The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2036-23

International Workshop: Quantum Chromodynamics from Colliders to Super-High Energy Cosmic Rays

25 - 29 May 2009

High energy neutrino astronomy

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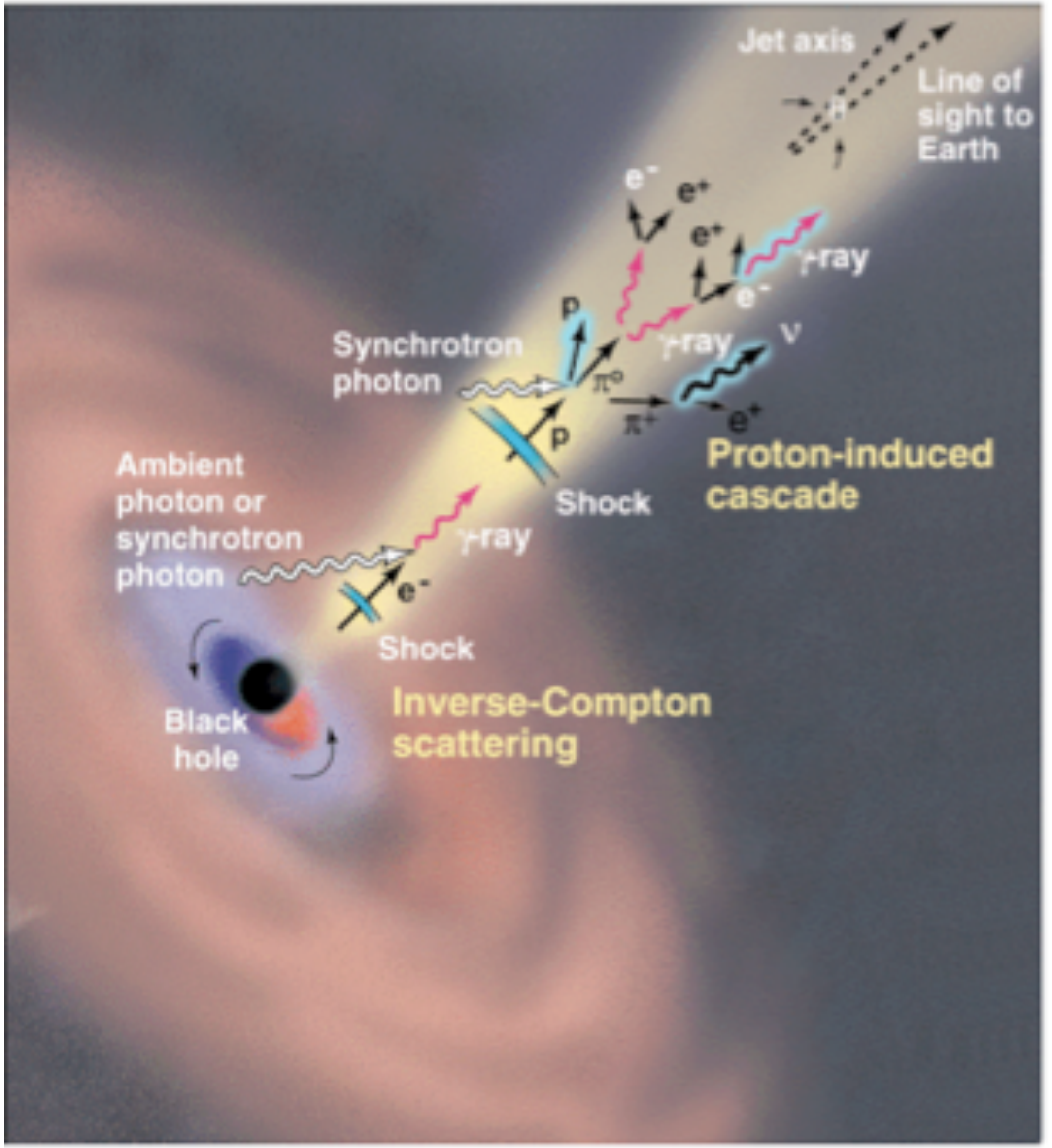
Particle Astrophysics

- Gamma astronomy (10 GeV to 100 TeV)
- Cosmic ray physics, spectrum, composition, anisotropy, astronomy at highest energies (TeV to 10^21 eV)
- Neutrino astronomy (100 GeV to 10^21 eV, also MeV)

High energy particles in the Universe

What are the cosmic accelerators that generate …

- Cosmic Rays
  - Observed up to 10^21 eV
  - Mostly diffuse flux, mass composition, spectrum
- Gamma Rays
  - Observed up to ~100 TeV
  - Numerous TeV point sources resolved
- Neutrinos
  - Atmospheric neutrinos observed beyond 100 TeV



Cosmic Rays and Neutrino Sources

Candidate sources (accelerators):

Cosmic ray related:

- SN remnants
- Active Galactic Nuclei
- Gamma Ray Bursts

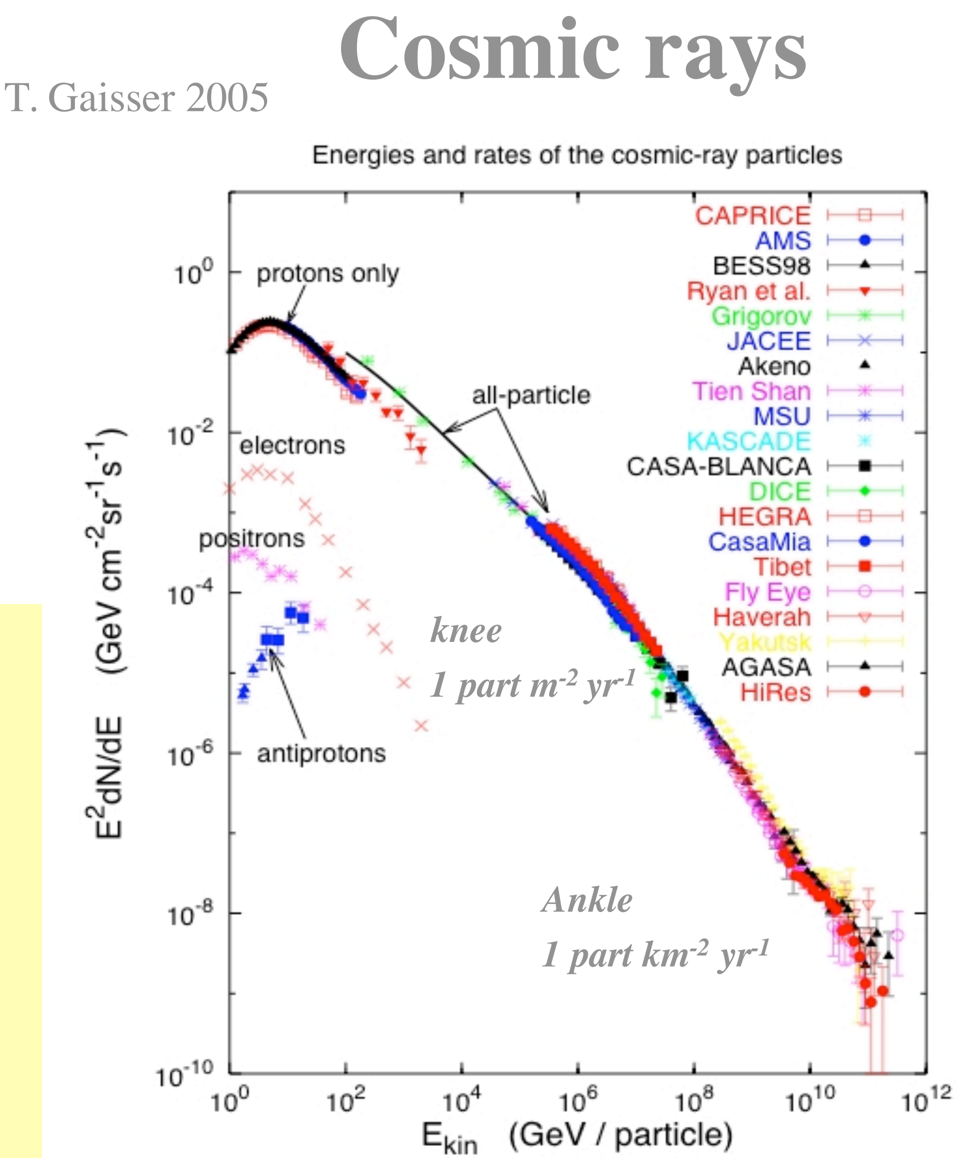
Other:

- Dark Matter
- Exotics

Guaranteed sources (known targets):

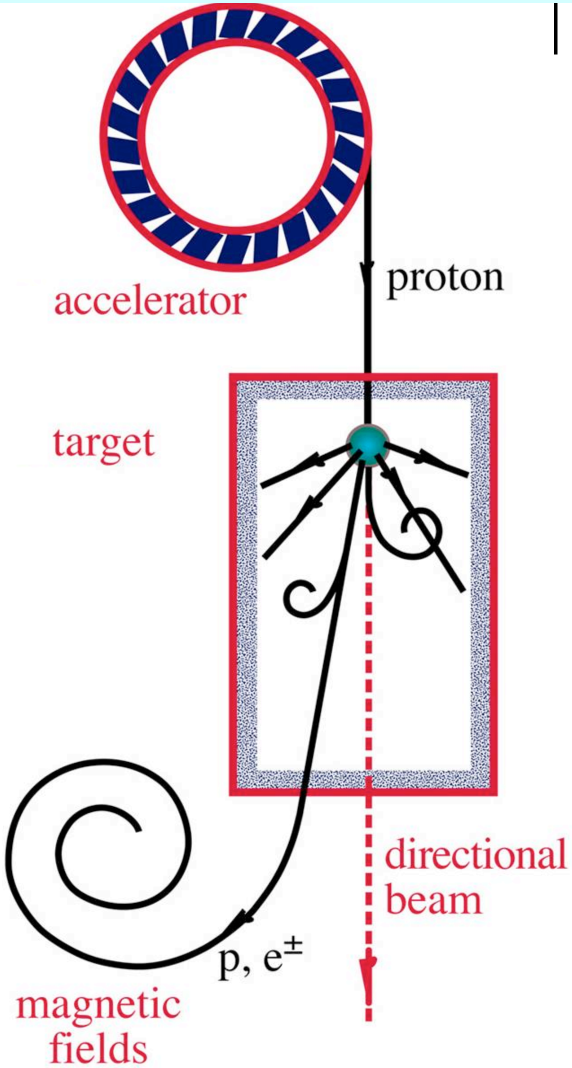
- Atmospheric neutrinos (from π and K decay)
- Galactic plane:
  CR interacting with ISM, concentrated on the disk
- GZK (cosmogenic neutrinos)

$$p\,\gamma \rightarrow \Delta^+ \rightarrow n\,\pi^+ \;(p\,\pi^0)$$



Neutrino production

Beam-dump model: $\pi^0 \rightarrow \gamma$-astronomy $\pi^\pm \rightarrow \nu$-astronomy



π^0 $\pi^\pm$

$\gamma\gamma$ $\nu_\mu \mu$

$\nu_e \nu_\mu e$

$\nu_e \nu_\mu \nu_\tau$

Neglecting γ absorption

$\varphi_\nu \sim \varphi_\gamma$

Targets: p or ambient γ

Integrated flux in neutrinos similar to that in photons

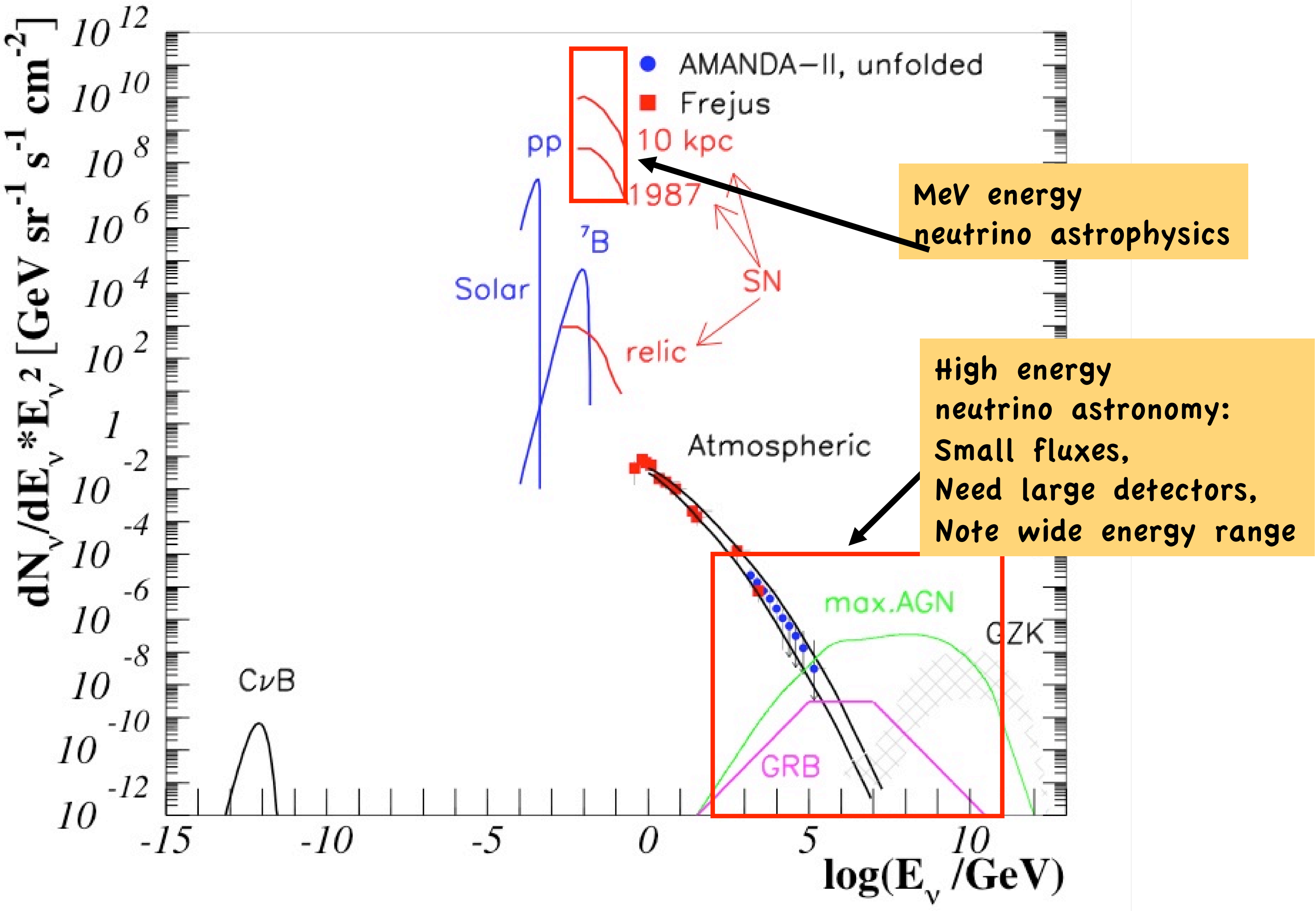
initial fluxes are

$\varphi_{\nu_e} : \varphi_{\nu_\mu} : \varphi_{\nu_\tau} = 1:2:0$

after oscillations

$\varphi_{\nu_e} : \varphi_{\nu_\mu} : \varphi_{\nu_\tau} = 1:1:1$

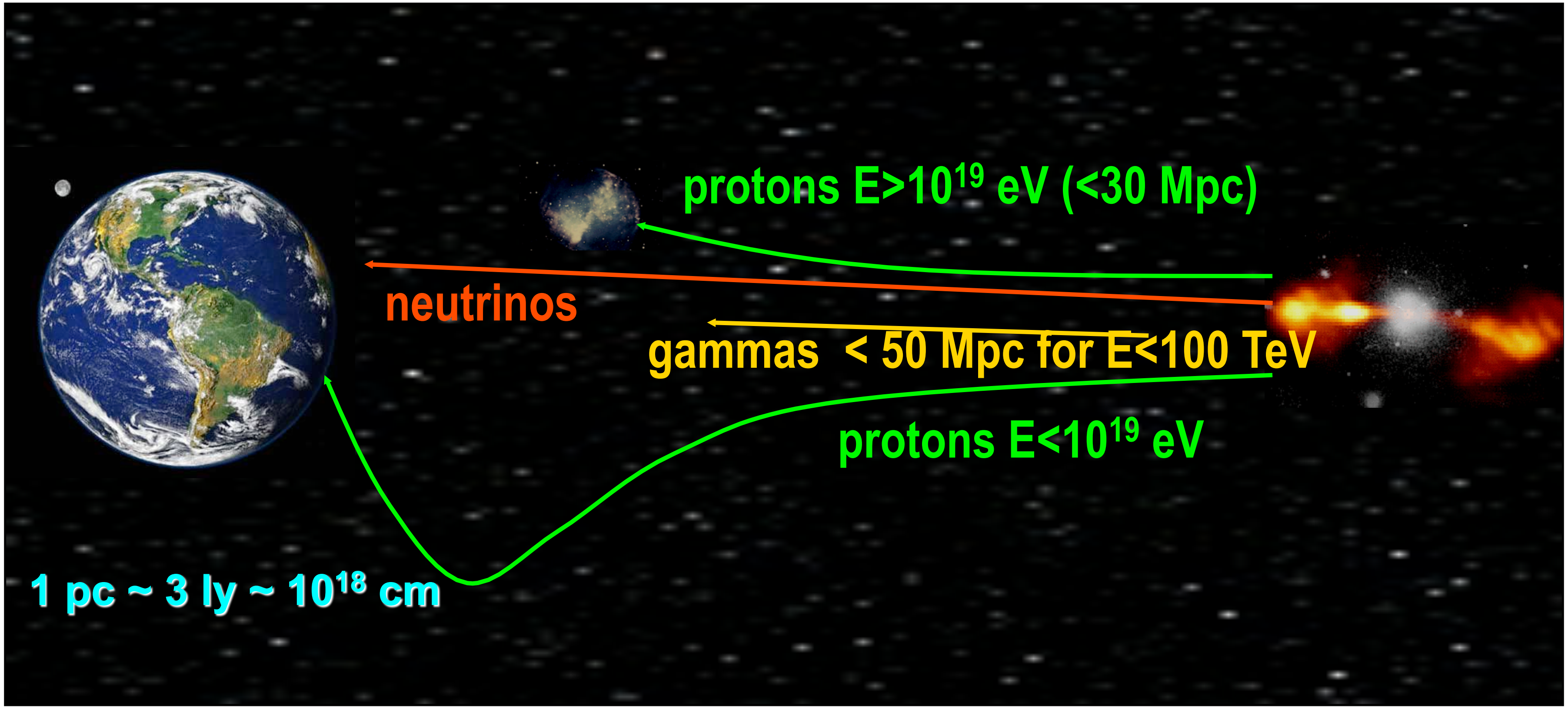
Neutrinos



AMANDA–II, unfolded
Frejus
10 kpc
1987
SN
relic
pp
Solar
⁷B
Atmospheric
max.AGN
GZK
GRB
CνB
MeV energy neutrino astrophysics
High energy neutrino astronomy: Small fluxes, Need large detectors, Note wide energy range
log(E_ν /GeV)
dN_ν/dE_ν *E_ν^2 [GeV sr^-1 s^-1 cm^-2]

Messengers from the Universe

Cosmic rays, Photons, Neutrinos



Other signatures for astrophysical origin: timing, energy

Universe is not transparent for HE photons or nuclei!

$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$

$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+$

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

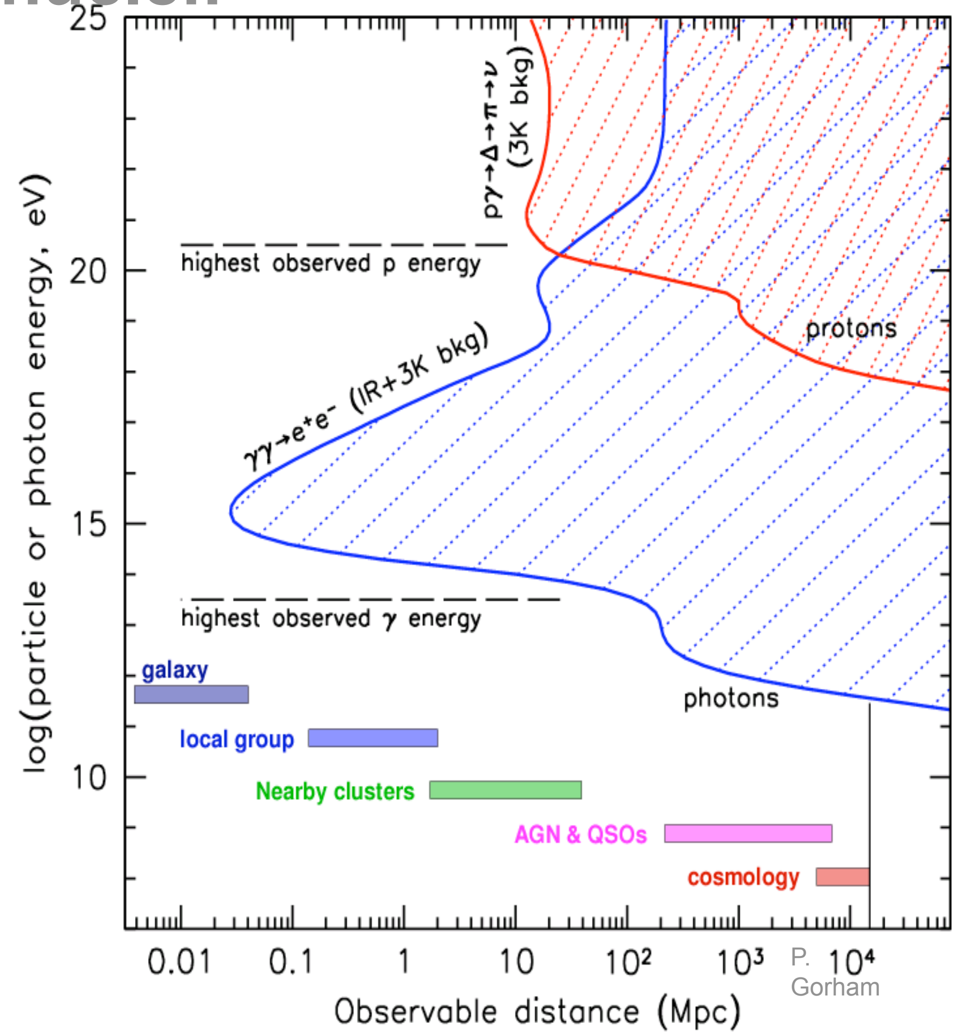
GZK - neutrinos

Protons deflected by magnetic field for

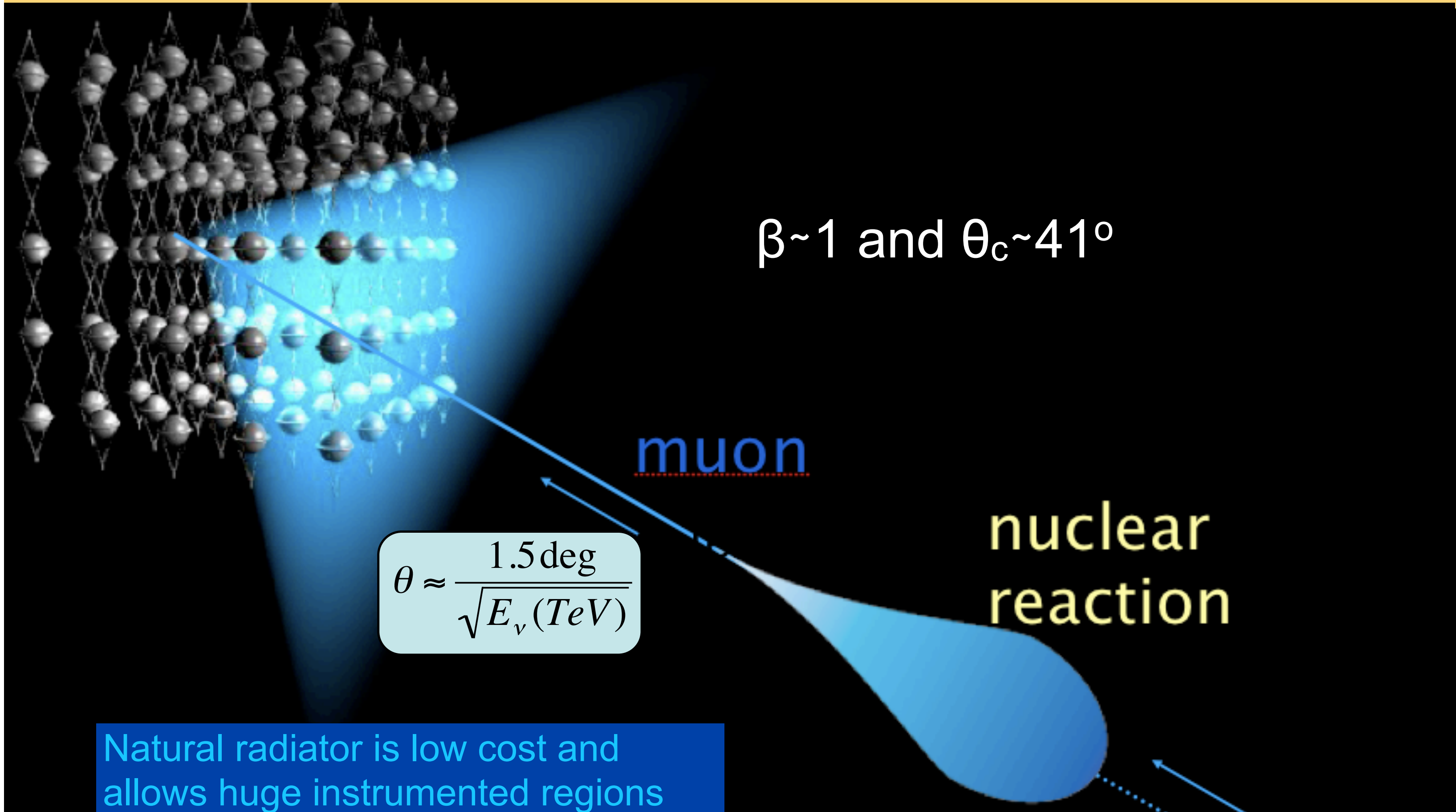
E < 10^{19} eV!

Not pointing back to the source!

Need neutrinos for high energy (>10TeV) astronomy!



Concept of large neutrino telescopes

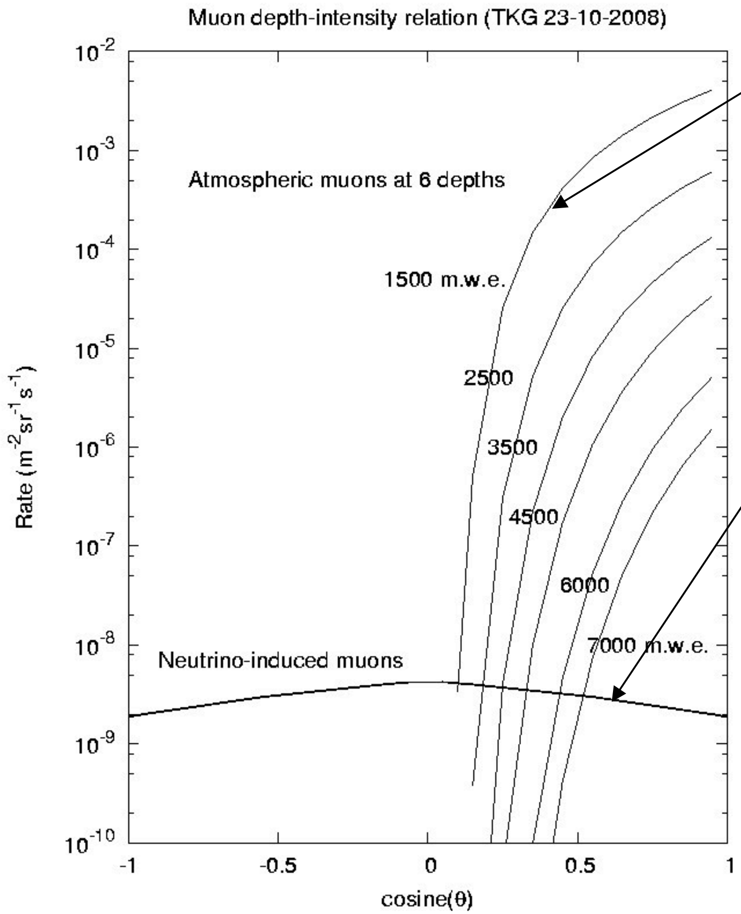


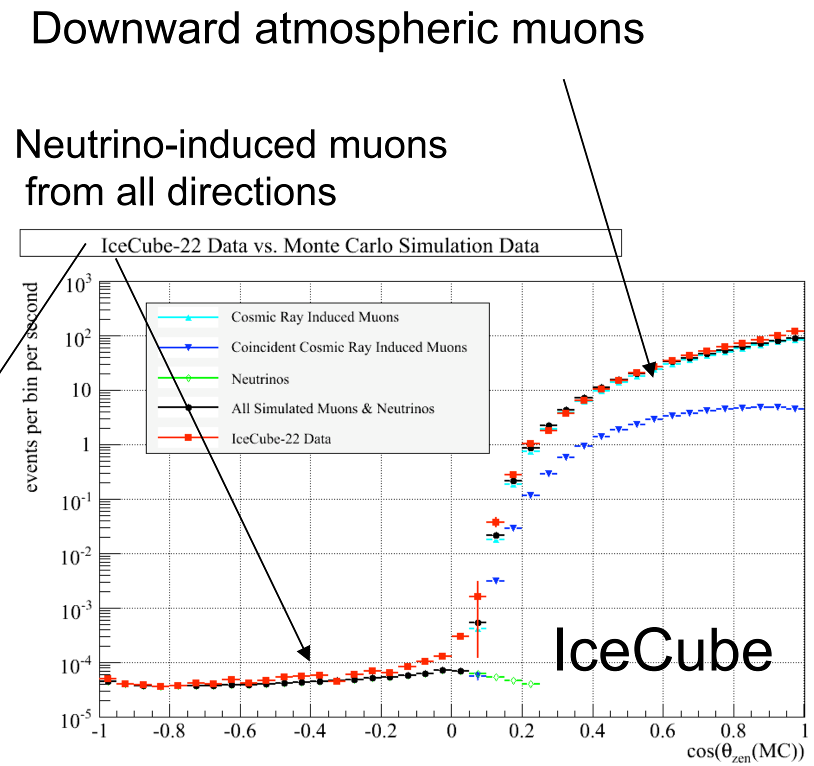
$$\theta \approx \frac{1.5\,\mathrm{deg}}{\sqrt{E_\nu(TeV)}}$$

Natural radiator is low cost and
allows huge instrumented regions
but it takes time to know it well!
Main systematic error source

Between 300-600 nm 2* 10^4 Cherenkov photons/m of a muon track
Perfect scaling with dE/dx as radiative losses increase above 10 TeV

Muons in ν telescopes





Patrick Berghaus et al., Cosmo-08 and ISVHECRI-08

Depending on depth BG/neutrino ratio: 10^3 (6000mwe) to 10^8 (1000mwe)

→Low energies: Use Earth as filter; look for neutrinos from below (GeV to PeV)

→High energies: Apply energy cut for downgoing atmospheric background (>PeV)

Neutrino Telescopes | Energy ranges

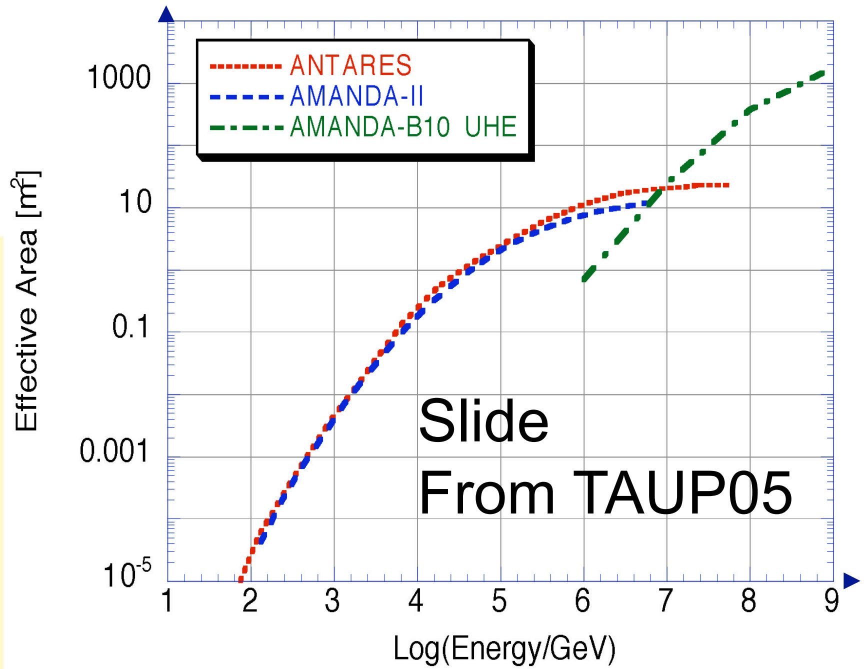
NT operate at a wide energy range:

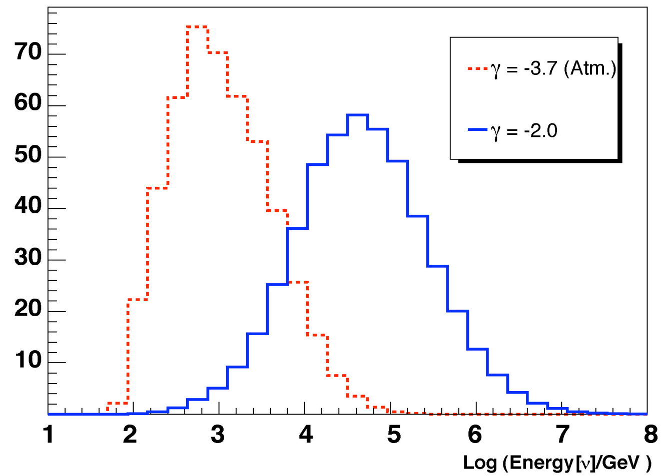
100 GeV to beyond 1 EeV

- The negative power law spectra of cosmic accelerators is compensated by the increasing effective detection area
- Effective area for ν_μ

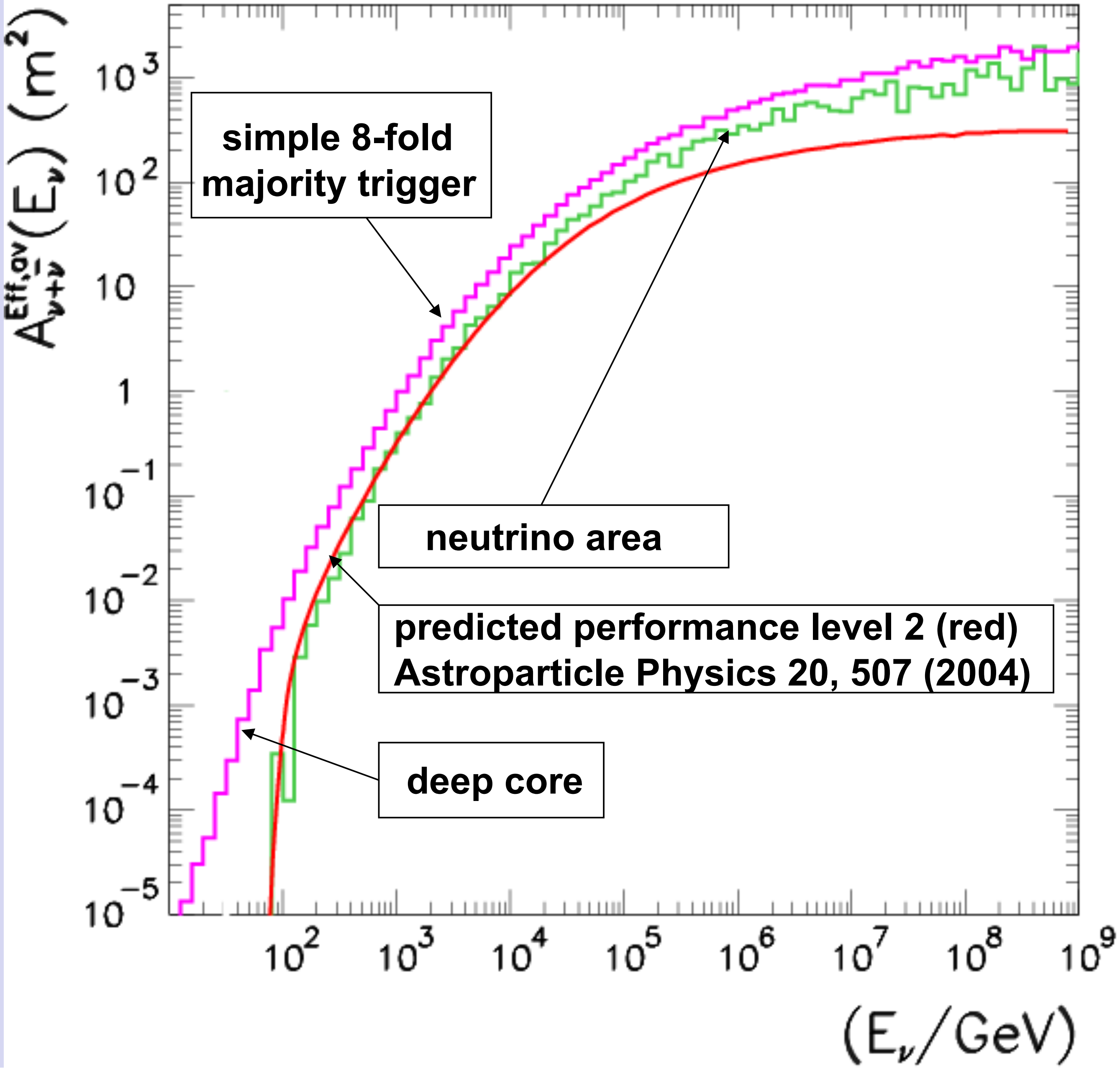
$$A^{\nu}_{eff} = \sigma \otimes P_{Earth} \otimes R_{\mu} \otimes \varepsilon_{eff}$$

- Why?
  - $\sigma \propto E_{\nu}$
  - Increase of muon range with energy
- Wide energy range unique to neutrino telescopes: much smaller for cosmic ray or gamma ray detectors.
- Sensitivities for diffuse signals comparable for cascades.





- Effective areas today



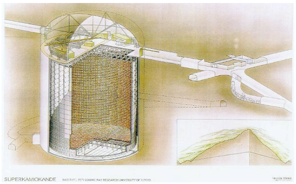
Deep water Cherenkov neutrino detectors

Low energy underground neutrino detectors provide important experiences and results (Frejus, MACRO, IMB, Kamioka, SuperK, SNO, ….)

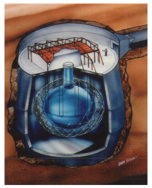
Telescopes for TeV energies:

- First envisioned by Greisen, Markov 1960
- Pioneering effort: DUMAND near Hawaii
- First and second generation telescopes in 90's, proof of principle : Baikal, AMANDA (S Pole), NESTOR (Greece).
- Current generation experiments and initiatives:
  - 50000m^2 scale: ANTARES, AMANDA (integrated in IceCube),
  - km scale: IceCube (running at ~50% size)
- Next generation:
  - IceCube almost complete (go from 59 to 86 strings by 2011)
  - Based on NESTOR, NEMO, ANTARES experiences→ km3NeT project, Mediterranean Sea.

Super-K

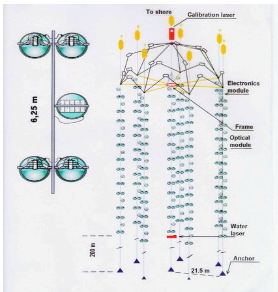


Not to scale!

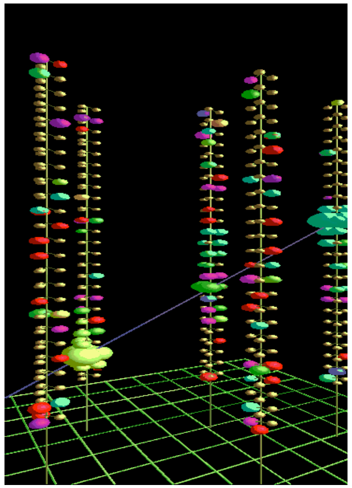


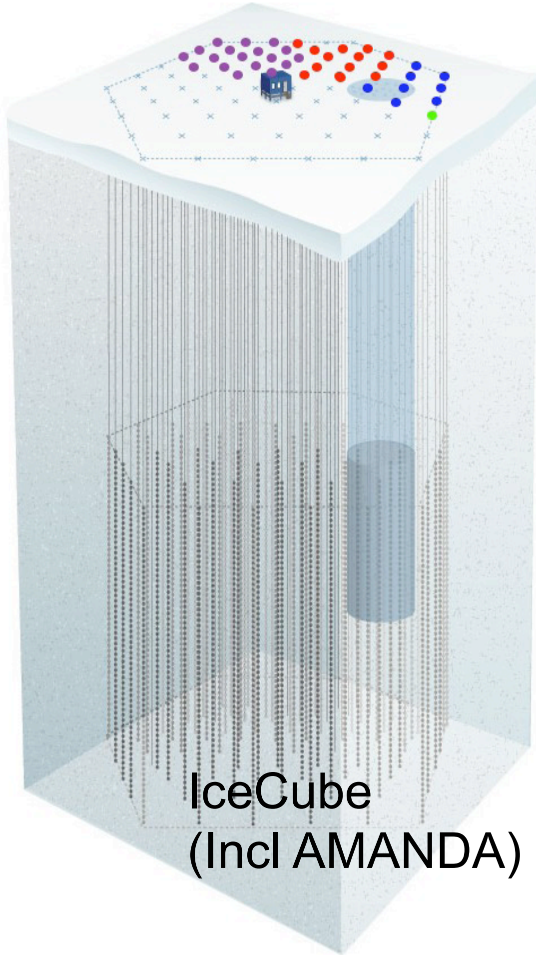
SNO

Baikal



ANTARES

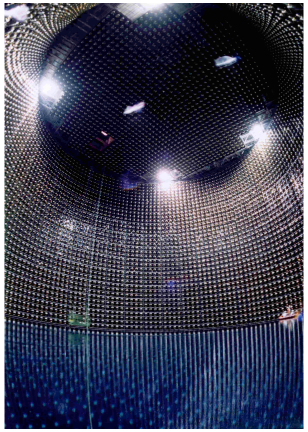




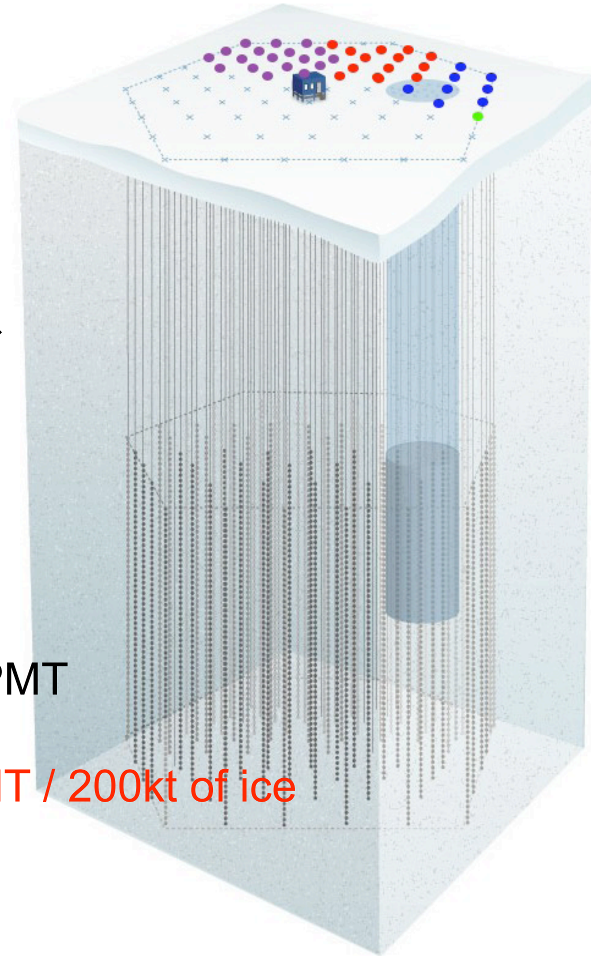
Albrecht Karle, UW-Madison
Albrecht Karle, UW-Madison

Maximize size of detector large spacing of PMT

- Challenge: maximize PMT spacing to maximize detector volume



PMT Cathode/unit mass:~10^-5



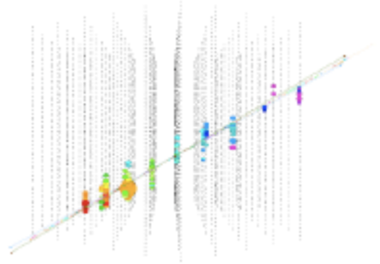
Super-K
11000 x 50cm PMT
50kt
One 50 cm PMT/5t

IceCube
5000 x 25cm PMT
1000 Mt
One 20 cm PMT / 200kt of ice

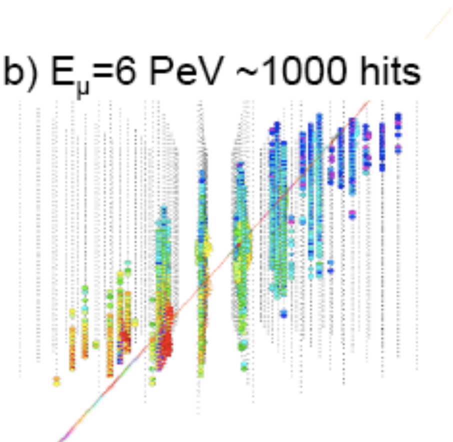
Neutrino Topologies

Muon neutrino

a) E_μ=10 TeV ~ 90 hits



b) E_μ=6 PeV ~1000 hits

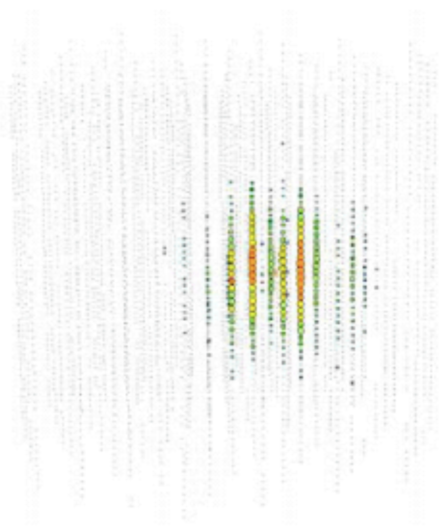


E ~ dE/dx, E> 1 TeV

Energy Res. : log(E)~0.3
Angular Res.: 0.8 -2 deg

Electron neutrino

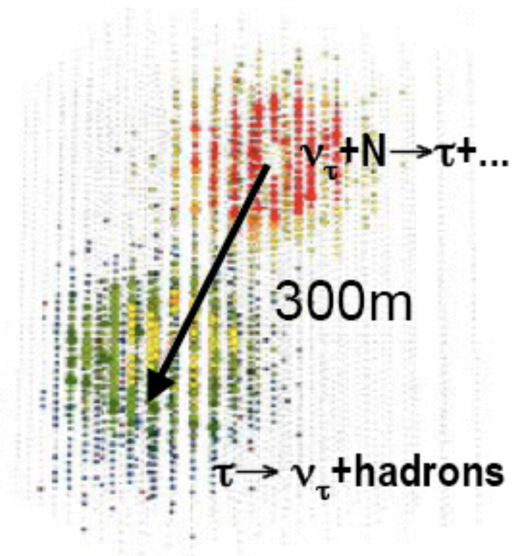
E = 375 TeV



Energy Res. log(E)~0.1-0.2
Poor Angular Resolution

Tau neutrino

E = 10 PeV

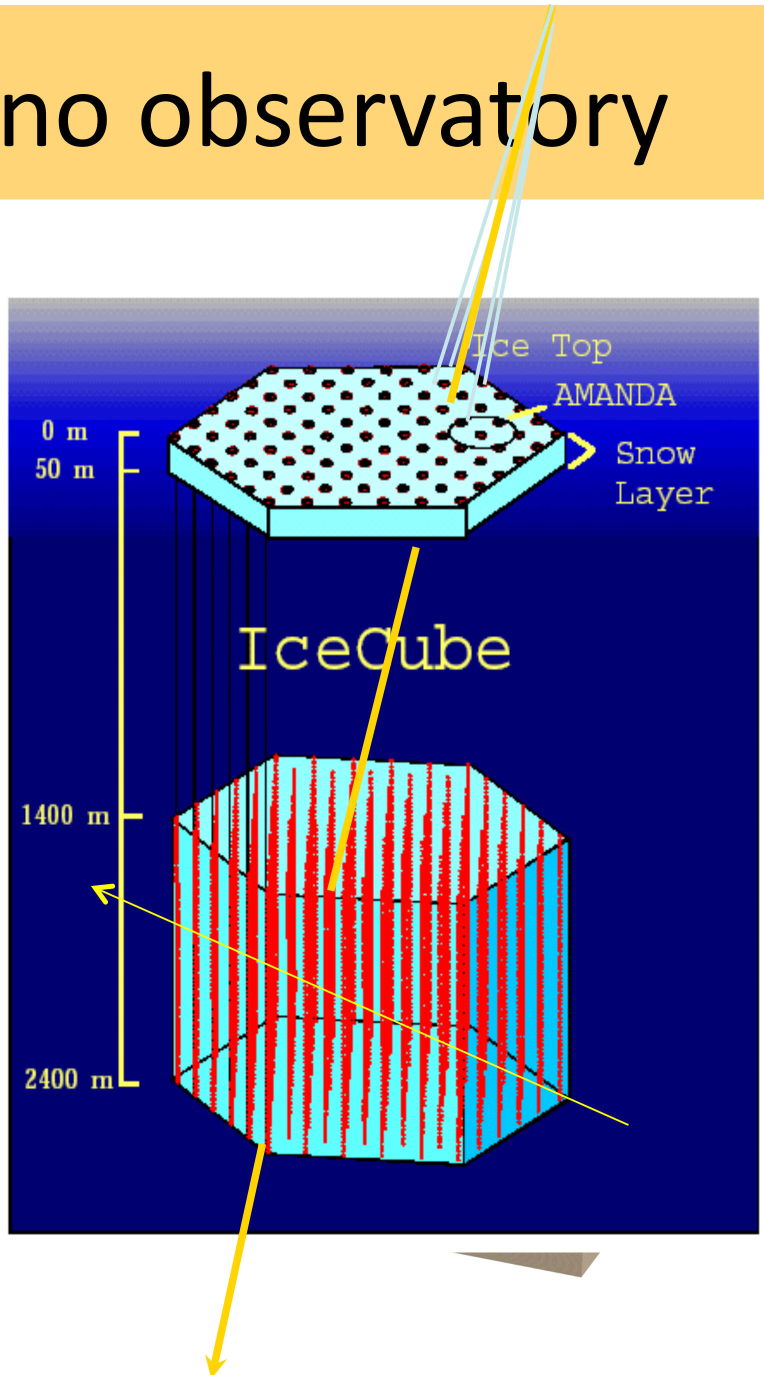


Double-bang signature above ~ 1 PeV
Very low background
Pointing capability
Best energy measurement

The IceCube neutrino observatory

Status

- Total of 59 strings and 118 IceTop tanks → over two thirds complete!
- Completion with 86 strings by 2011
- Detector is taking data during construction phase.



The IceCube Collaboration

USA:

Bartol Research Institute, Delaware
University of California, Berkeley
University of California, Irvine
Pennsylvania State University
Clark-Atlanta University
Ohio State University
Georgia Tech
University of Maryland
University of Alabama, Tuscaloosa
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

Sweden:

Uppsala Universitet
Stockholm Universitet

UK:

Oxford University

Netherlands:

Utrecht University

Switzerland:

EPFL

Germany:

DESY-Zeuthen
Universität Mainz
Universität Dortmund
Universität Wuppertal
Humboldt Universität
MPI Heidelberg
RWTH Aachen

Belgium:

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

Japan:

Chiba University

New Zealand:

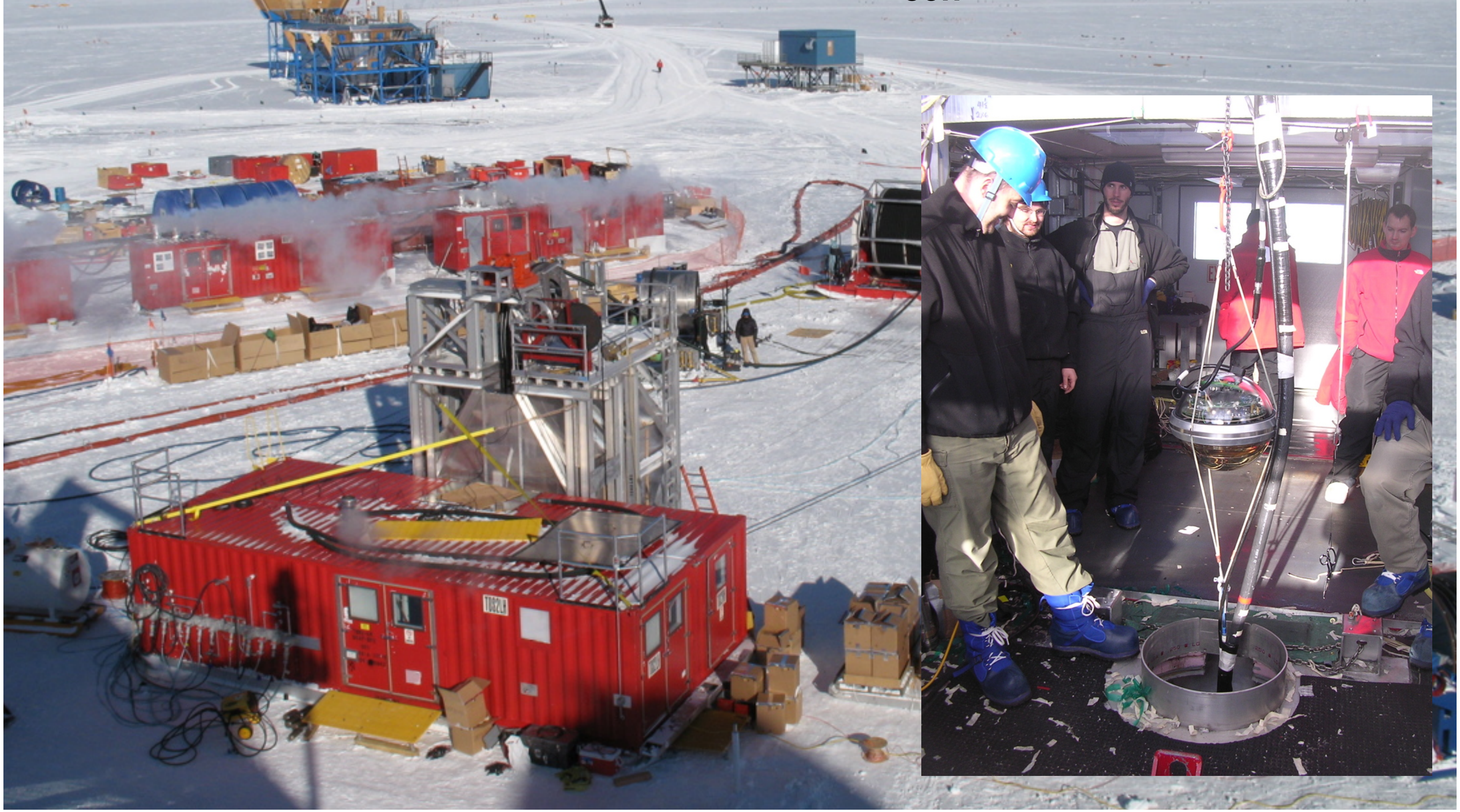
University of Canterbury

33 institutions, ~250 members

http://icecube.wisc.edu

IceCube
Construction site

- Hotwater drill
- Thermal power: 5 MW
- 60 cm diameter hole, 2m/min
- Time to complete: 35 hrs
- Time between two strings: ~50h



IceCube: Digital Optical Module (DOM)

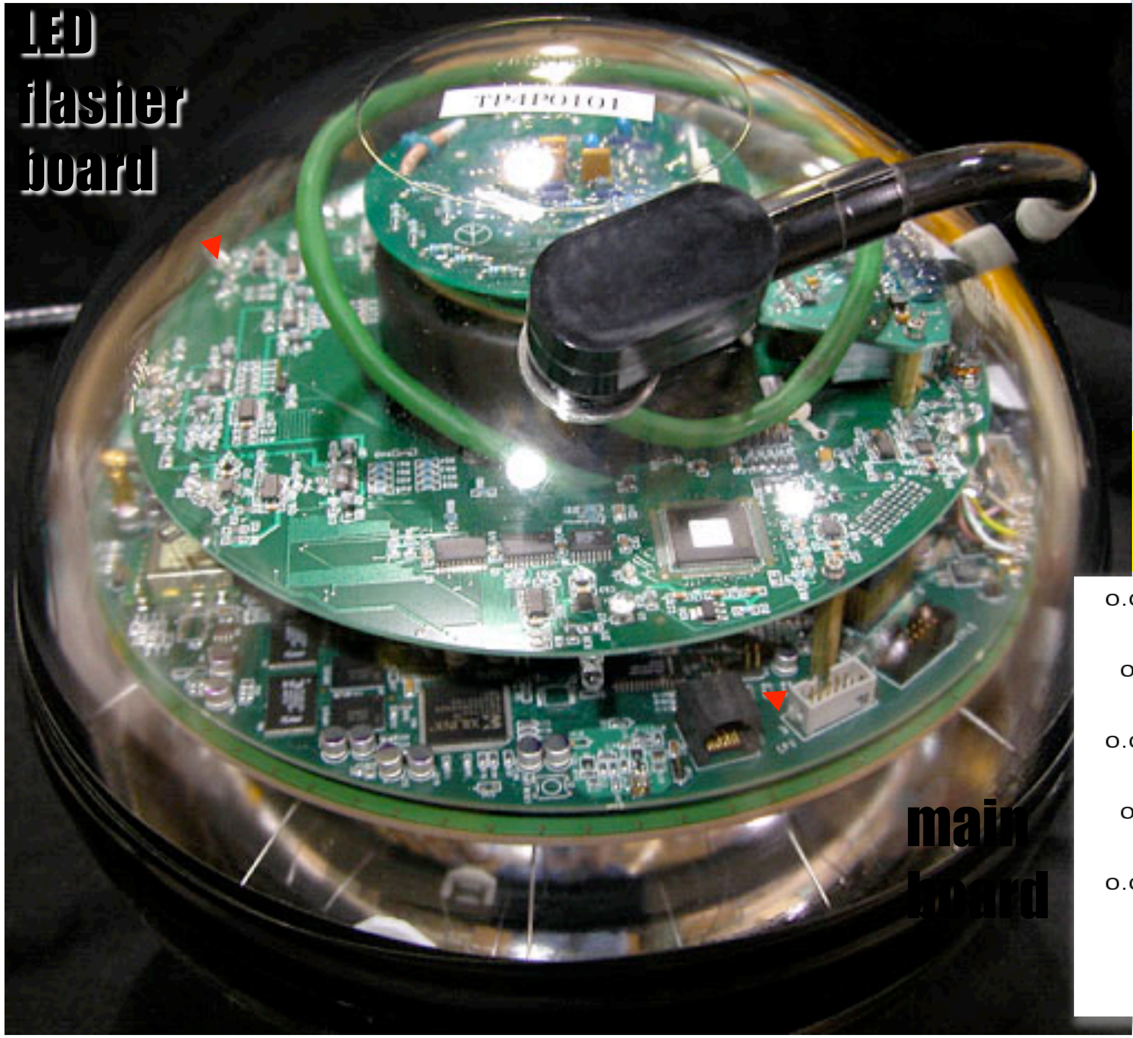
Local digitization and time stamping
(common requirement to all large detectors)

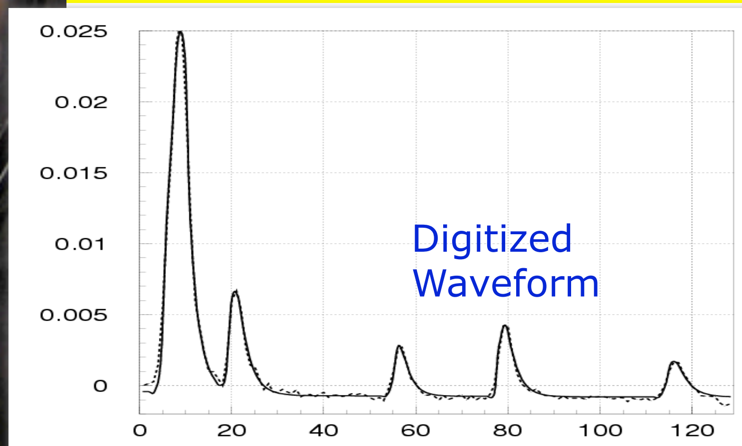
Design for high reliability!
Detectors are not accessible

PMT: 10 inch Hamamatsu
Power consumption: 3 W
Digitize at 300 MHz for 400 ns with custom chip
40 MHz for 6.4 μs with fast ADC
Dynamic range 500pe/15 nsec

Send all data to surface over copper
2 sensors/twisted pair.
Flasherboard with 12 LEDs

Clock stability: $10^{-10} \approx 0.1$ nsec / sec
Synchronized to GPS time every ≈10 sec
Time calibration resolution = 2 nsec



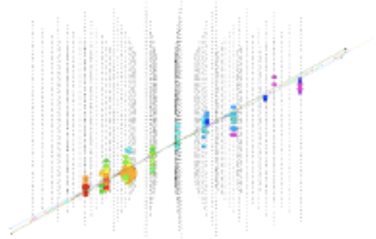


Neutrino Topologies in IceCube

Muons: increasing range helps with eff volume (vertex can be far outside)
Increasing nu cross section with energy helps at higher energies

Muon neutrino

a) E_μ=10 TeV ~ 90 hits



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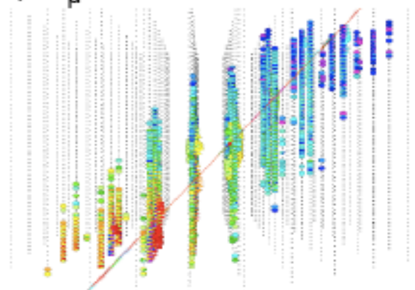

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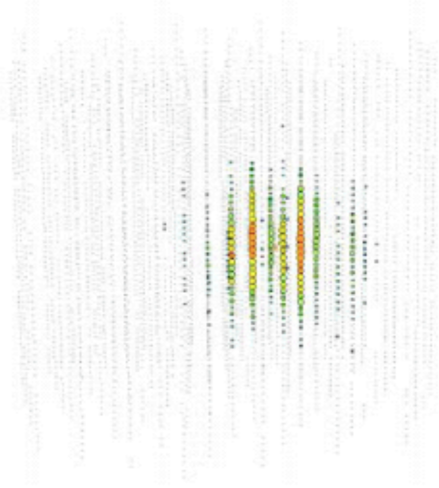

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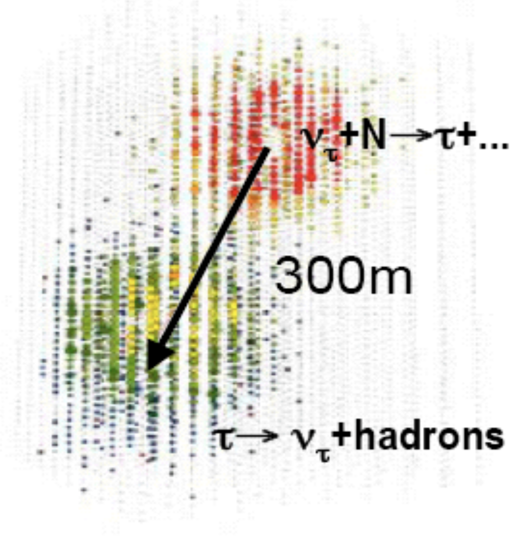
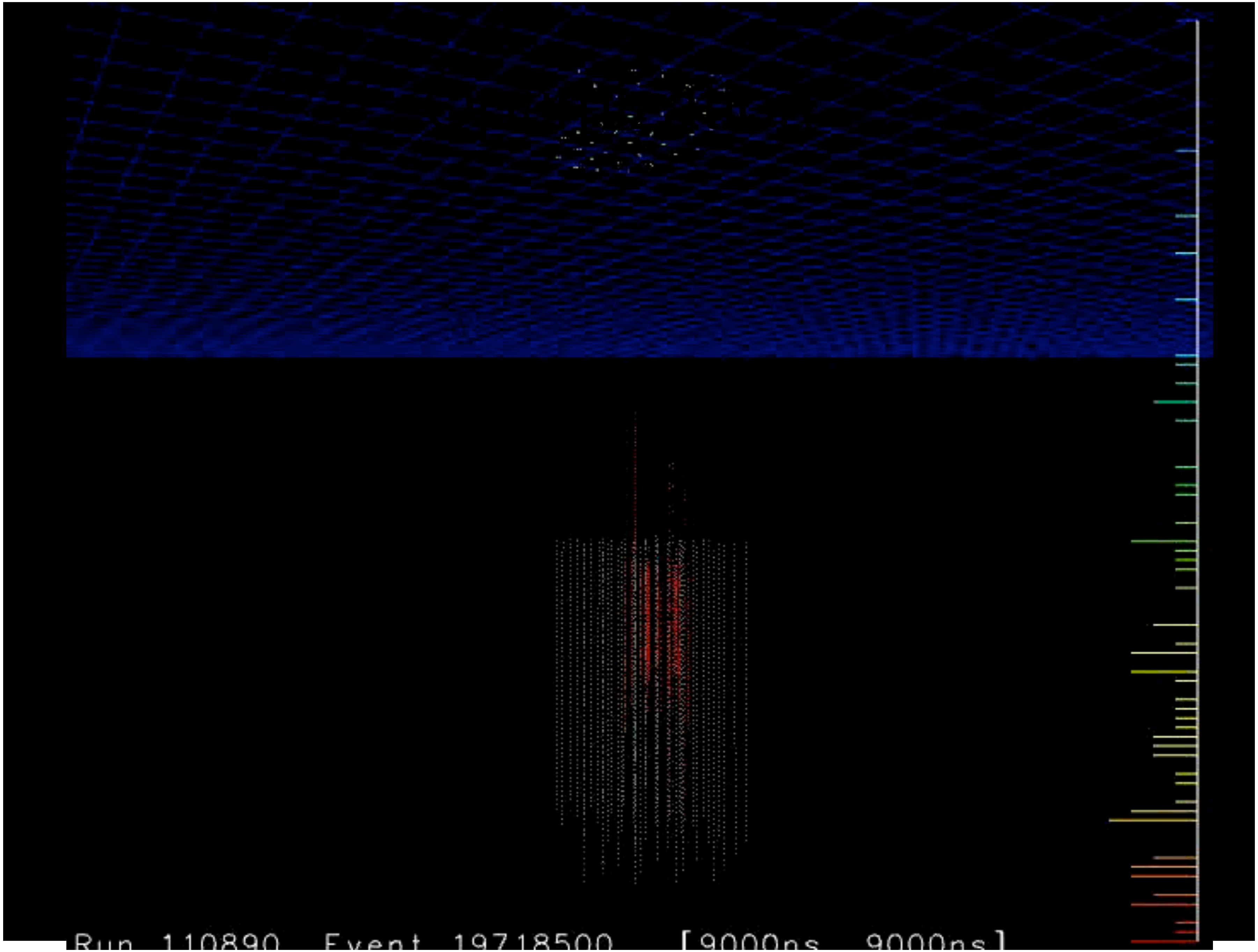
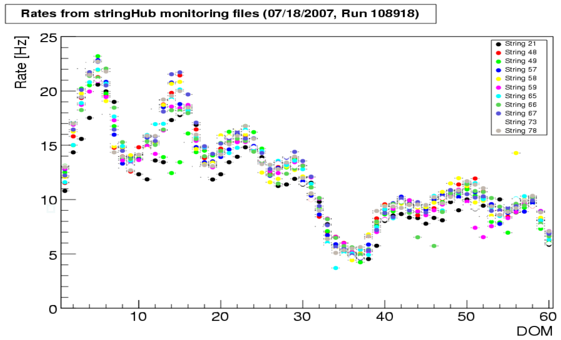
E = 10 PeV

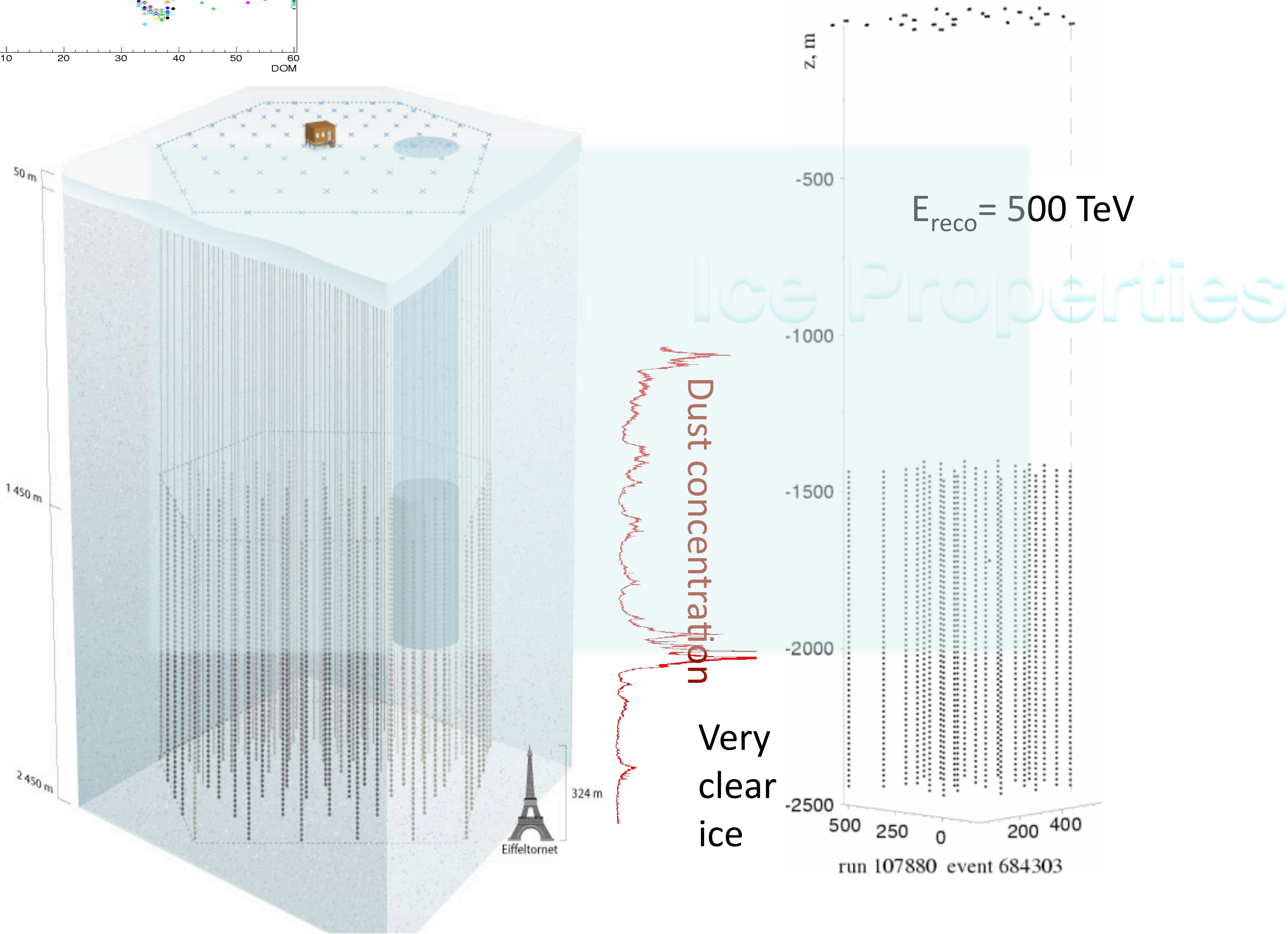


Double-bang signature above ~ 1 PeV
Very low background
Pointing capability
Best energy measurement

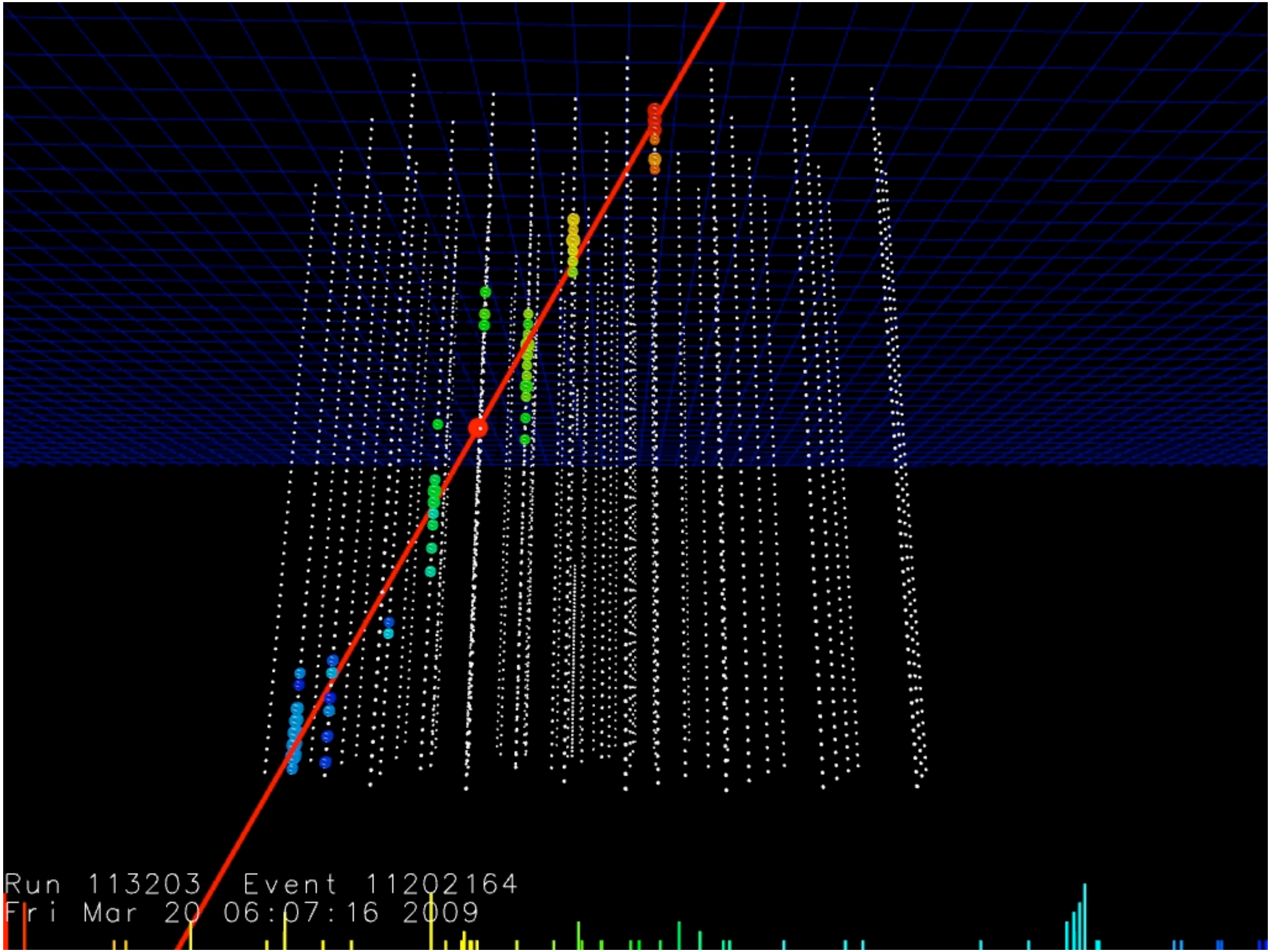

Run 110890 Event 19718500 [9000ns 9000ns]



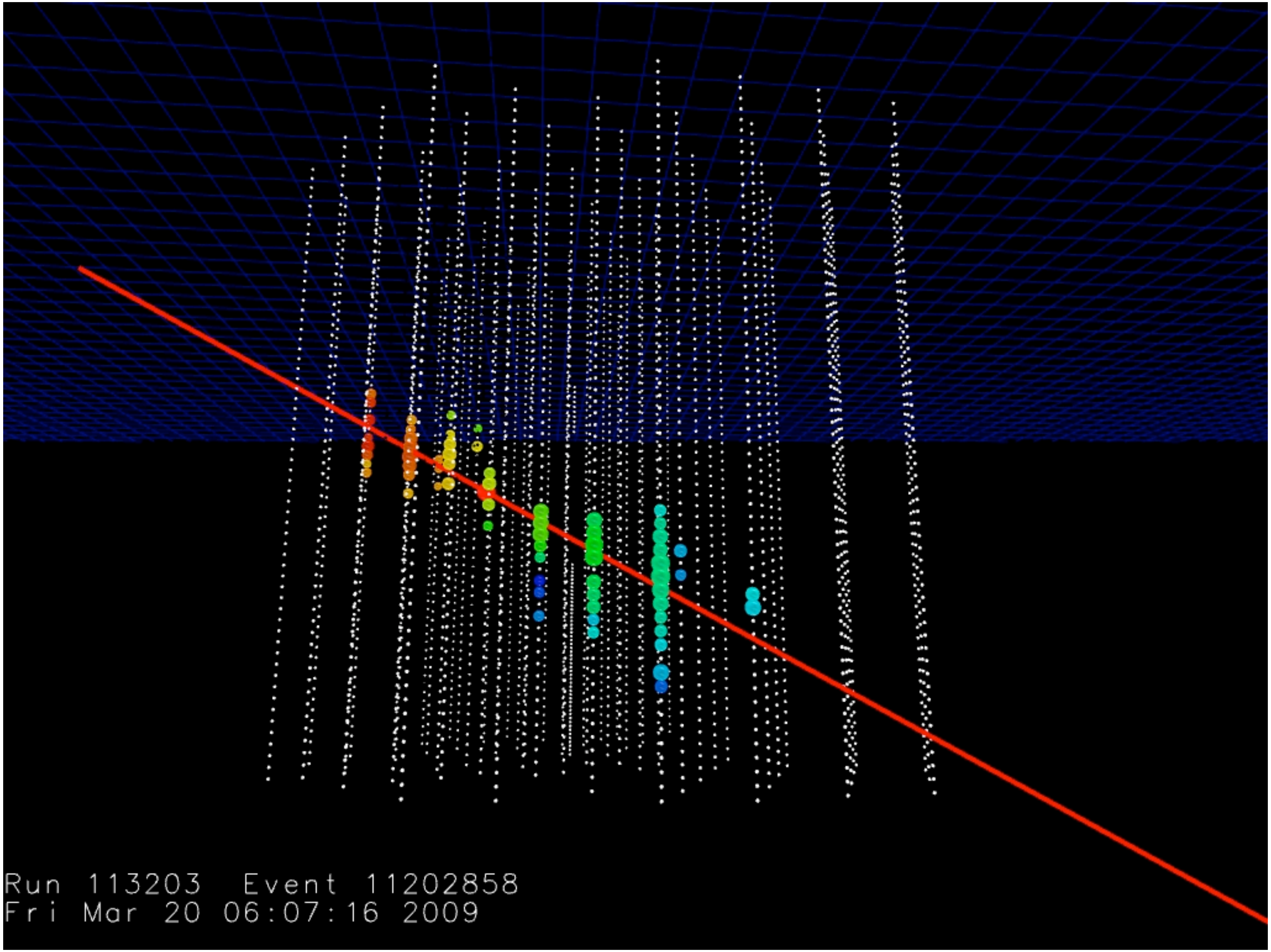
Rates from stringHub monitoring files (07/18/2007, Run 108918)
Rate [Hz]
DOM
String 21
String 48
String 49
String 57
String 58
String 59
String 65
String 66
String 67
String 73
String 78



Ice Properties
50 m
1 450 m
2 450 m
324 m
Eiffeltornet
Dust concentration
Very clear ice
z, m
-500
-1000
-1500
-2000
-2500
500 250 0 200 400
E_{reco}= 500 TeV
run 107880 event 684303



Run 113203 Event 11202164
Fri Mar 20 06:07:16 2009

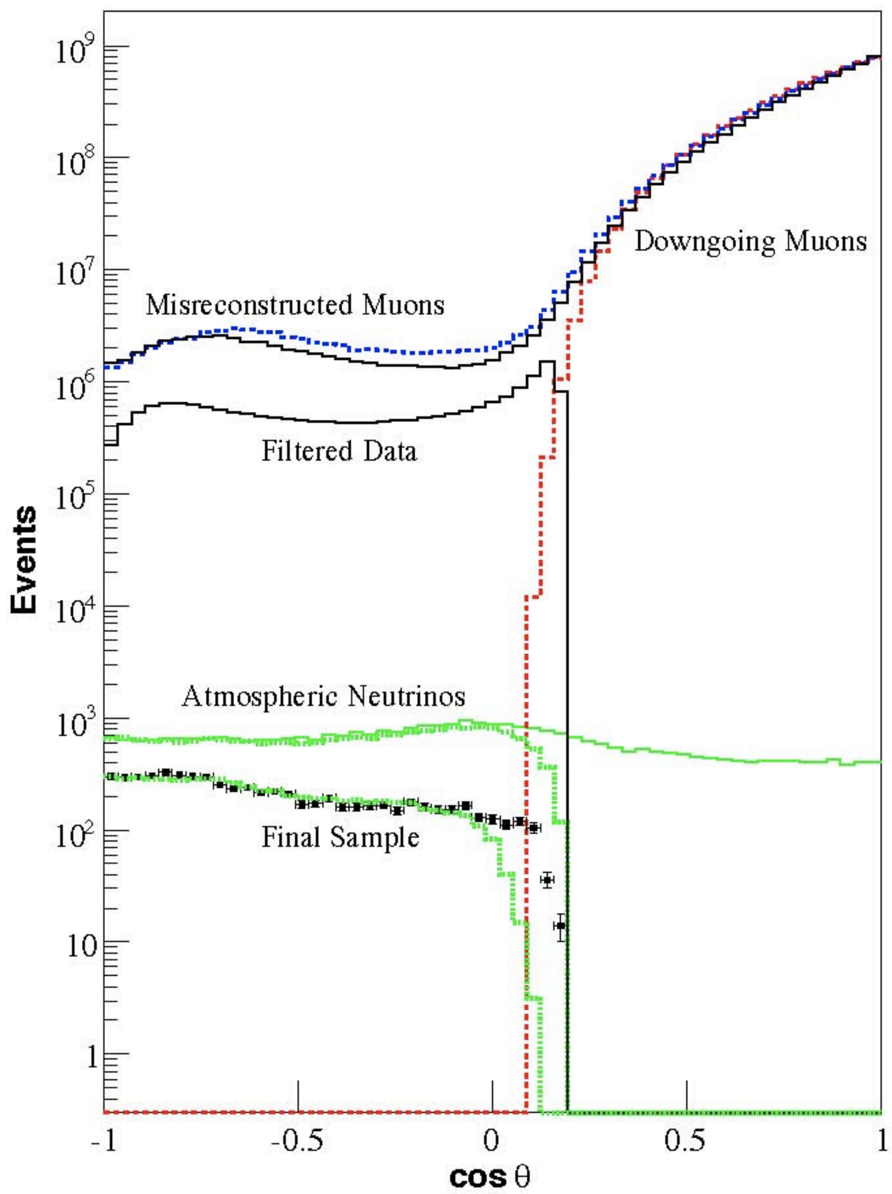

Run 113203 Event 11202858
Fri Mar 20 06:07:16 2009

7 year final event sample from AMANDA

7 years of data are shown

The figure illustrates the advance from trigger level to successive rejection of downgoing muon background.

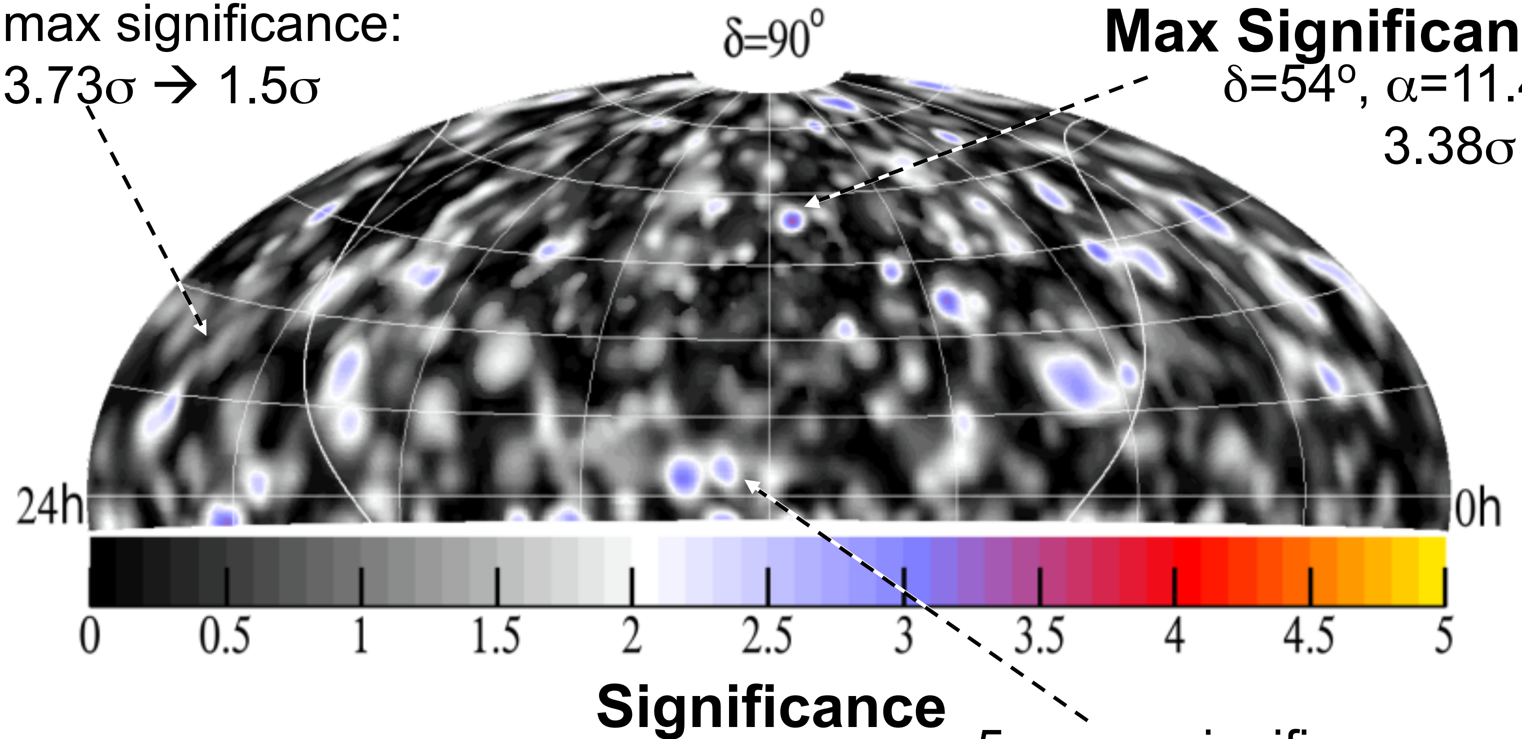
At the final sample, consisting of 6595 events, the data events agree well with the atmospheric neutrino simulation



Skymap of 7 years of AMANDA-II

3yr max significance:
3.73σ → 1.5σ

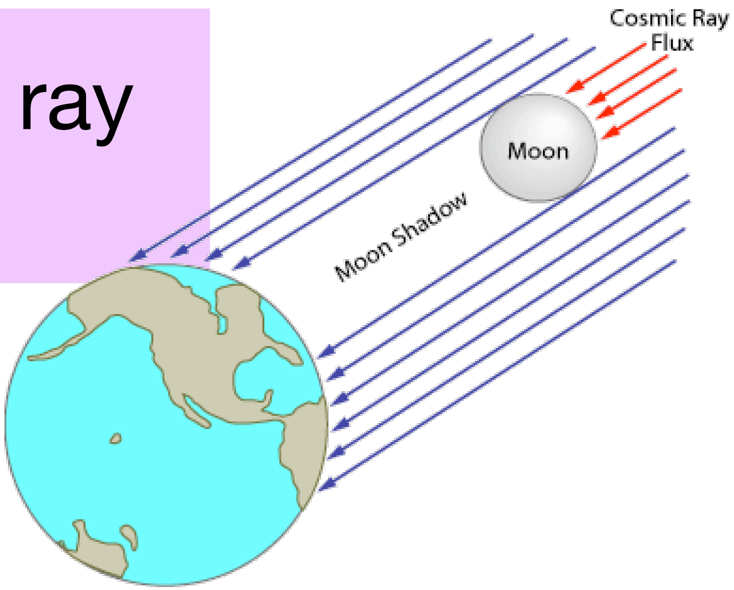
Max Significance
δ=54°, α=11.4h
3.38σ



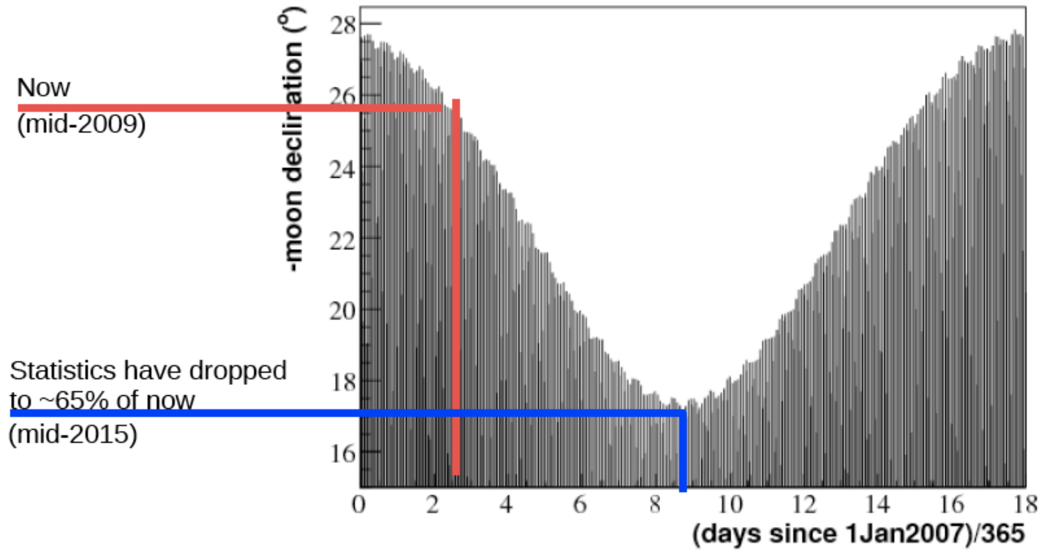
5yr max significance:
3.74σ → 2.8σ

95 of 100 data sets randomized in RA have a significance ≥ 3.38σ
--> No signal

IceCube observes cosmic ray moon shadow



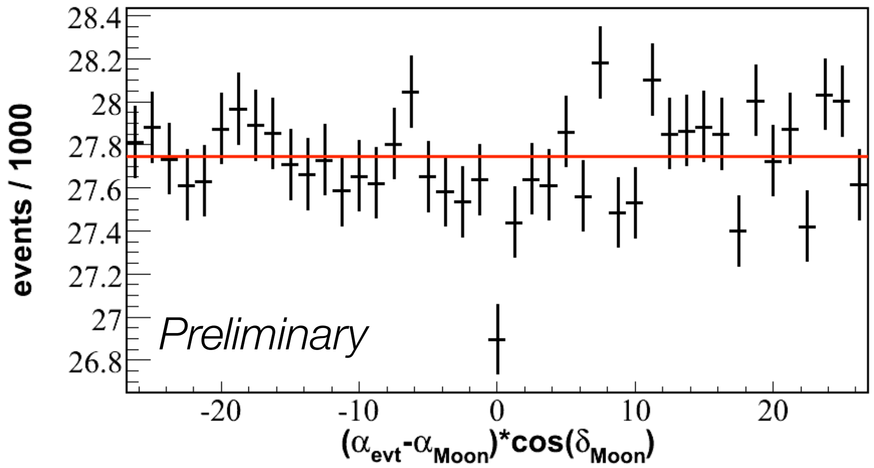
8 months of IC40 data, 9M muons,
13 cycles
0.7° radius bins around Moon position
Check of absolute positioning and coordinate transformations

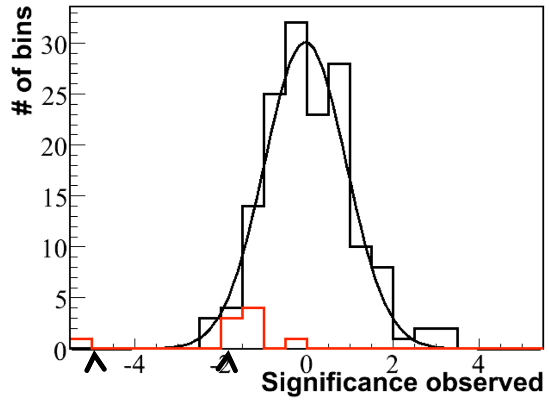


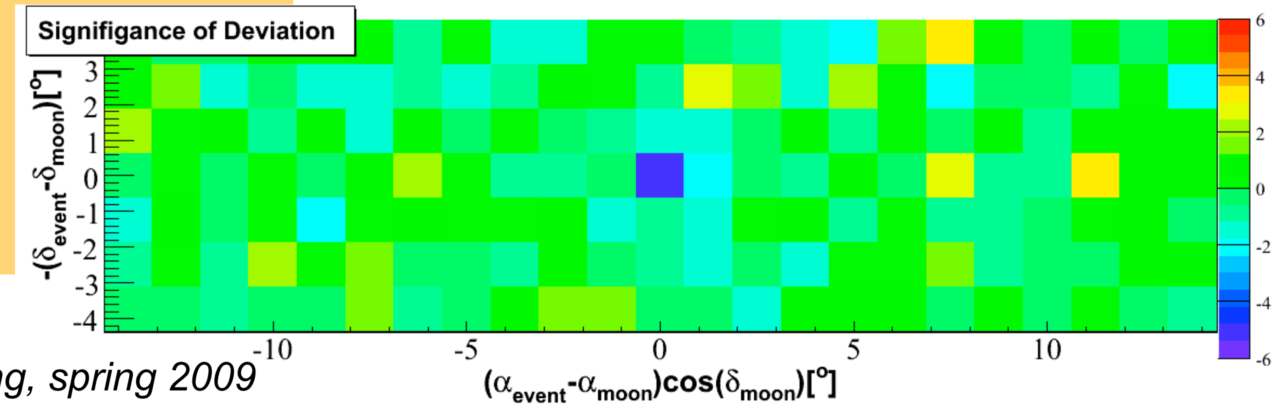
Moon shadow observed in muons

Preliminary

- Moon reaches an altitude of 28° at the South Pole
- Despite large zenith angle, sufficient statistics and angular resolution to analyze data for shadowing of cosmic ray primaries.
- Deficit: 5 σ (~900 events of ~28000) and consistent with expectation.
- IceCube works!
- More statistics will allow study of angular response function



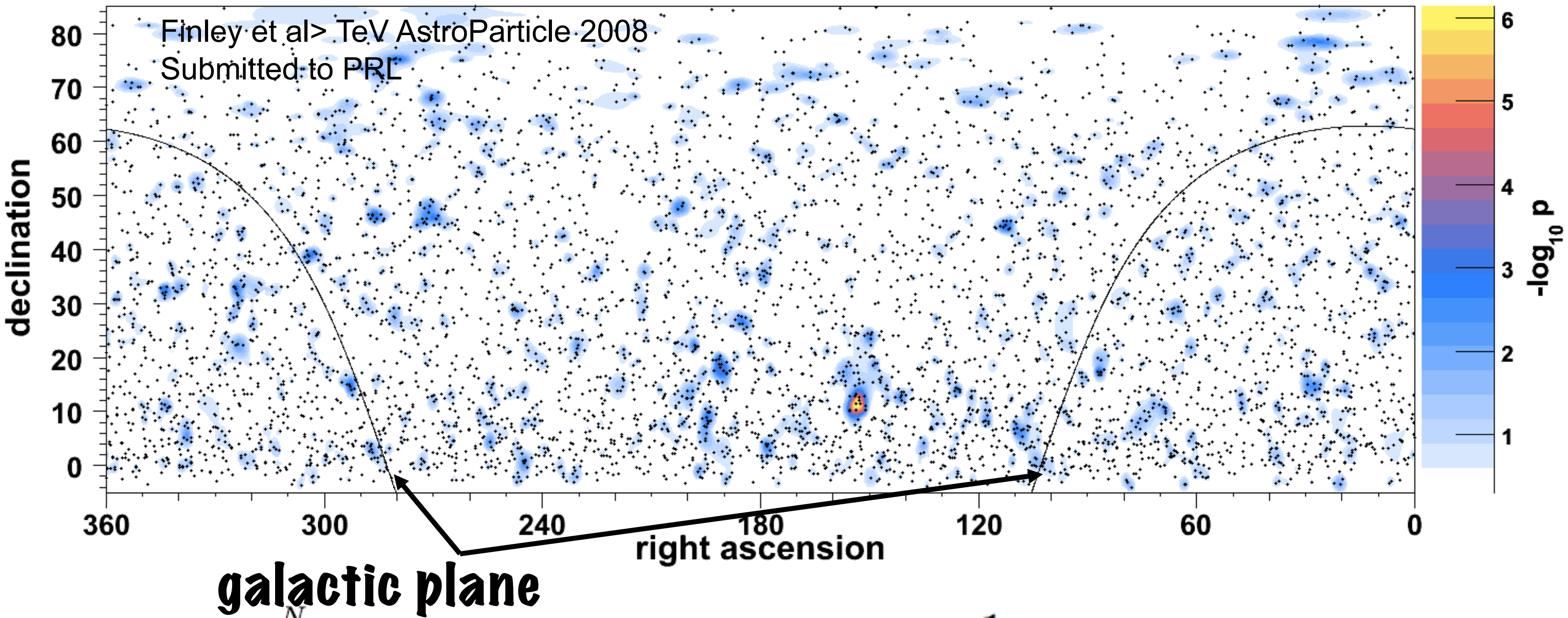




Gladstone et al. APS meeting, spring 2009

Pointsource search

Sky map with first 22 strings of the IceCube detector



$$\mathcal{L}(n_s,\gamma) = \prod_{i=1}^{N}\left(\frac{n_s}{N}\mathcal{S}_i(\gamma) + (1-\frac{n_s}{N})\mathcal{B}_i\right) \qquad \mathcal{S}_i = \frac{1}{2\pi\sigma_i{}^2}e^{-r_i{}^2/2\sigma_i{}^2}\cdot P(E_i|\gamma)$$

new unbinned search method

energy variables used

5114 neutrino candidates in 276 days livetime!

Hottest spot found at r.a. 153º , dec. 11º

pre-trial p-value: 7x 10^{-7} (4.8 σ)

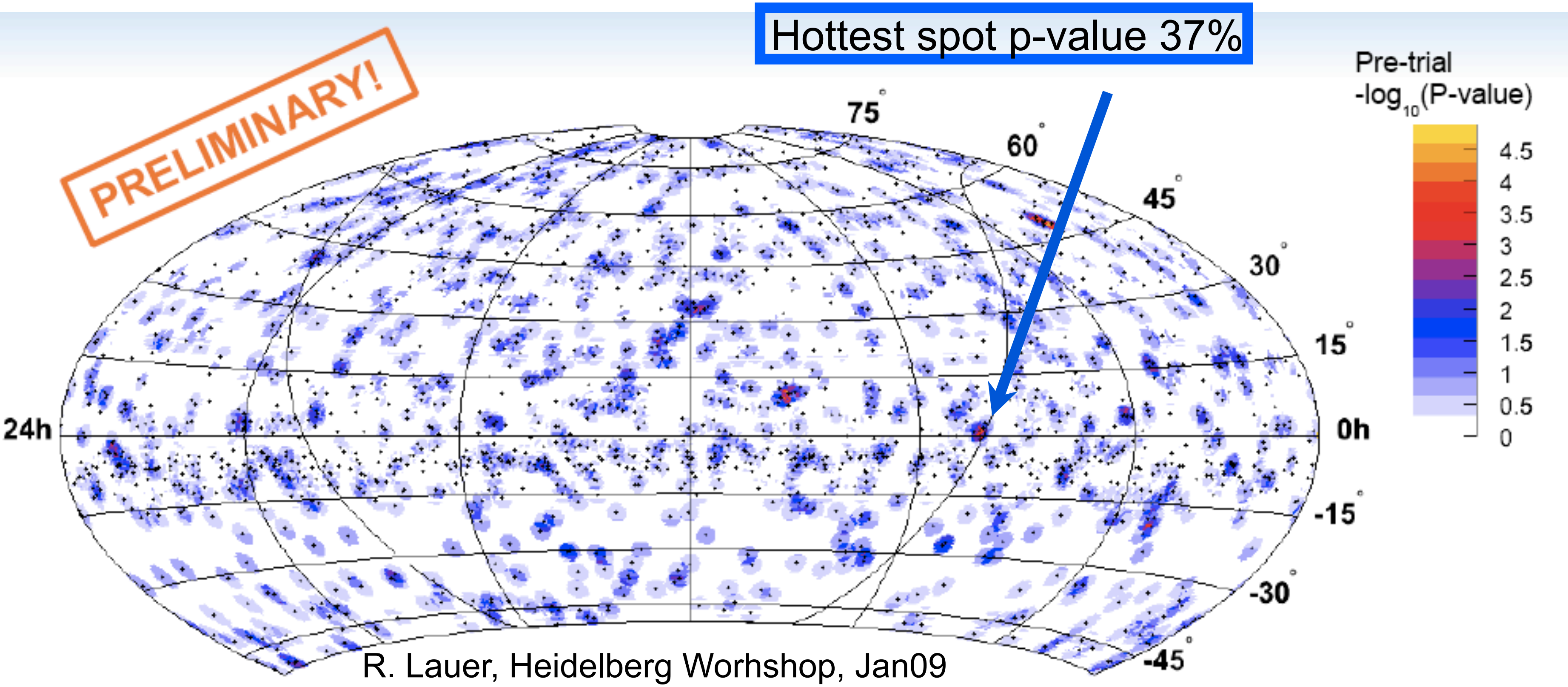
est. nSrcEvents = 7.7 est. γ = 1.65

Accounting for all trials, p-value for analysis is 1.34% (2.2 σ).

At this significance level, consistent with fluctuation of background.

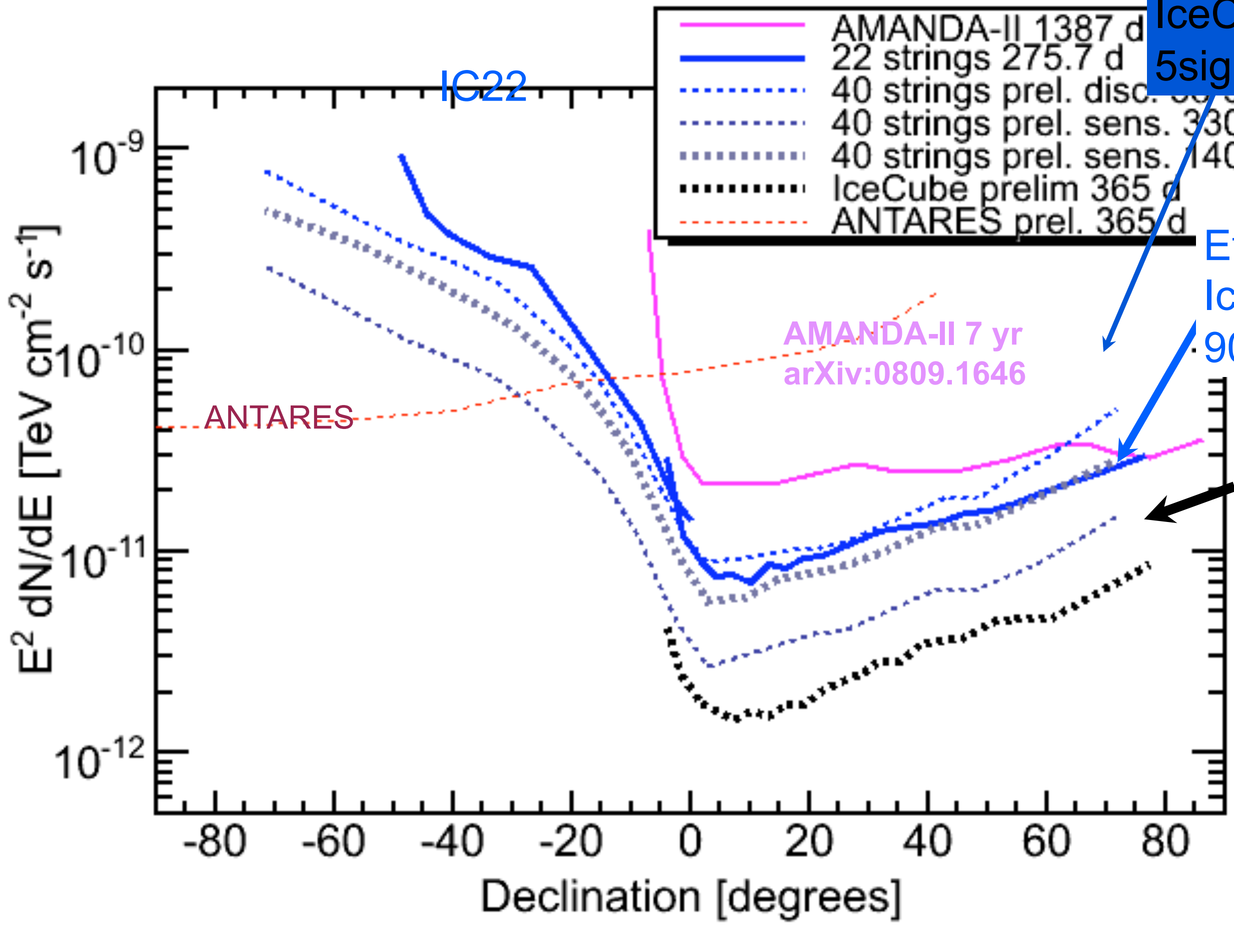
Pointsource search – all sky at high energies

Apply energy cut o(100 to 1000TeV) in downgoing hemisphere as needed
To reject the muon background.



R. Lauer, Heidelberg Worhshop, Jan09

What fluxes accessible by experiments?



E^{-2} Flux that 40 strings of IceCube can discover at 5sigma and 50% prob

E^{-2} Flux that 40 strings of IceCube can exclude at 90%cl

same for full IceCube

Search for neutrinos from GRB

GRB models

Waxman-Bahcall
PRL 78 (1997) 2292

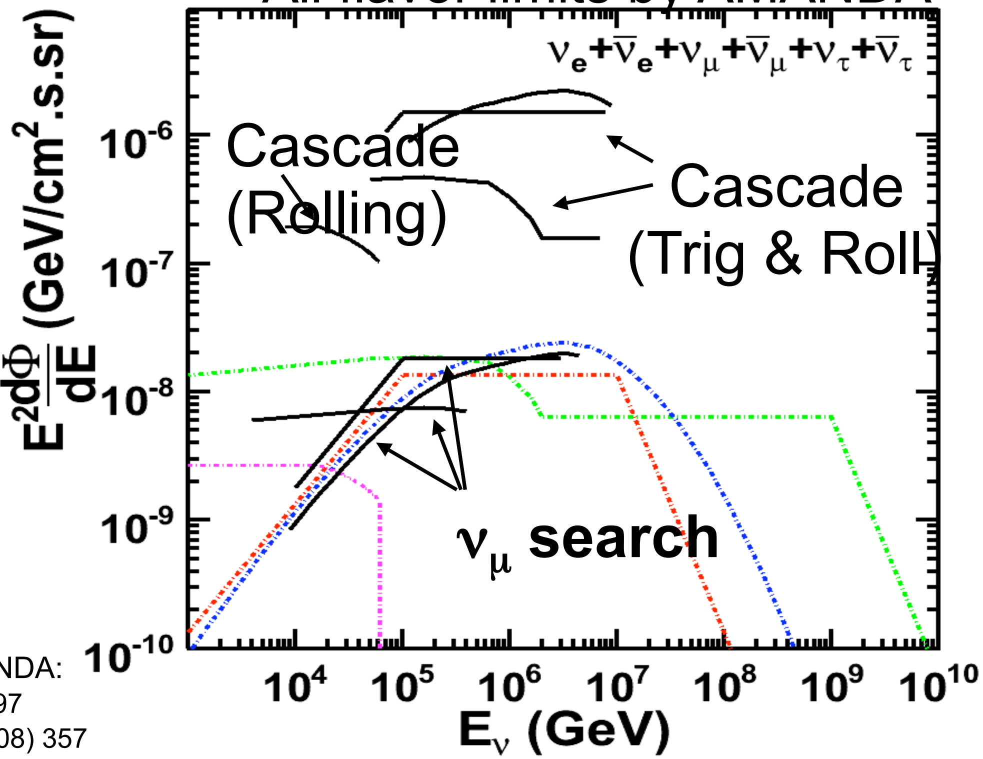
Murase-Nagataki A
PRD 73 (2006) 063002

Supranova,
Razzaque et al.
PRL 90 (2003) 241103

Choked bursts
Meszaros-Waxman
PRL 87 (2001) 171102

Limits on neutrinos from GRB from AMANDA:
-from cascades (ν_e, ν_τ), Ap.J. 664 (2007) 397
-from neutrino-induced muons, Ap.J 674 (2008) 357

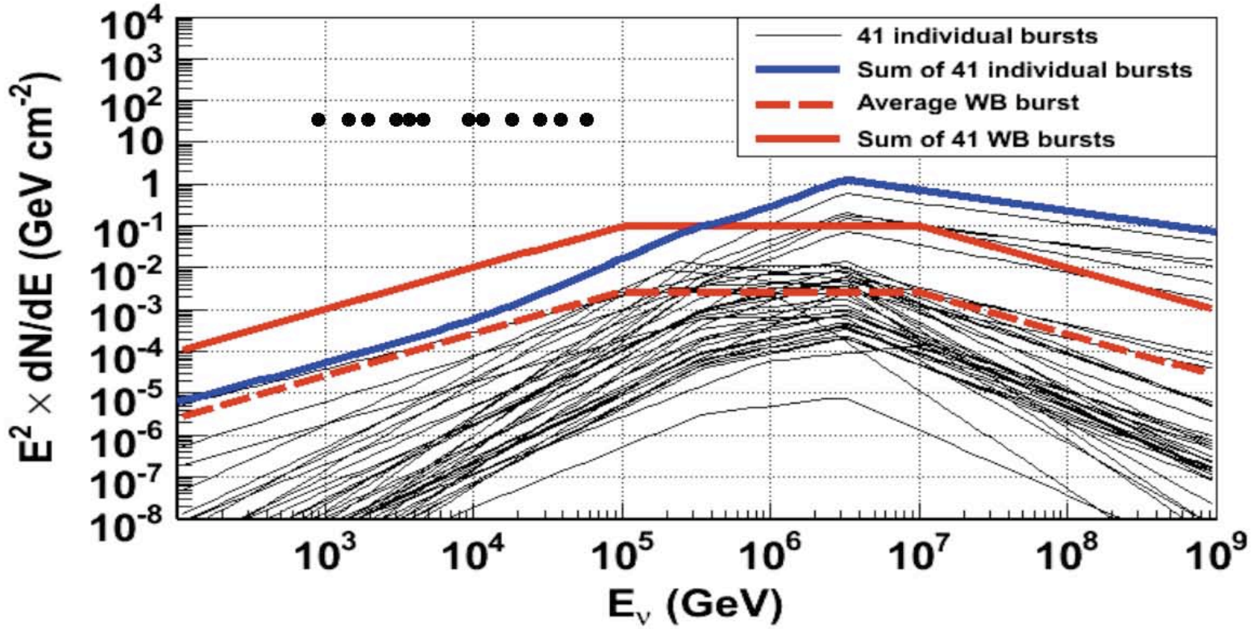
All flavor limits by AMANDA



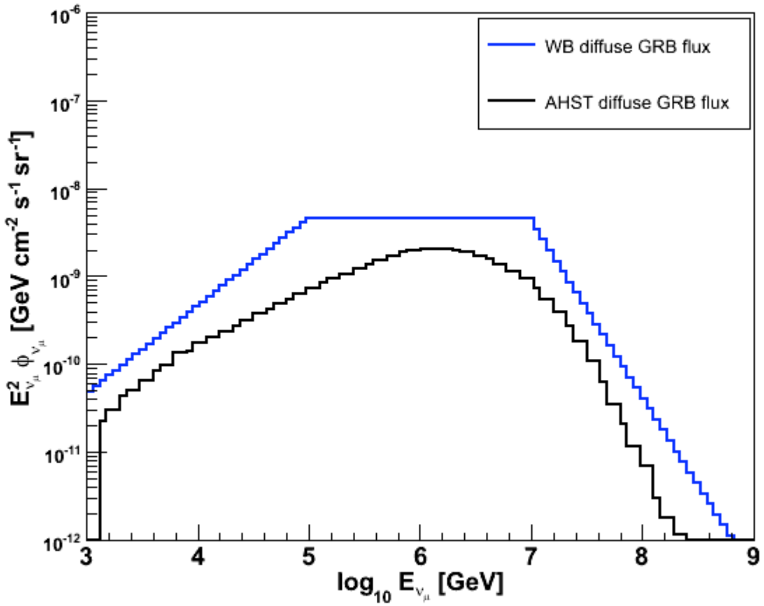
IceCube will be able to test GRB fireball model,
Decisive test of GRB as sources of HE cosmic rays

IceCube 22-strings: ν flux calculations

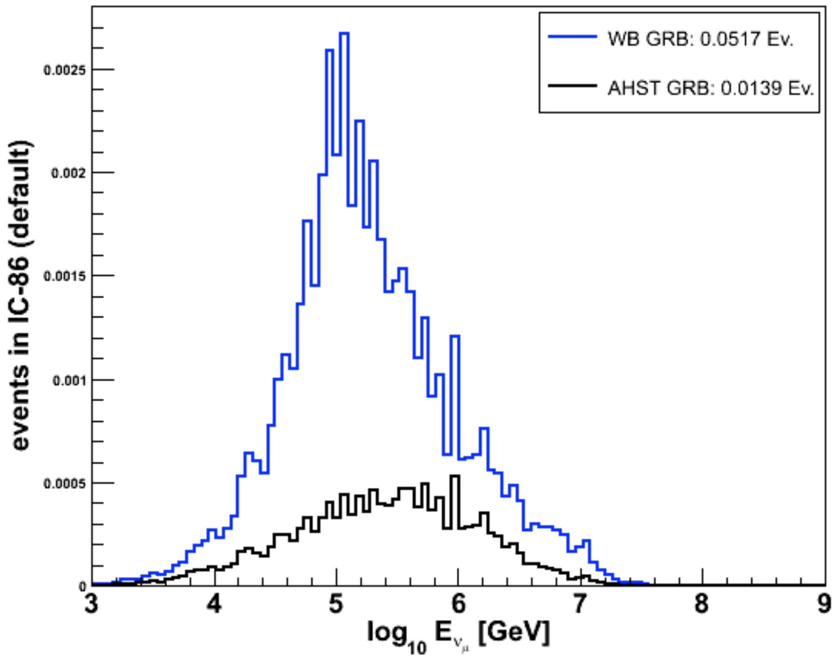
- June 2007 - April 2008
- 41 satellite-triggered northern bursts (mainly Swift) with usable IceCube data
- Calculation of individual burst spectra (Waxman-Bahcall GRB flux based on BATSE bursts)



Comparison of WB and AHST spectra

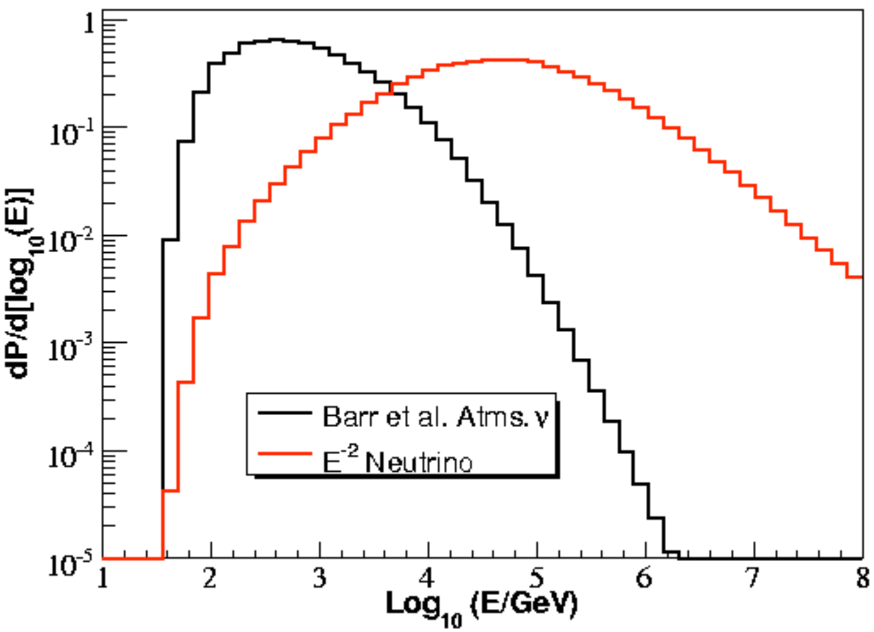


IceCube 86
WB: 10.6 total evts / year
No problem
(170 bursts per year)



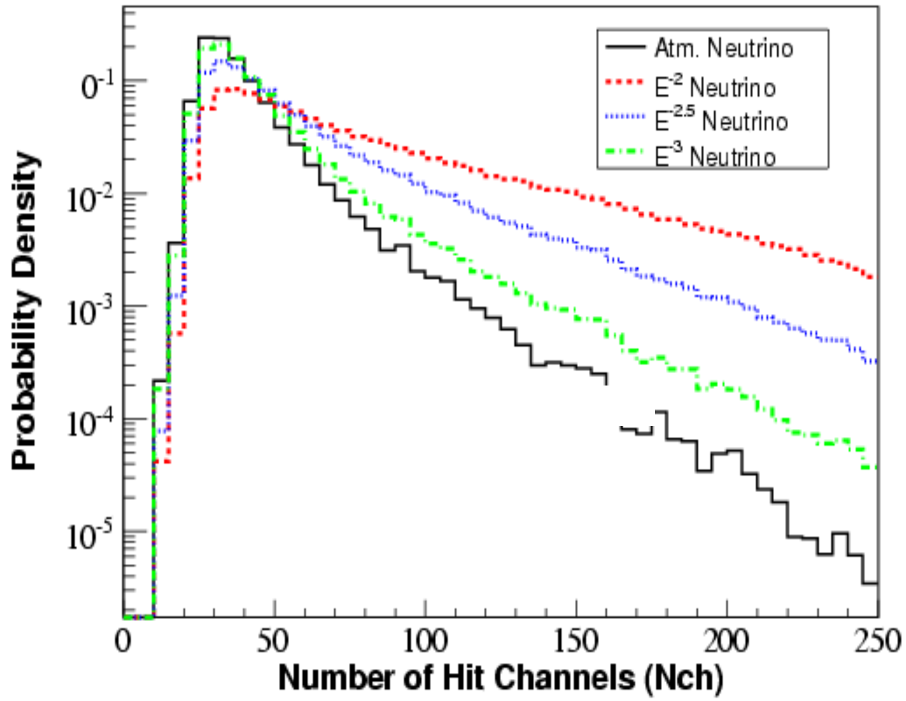
Significance of discovery
Is dominated by the high
energy events.
Median energy of events 100
to 300 TeV.

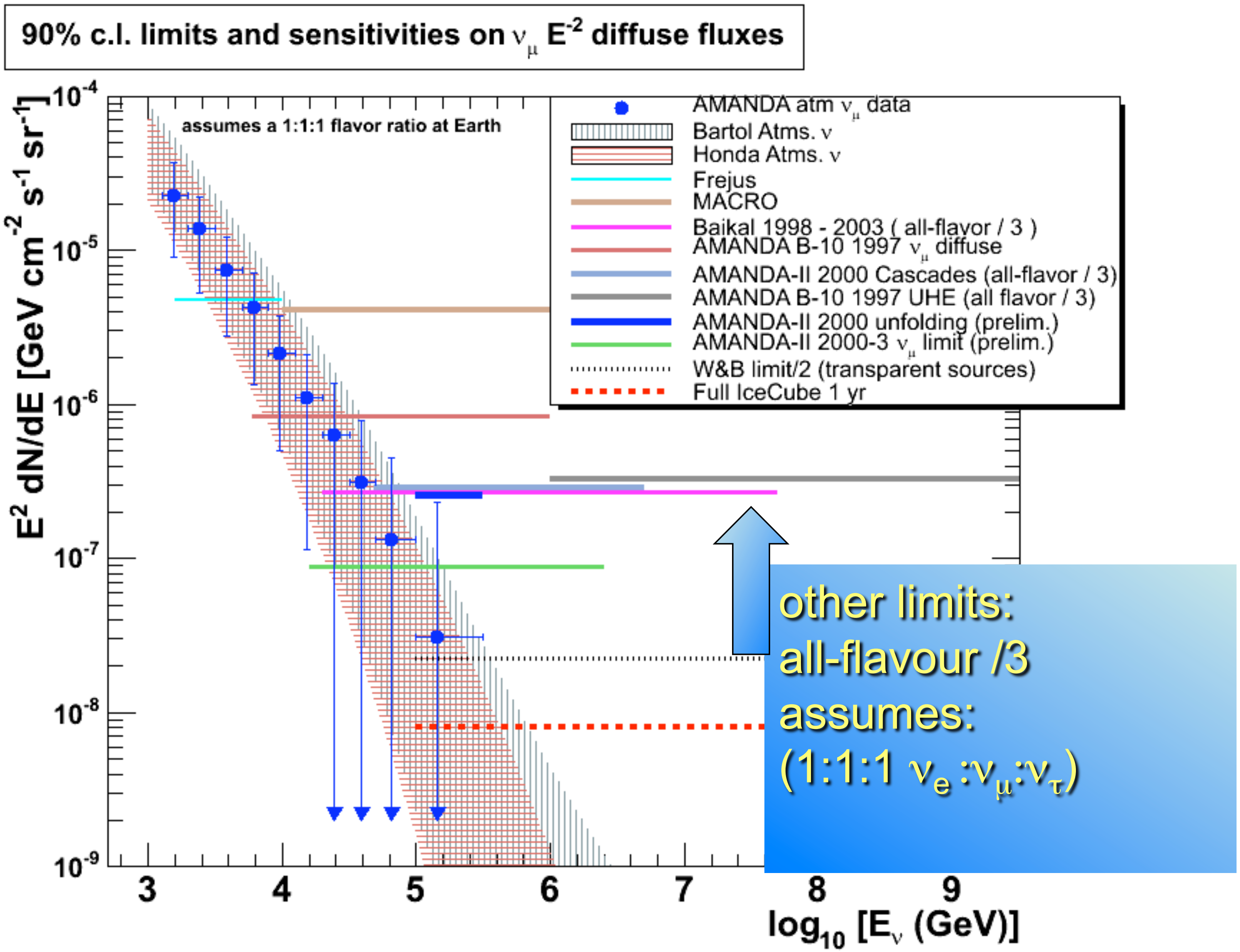
Monte Carlo: true neutrino energy



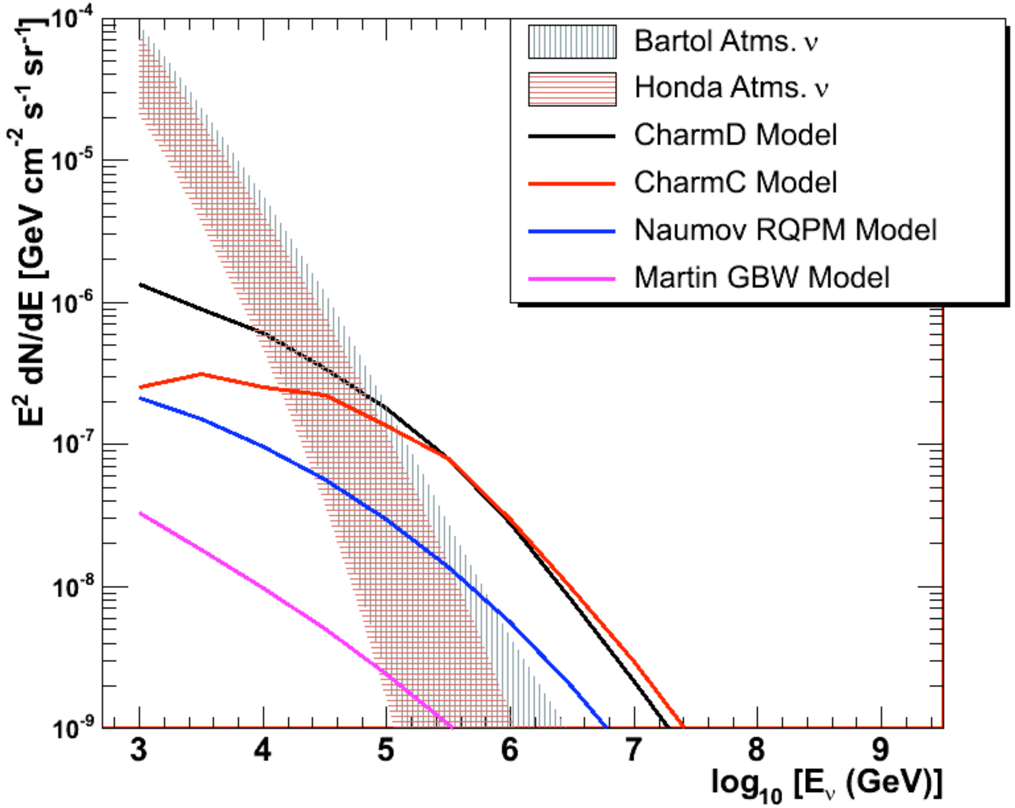
Diffuse fluxes

Monte Carlo: number of hit channels

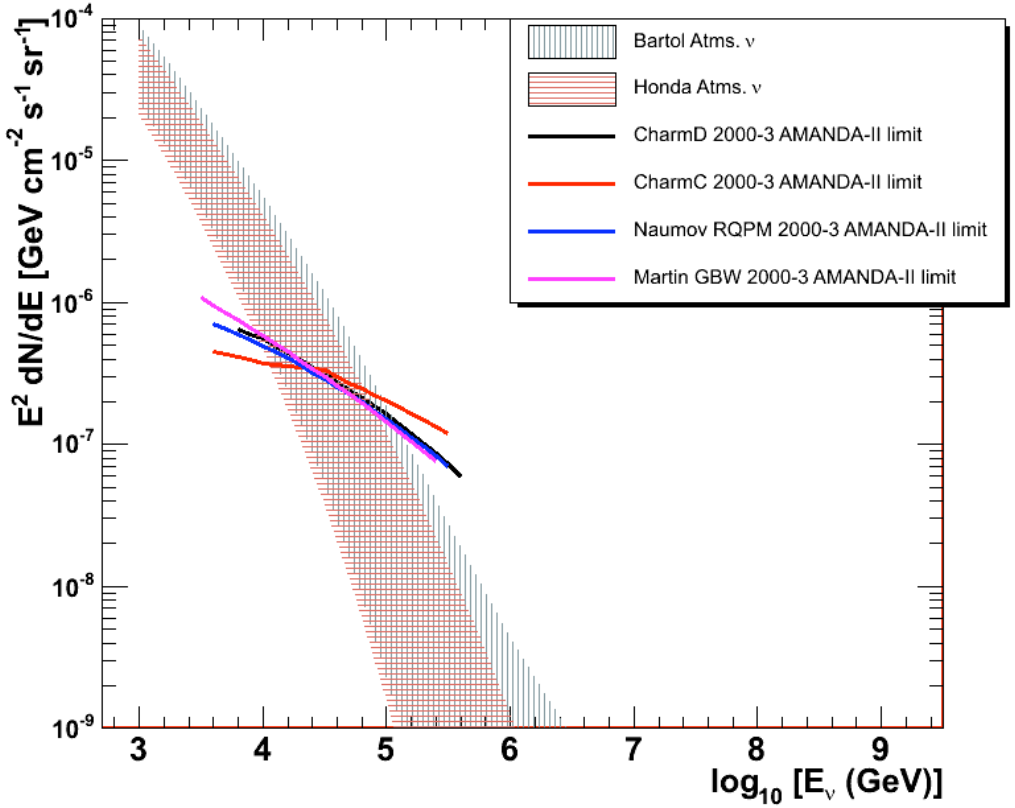



90% c.l. limits and sensitivities on ν_μ E^{-2} diffuse fluxes
assumes a 1:1:1 flavor ratio at Earth
E^2 dN/dE [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
3
4
5
6
7
8
9
$\log_{10}$ [E_ν (GeV)]
AMANDA atm ν_μ data
Bartol Atms. ν
Honda Atms. ν
Frejus
MACRO
Baikal 1998 - 2003 (all-flavor / 3)
AMANDA B-10 1997 ν_μ diffuse
AMANDA-II 2000 Cascades (all-flavor / 3)
AMANDA B-10 1997 UHE (all flavor / 3)
AMANDA-II 2000 unfolding (prelim.)
AMANDA-II 2000-3 ν_μ limit (prelim.)
W&B limit/2 (transparent sources)
Full IceCube 1 yr
other limits:
all-flavour /3
assumes:
(1:1:1 ν_e :ν_μ:ν_τ)

Models of charm production in the atmosphere

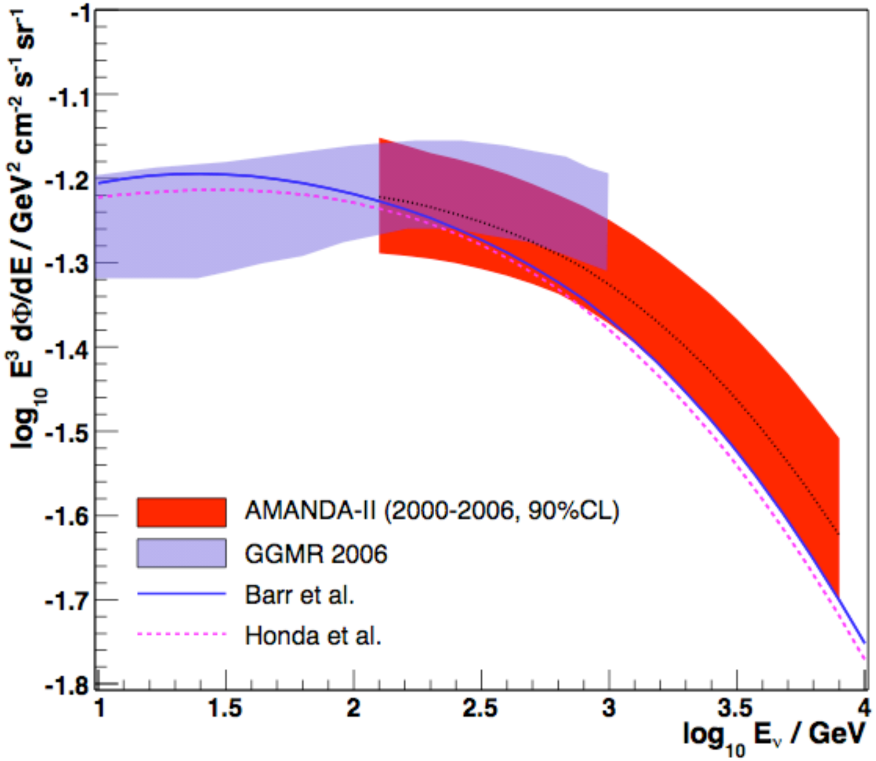


Models of charm production in atmosphere – limiting fluxes



Atmospheric ν's: Probe of New Physics

- atmospheric neutrino measurement important as background for other analyses
- look for nonstandard neutrino oscillations
- survival probability depends on energy and length of chord in the Earth
- VLI introduces velocity eigenstates distinct from mass and flavor
- new mixing angle ξ and phase η

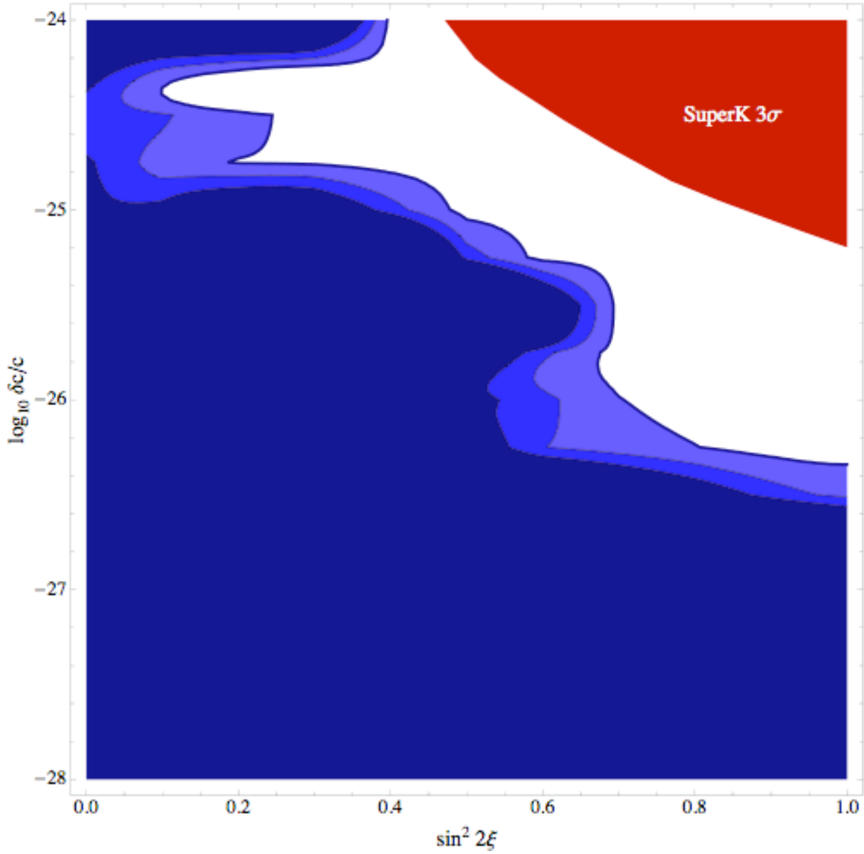


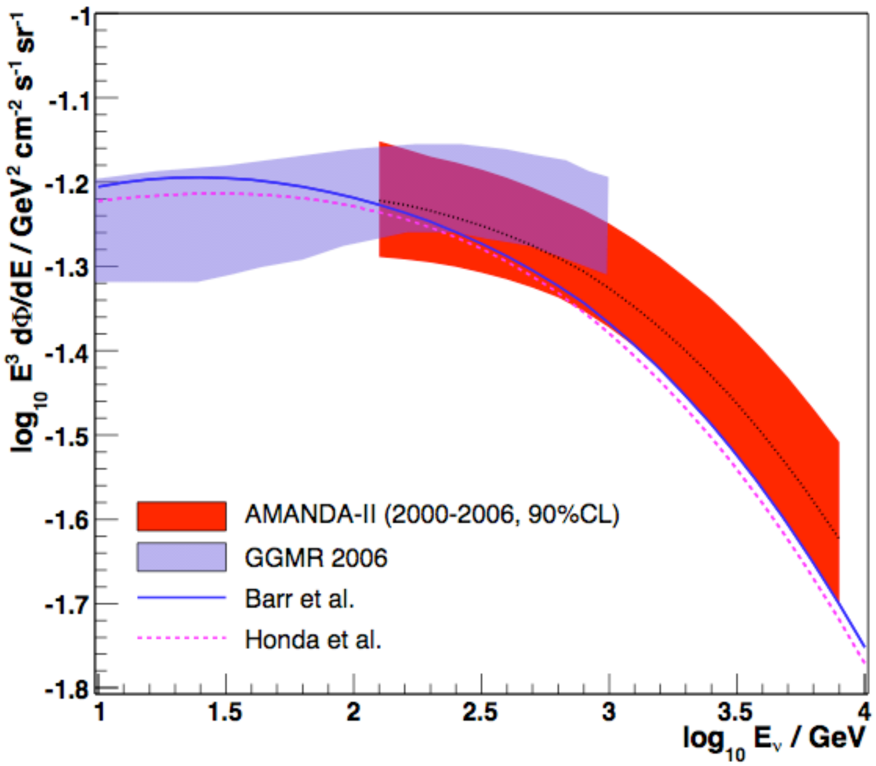
Atmospheric ν's: Probe of New Physics

•atmospheric neutrino measurement important as background for other analyses
•look for nonstandard neutrino oscillations
•survival probability depends on energy

Limits on Violation of Lorentz Invariance assuming maximal mixing:

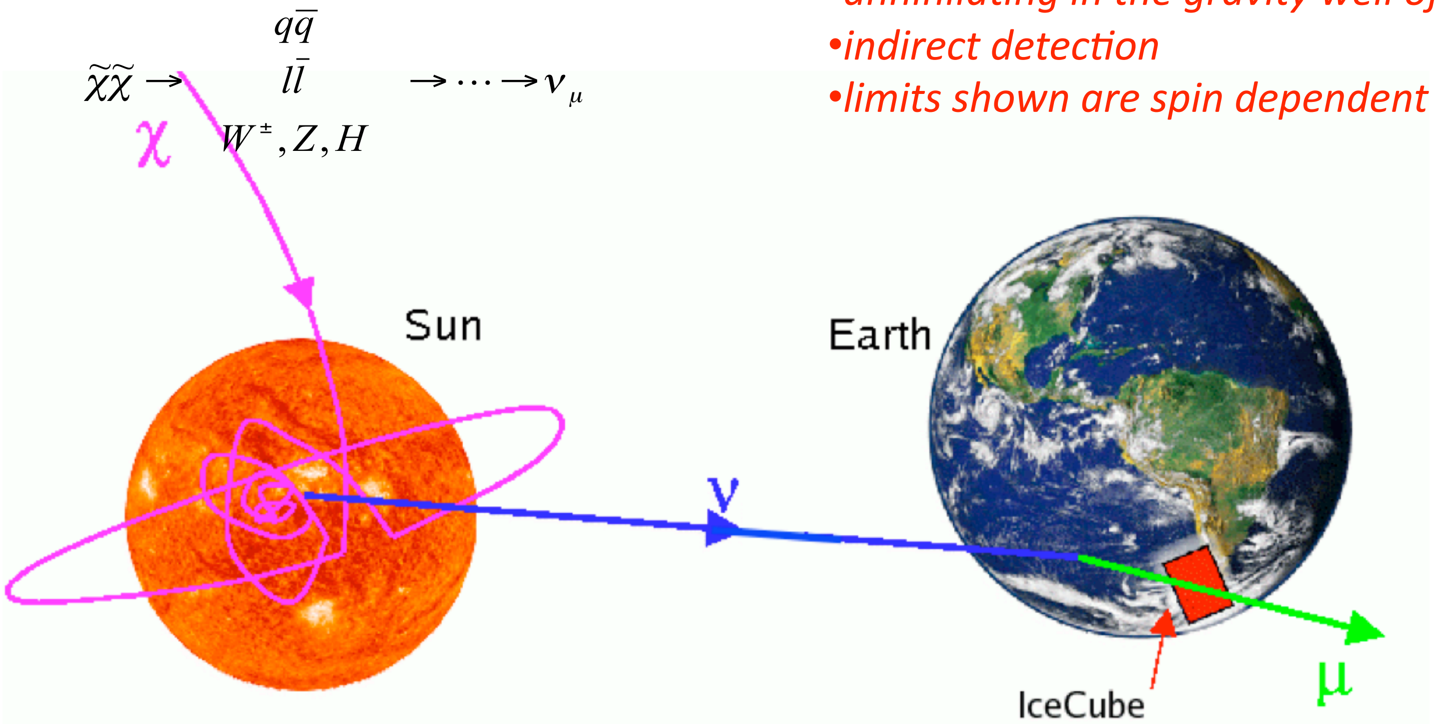
- SuperK+K2K limit*:
  $\delta c/c < 1.9 \times 10^{-27}$ (90%CL)
- This analysis:
  $\delta c/c < 2.8 \times 10^{-27}$ (90%CL)
- IceCube: sensitivity of $\delta c/c \sim 10^{-28}$
  Up to 700K atmospheric ν_μ in 10 years



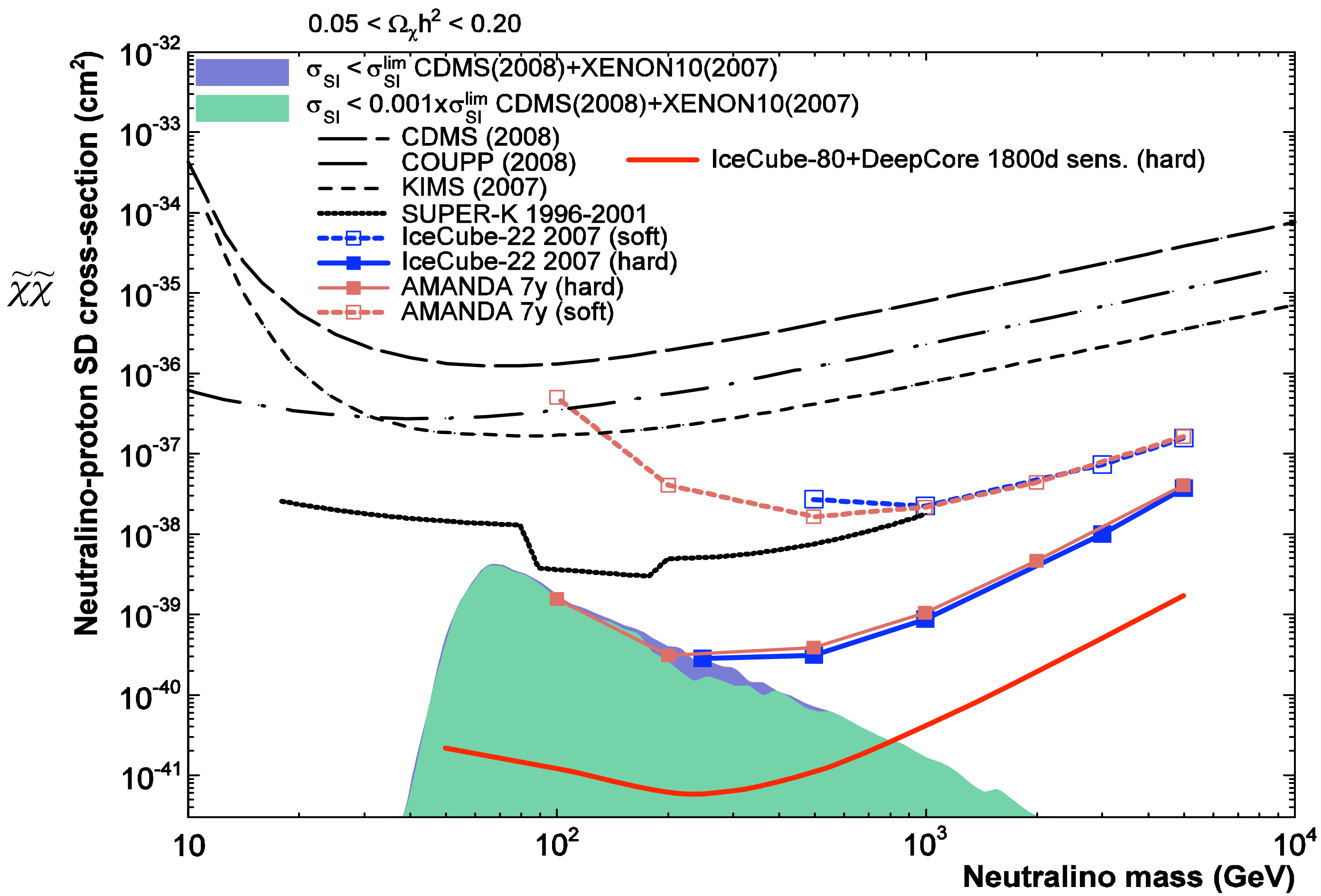


Search for dark matter, example: WIMPs in sun → neutrino flux at Earth

- *annihilating in the gravity well of the Sun*
- *indirect detection*
- *limits shown are spin dependent*



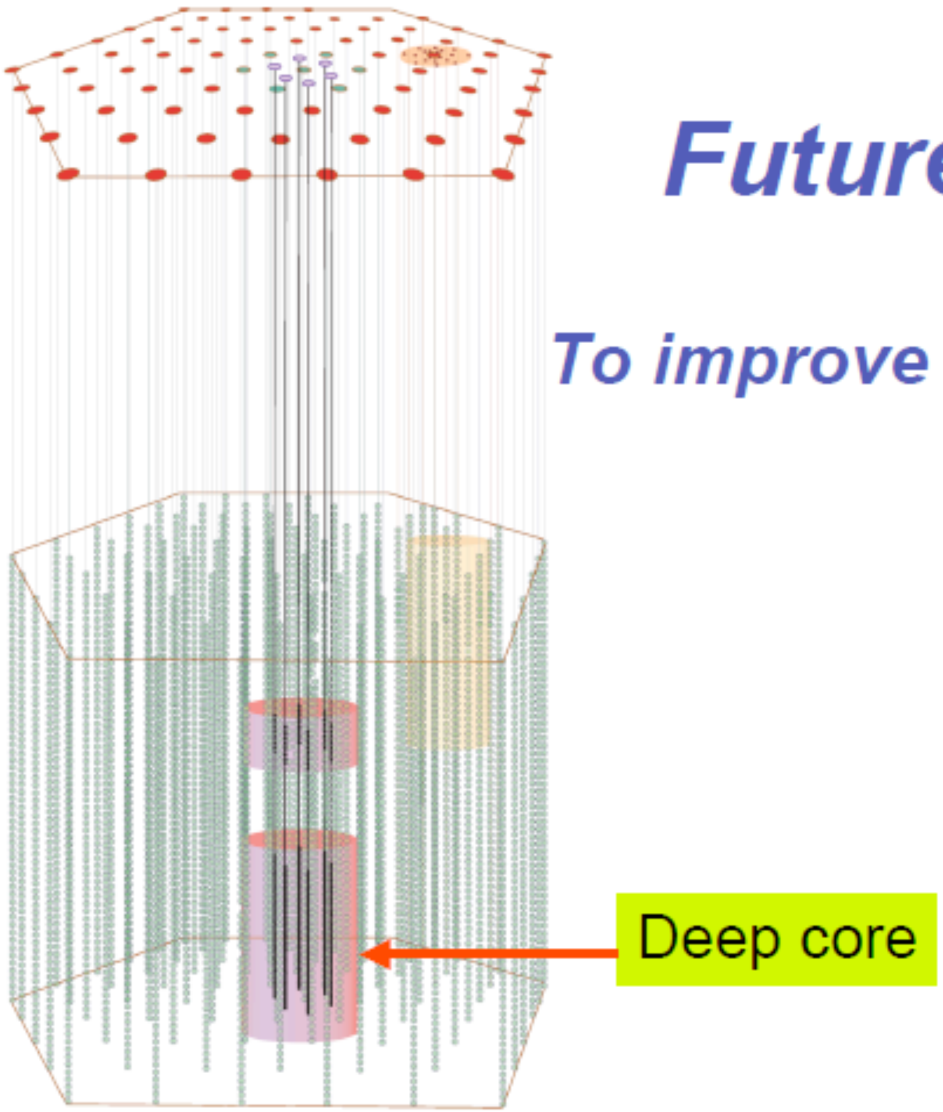
•See astro-ph 0903.2986 (Wikstrom and Edsjo) for method of converting muon flux to cross section limit.



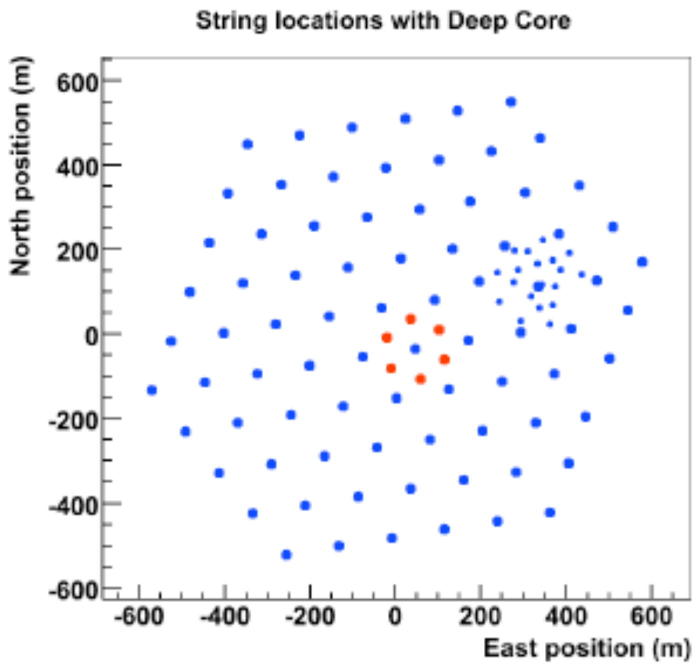
Deep core enhancement under construction will greatly enhance sensitivity.

Future: Deep Core

To improve low E event efficiency

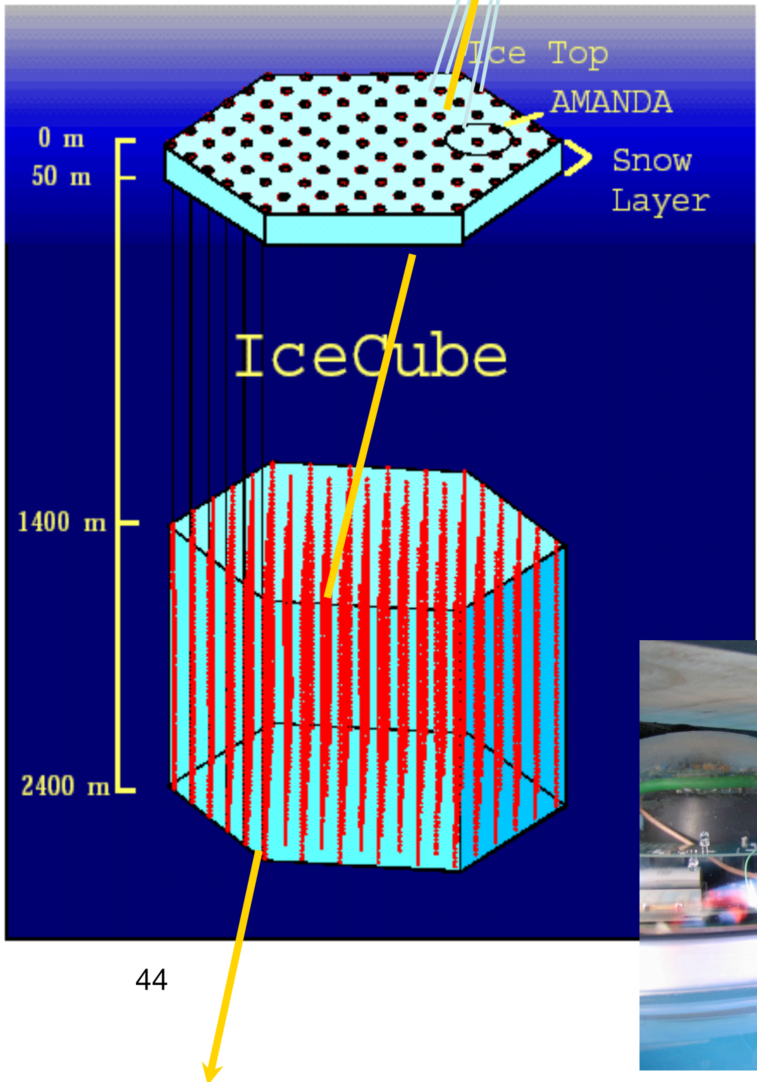


side view

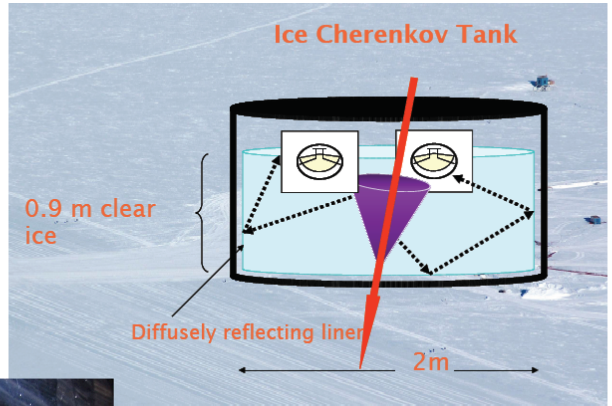


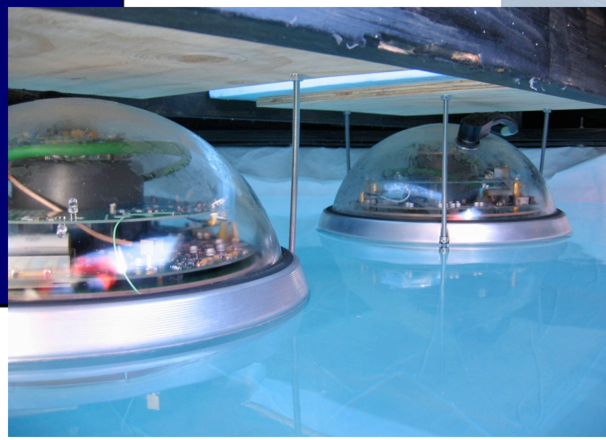
top view

Cosmic ray physics: IceCube with IceTop surface array



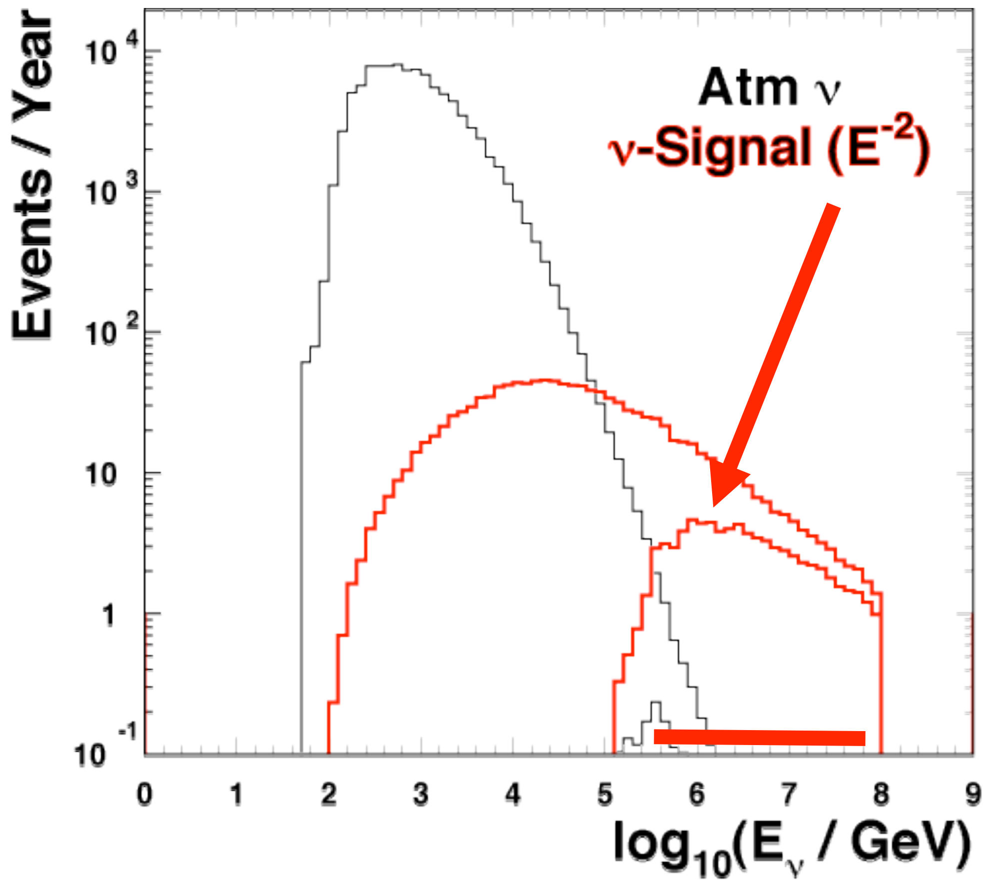
- Calibration
- Veto of HE shower background
- Cosmic Ray/air shower physics up to 10^{18} eV





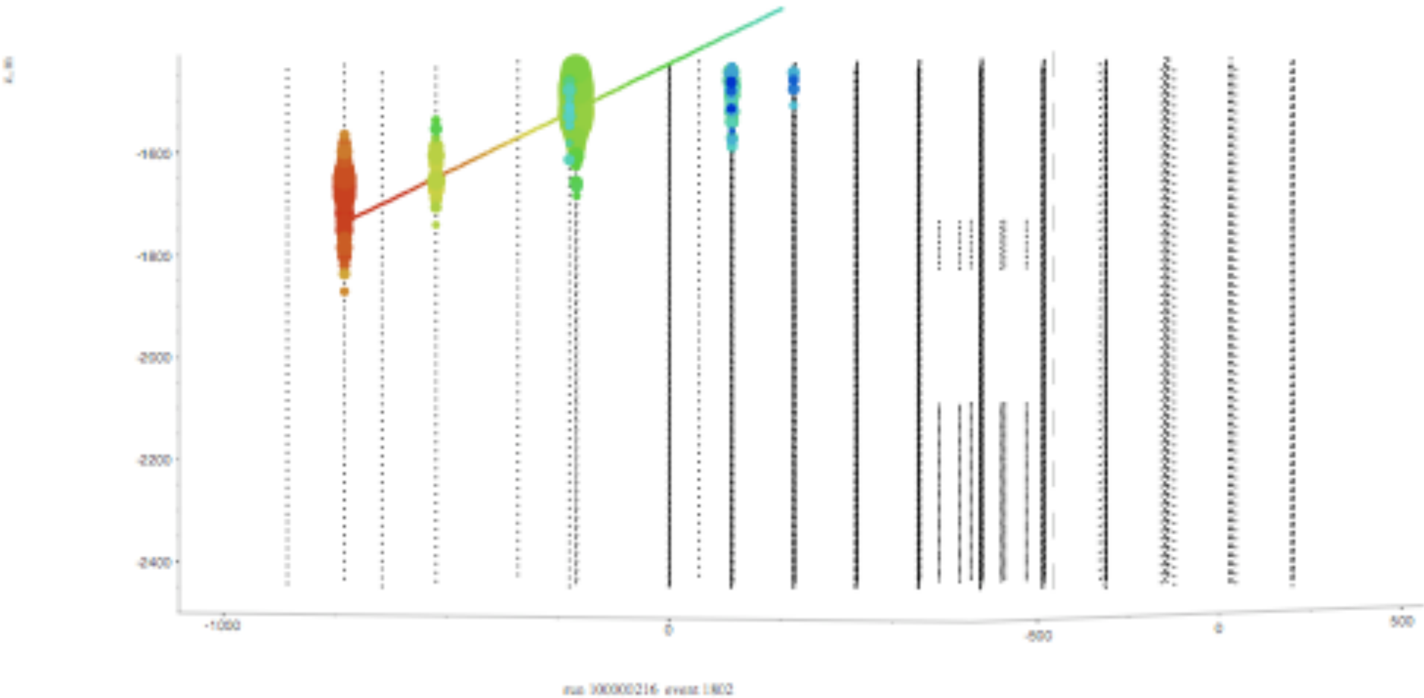
Diffuse E^{-2} ν_μ-spectrum peaks at 1 PeV (after atm. Background rejection)

- Neutrino event energy spectrum after energy cut for a 3 year diffuse analysis.
- Signal events peak at ~1PeV
- Optimize final detector configuration for higher energy range, to maximize sensitivity of IceCube.

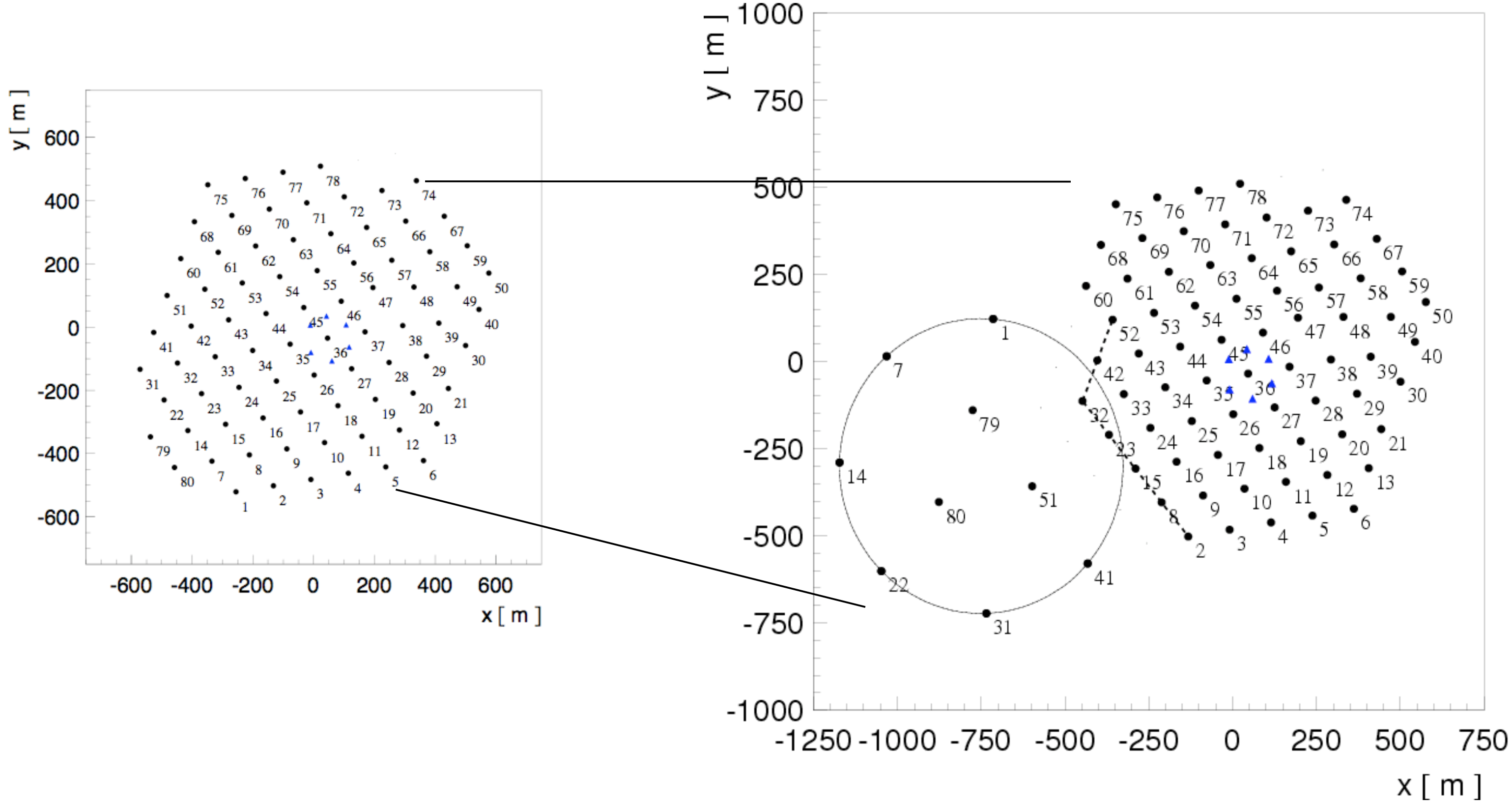


Optimizing end configuration of IceCube for lower and higher energies

- Low energy optimization, 10 to 100 GeV, is covered very effectively by Deep Core
- High energy optimization: configure last 9 strings tuned for higher energy response (~PeV)



Geometry of high energy optimized configuration



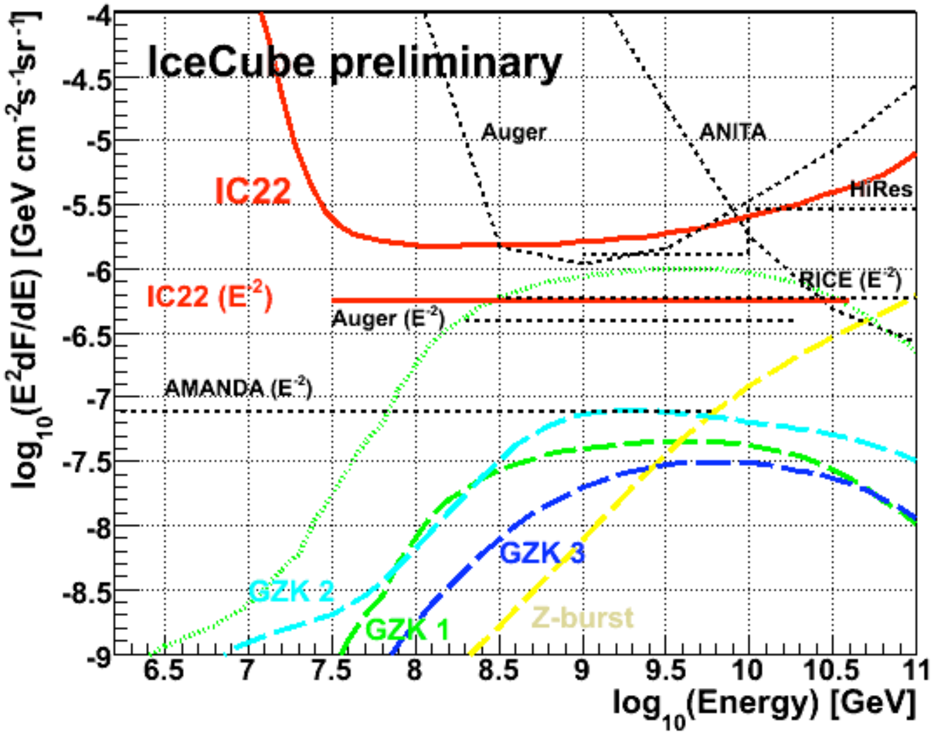
Drilling of 9 holes in the last season inside a circle with radius of 0.4 to 0.5 km is possible.

GZK flux event rates

Event rates:

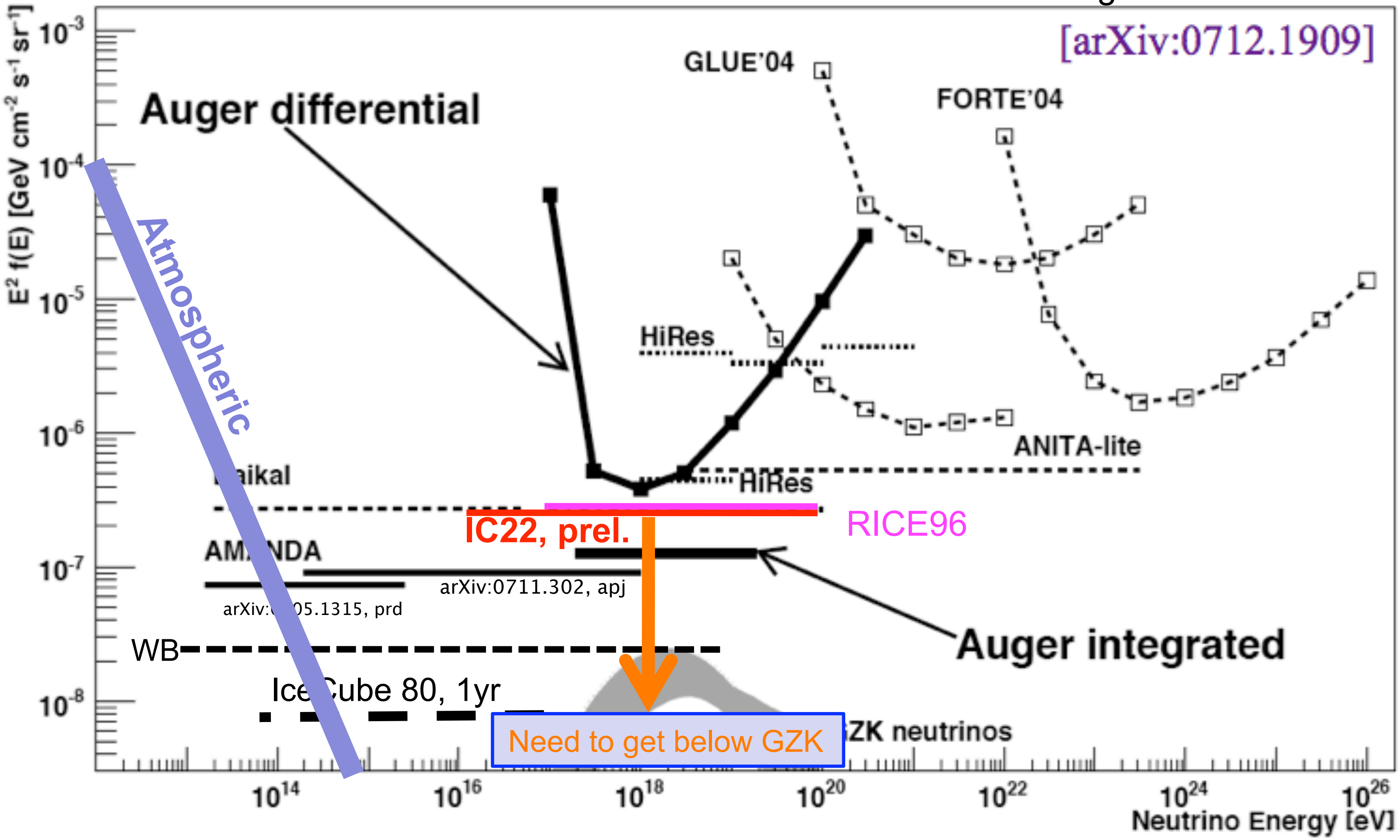
Flux: Engel, Seckel, Stanev, 2001)
= GZK3 in figure

- IC22 throughgoing, 240 days: 0.1 events/yr [no event seens, → ICRC report]
- IC80, total: o(0.5) event/yr
- IC110, high energy: o(1) event
- 10 x 10km^2 radio array: o(10) events/yr



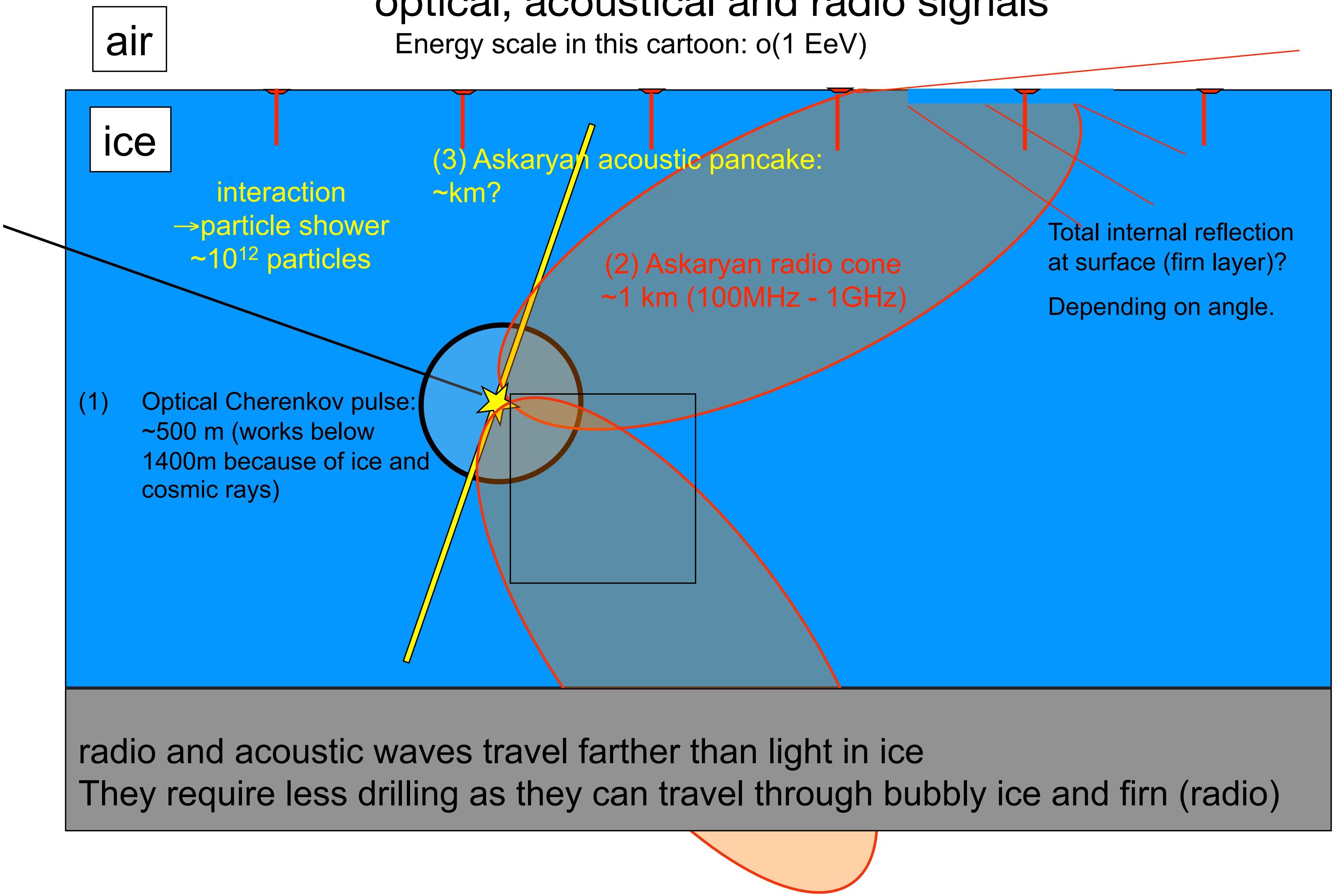
Diffuse fluxes limits at higher energies

Figure modified from



Neutrino induced cascades produce 3 types signals: optical, acoustical and radio signals

Energy scale in this cartoon: o(1 EeV)



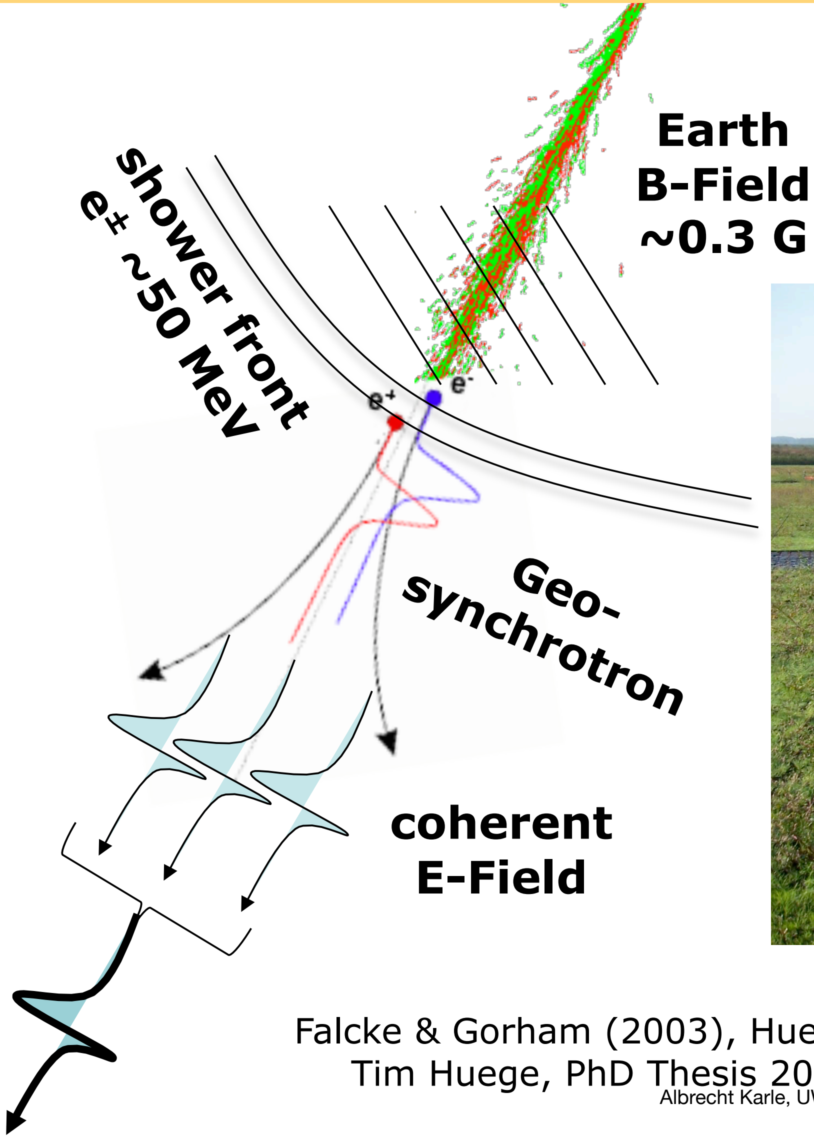
Radio detection of high energy showers

- Radio emission predicted by Askaryan
- Effect tested in SLAC experiment by members of ANITA collaboration

Two processes to distinguish

1. Geosynchrotron radiation of electrons and positrons in cosmic ray air showers in Earth magnetic field
2. Askaryan effect: Radio Cherenkov emission, net charge moving through dielectric medium at vacuum speed of light. Interesting frequency range: 50MHz to multi GHz.

Detection of air showers using
Coherent Geosynchrotron Radio Pulses in Earth Atmosphere



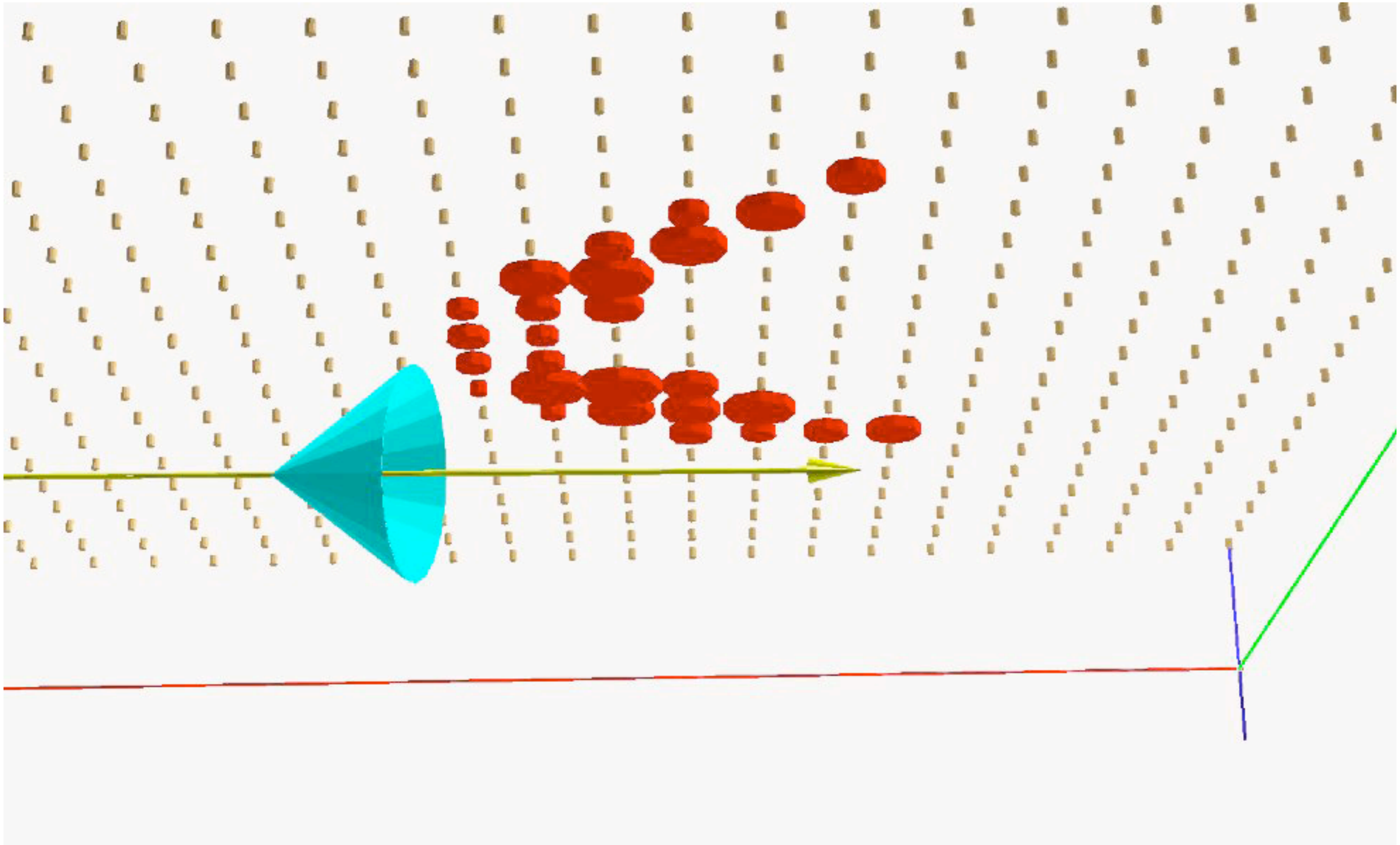
Successful measurements with LOPES array in conjunction with KASKADE air shower array

Next step LOFAR (center in Nijmegen, Netherlands):

~900 dipoles will see one shower

Falcke & Gorham (2003), Huege & Falcke (2004,2005)
Tim Huege, PhD Thesis 2005 (MPIfR+Univ Bonn

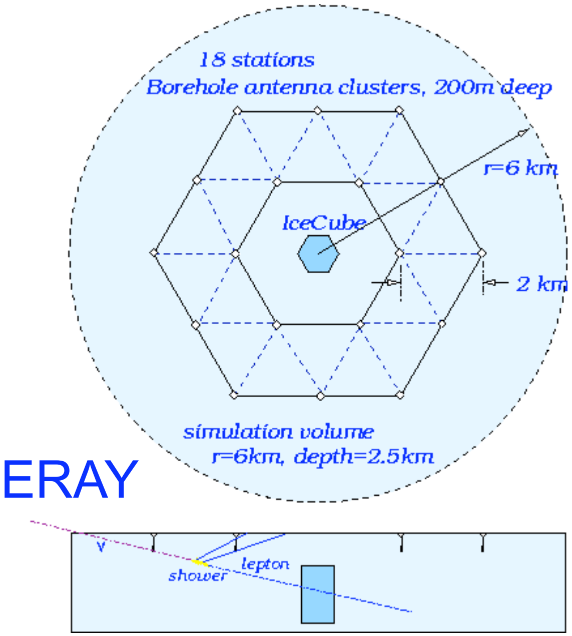
in-ice view of radio detection



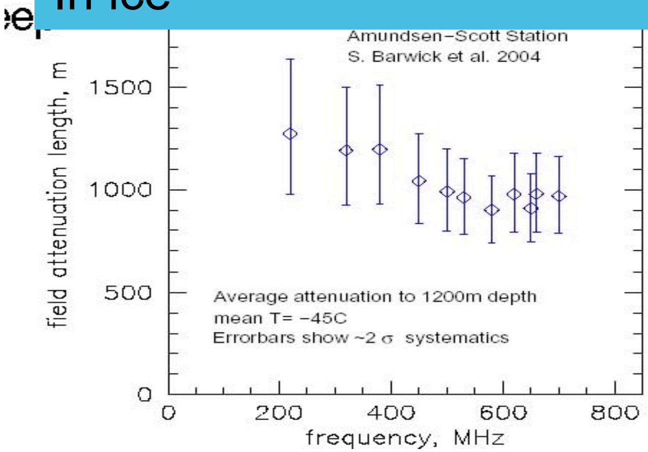
Future possibilities
UHE Radio Augmentation around IceCube
acoustic instrumentation

- GZK neutrinos ($10^{17-19.5}$ eV), at lowest possible cost: Fluxes may be very low, plan for few events/ 100km3/yr
- Must develop technology to scale beyond o(1000)km^3
- Hybrid events with IceCube
  - Primary vertex calorimetry in radio, HE muon or tau secondary in IceCube
  - Acoustic augmentation possible, but high threshold and requires deep drilling
- Understand medium and noise conditions

ICERAY

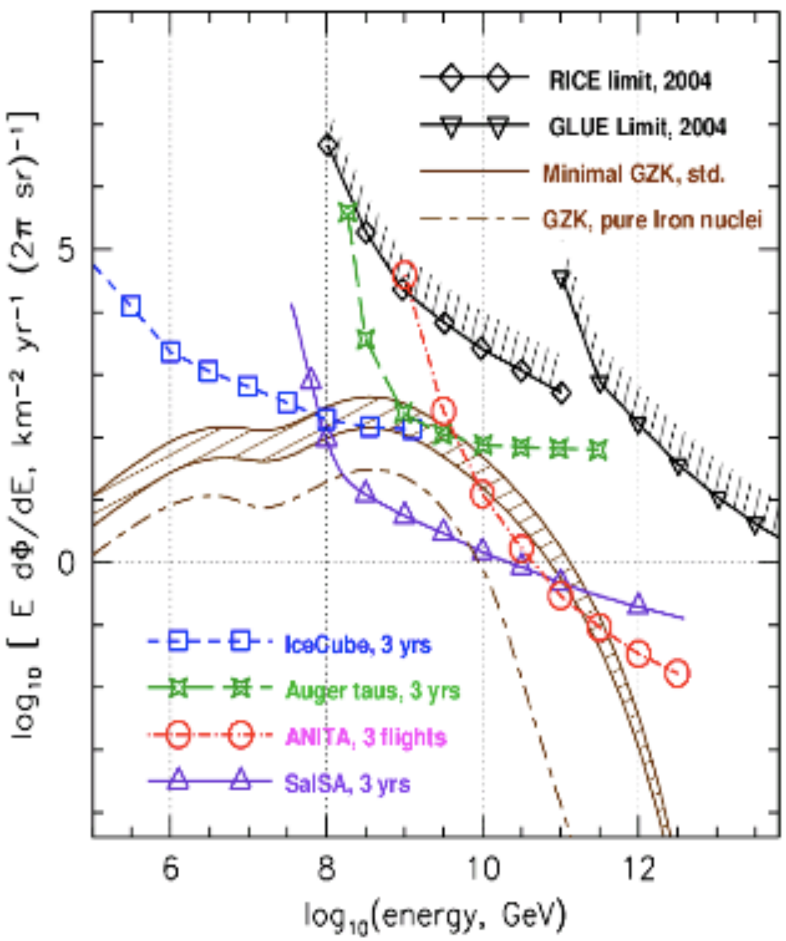


>Km scale attenuation length
In ice



Barwick et al., 2004

Existing Neutrino Limits and Potential Future Sensitivity



- RICE limits for 3500 hours livetime
- GLUE limits ~120 hours livetime
- ANITA sensitivity, 45 days total:
  - ~5 to 30 GZK neutrinos
- IceCube: high energy cascades
  - ~1.5-3 GZK events in 3 years
- Auger: Tau neutrino decay events
  - ~1 GZK event per year?
- **SalSA sensitivity, 3 yrs live**
  - **60-230 GZK neutrino events**

Conclusions

- Neutrino astronomy has made strong progress
- AMANDA and now IceCube have set the most constraining limits for astrophysical neutrinos.

The 5th IceCube construction season:

- **59 strings in operation!**
- **86 strings in 2011**

Analysis of first IceCube science run of IC40 underway.
Collaboration working on R&D for options for a larger GZK neutrino detector.

Did not cover all topics such as Supernova searches or neutrino physics,….