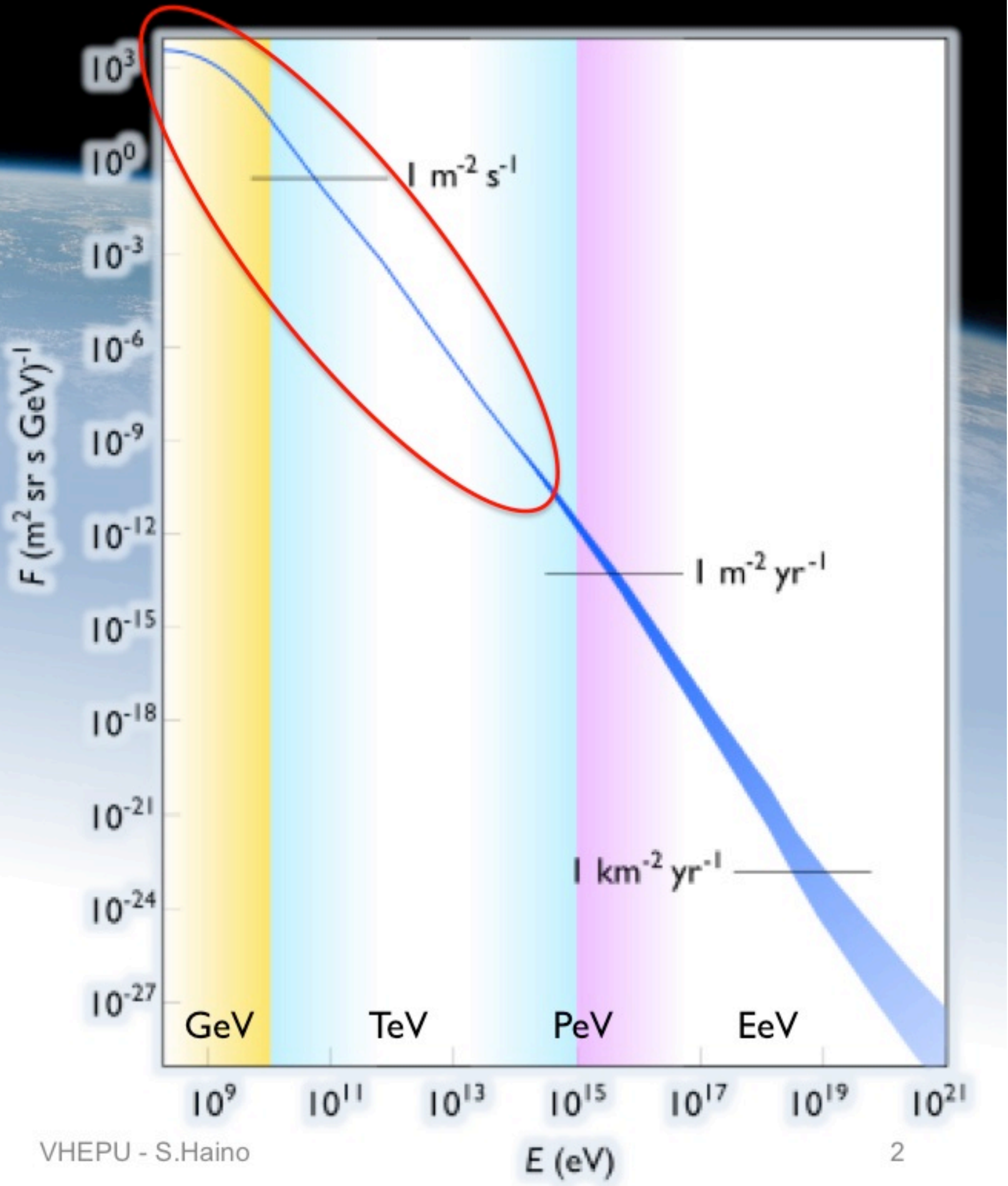
Cosmic rays nuclei in GeV to TeV

Sadakazu HAINO
Academia Sinica /Taiwan

August/2014
VHEPU
Rencontres du Vietnam

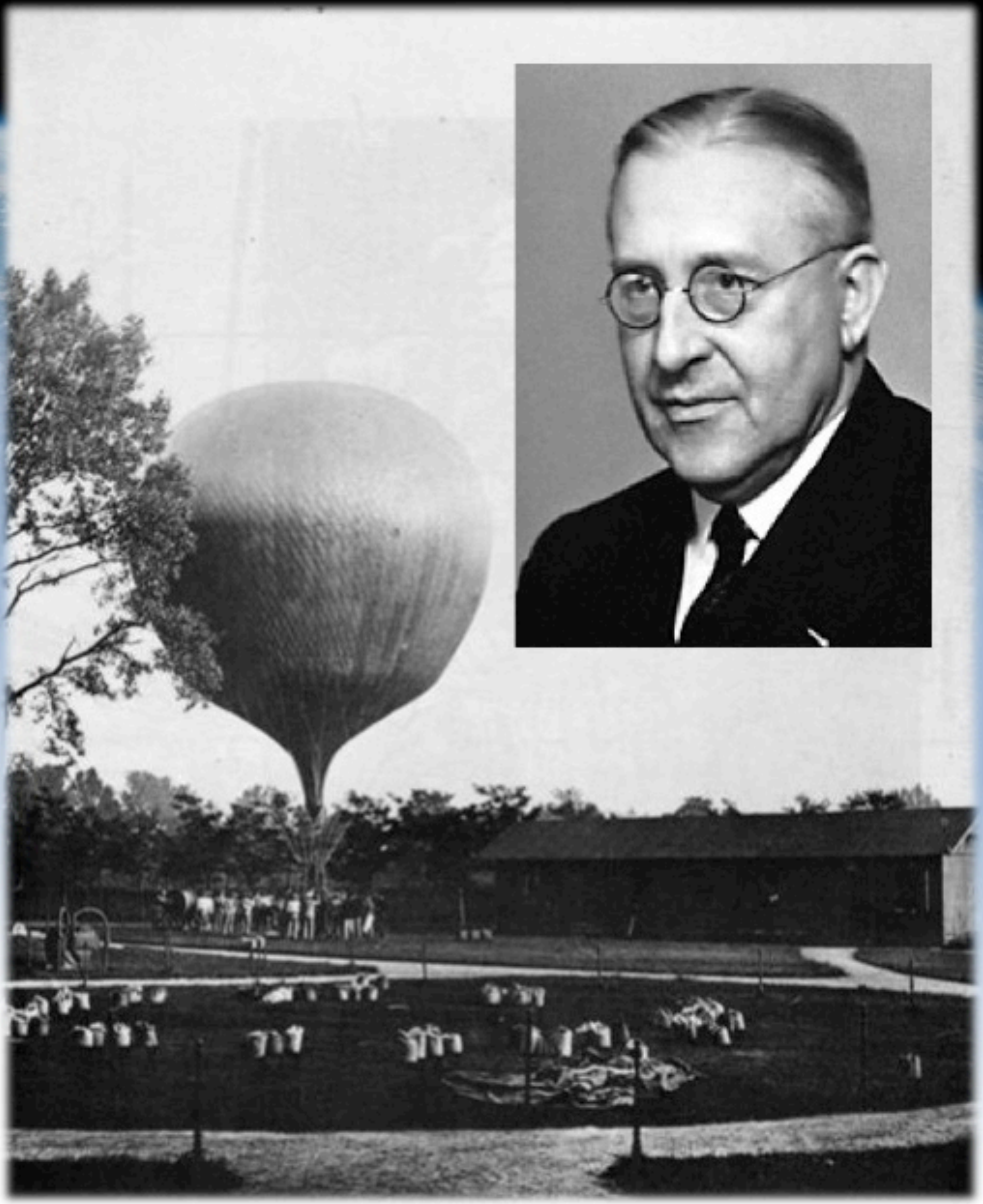
中央研究院
Academia Sinica

GeV-TeV : Direct measurements with balloons and in space



V. Hess
Discovery of cosmic rays in 1912

But he was never able to perform a direct detection of cosmic rays...



First measurement of differential energy spectra (1970)

VOLUME 28, NUMBER 15 PHYSICAL REVIEW LETTERS 10 APRIL 1972

Cosmic-Ray Proton and Helium Spectra above 50 GeV

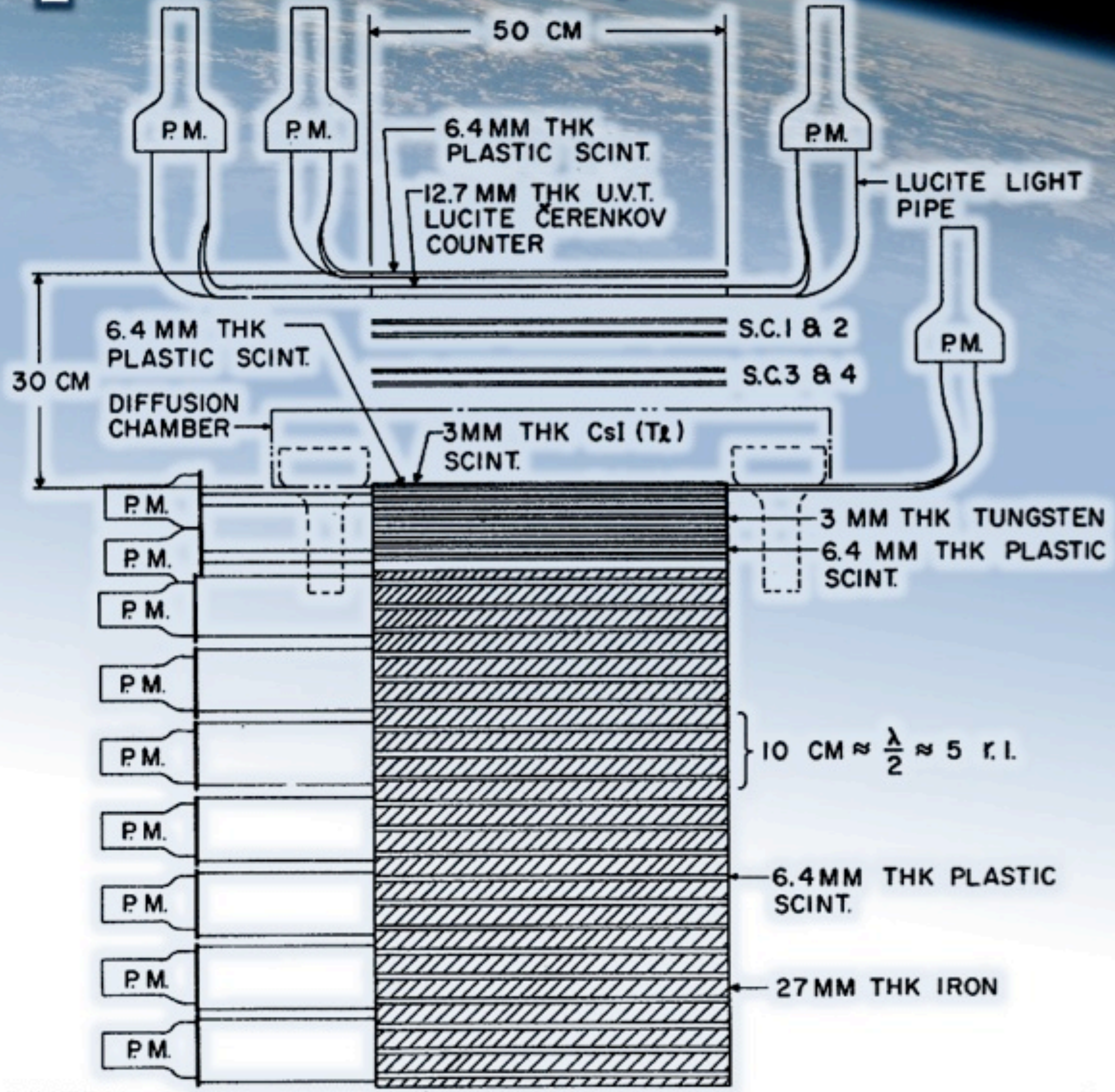
M. J. Ryan,* J. F. Ormes, and V. K. Balasubrahmanyan
Goddard Space Flight Center, Greenbelt, Maryland 20771

(Received 25 February 1972)

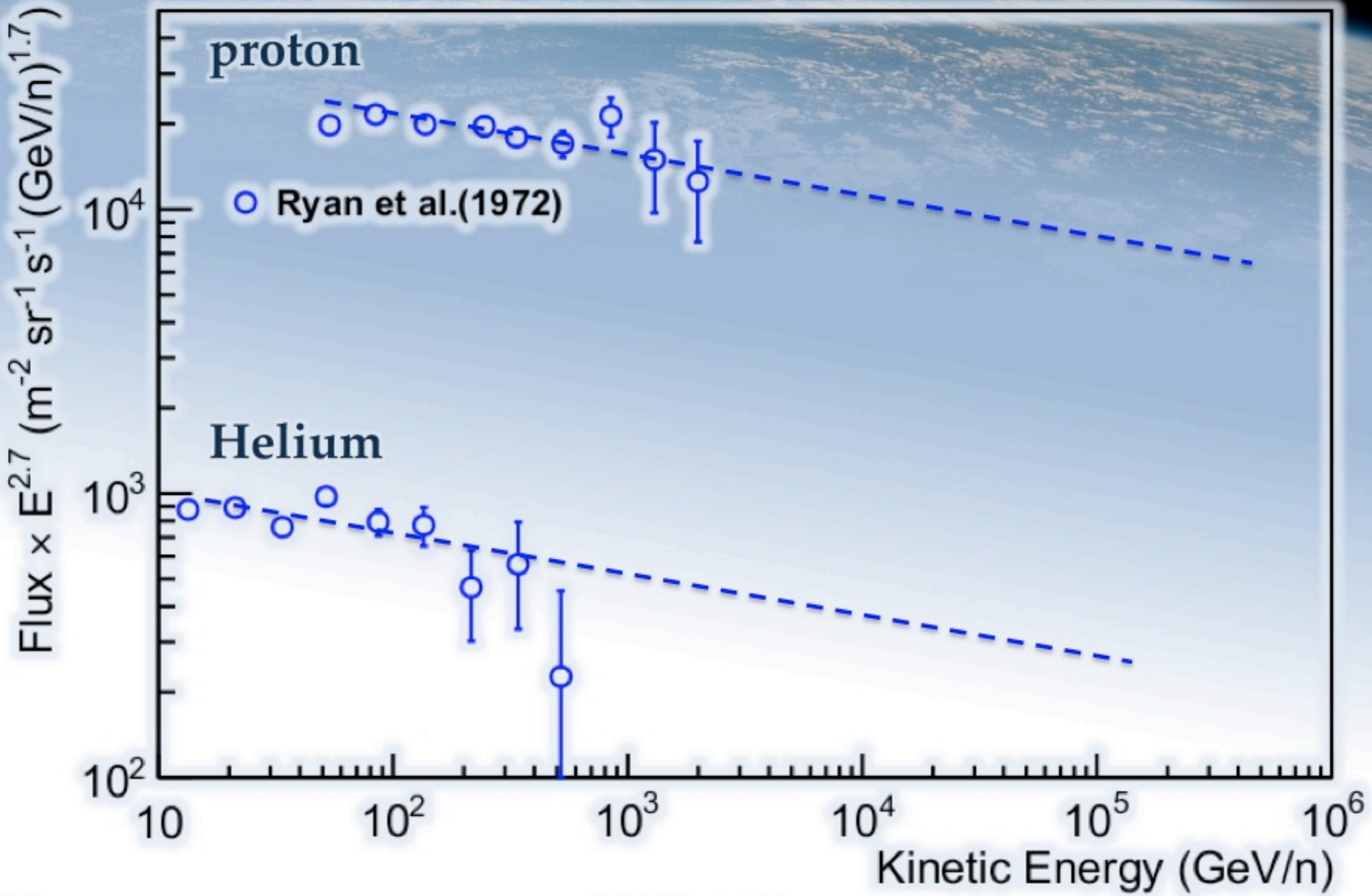
Differential energy spectra of cosmic-ray protons and He nuclei have been measured for the first time by an ionization spectrometer flown at balloon altitudes. The energy range extended from 50 to >1000 GeV. The observed differential intensities can be represented with power-law spectra with a slope of -2.75 ± 0.03 for protons and of -2.77 ± 0.05 for He nuclei. The proton-to-He ratio is 26 ± 3 at 40 GeV/nucleon and is constant within errors up to 400 GeV/nucleon.

First measurement of differential energy spectra (1970)

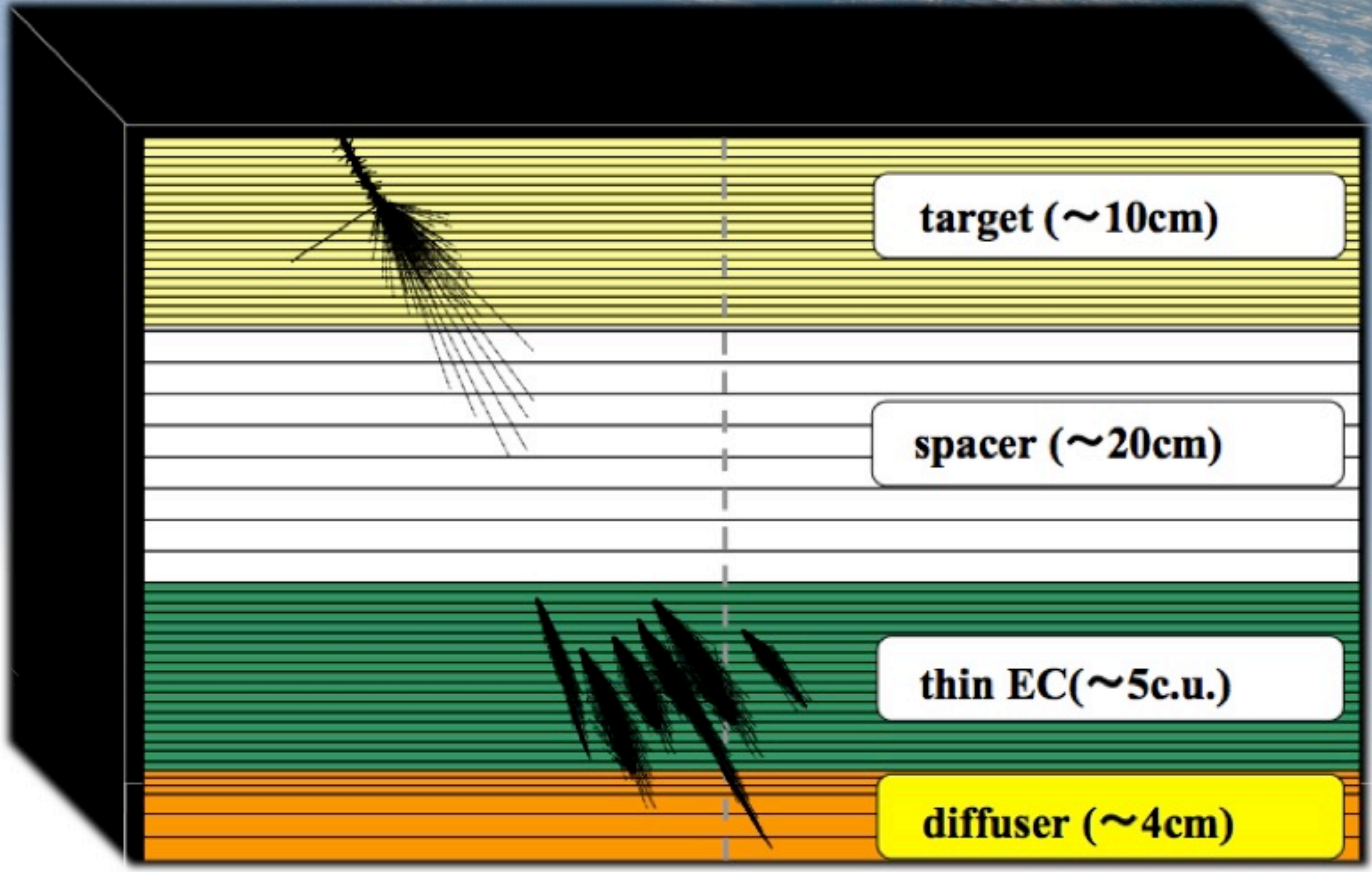
Calorimeter with 4 proton interaction length



First direct measurements (~1970)



RUNJOB : Emulsion Chamber (EC)

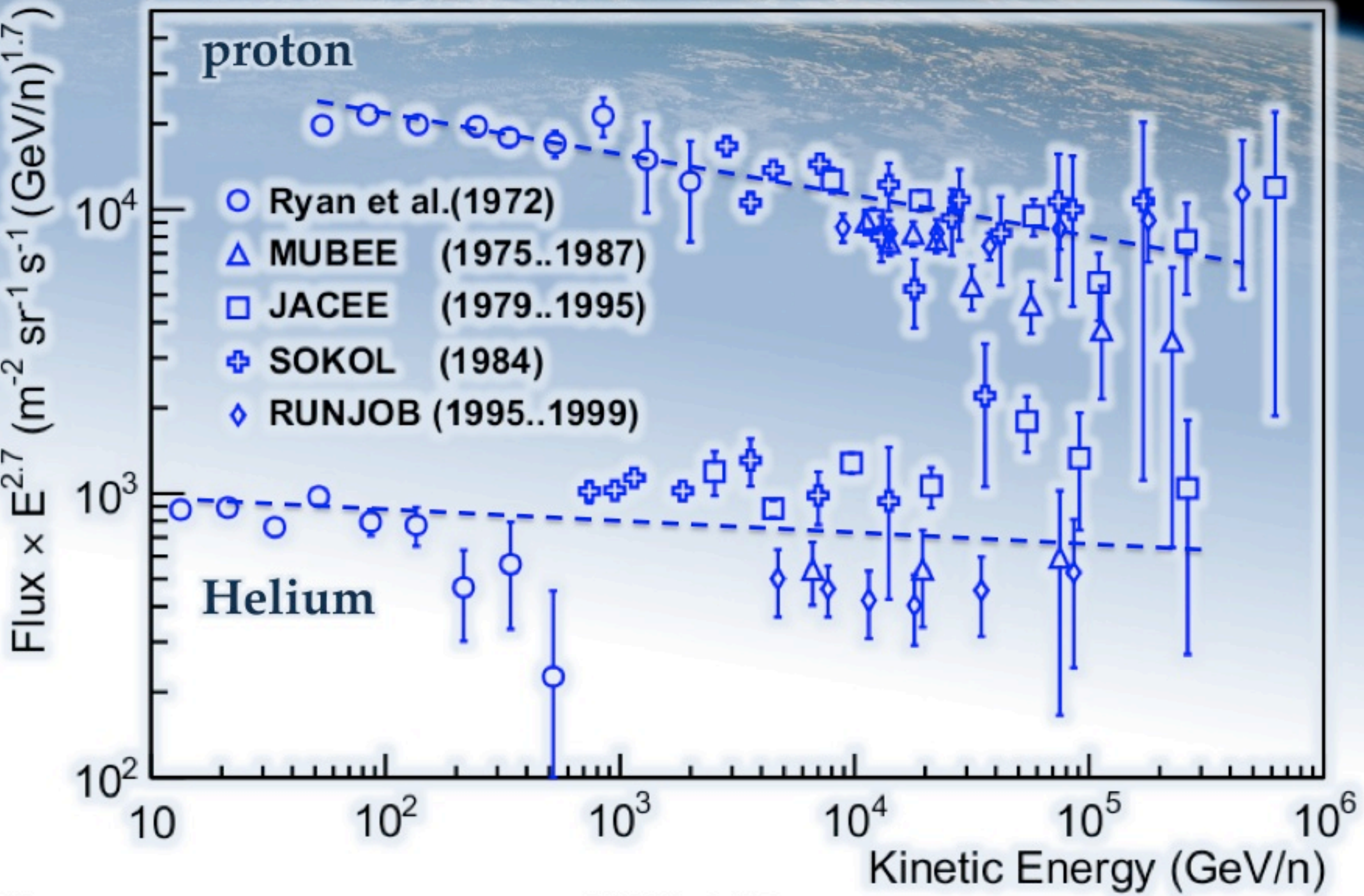

target (~10cm)

spacer (~20cm)

thin EC(~5c.u.)

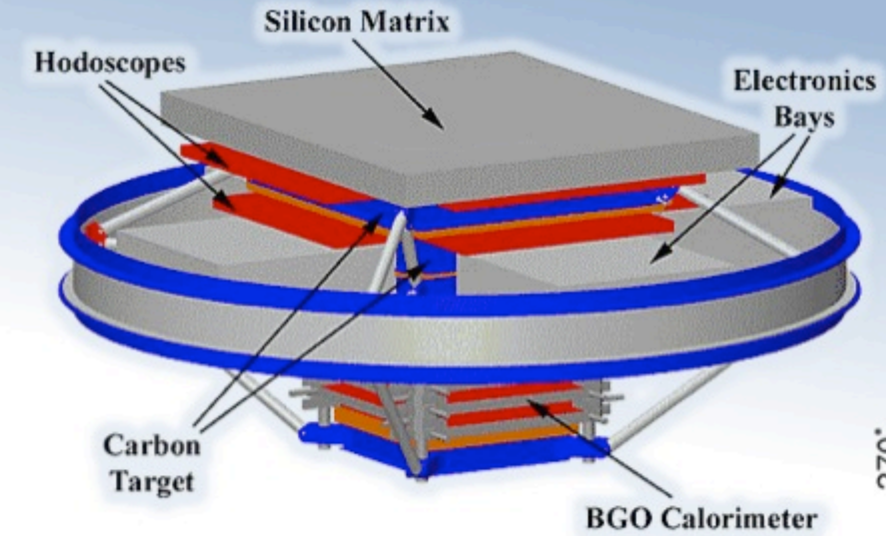
diffuser (~4cm)

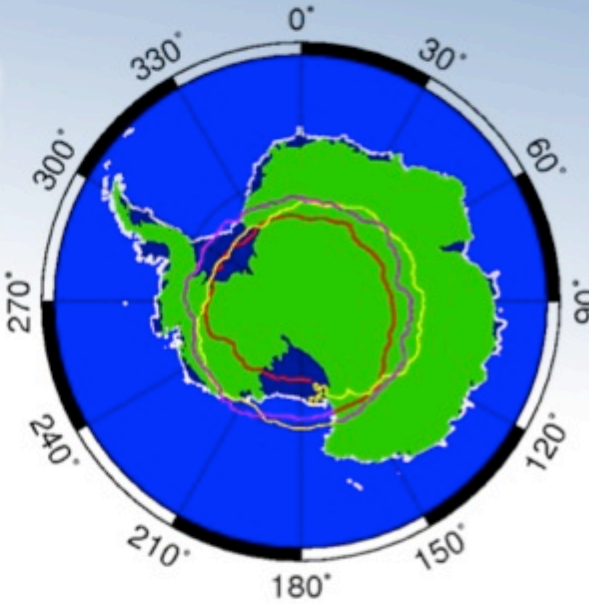
Measurements with EC (1980~1990)



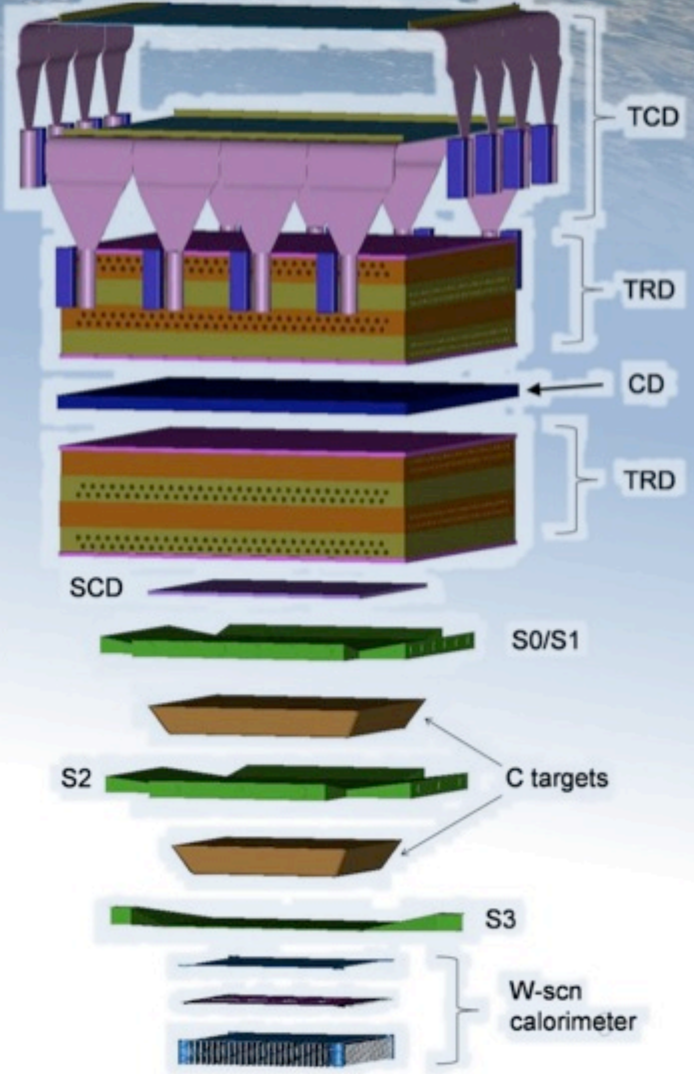
ATIC and CREAM

Advanced Thin Ionization Calorimeter (ATIC)

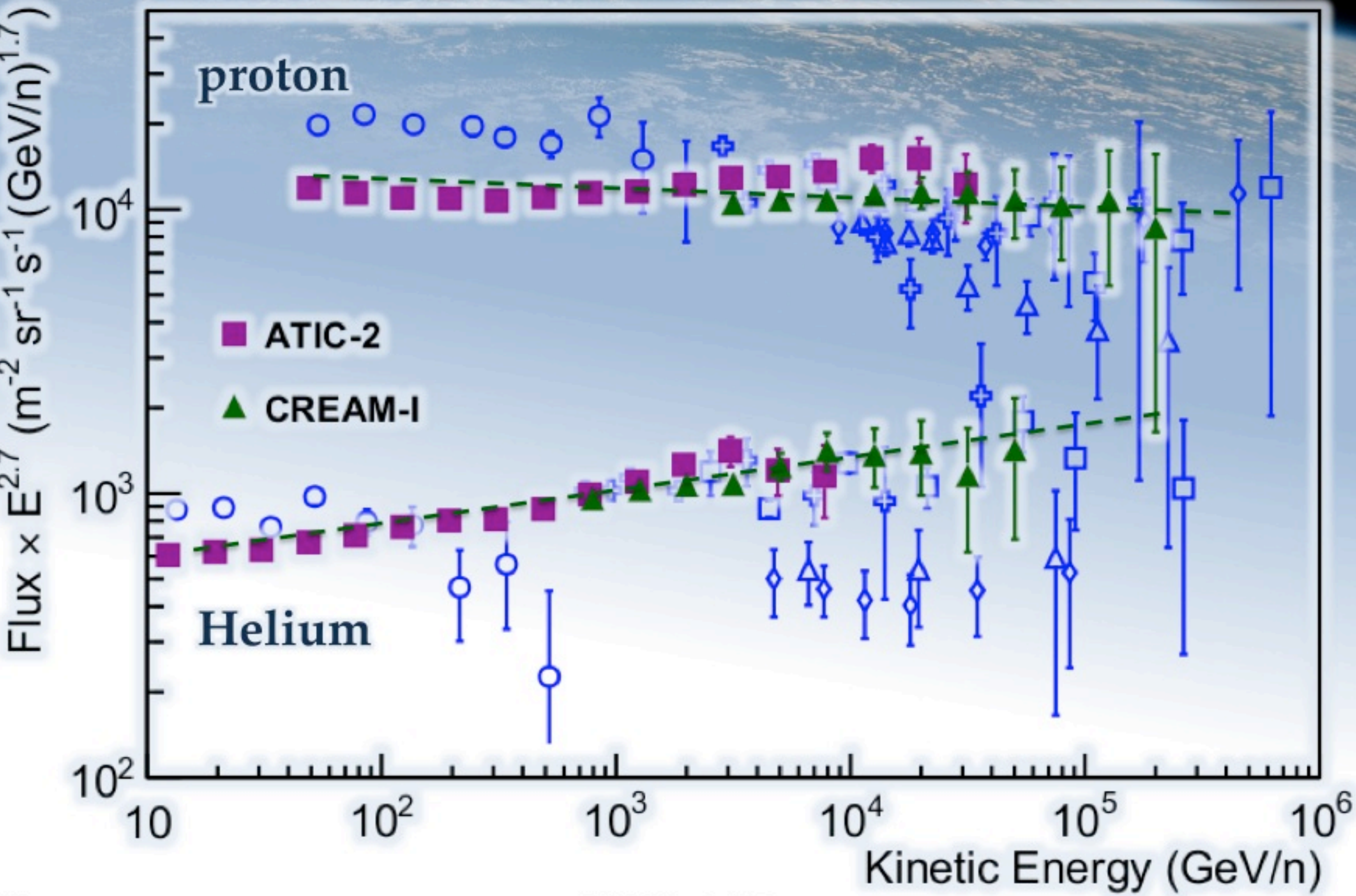




Cosmic Ray Energetics And Mass (CREAM)



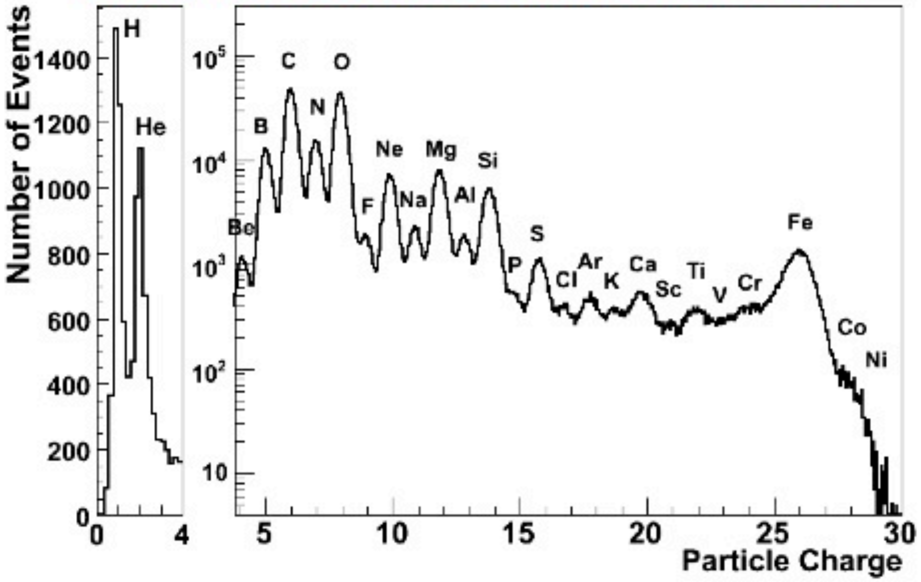
ATIC and CREAM



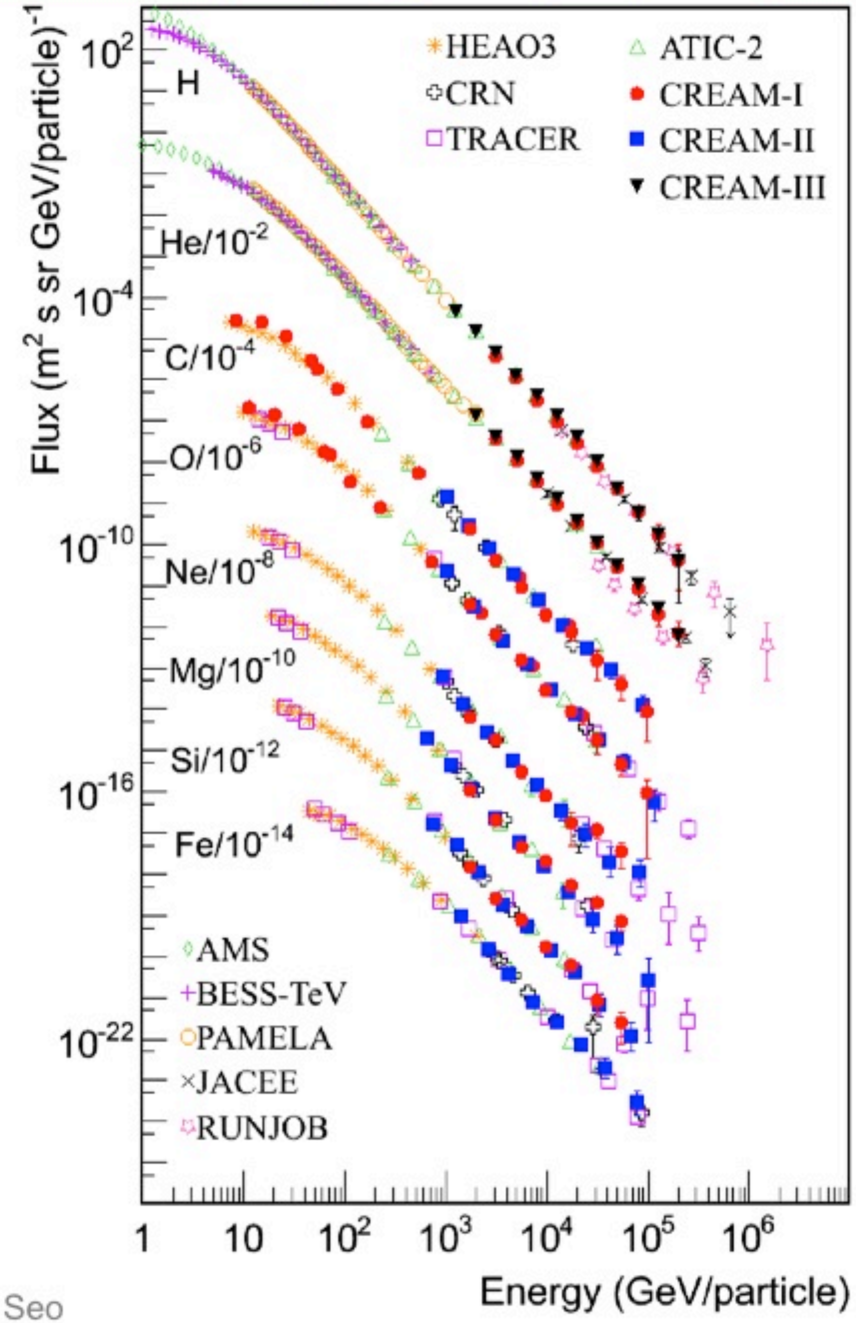
Elemental Spectra over 4 decades in energy

Ahn et al., ApJ **715**, *1400*, 2010; Ahn et al. ApJ **707**, *593*, 2009

Excellent charge resolution from SCD



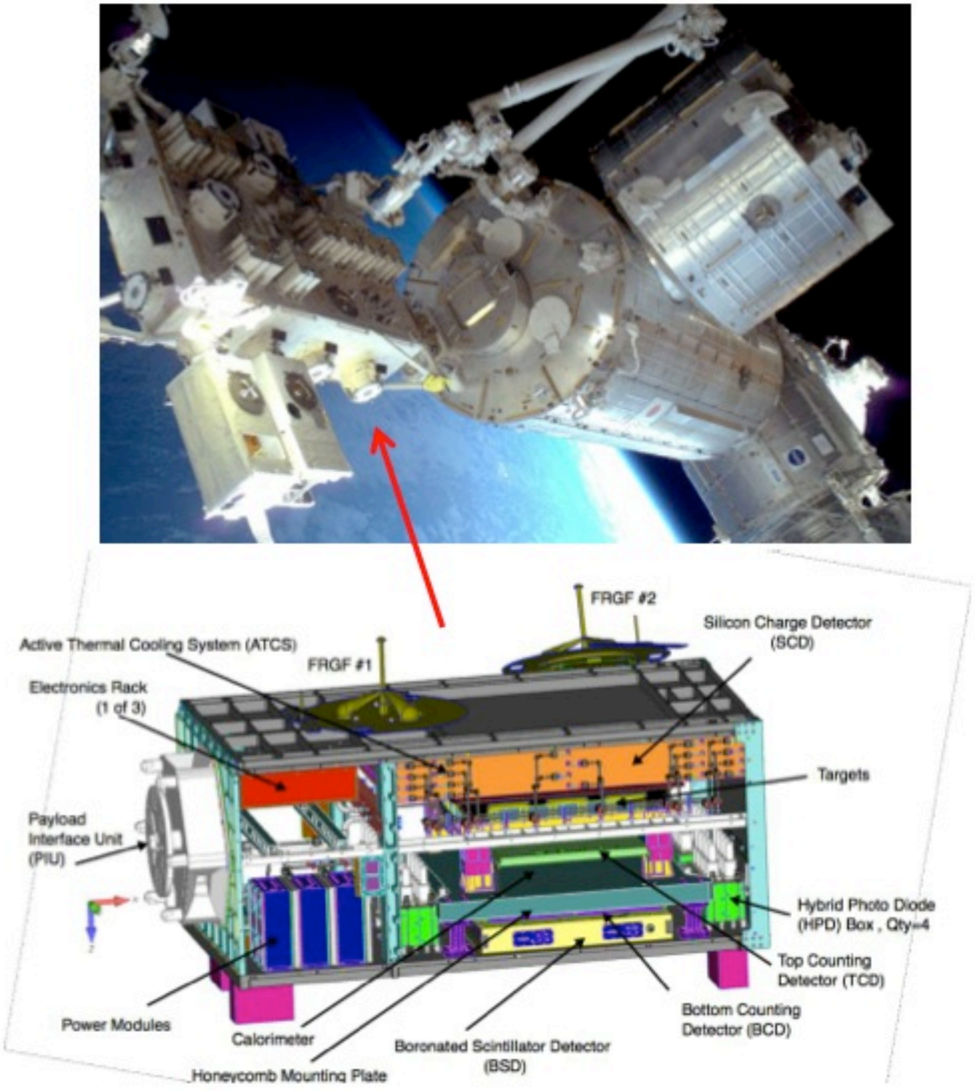
Distribution of cosmic-ray charge measured with the SCD. The individual elements are clearly identified with excellent charge resolution. The relative abundance in this plot has no physical significance



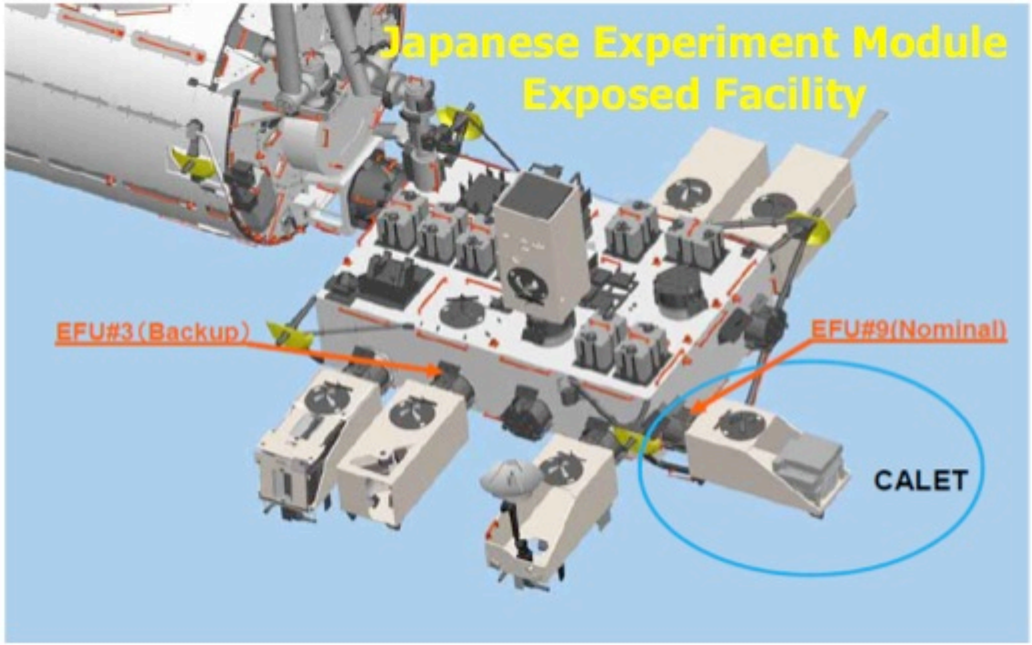
CREAM on the ISS

Mission Design

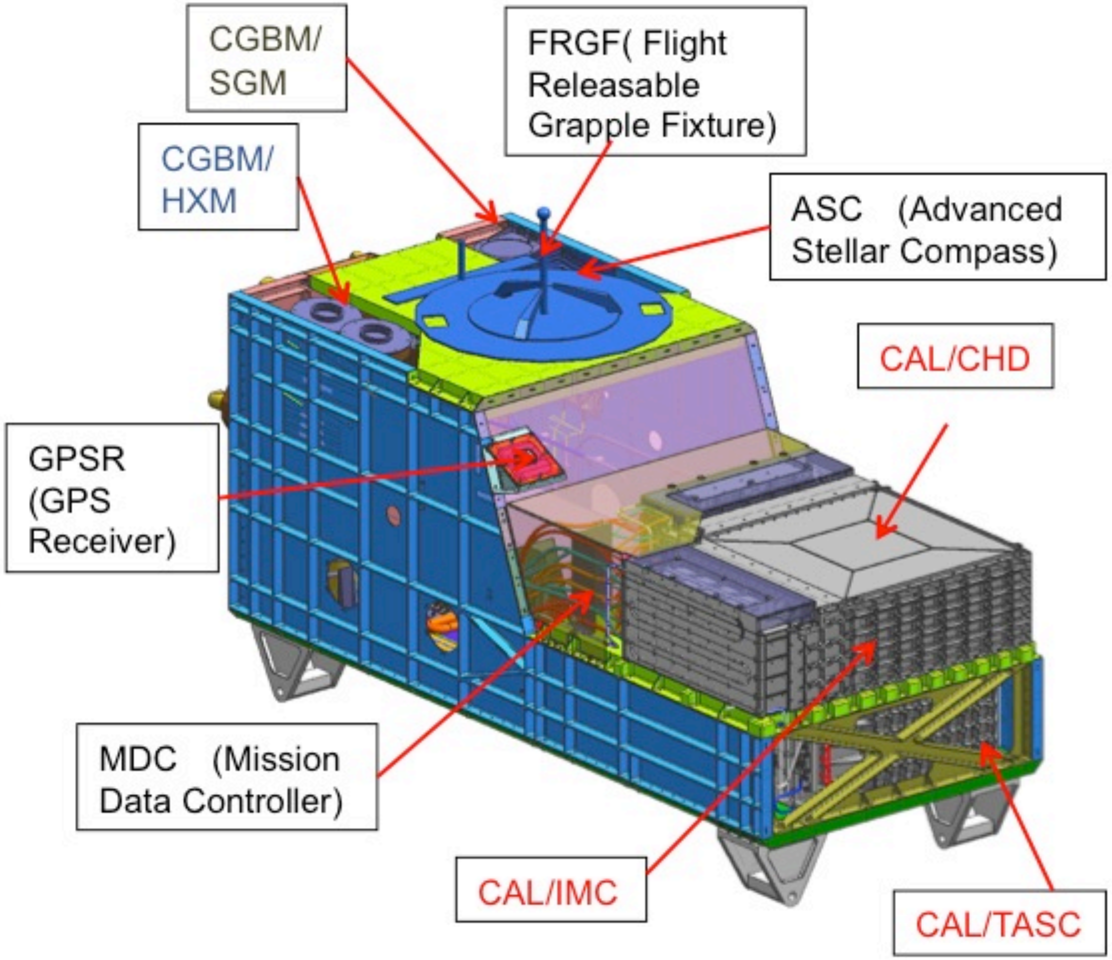
- Launch in Dec. 2014 ~ 2015
  - SpaceX-6 (External Cargo)
- ISS Location: JAXA's JEM-EF 2
- Mass
  - Up Mass: Payload- 1342 kg with reserves
  - Down Mass: 0 kg
- Power: Payload- 755 Watts
- Data rate: 350 kbps



CALET Payload Overview



☐ Launch carrier: HTV-5
☐ Planned location: JEM Port 9
☐ Launch target date: FY 2014
☐ Mission period: More than 2 years
(5 years target)
☐ Data rate:
  ➢ Medium data rate: 300 kbps
  ➢ Low data rate: 35 kbps (20-50kbps)



☐ Mass: 650kg (Max)
☐ JEM/EF Standard Payload Size
(1850L×800W×1000H in mm)
☐ Power: 650W (Nominal)

Magnetic Rigidity

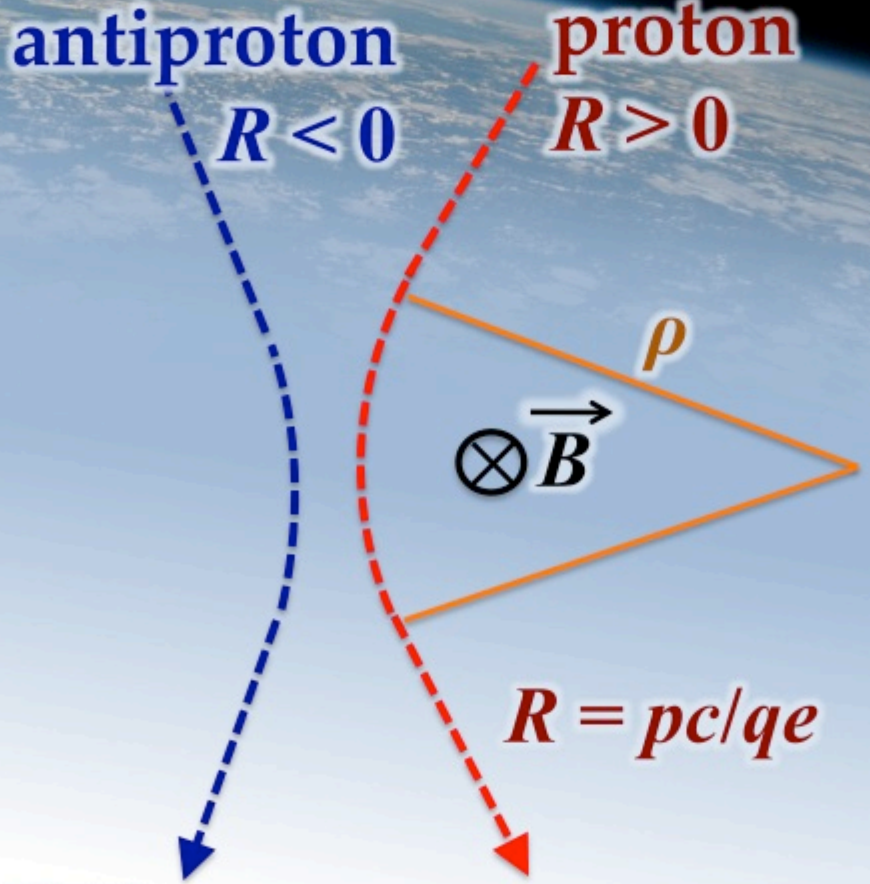
Curvature → Rigidity

$p = qe\rho B$ [eV/c]

$R = c\rho B$ ($R = pc/qe$ [V])

$R/\text{GV} \approx 0.3\ (\rho/\text{m})\ (B/\text{Testa})$

$q < 0 \rightarrow R < 0$



e.g.

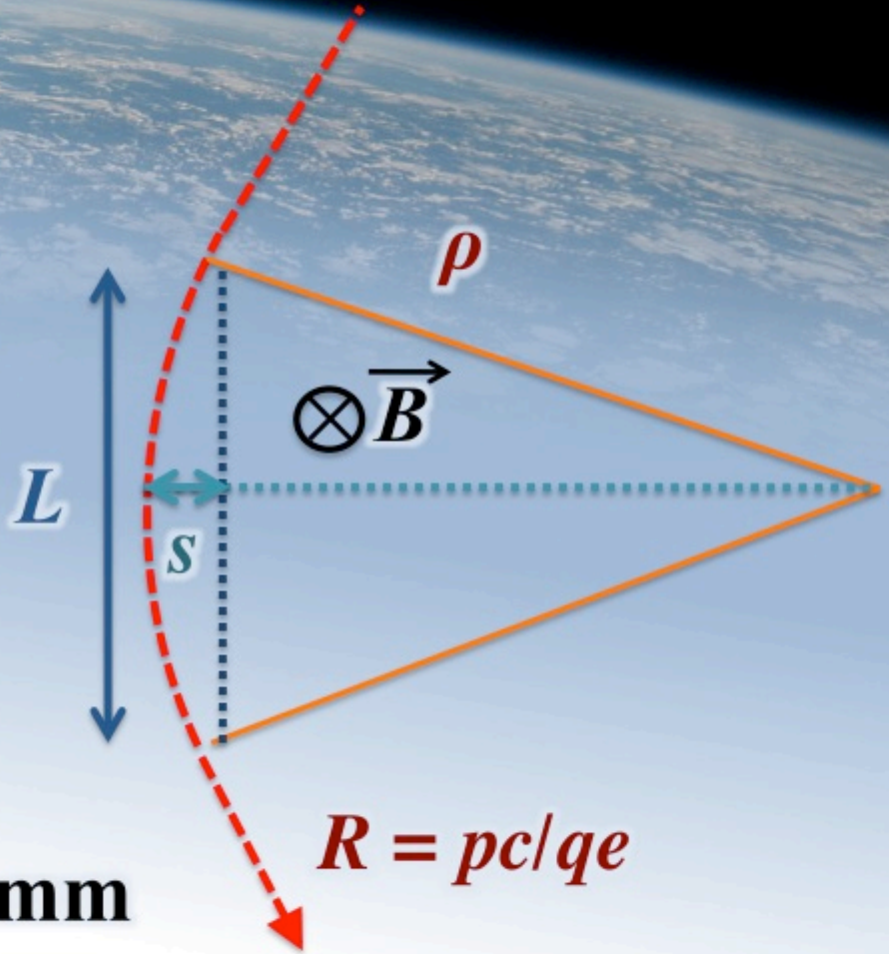
$p = 1$ GeV/c, $q = 1$ ($R = 1$ GV),

$B = 1$ Tesla → $\rho \approx 3.3$ m

Rigidity resolution

$$s \approx \frac{0.3BL^2}{8R}$$

$$\boxed{\Delta(1/R) = \frac{\Delta R}{R^2} \approx \frac{8\Delta s}{0.3BL^2}}$$



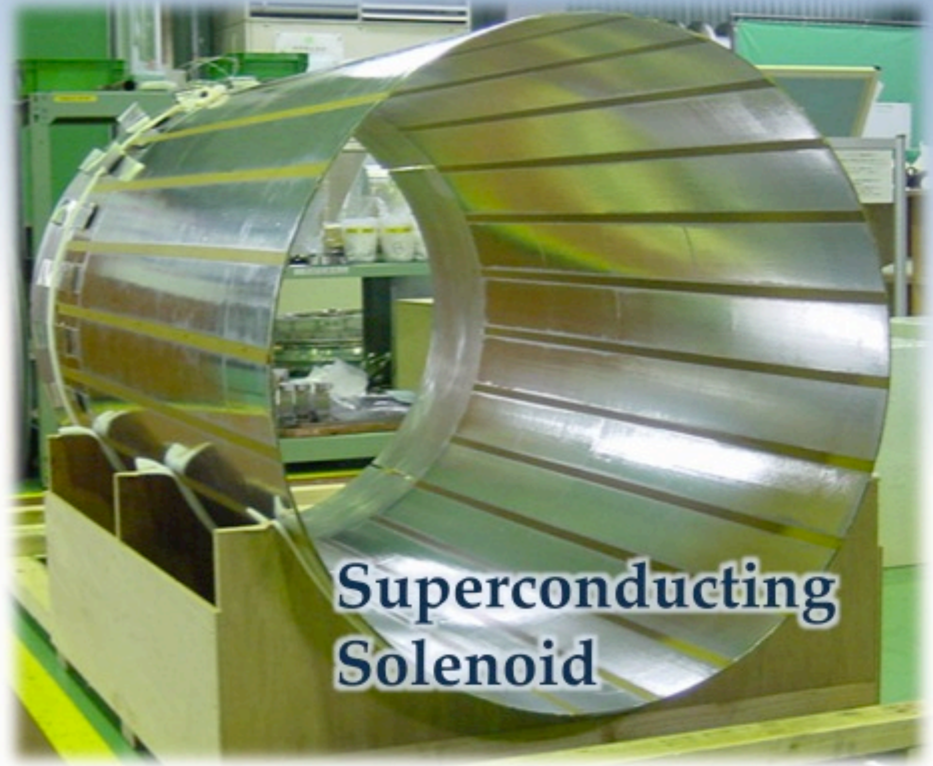
e.g.

$B = 1$ Tesla, $L = 1$ m, $\Delta s = 0.1$ mm

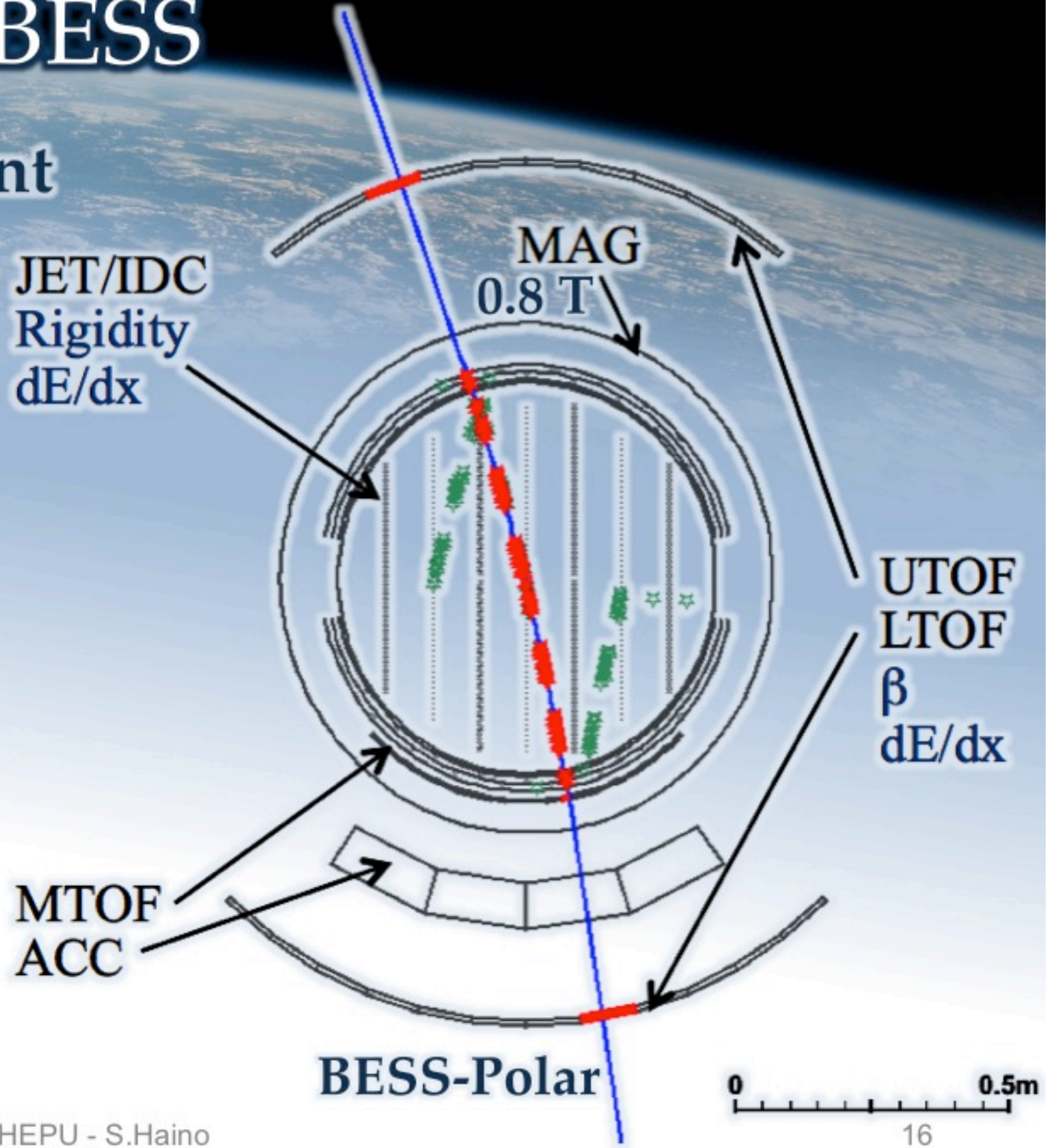
$\rightarrow \Delta R/R \approx 2.7\ \%\ (R = 10$ GV$)$

BESS

Balloon-borne Experiment with a Superconducting Spectrometer



Superconducting Solenoid



JET/IDC
Rigidity
dE/dx

MAG
0.8 T

UTOF
LTOF
β
dE/dx

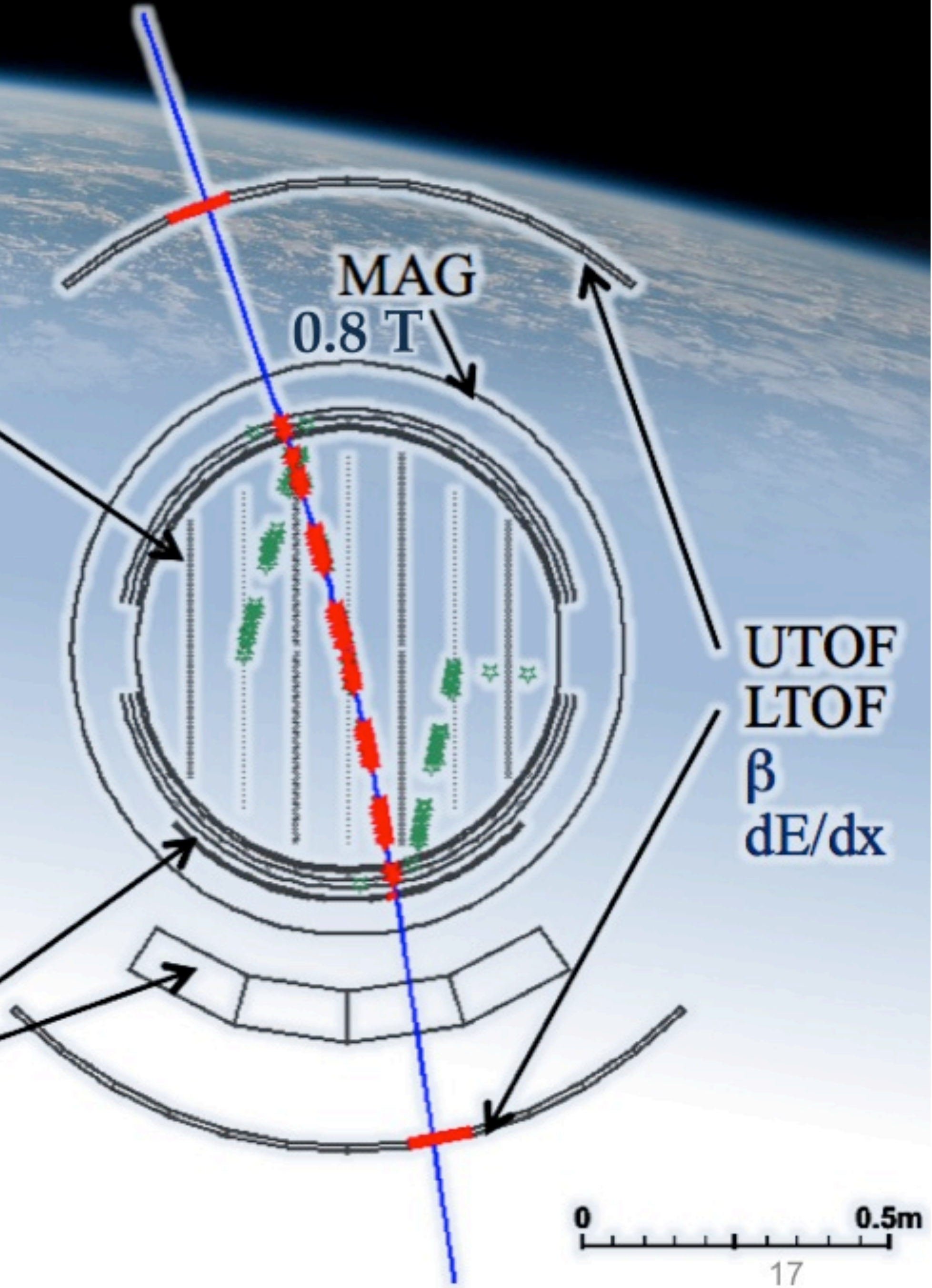
MTOF
ACC

BESS-Polar

BESS

Balloon-borne Experiment with a Superconducting Spectrometer

BESS-Polar in Antarctica



JET/IDC
Rigidity
dE/dx

MAG
0.8 T

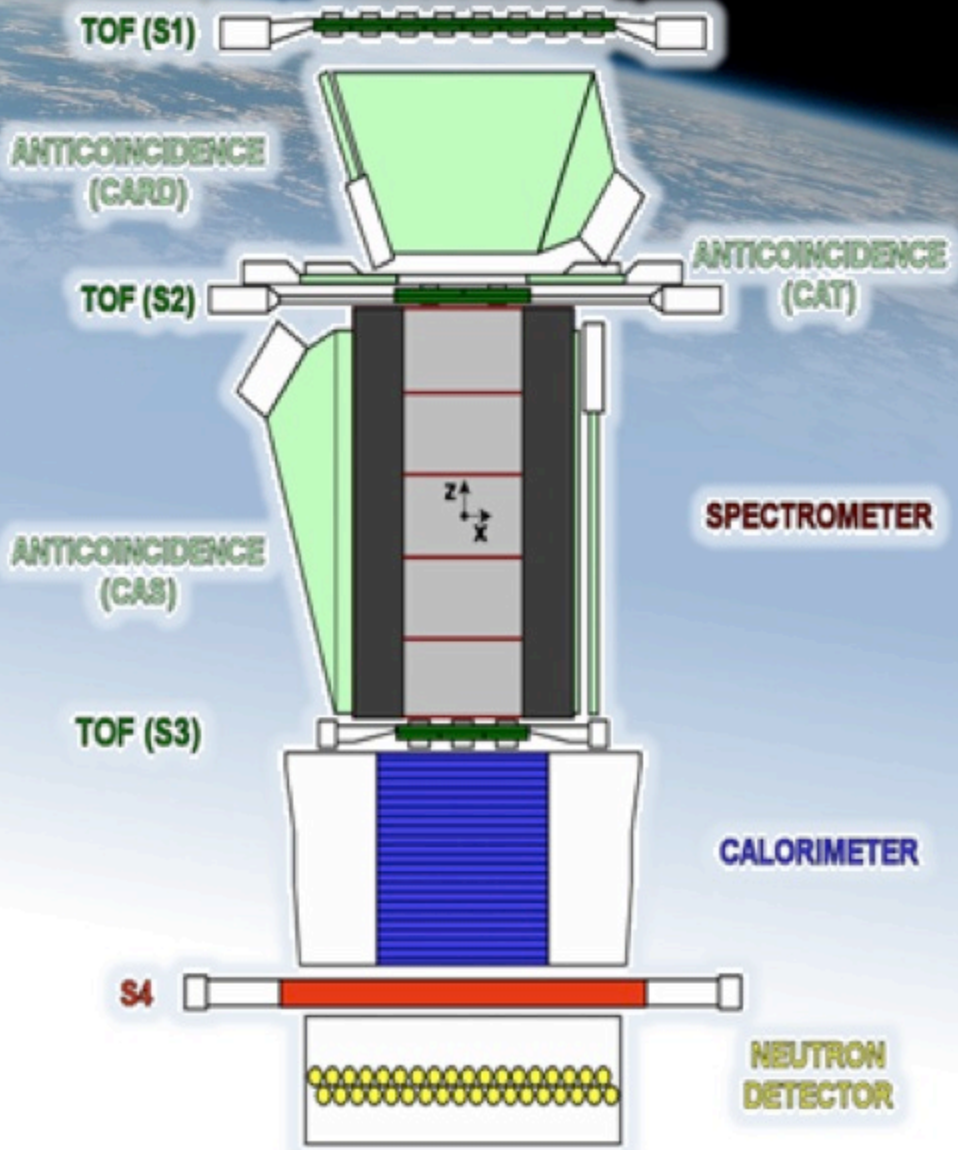
UTOF
LTOF
β
dE/dx

MTOF
ACC

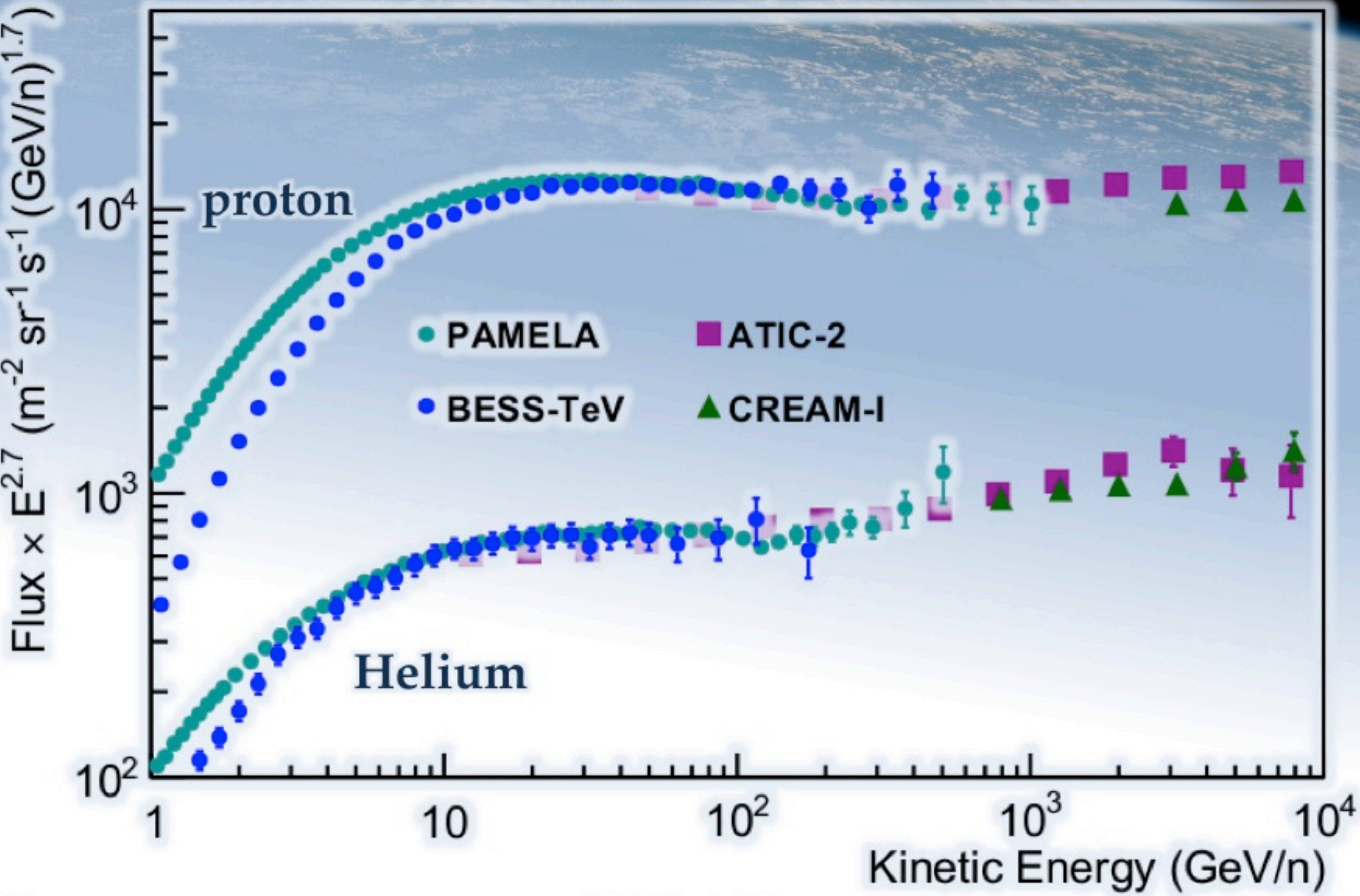
PAMELA

Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

Launched
in June/2006
by Soyuz-U rocket

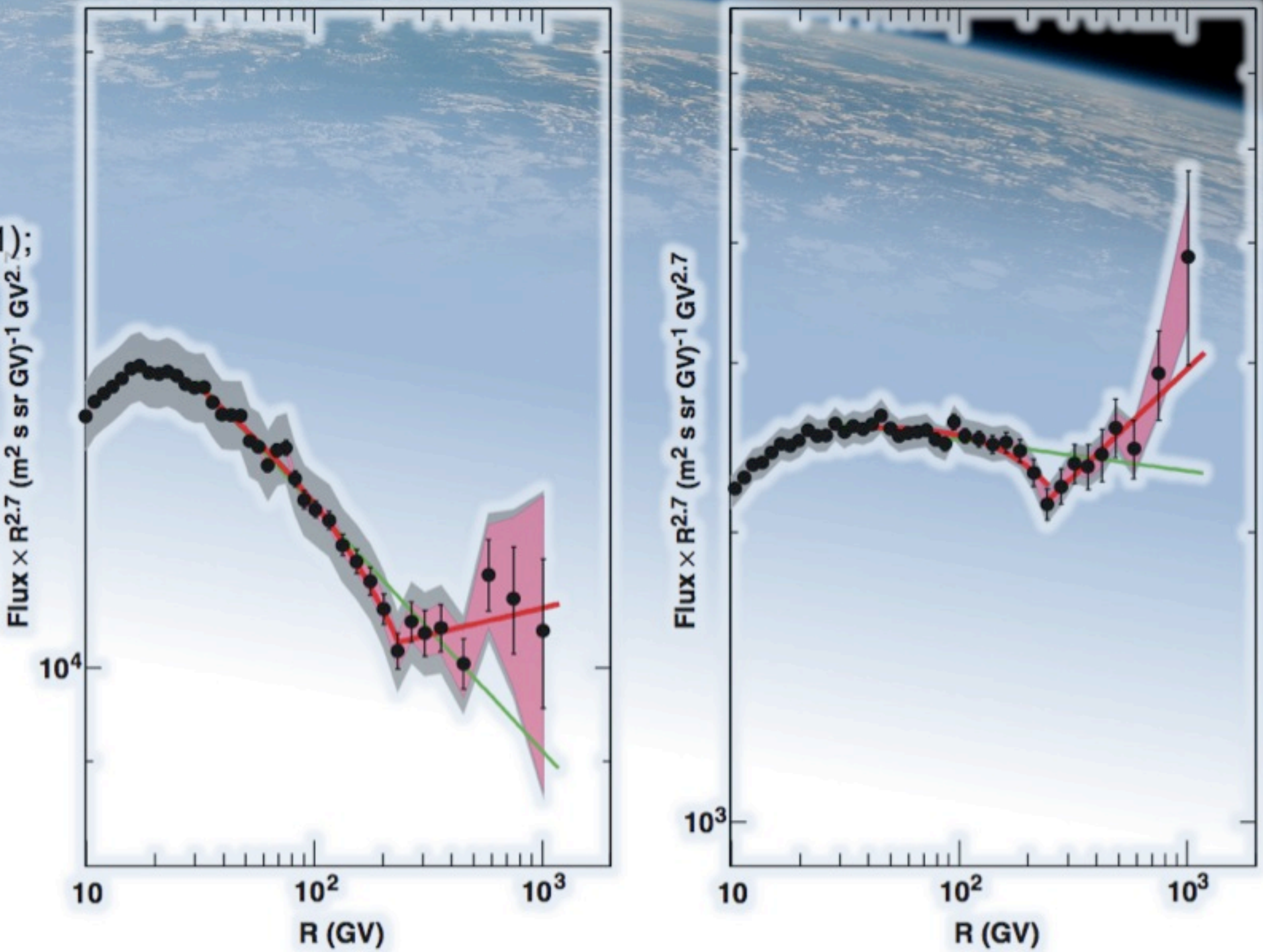


BESS and PAMELA

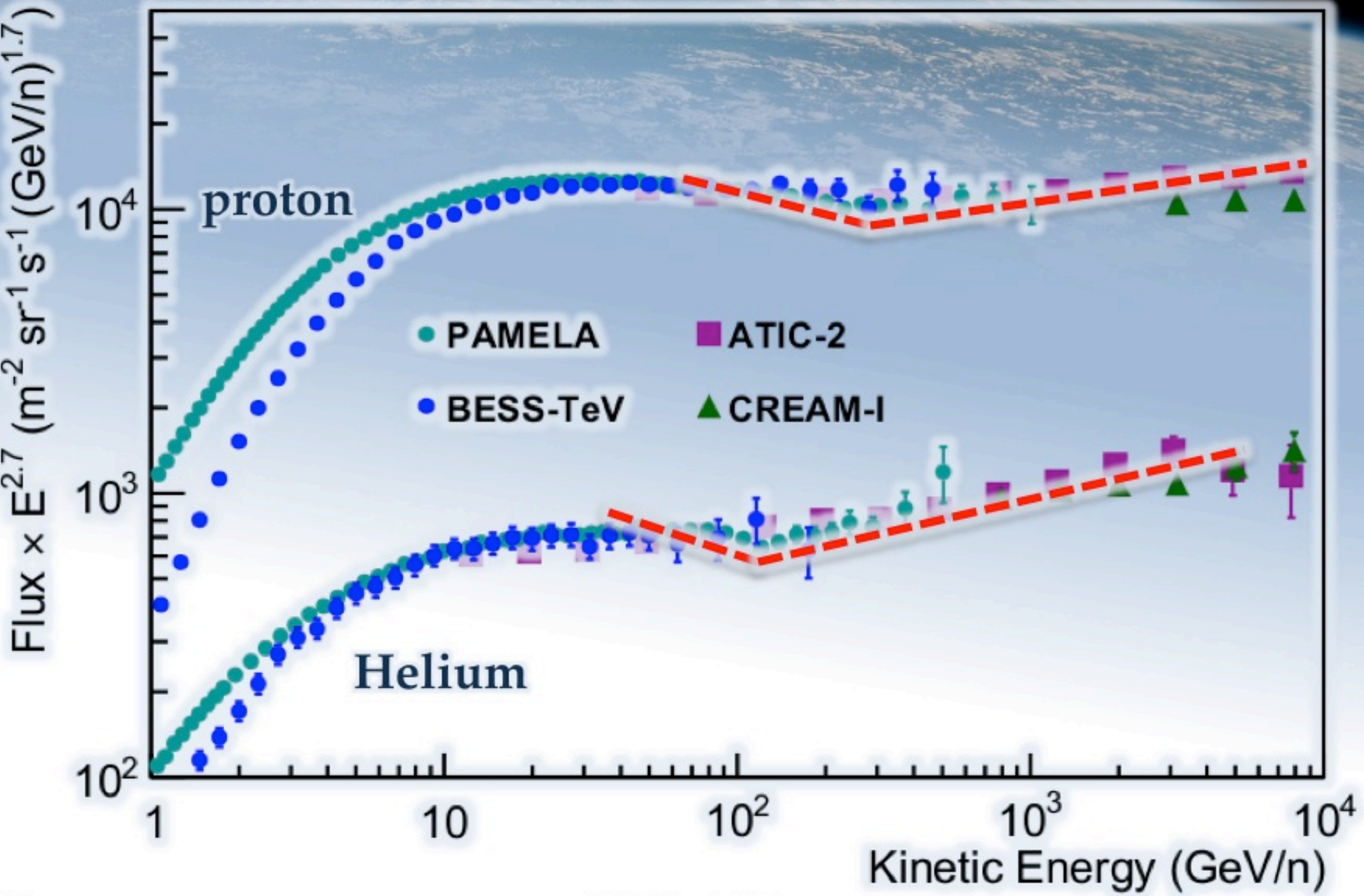


PAMELA break

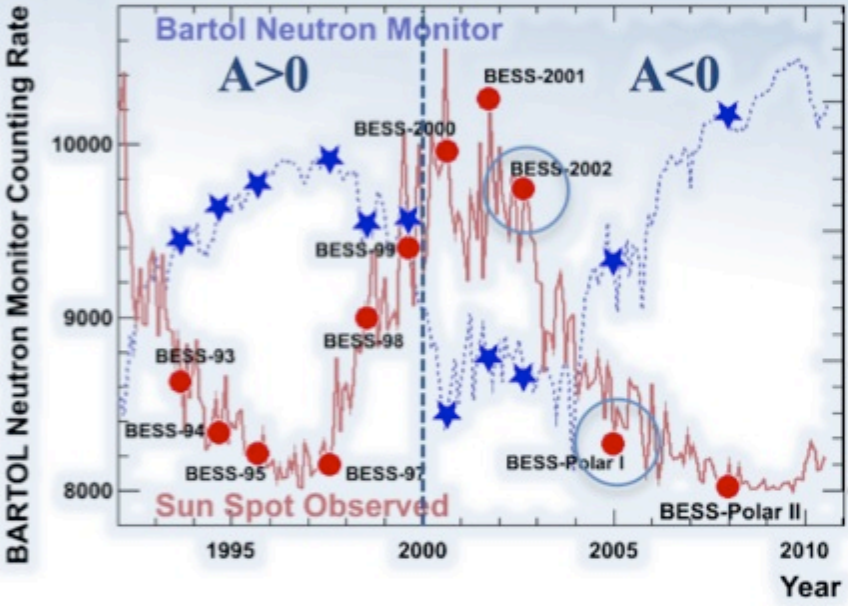
O. Adriani *et al.*
Science **332**, 69 (2011);

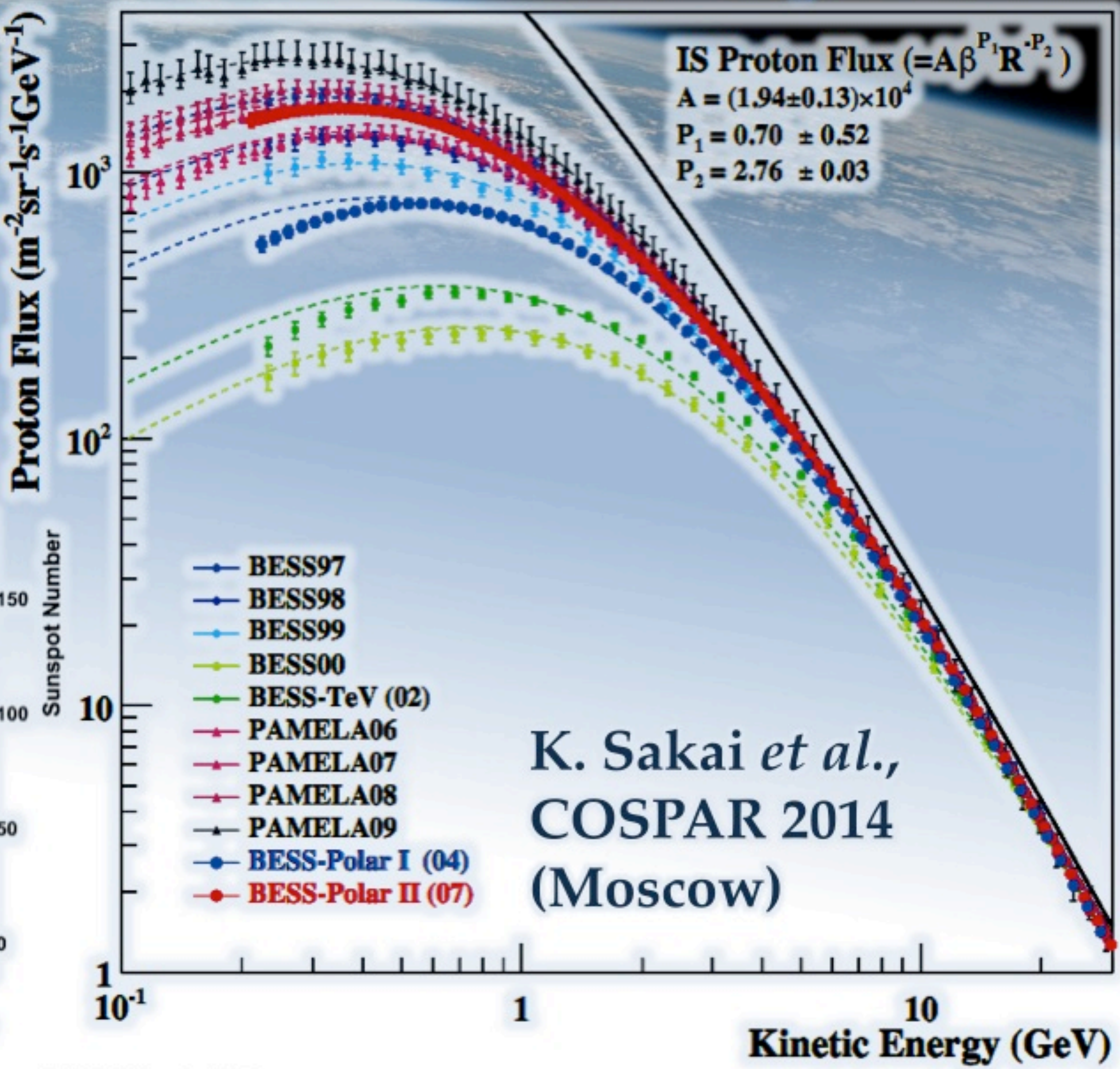


Break can connect GeV to TeV



Solar modulation traced over a cycle





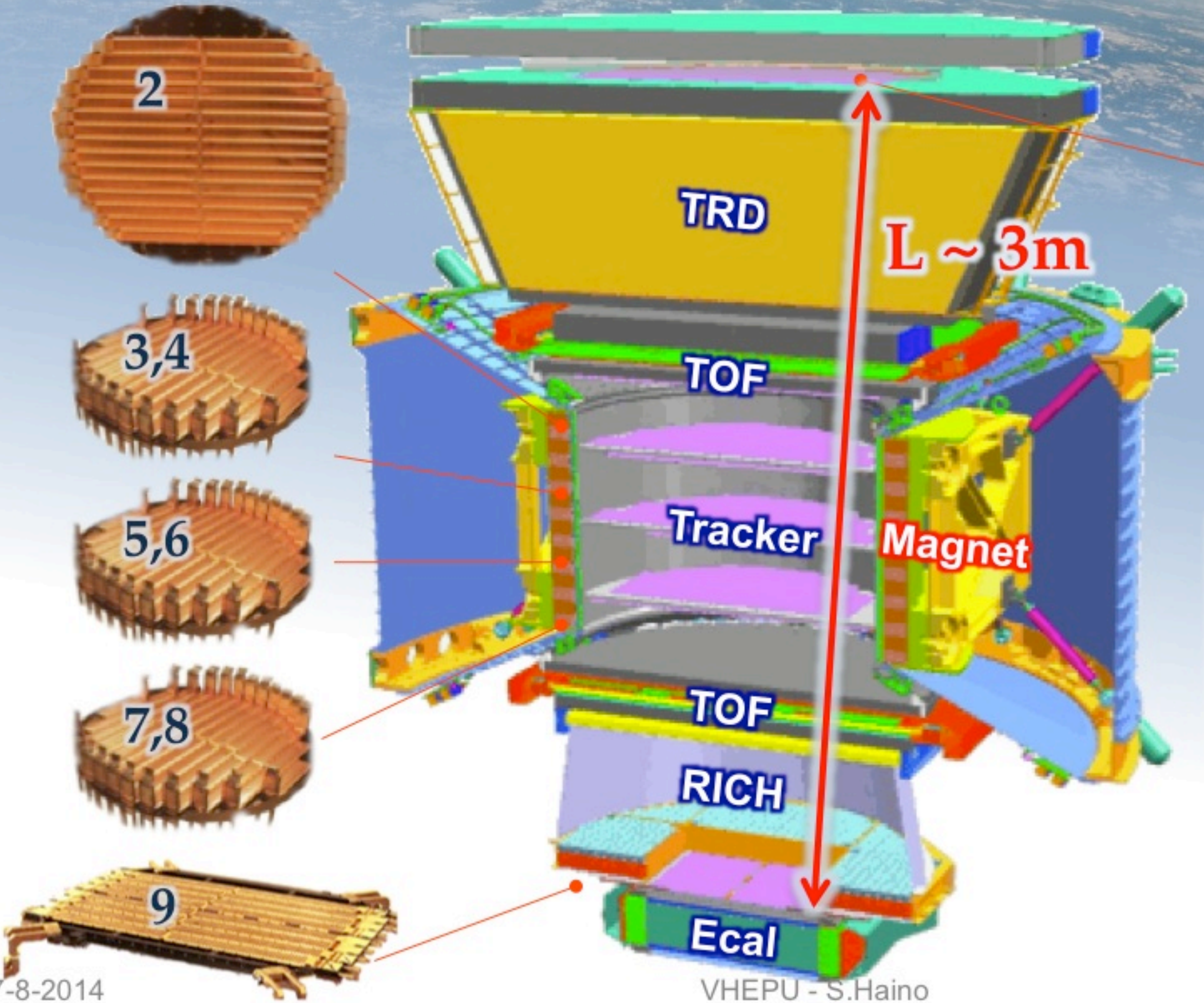
K. Sakai *et al.*,
COSPAR 2014
(Moscow)

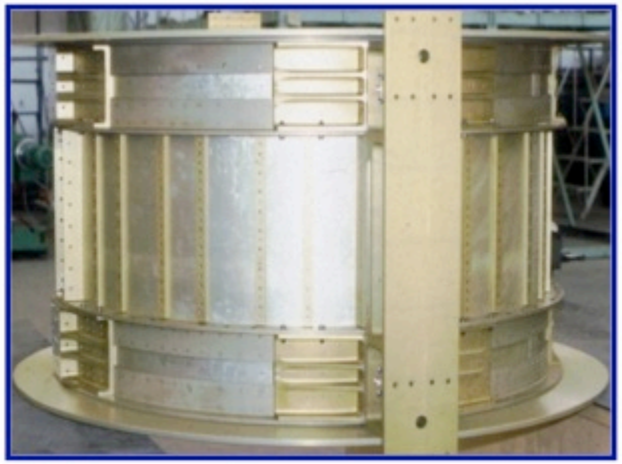
Alpha Magnetic Spectrometer (AMS-02) on the ISS

Installed on 19/May/2011

AMS is continuously recording
~16 billion Cosmic-Ray events every year...

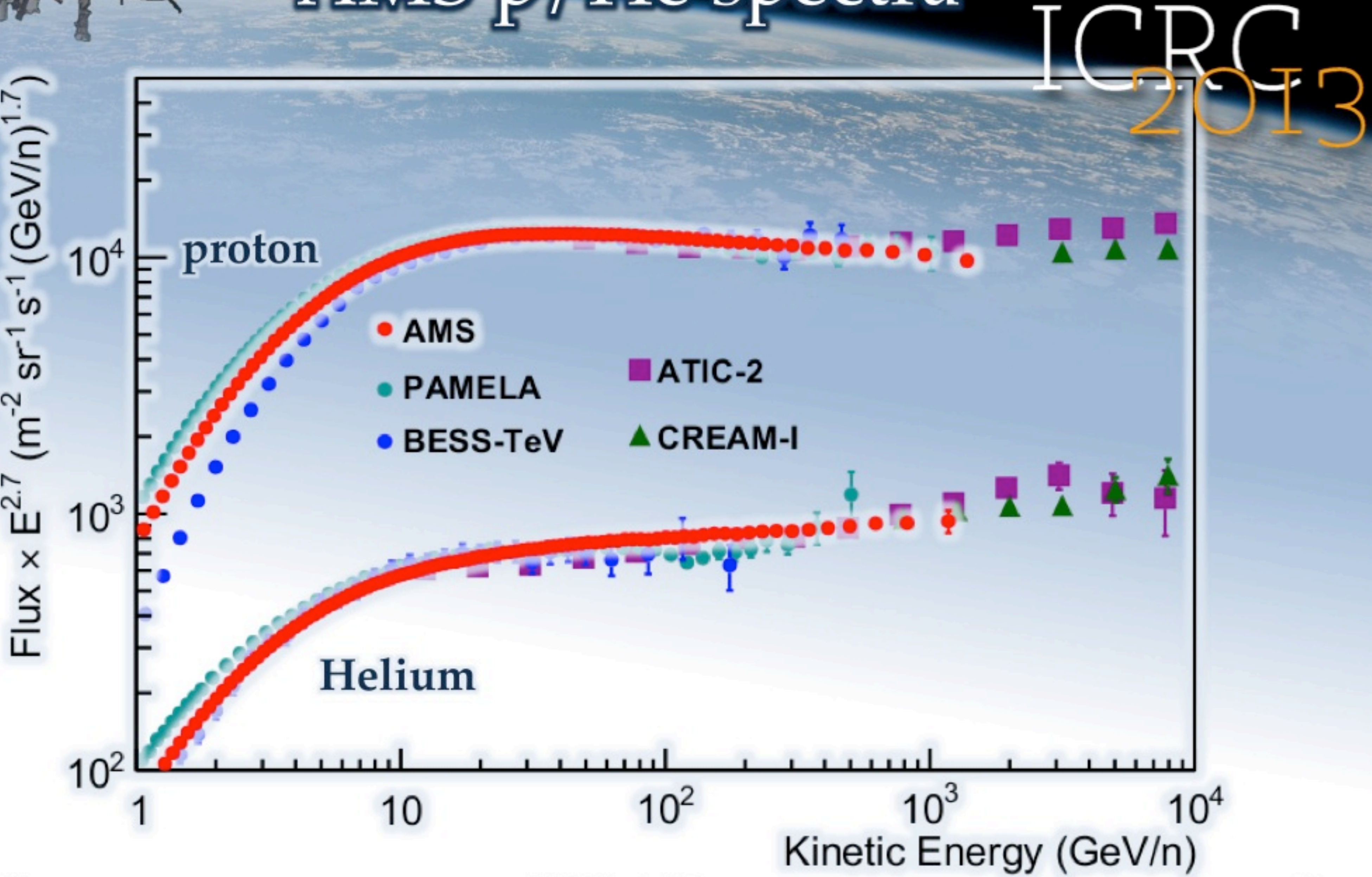
AMS – 9 layers of silicon tracker



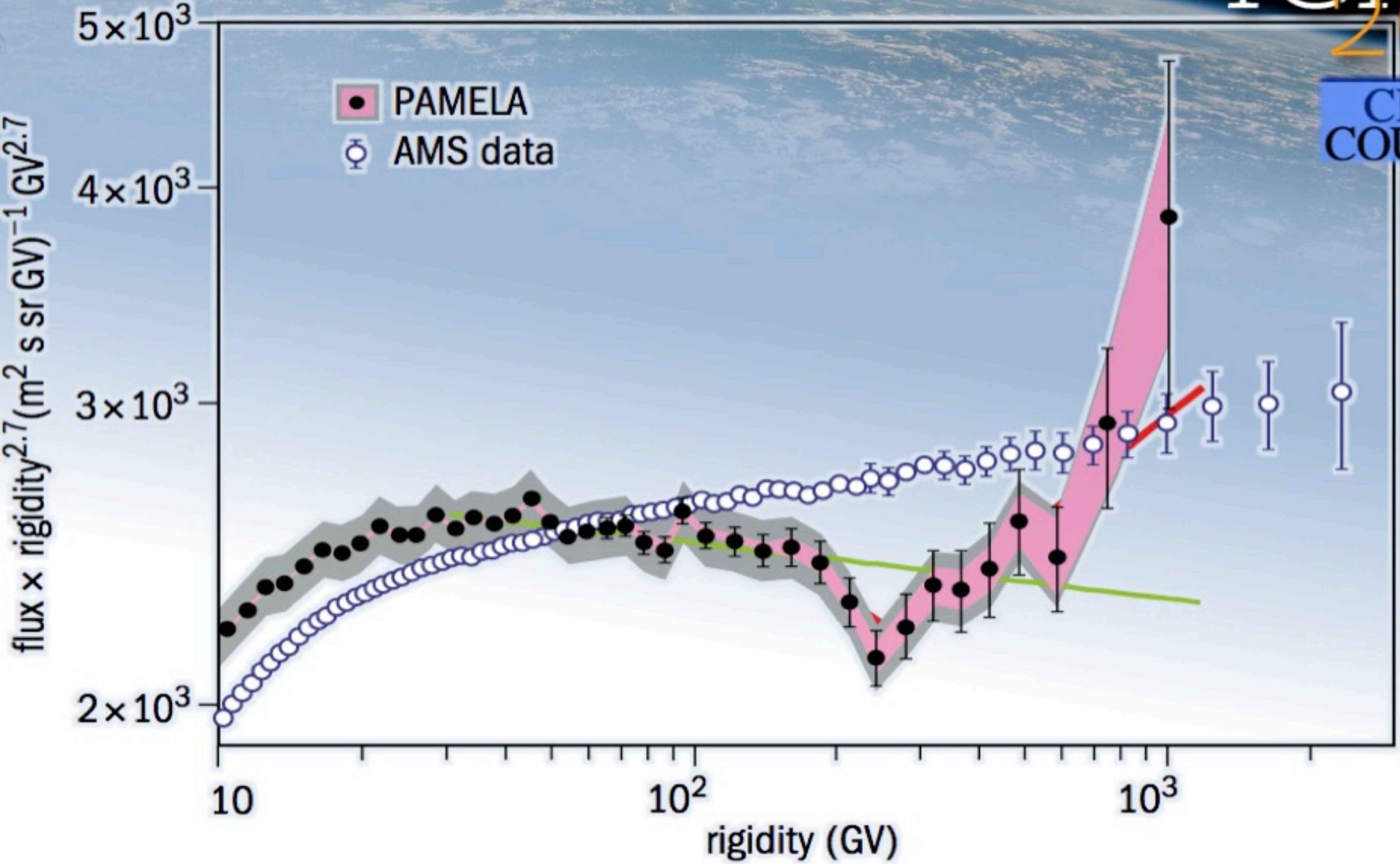


Magnet

AMS p/He spectra



He comparison



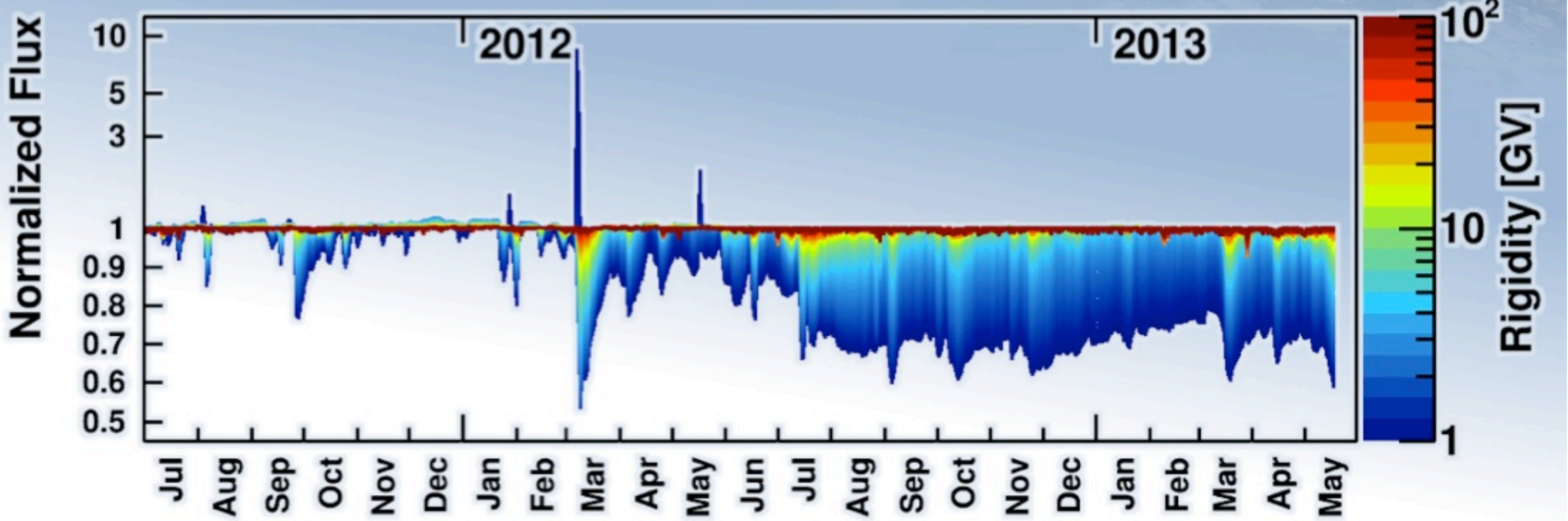
ICRC 2013

CERN COURIER

Daily Proton flux

ICRC 2013

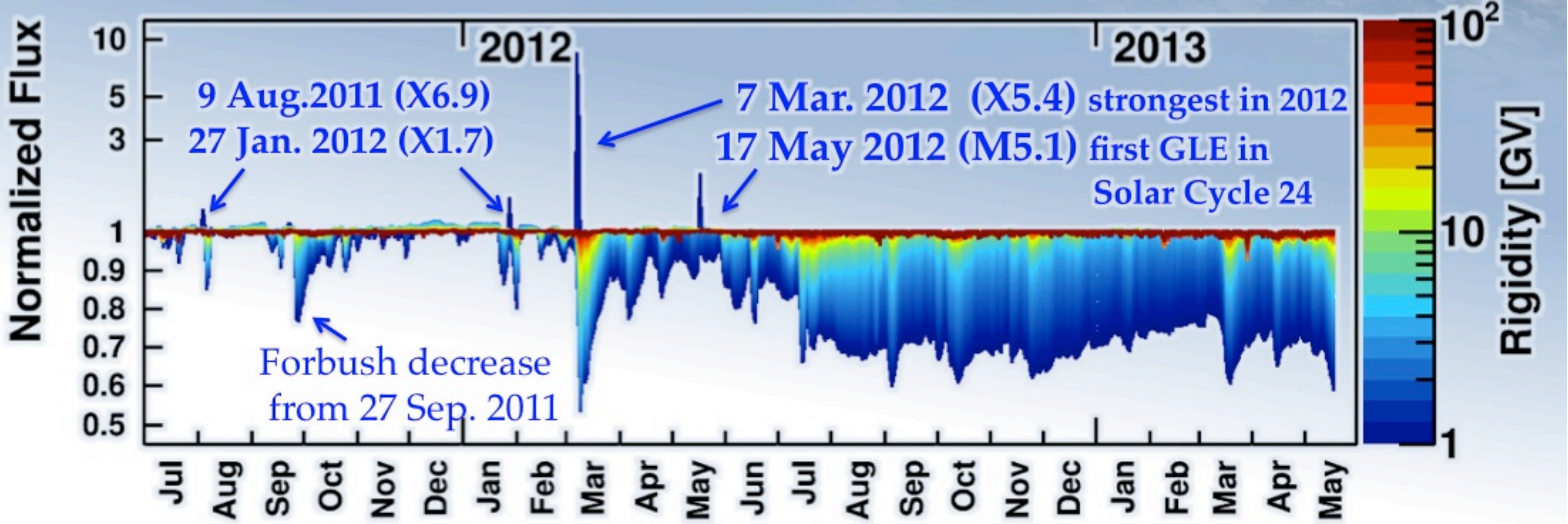
Stat. error : < ~1% (R < 20 GV)



Daily Proton flux

ICRC 2013

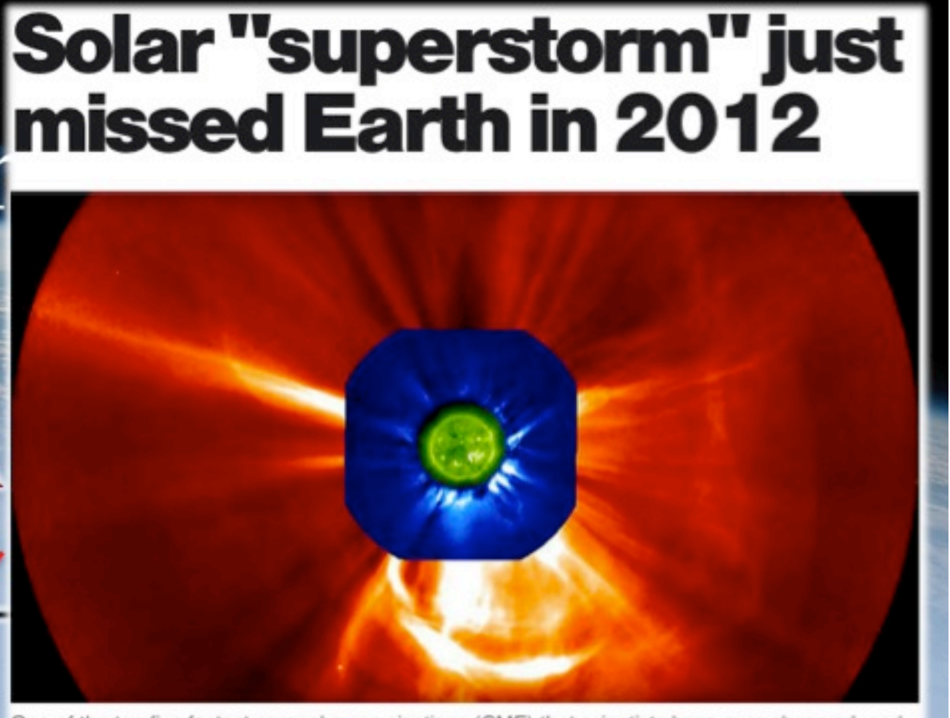
Stat. error : < ~1% (R < 20 GV)



Daily Proton

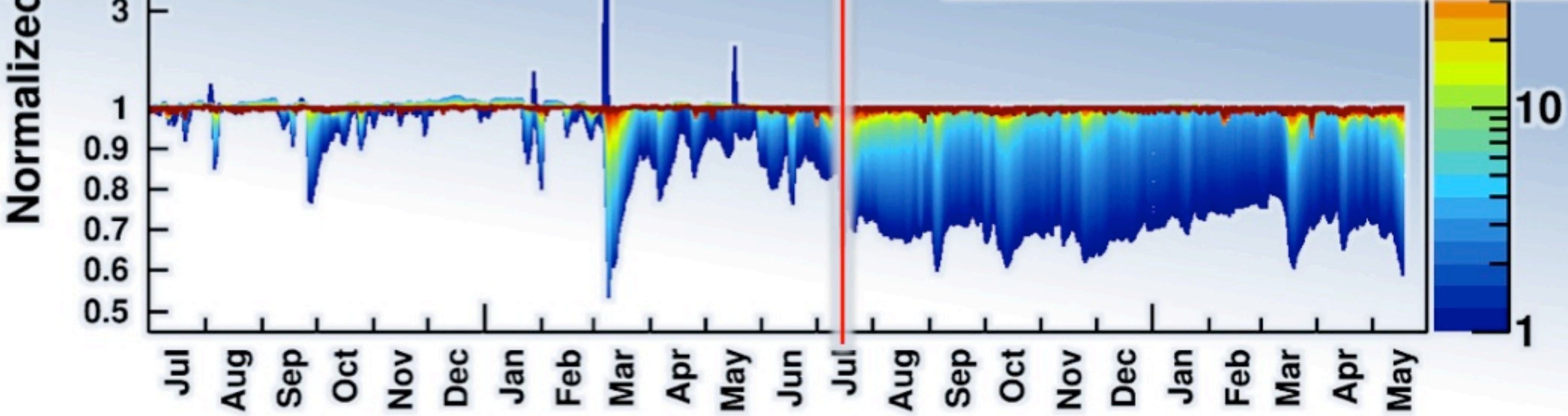
"If it had hit, we would still be picking up the pieces," Daniel Baker of the University of Colorado said in a statement released by NASA

July 23, 2014

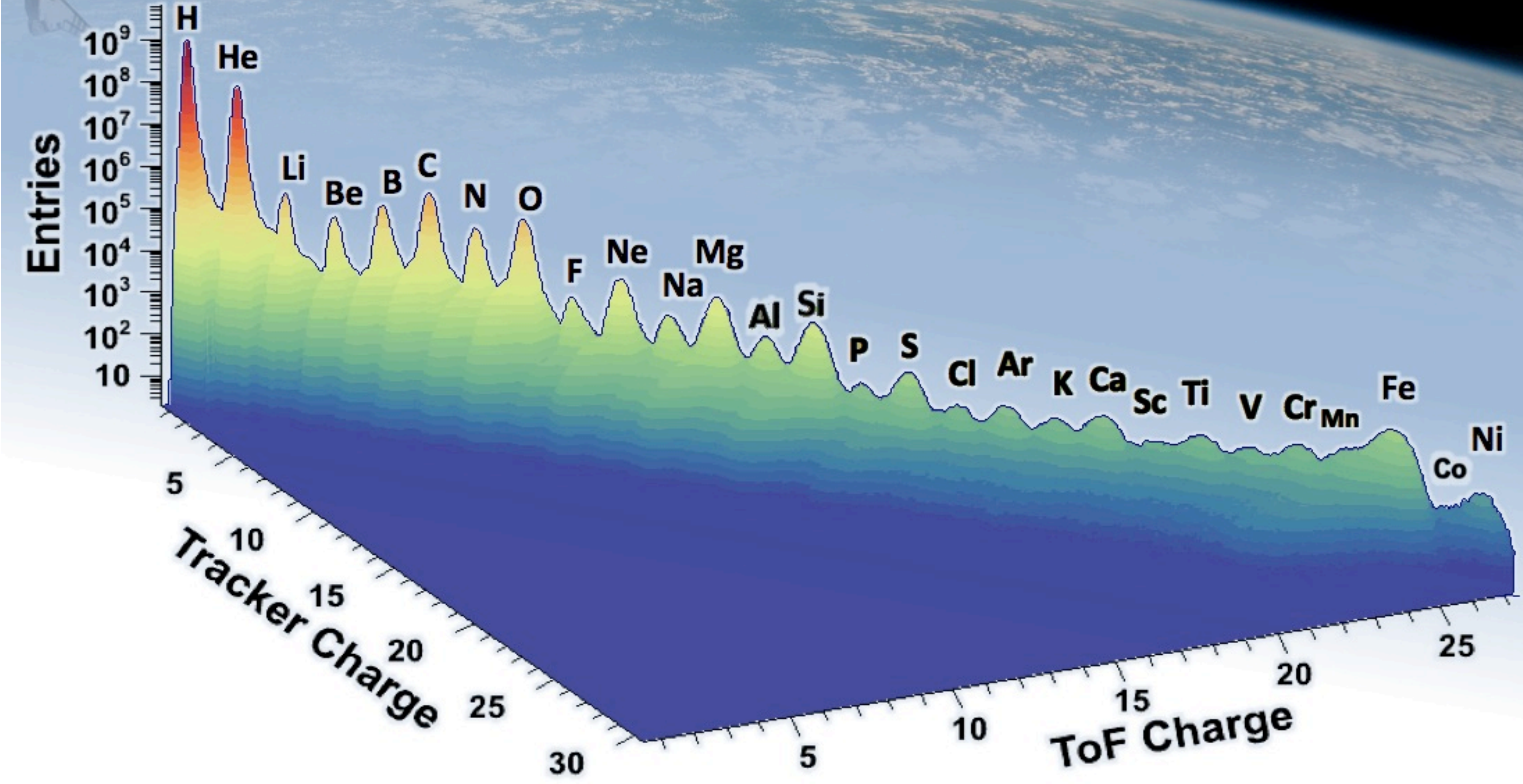


Solar "superstorm" just missed Earth in 2012

One of the top five fastest coronal mass ejections (CME) that scientists have ever observed, and the fastest observed by STEREO, blasted away from the sun on July 22, 2012. / NASA/STEREO



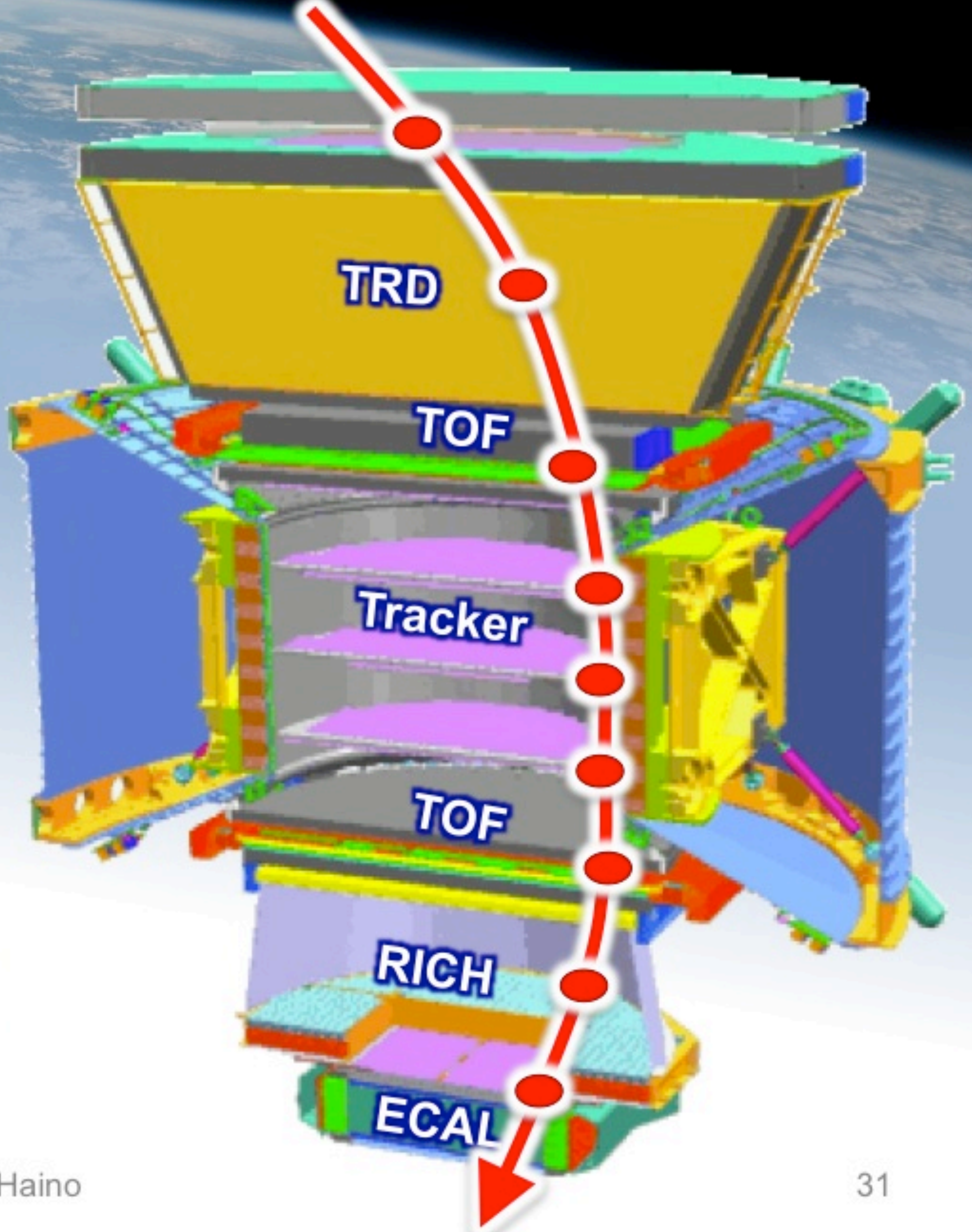
Nuclei identification in AMS



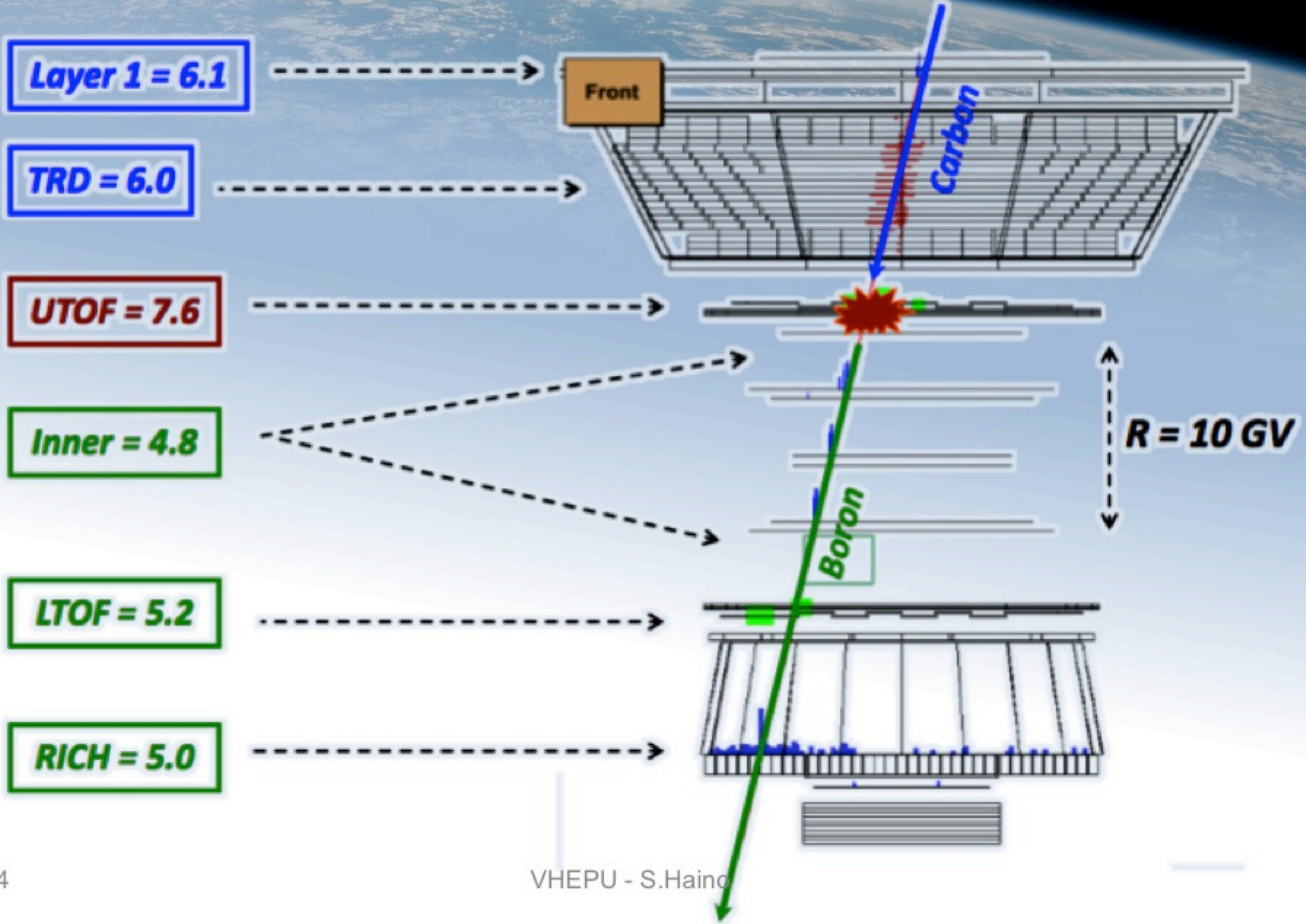
Multiple charge measurements

Charge resolution ΔZ (au)
for Carbon (Z=6)

- Tracker plane 1 : 0.30
- TRD : 0.33
- Upper TOF : 0.17
- Inner plane 2-8 : 0.15
- Lower TOF : 0.20
- RICH : 0.32
- Tracker plane 9 : 0.30



Detection of fragmentation



Layer 1 = 6.1

TRD = 6.0

UTOF = 7.6

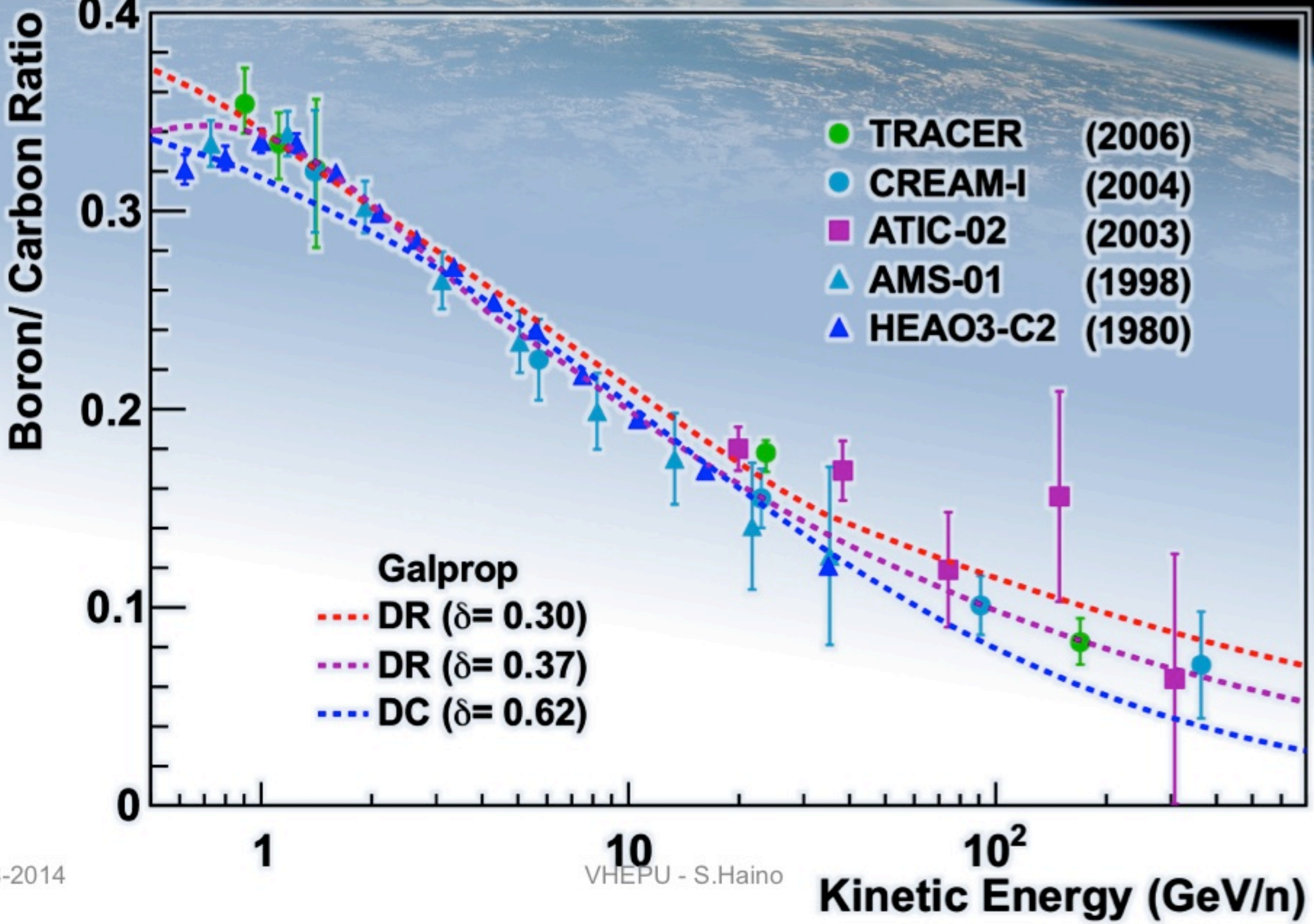
Inner = 4.8

LTOF = 5.2

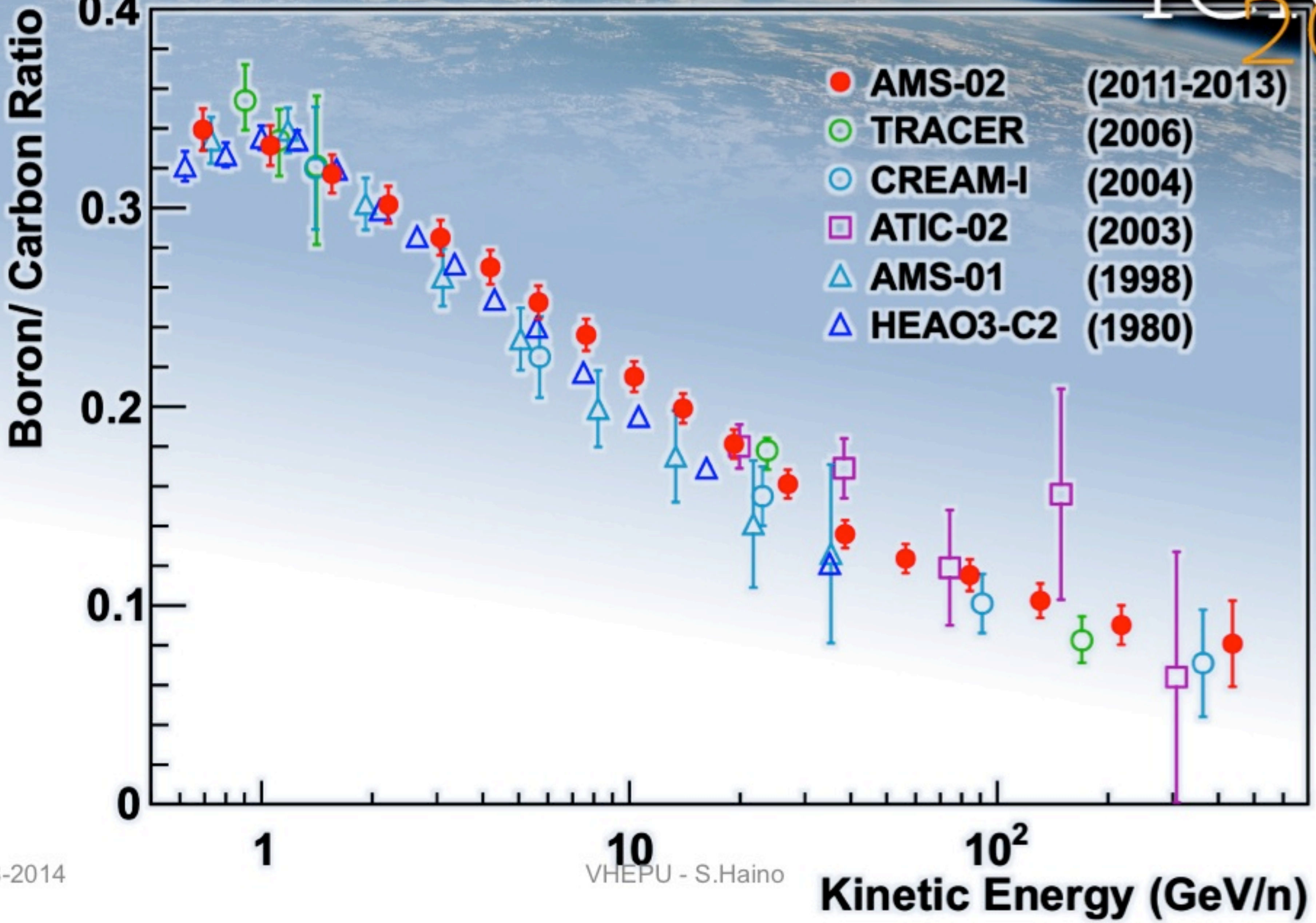
RICH = 5.0

R = 10 GV

B/C ratio – before AMS



B/C ratio


Boron/ Carbon Ratio
0.4
0.3
0.2
0.1
0
1
10
10^2
Kinetic Energy (GeV/n)
● AMS-02 (2011-2013)
○ TRACER (2006)
○ CREAM-I (2004)
□ ATIC-02 (2003)
△ AMS-01 (1998)
△ HEAO3-C2 (1980)

Beyond Fe ...

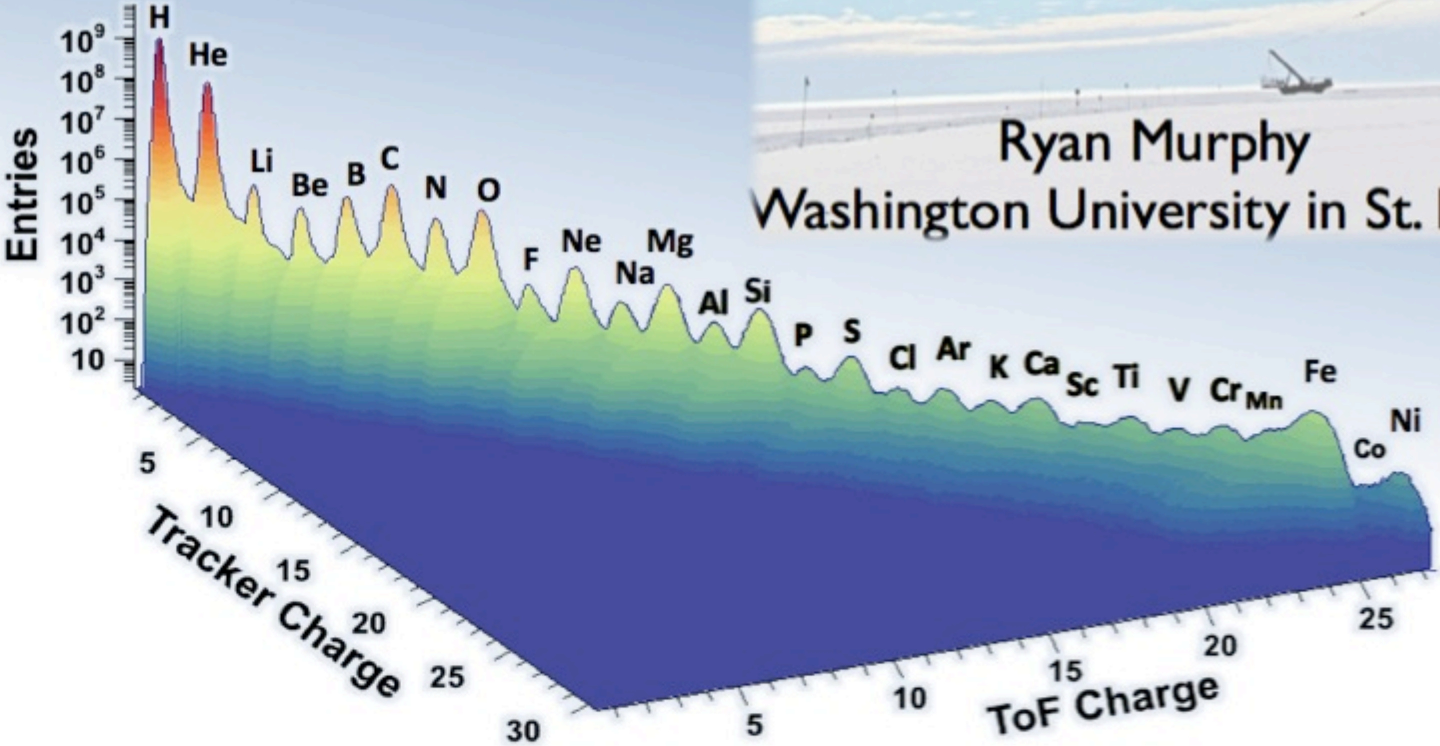
SUPER TIGER

WASH U · NASA GSFC

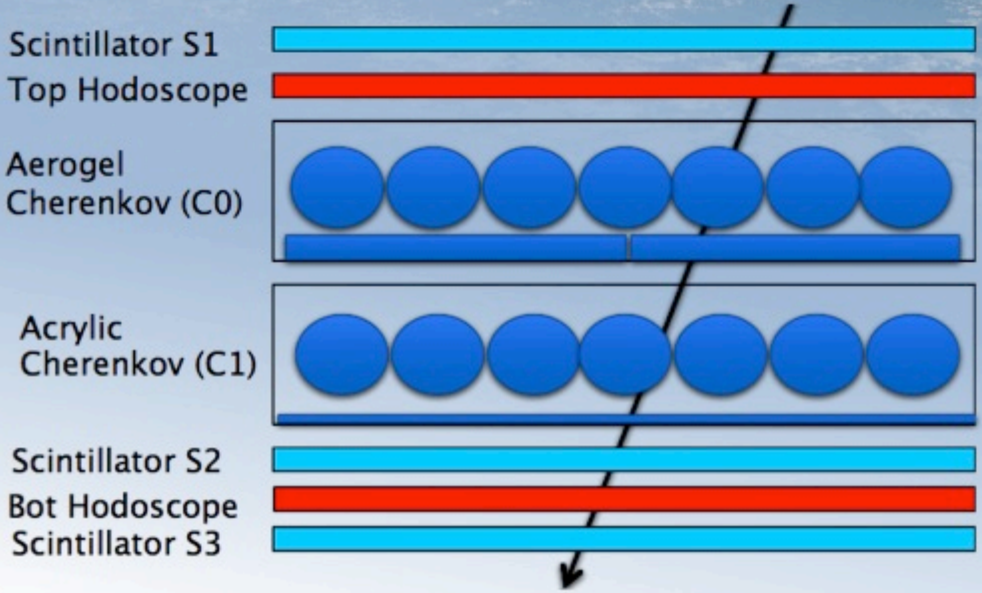
CALTECH · UMINN

Ryan Murphy
Washington University in St. Louis

APS April Meeting
April 5, 2014



SuperTIGER Instrument



Scintillator S1

Top Hodoscope

Aerogel Cherenkov (C0)

Acrylic Cherenkov (C1)

Scintillator S2

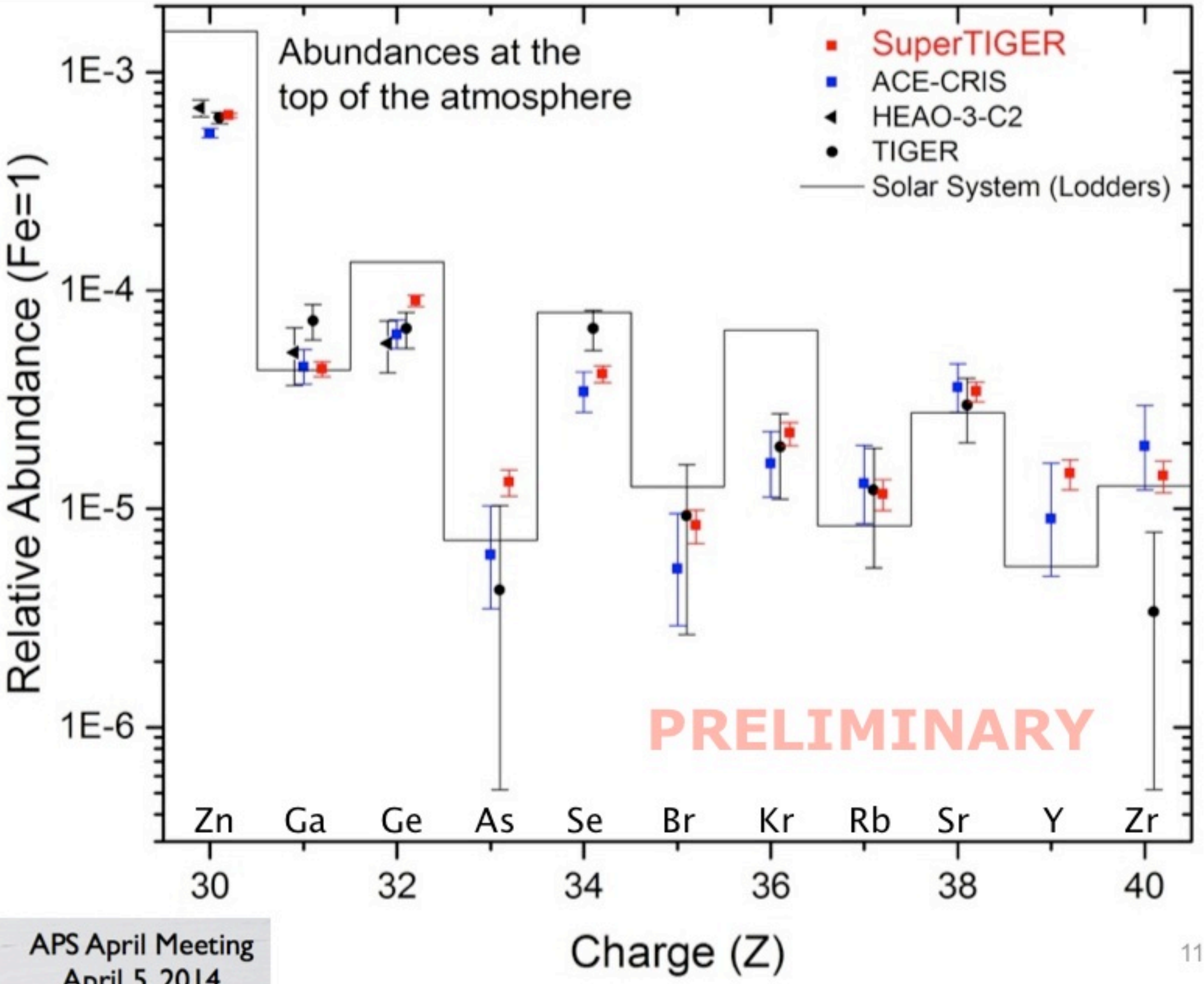
Bot Hodoscope

Scintillator S3

Balloon flight over Antarctica for 55 days
(NASA Heavy-Lift Scientific Balloon Record!)

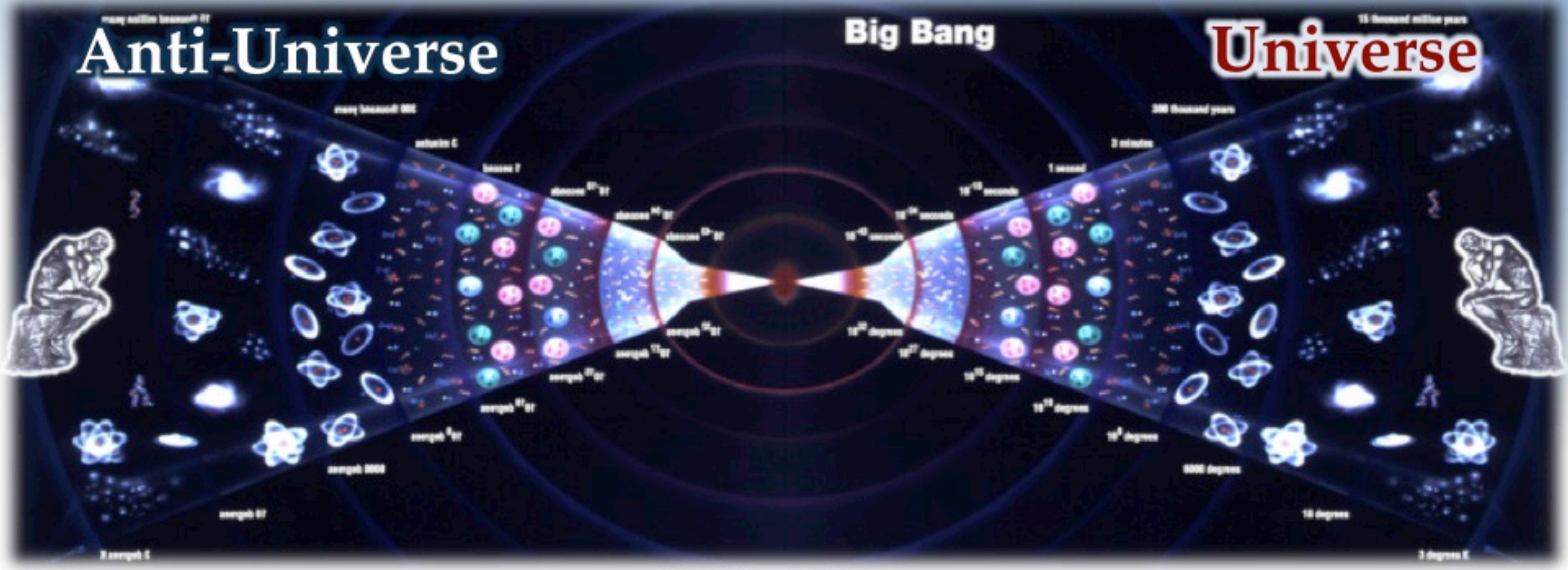
Preliminary Results

The results indicate that a mixed combination of standard Solar System material and Massive Star ejecta is needed to fit the data.

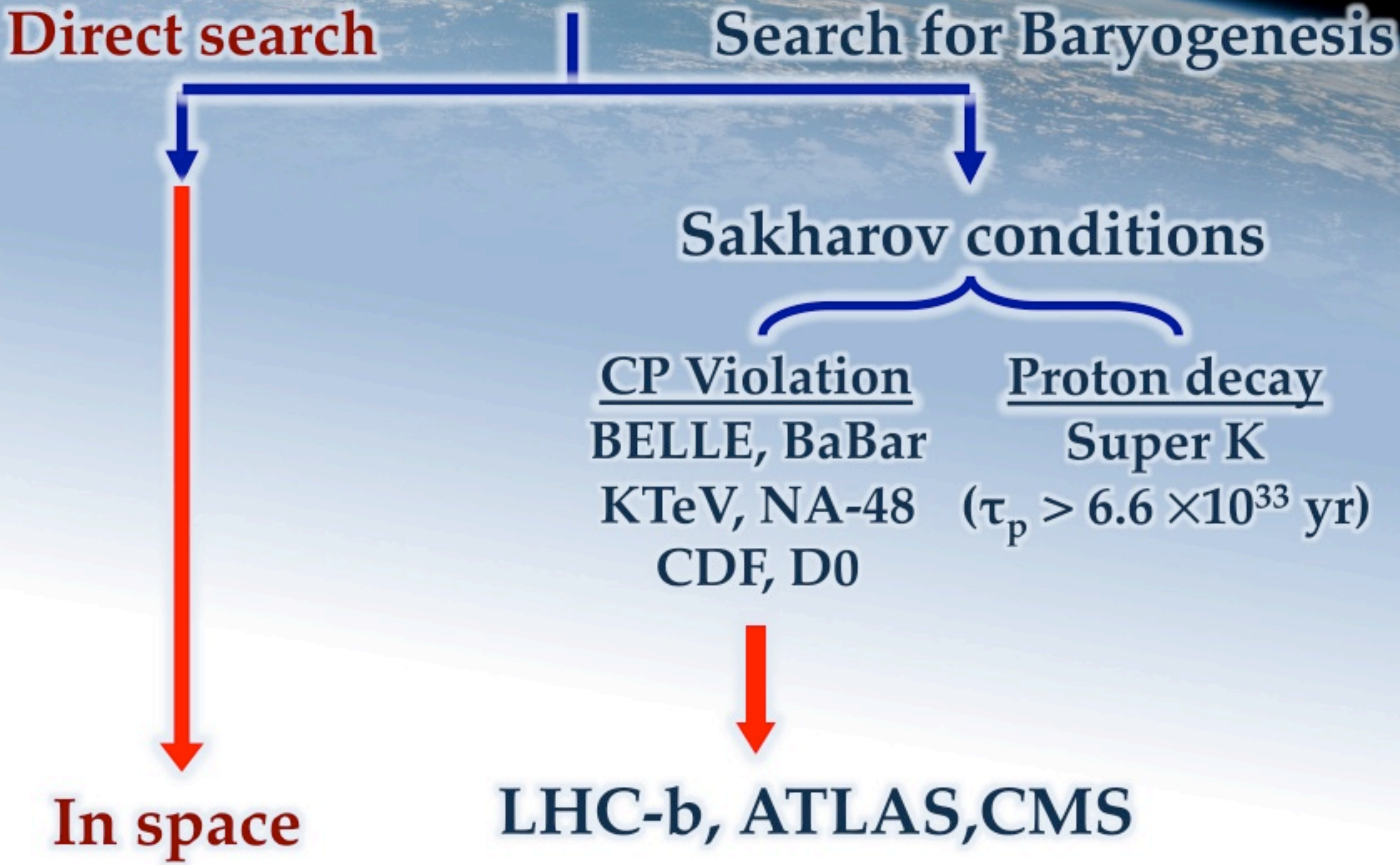


Search for antimatter

- Apparent asymmetry of matter and antimatter is one of the fundamental problems in cosmology
- Detection of anti-nuclei in Cosmic Rays will be a strong evidence of primordial Anti Matter



Matter / antimatter asymmetry



Direct search

Search for Baryogenesis

Sakharov conditions

CP Violation
BELLE, BaBar
KTeV, NA-48
CDF, D0

Proton decay
Super K
($\tau_p > 6.6 \times 10^{33}$ yr)

In space

LHC-b, ATLAS,CMS

PAUL A. M. DIRAC

Theory of electrons and positrons

Nobel Lecture, December 12, 1933

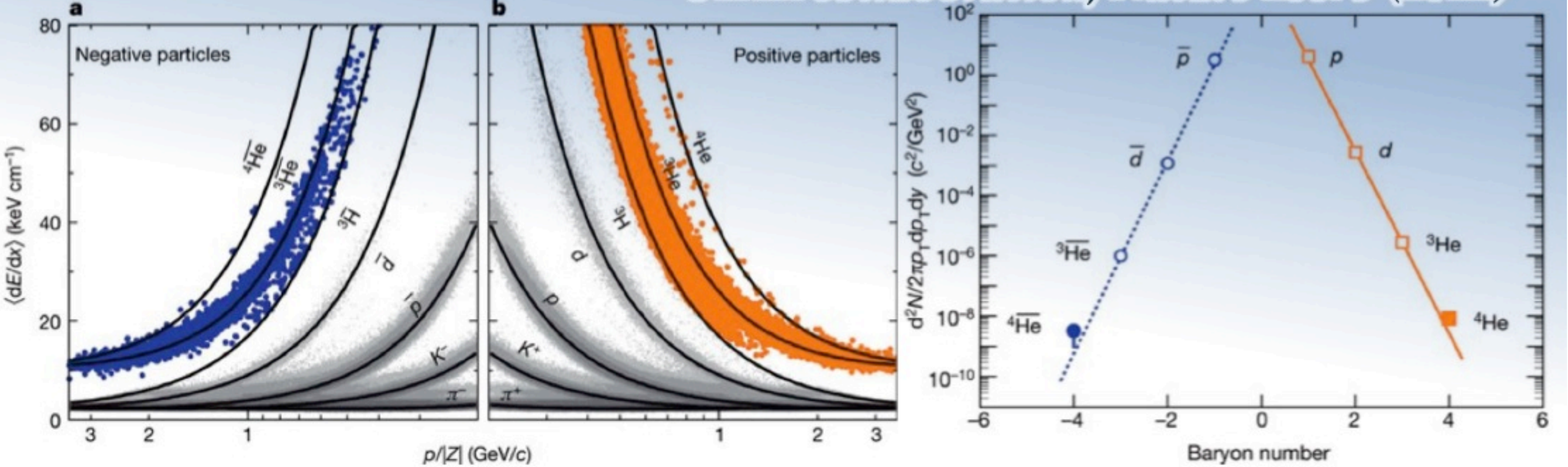
If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods.

Antimatter (anti-He) search

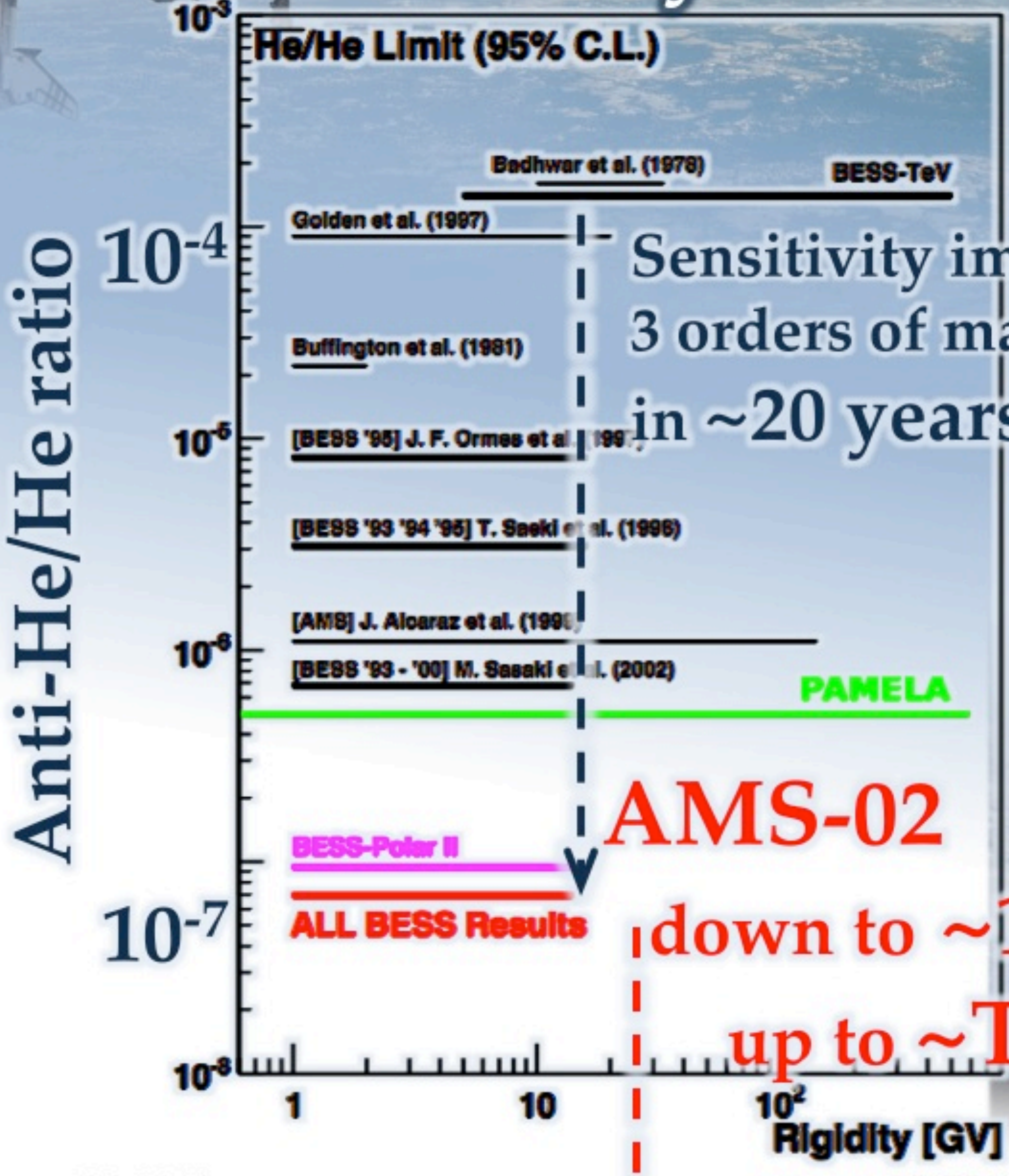
Anti-Helium

- Signal is quite distinctive
- Production in the collision is extremely small

STAR collaboration, Nature 10079 (2011)



History of antimatter search



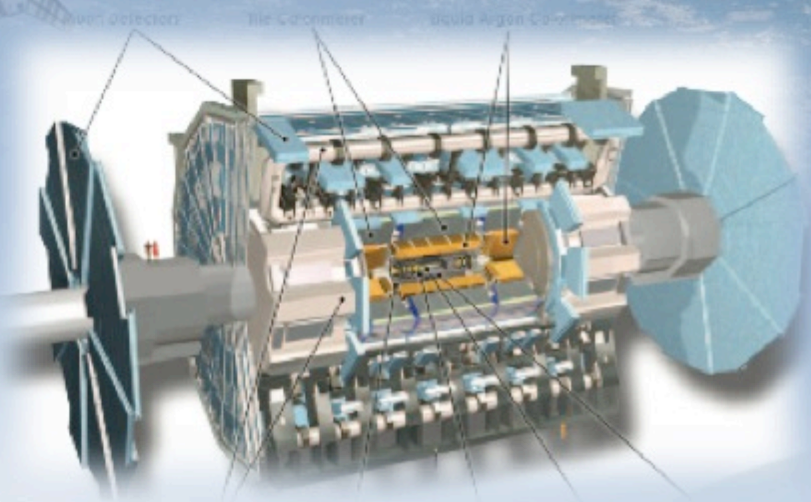
Sensitivity improved by 3 orders of magnitude in ~20 years

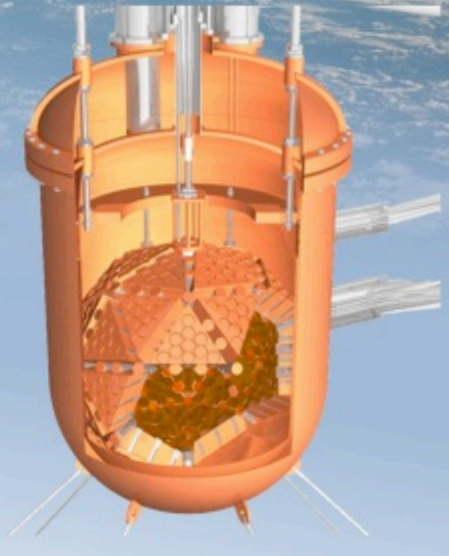
AMS-02

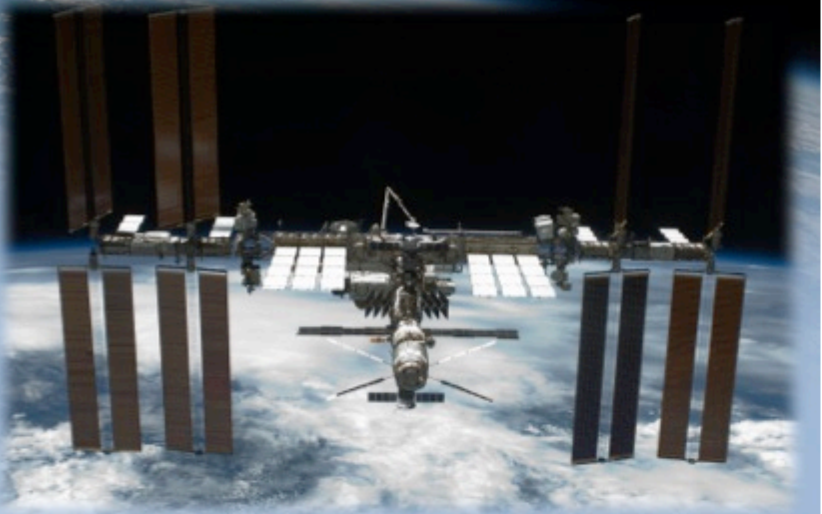
down to ~10^{-9}

up to ~TeV

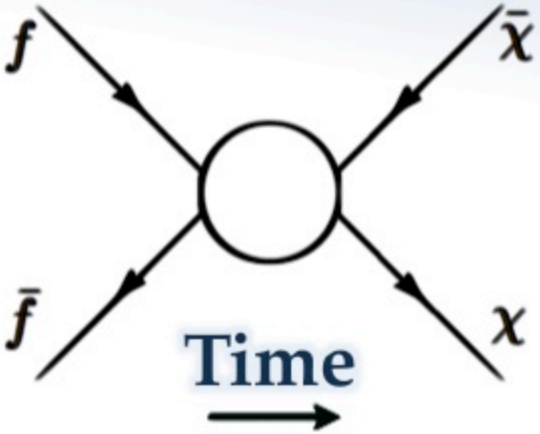
Dark Matter searches

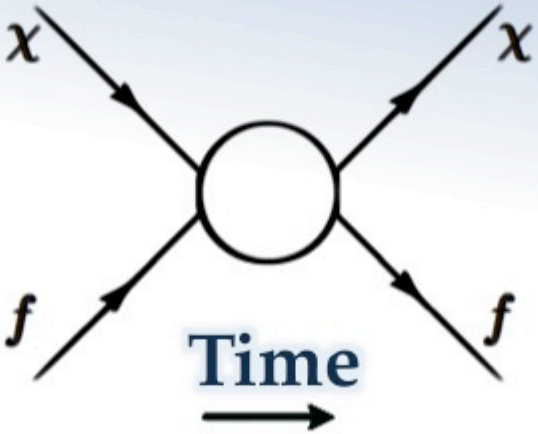


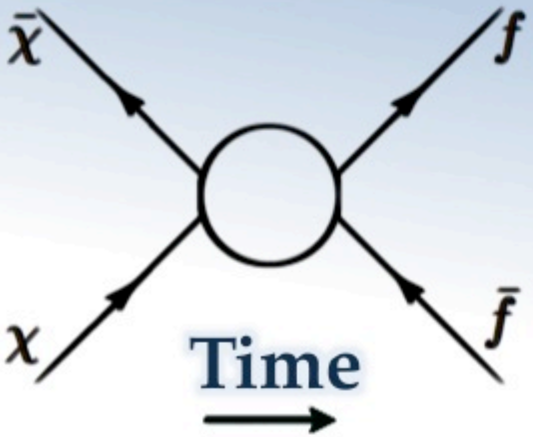




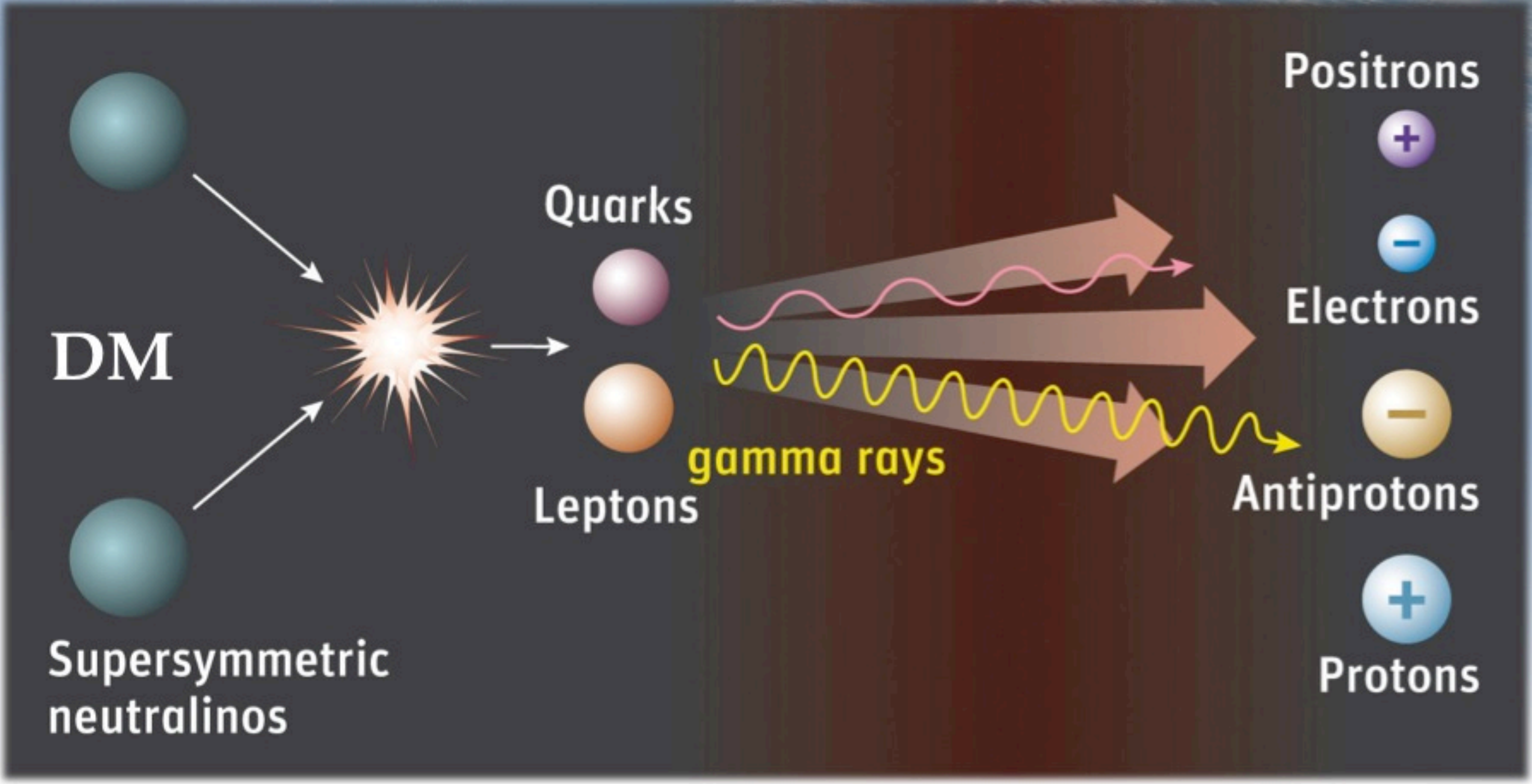
Colliders **Direct search** **Indirect search**



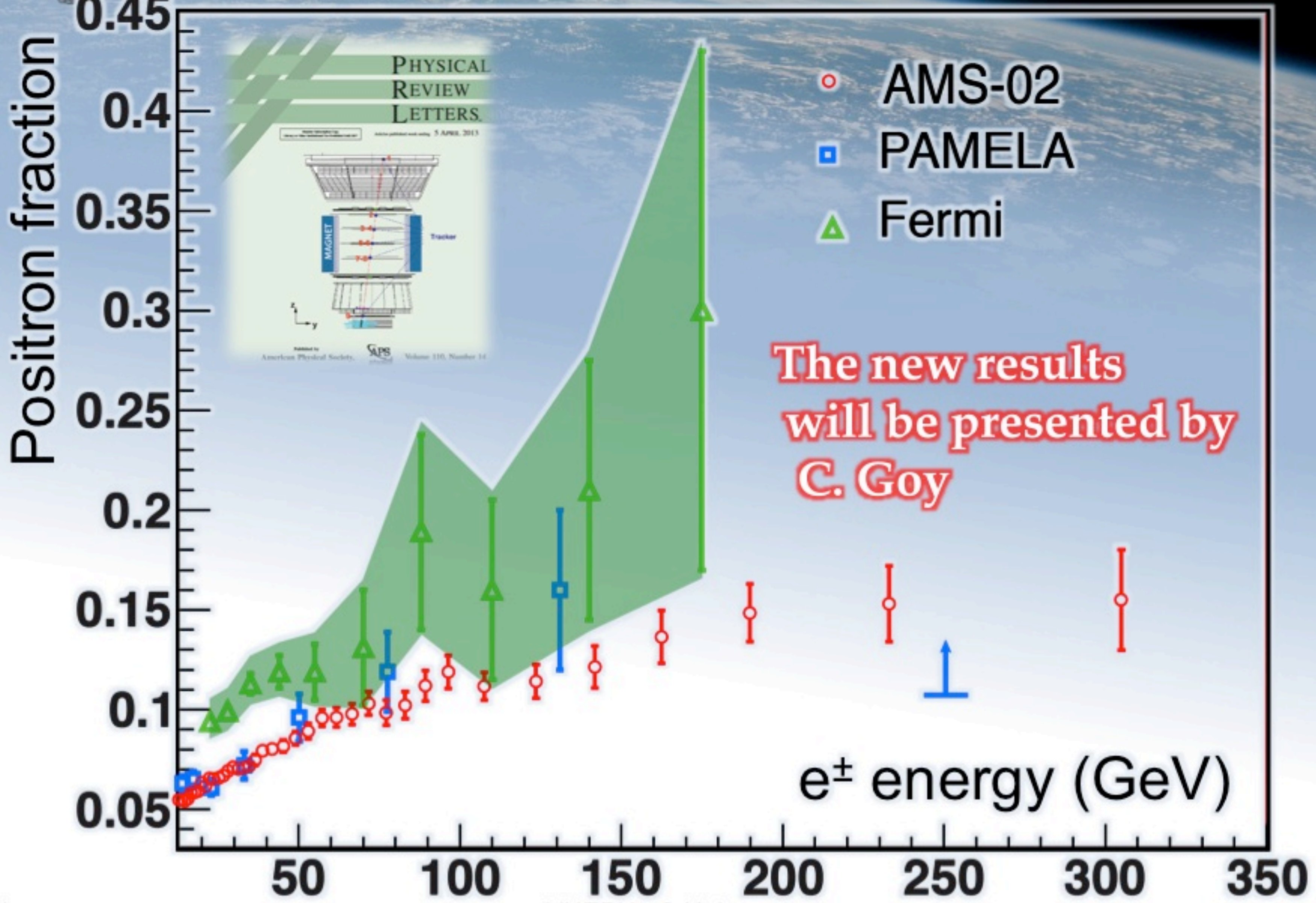




Annihilaiton of Dark Matter

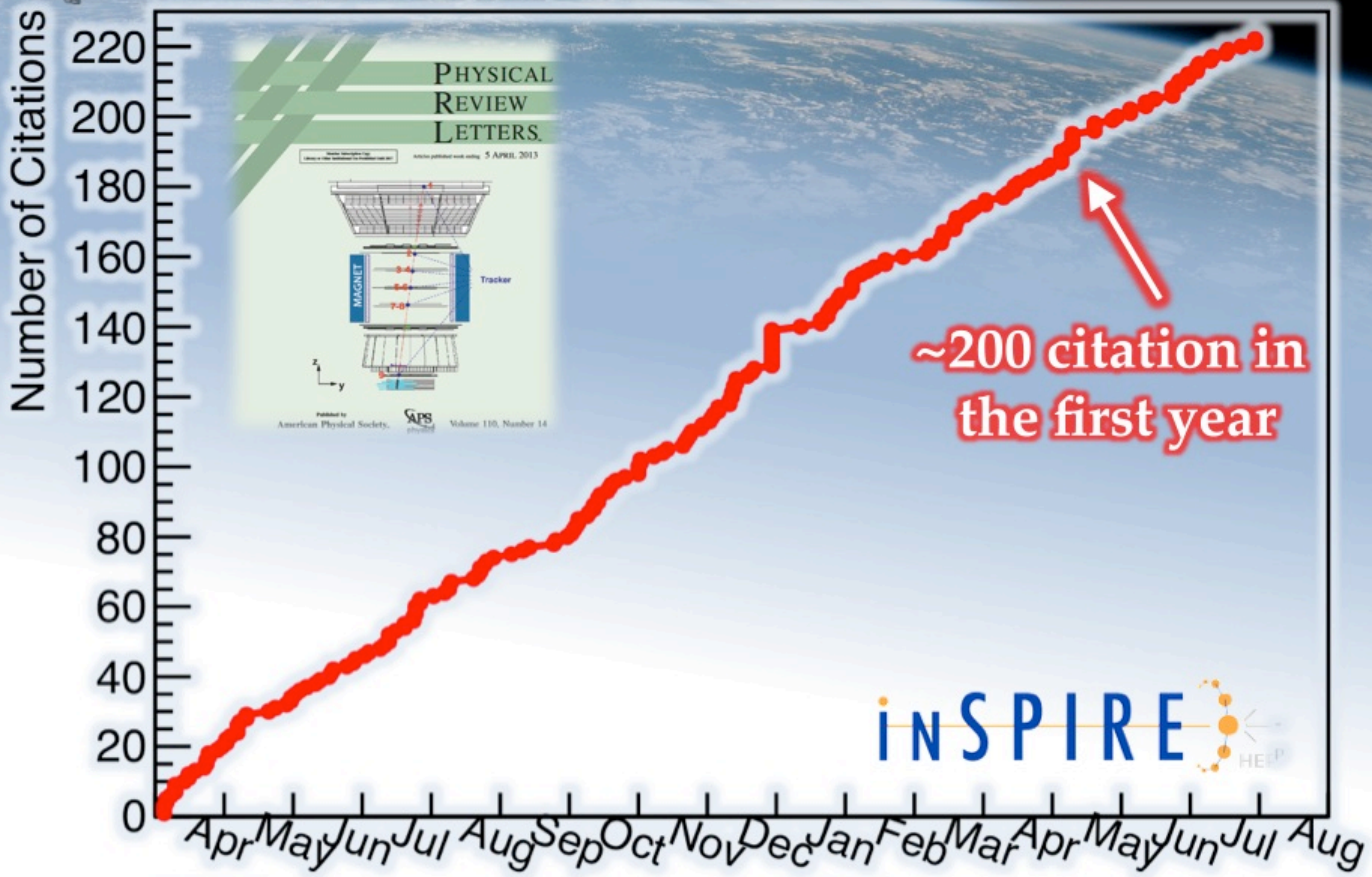


First results of AMS – e$^+$ fraction



The new results will be presented by C. Goy

Citation increasing ...

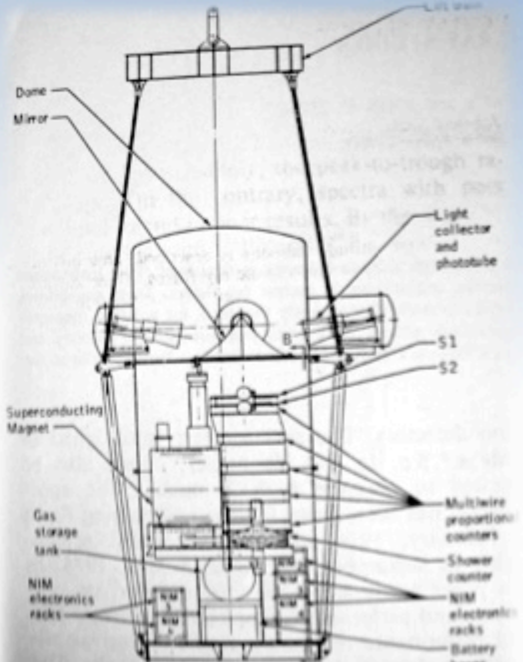


~200 citation in the first year

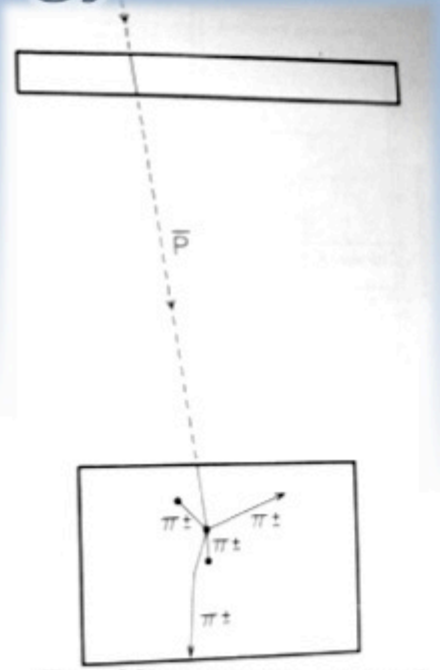
Cosmic Ray antiprotons in ~1980

First observation in 1979

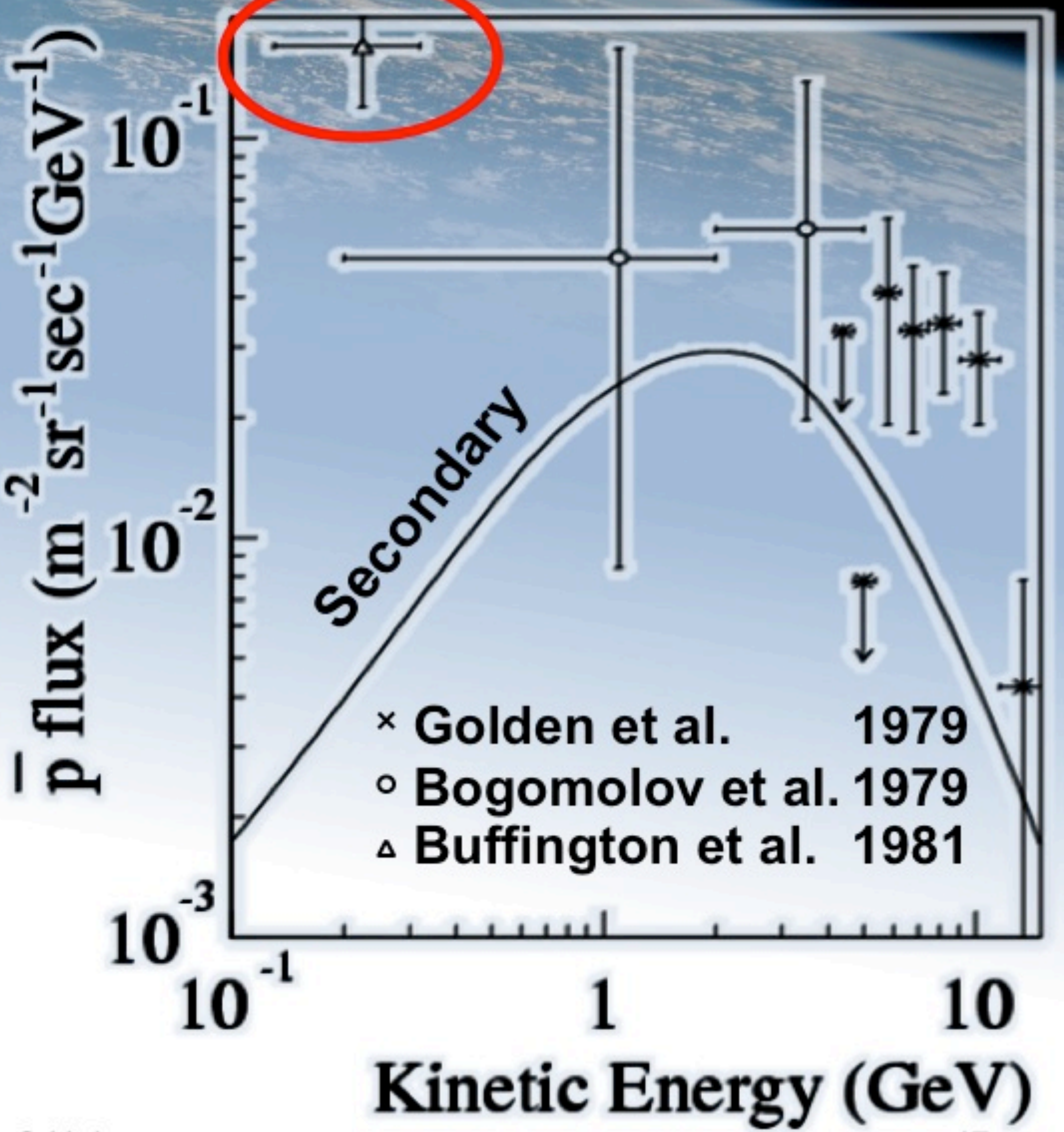
Significant excess in low energy



Golden et al.
Magnetic spectrometer



Buffington et al.
Spark chamber

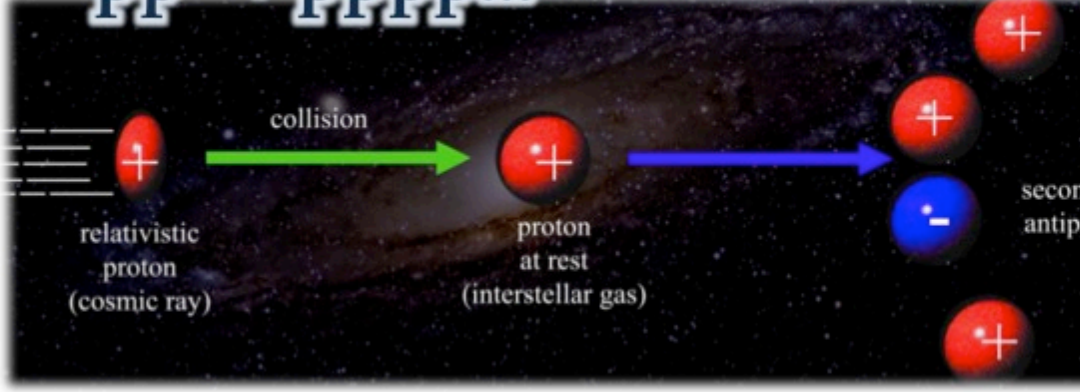


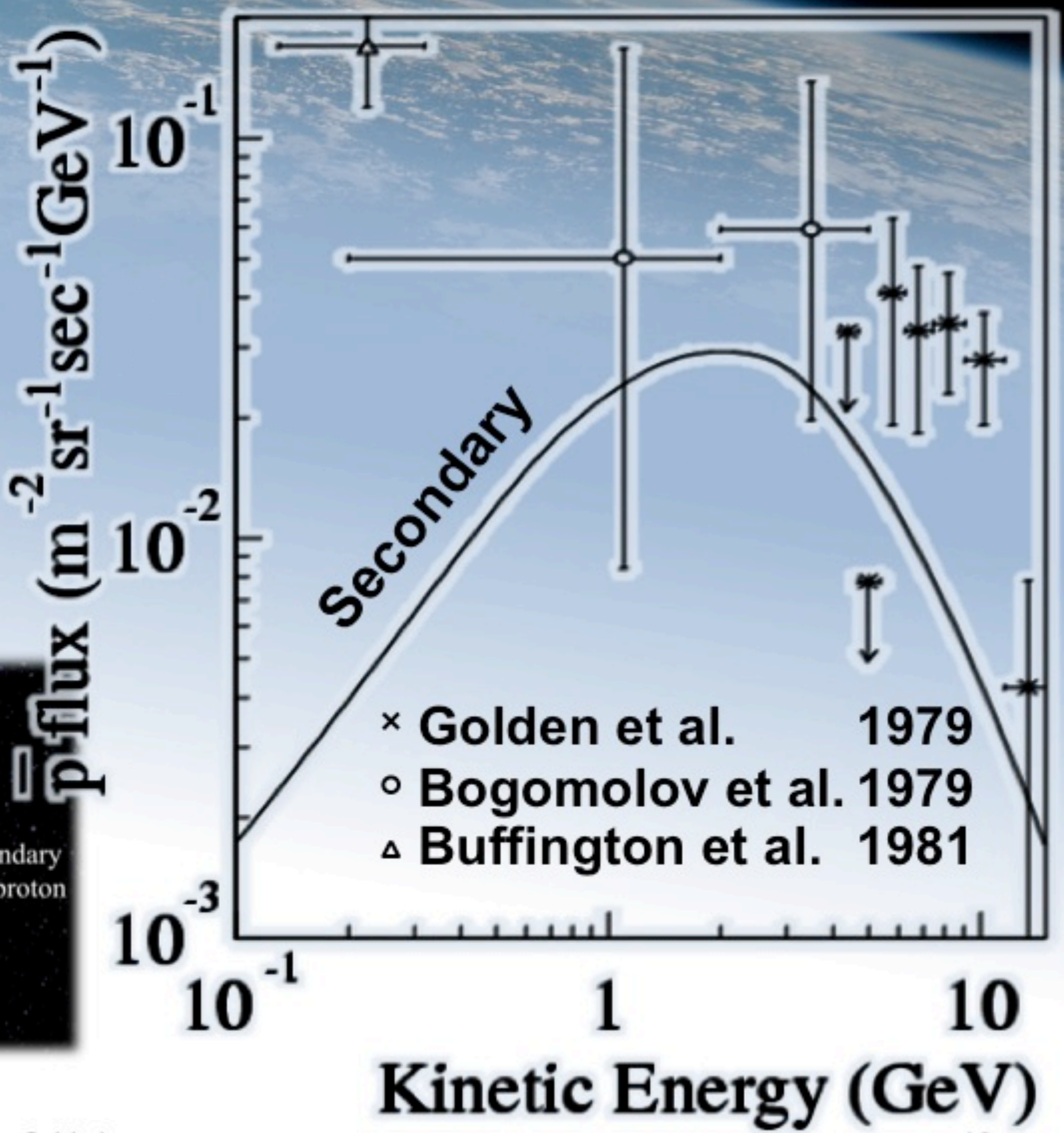
Antiproton production

- Kinematic constraints in low energy
- Spectrum has a peak at E_{kin}~2 GeV

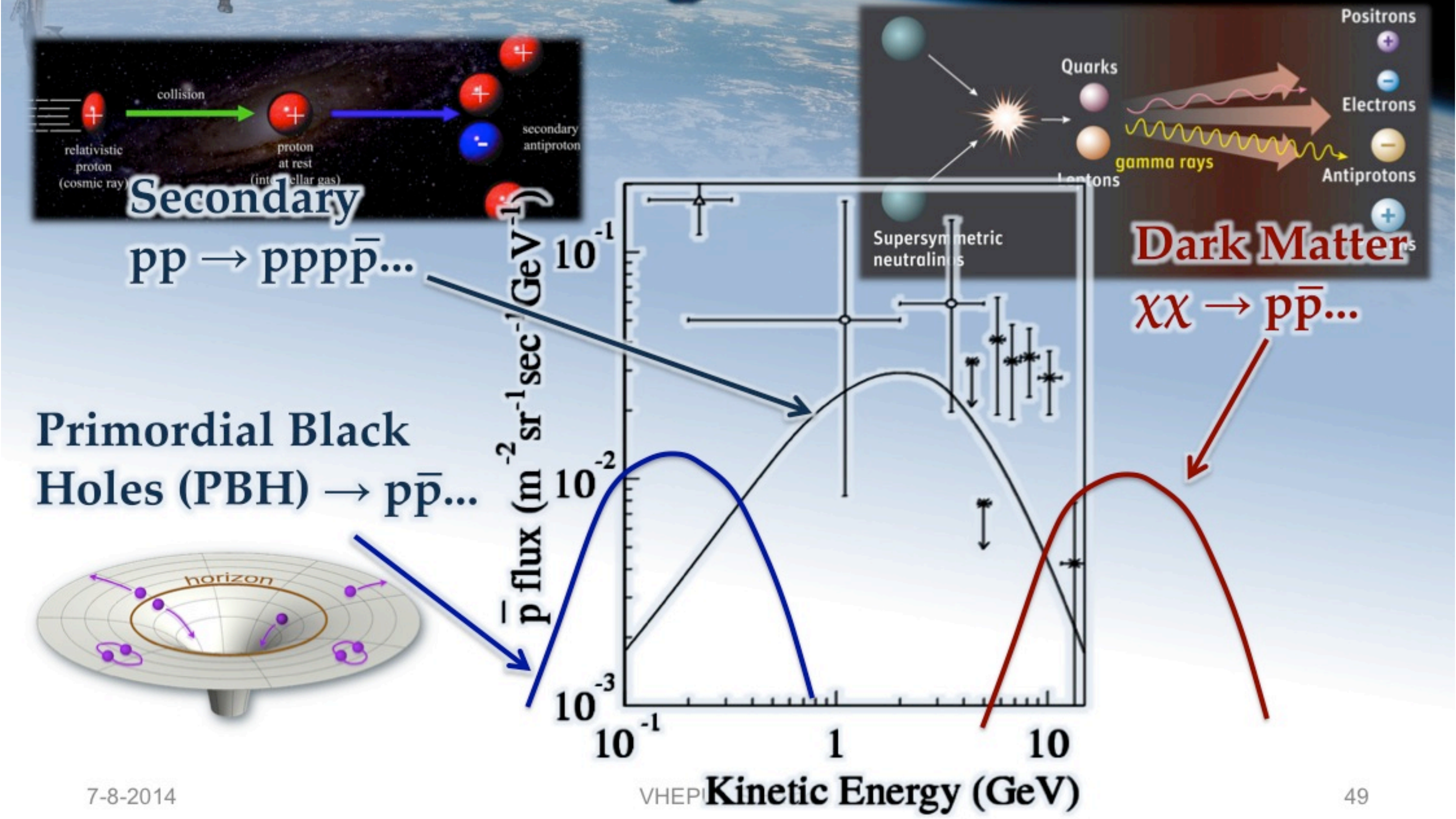
Secondary production

$pp \rightarrow ppp\bar{p}$...





Possible signal windows



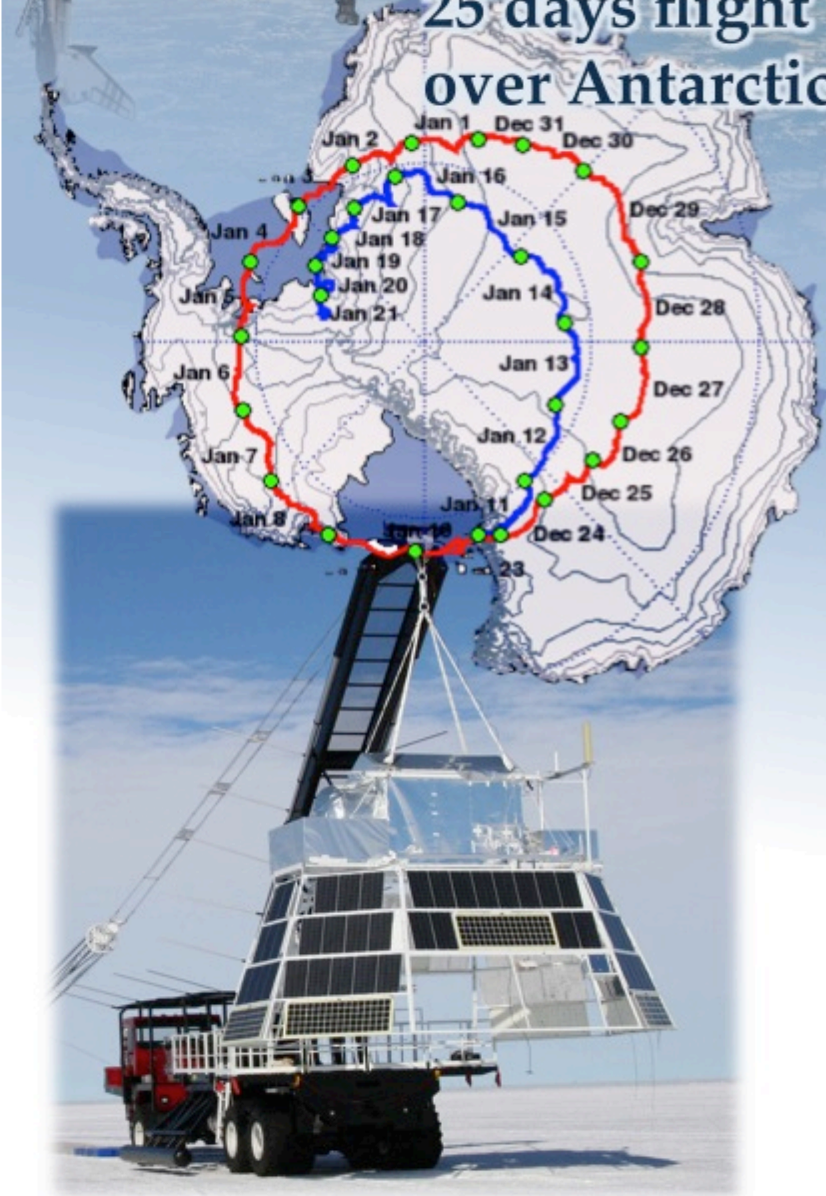
Secondary
$pp \rightarrow ppp\bar{p}$...

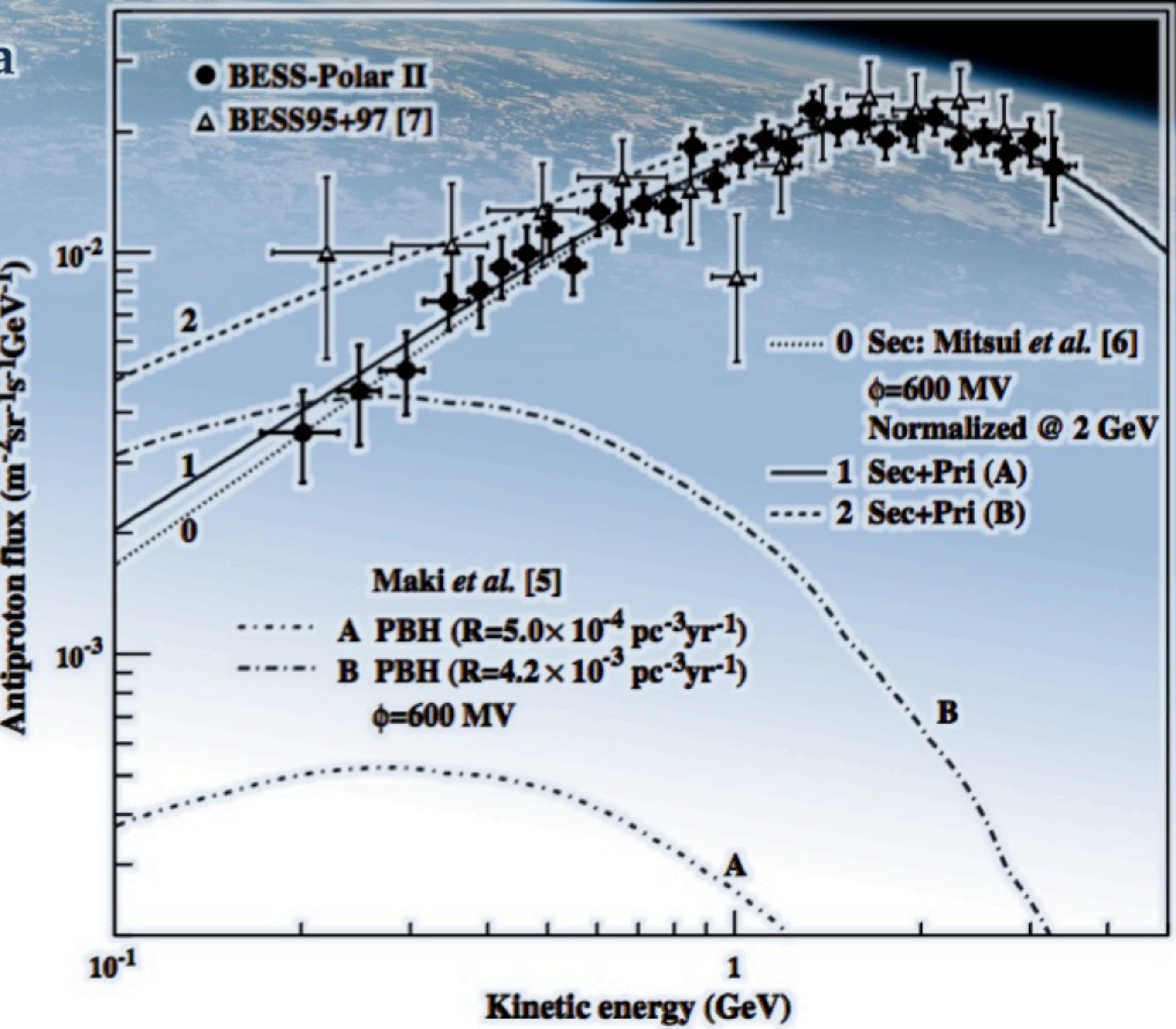
Dark Matter
$\chi\chi \rightarrow p\bar{p}$...

Primordial Black Holes (PBH) $\rightarrow p\bar{p}$...

BESS-Polar

25 days flight over Antarctica

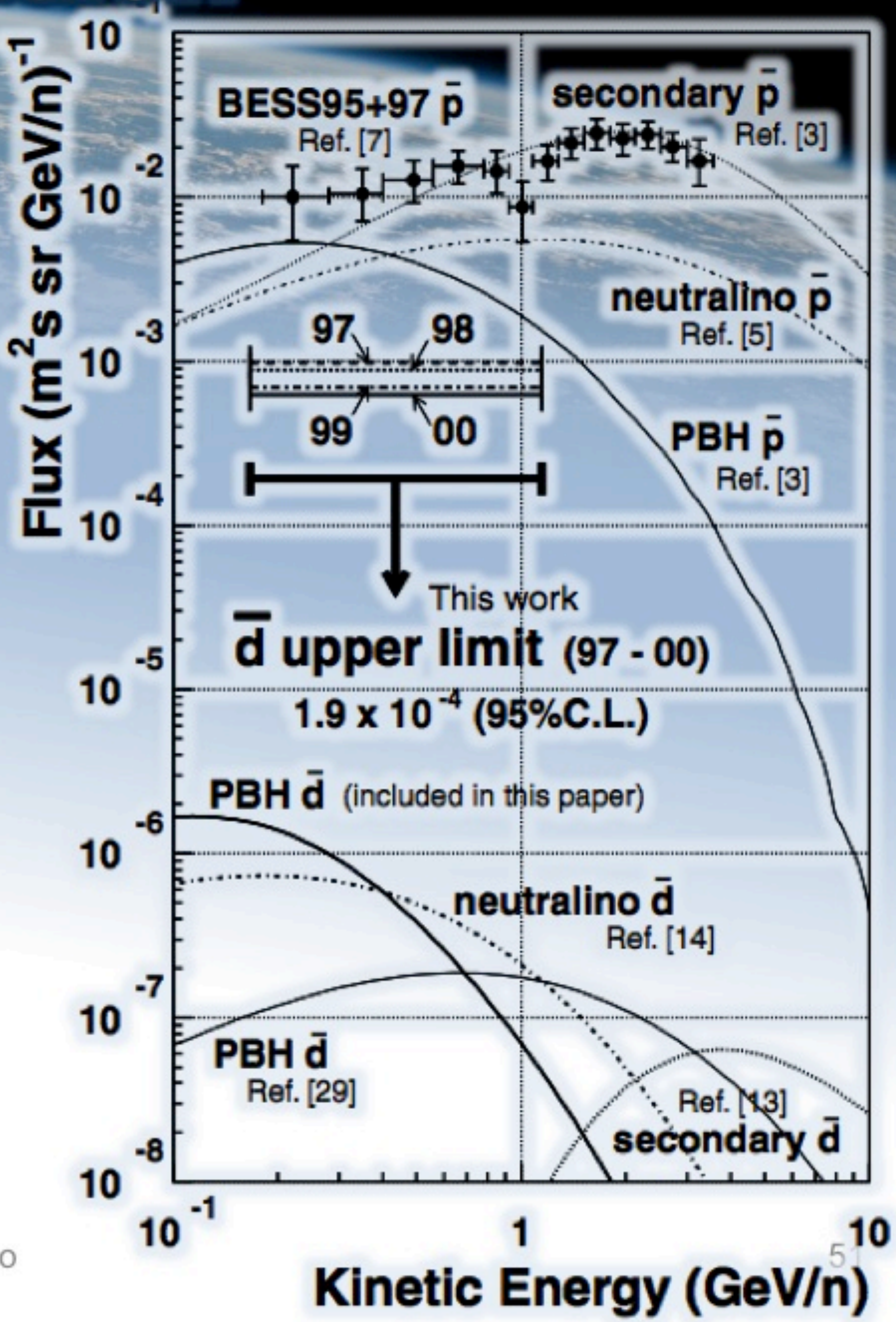




Anti-deuteron

- Secondary BG is much more suppressed than antiprotons
- The first upper limit published by BESS

H.Fuke et al., PRL 95 (2005) 081101



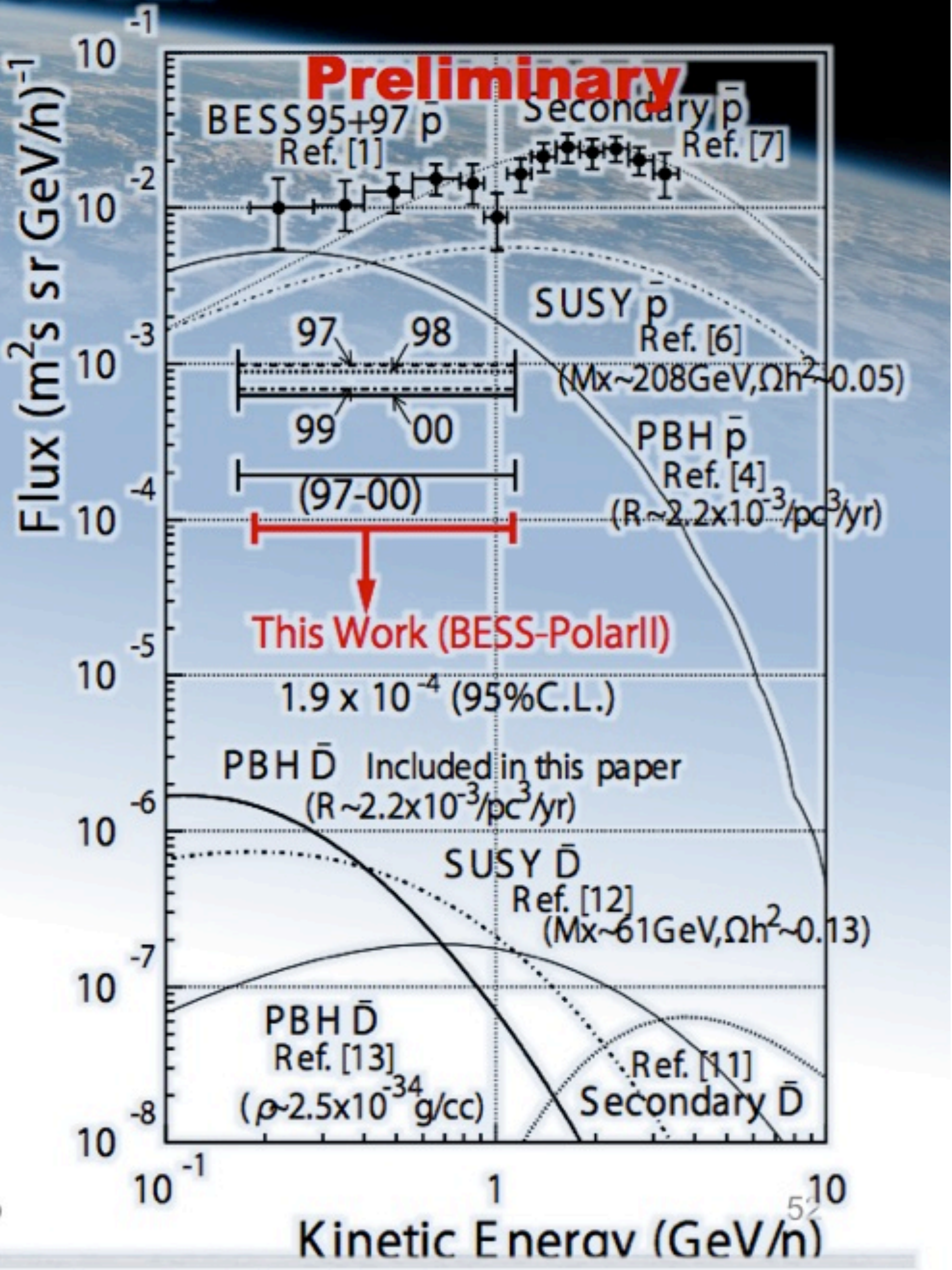
Anti-deuteron

- **Secondary BG is much more suppressed than antiprotons**
- **The first upper limit published by BESS**

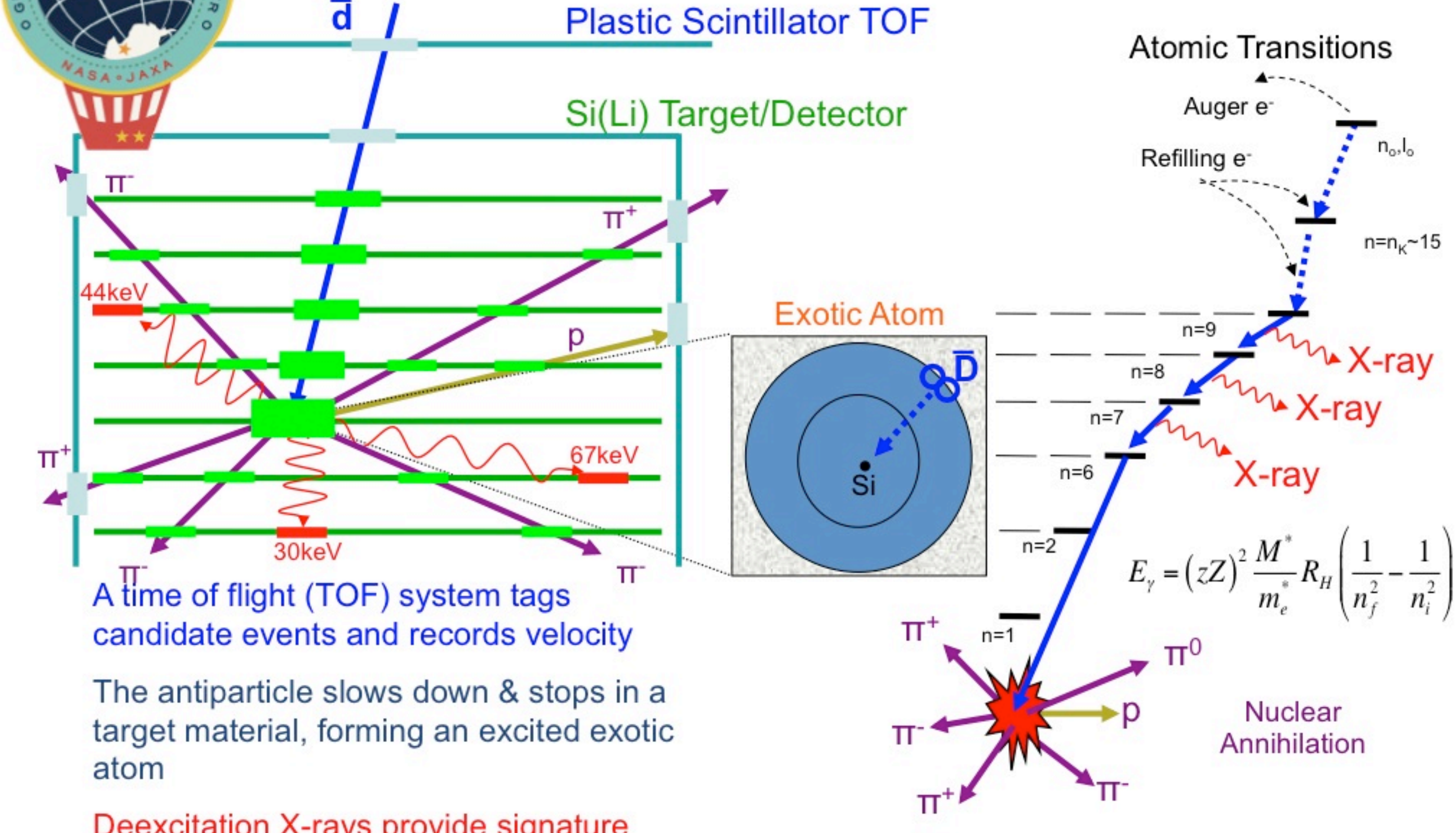
  H.Fuke et al., PRL 95 (2005) 081101

- **The new limit with BESS-Polar II**

  K.Yoshimura et al., COSPAR (2014) Moscow



GAPS detects atomic X-rays and annihilation products from exotic atoms



$$E_\gamma = (zZ)^2 \frac{M^*}{m_e^*} R_H \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$$

A time of flight (TOF) system tags candidate events and records velocity

The antiparticle slows down & stops in a target material, forming an excited exotic atom

Deexcitation X-rays provide signature

Annihilation products provide added background suppression

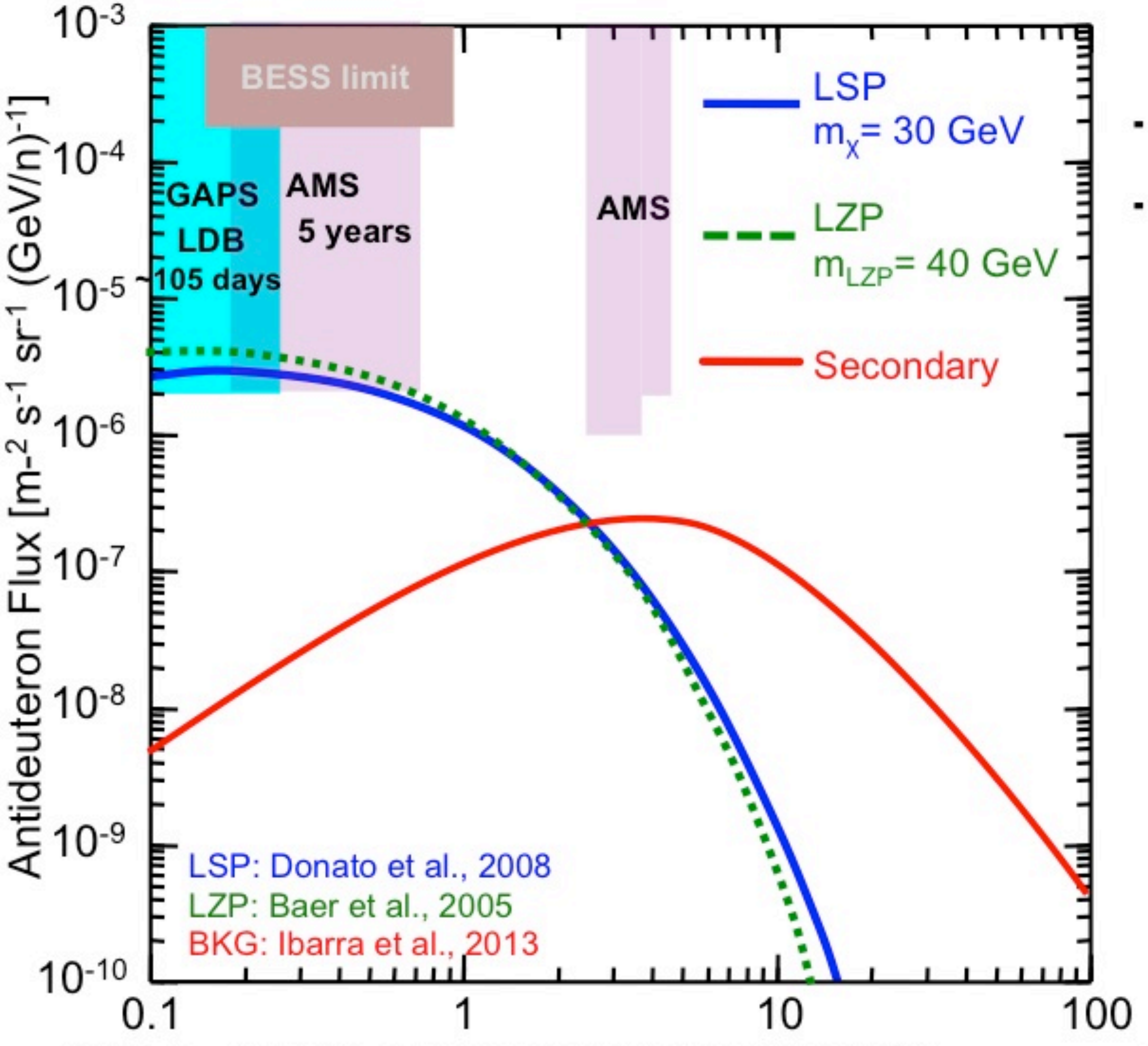
X-ray yields were measured at KEK in 2004 and 2005

C.J. Hailey Dark Matter 2014

Antideuterons provide clean DM signatures

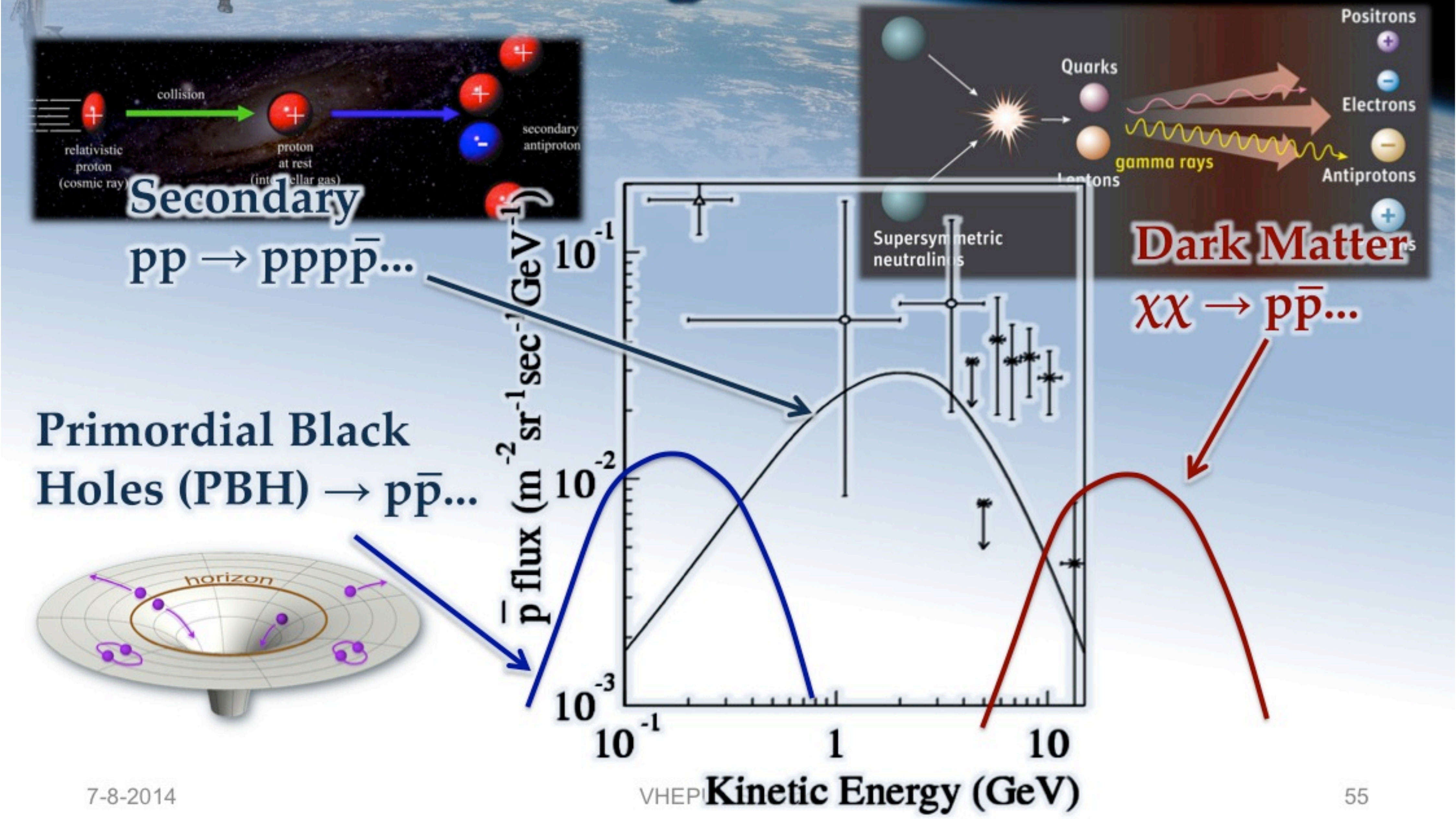
Background free at low energy!

GAPS Target :
Antarctic flight
in 2018-2019



Kinetic Energy per Nucleon [GeV/n]

Possible signal windows



Secondary

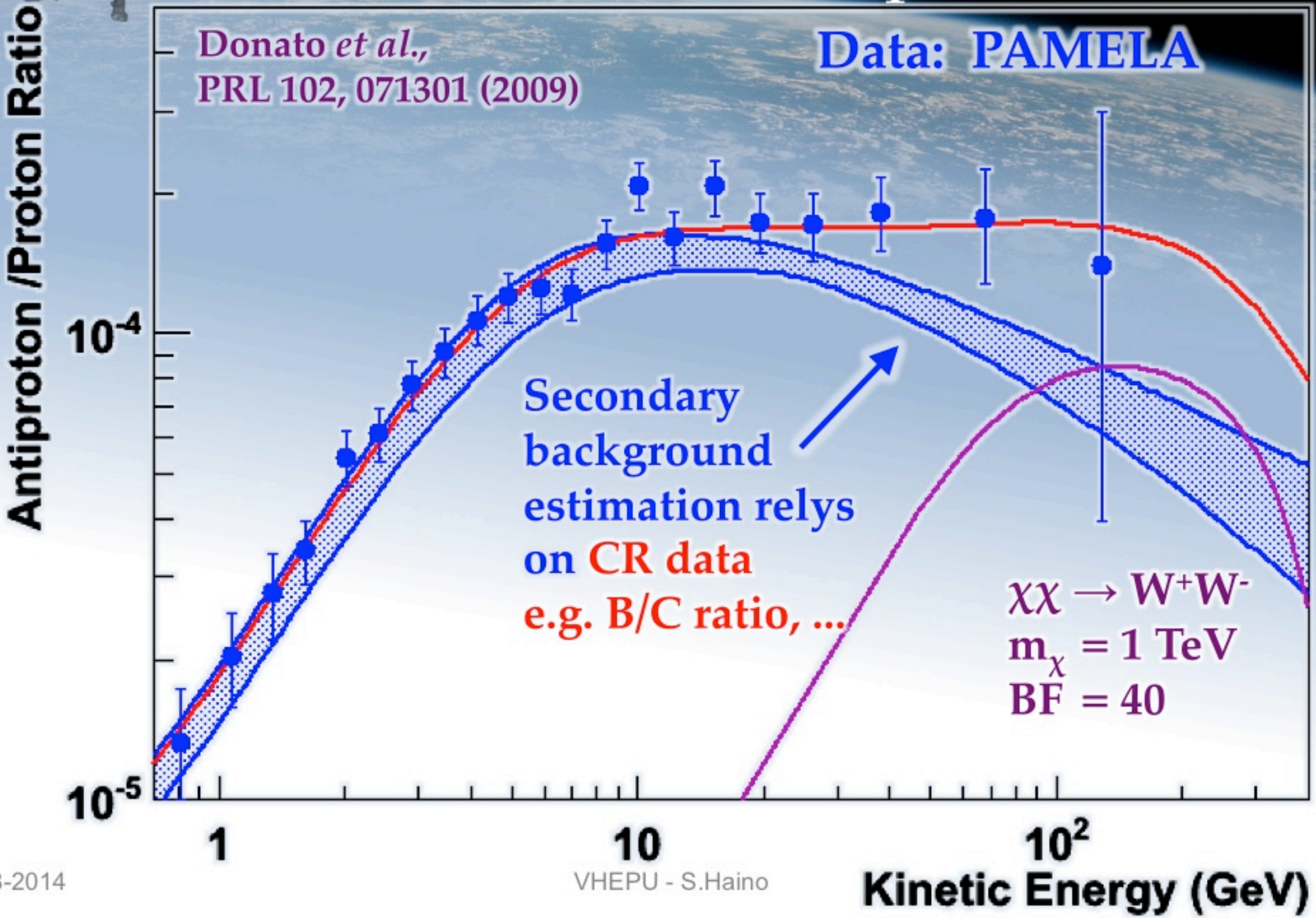
$pp \rightarrow ppp\bar{p}\ldots$

Dark Matter

$\chi\chi \rightarrow p\bar{p}\ldots$

Primordial Black Holes (PBH) → $p\bar{p}\ldots$

DM search with antiprotons



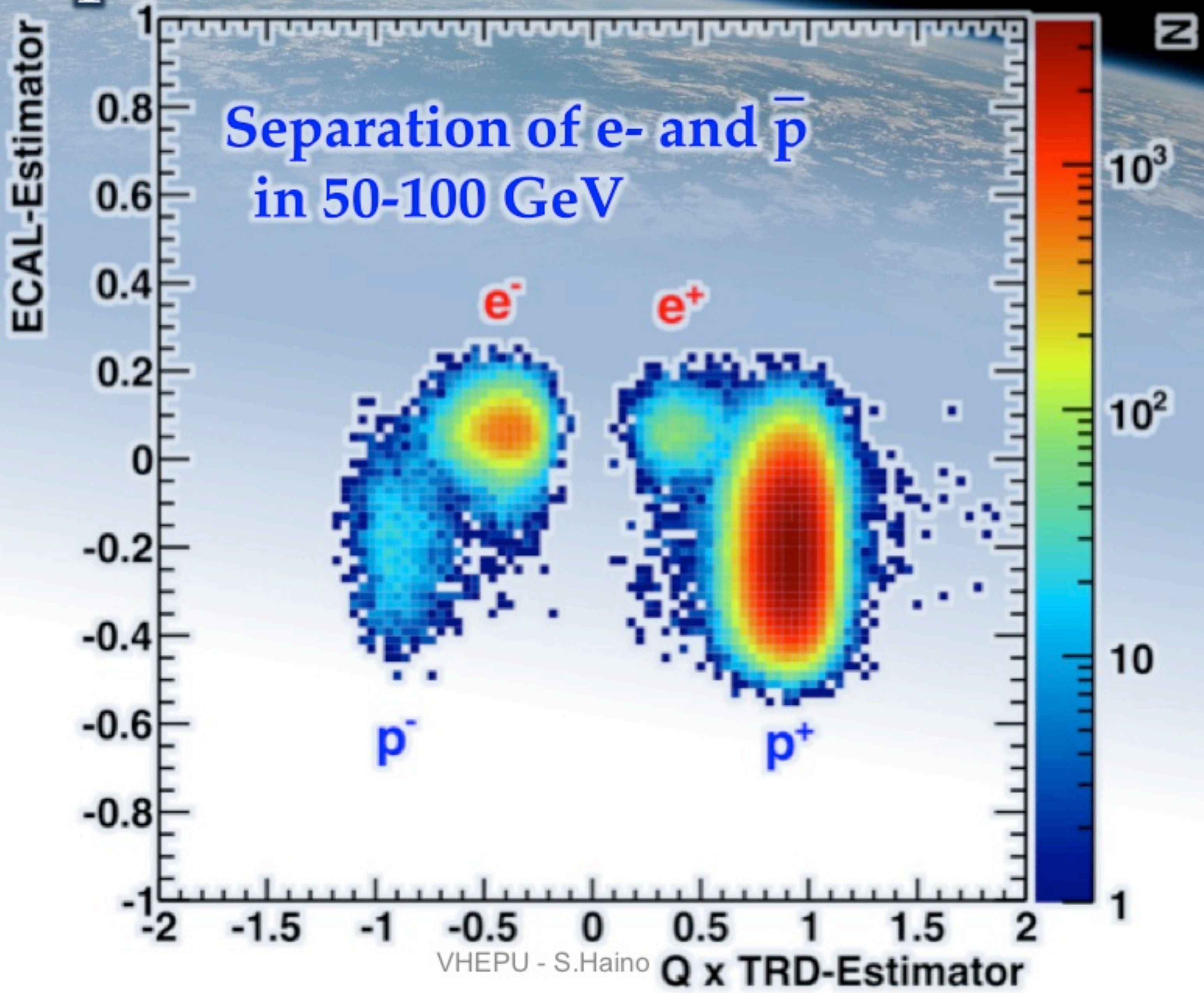
Donato *et al.*,
PRL 102, 071301 (2009)

Data: PAMELA

Secondary background estimation relys on CR data e.g. B/C ratio, ...

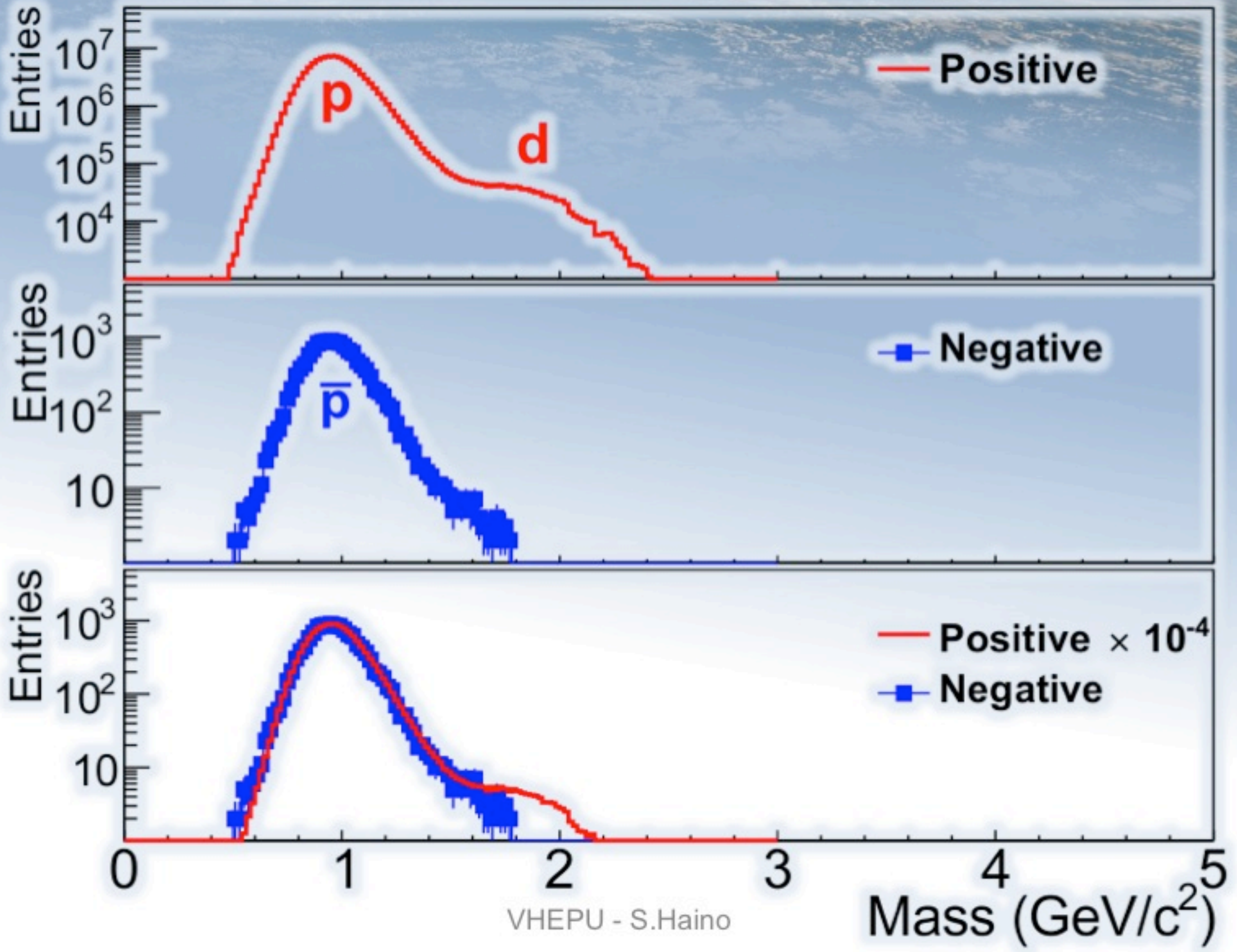
$\chi\chi \rightarrow W^+W^-$
$m_\chi = 1$ TeV
BF = 40

Antiproton identification in AMS

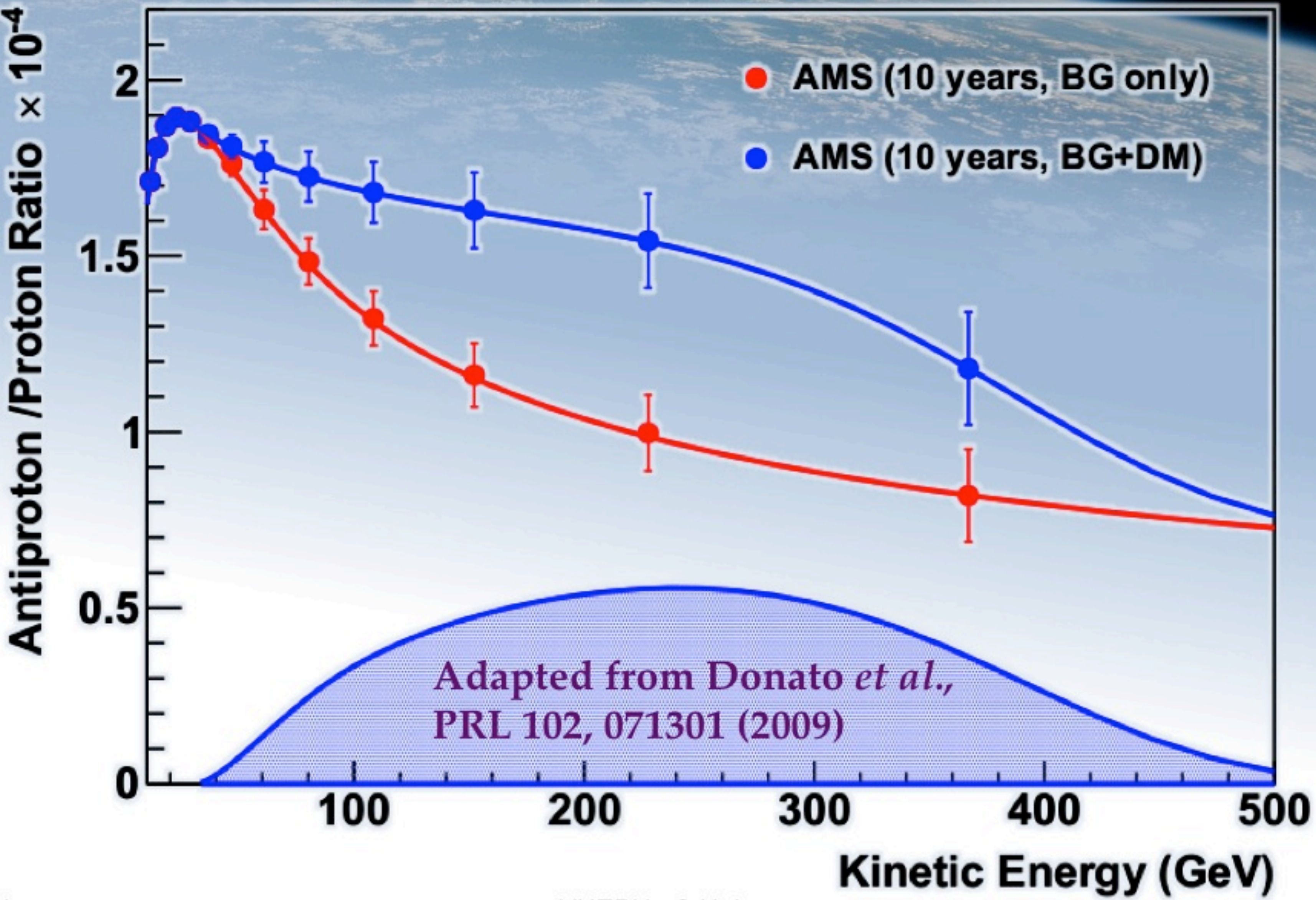


Antiproton identification in AMS

Mass reconstruction with RICH and Tracker at E~ 10 GeV



AMS Potential of DM search



Adapted from Donato *et al.*, PRL 102, 071301 (2009)

Summary – GeV-TeV cosmic ray nuclei

- **After one century since the discovery, cosmic rays open a new channel to study particle physics and cosmology as well as astrophysics**

- **AMS would provide (almost) all the ingredients with the single instrument**

- **Some balloon experiments are still unique; BESS-Polar, Super-TIGER, GAPS, ...**

The Cosmos is the Ultimate Laboratory.

The most exciting objective of AMS is to probe the unknown; to search for phenomena which exist in nature that we have not yet imagined nor had the tools to discover ...

S.Ting