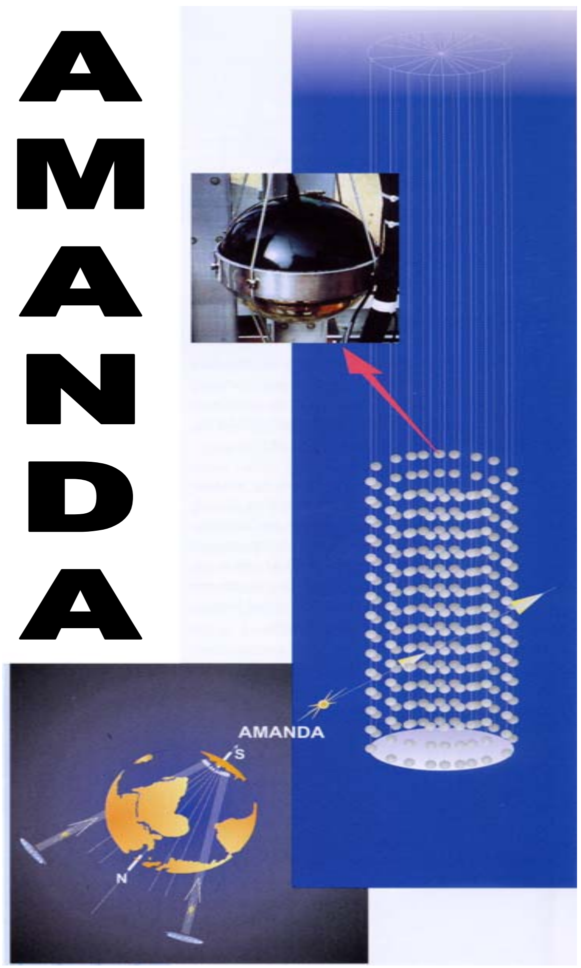
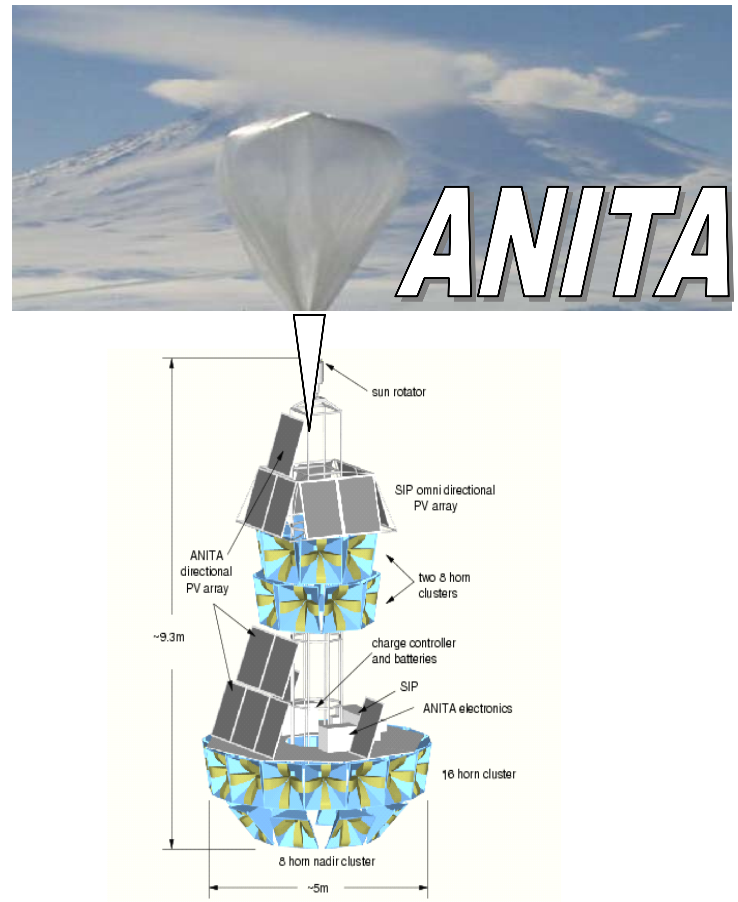
Neutrinos: Canaries in the Coal Mine

Steve Barwick, UC Irvine

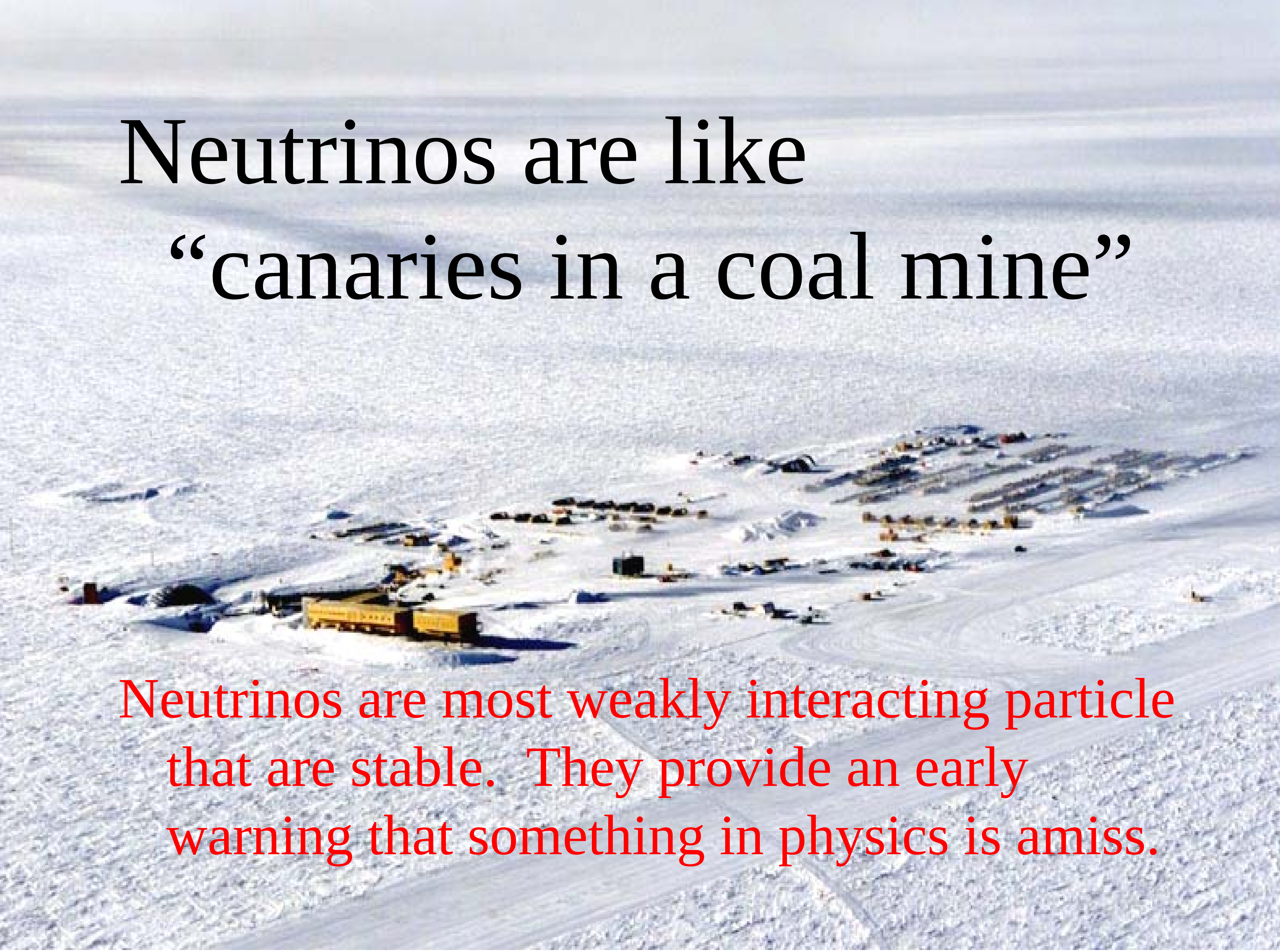




http://amanda.uci.edu

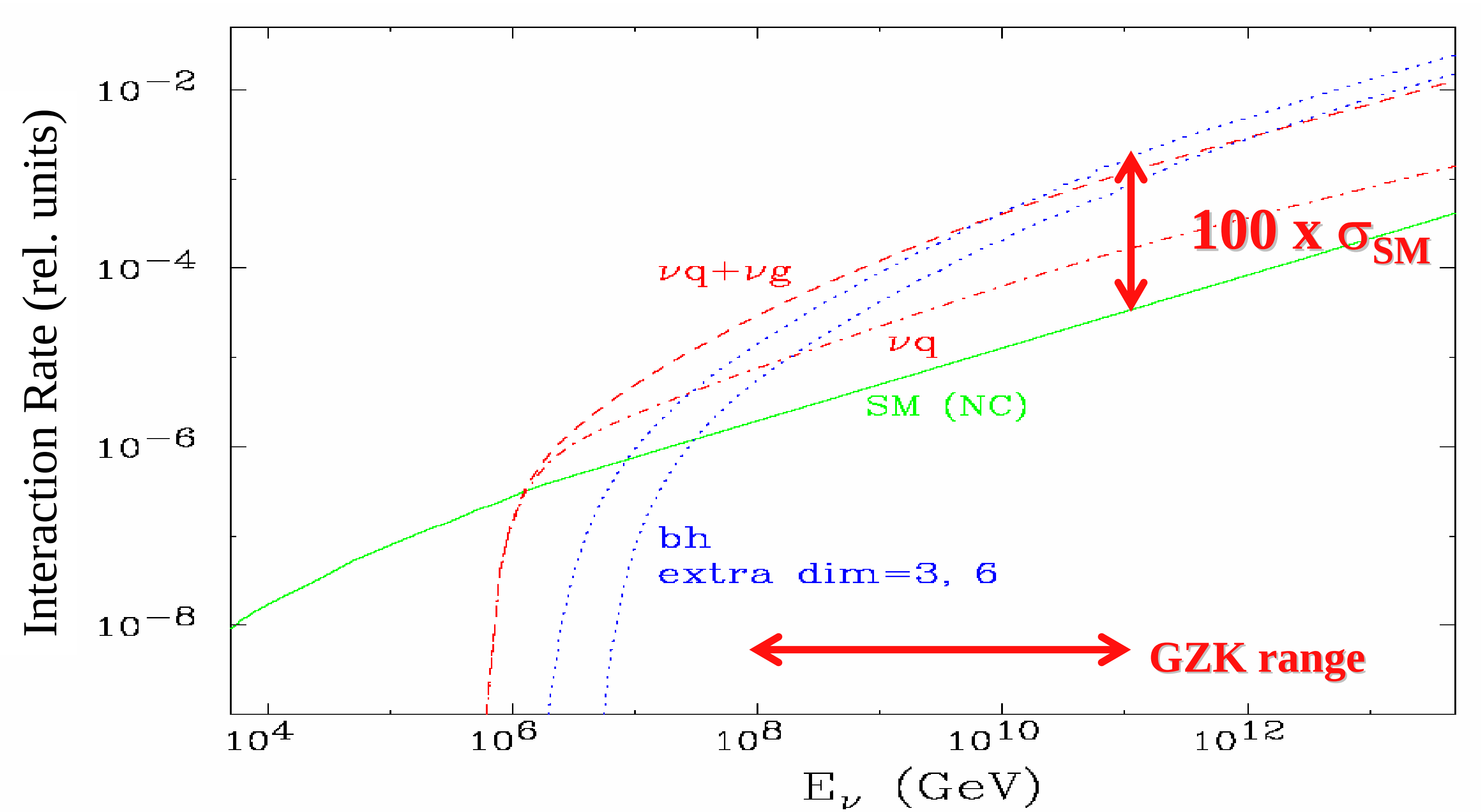
http://www.ps.uci.edu/~anita

Neutrinos are like “canaries in a coal mine”



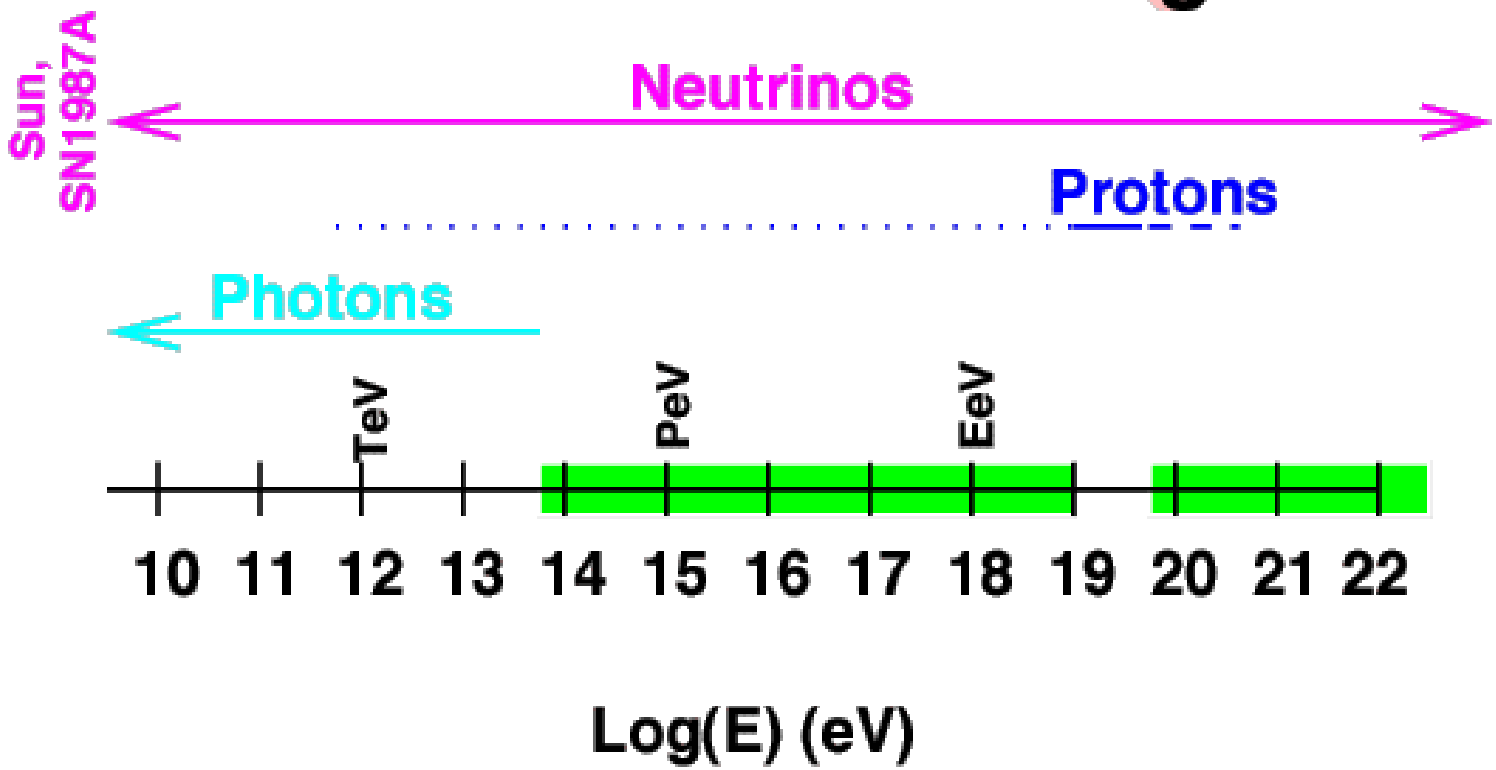
Neutrinos are most weakly interacting particle that are stable. They provide an early warning that something in physics is amiss.

EHE Neutrinos Explore Higher Dimensions



Friess, Hooper & Han astro-ph/0204112

Astronomical Messengers



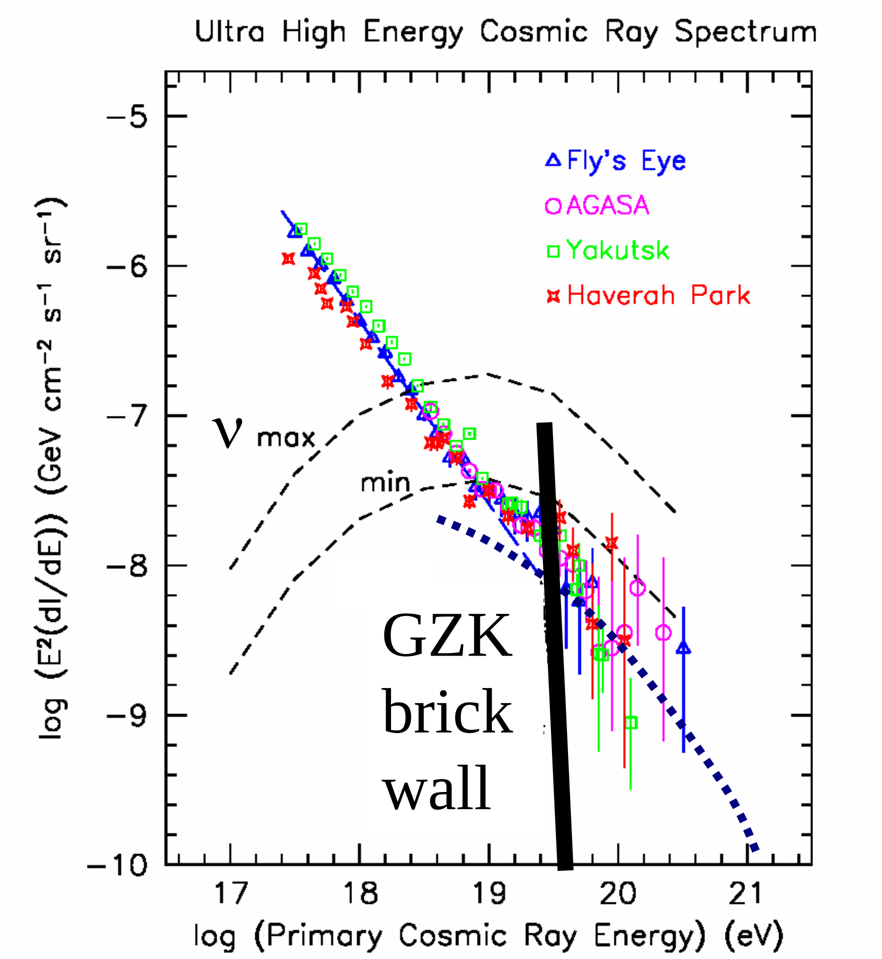
PHOTONS: not deflected, but: reprocessed in sources, absorbed in IR (100 TeV), and CBR

PROTONS: deflection in magnetic fields, GZK cutoff

NEUTRINOS: not absorbed or deflected, hard to see

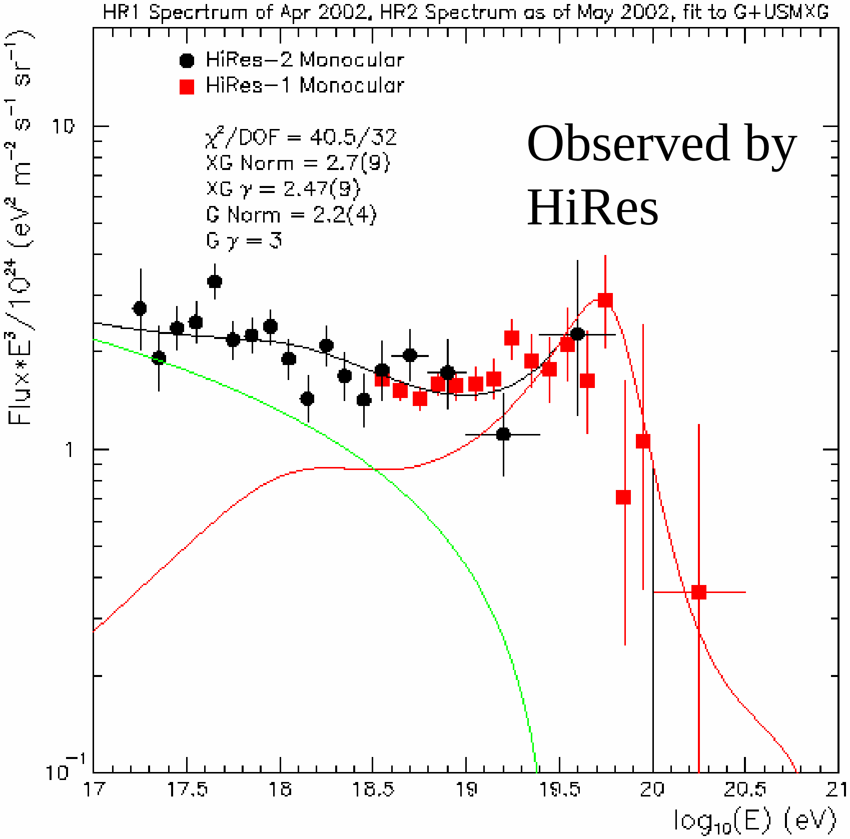
Motivation: GZK neutrinos are a guaranteed source

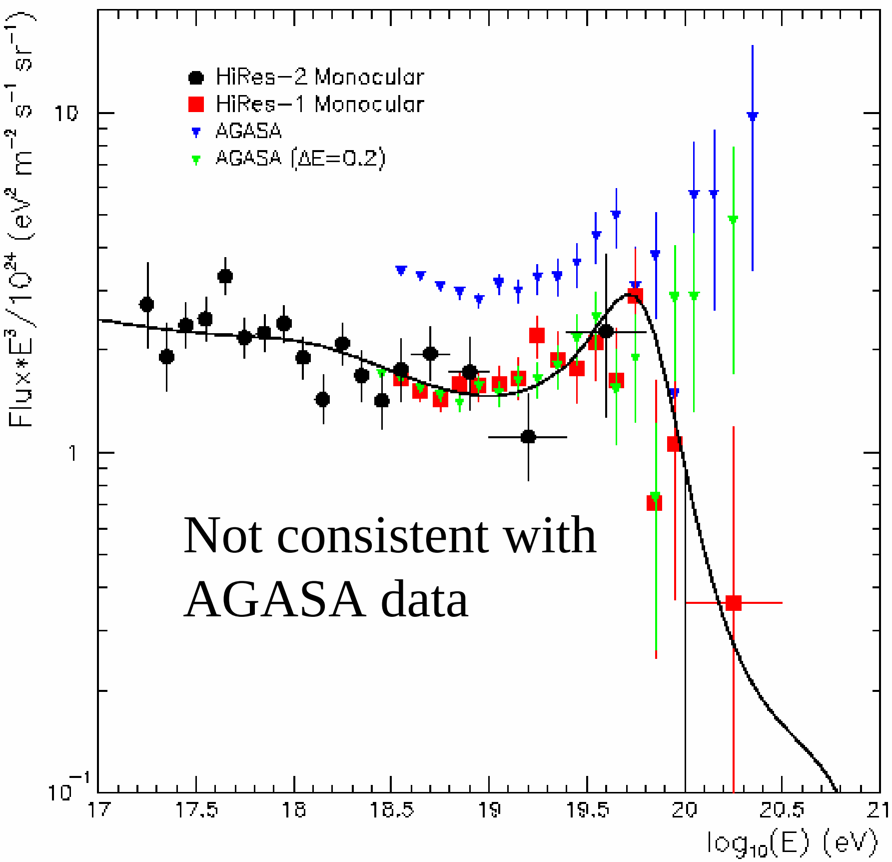
- Ultra-high energy cosmic rays:
  - From where??! And How??
- Standard Model:
  - Ordinary charged particles accelerated by distant sources: AGN, GRBs…
- If so: GZK neutrinos are the signature
  - Probably necessary and sufficient to confirm standard GZK model



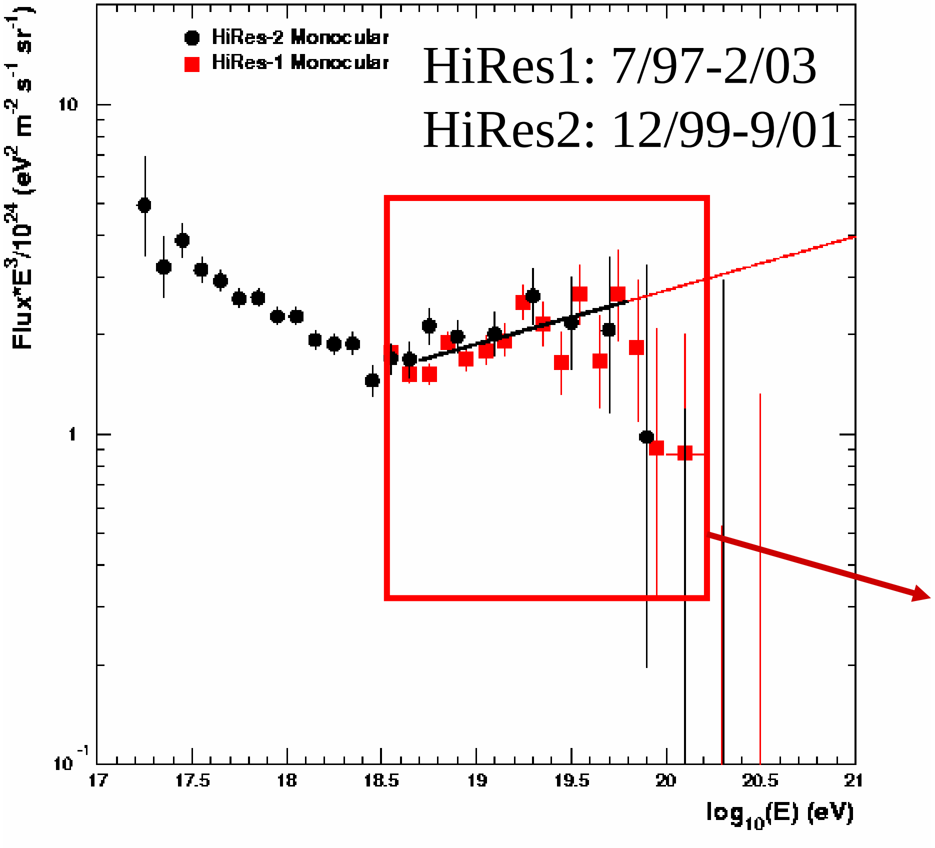
Data suggests GZK cutoff observed

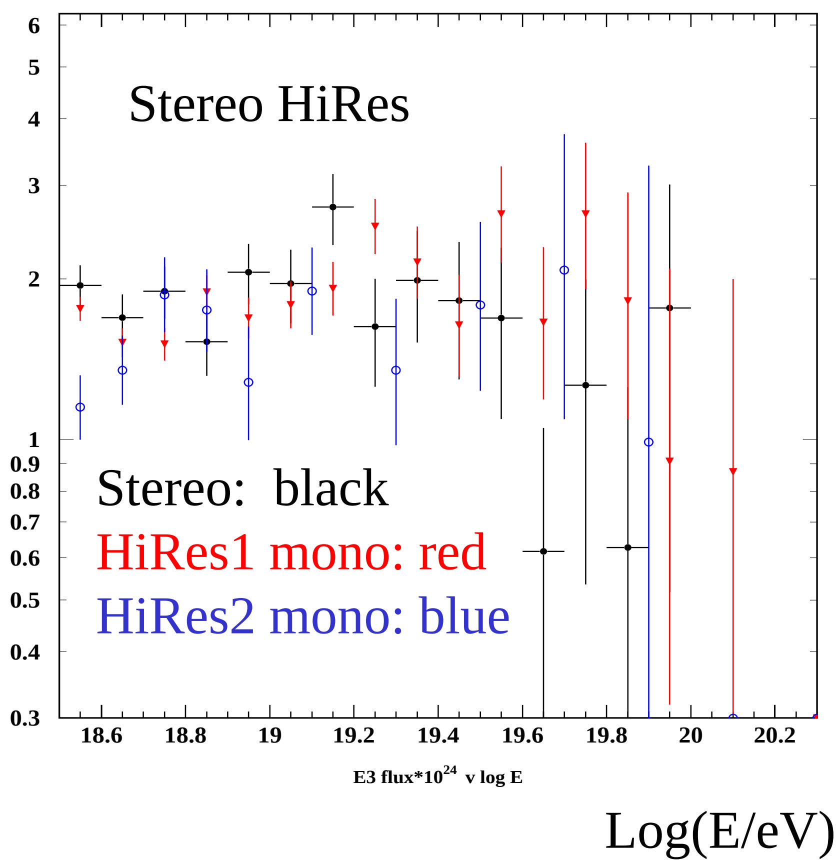
-or not



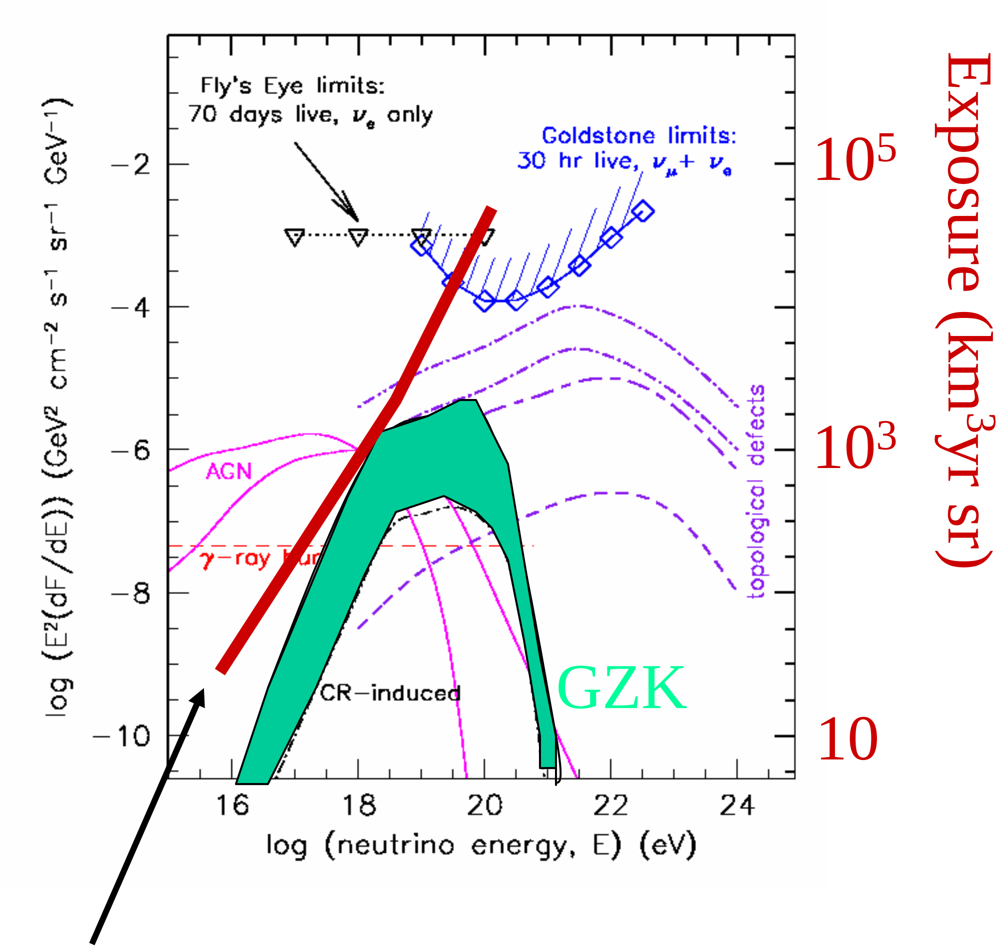


Latest Stereo HiRes strengthens case





Models of diffuse EHE Neutrinos



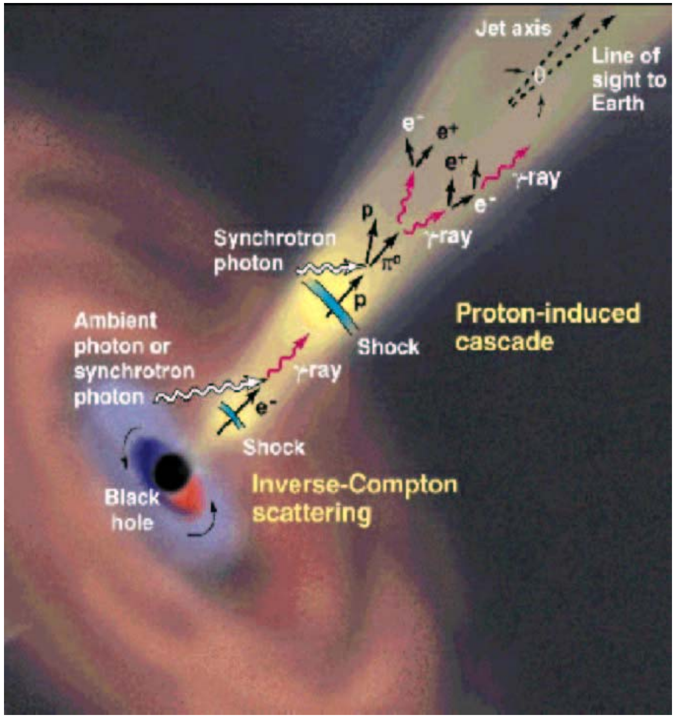
Required exposure to measure 10 events/decade at $E^2(dF/dE) = 10^{-7}$

Physics goals

- **Cosmic Ray origin**
  * candidate acceleration sites: Active Galactic Nuclei, Gamma Ray Bursts
  * Measure extra-terrestrial flux @ TeV – EeV energies

- **Dark matter / exotic particles**
  Indirect Dark Matter search: excess from Sun/Earth centre
  Magnetic monopoles : heavy and slow particles

- **SuperNova monitor of the Milky Way**
  bursts of low-energy neutrinos (global noise rate increase)



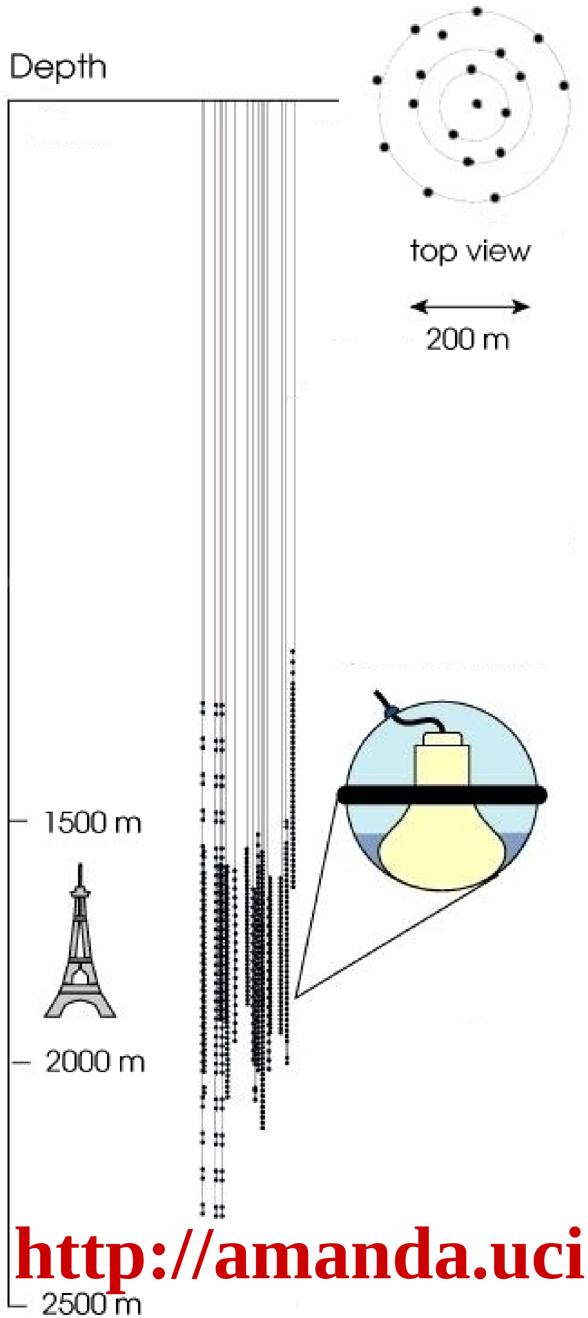
The AMANDA-II Collaboration

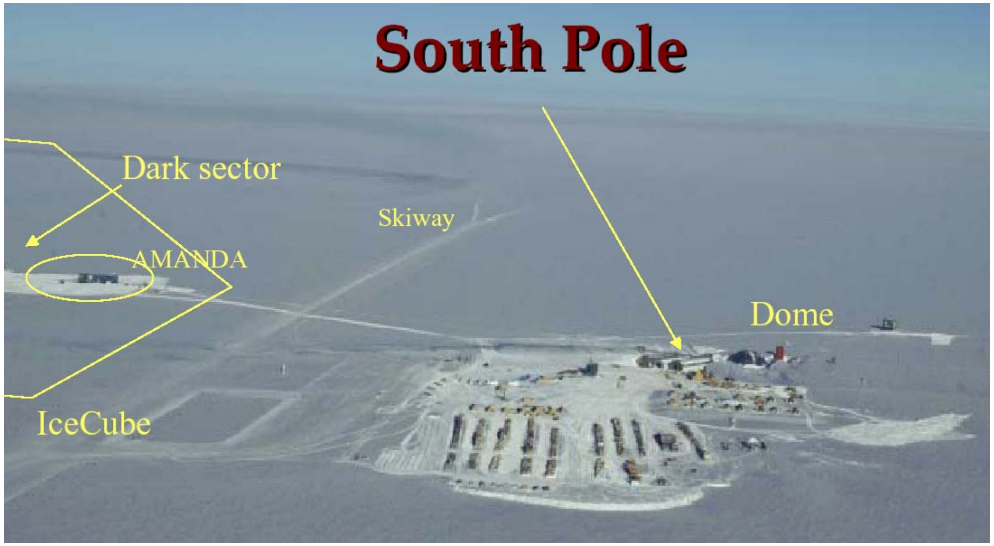
- **Bartol Research Institute, University of Delaware**
- **BUGH Wuppertal, Germany**
- **Universite Libre de Bruxelles, Brussels, Belgium**
- **DESY-Zeuthen, Zeuthen, Germany**
- **Dept. of Technology, Kalmar University, Kalmar, Sweden**
- **Lawrence Berkeley National Laboratory, Berkeley, USA**
- **Dept. of Physics, UC Berkeley, USA**
- **Dept. of Physics and Astronomy, UC-Irvine, USA**
- **Institute of Physics, University of Mainz, Mainz, Germany**
- **University of Mons-Hainaut, Mons, Belgium**
- **Fysikum, Stockholm University, Stockholm, Sweden**
- **Dept. of Physics, University of Alabama, USA**
- **Vrije Universiteit Brussel, Brussel, Belgium**
- **Dept. Fisica, Univ. Simon Bolivar, Caracas, Venezuela**
- **Dept. of Physics and Astronomy, Penn State University, College Station, USA**
- **Dept. of Astronomy, Dept. of Physics, University of Wisconsin, Madison, USA**
- **Physics Department, University of Wisconsin, River Falls, USA**
- **Division of High Energy Physics, Uppsala University, Uppsala, Sweden**

Institutions: 8 US, 9 European, 1 South American

AMANDA-II with TWR

South Pole 2km Deep Ice

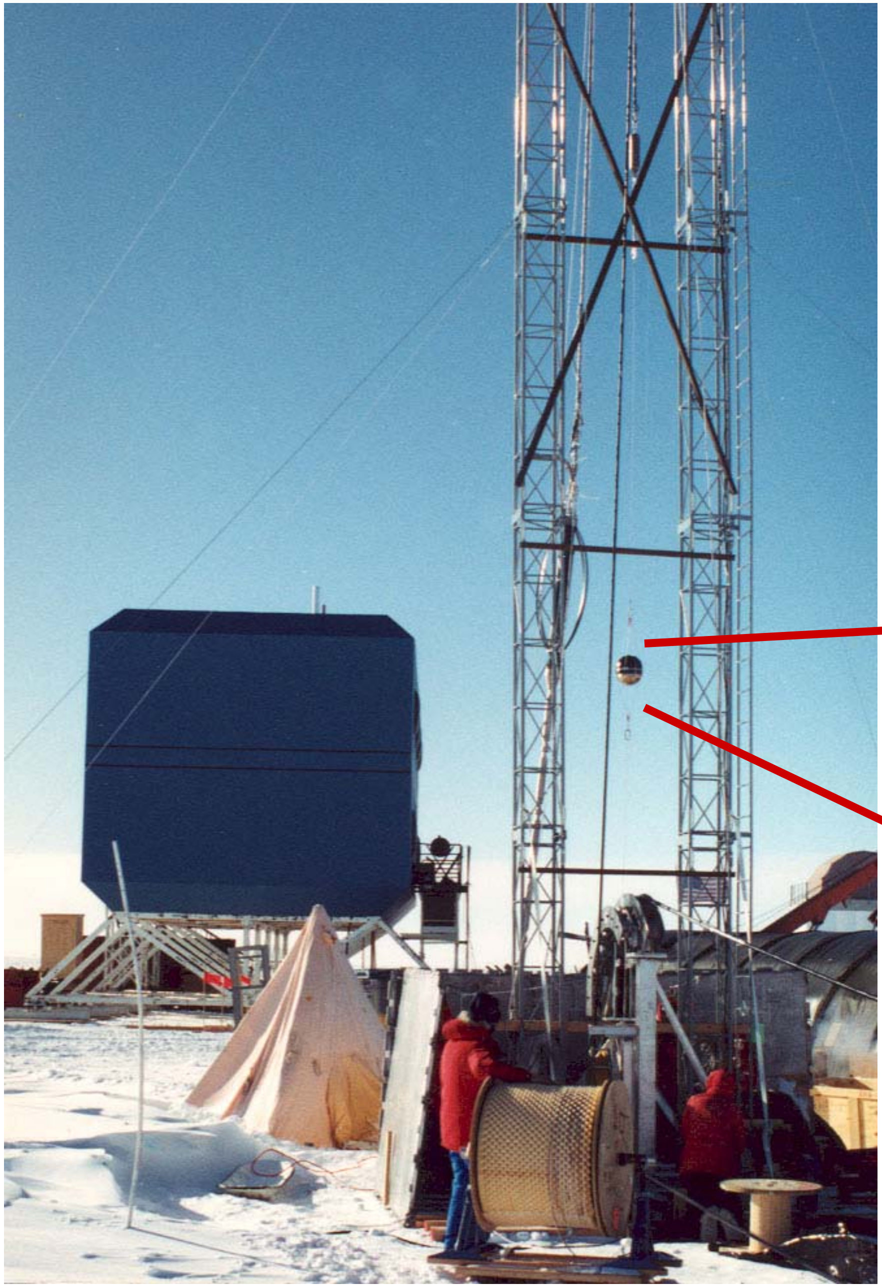


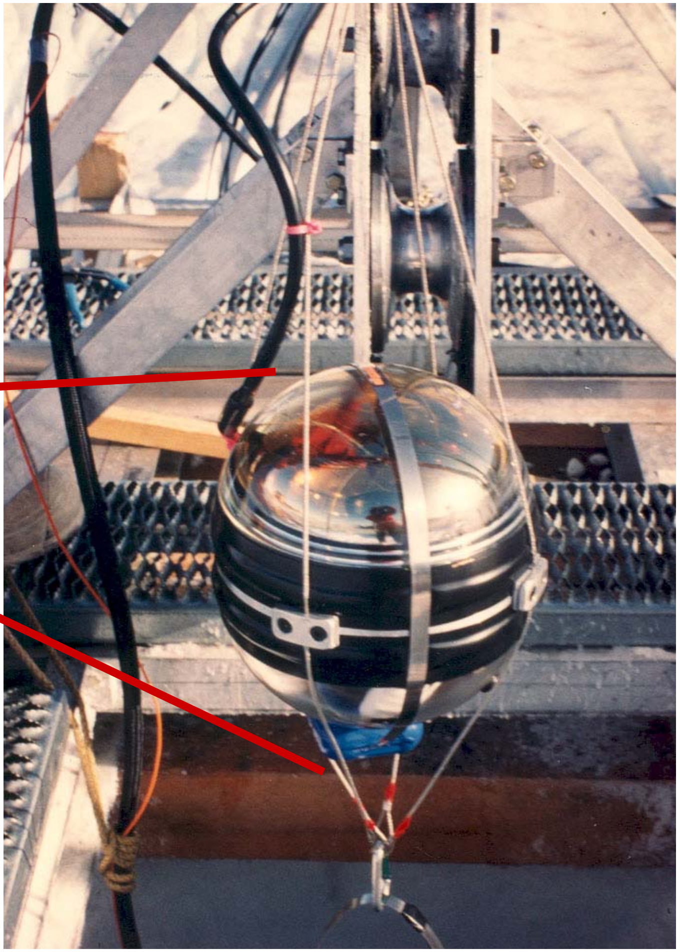


- AMANDA-II now reporting 97-00 data.
- Demonstrated technology after R&D period on ice properties and prototypes (10 years from start to finish)

http://amanda.uci.edu

Drill Camp - 1997

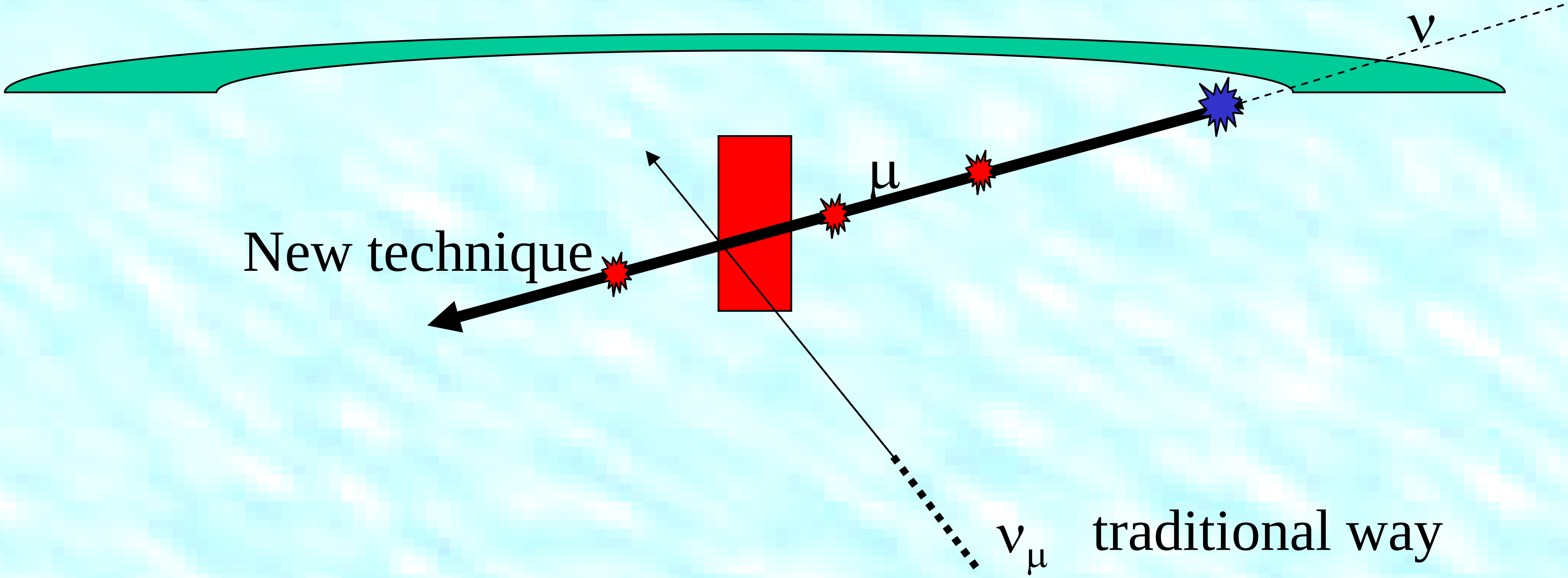




Deploying an AMANDA sensor at -40C.

Going down the hole

Science Potential/Opportunities of AMANDA-II

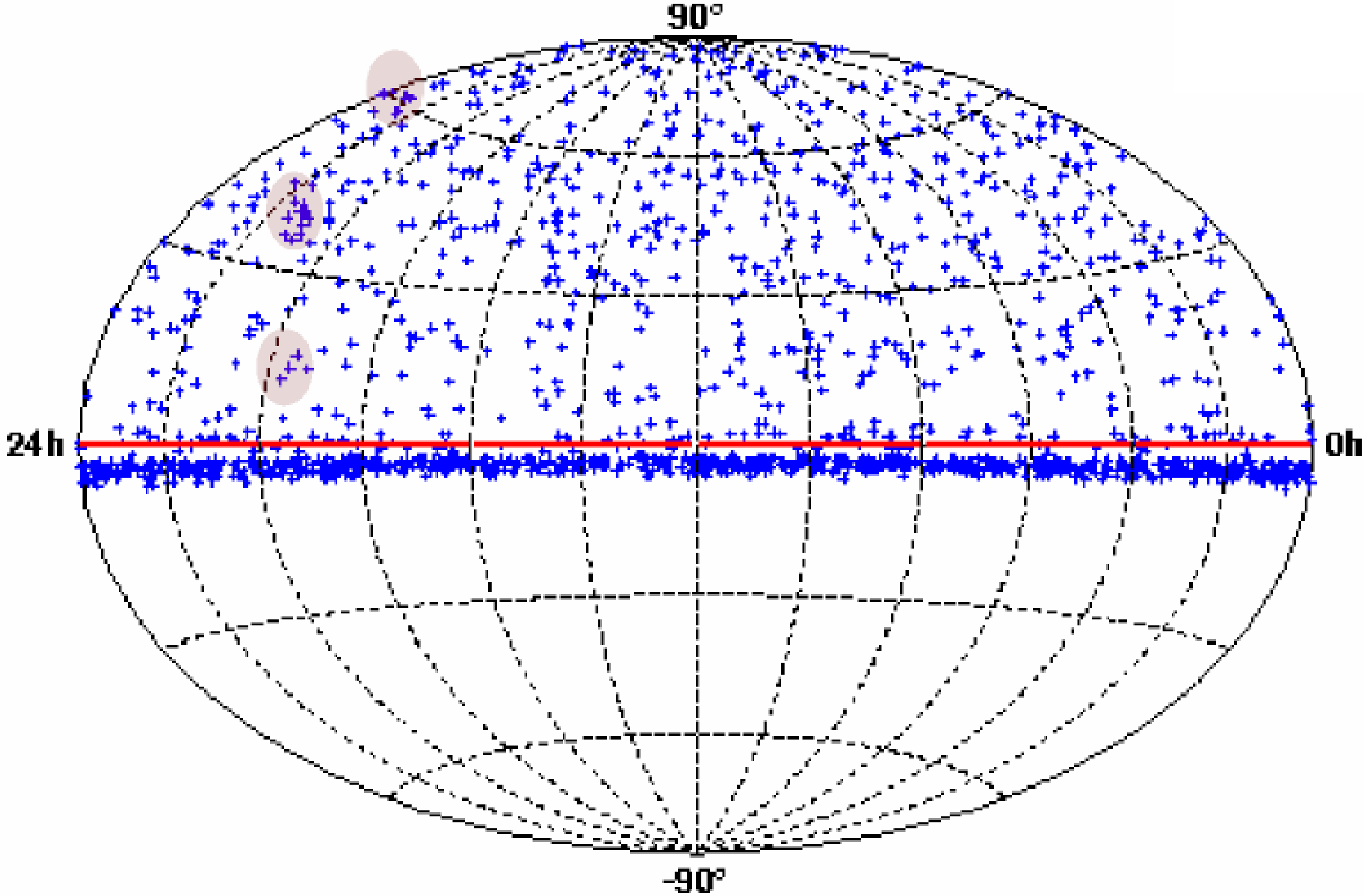


S. Barwick
ICRC, Aug 2001

Point Source Astronomy

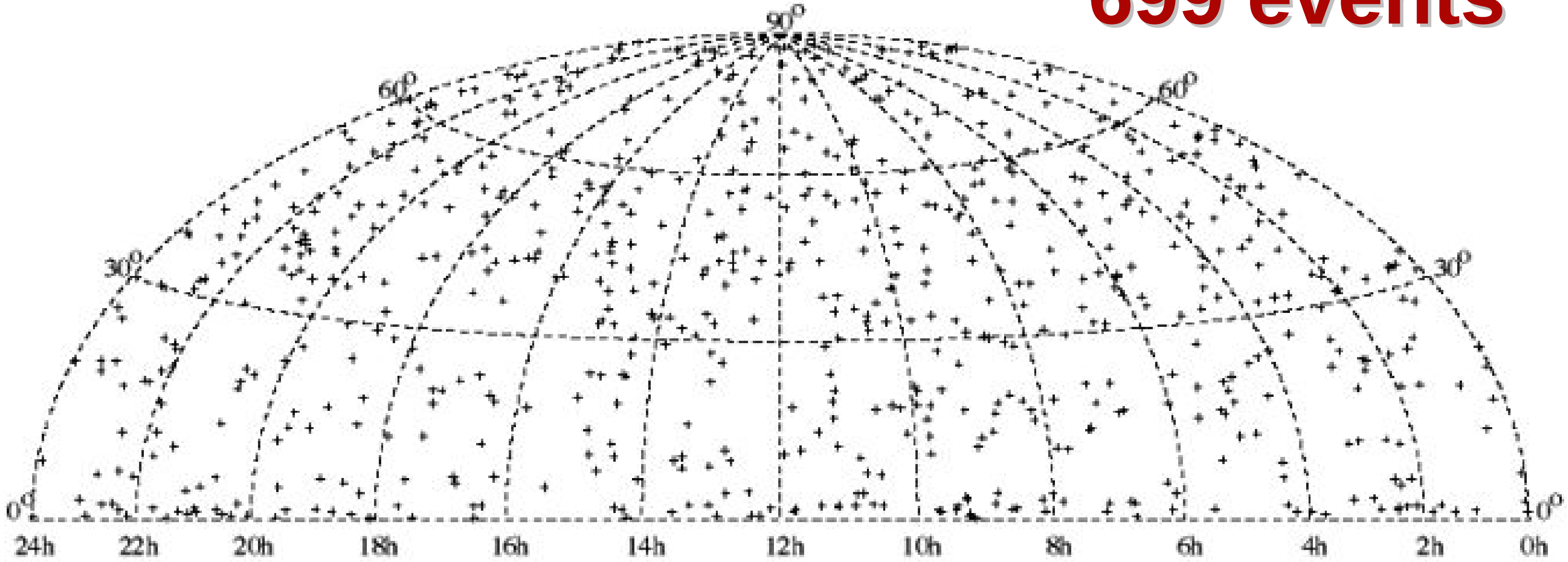
AMANDA II 2000

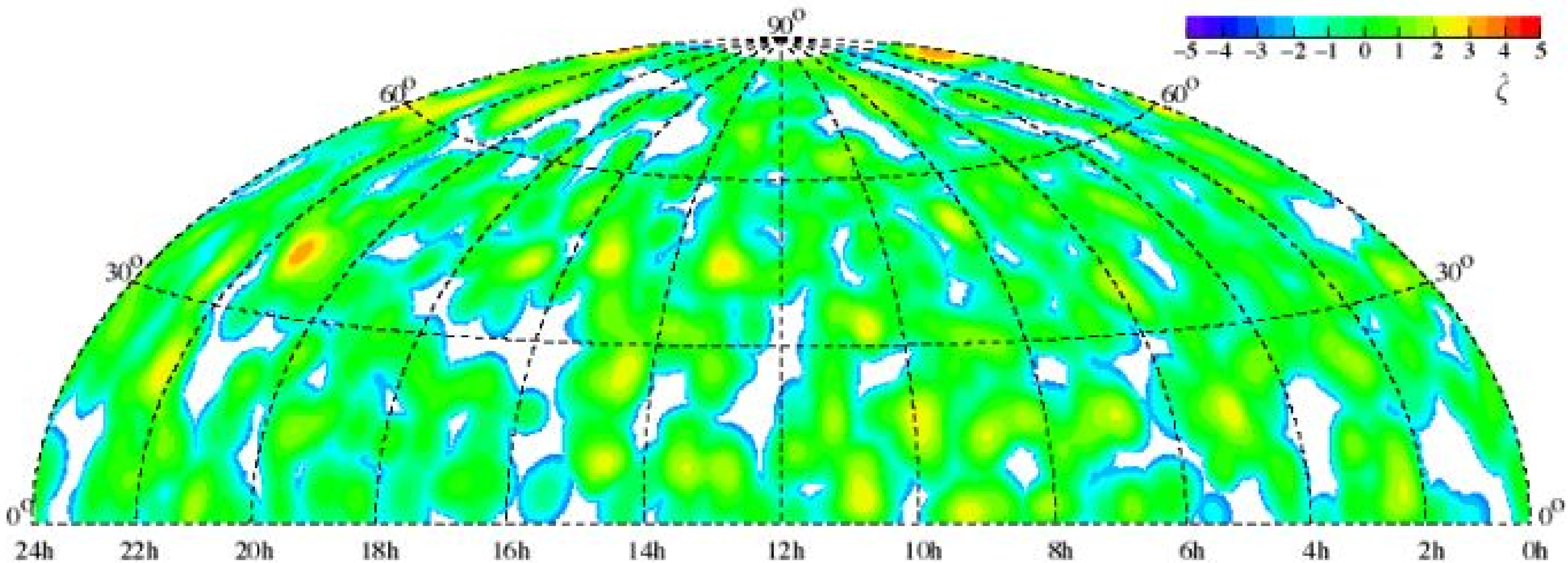
699 events

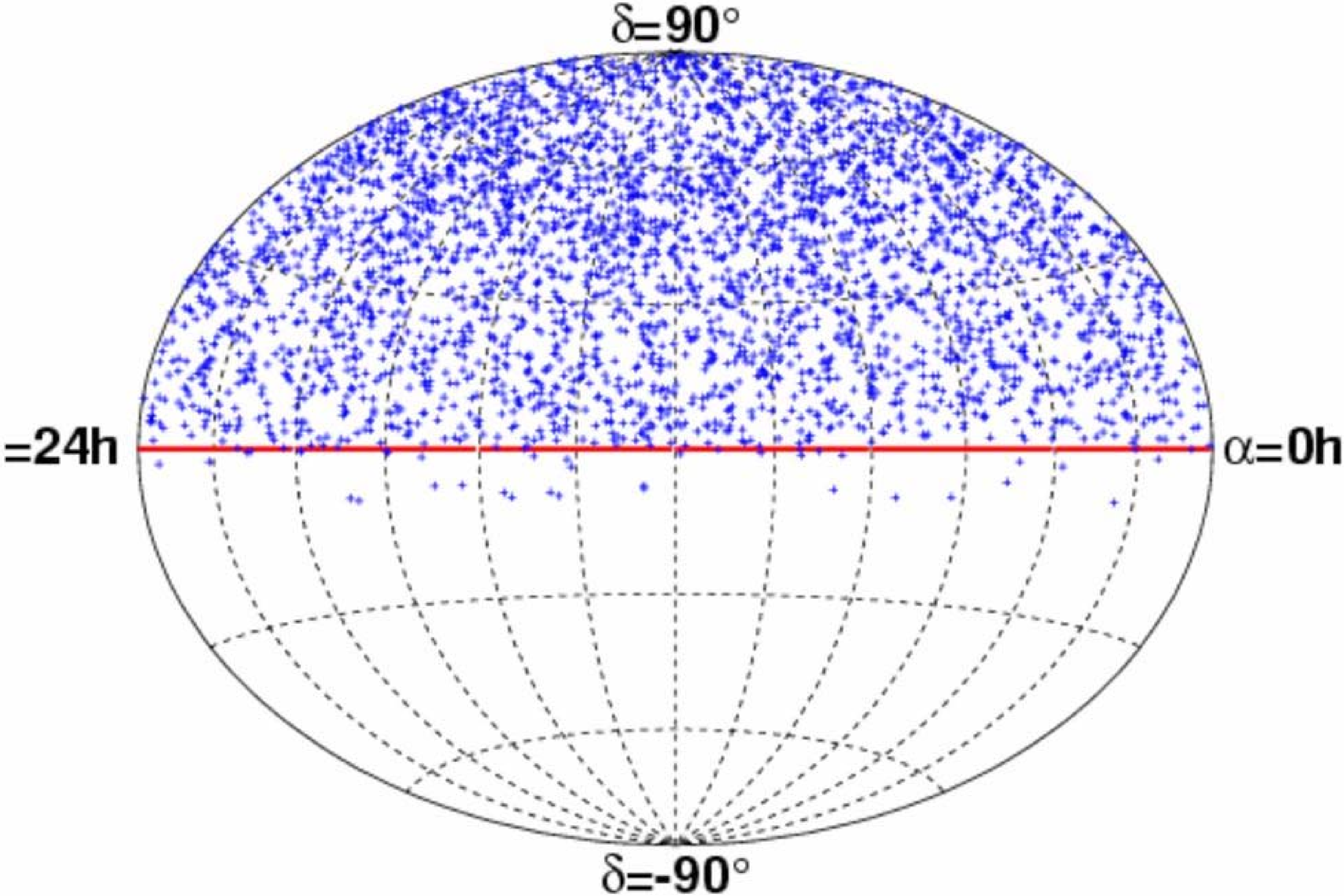


AMANDA-II 2000

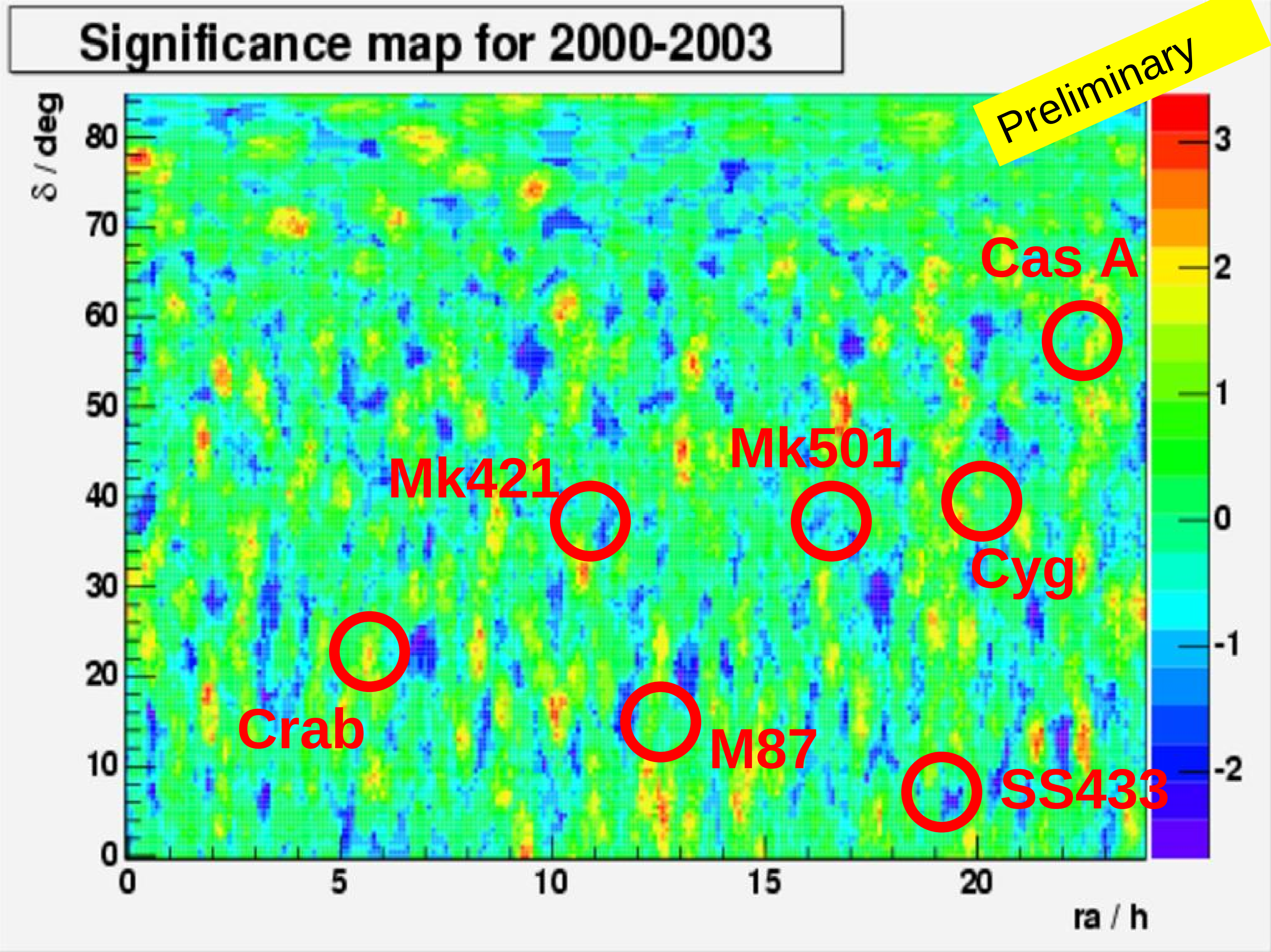
699 events



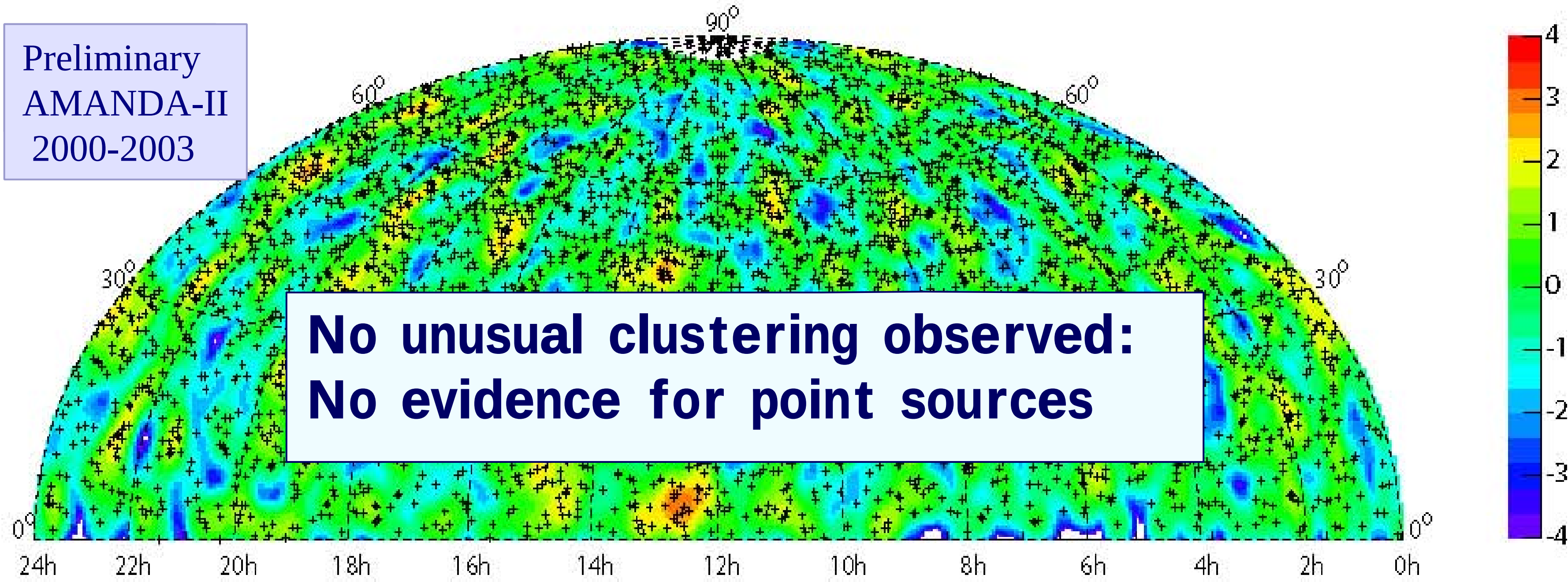




amanda: 2000-2003 **3369 events**


Significance map for 2000-2003
Preliminary
δ / deg
ra / h
Cas A
Mk501
Mk421
Cyg
Crab
M87
SS433
0
10
20
30
40
50
60
70
80
0
5
10
15
20
3
2
1
0
-1
-2

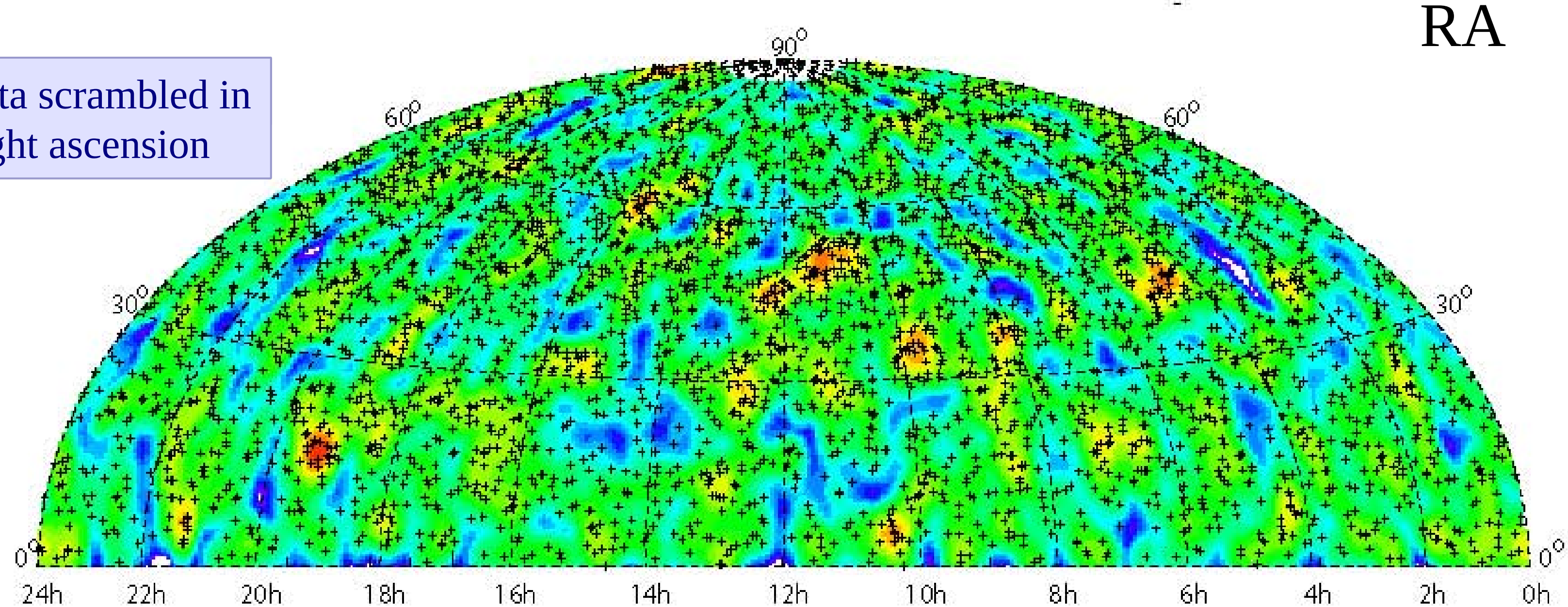
Preliminary
AMANDA-II
2000-2003



No unusual clustering observed:
No evidence for point sources

RA

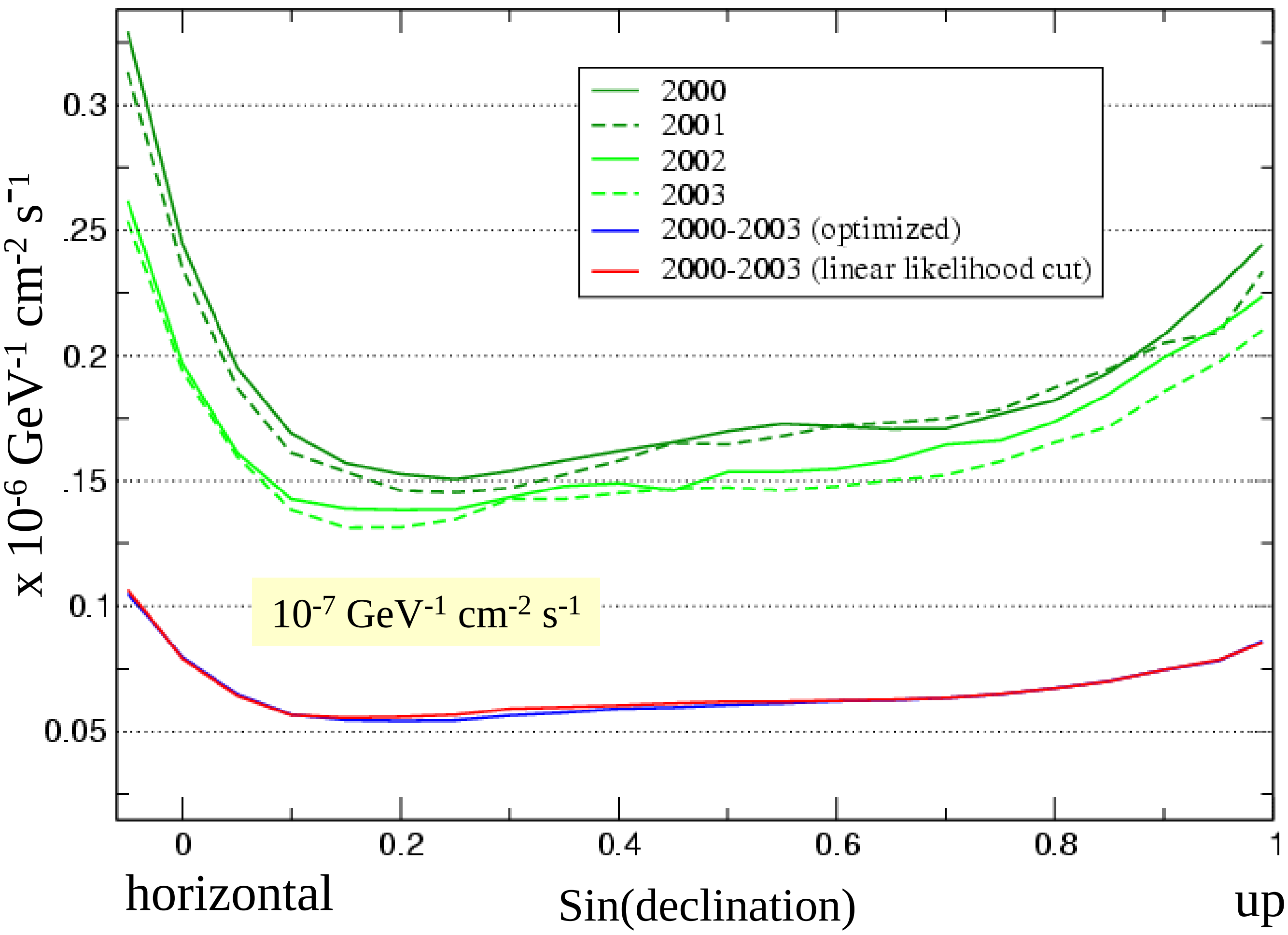
Data scrambled in
right ascension



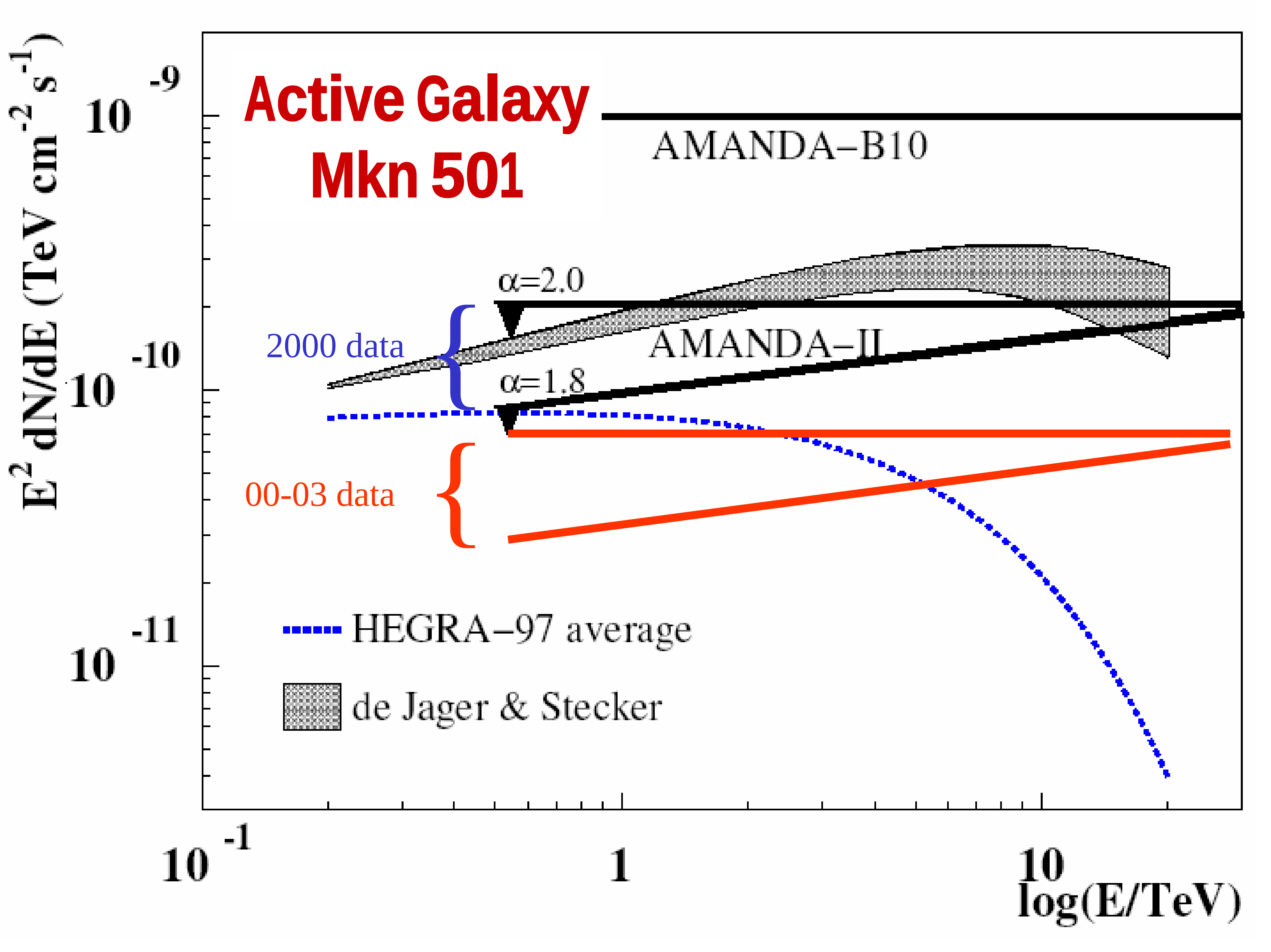
RA

Sensitivity is 3x better than published

Data 2000 : PRL 92, 071102 (2004)

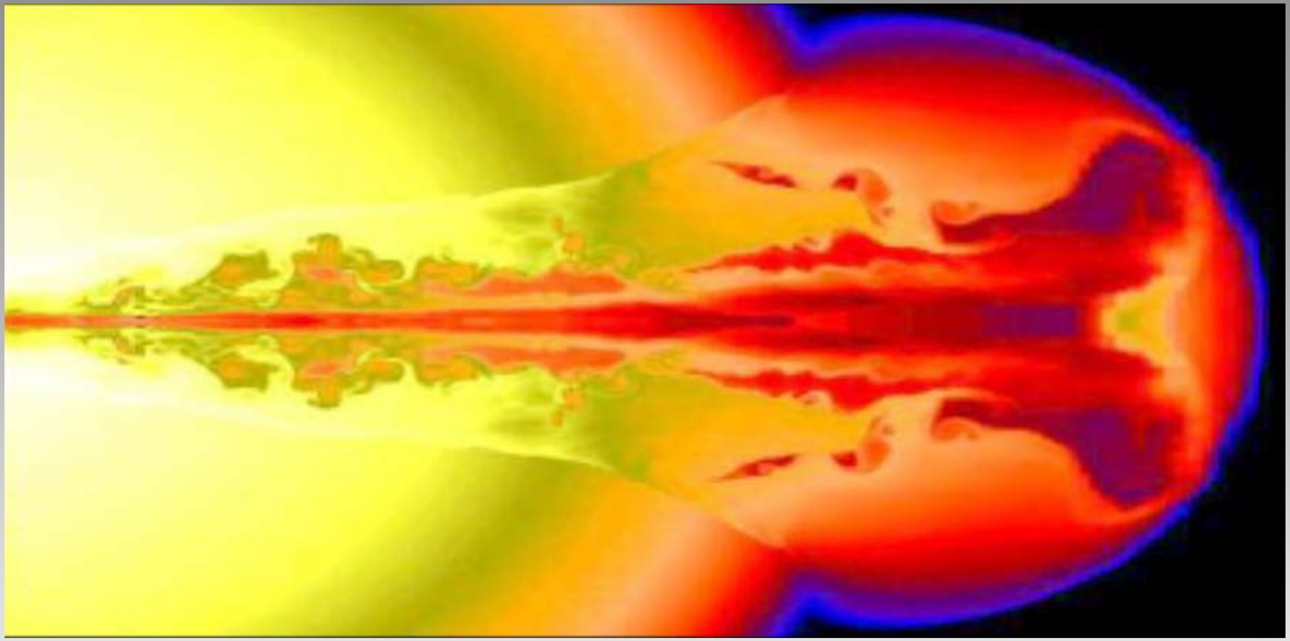


- **Full set of data from 2000–2003**
- **807 days livetime**



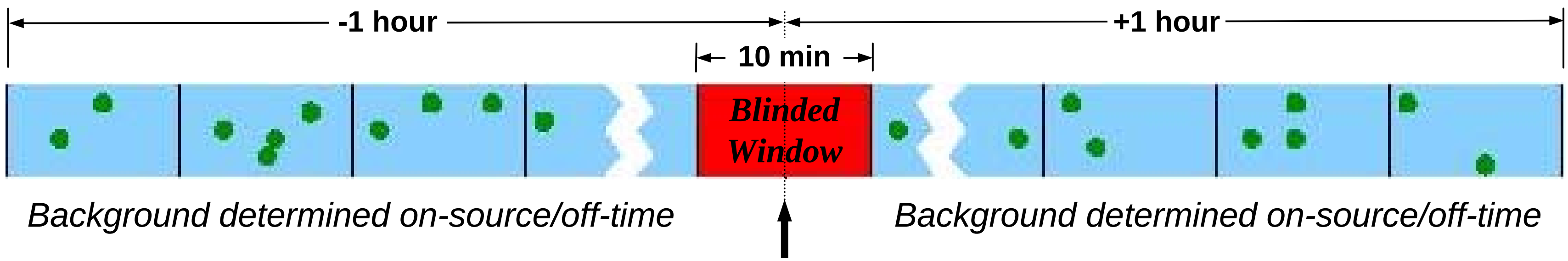
Active Galaxy
Mkn 501
AMANDA–B10
α=2.0
AMANDA–II
α=1.8
2000 data
00-03 data
HEGRA–97 average
de Jager & Stecker
E^2 dN/dE (TeV cm^{-2} s^{-1})
10^{-9}
10^{-10}
10^{-11}
10^{-1}
1
10
log(E/TeV)

Gamma Ray Bursts



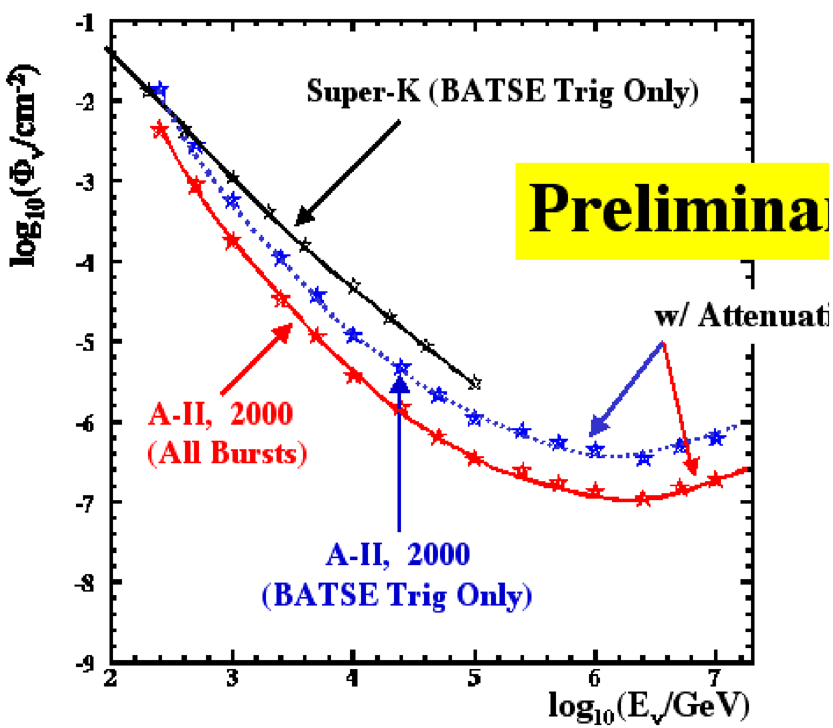
Shocks: external collisions with interstellar material or internal
Collisions when slower material is overtaken
by faster in the fireball.

Protons and photons coexist in the fireball



Green's Function Fluence Limit

following SuperKamiokande method (*2002ApJ, 578:317F*)

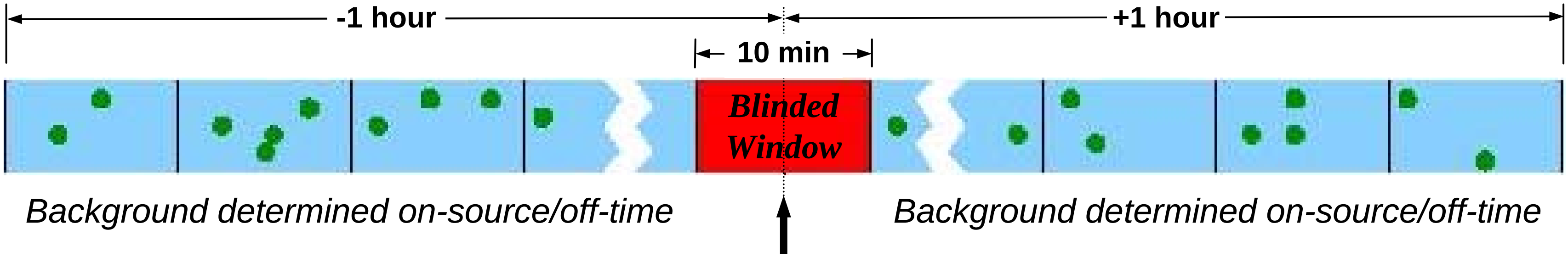


382 GRBs examined!

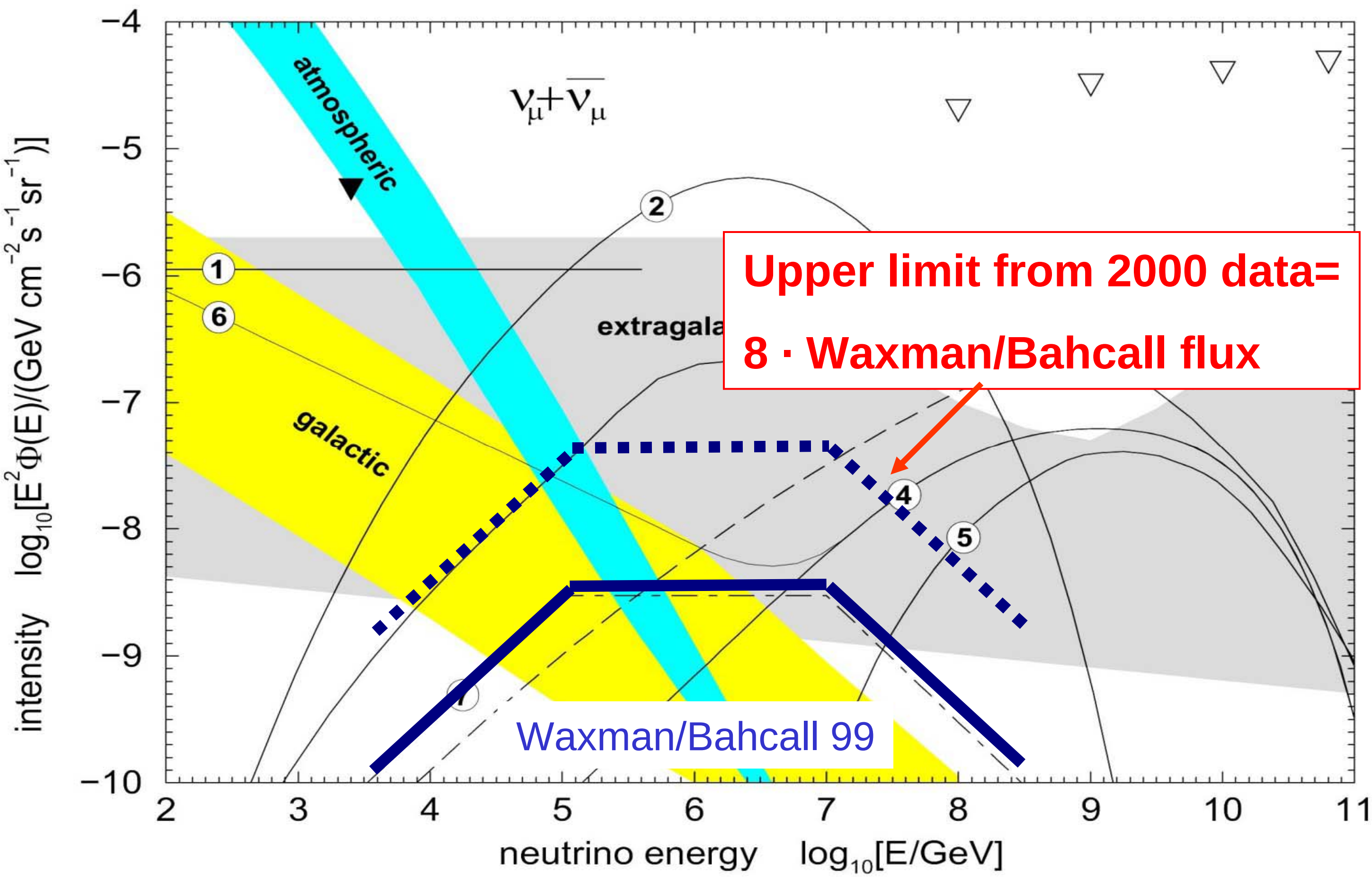
Year	Detector	N_{Bursts}	$N_{BG, Pred}$	N_{Obs}	Event U.L.
1997	B-10	78 (BT)	0.06	0	2.41
1998	B-10	94 (BT)	0.20	0	2.24
1999	B-10	96 (BT)	0.20	0	2.24
2000	A-II (2 analyses)	44 (BT)	0.83/0.40	0/0	1.72/2.05
2000	A-II	24 (BNT)	0.24	0	2.19
2000	A-II	46 (New)	0.60	0	1.88
97-00	B-10/A-II	312 (BT)	1.29	0	1.45

BT = BATSE Triggered   BNT = BATSE Non-Triggered   New = IPN & GUSBAD

No ν observed!



- Large effective areas (50 000 m^2 @ 1 PeV)



Stay Tuned:

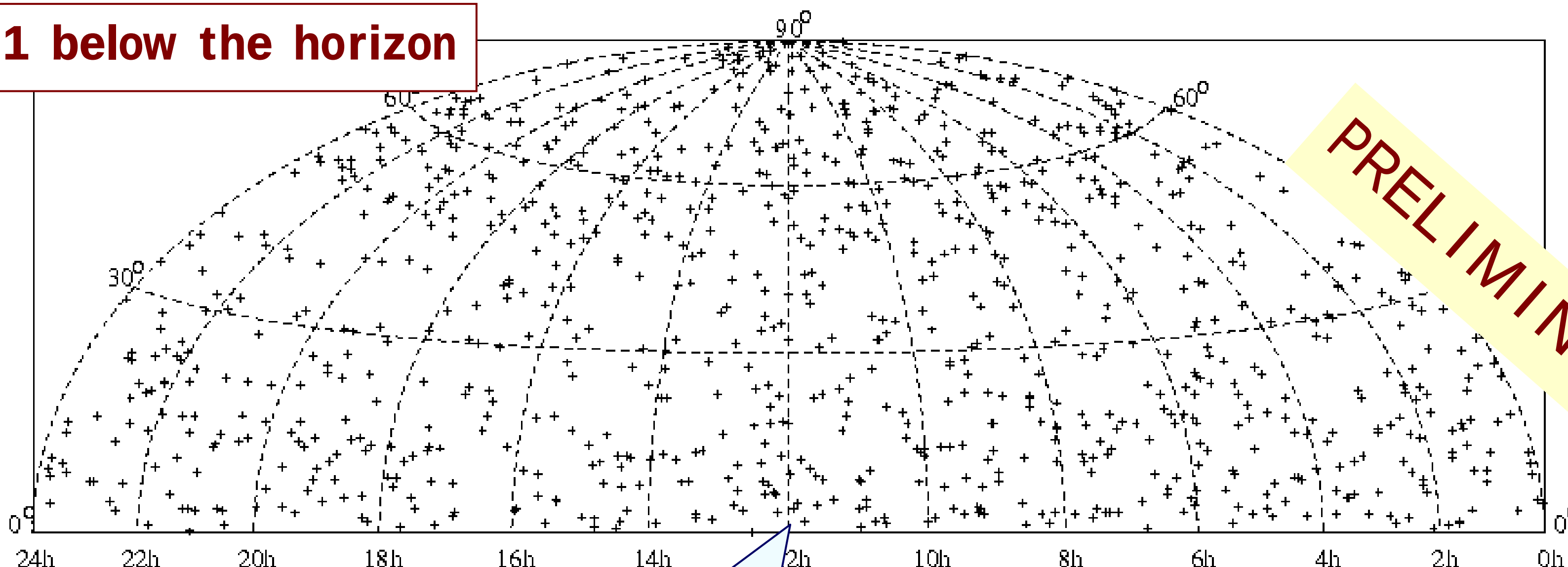
~2x GRBs
During '01-03

3 YEAR AMANDA POINT SOURCE SEARCH

Optimize cuts for E^{-2} spectra

- reduces lower energy atm nu

961 below the horizon



No clustering observed

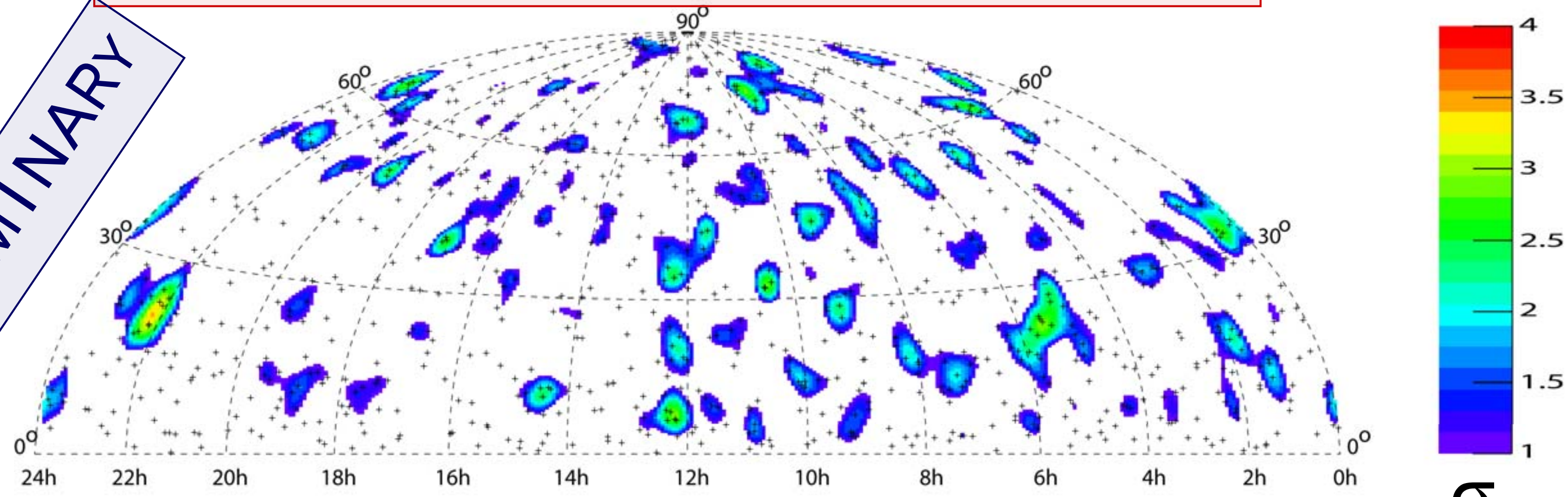
→ No evidence for point sources

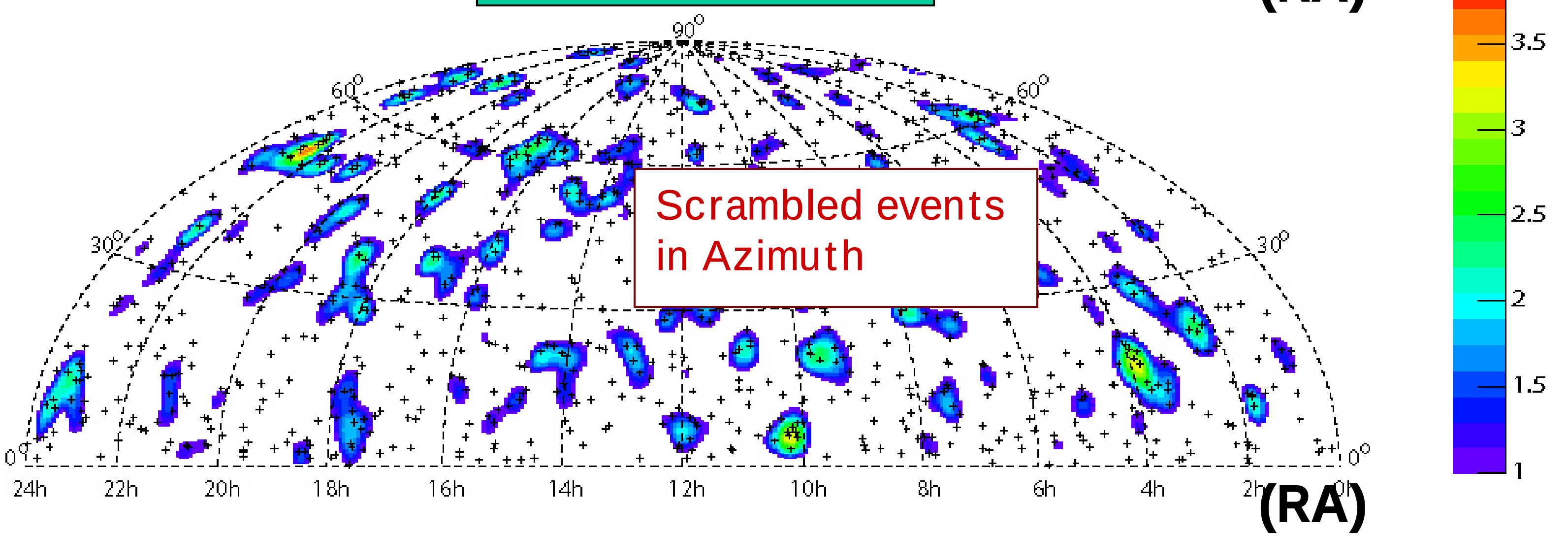
Livetime
2000: 197 days; 2001: 194 days;
2002: 213 days
2000+2001+2002: 922 events

SOURCE SIGNIFICANCE SKY-PLOT

MAP based on the 2000 + 2001+ 2002 DATA set

PRELIMINARY





Scrambled events in Azimuth

NO EXCESS beyond randomly expected → **Atmospheric Neutrinos!**

Diffuse Source Astronomy

Diffuse Limits in AMANDA-II

- Atmospheric Neutrino Spectrum

  E= 1-100 TeV

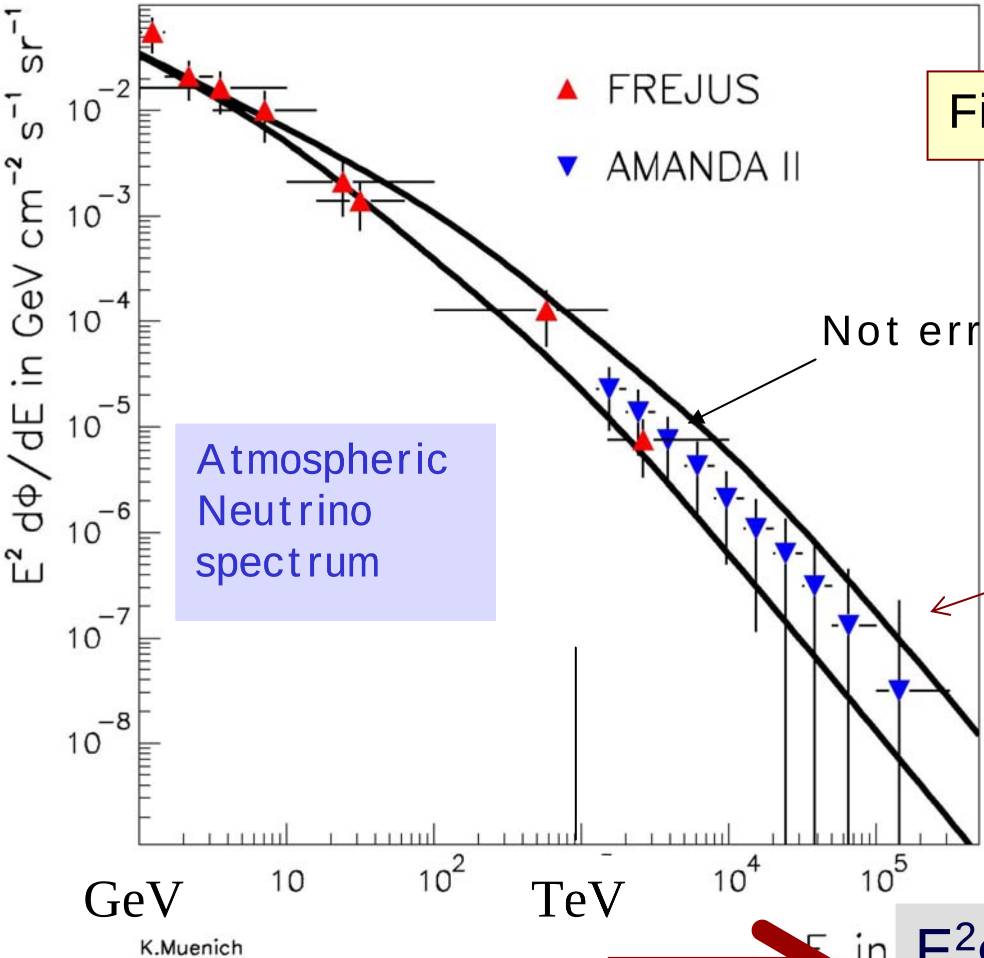
- Cascade Topologies

  E= 1-1000 TeV

- Downgoing EHE analysis

  $E=10^3 - 10^7$ TeV

DIFFUSE LIMITS: Atmospheric [ν_μ]



First spectrum > 1 TeV (up to 100TeV)

Not error bars!

Last few bins used to calculate the limit to Extraterrestrial E² neutrino flux

PRELIM.

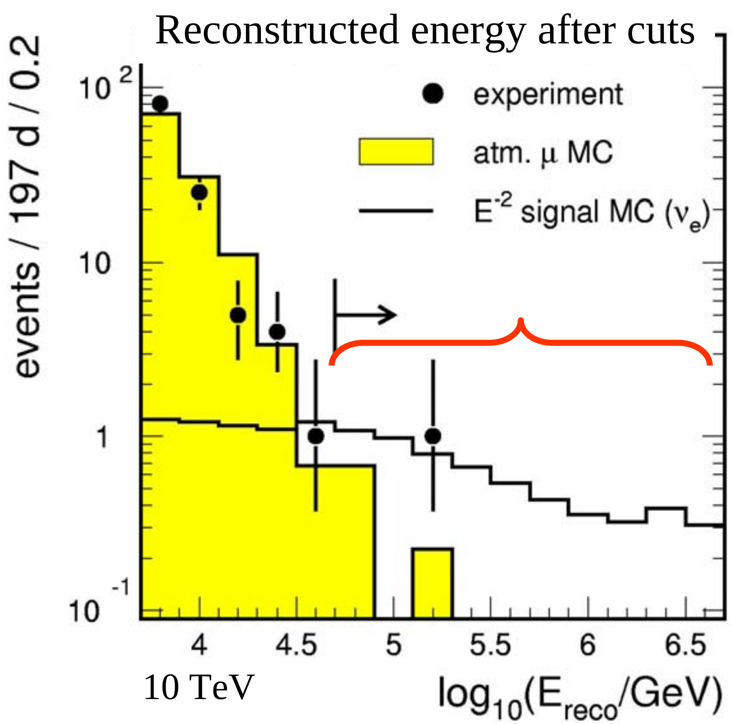
$E^2\Phi_\nu(E) < 2\text{x}10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1}

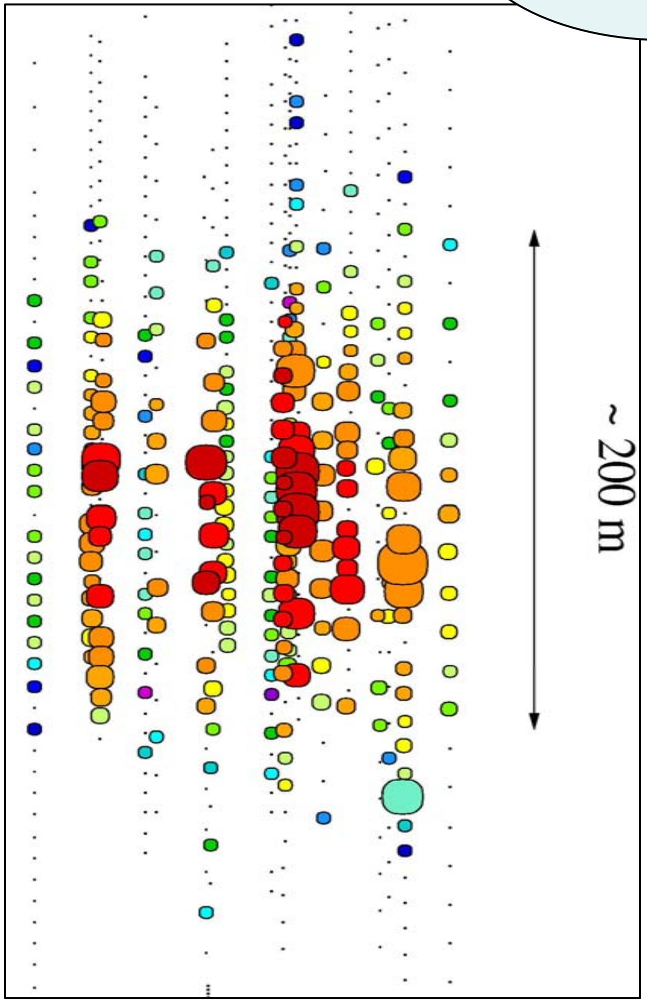
Includes 33% systematic uncertainty

DIFFUSE LIMITs: cascade events

Hadronic & em showers

- equal sensitivity to all neutrino flavors
- Event selection based on topology and energy



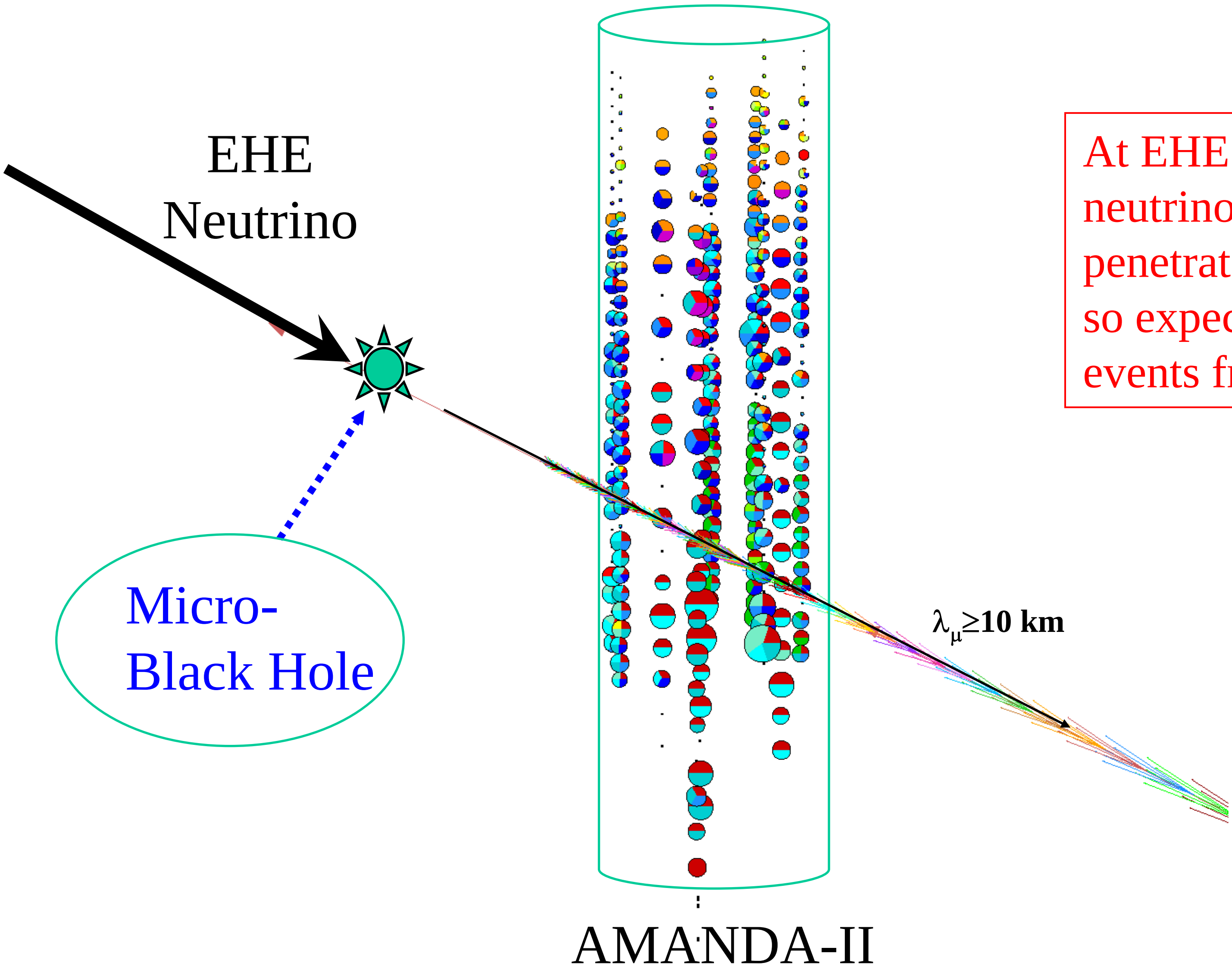


$$E^2\Phi_{\mathrm{all}\ \nu}(E) < 8.6\cdot10^{-7}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$$

Upper limit in 50-5000 TeV region

Accepted for publication Astroparticle Physics

South Pole Antarctica



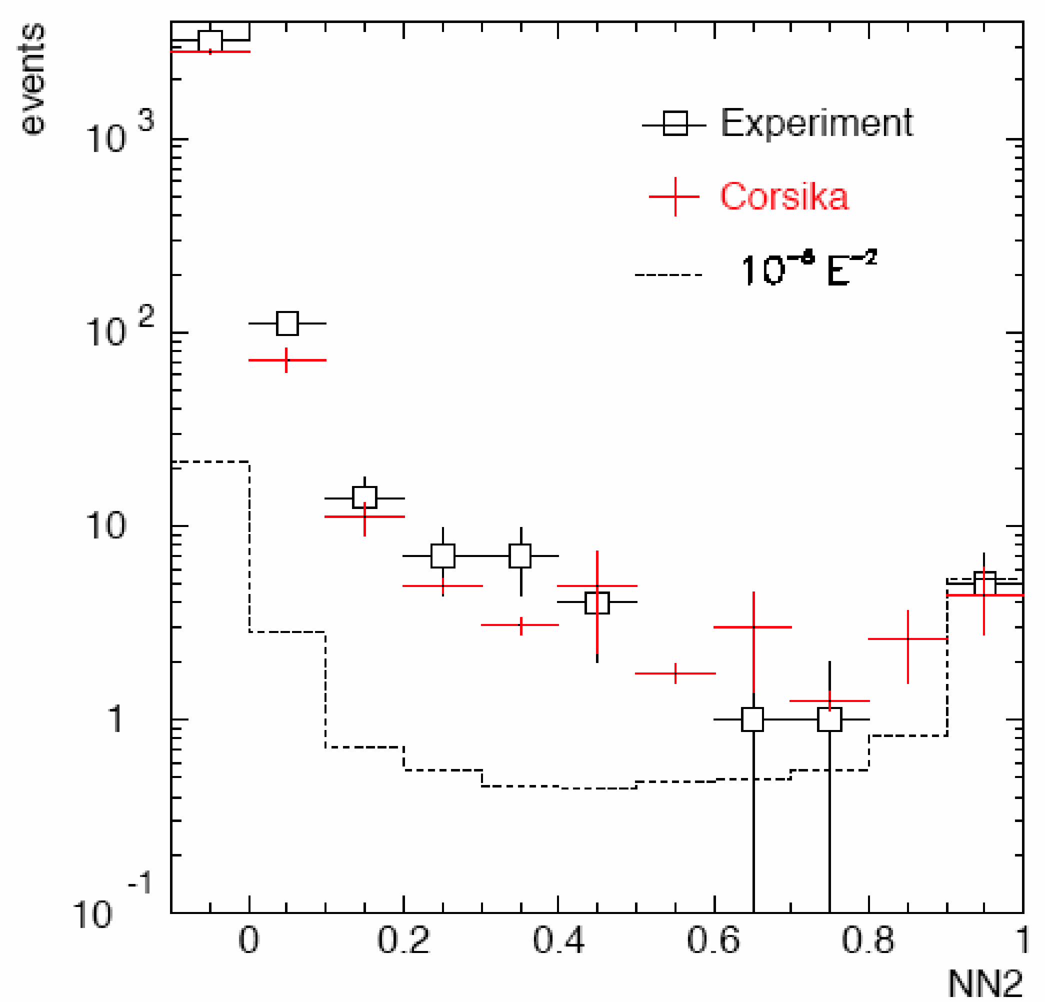
At EHE energies, neutrinos cannot penetrate the earth, so expect most events from horizon

DIFFUSE LIMITS: UHE [$\Phi_{all\ \nu}$]

N_{obs} = 5 events

N_{bgr} = 4.6 ± 36%

NO EXCESS OBSERVED

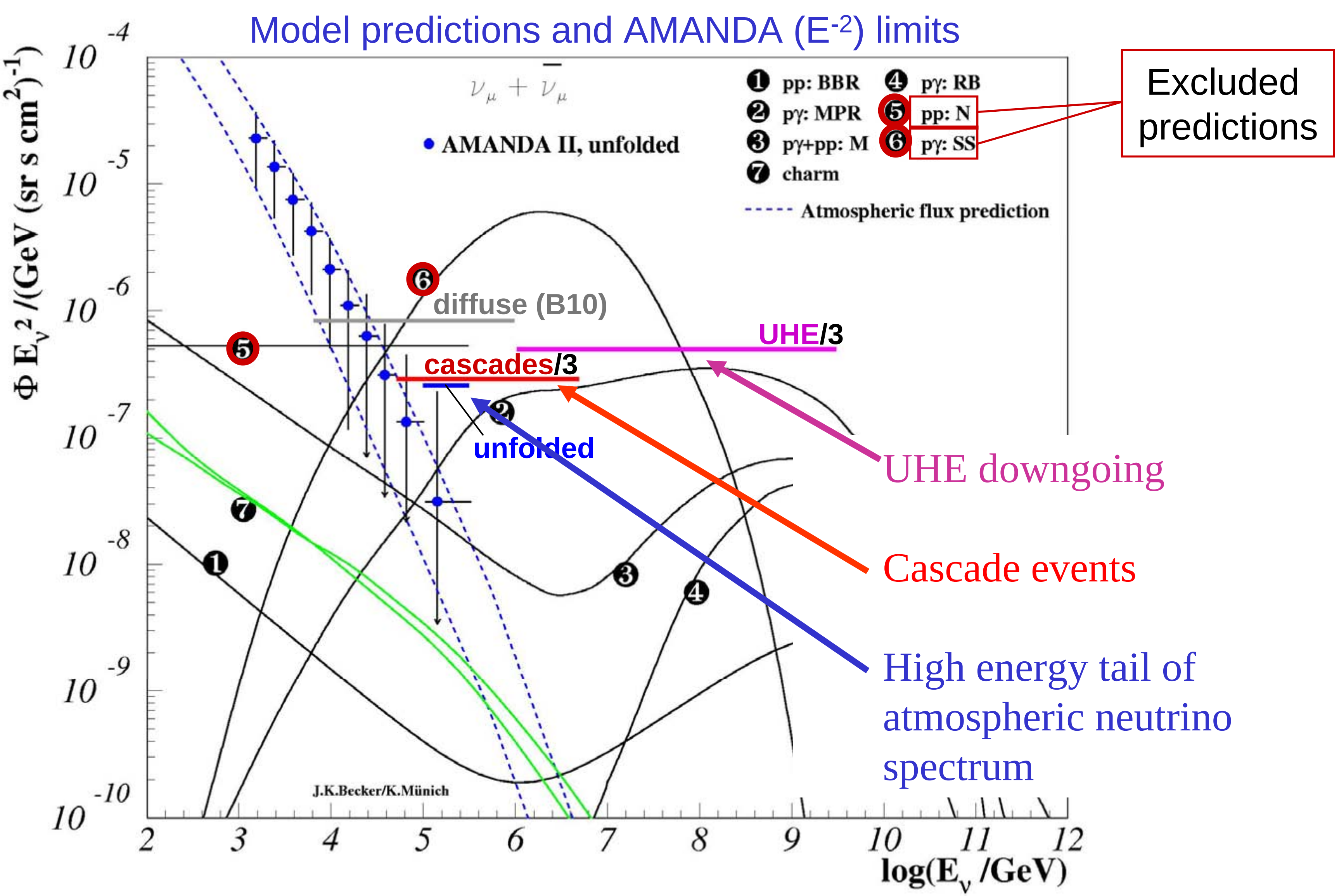


(ν_e:ν_μ:ν_τ = 1:1:1)

$E^2\ \Phi_{all\ \nu}(E)\ < 1.5\cdot10^{-6}$ GeV cm^{-2} s^{-1} sr^{-1}

AMANDA-II (TWR 2003): expected further improvement using Waveforms

DIFFUSE LIMITS: SUMMARY



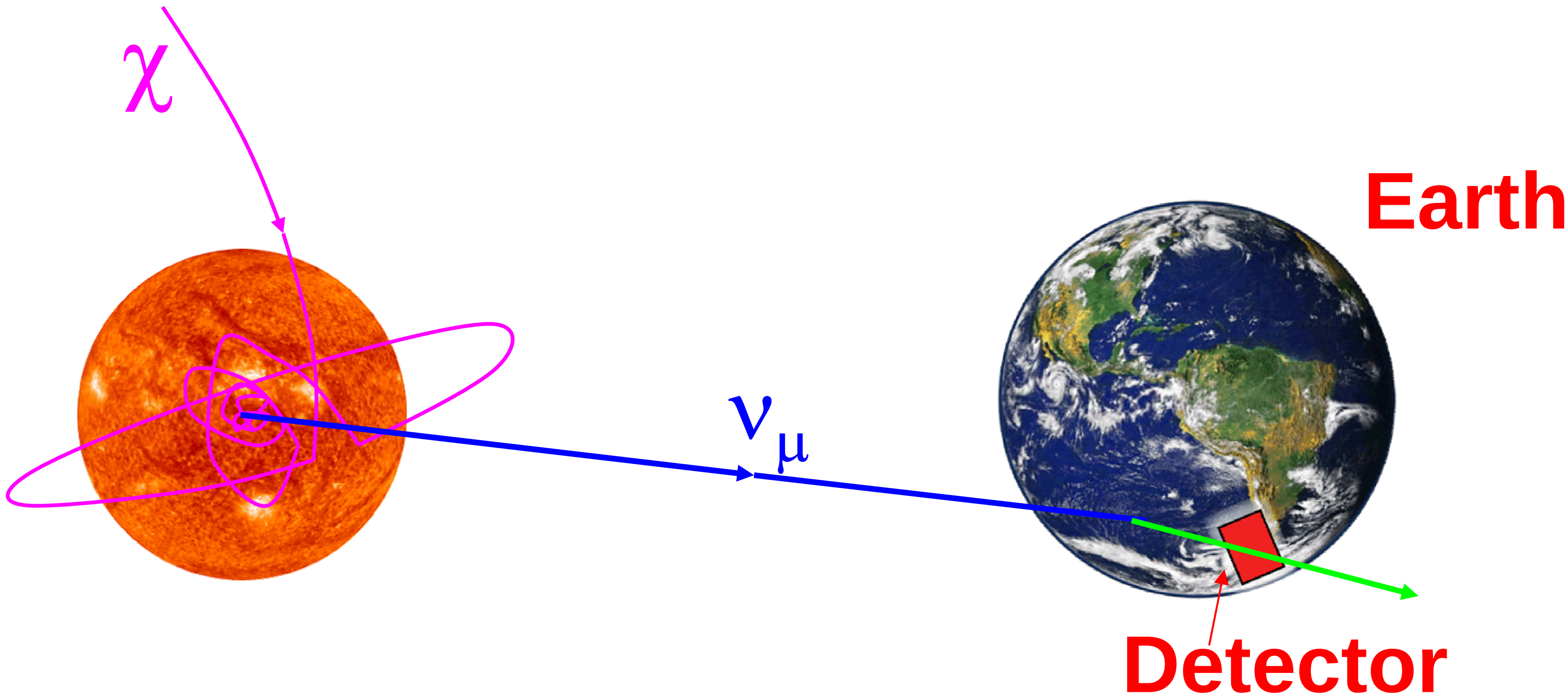
EXCLUDED PREDICTIONS

Specific predicted model spectra excluded by AMANDA

Reference	Prediction	Analysis	Detector
Szabo,Protheroe (1992)	SPH92L	Diffuse (97) [published]	AMANDA-B10
Protheroe (1997)	P96pγpp		
Stecker,Salamon (1996)	SSQC		
Szabo,Protheroe (1992)	SPH92L	Diffuse (00) [in progress]	AMANDA-II
Protheroe (1997)	P96pγpp		
Stecker,Salamon (1996)	pγ:SS		
Nellen et al.(1993)	pp:N		
Stecker(1991)	SDSS	Cascades (00) [submitted]	AMANDA-II
Stecker,Salamon (1996)	SS Quasar		
Szabo,Protheroe (1992)	SP u		
Szabo,Protheroe (1992)	SP l		
Protheroe (1996)	P pp+pγ		
Stecker,Salamon (1996)	S96	UHE (97) [submitted]	AMANDA-B10
Protheroe (1996)	P97		

Exotic Phenomena

WIMP Capture and Annihilation

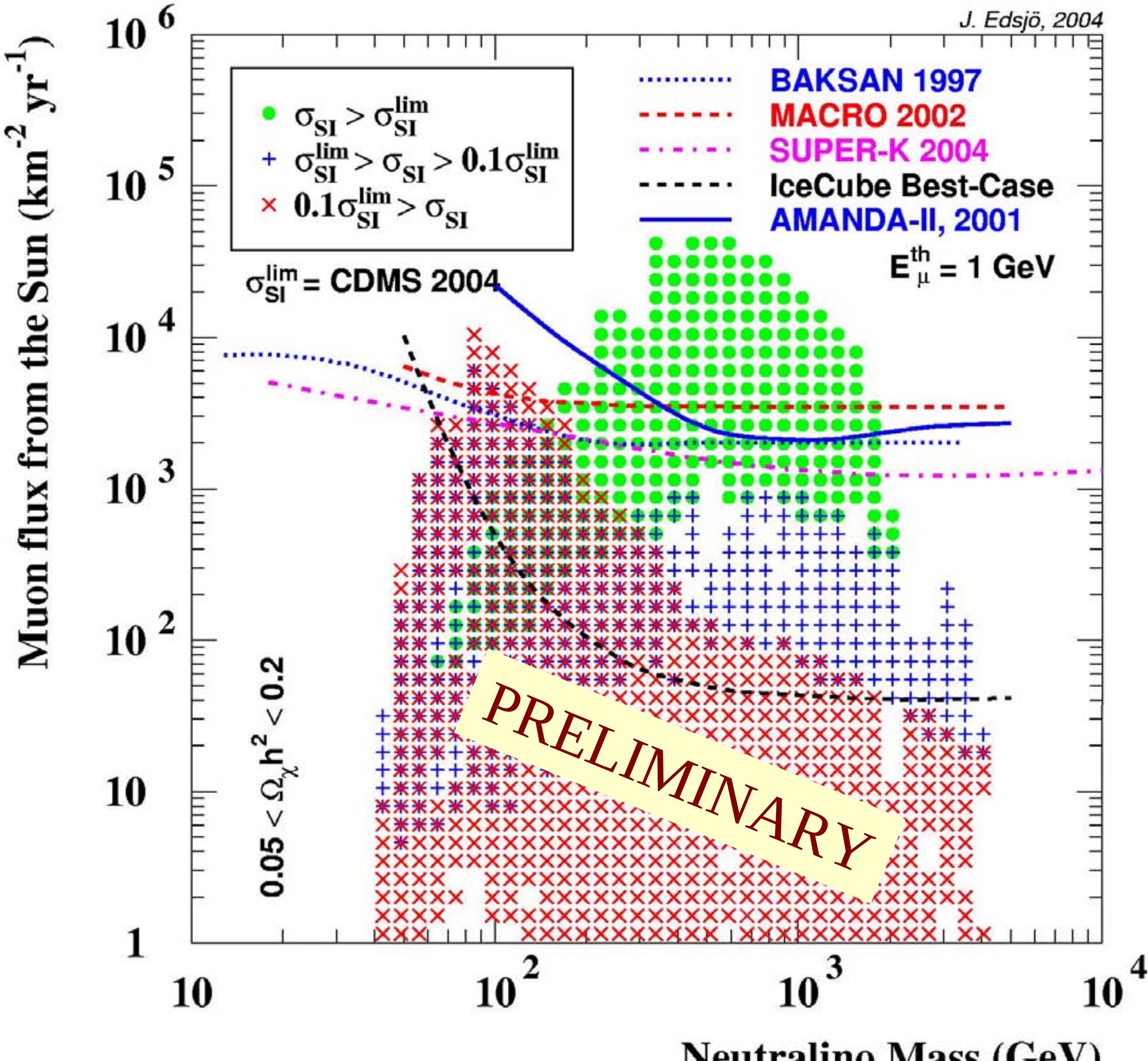


Sensitivity to the Muon Flux from WIMP Annihilation in the Center of the Sun

AMANDA-II results:

• based on 1 yr of data

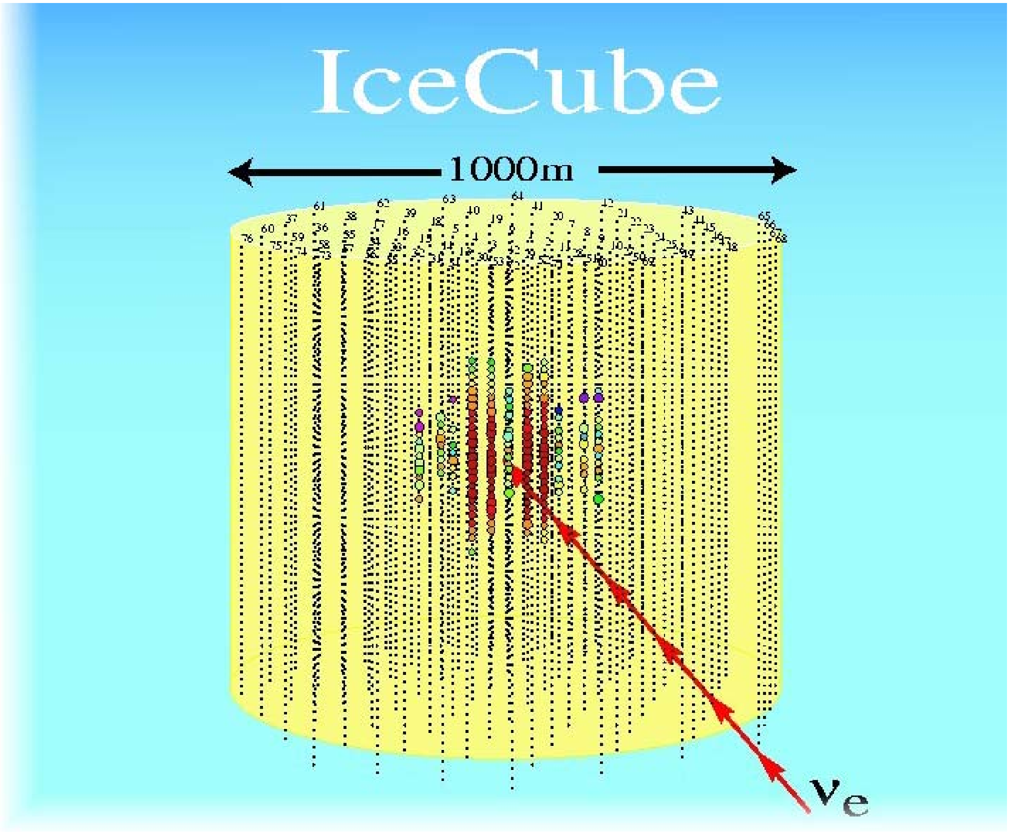
• 2 yr combined analysis soon



The Future of Neutrino Astonomy

ICECUBE

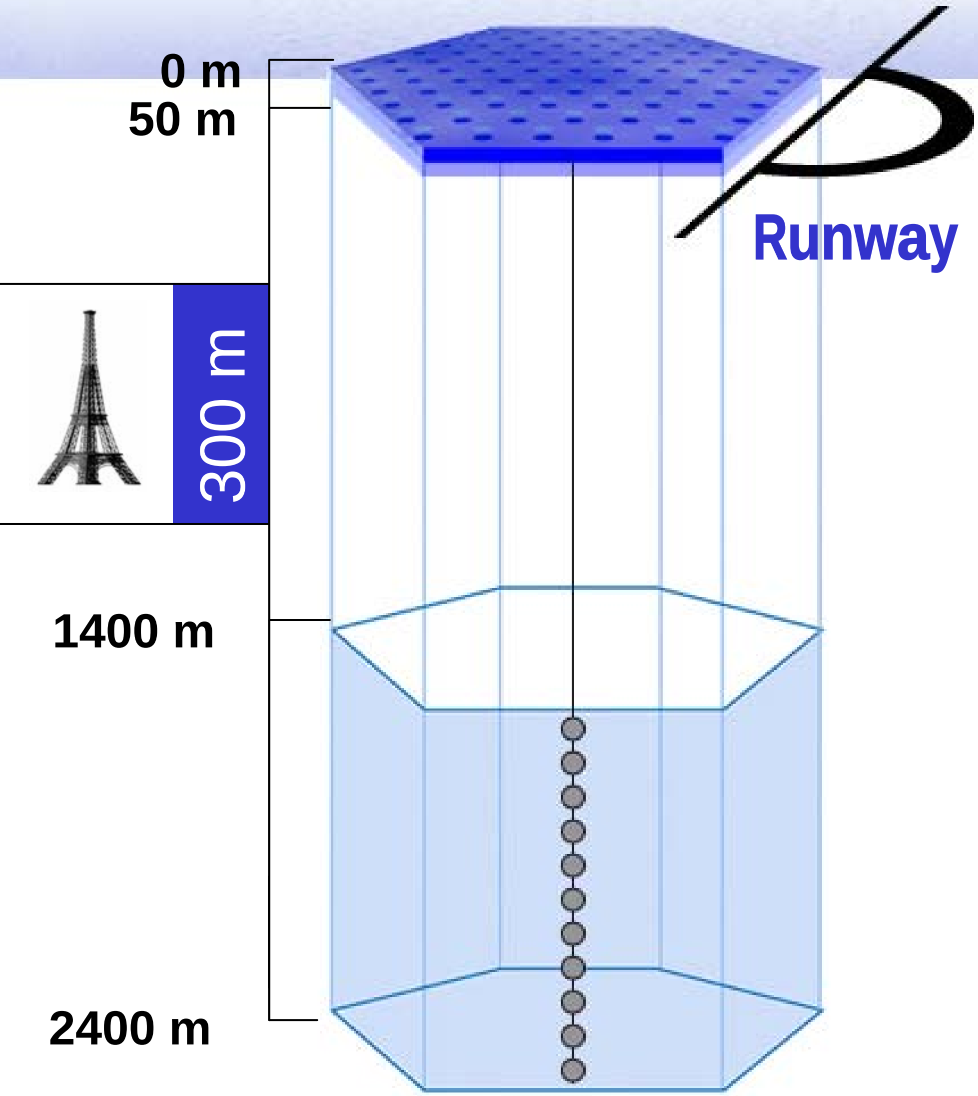
Perhaps First Km^3 Neutrino Detector ~2010



Ideally suited for $E_\nu < 10$ PeV

First funds 2002

- **70-80 strings, 60 PMT´s each;**
- **$V \approx 1\ km^3$, $E_{th} \sim 0.5-1$TeV**



IceCube

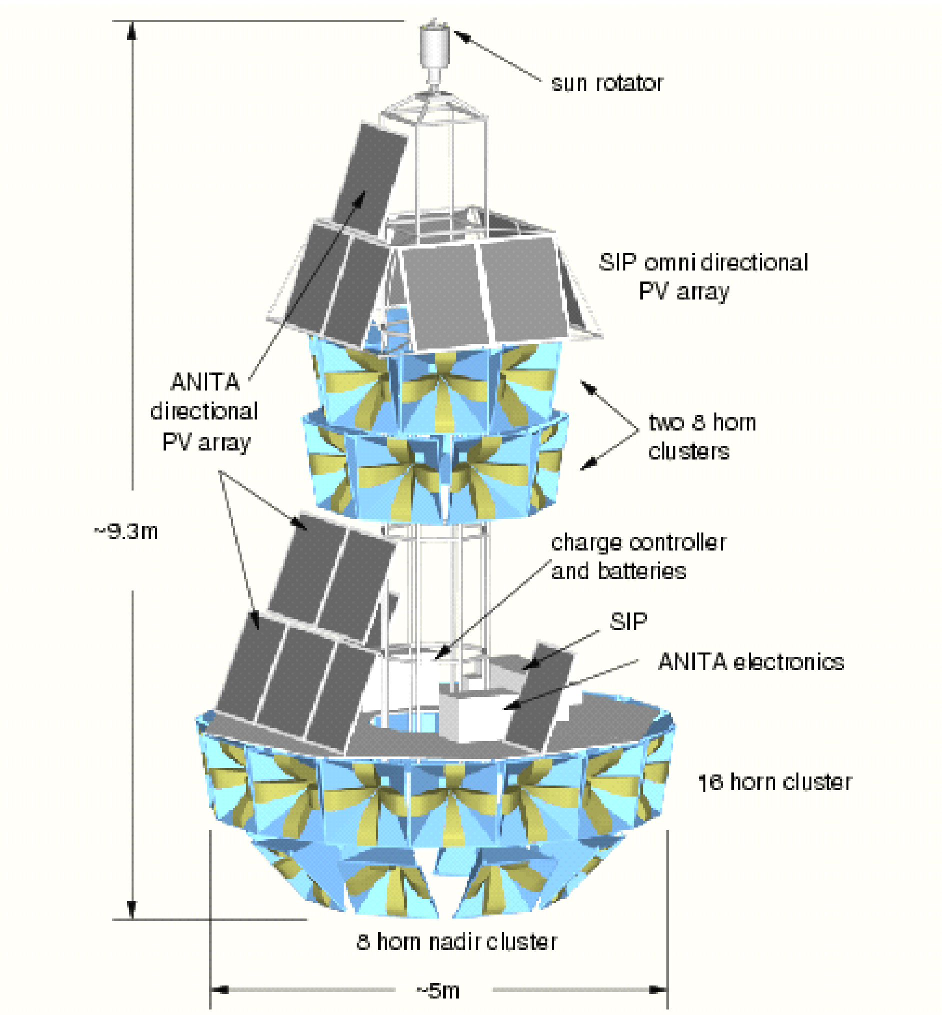
- 70-80 Strings
- 60 PMT/String
- Instrumented volume: 1 km3 (1 Gigaton)
- $272 M
- First string -Jan 05
- Completion - 2010

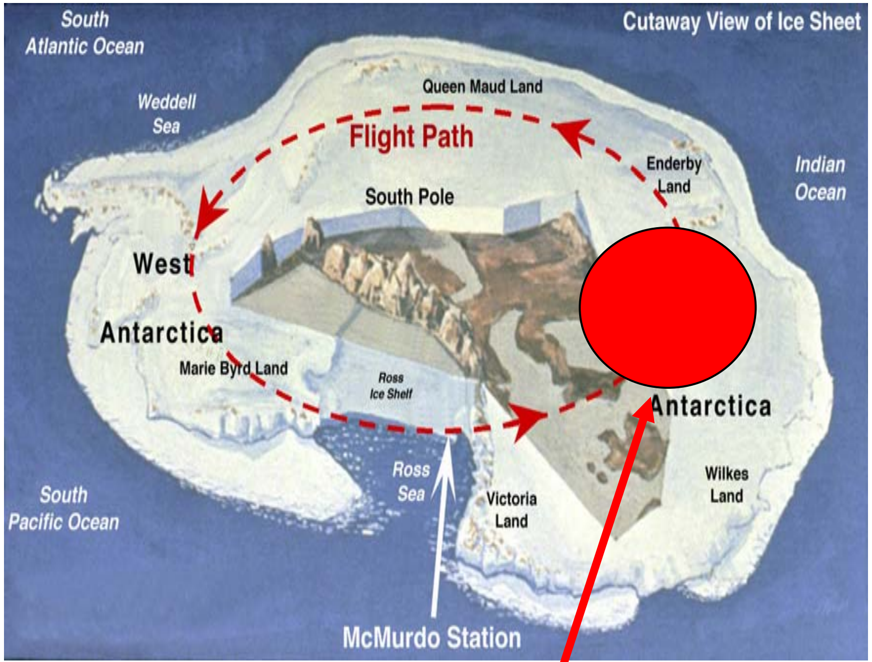
Hose-reel with hose, (Nov 2003)

Hose-reel at South Pole (Jan 2004)

ANtarctic Impulsive Transient Antenna

www.ps.uci.edu/~anita

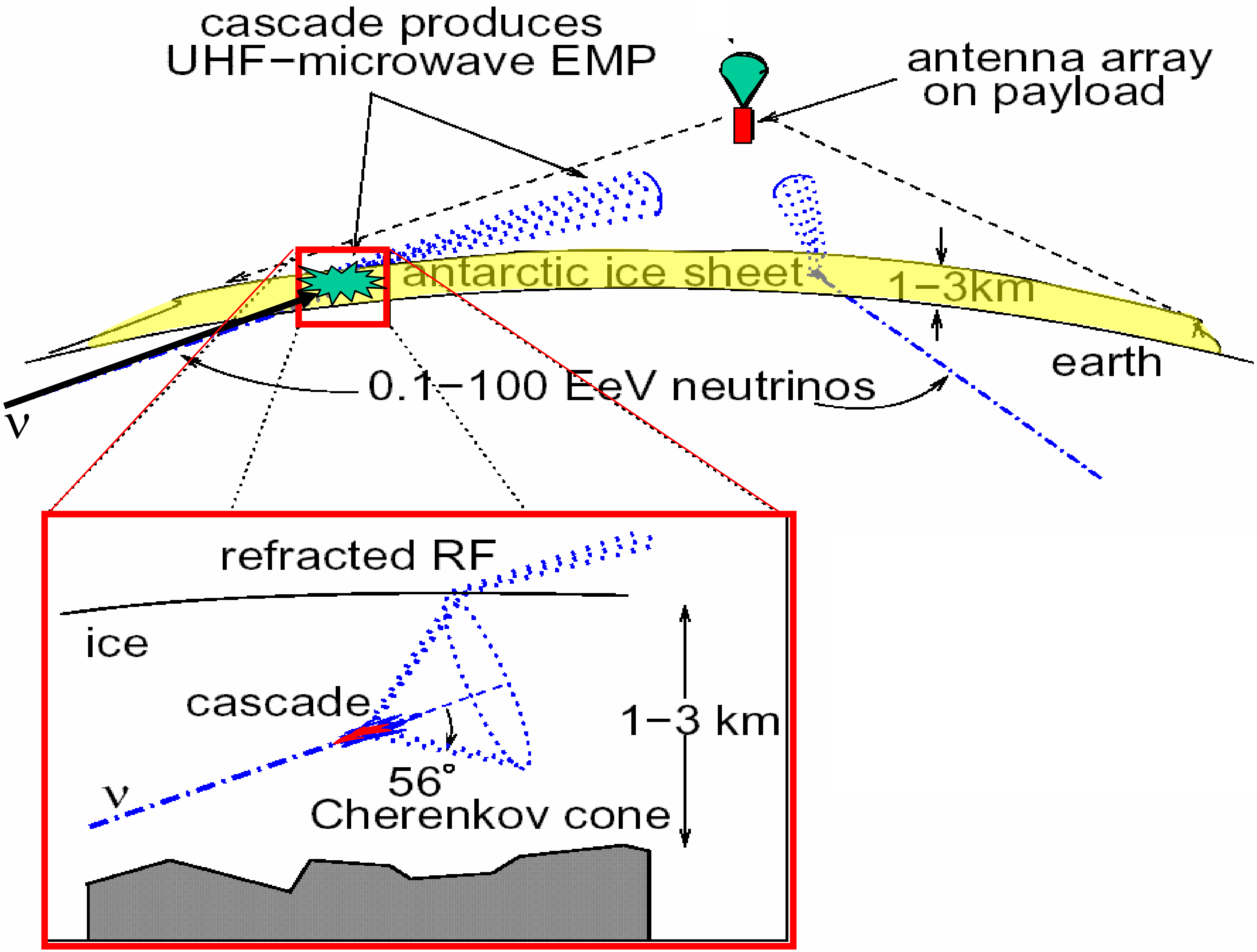




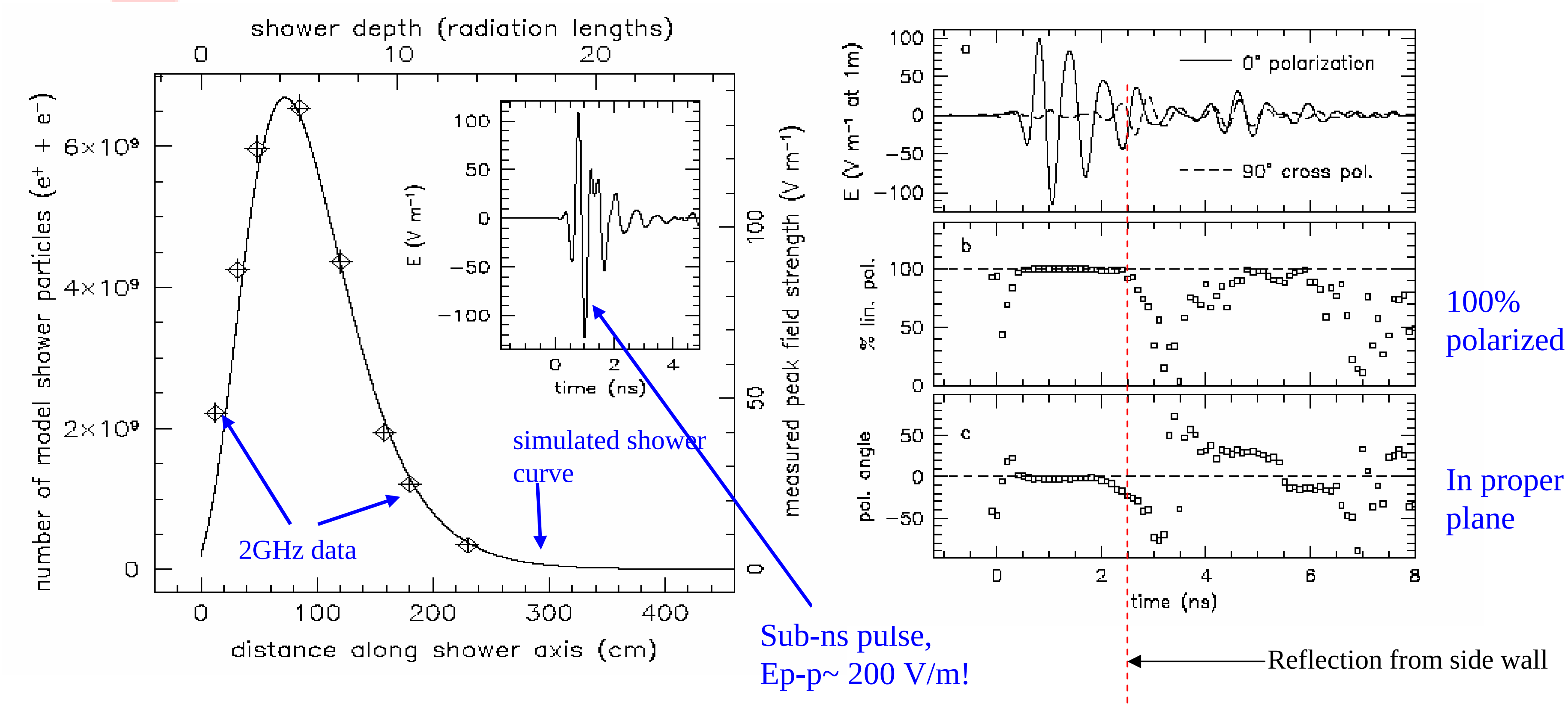
600 km radius,
1.1 million km^2

- NASA funding started 2003 for first launch in 2006
- Phase A approval for SMEX ToO mission, >2006

ANITA concept



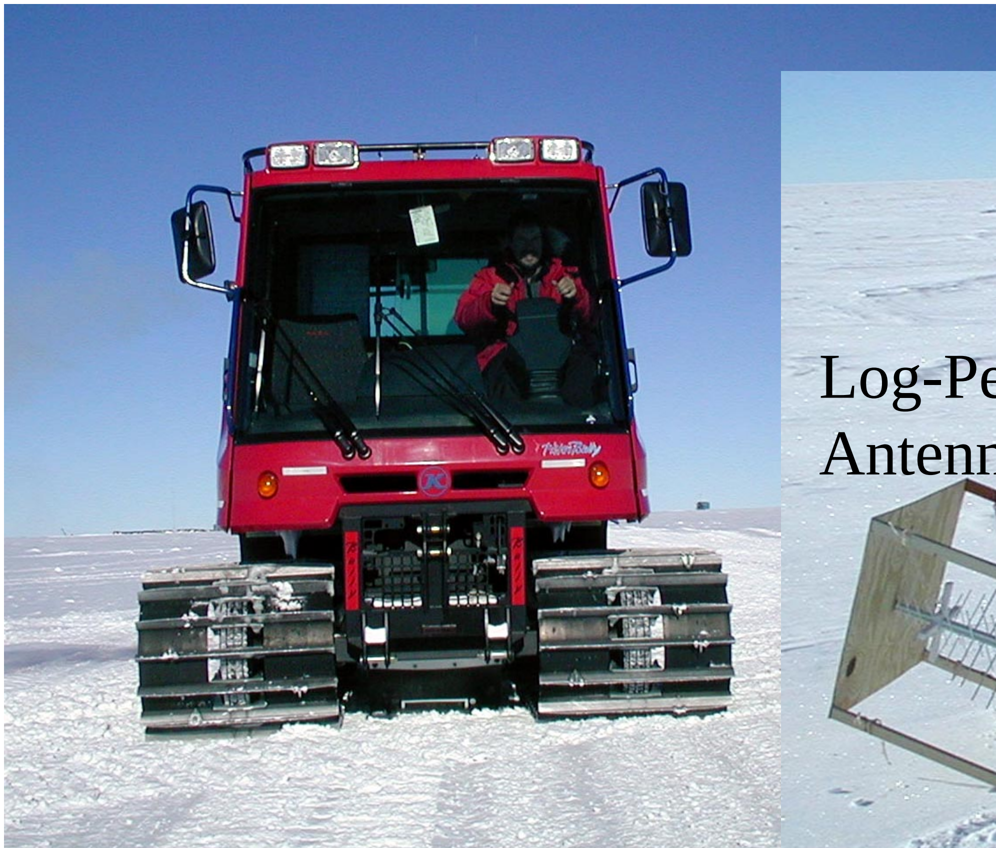
Shower profile observed by radio (~2GHz)

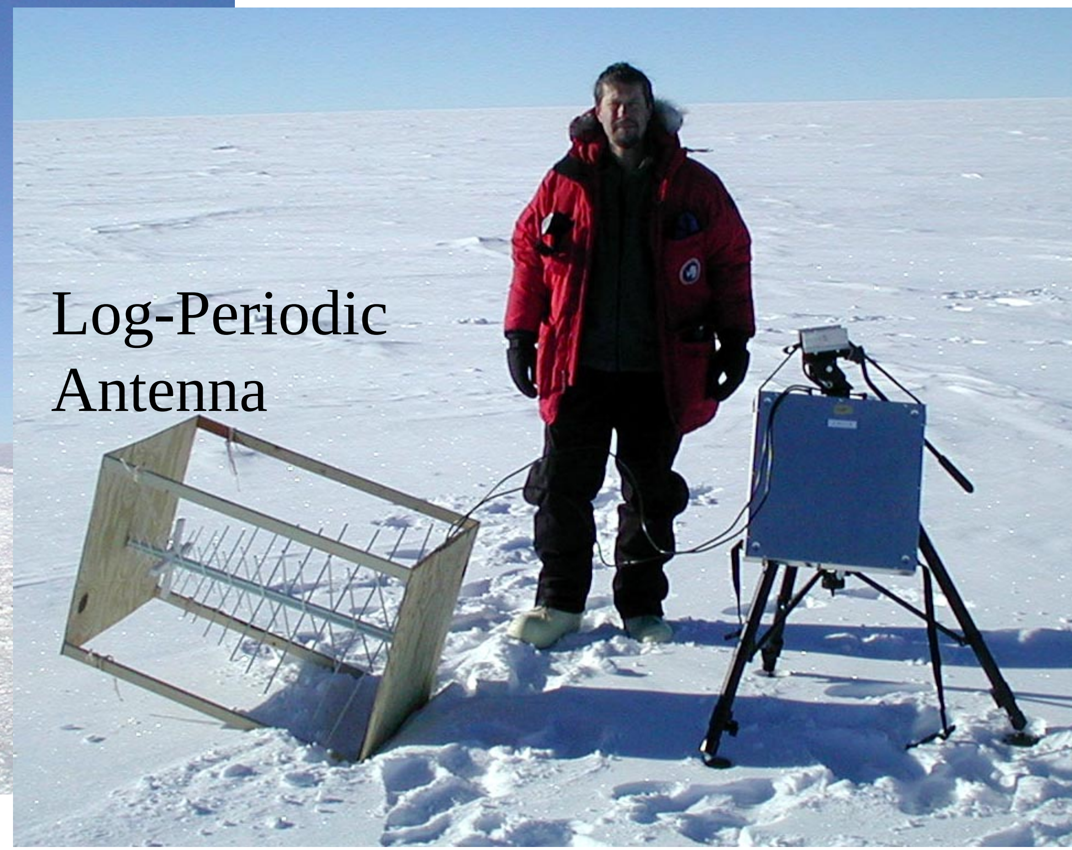


- Measured pulse field strengths follow shower profile very closely
- Charge excess also closely correlated to shower profile (EGS simulation)
- Polarization completely consistent with Cherenkov

Noise Tests at South Pole

- Ambient noise on the high plateau

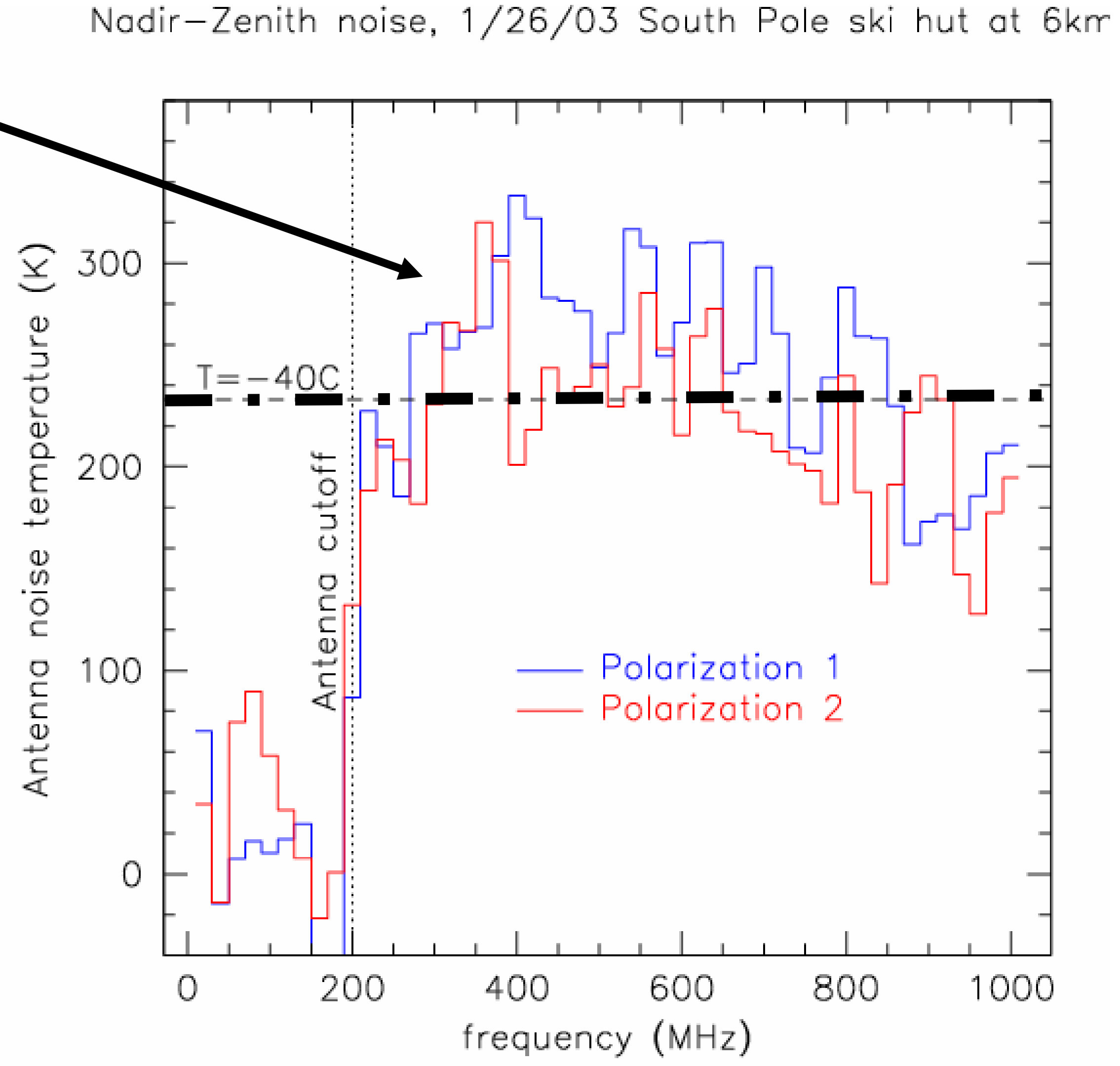




Initial Results from Polar Studies

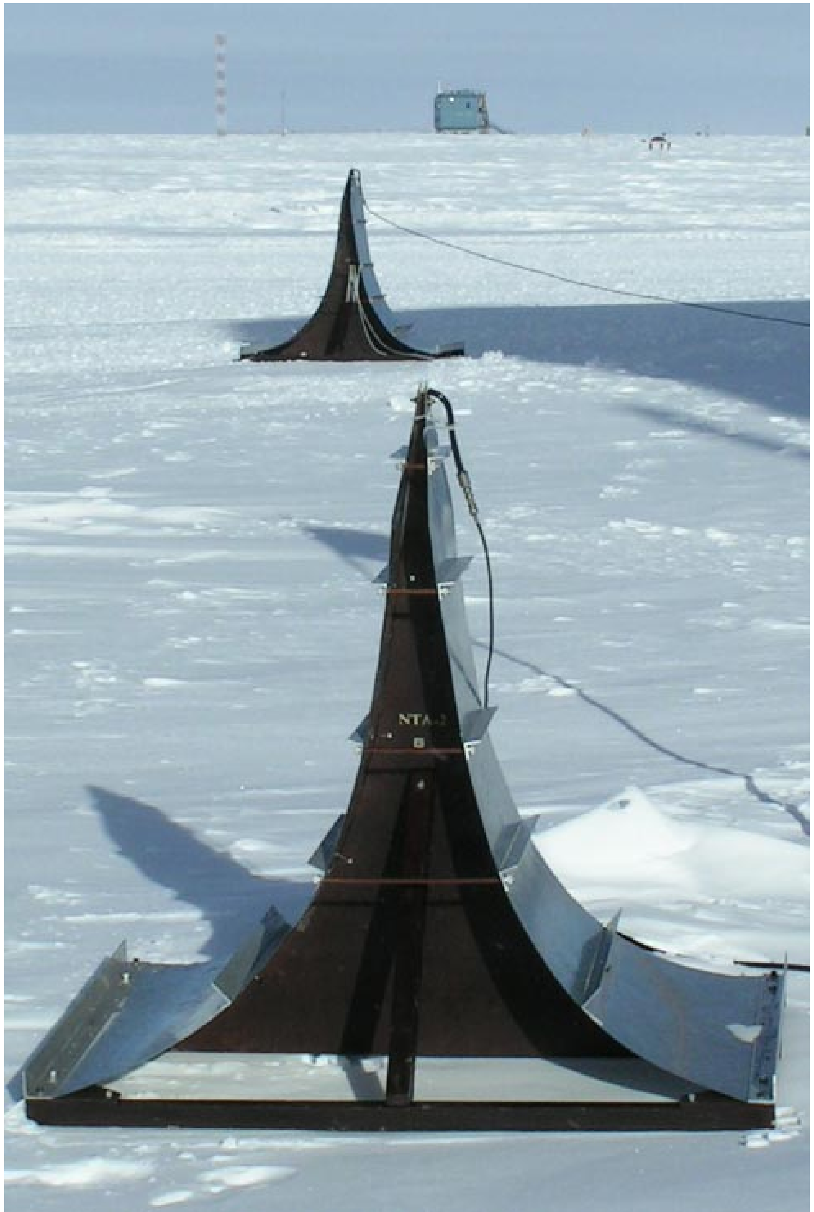
- It looks good so far

RF emission from ice



Ice Attenuation at South Pole

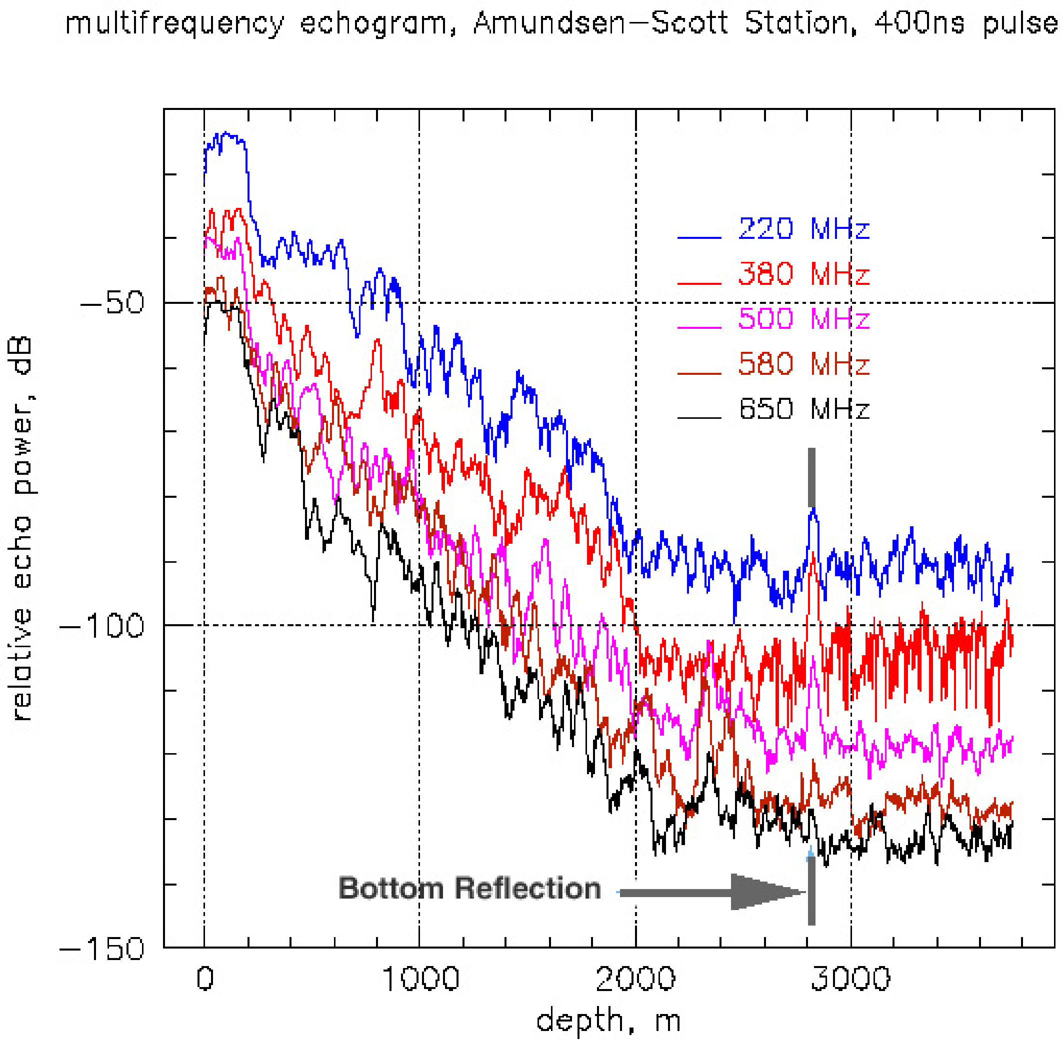
- from 200MHz to 700MHz



Jan. 2004

Ice Attenuation at South Pole

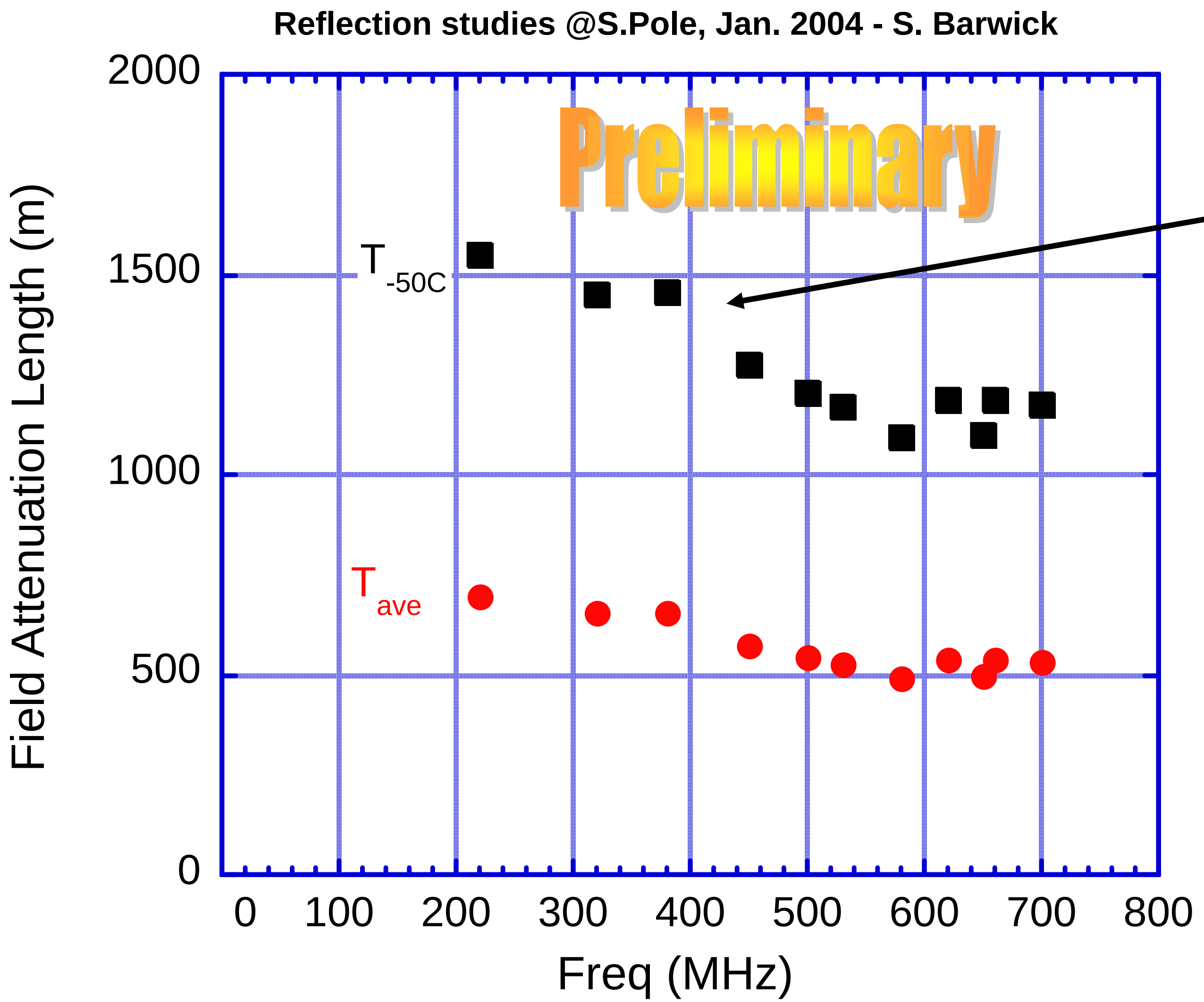
- from 200MHz to 700MHz



A clean reflection from the bottom implies that the attenuation lengths are very long!

Ice Attenuation at South Pole

- from 200MHz to 700MHz



Most of Antarctic ice is -50C!

Excellent transparency, compare to ~100 meter for light, it is 10x larger

ANITA-lite

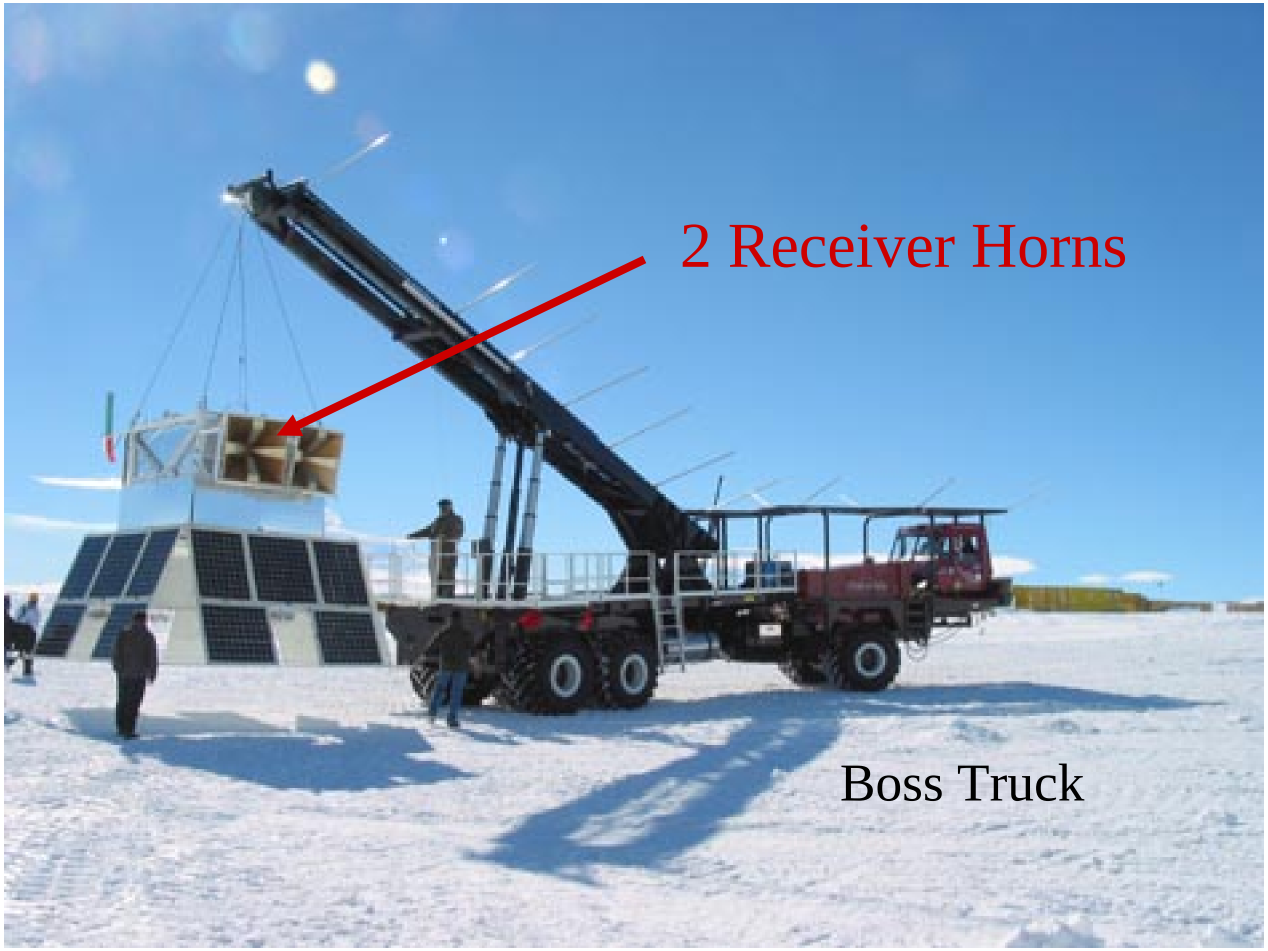
2 Receiver Horns

Electronics

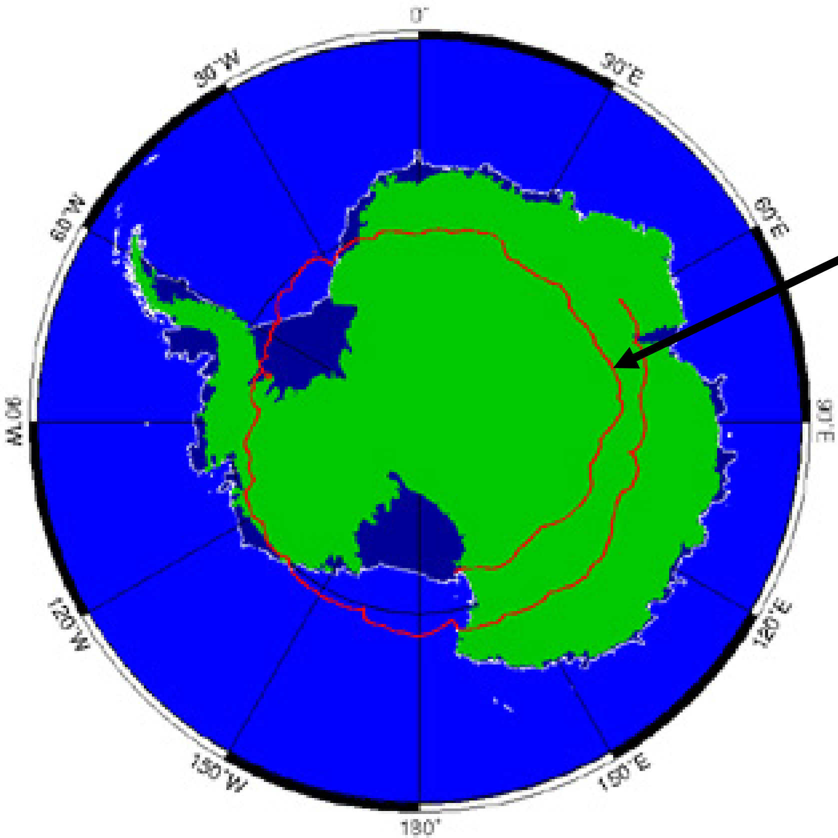
Piggyback on TIGER
Launch Dec '03

RF Survey of Antarctica

ANITA-lite prior to launch @ WF



ANITA-lite flight path 03/04

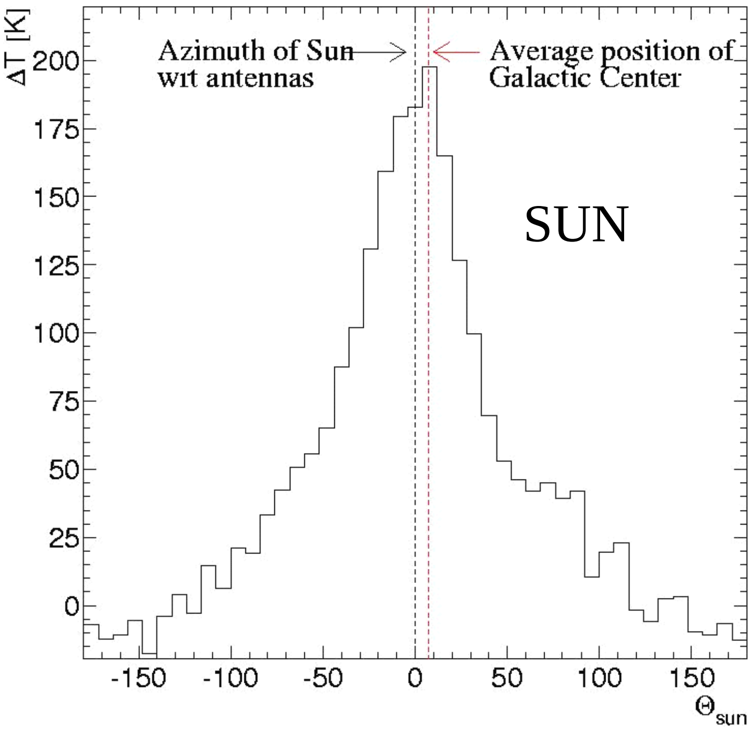


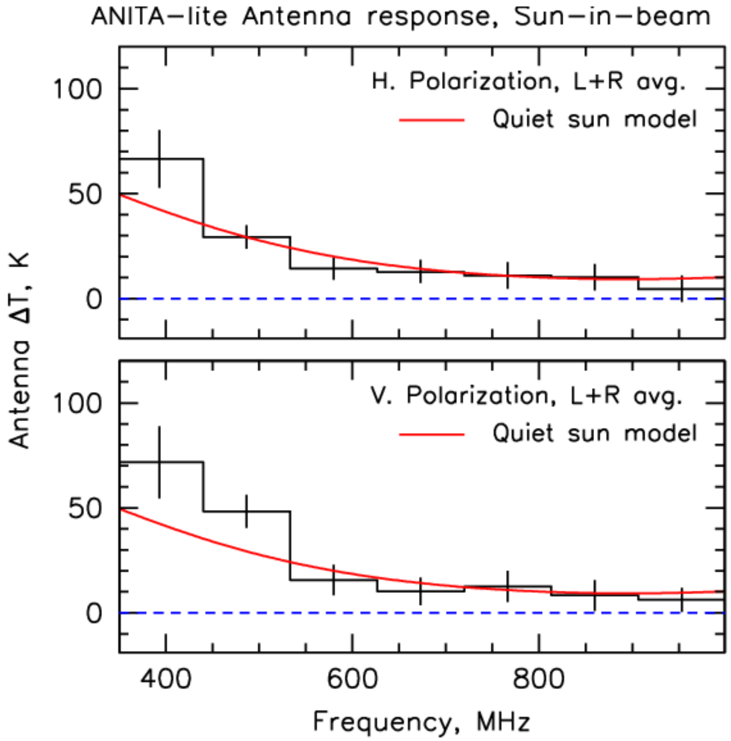
18 days at float altitude

1.25 revolutions, landing near Mawson Station

Data recovered in Feb 04

Initial results from ANITA-lite





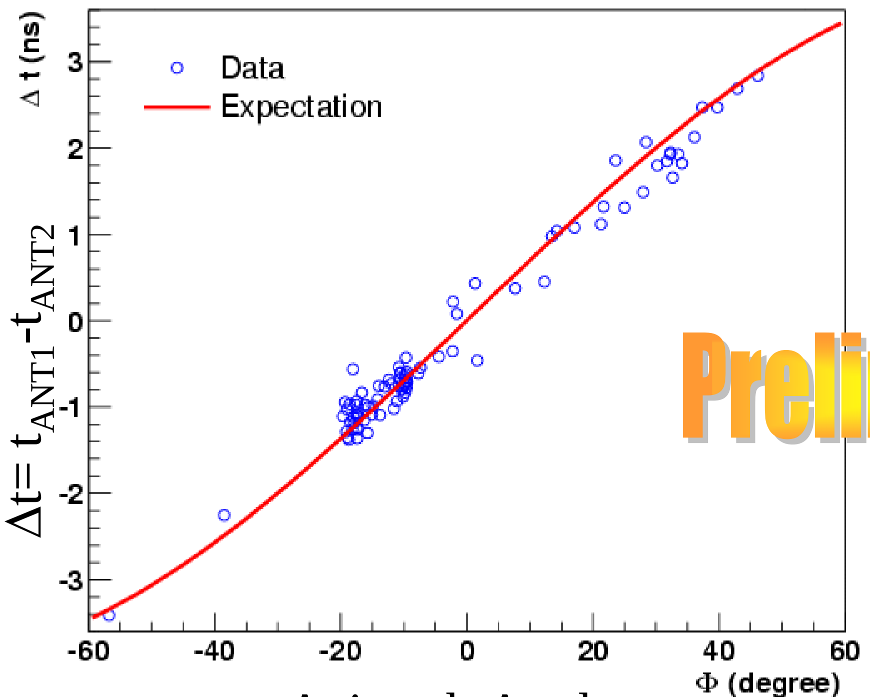
Antarctic Thermal noise measurements

-consistent with galactic+solar+kT_{ice}

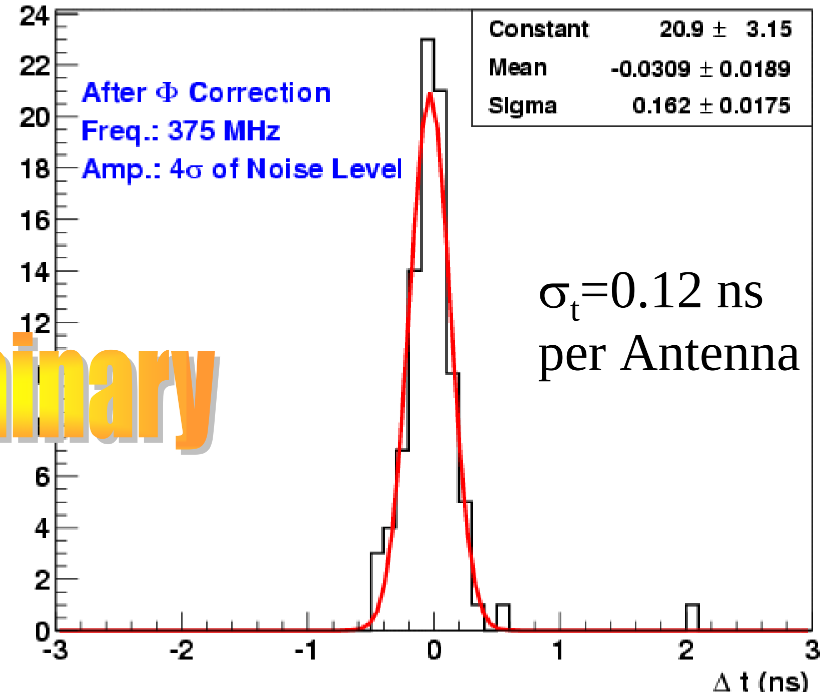
The ANITA-LITE antennas were able to discern the excess radio power in the direction of the Sun and the Galactic Center.

ANITA-lite timing resolution

Ground antenna transmits calib. pulse to Anita-lite @40km



Azimuth Angle



σ_t=0.12 ns
per Antenna

$\Delta t = t_{ANT1} - t_{ANT2}$

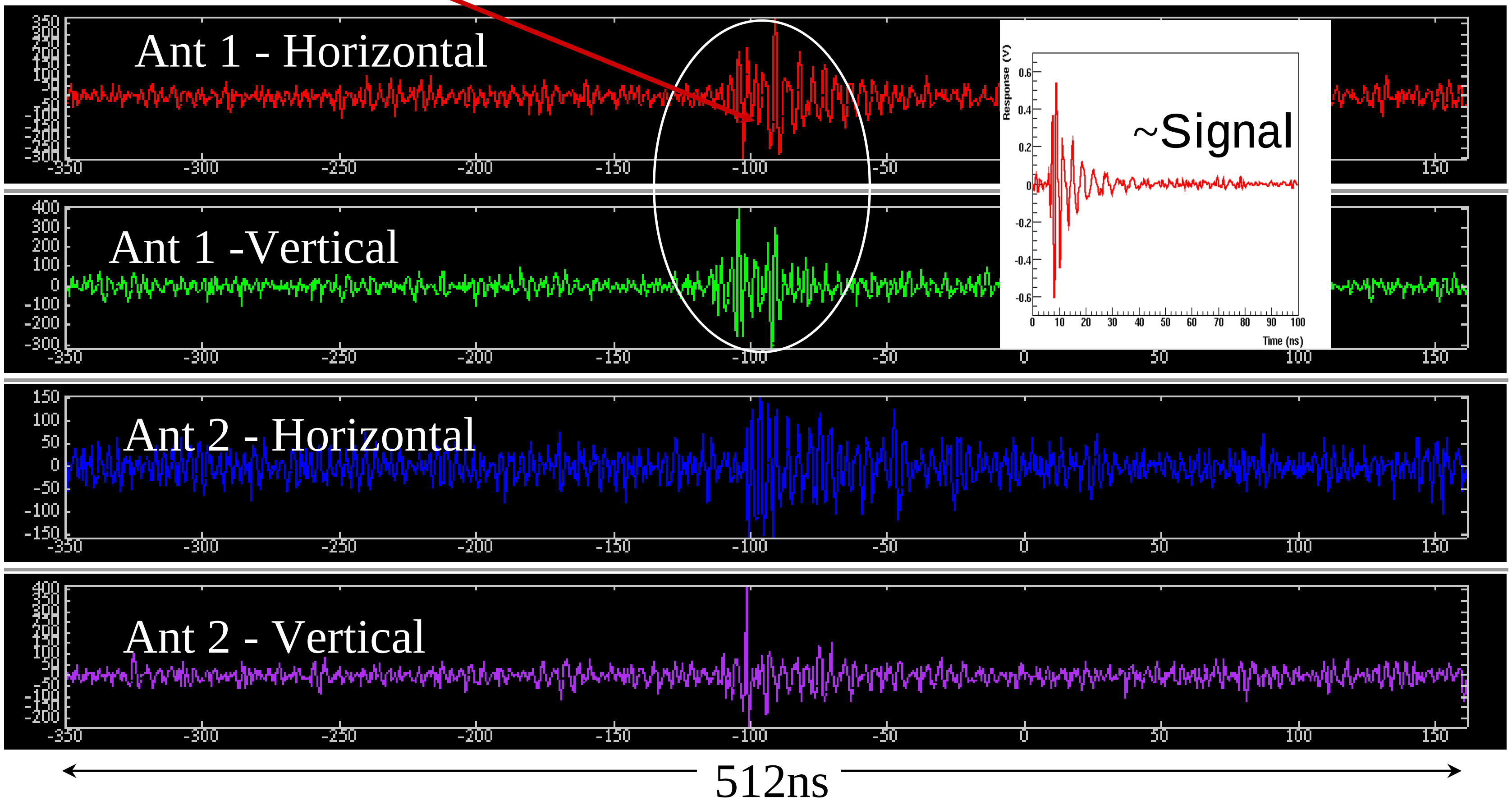
Expected Angular Resolution for ANITA

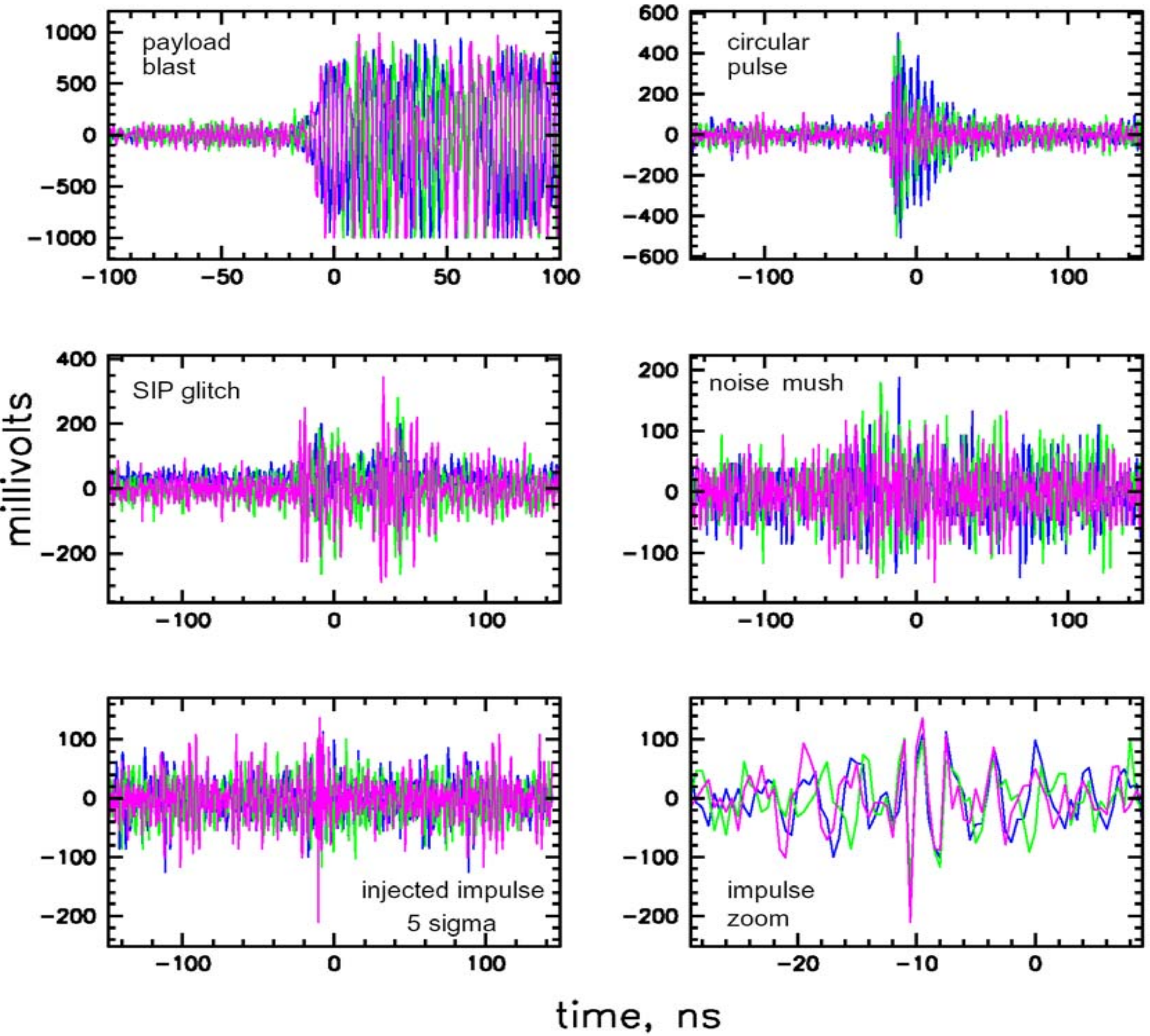
$\delta\theta \sim 0.5$ deg $\qquad$ $\delta\phi \sim 2$ deg

ANITA-lite BG event

Initial scan of data reveals no obvious ν signal

Duration is too large for ν - associated with local TRX

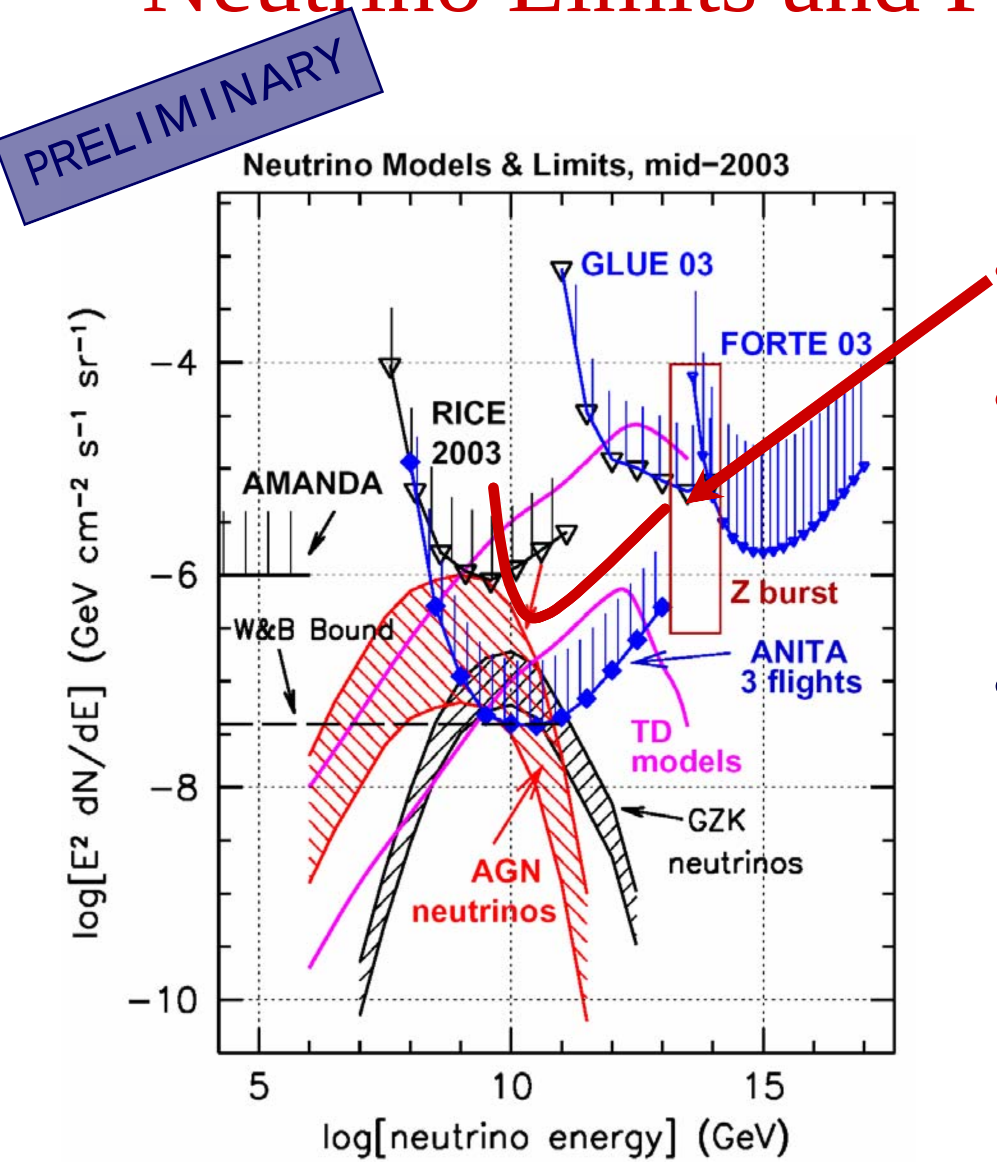




analysis

- Dominated by payload local noise
- Circularly polarized impulses (TDRSS relay turn-on?) are closes to **true impulses (but not)**
- Glitches from balloon support package (charge controller MOSFETS)
- **Injected 3 and 5 sigma signals** (overlain on actual thermal noise) used to test algorithm efficiency

Neutrino Limits and Projected Sensitivity



- **Anita-lite 03 sensitivity (7 days)**
- **ANITA sensitivity**:
  - ν_μ & ν_e included, full-mixing parameterized
  - 1.5-2 orders of magnitude gain
- These are all limits based on radio detection!

Why is ANITA a good idea?

- Frontier Science and very exciting
  - Win-win with GZK neutrinos
- Scans ice over 600km radius, and enormous detector volume!
- Radio signal can be calculated precisely and has been measured at high energy lab - unique signature!
- Energy resolution is relatively good
- Antenna can be absolutely calibrated by man-made radio transmitter embedded in deep hole (eg. Vostok)
- Clean signal
  - Linearly polarized, must originate in ice, distinct few ns time structure of pulse, “beam-off” in directions over water
- Balloon flight path is far from sources of confusing background

Revolutionary concept in EHE neutrino detection!

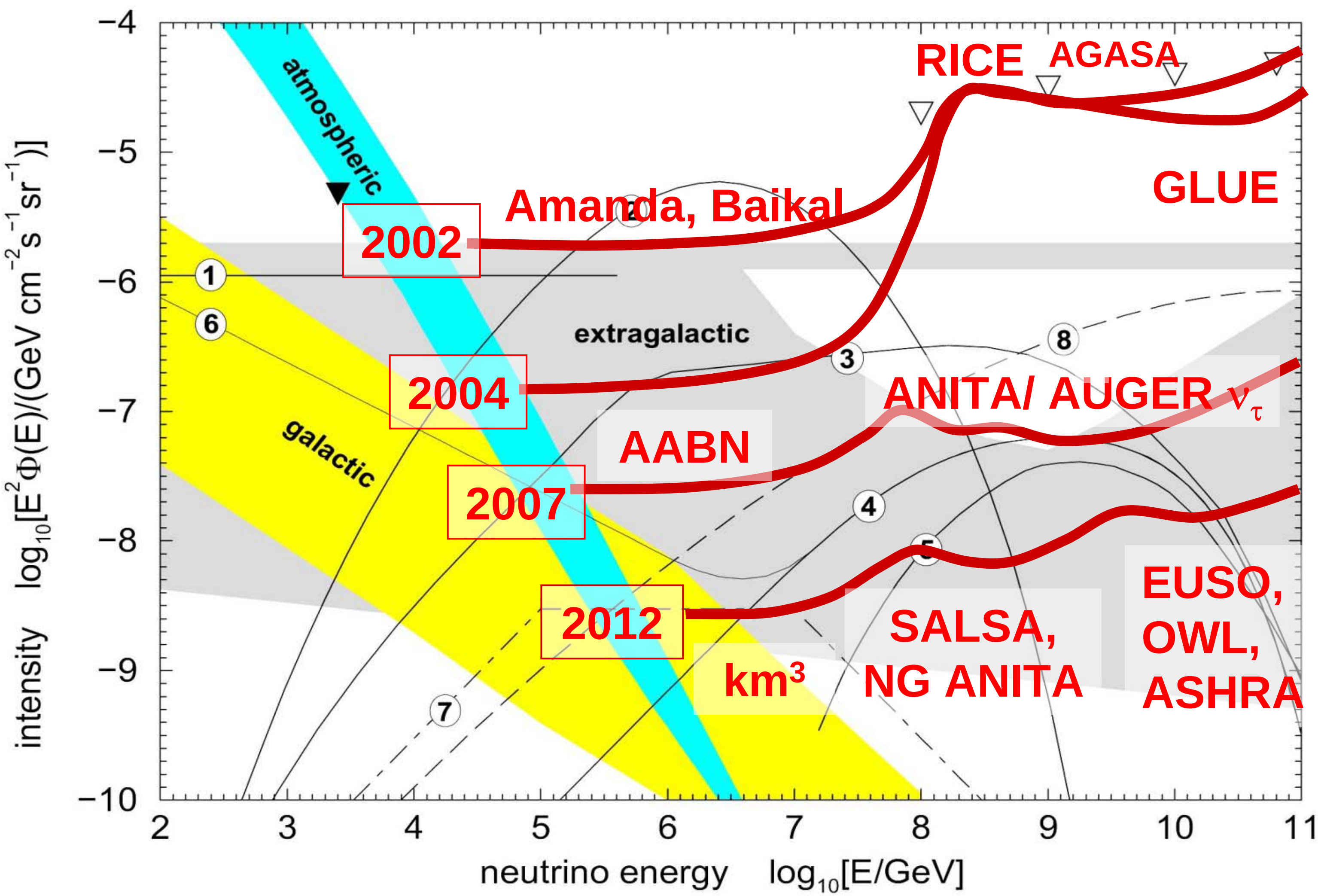
Outlook

- With AMANDA-II, the requisite tools to inaugurate multi-messenger astronomy are available.

- To probe the neutrino fluxes at highest energies, new techniques are being developed based on radio cherenkov detection.

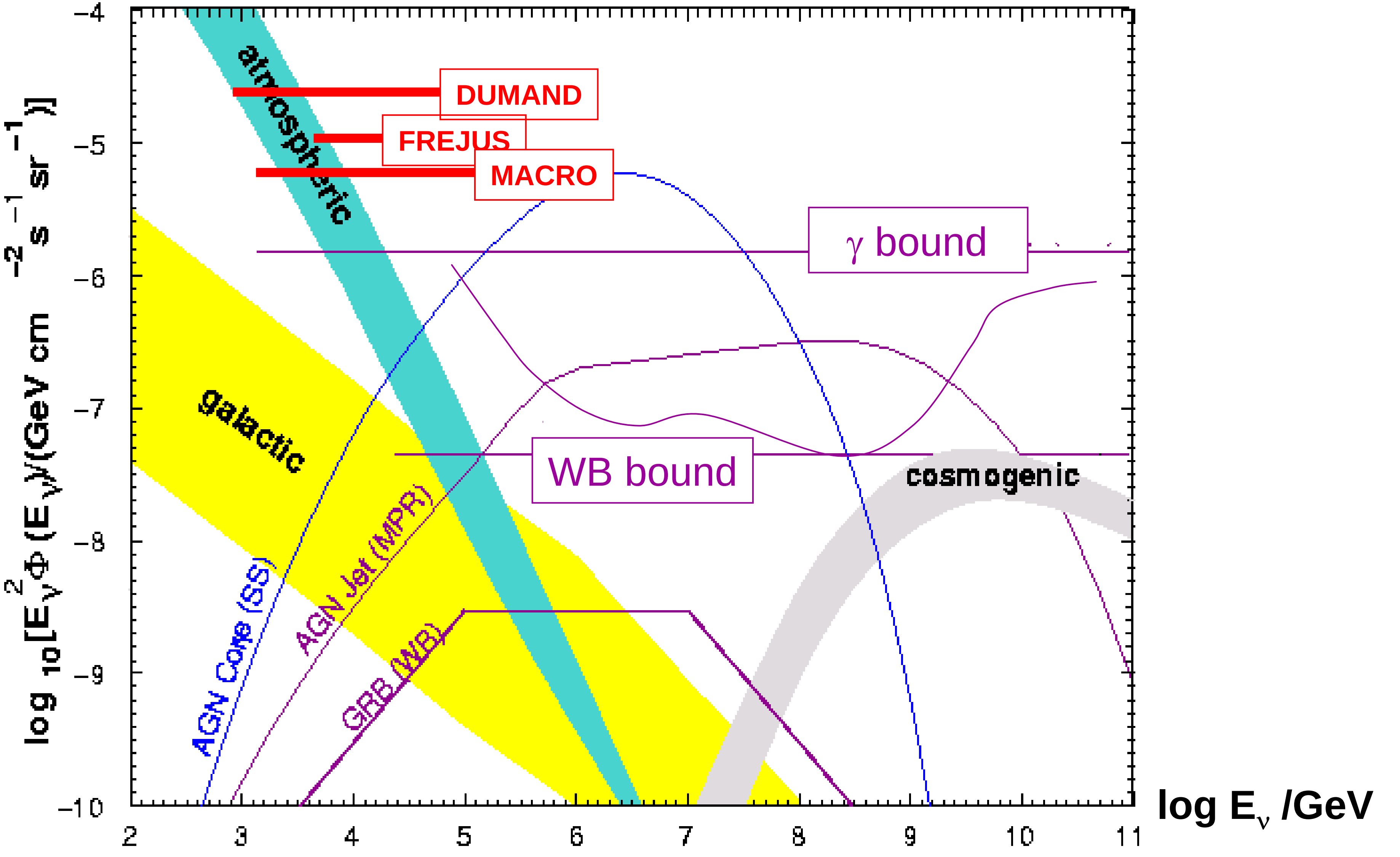
- ANITA extends search volume to 10^6 m^3.

High Energy Neutrino Roadmap

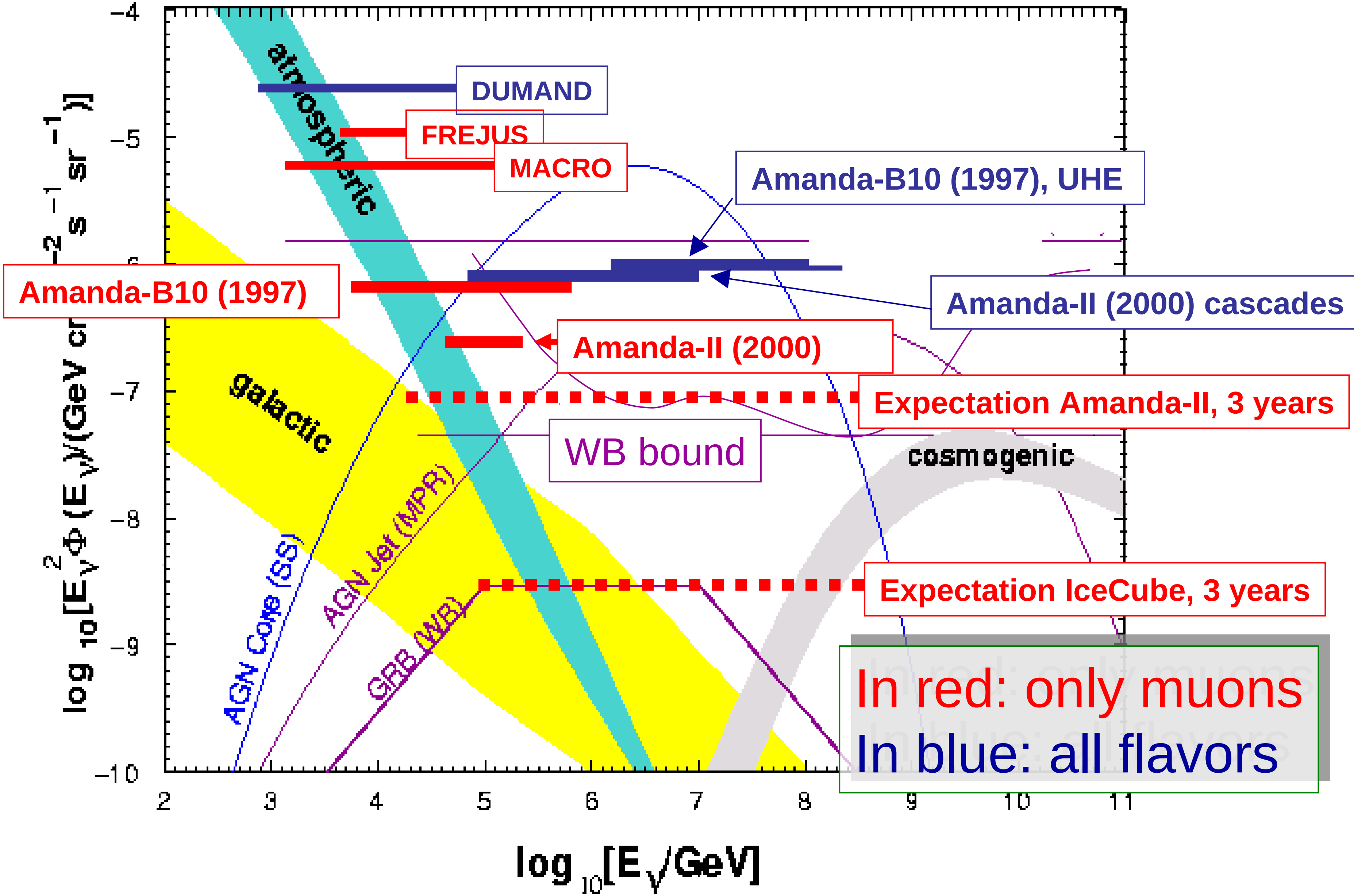


projection by Christian Spiering, 10/02

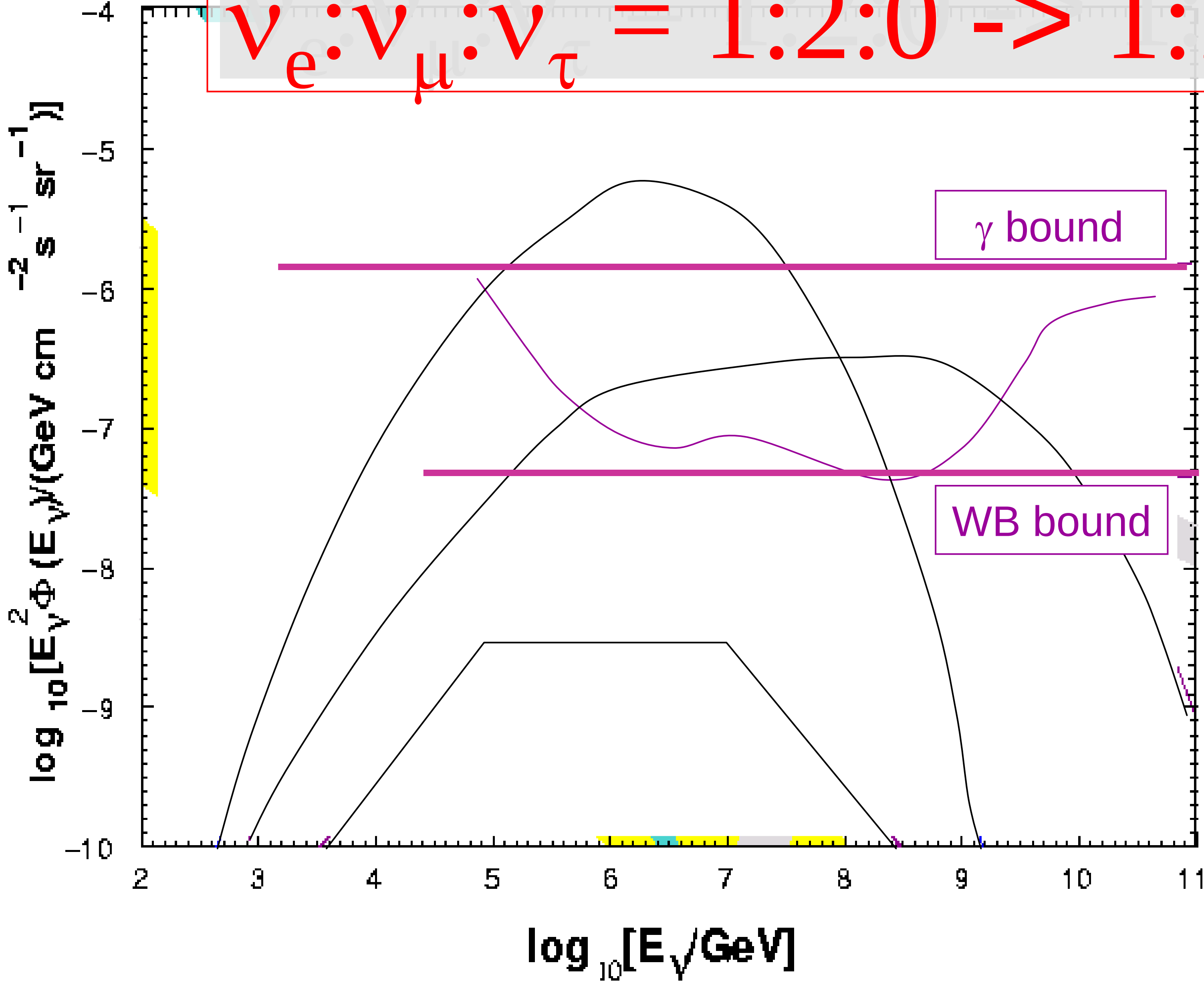
Models and Bounds

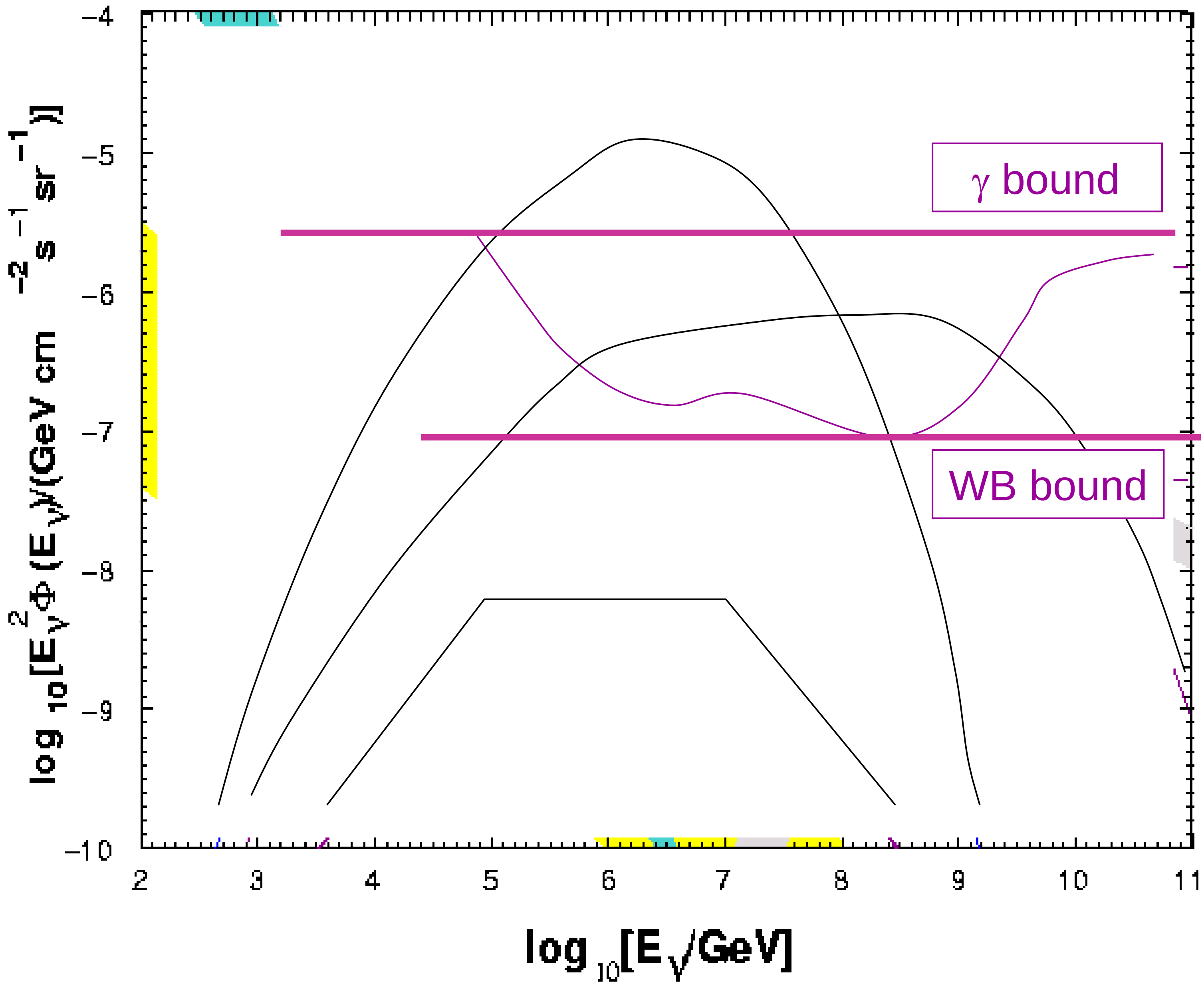


Experimental Limits



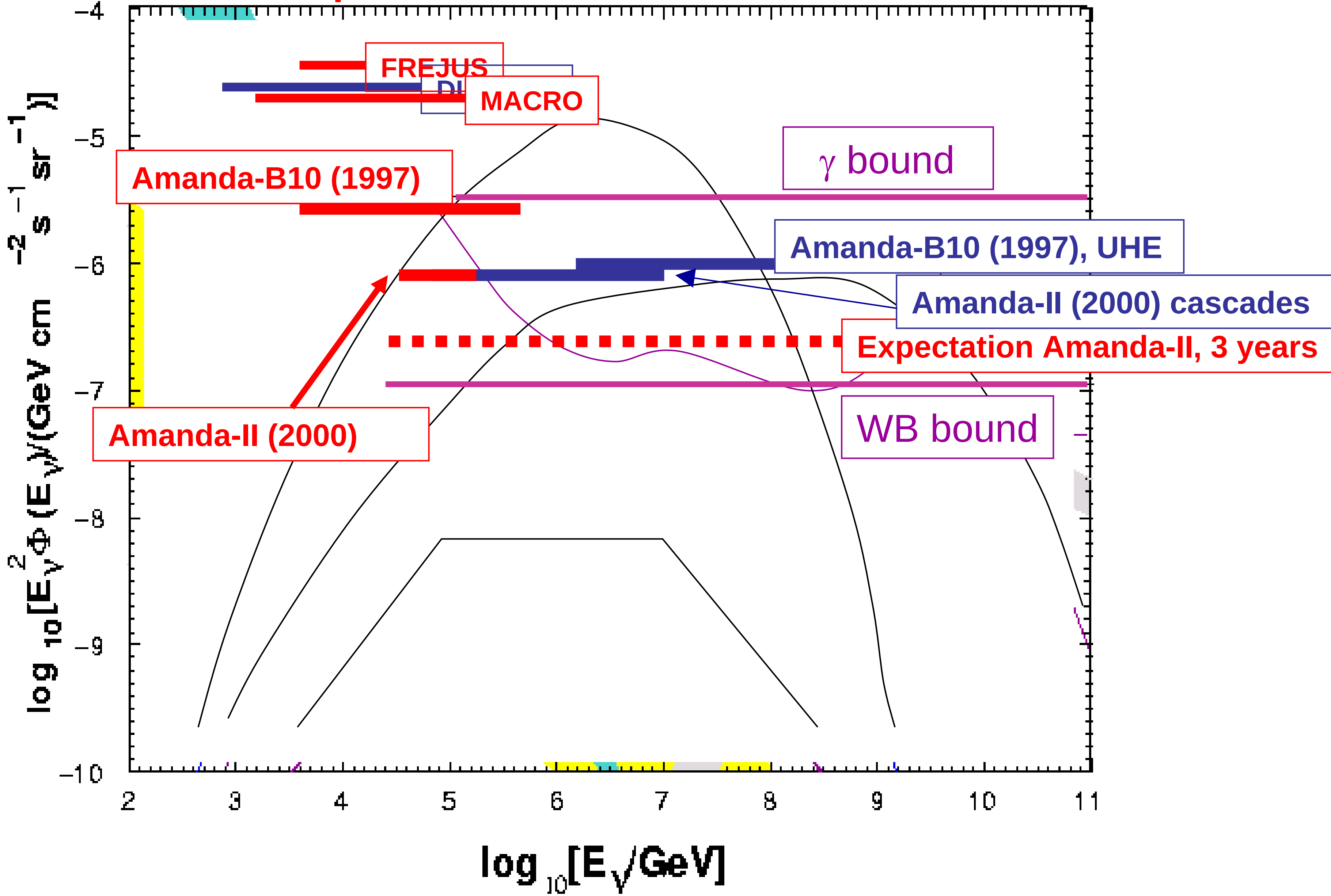
$\nu_e:\nu_\mu:\nu_\tau$ = 1:2:0 -> 1:1:1

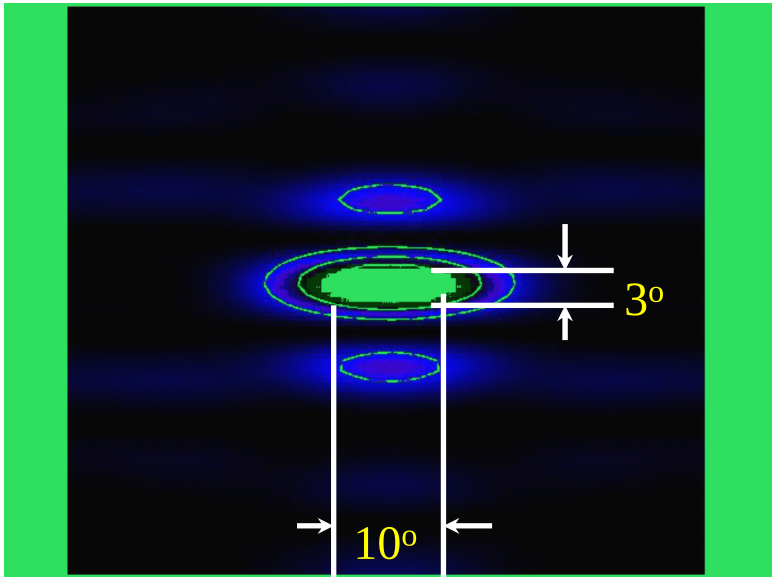




γ bound
WB bound
−4
−5
−6
−7
−8
−9
−10
2
3
4
5
6
7
8
9
10
11
log 10[E ν/GeV]
log 10[E ν 2 Φ (E ν)/(GeV cm −2 s −1 sr −1)]

Experimental all-flavor limits





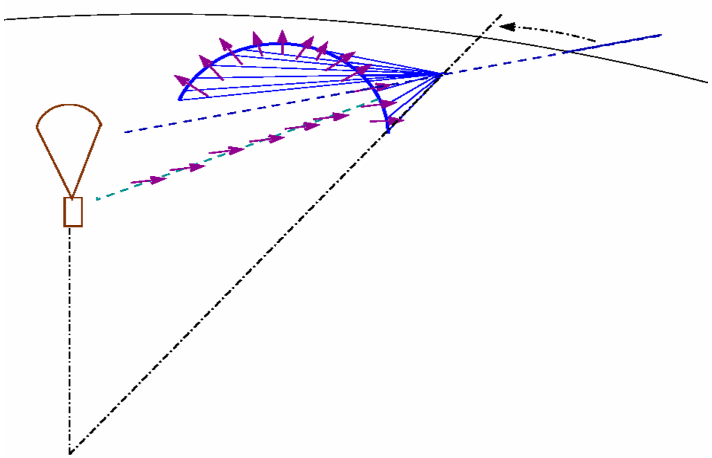
neutrino telescope

Pulse-phase interferometer (6 antennas):

gives intrinsic beamsize:

of ~3º elevation

by ~10º azimuth for arrival pulse



Improves by **~factor of 2** with better pulse timing, beam calibration

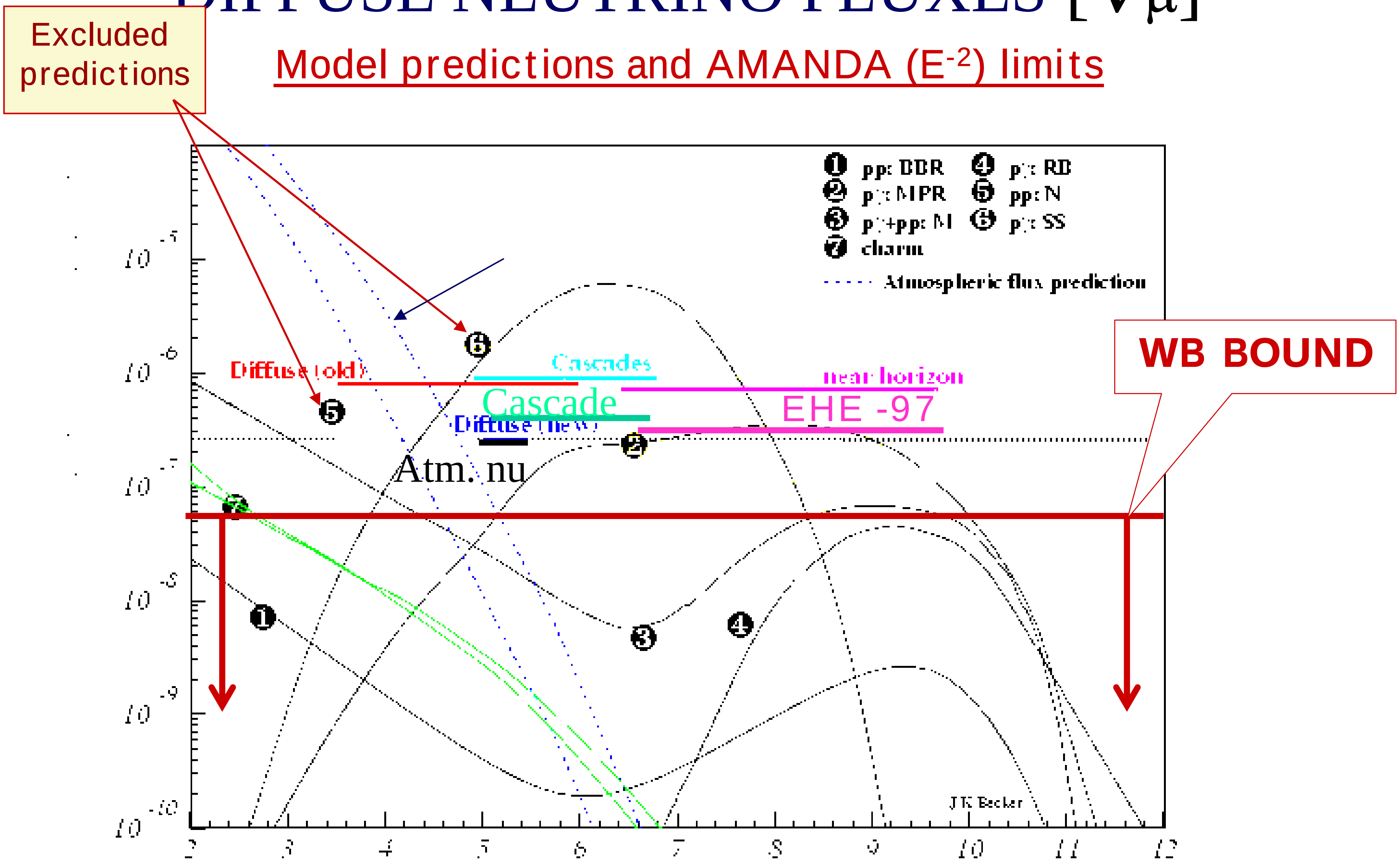
Neutrino direction constrained:

~1-2º in elevation by earth absorption, and

3-5º in azimuth by polarization angle

DIFFUSE NEUTRINO FLUXES [ν_μ]

Model predictions and AMANDA (E^{-2}) limits



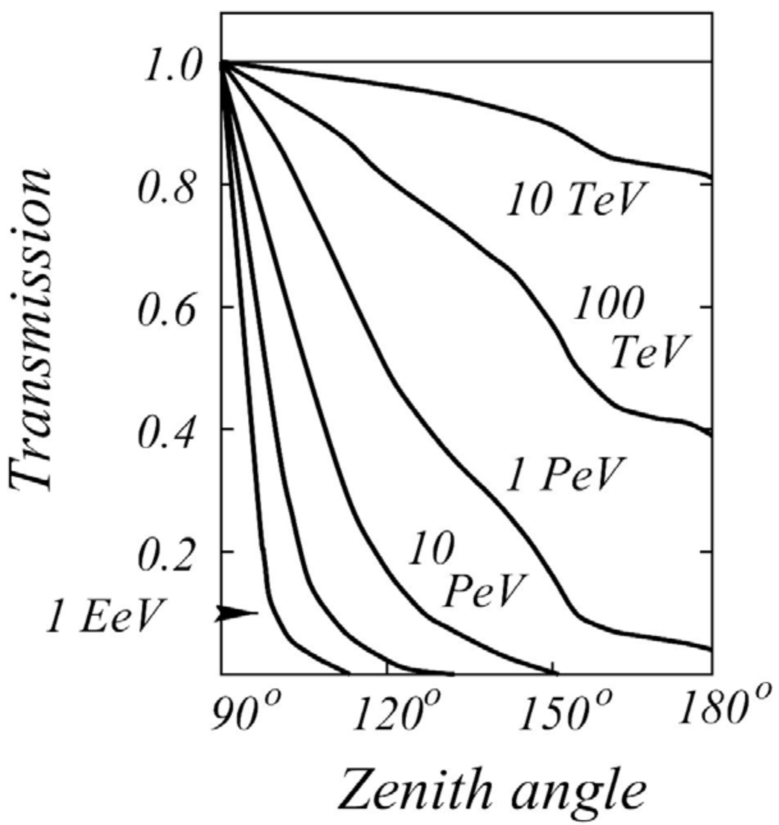
EeV (10^{18} eV) Science Goals

- GZK from $p+\gamma_{CMB}$
  - Detection would confirm highest energy cosmic rays are extragalactic and composed of ordinary stuff like protons, helium
  - Provides neutrinos to study predictions of Grand Unified Models, the Holy Grail of Particle Physics
  - Non-detection would be great surprise
- Supermassive Black Hole/ AGN models
  - Compared to searches at 1-100 TeV, probes a complementary set of models
  - Salamon and Stecker (‘95), Protheroe(‘97), Mannheim(‘95), Halzen and Zas(‘97)
- Exotic sources - physics of the early Universe
  - Topological defects, Heavy Boson decay, Z-burst, **micro-Blackholes**

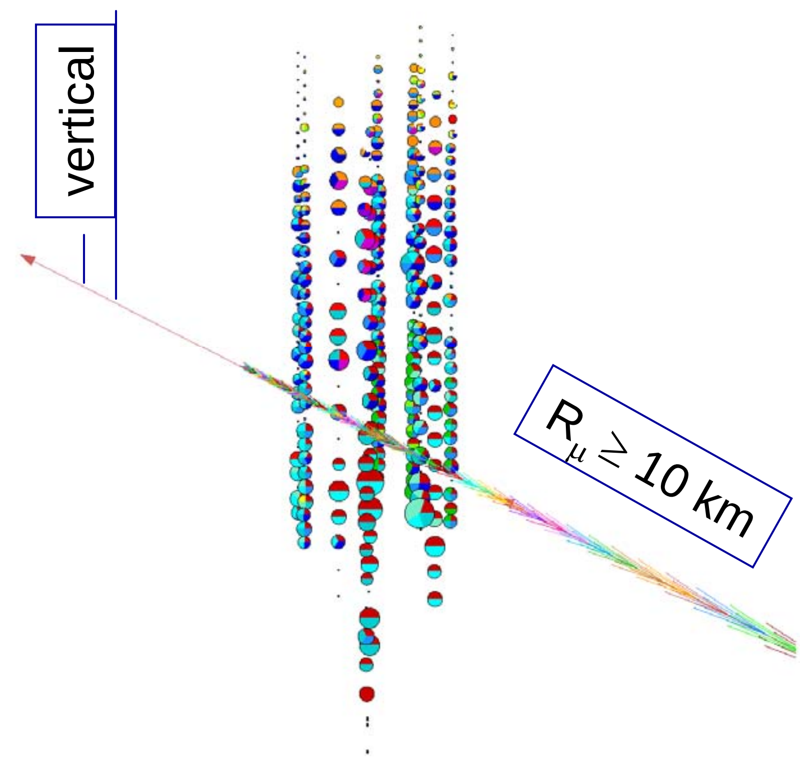
EHE Detection Guidelines

(E>10^{16} eV)

EHE ν do not penetrate earth

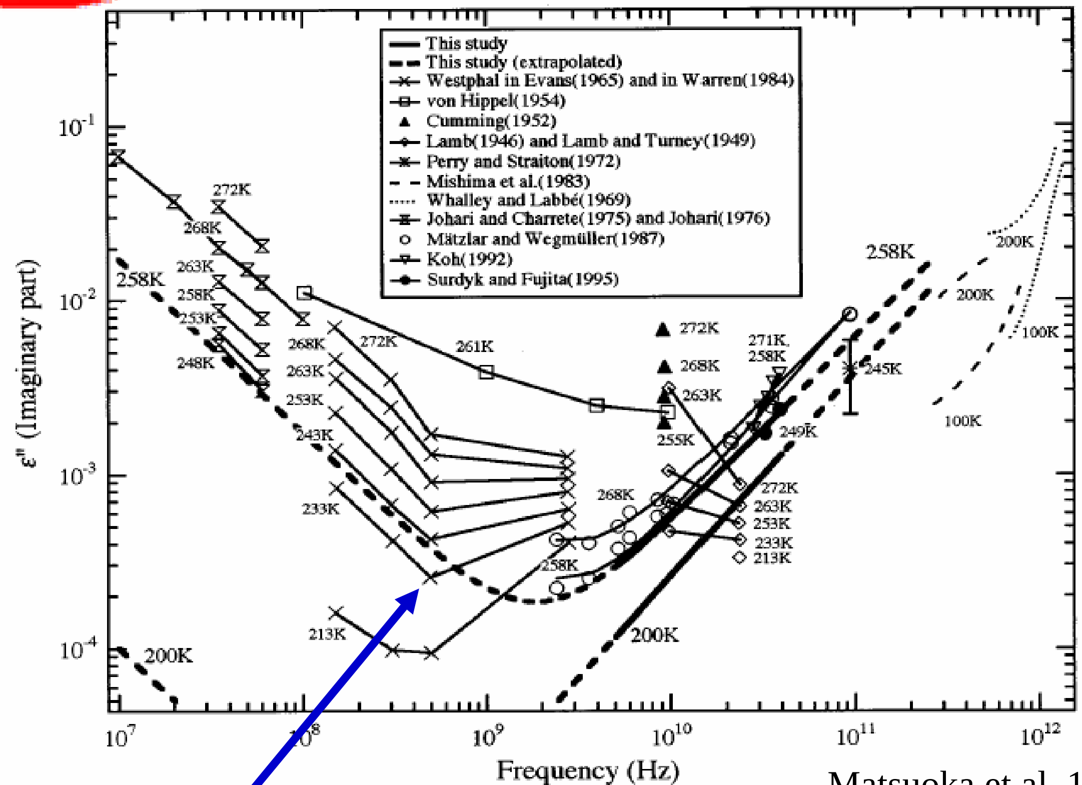


EHE events very bright; many PMTs detect multiple photons



bright horizontal MC track

Ice transparency



Matsuoka et al. 1996

FIG. 7. The ε" plotted logarithmically against frequency with temperature as a parameter. The bold lines represent fitted lines in this study with the parameters $B=1.747\times10^{-5}$, $C=1.168$ and $B=4.696\times10^{-5}$, $C=1.056$ at 200 and 258 K, respectively. The previous reported values are from Warren (Ref. 2).

Loss tangent a strong function of temperature

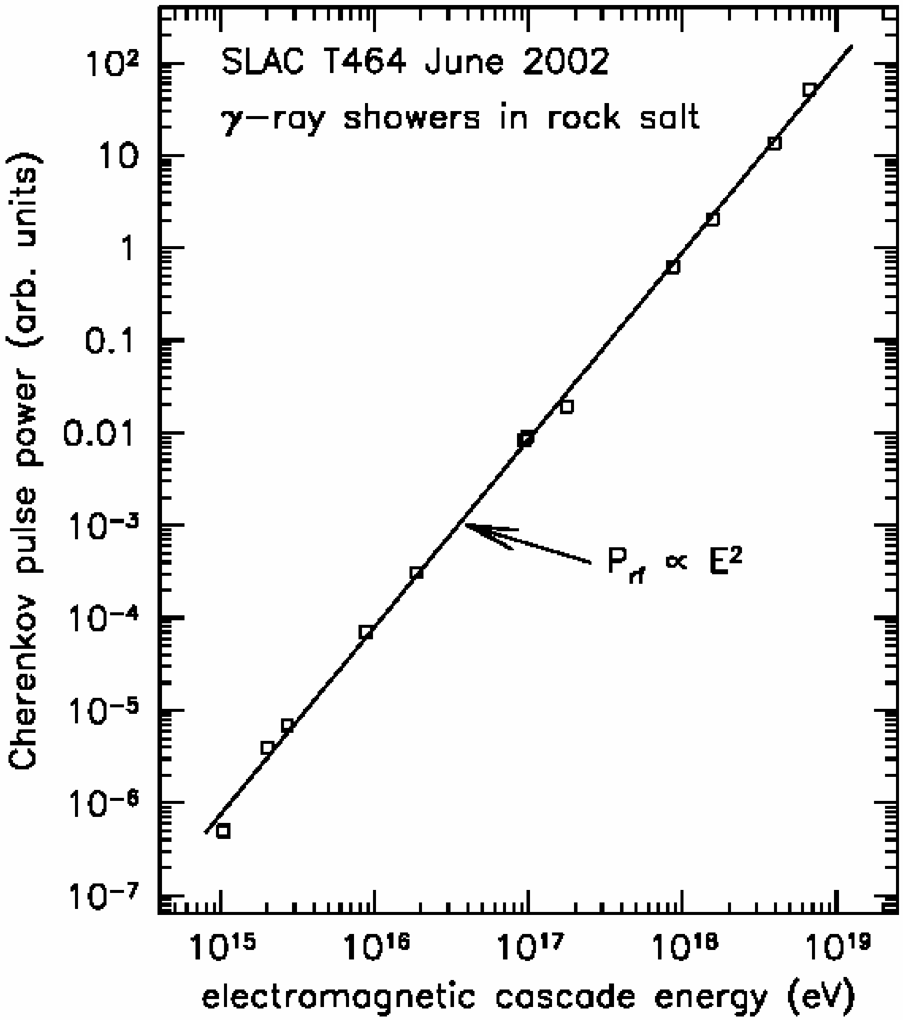
For cold ice, UHF (0.1-1GHz) best

Antarctic data approaches pure ice values

$L_\alpha = \lambda\,[\pi n\,(\varepsilon''/\varepsilon')]^{-1}$ ~ 6 km at 300 MHz & -60C (pure ice)

New results—SLAC T460 June 2002

Follow up experiment to SLAC T444, with rock-salt target



- Much wider energy range covered:
  - <1PeV up to 10 EeV
- Radio Cherenkov observed over 8 orders of magnitude in radio pulse power

Schedule for ANITA

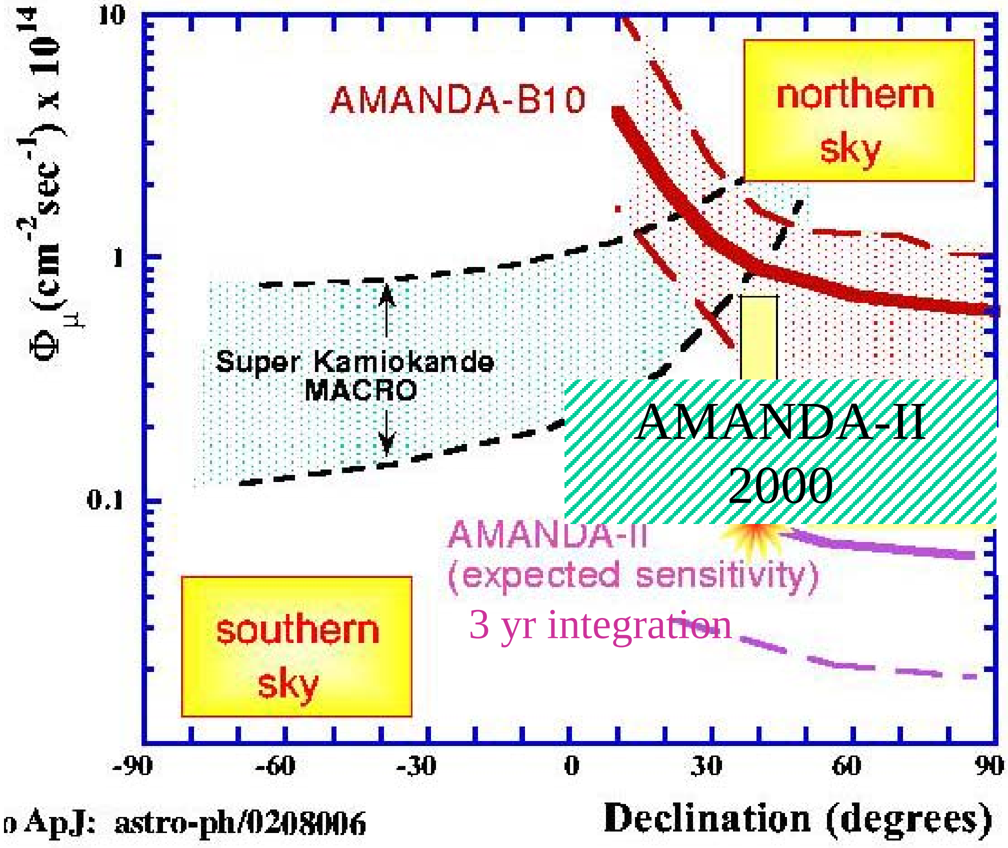
03/04	Fly ANITA-lite, measure attenuation lengths in ice
04	Recover ANITA-lite, analyze data, begin construction at UCI
05	Jan :Begin assembly and integration June: test partial instrument in New Mexico, mechanical Aug: Begin final integration and testing
06	June: NSBF integration in Palestine, TX Sept: Ship to Antarctica Dec : Integrate and Launch ANITA payload
07	Jan : Recover payload, ship back to UCI

Commensurate with graduate student lifetime!

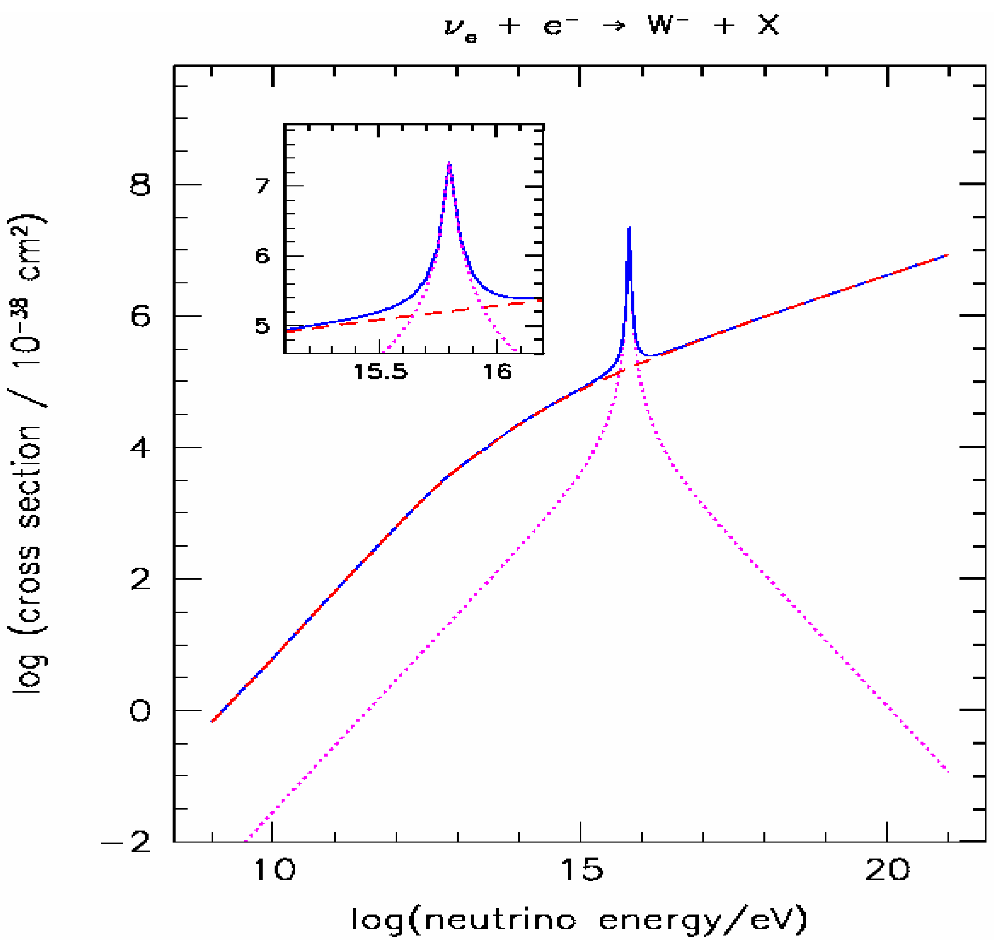
EHE ν Detectors: Summary

- Several next generation techniques underway
- Wide variety of technologies for Nth gen
  - (keep an eye on radio, space-based fluorescence, acoustic)
- INPAC can help assess the most promising technologies, guide the planning for the Nth generation detectors, and coordinate with similar efforts involving different messengers (gravity wave, cosmic ray, gamma ray)
- Nth gen detectors will be require more, perhaps a lot more, resources that need to be well managed

μ-Flux Limits for Point Sources



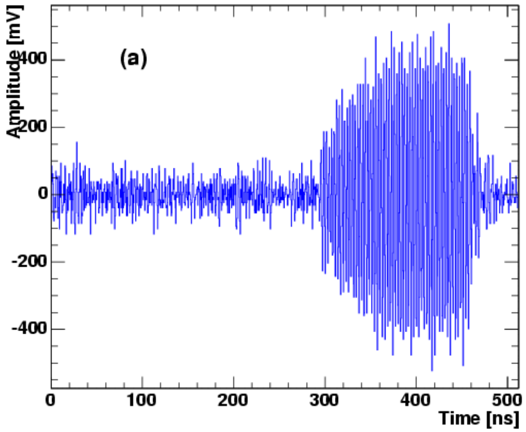
Astro-ph/0309585



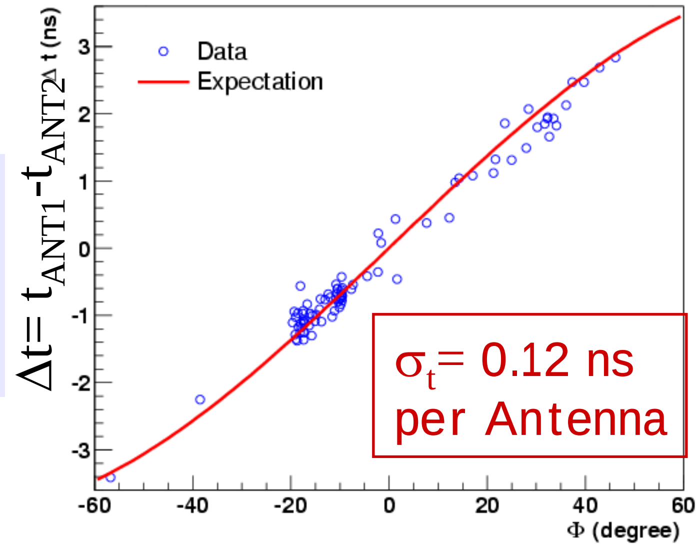
$\nu_e + e^- \rightarrow W^- + X$
log (cross section / 10^{-38} cm^2)
log(neutrino energy/eV)
8
6
4
2
0
−2
10
15
20
7
6
5
15.5
16

ANITA-lite timing resolution

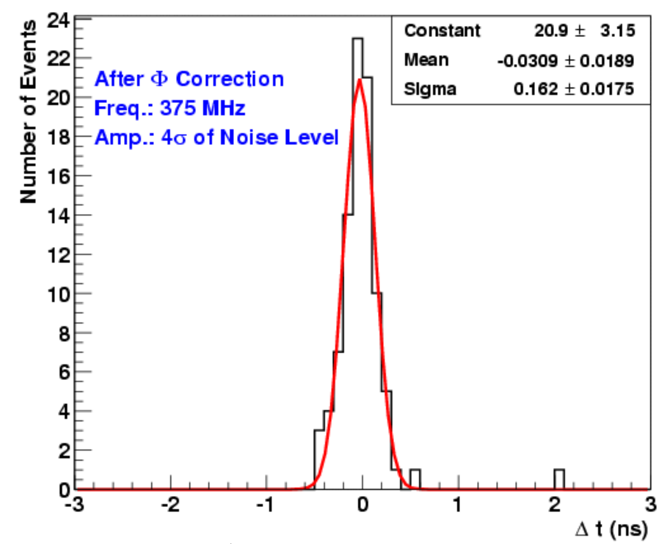
Ground antenna transmits
calib. pulse to Anita-lite @40km



UHF tone bursts were sent as a calibration signal to ANITA-LITE from the ground at the start of the flight.



- ANITA goal: 300 ps at ~3 sigma trigger threshold.
- ANITA-LITE already **50% better**!
- Critical to pulse interferometry.



$\Delta t = t_{ANT1} - t_{ANT2}$

Azimuth Angle

Expected Angular Resolution for ANITA

$\delta\theta \sim 0.5$ deg $\qquad$ $\delta\phi \sim 2$ deg