The ALPHA MAGNETIC SPECTROMETER

on the

INTERNATIONAL SPACE STATION

Kate Scholberg, MIT

OUTLINE

Search for ANTIMATTER

AMS Introduction
AMS-01 Shuttle Mission
AMS-02 on the ISS

AMS-02 Instrumentation focus:
Magnet, Tracker, TOF, Veto

Search for DARK MATTER

AMS-02 Instrumentation focus:
TRD, ECAL

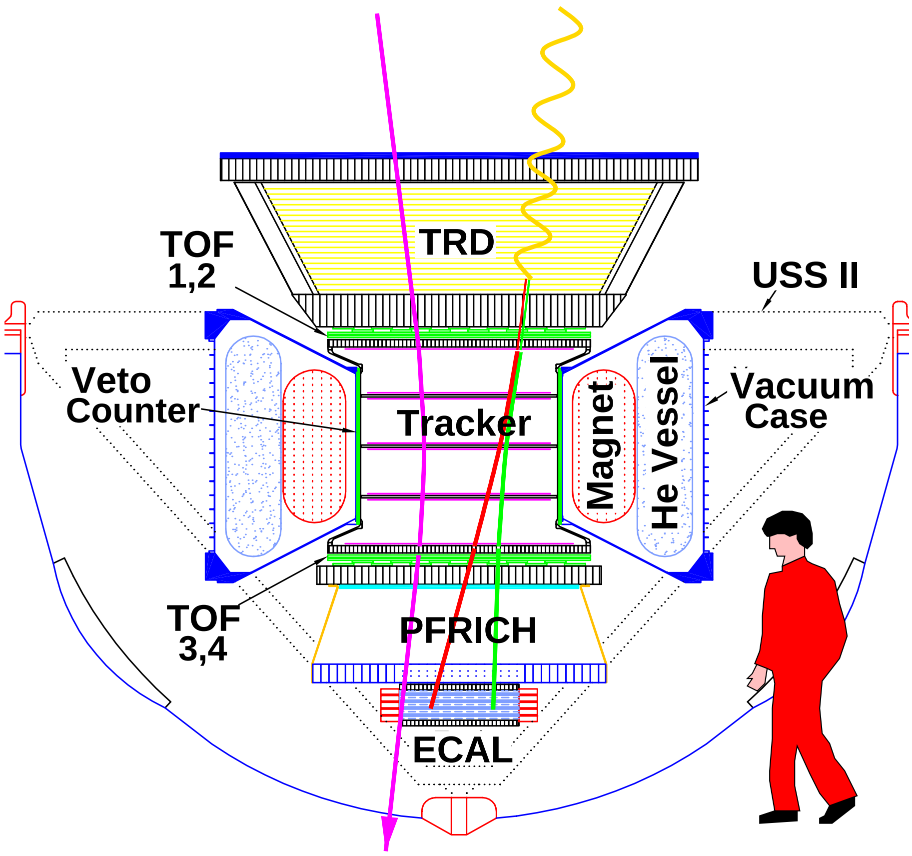
Search for OTHER EXOTIC MATTER

COSMIC RAY studies

AMS-02 Instrumentation focus:
RICH

The ALPHA MAGNETIC SPECTROMETER

A charged particle detector in space to study cosmic rays up to 1 TeV



NASA-DOE collaboration

Original AMS physics motivation:

Search for COSMIC ANTIMATTER

We're made of MATTER

Net Baryon number B>0

But laws of nature are (nearly) matter-antimatter symmetric...

What matter-antimatter asymmetry is expected?

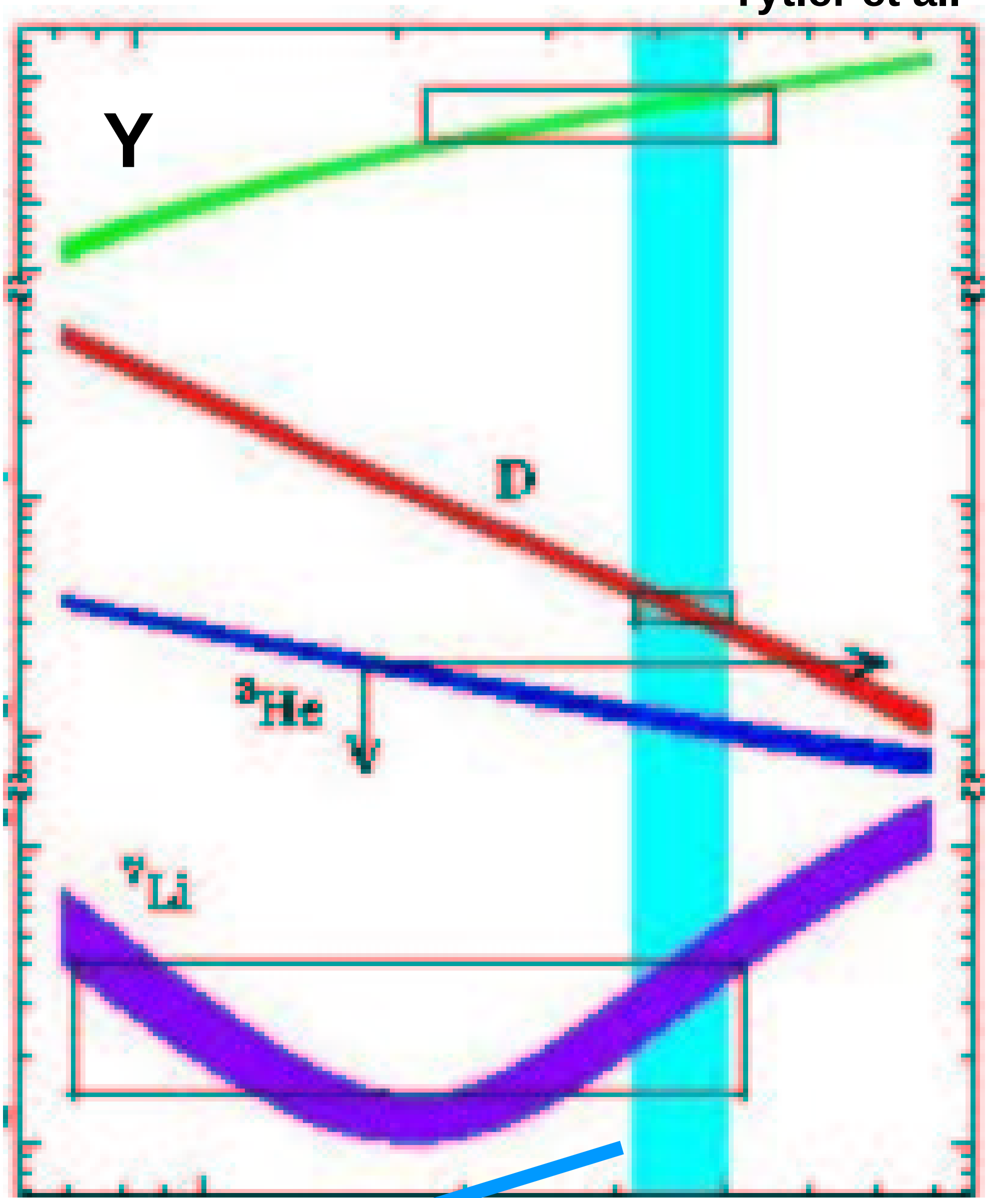
Assuming early universe with equal amounts of nucleons and antinucleons, expect:

$$\eta = \frac{(\eta_{b} - \eta_{\bar{b}})}{\eta_{\gamma}} = \frac{\eta_{B}}{\eta_{\gamma}} \sim 10^{-19}$$

"Annihilation Catastrophe"

BUT observations of light element abundances from BB nucleosynthesis:

Tytler et al.



Light element abundances

Baryon density

$\eta \sim 10^{-10}$ consistent with observations

9 orders of magnitude off! Why??

BARYOGENESIS

creates matter-antimatter asymmetry in early universe

In general, need:
(Sakharov conditions)

1. No thermal equilibrium

2. C violation

3. Baryon number violation

4. CP violation

1. No thermal equilibrium

Required during some period
in the early universe...
otherwise matter ↔ antimatter

Plausible: primordial phase
transitions happened

2. C violation

C: "charge conjugation" turns
particle ↔ antiparticle

If conserved, can't have
antimatter → matter

OK: C is not conserved
in weak interactions

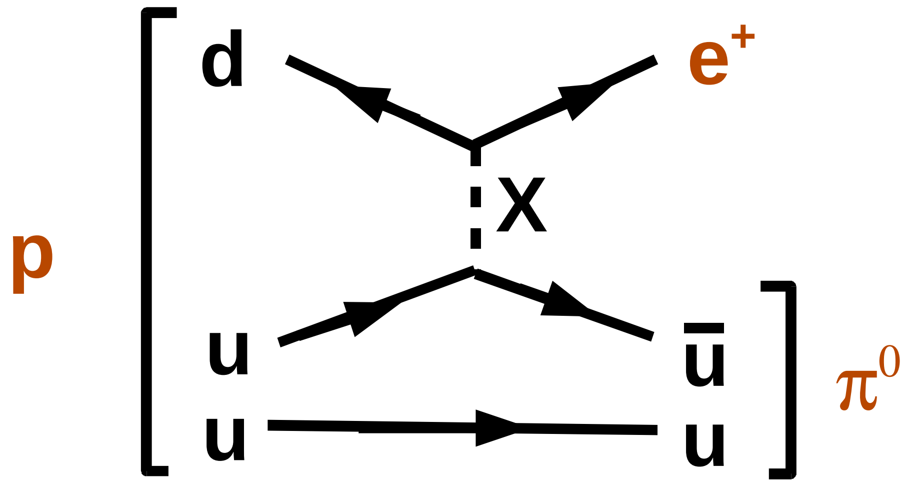
3. Baryon number violation?

e.g. proton decay

If B is conserved, can never get a net baryon number

B violation is natural in Grand Unified Theories

heavy X, Y bosons mediate transitions between quarks and leptons



BUT it has not been observed!

$p \to e^+\pi^0$ $\tau > 1.6 \times 10^{33}$ years

Just around the corner? ? ?

Nobody knows!!

4. CP Violation ?

charge conjugation ← C, P → parity (mirror flip)

If CP is conserved, interactions same for matter and parity-flipped antimatter

=> so can never get asymmetry

because $R(x \rightarrow B) = R(x \rightarrow \bar{B})$

CP violation *is* observed in weak interactions of K and B systems

... but it's a *small* effect

~parts per thousand

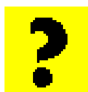
e.g. CP violating K_L decay to $\pi^+\pi^-$

has branching ratio~ $2.3\text{x}10^{-3}$

Different in high energy regime

e.g. hot early universe?

Not really understood...



So, not really clear if Sakharov conditions are satisfied

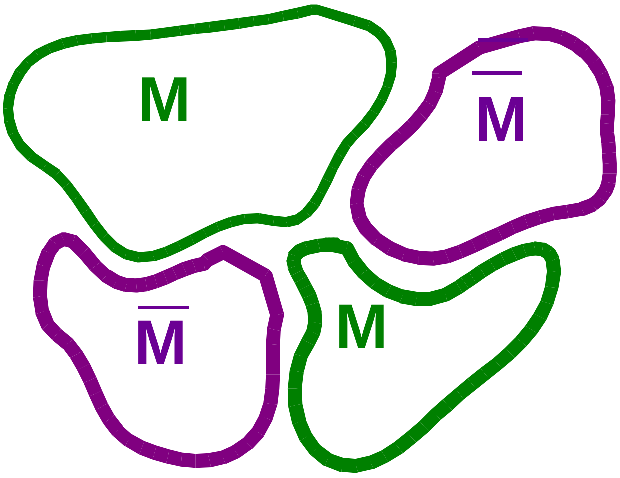
1. No thermal equilibrium ✓
2. C violation ✓
3. Baryon number violation ??
4. CP violation ?

Plenty of ideas for how to explain the net B, but overall the picture is very murky

Instead ask:

How much antimatter is out there?

Maybe the universe is matter-antimatter symmetric?



"Domains" of matter and antimatter freeze out with characteristic size d

Where is the antimatter?

Not too nearby: moon, planets, sun can't be antimatter...

- Apollo missions didn't blow up
- Meteorites don't spray γ's
- Solar wind is matter

etc.

Look for annihilation radiation:

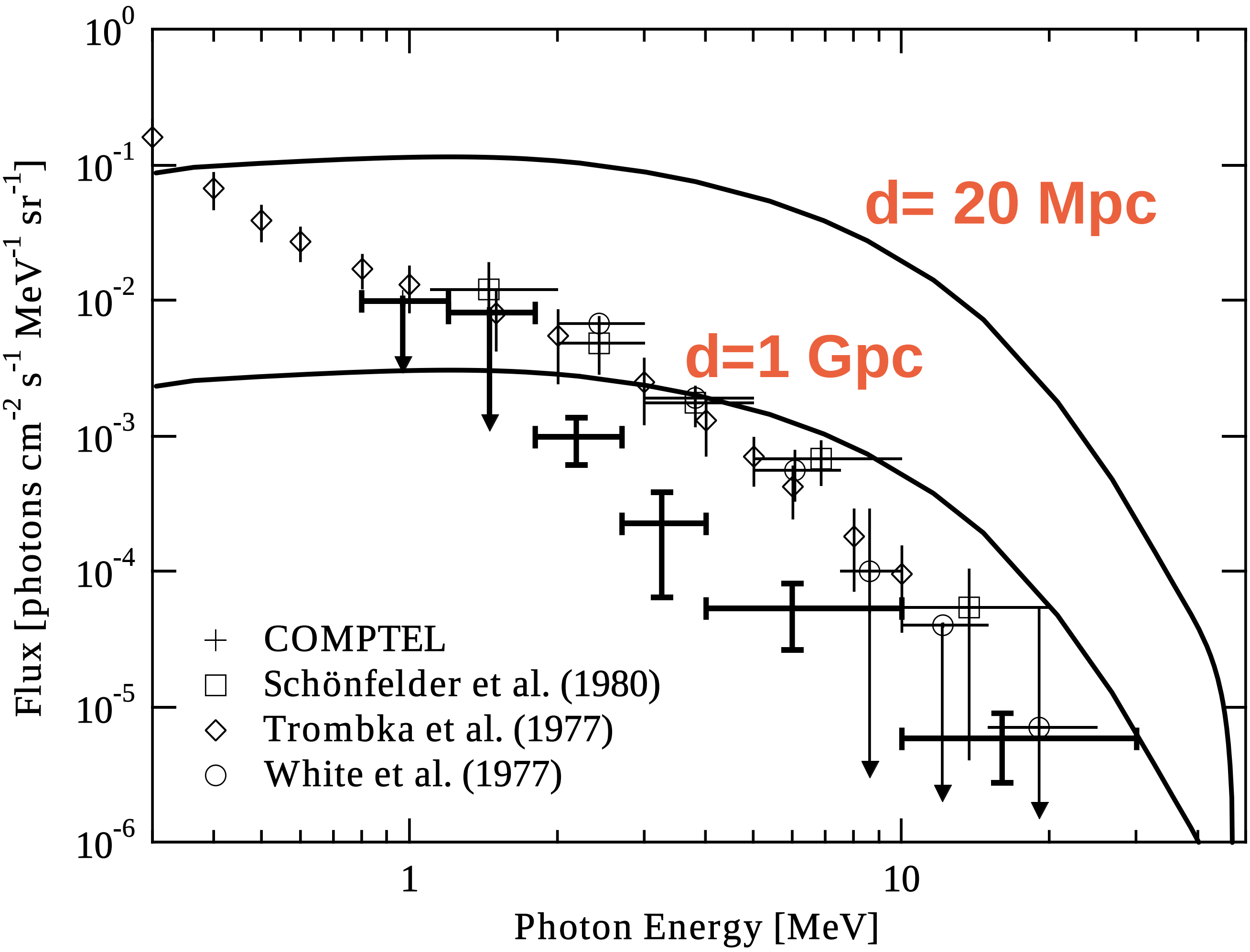
$$N + \bar{N} \to \pi^0 \to \boxed{\gamma + \gamma}$$

$$\to \pi^{\pm} \to \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu)$$

$$\mu^{\pm} \to e^{\pm} + \nu_e(\bar{\nu}_e) + \nu_\mu(\bar{\nu}_\mu)$$

Compare CGRO measurements of the cosmic diffuse gamma ray background with calculated annihilation flux

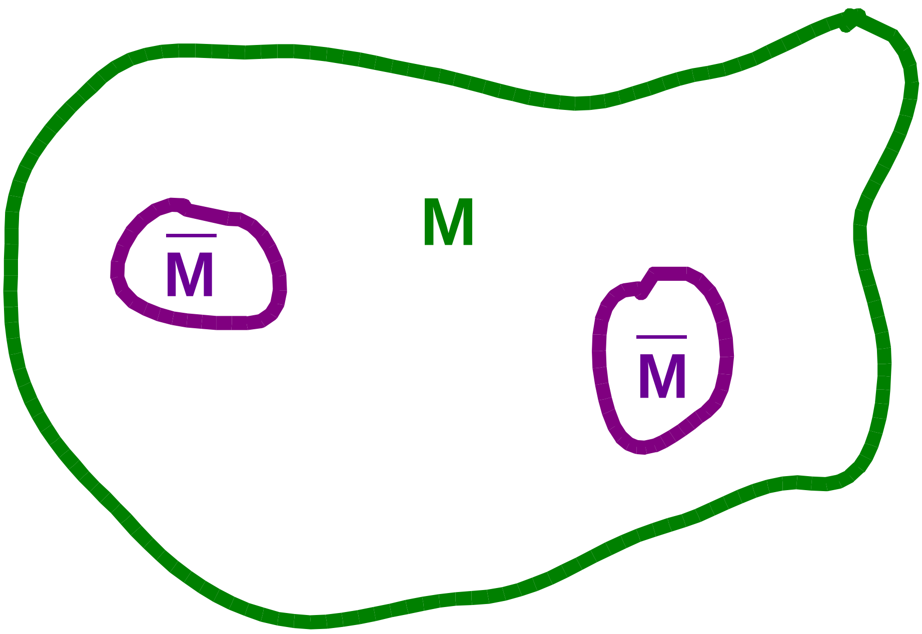
Cohen, De Rujula and Glashow astro-ph/9707087



Antimatter regions must be at least 1000 Mpc away...

...but...

Still possible: small pockets of antimatter



e.g. Sakharov et al., astro-ph/0111524

globular cluster-size regions
of mass <~ 10^3 to 10^5 solar masses

EXPERIMENTAL APPROACH

Look for antimatter in cosmic rays above the atmosphere

(because antimatter annihilates in the atmosphere)

e^+, $\bar{p}$ not too useful: they can be created easily as secondaries in cosmic ray collisions

$$\frac{\bar{N}}{\bar{p}} \sim e^{\frac{-(M_{\bar{N}}-M_{\bar{p}})c^2}{80\,\mathrm{MeV}}} \Rightarrow \frac{\overline{He}}{\bar{p}} \sim 10^{-10} \; ; \; \frac{\bar{C}}{\bar{p}} \sim 10^{-56}$$

antinucleon production strongly suppressed

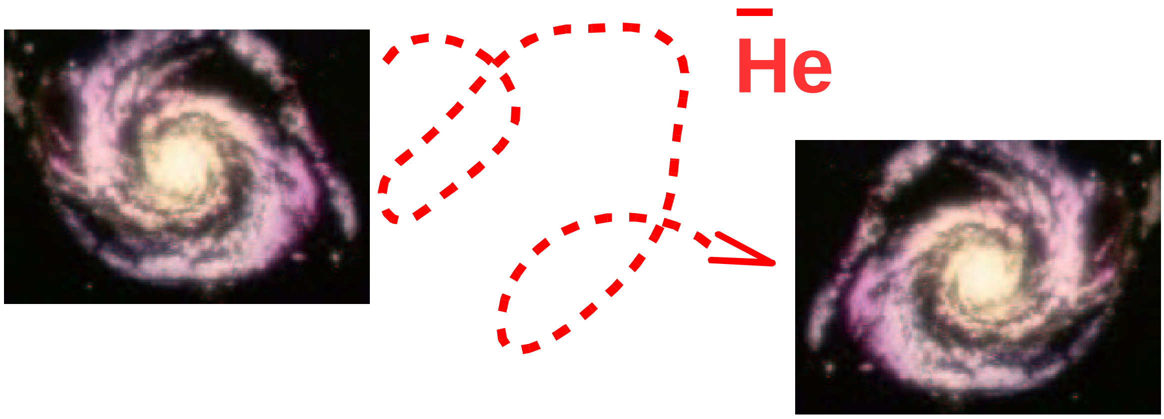
1 $\overline{\text{He}}$ nucleus: strongly suggestive of primordial antimatter

1 $\overline{\text{C}}$ nucleus: a smoking gun for nucleosynthesis in antistars!

Another problem:

ACCESSIBILITY

Many uncertainties
in understanding of intergalactic
cosmic ray transport...



- inter-galactic B fields?
- galactic winds?

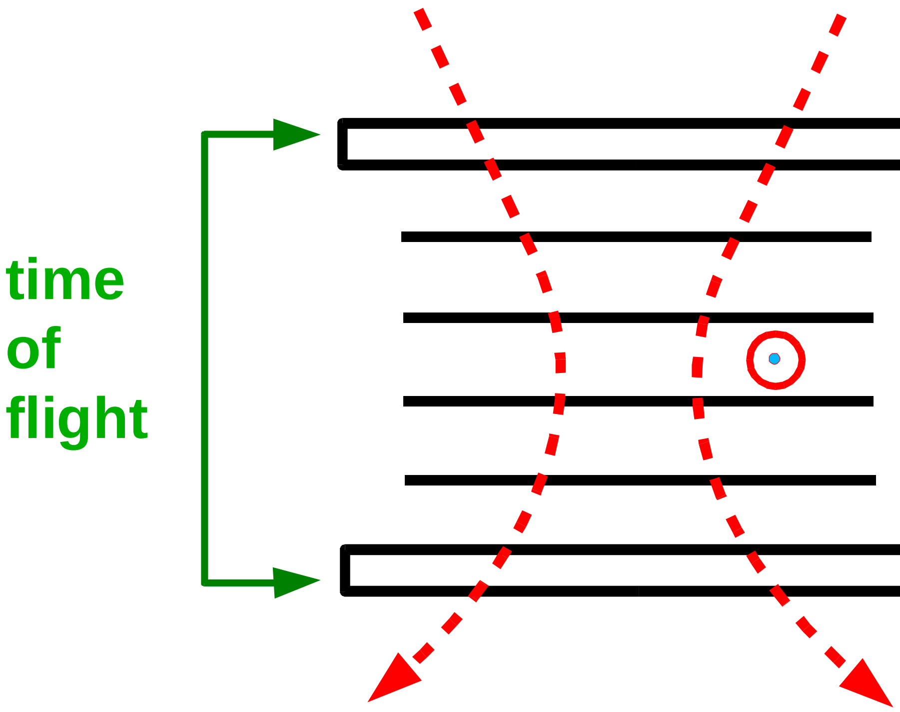
Higher rigidities more promising, since there may be a cutoff rigidity

=> look as high in energy as possible!

How to detect antimatter in space?

Basic idea: magnetic spectrometer

- magnet
- tracker
- time of flight



- p = γmv from curvature
- v from time of flight
- q magnitude from energy loss
- q sign from direction of curvature

m,q identifies particle

The AMS-01 Precursor Mission on the Space Shuttle

DOE/NASA International Collaboration

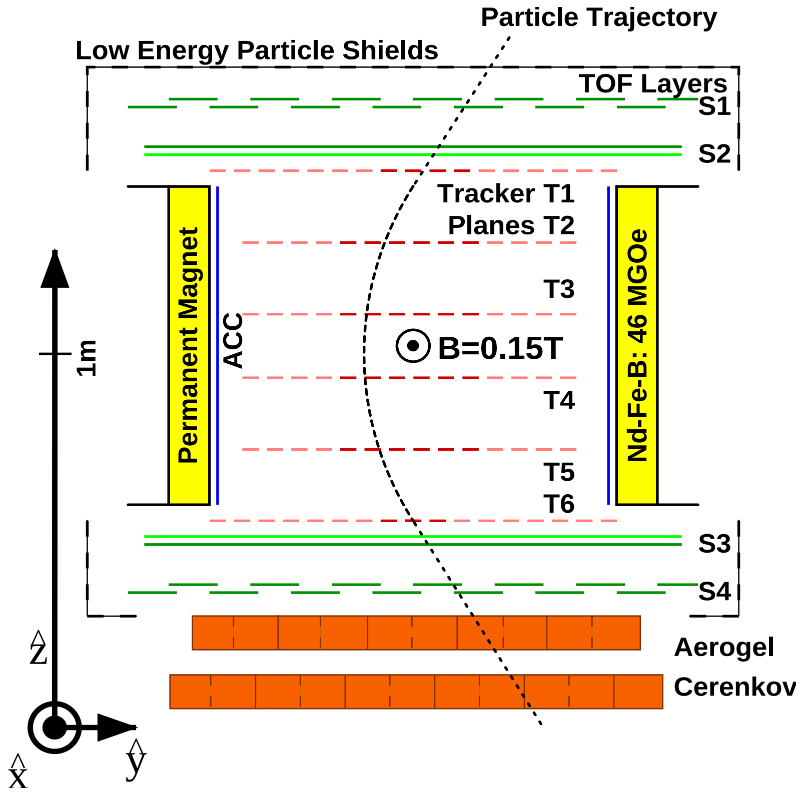
Permanent magnet, 0.15 T

Si tracker, TOF, Cherenkov

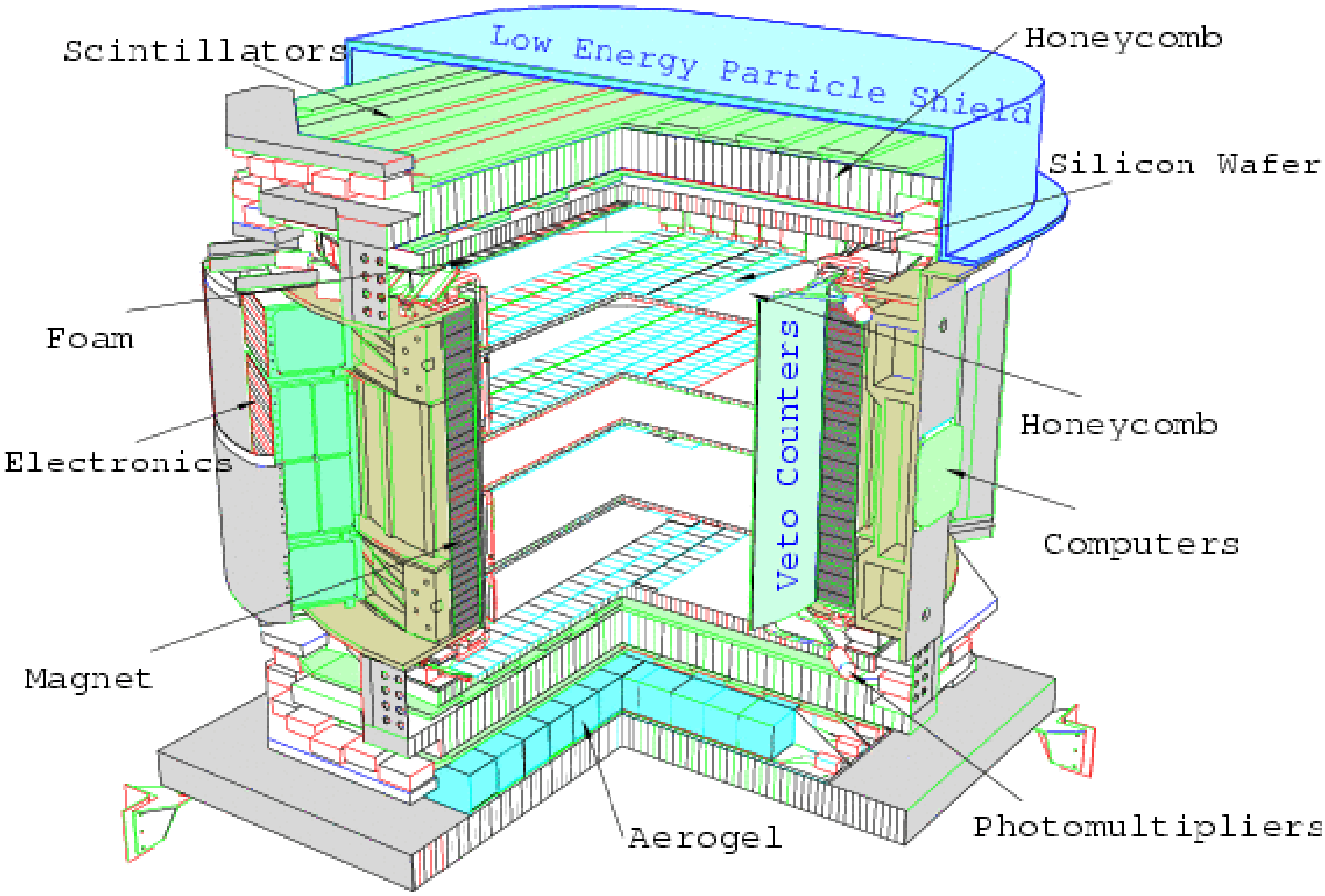
Flew June 2-12, 1998 on Discovery, STS-91

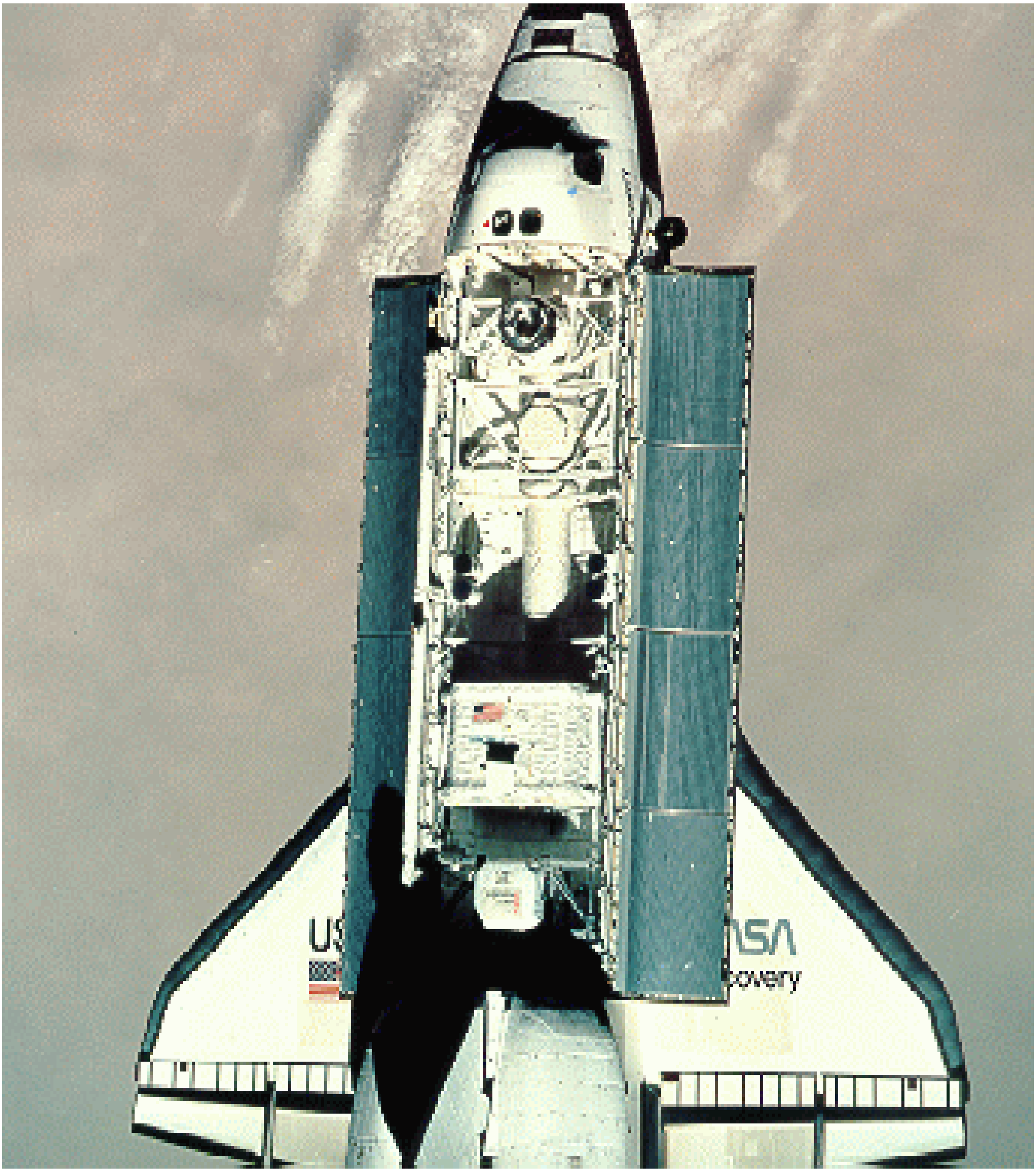
51.7 degree orbit, 320-390 km

~100 hours of data, 100 million particles



The AMS-01 Detector





AMS-01 Publications

"Search for antihelium in cosmic rays"

Phys. Lett. B461 (1999) 387.

"Protons in Near Earth Orbit"

Phys. Lett. B472 (2000) 215.

"Leptons in Near Earth Orbit"

Phys. Lett. B484 (2000) 10.

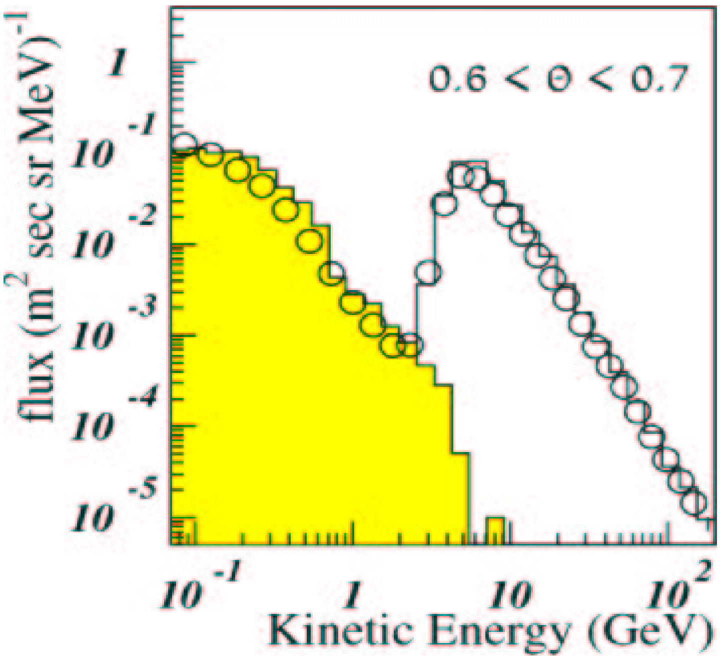
"Cosmic Protons"

Phys. Lett. B490 (2000) 27.

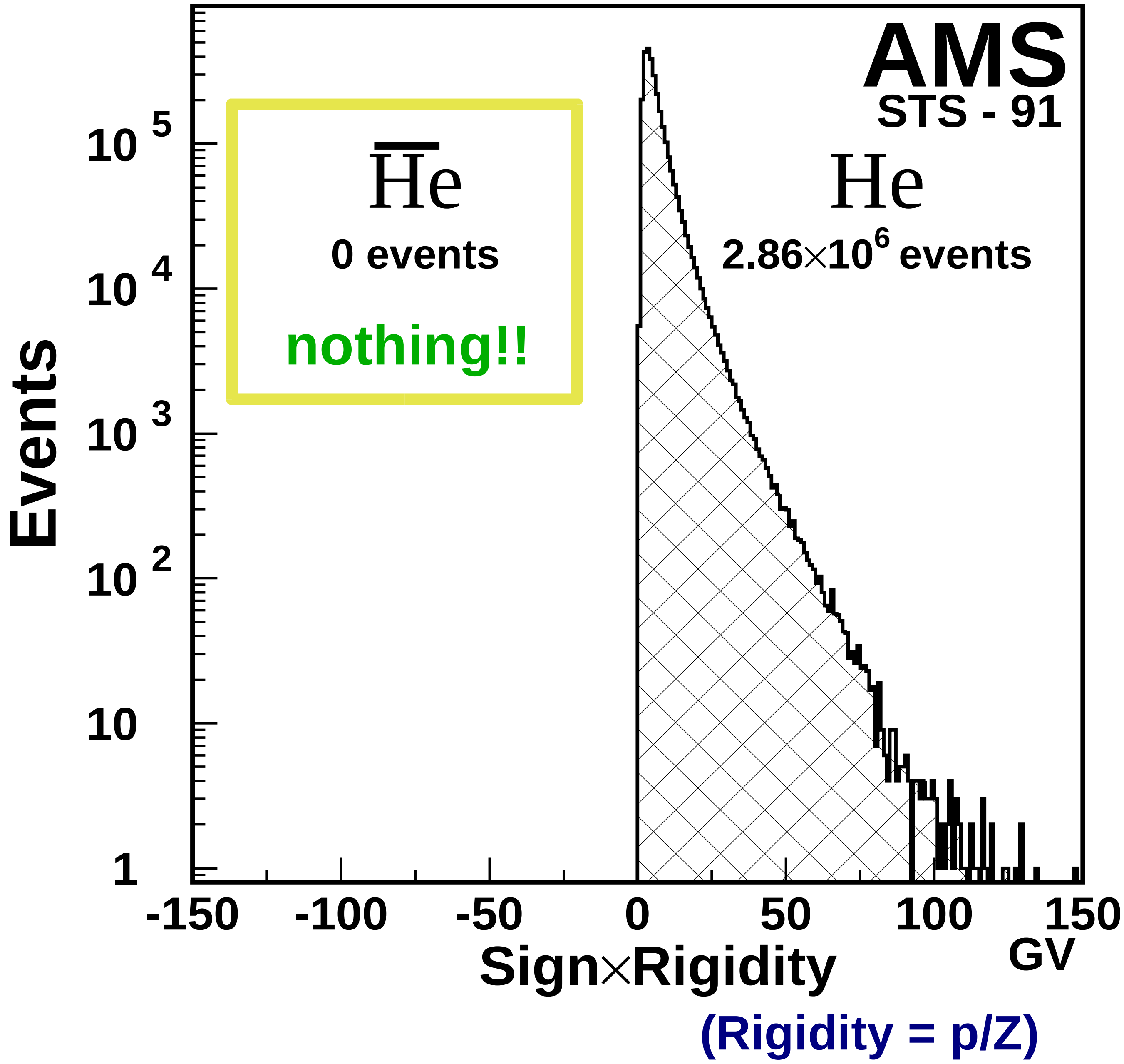
"Helium in Near Earth Orbit"

Phys. Lett. B494 (2000) 193.

Proton spectrum from AMS-01

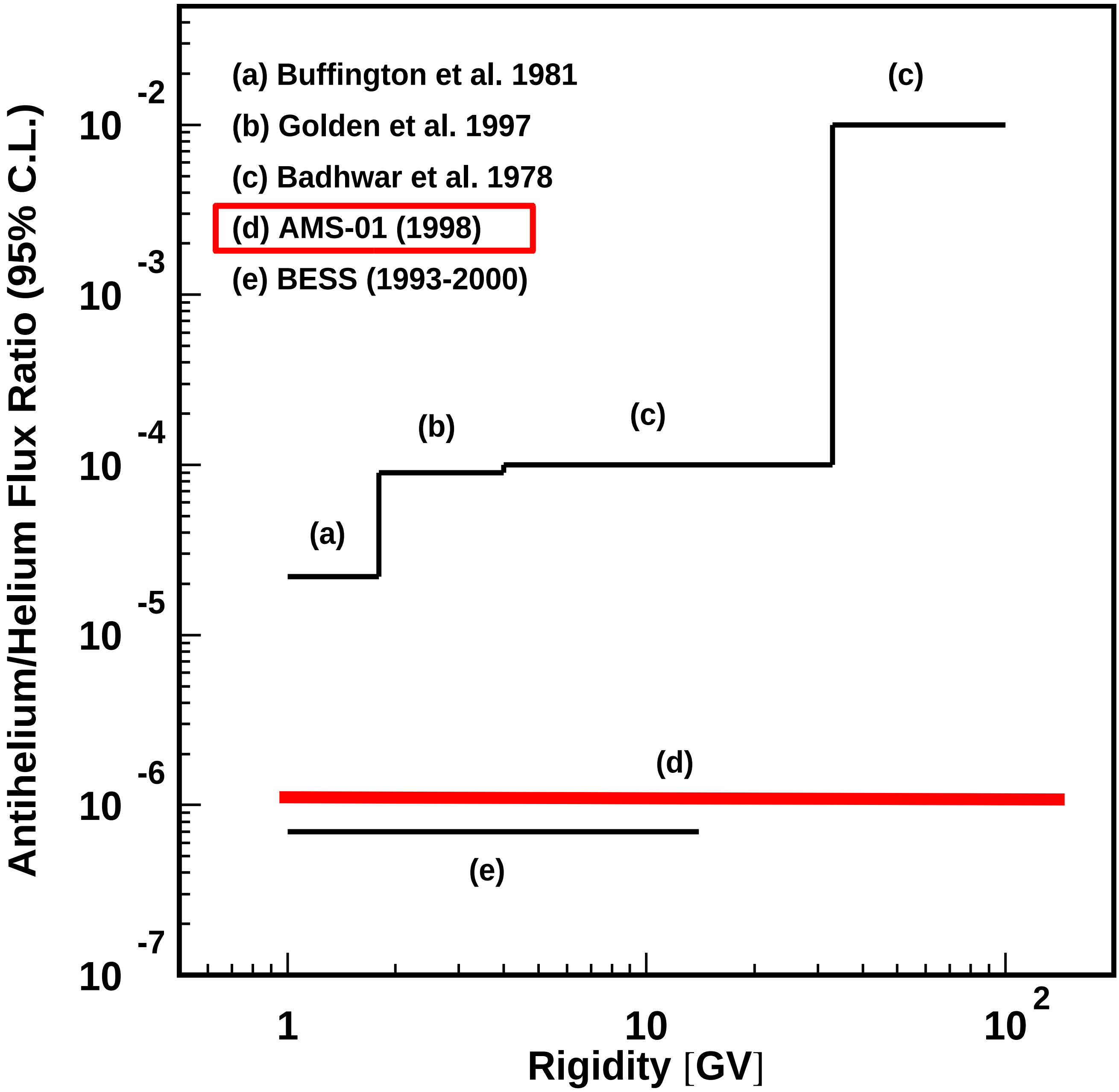


Results of AMS-01
$\overline{He}$ search |Z| =2



Also, no antinuclei found with |Z|>2

Limit on $\overline{He}$/He Ratio

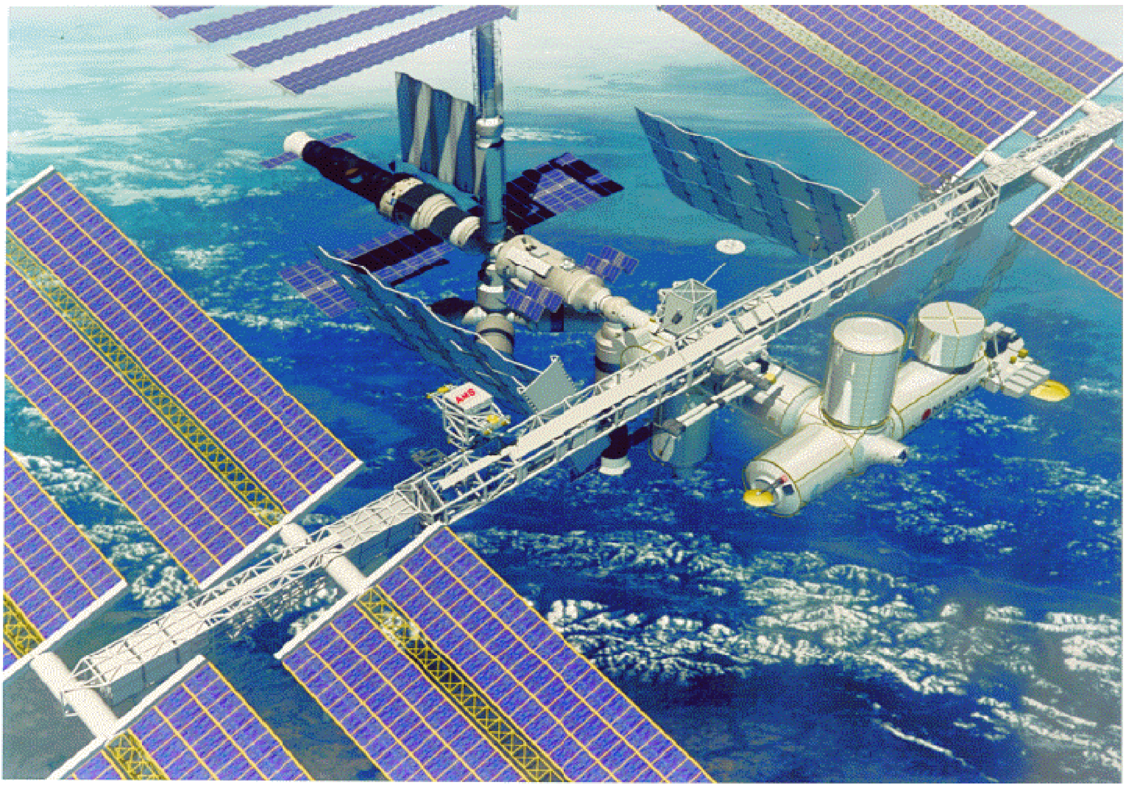


AMS-02 on ISS

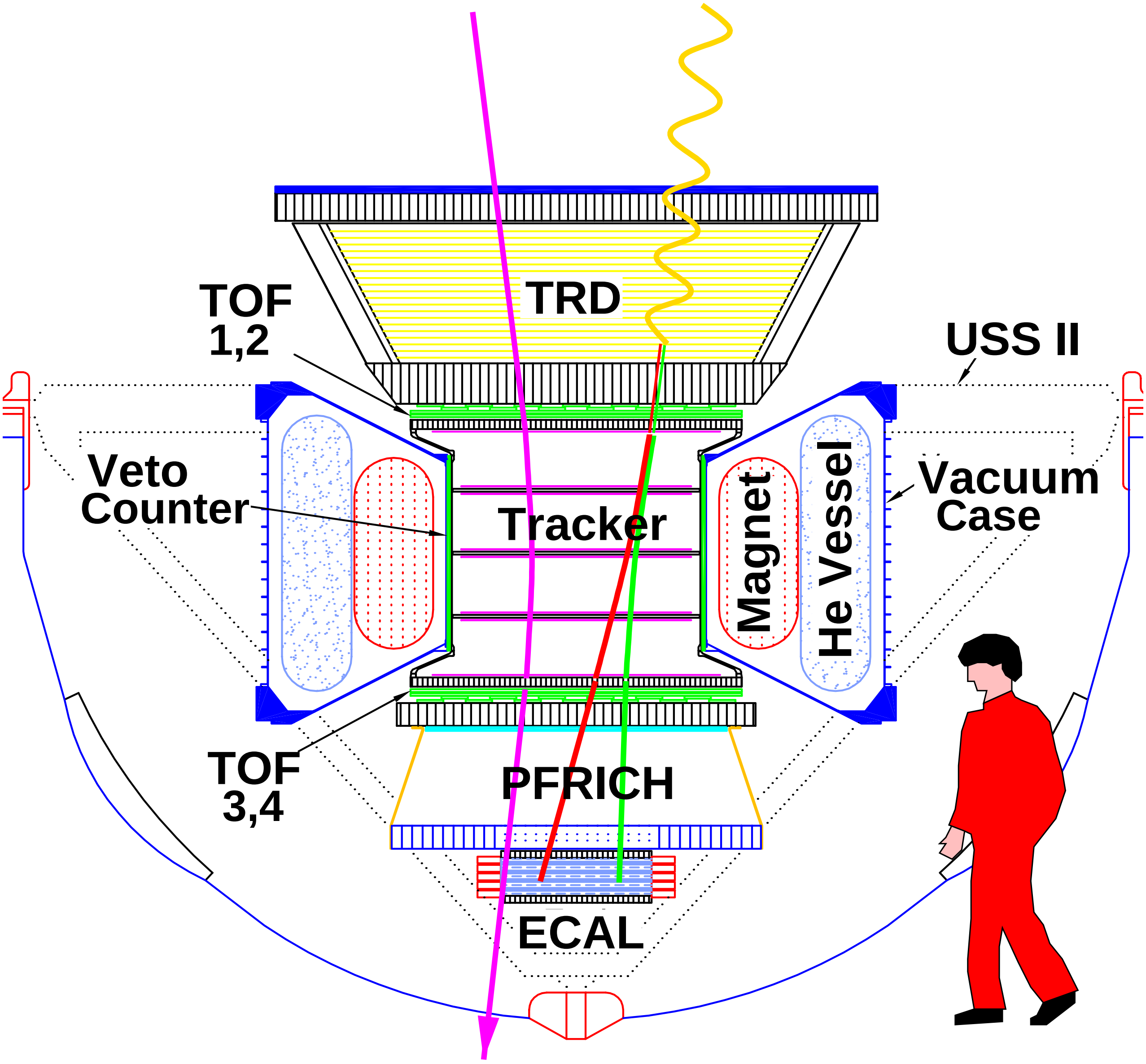
Launch 2005 for 3 year exposure

Now with a SUPERCONDUCTING magnet, 0.9 Tesla, allowing tracking up to ~ TeV

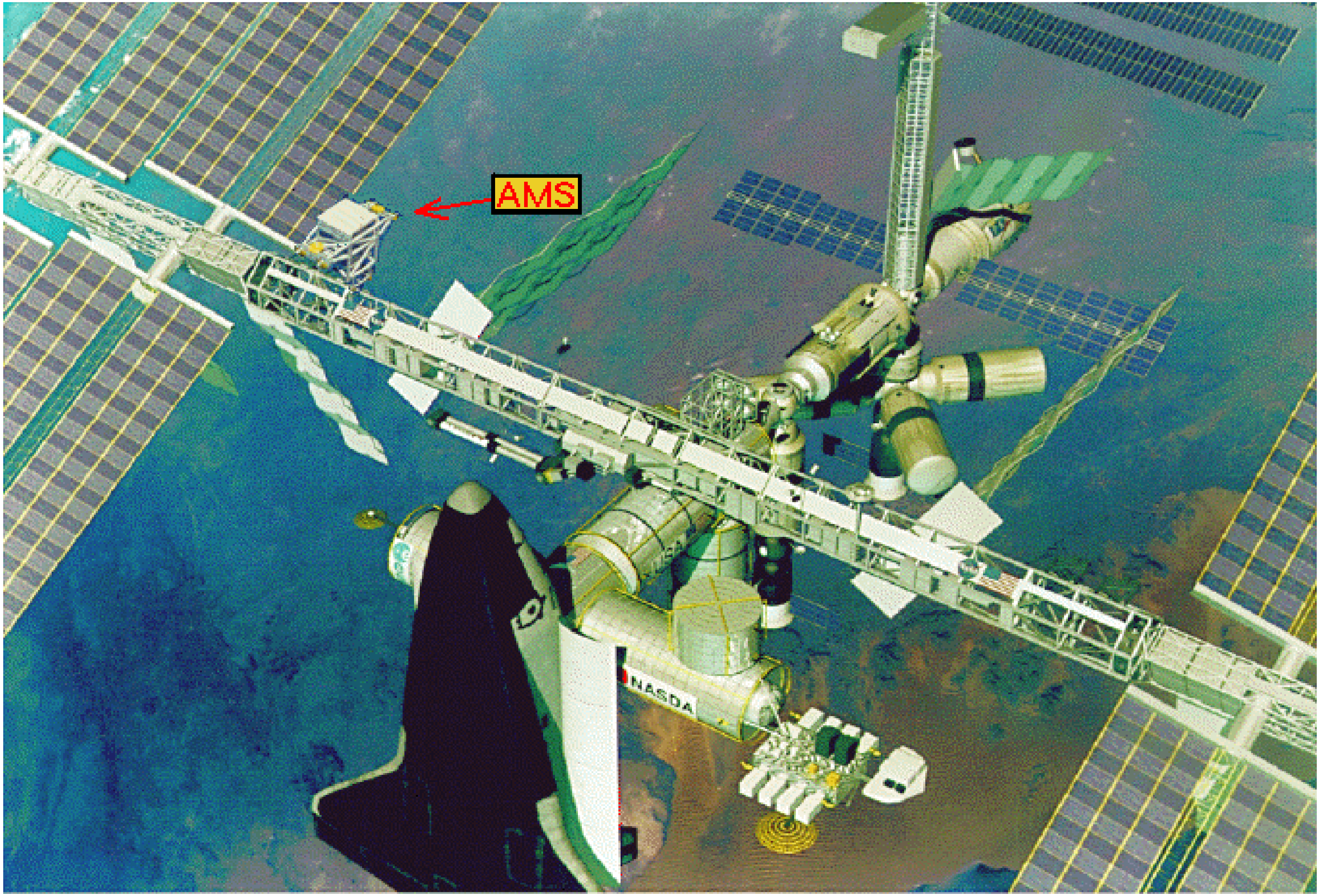
8 layers of Si strip tracker planes
Time of Flight scintillator counters
Transition Radiation Detector
Rich Imaging Cherenkov Detector
Electromagnetic Calorimeter



AMS-02 in the shuttle bay

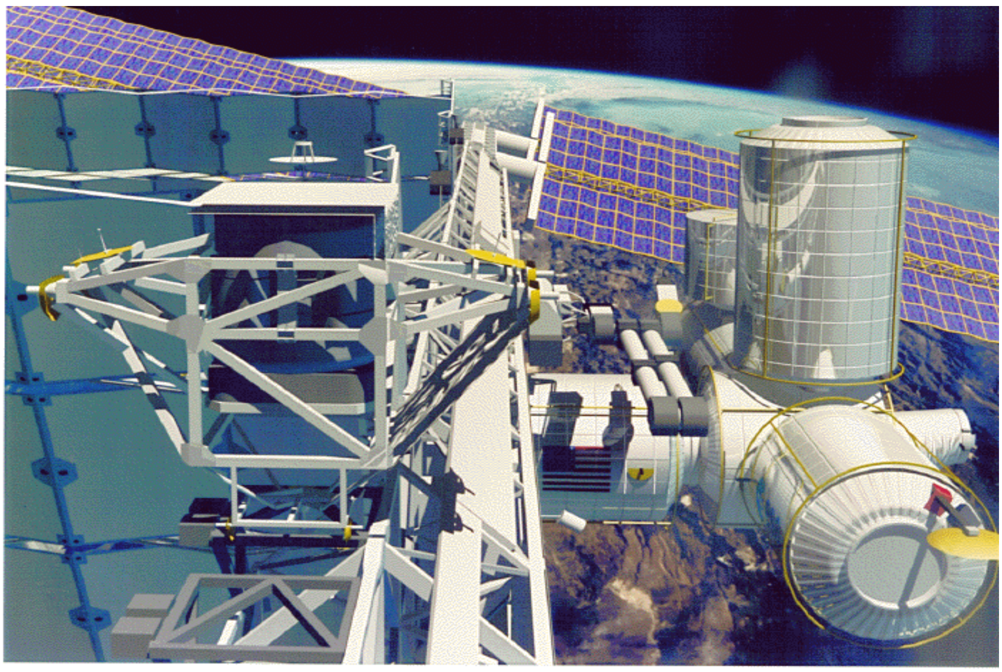


Acceptance ~0.5 m^2 sr

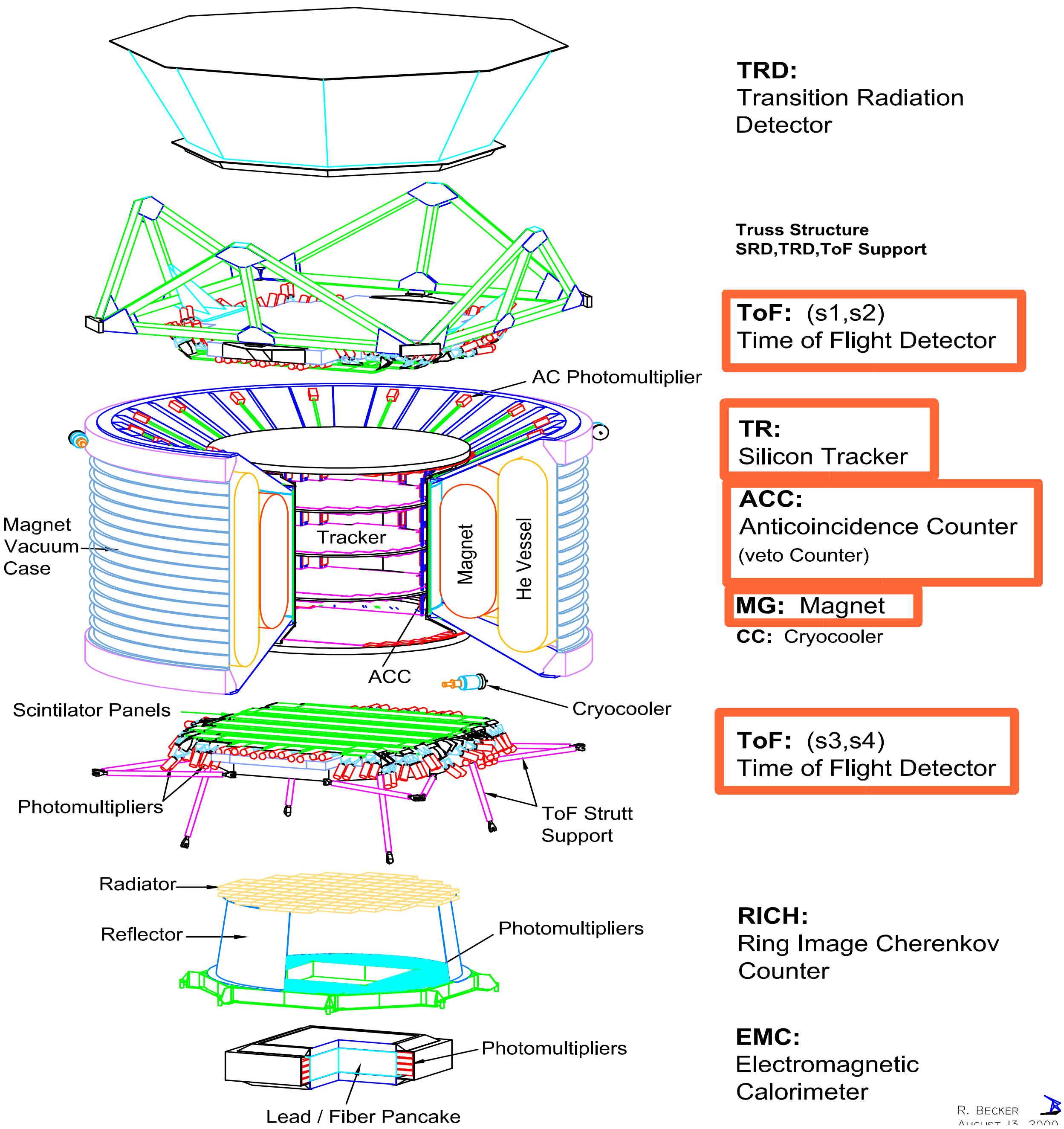

AMS
NASDA

Requirements for a detector in space

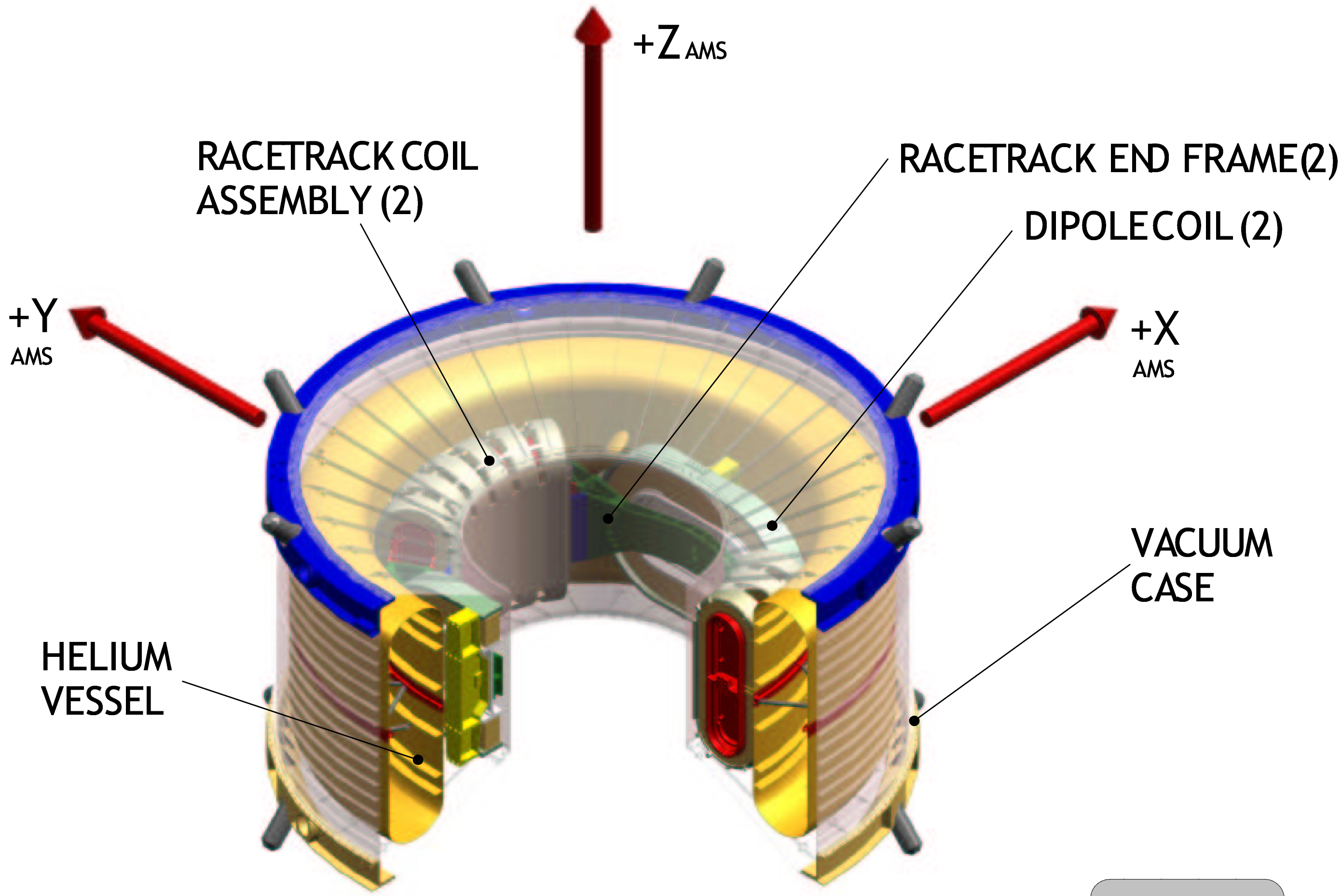
- Weight Limit: 14809 lb
- Temperature: -180^o to +50^o C
- Power consumption: 2 kW
- Data rate: 1 Mb/s
- 9g acceleration during takeoff
- Must operate in vacuum
- Must operate without services for 3 years



AMS-02 Exploded View



Focus on instrumentation needed for antimatter search



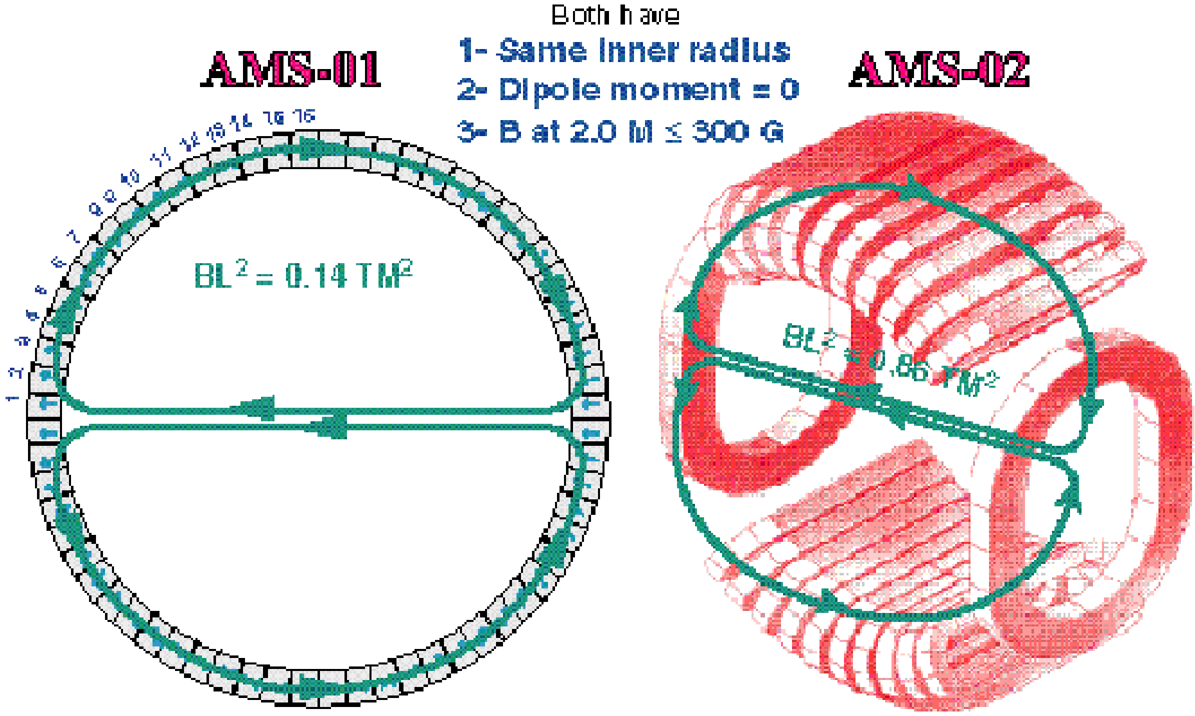
AMS-02 SUPERCONDUCTING MAGNET

SPACE CRYOMAGNETICS Ltd.

Want no net dipole moment to avoid torque on ISS

Rare earth magnet

Superconducting magnet

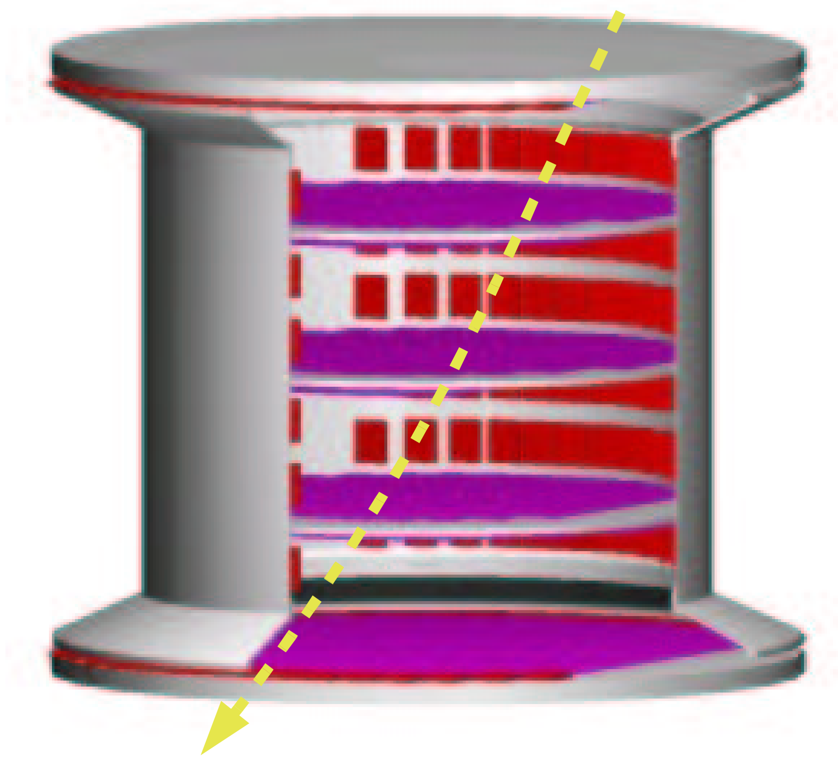


- NbTi Al-stabilized superconductor
- Cooled by superfluid helium
- Central field 0.87 T
- Operating current 450 A
- Stored energy 6 MJ

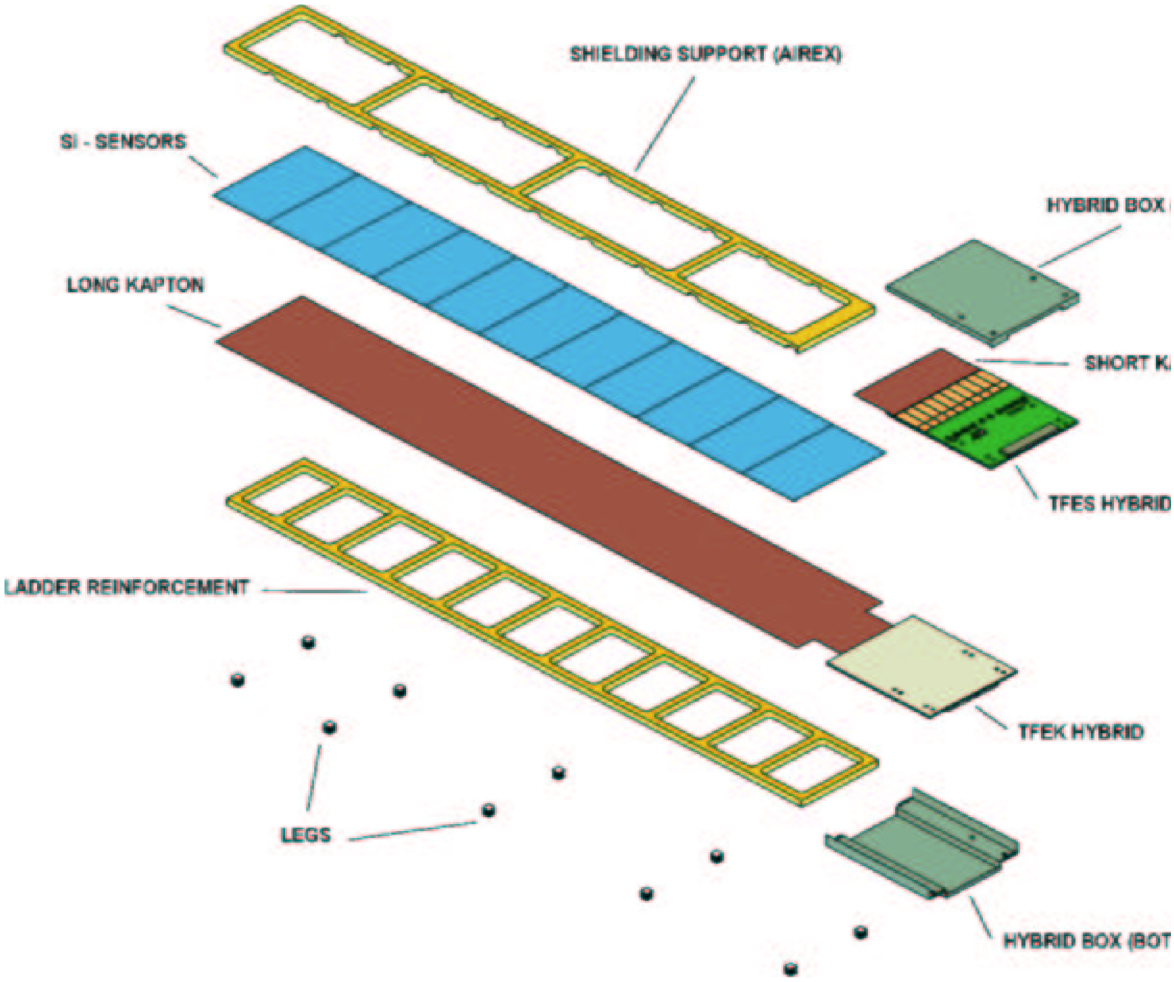
AMS-02 Silicon Tracker

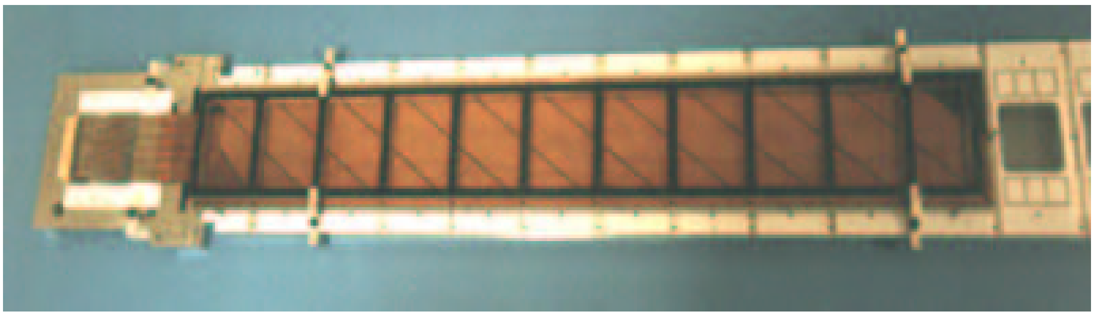
Measure curvature of track in B field to get momentum

Also measure energy deposition to get charge ($dE/dx \propto q^2$)



- **8 planes**
- **192 ladders**
- **7 square meters**
- **196,000 channels**



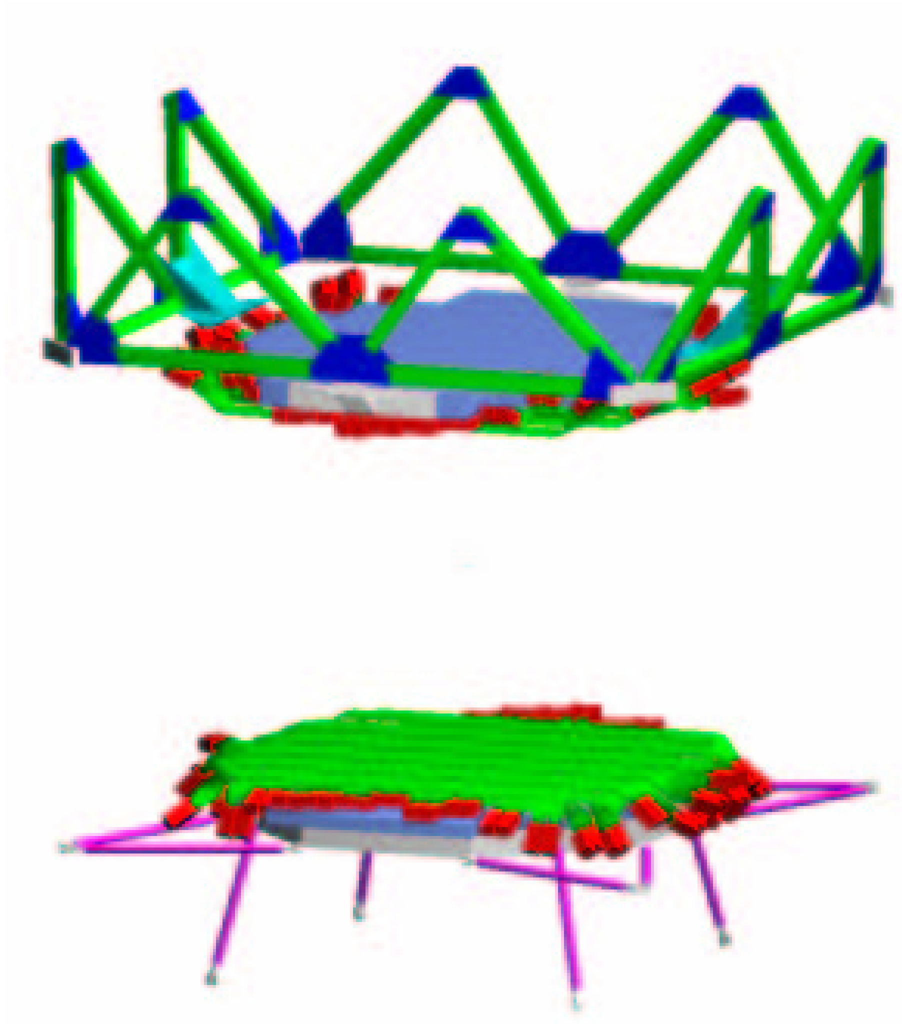


10 μm resolution in bending plane

30 μm resolution in non-bending plane

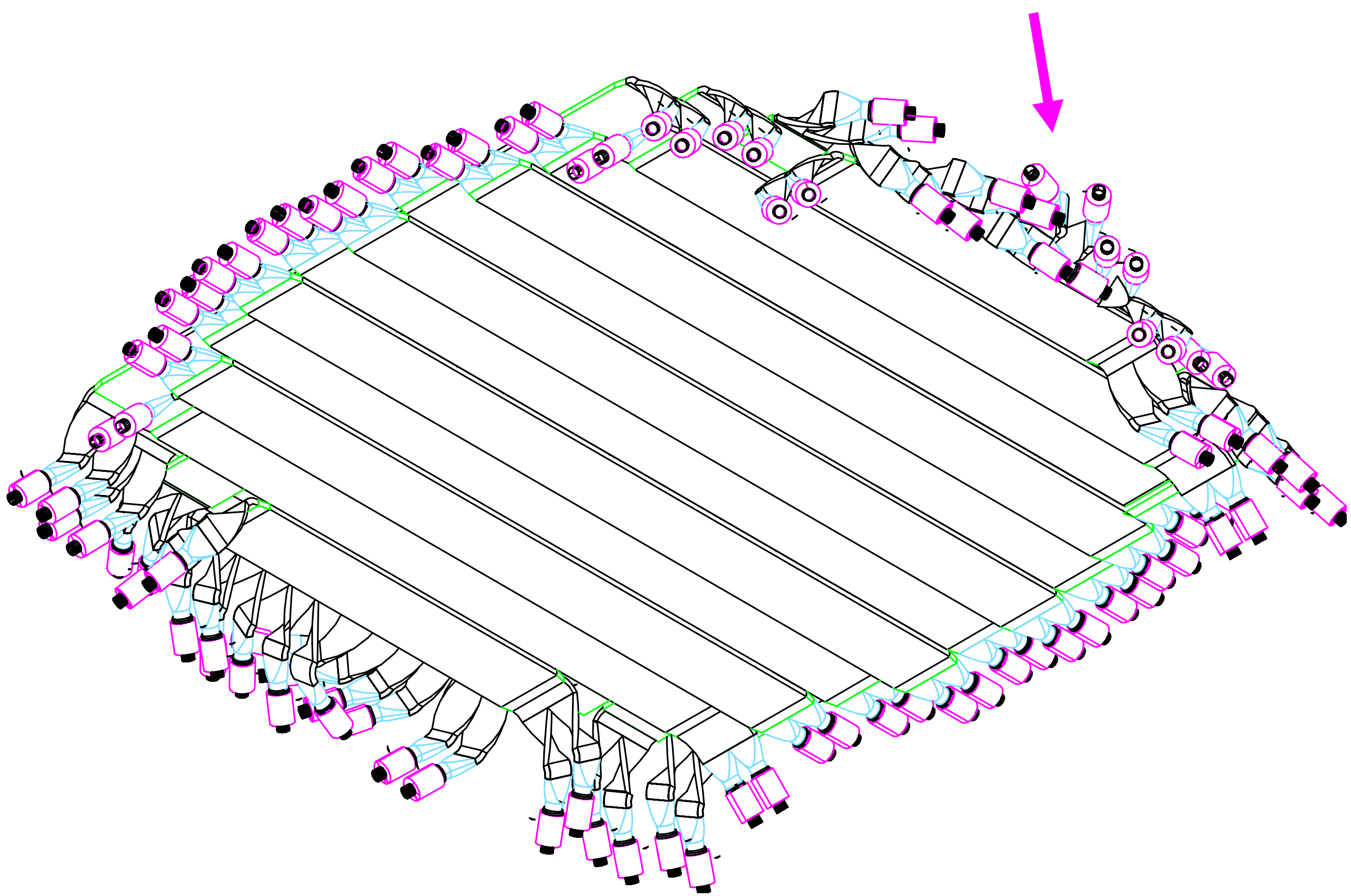
AMS-02 Time of Flight System (TOF)

- Velocity measurement
- Alternate dE/dx measurement
- Provides fast trigger



4 planes of scintillator viewed by photomultiplier tubes

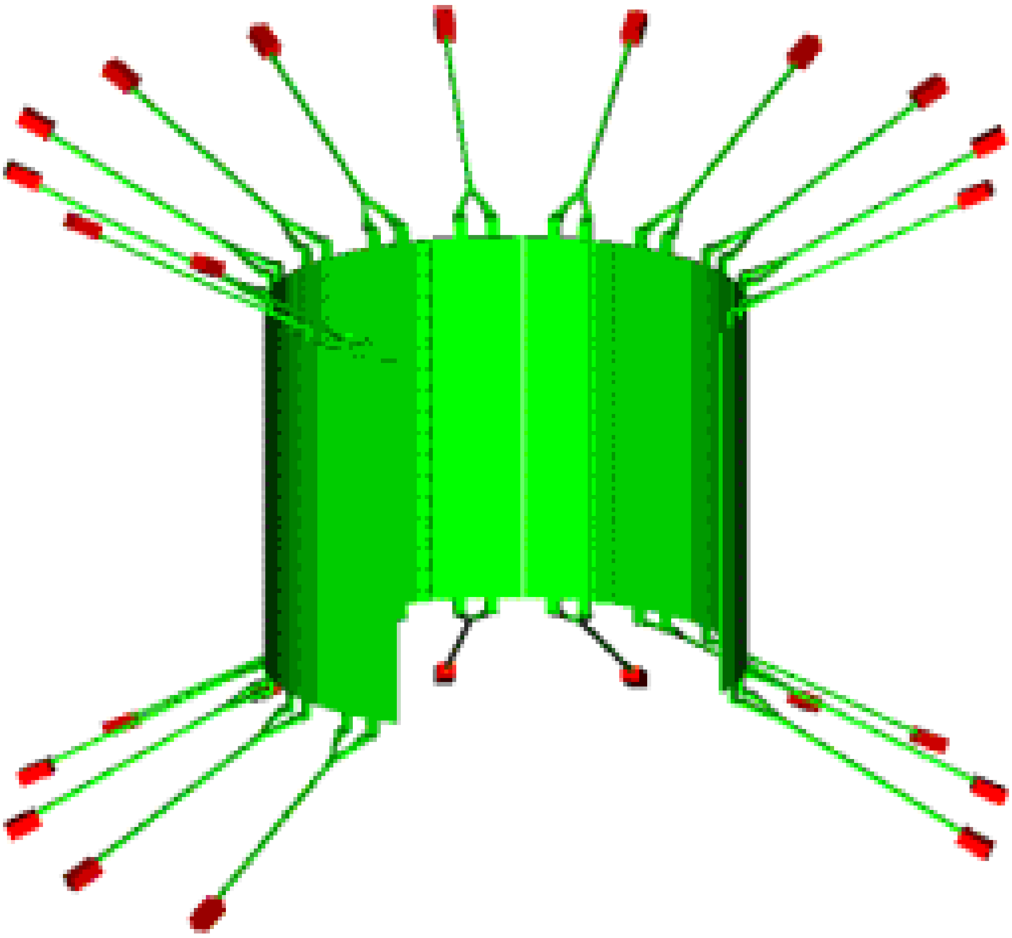
Phototubes and light guides bent
to optimize performance in magnetic field



120 ps time-of-flight resolution

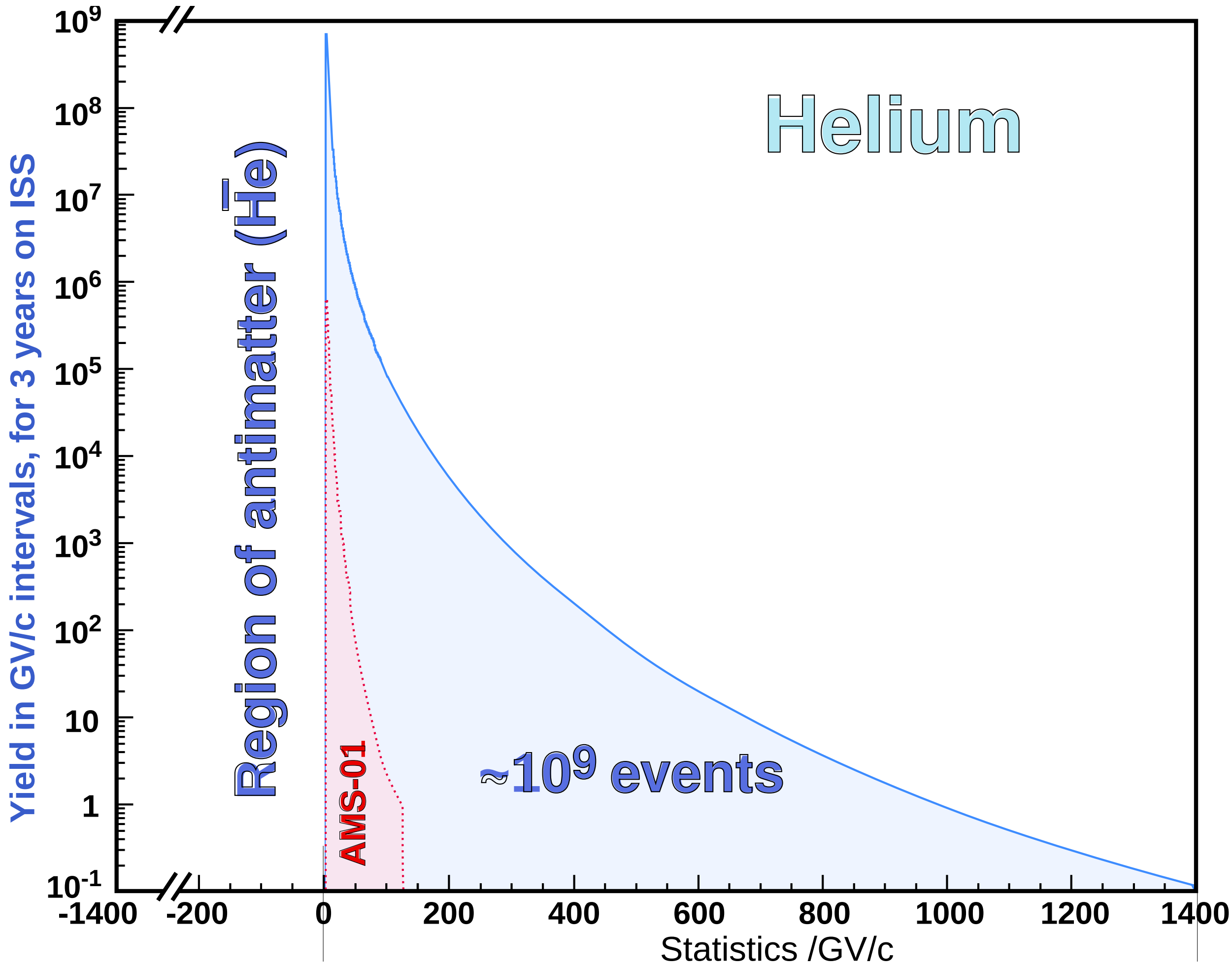
AMS-02 Anticoincidence Counter

Veto particles entering from side, multiple tracks to reduce trigger rate



scintillator with light guides, photomultiplier tubes

AMS-02 Sensitivity to Antihelium in 3 years



Sensitive to $\overline{He}/He \sim 10^{-9}$

out to ~ TeV energies

Summary of AMS Antimatter Search

Baryogenesis is not understood...

We don't even know whether there are concentrations of antimatter in the universe

An antinucleus is a smoking gun!

AMS-01 magnetic spectrometer on the Shuttle set limits

$\overline{\mathrm{He}}/\mathrm{He} \sim 10^{-6}$

AMS-02 on ISS will improve limits by 3 orders of magnitude

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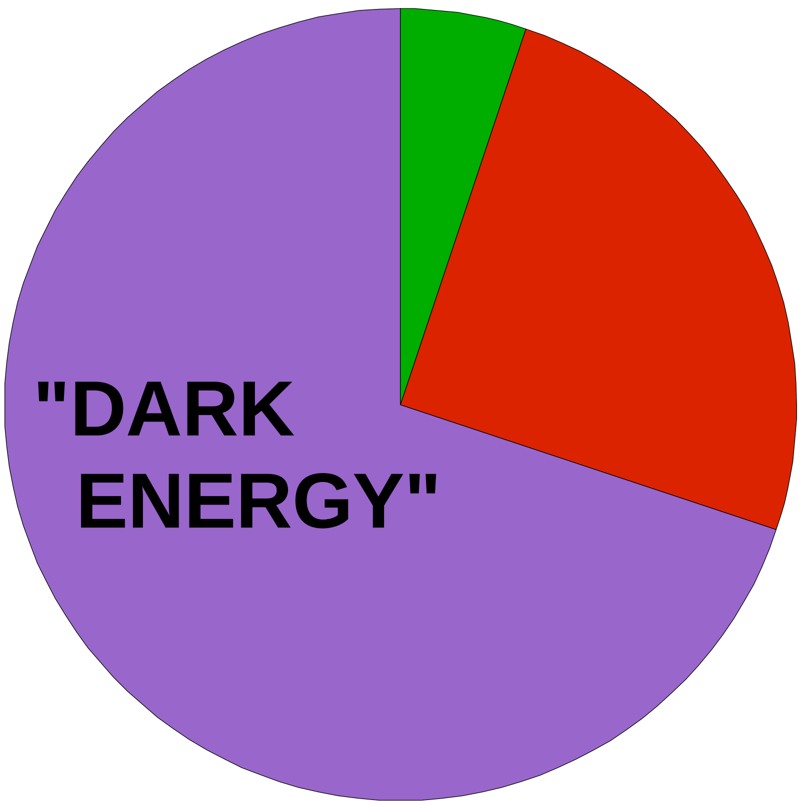
AMS-02 Instrumentation focus:
RICH

The DARK MATTER Mystery

Many independent measurements

- Galactic rotation curves
- Gravitational lensing, microlensing
- Cosmic microwave background
- Large scale structure
- Nucleosynthesis
- High z redshift surveys

Baryonic matter
(ordinary stuff) only ~5%!



Non-baryonic dark matter

~25% !!

One appealing hypothesis to explain non-baryonic dark matter:

Weakly Interacting Massive Particles (WIMPs)

that froze out after the Big Bang

e.g. NEUTRALINO χ

lightest stable supersymmetric particle

$$50\ \mathrm{GeV}/c^2 < m_\chi < 3\ \mathrm{TeV}/c^2$$

accelerator bound (LEP) ← lower limit; cosmological bound ← upper limit

Neutralinos could make up the Galactic halo

Local halo density ~ 0.3 GeV cm^{-3}
(but could be clumpy)

Signature of neutralino dark matter:

Look for
ANNIHILATION PRODUCTS

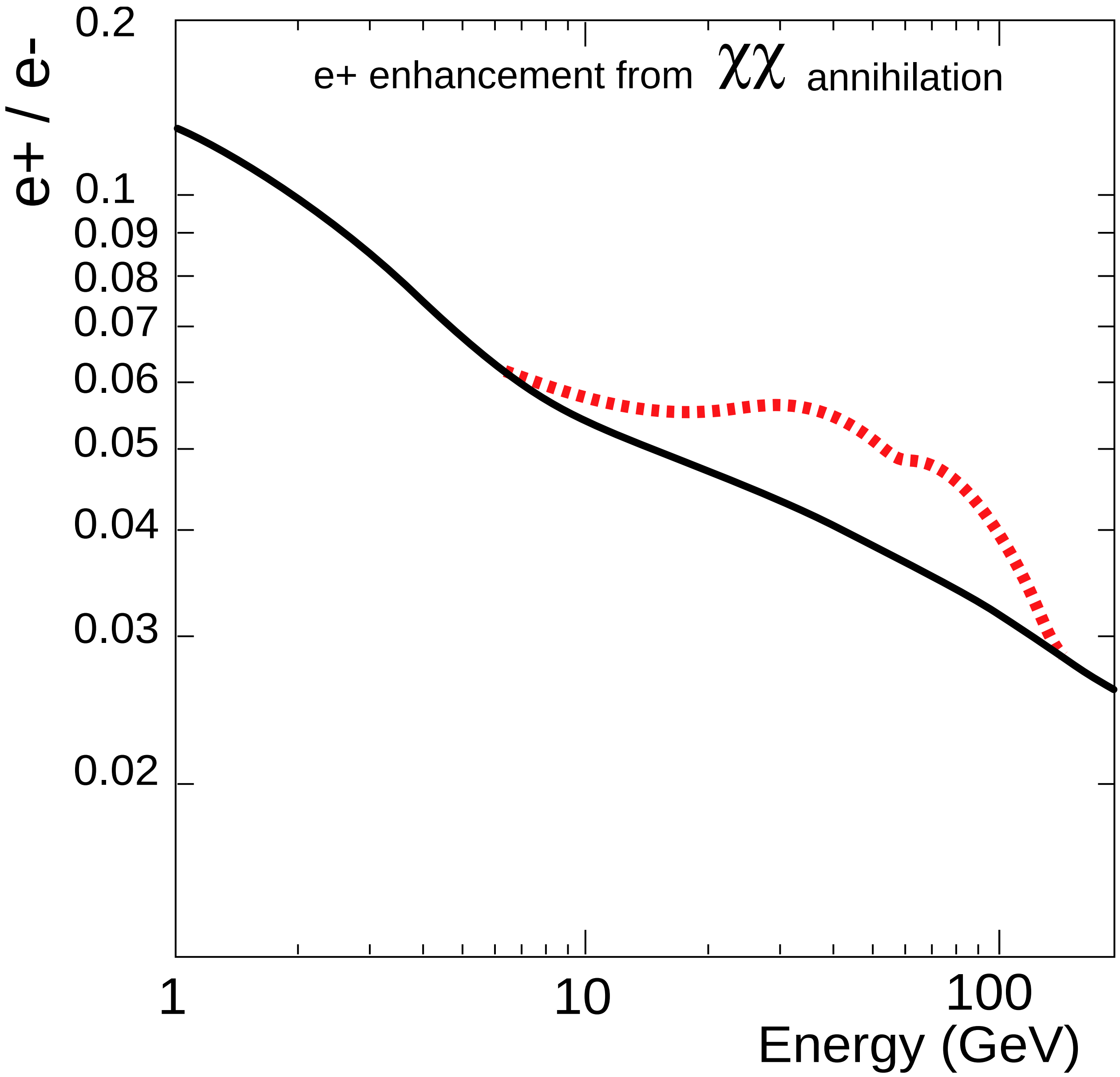
$$\chi\chi \rightarrow \begin{bmatrix} \text{gauge bosons} \\ \text{quarks} \\ \text{leptons} \end{bmatrix} \rightarrow \begin{bmatrix} e^+ \\ \bar{p} \\ \bar{d} \\ \gamma \\ \ldots \end{bmatrix}$$

Here, have background of SECONDARIES from CR collisions

=> look for ANOMALIES in the energy distribution

"bump in the spectrum"

Look for anomalous POSITRONS

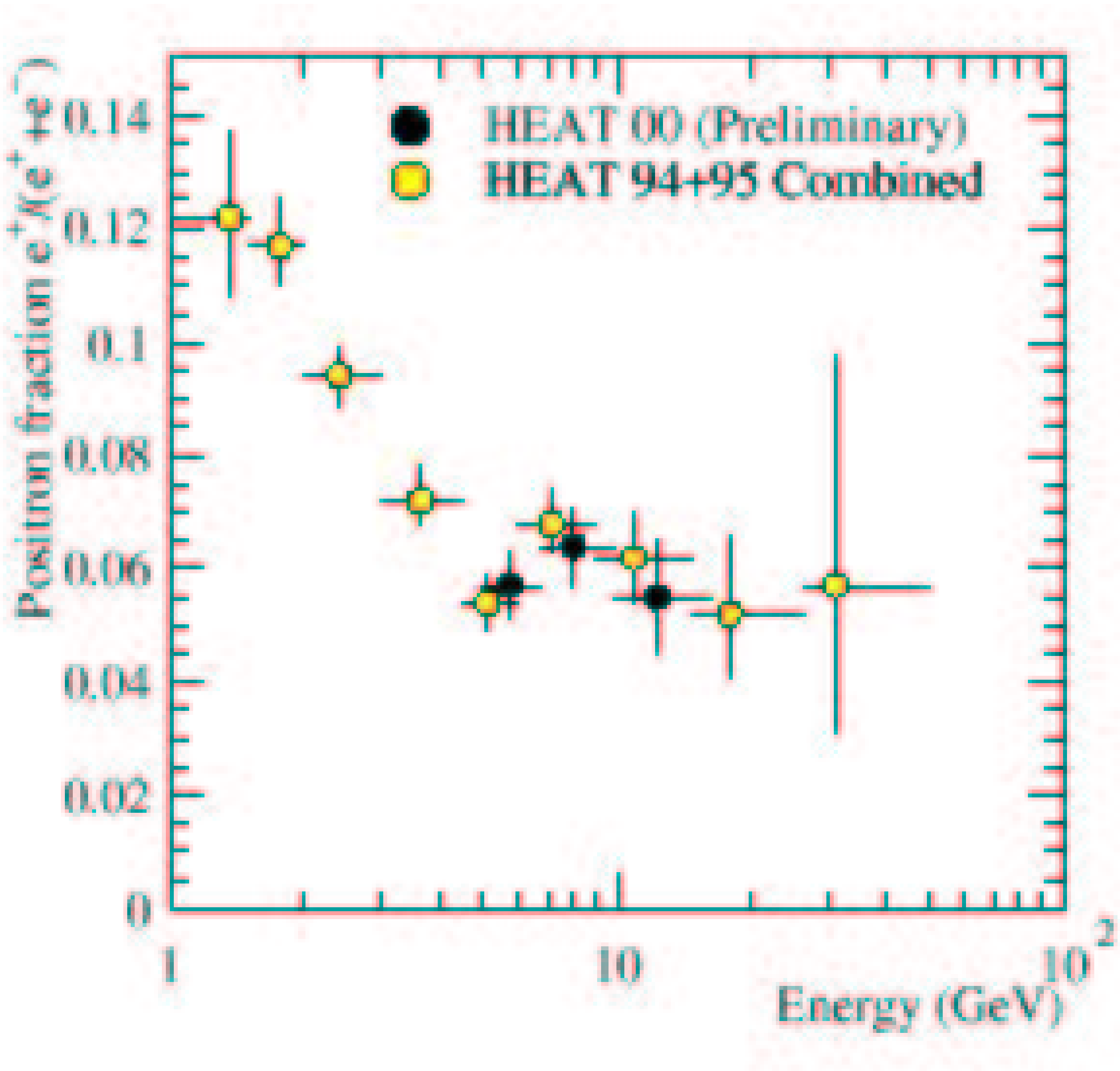


Expect bump around ~10-100 GeV

An intriguing hint from a balloon experiment, HEAT

hep-ph/9902162

Positron fraction vs energy

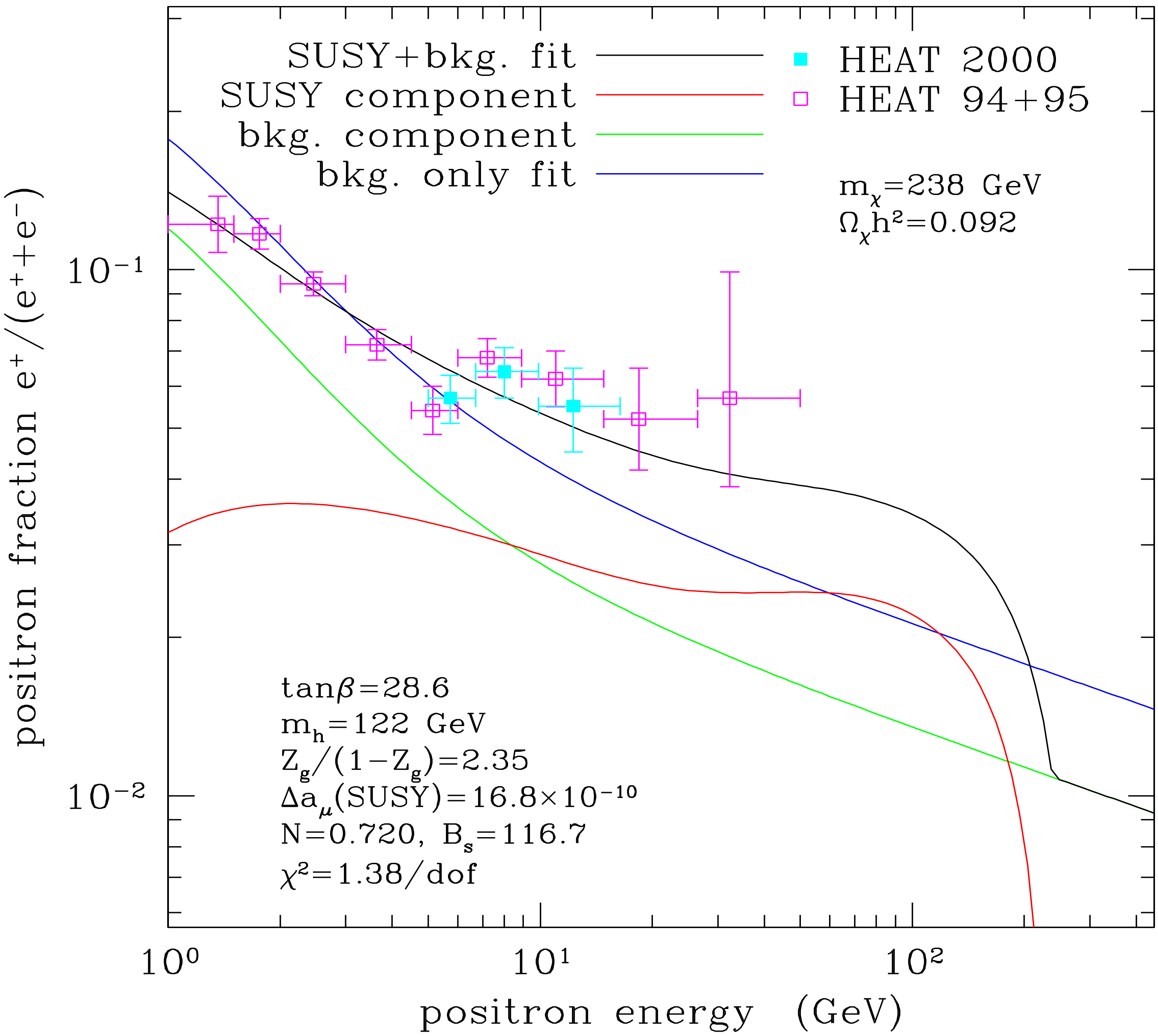


Bump at ~10 GeV seen with different instruments

Interpretation in terms of SUSY DM

Baltz et al. astro-ph/0109318

Fits require "boost factor" to enhance signal (plausible for clumpy DM)



What do you need to see an anomalous positron signal?

At ~ 10 GeV,
get 1 e^- for ~100 p,
get few e^+ for 100 e^-

=> need **excellent $e^{+/}$p separation**

Misidentification rate must be < 1 in 10^5

To achieve this:

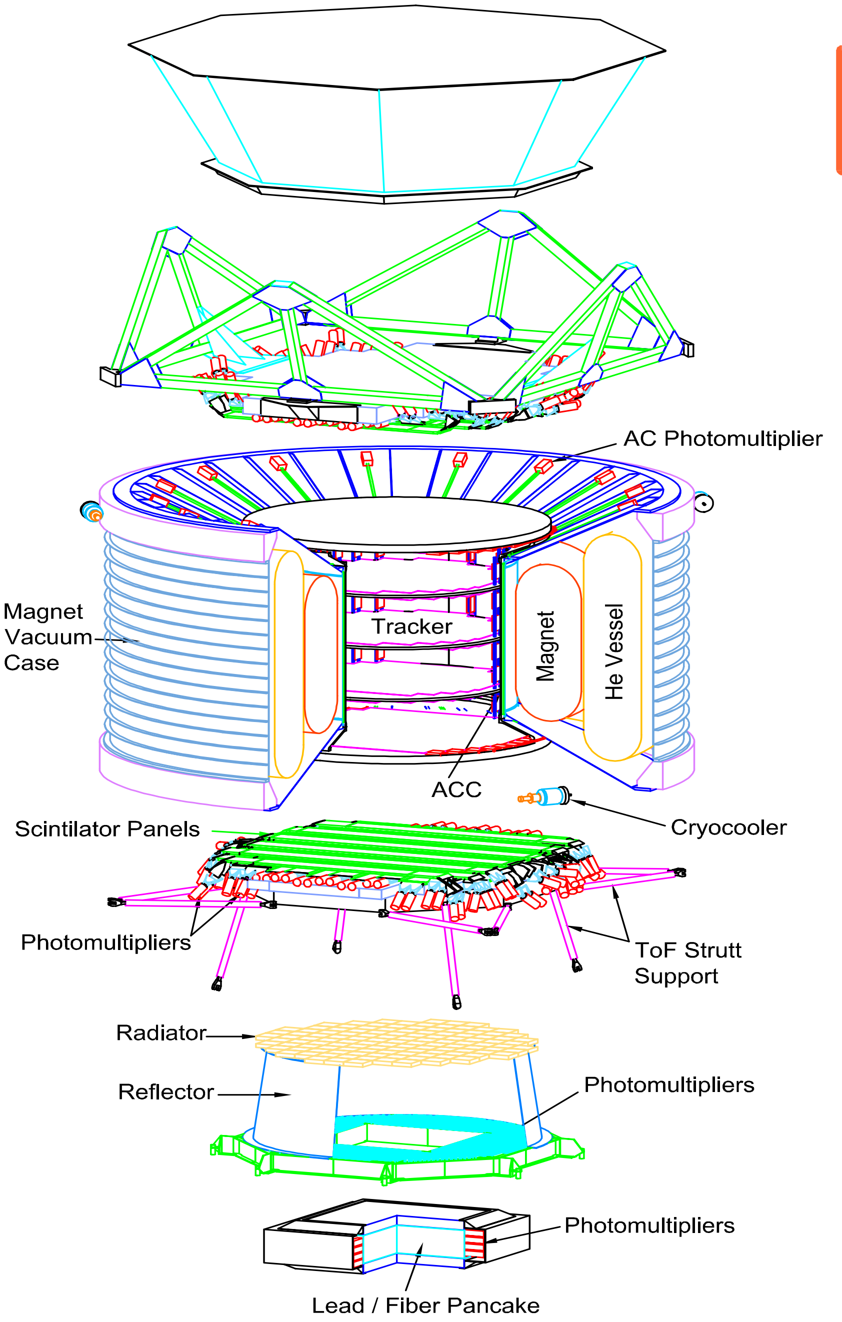
TRANSITION RADIATION DETECTOR (TRD)

proton rejection ~10^3

ELECTROMAGNETIC CALORIMETER (ECAL)

proton rejection ~10^3

AMS-02 Exploded View



TRD:
Transition Radiation
Detector

Truss Structure
SRD,TRD,ToF Support

ToF: (s1,s2)
Time of Flight Detector

TR:
Silicon Tracker

ACC:
Anticoincidence Counter
(veto Counter)

MG: Magnet
CC: Cryocooler

ToF: (s3,s4)
Time of Flight Detector

RICH:
Ring Image Cherenkov
Counter

EMC:
Electromagnetic
Calorimeter

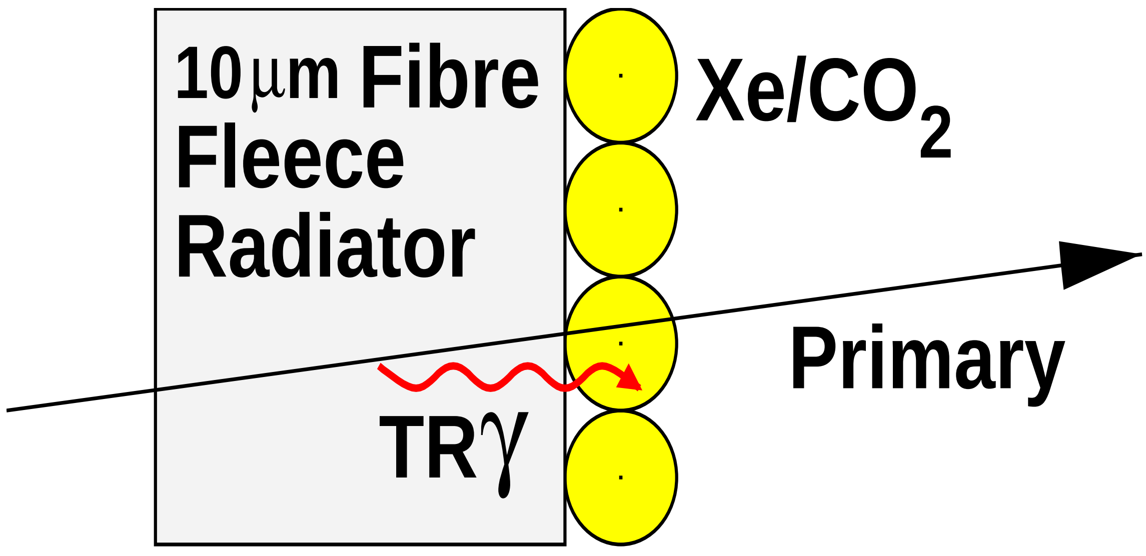
R. Becker

AMS-02 Transition Radiation Detector (TRD)

Transition radiation is produced when particles cross boundaries between materials with different dielectric properties

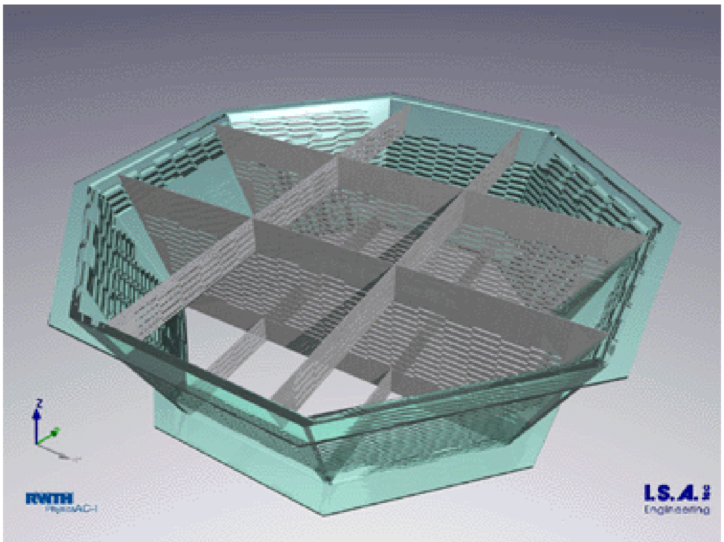
Significant for relativistic $\gamma = E/m >\sim 1000$

At >~ GeV energies,
electrons produce TR x-rays
protons do not



The AMS-02 TRD

20 layers of fleece radiators
(many dielectric interfaces)
-> 50% probability of TR photon per layer for few GeV electrons

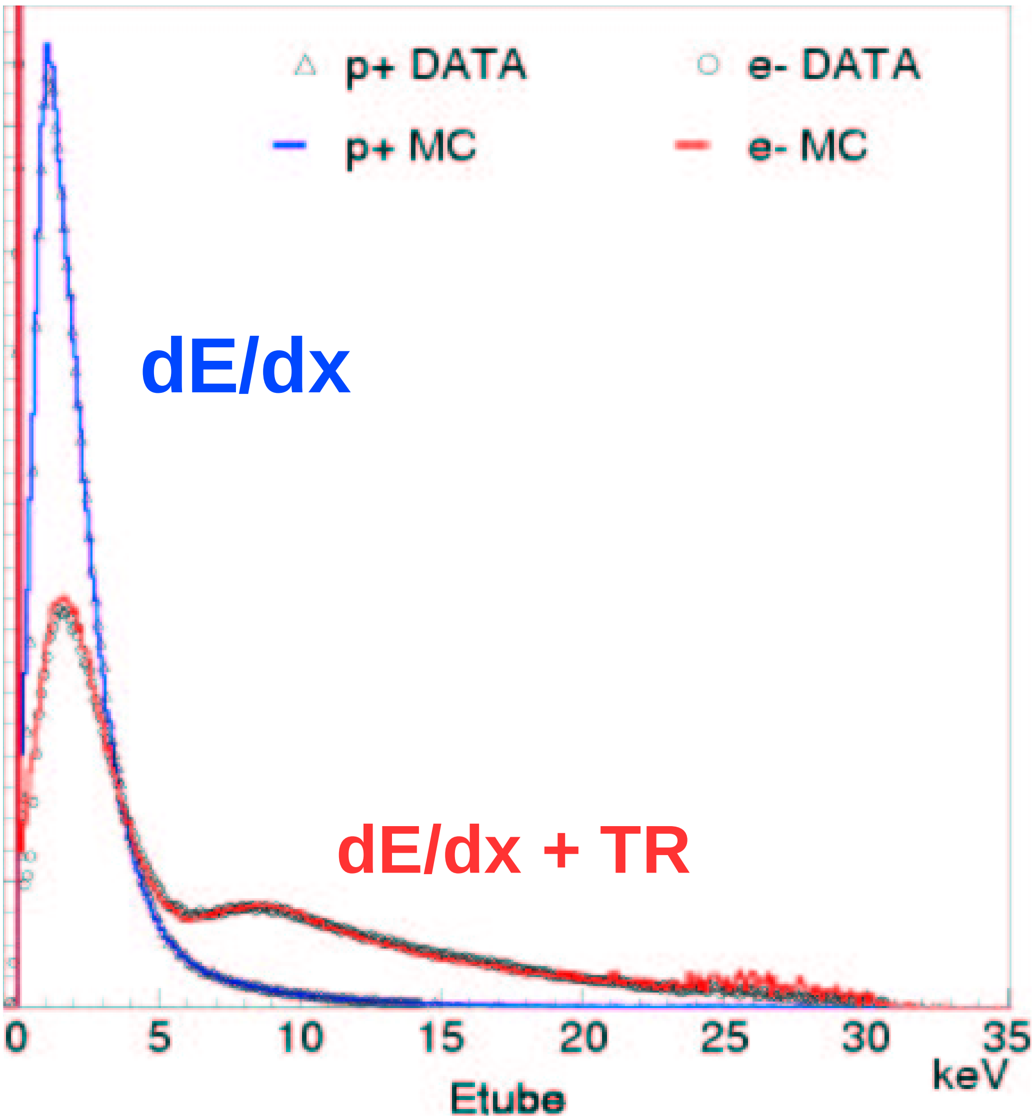


carbon fiber octagonal structure

20 layers of Xe/CO_2 filled straw tubes for dE/dx, TR x-ray detection

TRD Beam Test Data

Tube hit energy distribution



J. Orboeck , RWTH Aachen

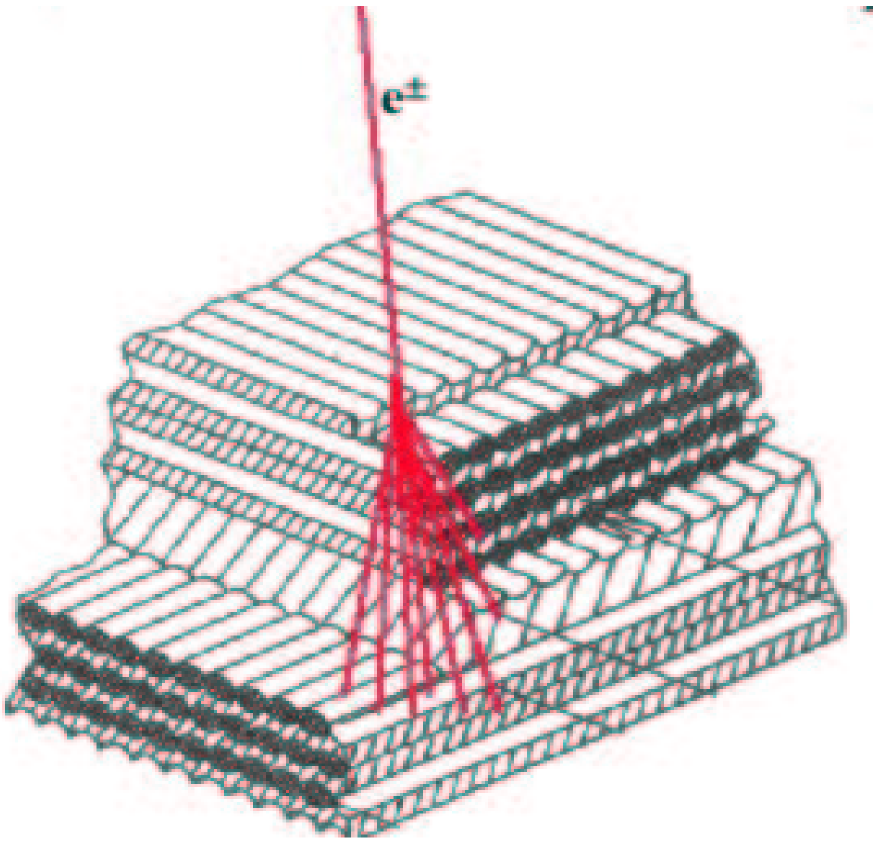
Protons and positrons are well separated; p rejection~10^3 in 20 layers

AMS-02 Electromagnetic Calorimeter (ECAL)

3D sampling calorimeter

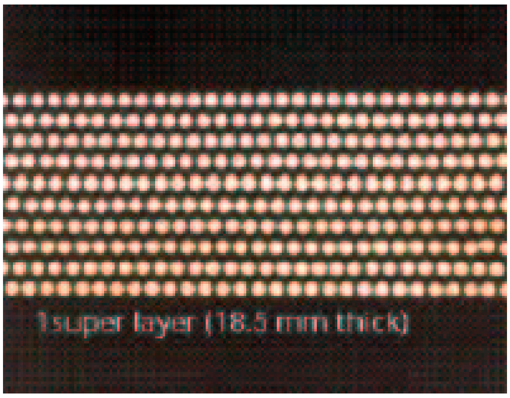
Protons and electrons create *showers with different shapes,* so they can be distinguished

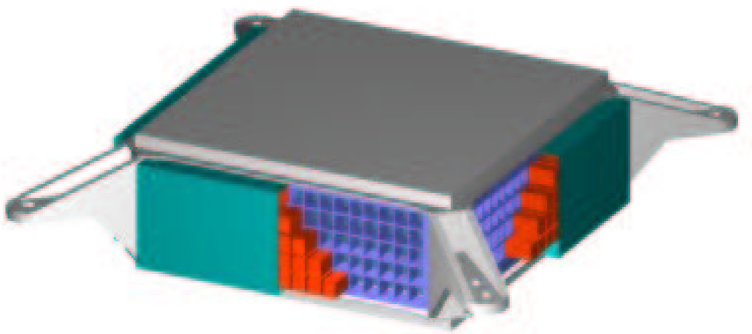
Sandwiched layers
of lead and scintillating fiber

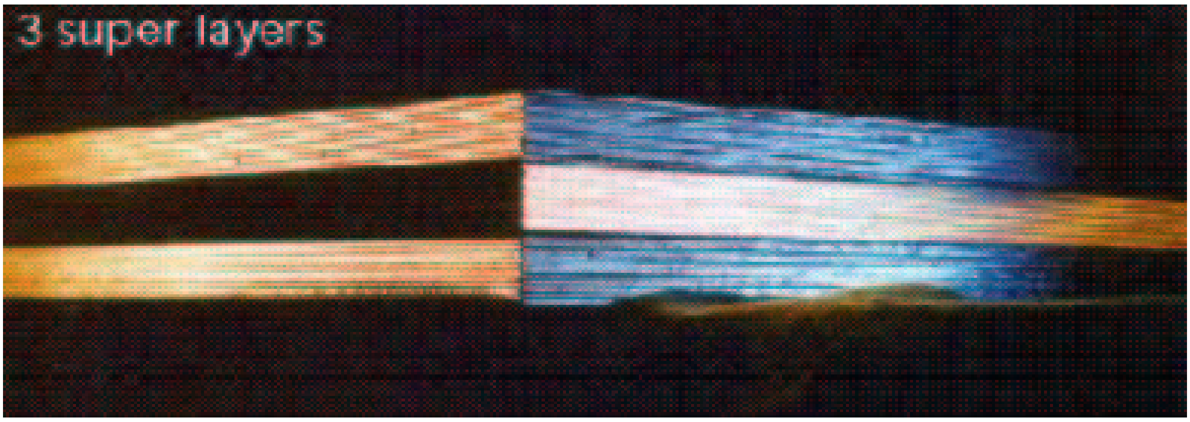


AMS-02 ECAL

9 superlayers of 10
fiber/lead planes each,
alternate in x and y
Scintillating fibers viewed by PMTs
Total radiation lengths: 15 X_0

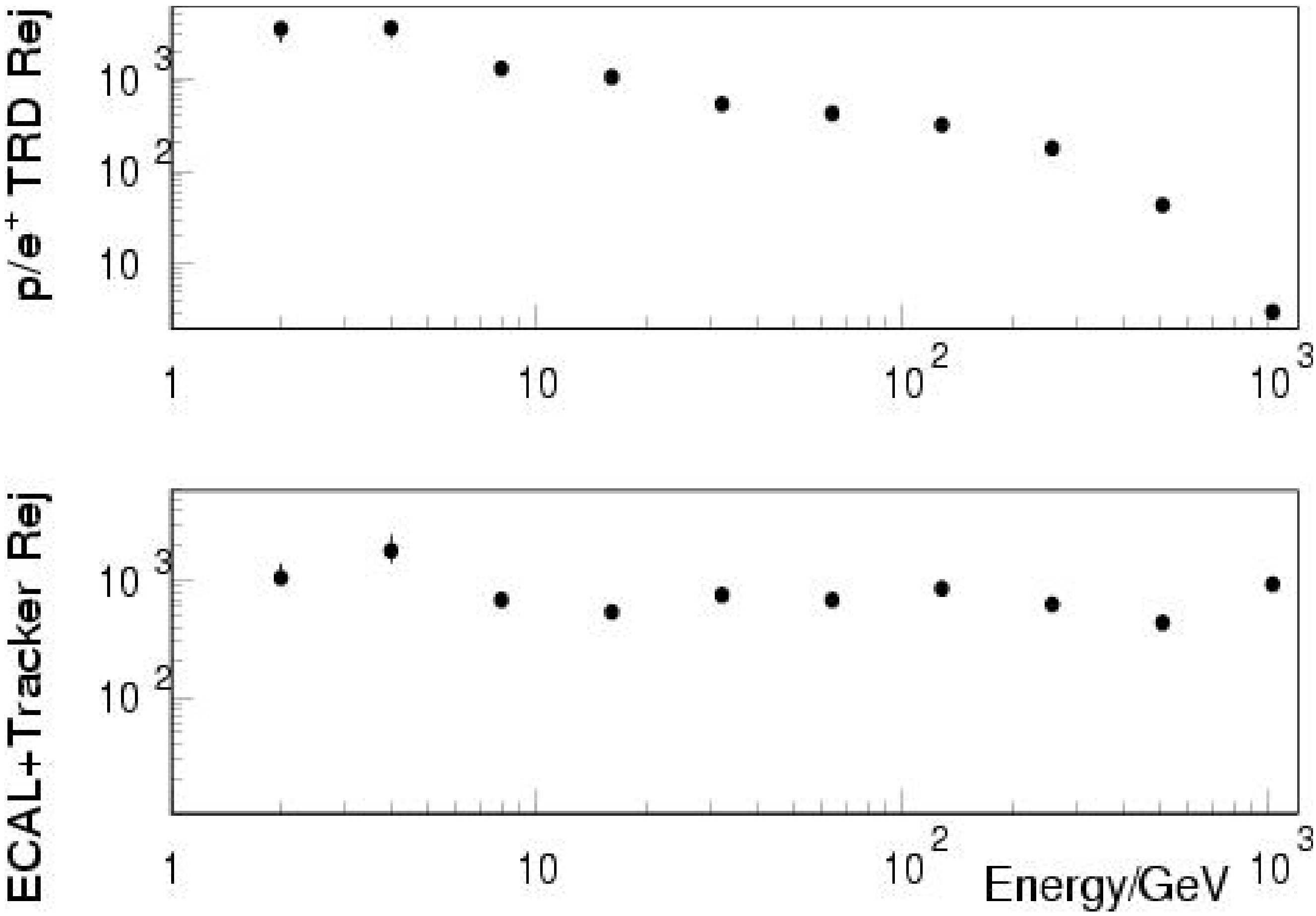






Expect proton rejection $\sim 10^3$

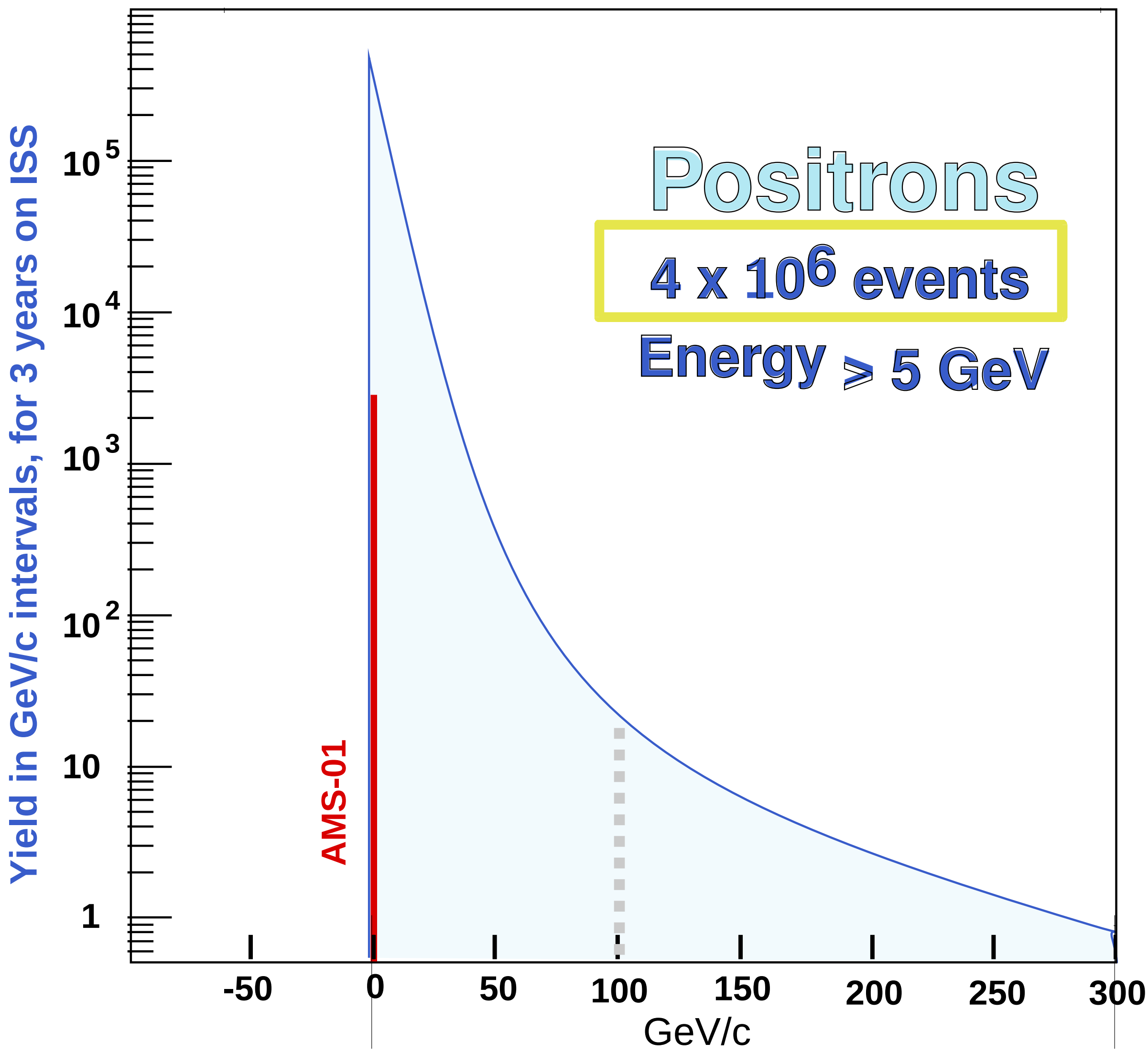
Proton rejection with TRD and ECAL



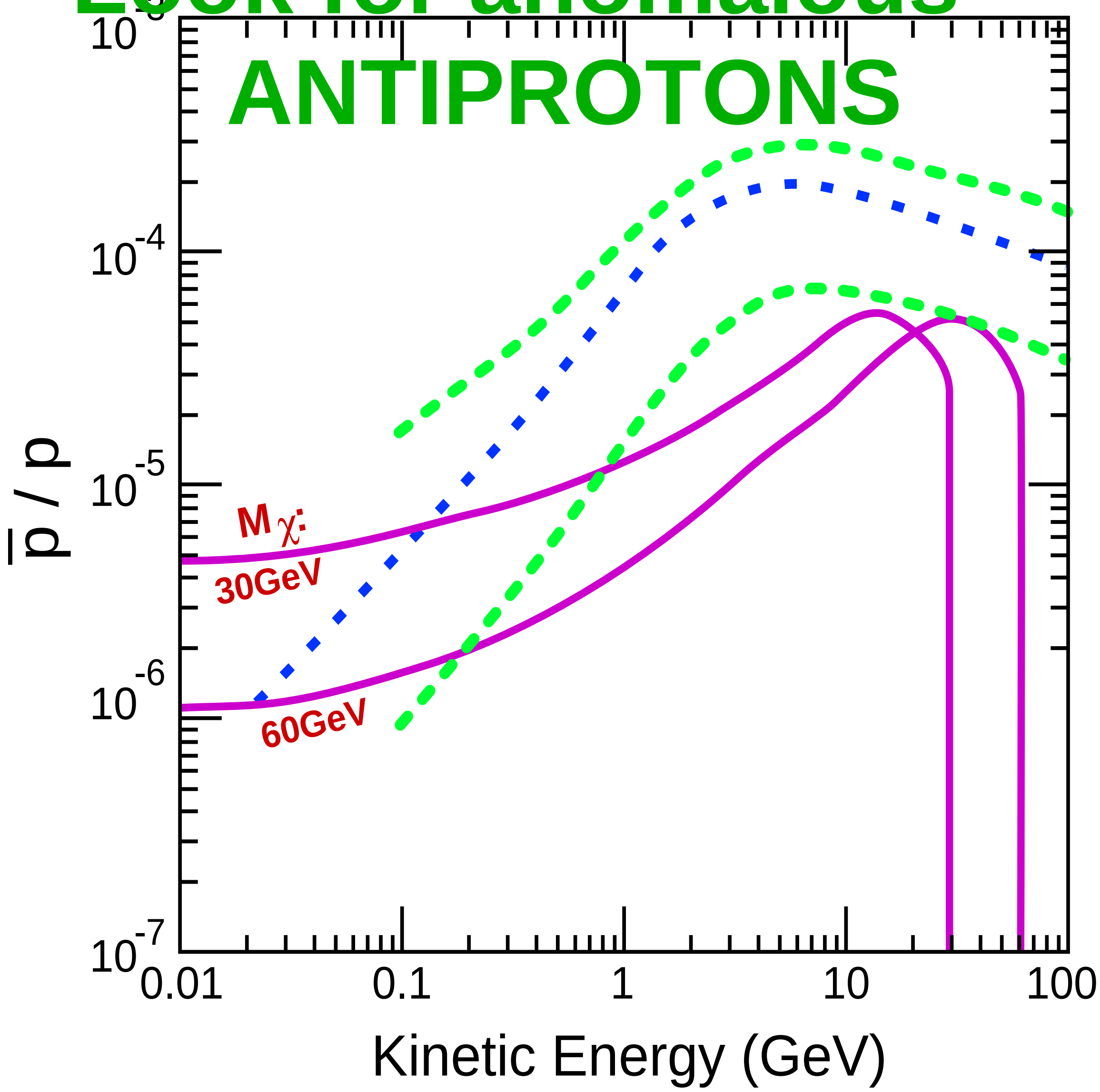
T. Siedenburg, RWTH Aachen

Excellent rejection in regime of interest for SUSY DM

AMS-02 Expected Positron Yield in 3 years



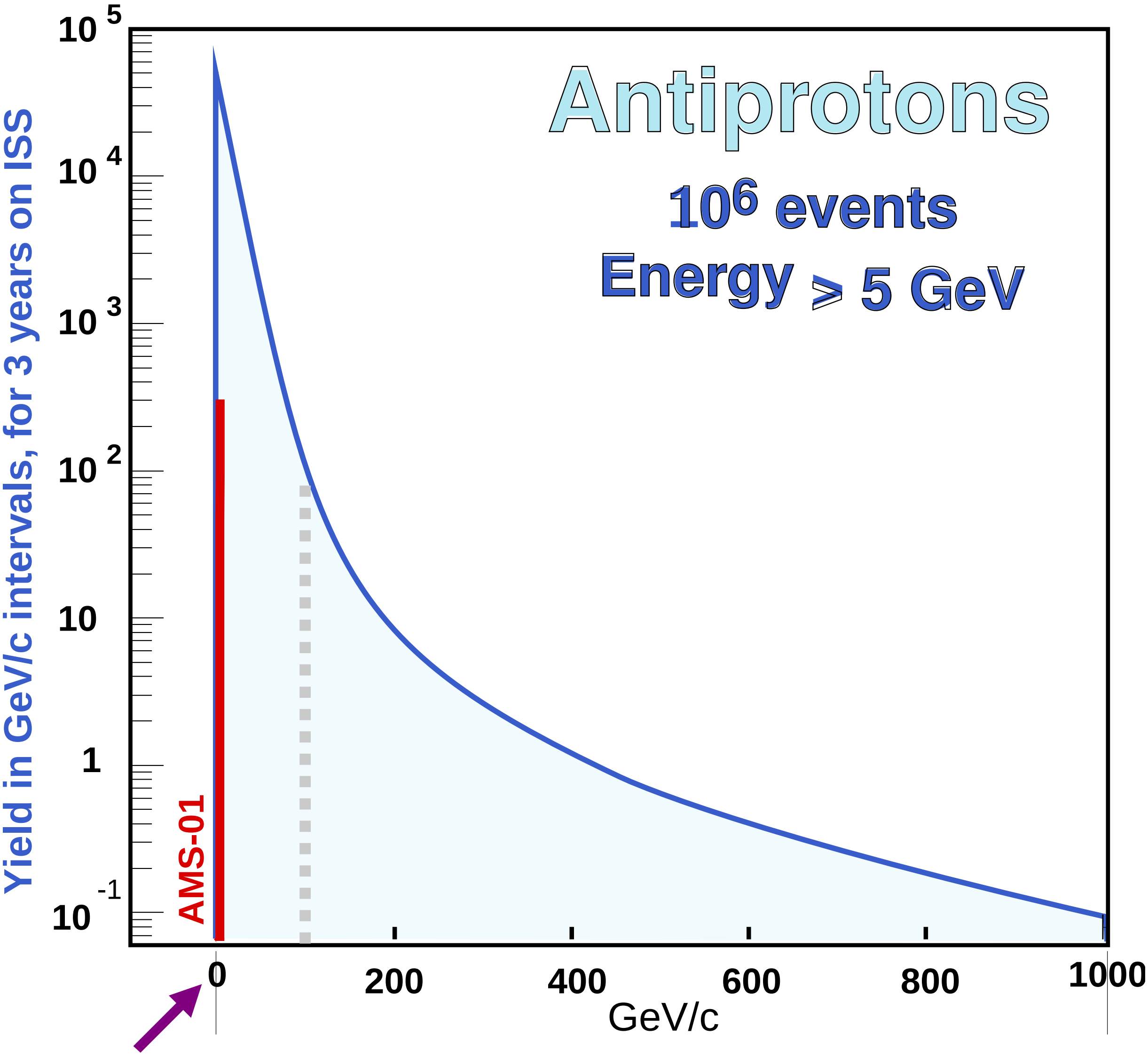
Look for anomalous ANTIPROTONS



In this case, low energies may have less background

y96

AMS-02 Expected Antiproton Yield in 3 years



SUSY DM signal at low energy, below geomagnetic cutoff

=> but will better understand CR background models

Can also look for
$\chi\chi$ annihilation via
γ-ray products

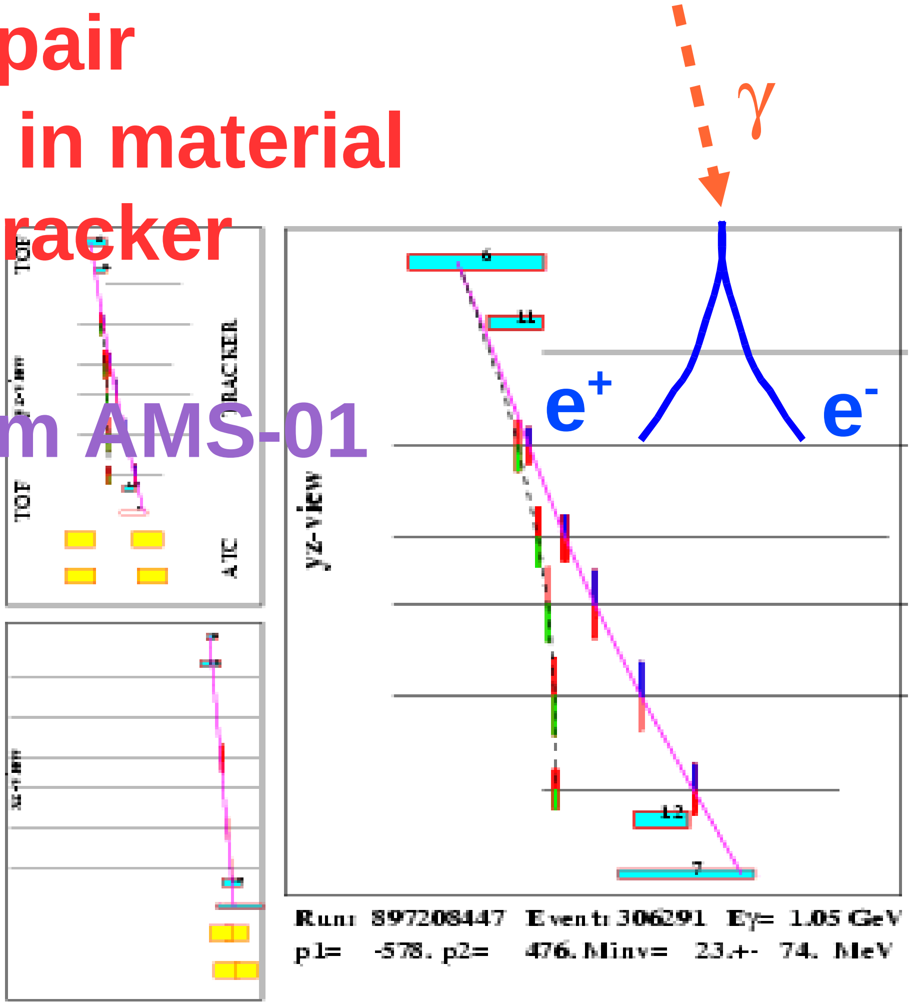
$\chi\chi \rightarrow$ [gauge bosons / quarks / leptons] $\xrightarrow{\text{hadronize}}$ γ's in showers

Continuum emission
at ~1/10 m_χ

Or, spectral line from
direct $\chi\chi$ -> γ's

AMS-02 has some γ-ray
detection capability

See γ's via pair production in material above the tracker



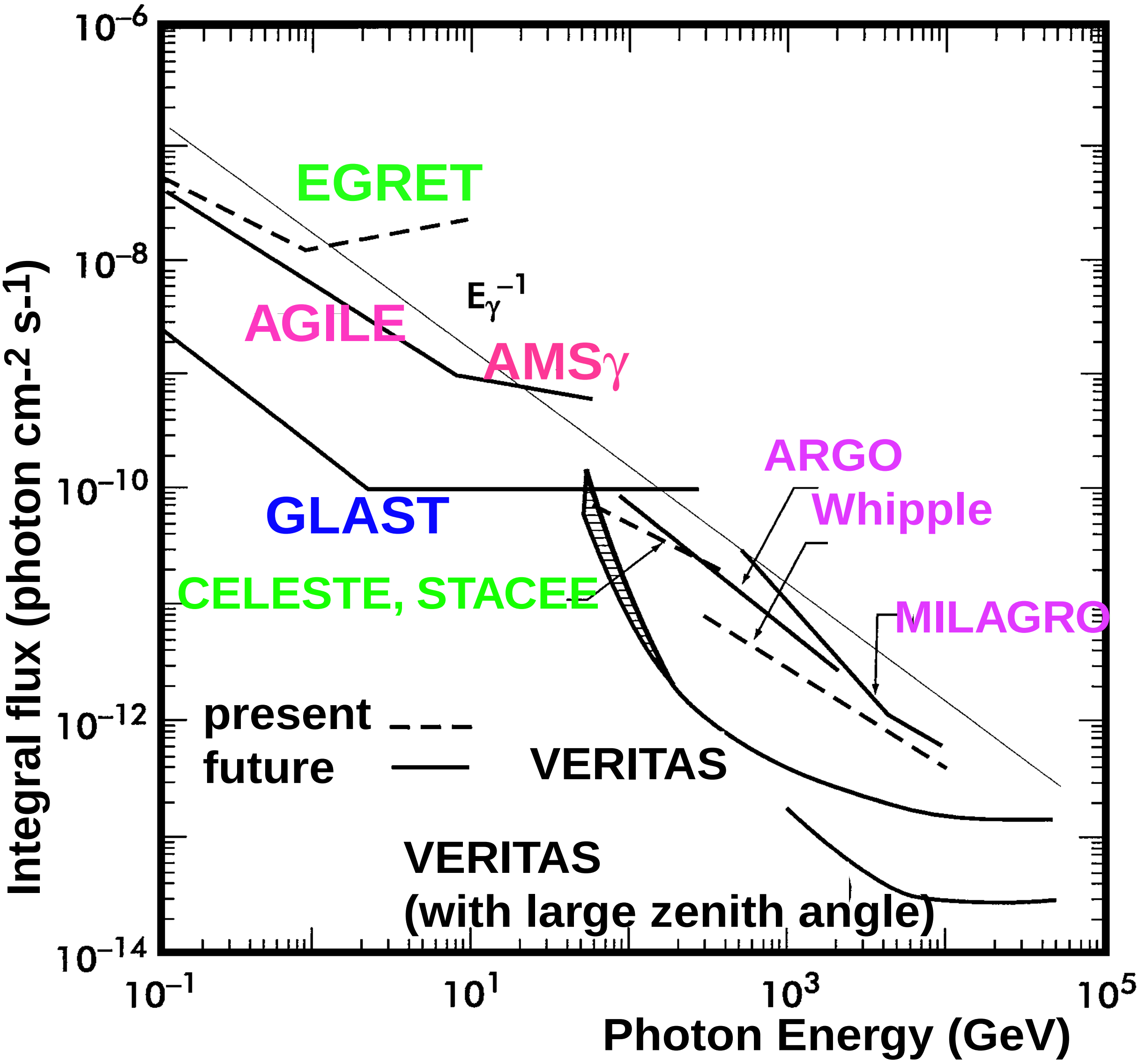
γ event from AMS-01

Also: γ -> em shower in ECAL

γ -> e^+e^-: ΔE/E~15%, $\sigma_\theta \sim 1/E_\gamma$

γ -> shower: ΔE/E~4%, $\sigma_\theta \sim 2^o$

AMS-02 Gamma Ray Sensitivity



- χχ annihilation γ's (some SUSY parameters)
- Astronomy: blazars, GRB's, diffuse flux

Note: can't point actively

Summary of AMS Dark Matter Search

AMS-02 is sensitive to non-baryonic dark matter (e.g. χ) via $\chi\chi$ annihilation products

Positrons in >~ 10 GeV range
- Hint from HEAT
- Need good proton rejection (TRD, ECAL)

Antiprotons in ~< 1 GeV range

Gamma rays in 10-100 GeV range
- (plus astrophysics)
- using tracker, ECAL

OUTLINE

Search for ANTIMATTER

AMS Introduction
AMS-01 Shuttle Mission
AMS-02 on the ISS

AMS-02 Instrumentation focus:
Magnet, Tracker, TOF, Veto

Search for DARK MATTER

AMS-02 Instrumentation focus:
TRD, ECAL

Search for OTHER EXOTIC MATTER

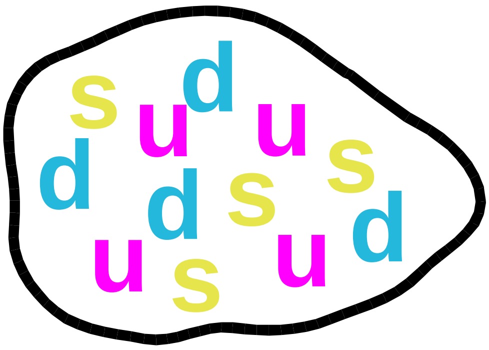
COSMIC RAY studies

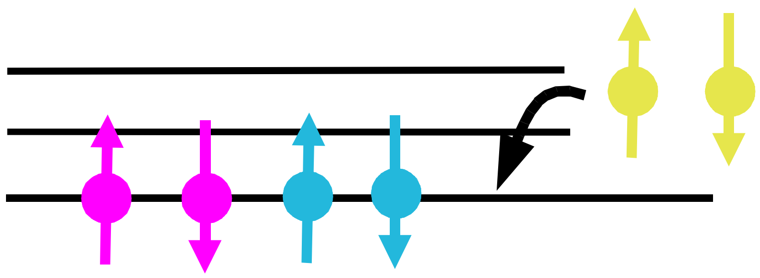
AMS-02 Instrumentation focus:
RICH

More exotic matter that AMS can look for:

"STRANGELETS"

mixtures of u,d,s quarks that may be stable, by virtue of low Fermi energy





Fit more *different* quarks in lowest available state

Strangelets may be stable, but how created?

Hard to create in laboratory
heavy ion collisions...
"making ice cubes in a furnace"

Probably were not created in early Universe (quark-hadron phase transition)

➔non-relativistic strangelets ruled out by CR experiments

➔also, unclear they could from in hot environment

BUT, strange quark matter could exist in

STRANGE STARS

made of quark matter

Possible strangelet component of cosmic ray flux create by collisions of strange stars?

$100 < A < 10^6$

Flux may be as high as 10^5 per year through AMS-02

J. Madsen

Would fragment in atmosphere

=> look in space

Expect $Z \sim 0.3\ A^{2/3}$

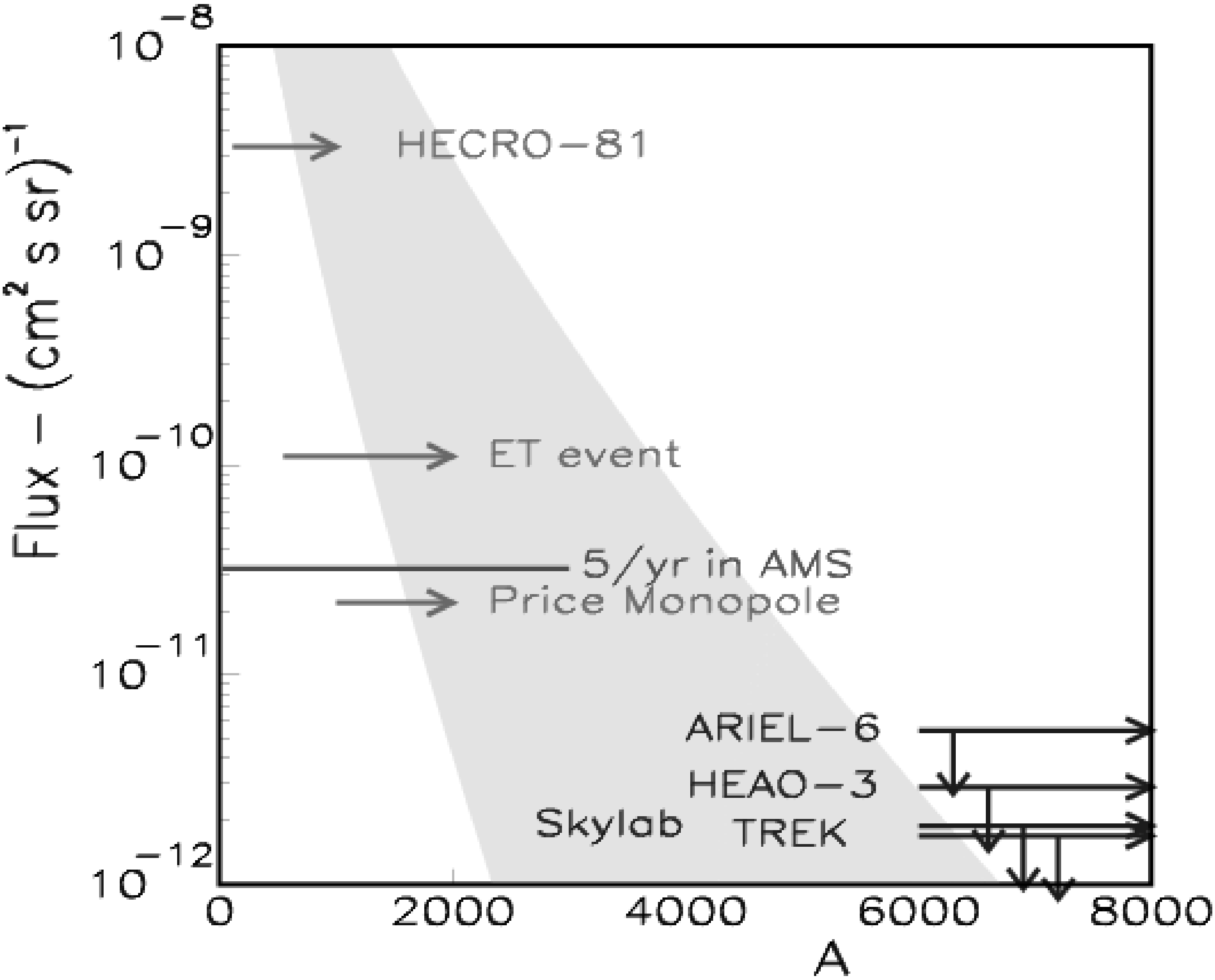
(nuclei: Z/A=0.33-0.67)

=> signature is anomalous Q/M

AMS-02 sensitive to 100<A<3000

Hints from previous CR experiments?

AMS-02 Sensitivity to Strangelets



Shaded region from rough estimate of strangelet creation and absorption in Galaxy **(Chikanian et al.)**

Finally: test

COSMIC RAY PROPAGATION

models by looking at light isotopes

"GALACTIC CHRONOMETERS"

e.g. ^{10}Be $t_{1/2} \sim 2 \times 10^6$ yr

^{9}Be stable

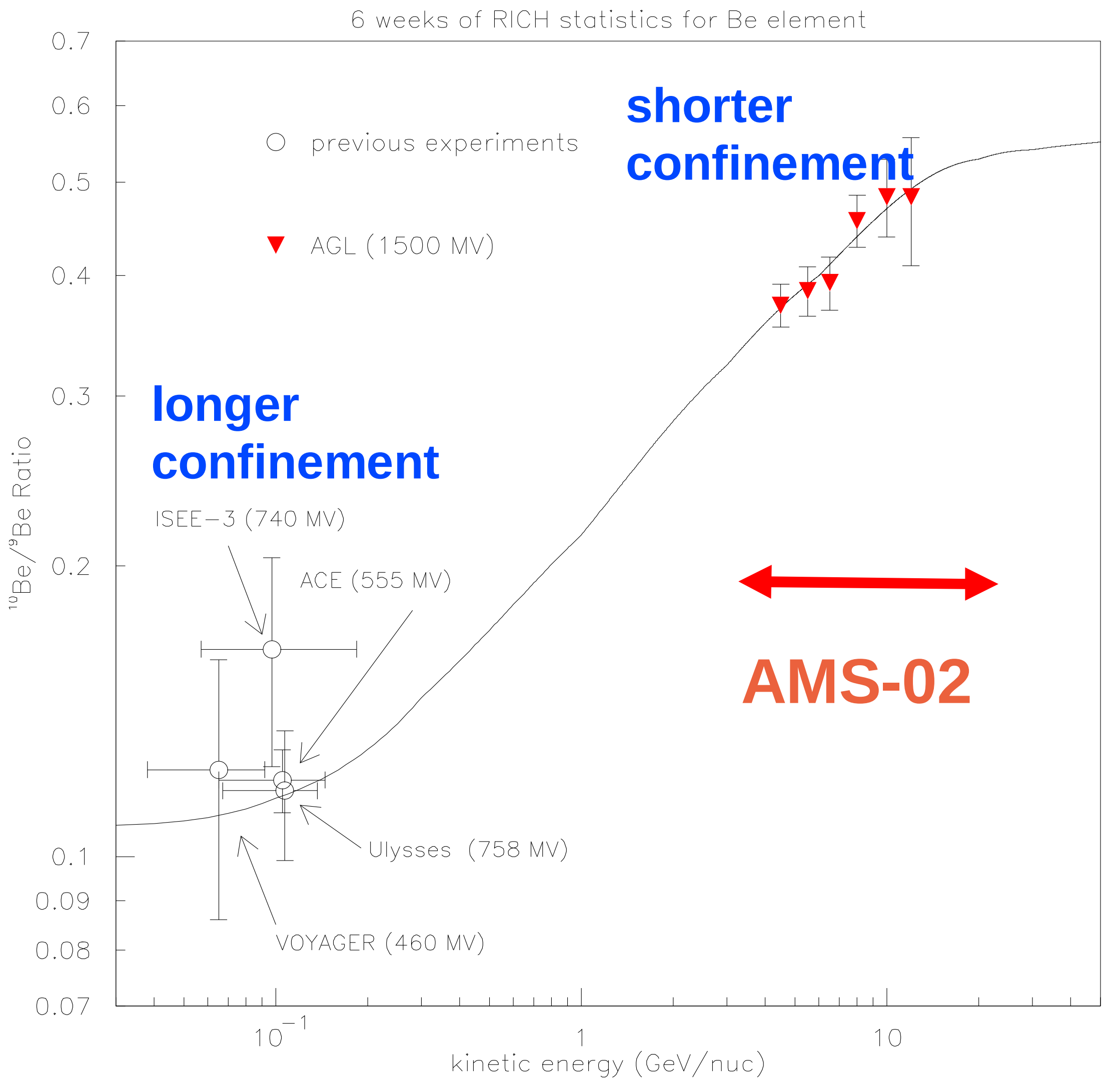
$^{10}Be/^{9}Be$ ratio measures Galactic confinement time

$^{10}Be/^{9}Be$ larger => shorter confinement

"Leaky Box Model"

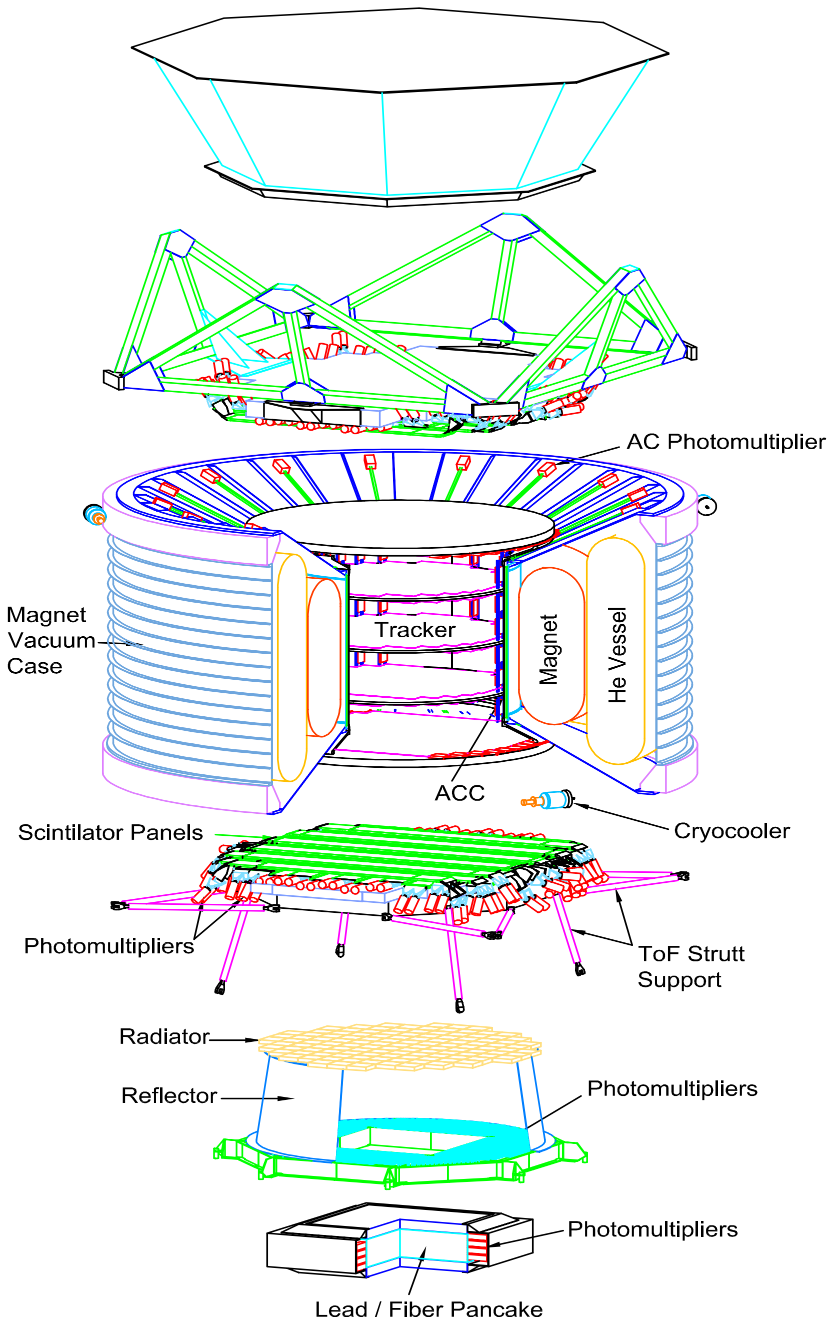
low energy CR trapped
high energy CR escape

Expect increase of $^{10}Be/^{9}Be$ with energy



AMS-02 can extend measurements to high energies

AMS-02 Exploded View



TRD:
Transition Radiation Detector

Truss Structure
SRD,TRD,ToF Support

ToF: (s1,s2)
Time of Flight Detector

TR:
Silicon Tracker

ACC:
Anticoincidence Counter
(veto Counter)

MG: Magnet
CC: Cryocooler

ToF: (s3,s4)
Time of Flight Detector

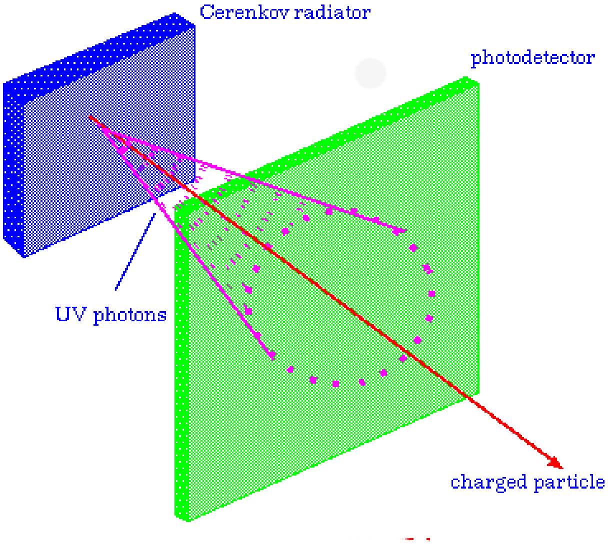
RICH:
Ring Image Cherenkov Counter

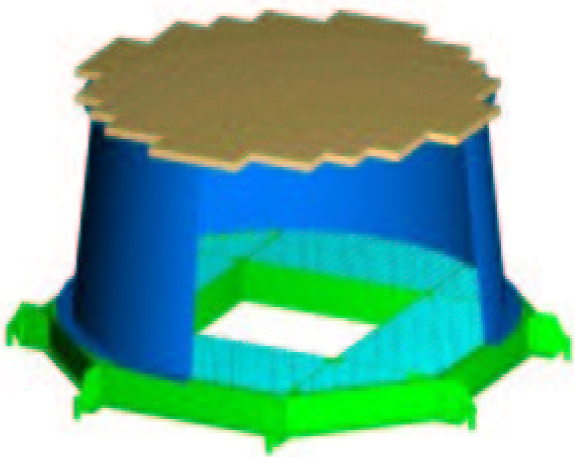
EMC:
Electromagnetic Calorimeter

R. Becker

AMS-02 Ring Imaging Cherenkov Detector (RICH)

Cherenkov radiation is emitted in a cone when a charged particle moves faster than the speed of light in a material

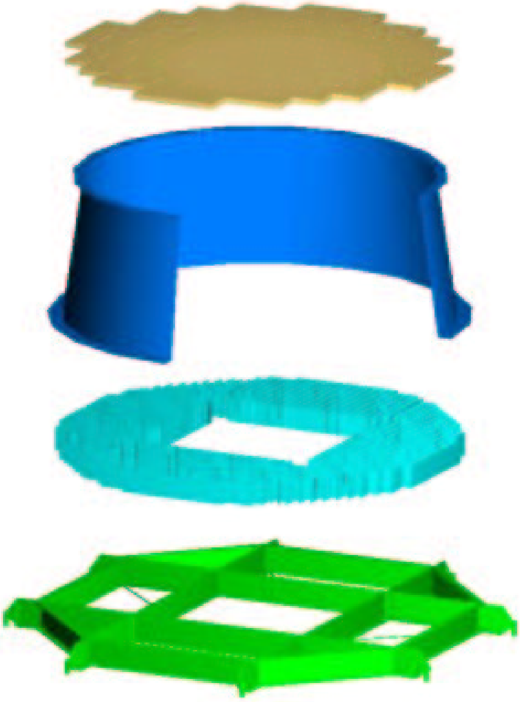




$$\cos\theta = \frac{1}{\beta n}$$

Precise velocity measurements from Cherenkov angle => measure mass

The AMS-02 RICH

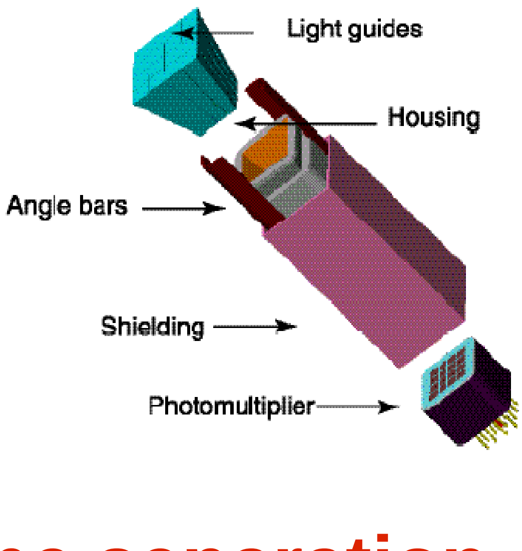


2 cm thick
aerogel radiator

reflector

1000 light guides
and
photomultipliers

Shielded
PMT



Achieve isotope separation
up to ~10 GeV/N, up to carbon

Summary of last two topics

STRANGELETS

Possibly stable quark matter
chunks in CR flux could be
formed by strange star collisons

Signature is anomalous Q/M

COSMIC RAY STUDIES

light isotope composition
sheds light on Galactic propagation

e.g $^{10}Be/^{9}Be$ ratio

AMS-02 RICH will help via
precise mass measurements to
10 GeV/nucleon

SUMMARY

AMS-02 will measure charged cosmic rays up to ~TeV energies for 3 years

ANTIMATTER SEARCH

AMS-01 $\overline{He}/He \sim 10^{-6}$

AMS-02 $\overline{He}/He \sim 10^{-9}$

DARK MATTER SEARCH

$\chi\chi$ annihilation -> e^{+}, $\overline{p}$, γ

STRANGE MATTER SEARCH

(and other exotic matter)

anomalous Q/M

COSMIC RAY PROPAGATION

light isotope abundances

THE UNEXPECTED??

Never been done before!