Cosmic Ray observations with the IceCube Observatory

Paolo Desiati

Wisconsin IceCube Particle Astrophysics Center
& Department of Astronomy

desiati@wipac.wisc.edu

University of Wisconsin - Madison

lectures outline

---

neutrino telescopes & the IceCube Observatory

observing the Universe

neutrino observations

cosmic ray observations

astrophysics & interdisciplinary sciences

outline

cosmic ray observations with IceCube

---

cosmic rays at Earth

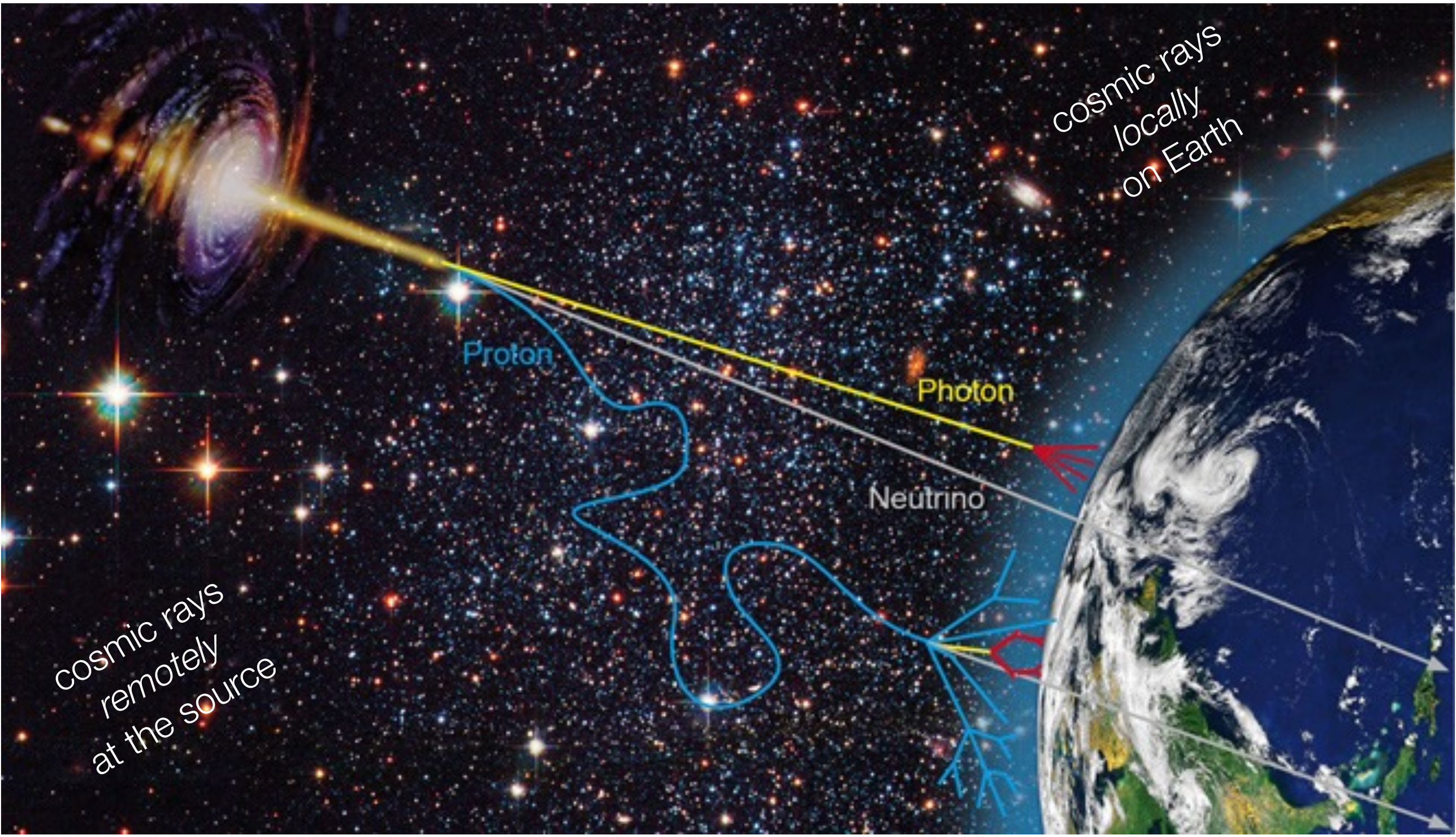
atmospheric muons and neutrinos

mass composition and energy of cosmic rays

the anisotropy of cosmic rays

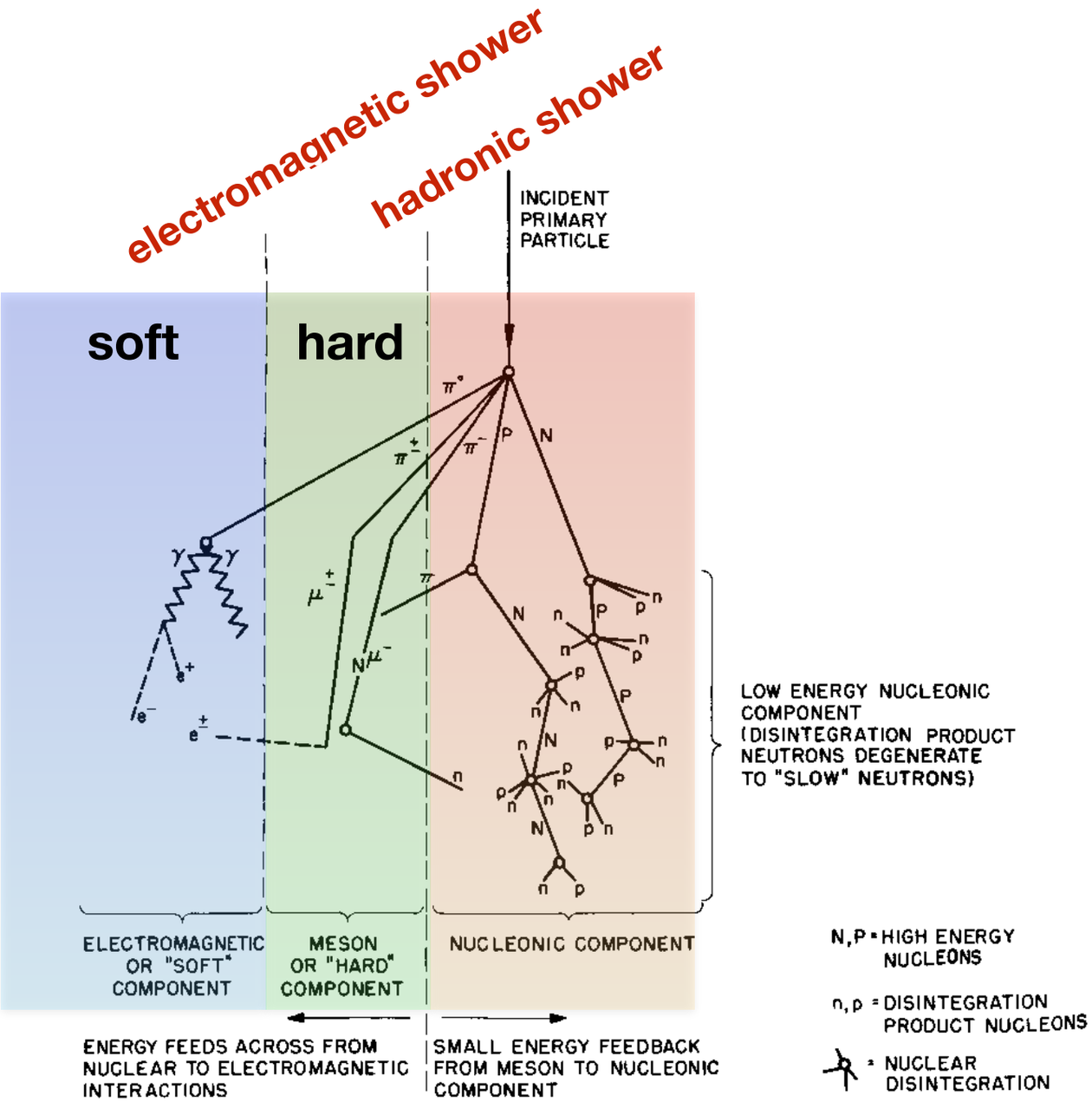
cosmic ray muons

cosmic rays
the long journey

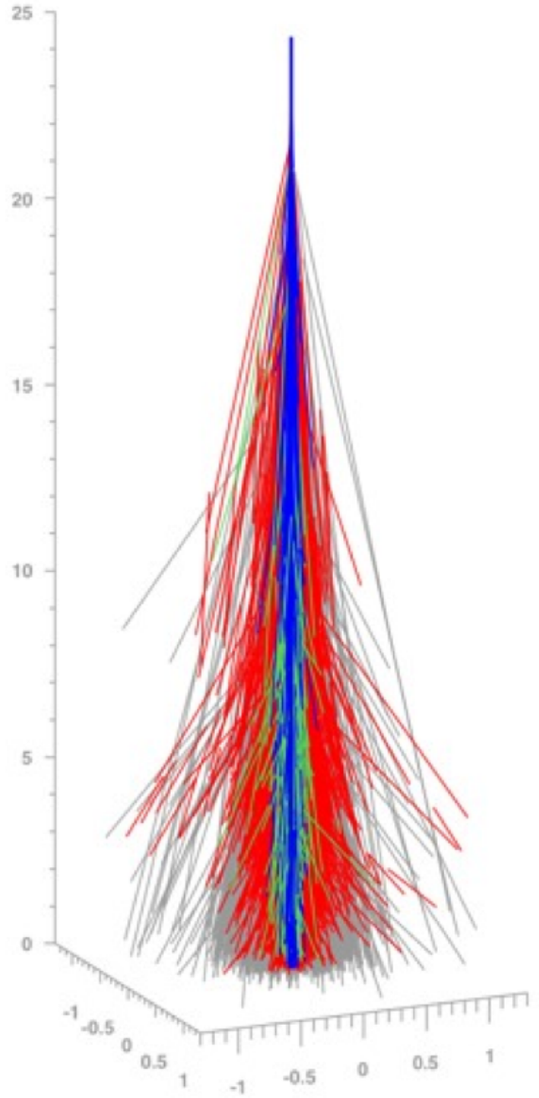


extensive air showers
penetrating cosmic radiation

- **atmospheric air showers** of particles are **extended**

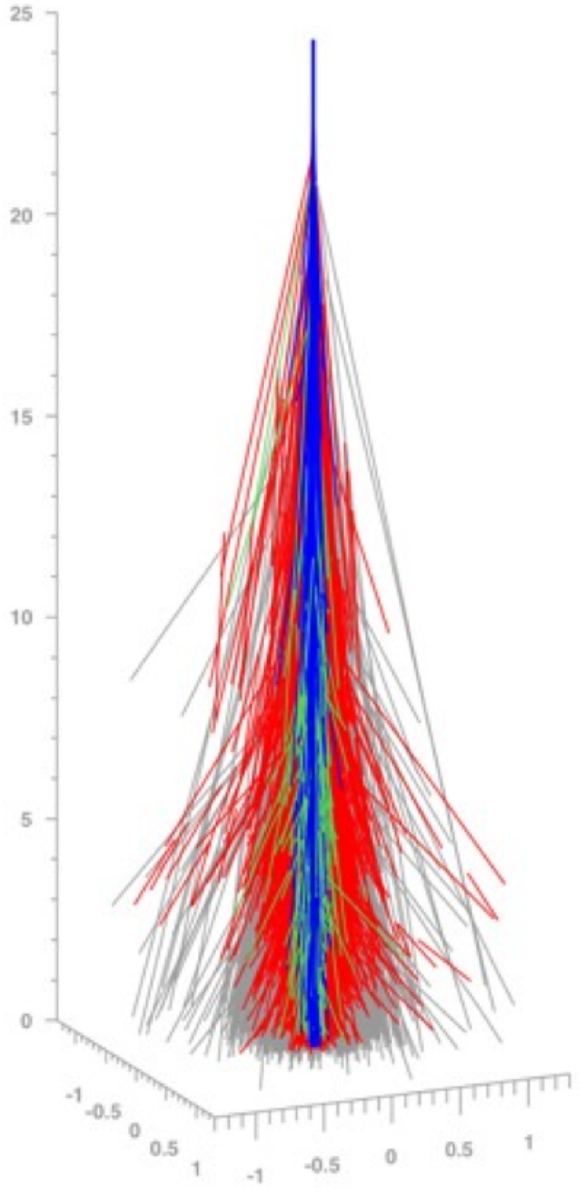


Schematic Diagram of Cosmic Ray Shower



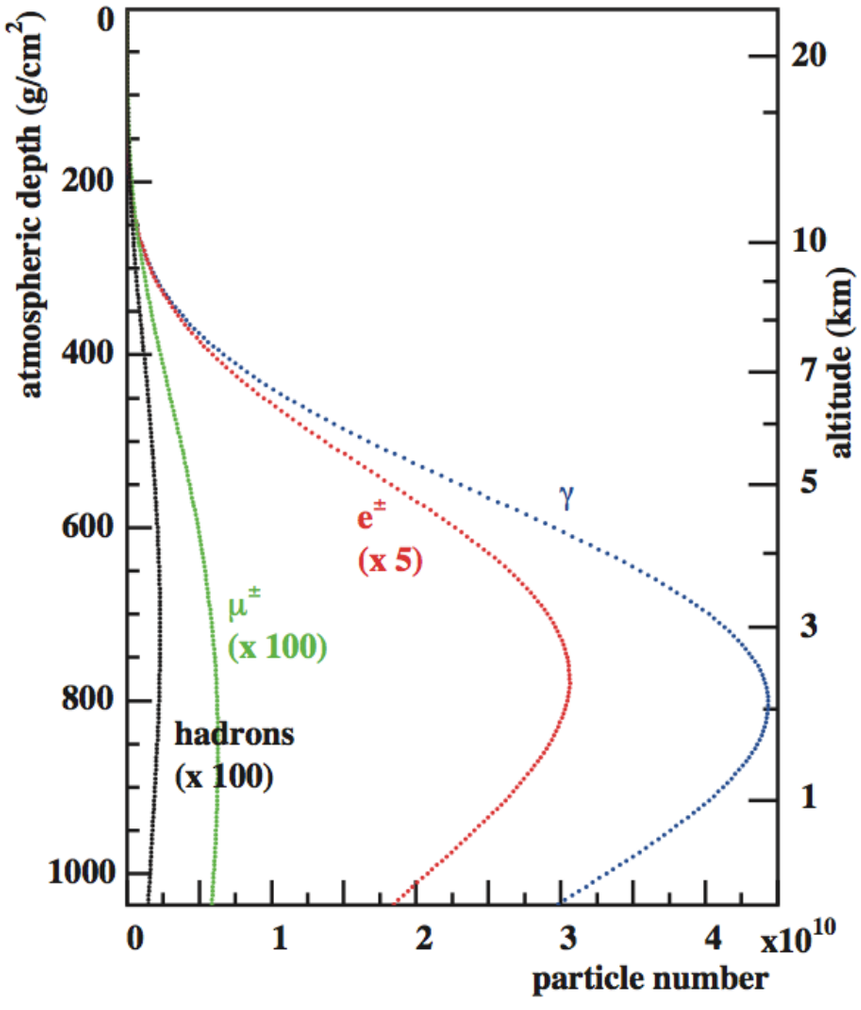
proton-induced shower of 10^{19} eV

extensive air showers



proton @ 10^{19} eV

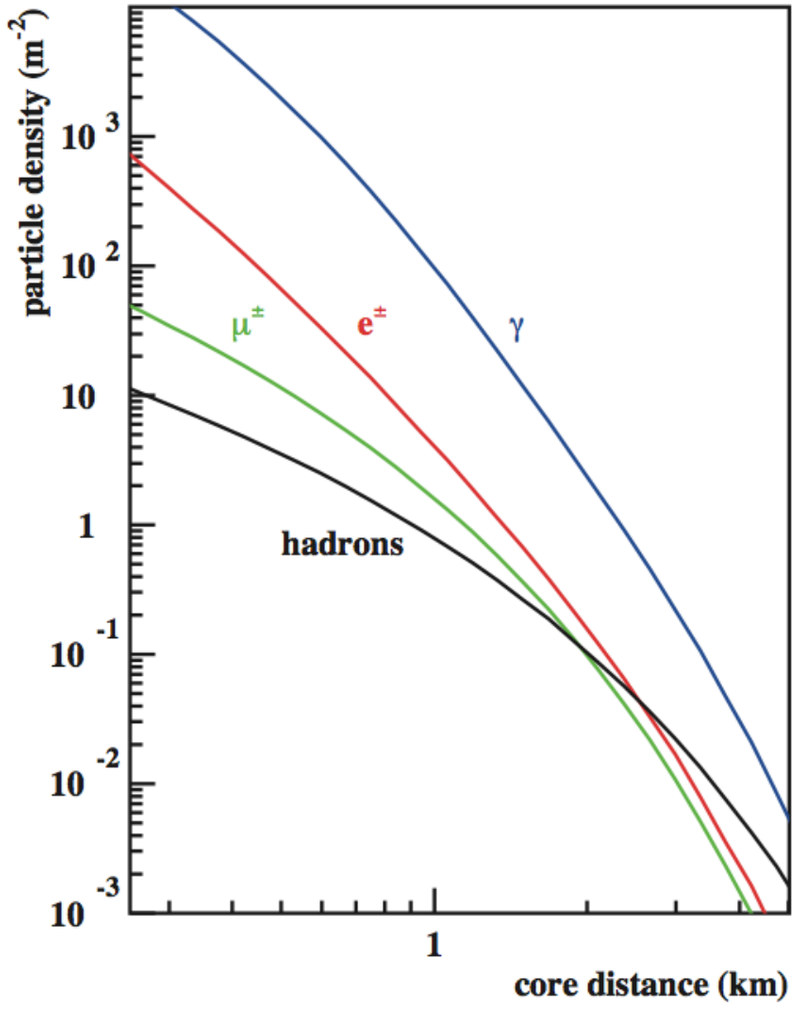
longitudinal profile



detected via:
Cherenkov light
fluorescence light of N_2

lateral profile

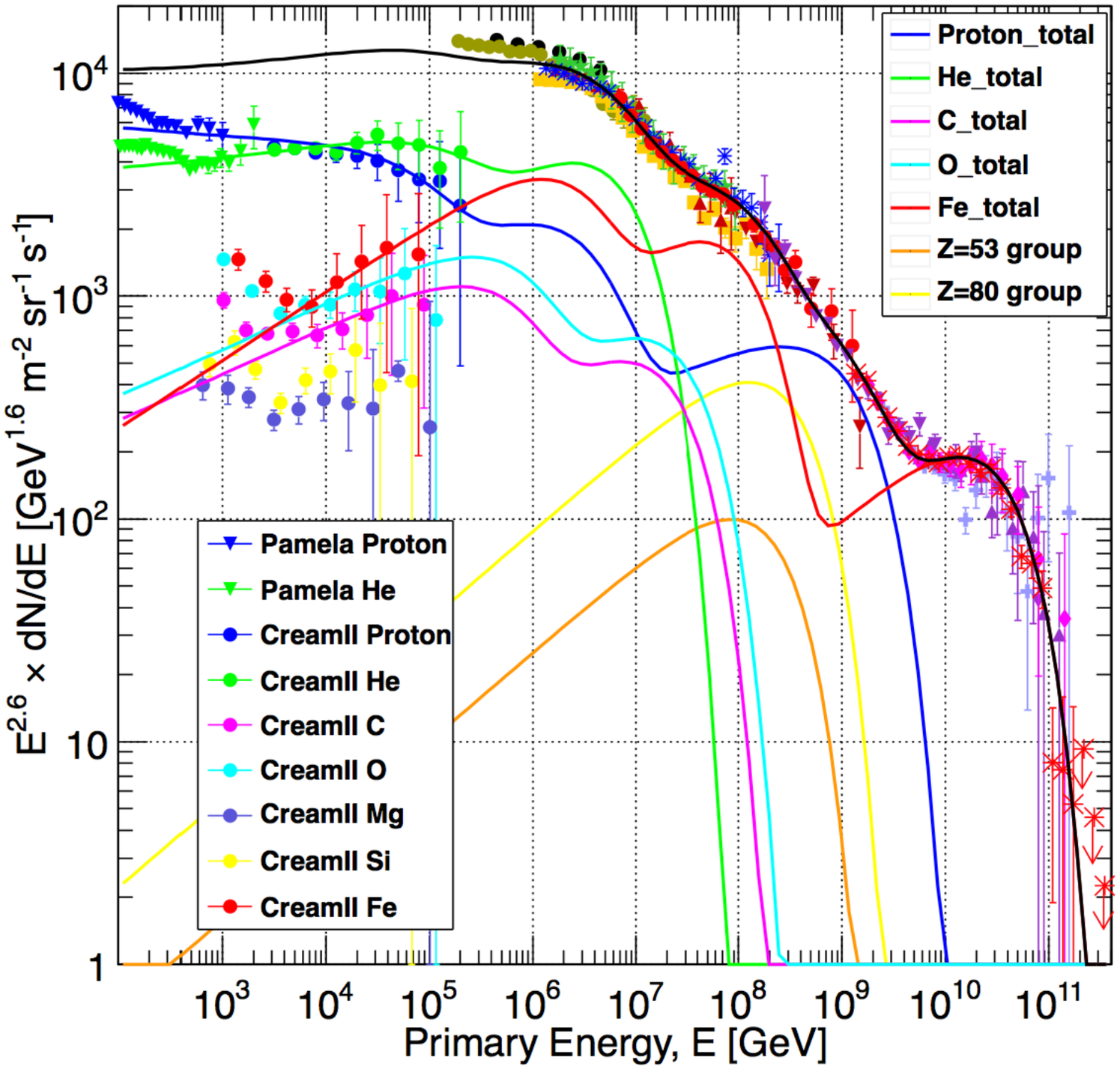
Engel, Pierog, Heck, ARNPS 2011



detected via:
particle detector array on the ground

primary cosmic rays
spectrum and composition

disentangle astrophysics and particle physics

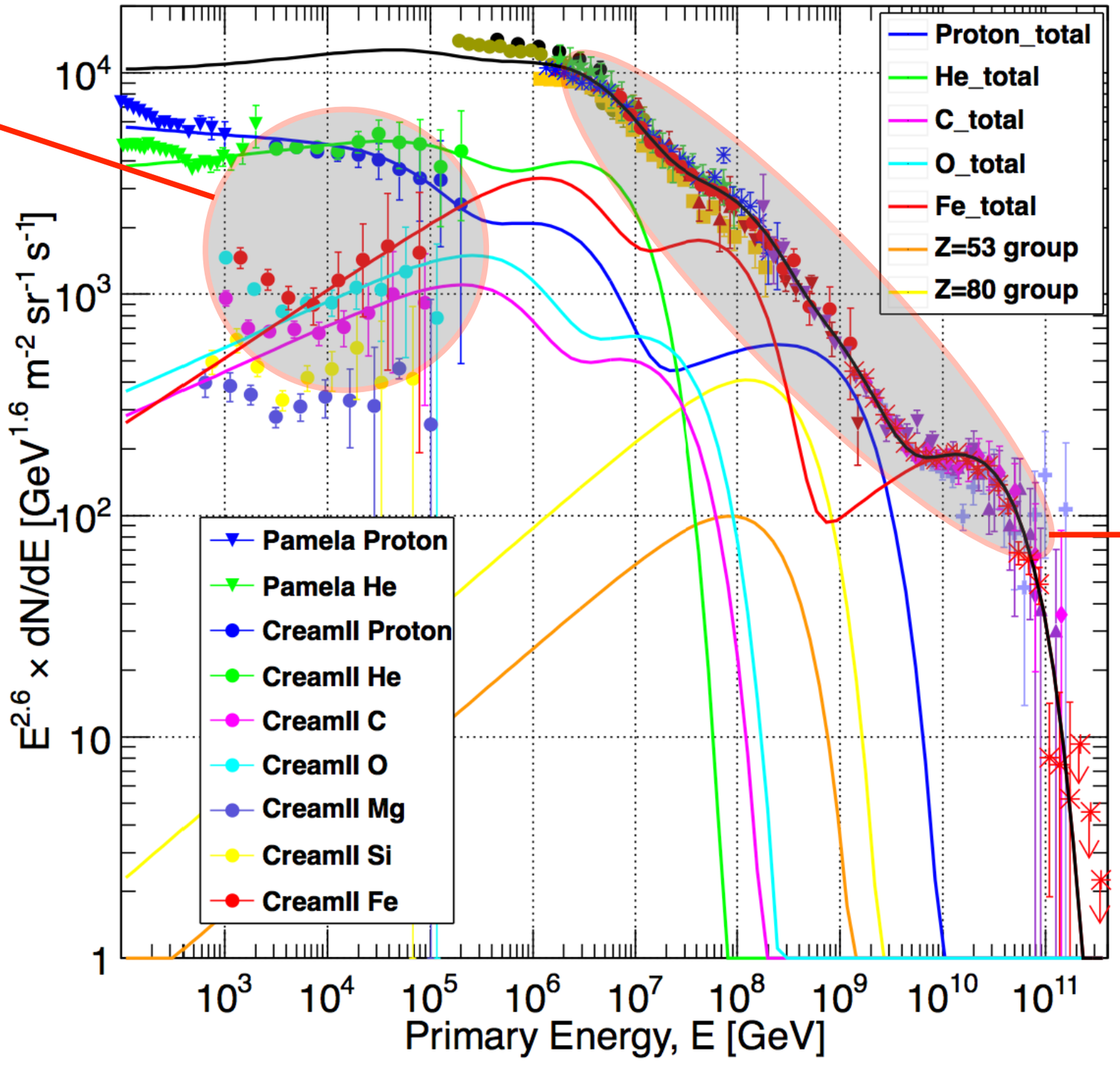


Gaisser, Stanev, Tilav
arXiv:1303.3565

primary cosmic rays
spectrum and composition

disentangle astrophysics and particle physics

direct measurements

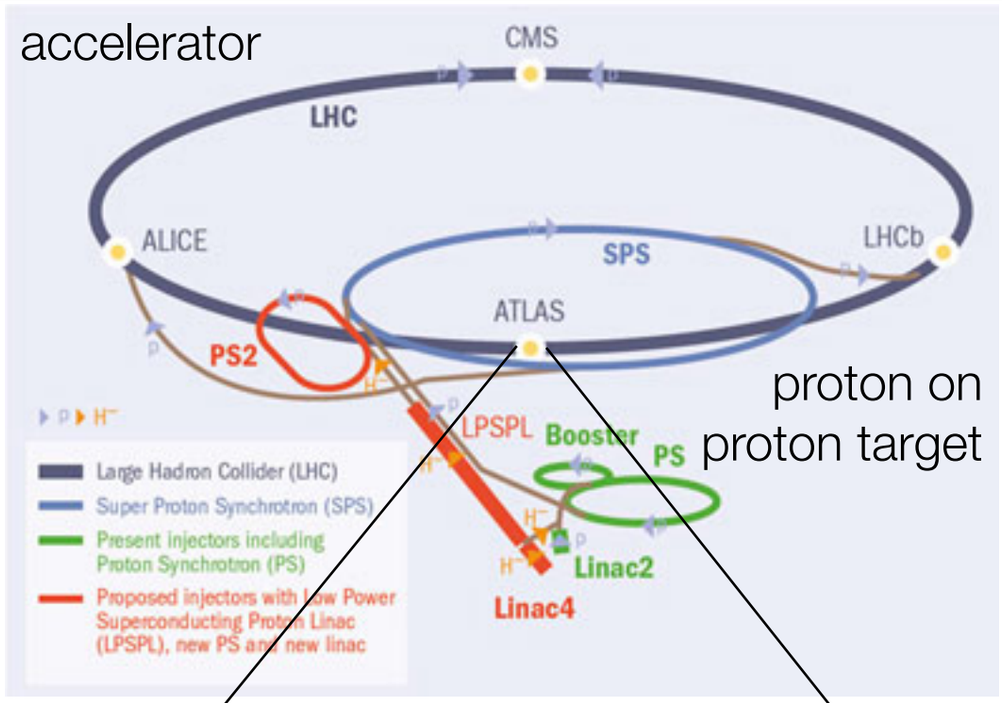


indirect measurements

Gaisser, Stanev, Tilav
arXiv:1303.3565

extensive air showers
a natural laboratory

accelerator

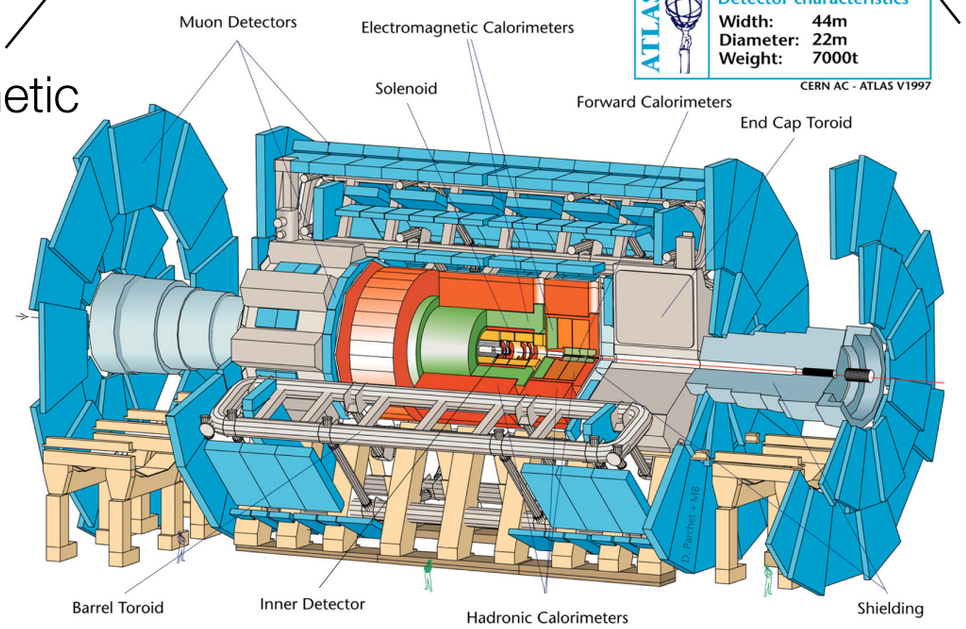


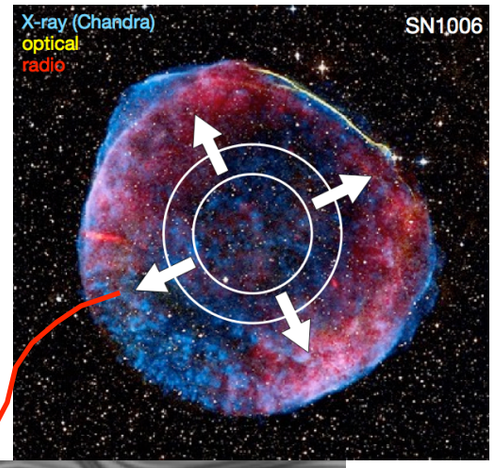
proton on proton target

propagation

detection

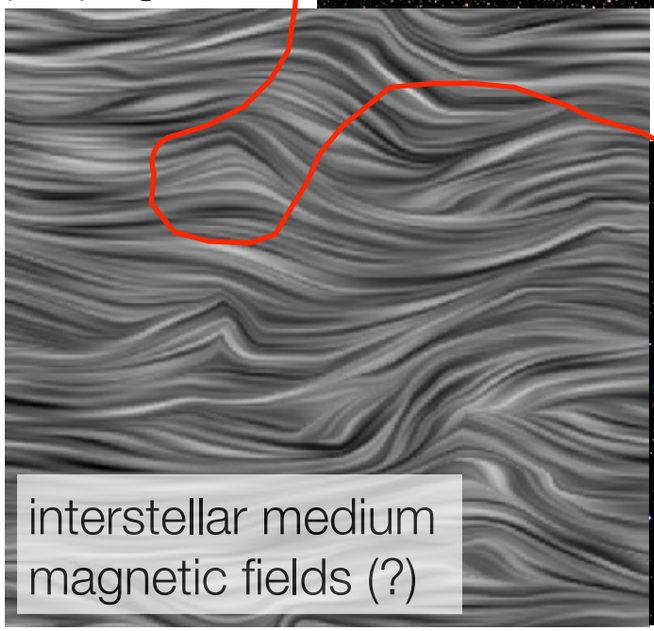
magnetic fields



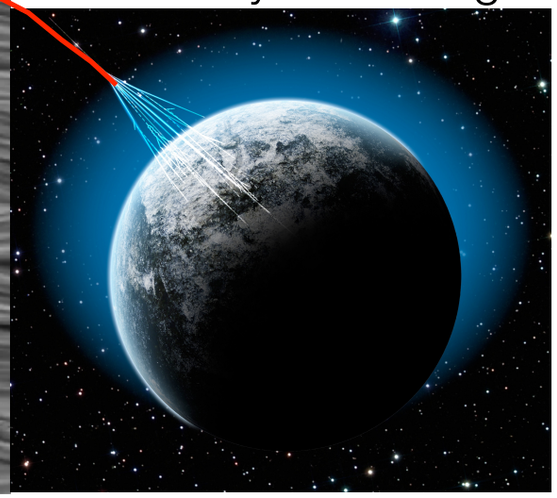


accelerator (?)

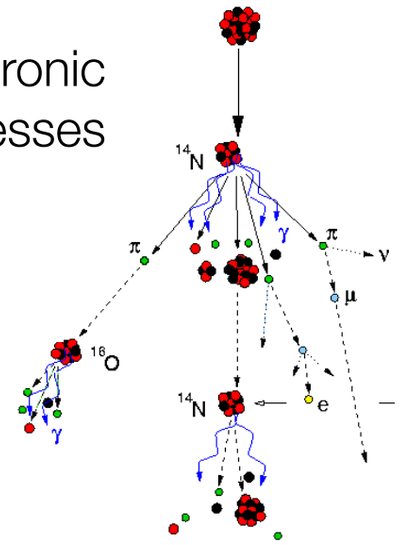
propagation

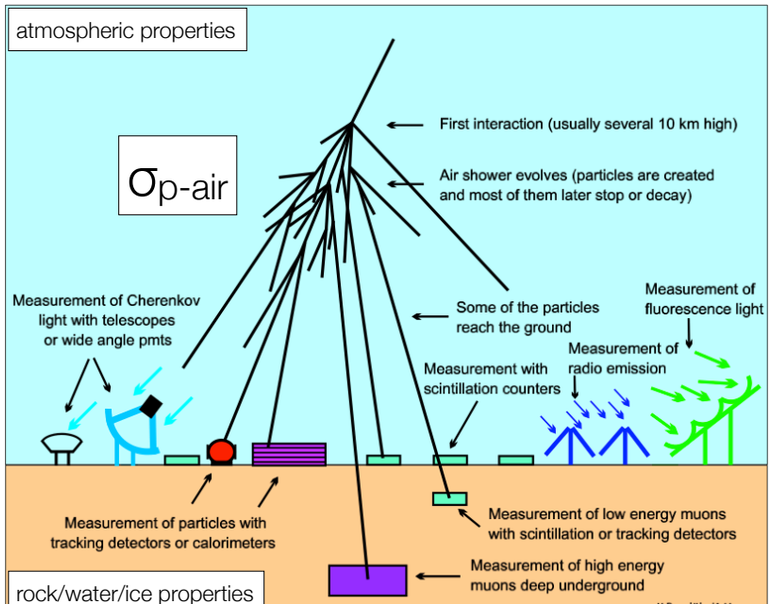


Earth atmosphere
dynamic target



nuclear & hadronic processes





detection

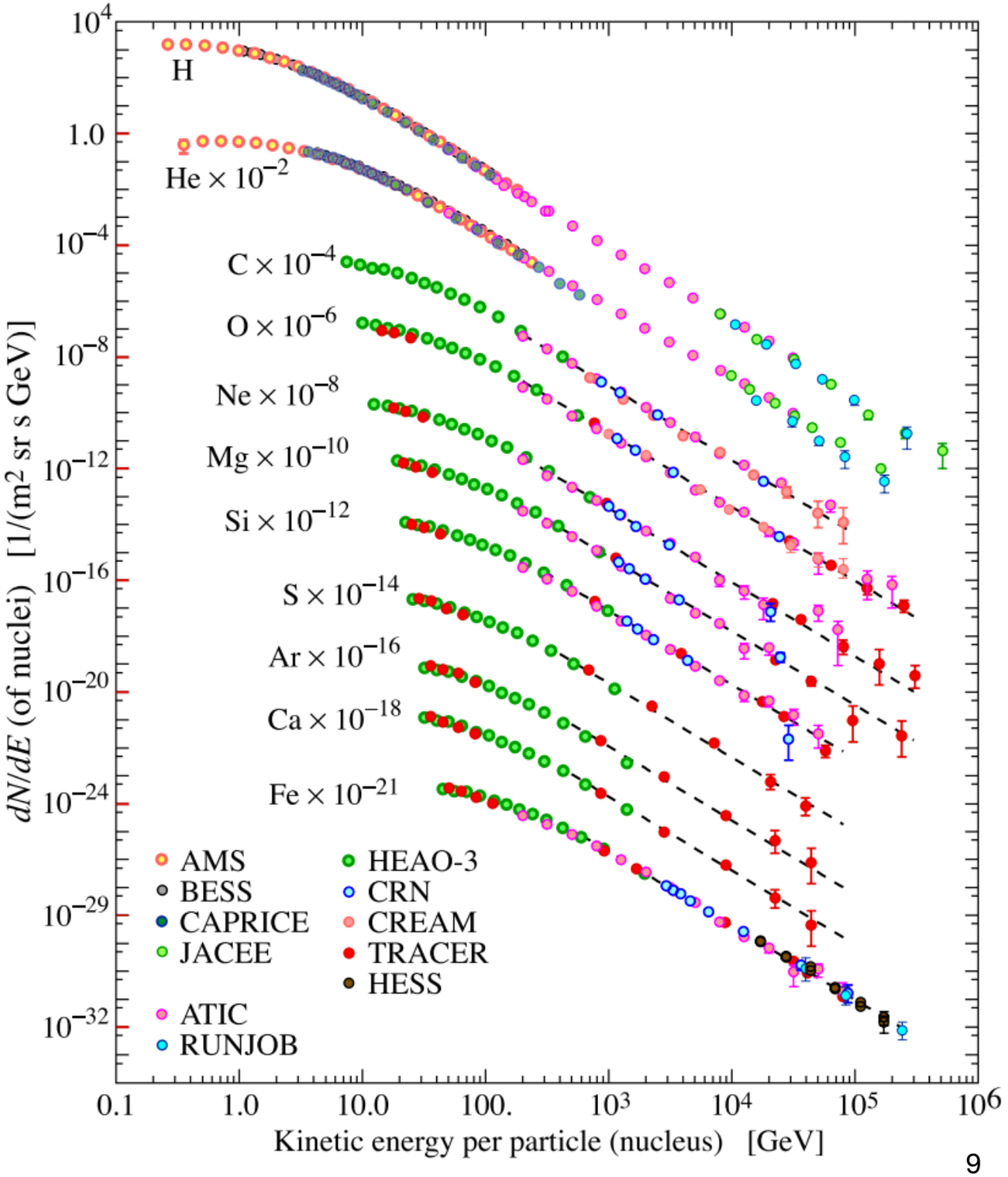
cosmic rays spectrum
direct observations

CREAM, ATIC, Bess-Polar
TRACER, TIGER

PAMELA, Fermi,
Gamma-400,...

AMS2, Calet,
ISS-CREAM, ...

(from PDG)



cosmic rays spectrum
direct observations

- energy spectrum has **fine** structures
- **broken** power law or spectral **concavity**

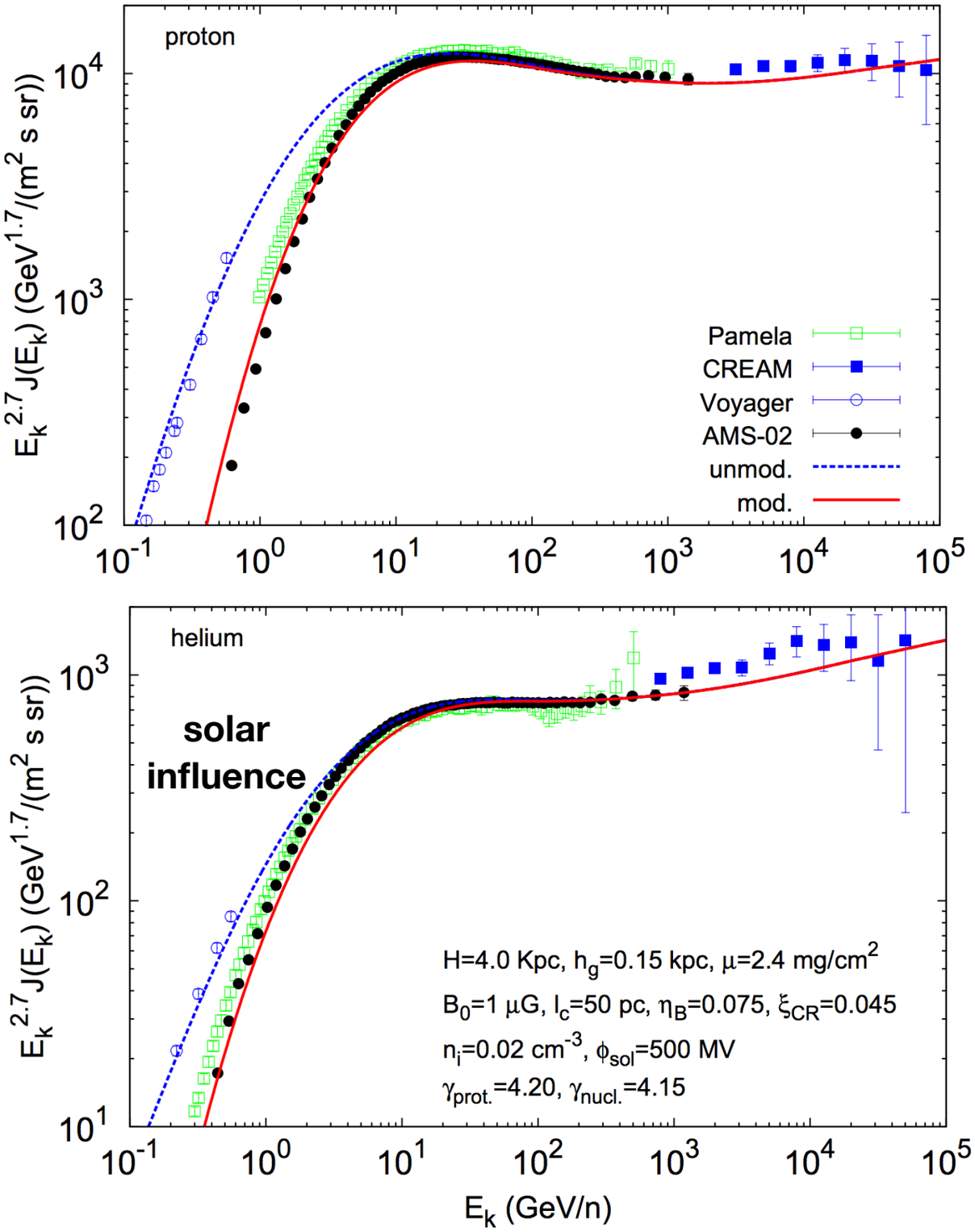
CREAM, ATIC, Bess-Polar
TRACER, TIGER

PAMELA, Fermi,
Gamma-400,...

AMS2, Calet,
ISS-CREAM, ...

Aloisio, Blasi, Serpico, A&A 2015

slope change
rigidity dependent ($\propto$ Z)



cosmic rays spectrum
direct observations

- energy spectrum has **fine** structures
- **broken** power law or spectral **concavity**

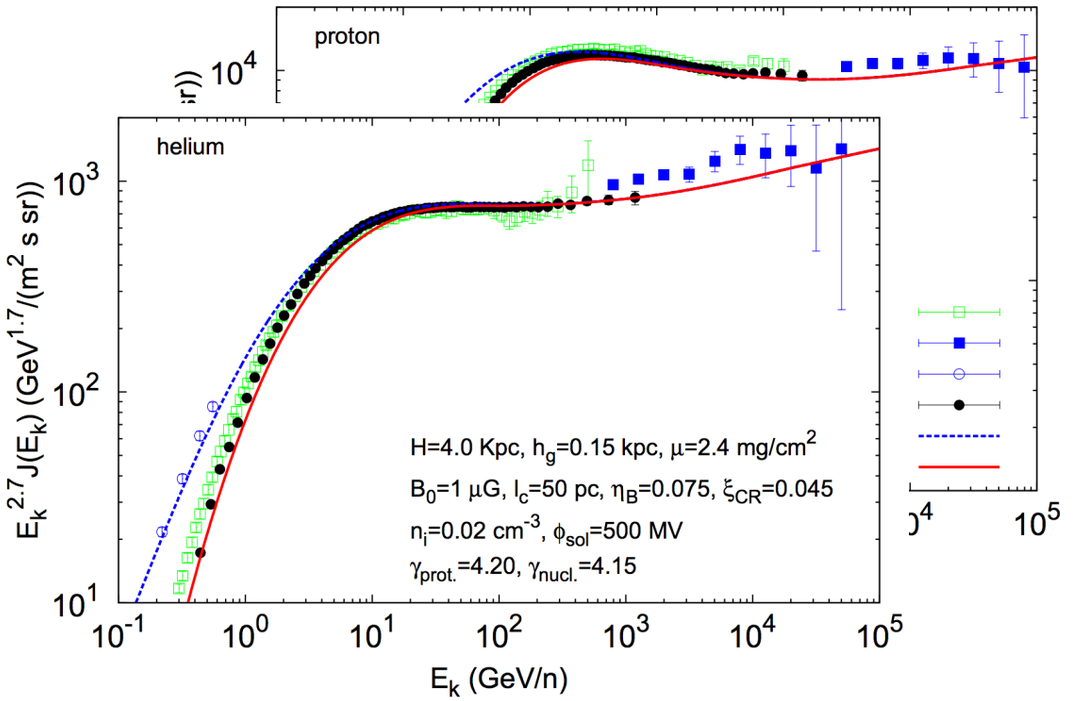
CREAM, ATIC, Bess-Polar
TRACER, TIGER

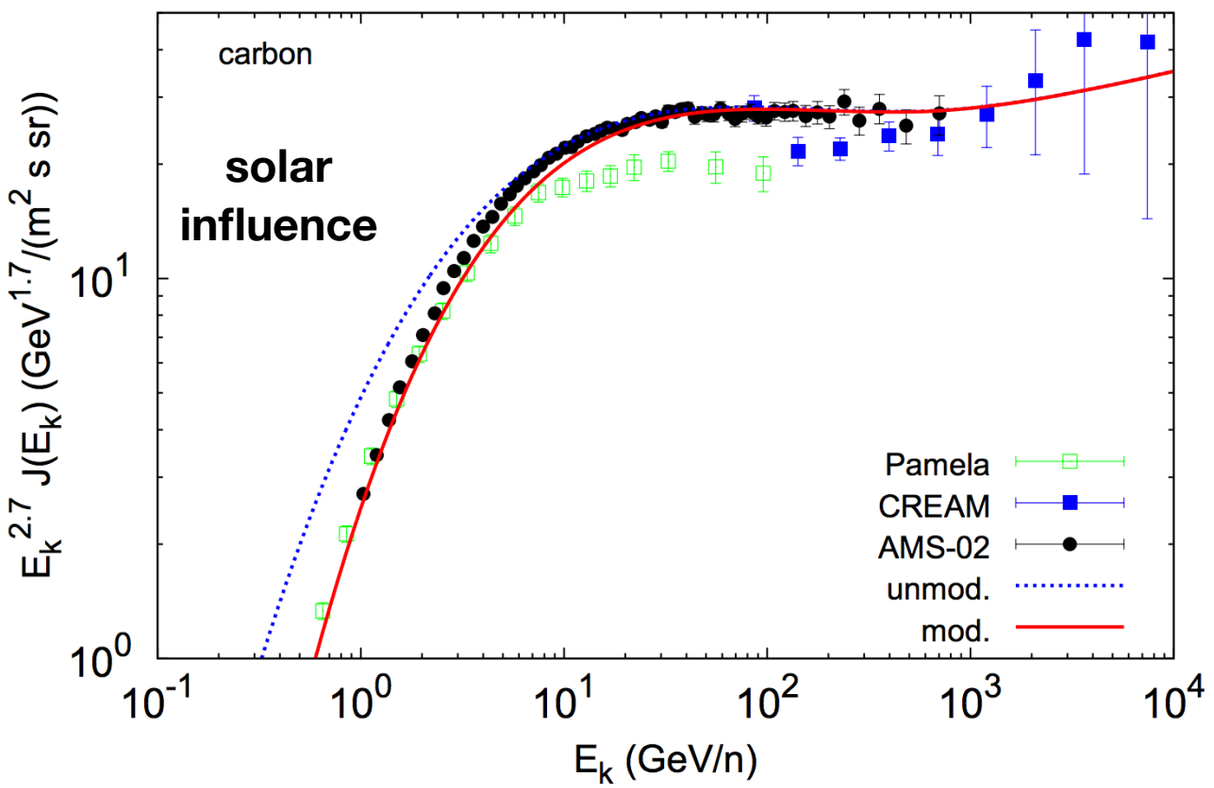
PAMELA, Fermi,
Gamma-400,...

AMS2, Calet,
ISS-CREAM, ...

Aloisio, Blasi, Serpico, A&A 2015

slope change
rigidity dependent ($\propto$ Z)

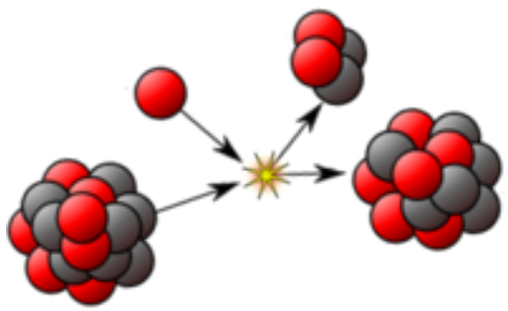




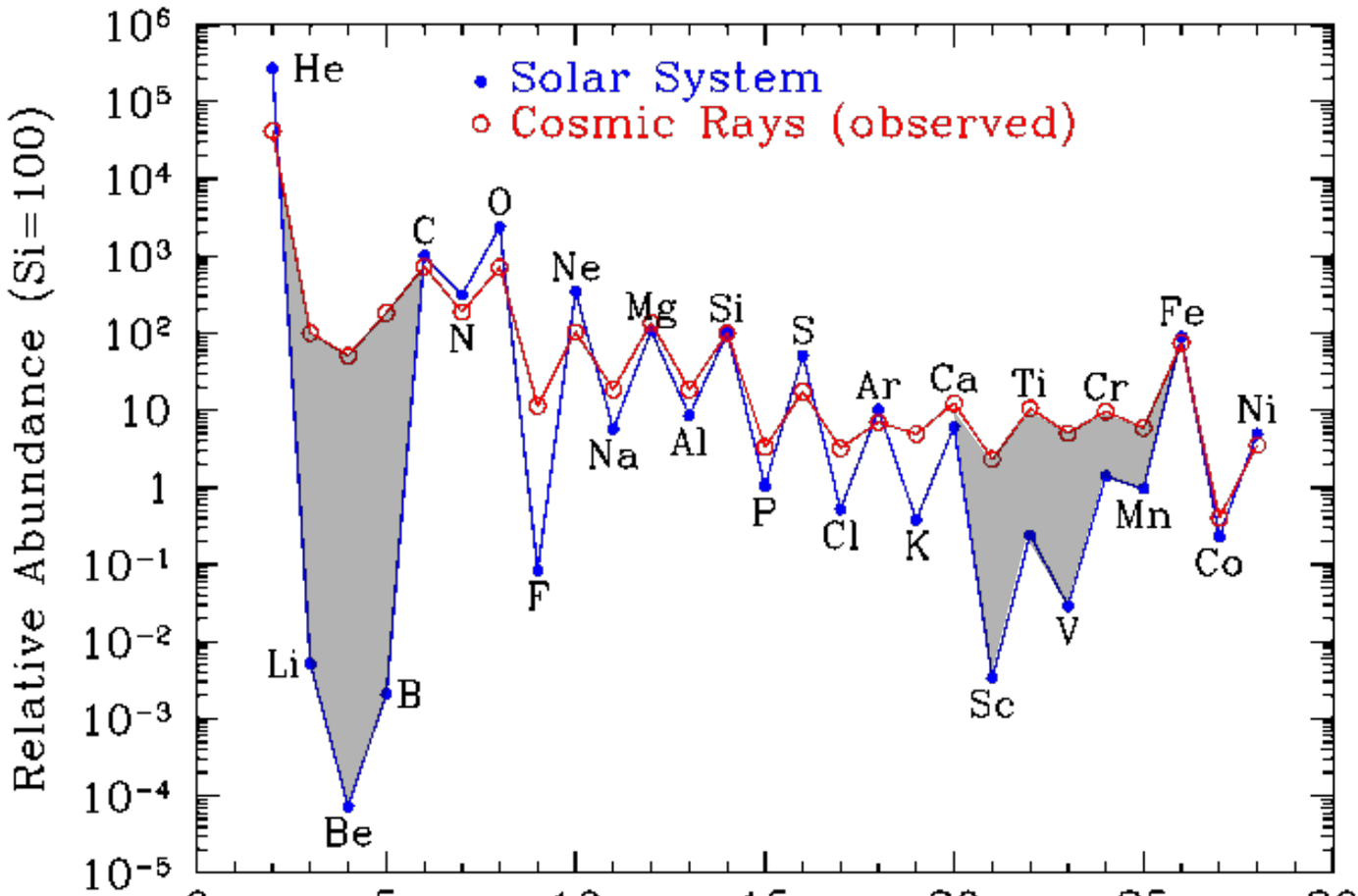
cosmic rays mass
direct observations

- cosmic rays **mass** composition **not very different** from our solar neighborhood

- differences from **nuclear fragmentation** in collisions with interstellar medium



- **isotopic composition** provides hints on origin and propagation of cosmic rays (OB associations)

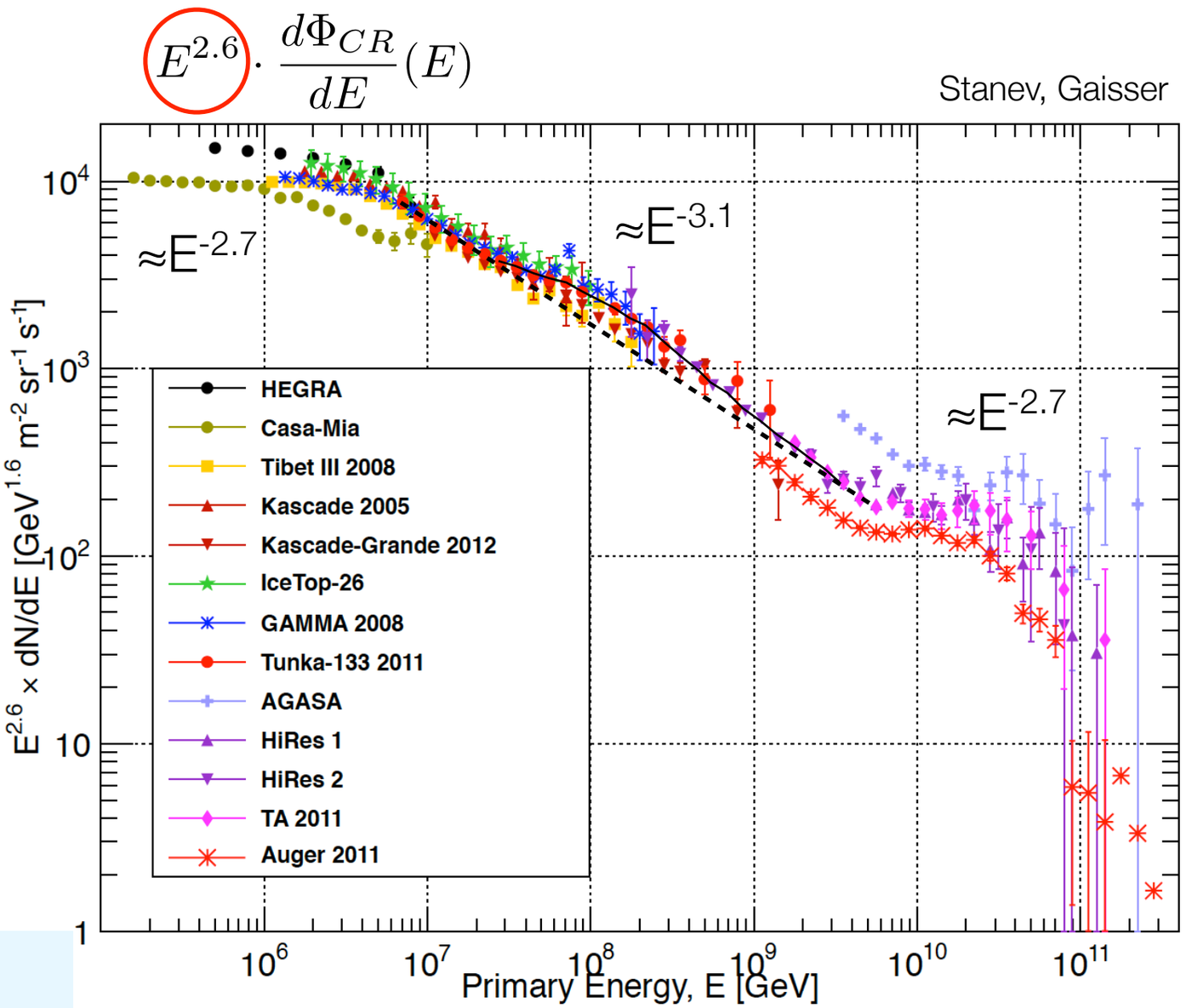


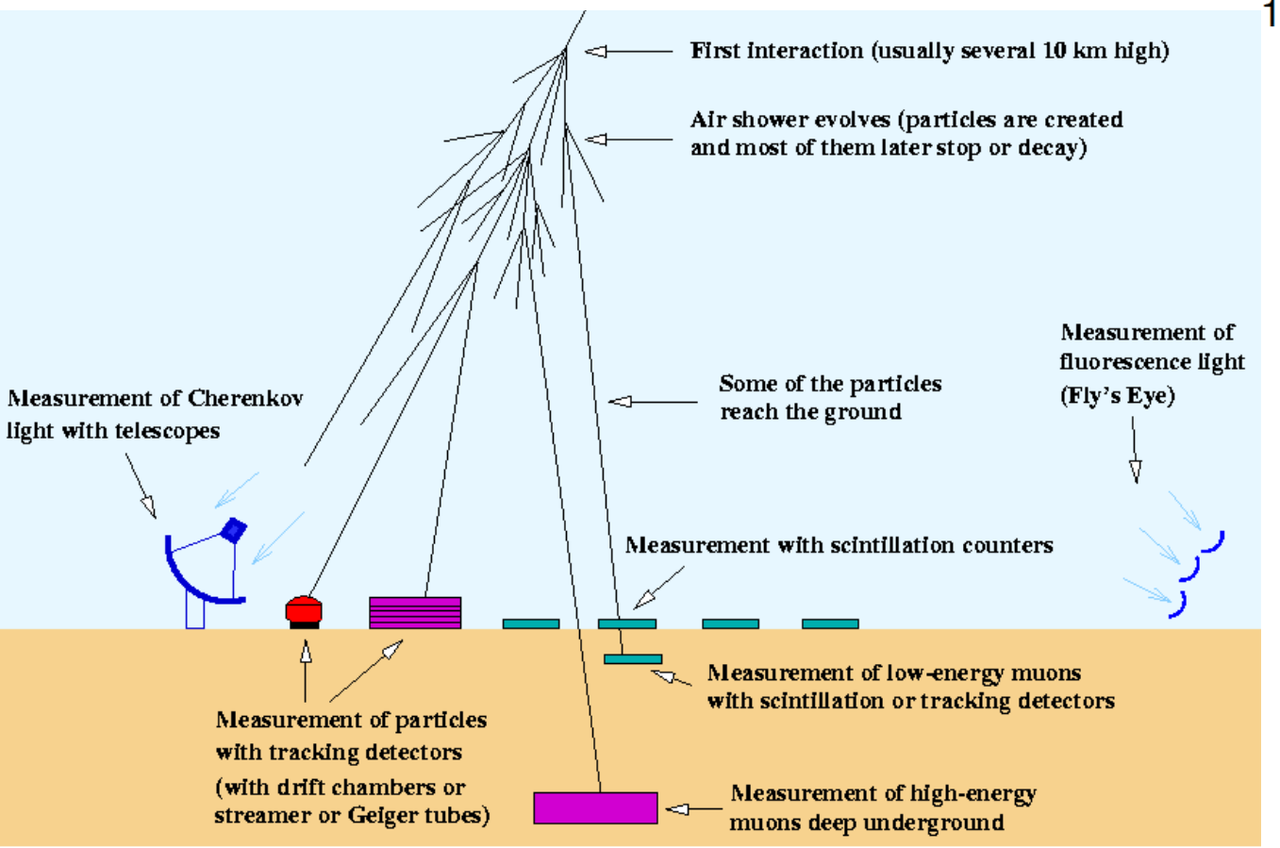
- information on **age** of cosmic rays & on **diffusion properties** at low energy (~GeV)

- at **high energy** changes in mass composition from rigidity-escape **escape** from the Galaxy

cosmic rays spectrum
indirect observations

- at **high energy** flux too small for direct observations
- ground-based, under-ground / water / ice detection

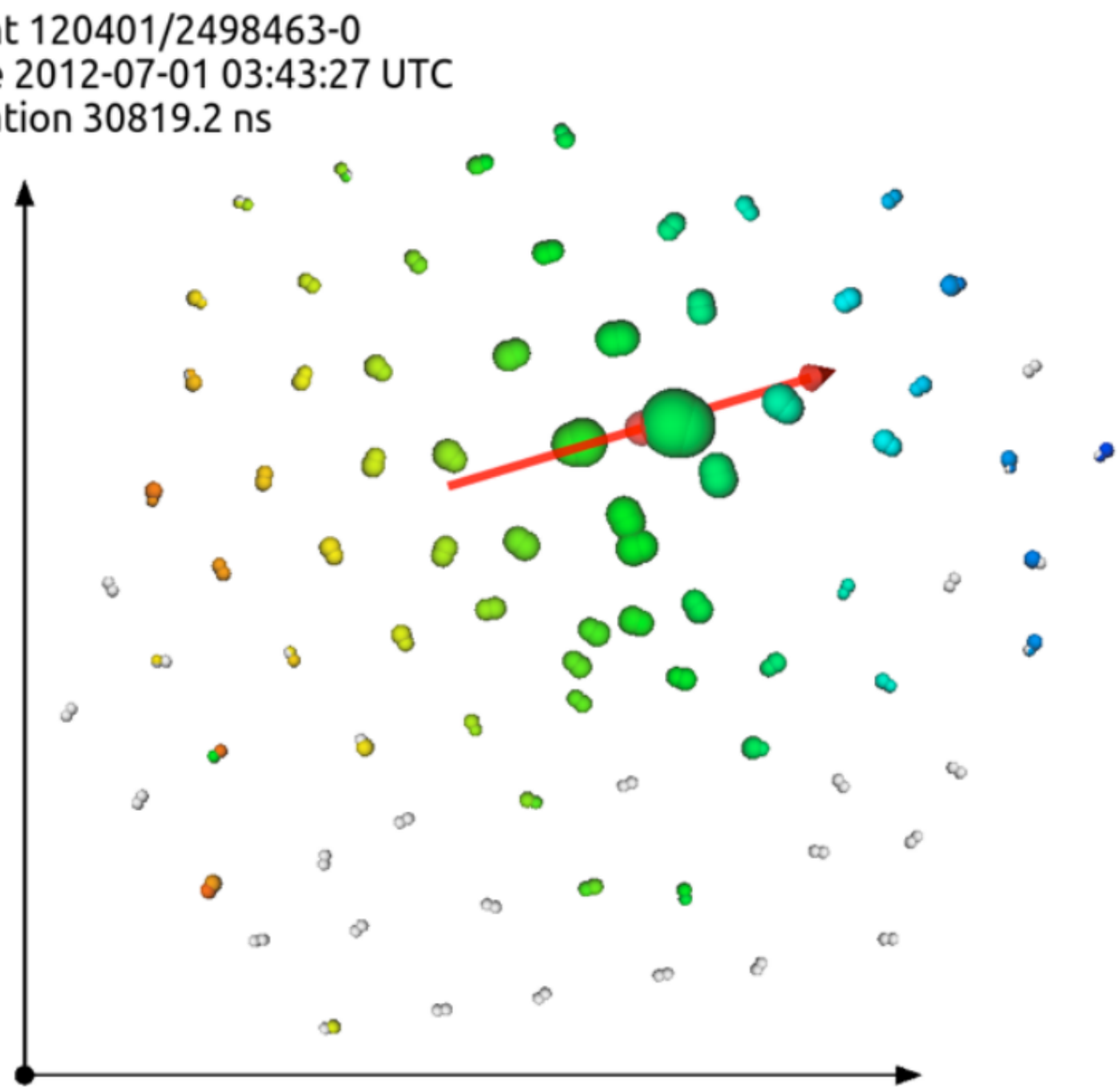


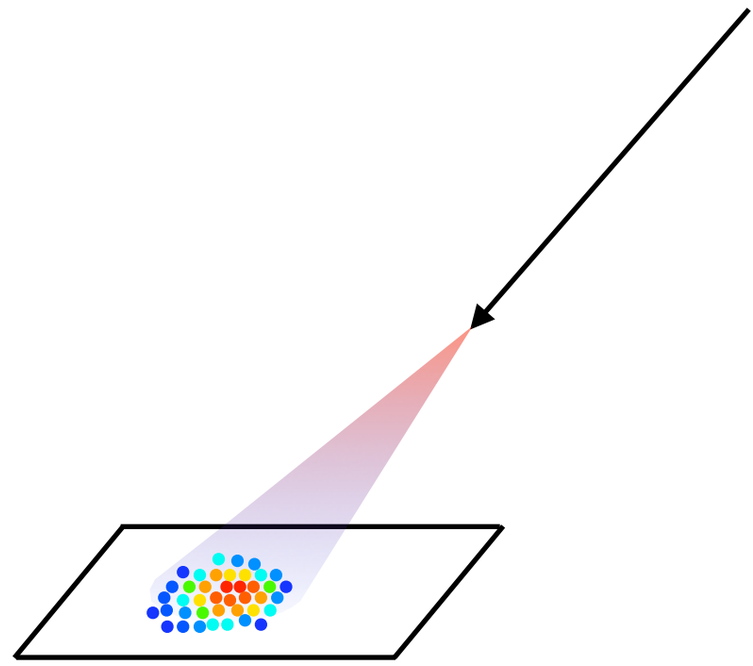


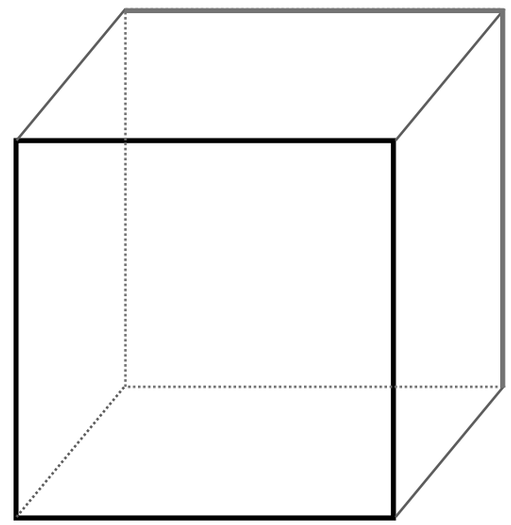
- **atmosphere** & **interaction** properties
- energy & mass observations **tangled**
- lower energy & mass **resolution**

cosmic rays spectrum

all-particle energy spectrum

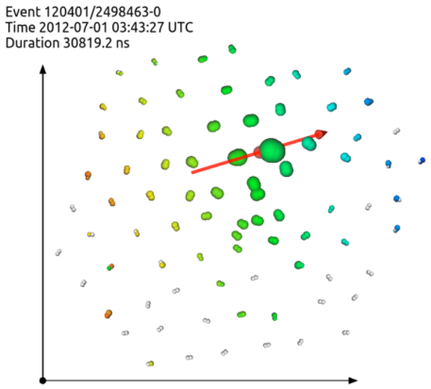


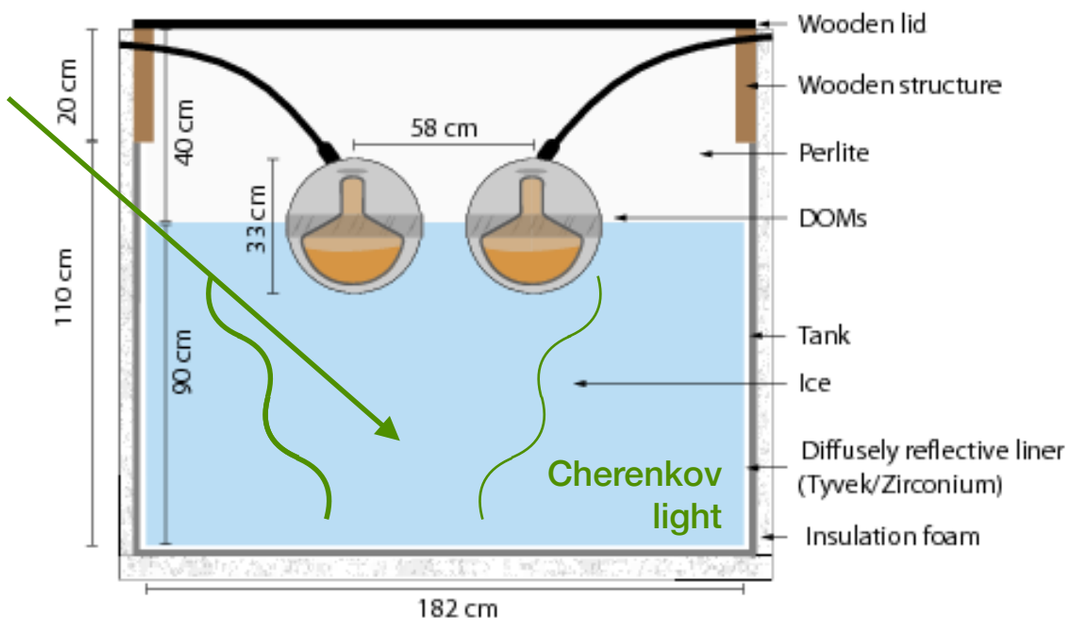


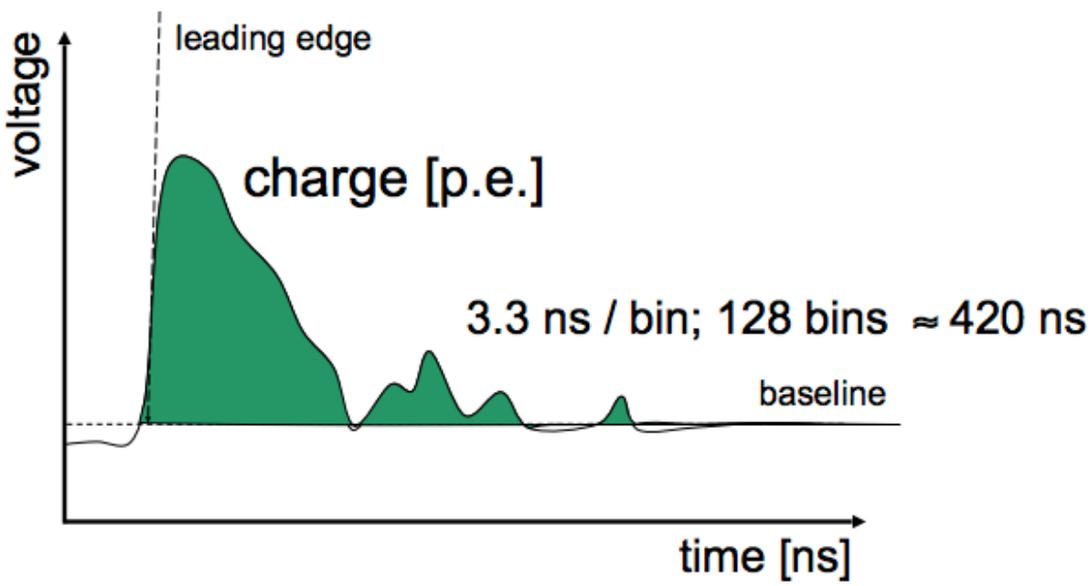


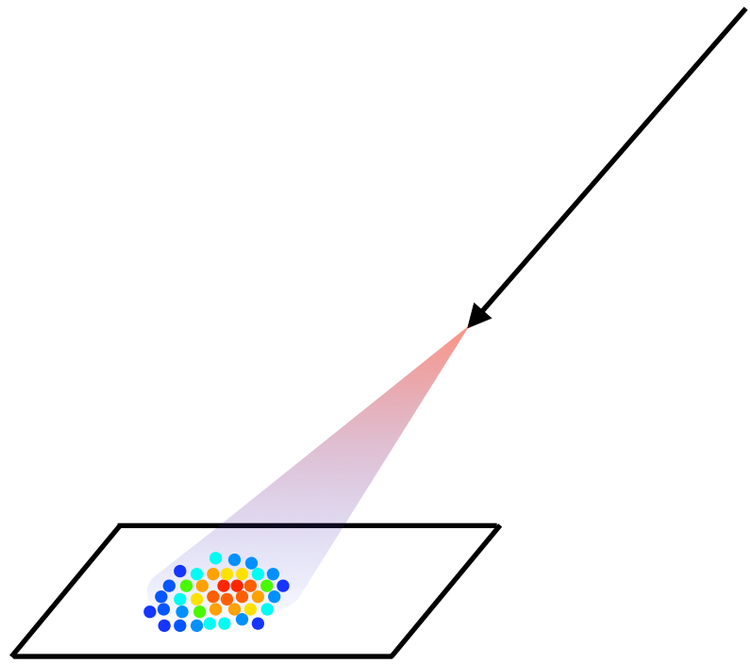
cosmic rays spectrum

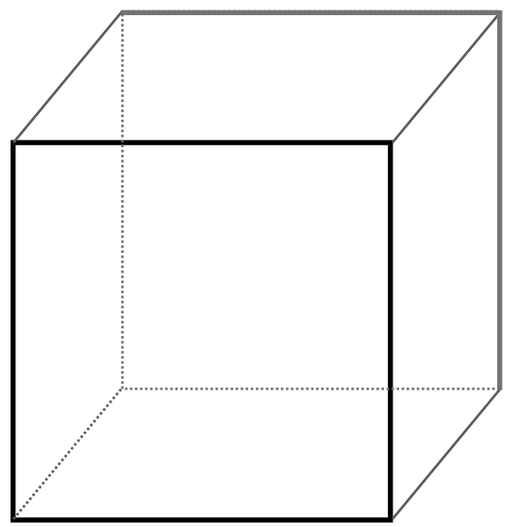
all-particle energy spectrum





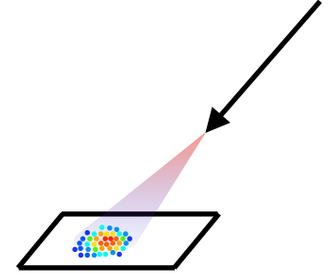


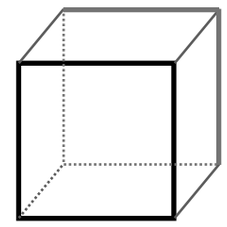


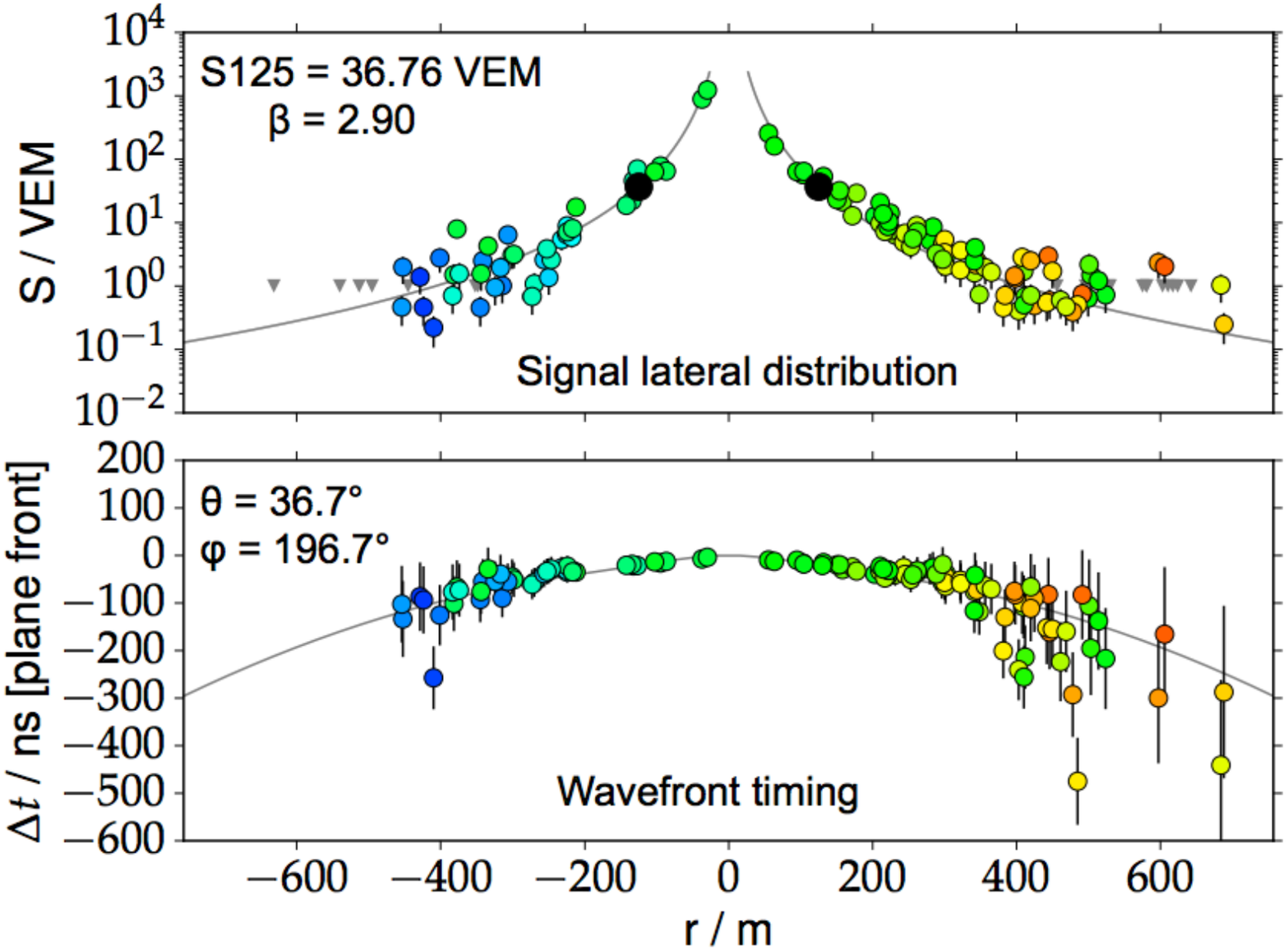


cosmic rays spectrum

all-particle energy spectrum







Signal lateral distribution:

$$S(r) = S_{125} e^{-\frac{d \sec\theta}{\lambda}} \left(\frac{r}{125\,\mathrm{m}}\right)^{-\beta-\kappa \log\left(\frac{r}{125\,\mathrm{m}}\right)}$$

Correction for attenuation in snow

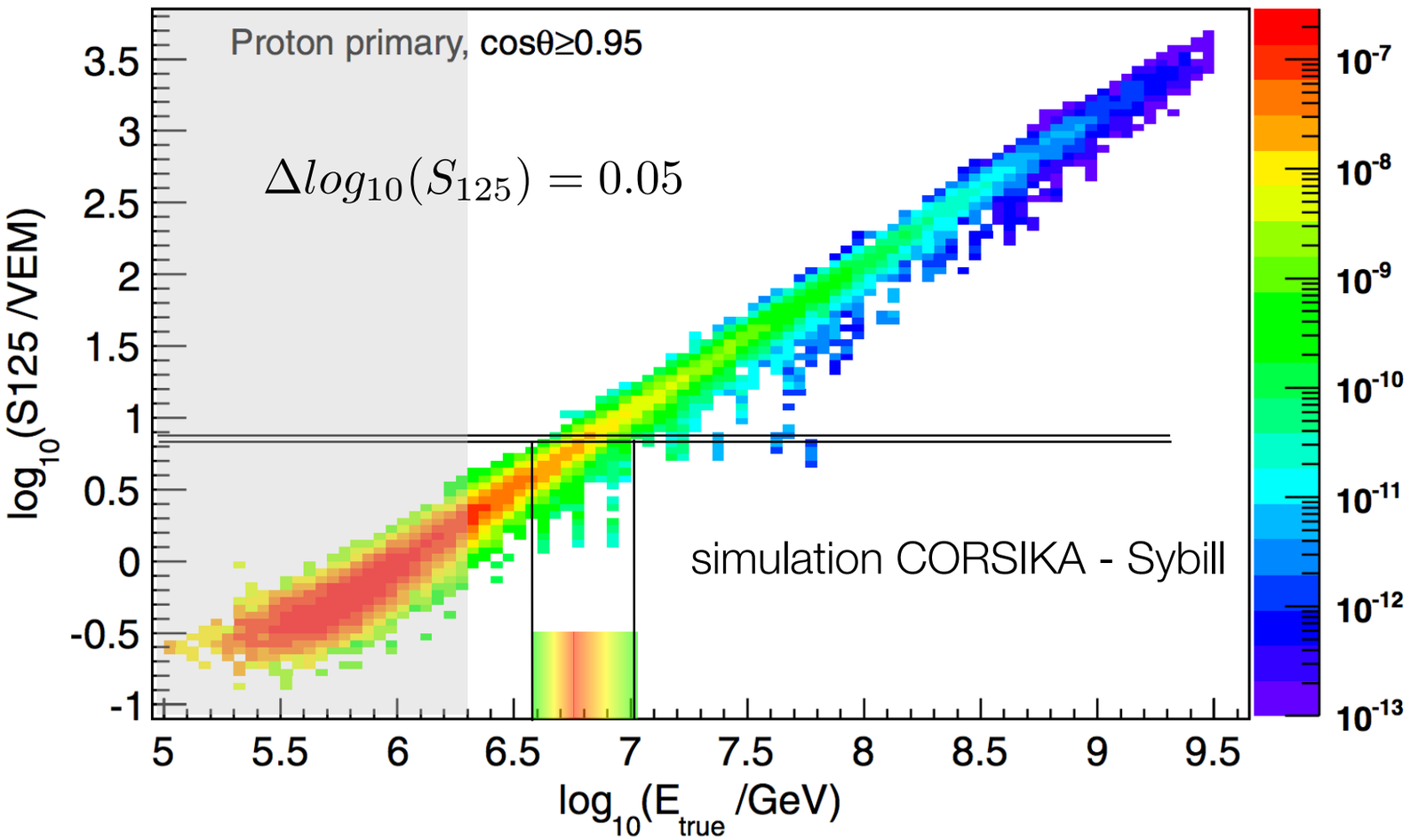
Wavefront timing:

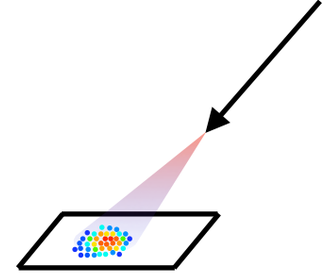
$$t(\vec{x}) = t_0 + \frac{1}{c}(\vec{x} - \vec{x}_c) \cdot \vec{n} + \Delta t(r)$$

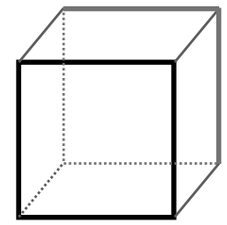
$$\Delta t(r) = ar^2 + b\left(1 - \exp\left(-\frac{r^2}{2\sigma^2}\right)\right)$$

cosmic rays spectrum

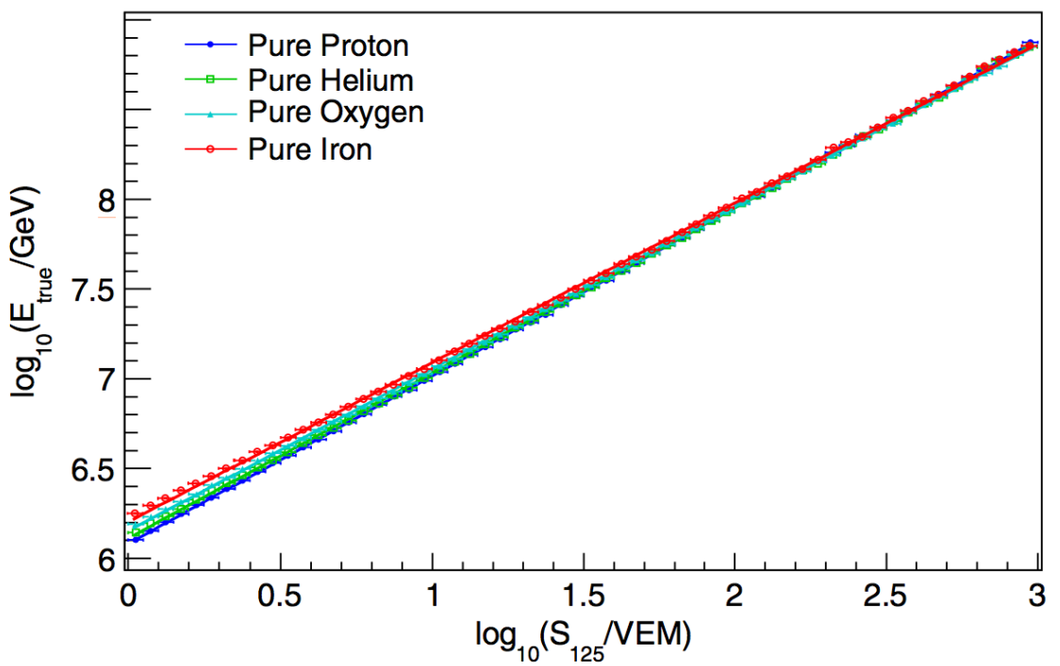
all-particle energy spectrum







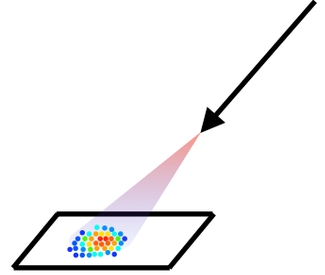
Aartsen et al. PRD 88 (2013) 042004

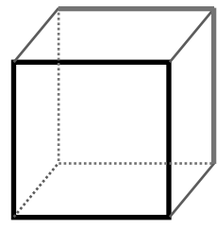


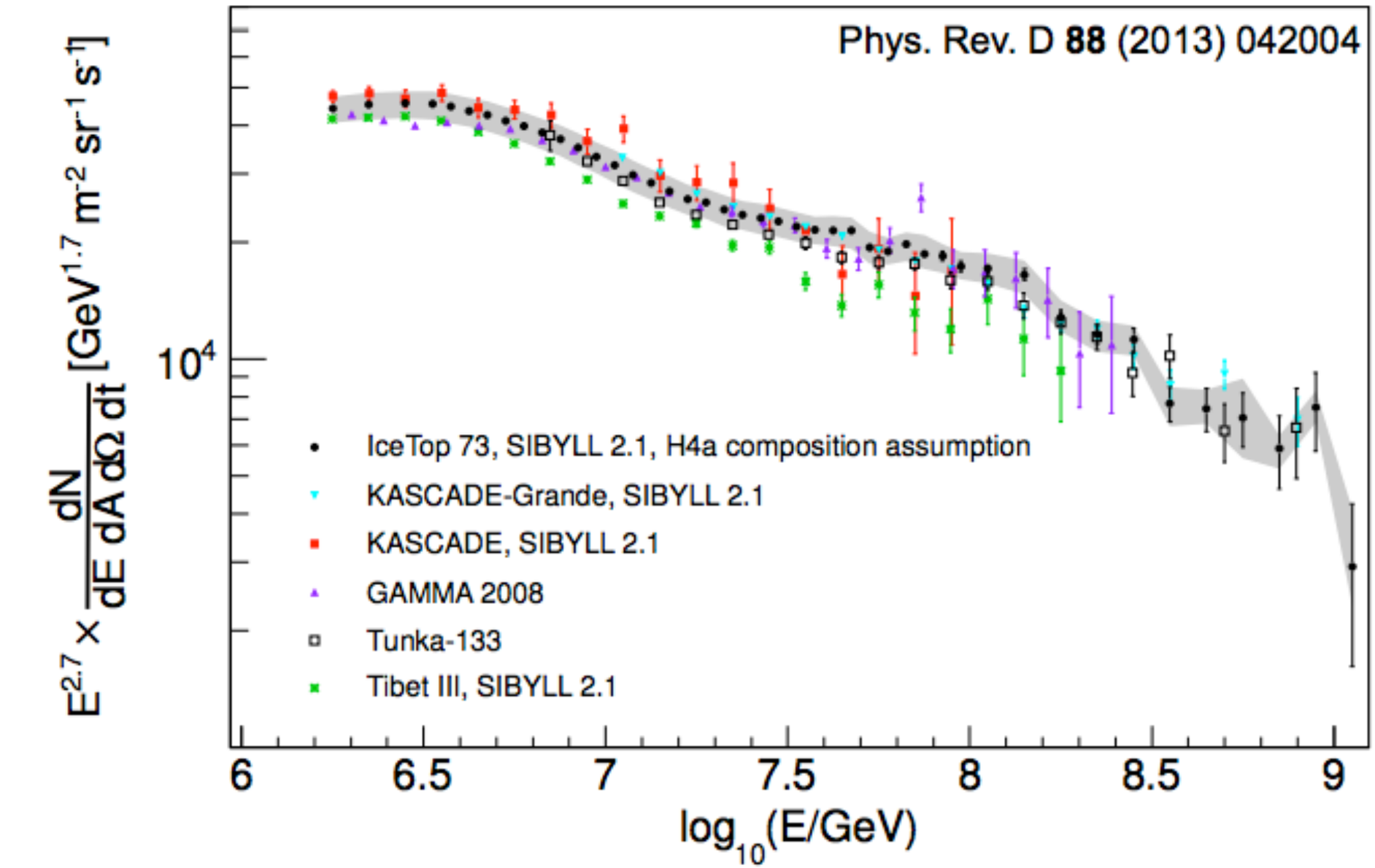
the relationship between S_{125} and primary energy depends on **mass** and **zenith angle**

cosmic rays spectrum

all-particle energy spectrum



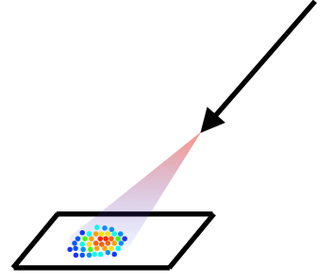


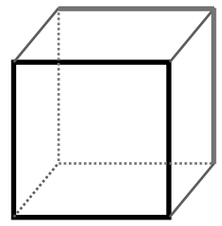


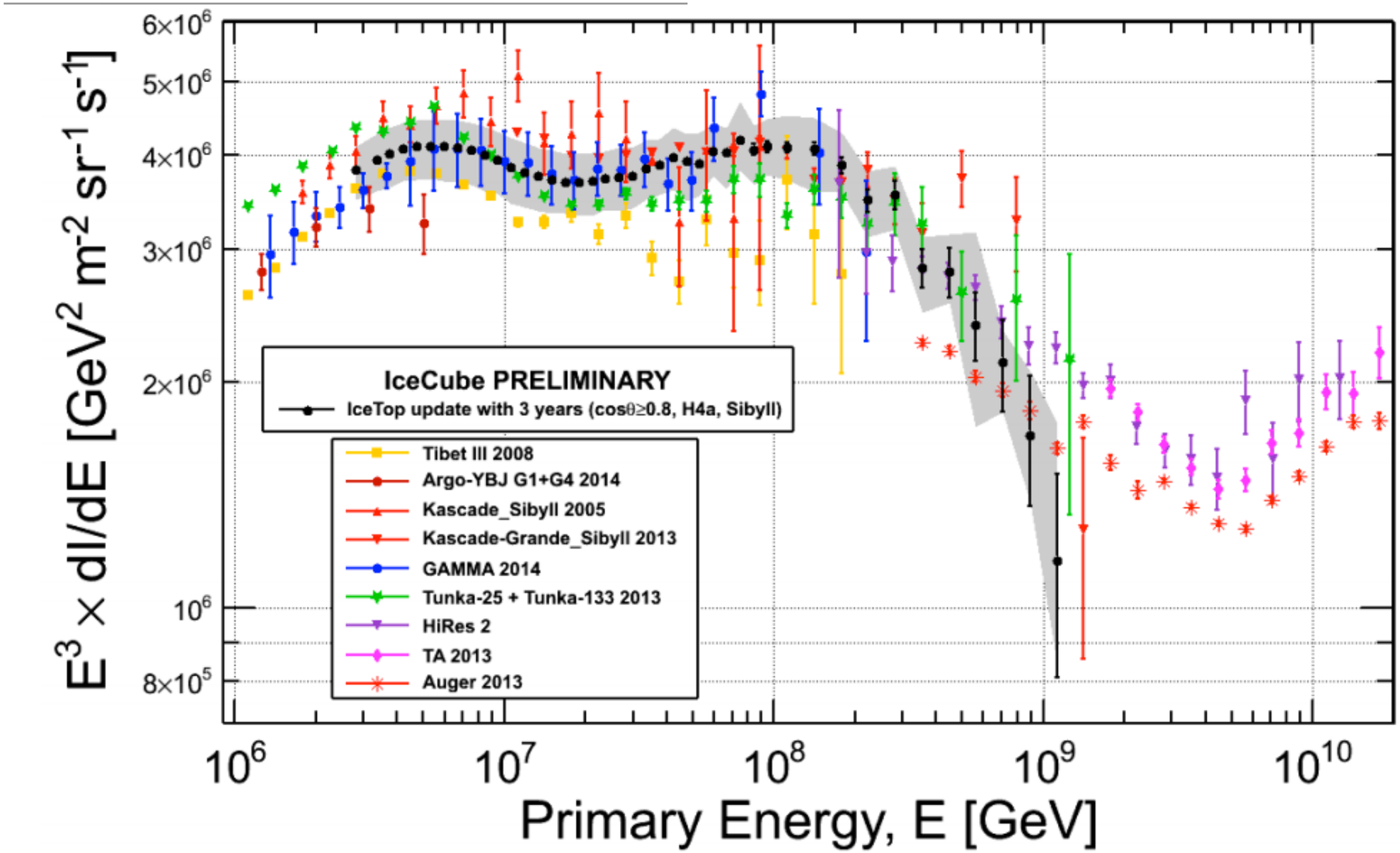
all-particle spectrum depends on the ***assumed*** mass composition of primary particles

cosmic rays spectrum

all-particle energy spectrum



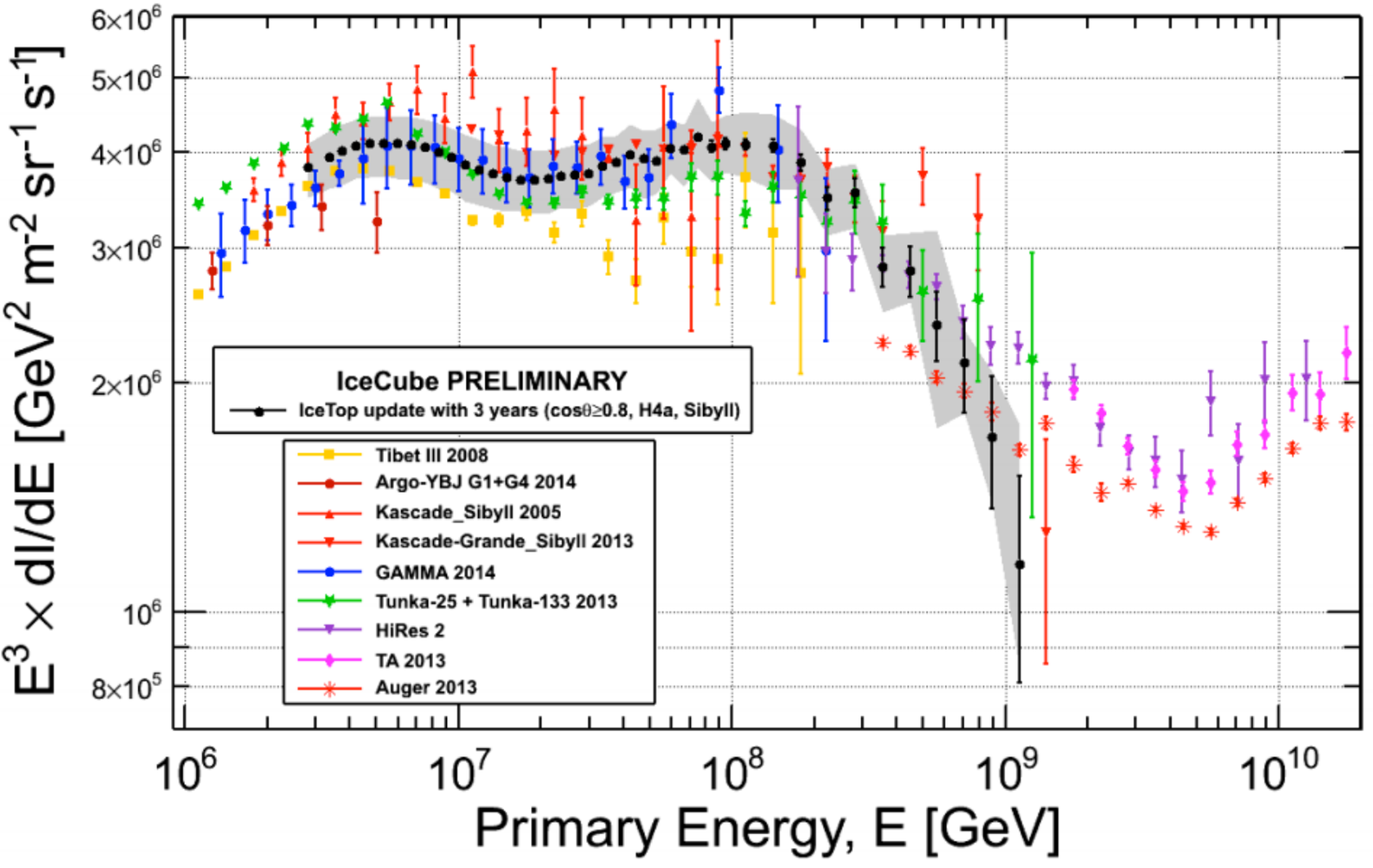


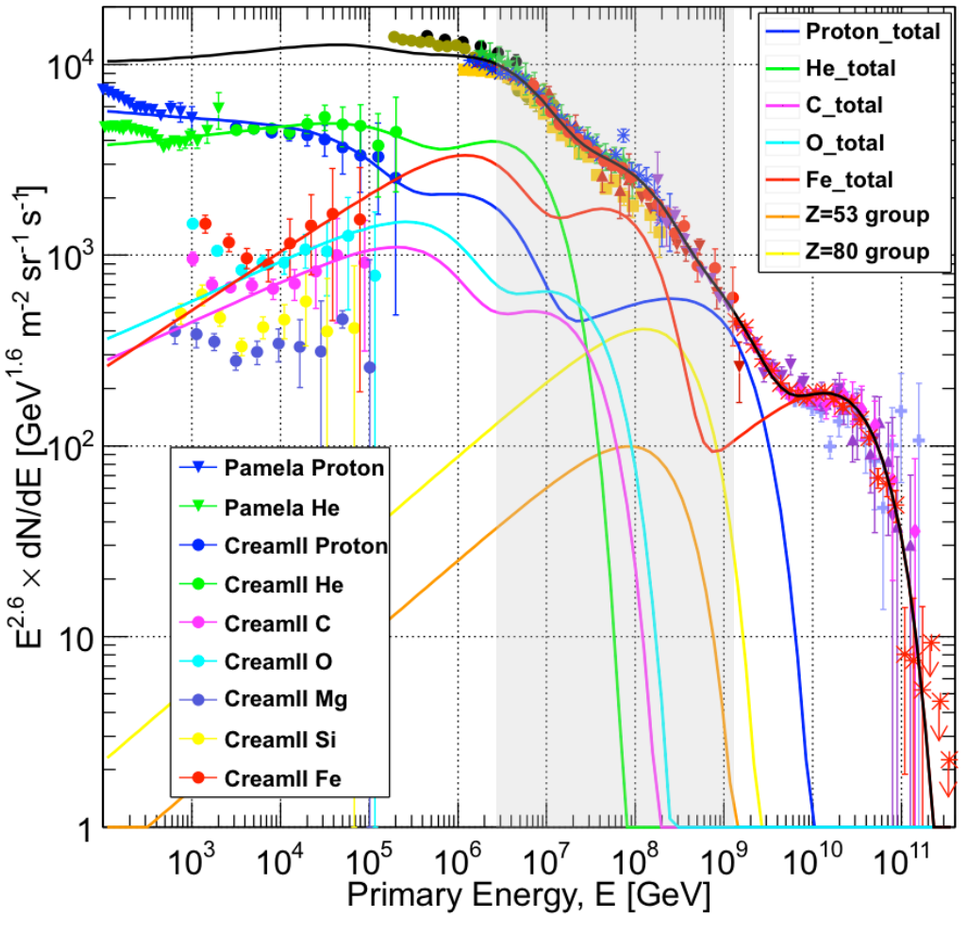


all-particle spectrum depends on the ***assumed*** mass composition of primary particles

cosmic rays spectrum

all-particle energy spectrum

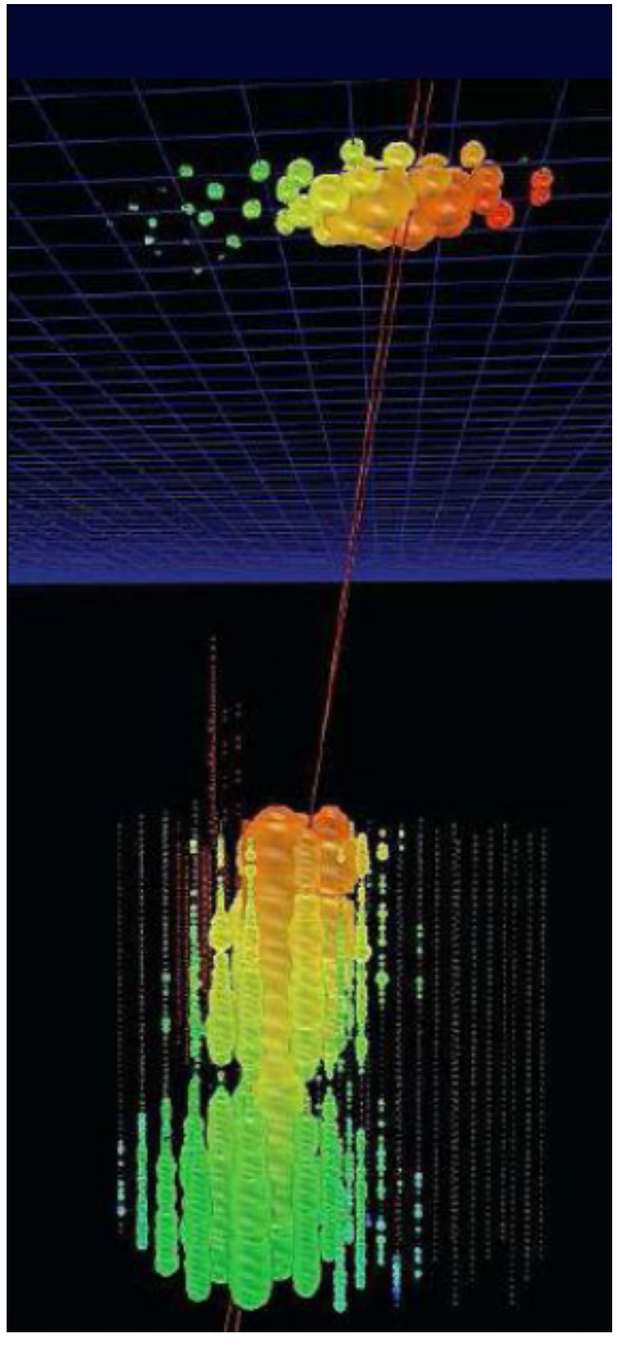


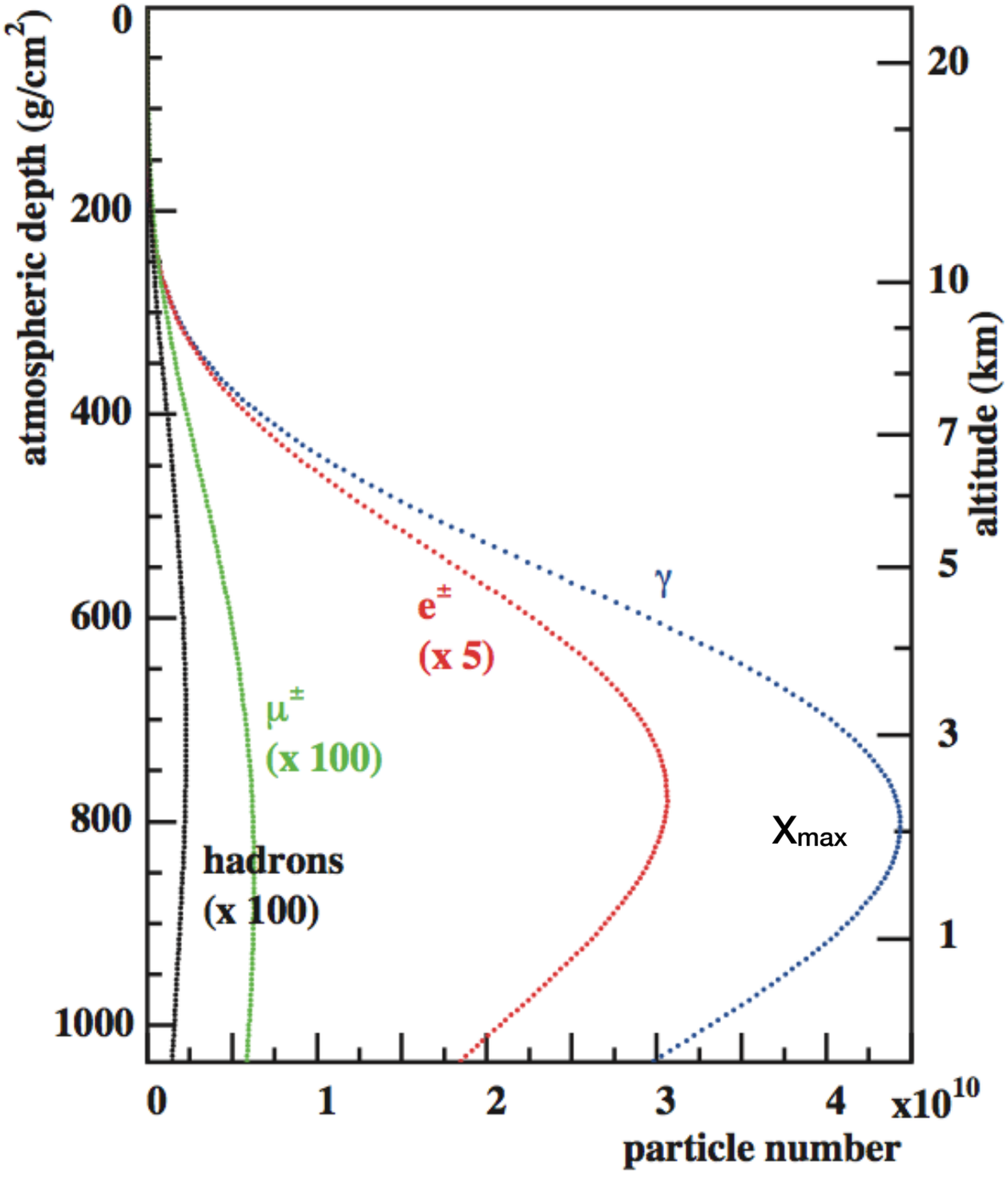


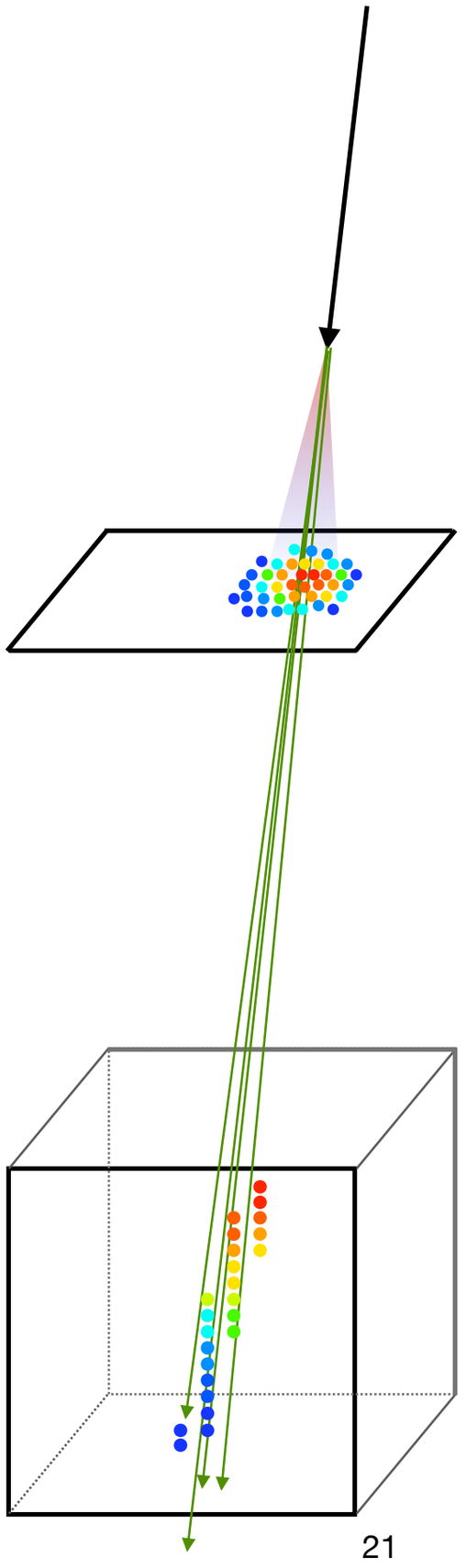
all-particle spectrum depends on the ***assumed*** mass composition of primary particles

cosmic rays composition

coincident events



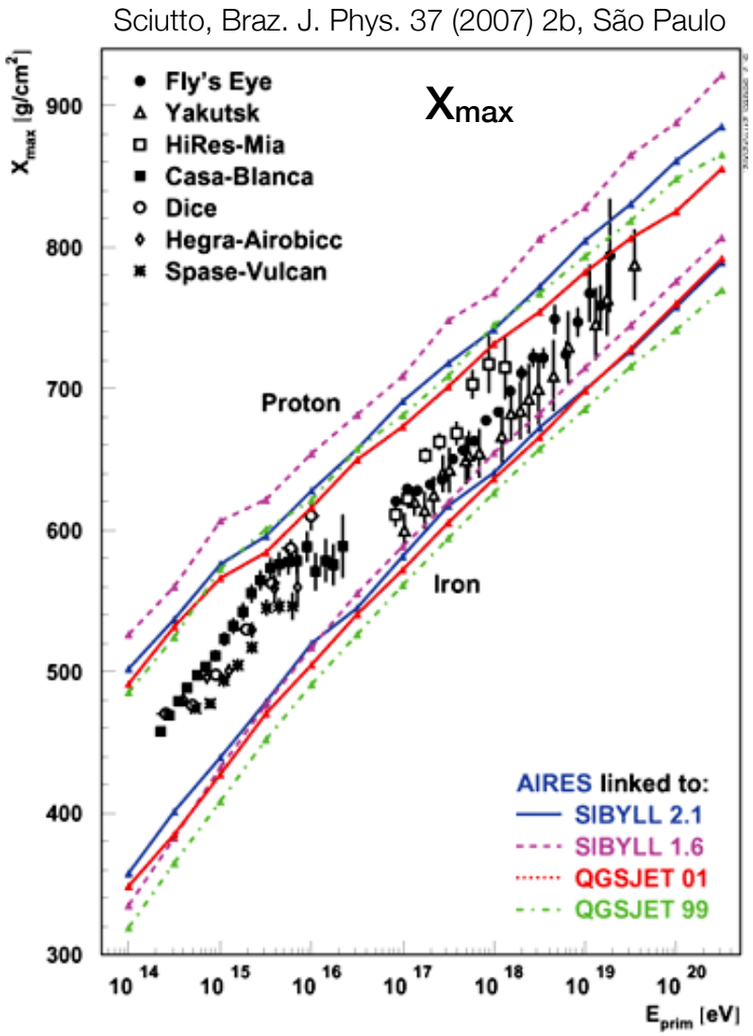




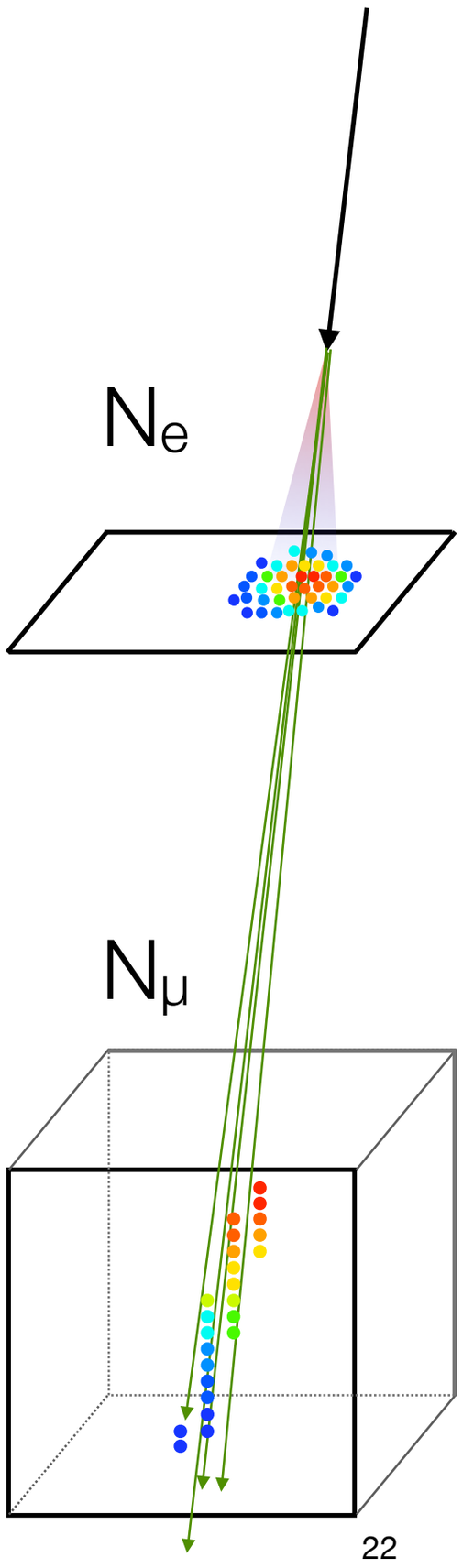
cosmic rays composition
coincident events

@Antarctica

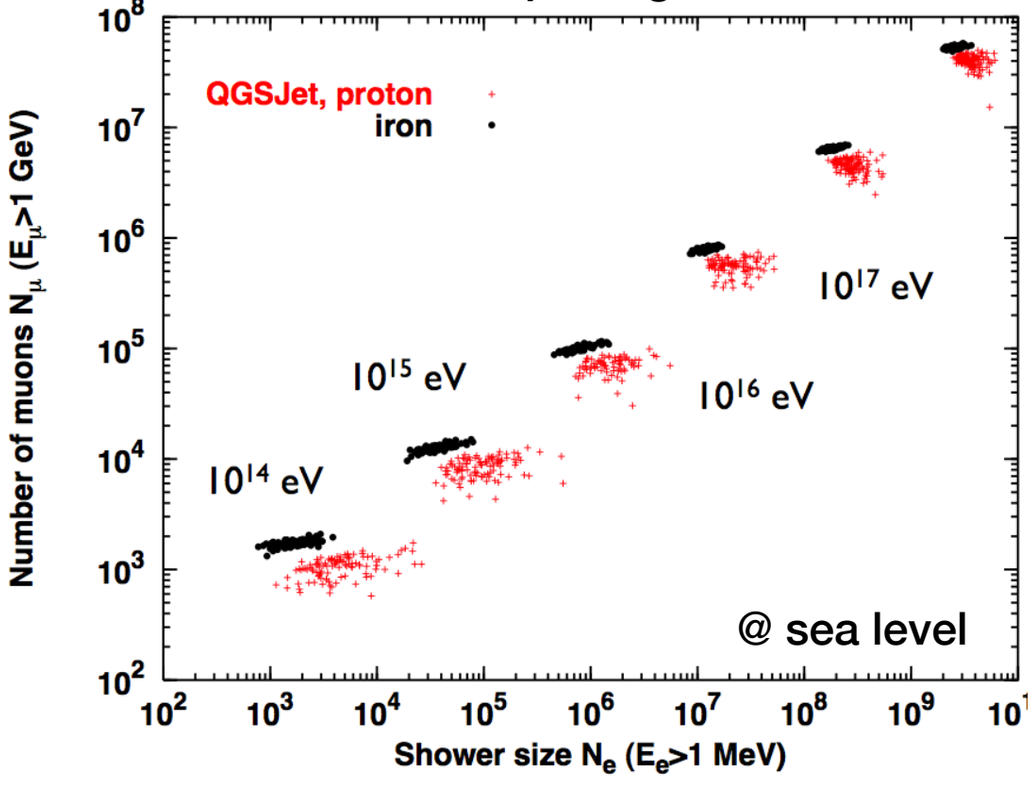
Sciutto, Braz. J. Phys. 37 (2007) 2b, São Paulo

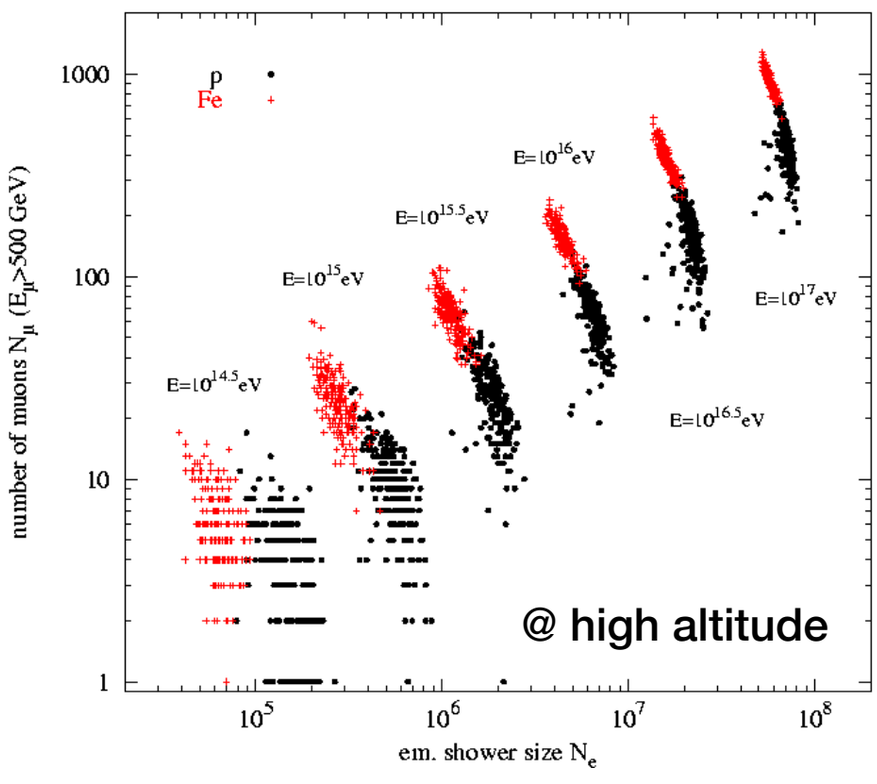


@sea level



simulations - Ralph Engel

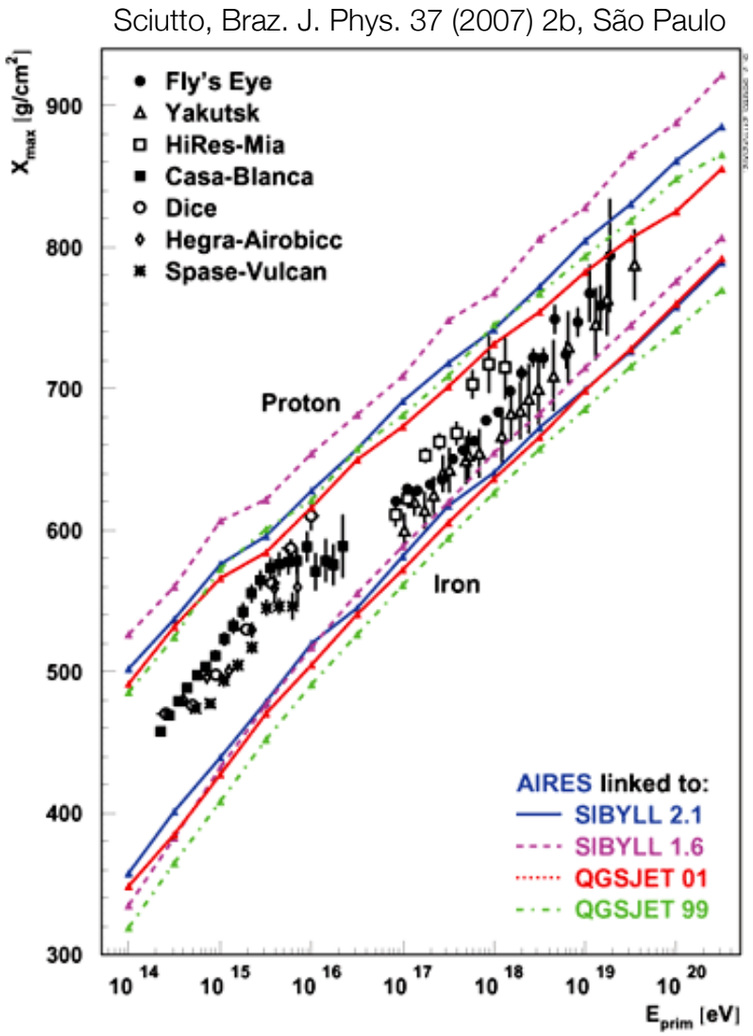




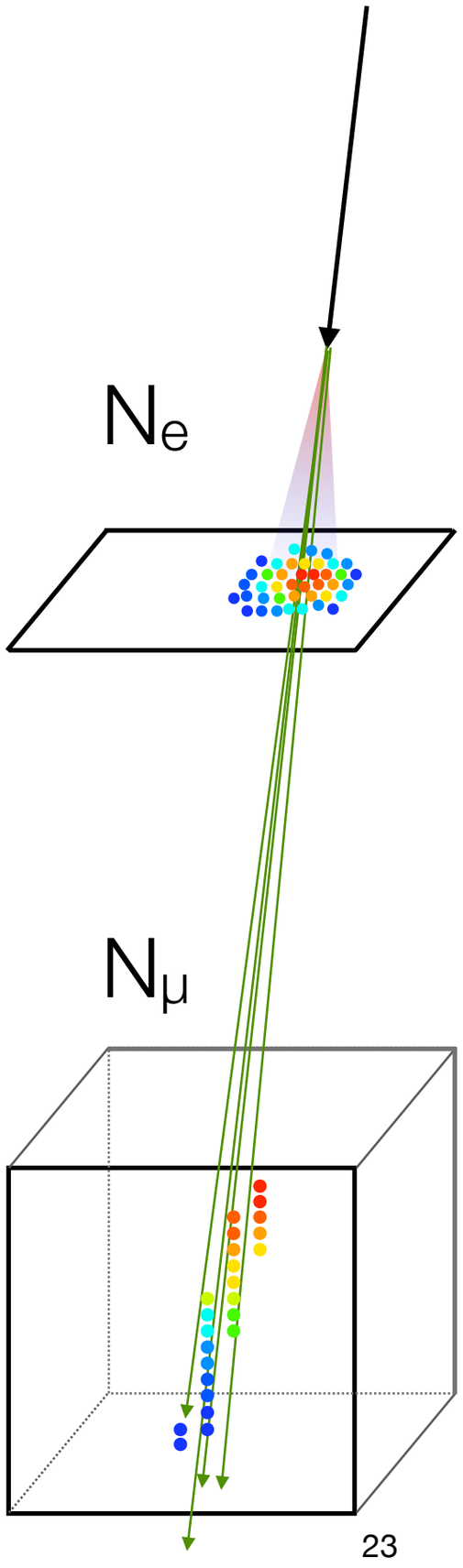
cosmic rays composition
coincident events

@Antarctica

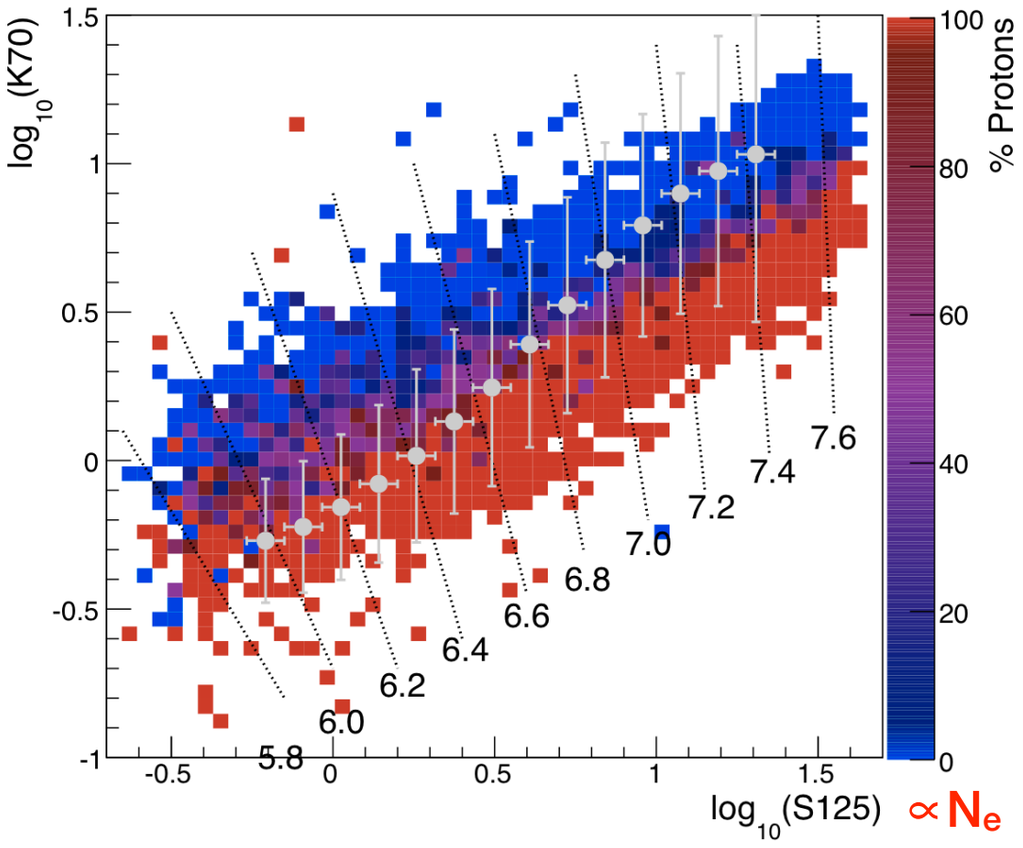
Sciutto, Braz. J. Phys. 37 (2007) 2b, São Paulo

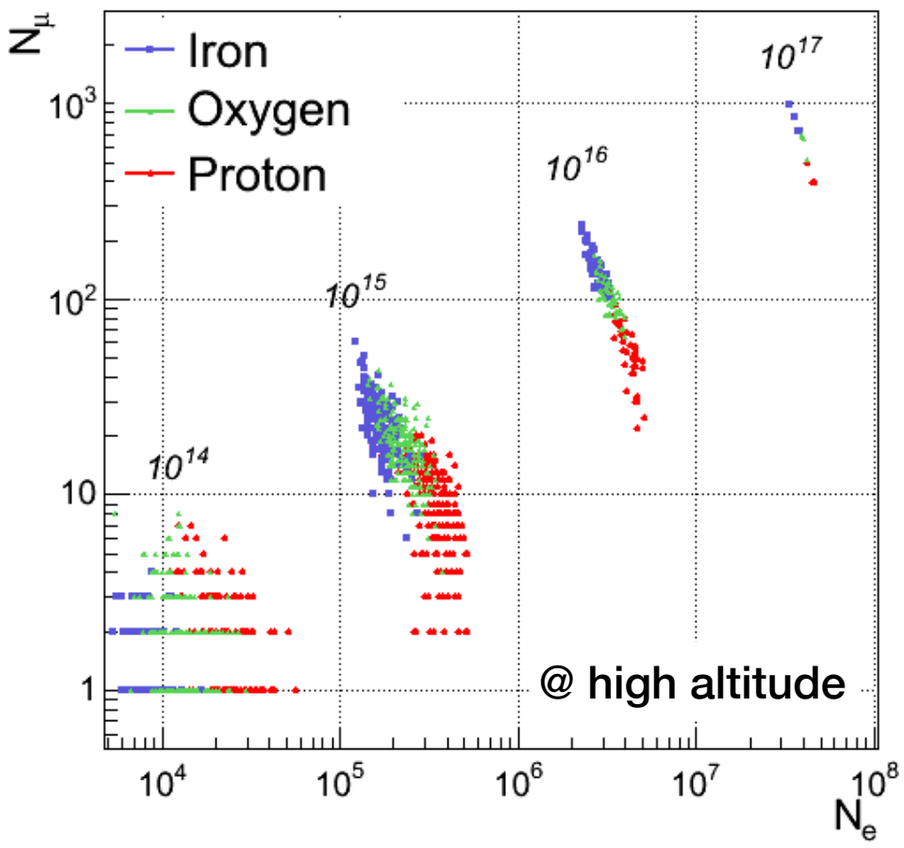


@sea level



$\propto N_\mu$



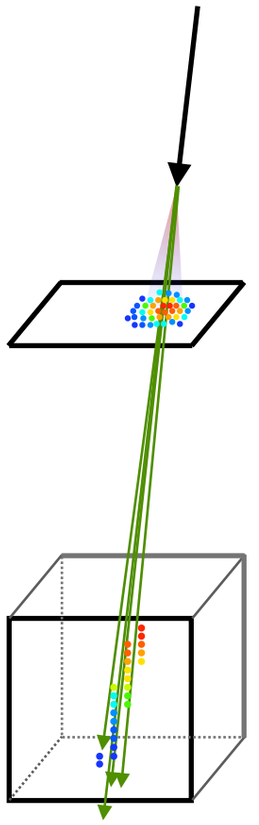


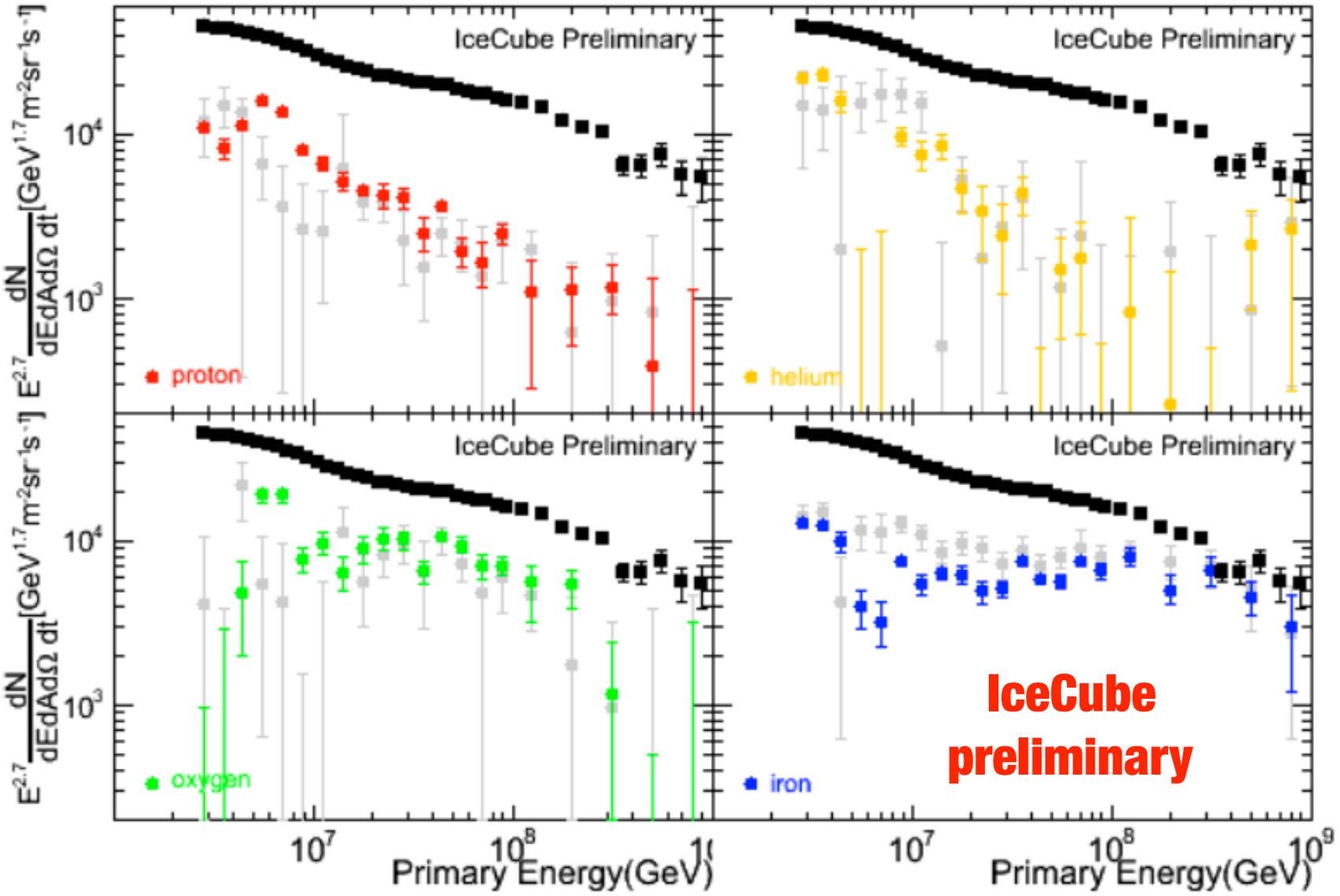
cosmic rays composition

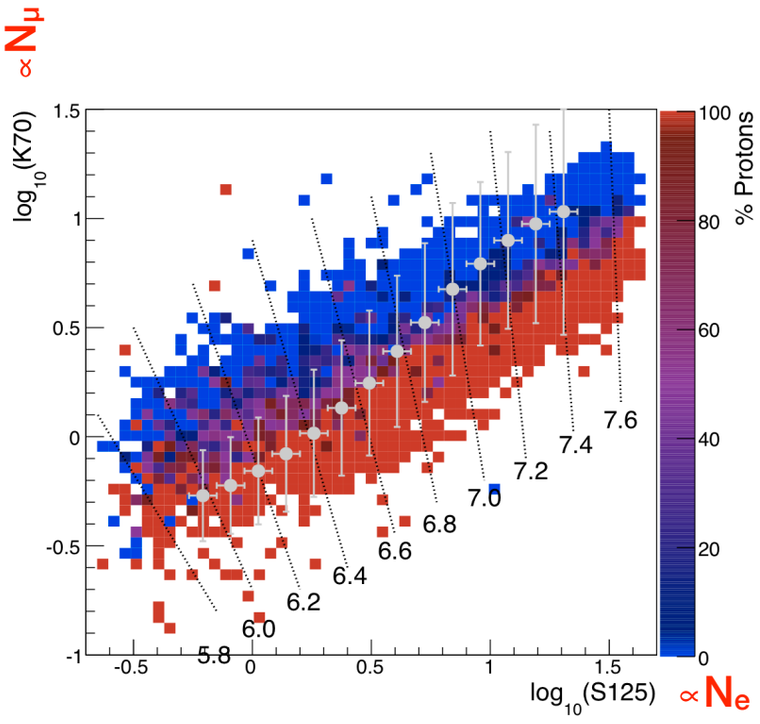
coincident events

Colors = SIBYLL 2.1
Grey = QGSJET-II-03

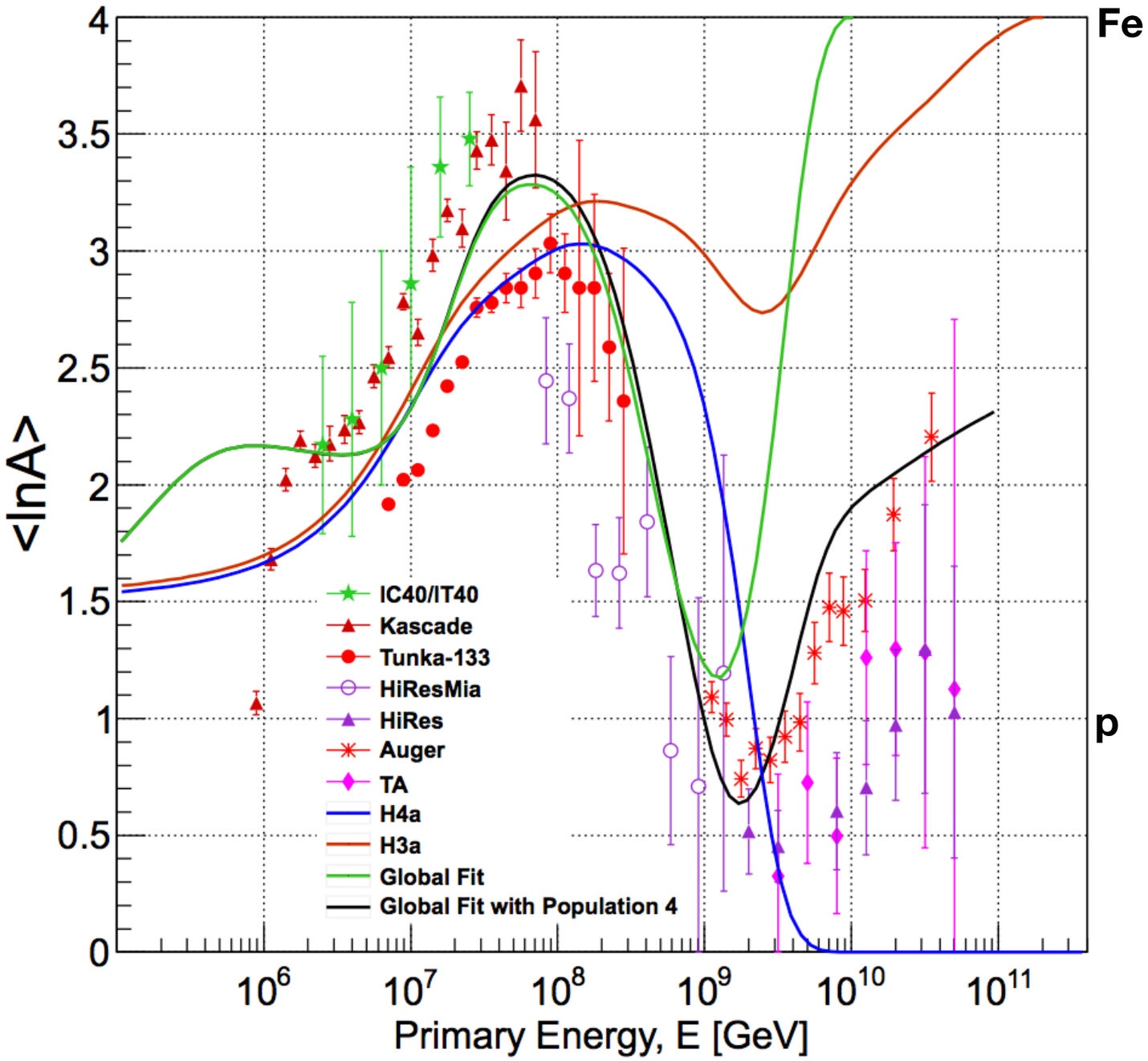
effect of hadronic interaction models





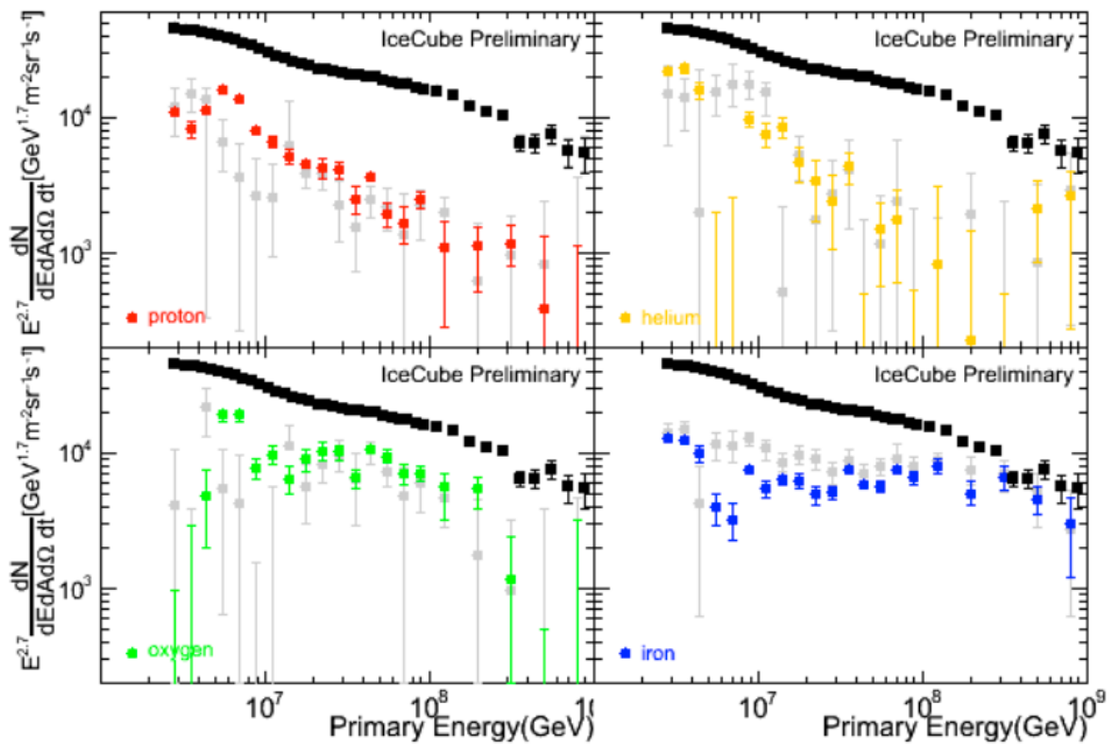


cosmic rays composition
other experiments

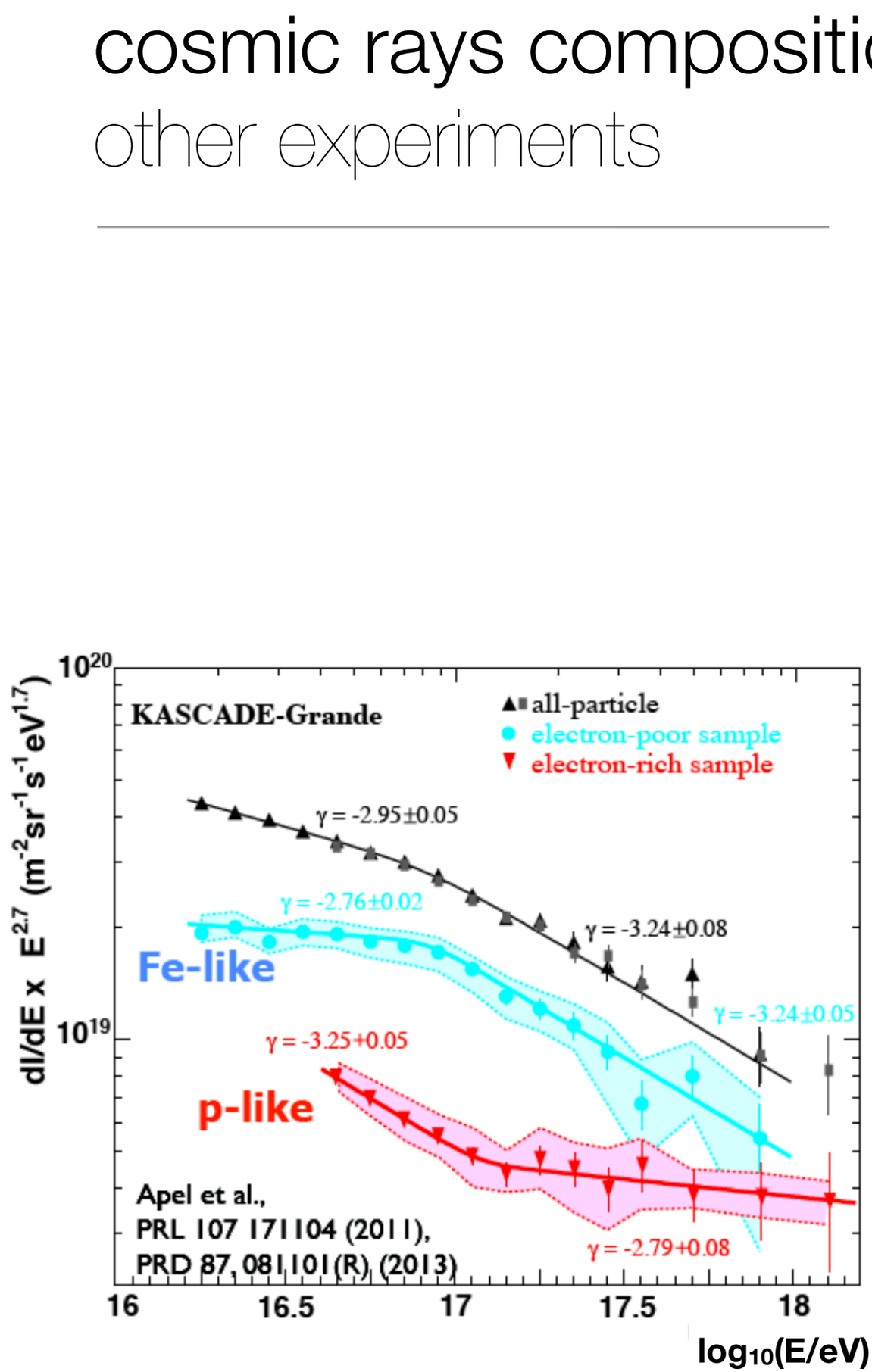


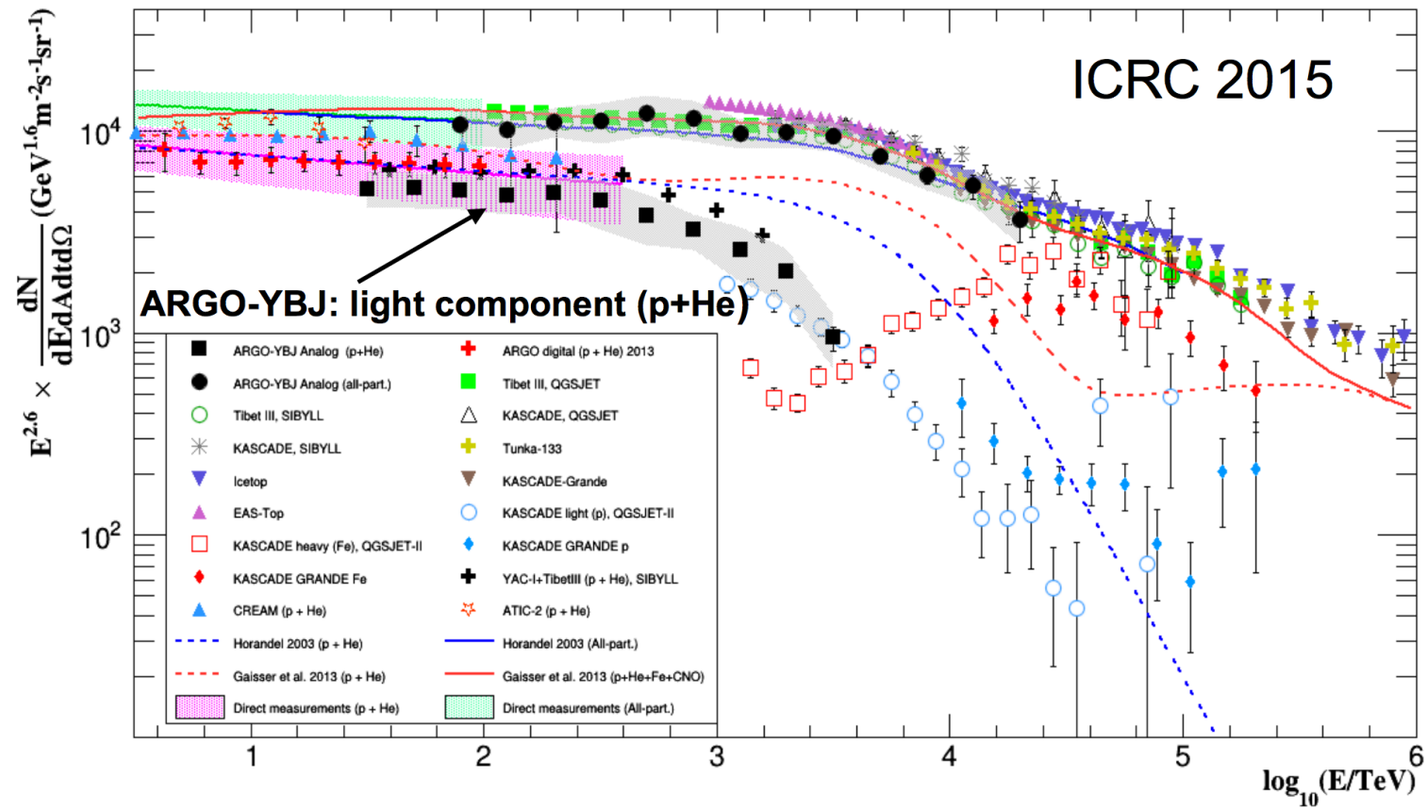
cosmic ray composition in **indirect** measurements is **DIFFICULT**

understanding **hadronic** interaction models at high energy is **NOT EASY**



cosmic rays composition
other experiments



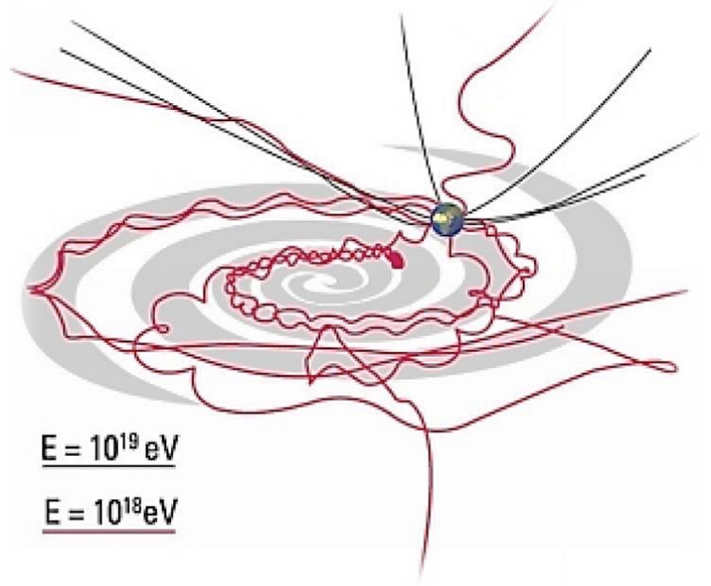


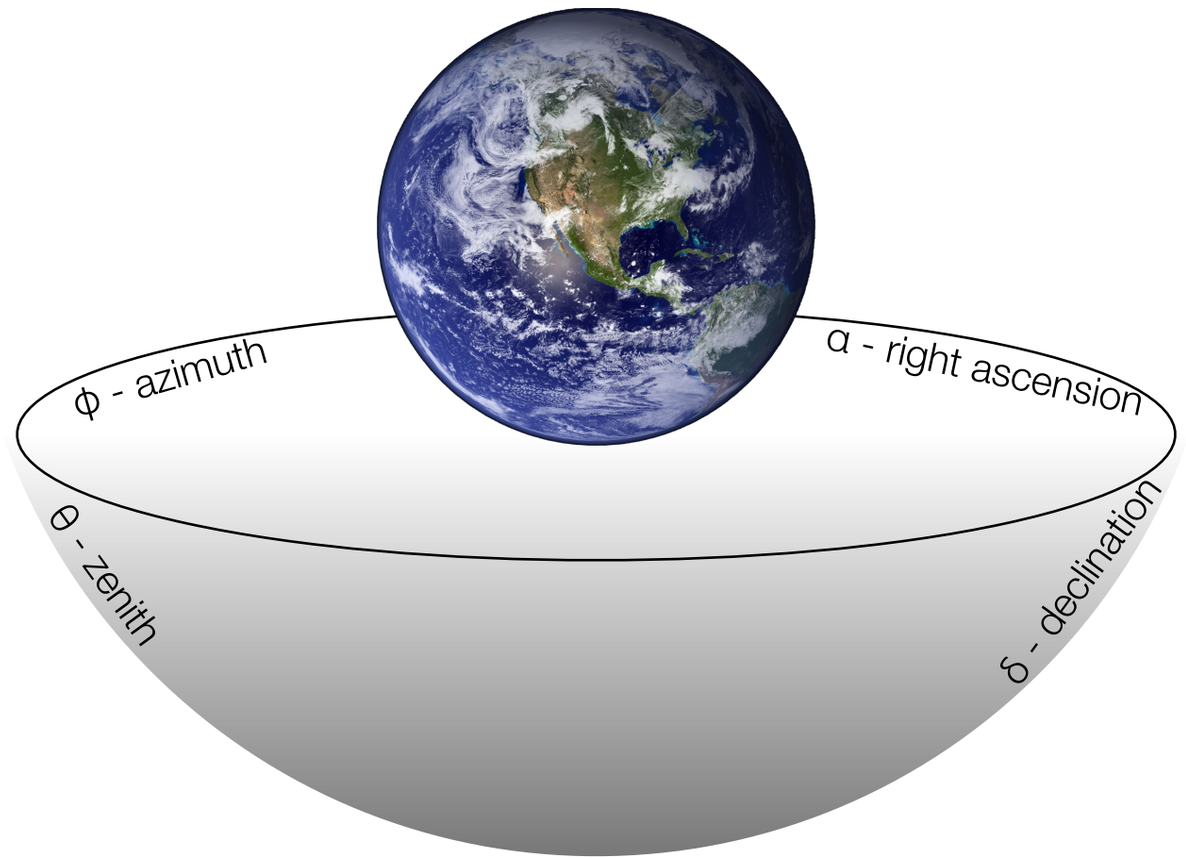
cosmic ray composition in **indirect** measurements is **DIFFICULT**

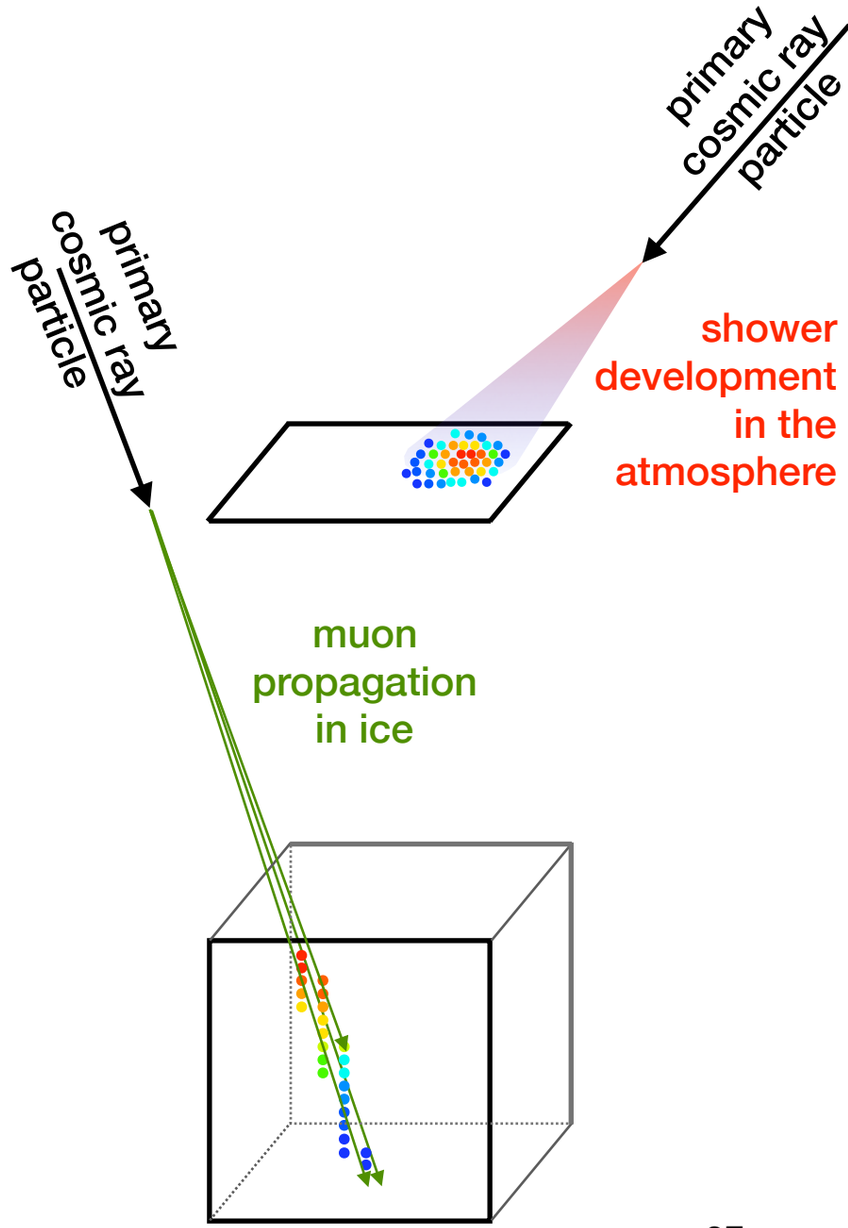
understanding **hadronic** interaction models at high energy is **NOT EASY**

cosmic rays anisotropy
arrival direction distribution

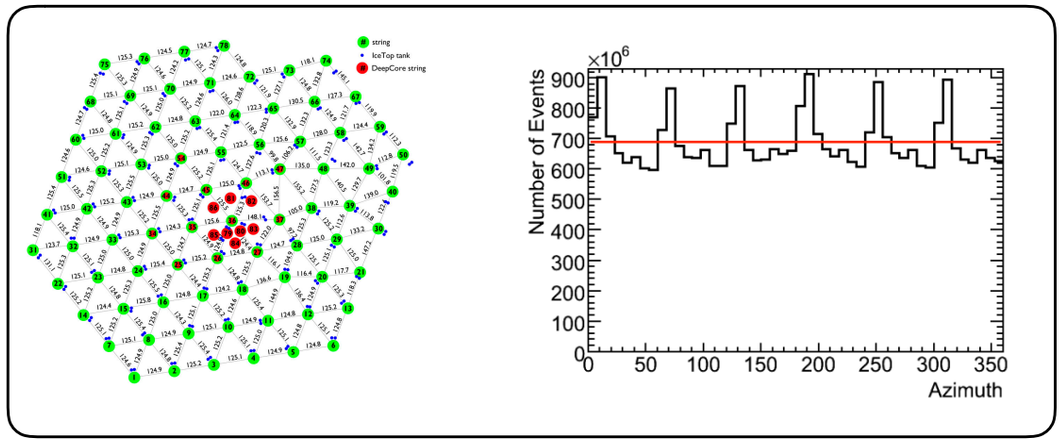
- cosmic rays expected to be ***almost*** isotropic
- ***scrambled*** by galactic magnetic field
- what does ***isotropy*** look like in IceCube ?



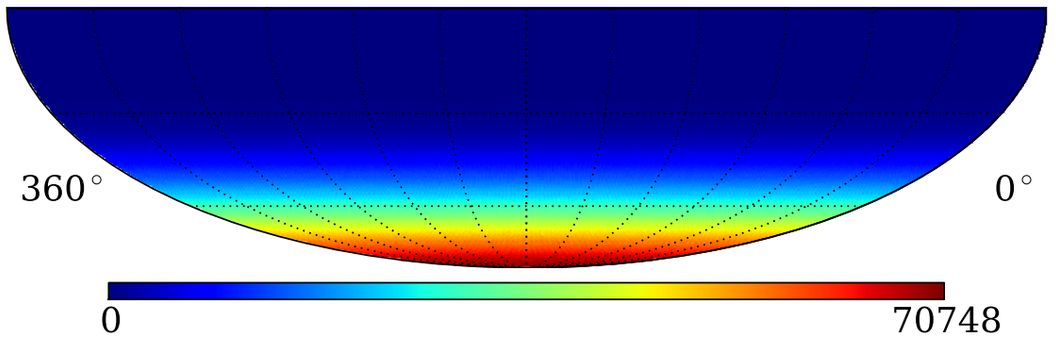




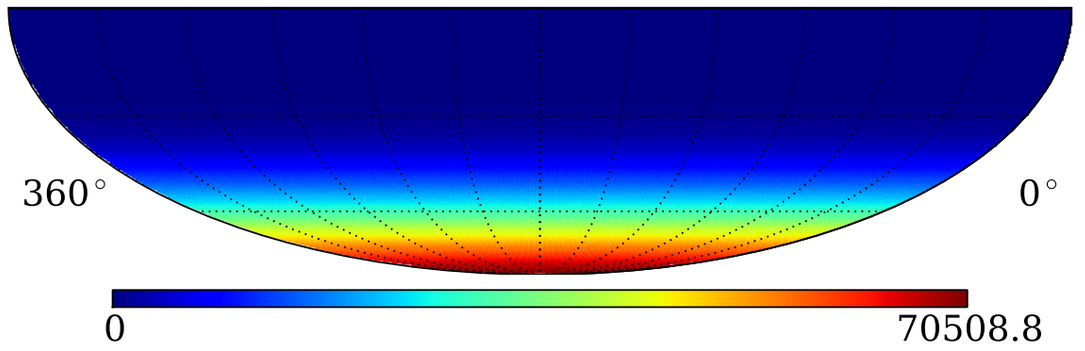
cosmic rays anisotropy
arrival direction distribution



raw map of events in equatorial coordinates $(\alpha,\delta)_i$

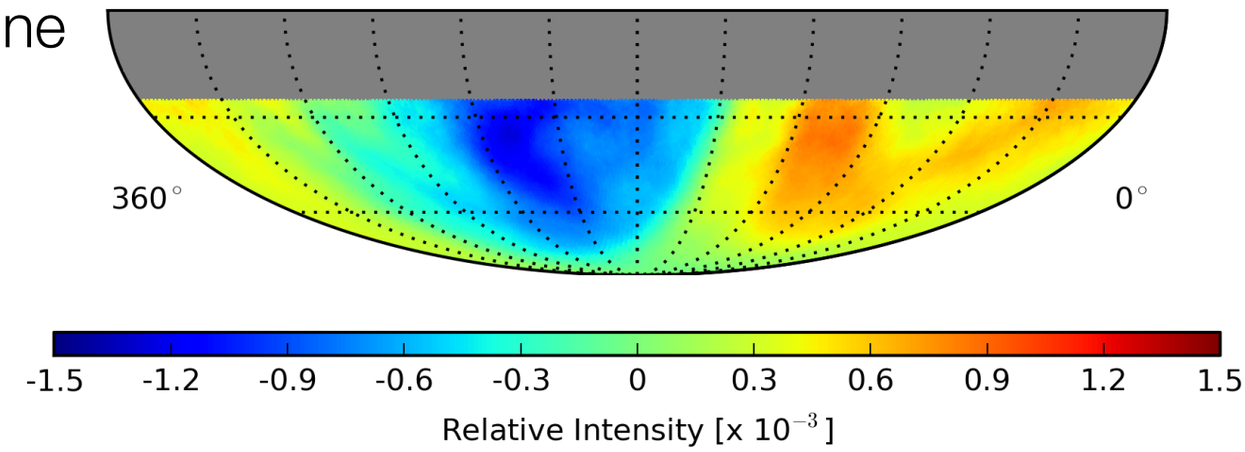


reference map from events scrambled over 24hr in α (or time)

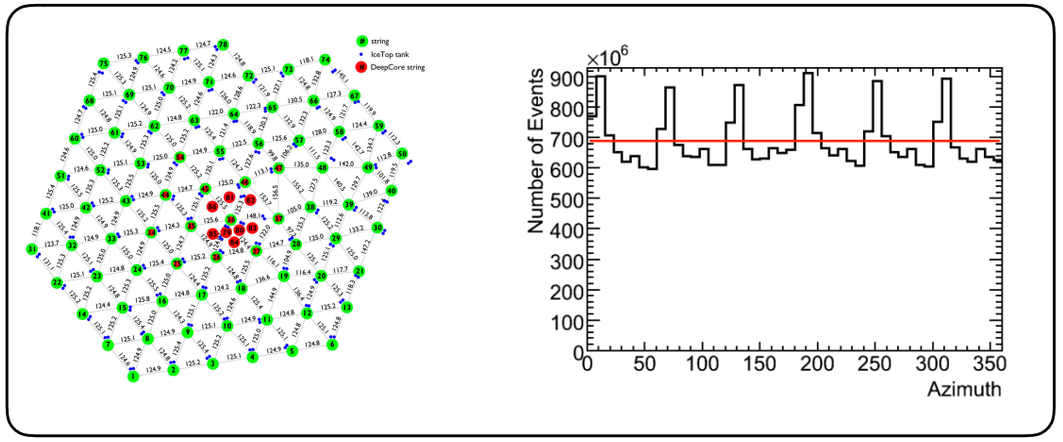


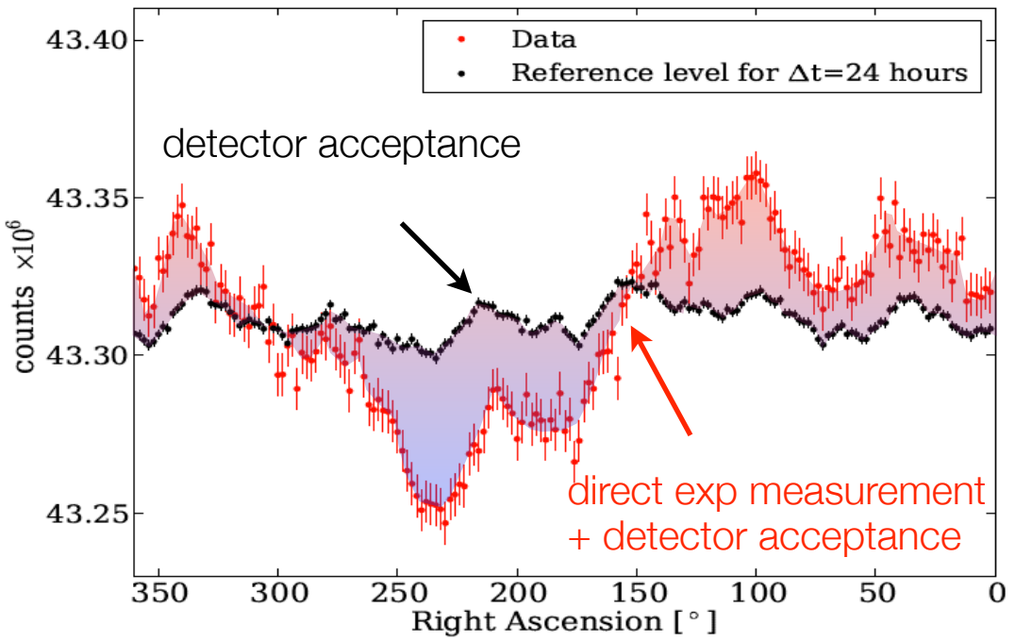
subtract reference map from raw map to determine the residual *relative intensity* map

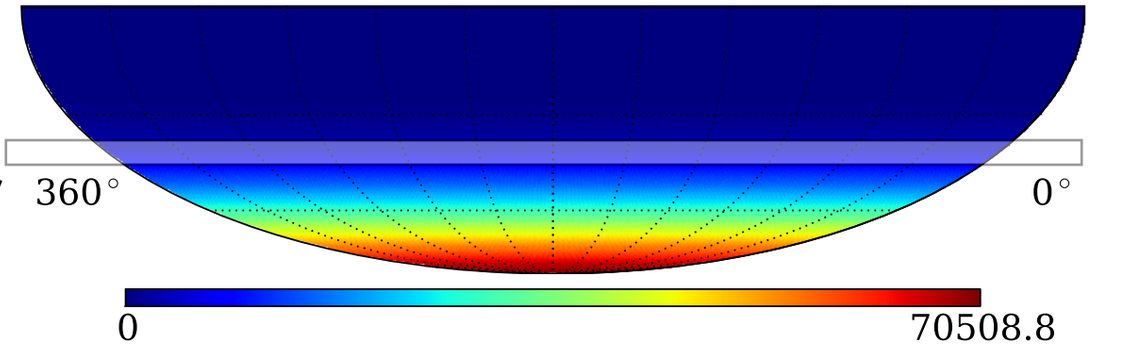
$$\frac{\Delta I}{\langle I \rangle} \equiv \frac{N_i - \langle N \rangle}{\langle N \rangle}$$



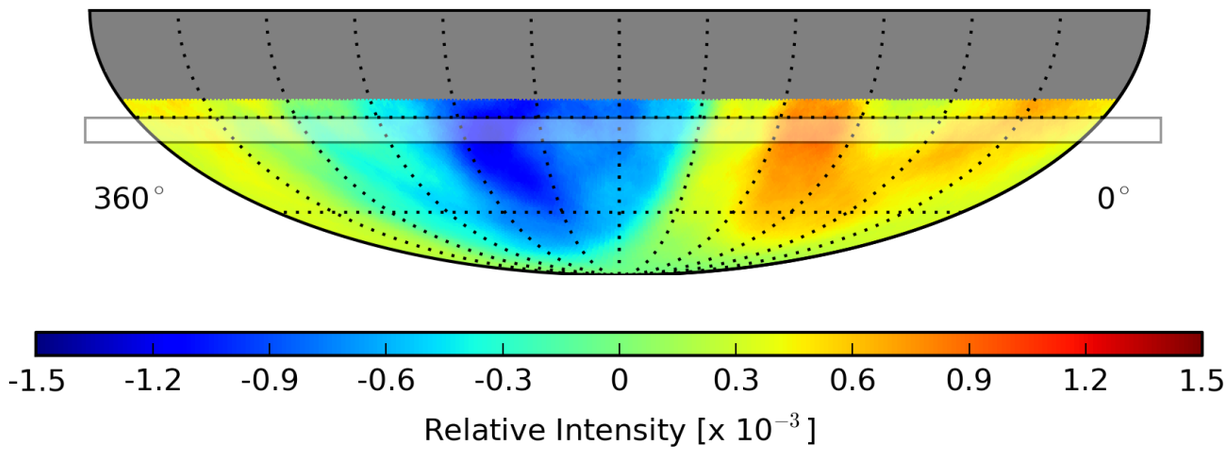
cosmic rays anisotropy
arrival direction distribution





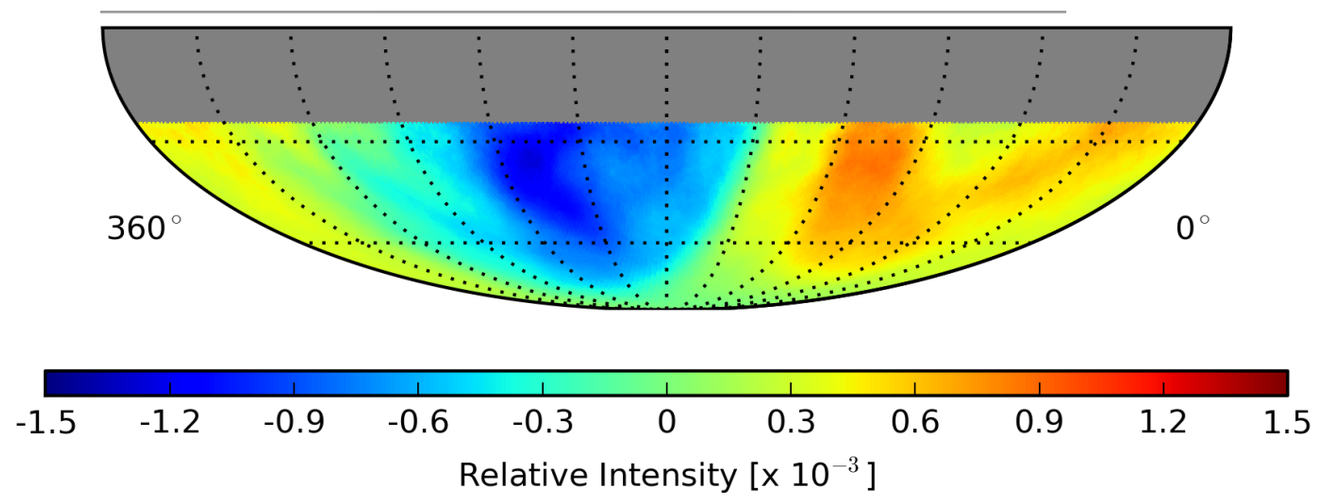


$$\frac{\Delta I}{\langle I \rangle} \equiv \frac{N_i - \langle N \rangle}{\langle N \rangle}$$

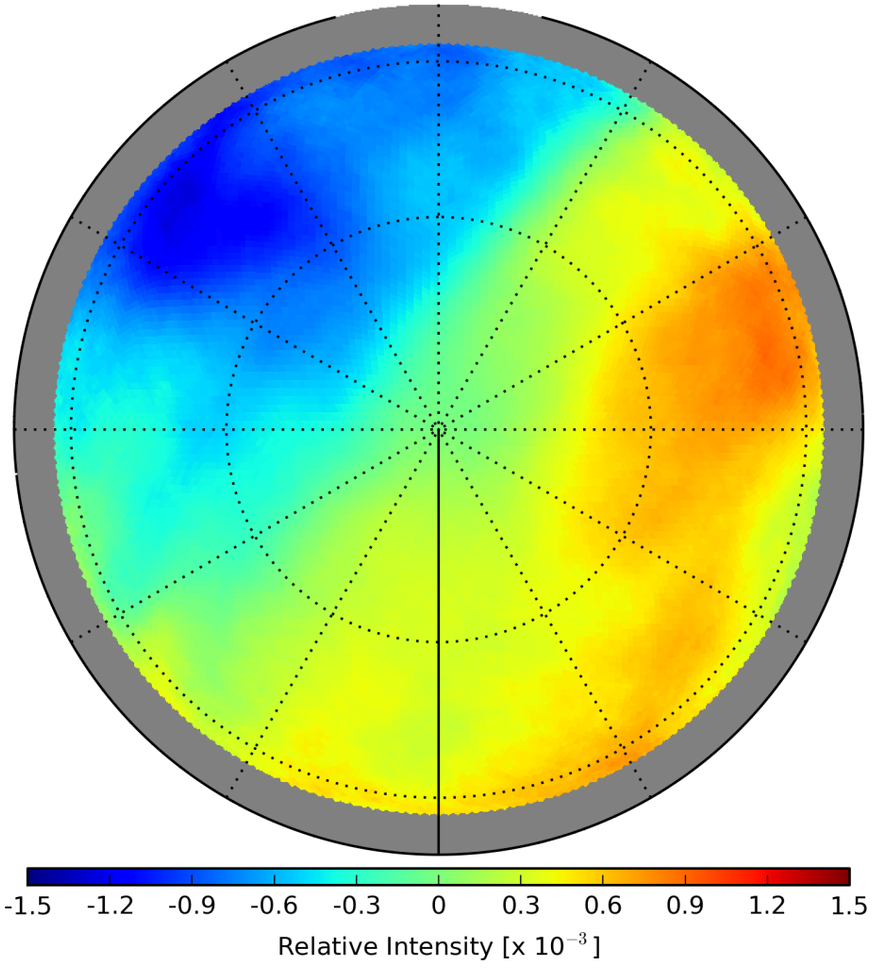


cosmic rays anisotropy

arrival direction distribution



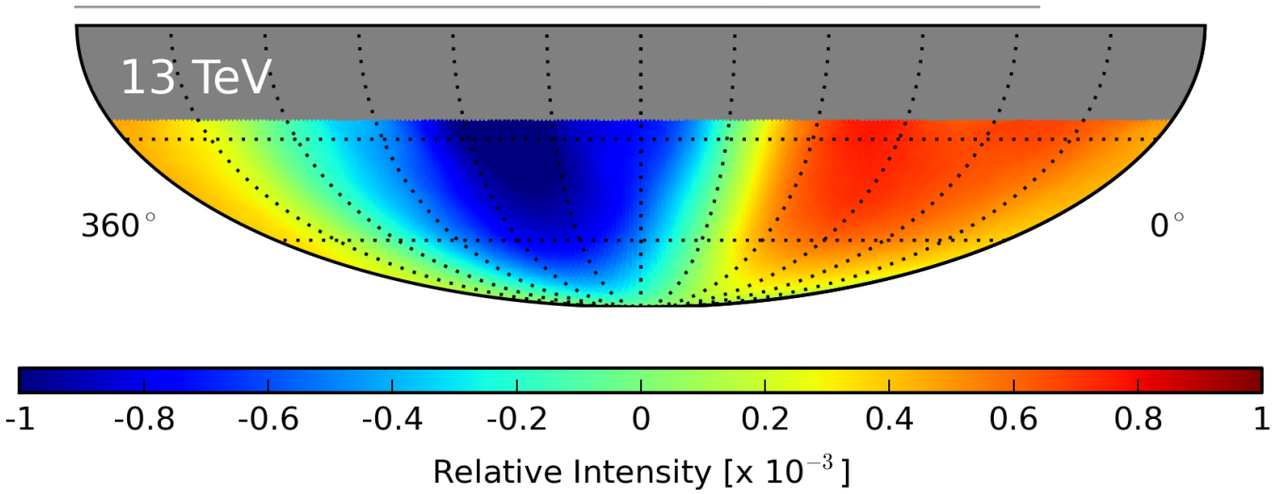
- 6 years of IceCube
- 300 billion events

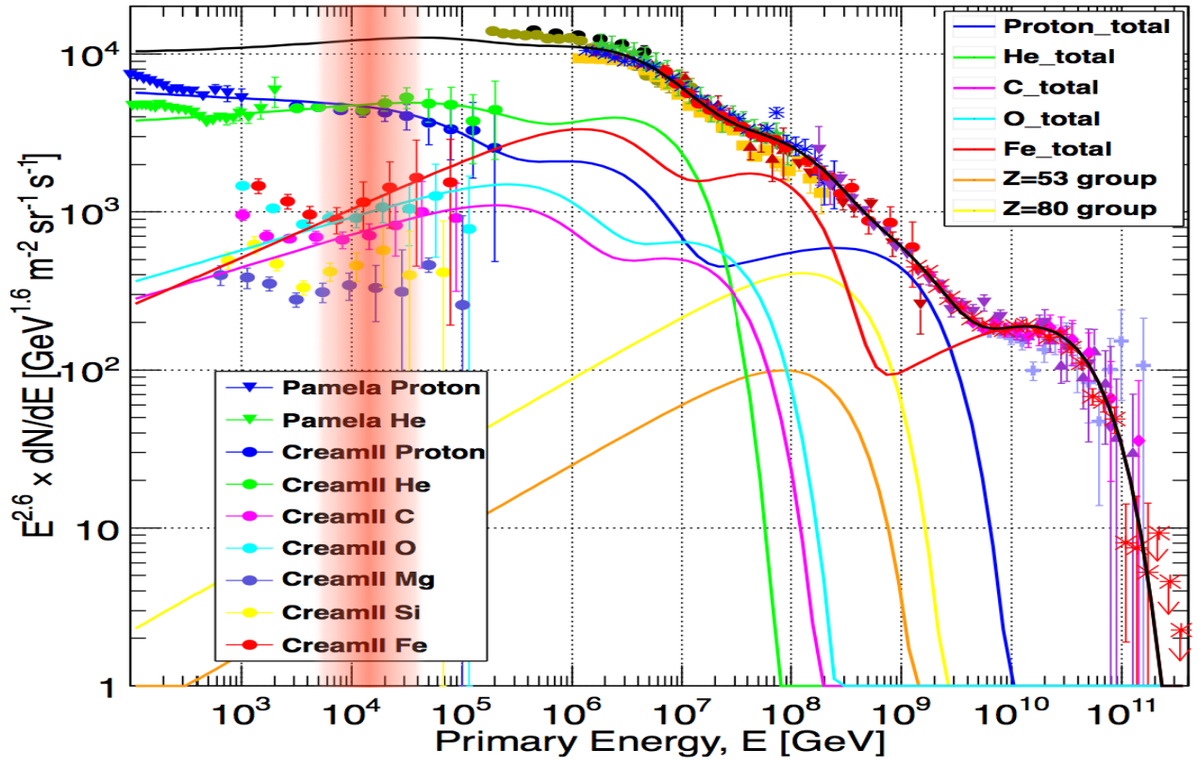


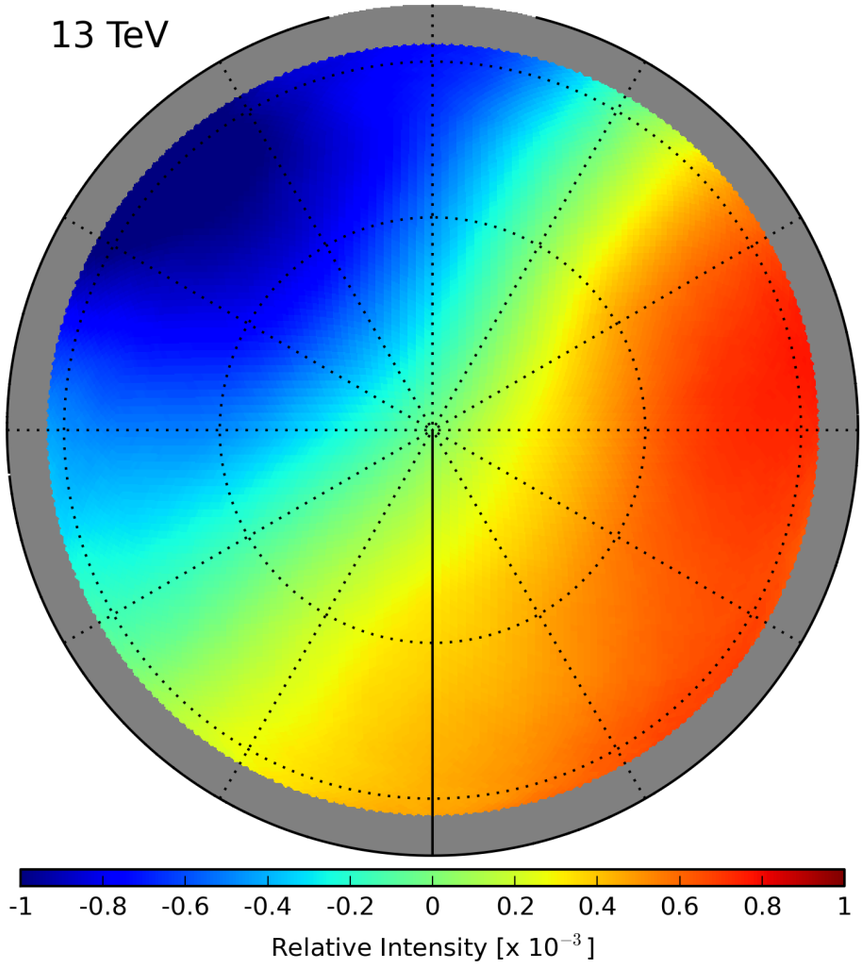
- anisotropy on the level of 10^{-3}
- median cosmic ray energy **20 TeV**
- trace sources ? Magnetic fields ?

cosmic rays anisotropy

arrival direction distribution





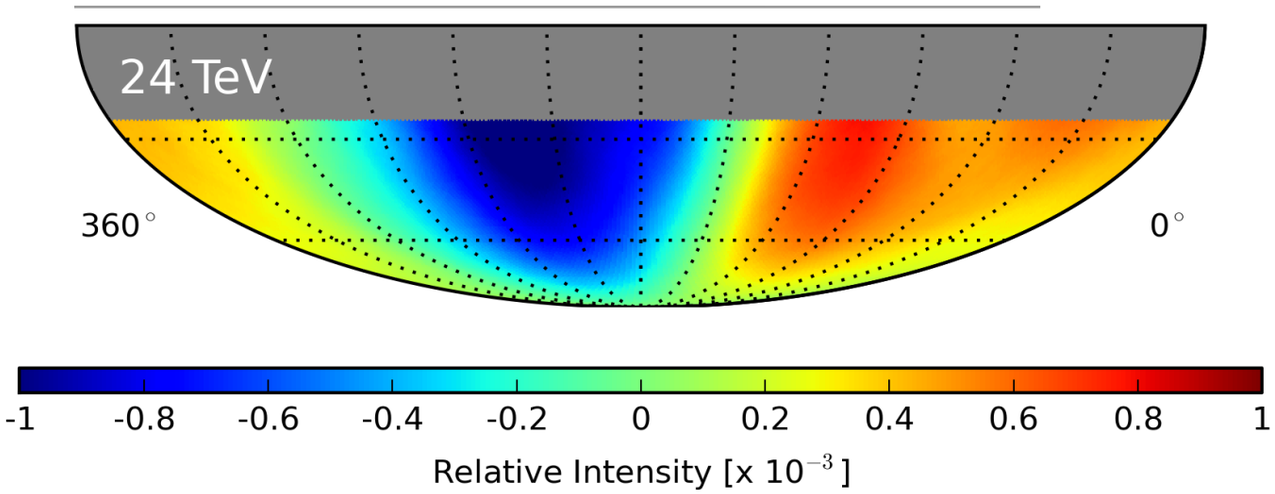


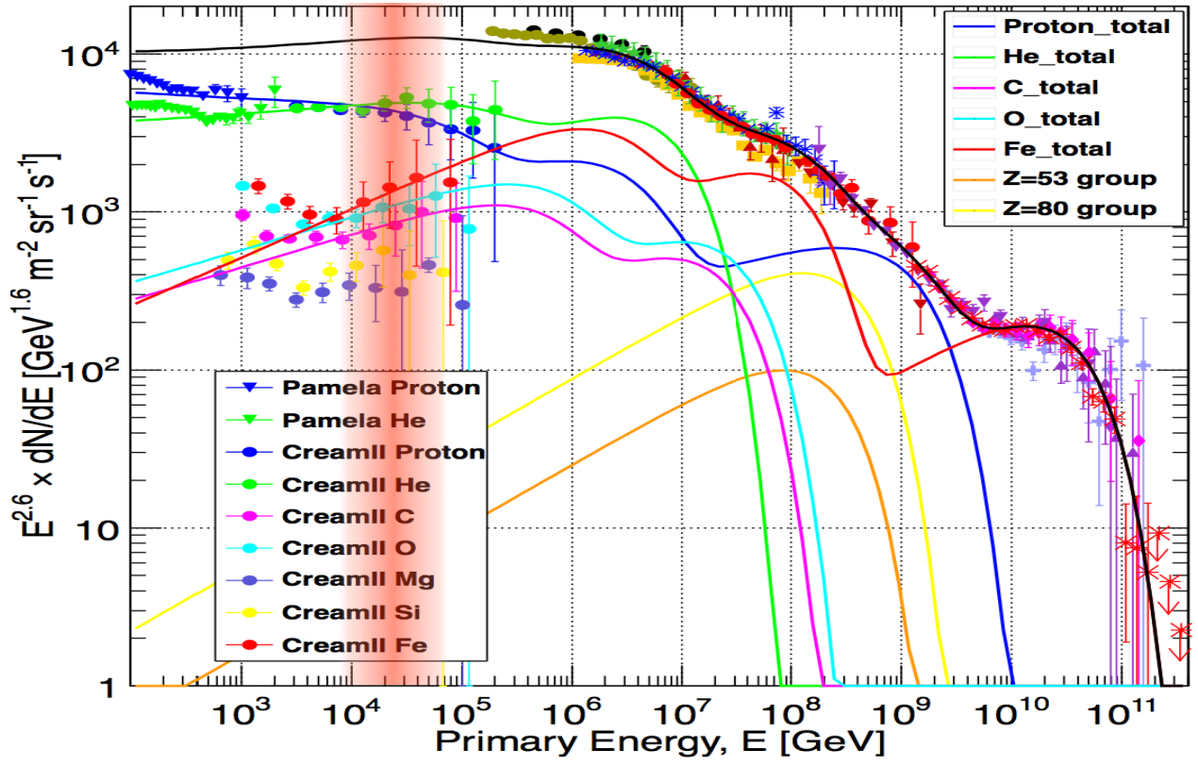
13 TeV

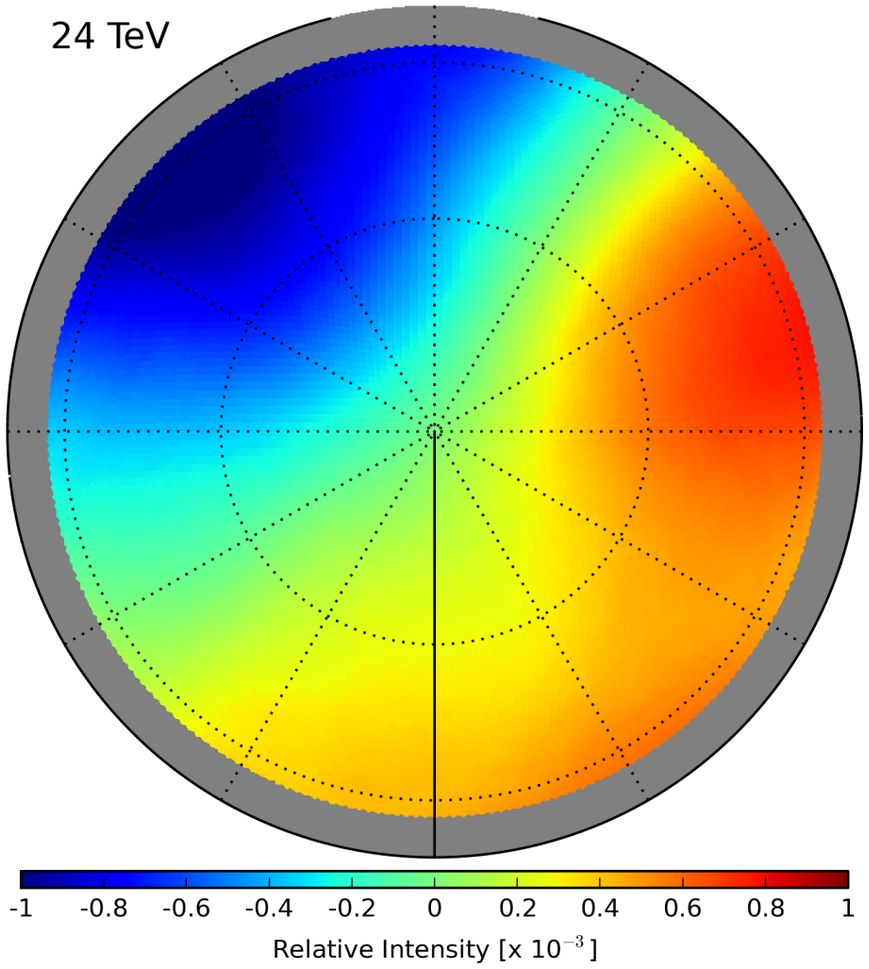
IceCube

cosmic rays anisotropy

arrival direction distribution





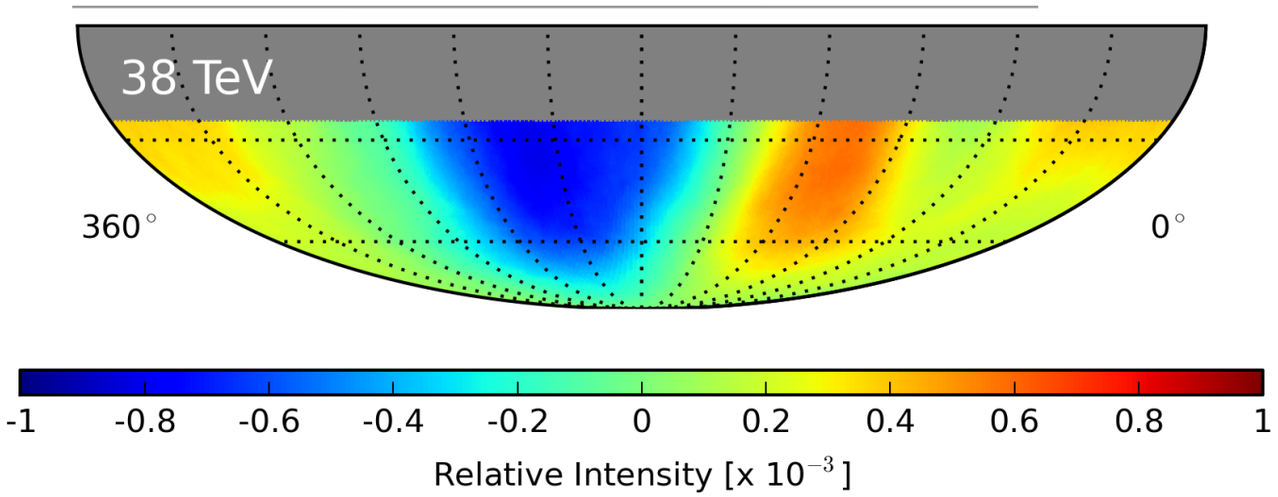


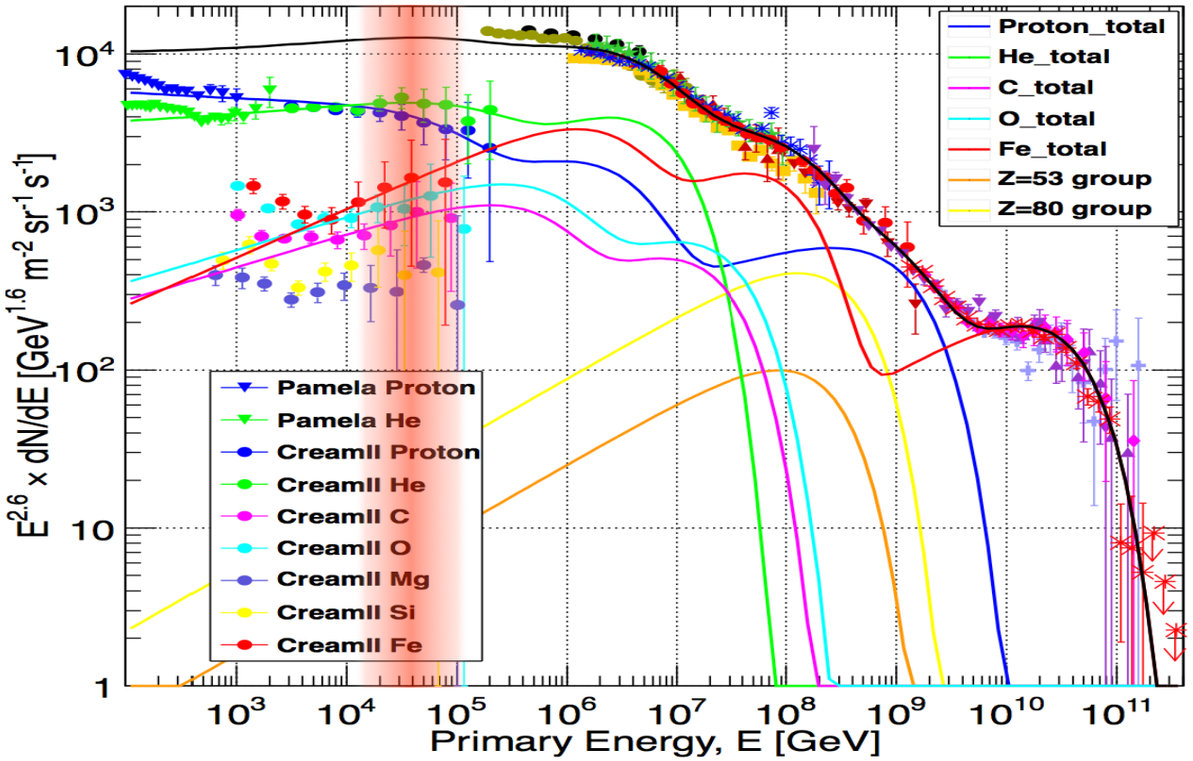
24 TeV

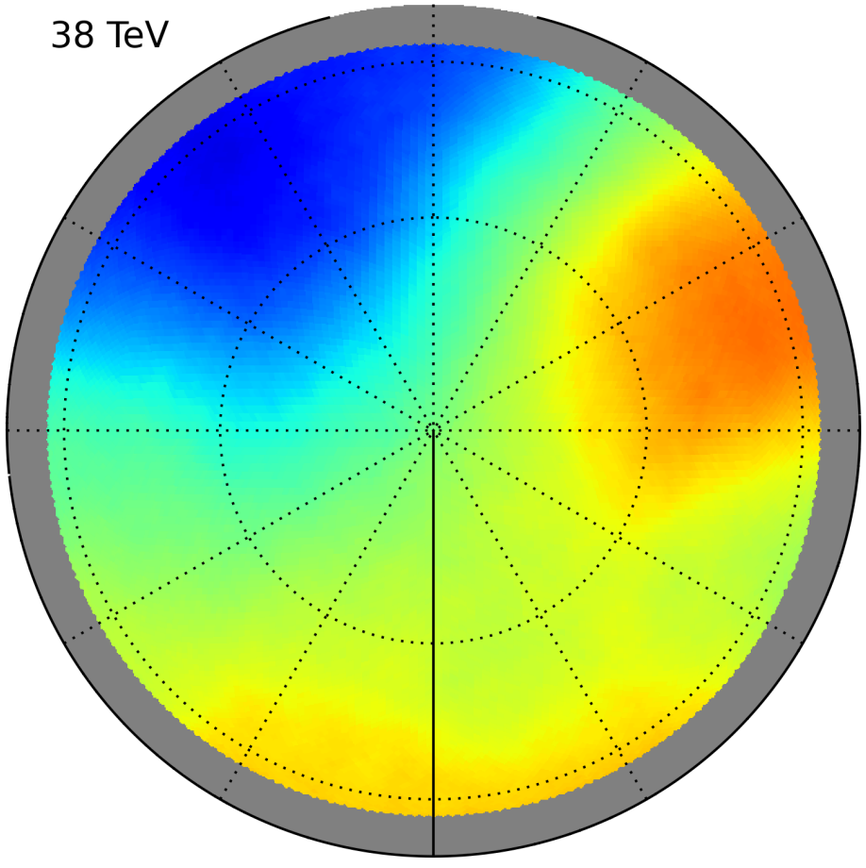
IceCube

cosmic rays anisotropy

arrival direction distribution





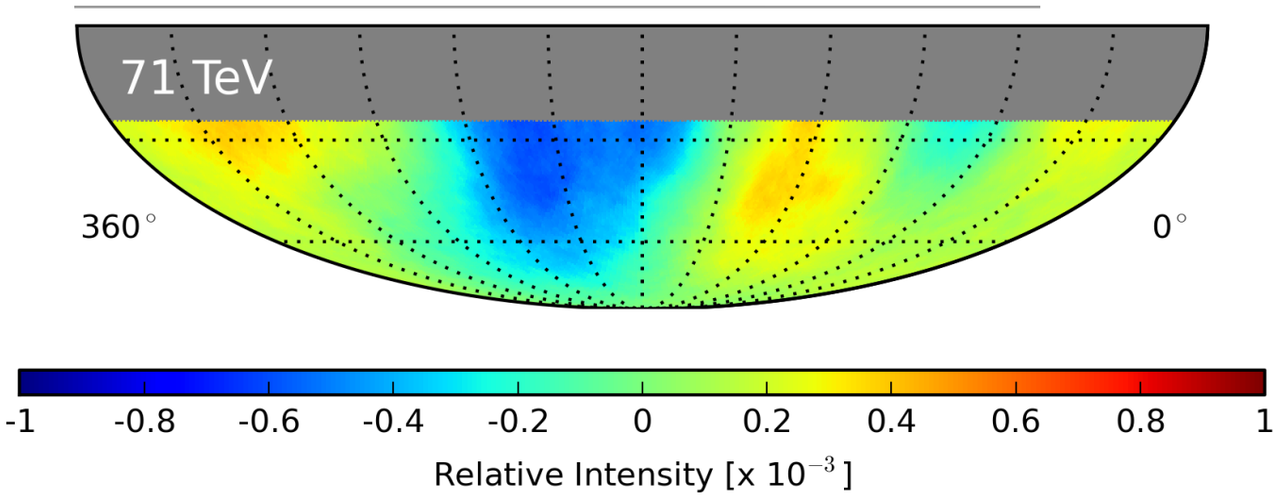


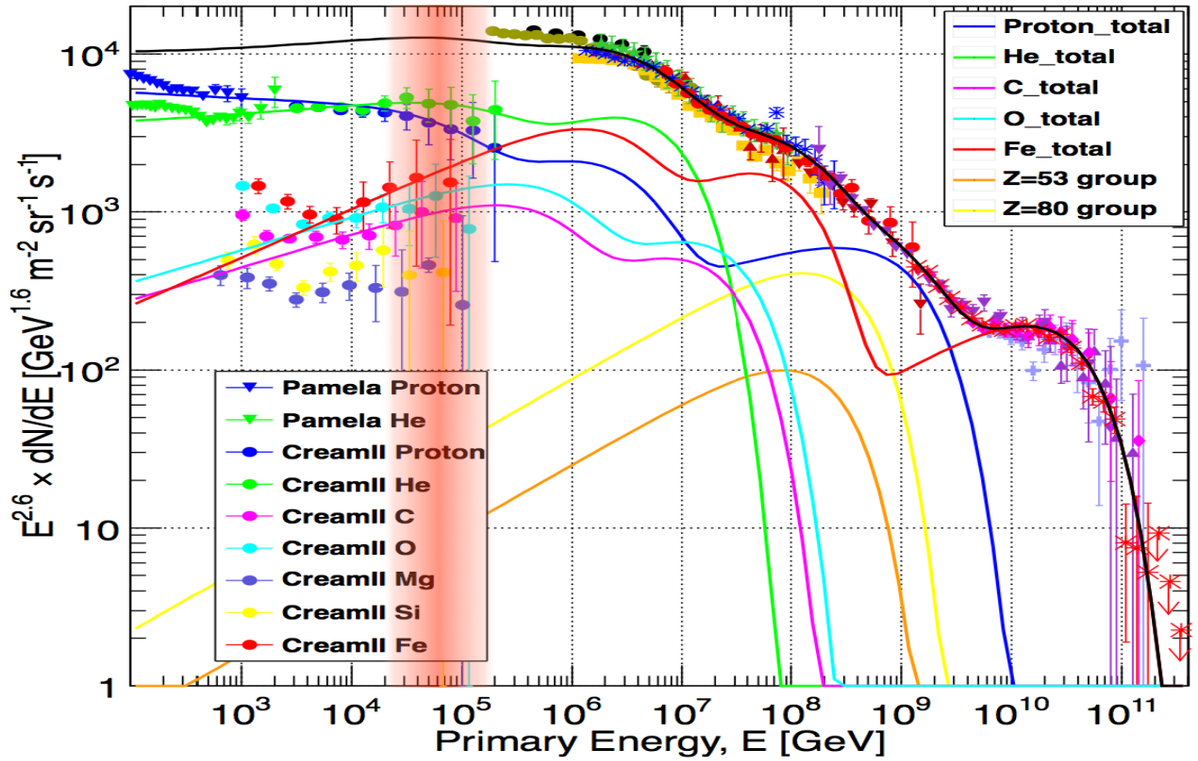
38 TeV

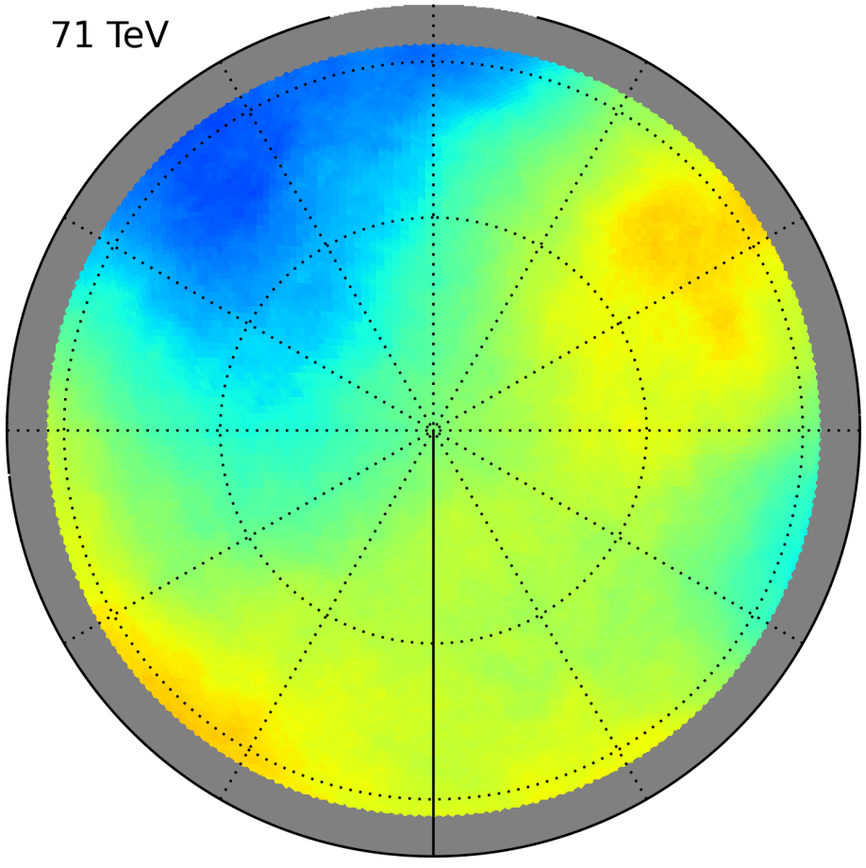
IceCube

cosmic rays anisotropy

arrival direction distribution





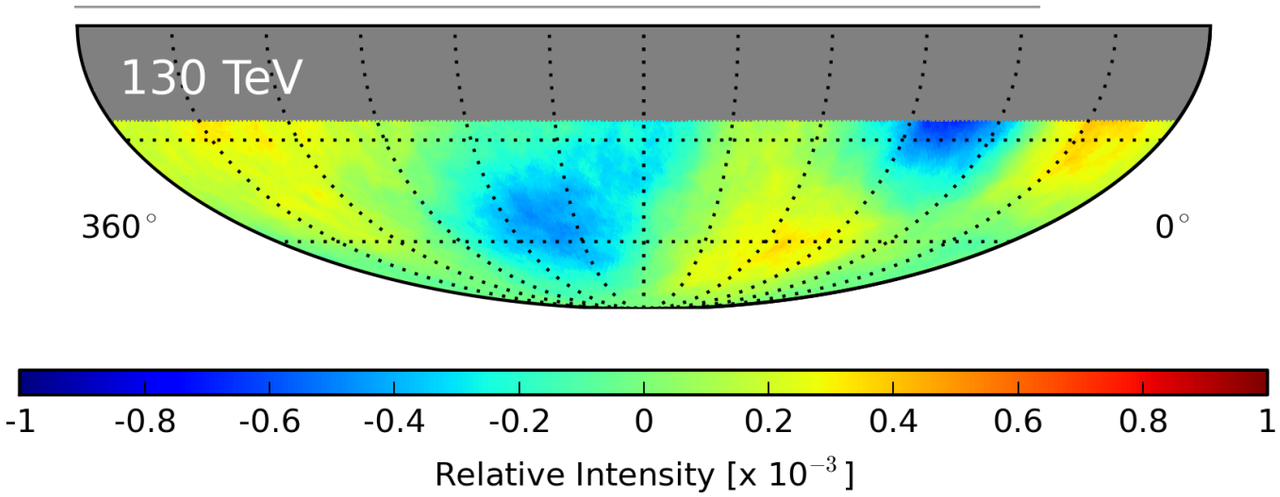


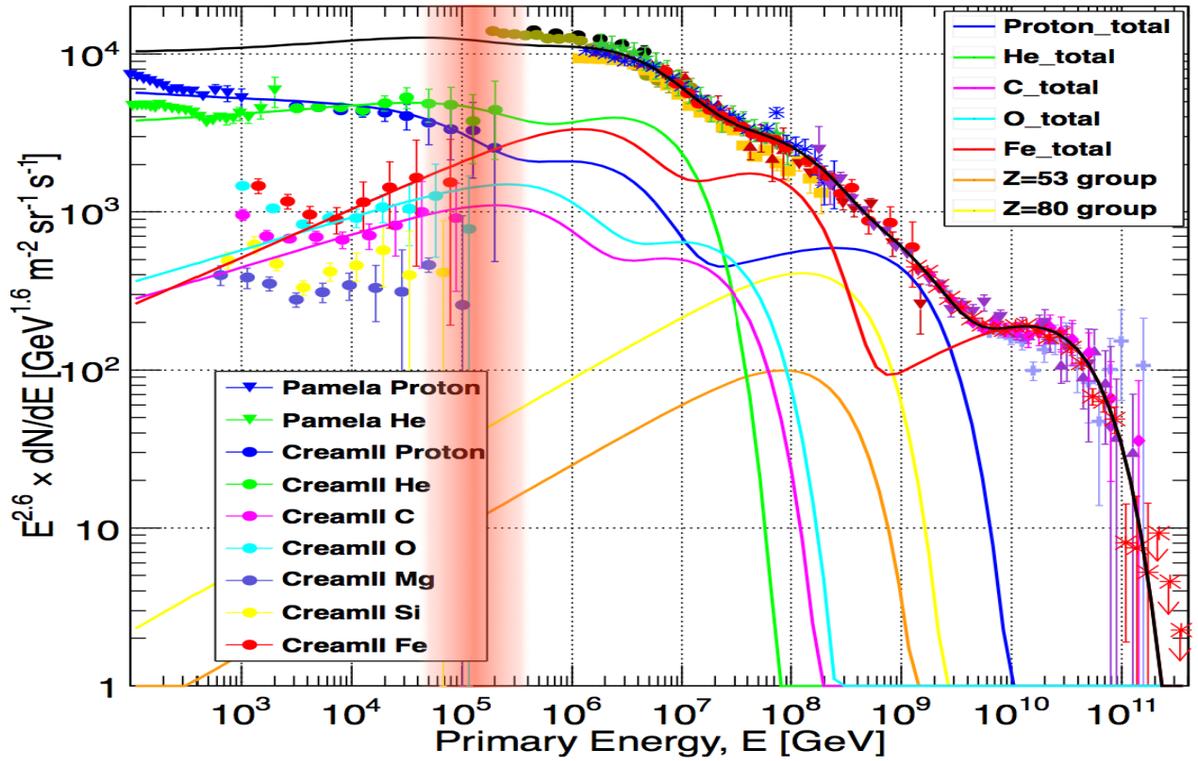
71 TeV

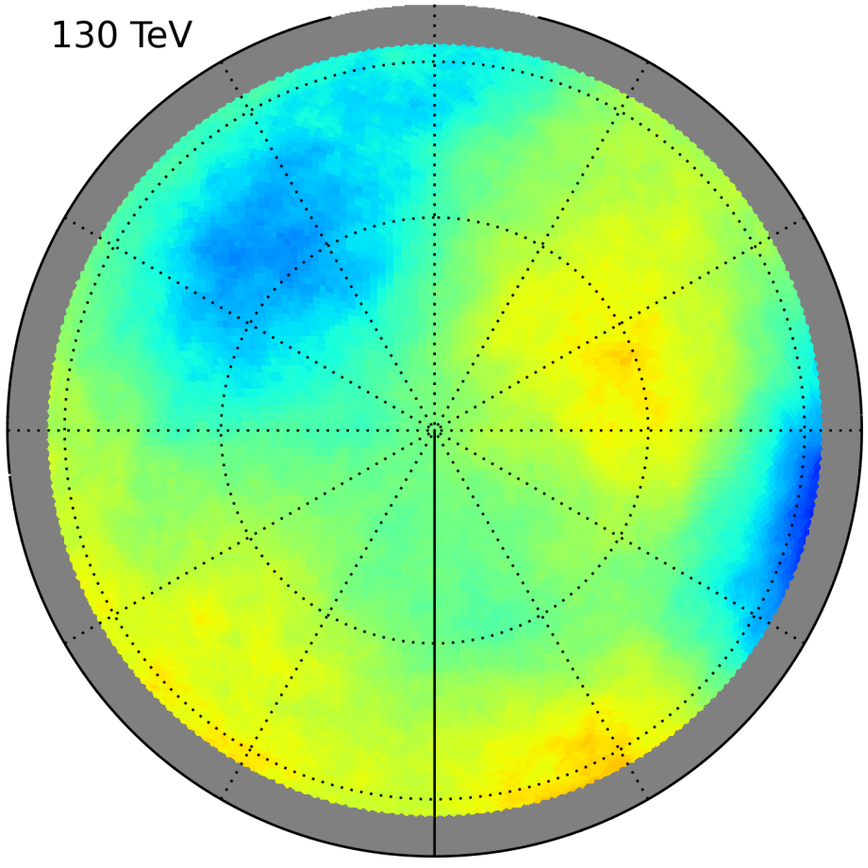
IceCube

cosmic rays anisotropy

arrival direction distribution





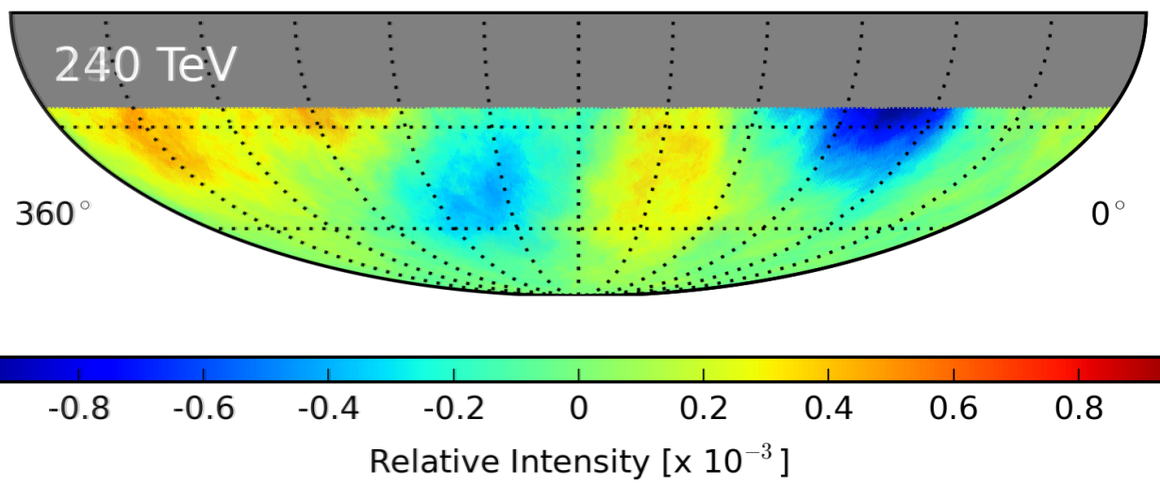


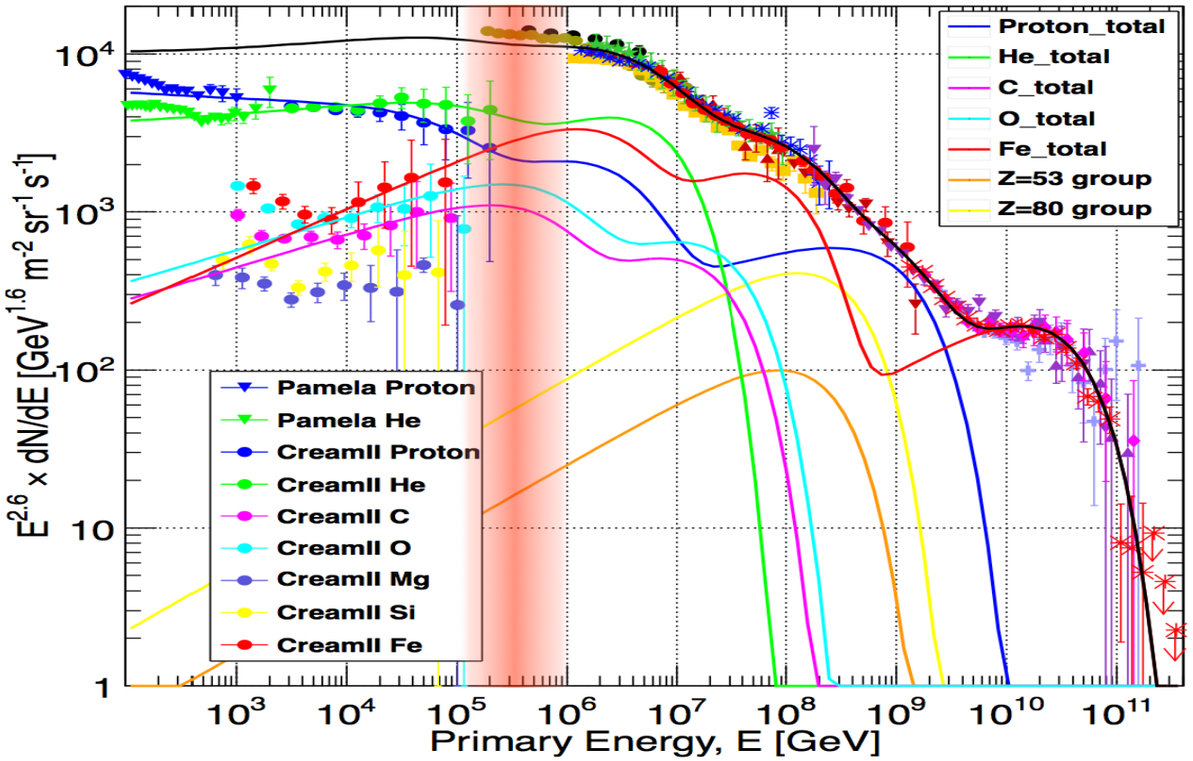
130 TeV

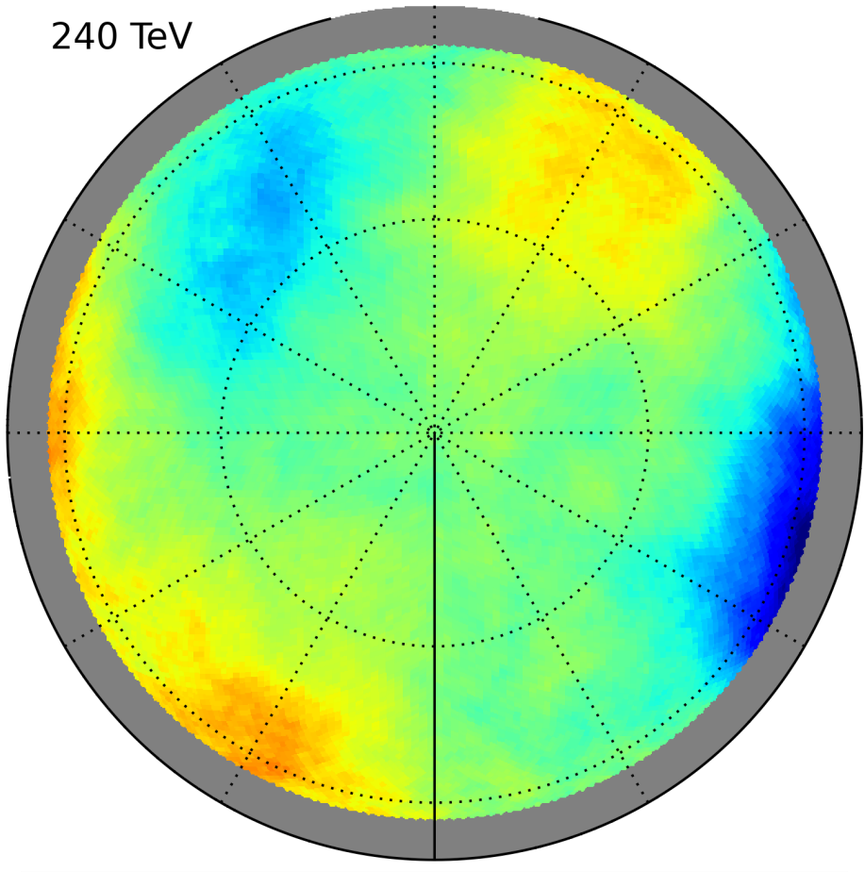
IceCube

cosmic rays anisotropy

arrival direction distribution



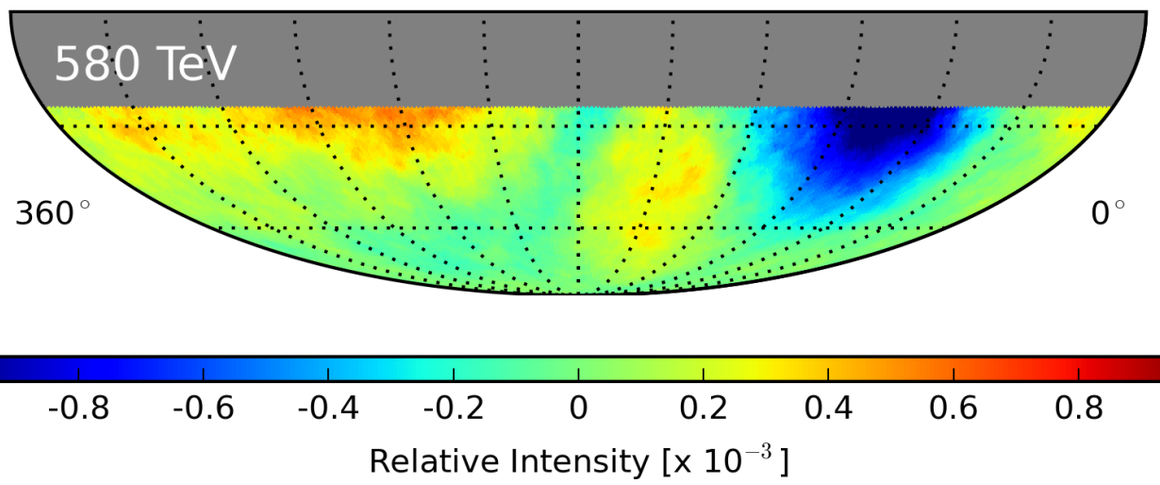


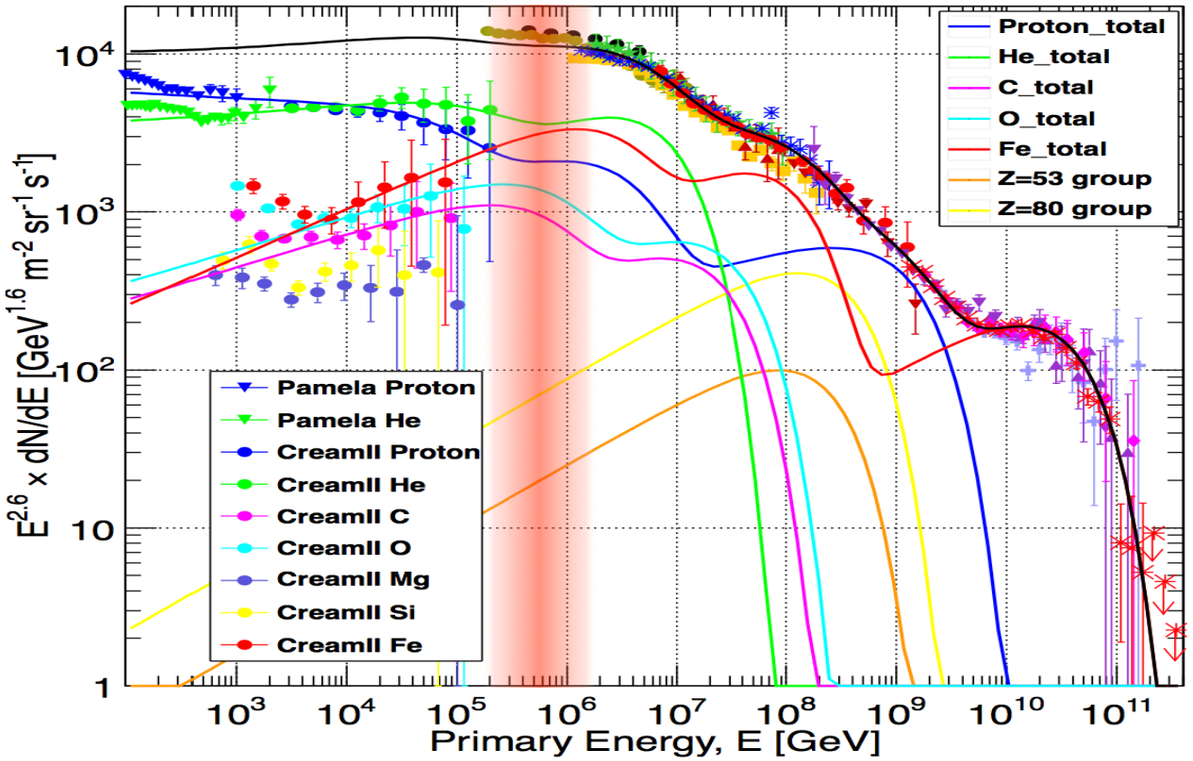


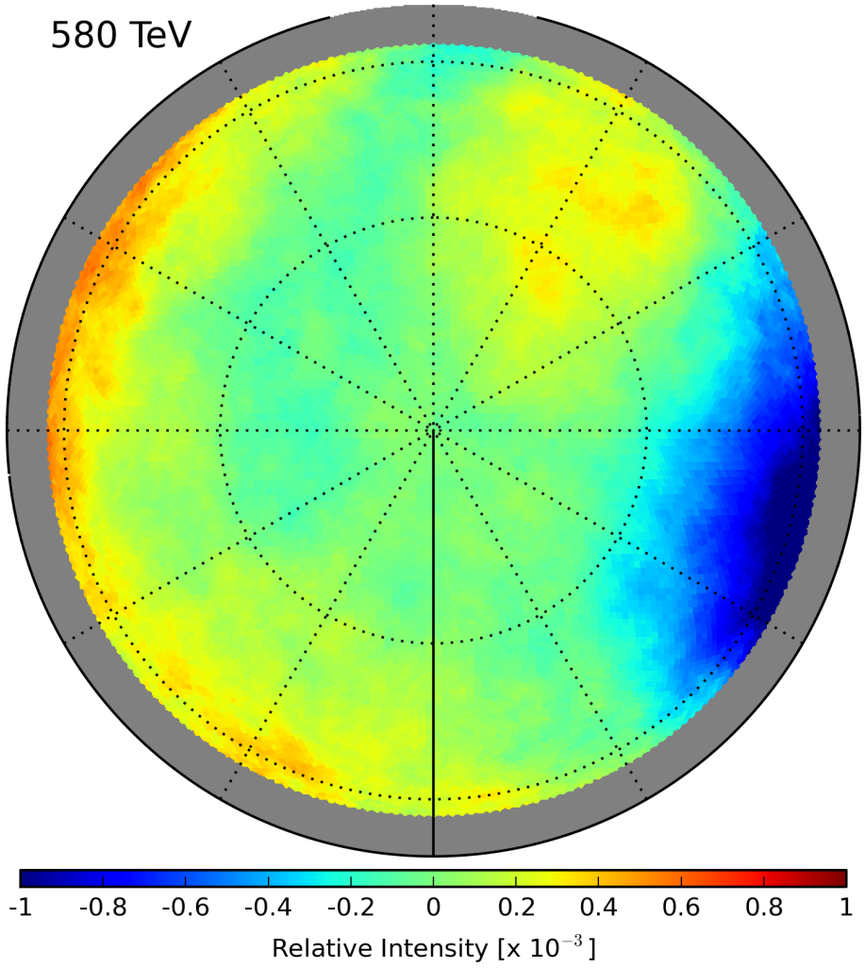
240 TeV **IceCube**

cosmic rays anisotropy

arrival direction distribution



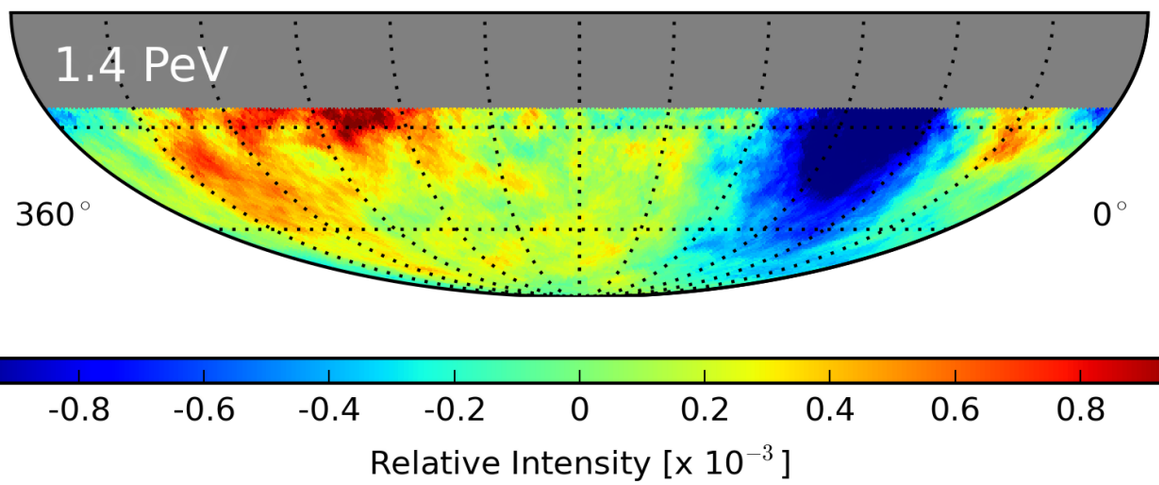


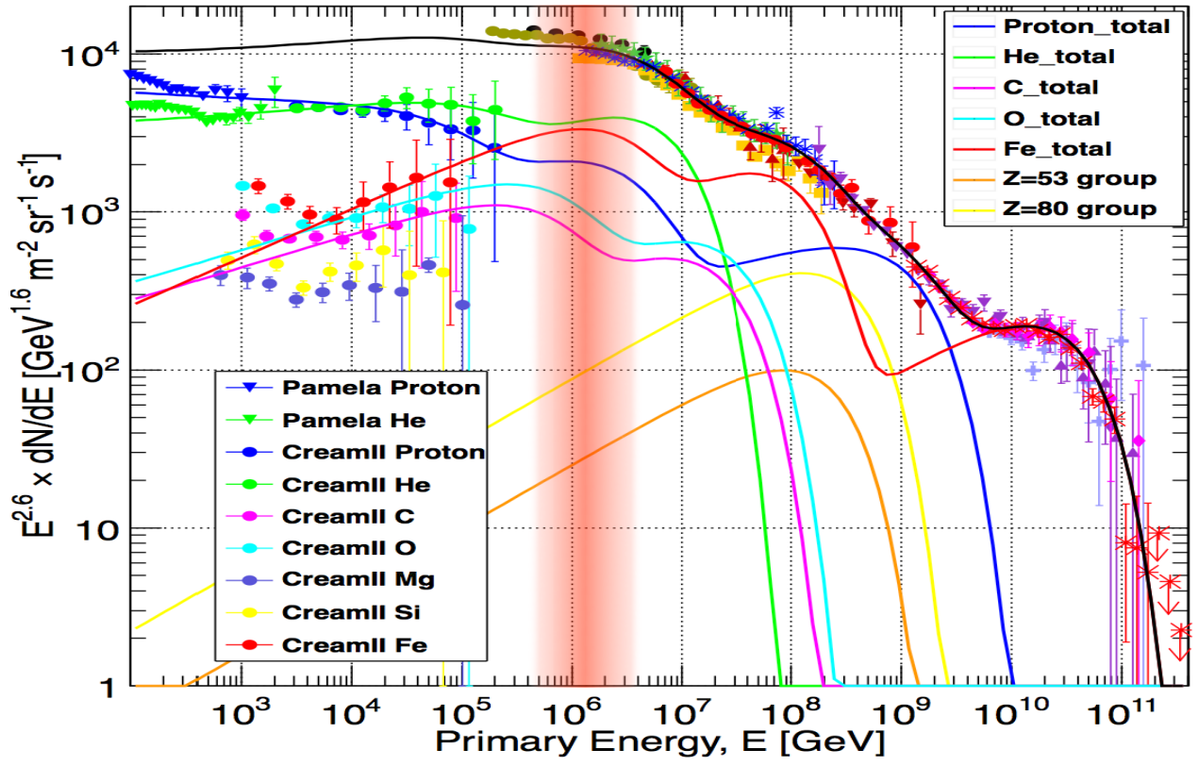


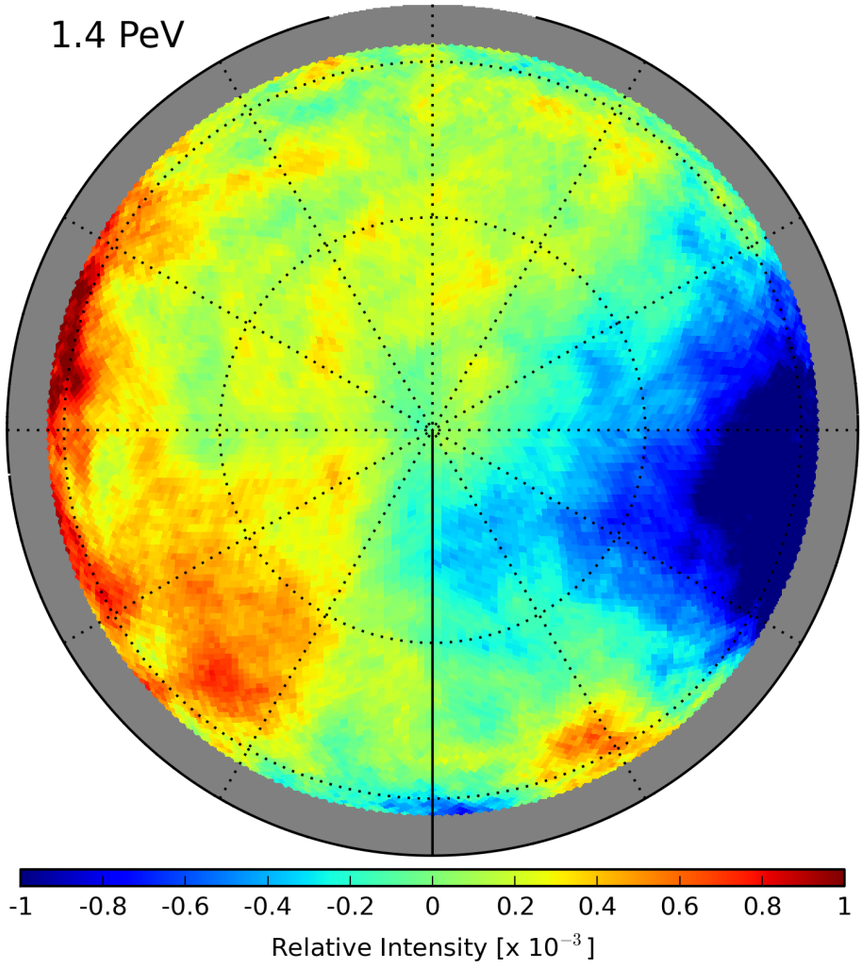
580 TeV **IceCube**

cosmic rays anisotropy

arrival direction distribution





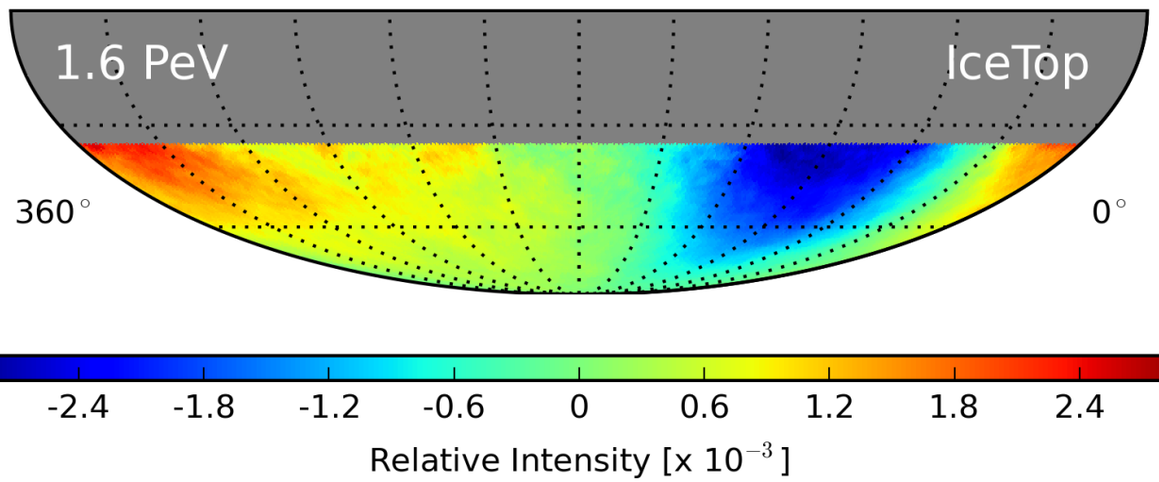


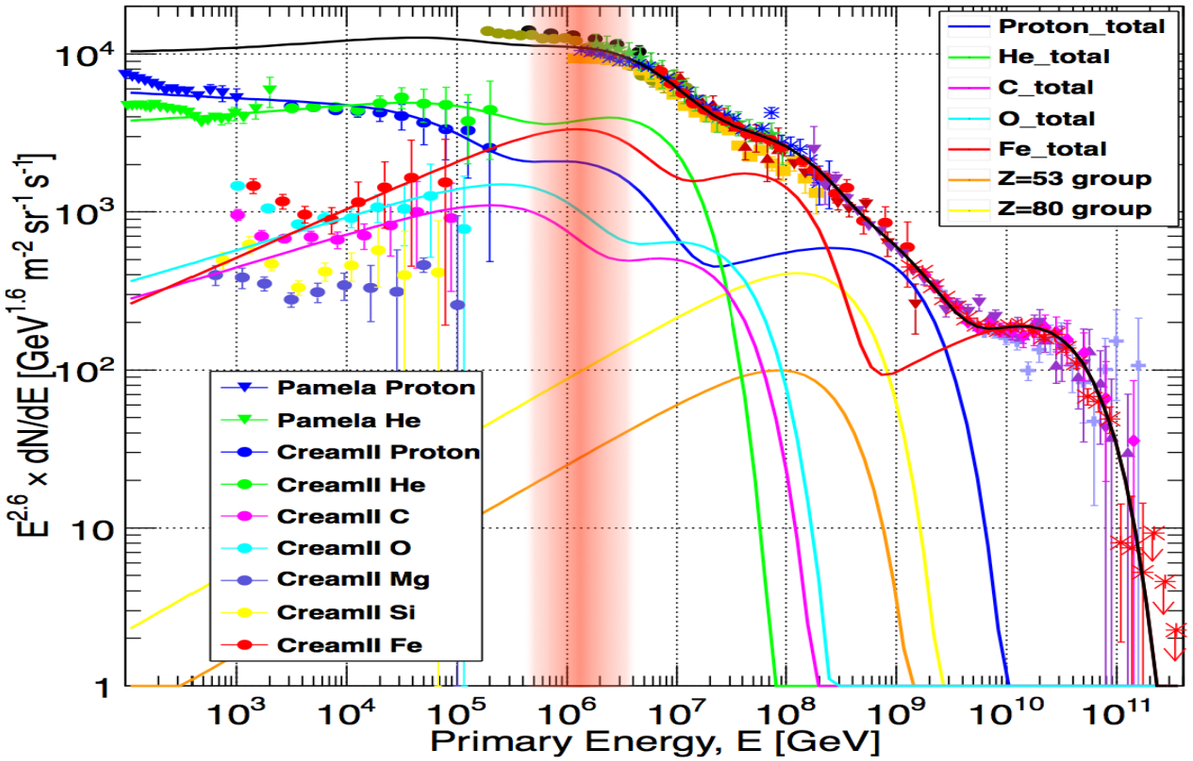
1.4 PeV

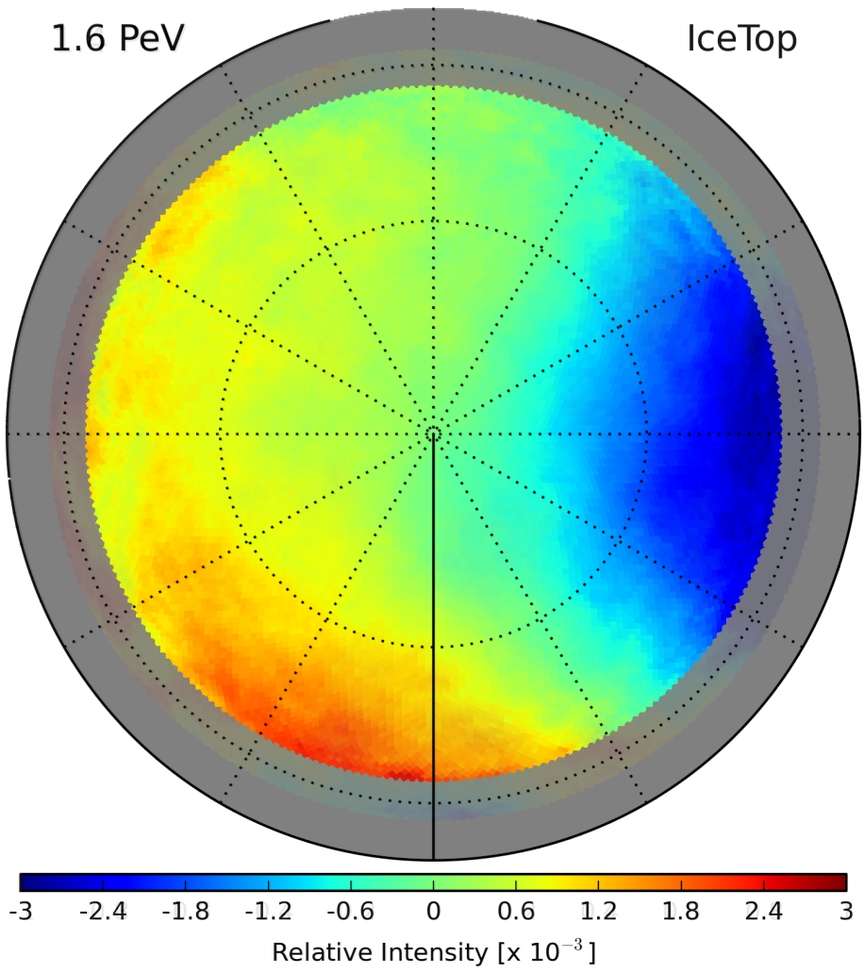
IceCube

cosmic rays anisotropy

arrival direction distribution



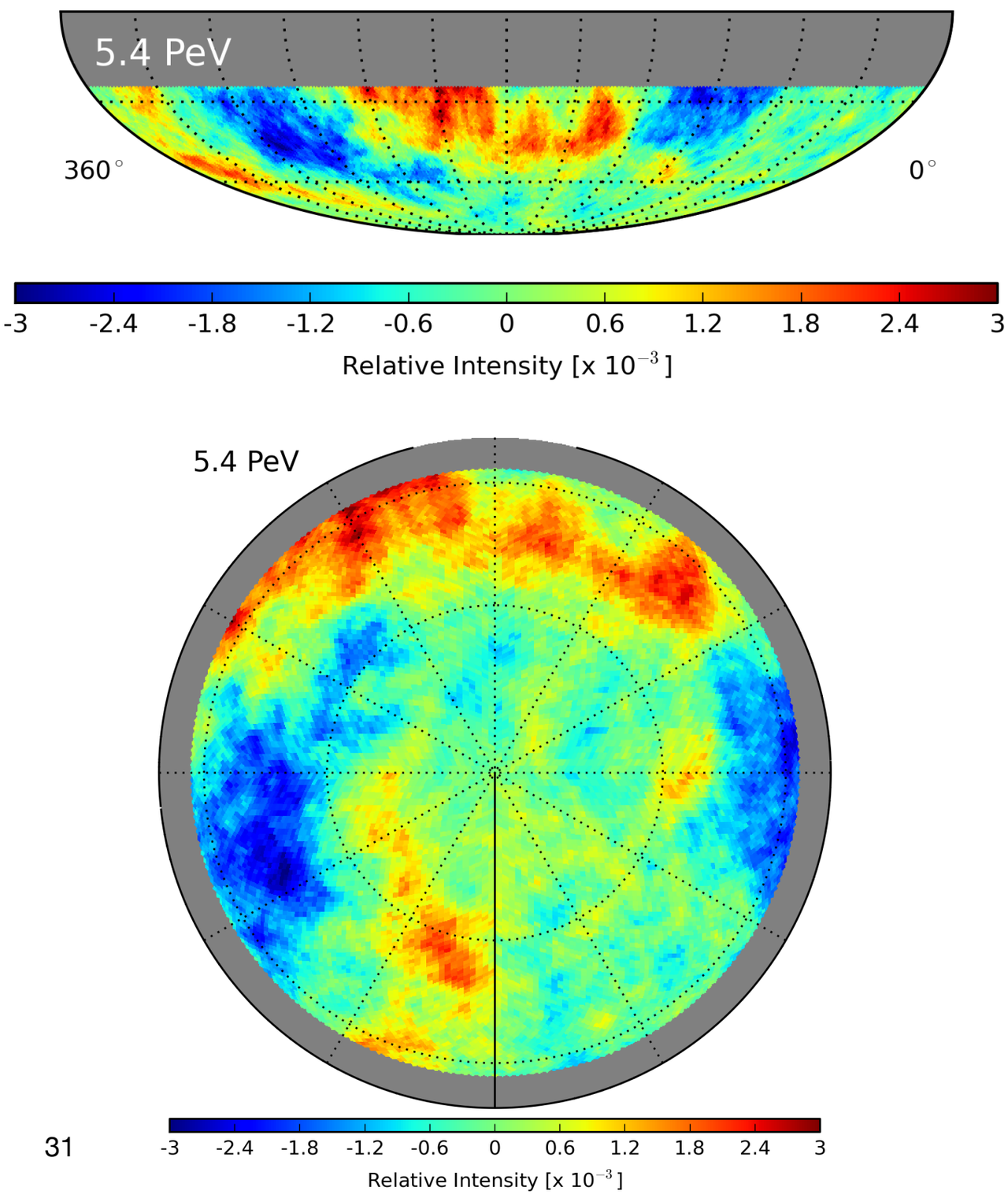


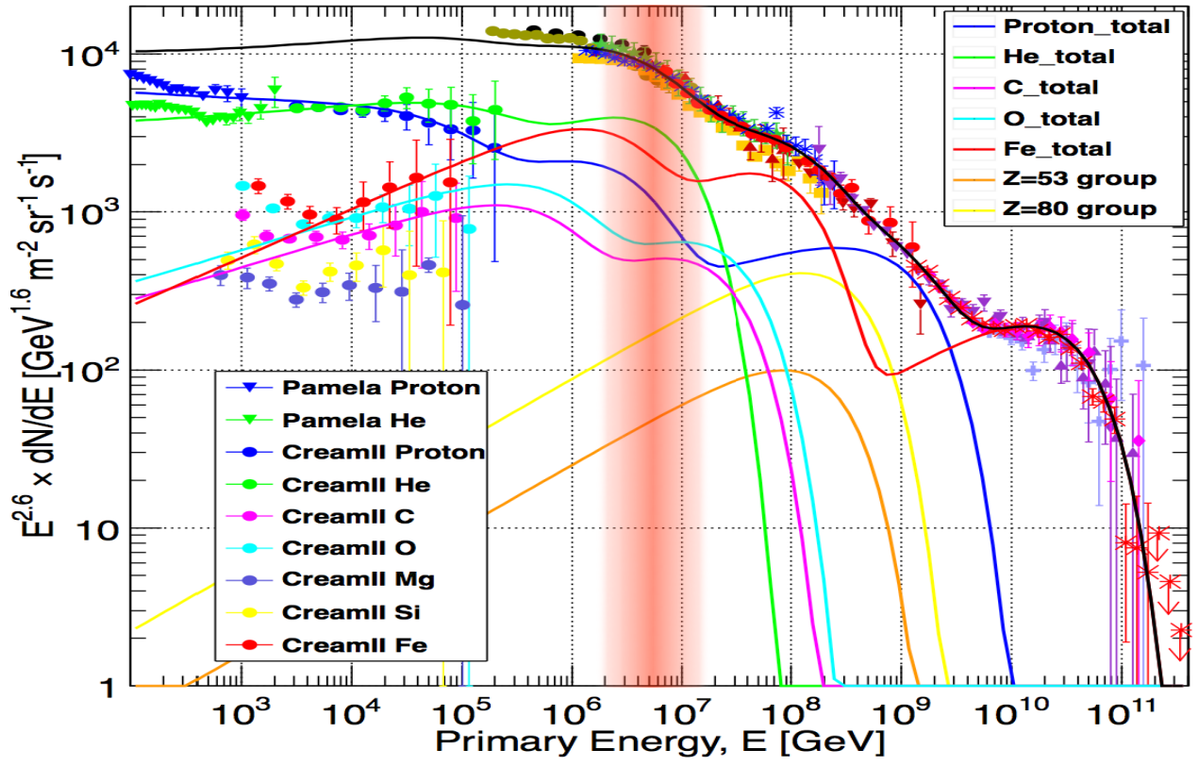


1.6 PeV **IceTop**

cosmic rays anisotropy

arrival direction distribution



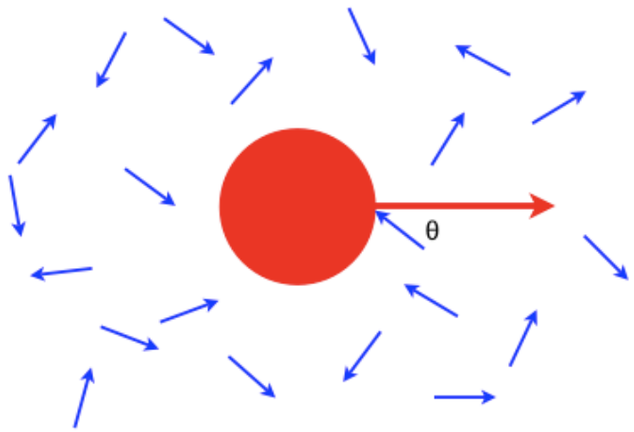


5.4 PeV **IceCube**

a known anisotropy

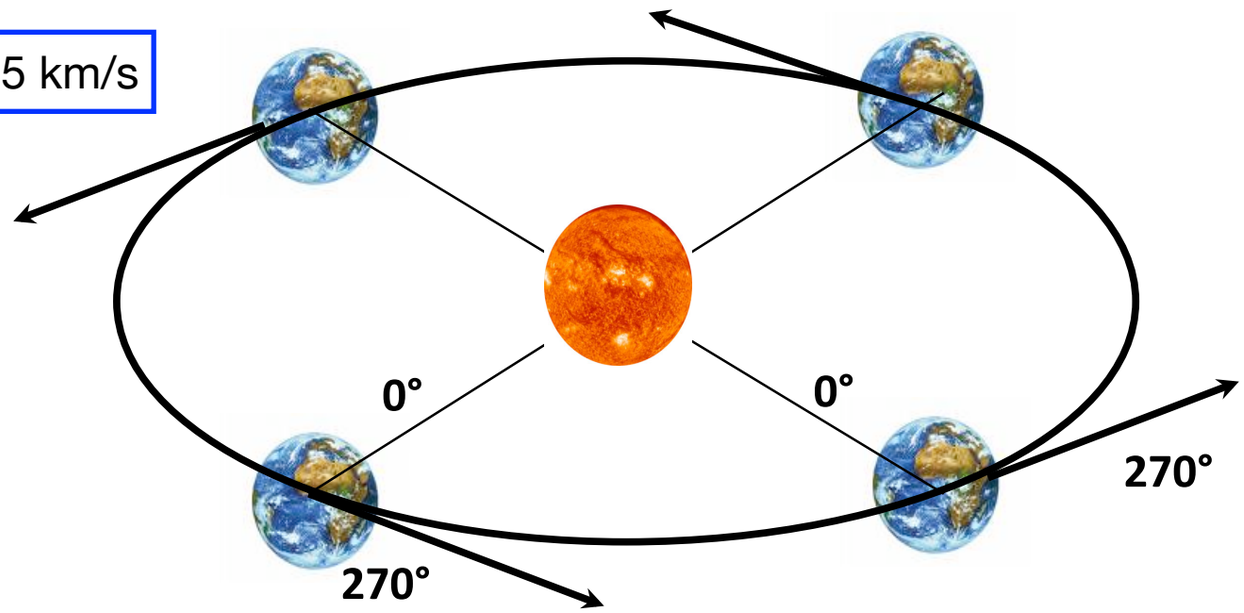
Earth's motion around the Sun

Compton & Getting, Phys. Rev. 47, 817 (1935)
Gleeson, & Axford, Ap&SS, 2, 43 (1968)

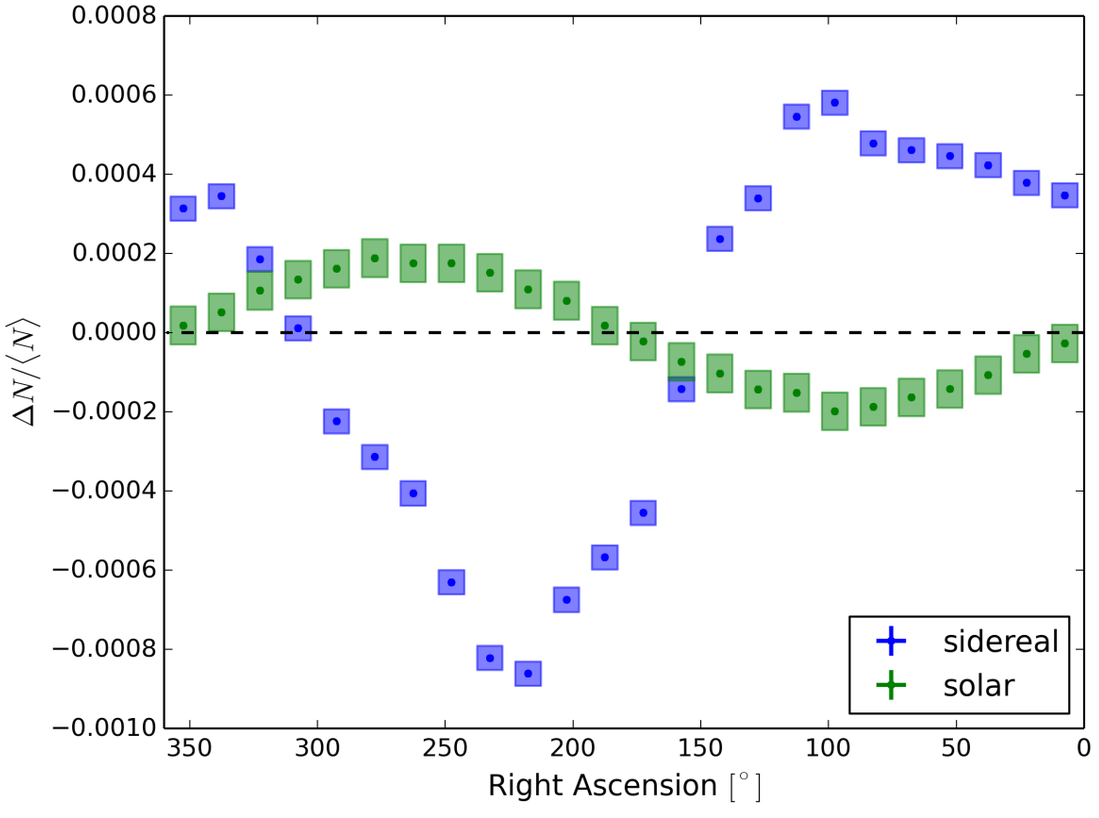


$$\frac{\Delta I}{I} = (\gamma + 2)\frac{v}{c}\cos\theta$$

v = 29.8 ± 0.5 km/s

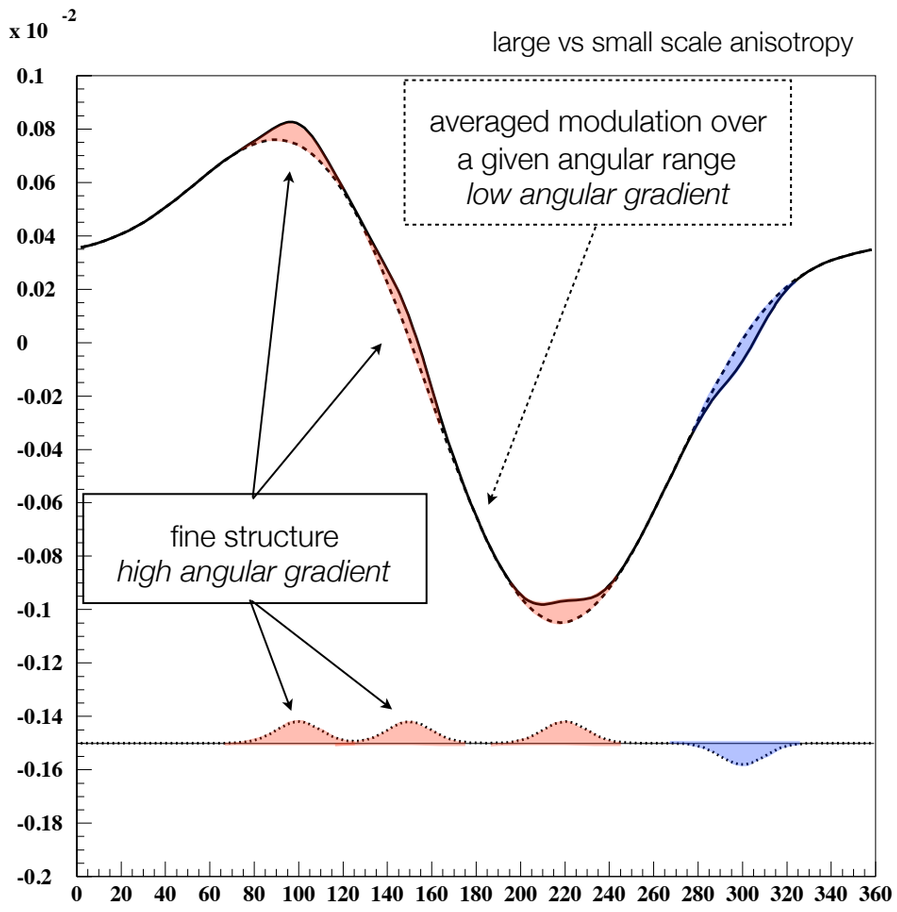


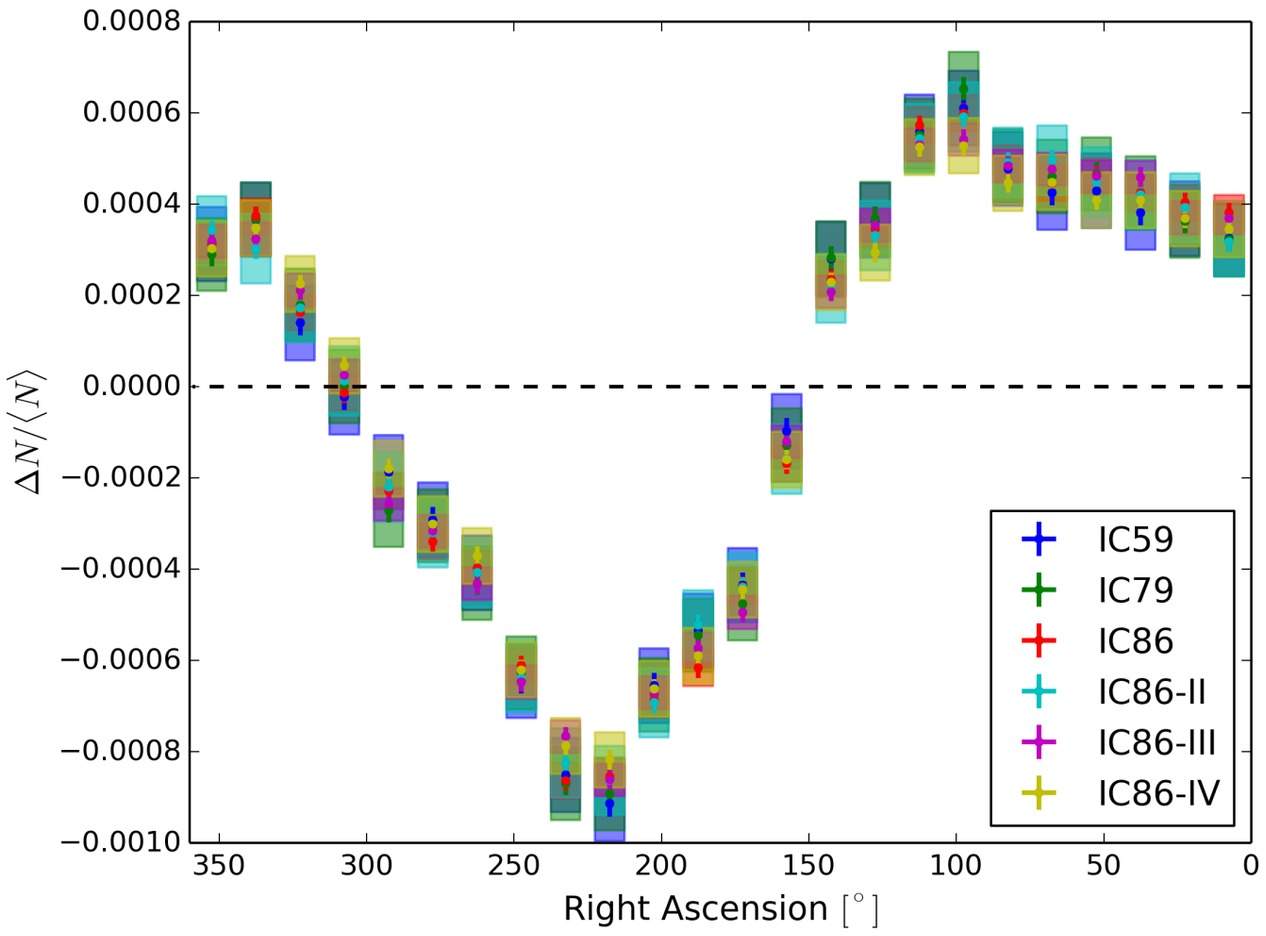
- produced by Earth's revolution around the Sun
- visible as **solar diurnal modulation**
- **predictable** and used as **benchmark**

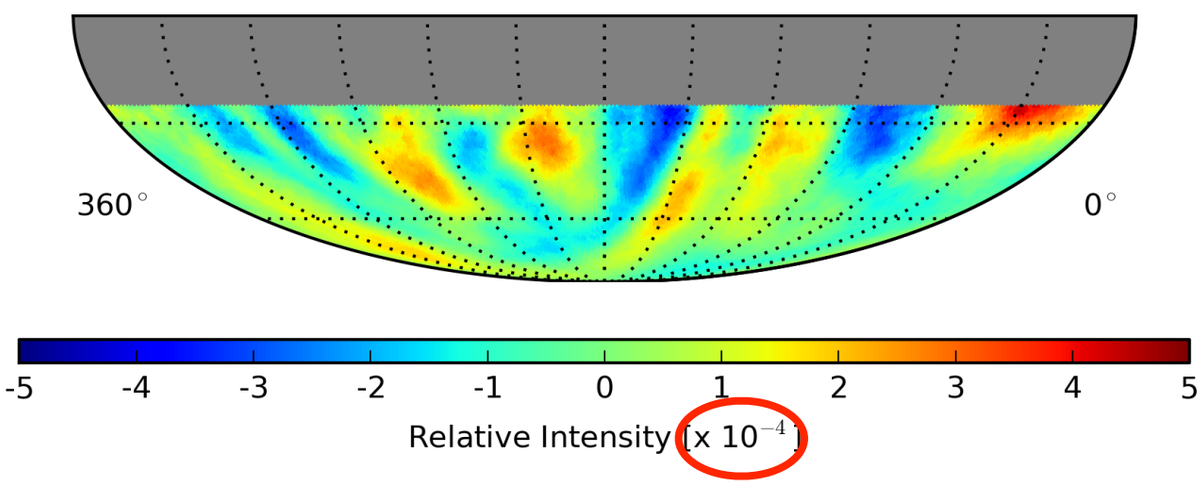


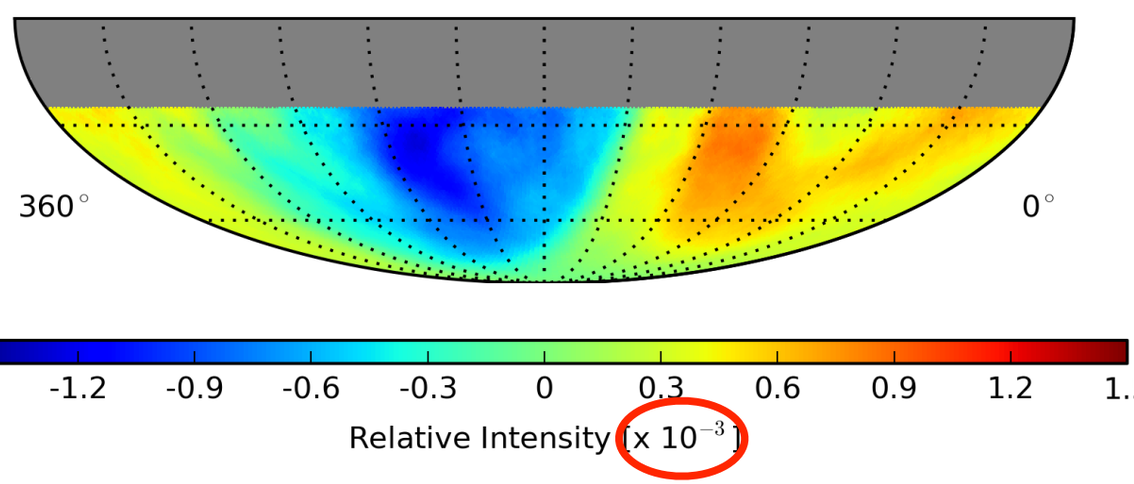
cosmic rays anisotropy

large and small angular scale



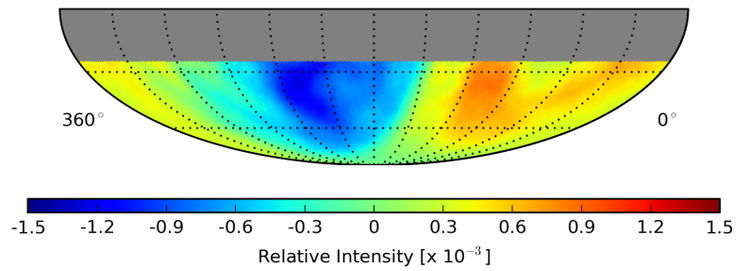


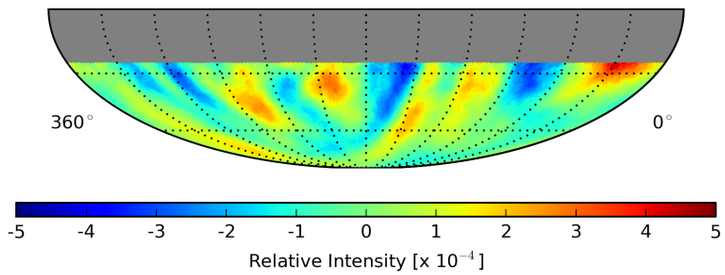


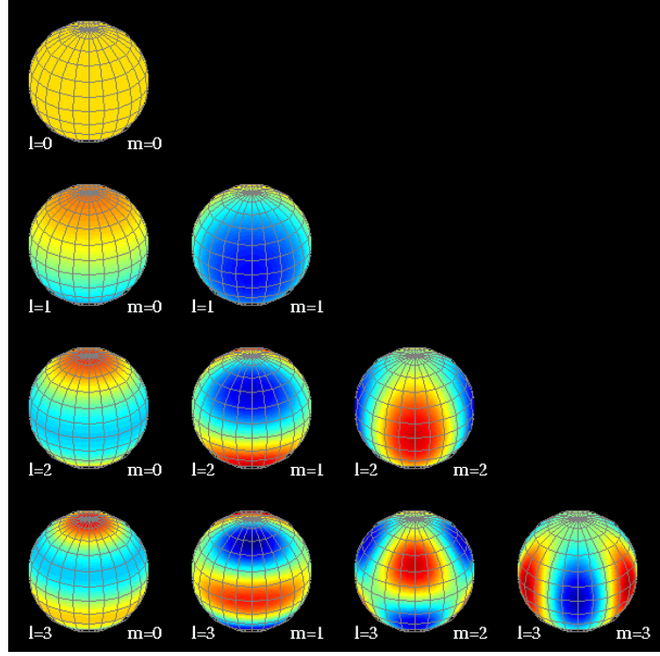


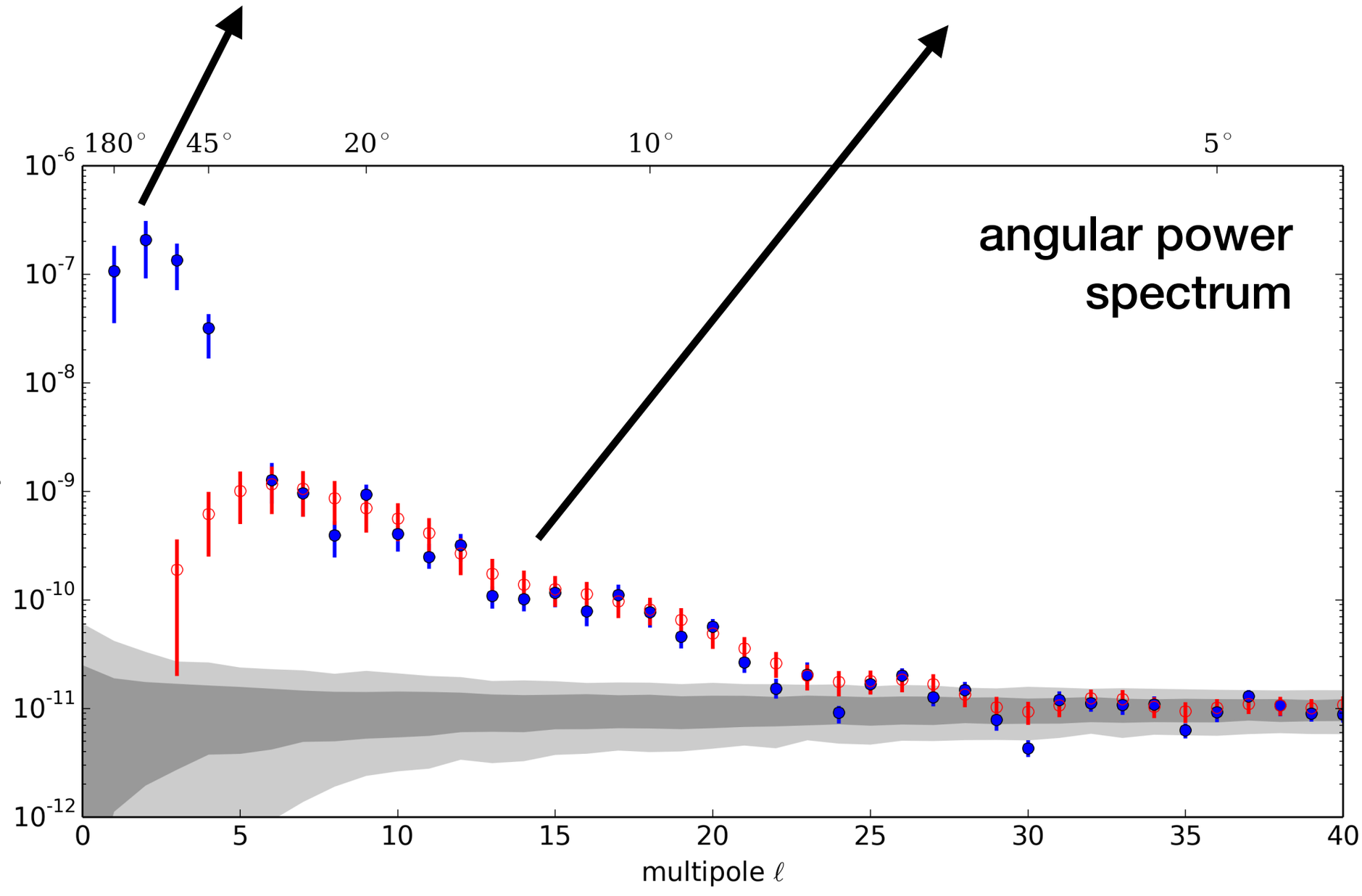
cosmic rays anisotropy

large and small angular scale

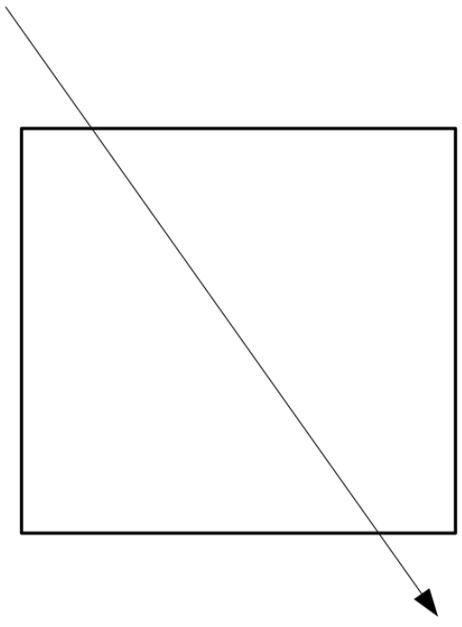
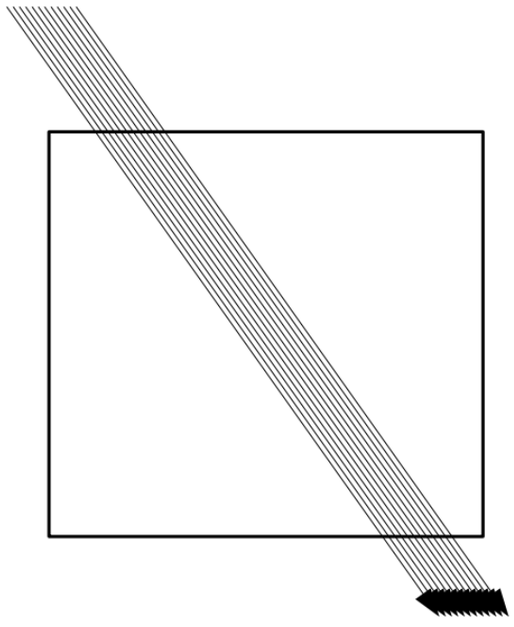
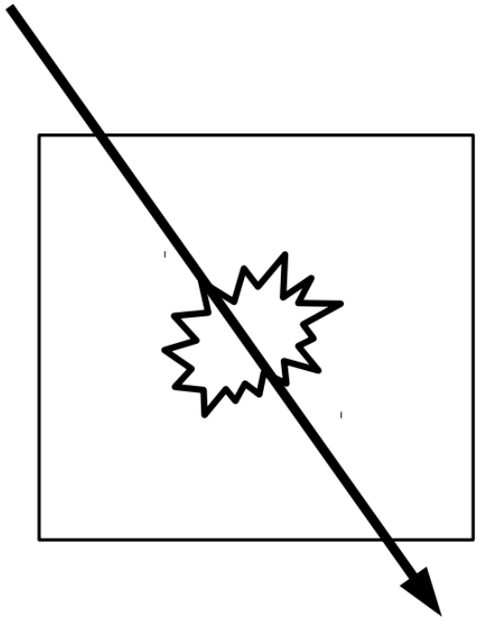


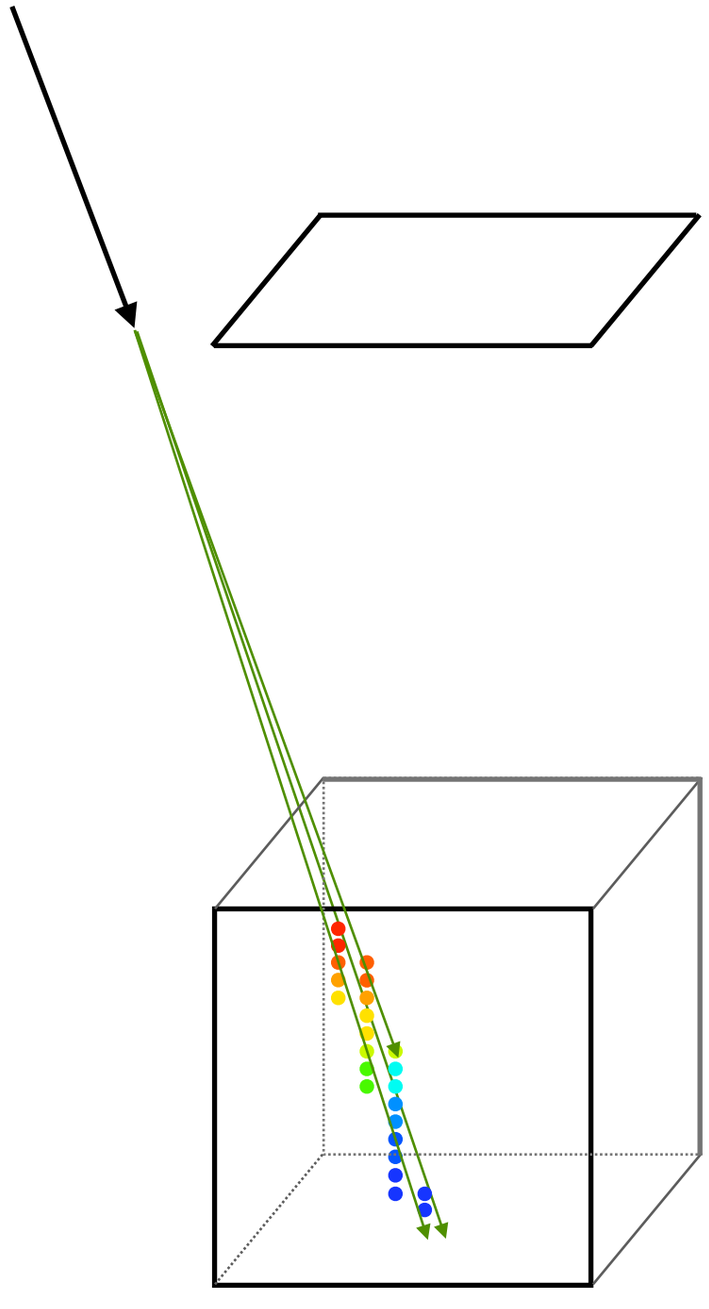




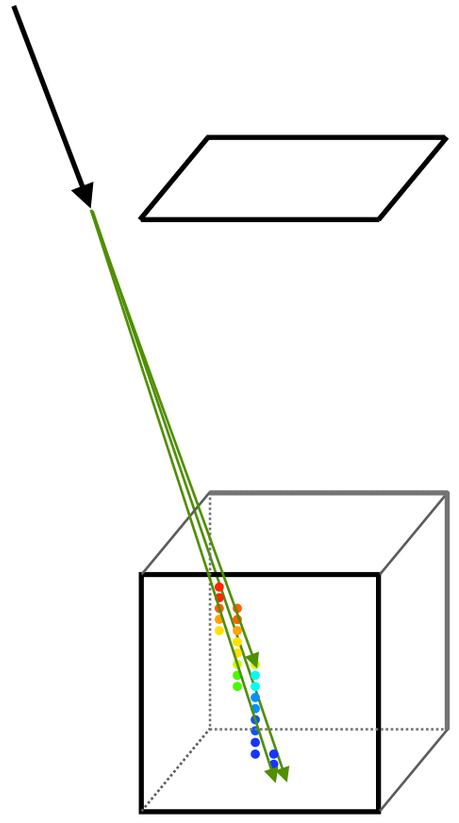


cosmic ray muons
bundle multiplicity

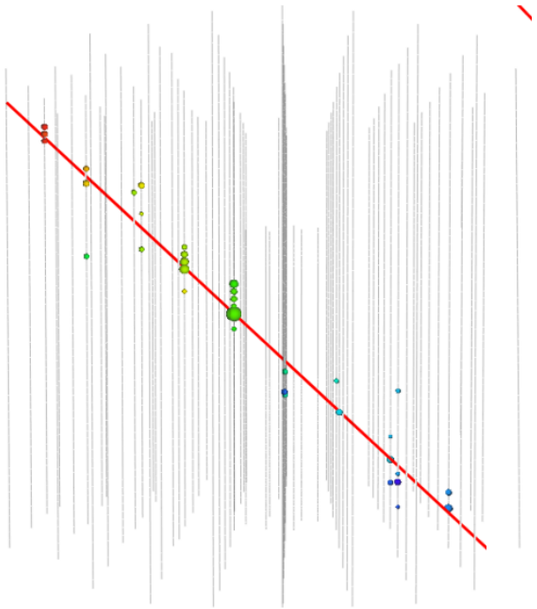
Low-Energy	Bundles	HE Muons
		
1,000/second	1/second	0.1/second
Minimum Ionizing	Minimum Ionizing	Stochastic
Single Muons	20-10,000 Muons	1 HE Muon, 10-100 others
10-100 TeV CR	1 PeV-1 EeV CR	100 TeV-10 PeV CR

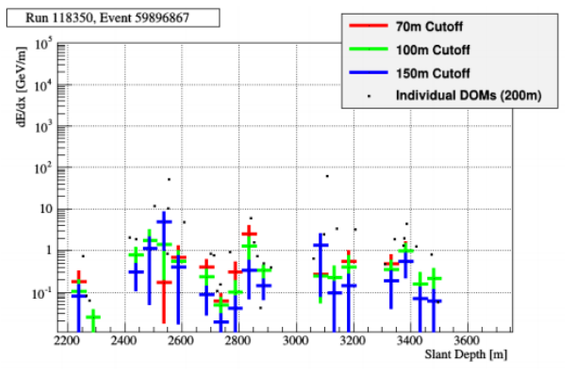


cosmic ray muons
bundle multiplicity



Low-Energy

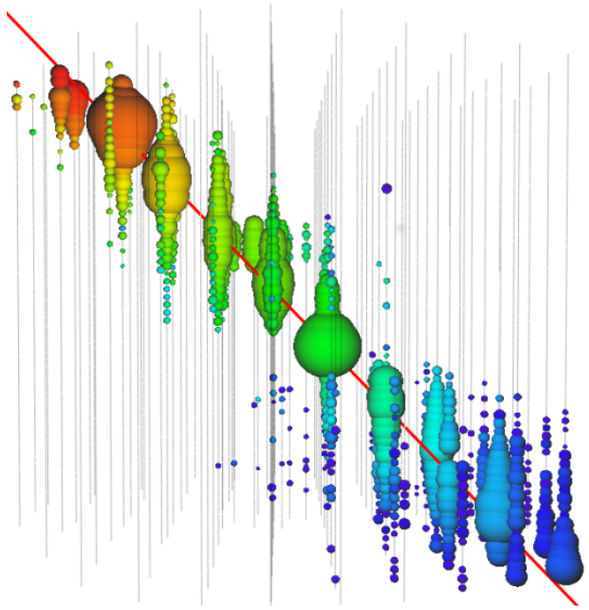


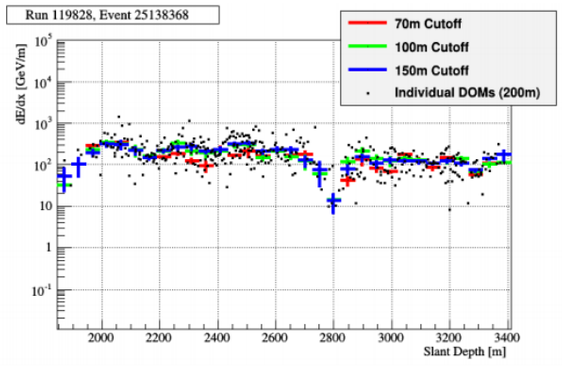


a muon, maybe two

minimum ionizing

Bundles

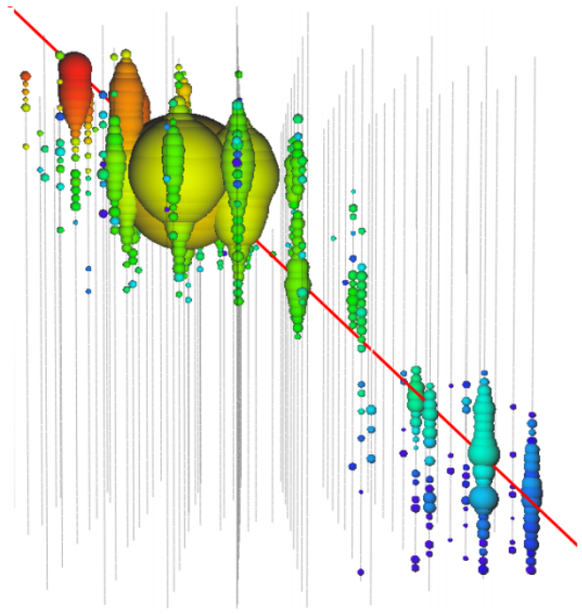


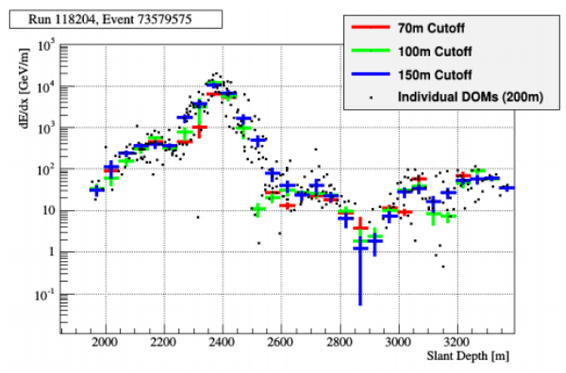


200-310 muons

minimum ionizing

HE Muons





640-1,650 TeV

stochastic energy losses

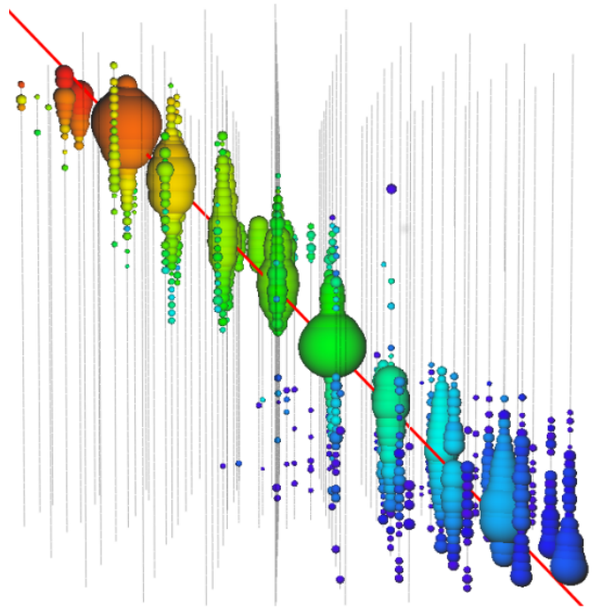
cosmic ray muons

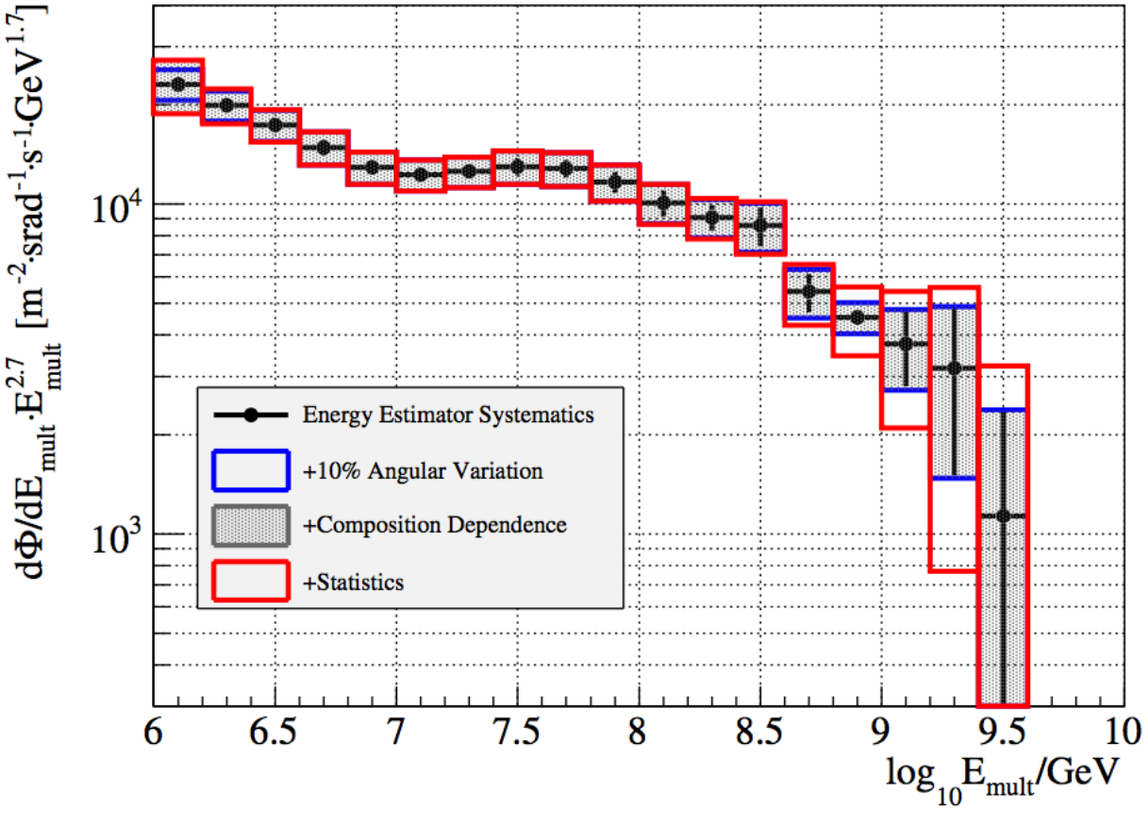
multiple muon spectrum

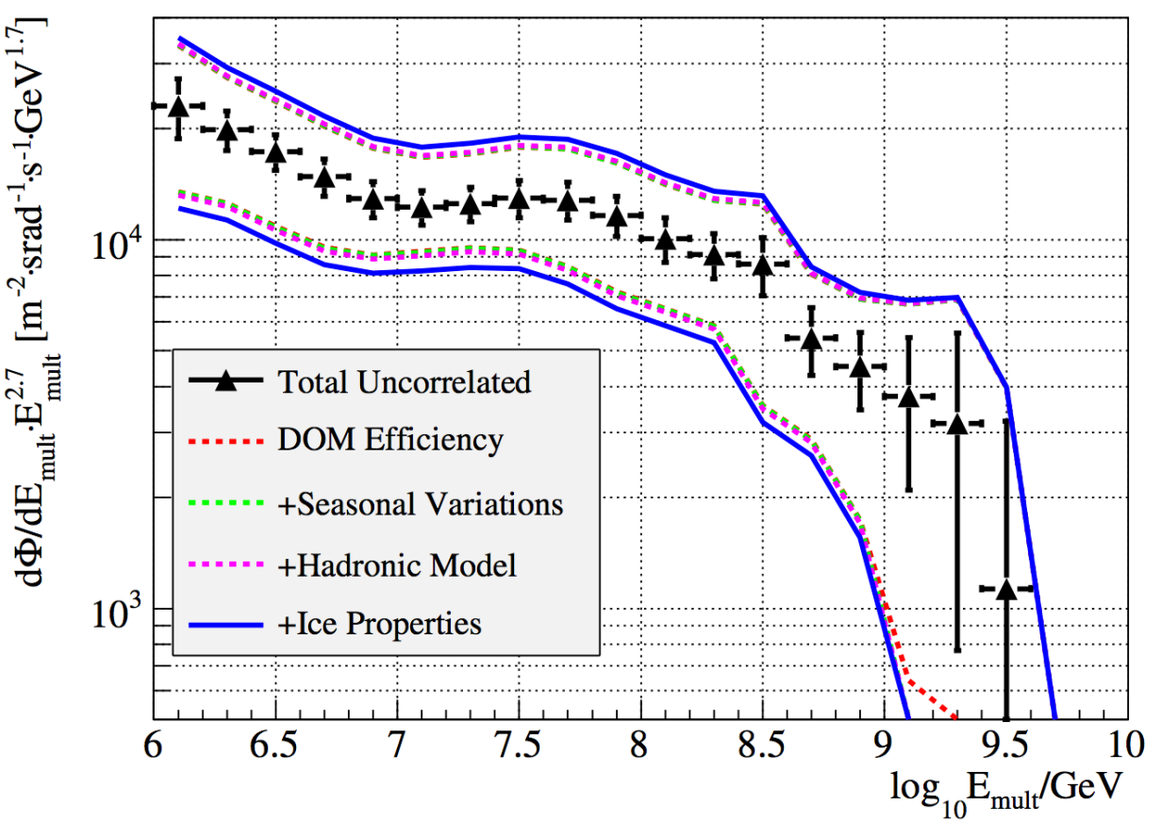
$$\sum E_\mu \propto N_\mu \propto E_{\text{prim}}^{\alpha} \cdot A^{1-\alpha}$$

$$E_{\text{mult}} \equiv E_{\text{prim}} \cdot (A/56)^{\frac{1-\alpha}{\alpha}}$$

Bundles



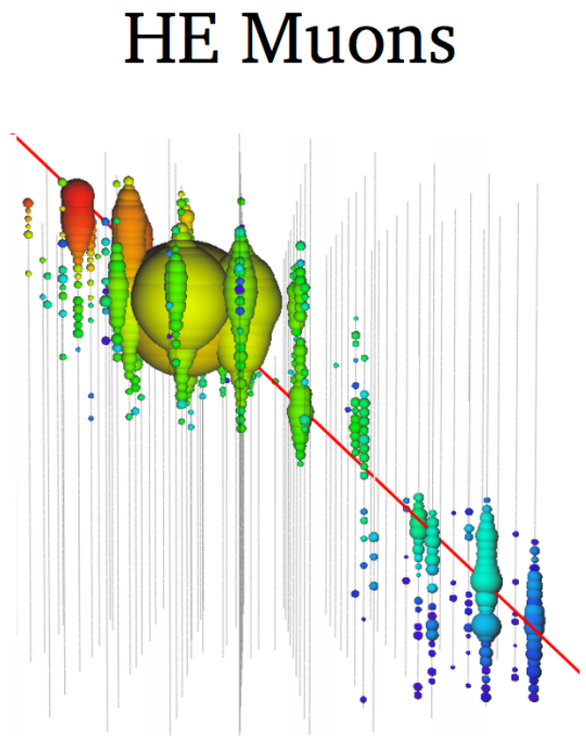


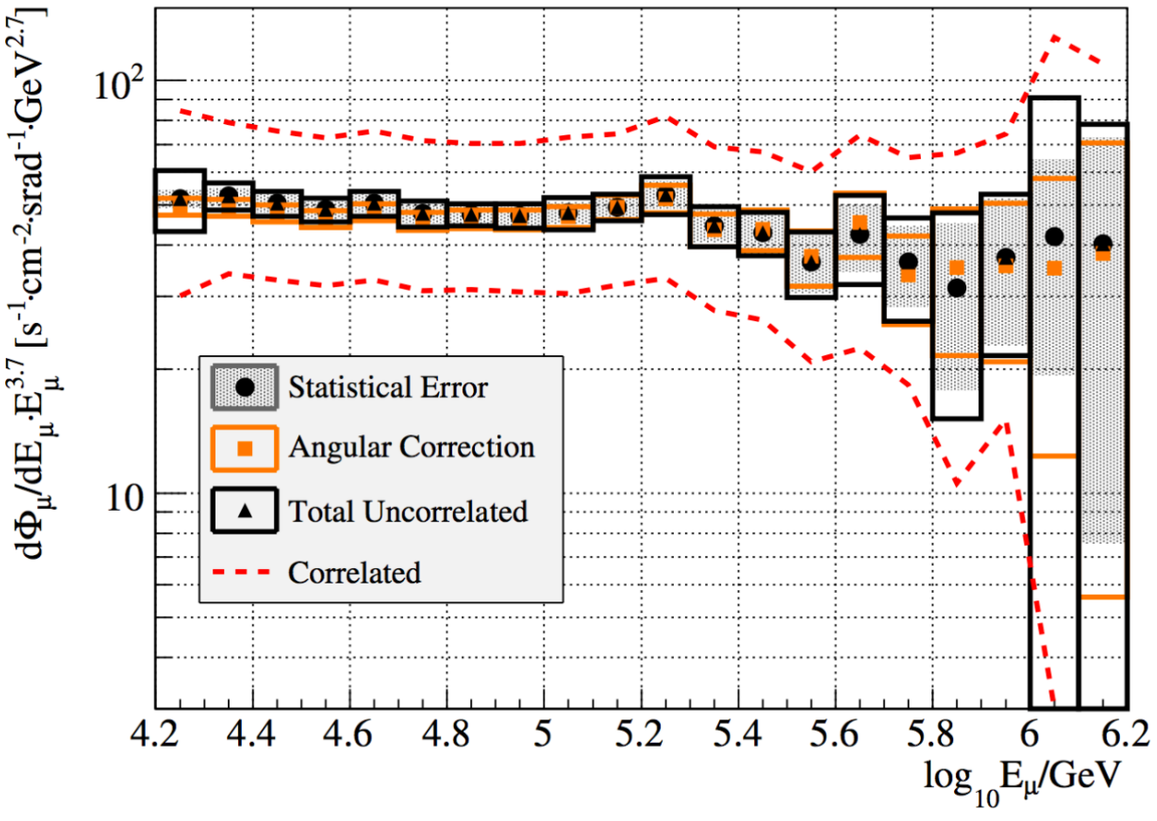


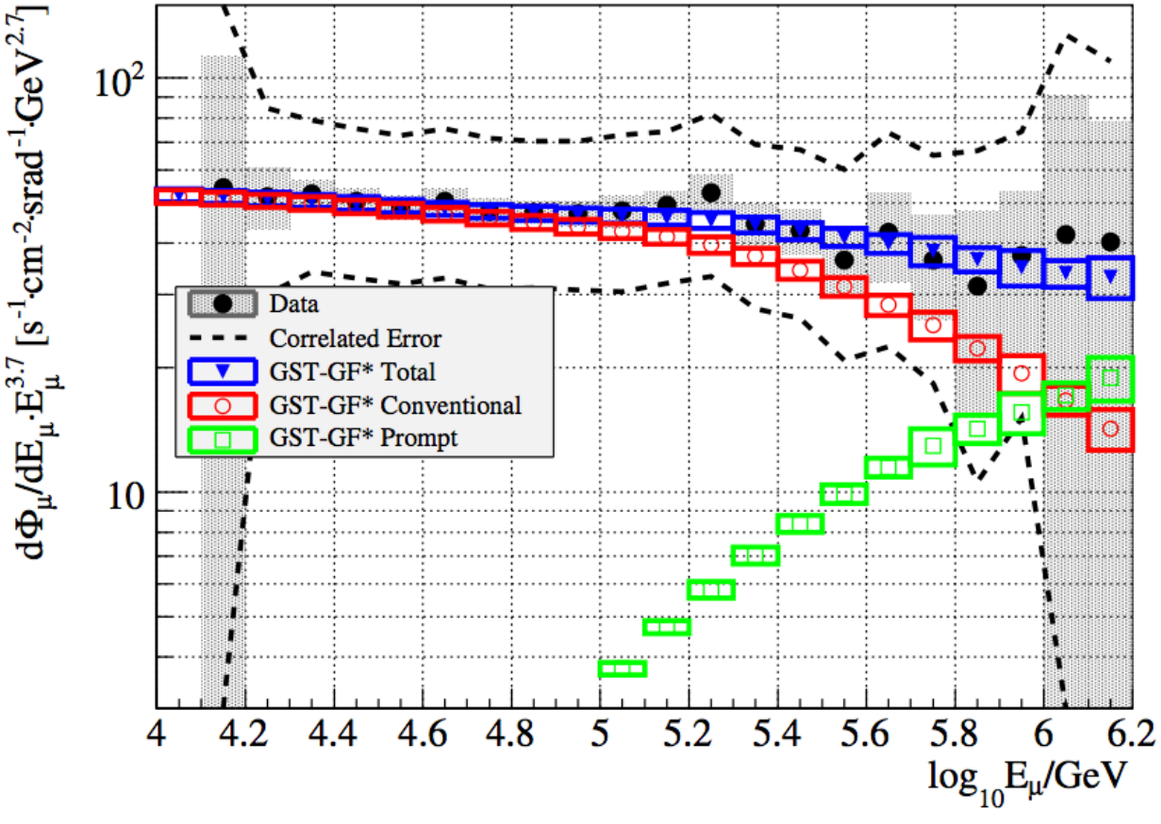
angular distribution not well described by models ~ statistical limitations

cosmic ray muons

high energy muon spectrum



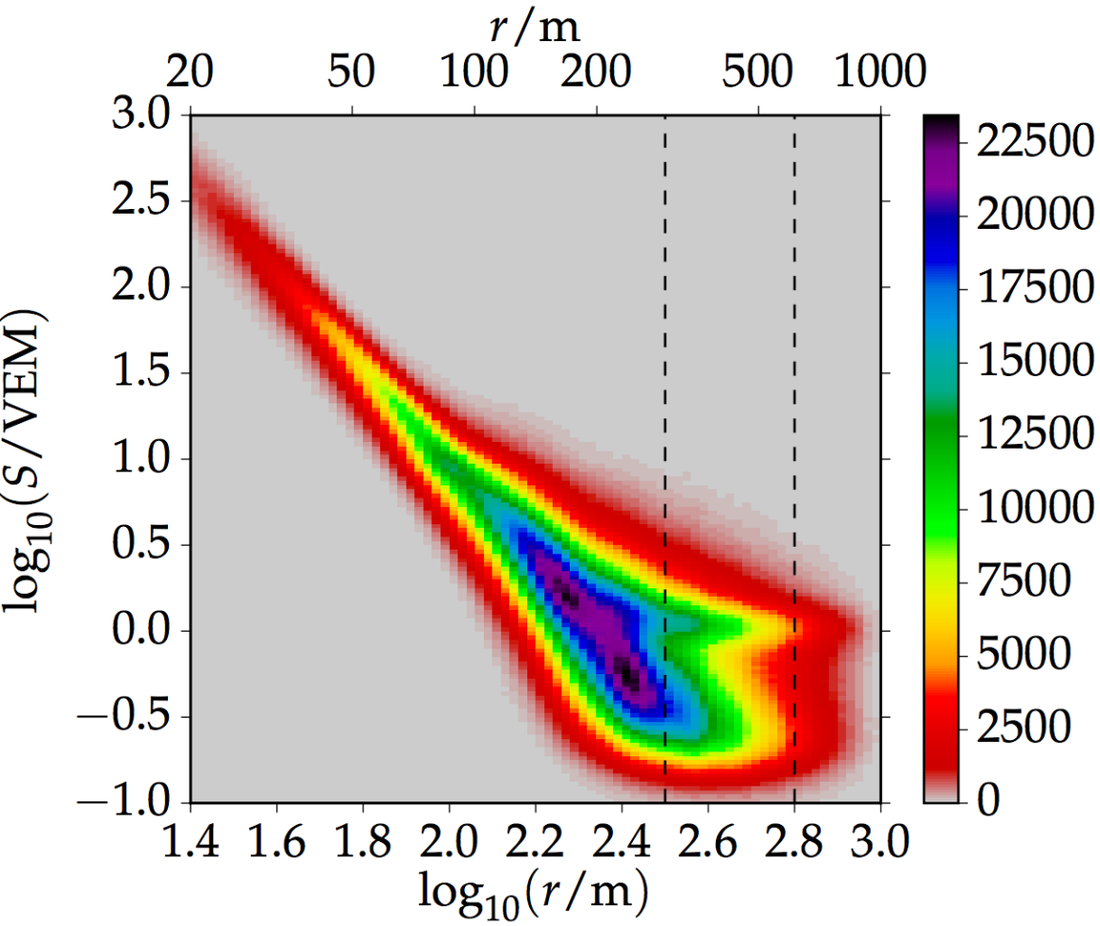




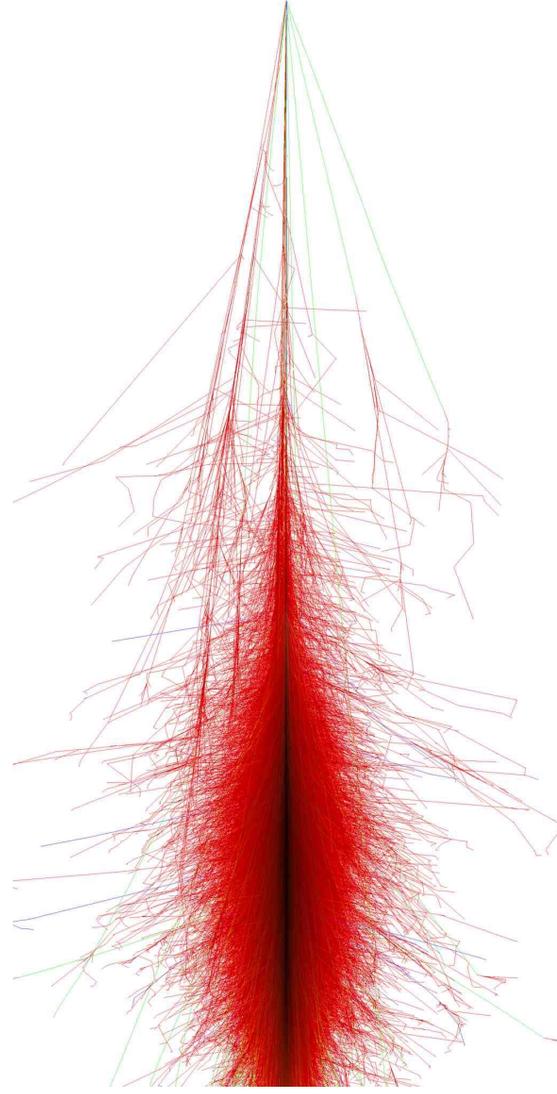
high energy excess of "*single*" muons - **prompt component** ?

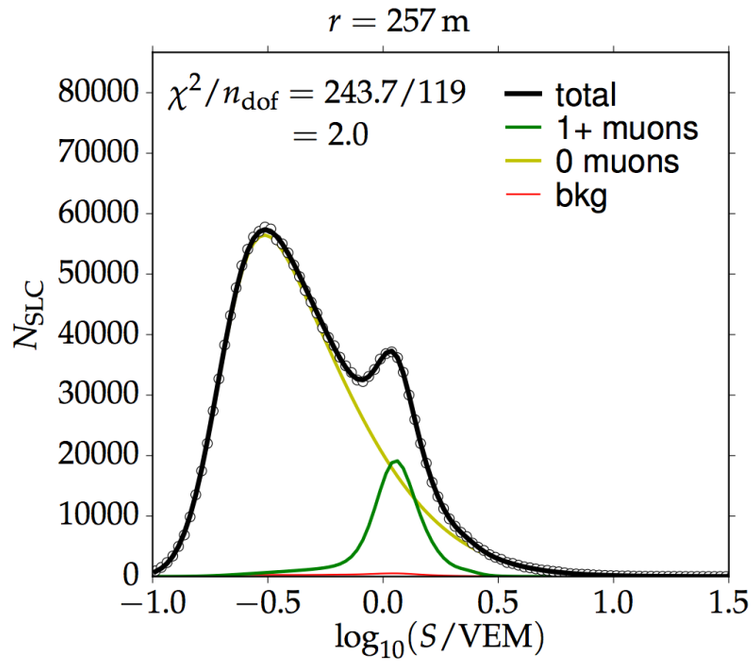
cosmic ray muons

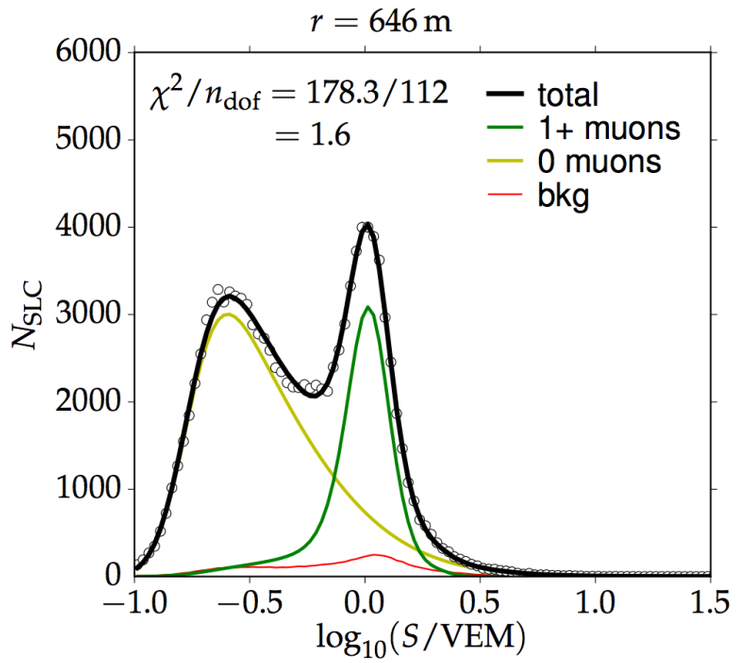
low energy muons in CR showers



muons at the **edge** of atmospheric showers



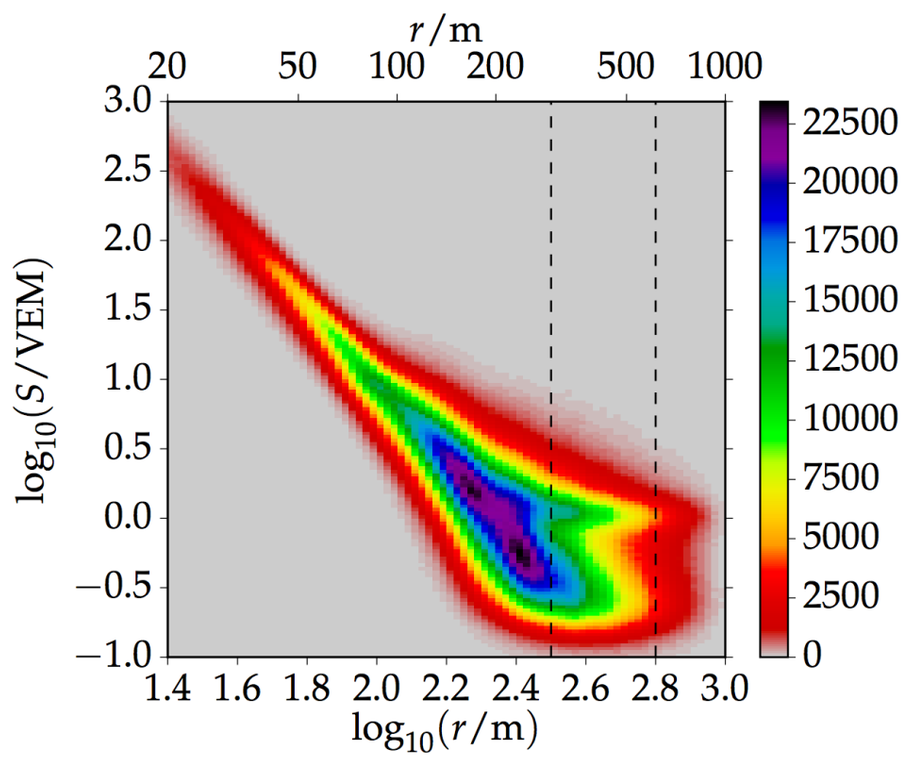


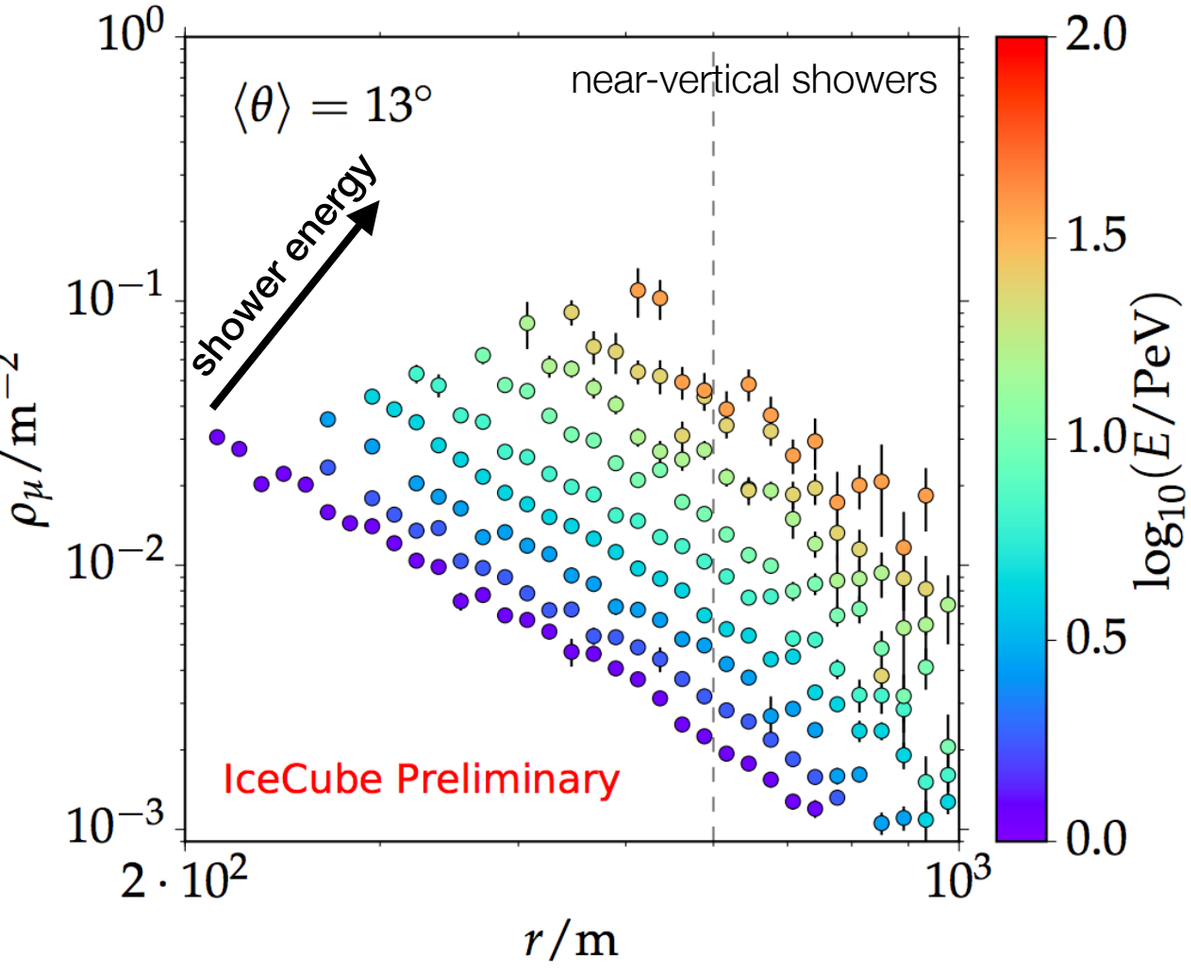


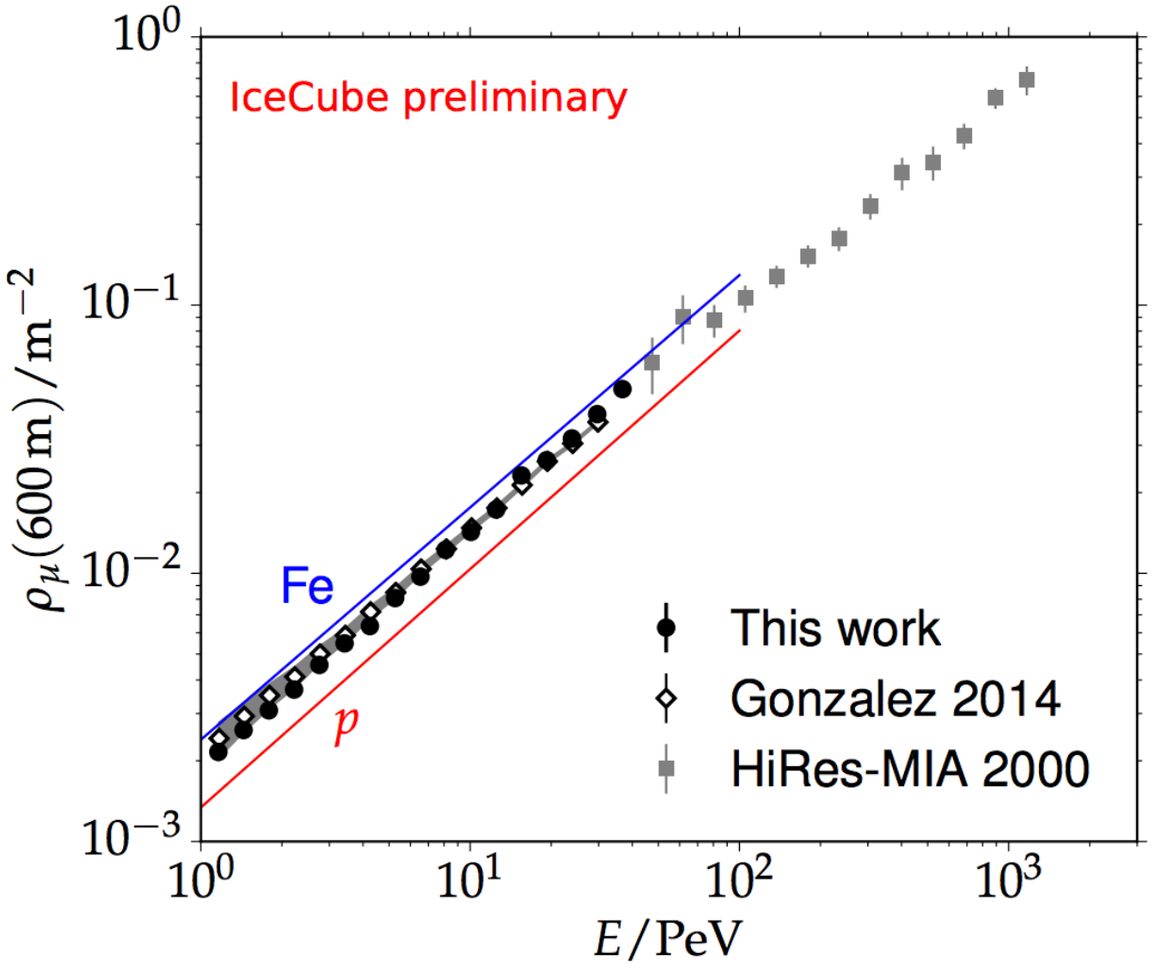
cosmic ray muons

low energy muons in CR showers

muons **lateral** distribution function
at 1-30 PeV CR energy







THANK YOU

NEXT:

- ASTROPHYSICS
- INTERDISCIPLINARY SCIENCES
- LIFE AT THE SOUTH POLE