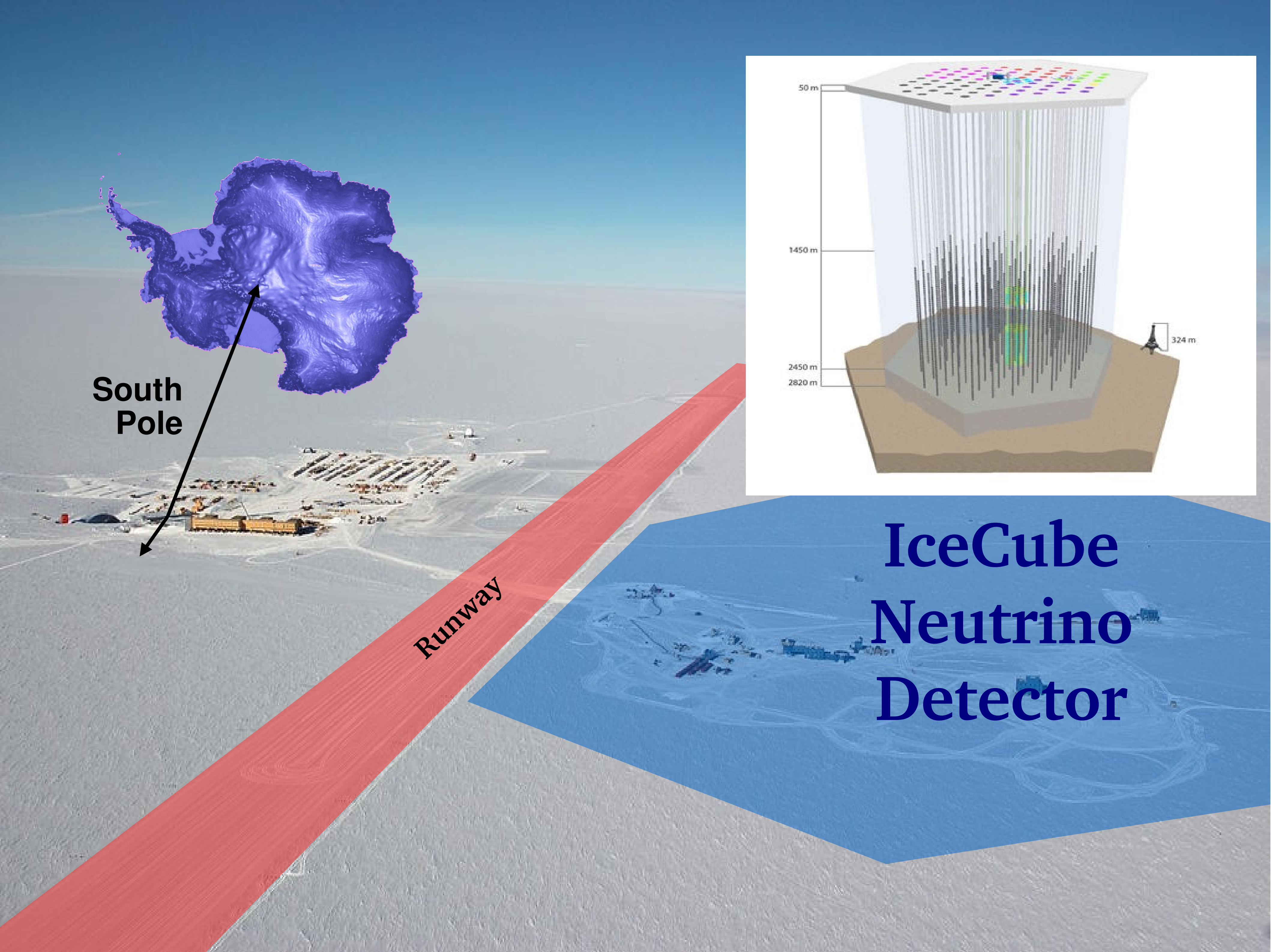
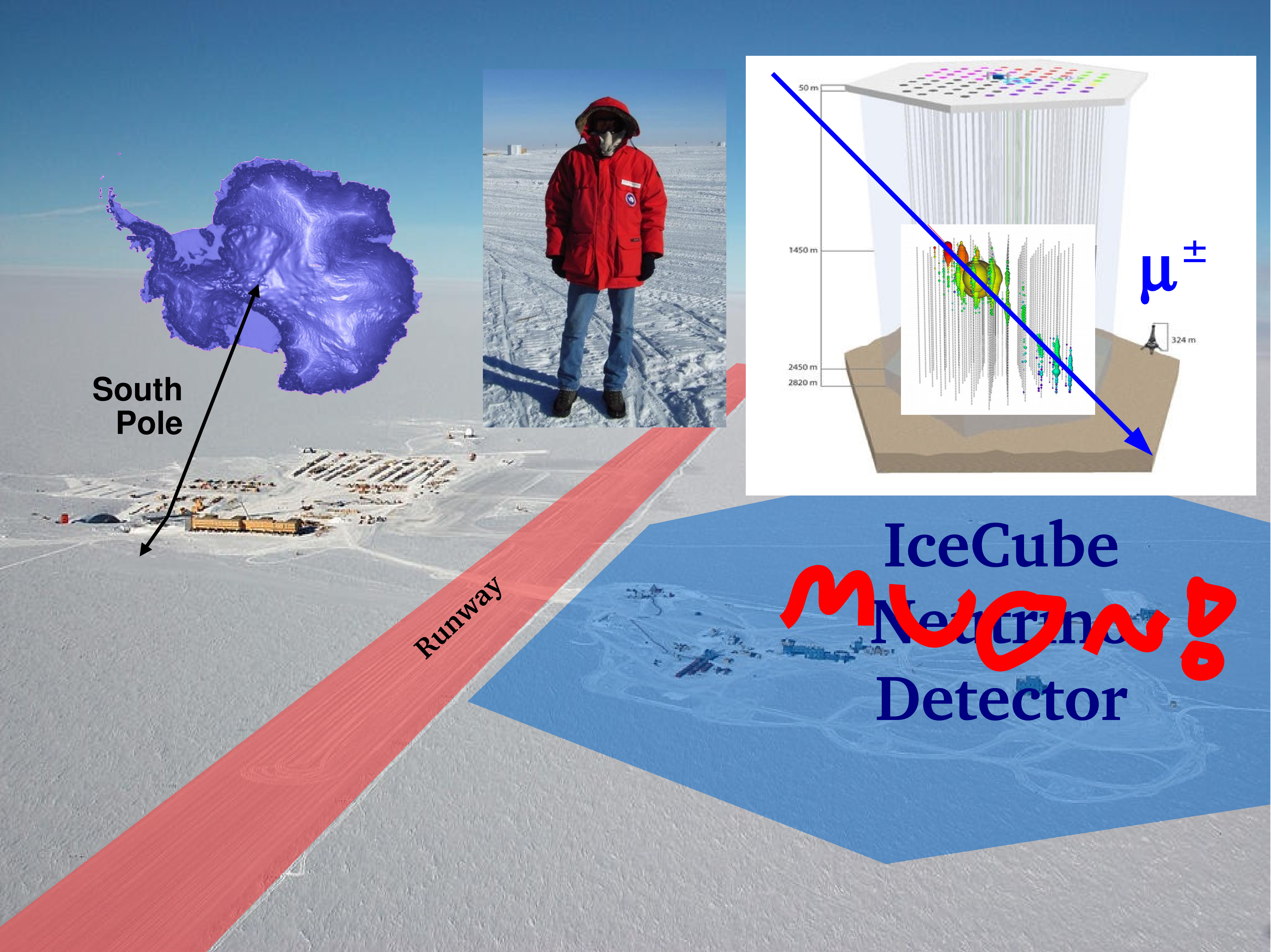
Cosmic Rays

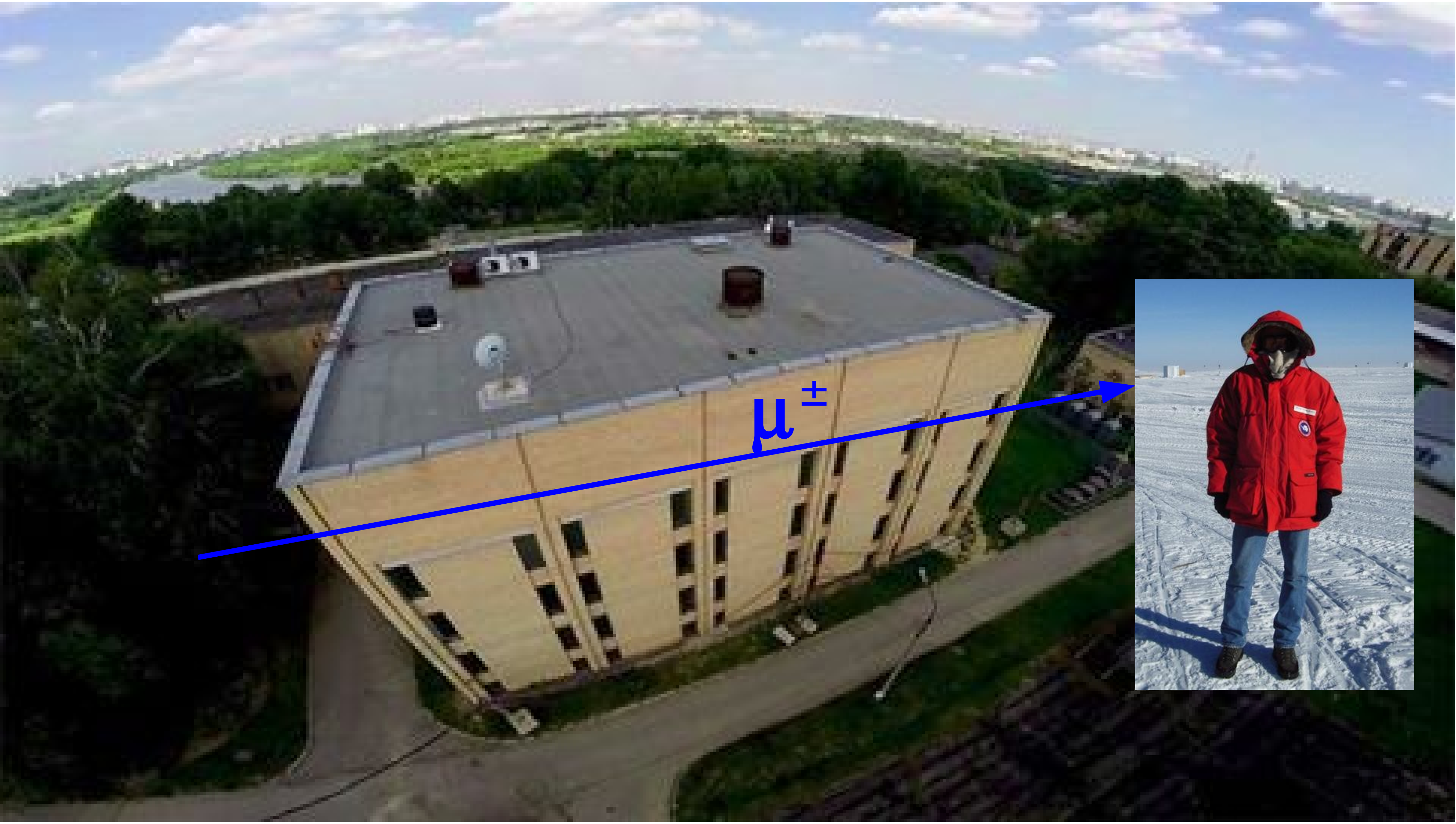
Patrick Berghaus


South Pole
Runway
50 m
1450 m
2450 m
2820 m
324 m
IceCube
Neutrino
Detector



South Pole
Runway
IceCube
Neutrino
Detector
muon!
μ±
50 m
1450 m
2450 m
2820 m
324 m

Unique Scientific Facility
Experimental Complex
NEVOD



IceCube Preliminary Design Document

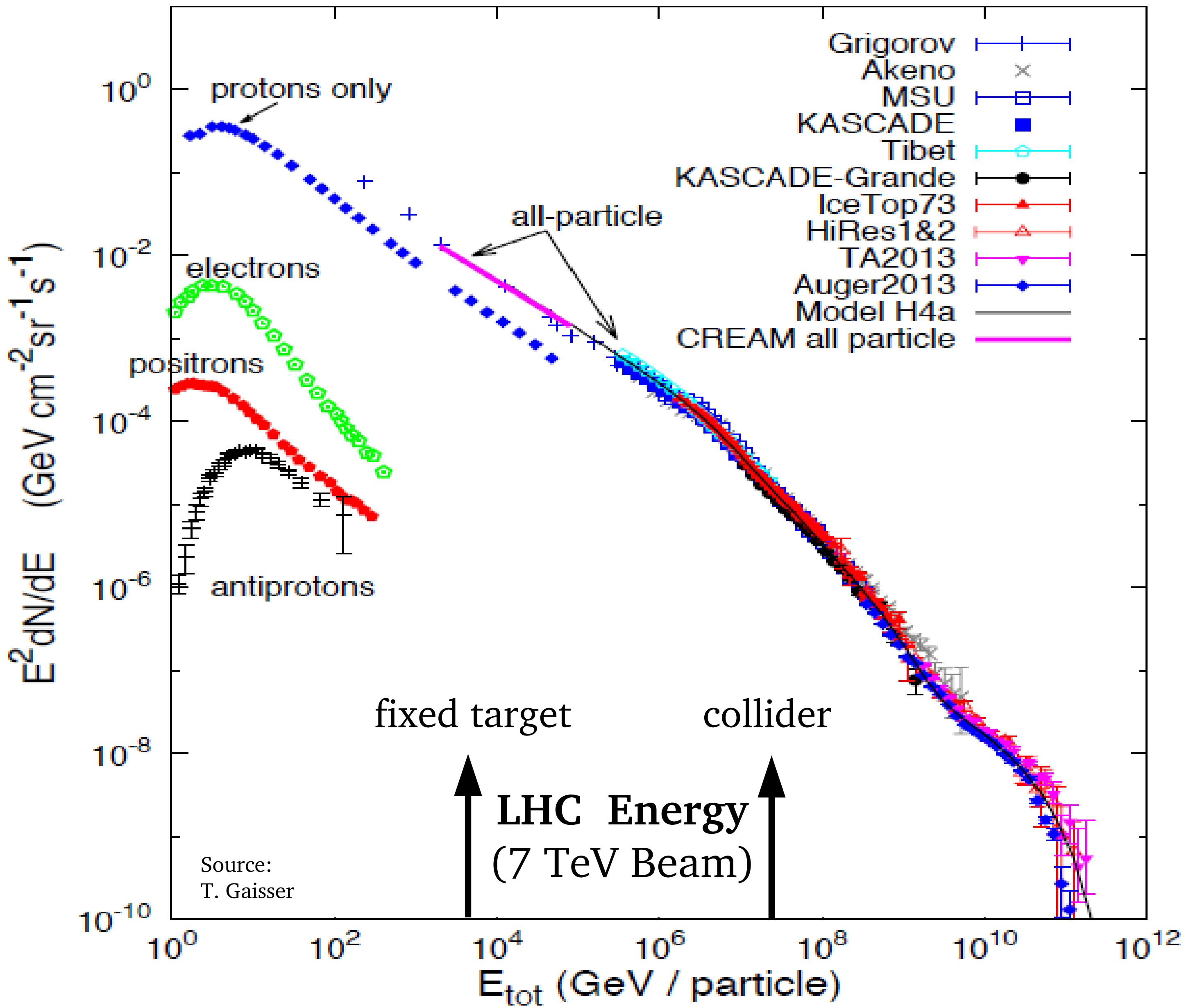
October 11, 2001/ Revision: 1.24

The IceCube Collaboration

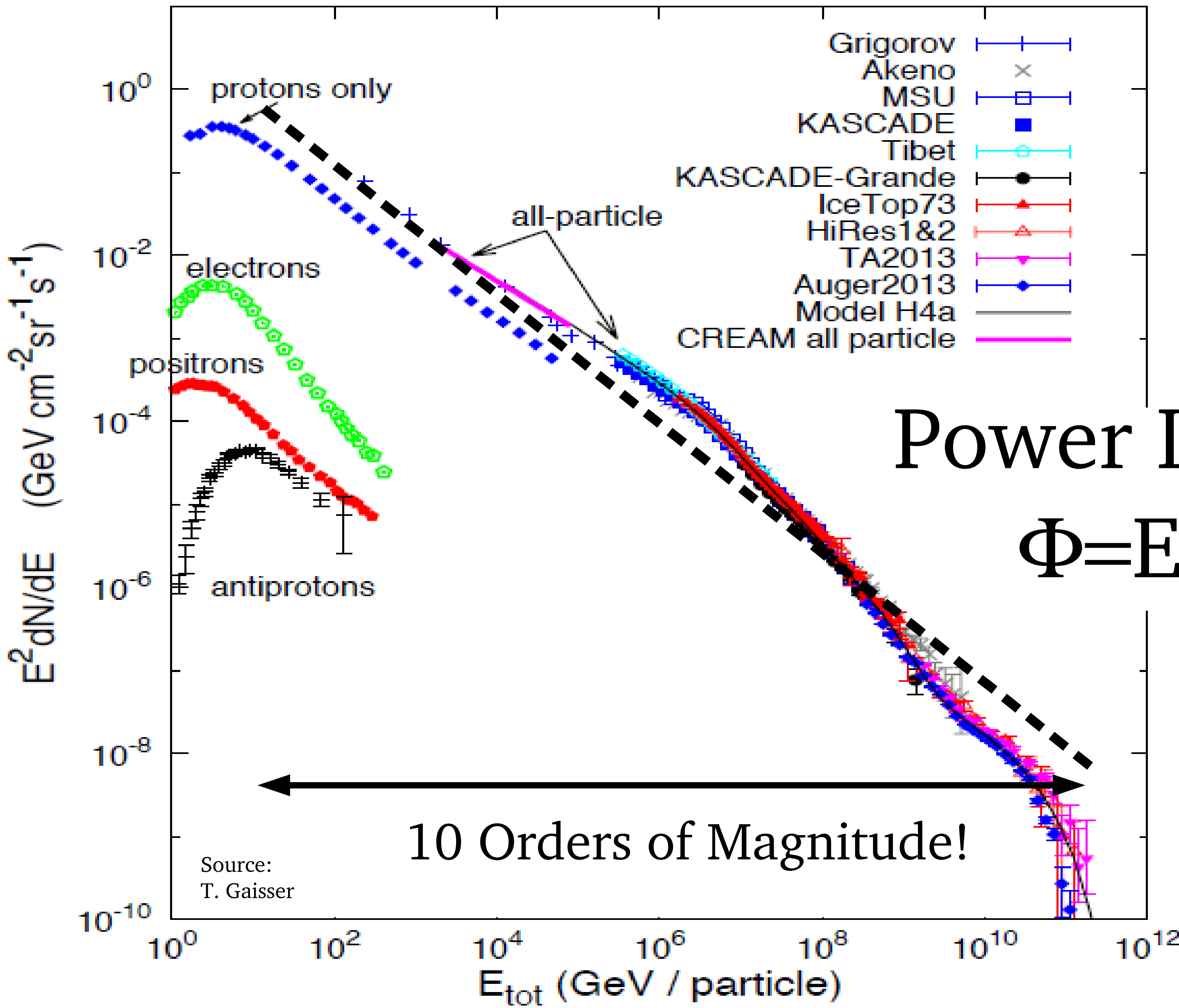
3 Science Motivation for Kilometer-Scale Detectors

The construction of neutrino telescopes is overwhelmingly motivated by their discovery potential in astronomy, astrophysics, cosmology and particle physics. To maximize this potential, one must design an instrument with the largest possible effective telescope area to overcome the small neutrino cross section with matter, and the best possible angular and energy resolution to address the wide diversity of possible signals. A well-designed neutrino telescope can

- search for high energy neutrinos from transient sources like Gamma Ray Bursts (GRB) or Supernova bursts;
- search for steady and variable sources of high energy neutrinos, e.g. Active Galactic Nuclei (AGN) or Supernova Remnants (SNR);
- search for the source(s) of the cosmic-rays;

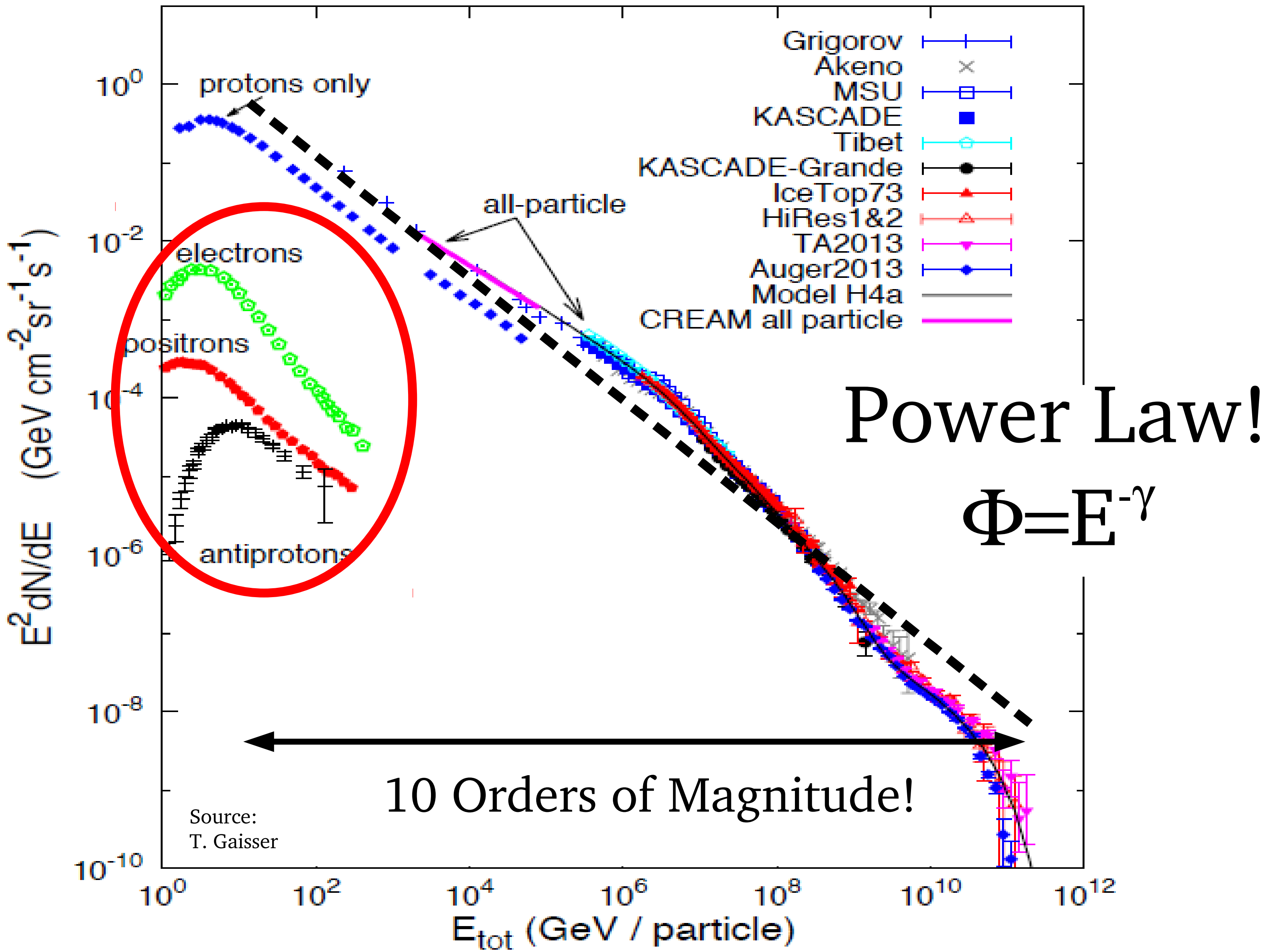


protons only
all-particle
electrons
positrons
antiprotons
Grigorov
Akeno
MSU
KASCADE
Tibet
KASCADE-Grande
IceTop73
HiRes1&2
TA2013
Auger2013
Model H4a
CREAM all particle
fixed target
collider
LHC Energy
(7 TeV Beam)
Source:
T. Gaisser
E²dN/dE (GeV cm⁻² sr⁻¹ s⁻¹)
E_tot (GeV / particle)

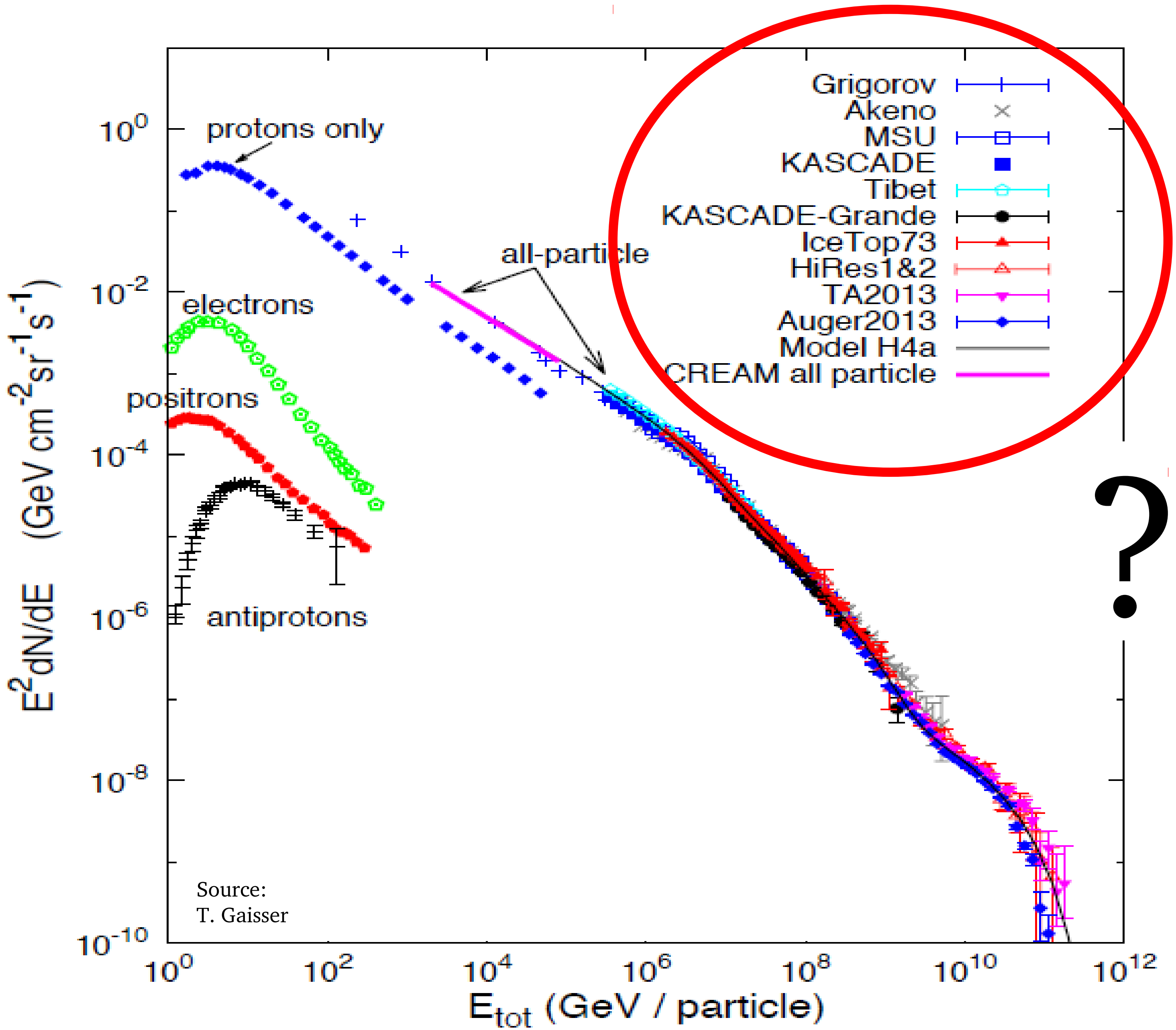


Power Law!

$\Phi = E^{-\gamma}$



>99% Atomic Nuclei



protons only
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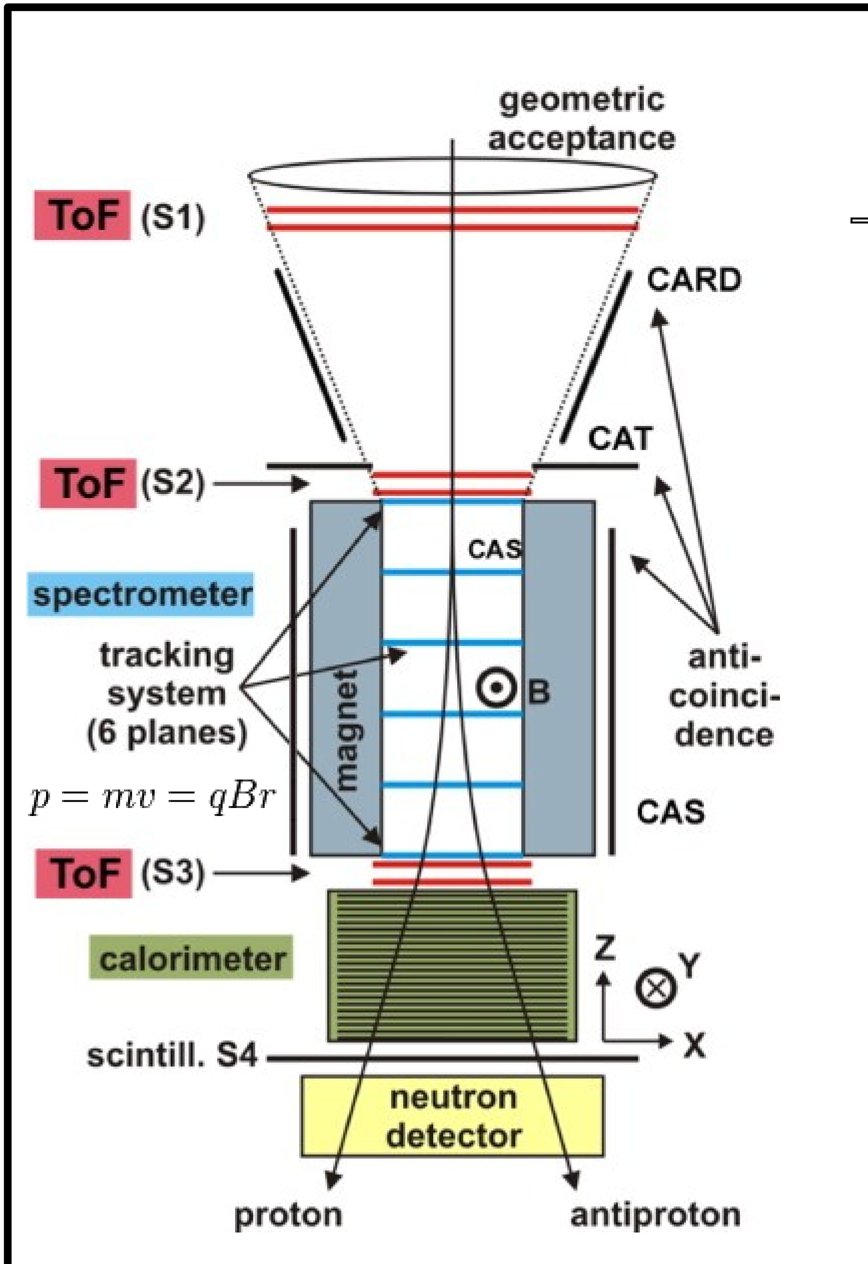
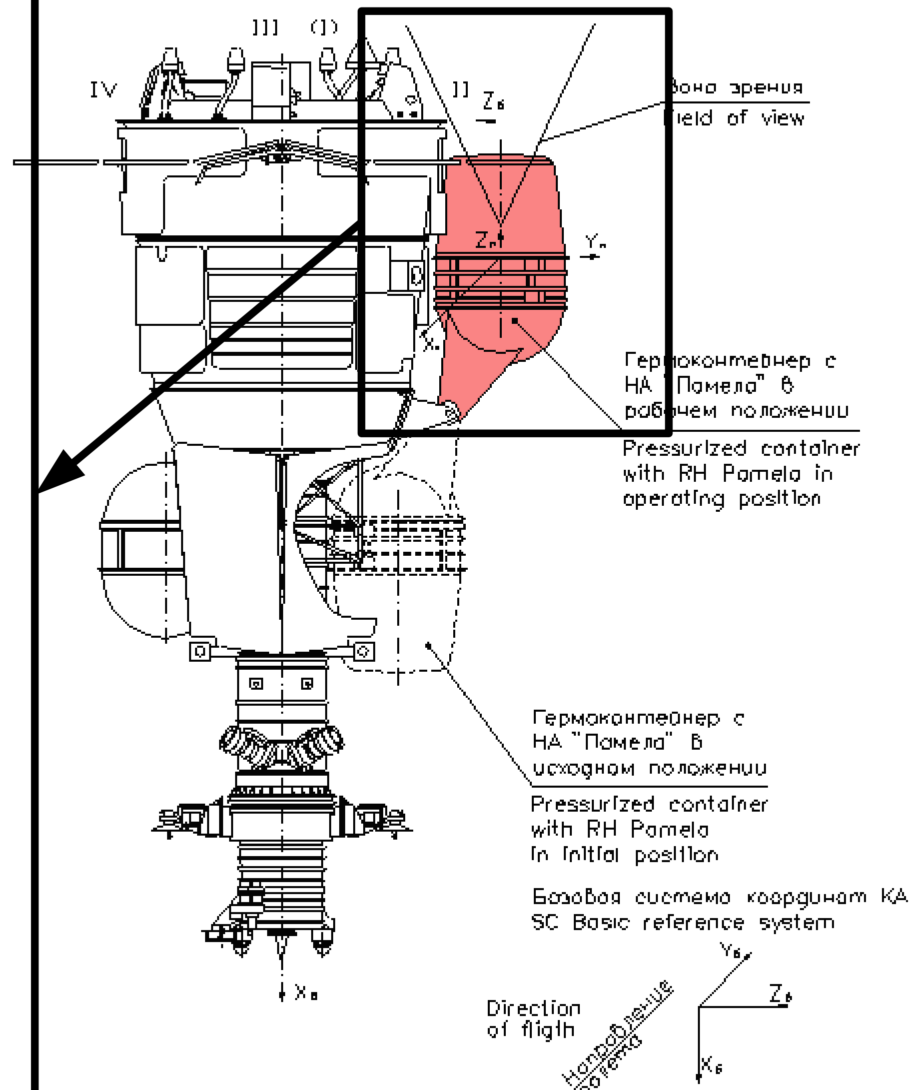
TA2013
Auger2013
Model H4a
CREAM all particle
$E^2 dN/dE$ (GeV cm^{-2}sr^{-1}s^{-1})
E_{tot} (GeV / particle)
Source:
T. Gaisser
?

Direct Observation: Example PAMELA*

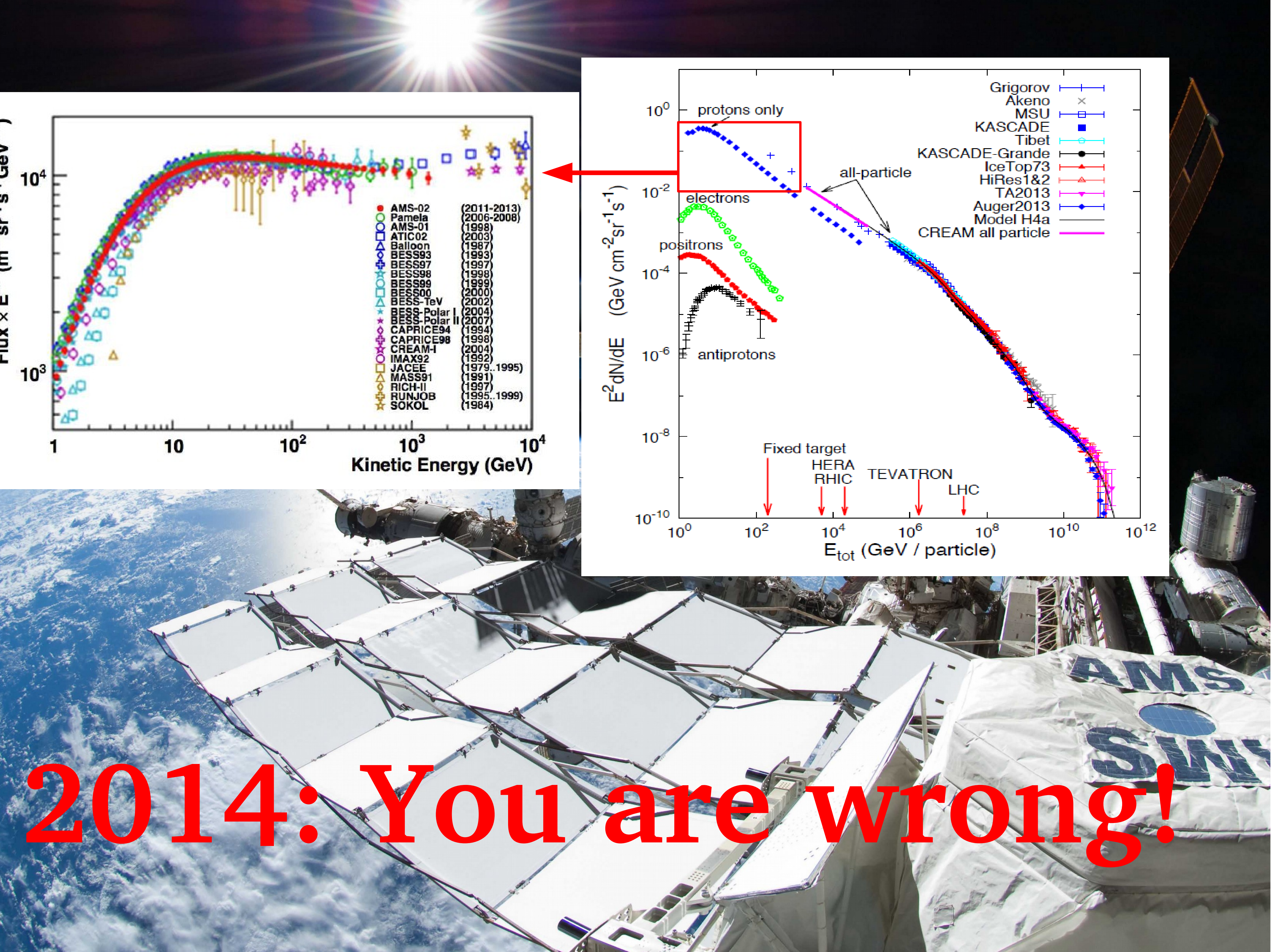




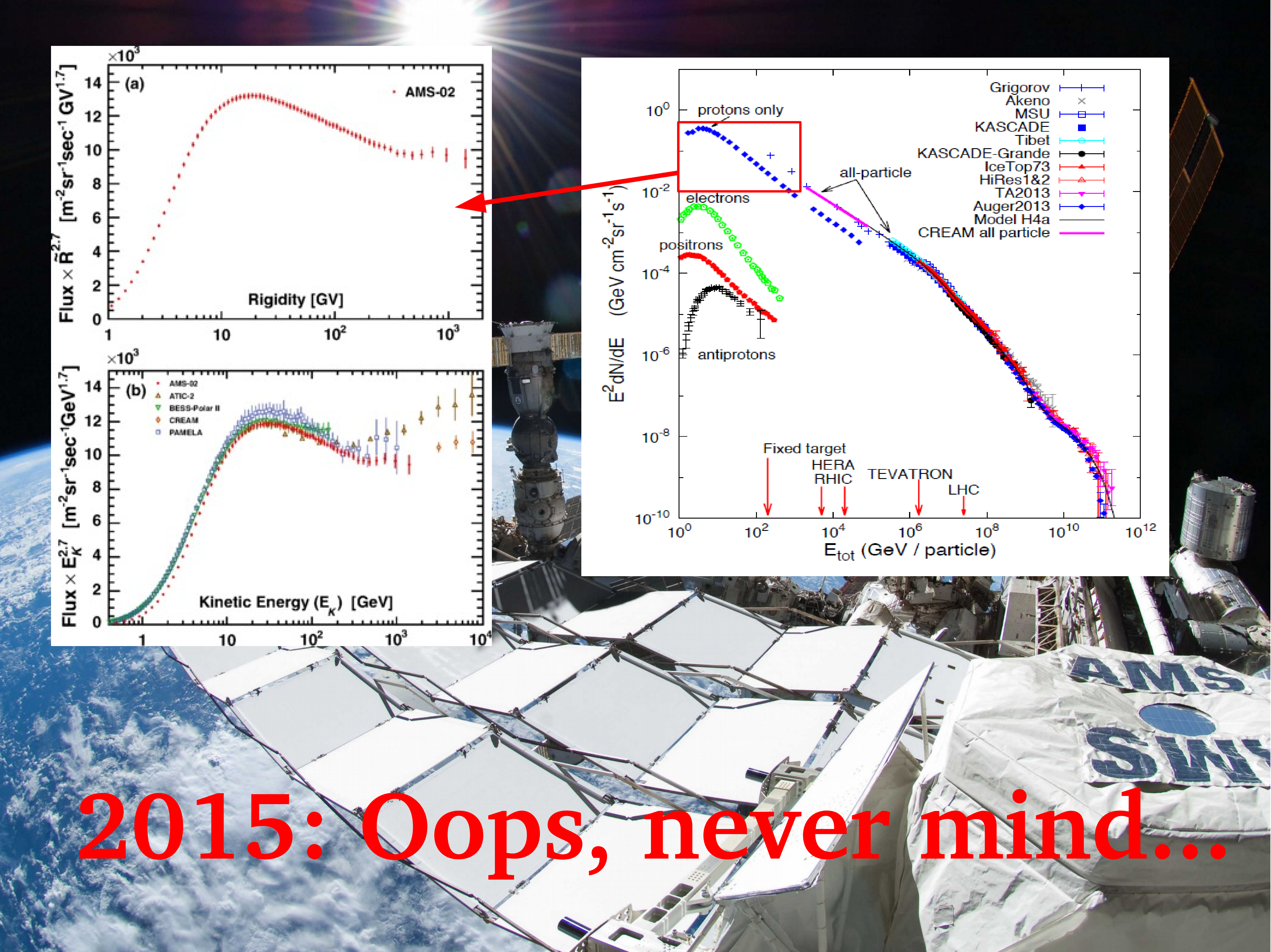
Earth Observation Satellite
“Resurs-DK-1” (2006)

*Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics


AMS
$ 2,000,000,000

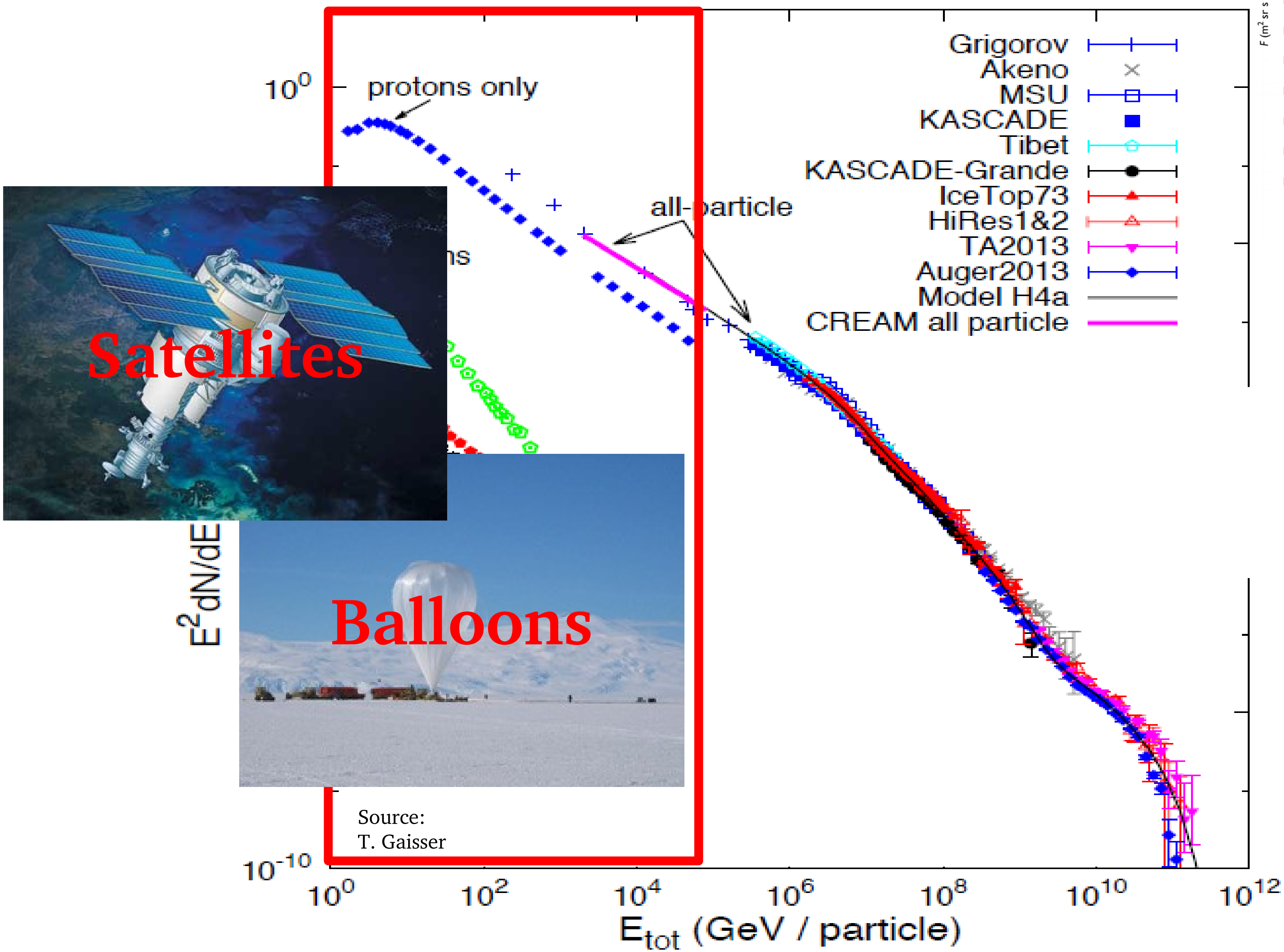


Kinetic Energy (GeV)
AMS-02 (2011-2013)
Pamela (2006-2008)
AMS-01 (1998)
ATIC02 (2003)
Balloon (1987)
BESS93 (1993)
BESS97 (1997)
BESS98 (1998)
BESS99 (1999)
BESS00 (2000)
BESS-TeV (2002)
BESS-Polar I (2004)
BESS-Polar II (2007)
CAPRICE94 (1994)
CAPRICE98 (1998)
CREAM-I (2004)
IMAX92 (1992)
JACEE (1979..1995)
MASS91 (1991)
RICH-II (1997)
RUNJOB (1995..1999)
SOKOL (1984)
Grigorov
Akeno
MSU
KASCADE
Tibet
KASCADE-Grande
IceTop73
HiRes1&2
TA2013
Auger2013
Model H4a
CREAM all particle
protons only
all-particle
electrons
positrons
antiprotons
Fixed target
HERA
RHIC
TEVATRON
LHC
$E^2 dN/dE$ (GeV cm^{-2}sr^{-1}s^{-1})
E_{tot} (GeV / particle)
AMS
2014: You are wrong!

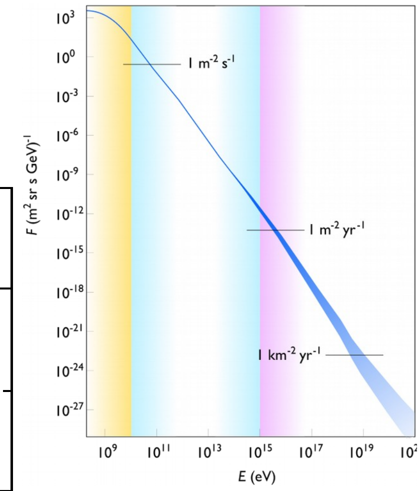


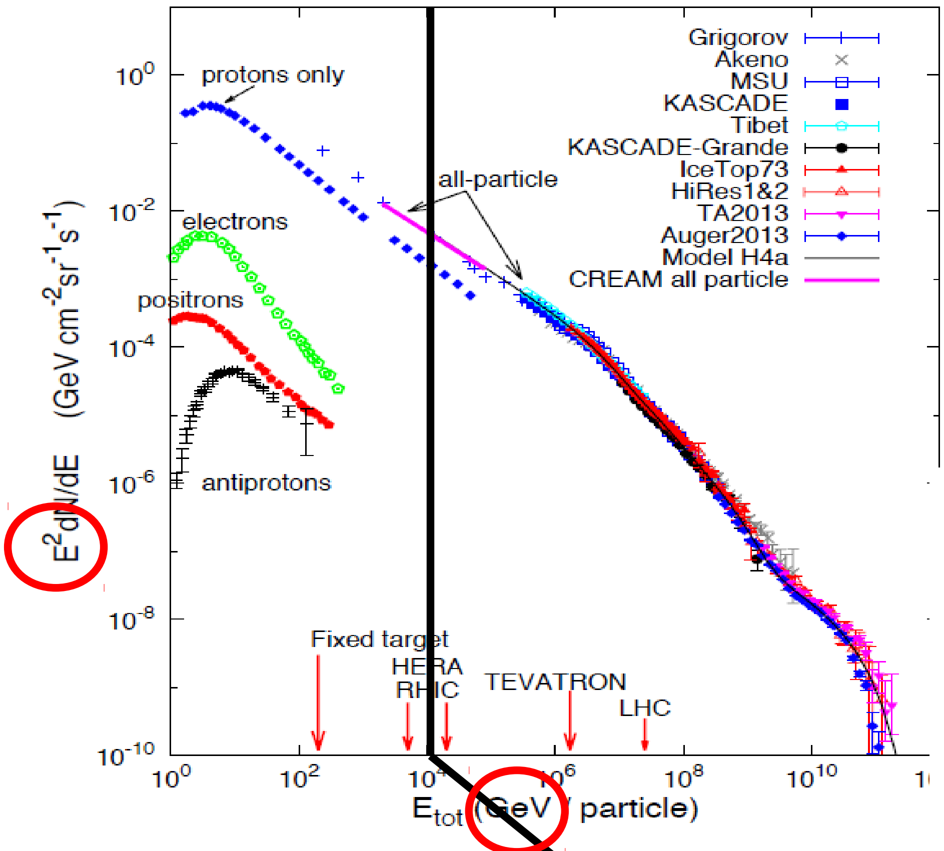
(a)
AMS-02
Flux × R̃^2.7 [m^-2sr^-1sec^-1 GV^1.7]
Rigidity [GV]
(b)
AMS-02
ATIC-2
BESS-Polar II
CREAM
PAMELA
Flux × E_K^2.7 [m^-2sr^-1sec^-1GeV^1.7]
Kinetic Energy (E_K) [GeV]
protons only
electrons
positrons
antiprotons
all-particle
Grigorov
Akeno
MSU
KASCADE
Tibet
KASCADE-Grande
IceTop73
HiRes1&2
TA2013
Auger2013
Model H4a
CREAM all particle
E^2dN/dE (GeV cm^-2sr^-1s^-1)
Fixed target
HERA
RHIC
TEVATRON
LHC
E_tot (GeV / particle)
AMS
2015: Oops, never mind...

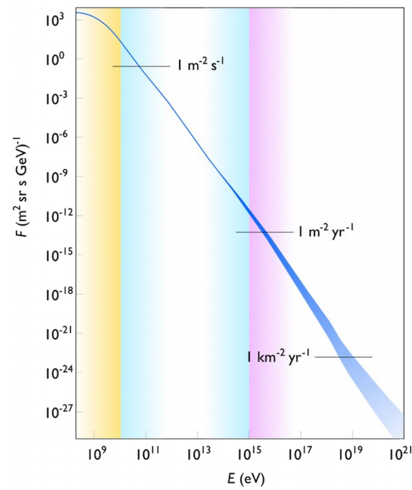
Direct



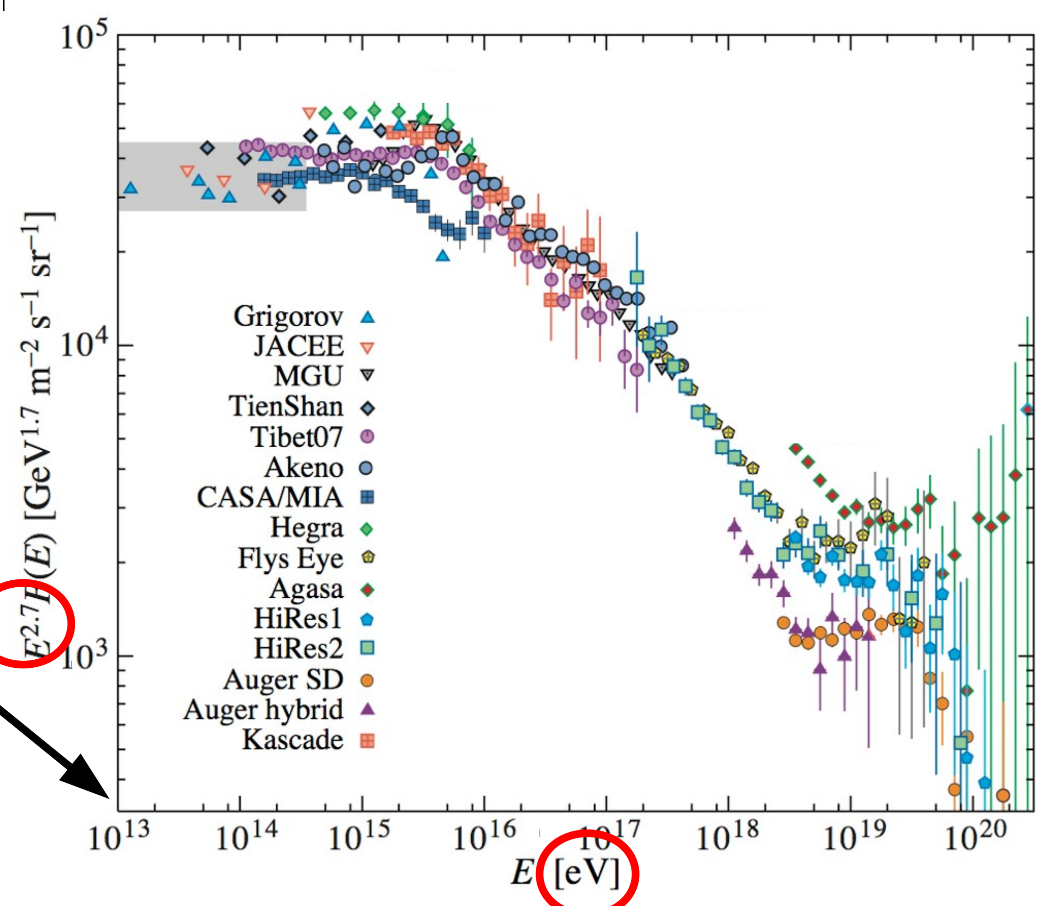
Source:
T. Gaisser



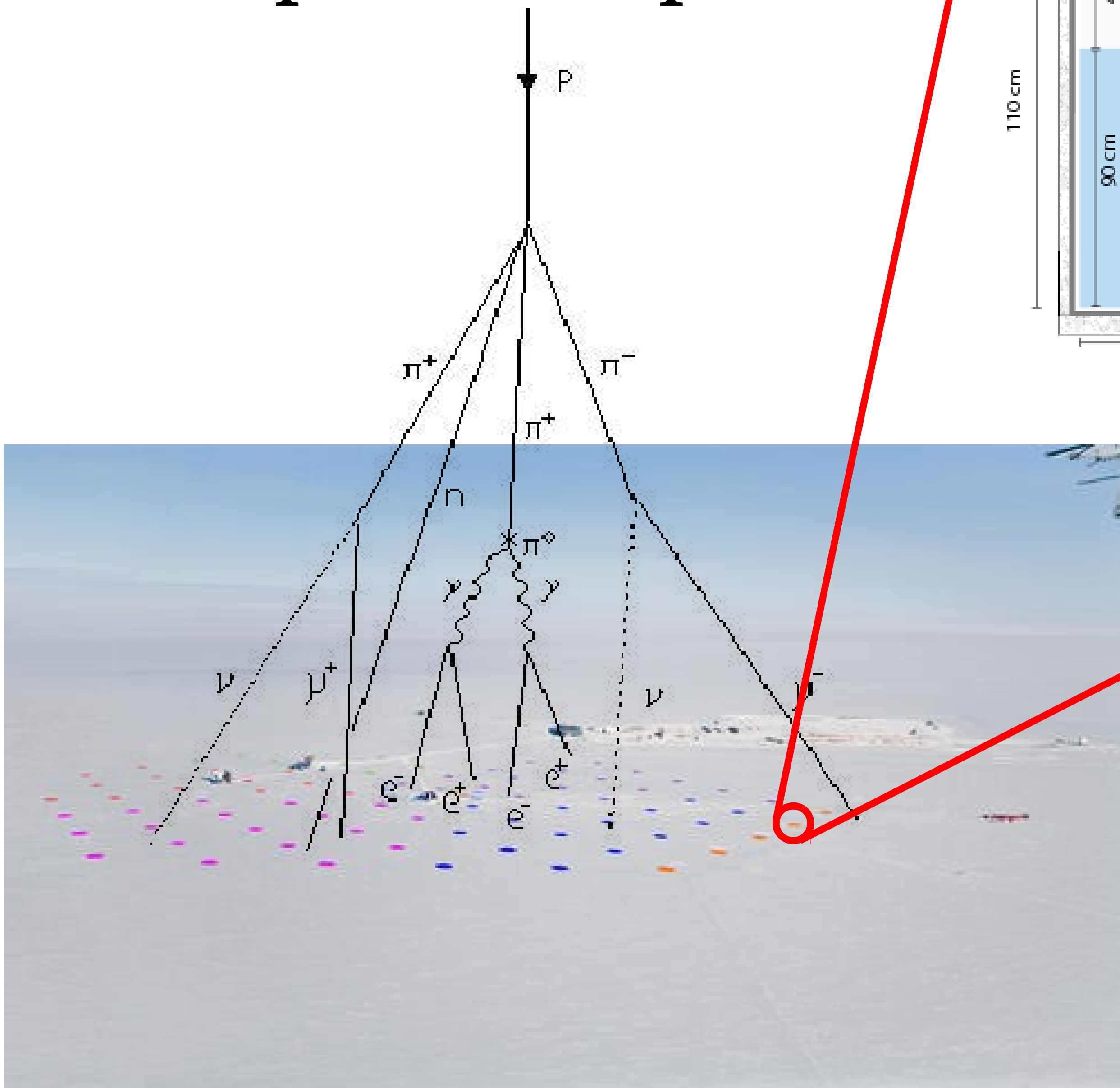


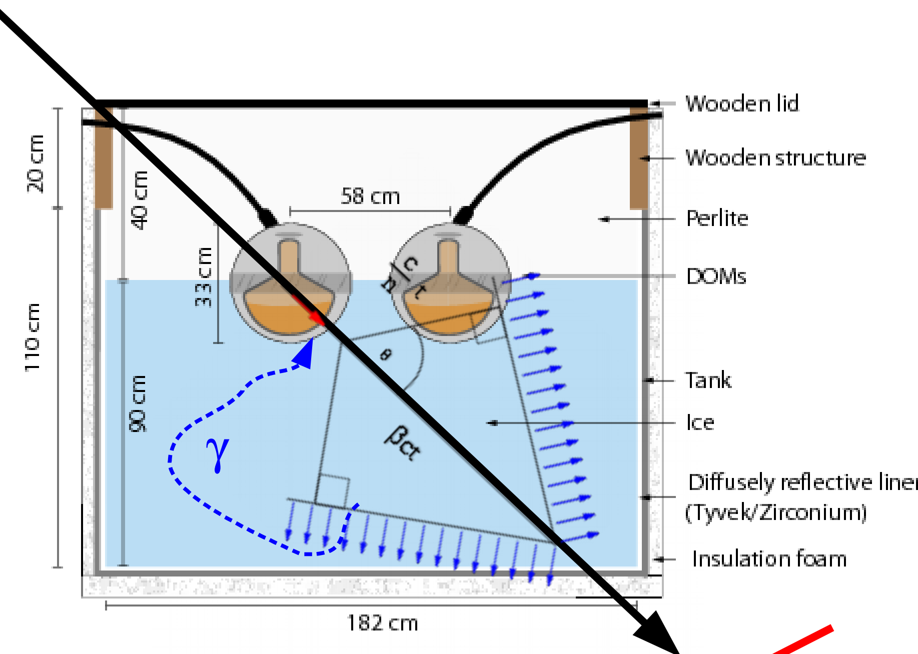


Above about 100 TeV, flux is too low for direct measurement!



Indirect Observation: Example IceTop





Nuclear Interactions

↓

Charged Particles

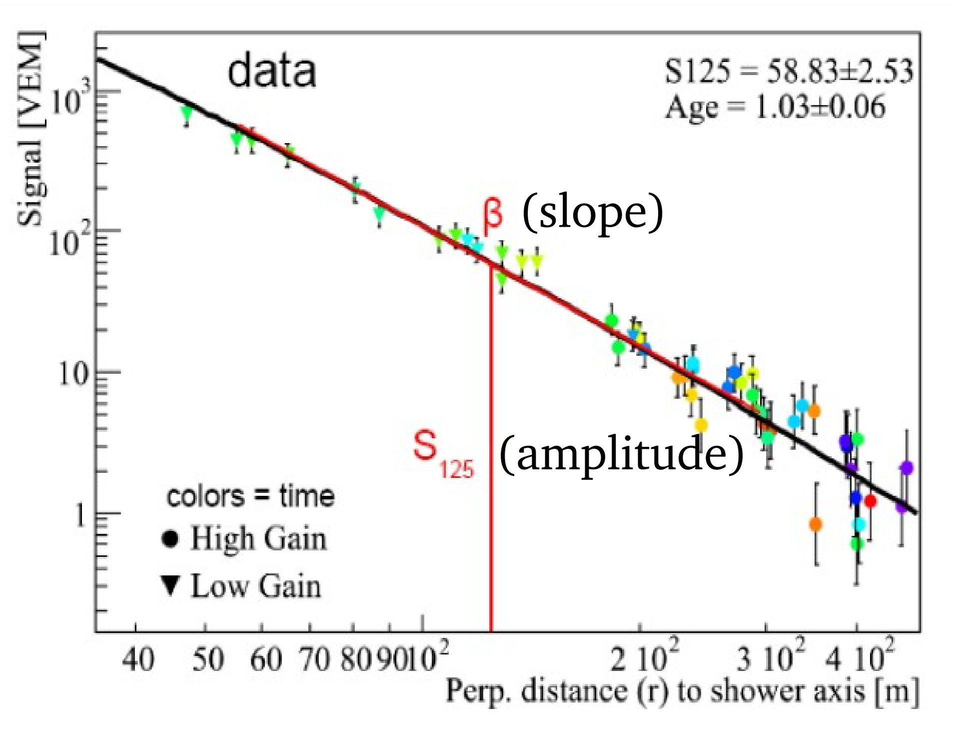
↓

Cherenkov Light

↓

Detector Signal

Indirect Observation: Example IceTop



Lateral shower profile at 125m

$$S(r) = S_{125}\left(\frac{r}{125m}\right)^{-\beta-\kappa\log_{10}\left(\frac{r}{125m}\right)}$$

S_{125} : signal at r = 125m

β : slope at r = 125m

κ = 0.303 fixed

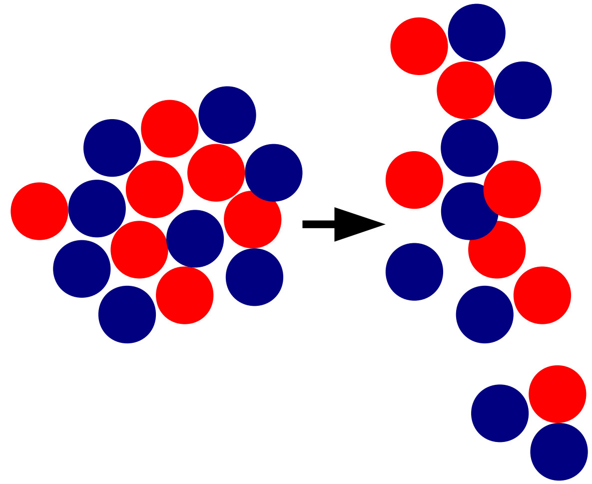
arXiv: 0711.0353

Primary Energy:

$E_{prim} = f(S_{125}, \theta_{zen})$

"Double-Logarithmic Parabola": Simulation-derived empirical description

Heavy Primary Nucleus



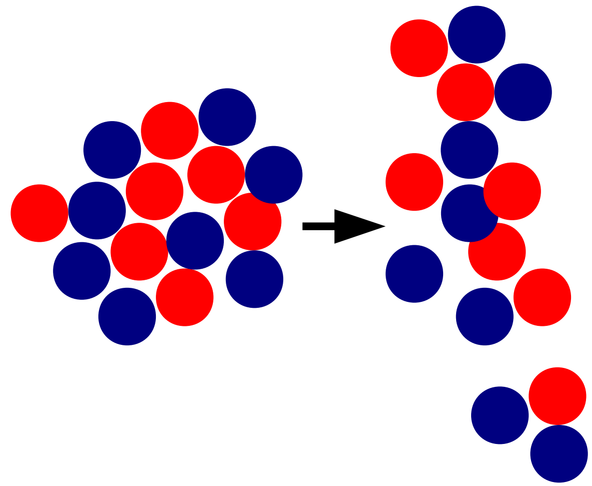
Early fragmentation in upper atmosphere

Indirect Observation: Elemental Composition

Proton Primary

“Punches through” to denser atmosphere

Heavy Primary Nucleus

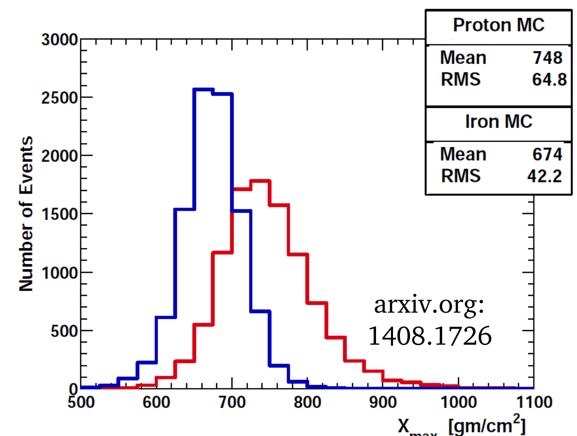


Early fragmentation in upper atmosphere

Proton Primary

Shower Maximum

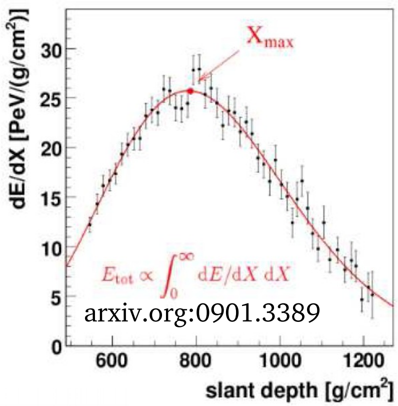
"x_{max}" [g/cm^2]

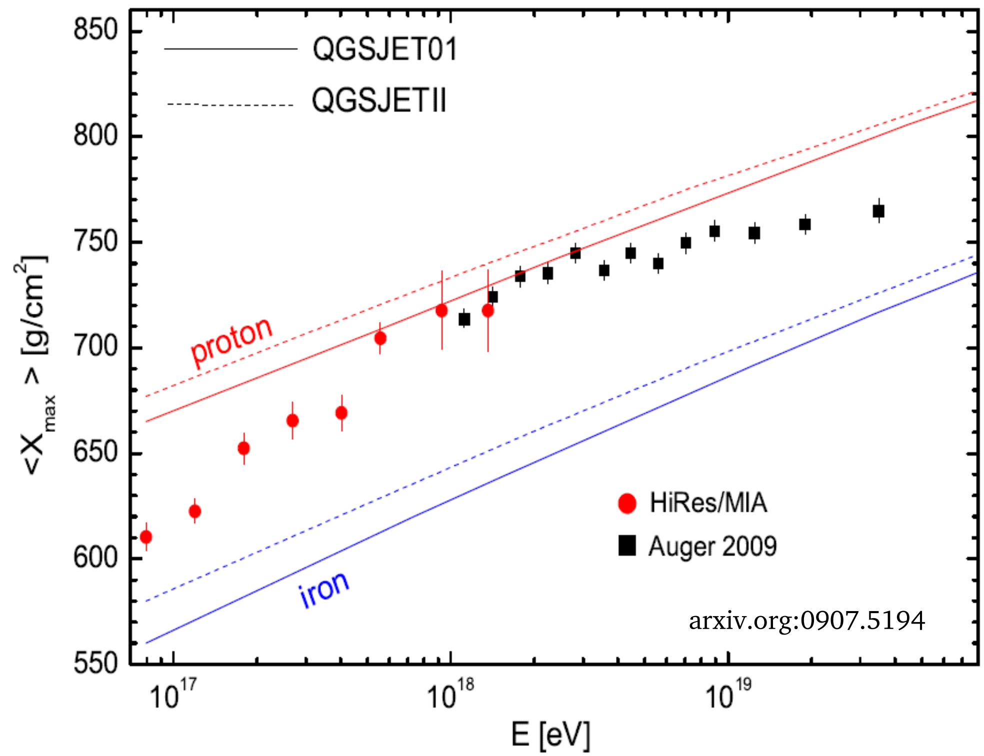


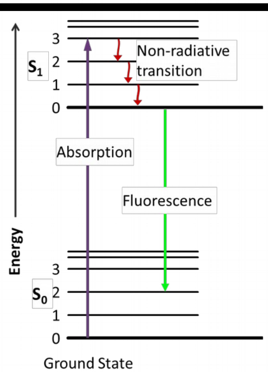
Simulated Data, $E_{prim} > 10^{18.2}$ eV

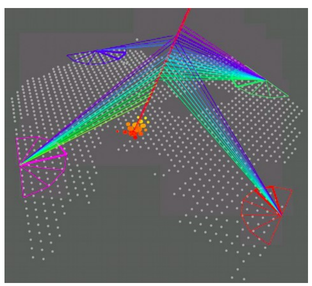
"Punches through" to denser atmosphere

Shower Maximum: Composition

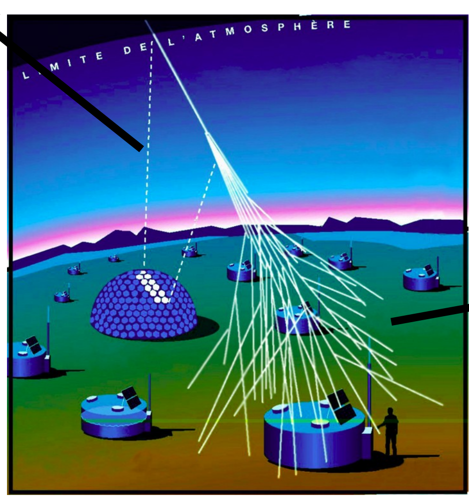




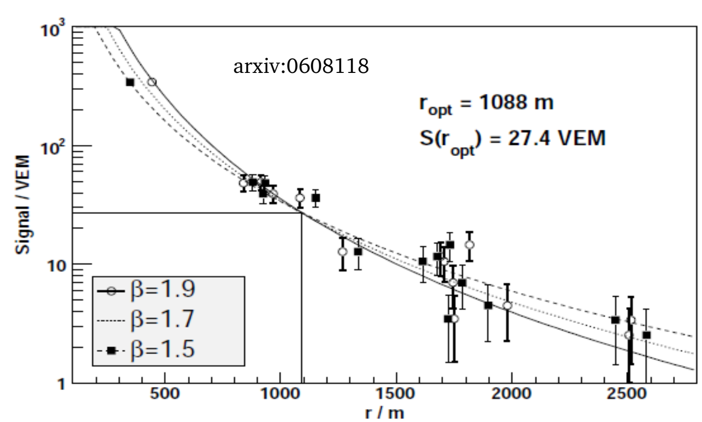




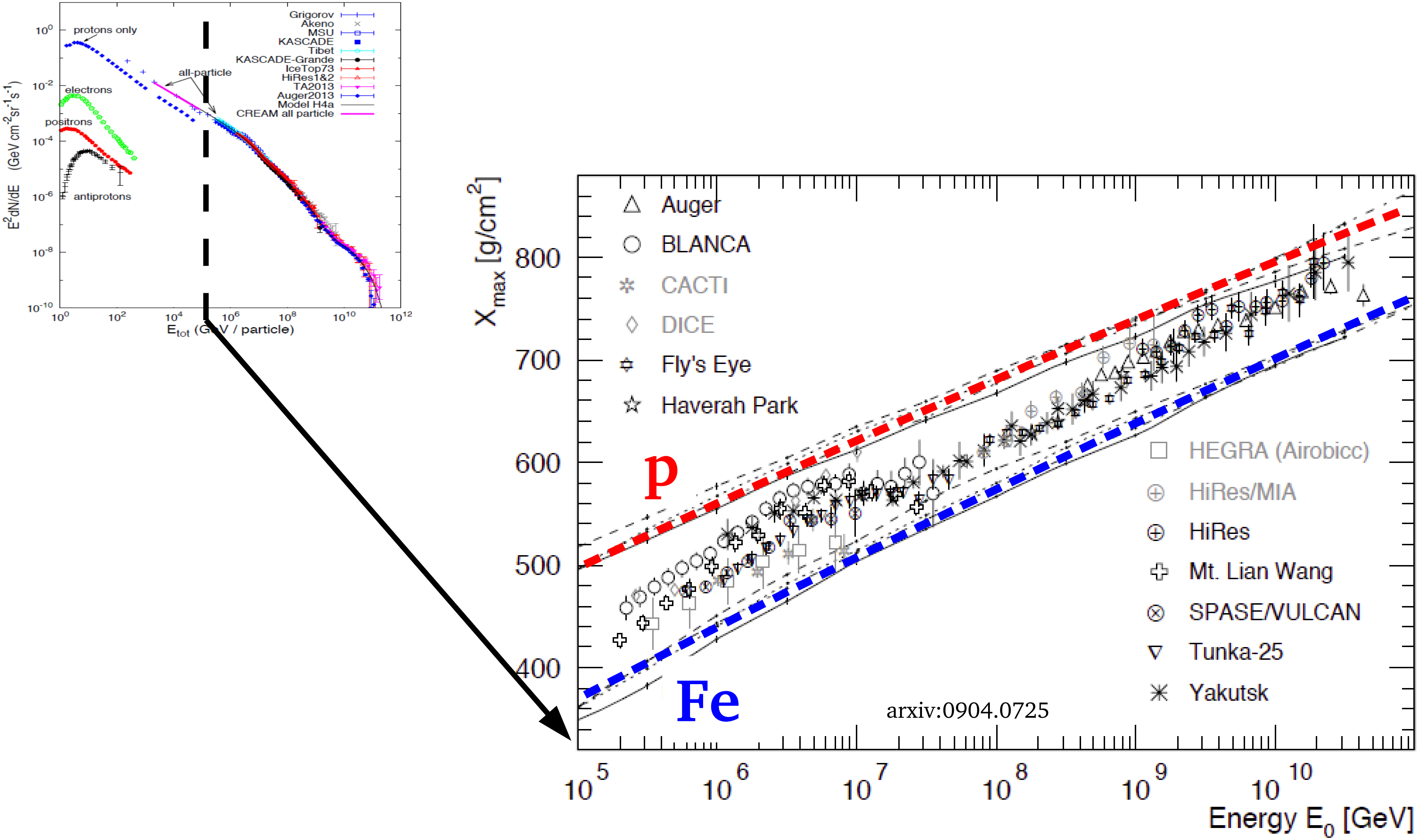
Atmospheric Fluorescence



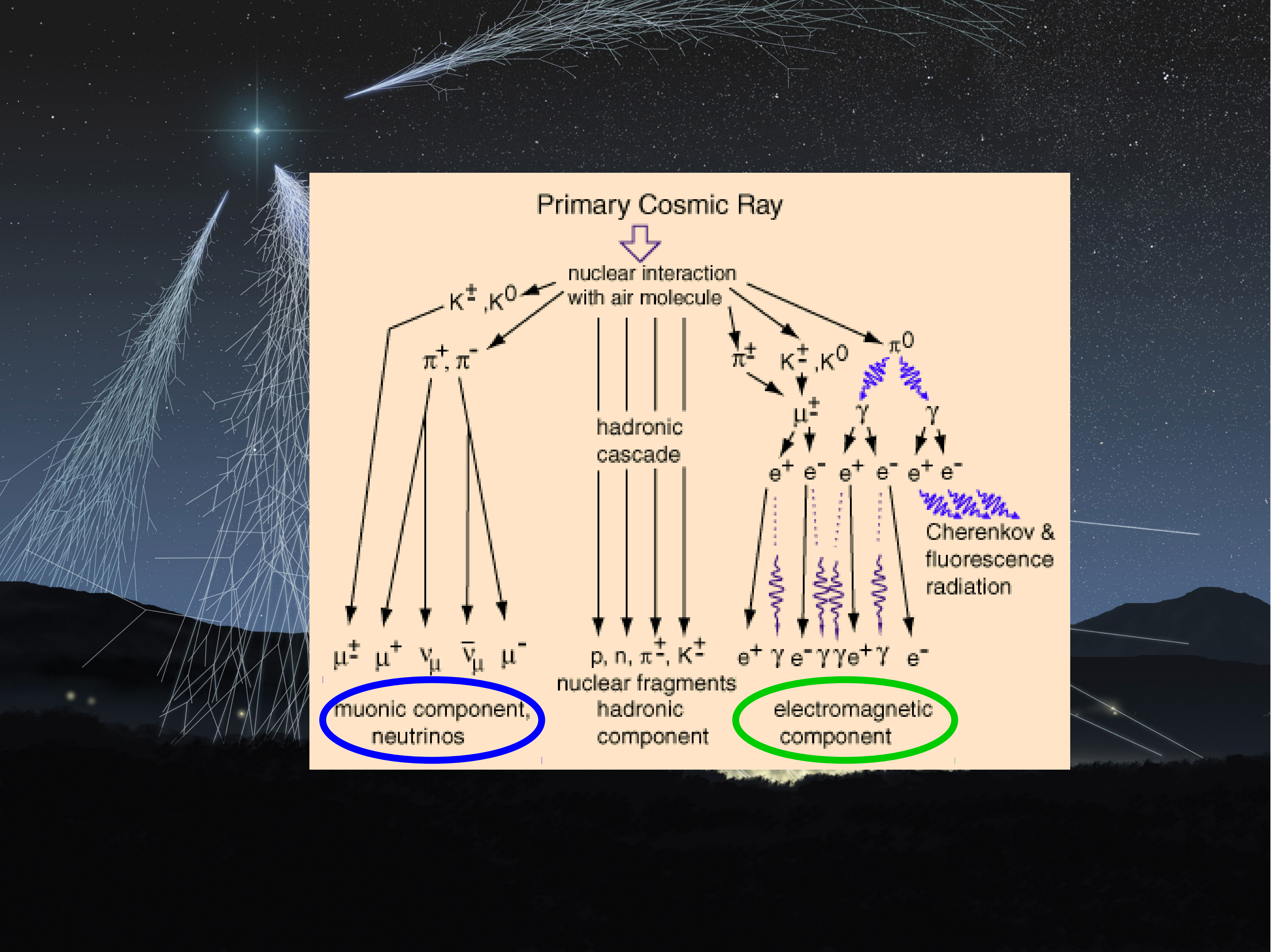
Lateral Extension: Energy



$$S = k \left(\frac{r}{r_s}\right)^{-\beta} \left(1 + \frac{r}{r_s}\right)^{-\beta}$$



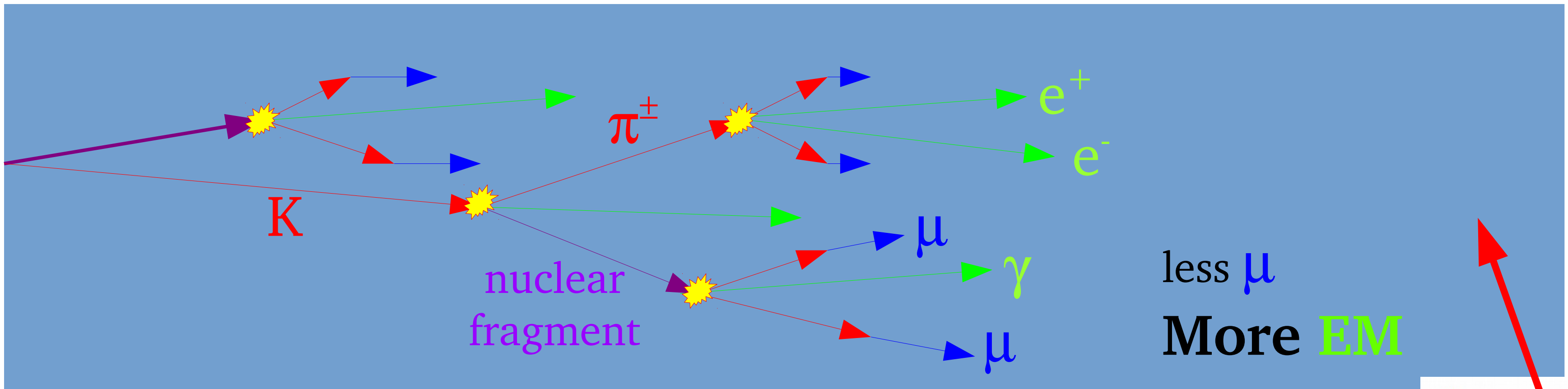
CR Primary Composition with Shower Maximum Measurement

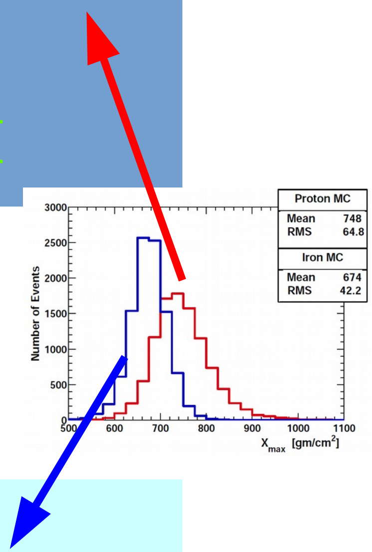


Primary Cosmic Ray
nuclear interaction with air molecule
K±, K0
π+, π-
hadronic cascade
π±
K±, K0
π0
μ±
γ
γ
e+ e- e+ e- e+ e-
Cherenkov & fluorescence radiation
μ± μ+ νμ ν̄μ μ-
p, n, π±, K±
nuclear fragments
hadronic component
e+ γ e- γ γ e+ γ e-
muonic component, neutrinos
electromagnetic component

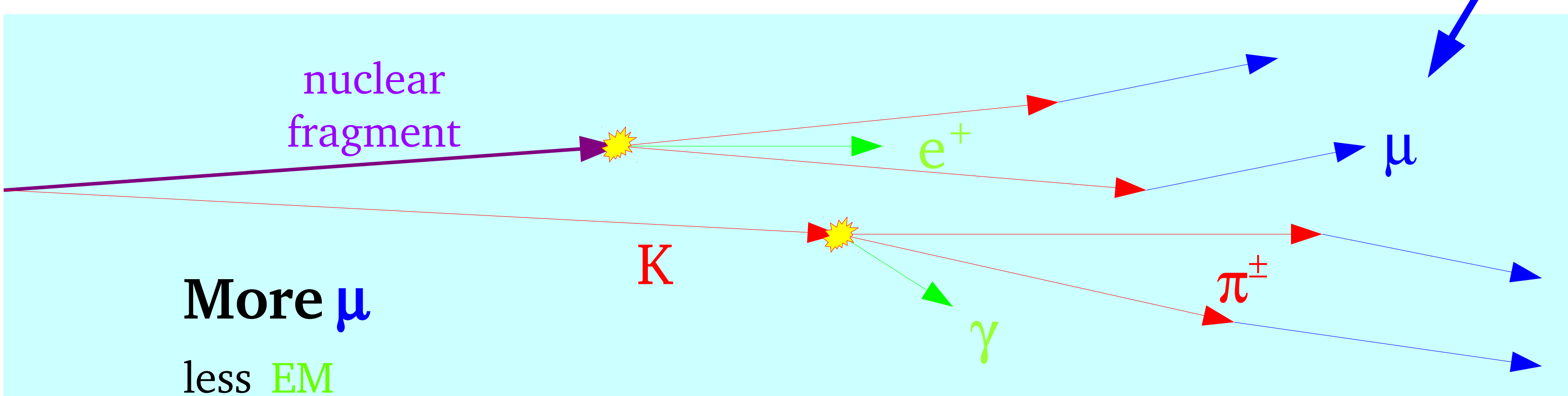
Muonic vs. Electromagnetic

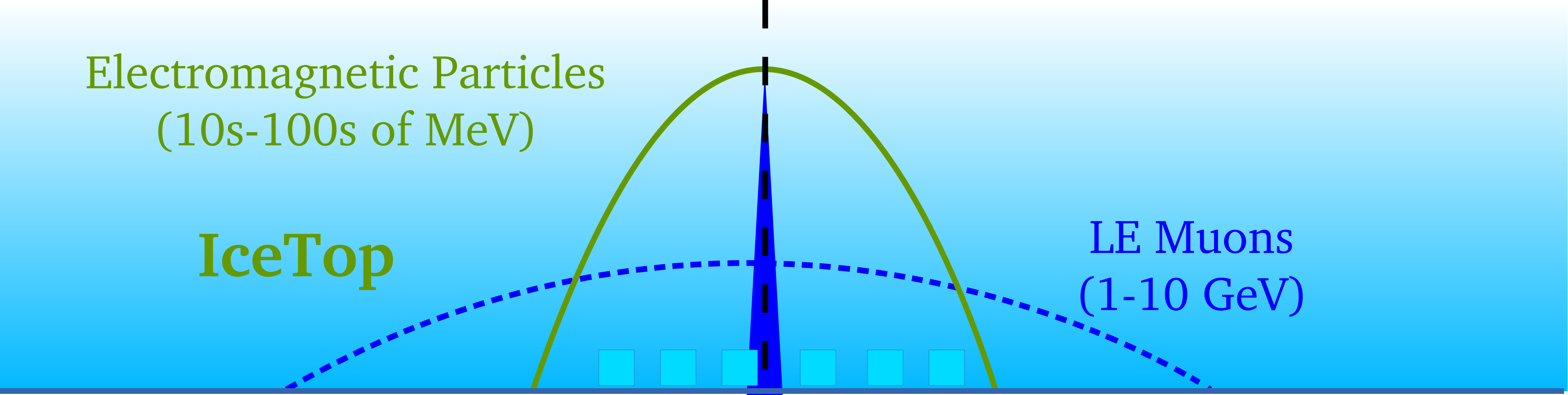
Dense air: short mean free path, **more reinteractions** , fewer meson decays



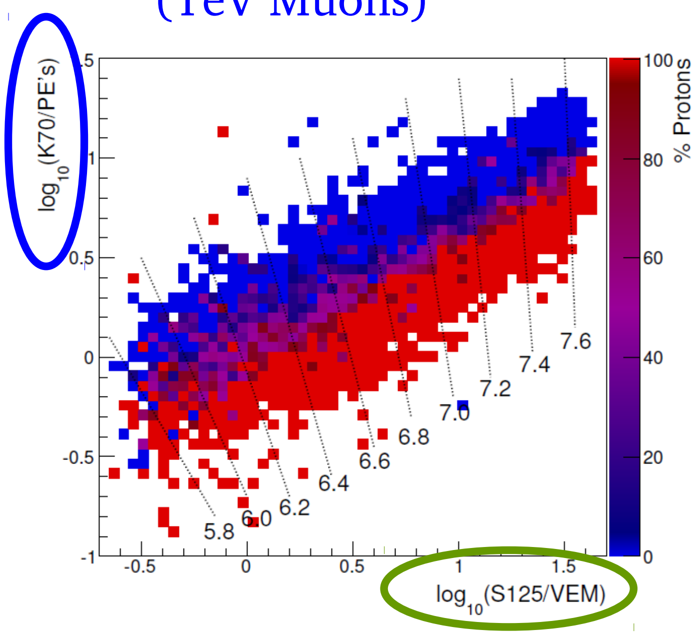


Thin air: long mean free path, fewer reinteractions , **more meson decays**

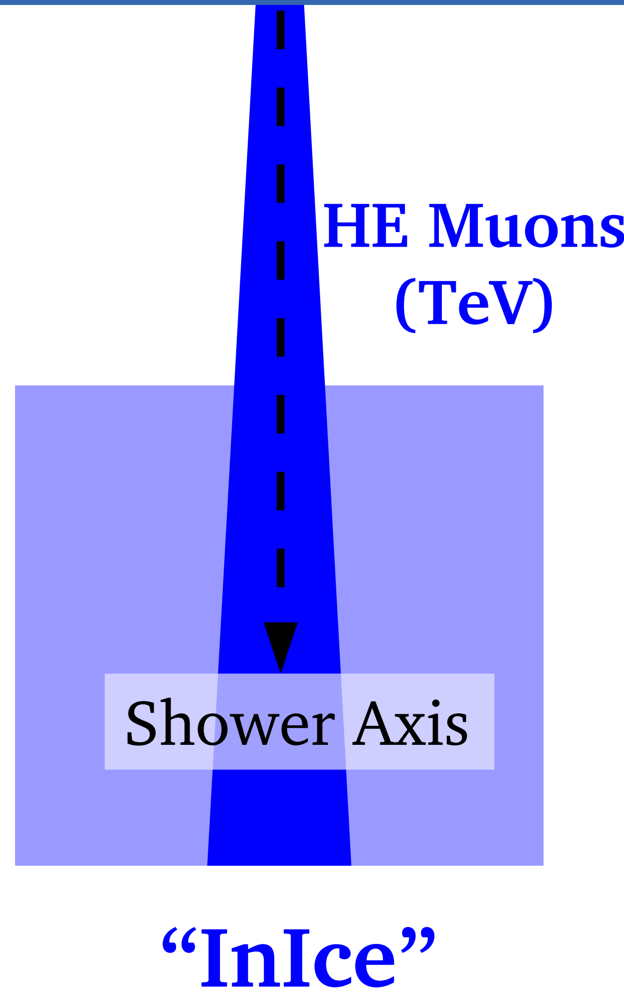




Deep (2km) Measurement
(TeV Muons)



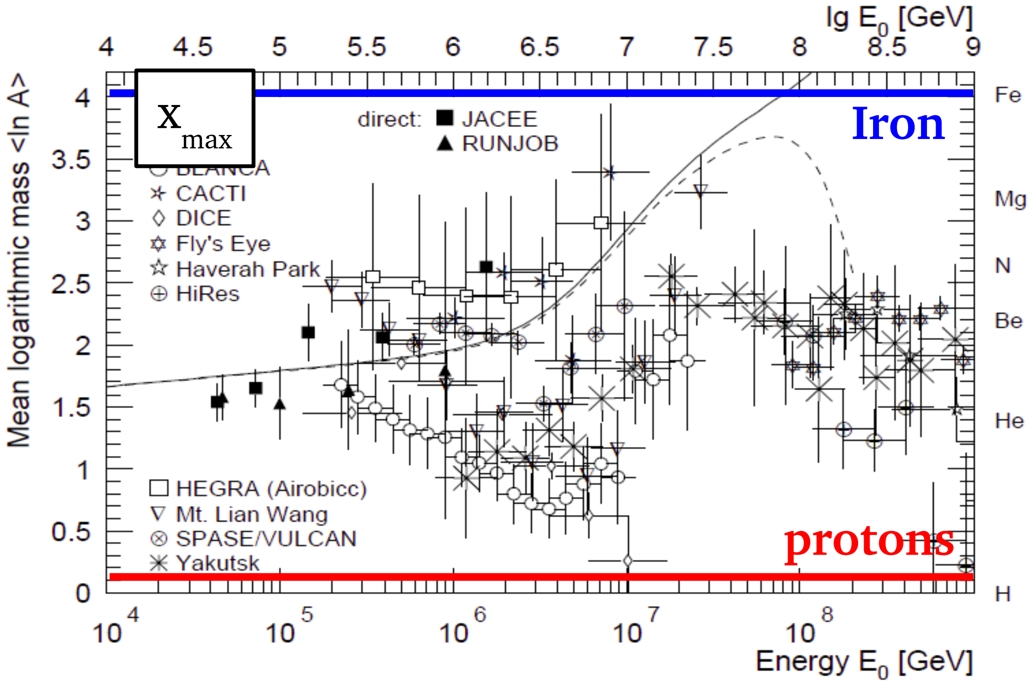
Surface Measurement
(electromagnetic)

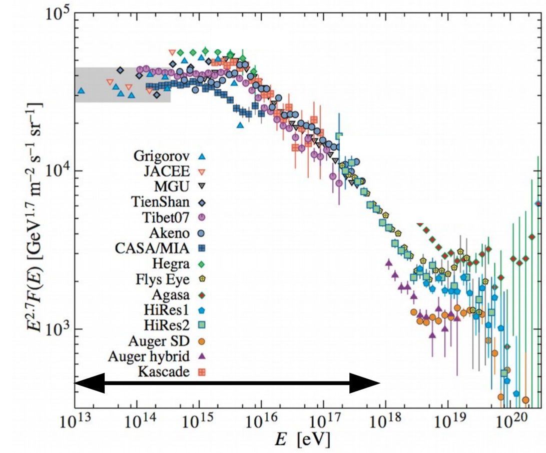


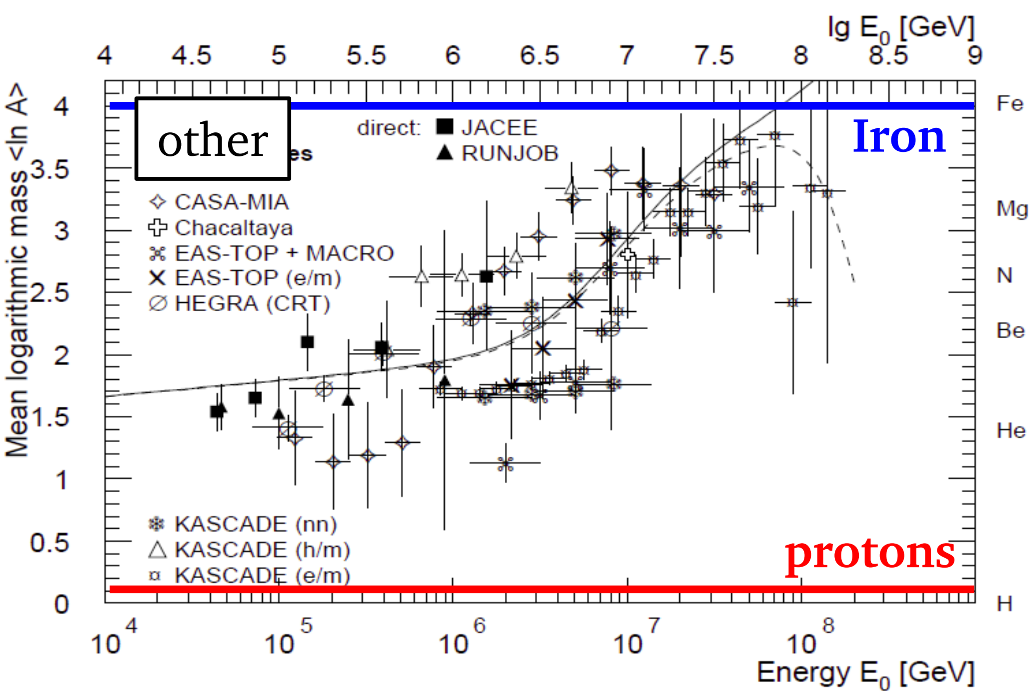
Ratio of EM particles to muons depends on primary type

Heavy: +mu -EM
Light: -mu +EM

≈2.5x more muons in Fe showers than p

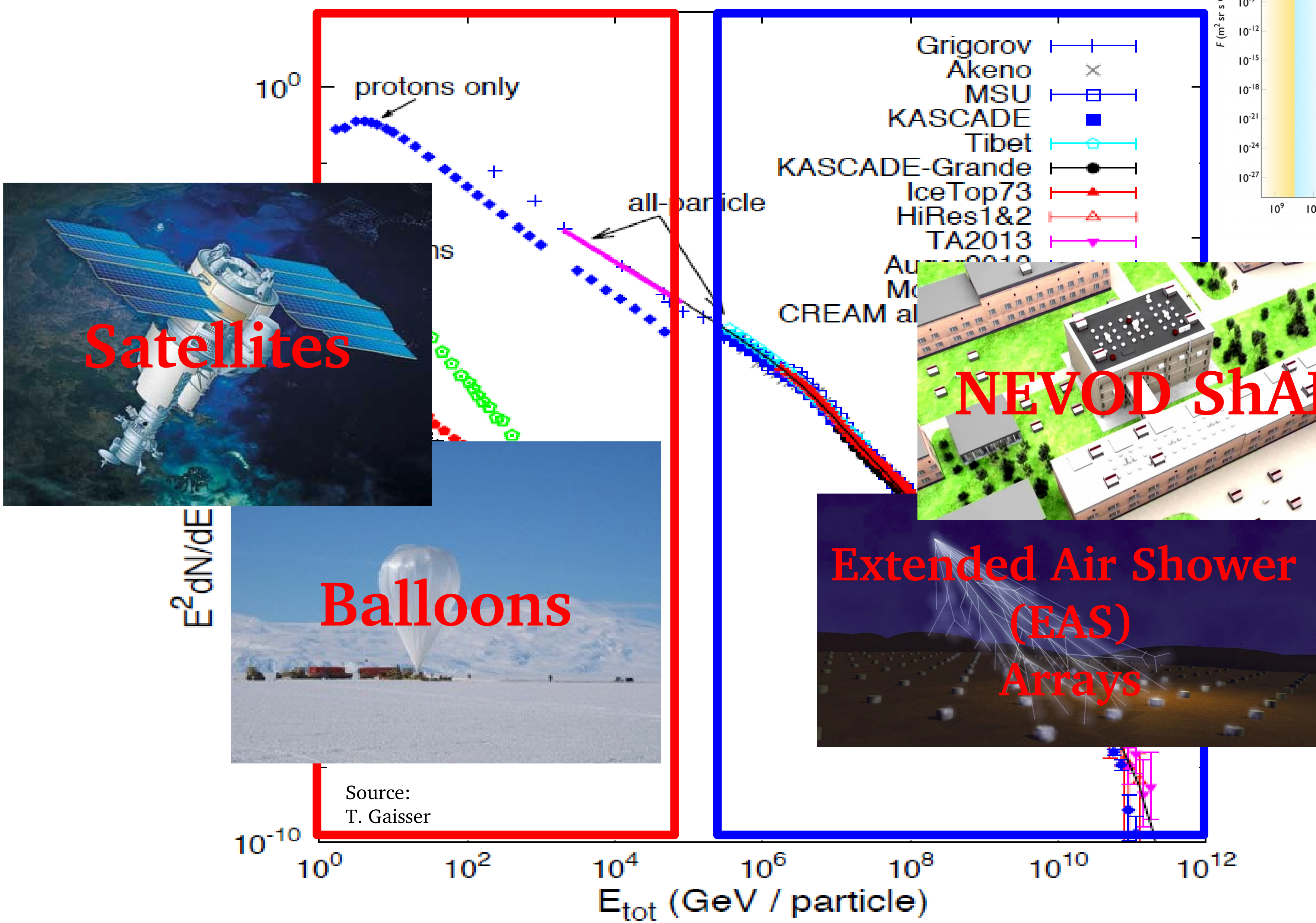


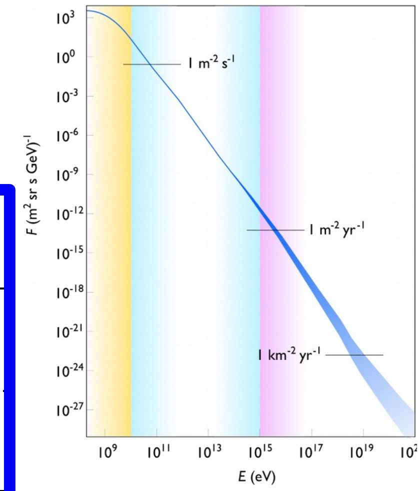


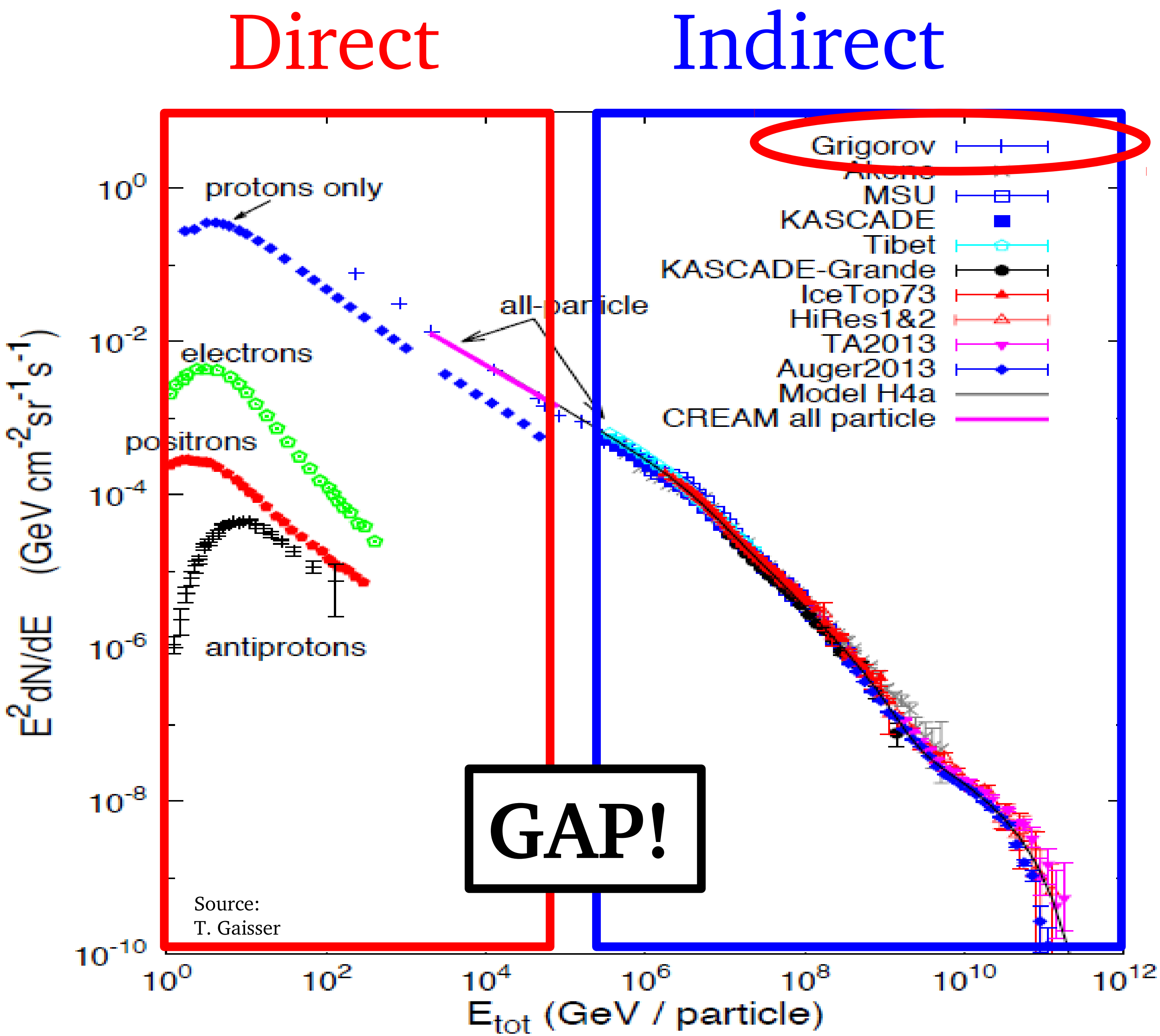


Measurements are not always consistent!

Direct Indirect






Direct
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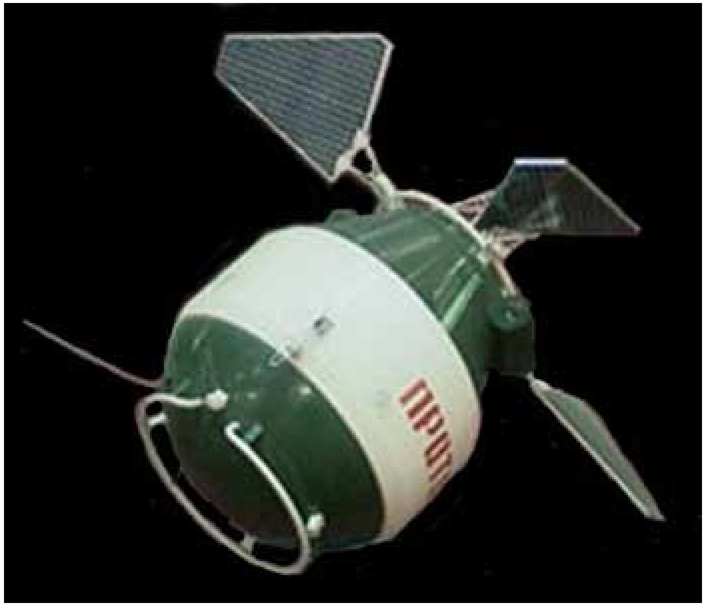
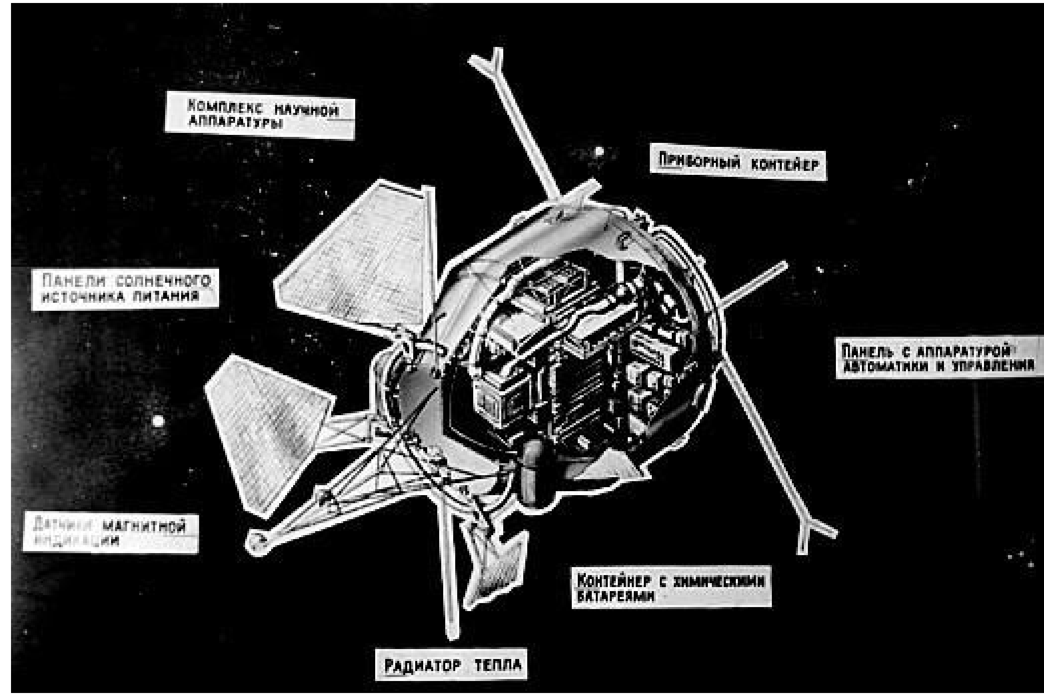
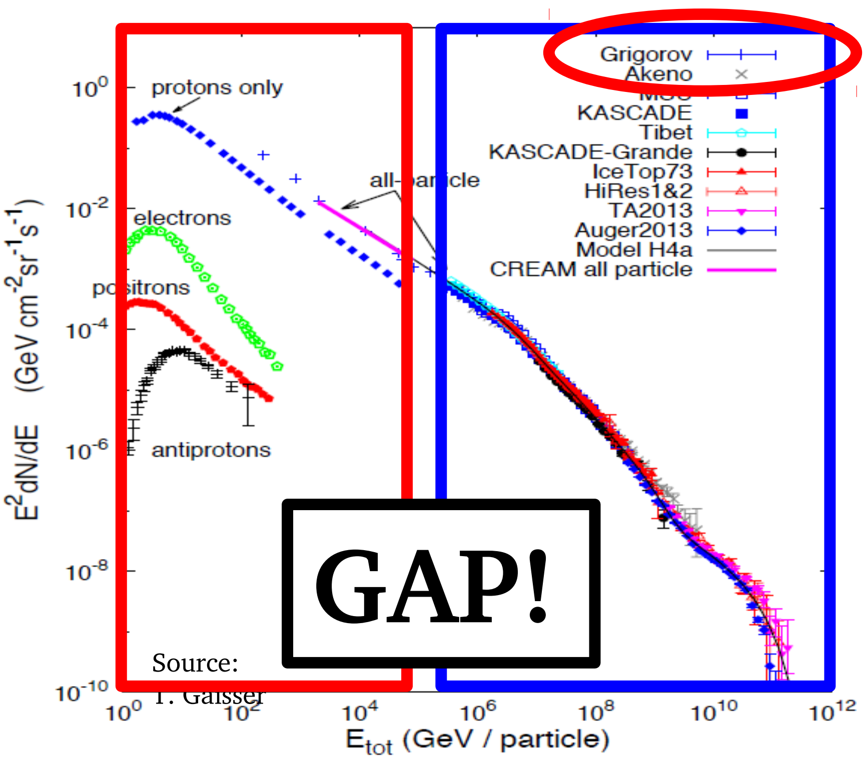


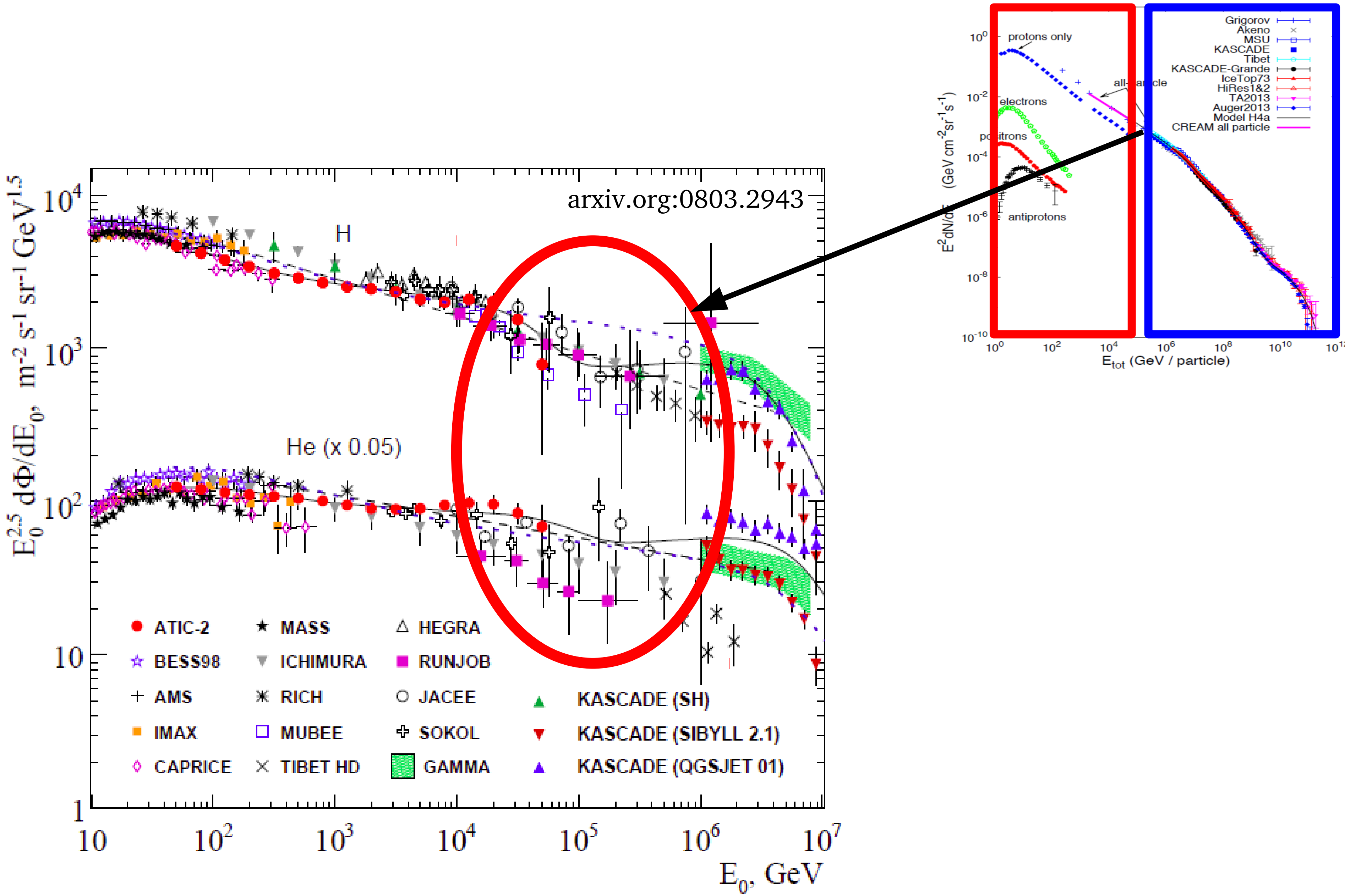




“Proton” Satellites (1-3,4)

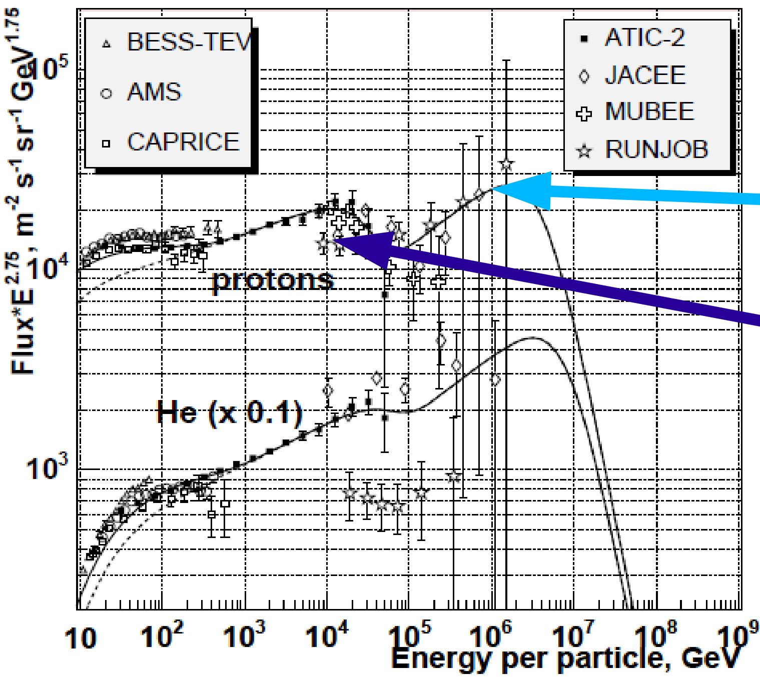
Launched between 1965 and 1968

Proton 4: Most Massive Scientific Satellite Ever (17t)



arxiv.org:0803.2943
H
He (x 0.05)
$E_0^{2.5}\,d\Phi/dE_0$, $m^{-2}\,s^{-1}\,sr^{-1}\,GeV^{1.5}$
E_0, GeV
ATIC-2
BESS98
AMS
IMAX
CAPRICE
MASS
ICHIMURA
RICH
MUBEE
TIBET HD
HEGRA
RUNJOB
JACEE
SOKOL
GAMMA
KASCADE (SH)
KASCADE (SIBYLL 2.1)
KASCADE (QGSJET 01)
protons only
electrons
positrons
antiprotons
all-particle
Grigorov
Akeno
MSU
KASCADE
Tibet
KASCADE-Grande
IceTop73
HiRes1&2
TA2013
Auger2013
Model H4a
CREAM all particle
E^2dN/dE (GeV $cm^{-2}sr^{-1}s^{-1}$)
E_{tot} (GeV / particle)

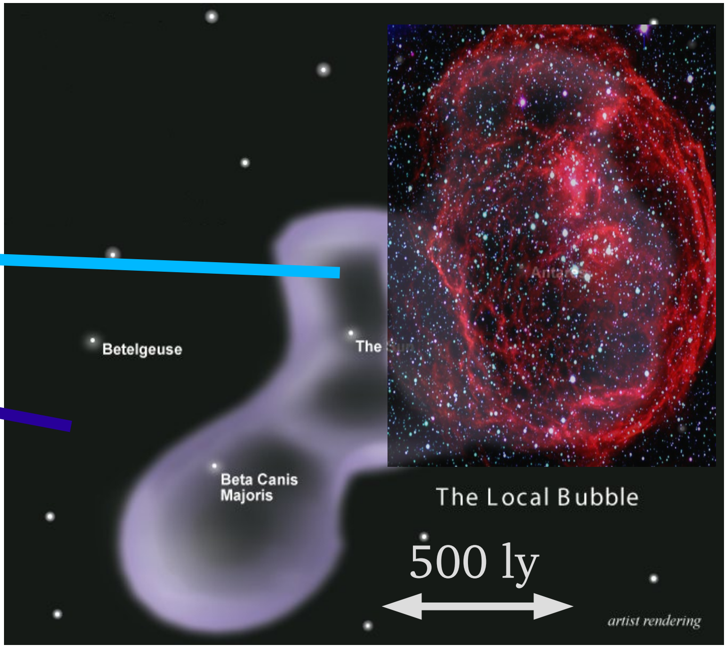
Two, Three, Many Populations?



astro-ph/0601475

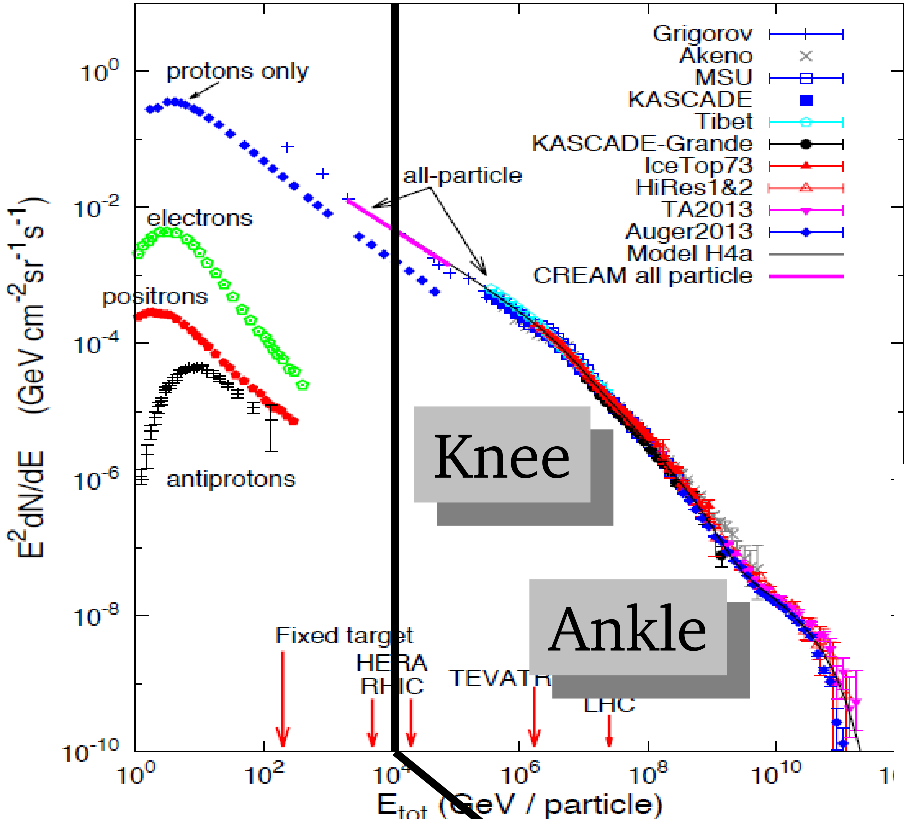
Table 2. Parameters for three classes of sources. Class I: SN into ISM; class II: SN in the Superbubble, class III: Novae.

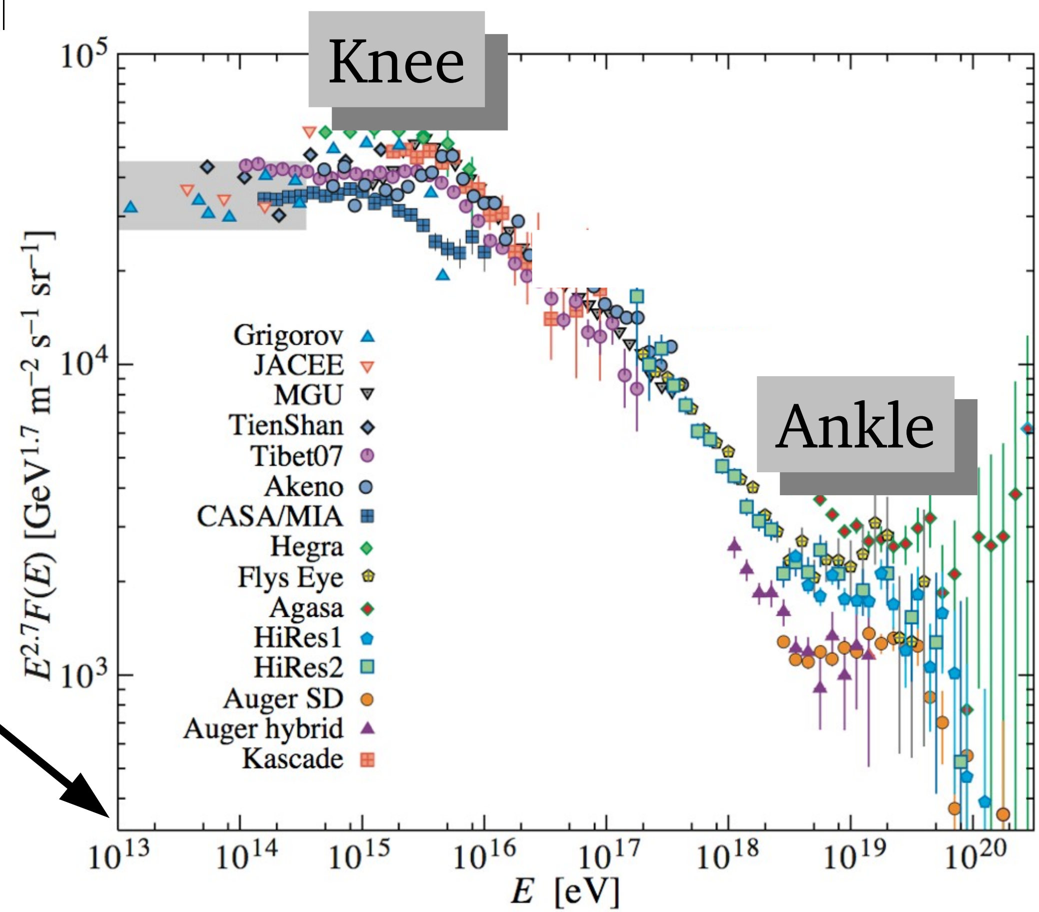
Class	α	$R_{max}[GV]$	γ	γ_k
I	2.3	5×10^4	2.63	8
II	2.1	4×10^6	2.43	4.5
III	2.57	2×10^2	2.9	4.5



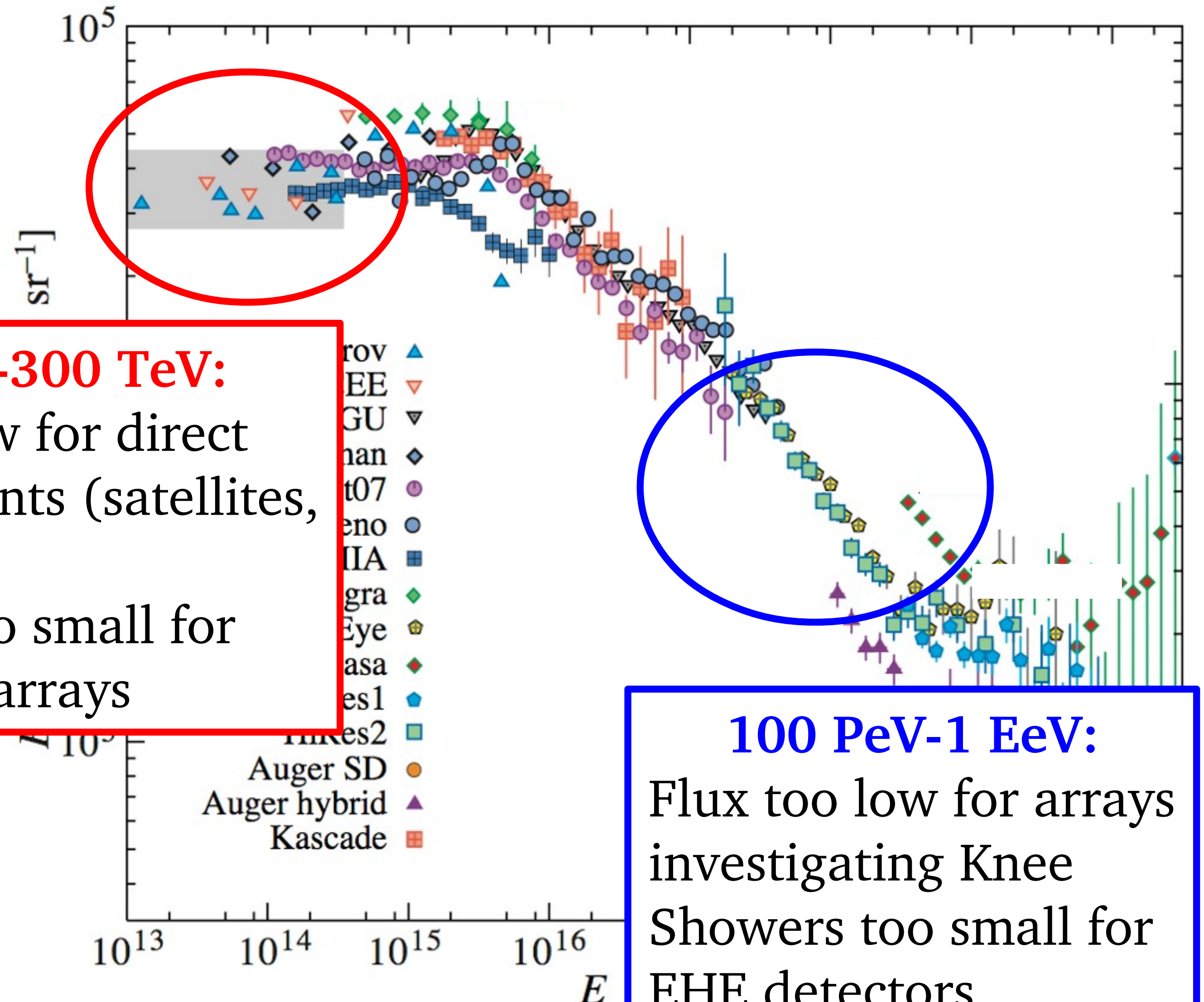
Proposal by Zatsepin and Sokolskaya:
Supernovae inside and outside
of "Local Superbubble"
(Caused by Supernova about 10 My ago)

Air Shower Arrays:
Detectors usually optimized for either Knee (EHE, 10^{15} eV) or Ankle (UHE, 10^{18} eV) region!





CR Measurement Gaps



30 TeV-300 TeV:

Flux too low for direct measurements (satellites, balloons)

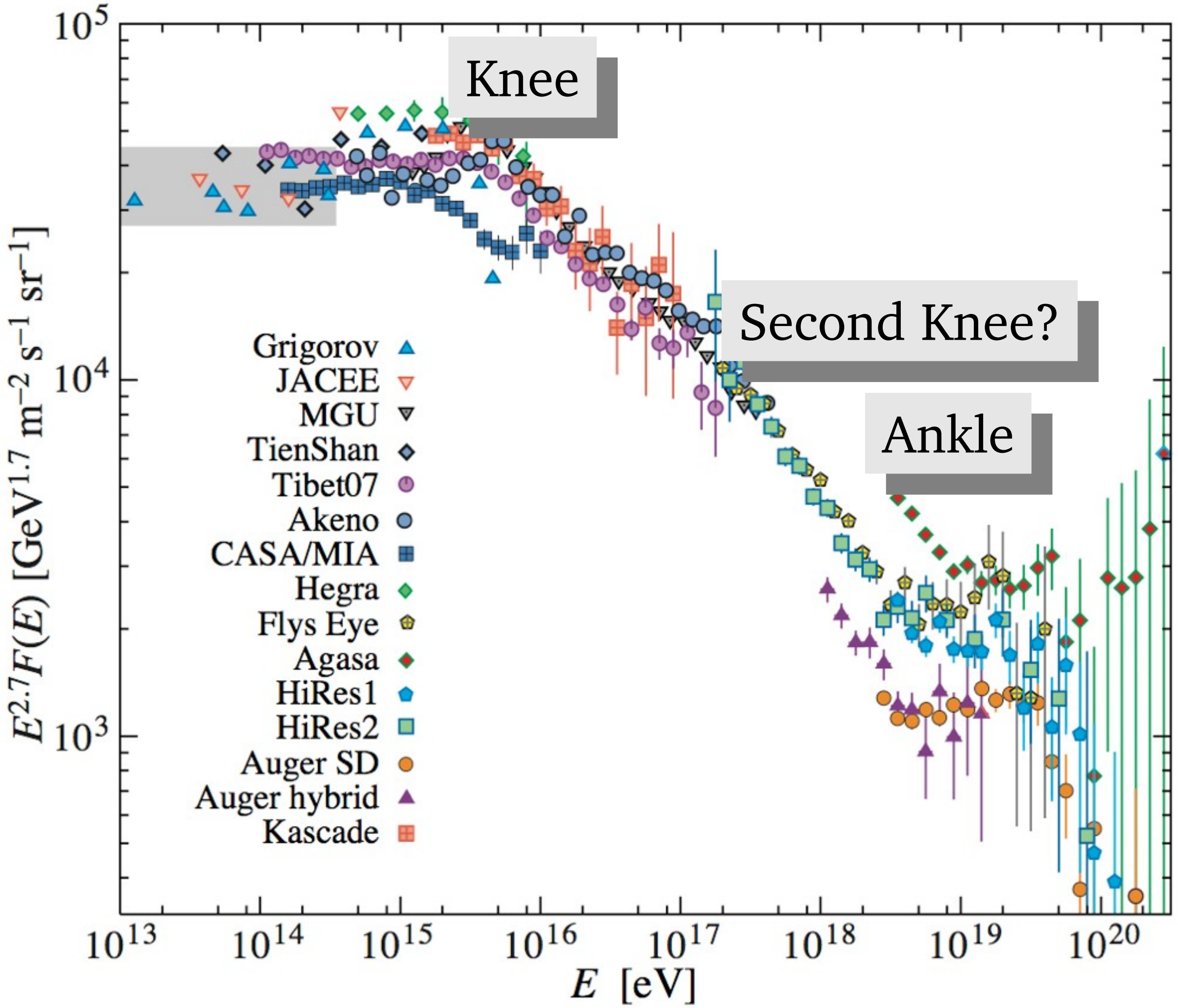
Showers too small for air shower arrays

100 PeV-1 EeV:

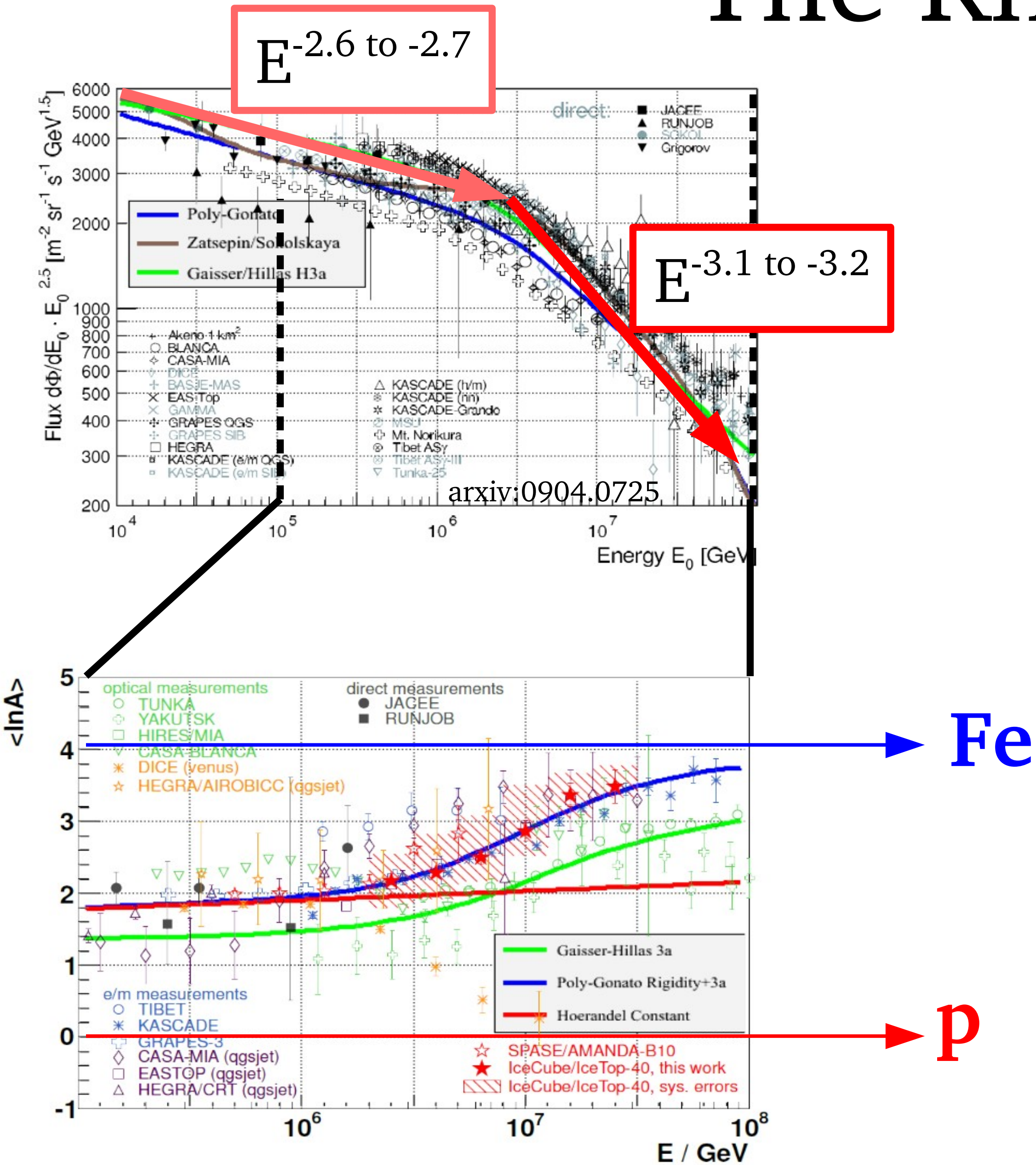
Flux too low for arrays investigating Knee

Showers too small for EHE detectors

CR Spectrum Features



The Knee



I. Steepening of CR Spectrum

II. Heavier Primary Composition

Primary Cosmic Radiation and Extensive Air Showers.

B. Peters

Institute for Theoretical Physics, University of Copenhagen - Copenhagen

(ricevuto il 19 Agosto 1961)

Irregularities which so far have found no adequate plausible explanation have been reported by various investigators at a shower size corresponding to a primary energy of about 10^{15} eV. Each of these observations seems to support the hypothesis that a rather sharp rigidity cut-off occurs in the source which supplies most cosmic ray particles below this energy.

Rigidity: E/Z

Resistance to deflection by magnetic field

All considered models with a (rigidity-dependent) knee are motivated by the fact that both acceleration and propagation in models involving collisionless diffusion in magnetized plasmas lead to the expectation of a rigidity-dependent cutoff for each individual component with a particle charge Z, $E_{\mathrm{cut},Z} \propto Z$ [32–36].

Example: "Poly-gonato" Model

Knee caused by sharp cutoff in individual components

Naturally explains composition change

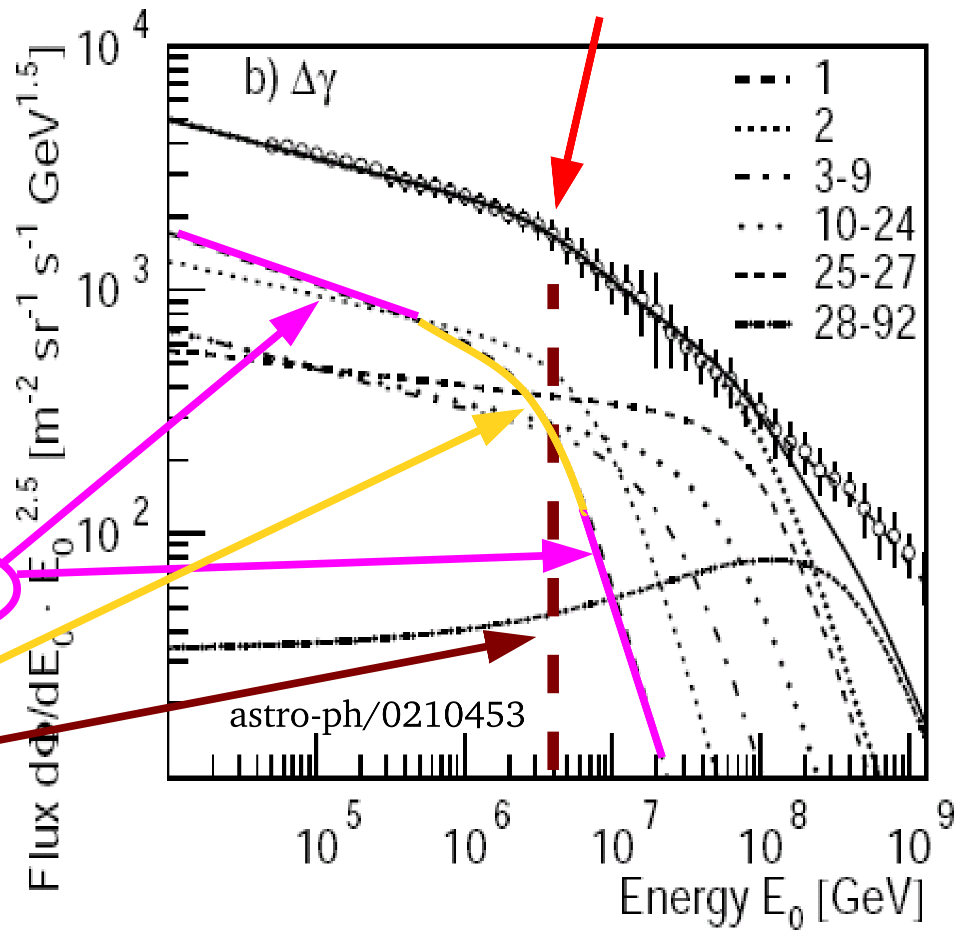
Smoothness of Transition

Slope Change

$$\frac{d\Phi_z}{dE_0} = \Phi_Z^0 \left[1 + \left(\frac{E_0}{E_{trans}} \right)^{\epsilon_c} \right]^{\frac{-\Delta\gamma}{\epsilon_c}}$$

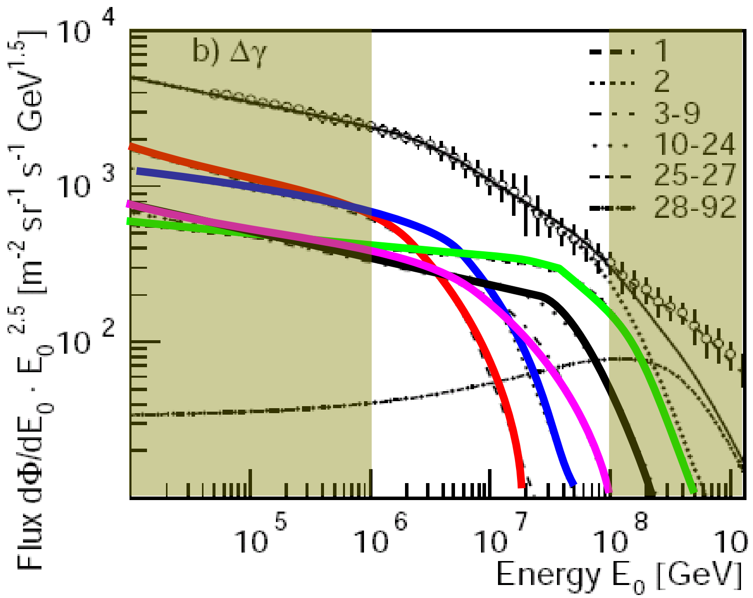
Transition Energy

CR-Knee

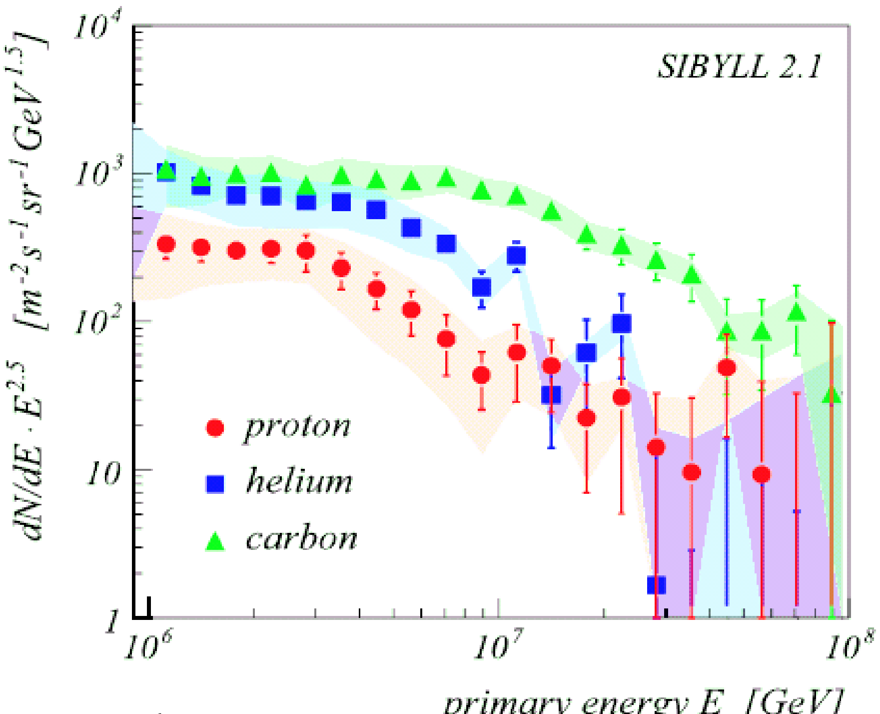


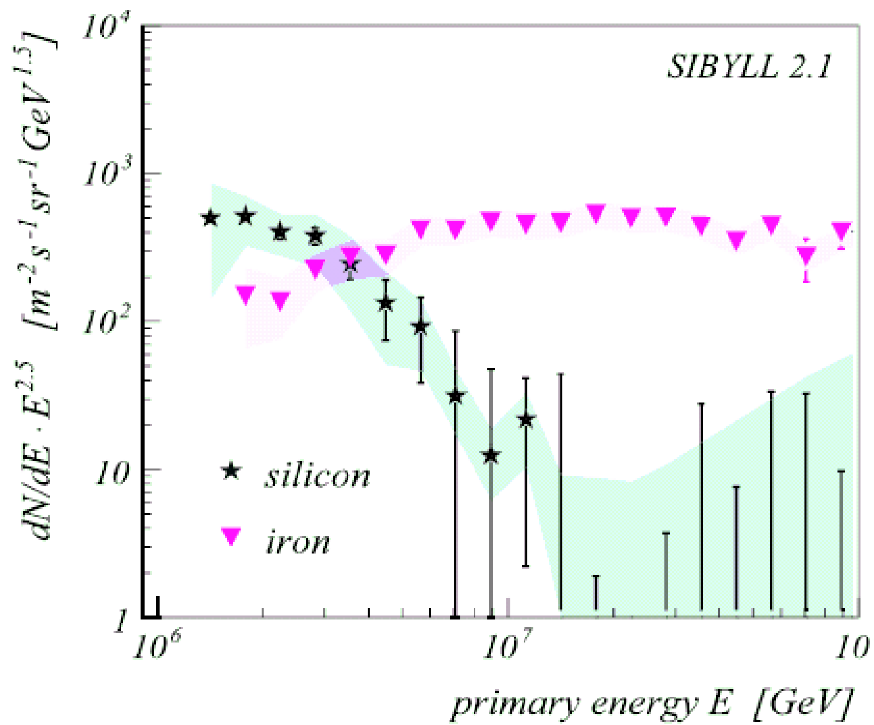
Primary composition becomes heavier

KASCADE Composition Measurement



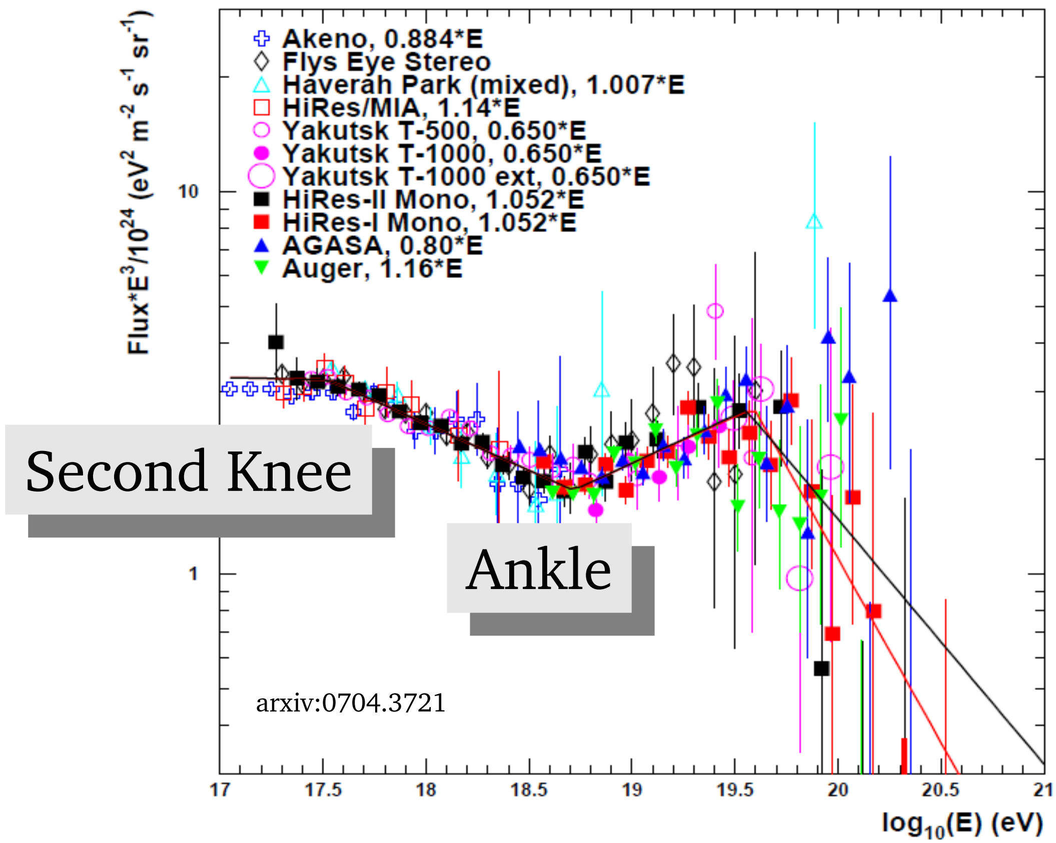
General picture more or less confirmed





astro-ph/0505413

The View from Above



Experiment ($reference$)	χ^2/DOF	Slope Below	Break Point $\log_{10}\left(\frac{E}{eV}\right)$	Slope Above
Akeno (Nagano et al. 1992)	8.3/13	3.04 ± 0.02	17.8 ± 0.2	3.25 ± 0.12
Fly's Eye (Bird et al. 1993)	13.7/18	3.04 ± 0.05	17.60 ± 0.06	3.27 ± 0.02
HiRes/MIA (Abu-Zayyad et al. 2001)	2.5/5	3.02	17.6 ± 0.2	3.23 ± 0.14
Haverah Park (Ave et al. 2003a)	1.4/5			3.32 ± 0.05
Yakutsk T-500 (Egorova et al. 2004)	45.2/15			3.213 ± 0.012
HiRes (Abbasi et al. 2007a)	8.55/15			3.26 ± 0.02
Global Fit (at Fly's Eye E scale)	109.4/93	3.02 ± 0.01	17.52 ± 0.02	3.235 ± 0.008

Compilation of EHE air shower array results

Measurements Re-Scaled for Consistency

2nd Knee: **17.5 (300 PeV)**
Ankle: **18.6 (4 EeV)**

“Traditional” Picture

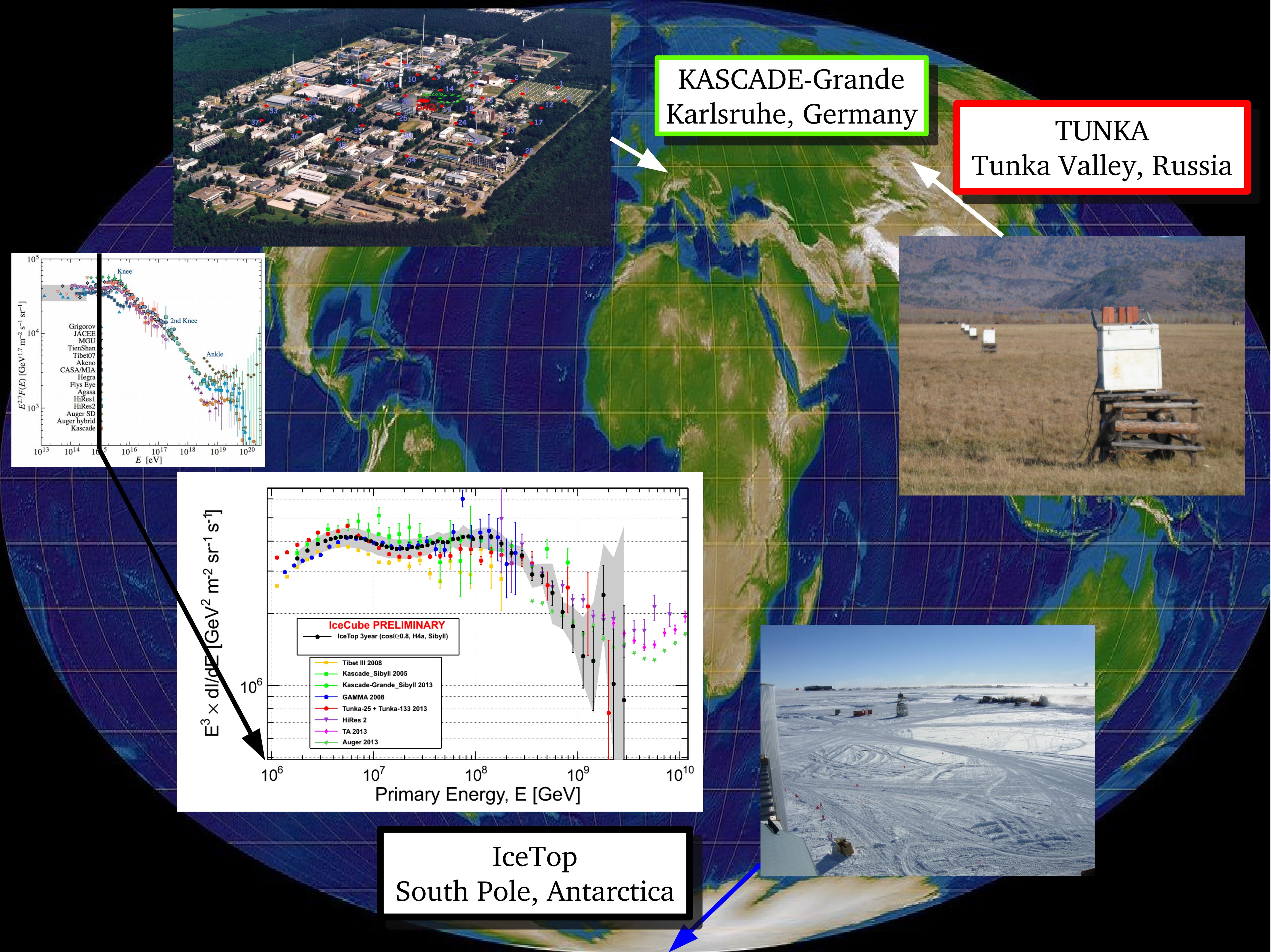
Knee: ≃4PeV

2ndKnee: ≃300PeV

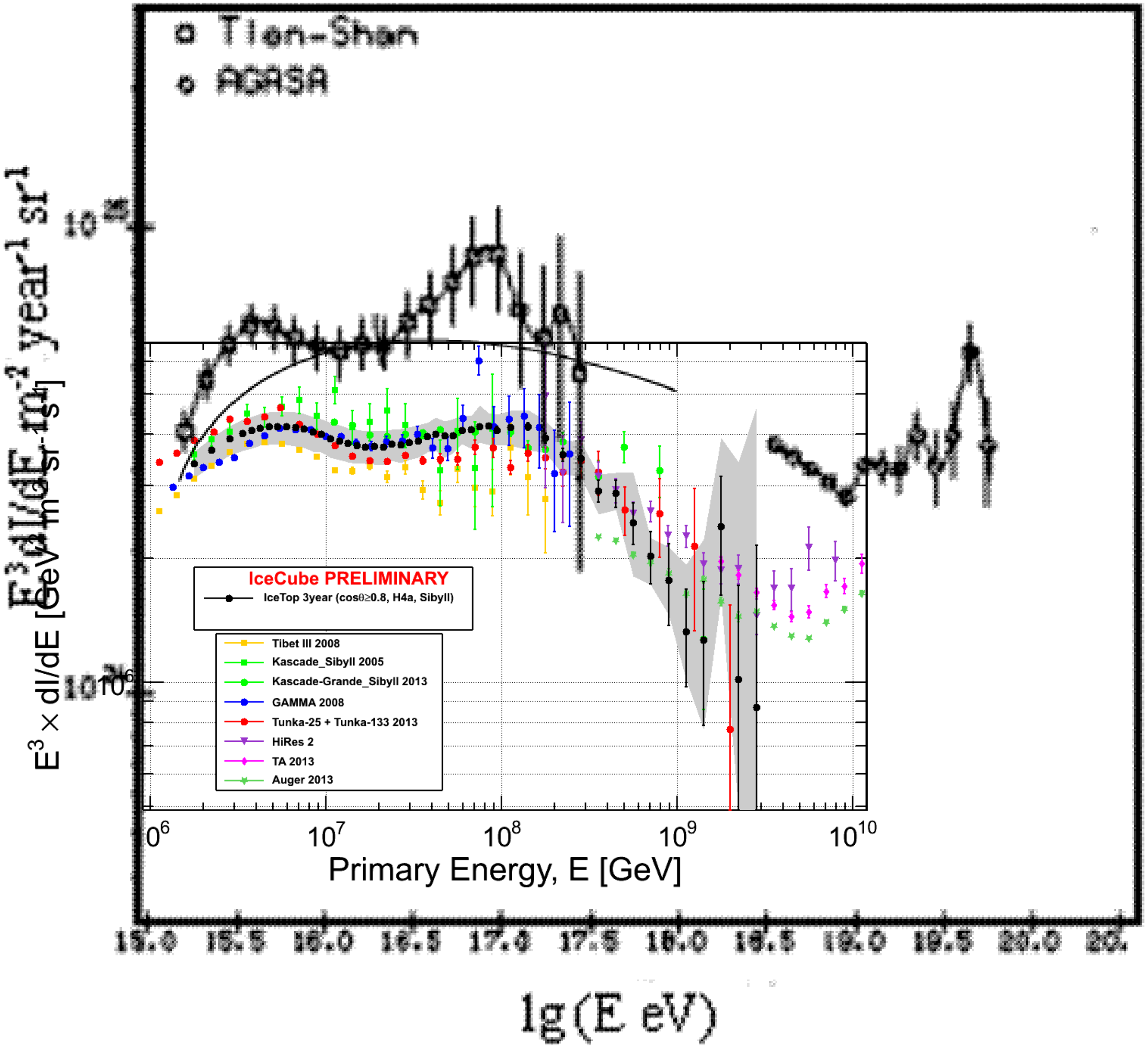
Ankle: ≃3EeV

Current Situation

Knee and Second Knee

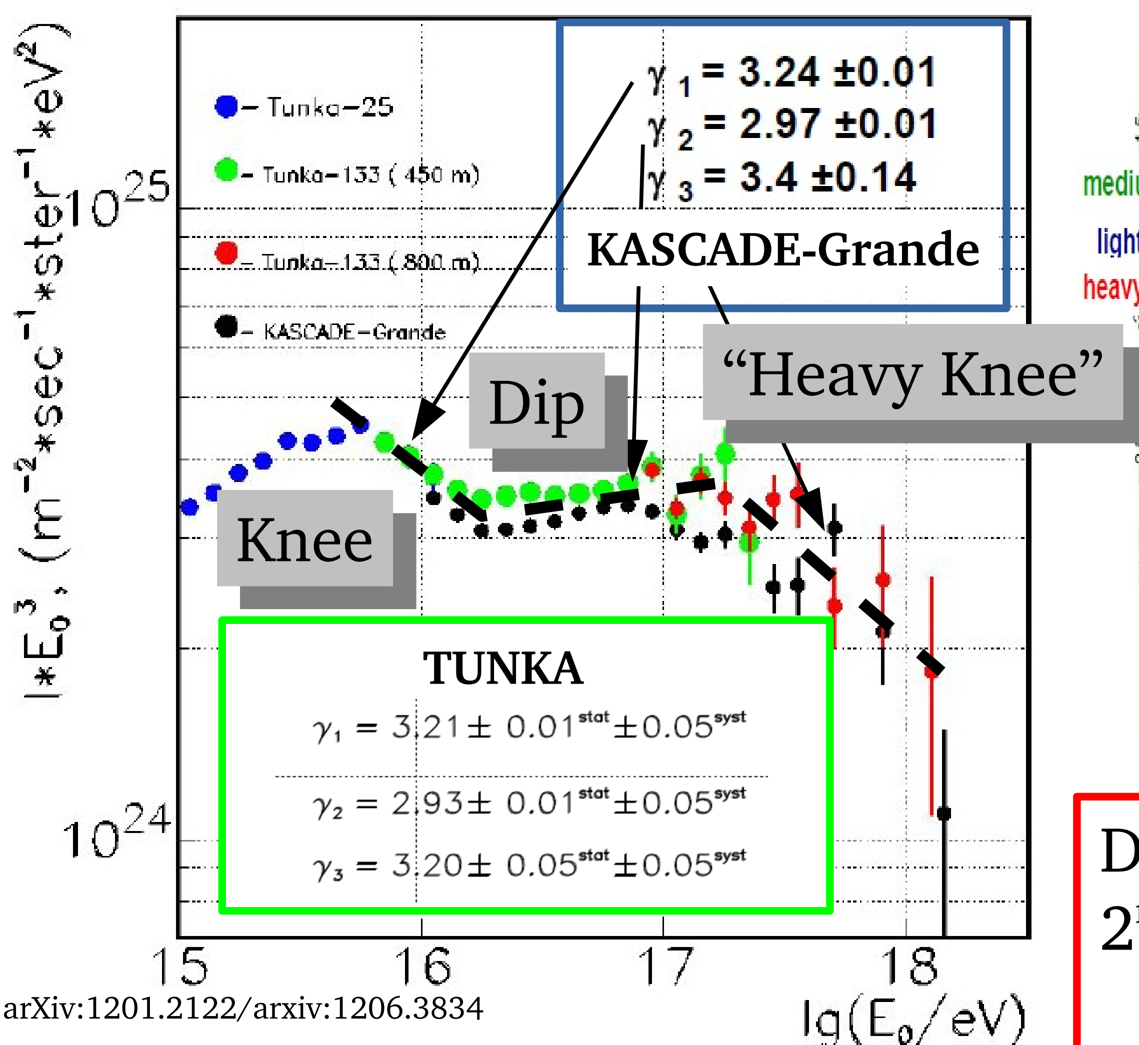


KASCADE-Grande
Karlsruhe, Germany
TUNKA
Tunka Valley, Russia
IceTop
South Pole, Antarctica
Knee
2nd Knee
Ankle
Grigorov
JACEE
MGU
TienShan
Tibet07
Akeno
CASA/MIA
Hegra
Flys Eye
Agasa
HiRes1
HiRes2
Auger SD
Auger hybrid
Kascade
$E^{2.7}F(E)$ [GeV$^{1.7}$ m^{-2} s^{-1} sr^{-1}]
E [eV]
IceCube PRELIMINARY
IceTop 3year (cosθ≥0.8, H4a, Sibyll)
Tibet III 2008
Kascade_Sibyll 2005
Kascade-Grande_Sibyll 2013
GAMMA 2008
Tunka-25 + Tunka-133 2013
HiRes 2
TA 2013
Auger 2013
$E^3 \times dI/dE$ [GeV^2 m^{-2} sr^{-1} s^{-1}]
Primary Energy, E [GeV]

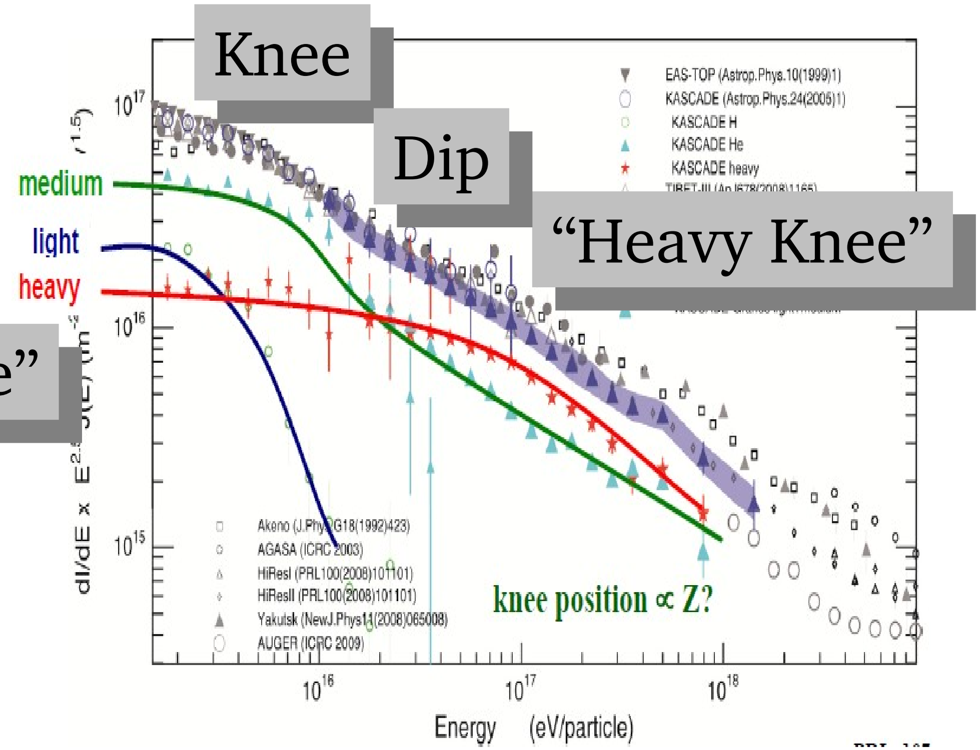


S. B. Shaulov et al. : The form of the CR energy spectrum up to 10^{18} eV
First shown in 2001, published December 2009

New PeV Cosmic Ray Paradigm



arXiv:1201.2122/arxiv:1206.3834



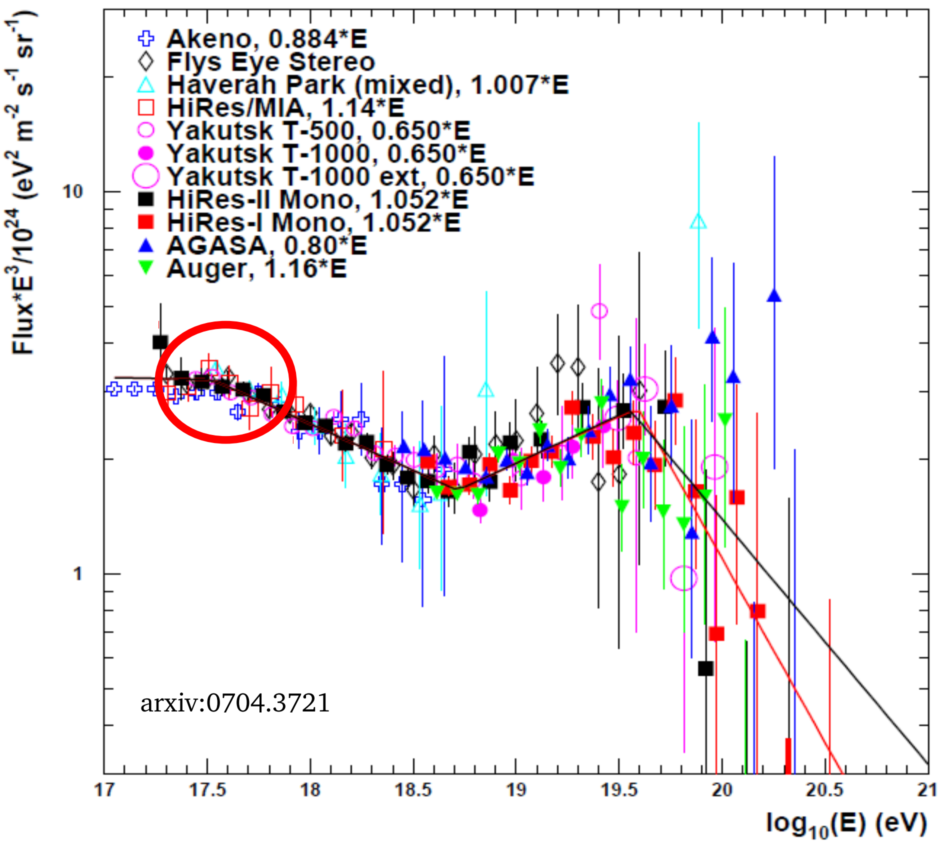
Dip/Concavity around 10-20 PeV
2nd Knee around **100 PeV**

Different Knee behavior for light/heavy primaries?

IceTop

E range	$I_0 \pm$ stat.	$\gamma \pm$ stat. $\pm$ sys.	χ^2/ndf
6.20–6.55	$(2.107 \pm 0.06) \times 10^4$	$2.648 \pm 0.002 \pm 0.06$	206/2
6.80–7.20	$(3.739 \pm 0.34) \times 10^7$	$3.138 \pm 0.006 \pm 0.03$	14/6
7.30–8.00	$(7.494 \pm 1.29) \times 10^5$	$2.903 \pm 0.010 \pm 0.03$	19/12
8.15–8.90	$(4.952 \pm 1.65) \times 10^9$	$3.374 \pm 0.069 \pm 0.08$	8/6

The View from Both Sides



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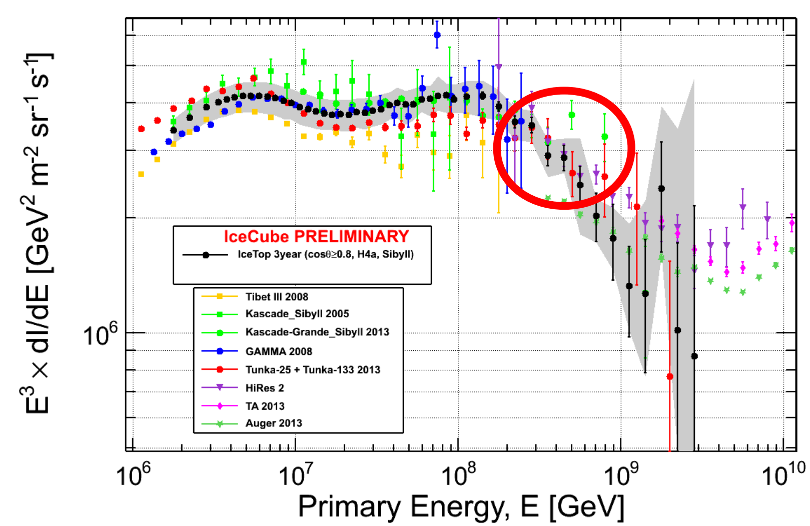
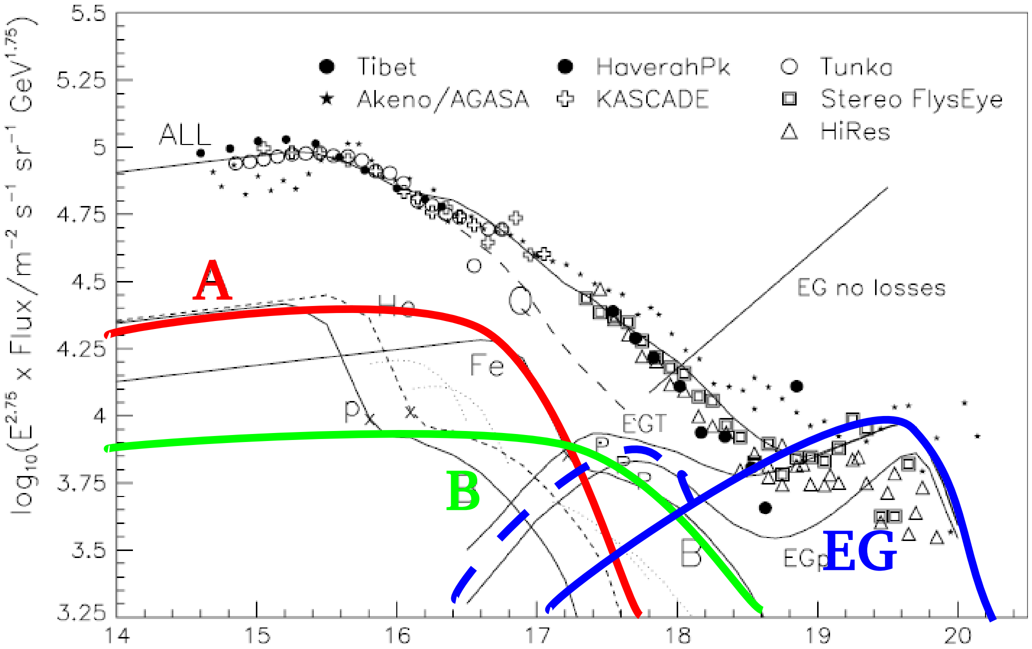
Real Feature?
Additional Population?



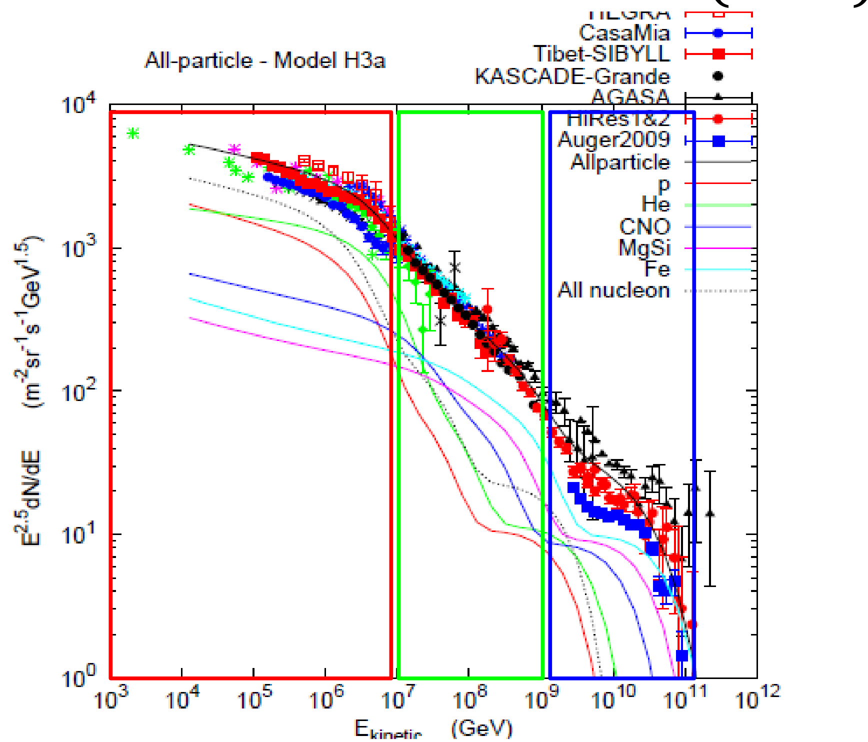
H(illas) 3a Model

Original Hillas Proposal



A M Hillas 2005 J. Phys. G: Nucl. Part. Phys. 31 R95

Gaisser Parametrization (**H3a**)

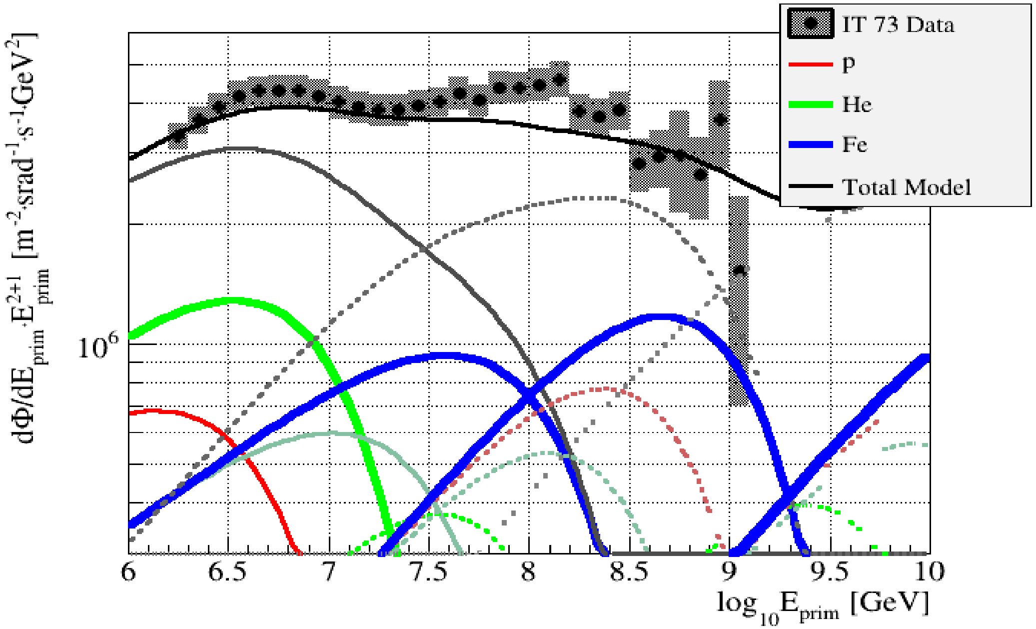


Galactic   Single Source?   Extragal.

Second Knee caused by
intermediate component
(single source?)
Extragalactic Flux included

exponential cutoff: $\phi_i(E) = \Sigma_{j=1}^{3} a_{i,j}\, E^{-\gamma_{i,j}} \times \exp\left[-\frac{E}{Z_i R_{c,j}}\right]$

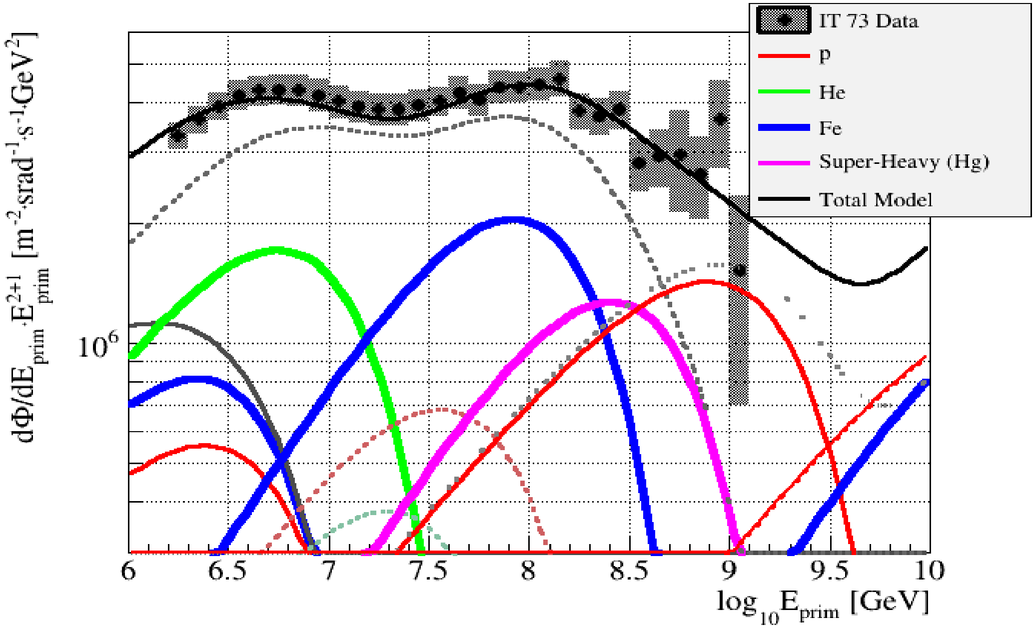
R_c	γ	p	He	CNO	Mg-Si	Fe
γ for Pop. 1	—	1.66	1.58	1.63	1.67	1.63
Population 1: 4 PV	see line 1	7860	3550	2200	1430	2120
Pop. 2: 30 PV	1.4	20	20	13.4	13.4	13.4
Pop. 3 (mixed): 2 EV	1.4	1.7	1.7	1.14	1.14	1.14



Gaisser Hillas 3 Population

Helium from Population 1
Iron from Pop. 1 and 2

Data: arxiv:1303.3565
Models: arxiv.org:1307.3795

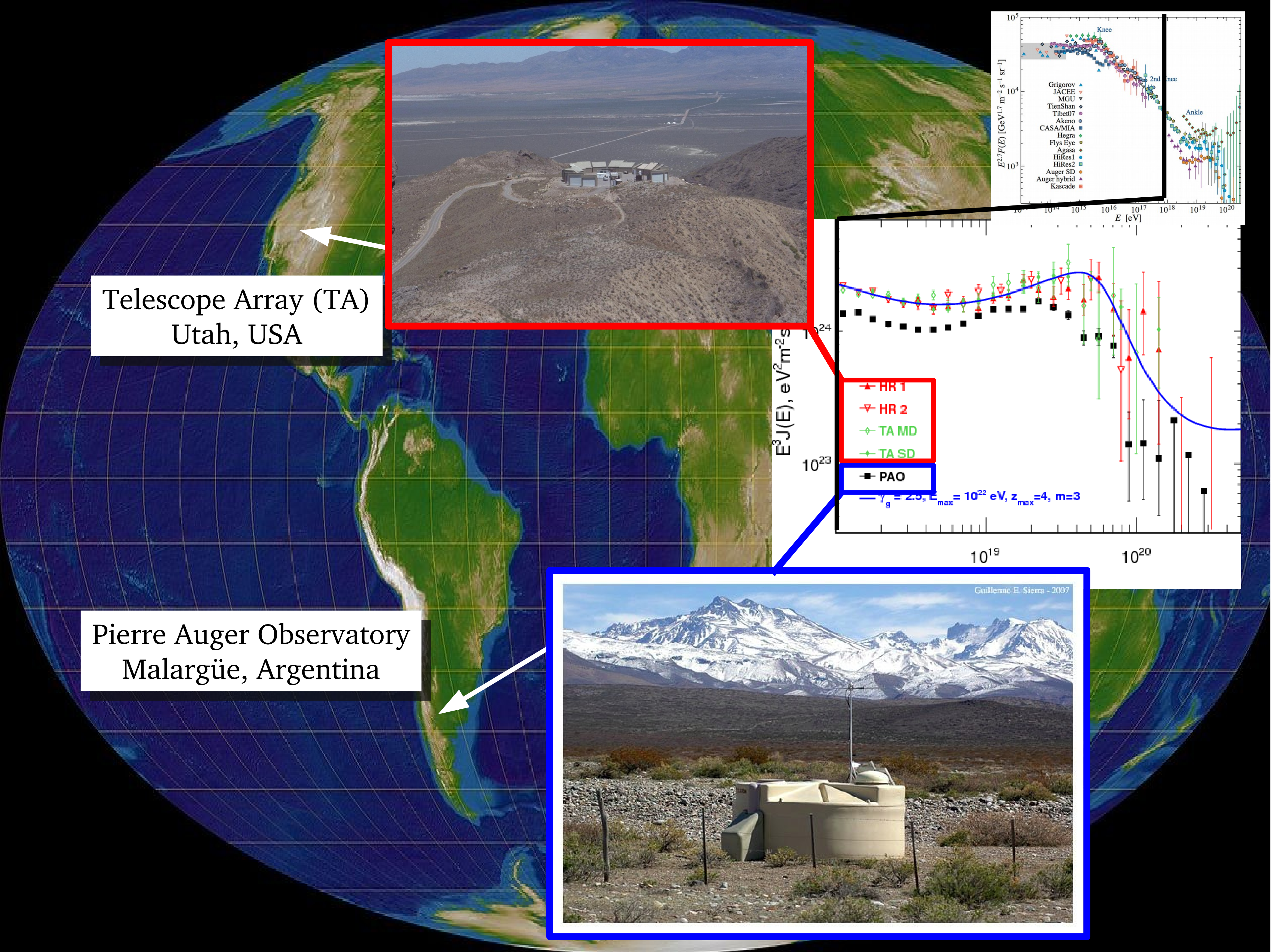


Gaisser Stanev Tilav "Global Fit"

Peaks explained by
He and Fe from same
Population!
But: Requires Super-Heavy
Elements (A>200)

Current Situation

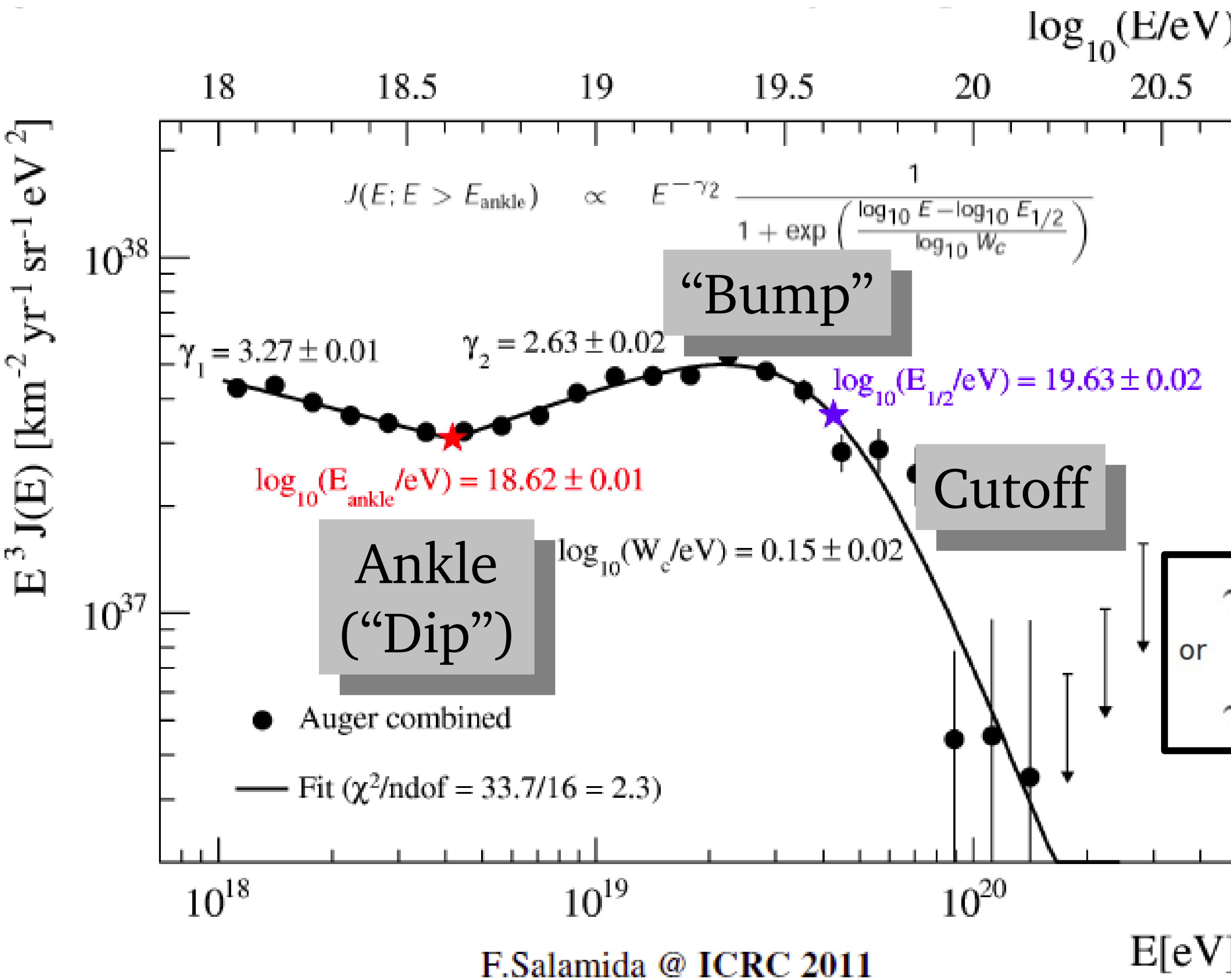
Ankle



Telescope Array (TA)
Utah, USA
Pierre Auger Observatory
Malargüe, Argentina
Knee
2nd Knee
Ankle
Grigorov
JACEE
MGU
TienShan
Tibet07
Akeno
CASA/MIA
Hegra
Flys Eye
Agasa
HiRes1
HiRes2
Auger SD
Auger hybrid
Kascade
E [eV]
HR 1
HR 2
TA MD
TA SD
PAO
Guillermo E. Sierra - 2007

Shortly after the discovery of the cosmic microwave background in 1965, it was pointed out that the spectrum of cosmic rays should steepen fairly abruptly above about 4 x 10^{19} eV

arXiv:1310.0325



$$\gamma_{\mathrm{CMB}} + p \to \Delta^+ \to p + \pi^0,$$

or

$$\gamma_{\mathrm{CMB}} + p \to \Delta^+ \to n + \pi^+.$$

Greisen K 1966 *Physical Review Letters* **16** 748

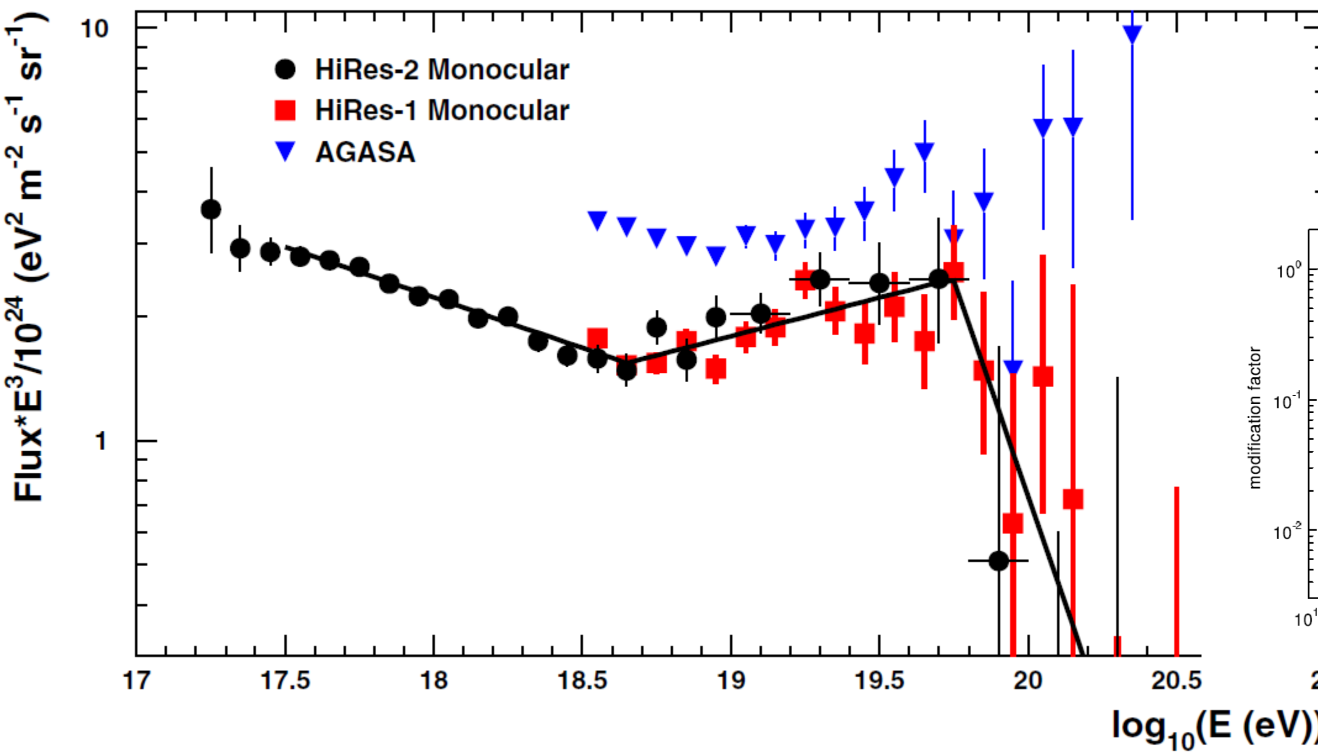
Zatsepin G T and V A Kuz'min 1966 *Zh. Eksp. Teor. Fiz. Pis'ma Red.* **4** 144

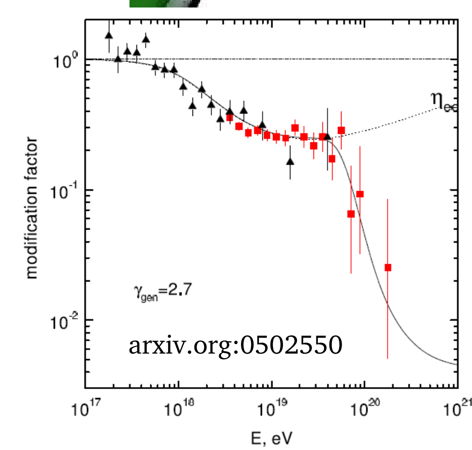
PRL **100**, 101101 (2008) PHYSICAL REVIEW LETTERS week ending 14 MARCH 2008

First Observation of the Greisen-Zatsepin-Kuzmin Suppression

R. U. Abbasi,[1] T. Abu-Zayyad,[1] M. Allen,[1] J. F. Amman,[2] G. Archbold,[1] K. Belov,[1] J. W. Belz,[1] S. Y. Ben Zvi,[3] D. R. Bergman,[4,*] S. A. Blake,[1] O. A. Brusova,[1] G. W. Burt,[1] C. Cannon,[1] Z. Cao,[1] B. C. Connolly,[3] W. Deng,[1] Y. Fedorova,[1] C. B. Finley,[3] R. C. Gray,[1] W. F. Hanlon,[1] C. M. Hoffman,[2] M. H. Holzscheiter,[2] G. Hughes,[4] P. Hüntemeyer,[1] B. F Jones,[1] C. C. H. Jui,[1] K. Kim,[1] M. A. Kirn,[5] E. C. Loh,[1] M. M. Maestas,[1] N. Manago,[6] L. J. Marek,[2] K. Martens,[1] J. A. J. Matthews,[7] J. N. Matthews,[1] S. A. Moore,[1] A. O'Neill,[3] C. A. Painter,[2] L. Perera,[4] K. Reil,[1] R. Riehle,[1] M. Roberts,[7] D. Rodriguez,[1] N. Sasaki,[6] S. R. Schnetzer,[4] L. M. Scott,[4] G. Sinnis,[2] J. D. Smith,[1] P. Sokolsky,[1] C. Song,[3] R. W. Springer,[1] B. T. Stokes,[1] S. B. Thomas,[1] J. R. Thomas,[1] G. B. Thomson,[4] D. Tupa,[2] S. Westerhoff,[3] L. R. Wiencke,[1] X. Zhang,[3] and A. Zech[4]

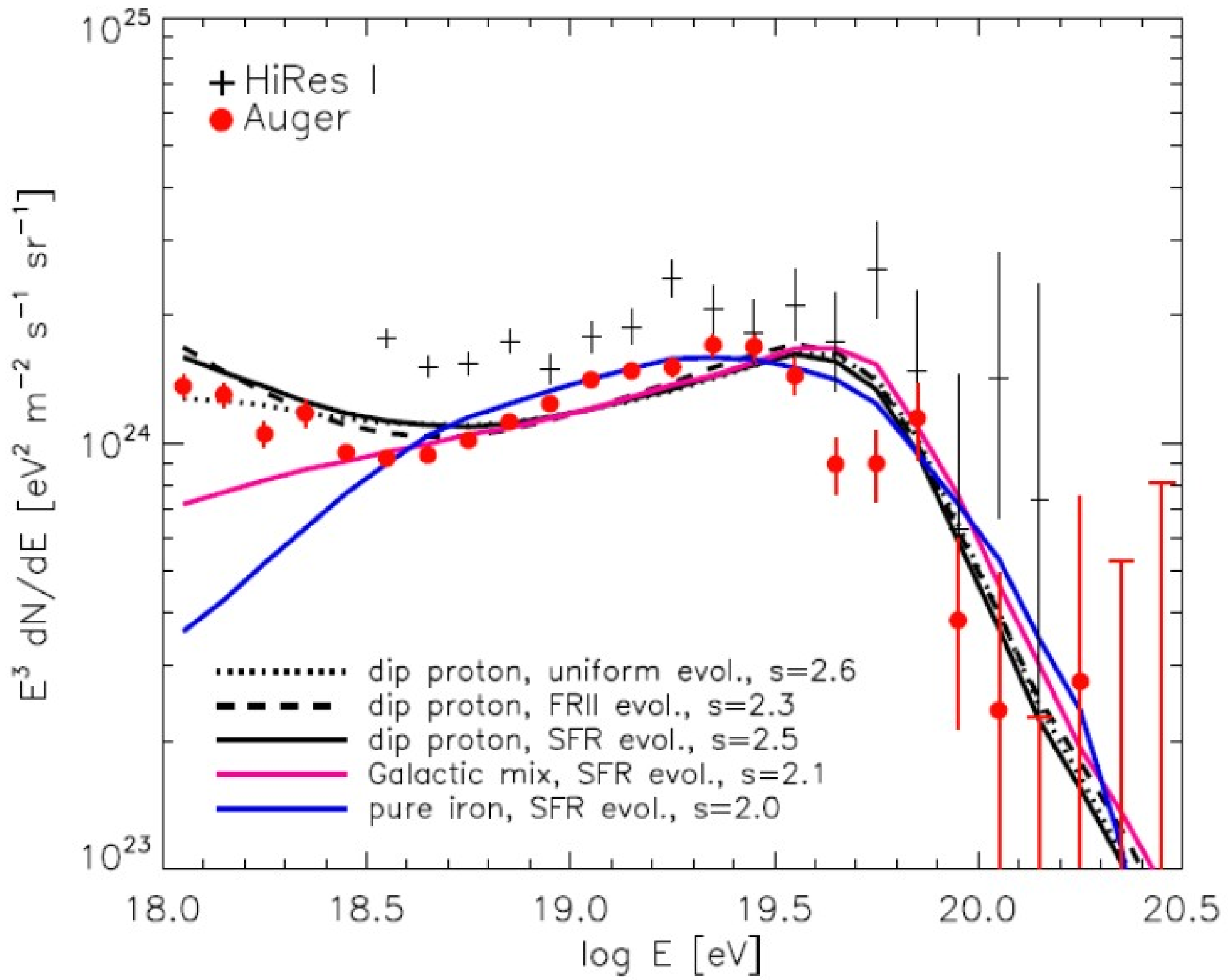
(High Resolution Fly's Eye Collaboration)

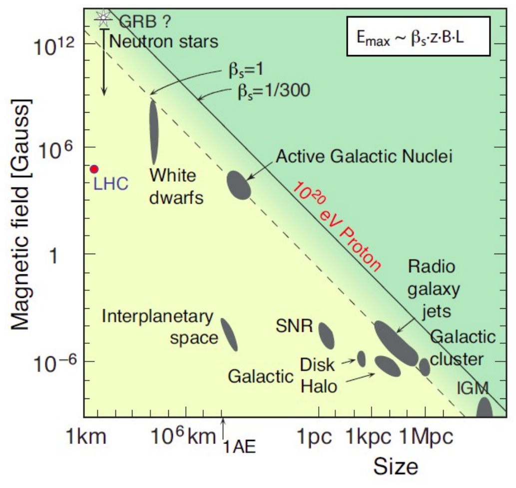




Although there is now little doubt that a suppression of the spectrum exists near the energy predicted, it is by no means certain that this is a manifestation of the GZK-effect as it might be that this energy is also close to the maximum to which sources can accelerate particles, with the highest-energy beam containing a large fraction of **nuclei heavier than protons.**

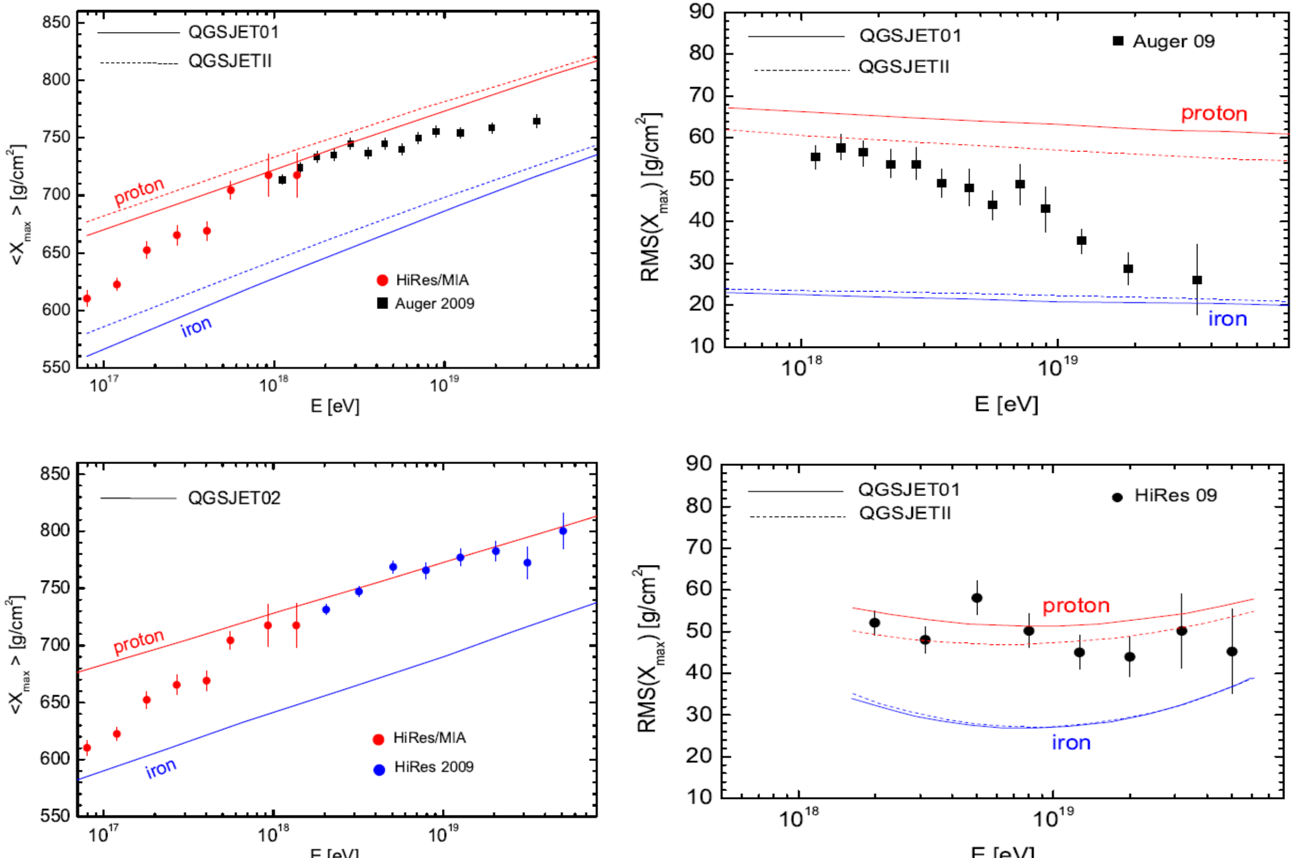
arXiv:1310.0325





“Hillas Plot”

UHE CR Primary Composition



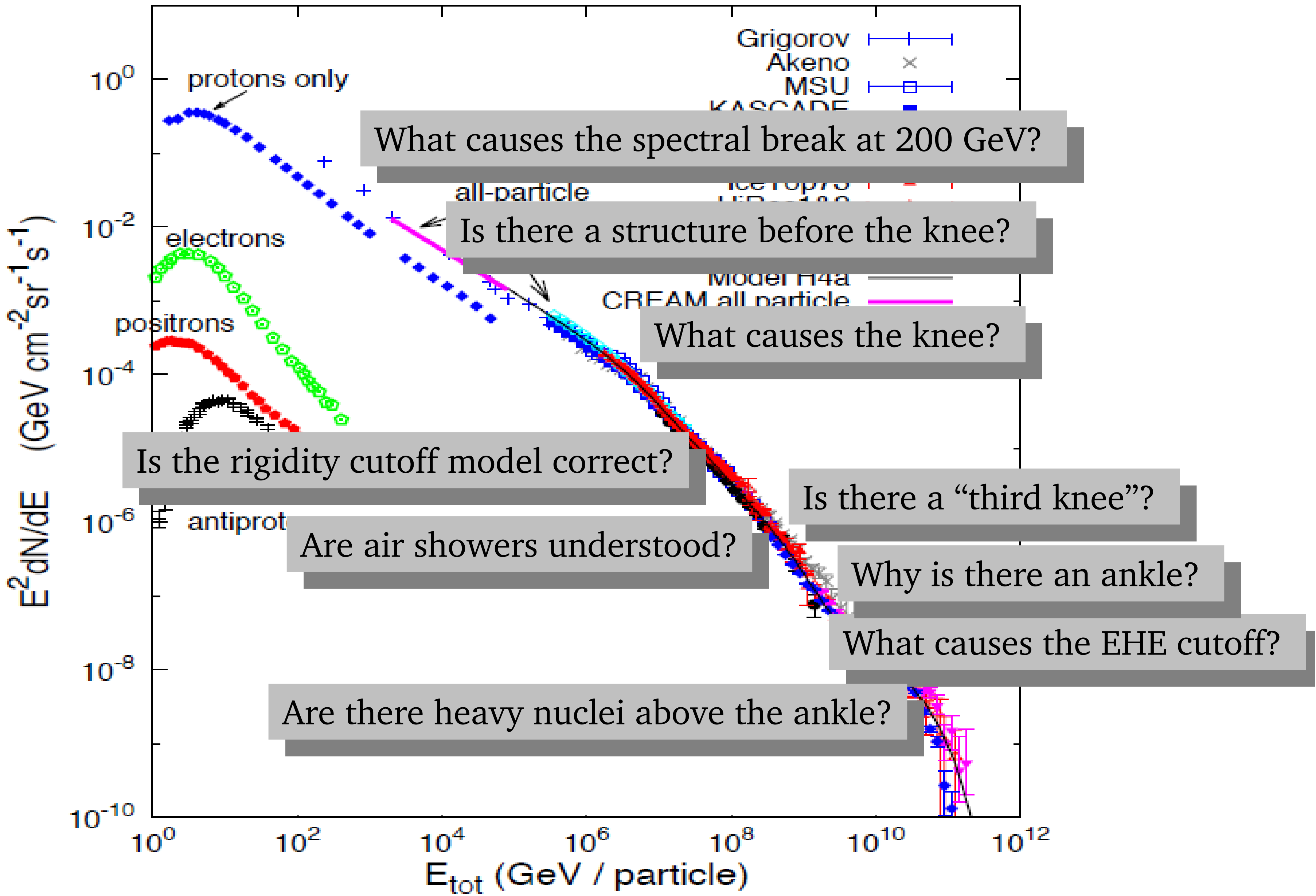
arXiv:0907.5194

Auger:
Mixed!

HiRes/TA:
Protons!

Open Questions:
Nature of Ankle
GZK Cutoff vs. End of Acceleration

Open Questions (NOT complete)!



Open Questions (NOT complete)!

What causes the spectral break at 200 GeV?

Is there a structure before the knee?

What causes the knee?

Is the rigidity cutoff model correct?

Is there a “third knee”?

Are air showers understood?

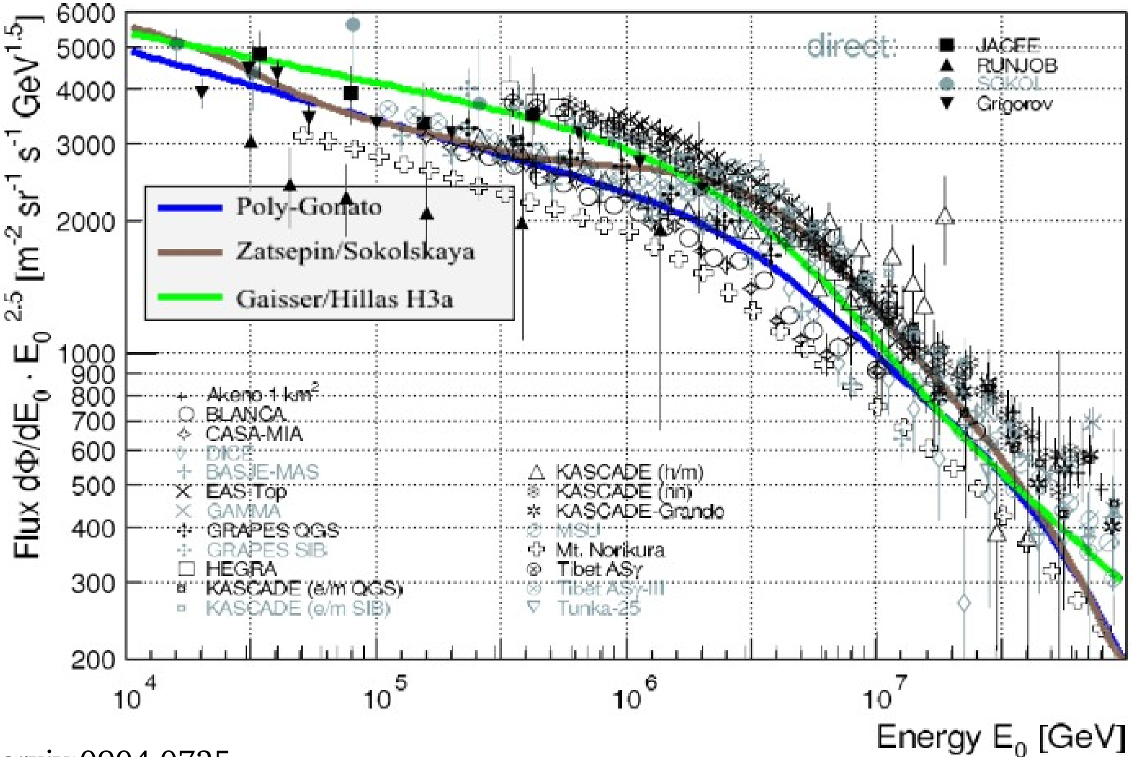
Why is there an ankle?

What causes the EHE cutoff?

Are there heavy nuclei above the ankle?

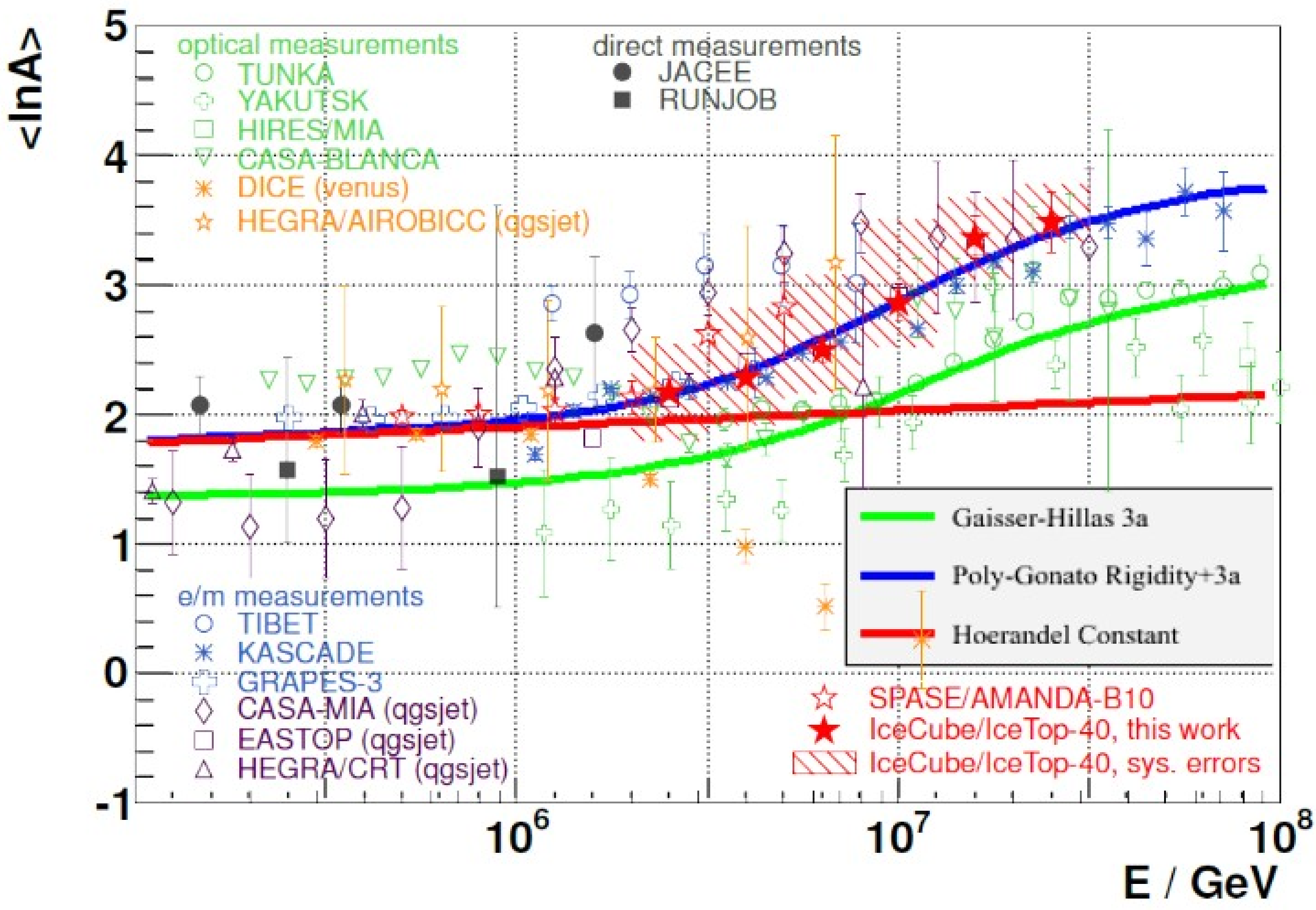
Where do they come from?

The Knee

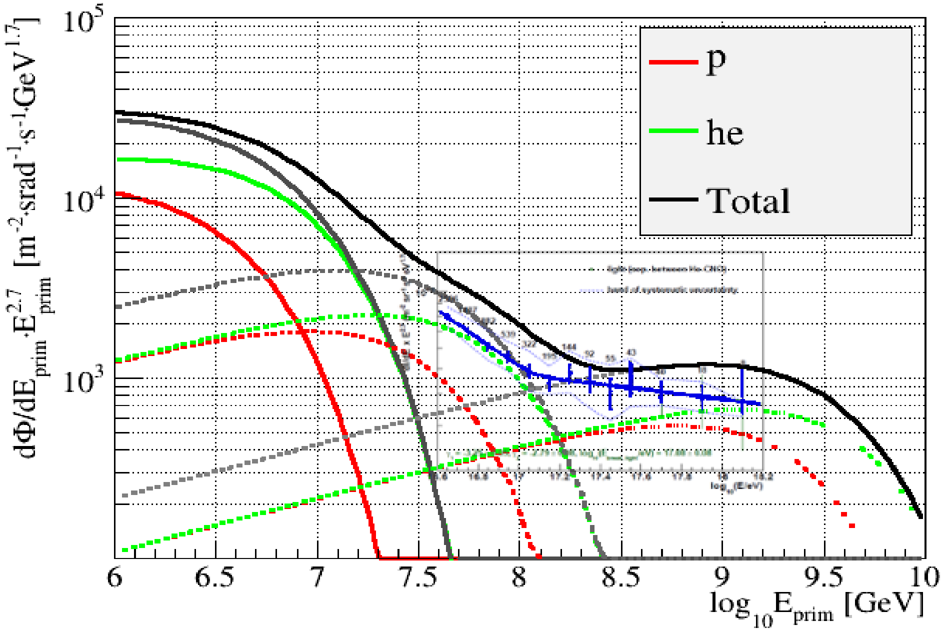


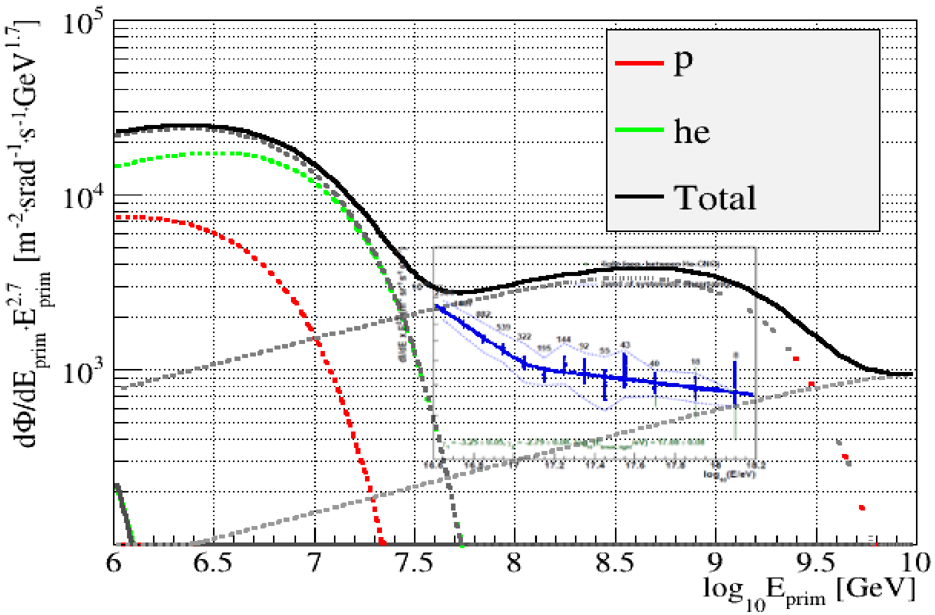
arxiv:0904.0725

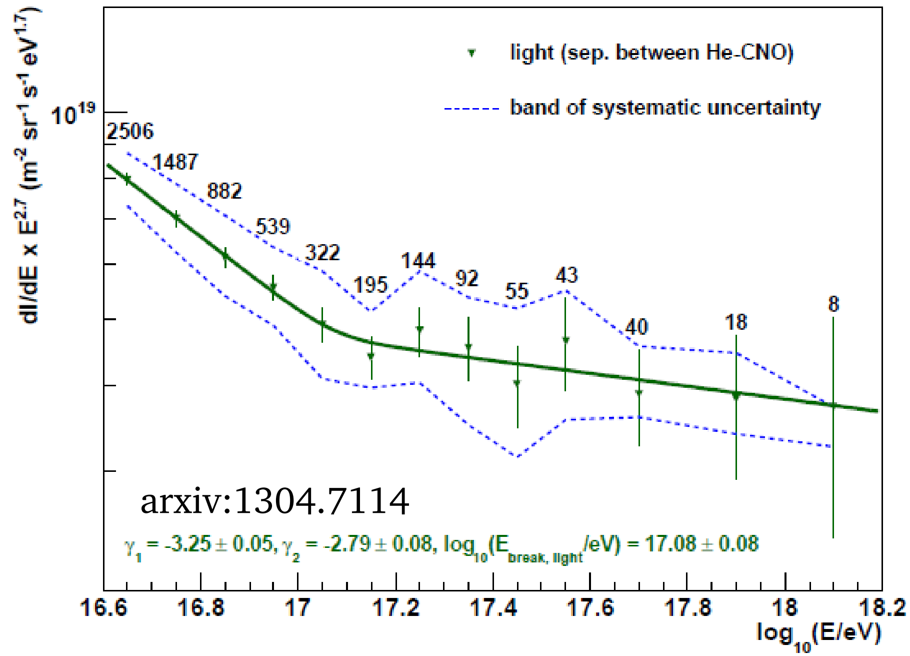
Knee Composition and Models



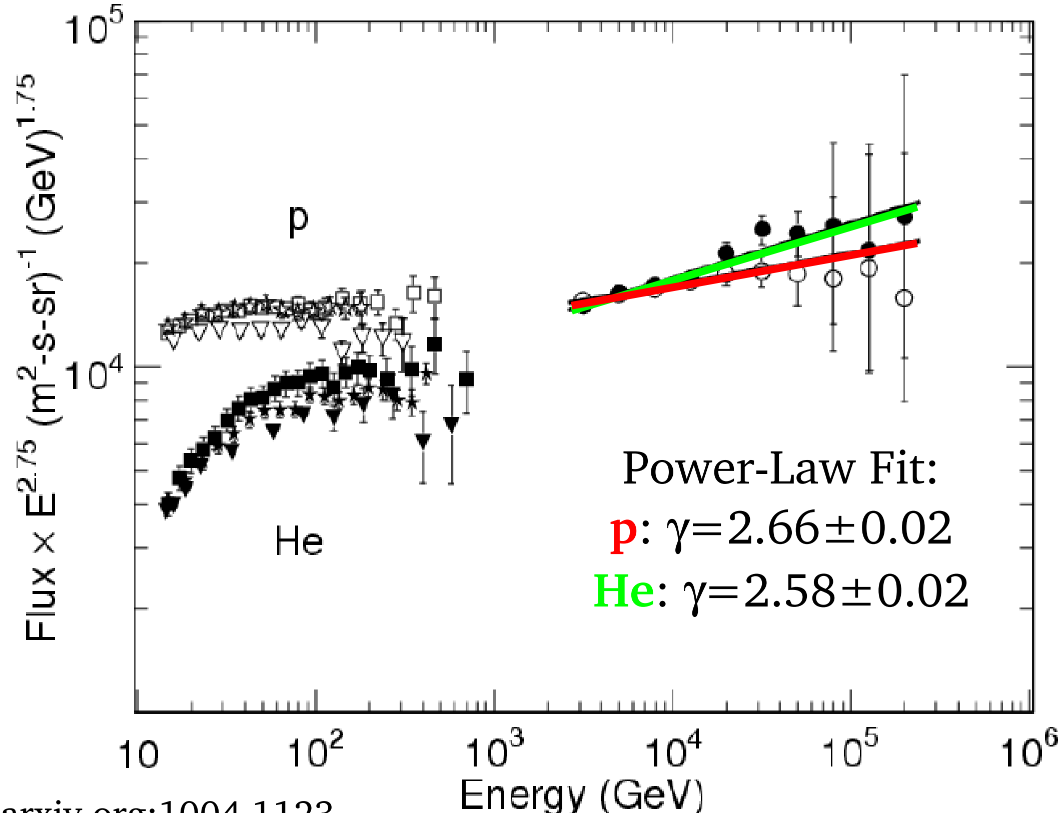
KASCADE Light Elements







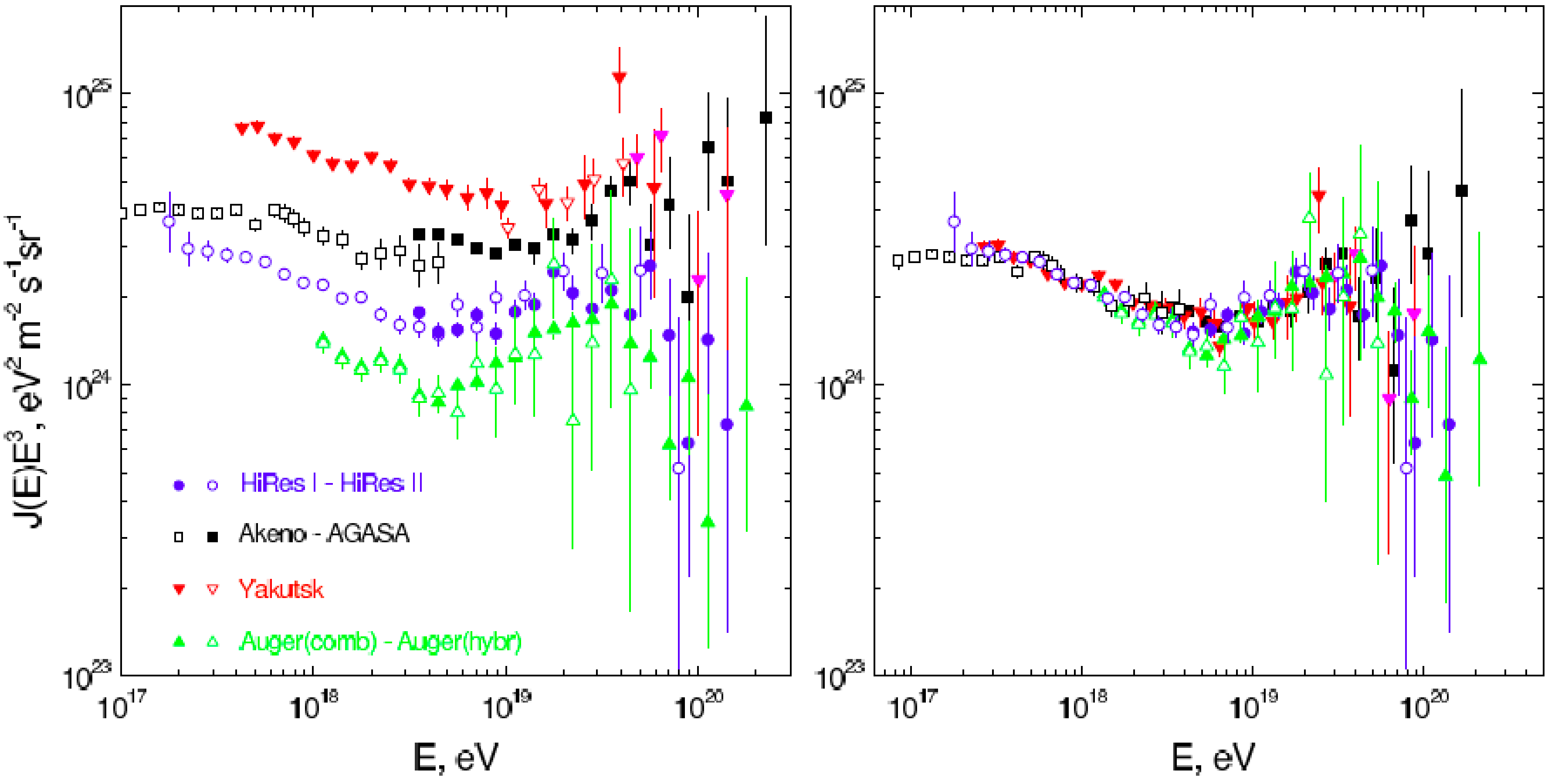
Before The Knee: CREAM



arxiv.org:1004.1123

Nucleon spectrum probably harder than 2.7

IC59 diffuse analysis: γ=2.583±0.023(stat.)



J(E)E³, eV² m⁻² s⁻¹sr⁻¹
10^25
10^24
10^23
10^17
10^18
10^19
10^20
E, eV
HiRes I - HiRes II
Akeno - AGASA
Yakutsk
Auger(comb) - Auger(hybr)