Etat actuel et Perspectives de la Physique d'Astro-Particule

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Cartigny
Journée de Reflexion
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- Introduction
  - History of Cosmic Ray Studies: Origin, Propagation, Spectrum, Composition
- Selected Experiments & Results
  - Ground-based Experiments
  - Balloons
  - Space-based Experiments
- Future Projects
- Conclusions

Introduction ... - History of CR

- First observation of Cosmic Rays (CR) by V.F. Hess (1912) in balloon flights
- Various topics of CR during history
  - Study of basic properties of *electricity and magnetism*
  - Then, *particle physics* before large accelerators: Discoveries of e^+, $\mu^\pm$, $\pi^\pm$, $K^\pm$, K^0, Λ^0, Δ, Ξ^-, $\Sigma^\pm$ all with CR's
  - Afterwards, *astrophysics* studying galactic sources of low energy CR's, magnetic fields in heliosphere and acceleration mechanisms in supernovae shockwaves
  - Today, *nuclear astrophysics* of stars/supernovae, *particle physics* in the TeV range, *cosmology* of microwave and IR background, *unexplored physics* at extremely high energies

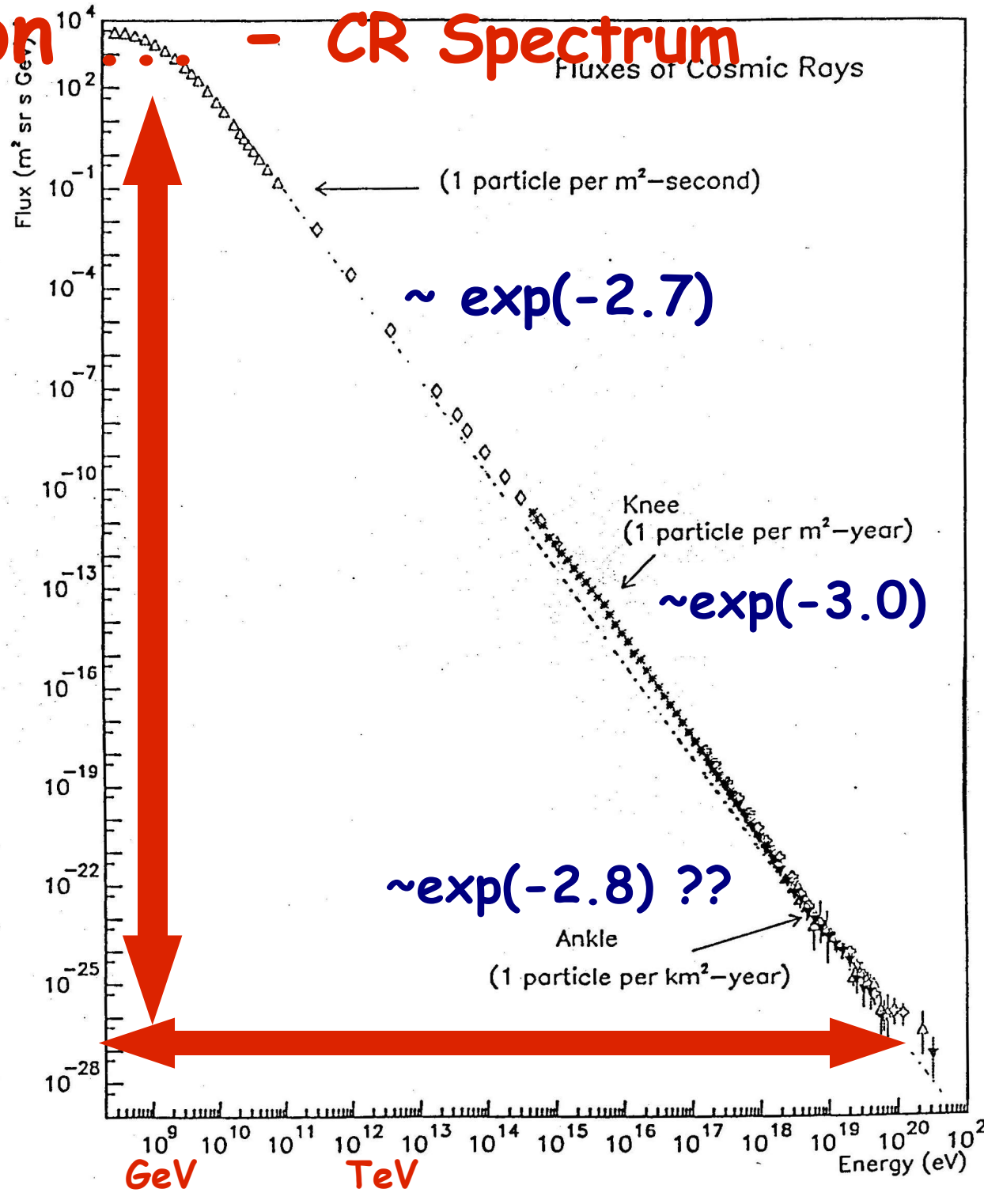
... Introduction ... - Goal

Two step process

- Understand and calibrate nature's beam (cosmic rays) by more measurements of *composition* and *spectra*, improved theory and simulation
- Search for new physics with promising discovery potential:
  - nuclear antimatter, strange states of matter
  - indirect search of dark matter using $\bar{p}$, $\bar{D}$, e^+ and γ rays
  - ultra heavy particle searches at extreme energies

... Introduction ... - CR Spectrum

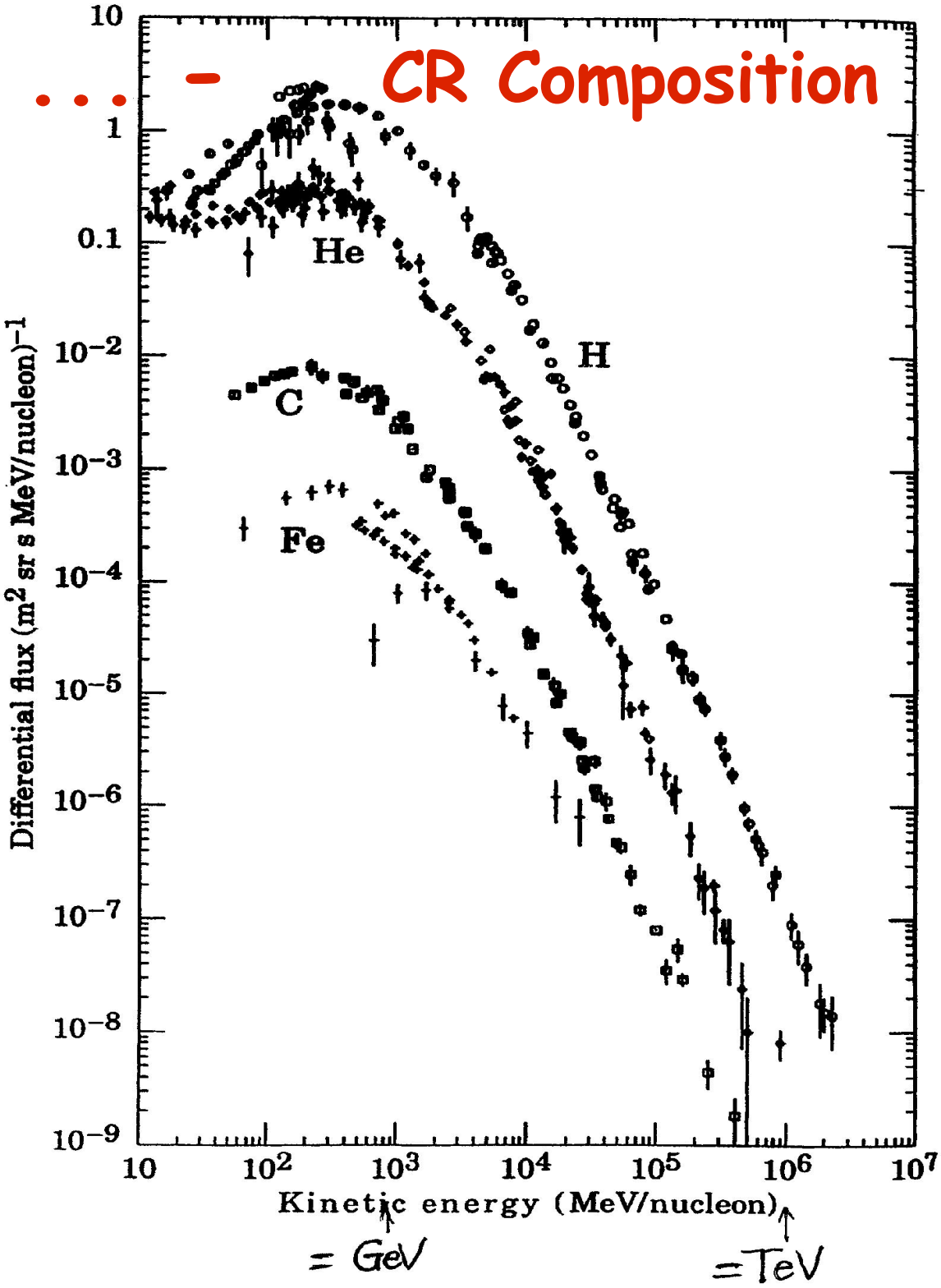
- Cosmic Rays (CR) from ~1 GeV
- produced and accelerated in supernovae explosions
- >12 orders in Energy
- >30 orders in Flux
- Power law
- Knee region not yet well understood:
  - Acceleration mechanism
  - Propagation mechanism
  - Elementary composition
  - a new particle
- Ankle region stat. limited



... Introduction ...

- p and He nuclei are dominant (90% p, 9% He)
- All elements are present up to Uranium
- Atoms reach heliosphere fully ionized
- Absolute fluxes and spectrum shapes are fundamental for calculation of atmospheric ν fluxes

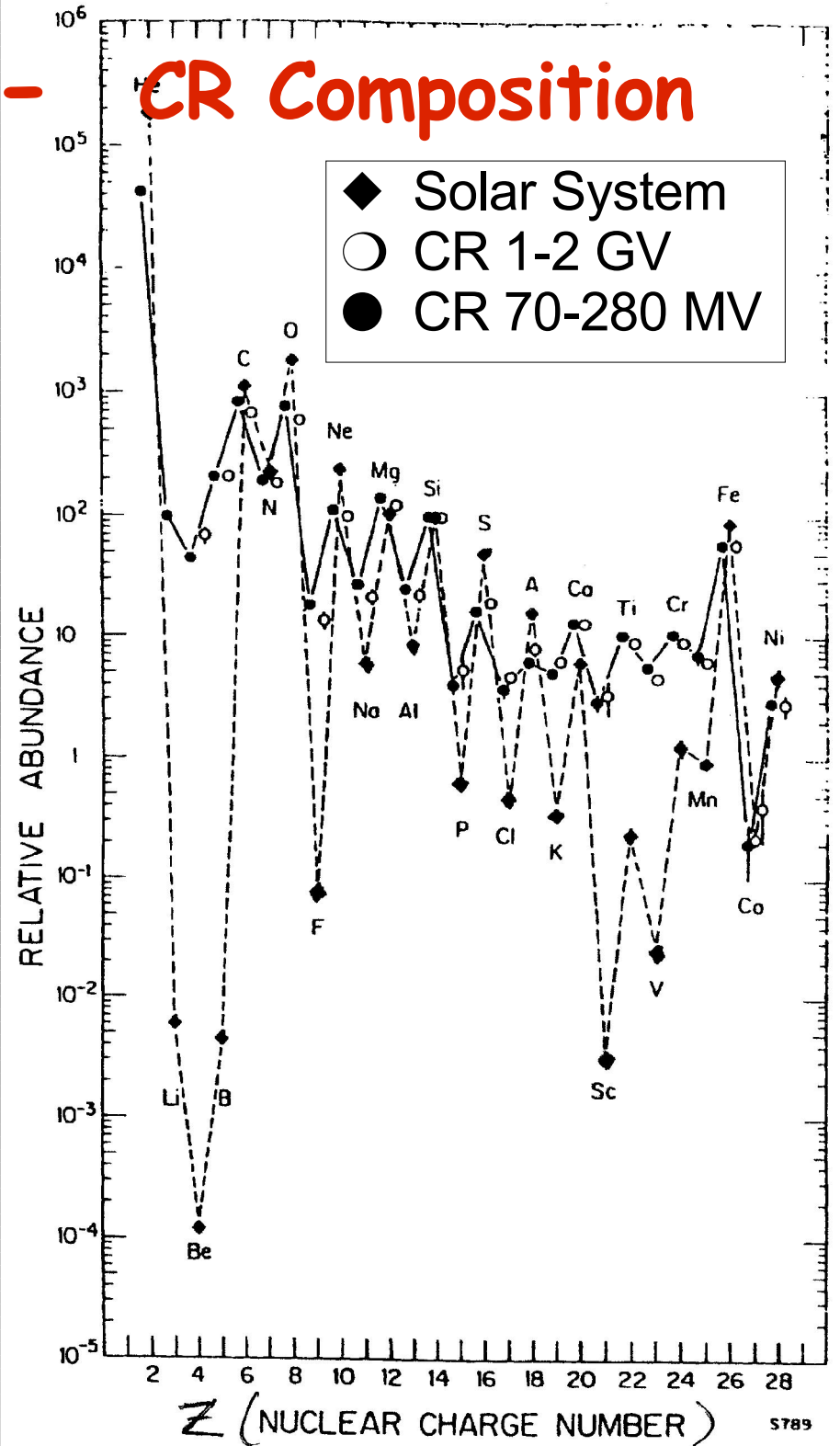
- CR Composition



... Introduction ...

- Chemical composition of CR similar to solar elements, but:
  - 1) Li, Be, B enriched
  - 2) Sc, Ti, V, Cr, Mn enriched
- These ions (apart Li) are not produced in primordial nucleo-synthesis, nor in stars
  - 1) produced by spallation reactions between p, α with C, N, O in supernovae explosions
  - 2) spallation from Fe, produced in interstellar medium

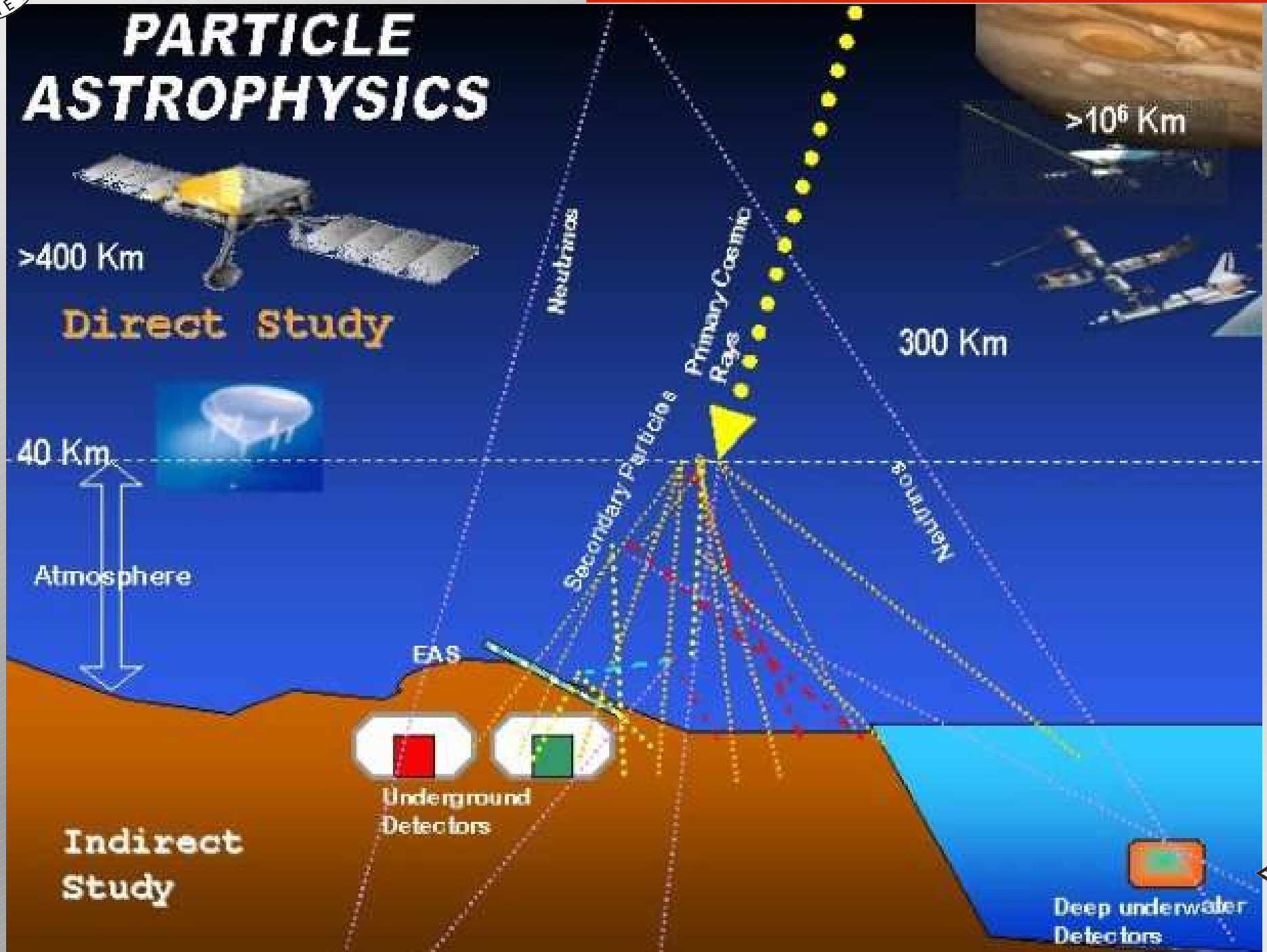
- CR Composition



... Introduction ... - GCR Acceleration

- Shockwave Acceleration in Supernovae explosions
  - diffusive shock acceleration:
    repeated acceleration while travelling through interstellar medium (ISM)
  - BUT: Upper limit of energy of 10^{13}-10^{14} eV
- Acceleration to higher energies needs further models
- More data could help to clarify these issues
- GCR's also need to propagate through ISM
  - different models: LBM, DHM
  - no time to discuss here

... Introduction



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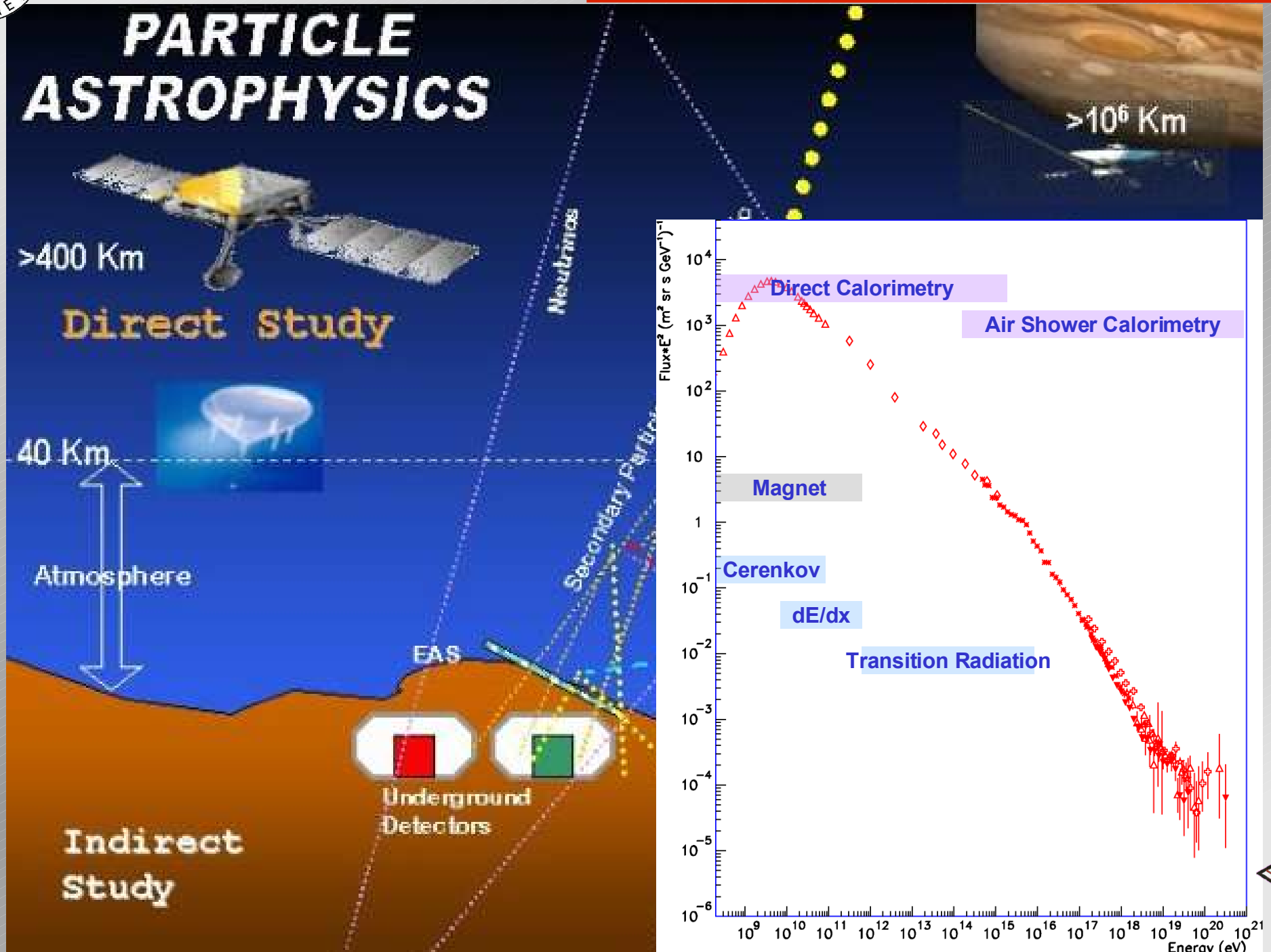


. . . Introduction

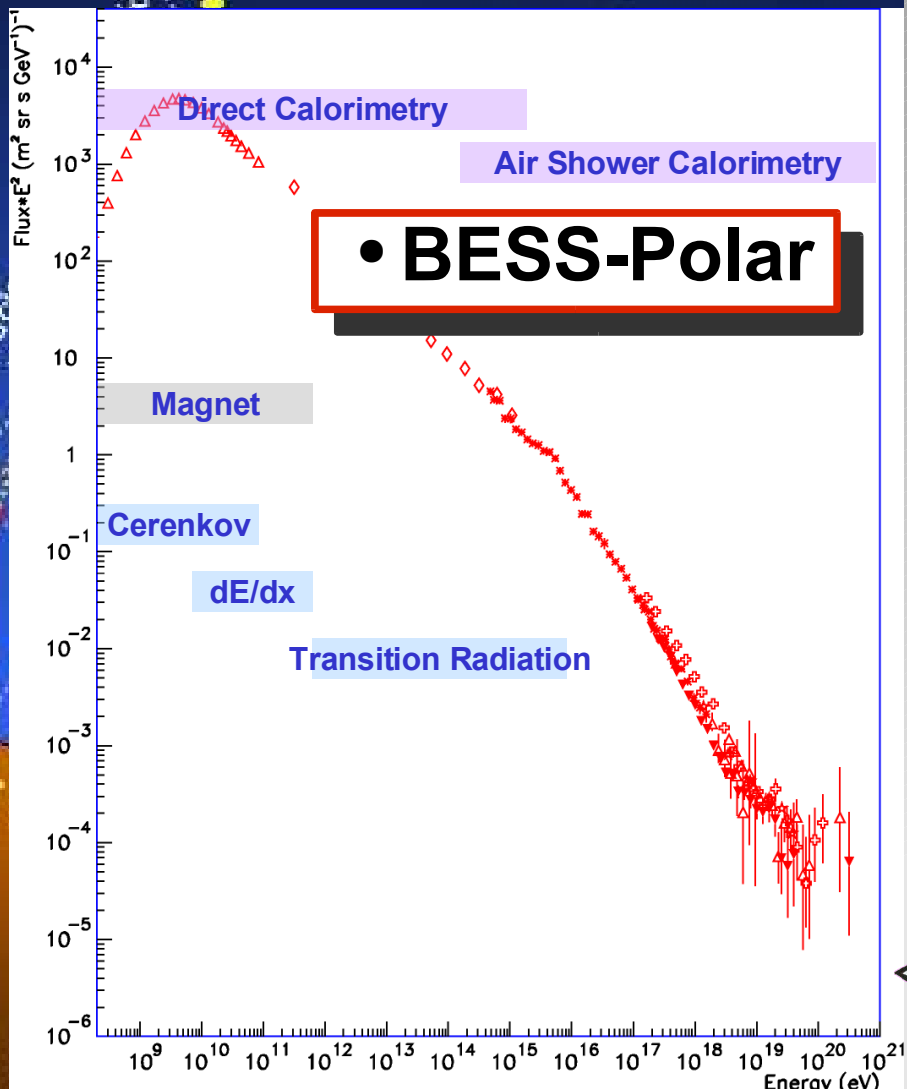
- AMS-01

- PAMELA
- AMS-02

- BESS
- RUNJOB
- ATIC

- BESS-Polar

- L3+C
- AUGER (EA)



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- AMS-01

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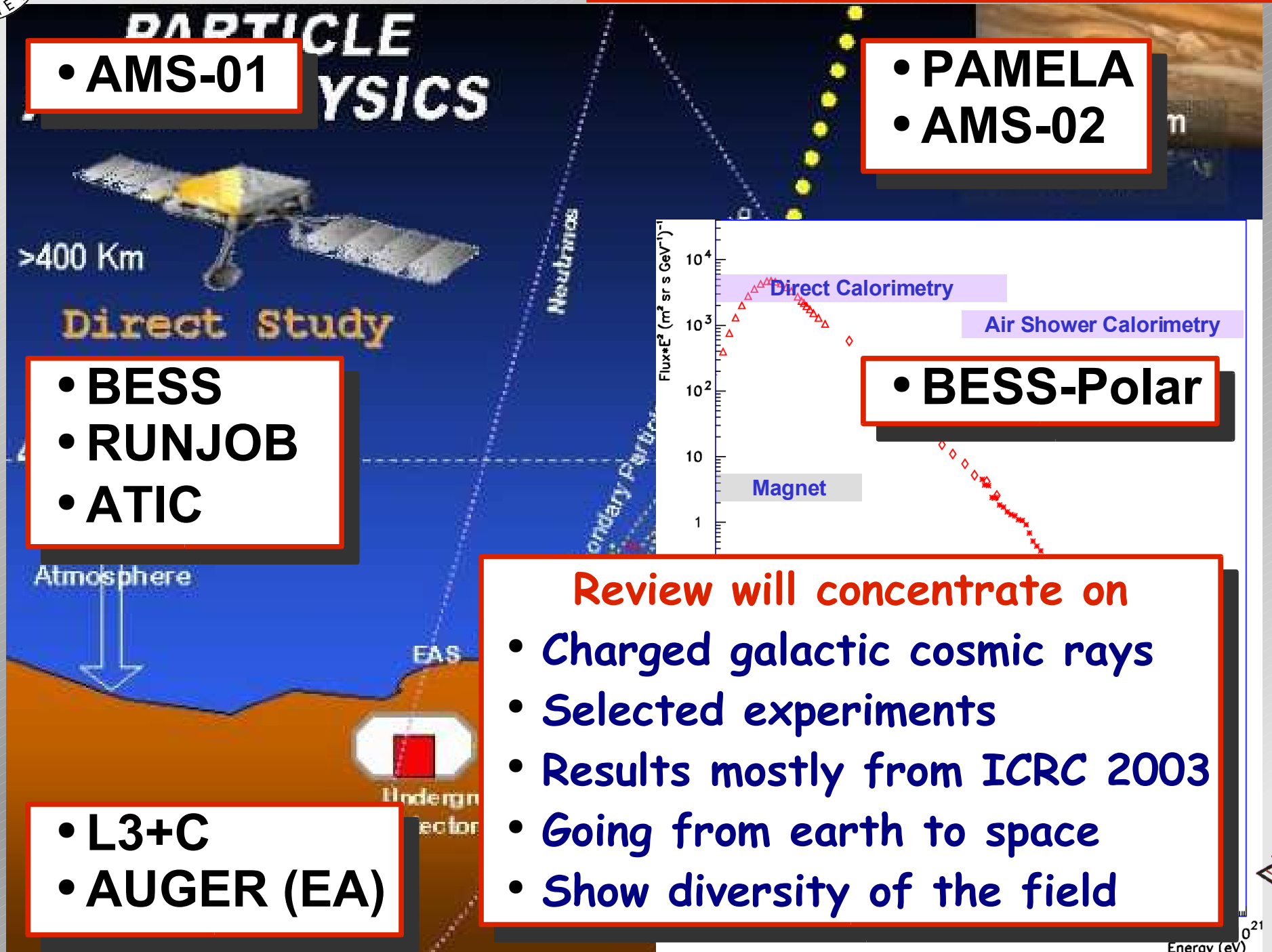

- BESS
- RUNJOB
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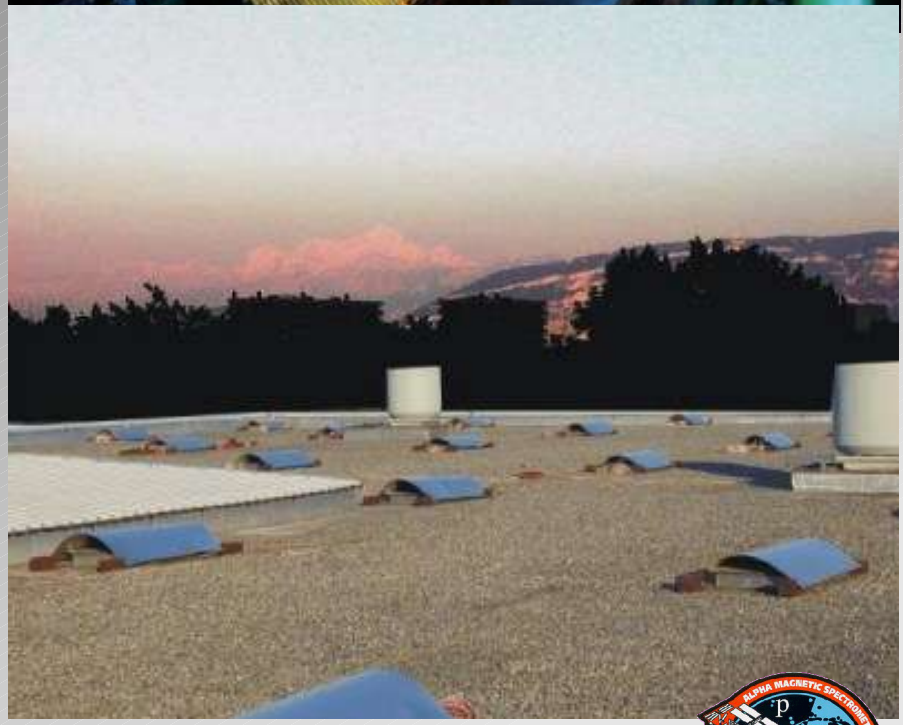
Review will concentrate on

- Charged galactic cosmic rays
- Selected experiments
- Results mostly from ICRC 2003
- Going from earth to space
- Show diversity of the field

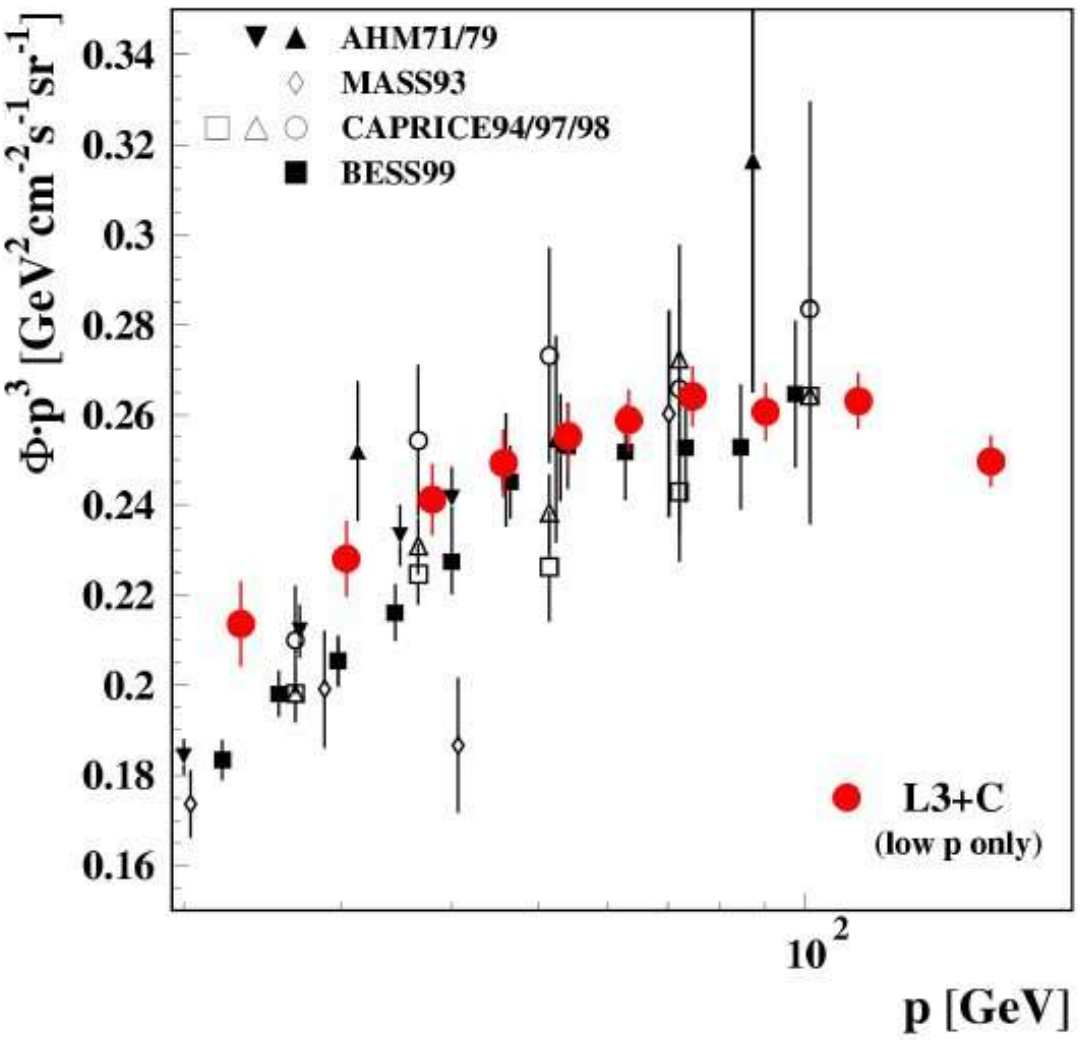
Selected Results (Ground) - L3 cosmics

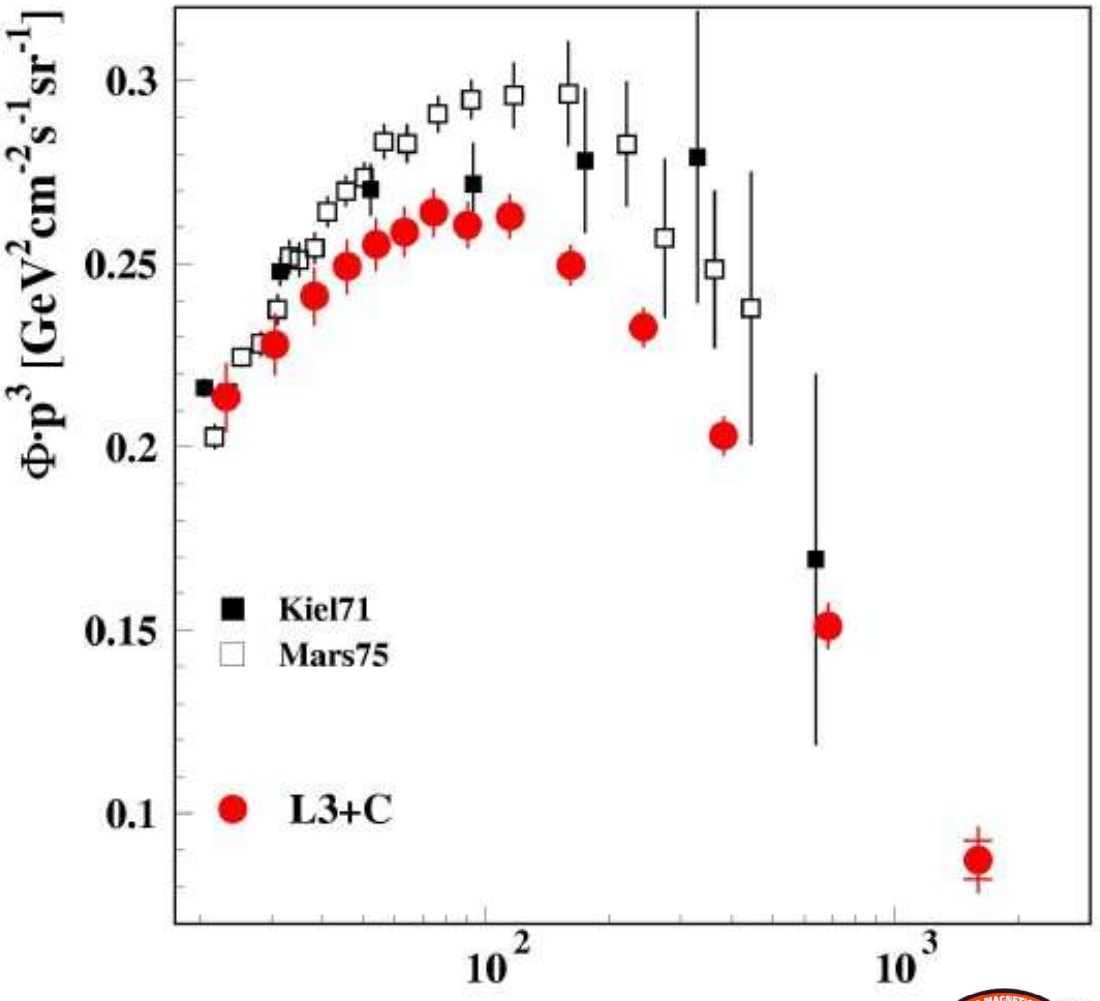
- Apparatus
  - L3-detector (0.5 T Magnet)
    High-precision drift chambers,
    202 m^2 of scintillators
  - Air-shower detectors
    50 scintillators
    covered area 30m x 54m
- Physics
  - μ-momentum spectra,
    charge ratio and angular dep.
  - limits on primary antiprotons
    ~1 TeV using the Moon shadow
  - primary cosmic-ray composition
  - Search for bursts, exotic events



Selected Results (Ground) - L3 cosmics

- μ-Momentum spectrum from L3+C



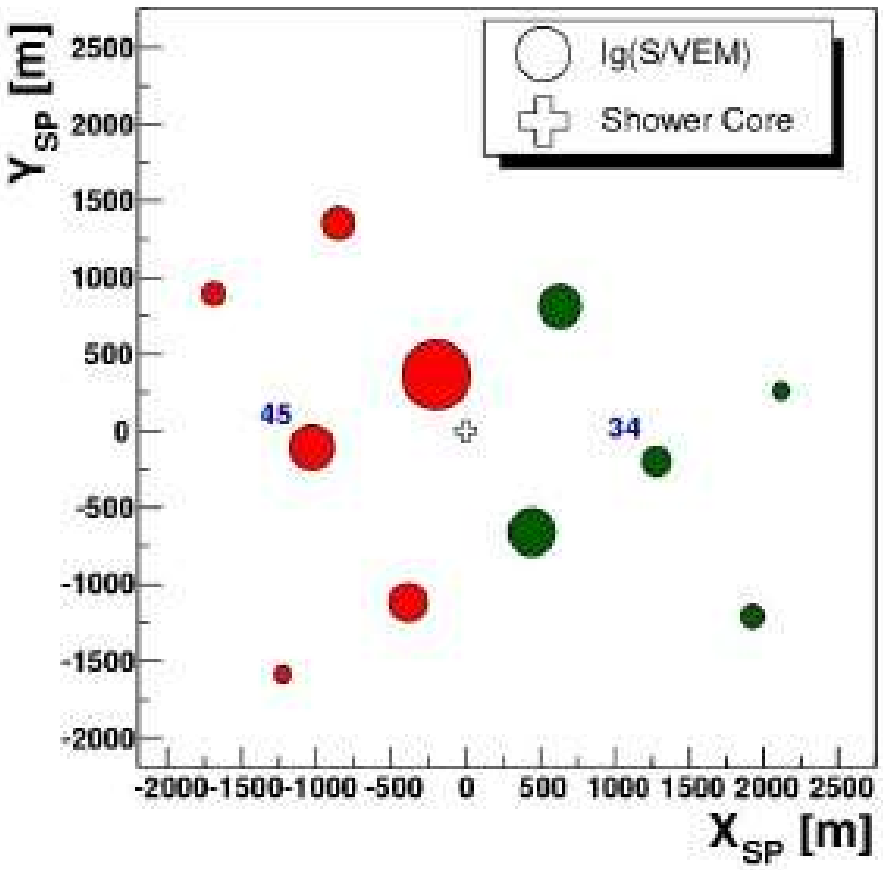


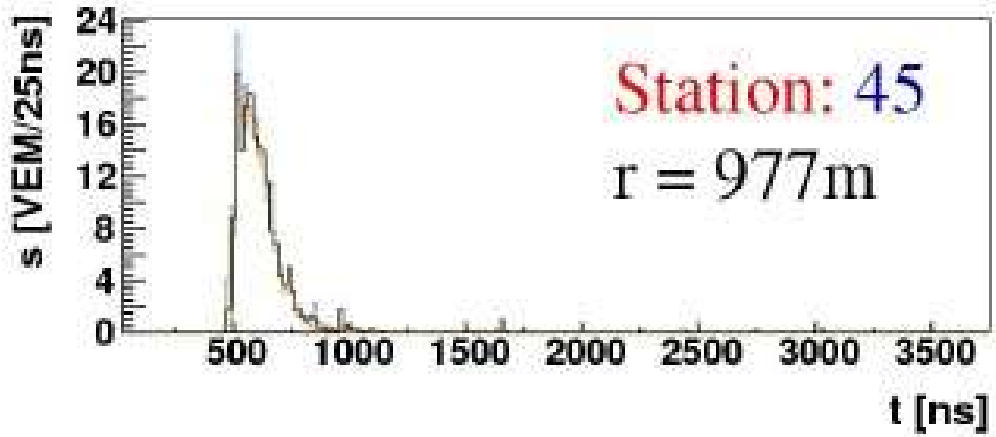
Selected Results (Ground) - Auger

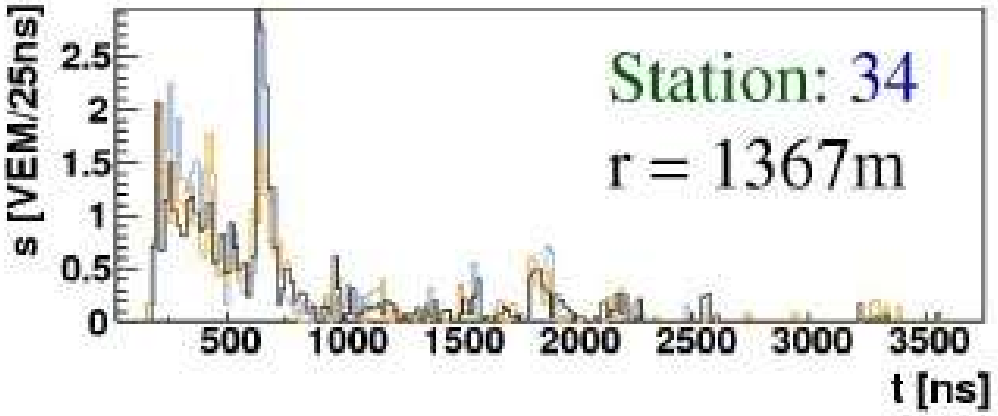
- Apparatus
  - full-sky coverage 7350 km^2sr
  - 24 fluorescence detectors
  - final configuration:1600 water tanks to cover 3000 km^2
  - Setup started in 1999 nearby Mendoza, Argentina (-2005)
  - Engineering array: 40 tanks, 2 prototype telescopes

- Physics
  - CR studies above 10^{19} eV as a function of Z
  - study events above GZK-cutoff (absorption by cosmic microwave background) and trace them back!

Selected Results (Ground) - Auger



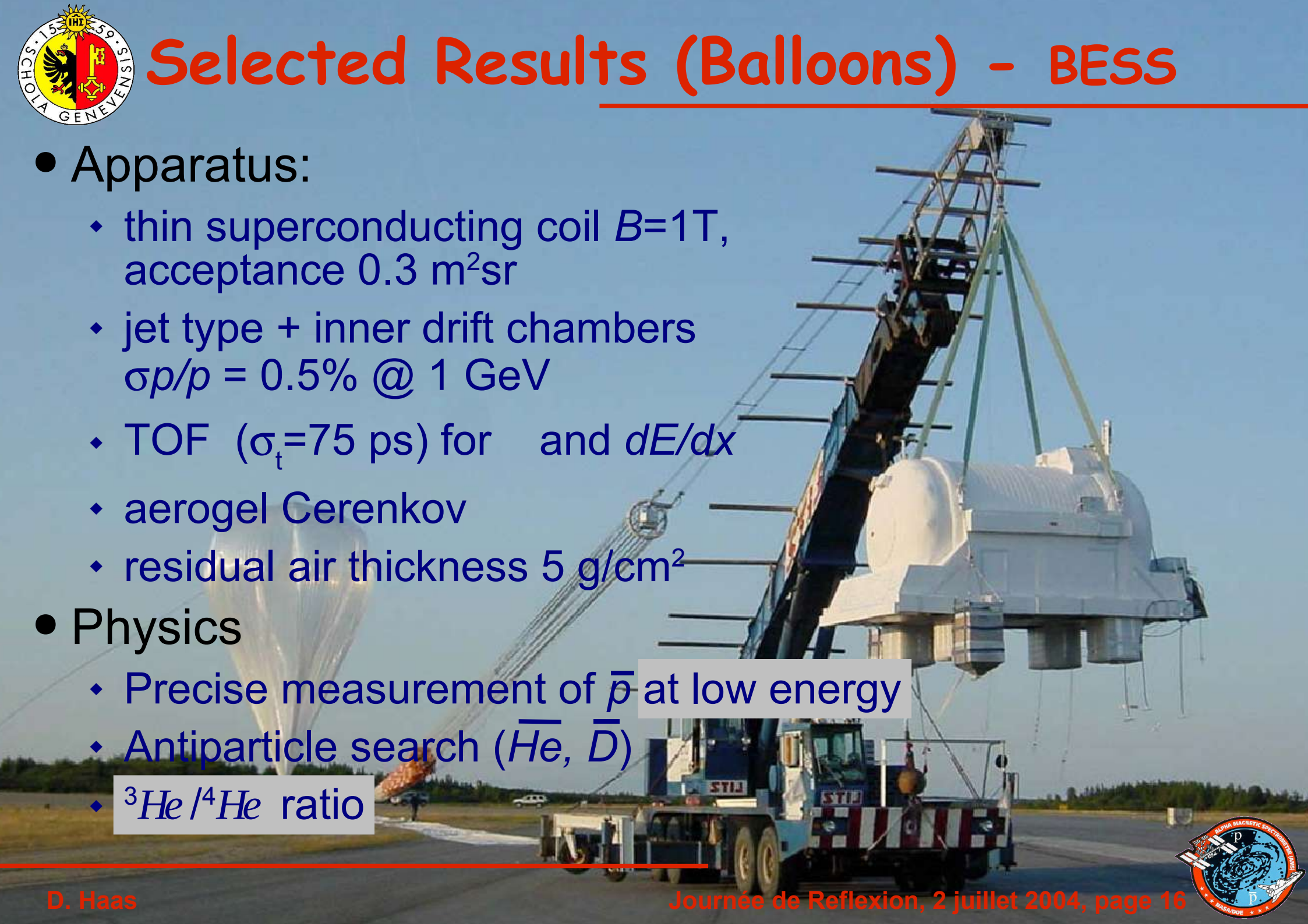




- 11-tank shower event, Energy ~2-3 10^{19}eV
- Close to core, substantial pulse-heights (Station 45)
- Further away, individual pulses from electrons and muons (Station 34)

Selected Results (Balloons) - BESS

- Apparatus:
  - thin superconducting coil B=1T, acceptance 0.3 m^{2}sr
  - jet type + inner drift chambers $\sigma p/p$ = 0.5% @ 1 GeV
  - TOF (σ_t=75 ps) for and dE/dx
  - aerogel Cerenkov
  - residual air thickness 5 g/cm^2
- Physics
  - Precise measurement of $\bar{p}$ at low energy
  - Antiparticle search ($\overline{He}$, $\overline{D}$)
  - $^3He/^4He$ ratio



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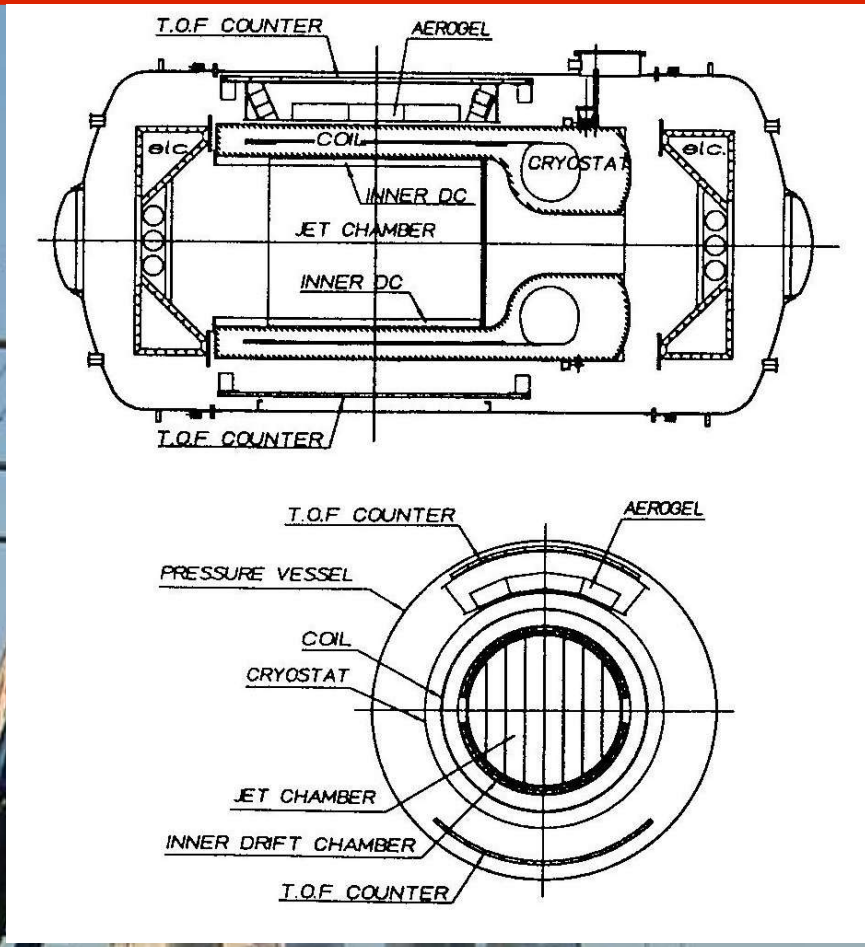
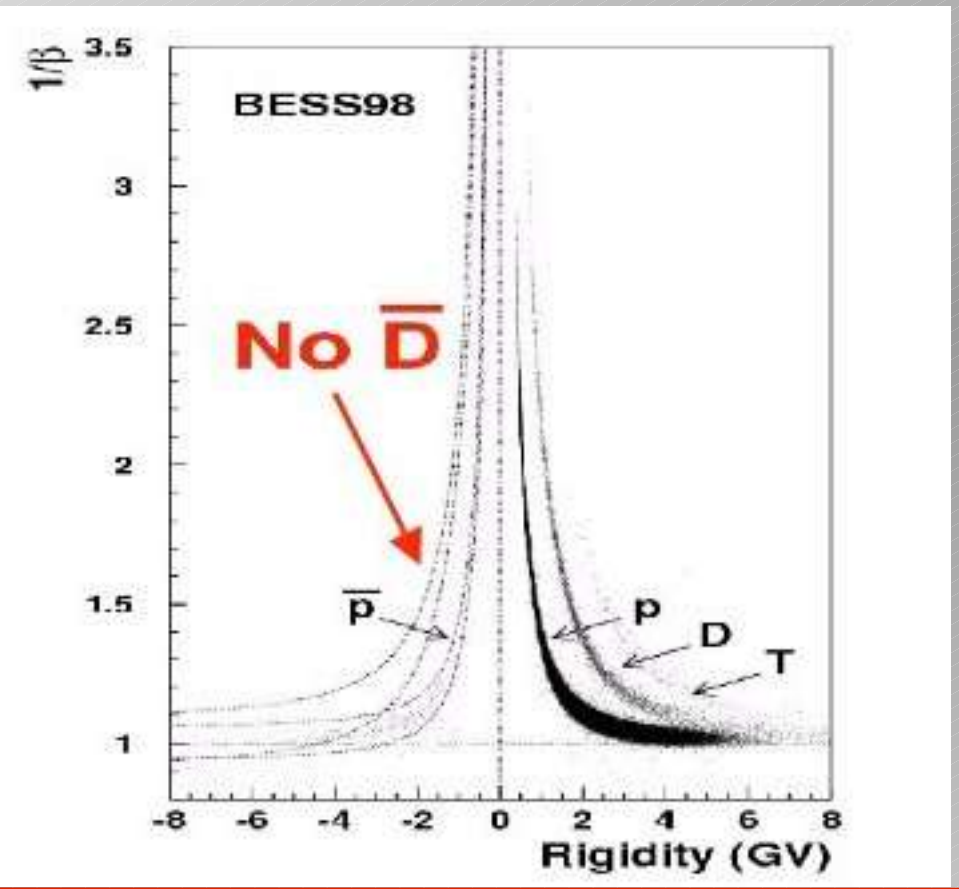
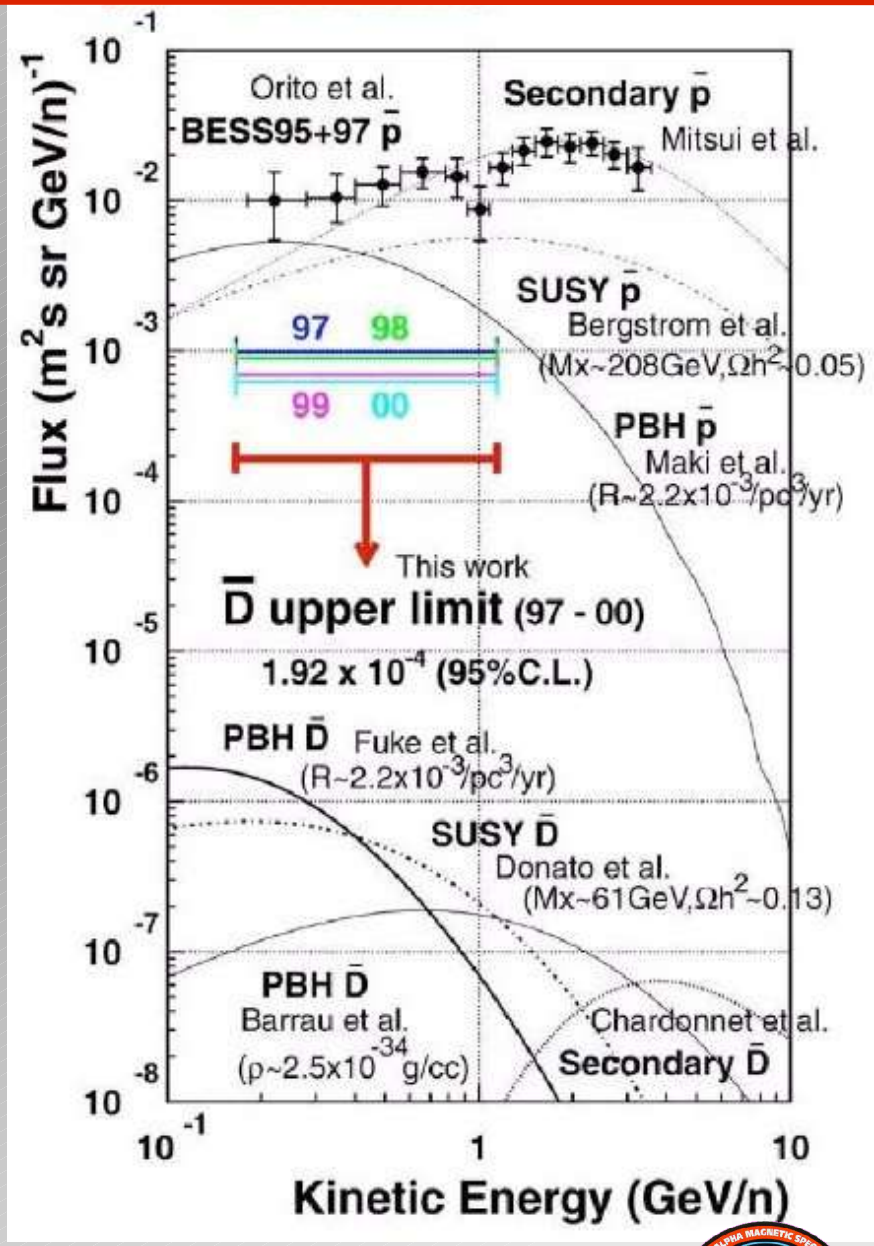


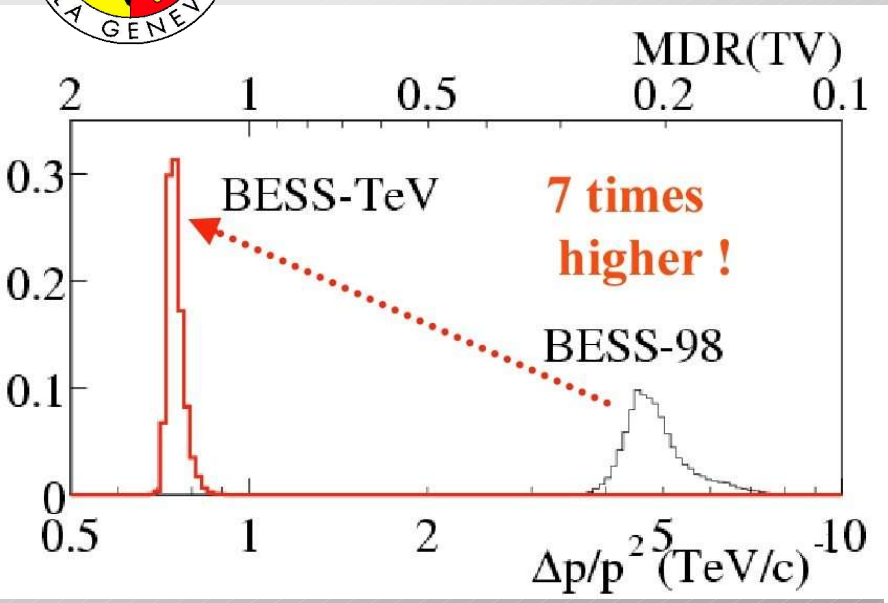
Selected Results (Balloons) - BESS

- Antideuteron upper limit
  1.92×10^{-4} $(m^2 s\ sr\ GeV/n)^{-1}$
- measured during flights from
  1997-2000

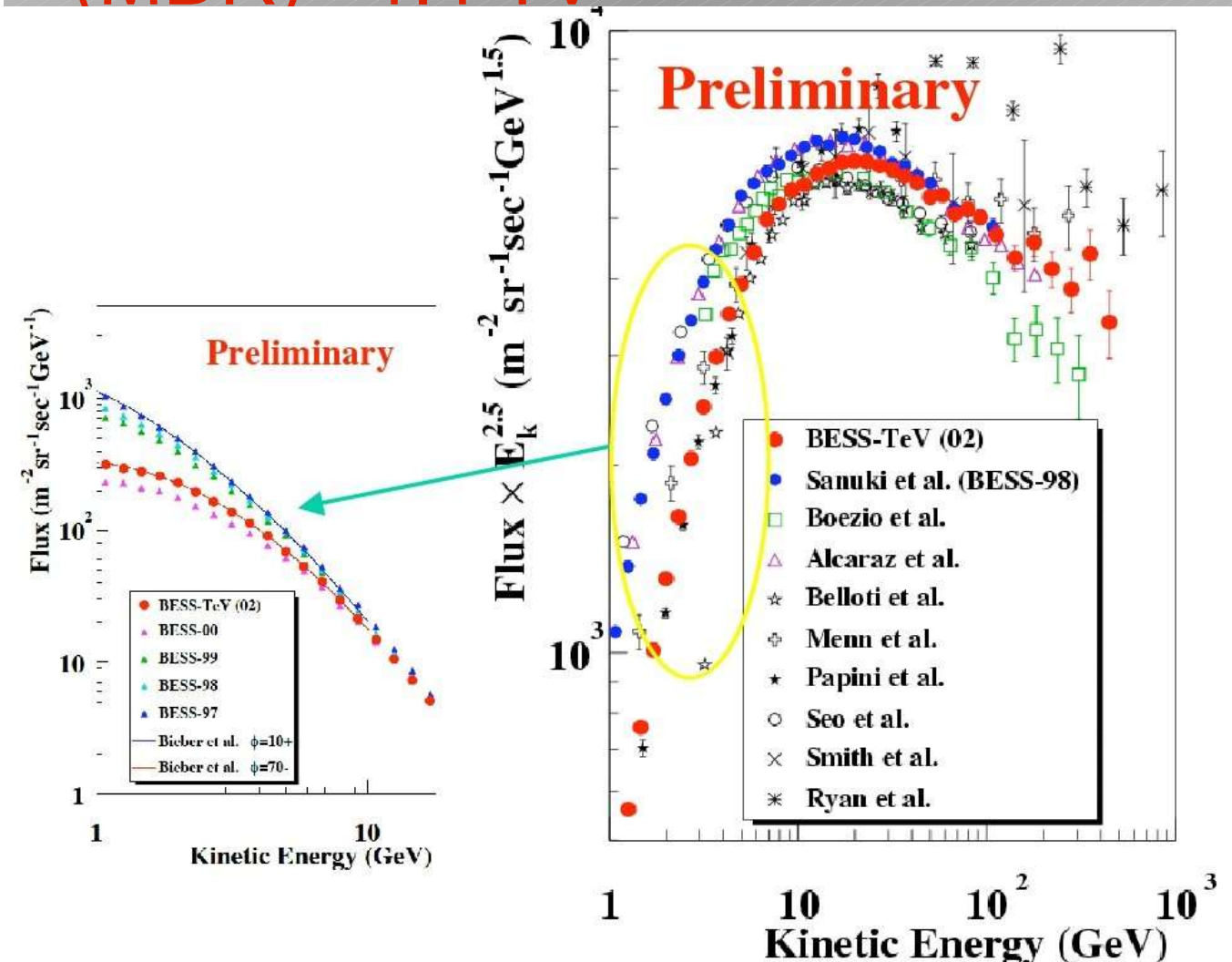




Selected Results (Balloons) - BESS-TeV



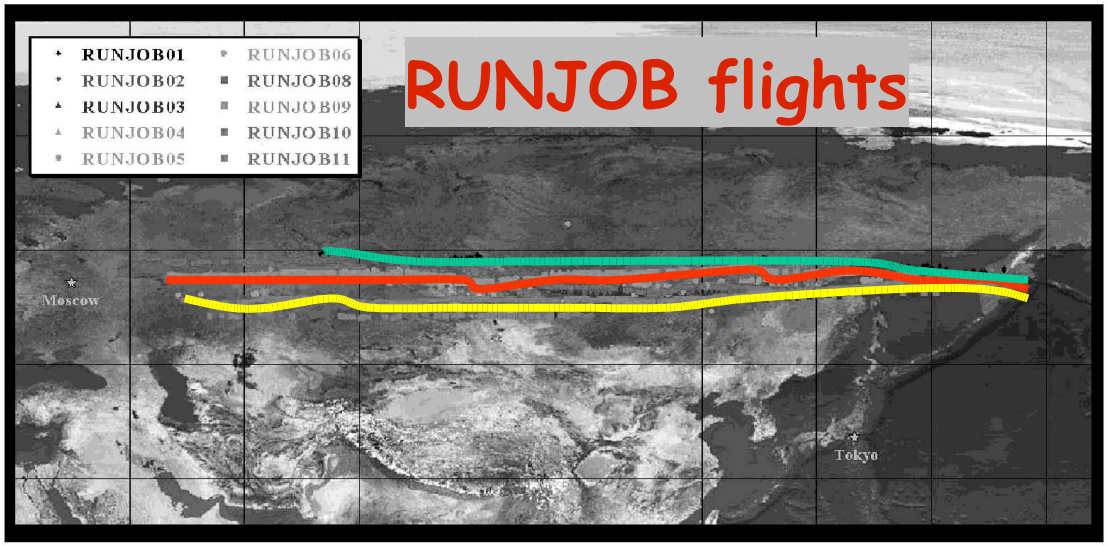
- BESS-TeV improved resolution
  $\Delta p/p^2$=0.7 (TeV/c)$^{-1}$
  Maximum Detectable Rigidity (MDR) =1.4 TV



- Proton spectrum measured up to 500 GeV
- Good agreement with BESS-98 and AMS-01

Selected Results (Balloons) - ATIC Runjob

- ATIC/RUNJOB: 2 quite different experiments, but similar goals:
  - probe spectrum up to knee region
  - ATIC → 10 TeV/n, Runjob → 100 TeV/n
- Understanding of knee important for study of propagation/acceleration mechanisms

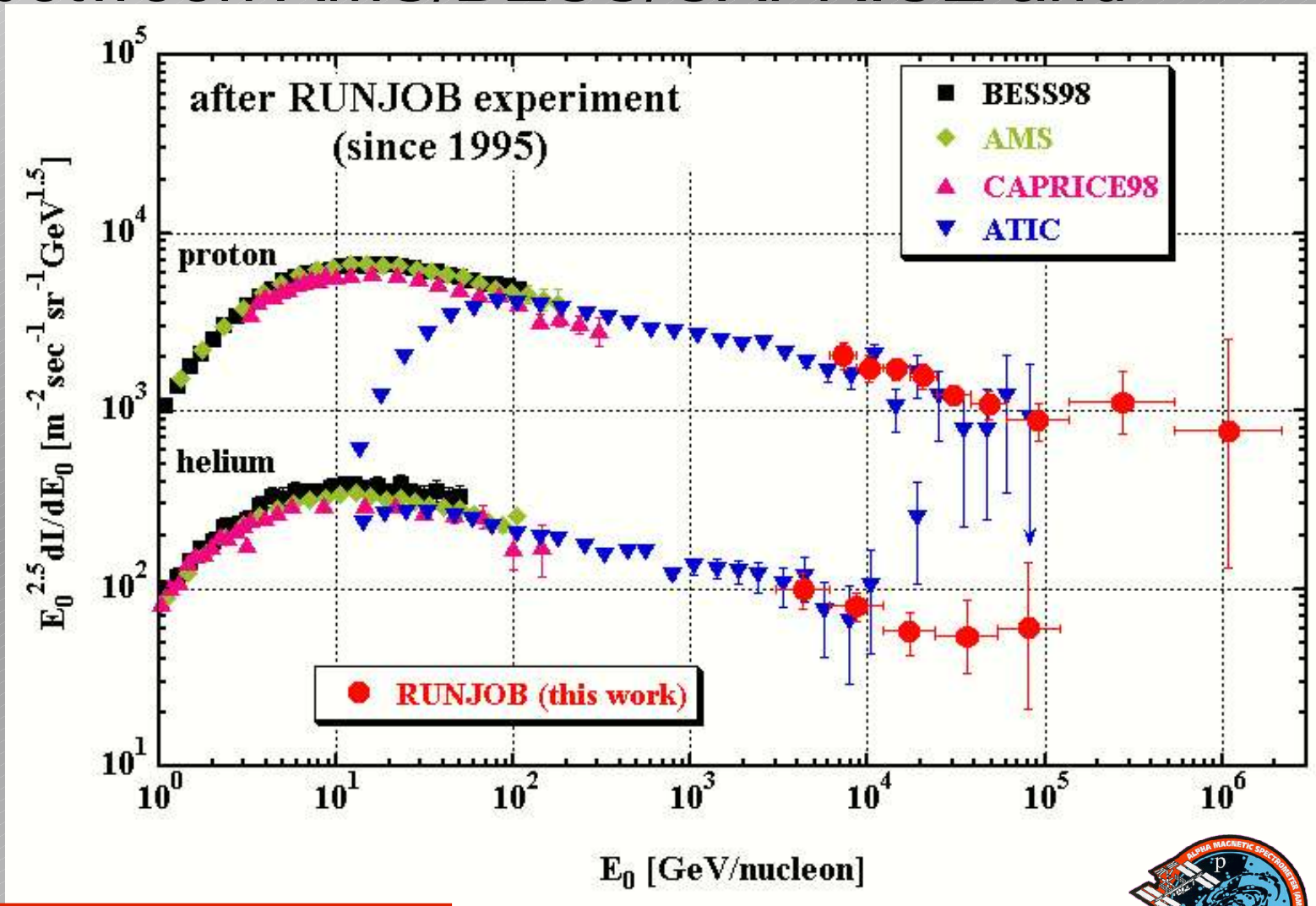


RUNJOB flights


ATIC Instrument

Selected Results (Balloons) - ATIC Runjob

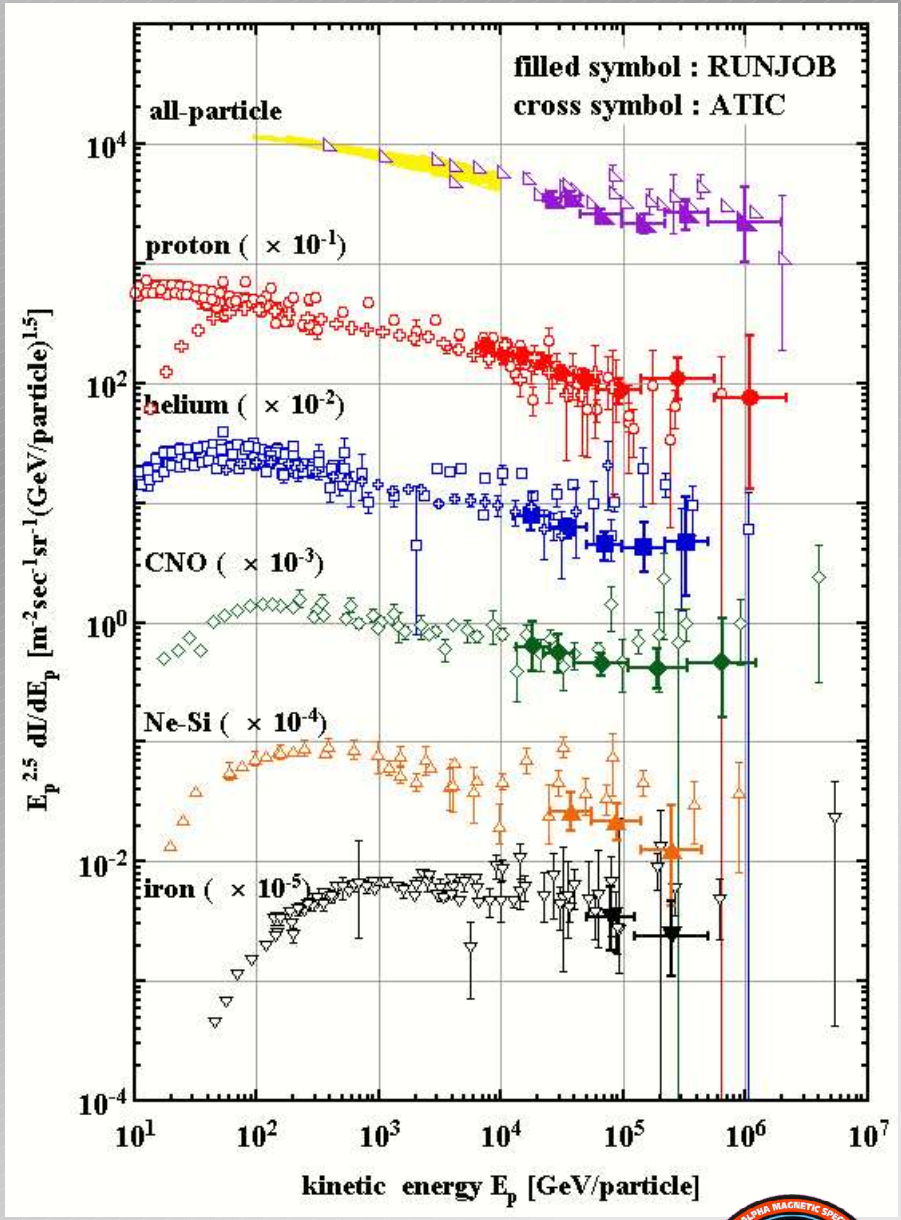
- ATIC *normalized* to data from AMS/BESS/CAPRICE
- ATIC fills gap between AMS/BESS/CAPRICE and RUNJOB
- Good agree-ment for the observed spectra



Selected Results (Balloons) - ATIC Runjob

- Slope determination dominated by ATIC data

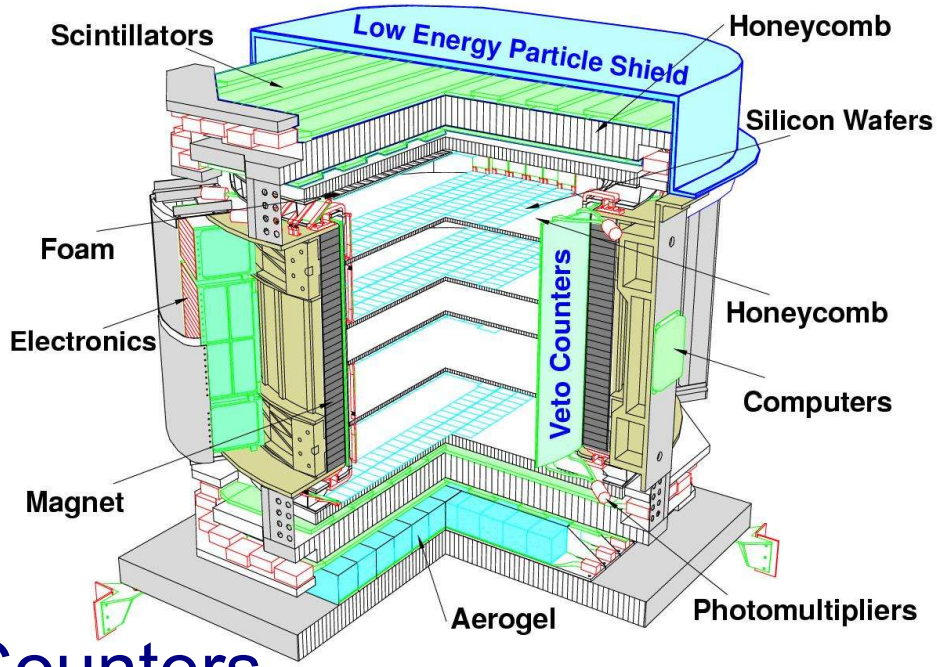
protons	Ekin	Fit
AMS+BESS+IMAX	30-200	-2.71±0.07
ATIC	100-10000	-2.71±0.01±??
1+2+JACEE+RUNJOB	30-100000	-2.71±0.01±??
Helium	**Ekin**	**Fit**
AMS+BESS+IMAX	30-200	-2.72±0.12
ATIC	100-10000	-2.71±0.02±??
1+2+JACEE+RUNJOB	30-100000	-2.71±0.02±??



- Preliminary ATIC data favors identical slopes ~2.71
- BESS-TeV not yet included will improve accuracy...

Selected Results (Space) - AMS-01

- AMS-01 Pilot Experiment
  STS 91,June 2-12, 1998
- Apparatus:
  - Permanent magnet BL^2=0.14T
  - TOF 4 planes
  - 2.1 m^2 silicon tracker, 6 planes
  - Cerenkov and Anticoincidence Counters

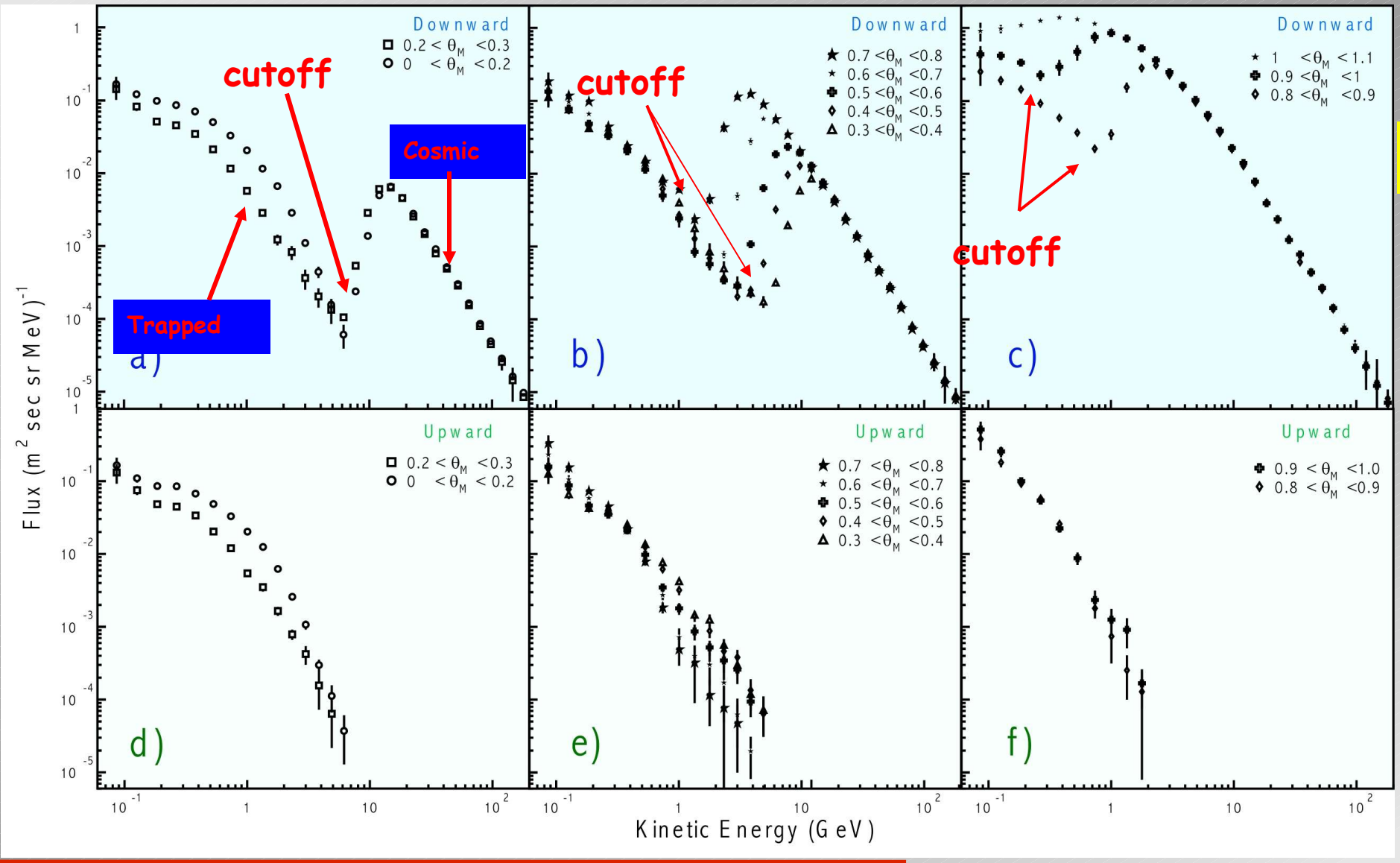


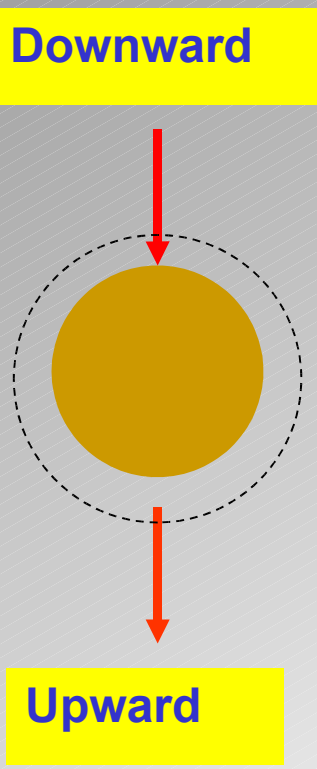
- Physics:
  - Flux measurements of $e^{\pm}$, p, $\bar{p}$, D, He and $\overline{He}$, heavy ions
  - detection of secondary fluxes geomagnetic field effect
  - antimatter sensitivity $\overline{He}/He \sim 10^{-6}$

Selected Results (Space) - AMS-01

- Measured proton spectra

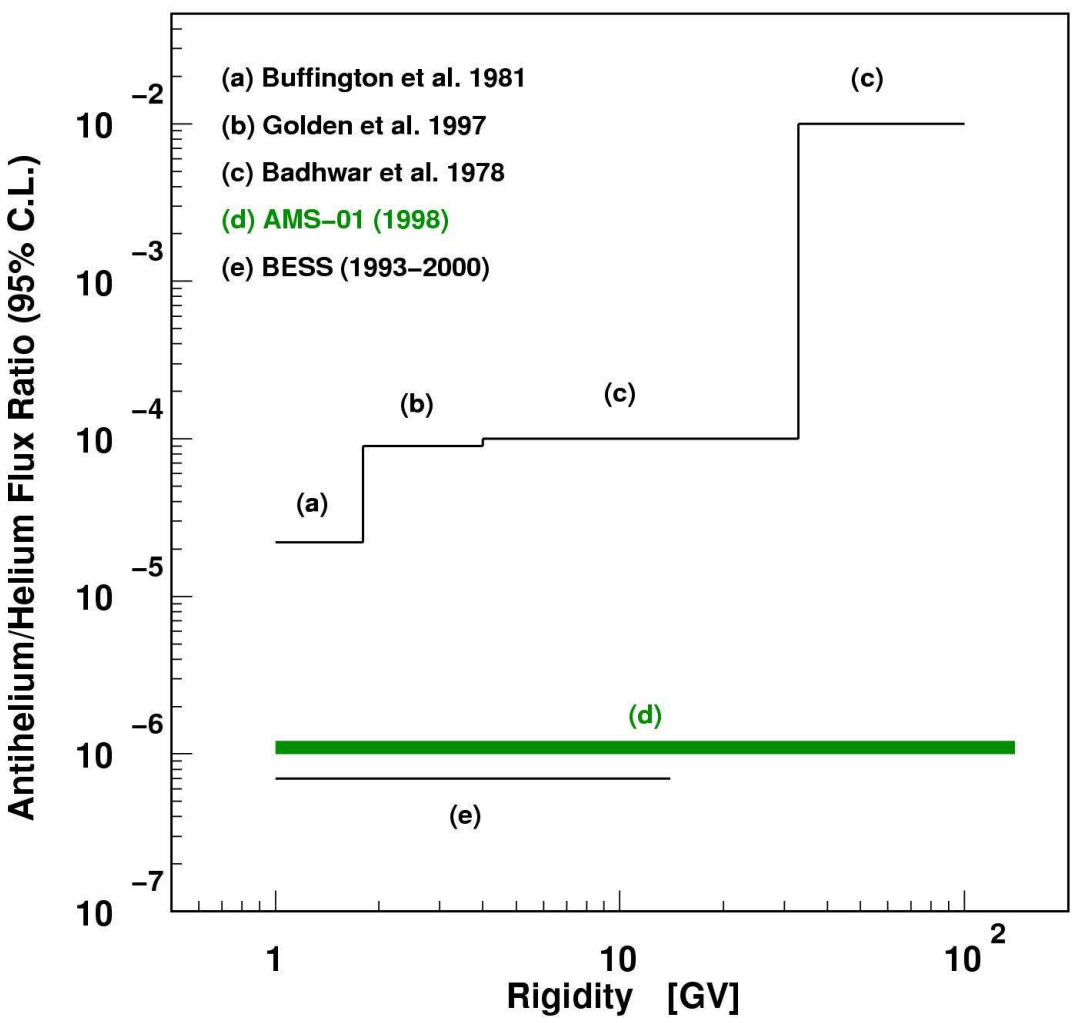
Phys. Lett. B 472 (2000) 215

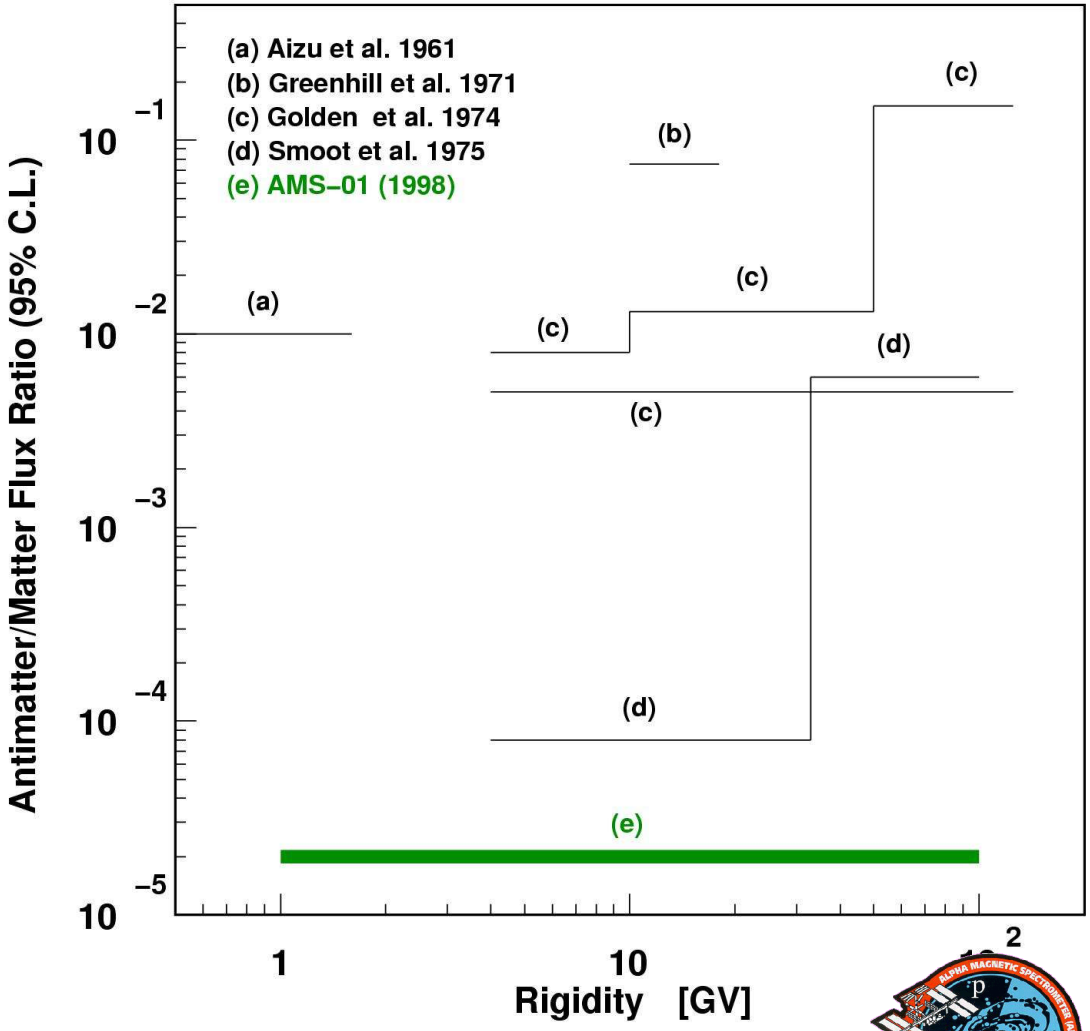




Selected Results (Space) - AMS-01

- Competitive limits on $\overline{He}$ and Antimatter have been obtained in the 10-day test-flight





Technical Progress - Balloons

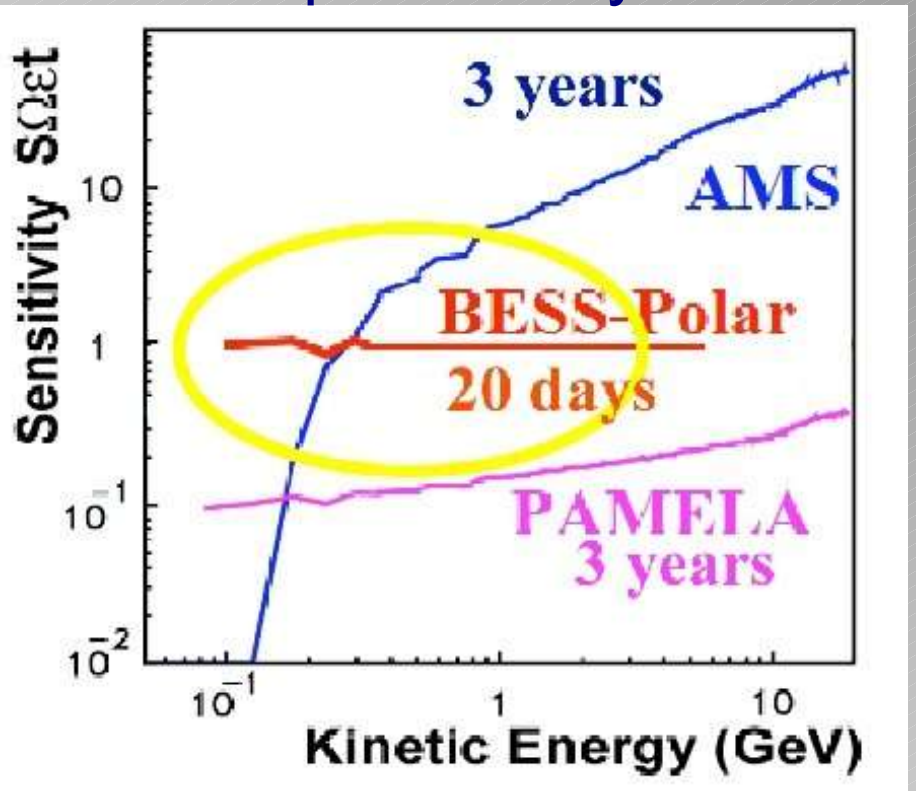
- Bess improved on every mission

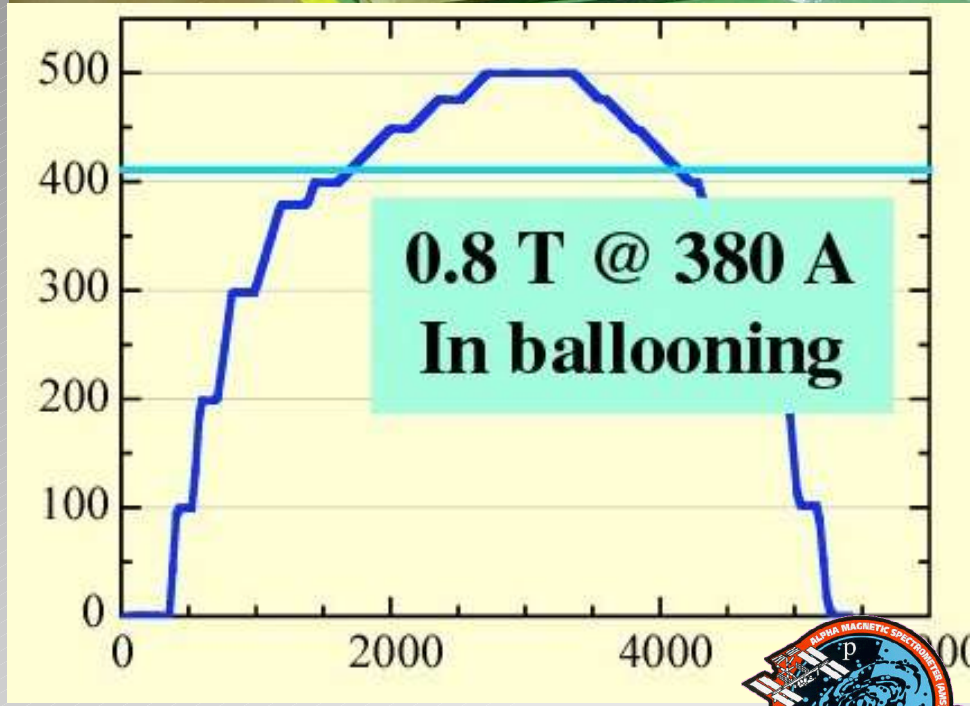
BESS-93,94	BESS-95	BESS-97,98	BESS-99,00	BESS-TeV	BESS-Polar
σ_{TOF} =300 ps	Larger Vessel σ_{TOF} =110 ps	σ_{TOF} =70 ps Aerogel C 97 n=1.03 $\bar{p}$ 0.2-3.5 GeV 98 n=1.02 $\bar{p}$ 0.2-4.2 GeV	Shower Counter 2X$_0$ Lead e/μ sep.	Larger Vessel New ODC's New JET/IDC's p/He up to 1 TeV	No Vessel New Mag (ultra thin)
$\bar{p}$ 0.2-0.6 GeV	$\bar{p}$ 0.2-1.4 GeV		$\bar{p}$ 0.2-4.2 GeV	$\bar{p}$ 0.2-4.2 GeV	$\bar{p}$ 0.1-4.2 GeV

- Flight durations from a few hours to ~1 month (TIGER)
- RUNJOB directly measures knee-region

Future Projects (Balloons) - BESS Polar

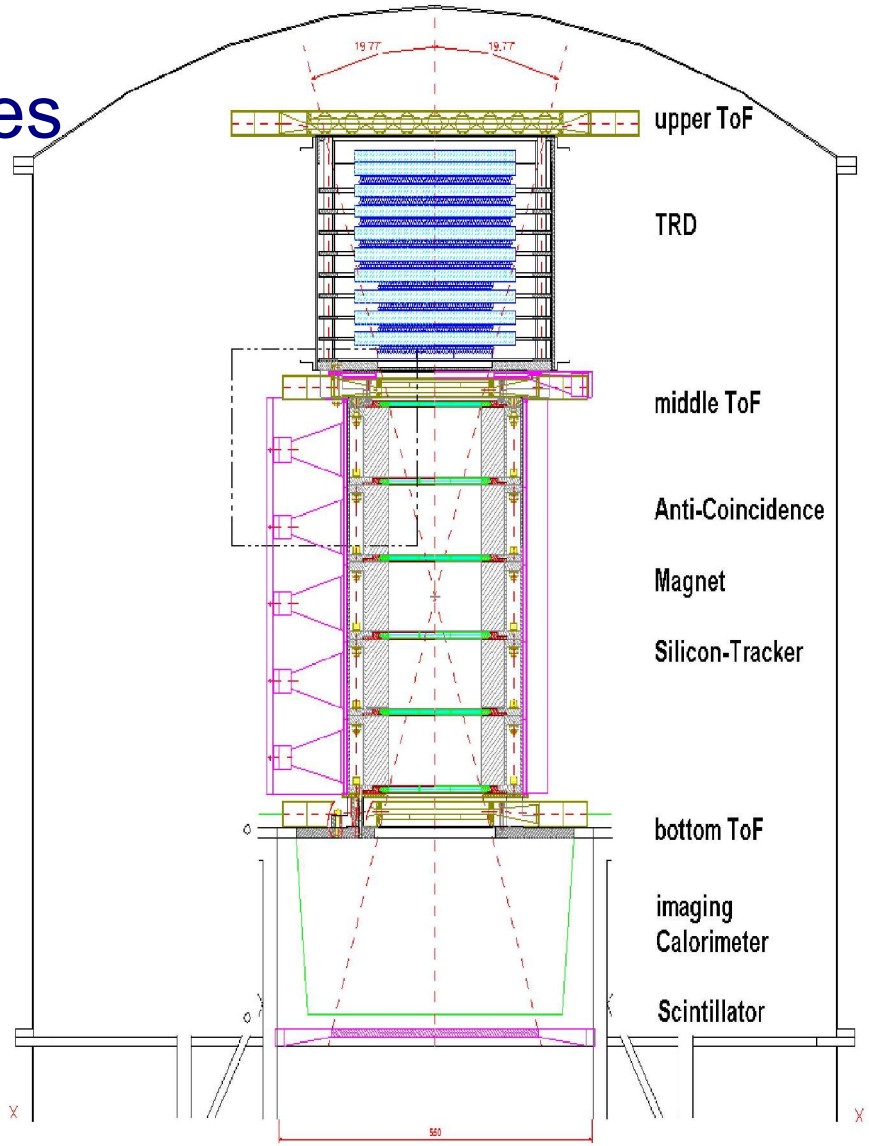
- Thin Solenoid Coil completed and tested up to 1.05 T
- Ideal for low energy
  - low magnetic cut-off regions
  - flight during solar minimum (2004-2006)
  - complementary with PAMELA/AMS



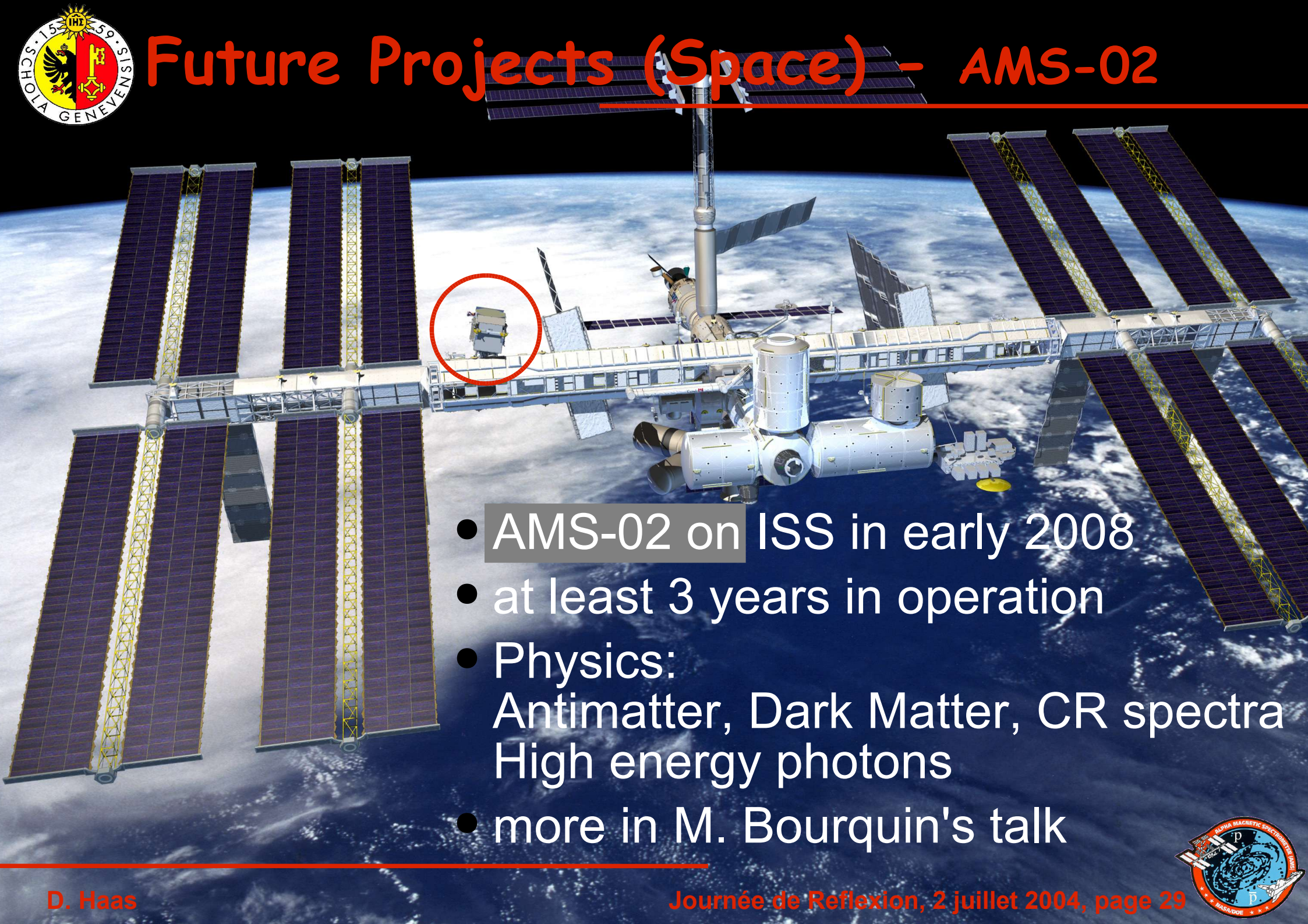


Future Projects (Space) - PAMELA

- Apparatus (ready to fly end 2004)
  - GF 20.5 cm^2sr for high energy particles
  - Angular aperture of 19°x16°
  - Spatial res.: 4 μm (BV), 15 μm (NBV)
  - Maximum Detectable Rigidity (MDR) ~740 GV
  - TOF accuracy <100 ps
  - *e/p* discrim. better than $2x10^5$
- Physics
  - *p* from 80 MeV - 190 GeV
  - e^+ 50 MeV - 270 GeV
  - $\overline{He}/He \sim 10^{-7}$
  - nuclei spectra (*H*-*O*) 100 MeV/n - 200 GeV/n



Future Projects (Space) - AMS-02



- AMS-02 on ISS in early 2008
- at least 3 years in operation
- Physics:
  Antimatter, Dark Matter, CR spectra
  High energy photons
- more in M. Bourquin's talk

Comparison - BESS/PAMELA/AMS-02

	BESS-Polar	PAMELA	AMS-02
Acceptance (m^2sr)	0.3	0.002	0.5
MDR (GV)	150	740	2500
Flight duration (days)	10+20	1000	1000
Flight Altitude (km)	36	690	350
Residual air (g/cm^2)	5	-	-
Weight (tons)	1.5	0.38	~7
Power consumption (W)	600	345	2000
Magnetic field (Tesla)	0.8-1	0.4	0.87
Flight latidude (deg.)	80	±70	±52
Energy region (GeV)	> 0.1	> 0.1	~ > 0.5
Flight vehicule	Balloon	Satellite	ISS
# of events for:			
protons (range in GeV/n)	$3\ 10^9$ (0.2-200)	$3\ 10^8$ (0.08-700)	$2\ 10^{10}$ (0.5-2500)
antiprotons	$3\ 10^4$ (0.2-4)	$3\ 10^4$ (0.08-190)	$3\ 10^6$ (0.08-700)
e^-	-	$6\ 10^6$ (0.05-2000)	$6\ 10^8$ (0.5-5000)
e^+	-	$3\ 10^5$ (0.05-270)	$3\ 10^7$ (1-400)
Anti-He/He	$3\ 10^{-8}$	$7\ 10^{-8}$	$1\ 10^{-9}$
Anti-D/D	10^{-5}	-	$3\ 10^{-7}$

Conclusions

- Exciting times for study of Astroparticles
- Precise measurements are available and upcoming to help understand key questions of Cosmology
- Future direct and indirect measurements all promising
  - Auger: to access ultra-high energies above GKZ-cutoff
  - Balloon-flights will soon last several months, thus improving statistics essentially
  - Space experiments like PAMELA/AMS-02 are first class technological challenge, but will hopefully be rewarded
- Rich and diversified physics program

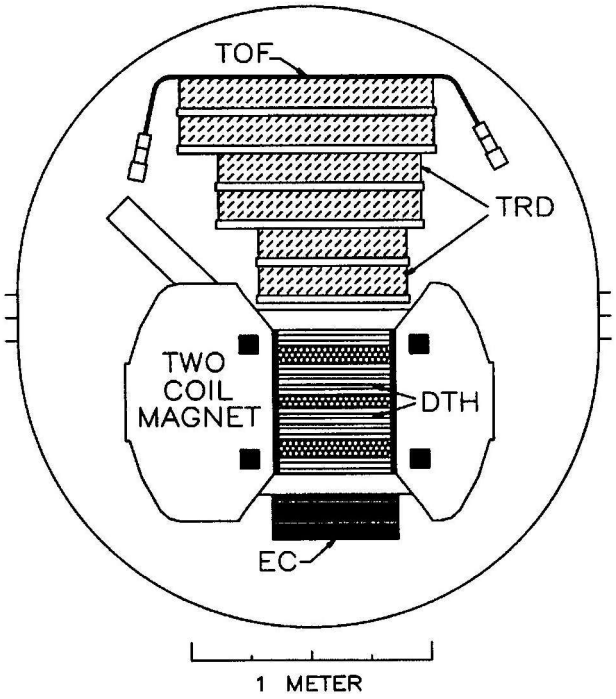
Backup Slides

... Introduction ... - GCR Propagation

- GCRs must propagate through ISM before they can reach us
- Diffusive transport equations describe both Propagation and Acceleration
- Current models are:
  - Leaky Box Model (LBM): GCRs propagate freely in the containment volume, constant density in volume (often good enough)
  - Diffusion Halo Models (DHM): diffusion operator not constant, thus density of CRs decreases with distance from the galactic plane, more realistic!
- Isotopes like ^{10}Be can be used to study propagation models, they serve as *'propagation clocks'*

Selected Results (Balloons) - HEAT

- Apparatus
  - Superconducting magnet
  - Drift tube hodoscope tracking chamber
  - Time Of Flight (TOF) with 2 scintillator layers
  - Transition Radiaton Detector (TRD) on top
  - Electromagnetic Calorimeter (EC): measure $e^{\pm}$ and discriminate against hadrons

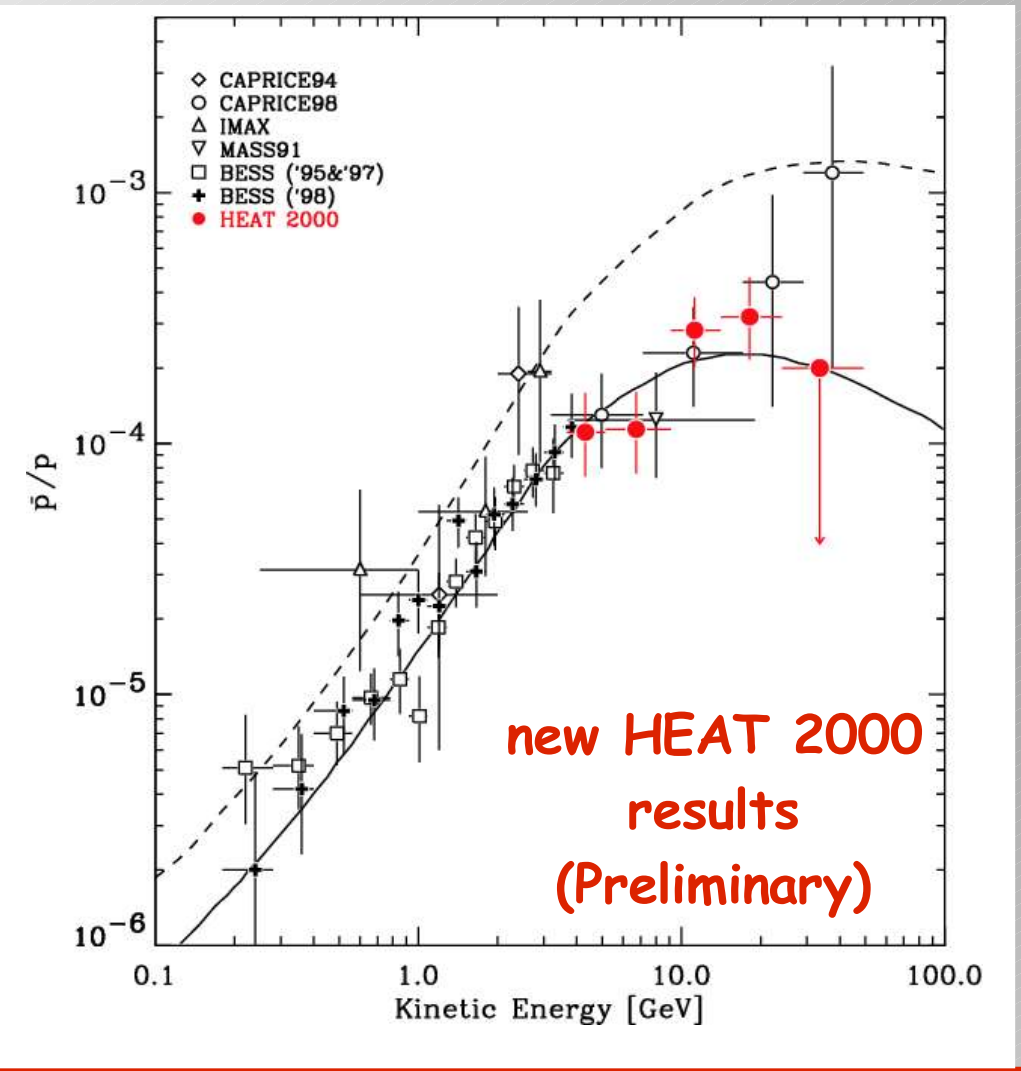


1994 apparatus

- Physics
  - Observation of e^+ and e^- from 1-50/100 GeV
  - Observation of $\bar{p}/p$ ratio from 4.5-50 GeV
  - Launch: May 1994 (Fort Sumner/NM), August 1995, Spring 2000 (Lynn Lake Manitoba)

Selected Results (Balloons) - HEAT

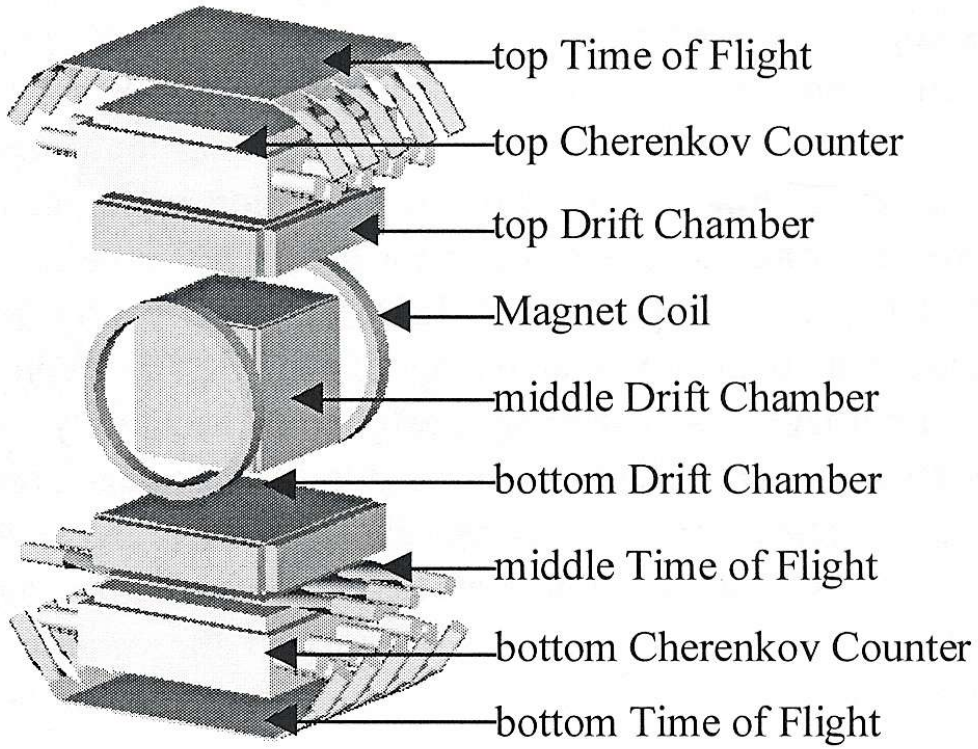
- Positrons and Antiprotons probe the structure of the ISM and the primary nucleon component

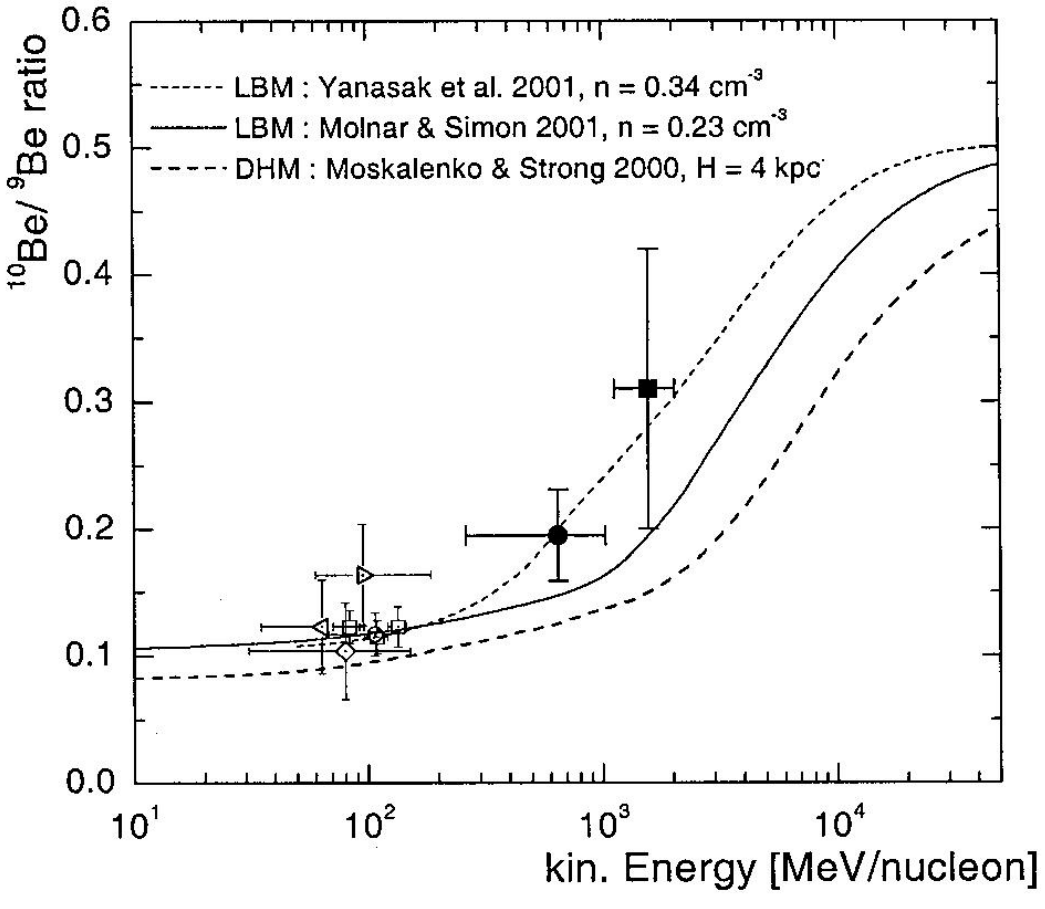


- New results do not support hard nucleon injection spectrum models
  Beach et. al. Phys. Rev. Lett. 87, 271101 (2001)
- Measurements consistent with pure secondary production of antiprotons
- Measurements agree with 'standard spectrum' calculated by Moskalenko et al
  [A&A 338, L75 (1998)]

Selected Results (Balloons) - ISOMAX

- Apparatus
  - Superconducting magnet
  - Drift Chambers
  - TOF & Cerenkovs

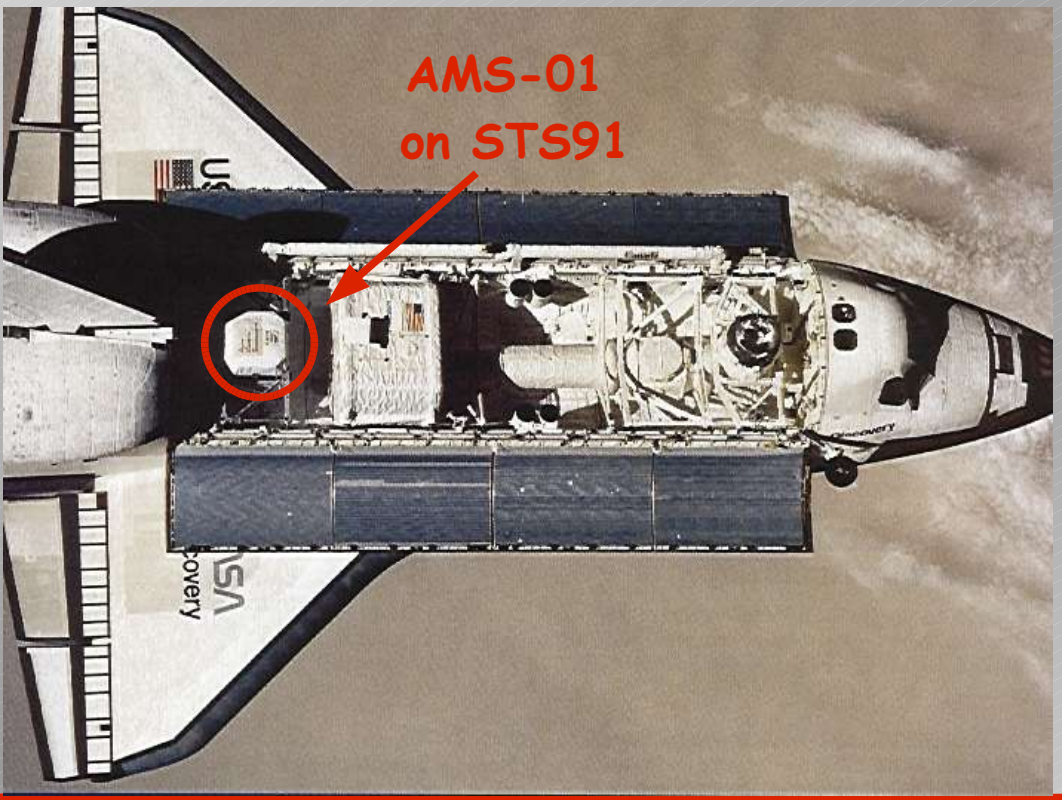


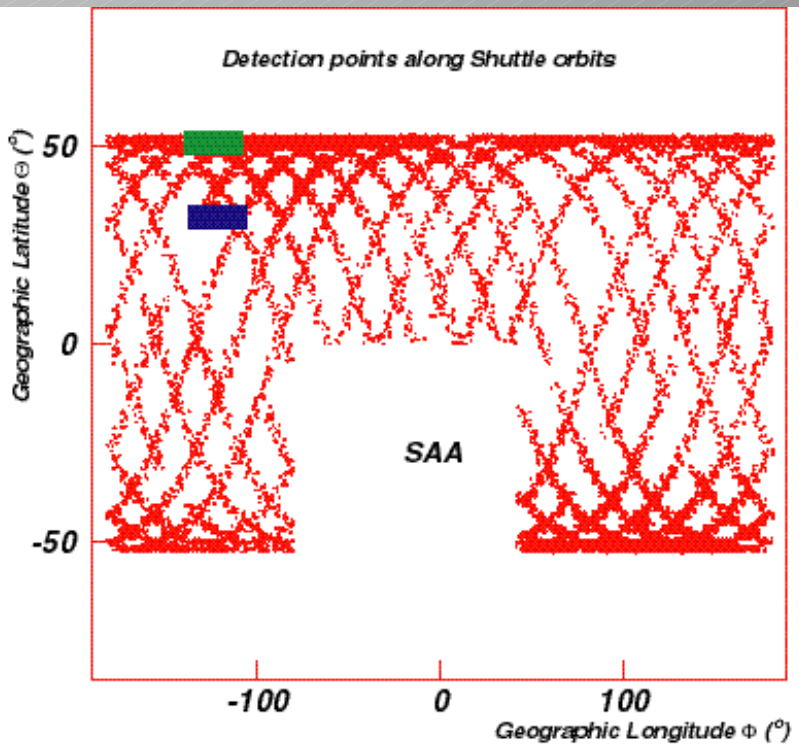


- Physics
  - Isotopic composition of light isotopes ($3 < Z < 8$)
  - Energy range up to 4 GeV/n

Selected Results (Space) - AMS-01

- Geographical coverage much better for satellites than for balloons
- Exposure times high

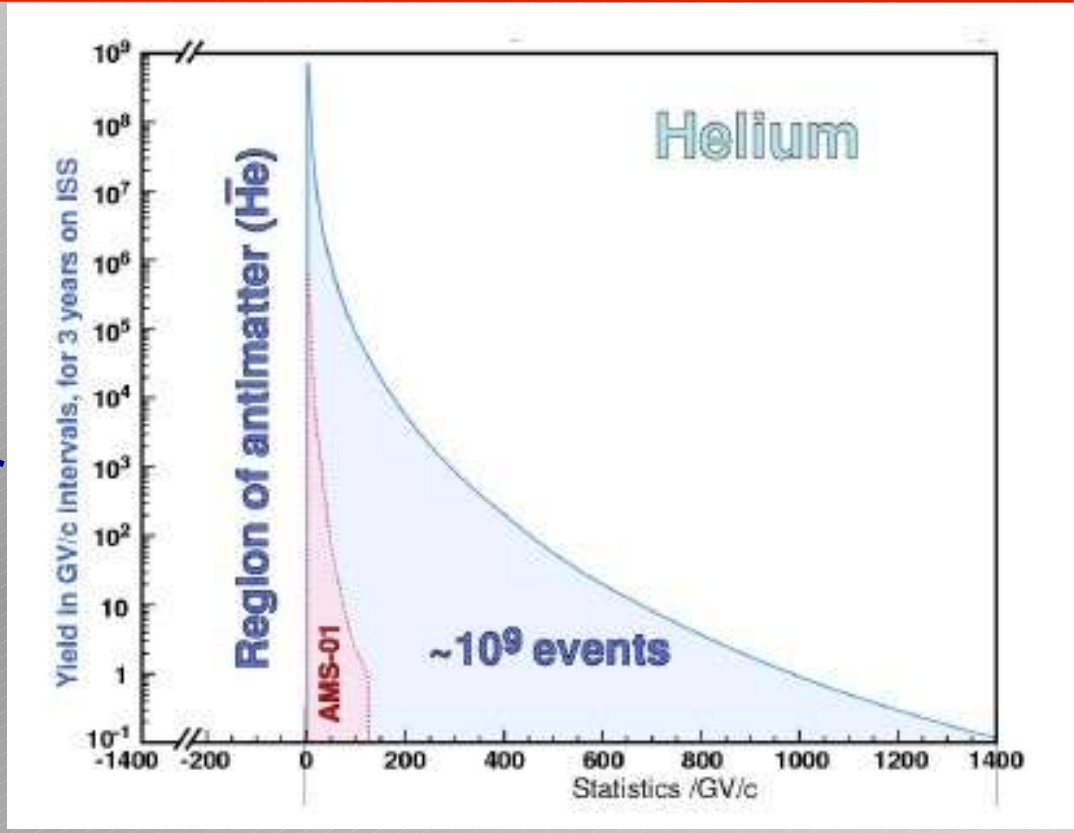




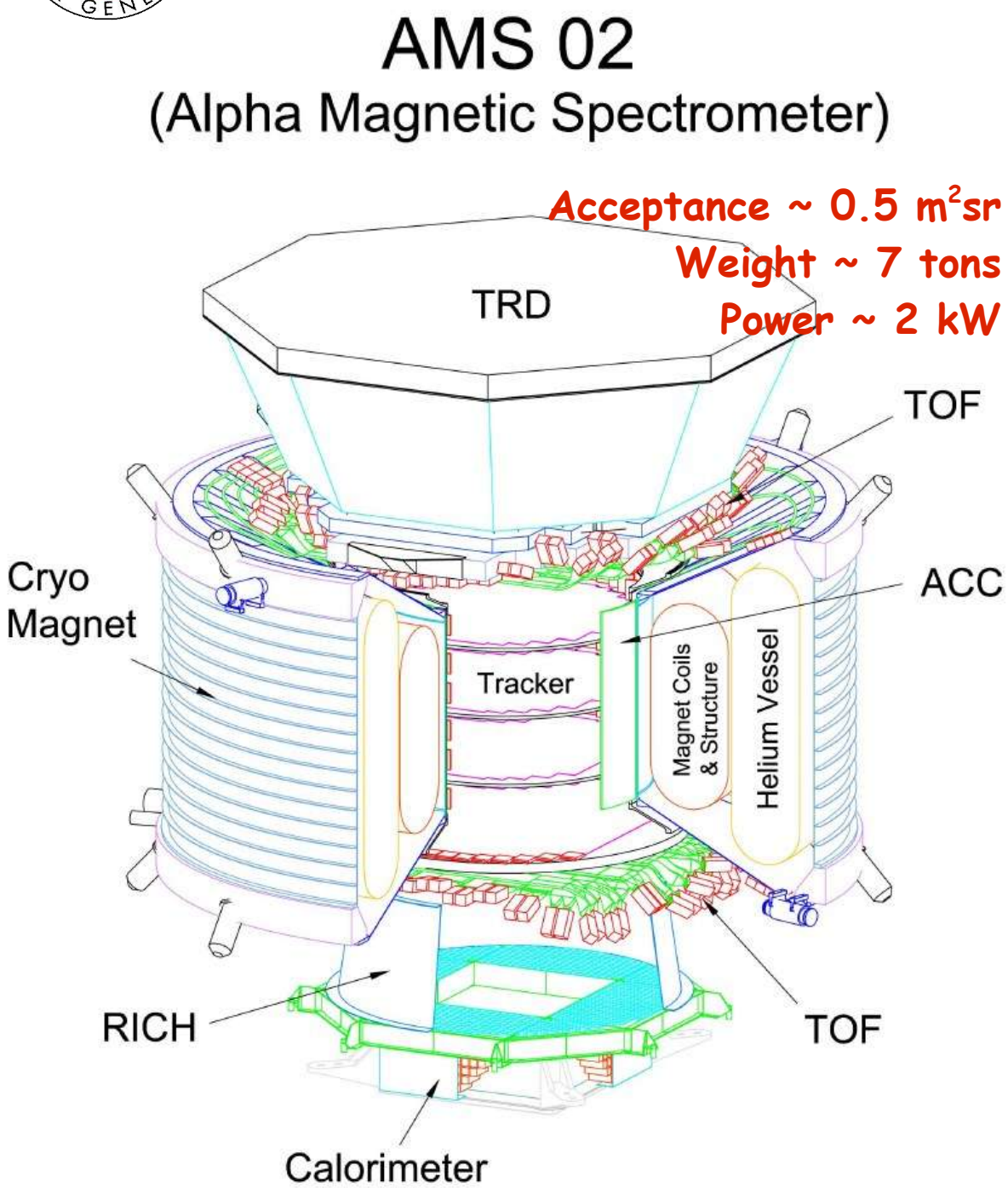
	Cutoffs(GV)	Latitudes	Longitudes
AMS		+/- 51.7	all (SAA excluded)
BESS98	<0.5		(Lynn Lake - Canada)
CAPRICE94		+56.5 N	101-117 W (Lynn Lake - Canada)
MASS91	4.3	+34 N	104 W (Forth Sumner)
IMAX92	0.37-0.63	+56.5 N	101-118 W (Lynn Lake - Canada)
LEAP87	0.6-1.1	n.a.	n.a. (Prince Albert - Canada)

Future Projects (Space) - AMS-02

- Search for Antimatter
  $\Rightarrow$ Improve Limits of AMS01
  - Increased Sensitivity
  - Energy Range of $\mathcal{O}$(1 TeV/n)
  - Anti-Helium $\Rightarrow$ Cosmic Antimatter
  - Anti-Carbon $\Rightarrow$ Anti-Stars
- Search for Dark Matter
  - High statistics for $e^{\pm}$
  - Antiprotons, $\bar{D}$ and γ Spectra
- Cosmic Ray Studies
  - Precision measurements of light isotopes
- Sources of High Energy Photons



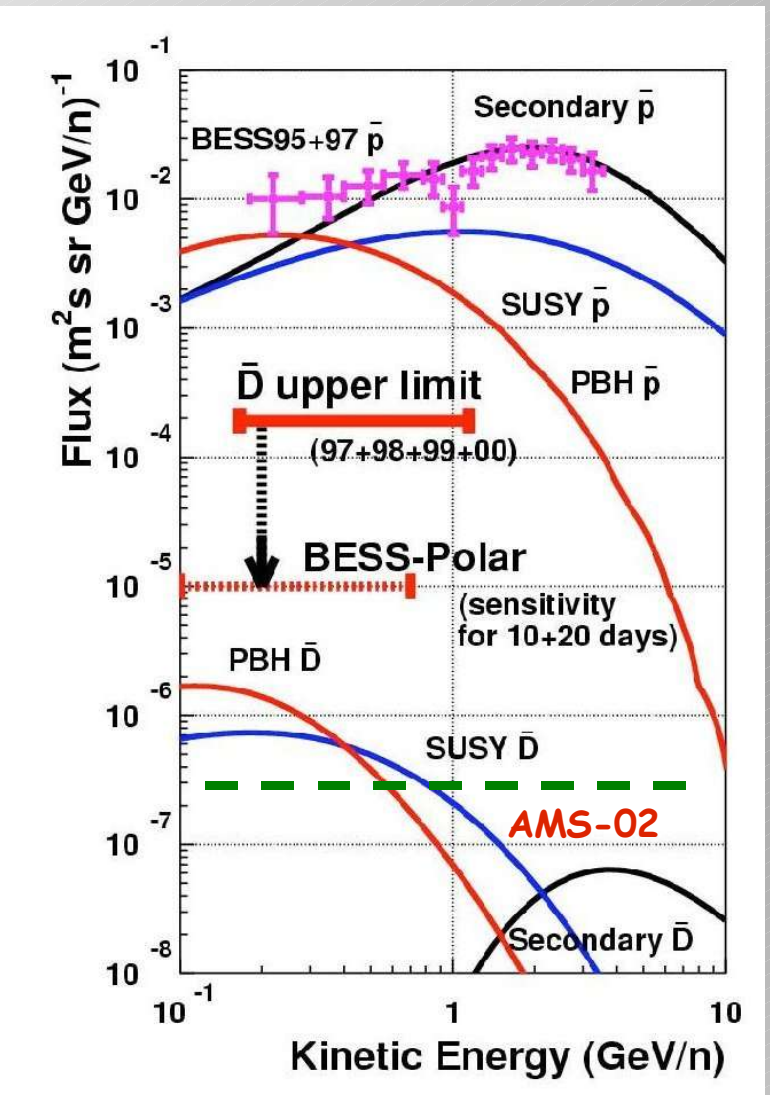
Future Projects (Space) - AMS-02

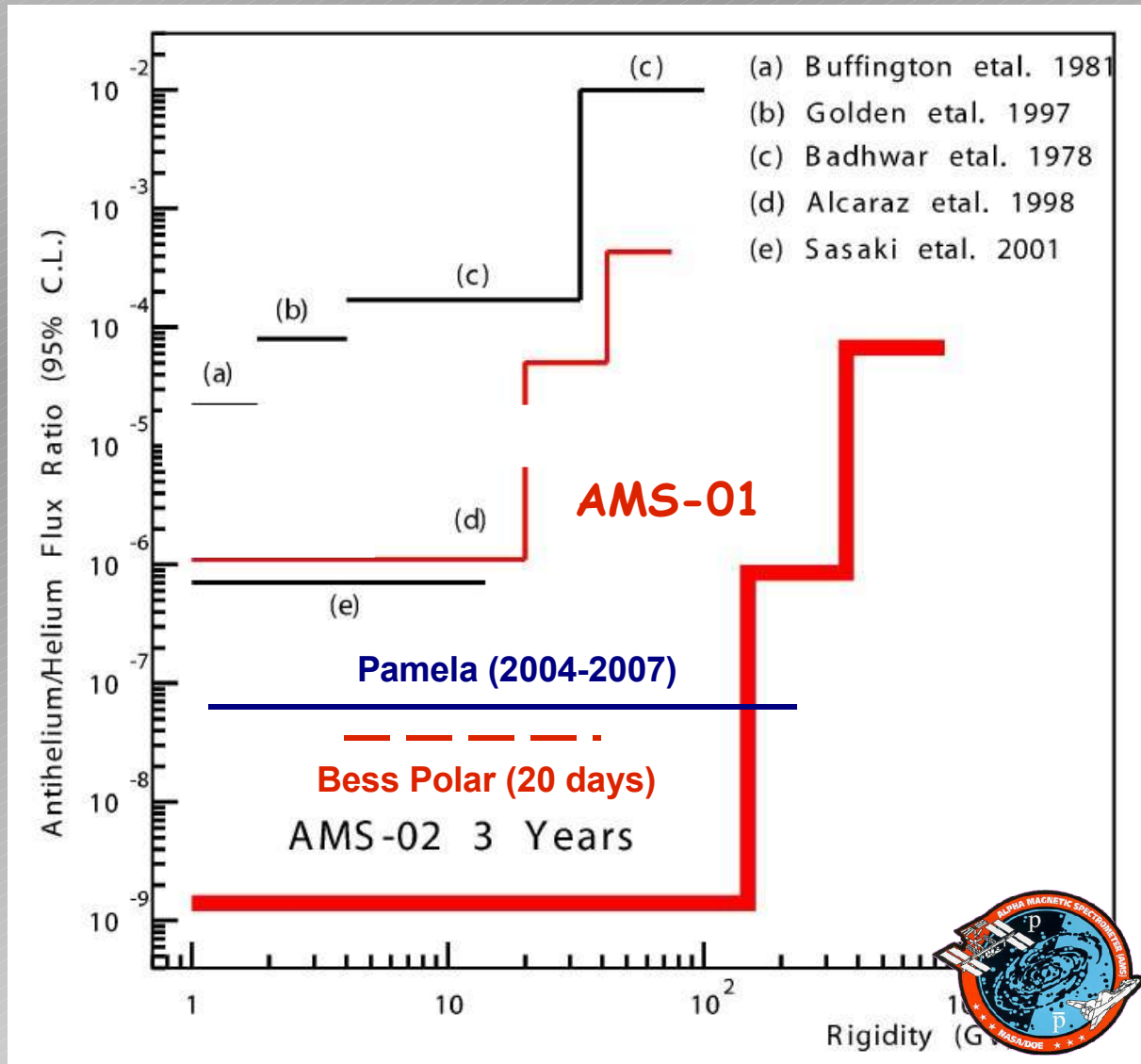


- Superconducting Magnet
  - 14 coils, total dipole moment=0
  - Reservoir for 3 years, B ~0.87 T
- Tracker
  - 2264 sensors, ~6.4m^2
  - ~200k channels on 8 layers
- Transition Radiation Det (TRD)
  - 328 modules (straw t./fleece r.)
  - 20 layers on octagonal shape
- Time Of Flight (TOF)
  - 4 scintillator planes, 34 paddles
  - 2/3 PMs at both ends
- Ring Imaging Cherenkov (RICH)
  - aerogel and sodium fluoride
  - pixel granularity 8.5 x 8.5 mm^2
- Electromagnetic Calorimeter
  - lead-scintillating fibers sandwich
  - 9 superlayers, ~15 X_0

Future Projects (Space) - AMS-02

- Search for antimatter at the 10^{-9} level of sensitivity for *He* with AMS-02 on the ISS
- $\bar{D}$ limit could test SUSY





Future Projects (Space) - AMS-02

- Expected Isotopic components from AMS-02