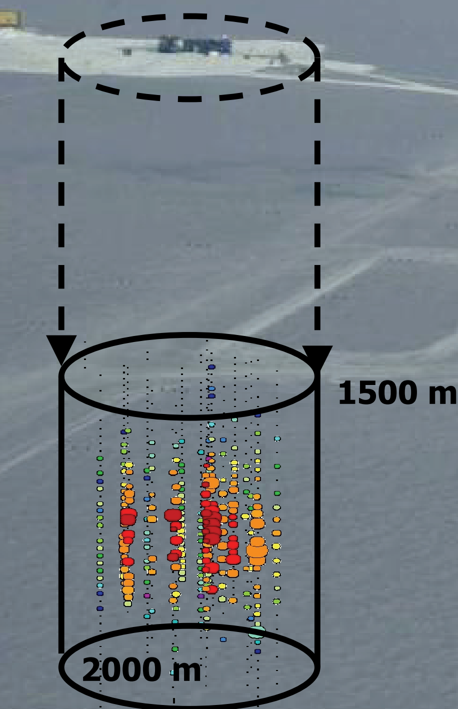
Status of IceCube and Results from AMANDA

http://amanda.uci.edu

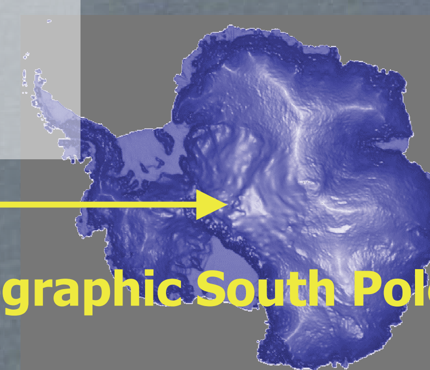
http://icecube.wisc.edu



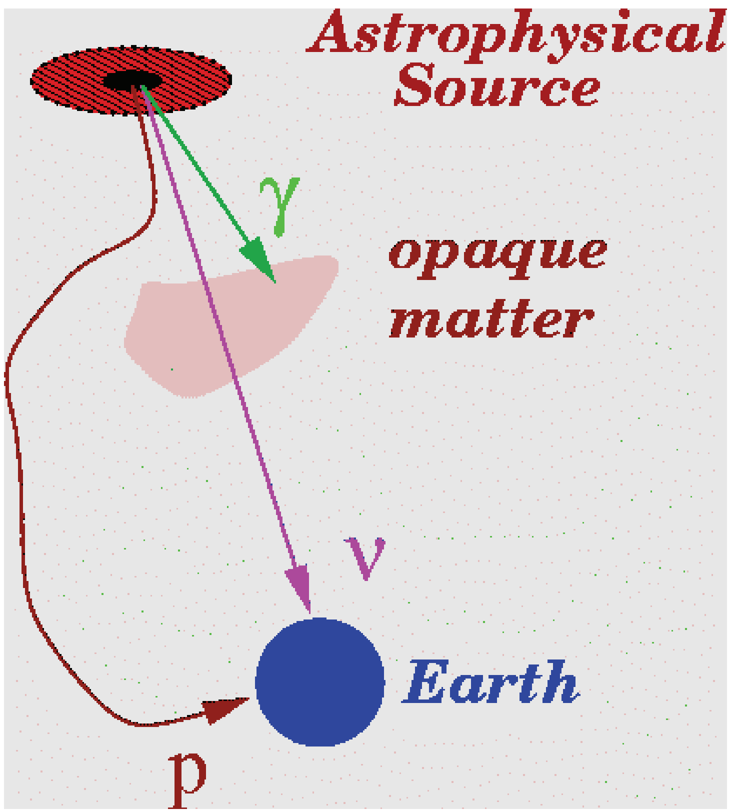
Christopher Wiebusch
Bergische Universität Wuppertal

From Colliders to Cosmic Rays

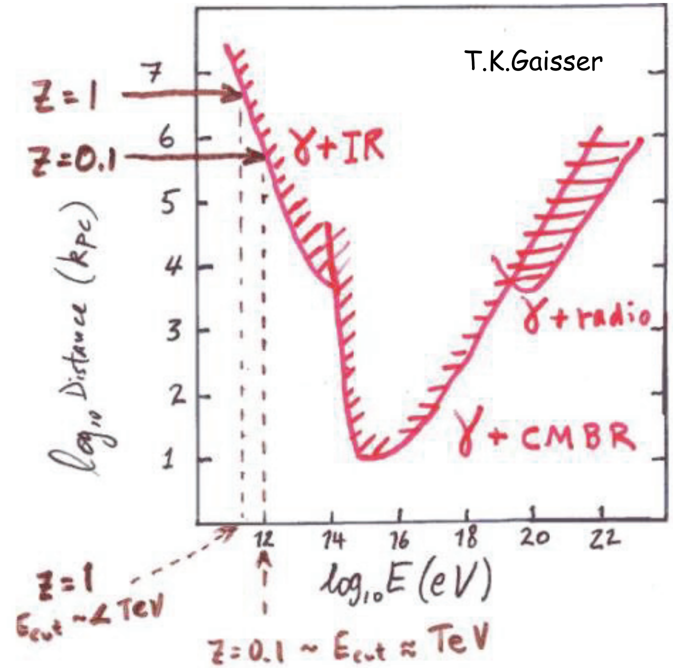
Prague, 11.September 2005

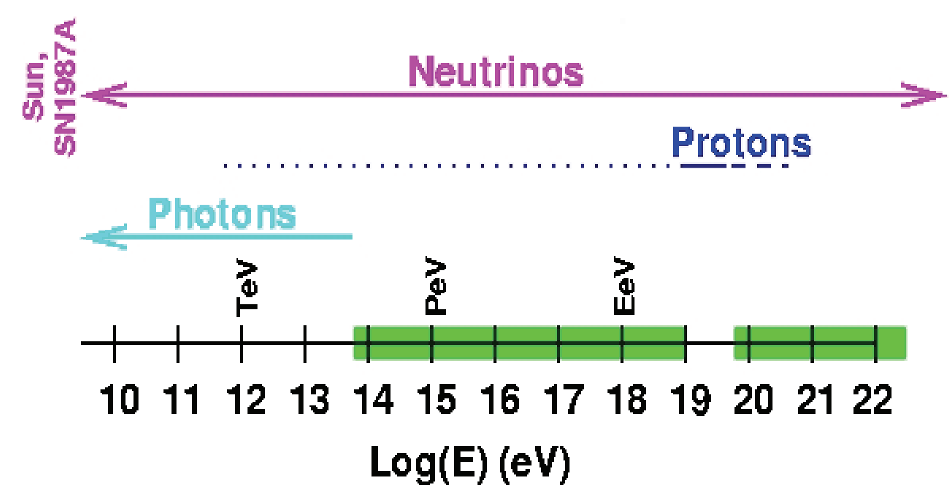


High Energy Neutrino Astronomy



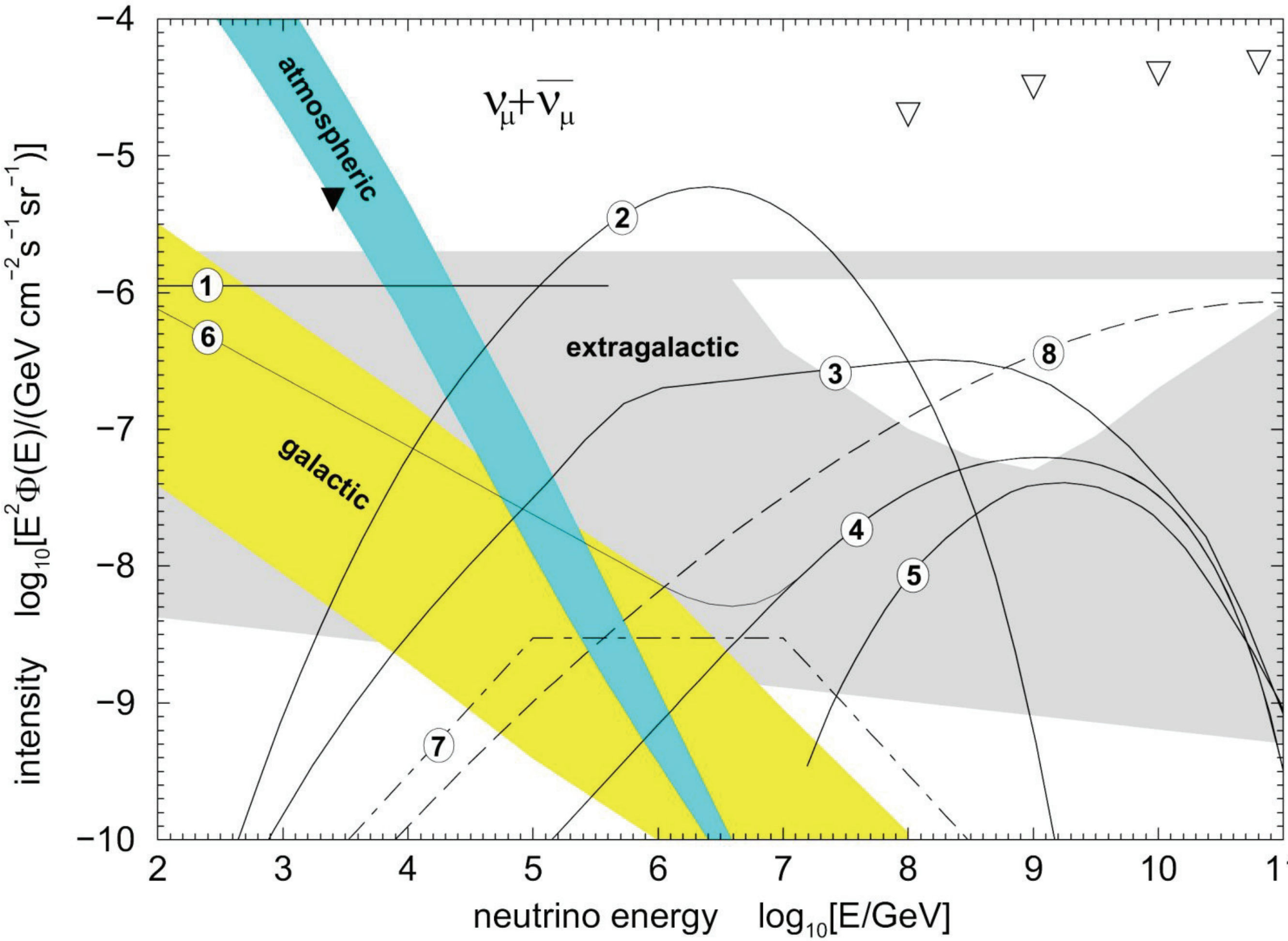
Transmission of the universe for γ





ν_e	:	ν_μ	:	ν_τ	
1	:	2	:	0	(generic)
1	:	1	:	1	(oscillations)

Diffuse Fluxes: Predictions and Limits



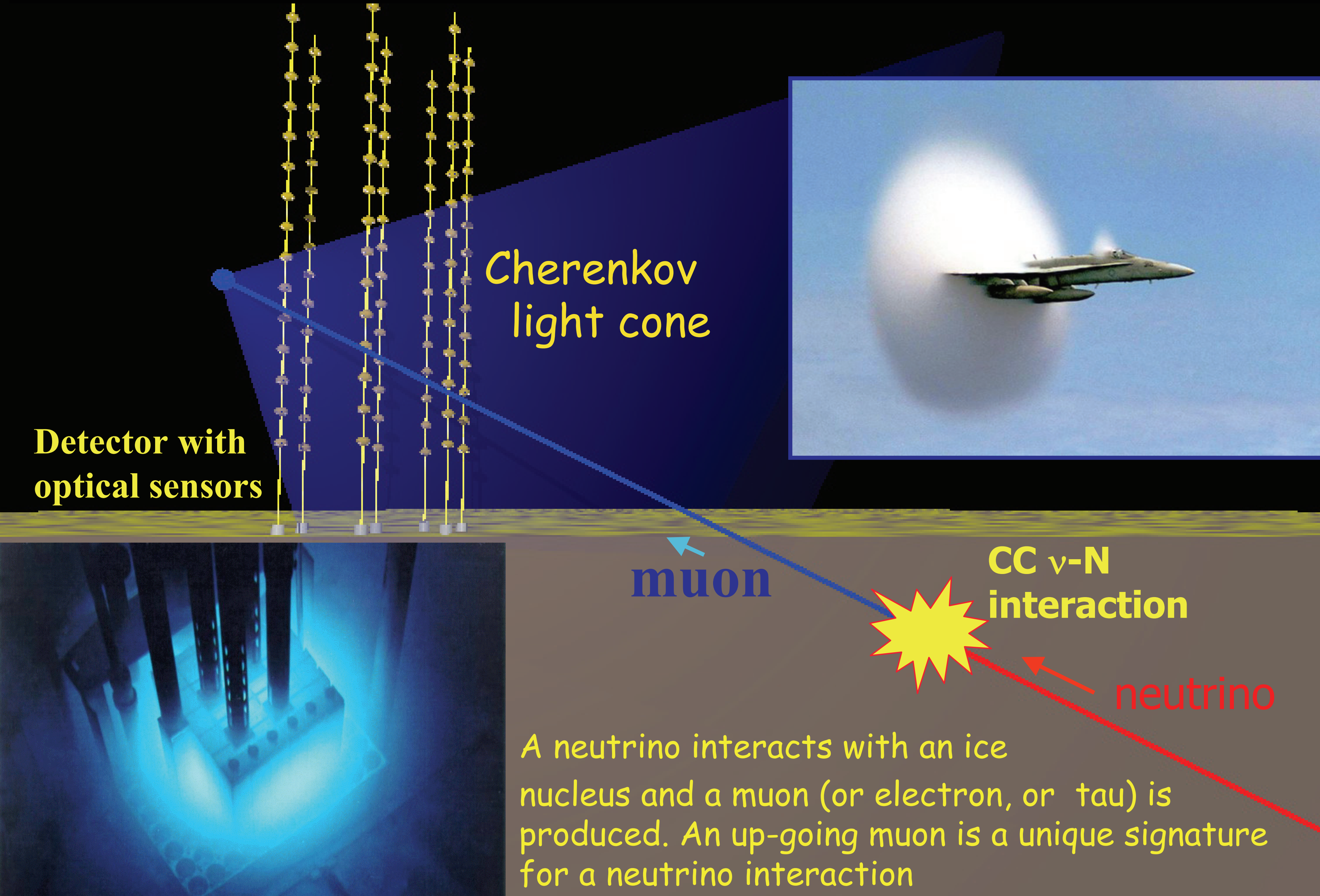
1 pp core AGN (Nellen)
2 pγ core AGN
Stecker & Salomon)
3 pγ „maximum model“
(Mannheim et al.)
4 pγ blazar jets (Mannh)
5 pγ AGN
(Rachen & Biermann)
6 pp AGN (Mannheim)
7 GRB
(Waxman & Bahcall)
8 TD (Sigl)

▼ Frejus
▽ Fly‘s Eye

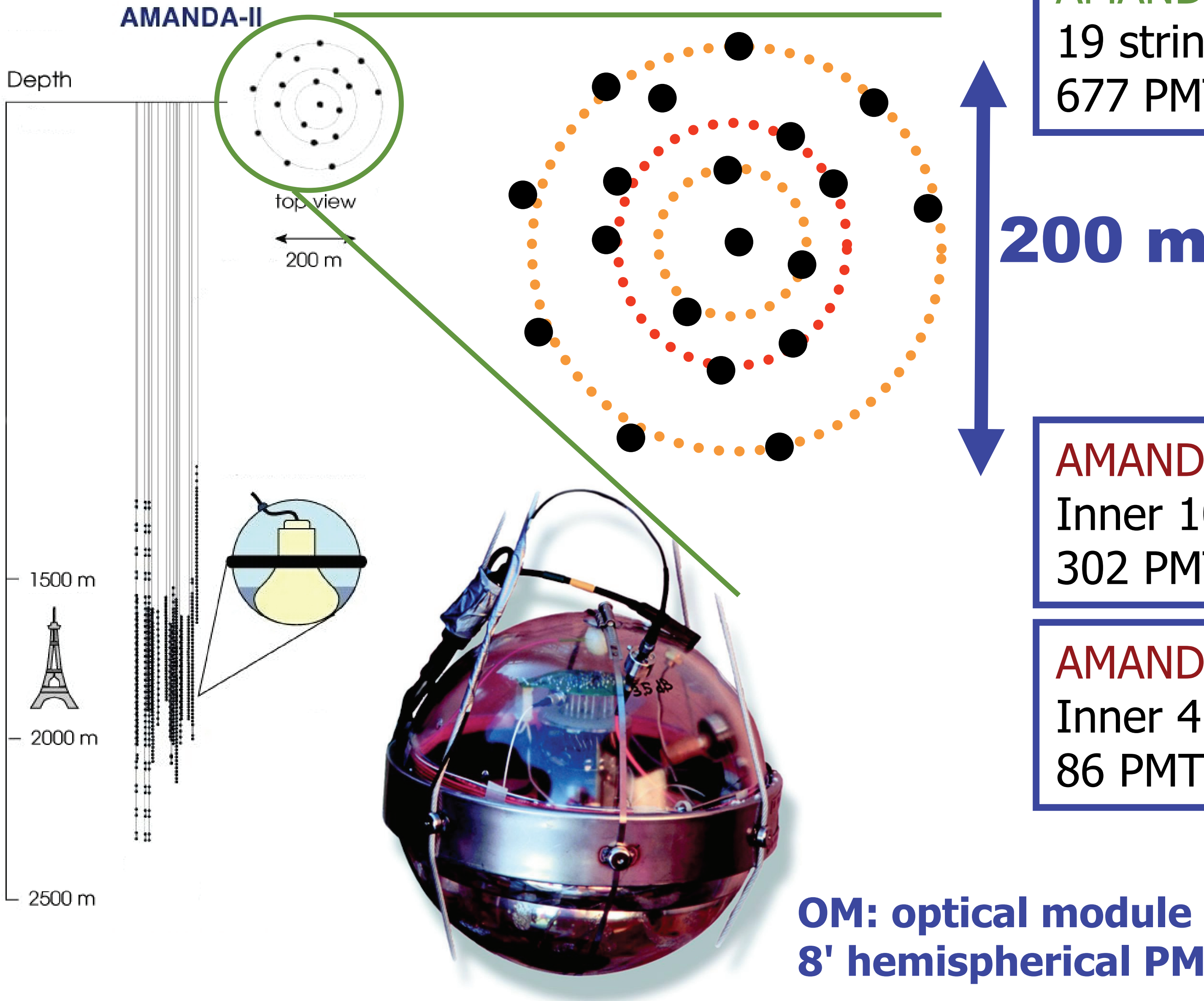
Mannheim & Learned, 2000

Neutrino Detection

requires large target mass and shielding against other cosmic rays



The AMANDA Neutrino Telescope



AMANDA-II, since 2000
19 strings
677 PMTs (8')

AMANDA-B10 1997-1999
Inner 10 strings
302 PMTs (8')

AMANDA-B4 1996
Inner 4 strings
86 PMTs (8')

OM: optical module with an 8' hemispherical PMT

AMANDA Event Signatures: "Tracks"

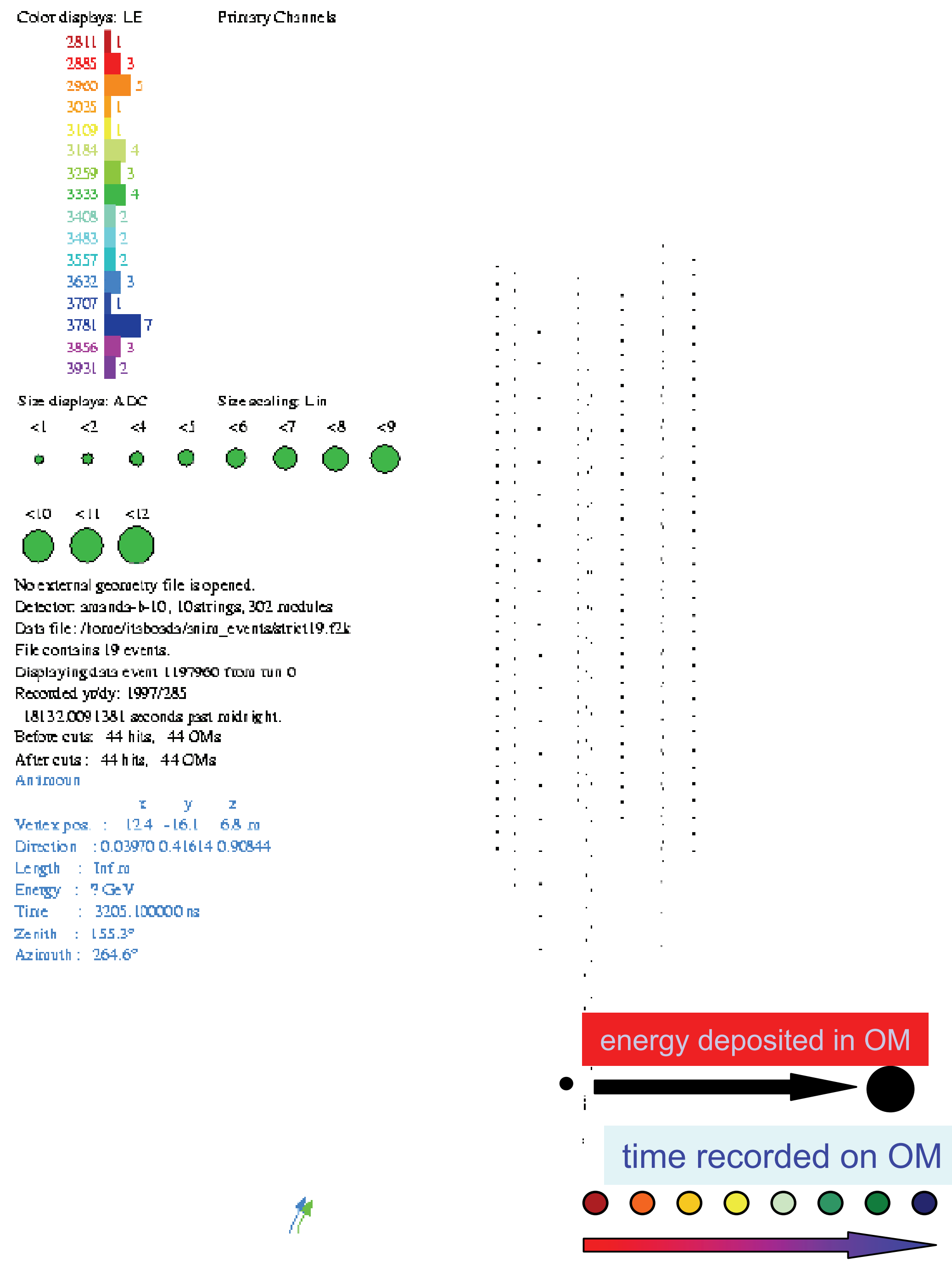
CC ν_μ interactions

$\rightarrow$ Muon tracks

$$\boxed{\nu_\mu + N \rightarrow \mu + X}$$

Largest effective Volume

$\rightarrow$ "discovery channel"



Proposed by Markov 1960

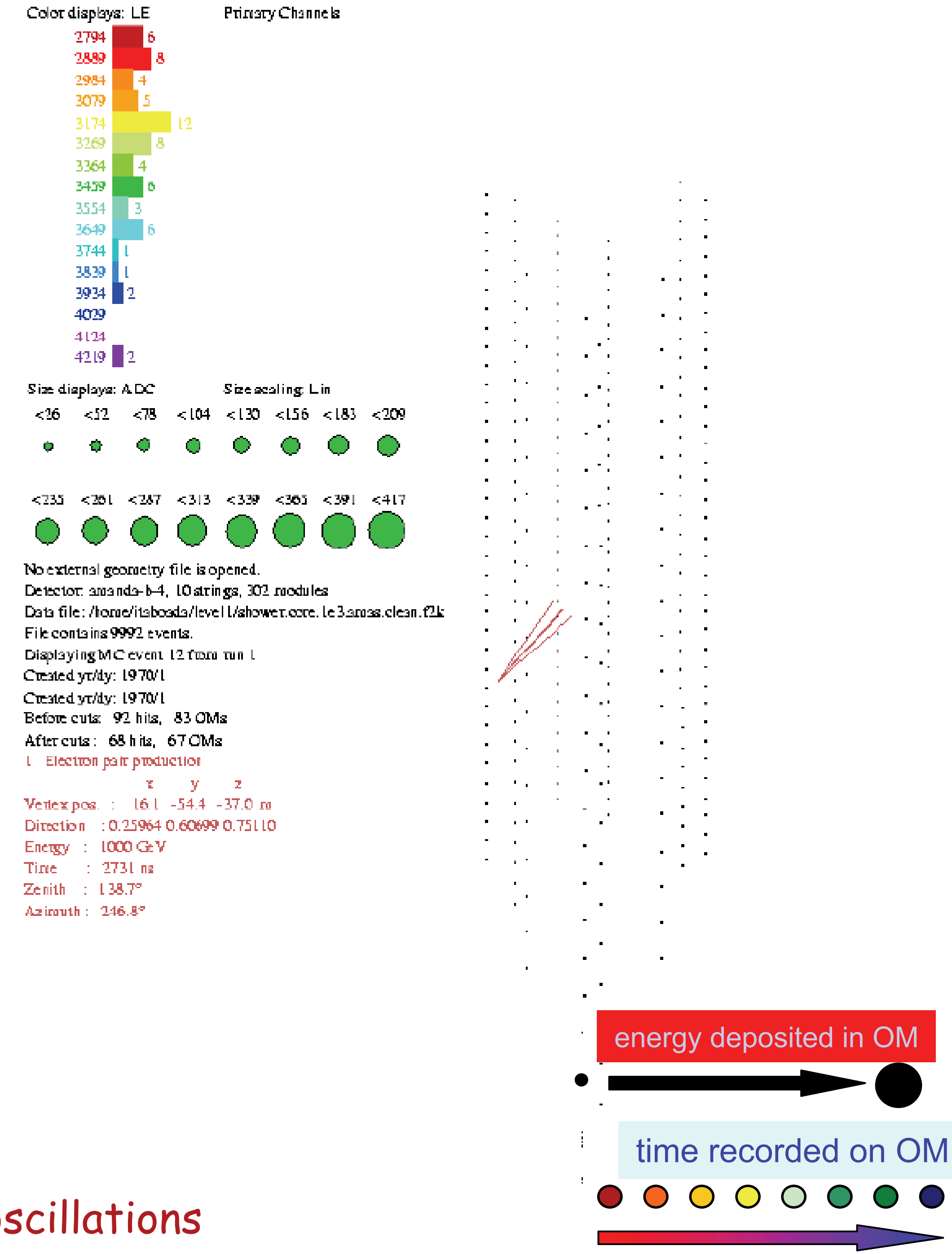
AMANDA Event Signatures: “Cascades”

CC ν_e and ν_τ interactions:

$$\nu_{e,\tau} + N \rightarrow (e,\tau) + X$$

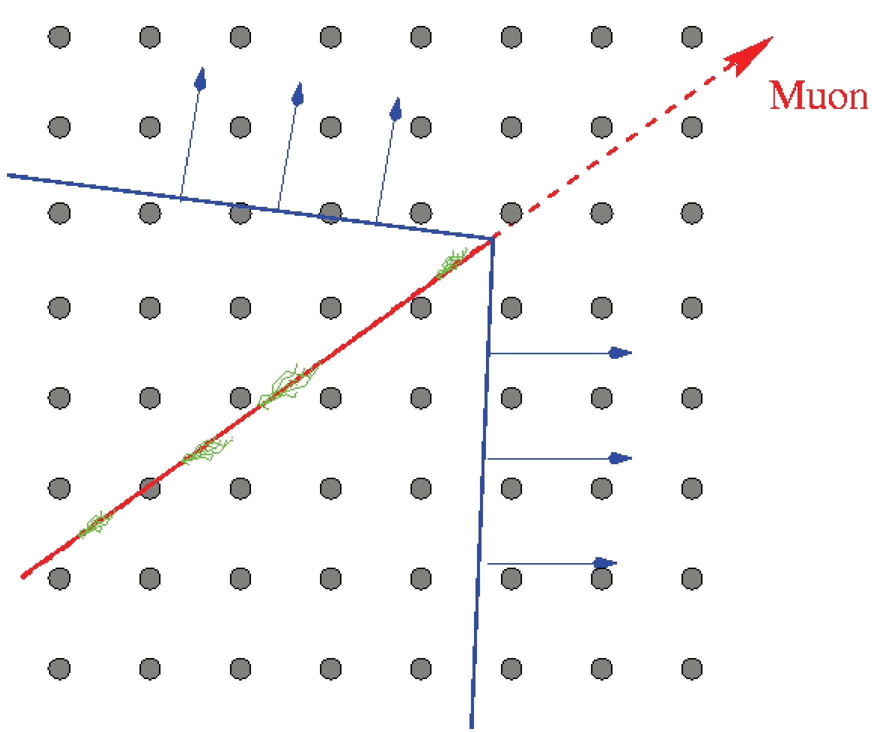
NC ν_x (all flavors) interactions:

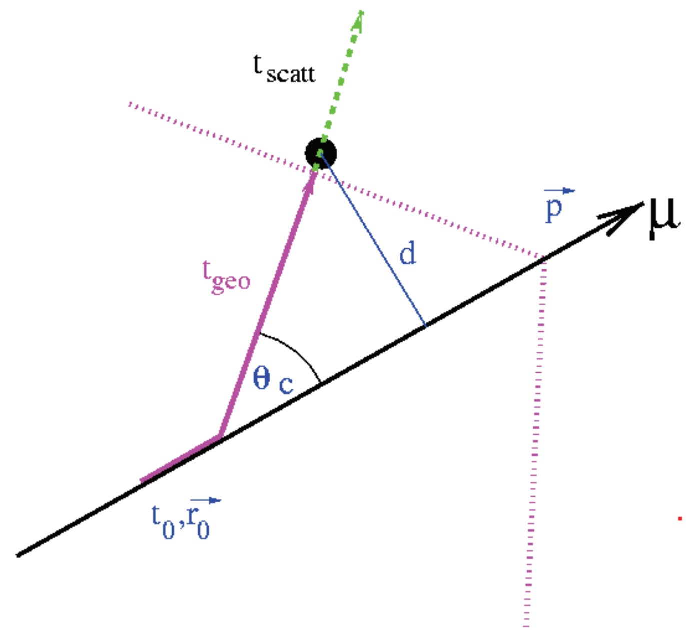
$$\nu_x + N \rightarrow \nu_x + X$$

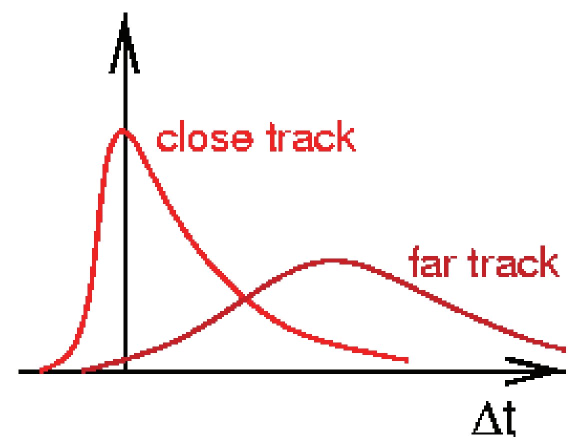


- Smaller effective volume
- Poorer angular resolution
- Better energy measurement
- Less atmospheric background
- Larger angular acceptance
- Larger signal due to neutrino oscillations

Maximum Likelihood Reconstruction



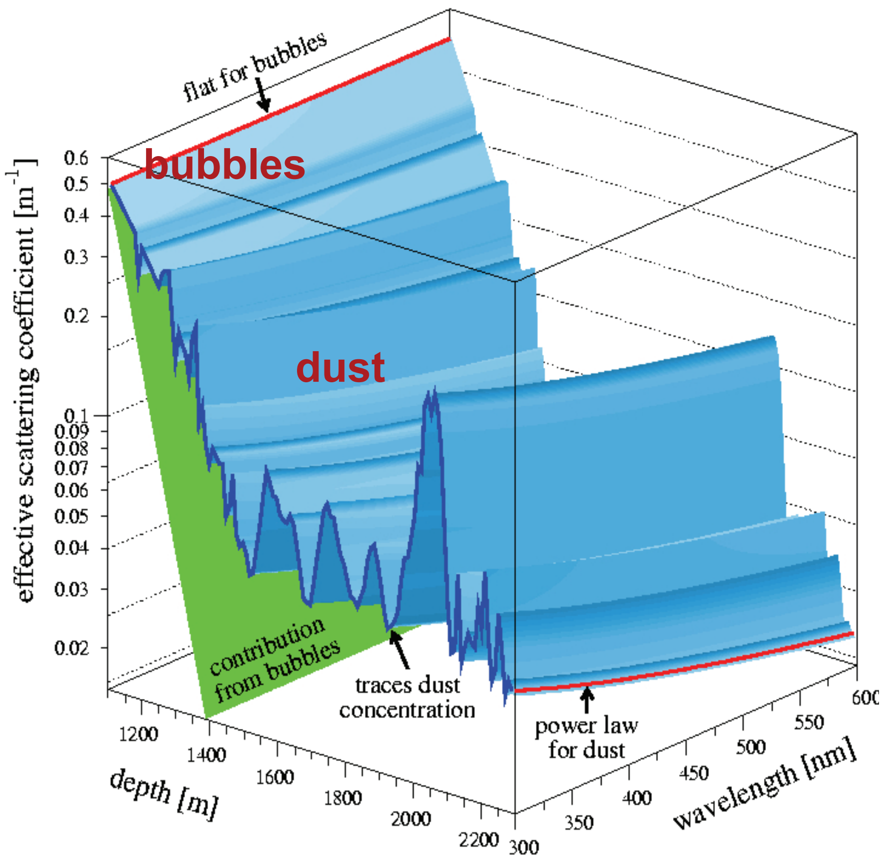


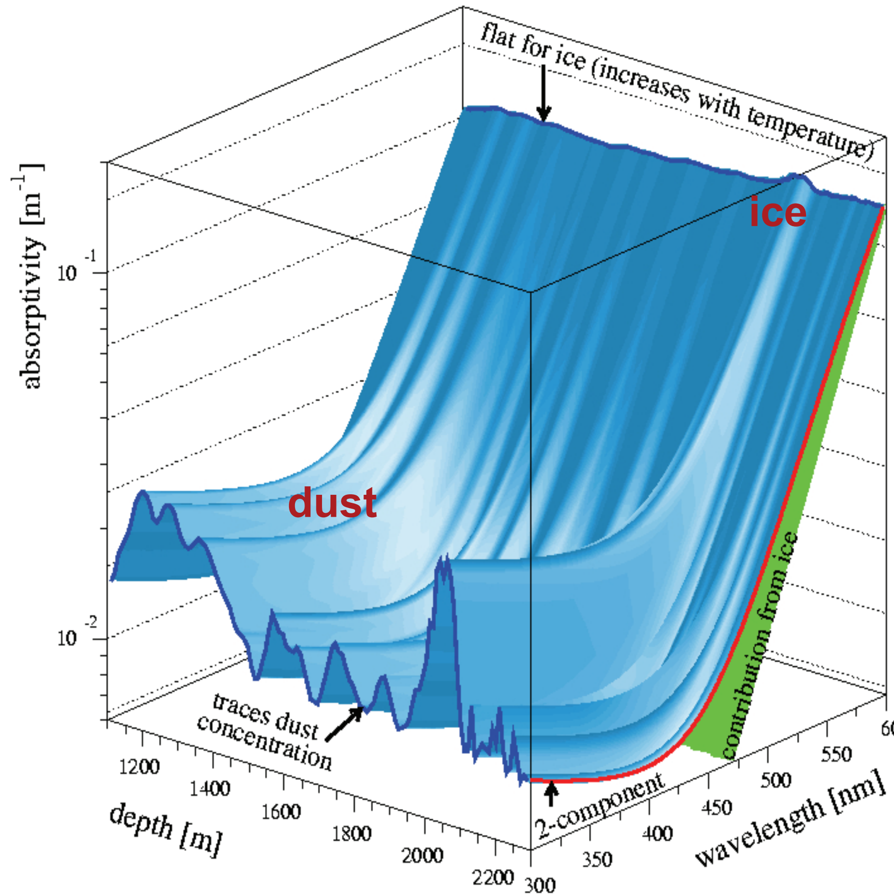


Variation of track parameters until the spectrum of arrival times has highest Likelihood.
Scattering results in a distance dependent time-delay relative to the Cherenkov cone.

Nucl. Instr.Meth. A 524 (2004) 169-194 (astro-ph/0407044)

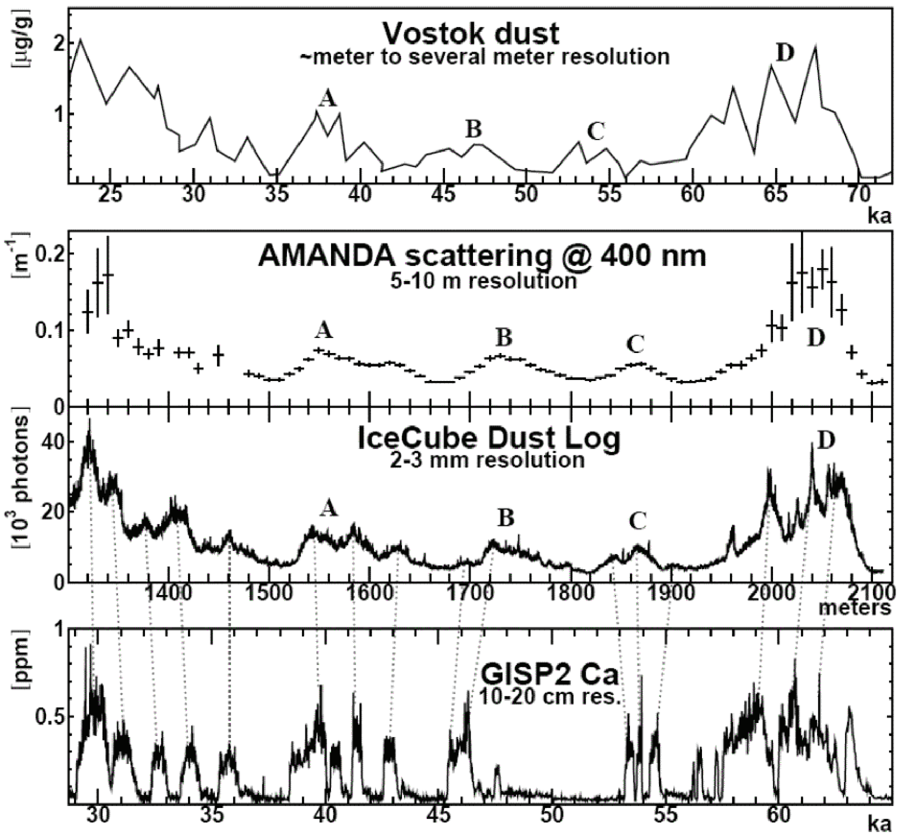
Optical Properties, Scattering & Absorption

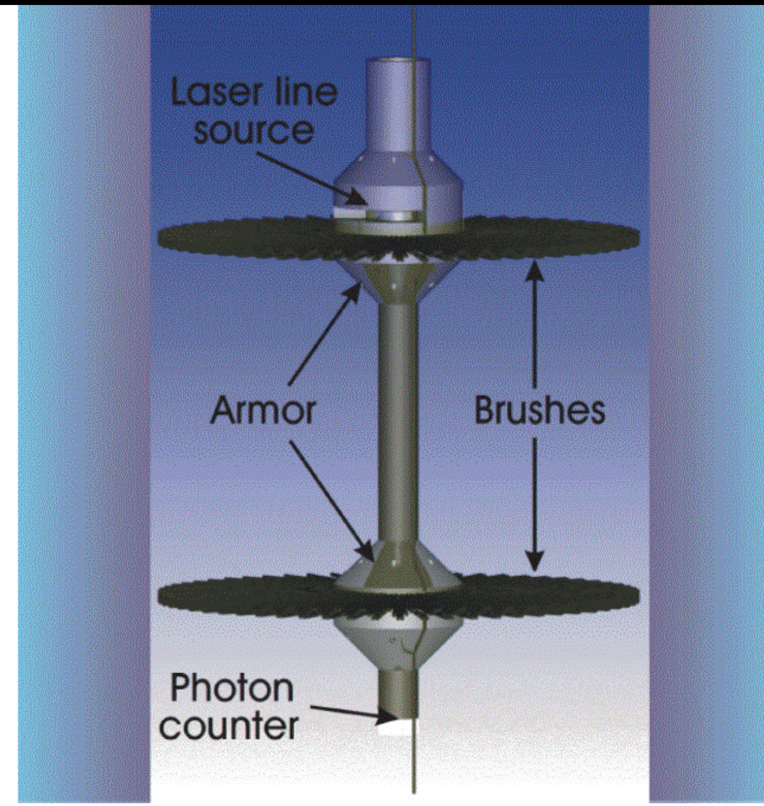


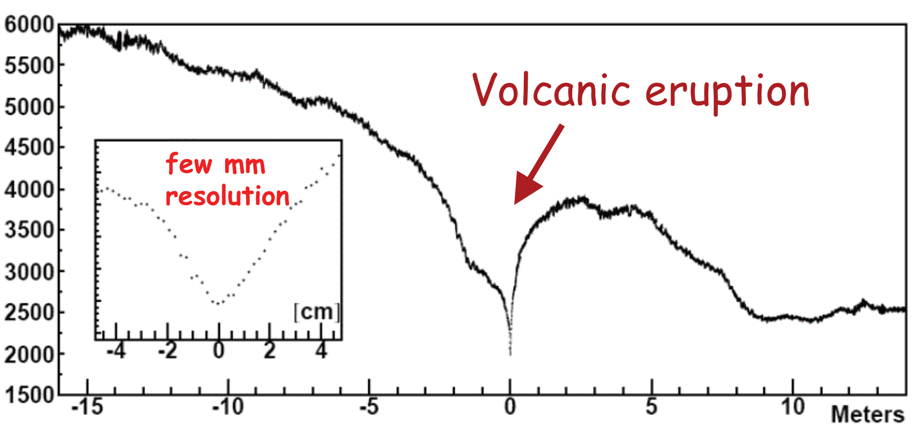


Average optical parameters of AMANDA Ice (400 nm): λ_{abs}~110 m λ_{sca}~25 m

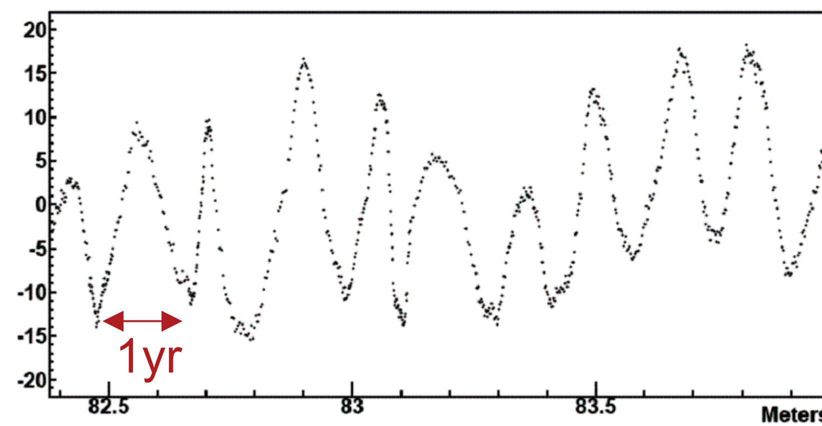
Dust logger (deployed Jan 2005)



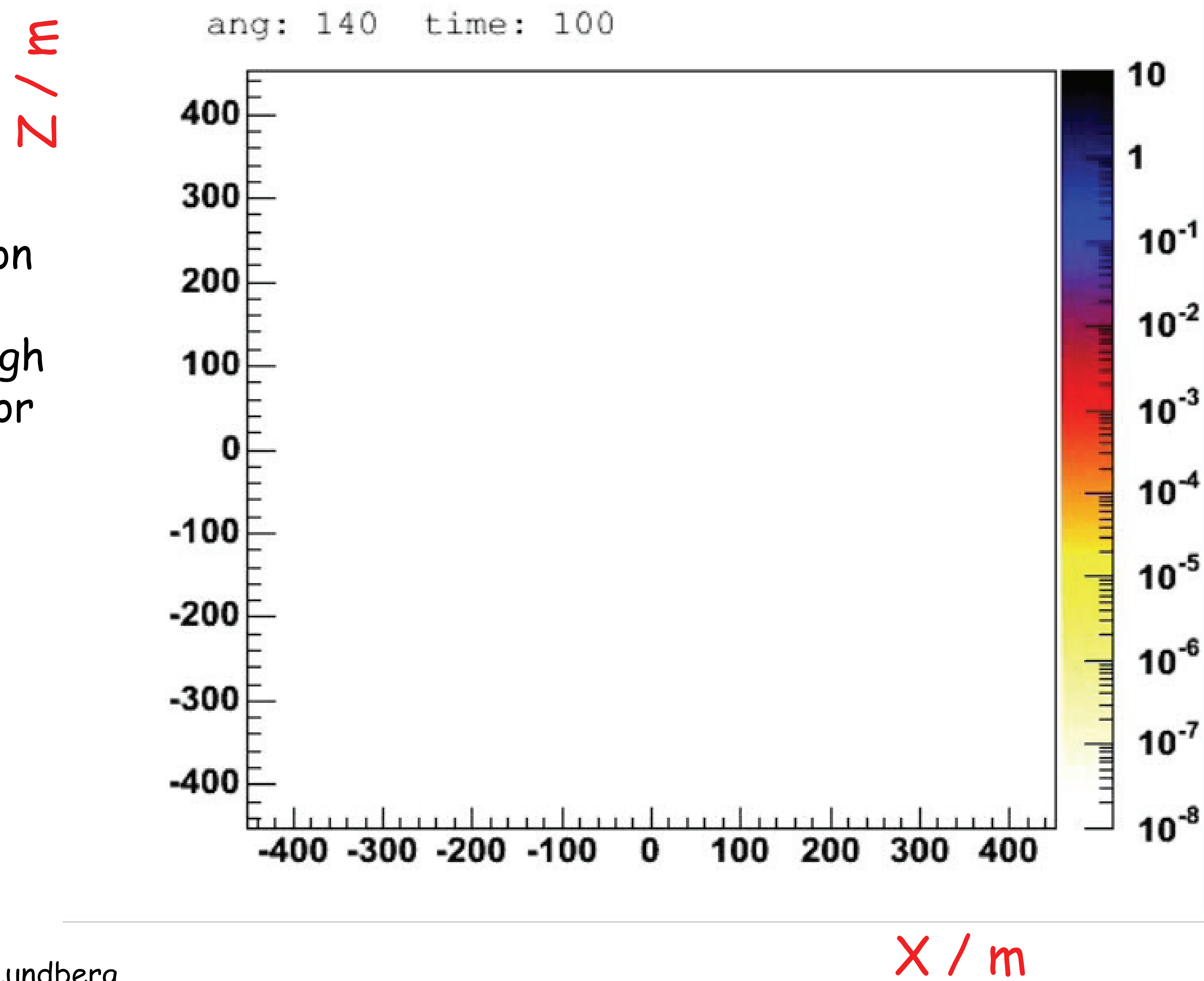




Seasonal variations of the bubble density



Propagation of Cherenkov photons through layered ice



Simulation of the propagation of Cherenkov photons through Amanda Ice for an up-going muon

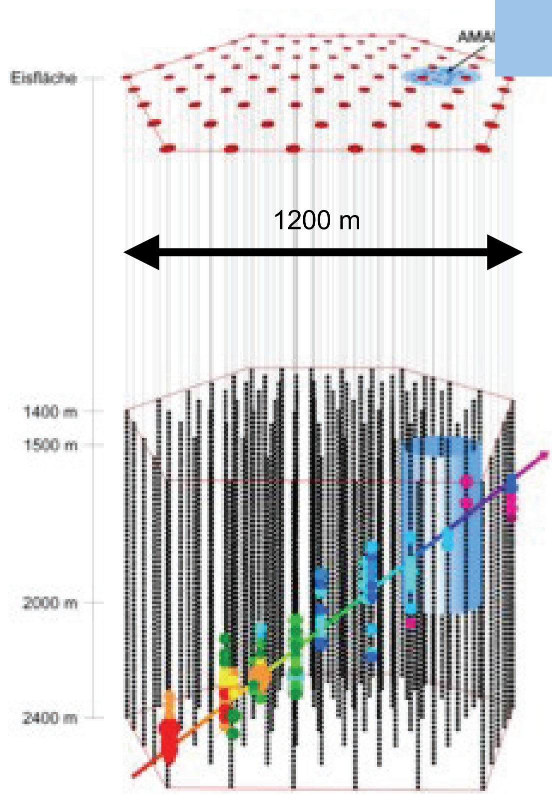
Animation by Johan Lundberg

The IceCube Neutrino Telescope

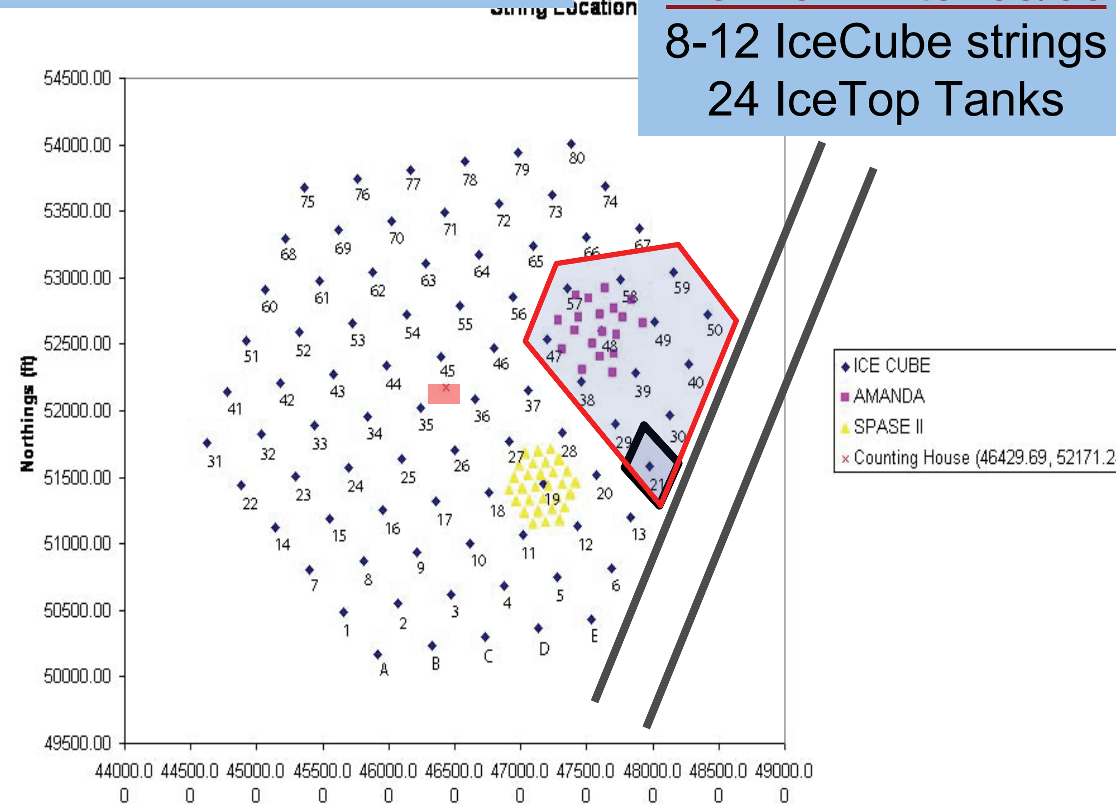
IceCube (InIce)
80 strings
60 OMs/string
17 m vertical spacing
125 m between strings

IceTop
160 tanks
frozen-water tanks
2 OMs / tank

First year deployment (Jan 2005)
1 IceCube string (60 OMs) at 2450 m
8 IceTop Tanks (16 OMs)



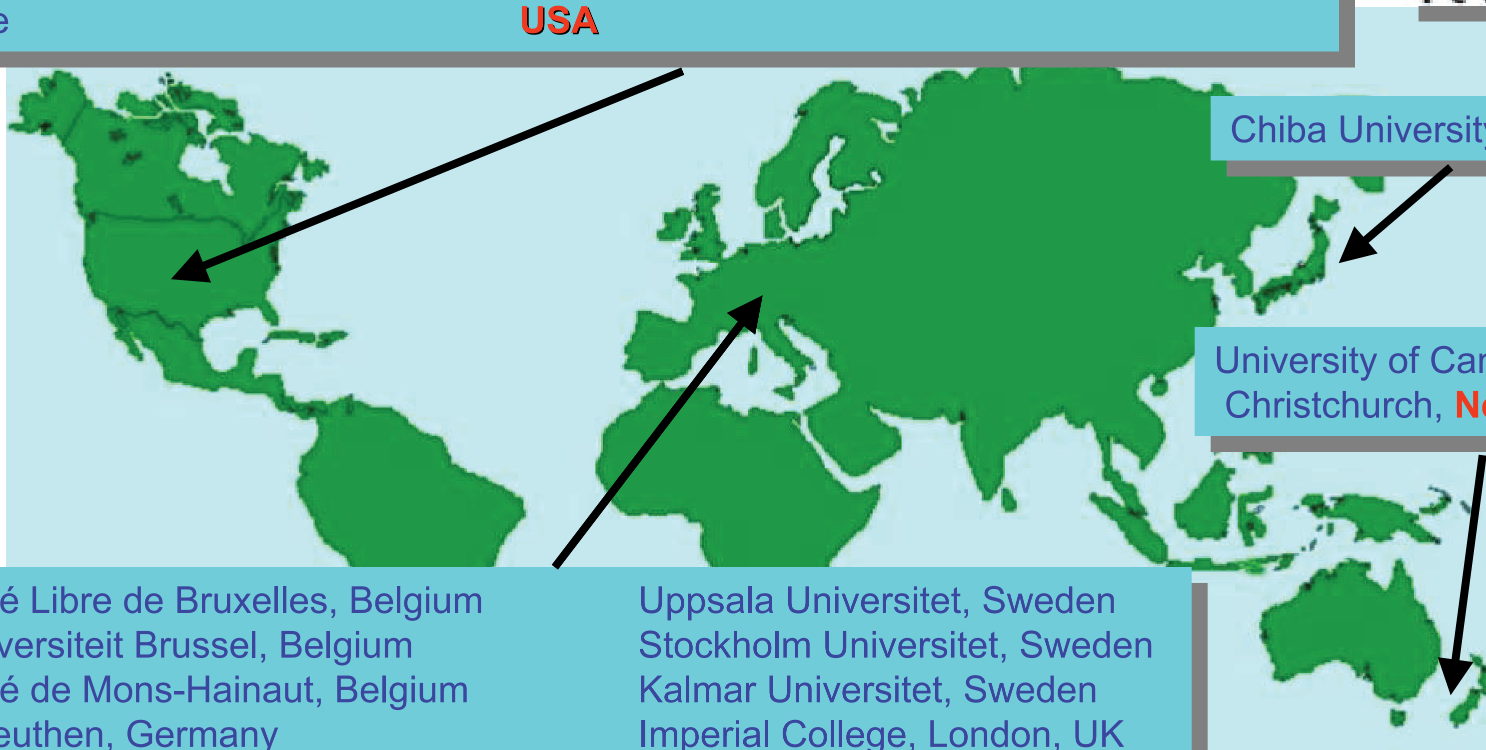
Plan for winter 05/06
8-12 IceCube strings
24 IceTop Tanks



The IceCube Collaboration

Bartol Research Inst, Univ of Delaware
Pennsylvania State University
University of Wisconsin-Madison
University of Wisconsin-River Falls
LBNL, Berkeley
UC Berkeley
UC Irvine

Univ. of Alabama
Clark-Atlanta University
Univ. of Maryland
IAS, Princeton
University of Kansas
Southern Univ. and A&M College, Baton Rouge
USA



Chiba University, **Japan**

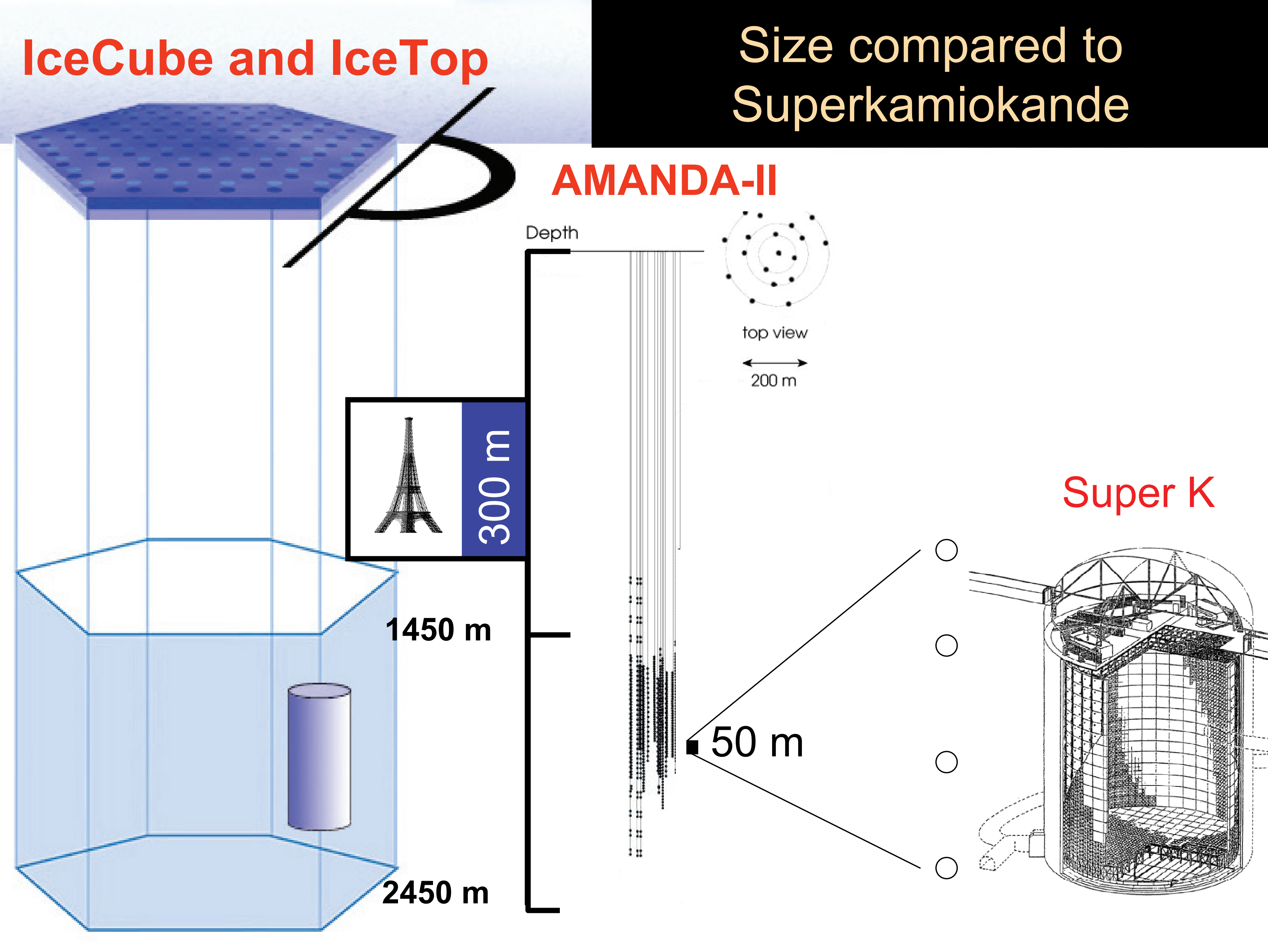
University of Canterbury, Christchurch, **New Zealand**

Université Libre de Bruxelles, Belgium
Vrije Universiteit Brussel, Belgium
Université de Mons-Hainaut, Belgium
DESY-Zeuthen, Germany
Universität Dortmund, Germany
Gutenberg Universität Mainz, Germany
Bergische Universität Wuppertal, Germany
Humboldt Universität zu Berlin, Germany

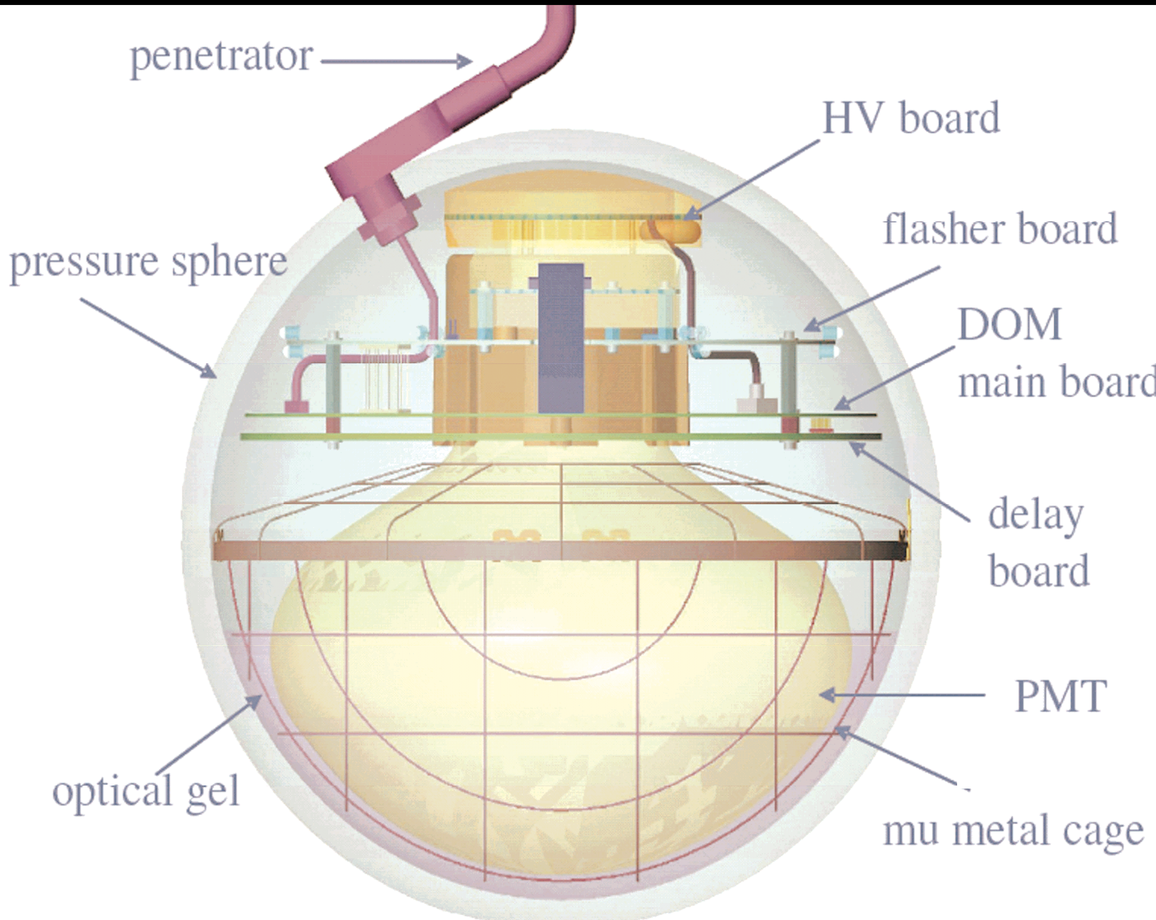
Uppsala Universitet, Sweden
Stockholm Universitet, Sweden
Kalmar Universitet, Sweden
Imperial College, London, UK
University of Oxford, UK
Utrecht University, Utrecht, NL
Europe

http://icecube.wisc.edu

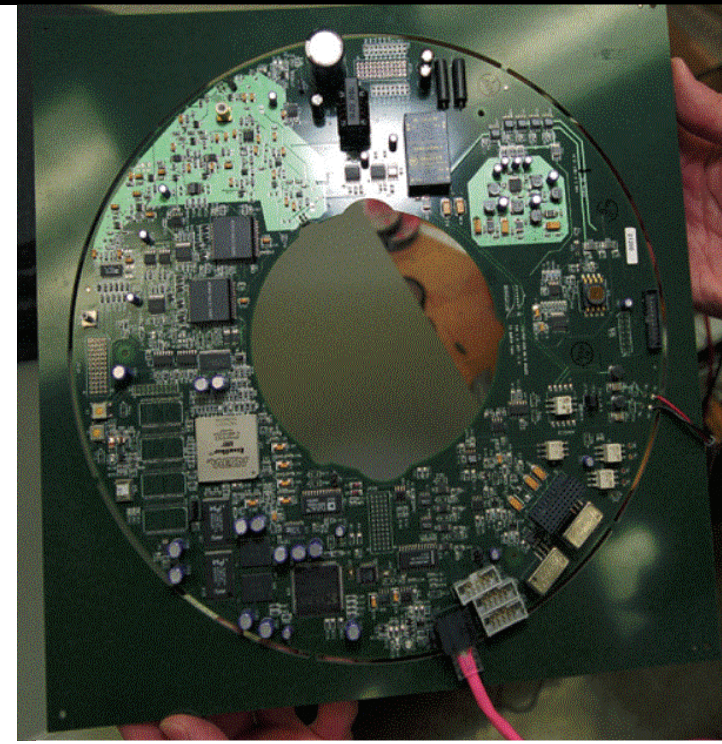
Size compared to Superkamiokande

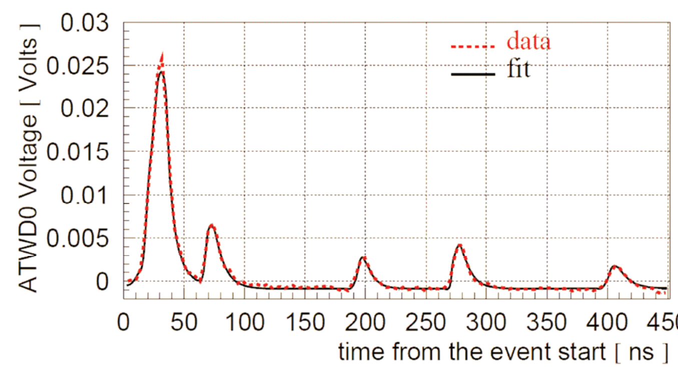


Digital Optical Module for IceCube



10" Hamamatsu R-7081



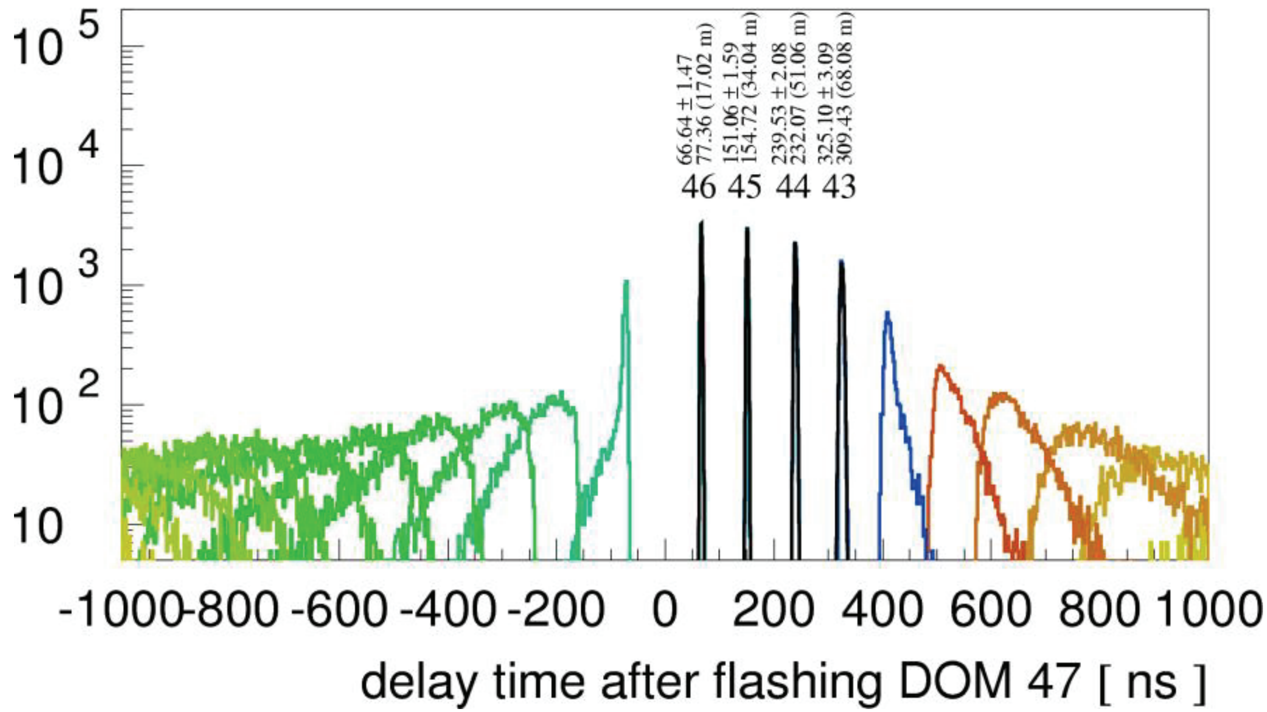


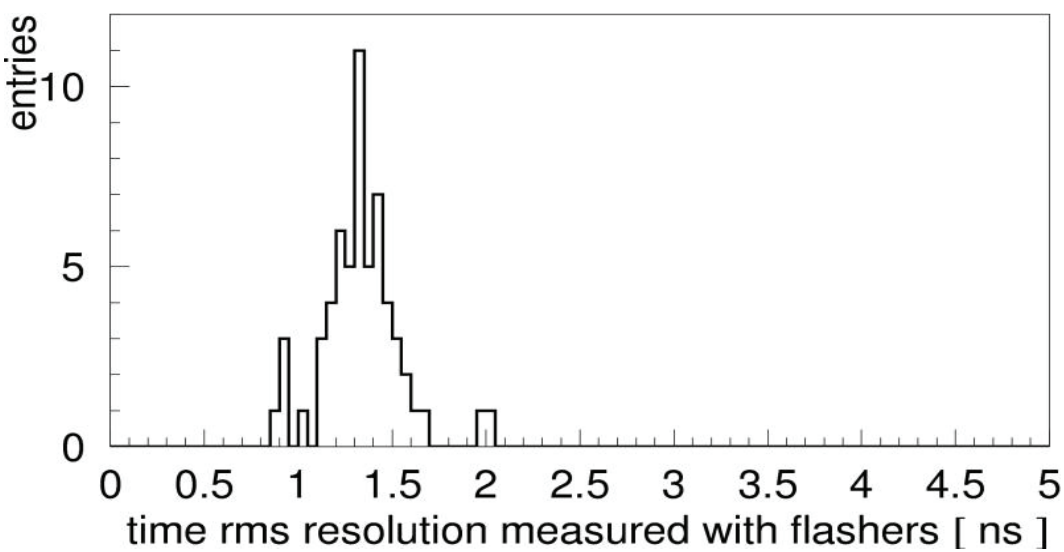
Full digitization of the PMT signals (300 MHz)

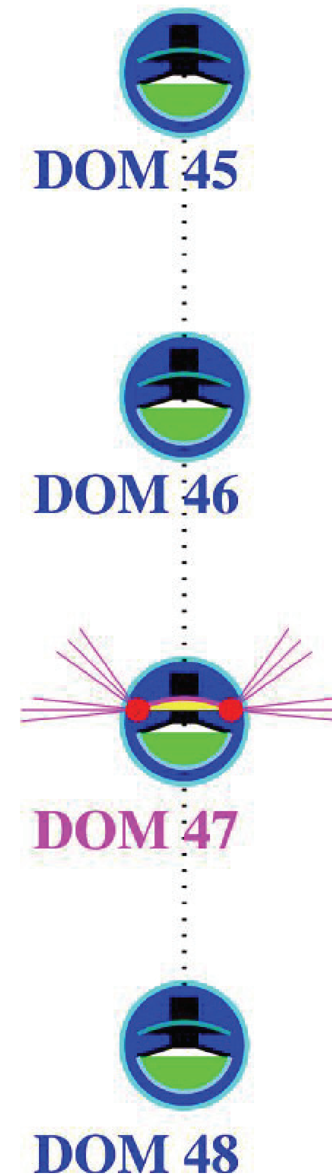
- Dead Time: < 1% dead time
- Dynamic range ~200 p.e./15 ns
- Synchronization with the Surface: < 3ns

Experience with the digital string 18 in AMANDA (submitted to NIM A)

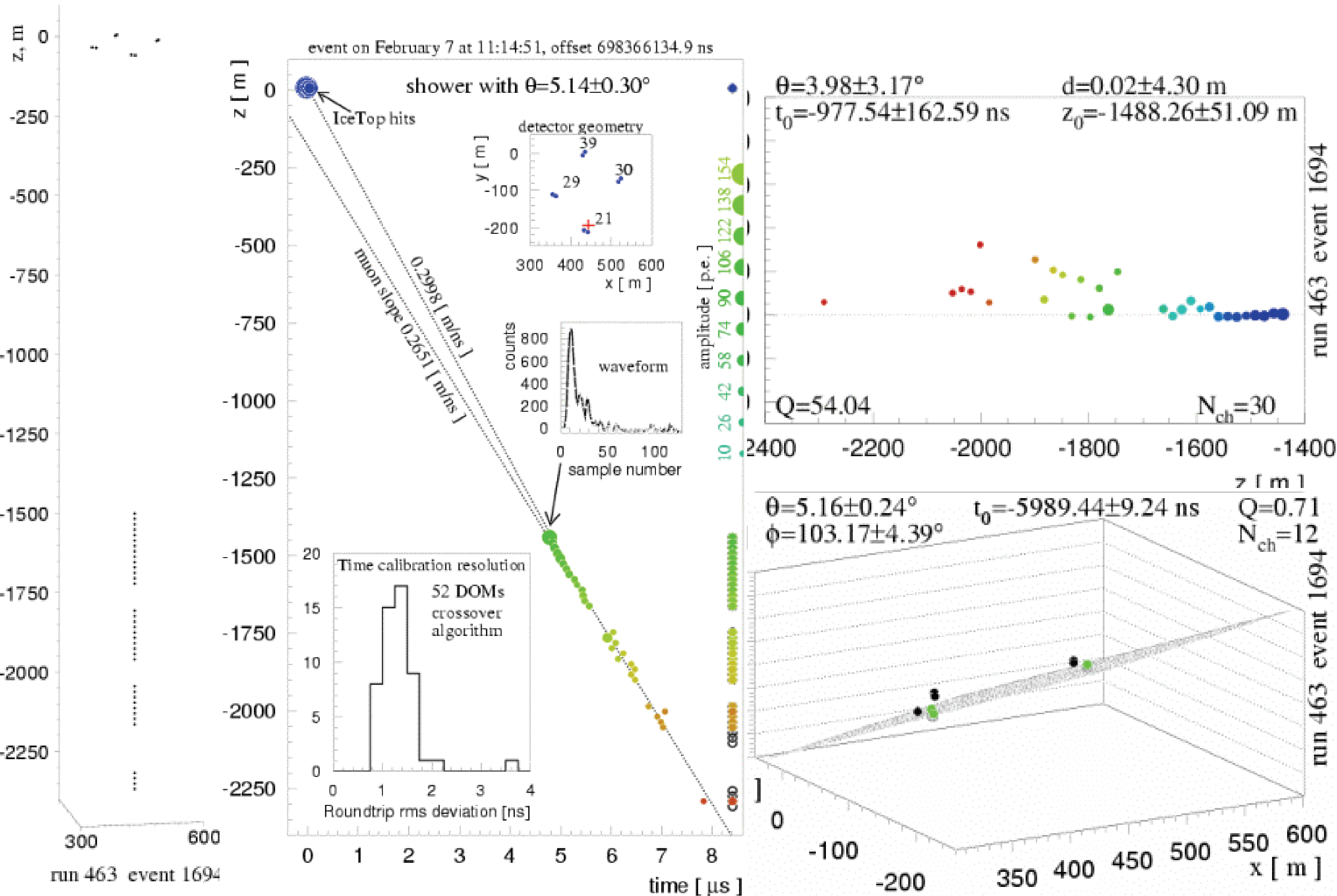
Timing verification with flashers



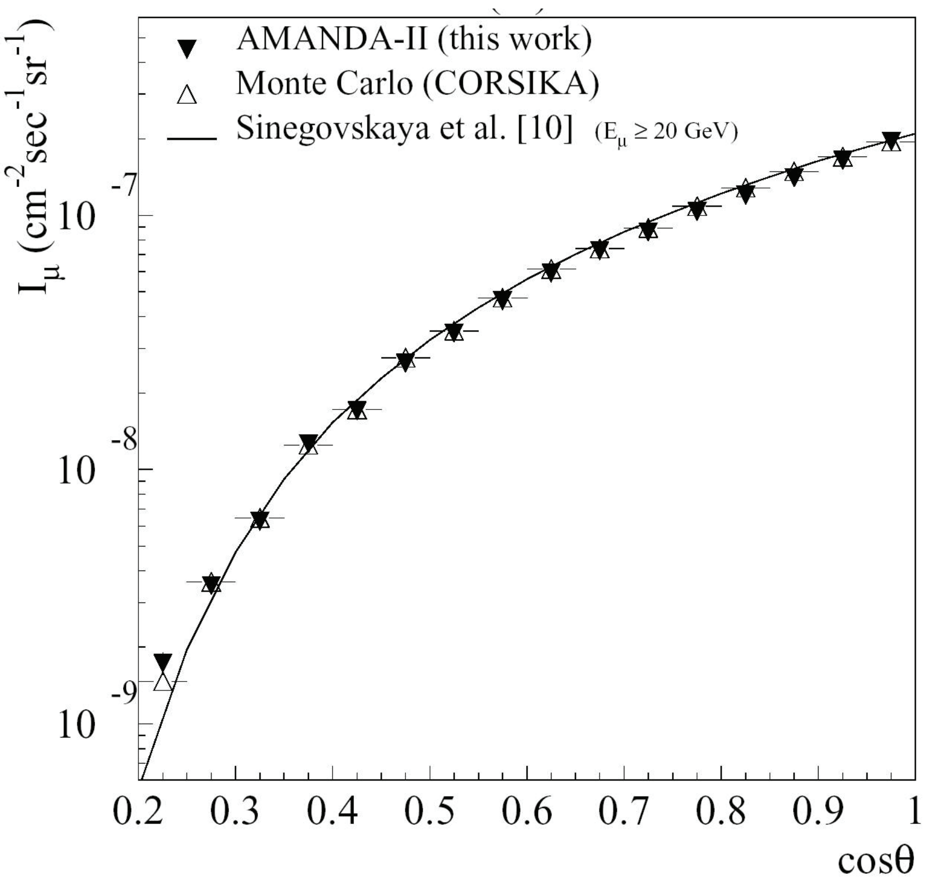


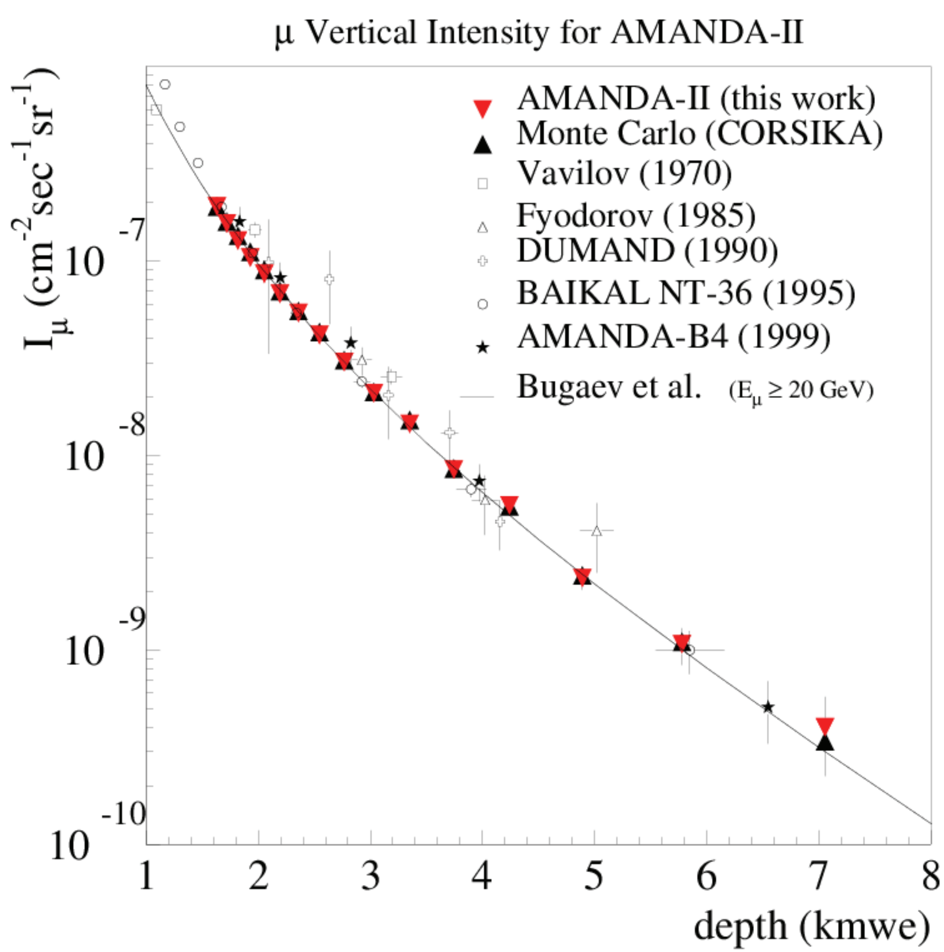


The first IceCube-IceTop coincident event



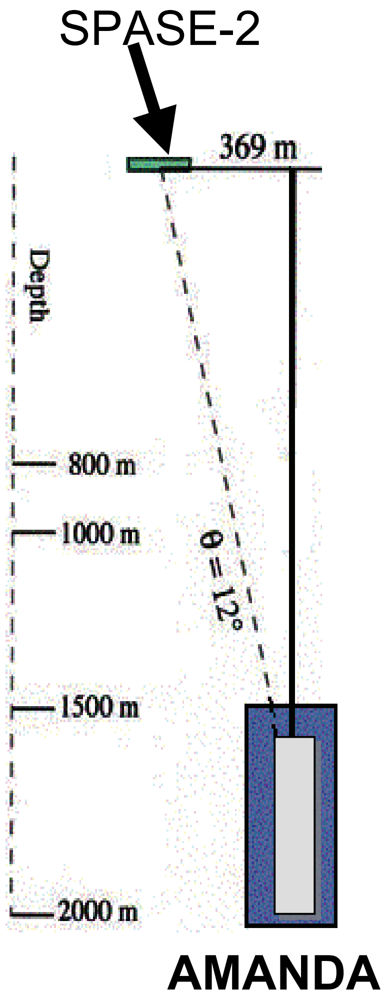
Atmospheric muons

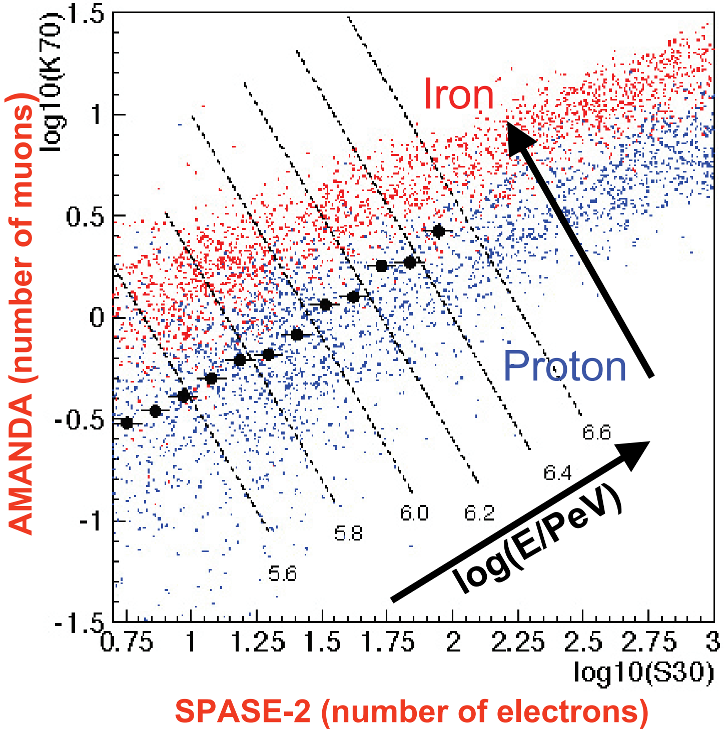


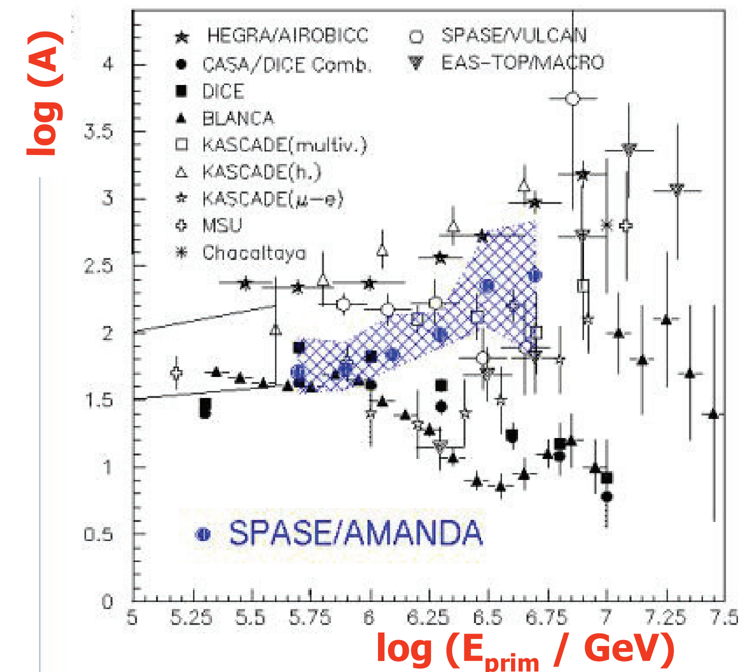


Angular distribution of down-going atmospheric muons is translated to the depth intensity distribution

Spase/Amanda: Measurement of the CR composition







SPASE-2 → electron number
AMANDA B10 → muon number (>400 GeV)

400 TeV – 6 PeV: Increase of the Atomic Mass
⇒ composition change around the knee

Rawlins et al, Proc. 28th ICRC, Tsukuba 1 (2003) 173

Search for diffuse fluxes of high energy neutrinos

Signature:

Excess of events with high energy over the steeply falling background of atmospheric neutrinos

- Energy spectrum of observed atmospheric ν_μ
- Search for high energy cascades
- Search for ultra-high energy events

All AMANDA analyses follow a strict blindness principle:

- Access to physics data is prohibited until the full analysis is finalized
- No posterori change of the analysis (e.g. cuts) after unblinding.
- Definition of standard procedures for each type of analysis e.g.:
  - Diffuse fluxes: Develop analysis on 20% of the data (which is later discarded)
  - Point sources: Work with randomized sky coordinates
- Unblinding requests are reviewed and approved by the collaboration

Energy spectrum of atmospheric ν_μ from 1TeV – 100 TeV (year 2000 data)

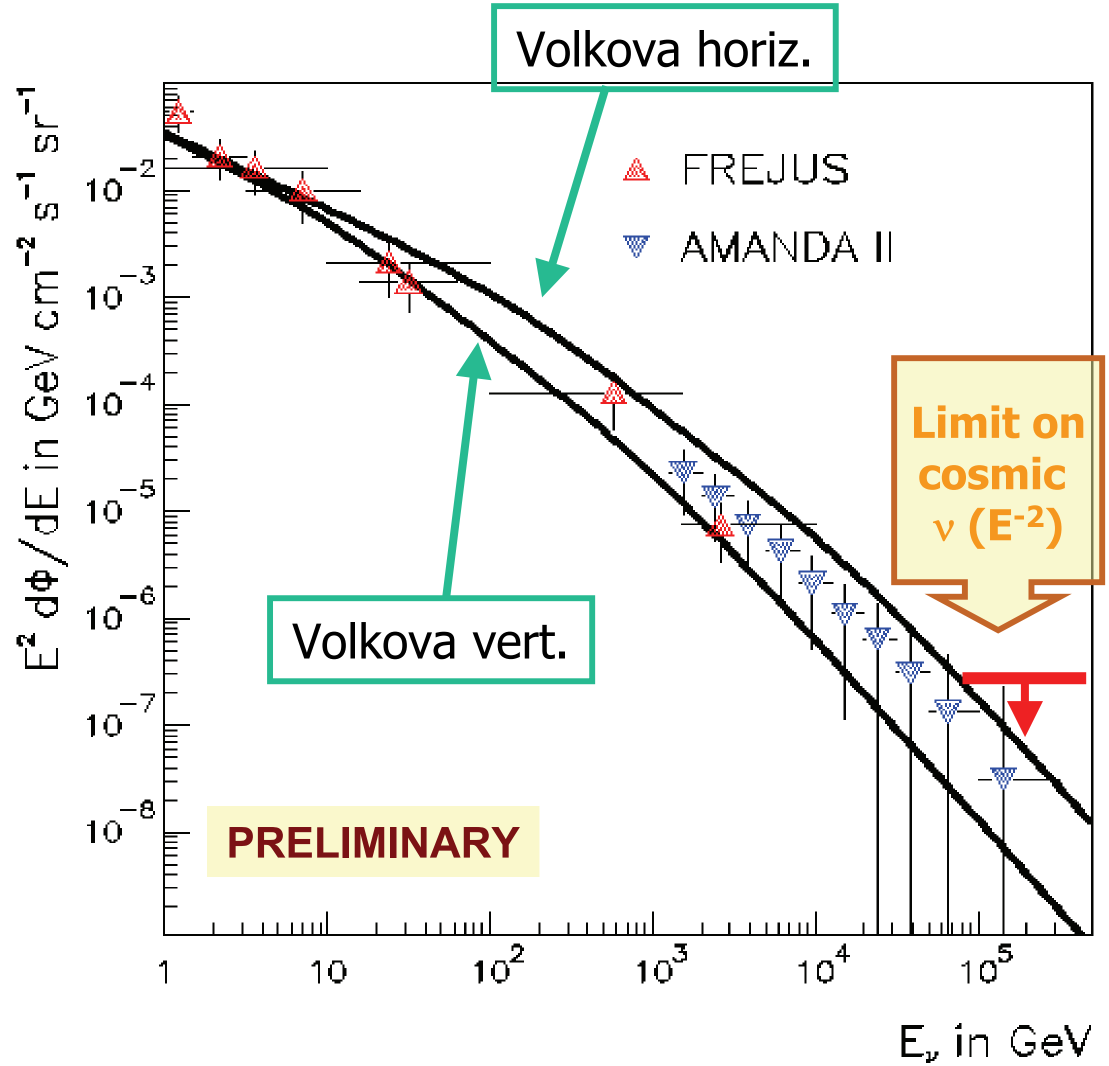
Light in the detector
⇒ Muon energy in the detector
⇒ ν energy spectrum
(regularized unfolding, Blobel)

Spectrum of atmospheric ν_μ
(~700 events from 2000)

$\gamma = 3.56 \pm 0.20$ (stat.)

⇒ Flux is in agreement with the expectation for atmospheric neutrinos (and with Frejus : $\gamma = 3.66 \pm 0.05$ (stat.))

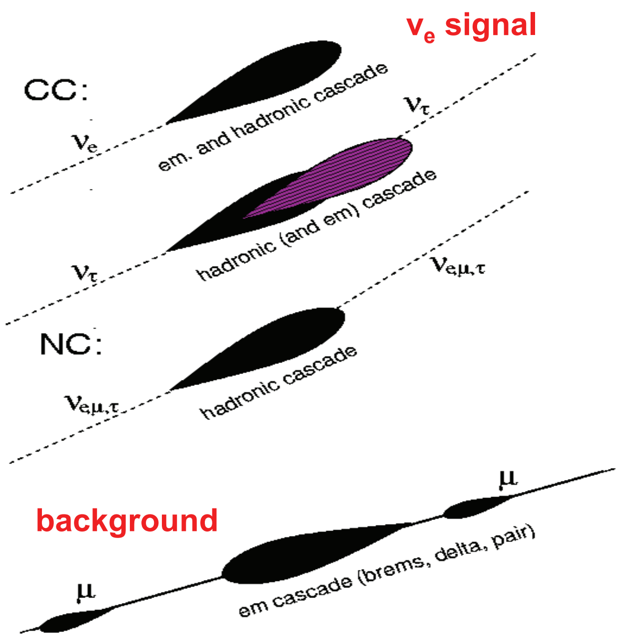
⇒ Exclusion of any significant contribution from extraterrestrial sources

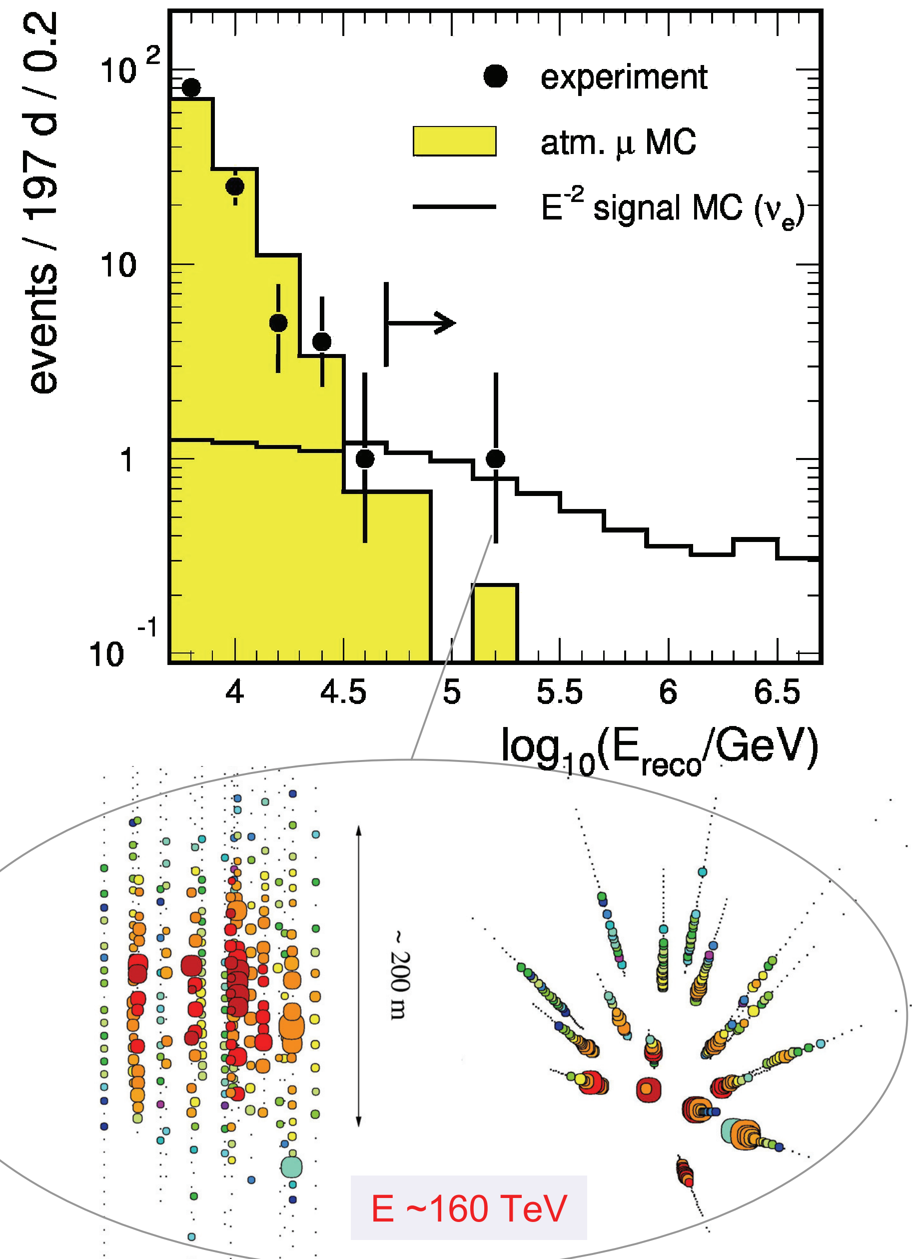


$E^2\,\Phi(\nu_\mu+\bar{\nu}_\mu) < 2.6 \cdot 10^{-7}$ GeV s^{-1} cm^{-2} sr^{-1} (incl.syst.errors)

Search for cascade events (year 2000 data)

Cascades: 4π coverage, sensitive to all flavors





N_{obs} = 1 event E > 30 TeV

$N_{atm\ \mu} = 0.90^{+0.69}_{-0.43}$

$N_{atm\ \nu} = 0.06^{+0.09}_{-0.04} \pm 25\%_{norm}$

$E^2\,\Phi(\Sigma\,\nu_x) < 8.6 \cdot 10^{-7}$ GeV s^{-1} cm^{-2} sr^{-1} (incl.syst.errors)

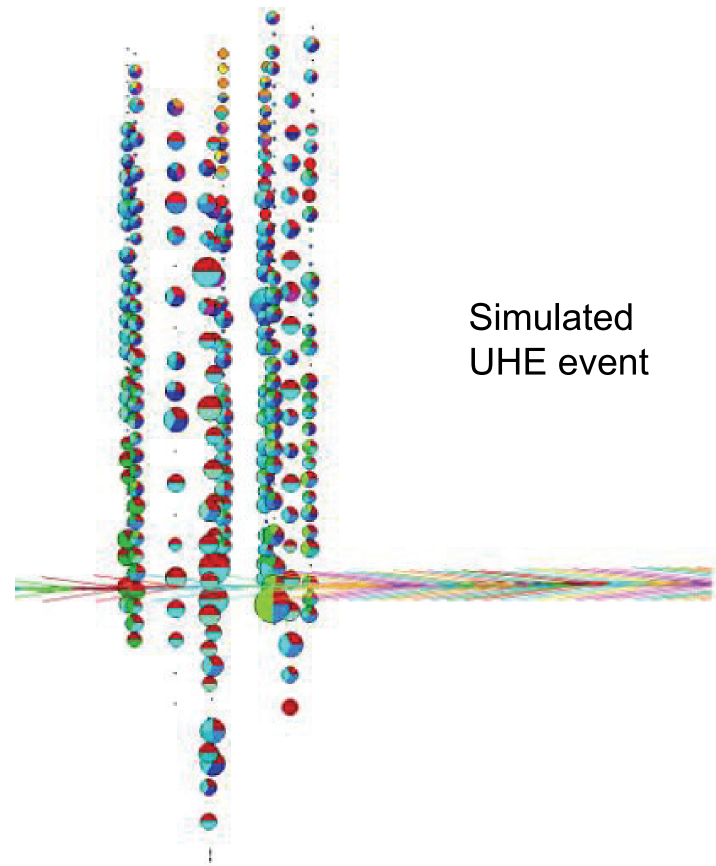
Astroparticle Physics 22 (2004) 127

Diffuse PeV-EeV (UHE) Neutrino Search (1997 data)

Earth opaque to PeV neutrinos
- do not reject downgoing and horizontal events

Extremely bright events
- Detector in saturation and no directional reconstruction

Background: Large bundles of (low energy) muons (E_{th}>400GeV, 1.5km depth)
Signal: Single high energy muons
Selection: Topological variables



Simulated UHE event

N_{obs} = 5 events

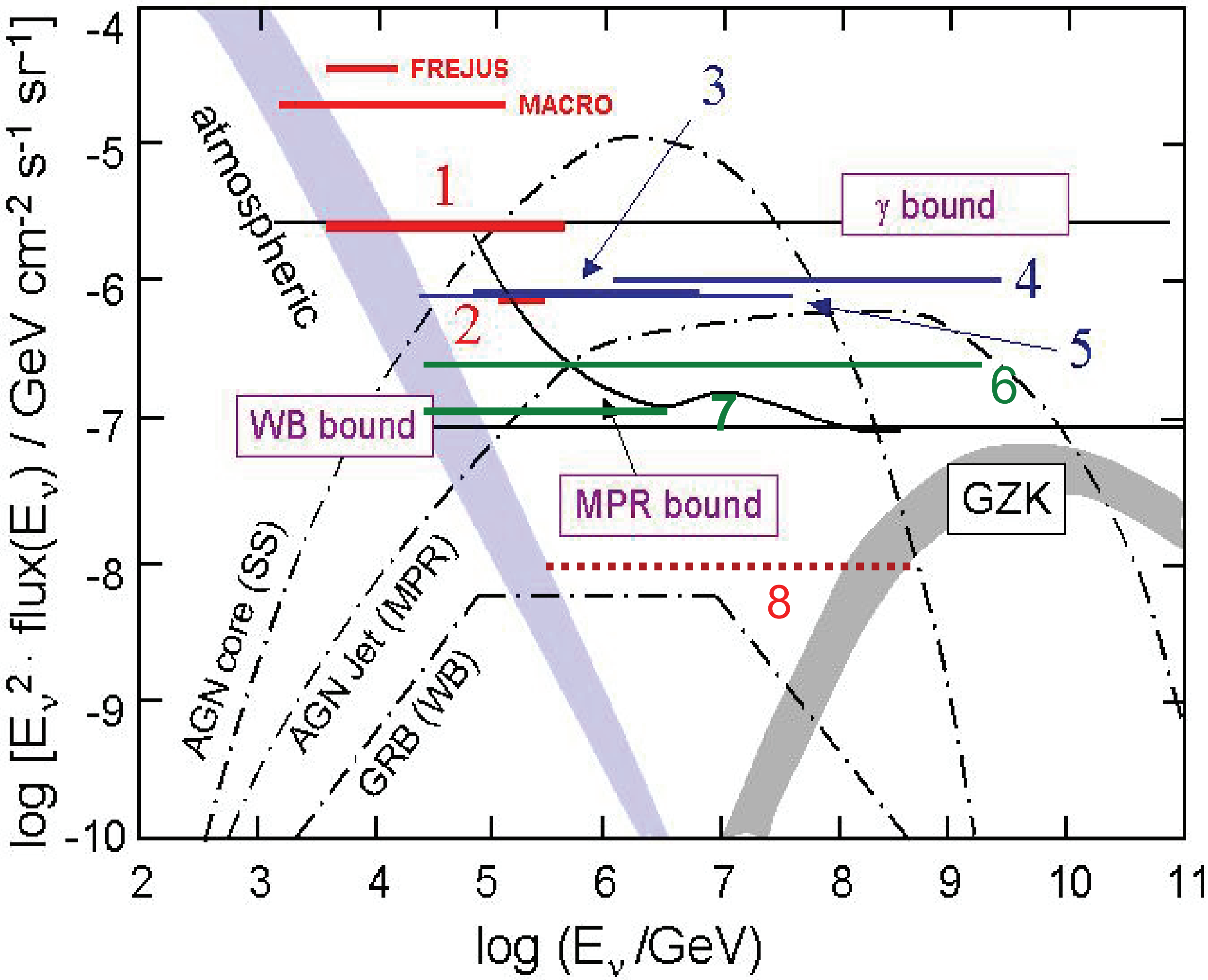
N_{bgr} = 4.6 ± 36% events

Limit on diffuse E^{-2} ν flux
$\Phi_\nu E^2 < 0.99 \cdot 10^{-6}$ GeV cm^{-2} s^{-1} sr^{-1}
(1 PeV < E < 3 EeV)

Data for 2000 in preparation, factor ~4 gain in sensitivity

Astroparticle Physics 22 (2005) 339

Limits for diffuse neutrino fluxes (all flavors)



AMANDA

1: B10, 97, ↑μ
2: A-II, 2000, unfold.
3: A-II, 2000, cascade
4: B10, 97, UHE
5: 98-03, Baikal cascade
6: A-II, 2000, UHE sens.
7: A-II, 2000-03 ↑μ sens.
8: IceCube 3 years

Some AGN models excluded at 90% CL :

Szabo-Protehoe 92

Stecker, Salamon. Space Sc. Rev. 75, 1996

Protehoe. ASP Conf series, 121, 1997

limits on all-flavors ($\sum \nu_e + \overline{\nu}_e + \nu_\mu + \overline{\nu}_\mu + \nu_\tau + \overline{\nu}_\tau$)

1:1:1 flavor flux ratio

Exp. ν_μ limits are multiplied with a factor 3

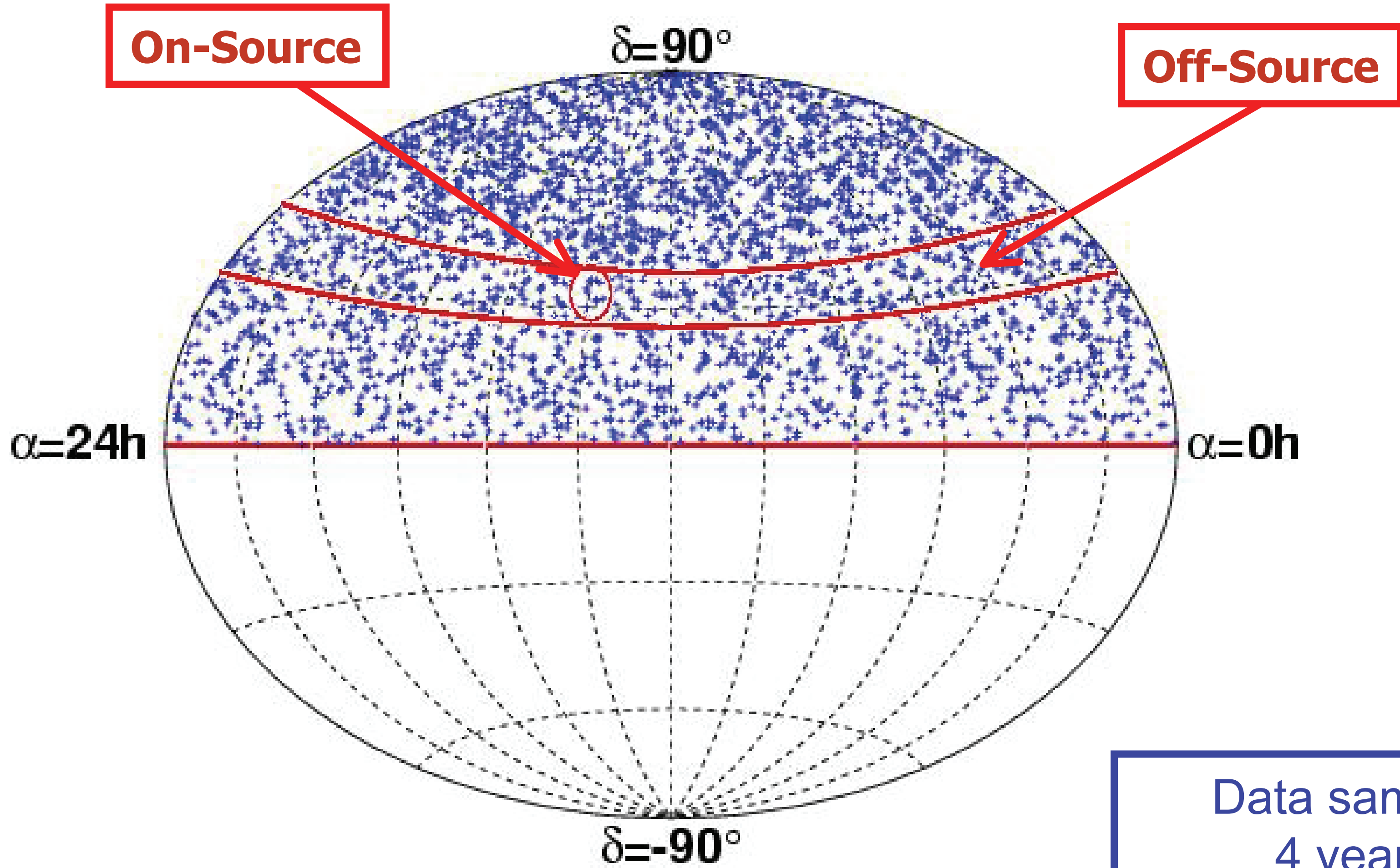
Search for astrophysical sources of high energy neutrinos

Signature:

Excess of ν_μ from the source direction

- Unbiased search for clusters
- Inspection of known objects (usual suspects)
- Transient sources using multi-wavelength correlations
- Transient sources using rolling timeslices
- Source stacking
- Dark matter annihilation in the Earth and the Sun
- Neutrinos in coincidence with Gamma Ray Bursts

Search for point sources of cosmic neutrinos



3369 *events*

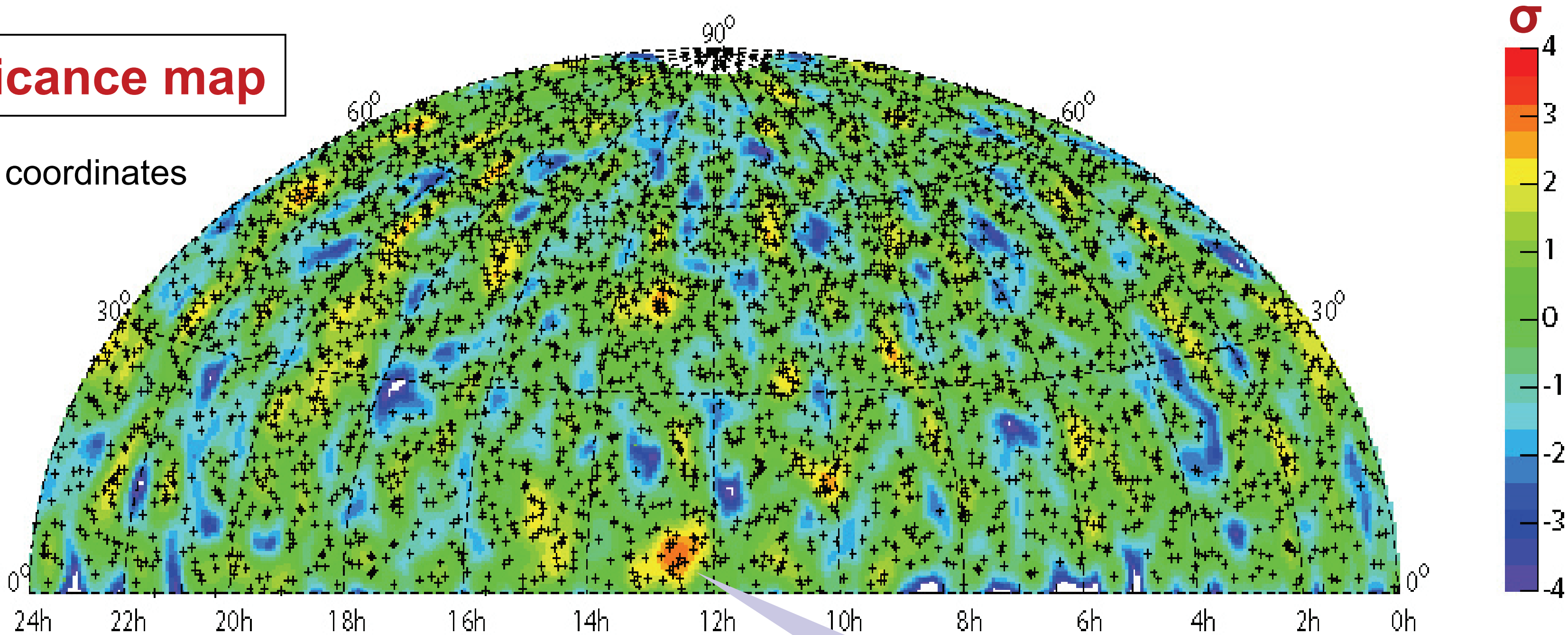
3438 (±30%) **atm. ν MC**

Data sample:
4 years
(2000-2003)
Livetime: 807 Tage
purity ≈ 95%

Search for clusters of events

significance map

equatorial coordinates

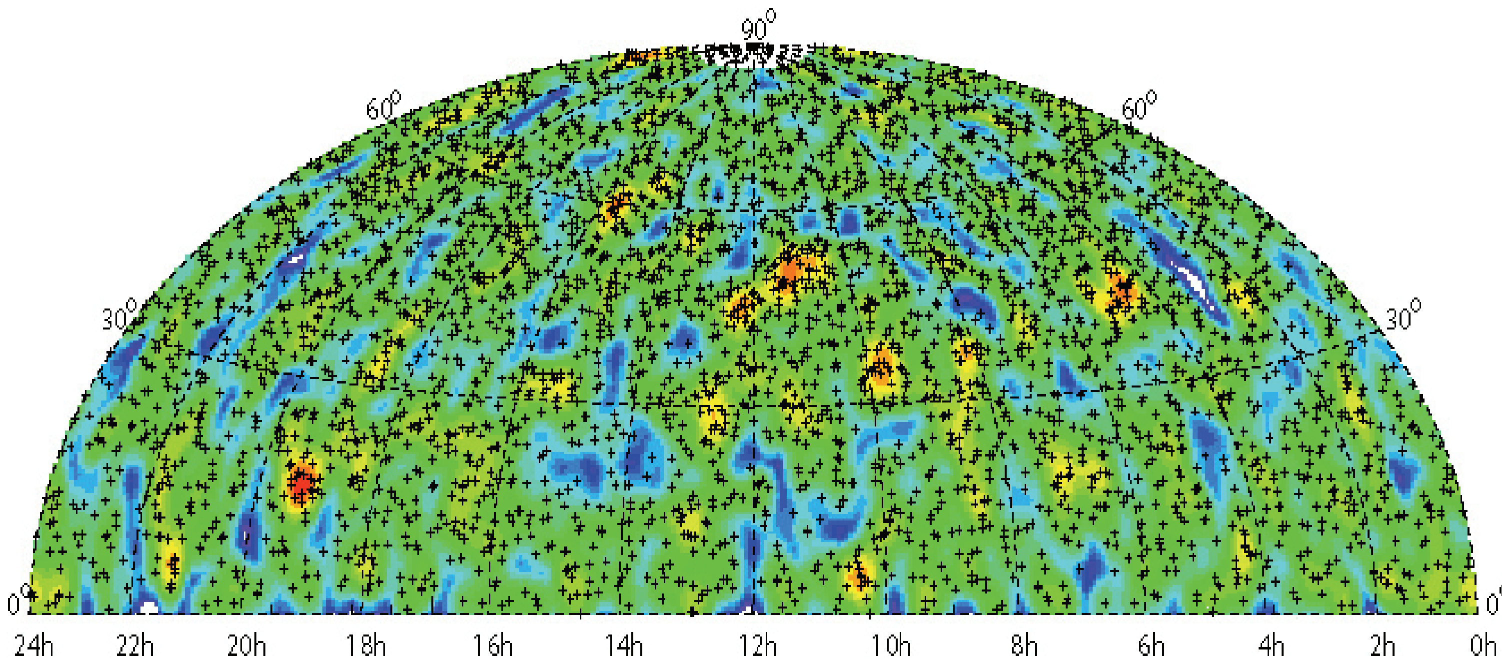


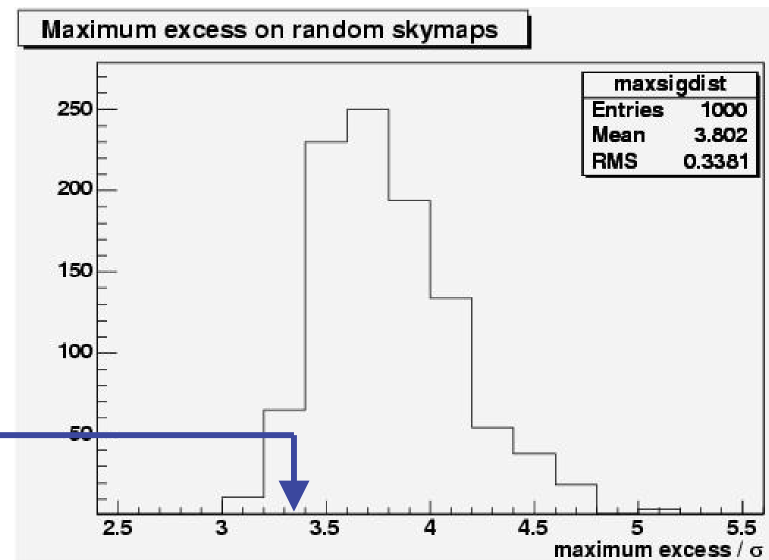
Unbinned statistical analysis: construct event density considering the angular resolution individually for each event

largest deviation: 3.35σ <u>before</u> trial factor correction

Probability of a background fluctuation: ~92%
No statistically significant excess

Estimation of the trial factor by randomized sky maps





Simulate 1000 Random Skymaps by scrambling the right ascension
→ significances > 3σ are very likely

probability of a background fluctuation

$P(>3.35\sigma) = 92\%$

Search for excesses in coincidence with known-objects

33 Objects tested, a few results shown:

Preliminary upper limits (90% CL) , $10^{-8} cm^{-2} s^{-1}$, $E_\nu > 10$ GeV

SNRs MicroQuas. Blazars

Source	Total Obs. Events	Total Back. Events	Flux Upper Limit (90% CL)
Markarian 421	6	5.58	0.68
1ES1959+650	5	3.71	0.38
SS433	2	4.50	0.21
Cygnus X-3	6	5.04	0.77
Cygnus X-1	4	5.21	0.40
Crab Nebula	10	5.36	1.25

maximum significance for 33 sources

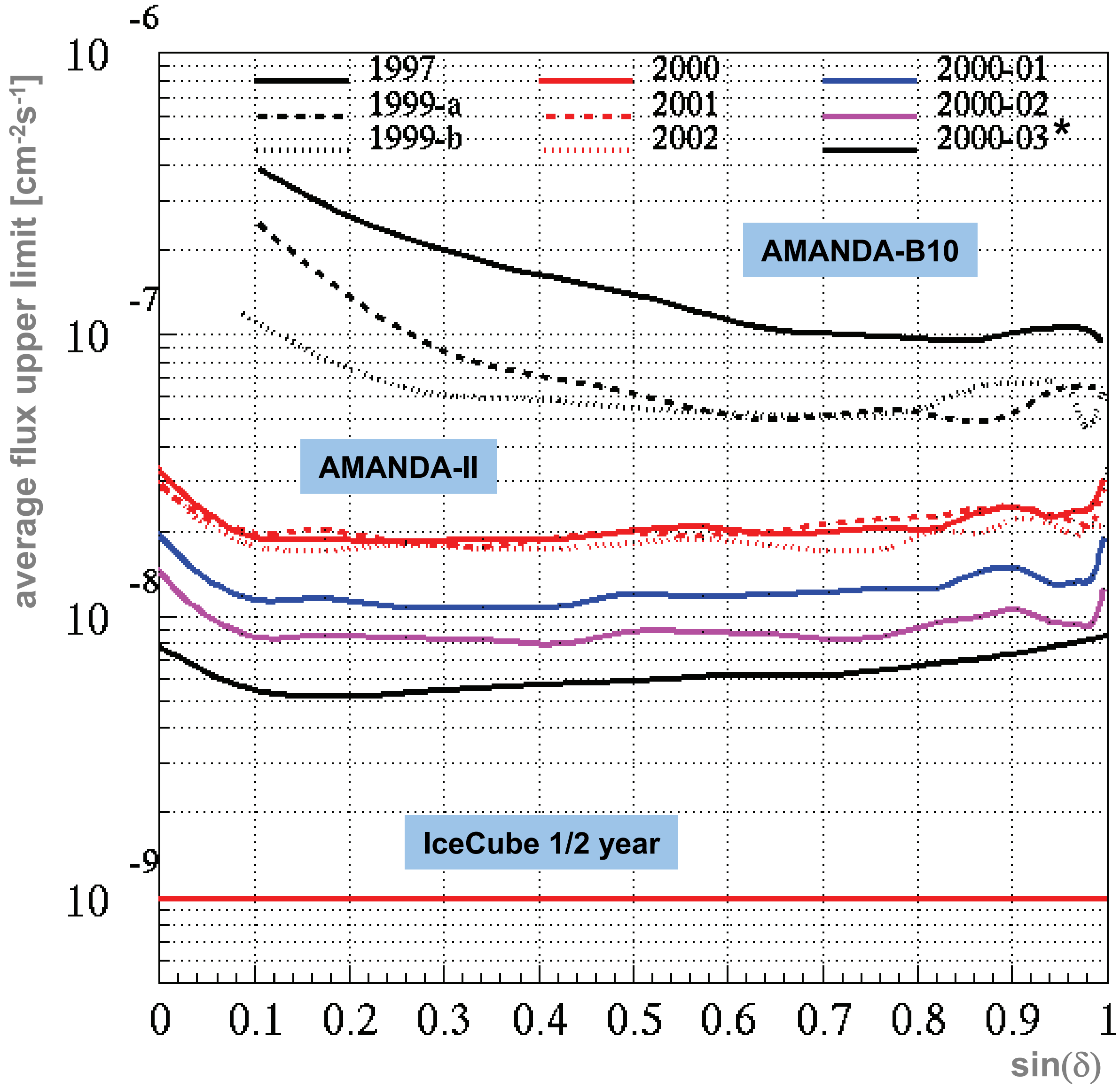
Largest excess ~1.7σ from Crab Nebula: Not statistically significant

Simulation results in a probability of 64% to observe a maximimum significance of $\geq 1.7\sigma$

(taking into account the number, sky position and overlap of search bins)

Sensitivity F_ν/F_γ~2 for Markarian 421

Average point source sensitivity versus declination



Average limit: 2000-2003

$\Phi_\nu^{lim} \approx 0.68 \cdot 10^{-8}\ \mathrm{cm^{-2}s^{-1}}$

δ declination $\begin{cases} \delta=0^\circ \rightarrow \\ \delta=90^\circ \uparrow \end{cases}$

1997 : ApJ 583, 1040 (2003)
2000 : PRL 92, 071102 (2004)
2000-02 : PRD 71 077102 (2005)
IceCube: Astrop Phys 20, 507 (2004)

Search for transient sources (multi-wavelength)

Hypothesis:

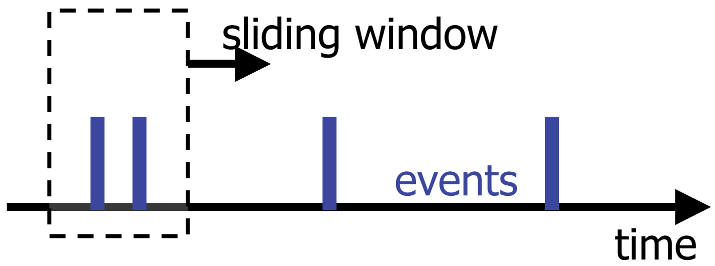
- neutrinos are emitted in coincidence with electromagnetic flare emissions
- Search for events in coincidence with known periods of strong photon acitvity
- Wavelengths investigated: X-ray for Blazars and radio for Microquasars

Source	EM light curve source	Livetime in periods of high activity	Nr. of ν events in high state	Expected backgr. in high state
Markarian 421	ASM/RXTE	141 days	0	1.63
1ES1959+650	ASM/RXTE	283 days	2	1.59
Cygnus X-3	Ryle Telesc.	114 days	2	1.37

Periods and sources selected on the basis of the ***available** multi-wavelength information*

→ no statistically significant effect observed

Search for transient sources (rolling search)



No a-priori hypothesis on the time of occurrence

- time window:
  - 20 days for galactic objects
  - 40 days for extragalactic objects
- angular bin: 2.25°-3.75°

Source	Nr. of n events (4 years)	Expected backgr. (4 years)	Period duration	Nr. of doublets	Probability for highest multiplicity
Markarian 421	6	5.58	40 days	0	Close to 1
1ES1959+650	5	3.71	40 days	1	0.34
3EG J1227+4302	6	4.37	40 days	1	0.43
QSO 0235+164	6	5.04	40 days	1	0.52
Cygnus X-3	6	5.04	20 days	0	Close to 1
GRS 1915+105	6	4.76	20 days	1	0.32
GRO J0422+32	5	5.12	20 days	0	Close to 1

… 12 candidate sources → no statistically significant effect observed

Source stacking

Superimpose positions of objects with similar morphology

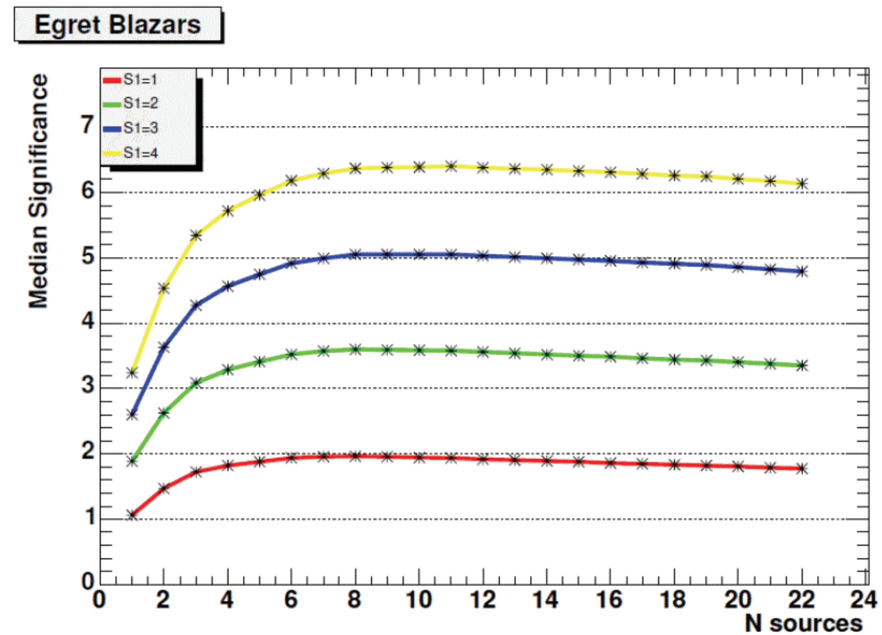
A priori define hypothesis

- catalogues
- number of sources
- angular binsize

Hypothesis here:
Optical depth unknown! Select objects of similar type.
Neutrino flux is correlated to the photon luminosity at some wave-length

No specific model assumption

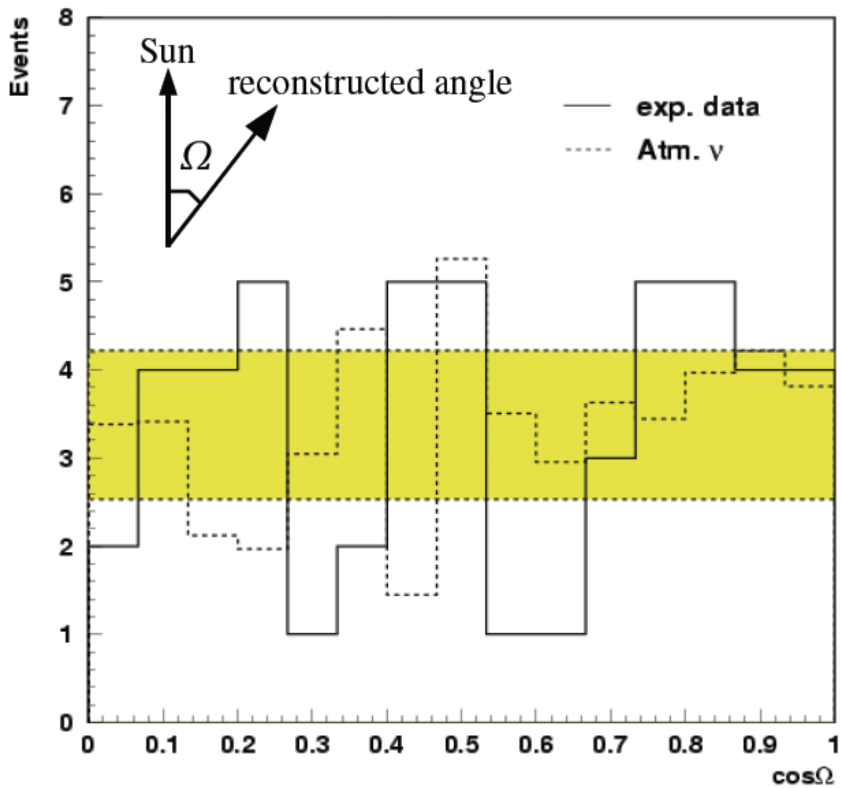
→ no statistically significant effect observed for the year 2000



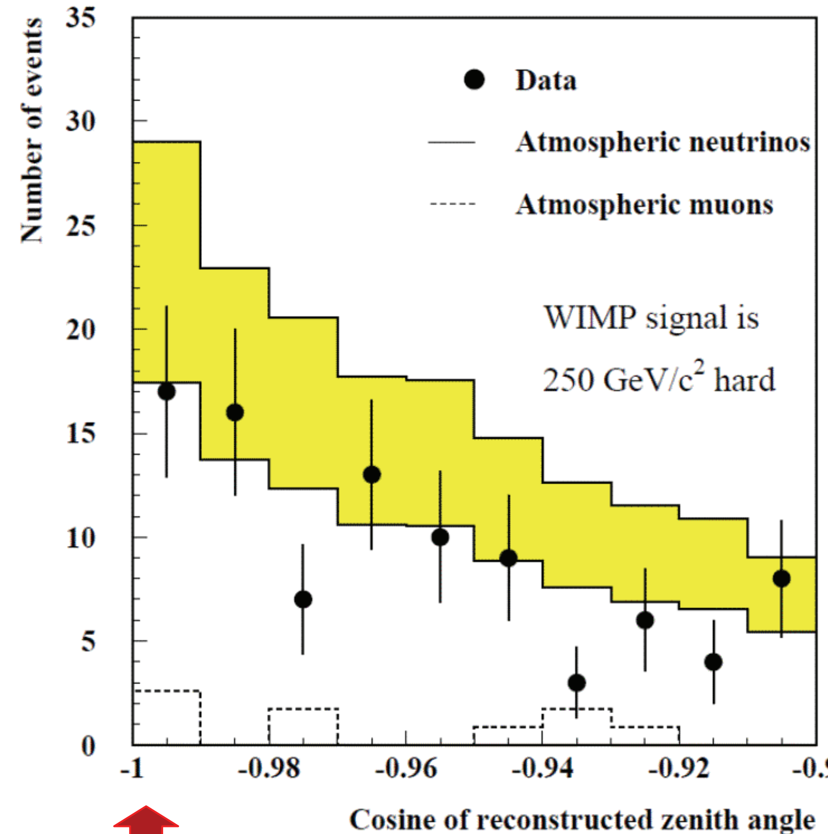
sample	N_{src}	N_ν^{obs}	N_ν^{bg}	$\phi_{90\%}$
GeV blazars	8	12	20.5	1.5
unid. GeV sources	22	62	60.1	2.6
IR blazars	11	30	34.1	2.0
keV blazars (HEAO-A)	3	7	11.0	1.4
keV blazars (ROSAT)	8	19	25.8	1.8
TEV blazars	5	14	18.3	1.5
GPS and CSS	8	16	22.7	1.7
FR-I galaxies	1	2	2.5	0.7
FR-I without M87	17	28	45.0	2.4
FR-II galaxies	17	58	53.8	2.6
radio-weak quasars	11	29	32.5	2.1

(10^{-8}cm^{-2}s^{-1}, E_ν>10 GeV)

Search for Wimp annihilation in the Sun and Earth



data from 2001



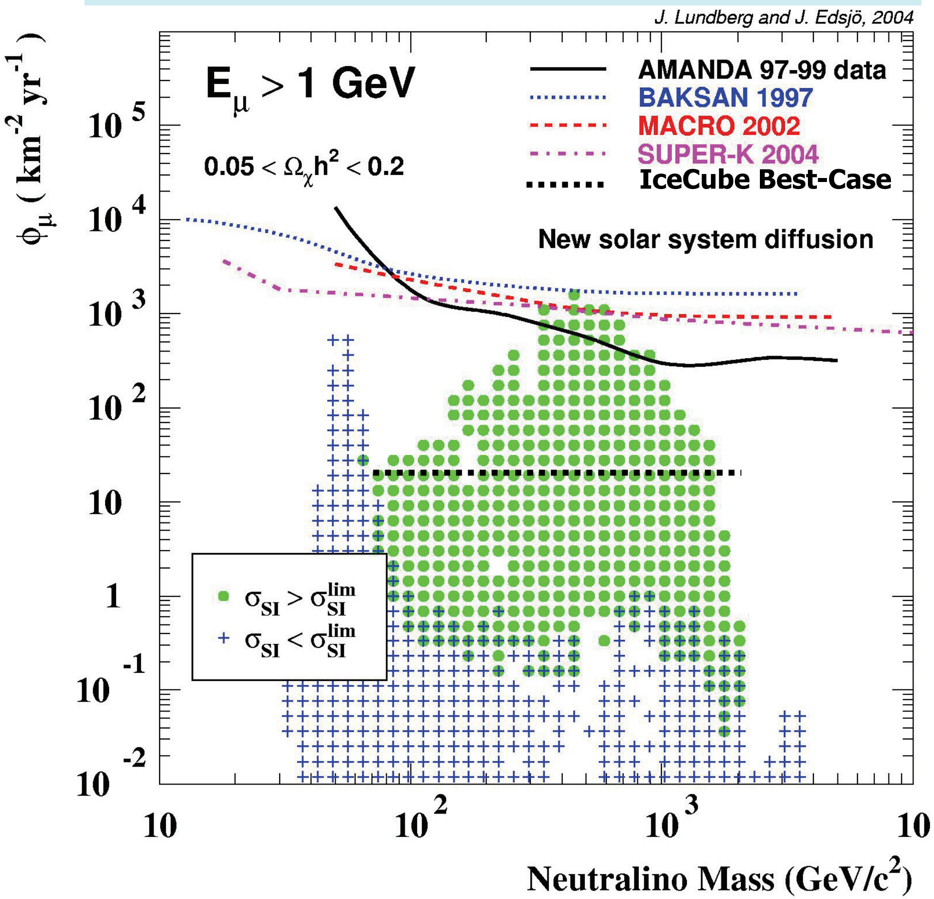
Sun

Earth

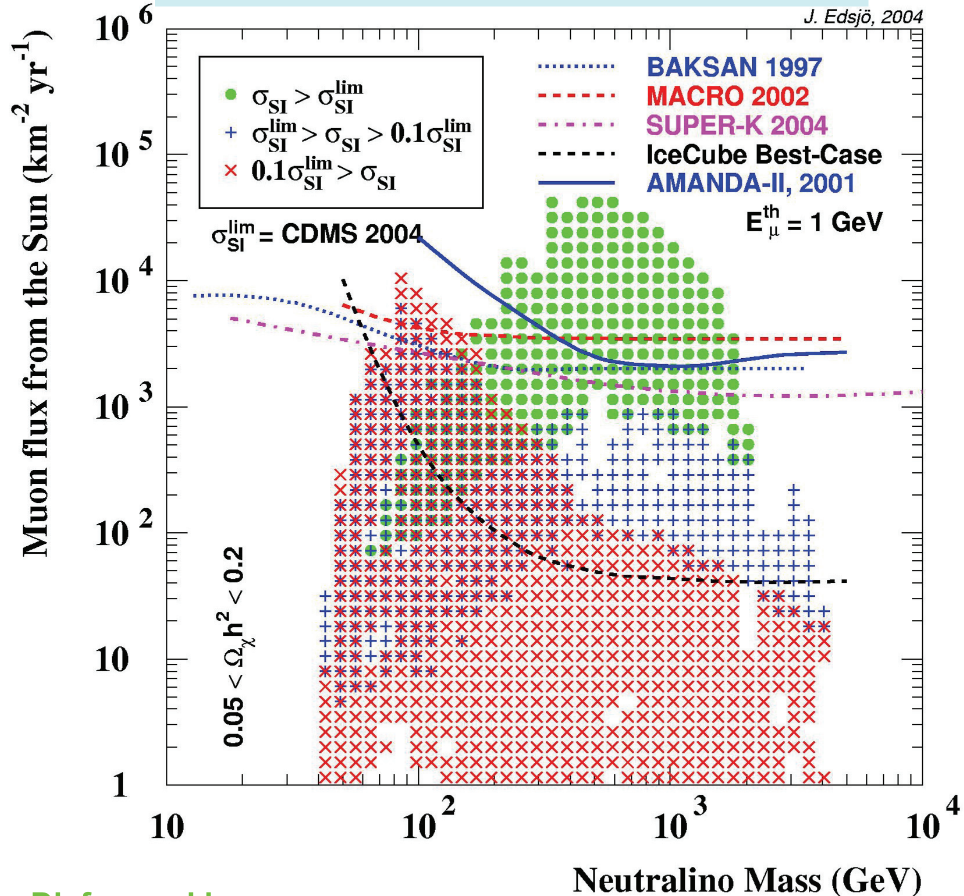
data from 1997-1999

Limits on the annihilation of Neutralinos

Limits on muon flux from Earth center



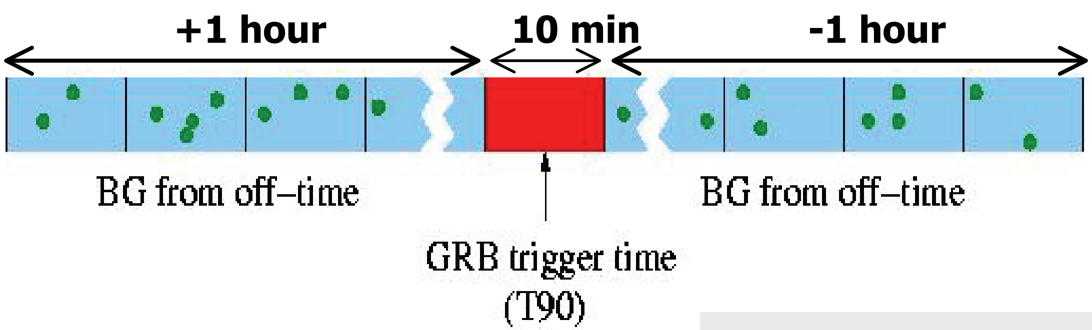
Limits on muon flux from Sun



Disfavored by direct search (CDMS II)

PRELIMINARY

Neutrinos from Gamma Ray Bursts



Using space and time coincidence leads to a very low background.

Year	Detector	N_{Bursts}	$N_{BG, Pred}$	N_{Obs}	Event U.L.
1997	B-10	78 (BT)	0.06	0	2.41
1998	B-10	94 (BT)	0.20	0	2.24
1999	B-10	96 (BT)	0.20	0	2.24
2000	A-II (2 analyses)	44 (BT)	0.83/0.40	0/0	1.72/2.05
97-00	B-10/A-II	312 (BT)	1.29	0	1.45

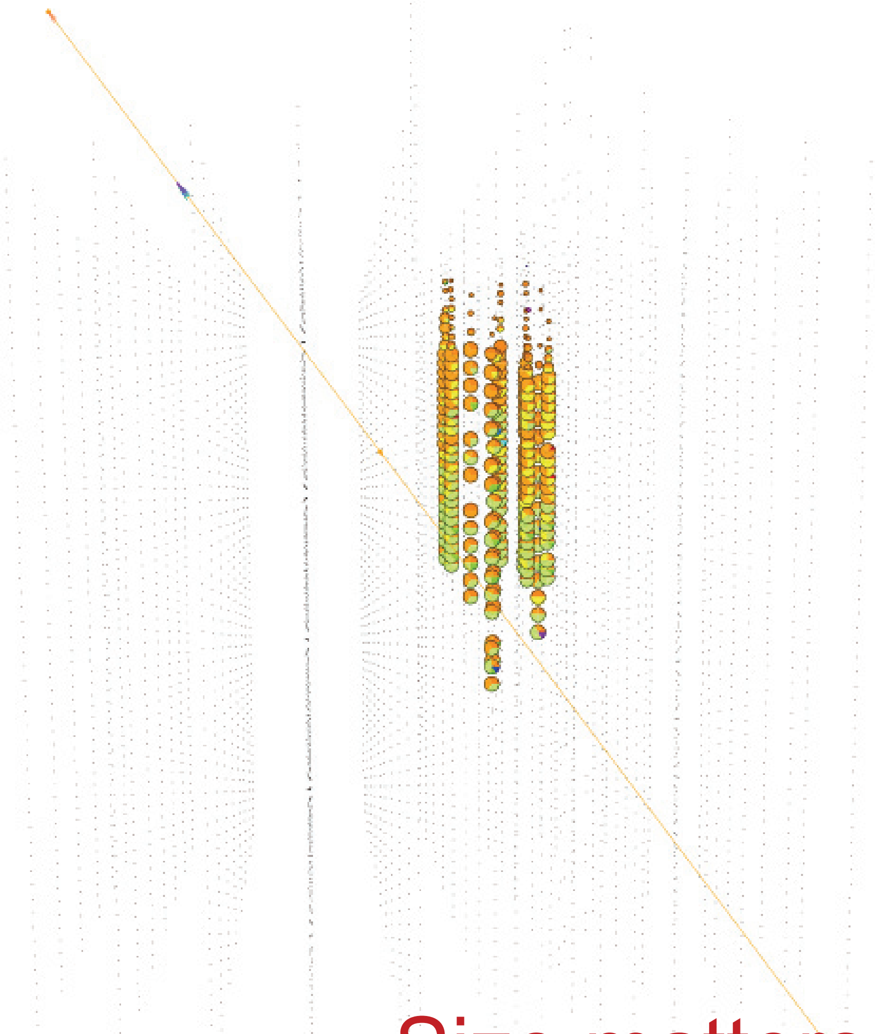
No observed signal

Only ~1 order of magnitude above Waxmann&Bahcall prediction

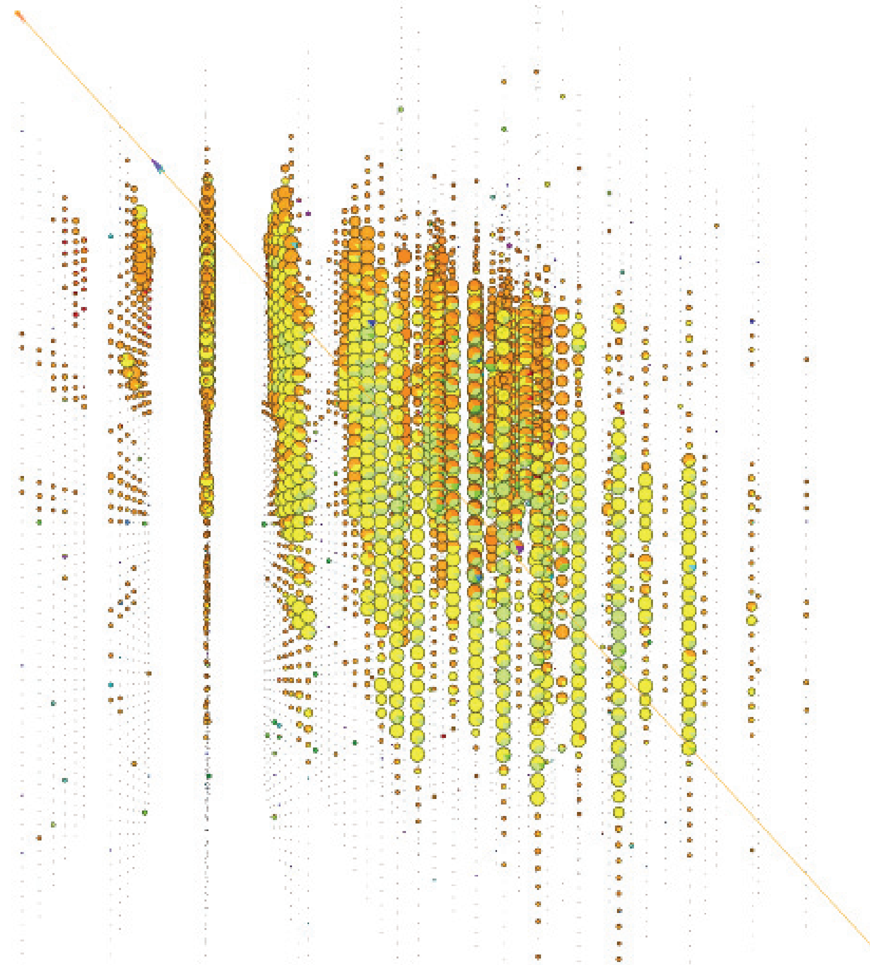
year	# GRB	from	preliminary upper limit assuming WB spectrum (E_B at 100 TeV and Γ = 300)
'97-'00	312	BATSE triggered bursts	$E^2 d\Phi_\nu/dE = 4 \cdot 10^{-8}$ GeV s^{-1} cm^{-2}
'00-'03	139	BATSE & IPN bursts	$E^2 d\Phi_\nu/dE = 3 \cdot 10^{-8}$ GeV s^{-1} cm^{-2}

Simulated 2×10^{19} eV muon event

in AMANDA

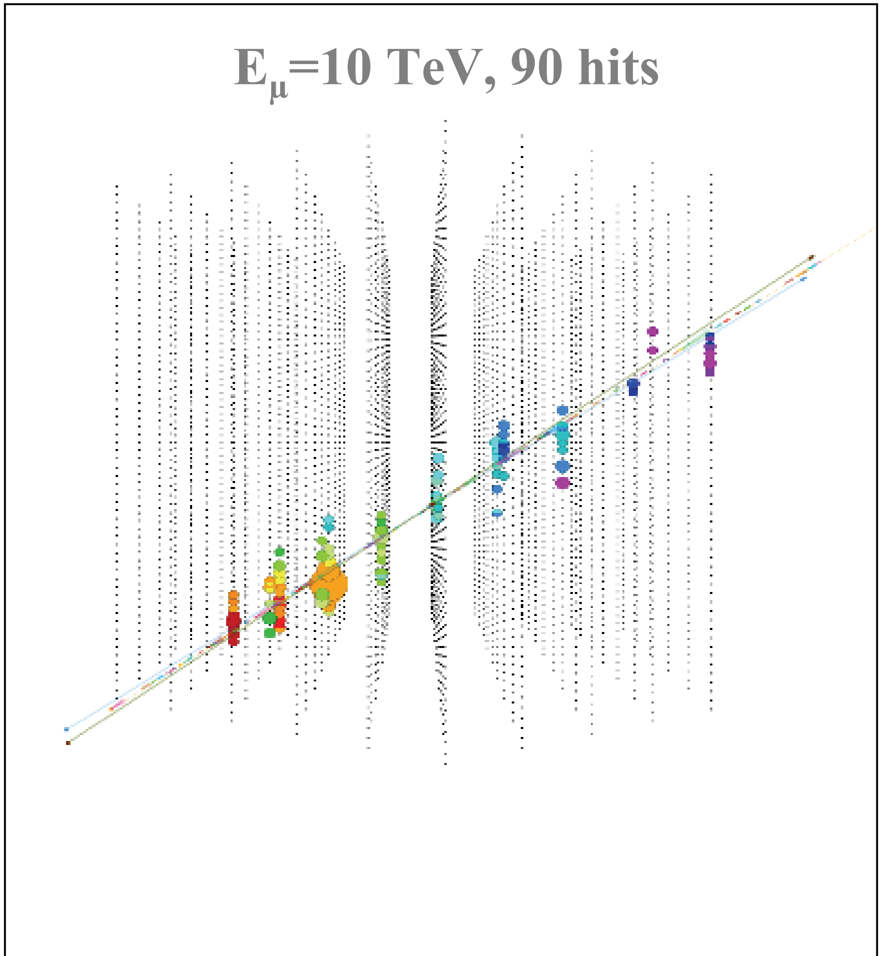


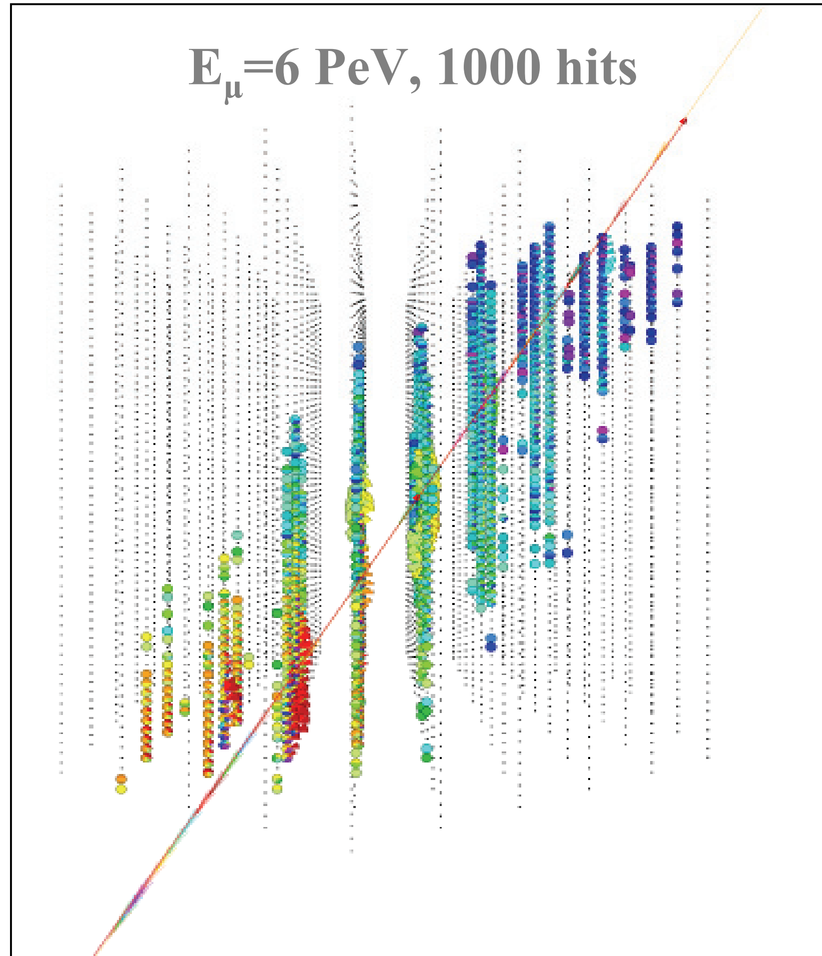
in IceCube



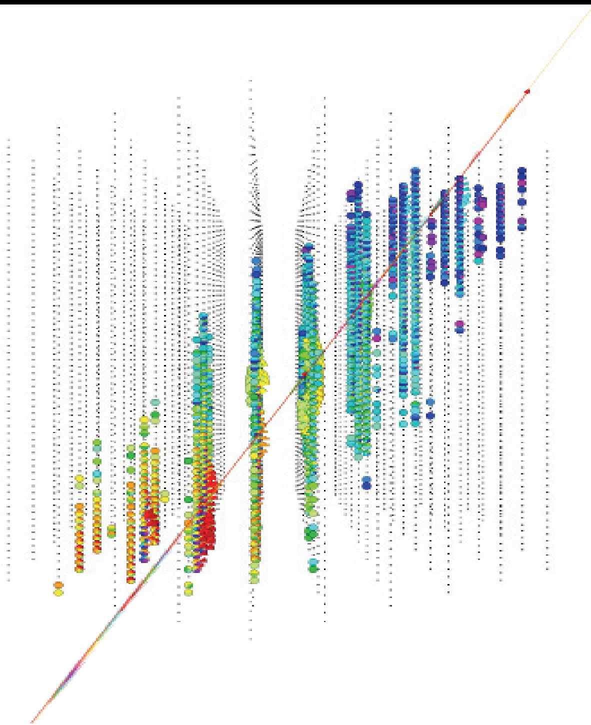
Size matters for high energies!

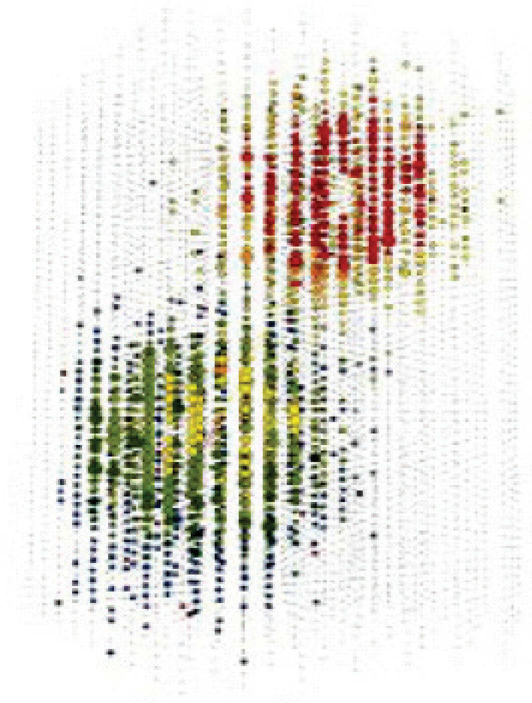
IceCube : simulated μ track events

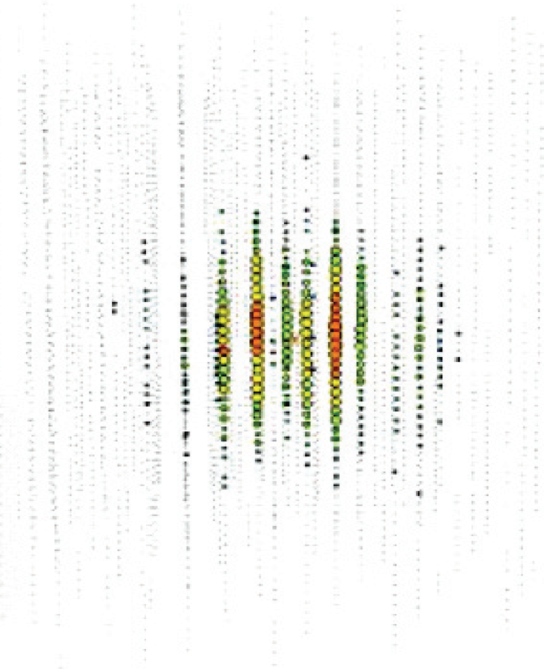




IceCube All-Flavor Neutrino Detection







$\nu_\mu \rightarrow \mu$

$E_\mu = 6$ PeV

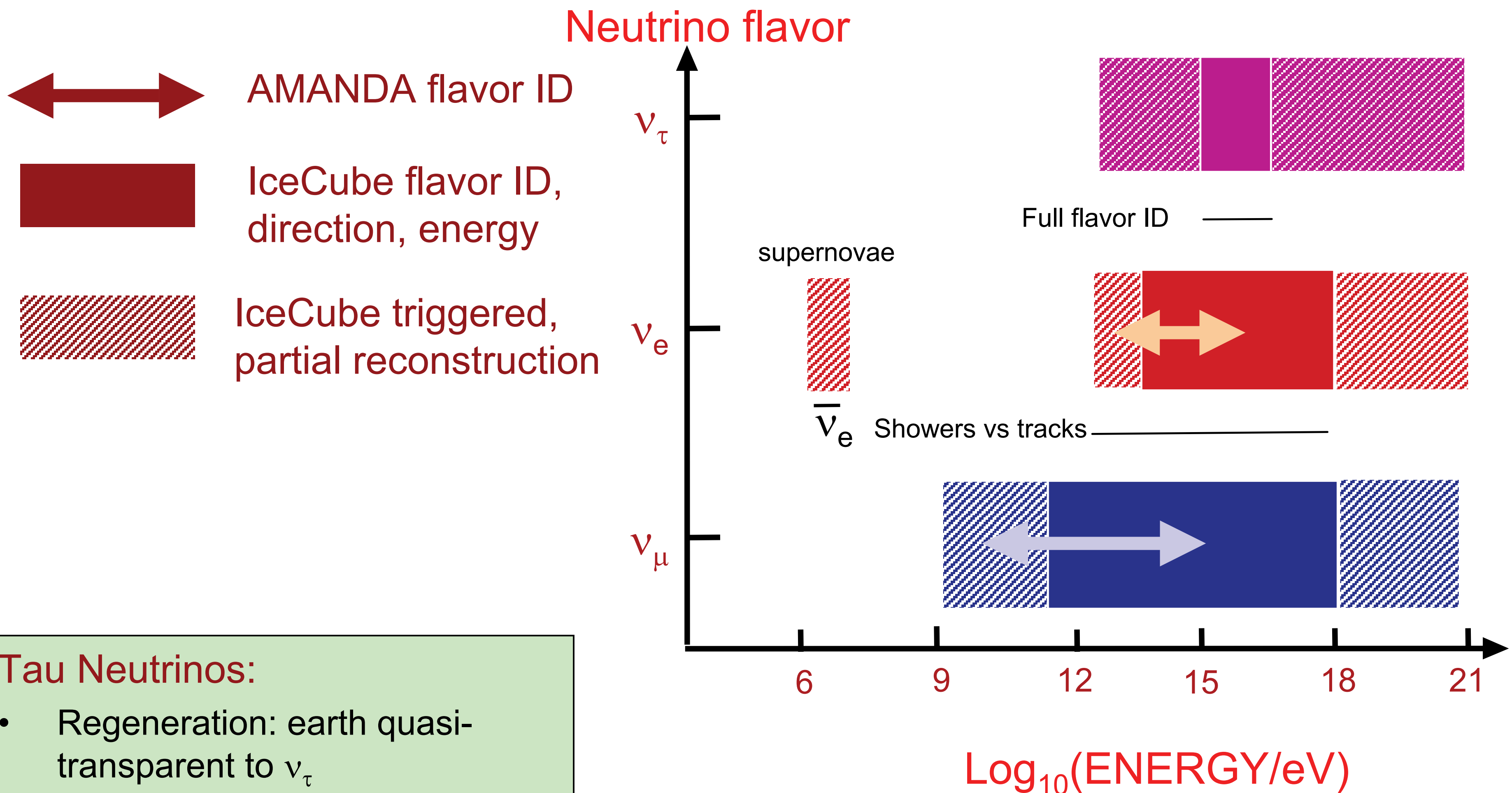
$\nu_\tau \rightarrow \tau +$ "cascade"

$E_\tau = 10$PeV
(~300m separation)

$\nu_e \rightarrow e$

$E_e = 375$ TeV

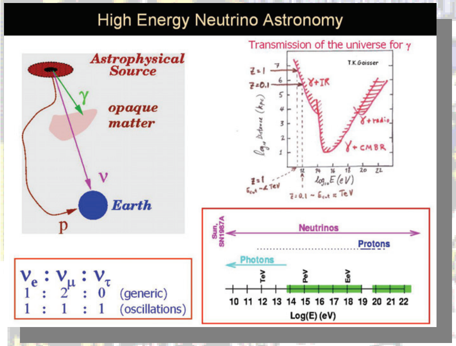
Neutrino flavor identification



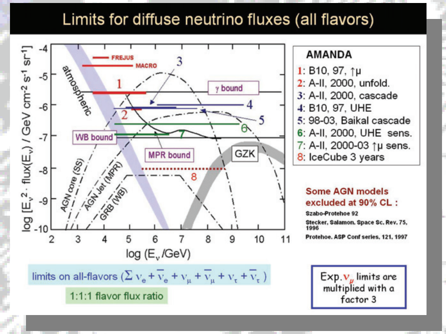
Tau Neutrinos:

- Regeneration: earth quasi-transparent to ν_τ
- Enhanced μ & cascade rate due to secondary ν_μ, ν_e

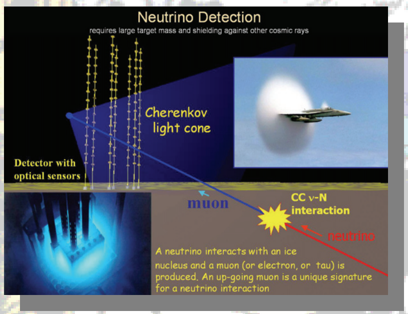
Summary



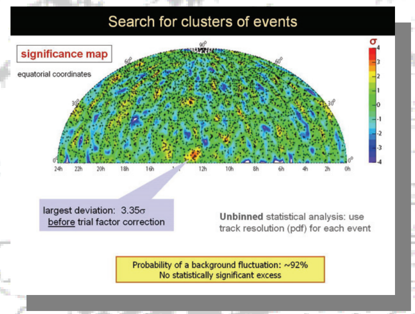
Cosmic neutrinos are the ideal messengers to investigate the high energy universe



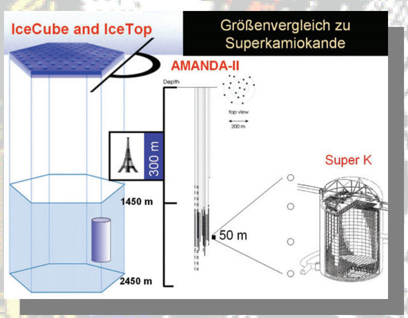
No excess in the flux of high energy neutrinos has been found yet



Muons and cascades are detected by the emitted Cherenkov light

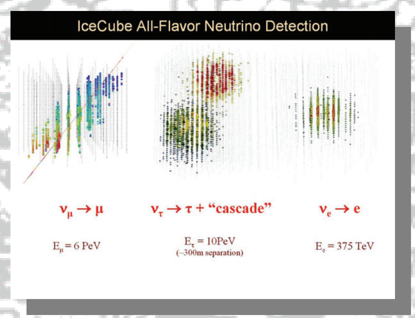


No sources of astrophysical neutrinos have been identified yet



AMANDA-II is taking data since 2000

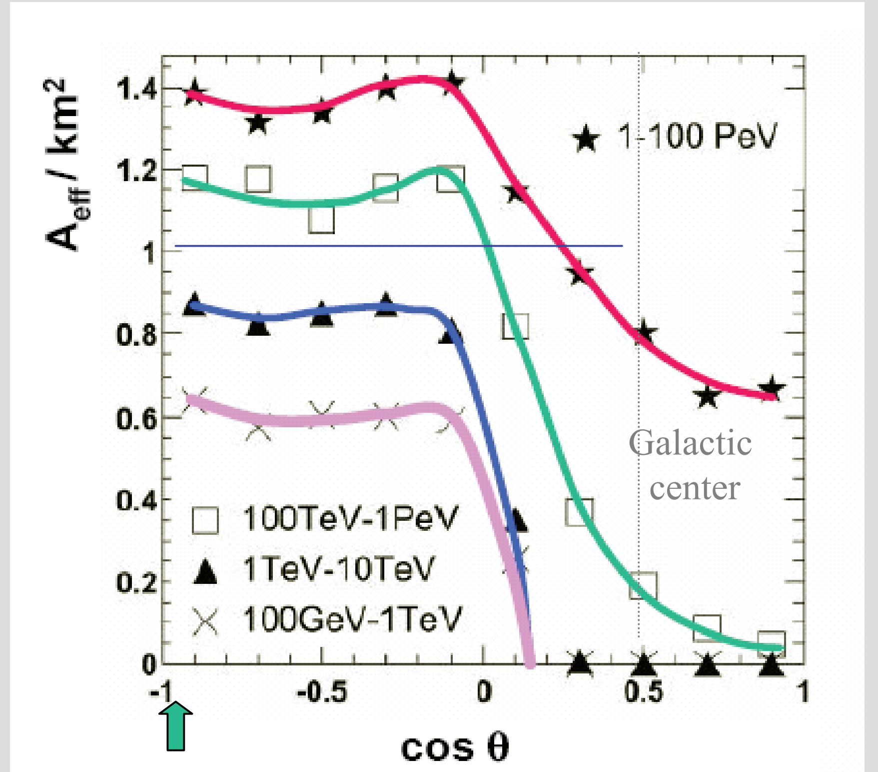
Construction of IceCube has started

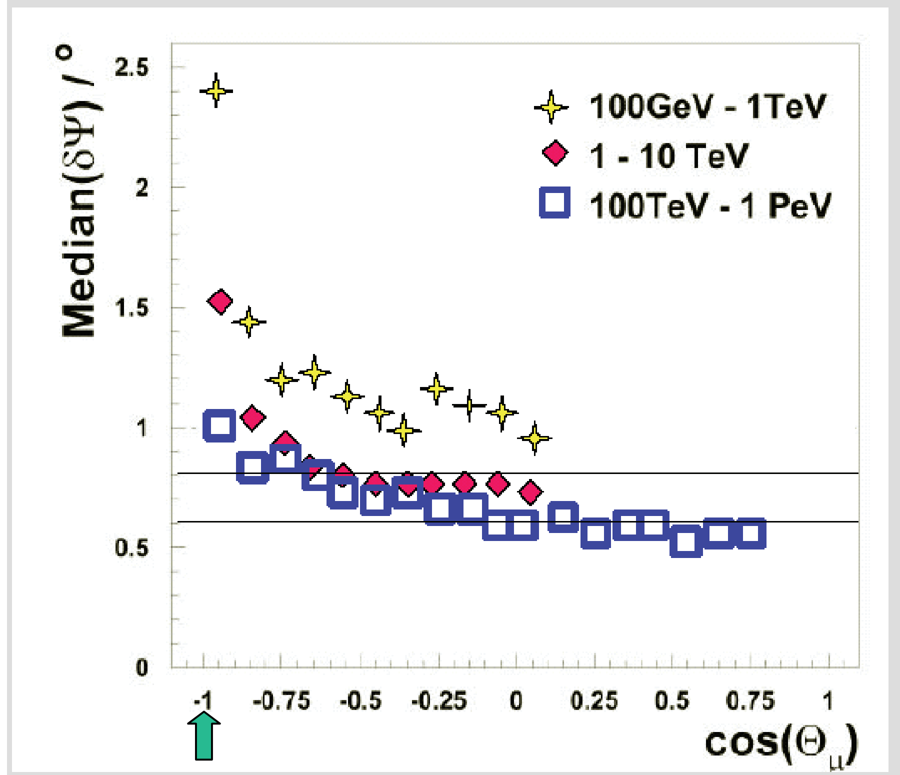


IceCube's allows for the detection of all neutrino flavours with a sufficient sensitivity to cover the range of predicted neutrino fluxes

IceCube

Effective Area and Angular Resolution for Muons



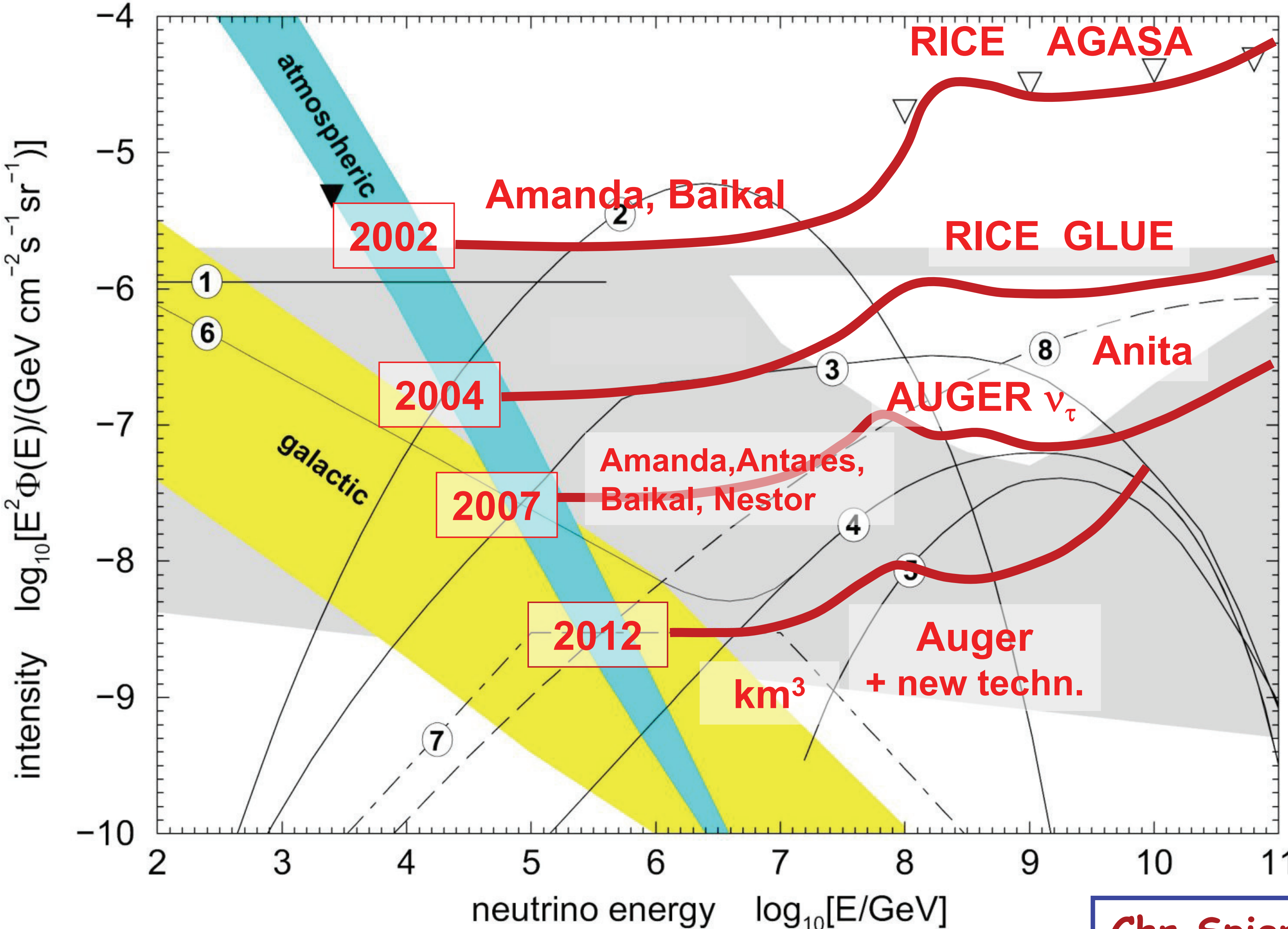


- for a E^{-2} ν_μ spectrum
- with quality selection and BG suppression (atm μ reduction by $\sim 10^6$)

- Median angular reconstruction error ~ 0.8°
- Based on standard AMANDA reconstruction only Substantial improvement expected using waveform info, especially at high energy

Energy resolution: $\sigma[\log_{10}(E_\mu)] \approx 20\%$-$30\%$

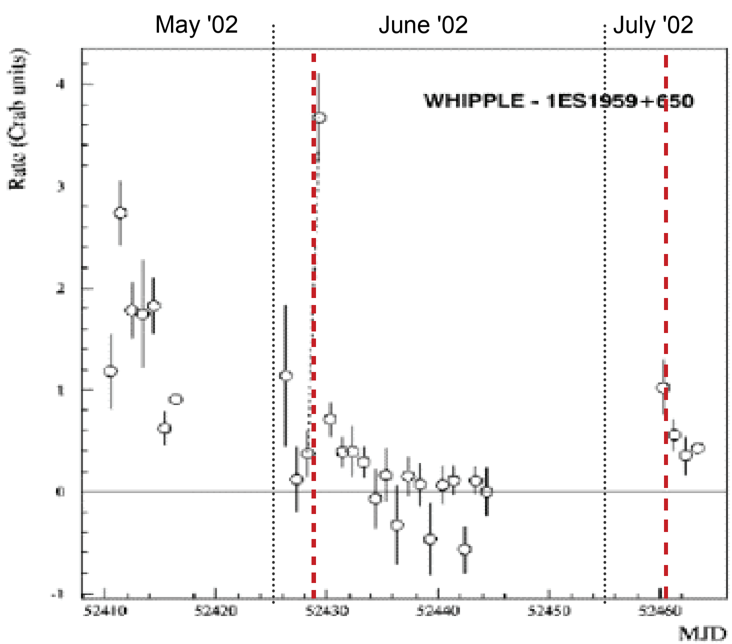
Achieved and expected sensitivities to diffuse fluxes



Chr.Spiering

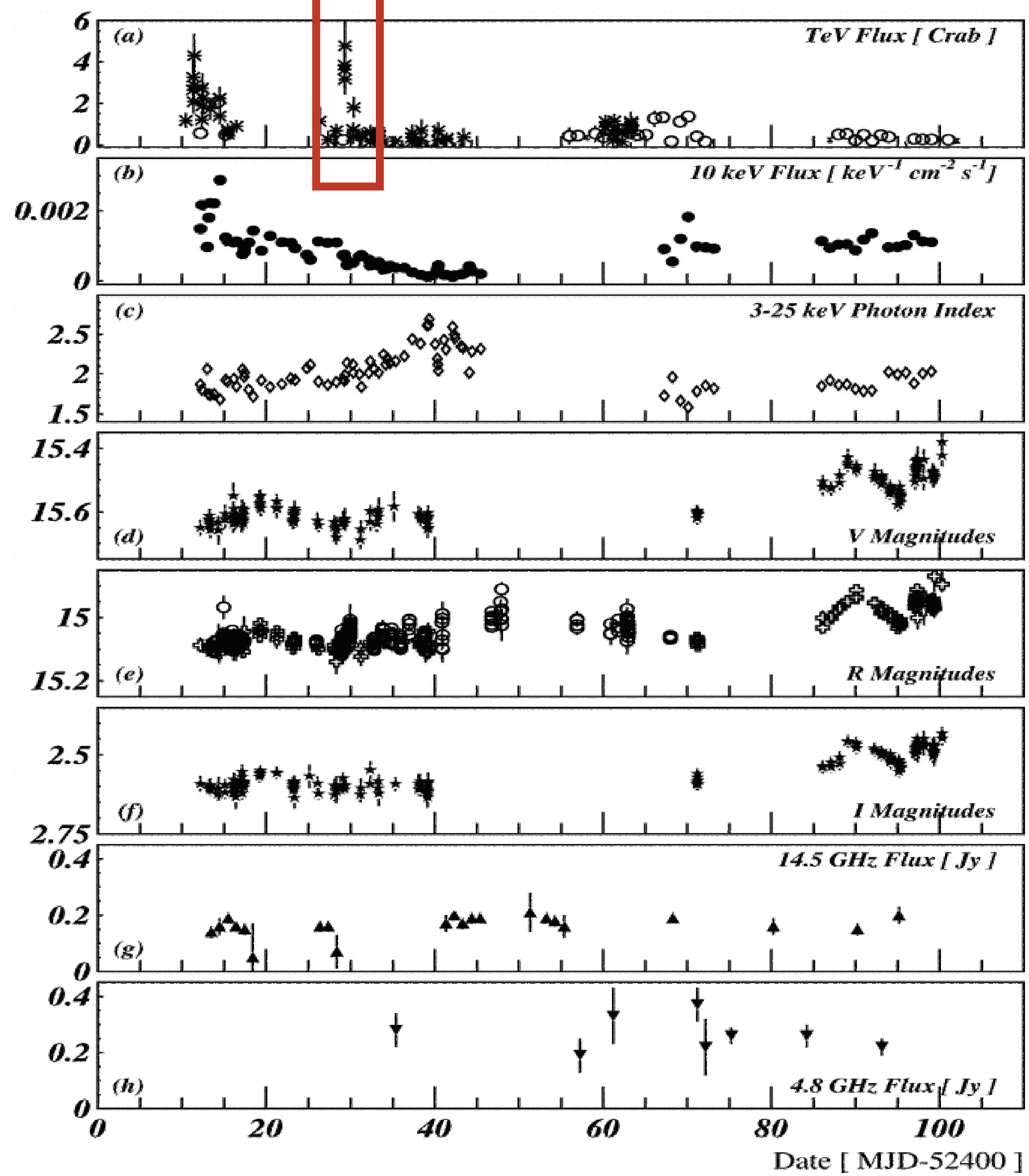
The orphan flare from 1ES1959+650

Observation of a strong flare with Whipple
No observation with Hegra
No X-ray emission
One neutrino event in coincidence



No significanct observation
No proper a priori hypothesis
-> (Large trial factor)

ApJ 601, 151 (2004)



Time Calibration