Extensive Air Shower and cosmic ray physics above 10^{17} eV

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Outline:

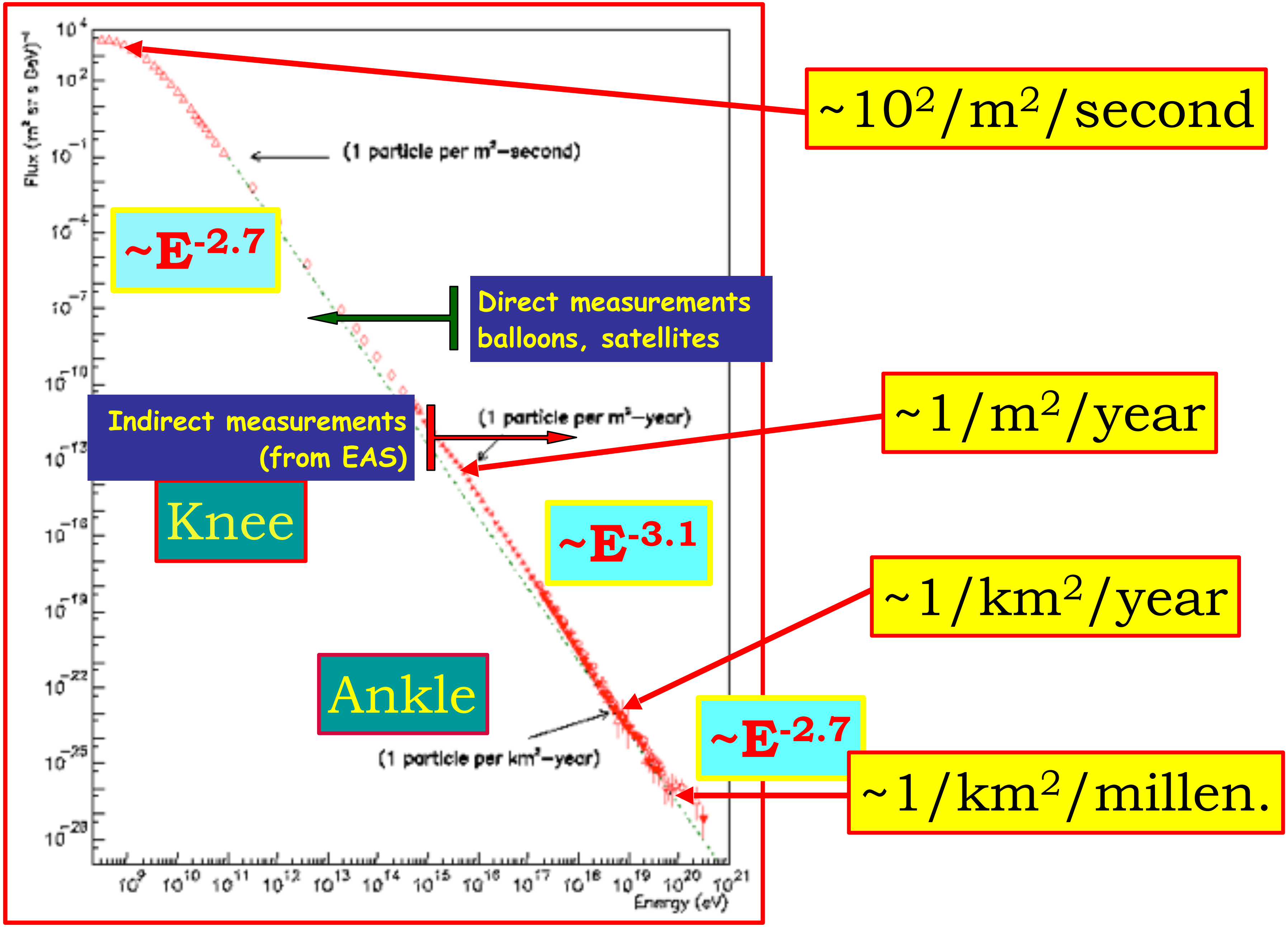
» Part I: A general overview of cosmic ray science.

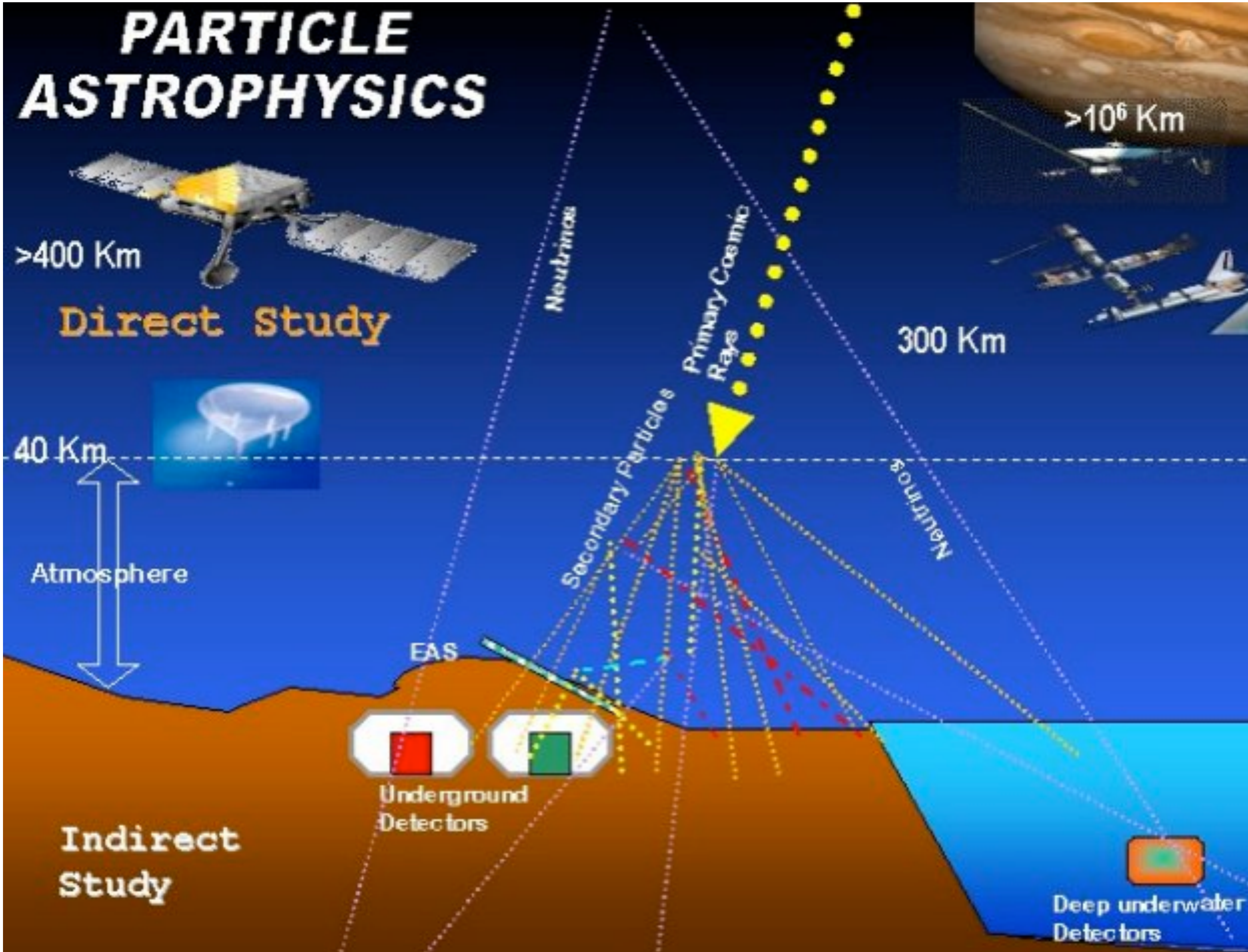
» Part II: The interconnection between cosmic ray and particle physics.

» I will mention aspects that will be discussed in detail in the talks that follow in this session (S. Ostapchenko, R. Ulrich, D. Veberic, R. Abbasi).

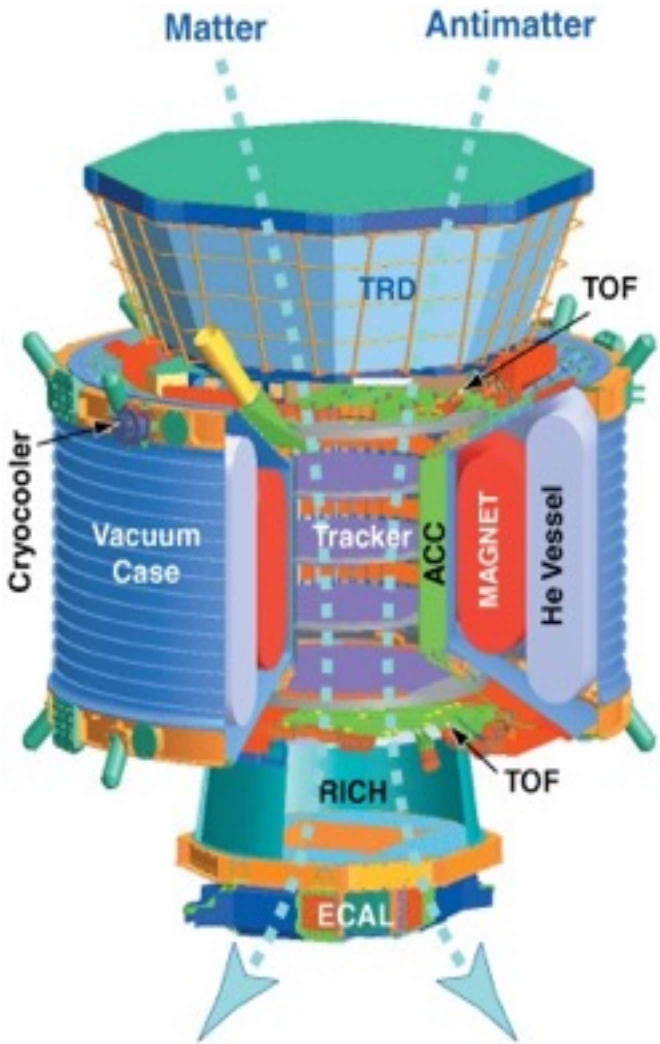
» A few key slides taken by J. Pinfold and R. Engel review talks at ICRCs 2013 and 2015.

Part I:
A general overview of cosmic ray science

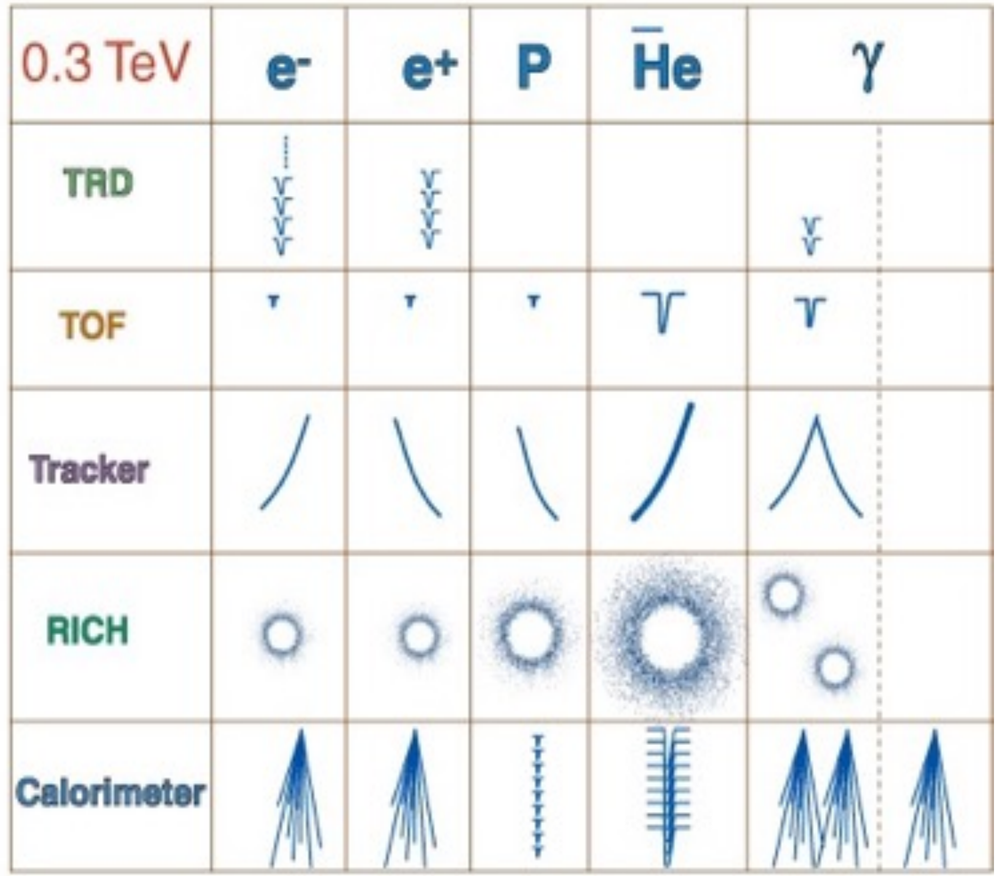

~10²/m²/second
(1 particle per m²–second)
~E^-2.7
Direct measurements
balloons, satellites
Indirect measurements
(from EAS)
(1 particle per m²–year)
~1/m²/year
Knee
~E^-3.1
~1/km²/year
Ankle
~E^-2.7
(1 particle per km²–year)
~1/km²/millen.
Flux (m² sr s GeV)⁻¹
Energy (eV)


PARTICLE
ASTROPHYSICS
>400 Km
Direct Study
>10⁶ Km
300 Km
Neutrinos
Primary Cosmic Rays
Secondary Particles
40 Km
Neutrinos
Atmosphere
EAS
Underground
Detectors
Indirect
Study
Deep underwater
Detectors

AMS: A TeV Magnetic Spectrometer in Space (3m x 3m x 3m, 7t)



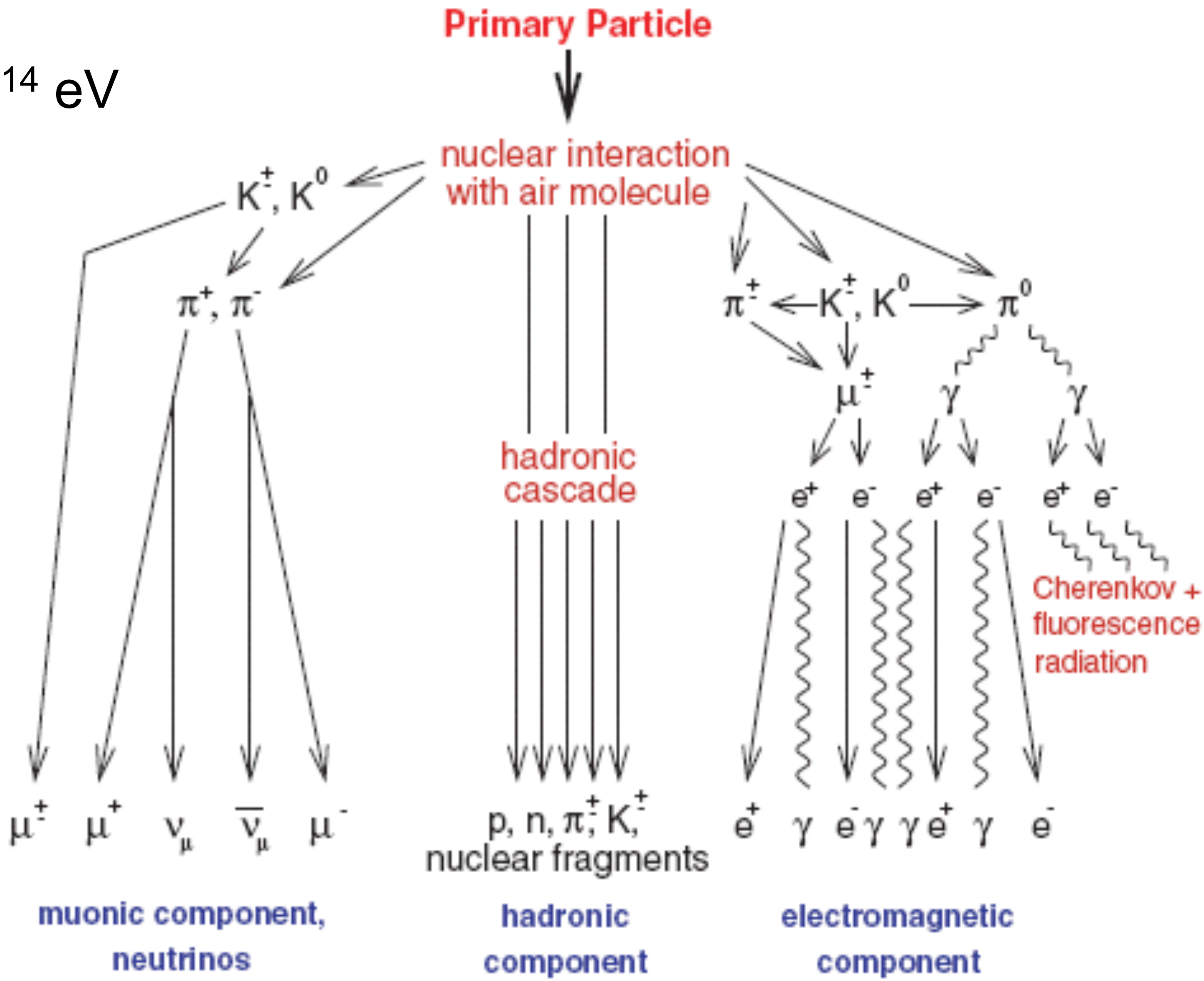
300,000 channels of electronics Δt = 100 ps, Δx = 10μ



E < 10 [14] eV

Extensive Air Showers (EAS)

E > 10 ^{14} eV



Air showers: electromagnetic and hadronic components

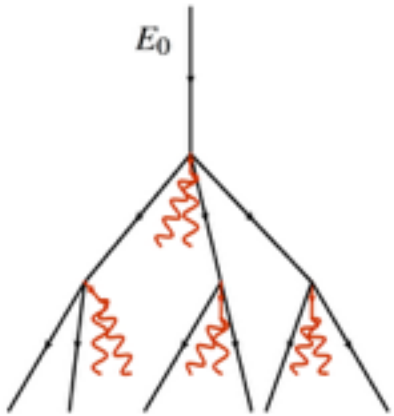
Hadronic energy

$$\frac{2}{3}E_0$$

$$\frac{2}{3}\left(\frac{2}{3}E_0\right)$$

$\vdots$

$$E_{\mathrm{had}} = \left(\frac{2}{3}\right)^n E_0$$



After n generations ...

$n = 5,\ \ E_{\mathrm{had}} \sim 12\%$

$n = 6,\ \ E_{\mathrm{had}} \sim 8\%$

Electromagnetic energy

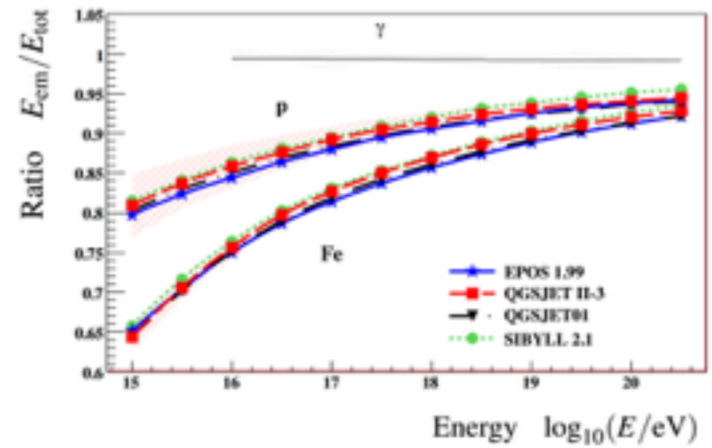
$$\frac{1}{3}E_0$$

$$\frac{1}{3}E_0 + \frac{1}{3}\left(\frac{2}{3}E_0\right)$$

$\vdots$

$$E_{\mathrm{em}} = \left[1 - \left(\frac{2}{3}\right)^n\right] E_0$$

(RE, Pierog, Heck, ARNPS 2011)



Very efficient transfer of hadronic energy to em. component

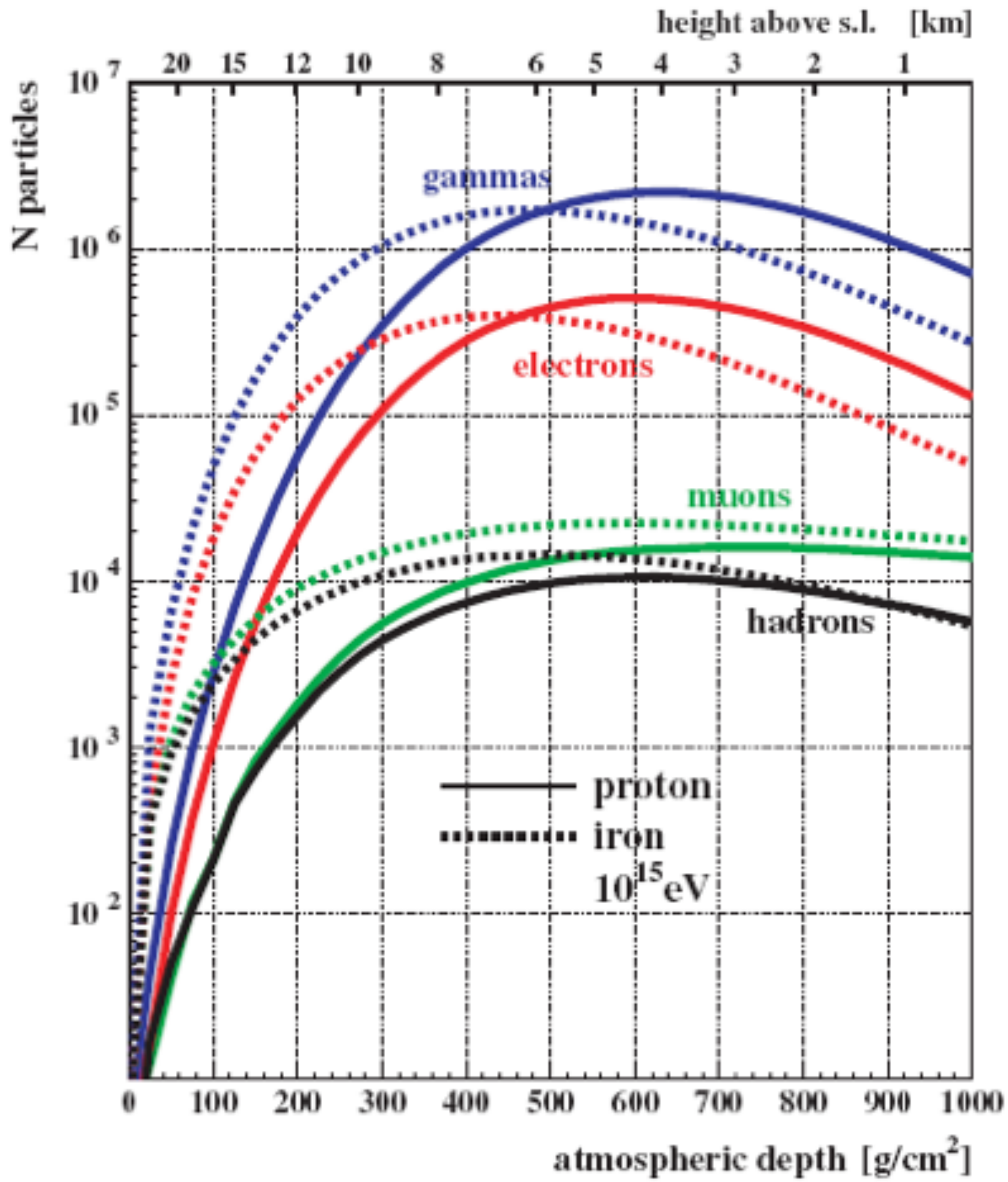
High-energy interactions most important

(Matthews, APP22, 2005)

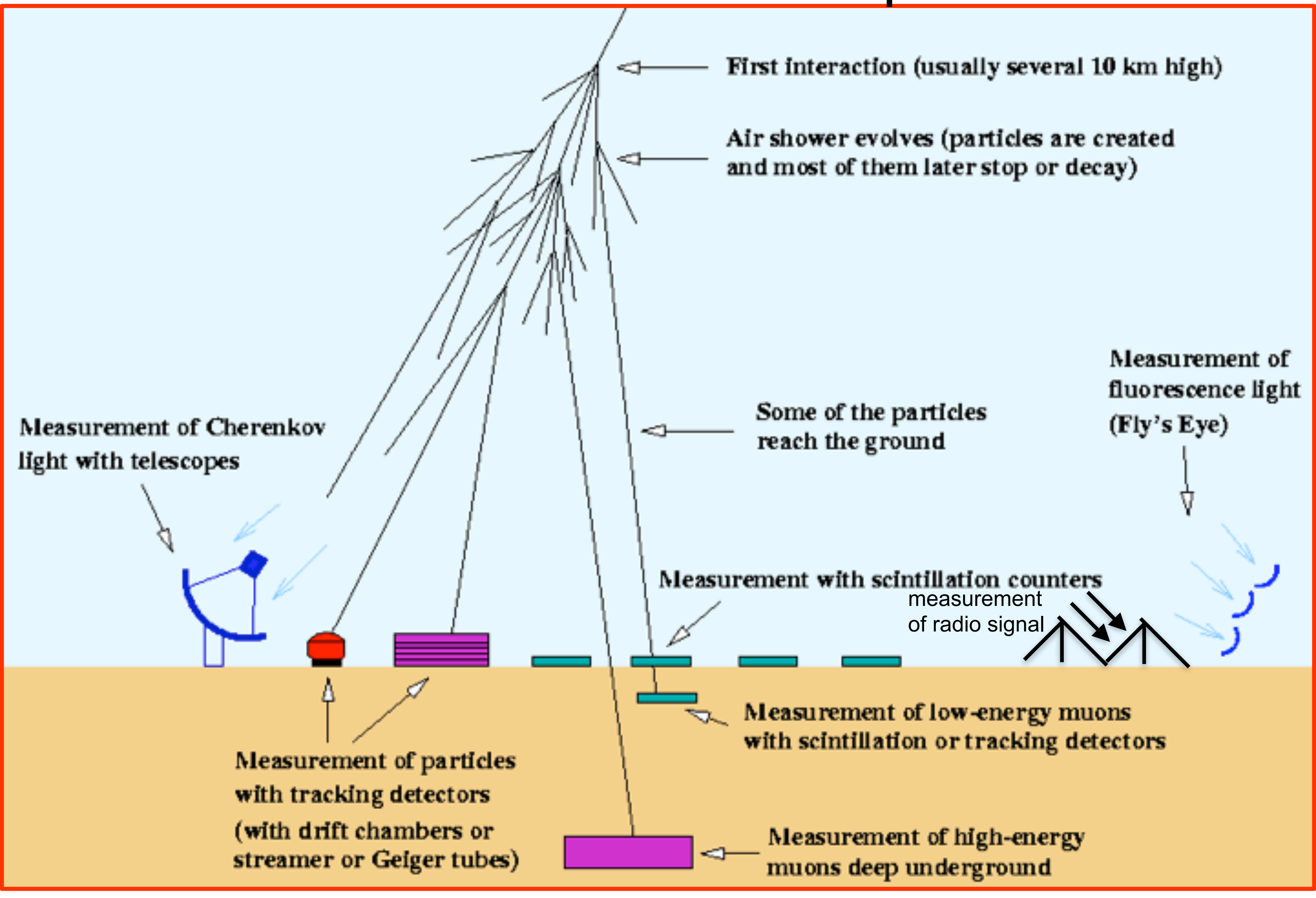
Development in atmosphere of EAS produced by protons or Fe nuclei at E=10^{15} eV

Hadronic Interaction Models needed to simulate the particle interactions in atmosphere:
EPOS, QGSjet, SIBYLL,…

They are embedded in a software that simulates the EAS cascade in atmosphere such as CORSIKA.

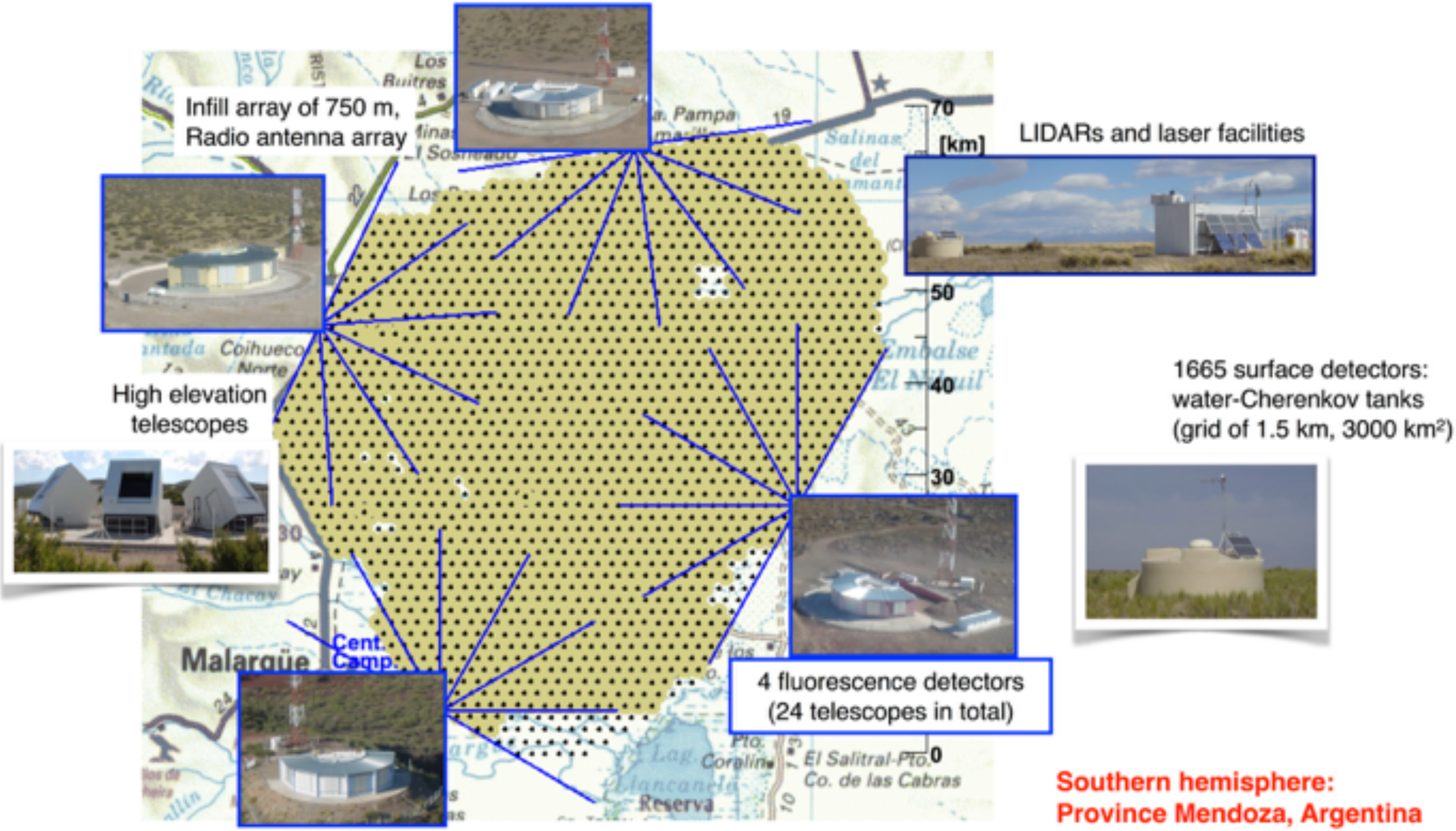


EAS detection techniques



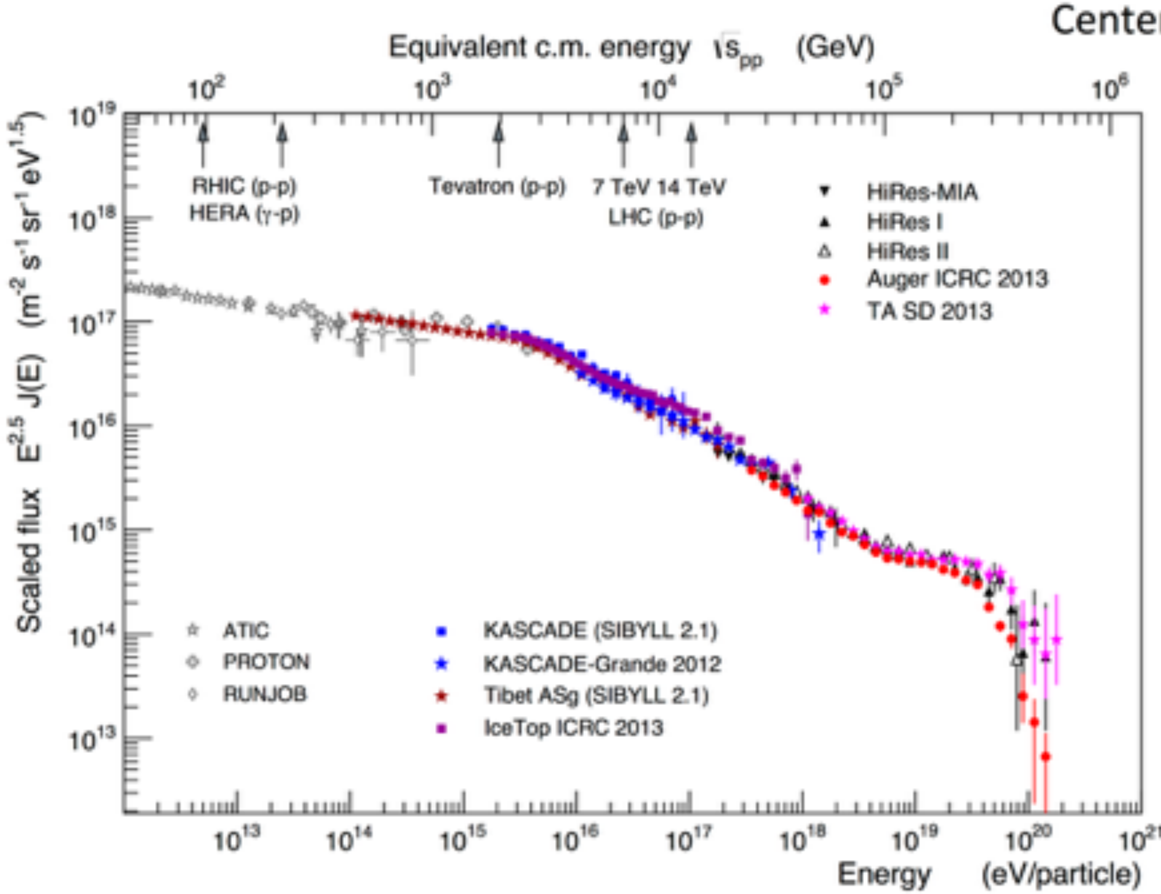
$E > 10^{17}$ eV

The Pierre Auger Observatory



Cosmic ray flux and interaction energies

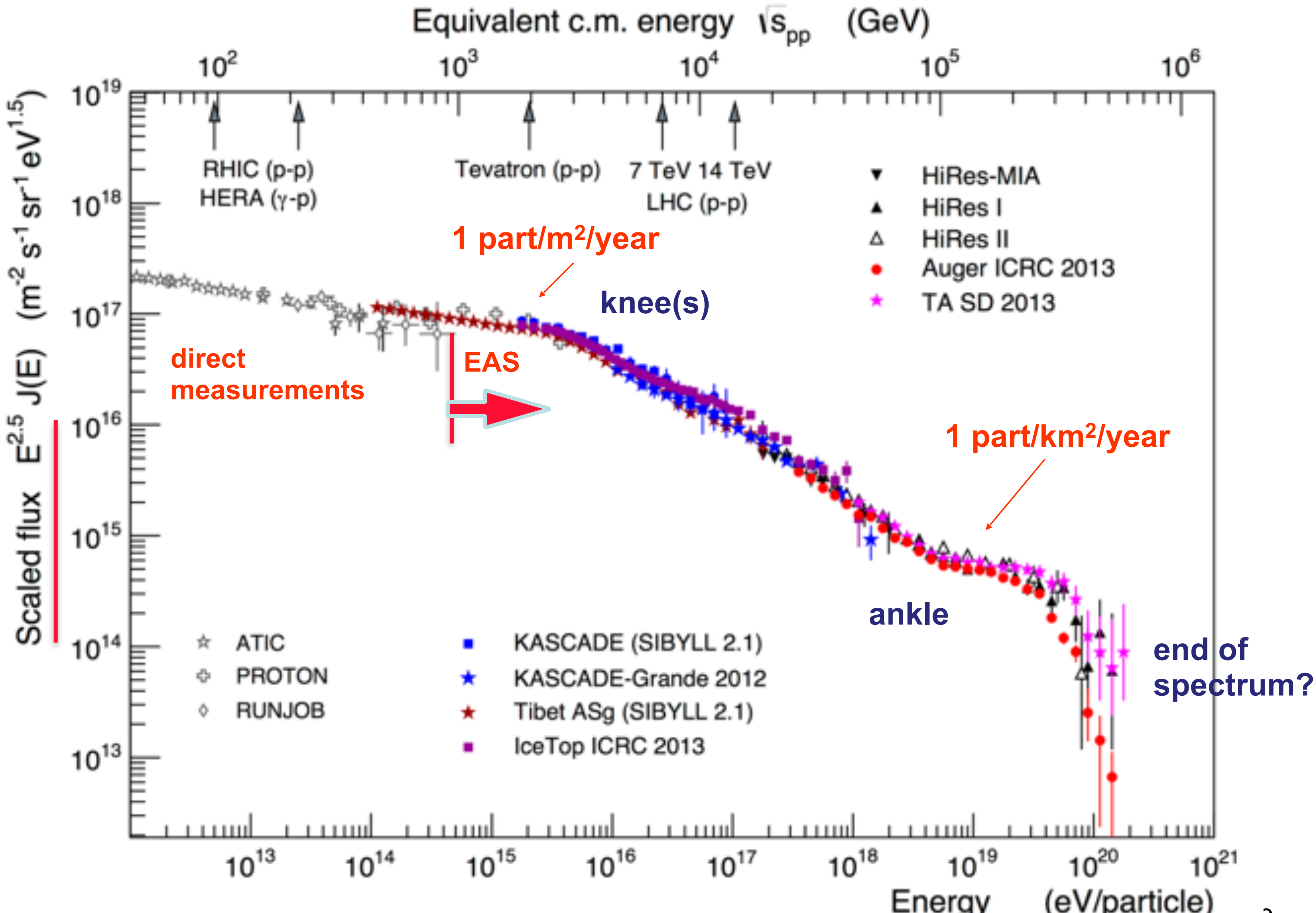
Center-of-mass energy



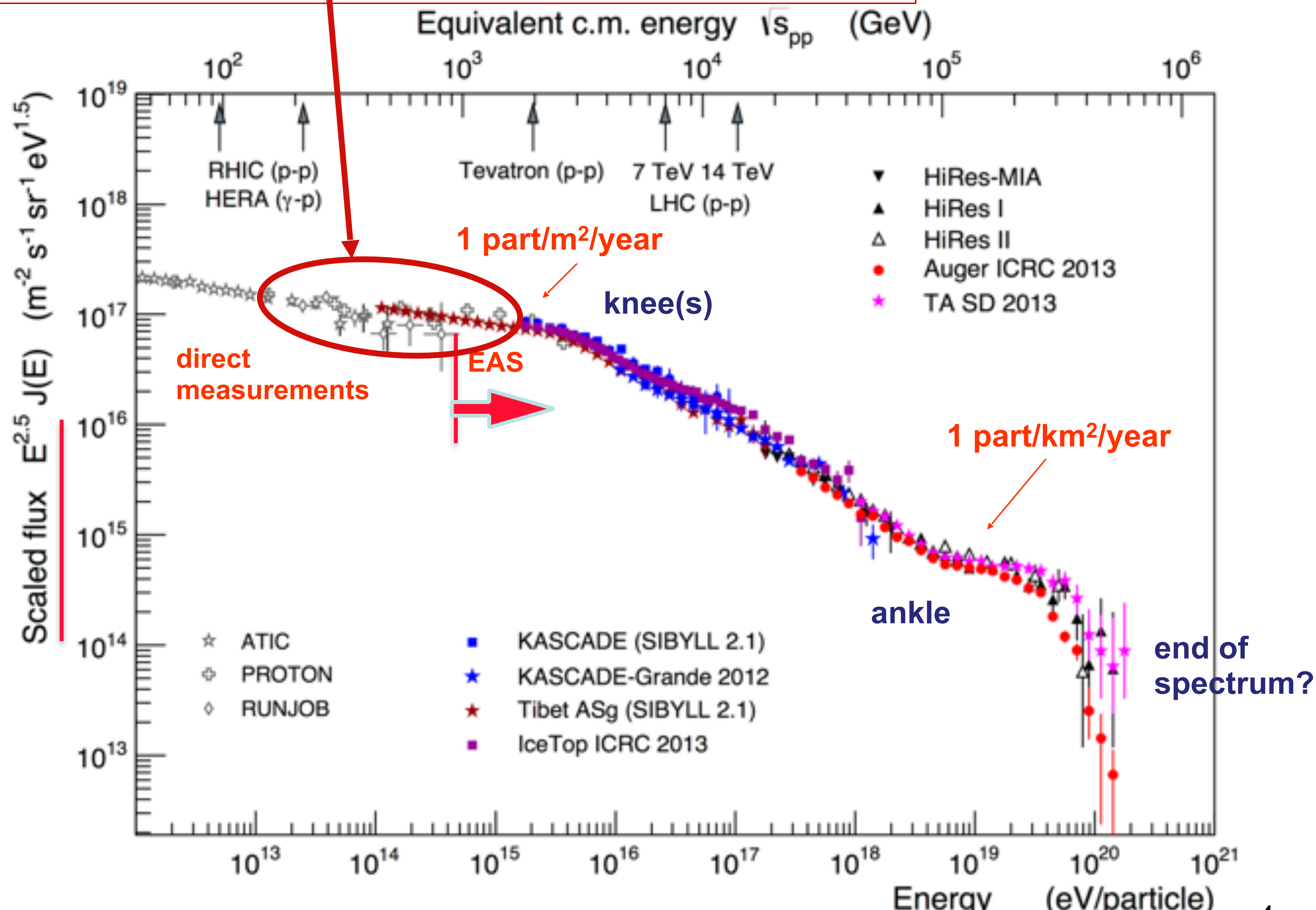
Laboratory energy

R. Engel (KIT)

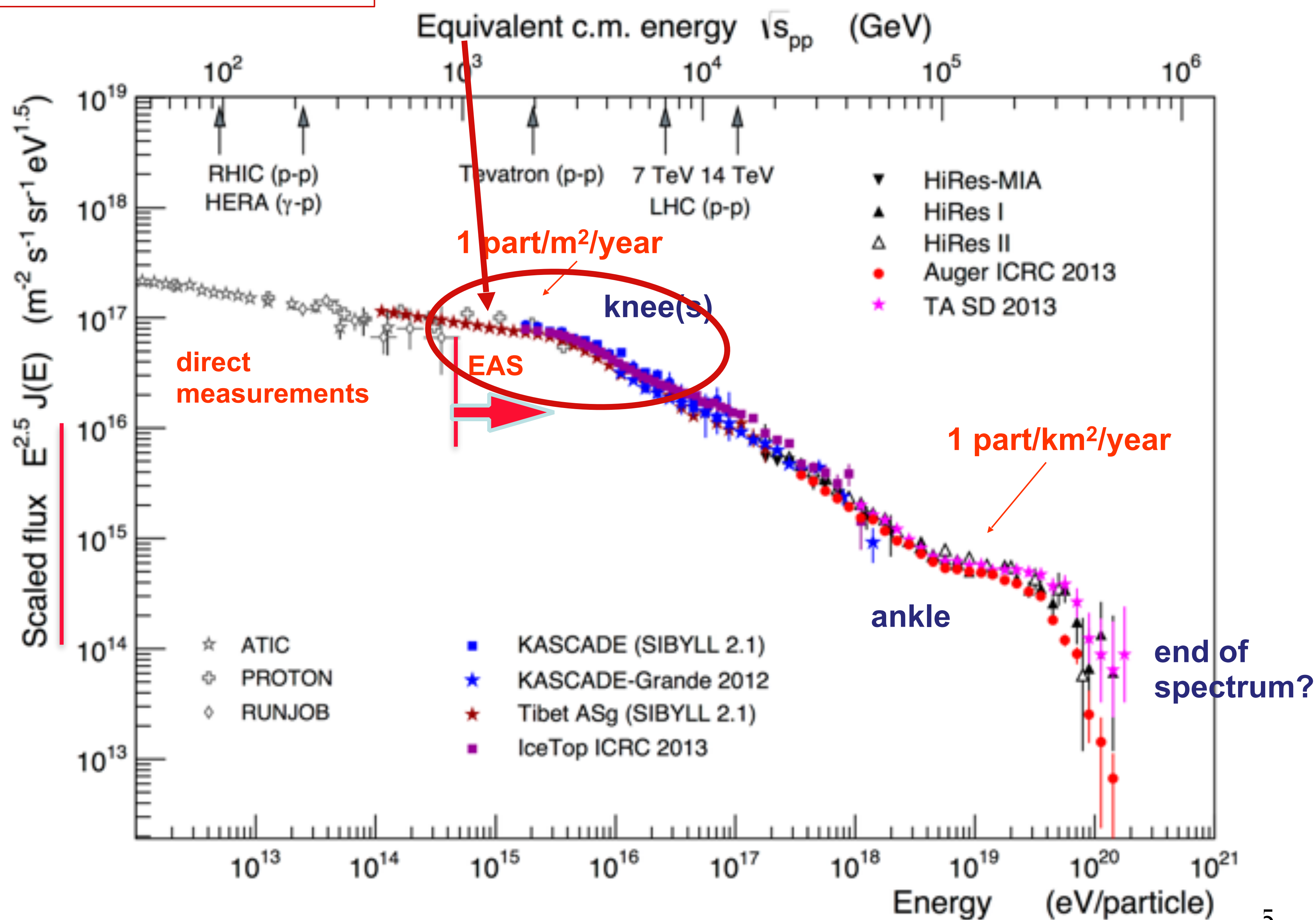
COSMIC RAY SPECTRUM



Technical: direct to ground based experiments



Origin of the knee?



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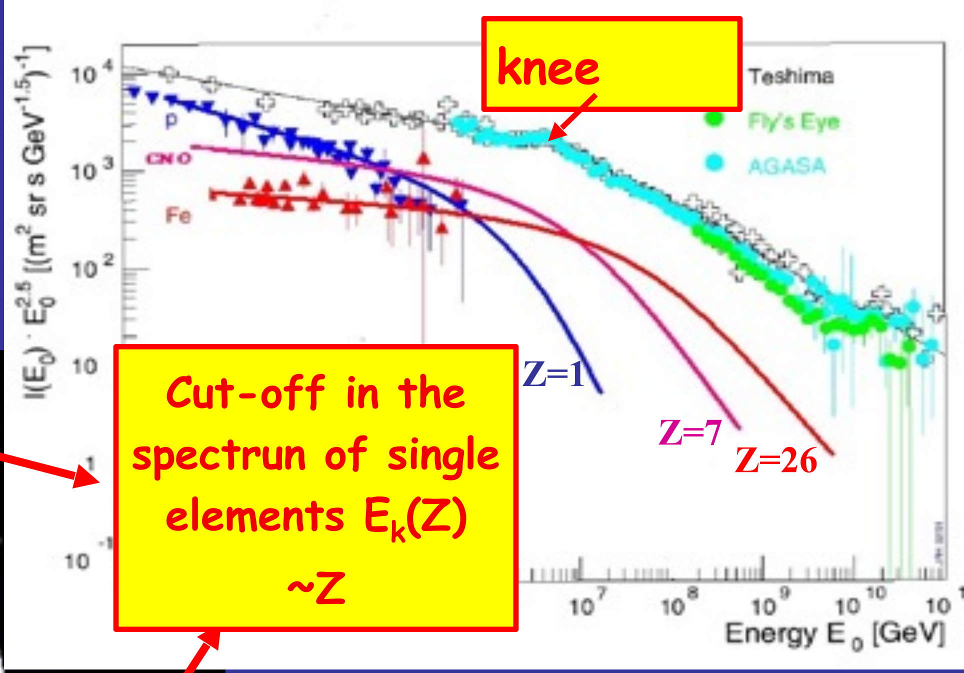
What is the origin of the knee?

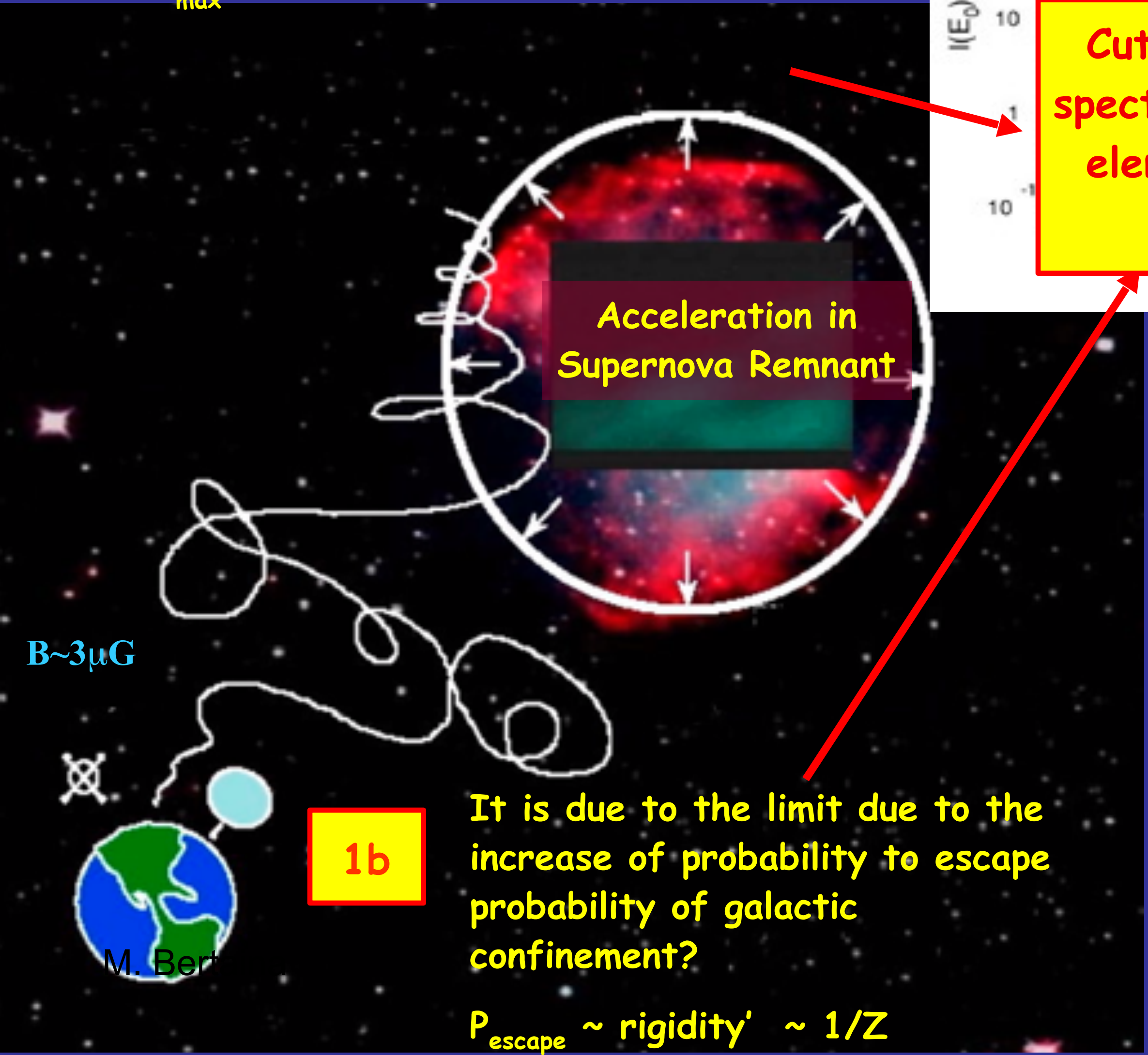
1a The energetic limit of the acceleration mechanism of galactic c.r.?

$E_{max} \sim Z \cdot 10^{15}$ eV



knee

Cut-off in the spectrun of single elements $E_k(Z)$ ~Z

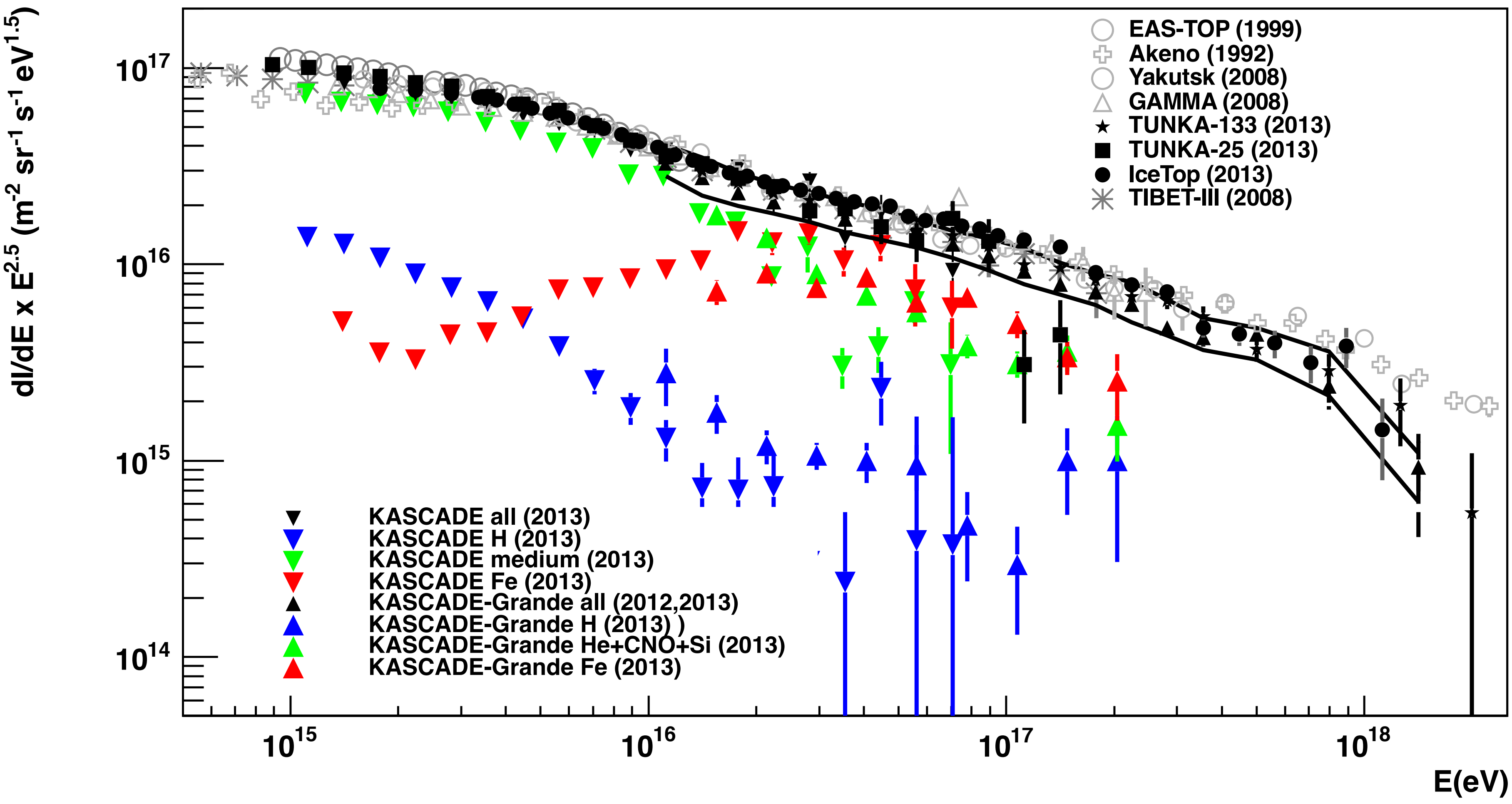


Acceleration in Supernova Remnant

1b It is due to the limit due to the increase of probability to escape probability of galactic confinement?

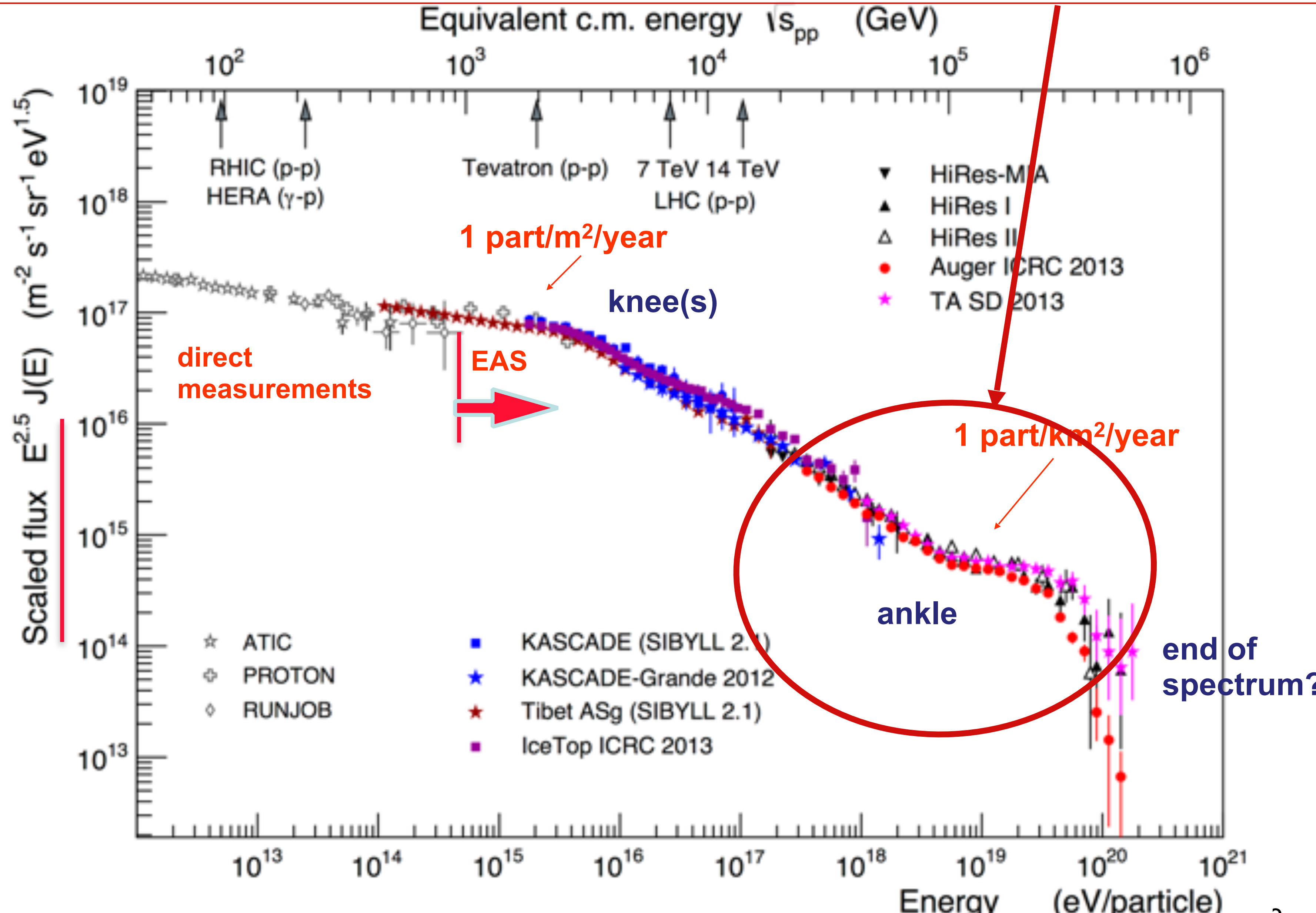
$P_{escape} \sim$ rigidity' $\sim 1/Z$

Results in the knee region



M.B., Comptes Rendus (2014)

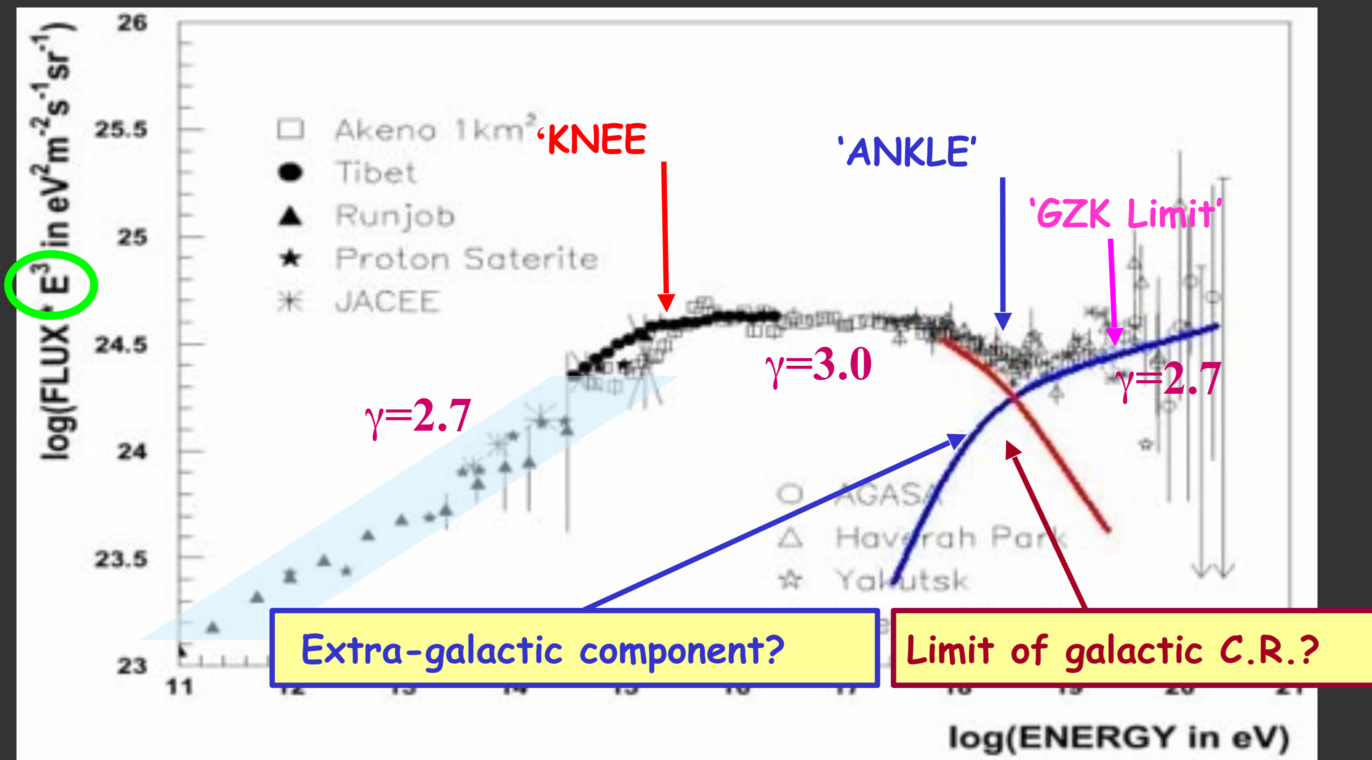
Origin of the ankle? (transition between galactic/extra-galactic CRs)



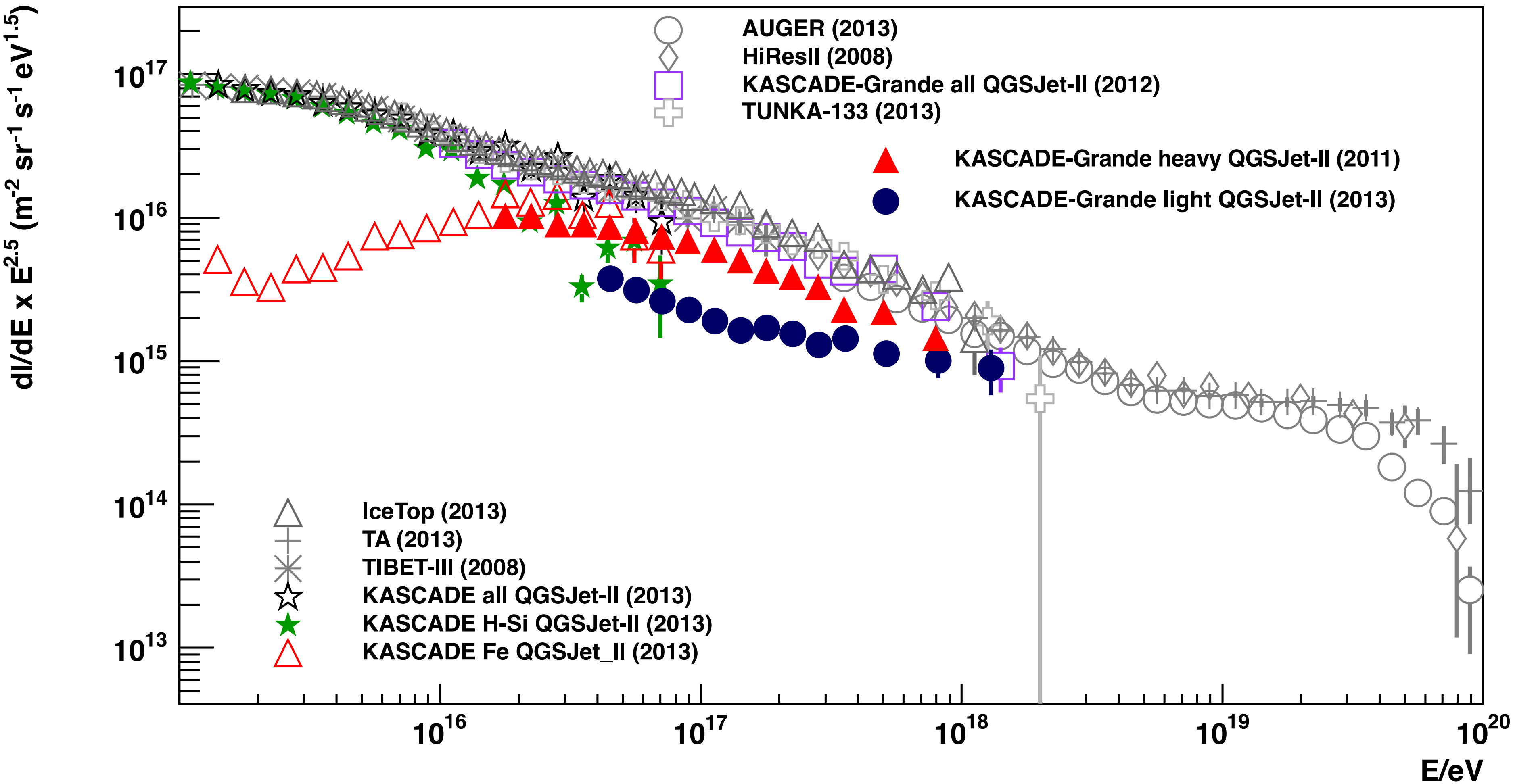
R. Engel (KIT)

2

…the ankle marks the transition between galactic and extra galactic cosmic rays ?

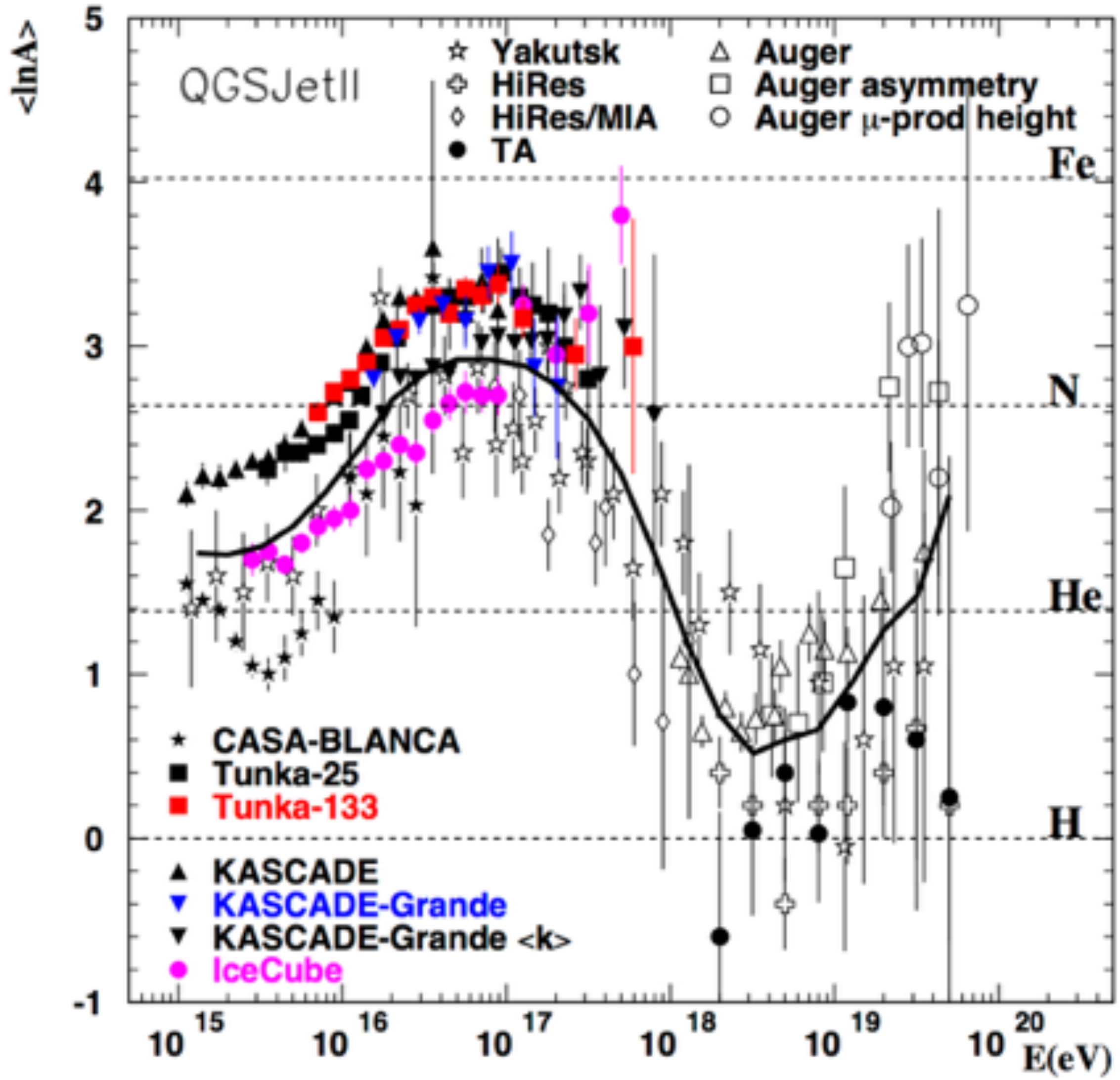


KASCADE-Grande results:



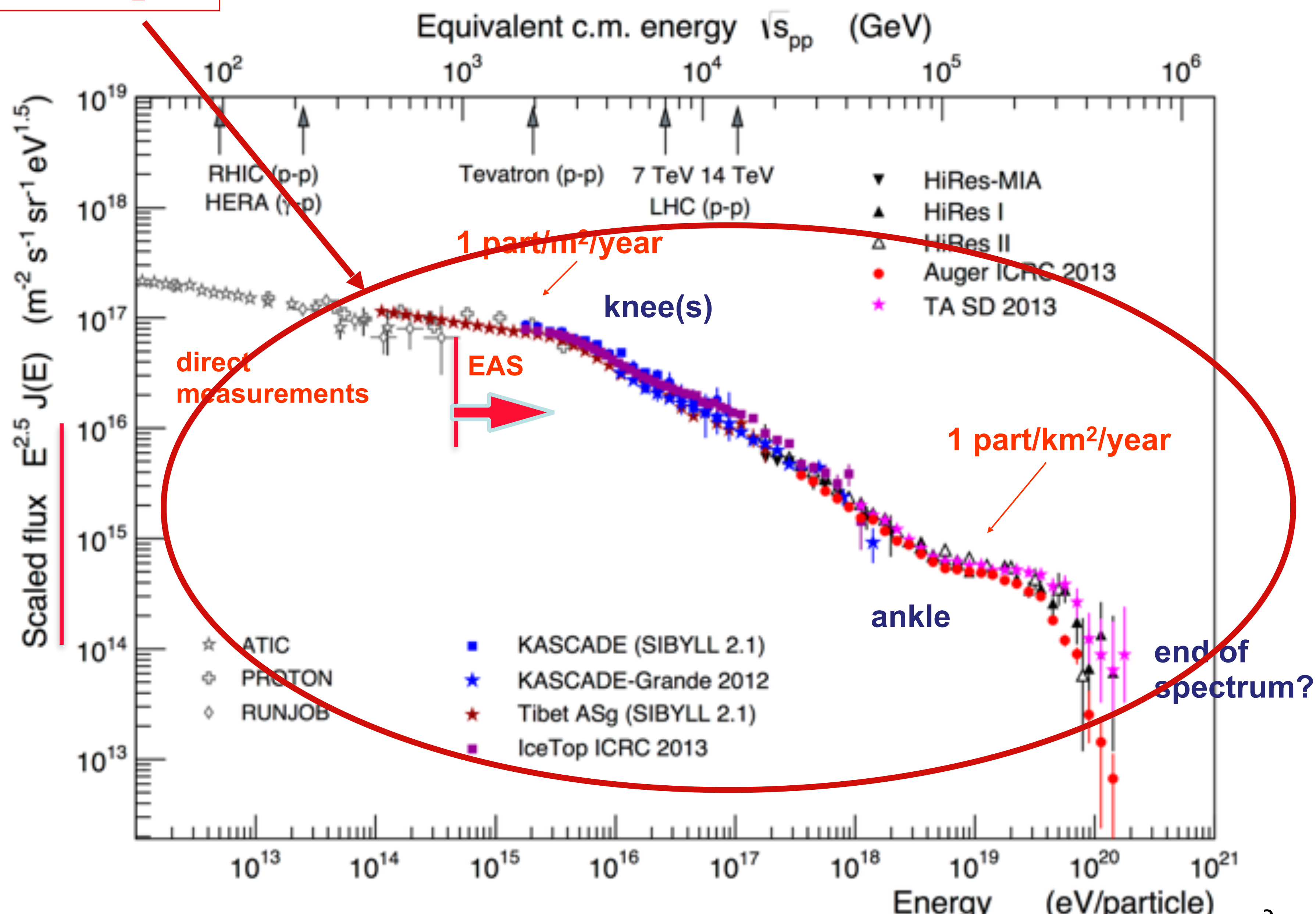
M.B., Comptes Rendus (2014)

Composition vs Energy



M.B., Comptes Rendus (2014)

Anisotropies



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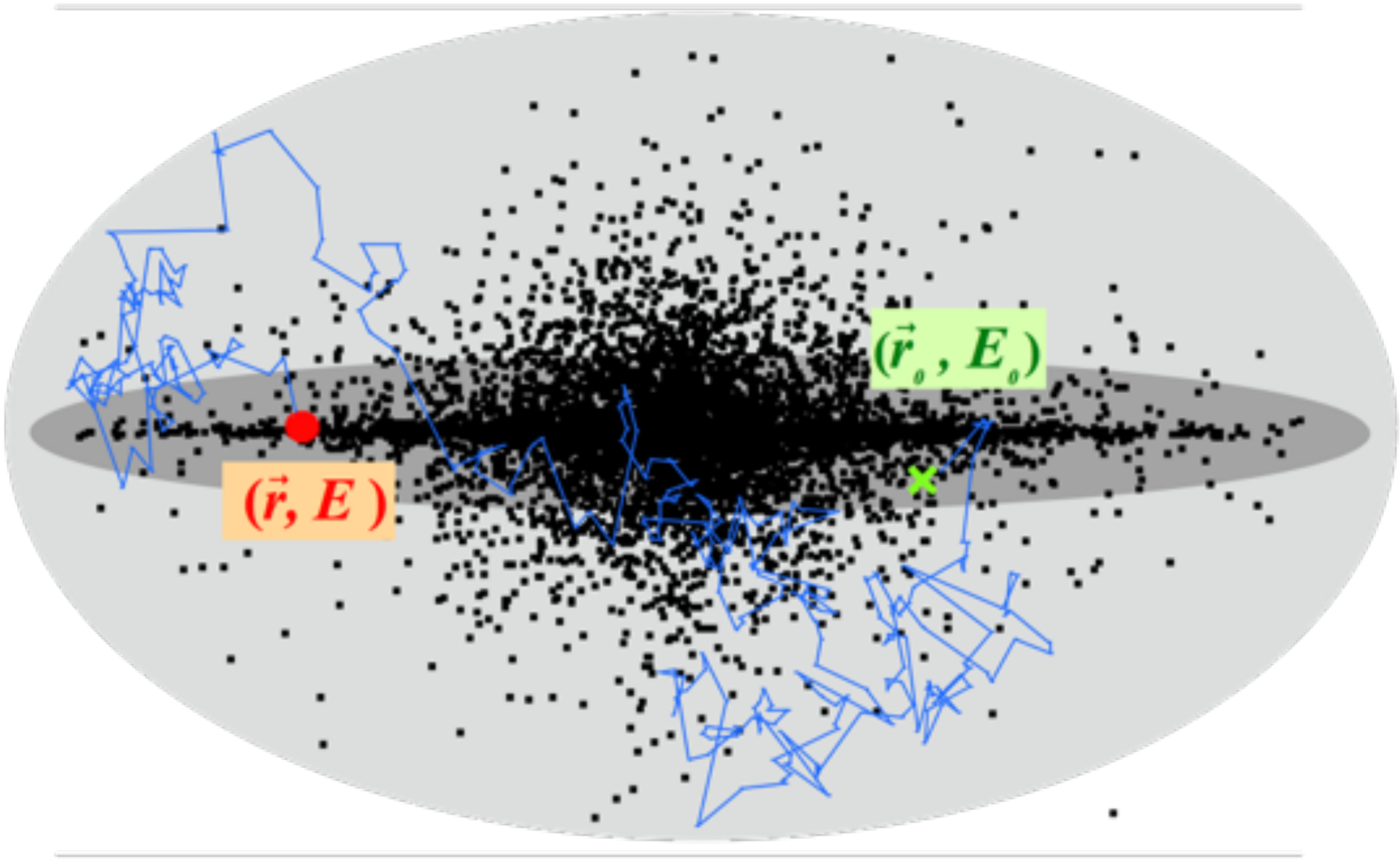
Random path of Cosmic Rays

$\Phi\,(r, E; r_0, E_0)$: structure function

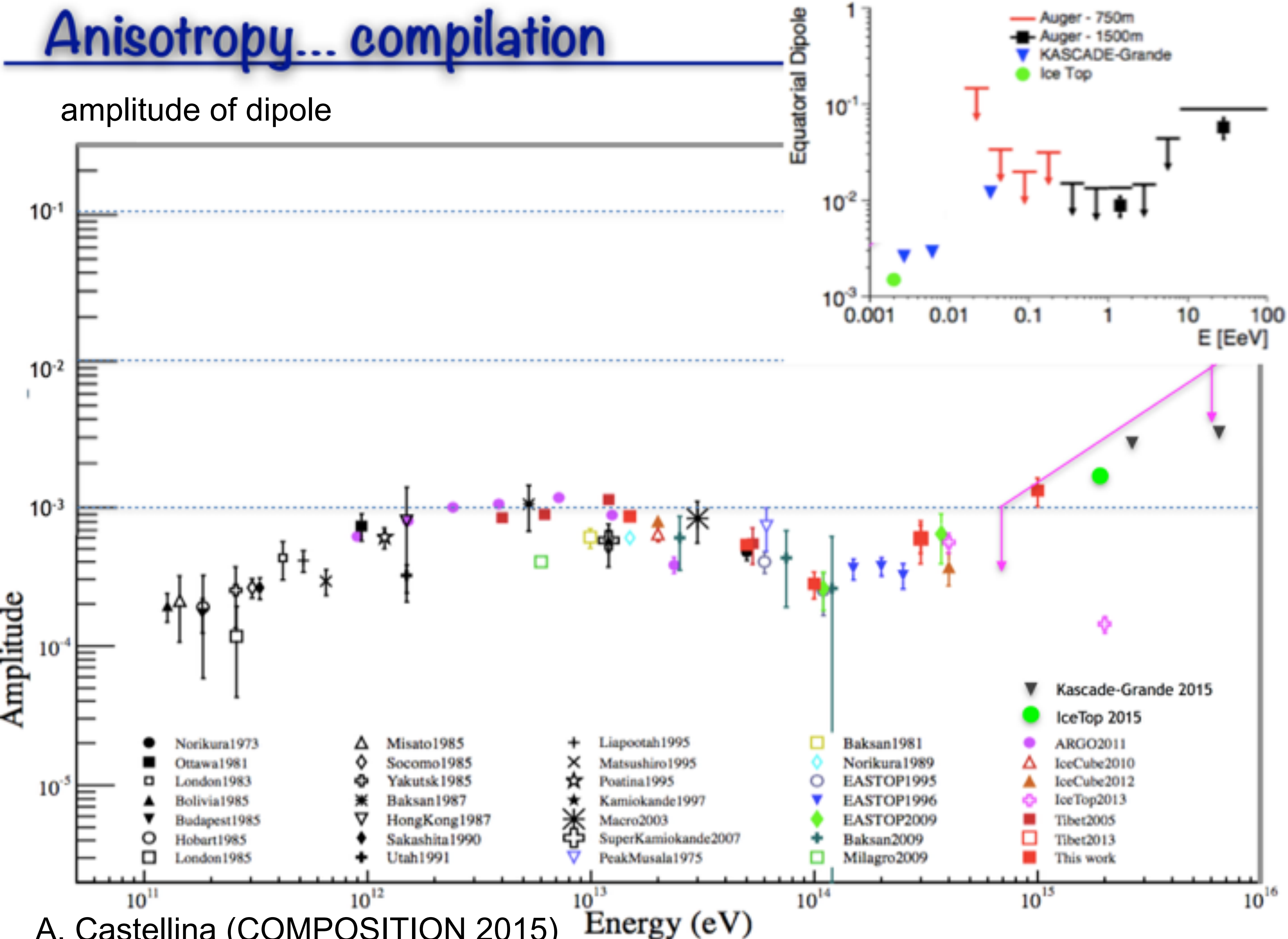


● : solar system $\vec{r}\ (r \sim 10\text{kpc},\ z \sim 0)$

× : source $\vec{r}_0\ (r_0,\ z_0)$

Anisotropy... compilation

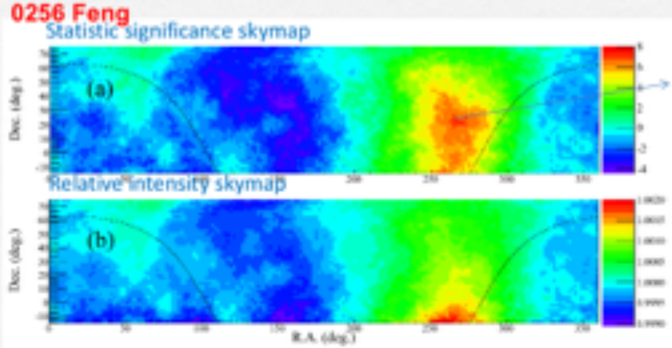
amplitude of dipole



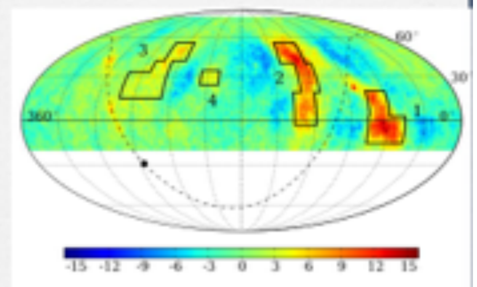
A. Castellina (COMPOSITION 2015)

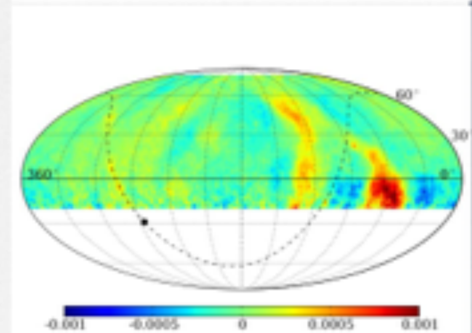
Low-Energy Anisotropy

Tibet
0256 Feng

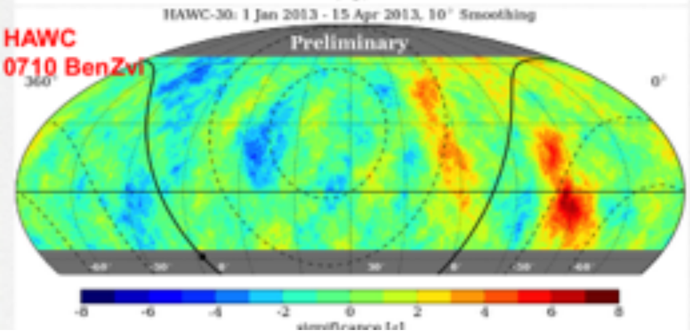


ARGO
1143 Iuppa

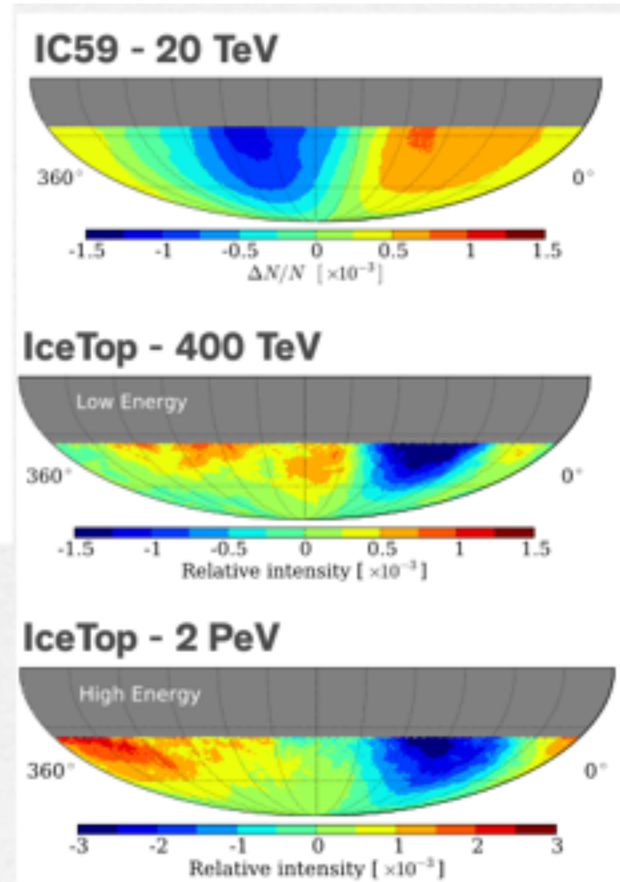




HAWC
0710 BenZvi



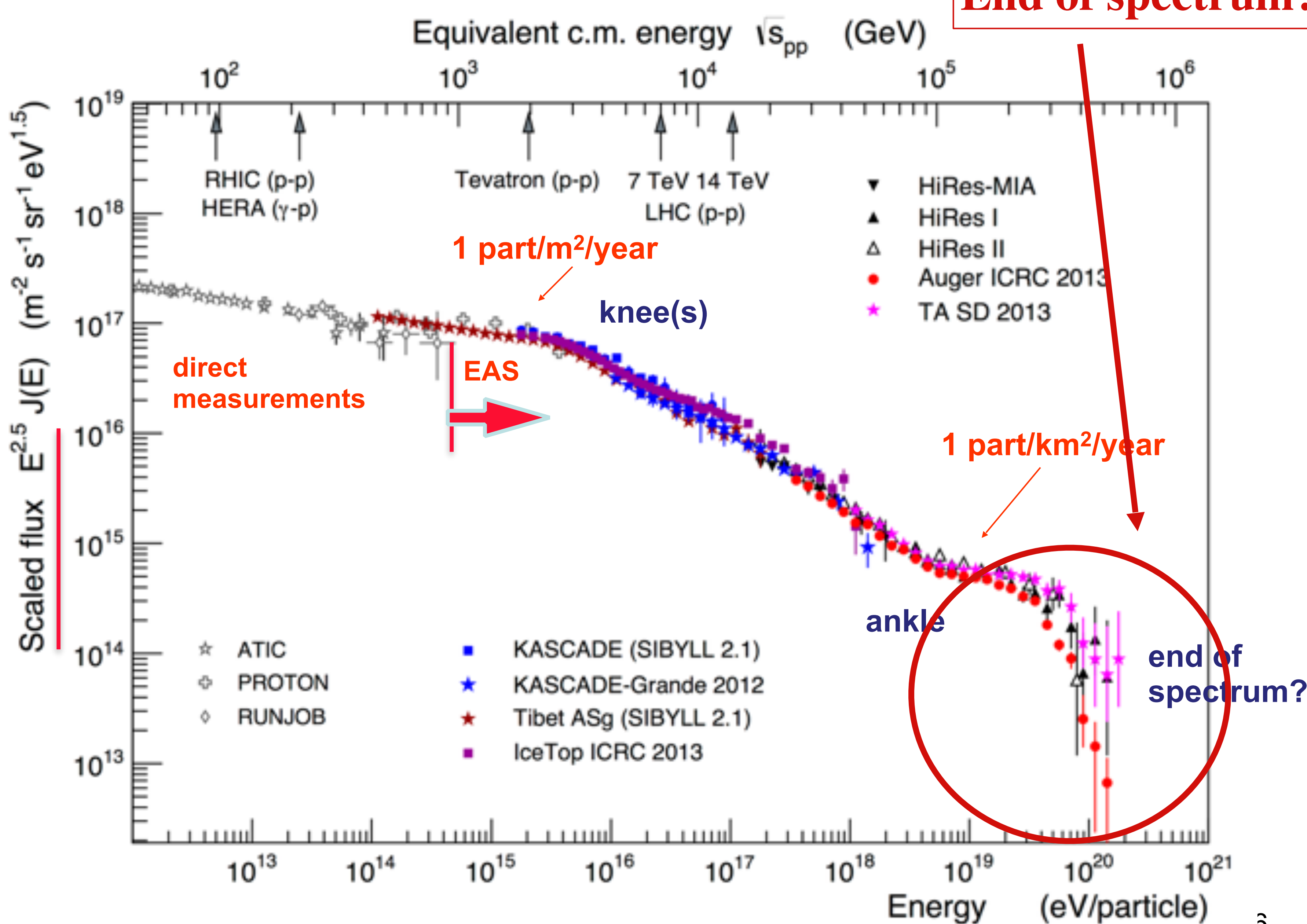
IceCube & IceTop



Where does this anisotropy comes from?
Why it changes above hundred TeV?

Tsunesada, ICRC 2013

End of spectrum?

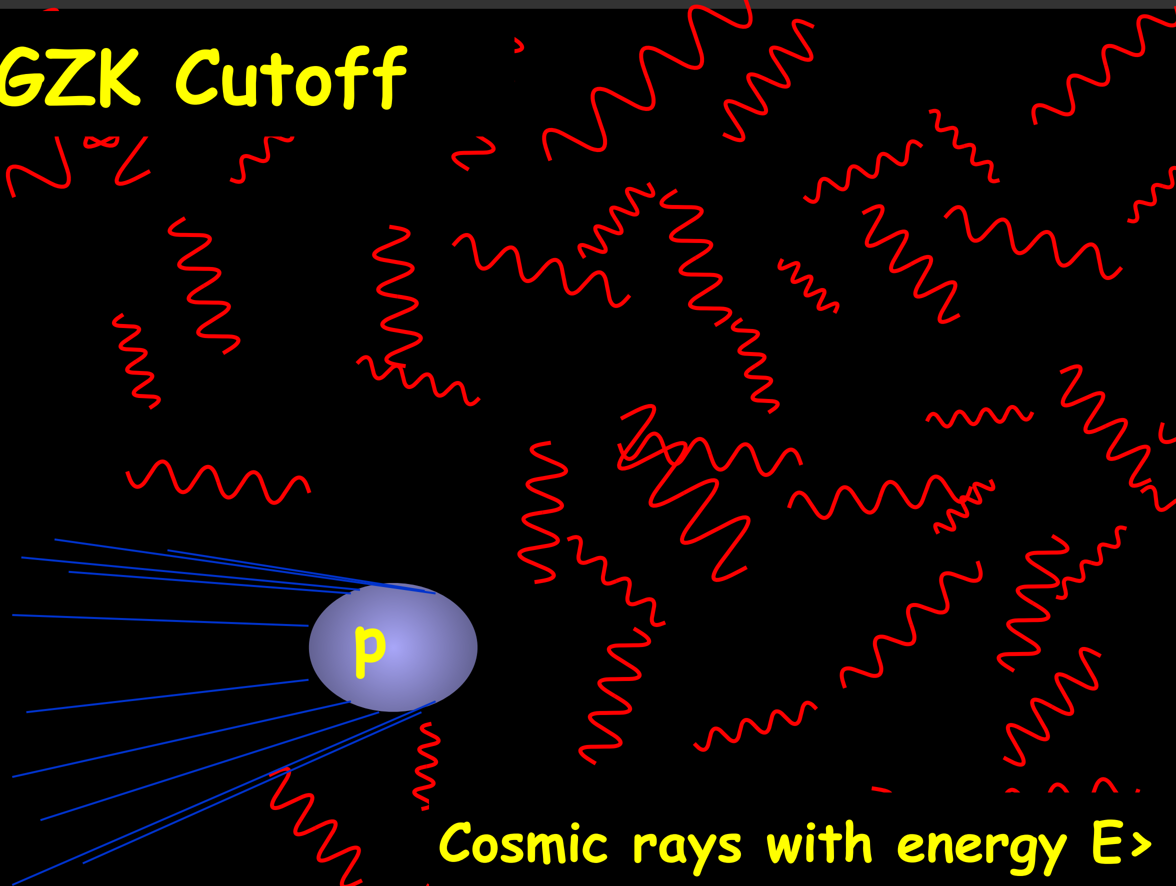


R. Engel (KIT)

The cosmic microwave background at 3 ^{0}K makes the Universe opaque to the cosmic rays of extreme energy

K. Greisen - G.T.Zatsepin & V.A.Kuz'min (1966)

GZK Cutoff



$p+\gamma \rightarrow p+\pi^0$

$p+\gamma \rightarrow n+\pi^+$

$E_{thr}=6.8\ 10^{19}$ eV

$l=1/\sigma\rho=6$Mpc

$\rho \sim 410\ \gamma/cm^3$

$\sigma=135$mbarn

Cosmic rays with energy $E > 7 \cdot 10^{19}$ eV must have their sources within 50Mpc

ORIGIN and PROPAGATION of UHECRs

GZK cut-off for protons

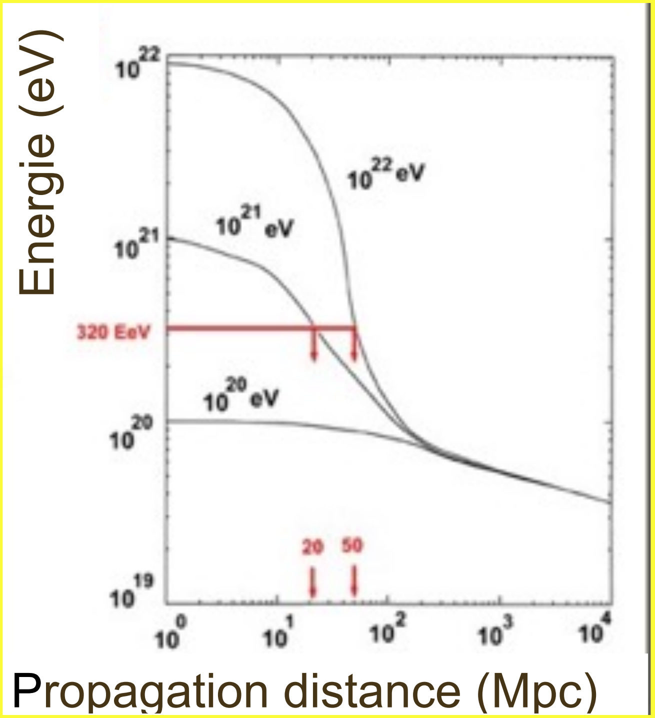
$$p + \gamma_{2,7K} \rightarrow \Delta \rightarrow n + \pi^{+}$$
$$p + \gamma_{2,7K} \rightarrow \Delta \rightarrow p + \pi^{0}$$
$$p + \gamma_{2,7K} \rightarrow \Delta \rightarrow p + e^{+} + e^{-}$$

Photo-dissociation for heavier nuclei

$$A + \gamma_{2,7K} \rightarrow (A-1) + N$$
$$A + \gamma_{2,7K} \rightarrow (A-2) + 2N$$
$$A + \gamma_{2,7K} \rightarrow A + e^{+} + e^{-}$$

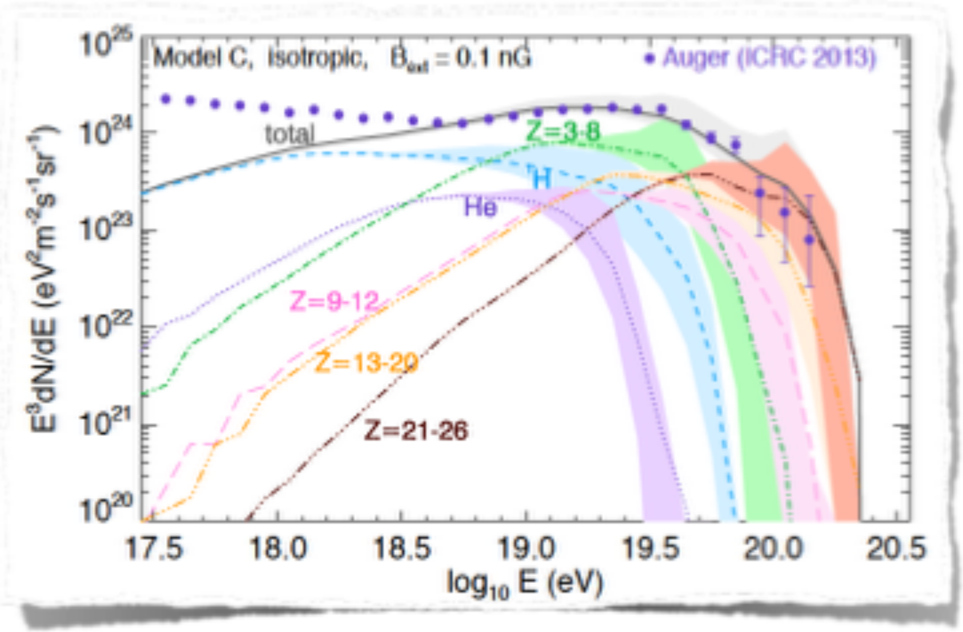
Laboratory System:
E proton = 10^{20} eV; E photon: 0.5 meV

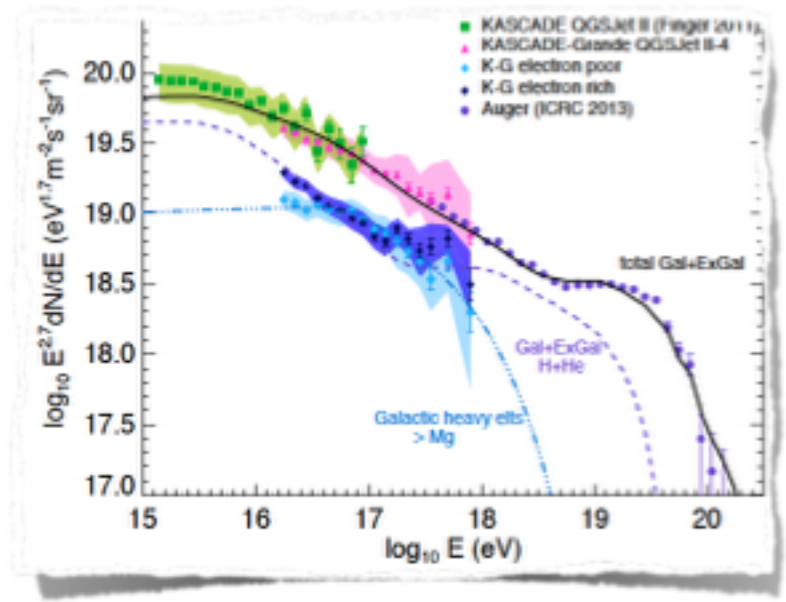
Proton reference system:
E proton = 0 eV ; E photon: 300 MeV



Cosmic rays with energy E> $7 \cdot 10^{19}$ eV must have their sources within 50Mpc

Other possibility: end of spectrum due to the fact that sources are running out of steam

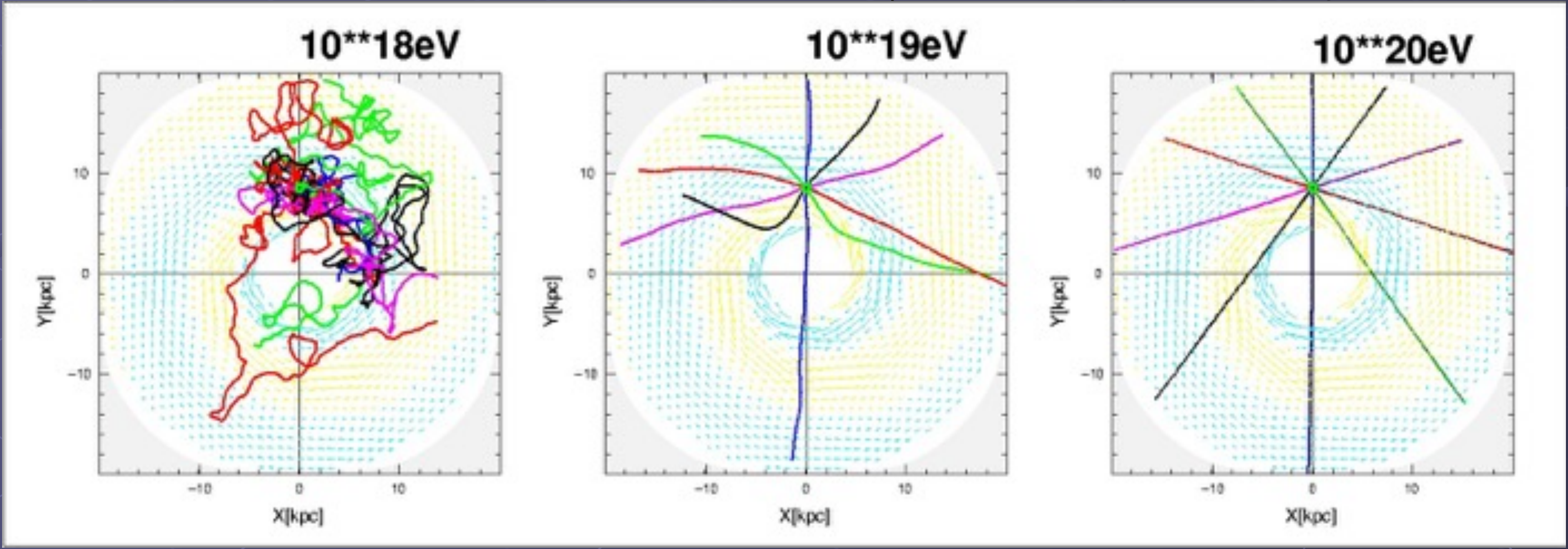




Globus et al. (ICRC 2015)

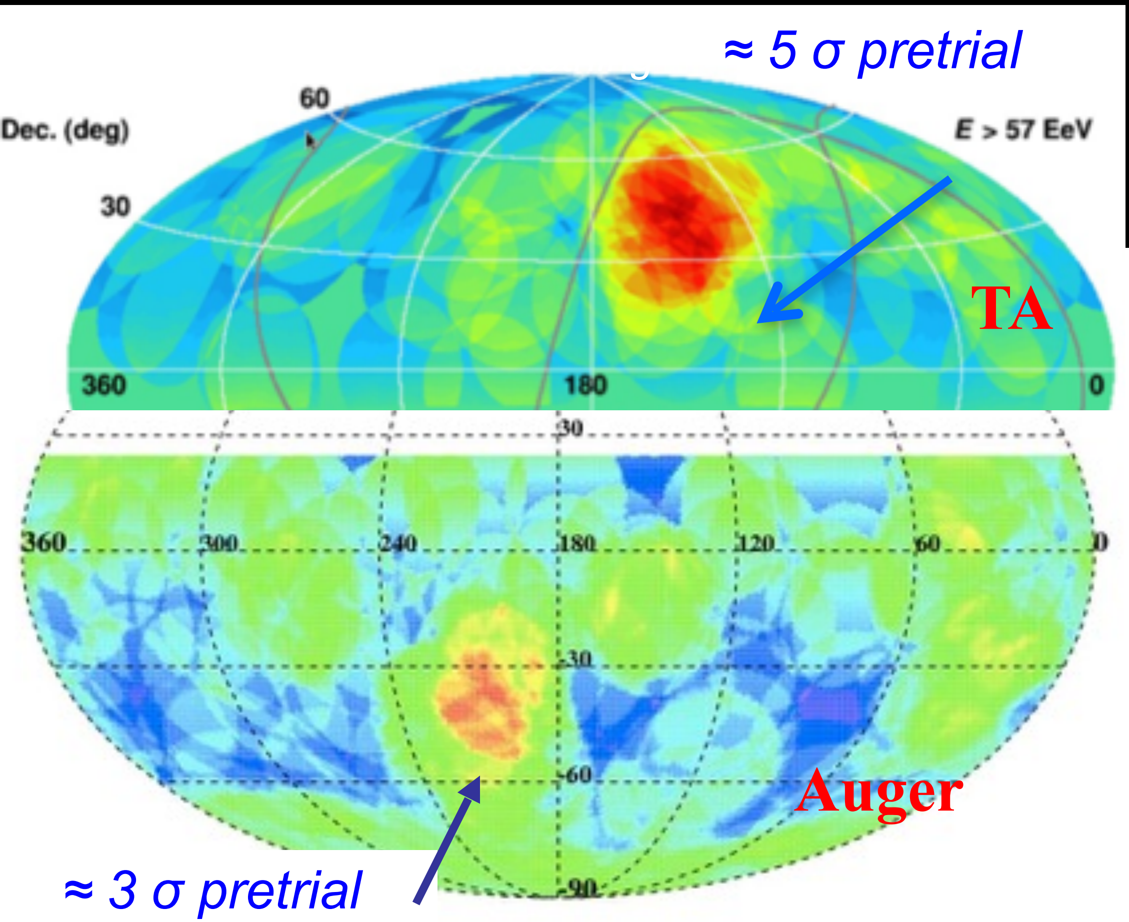
Cosmic Ray Propagation in our Galaxy

- Deflection angle < 1 degree at 10^{20}eV for protons

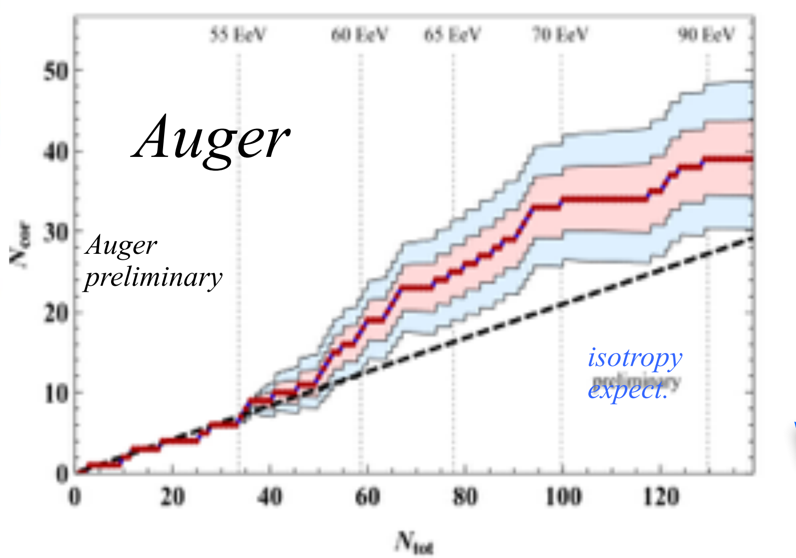


Anisotropy Hints >60 EeV

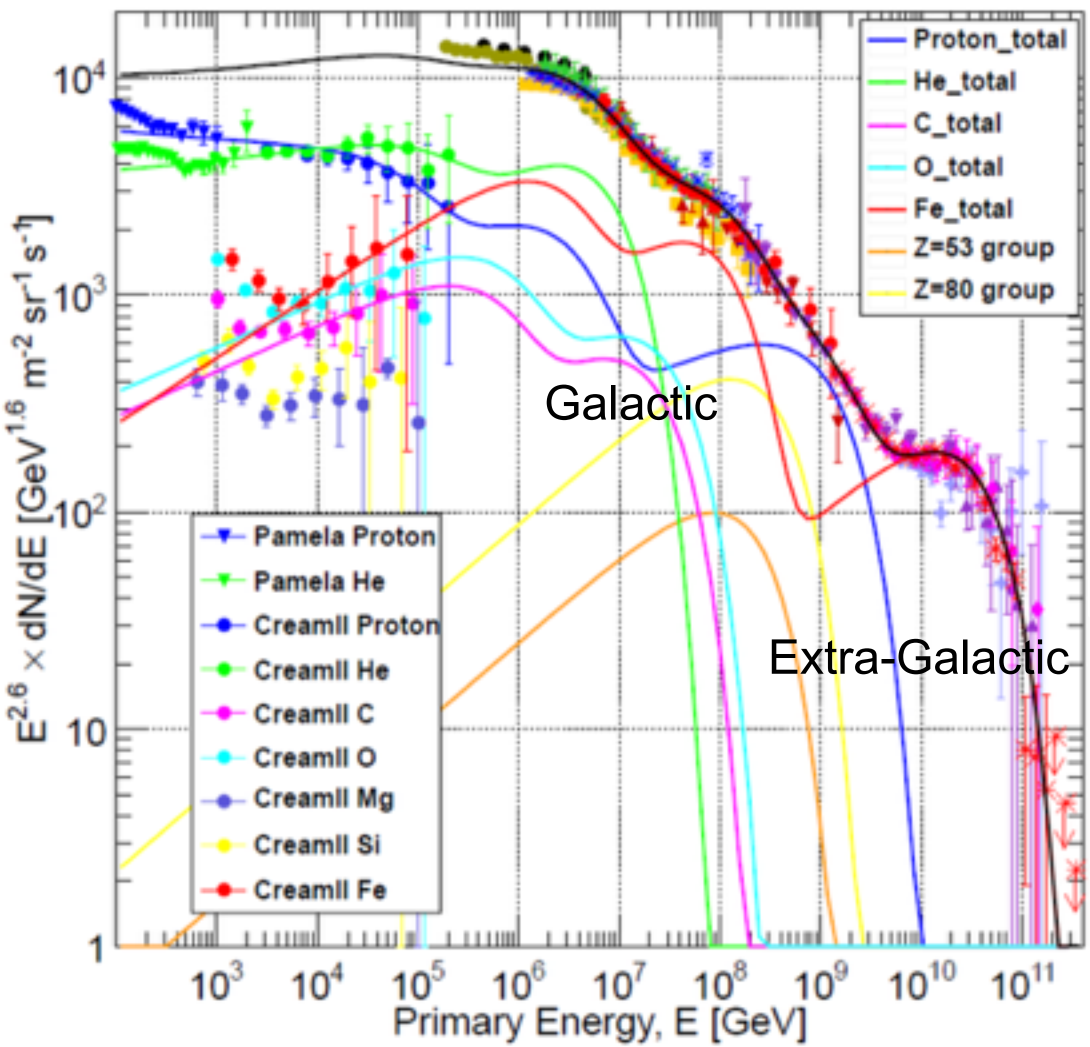
Statistically limited evidence for Comic Ray Anisotropy above $5.7\text{x } 10^{19}$ eV in the North and South



# of events correlating with AGN,
ordered in energy (integral plot)



The connection with the 'knee' and the highest energies

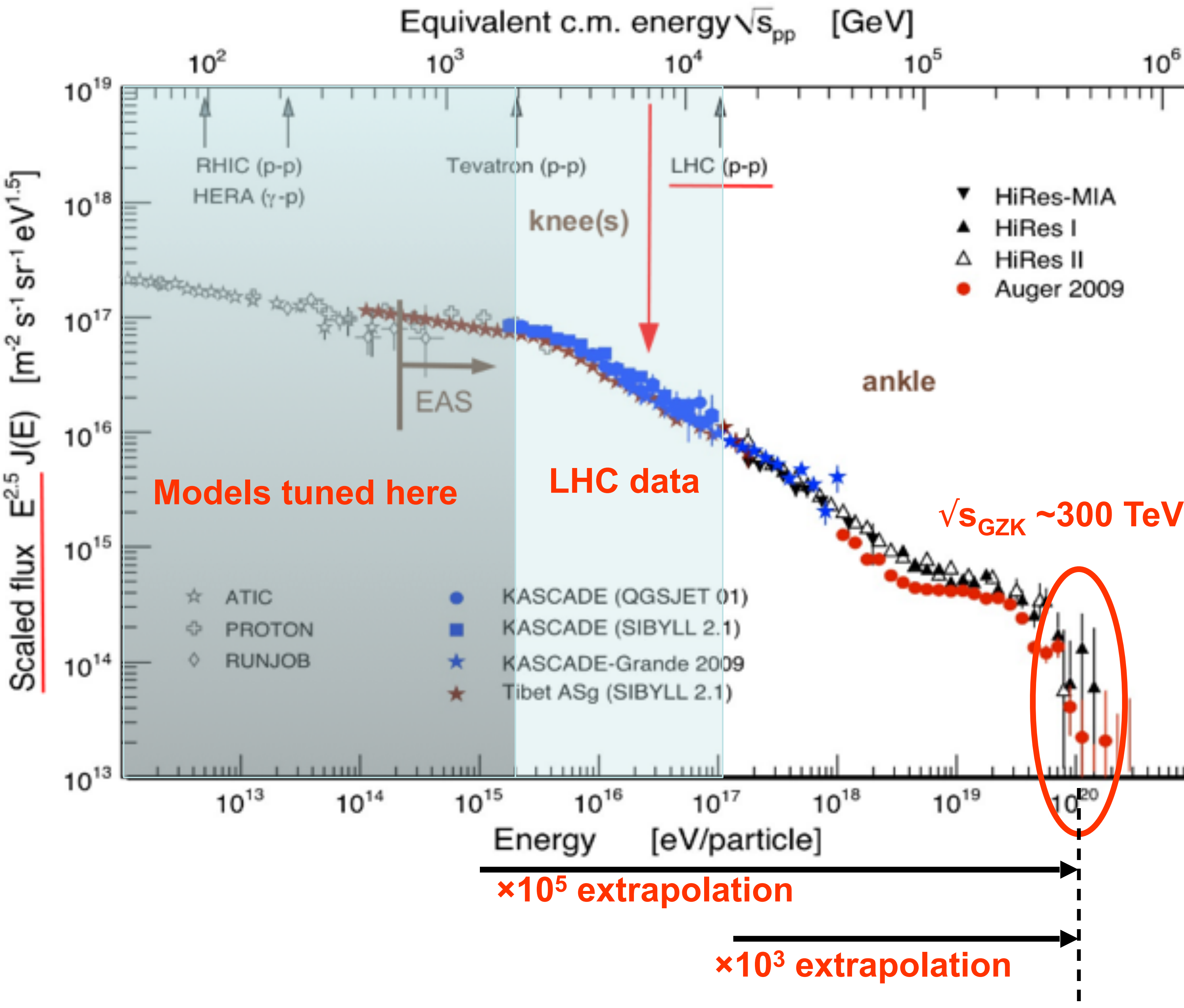


Acceleration limit:

$E_{max\_z} = Ze \times R = Z \times E_{max\_p}$,

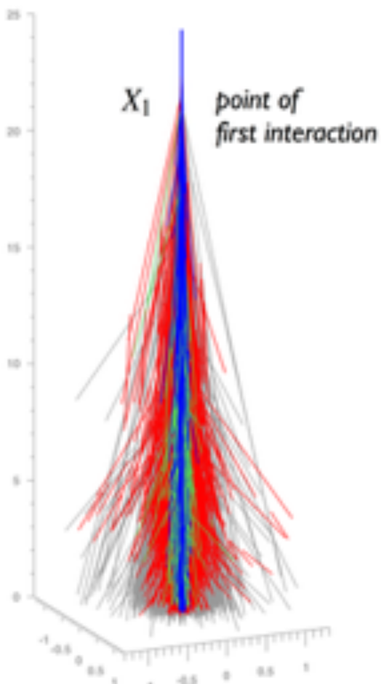
where rigidity R = Pc/Ze

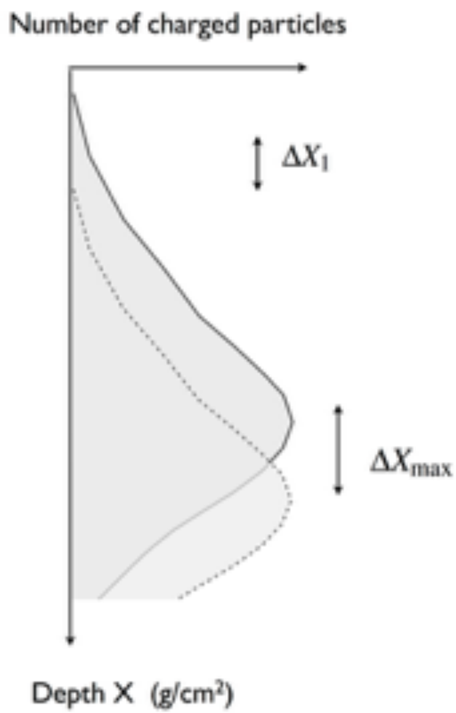
Part II:
The interconnection between cosmic rays and particle physics



Equivalent c.m. energy $\sqrt{s_{pp}}$ [GeV]
RHIC (p-p)
HERA (γ-p)
Tevatron (p-p)
LHC (p-p)
knee(s)
ankle
EAS
HiRes-MIA
HiRes I
HiRes II
Auger 2009
Models tuned here
LHC data
$\sqrt{s}_{GZK}$ ~300 TeV
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2009
Tibet ASg (SIBYLL 2.1)
Scaled flux $E^{2.5}$ J(E) [m^{-2} s^{-1} sr^{-1} $eV^{1.5}$]
Energy [eV/particle]
×10^5 extrapolation
×10^3 extrapolation

Measurement of proton-air cross section



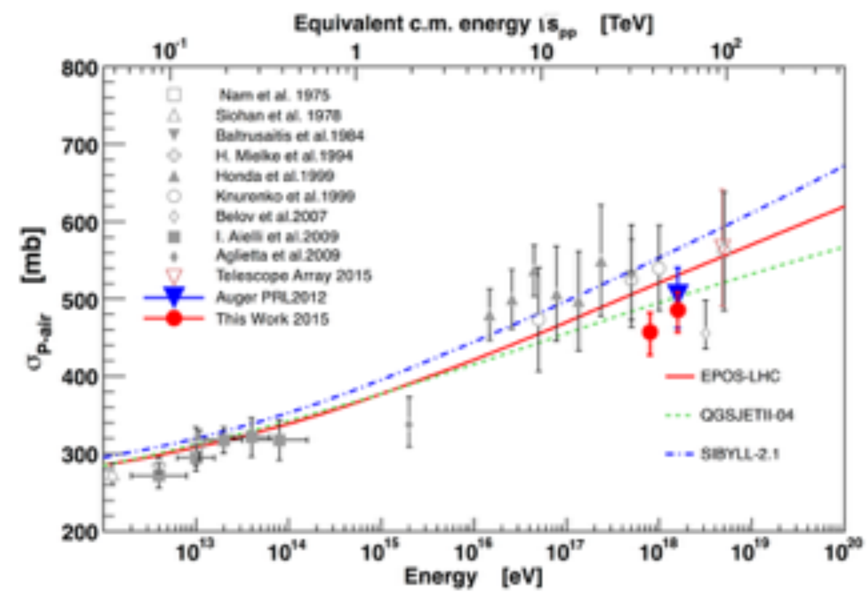


$$\frac{\mathrm{d}P}{\mathrm{d}X_1} = \frac{1}{\lambda_{\mathrm{int}}} e^{-X_1/\lambda_{\mathrm{int}}}$$

$$\sigma_{\mathrm{p-air}} = \frac{\langle m_{\mathrm{air}} \rangle}{\lambda_{\mathrm{int}}}$$

Difficulties

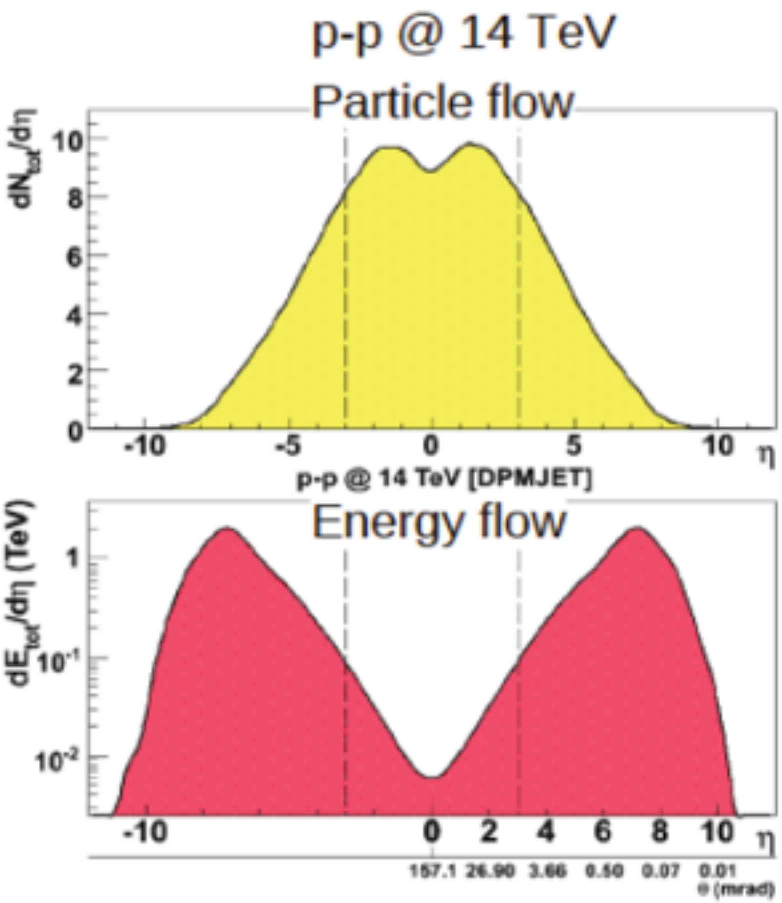
- mass composition
- fluctuations in shower development (model needed for correction)

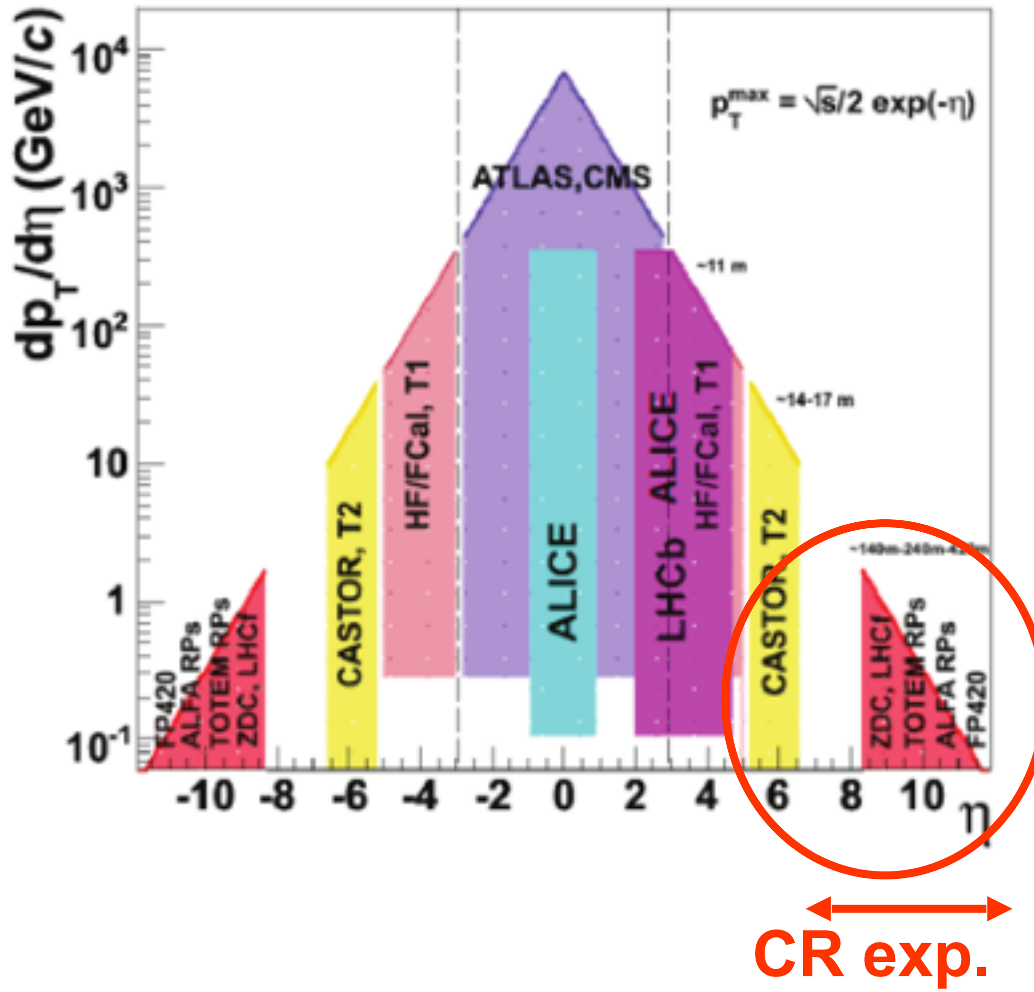


(Auger PRL 109, 2012; Telescope Array 1505.01860)

R. Engel (ICRC 2015)

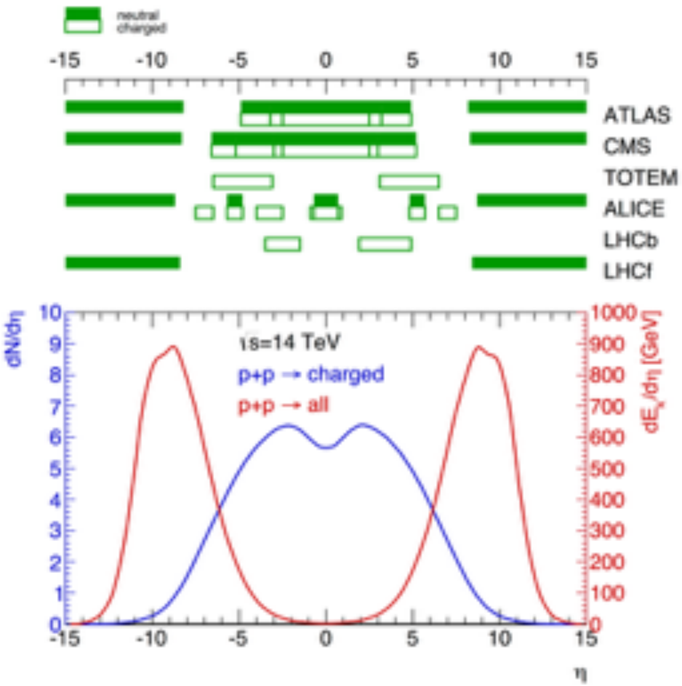
Rapidity regions of CR experiments and LHC detectors

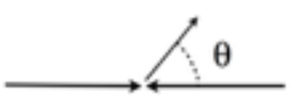




Pinfold, ICRC 2013

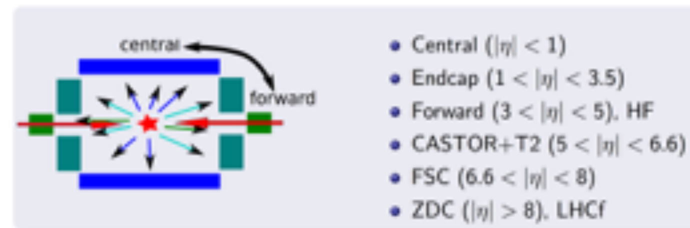
Challenge of limited phase space coverage

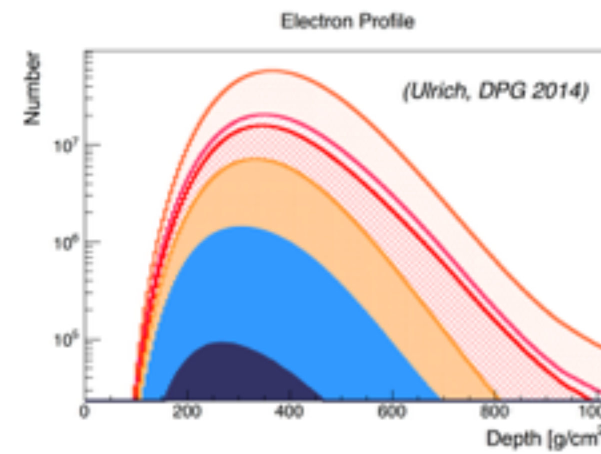




$$\eta = -\ln\tan\frac{\theta}{2}$$

η	deg.	mrad.
3	5.7	97
5	0.77	10
8	0.04	0.7
10	0,005	0,009





More than 50% of shower from η > 8

(Salek et al., 2014)

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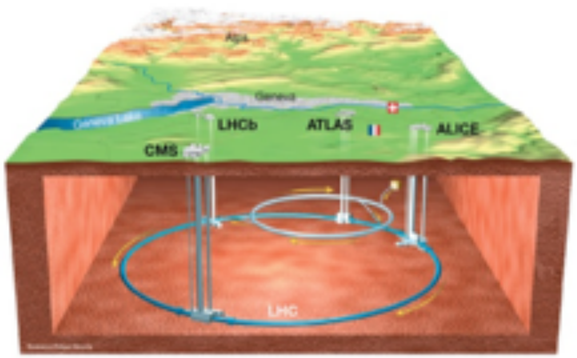
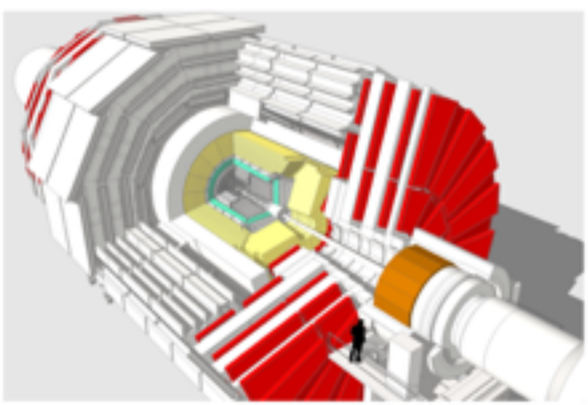
R. Engel (ICRC 2015)

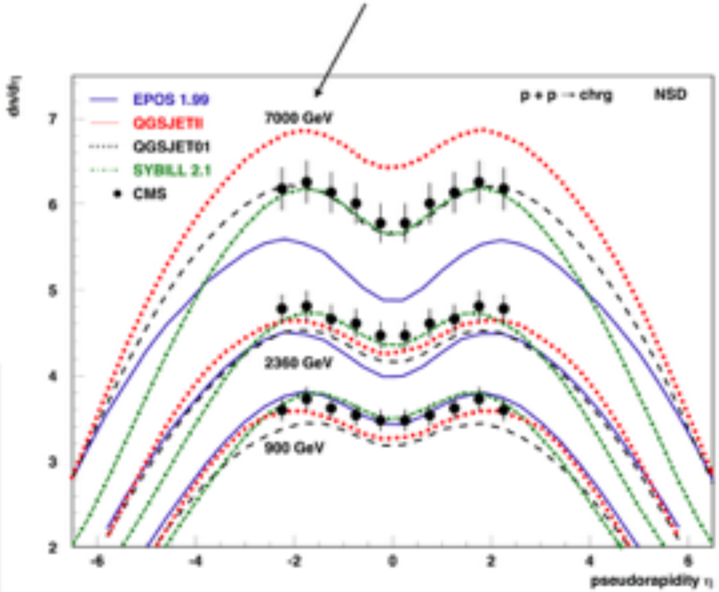
Charged particle distribution in pseudorapidity





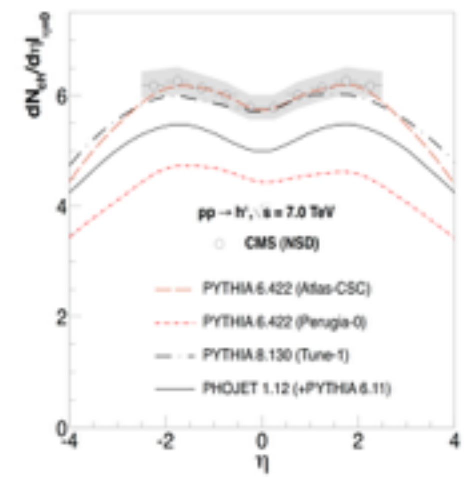
(data from all LHC experiments, CMS shown as example)

Protons: $E_{lab} = 3 \times 10^{16}$ eV



Detailed LHC comparison

(D'Enterria et al., APP 35, 2011)



Models for air showers typically better in agreement with LHC data

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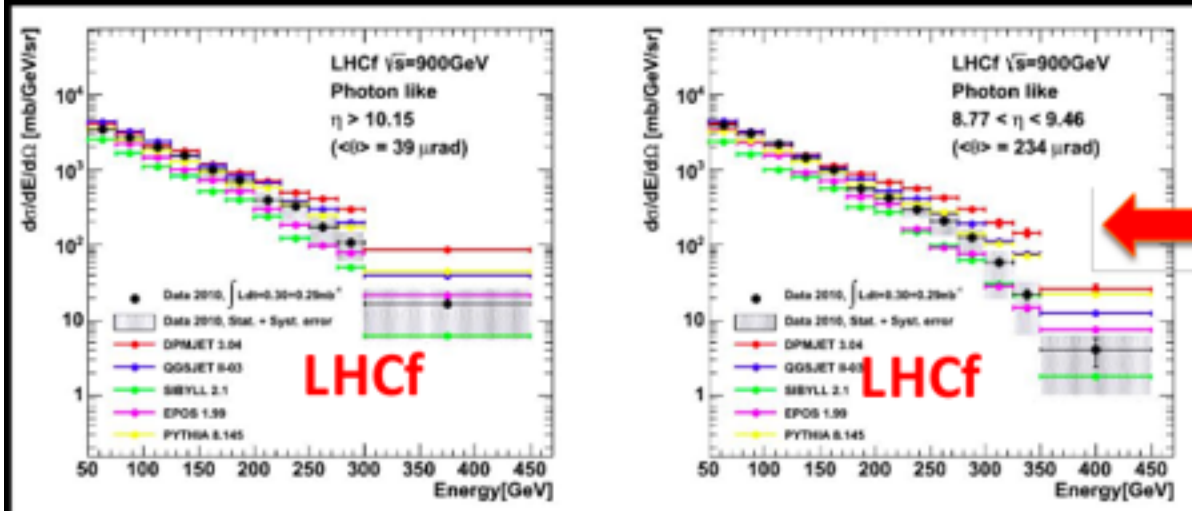
Forward Spectra

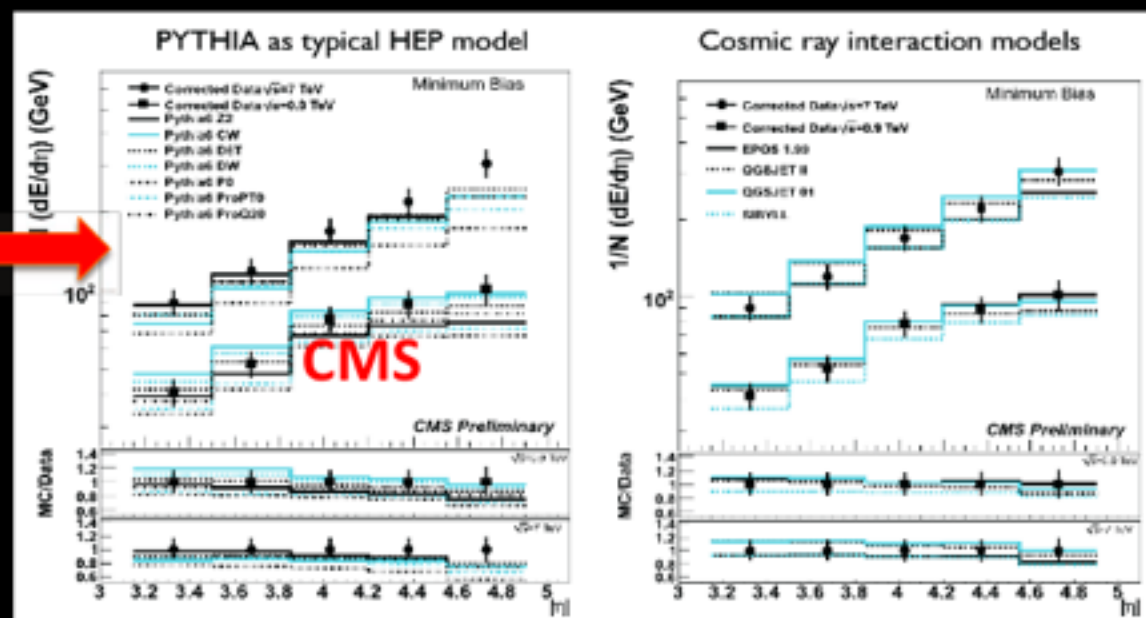


pp → γ + X

Model predictions bracket the LHC data

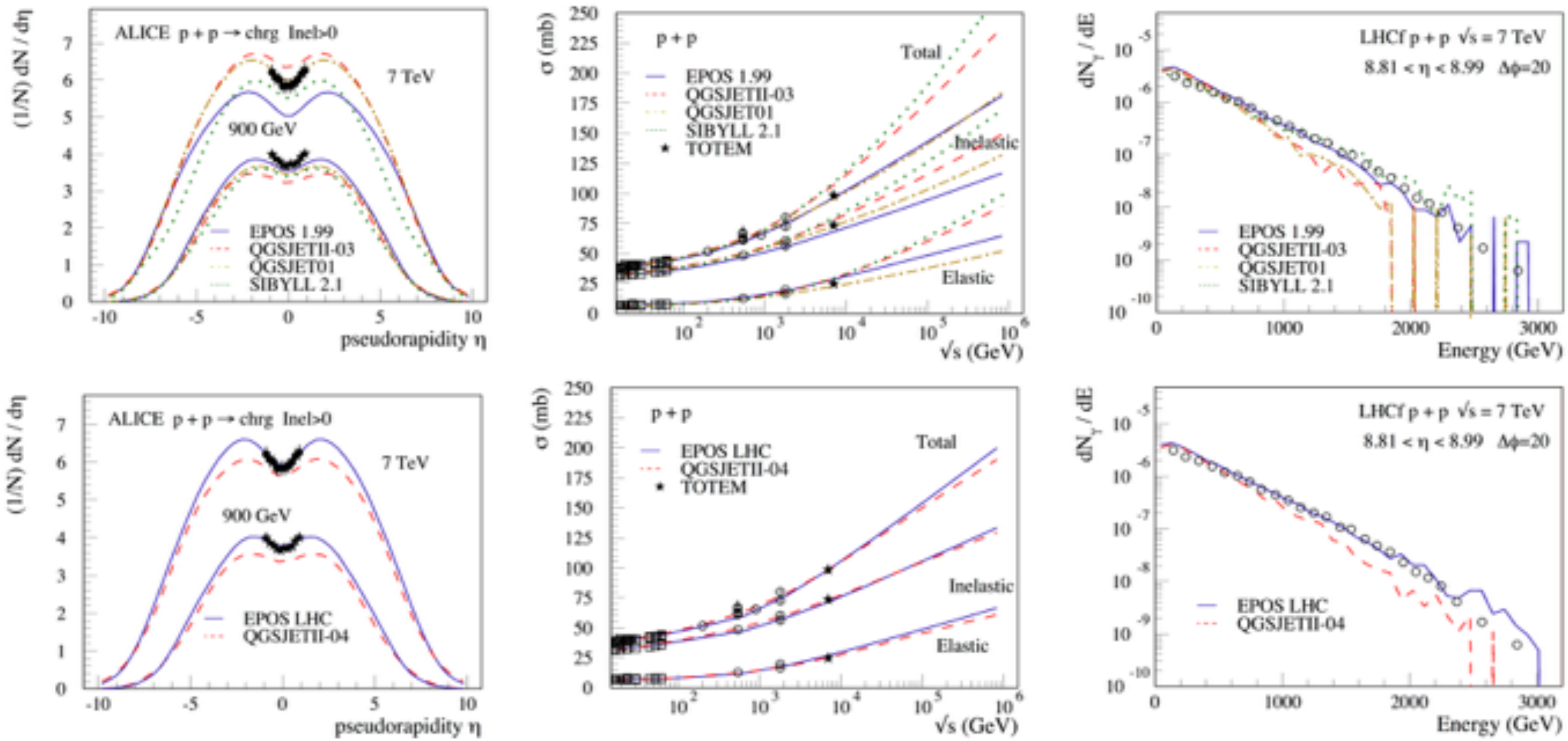
MINIMUM BIAS

CR interaction models can yield better results Than HEP models



Pinfold, ICRC 2013

Examples of tuning interaction models to LHC data



(Pierog 2013, 2014)

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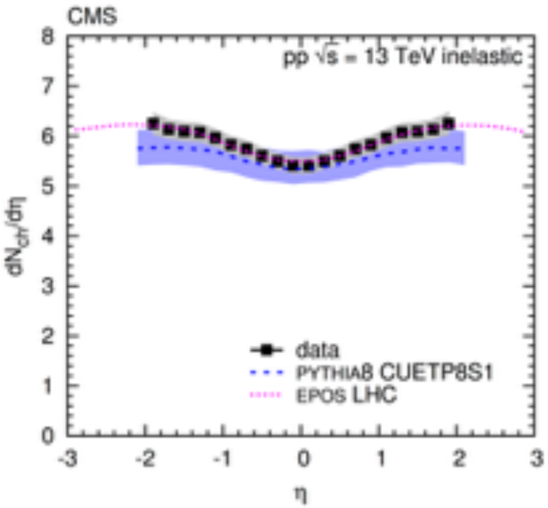
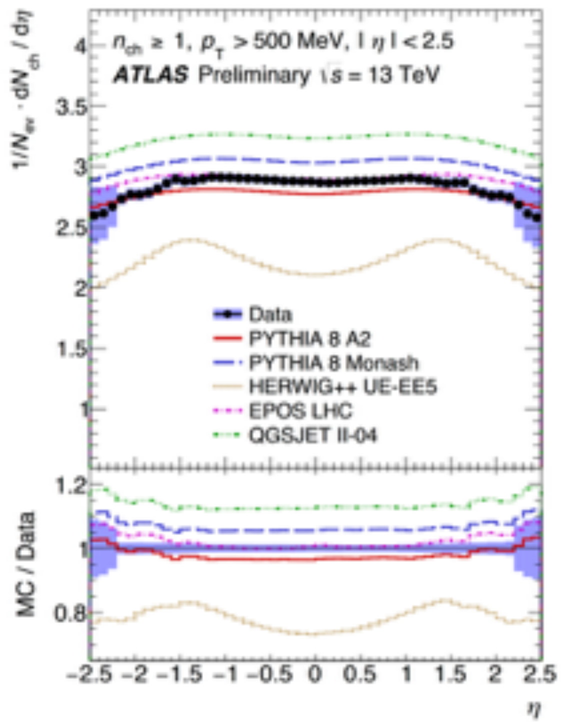
R. Engel (ICRC 2015)

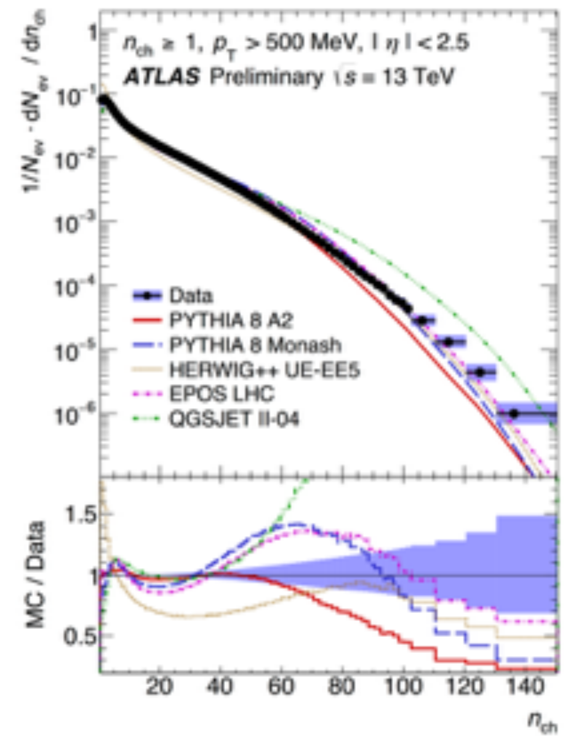
First LHC data at 13 TeV c.m. energy

(CMS, 1507.05915)



Good agreement with data !





(ATLAS, EPS Geneva 2015)

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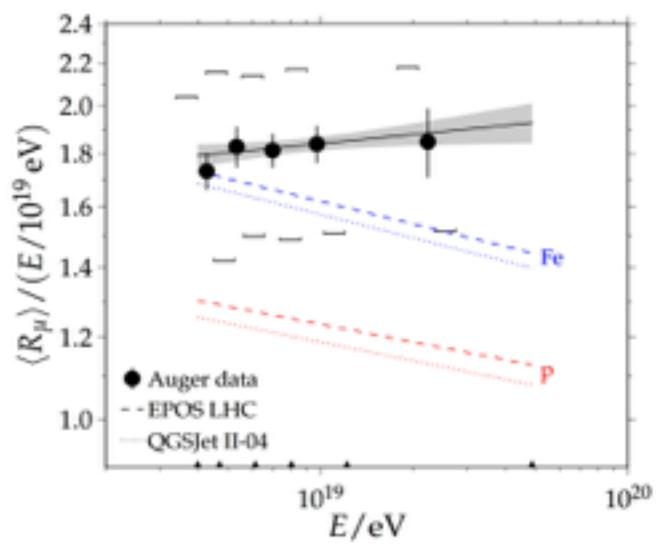
Shortcomings of the hadronic interaction models

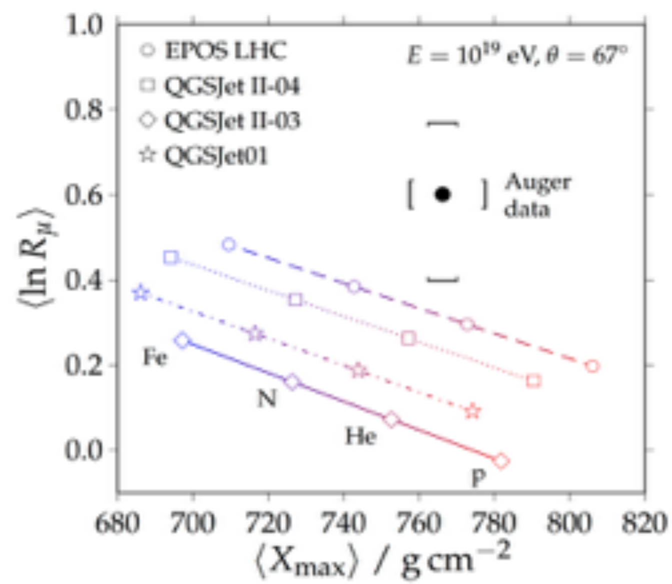
Muon number in inclined showers

Number of muons in showers with θ>60°



(Auger, PRD91, 2015)

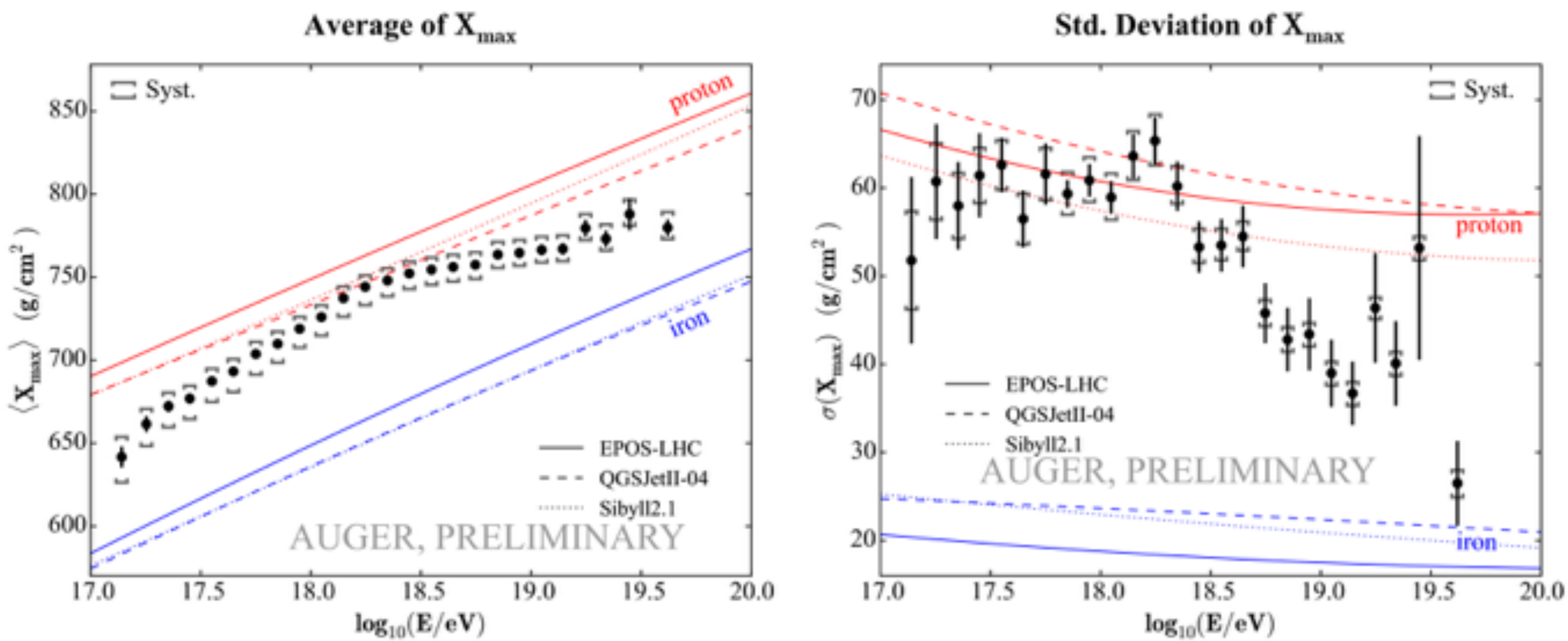
Combination of information on mean depth of shower maximum and muon number at ground



Several measurements: indications for muon discrepancy

R. Engel (ICRC 2015)

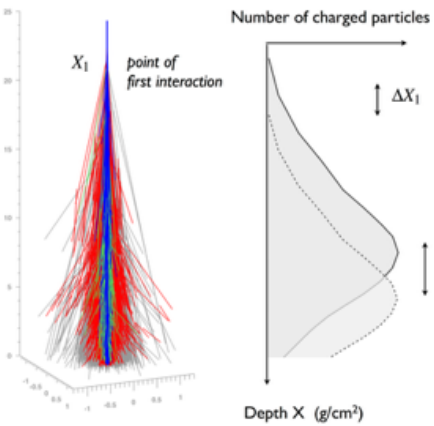
Average shower maximum and RMS



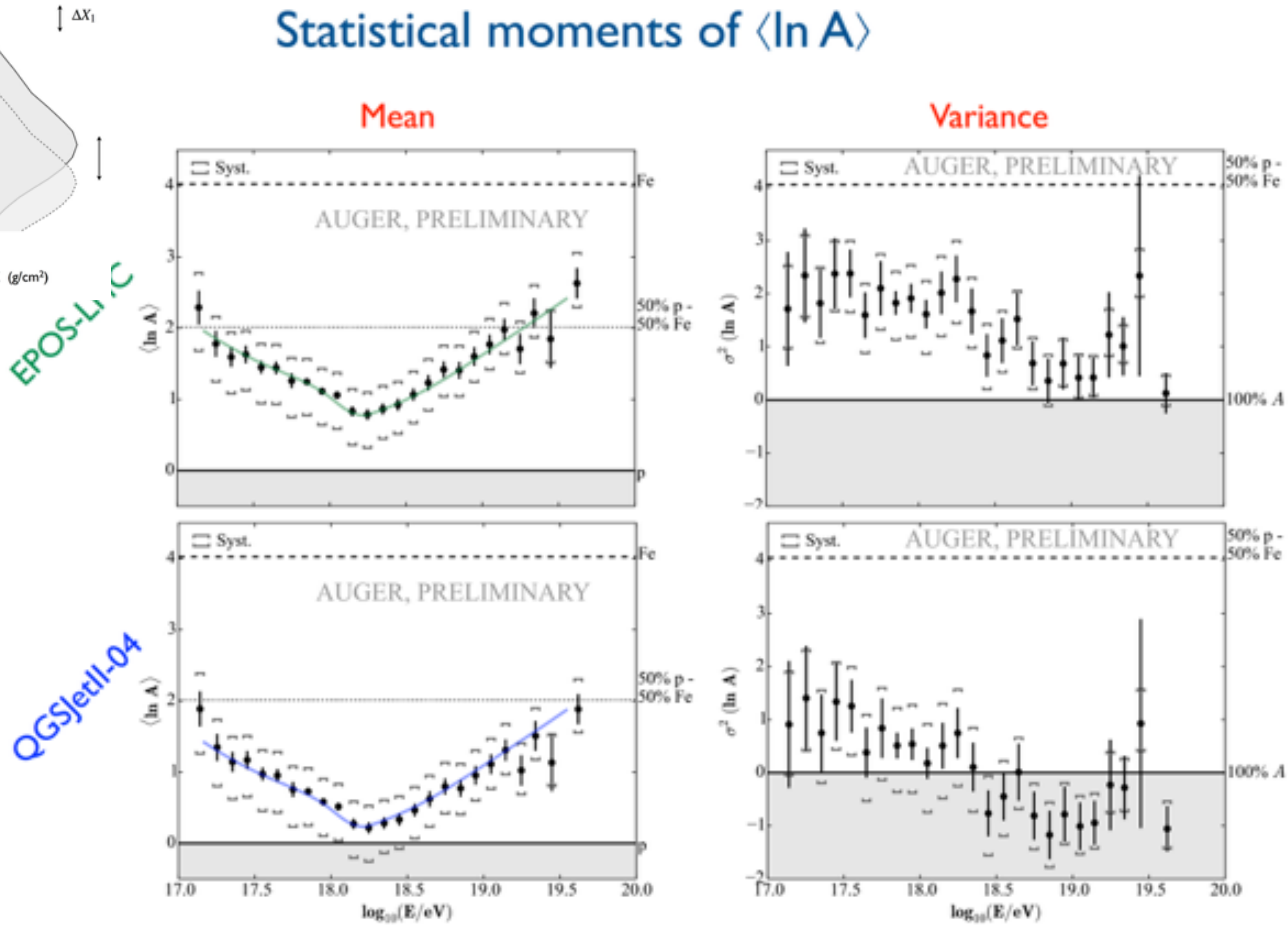
Dip model (ankle due to pure proton flux) seems to be ruled out

Pierre Auger Collaboration (ICRC 2015)

Shortcomings of the hadronic interaction models



Xmax distributions



Pierre Auger Collaboration (ICRC 2015)

CONCLUSIONS

A review of the current understanding of cosmic ray data at different energies has been presented.

The interpretation of CR data requires the knowledge of the physics of hadronic interactions in atmosphere, but at the same time provides a means to cross-check the validity of the physics principles embedded in the models.

Hadronic interaction models do a fairly well job not only in the interpretation of EAS cascades in atmosphere but also of LHC data.

However, shortcomings exist! LHC data are extremely helpful in fine tuning the models and give solid bases for the extrapolation at high energies.

CR remain the sole mean to test hadronic interactions at energies well beyond those reachable with colliders.

CRs and accelerator data provide an excellent mix of information to understand the physics of interactions!

THANK YOU