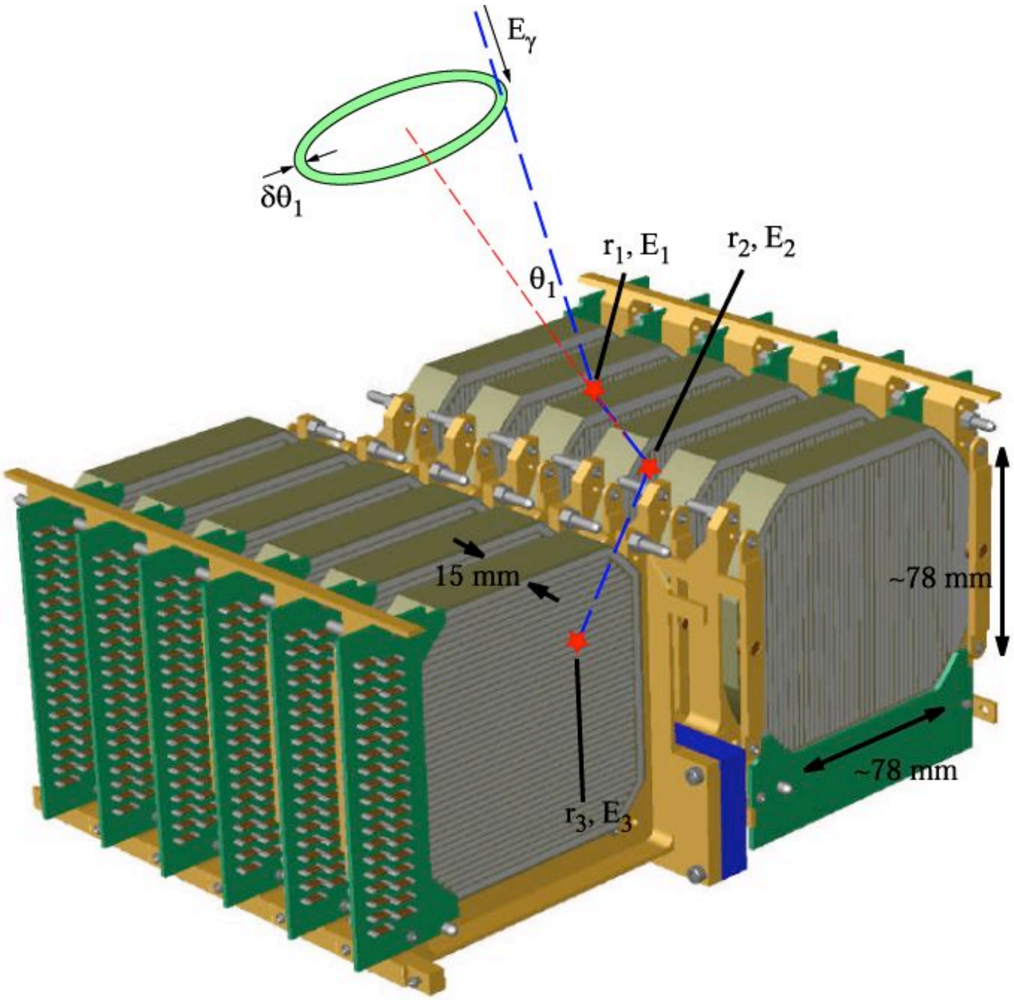
Compton Telescopes for High Energy Astrophysics



Steve Boggs
Department of Physics, SSL
University of California, Berkeley

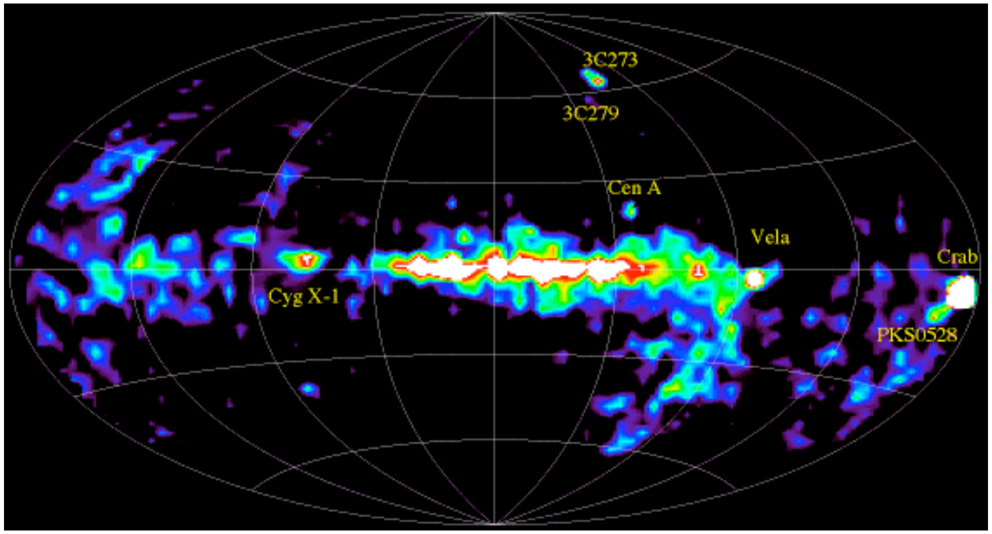
Cosmic High Energy Laboratories

Why MeV gamma-rays?

Unique 0.2-10 MeV Science

- nuclear lines
- e-/e+ mass, annihilation
- peak emission: AGN, BHs, GRBs
- polarization

COMPTEL 1-30 MeV Source Catalog

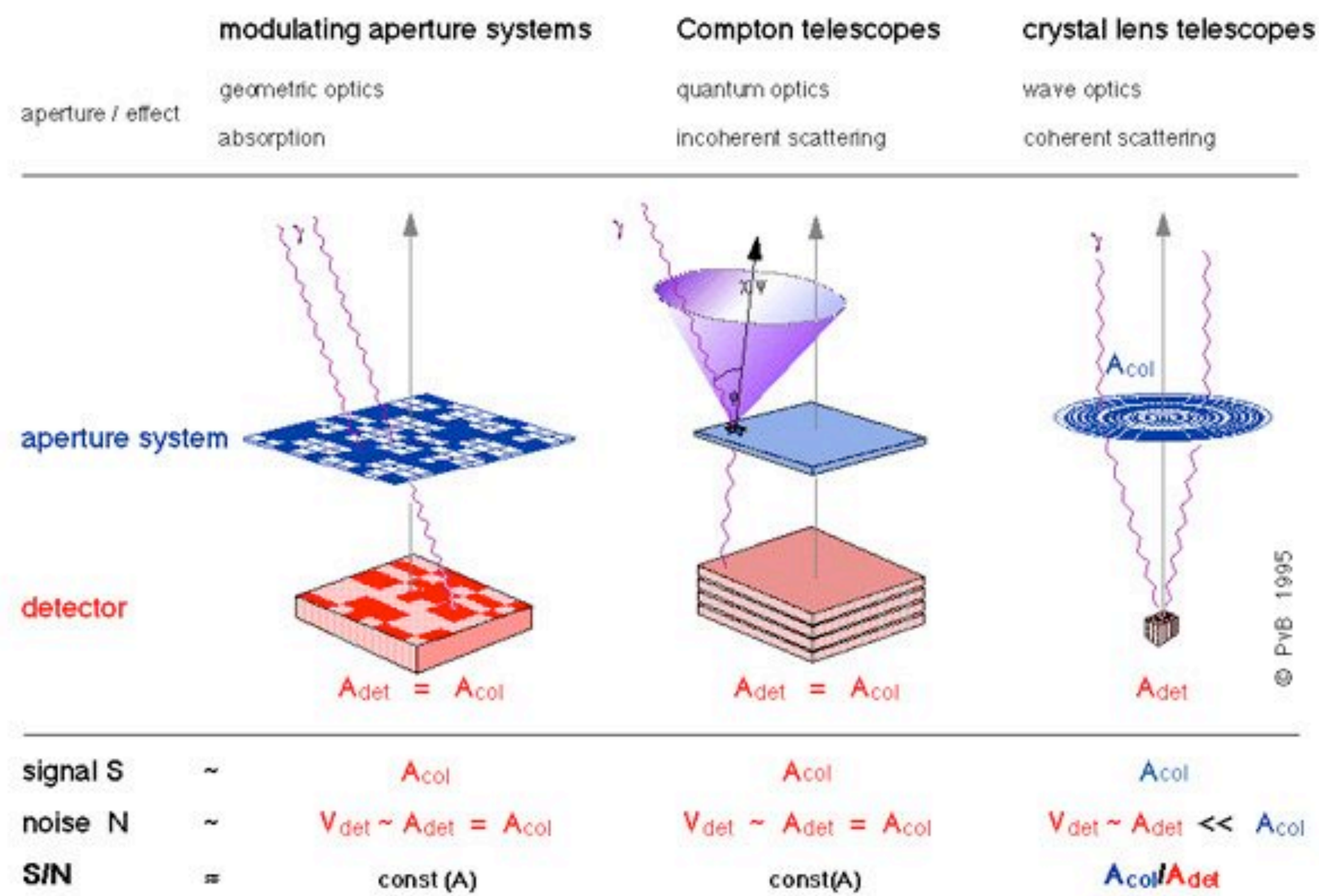


(Schönfelder et al. 2000)

Sources (5 yr)	COMPTEL	ACT
Supernovae	1	100-200
AGN	15	200-500
Galactic	23	300-500
GRBs	31	1000-1500
Novae	0	25-50

"…to explore the profound mysteries of life, space, time and the workings of the universe."

-NASA Space Science Enterprise Strategy 2003



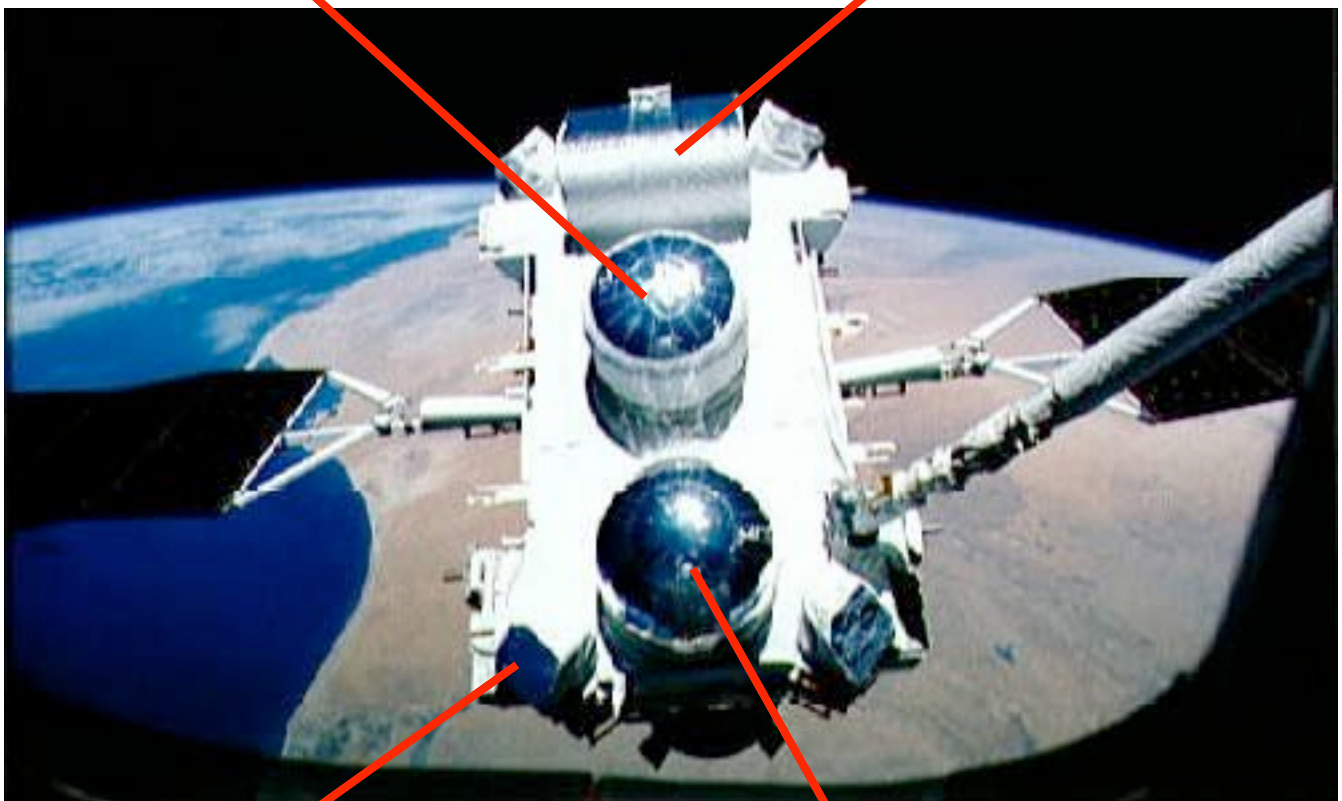
$$\cos\theta = 1 + \frac{m_e c^2}{E_\gamma} - \frac{m_e c^2}{E_\gamma - E_1}$$

(from P. von Ballmoos)

Compton Gamma-Ray Observatory
(1991-2000)

COMPTEL
(0.8-30 MeV)

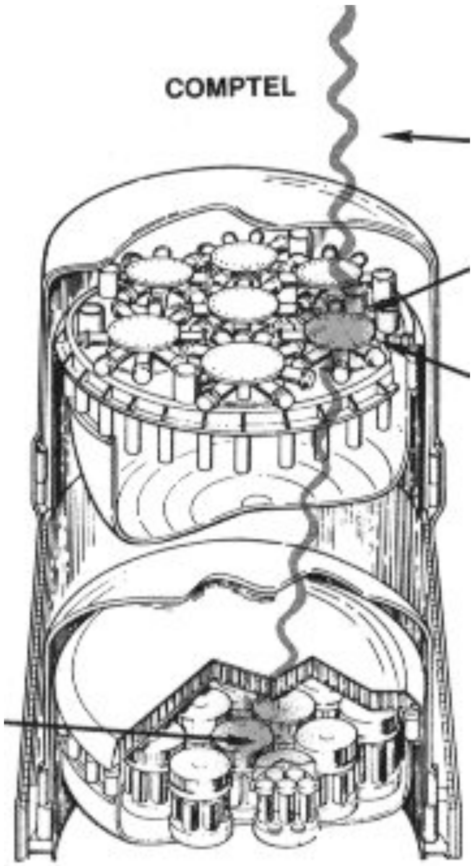
OSSE
(50 keV – 10 MeV)



BATSE
(20-600 keV)

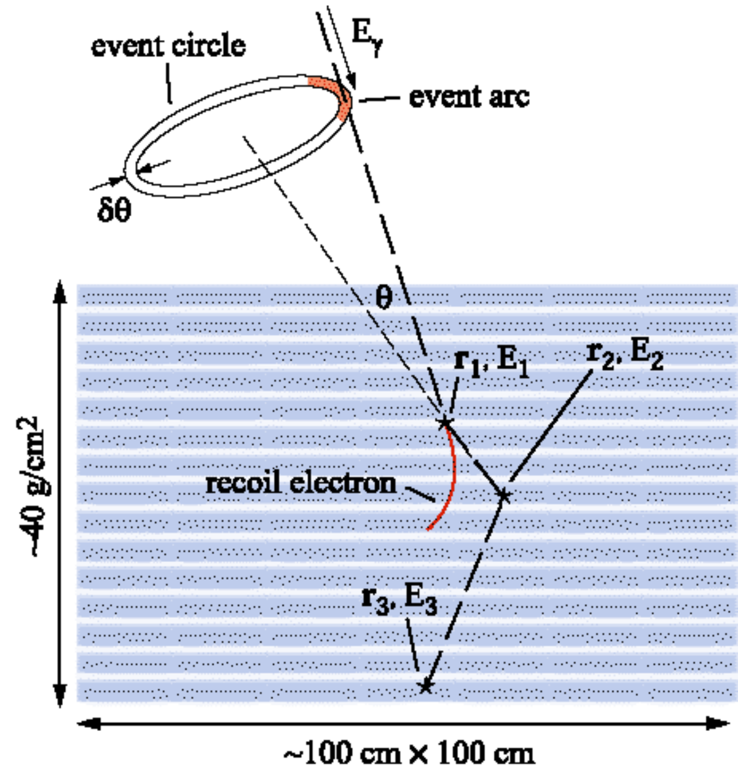
EGRET
(20 MeV – 30 GeV)

Compton Telescopes: Then & Now



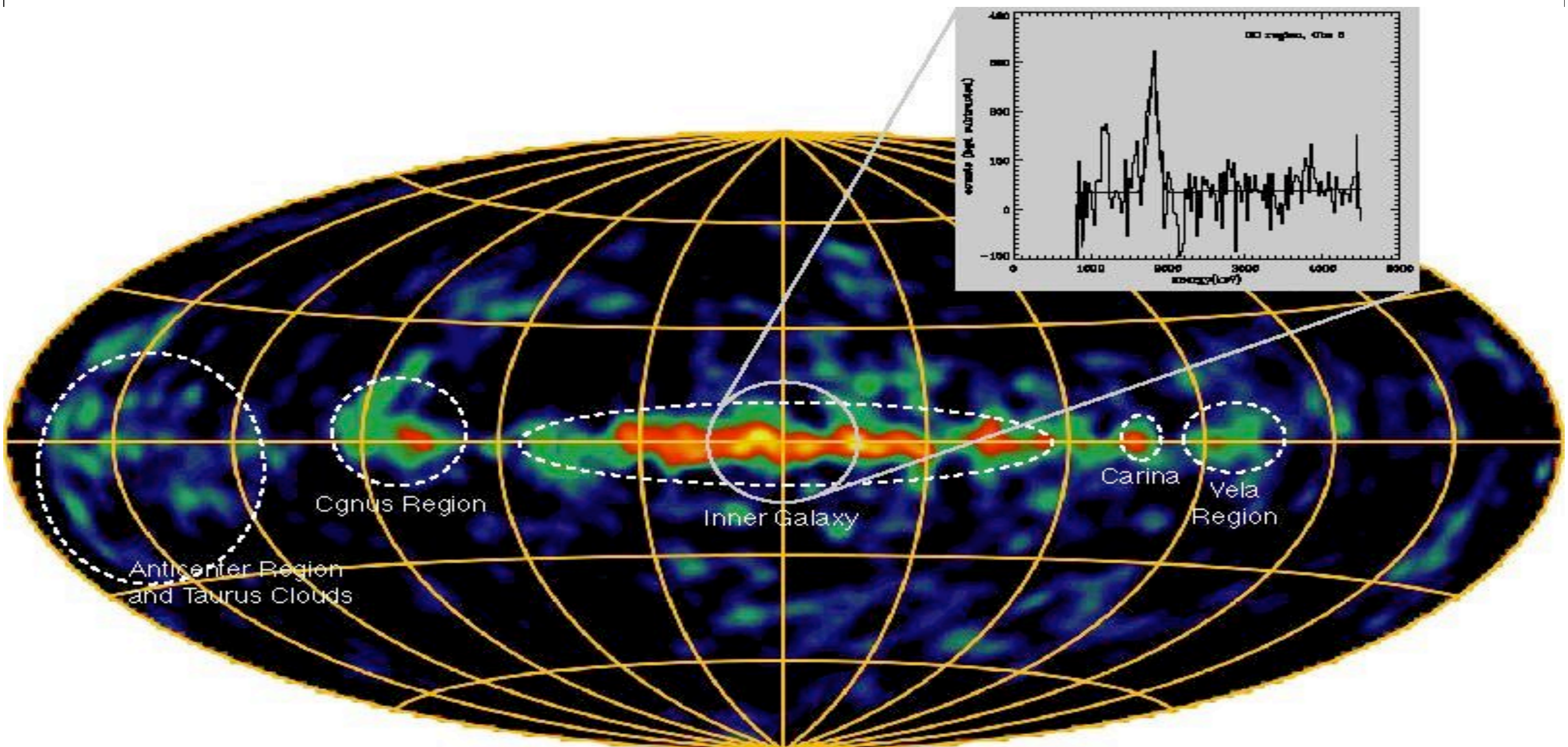
CGRO/COMPTEL
- ~40 cm^3 resolution
- $\Delta E/E \sim 10\%$
- 0.1% efficiency

3 decades…



ACT Enabling Detectors
- 1 mm^3 resolution
- $\Delta E/E \sim 0.2\text{-}1\%$
- 10-20% efficiency
- background rejection
- polarization

^{26}Al (1.809 MeV), τ~1Myr



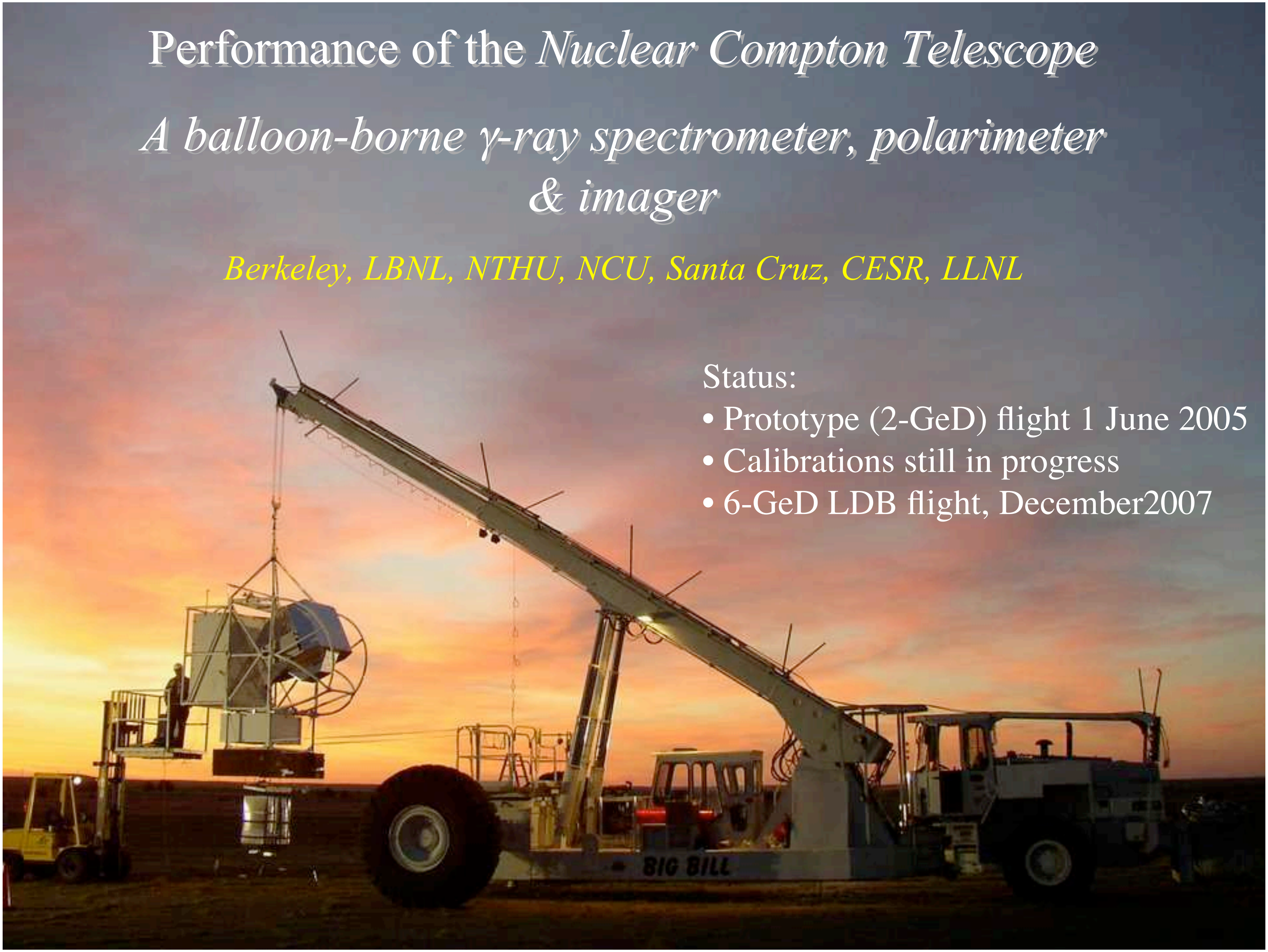
(Oberlack et al., 1996; Pluschke et al., 2001)

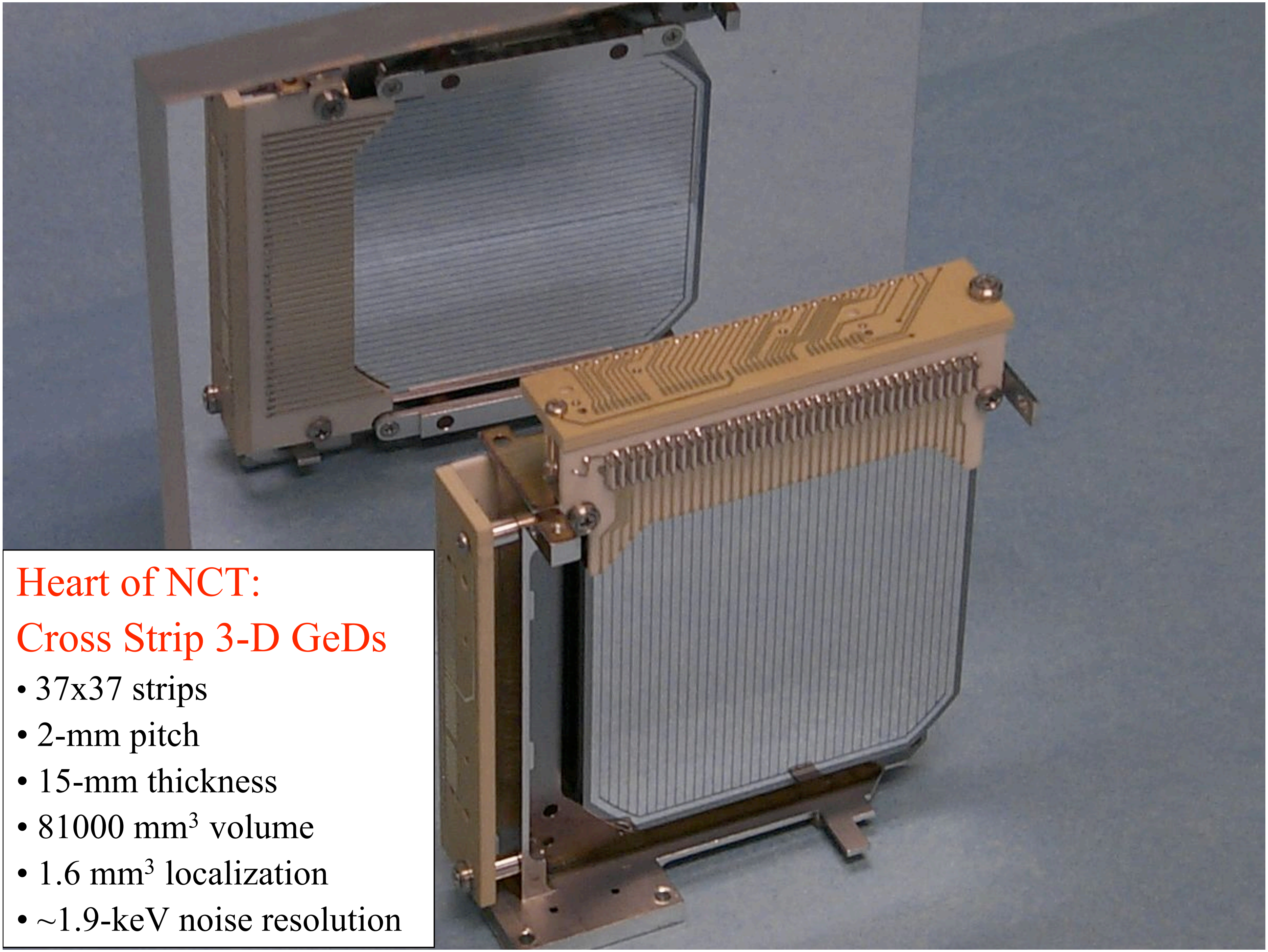
Performance of the *Nuclear Compton Telescope*

A balloon-borne γ-ray spectrometer, polarimeter & imager

Berkeley, LBNL, NTHU, NCU, Santa Cruz, CESR, LLNL

Status:
- Prototype (2-GeD) flight 1 June 2005
- Calibrations still in progress
- 6-GeD LDB flight, December2007

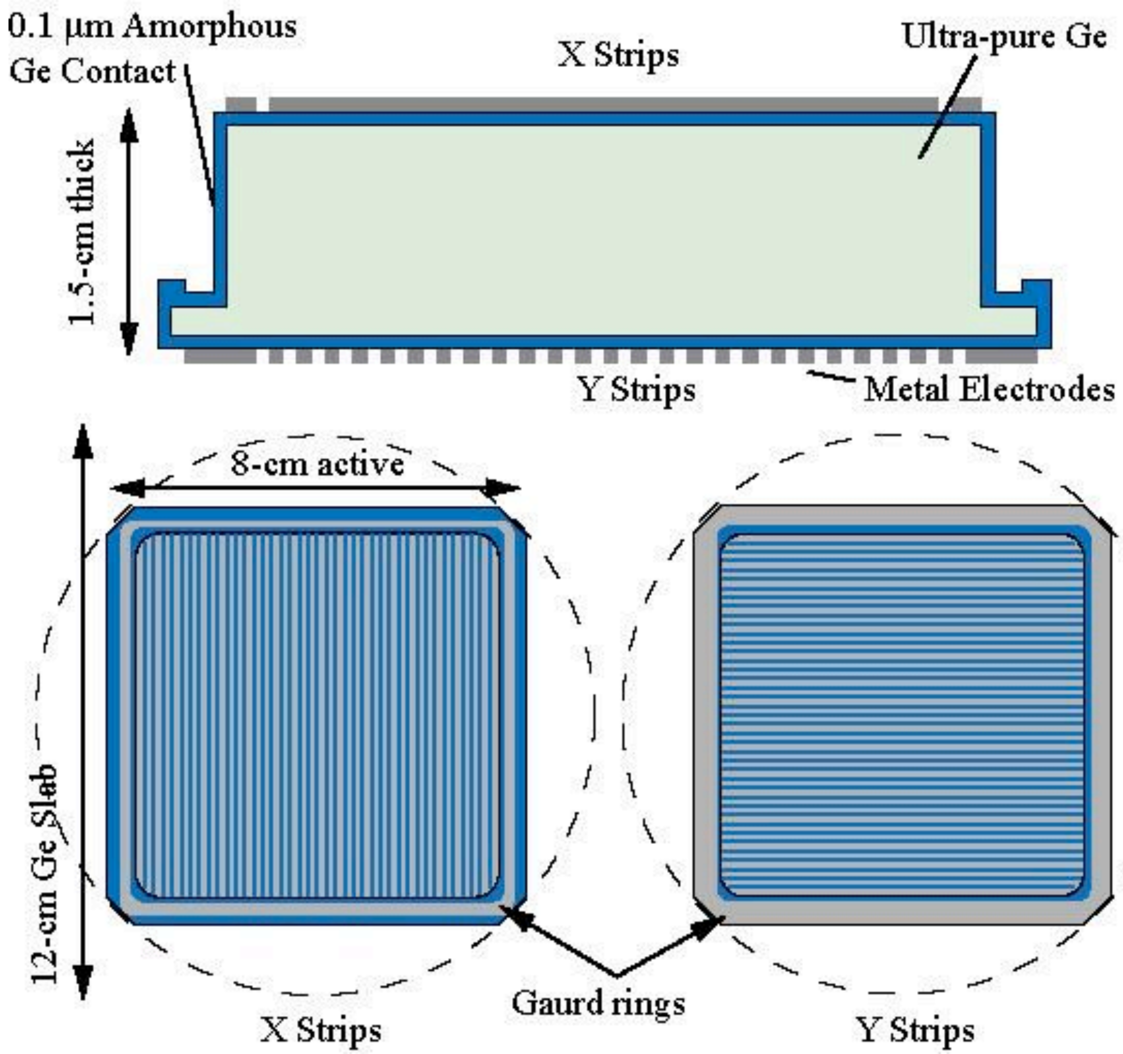




Heart of NCT:
Cross Strip 3-D GeDs

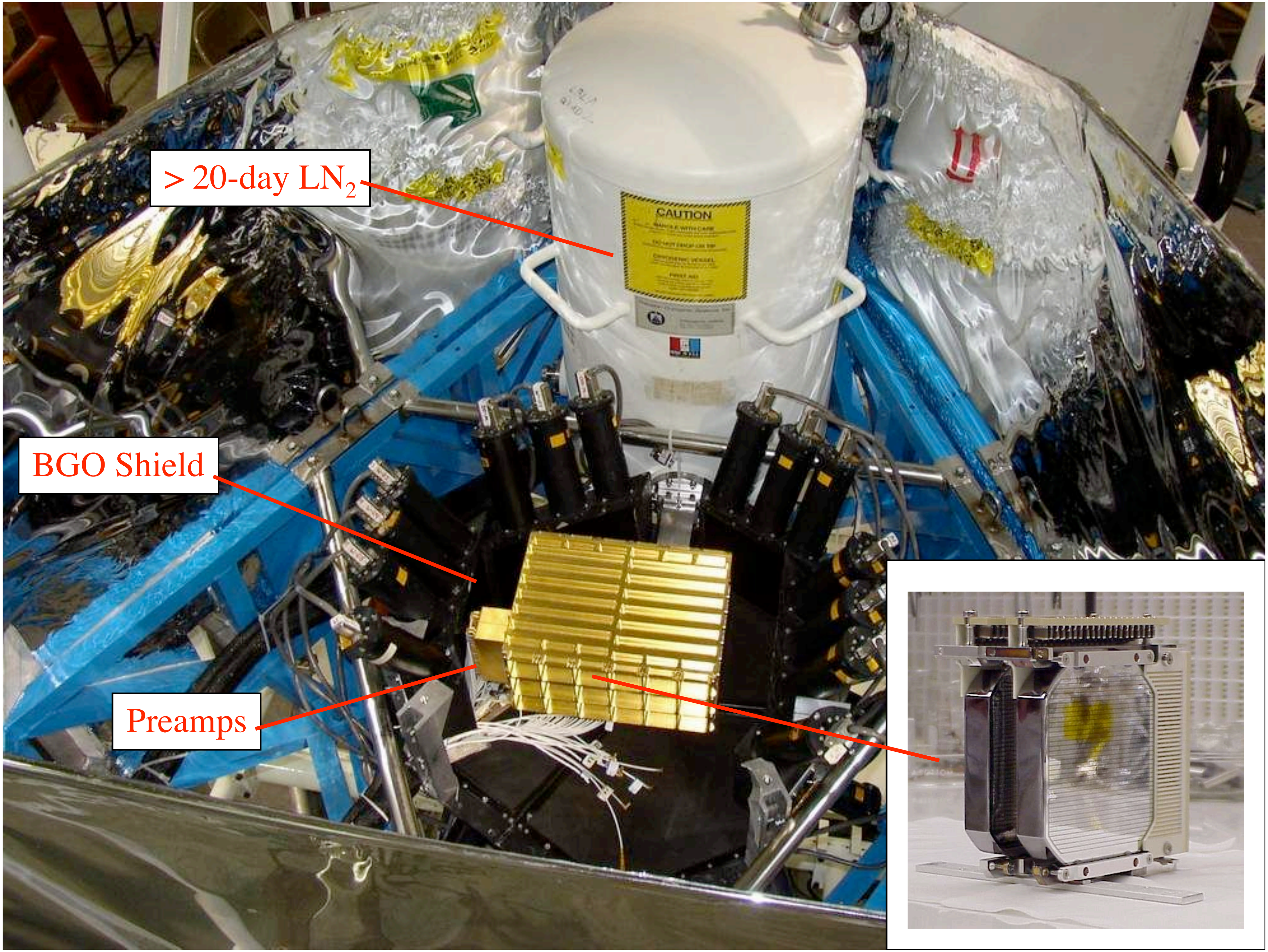
- 37x37 strips
- 2-mm pitch
- 15-mm thickness
- 81000 mm^3 volume
- 1.6 mm^3 localization
- ~1.9-keV noise resolution

3D GeD Design

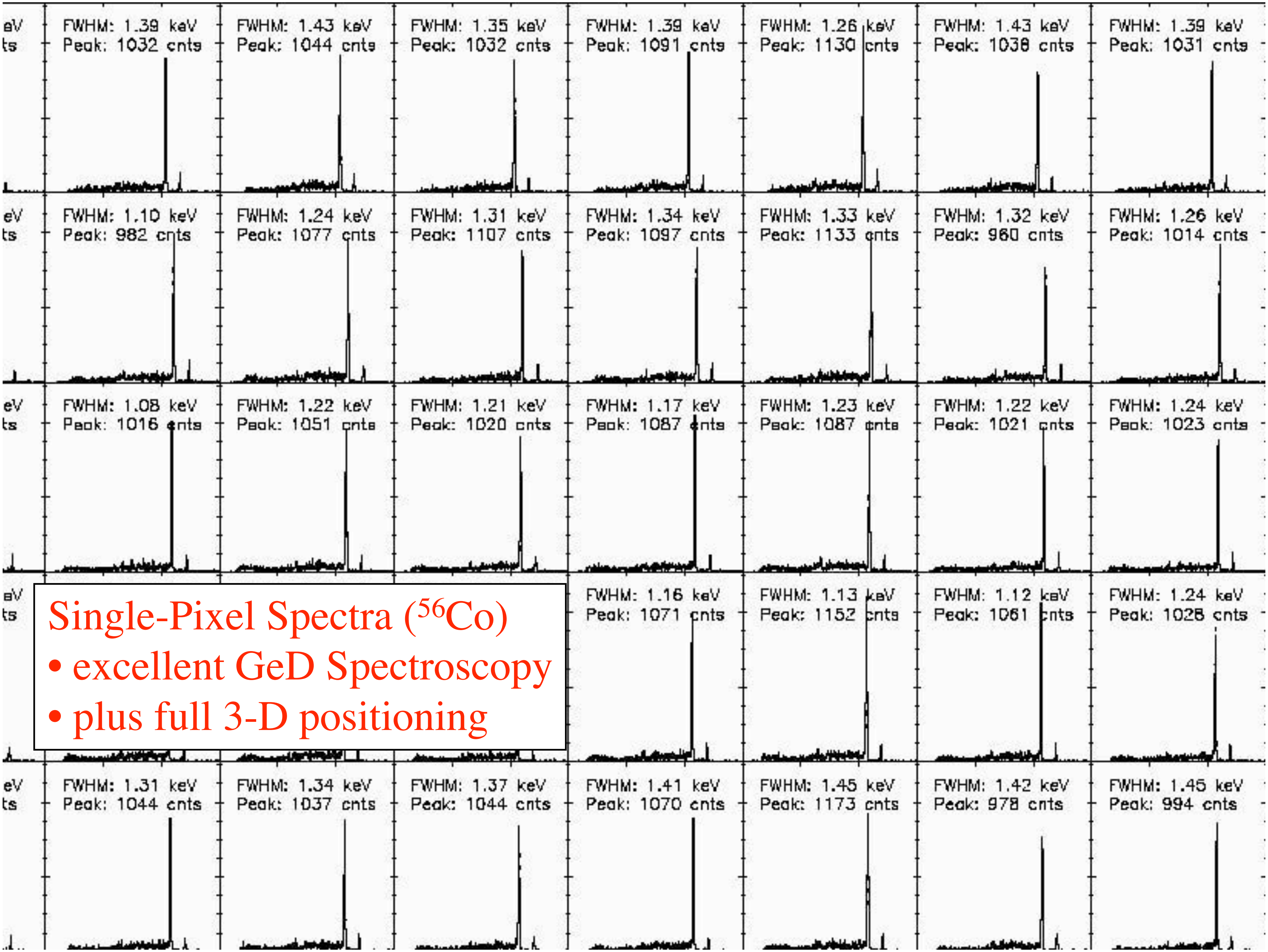


(Luke et al. 1992, 1994)

NCT in its LDB Flight Gondola



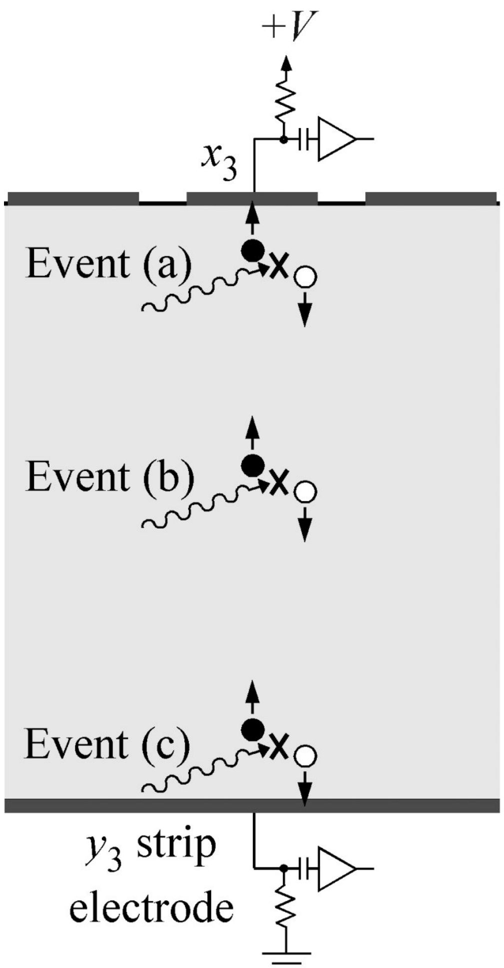
> 20-day LN_2
BGO Shield
Preamps
CAUTION

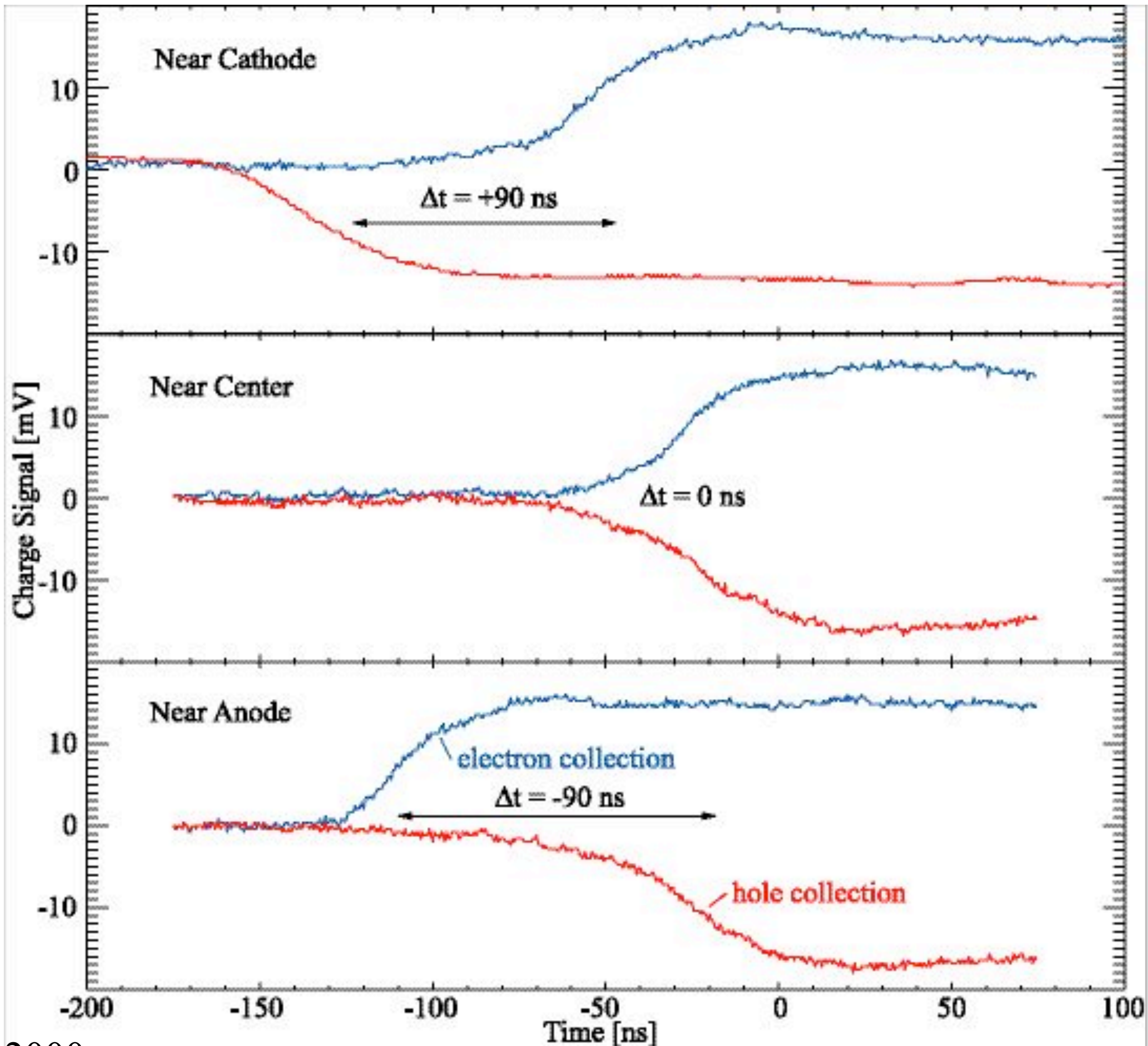


Single-Pixel Spectra (^{56}Co)

- excellent GeD Spectroscopy
- plus full 3-D positioning

3-D Positioning

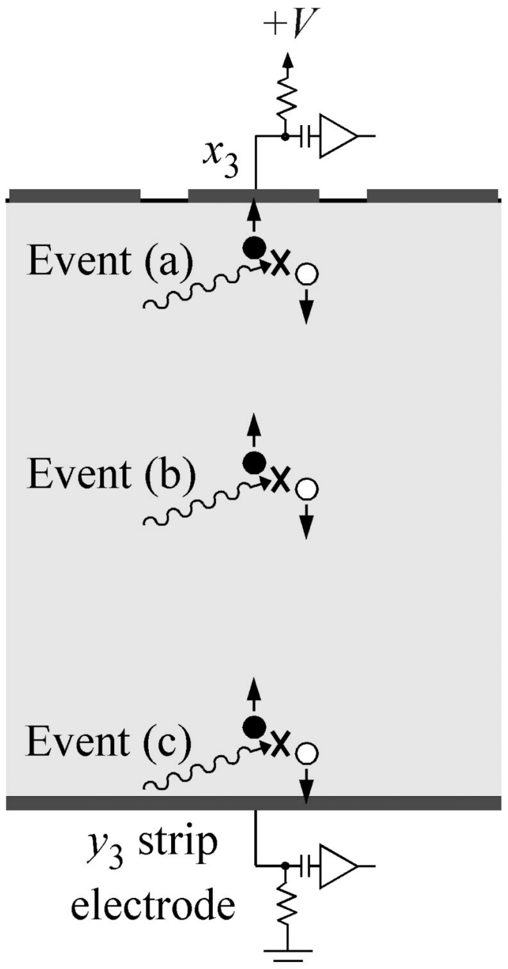


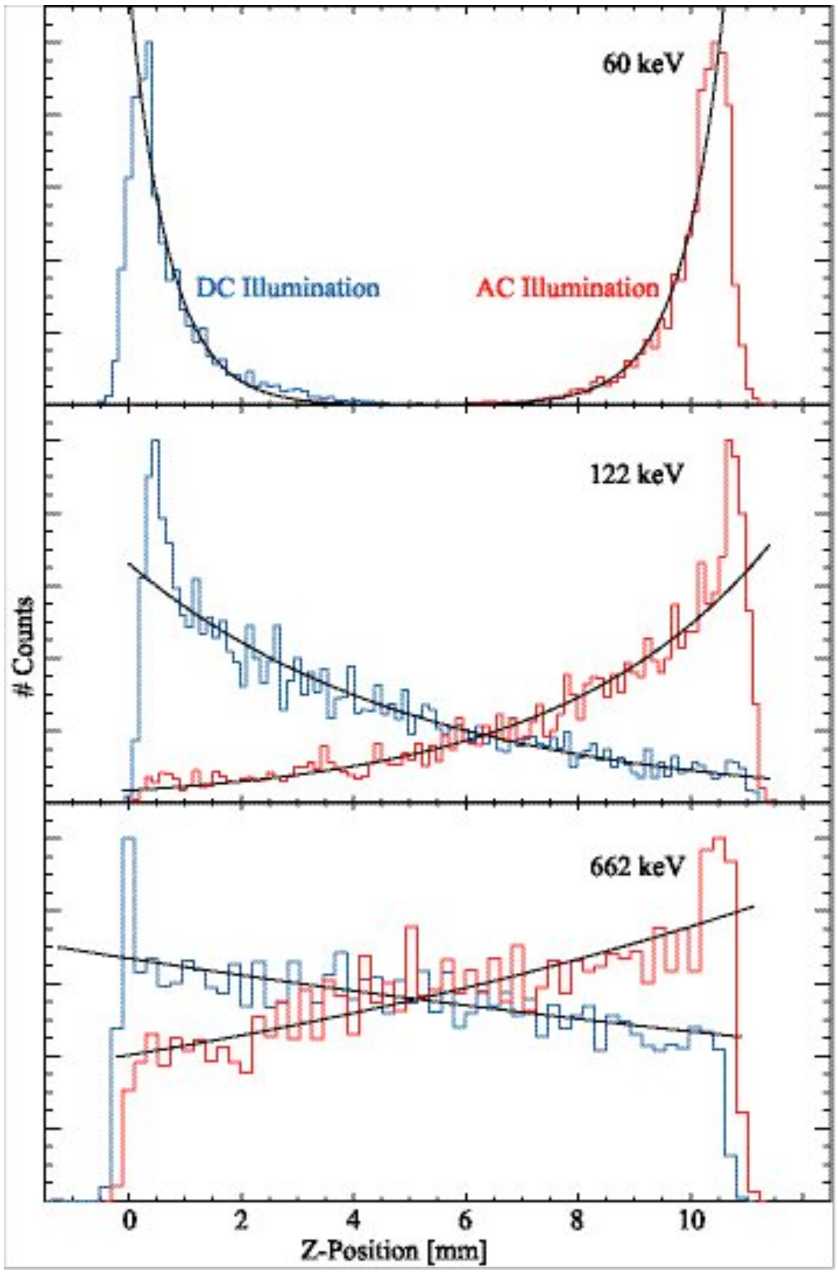


(Amman & Luke, NIM A452, 2000.

Amrose et al., IEEE, 2001.)

3-D Positioning



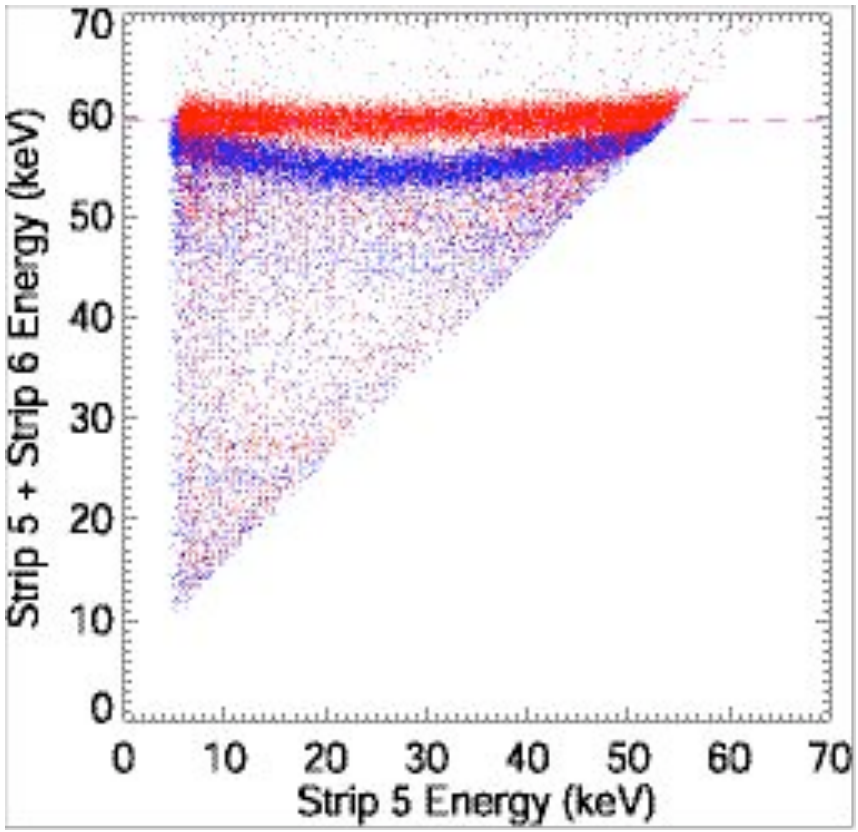


(Amman & Luke, NIM A452, 2000.

Amrose et al., IEEE, 2001.)

Charge Sharing Between Strips

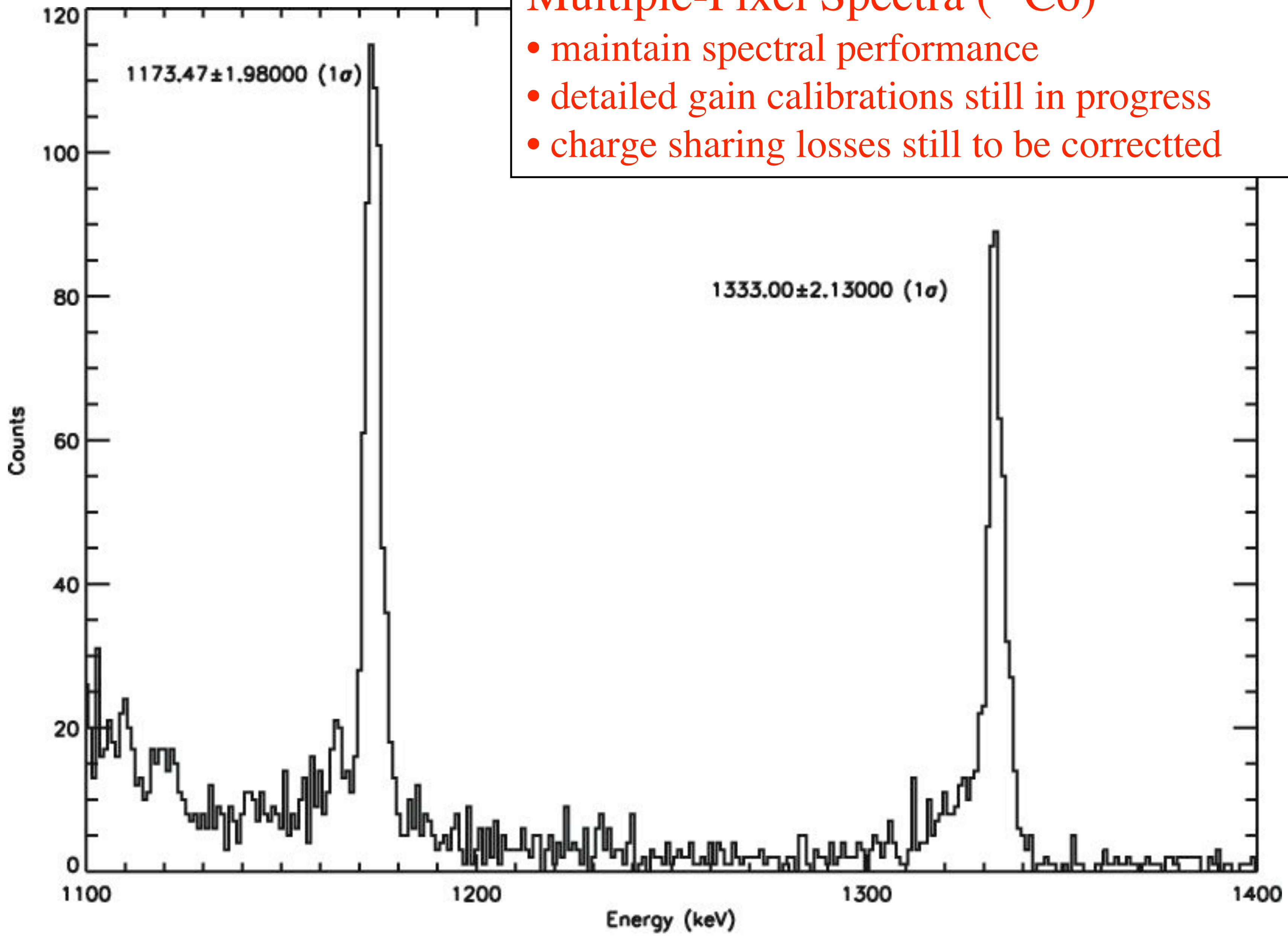
- # shared events, and charge loss proportional to gap size
- charge loss uniform across detector
- minimized in flight detector design
- correctable

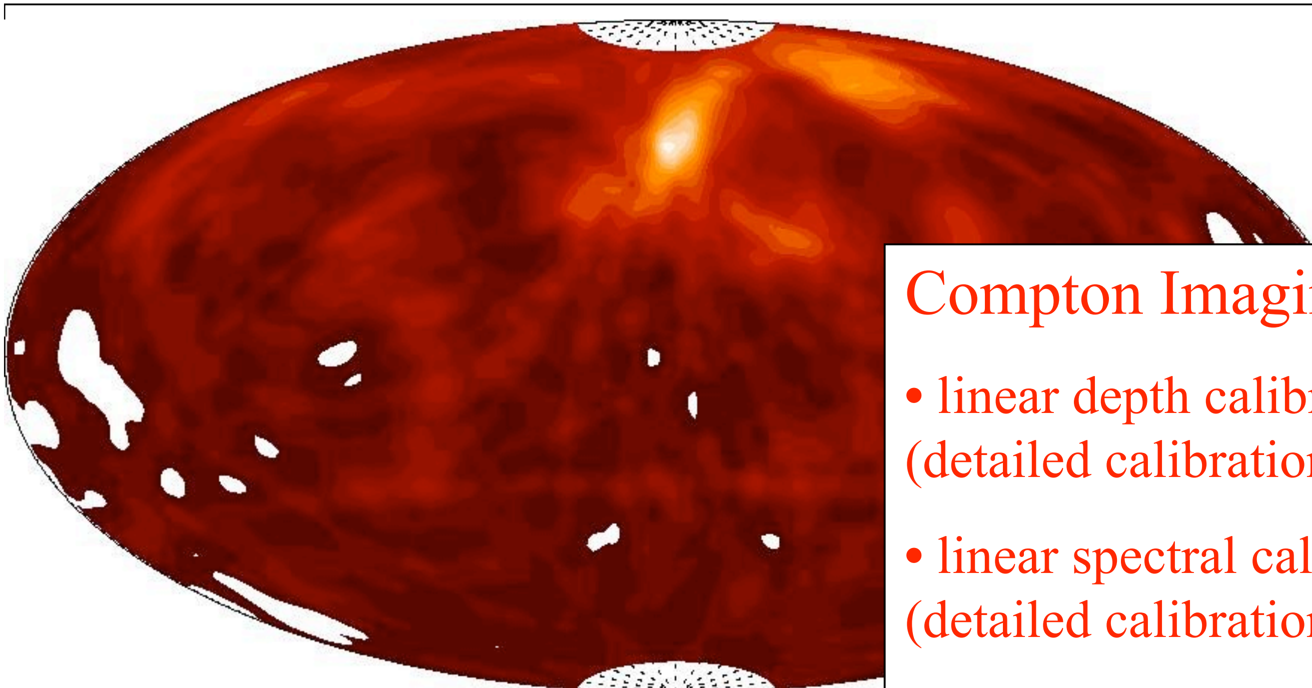


(Coburn et al., IEEE, 2001.)

Multiple-Pixel Spectra (^{60}Co)

- maintain spectral performance
- detailed gain calibrations still in progress
- charge sharing losses still to be correctted





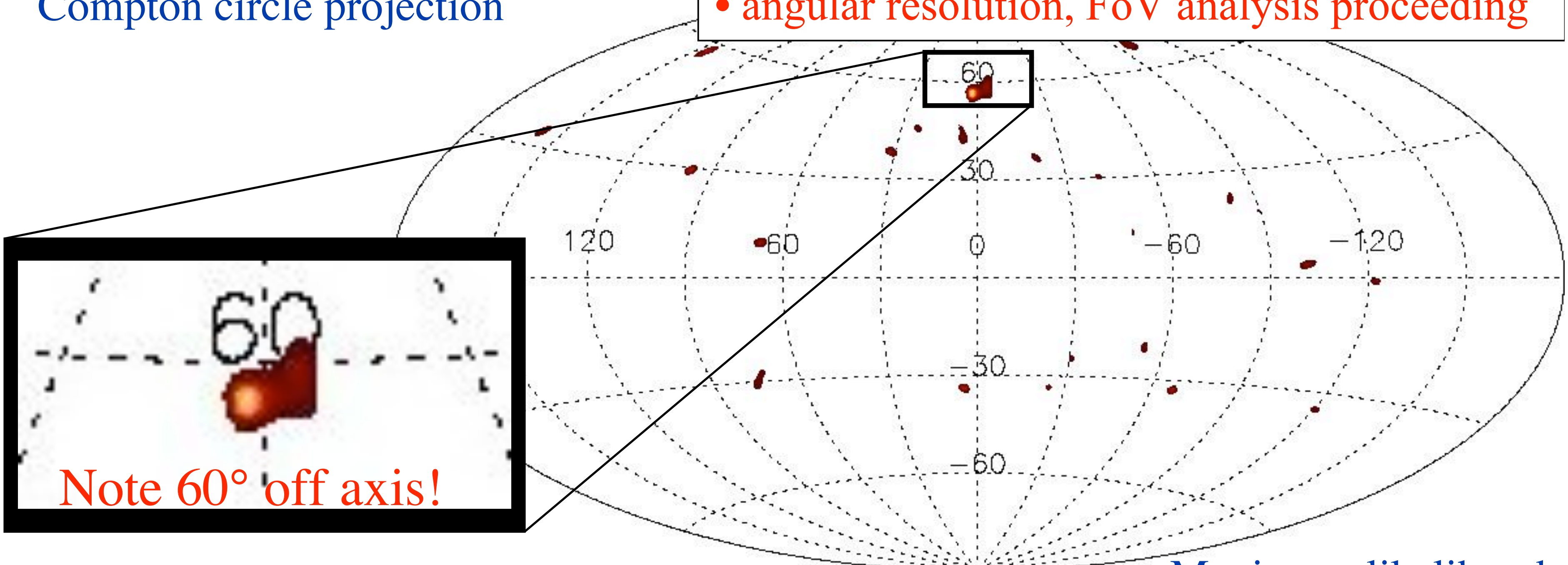
Compton circle projection

Compton Imaging ^{60}Co (1.173 MeV)

- linear depth calibration
(detailed calibration nearly complete)

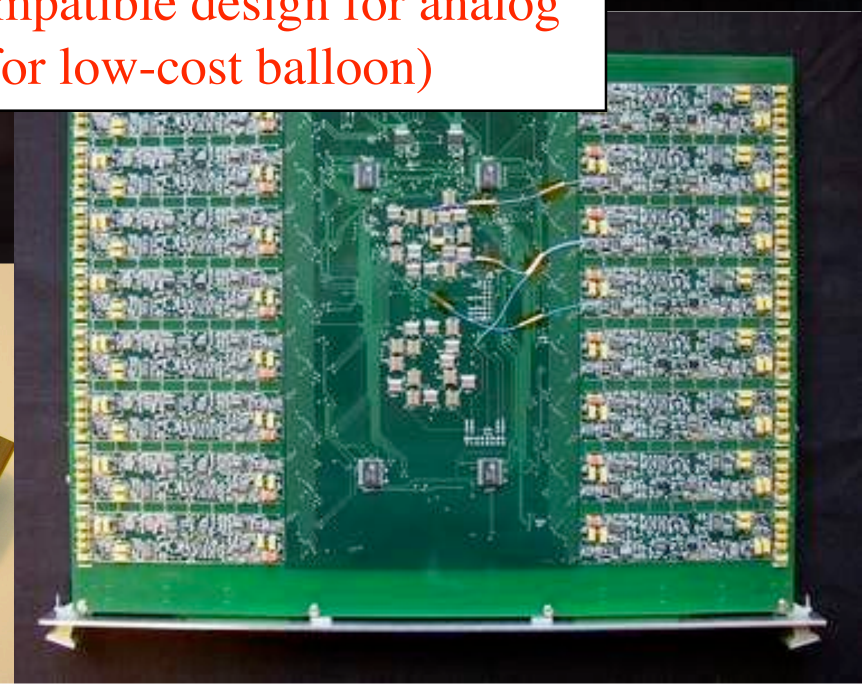
- linear spectral calibration
(detailed calibration nearly complete)

- angular resolution, FoV analysis proceeding



Maximum likelihood

Detector Electronics

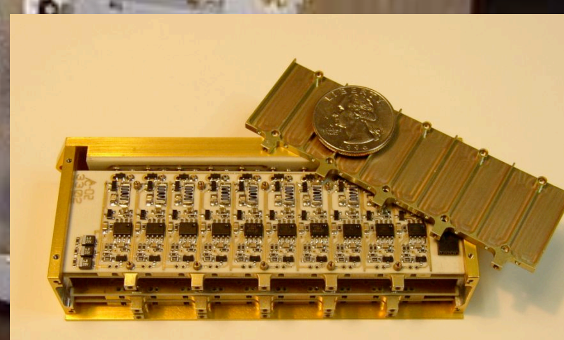


Performance:

- 4 μs shapers, ~1.9 keV FWHM noise resolution, 10 keV threshold
- 10-ns timing, 0.4-mm FWHM depth for interactions >40 keV

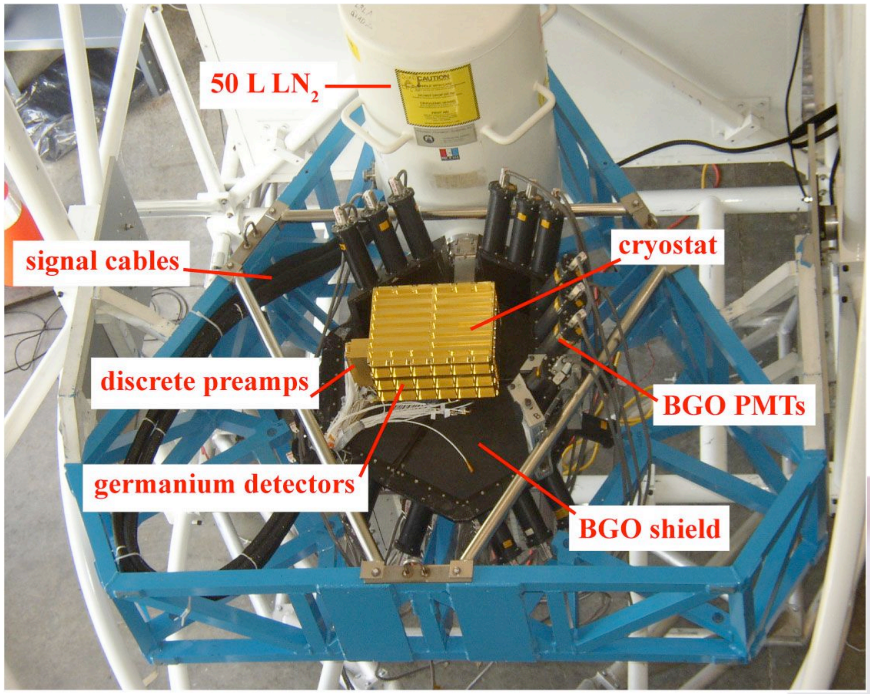
Current near-term goals:

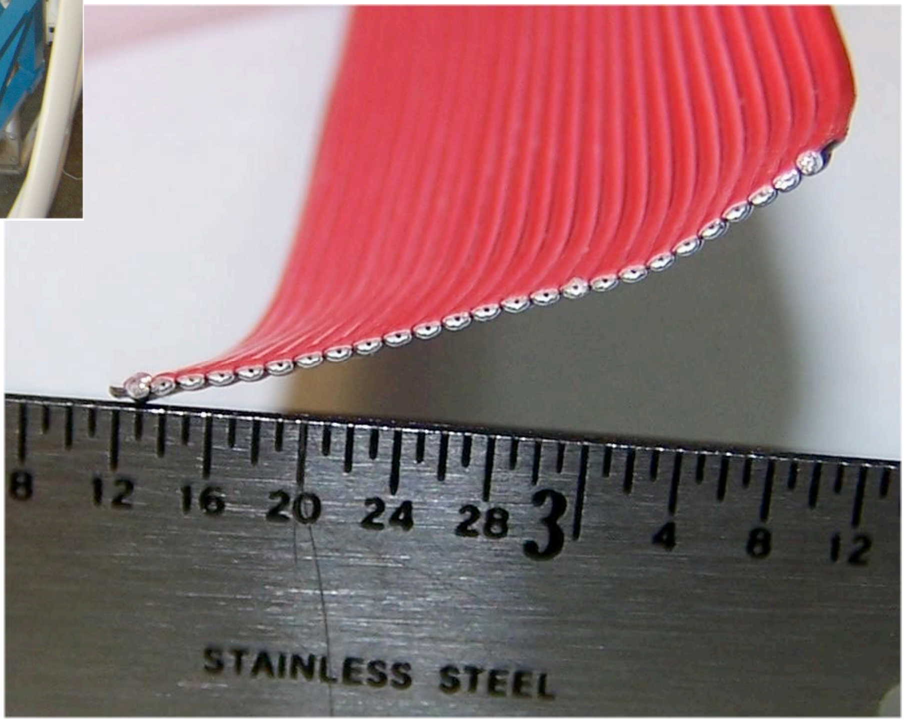
- drop preamp power by 5× to 24 mW/chn
- develop ASIC-compatible design for analog readout (currently for low-cost balloon)

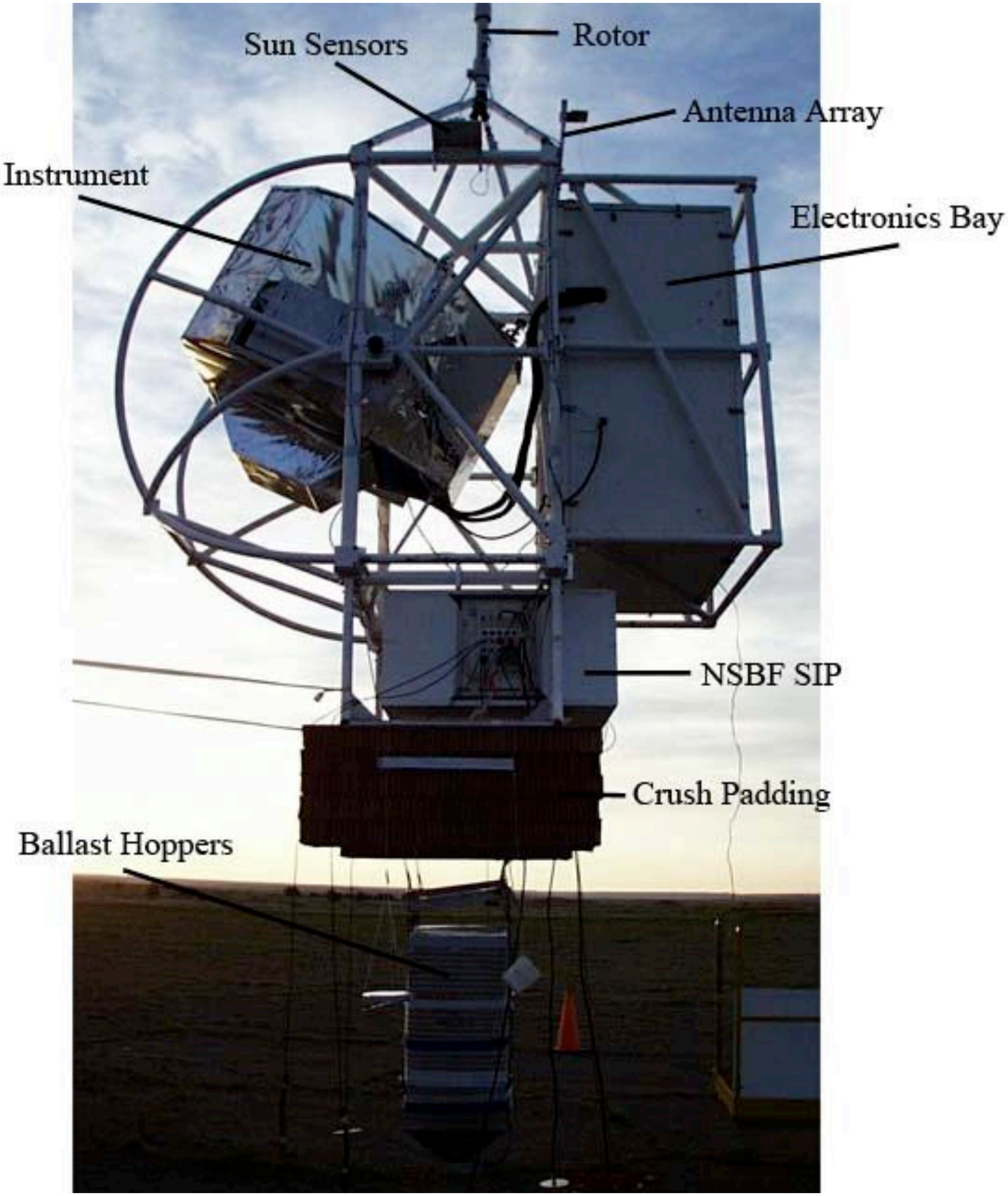


Preamplifiers (40/box)

Signal Cabling







NCT Gondola

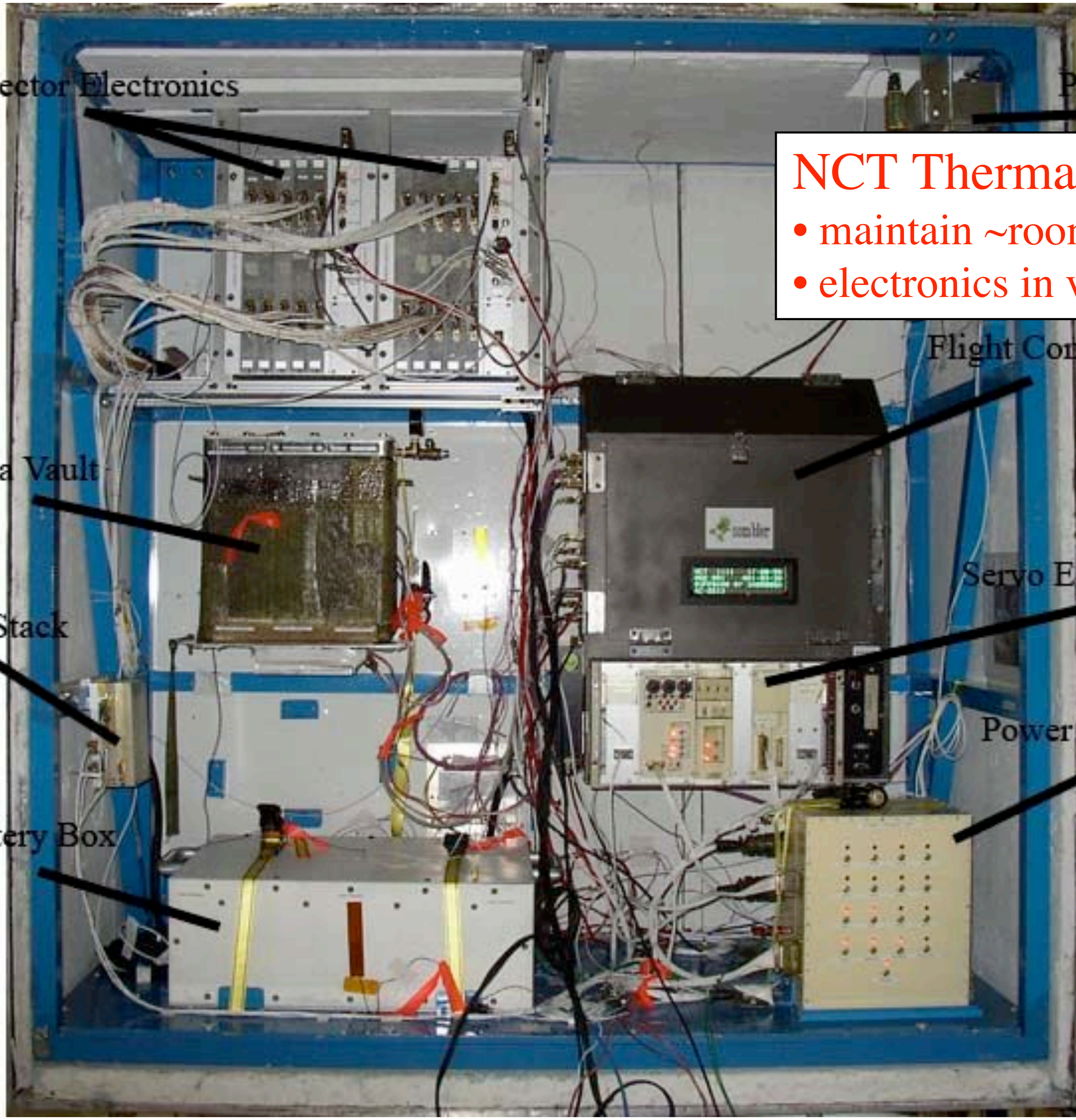
- LDB compatible (w/ power upgrades…)
- fully automated control
- azimuthal pointing implemented
- battery powered
- 20+ days LN2
- ground telemetry + on-board data storage
- magnetometer aspect & pointing

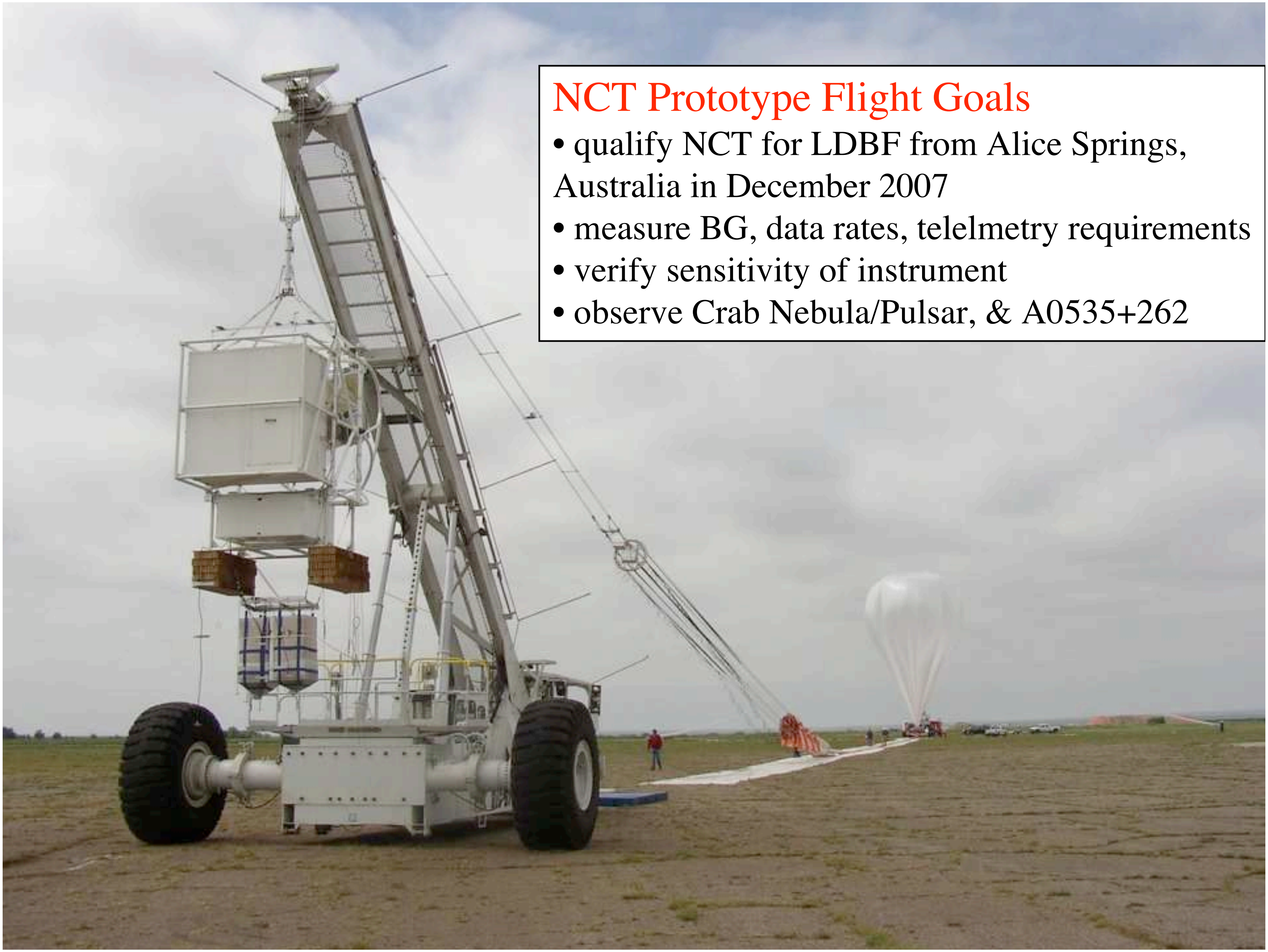
Upgrades:

- solar power
- differential GPS

NCT Thermal Enclosure

- maintain ~room T, passive
- electronics in vacuum



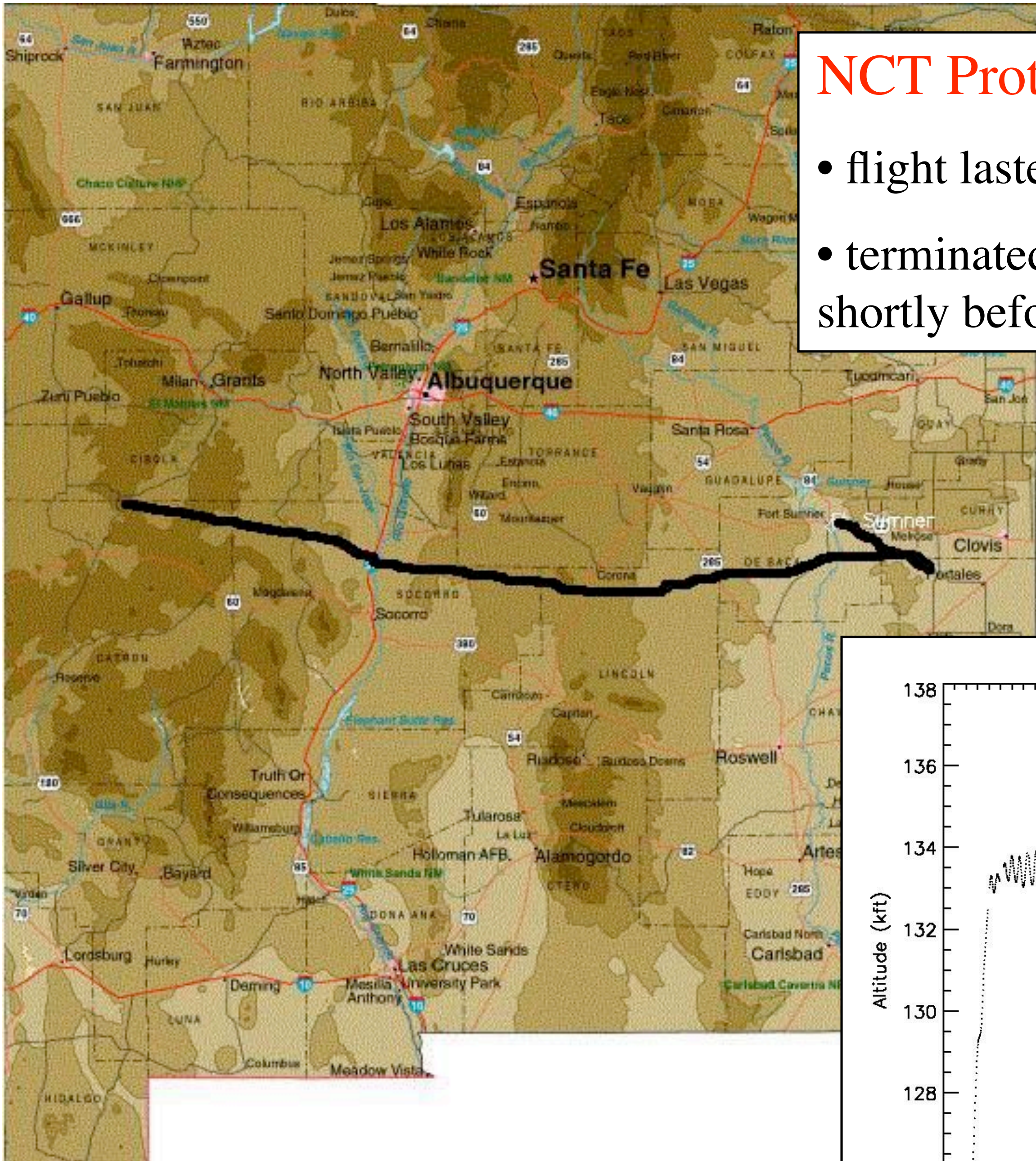


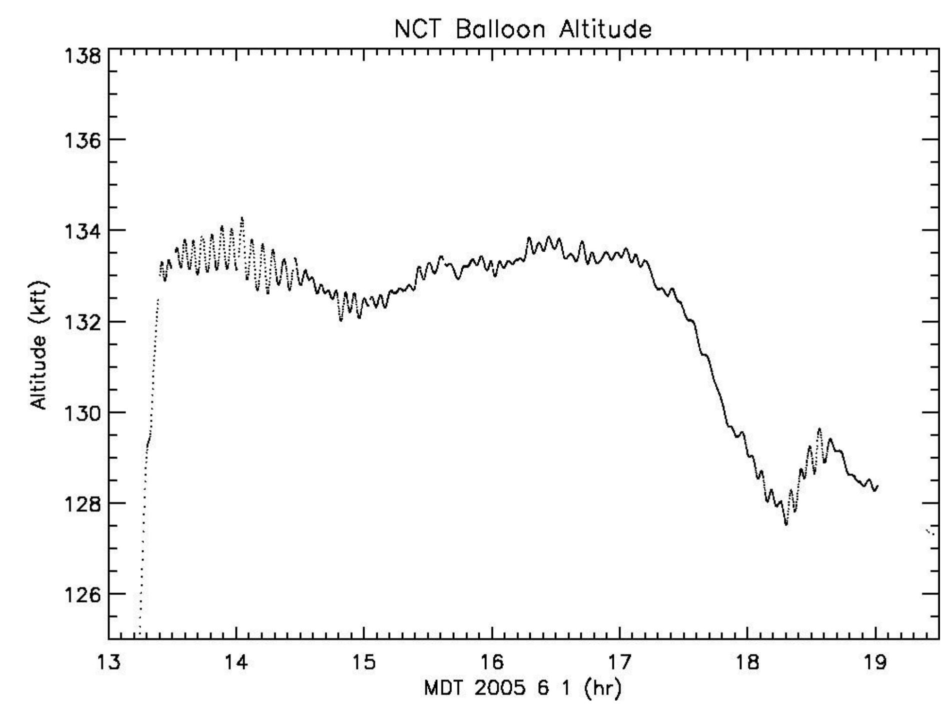
NCT Prototype Flight Goals

- qualify NCT for LDBF from Alice Springs, Australia in December 2007
- measure BG, data rates, telelmetry requirements
- verify sensitivity of instrument
- observe Crab Nebula/Pulsar, & A0535+262

NCT Prototype Flight, 1 June 2005

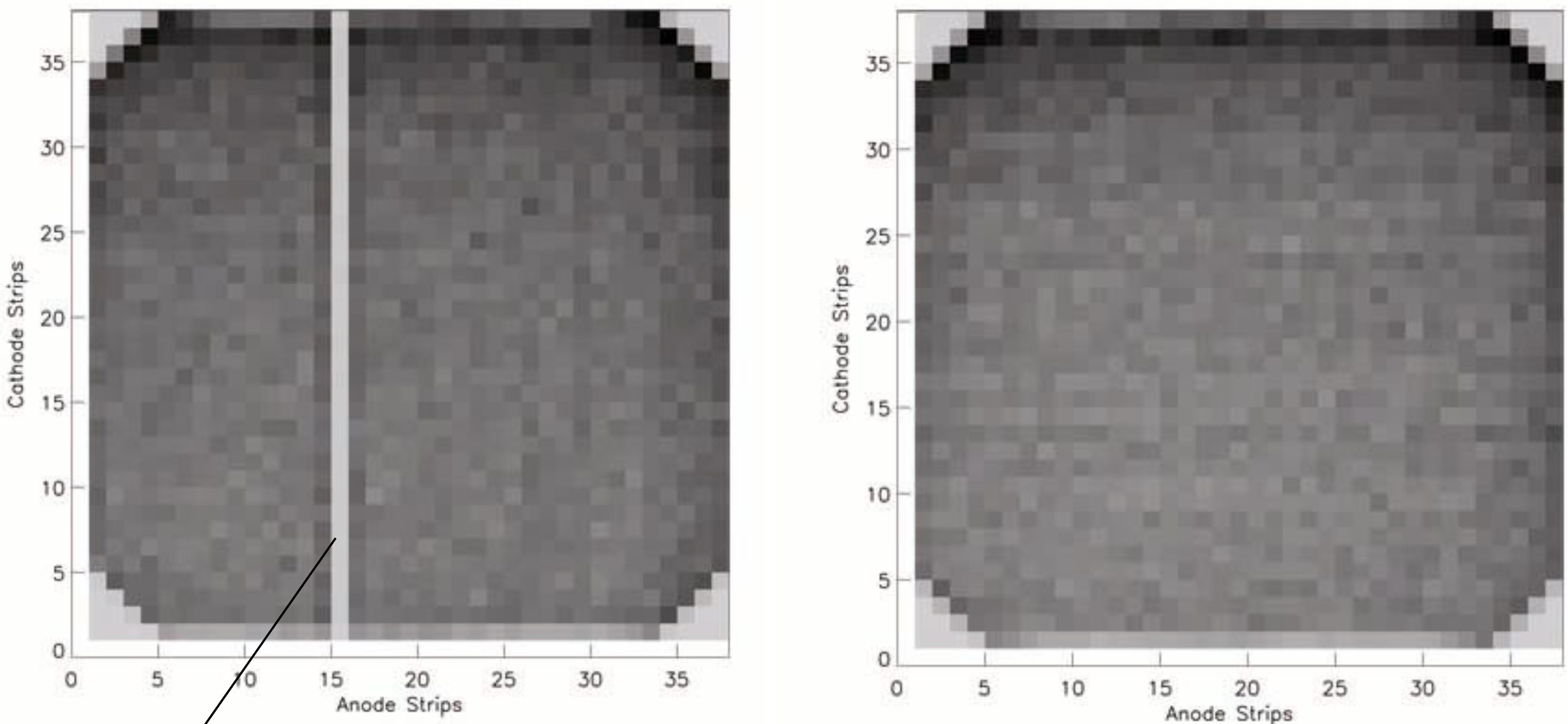
- flight lasted ~9 hrs, with 5.5 hrs at float
- terminated over western New Mexico shortly before local sunset





Flat Fields

(obtained at float)

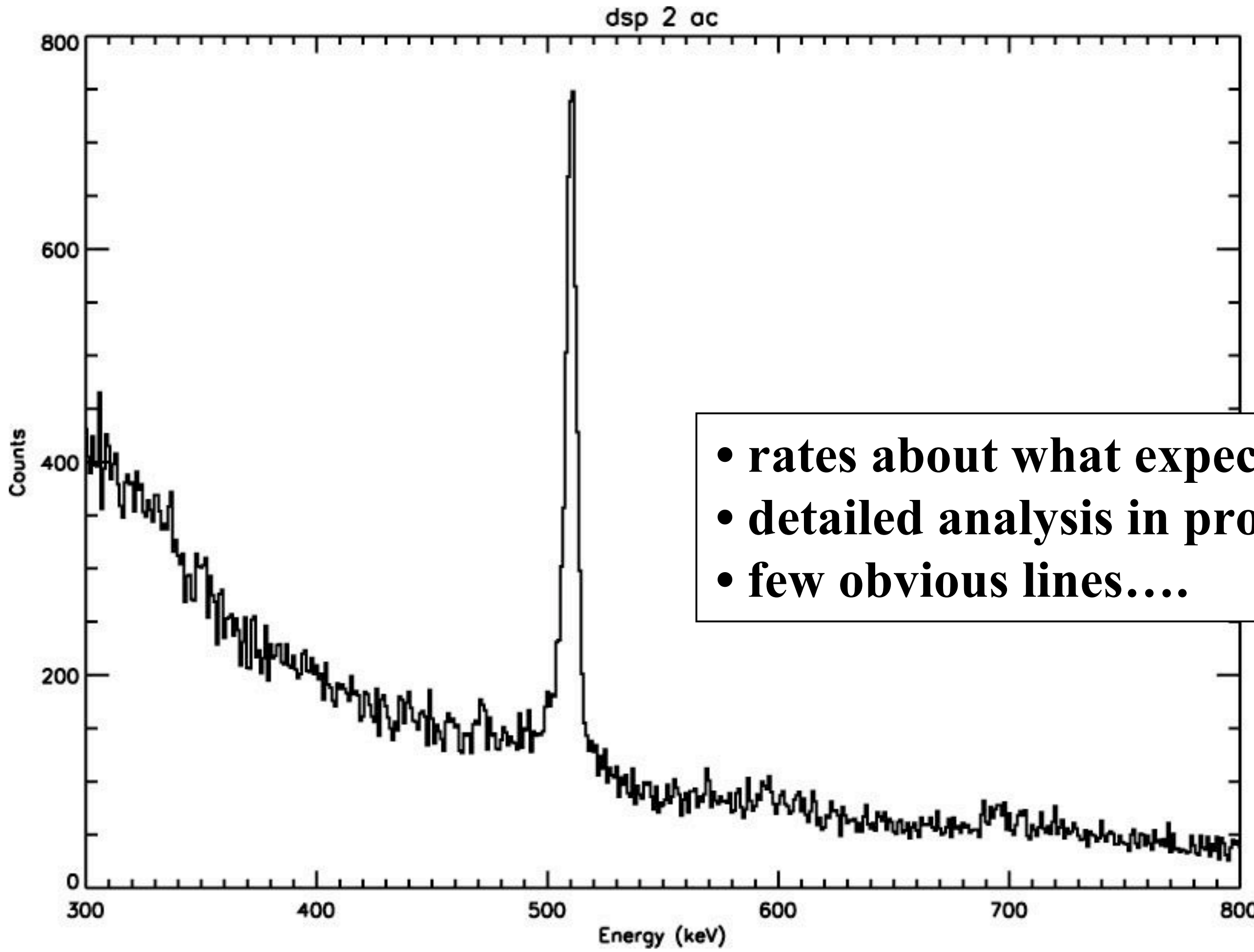


Detector 0

Detector 1

(missing strip due to bad contact in cryostat, fixed by balloon landing….)

Background Spectra

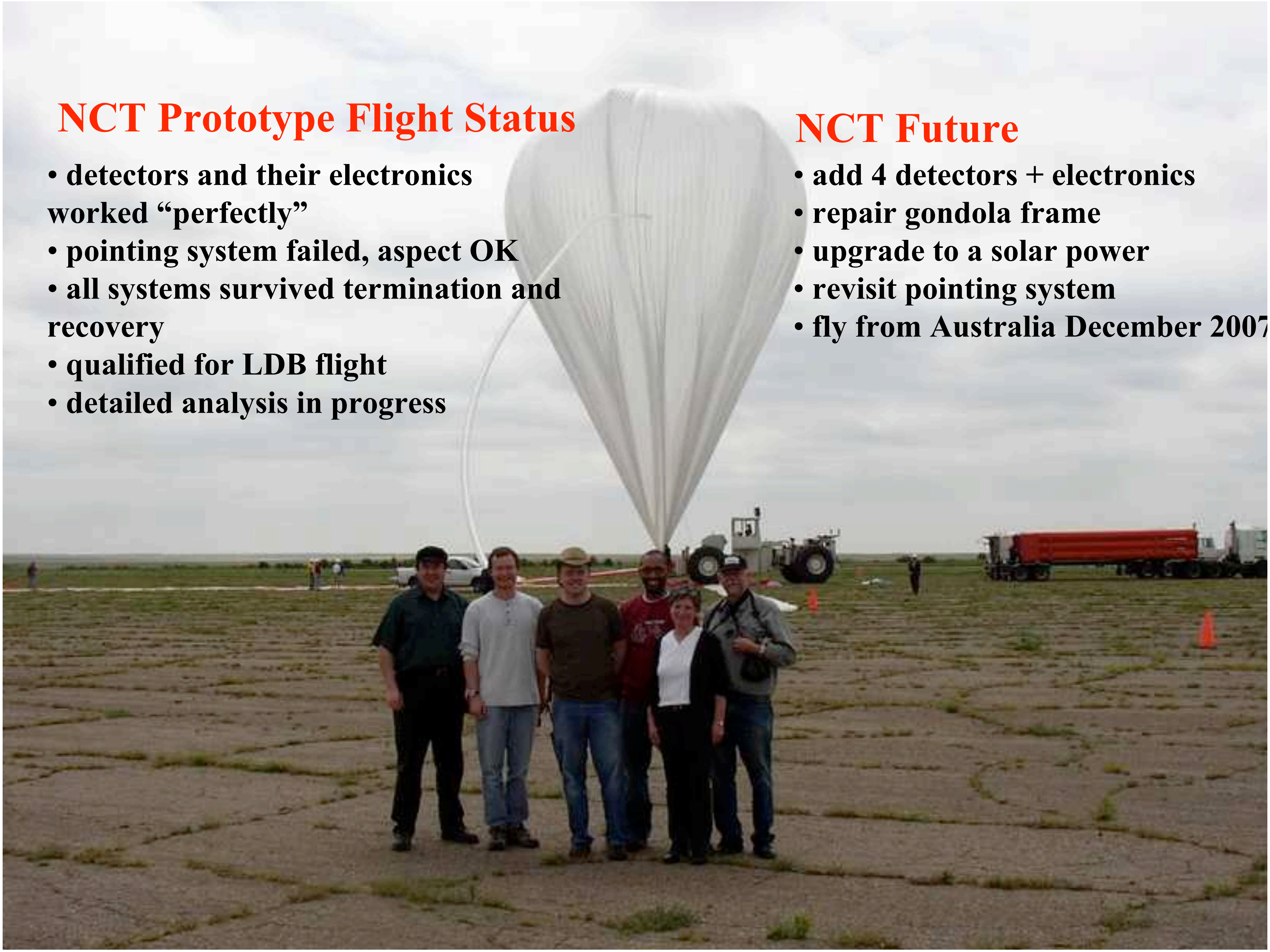


- rates about what expected
- detailed analysis in progress
- few obvious lines….

Recovery

Minimal, mostly cosmetic damage
To the Gondola

Instrument and all electronics
Currently working perfectly in the
Laboratory



NCT Prototype Flight Status

- detectors and their electronics worked “perfectly”
- pointing system failed, aspect OK
- all systems survived termination and recovery
- qualified for LDB flight
- detailed analysis in progress

NCT Future

- add 4 detectors + electronics
- repair gondola frame
- upgrade to a solar power
- revisit pointing system
- fly from Australia December 2007

Advanced Compton Telescope (ACT):

Type Ia Supernovae

Cosmic Yardsticks, Alchemists

Goal: study ^{56}Ni & ^{56}Co emission from the core of Type Ia supernovae.

1. **Standard Candles** -- characterize the ^{56}Ni production, relation to optical
2. **Explosion Physics** -- uniquely distinguish explosion physics
3. **SNe Ia Rate, Local & Cosmic** -- direct rates unbiased by extinction

We define the science requirements in terms of the following objective:

ACT must be able to strongly distinguish typical deflagration models from delayed detonation models, even if the supernovae distances are unknown.

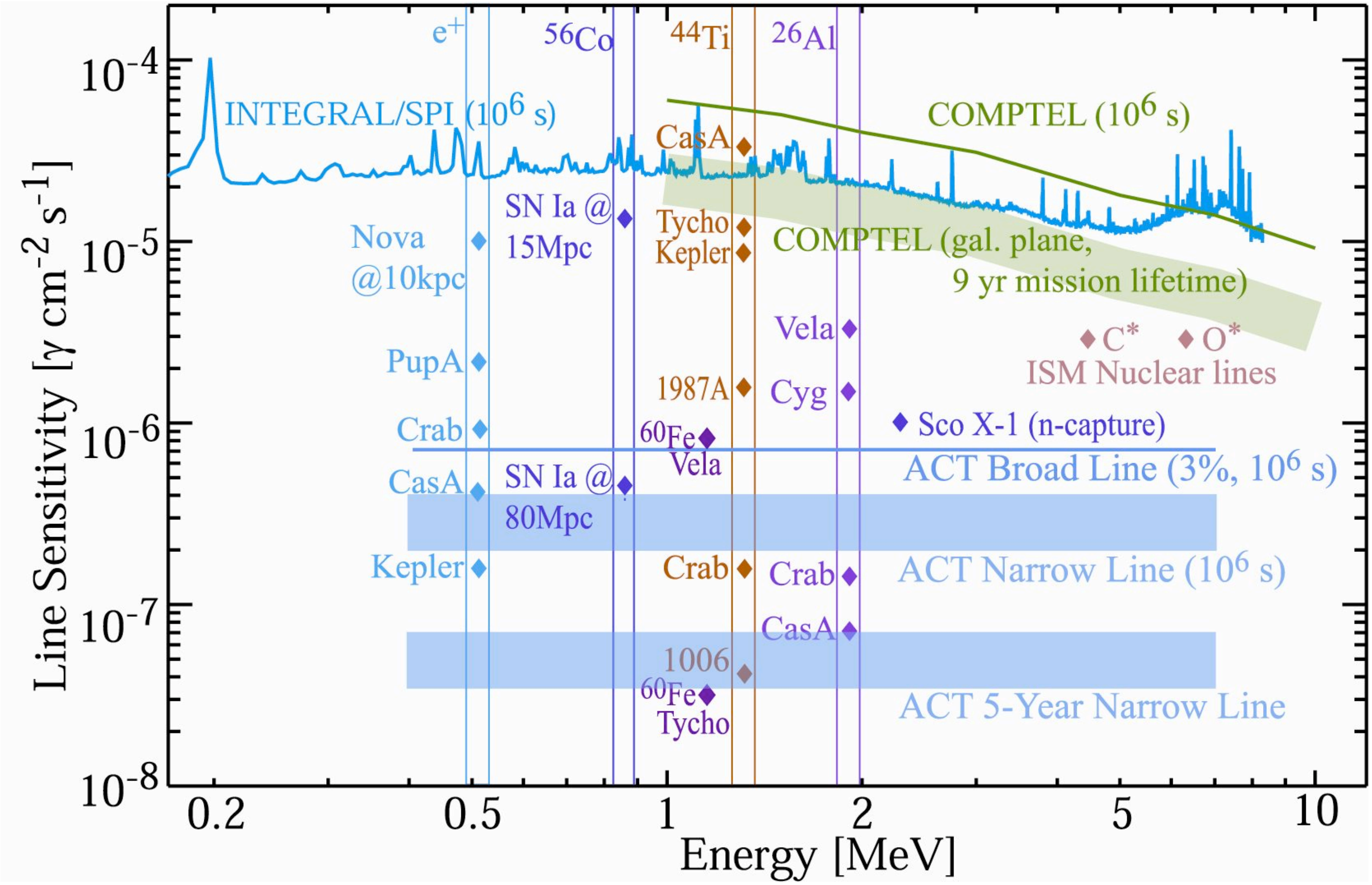
Leading to instrumental requirements:

- broad (3%) line sensitivity at 847 keV: $\sim 7\times10^{-7}$ ph/cm^2/s
- spectral resolution: $\Delta E/E < 1\%$
- wide field of view: 25% sky

….these lead to 40-50 detections/year (5 @ 15σ)!

Nuclear Line Sensitivity

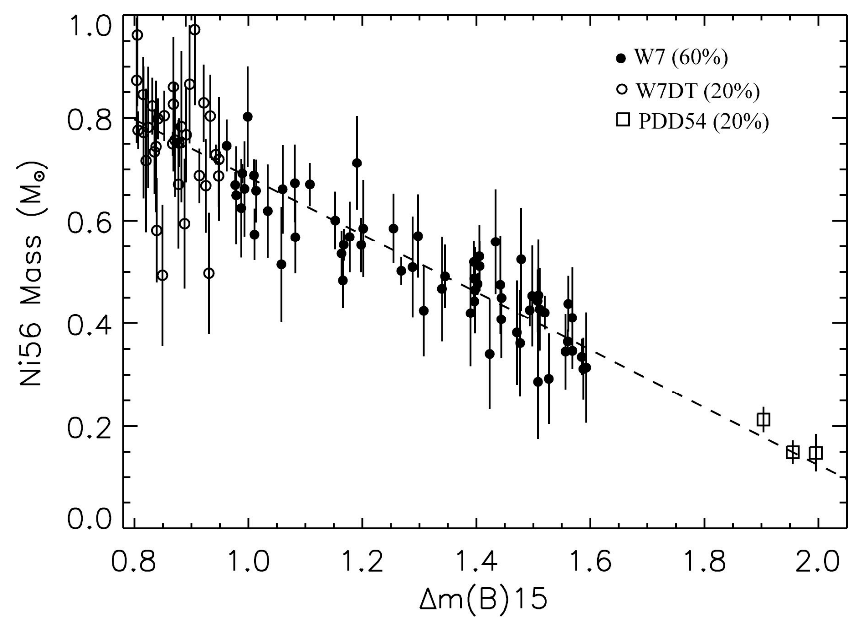
Primary science requirement: systematic study of SNIa spectra, lightcurves to uniquely determine the explosion mechanism, ^{56}Co (0.847 MeV) abundances.

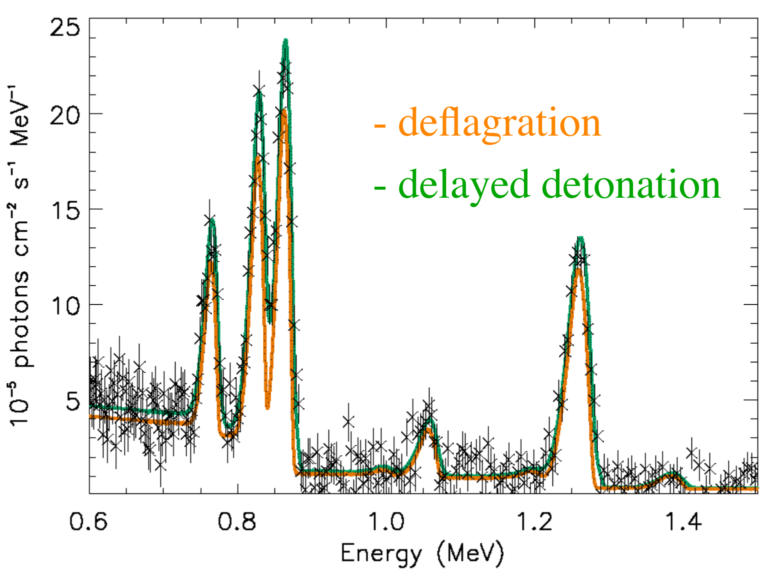


Standard Candle

characterize ^{56}Ni production

Requirements: measurement of ^{56}Ni production in >100 SNe at >5σ levels.





Explosion Physics

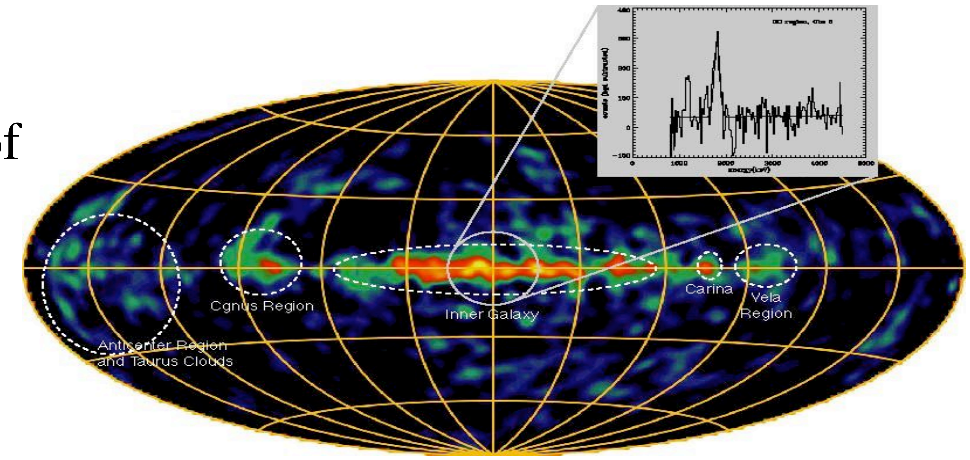
flame propagation, dynamics

Requirements: high sensitivity (>15σ) lightcurves and high-resolution spectra (ΔE/E<1%) of several SNe Ia events of each subclass over the primary 5-year survey.

History of nucleosynthesis in our Galaxy

Nuclear Radioactive Emission

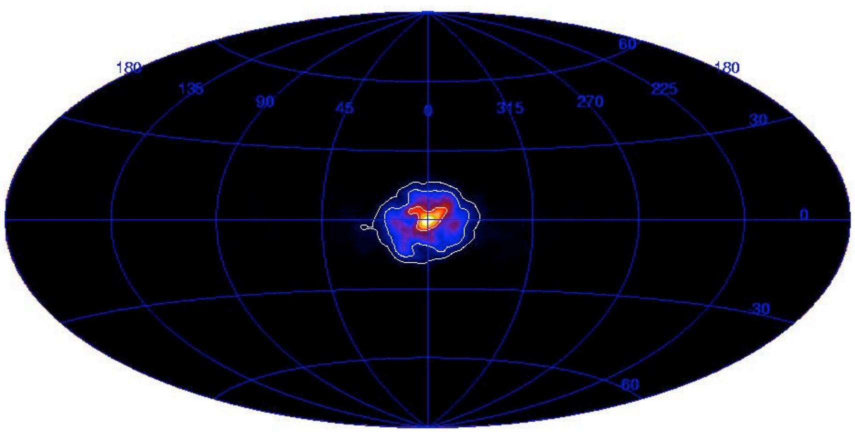
✓ resolve ^{60}Fe, ^{26}Al, e^+ into hundreds of regions, supernova remnants
✓ identify recent galactic SNe: ^{44}Ti
✓ novae: ^{22}Na, e^+
✓ solar flares and quiescent emission



(Oberlack et al. 1996)

Exotic physics at our Galaxy's core?

Electron-Positron Annihilation



✓ SN Ia, novae, black holes: less likely…
✓ MeV dark matter annihilation/decay?
✓ ACT will provide detailed morphology, spectra of the line & underlying continuum

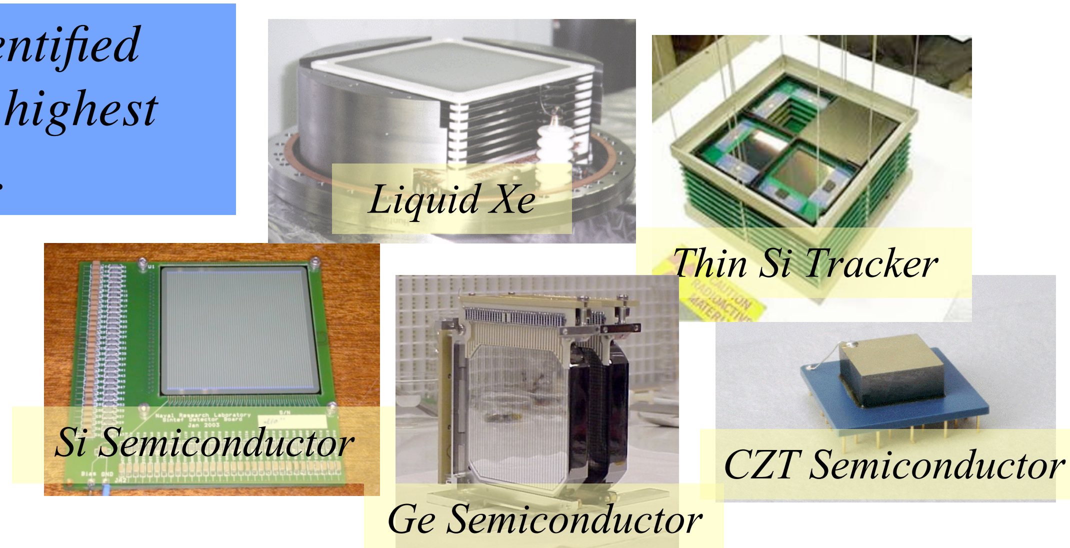
(Knoedlseder et al., 2005)

ACT Enabling Technologies

The ACT Vision Mission study identified the most promising detectors and highest priority technology developments.

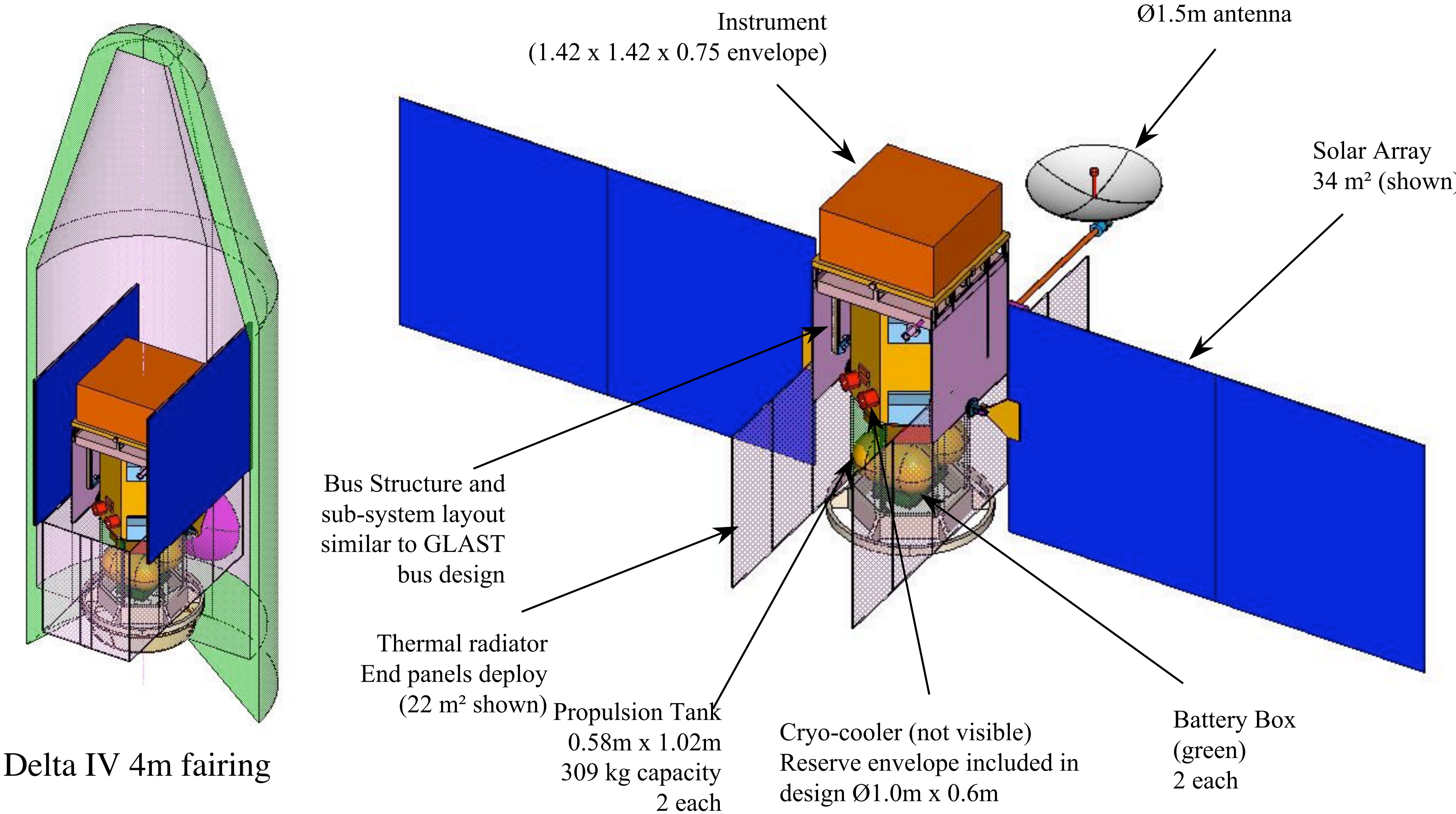
Highest recommendations:

- low-power readouts
- Ge, Si strip detectors

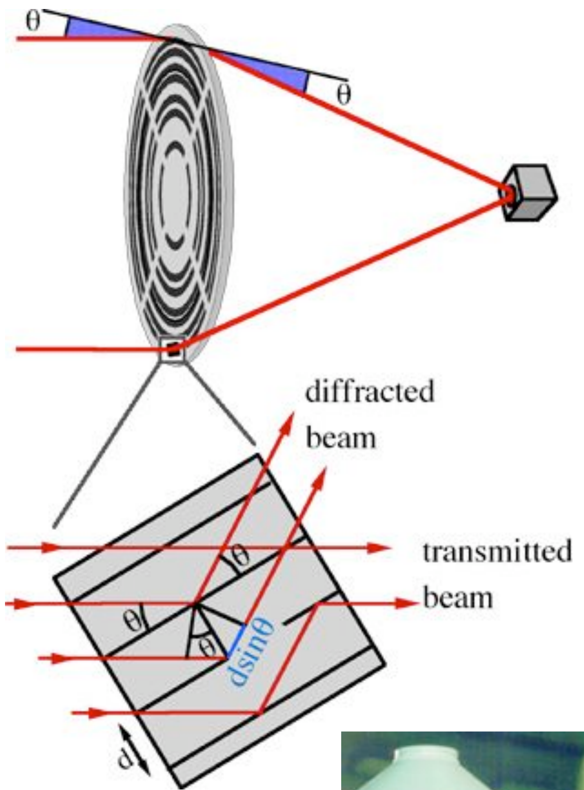


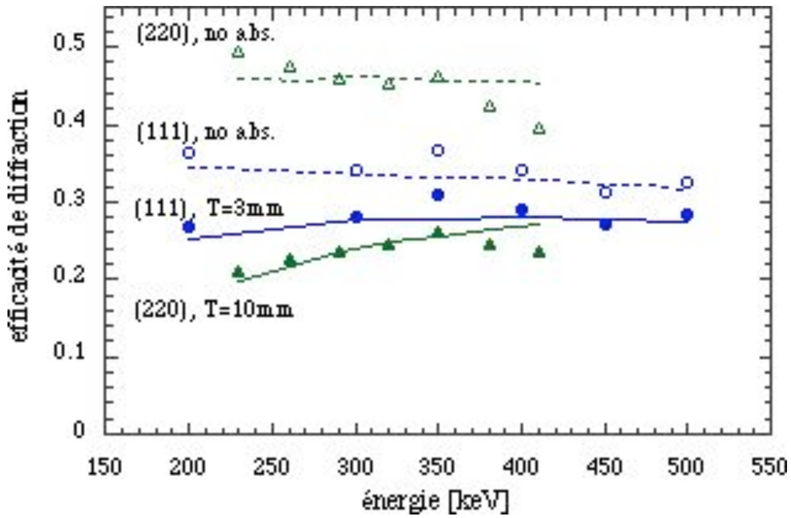
Property	Ge Strip	Si Strip	Liquid Xe	CZT Strip	Xe μWell
ΔE/E (1 MeV)	0.2-1%	0.2-1%	3%	1%	1.7%
Spatial Resol.	<1-mm^3	<1-mm^3	<1-mm^3	<1-mm^3	0.2-mm^3
Z density	32 5.3 g/cm^3	14 2.3 g/cm^3	54 3.0 g/cm^3	48 8.3 g/cm^3	54 (3 atm) 0.02 g/cm^3
Volume (achvd.)	130 cm^3	60 cm^3	3000 cm^3	4 cm^3	50 cm^3
Operating T	-190° C	-30° C	-100° C	10° C	20° C

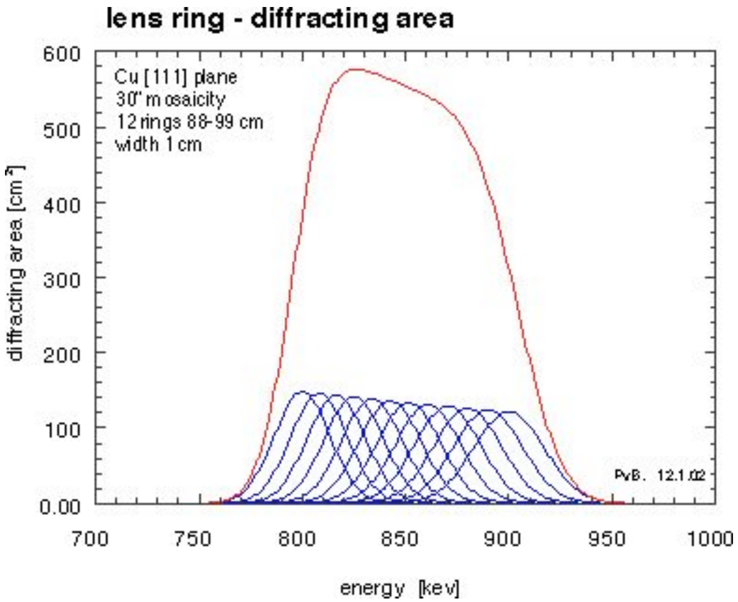
ACT Mission Configuration



Laue Lens: Focusing γ-rays

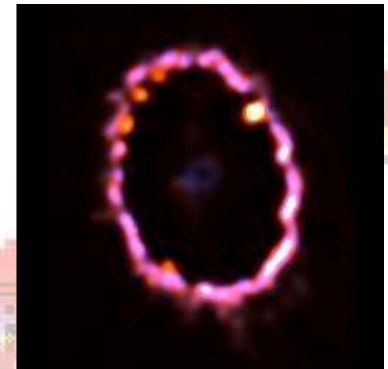






von Ballmoos et al., CESR, Toulouse

ACT Science Overview



Where do the chemical building blocks of life, planets, stars originate?

How do the chemical elements evolve?

What powers supernovae explosions?

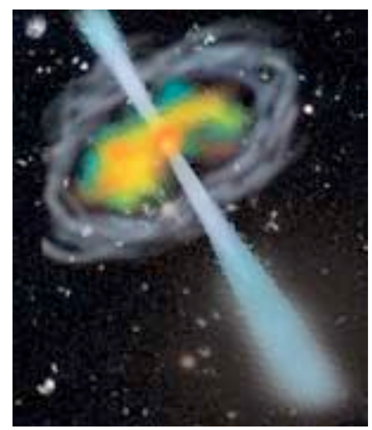
Resolved spectroscopy and flux of nuclear lines from the heart of supernovae

(J. Wilms)

What is the physics at the edge of a black hole?

How do matter & antimatter behave in extreme environments?

Spectroscopy, polarization, and timing of photons from black holes, neutron stars, and novae



When did the first stars form?

Can gamma-ray bursts measure the geometry of the Universe?

Gamma-ray burst localization, spectroscopy, polarization and timing