overview of **AMANDA & IceCube**

as a framework: high energy neutrino astronomy

results from AMANDA

IceCube: status and first events

Outlook

Carlos de los Heros, Uppsala University

neutrino astronomy

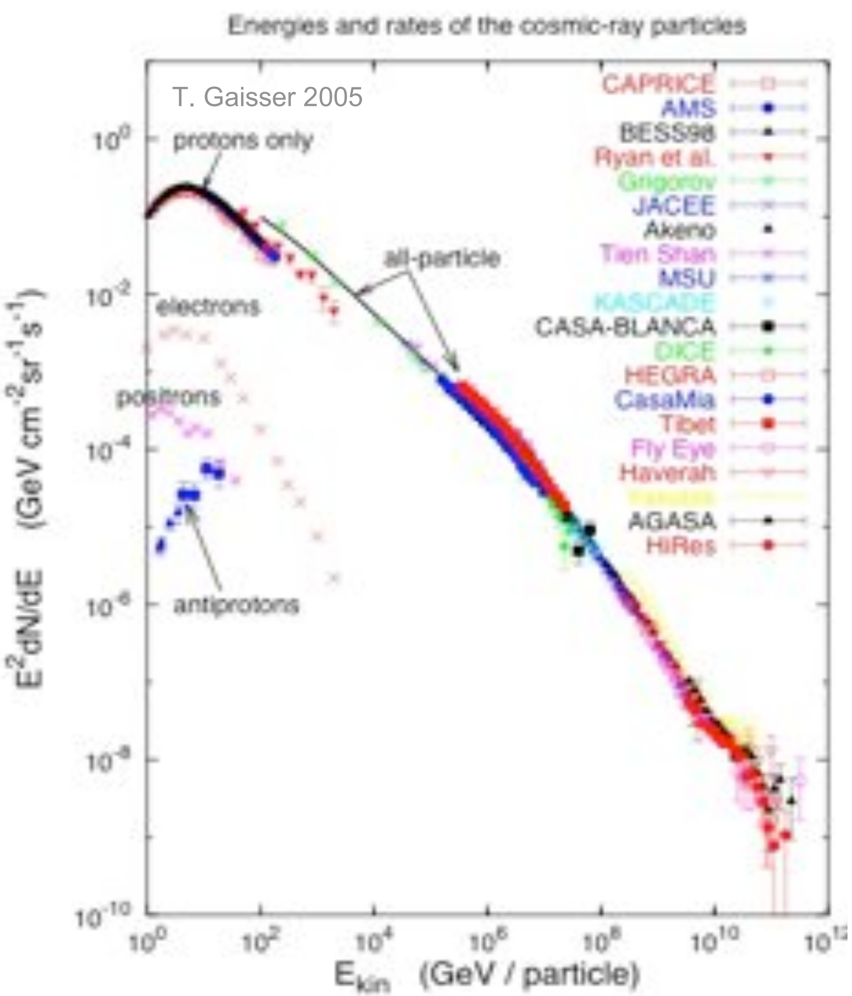
- **nature accelerates particles to ~10 ^{6} times the CM energy of LHC!**

  → acceleration sites must sit somewhere

candidate sources:

- SNe remnants, μquasars
- active galactic nuclei
- gamma ray bursts

} proton accelerators ?

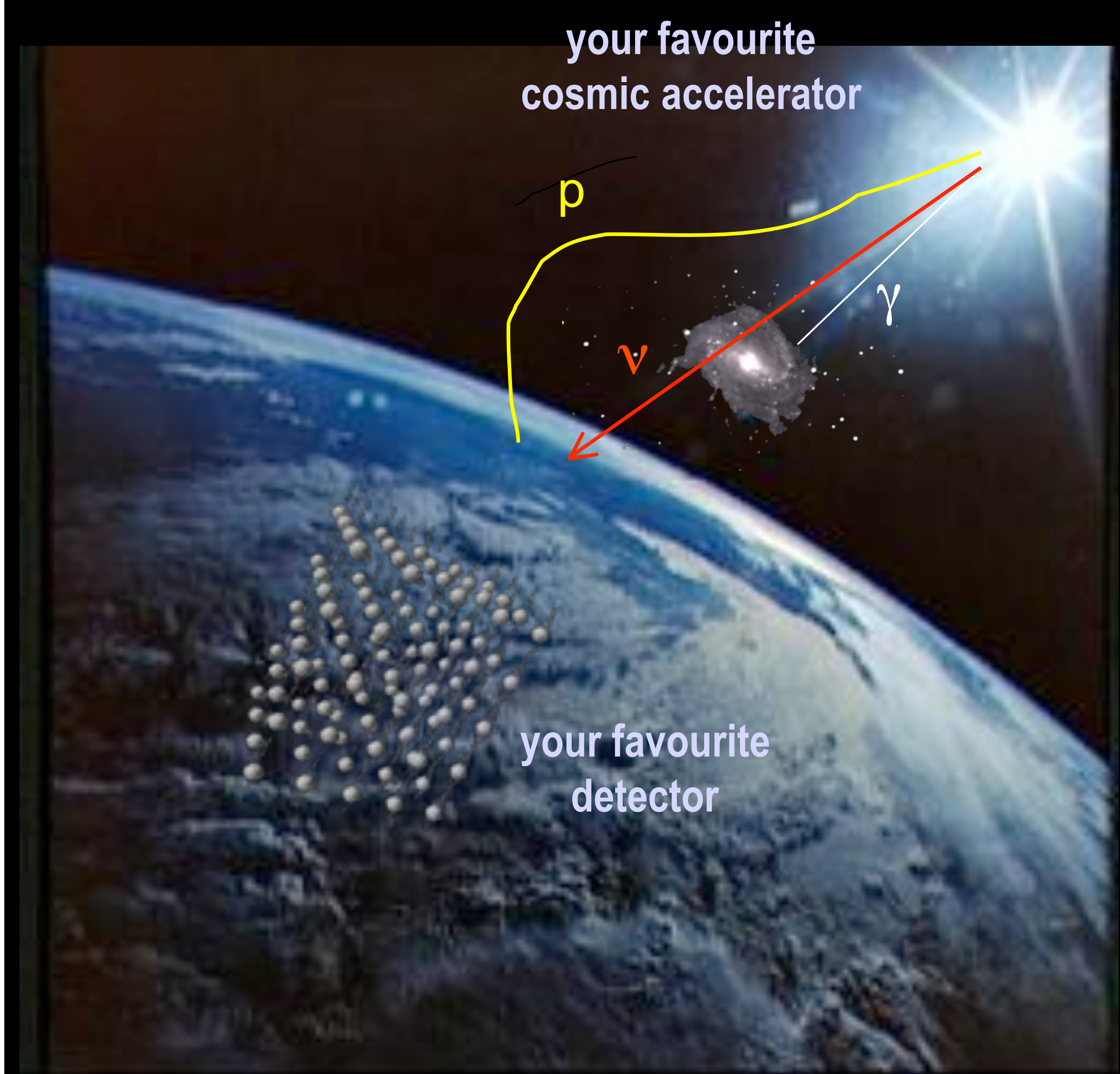


guaranteed sources:

…we know the beam and target are there…

- **atmosphere: neutrinos from π & K mesons decays**
- **galactic plane:**
  - CR interacting with ISM, concentrated on the disk
- **Cosmic Microwave Background (diffuse):**
  - UHE $p\,\gamma \rightarrow \Delta^+ \rightarrow n\,\pi^+$ ($p\,\pi^0$)

particle propagation in the Universe



production:

neutrino production at source:

p+γ or p+p collisions give pions:

$\pi \to \mu_\nu + \nu_\mu \;\rightarrow\; \mu_\nu \to e^- + \nu_\mu + \nu_e$

neutrino flavors: $\nu_e : \nu_\mu : \nu_\tau$ 1:2:~0 at sou

Expect 1:1:1 at detector

propagation:

photons: can be absorbed on intervening matter or radiation;

protons: deviated by magnetic fields

at high-enough energies:

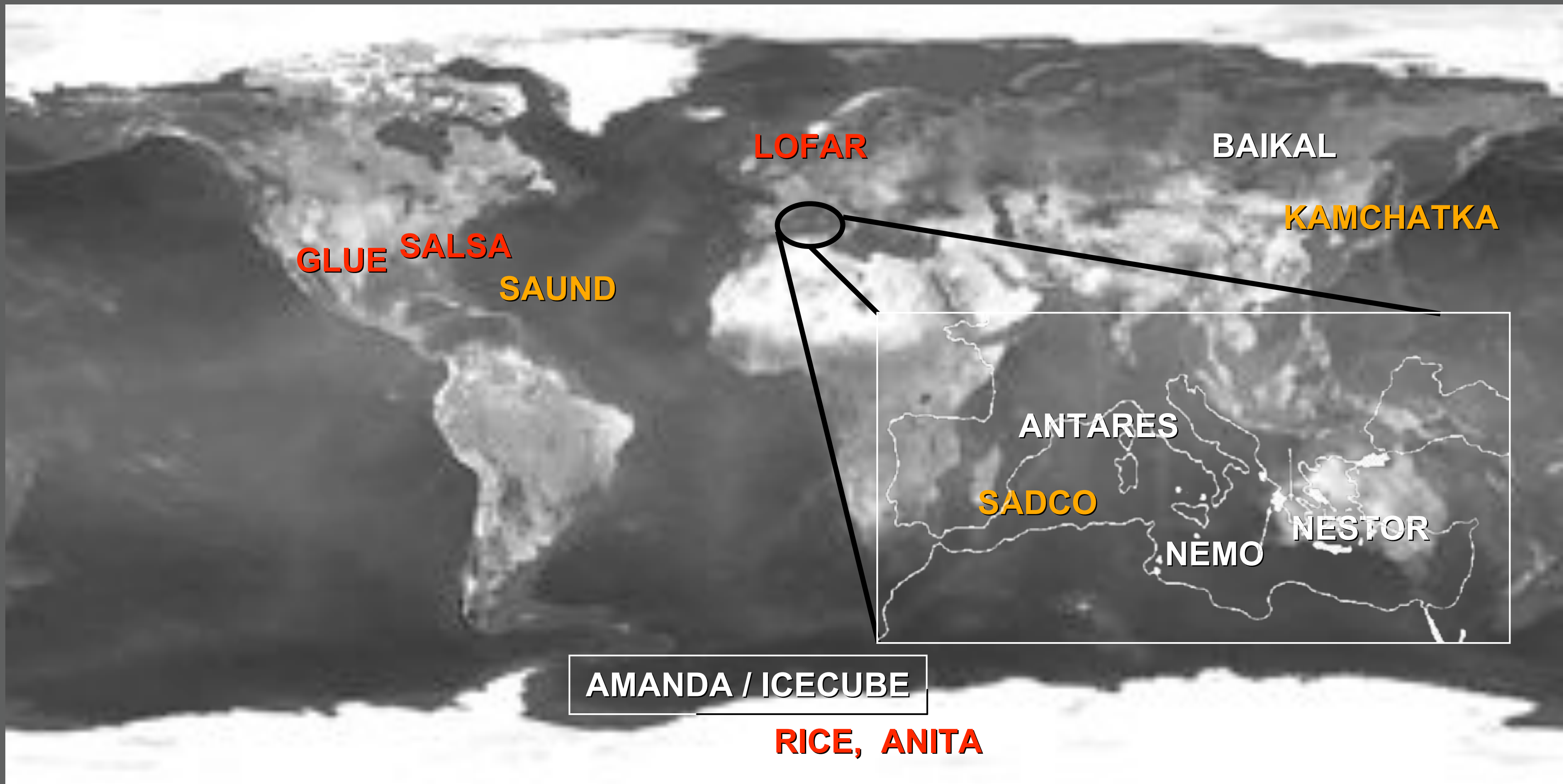
p and γ react with the CMB bckgr.

ν's will get to you

however:

ν's extremely difficult to detect!

current HE neutrino detection efforts



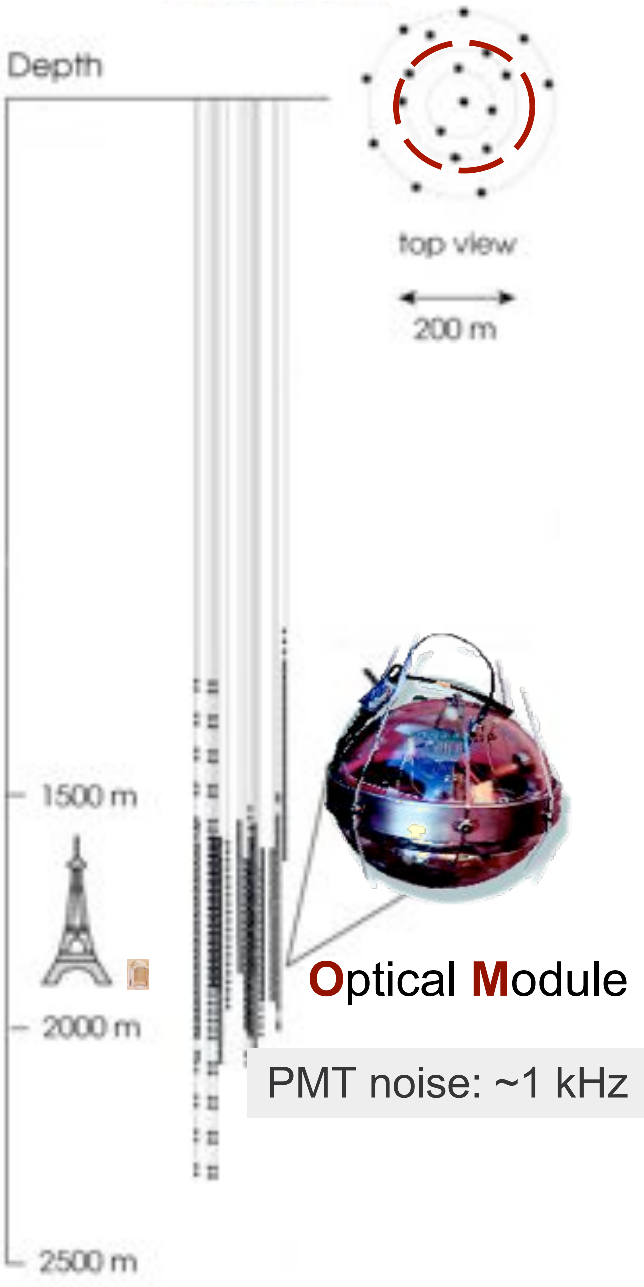
OPTICAL

RADIO

ACOUSTIC

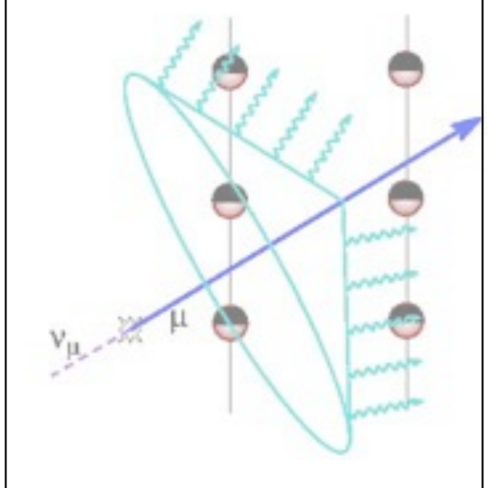
@ extremely high energies ($E>10^{18}$ eV)

the AMANDA detector

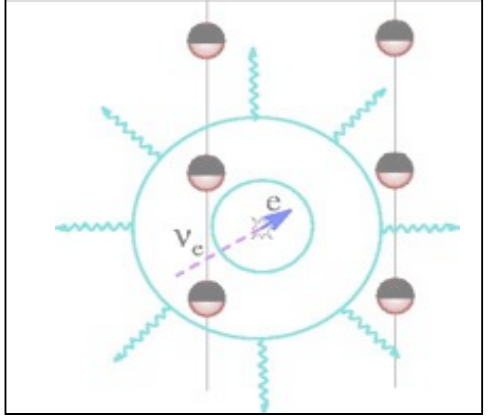


signatures

O(km) long muon tracks



O(10m) cascades, ν_e ν_τ neutral current



$$\Theta_{\mu\nu} \approx 0.7^\circ \cdot (E_\nu / \mathrm{TeV})^{-0.7}$$

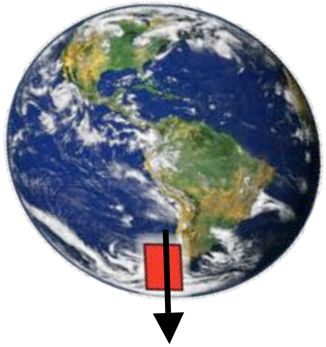
AMANDA-B10

- 10 strings with 302 optical modules
- 450 m height, 1500 m depth
- data years: 1997/99

AMANDA-II

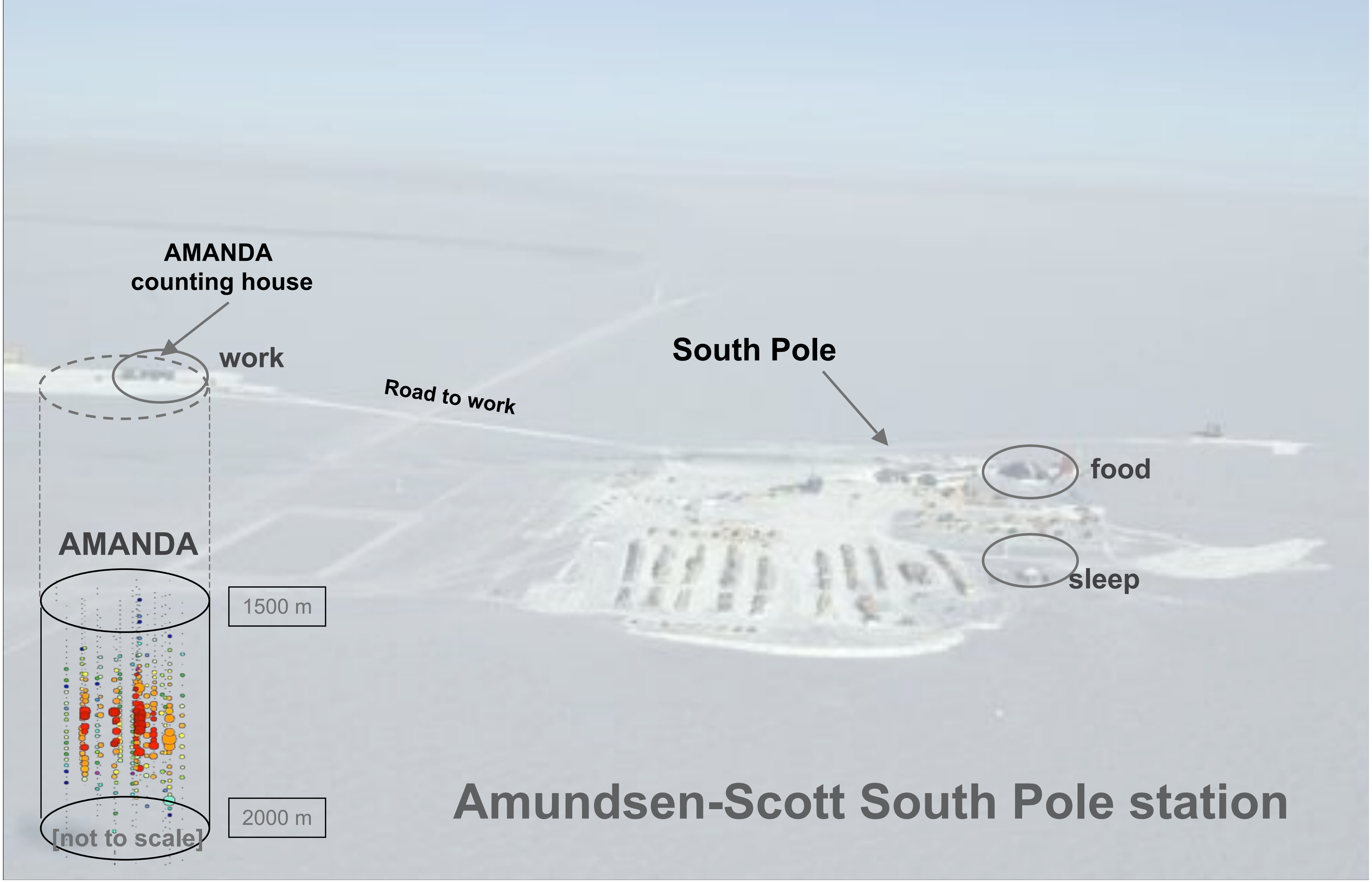
- 19 strings, 677 OMs
- running since 2000
- new DAQ with FADC since 2003

"Up-going" (from Northern sky)



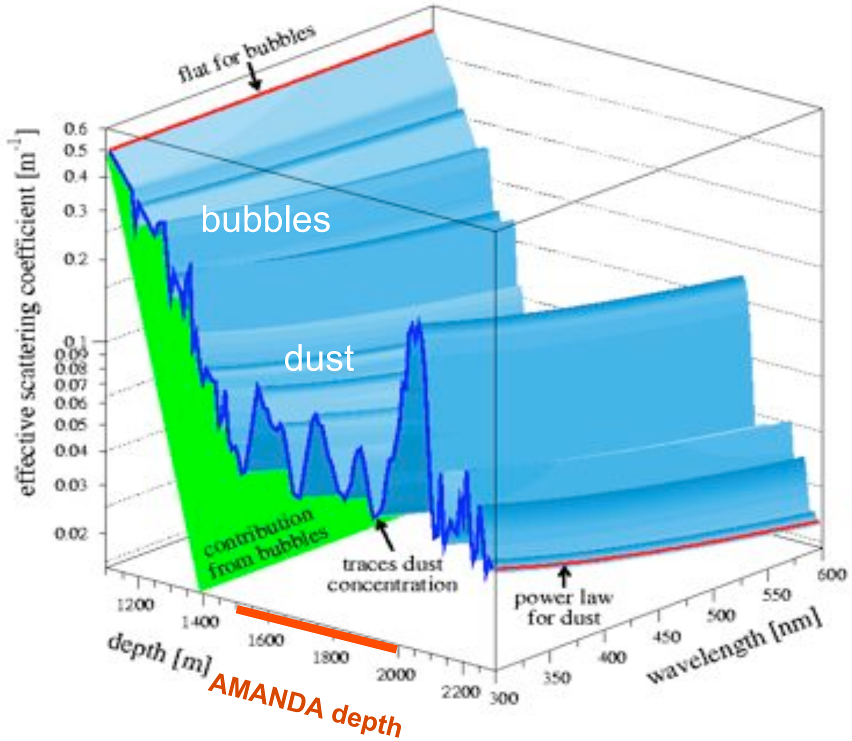
"Down-going" (from Southern sky)

the site

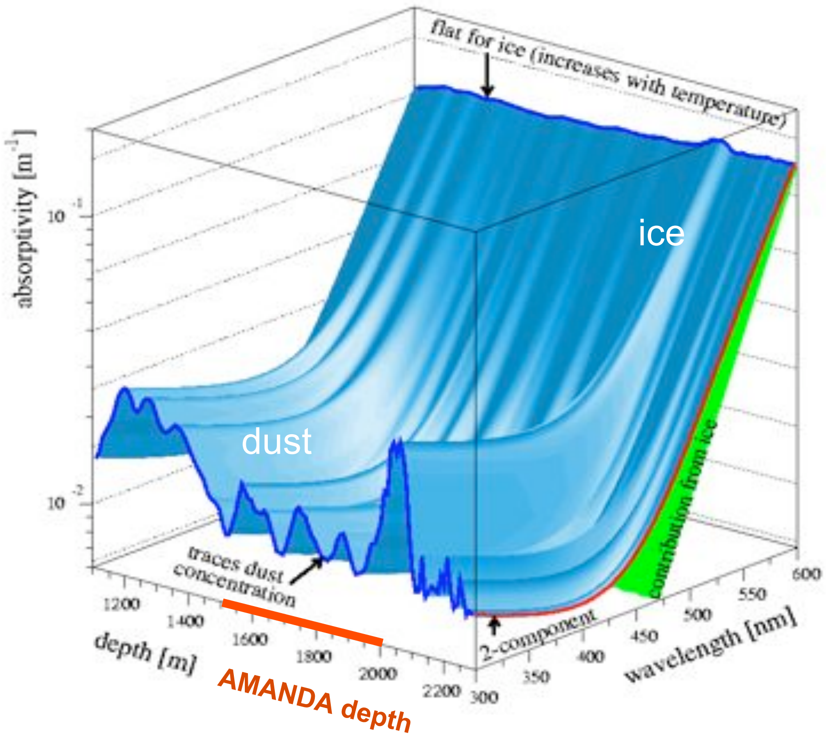

AMANDA
counting house
work
Road to work
South Pole
food
sleep
AMANDA
1500 m
2000 m
[not to scale]
Amundsen-Scott South Pole station

detector medium: nice ice

effective scattering length



absorption length

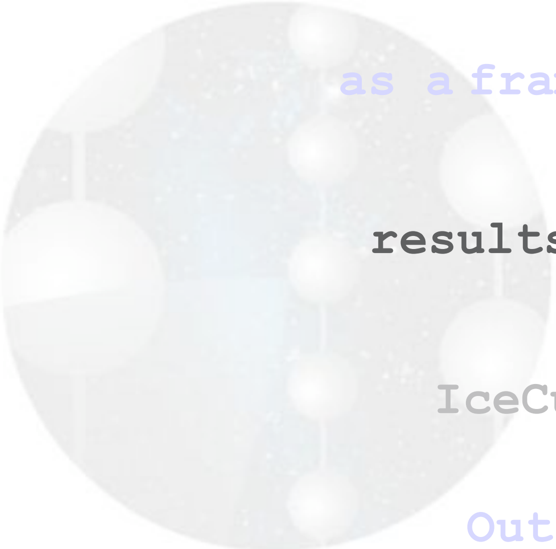


optical properties:

data from calibration light sources deployed along the strings and from cosmic ray muons.

on average:

absorption length @ 400 nm	eff. Scattering length @ 400 nm
110 m	20 m



as a framework: high energy neutrino astronomy

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Outlook

in this talk:

AMANDA results from:

→ atmospheric neutrinos

→ searches for an extra-terrestrial ν flux:

→ galactic plane

→ diffuse

→ point source

→ transient (known 'flary' objects & GRBs)

→ search for dark matter in the form of WIMPs:

→Excess of neutrinos from the center of the Sun/Earth

→ Other topics: cosmic ray composition, gamma-ray astronomy with muons, supernova searches, exotic particles

- agreed AMANDA collaboration strategy: **analyses are done 'blind'**.
cuts optimized on a % of data or on a time-scrambled data set.
- systematic uncertainties (can be big in our case) included in limit calculations

AMANDA detector performance

muons:

pointing resolution: **1.5° - 2.5°**

$\sigma(\log(E_{reco}/E_{true}))$: **0.3 – 0.4**

coverage: **2π**

cascades: ($e^{\pm}$, $\tau^{\pm}$, neutral current)

pointing resolution: **30° - 40°**

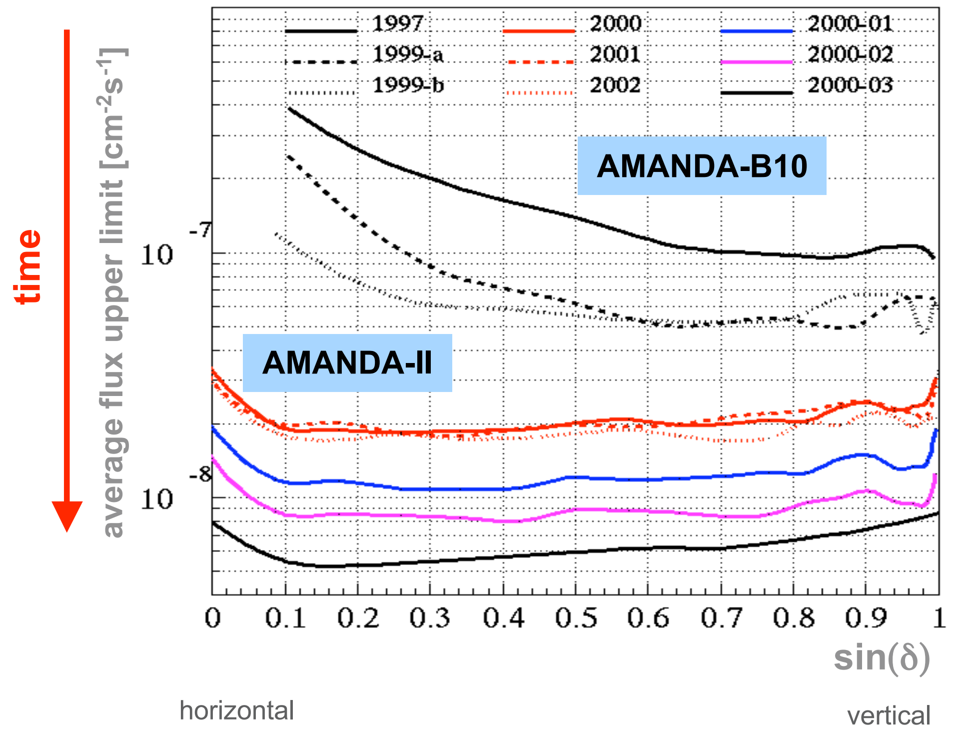
$\sigma(\log(E_{reco}/E_{true}))$: **0.1 – 0.2**

(5TeV < E < 5PeV)

coverage: **4π**

μ effective area: **>10000** m^2 for E_μ>1TeV

Average upper limit = sensitivity (δ>0°)
(integrated above 10 GeV, E^{-2} signal)



known beam: atmospheric neutrinos

atmospheric neutrinos:

- guaranteed test beam
- background for other searches

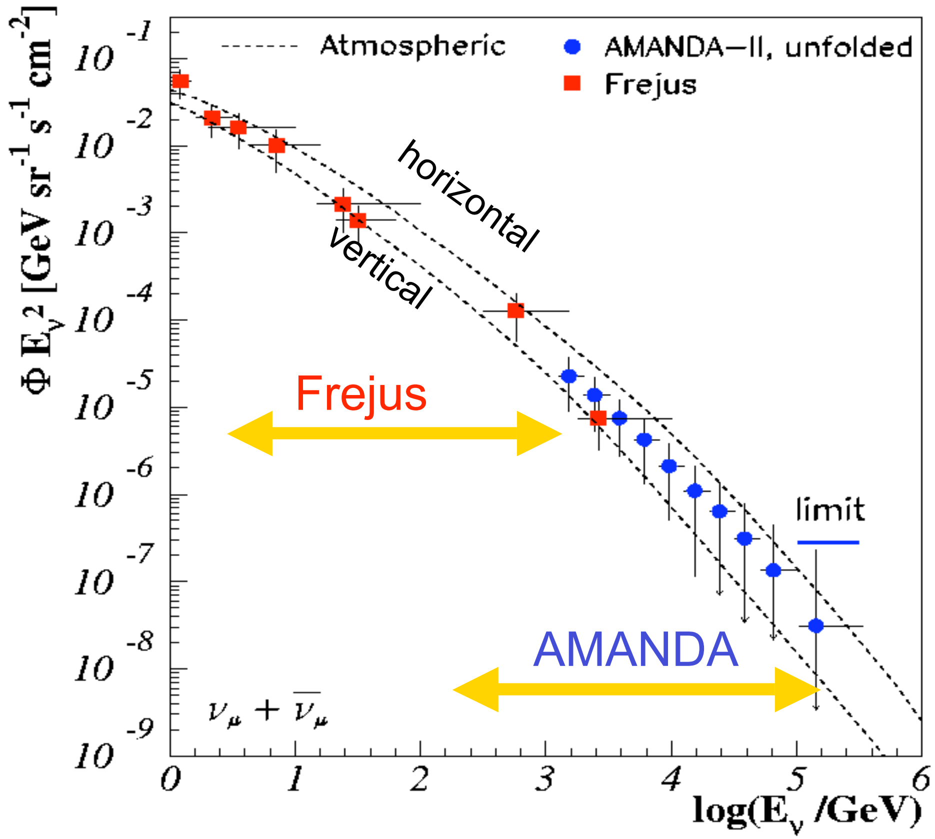
▸ reconstruct energy of up-going μ`s

▸ obtain ν energy spectrum from regularized unfolding

set limit on cosmic neutrino flux:

→ how much E^{-2} cosmic ν - signal allowed within uncertainty of highest energy bins?

first spectrum > 1 TeV (up to 300 TeV)
- matches lower energy Frejus data

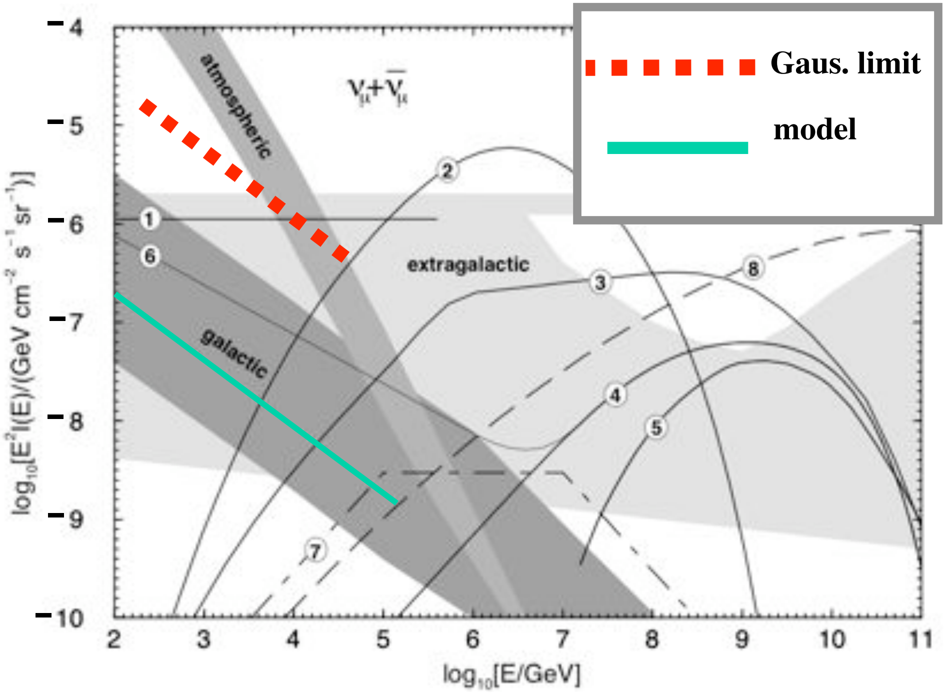


limit on diffuse E^{-2} ν_μ flux (100 -300 TeV): $E^2\Phi_{\nu_\mu}(E) < 2.6\cdot10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1}

ν's from the galactic plane

- **location of AMANDA not optimal** ➔ reach only outer region of the galactic plane: $33^o<\delta<213^o$
- **three signal ansatz:**

  line source, Gaussian source, diffuse source
- **limits include systematic uncertainty** of 30% on atm. ν flux
- **energy range**: 0.2 to 40 TeV



data sample 2000-03: 3369 ν evts:

on-source region	on-source events	expected background	90% event upper limit	line source limit $GeV^{-1}\ cm^{-2}\ s^{-1}\ rad^{-1}$	diffuse limit $GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}$	gaussian limit $GeV^{-1}\ cm^{-2}\ s^{-1} sr^{-1}$
±2.0°	**128**	**129.4**	**19.8**	**6.3×10^{-5}**	**6.6×10^{-4}**	—
±4.4°	**272**	**283.3**	**20.0**	—	—	**4.8×10^{-4}**

search for HE neutrinos from the cosmos

strategies in the search for point sources:

- **diffuse** flux with no time-space correlations.
  - from high energy tail of atmospheric ν_μ, 100 – 300 TeV
  - from cascades @ higher energies, 50 TeV < E < 5 PeV
- spatial correlation with **steady** objects
  - search for clusters of events (w. or w/o catalogue)
  - stacking of same-type of point source candidates
- space and/or time correlation with **transient** phenomena
  - known active flary periods of TeV gamma sources
  - coincidence with GRBs

energy regions:

analyses optimized for ν_μ

(**reduced sensitivity to ν_e and ν_τ**)

HE: TeV < E_ν < PeV

- search confined to up-going tracks

UHE: E_ν > PeV

- Earth opaque: search in the upper hemisphere and close to the horizon

all-flavour

Cascades: TeV < E_ν < PeV

- 4π sensitivity

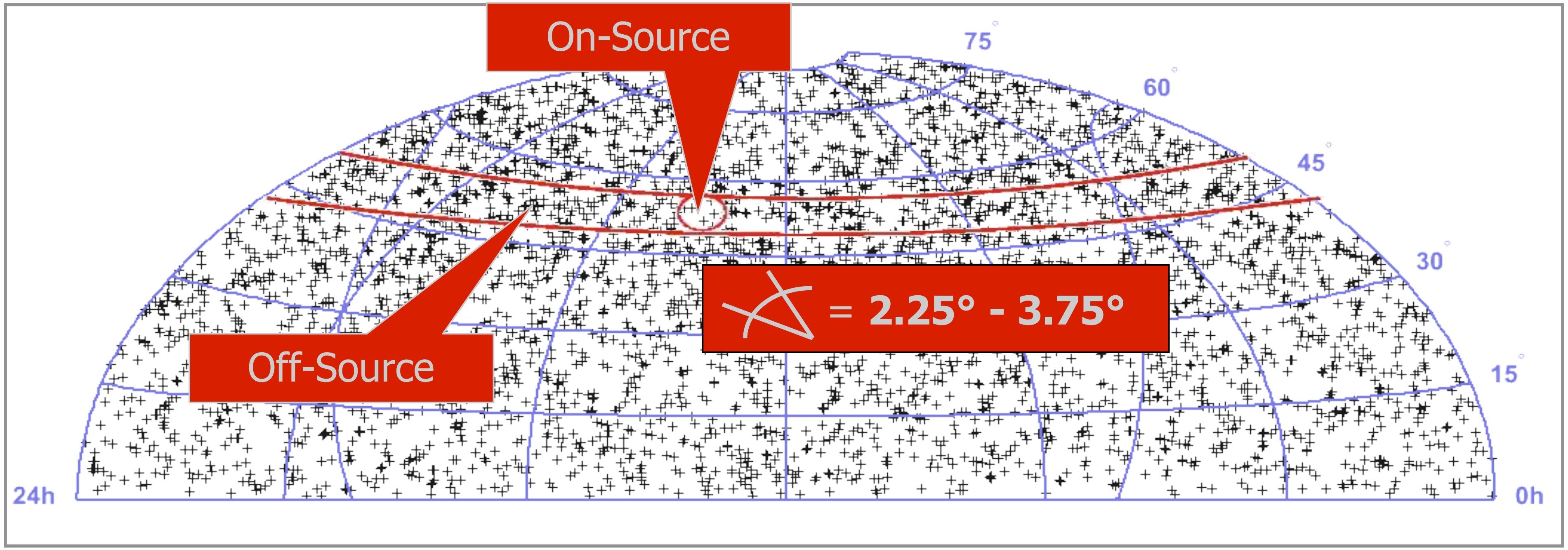
search for point sources in the northern sky

data from 2000-2004 (1001 days)

4282 ν from northern hemisphere

4250 $^{+300}_{-1000}$ ν expected from MC atmospheric background

- search for excesses of events on:
  - **a grid on the full Northern Sky**
  - **a set of selected candidate sources**
  - **stacked search of generic source classes**



Atm-ν Background from 'off-source' data → only statistical error ~ 7%

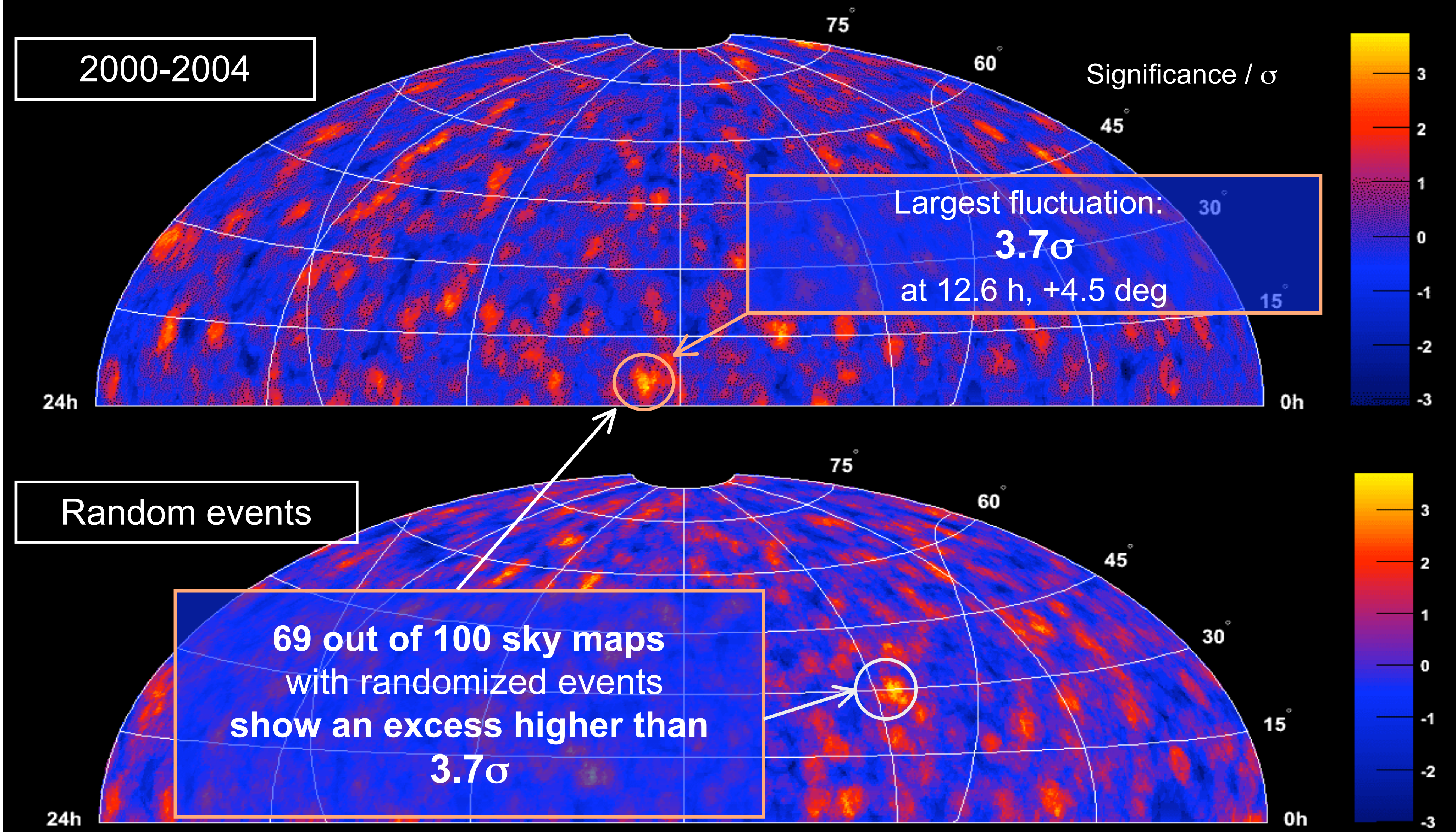
Flux upper limits by comparison to signal simulation (E^{-2} spectrum)

search for clusters of events from known objects

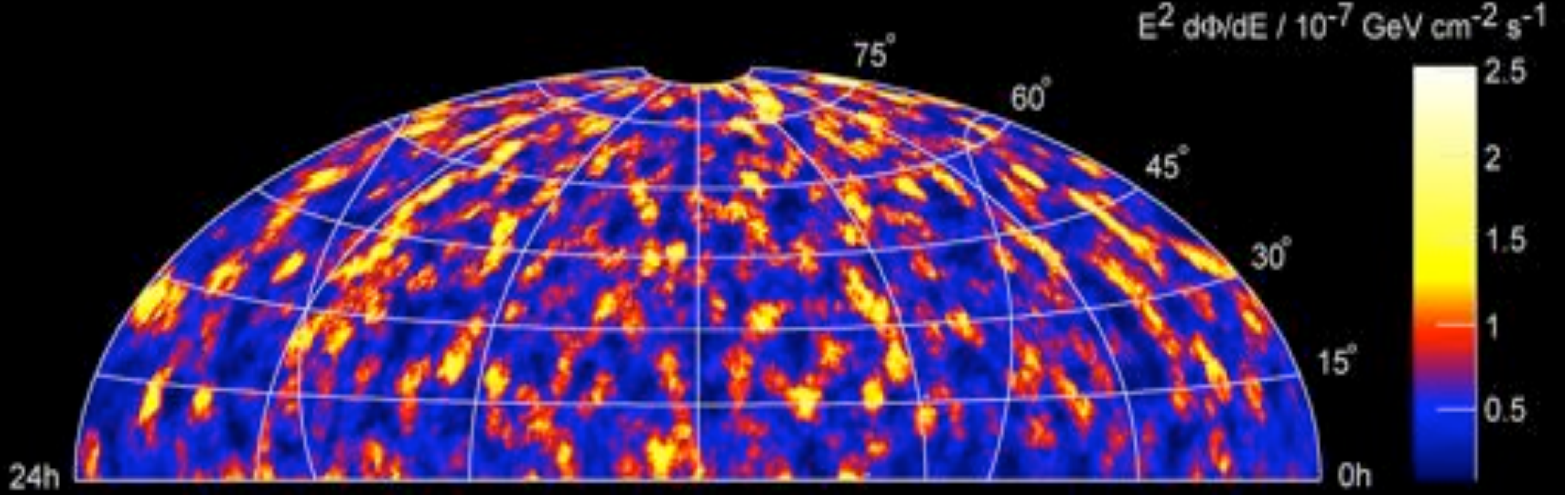
	Source	Events observed/ background (2000-2004)	Excess parameter -log10 P	Flux upper limit (15% sys, 7% stat) Φ_0 @ 90% CL [10^{-7} GeV cm^{-2}s^{-1}] for $\Phi = \Phi_0 E^{-2}$	
				$\Phi_0(\nu_\mu)$	$\Phi_0(\nu_\mu+\nu_\tau)$ (1:1)
AGN	**Markarian 421**	**6 / 7.37**	0.13	0.42	0.74
	Markarian 501	**8 / 6.39**	0.51	0.85	1.47
	1ES1959+650	**5 / 4.77**	0.29	0.78	1.35
	M87	**6 / 6.08**	0.25	0.49	0.87
	3C273	**8 / 4.72**	0.98	1.00	1.80
Microquasar	**SS433**	**4 / 6.14**	0.06	0.27	0.48
	LSI +61 303	**5 / 4.81**	0.28	0.74	1.26
	Cygnus X-1	**8 / 7.01**	0.39	0.77	1.32
	Cygnus X-3	**7 / 6.48**	0.50	0.68	1.18
SNR	**Cassiopeia A**	**5 / 6.00**	0.15	0.51	0.89
	Crab Nebula	**10 / 6.74**	0.84	1.02	1.78

- … out of 32 sources in candidate list
- No significant excess, no indication for a neutrino source
- Systematic error of 15% on signal prediction included in limits

grid search for point sources



grid search for point sources: limit map



90% confidence level flux upper limits for the northern hemisphere
(15% systematic error included)

diffuse flux search

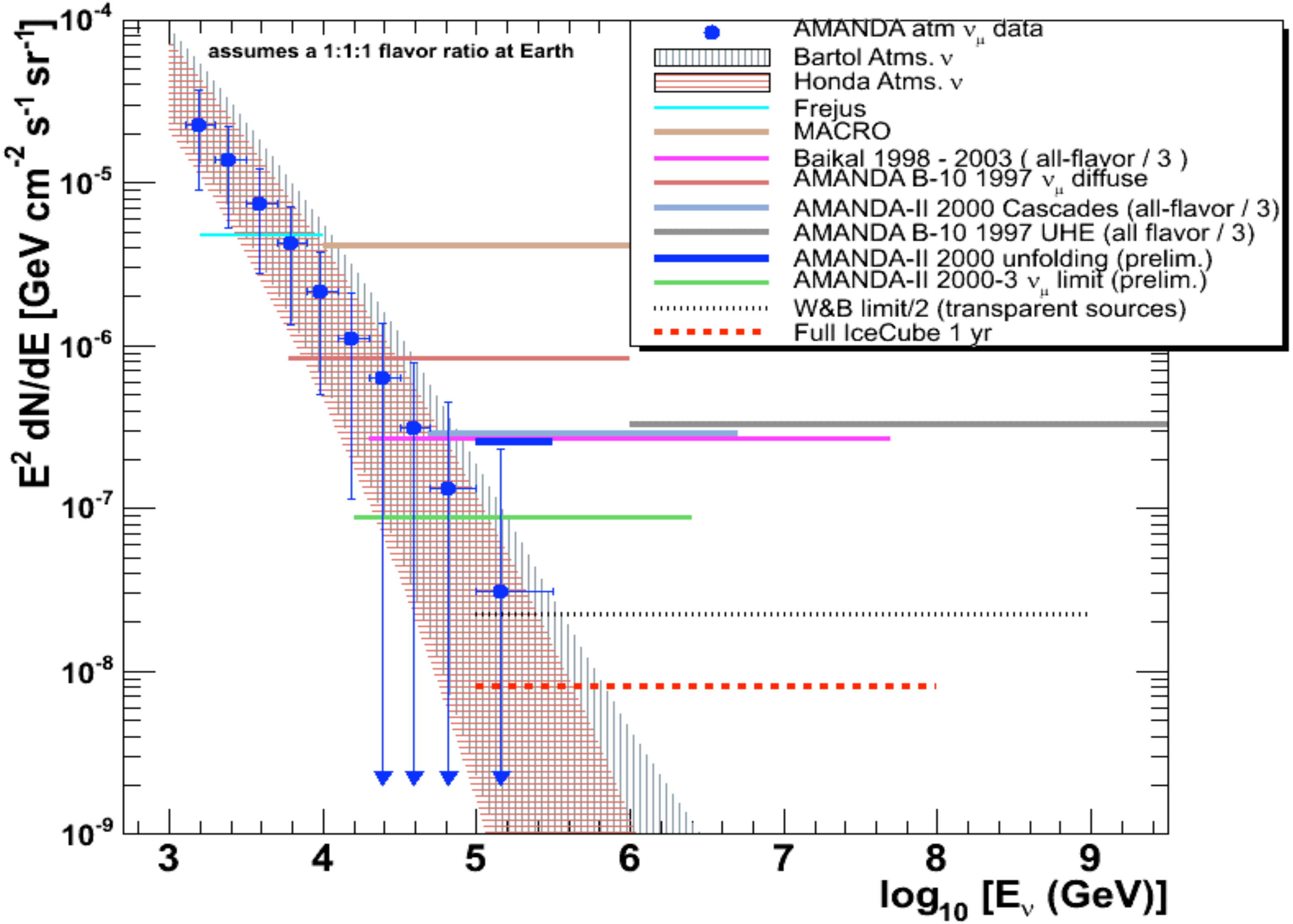
- Sample of atmospheric neutrinos optimized for best sensitivity
- MC prediction normalized to data in the range $50<N_{hit\ OMs}<100$
- Search for signal in the $N_{hit\ OMs}>100$ region

2000-2003

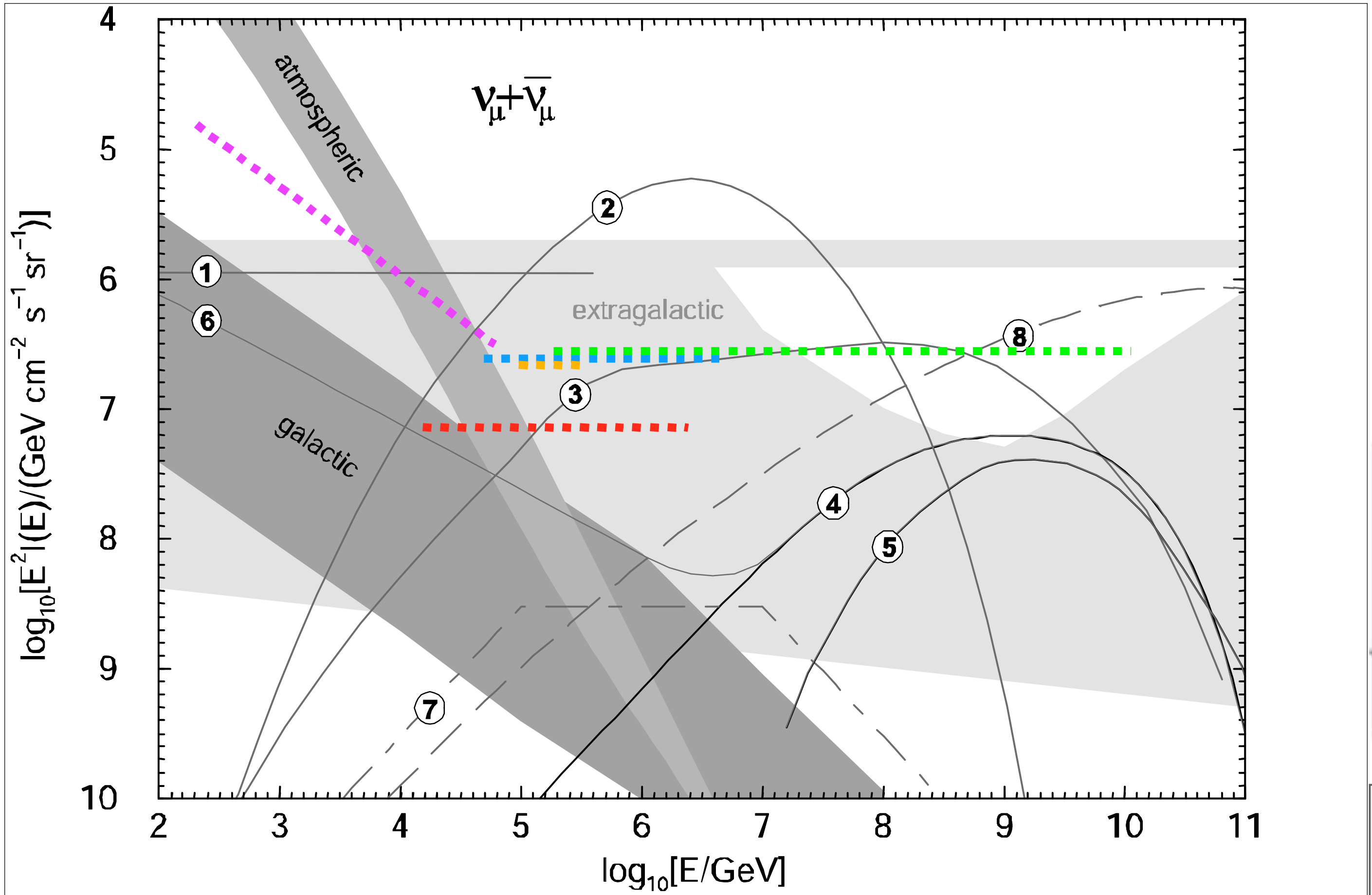
Exp. background
6.1
Sensitivity to $E^2\,\Phi(\nu_\mu)$
$8.8\ 10^{-8}$ GeV cm^{-2} s^{-1}
Energy range
16 TeV < E < 2.5 PeV

Observed events
6
Limit to $E^2\,\Phi(\nu_\mu)$ (90% CL, 35% syst.)
$8.8\ 10^{-8}$ GeV cm^{-2} s^{-1}

AMANDA diffuse limits



AMANDA diffuse limits compared with models



Galactic plane analysis 2000-2003, ν_μ

Non-contained events 2000, all flavor limit / 3

Cascade events 2000, all flavor limit / 3

Spectral unfolding 2000, ν_μ limit

Diffuse analysis 2000-2003, ν_μ

1) Nellen et al: pp interactions in the core of AGNs
2) Stecker & Salamon: p-γ interactions in the core of AGNs
3) Mannheim et al: p-γ interactions in extragalactic photoproduction sources
4) Mannheim: p-γ interactions in blazar jets
5) Rachen & Biermann: p-γ interactions in radio galaxies
6) Mannheim: pp interactions in host galaxies of blazar jets
7) Waman & Bahcall: gamma-ray bursts
8) Sigl et al and Birkel & Sarkar: topological defects

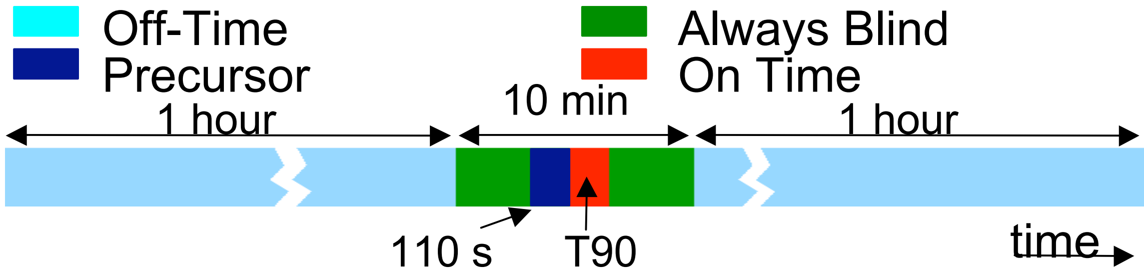
limits for specific flux predictions:

- cuts optimized for each case.
- some models excluded at 90% CL:

Szabo-Protehoe 92. Proc. HE Neutr. Astrop. Hawaii 1992.
Stecker, Salamon. Space Sc. Rev. 75, 1996
Protheroe. ASP Conf series, 121, 1997

search for ν's correlated with GRBs

low background analysis due to both space and time coincidence search!



- catalogues: BATSE+IPN3
- bckg. Stability required within ±1 hour from burst
- several search techniques:
  - **coincidence with T90**
  - **precursor (110s before T90)**
  - **cascades (all flavour, 4π!)**
    - **-coincident with T90**
    - **-rolling time window (no catalogue)**

year	# GRBs	from	preliminary 90%CL 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 cm^{-2}s^{-1} sr^{-1}
'00 - '03	139	BATSE & IPN bursts	$E^2 d\Phi_\nu/dE = 3 \cdot 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}
'01 - '03	50	IPN bursts	(Assuming the Razzaque model) $E^2 d\Phi_\nu/dE = 5 \cdot 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}
'01	(425)	Rolling window	$E^2 d\Phi_\nu/dE = 2.7 \cdot 10^{-6}$ GeV cm^{-2}s^{-1}sr^{-1}
'00	73	BATSE triggered bursts	$E^2 d\Phi_\nu/dE = 9.5 \cdot 10^{-7}$ GeV cm^{-2}s^{-1}sr^{-1}

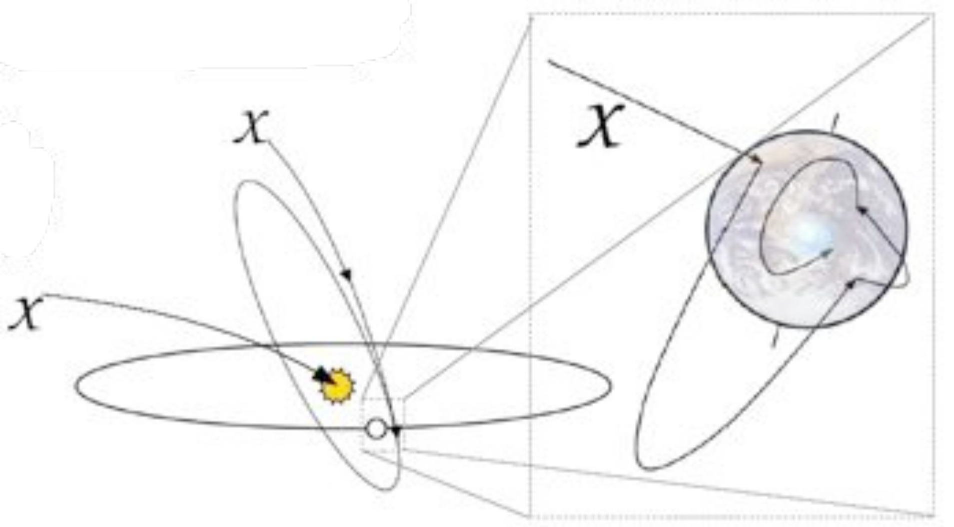
search for DM candidates in the Sun/Earth

- **$\Omega_m \approx 30\%$, $\Omega_b \approx 4\%$**

→ non-baryonic matter

→ MSSM candidate: the neutralino, χ

χ may exist as relic gas in the galactic halo



gravitational accumulation in Sun/Earth makes 'indirect' searches with neutrino telescopes possible

neutralino-induced neutrinos:

$$\chi\chi \rightarrow \left\{ \begin{matrix} q\bar{q} \\ l^+l^- \\ W, Z, H \end{matrix} \right\} \rightarrow \nu$$

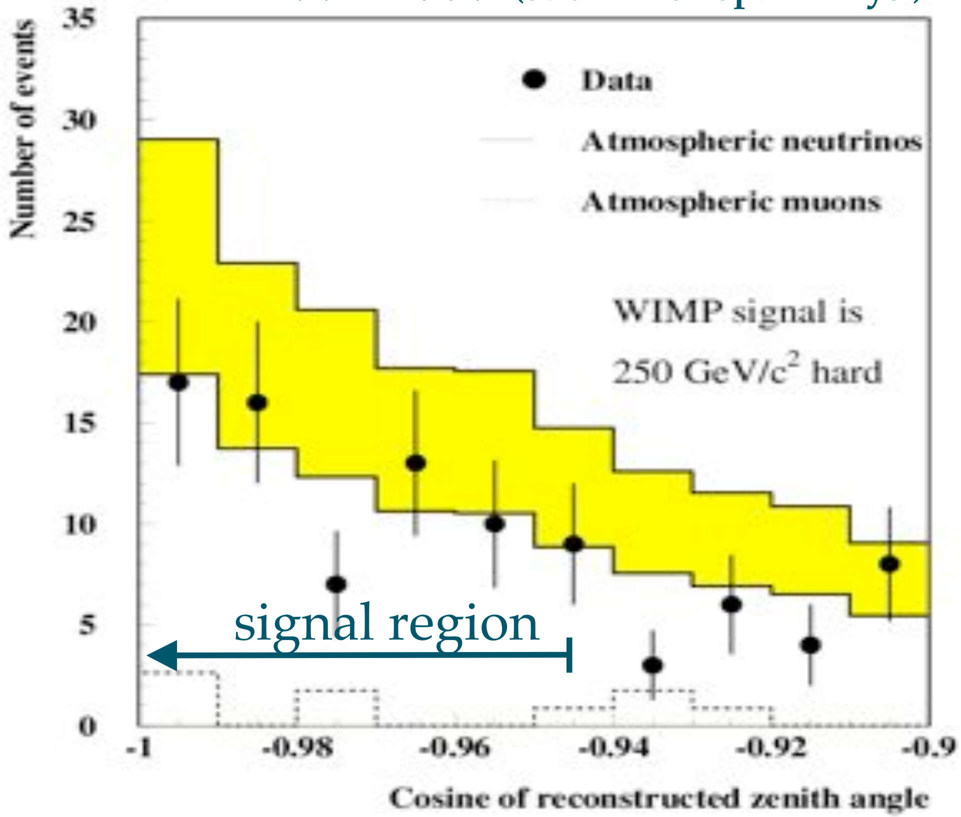
signature: ν excess from Sun/Earth's center direction

A lot of physics (ie. uncertainties) involved:

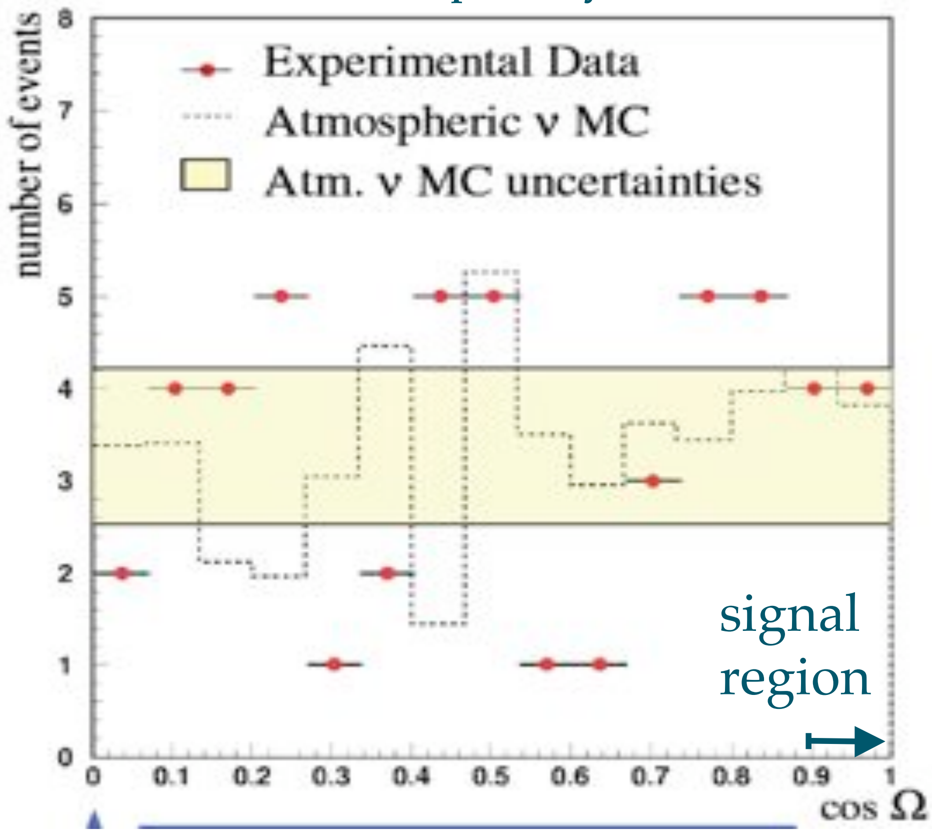
- relic density calculations
- DM distribution in the halo
- velocity distribution
- χ properties (MSSM)
- interaction of χ with matter (capture)

no excess of neutralino induced muons

Earth 1997-1999 **(subm. Astropart. Phys.)**



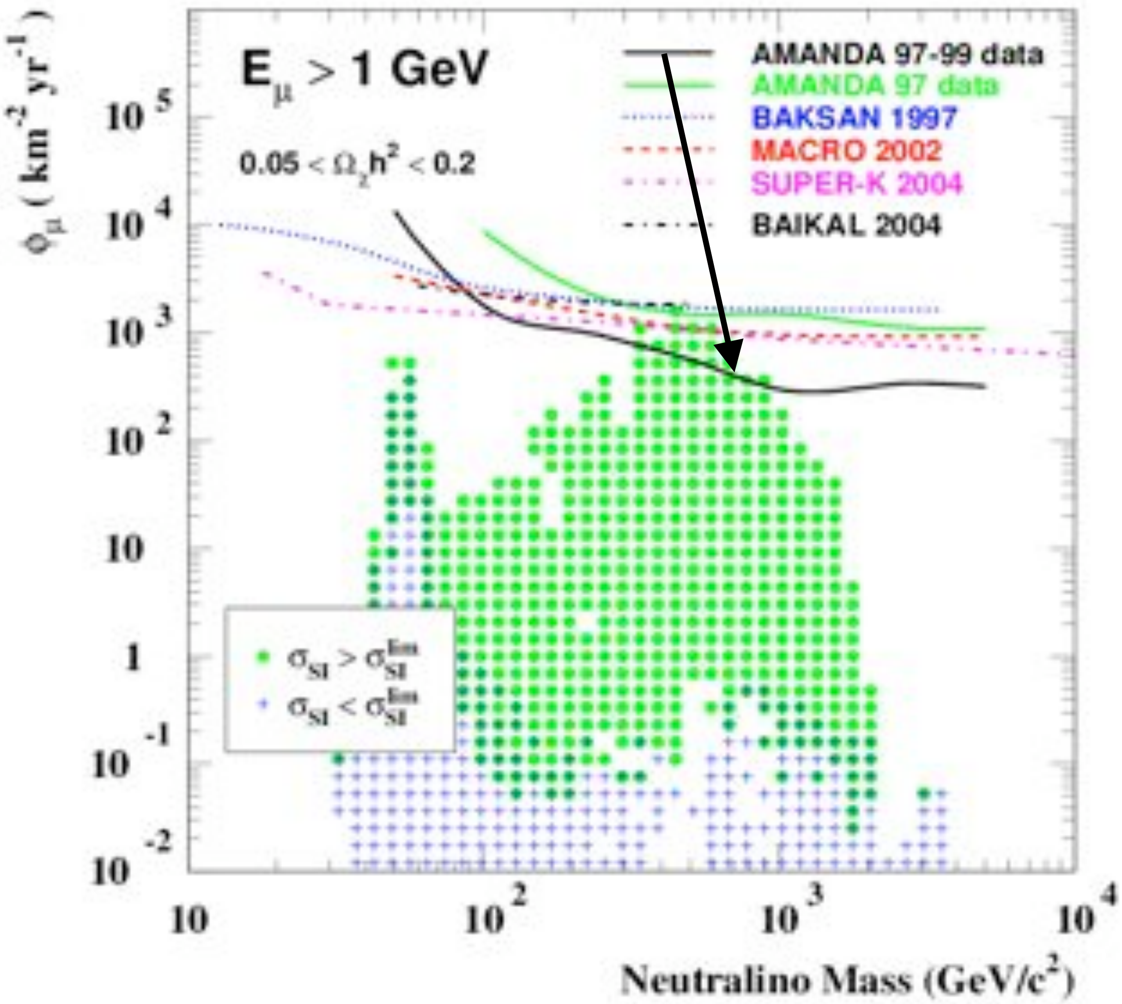
Sun 2001 **(Astropart. Phys. 24(2006)459-466)**



- No excess observed → upper limit on muon flux from neutralino annihilation in Sun or Earth
- # of observed events for given model & nb expected from atmospheric ν → upper limit on # signal events (90% CL)
- Effective volume (sensitivity to signal) from MC

→ **upper limit on muon flux Φ_μ (E_μ>1 GeV) from neutralino annihilations**

muon flux limit: Earth analysis

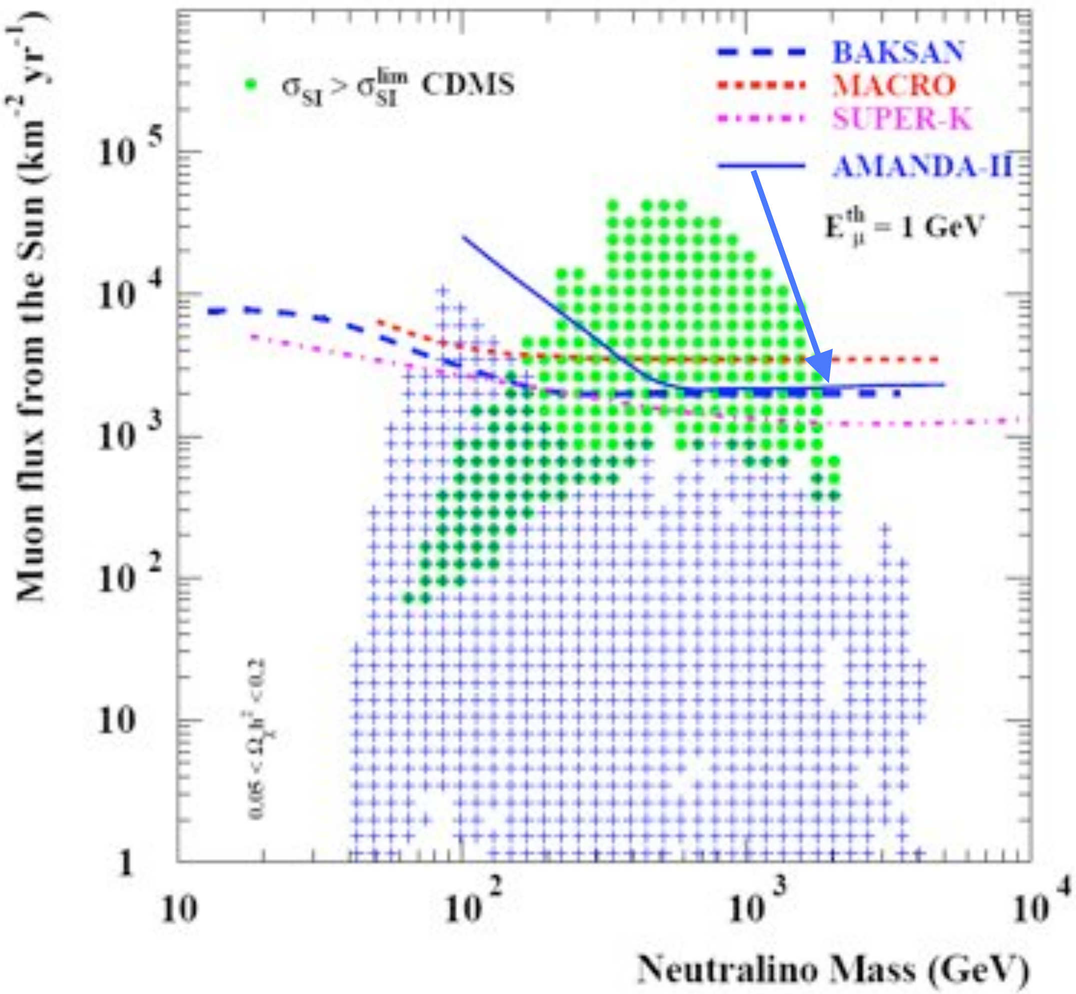


(accep. Astropart. Phys.)

- Improvement wrt ’97 pub:
  - 3x statistics
  - Better reconstructions
  - Filter optimised for each model
- MSSM models predictions
  - disfavoured by CDMS
- Ongoing improvements:
  - AMANDA II data 2001-05
  - New trigger lowers E_{th} - expect improvement for $m(\chi^0_1) < 100$ GeV

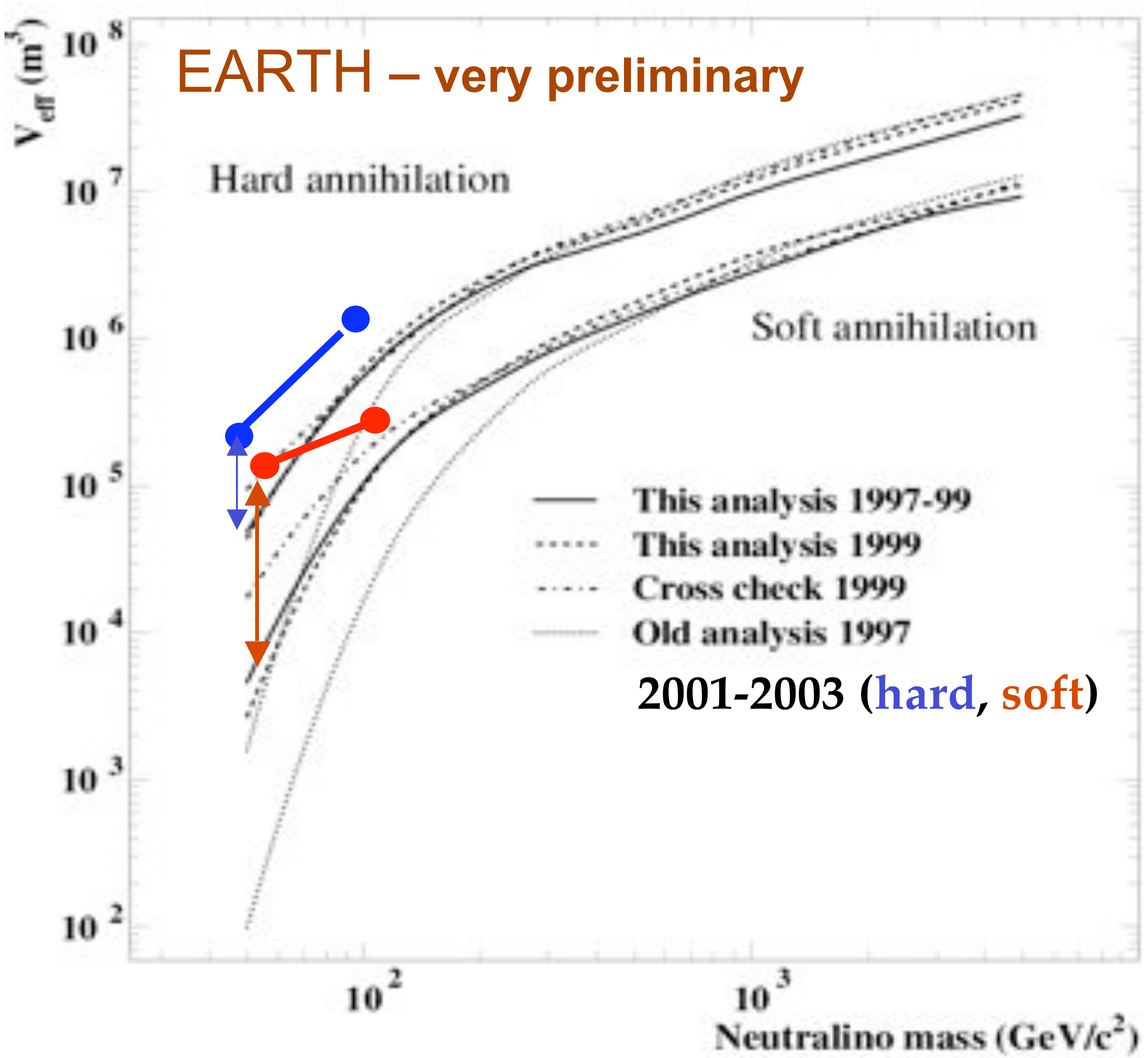
muon flux limit: Sun analysis

(Astropart. Phys. 24(2006)459-466)



- 1st AMANDA II solar neutralino result (2001data)
- 200m diameter enables robust reconstruction of horizontal tracks
- Ongoing improvements:
  - Statistics 2000-05
  - Trigger for low energies
  - Better reco horizontal tracks
  - Combination AMANDA-IceCube 9 strings

AMANDA-II prospects



Improvements

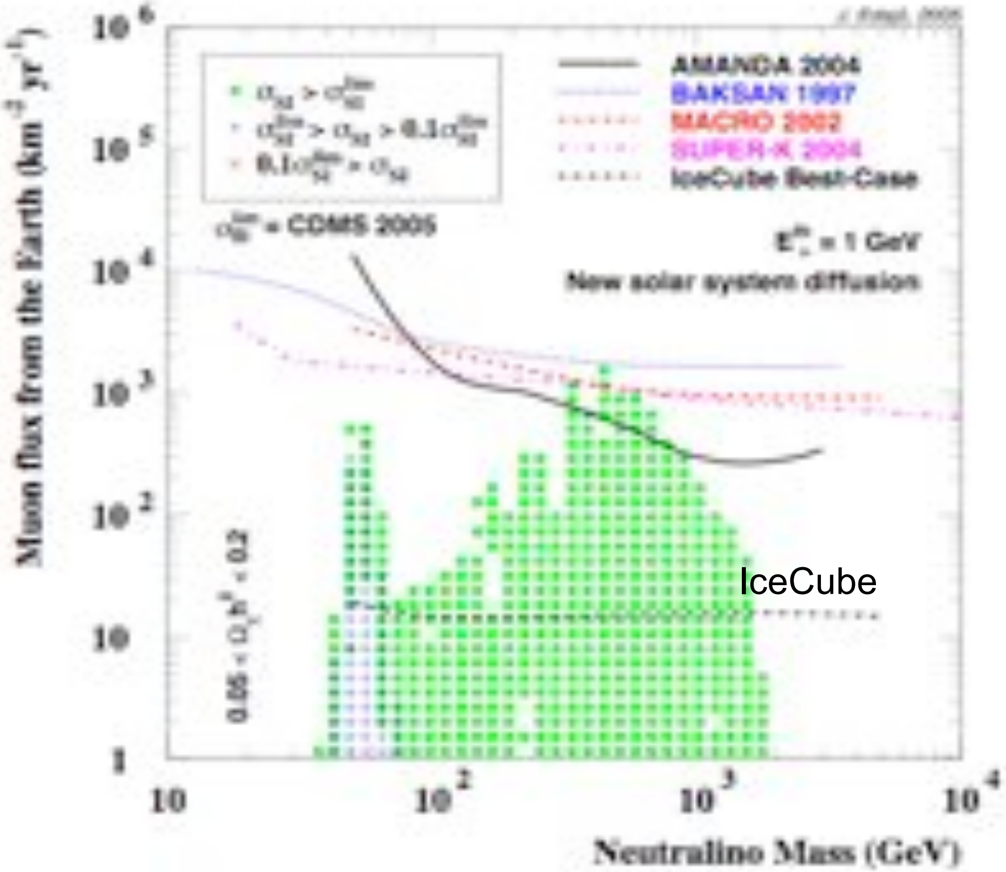
- more statistics: 2001-2003 data set
- improved reconstructions
- new trigger lowers E_{thresh}!

(hard annihilation: xx→ WW

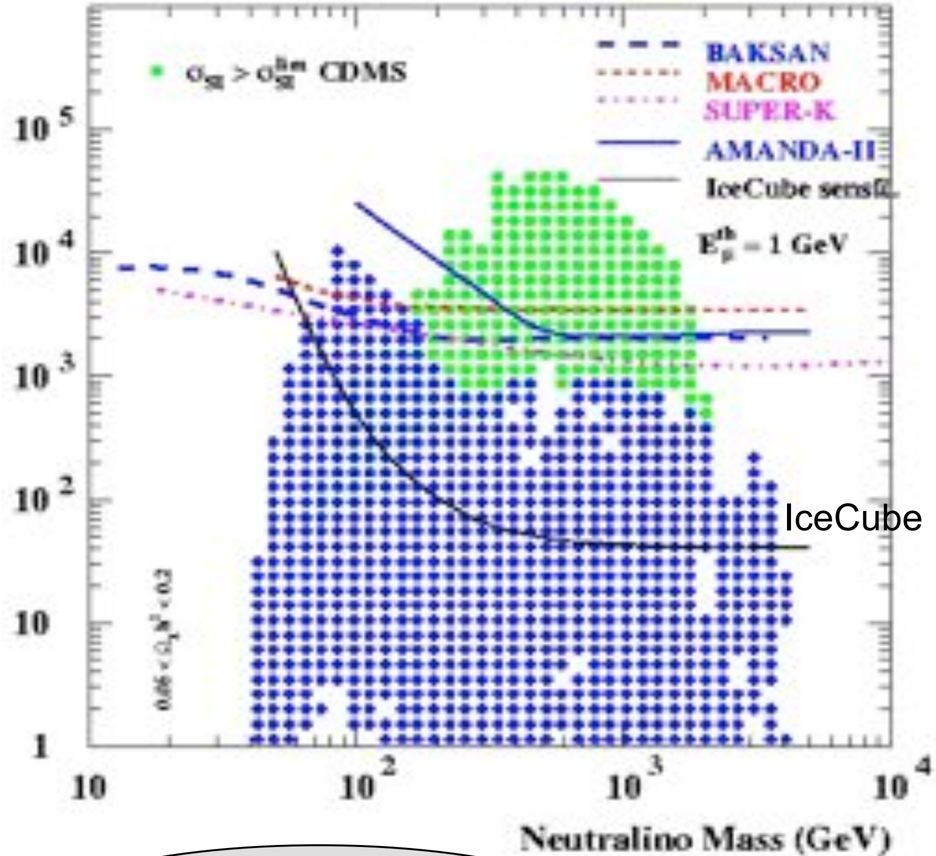
soft annihilation: xx → bb)

IceCube prospects

Earth



Sun



Competitive with direct searches

other particle searches

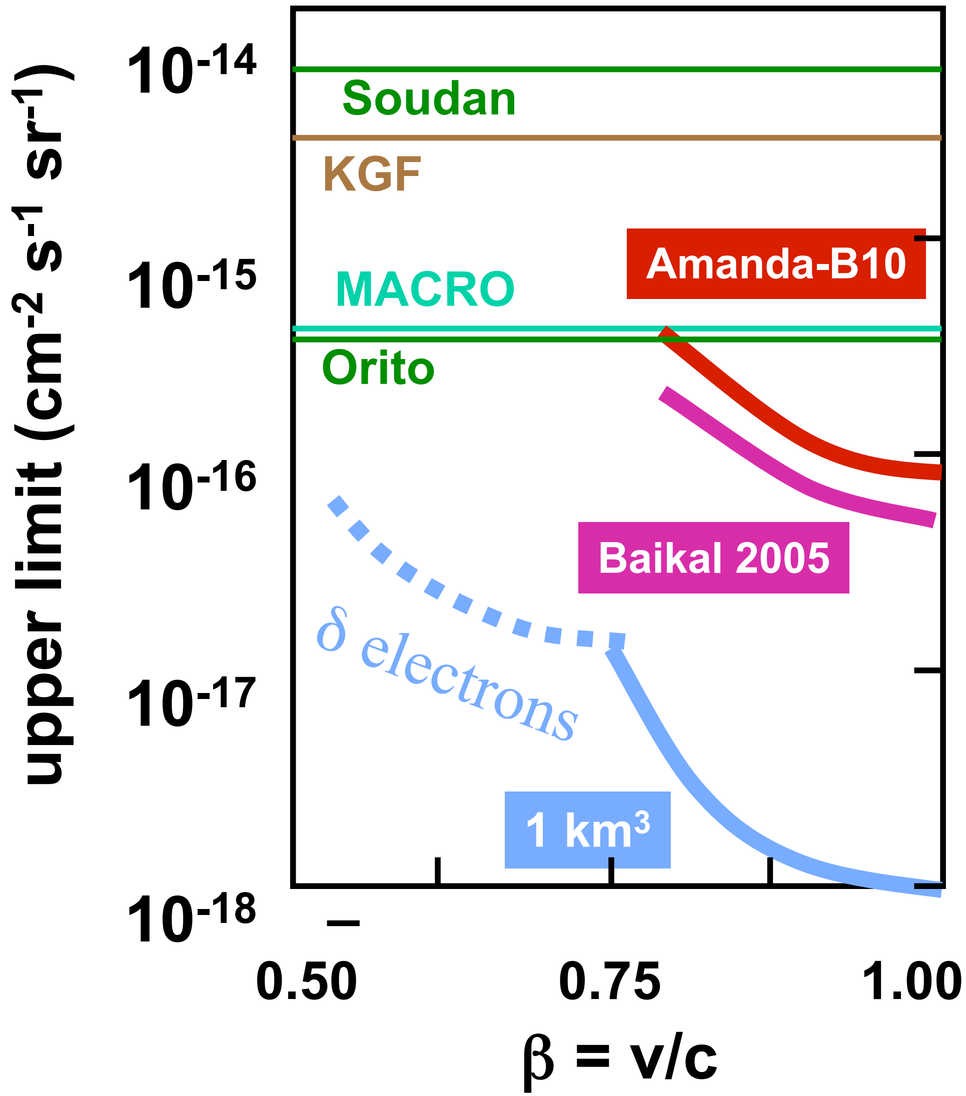
e.g. **magnetic monopoles:**

Cherenkov-light ∝ **$(n \cdot g/e)^2$**

$(1.33*137/2)^2$

→ 8300 times brighter than μ's!

signature:
'slowly' moving bright particles



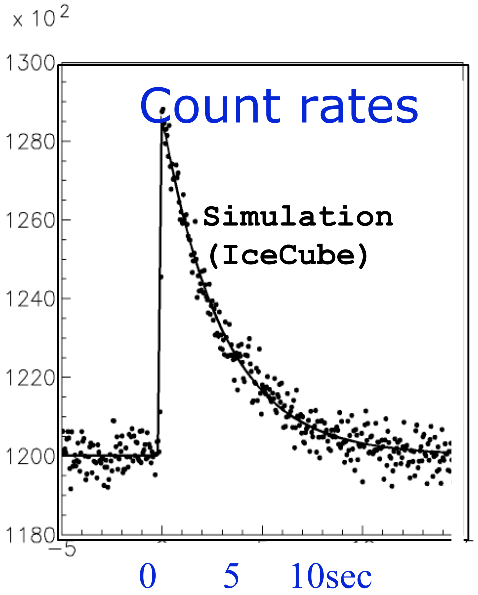
Supernovae search

Bursts of low-energy (MeV) neutrinos
from core collapse supernovae

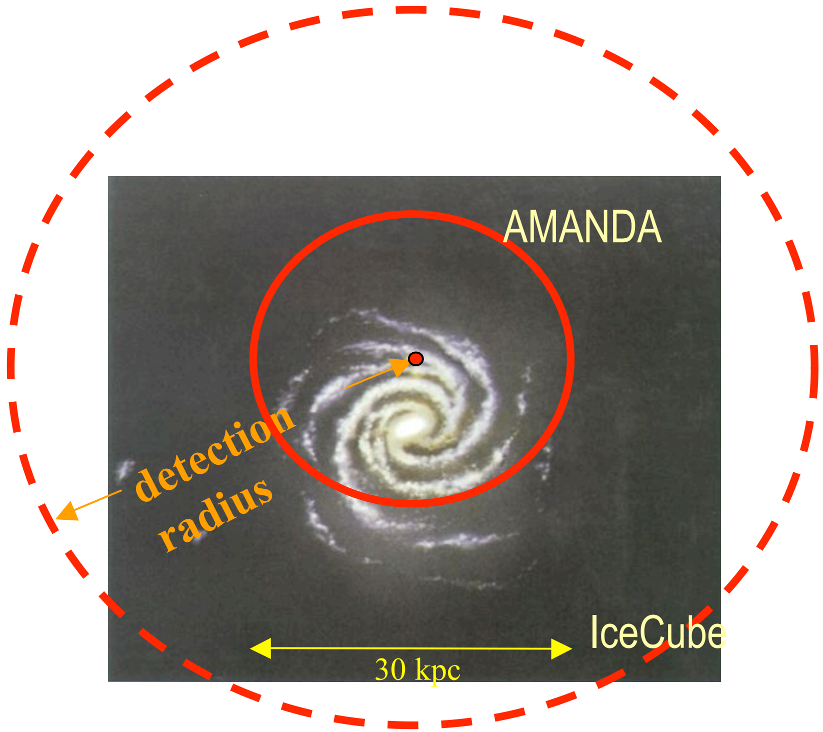
$$\nu_e + p \rightarrow n + e^+$$

The produced positron is emitted almost isotropically

Detection via rate increase of the dark noise rate



SNEWS (SuperNova Early Warning System)
is a collaborative effort among Super-K, SNO, LVD, KamLAND, AMANDA, BooNE and gravitational wave experiments



- AMANDA sees 90% of the galaxy
- IceCube will see out to the LMC
  (Large Magellanic Cloud, ~50 kpc)

as a framework: high energy neutrino astronomy

results from AMANDA

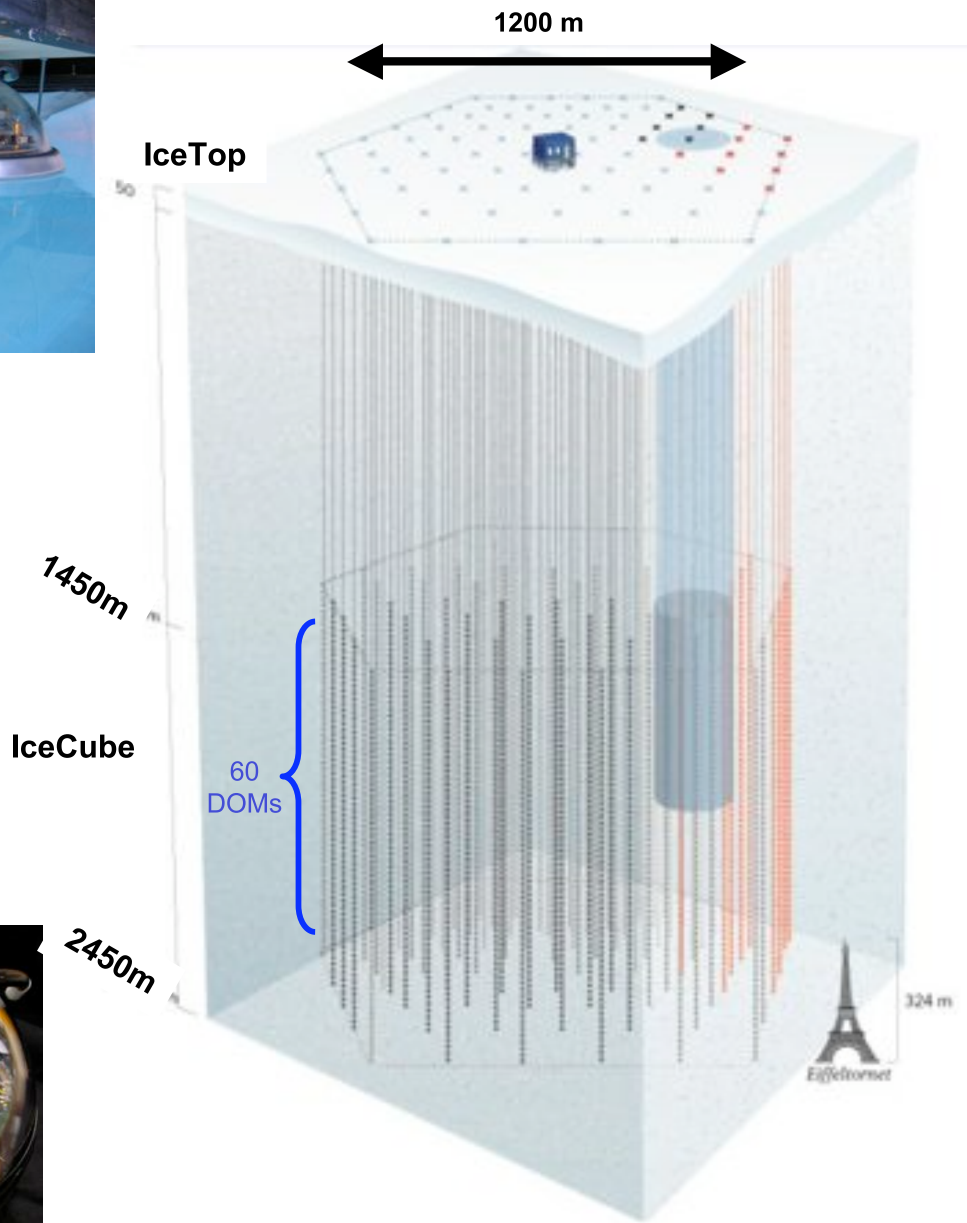
IceCube: status and first events

Outline

the IceCube observatory: IceCube+IceTop

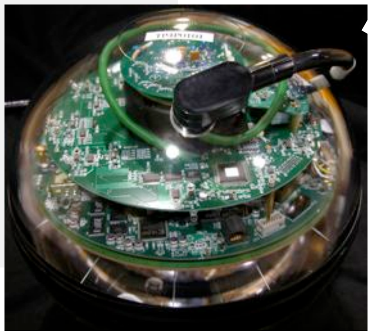
surface array: **IceTop**

- 80 stations air shower array (one per IceCube string)
- similar station concept as Auger
- 2 tanks (2 DOMs each) per station
- 125 m grid, 1 km^2 at 690 g/cm^2



deep ice array: **IceCube**

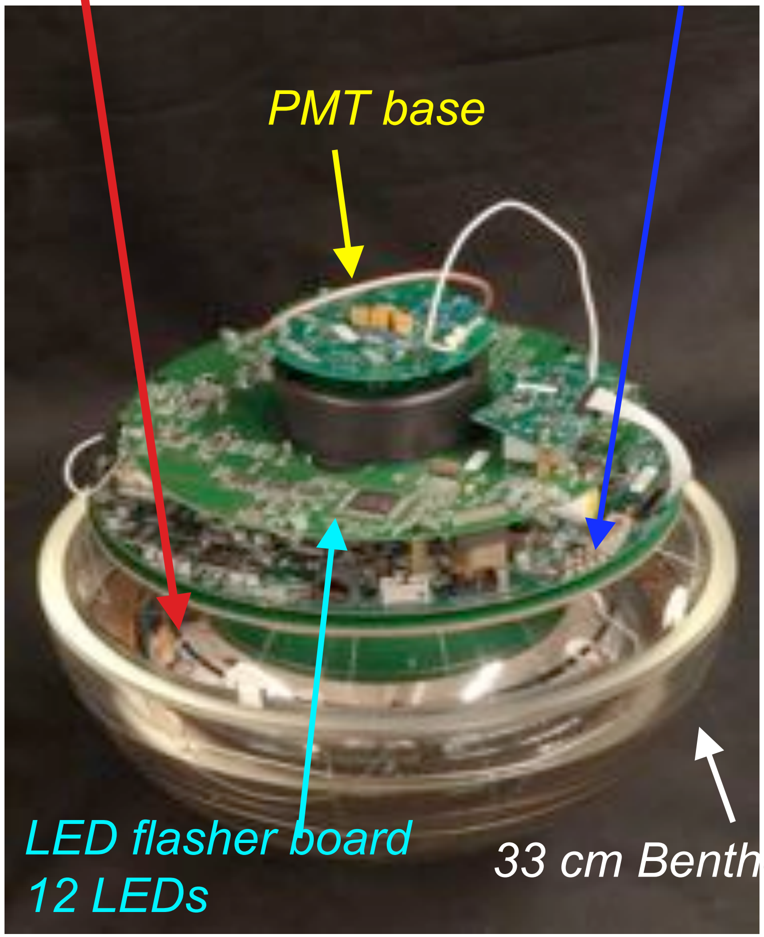
- digital readout technology (DOMs)
- 80 strings, 60 DOM's each
- 17 m DOM spacing
- 125 m between strings
- hexagonal pattern over 1 km^{2}x1 km



the **D**igital **O**ptical **M**odule

Each DOM is an autonomous data collection unit

Power consumption: 3W

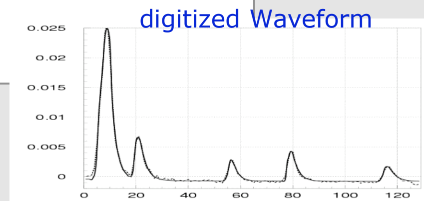


- Measures arrival time of every photon
- 2 Analog Transient Waveform Digitizers at 300 MHz for 400 ns range and FADC recording at 40 MHz 6.6 μs range (event duration in ice)
- Dynamic range 500pe/15 nsec, 25000 pe/6.4 μs

Send all data to surface over 3.3 km twisted pair copper cable: power, data and time stamping

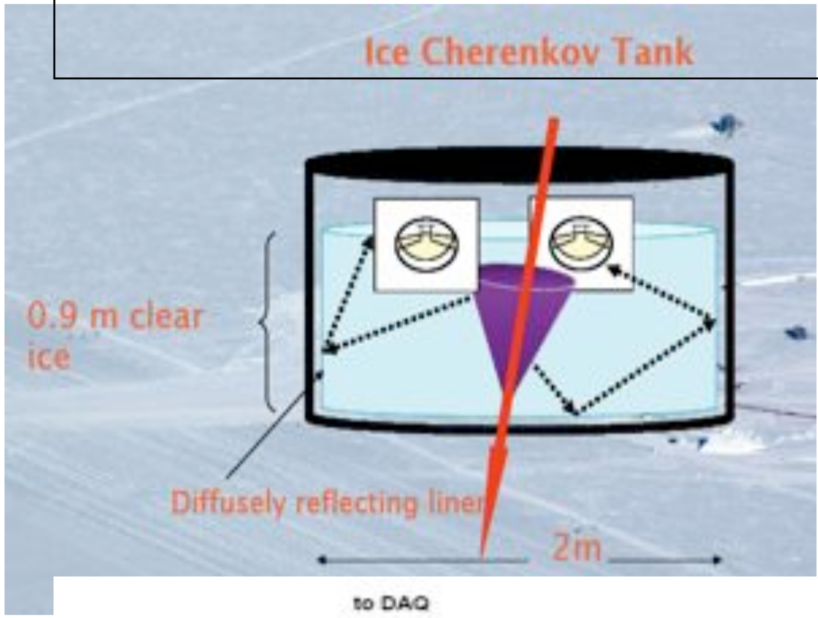
Clock stability: 10^{-10} ≈ 0.1 nsec / sec
Synchronized to GPS time every ≈5 sec at 2 ns precision

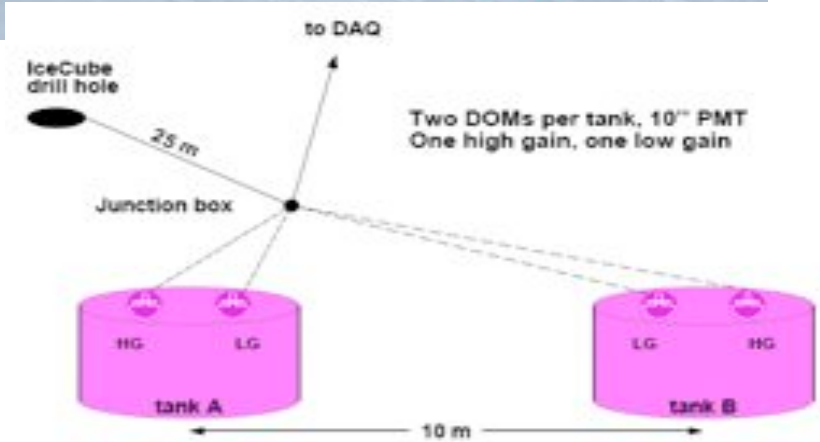
- Dark Noise rate ~ 350 Hz
- Local Coincidence rate ~ 15 Hz
- Deadtime < 1%
- Timing resolution ≤ 2-3 ns

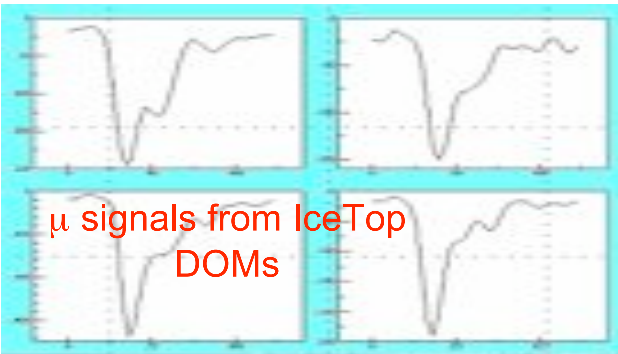


Data rate full detector:
120 GB/day raw
30 GB/day satellite bandwidth

IceTop

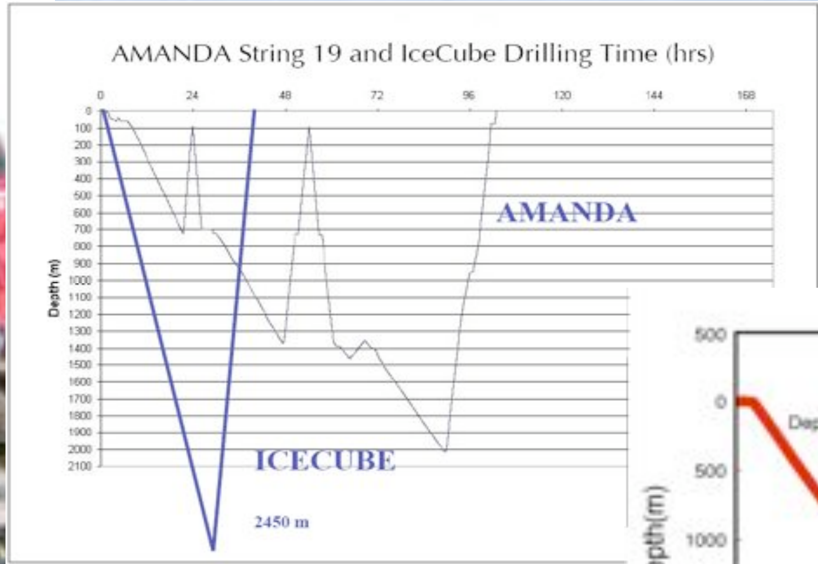

Ice Cherenkov Tank
0.9 m clear ice
Diffusely reflecting liner
2m

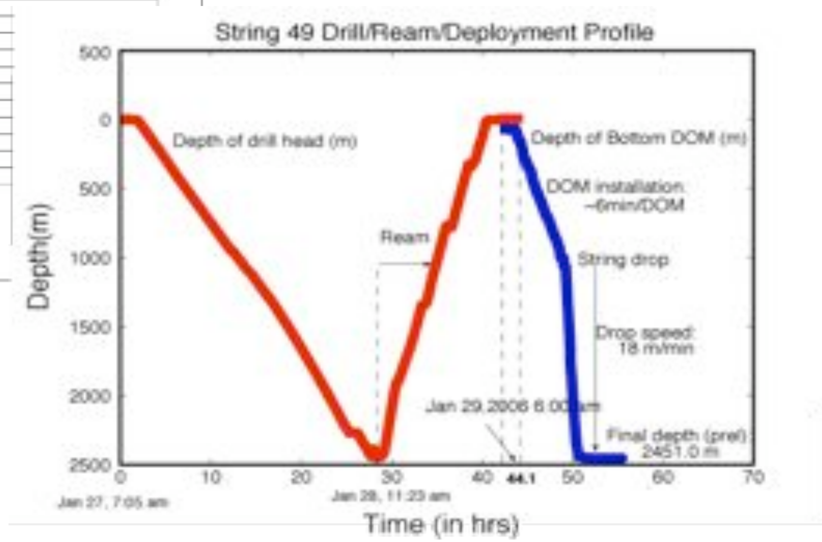

to DAQ
IceCube drill hole
25 m
Junction box
Two DOMs per tank, 10" PMT
One high gain, one low gain
HG
LG
LG
HG
tank A
tank B
10 m


μ signals from IceTop DOMs

drilling site

the drilling experience



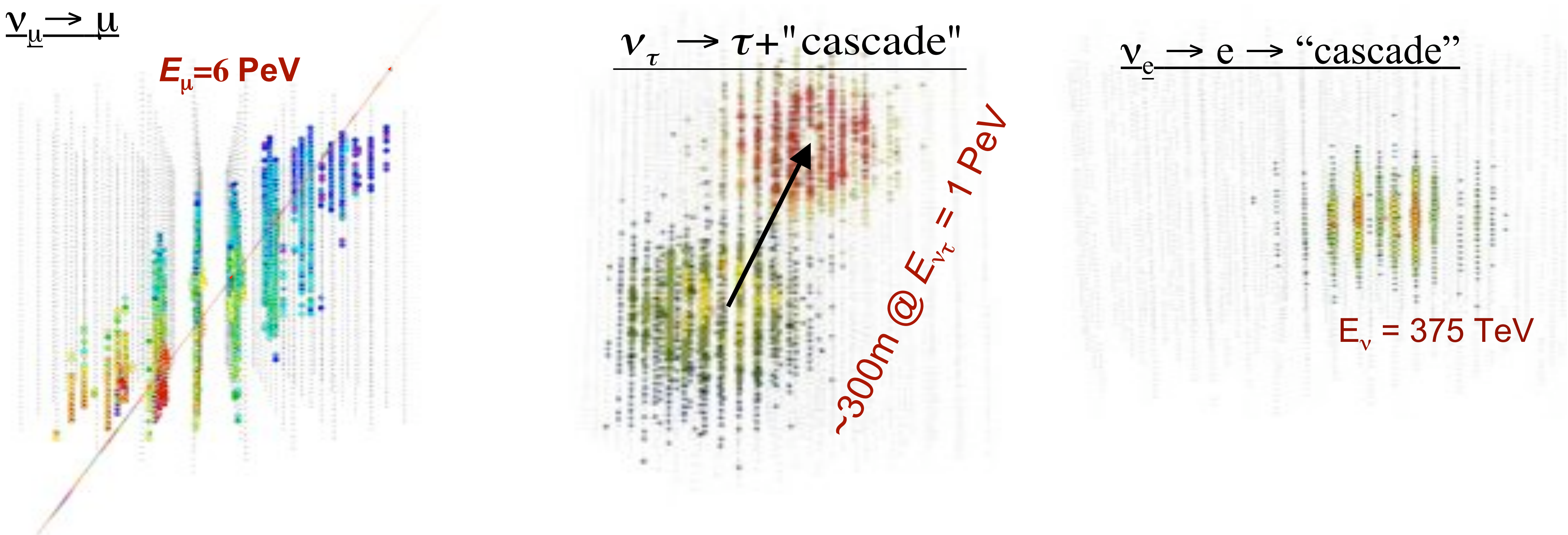


5MW x 30 hrs = 0.56 TJ!

AMANDA drilling (1950m) 90 hrs deployment: 18 hrs

IceCube drilling (2450m) 40 hrs, deployment: 10 hours

IceCube: an all-flavor neutrino telescope



•IceCube will be able to identify

- μ tracks from ν_μ for E_ν > 100 GeV
- cascades from ν_e for E_ν > 10 TeV
- ν_τ for E_ν > 1 PeV

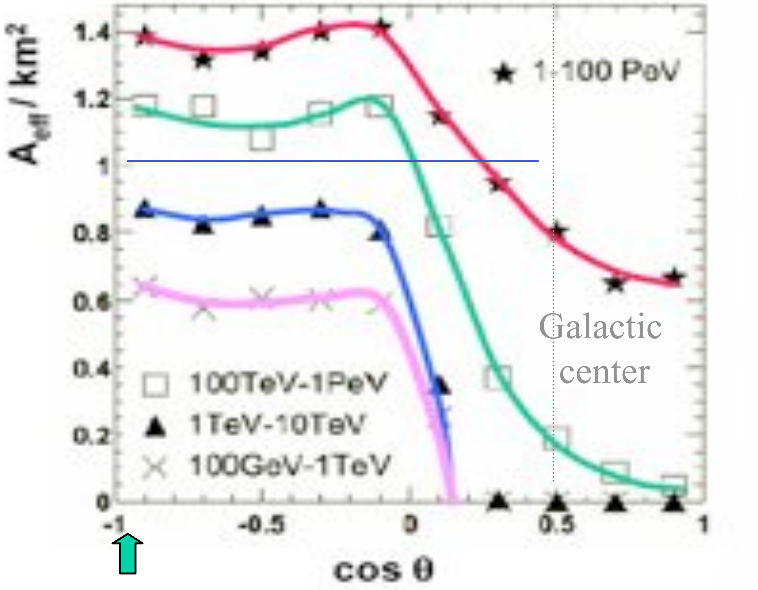
•background

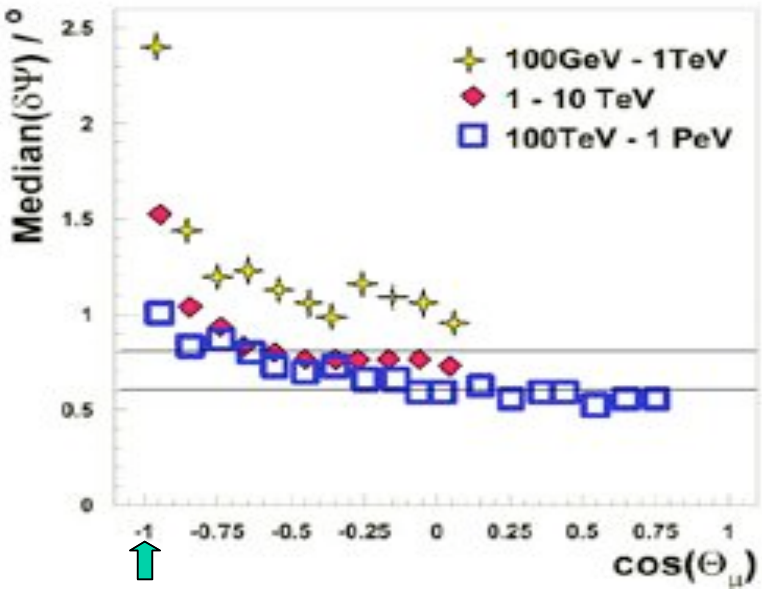
mainly downgoing μ bundles

(+ uncorrelated coincident μ's)

- exp. rate at trigger level ~1.7 kHz
- atm. ν_μ rate at trigger level ~300/day

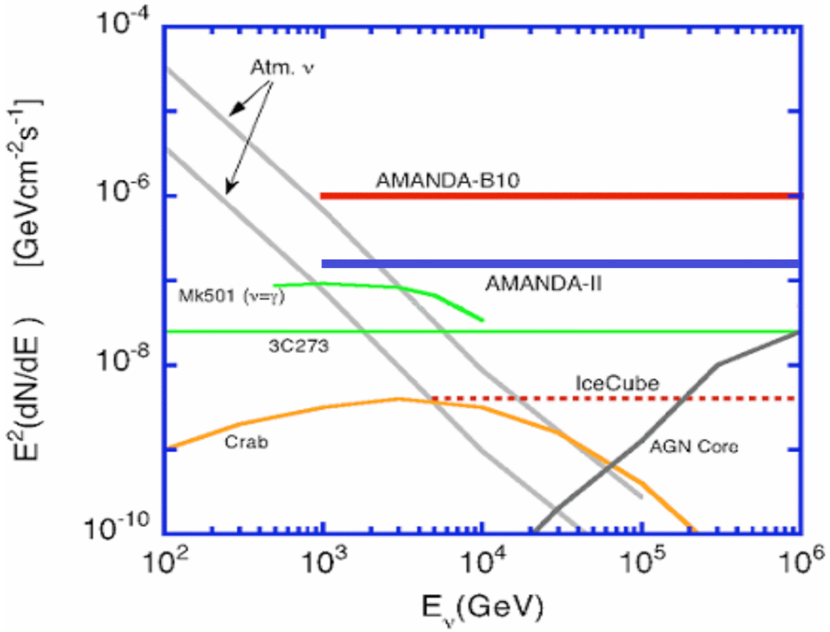
IceCube: A_{eff} and resolution



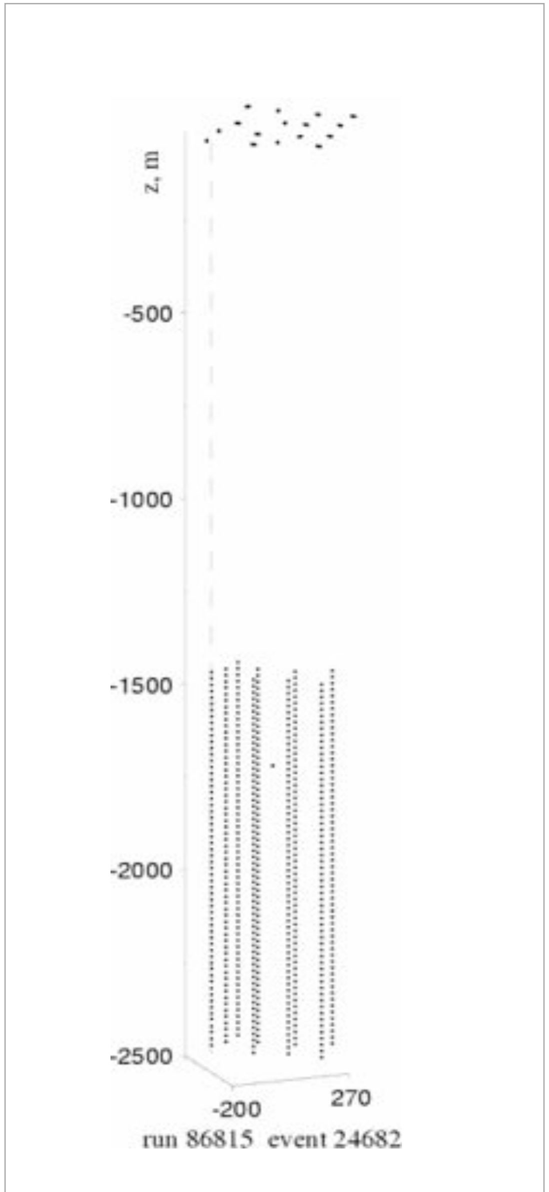


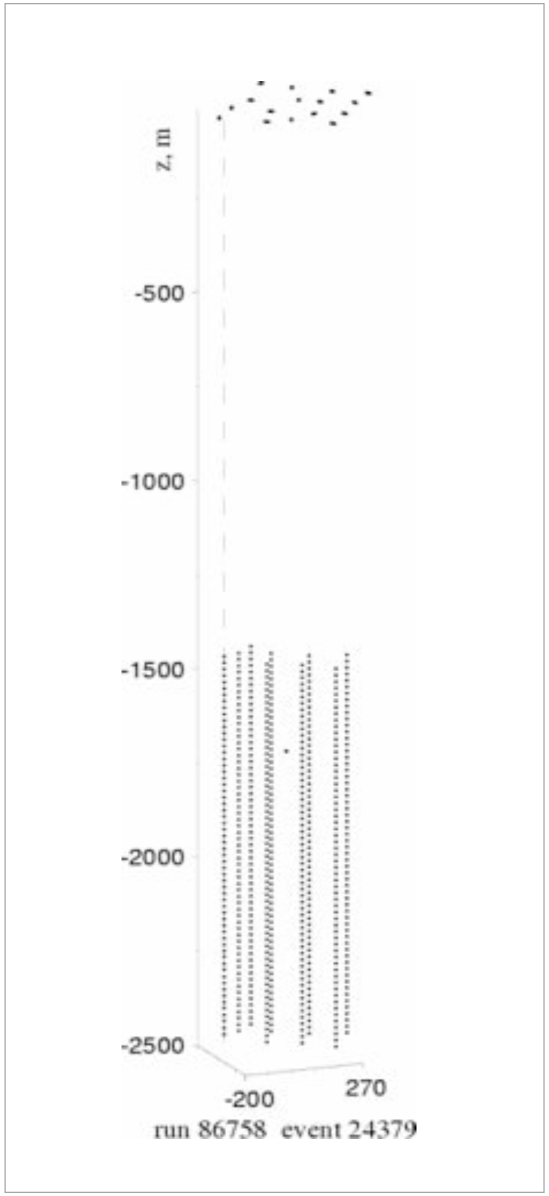
E_{ν_μ} < 1 PeV: focus on the Northern sky,
E_ν > 1 PeV: sensitive aperture increases with energy
→ full sky observations possible

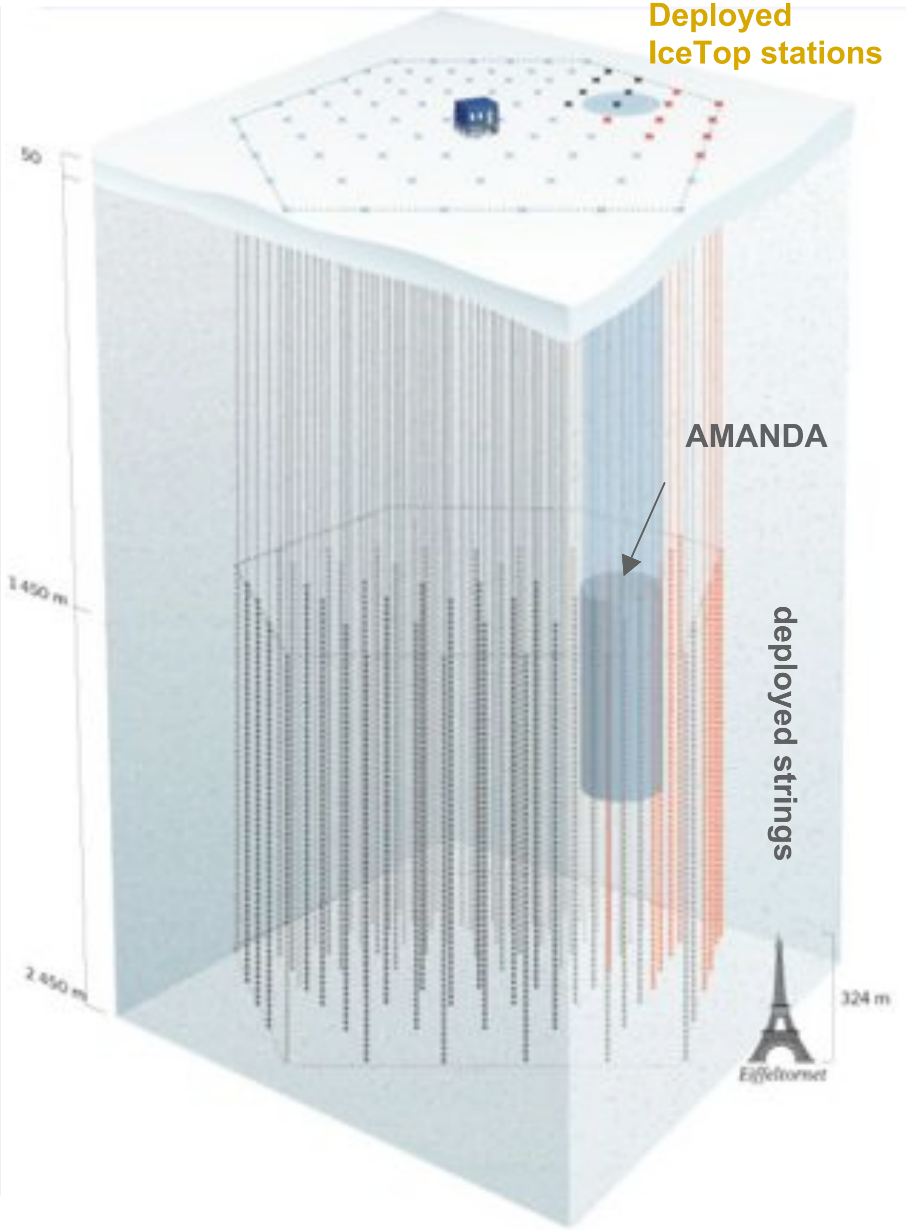
1 year sensitivity $E^2 \cdot d\Phi/dE$	
diffuse	point
$8.1 \cdot 10^{-9}$ [$cm^{-2}s^{-1}sr^{-1}GeV$]	$5.5 \cdot 10^{-9}$ [$cm^{-2}s^{-1}GeV$]



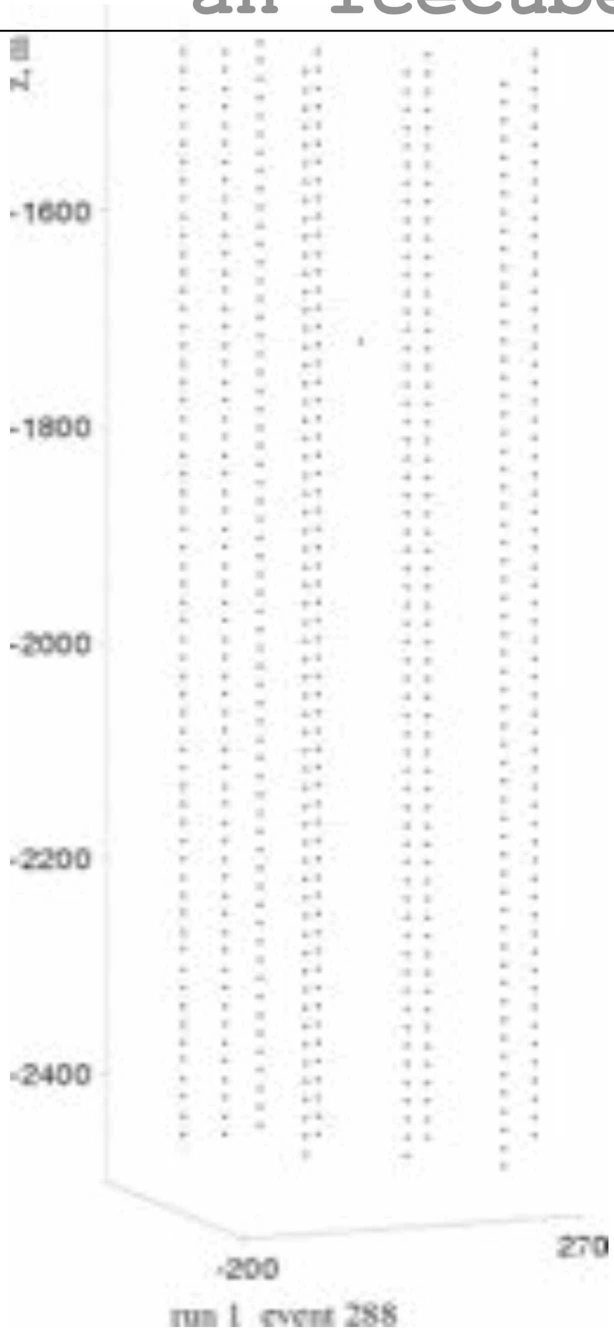
an IceCube/IceTop events

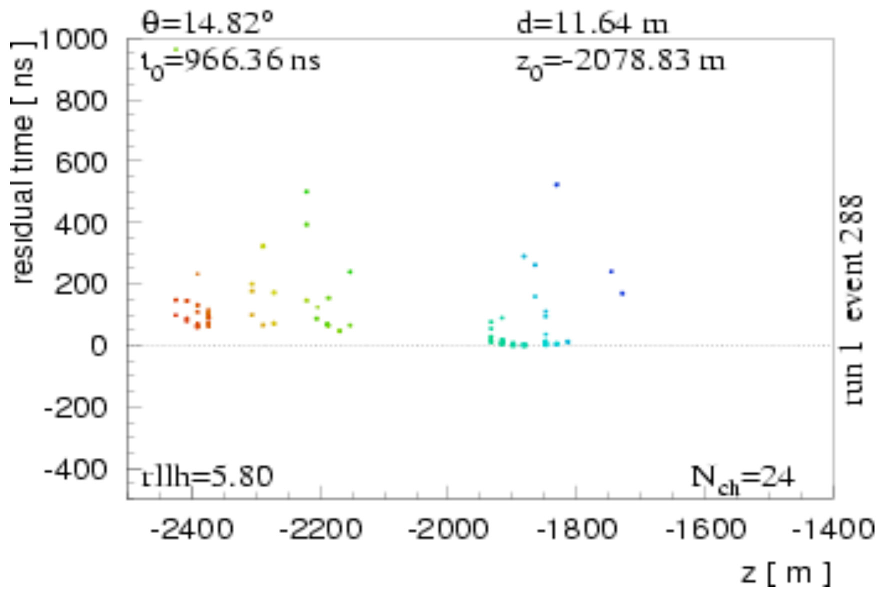




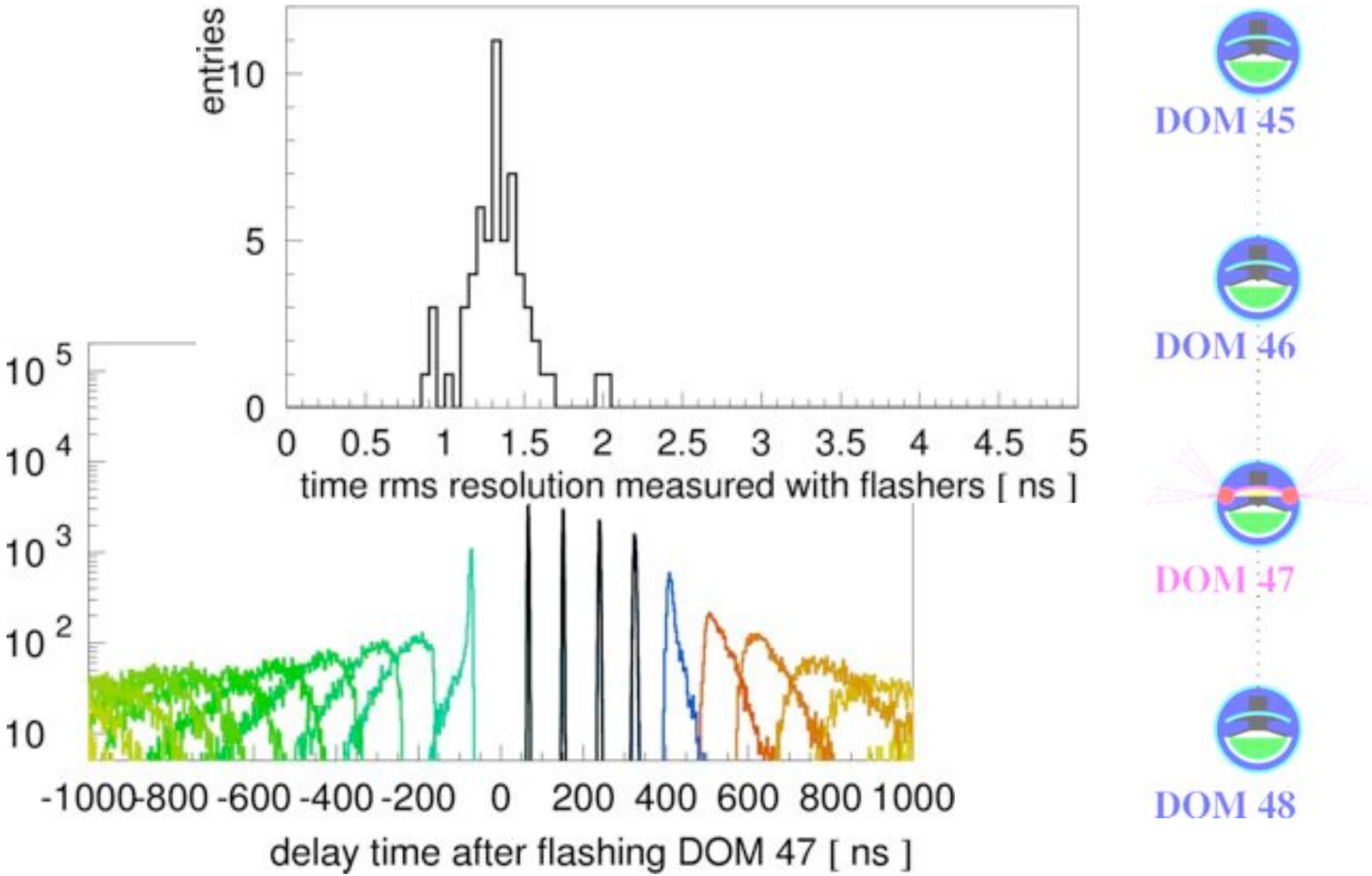


an IceCube-9 neutrino candidate





timing verification with flashers



as a framework: high energy neutrino astronomy

results from AMANDA

IceCube: status and first events

Outlook

outlook

•a wealth of physics results from AMANDA-II on several topics

•multi-year analyses in progress: improvements expected soon

•sensitivity reaching the level of current predictions of ν production in AGN. Some models already excluded @ 90%CL

• first Km^3 project (IceCube) started at the South Pole: taking data with 9 strings+32 IceTop tanks (3x size of AMANDA)

•12 additional strings to be deloyed next season (and so on till completion)

• performance consistent with specifications