高エネルギー電子、ガンマ線

森　正樹

CRC宇宙線将来計画シンポジウム、2005年12月5-6日、宇宙線研究所

高エネルギー電子の伝播

- Diffusion-loss equation

$$\frac{\mathrm{d}N(E)}{\mathrm{d}t} = D\nabla^2 N(E) + \frac{\partial}{\partial E}[b(E)N(E)] + Q(E,t)$$

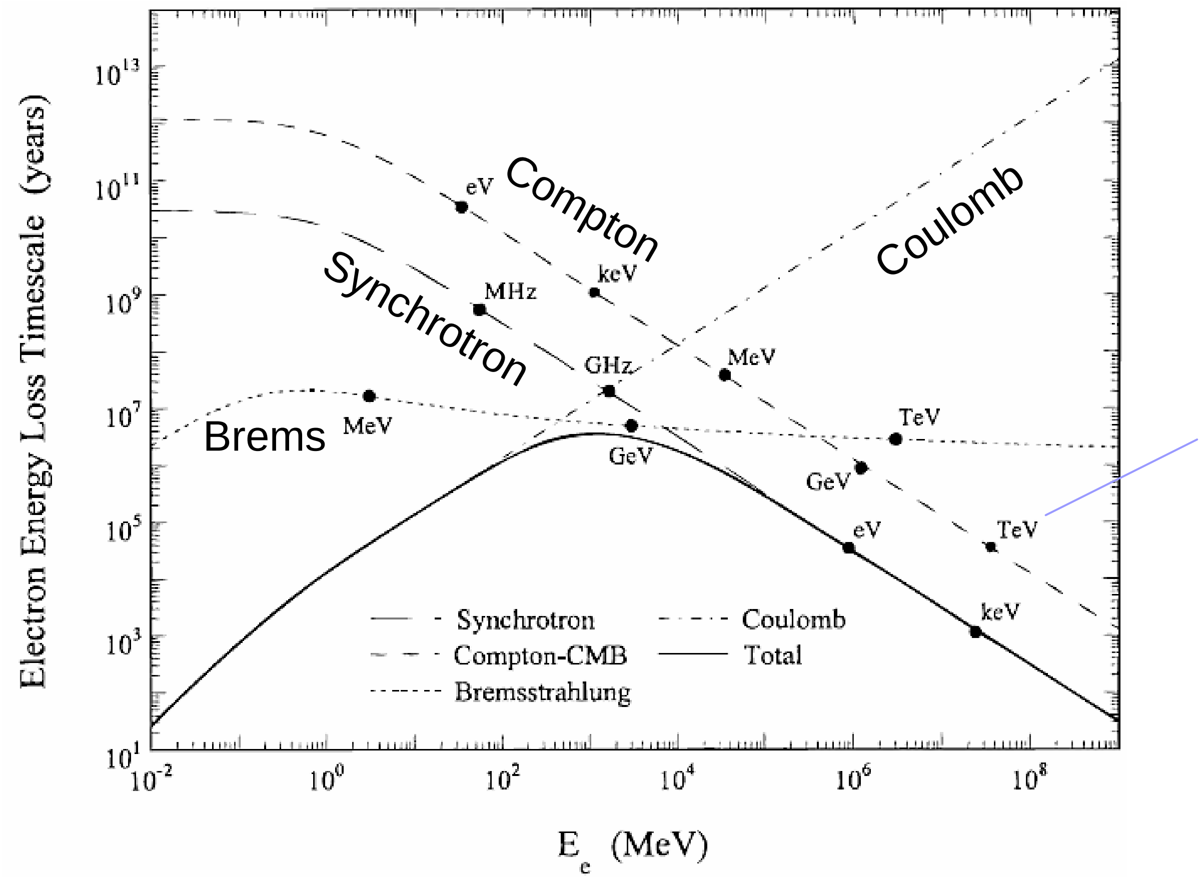
D: 拡散係数

$$b(E) = -\frac{\mathrm{d}E}{\mathrm{d}t} = A_1\left(\ln\frac{E}{mc^2} + 19.8\right) + A_2 E + A_3 E^2$$

A_1: 電離損失
A_2: 制動放射
A_3: 逆コンプトン＆シンクロトロン損失
Q: 電子源

Sturner et al., ApJ 490, 619 (1997)

高エネルギー電子のエネルギー損失時間スケール



Typical photon energy

FIG. 10.—The electron energy-loss timescales, $E/\dot{E}$, due to synchrotron emission, bremsstrahlung, Compton scattering of the CMB, and Coulomb collisions for the case of $n_{\mathrm{SNR}} = 4\ \mathrm{cm}^{-3}$, $B_{\mathrm{SNR}} = 20\ \mu\mathrm{G}$ ($n_{\mathrm{ISM}} = 1\ \mathrm{cm}^{-3}$, $B_{\mathrm{ISM}} = 5\ \mu\mathrm{G}$), and an electron temperature $T_e = 10^8$ K. Note how Coulomb losses dominate below 100 MeV, bremsstrahlung losses dominate near 1 GeV, and synchrotron losses dominate above 100 GeV. We find that for these parameter values, Compton scattering losses do not dominate at any energy. Also note that electrons with kinetic energies near 1 GeV have the longest energy-loss timescale. On each radiative loss curve, we indicate the typical photon energy emitted by an electron with the given kinetic energy via that mechanism. This shows that radio synchrotron emission and GeV gamma-ray bremsstrahlung emission will endure for the longest time after the electron source has turned off, while MeV bremsstrahlung, keV synchrotron emission, and TeV Compton photons will decrease the fastest.

Why 高エネルギー電子？

- 到達距離が短い
  ○　候補天体が絞れる、到来方向が異方性を持つ
  ×　関係する天体の数が少ない
- 寿命が短い
  ○　候補天体が特定される
  ×　遠方まで測れない
- 高エネルギーで損失大
  ○　カットオフと距離が関連
  ×　統計が稼げない
- 電荷を持つ
  ○　較正ビームが容易に得られる
  ×　到来方向を絞れない

宇宙線電子スペクトルの観測

Ohishi et al., ApJ 610, 868 (2004)

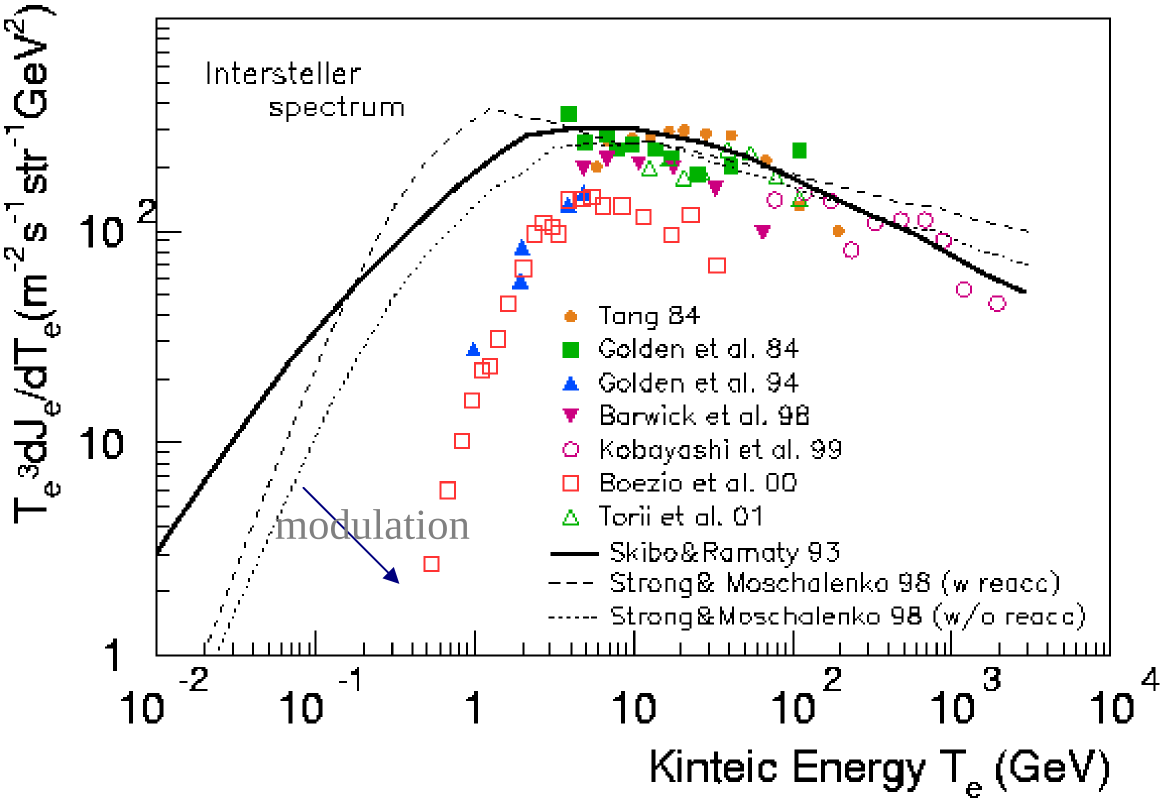
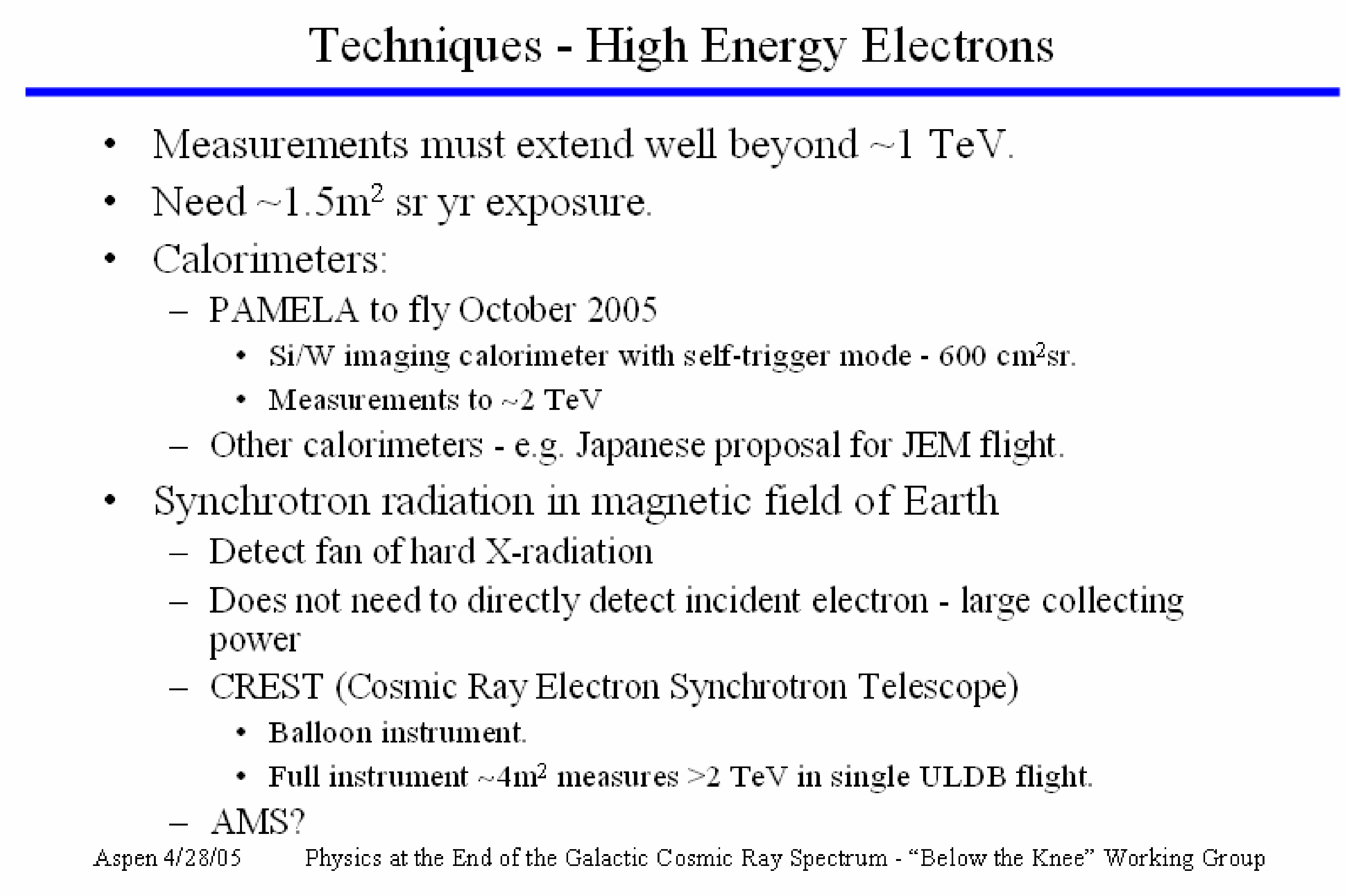


Fig. 2.—Adopted cosmic-ray electron spectrum in the Galaxy. The model curves are taken from Skibo & Ramaty (1993), Moskalenko & Strong (1998), and Casadei & Bindi (2003). (The two lines for Moskalenko & Strong 1998 show models with and without reacceleration of the cosmic rays.) Also plotted are direct observations of the local electron spectrum (Tang 1984; Golden et al. 1984, 1994; Barwick et al. 1998; Kobayashi et al. 1999; Boezio et al. 2000; Torii et al. 2001), but note that these are affected by solar modulation.

“Below the Knee” Working Group Report - Day 3

Binns, Hörandel, Mitchell, Moskalenko, Müller, Streitmatter, Takita, Vacchi, Yodh, *et al.*

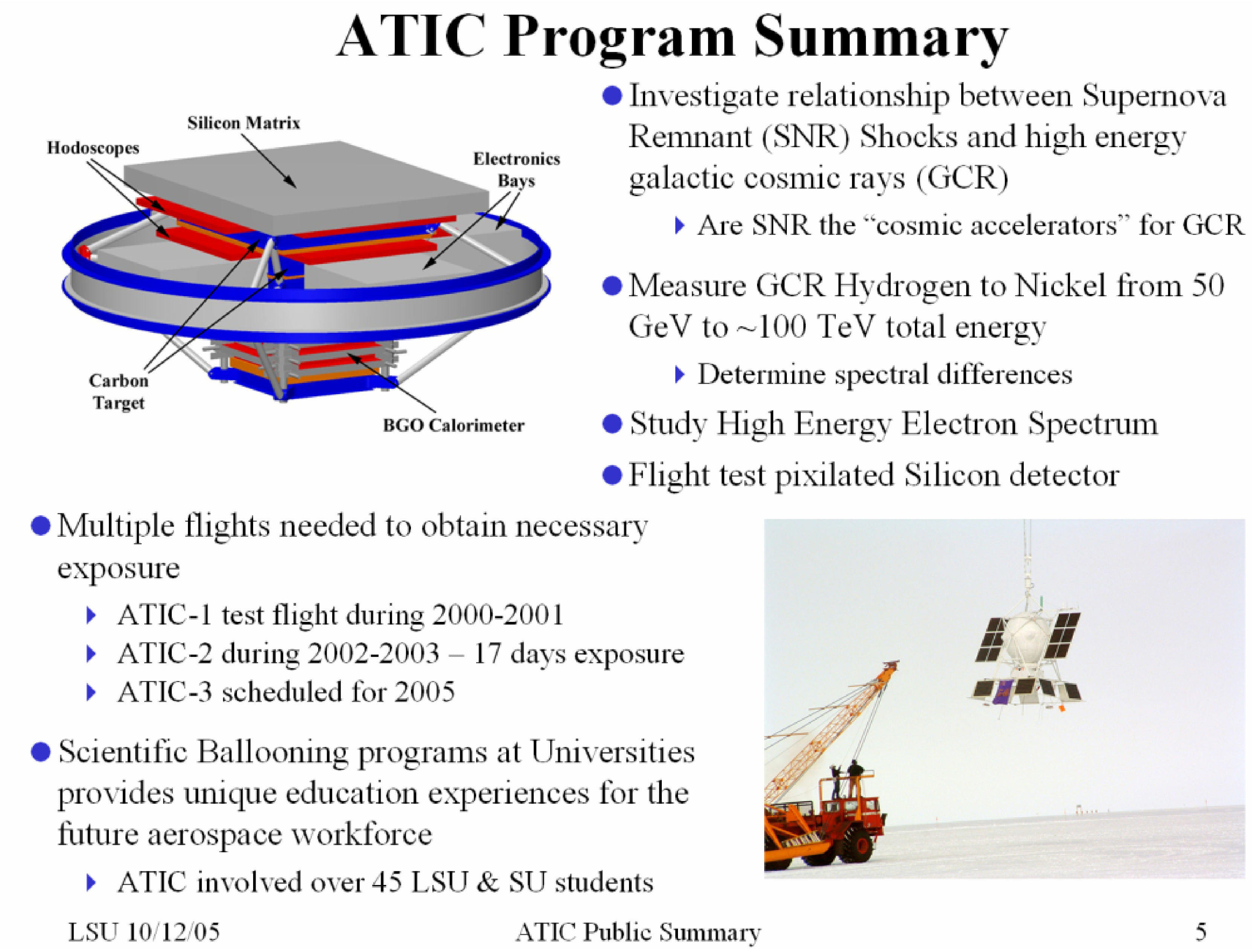


Techniques - High Energy Electrons

- Measurements must extend well beyond ~1 TeV.
- Need ~1.5m^2 sr yr exposure.
- Calorimeters:
  - PAMELA to fly October 2005
    - Si/W imaging calorimeter with self-trigger mode - 600 cm^{2}sr.
    - Measurements to ~2 TeV
  - Other calorimeters - e.g. Japanese proposal for JEM flight.
- Synchrotron radiation in magnetic field of Earth
  - Detect fan of hard X-radiation
  - Does not need to directly detect incident electron - large collecting power
  - CREST (Cosmic Ray Electron Synchrotron Telescope)
    - Balloon instrument.
    - Full instrument ~4m^2 measures >2 TeV in single ULDB flight.
  - AMS?

Reports at ICRC2005

- Experiments Presenting Analyzed Flight Data, Active Detectors
  - **TRACER, ATIC, BESS, TIGER, BETS, CPDS, MARIE**
- Experiments Presenting Analyzed Flight Data, Passive Detectors
  - **RUNJOB, CAKE**
- Experiments With Recent Data, Analysis Underway
  - **BESS-Polar, CREAM**
- Experiments With Advanced Hardware
  - **PAMELA, AMS-02**
- New Experiments
  - **CALET, CREST, NUCLEON, INCA**

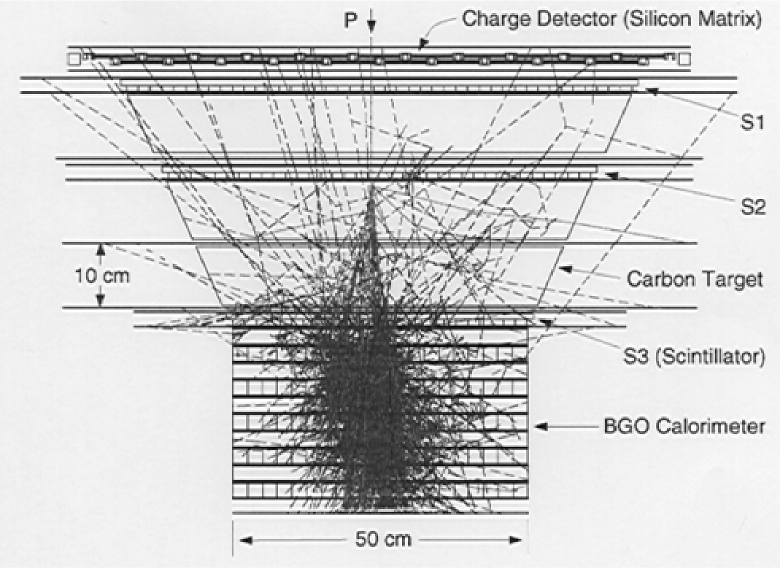


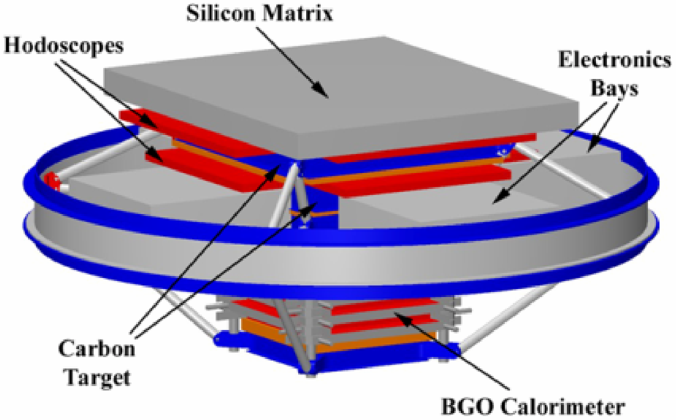
ATIC Program Summary

- Investigate relationship between Supernova Remnant (SNR) Shocks and high energy galactic cosmic rays (GCR)
  - Are SNR the "cosmic accelerators" for GCR
- Measure GCR Hydrogen to Nickel from 50 GeV to ~100 TeV total energy
  - Determine spectral differences
- Study High Energy Electron Spectrum
- Flight test pixilated Silicon detector
- Multiple flights needed to obtain necessary exposure
  - ATIC-1 test flight during 2000-2001
  - ATIC-2 during 2002-2003 – 17 days exposure
  - ATIC-3 scheduled for 2005
- Scientific Ballooning programs at Universities provides unique education experiences for the future aerospace workforce
  - ATIC involved over 45 LSU & SU students

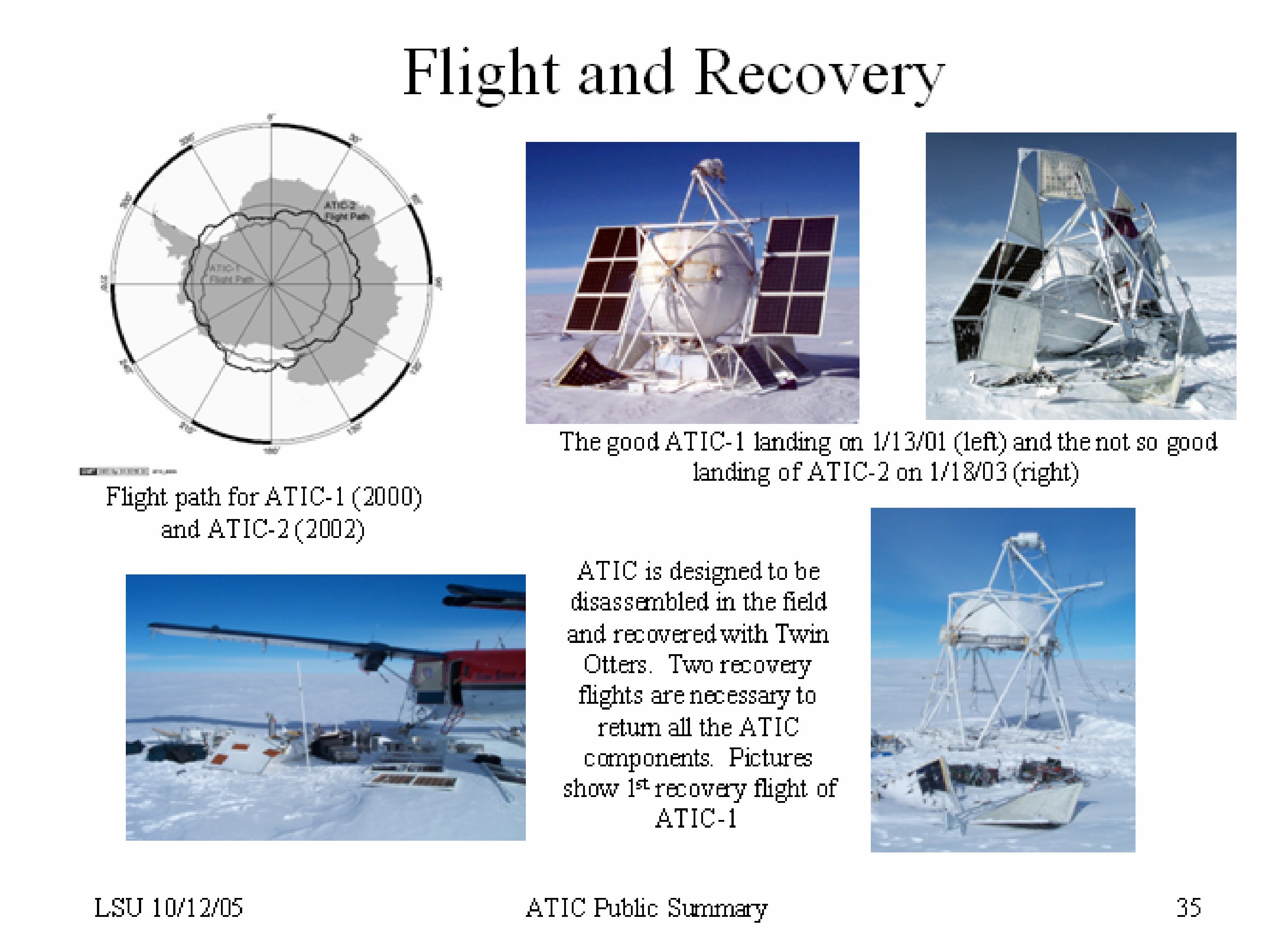
ATIC Instrument Summary

- Ionization Calorimetry only practical method to measure high energy light elements
  - Silicon Matrix has 4,480 pixels to measure GCR charge in presence of shower backscatter
  - Plastic scintillator hodoscope, embedded in Carbon target, provides event trigger plus charge & trajectory information
  - Fully active calorimeter includes 320 Bismuth Germinate (BGO) crystals to foster and measure the nuclear - electromagnetic cascade showers
  - Geometrical factor: 0.24 m^{2}sr (S1 – S3 – BGO6)





ATIC-1 and ATIC-2 flights



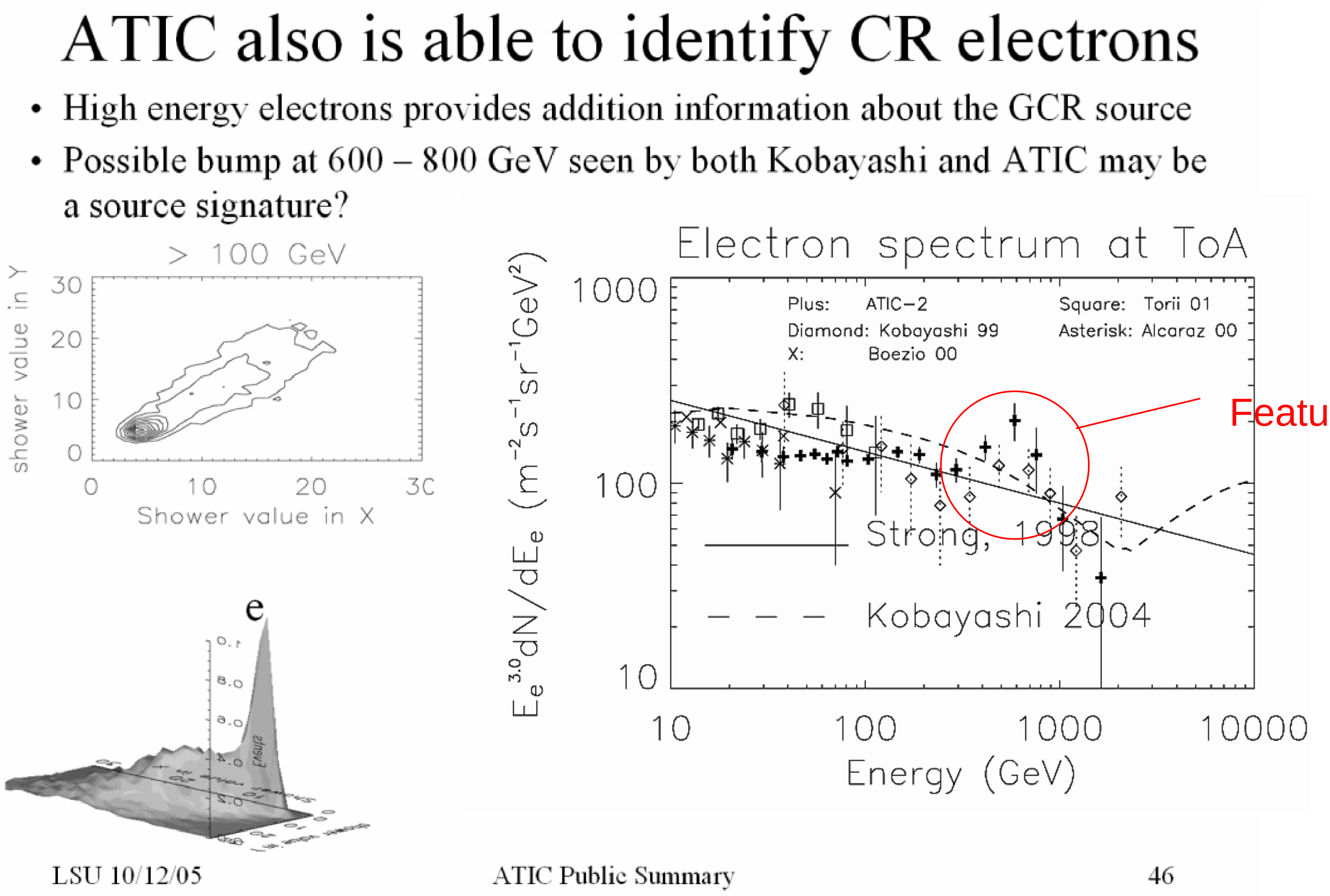
Flight and Recovery

Flight path for ATIC-1 (2000) and ATIC-2 (2002)

The good ATIC-1 landing on 1/13/01 (left) and the not so good landing of ATIC-2 on 1/18/03 (right)

ATIC is designed to be disassembled in the field and recovered with Twin Otters. Two recovery flights are necessary to return all the ATIC components. Pictures show 1st recovery flight of ATIC-1

ATIC results



ATIC also is able to identify CR electrons

- High energy electrons provides addition information about the GCR source
- Possible bump at 600 – 800 GeV seen by both Kobayashi and ATIC may be a source signature?

Feature??

PAMELA

Flight model before delivery to Samara, March 2005

Launch Dec. 2005
from Baikonur

Orbital inclination: 70.4°

Life Time: > 3 years

Resurs
-DK1

A Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

PAMELA DETECTOR

Anticoncidence system

Multiple particles rejection

Anticoincidence system

Defines tracker acceptance

Plastic scintillator + PMT

Si-W Calorimeter

Imaging Calorimeter : reconstructs shower profile discriminating e^+/p and p/e^- at level of ~ 10^{-5}

Energy Resolution for $e^\pm$ $\Delta E/E = 15\% / E^{1/2}$.

Si-X / W / Si-Y structure

22 W planes

$16.3\ X_0 / 0.6\ I_0$

Time-of-flight

Level 1 trigger

particle identification (up to 1GeV/c)

dE/dx

Plastic scintillator + PMT

Time Resolution ~ 70 ps

Si Tracker + magnet

Permanent magnet B=0.4T

6 planes double sided Si strips 300 µm thick

Spatial risolution ~3µm

MDR = 1000 GV/c

S4 and Neutron detectors

Identify hadron interactions

Plastic Scintillator

36 ^{3}He counters in a polyetilen moderator

M.Circella, NIM A158, 513 (2004)

PAMELA detector

Overall mass: 450kg

Power consumption: 350W

0.48T magnet

Spectrometer: 20.5cm^{2}sr

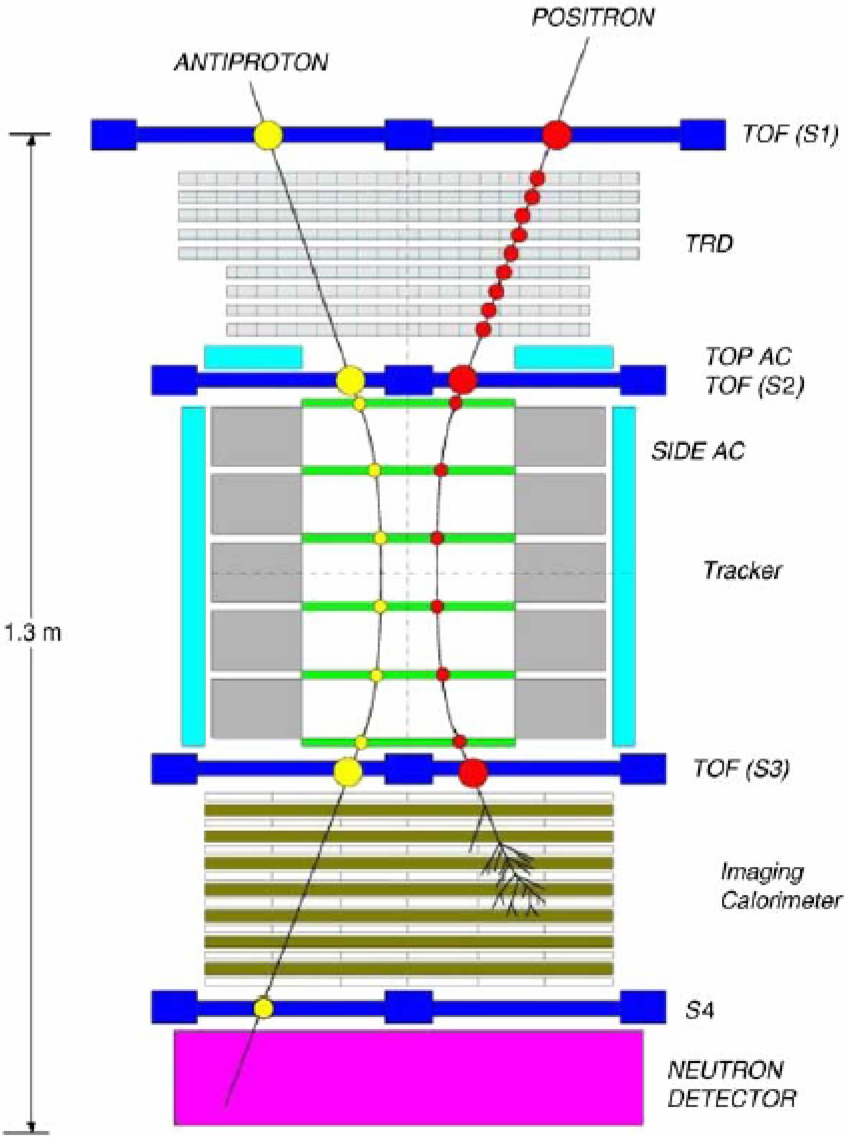
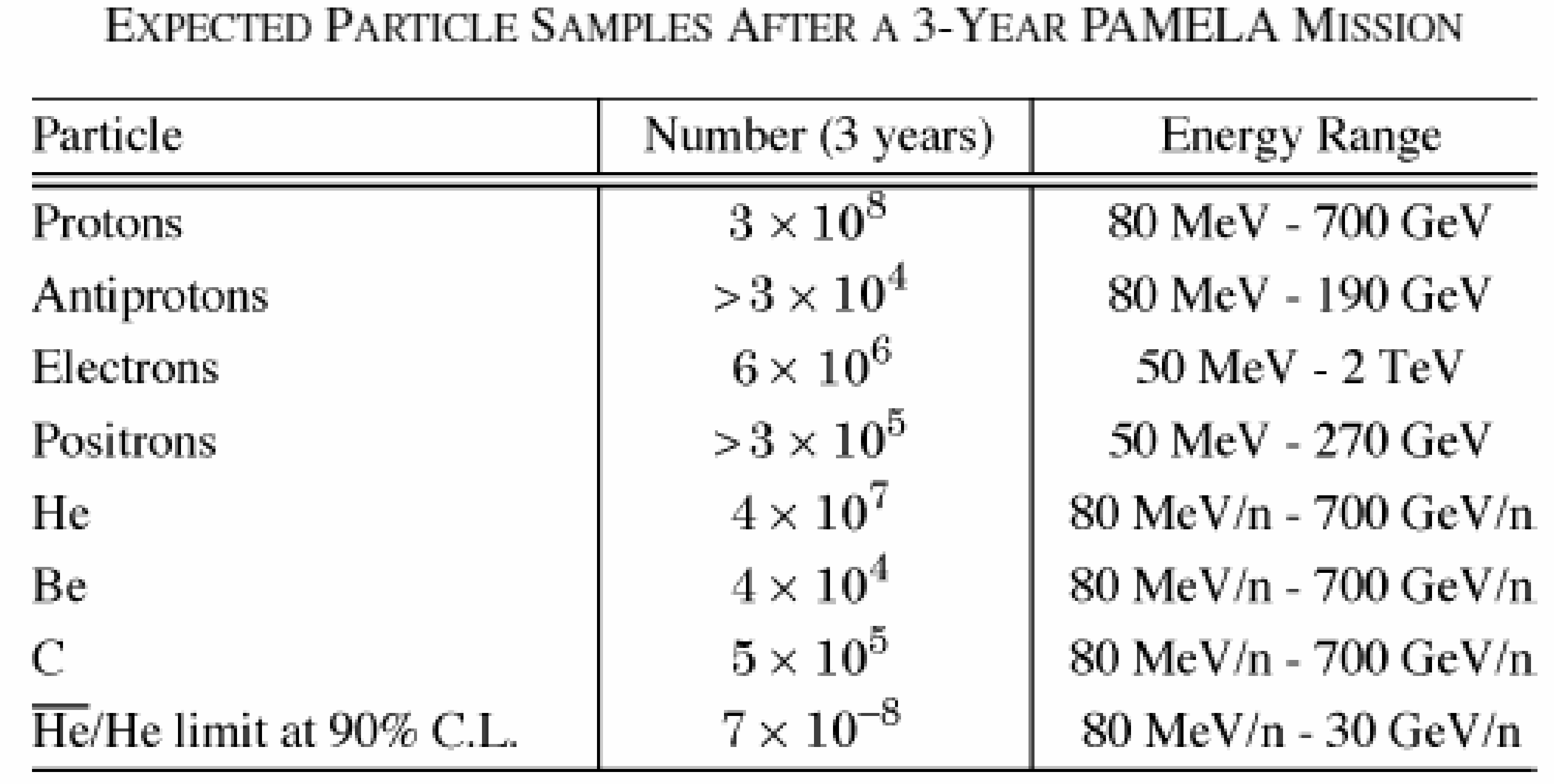


Fig. 2. Schematic view of the PAMELA apparatus: the magnetic spectrometer, equipped with a silicon microstrip tracking system, is complemented by a three-planes scintillator ToF system, a TRD and a silicon–tungsten calorimeter. A scintillator shower tail catcher and a neutron detector are located below the calorimeter. The magnetic spectrometer is surrounded by a scintillator anticoincidence system. An antiproton and a positron event are also shown in order to illustrate the signatures of different particles in the apparatus.

M.Bongi, IEEE Trans.Nucl.51, 854 (2004)

3-year PAMELA mission

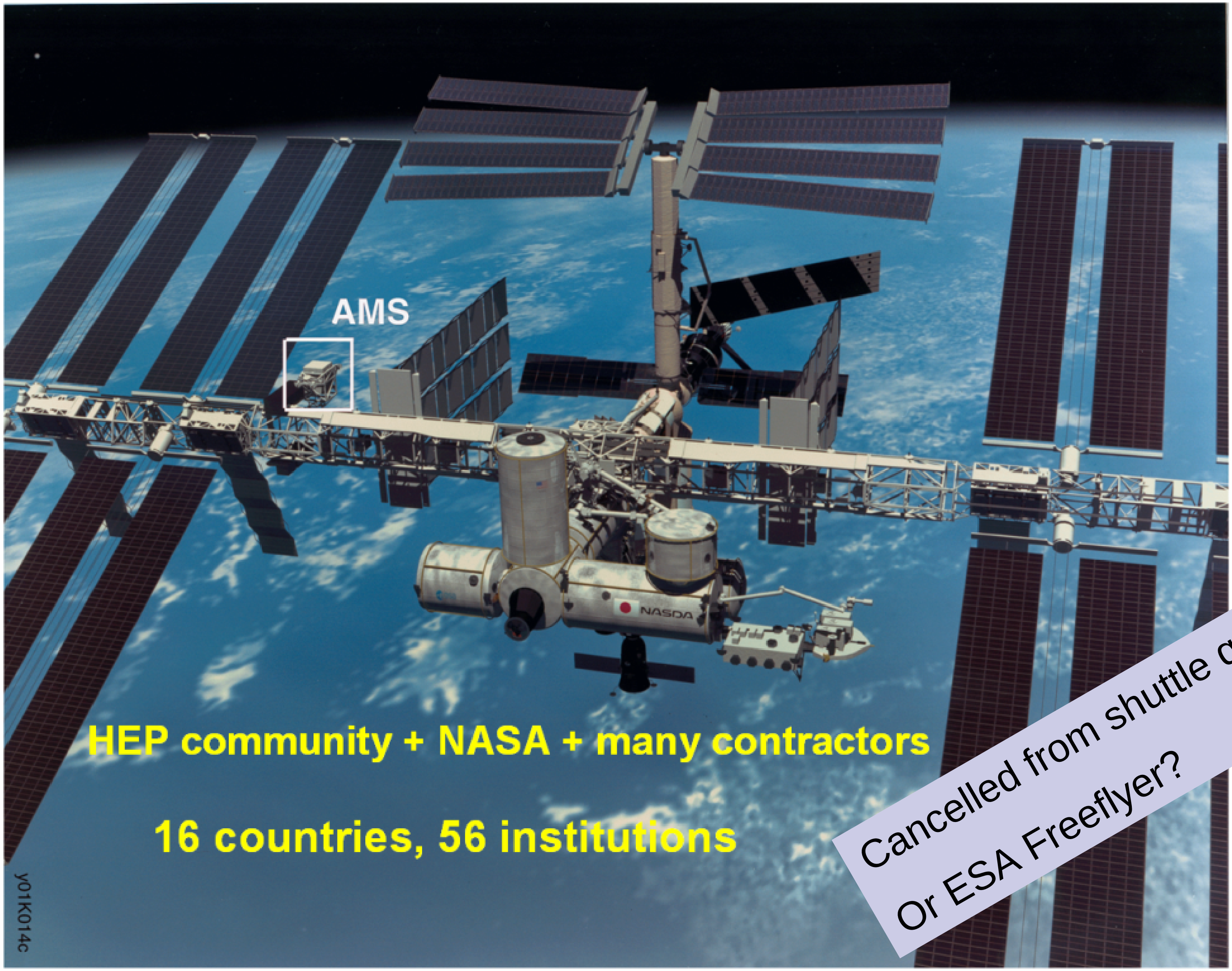


Expected Particle Samples After a 3-Year PAMELA Mission

Particle	Number (3 years)	Energy Range
Protons	3×10^{8}	80 MeV - 700 GeV
Antiprotons	$>3 \times 10^{4}$	80 MeV - 190 GeV
Electrons	6×10^{6}	50 MeV - 2 TeV
Positrons	$>3 \times 10^{5}$	50 MeV - 270 GeV
He	4×10^{7}	80 MeV/n - 700 GeV/n
Be	4×10^{4}	80 MeV/n - 700 GeV/n
C	5×10^{5}	80 MeV/n - 700 GeV/n
$\overline{\text{He}}$/He limit at 90% C.L.	7×10^{-8}	80 MeV/n - 30 GeV/n

- MDR ≈ 1000 GV
- 90% Efficiency for electrons and positrons while having a proton rejection factor > 10^6

AMS-2: Stupendous Scale of Activity



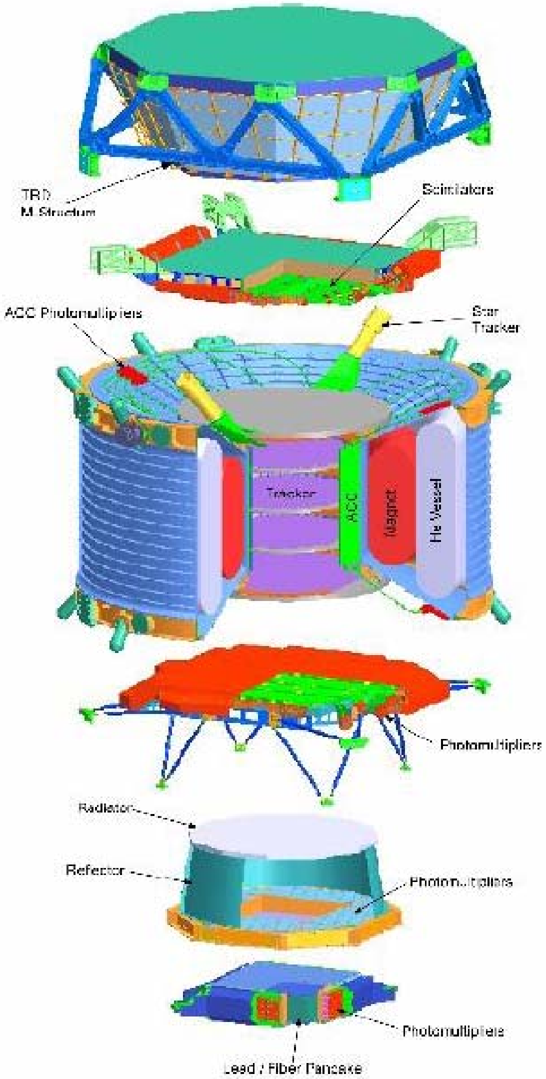
HEP community + NASA + many contractors

16 countries, 56 institutions

Cancelled from shuttle queue?
Or ESA Freeflyer?

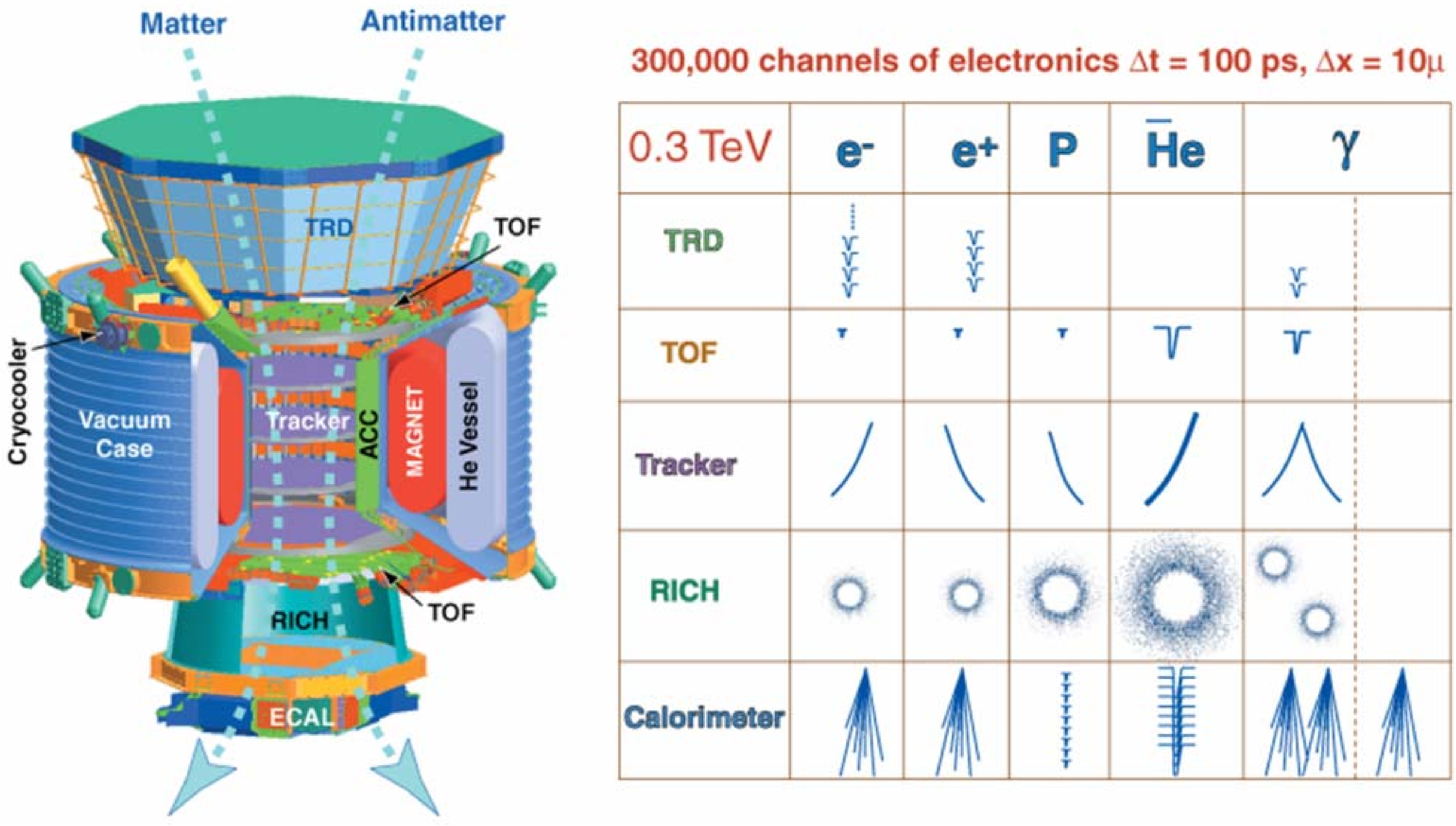
AMS-02 on International Space Station

- **Improved capabilities**
  - Larger acceptance (~ 0.5 m^2·sr)
  - Superconduction magnet
    a magnetic field $\sim$ 6 times larger
  - Larger silicon Tracker
    8 layers ~ 6.7 m^2 of double-sided silicon
  - a momentum resolution improved
    by a factor ~ 10
- **New Detector systems**
  - Transition Radiation Detector (TRD)
  - New Cherenkov detector (RICH)
  - Electromagnetic Calorimeter (ECAL)
  - 2 camera Star Tracker and GPS system
- **A total of 227300 channels** producing 7 Gbit/s, reduced by electronics to 2 Mbit/s downlink rate (A. Lebedev, X. Cai og-15)

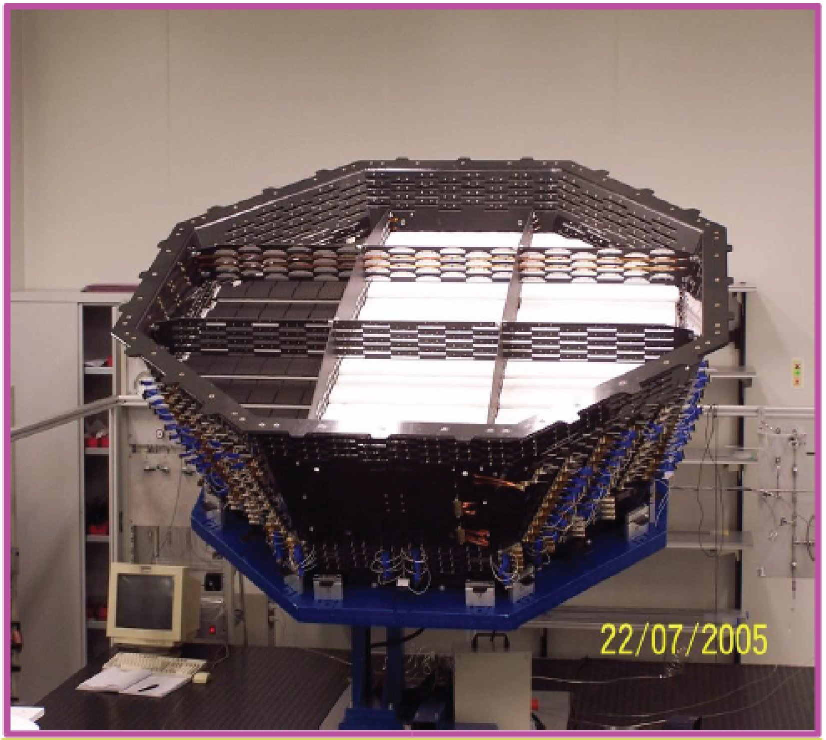


AMS: A TeV Magnetic Spectrometer in Space (3m x 3m x 3m, 7t)

300,000 channels of electronics $\Delta t = 100$ ps, $\Delta x = 10\mu$



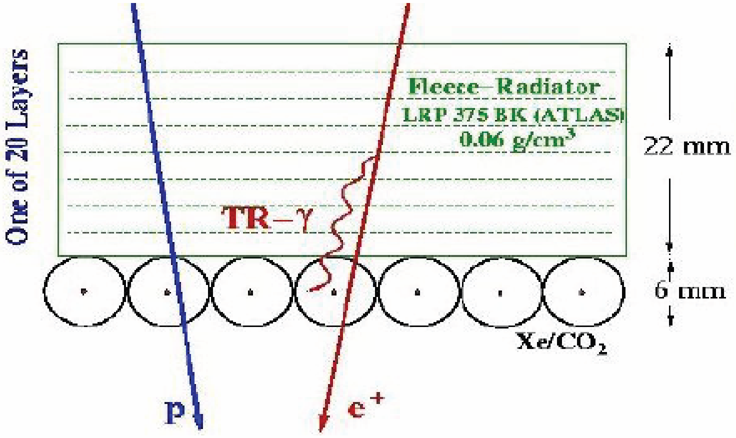
AMS-02 Transition Radiation Detector

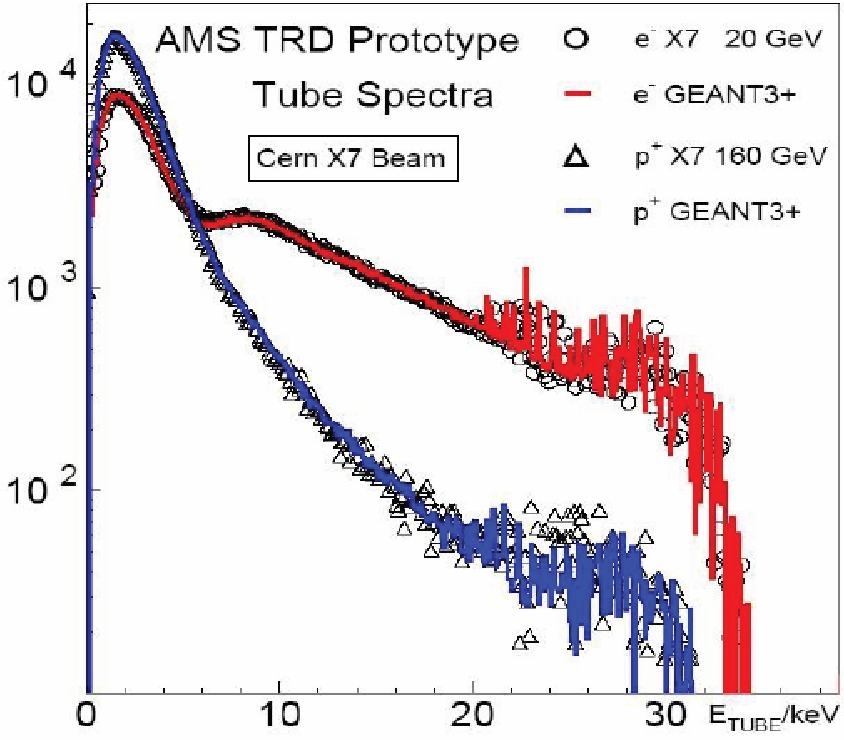


- *20 layers assembled in octagonal structure.*
- *328 modules of fleece and straw tubes.*

h/e rejection of 10^2-10^3

(in the range 300 → 3 GeV)





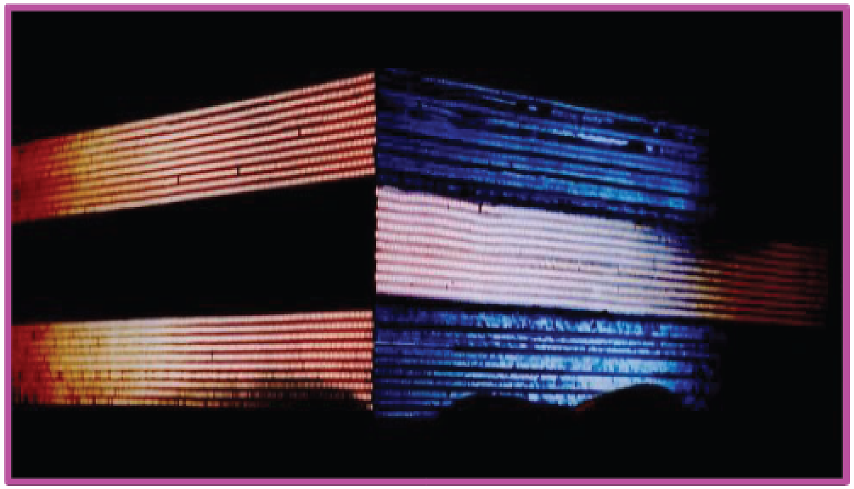
AMS-02 Electromagnetic Calorimeter

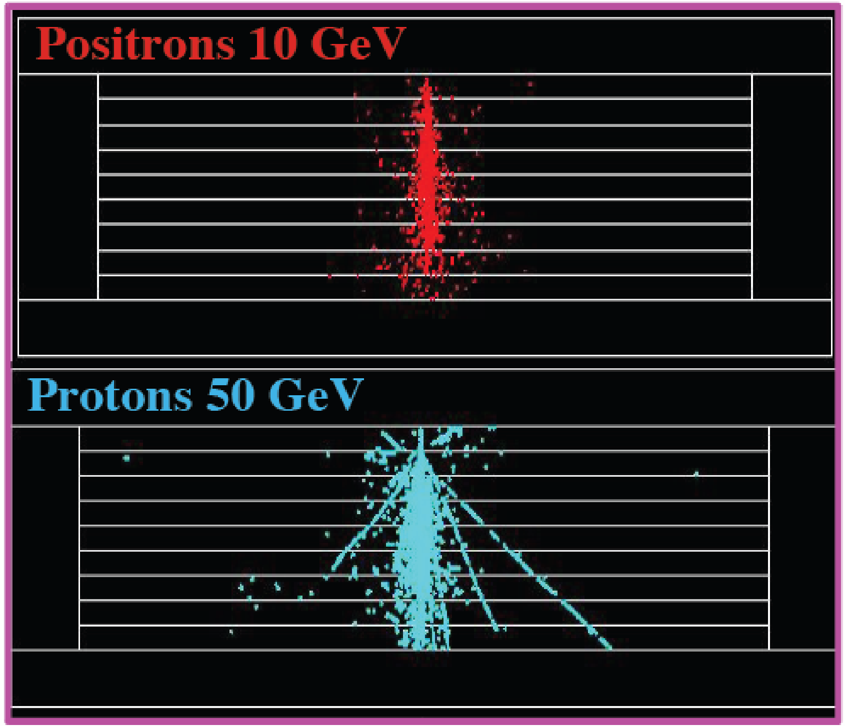
9 super layers of Sci-Fi/Lead ($16X_o$)

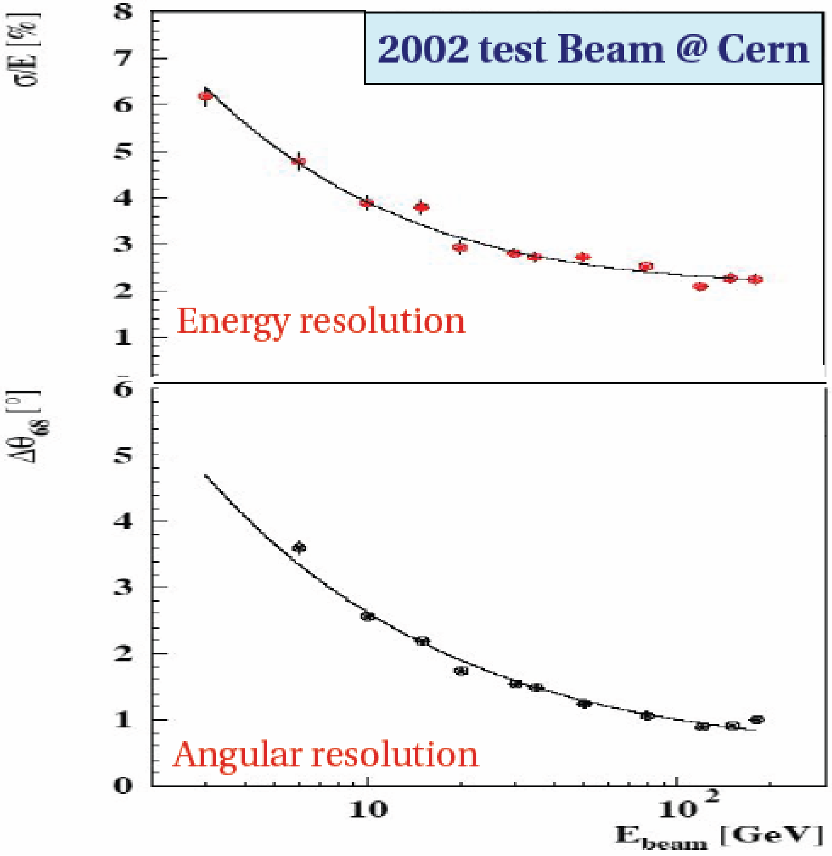
(324 multianode PMTs)

$\sigma(E)/E = 3\%$ @ 100GeV

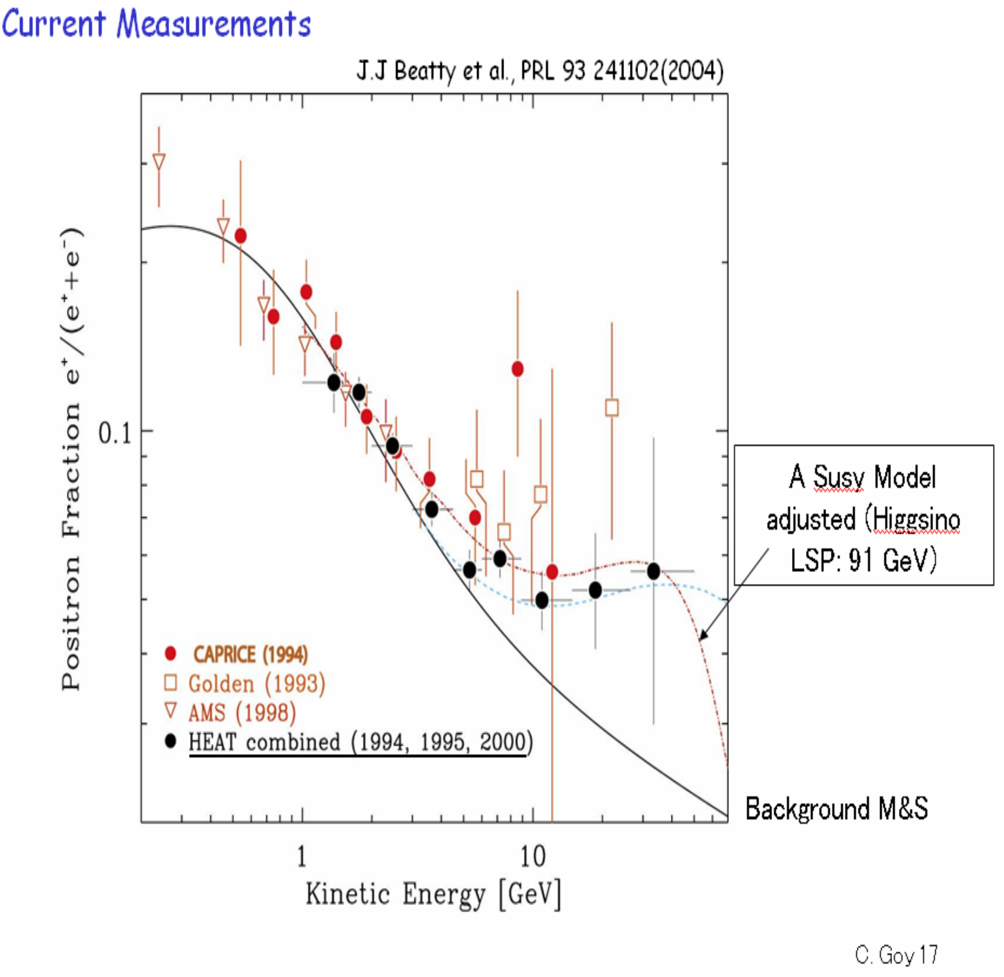
p/e rejection of 10^3







Positrons



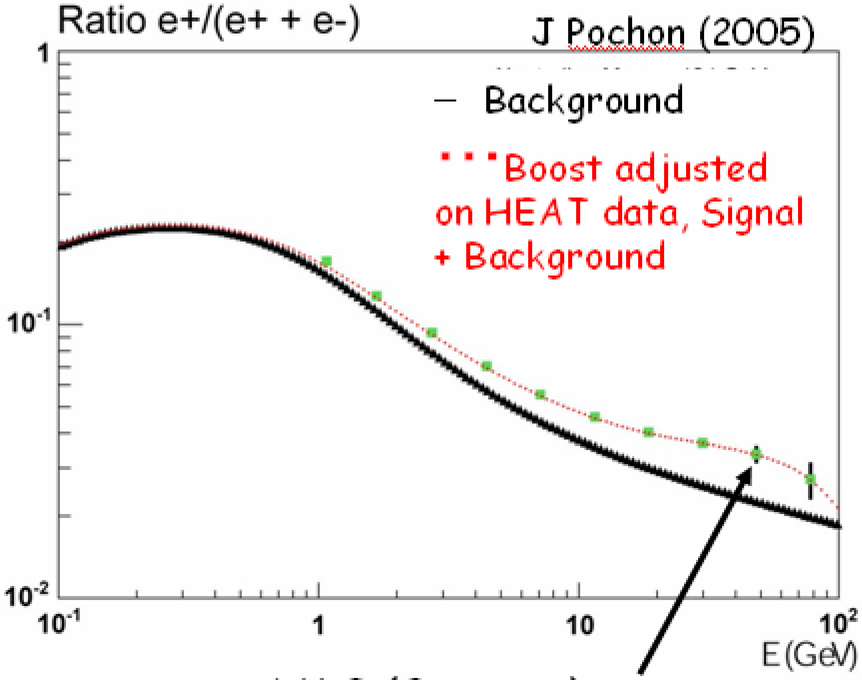
Current Measurements

J.J Beatty et al., PRL 93 241102(2004)

A Susy Model adjusted (Higgsino LSP: 91 GeV)

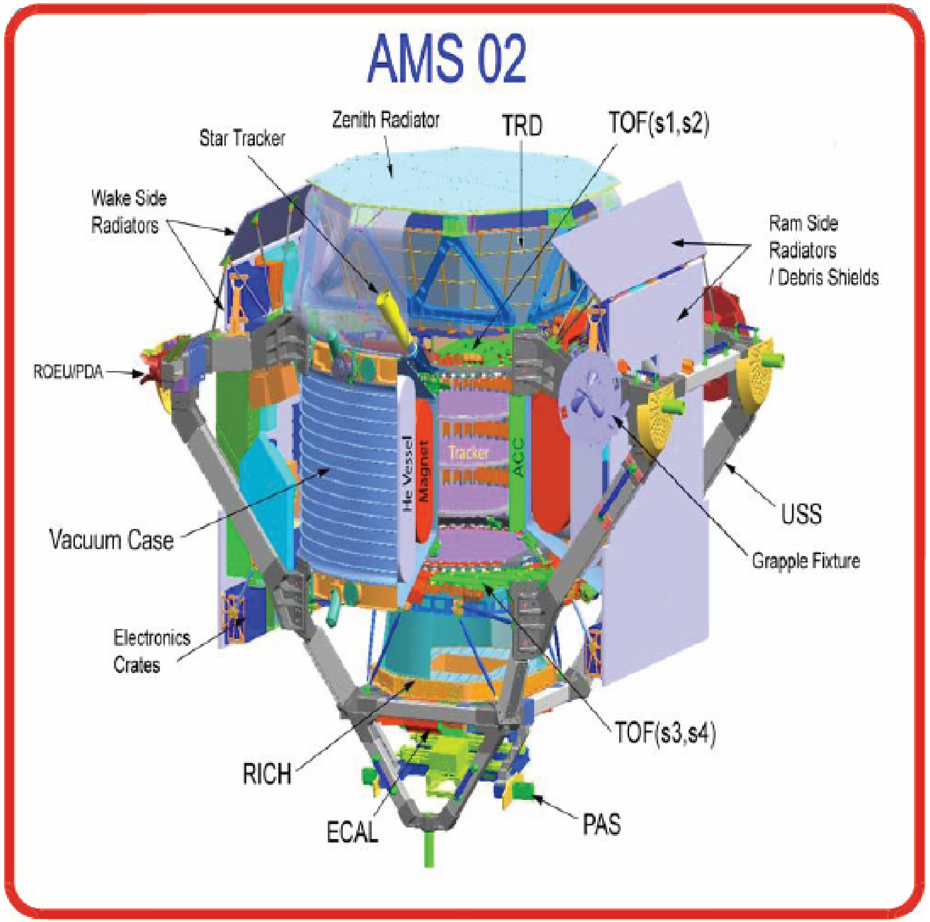
Background M&S

C. Goy 17



- AMS (3 years)
- m_χ = 124 GeV
- $\chi\chi \rightarrow WW$ (56 %)

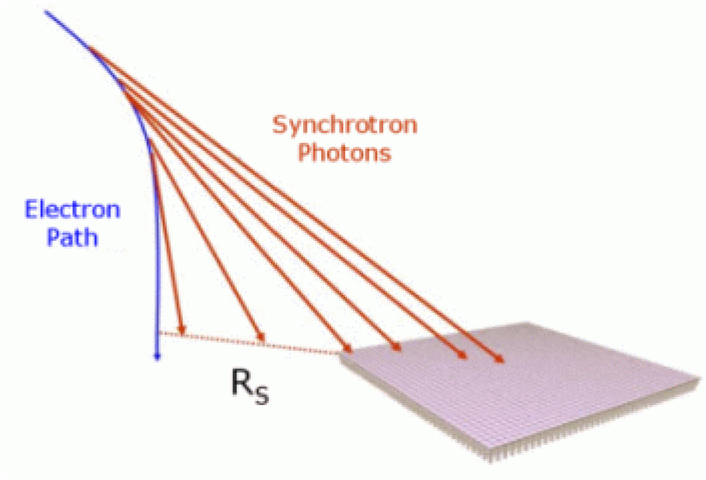
Conclusions



- *AMS-02 is approved by NASA to operate on the ISS for* **3 years at least.**
- *AMS-02 will be* **fully assembled** *end 2007.*
- *AMS-02* **large acceptance** *and* **long exposure time** *outside the Earth's atmosphere, will allow an unprecedented sensitive search for Antimatter, Dark Matter and studies of Cosmic Rays.*
- *Interesting* **Galactic and Extragalactic Gamma Ray** *measurements can be made.*

Cosmic Ray Electron Synchrotron Telescope

1- 50 TeV electron measurement



CREST will detect high-energyelectrons by measuring the X-ray synchrotron photons generated by these electrons in the Earth's magnetic field. This method achieves very large detector apertures, since the instrument need only intersect a portion of the line of photons (which extend over hundreds of meters of space) and not necessarily the electron itself. Conceptually, the detector has an effective area determined by the dimension RS, and not the physical size of the detector.

To discriminate against background photons, two characteristics of the radiation must be exploited - the formation of a line of photons at the detector, and the very short time interval over which these photons are detected. These requirements lead to a spatially segmented detector with good (i.e. <2ns) timing resolution.

The CREST instrument will consist of a 2m x 2m array of 1600 BGO crystals, each viewed by a photomultiplier tube.

*** CREST-1 Realization of detector with BGO and BaF_2**

- **1 KeV - 10 MeV Photons**

*** Test flight**

Stephens and Balasubrahmanyan, J. Geophys. Res. A10, 7822, (1983)

CREST-1

96 scintillator crystals (50 mm dia. x 10 mm) surrounded by a veto system

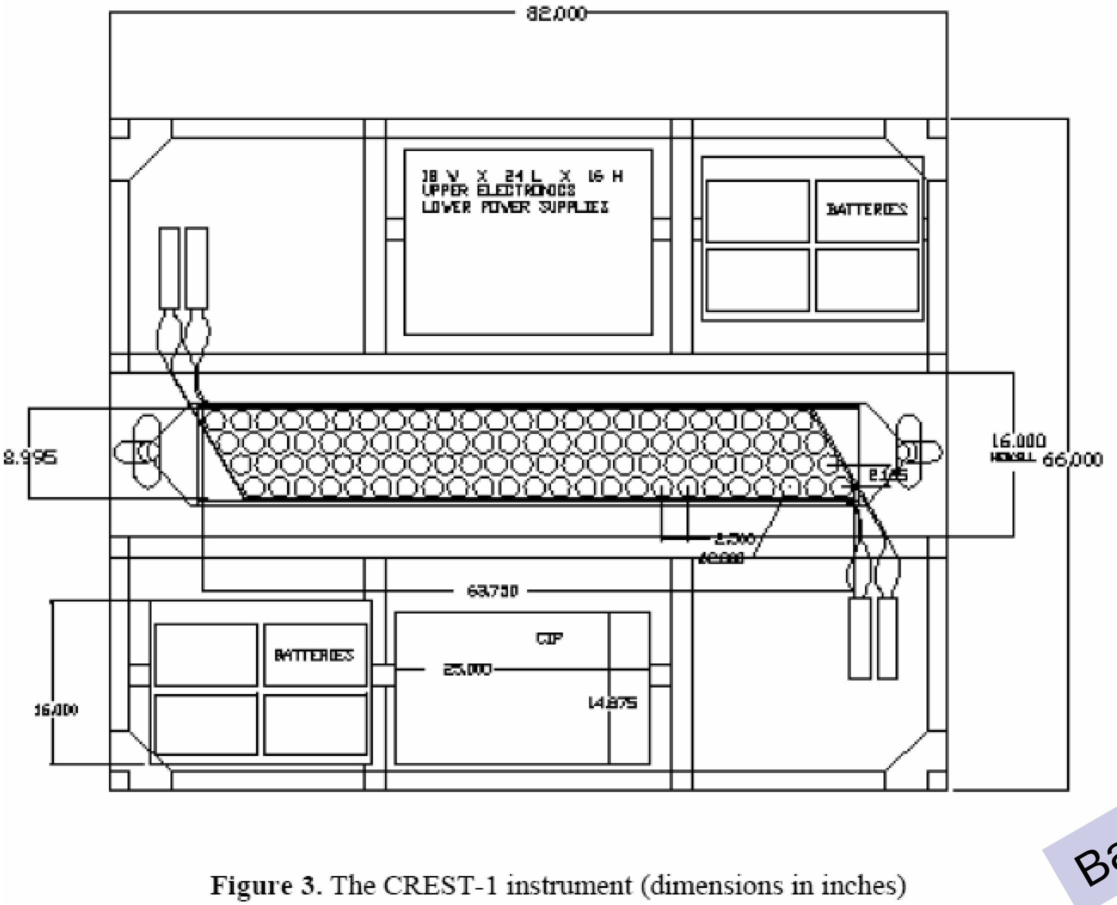


Figure 3. The CREST-1 instrument (dimensions in inches)

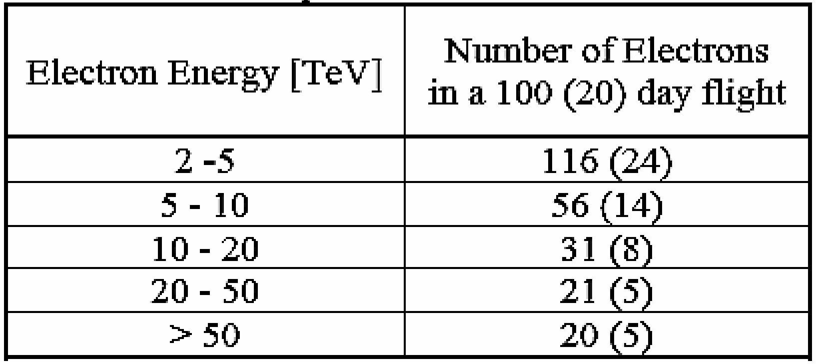
Background level?

“CREST-1 will be flown in late August, 2005 from Ft. Summer, New Mexico.”

CREST-2

- 1600 crystals
- ULDB or LDB balloon flight

Table 1. Expected number of electrons



Electron Energy [TeV]	Number of Electrons in a 100 (20) day flight
2 -5	116 (24)
5 - 10	56 (14)
10 - 20	31 (8)
20 - 50	21 (5)
> 50	20 (5)

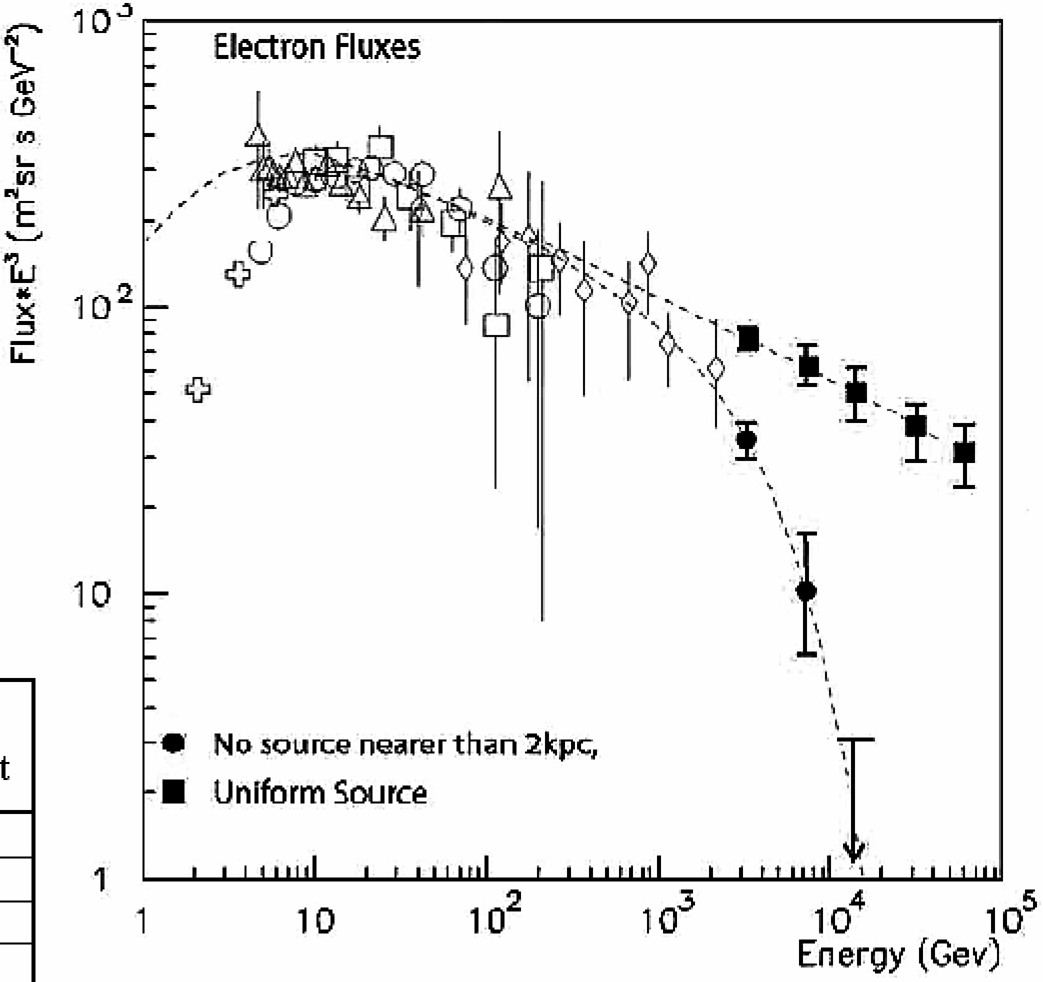
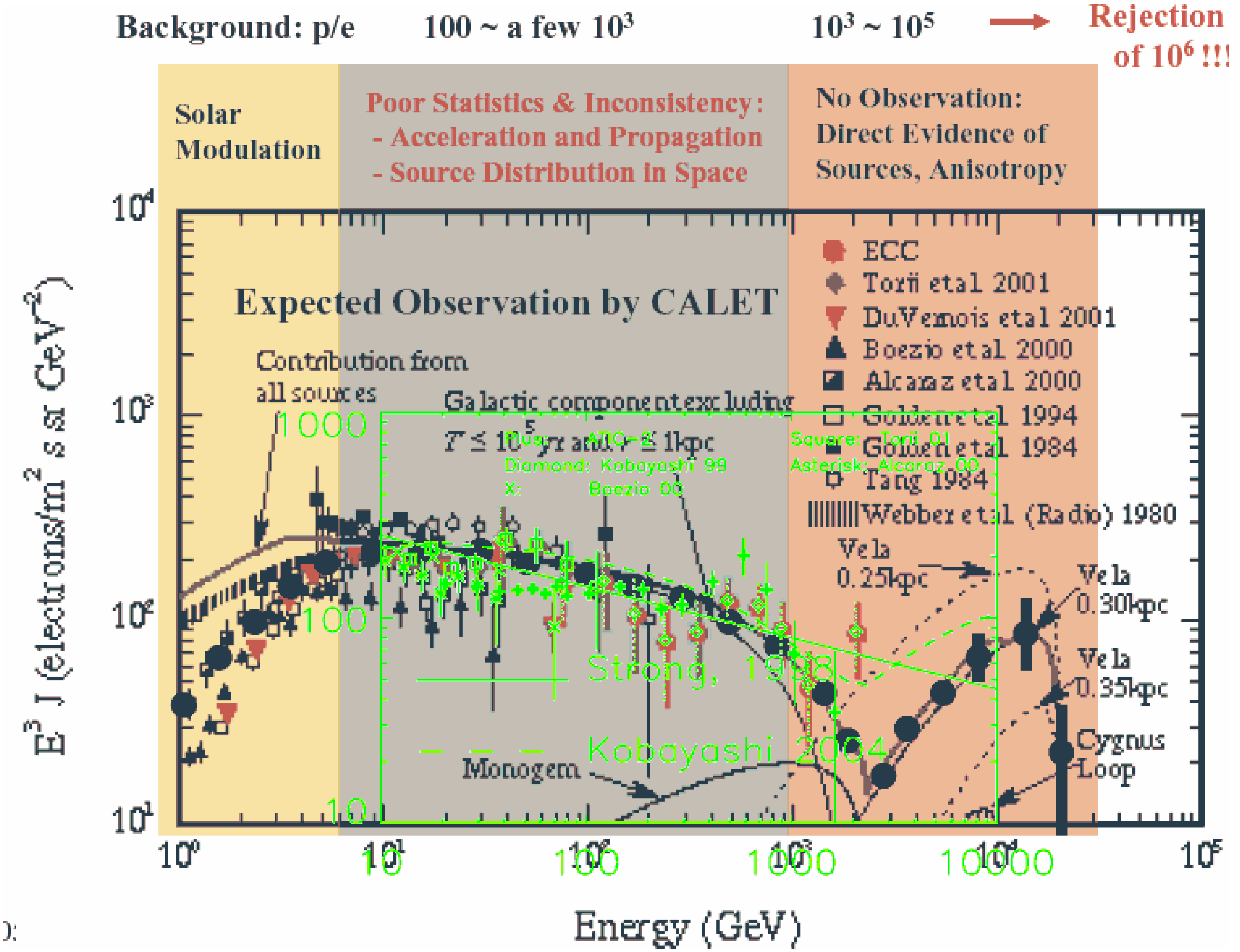


Figure 4. Electron flux spectrum

Feature in the spectrum?

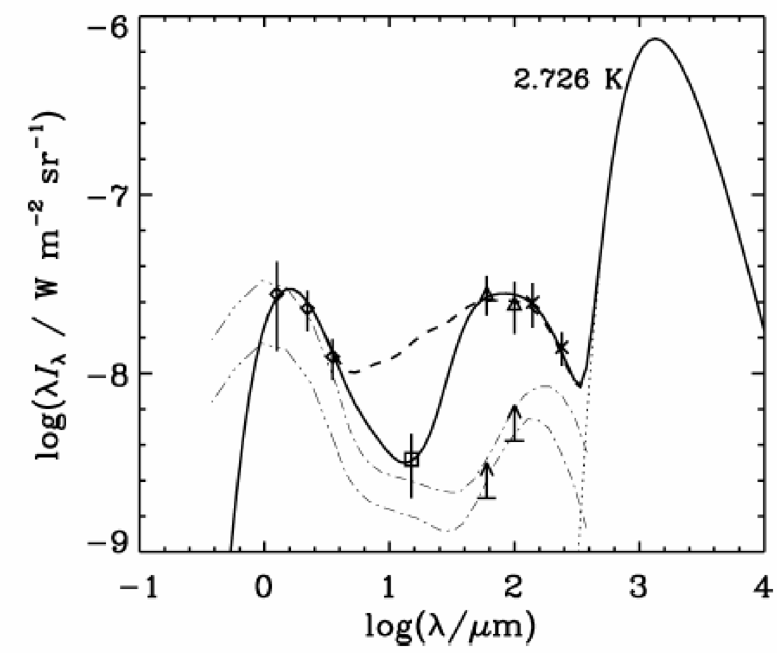


宇宙ガンマ線 vs 宇宙線電子

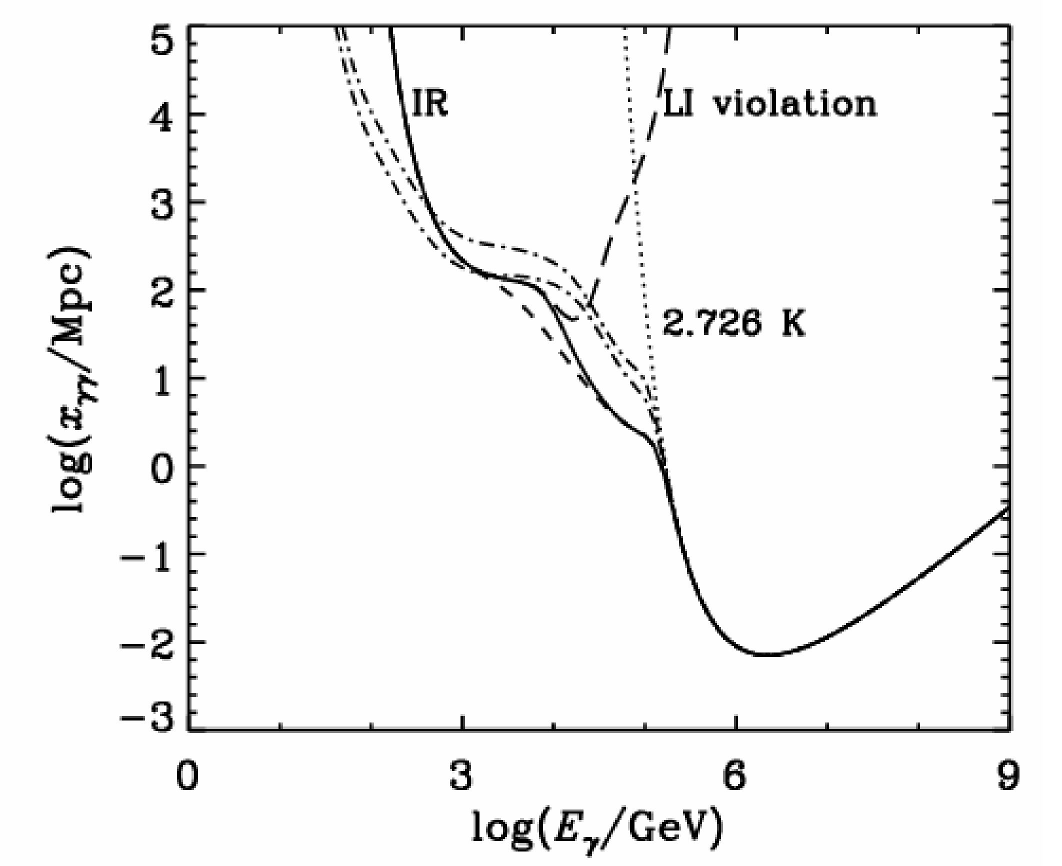
- 到達距離
  γ　宇宙論的に大きい
  (が、赤外線 (@TeV)・CMBR (@PeV)による吸収で限界）
  ｅ エネルギー損失のため有限
- 寿命
  γ　無限大
  ｅ エネルギー損失のため有限
- 電荷
  γ　持たないため直進
  ｅ 銀河磁場・地球磁場により曲げられる
- 識別
  γ　荷電宇宙線はアンタイ層で排除（人工衛星の場合）
  ｅ 荷電宇宙線は電荷の大きさでは排除不可
  （符号、比電荷、相互作用などで識別）

Protheroe and Meyer, PL B493, 1 (2000)

ガンマ線の到達距離



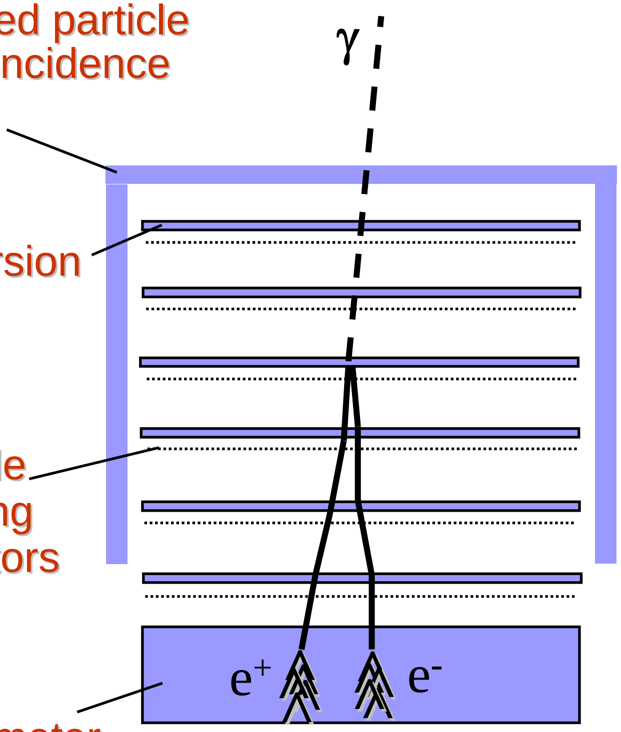
Infrared background field



Mean free path for photon–photon pair production in the infrared–microwave background radiation.

Pair Compton telescope

Principle of Operation

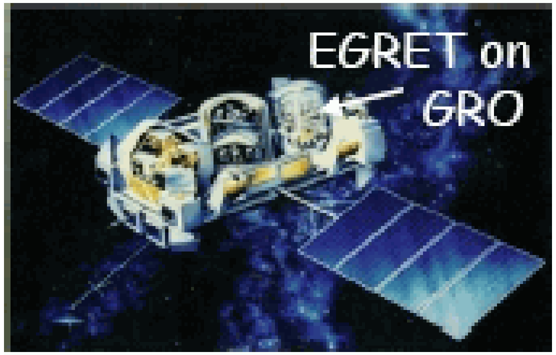


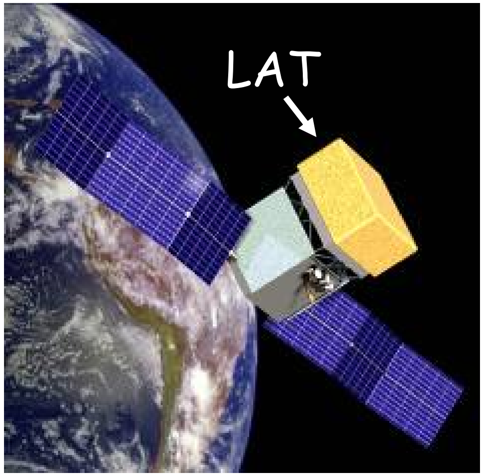
Charged particle anticoincidence shield

Conversion foils

Particle tracking detectors

Calorimeter (energy measurement)

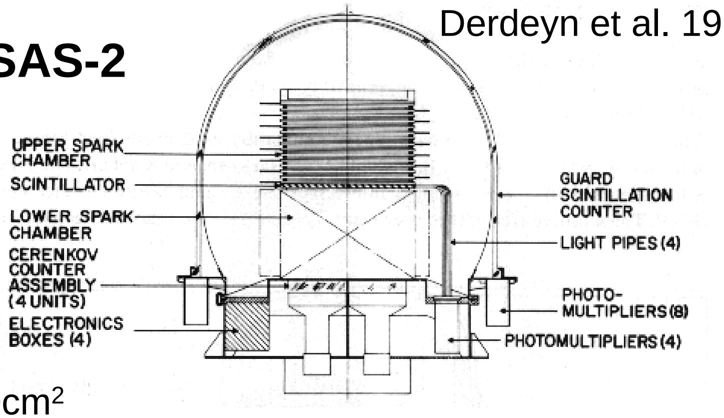




SAS-2/COS B/EGRET

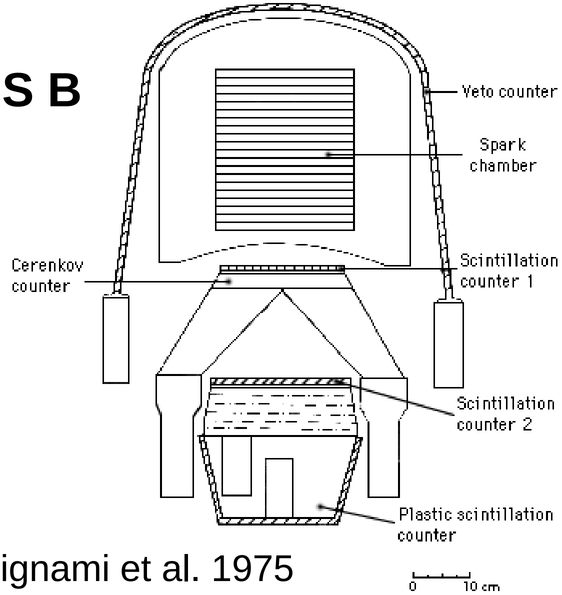
SAS-2

Derdeyn et al. 1972



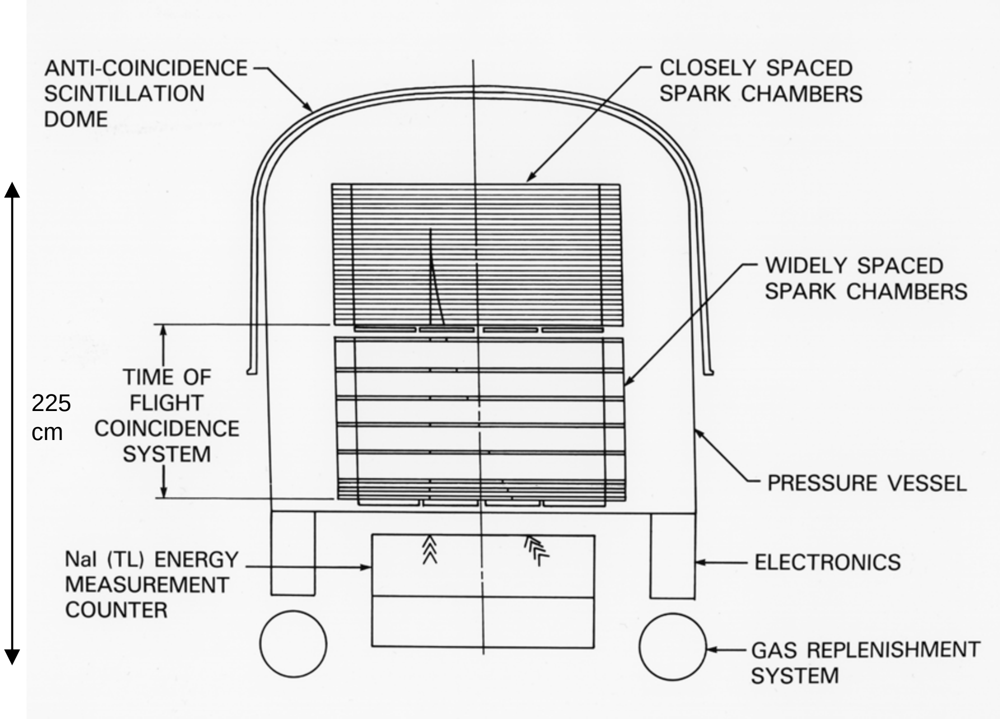
$540 cm^2$

COS B



Bignami et al. 1975

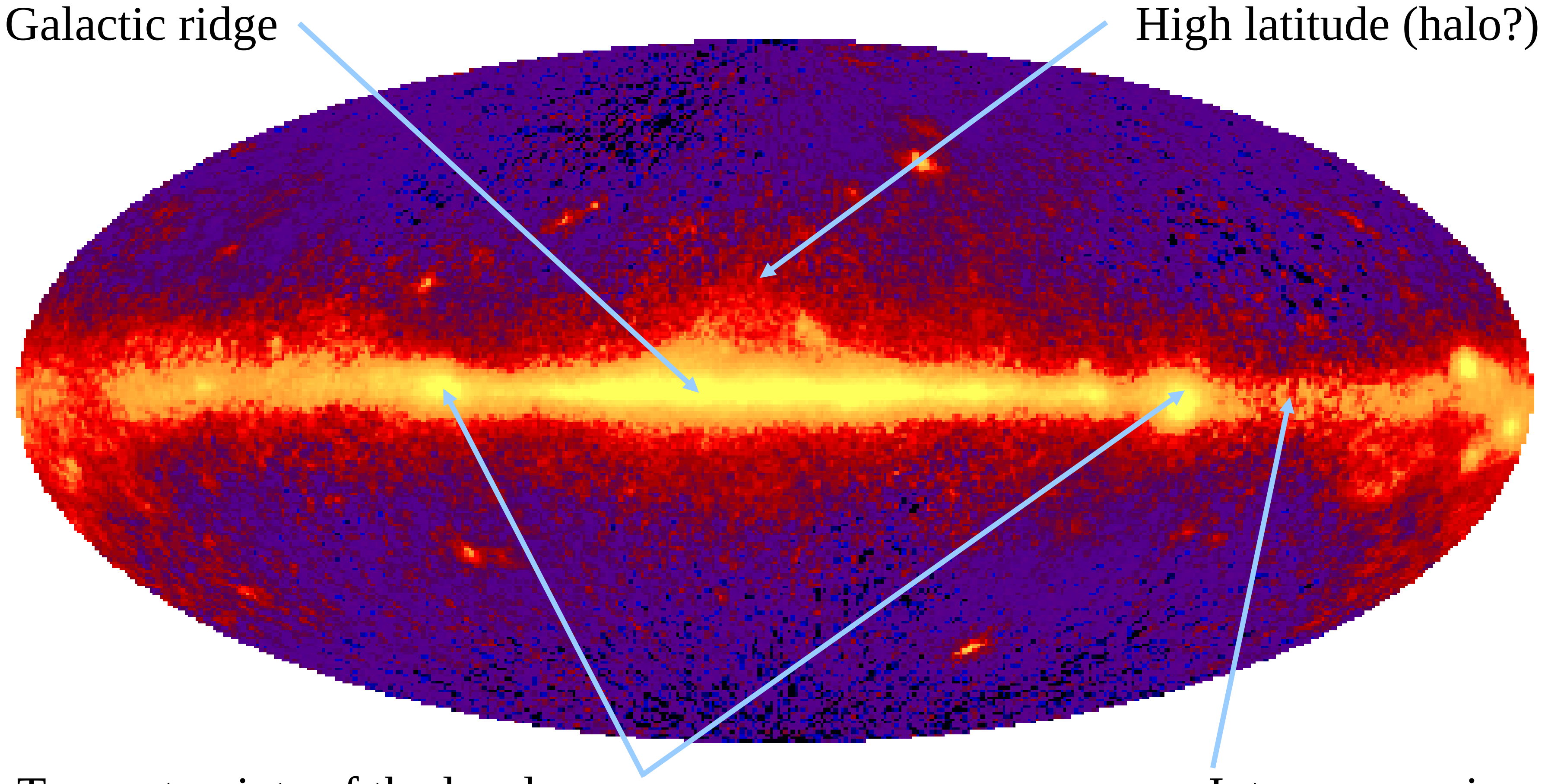
CGRO/EGRET



Fichtel et al. 1978

S.Hunter, GLAST meeting, Oct.2004

GeV gamma-ray sky by EGRET



Galactic ridge

High latitude (halo?)

Tangent points of the local arm

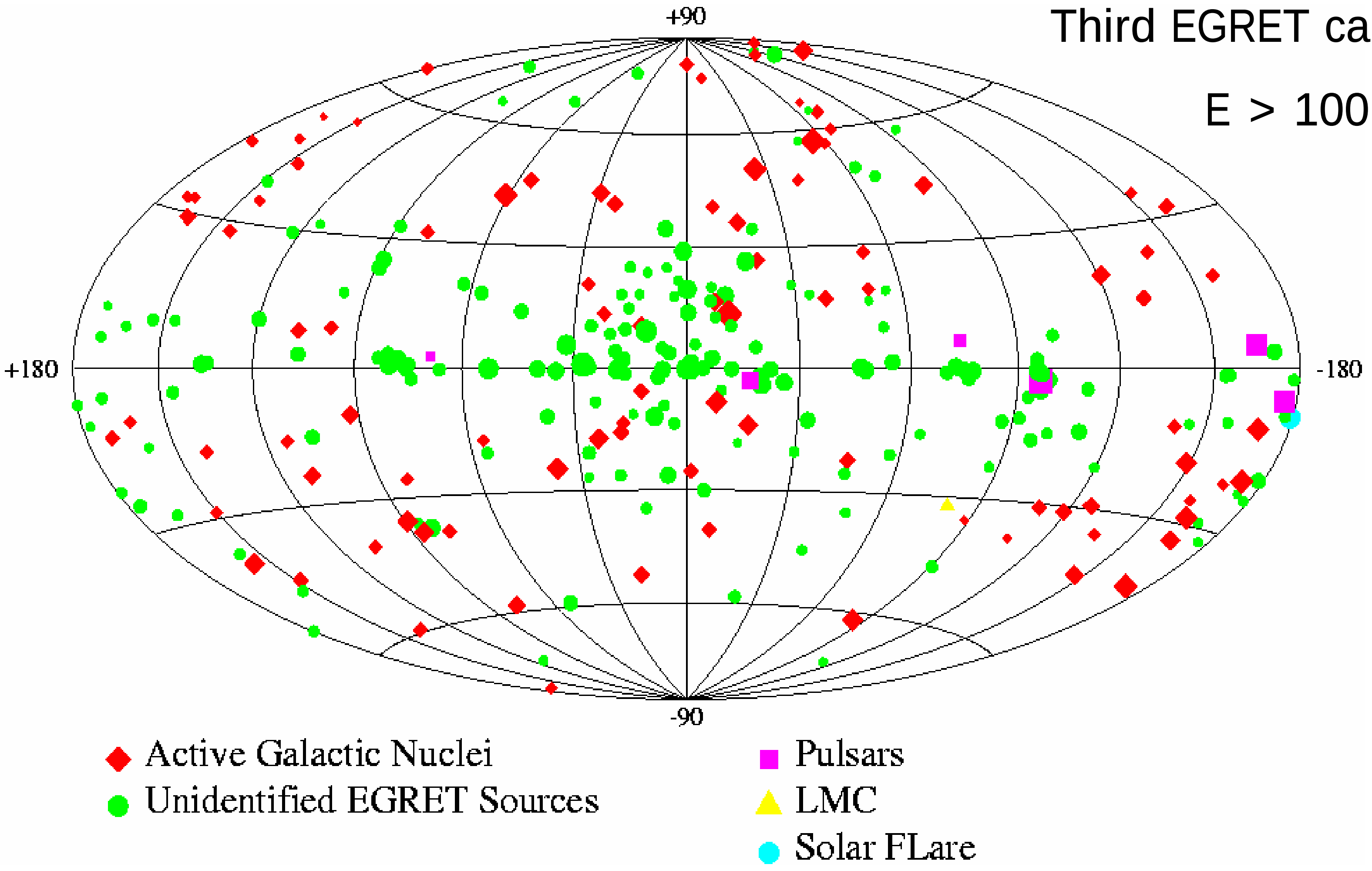
Inter-arm region

R.C.Hartman et al, ApJS 1999

3EG catalog map

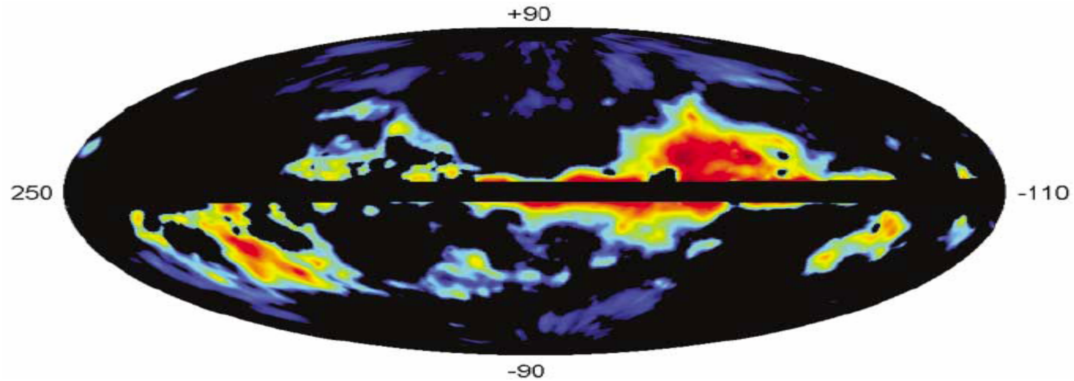
Third EGRET catalog

E > 100 MeV



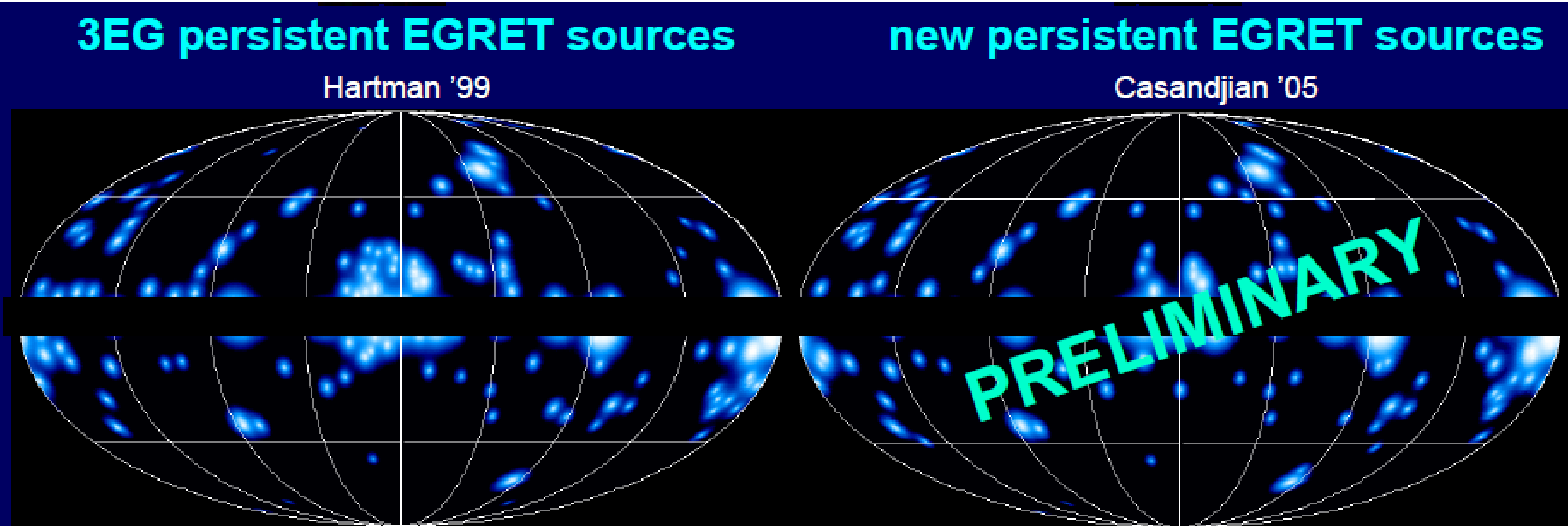
Dark gas contribution?

Grenier, Casandjian & Terrier, Science 307, 1292 (2005)



Clouds of dark gas (39 σ)! with N(H) column-densities comparable to N(HI) and 2N(H_2)

Grenier & Casandjian, GLAST meeting (Aug. 2005)



3EG persistent EGRET sources

Hartman '99

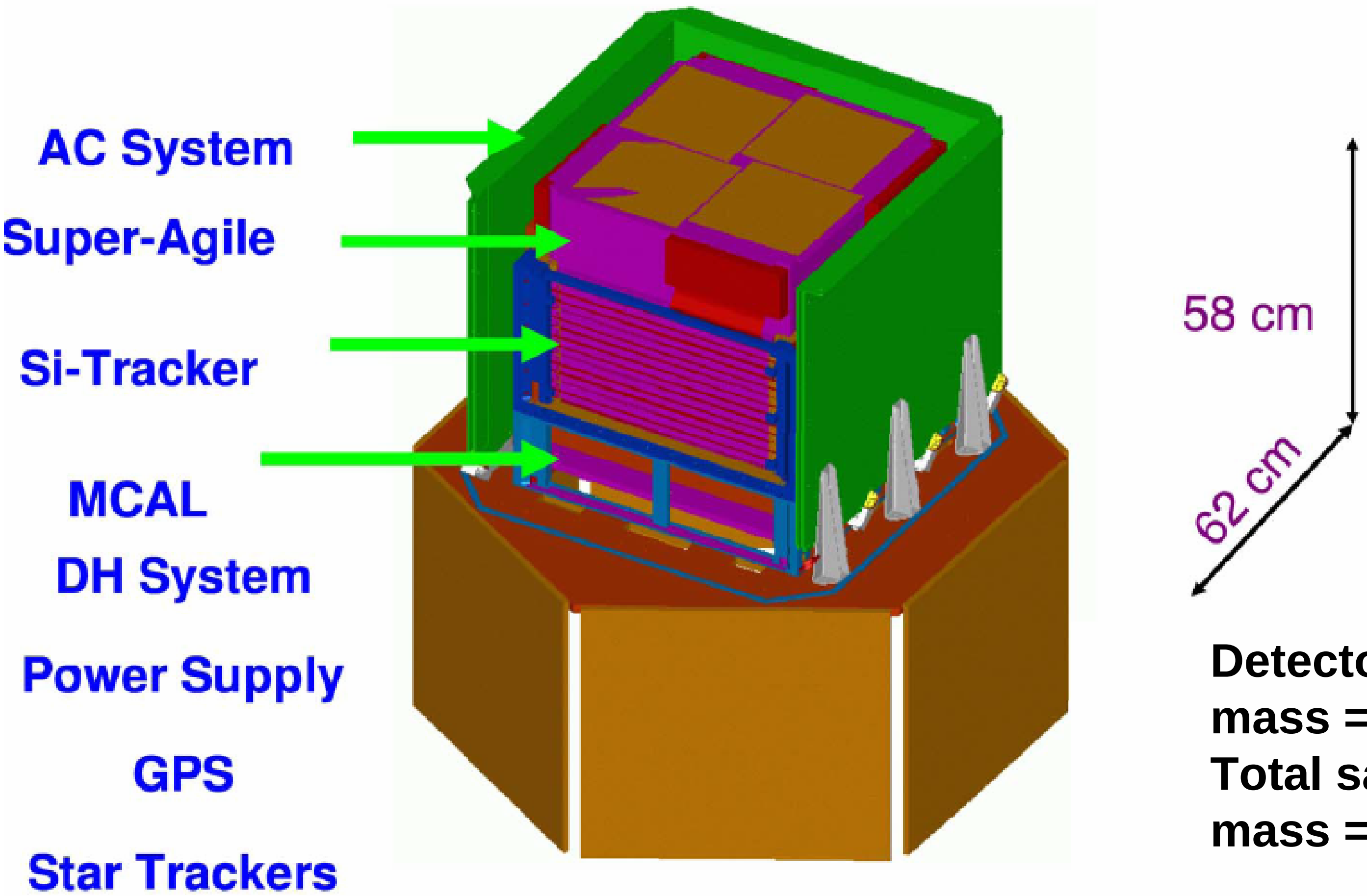
new persistent EGRET sources

Casandjian '05

AGILE

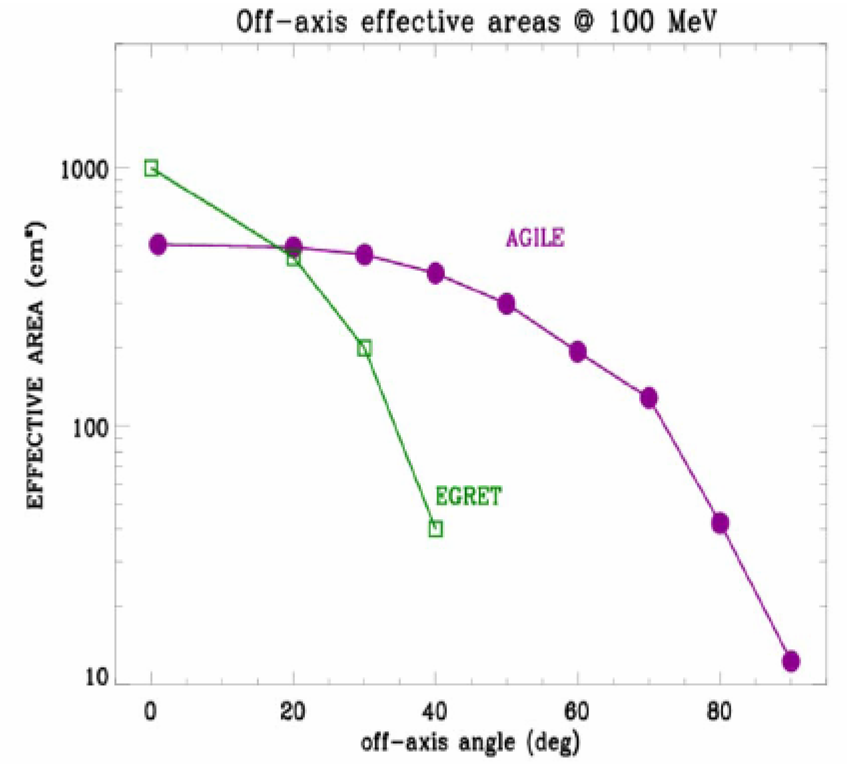
**ASI (Italian Space Agency)
small scientific mission, started in 1998.**

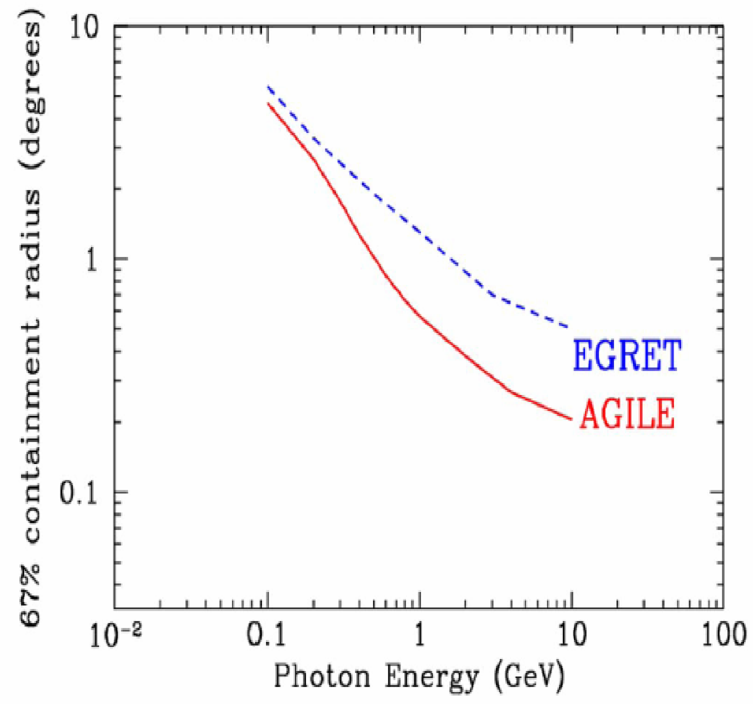
The AGILE scientific instrument



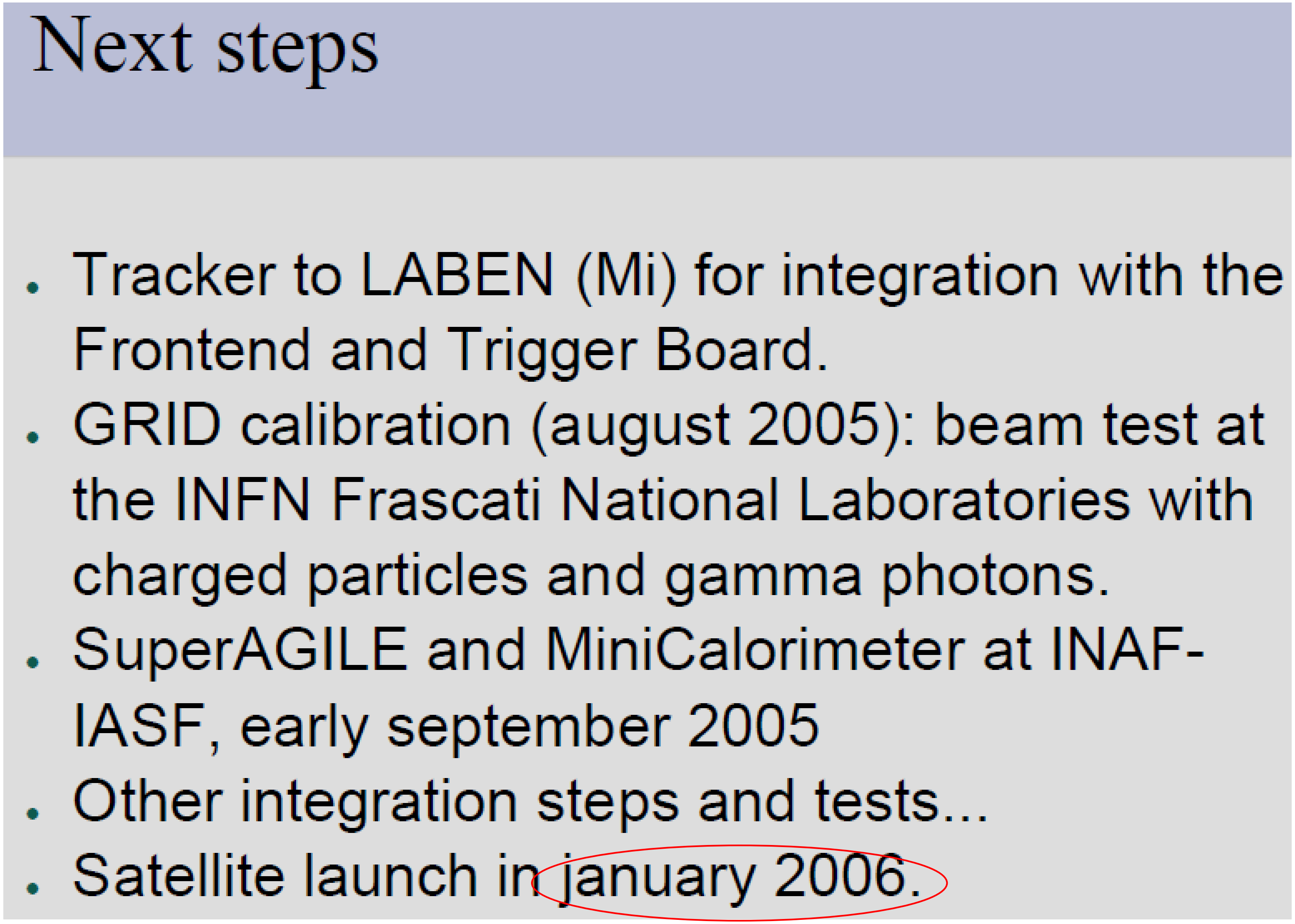
**Detector
mass = 120 kg
Total satellite
mass = 330 kg**

AGILE performance





AGILE status



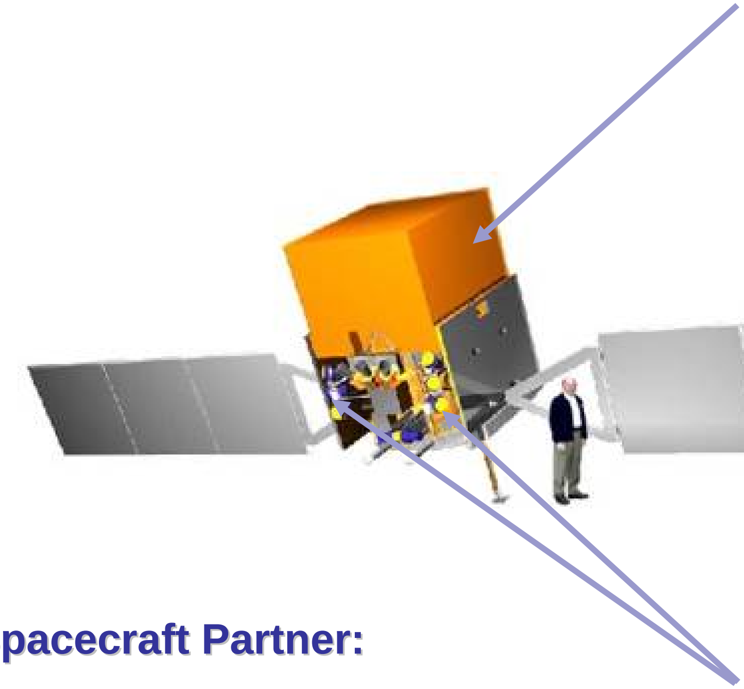
Next steps

- Tracker to LABEN (Mi) for integration with the Frontend and Trigger Board.
- GRID calibration (august 2005): beam test at the INFN Frascati National Laboratories with charged particles and gamma photons.
- SuperAGILE and MiniCalorimeter at INAF-IASF, early september 2005
- Other integration steps and tests...
- Satellite launch in january 2006.

GLAST

(Gamma-ray Large Area Telescope)

GLAST measures the direction, energy and arrival time of celestial gamma rays.



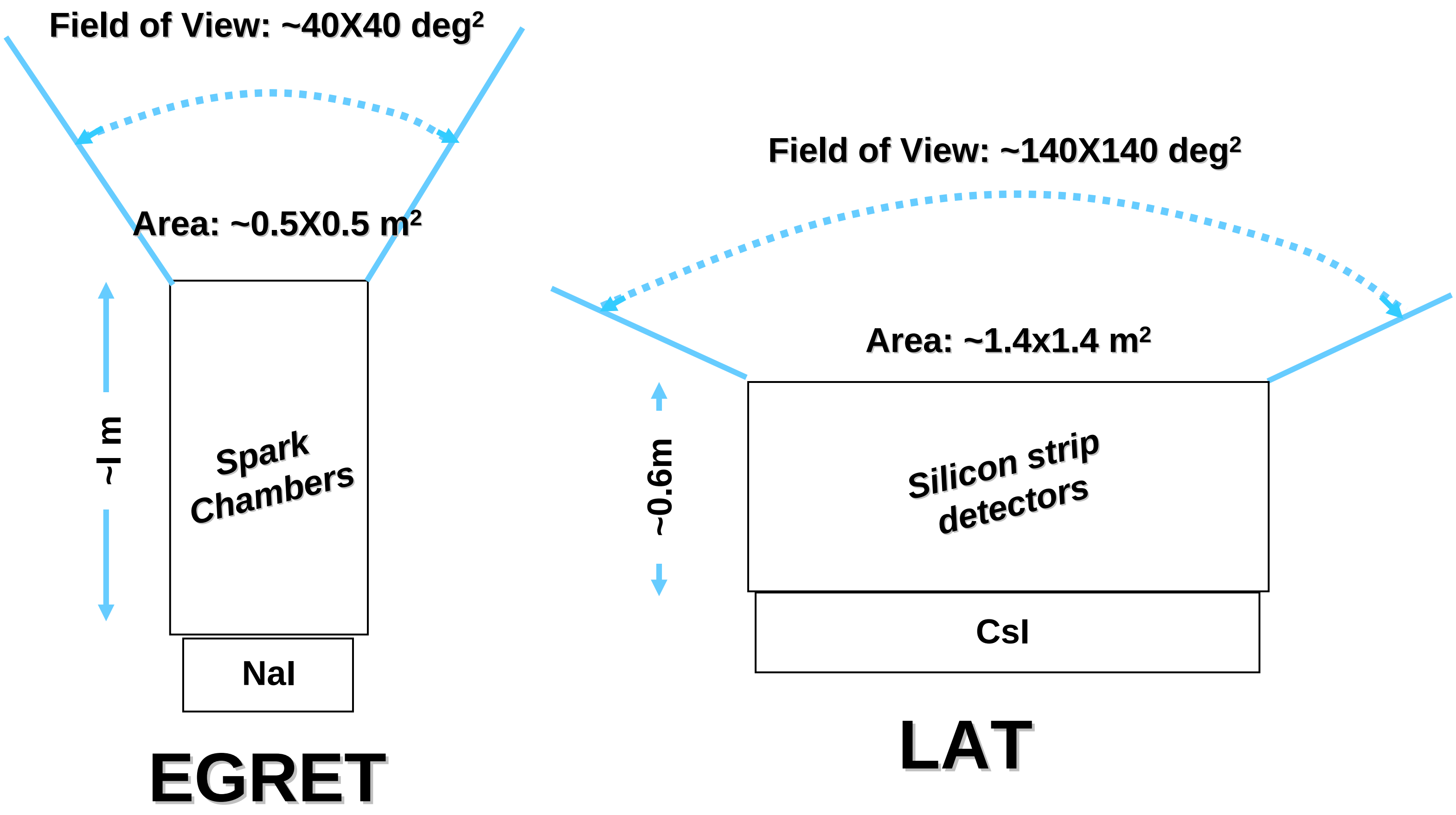
- **Large Area Telescope (LAT)** measures gamma-rays in the energy range ~20 MeV to 300+ GeV. *No other telescope currently covers this range.*

- **GLAST Burst Monitor (GBM)** provides correlative observations of transient events in the energy range 10 keV – 25 MeV.

Spacecraft Partner:

SPECTRUMASTRO
GENERAL DYNAMICS

Comparison of EGRET and GLAST



Field of View: ~40X40 deg^2

Area: ~0.5X0.5 m^2

~l m

Spark Chambers

NaI

EGRET

Field of View: ~140X140 deg^2

Area: ~1.4x1.4 m^2

~0.6m

Silicon strip detectors

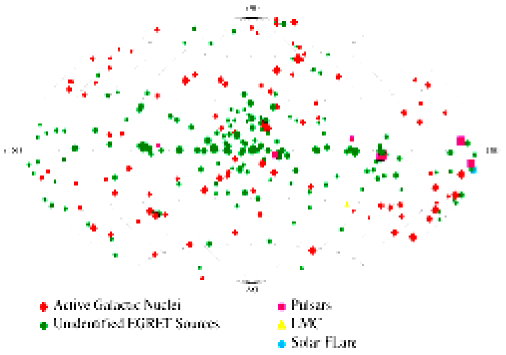
CsI

LAT

Comparison of numbers

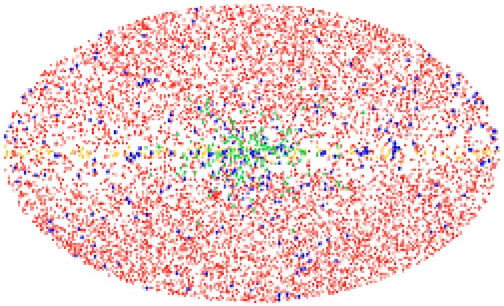
3rd EGRET Catalog

E > 100 MeV



LAT Simulation

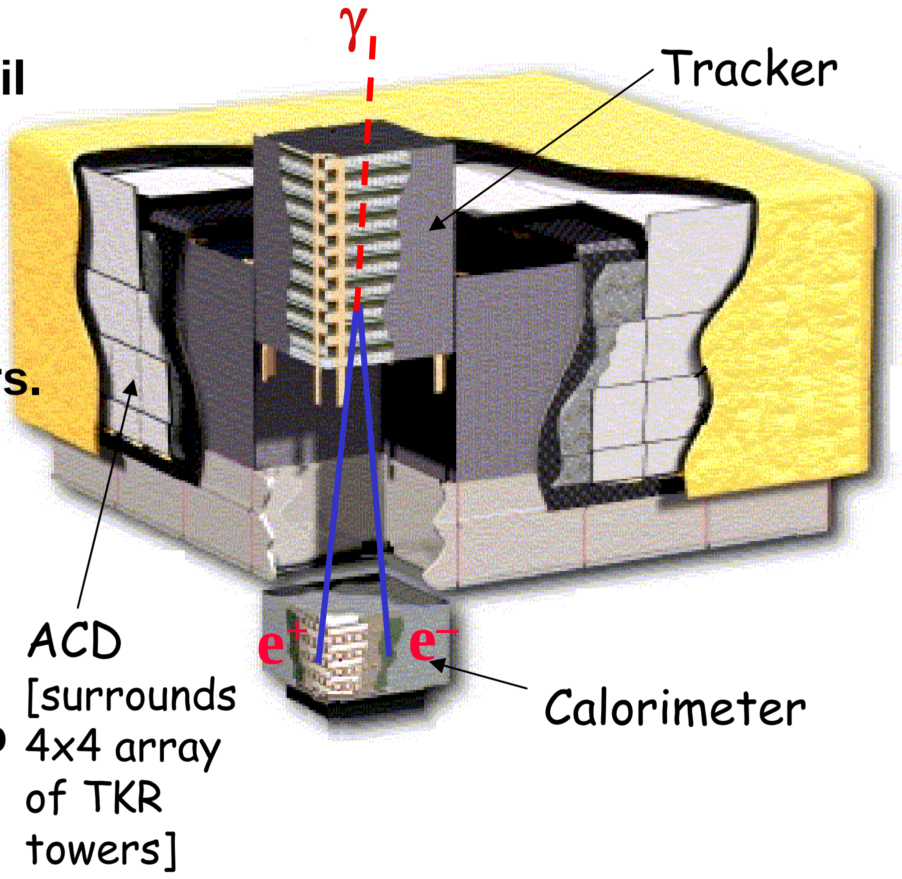
E > 100 MeV



			Factor
Energy	20 MeV – 30 GeV	20 MeV – 300+ GeV	10
Energy Resolution	~10%	~10%	1
Peak Effective Area	1500 cm^2	>8000 cm^2	6
Field of View	0.5 sr	>2.0 sr	4
Sensitivity (1 yr)	~10^{-7} γ cm^{-2} s^{-1}	<6 10^{-9} γ cm^{-2} s^{-1}	20
Localization	15’	<0.5’	30
Deadtime	100 ms	<50 μs	>2000

Overview of LAT

- <u>**Precision Si-strip Tracker (TKR)**</u>
  18 XY tracking planes with tungsten foil converters. Single-sided silicon strip detectors (228 µm pitch) Measure the photon direction; gamma ID.
- <u>**Hodoscopic CsI Calorimeter(CAL)**</u>
  Array of 1536 CsI(Tl) crystals in 8 layers. Measure the photon energy; image the shower.
- <u>**Segmented Anticoincidence Detector (ACD)**</u> **89 plastic scintillator tiles. Reject background of charged cosmic rays; segmentation mitigates self-veto effects at high energy.**
- <u>**Electronics System**</u> **Includes flexible, robust hardware trigger and software filters.**

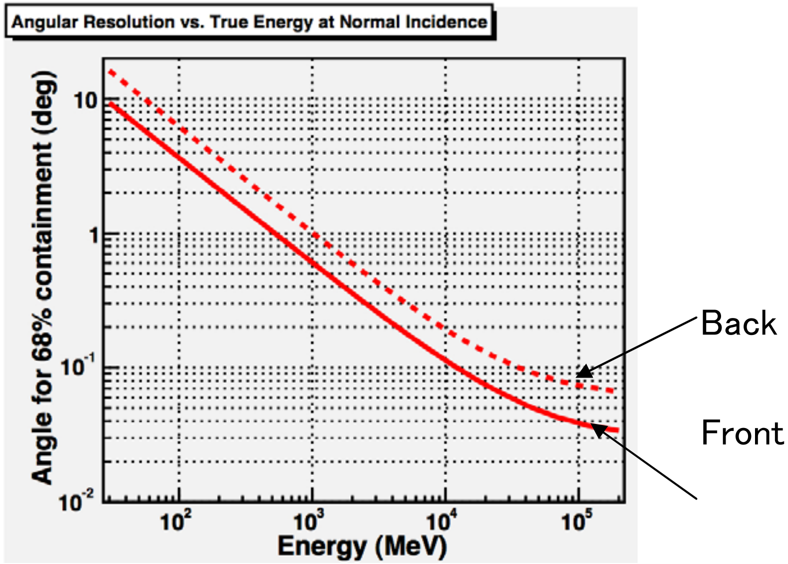


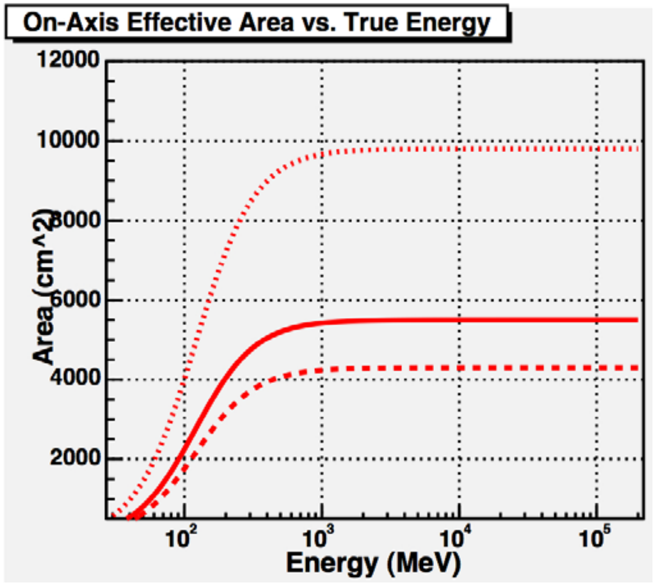
Systems work together to identify and measure the flux of cosmic gamma rays with energy 20 MeV - >300 GeV.

Gamma-ray simulation

LAT performance

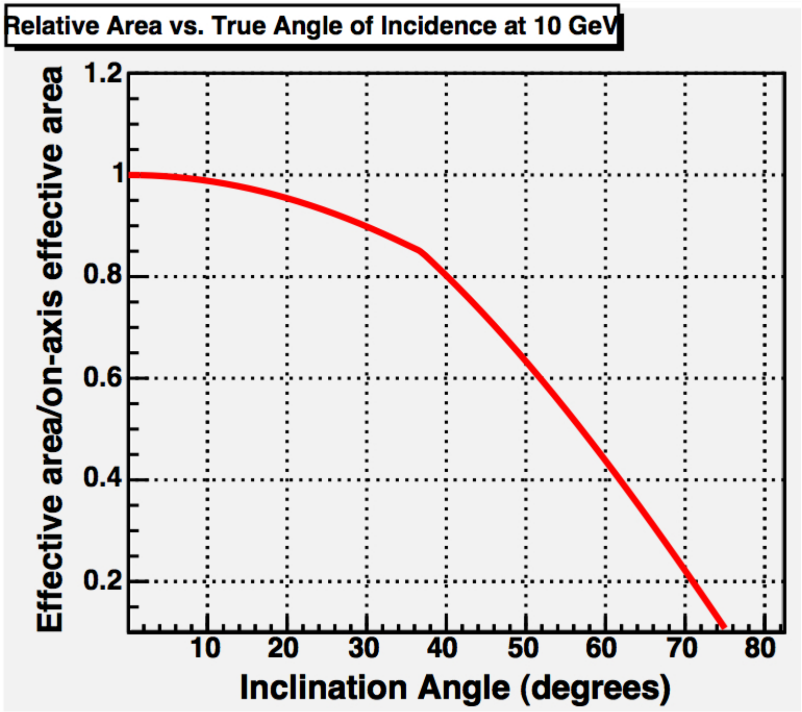
- Angular resolution improves rapidly as a function of energy.
  - Less dominated by background at higher energies.
- Effective area remains flat from 1 GeV up to at least 300 GeV





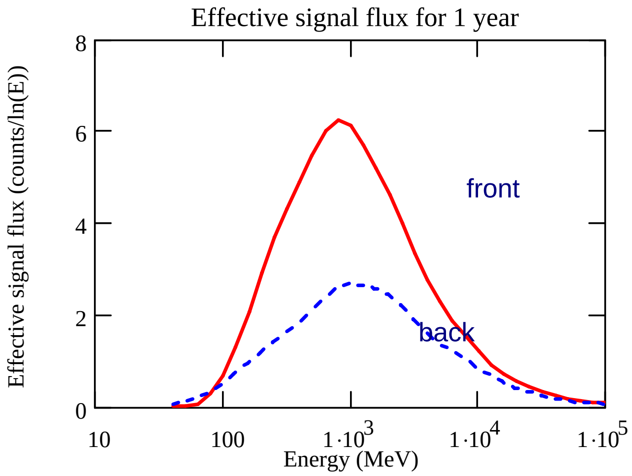
LAT field-of-view

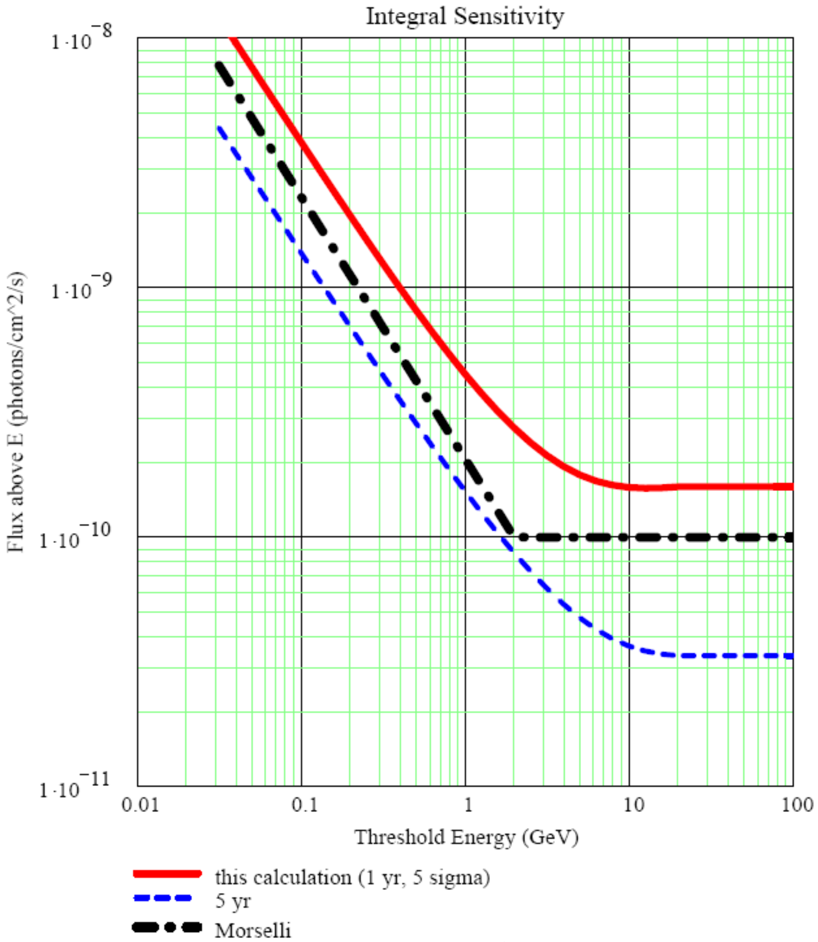
- The LAT is self triggering and has a large aspect ratio, this results in a very large field of view.
- The angular resolution also varies as a function of inclination angle, this effect is stronger at lower energies.



LAT sensitivity - I

- Sensitivity for 1 year (red) and 5 years (blue) in survey mode (does not include electronic deadtime and SAA passages).
- Assumes a source with -2.1 spectrum.
- Assume a diffuse background flux of 1.5e-5 phcm^{-2}s^{-1}
- Peak sensitivity is at a few GeV.

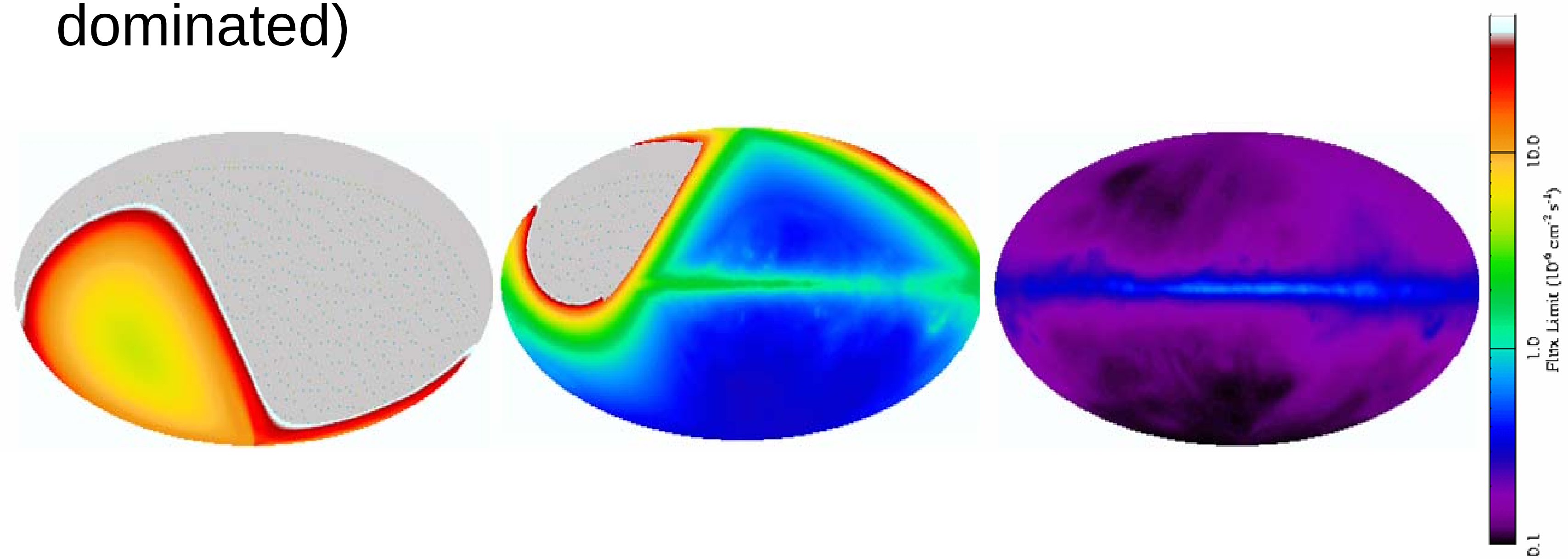




$5\sigma/5$photons

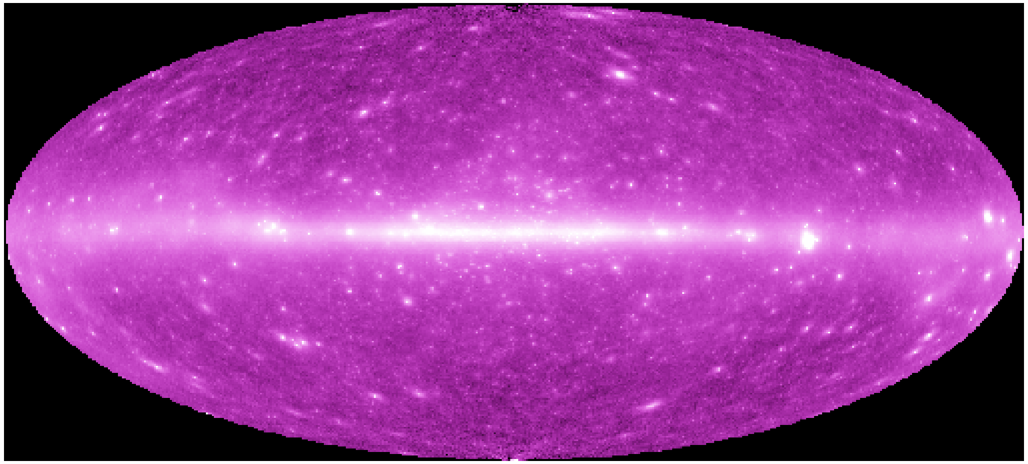
LAT sensitivity -II

- A single curve does not tell the full story.
- The sensitivity is a function of spectral index.
- Sensitivity will be a strong function of position with respect to the Galactic plane.
- As one moves to higher and higher energies (and shorter timescales) this becomes less true (no longer background dominated)



Simulated GLAST sky

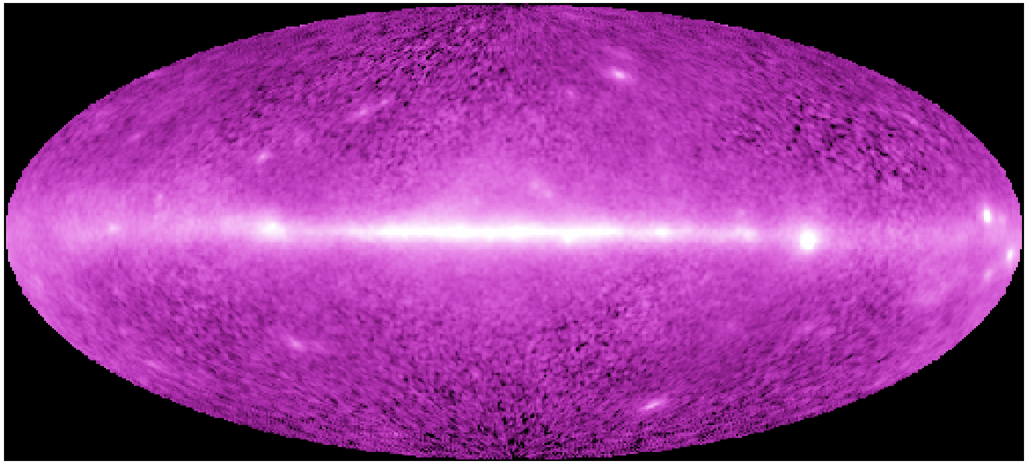
Simulated GLAST Sky Survey (E > 100 MeV)



GLAST

1 year

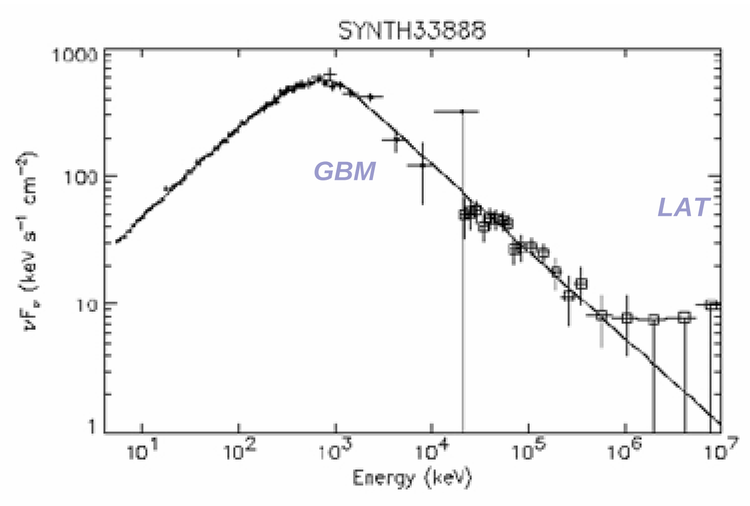
EGRET Data for Phases 1-5 (smoothed slightly to reduce statistical fluctuations)



EGRET

Phase 1-5

GBM (GLAST Burst Monitor)



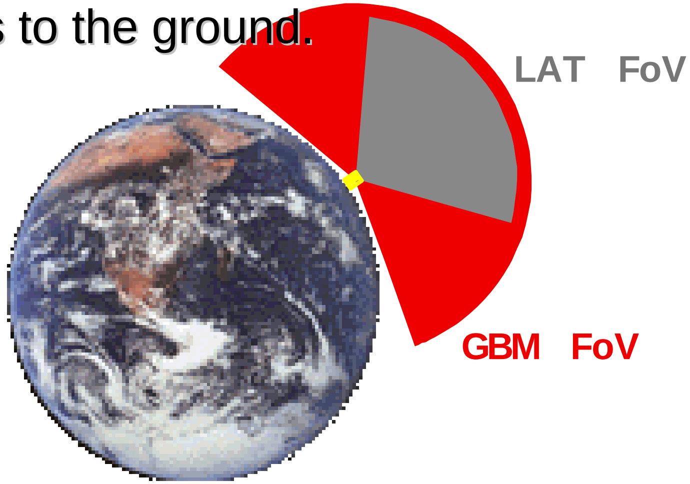
Simulated GBM and LAT response to time-integrated flux from bright GRB 940217

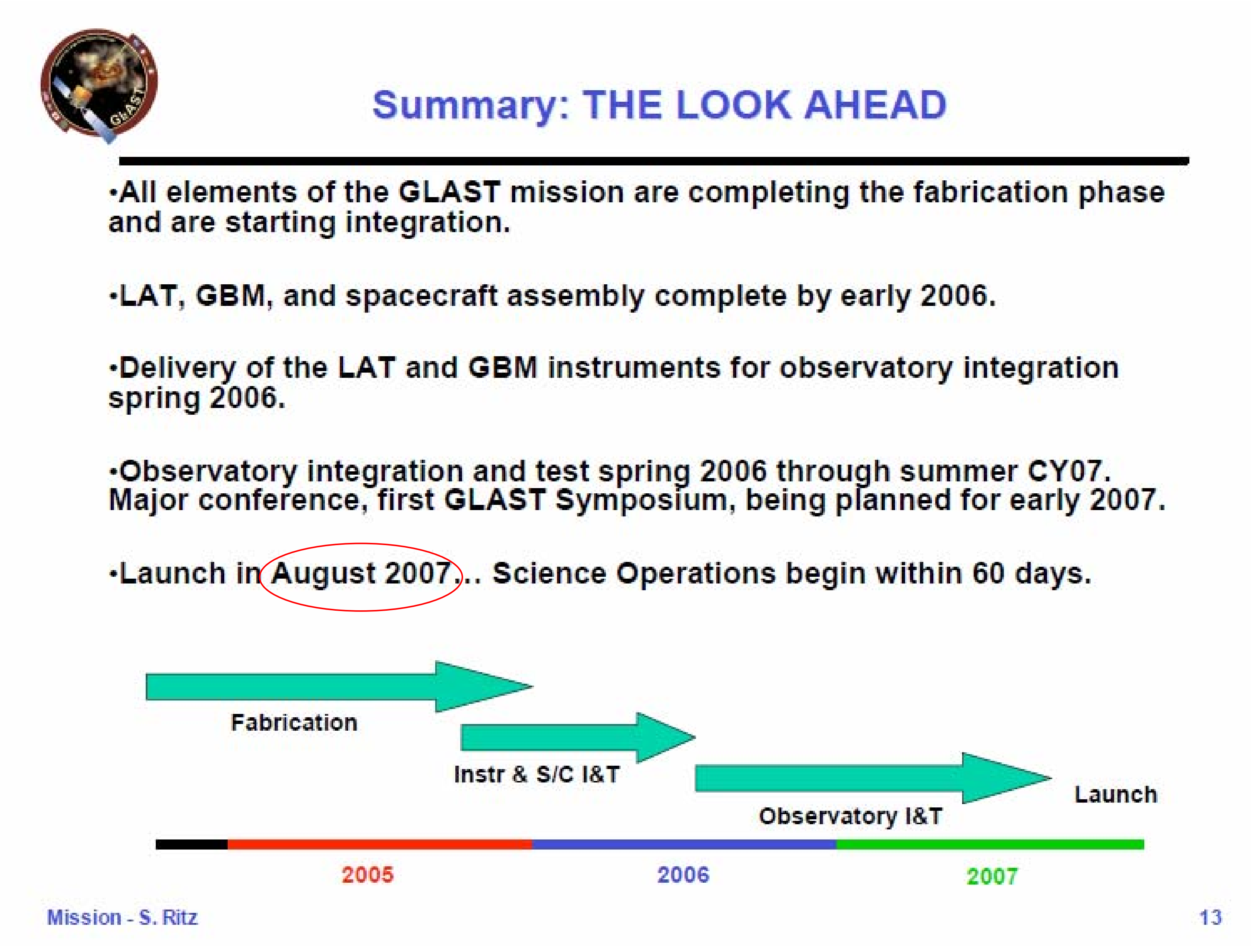
Spectral model parameters from CGRO wide-band fit

1 NaI (14 º) and 1 BGO (30 º)

Provides:

- spectra for bursts from 10 keV to 30 MeV, connecting frontier LAT high-energy measurements with more familiar energy domain;
- wide sky coverage (8 sr) -- enables autonomous repoint requests for exceptionally bright bursts that occur outside LAT FOV for high-energy afterglow studies (an important question from EGRET);
- burst alerts to the ground.





Summary: THE LOOK AHEAD

- •All elements of the GLAST mission are completing the fabrication phase and are starting integration.
- •LAT, GBM, and spacecraft assembly complete by early 2006.
- •Delivery of the LAT and GBM instruments for observatory integration spring 2006.
- •Observatory integration and test spring 2006 through summer CY07. Major conference, first GLAST Symposium, being planned for early 2007.
- •Launch in August 2007... Science Operations begin within 60 days.

Fabrication

Instr & S/C I&T

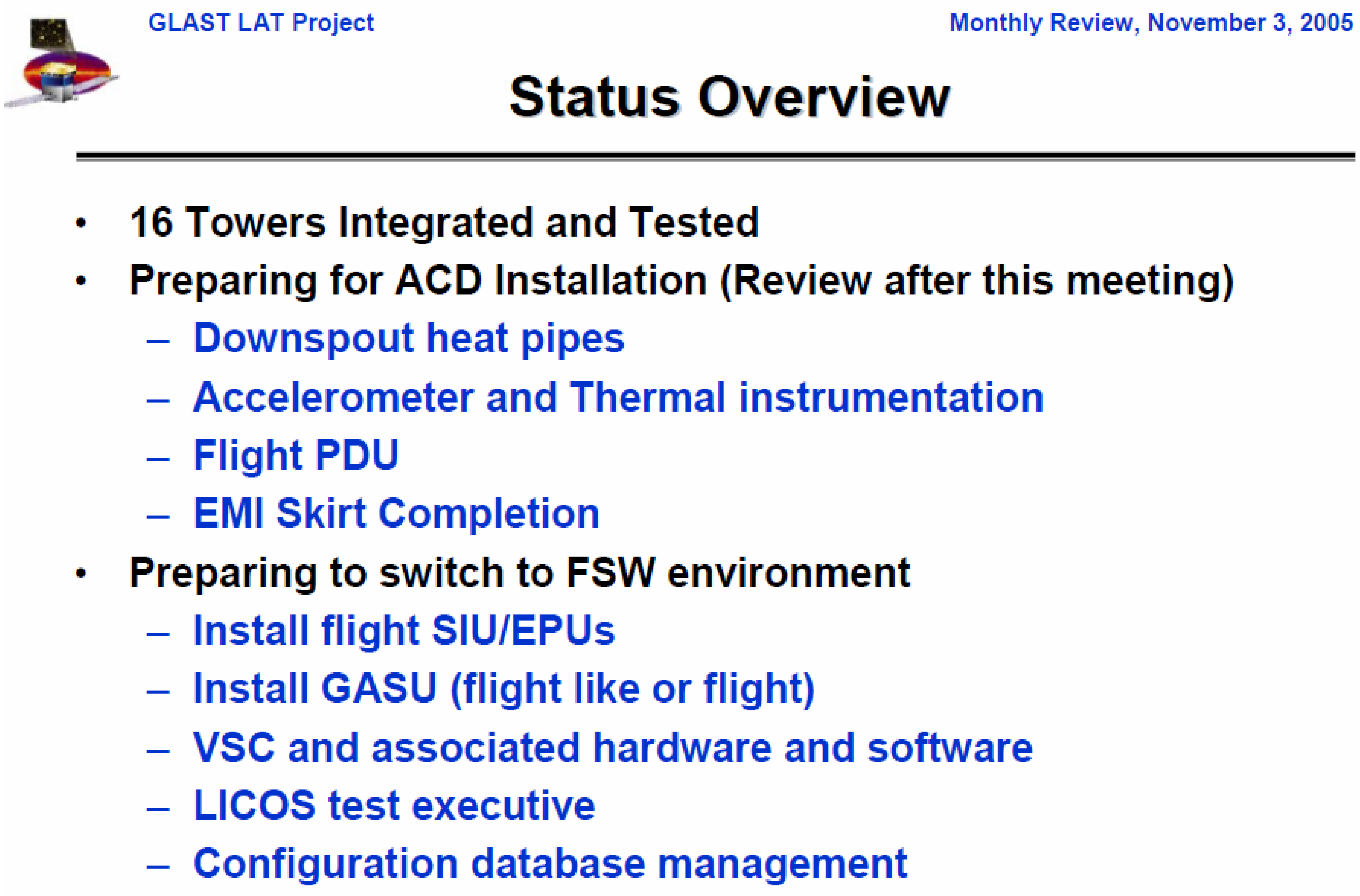
Observatory I&T

Launch

2005

2006

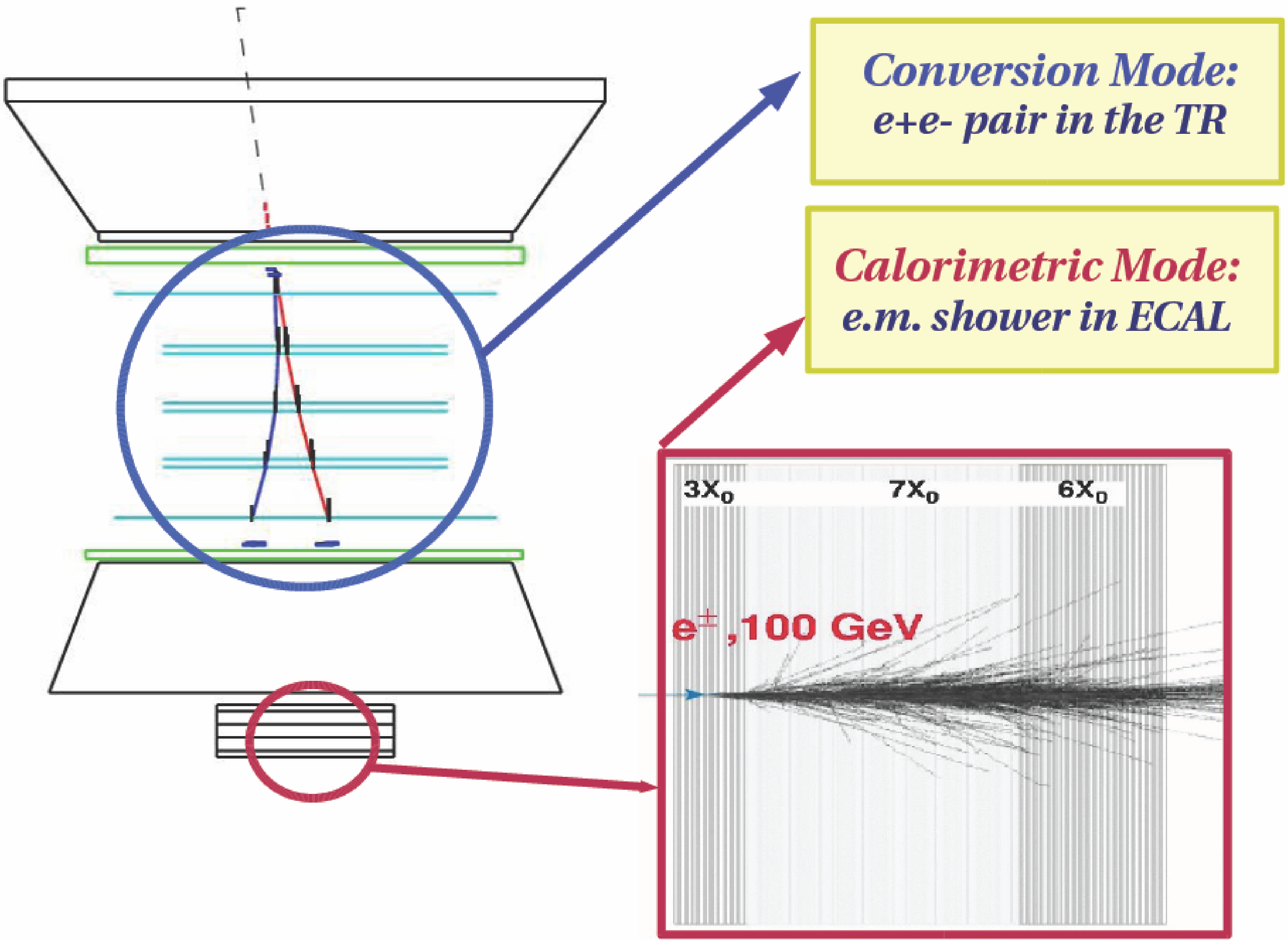
2007



Status Overview

- 16 Towers Integrated and Tested
- Preparing for ACD Installation (Review after this meeting)
  - Downspout heat pipes
  - Accelerometer and Thermal instrumentation
  - Flight PDU
  - EMI Skirt Completion
- Preparing to switch to FSW environment
  - Install flight SIU/EPUs
  - Install GASU (flight like or flight)
  - VSC and associated hardware and software
  - LICOS test executive
  - Configuration database management

γ-Ray Detection with AMS-02

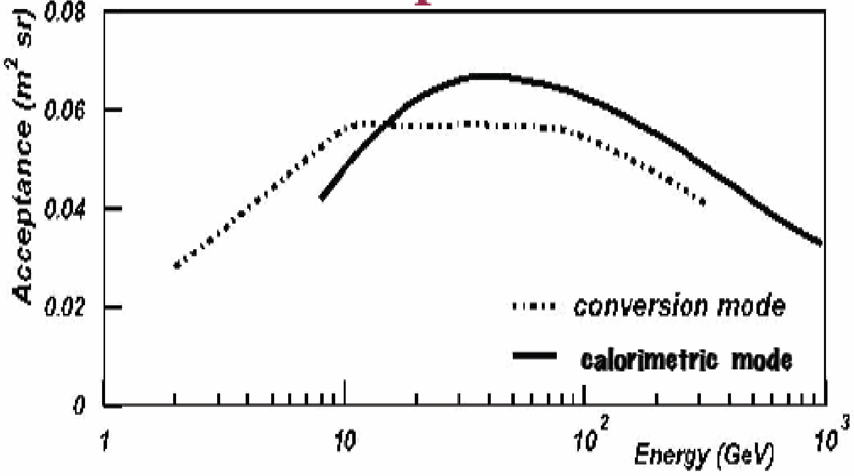


Conversion Mode:
e+e- pair in the TR

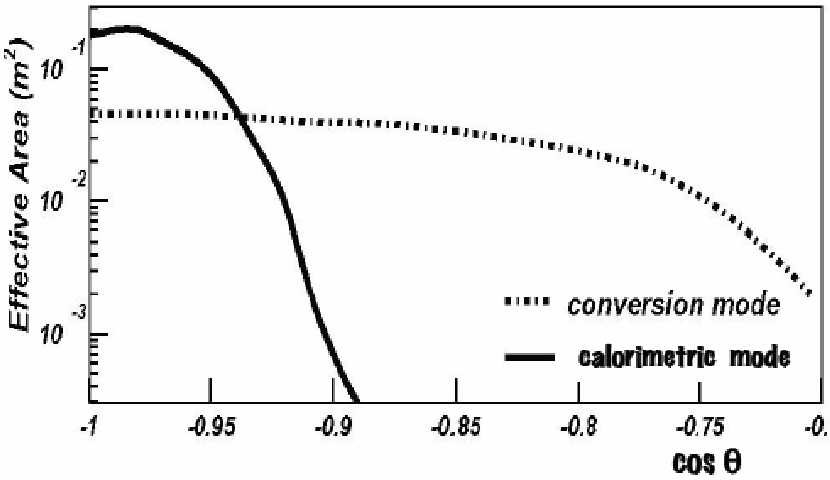
Calorimetric Mode:
e.m. shower in ECAL

AMS-02 Tracker and Ecal Performances

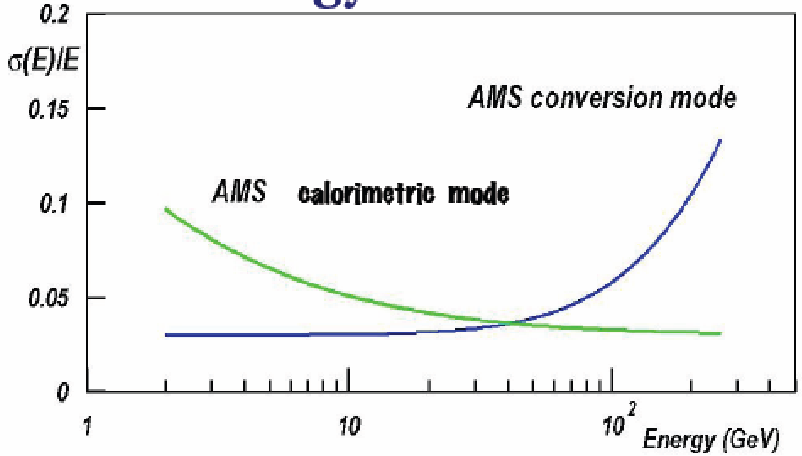
Acceptance



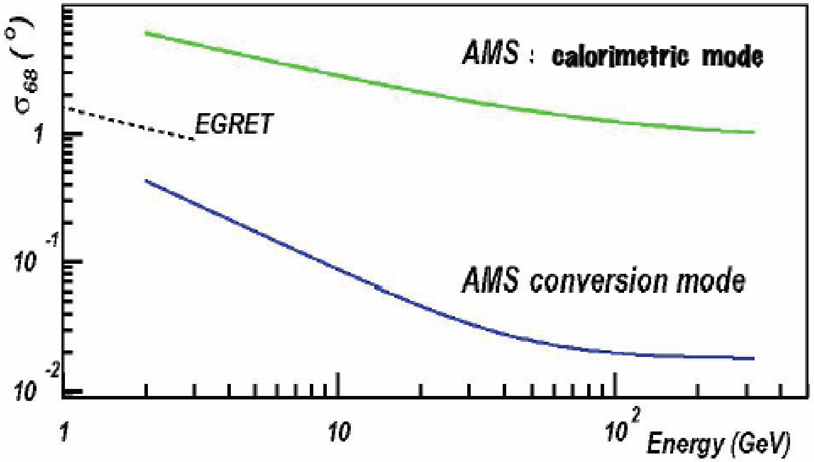
Effective Area



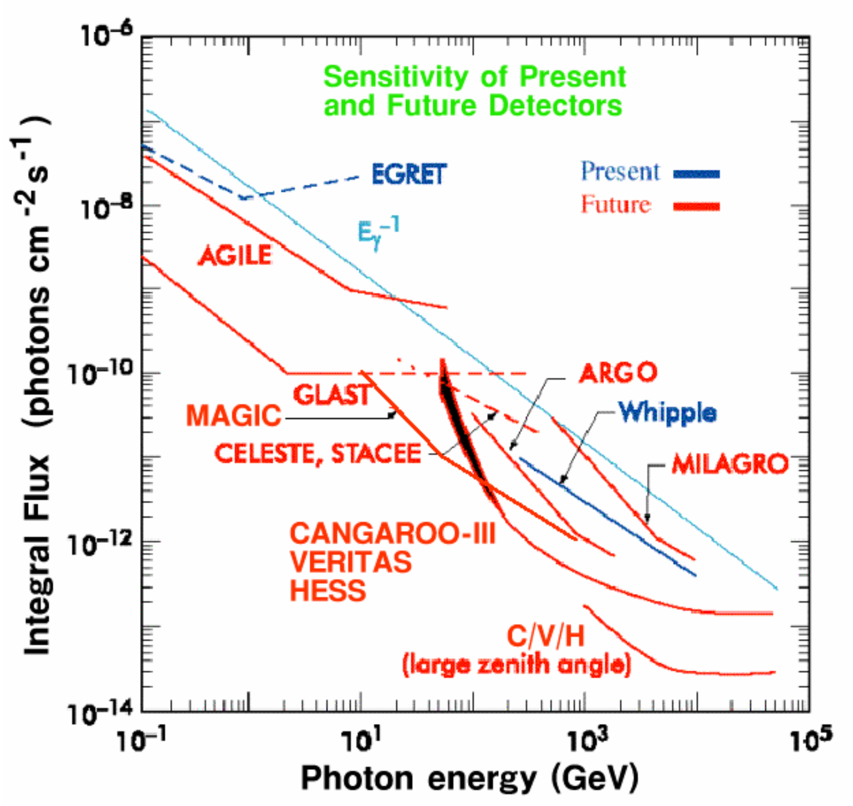
Energy Resolution

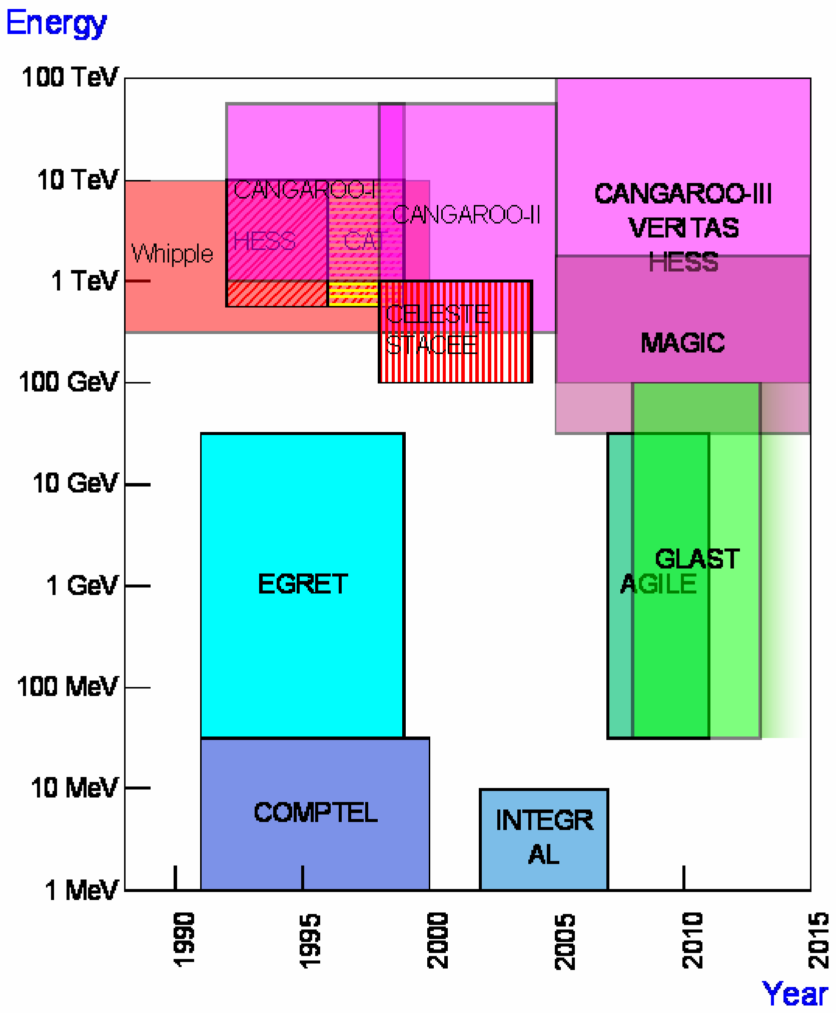


Angular resolution



Gamma-ray sky sensitivity & coverage





Summary

- 宇宙線電子
  - 到達距離が短いため近傍の情報を持つ。
  - GeV領域は$e^+/(e^++e^-)$比を含め精密測定されていくであろう。
  - TeV領域の観測計画は少ない。
- ガンマ線
  - GeV領域は宇宙論的な到達距離を持つ。
  - GLASTはGeV領域の良いMapを作るであろう。
  - 「10-100GeV gap」問題は宇宙から？地上から？