Cosmic Ray Physics with the IceTop Air Shower Array

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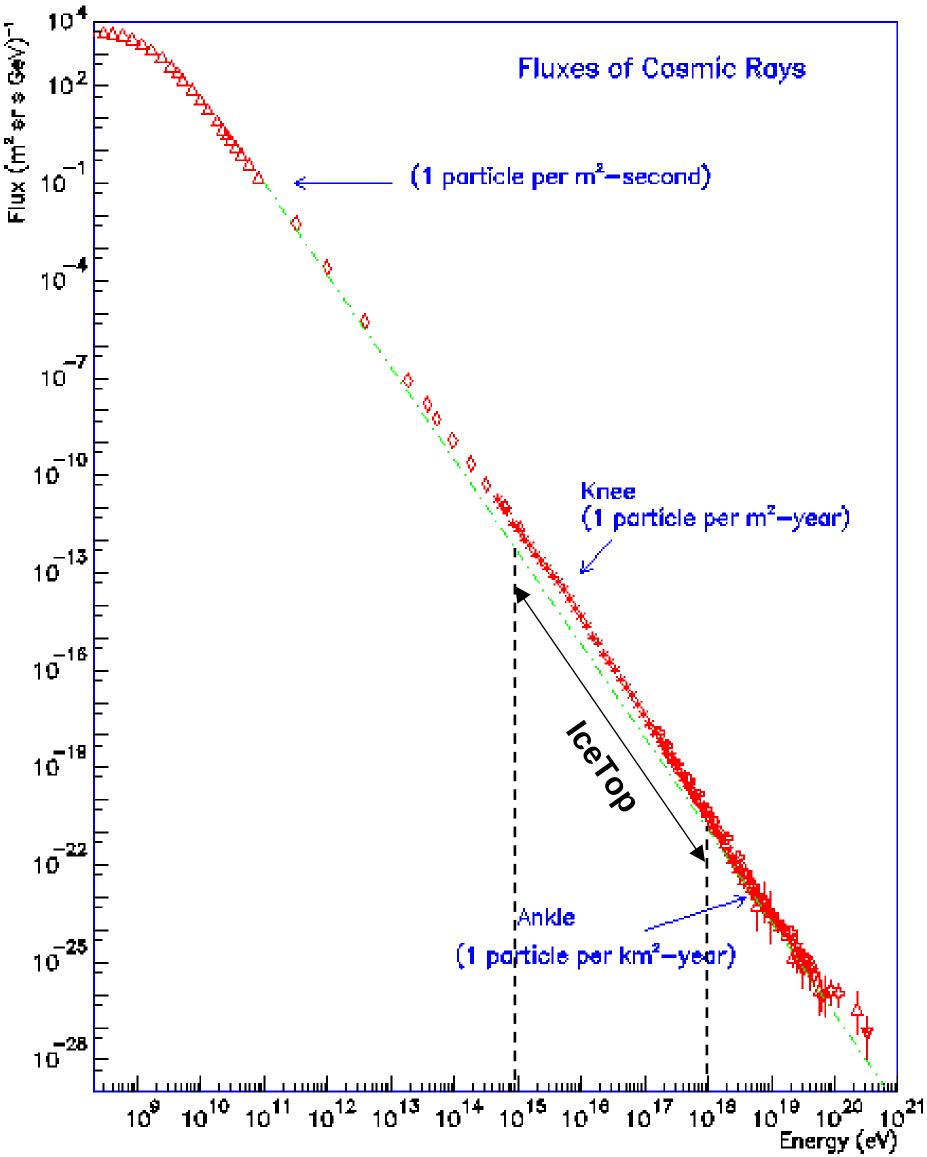
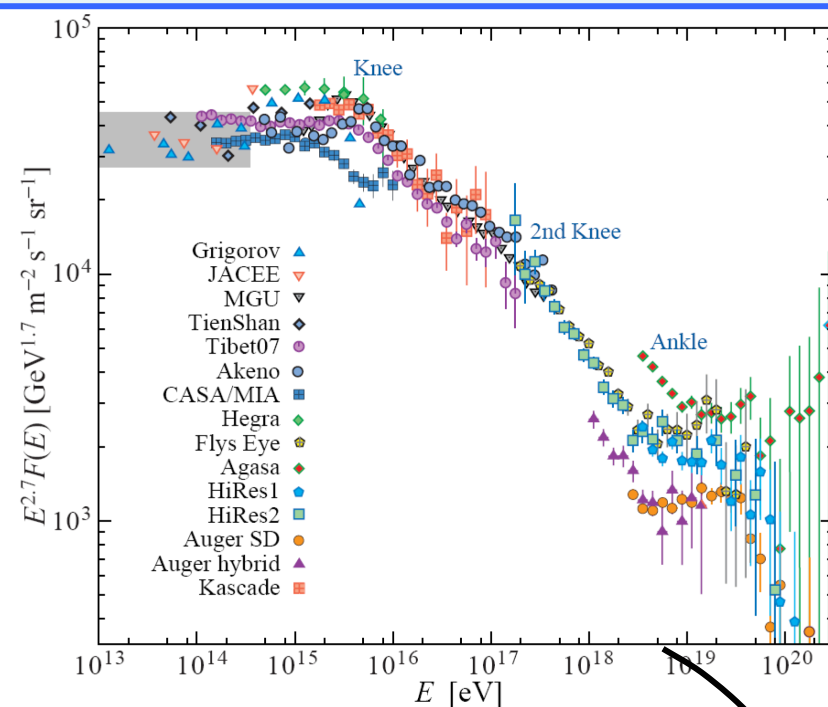
Humboldt-Universität zu Berlin

Outline

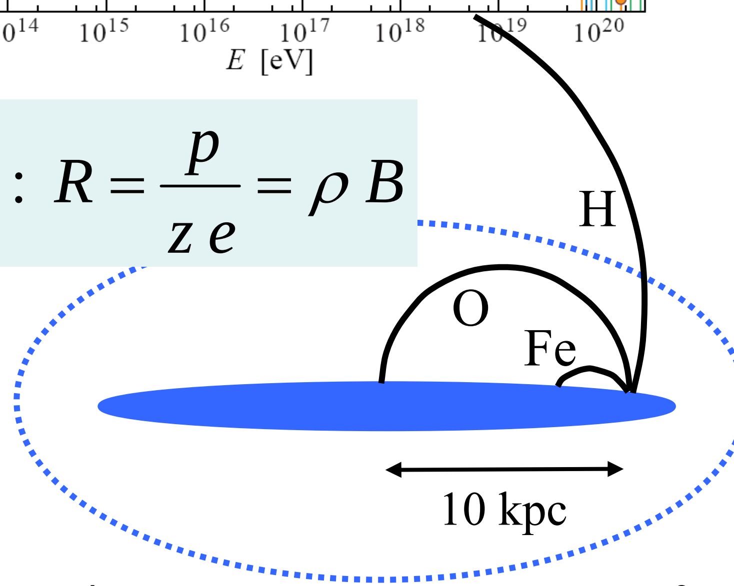
- **Cosmic rays: what IceCube/IceTop can contribute**
- **IceTop: the air shower array of IceCube**
- **Energy spectra**
- **Methods of composition determination**
- **IceTop-InIce coincidences → composition**
- **... and more:**
  heliospheric, atmospheric physics with IceTop

Energy Spectrum at the Knee

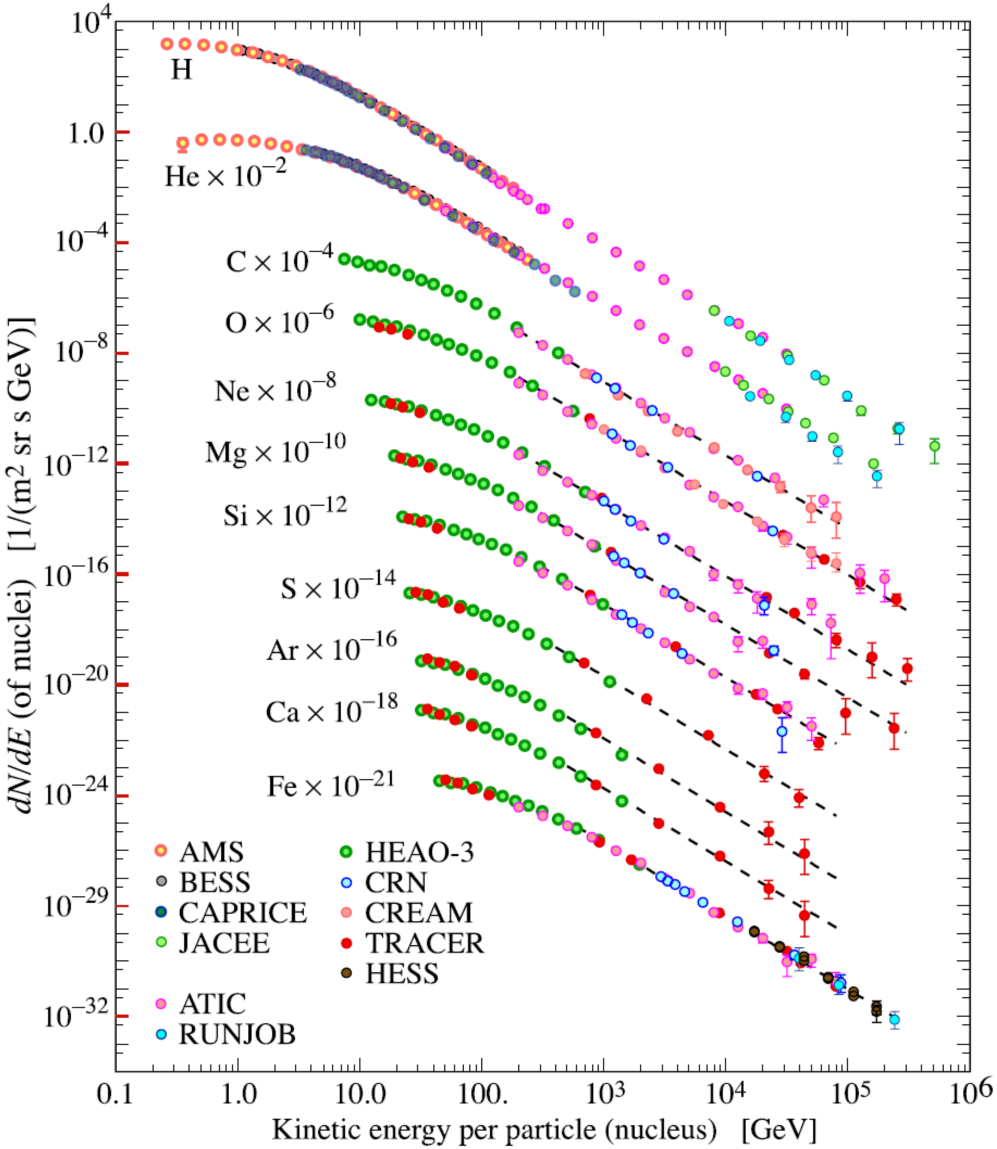




$$\text{Rigidity}: \; R = \frac{p}{z\,e} = \rho\, B$$



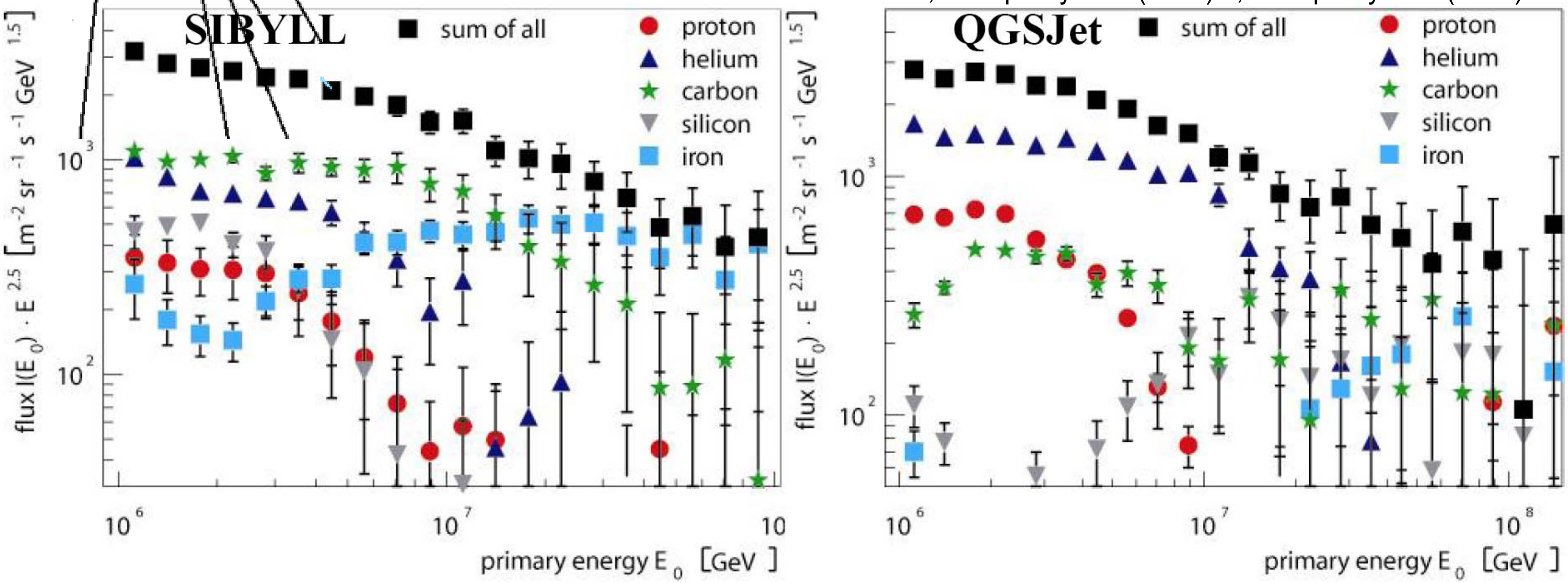
CR Composition from Direct Measurements



...and from Indirect Measurements

KASCADE results

KASCADE Coll., Astrop.Phys. 24 (2005) 1; Astrop.Phys. 31 (2009) 86



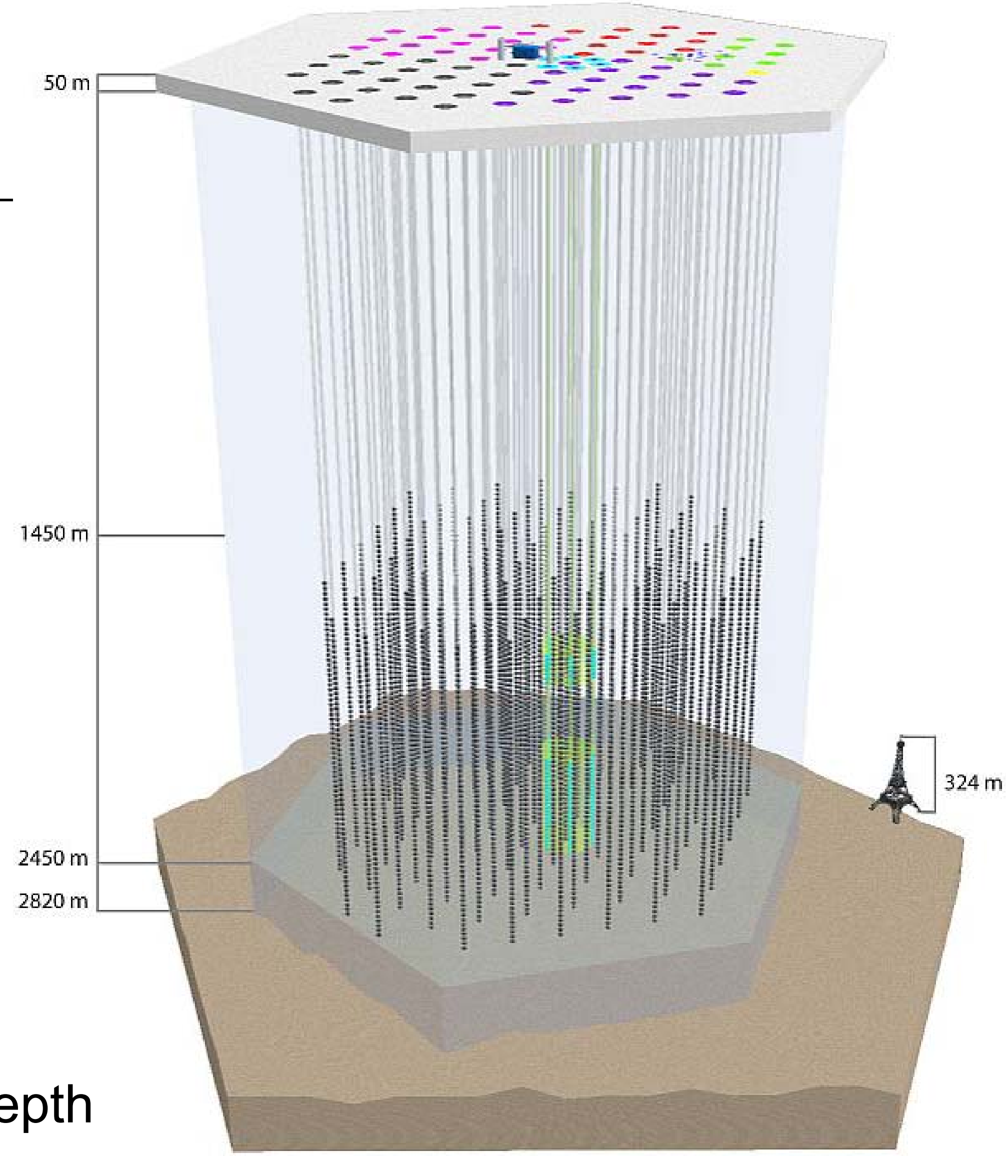
relative abundances depend very much on high-energy hadronic models

IceTop – Surface Array of IceCube

IceTop – air shower detector
80 stations on 1 km^2

IceCube – Neutrino/Muon detector
4800 optical modules in 1 km^3 ice
depth: 1450 – 2450 m

specialty for cosmic ray physics:
combination of both detectors
air shower + penetrating muons in depth



The IceCube Collaboration

Canada:
University of Alberta

USA:
Bartol Research Institute, Delaware
Pennsylvania State University
UC Berkeley
UC Irvine
Clark-Atlanta University
University of Maryland
University of Wisconsin-Madison
University of Wisconsin-River Falls
Lawrence Berkeley National Lab.
University of Kansas
Southern University and A&M College, Baton Rouge
University of Alaska, Anchorage
Ohio State University
University of Alabama
Georgia Institute of Technology

Sweden:
Uppsala Universitet
Stockholm Universitet

UK:
Oxford University

Switzerland:
EPFL

Germany:
Universität Mainz
DESY-Zeuthen
Universität Dortmund
Universität Wuppertal
Humboldt Universität
MPI Heidelberg
RWTH Aachen
Universität Bonn
Universität Bochum

Belgium:
Université Libre de Bruxelles
Vrije Universiteit Brussel
Universiteit Gent
Université de Mons-Hainaut

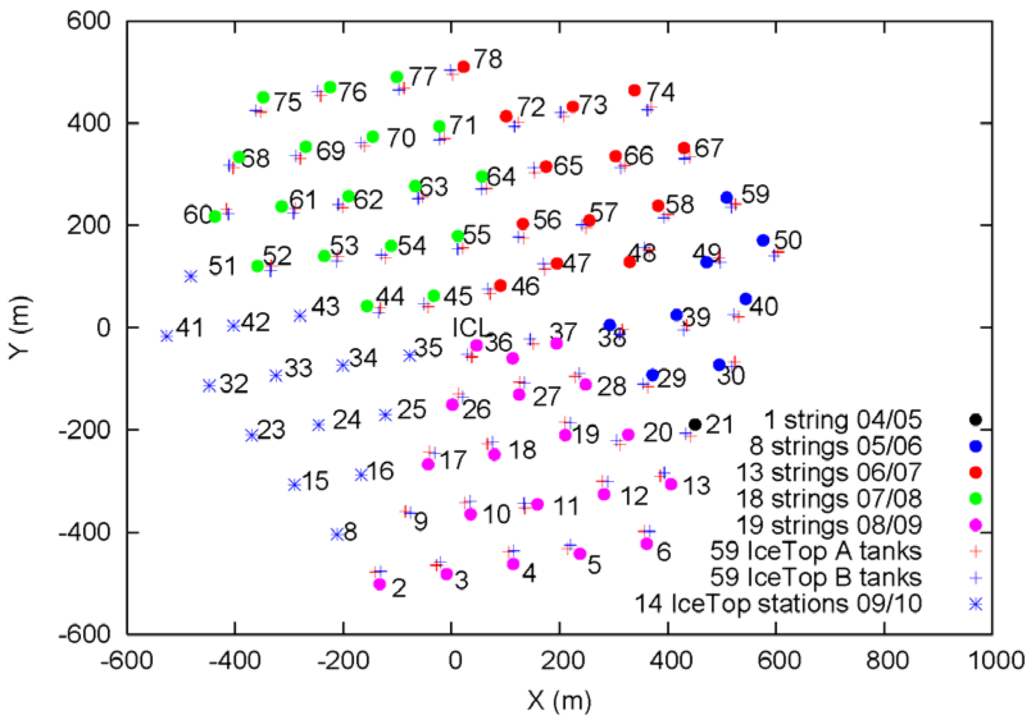
Japan:
Chiba University

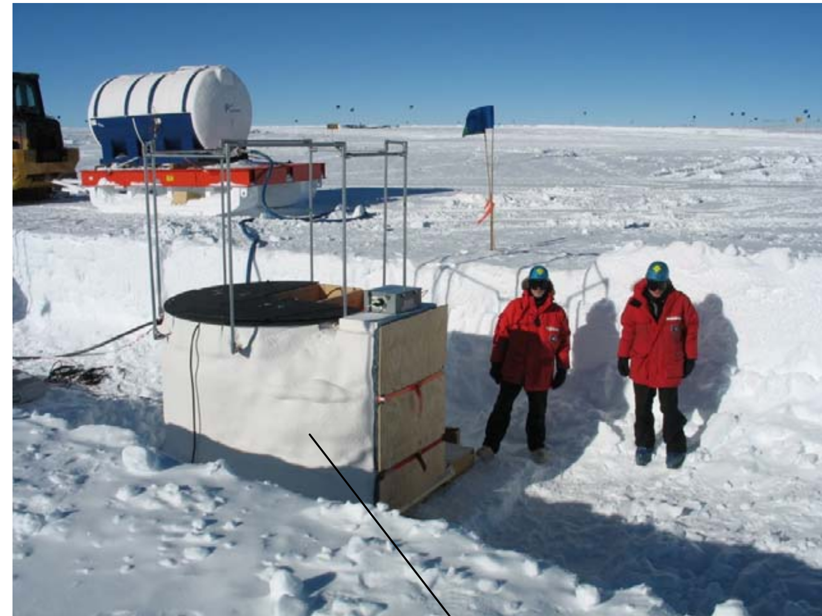
University of West Indies

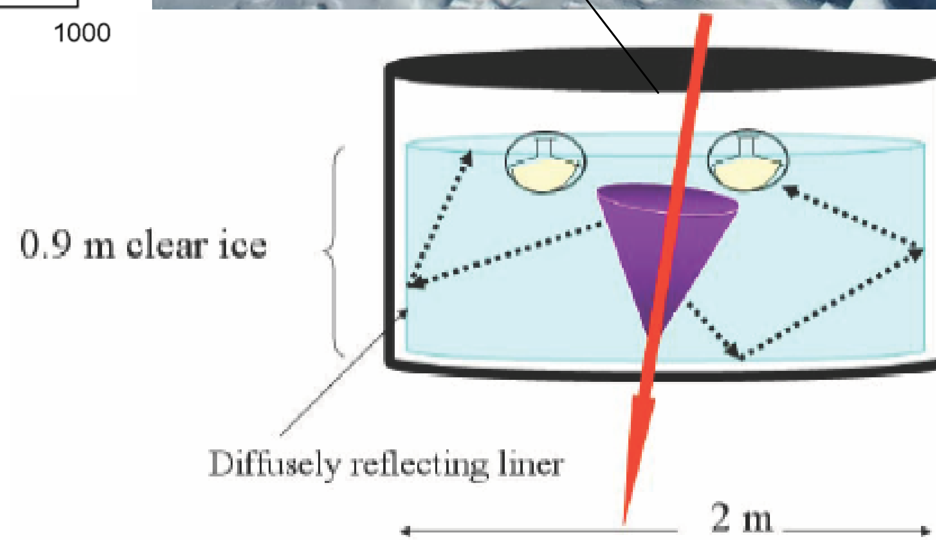
New Zealand:
University of Canterbury

~36 institutions, ~250 members
http://icecube.wisc.edu

IceTop Detector Array 2009/10



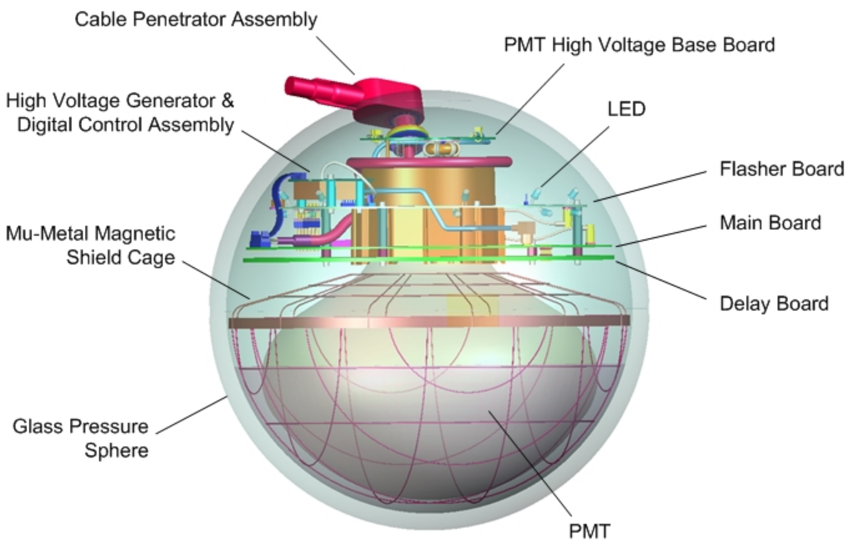


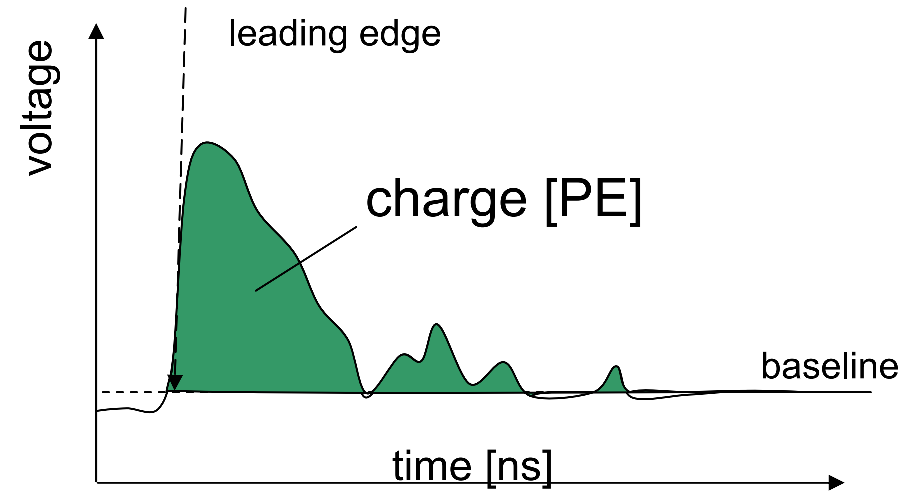


after 2009/10 season

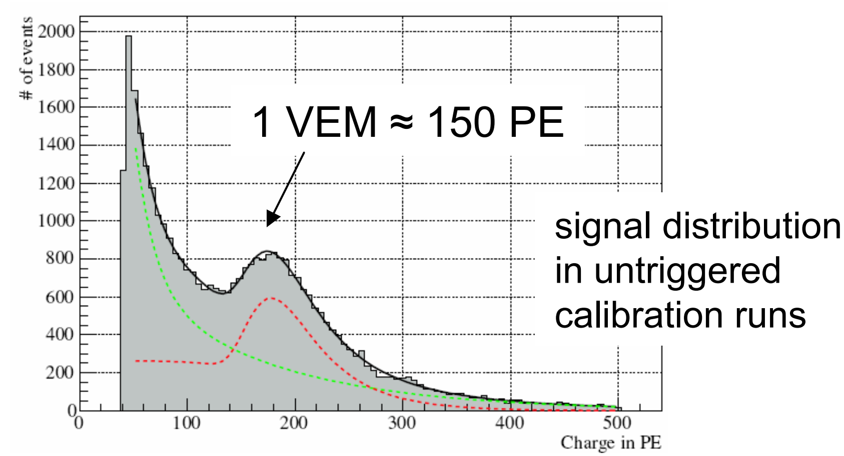
73 stations (146 tanks)

IceTop Signal Recording

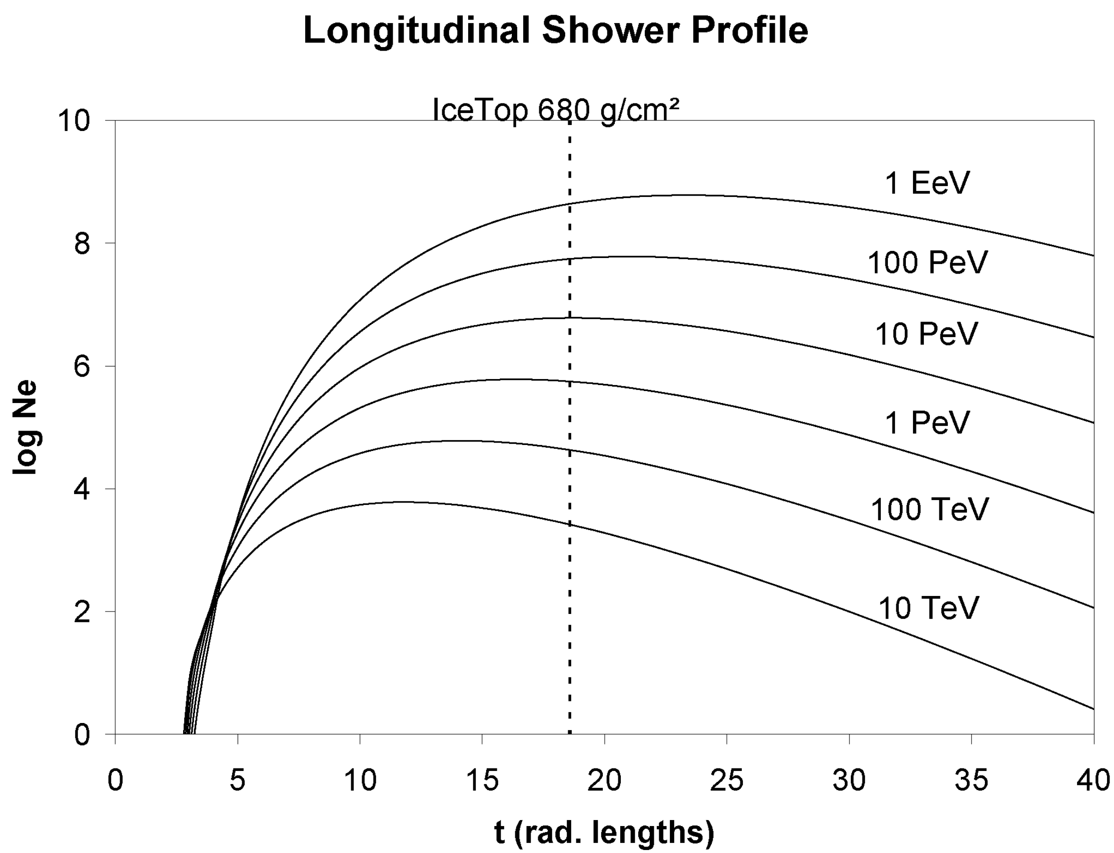




conversion to
Vertical **E**quivalent **M**uons



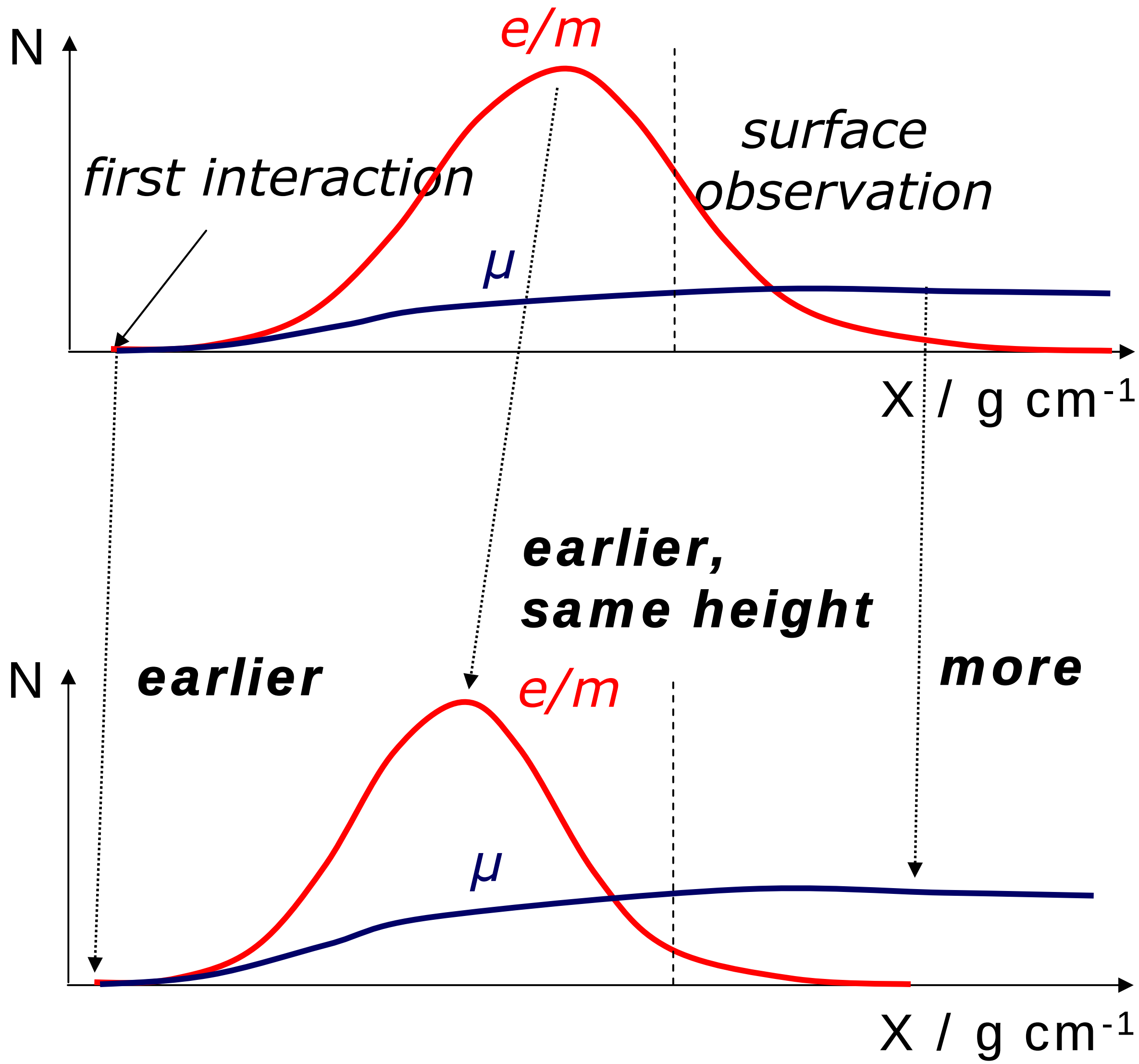
Longitudinal Shower Profile



Gaisser-Hillas Formula:

$$N_e(X) = N_{e,max} \left(\frac{X - X_1}{X_{max} - X_1} \right)^{\frac{X_{max} - X_1}{\lambda}} \exp \frac{X_{max} - X}{\lambda}$$

Shower Development for Different Nuclei



proton

heavier nucleus:

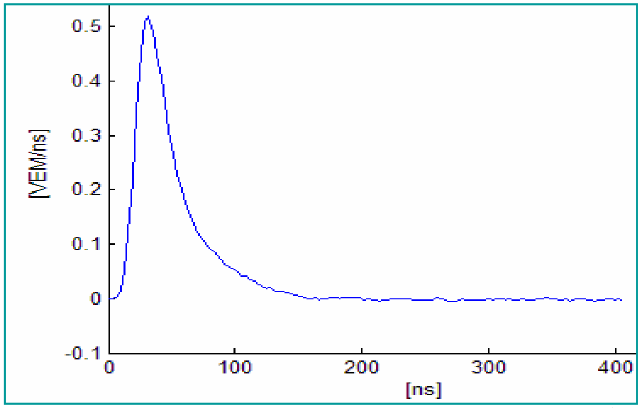
- earlier maximum
- more muons

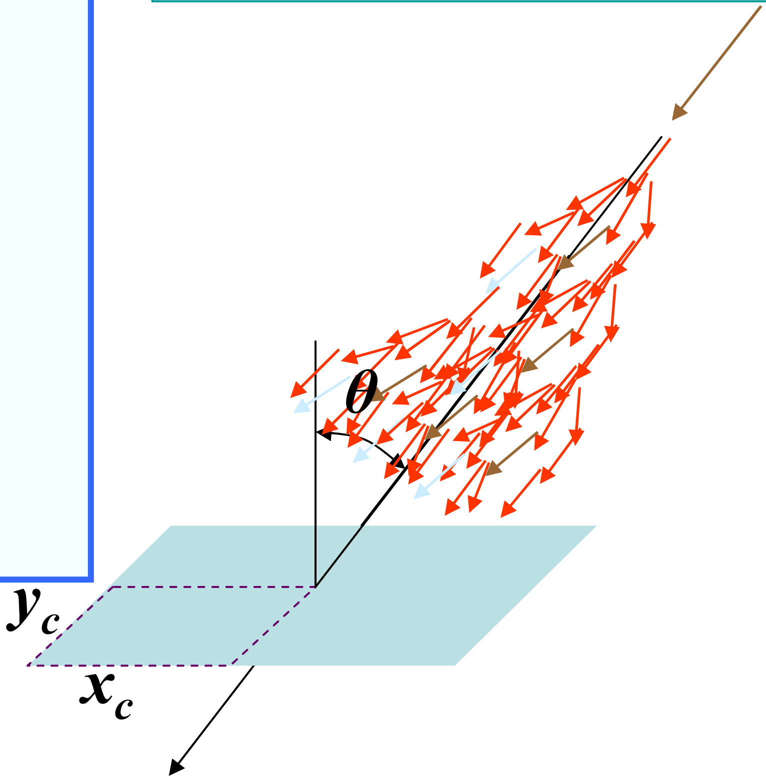
Air Shower Reconstruction

$$\text{tank signals} = (\vec{x}_i, q_i, t_i)$$

$$\Downarrow$$

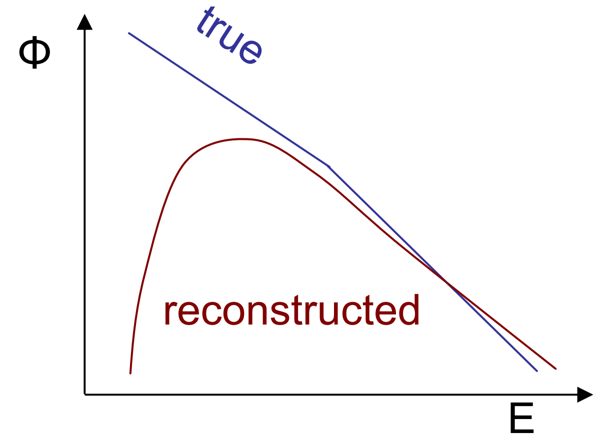
- shower direction: θ, φ
- shower centre x_c, y_c
- primary energy: E_0
  (with ***mass hyp.)***
- shower age: s

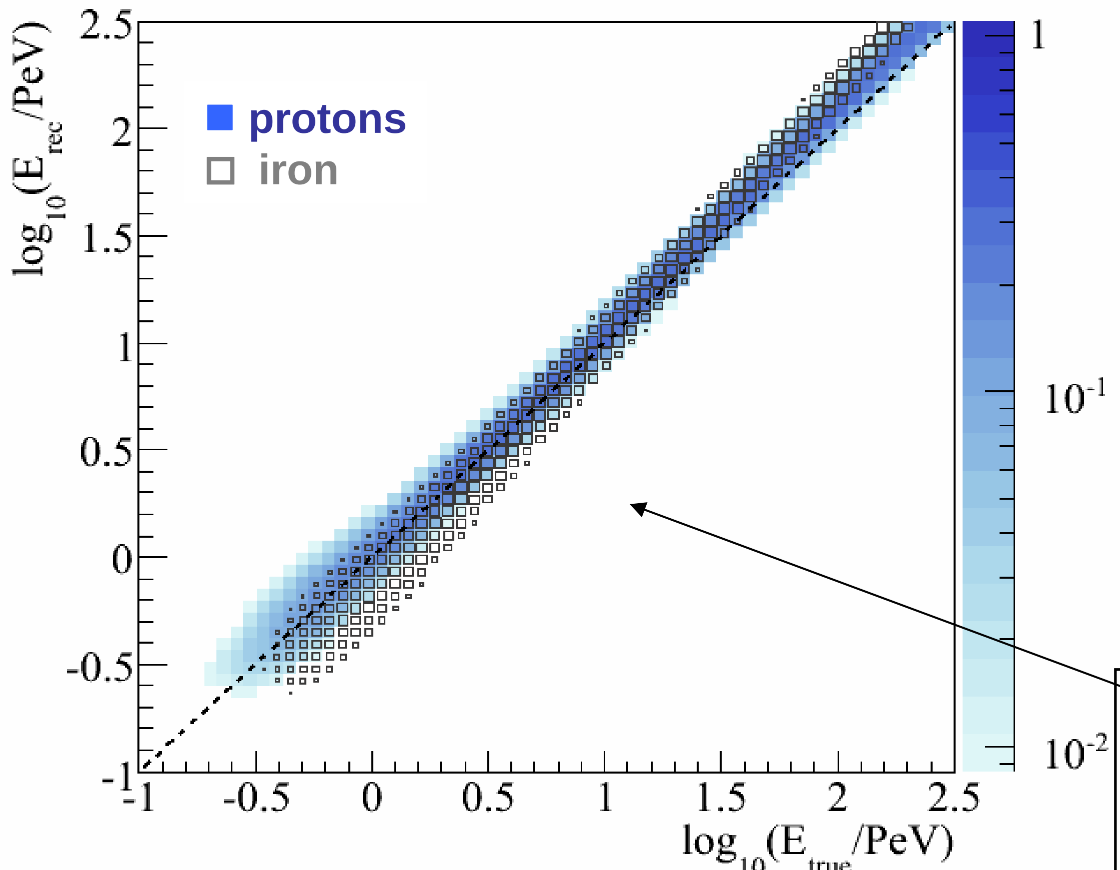




Response Matrix

$$\vec{S}_{rec} = \boldsymbol{R}\,\vec{S}_{true}$$





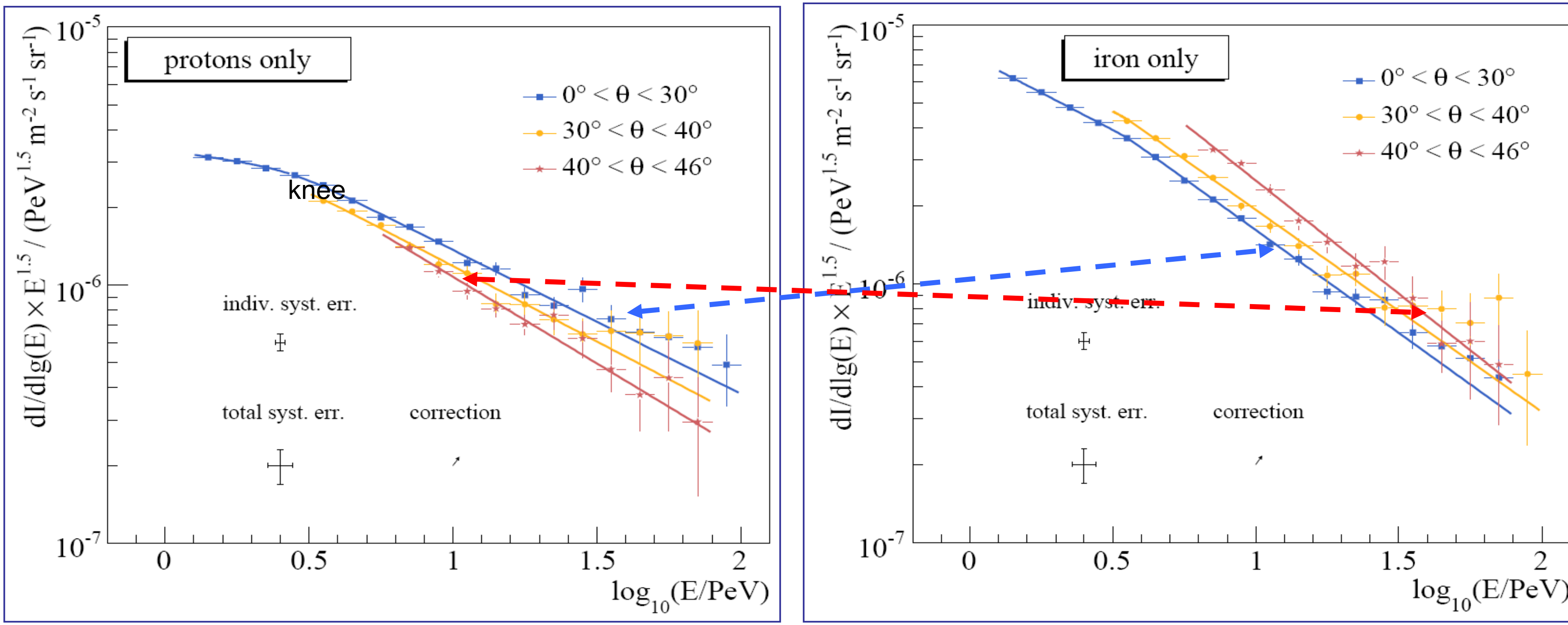
Response **R** includes:

- smearing,
- acceptance,
- mis-reconstruction

more diagonal for protons because energy is determined with **proton hypothesis**

Unfolding with a) proton or b) iron

- Preliminary Results! -



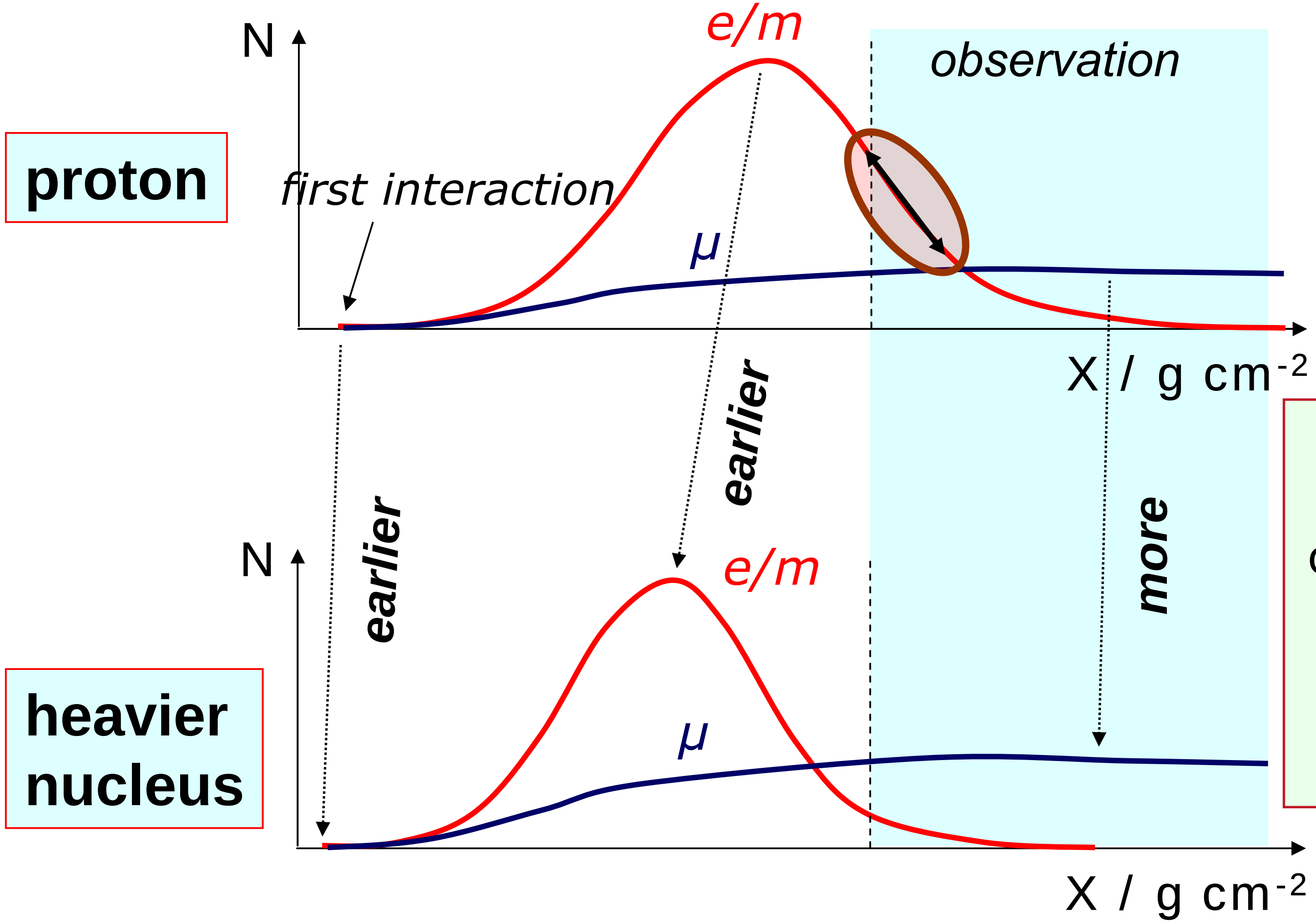
→ Flux not isotropic for proton or iron only assumptions

→ Mixed composition needed!

→ Isotropy requirement leads to

Composition sensitivity with IceTop only!

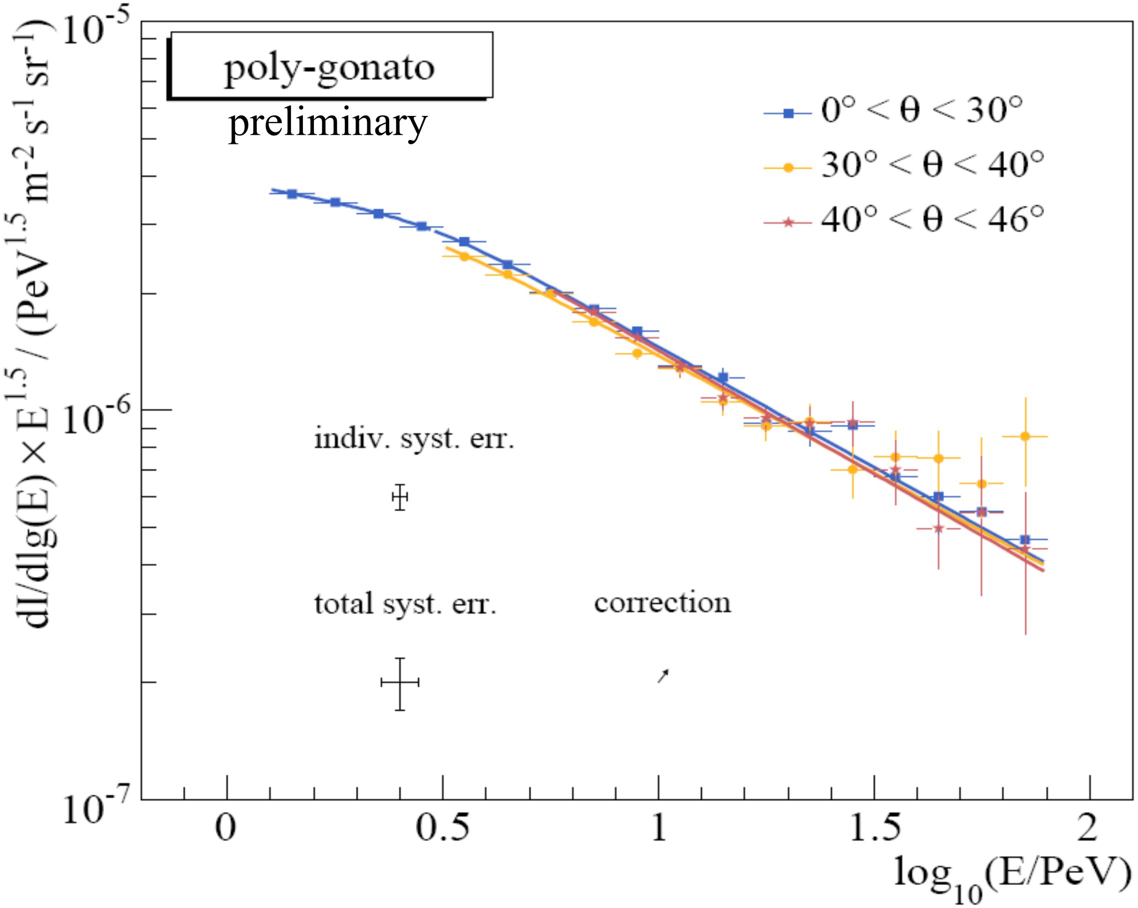
Shower Development for Different Nuclei



South Pole atmospheric depth 680 g/cm^2

close to shower maximum for ~ 1 PeV

Unfolding with Composition Models



fits in angular bins:

- proton only
- iron only
- 2-component model
- poly-gonato model

$$\frac{dI}{d\log_{10}E} = I_{\mathrm{PeV,lg}} \cdot \left(\frac{E}{1\,\mathrm{PeV}}\right)^{\gamma_1+1} \cdot \left(1 + \left(\frac{E}{E_{\mathrm{knee}}}\right)^{\varepsilon}\right)^{(\gamma_2-\gamma_1)/\varepsilon}$$

Generating the Response Matrix for Different Models

model		A	Z	$I_{\mathrm{PeV,lg}}$ $10^{-6}\,\mathrm{m^{-2}\,s^{-1}\,sr^{-1}}$	$-\gamma_1$	$-\gamma_2$	E_{knee} PeV
only protons	H	1.0	1.0	5.47	2.66	3.08	3.08
poly-gonato	H	1.0	1.0	1.61	2.71	$-\gamma_1 + 2.1$	4.49
	He	4.0	2.0	1.71	2.64	$-\gamma_1 + 2.1$	$Z \cdot E_{\mathrm{knee,H}}$
	CNO	14.2	7.1	0.673	2.67	$-\gamma_1 + 2.1$	$Z \cdot E_{\mathrm{knee,H}}$
	Mg-S	27.2	13.5	0.514	2.64	$-\gamma_1 + 2.1$	$Z \cdot E_{\mathrm{knee,H}}$
	Mn-Fe	55.7	25.9	0.997	2.57	$-\gamma_1 + 2.1$	$Z \cdot E_{\mathrm{knee,H}}$
two-comp.	H	1.0	1.0	3.89	2.67	3.39	4.1
	Fe	1.0	1.0	1.95	2.66	–	–
only iron	Fe	56.0	26.0	5.47	2.66	3.08	3.08

Preliminary Results with Poly-Gonato Model

S.Klepser et al., ICRC 2007

- 1 month of data only
- 26/80 of the detector
- 1 to 80 PeV

E_{knee} = (3.1 ± 0.3 (stat.) ± 0.3 (sys.)) PeV

γ_1 = 2.71 ± 0.07 (stat.) (prelim)

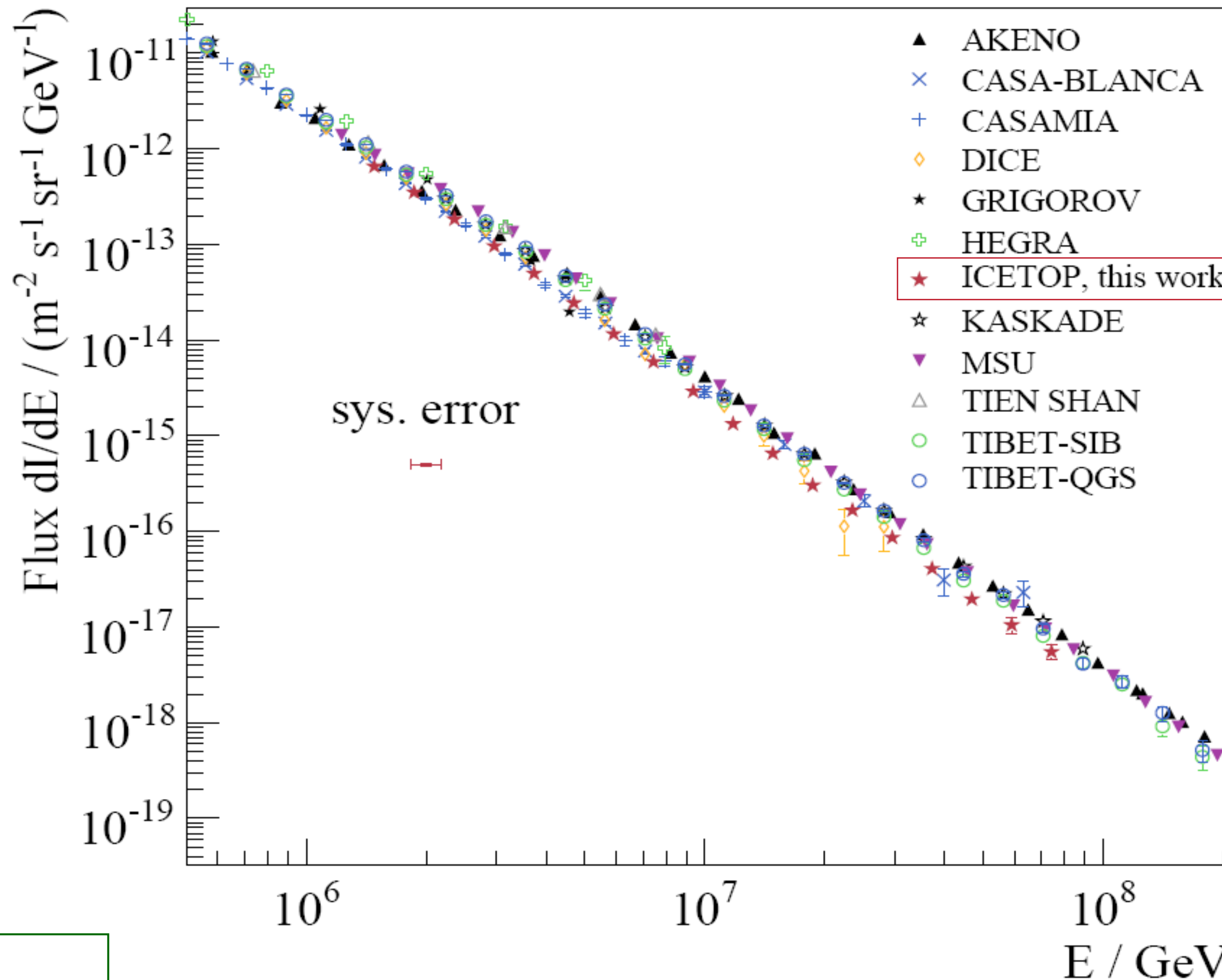
γ_2 = 3.110 ± 0.014 (stat.) ± 0.08 (sys.)

$$\frac{dI}{d\log_{10}E} = I_{\mathrm{PeV,lg}} \cdot \left(\frac{E}{1\,\mathrm{PeV}}\right)^{\gamma_1+1} \cdot \left(1 + \left(\frac{E}{E_{\mathrm{knee}}}\right)^{\varepsilon}\right)^{(\gamma_2-\gamma_1)/\varepsilon}$$

Systematics: ≈ 9 – 11 % in E

first IceTop analysis for energy spectrum
→ we know now our main systematics

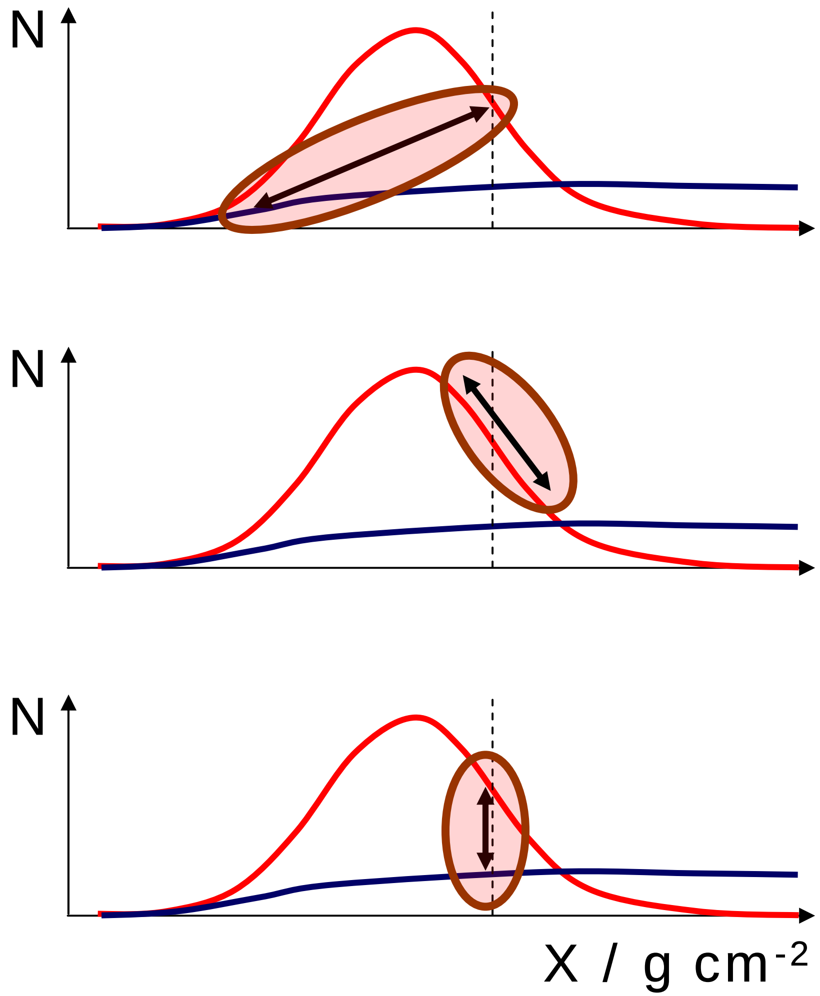
Comparison with other Experiments



S.Klepser, Dissertation
Humboldt Univ. Berlin June 2008

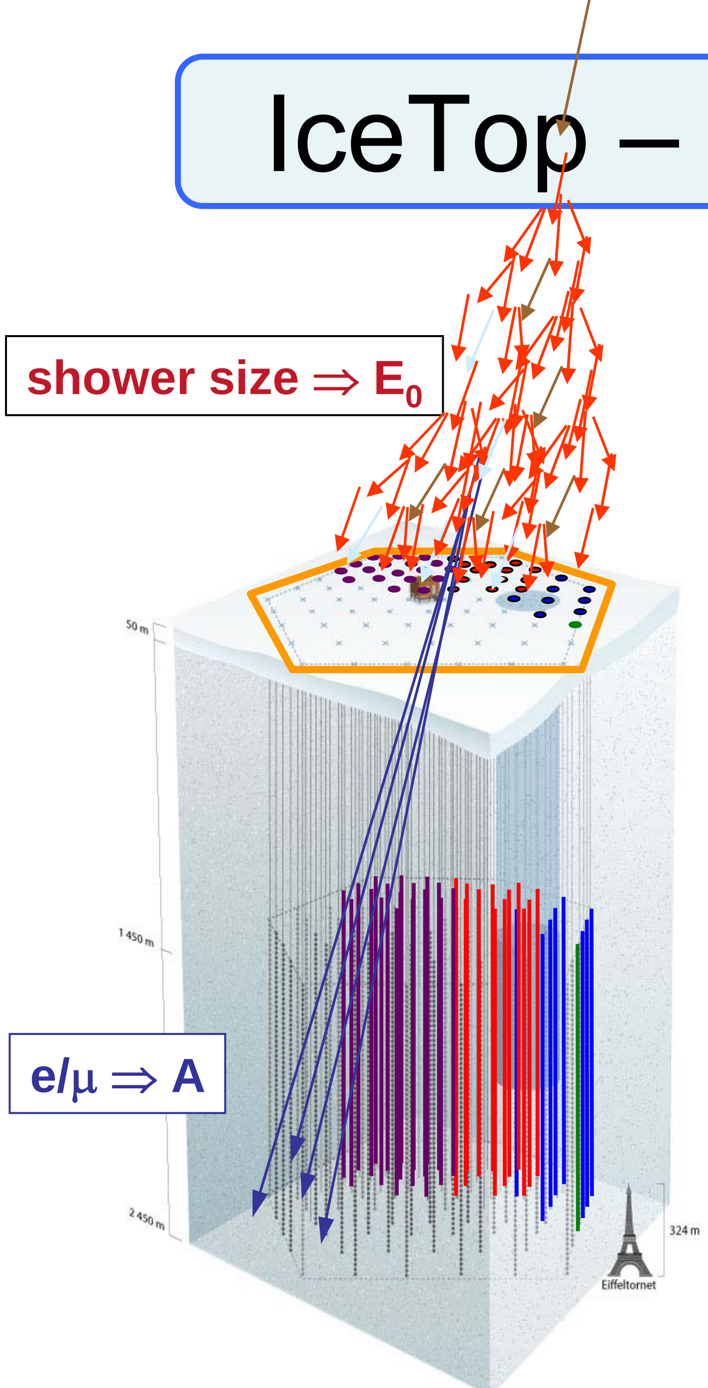
IceTop Prospects for
Composition Analyses

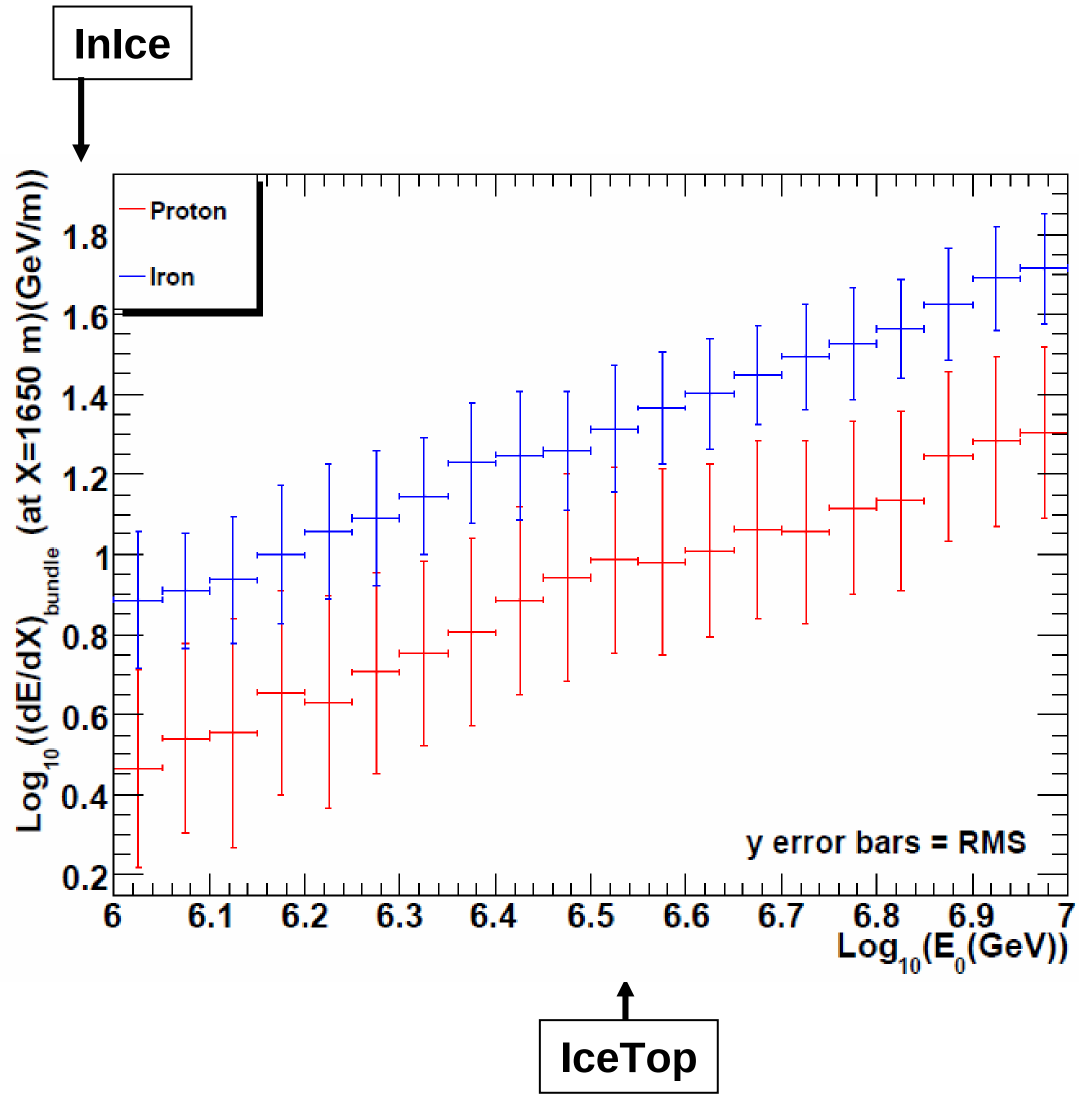
- IceTop – InIce coincidences
- IceTop: zenith angle dependence of shower development
- Muon counting with IceTop



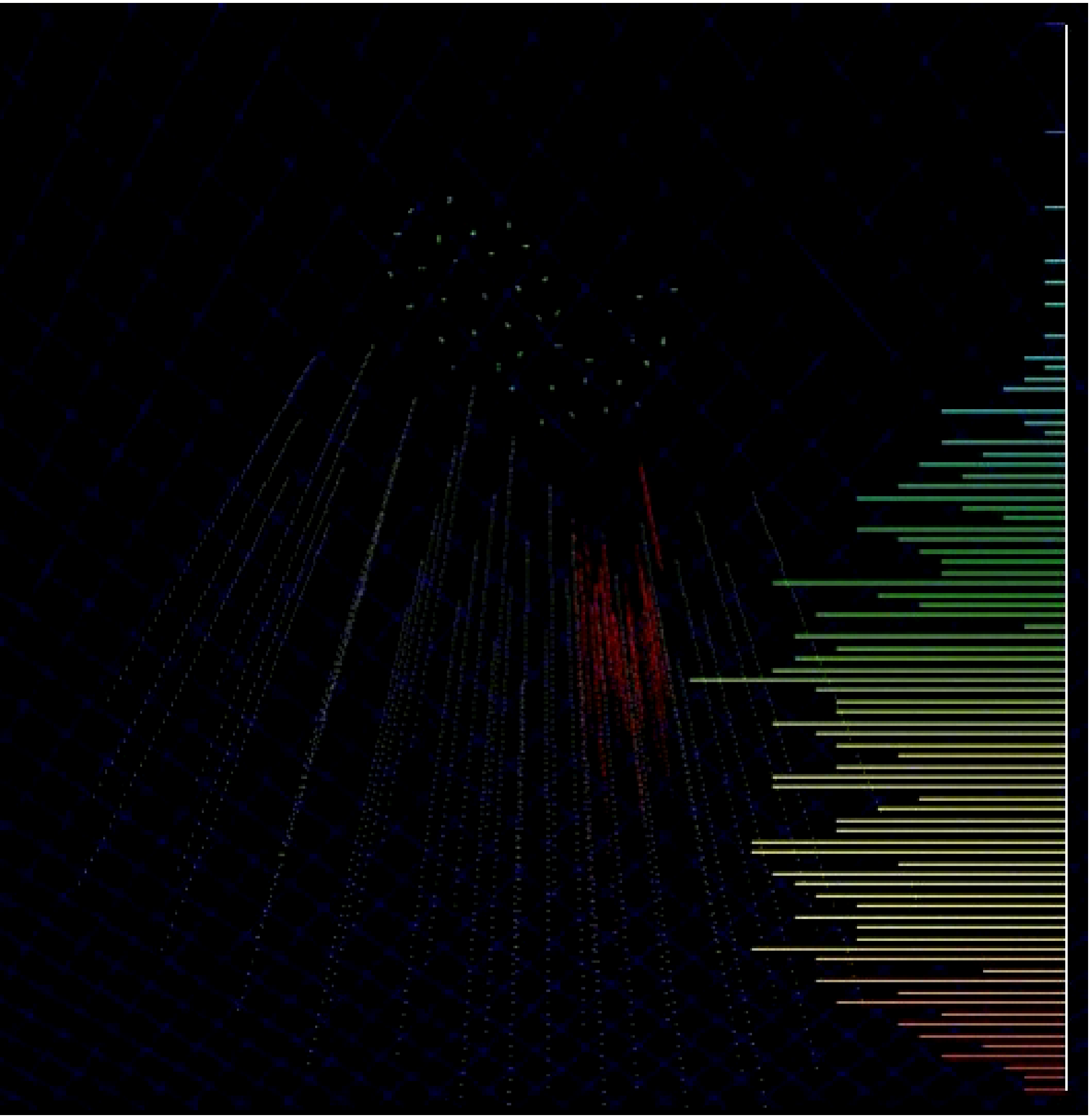
Complementary methods
⇓
test of models

IceTop – InIce Coincidences

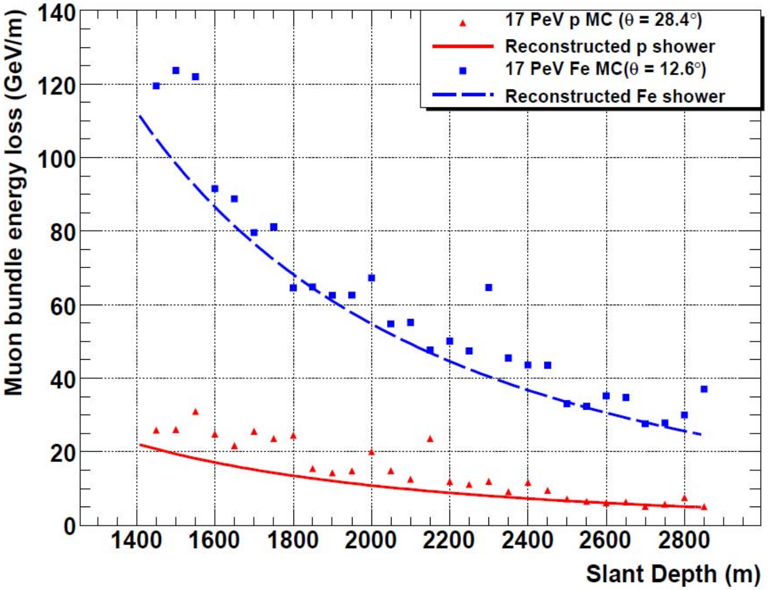




An IceCube – IceTop Coincident Event



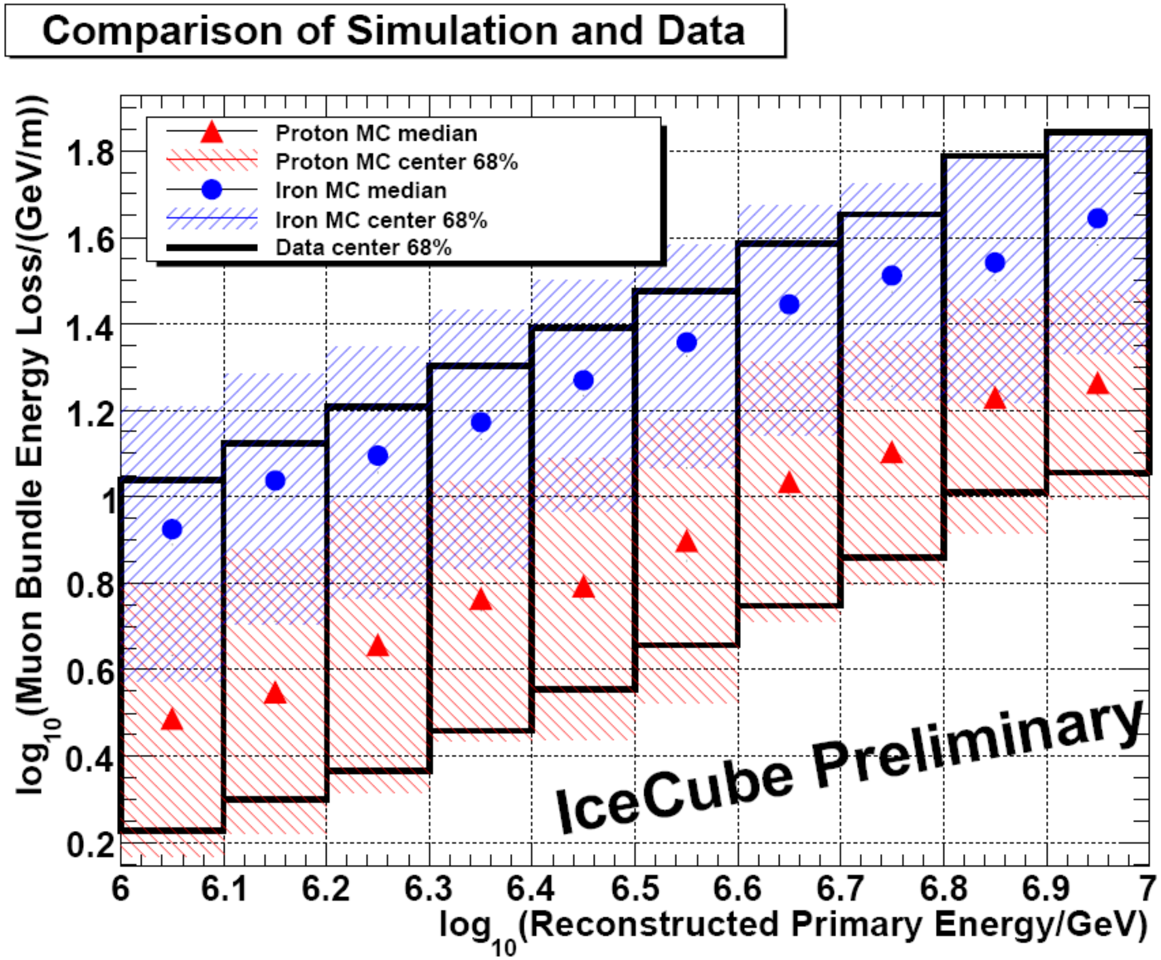
Tom Feusels, Gent



HE muons in IceCube
come from first interactions

→ complementary sensitivity
to muon counting at the surface

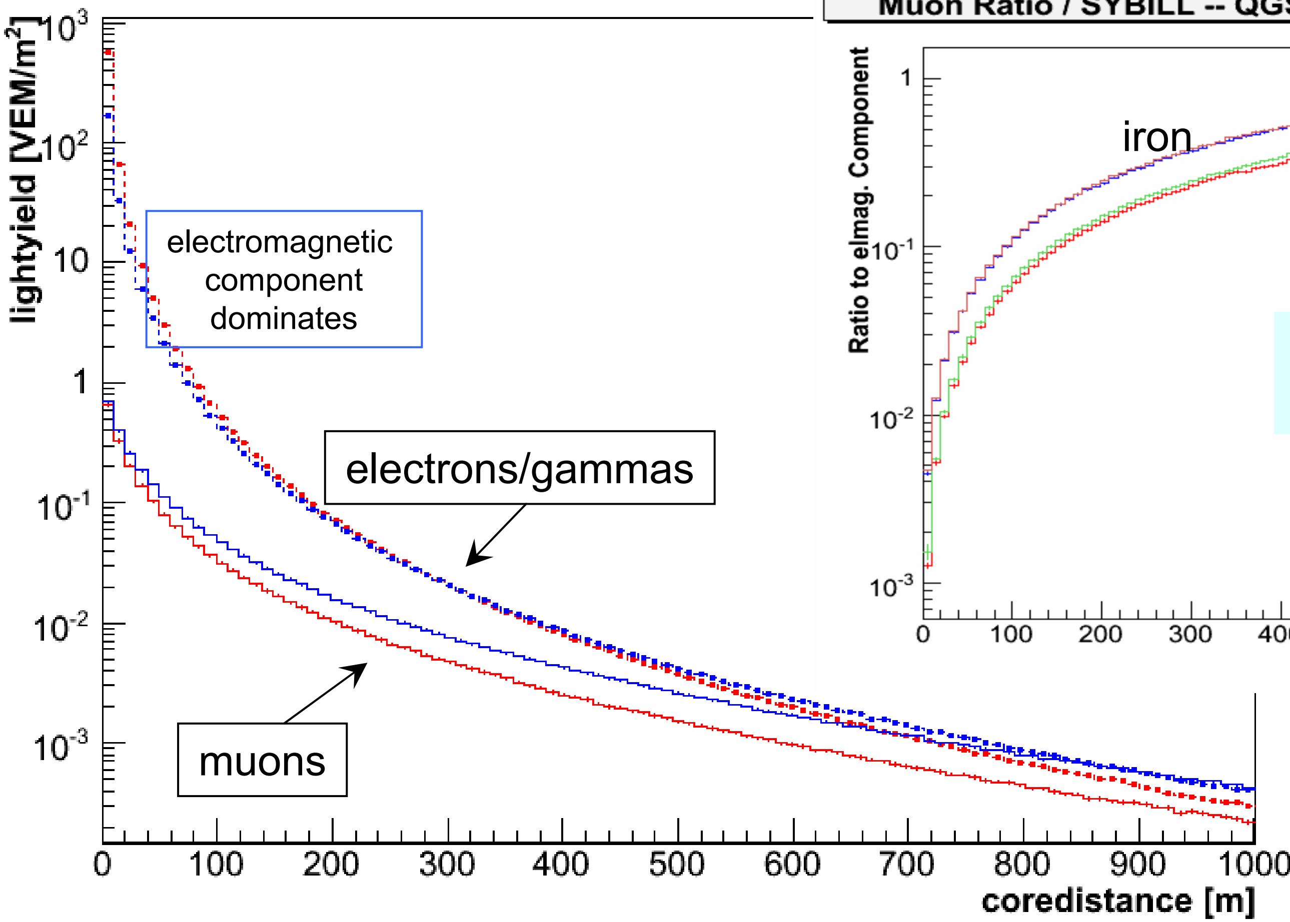
Composition-dependence: factor 2 - 3 between p and Fe

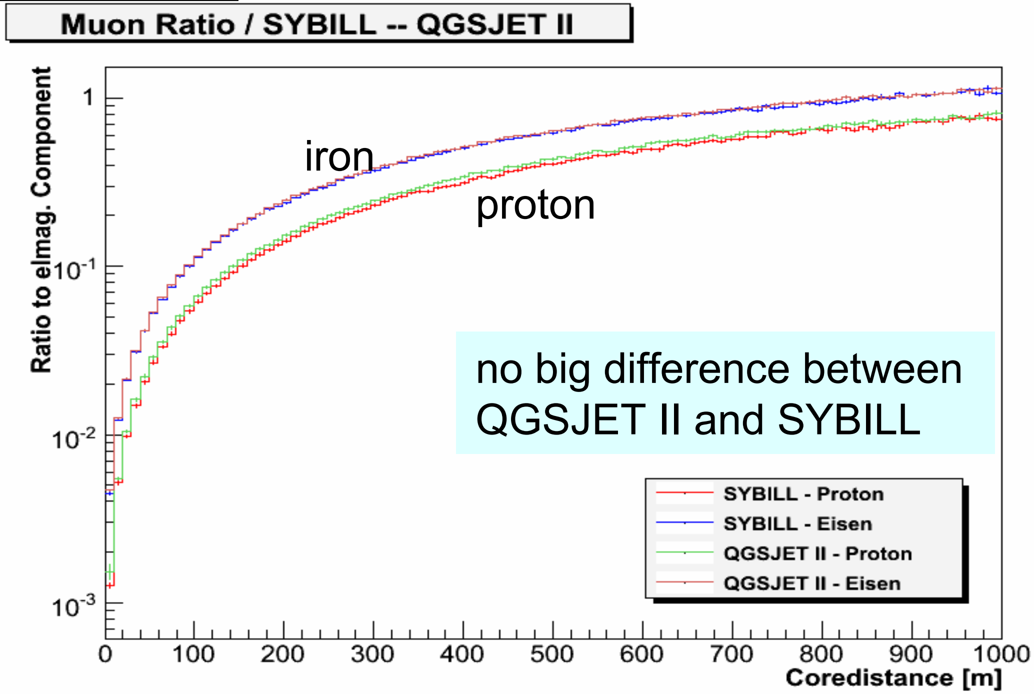


T. Feusels, J. Eisch, C. Xu (IceCube, ICRC 2009, paper 0518)

Muon Fraction in IceTop

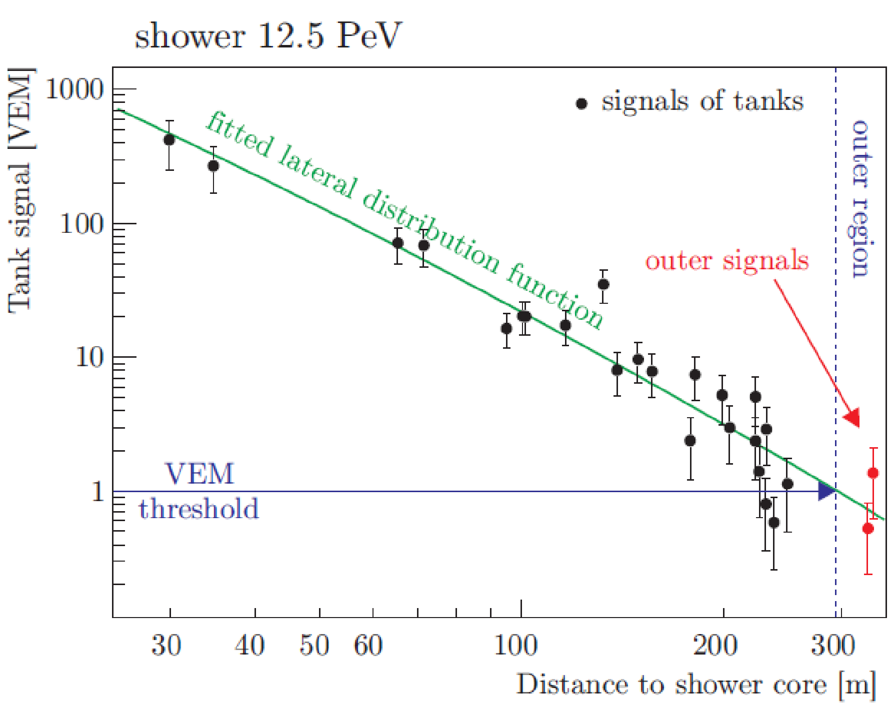
Proton – Iron / 1 PeV, vertical / CORSIKA (Sybill + Fluka)

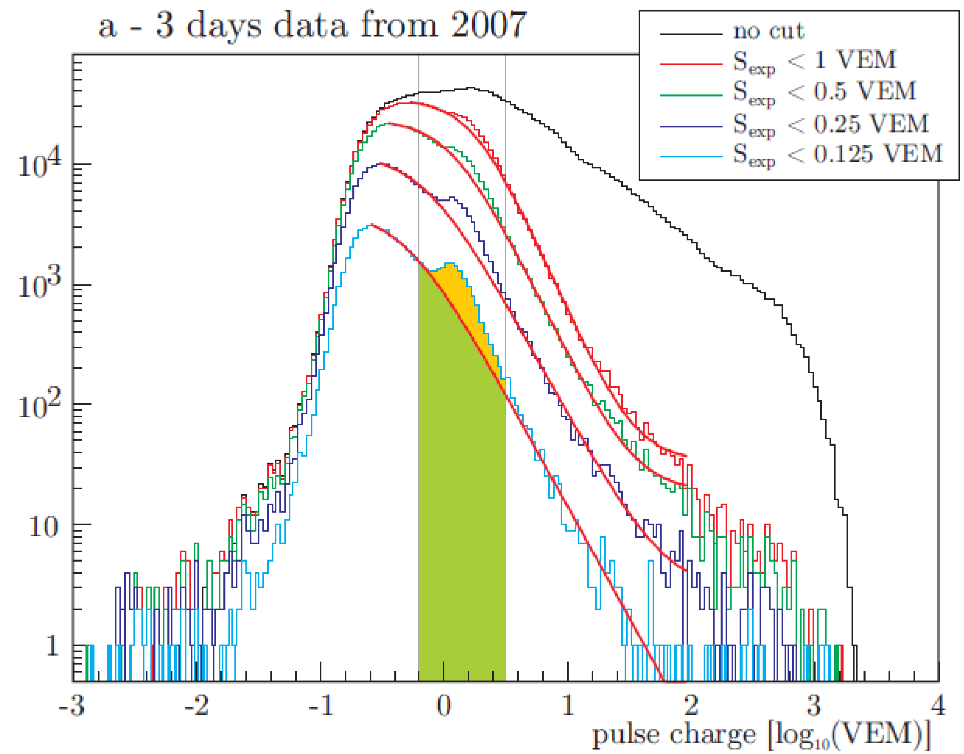




Muons at the Surface

Adam Lucke, 2008

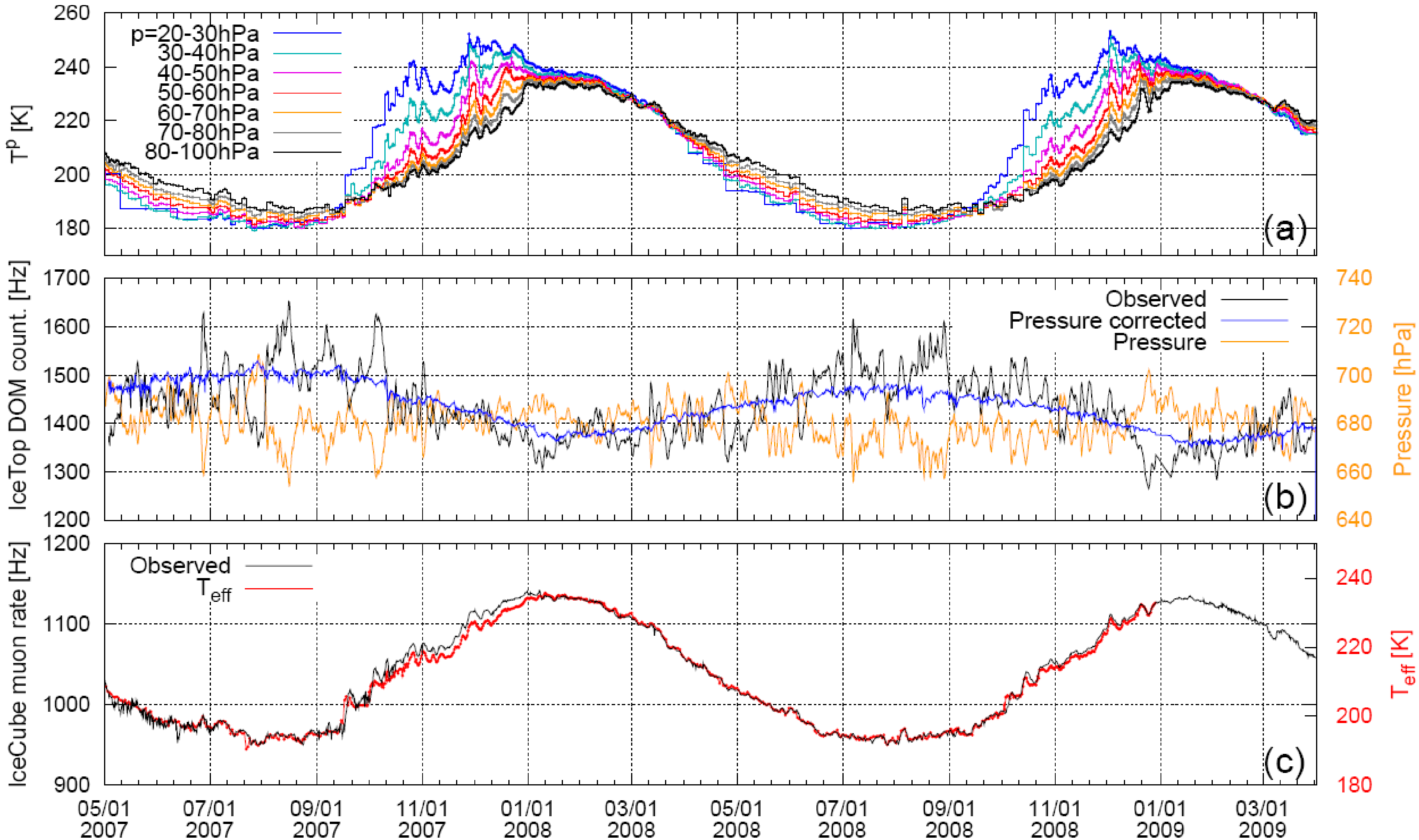




Muon abundance sensitive on mass

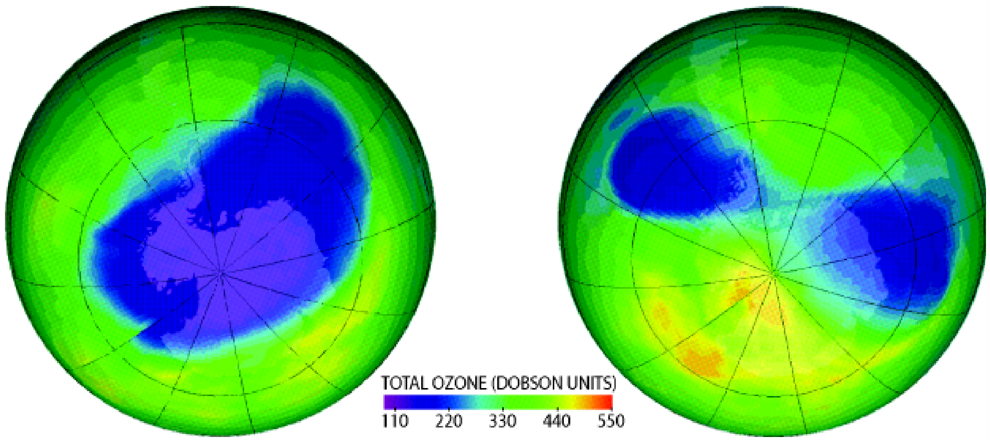
- in addition: “Soft” Local Coincidence → measure single muons
- alternative (?): analysis of rise time of signal pulses

Atmospheric Variations as observed by IceCube



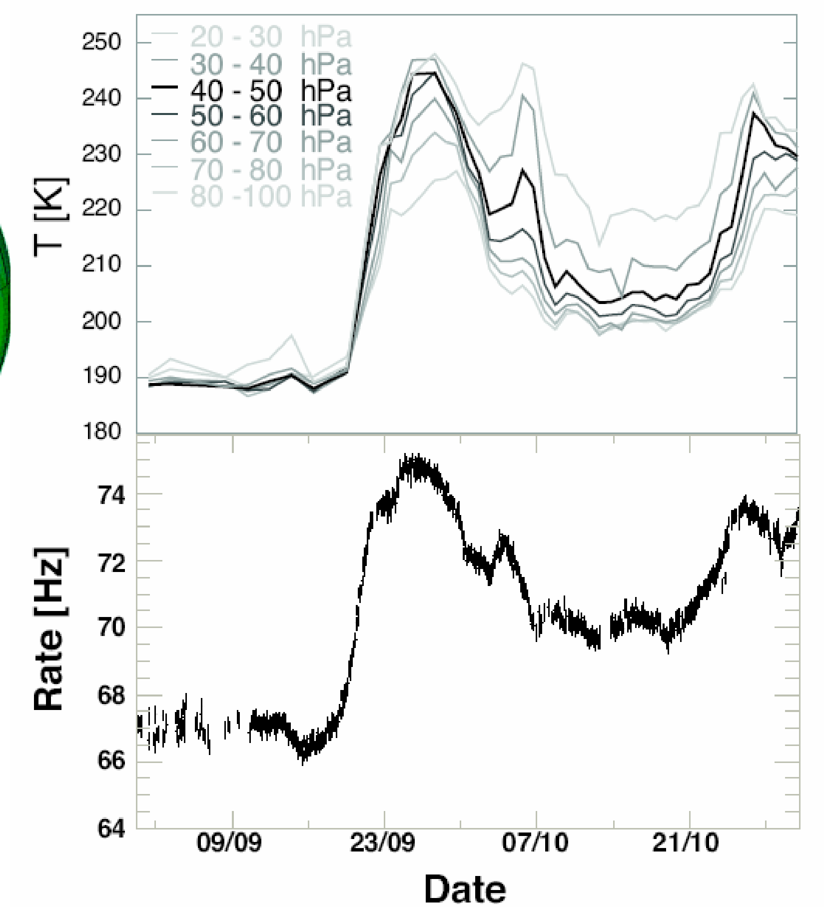
Ozon Layer Temperature

Ozone concentration over the southern hemisphere



Sept. 20th 2002

Sept. 25th 2002



The Antarctic ozone layer is at pressure levels of 20-120 hPa where also the first cosmic ray interactions occur.

IceCube closely probes the temporal behavior of the stratospheric temperatures and the ozone hole dynamics

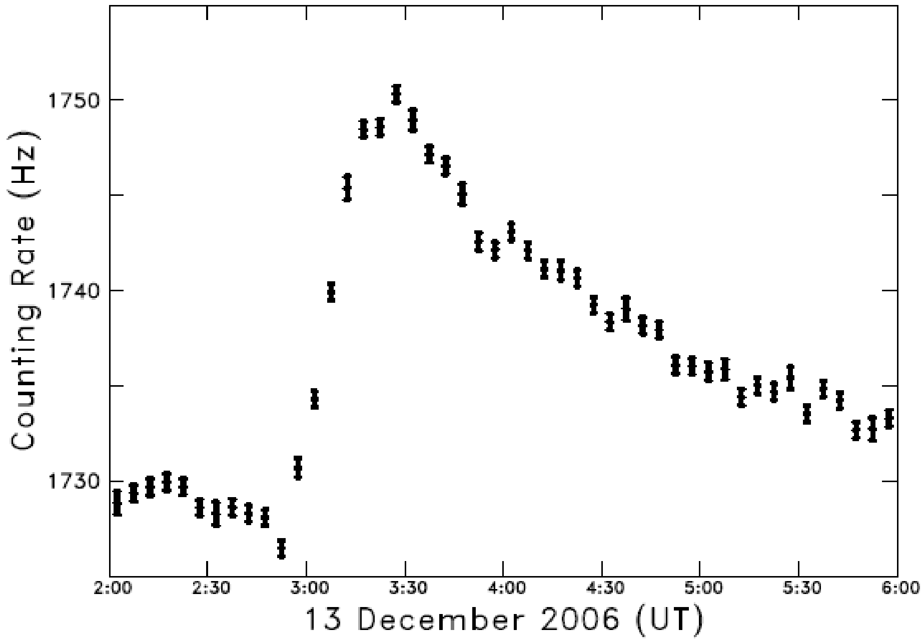
Heliospheric Physics

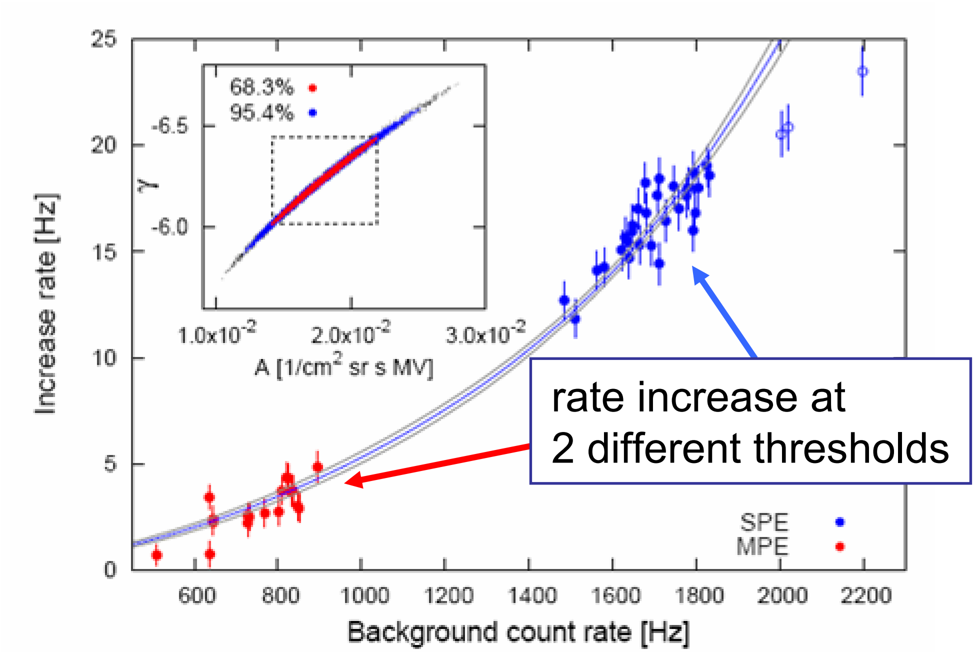
13 Dec 2006 Solar Flare Detection by IceTop

[ApJ Lett., 689: L65–L68, 2008]

On 2006 December 13 the IceTop air shower array at the South Pole detected a major solar particle event.

... the response of the IceTop tanks with multiple thresholds deployed at high altitude with no geomagnetic cutoff,

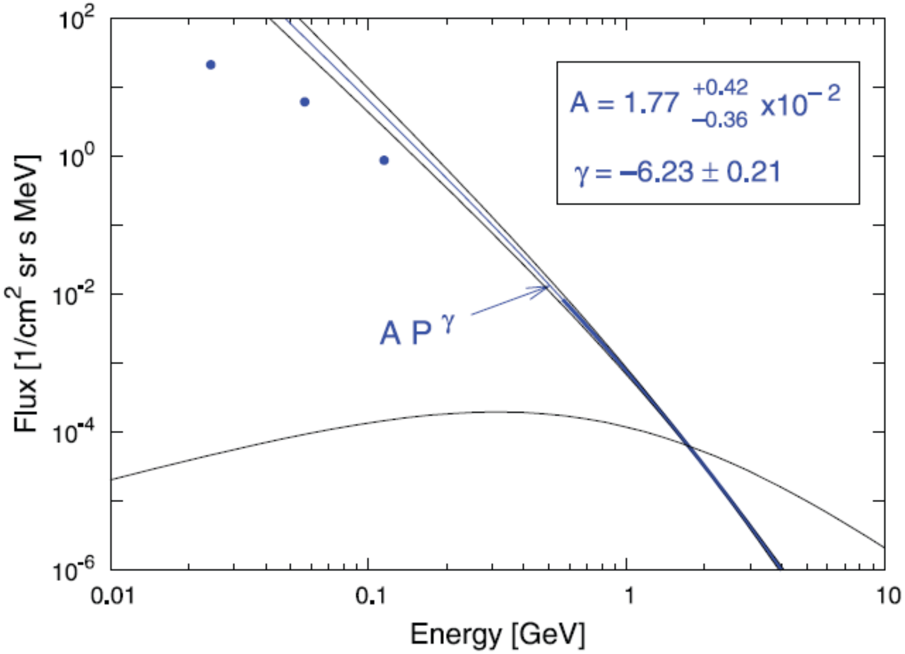




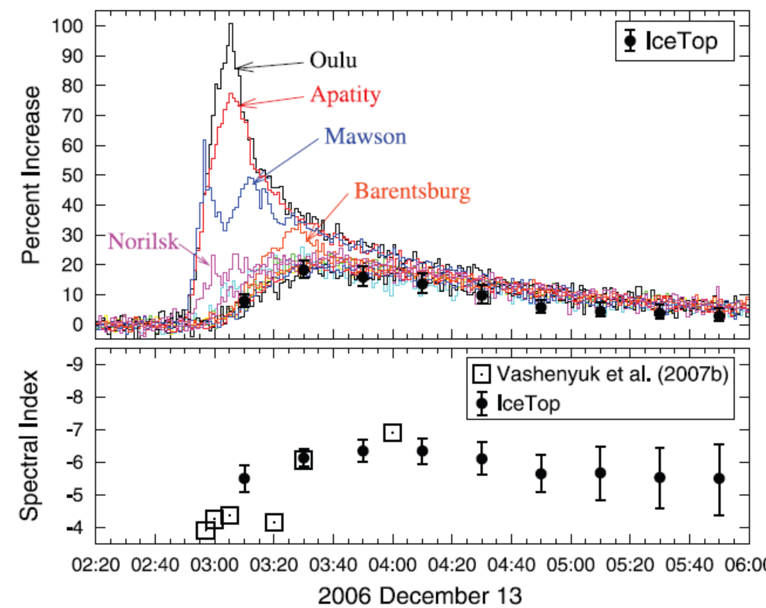
Heliospheric Physics with IceTop

By numerically simulating the response of the IceTop tanks, we determined the particle energy spectrum in the energy range 0.6–7.6 GeV.

This is the first such spectral measurement using a single instrument with a welldefined viewing direction.



comparison with neutron detectors



plans for improved resolution of solar particle spectra:
take **differential energy spectra** („multi-threshold“ rates)

Summary

- first preliminary IceTop **energy spectrum** for 26/80 of the detector, 1 month

- the spectrum was analysed in terms of **composition** models

  exploiting the **zenith angle dependence** of shower development on the composition

- **prospects for composition analysis up to 1 EeV:**
  - IceTop-InIce coincidence yielding:

    energy – muon number correlations
  - muon counting in IceTop
  - complementary methods $\Rightarrow$ test of models

- other science topics open up:
  - atmosphere, sun, ...


The End