Recent Advances
in
Galactic Cosmic Ray Observations

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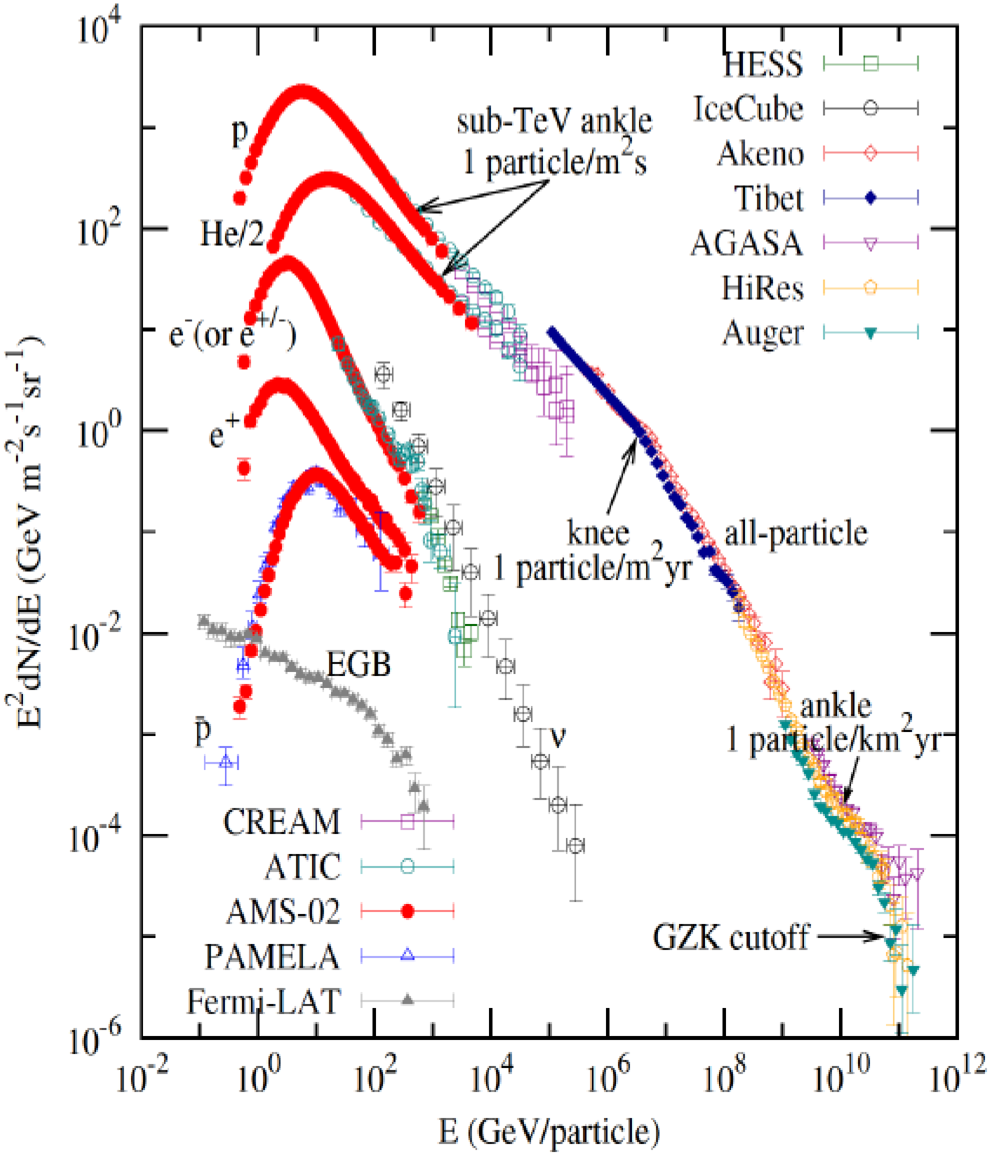
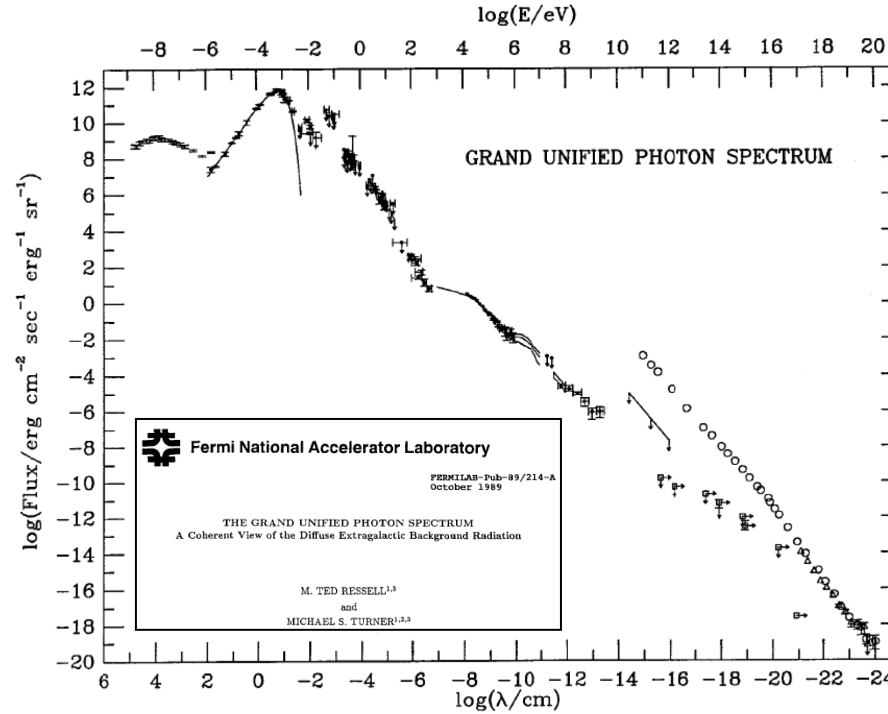
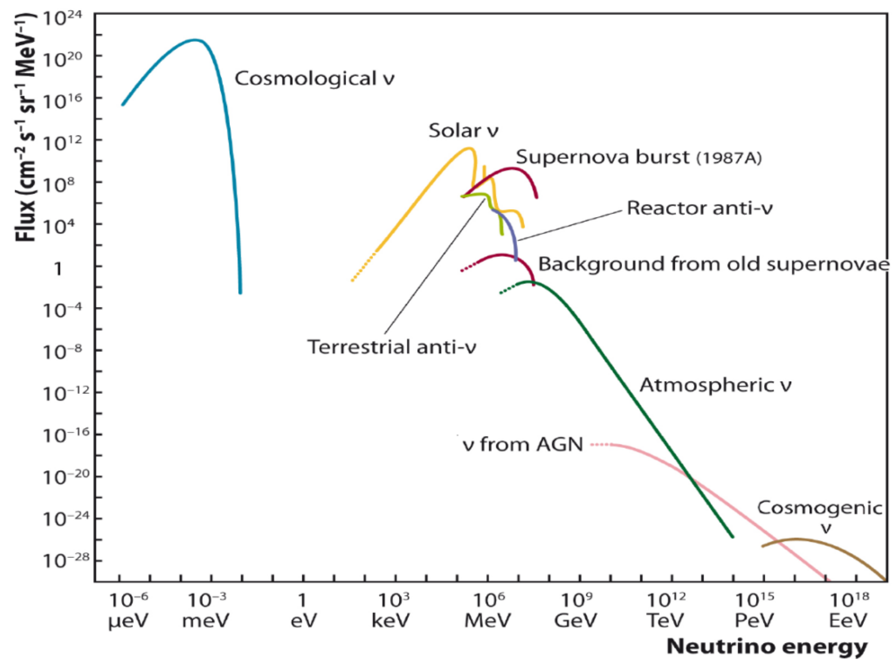
L'Aquila , Italy

7th HERD workshop, CERN , November 6-7, 2018

Our landscape(s)

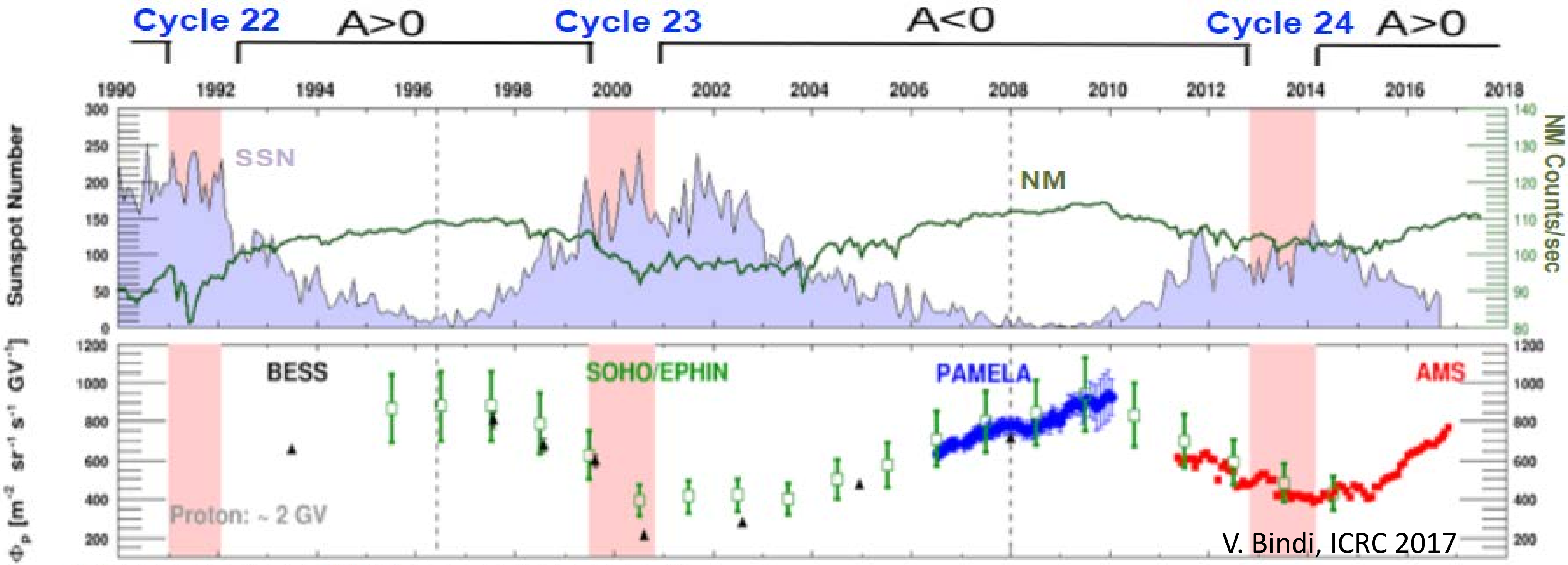


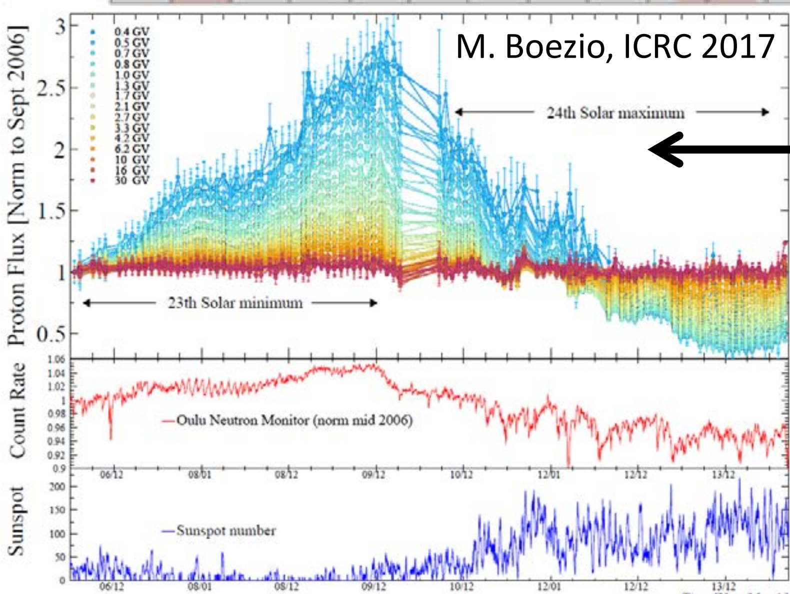




G S
S I

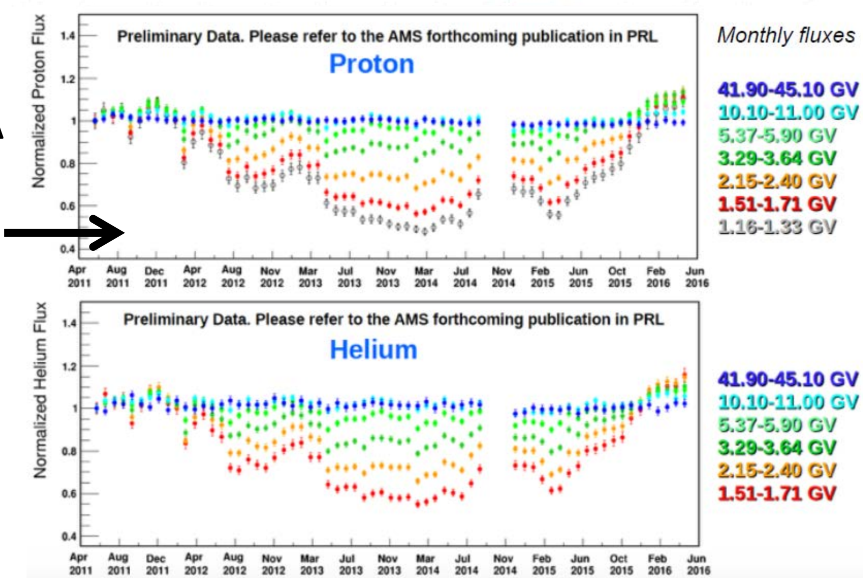
Solar modulations





PAMELA ←

AMS →



AUGER: large scale anisotropy

Science **357**, 1266–1270 (2017) 22 September 2017

COSMIC RAYS

Observation of a large-scale anisotrop in the arrival directions of cosmic rays above 8×10^{18} eV

The Pierre Auger Collaboration*†

Cosmic rays are atomic nuclei arriving from outer space that reach the highest energies observed in nature. Clues to their origin come from studying the distribution of their arrival directions. Using 3×10^4 cosmic rays with energies above 8×10^{18} electron volts, recorded with the Pierre Auger Observatory from a total exposure of 76,800 km^2 sr year, we determined the existence of anisotropy in arrival directions. The anisotropy, detected at more than a 5.2σ level of significance, can be described by a dipole with an amplitude of $6.5^{+1.3}_{-0.9}$ percent toward right ascension $\alpha_d = 100 \pm 10$ degrees and declination $\delta_d = -24^{+12}_{-13}$ degrees. That direction indicates an extragalactic origin for these ultrahigh-energy particles.

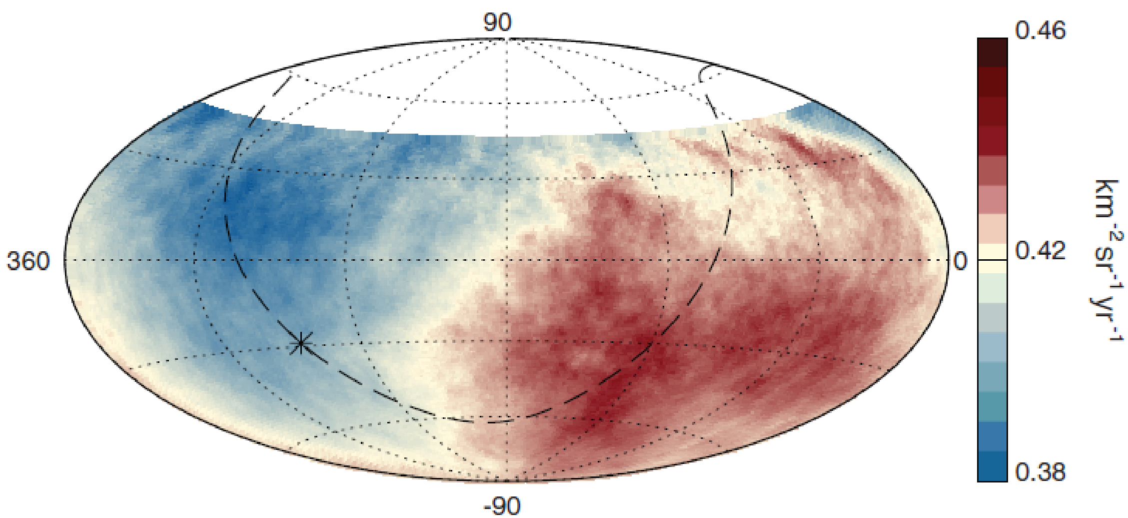


Fig. 2. Map showing the fluxes of particles in equatorial coordinates. Sky map in equatorial coordinates, using a Hammer projection, showing the cosmic-ray flux above 8 EeV smoothed with a 45° top-hat function. The galactic center is marked with an asterisk; the galactic plane is shown by a dashed line.

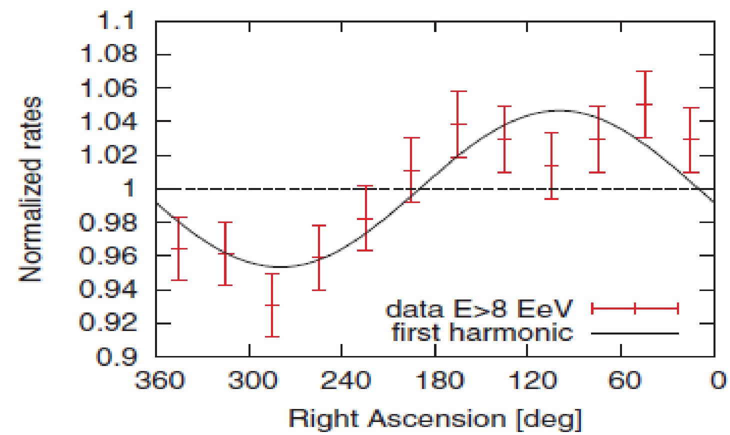
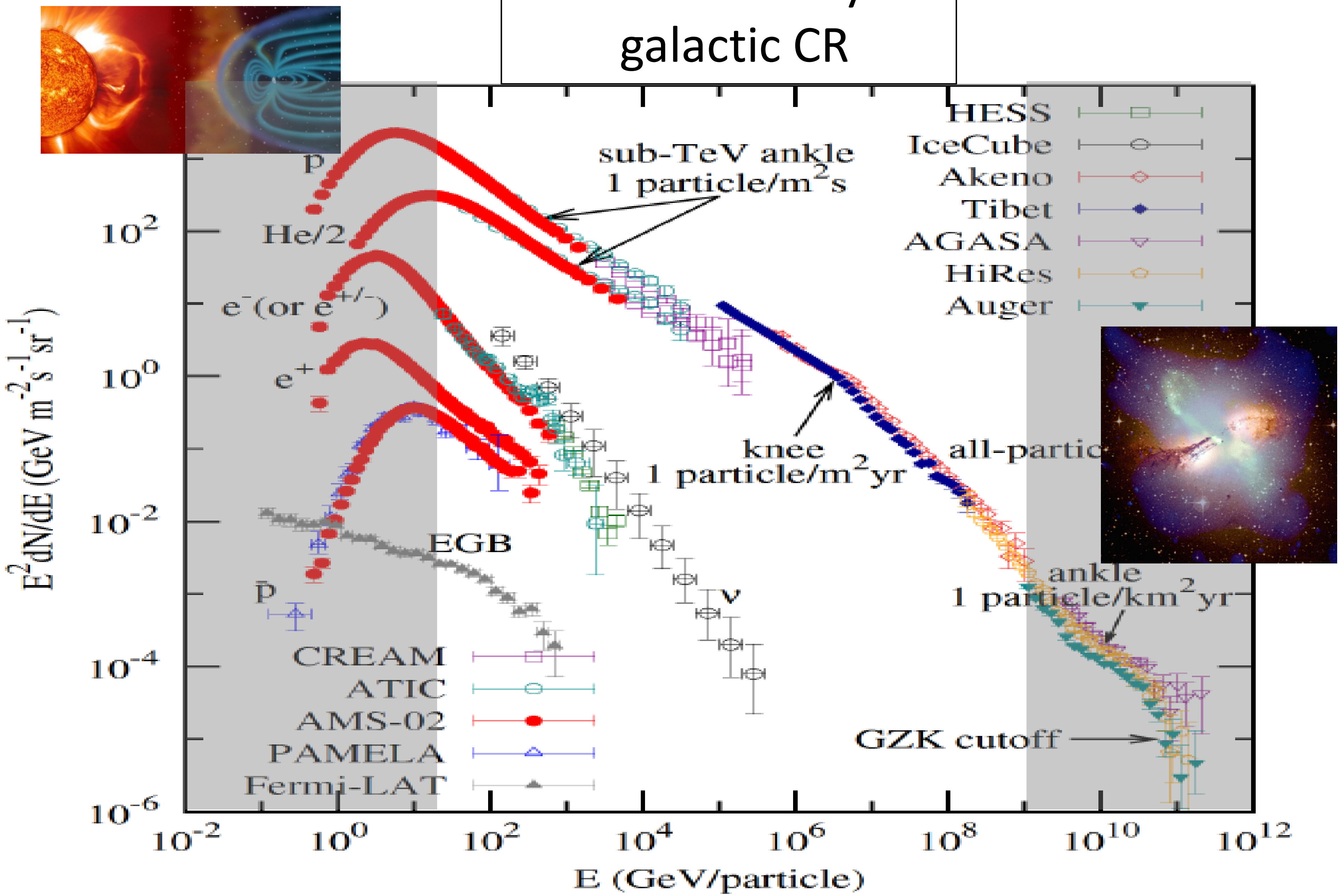
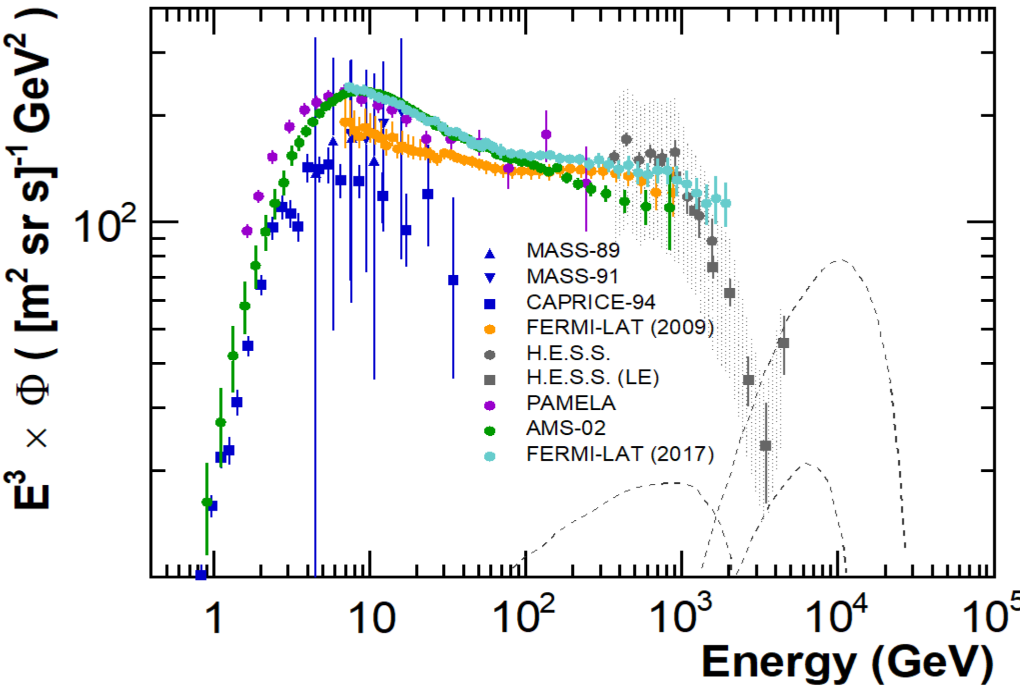


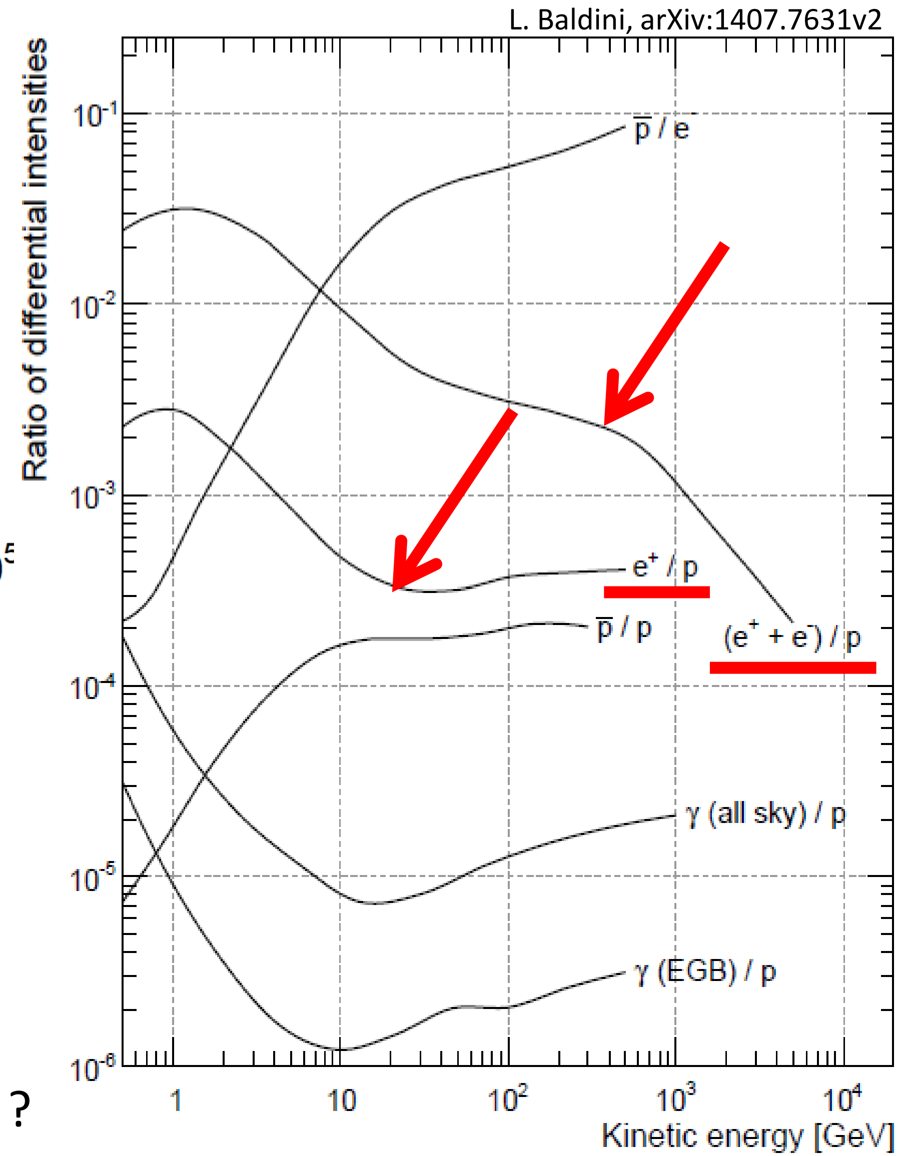
Fig. 1. Normalized rate of events as a function of right ascension. Normalized rate for 32,187 events with $E \geq 8$ EeV, as a function of right ascension (integrated in declination). Error bars are 1σ uncertainties. The solid line shows the first-harmonic modulation from Table 1, which displays good agreement with the data ($\chi^2/n = 10.5/10$); the dashed line shows a constant function.

Unbiased study of galactic CR



The electron + positron signal



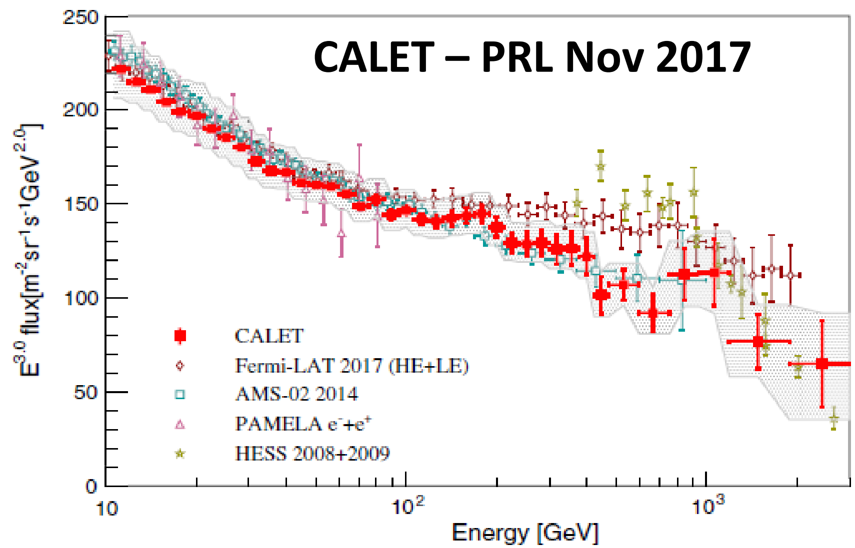


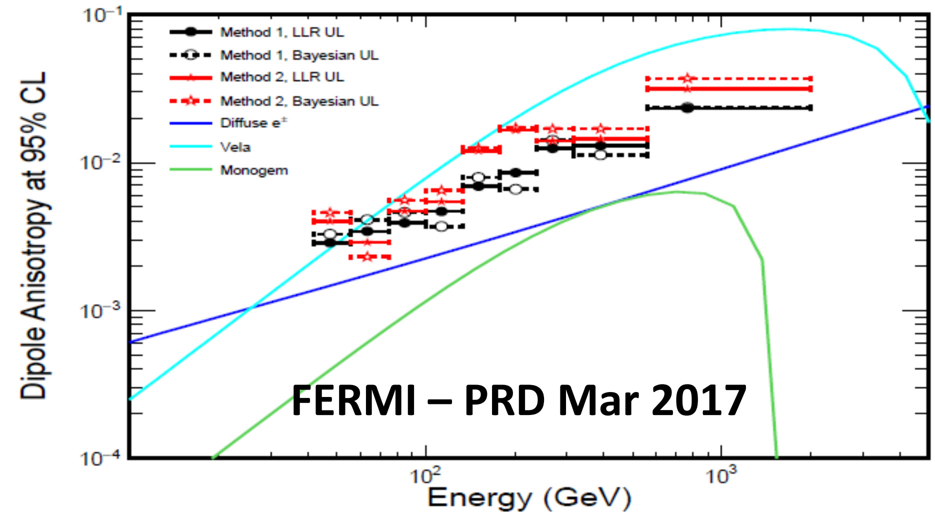
- Small fluxes and ~ E^{-3} spectra
- Cut-off at about 1 TeV ?

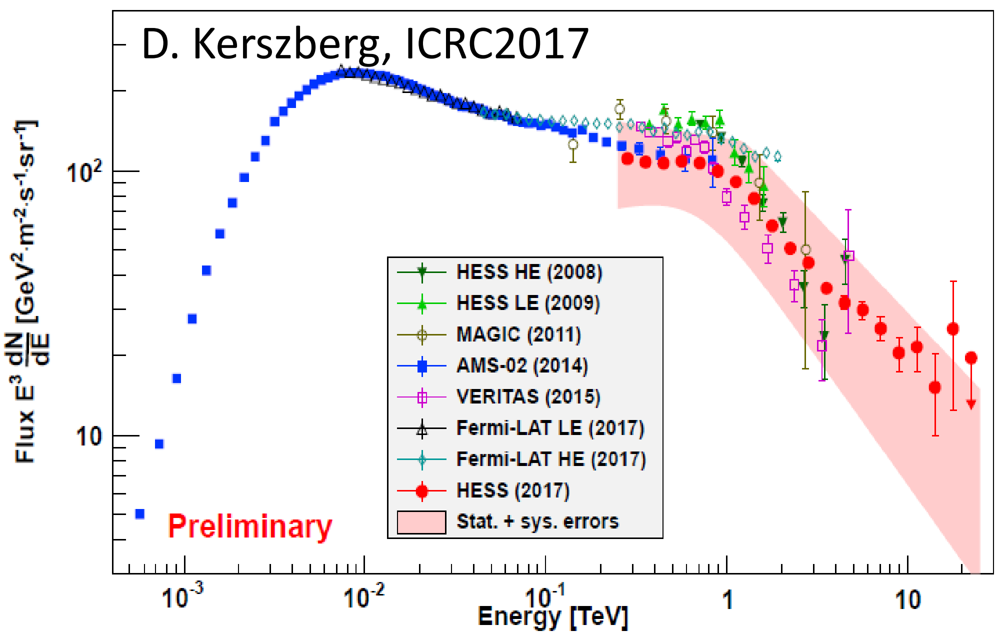
TeV sources:

- T < 10^5 yr and D < 1 kpc
- Nearby CR sources: large anisotropies ?
- Contributions from DM annihilation/decay ?

Recent results on $e^- + e^+$







AMS
Single power law up to 0.8 TeV

FERMI
Stringent limits on anisotropy

HESS
preliminary evidence for a break at 0.9 TeV

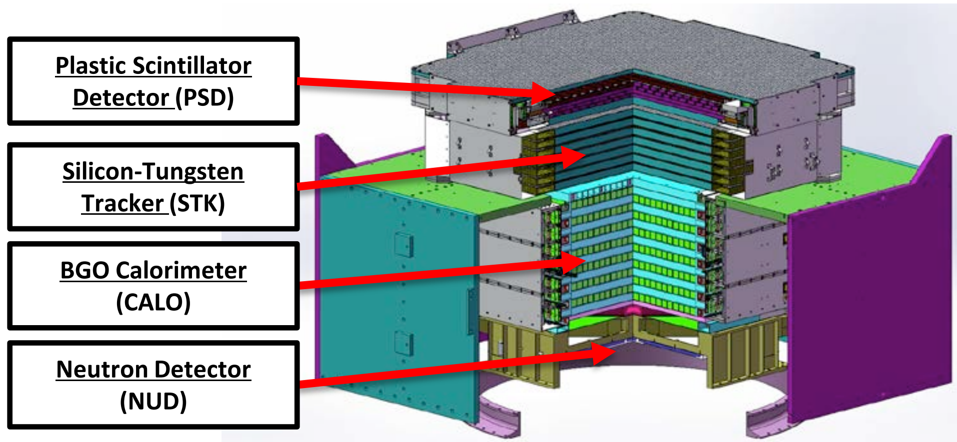
CALET
compatible with a single power law up to 2.5TeV, but large fluctuations at high energy

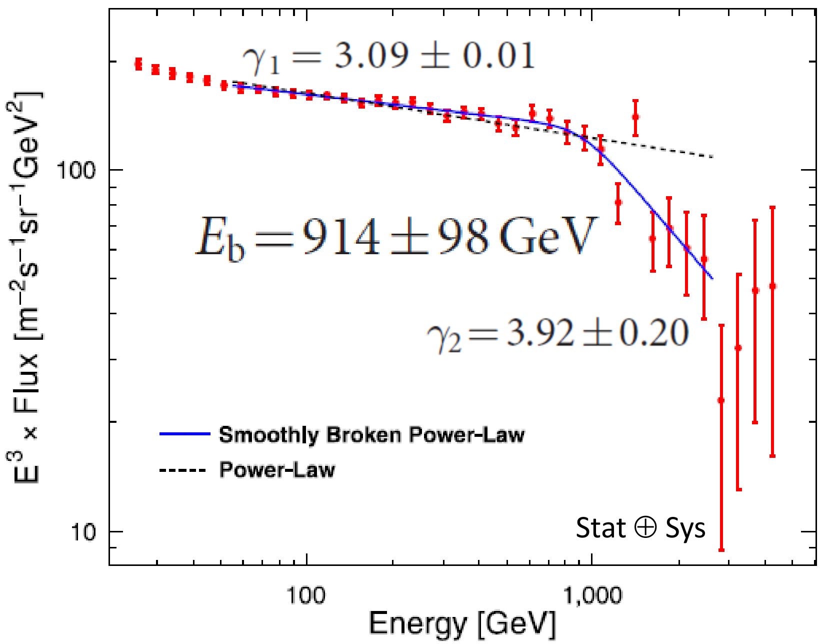
Nov 29, 2017: first DAMPE result

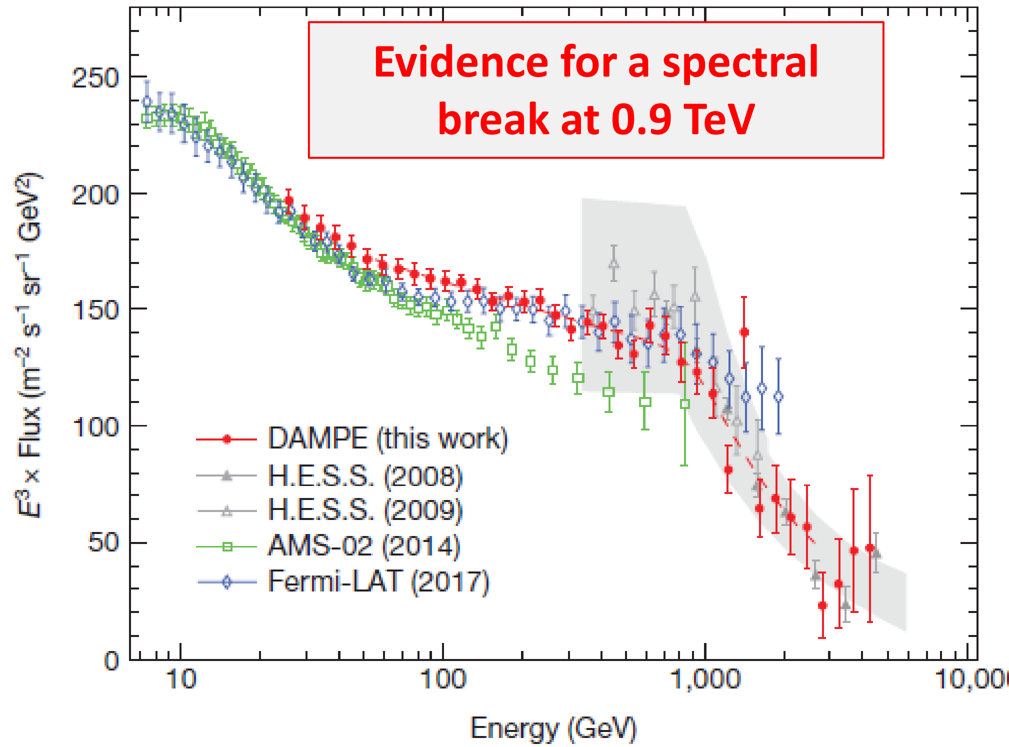
LETTER nature International weekly journal of science
doi:10.1038/nature24475

Direct detection of a break in the teraelectronvolt cosmic-ray spectrum of electrons and positrons

DAMPE Collaboration*

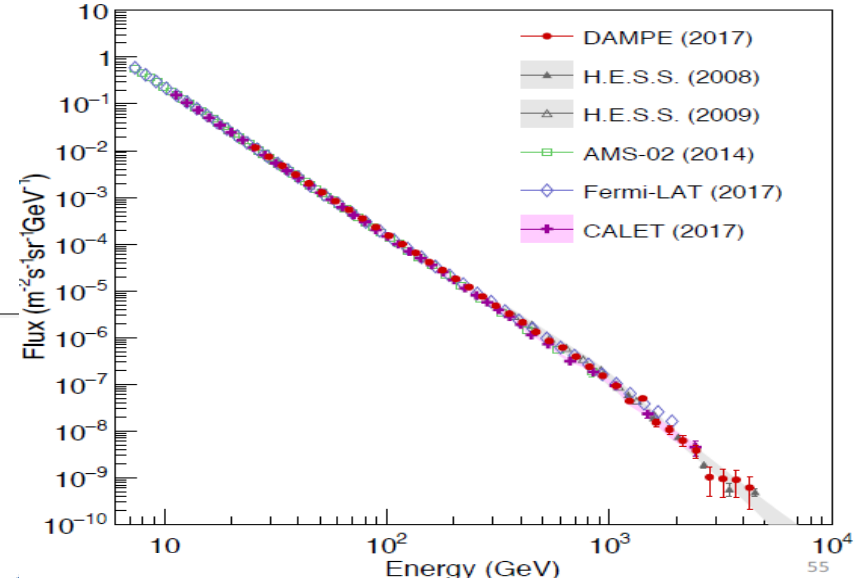


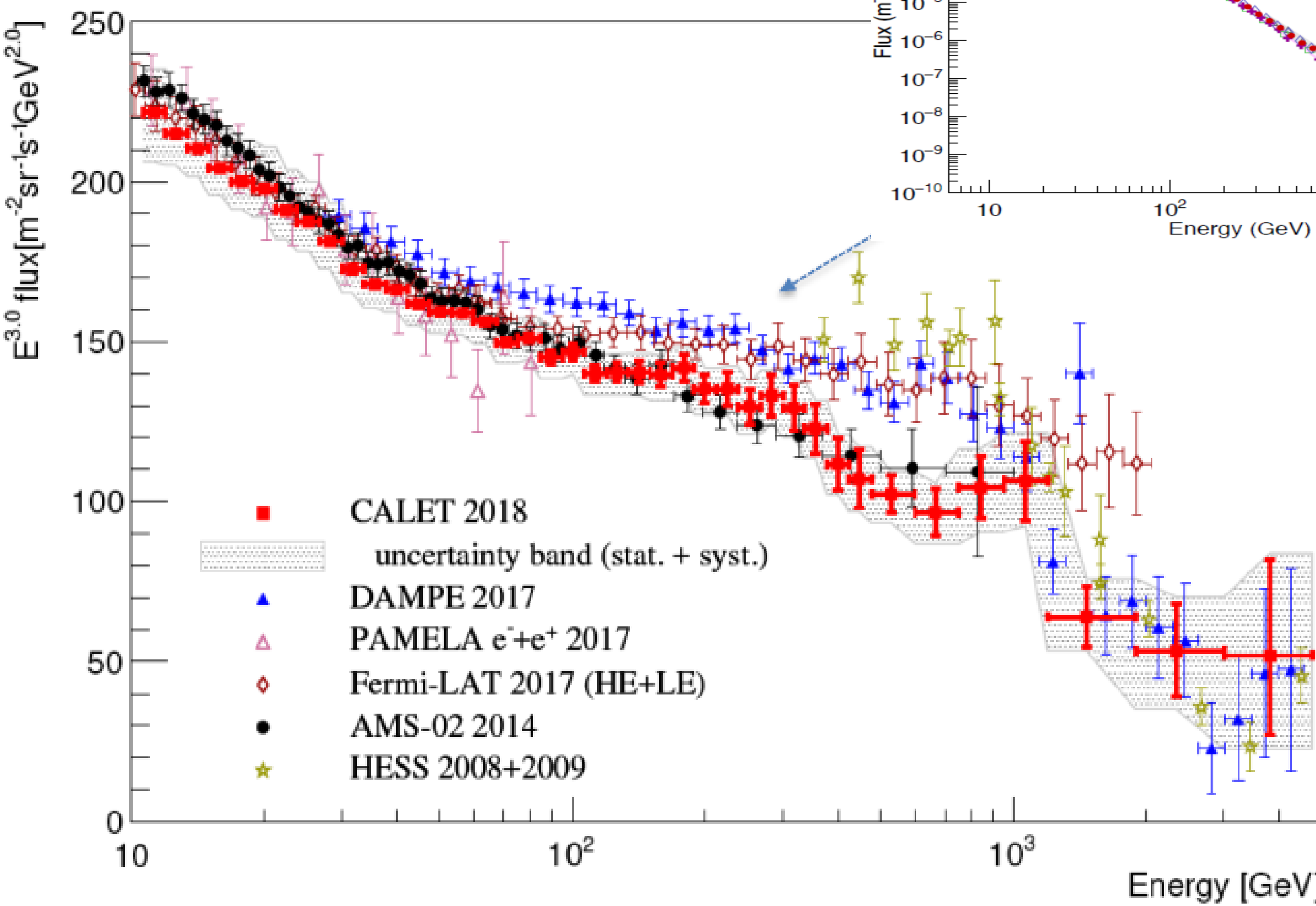




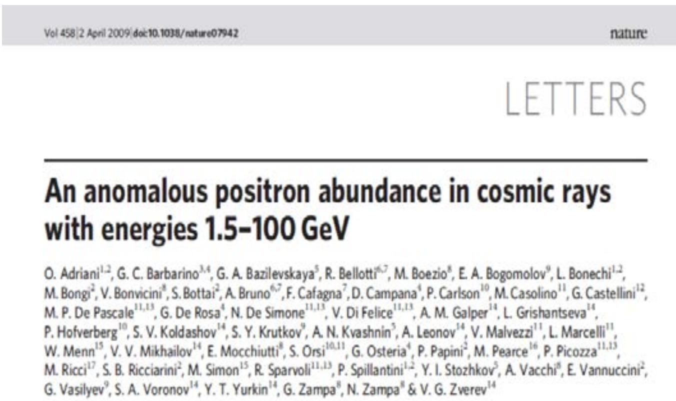
- 530 days
- 2.8 billions CR events
- 1.5 million CREs above 25 GeV

The all-electron flux





Antimatter: the positron fraction

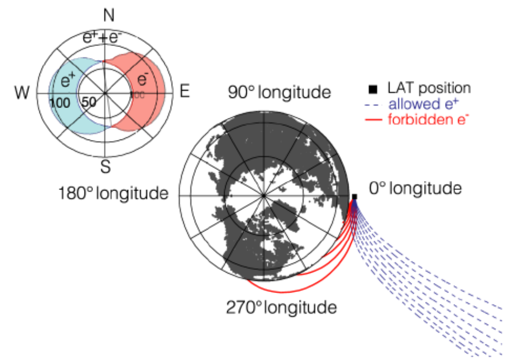


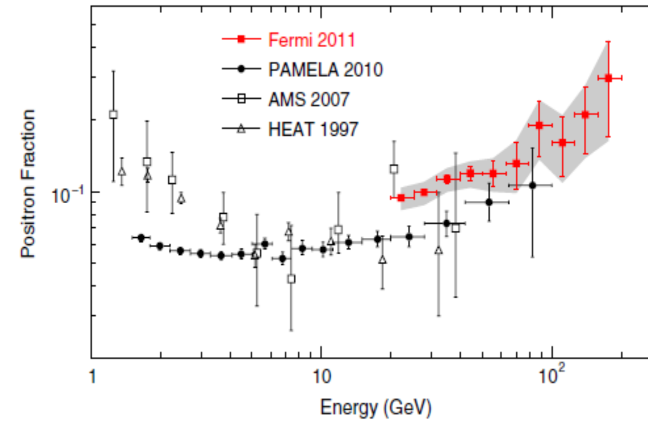
Vol 458 | 2 April 2009 | doi:10.1038/nature07942 nature

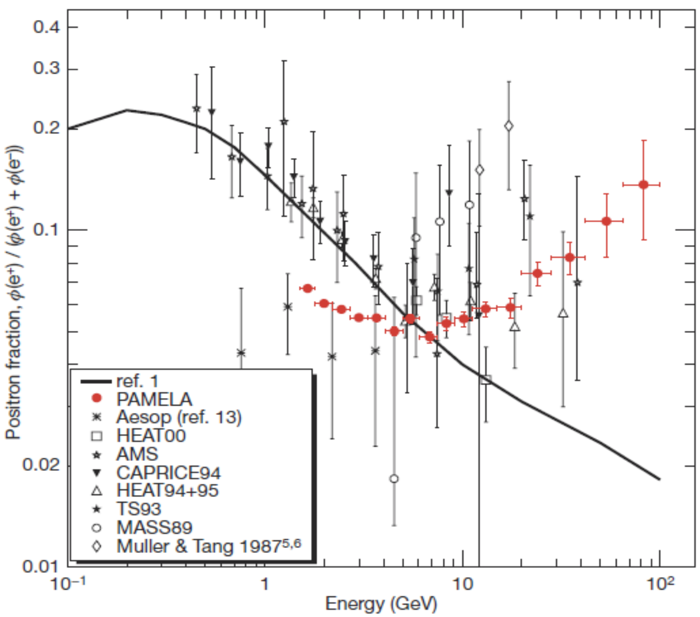
LETTERS

An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

O. Adriani[1,2], G. C. Barbarino[3,4], G. A. Bazilevskaya[5], R. Bellotti[6,7], M. Boezio[8], E. A. Bogomolov[9], L. Bonechi[1,2], M. Bongi[2], V. Bonvicini[8], S. Bottai[2], A. Bruno[6,7], F. Cafagna[7], D. Campana[4], P. Carlson[10], M. Casolino[11], G. Castellini[12], M. P. De Pascale[11,13], G. De Rosa[4], N. De Simone[11,13], V. Di Felice[11,13], A. M. Galper[14], L. Grishantseva[14], P. Hofverberg[10], S. V. Koldashov[14], S. Y. Krutkov[9], A. N. Kvashnin[5], A. Leonov[14], V. Malvezzi[11], L. Marcelli[11], W. Menn[15], V. V. Mikhailov[14], E. Mocchiutti[8], S. Orsi[10,11], G. Osteria[4], P. Papini[2], M. Pearce[16], P. Picozza[11,13], M. Ricci[17], S. B. Ricciarini[2], M. Simon[15], R. Sparvoli[11,13], P. Spillantini[1,2], Y. I. Stozhkov[5], A. Vacchi[8], E. Vannuccini[2], G. Vasilyev[9], S. A. Voronov[14], Y. T. Yurkin[14], G. Zampa[8], N. Zampa[8] & V. G. Zverev[14]



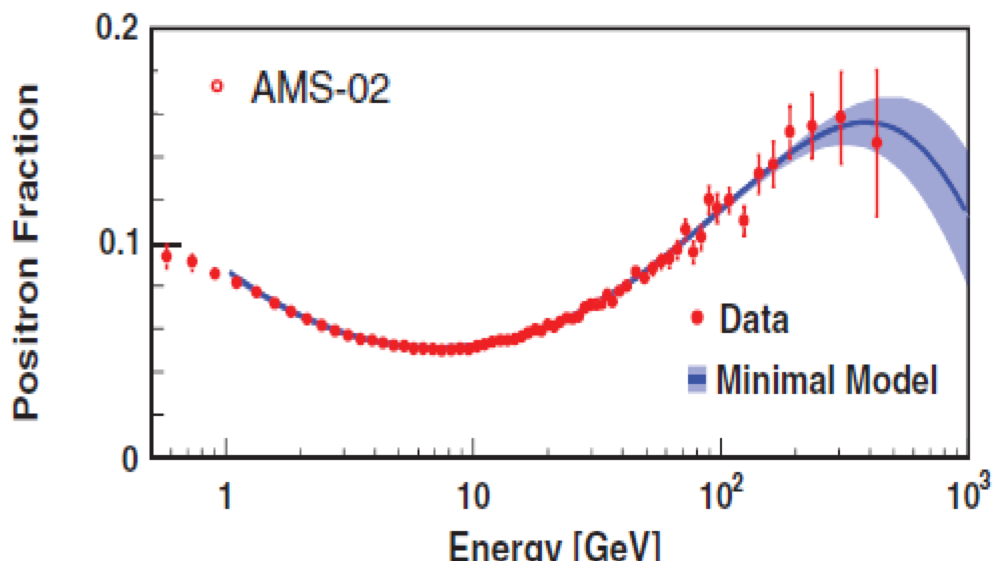




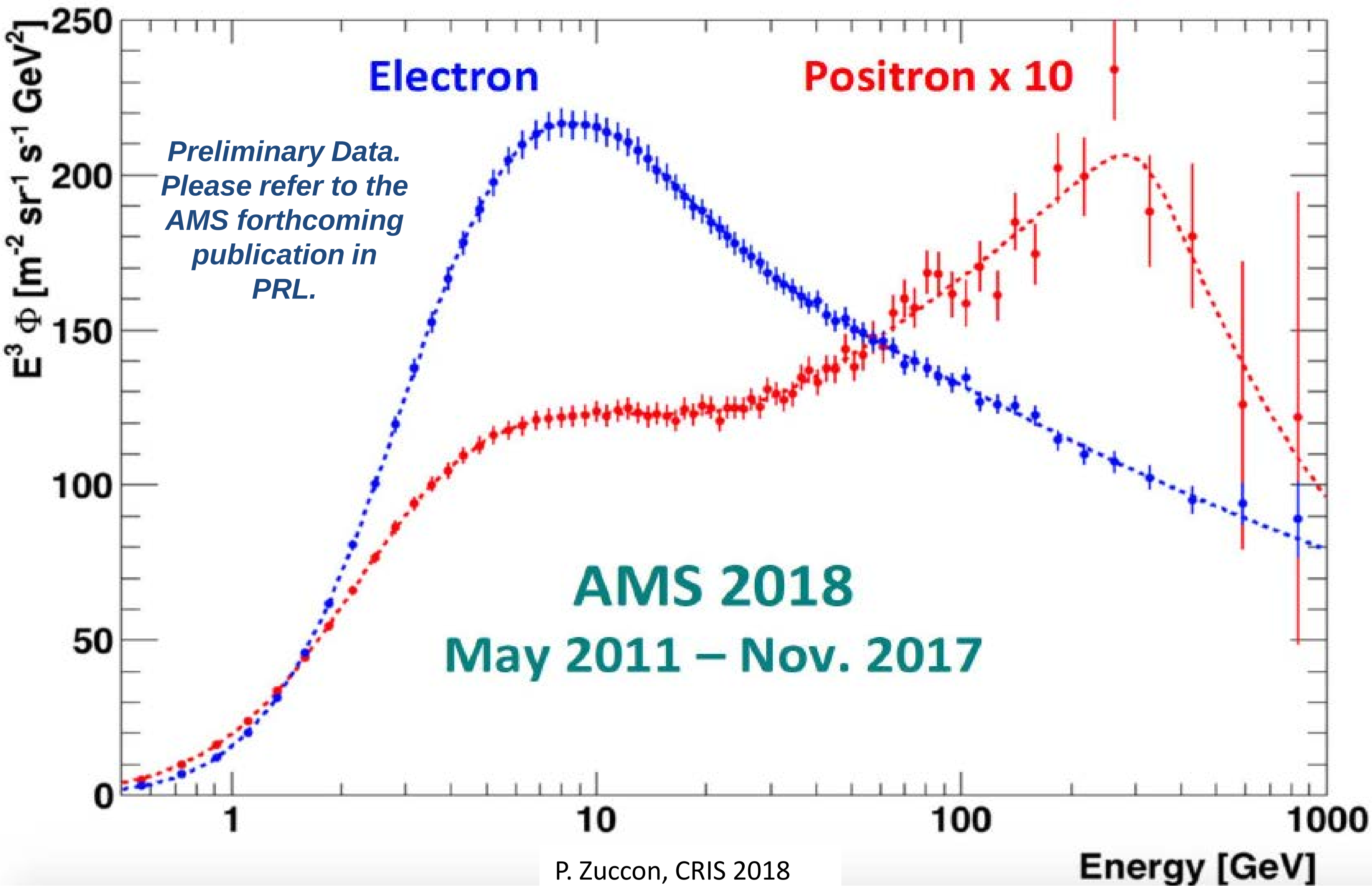
First "anomalous" results from PAMELA.

Extended and precise measurements by AMS-02

Drop above 300 GeV ?

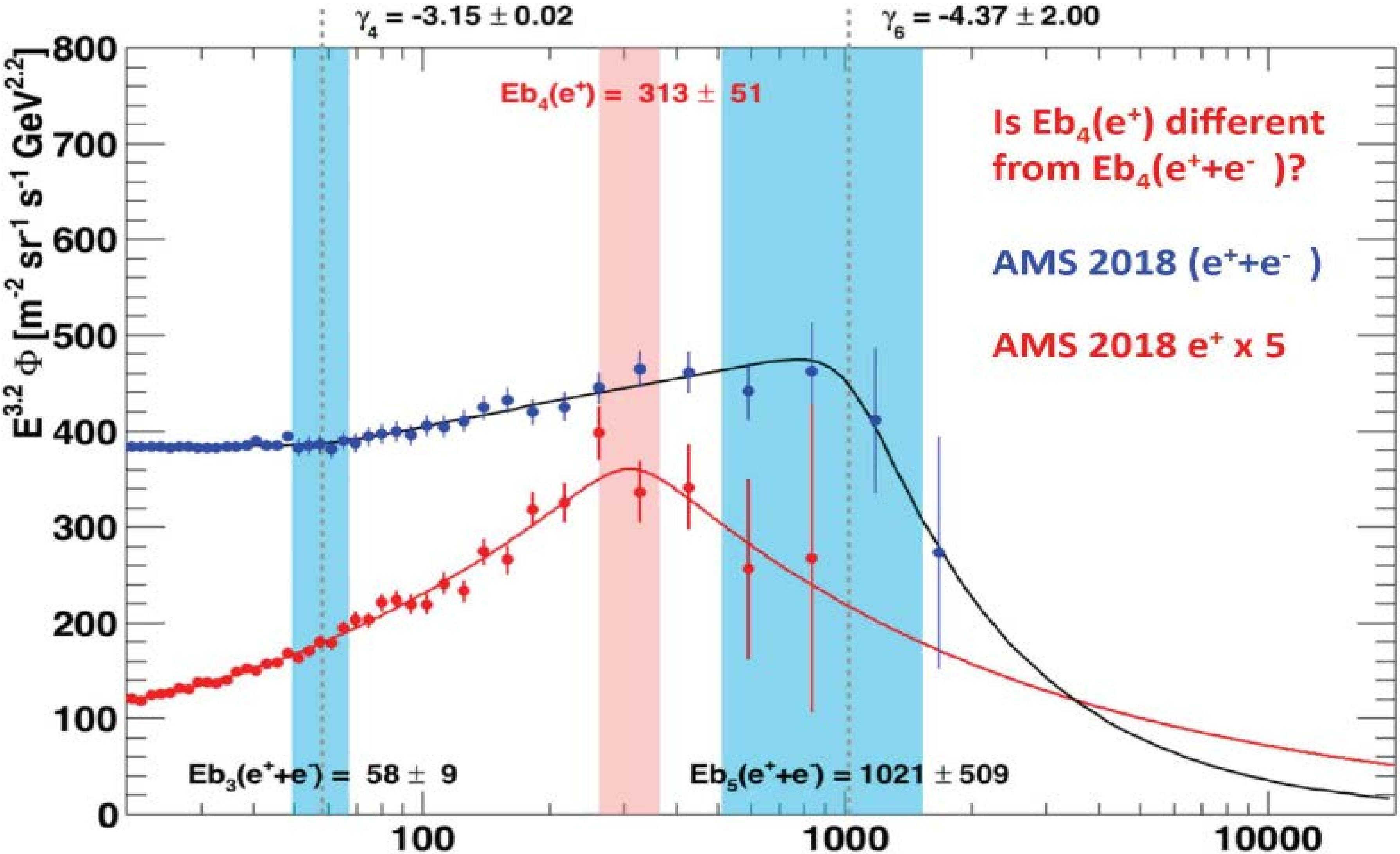


The e^+ and e^- fluxes with AMS-02



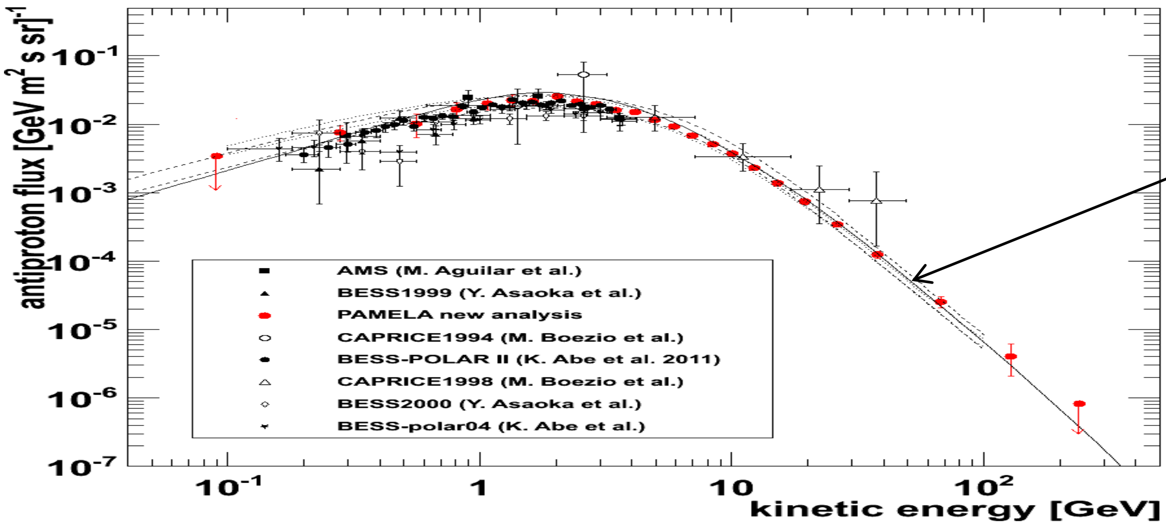
P. Zuccon, CRIS 2018

All-electrons vs positrons

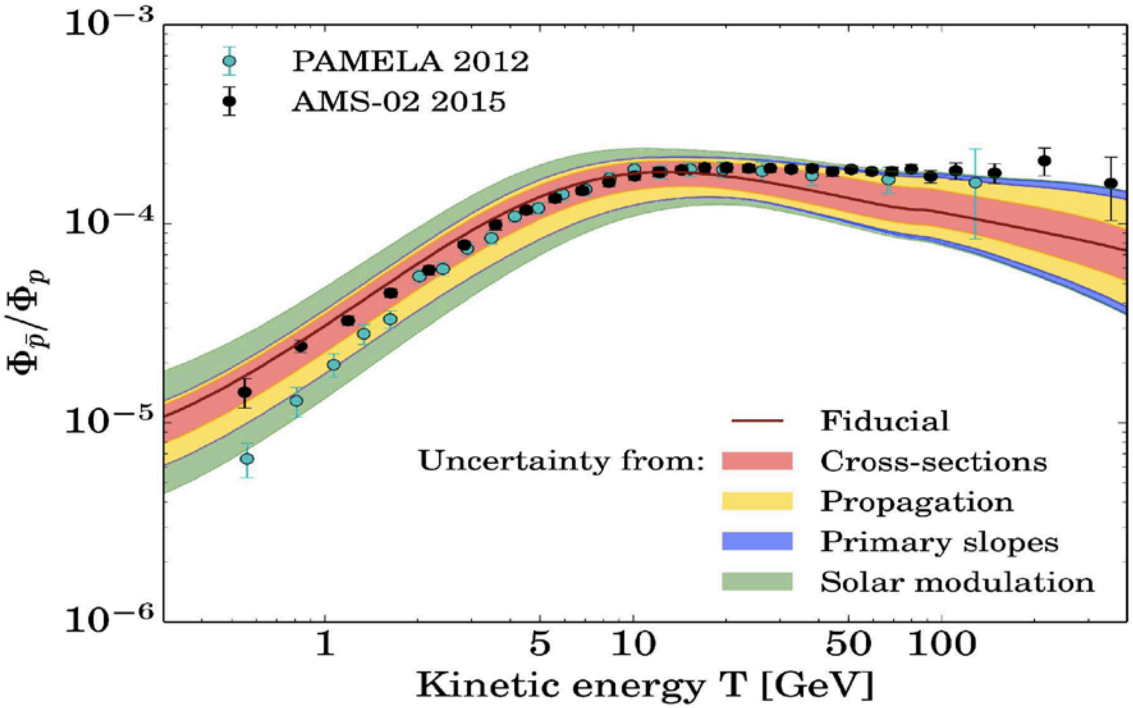


P. Zuccon, CRIS 2018

Antimatter: antiprotons



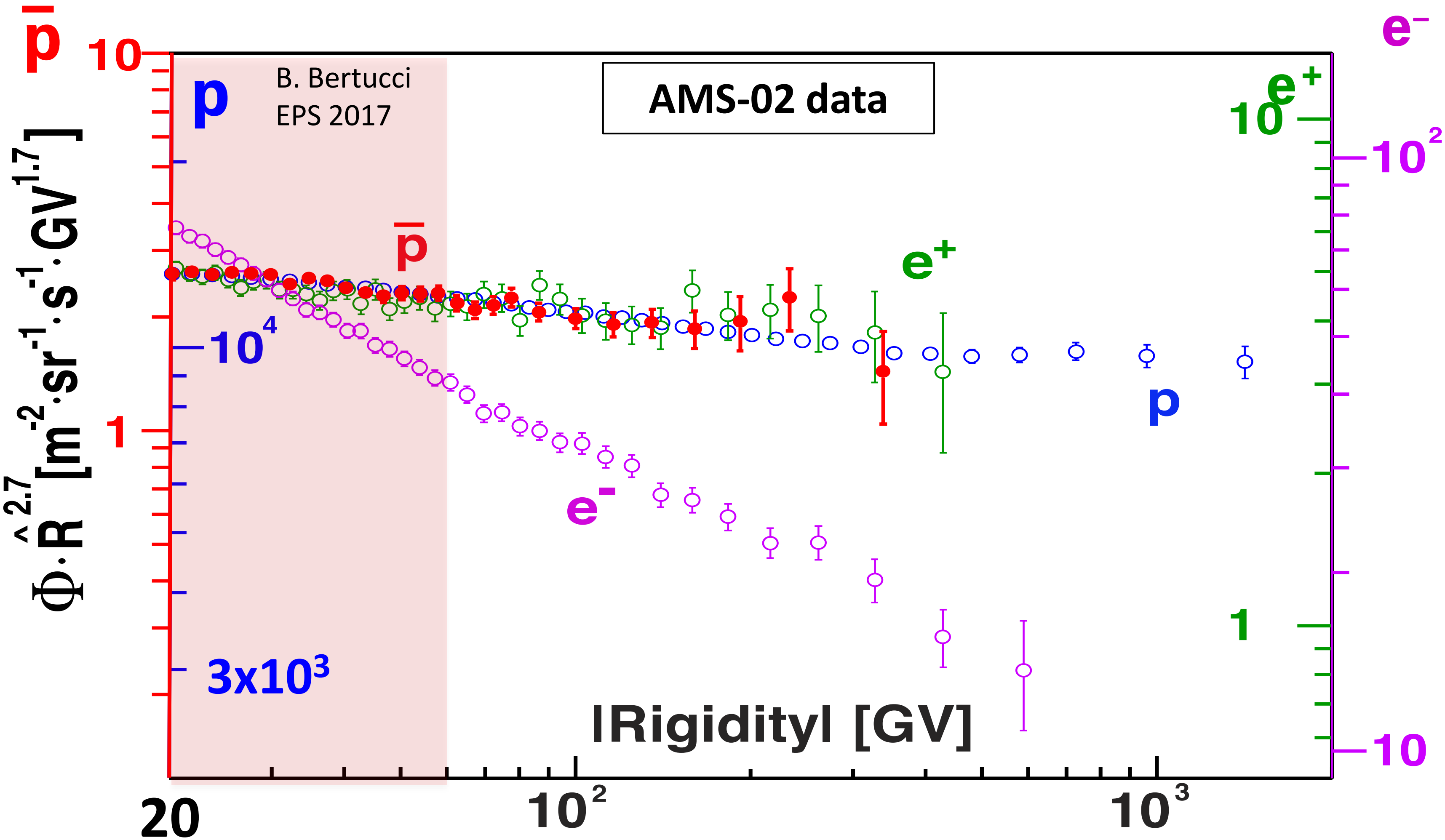
Antiproton flux consistent with secondary production calculations



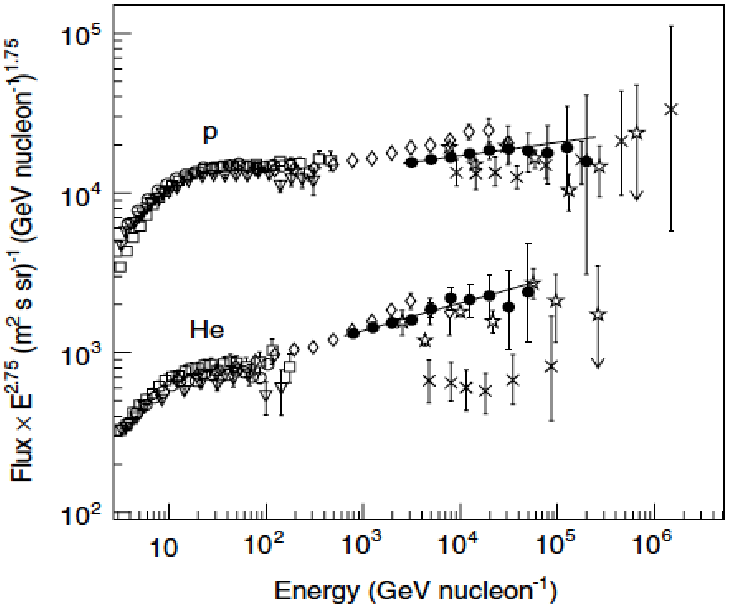
New measurements at accelerators (e.g. LHCb) in order to lower the systematic uncertainty on secondary production calculations

Secondary or primary origin ?

Same spectral dependence for protons, antiprotons and positrons
Softer spectrum for electrons

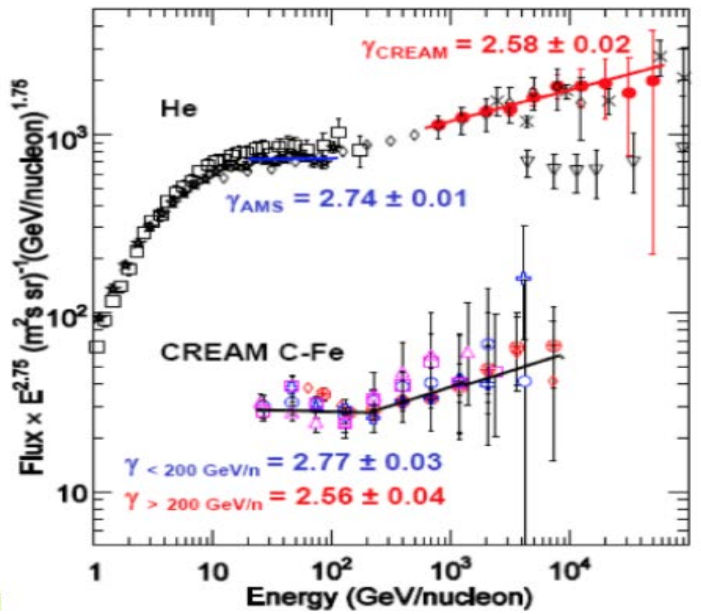


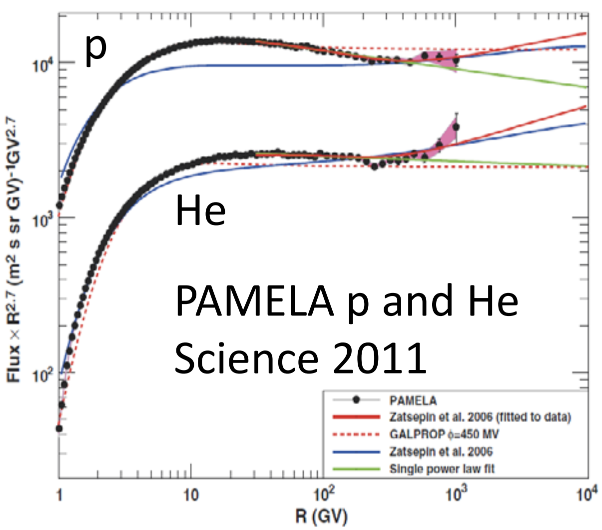
Proton and helium: (discrepant) hardenings



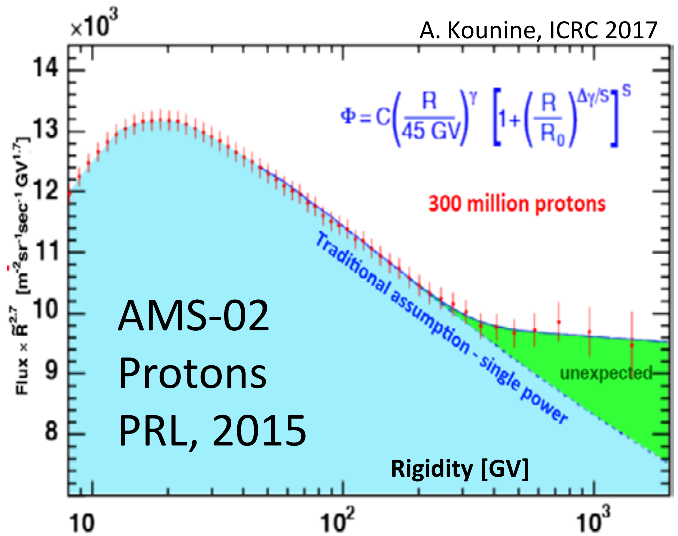
CREAM
First hints for Hardenings.

PAMELA and AMS
Direct detection fo the break at about 250GeV/n

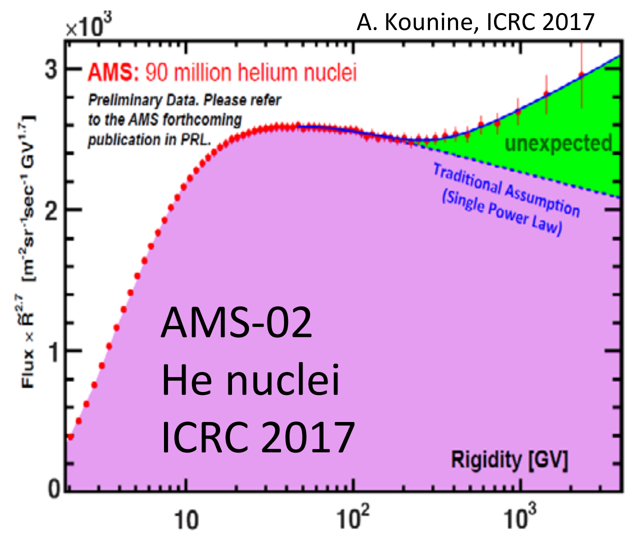




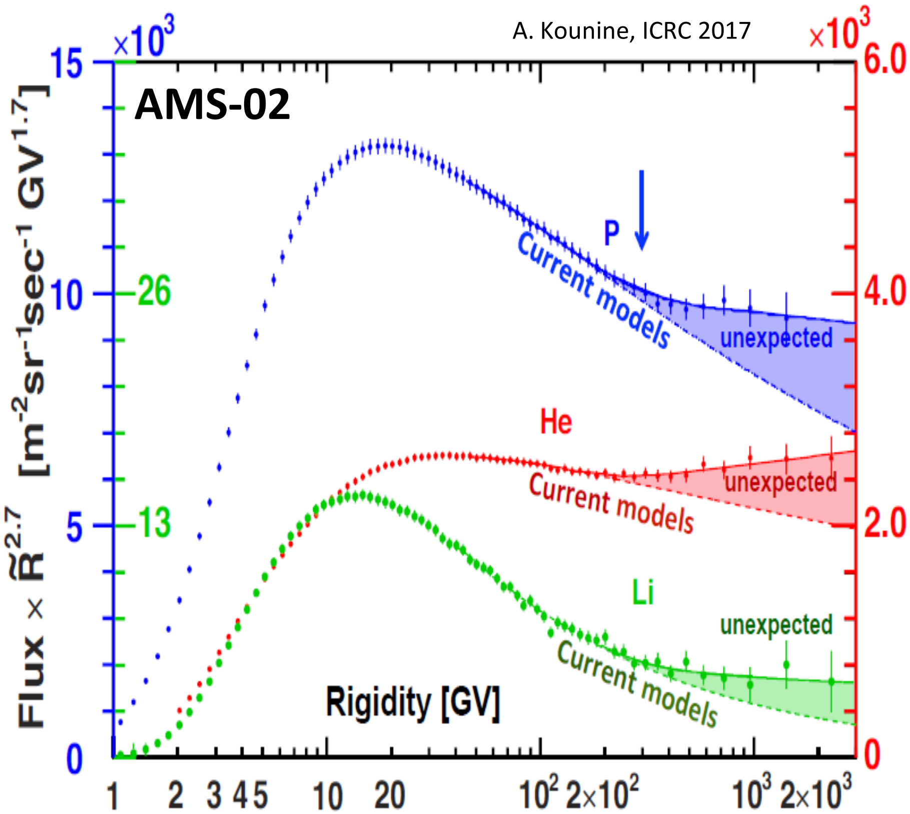
A. Kounine, ICRC 2017

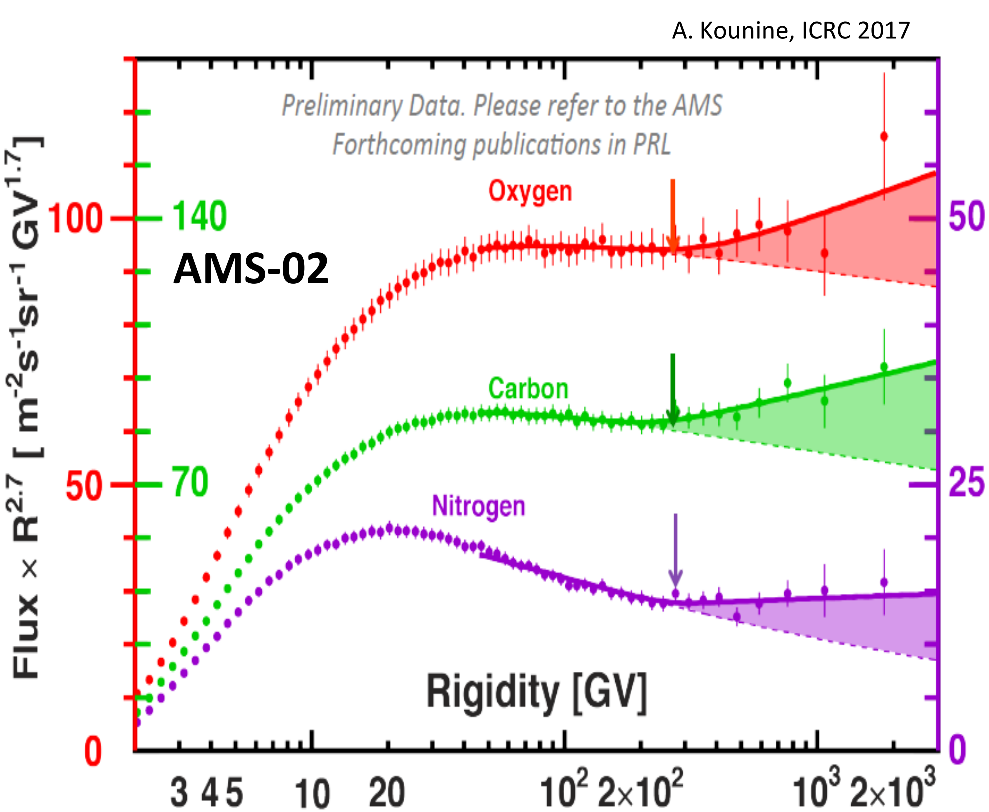


A. Kounine, ICRC 2017



Similar hardenings for other nuclei





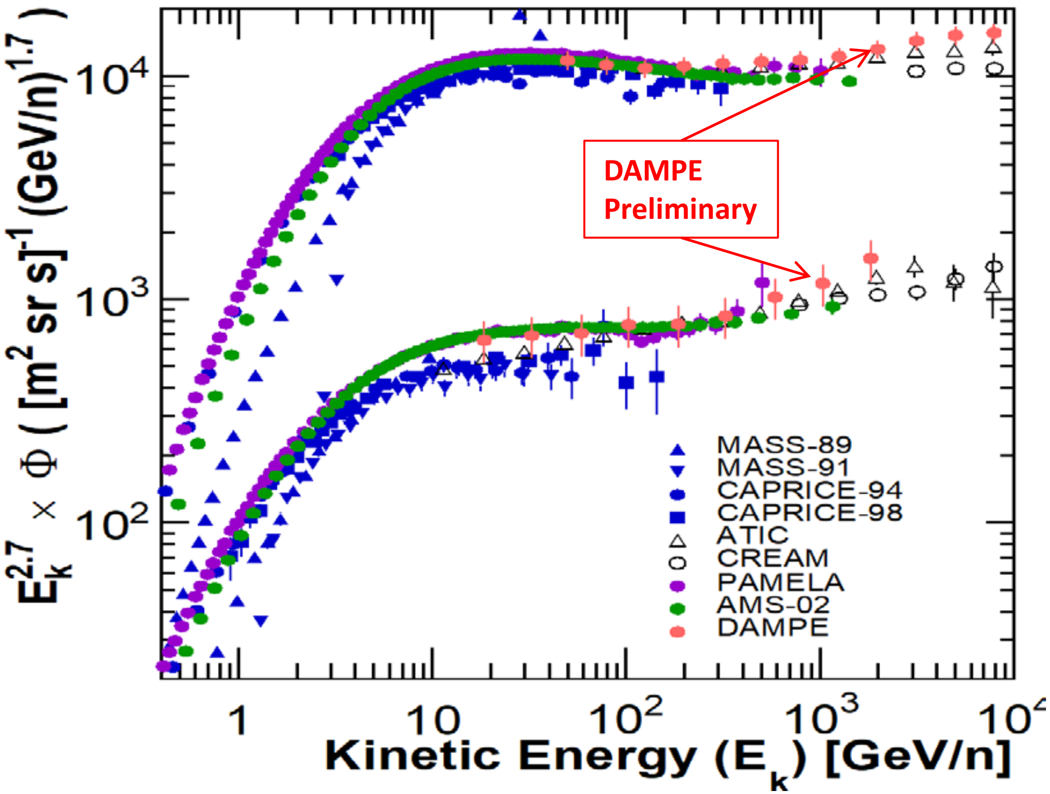
Acceleration or propagation effect ? Both ?

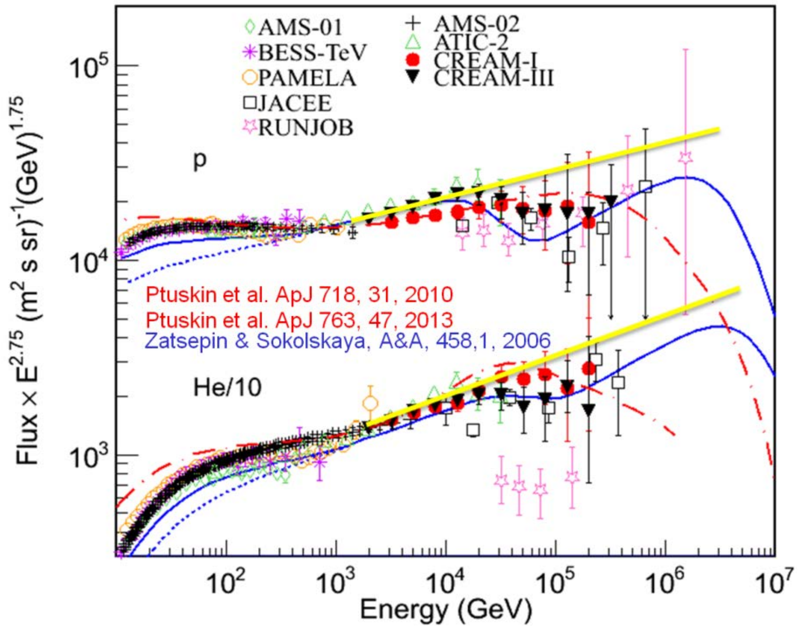
Need for precise measurements of secondary productions (B/C,..)

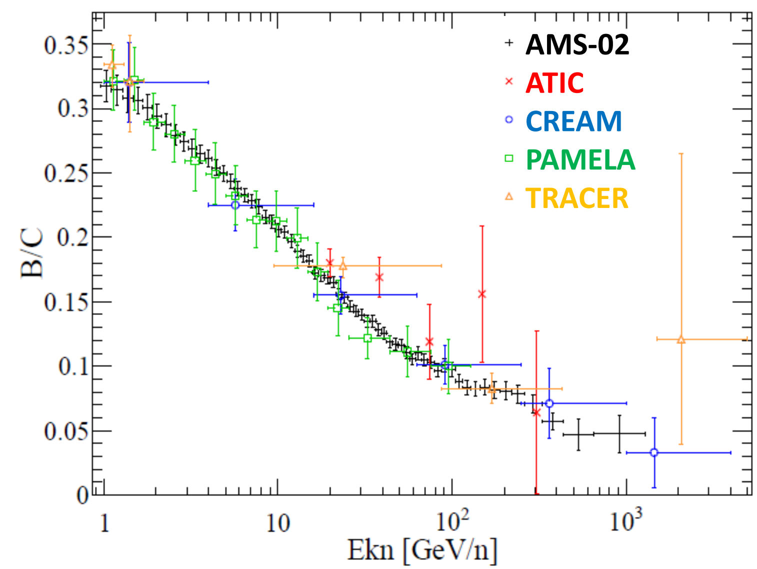
and

extensions in the 1-100 TeV energy region with large acceptance (an good resolution) calorimeters in space

Higher energy and secondaries…







1-100 TeV

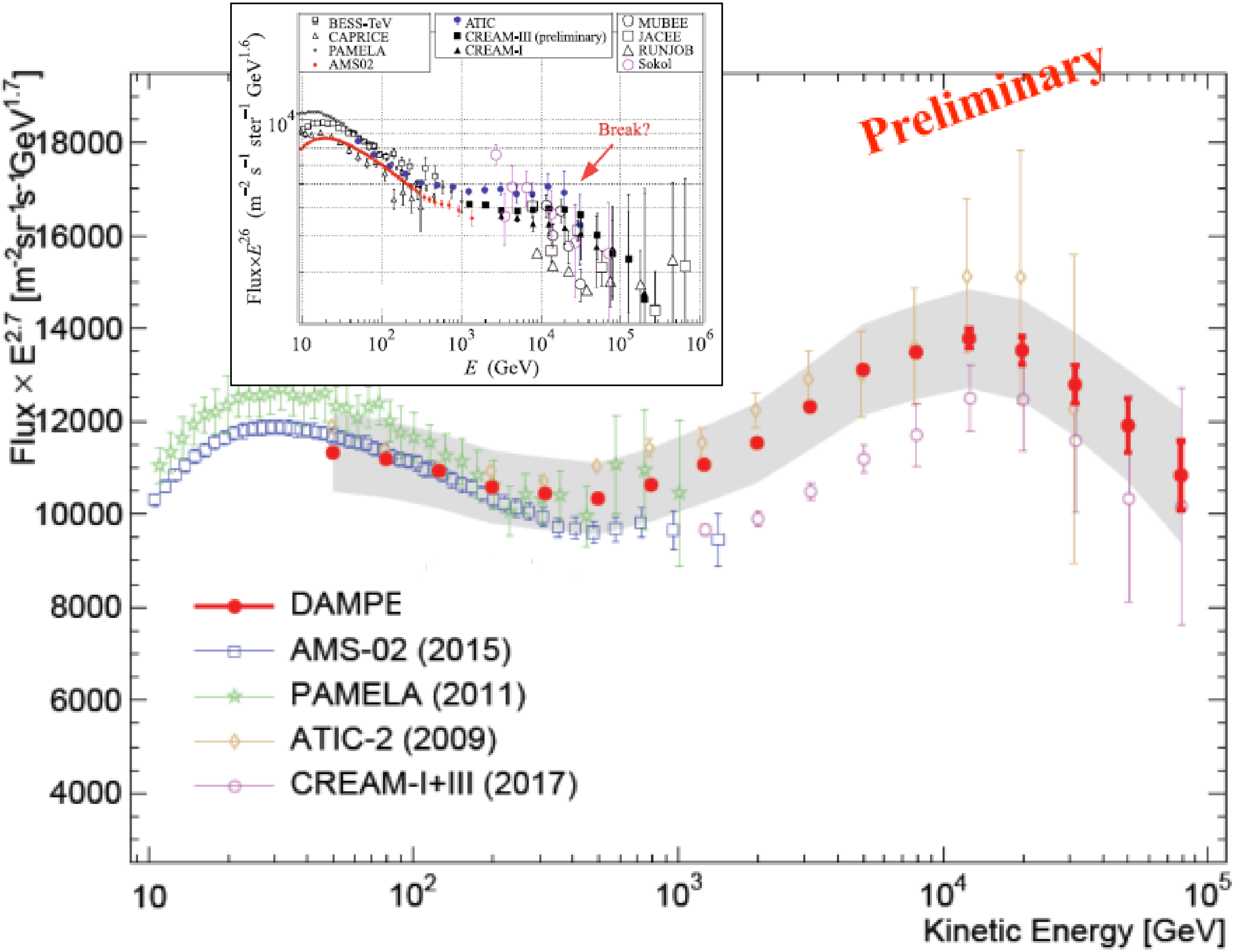
Explored by CREAM & NUCLEON

Preliminary results from DAMPE, CALET

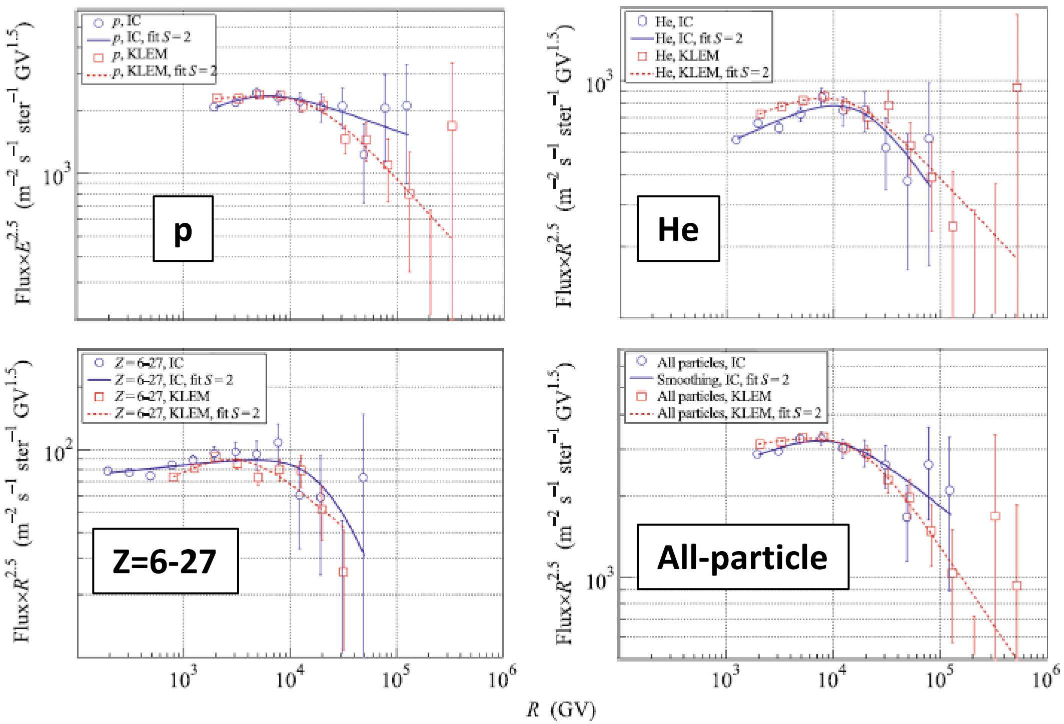
ISS-CALET taking data..

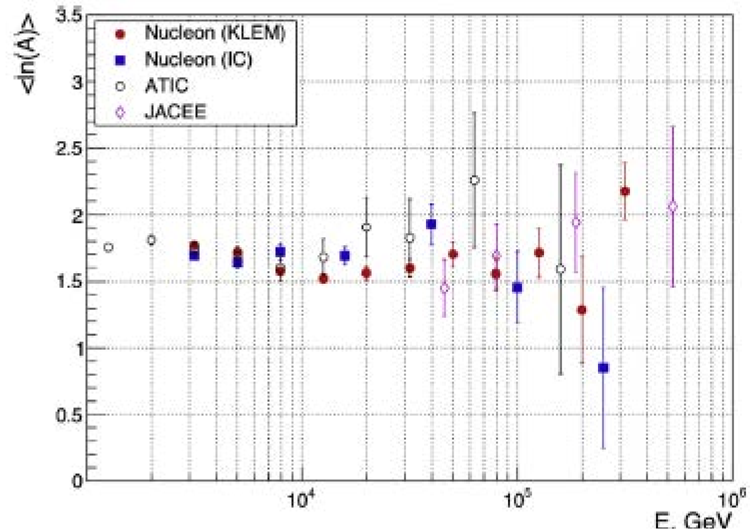
Go to higher energies: HERD

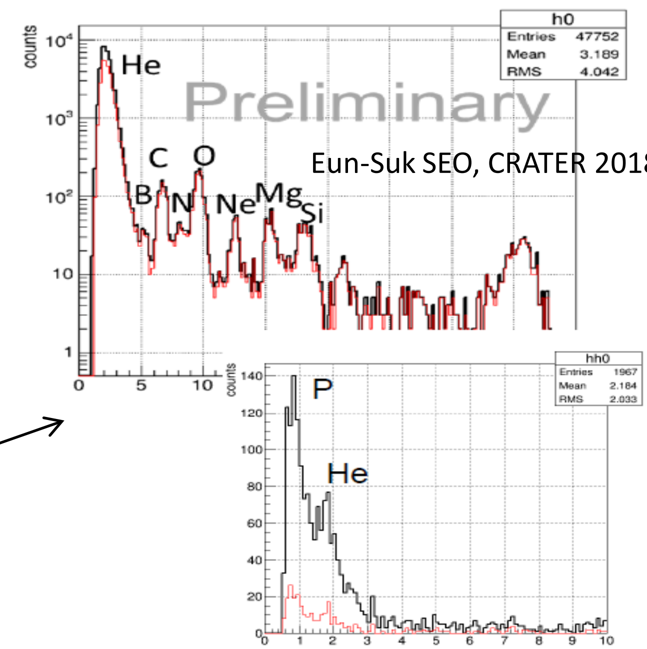
DAMPE preliminary proton flux



Other nuclei and larger energies







Nuclear spectra from NUCLEON (2018)

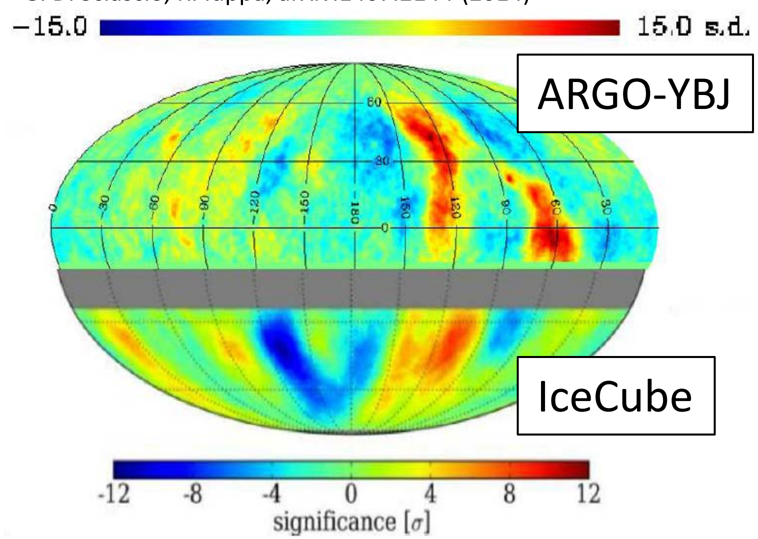
First data from ISS-CREAM

Anisotropies below the knee

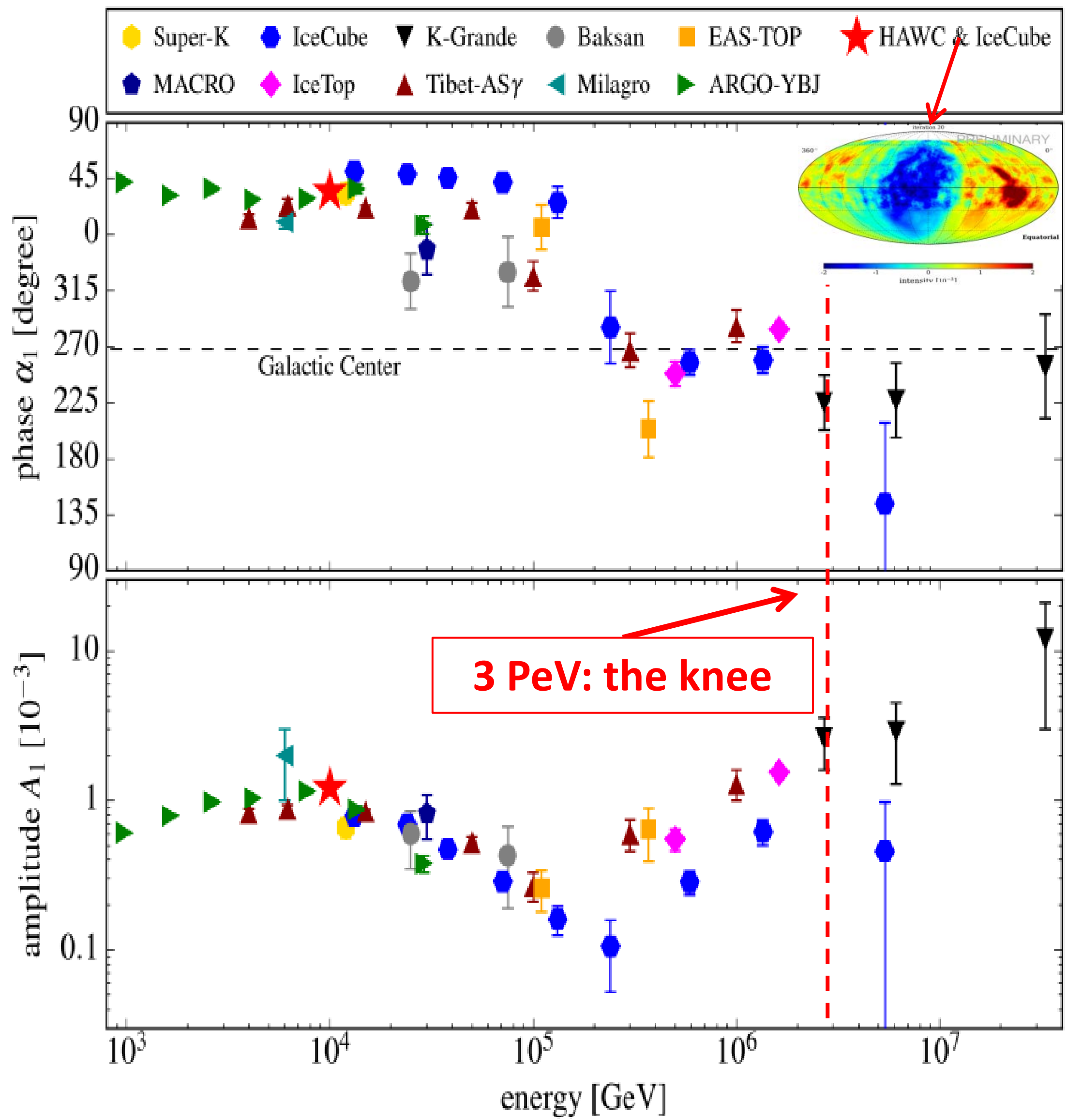
Large Scale anosotropies (LSA) at the level of 10^{-4}-10^{-3} in the multi TeV region with stable phase.
Change in phase and amplitude above 100TeV, below the all-particle knee.

Medium/Small scale anisotropies (MSA) in the few TeV range

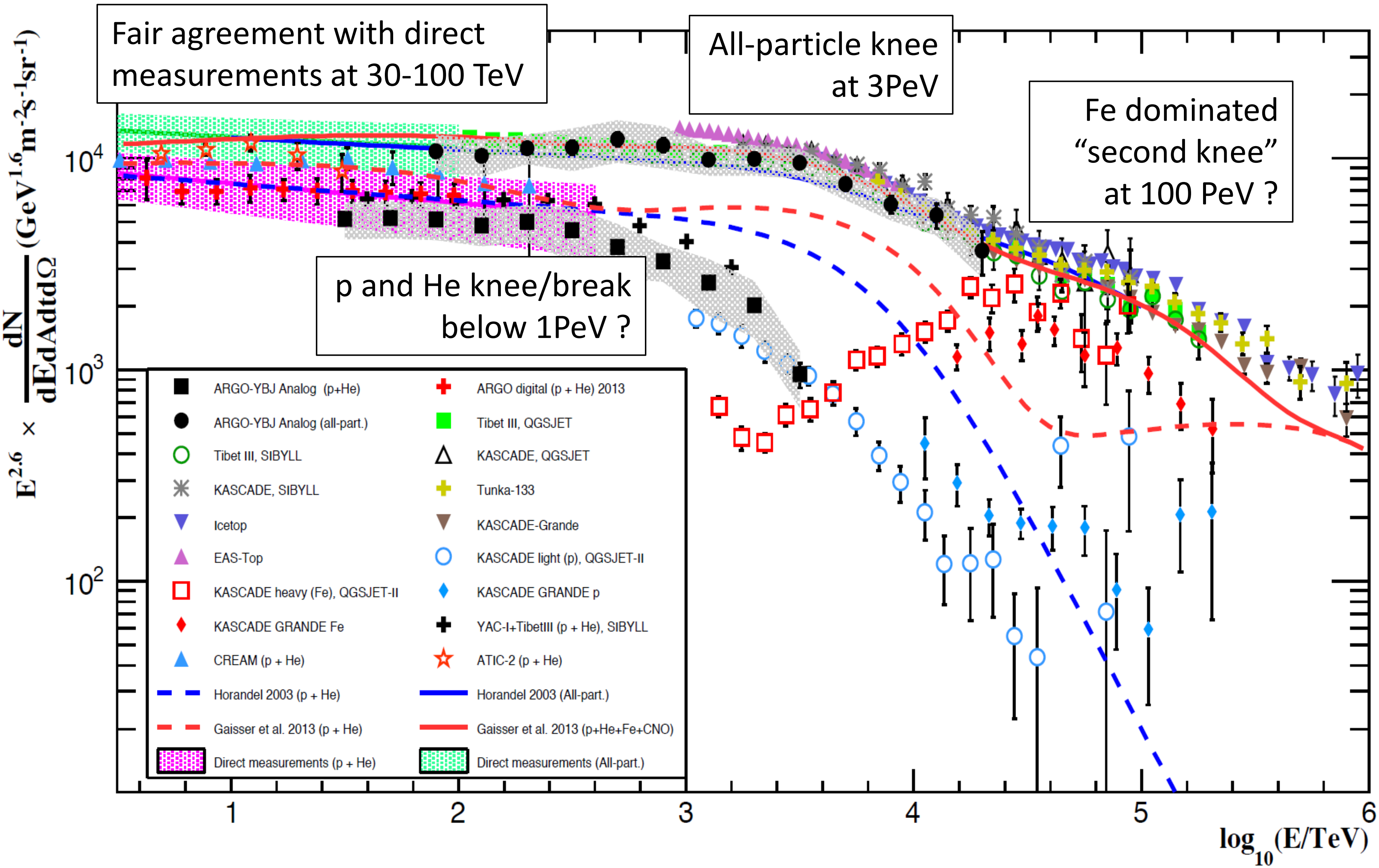
G. Di Sciascio, R. Iuppa, arXiv:1407.2144 (2014)



D. Caprioli ICRC 2017



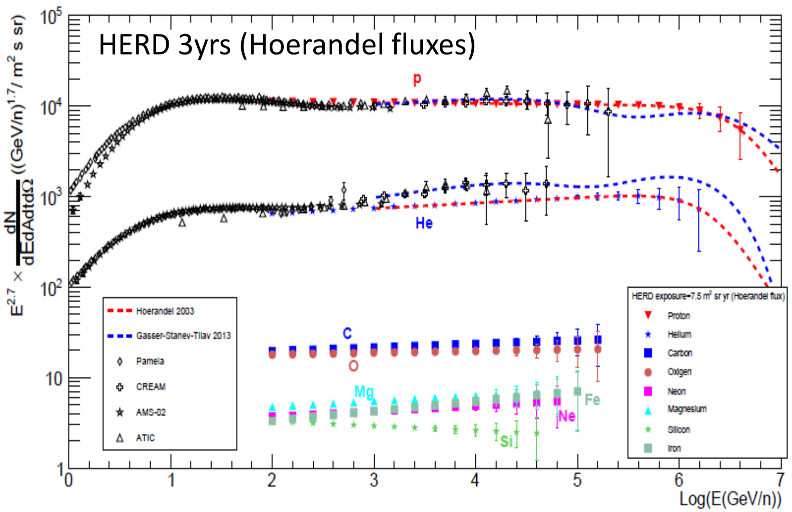
Spectra form EAS up to 100 PeV

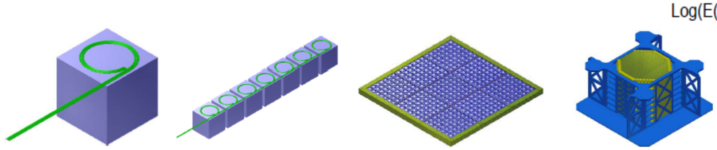


HERD: towards the knee from space

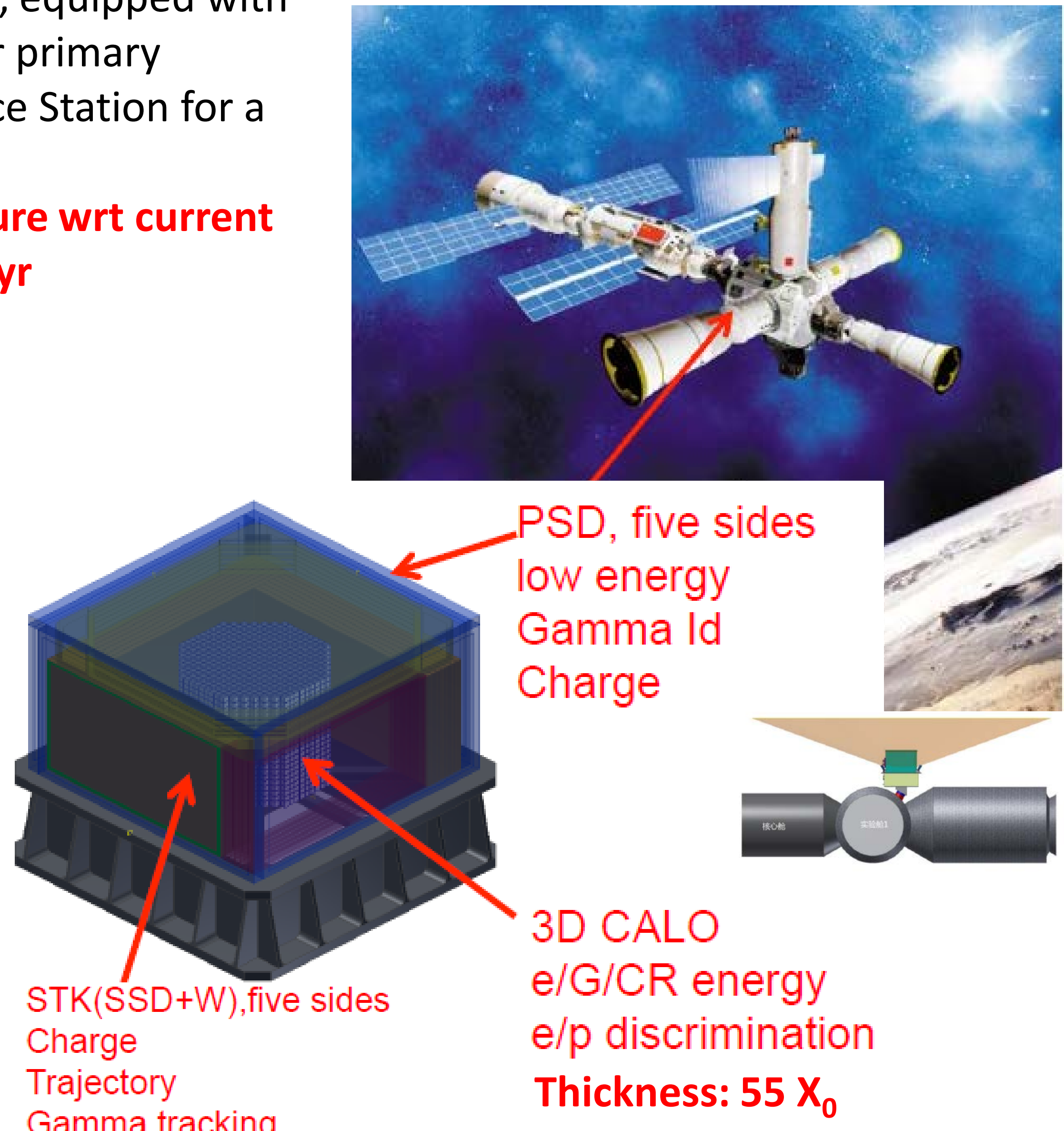
Large acceptance, deep, 3D calorimeter, equipped with silicon tracker and plastic scintillators for primary identification, onboard the Chinese Space Station for a long duration mission.

One order of magnitude jump in exposure wrt current generation CR experiment: 10-15 m^2 sr yr





item	Value	Note
Type of crystal	LYSO	
Nuclear Interaction Length	3	~ 21 LYSO crystals
Number of crystals	~7500	
Crystal dimension	3cm*3cm*3cm	
Fiber readout	3 WLSF/crystal	Low range, high range & trigger



From my talk at the last HERD workshop

Requirements… (1)

Protons & nuclei

- (Spectral Hardening)/evolutions
- Spectral indexes
- Early knee
- Individual knees
- Anisotropy (vs mass)

- $\sigma_E/E < 40\%$ for had. showers
- $\sigma_Z < 0.2\text{-}0.3$ e
- $GF \times T > 2.5\ m^2 sr \times 5 yr$
- Dynamic Range $\geq 10^7$
- N_{evt} @100 TeV $\geq 10^6$; $\Delta\theta<5°$

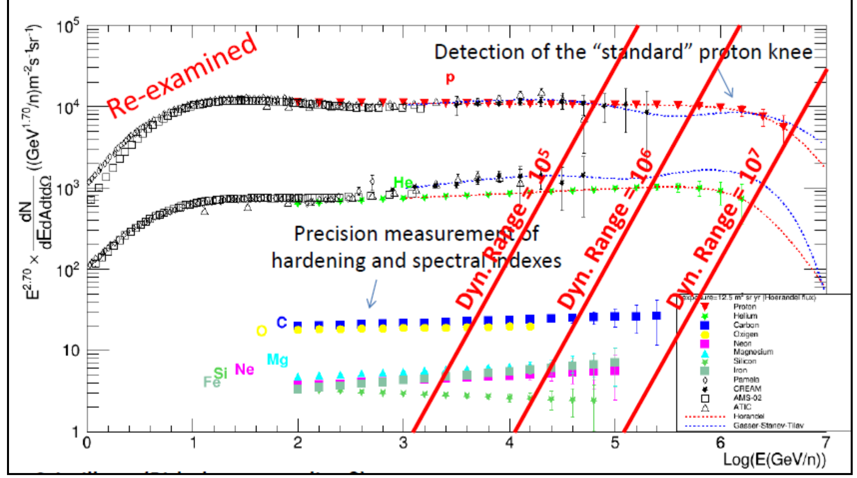
Electrons

- (Cutoff at 1 TeV)
- Nearby sources
- Anisotropy
- DM signatures
- e^+/e^- separation using geo-B

- $\sigma_E/E < 5\%$ for e.m. showers
- $GF \times T > 3.6\ m^2 sr \times 5 yr$
- e/p separation $\geq 10^6$
- Dynamic Range $\geq 2\cdot10^5$
- N_{evt} above 1TeV $\geq 10^4$; $\Delta\theta<3$

HERD workshop - Rome, February 2017 Ivan De Mitri

Nuclei up to Fe (HERD , 5 years , Hoerandel fluxes)



Requirements… (2)

- $\sigma_E/E < 40\%$ for had. showers
- $\sigma_Z < 0.2\text{-}0.3$ e
- $GF \times T > 2.5\ m^2 sr \times 5 yr$
- Dynamic Range $\geq 10^7$
- N_{evt} @100 TeV $\geq 10^6$; $\Delta\theta<5°$

- $\sigma_E/E < 5\%$ for e.m. showers
- $GF \times T > 3.6\ m^2 sr \times 5 yr$
- e/p separation $\geq 10^6$
- Dynamic Range $\geq 2\cdot10^5$
- N_{evt} above 1TeV $\geq 10^4$; $\Delta\theta<3°$

- CALO: $L > 2\ \Lambda$
- PSD/STK: Dyn. Range $\geq 10^3$
- PSD: high segmentation
- CALO : mass > 0.9 ton
- CALO: Dynamic Range $\geq 10^7$
- CALO: $L > 30\ X_0$
- PSD: efficiency > 98%
- CALO: imaging
- Neutron Detector ?
- Trigger / prescaling
- Calibrations (mips, geo-cutoff,..)
- CALO: dual readout

HERD workshop - Rome, February 2017 Ivan De Mitri 18

Starting from current design:
- Maximize acceptance (calorimeter mass) and dynamic range.
- Ensure ion identification up to iron.
- Provide smart on-orbit calibration tools.
- Carefully optimize the trigger logics
- …

Need detailed simulations and a dedicated "task force"

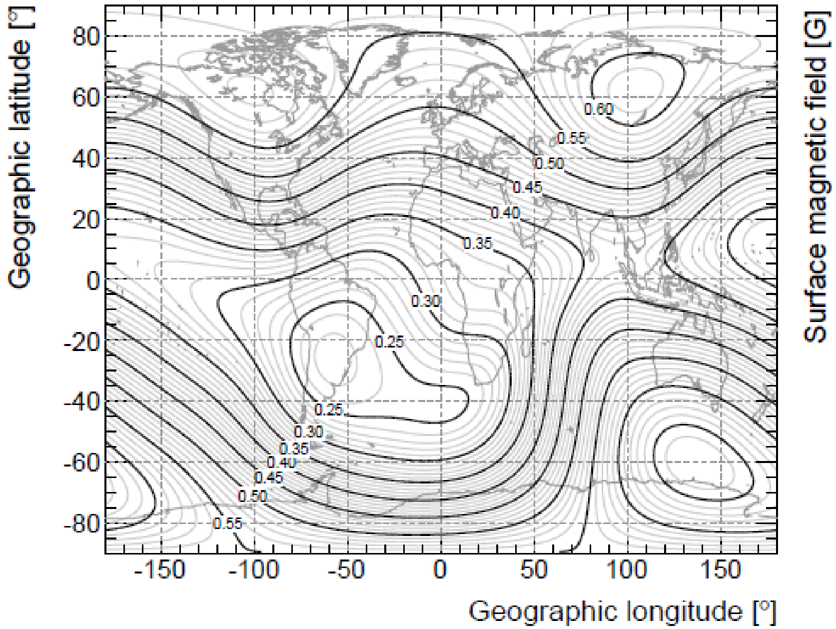
Much more stuff…

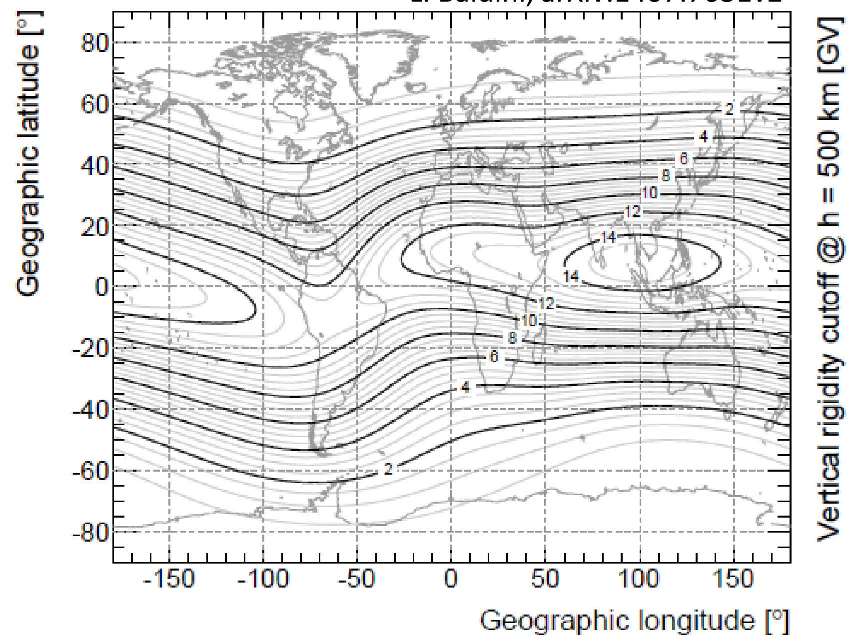
-More on direct measurements
-Indirect measurements
-Gammas and neutrinos

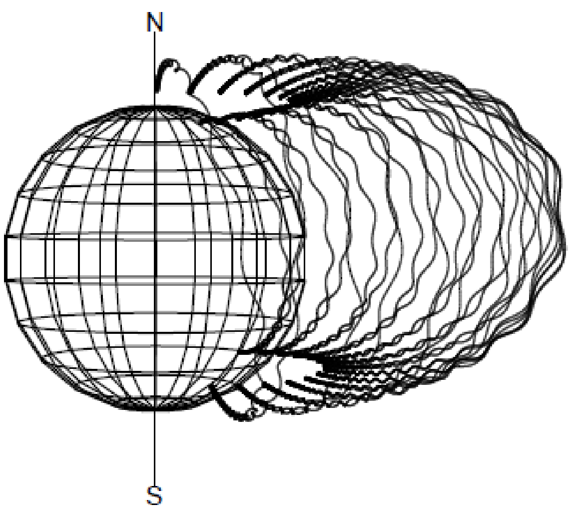
"The time is gone, the ~~song~~ talk is over,
thought I'd something more to say…."
Time, The dark side of the moon (1973)

The effects of the Geomagnetic field

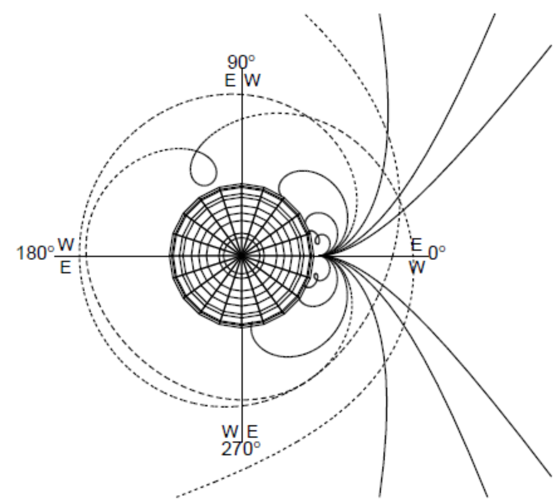
L. Baldini, arXiv:1407.7631v2



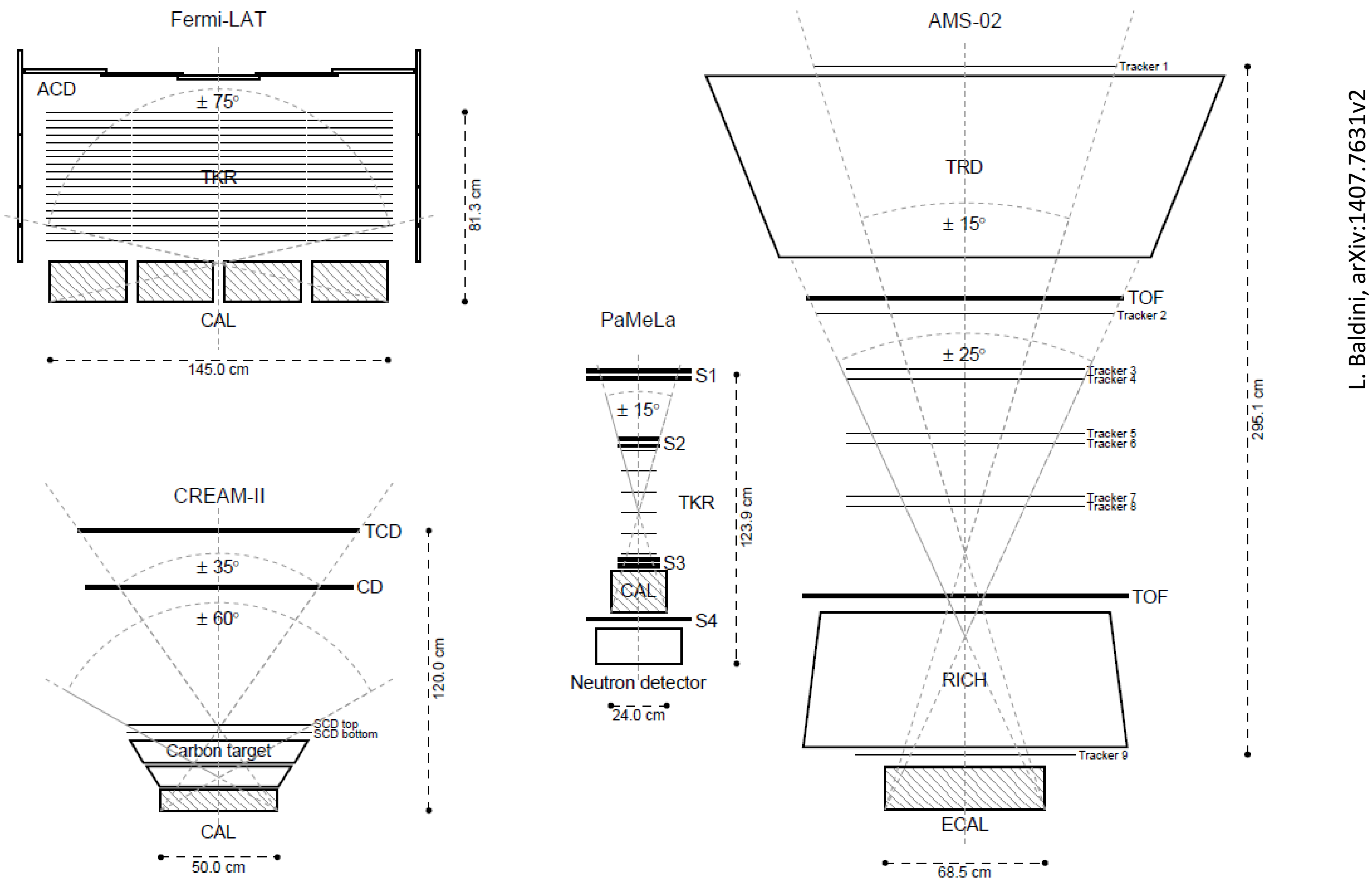




Rigidity cutoff
South Atlantic Anomaly
Van Allen belts
………
prescaling triggers
veto SAA
…..



Calorimetry vs Spectrometry



Acceptance (energy reach) vs Resolution (spectral features , antimatter)

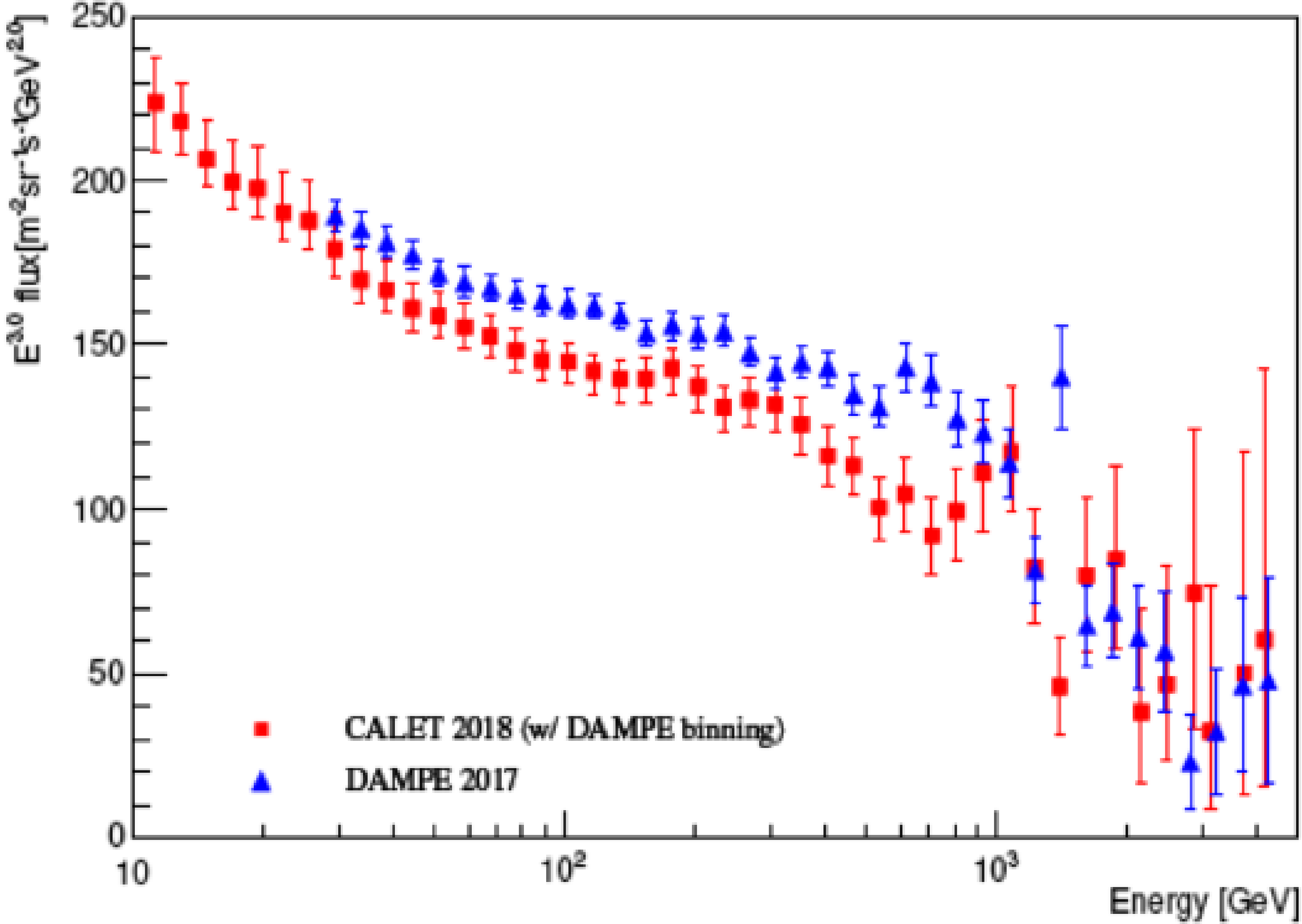
Typical detector elements for **charged particle direct measurements**

What we want to know:
- **Incoming direction**
- **Energy**
- **Particle type**

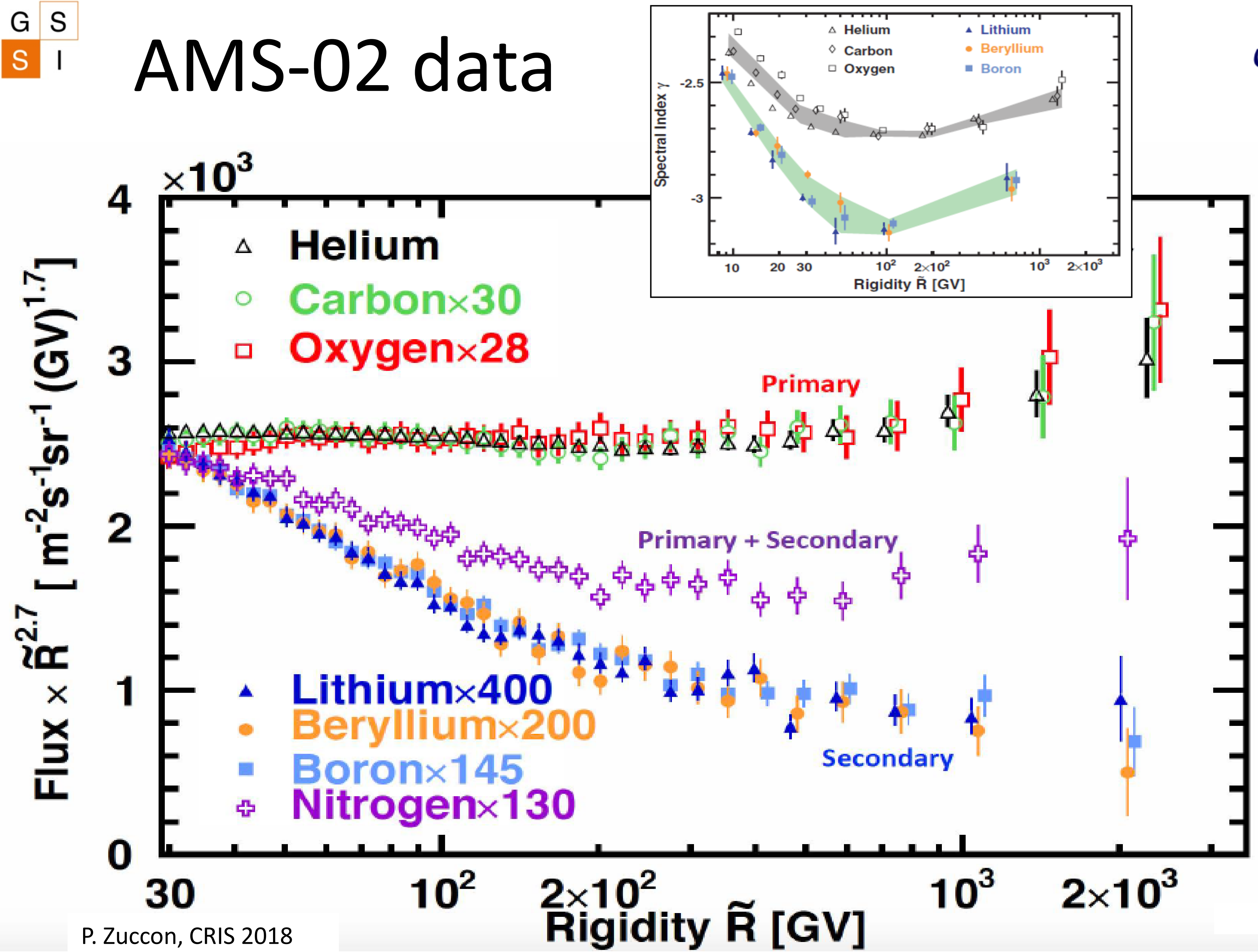
Issues:
- Limited weight and size
- Power budget
- Thermal and mechanical models
- Calibration
- Space “wheather”

How to do:
- Tracking system (Si trackers, …..)
- Magnetic spectrometer (particle rigidity, charge sign)
- Particle Identification (TRD’s, Cherenkov,…)
- dE/dx measurements (particle charge)
- Calorimeter (e.m. homogeneous or sampling calorimeter)
- Veto system (scintillator layer, …)
- Time of Flight (particle identification,…)
- Neutron detector (hadron / e.m. shower separation)

All electrons: DAMPE and CALET



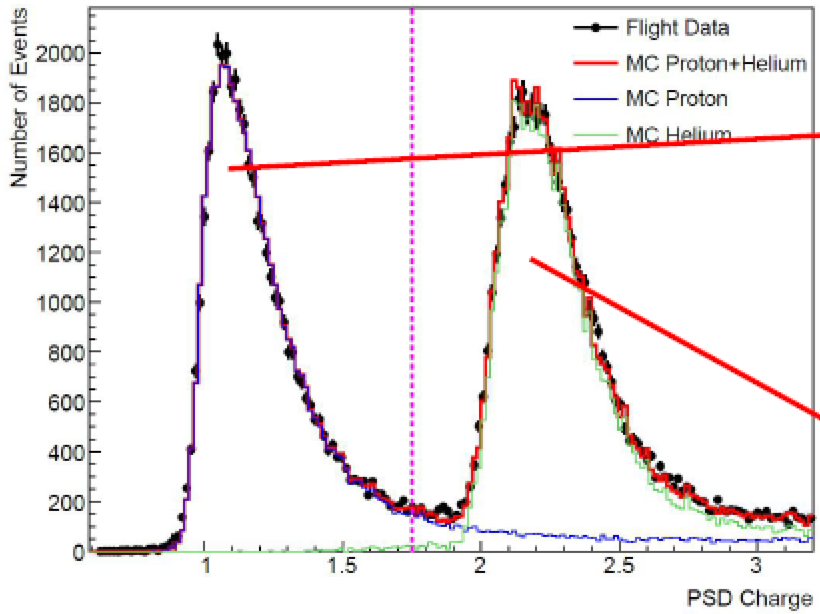
AMS-02 data

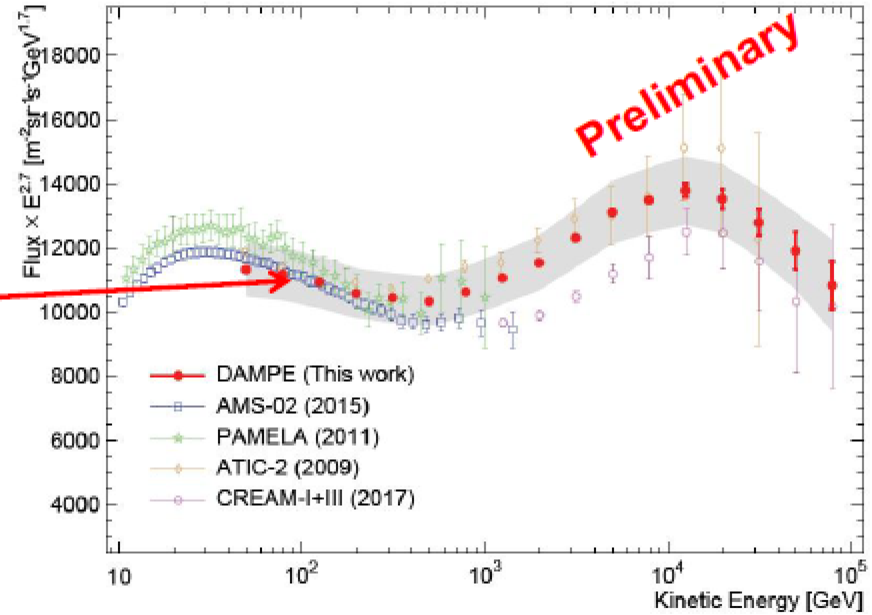


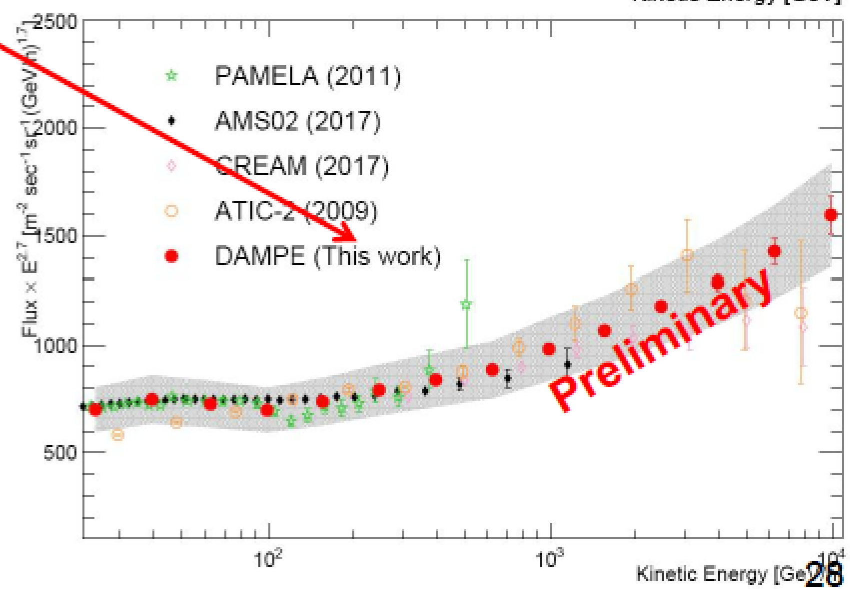
P. Zuccon, CRIS 2018

DAMPE p and He

[450-550] GeV

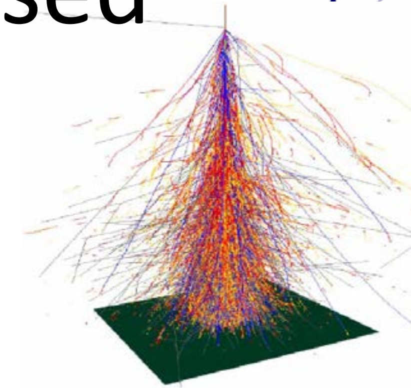






See talks E1.5-0019-18 (proton), E1.5-0018-18 (helium) on 19th

Space-Balloon vs Ground based



Direct measurements

Requirements:

Calorimetry vs Spectrometry

Large acceptances

<20% resolutions

Output:

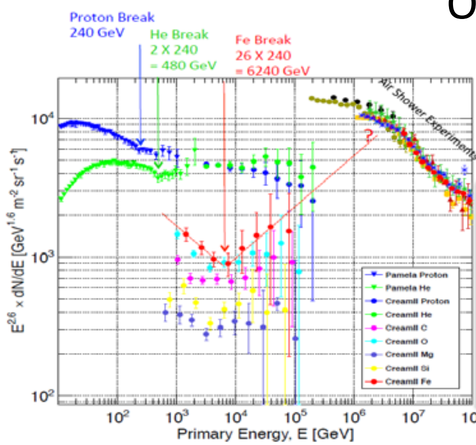
Fully explore the sub-PeV region

Limitations:

Surface/weight limited

Hard to reach the all-particle knee

Need high technology



Indirect measurements

Requirements:

Multi-Hybrid approach

Operate at (not too) high altitude

Large surfaces / samplings

Output:

Reach the highest energies

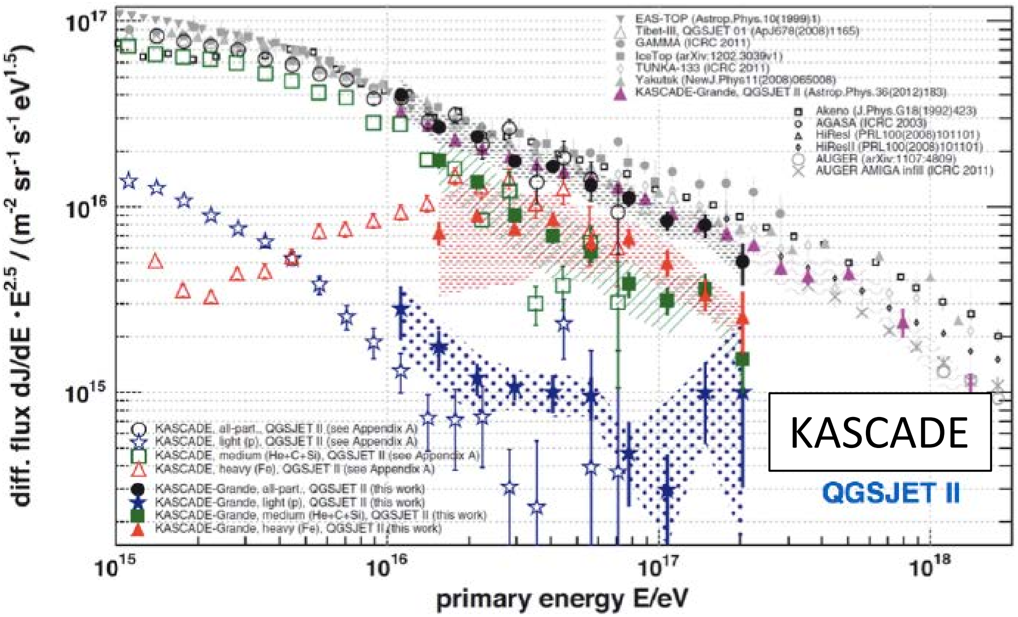
Limitations:

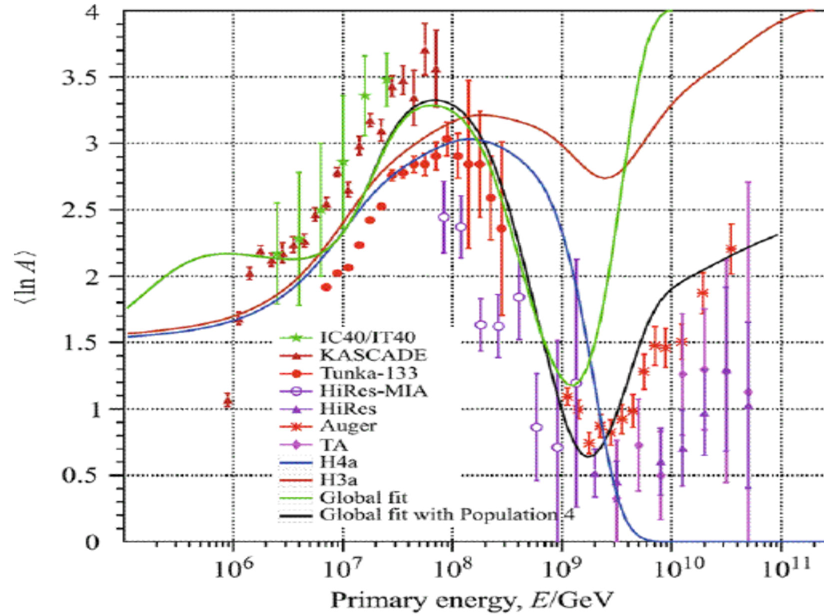
Poor mass resolution

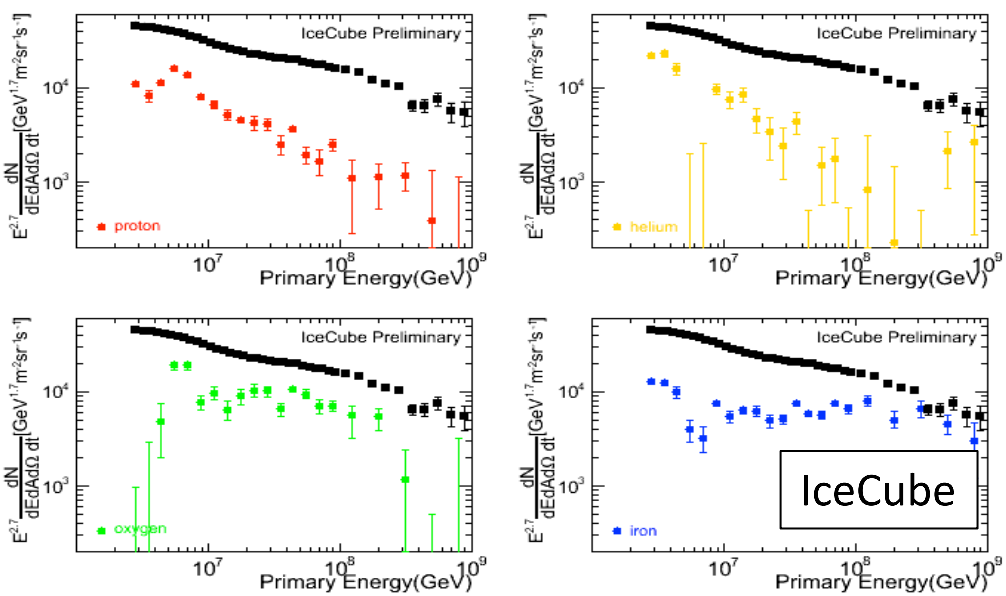
Intrinsically limited by systematics

Large model dependence

Composition across the knee and beyond





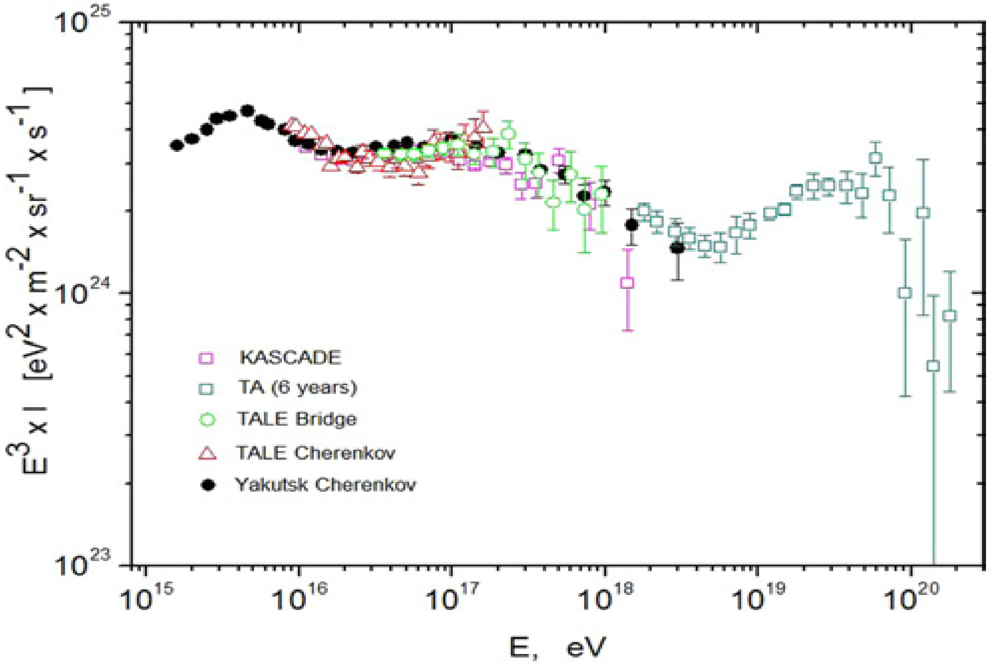


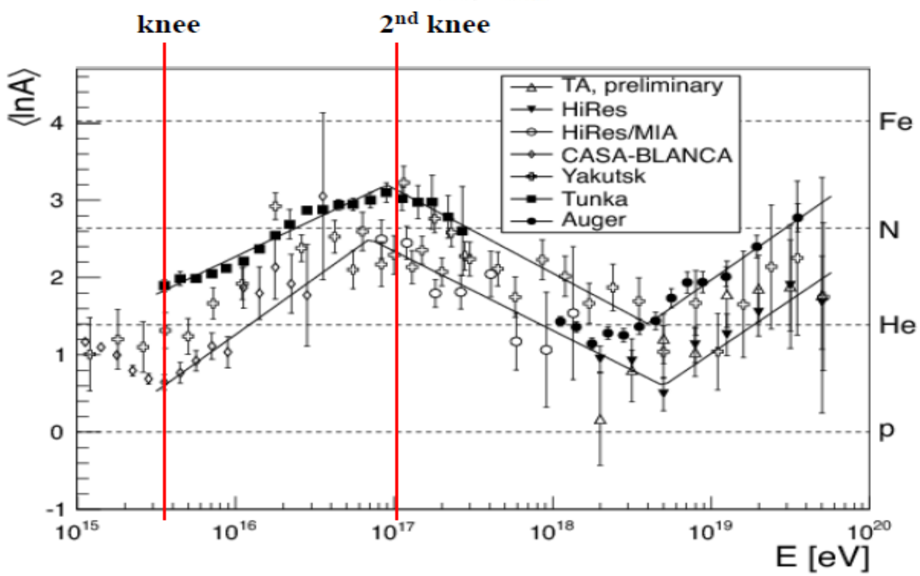
- Heavier across the all-particle knee
- Heavy at 100 PeV
- Light at the ankle

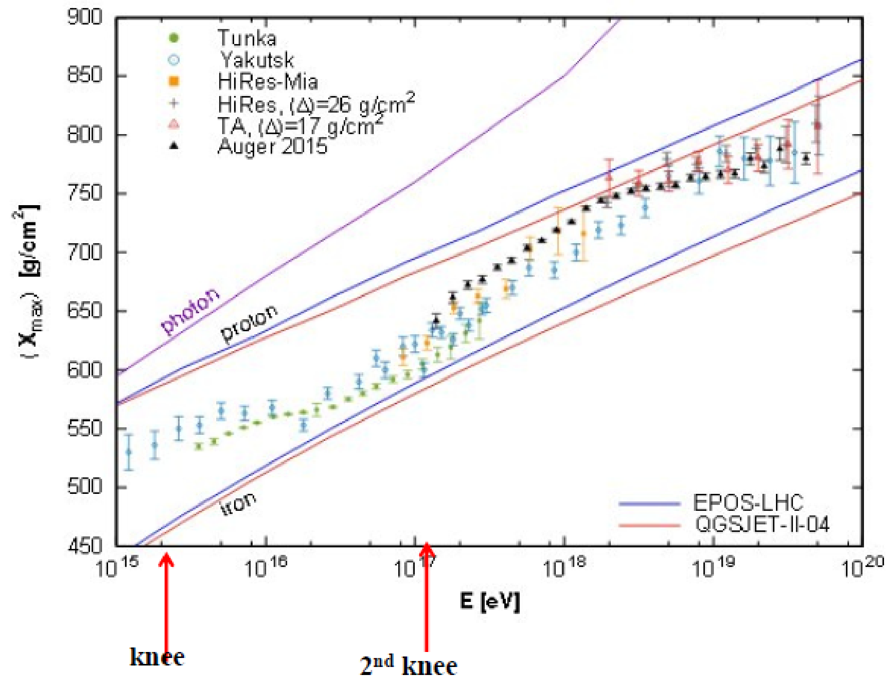
Large systematic uncertanties due to:

- shower-to-shower fluctuations
- shower sampling
- muon content measurement
- energy estimators
- hadronic interaction modeling
- ...

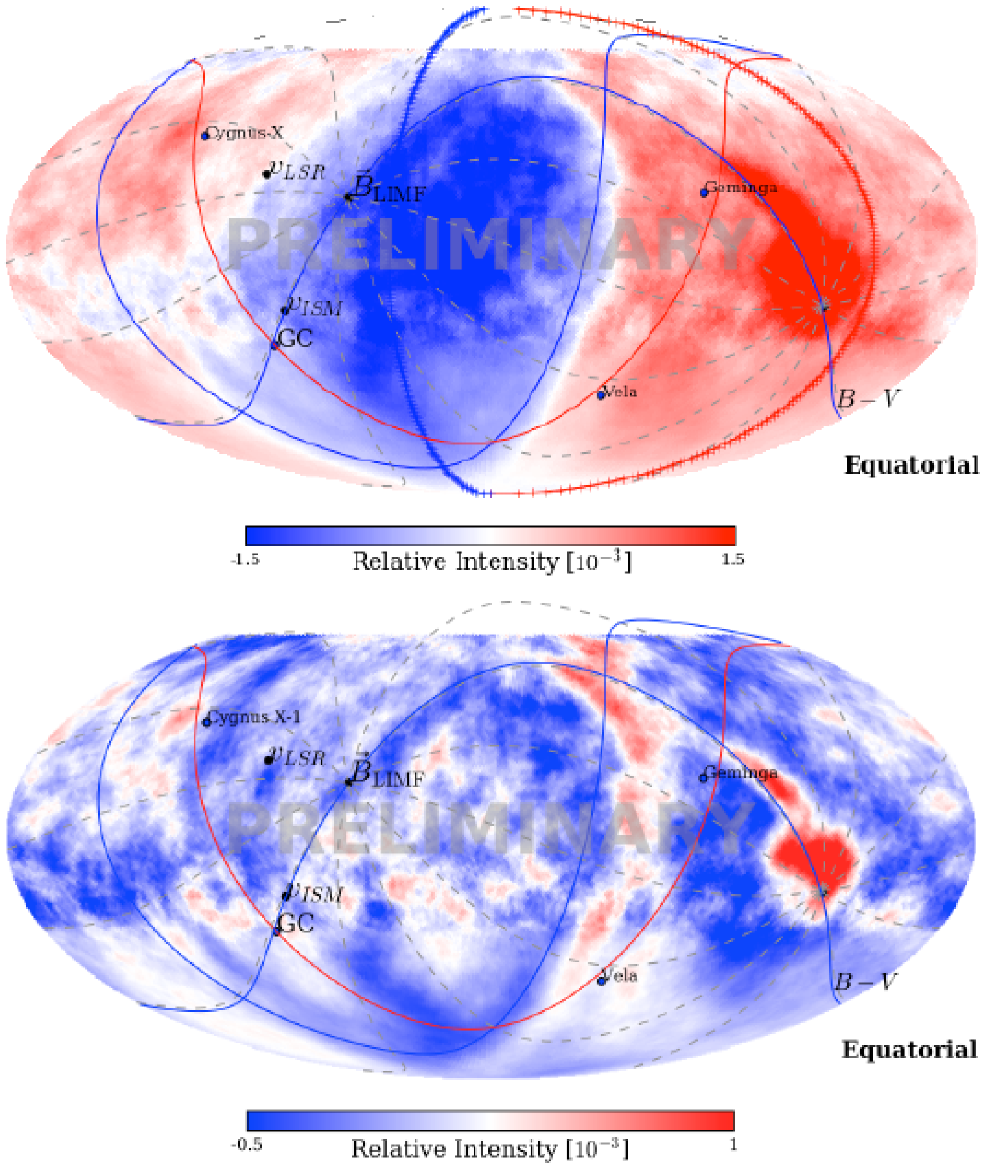
Not simple evolution toward the ankle







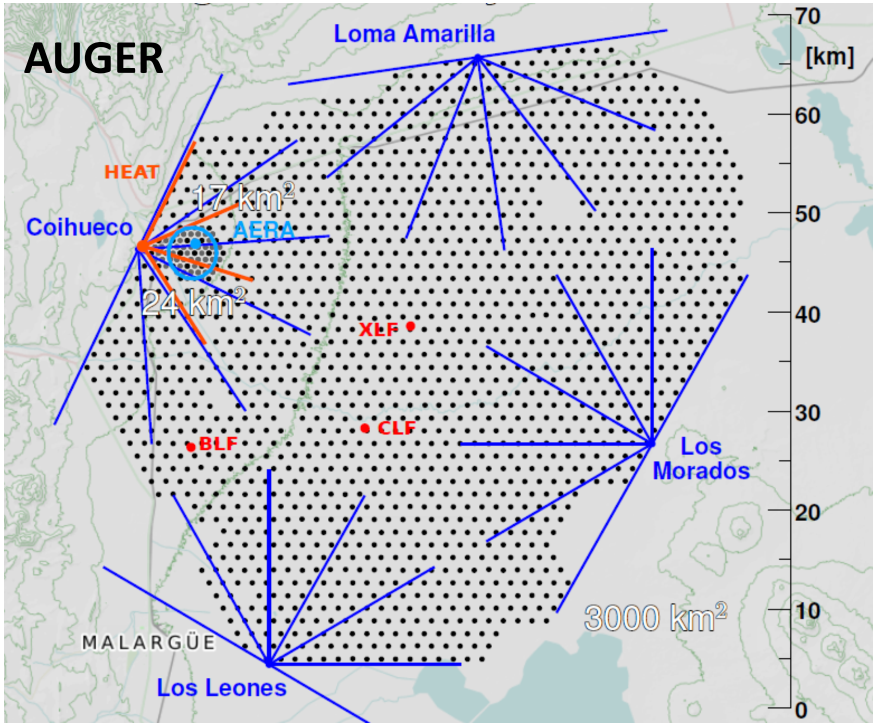
Cosmic ray anisotropy



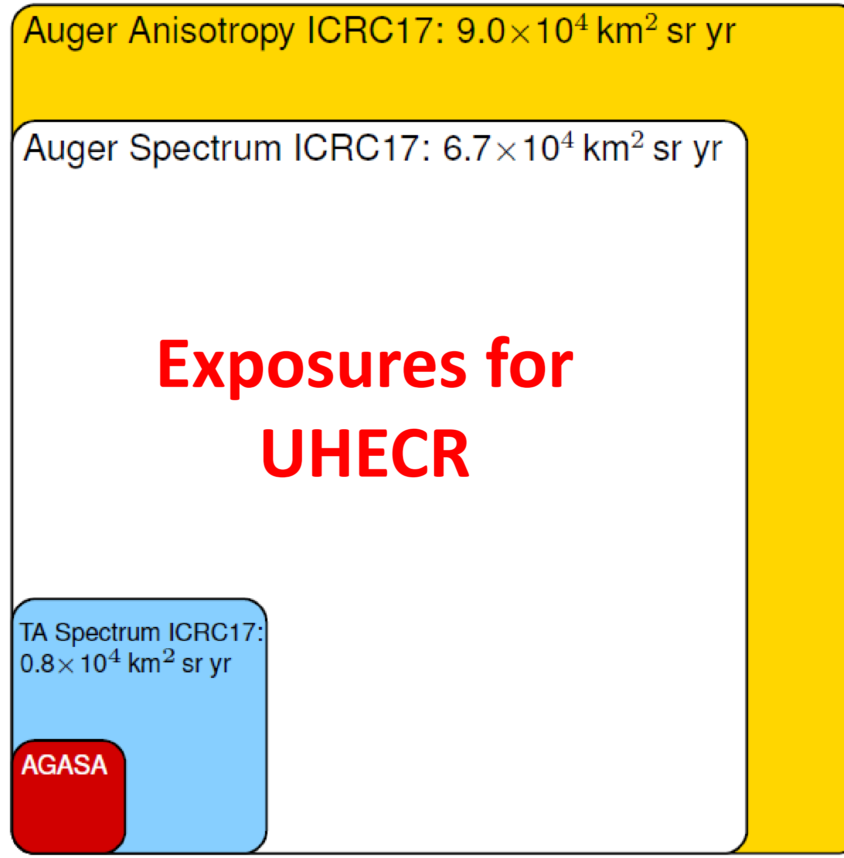
- Large-scale (top) and small-scale (bottom) anisotropy in the cosmic ray arrival direction distribution, jointly fit by HAWC and IceCube
- Median energy is approximately 10 TeV
- Apparent alignment between dipole anisotropy and local magnetic field
- Possible connection to local sources complicated by unknown diffusion coefficient, heliospheric effects

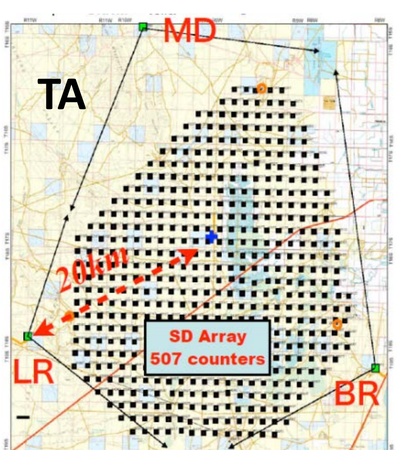
13

UHECR: AUGER and Telescope Array



M. Unger, ICRC 2017



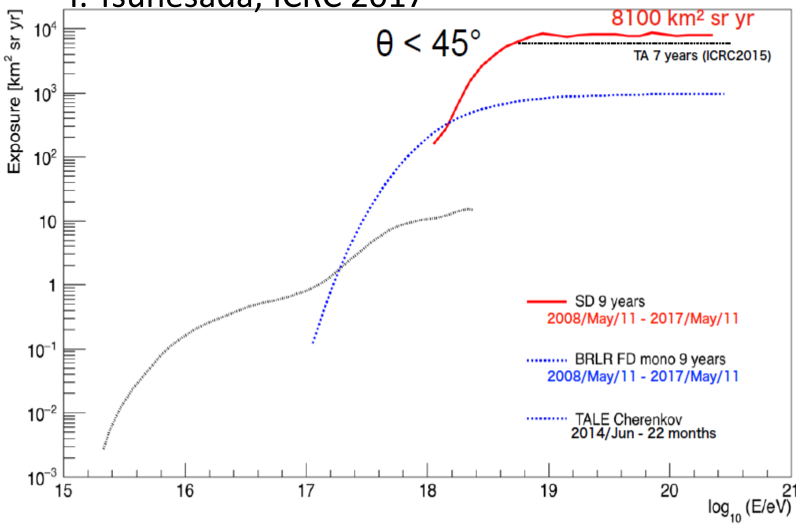


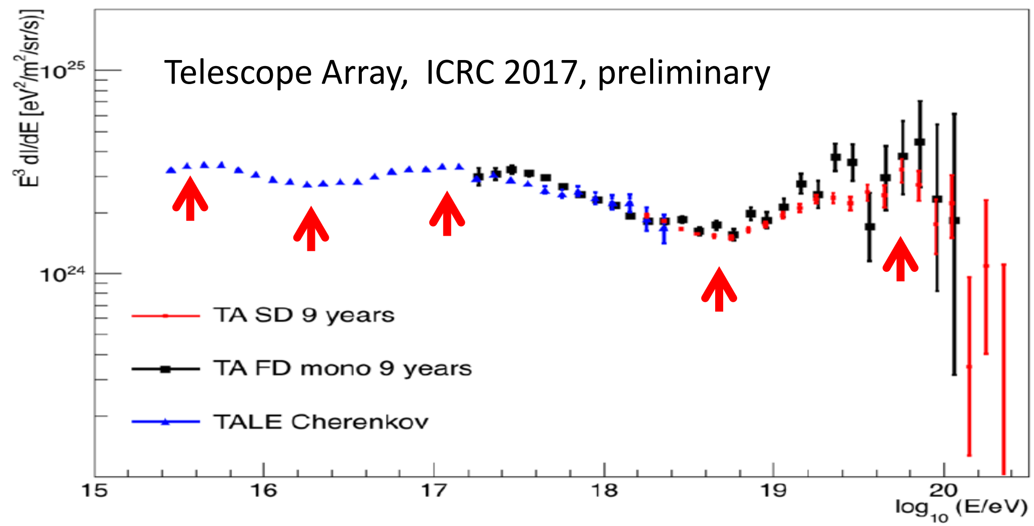
Measurements of the:
- **Energy spectrum** (Hybrid techniques : FD, SD, ...)
- **Mass composition** (Shower development, muons, risetime,...)
- **Anisotropies** (different scales and energies)

Also sensitivity to **UHE photons and neutrinos**

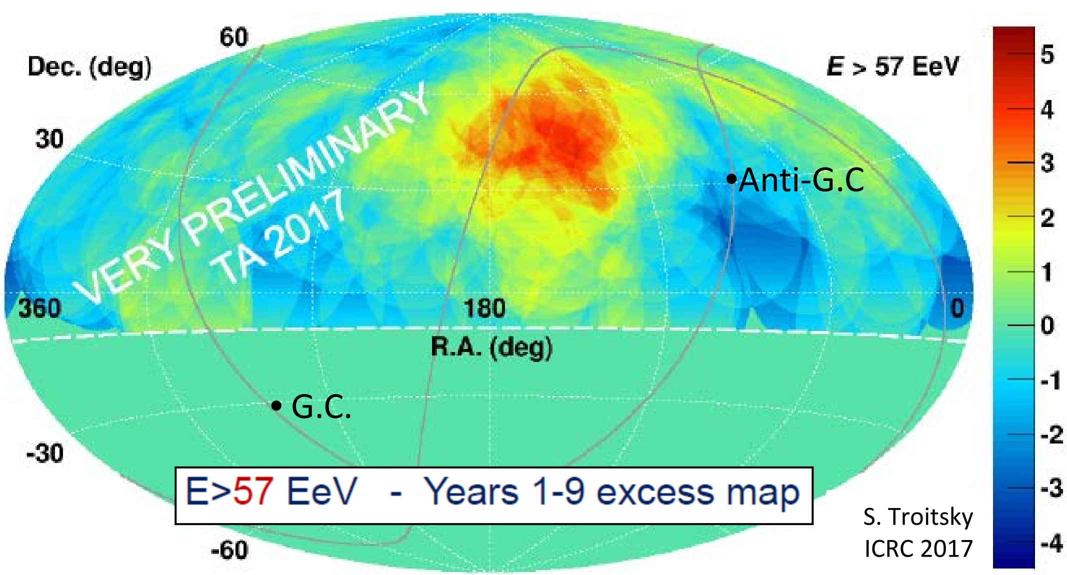
UHECR: TA spectrum and hot spots

Y. Tsunesada, ICRC 2017





Spectrum measured starting from the knee, using the low energy extension of the array TALE



Hot spot at

RA=144.3° DEC=+40.3°

Best circle radius: 25°

Local significance: 5σ

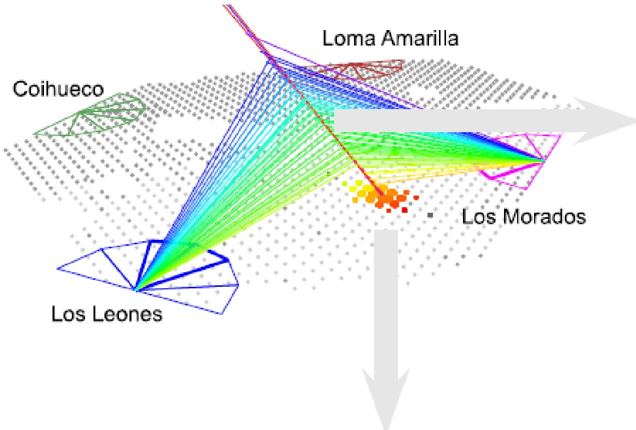
Gloal significance: 3σ

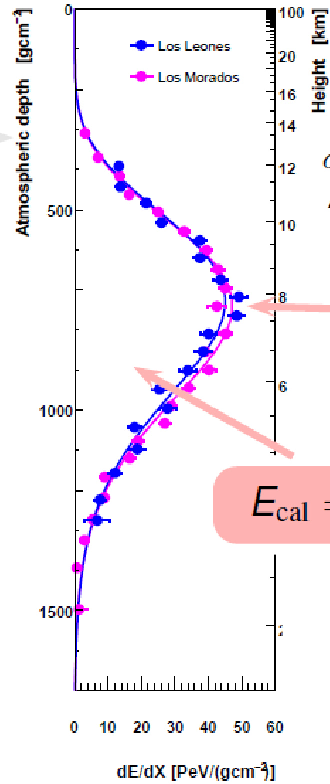
Indications for

- LSA above 57 EeV
- DEC dependence of the spectrum
- Cold spot (same place , lower E)

AUGER : EAS hybrid detection

M. Unger, ICRC 2017



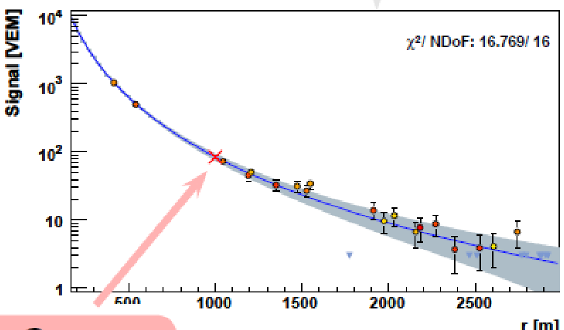


$\sigma_{X_{\mathrm{max}}} \leq 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \leq 10\,\mathrm{g/cm^2}$

X_{max}

$E_{\mathrm{cal}} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$

$\sigma_E/E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 15\,\%$

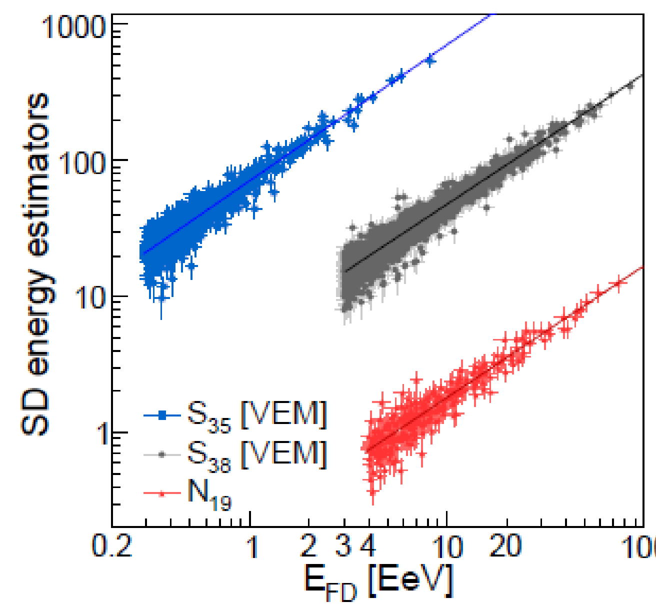


S_{1000}

$E_{\mathrm{surface}} = f(S_{1000}, \theta)$

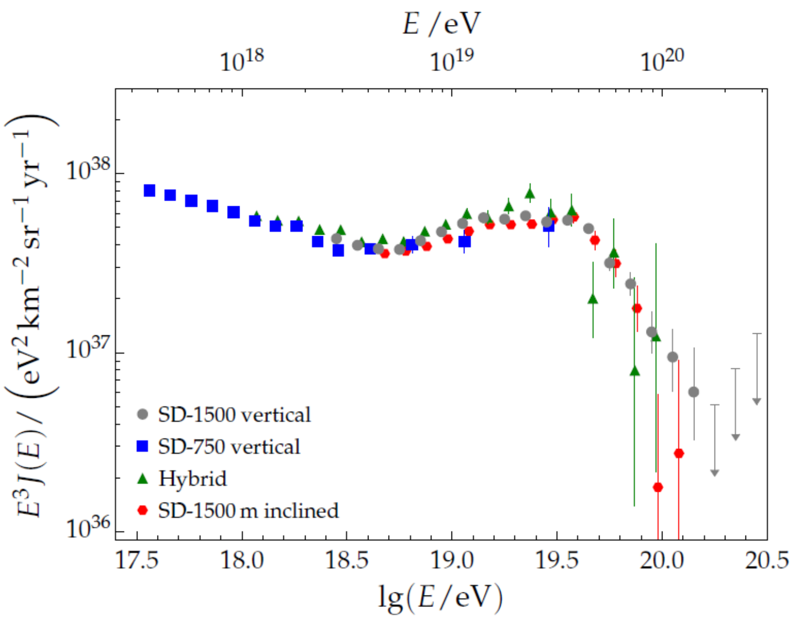
Calorimetric energy measurement with the FD

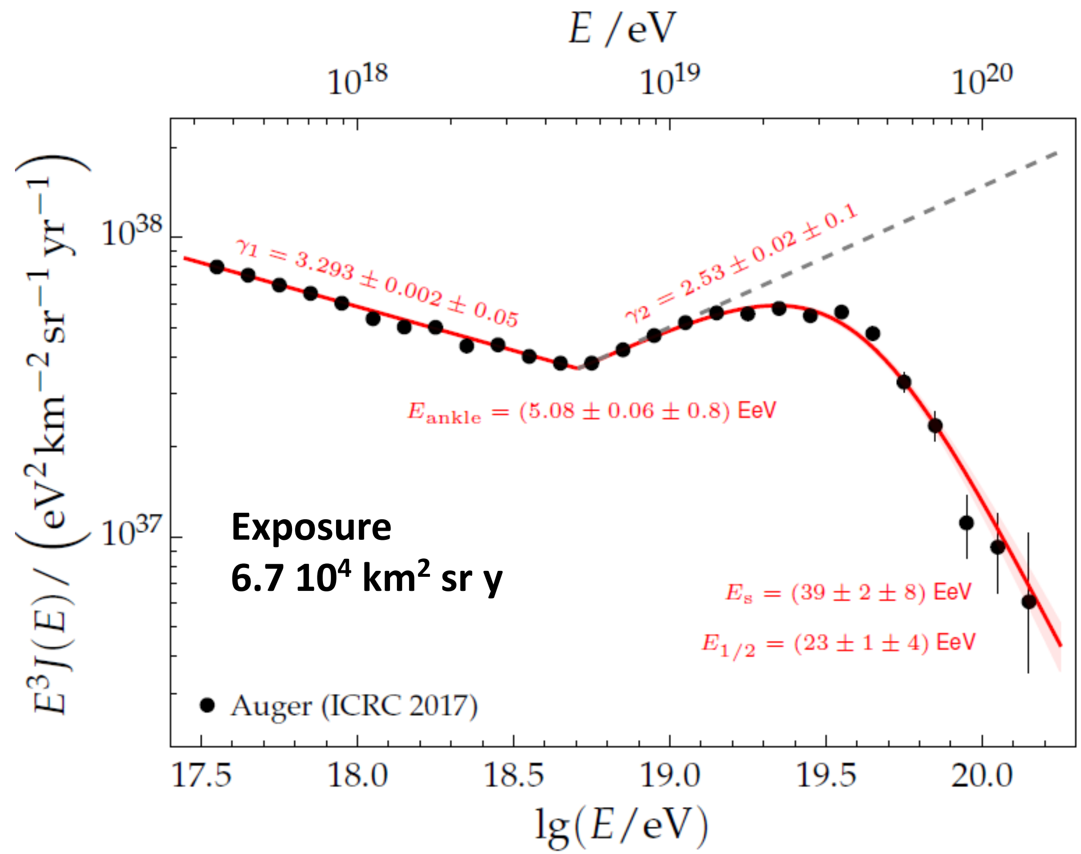
Energy calibration of SD observables using FD data

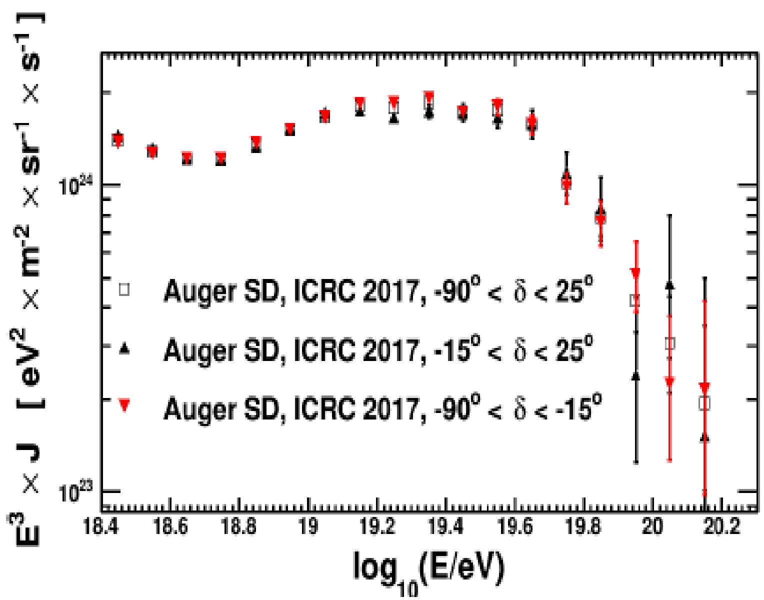


Very good **energy** (8% stat , 15% sys) and $\mathbf{X_{max}}$ (lower than 10g/cm2 stat and 10g/cm2 sys) resolutions and uncertainties.

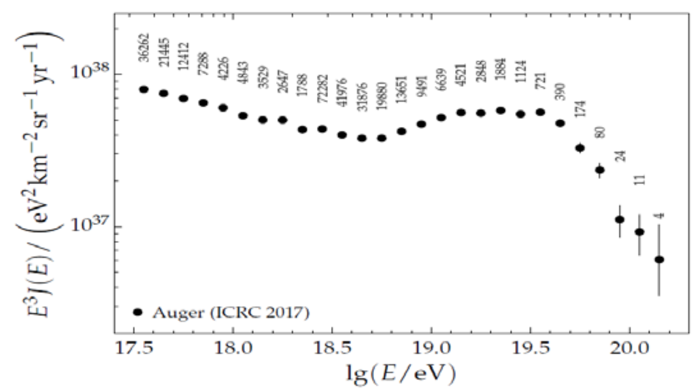
AUGER: The energy spectrum





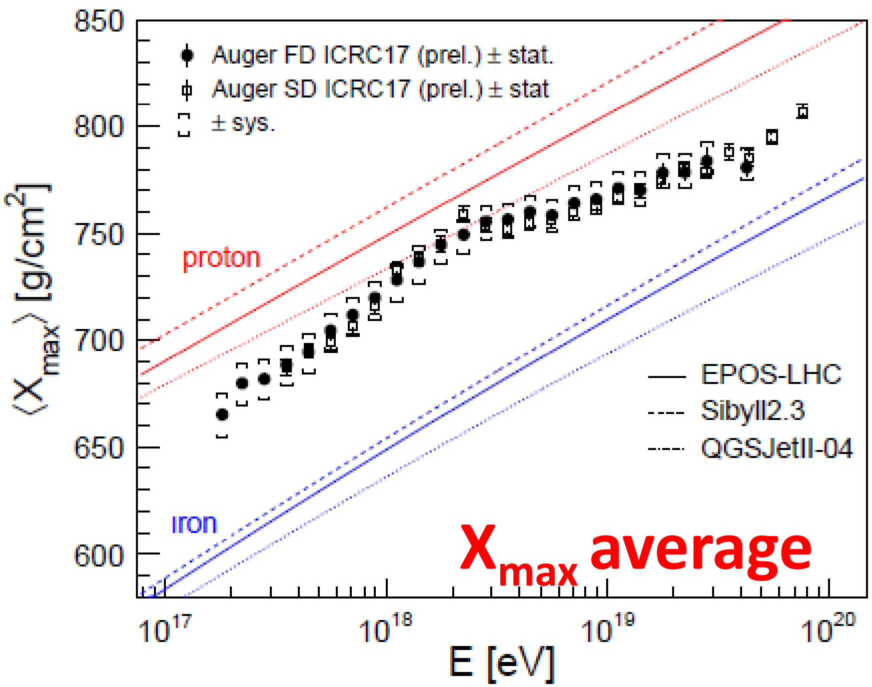


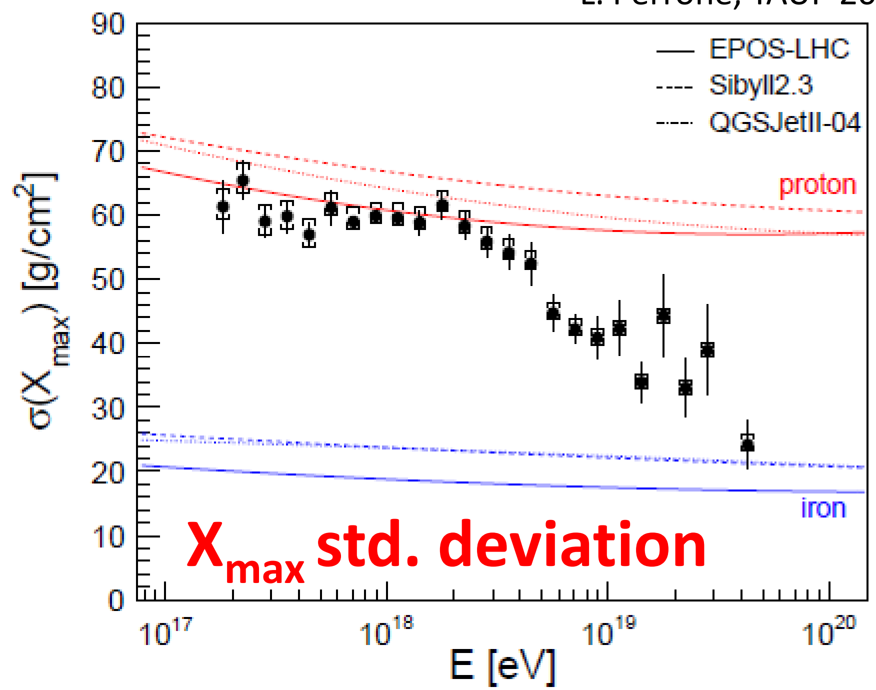
No indications for a dependence on declination



AUGER: composition

L. Perrone, TAUP 2017



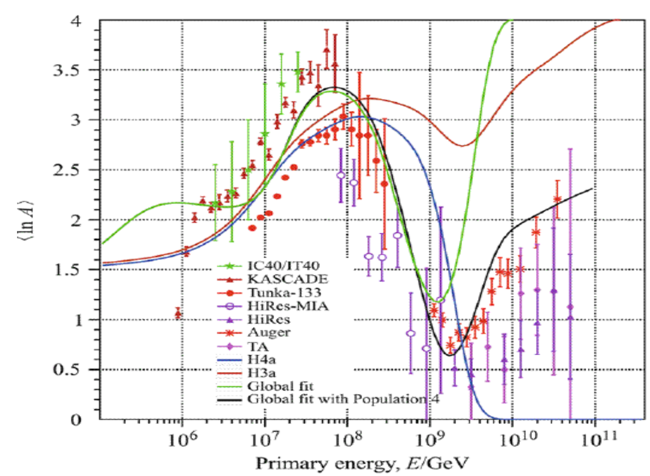


Evolving composition

large proton fraction at the ankle

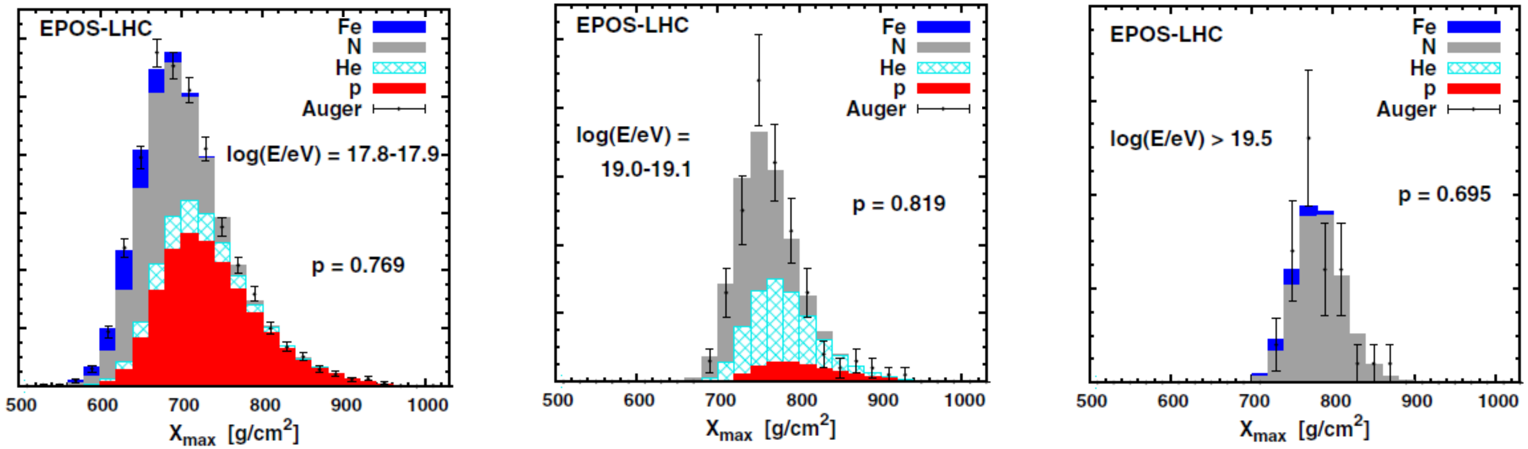
increase of the mean mass above and below ~ 2 EeV

Interpretation depends on hadronic interaction models



AUGER: composition (2)

Four mass groups fit of X_{max} FD data p-He-N-Fe

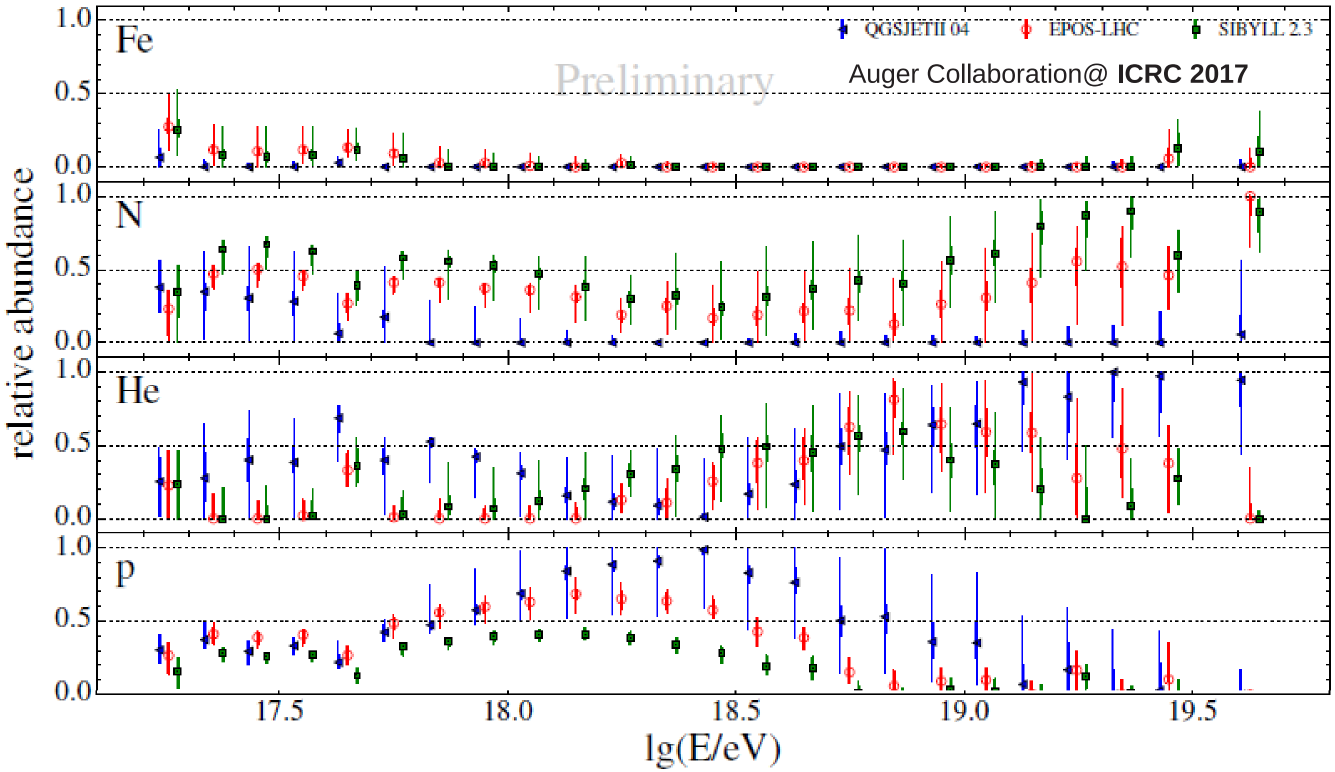


Fe

N

He

p



p/He domination at the ankle

Heavier components take over with energy

Hadint systematics

AUGER: medium scale anisotropy

Details and more in
Roger Clay's talk this afternoon

New study motivated by Fermi-LAT observations of high-energy gamma rays

AGN from 2FHL catalog.
17 bright objects within 250 Mpc.
Flux >50GeV as proxy for UHECR

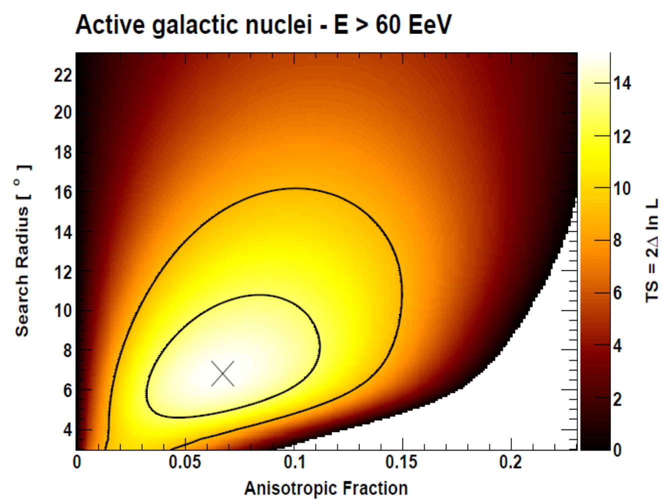
Starburst Galaxies 23 bright objects within 250 Mpc. Radio Flux > 1.4 GHZ as proxy for UHECR

Method: sky model as the sum of an isotropic fraction plus the anisotropic component from selected sources f_{ani}

Test statistics (TS): likelihood ratio

$$TS=2\log[L(\Psi,f_{ani})/L(f_{ani}=0)]$$

f_{ani} and Ψ (search radius) free parameters

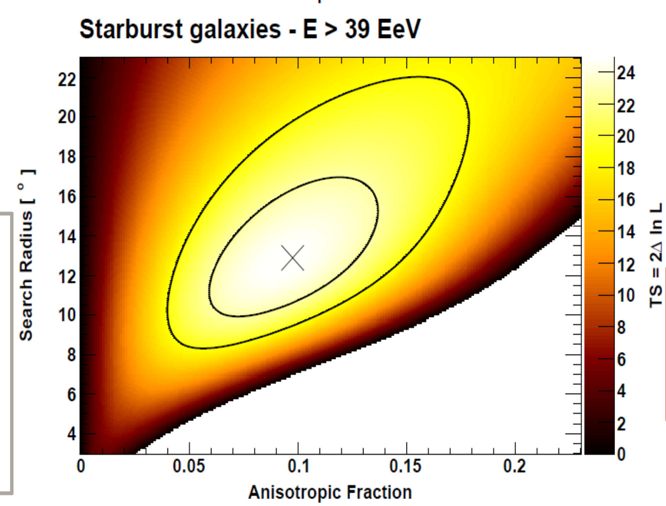


PRELIMINARY!
Auger @ ICRC2017

TS = 15.2 E_{th}> 60 EeV

f_{ani} ~ 7% Ψ = 7°

post-trial probability
3×10^{-3} (~ 2.7 σ)



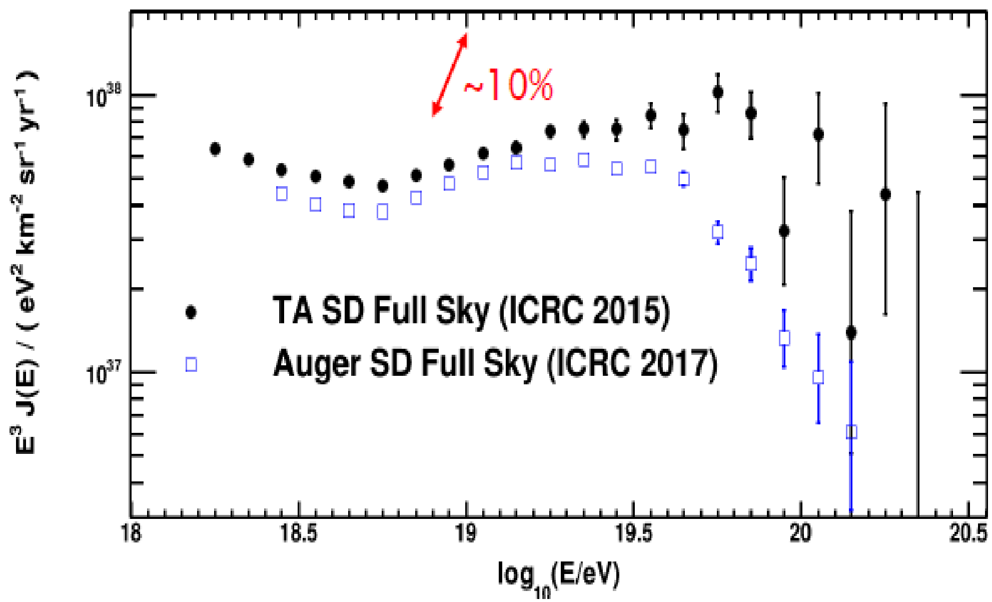
TS = 24.9 E_{th}> 39 EeV

f_{ani} ~ 10% Ψ = 13°

post-trial probability
4×10^{-5} (~ 4.9 σ)

L. Perrone, TAUP 2017

AUGER – TA comparison: spectrum



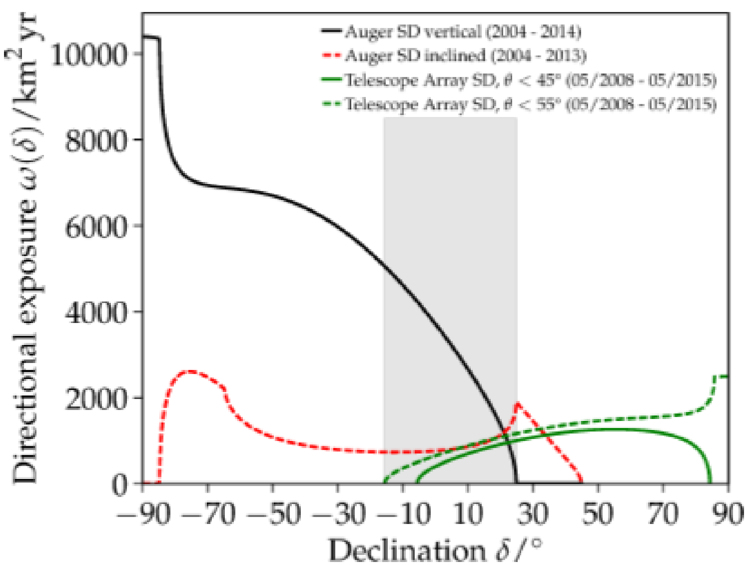
Energy scale shift well within the quoted systematics (14% Auger, 21% TA)

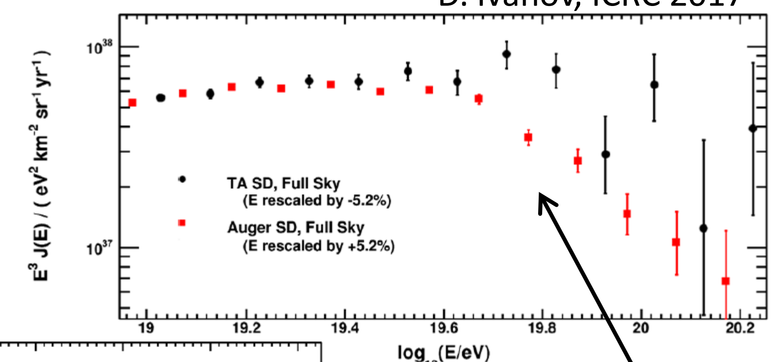
Energy dependence of the shift smaller than 5%

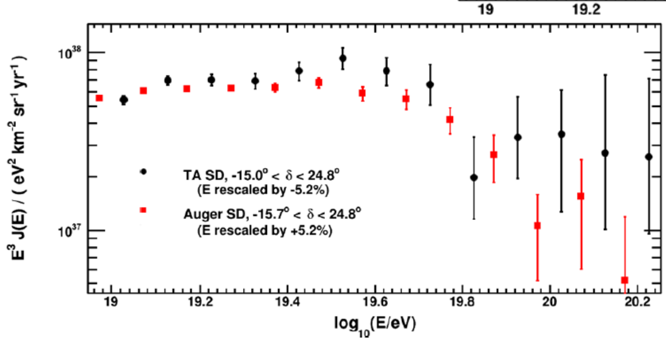
Differences above 50EeV ?

Better greement in the common declination band

D. Ivanov, ICRC 2017







Full sky

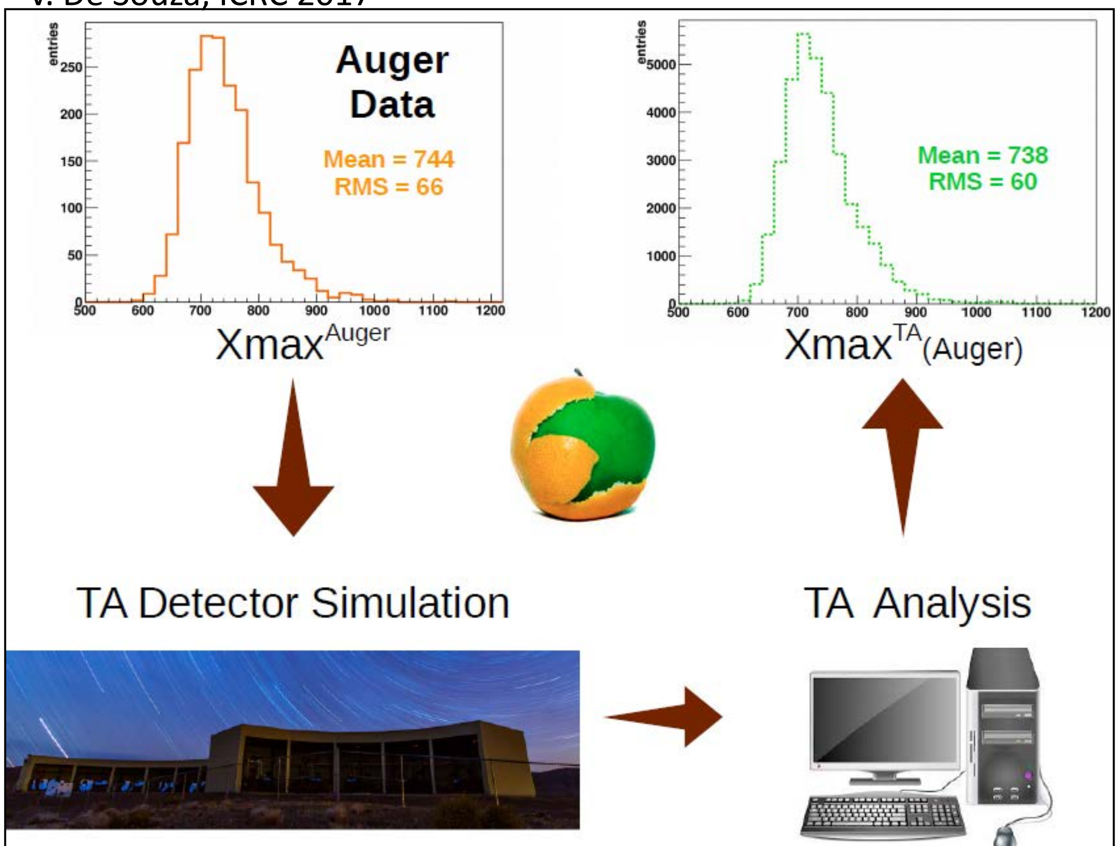
Common declination band

AUGER – TA comparison: composition

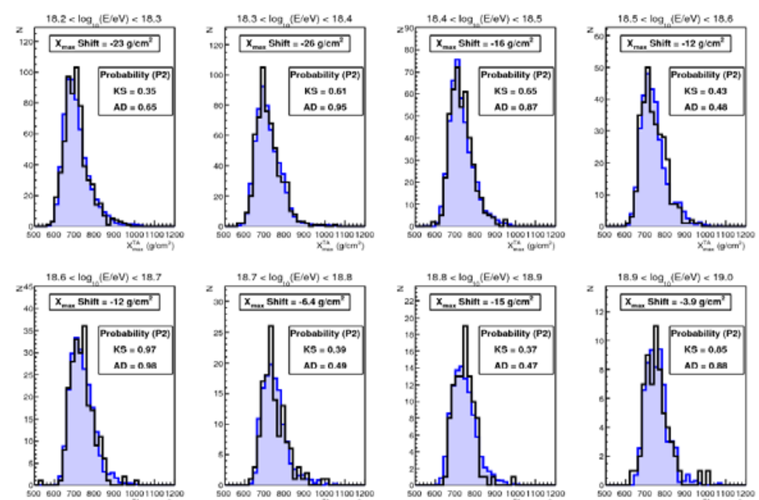
Long debate since TA data suggest a proton dominated scenario, while AUGER a mixed one

Joint group from AUGER and TA collaborations.
Use of proper simulation and analysis chain of both experiments.
Test AUGER-mix composition as input to TA simulation and compare with TA data

V. De Souza, ICRC 2017



TA and Auger composition measurements (Xmax) agree within the systematics 18.2 < log10(E/eV) < 19.0



AUGER Upgrade

M. Unger, ICRC 2017

Open issues

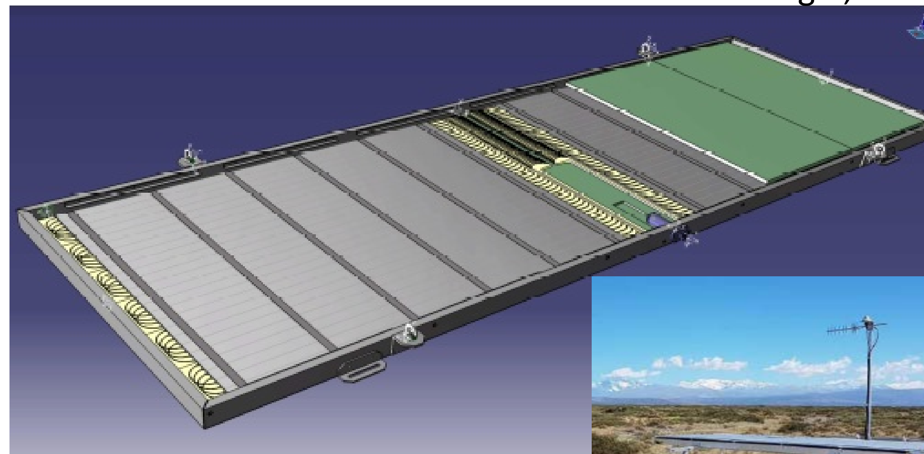
Origin of the flux suppression

Proton fraction at UHE

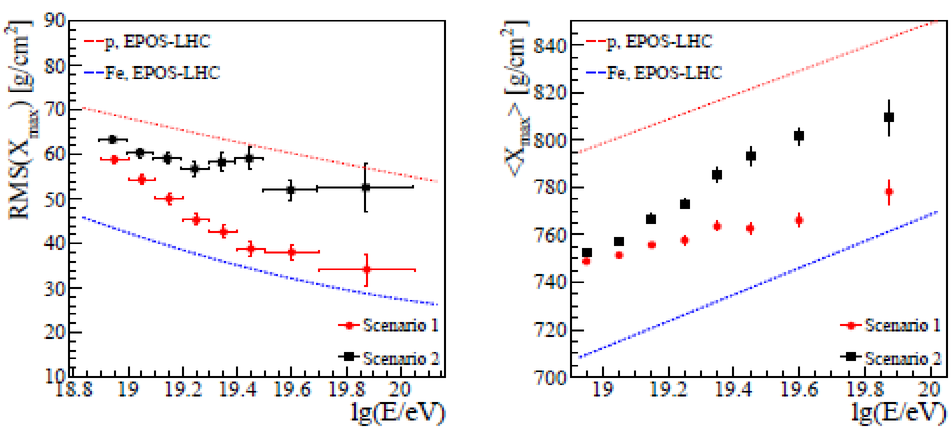
Rigidity-dependence of anisotropies

Hadronic physics above √s=140 TeV

Need large exposure detector with composition sensitivity



3.8 m² (1 cm thick) scintillators on each station



Scenario 1 : maximum rigidity

Scenario 2: photo-disintegration

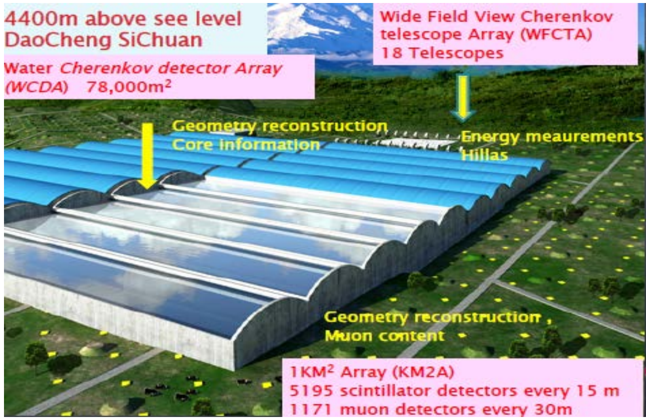
Moreover

- Upgraded and faster electronics
- Extension of the dynamic range
- Cross check with underground buried AMIGA detectors
- Extension of the FD duty cycle

New projects and R&D programs for EAS detection

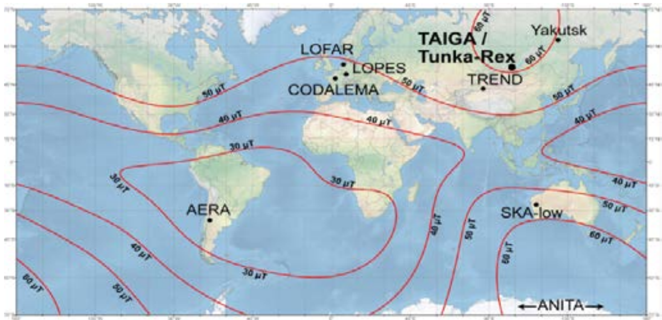
LHAASO

Km^2 size array at high altitute 4400 m a.s.l. , DaoCheng , China
Hybrid approach: Water Cherenkov – Cherenkov Telescopes – Muon detectors – Scintillator array
Optimized for VHE gamma-ray astronomy
CR physics from 5TeV up to 100 PeV



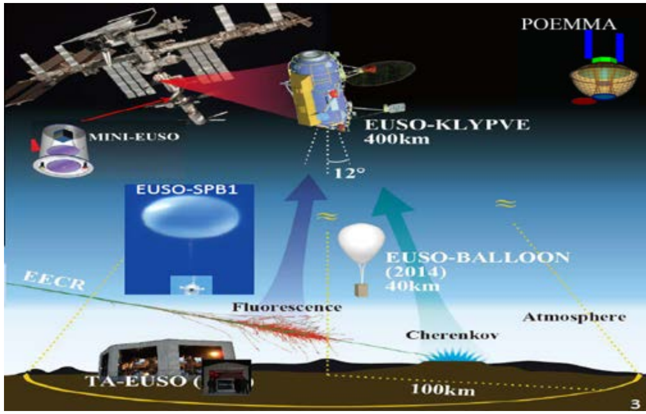
EAS RADIO detection

Several ongoing projects around the world: AERA (at AUGER), ARIANNA, CODALEMA, LOFAR, SKA-low, TREND, TUNKA-REX, YAKUTSK
First results for energy spectra and X_{max}



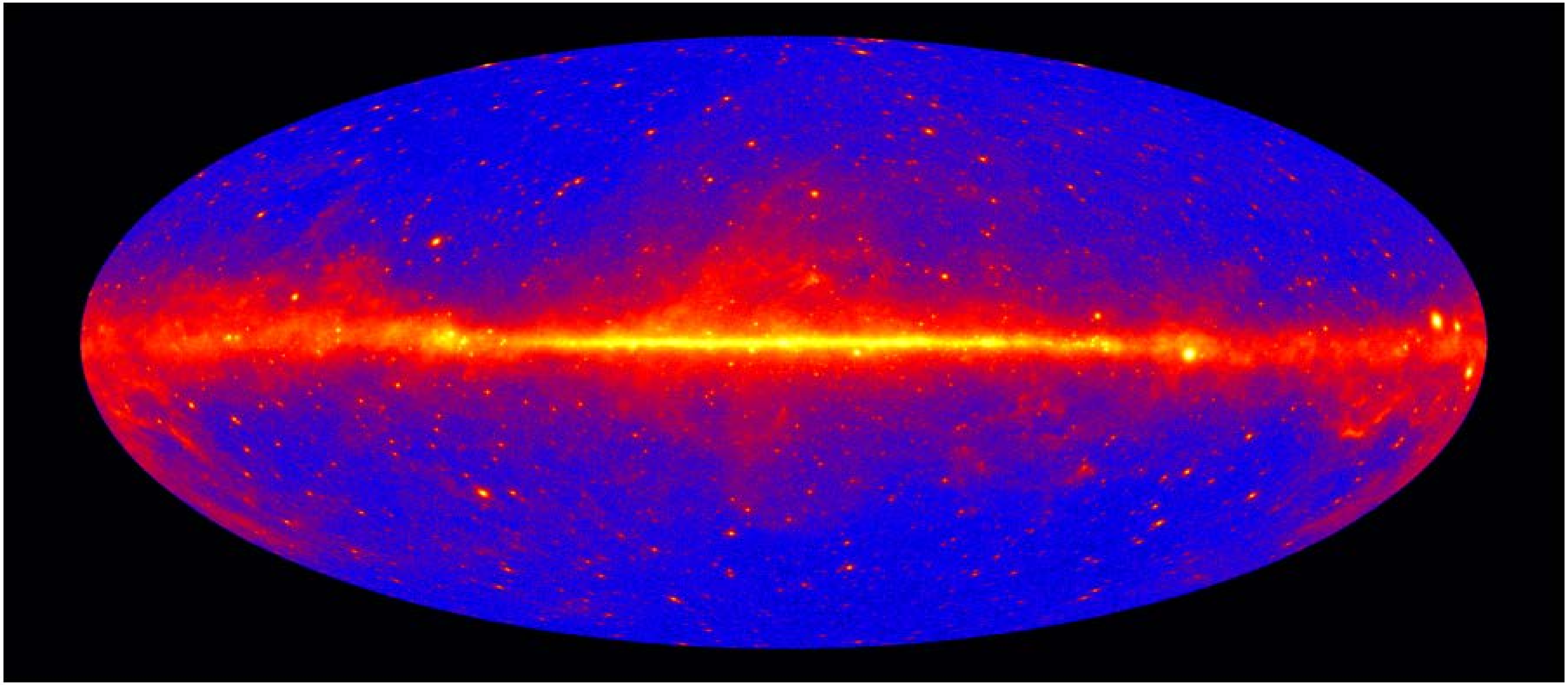
EAS from space

Detection of fluorescence and Cerenkov light from space.
Big jump in exposure
Several programs for detector R&D and UV background study: SPHERE-2, TUS, EUSO-TA, EUSO-SPB, Mini-EUSO, KLYPVE-EUSO
POEMMA: UHECR, cosmogenic neutrinos form Earth limb



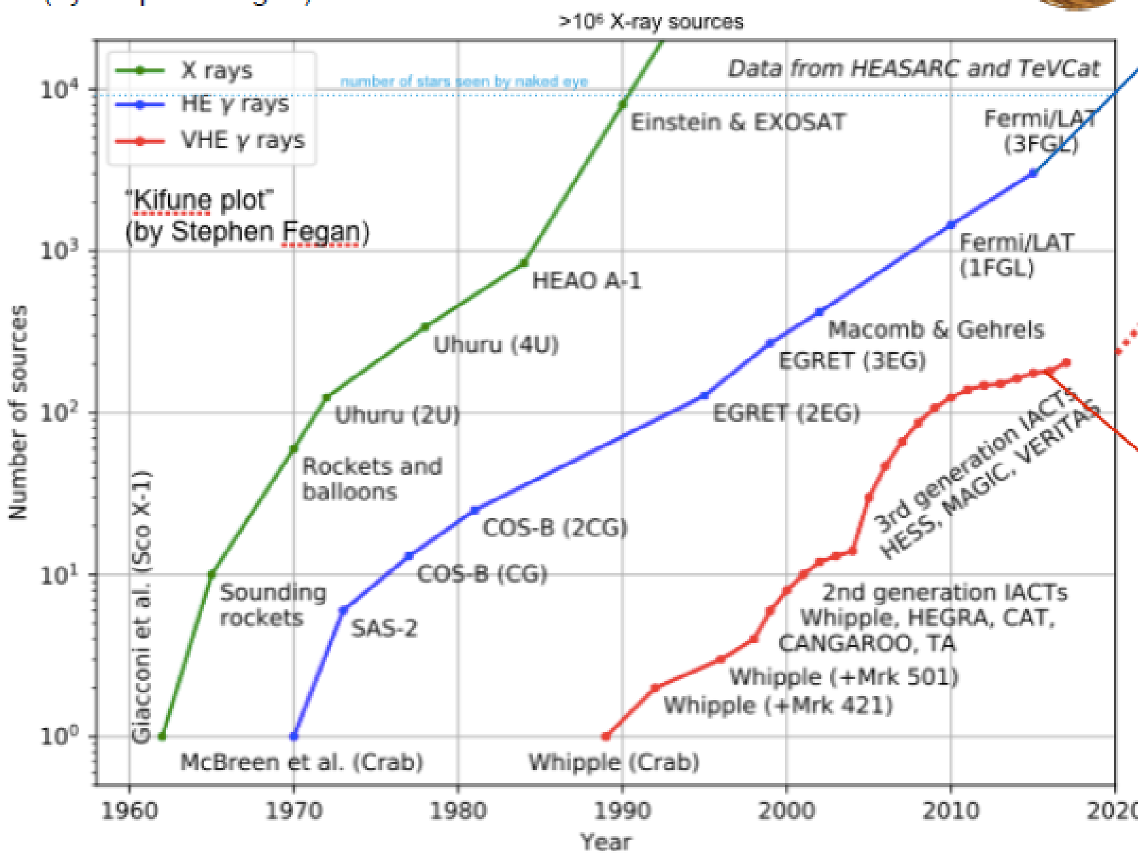
Gamma Rays

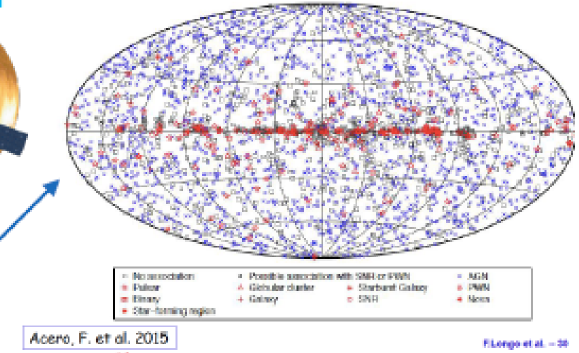
Fermi sky in 7 years



Gamma-ray Sources & Detection Technique Advancement

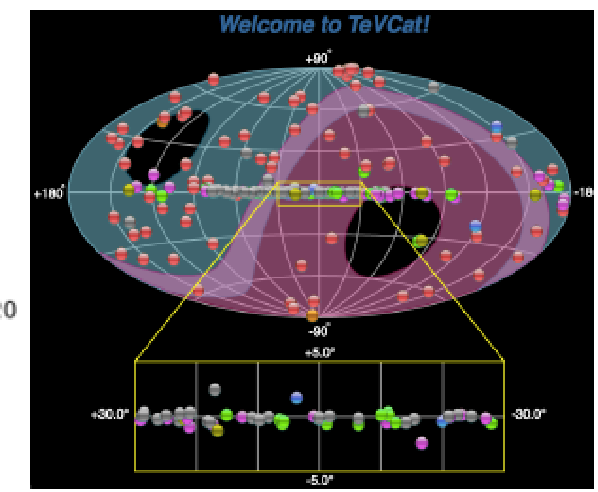
"Kifune plot"
(by Stephen Fegan)





CTA

3FGL 3034 sources > 100 MeV
95% extragalactic!
21% BL Lacs
16% FSRQ
19% unclassified blazars +
22% unassociated high lat
Still lots of classification work to come! (CTA, HAWC, LHAASO, SPACE??...)

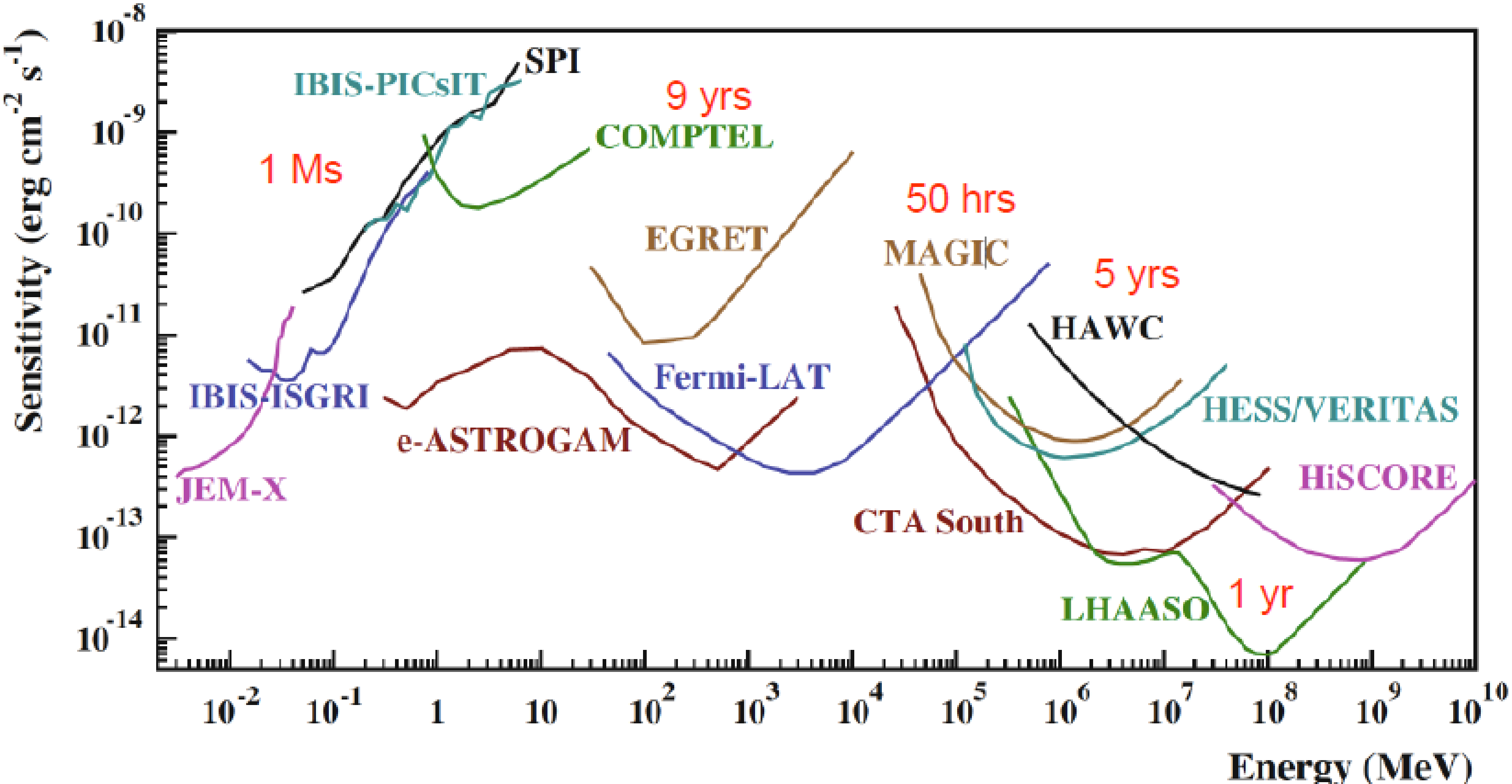


About 210 TeV sources > 100 GeV
~37% discovered day H.E.S.S.
(exposure to the Galaxy matters!)

tevcat.uchicago.edu

T. Montaruli | CRIS2018 | June 18, 2018

Gamma-ray instruments



De Angelis, Mallamaci, arXiv:0805.05642

Gamma (and CR) sources

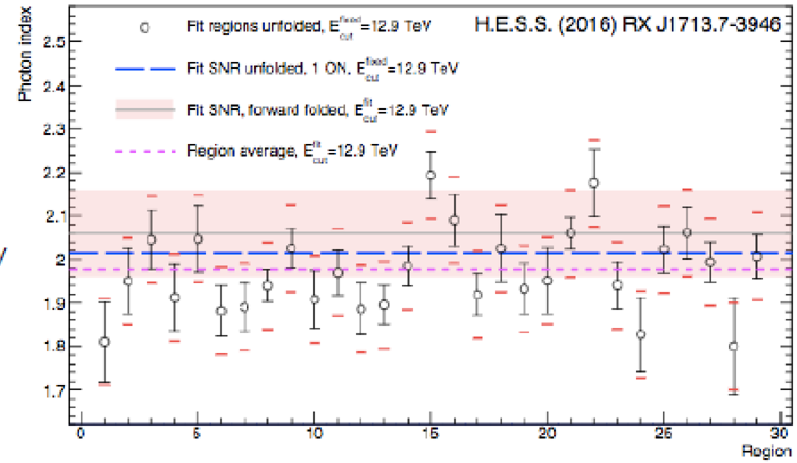
Morphology…

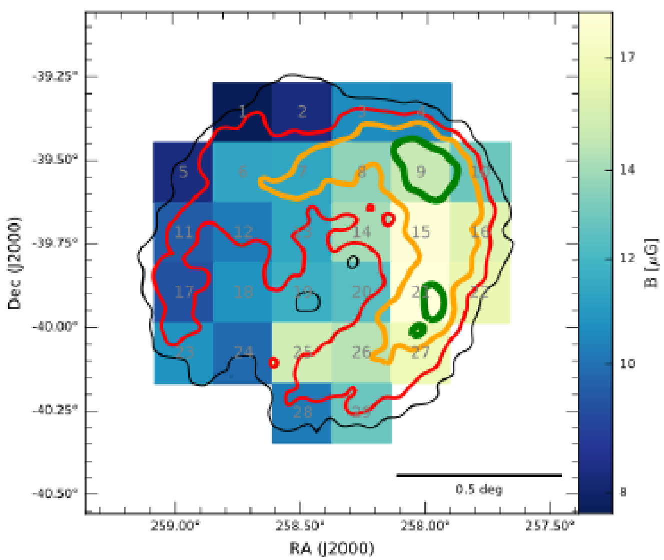
- Spectrum characteristics
  - Best described by broken power-law + exponential cutoff
  - Pure power-laws don't describe data
- Hadronic model
  - Break results from higher energy CRs diffusing faster into cold, dense MC clumps (e.g. Gabici & Aharonian 2014)
  - E_{break} depends on SNR age and density profile; E_c ~100 TeV
- Leptonic model
  - B ~ 10 – 15 μG, E_{break} ~2 TeV
  - Break requires 2nd electron population, or additional seed photon field. Detailed hydro-CR codes can reproduce observed emission

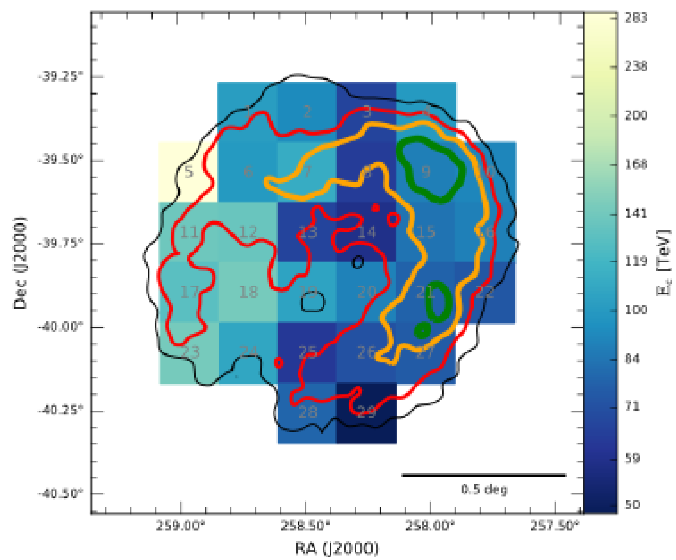
→ No clear case for either leptonic or hadronic accelerator

HESS https://arxiv.org/pdf/1609.08671.pdf

S. Ohm, ISVHECRI







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GSSI

CR-gamma-neutrino connection

INFN

Fermi Gamma-ray Space Telescope

MW follow-up of IC170922

- The GCN notice triggered **follow-up** by ground and space-based instruments to help identifying a possible astrophysical source for the candidate ν:
  - **Fermi-LAT**: detected an **increased γ-ray activity of the known γ-ray source TXS 0506+056** (3FGL J0509.4+0541) inside the IC error region, redshift unknown
  - **AGILE**: confirmed the enhanced γ-ray activity
  - ***IACTS:* MAGIC** (detection of VHE γ-rays from direction consistent with ν event), **HAWC** and **HESS** (upper limits)
  - ***Radio:*** detection of flux variability
  - ***X-ray:* Swift-XRT** (detection), **INTEGRAL** (upper limits)
  - ***Optical*: ASAS-SN** (enhanced flux), **Liverpool telescope** (optical spectrum)