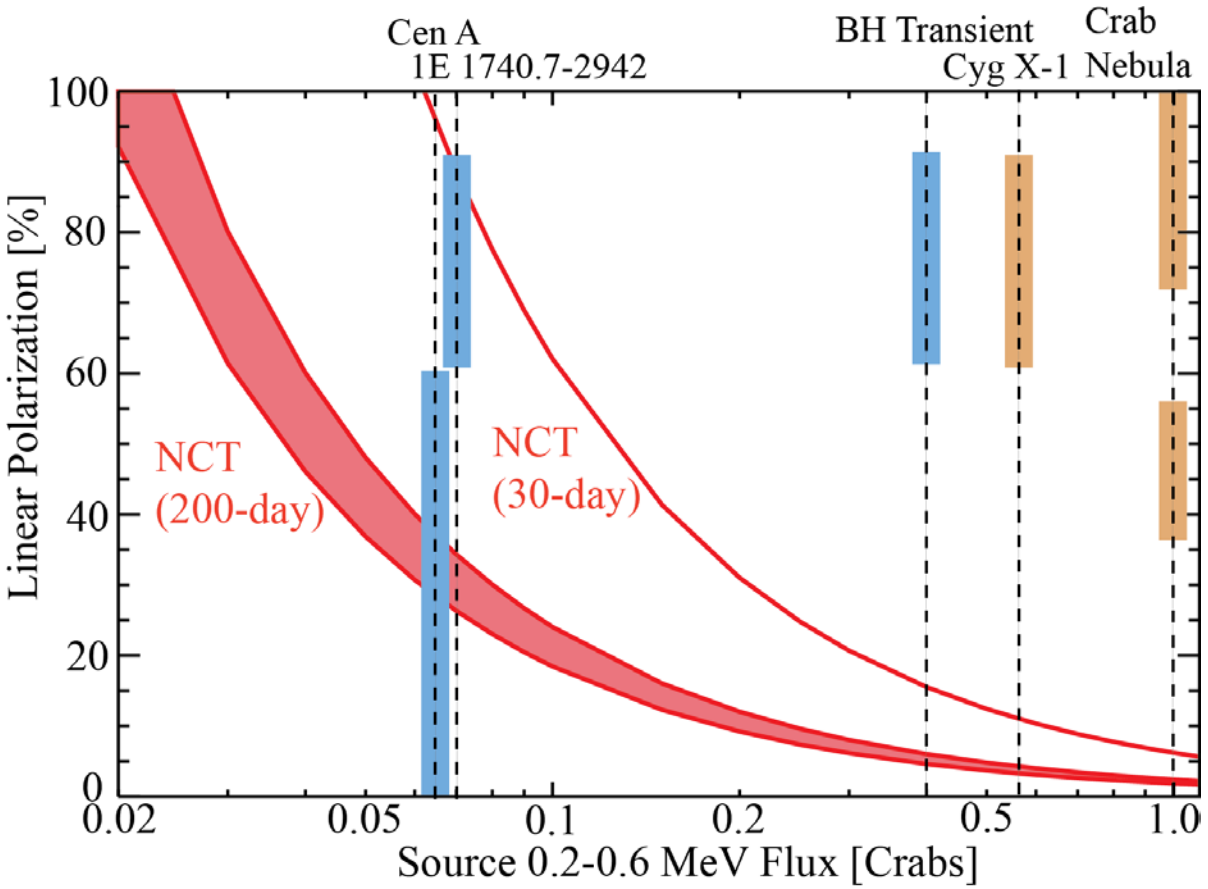
Continuum Sensitivity

3π, ΔE=E, all 1 Ms pointed, except COMPTEL and NCT



Polarization Performance

3-sigma minimal detectable polarization



Orange: Measured polarization (from Cyg X-1 and Crab)

Blue: Estimated polarization

Further detector developments

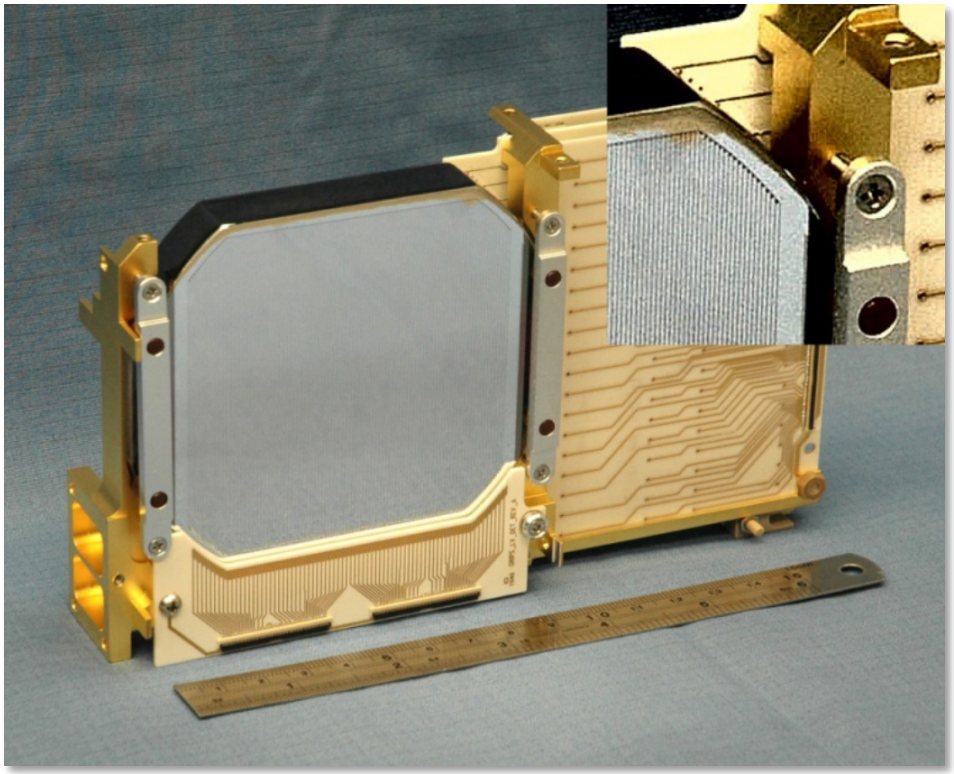
... in connection with GRIPS (= NCT-like system for solar observations):

Improved Germanium detectors with 0.5 mm instead of 2.0 mm strip pitch:

- ✓ Better interaction resolution
  - ➢ Better event reconstruction performance
  - ➢ Better background suppression
  - ➢ Better angular resolution (up to 1.6 degree)
  - ➢ Better sensitivity

Switch to ASIC read-out instead of discrete read-out

- ✓ lower power consumption
- ✓ lower mass
- ✓ enables more channels and thus better resolution

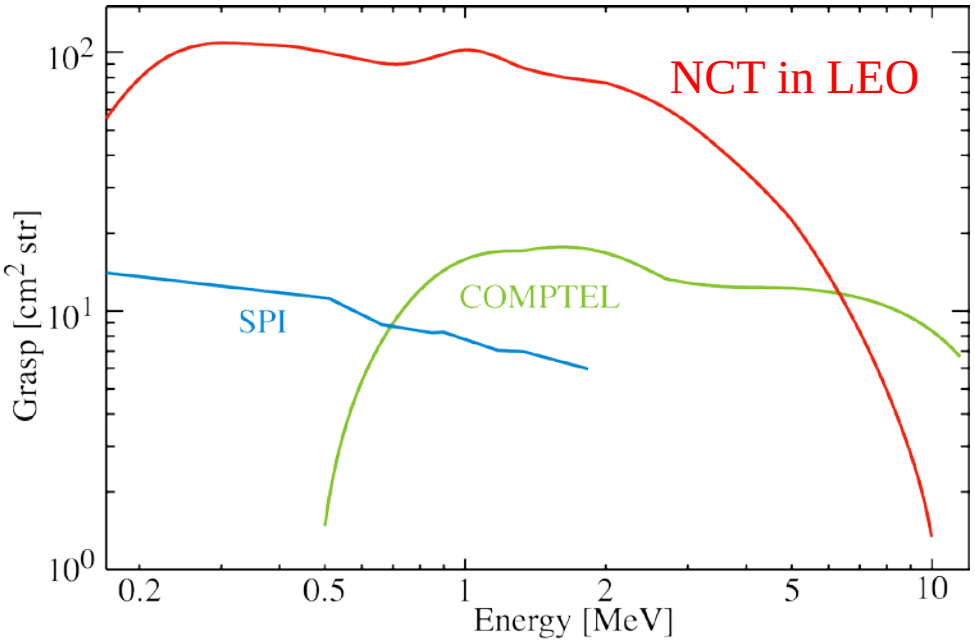


GRIPS Germanium detector

Ultimate Goal: A NCT Space Mission

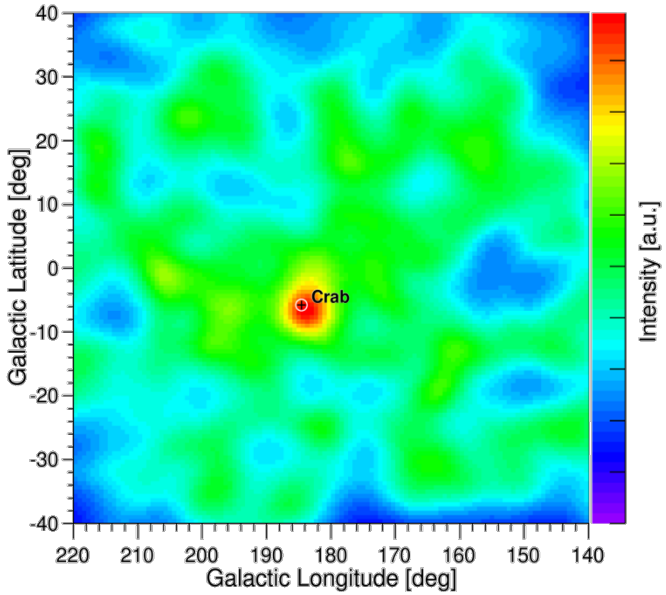
Advantages compared to balloon mission:

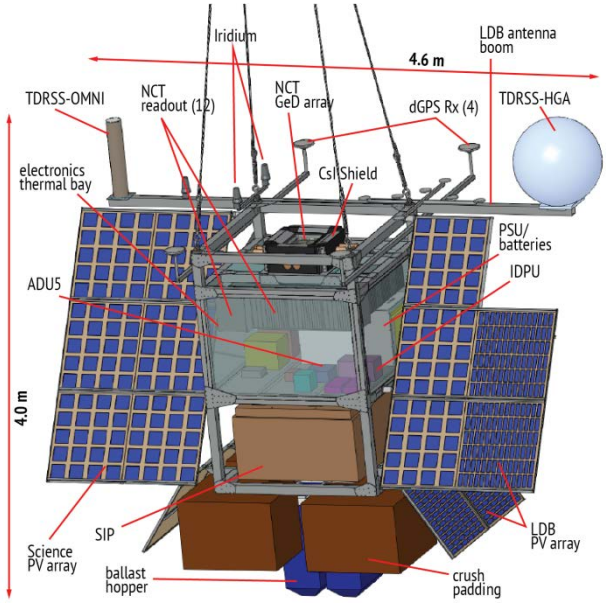
- No atmospheric absorption
- Less background
- Less event cuts needed
  - ➢ More effective area
- Larger field-of-view – at L2 and using a boom almost 4π is possible!
  - ➢ Monitor all the sky all the time!
- Longer mission



Thank you


BIG BILL


Crab
Galactic Latitude [deg]
Galactic Longitude [deg]
Intensity [a.u.]
40
30
20
10
0
-10
-20
-30
-40
220
210
200
190
180
170
160
150
140


Iridium
LDB antenna boom
4.6 m
TDRSS-OMNI
NCT readout (12)
NCT GeD array
dGPS Rx (4)
TDRSS-HGA
electronics thermal bay
CsI Shield
PSU/ batteries
IDPU
ADU5
4.0 m
SIP
Science PV array
ballast hopper
crush padding
LDB PV array