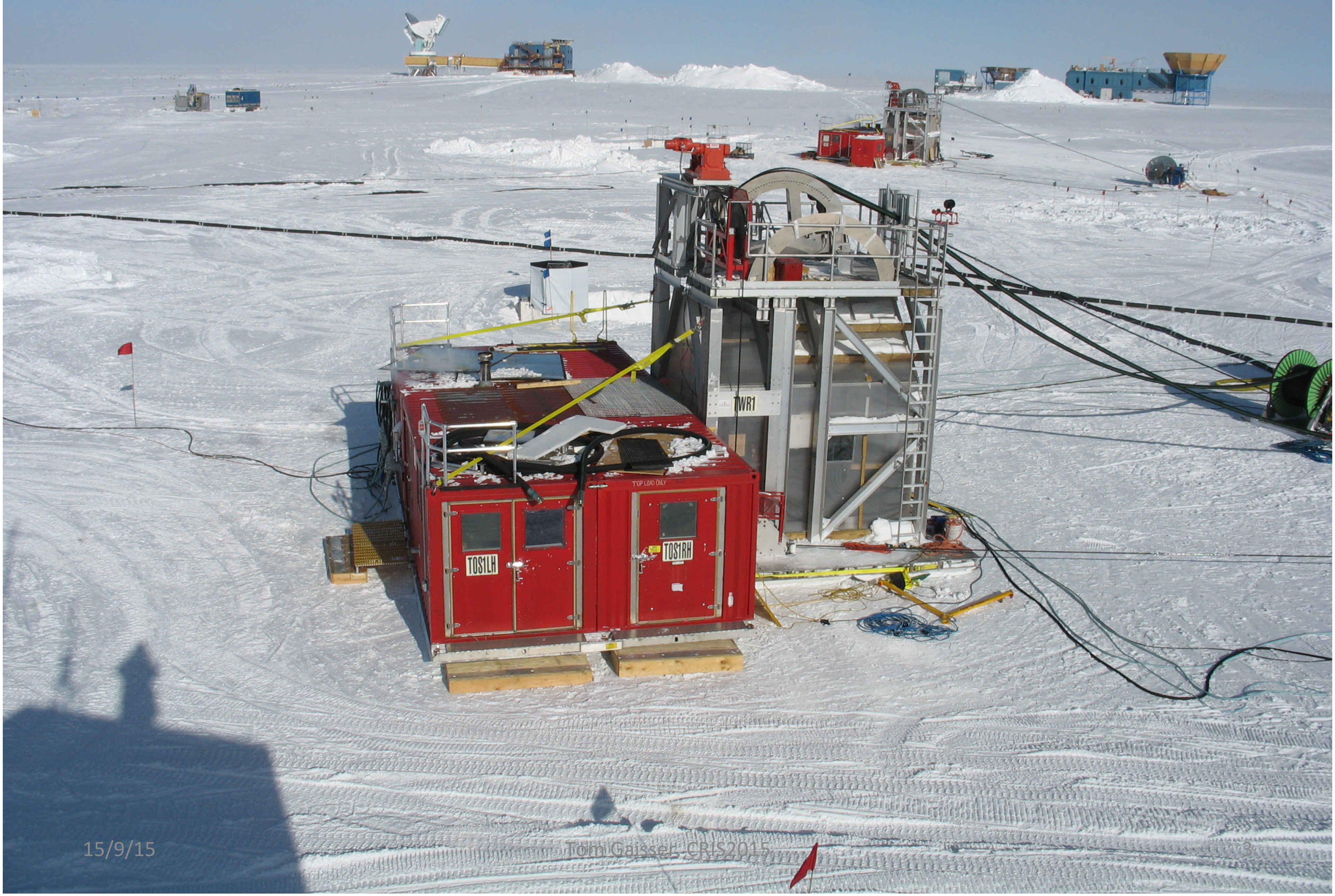
Primary spectrum and composition with IceCube/IceTop

CRIS 2015

Outline

- Historical introduction
- Spectrum and Composition with coincident events
  - Use showers that pass through both IceTop and the deep array of IceCube
- Measuring muons at the surface
- Structure in the primary spectrum
- Future

Construction: 2004-2011



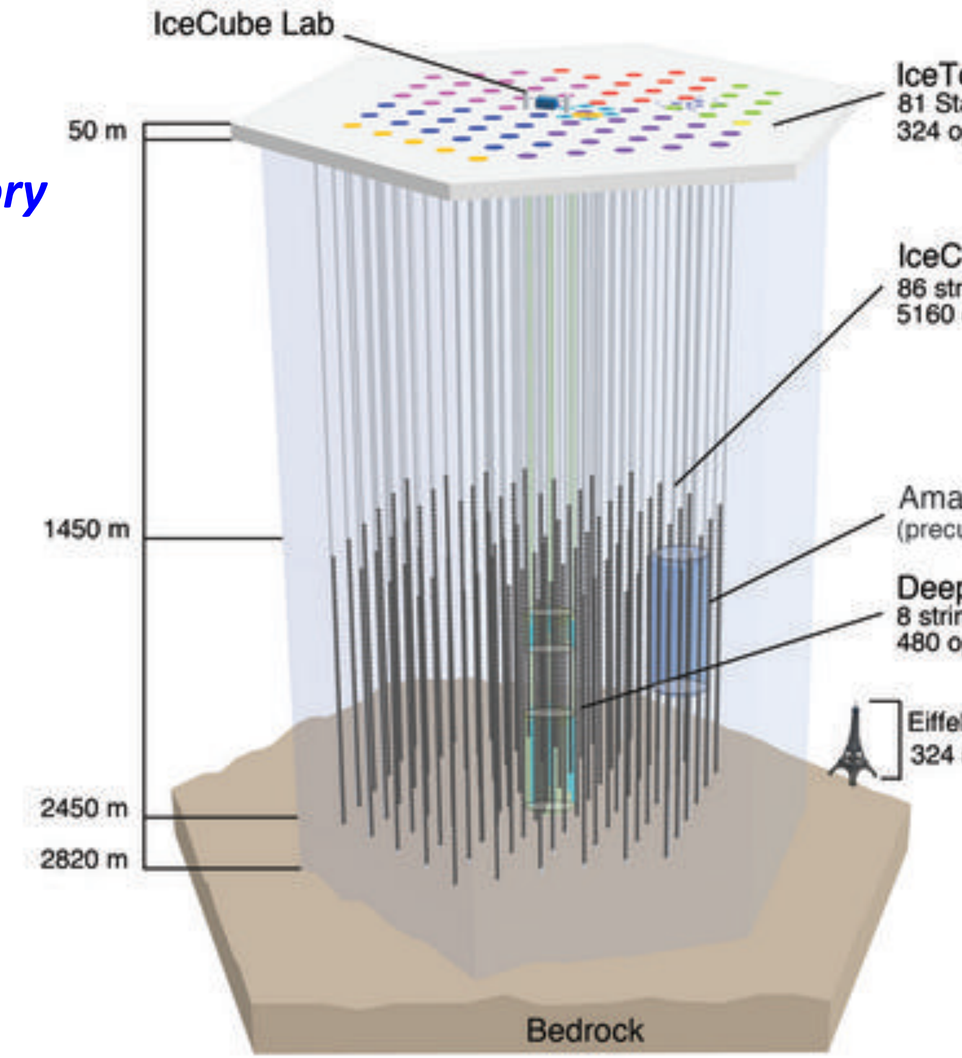
Deployment history

2002: proposal
2003-04 staging

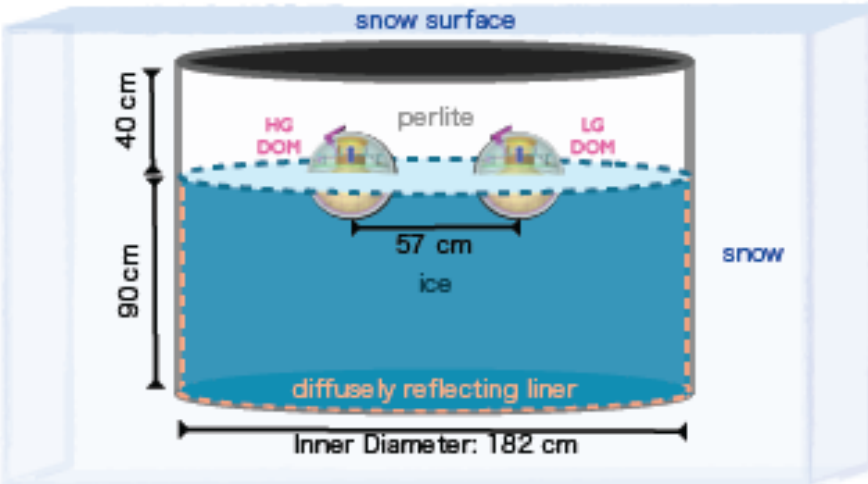
2004-05	1	4
2005-06	9	16
2006-07	22	26
2007-08	40	40
2008-09	59	59
2009-10	79	73
2010-11	86	81

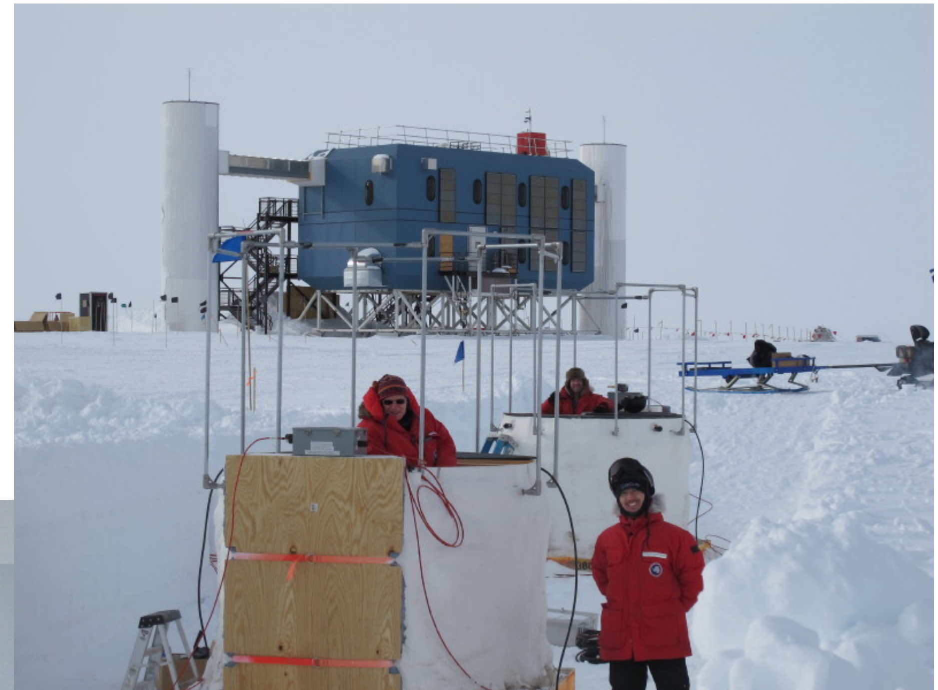
Deep strings

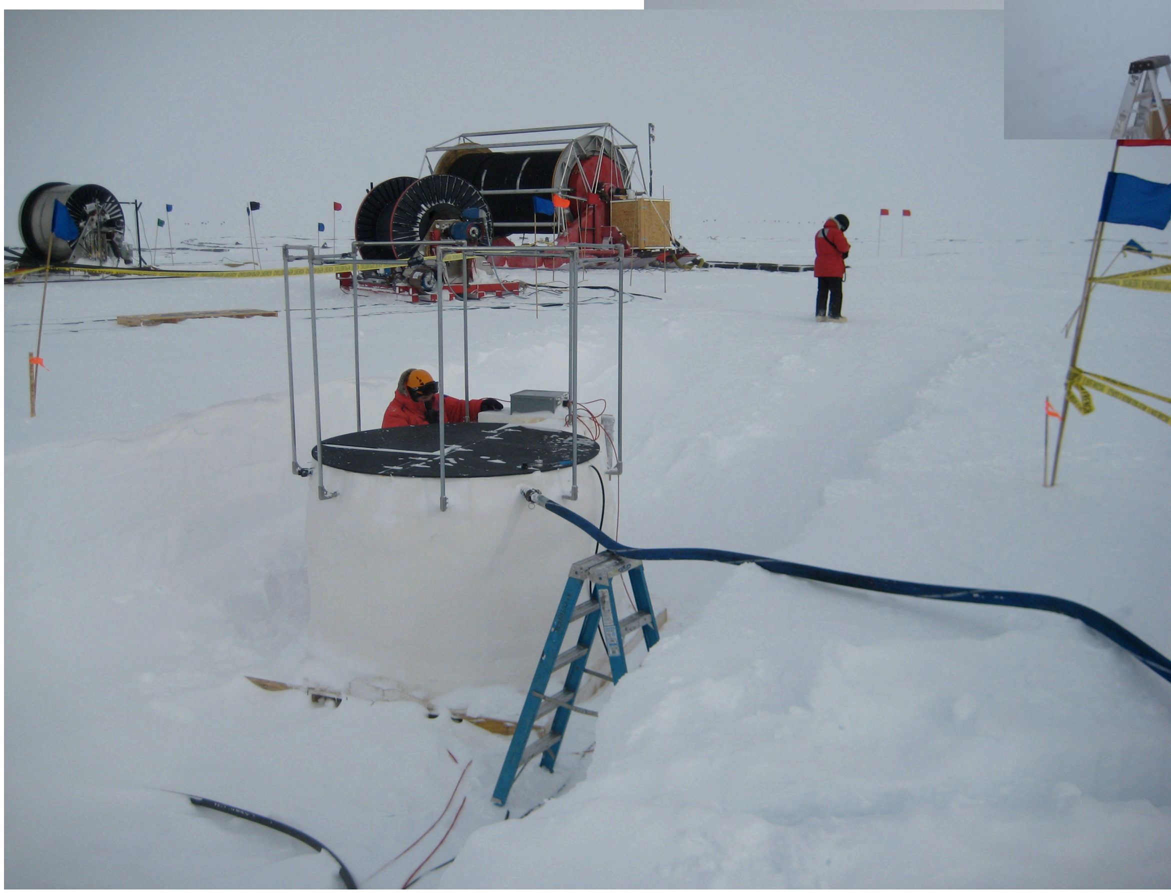
Surface stations



> 5400 Digital Optical Modules


snow surface
40 cm
90 cm
perlite
HG DOM
LG DOM
57 cm
ice
snow
diffusely reflecting liner
Inner Diameter: 182 cm





A 3-D cosmic-ray detector:

Two different kinds of events

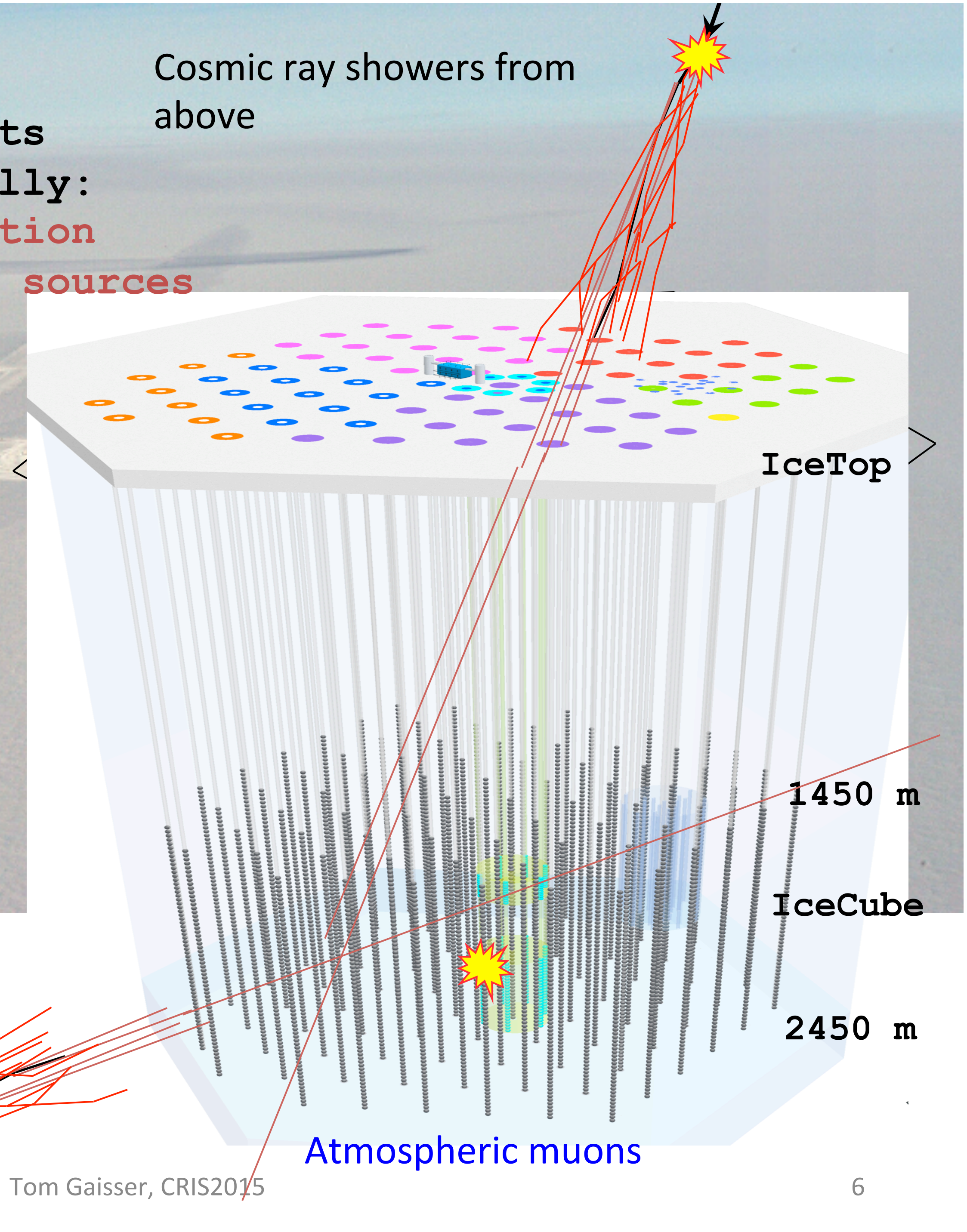
Closely related scientifically:

- Cosmic rays after propagation
- Neutrinos from cosmic ray sources
- $\nu_e : \nu_\mu : \nu_\tau$ = 1:2:0 → 1:1:1

South Pole
2835 m.a.s.l.

Neutrinos from all directions

- *ν_μ-induced μ (from below)*
- *all flavors starting inside detector*



Aperture for coincident events:
$A\Omega \approx 0.26\ \text{km}^2\ \text{sr}$

Pre-history

1950-52 in a salt mine at 1574 m.w.e. in Ithaca, NY with 4 surface detectors and 1 m^2 muon counters underground. Acceptance: ~ 0.01 m^2 sr: Barrett, Bollinger, Cocconi, Eisenberg, Greisen, Revs. Mod Phys. 24 (1952) 133-178

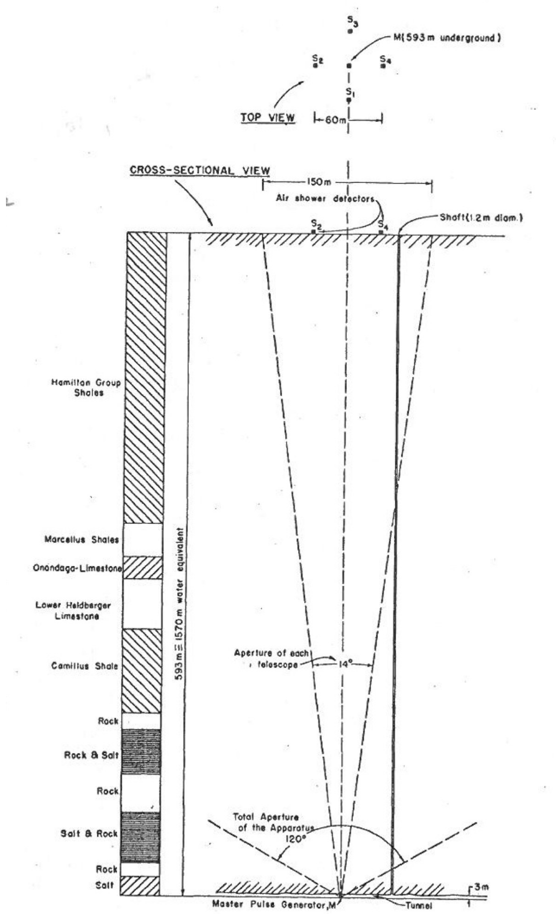
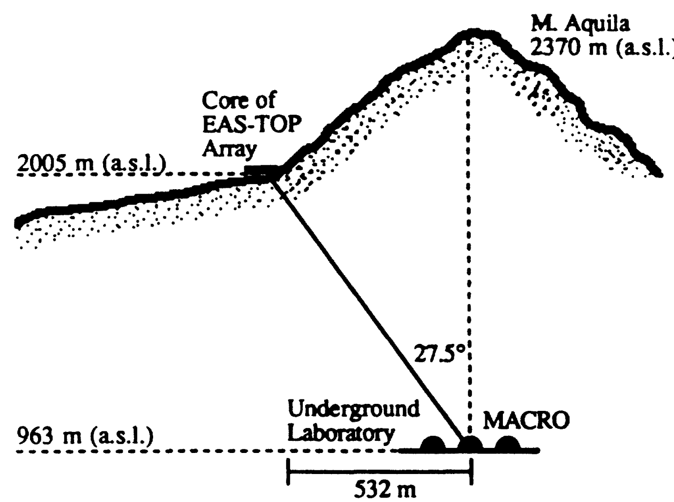


FIG. 11. Diagram showing relative positions of the counters underground and on the surface of the ground in the experiments on the association of mesons with extensive air showers. The composition of the ground is shown in the scale at the left.

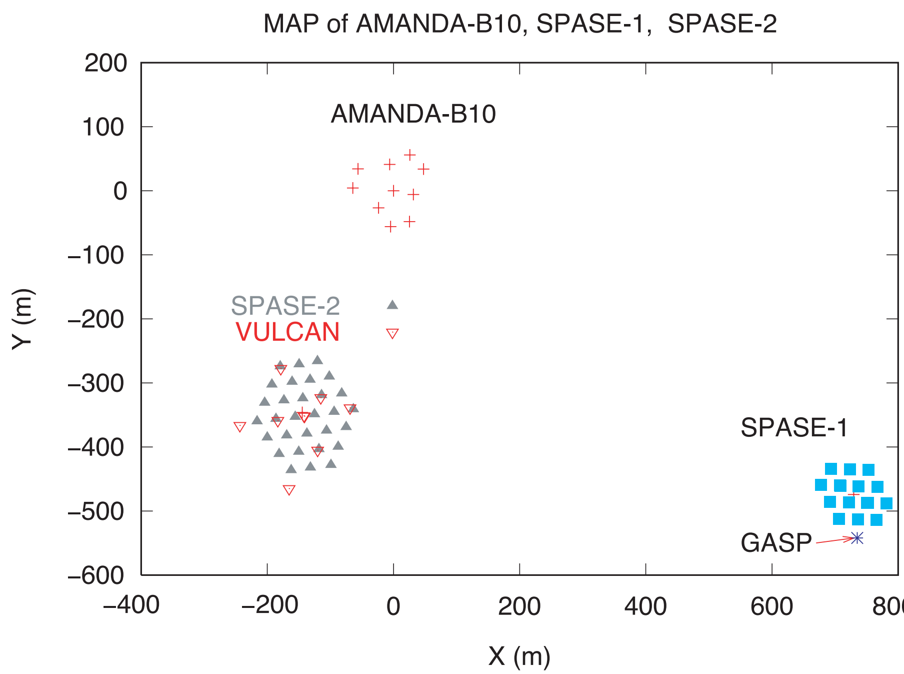
EASTOP MACRO, R. Bellotti et al., PRD 42 (1990) 1396-1403
AΩ ~ 100 m^2 sr



SPASE-2 1995

Daniele Martello building SPASE-2

SPASE – AMANDA: $A\Omega \sim 100\ m^2\ sr$



Survey of AMANDA from SPASE-1 and SPASE-2
NIM A 522 (2004) 347-359

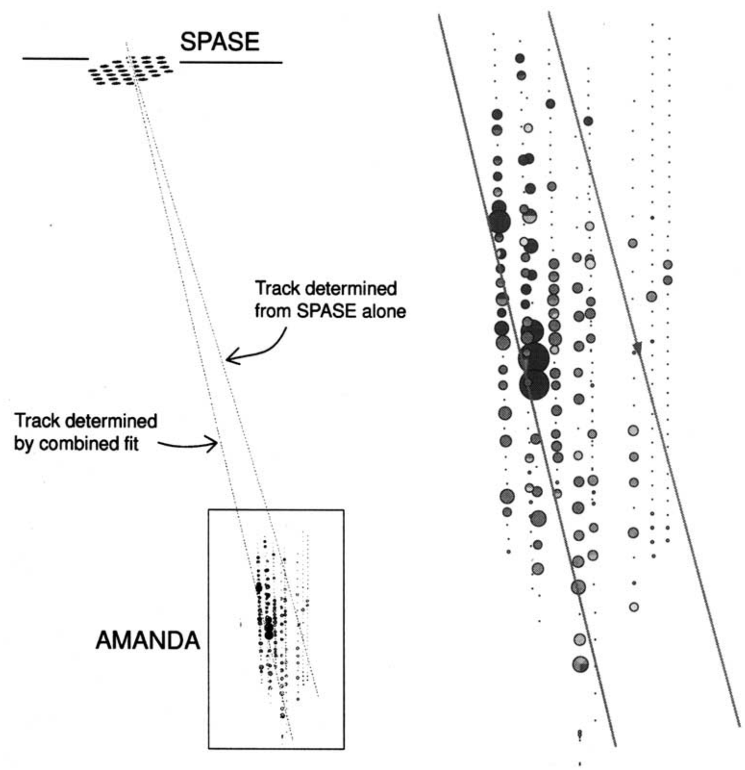
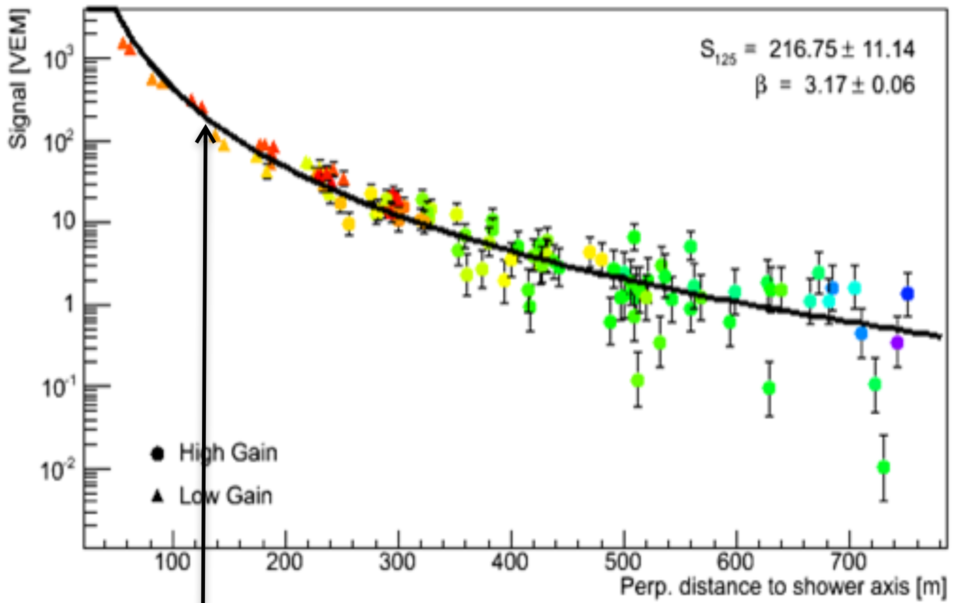
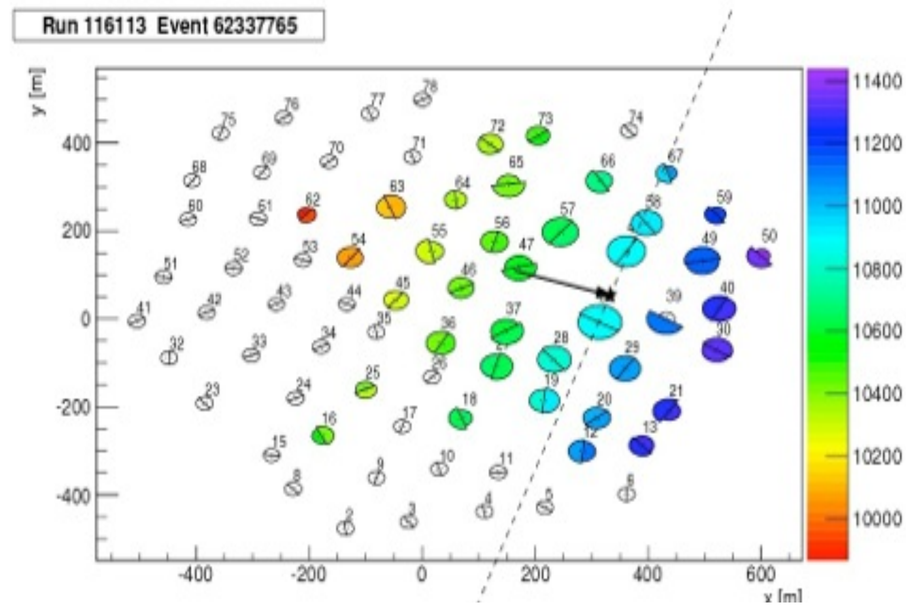


Fig. 1. SPASE/AMANDA coincidence event from 1997 data.

Composition at the knee with SPASE-2/AMANDA B10,
Astropart. Phys. 21 (2004) 565-581

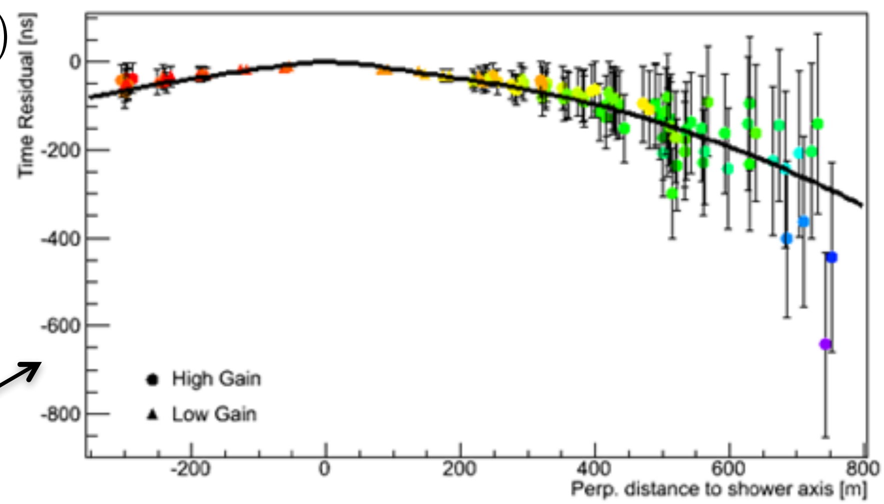
Shower reconstruction in IceTop





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

Attenuation due to snow

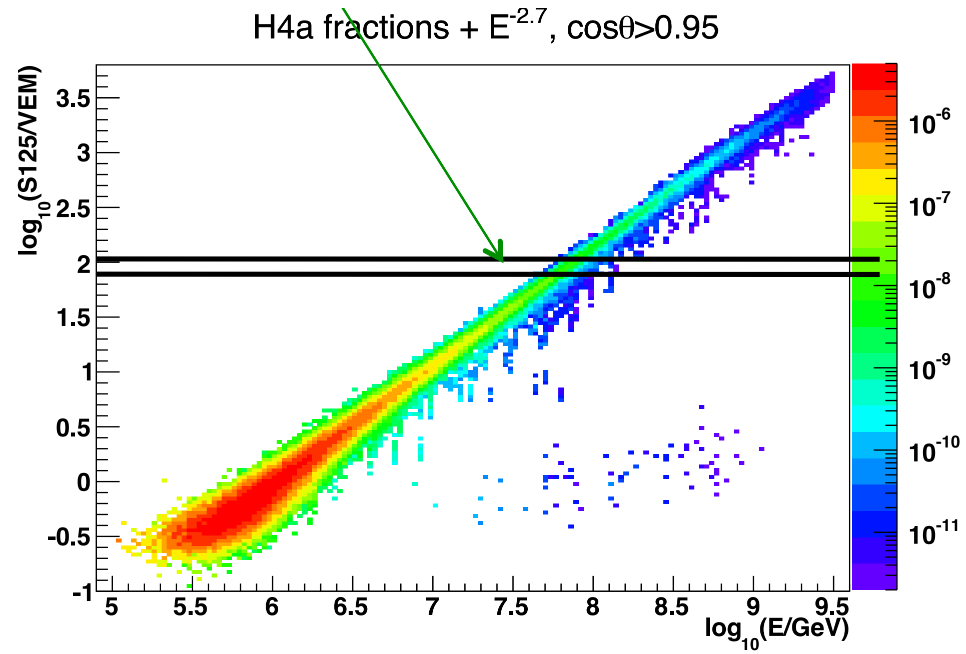


$$t(\boldsymbol{x}) = t_0 + \left(\frac{\boldsymbol{x}_c - \boldsymbol{x}}{c}\right) \cdot \boldsymbol{n} + \Delta t(R)$$

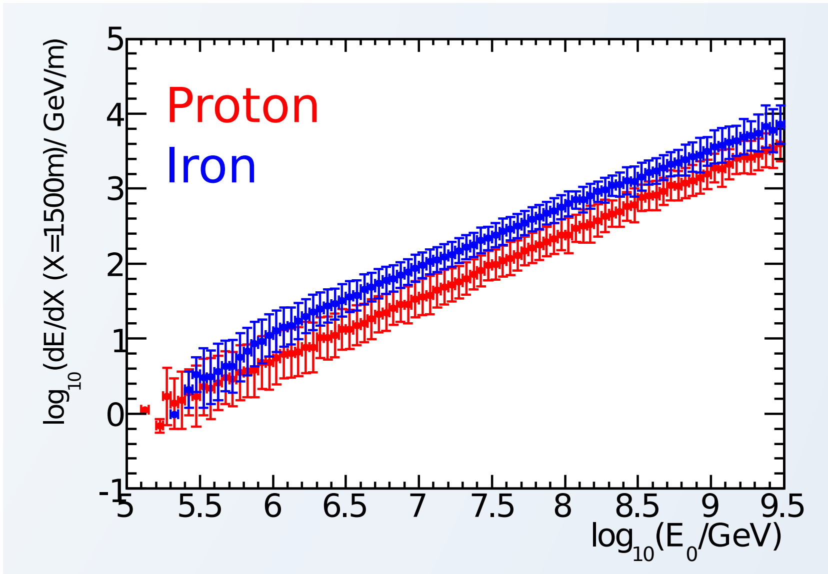
$$\Delta t(R) = aR^2 + b\left(\exp\left(-\frac{R^2}{2\sigma^2}\right) - 1\right)$$

Simulations

Mean primary E for given S_{125}

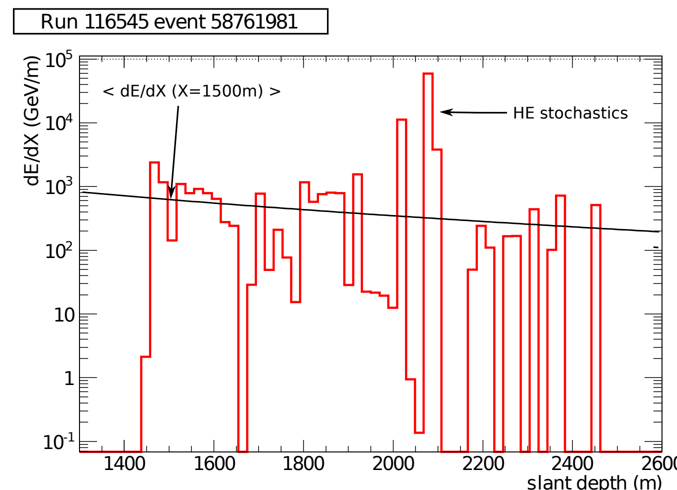


Muon energy loss (GeV/m) at 1500 m for p and Fe



Composition from coincident events

- Select events contained in IceTop + deep array
- Reconstruct trajectory
  - Find S_{125} of shower at surface
  - Measure dE/dX in ice



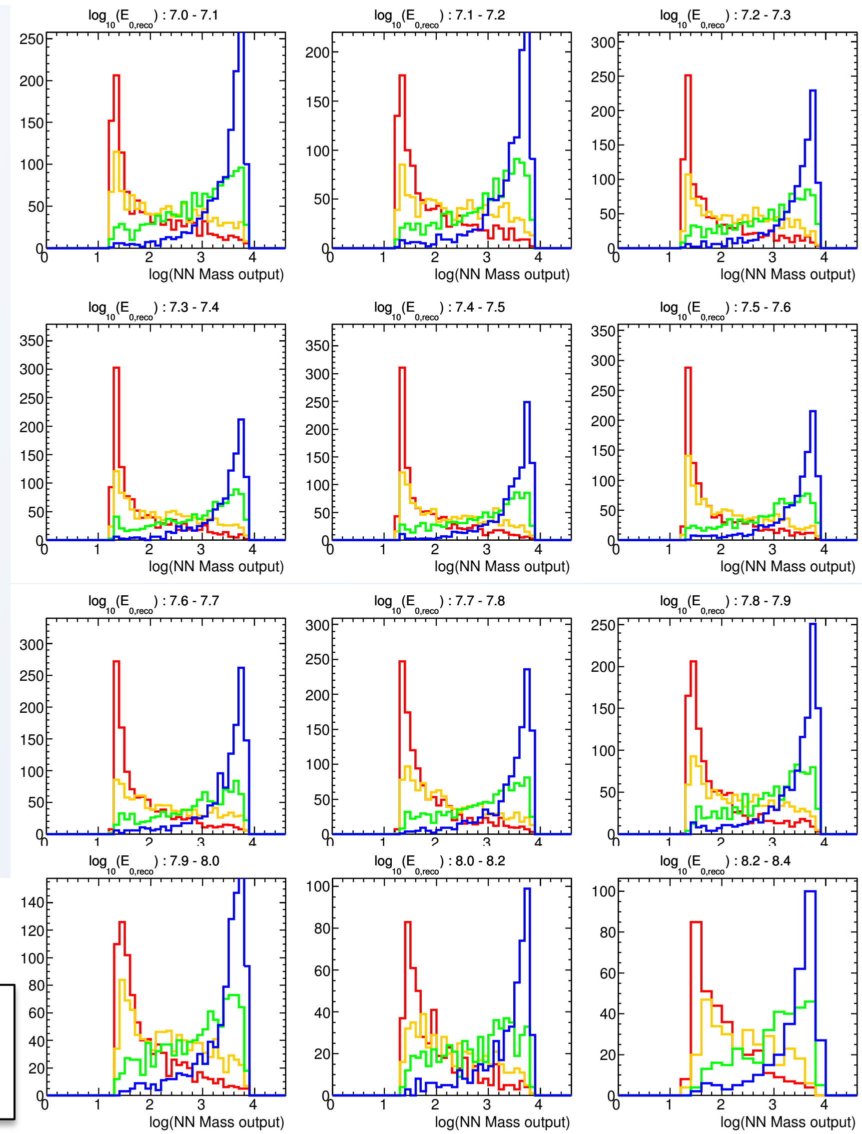
- Construct neural network
  - Input: 5 variables, S_{125}, θ , dE/dX@1500 m, stochastic losses (big), stochastic losses (small)
  - Output: primary energy, index for mass

Composition from neural network

Construct template histograms of NN primary mass

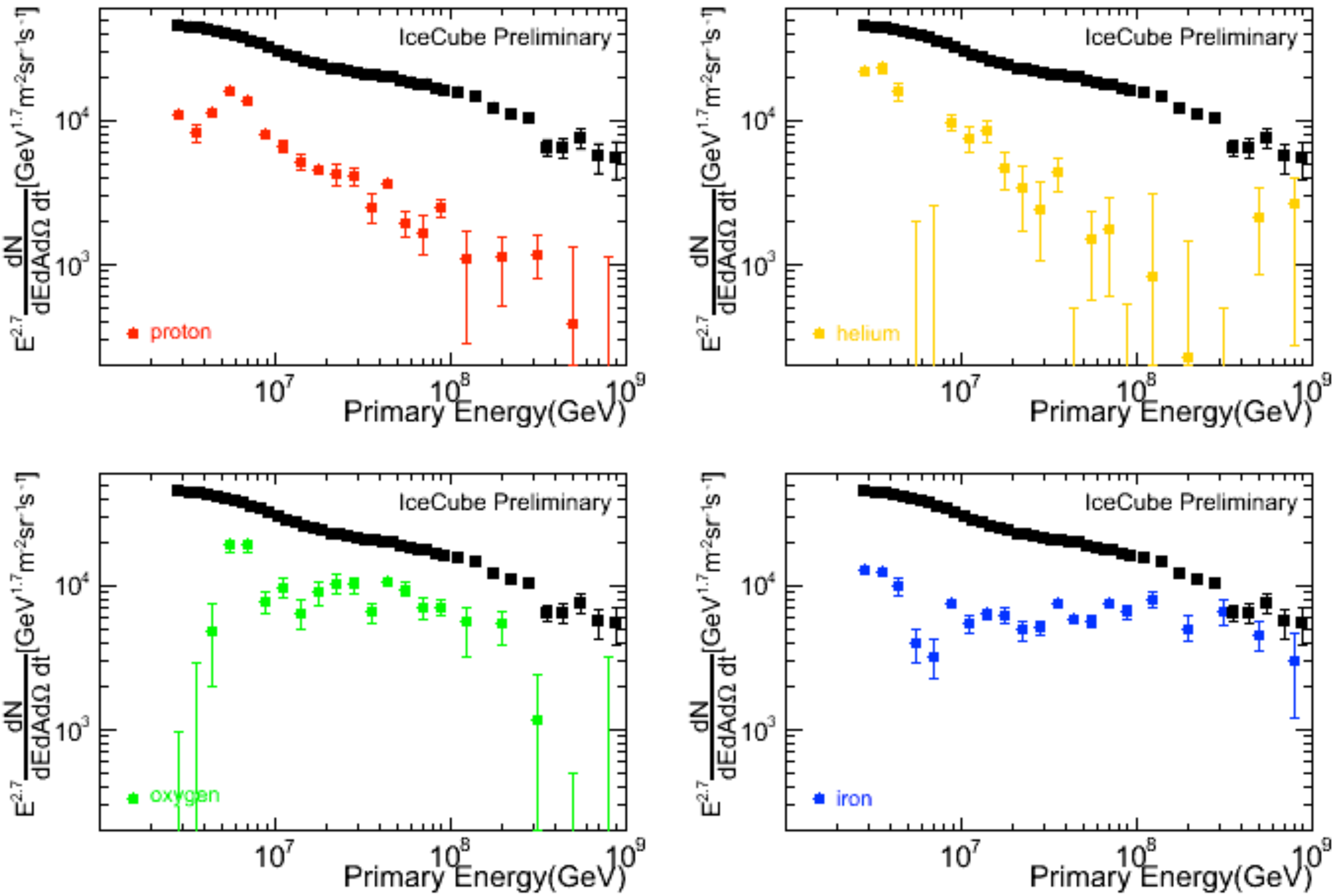
Within each bin of reconstructed energy, compare templates for Monte Carlo (four types: H, He, O, Fe)

Run experimental data through the same NN procedure, and find the fractions of each element that best reproduce the template histogram of the data.



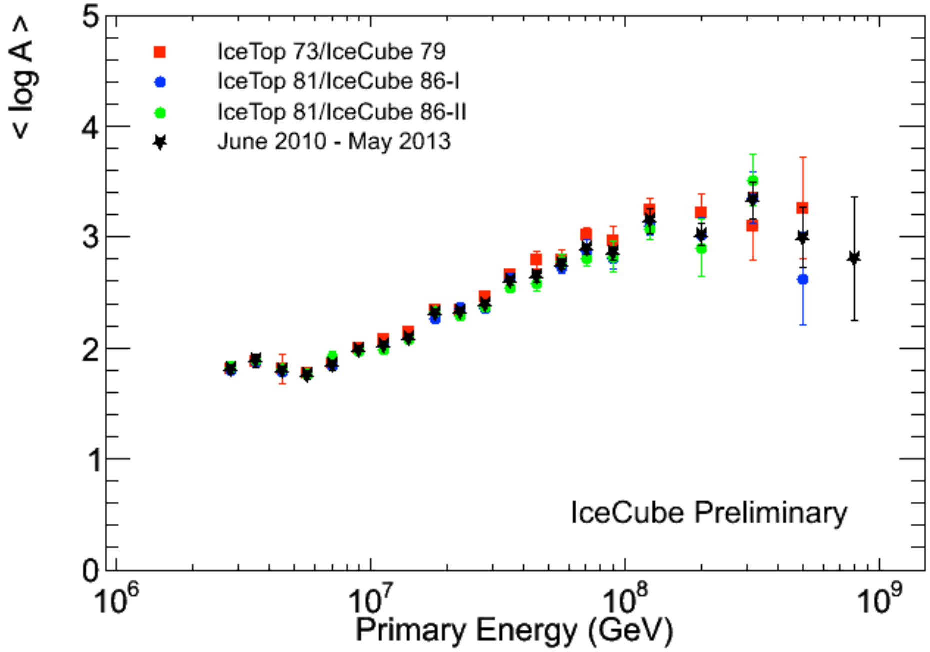
Katherine Rawlins, IceCube, TAUP 2015

Spectra of 4 elemental groups

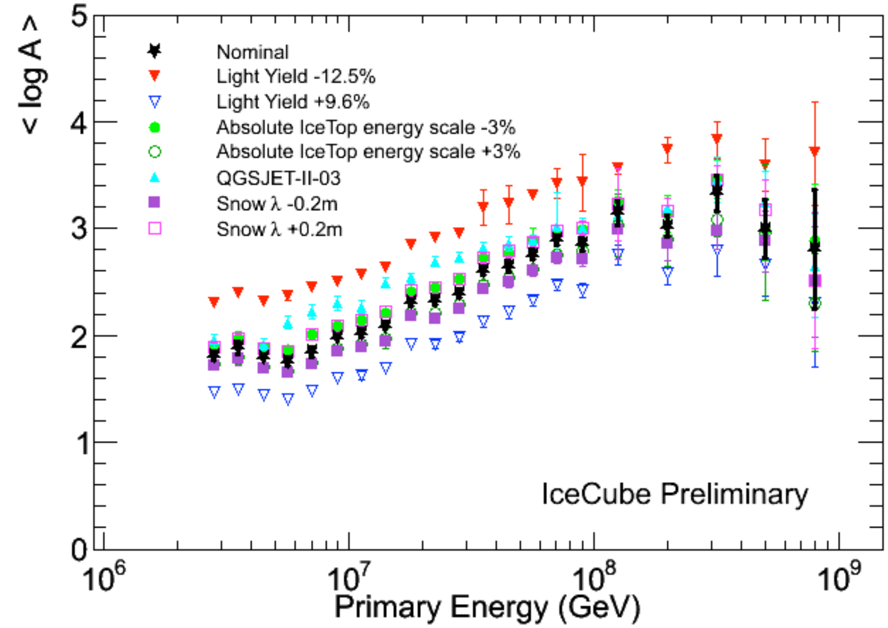


Statistical and fit uncertainties only

Mean ln(A)



< log A >
IceTop 73/IceCube 79
IceTop 81/IceCube 86-I
IceTop 81/IceCube 86-II
June 2010 - May 2013
IceCube Preliminary
Primary Energy (GeV)



< log A >
Nominal
Light Yield -12.5%
Light Yield +9.6%
Absolute IceTop energy scale -3%
Absolute IceTop energy scale +3%
QGSJET-II-03
Snow λ -0.2m
Snow λ +0.2m
IceCube Preliminary
Primary Energy (GeV)

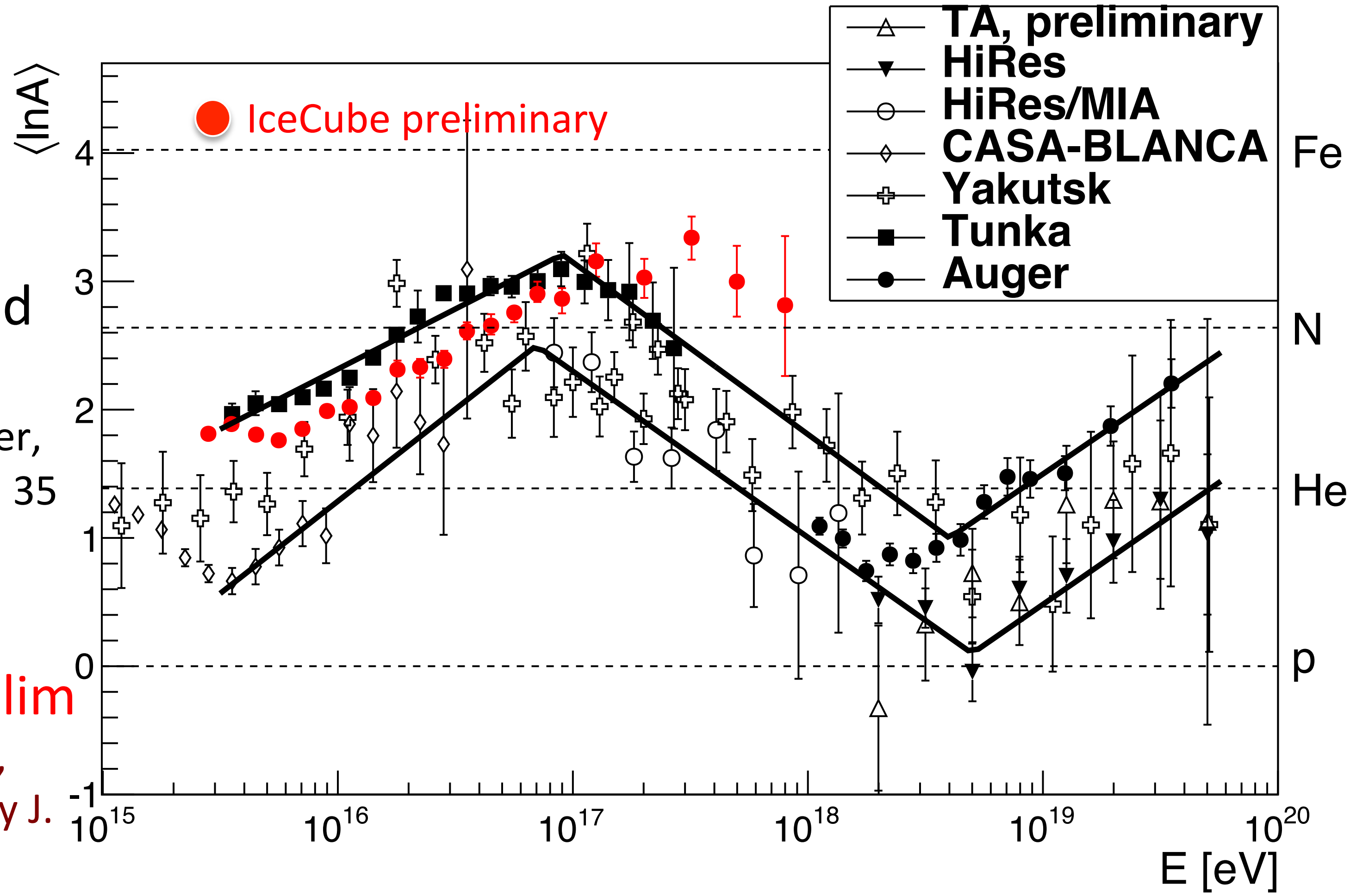
Compare < ℓn(A)>

Plot: inferred from Xmax

Kampert & Unger, Astropart. Phys. 35 (2012) 660-678

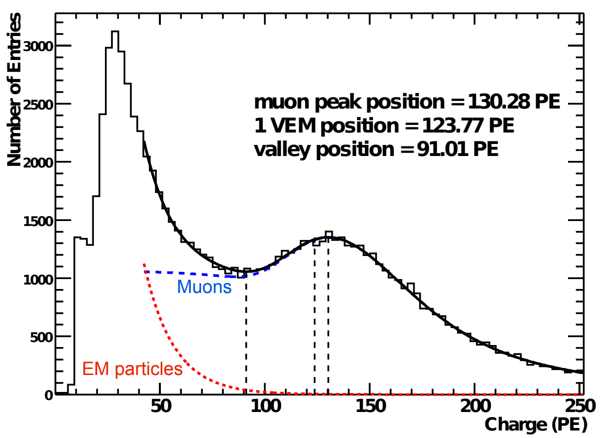
Red points: IceCube prelim

T.Feusels thesis, results shown by J. Gonzalez @ UHECR2014



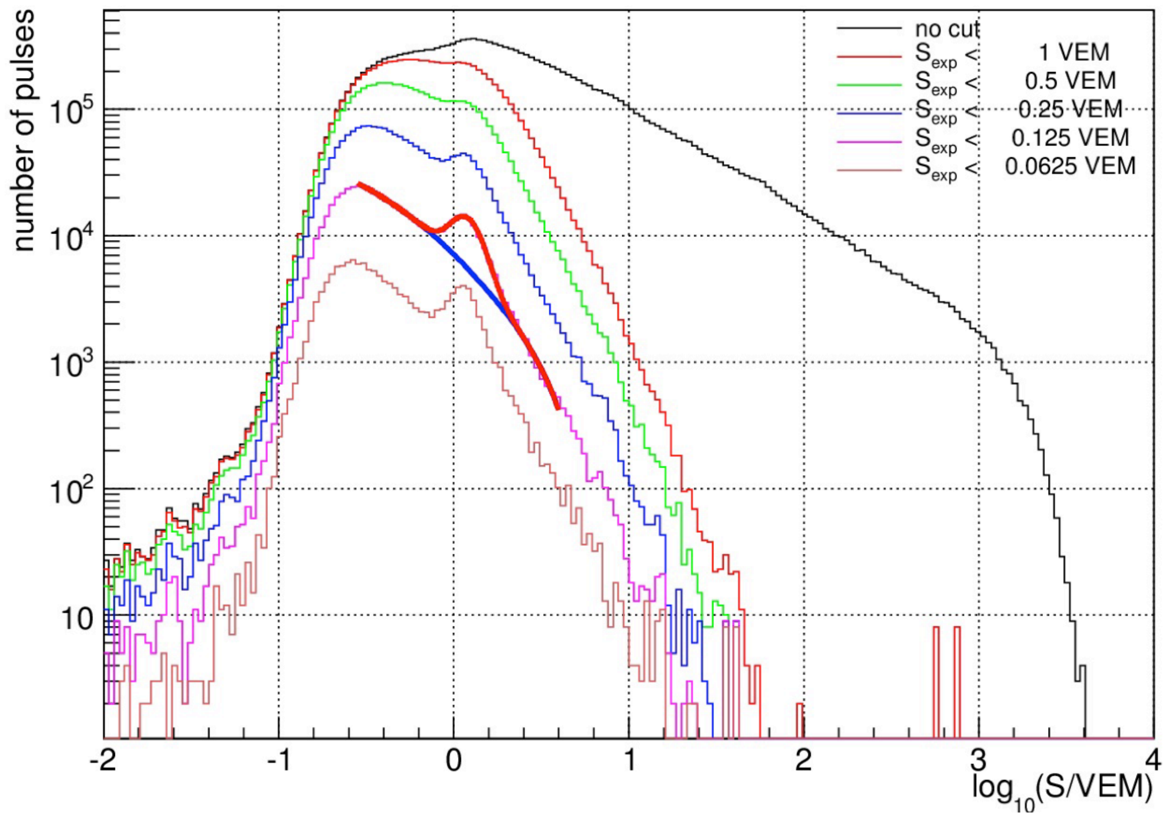
Surface muons in IceTop: the idea

Use the fact that we know very well the signal of muons in tanks from our calibration procedure.



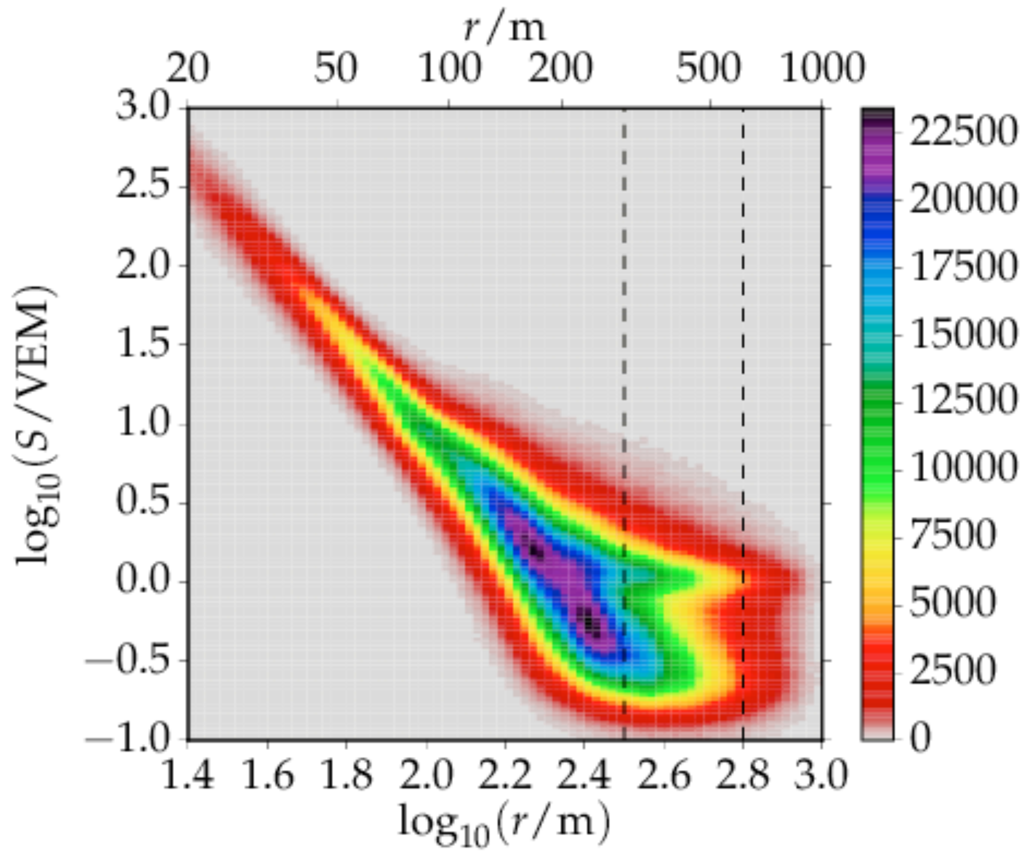
Calibration run for DOM 61-61 (ICRC 2011, arXiv:1111.2735, A van Overloop for IceCube

Look for the muon signal to appear in the periphery where the expected em signal is < 1 VEM



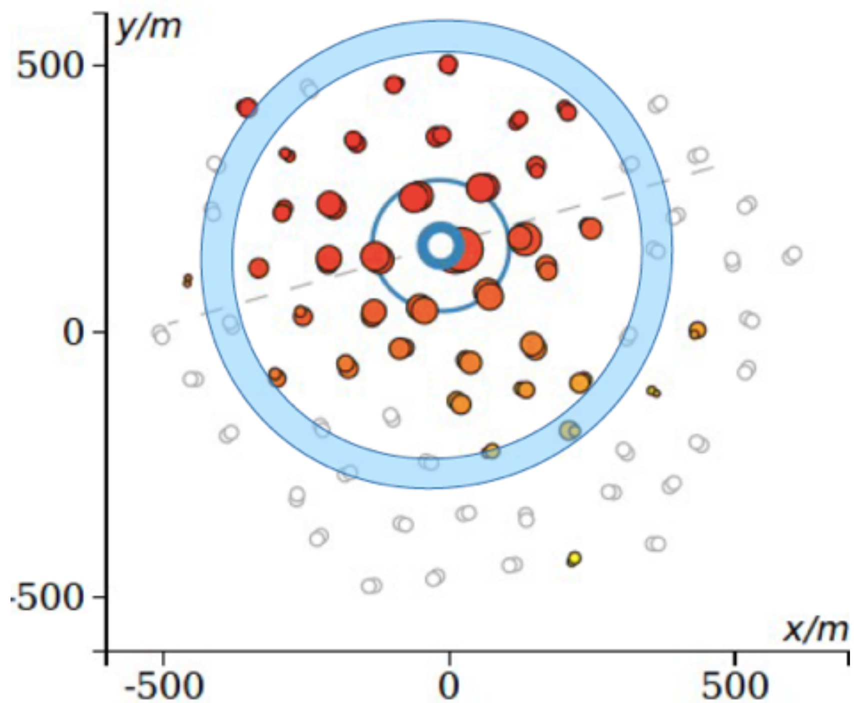
H. Kolanoski, for IceCube, ICRC Beijing, 2011

Implementation*



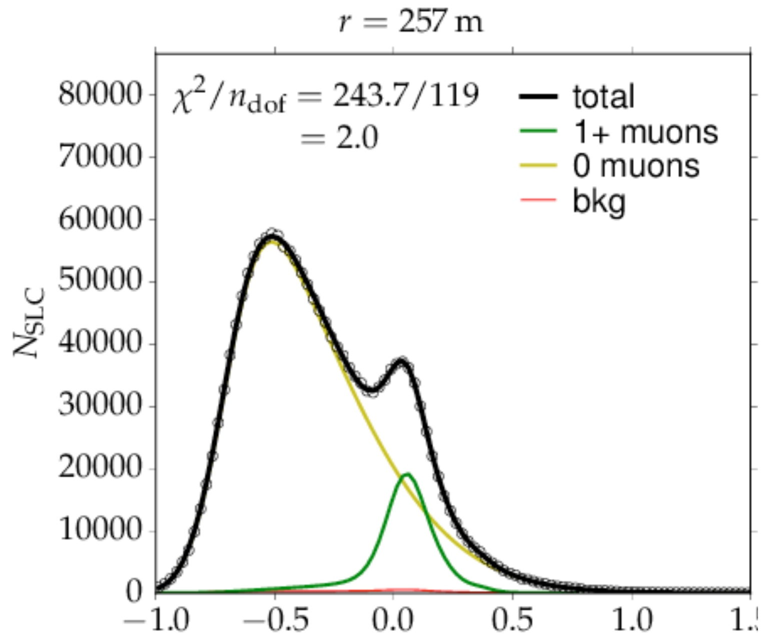
*Javier Gonzalez, ISVHECRI 2014 (arXiv:1501.03415)
Hans Dembinski, ICRC 2015

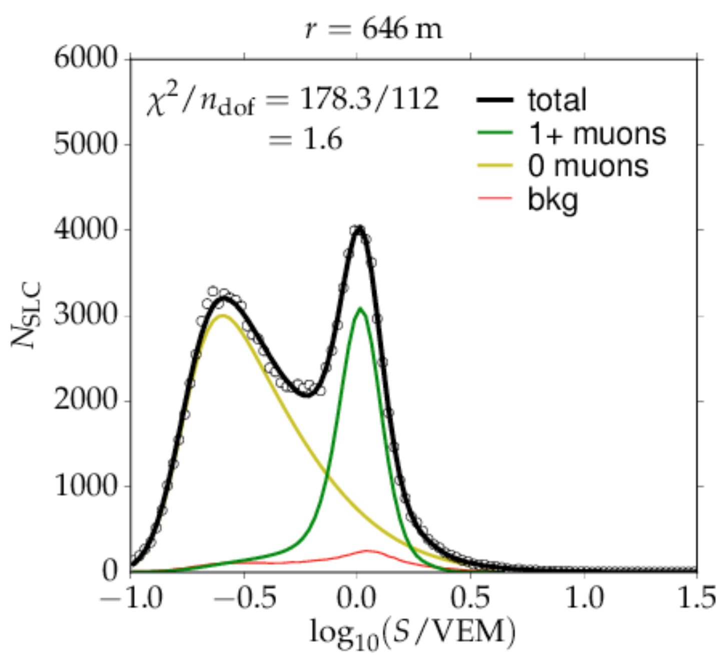
How the muon density is extracted

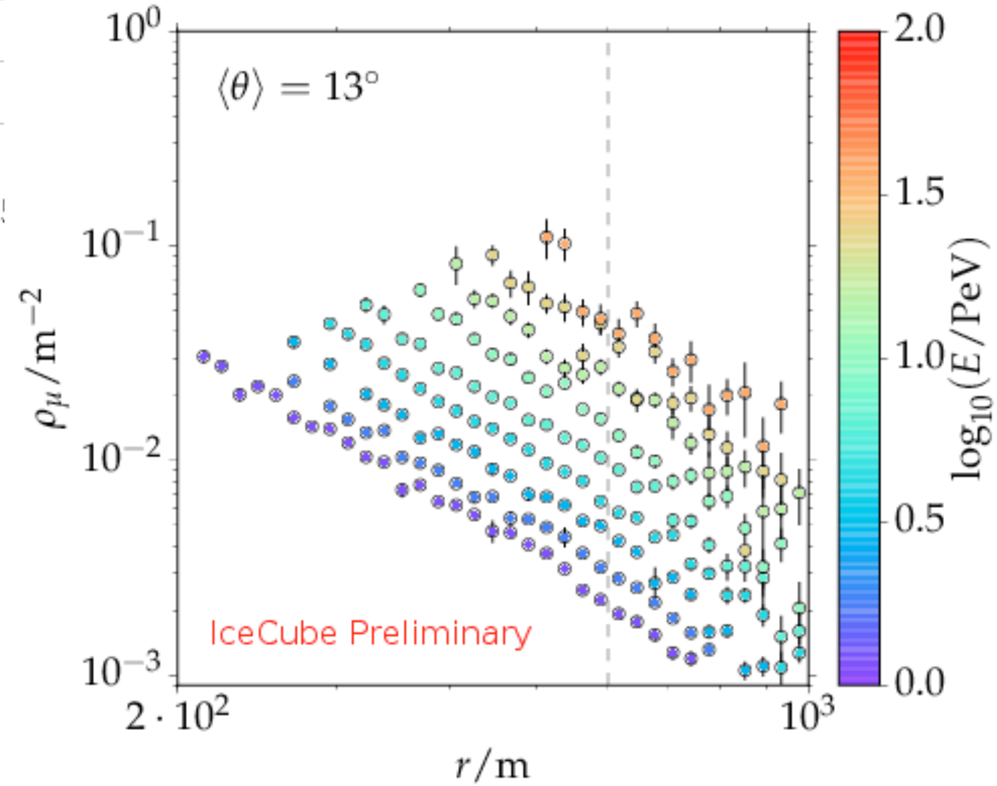


$$\rho_\mu \approx \frac{N_{\text{tanks in ring with }\mu}}{N_{\text{tanks in ring}}}\frac{1}{A_{\text{tank}}}$$

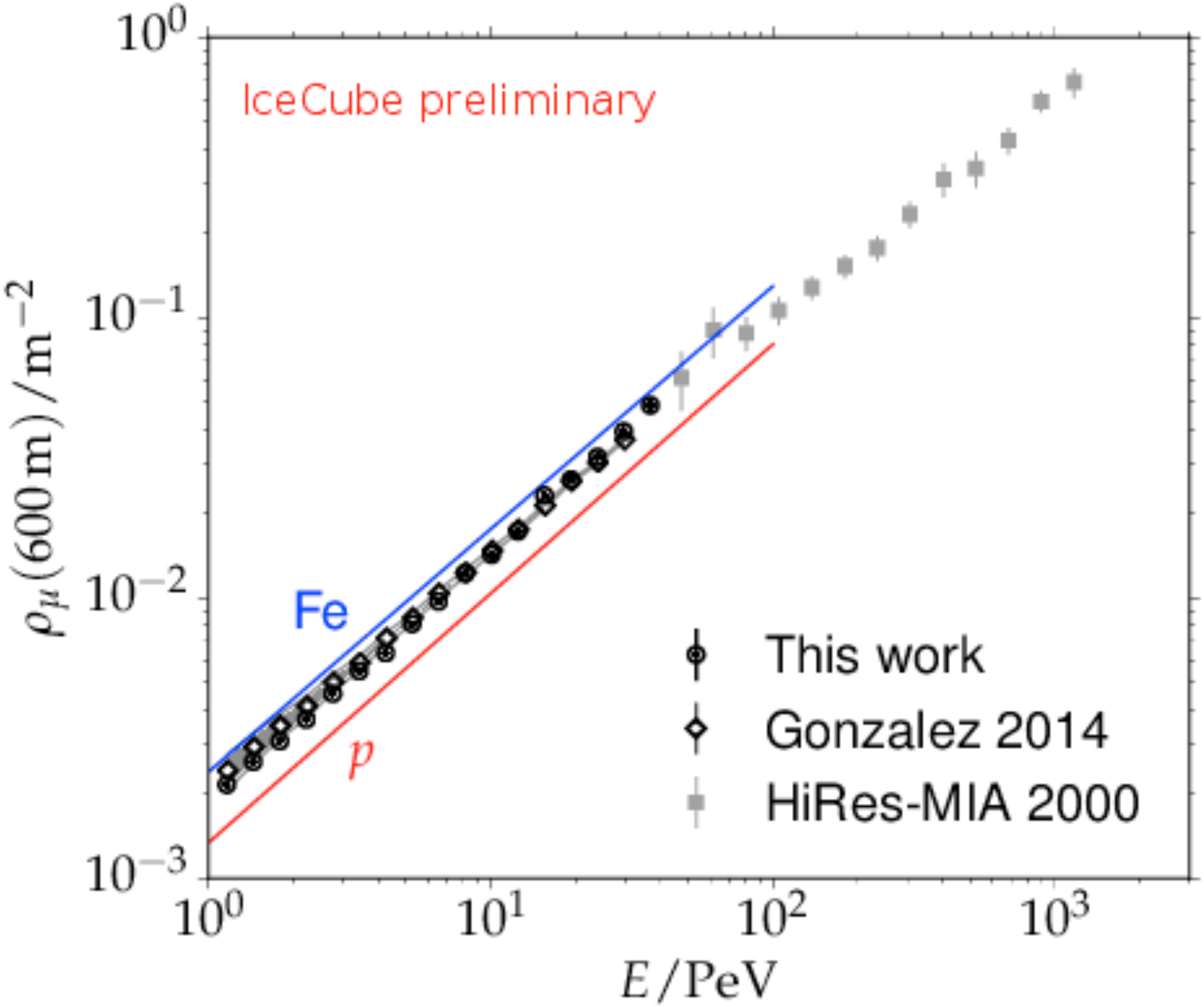
ρ_μ vs r & E


r = 257 m
$\chi^2/n_{dof} = 243.7/119 = 2.0$
total
1+ muons
0 muons
bkg
N_{SLC}

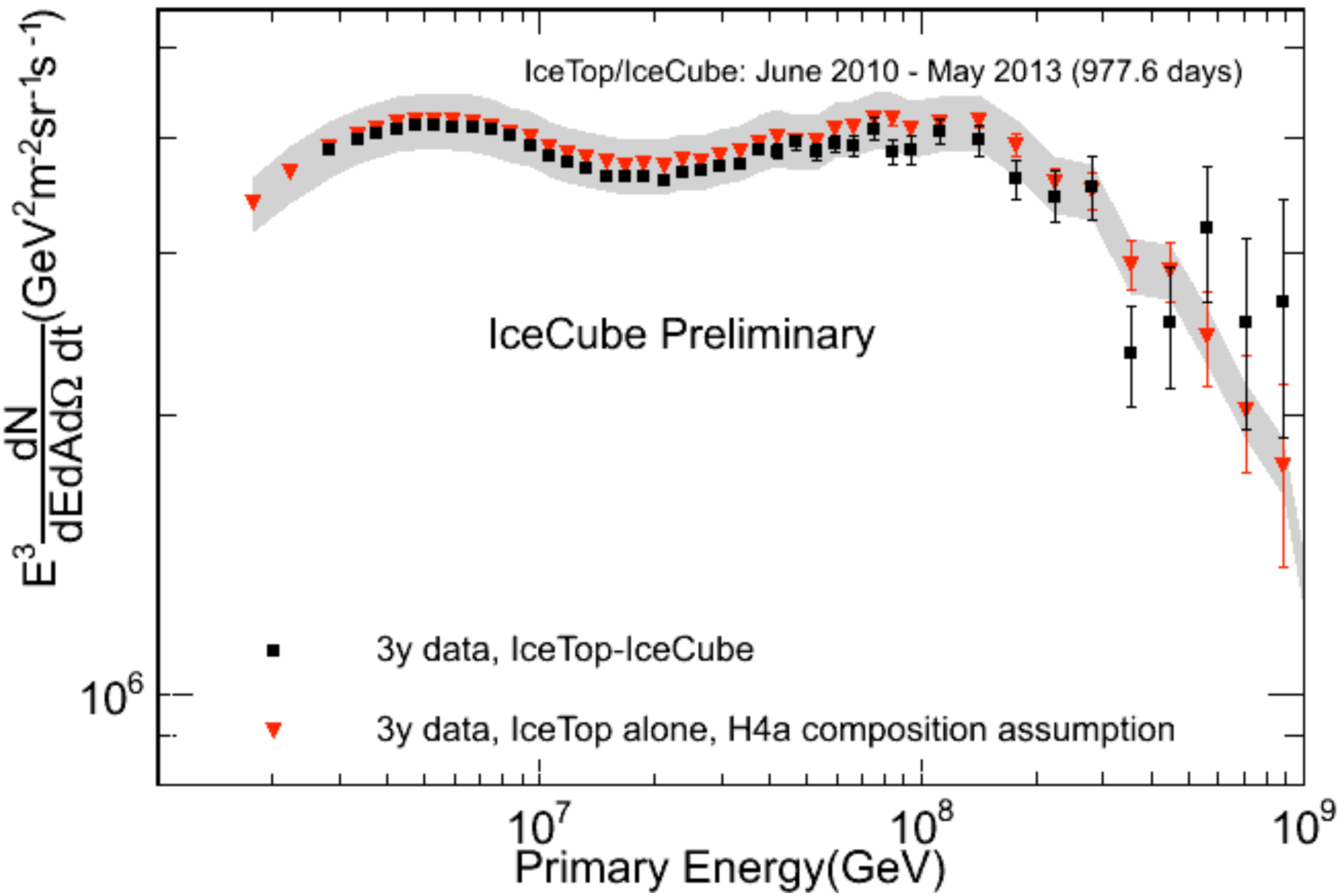

r = 646 m
$\chi^2/n_{dof} = 178.3/112 = 1.6$
total
1+ muons
0 muons
bkg
N_{SLC}
$\log_{10}(S/VEM)$


$\langle\theta\rangle = 13°$
IceCube Preliminary
ρ_μ/m^{-2}
r/m
$\log_{10}(E/PeV)$

Muon density at 600 m

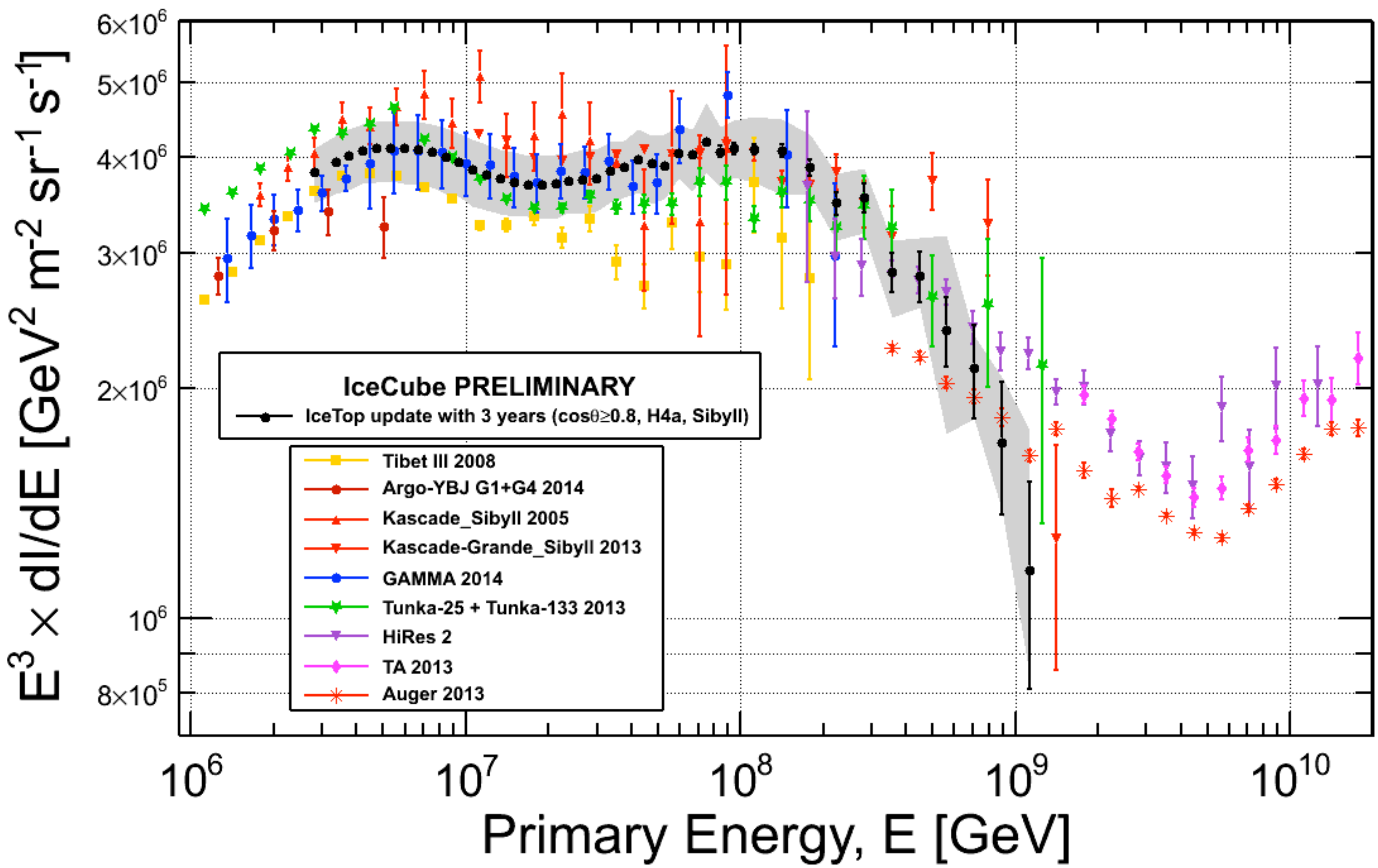


Spectrum

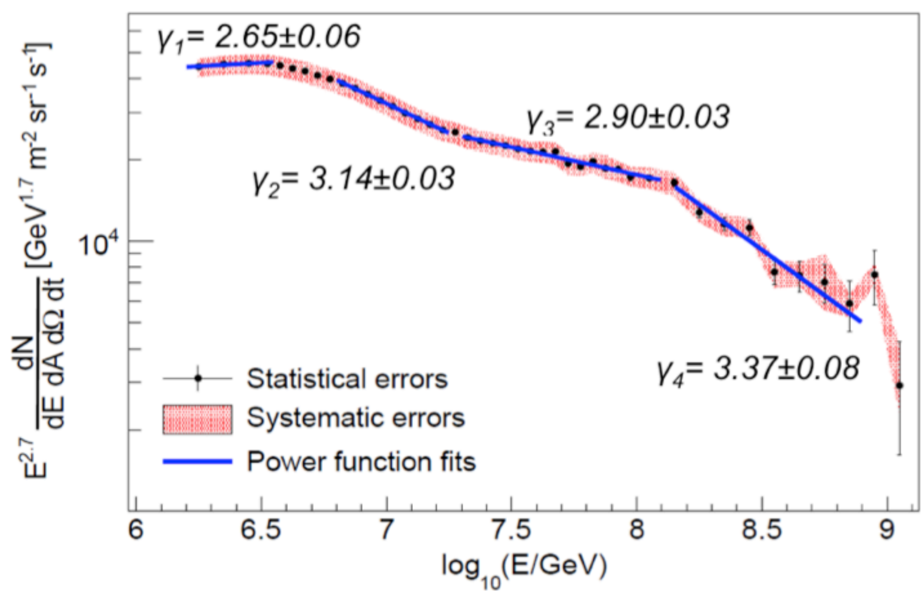


IceTop/IceCube: June 2010 - May 2013 (977.6 days)
IceCube Preliminary
3y data, IceTop-IceCube
3y data, IceTop alone, H4a composition assumption
10^6
10^7
10^8
10^9
Primary Energy(GeV)
E^3 dN/dEdAdΩ dt (GeV^2m^-2sr^-1s^-1)

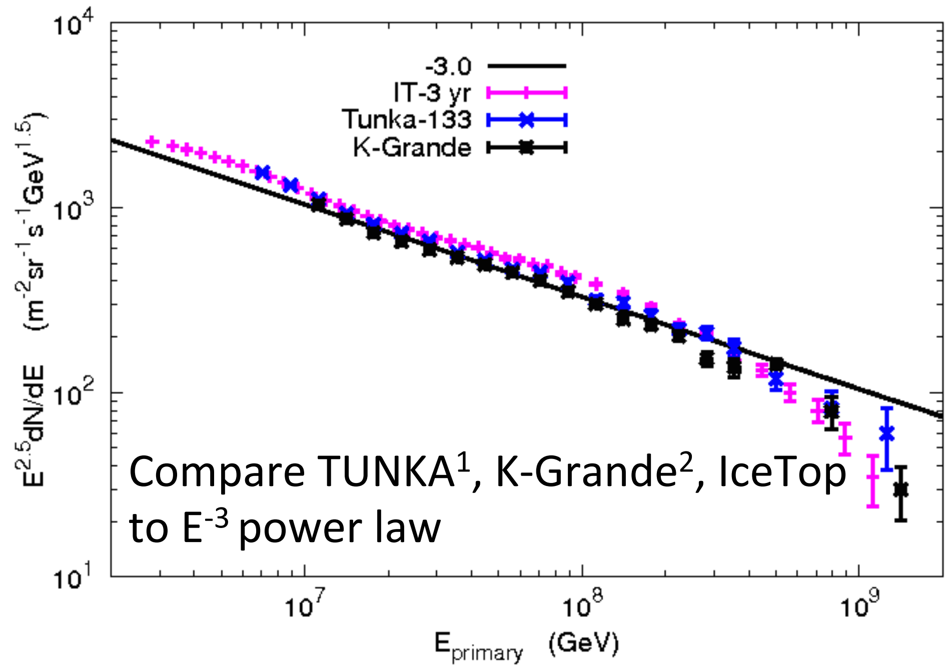
Spectrum comparison



Structure in spectrum



IceTop only, one year PR D88 (2013) 042004



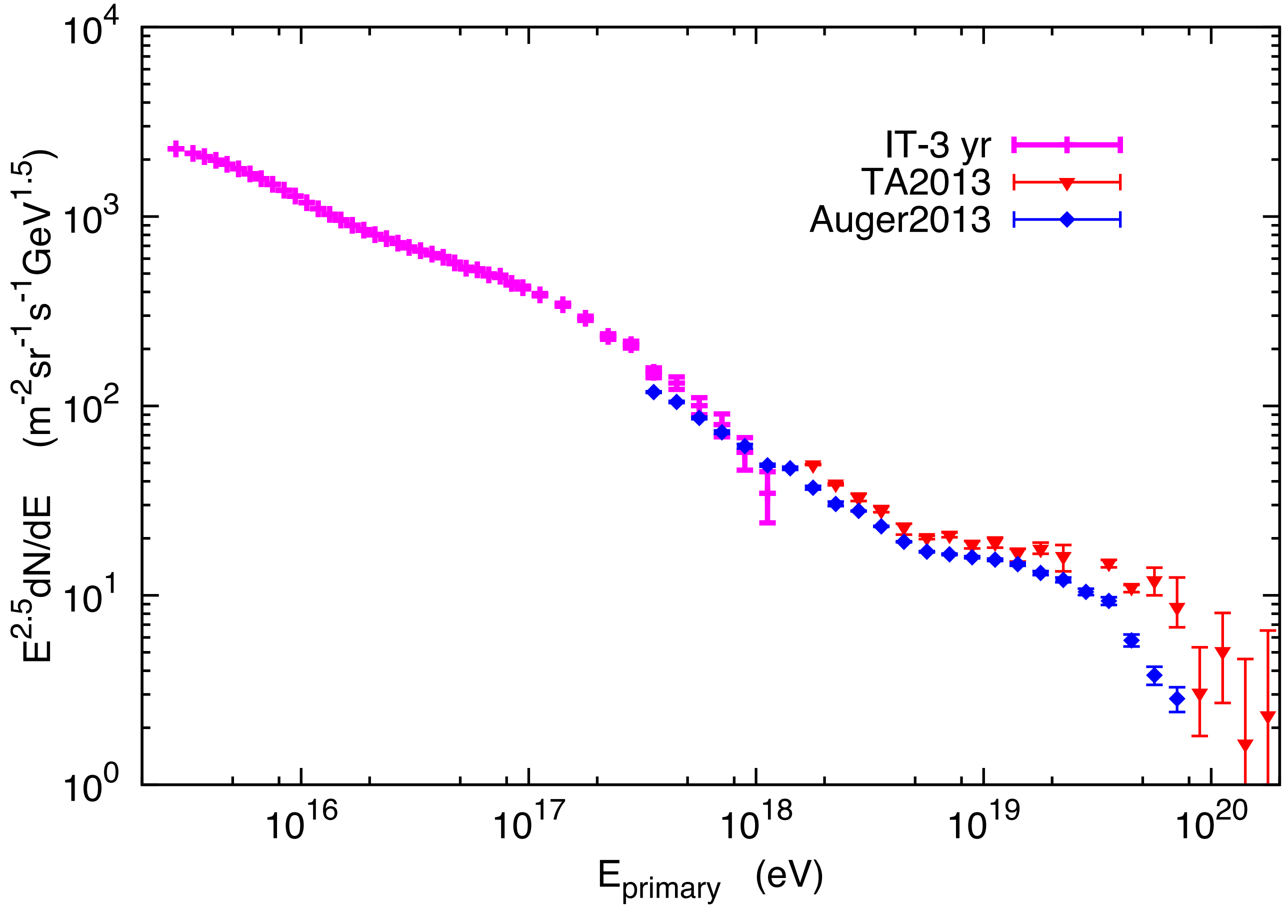
Compare TUNKA[1], K-Grande[2], IceTop to E^{-3} power law

[1] Prosin et al., NIM A756 (2014) 94-101

[2] Apel et al., Astropart. Phys. 36 (2012) 183-194

Similar structure in TALE + TACherenkov

Global view of spectrum



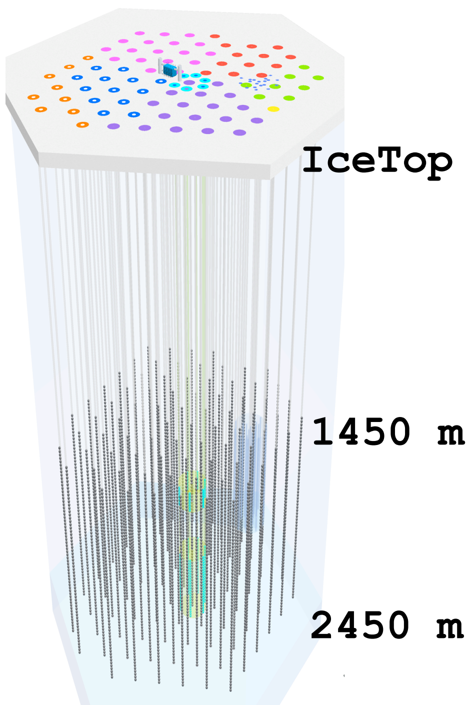
IceCube Gen2

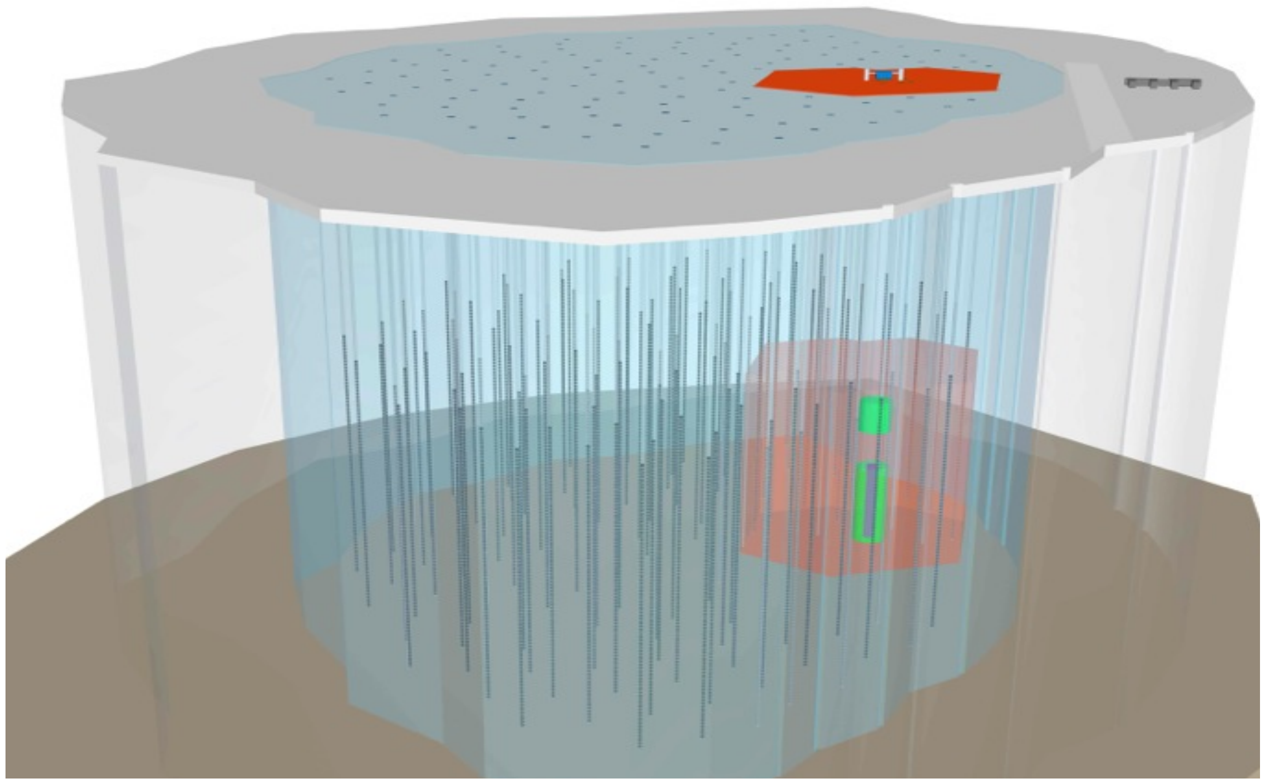
arXiv:1412.5106

125 m string spacing ⟶ 250 m

1 km^2 area ⟶ 6 km^2

Aperture: 0.26 km^2 sr ⟶ ~ 10 km^2 sr





Concluding remarks

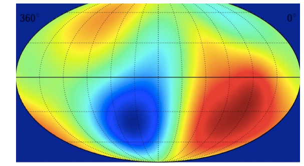
- Structure in the spectrum
  - Hardening around $10^{16.2}$ eV
  - "Second knee" steepening around $10^{17.3}$ eV
- Surface muons:
  - ρ_{600} between p and Fe to $10^{16.5}$ eV
  - Excess muon problem begins at higher E?
- Coincident analysis:
  - Energy spectrum independent of composition assumptions
  - consistent with IceTop only spectrum, which has much higher statistics
  - increase in $<\ell n(A)>$ from $10^{15.3}$ to $>10^{17}$ eV

Extras: anisotropy if time

equatorial coordinates

cosmic ray anisotropy

Sky-map with HAWC is in progress

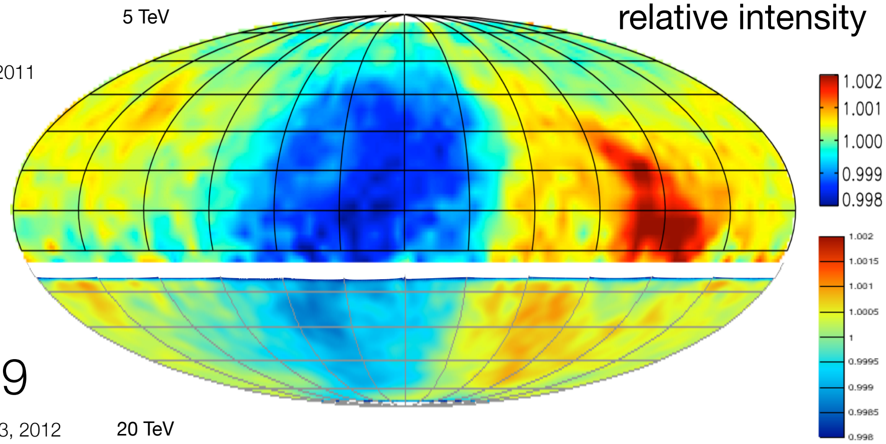


Tibet-III

Amenomori et al., ICRC 2011

5 TeV

relative intensity



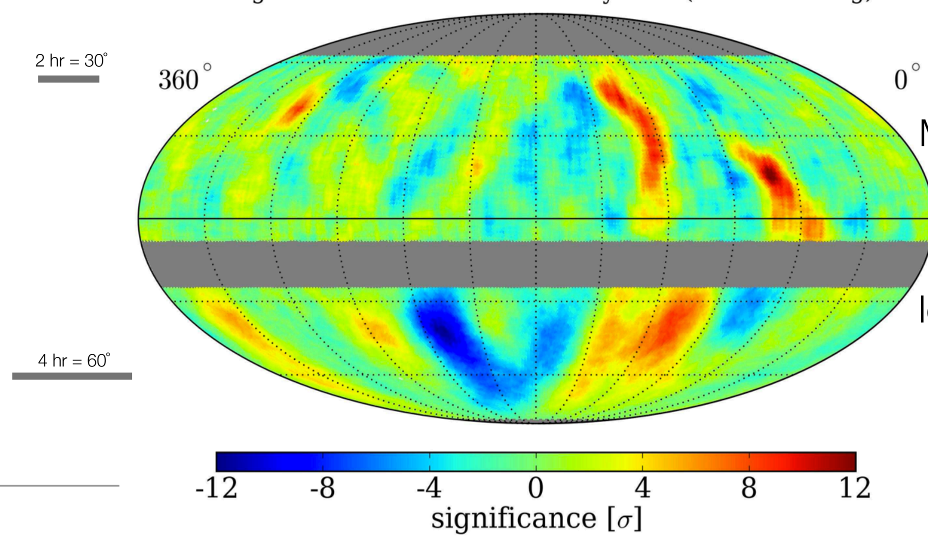
IceCube-59

Abbasi et al., ApJ, **746**, 33, 2012

20 TeV

large scale anisotropy

statistical significance



Milagro 1 TeV

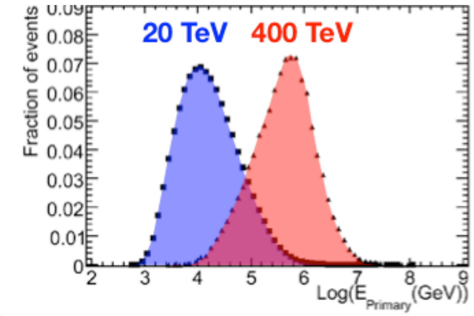
Abdo et al., PRL, **101**, 221101, 2008

IceCube 20 TeV

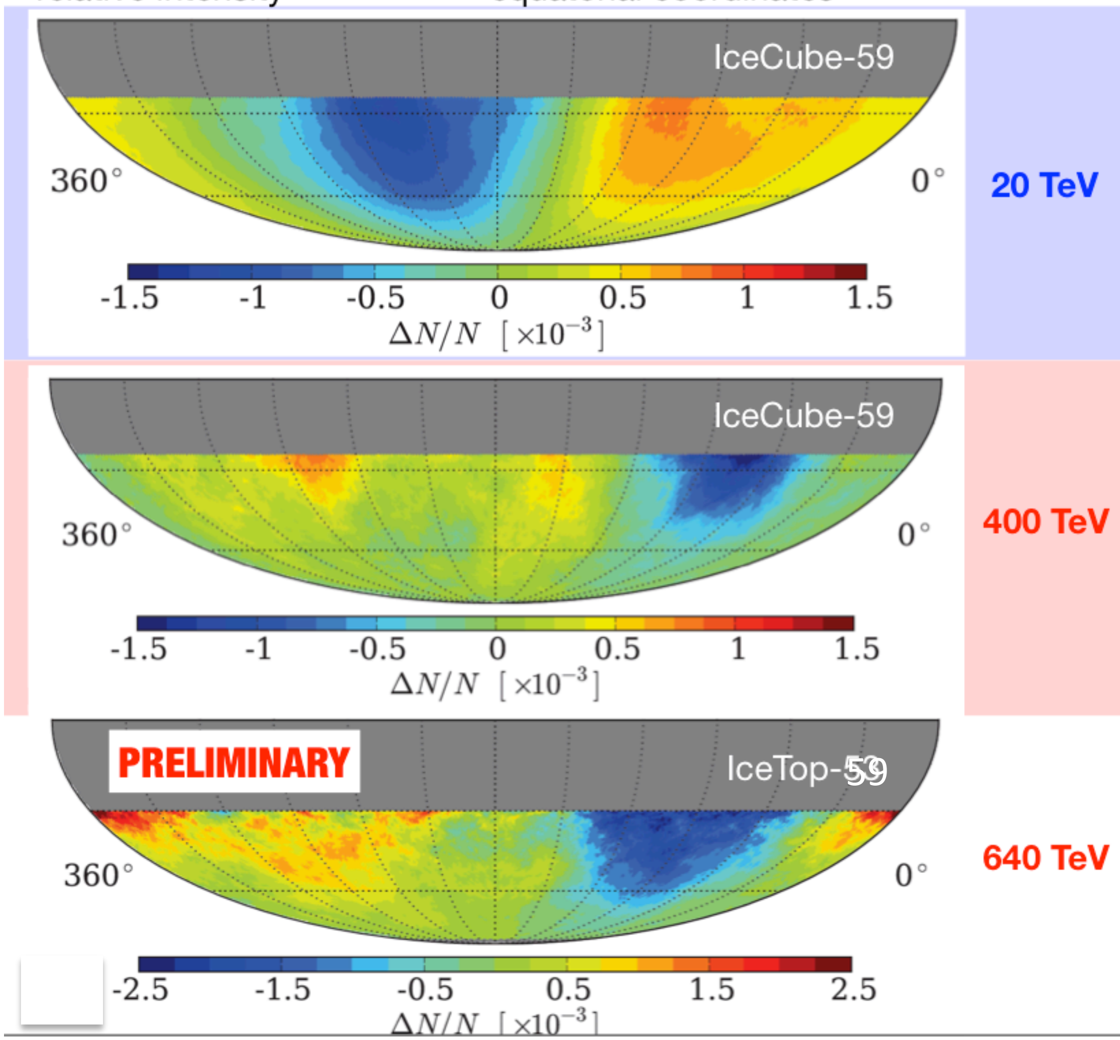
Abbasi et al., ApJ, **740**, 16, 2011

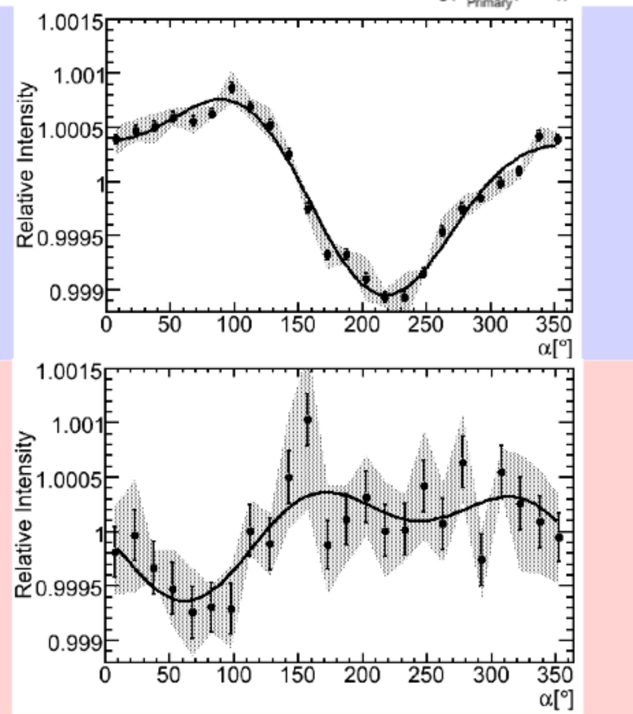
small scale anisotropy

cosmic ray anisotropy



relative intensity equatorial coordinates





Abbasi et al., ApJ, **746**, 33, 2012

Santander et al., arXiv:1205.3969