One century of cosmic rays
The status of current research: experiments

Roberto Battiston
University and INFN of Perugia

Schinege 2012
Lecce
[illegible] 21th 2012

Outline

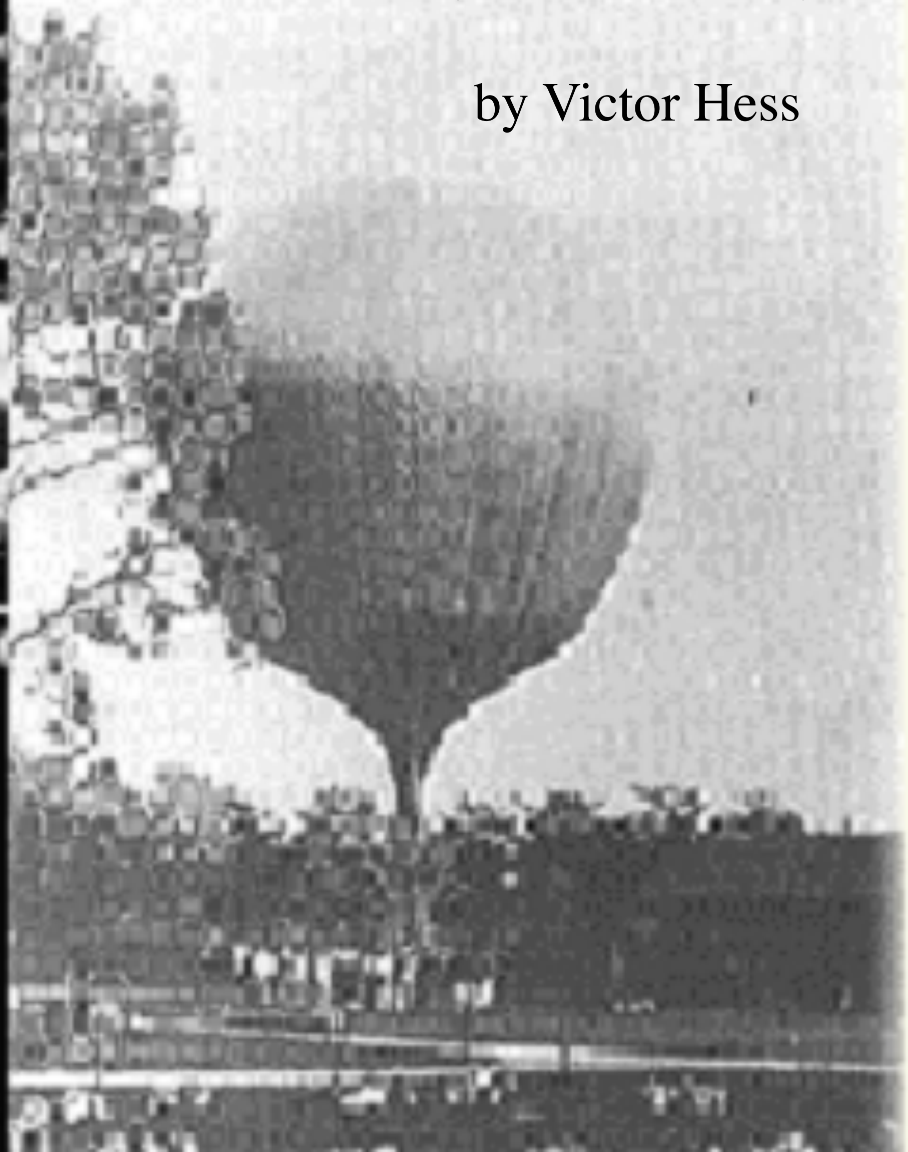
-The discovery of Cosmic Rays

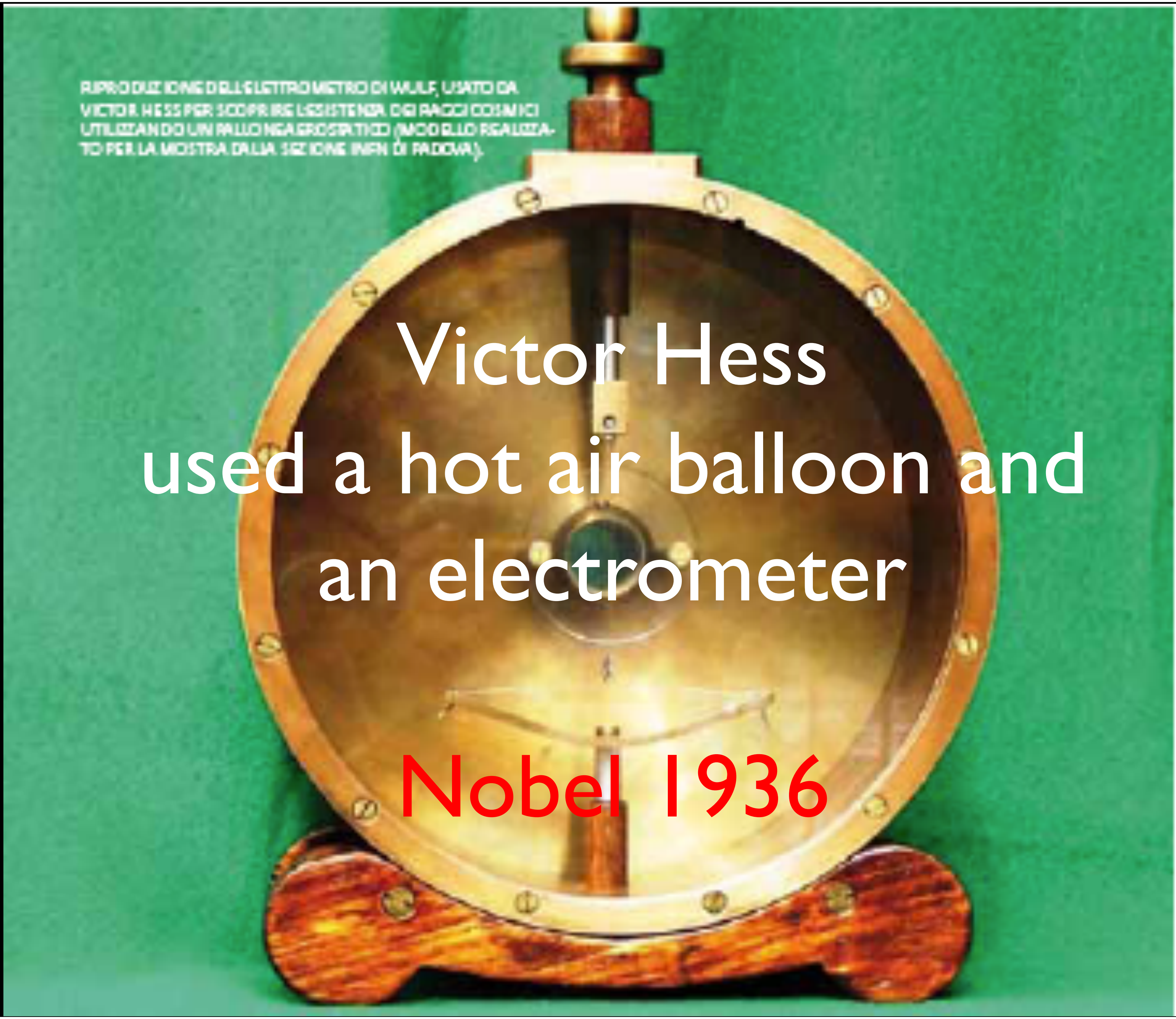
Topics in Cosmic Rays physics one century after Hess
-Cosmic Ray composition
-Cosmic Ray spectrum
-Very High and Ultra High Energy Cosmic Rays
-Conclusions

note: this is NOT a systematic review !

1912 Discovery of Cosmic Rays

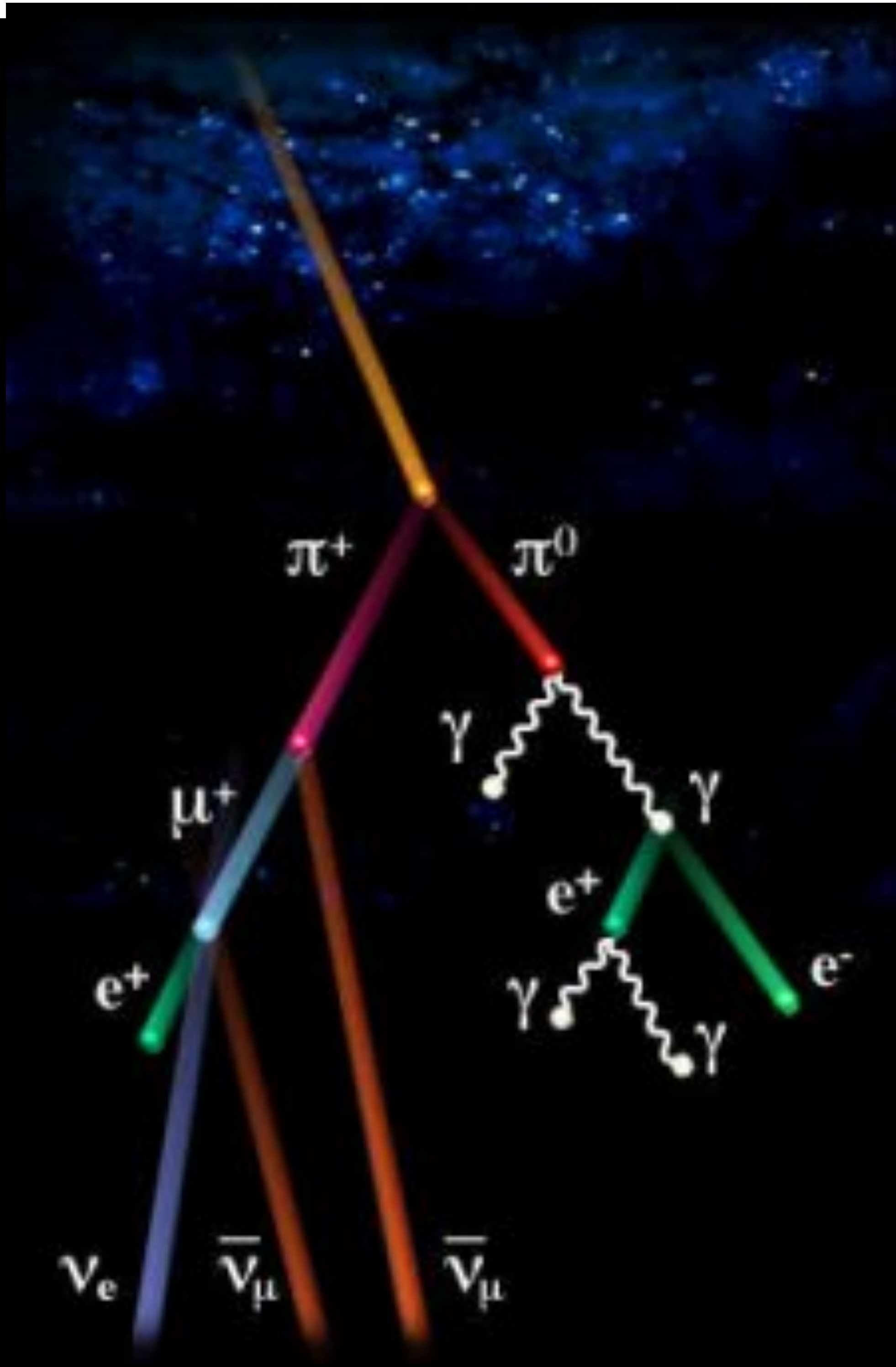
by Victor Hess

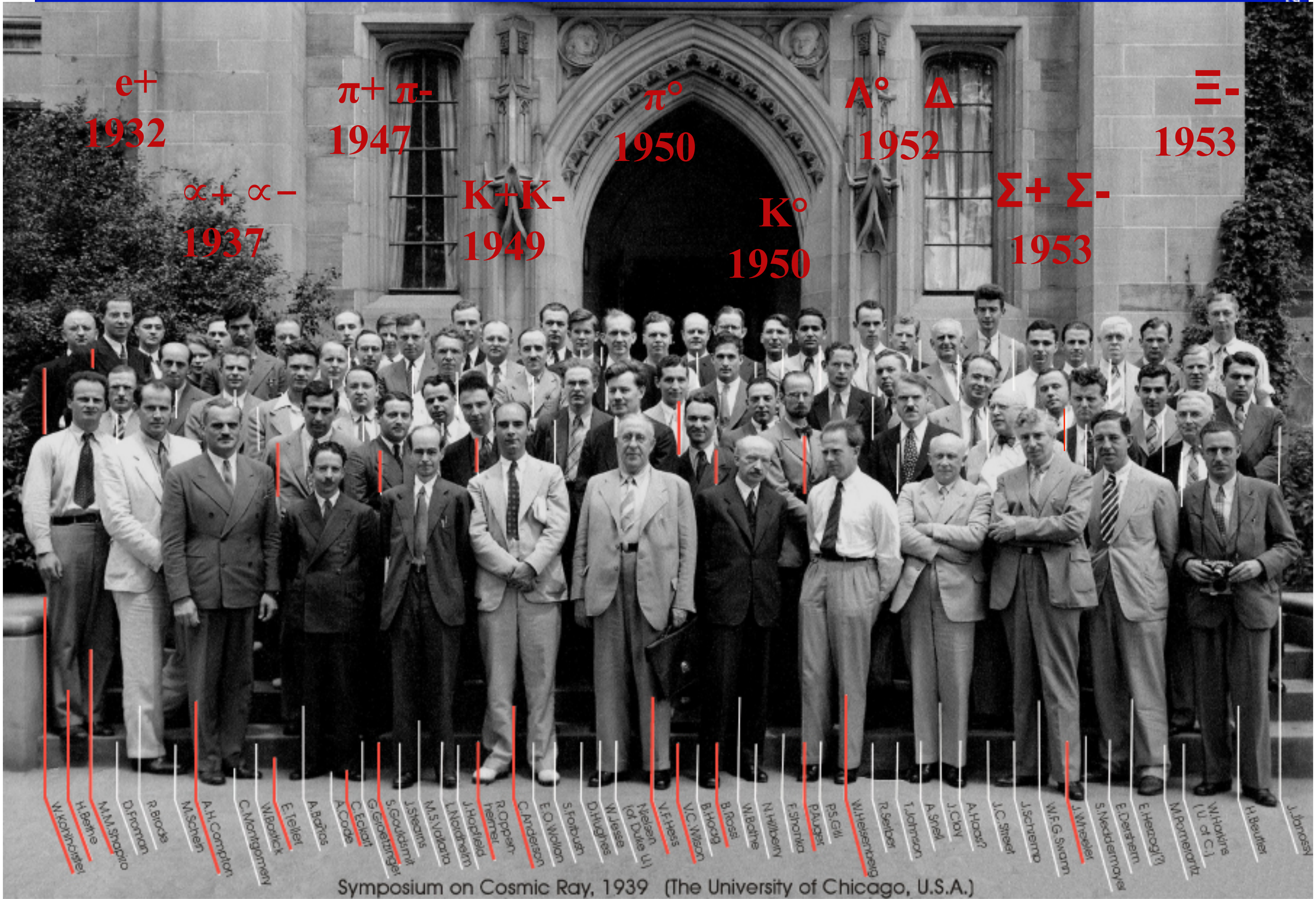




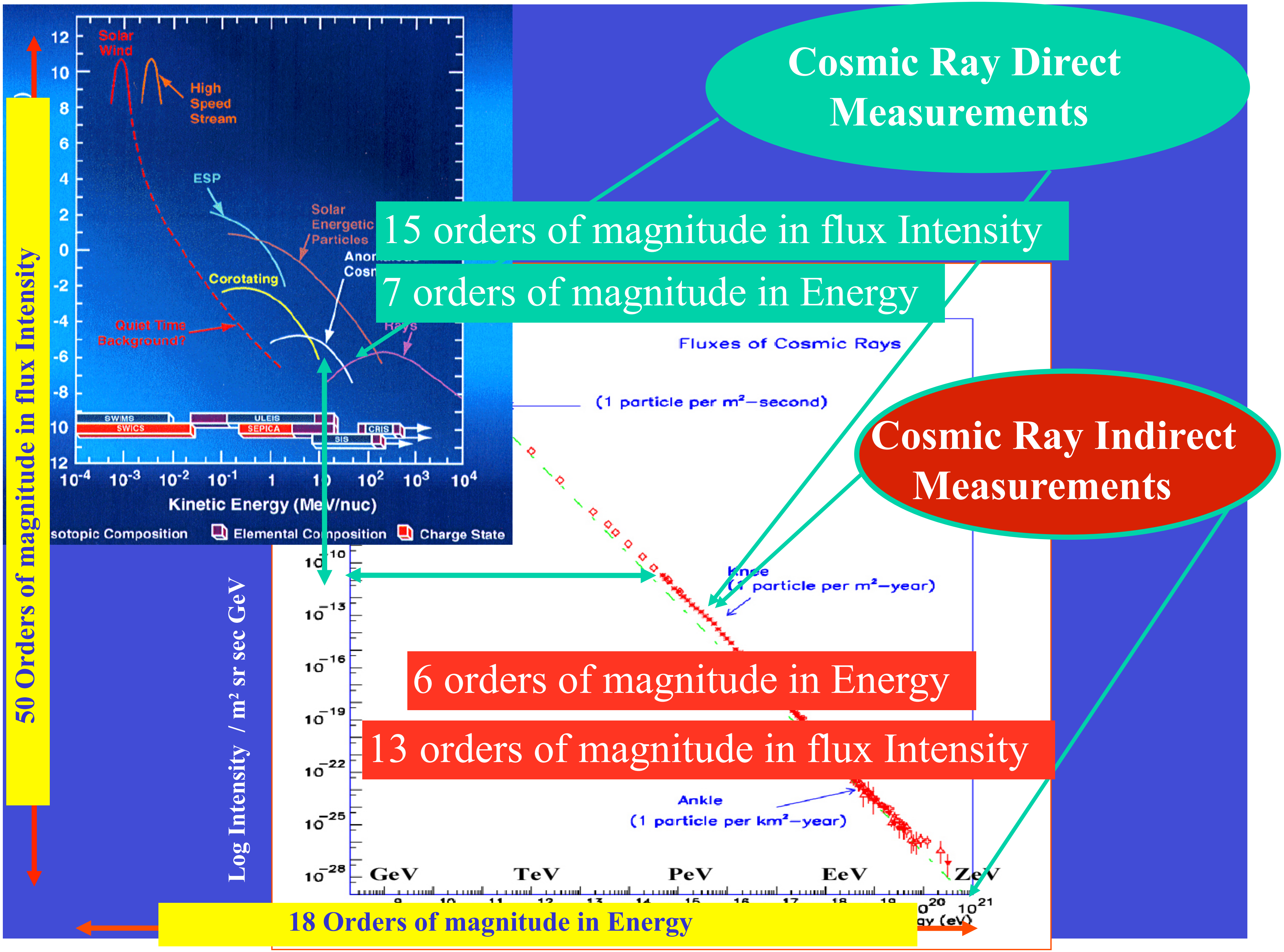
Victor Hess used a hot air balloon and an electrometer

Nobel 1936

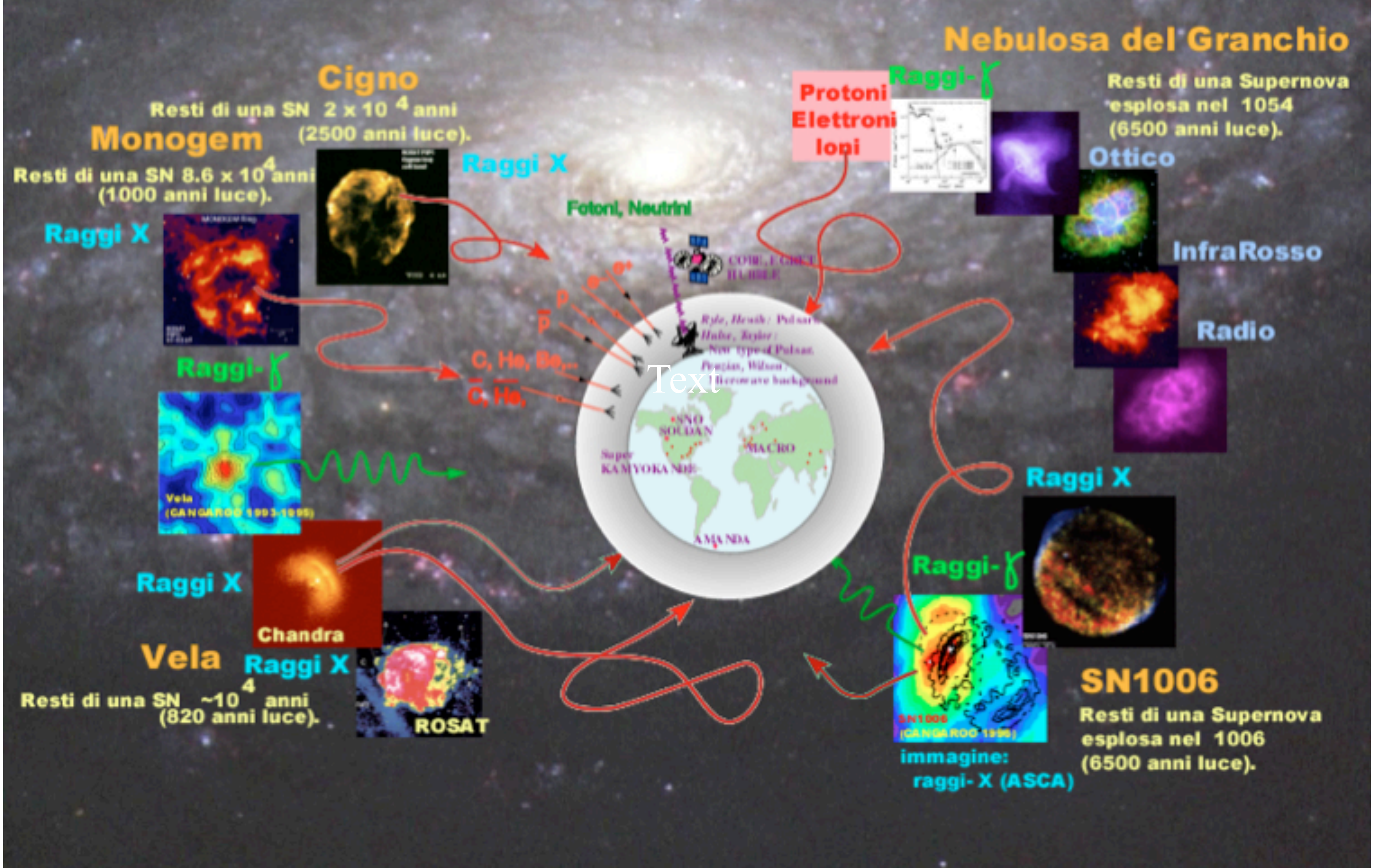

π+
π0
γ
γ
μ+
e+
e+
e-
γ
γ
νe
ν̄μ
ν̄μ



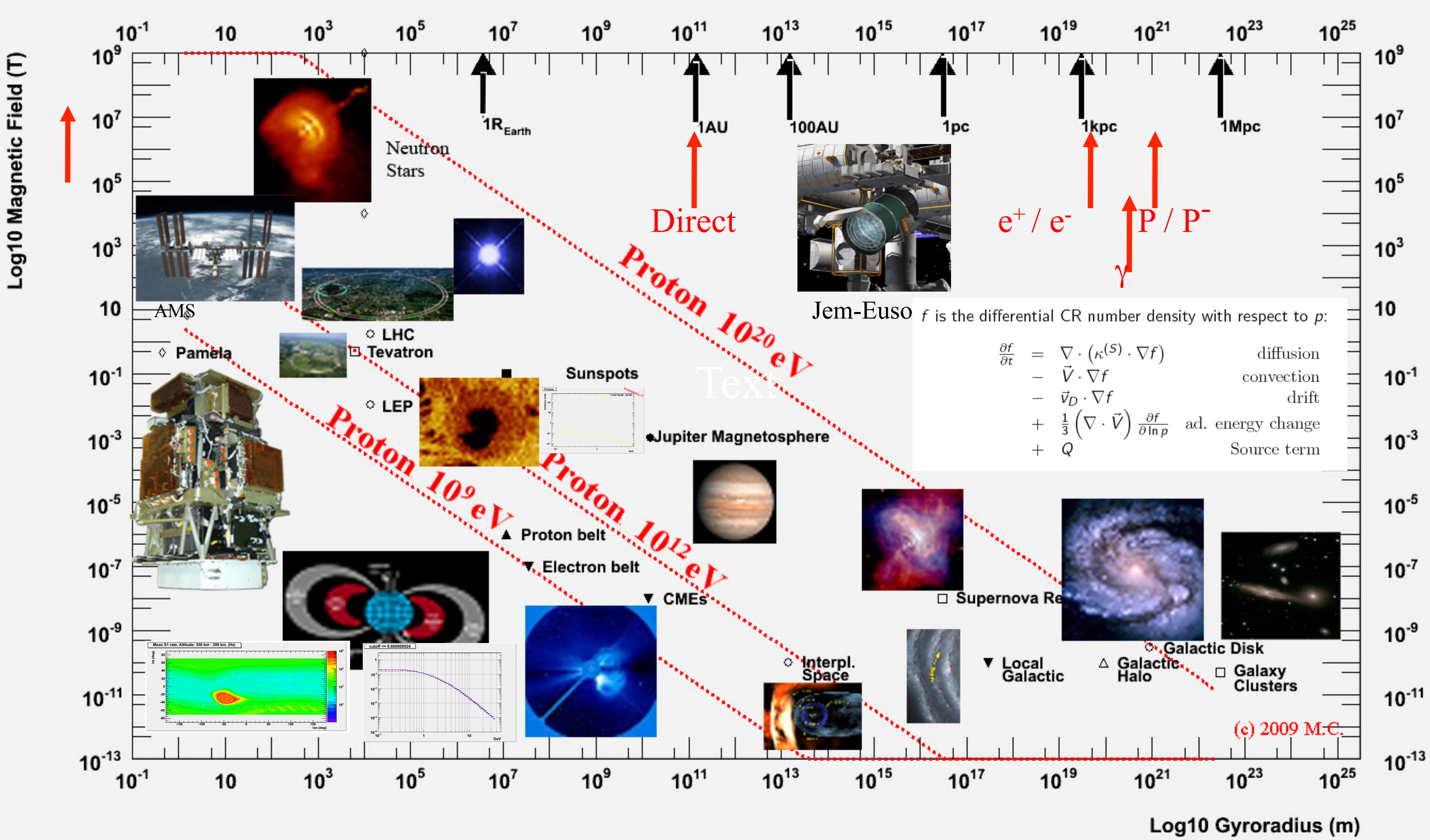
Symposium on Cosmic Ray, 1939 (The University of Chicago, U.S.A.)


Cosmic Ray Direct Measurements
15 orders of magnitude in flux Intensity
7 orders of magnitude in Energy
Cosmic Ray Indirect Measurements
6 orders of magnitude in Energy
13 orders of magnitude in flux Intensity
50 Orders of magnitude in flux Intensity
18 Orders of magnitude in Energy
Log Intensity / m² sr sec GeV
Fluxes of Cosmic Rays
(1 particle per m²—second)
(1 particle per m²—year)
Ankle
(1 particle per km²—year)
GeV
TeV
PeV
EeV
Solar Wind
High Speed Stream
ESP
Solar Energetic Particles
Corotating
Quiet Time Background?
SWIMS
SWICS
ULEIS
SEPICA
CRIS
SIS
Kinetic Energy (MeV/nuc)
Elemental Composition
Charge State

Where the Cosmic Rays come from ?

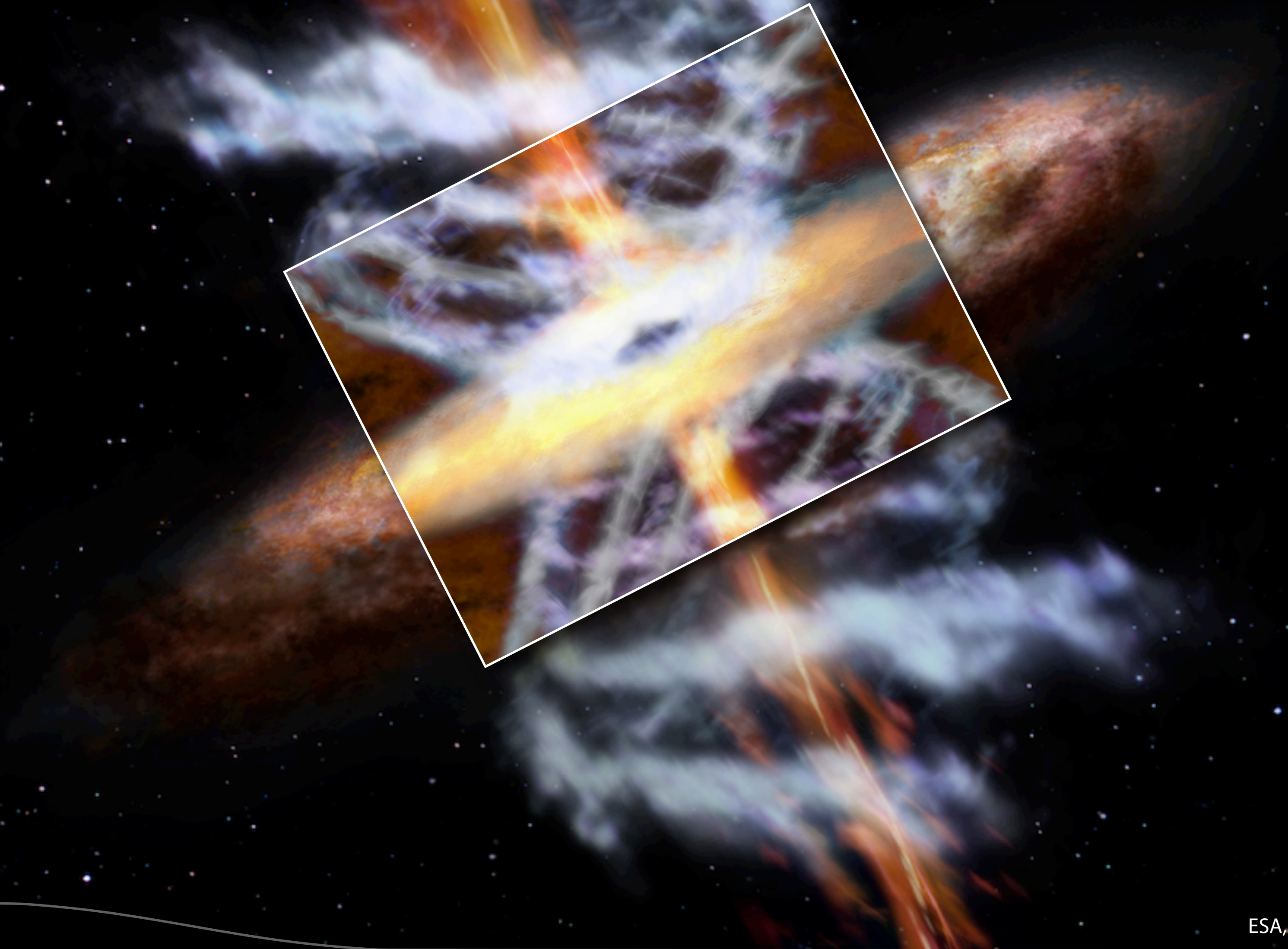


Cosmic Ray Physics in the Hillas Plot



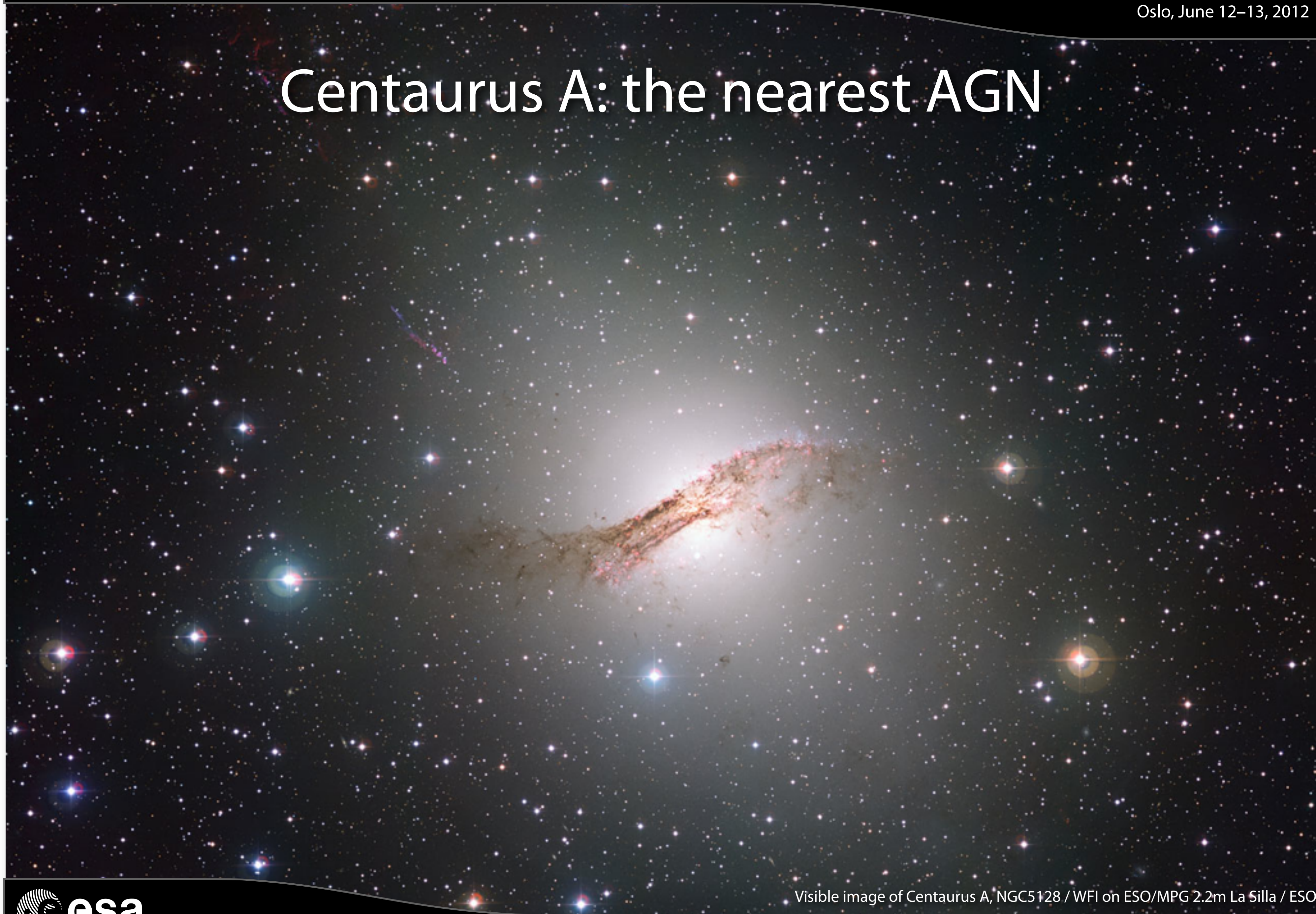
Where Cosmic Rays comes from ?

e.g. outflows from central black holes in AGNs



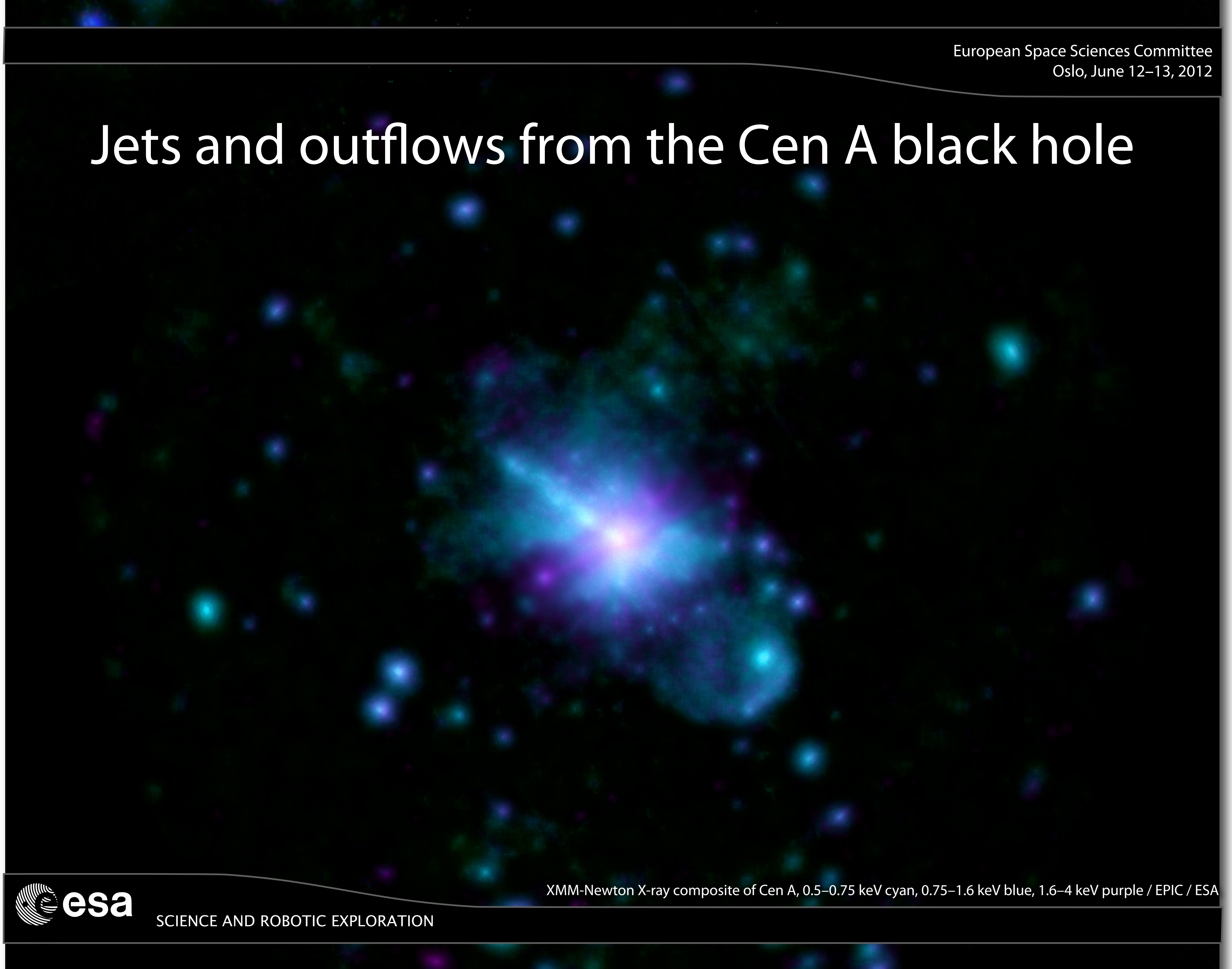
ESA, AOES Medialab

Centaurus A: the nearest AGN



Visible image of Centaurus A, NGC5128 / WFI on ESO/MPG 2.2m La Silla / ESO

Jets and outflows from the Cen A black hole



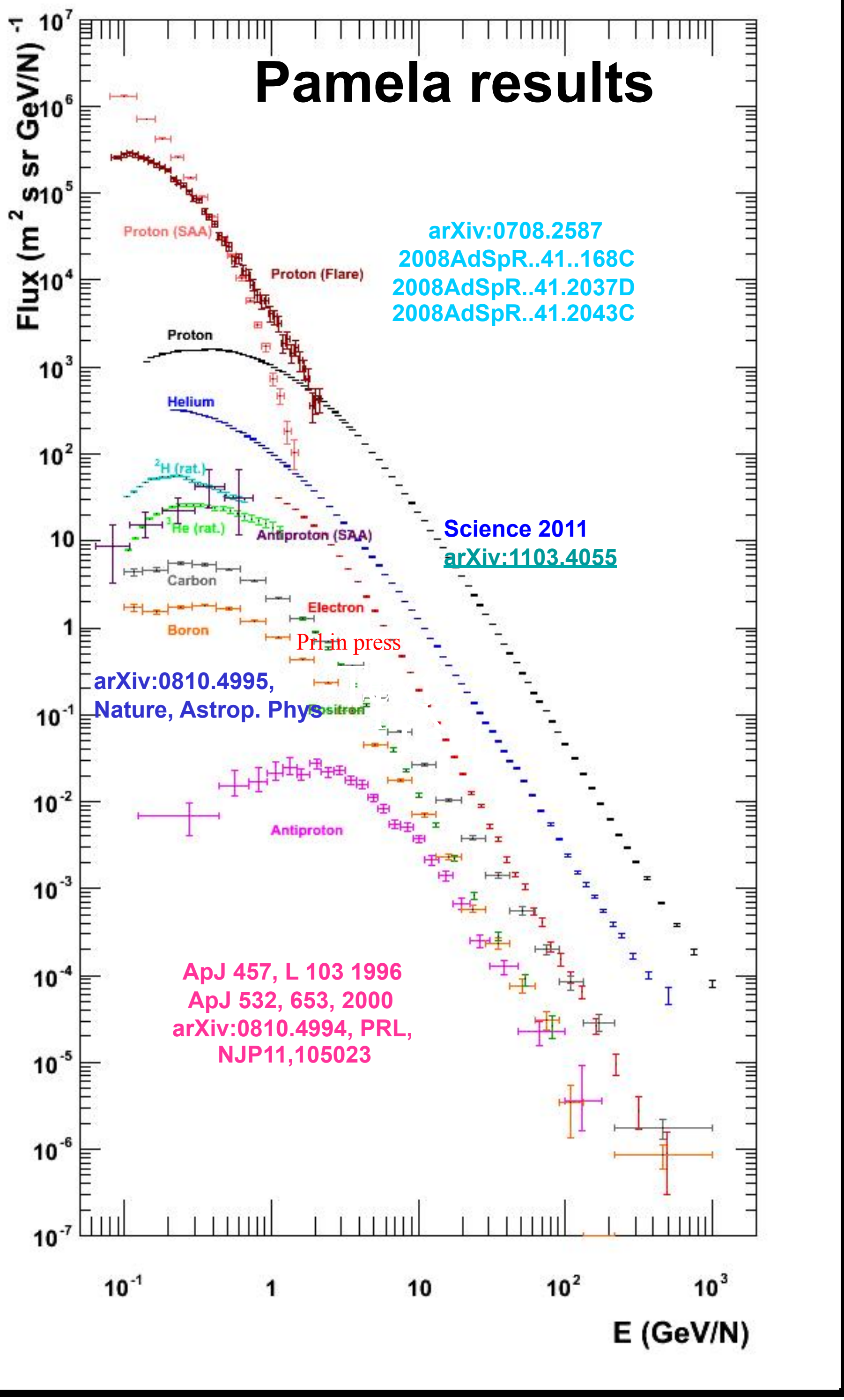
XMM-Newton X-ray composite of Cen A, 0.5–0.75 keV cyan, 0.75–1.6 keV blue, 1.6–4 keV purple / EPIC / ESA

Jets and outflows from the Cen A black hole

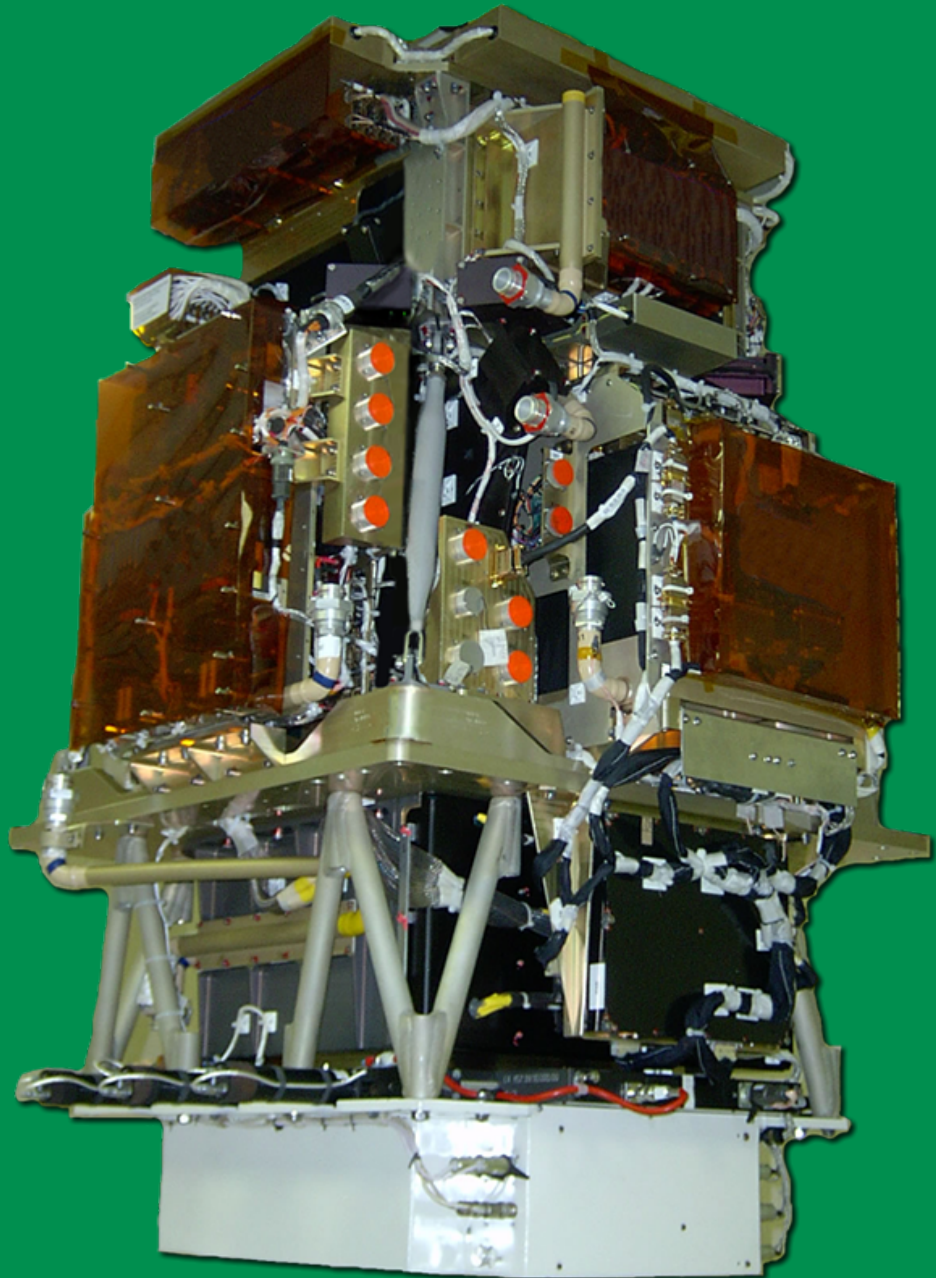
XMM-Newton X-ray + Herschel PACS + SPIRE far-IR (yellow, red) / Wilson / ESA

Data from Space Atmosphere and Ground based experiments

Cosmic Rays in 2012



PAMELA



Magnetic spectrometer

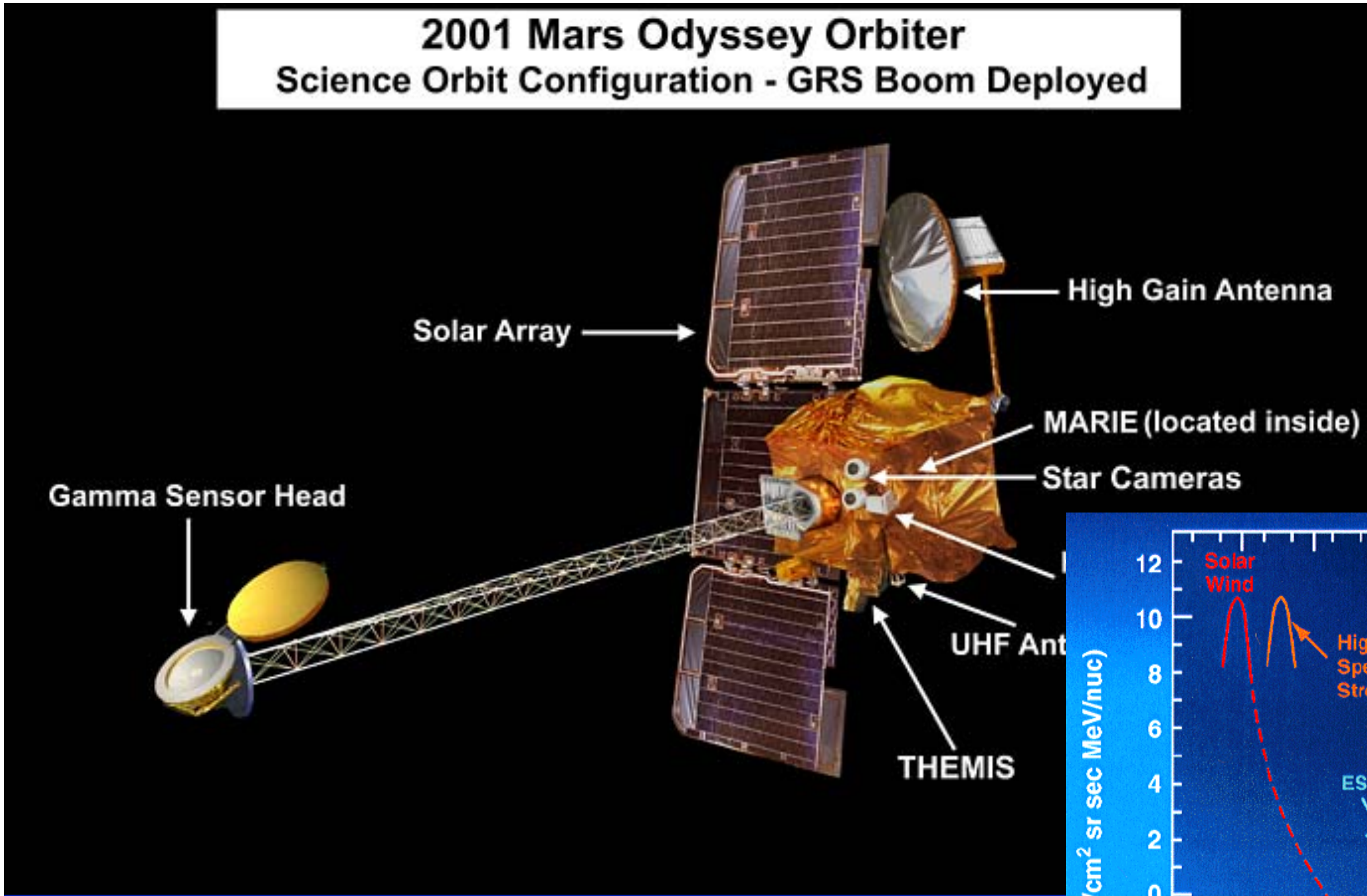
Measurement of CR composition

-> antimatter
-> dark matter
-> propagation
-> solar physics

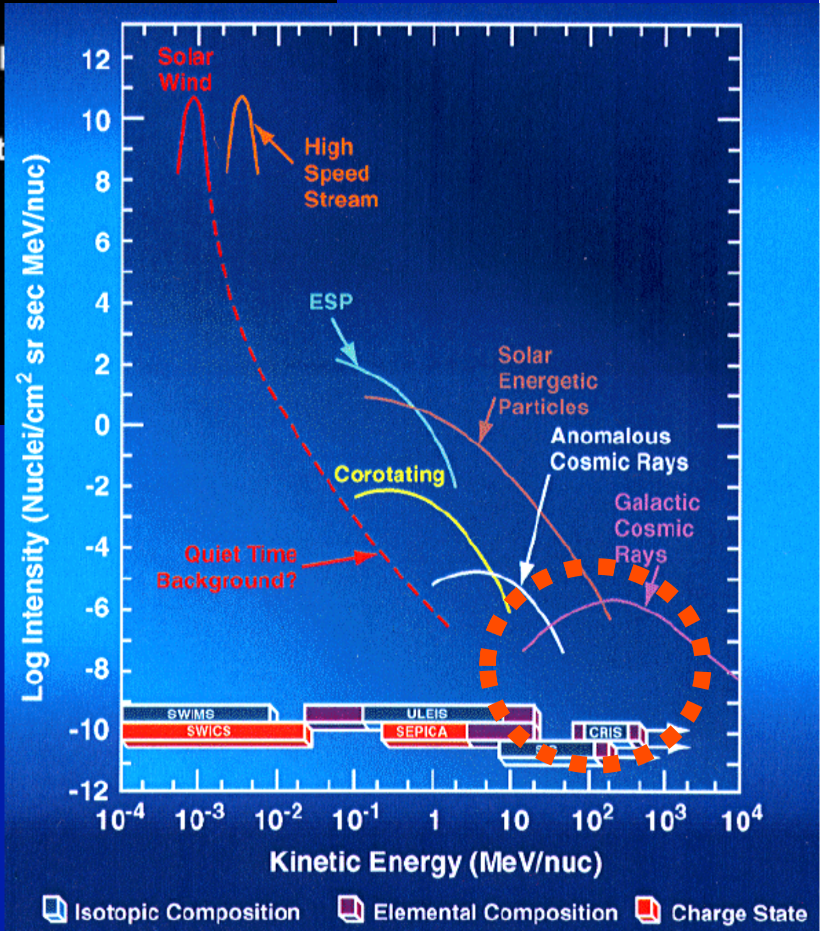
GF ~21.5 $cm^2 sr$

Mass: 470 kg

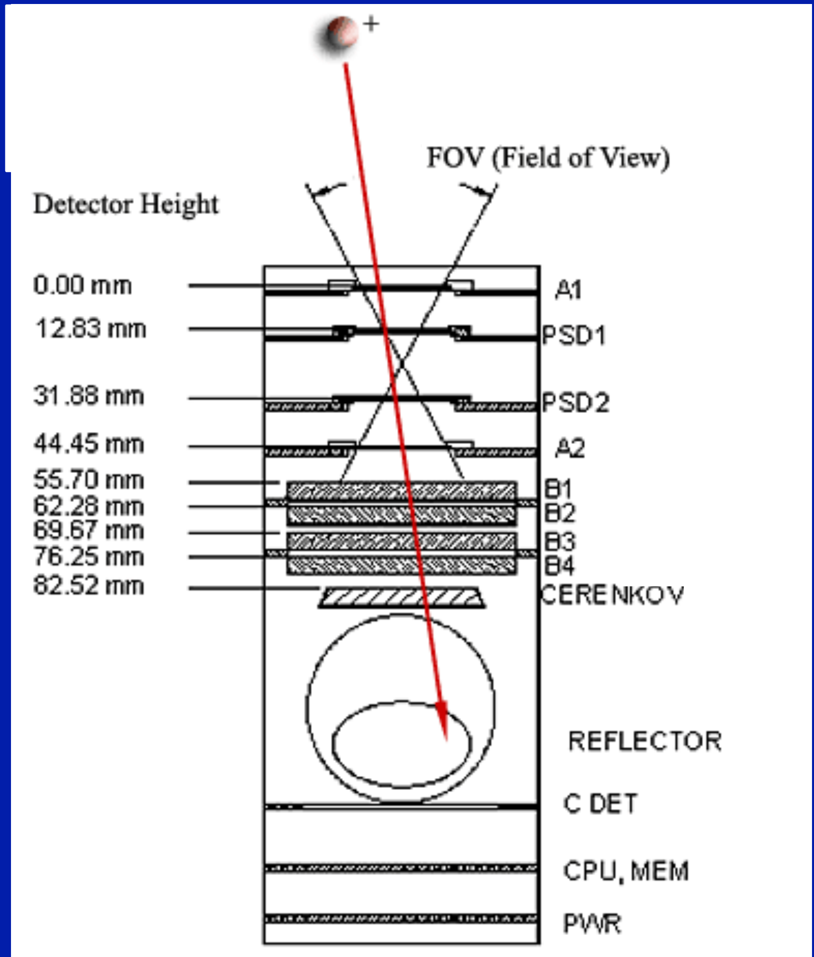
Size: 130x70x70 cm^3

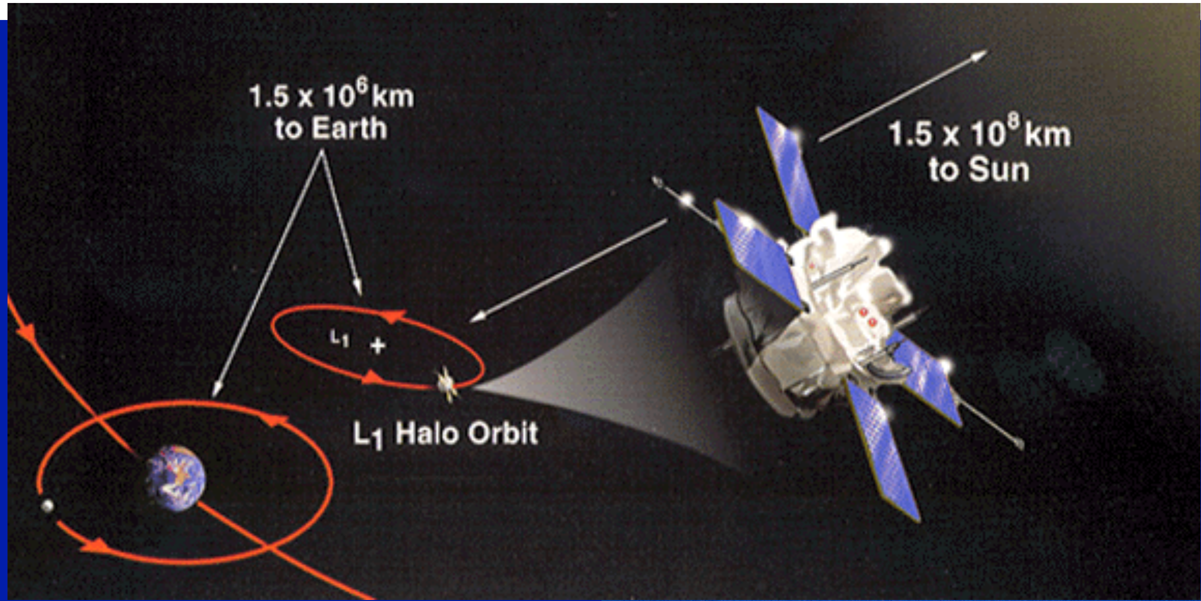


MARIE 2001 Odyssey Spacecraft

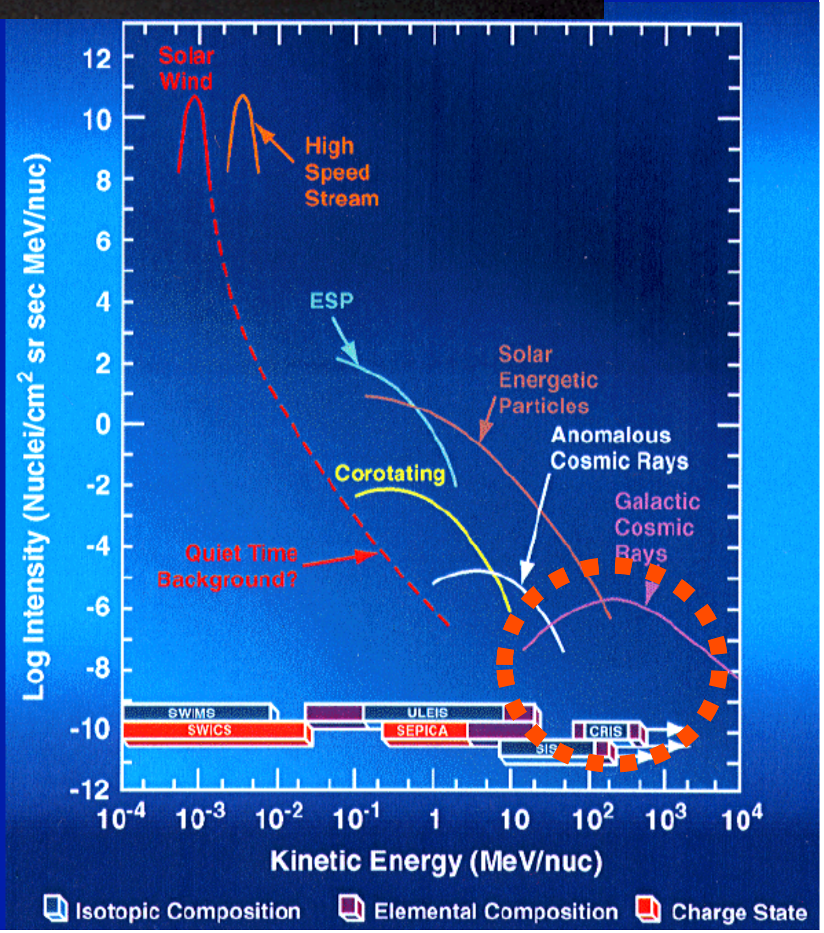


MARIE Instrument



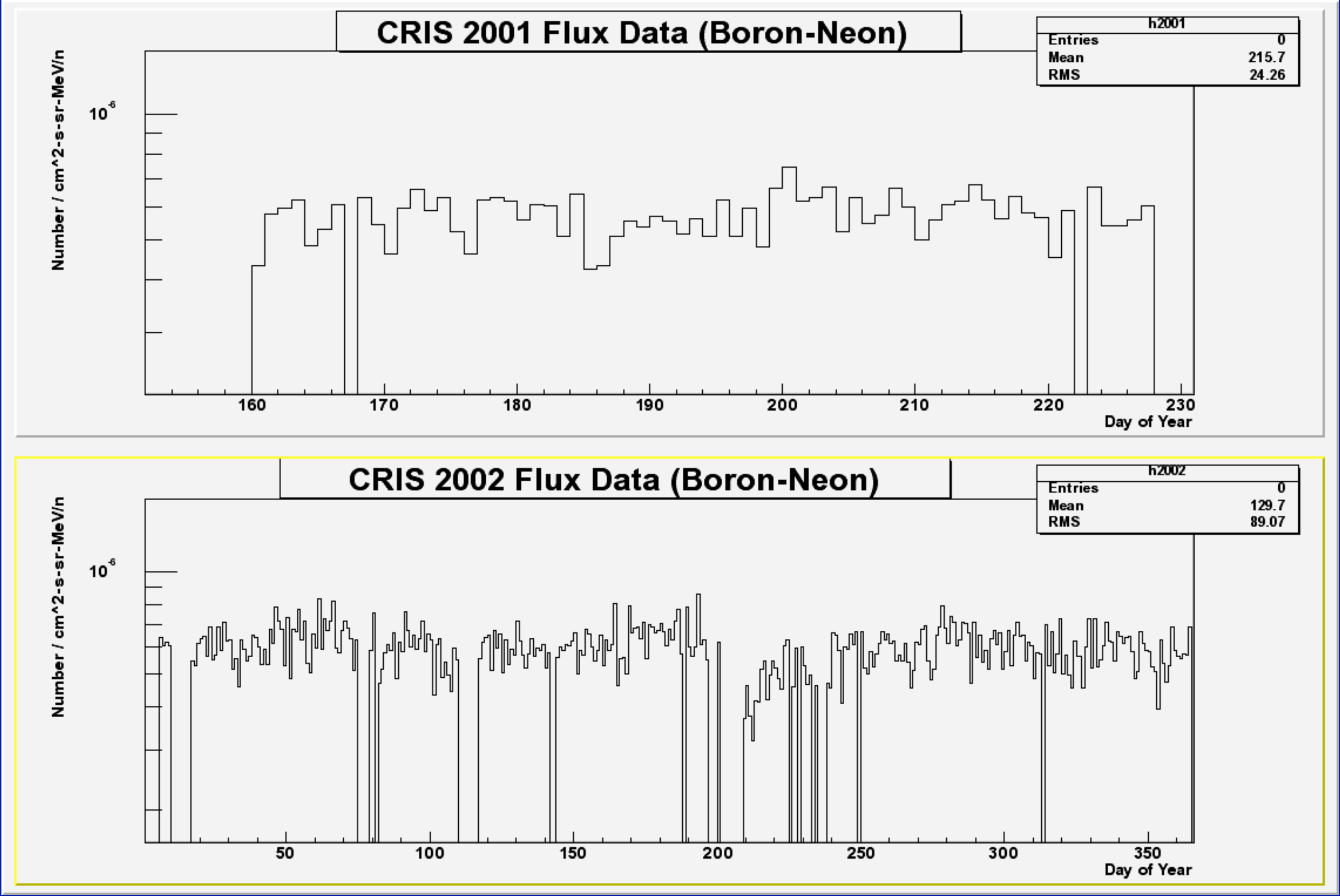


Cosmic Ray Isotope Spectrometer (CRIS)



- Launched August 25, 1997
- In orbit around L1 point.
- Elements, isotopes, and charge states Z = 1 – 30
- Energies from ~10 eV/n (solar wind) to ≥500 MeV/n (galactic)
- > 100 cm^2 sr

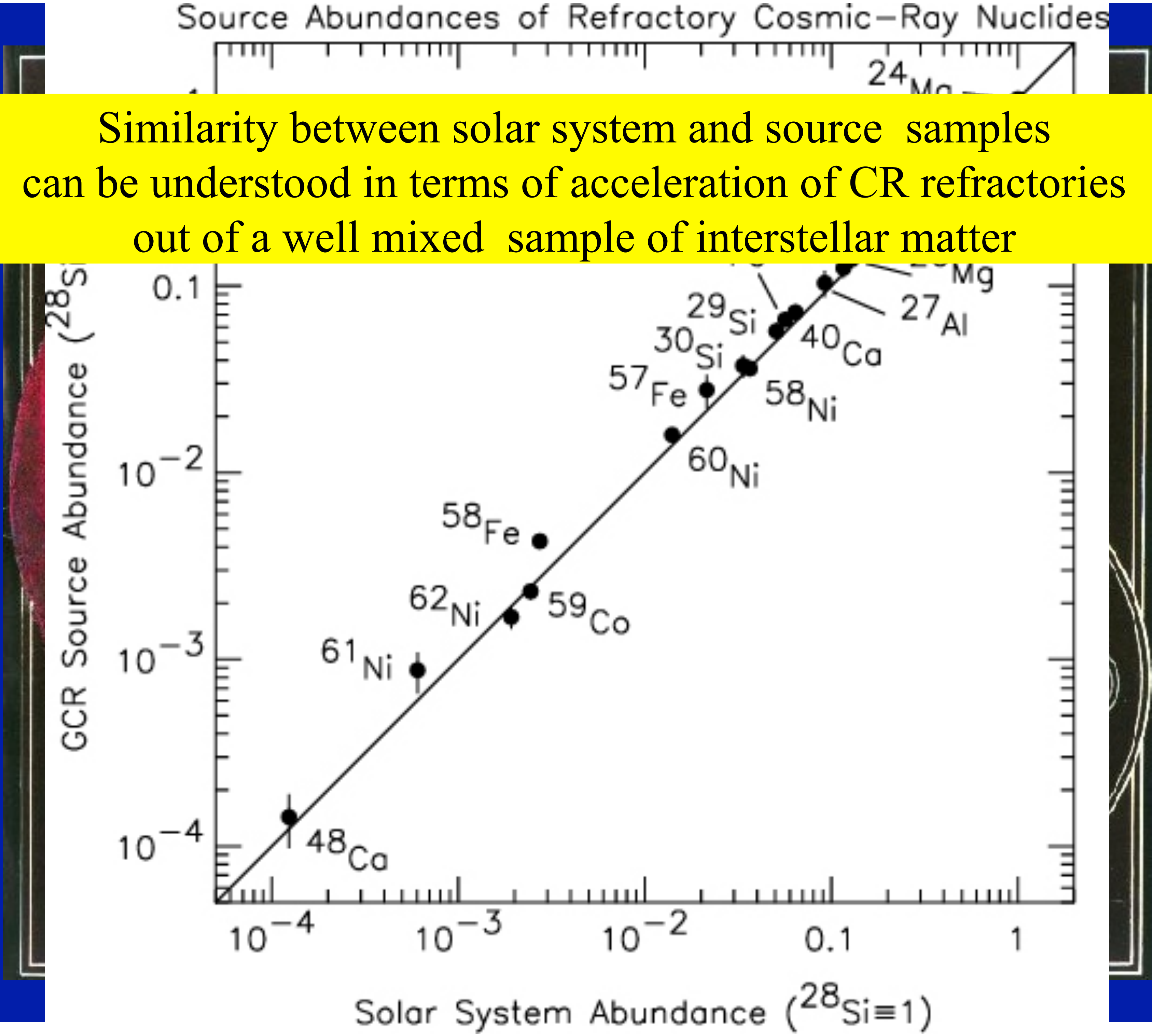
Flux Comparison with ACE/CRIS



"Mars orbit flux data and near Earth flux data agree within the experimental errors"

→ input to dose calculation on Mars surface (weak B_{field})

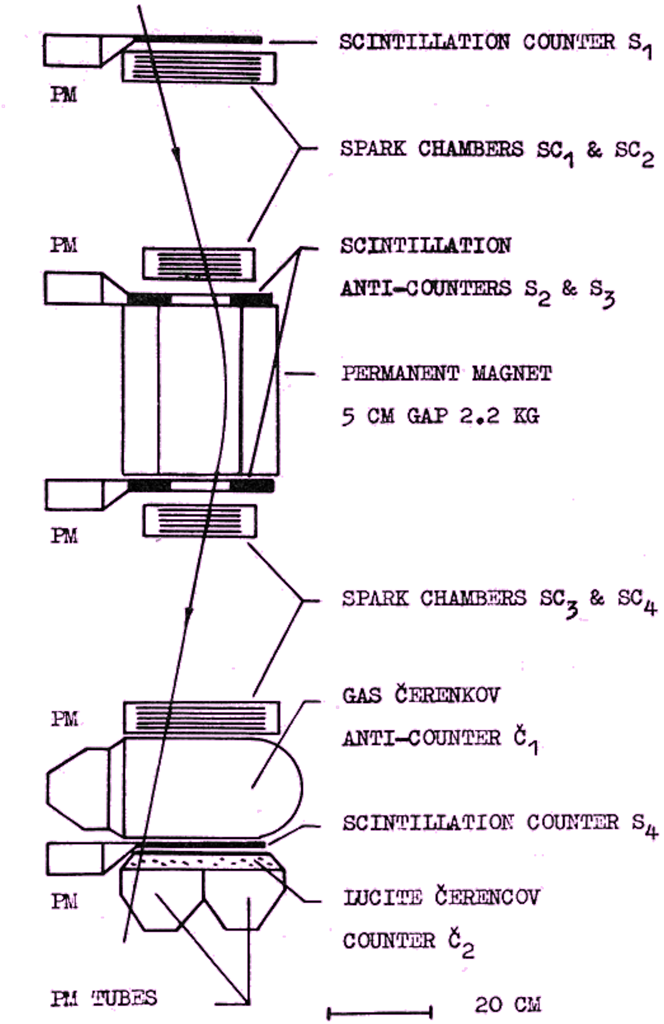
Similarity between solar system and source samples can be understood in terms of acceleration of CR refractories out of a well mixed sample of interstellar matter

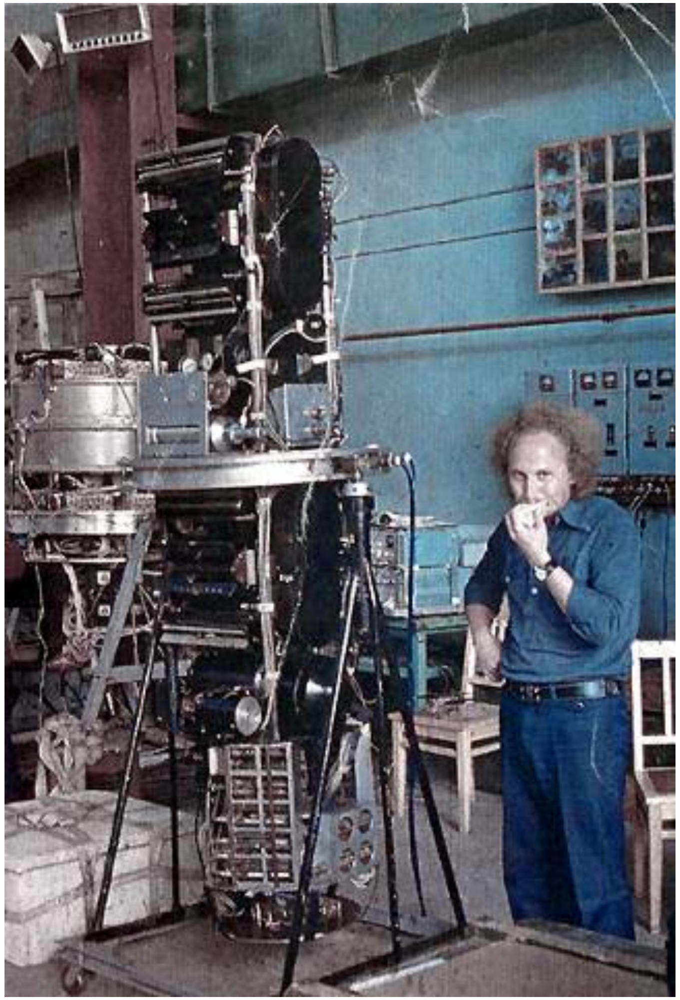


Cosmic Ray Composition
(low energy)

Antiprotons in cosmic rays

Discovery of antiprotons in CR, 1979





$\bar{p}$/p ratio

6 x 10^{-4}

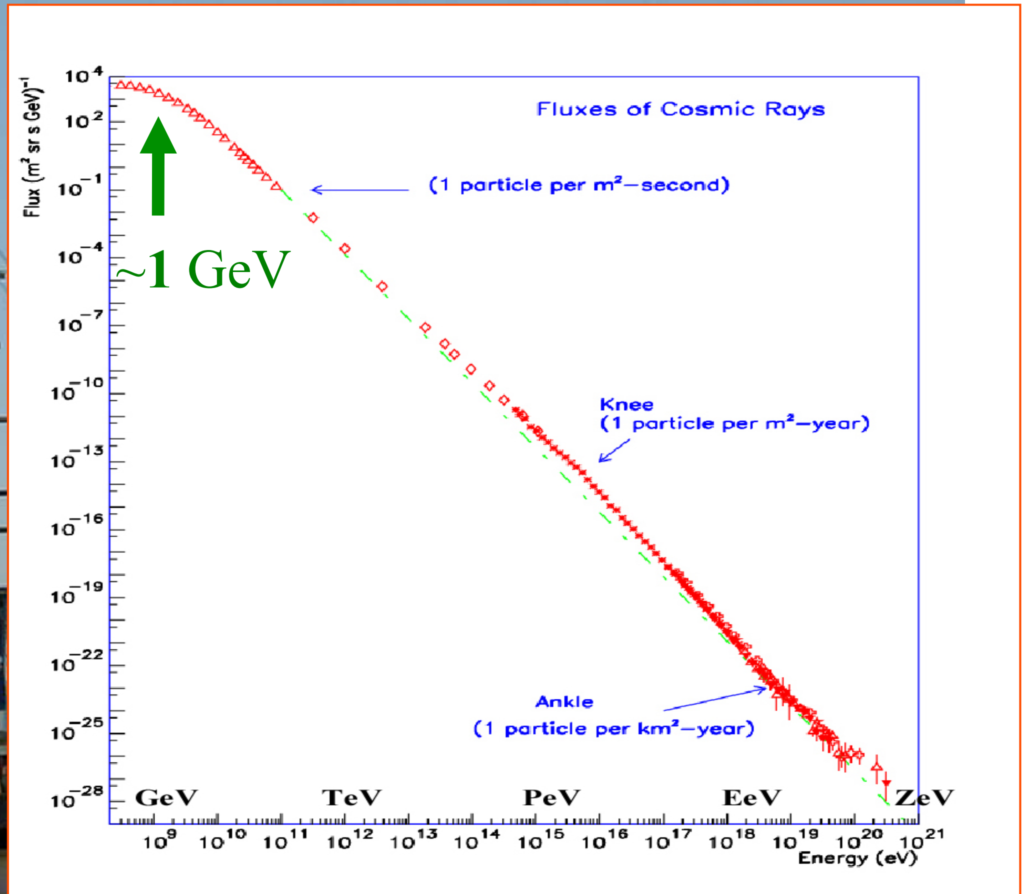
2-5 GeV

From
Robert E. Streitmatter

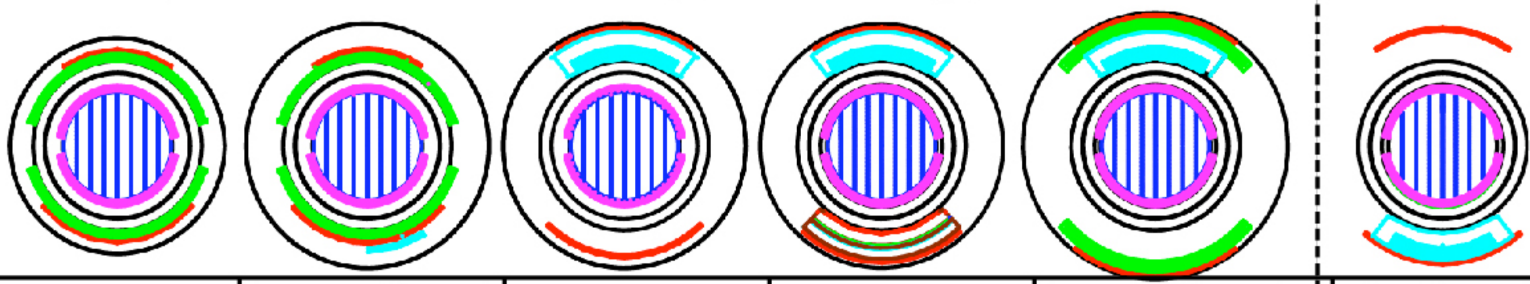
Bogomolov, E.A. et al. 1979, Proc. 16th ICRC, Kyoto, 1, 330,
“A Stratospheric Magnetic Spectrometer Investigation of the Singly Charged Component Spectra and Composition of the Primary and Secondary Cosmic Radiation”

BESS


LITZ
LITZ


Fluxes of Cosmic Rays
Flux (m² sr s GeV)⁻¹
(1 particle per m²–second)
~1 GeV
Knee
(1 particle per m²–year)
Ankle
(1 particle per km²–year)
GeV
TeV
PeV
EeV
ZeV
Energy (eV)

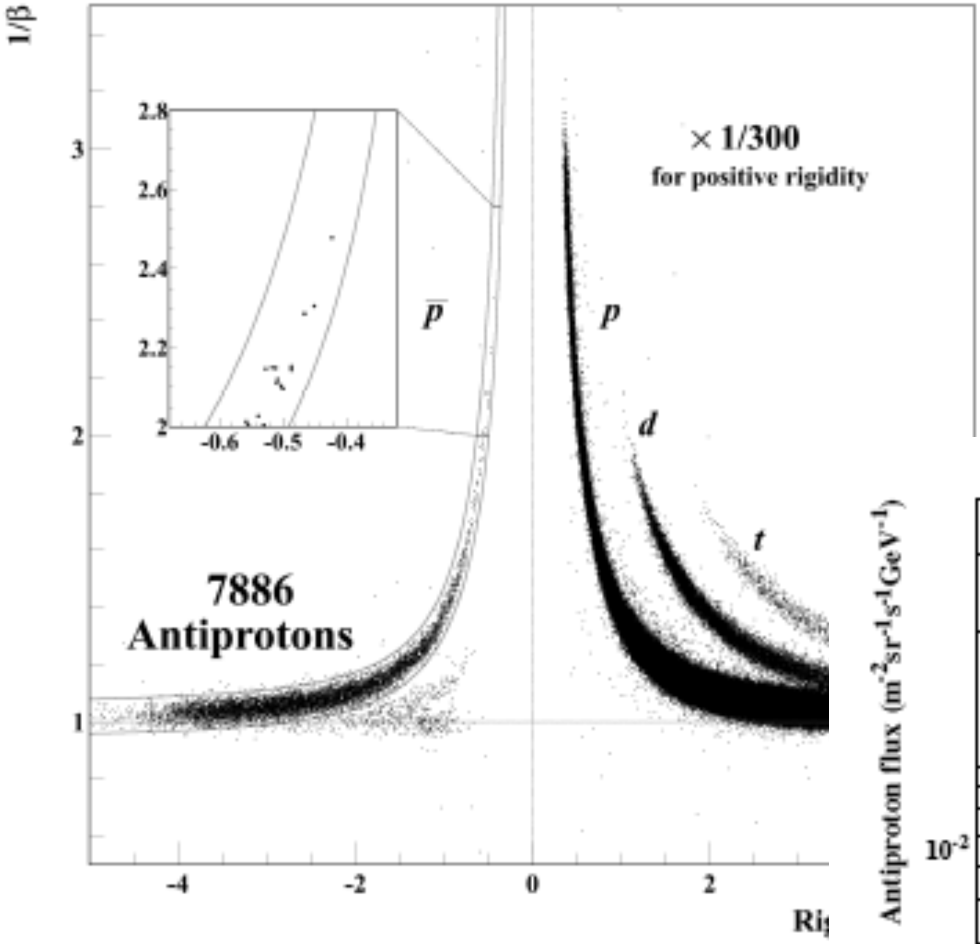
BESS Spectrometer Progress



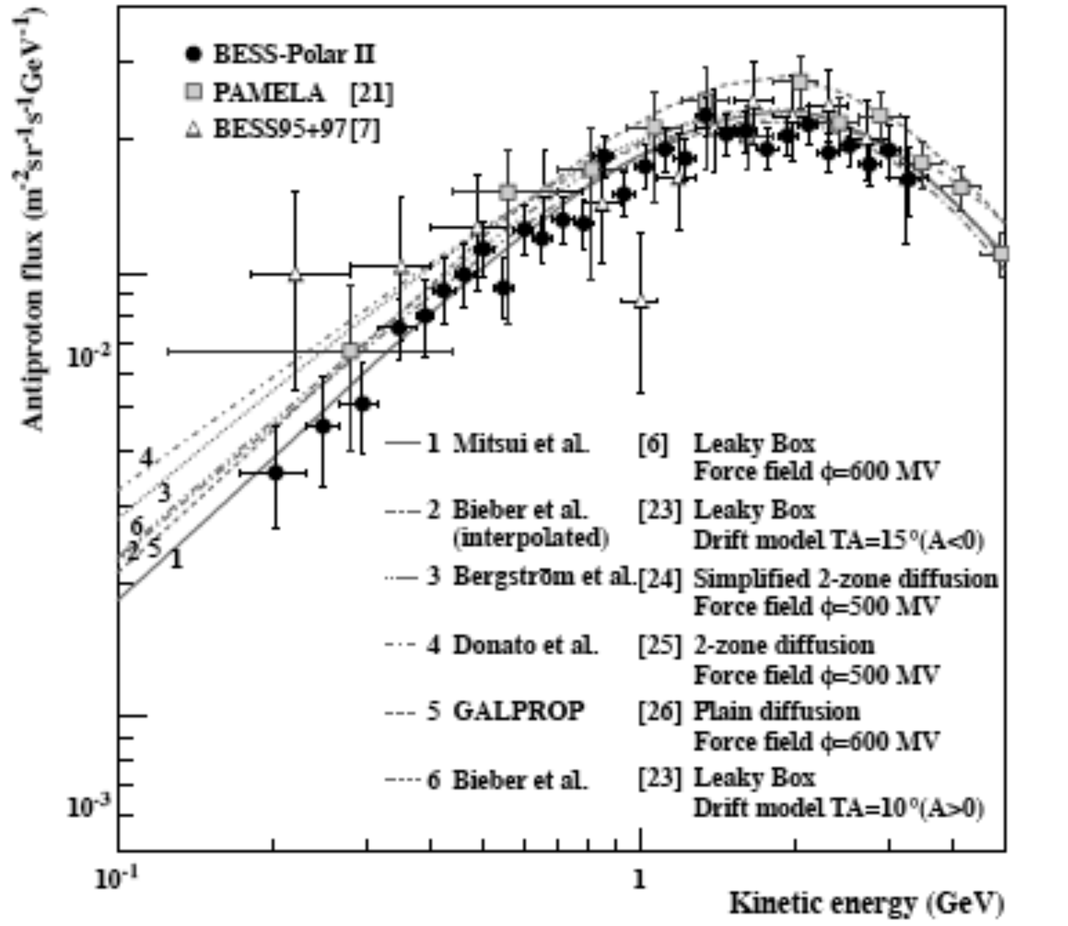
BESS-93,94	BESS-95	BESS-97,98	BESS-99,00	BESS01,02 BESS-TeV	⇒Future BESS-Polar
	Larger Vessel			Larger Vessel	No Vessel
σ_{TOF} =300 ps	σ_{TOF} =110 ps	σ_{TOF} =70 ps Aerogel C 97 n=1.03 $\bar{p}$ 0.2-3.5 GeV 98 n=1.02	Shower Counter $2X_0$ Lead e/μ sep.	New ODC's New JET/IDC's p/He up to 1 TeV	New Mag (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	$\bar{p}$ 0.2-4.2 GeV	$\bar{p}$ 0.1-4.2 GeV

BESS improved in every 9 successful flights

Maximizing advantages in Balloon Experiments



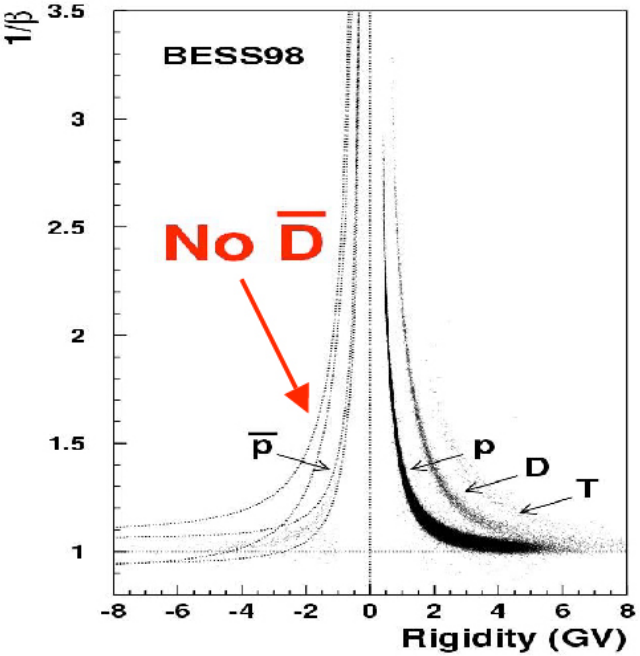
BESS Abe et al . arXiv:1107.6000v2



Antideuteron Upper Limit

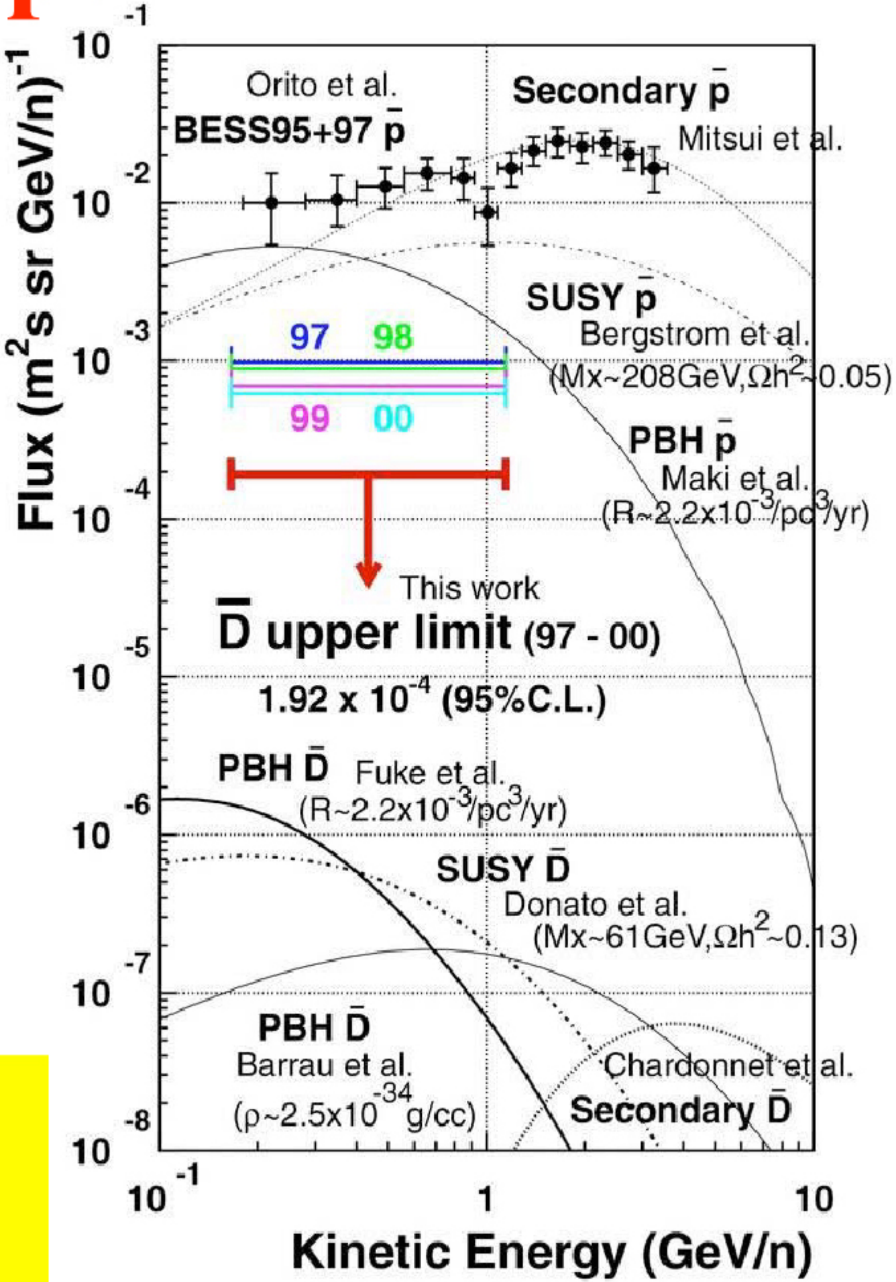
(Fuke et al., OG1,1,-P)

$\overline{D}$ searched in BESS-97, 98, 99, 00

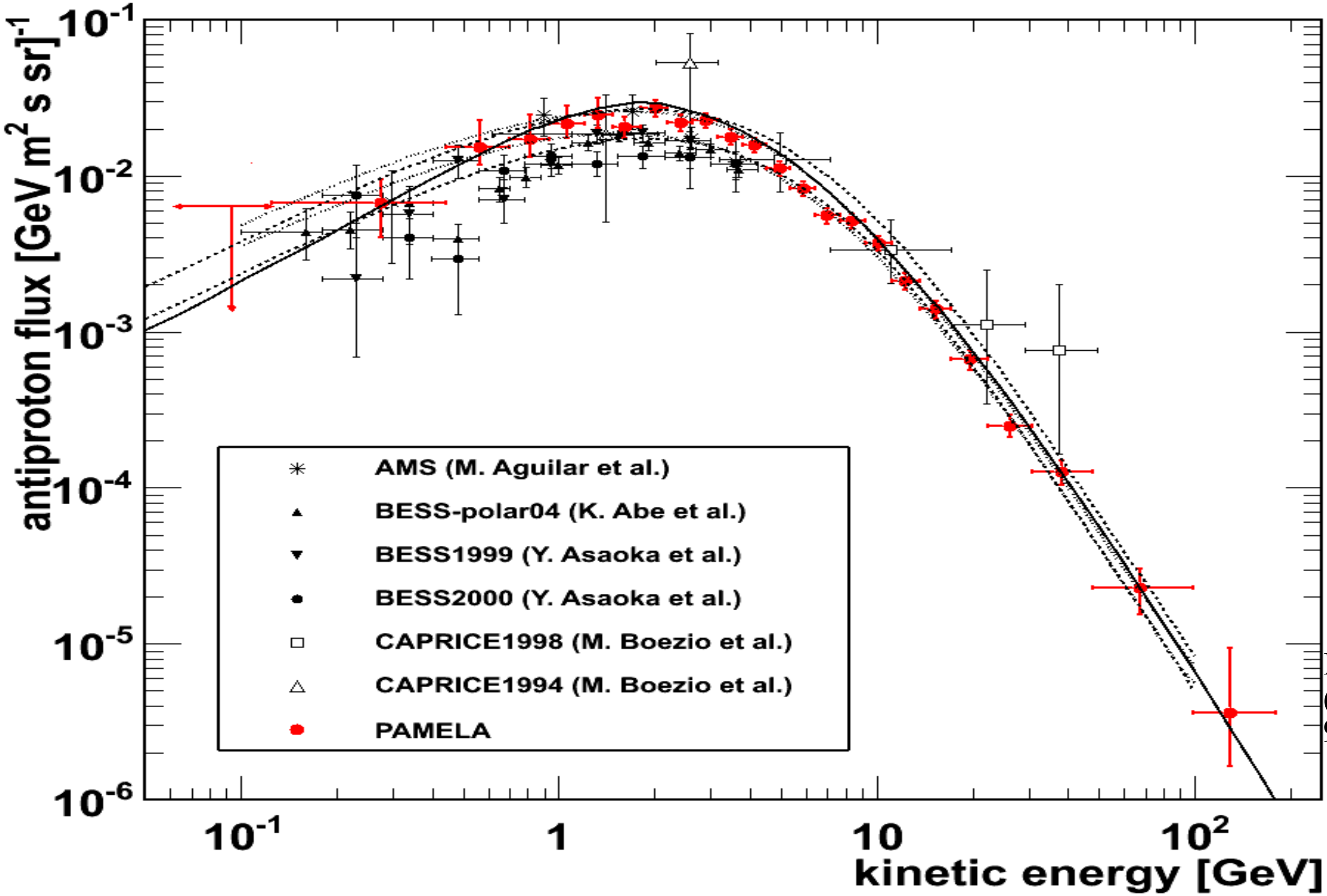


$\overline{D}$ upper limit, for the first time,

1.92 x 10^{-4} $(m^2s.sr.GeV/n)^{-1}$



Antiproton Flux
(0.06 GeV - 180 GeV)



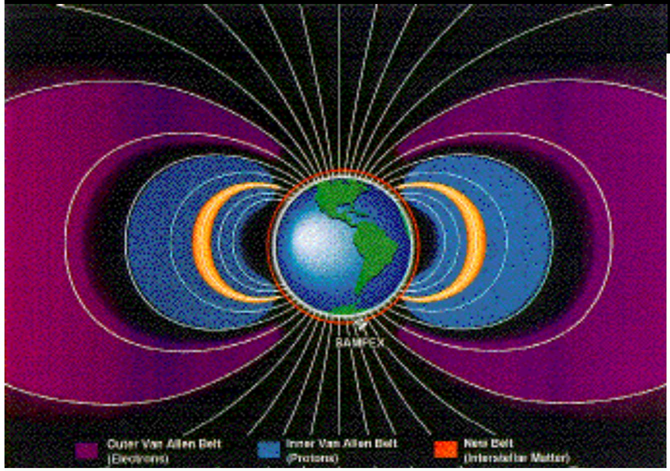
Donato et al.
(ApJ 563 (2001) 172)

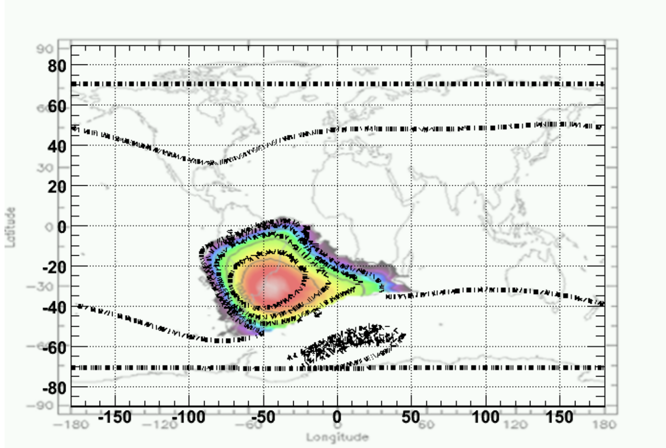
Ptuskin et al.
(ApJ 642 (2006) 902)

PRL. 105, 121101 (2010)

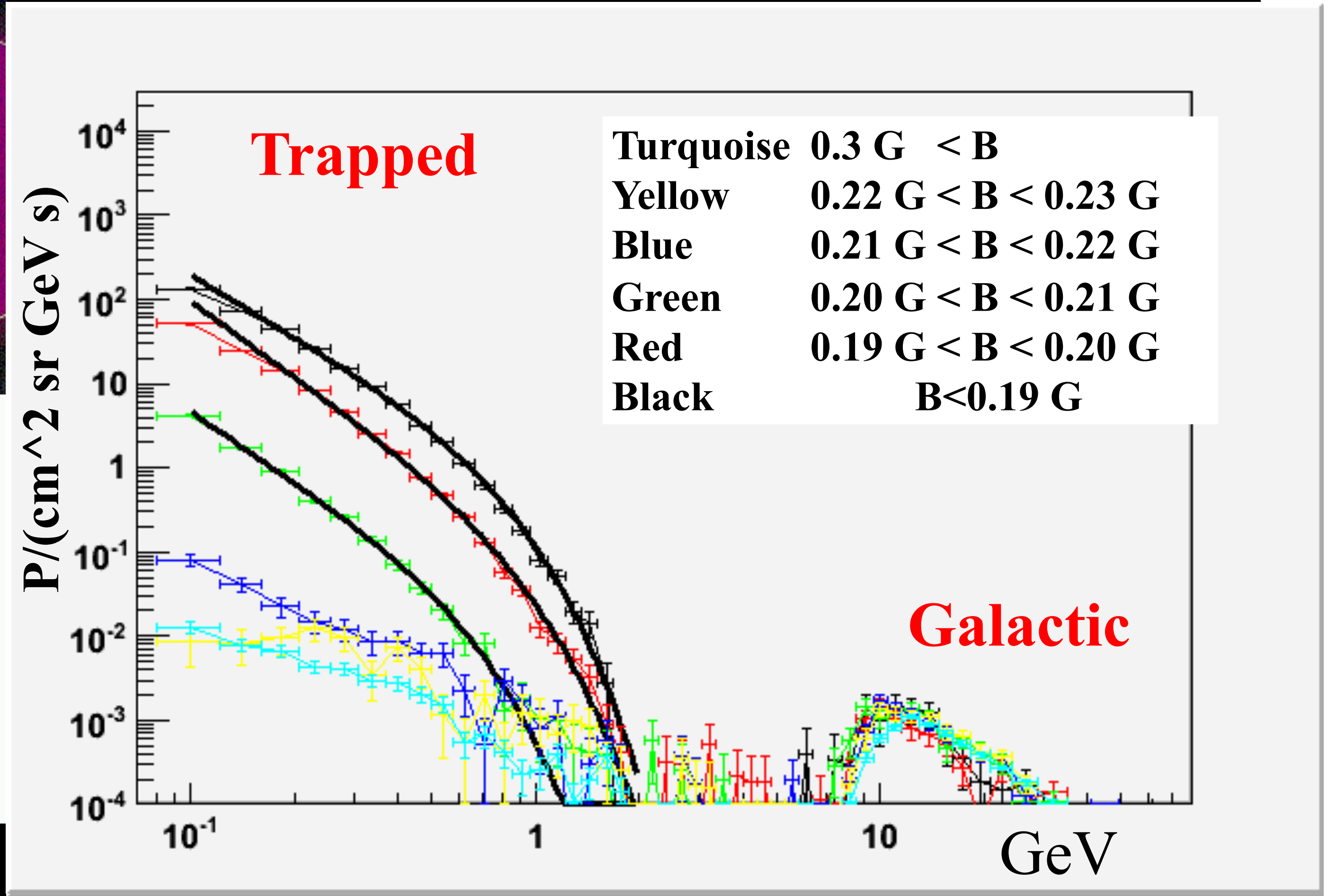
Trapped proton flux in the Van Allen belt (South Atlantic Anomaly)

Arxiv 0810.4980v1



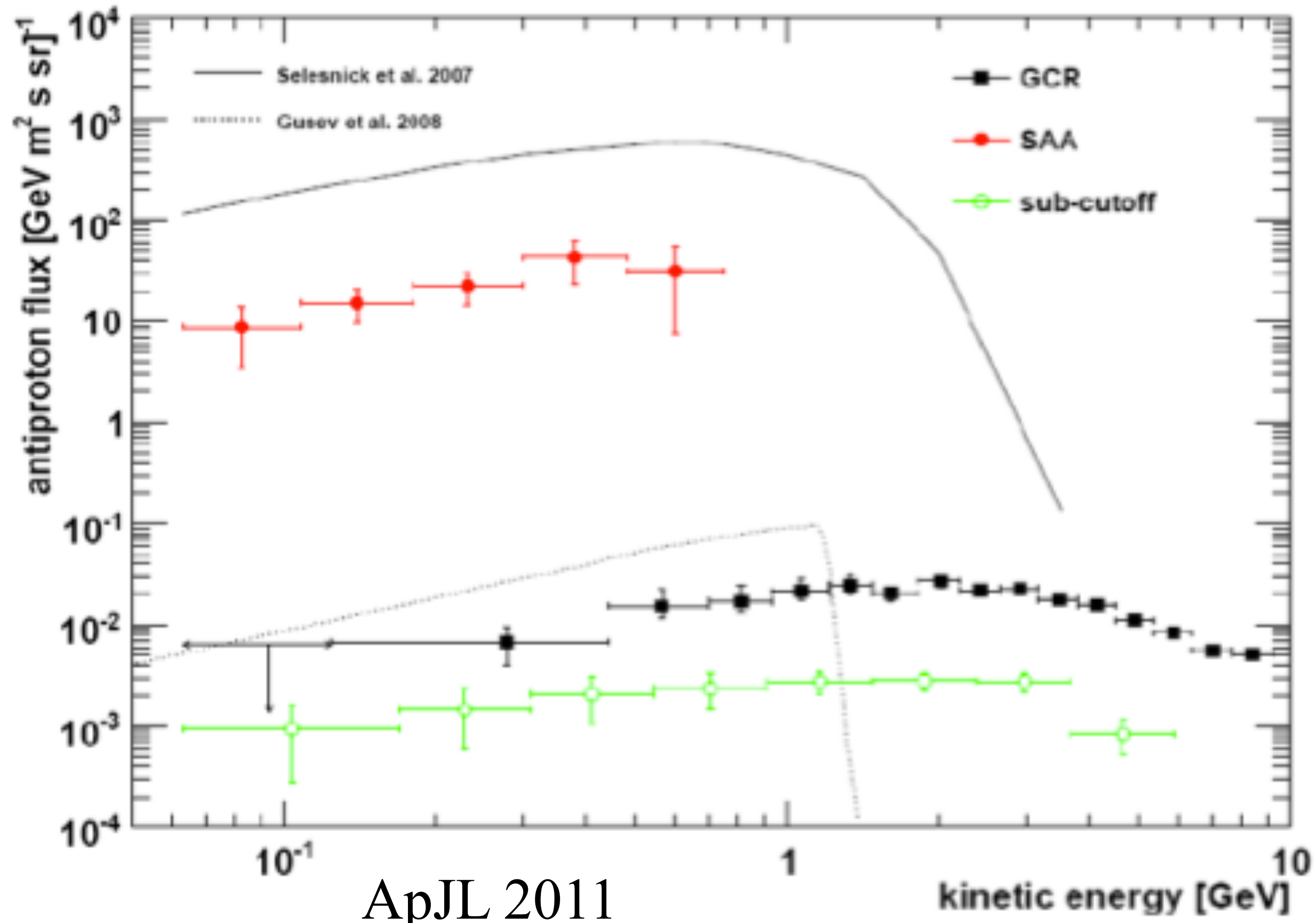


Integral Pamela flux
(E>35 MeV)
(PSB97 plot by SPENVIS project, model by BIRA-IASB)



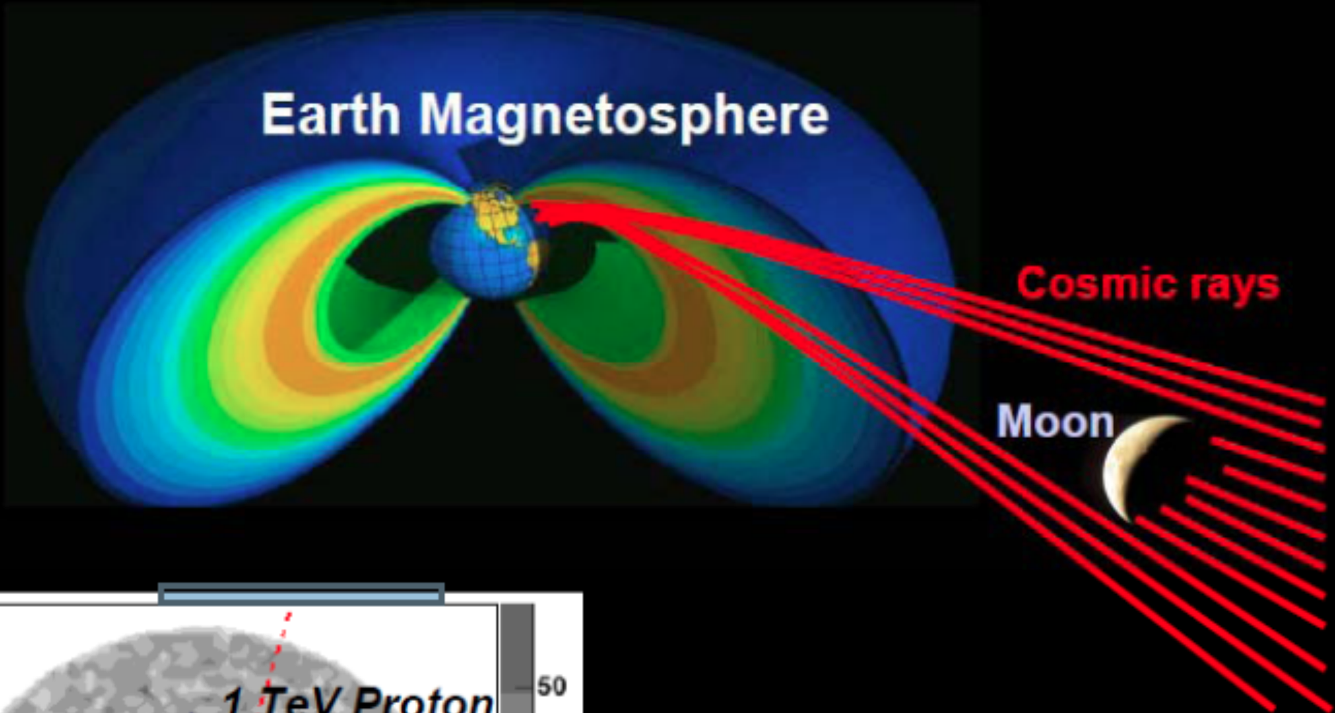
$$\Phi = A\, E^{-(\gamma_0+\gamma_1 E)}$$

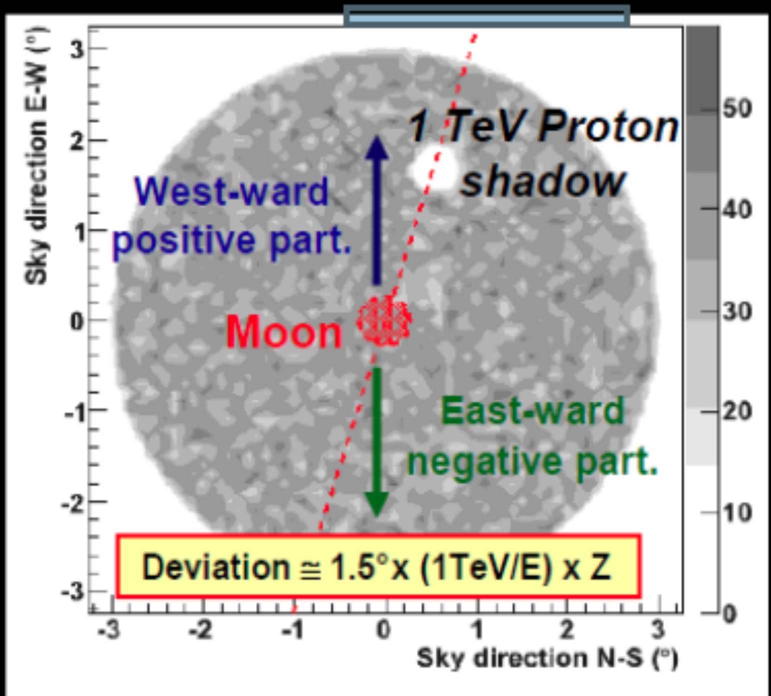
	A	γ_0	γ_1	χ^2/ndf
nero	0.11±0.01	6.0±0.4	3.1±0.5	7.1
rosso	(2.3±0.3) 10^{-2}	5.9±0.5	2.6±0.6	6.8
verde	(5±3) 10^{-4}	8.1±1.8	4.7±1.8	10.


antiproton flux [GeV m^2 s sr]$^{-1}$
Selesnick et al. 2007
Gusev et al. 2008
GCR
SAA
sub-cutoff
kinetic energy [GeV]

ApJL 2011

Earth-Moon spectrometer





The Moon shadow position depends on:

- CR charge
- CR kinetic energy

Moon shadow
ARGO
<E> = 1.4 TV
Large statistics

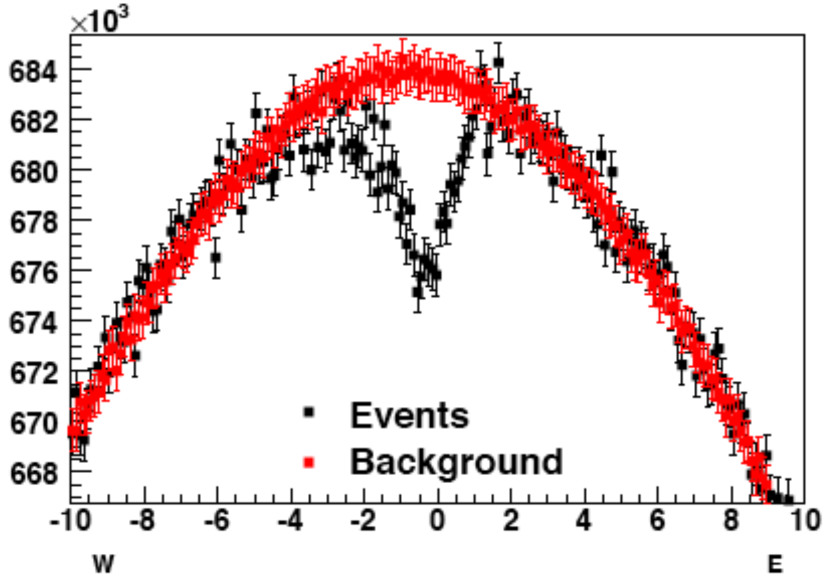


Figure 1: Deficit of CRs around the Moon position projected along the R.A. direction. Showers with N>60 recorded from July 2006 until November 2009 are shown.

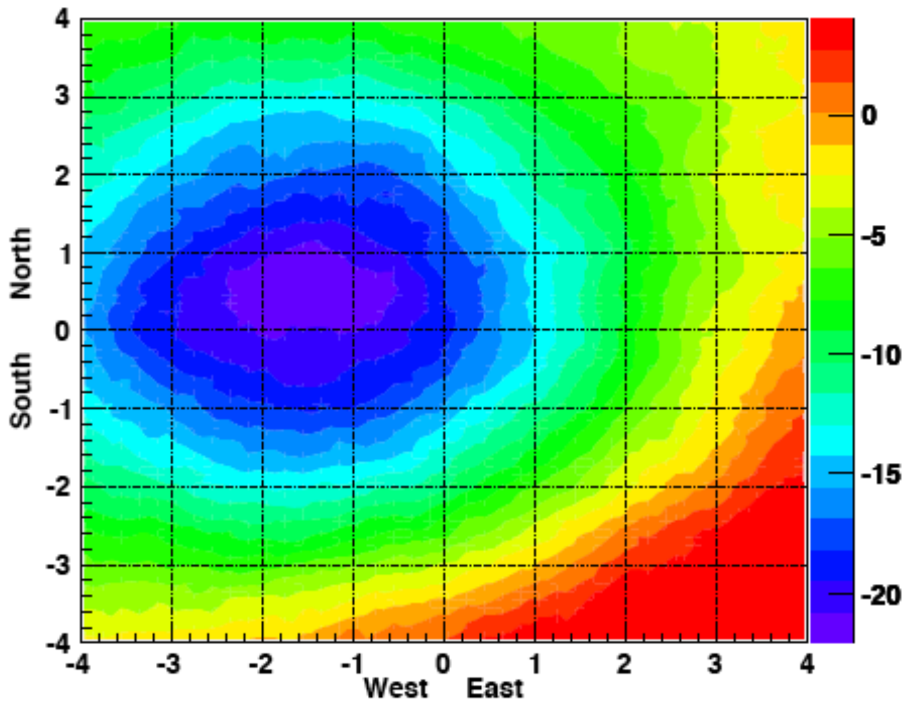


Figure 2: Moon shadow significance map. It collects all the events detected by ARGO-YBJ from July 2006 until November 2009. The event multiplicity is $20 \leq N < 40$ and zenith angle $\theta < 50°$. The color scale gives the statistical significance.

Moon /Sky = 6 10^{-5}

AMS lower statistics but:
- likely better angular resolution
- May exploit <E> = 100 GV

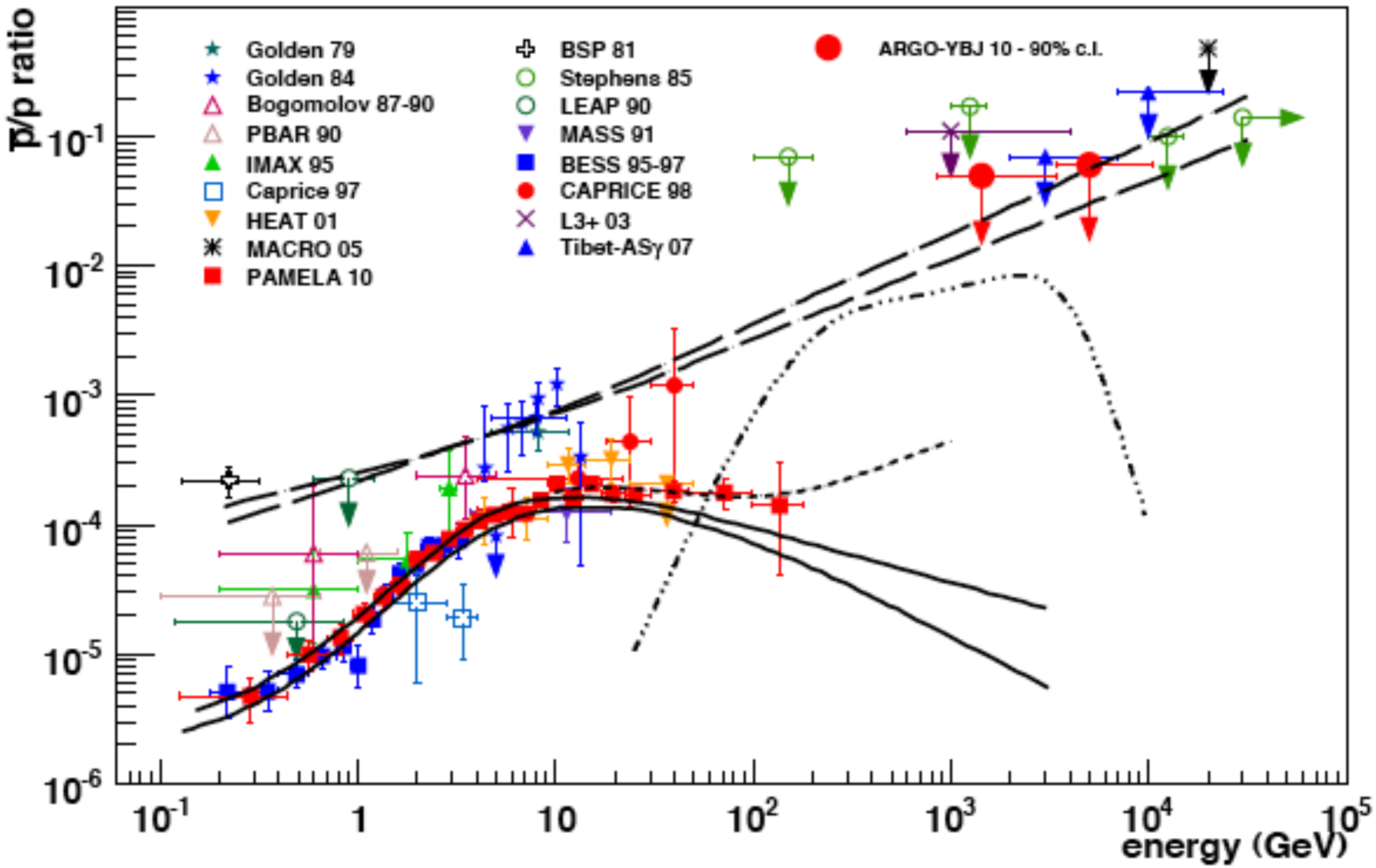
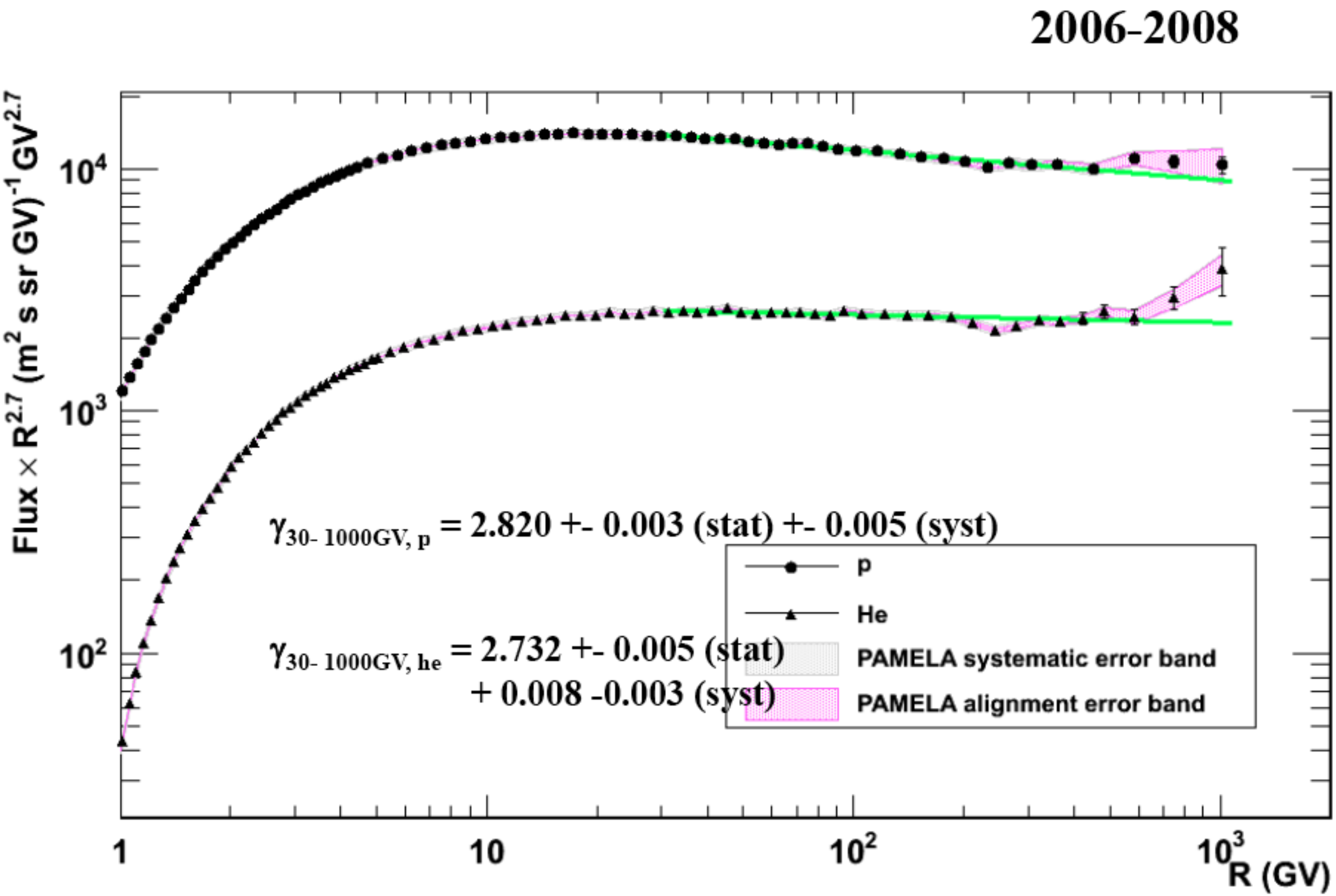


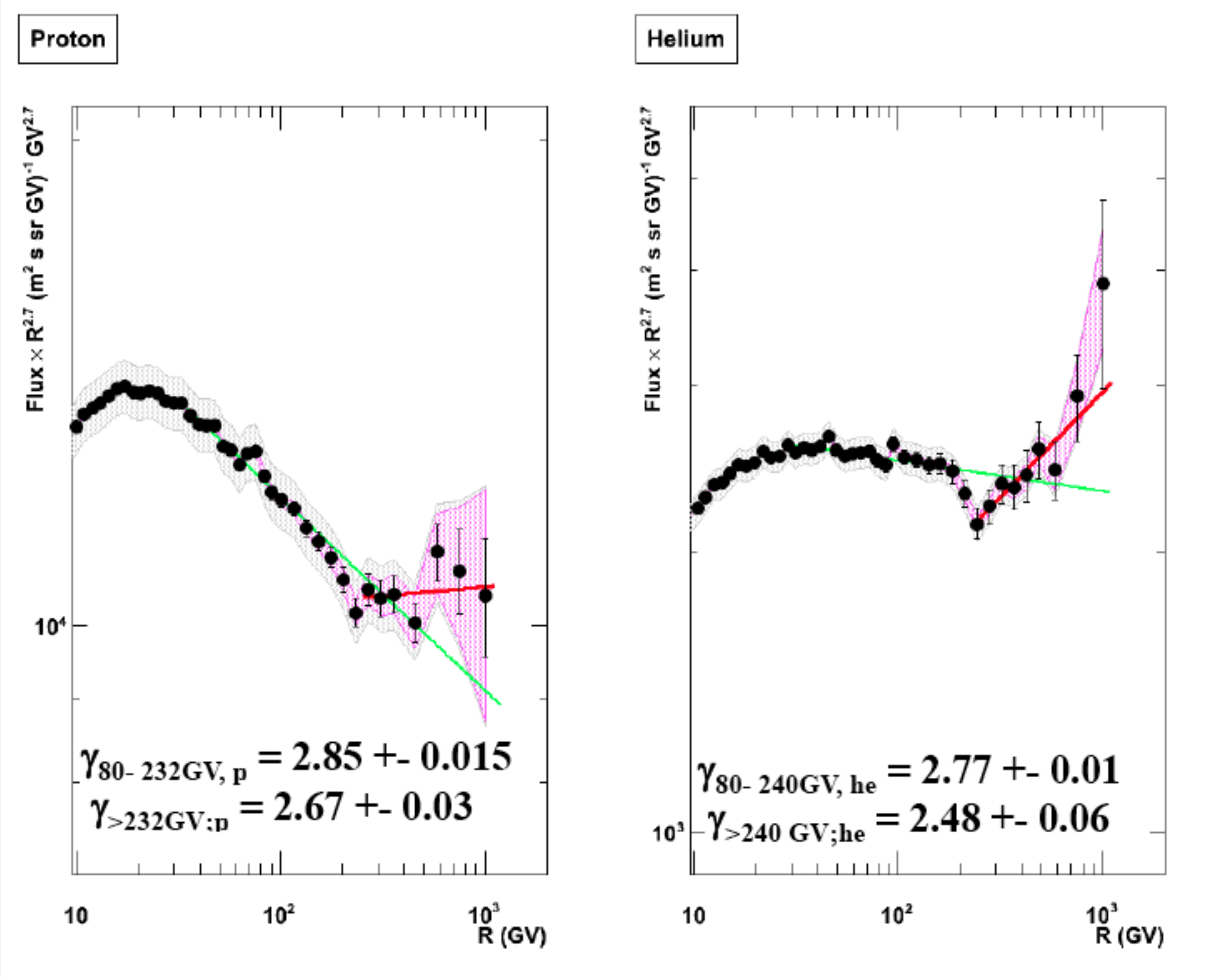
Figure 4: The $\bar{p}/p$ flux ratio obtained with the ARGO-YBJ experiment compared with all the available measurements and some theoretical predictions (see text).

Cosmic Ray Spectrum

Proton and Helium

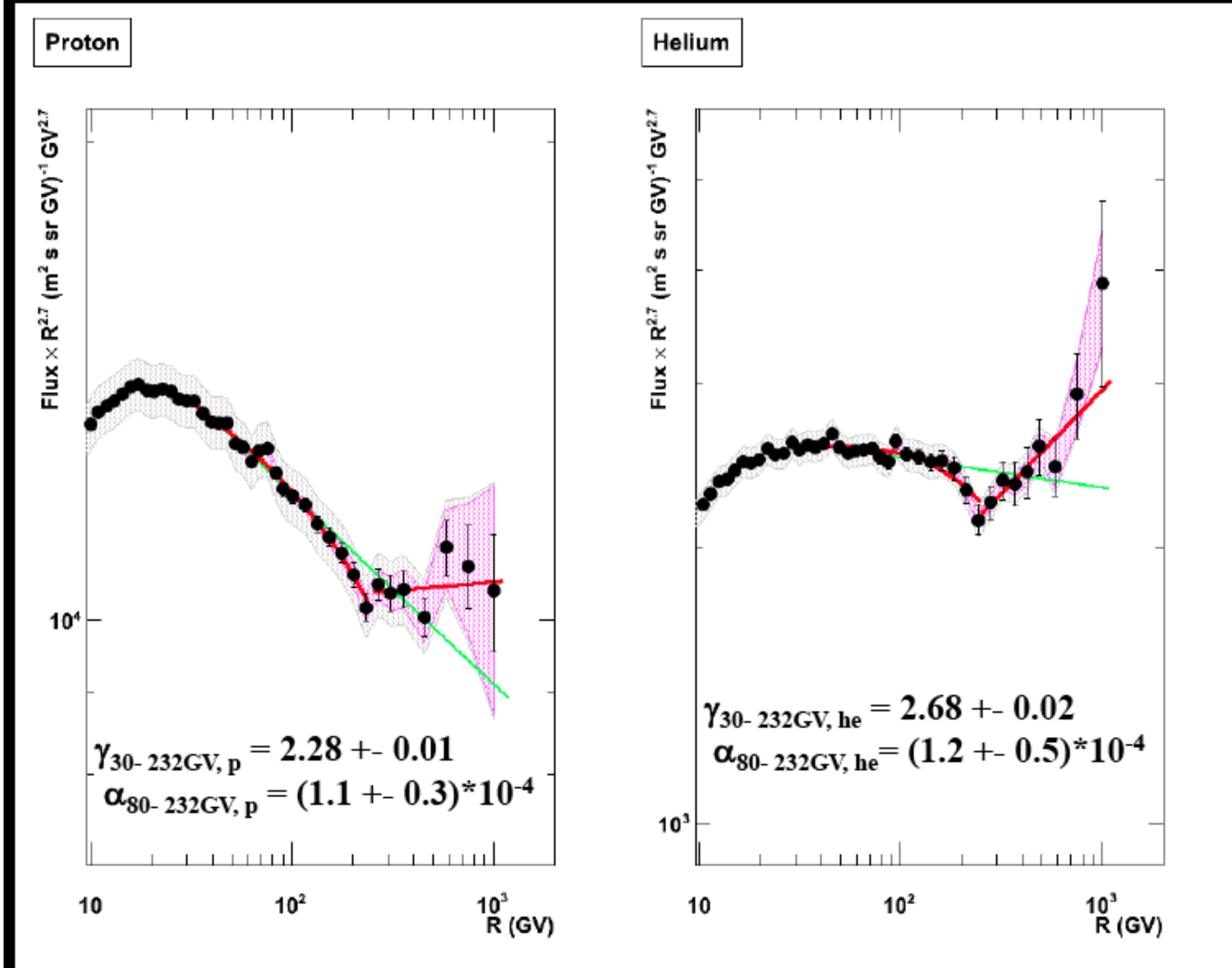

2006-2008
Flux × R^2.7 (m^2 s sr GV)^-1 GV^2.7
10^4
10^3
10^2
1
10
10^2
10^3
R (GV)
γ30- 1000GV, p = 2.820 +- 0.003 (stat) +- 0.005 (syst)
γ30- 1000GV, he = 2.732 +- 0.005 (stat)
+ 0.008 -0.003 (syst)
p
He
PAMELA systematic error band
PAMELA alignment error band

Deviations from power law: a) R>240 GV



1. Additional source(s) above 240 GV
2. Fisher and T student test reject single power law to better than 99.7 CL

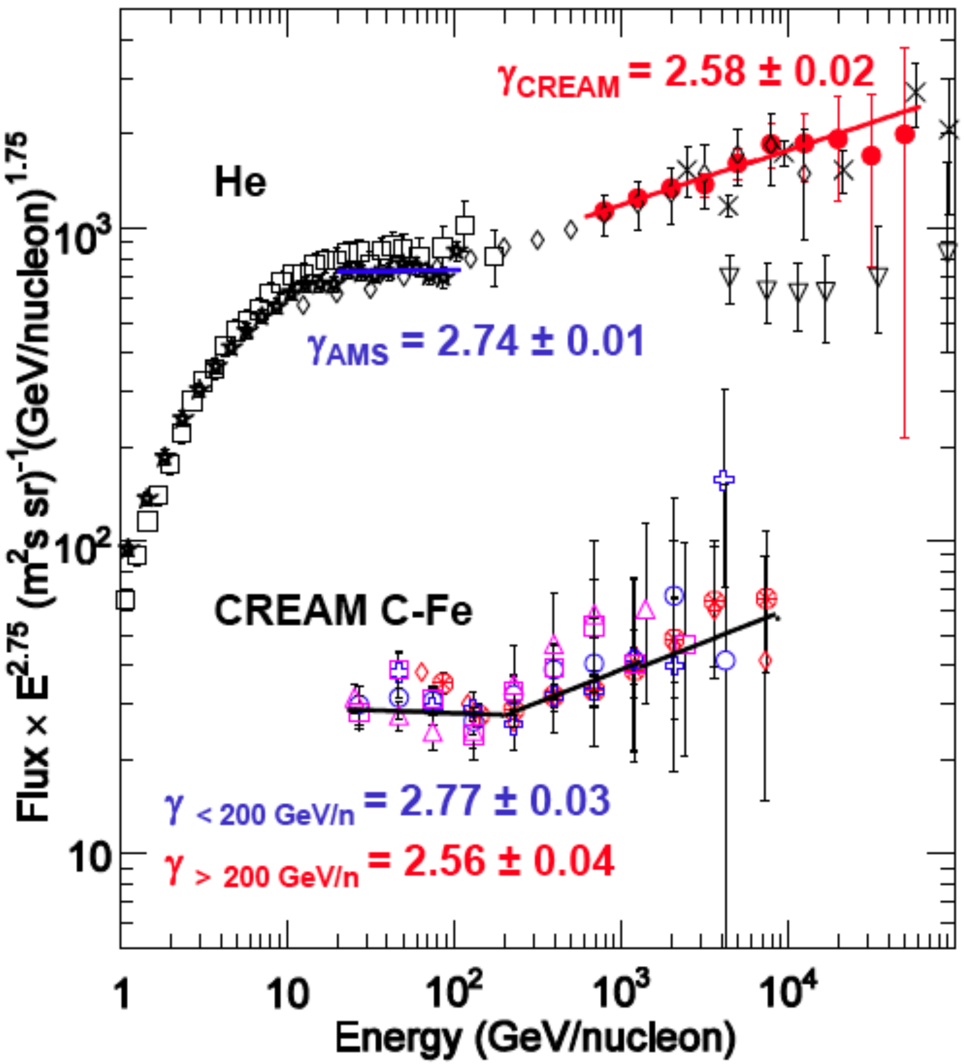
Deviations from power law: a) R<240 GV?



- The spectrum softens at 30-240 GV
- Single power law is also ruled out at lower rigidities

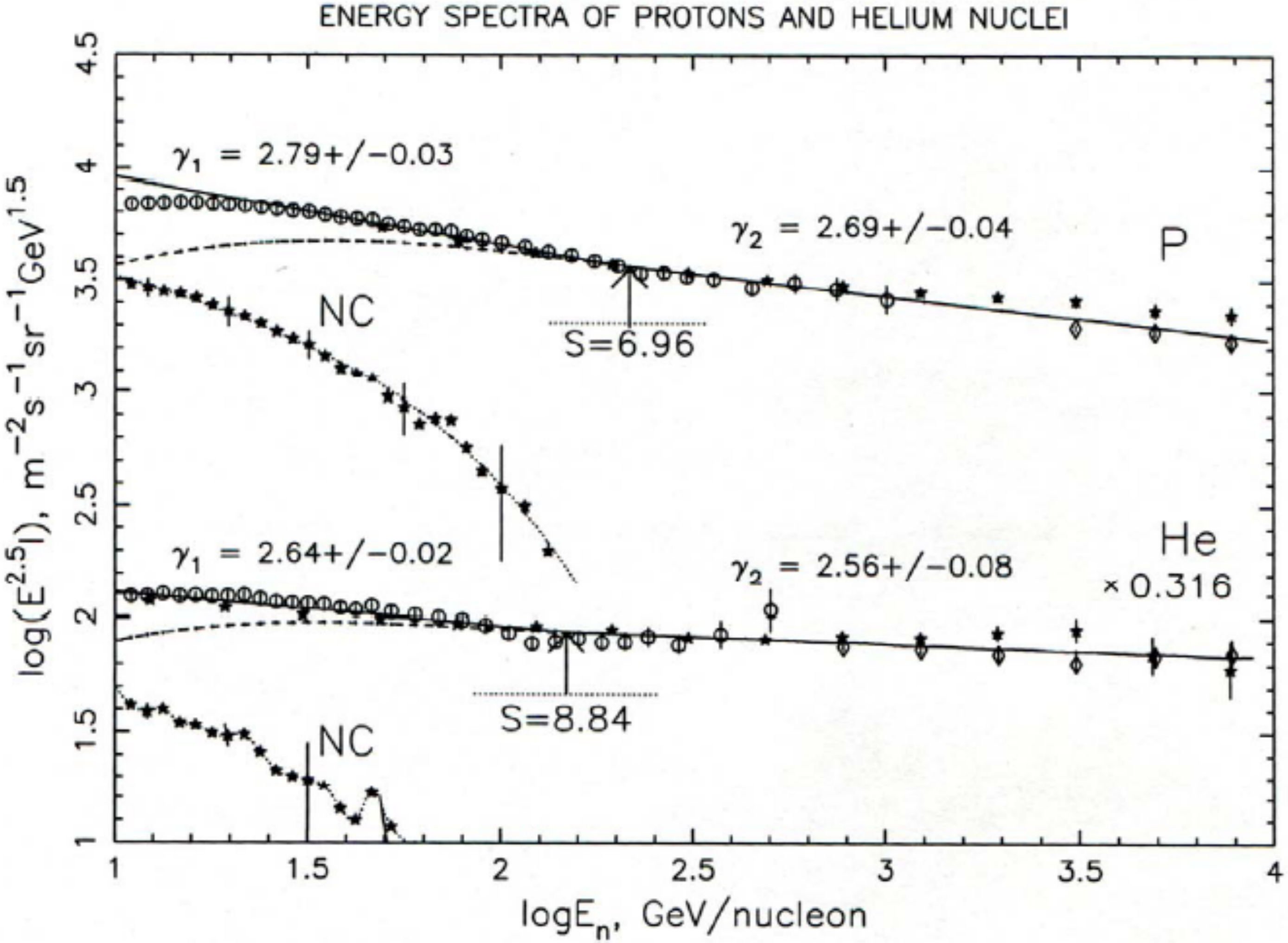
Not a single power law

Ahn et al. (CREAM Collaboration) ApJ **714**, *L89*, 2010



- Evidence for concavity due to cosmic ray interactions with the shock? (Ellison et al. *ApJ* **540**, 292,2000)
- A local source of hadrons?
- Effect of a non-uniform distribution of sources? (Ptuskin et al., ApJ. **718**, *31-36*, 2010; Zatsepin & Sokolskaya, A&A 458, 1, 2006. Erlykin & Wolfendale *A&A* **350**, L1,1999)
- Effect of distributed acceleration by multiple remnants (Medina-Tanco & Opher *ApJ* 411, 690, 1993)
- Superbubbles? (Butt & Bykov, *ApJ* **677**, L21, 2008; Ohira & Ioka, ApJL. *729*, L13-L17, 2011)
- Related to 10 TeV anisotropy reported by Milagro etc.? (Abdo et al. *PRL*, **101**, 221101, 2008)

•Energy Spectra of Protons and Helium Nuclei



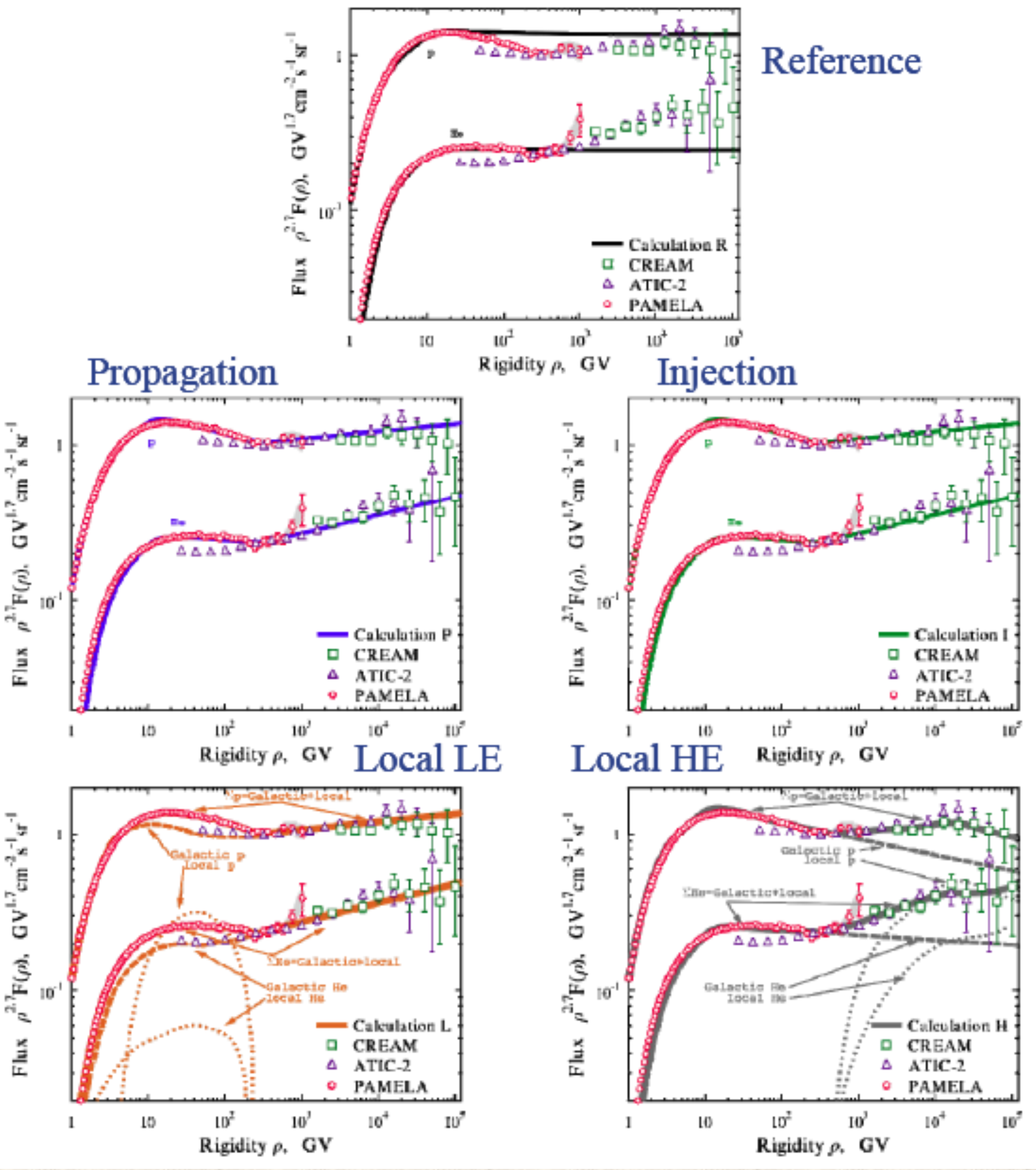
Data from PAMELA, CREAM and ATIC.

Wolfendale #1353

Observation	*Scenario R/S*	*Scenario P*	*Scenario I (a)*	*Scenario I (b)*	*Scenario L*	*Scenario H*
The break (hardening of p and He spectra at ρ_{br}), Figure 3	No	Yes, due to a break in the diffusion coefficient	Yes, due to a break in the injection spectrum	Yes, due to the assumption of a composite source	Yes, due to the assumption of a local low energy source	Yes, due to the assumption of a local high energy source
The 'dip' (softening of CR spectra at $\rho < \rho_{br}$), Figure 3	No	No, unless the diffusion coefficient has a corresponding 'dip'	No	No, but the 'dip' can be explained by assuming that the low-energy Galactic source turns over below ρ_{br}.	Yes	No
Difference between p and He spectra, see Figures 3 and 4	Yes, if parameters are tuned to increase grammage and cross sections, as in *Scenario S*.	Yes, phenomenologically introduced	Yes, phenomenologically introduced	Yes, phenomenologically introduced	Yes, phenomenologically introduced	Yes, phenomenologically introduced
Continuity of *p*/He ratio at ρ_{br}, Figure 4	Yes, but does not match the value of *p*/He ratio	Yes, no additional assumptions	Yes, no additional assumptions	Yes, but only if the different source classes inject with the same *p*/He ratio at ρ_{br}	Yes, but only if the local and Galactic sources classes inject with the same *p*/He ratio at ρ_{br}	Yes, but only if the local and Galactic sources classes inject with the same *p*/He ratio at ρ_{br}
CR anisotropy due to diffusive escape of CRs above 1 TeV, Figure 6	Overpredicts	Overpredicts, but less than other scenarios	Overpredicts	Overpredicts, but the possibility of different spatial distributions of the two source classes must be considered	Overpredicts	Overpredicts; the local source, if it extends above 1 TeV, may affect anisotropy
B/C ratio above 1 GeV/nuc, Figure 7	Yes	Yes, but differs from other scenarios above ρ_{br}; possible discrimination with more accurate data	Yes	Yes	Yes, by construction	Yes
$\bar{p}$ flux (PAMELA), Figure 8	Yes, above a few GeV	Yes, but differs from other scenarios above ρ_{br}	Yes, above a few GeV	Yes, above a few GeV	No	Yes, above a few GeV
γ-ray observations of *Fermi*-LAT, Figure 10	Yes	Yes	Yes	Yes	No	Yes

#1201 - Moskalenko

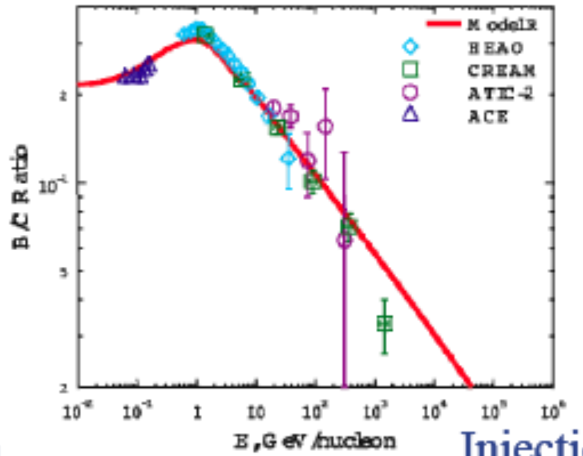
P and He spectra in different scenarios



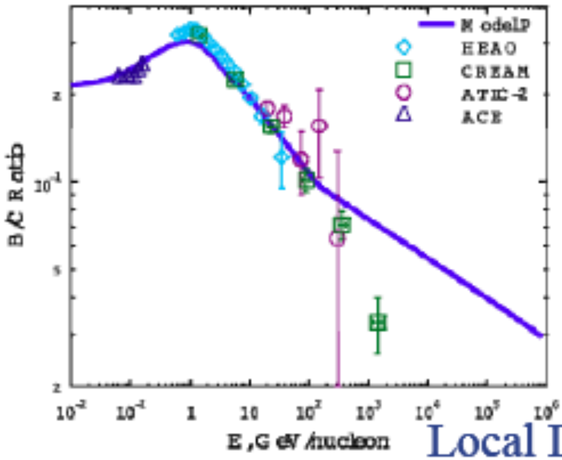
- All scenarios are tuned to the data, except the Reference scenario
- Scenarios L and H: the local source component is calculated by the subtraction of the propagated Galactic spectrum from the data
- The local source is assumed to be close to us, so no propagation; only primary CR species

B/C ratio in different scenarios

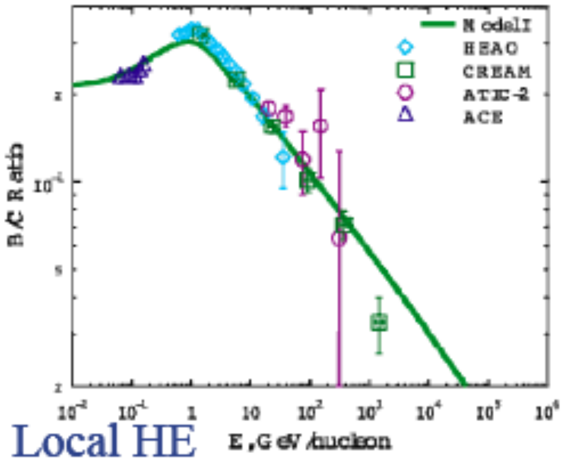
Reference



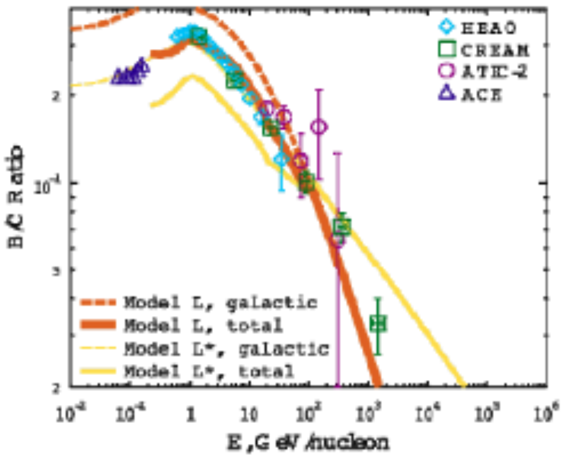
Propagation



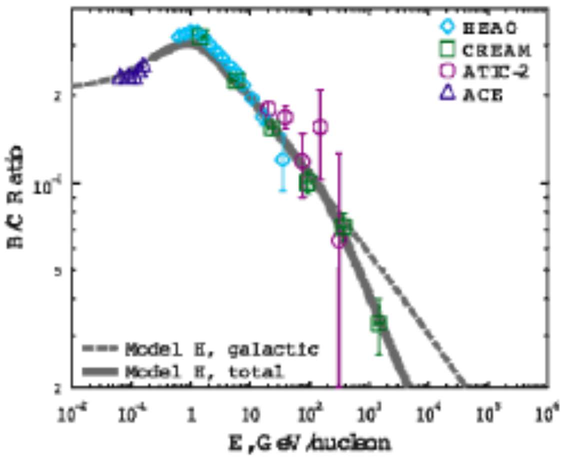
Injection



Local LE

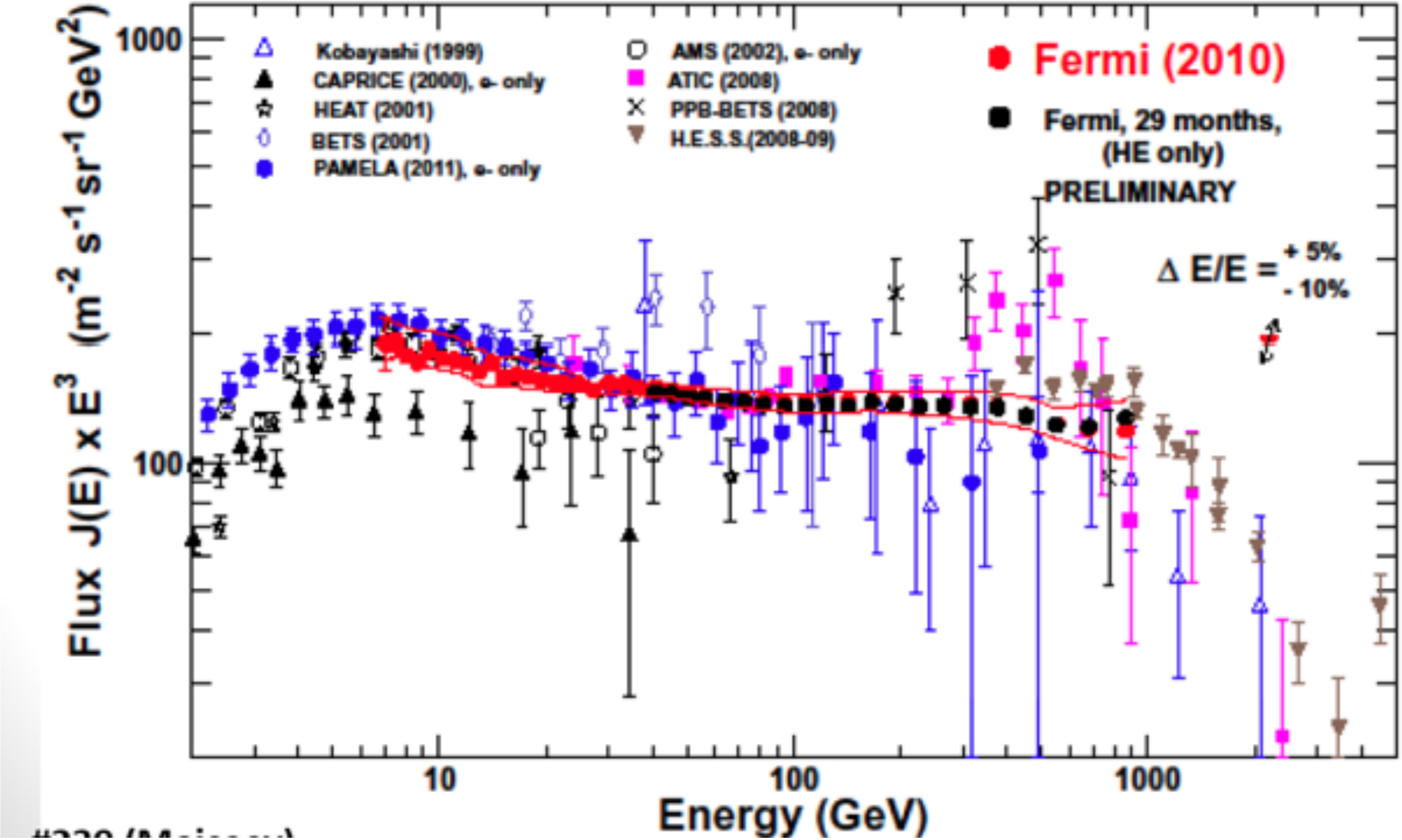


Local HE



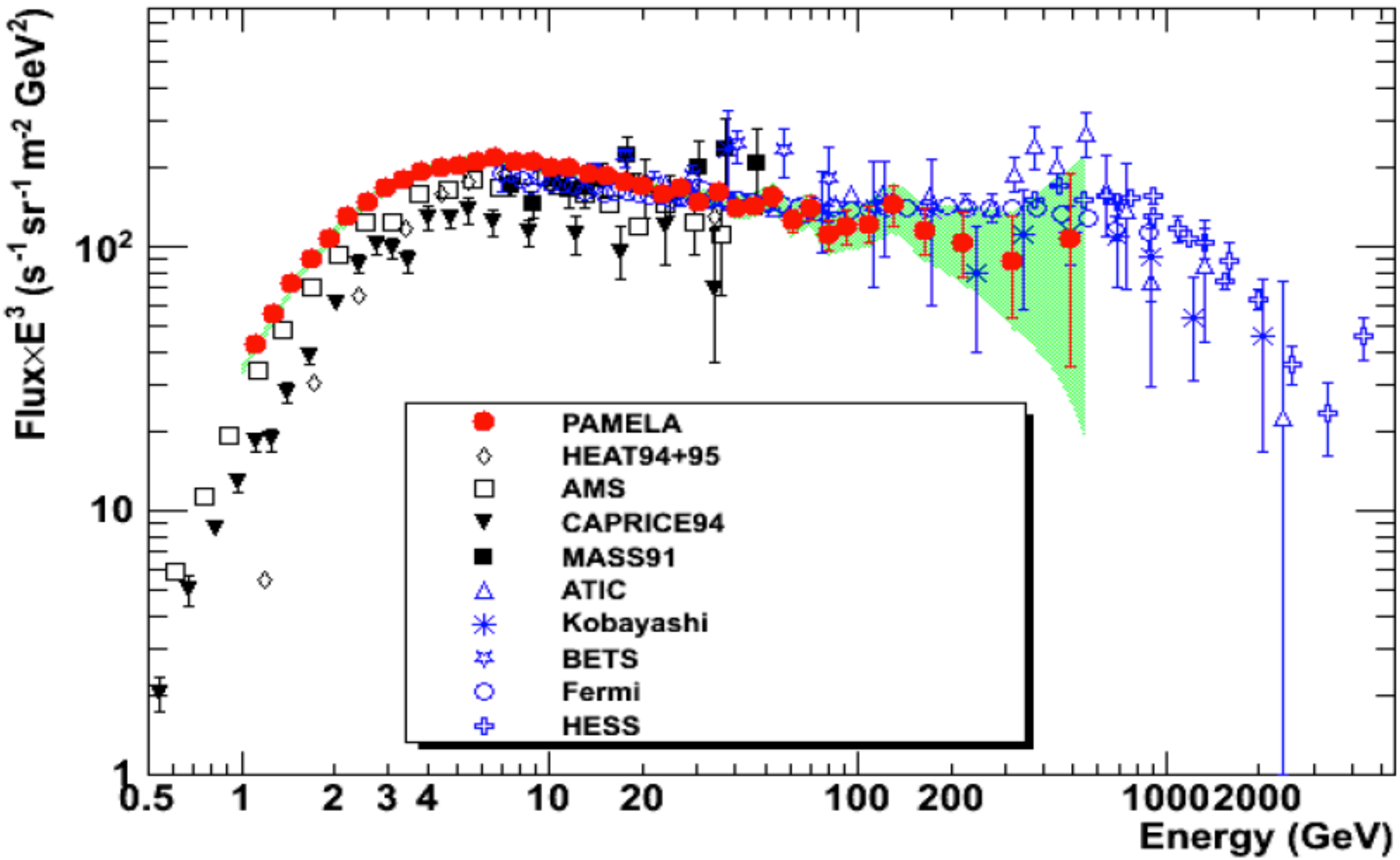
- All scenarios reproduce B/C below ~300 GeV/nucleon
- Above 300 GeV/nucleon B/C is flatter in Scenario P
- Local sources are assumed to produce only primary isotopes
- B/C is steeper in scenario L and H, but due to the different reasons
  - Scenario L: P-L index of the diffusion coefficient steepens to 0.67
  - Scenario H: there is no Boron in the local source, but there is Carbon

Electrons and Positrons



Kobayashi (1999)
CAPRICE (2000), e- only
HEAT (2001)
BETS (2001)
PAMELA (2011), e- only
AMS (2002), e- only
ATIC (2008)
PPB-BETS (2008)
H.E.S.S.(2008-09)
Fermi (2010)
Fermi, 29 months, (HE only)
PRELIMINARY
Δ E/E = + 5% - 10%
Flux J(E) x E³ (m⁻² s⁻¹ sr⁻¹ GeV²)
Energy (GeV)

PAMELA Spectrum (e- only)



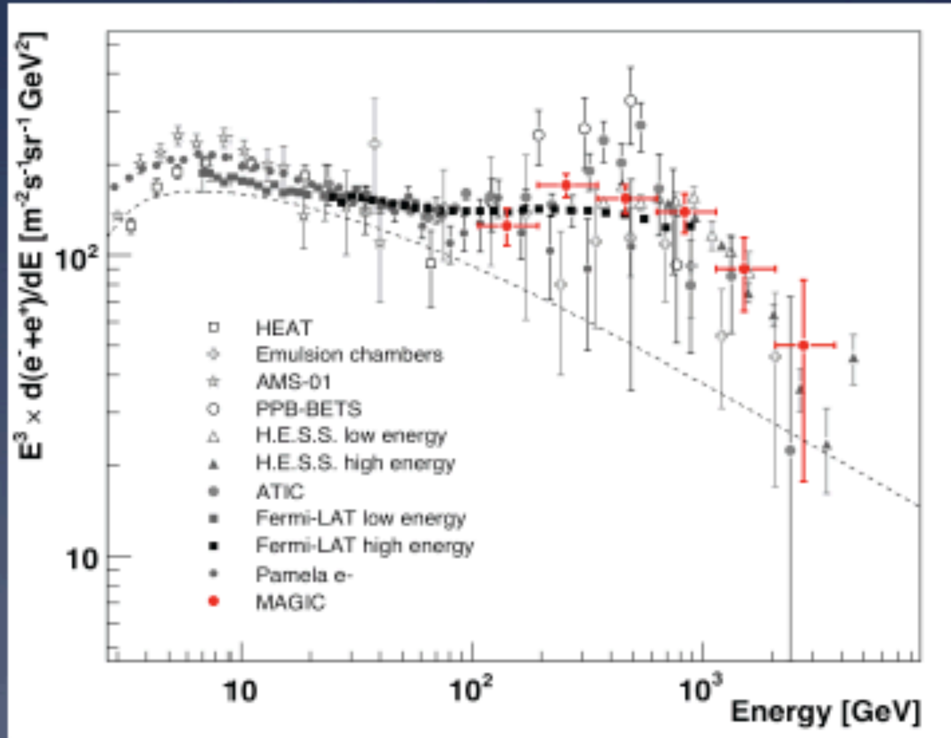
#815 (Mocchiutti)

CR $e^- + e^+$ spectrum

- First results based on only 14h of data, taken in 2009/2010
- Measured $e^{\pm}$ spectrum in the energy range between:

  100 GeV and 3 TeV.

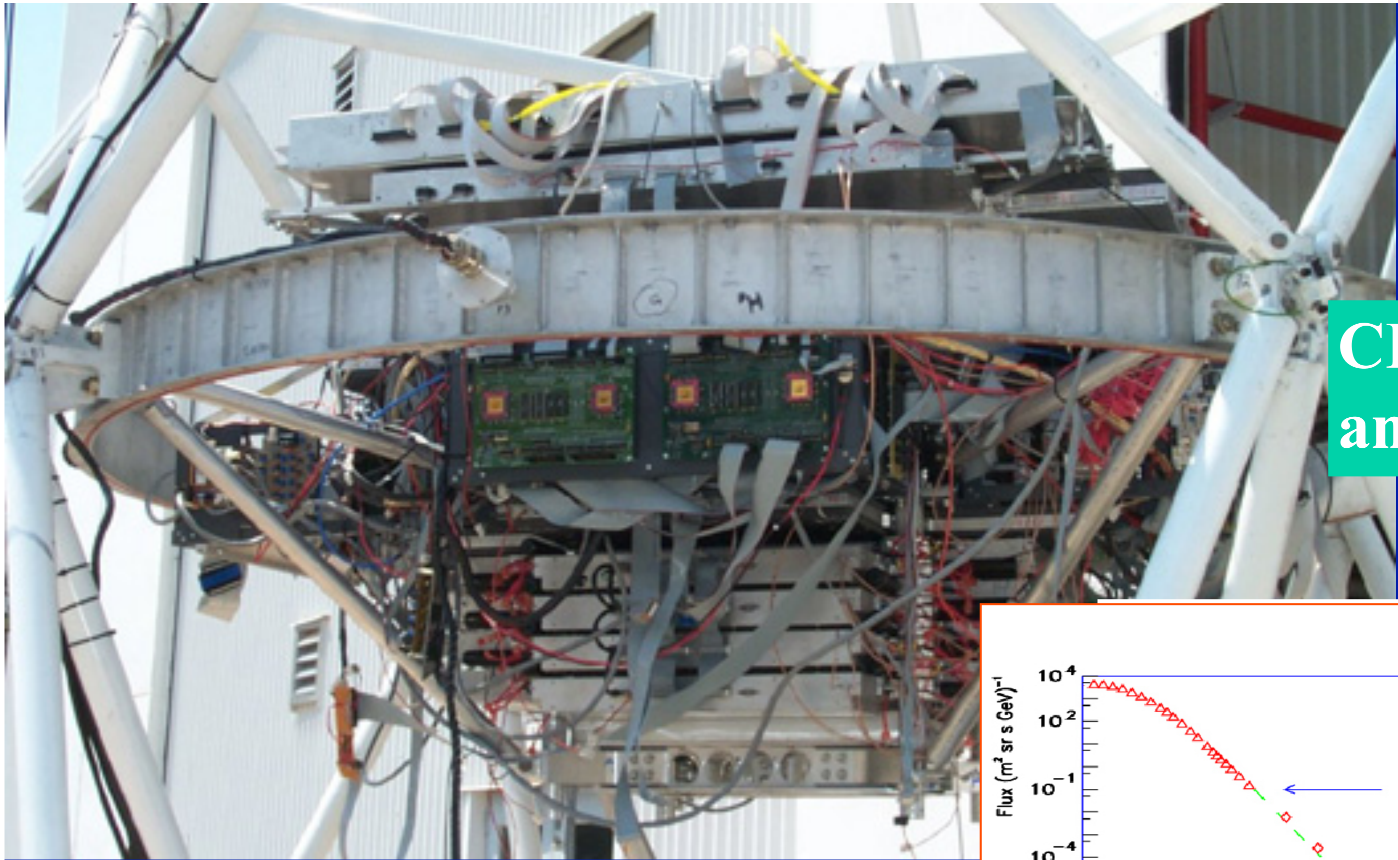
- Spectrum in good agreement with previous measurements --> Deviates from bg. model.

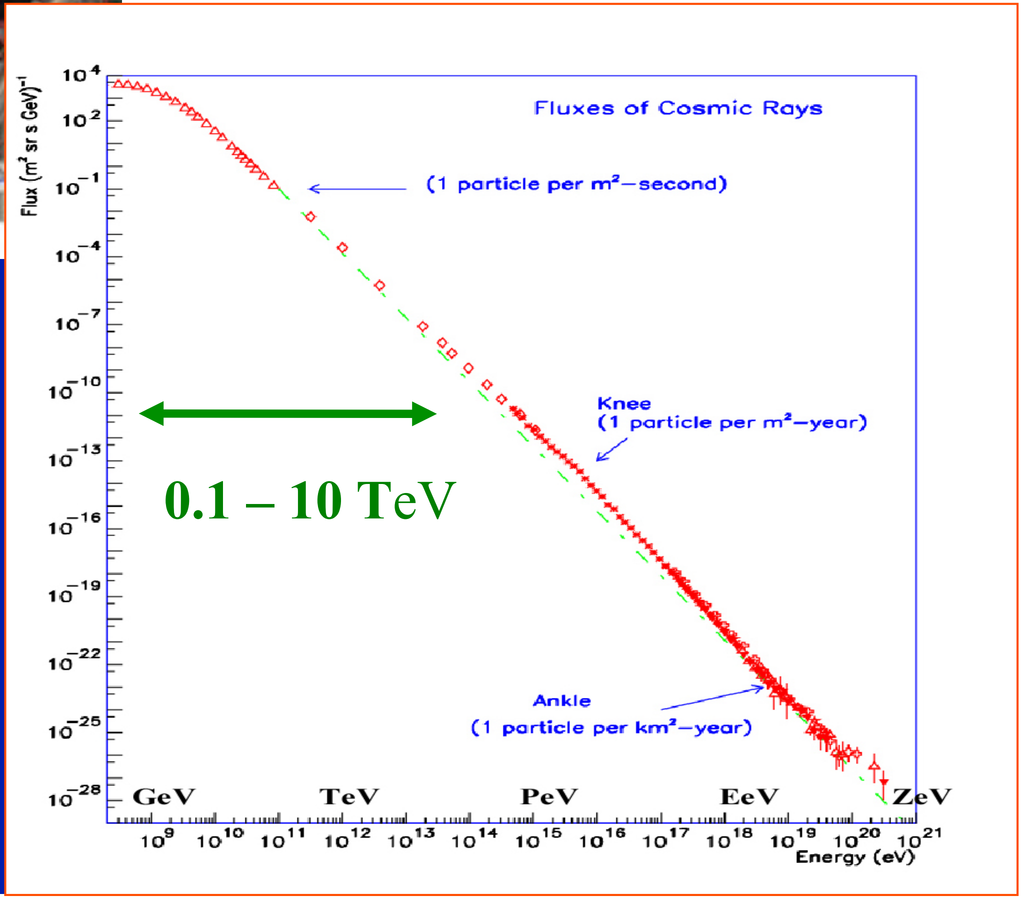


- Possible explanation for the excess:
  - Secondary e- from interactions of CRs with ISM
  - Supernova explosions
  - Pulsars
  - DM

ATIC

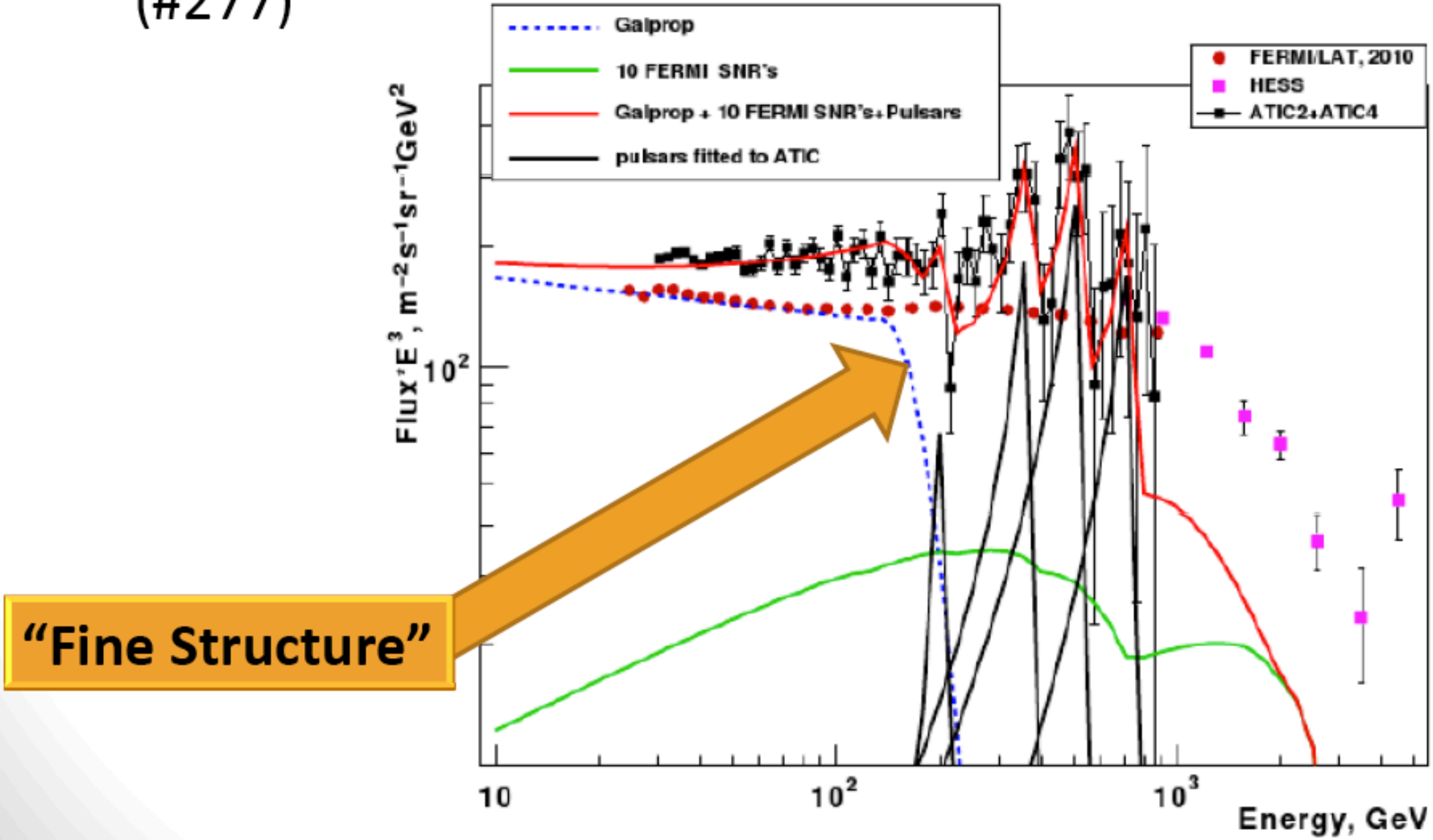
CR Composition and Spectra < 10TeV



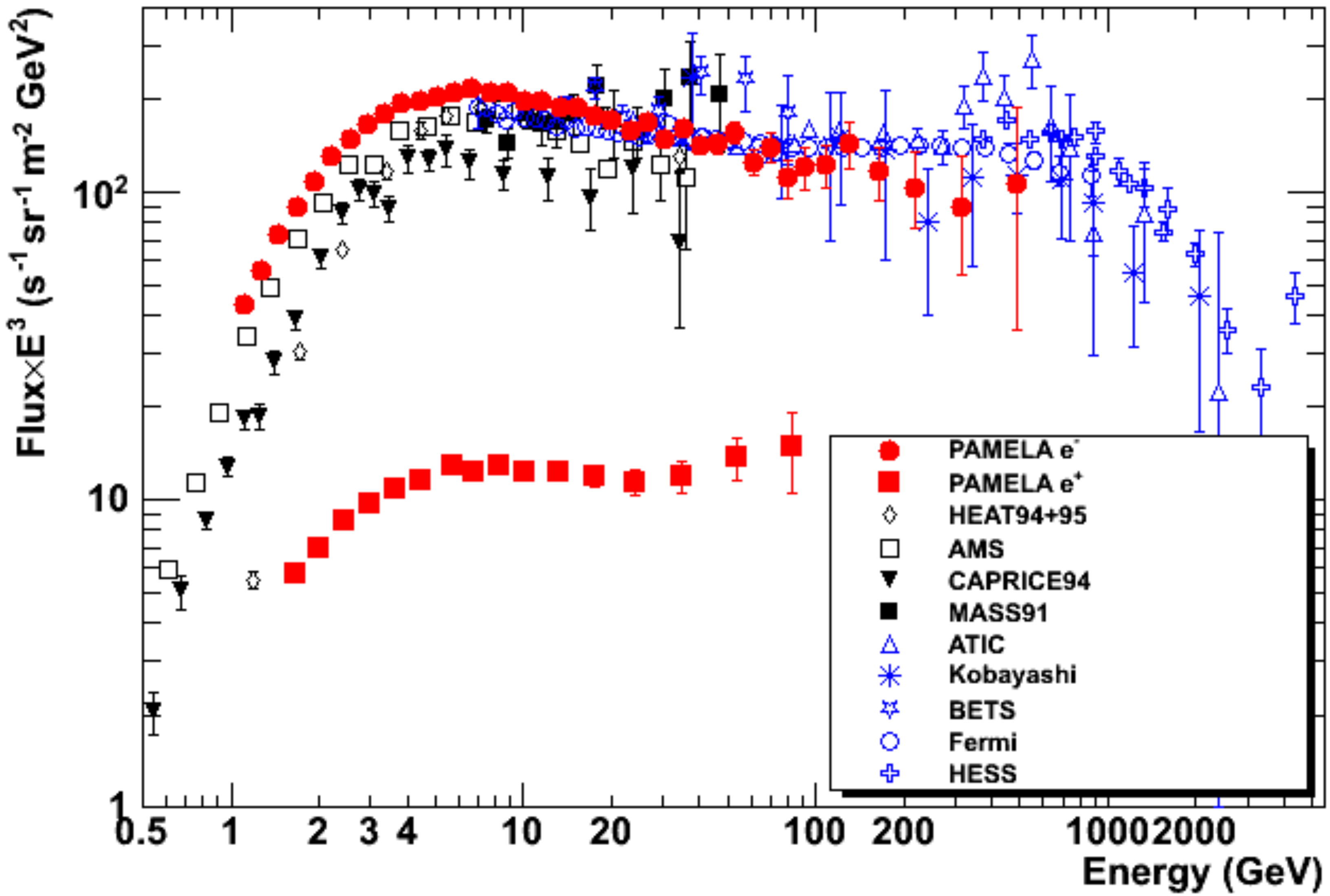


Electrons

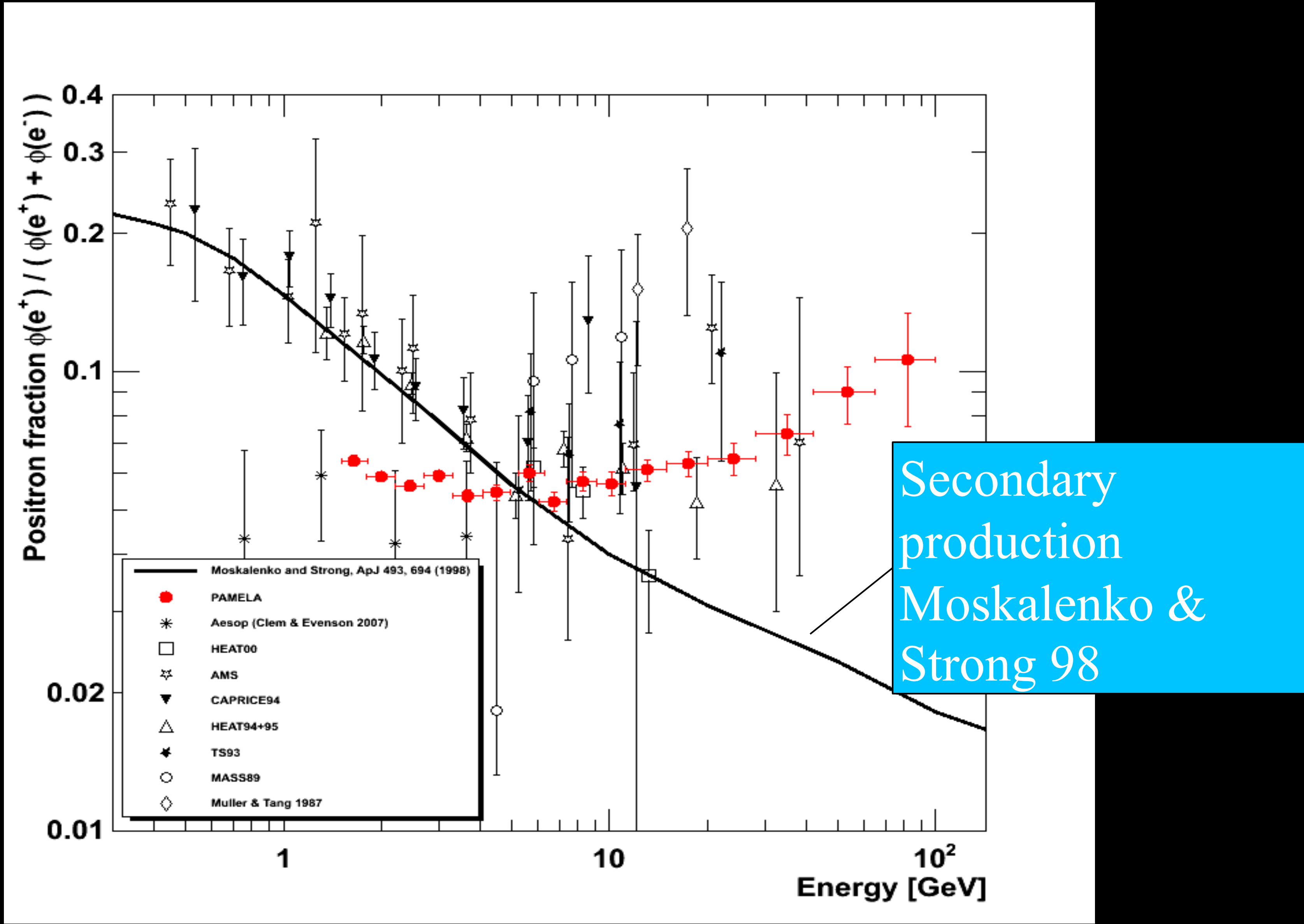
- Reanalysis of ATIC2 and ATIC4 data by Panov (#277)



Positron flux

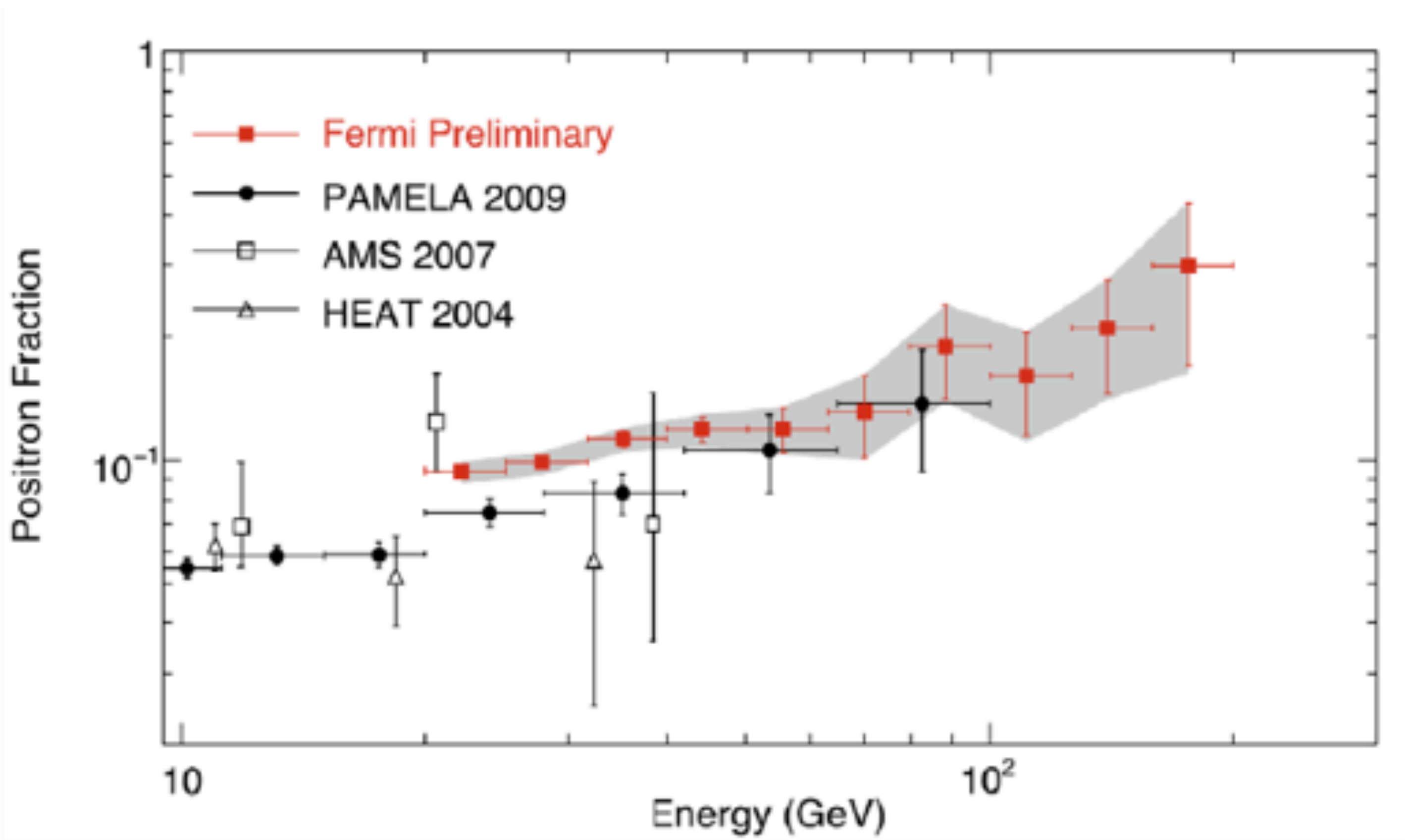


Positron to Electron fraction : the PAMELA result



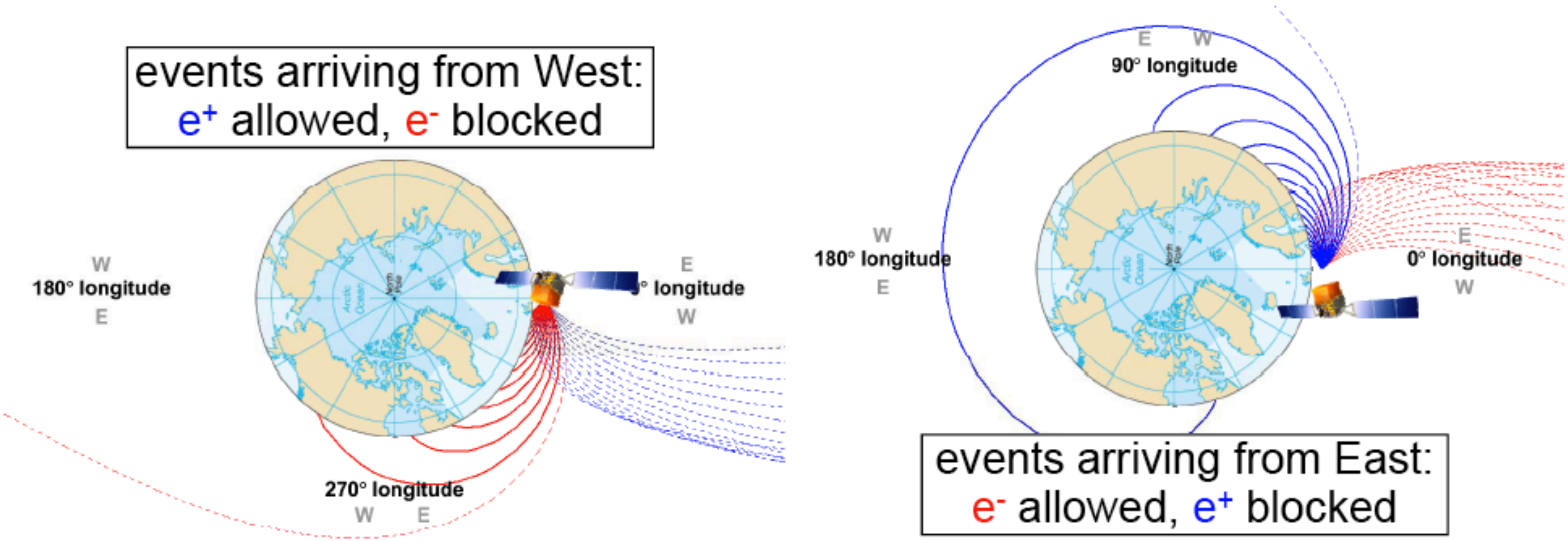
Adriani et al, Nature 458, 697, 2009 and Astropart. Phys. 34 (2010) 1

Final results: positron fraction



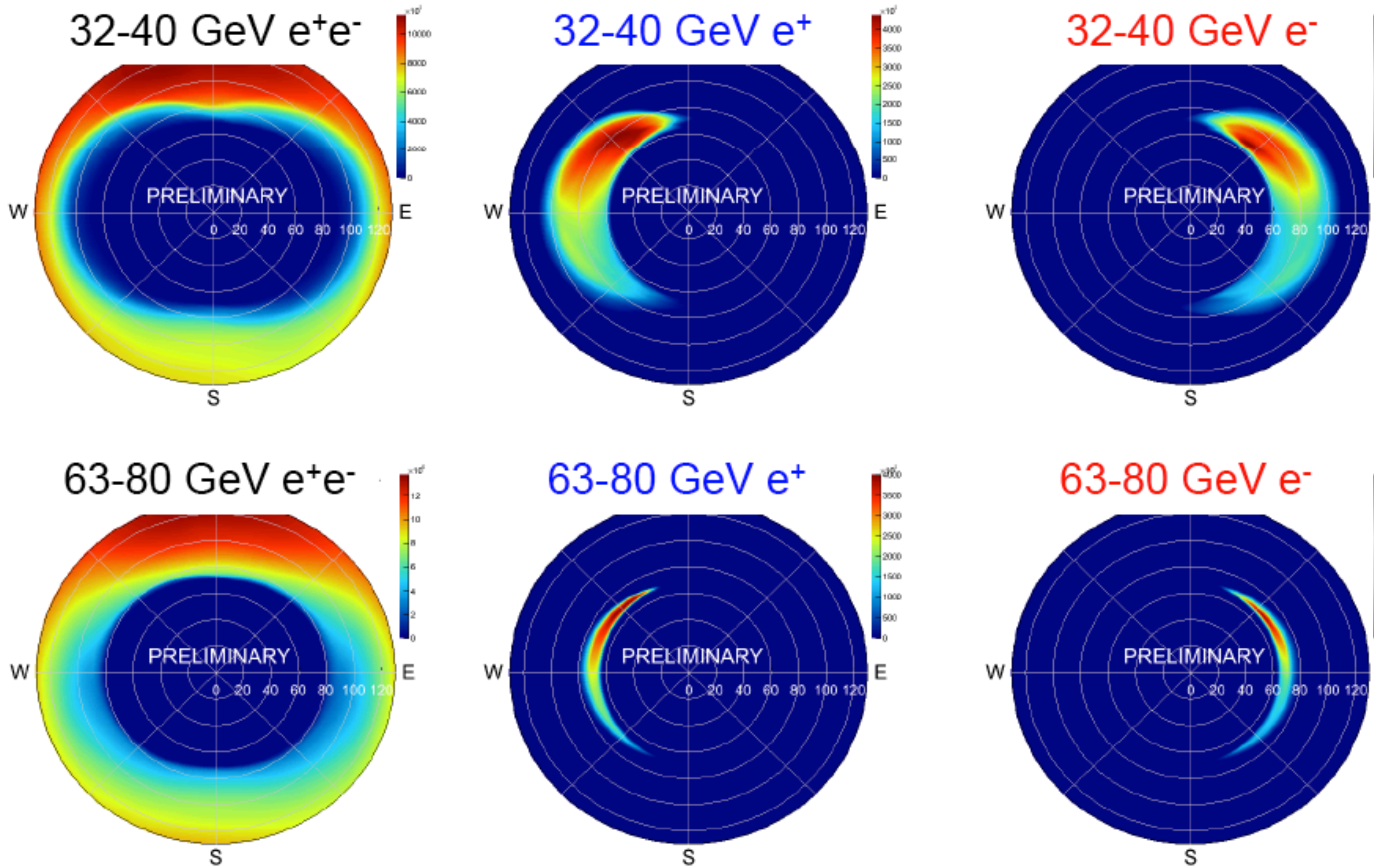
- Fraction = $\varphi(e^+) / [\varphi(e^+) + \varphi(e^-)]$
- We don't use the both-allowed region except as a cross check
- **Positron fraction increases with energy from 20 to 200 GeV**

Geomagnetic field + Earth shadow = directions from which only electrons or only positrons are allowed



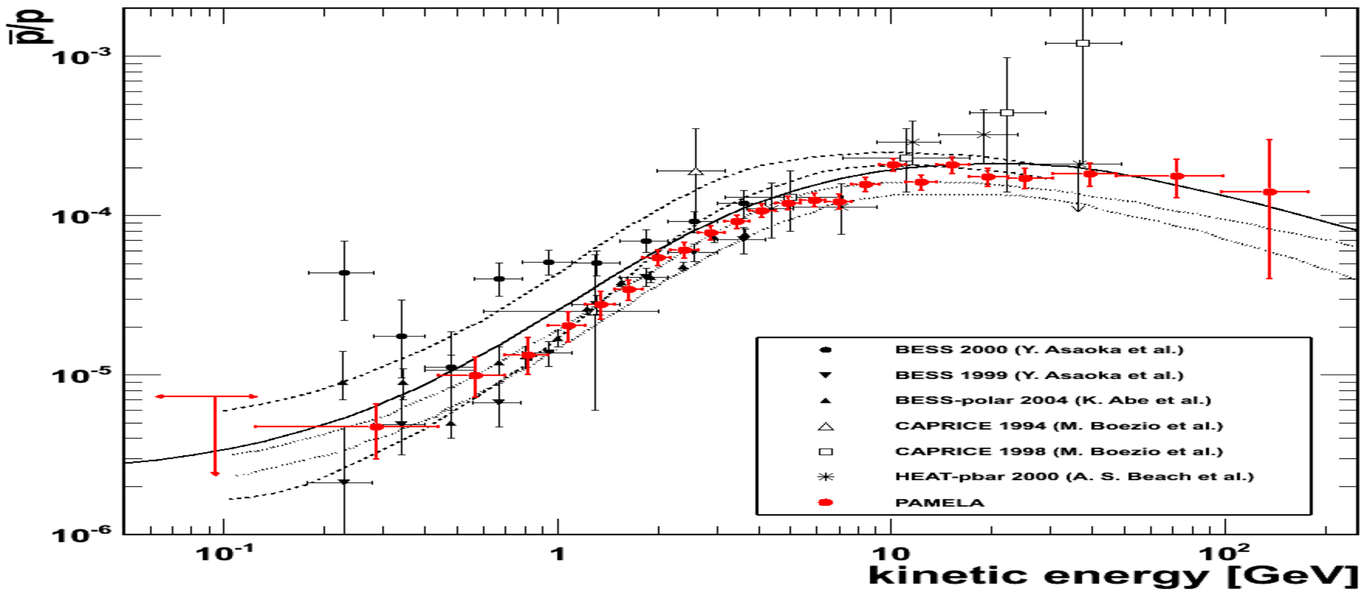
- For some directions, e^- or e^+ forbidden
- Pure e^+ region looking West and pure e^- region looking East
- Regions vary with particle energy and spacecraft position
- To determine regions, use code by Don Smart and Peggy Shea (numerically traces trajectory in geomagnetic field)
- Using International Geomagnetic Reference Field for the 2010 epoch

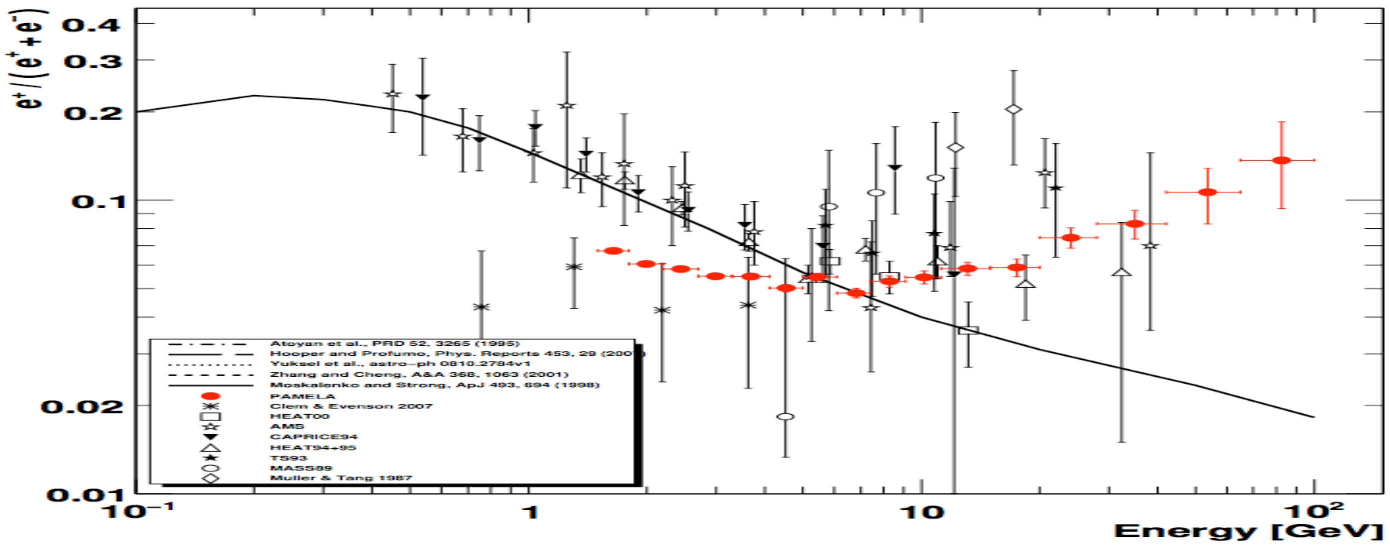
Exposure maps: 2 example energy bins for all 3 regions



Exposure units: m^2 s

A Challenging Puzzle for Dark Matter Interpretation

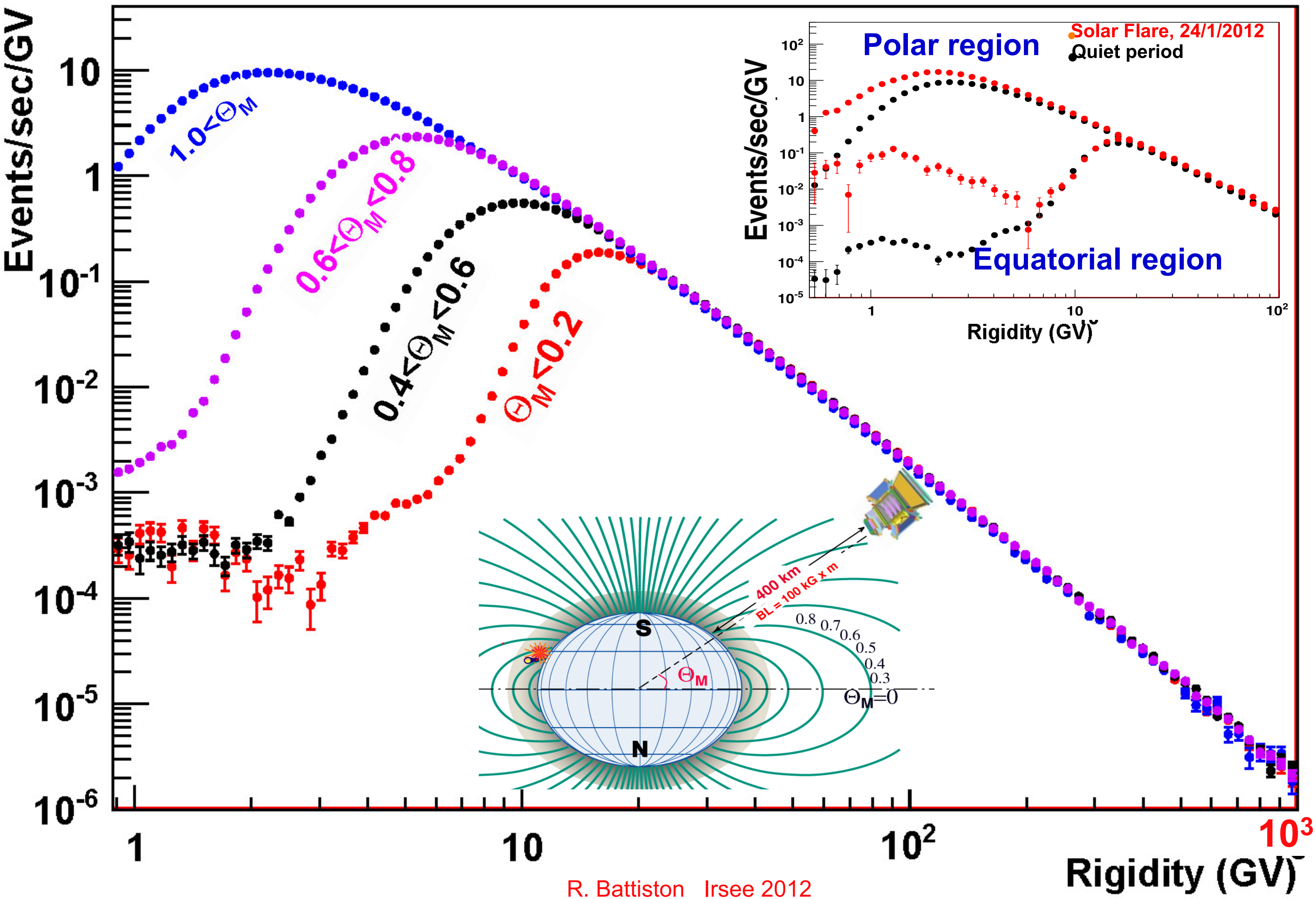





Launch of AMS-02
on STS-134
May 16th 27th, 2011 @ 08:56 AM

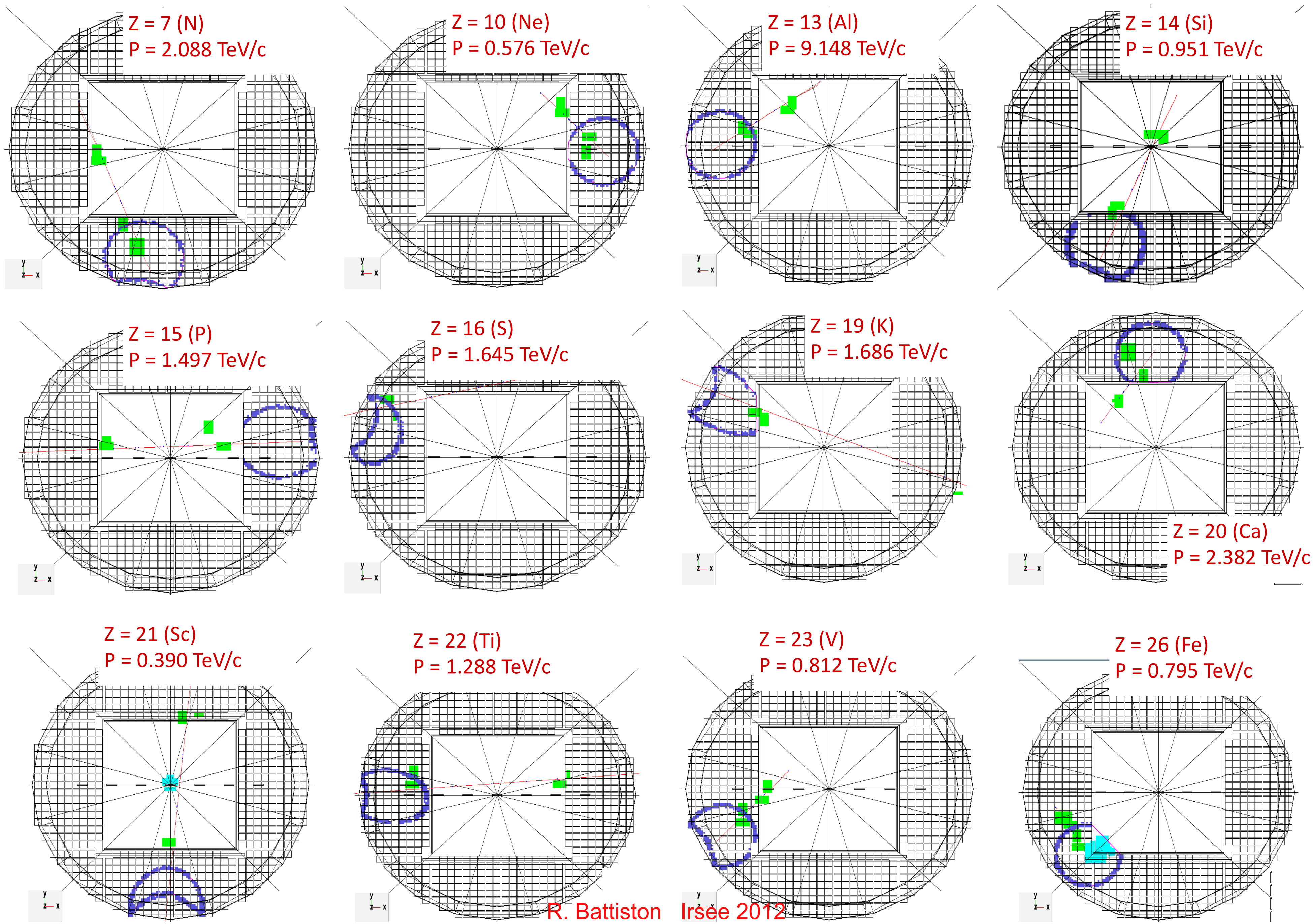

AMS
AMS

AMS data: He rate



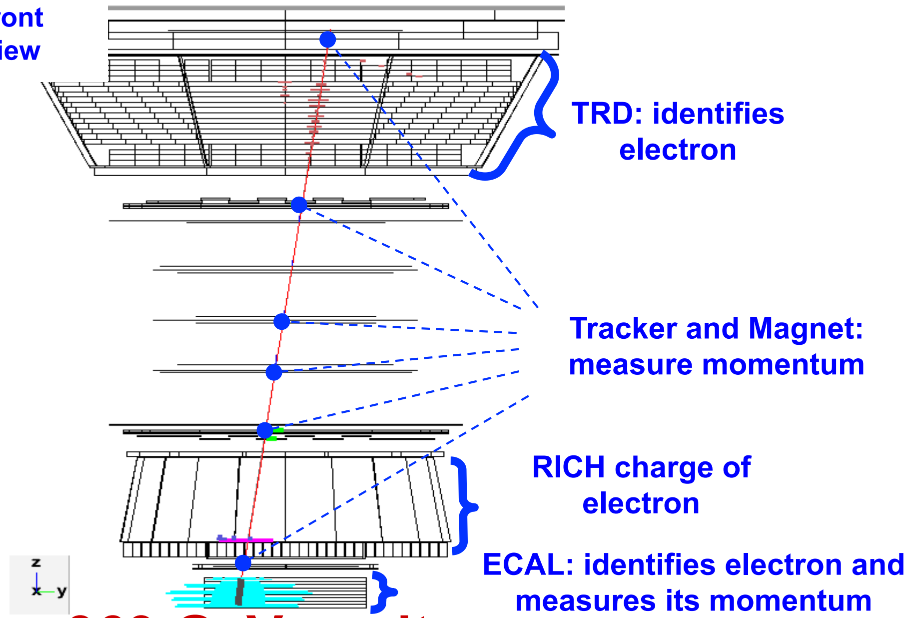
R. Battiston Irsee 2012

AMS data: Nuclei in the TeV range

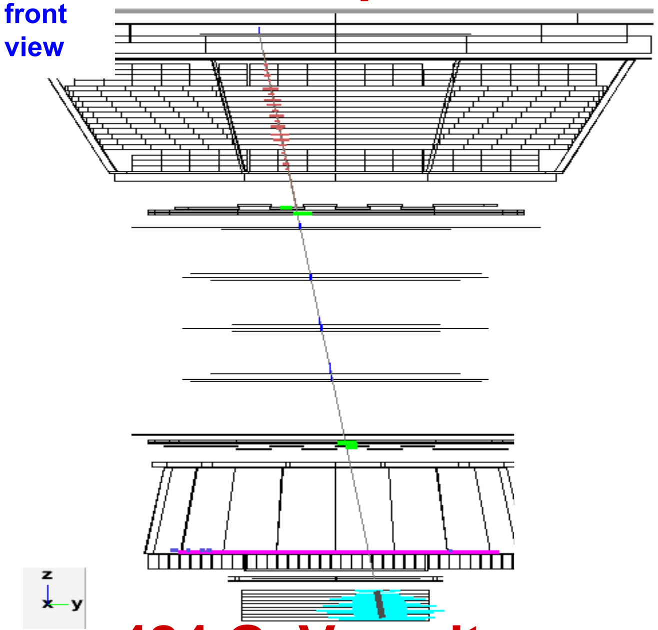


AMS data: High energy $e^{\pm}$

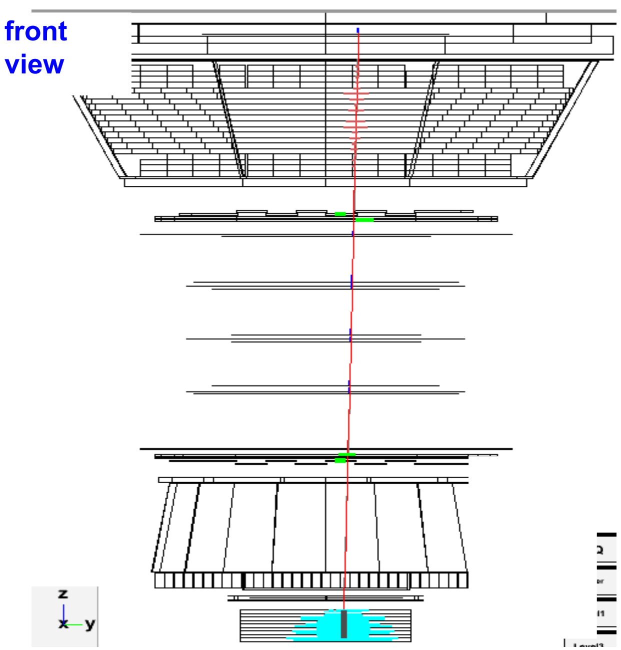
1.03 TeV electron



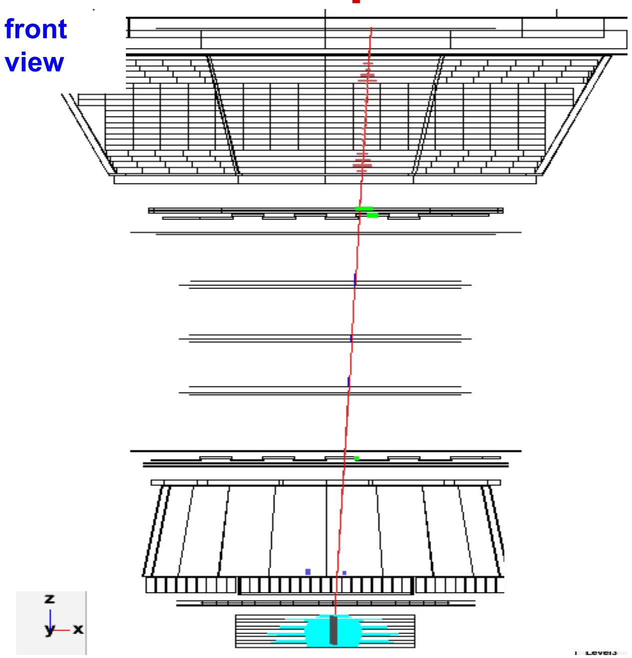
205 GeV positron



369 GeV positron

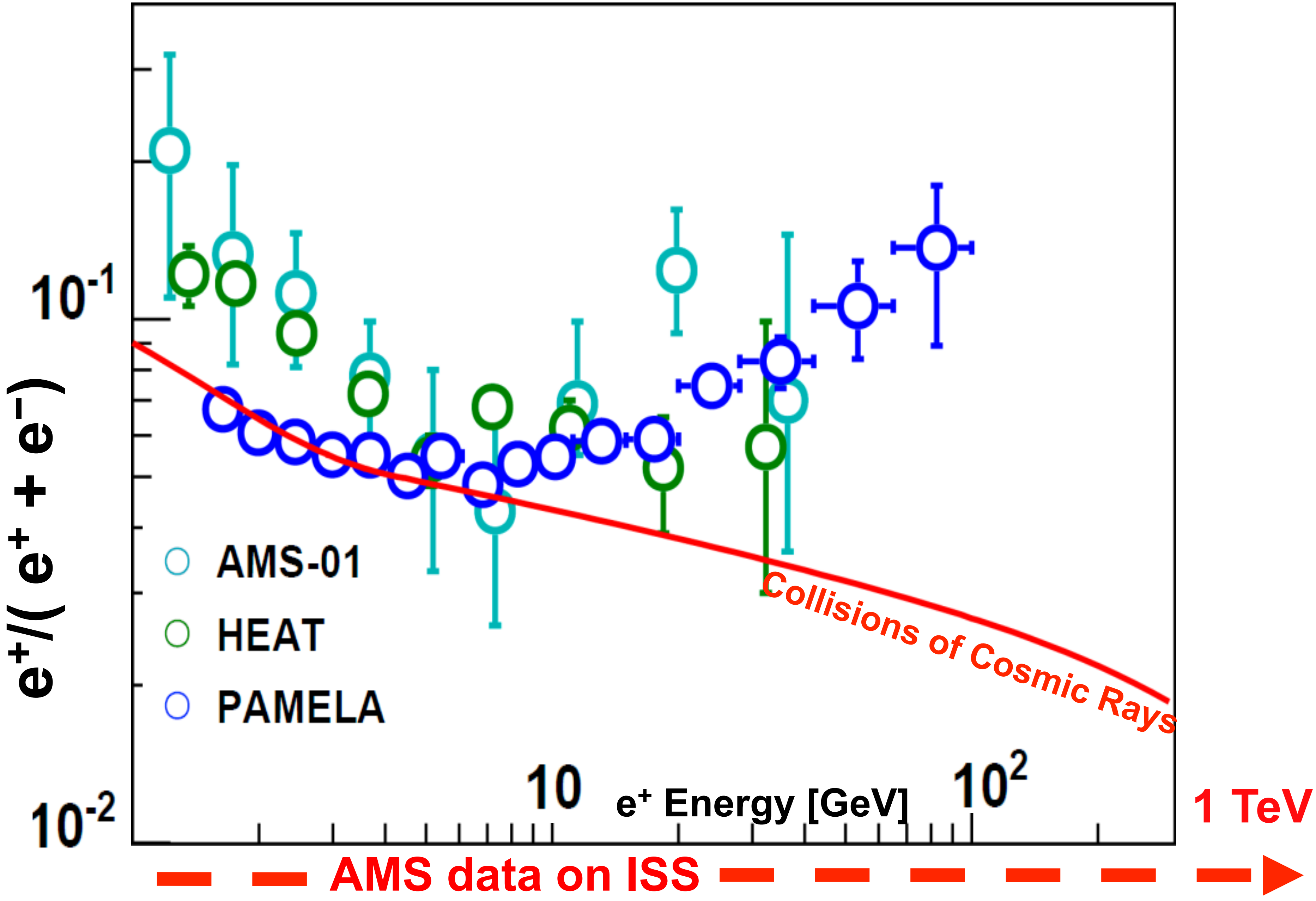


424 GeV positron

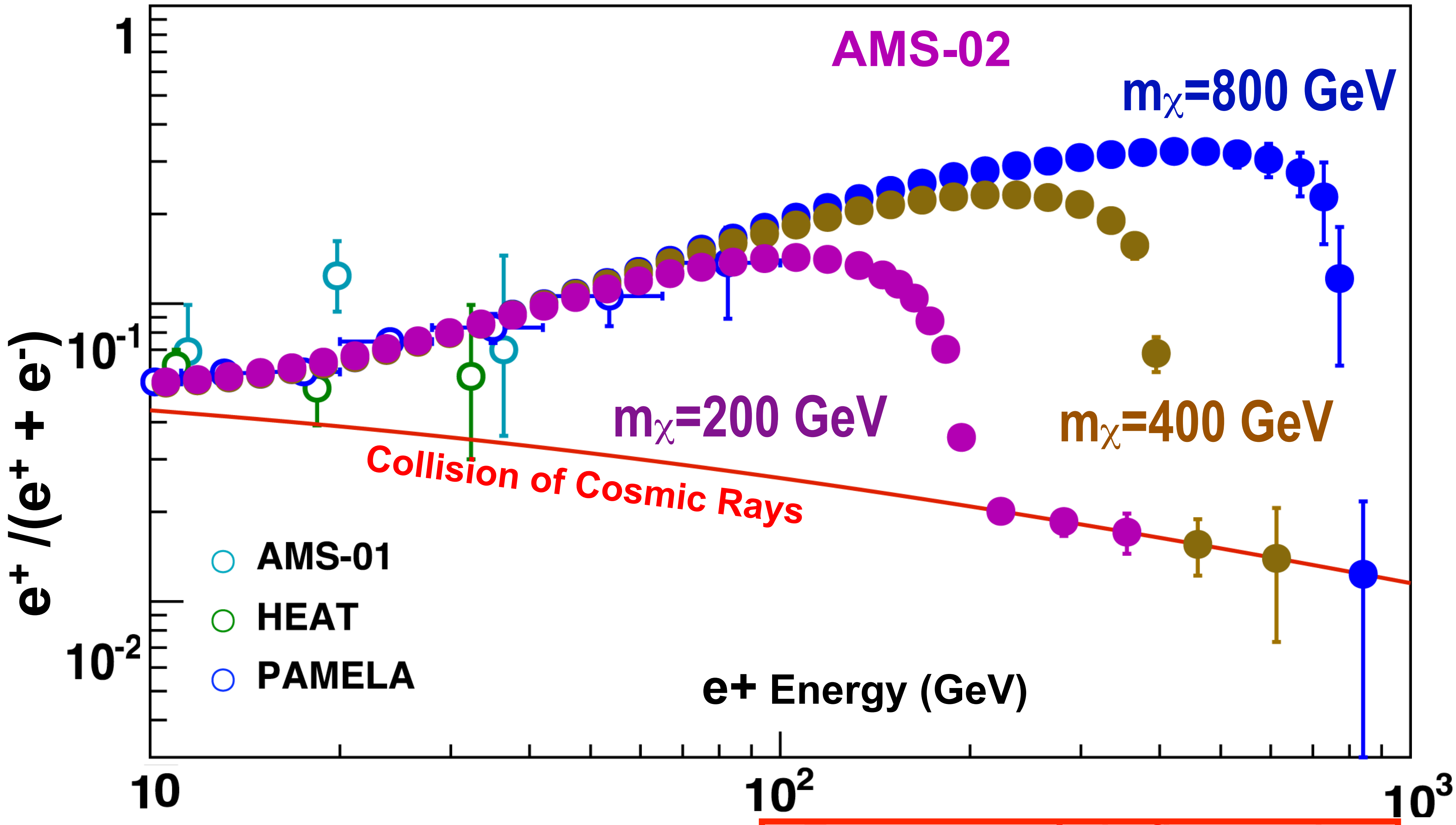


The physics of AMS include:

The Origin of Dark Matter

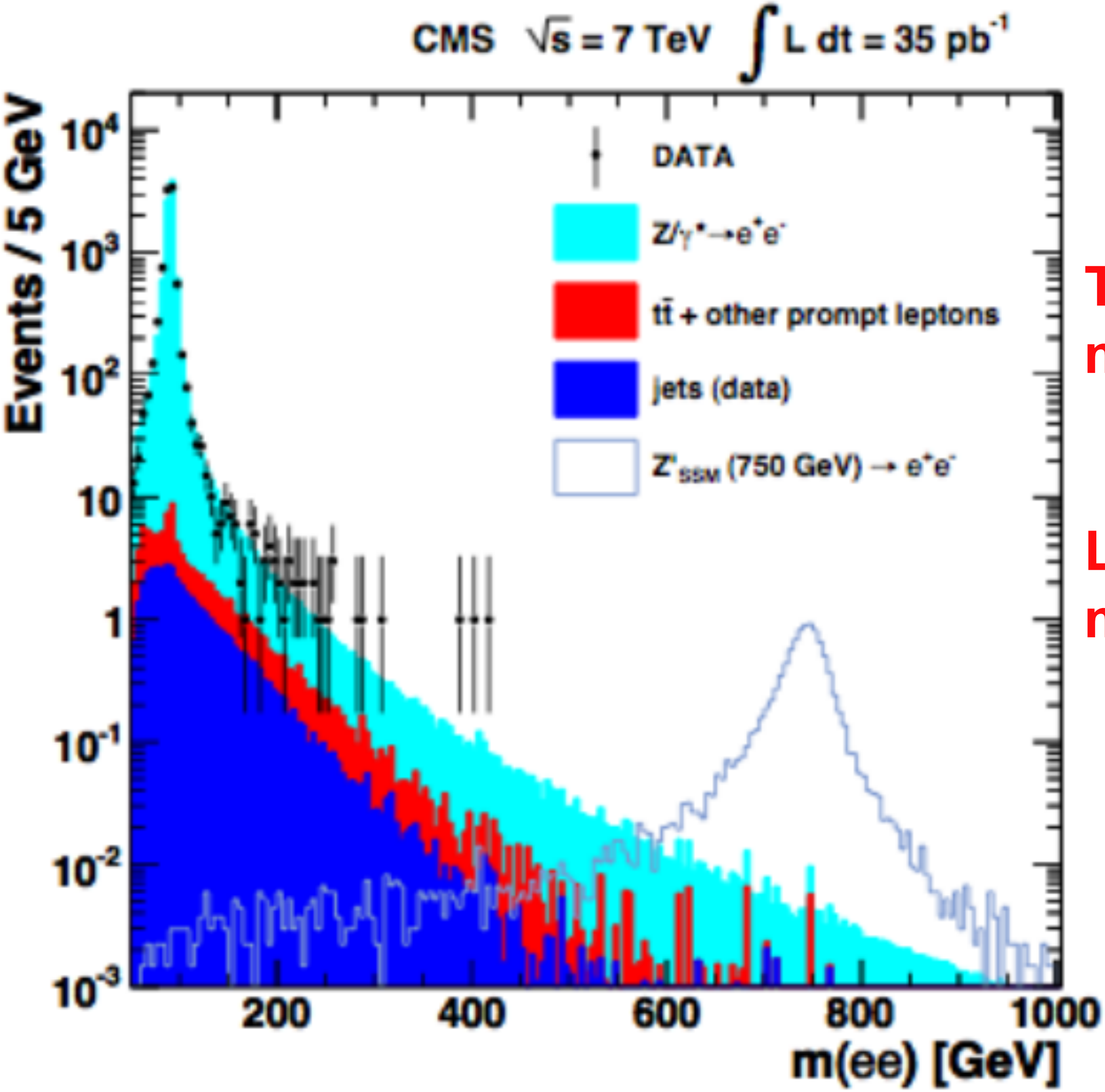


Detection of High Mass Dark Matter from ISS
MC simulations



Events sample in first weeks

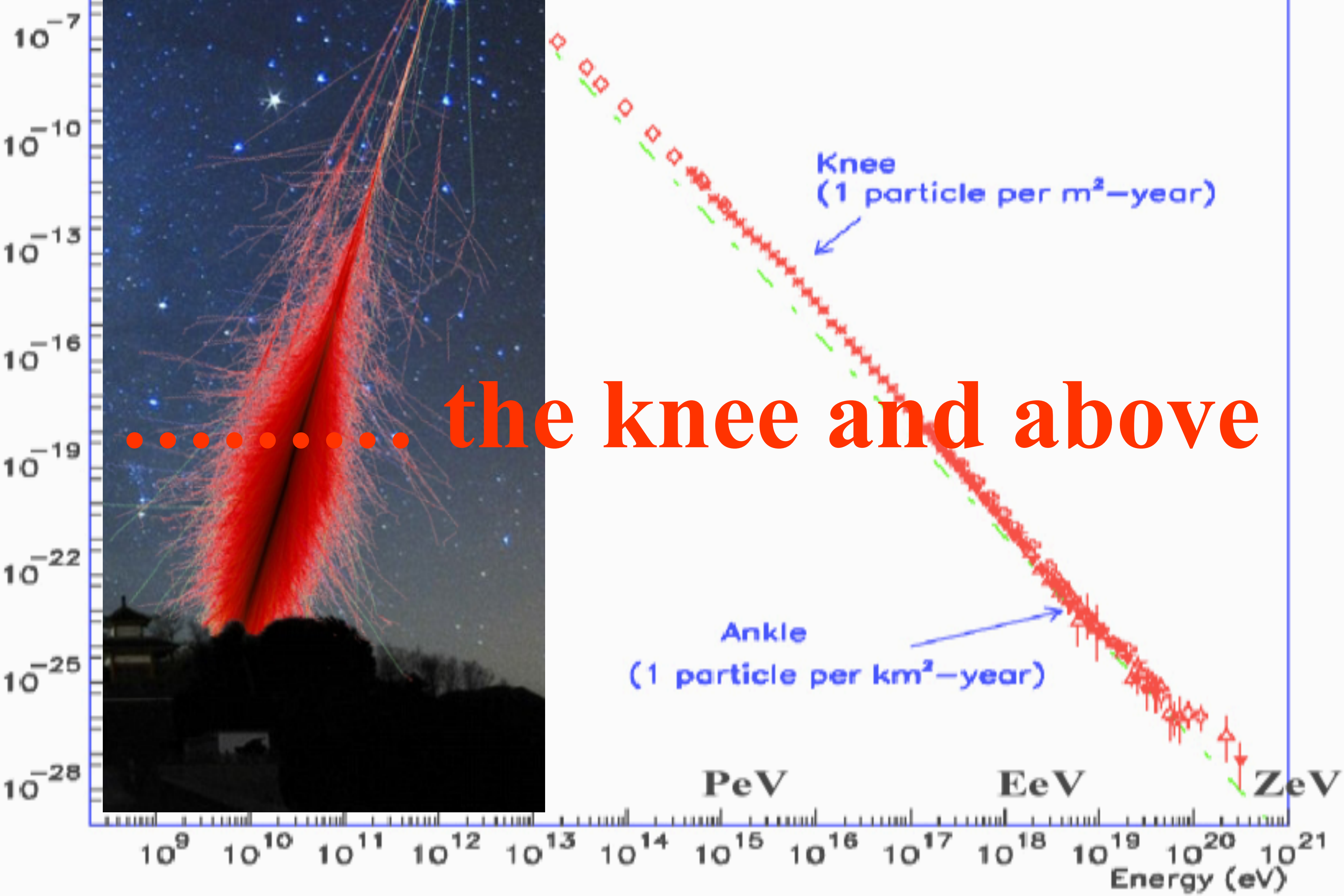
Particle energies observed in space by AMS-02 are already higher than at LHC detectors



Today :
max Pt = 250 GeV

Later :
max Pt = 500 GeV

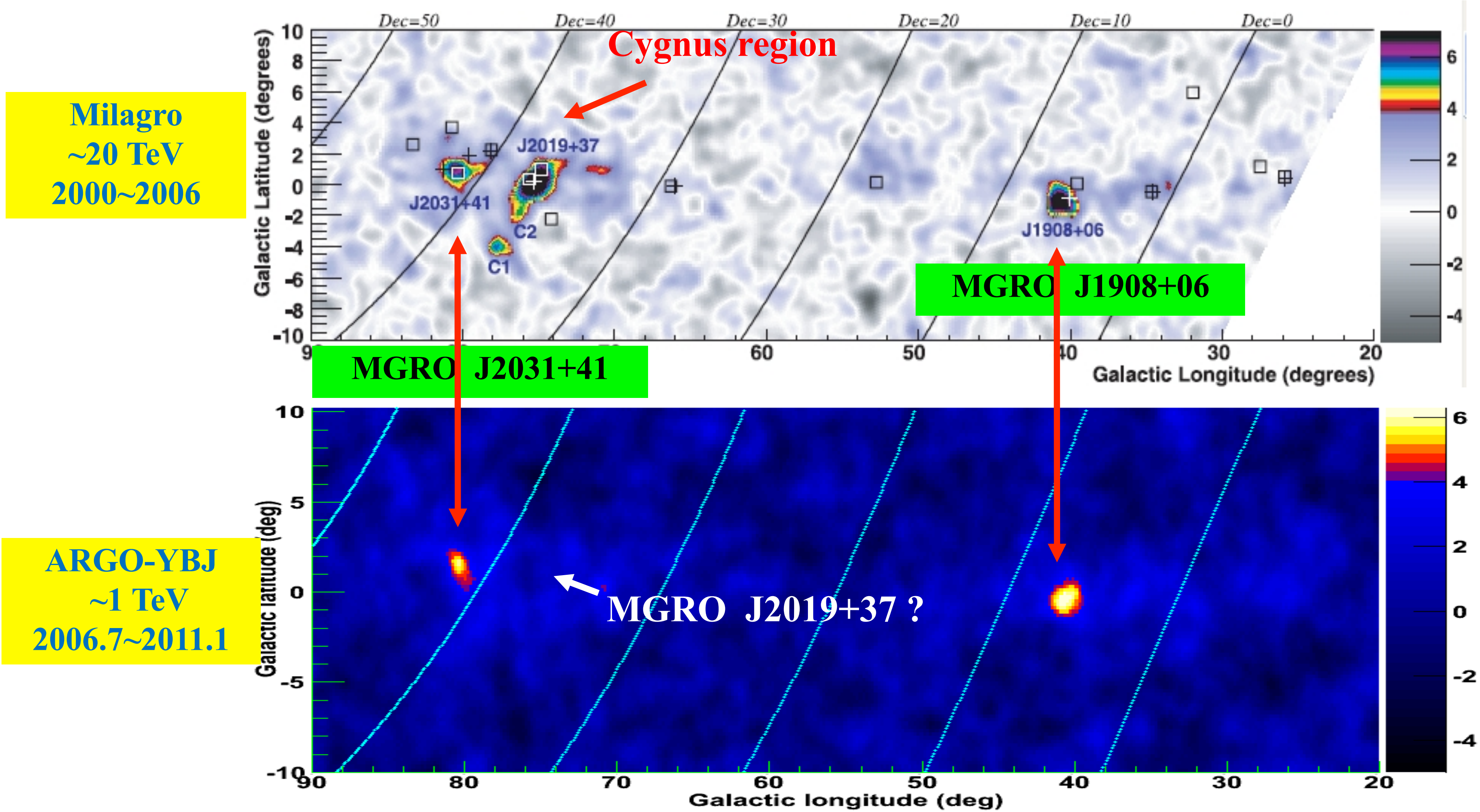
……… the knee and above



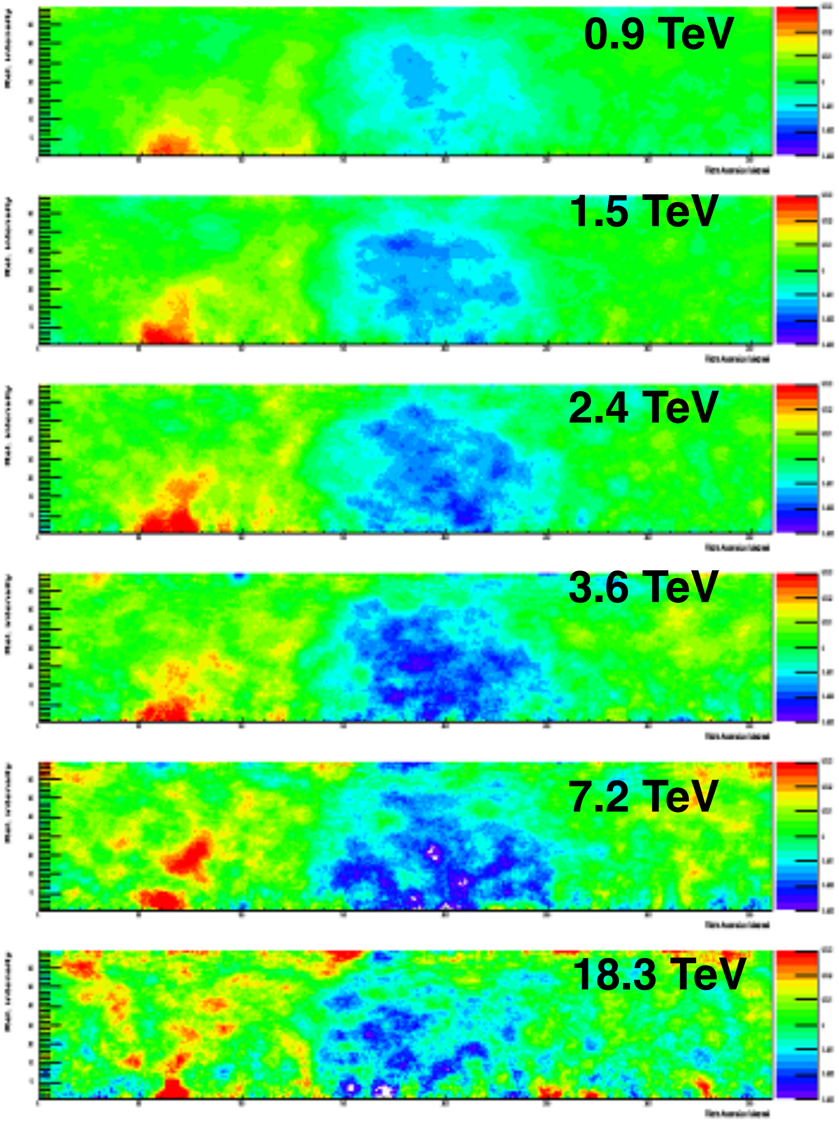
The ARGO-YBJ experiment

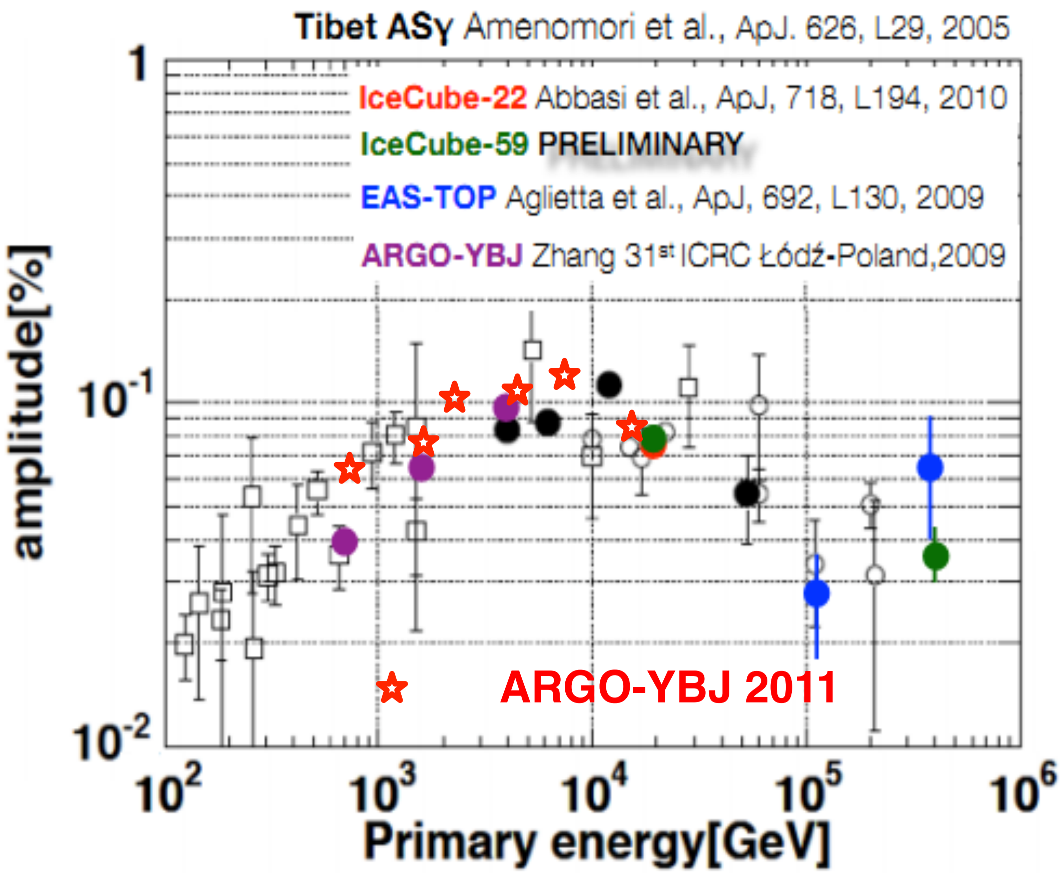
Galactic plane survey

Abdo et al., 2007



Large scale CR anisotropy vs energy





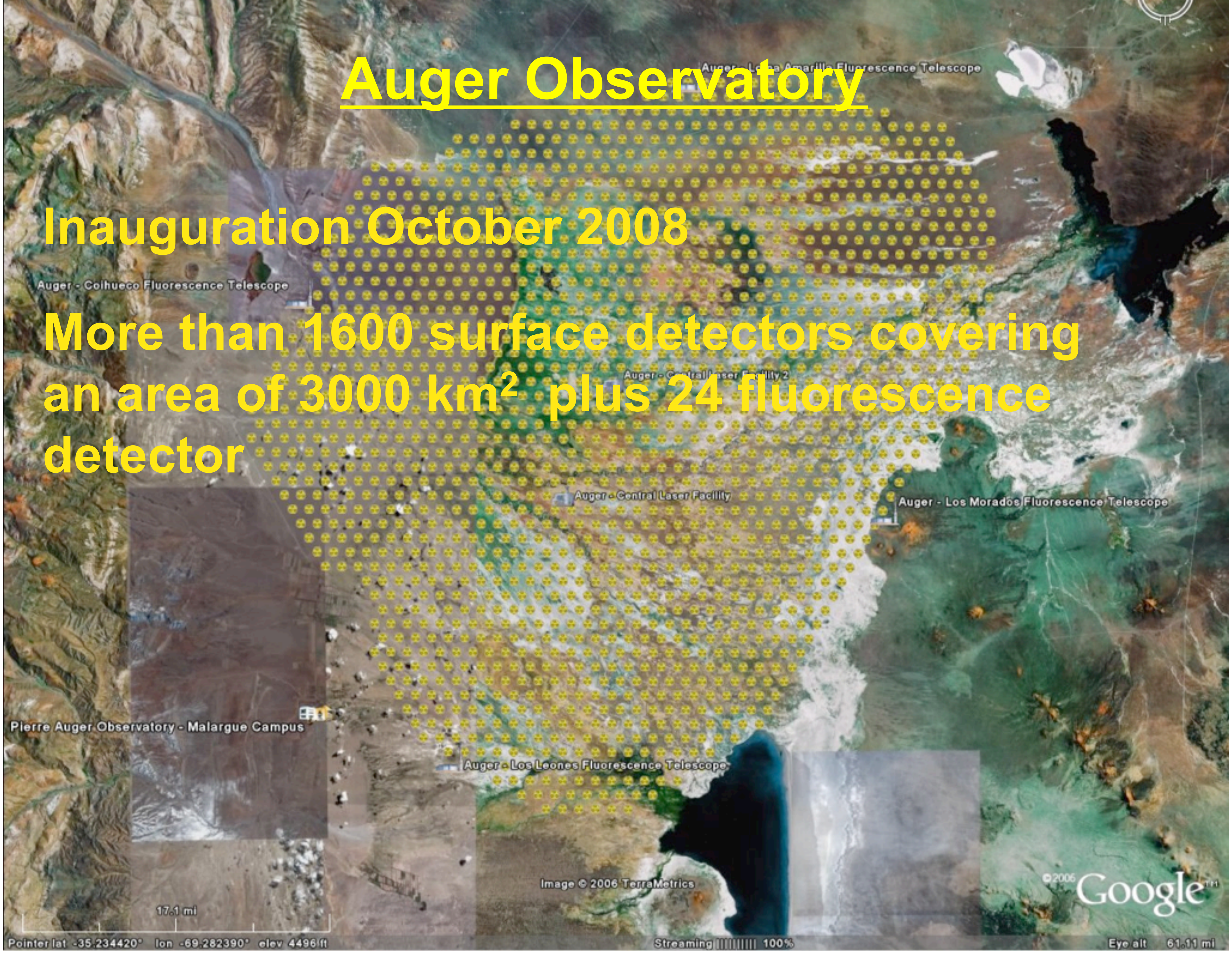
The tail-in broad structure appears to dissolve to smaller angular scale spots.

UHECR Energy Spectrum

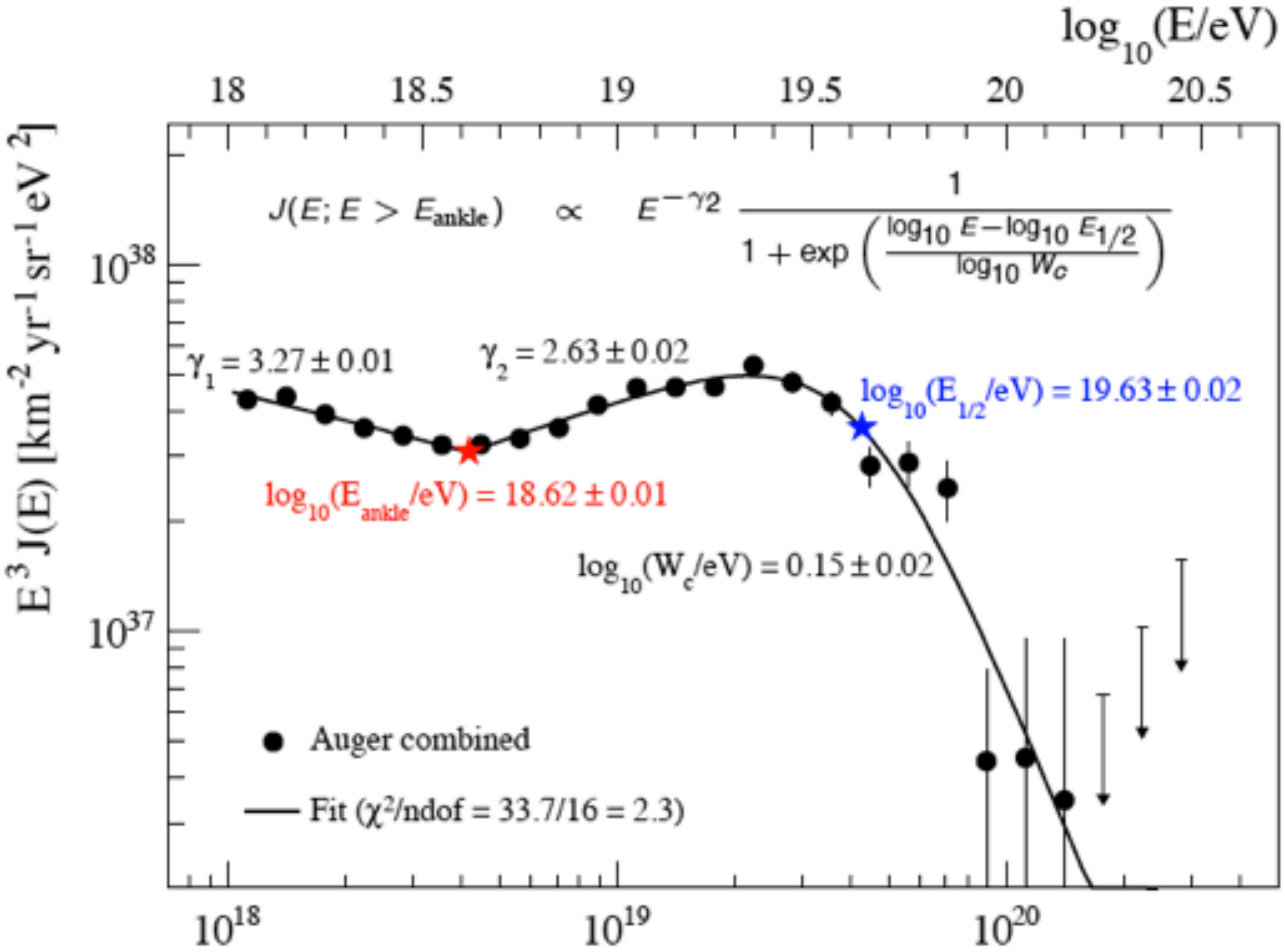
Auger Observatory

Inauguration October 2008

More than 1600 surface detectors covering an area of 3000 km^2 plus 24 fluorescence detector

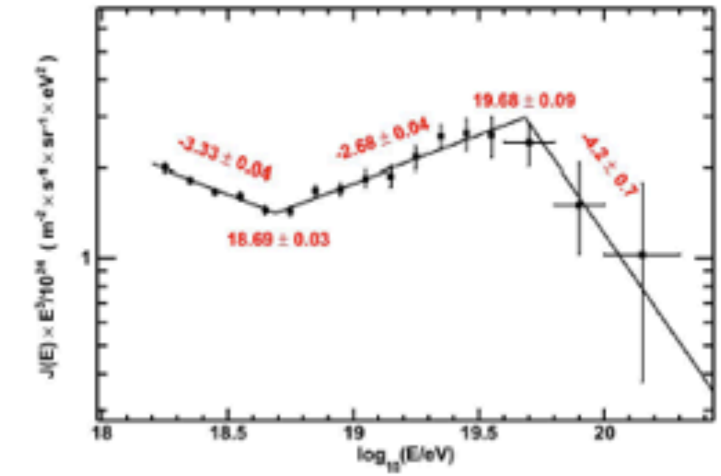


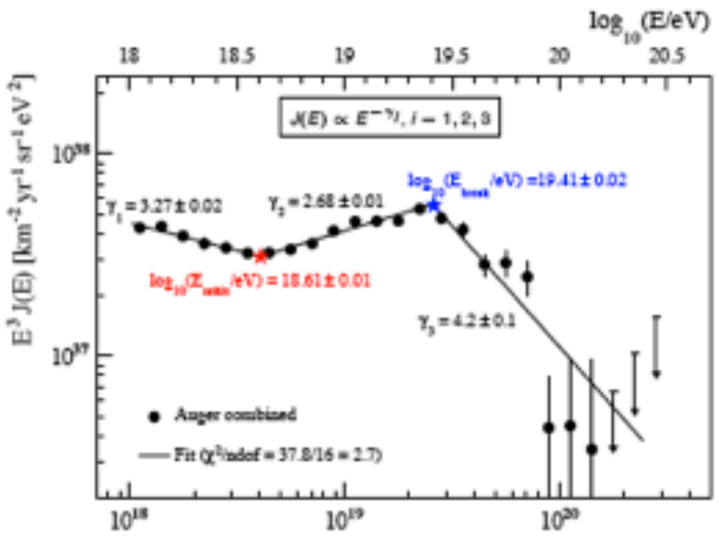
Auger Vertical Spectrum



F. Salamida [Auger Coll.], icrc893

Comparison of spectral features



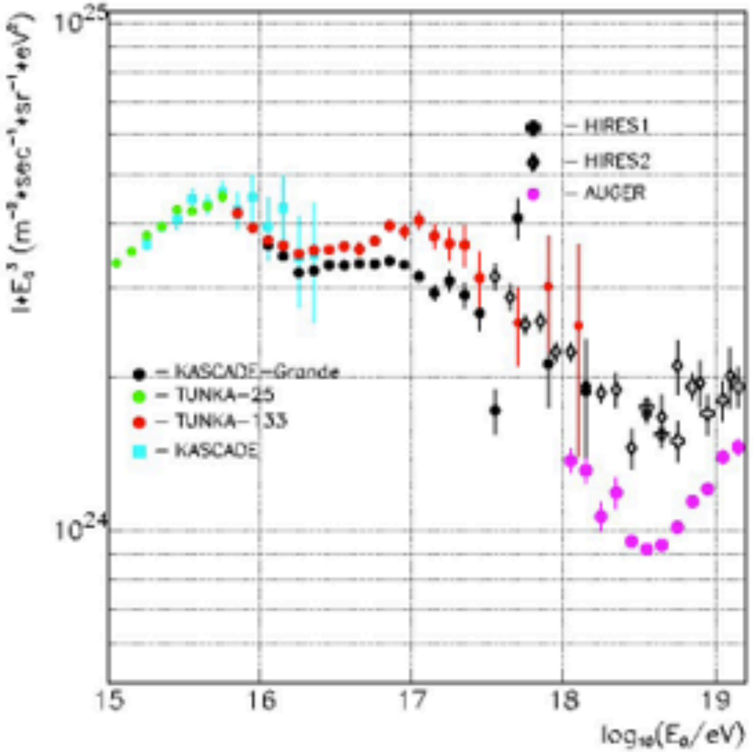


	TA	Auger
γ_1	3.33 ± 0.04	3.27 ± 0.02
γ_2	2.68 ± 0.04	2.68 ± 0.01
γ_3	4.2 ± 0.7	4.2 ± 0.1
$\lg(E_1/\mathrm{eV})$	18.69 ± 0.03	18.61 ± 0.01
$\lg(E_2/\mathrm{eV})$	19.68 ± 0.09	19.41 ± 0.02

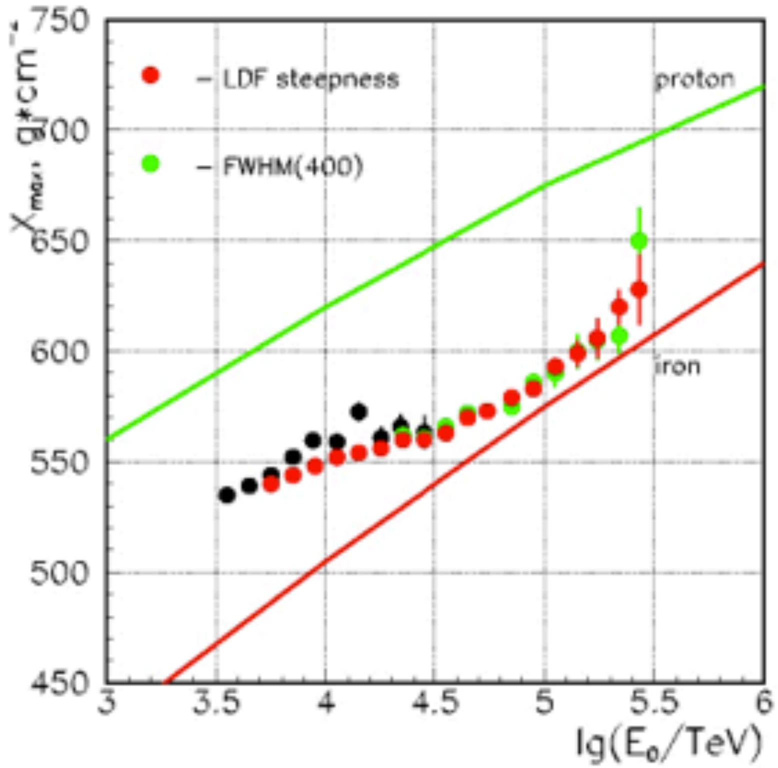
B. Stokes [TA Coll.], icrc1297

F. Salamida [Auger Coll.], icrc893

Spectrum and X_{max} from Tunka133



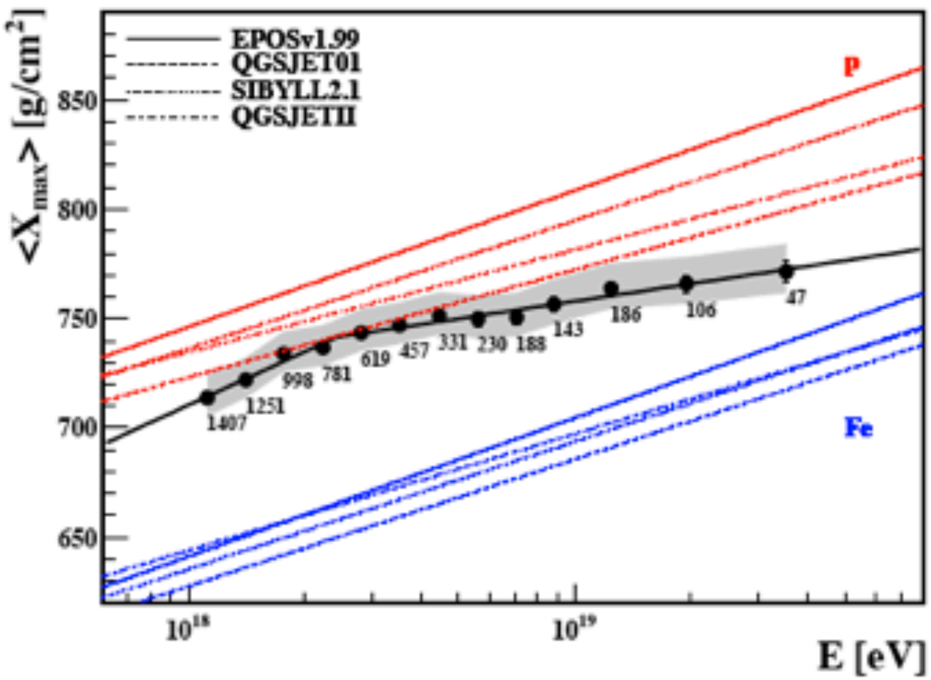
L.A. Kuzmichev [Tunka Coll.], icrc250



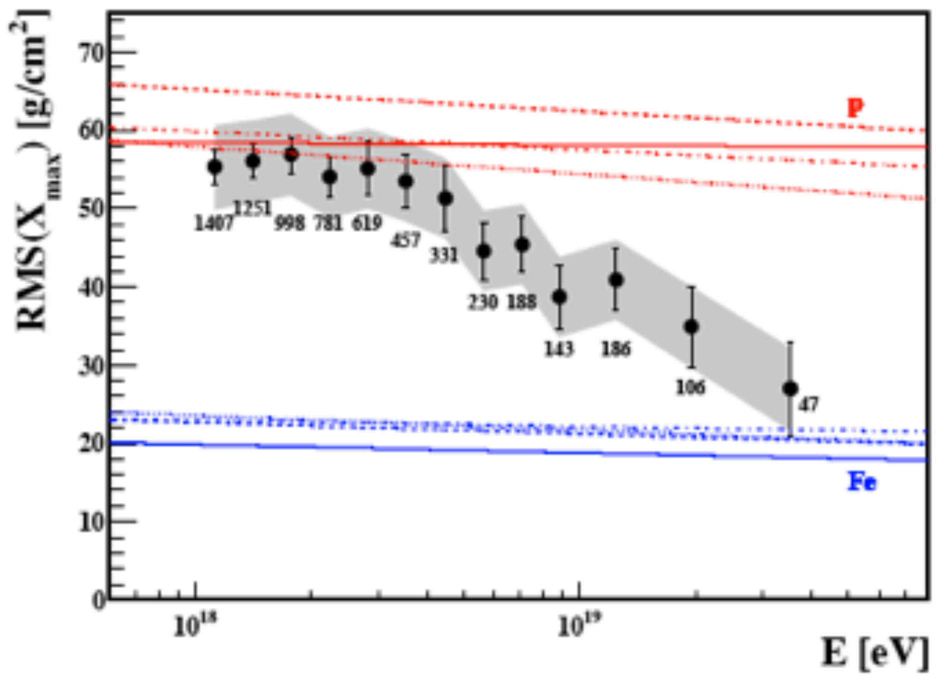
V. Prosin [Tunka Coll.], icrc184

Longitudinal EAS Development with Auger FD

average depth

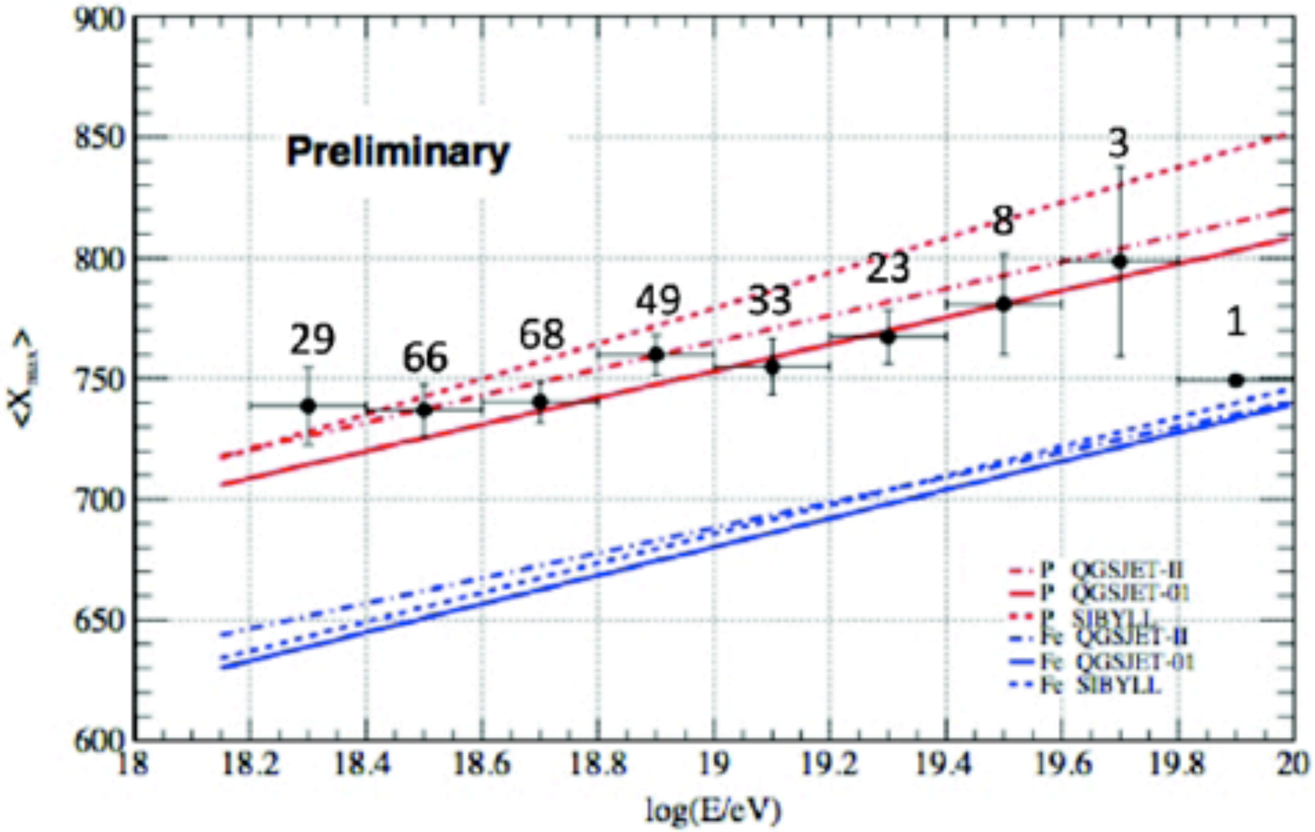


fluctuations



P. Facal [Auger Coll.], icrc725

Longitudinal EAS Development with TA Stereo FD

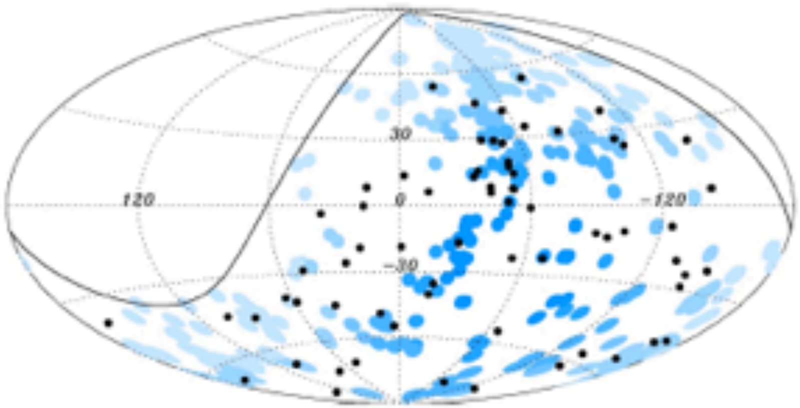


A. Tameda [TA Coll.], icrc1268

UHE Correlation with AGNs within GZK-sphere?

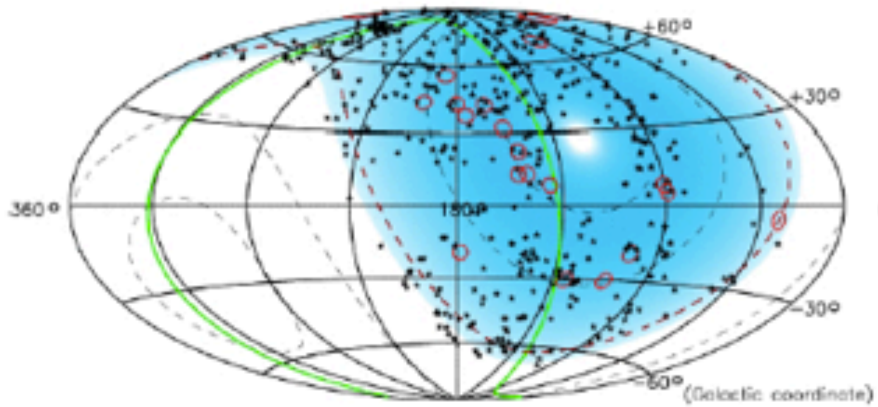
VCV catalogue, E> 57 EeV, z<0.018, distance < 3.1 deg.

Auger



28 out of 84 correlate

TA

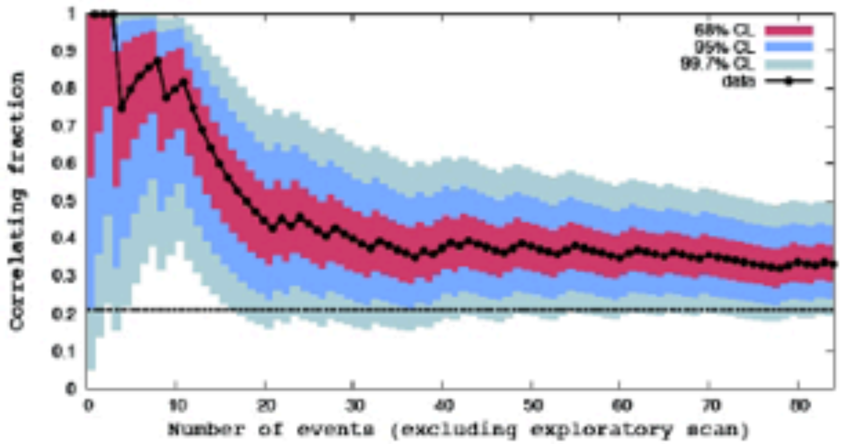


8 out of 20 correlate

UHE Correlation with AGNs within GZK-sphere?

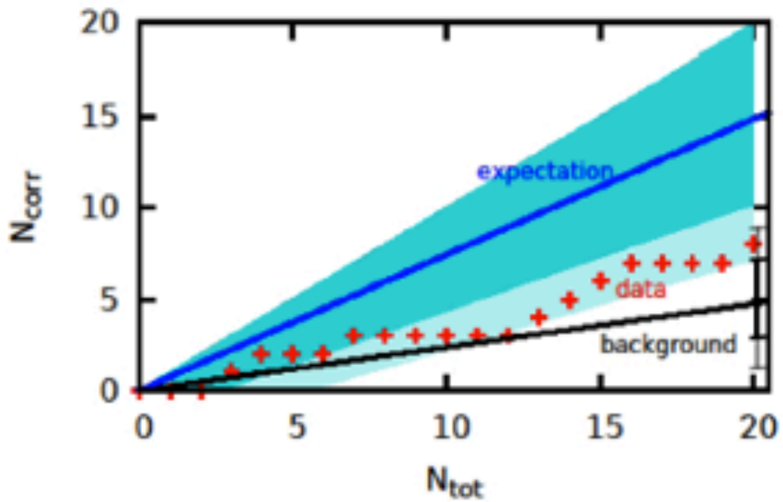
VCV catalogue, E> 57 EeV, z<0.018, distance < 3.1 deg.

Auger



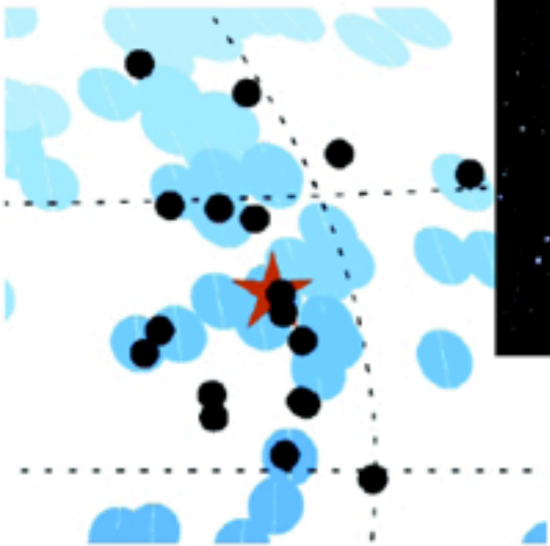
$P = 0.006,\ f = 33 \pm 5\%$

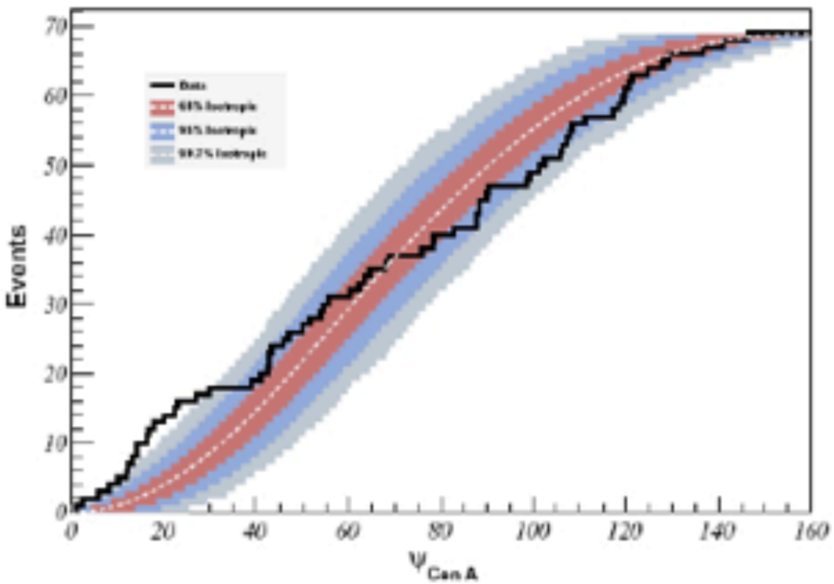
TA



compatible with isotropy and updated (!) Auger

UHERs from CenA?



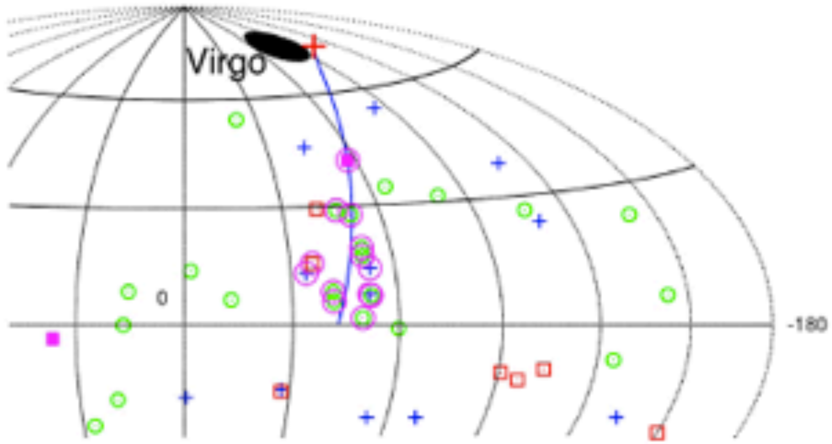


13/62 within 18 deg., expect 3.2

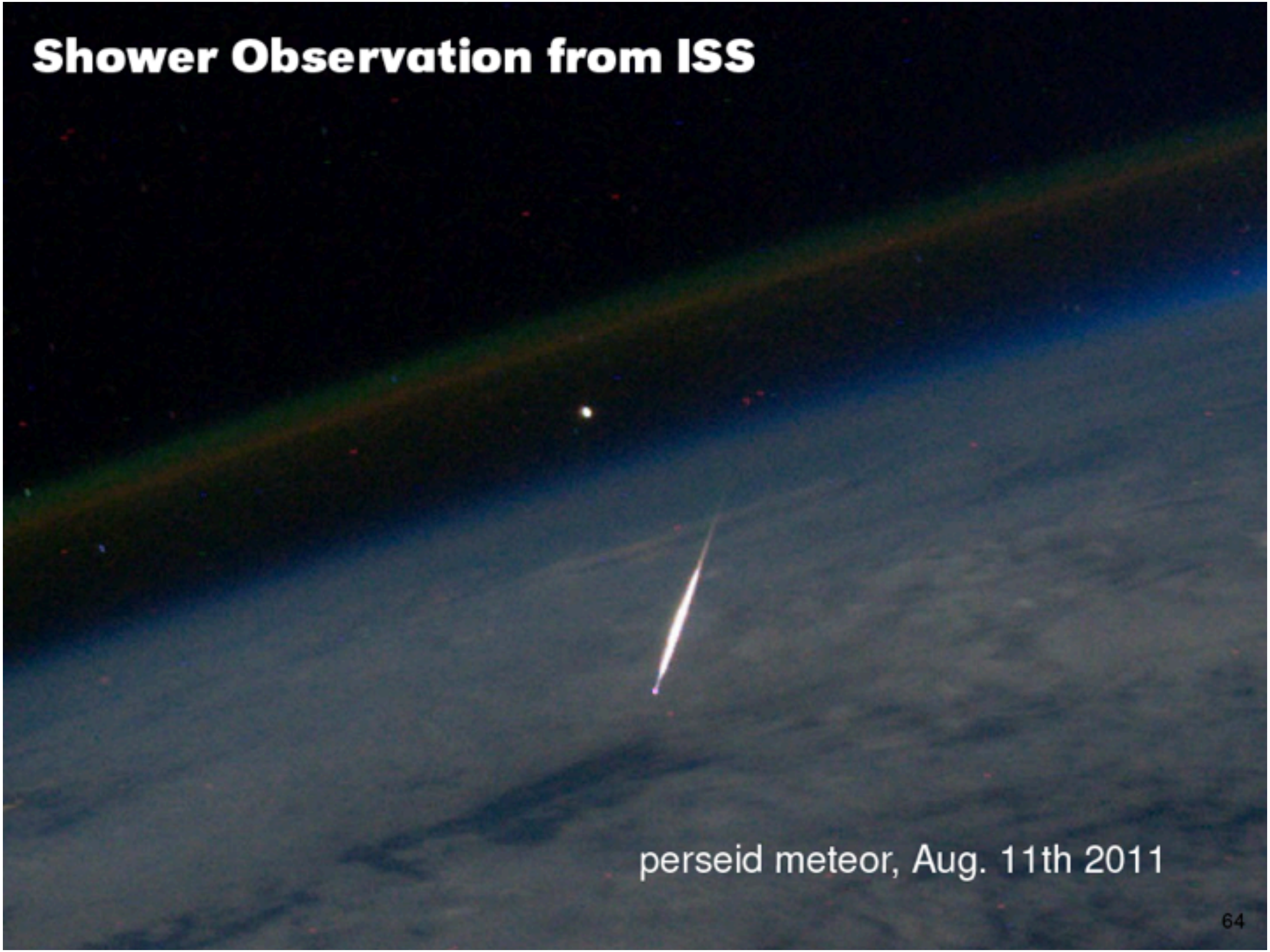
limits on source composition?

E.M. Santos [Auger Coll.], icrc868

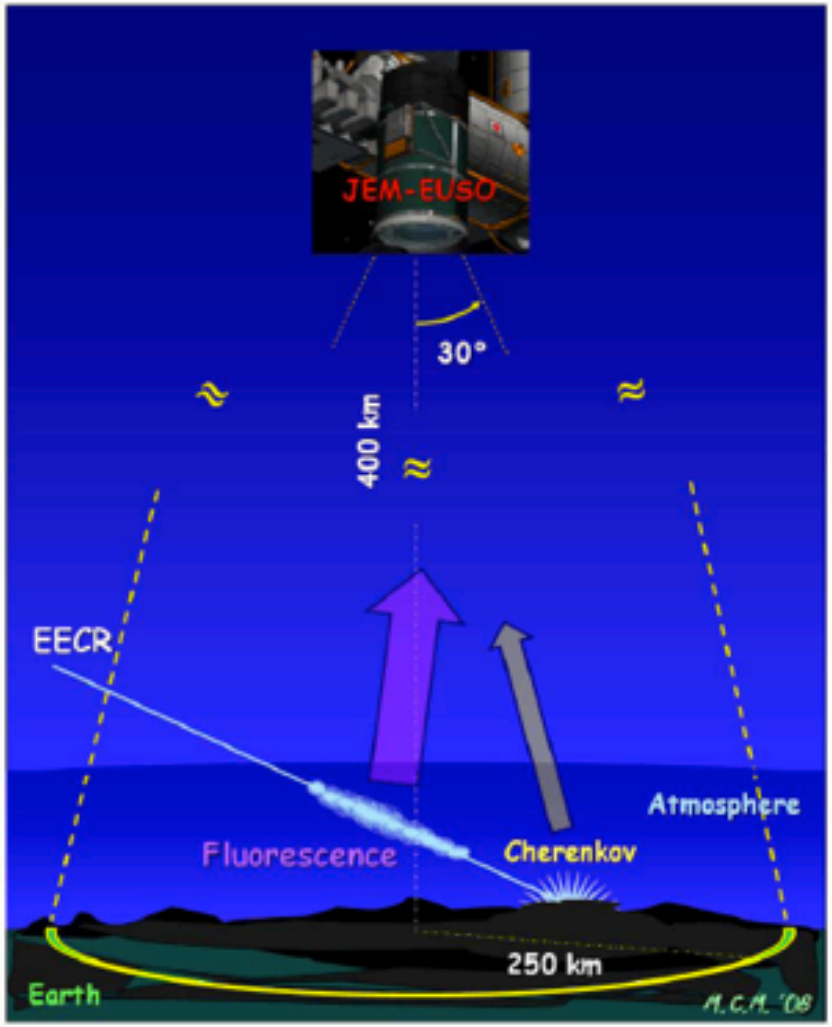
... or Virgo?



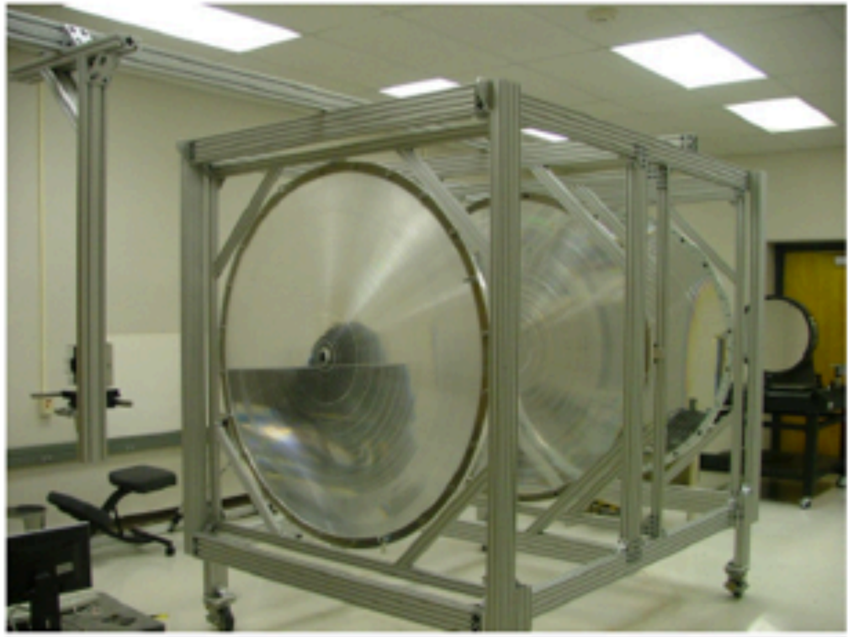
Giacinti&Semikoz, icrc171

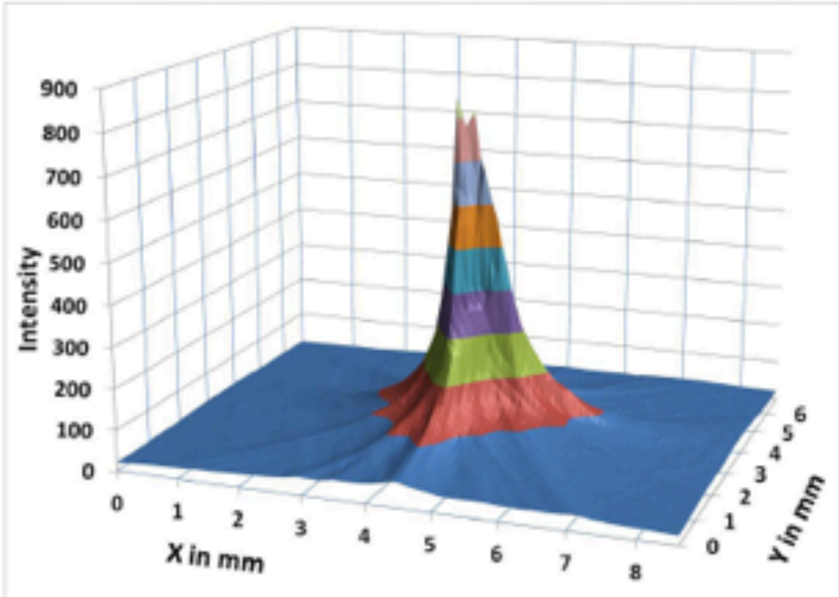

Shower Observation from ISS
perseid meteor, Aug. 11th 2011

JEM-EUSO Optics Prototype



J.H. Adams [JEM-EUSO Coll.], icrc1100





JEM-EUSO Exposure

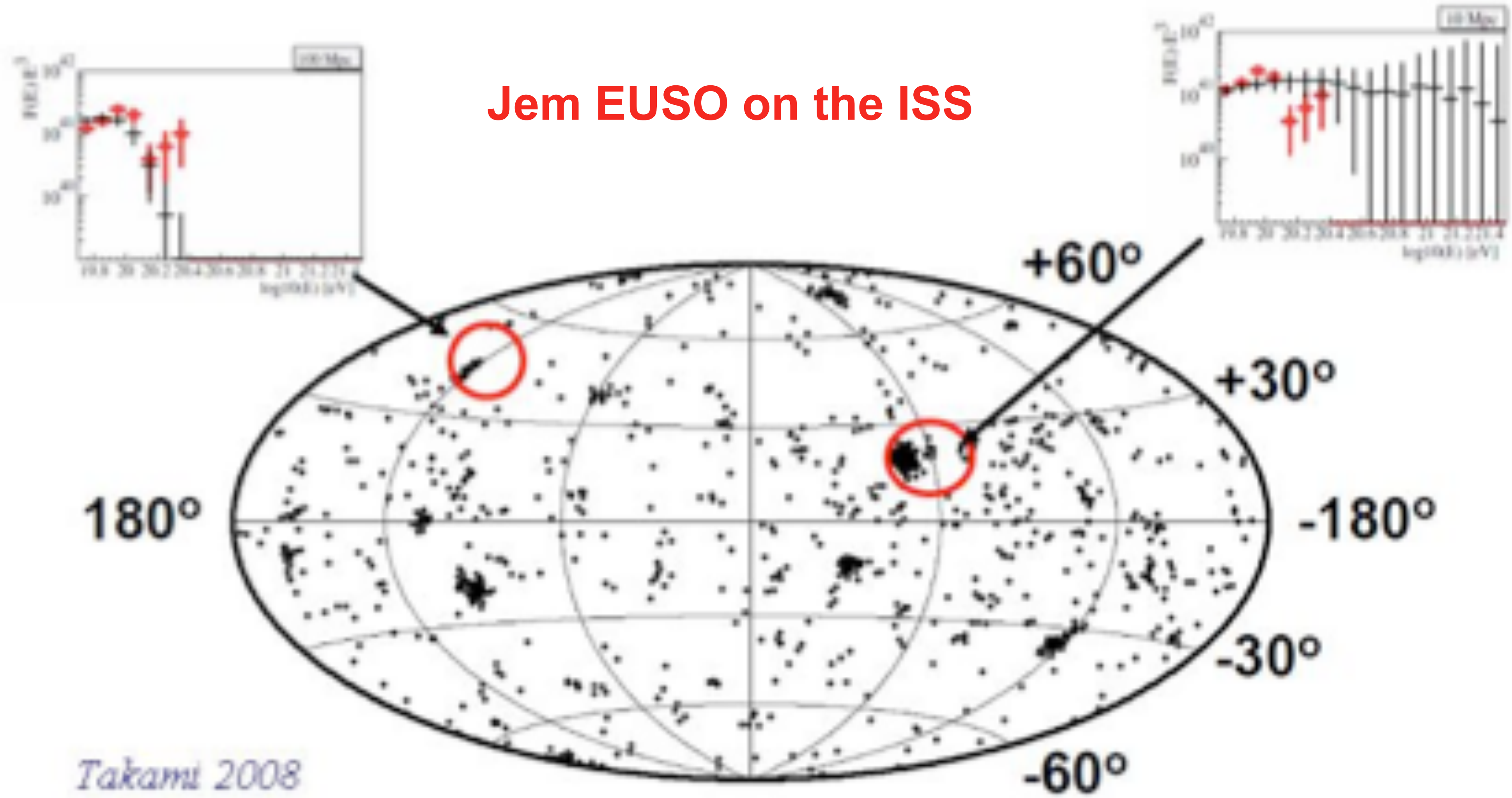
using Universitetsky Tatiana satellite data

Observatory	Aperture km² sr	Status	Start	Lifetime	Duty cycle	Annual Exposure km² sr yr	Relative to Auger
Auger	7,000	Operations	2006	4 (16)	1	7000	1
TA	1,200	Operations	2008	2 (14)	1	1,200	0.2
TUS	30,000	Developed	2012	5	0.14	4,200	0.6
JEM-EUSO ($E \approx 10^{20}$ eV)	430,000	Design	2017	5	0.14	60,000	9
JEM-EUSO (highest energies) Tilted mode 35°	1,500,000	Design	2017	5	0.14	200,000	28

- 2013: launch JEM-EUSO balloon from Kiruna
- 2017: launch to ISS using Japanese HII Transfer Vehicle (HTV)?

T. Ebisuzaki [JEM-EUSO Coll.], icrc120

Jem EUSO on the ISS



JEM-EUSO sky simulated
with 1,000 events

Conclusions

- One century after their discovery, Cosmic Rays are still a very active area of research
- Many questions about their origin, composition, spectrum remains
- Very powerful detectors have been developed, contributing to impressive improvements in experimental accuracy
- Still, the experimental ingenuity is challenged to answer some of the most difficult questions
- Exactly as it was for Hess, 100 years ago