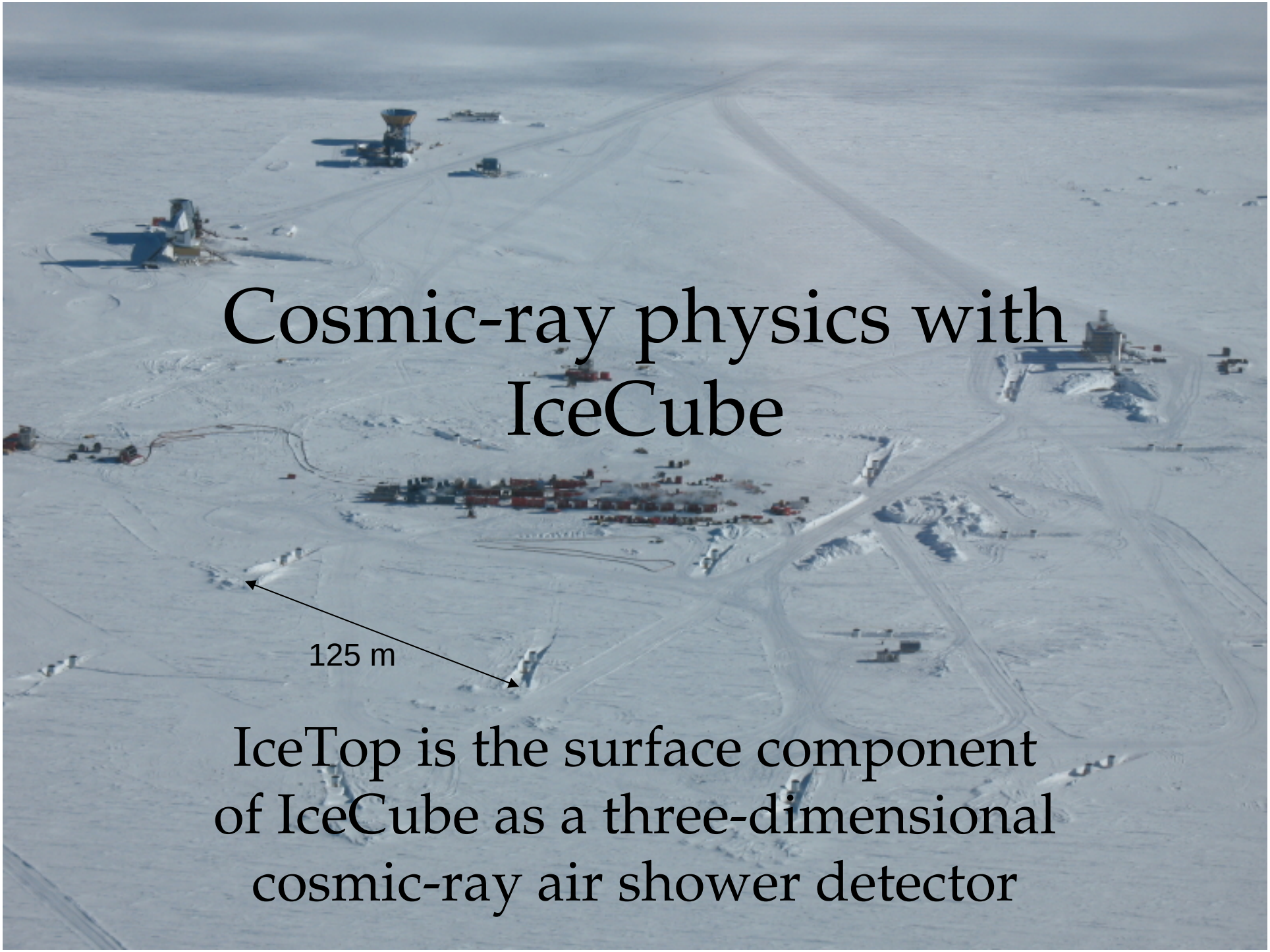


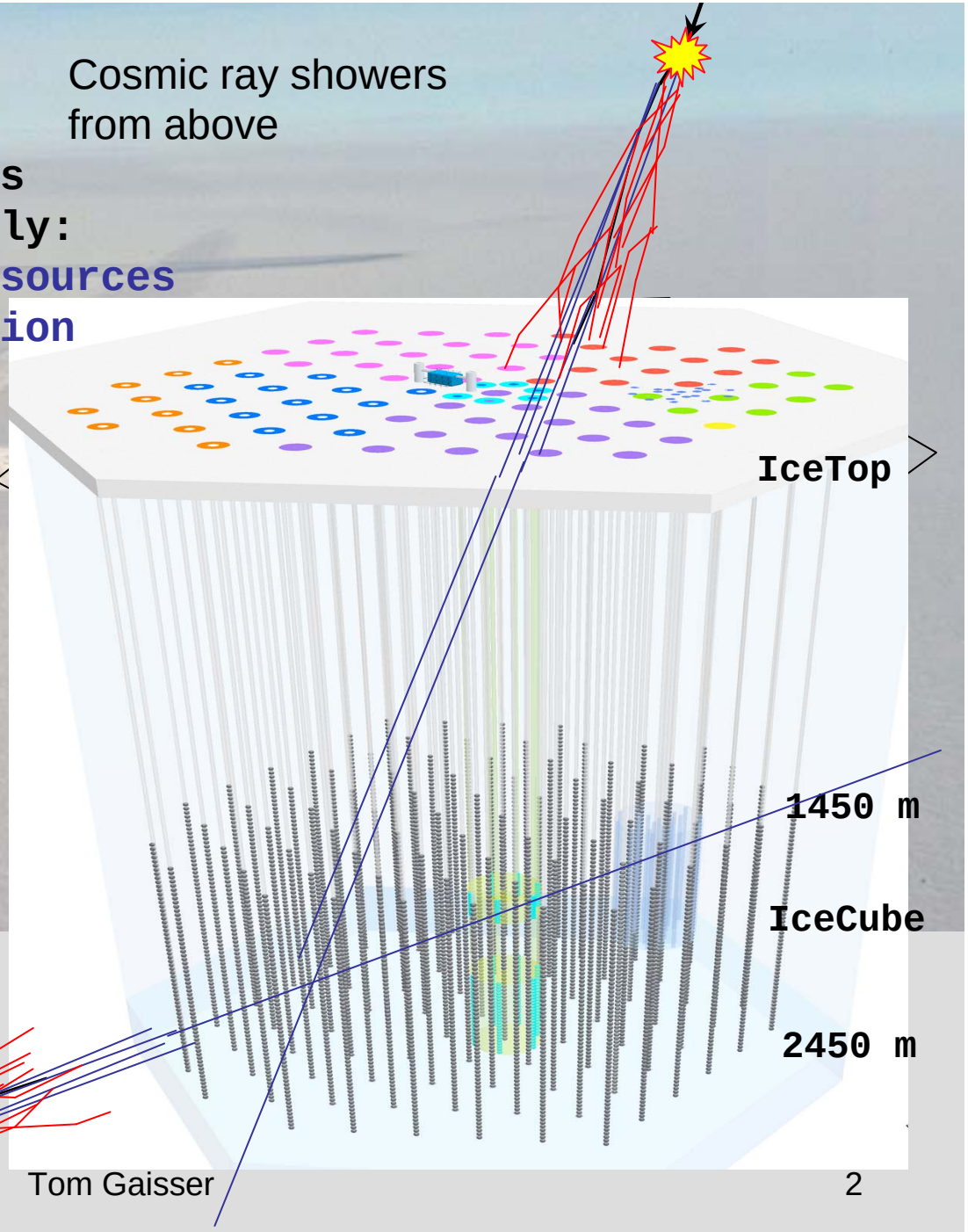
Cosmic-ray physics with IceCube

IceTop is the surface component of IceCube as a three-dimensional cosmic-ray air shower detector

Two different kinds of events
Closely related scientifically:

- **Neutrinos from cosmic ray sources**
- **Cosmic rays after propagation**

Cosmic ray showers
from above



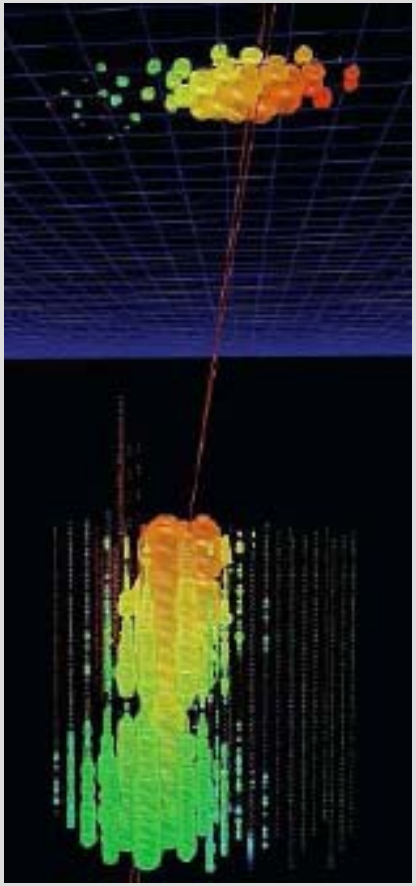
South Pole
2835 m.a.s.l.

Neutrinos from all directions

Primarily ν_μ-induced μ from below

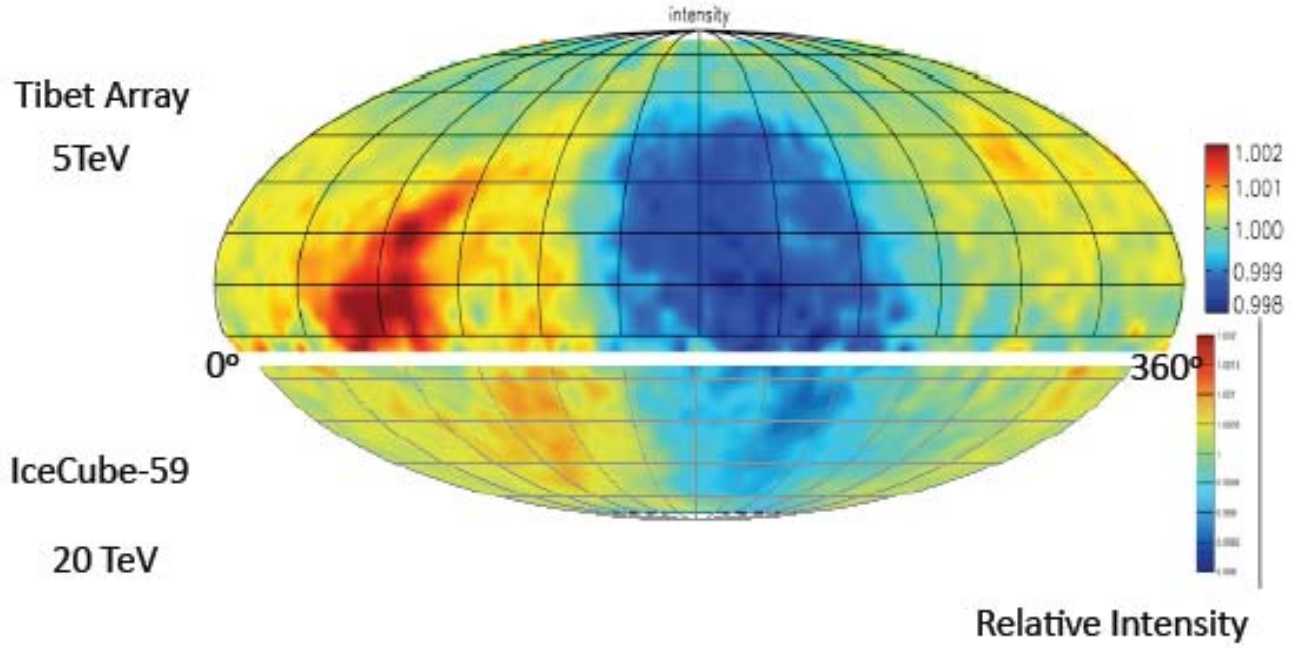
Cosmic-ray physics with IceCube

- IceCube sees cosmic ray events from all directions
  - 30,000 atmospheric ν/year
  - 100 billion atmospheric μ/year
  - 1 billion air showers/yr in IceTop
  - ~10% in coincidence with deep IceCube
- Spectrum/composition:
  - TeV to EeV



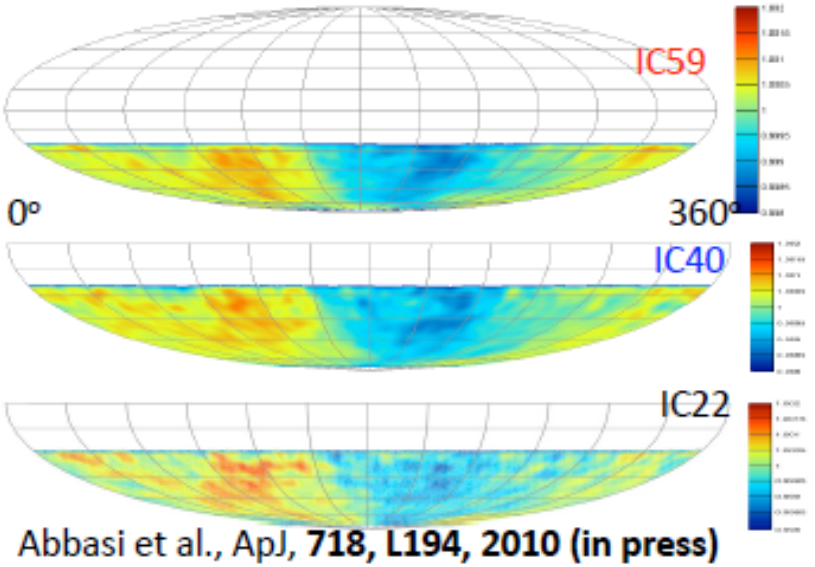
Huge μ statistics allows study of anisotropy @ < 1 per mil

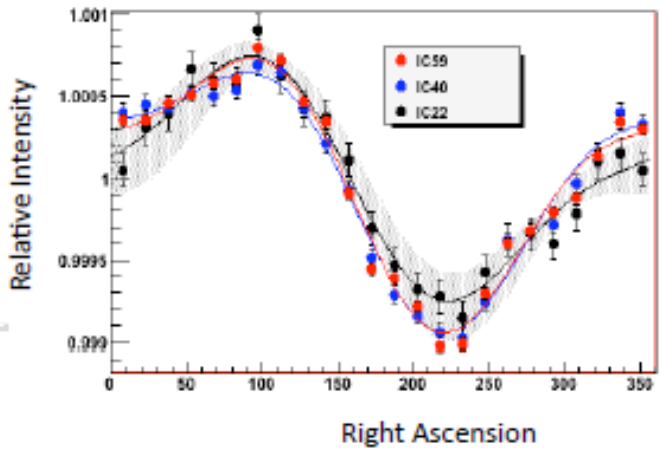
Comparison to the Northern Hemisphere Tibet Array and IceCube



Anisotropy is a continuation of previously measured large scale anisotropy observed in northern locations.

Relative Intensity of Cosmic Rays (IC22, IC40 & IC59)





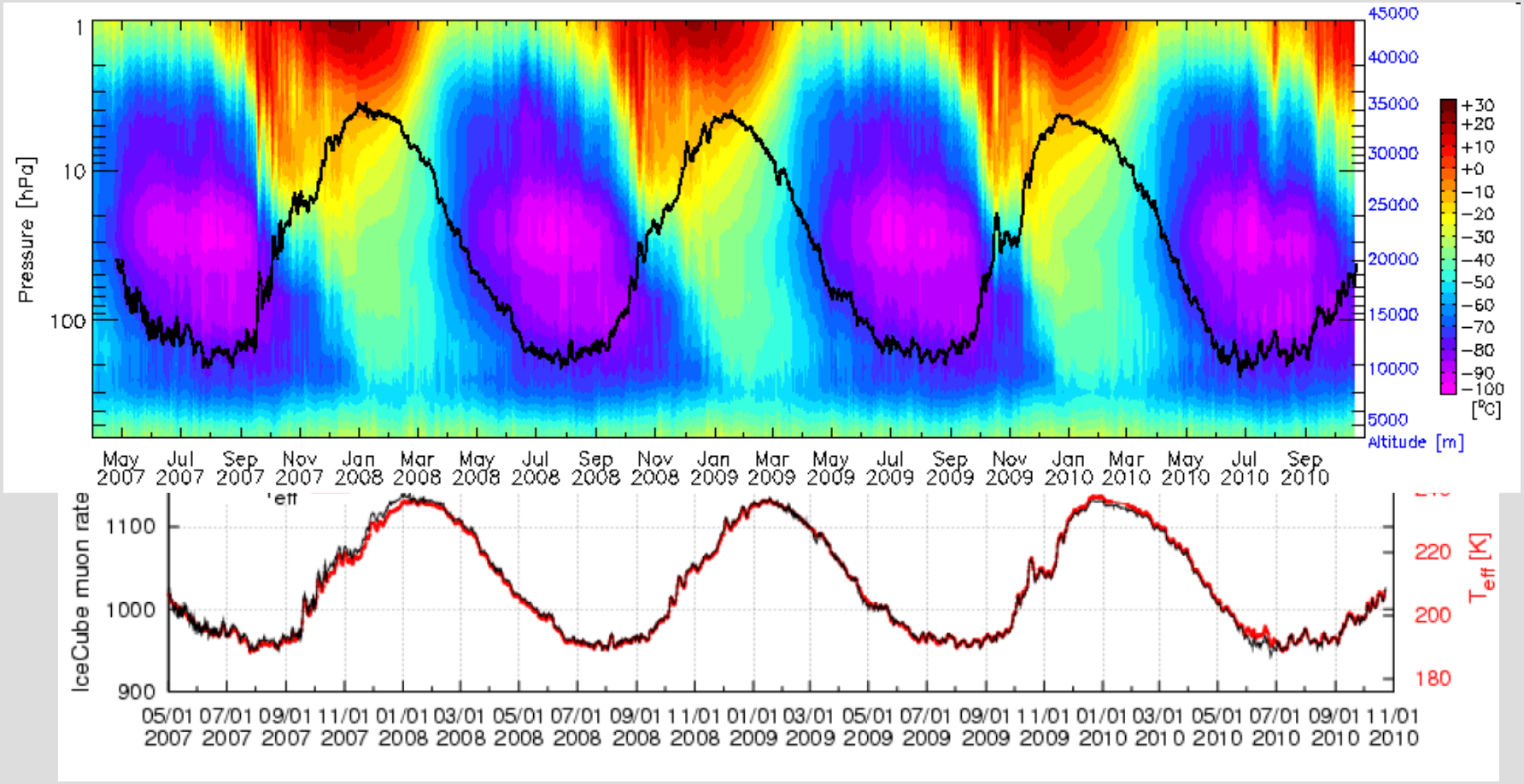
Abbasi et al., ApJ, **718, L194, 2010 (in press)**

Year	Rate (Hz)	LiveTime(Days)	CR Median Energy (TeV)	Median Angular Resolution (degrees)	Number of Events (billion)
2007-IC22	240	~226	~19	3	~4
2008-IC40	780	~324	~19	3	~15
2009-IC59	1300	~324	~19	3	~23

From presentation of R. Abbasi, SNOPAC 2011

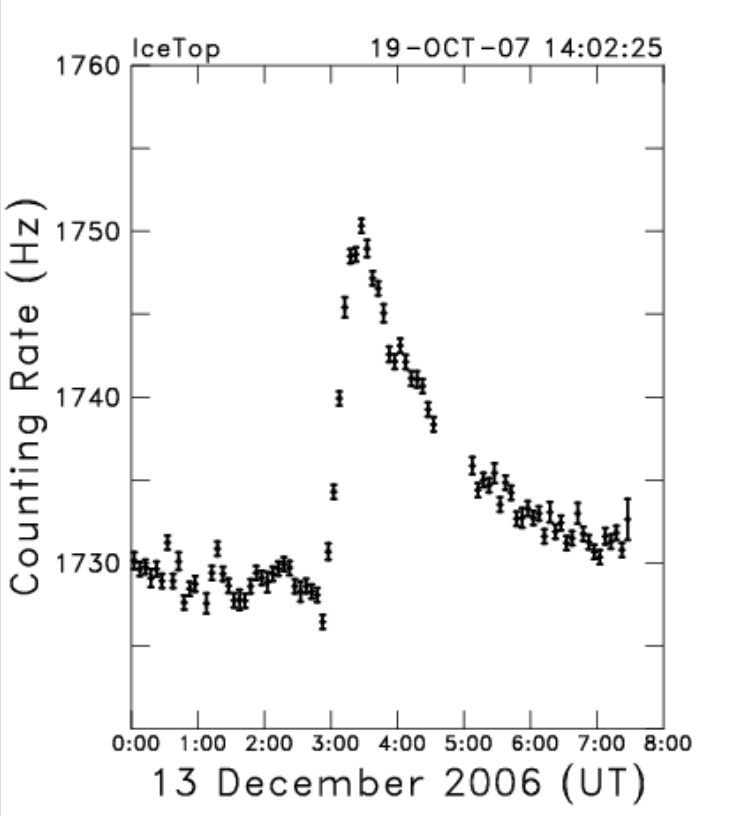
Weather with IceCube

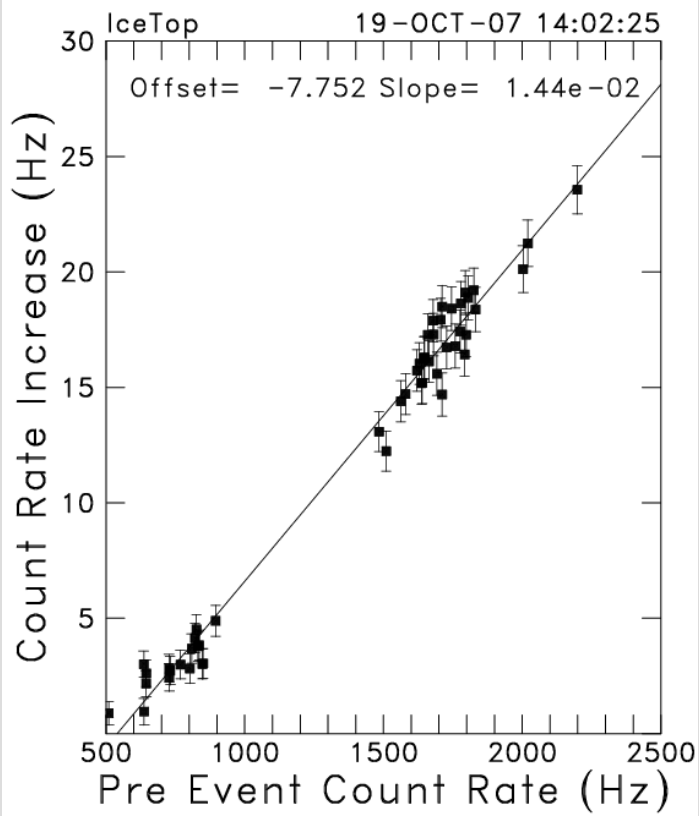
- Muon production samples stratospheric temperature
  - Higher T, lower ρ, more $\pi^{\pm}$ decay before interaction → more μ



Solar & heliospheric physics

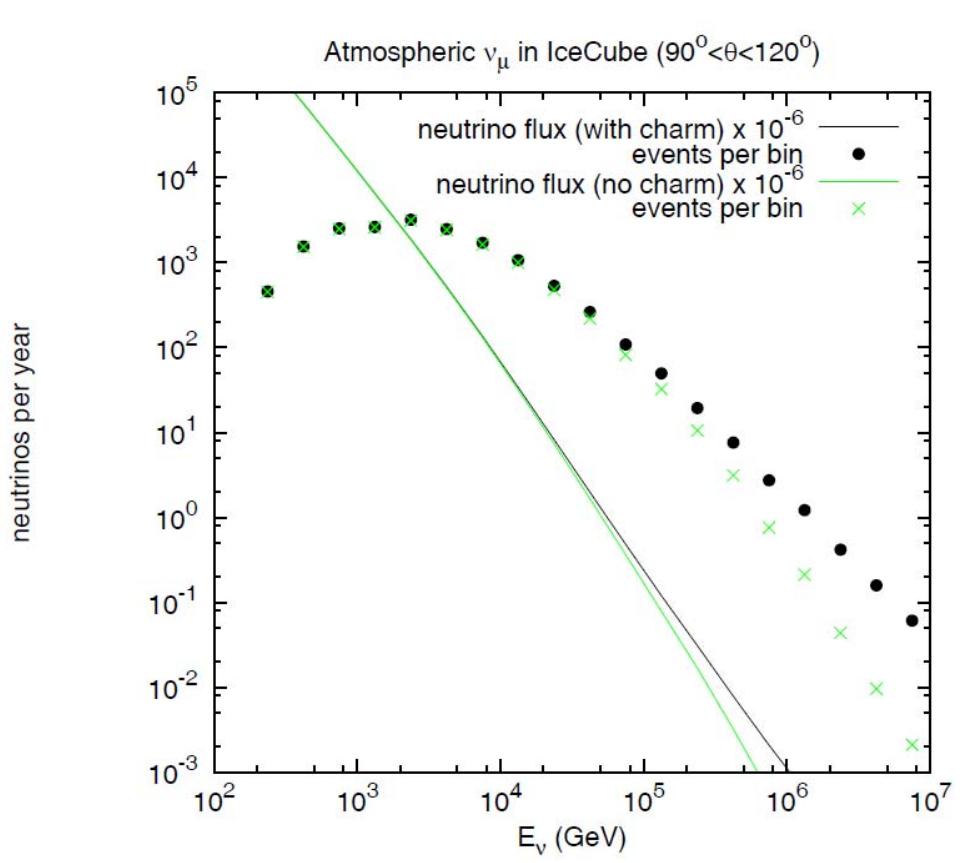
- ~2 kHz rate per IceTop tank with 162 tanks
  - study of solar cosmic ray events & solar modulation with fine time resolution & spectral resolution





Energy range of atmospheric ν_μ

- Most events
  - 0.3 to 10 TeV
  - E_{CR} ~ 3 to 100 TeV/nucleon
- Rate (>100 TeV)
  - Prompt ν (charm)
  - ~100's per yr
  - Absorption in Earth distorts angular dist.



Neutrino effective area

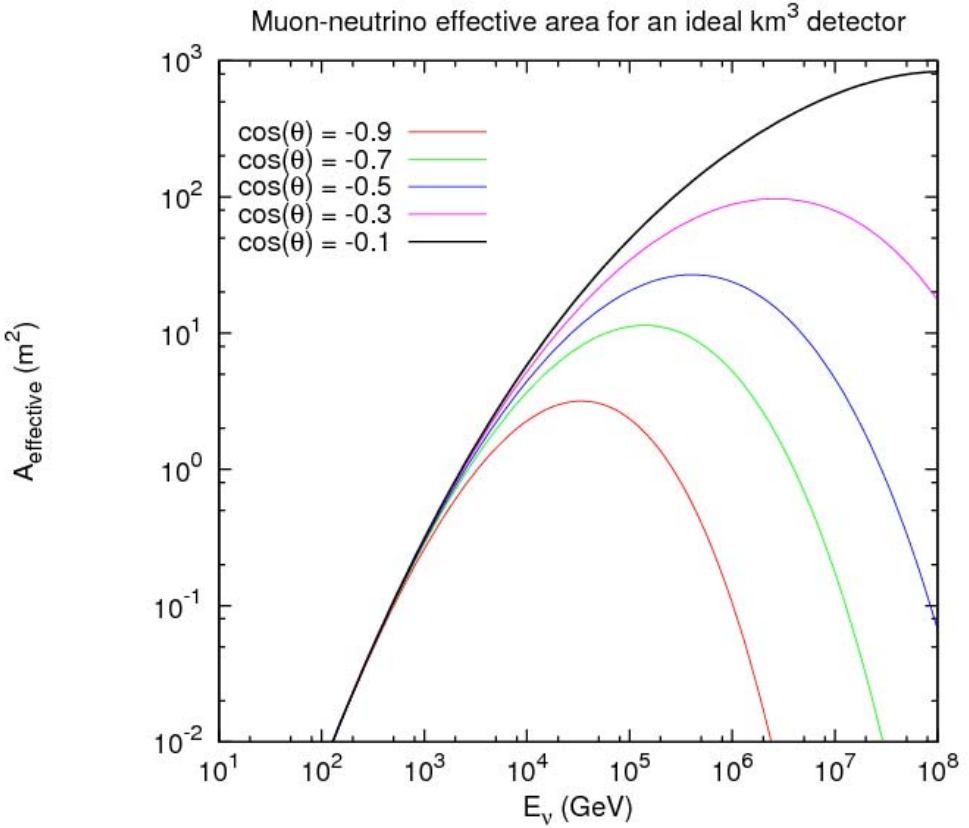
$$A_{eff}(\theta, E_\nu) = \epsilon(\theta)\, A(\theta)\, P_\nu(E_\nu, E_{\mu,min})\, e^{-\sigma_\nu(E_\nu) N_A X(\theta)}$$

($P_\nu \sim \sigma_\nu X R_\mu$)

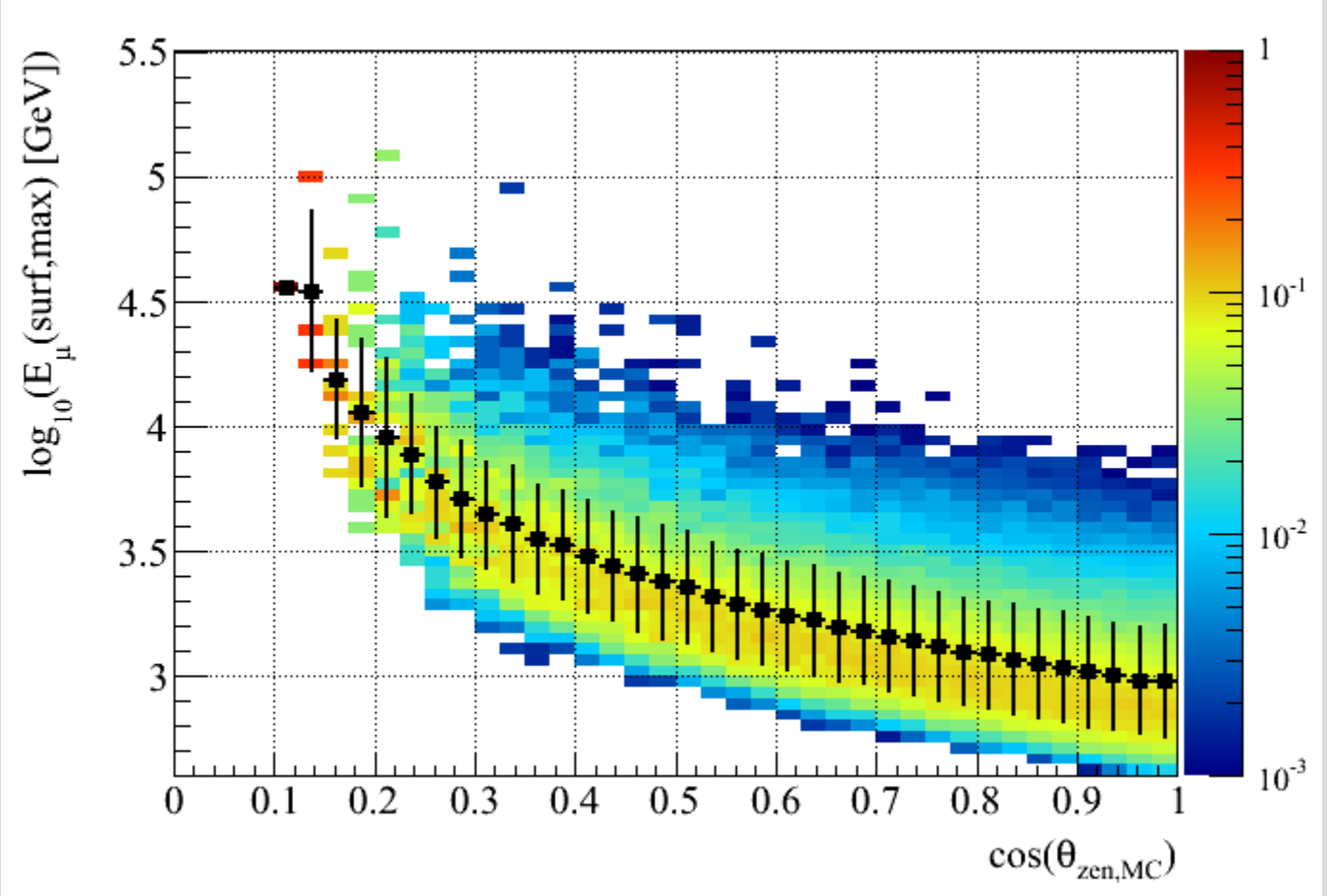
- Rate:

$= \int \phi_\nu(E_\nu) A_{eff}(E_\nu) dE_\nu$

- Earth absorption
  - Starts 10-100 TeV
  - Biggest effect near vertical
  - Higher energy ν's absorbed at larger angles



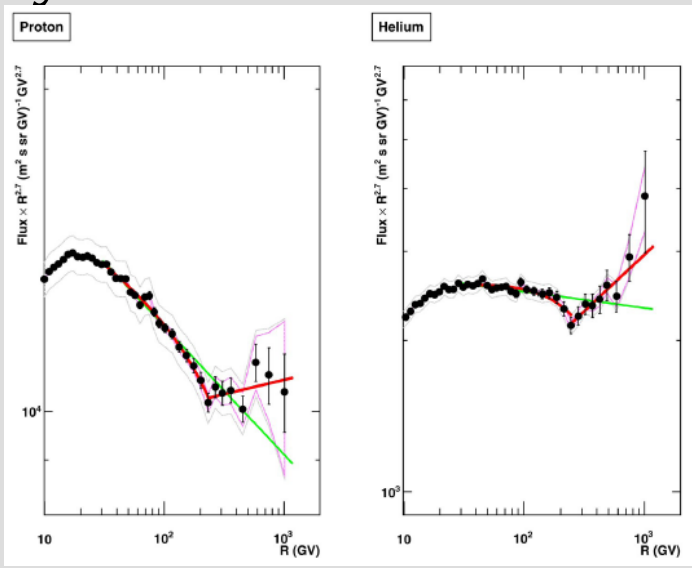
Atmospheric muons in IceCube



Similar energy range to atmospheric ν

Primary composition with μ & ν

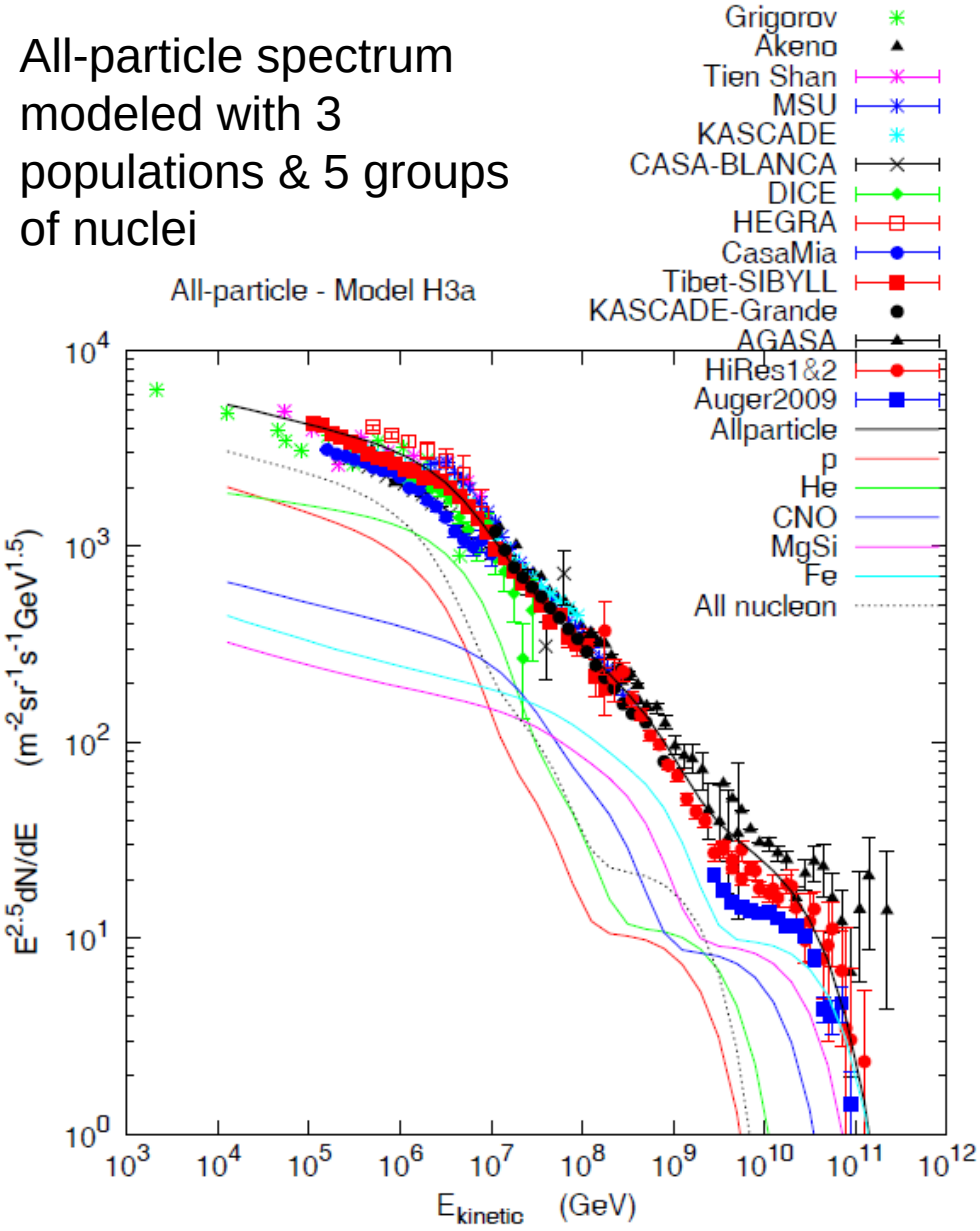
- Calibration criterion: consistency of
  - Primary spectrum / composition
  - Spectrum & angular distribution of μ and ν
- Interesting region for primary spectrum/composition
  - ATIC, CREAM, PAMELA
    - Spectra harder E > 200 GeV/A

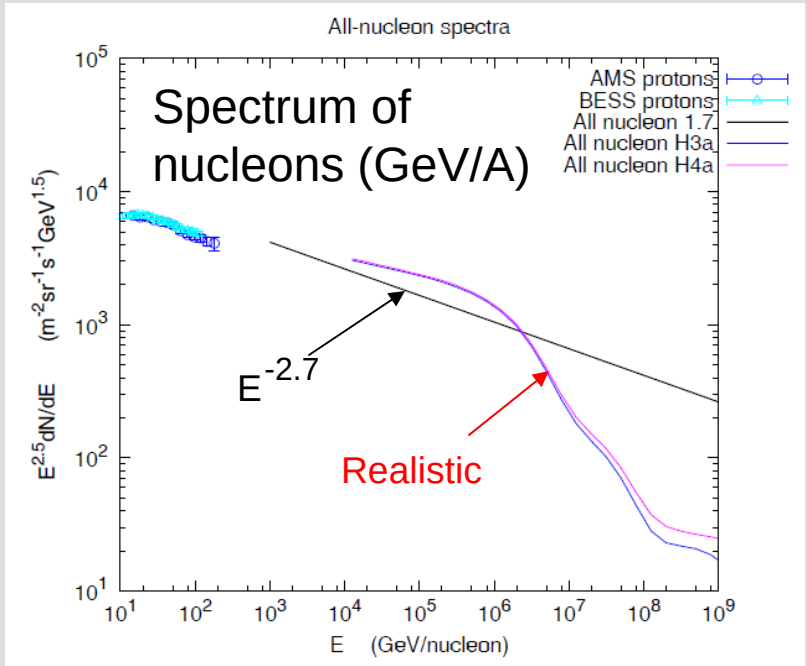


PAMELA, Adriani et al., arXiv:1103.4055

Primary spectrum & composition affect atmospheric neutrinos

All-particle spectrum modeled with 3 populations & 5 groups of nuclei

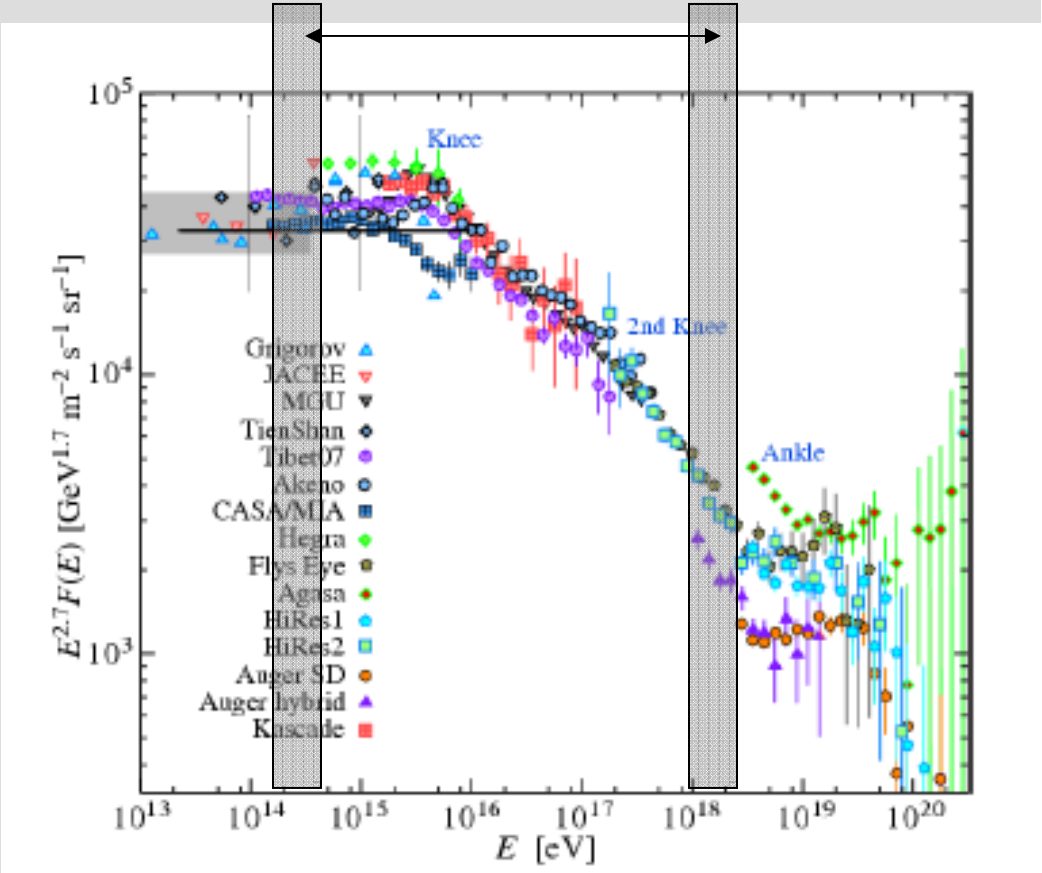




Spectrum/composition with IceCube/IceTop

- Threshold energy
  - $\leq$ 300 TeV
- Maximum energy
  - Limited by km^2 size
  - Coincident events
    - A Ω = 0.3 km^2 sr
    - E_{max} = EeV
  - IceTop only ($\theta < 60^o$)
    - A Ω = 3 km^2 sr
    - E_{max} = 3 EeV
  - In-ice trigger & reco
    - E_{max} = 3 EeV

< PeV **≥ EeV**



Anchor to direct measurement of composition ~300 TeV

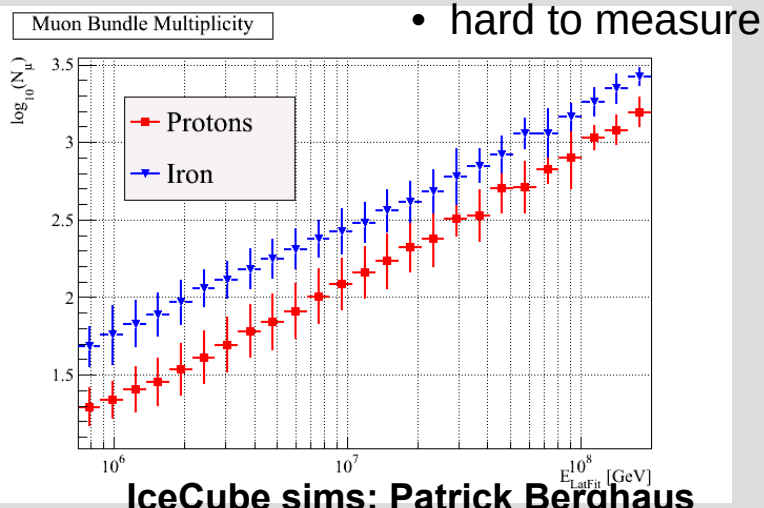
Look for transition to extra-galactic < EeV

Composition from IceTop, In-ice coincident events

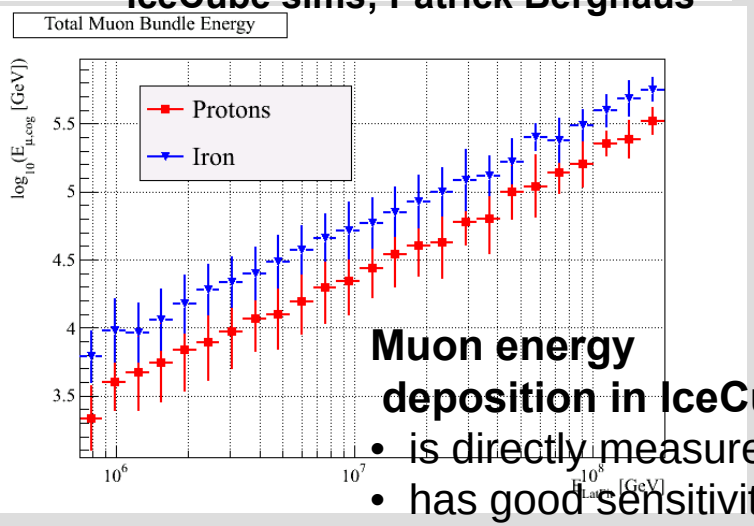
- Reconstruct muon bundle to get energy deposition by muons in deep IceCube
- Reconstruct surface shower to get $E_{primary}$
- Require consistency with angular distribution and μ/e measured on the surface

Muon multiplicity

- hard to measure



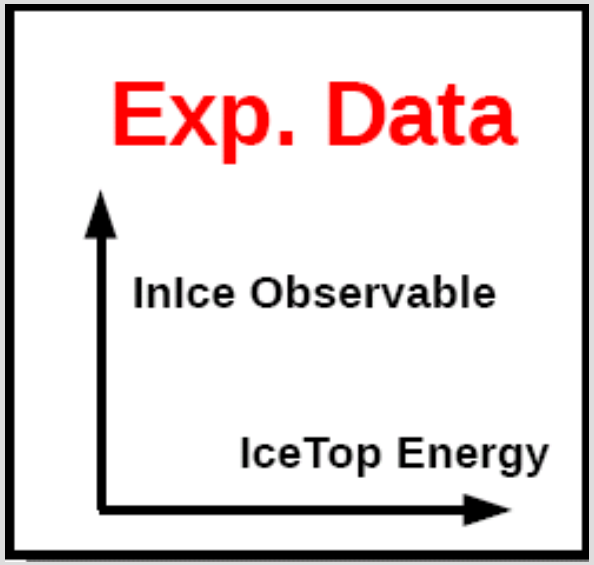
IceCube sims; Patrick Berghaus



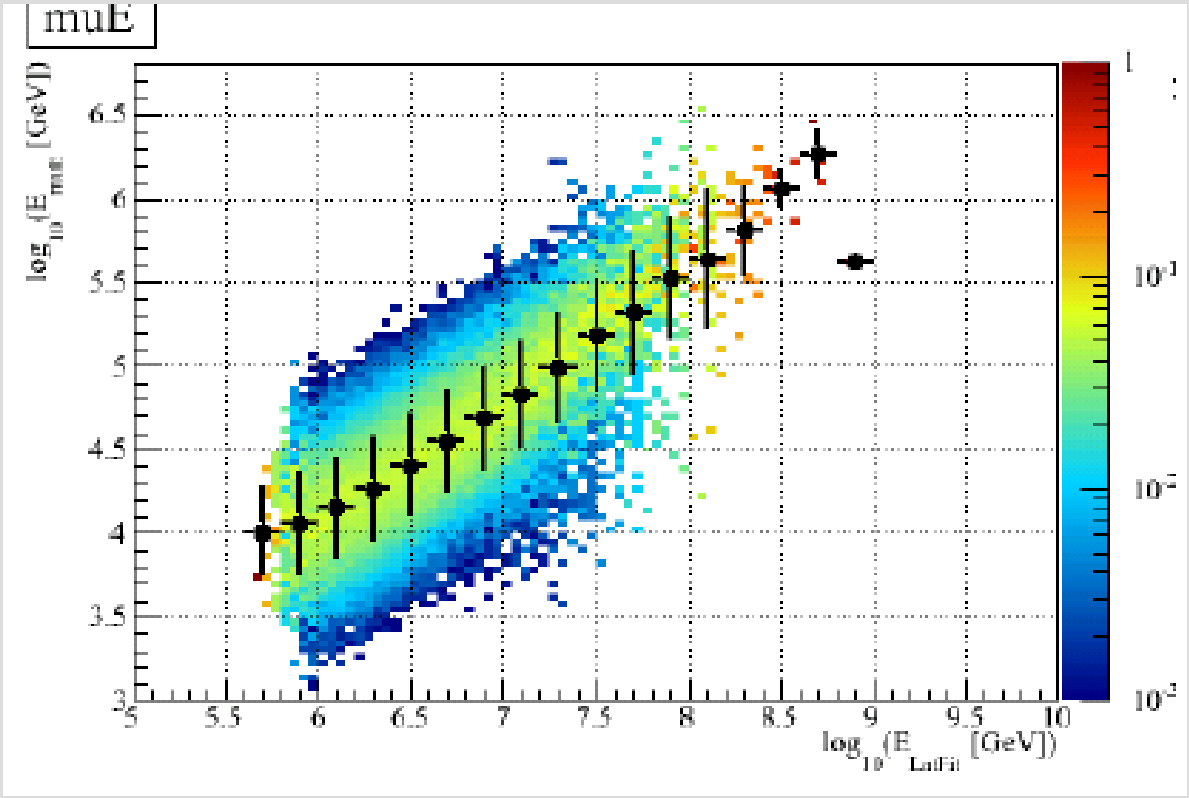
Muon energy deposition in IceCube

- is directly measured
- has good sensitivity

Composition from IceTop, In-ice coincident events

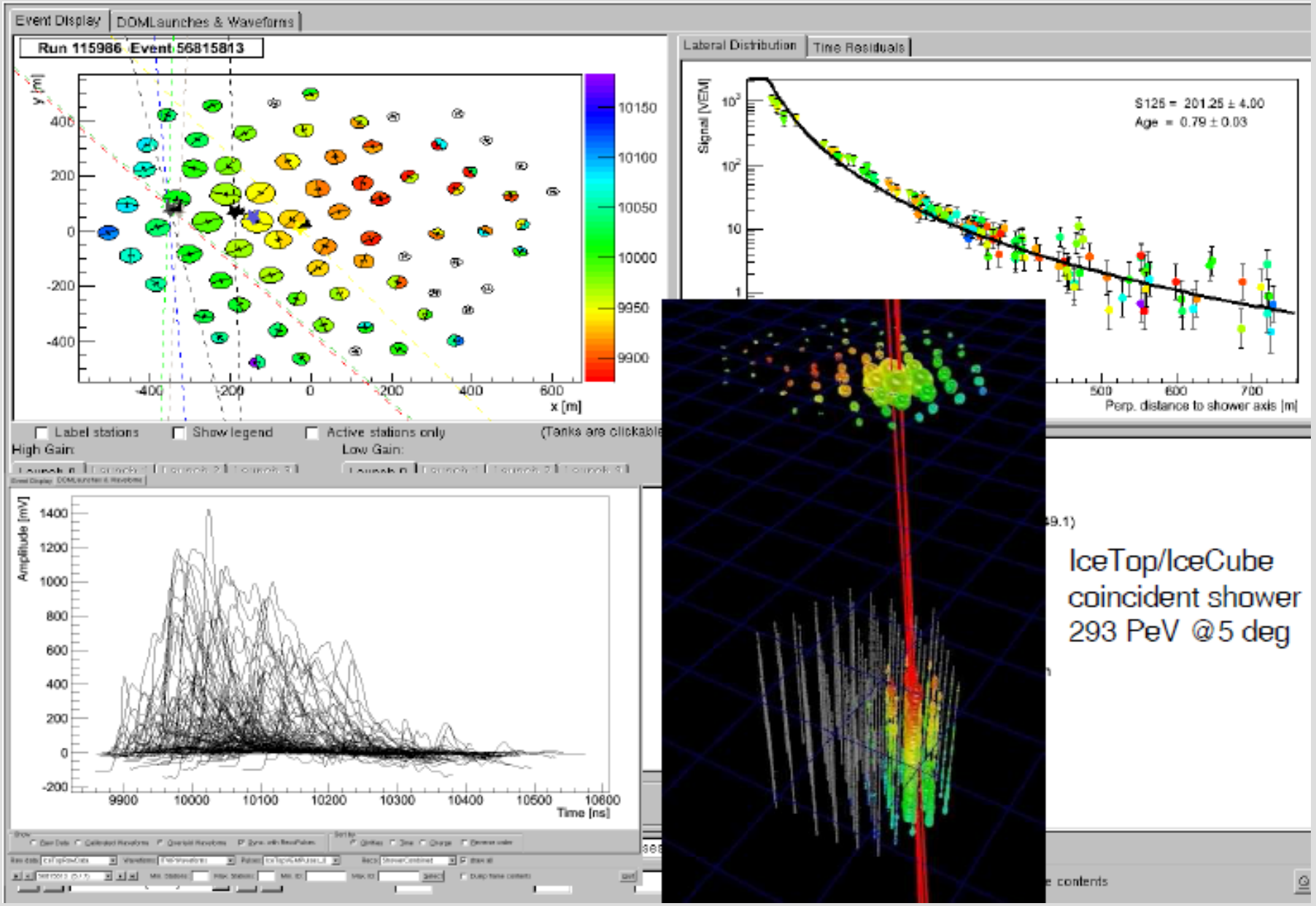


Patrick Berghaus, Sept 2009
--IceCube collaboration mtg

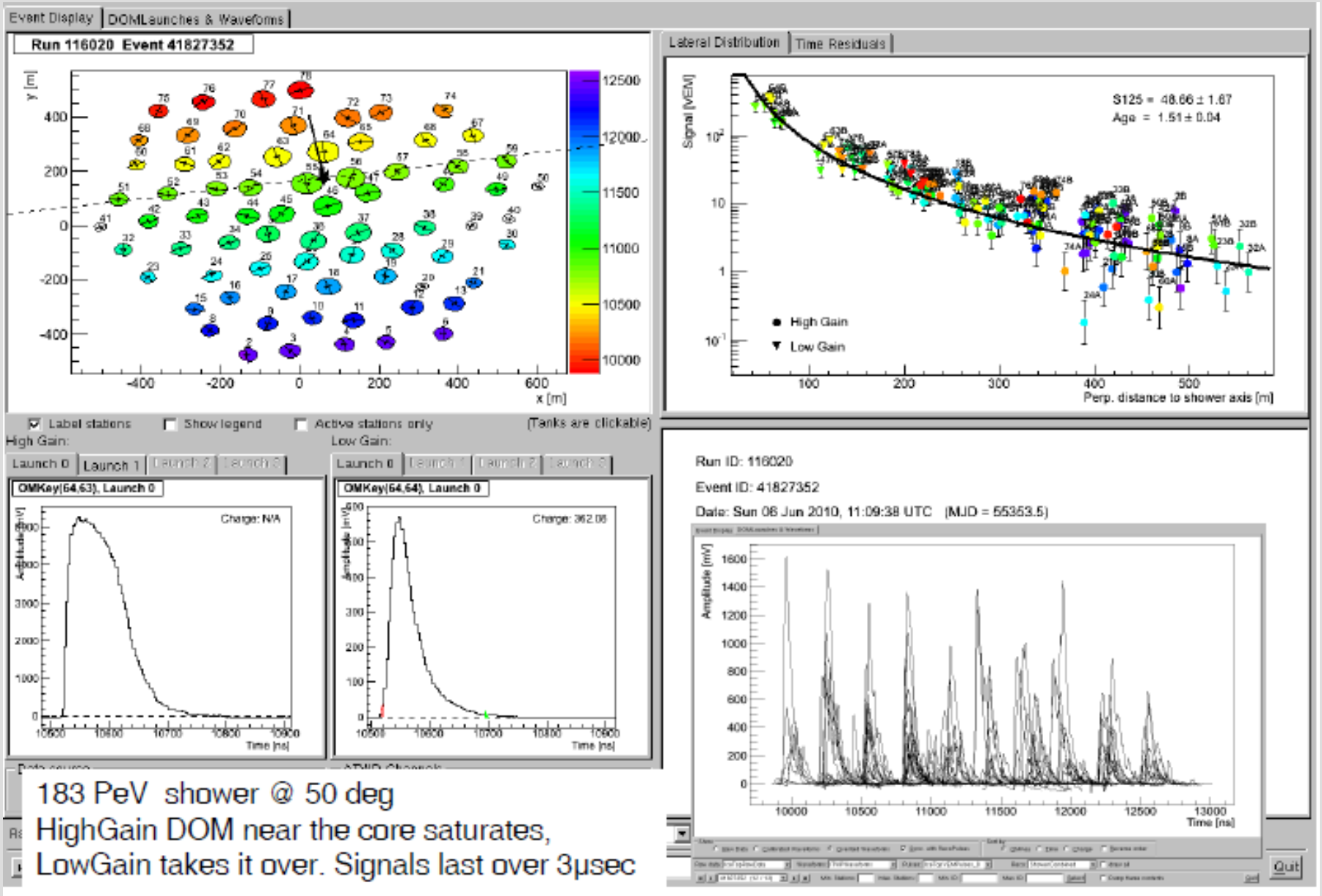


Good experimental correlation
Simulations & study of systematics is in progress

Recent data (June 2010, large, vertical event)



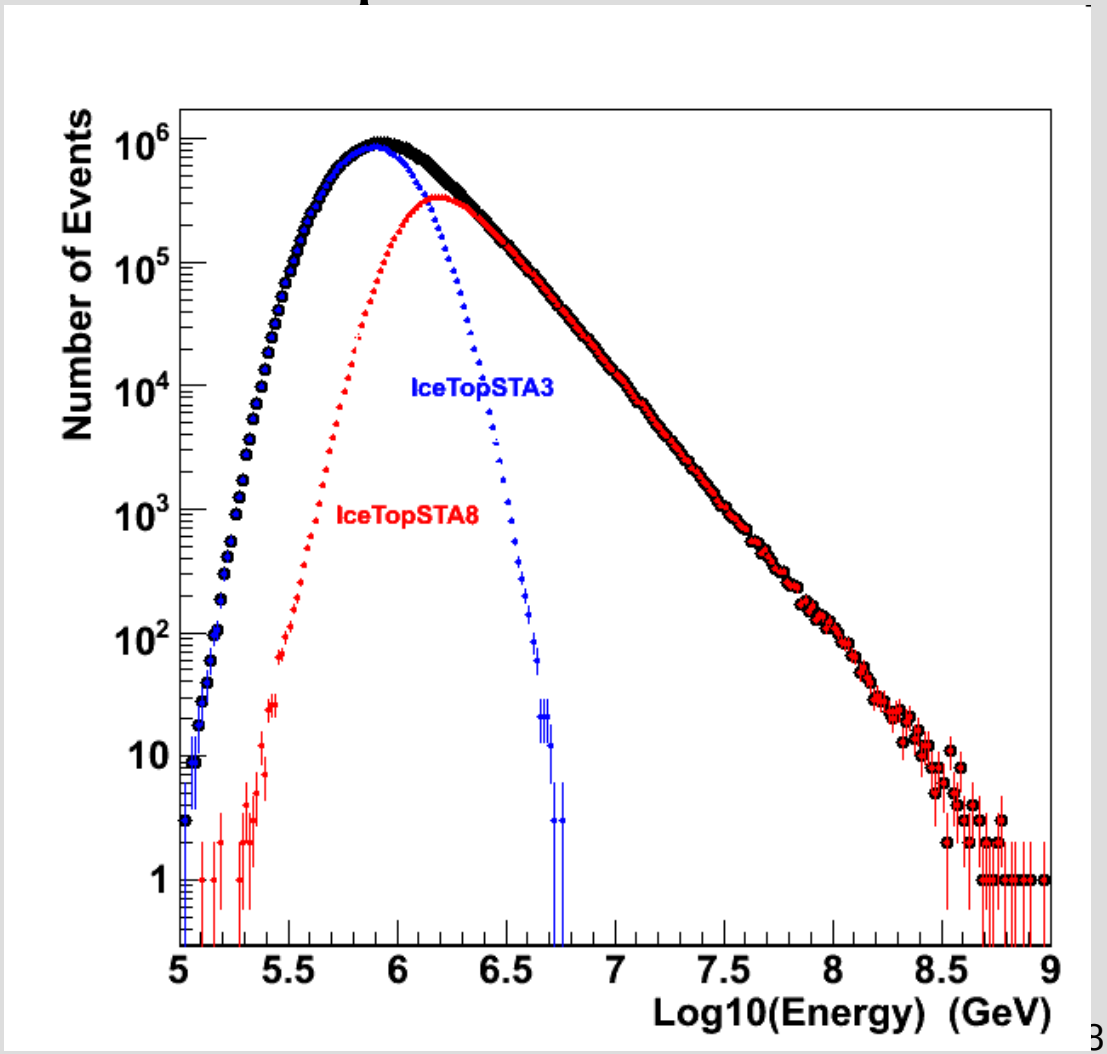
Large, inclined event in IceTop-73



183 PeV shower @ 50 deg
HighGain DOM near the core saturates,
LowGain takes it over. Signals last over 3μsec

Current IceTop size spectrum

Six months IceTop-73 2010/11

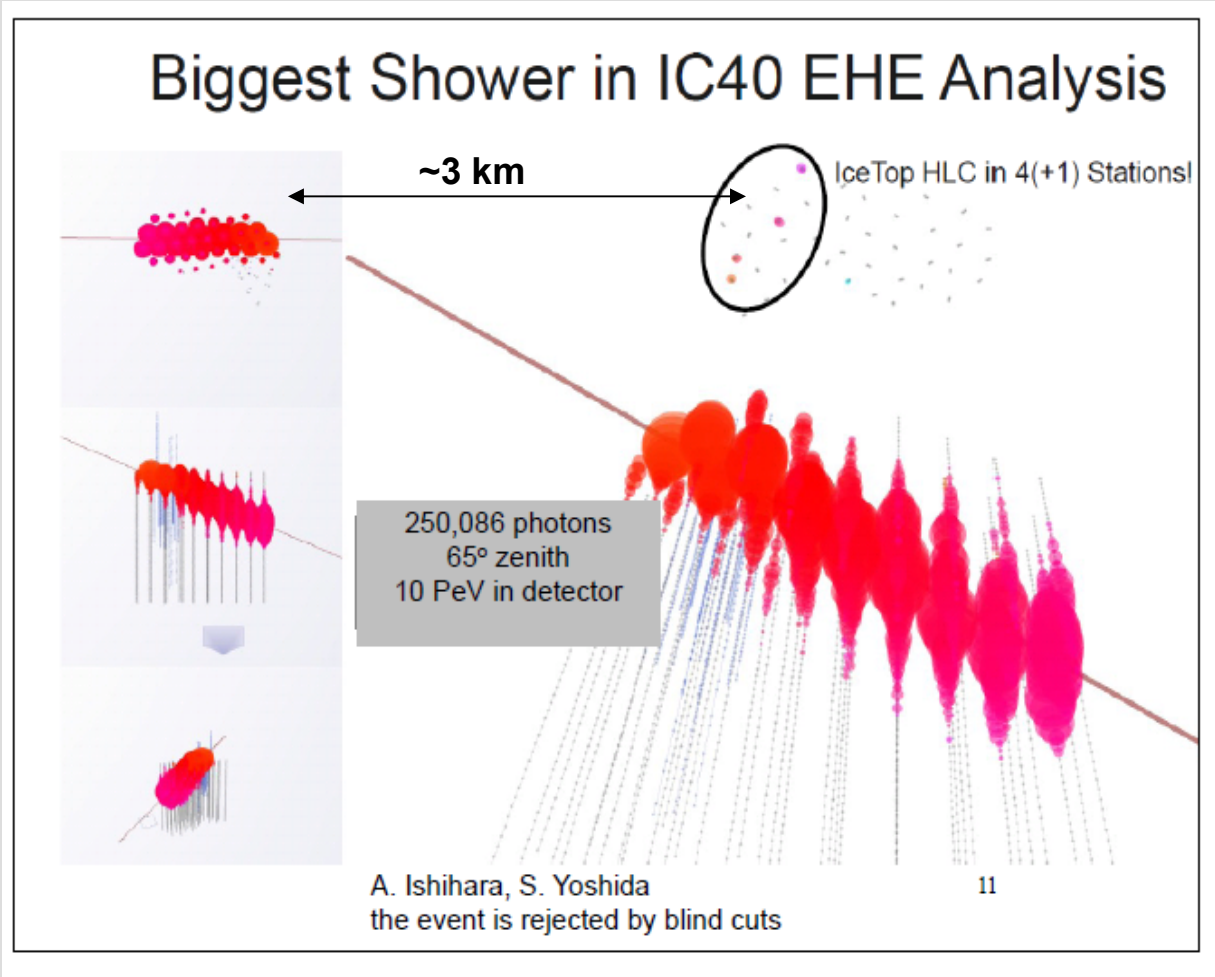


Extending the range of IceTop

- With present array we can use events reconstructed in deep ice that pass outside of IceTop
- Two benefits:
  1. Veto for horizontal GZK neutrino candidates
  2. Spectrum / composition physics
- To illustrate 2
  - I need a figure that shows trigger efficiency to get 3 or more IceTop stations as a function of primary energy and distance of the shower core from center of IceTop.

IceTop as a veto

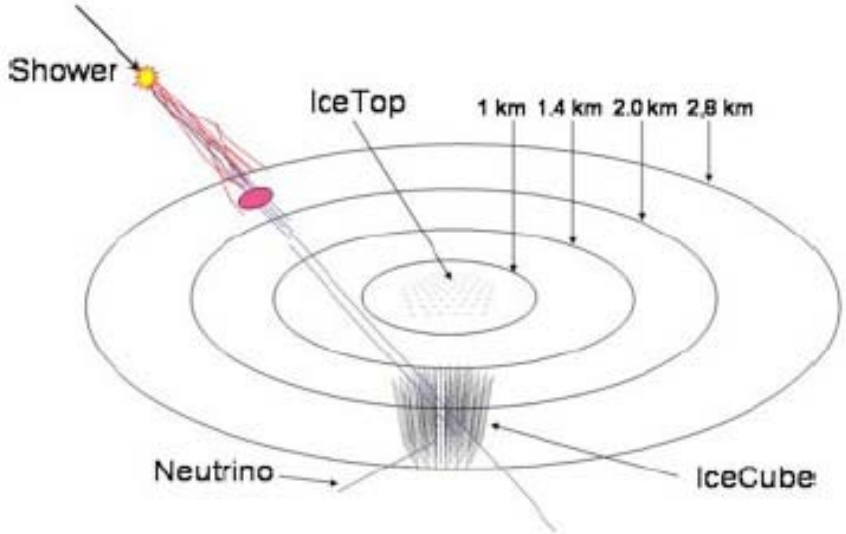
Present Icetop improves point source sensitivity by a factor of 2 for overhead sources



Radio Air Shower Test Array

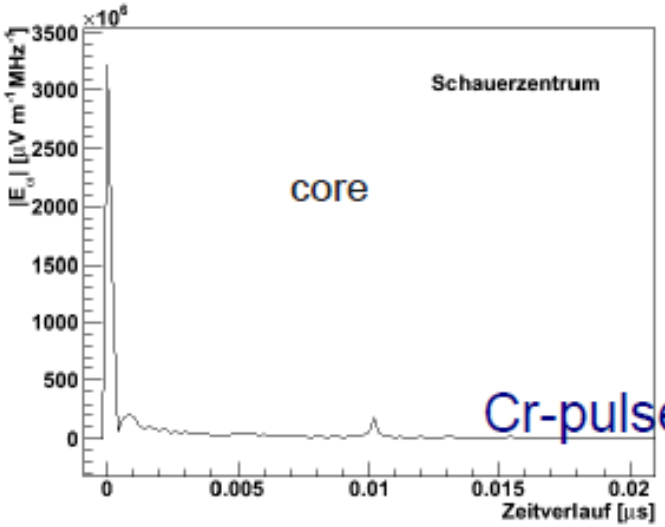
Symbiotic with ARA

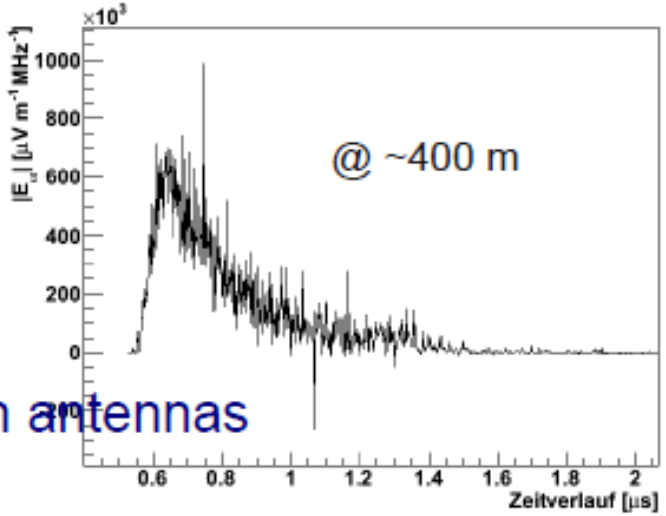
- RASTA is a project for observing EAS via radio signals, using *Geo-synchrotron Effect*:
  Charged particles emit radio waves in the magnetic field of the earth



Radio Air Shower Test Array: simulation

- Showers are simulated with CORSIKA
- The radioemission of the shower is simulated with „REAS 2“, gives output of the antenna response on designated positions
  → more detail, useful also for IceTop/InIce alone
- Alternative routine for parametrized (REAS 1) radio showers (by S. Böser)





Cr-pulses in antennas

Prospects for RASTA

- Energy range
- Area
- Relation to ARA
- Proposed timeline & cost

Summary comments

- High rate of atmospheric μ → fine resolution for
  - Anisotropy
  - Temperature effects
  - Solar, heliospheric studies with IceTop
- Primary spectrum & composition
  - To > 100 TeV with atmospheric μ, ν
  - IceTop, IceCube coincidenct events extend to EeV
    - Uniform acceptance from below knee to EeV
    - Look for transition to extra-galactic component E $\leq$ EeV
- Extend IceTop acceptance for veto and science
  - Use events with cores outside IceTop
  - Build RASTA