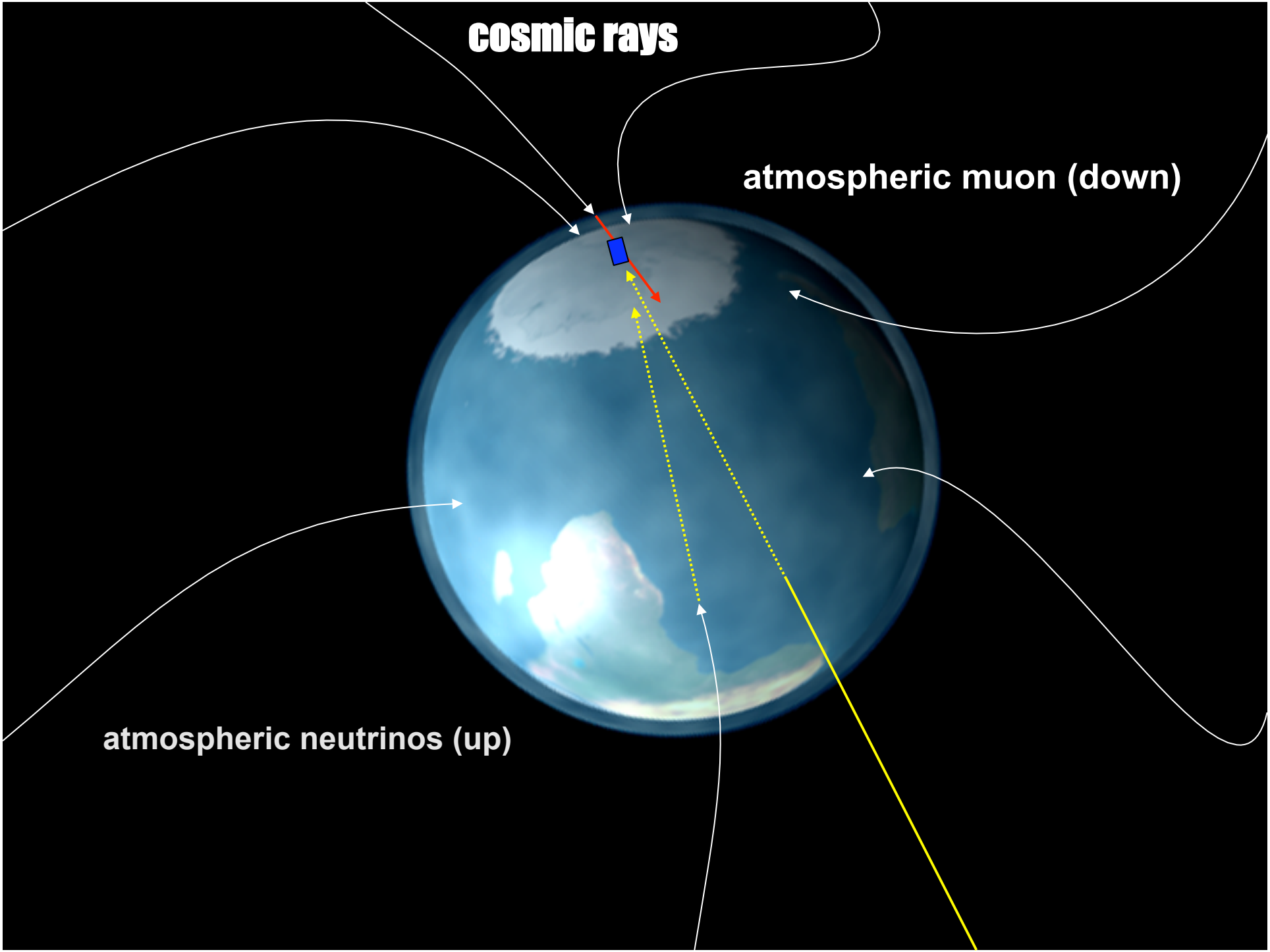
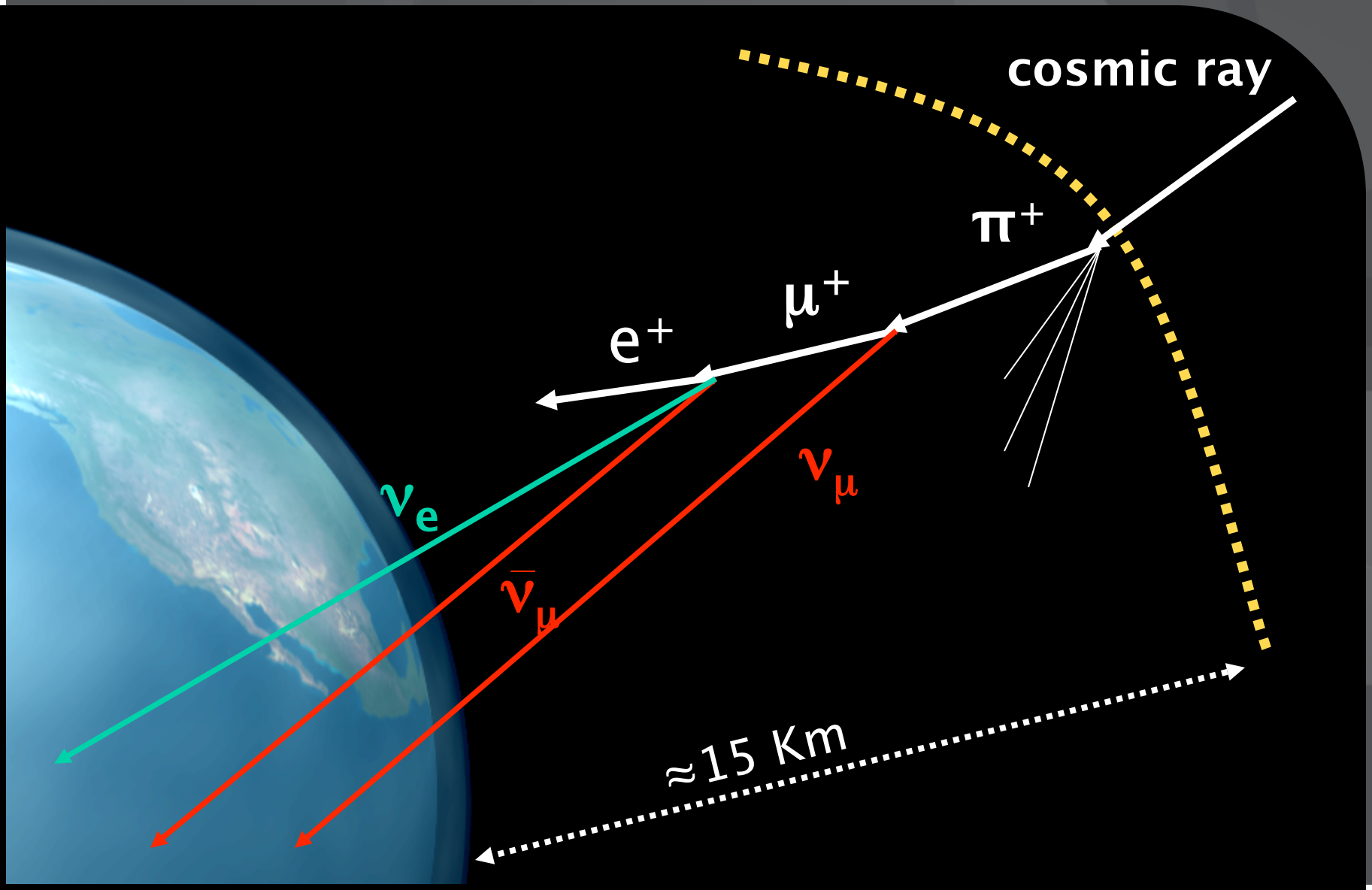
AMANDA: proof of concept


cosmic rays
atmospheric muon (down)
atmospheric neutrinos (up)

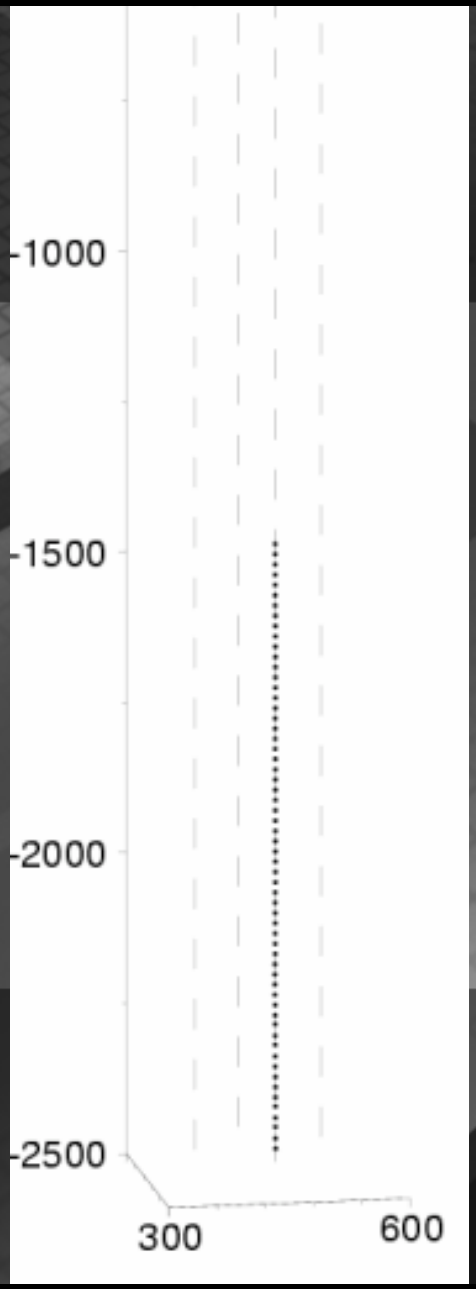
atmospheric neutrinos

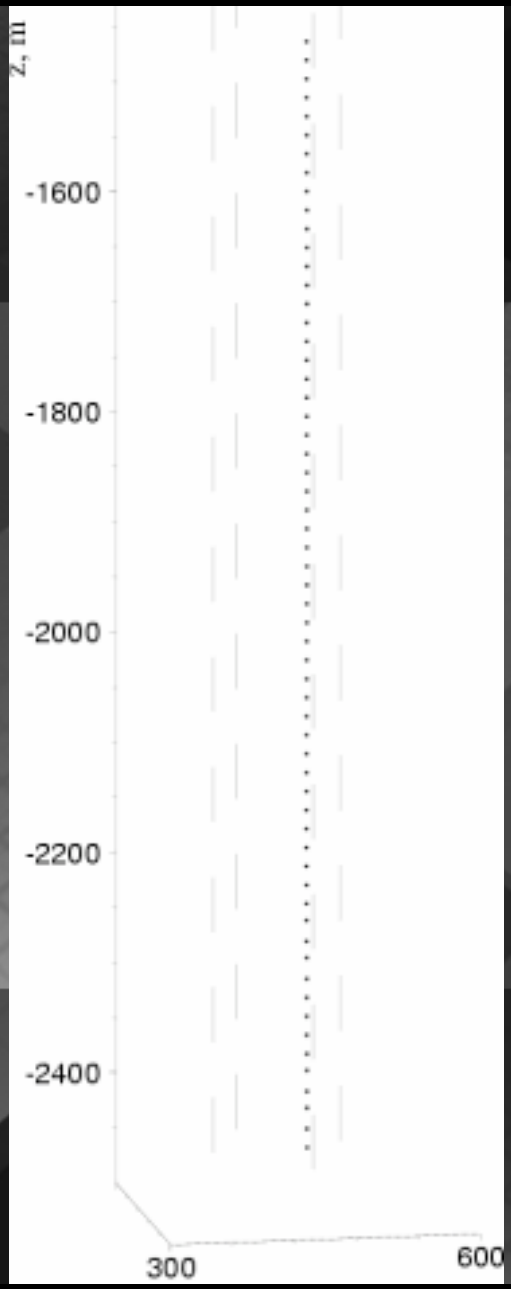


down

background cosmic ray muon produced in the atmosphere

80 per second



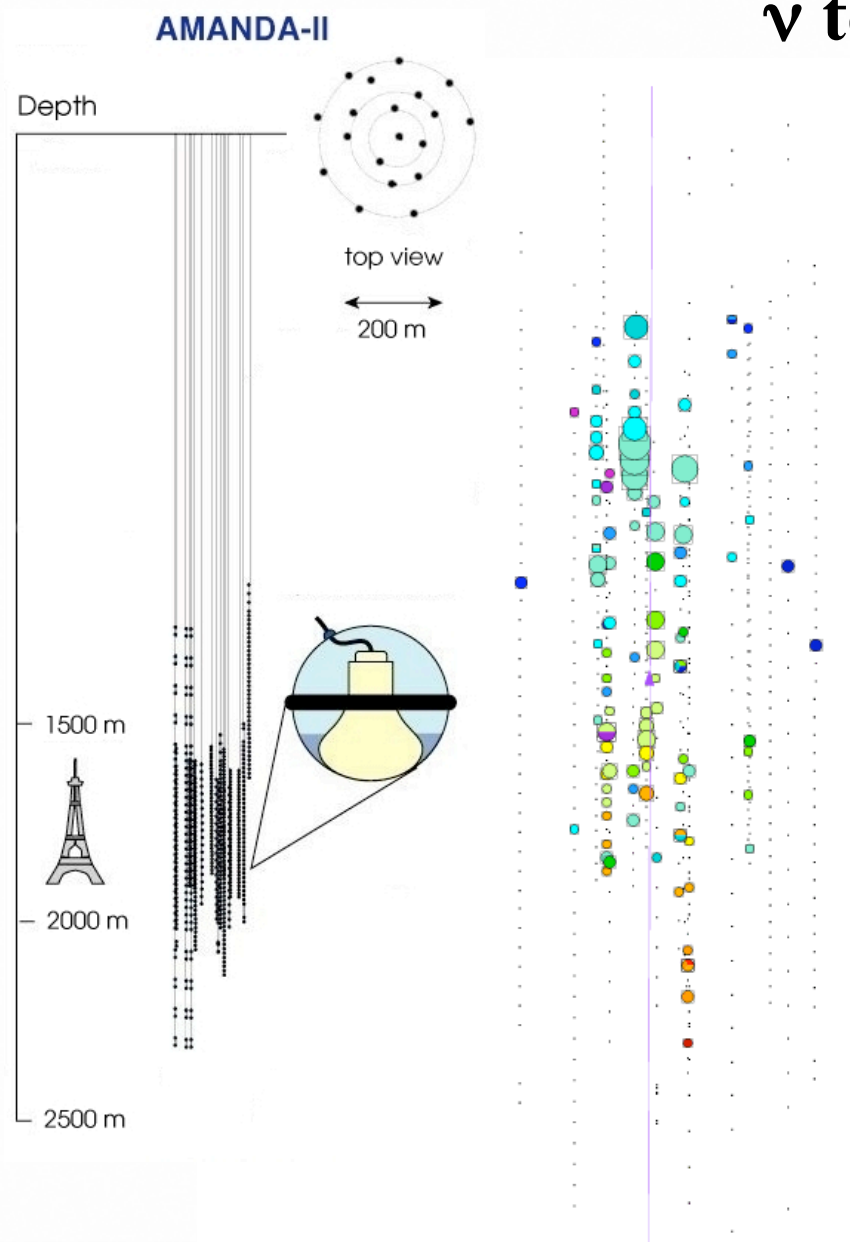


up

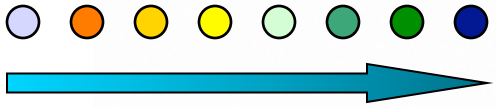
neutrino traveled through the earth

4.8 per day

ν telescope : AMANDA event



energy deposited in OM

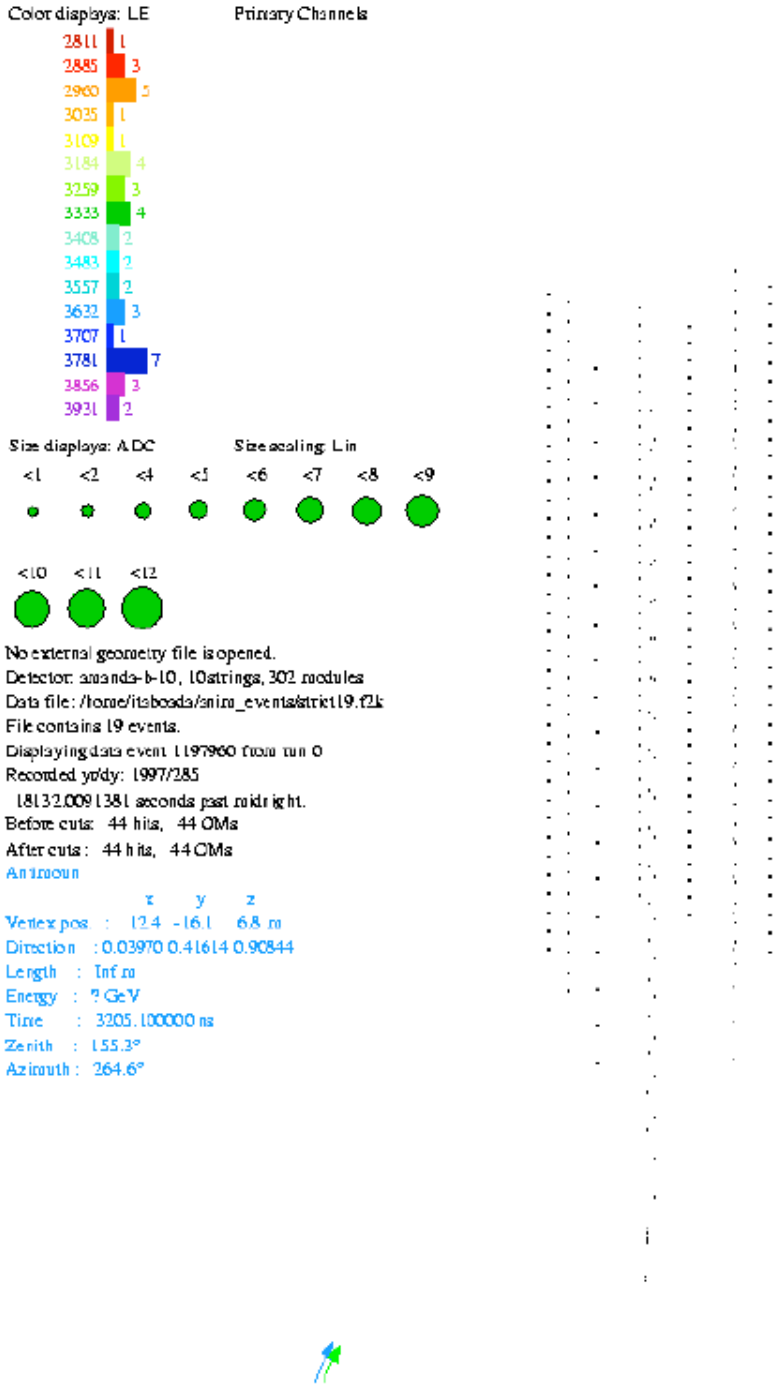


time recorded on OM

AMANDA Event Signatures: Muons

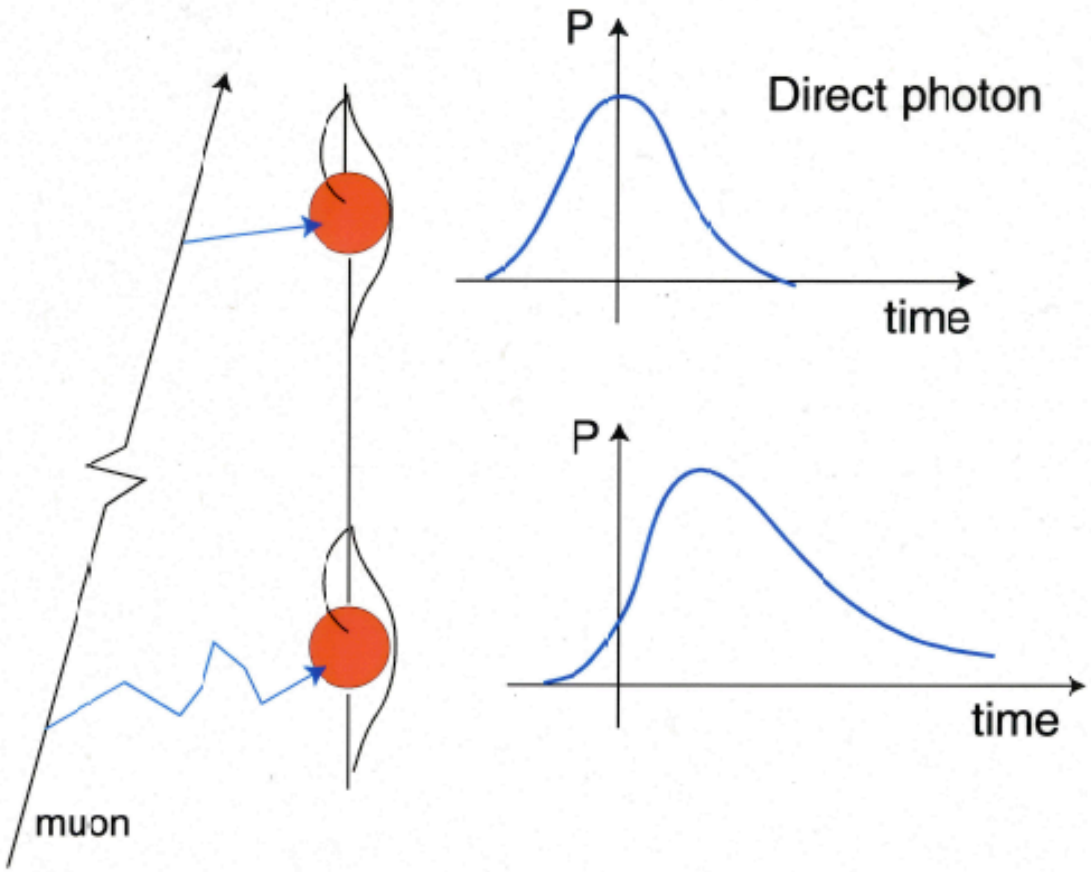
muon neutrino interaction → track

$$\nu_\mu + N \rightarrow \mu + X$$



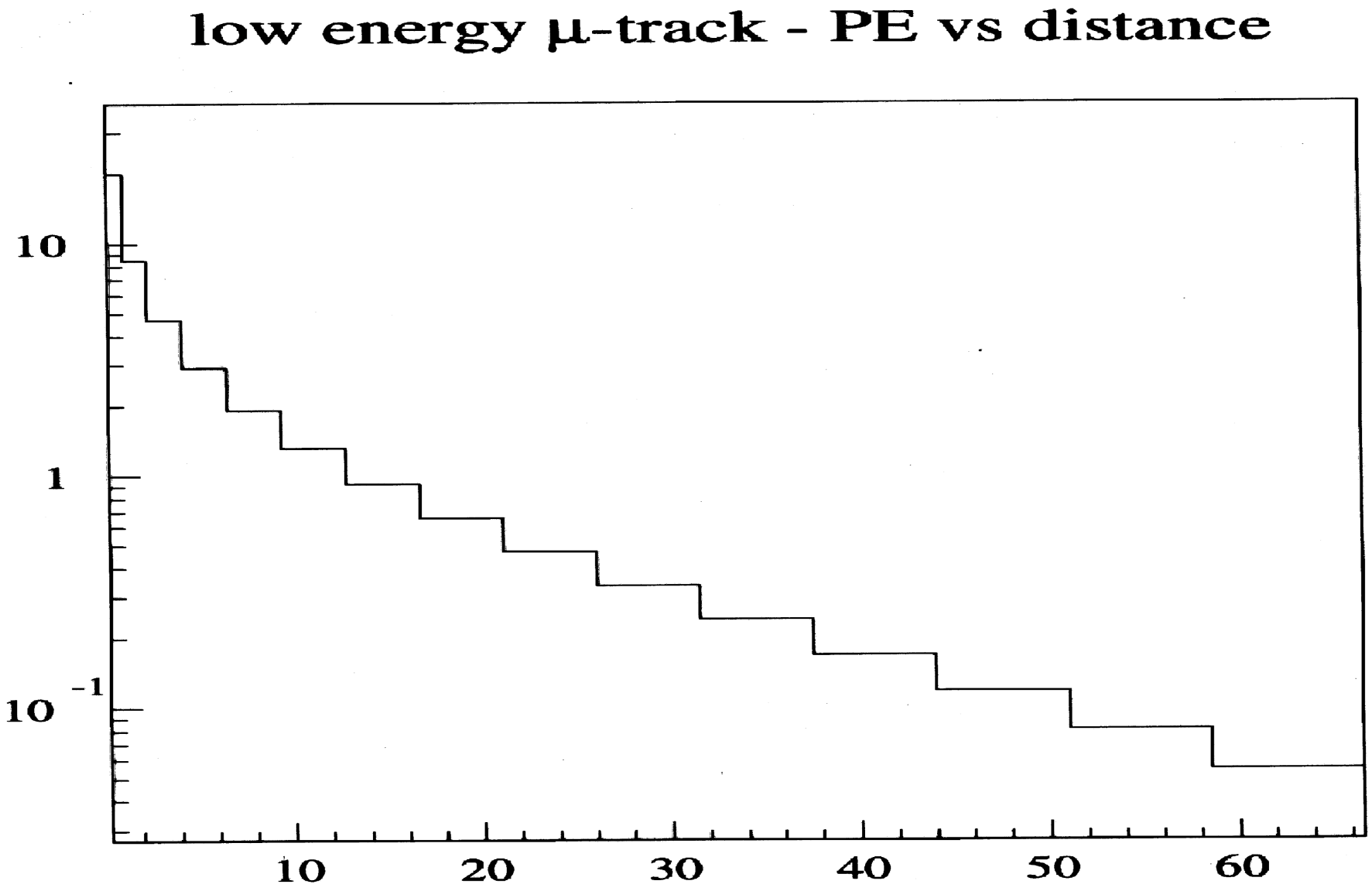
Event Reconstruction

- Time residuals:

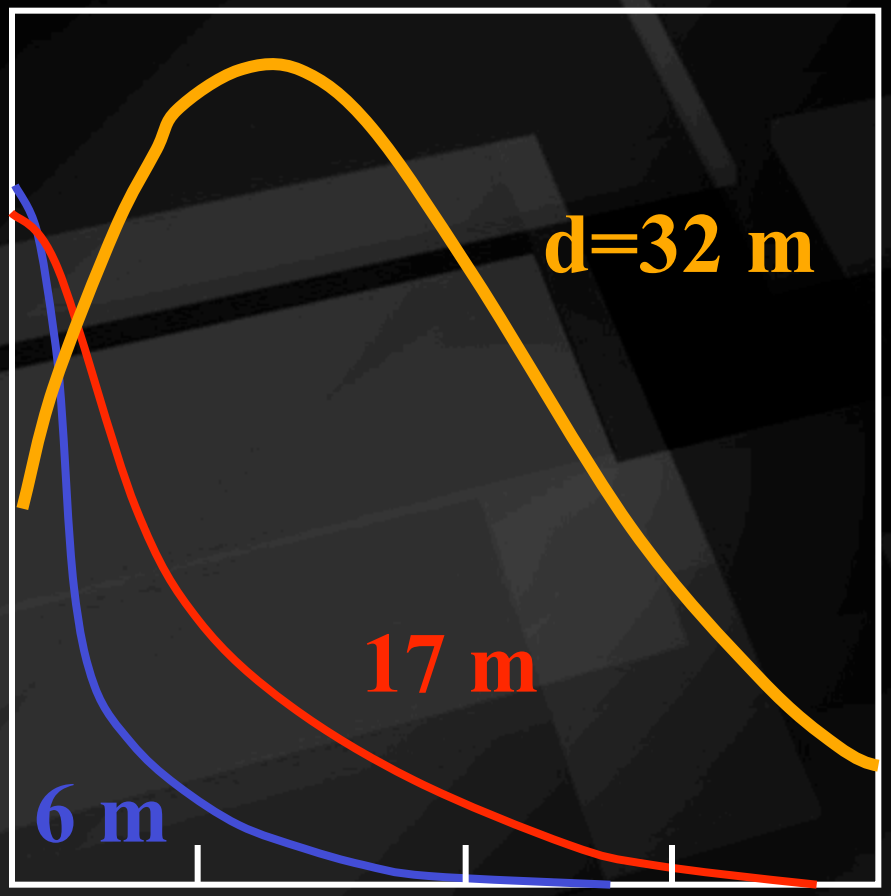


- Tracks are recontructed by maximum likelihood
- Bayesian likelihood takes into account up-down asymmetry of the muon flux:

$$P(H \mid E) = L(E \mid H)\, P(H)$$

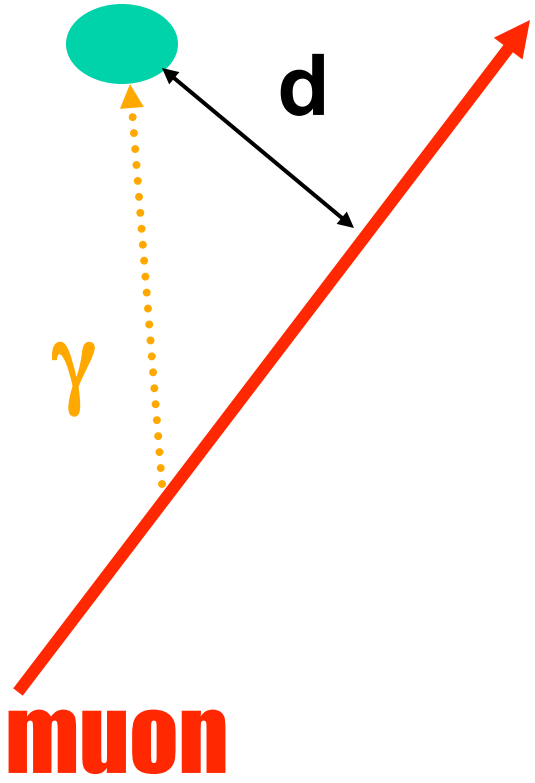

low energy μ-track - PE vs distance
10
1
10 -1
10
20
30
40
50
60

AMANDA: time delay due to scattering

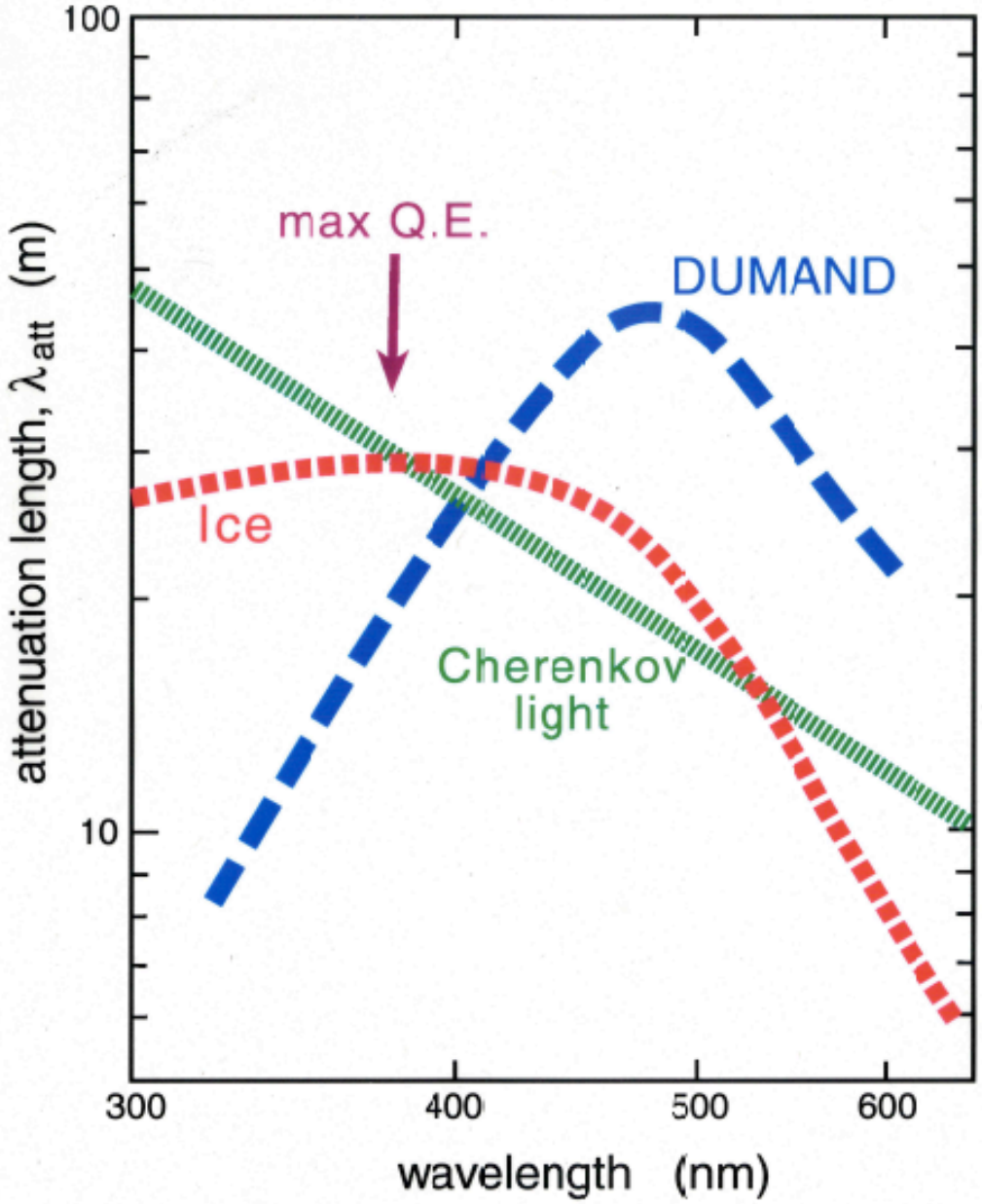


3 50 200 400 700

delay, nsec



blue: $\lambda_{abs} > 100\,m$ $\lambda_{sc} \simeq 25\,m$



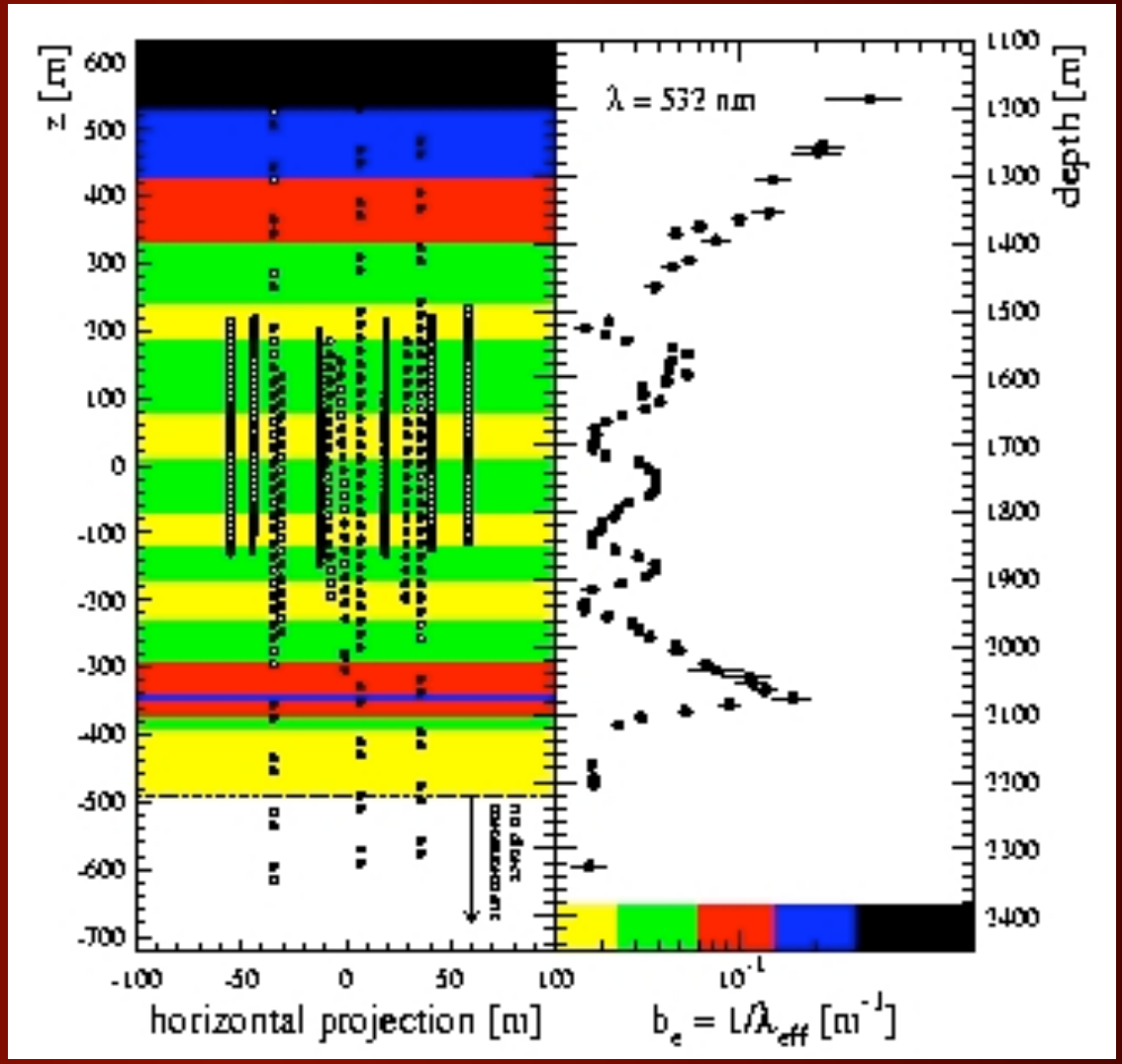
Understanding Ice and Calibrating AMANDA

- *In situ light sources*
  - Ice properties
  - Relative PMT timing, gain
  - Response to electromagnetic showers
  - crosstalk
- *Downgoing cosmic-ray muons*
  - Relative PMT timing, gain
- *AMANDA-SPASE coincidences*
  - Directionality
  - Ice properties
- *Atmospheric neutrinos*
  - Full detector response

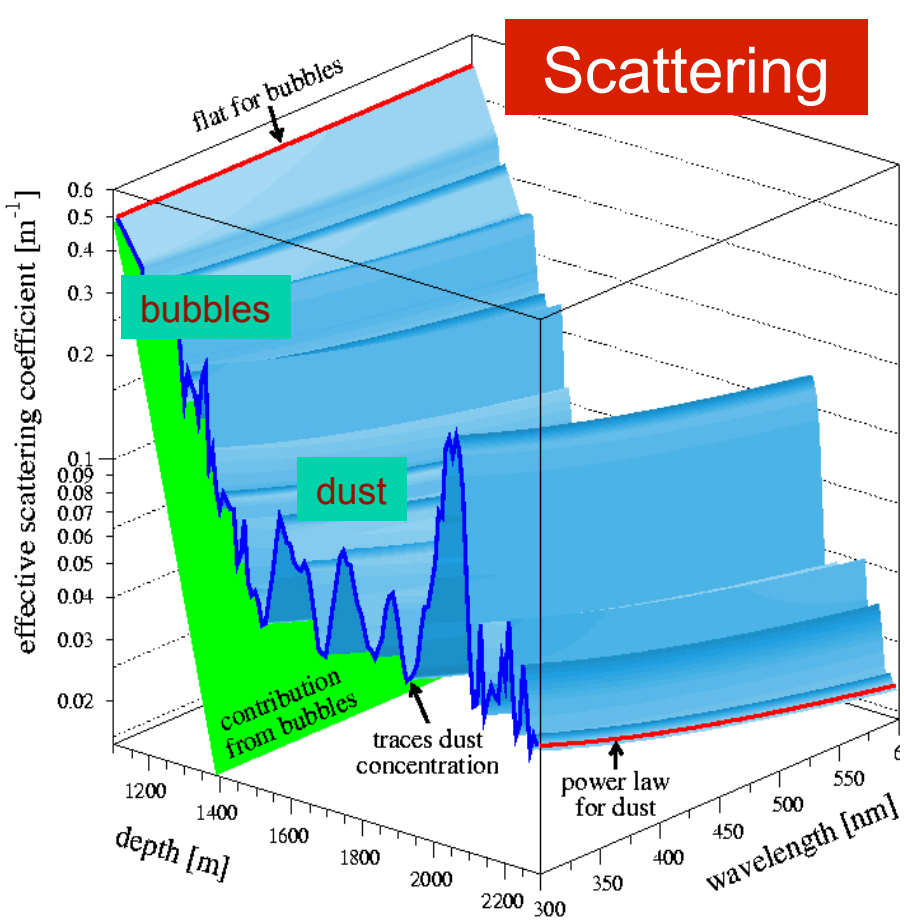
Ice Properties

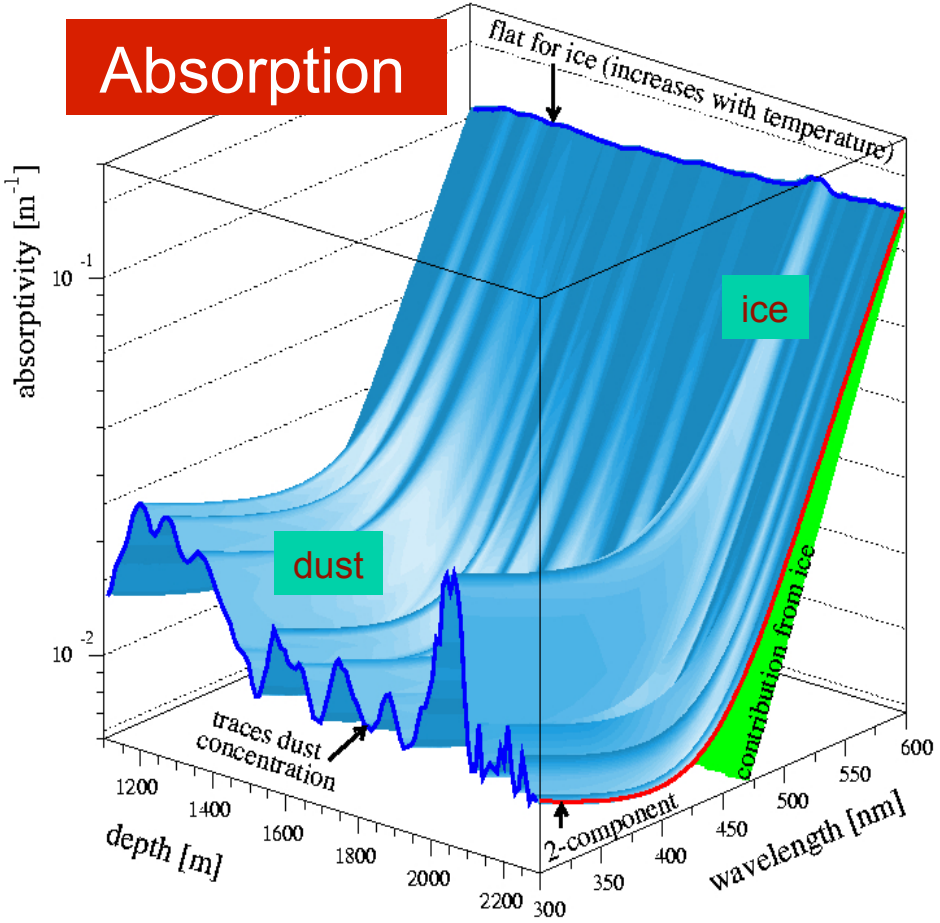
- most challenging initial problems now understood using *in situ* lasers and LEDs
  - Disappearance of bubbles
  - Mapping of dust layers

- $\lambda_{scatter}$: 6 m - 52 m
- λ_{abs} : 9 m - 240 m



optics of ice



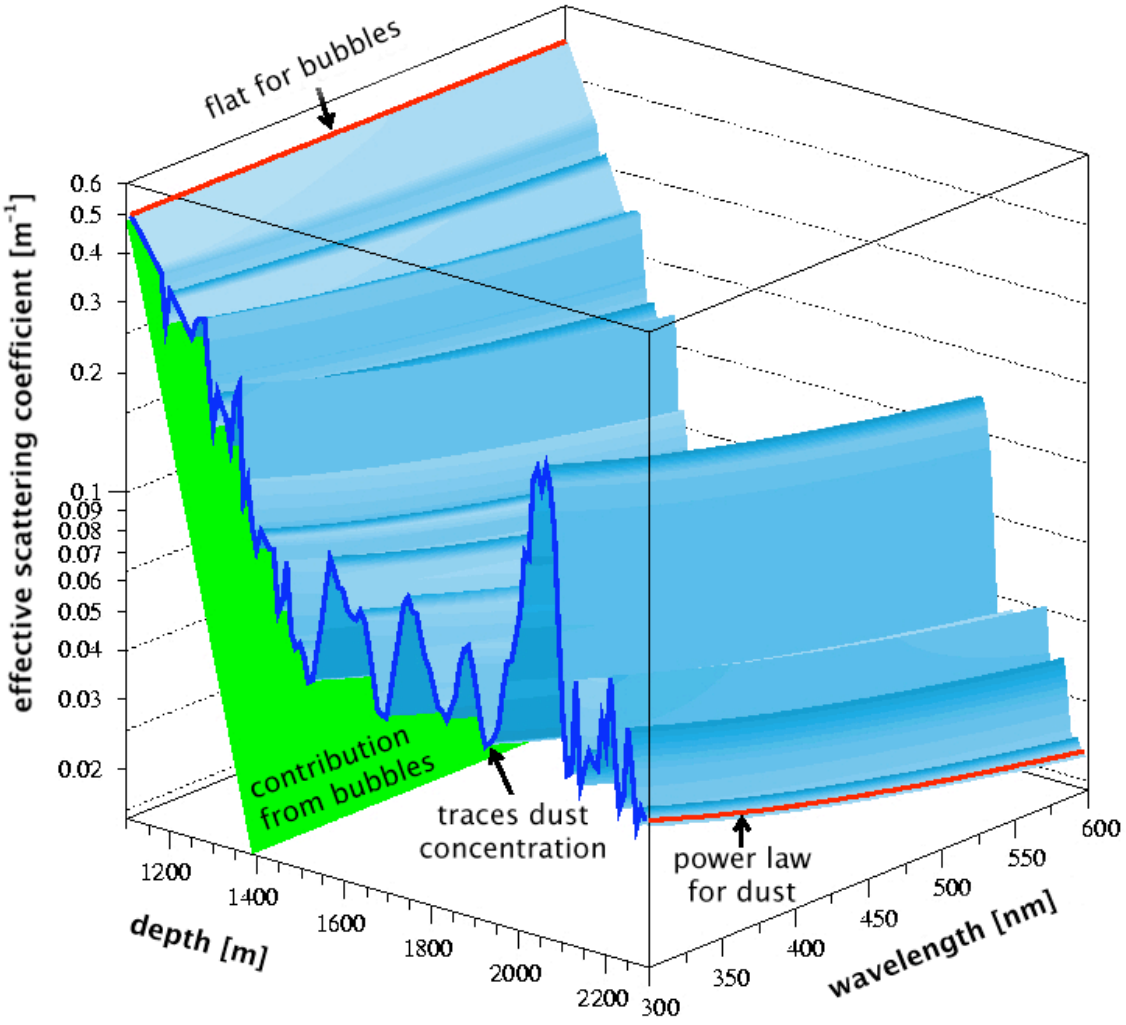


Measurements:

- in-situ light sources
- atmospheric muons

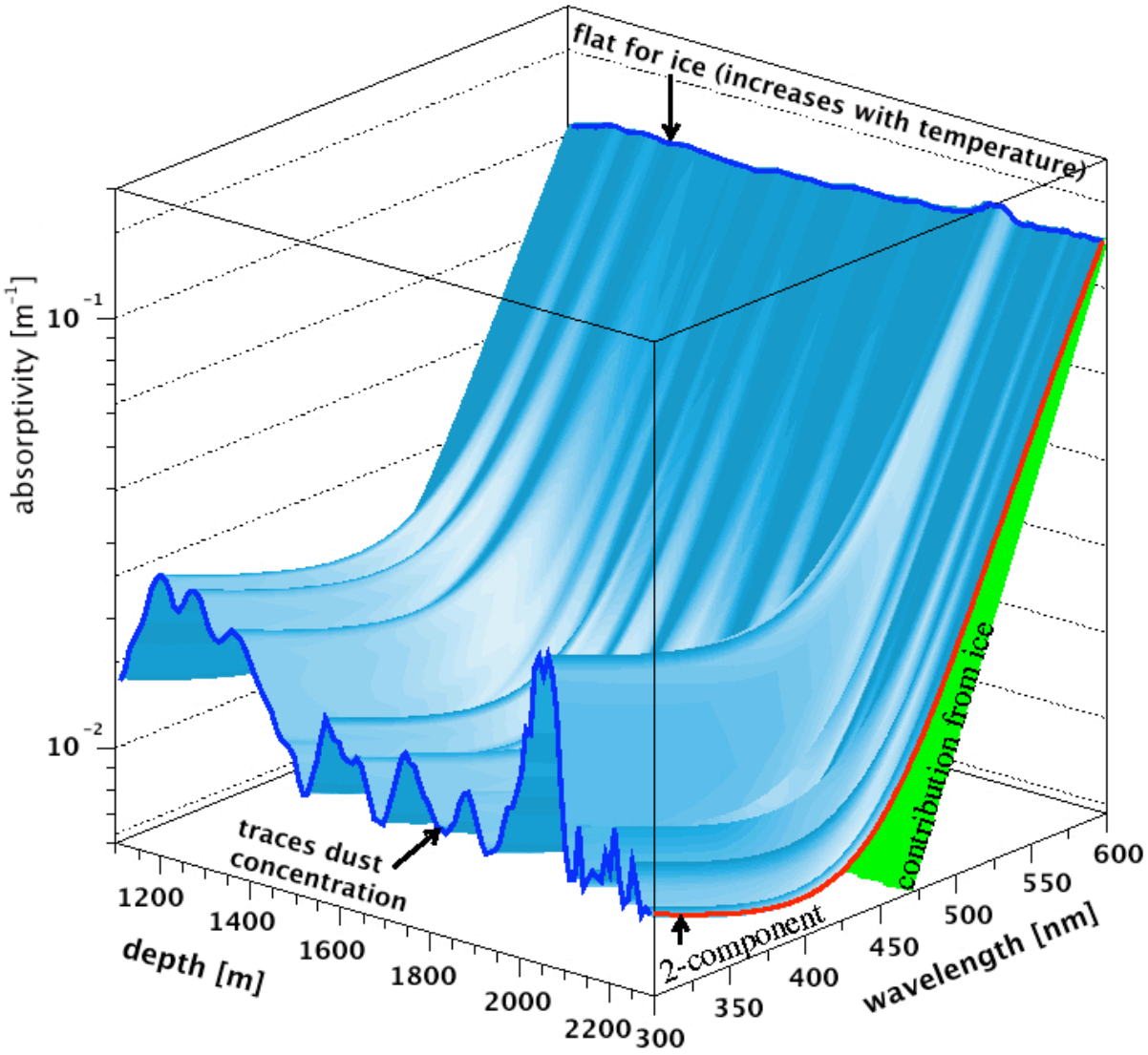
- **scattering length 6 ~ 52 m**
- **absorption length 9 ~ 240 m**
- **sterile medium**

Scattering in AMANDA ice

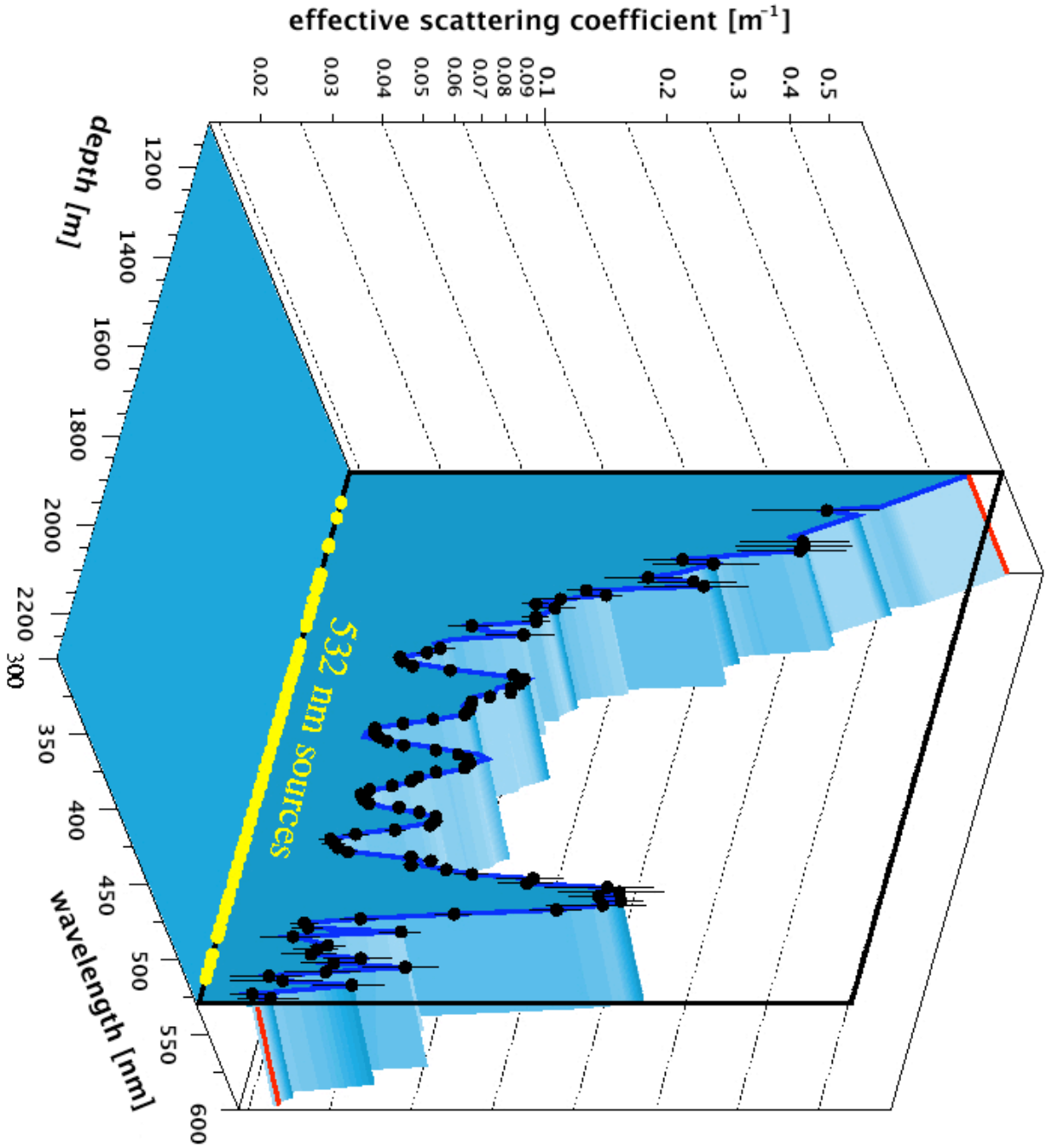


effective scattering coefficient [m^{-1}]

Absorption in AMANDA ice

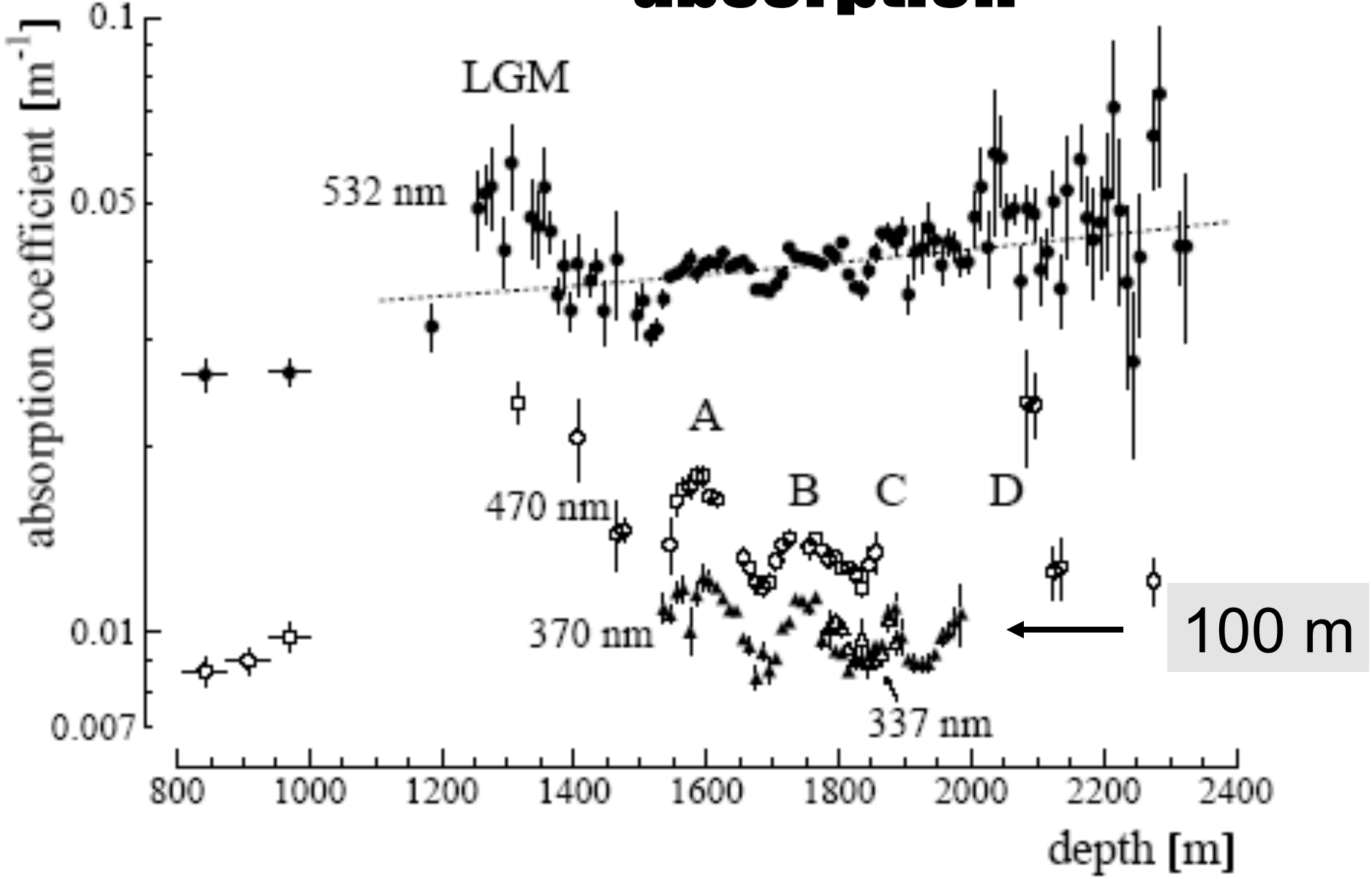


absorptivity [m^{-1}]

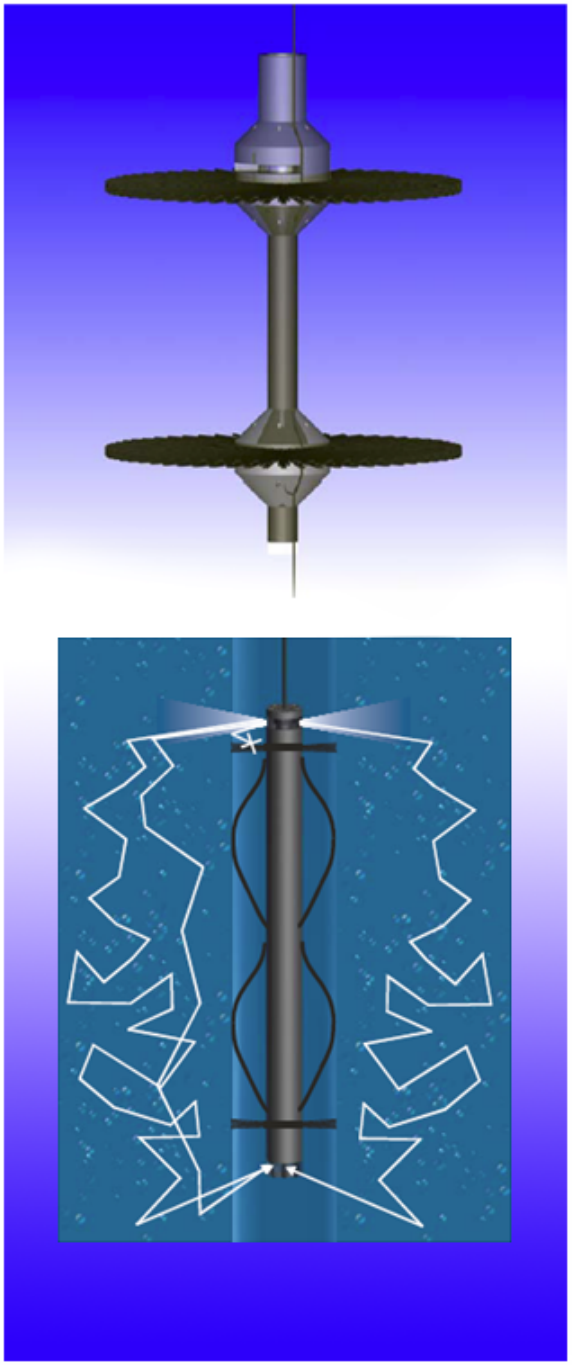


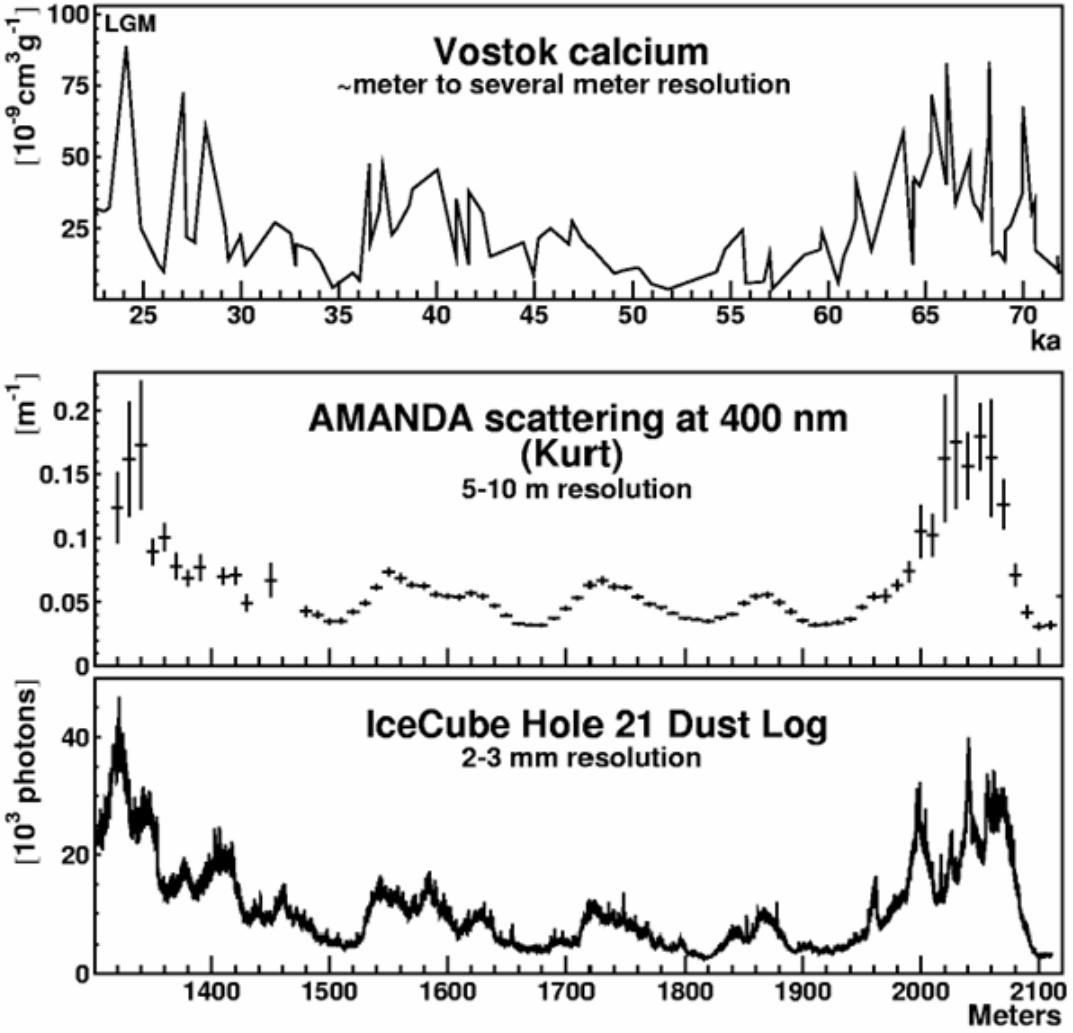
effective scattering coefficient [m^{-1}]

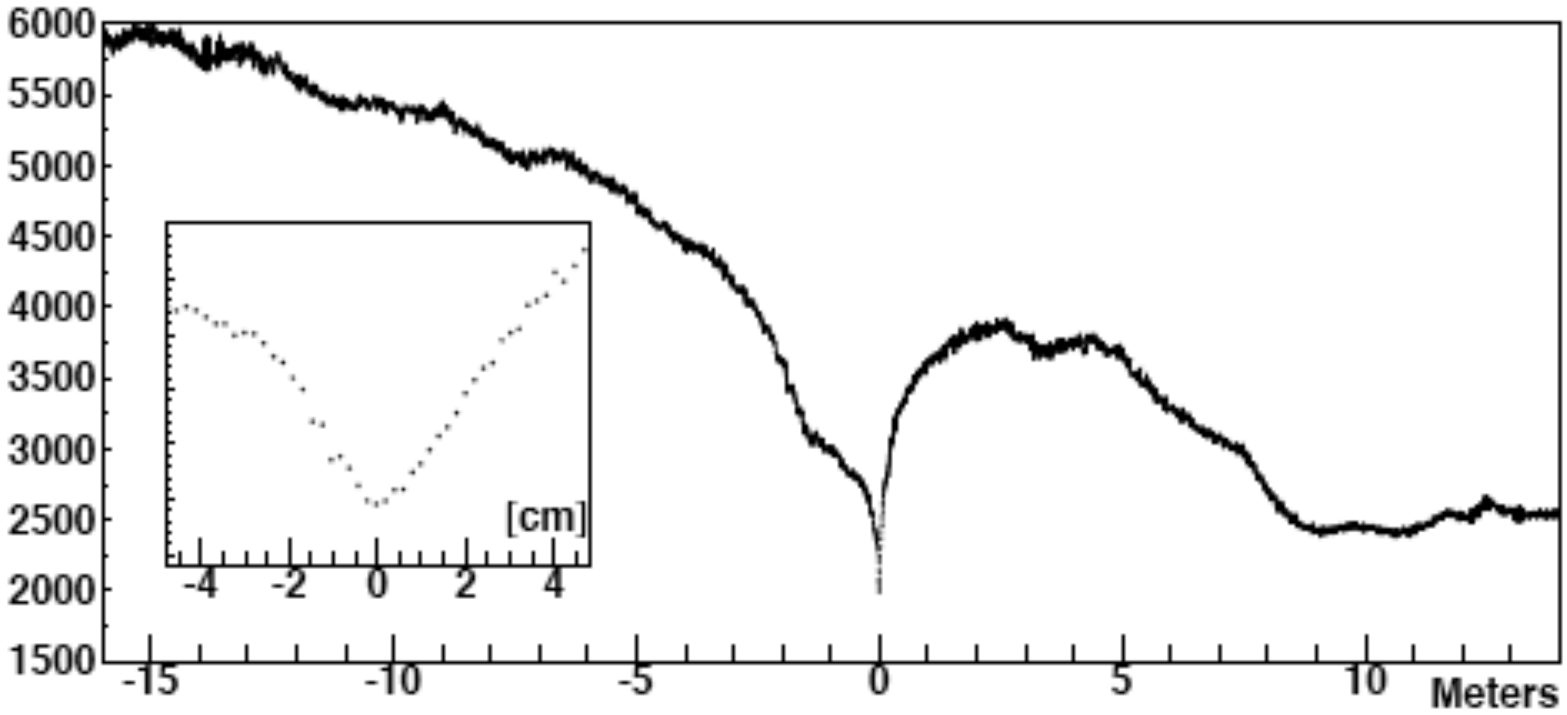
absorption


absorption coefficient [m^{-1}]
0.1
0.05
0.01
0.007
LGM
532 nm
470 nm
370 nm
337 nm
A
B
C
D
100 m
800
1000
1200
1400
1600
1800
2000
2200
2400
depth [m]

Glaciology with Light

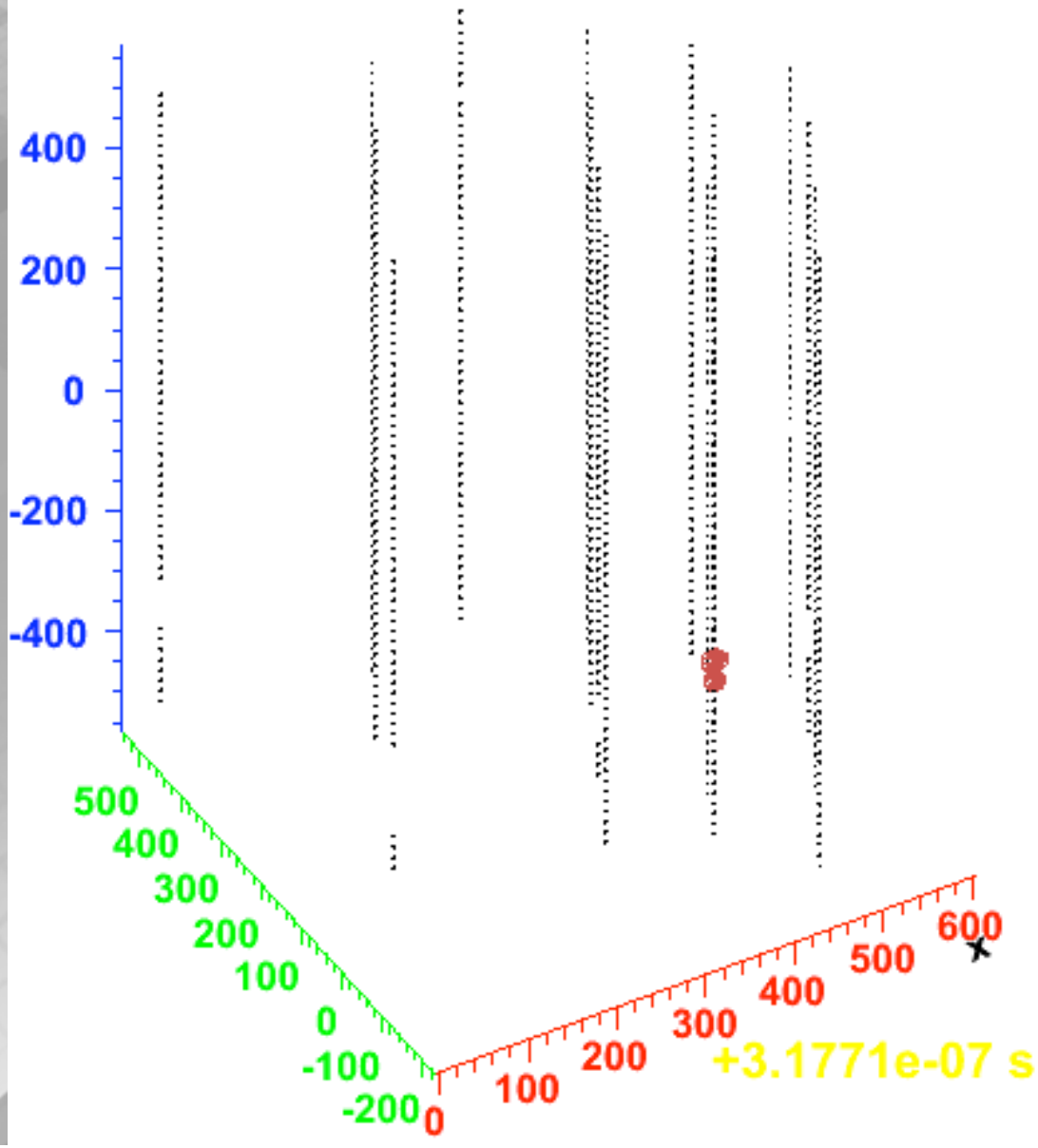




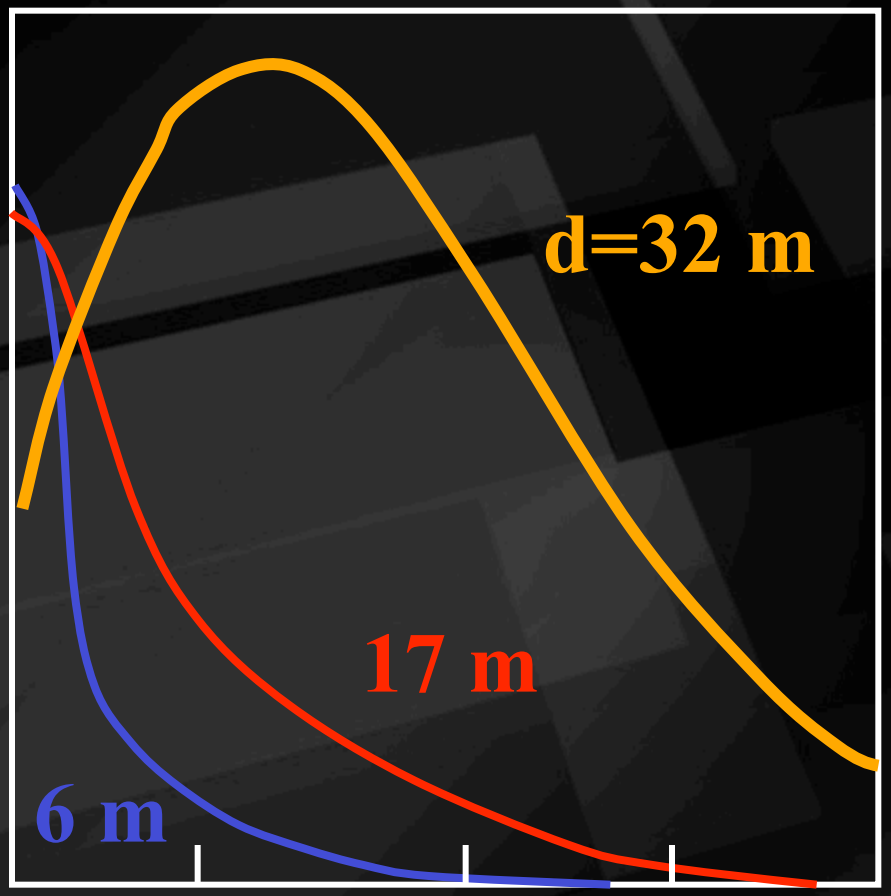


volcanic ash layer

light travels 600 meters

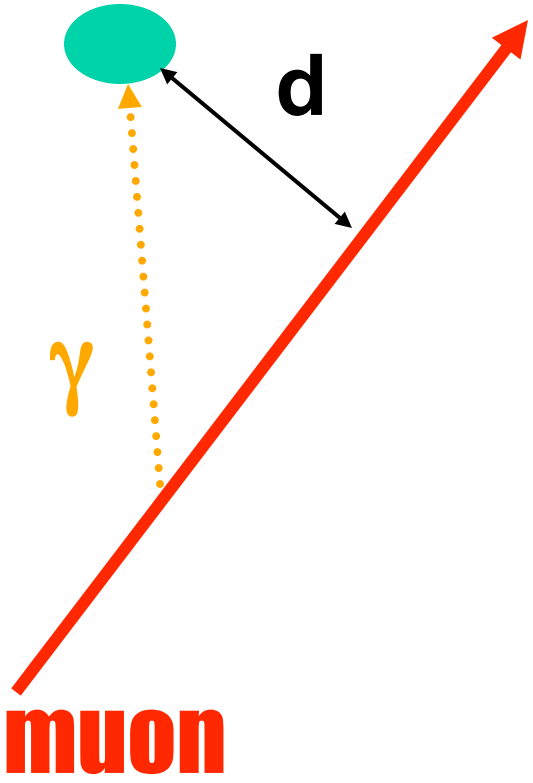


AMANDA: time delay due to scattering



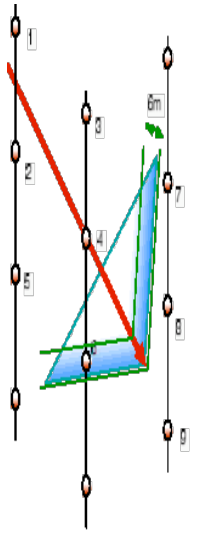
3 50 200 400 700

delay (nsec)



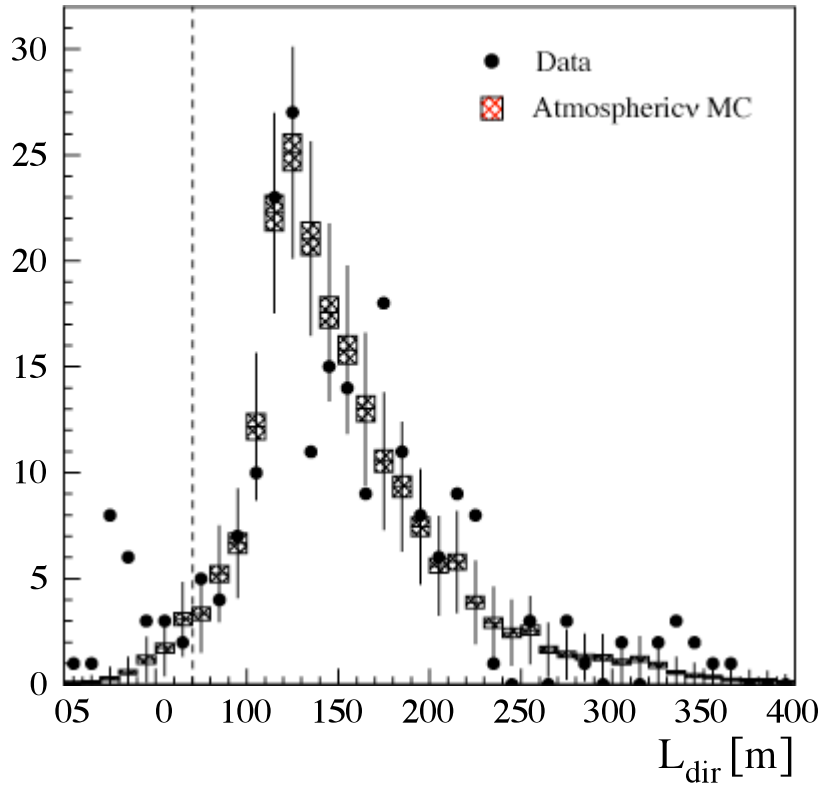
event reconstruction

- Maximum Likelihood method
- Take into account time profiles of expected photon flight times
- Bayesian approach – use prior knowledge of expected backgrounds and signals



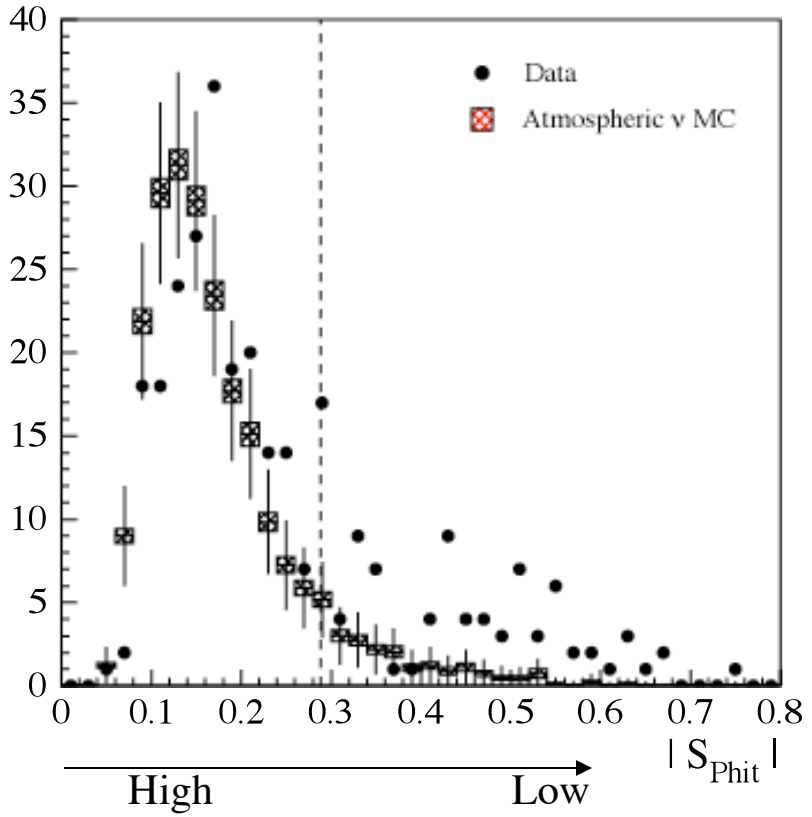
Quality parameters: Example 1: The track length

- Short track length = more likely to be background



Quality parameters: Example 2: The smoothness

- The smoothness is a measure of how regular the photon density is distributed along the track.
- A well reconstructed muon track is more likely to have a high smoothness.

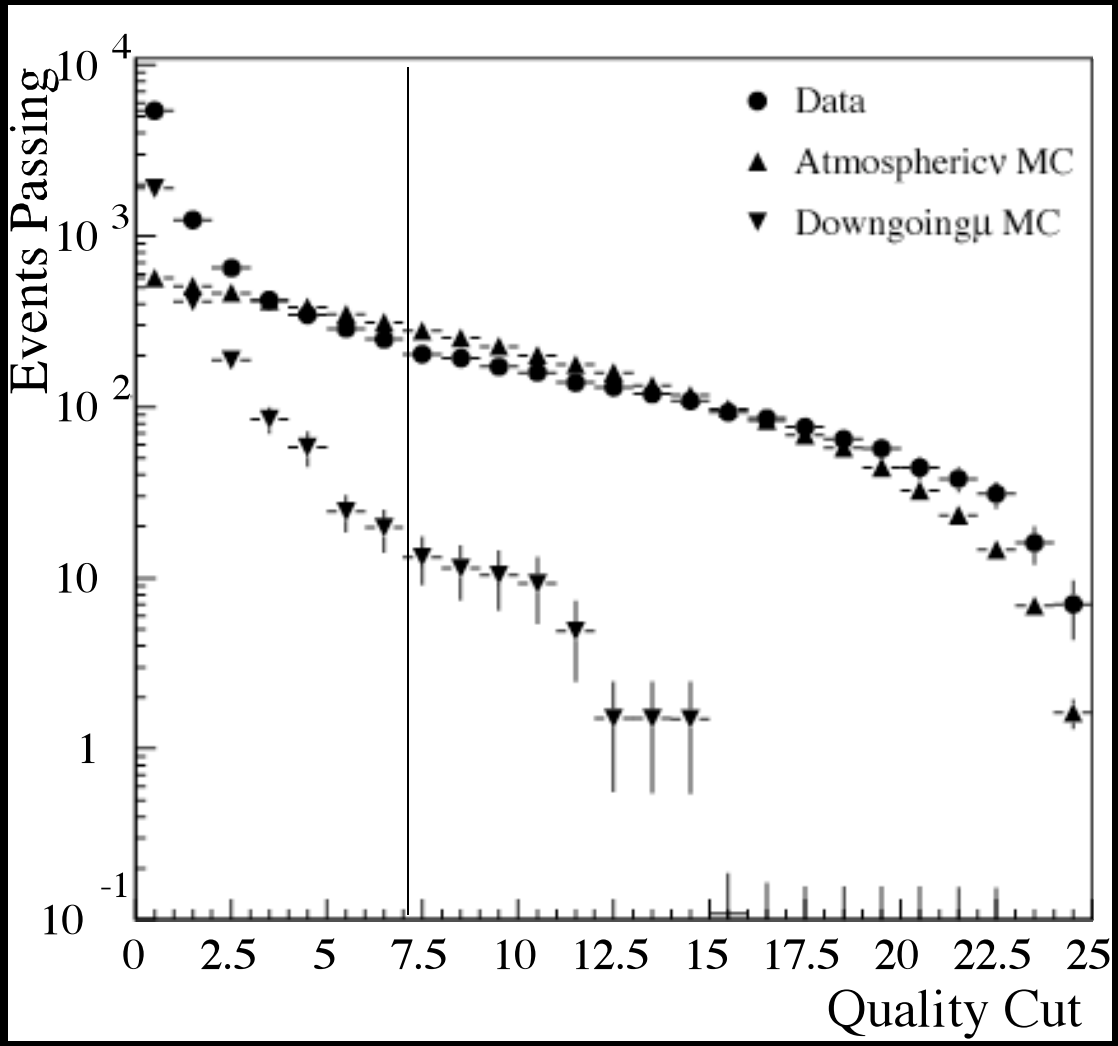


Quality Parameters

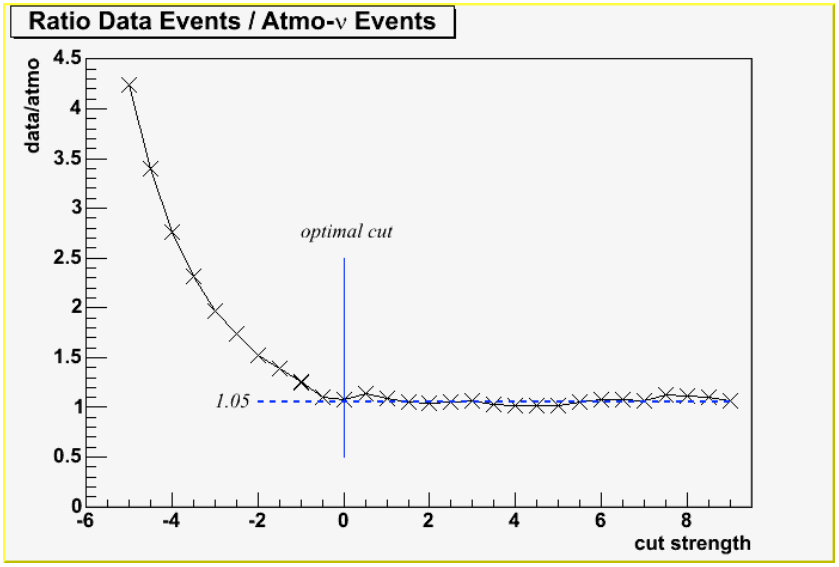
- Likelihood
- Zenith angle mismatch between two types of fits.
- Sphericity of Hits (Brem?)
- Track Length (is an energy cut, too)
- Smoothness of hits along the track
- Number of unscattered photons

- Combine 6 to a single event quality parameter.
- Only 2 for completed detector!

quality cut

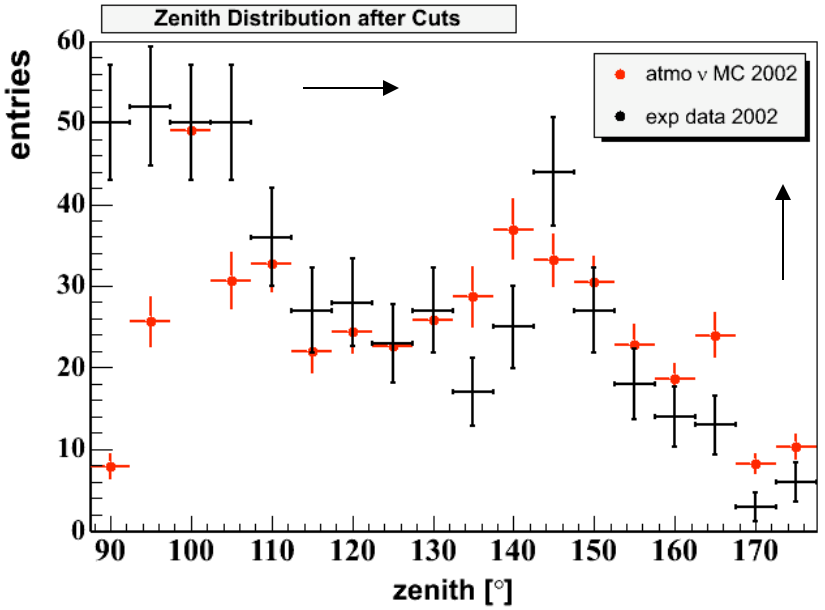

Events Passing
10^4
10^3
10^2
10
1
10^{-1}
Data
Atmosphericν MC
Downgoingμ MC
0
2.5
5
7.5
10
12.5
15
17.5
20
22.5
25
Quality Cut

2002 `standard` analysis



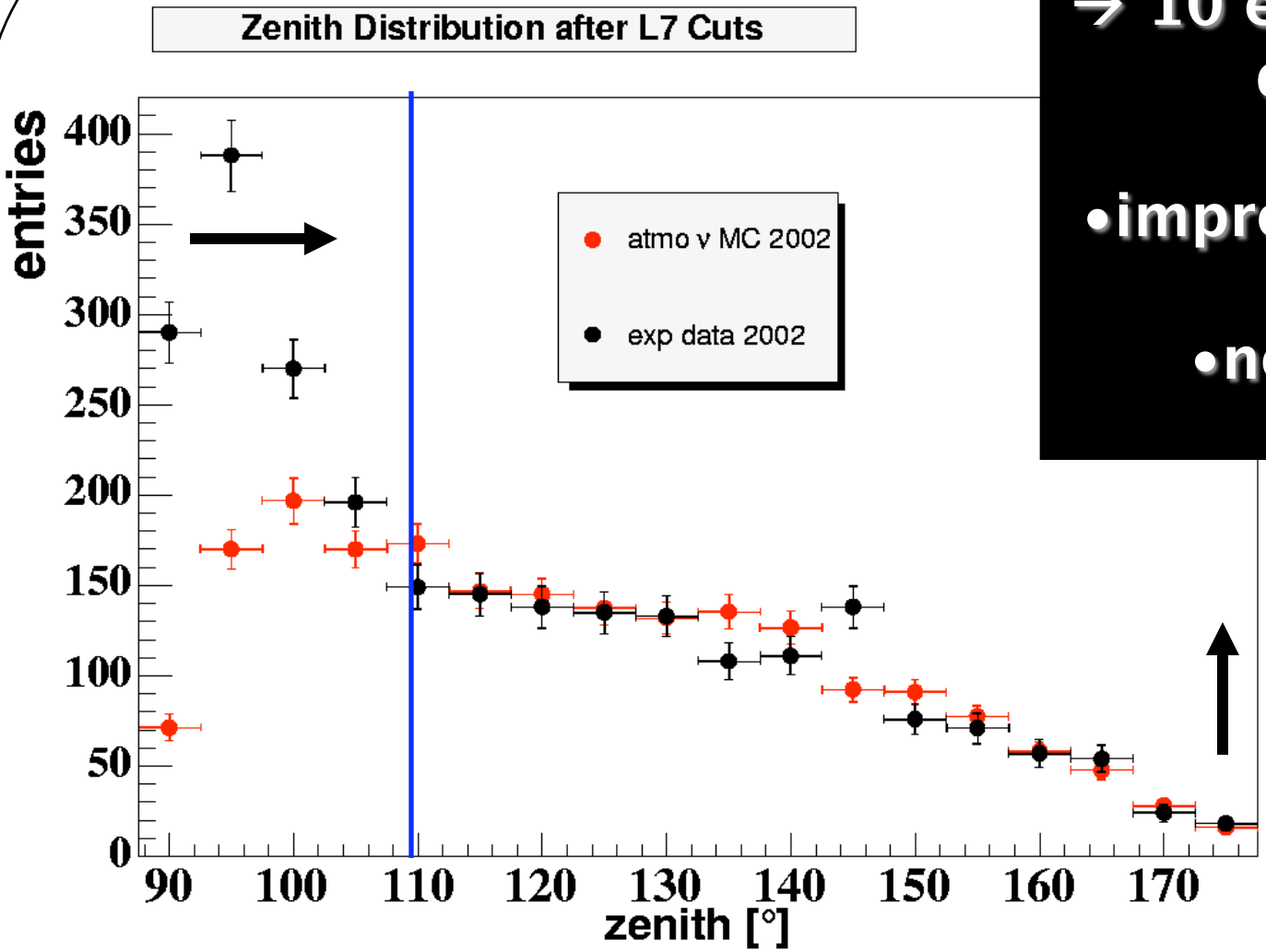
- normalization **data/atmo-ν-MC** determined by tightening the cuts

- Zenith distribution after final cuts



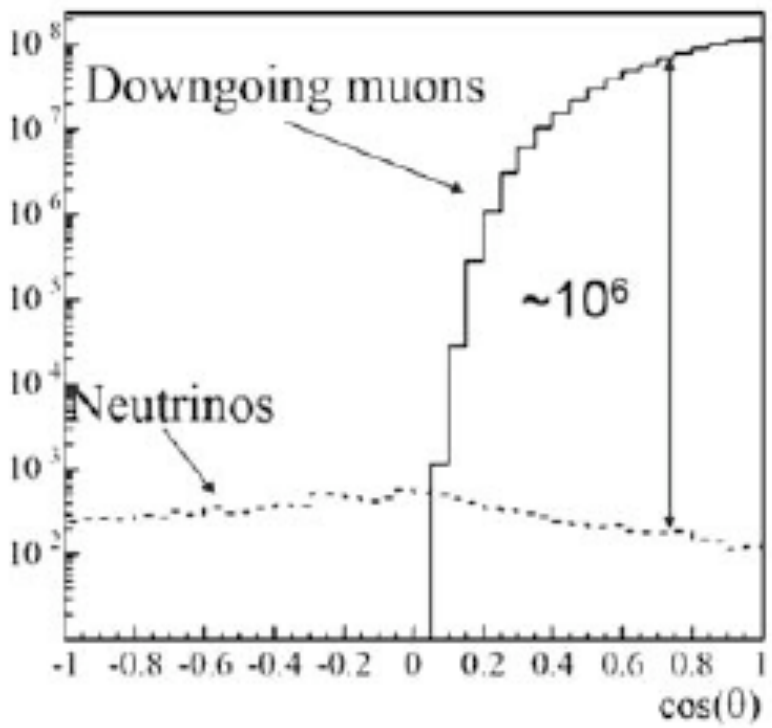
Optimized 2002 analysis

zenith distribution

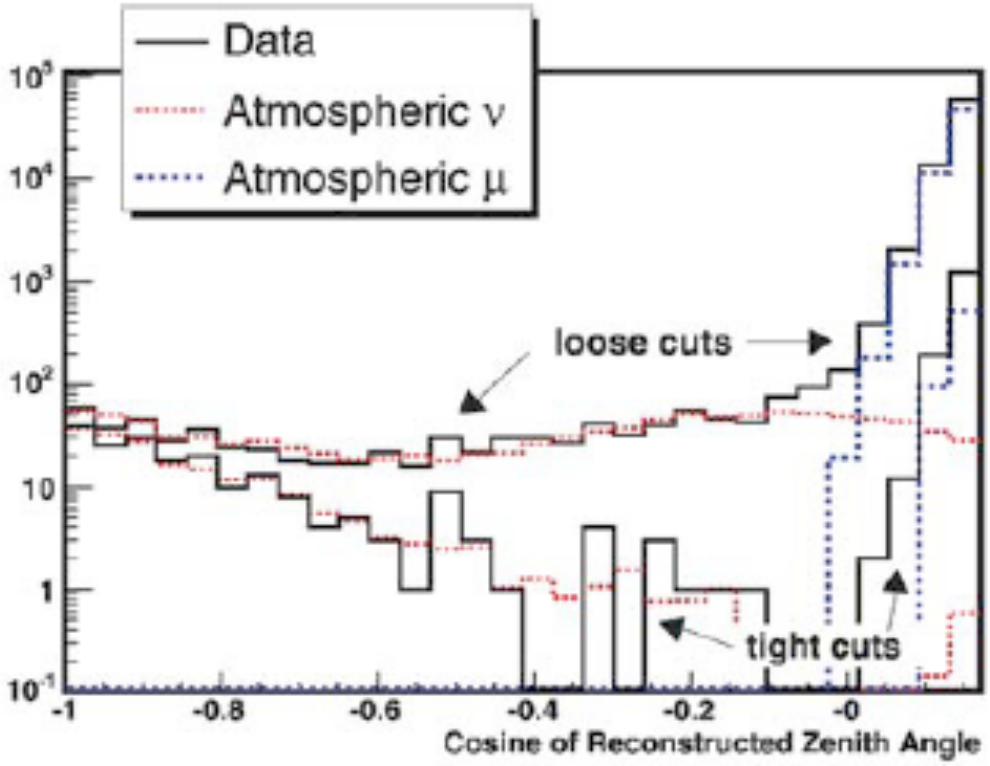


→ 10 events per day:

- improved reco
- no cuts


Downgoing muons
~10^6
Neutrinos
cos(θ)

(a)


Data
Atmospheric ν
Atmospheric μ
loose cuts
tight cuts
Cosine of Reconstructed Zenith Angle

(b)

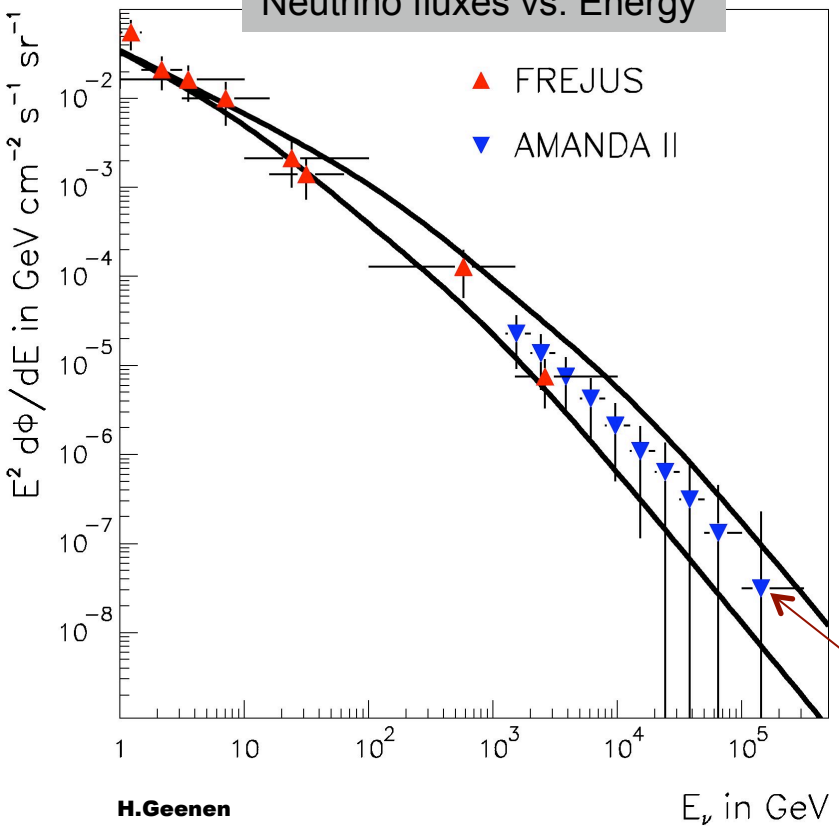
ATMOSPHERIC ν & DIFFUSE FLUX LIMITS [ν_μ]

Neural Network
energy reconstruction
Regularized unfolding
→ energy spectrum

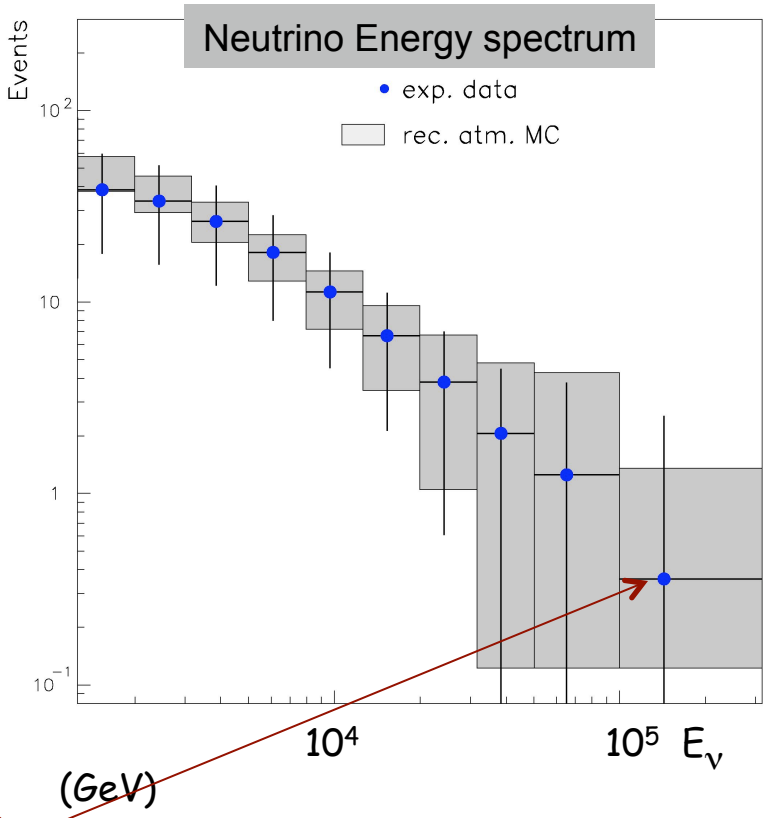
AMANDA test beams: atmospheric ν and μ

First spectrum > 1 TeV (up to 100TeV)

Neutrino fluxes vs. Energy



Neutrino Energy spectrum



Last bin info to calculate the limit to Extraterrestrial E^2 neutrino flux

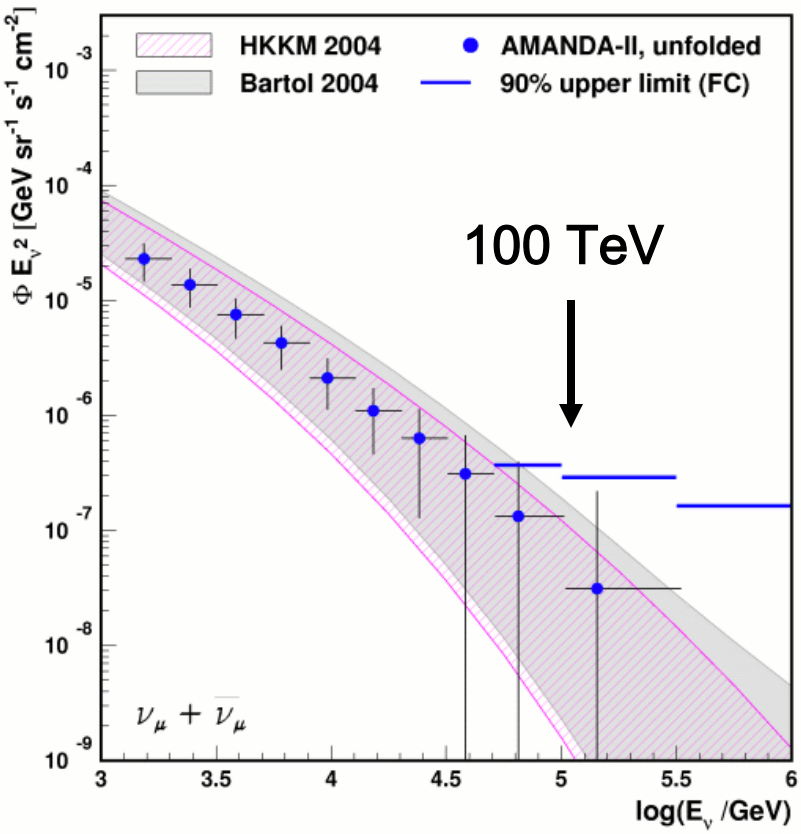
Previous analysis publication

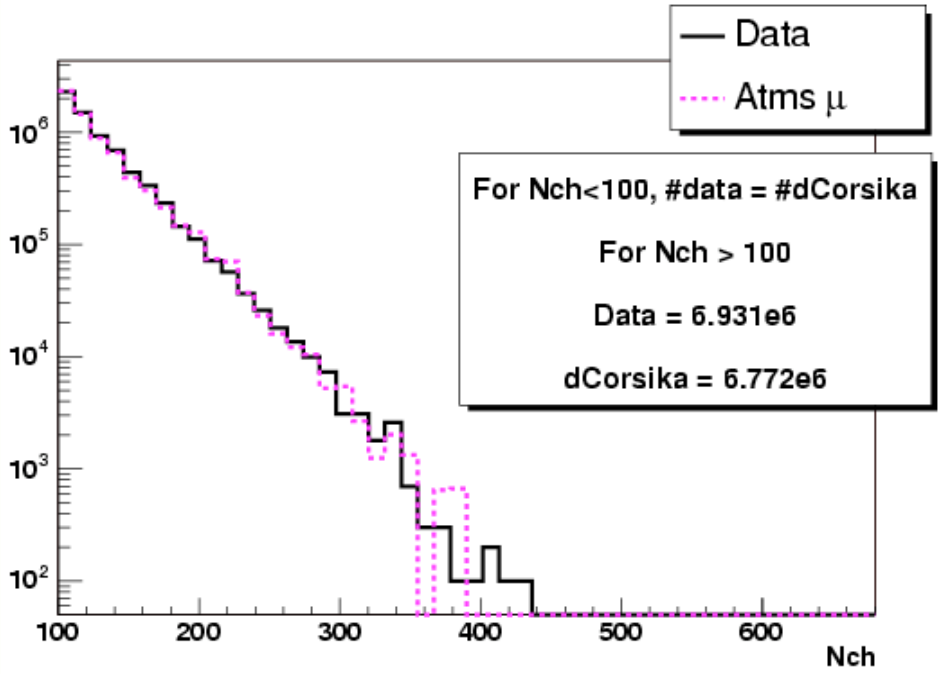
Phys. Rev. Lett. 90 251101 (2003)

Includes 33% systematic uncertainty

$$E^2\Phi_{\nu_\mu}(E) < 2.58\cdot10^{-7}\ \text{GeV cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$$

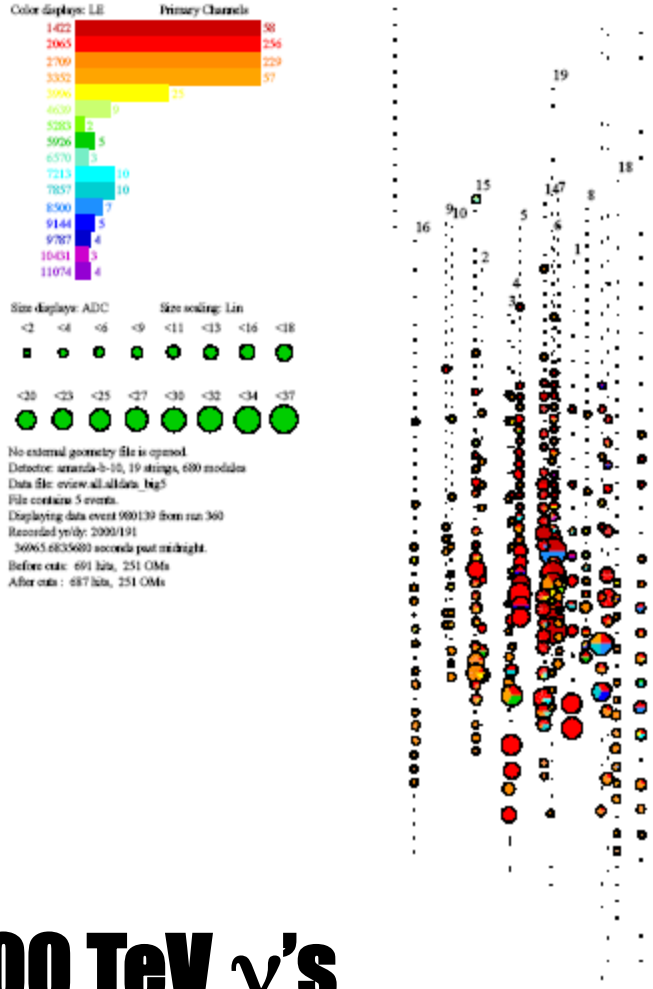
calibration on cosmic ray neutrinos and muons

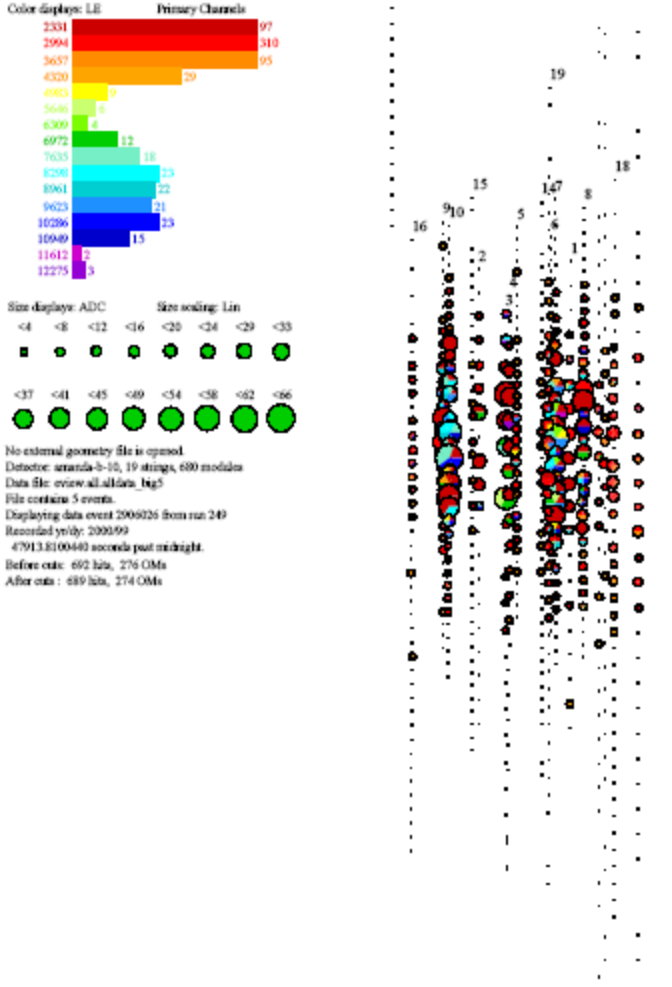




inverted analysis: use atmospheric muons to benchmark MC

- atmospheric ν_μ spectrum

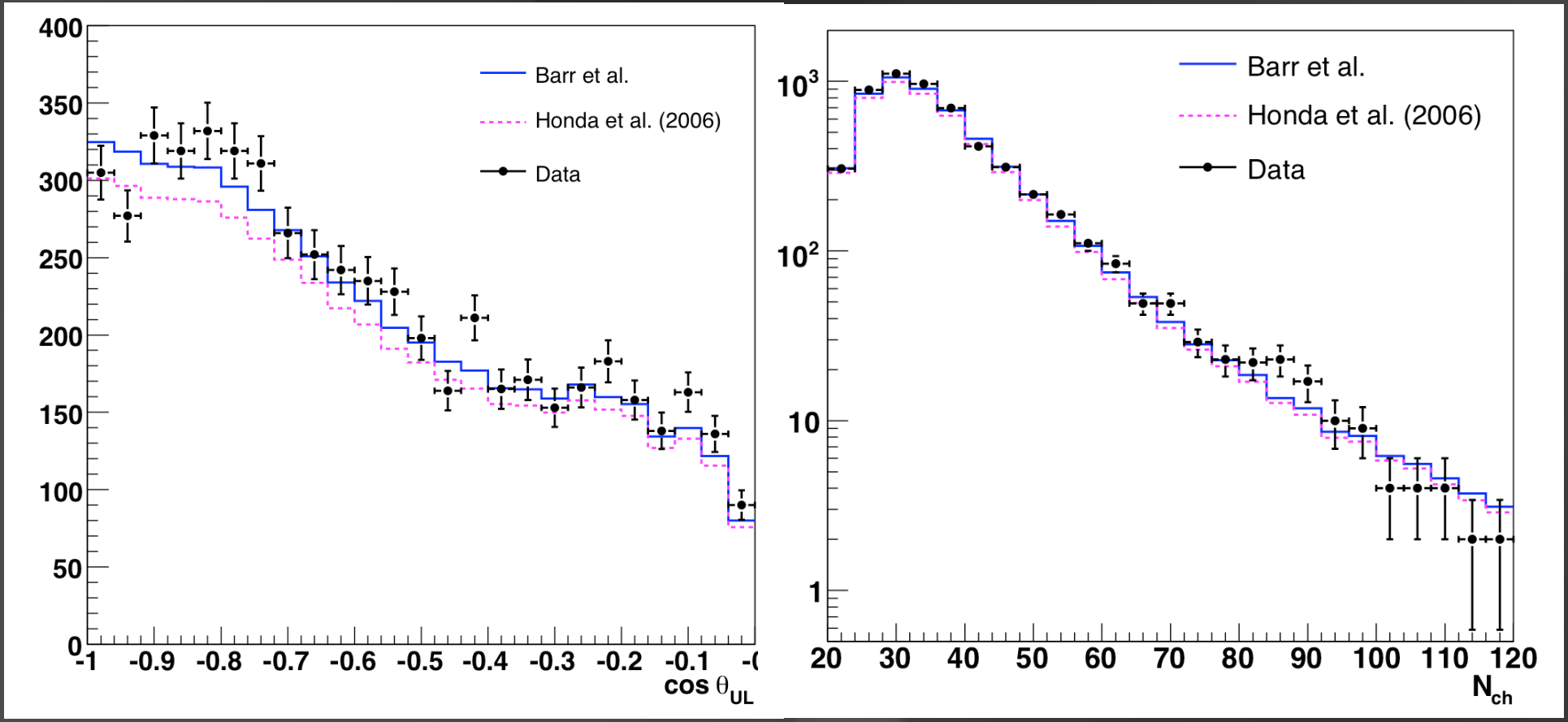

Color displays: LE
Primary Channels
Size displays: ADC
Size scaling: Lin
No external geometry file is opened.
Detector: amanda-b-10, 19 strings, 680 modules
Data file: eview.all.alldata_big5
File contains 5 events.
Displaying data event 980139 from run 360
Recorded yr/dy: 2000/191
36965.6835680 seconds past midnight.
Before cuts: 691 hits, 251 OMs
After cuts : 687 hits, 251 OMs


Color displays: LE
Primary Channels
Size displays: ADC
Size scaling: Lin
No external geometry file is opened.
Detector: amanda-b-10, 19 strings, 680 modules
Data file: eview.all.alldata_big5
File contains 5 events.
Displaying data event 2906026 from run 249
Recorded yr/dy: 2000/99
47913.8100440 seconds past midnight.
Before cuts: 692 hits, 276 OMs
After cuts : 689 hits, 274 OMs

100 TeV ν's

AMANDA: 7 years

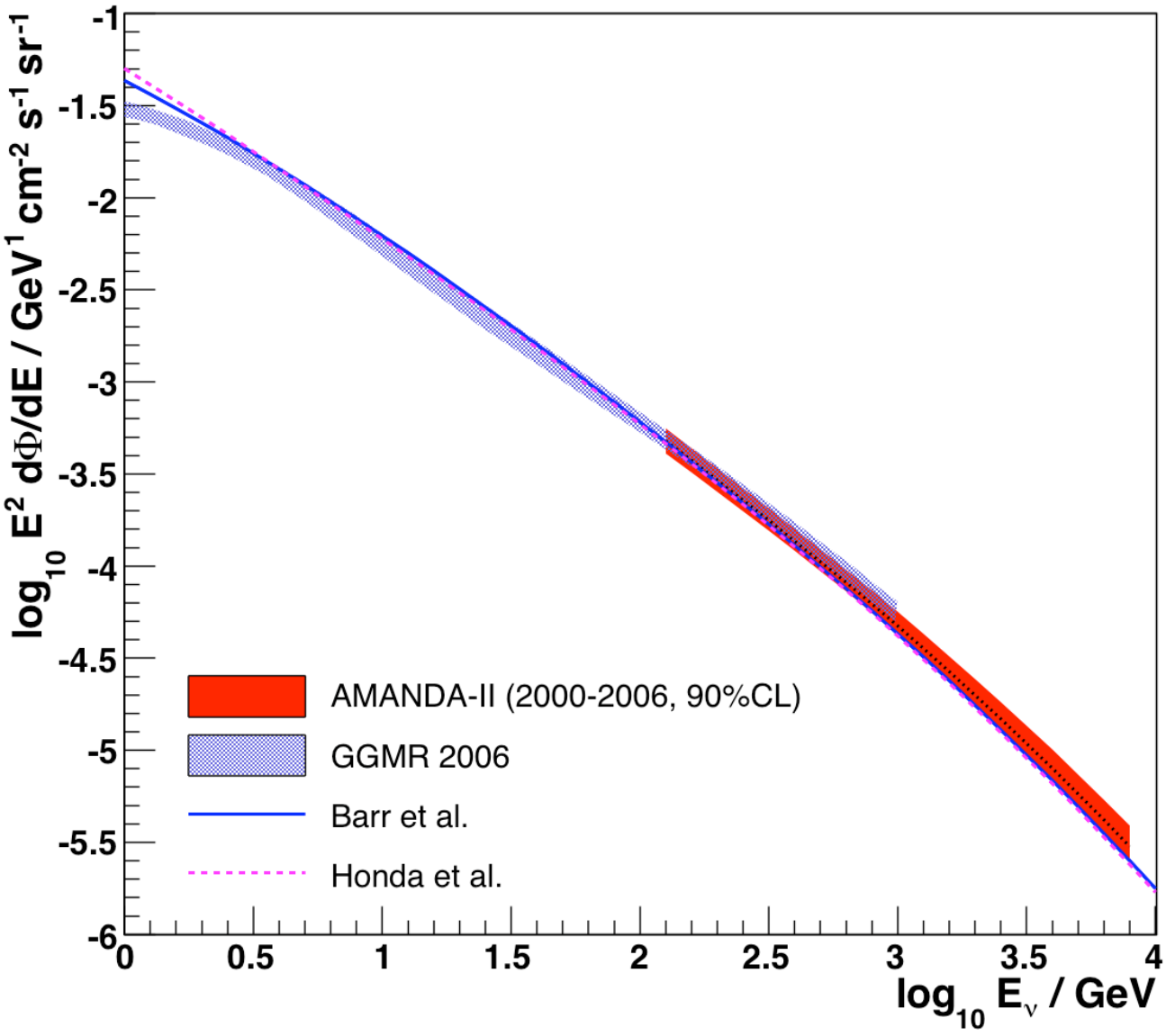
atmospheric neutrino spectrum

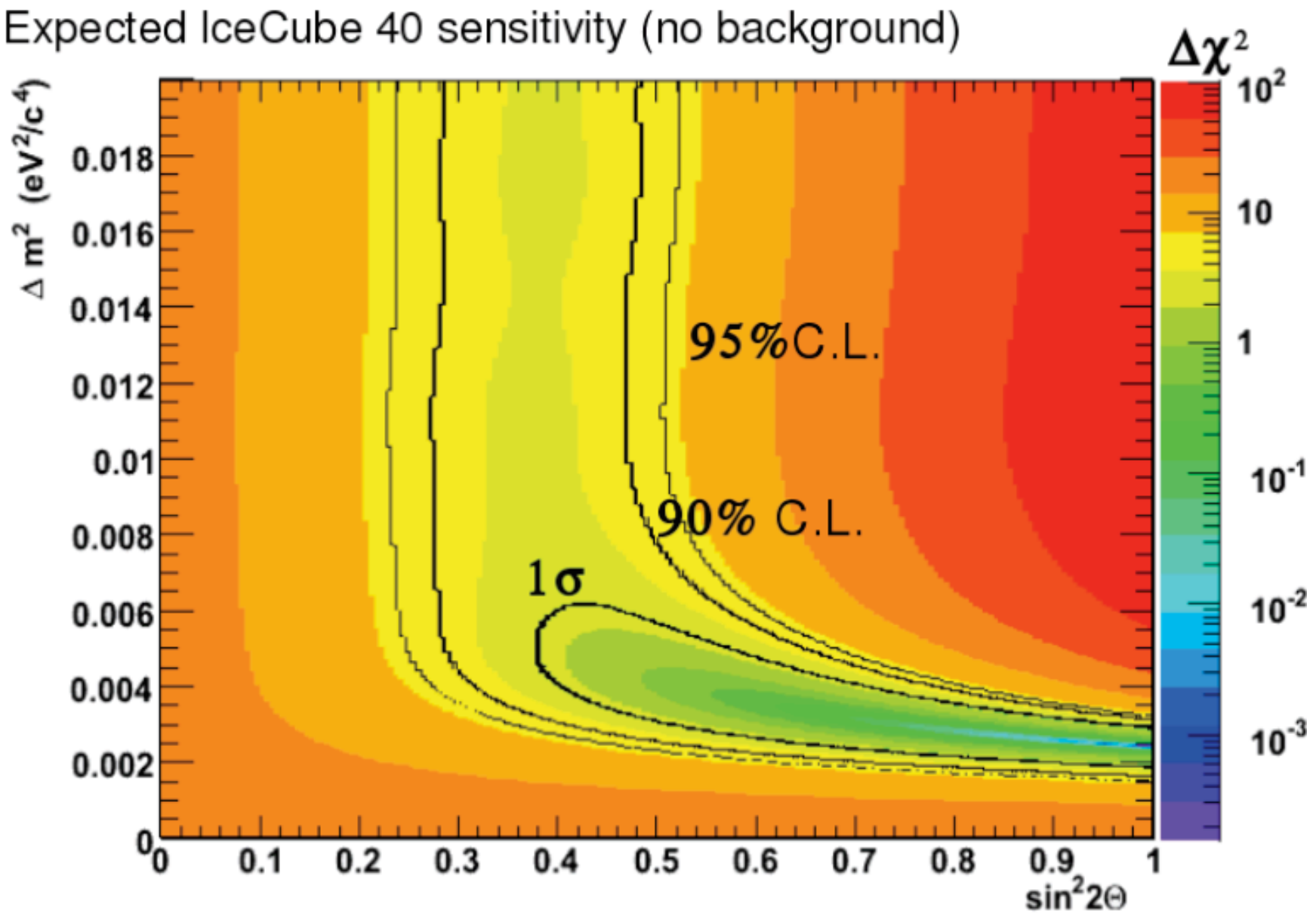


zenith angle

number of PMT

AMANDA: final sample for atmospheric ν's (6163 events)



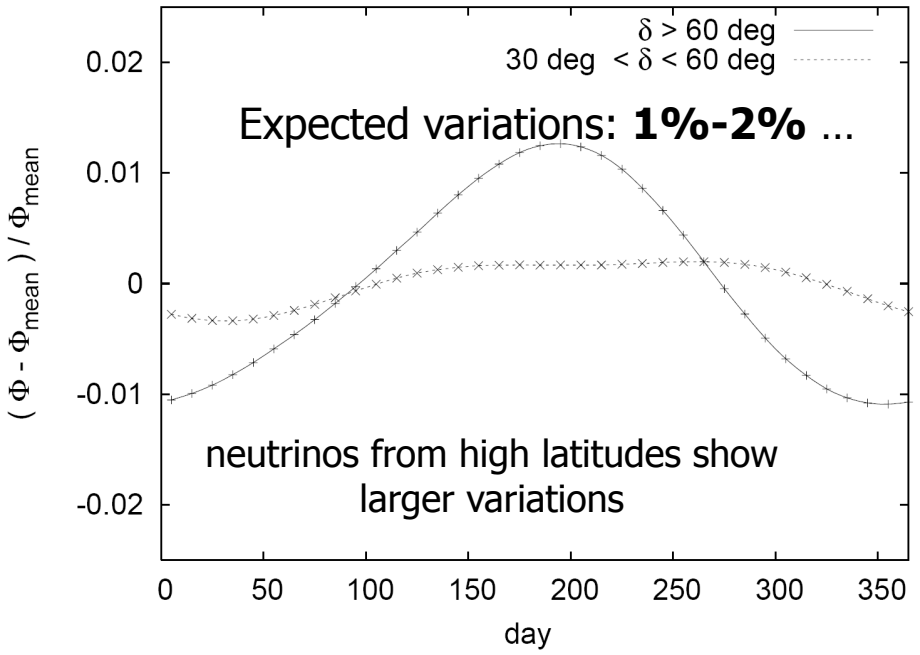

Expected IceCube 40 sensitivity (no background)
Δχ²
10²
10
1
10⁻¹
10⁻²
10⁻³
Δ m² (eV²/c⁴)
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
sin²2Θ
95%C.L.
90% C.L.
1σ

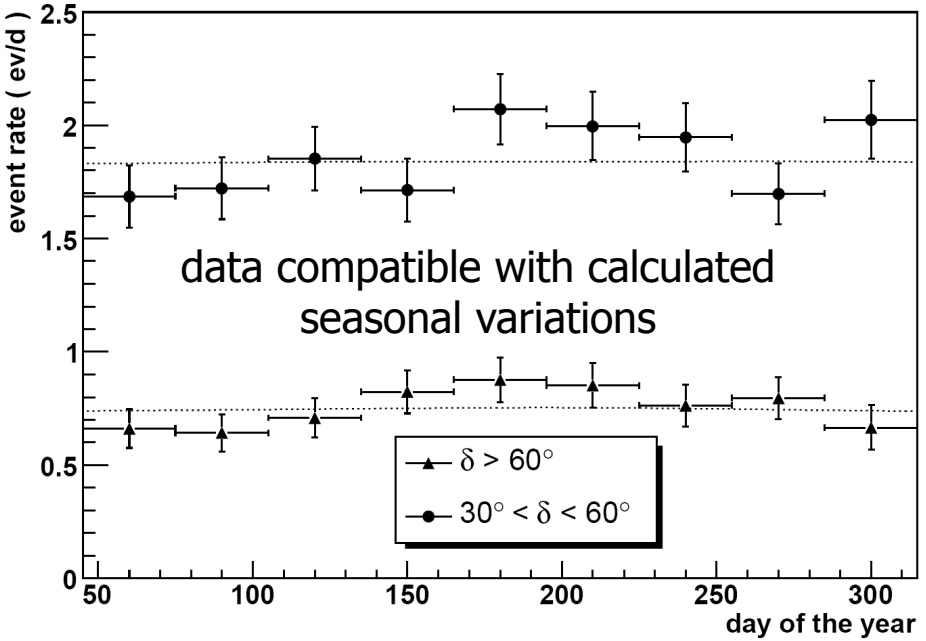
atmospheric neutrinos – a high precision measurement

Channel	E_{th} (@ AMANDA)	Source ($\varepsilon_{\pi,k}$)
Muons	≈ 400 GeV	≈ Pions (115 GeV)
Neutrinos	≈ 50 GeV	≈ Kaons (850 GeV)

E » critical energy $\varepsilon_{\pi,k}$: interaction dominate over decay

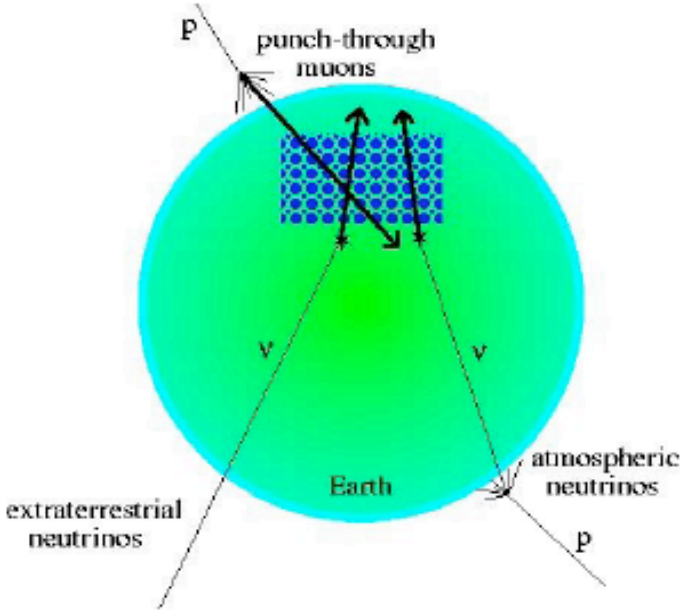
temperature increase ⇒ density decrease ⇒ more decays than interactions





IceCube

IceCube Events

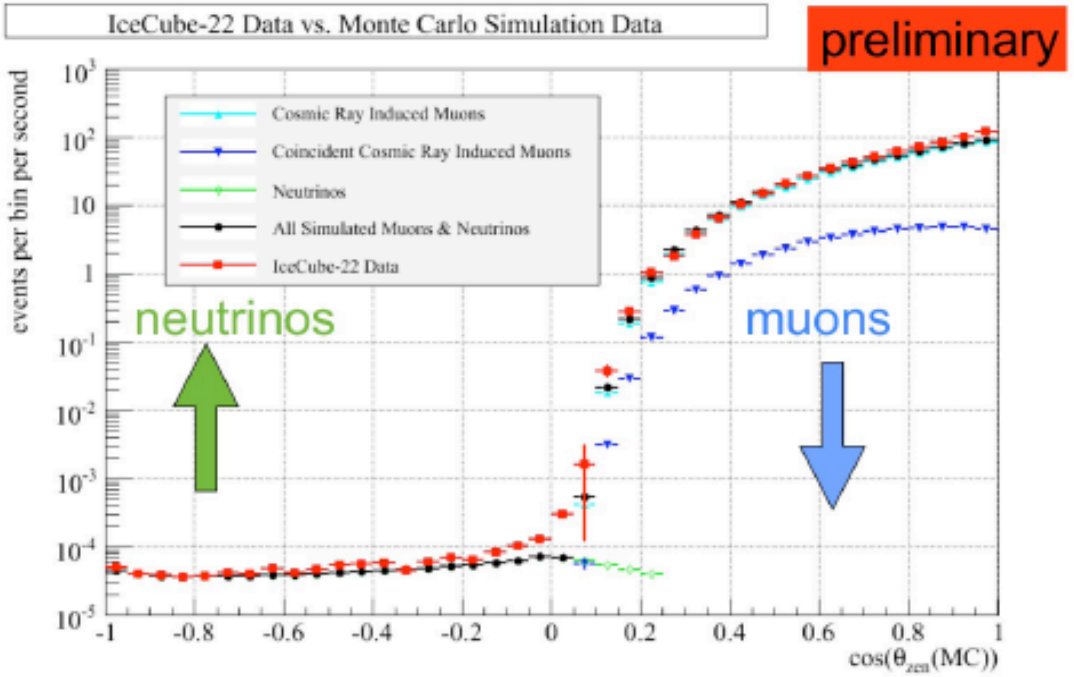


Strings	μ rate	ν rate
AMANDA	80 Hz	4.8 / day
IC22	550 Hz	28 / day
IC40*	1200 Hz	110 / day
IC80*	1650 Hz	220 / day

AMANDA: $O(10^9)$ events/yr
IceCube: $O(10^{10})$ events/yr

Step 1: Remove background of downgoing muons

Step 2: Isolate extraterrestrial events from "irreducible" background of atmospheric neutrinos



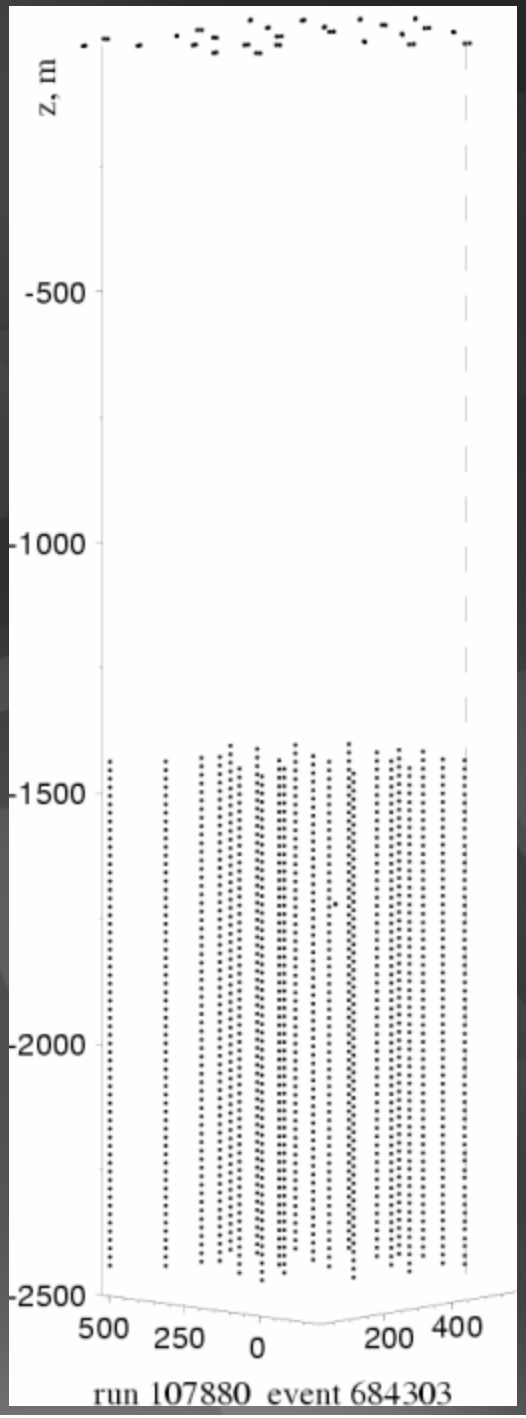
with 22 strings:

background:
downgoing cosmic ray muons

~ 550 per second

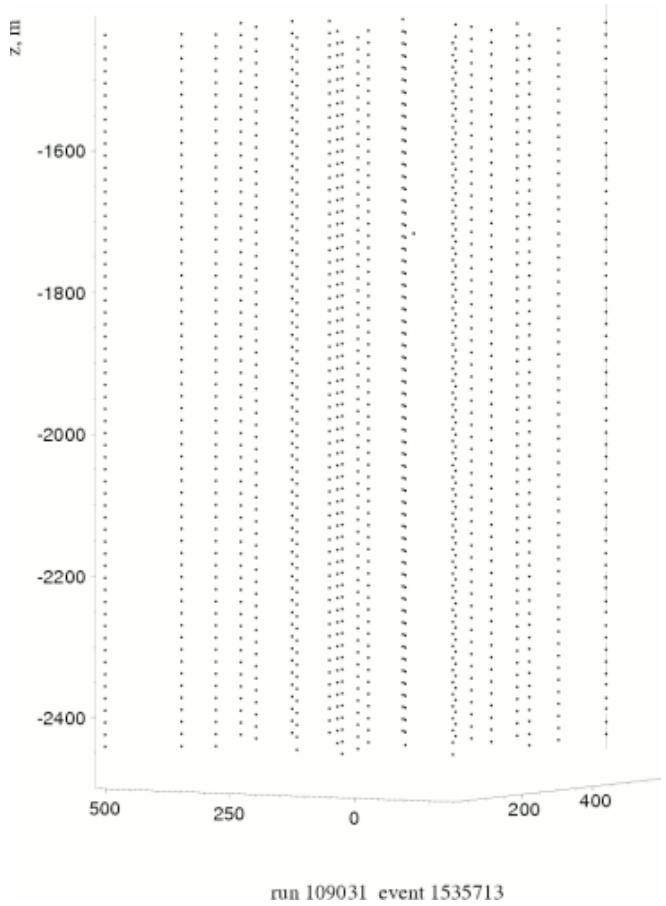
signal:
upgoing muons initiated by neutrinos

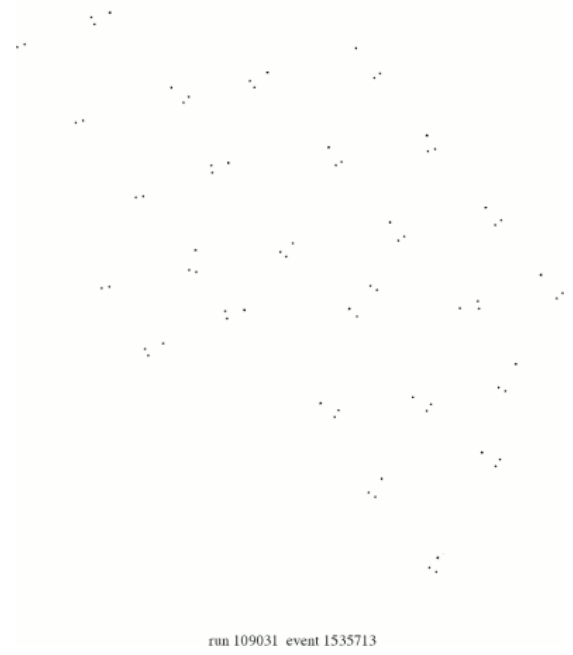
~ 1 per hour

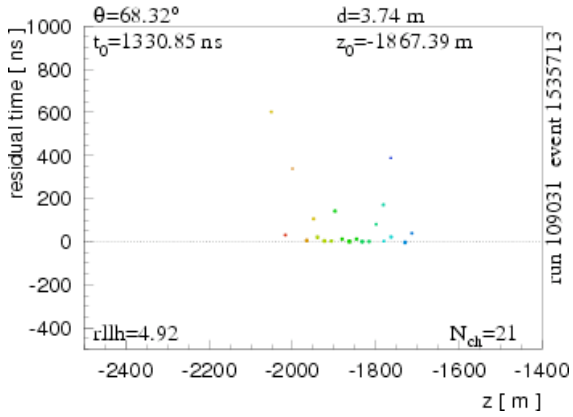


one in 10^6 muon tracks is produced by a neutrino

Neutrino event selection in IC22 and strategy for analyzing the neutrino energy spectrum

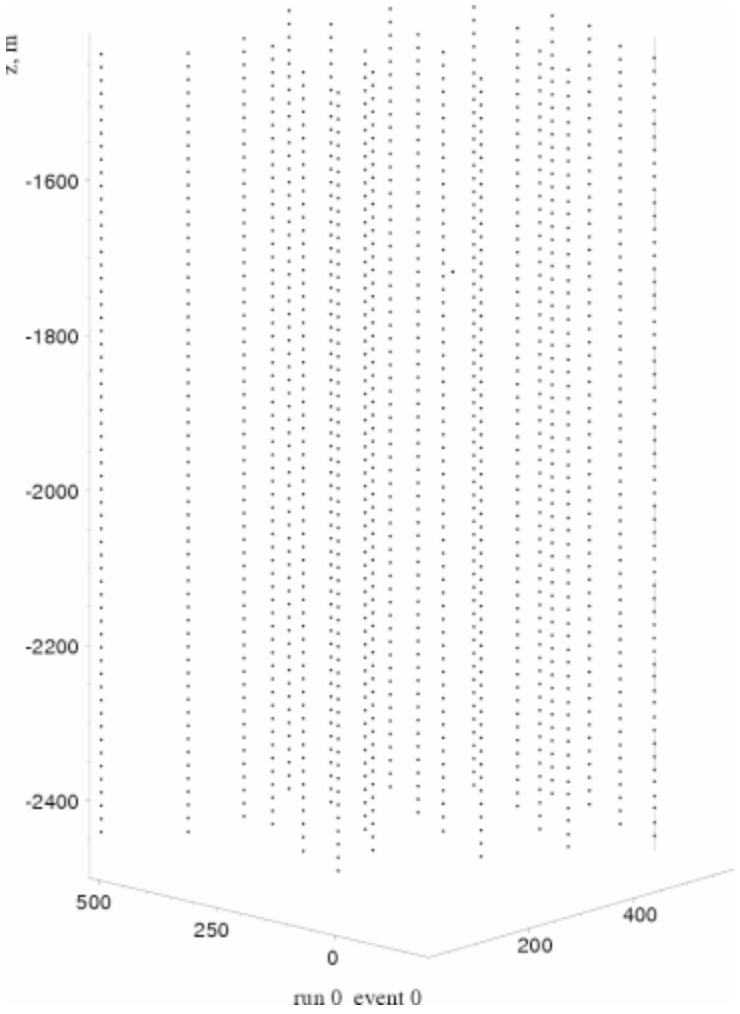






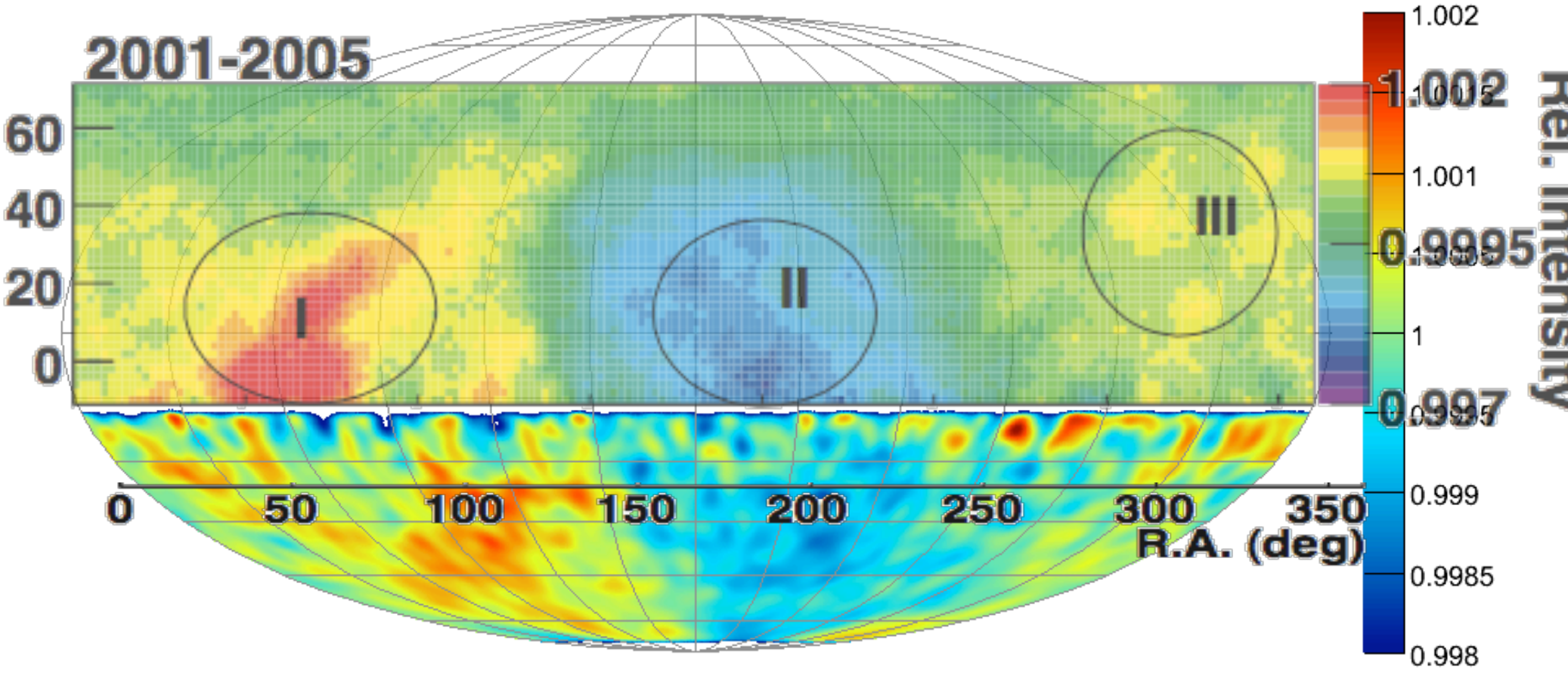
Dmitry Chirkin, *UW Madison*

October 27, 2008



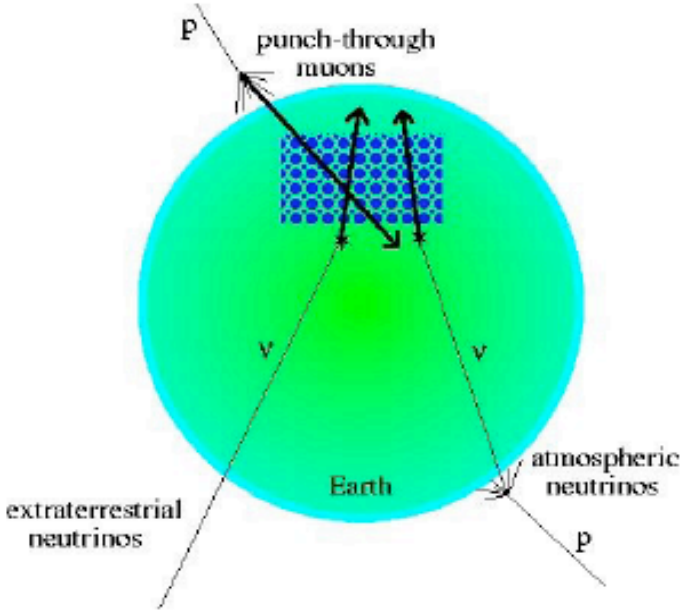
IceCube 22

first look at the Southern hemisphere: the muon sky is not isotropic



Tibet array: northern hemisphere

IceCube Events

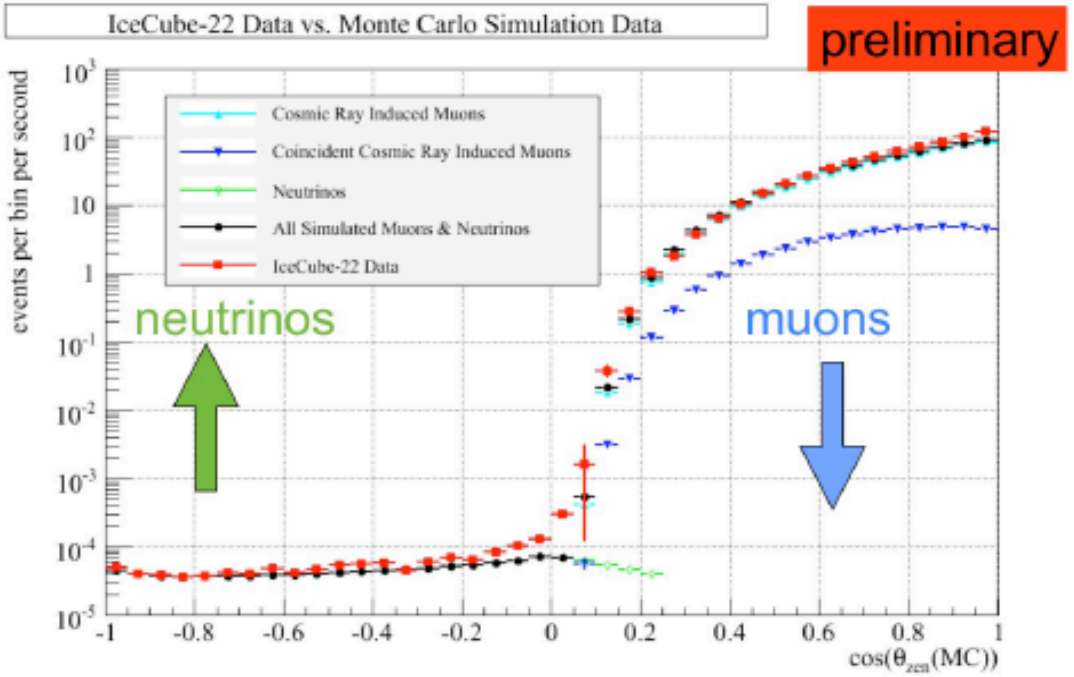


Strings	μ rate	ν rate
AMANDA	80 Hz	4.8 / day
IC22	550 Hz	28 / day
IC40*	1200 Hz	110 / day
IC80*	1650 Hz	220 / day

AMANDA: $O(10^9)$ events/yr
IceCube: $O(10^{10})$ events/yr

Step 1: Remove background of downgoing muons

Step 2: Isolate extraterrestrial events from "irreducible" background of atmospheric neutrinos



IceCube (1/2) turns the corner at the horizon