Status and Results from AMANDA/IceCube

Patrick Berghaus
IceCube
University of Wisconsin, Madison

IceCube Collaboration

USA:
Bartol Research Institute, Delaware
Univ. of Alabama
Pennsylvania State University
UC Berkeley
UC Irvine
Clark-Atlanta University
Univ. of Maryland
IAS, Princeton
University of Wisconsin-Madison
University of Wisconsin-River Falls
LBNL, Berkeley
University of Kansas
Southern University and A&M College, Baton Rouge

Sweden:
Uppsala Universitet
Stockholm Universitet

UK:
Imperial College, London
Oxford University

Netherlands:
Utrecht University

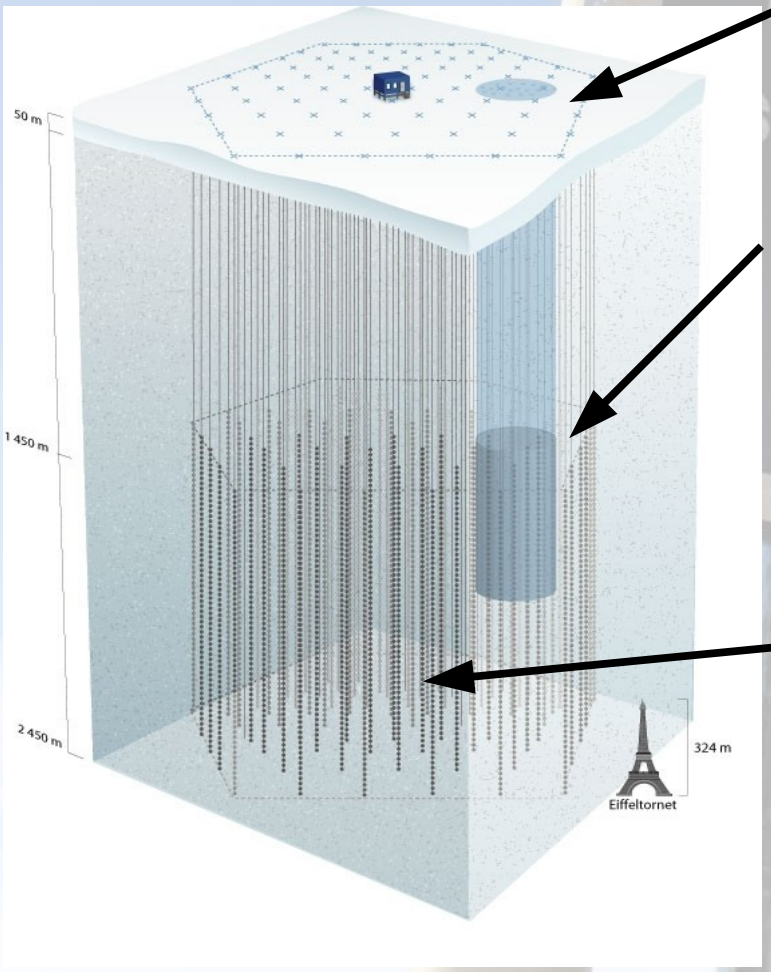
Germany:
Universität Mainz
DESY-Zeuthen
Universität Dortmund
Universität Wuppertal
Humboldt-Universität Berlin
Universität Aachen

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

Japan:
Chiba University

New Zealand:
University of Canterbury

IceCube: Components



IceTop(Air Showers):

- 1km² instrumented
- 160 Water(Ice-)tanks with 2 DOMs Each

Amanda:

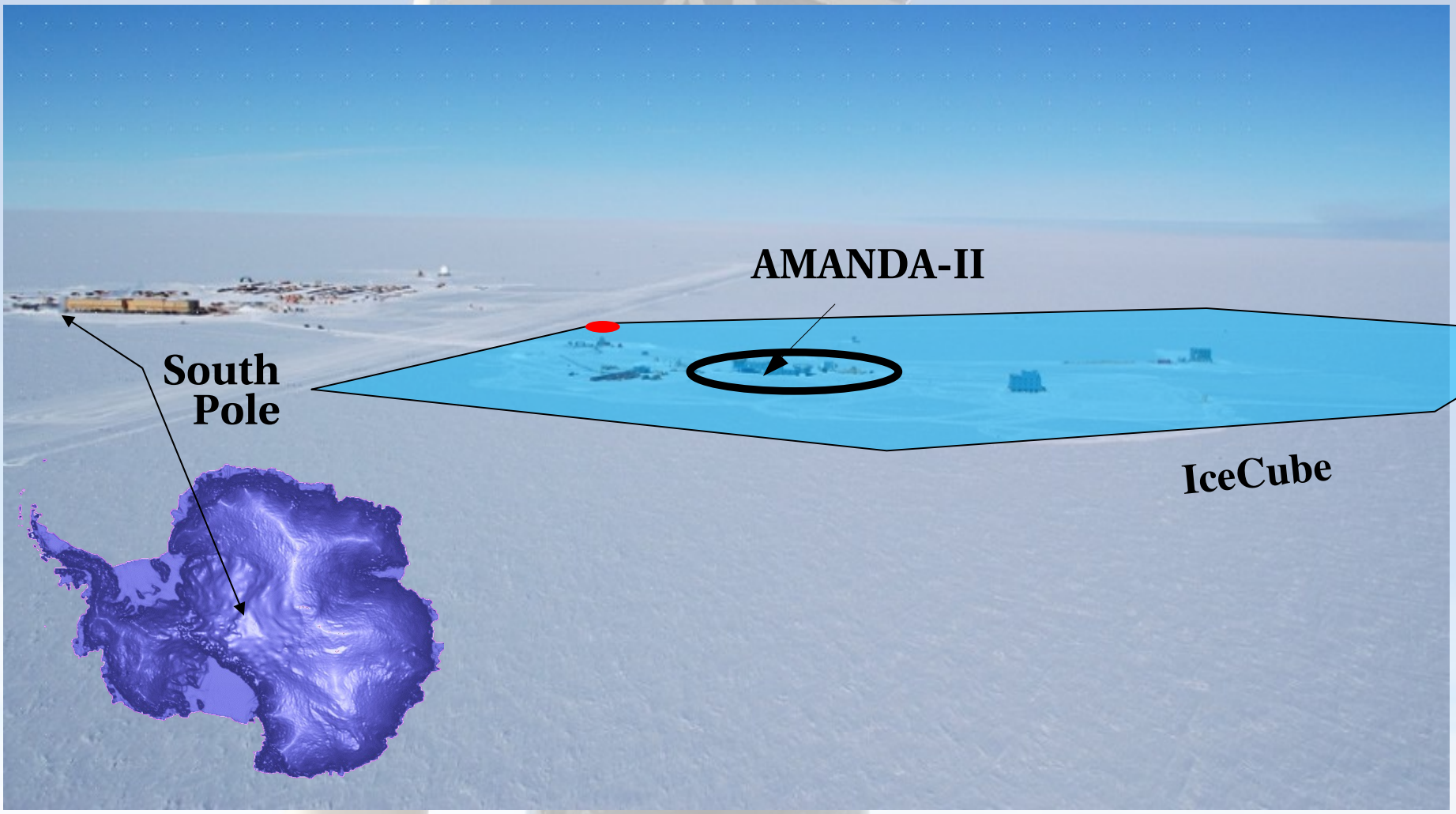
- Ø=200m, h=500m (0.02 km³)
- Amanda B-10:
  - 302 Optical Modules (OMs) on 10 Strings (97-99)
- Amanda II:

  677 OMs on 19 Strings (from 2000)

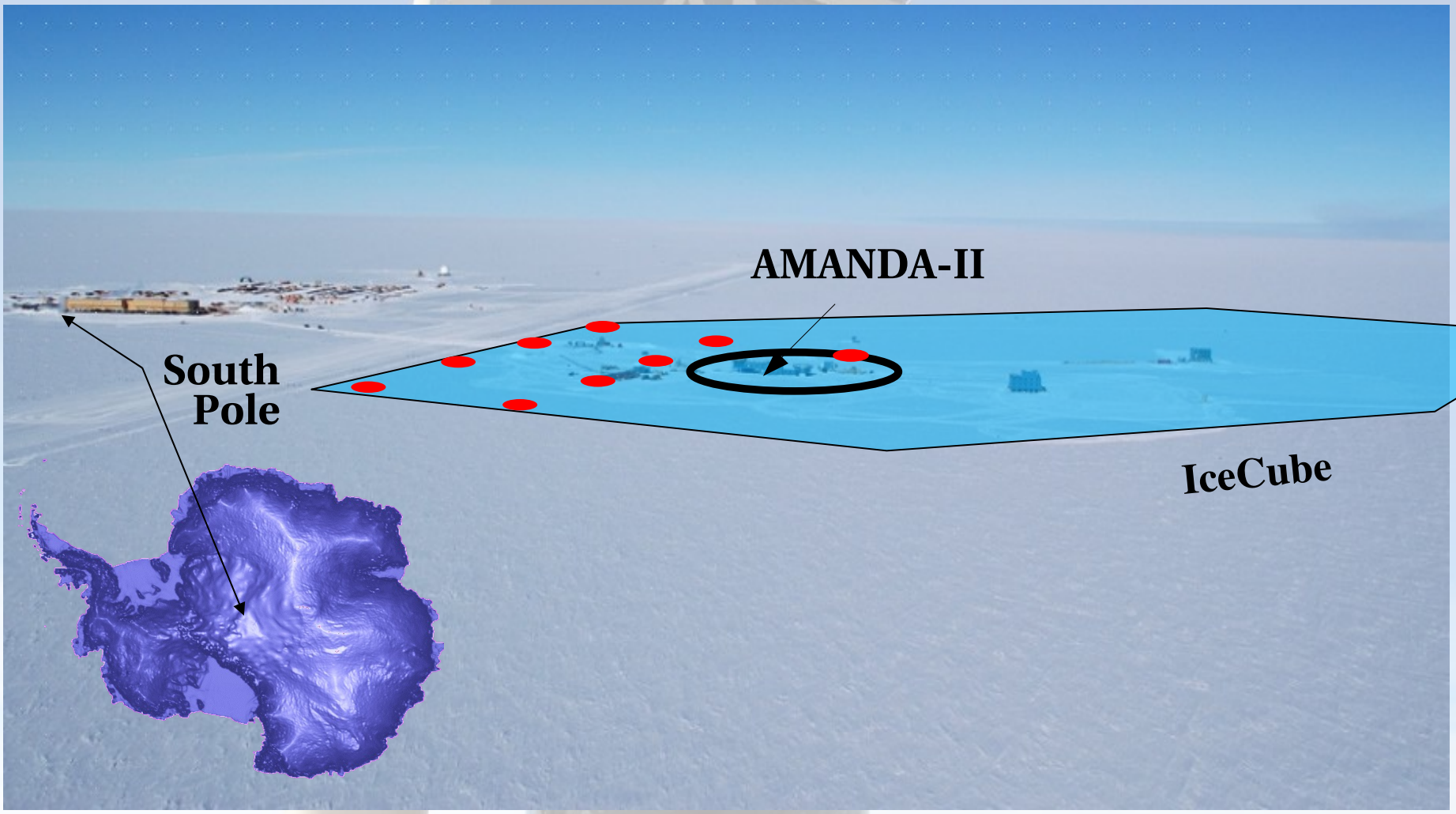
InIce:

- 1km x1 km² instrumented
- 4800 Digital Optical Modules (DOMs) on 80 strings
- 2007: 22 Strings deployed (“IC22”)

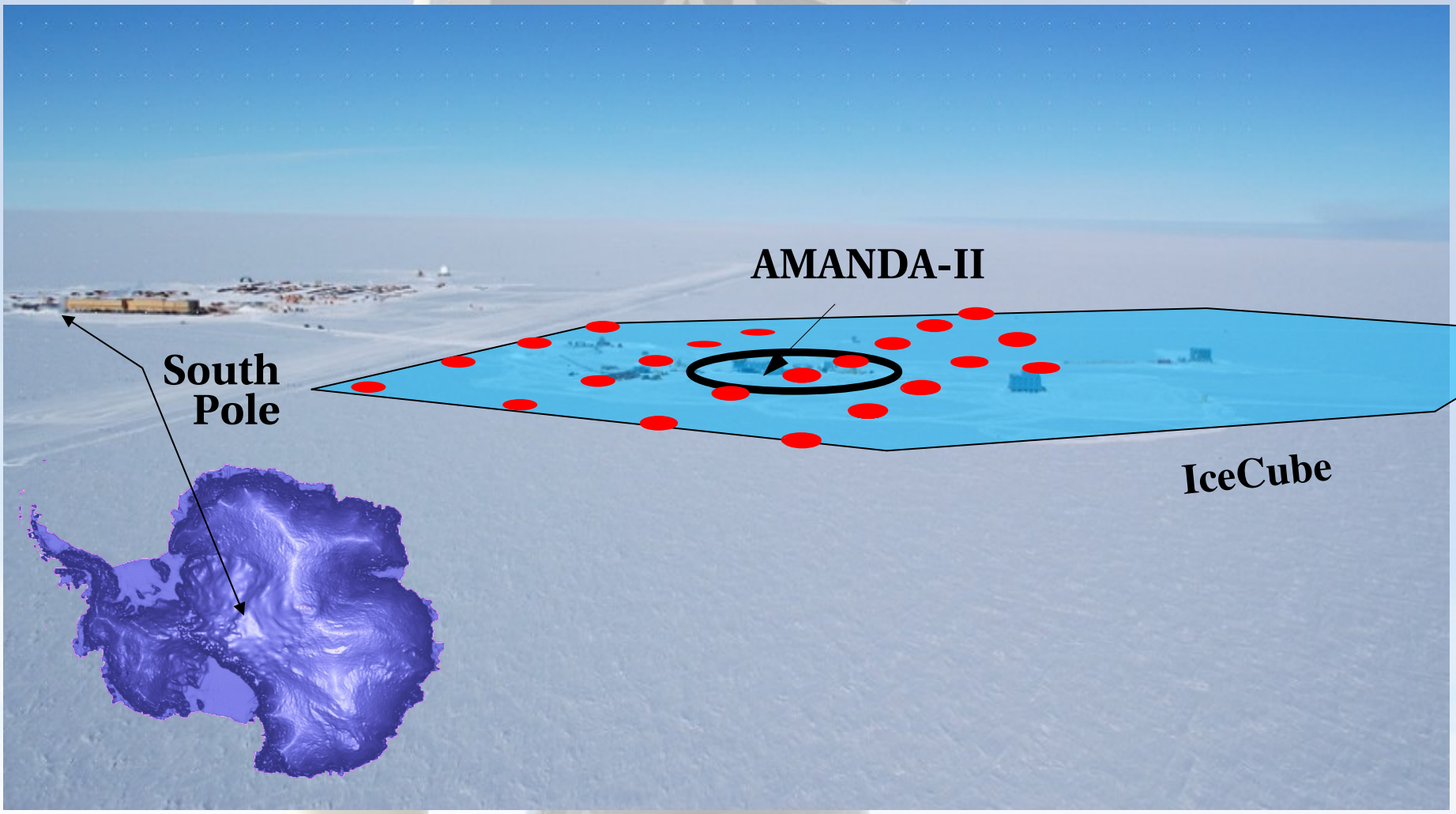
2005: 1 string



2006: 9 strings

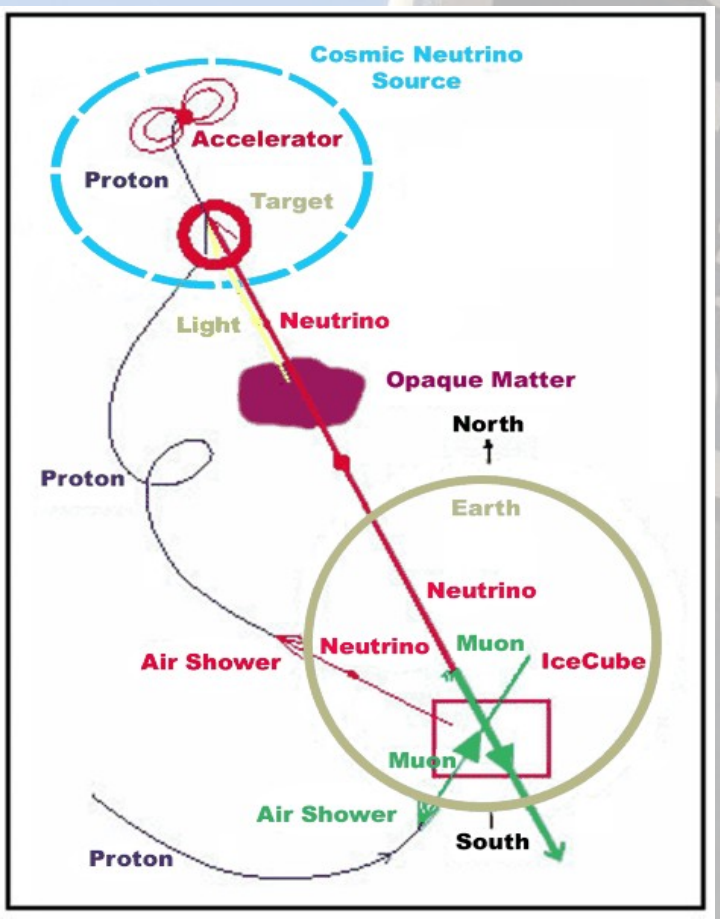


2007: 22 strings

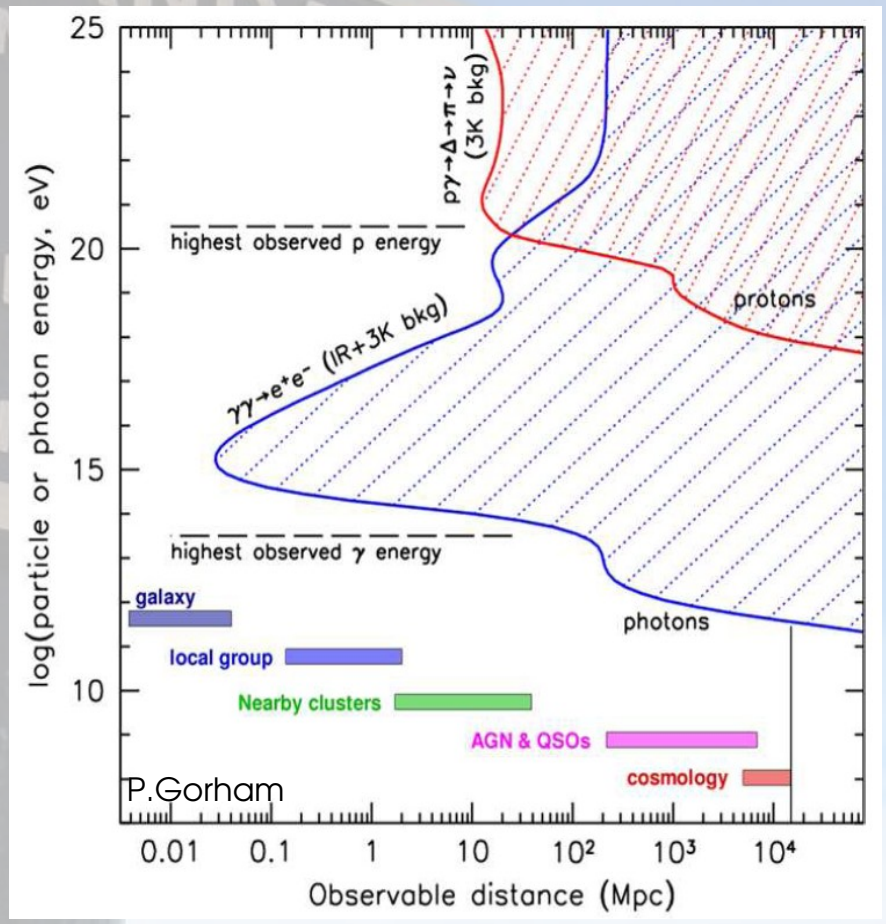


Basics

Production

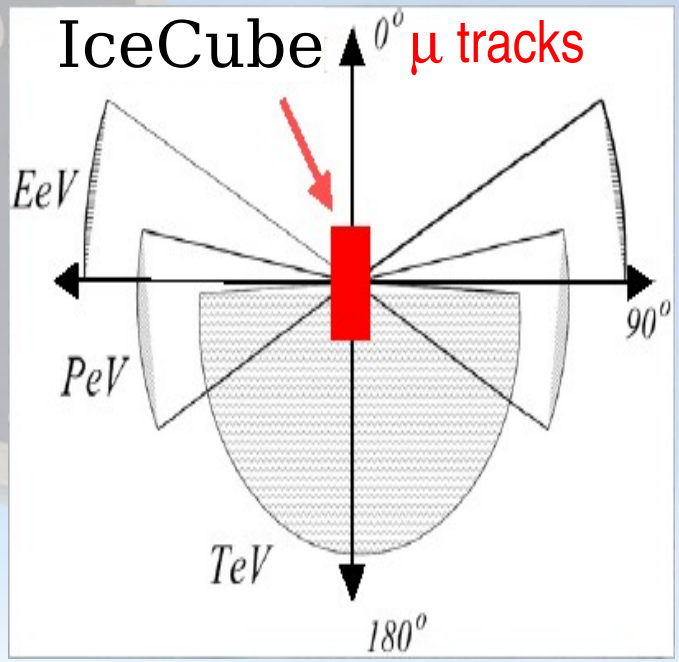


Reach

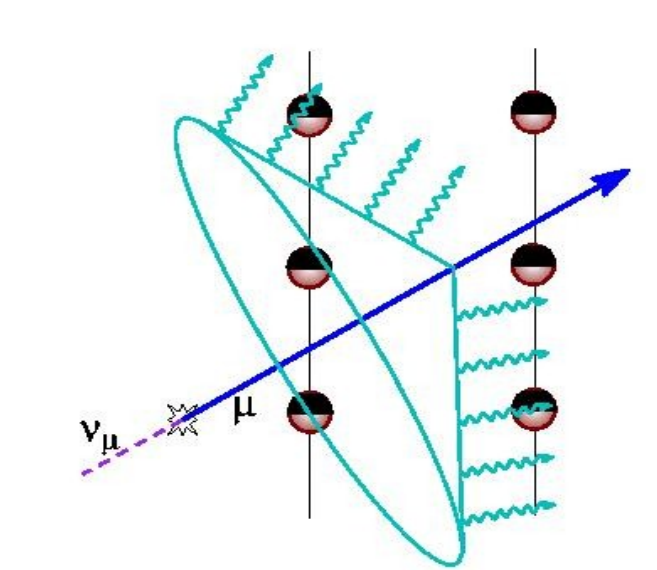


(Potential) Neutrino Sources

Energy	Analysis	Source
GeV - TeV	Atmosph. ν WIMPs	Atmosphere Earth, Sun
TeV - PeV	Diffuse Flux Point Sources GRB	Outer Space
PeV - EeV	UHE ν	AGN, Top. Defects …



Neutrino Events (AMANDA)

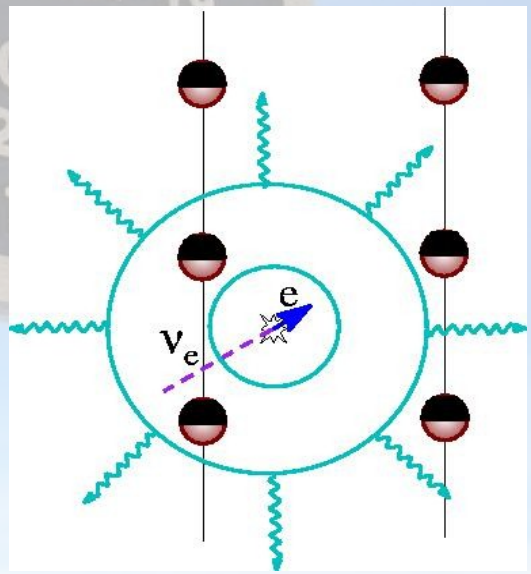


Muon Tracks (100m-10km length)

Angular Resolution	~ 3°
Energy Resolution	0.3 – 0.4[$\log_{10}$(E/TeV)]
Coverage	**2π srad (North)**
Energy Range	~ 50 GeV to 100 PeV

Event Rate:

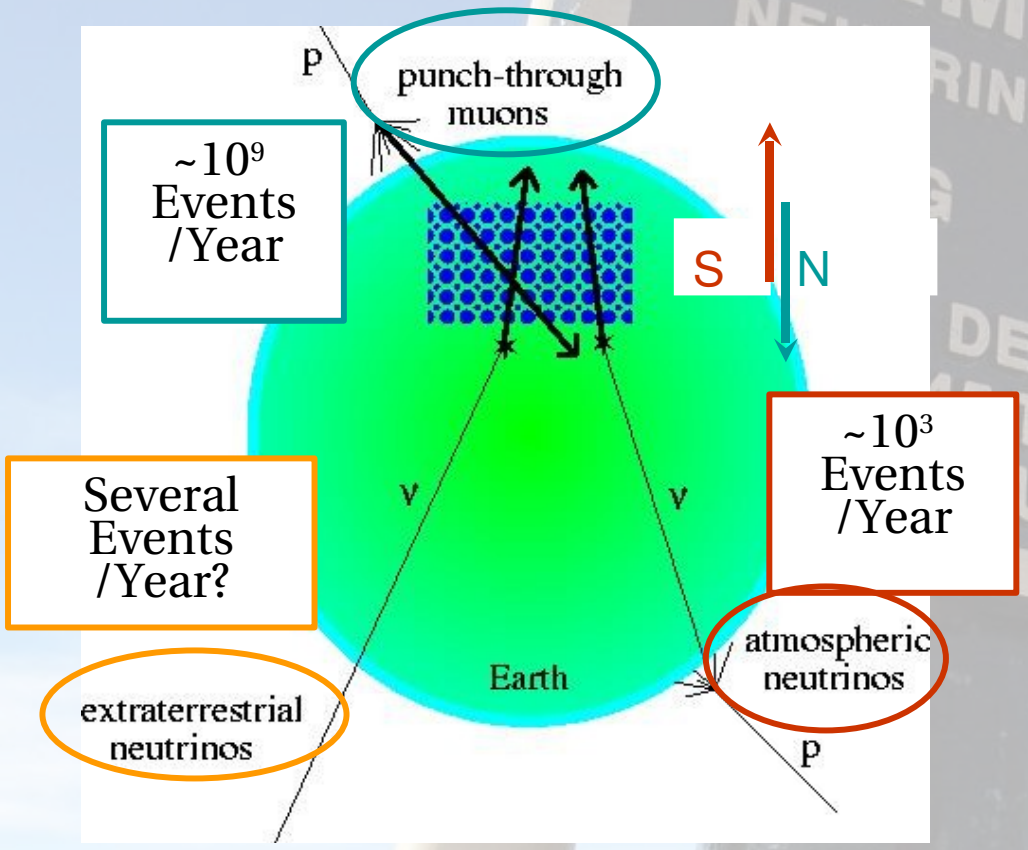
~ 80 Hz

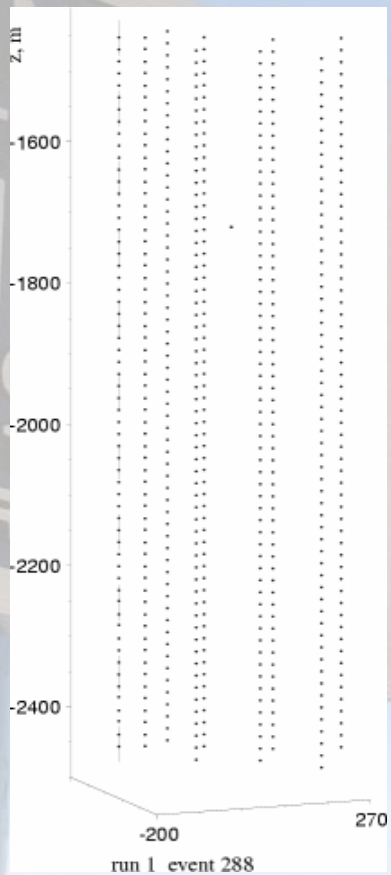


NC, ν_e/ν_τ CC cascades (length: few meters)

Angular Resolution	30 - 40°
Energy Resolution	0.1 – 0.2[$\log_{10}$(E/TeV)]
Coverage	**4 π srad**
Energy Range	~ 50 TeV to 100 PeV

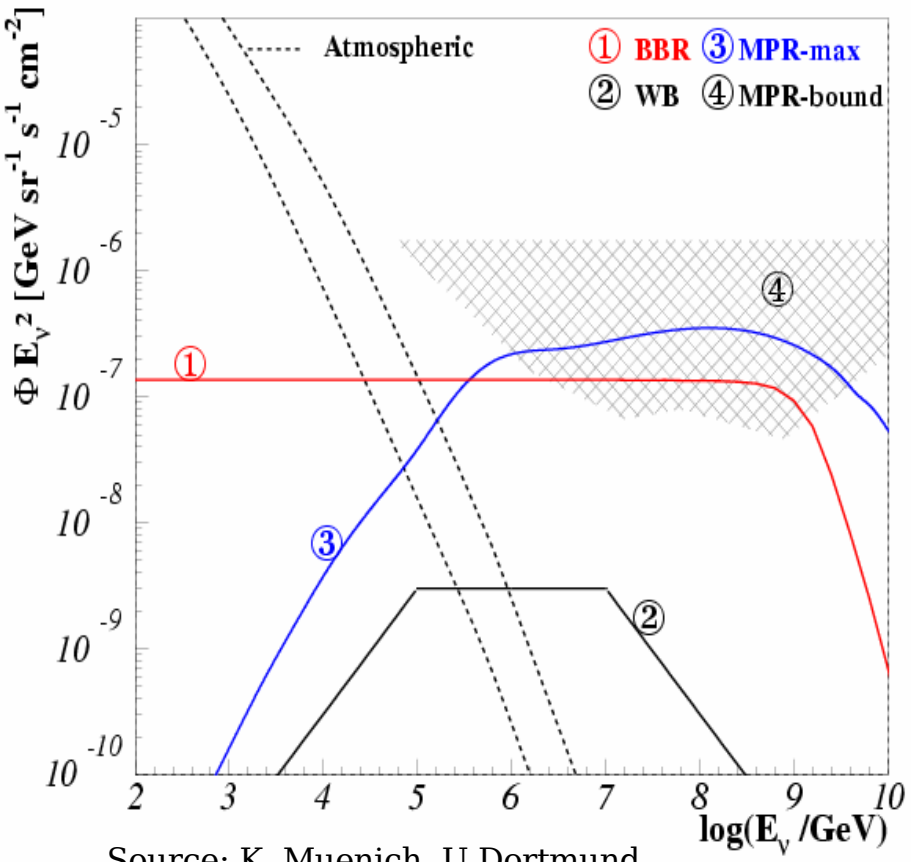
Events





IceCube 9-string muon neutrino candidate

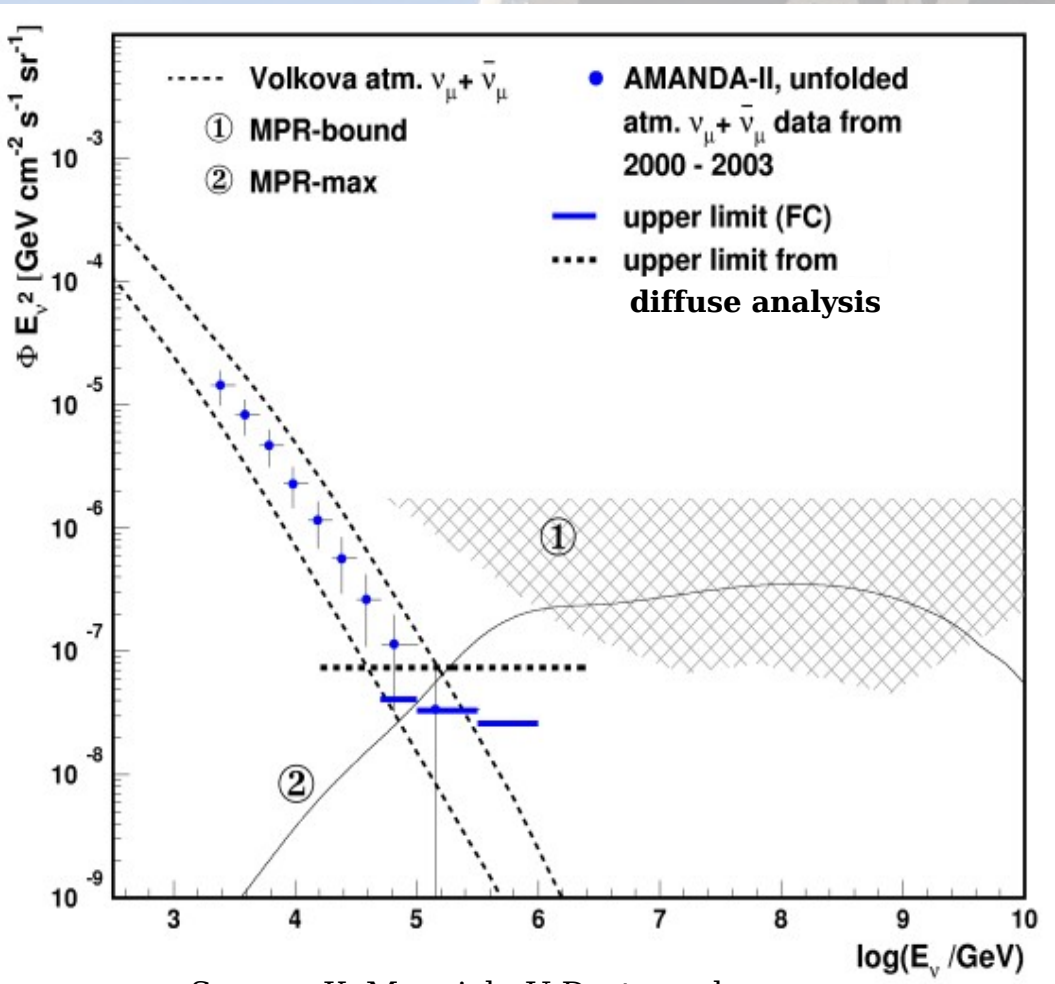
Diffuse Flux



Source: K. Muenich, U Dortmund

- Atmospheric neutrino flux follows $E^{-3.7}$
- Search for extra-galactic contribution
  - **AGN (1) (Becker/Biermann/ Rhode)**
  - **AGN (3 and 4) (Mannheim/Protheroe/ Rachen)**
  - GRBs (2) (Waxman/Bahcall)

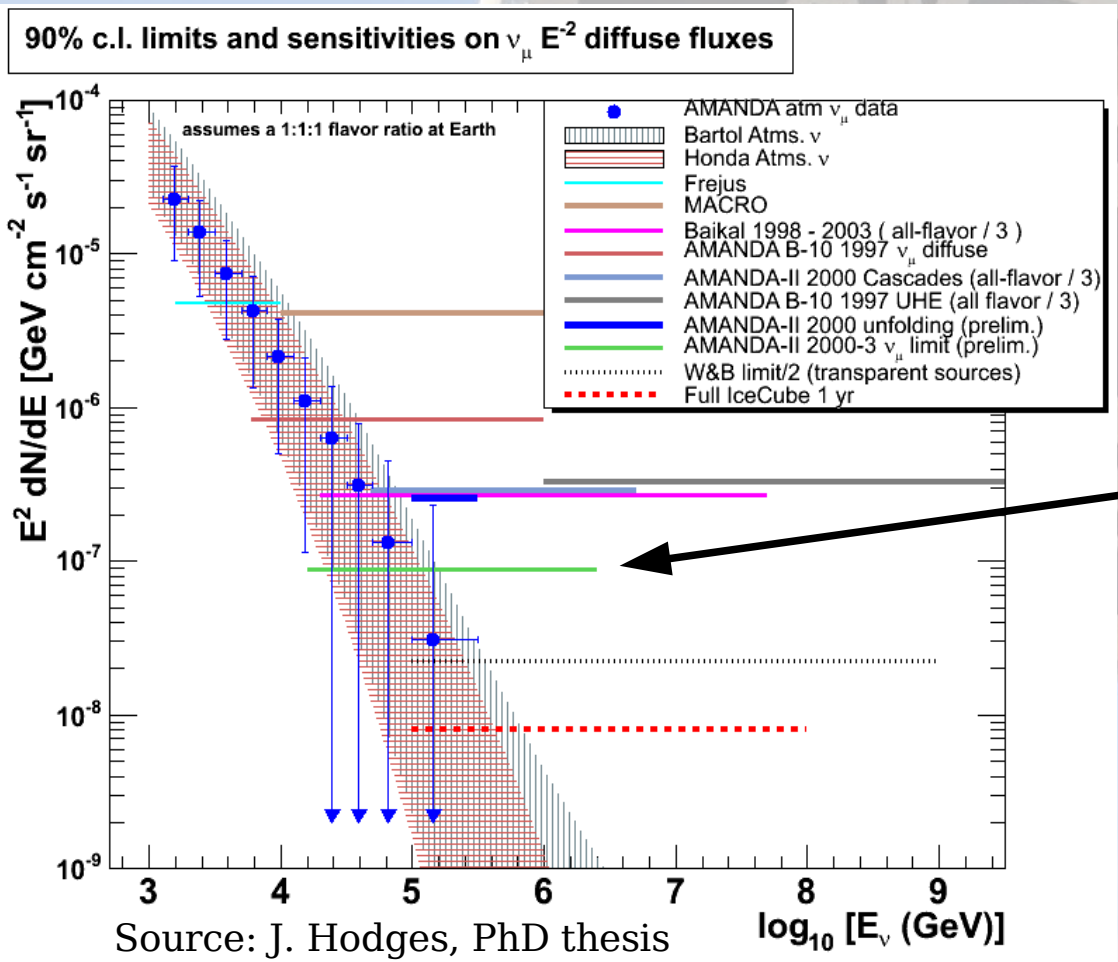
Atmospheric Neutrino Spectrum



Source: K. Muenich, U Dortmund

- Unfolded Energy Spectrum
- Consistent with Theory
- Only actual AMANDA/IceCube neutrino source (so far)!

Diffuse Flux Limit



Source: J. Hodges, PhD thesis

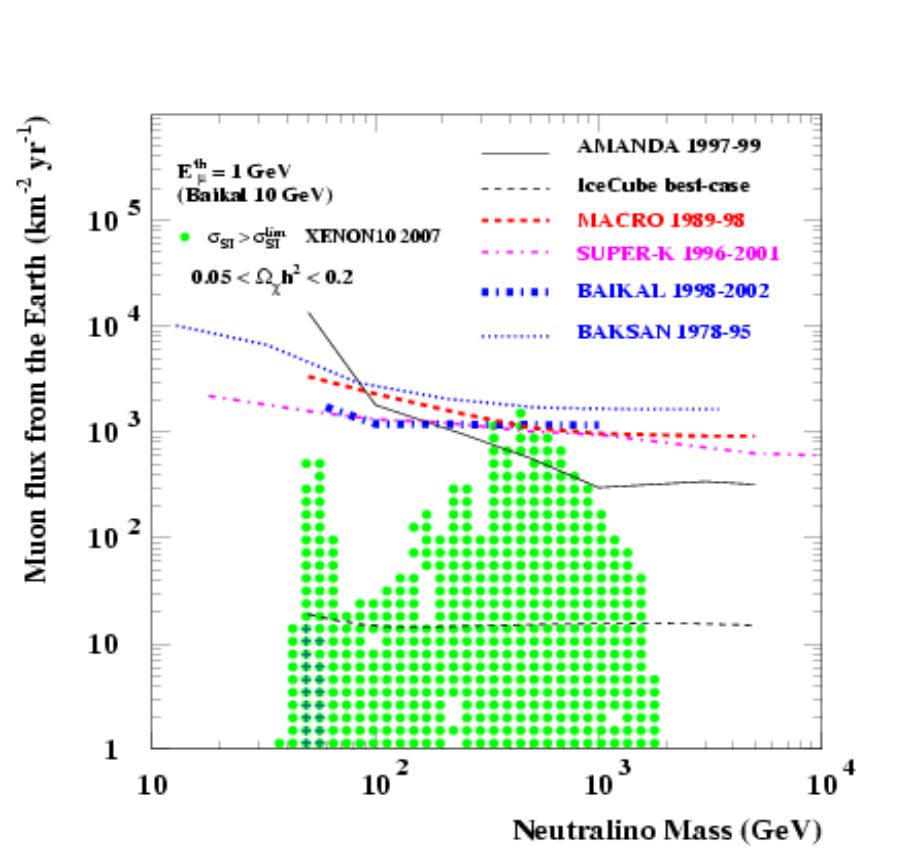
Latest Result

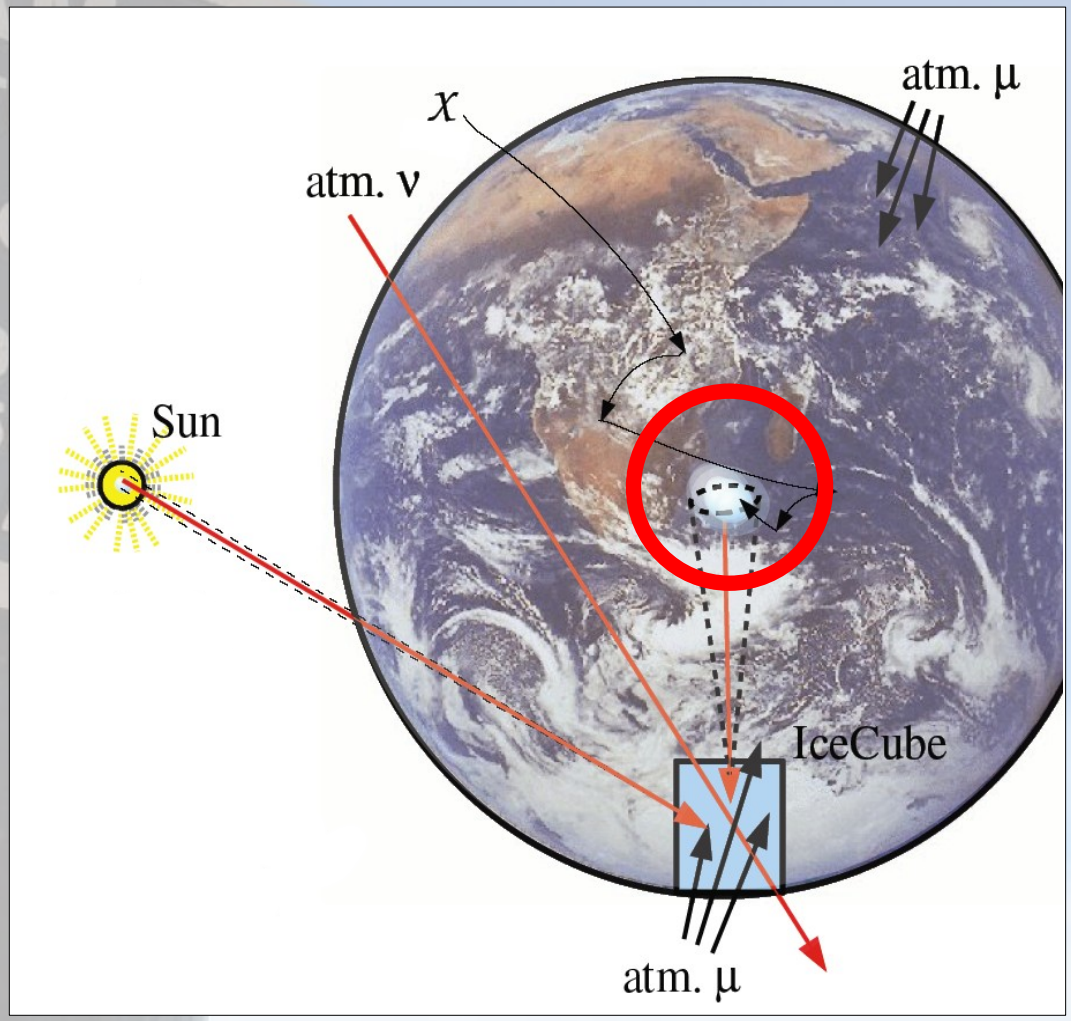
(4-year AMANDA)

astro-ph/0705.1315

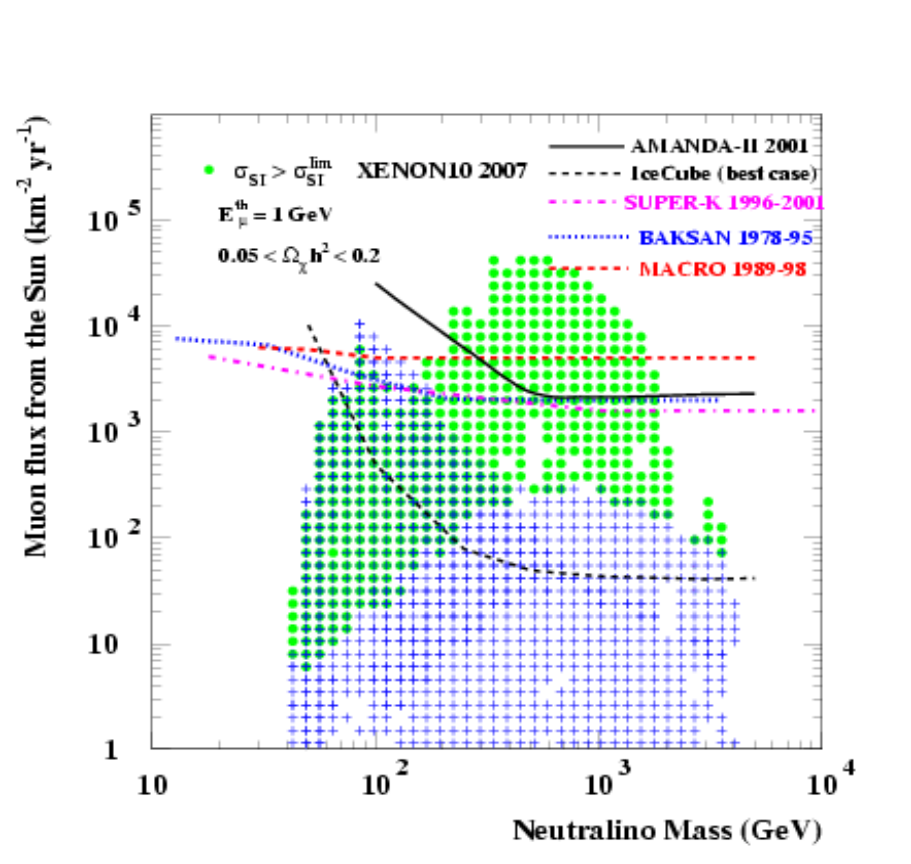
Accepted by PRD

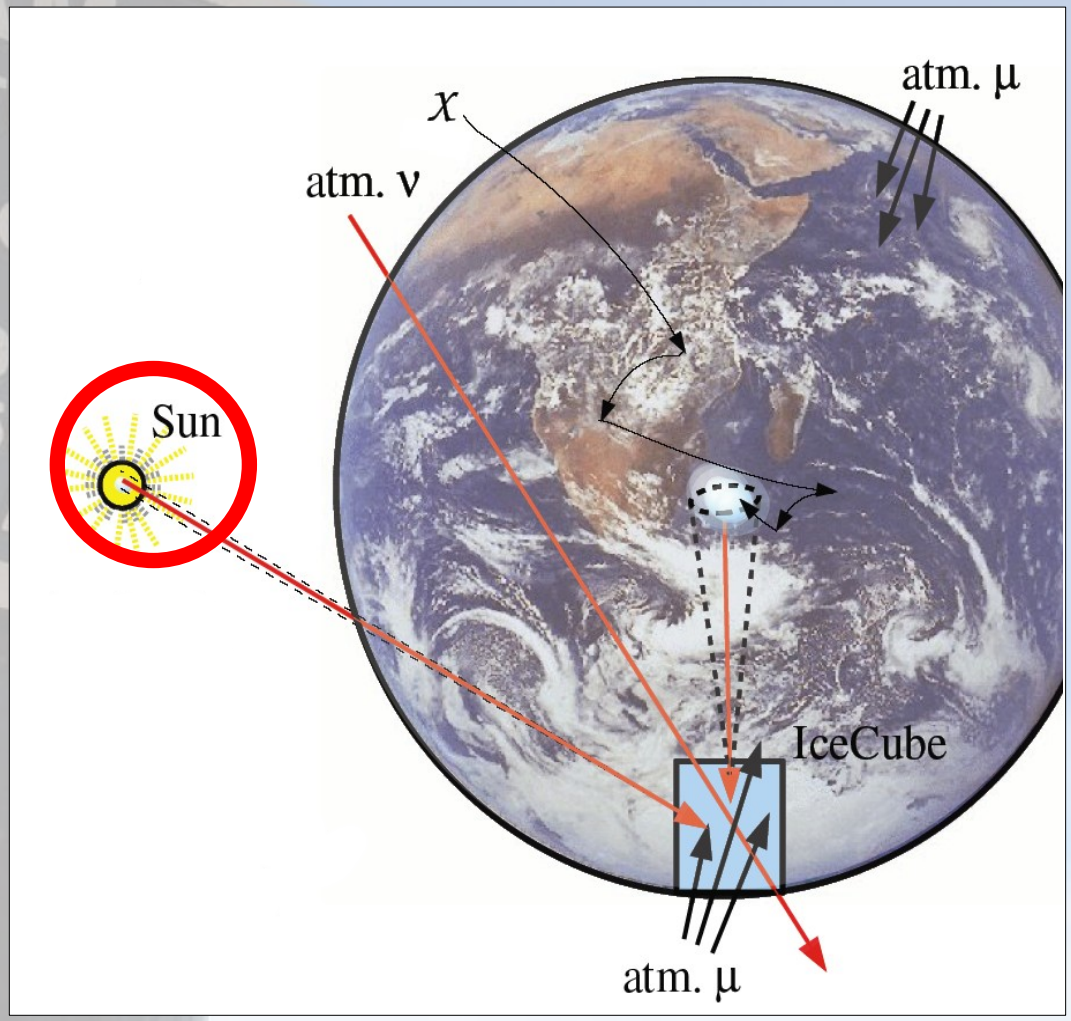
WIMPs (Neutralinos)



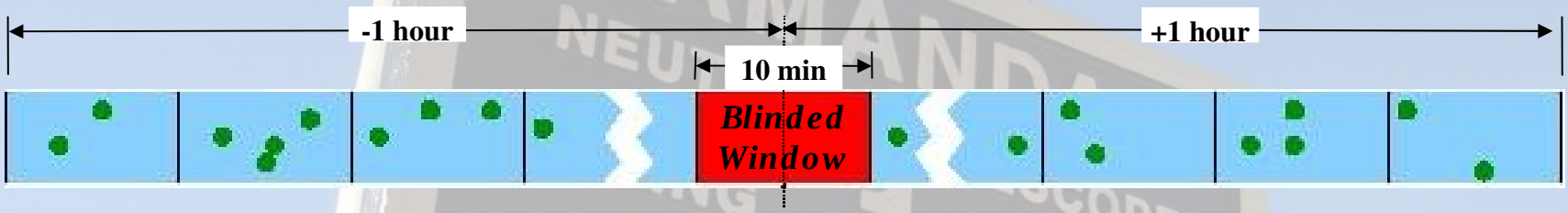


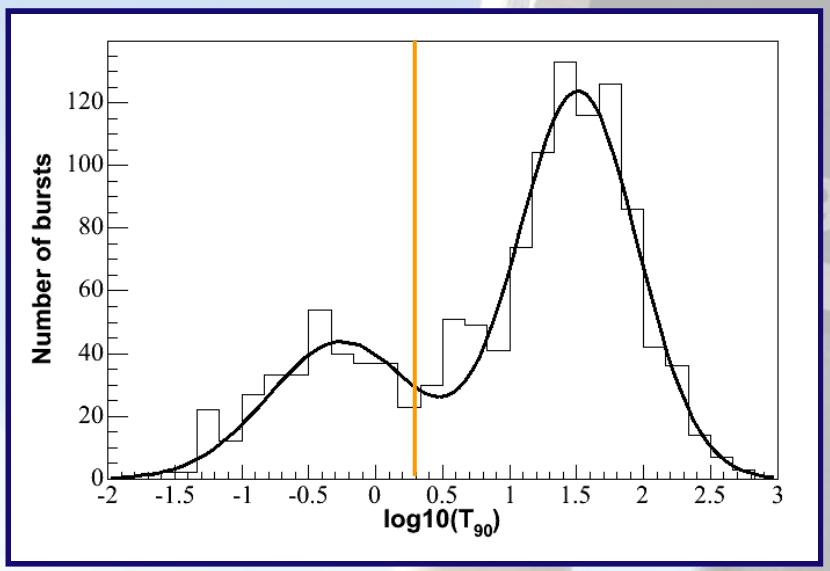
WIMPs (Neutralinos)

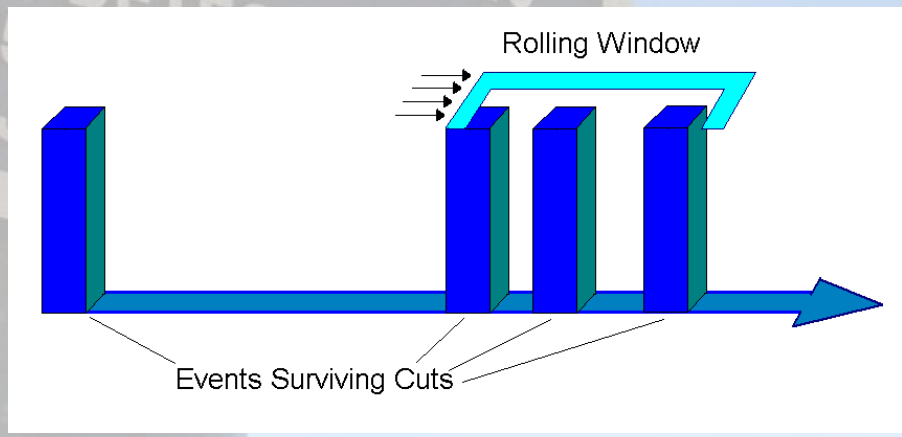




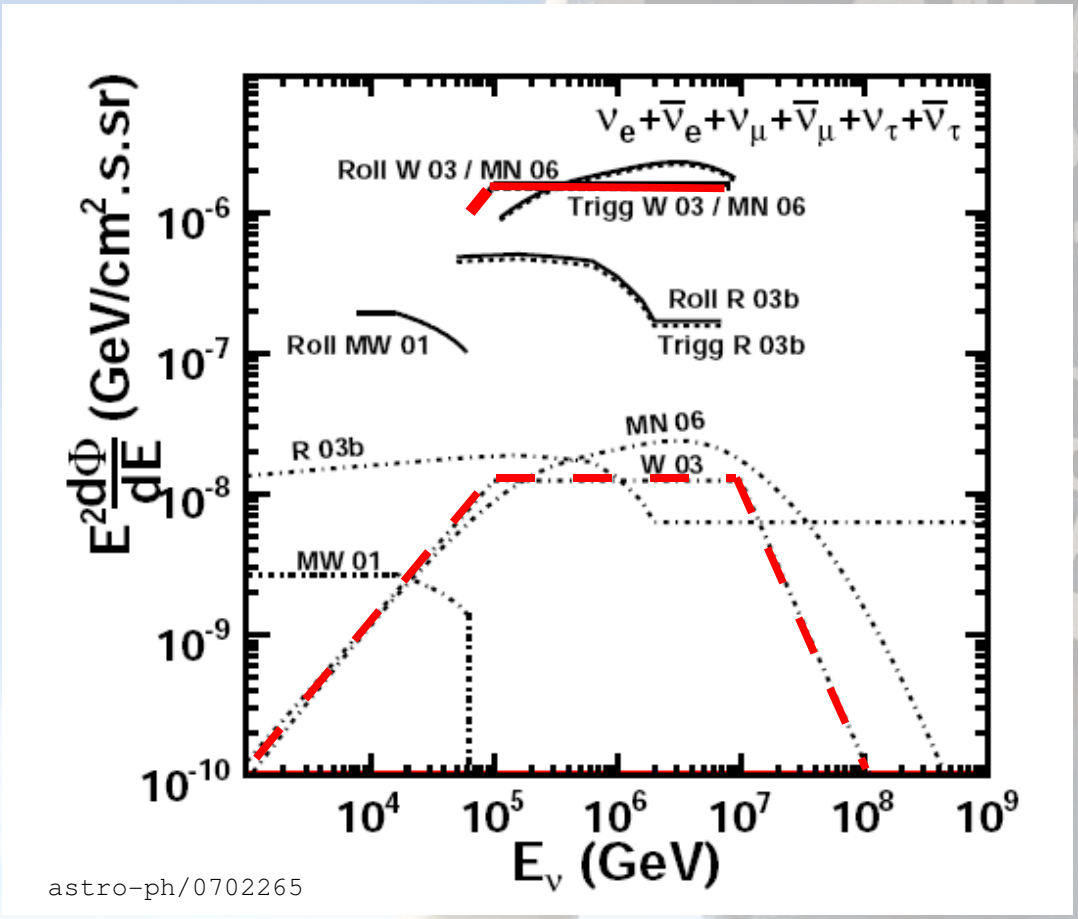
GRB (Method)


-1 hour
+1 hour
10 min
Blinded Window


Number of bursts
log10(T90)


Rolling Window
Events Surviving Cuts

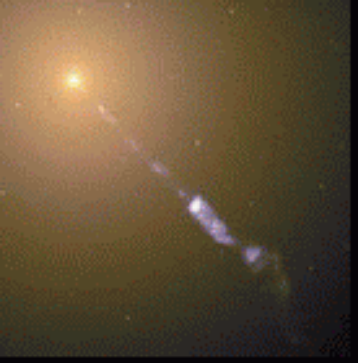
GRB (Limit)



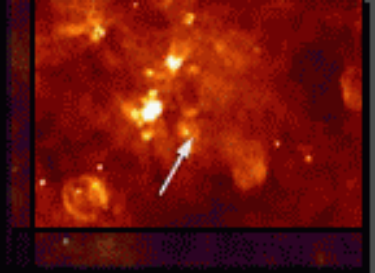
astro-ph/0702265

(slowly) approaching WB Flux

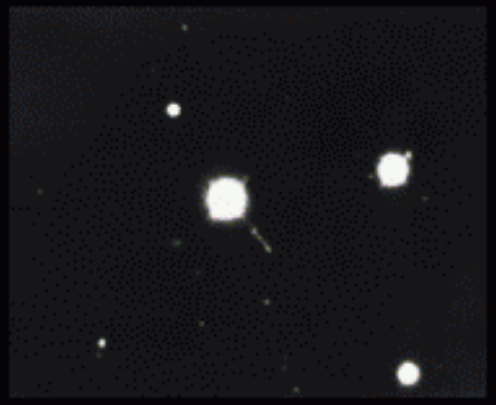
Point Source Search



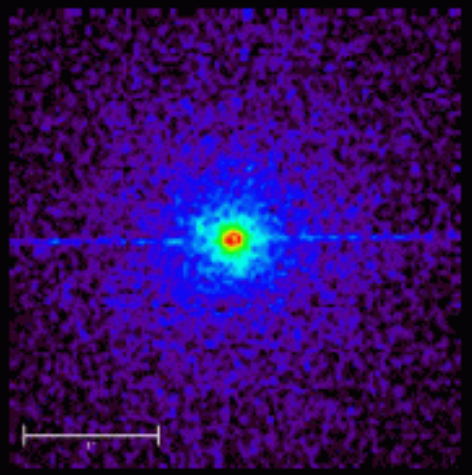
nearby AGN M87 (HST)



Magnetar SGR 1806-20



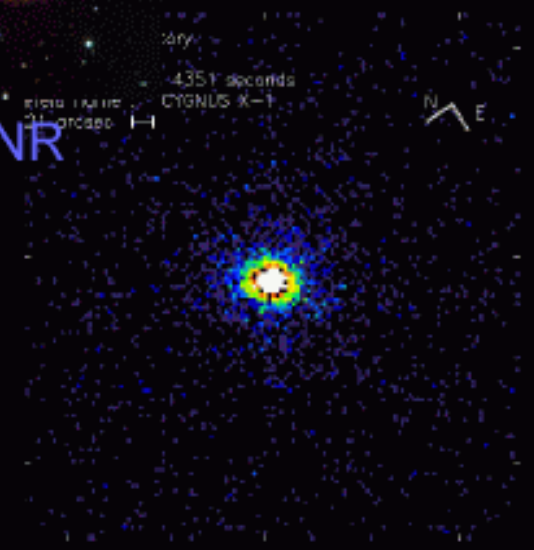
Quasar 3C273 Kitt Peak



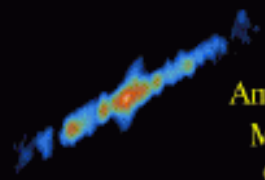
Cygnus X-3 x-ray (Chandra)

Crab nebula SNR

BL Lac Markarian 421



Cygnus X-1

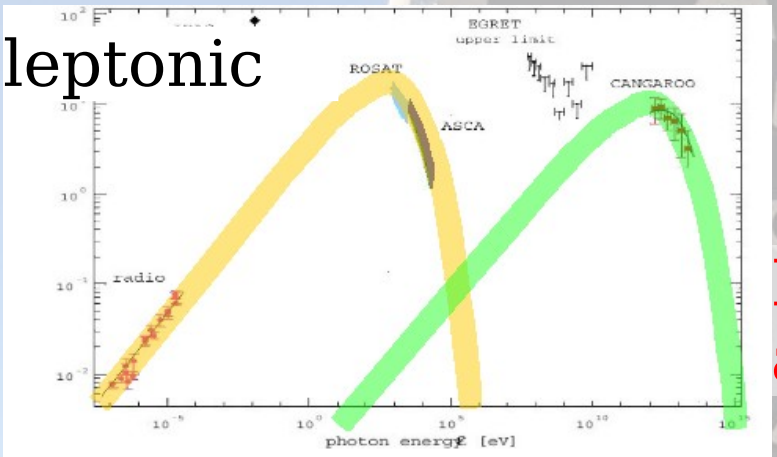


Amy Mioduszewski
Michael Rupen
Craig Walker
Greg Taylor

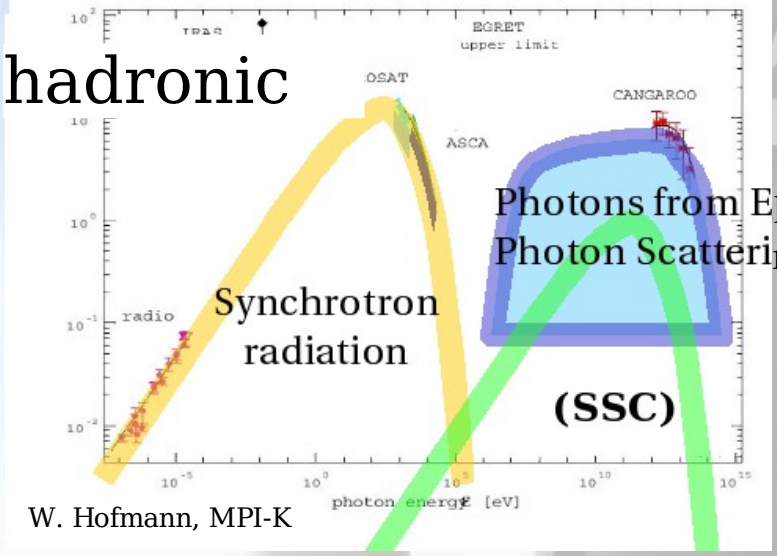
Microquasar SS433 (VLBA)

Leptonic vs. Hadronic

leptonic

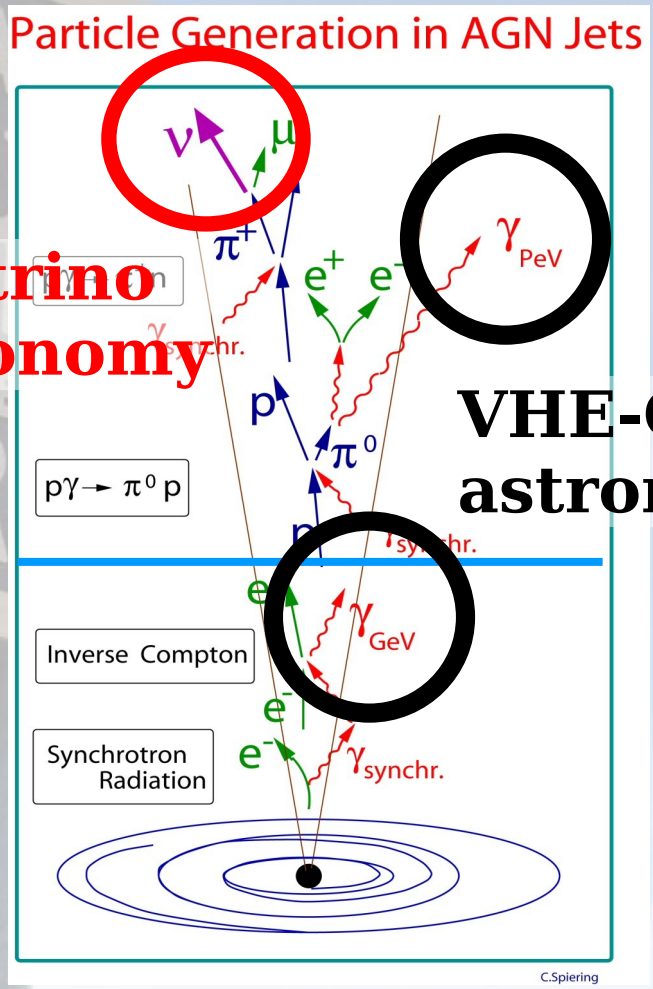


hadronic



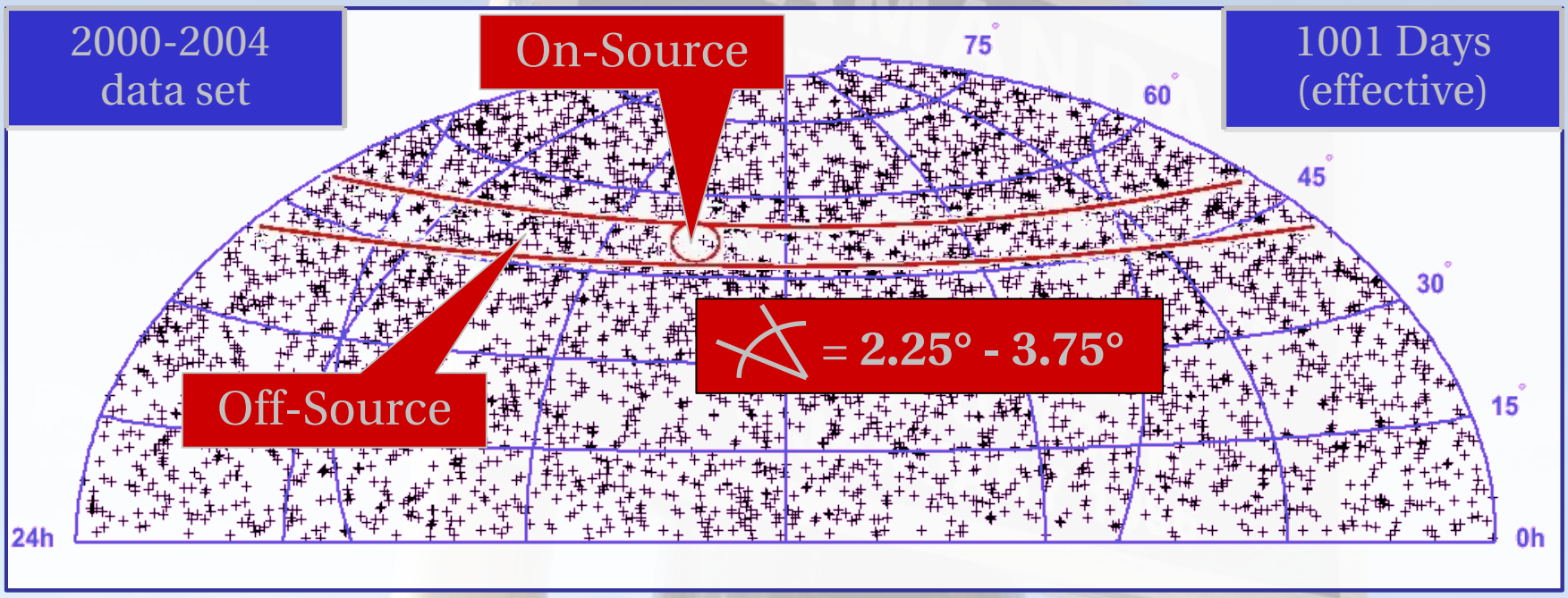
W. Hofmann, MPI-K

Neutrino astronomy



VHE-Gamma astronomy

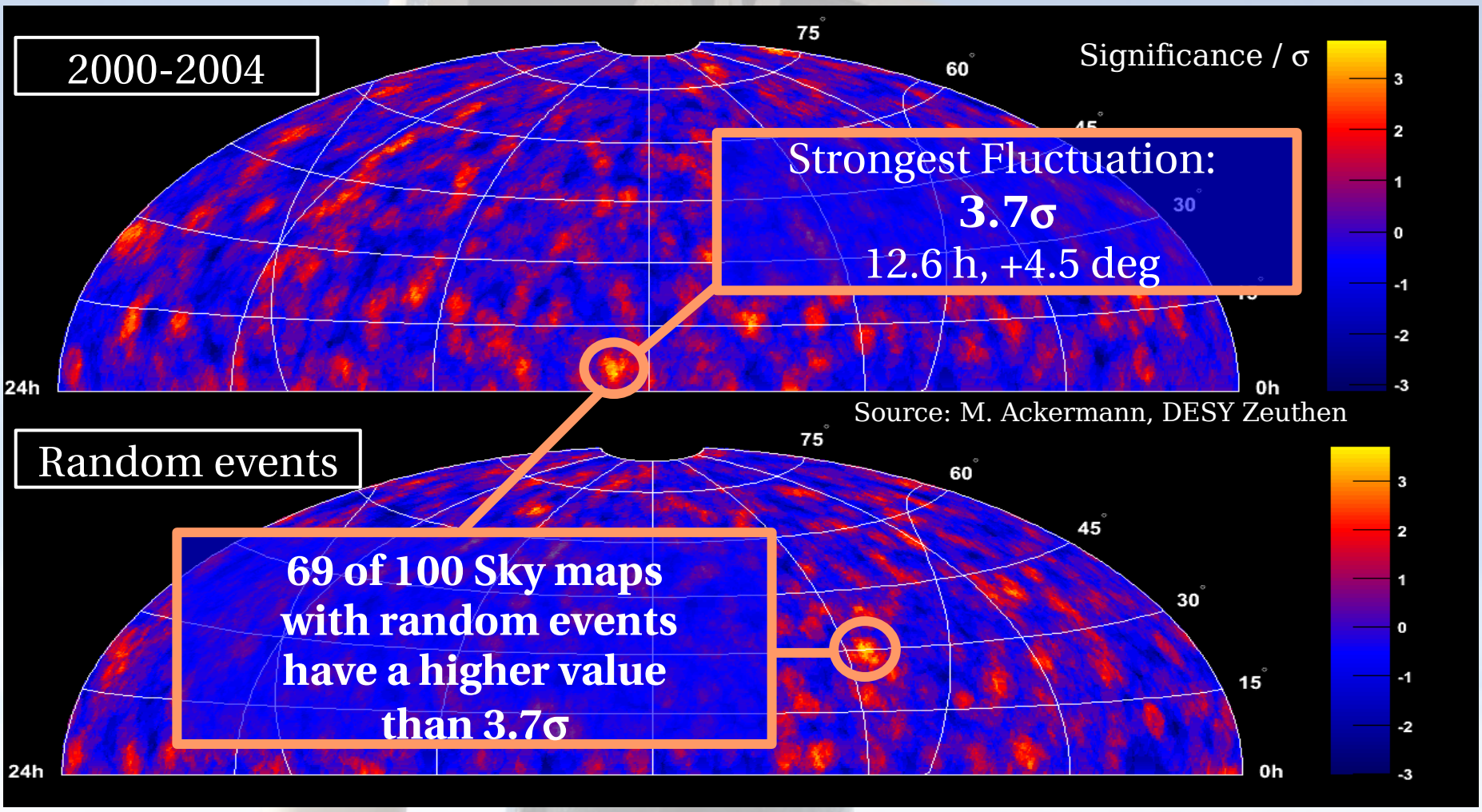
Data Set (AMANDA II)



Source: M. Ackermann, DESY Zeuthen

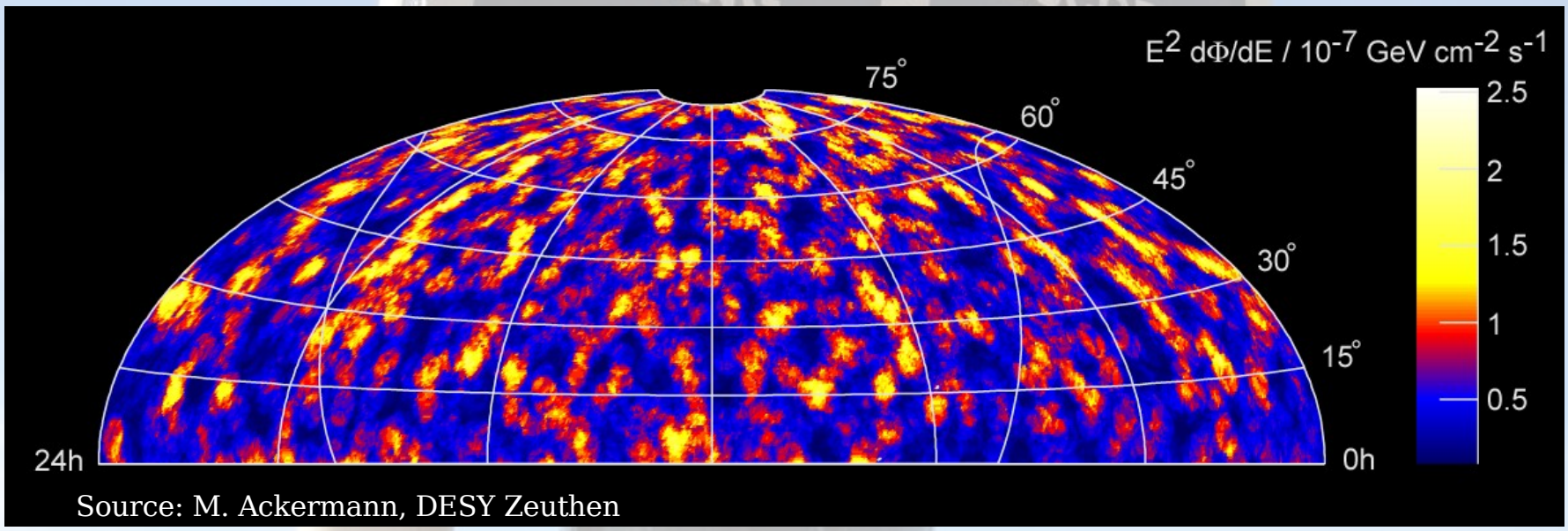
Neutrino-Data Set:	**4282 Events**
MC (atm. ν):	**3627 – 4912 Events**

Significance



Flux Limit (2000-2004)

- 90% CL upper flux limit in 0.5-degree bins for the northern hemisphere



Source: M. Ackermann, DESY Zeuthen

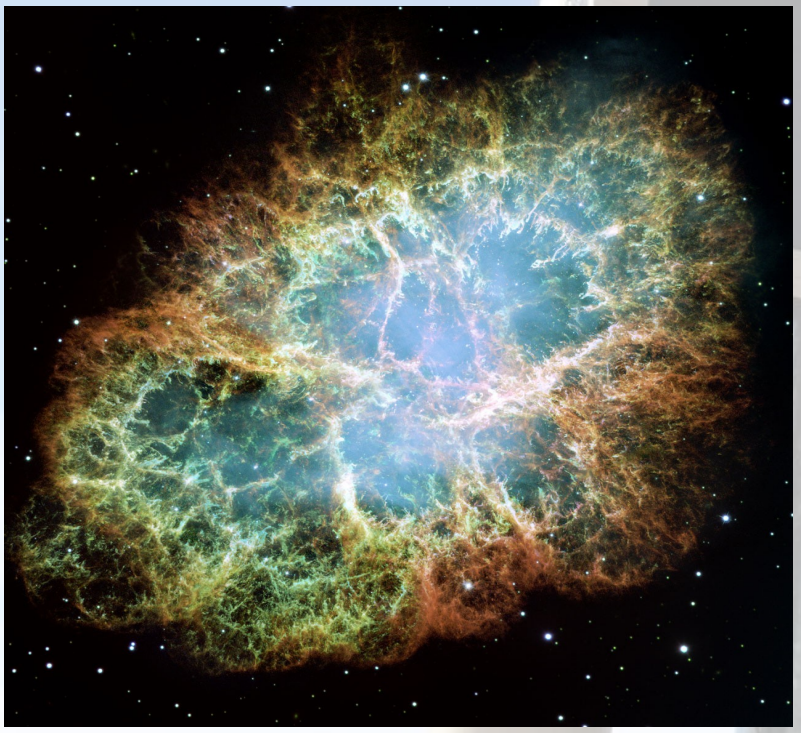
Specific Sources

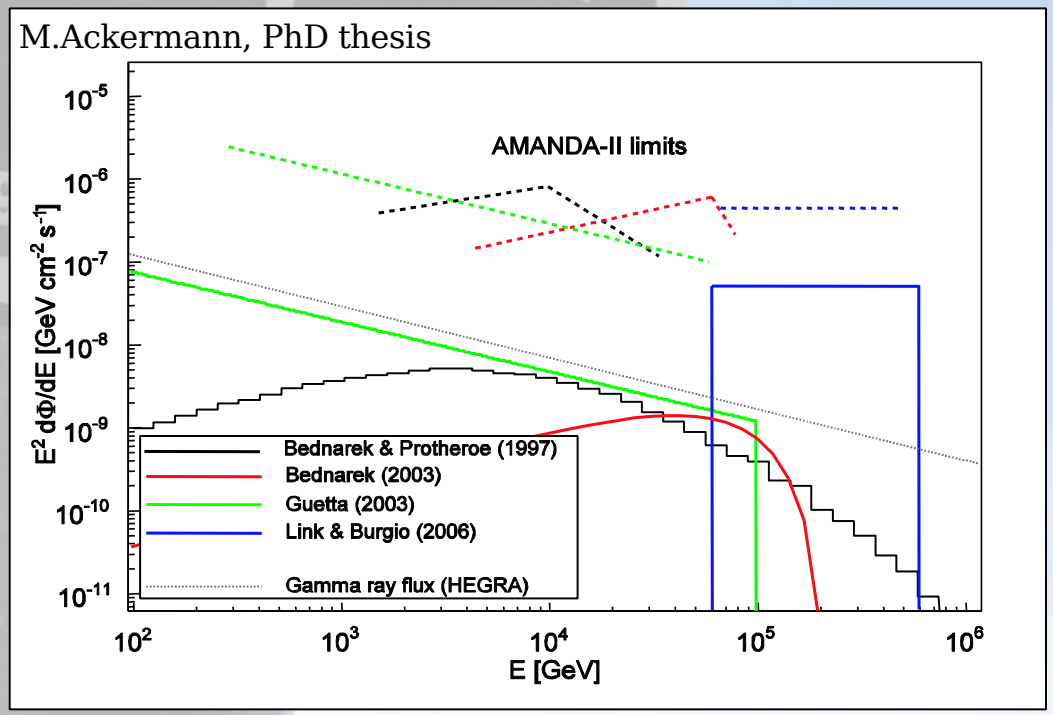
	Source	Events observed/ background (2000-2004)	Excess parameter -log10 P	Flux upper limit (15% sys, 7% stat) Φ_0 @ 90% CL [10^{-7} GeV cm^{-2}s^{-1}] for $\Phi = \Phi_0 E^{-2}$	
				$\Phi_0(\nu_\mu)$	$\Phi_0(\nu_\mu+\nu_\tau)$ (1:1)
AGN	Markarian 421	**6 / 7.37**	0.13	0.42	0.74
AGN	Markarian501	**8 / 6.39**	0.51	0.85	1.47
AGN	1ES1959+650	**5 / 4.77**	0.29	0.78	1.35
AGN	M87	**6 / 6.08**	0.25	0.49	0.87
AGN	3C273	**8 / 4.72**	0.98	1.00	1.80
Microquasar	SS433	**4 / 6.14**	0.06	0.27	0.48
Microquasar	LSI +61 303	**5 / 4.81**	0.28	0.74	1.26
Microquasar	Cygnus X-1	**8 / 7.01**	0.39	0.77	1.32
Microquasar	Cygnus X-3	**7 / 6.48**	0.50	0.68	1.18
SNR	Cassiopeia A	**5 / 6.00**	0.15	0.51	0.89
SNR	Crab Nebula	**10 / 6.74**	0.84	1.02	1.78

- 32 sources selected to reduce **trial factor**
- **No indication for neutrino point sources**

Crab Nebula

- Guetta & Amato: Rescaling of gamma ray flux ($N_{,exp}=0.16$)
- Bednarek & Protheroe: Heavy nuclei accelerated in outer gap ($N_{,exp}=0.08$)
- Bednarek: Time evolution of pulsar wind nebula ($N_{,exp}=0.03$)
- Link & Burgio: Ions accelerated near pulsar surface ($N_{,exp}=1.2$)



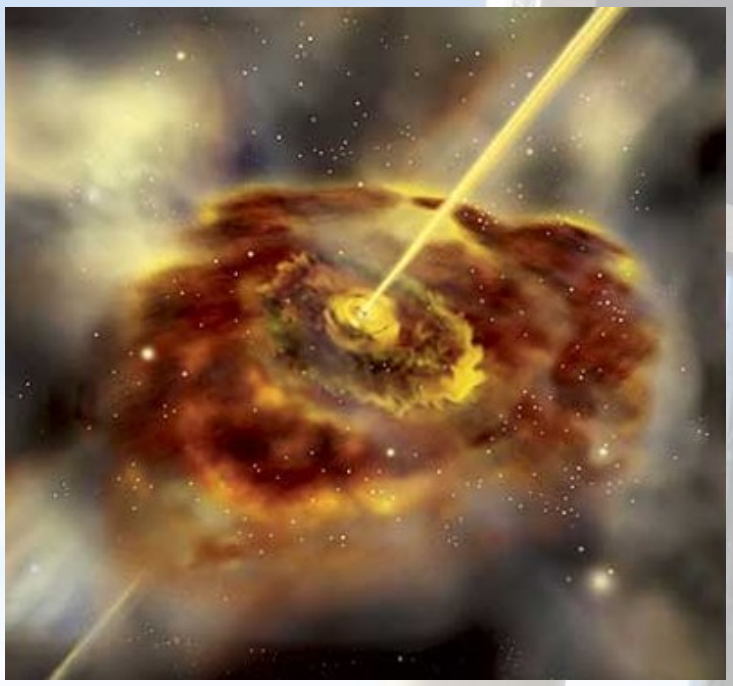


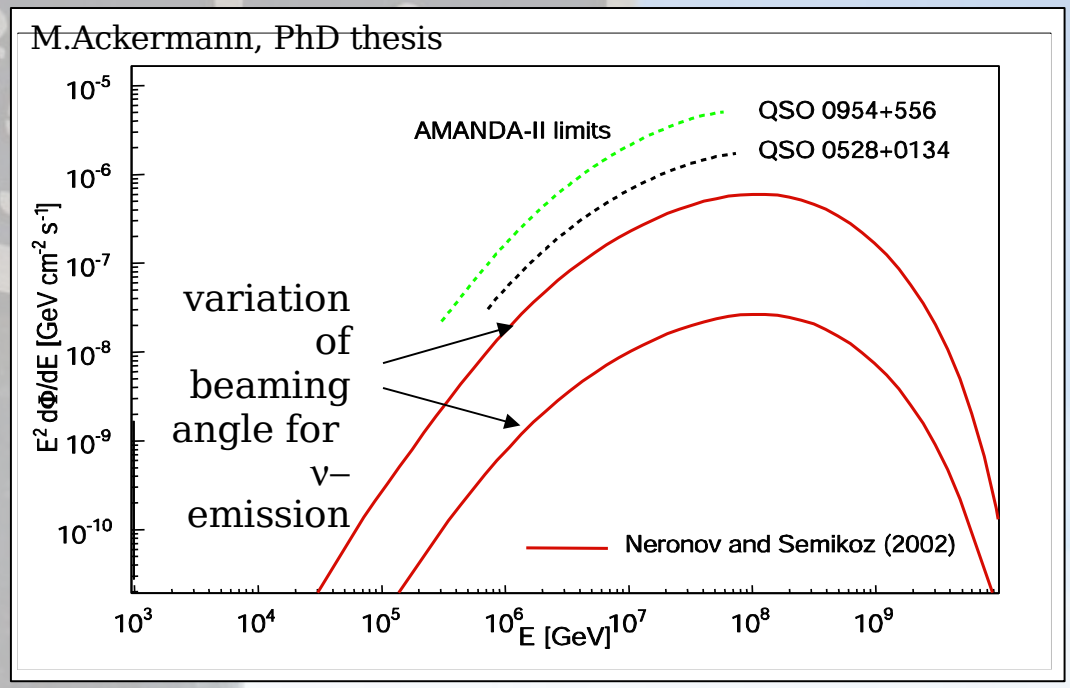
GeV-AGN

- Neronov and Semikoz: Model for "typical GeV loud Blazar", pγ-interaction in the AGN core

$N_{\nu,exp}$ = **0.04 - 1.1** (QSO 0528+134)

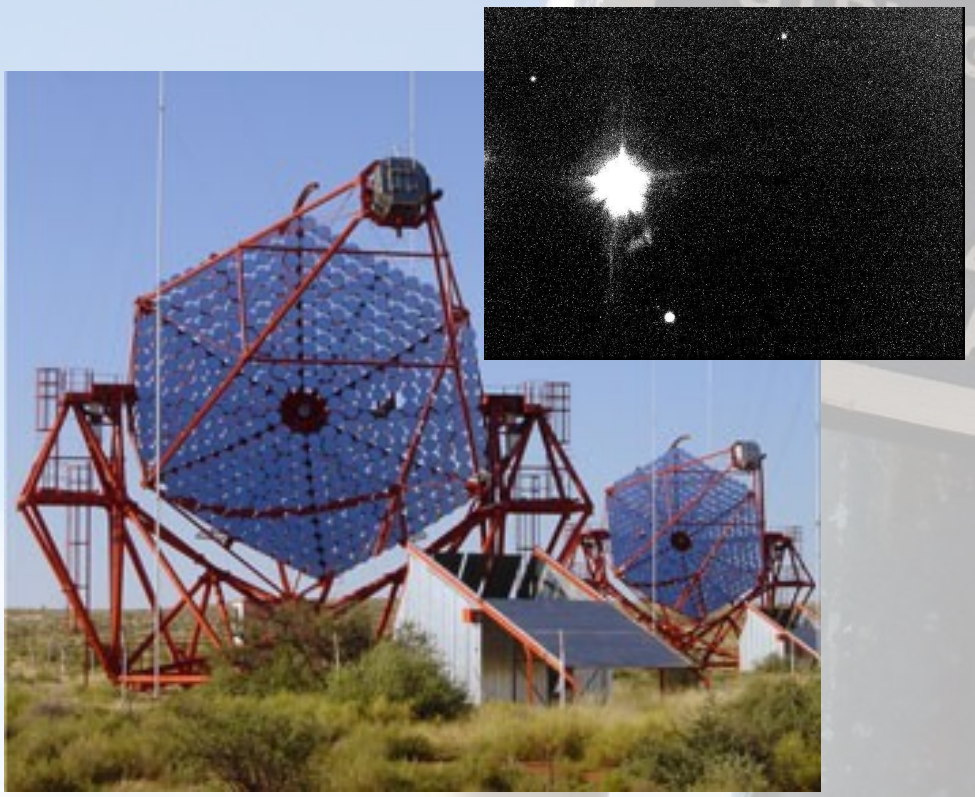
$N_{\nu,exp}$ = **0.006 – 0.14** (QSO 0954+556)

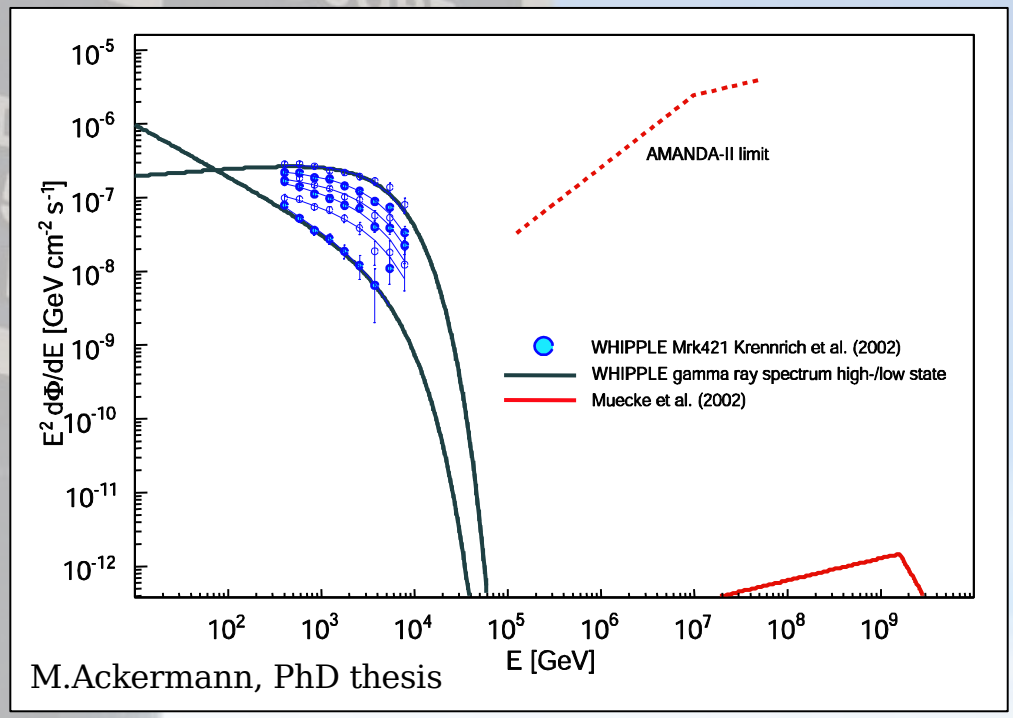




Markarian 421

- Muecke et al.: Model of Markarian 421 as High frequency peaked BLLac in the Proton Synchrotron Blazar model ($\mathbf{N_{\nu,exp} \sim 0}$)

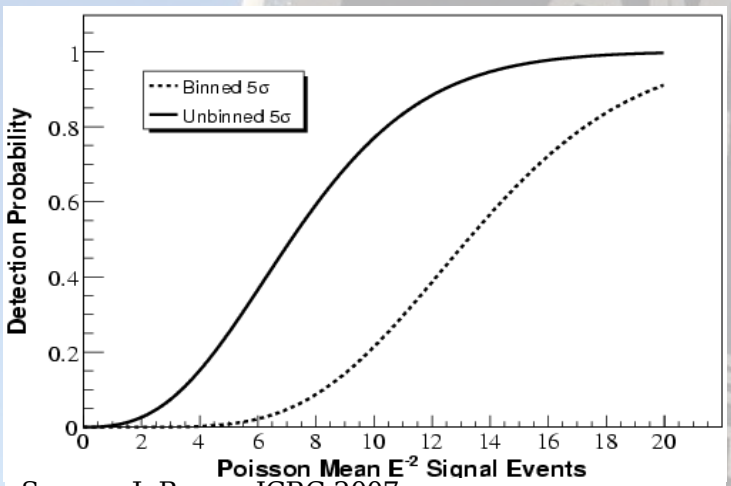




M.Ackermann, PhD thesis

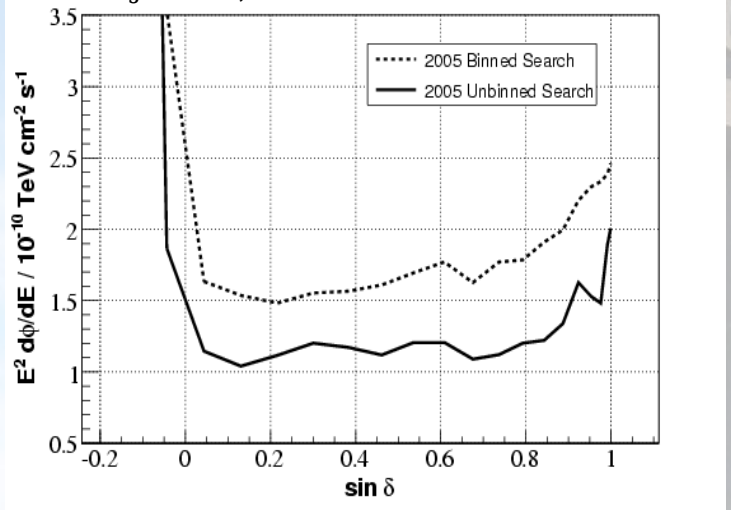
Unbinned Search

Detection Probability



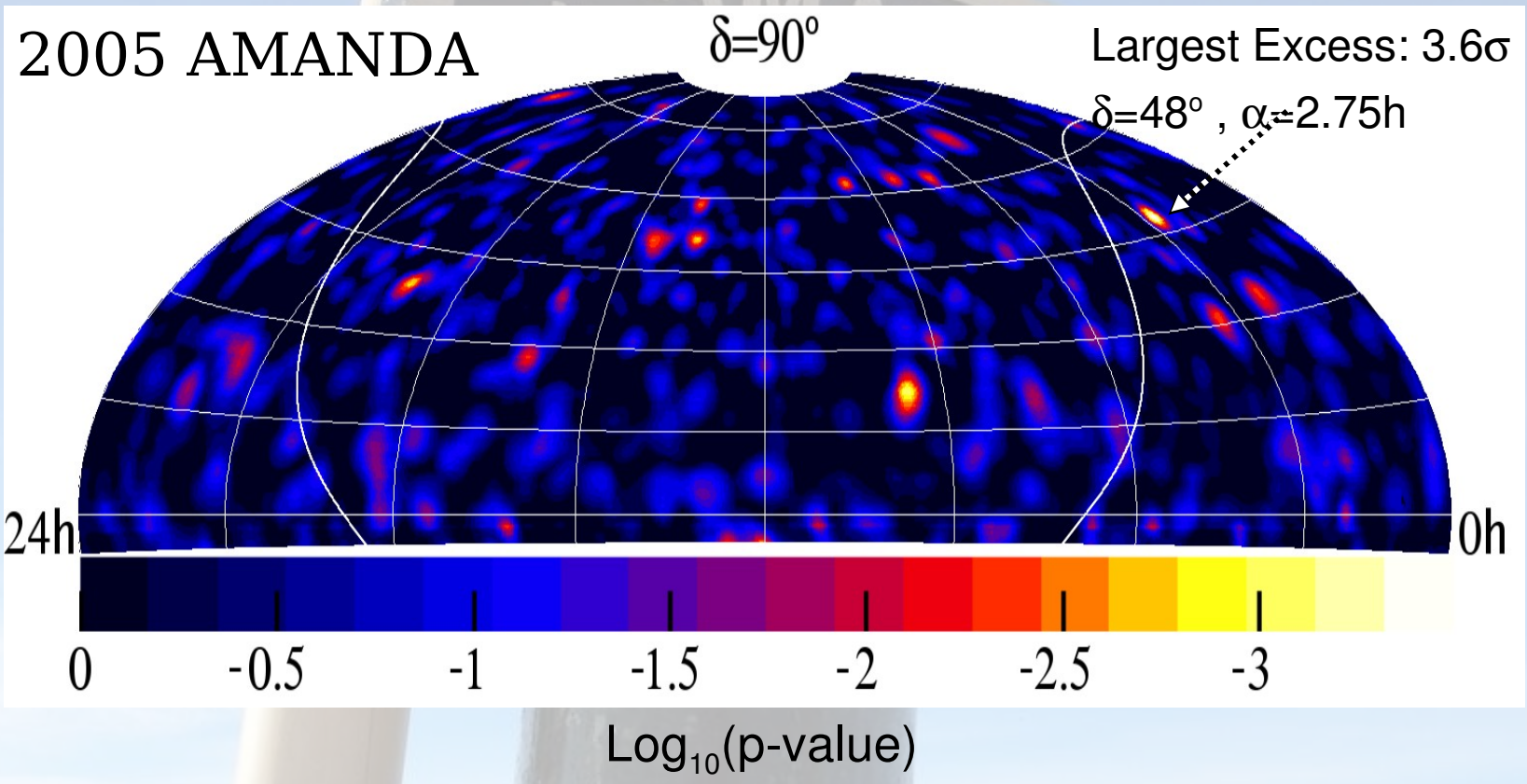
Source: J. Braun, ICRC 2007

Flux Limit



- Uses likelihood parameter to assess resolution and probability of event to be a neutrino
- Significant improvement over binned method

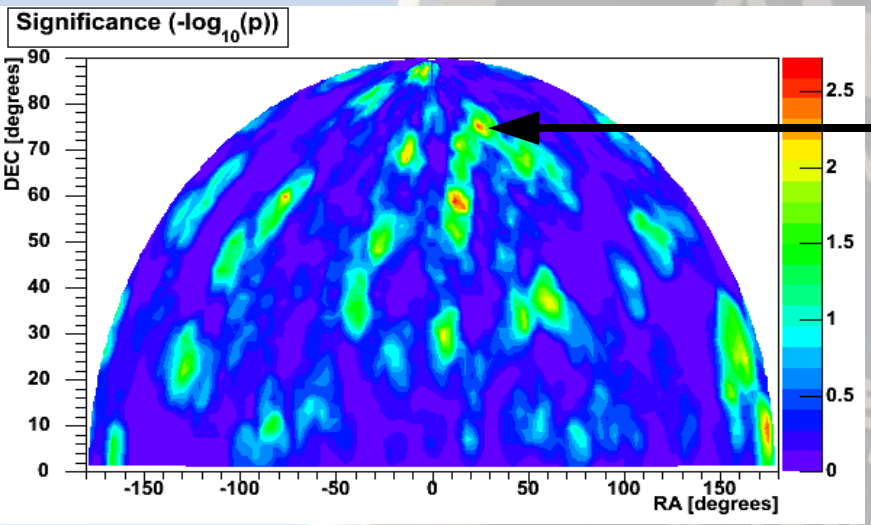
Unbinned Search



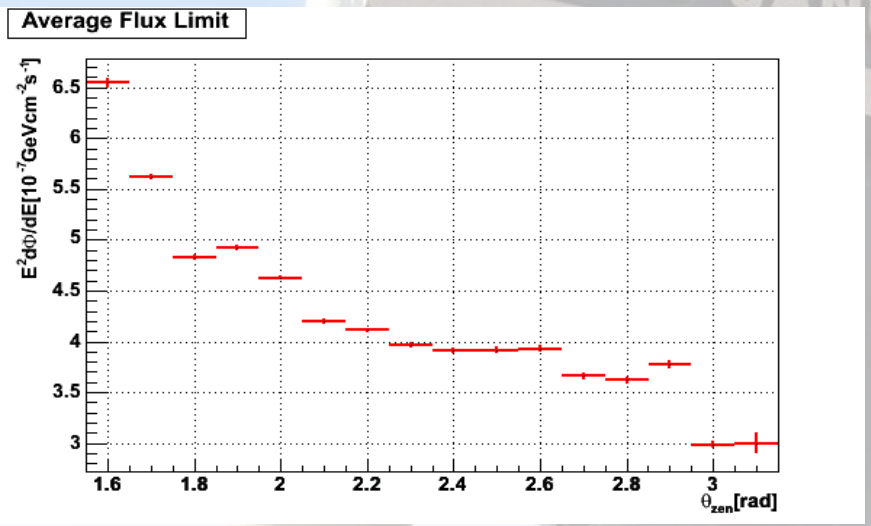
69 out of 100 sky maps randomized in RA contain an excess of at least 3.6σ

Source: J. Braun, ICRC 2007

AMANDA B10 (97-99)



Highest Excess:
DEC: +71.16deg
RA: 3h 44min



- Completes AMANDA Point Source Analyses
- 45% of random skies have higher excess

"Stacking"-Analysis

- Search for excess of events by summing over potential sources of same type
- Assumption: Neutrino Flux is proportional to electromagnetic luminosity
- Photon wavelength depends on type of source (radio, IR, optical, x-ray)
- For most classes fewer events than expected from pure background

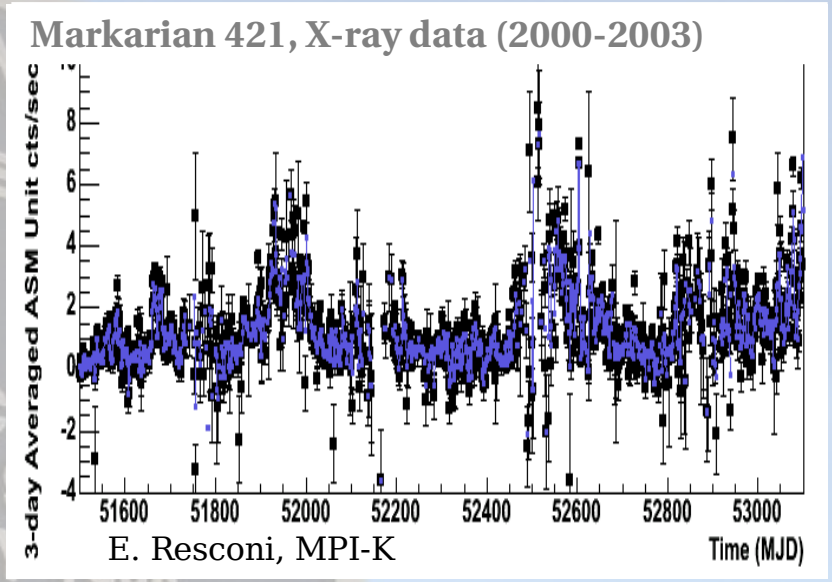
Source class	N_{src}	Limit
IR Blazars	11	1.2
keV Blazars (HEAO-A)	3	0.59
keV Blazars (ROSAT)	8	0.63
GeV Blazars	8	0.32
Uni. GeV sources	22	3.2
TeV Blazars	5	0.69
GPS and CSS	8	0.57
FR-I Galaxies	1	0.54
FR-I Galaxies (no M87)	17	0.43
FR-II Galaxies	17	3.5
Radio-weak sources	11	1.3

A. Gross, Ph.D thesis, University of Dortmund
Achterberg et al., "On the selection of AGN …", Accepted by Astropart. Phys.

[10^{-7} GeV cm^{-2}s^{-1}] (E^{-2}-Spectrum)

Time-dependent Analysis

- Search for events during periods of enhanced neutrino emission
- Criteria: Information from electromagnetic measurements and theoretical models
- Information used already:
  - X-ray flux from RXTE for Blazars
  - TeV flux from Cherenkov telescopes

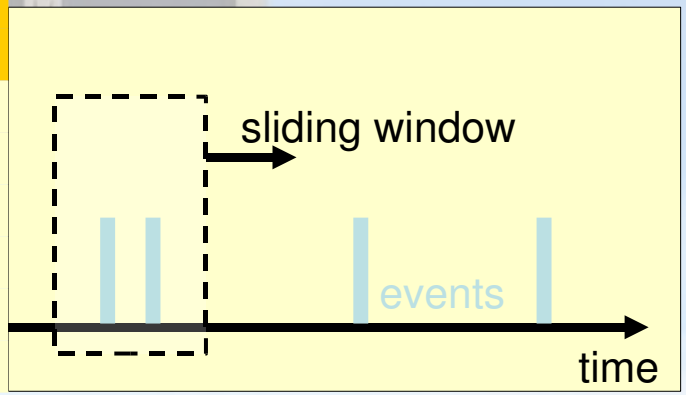


Source	EM light curve source	Livetime in periods of high activity	Nr. of ν events in high state	Expected backgr. in high state
Markarian 421	ASM/RXTE	141 days	0	1.63
1ES1959+650	ASM/RXTE	283 days	2	1.59
Cygnus X-3	Ryle Telesc.	114 days	2	1.37

Sliding Window

Search for pairs of events during certain time frame (20/40 days)

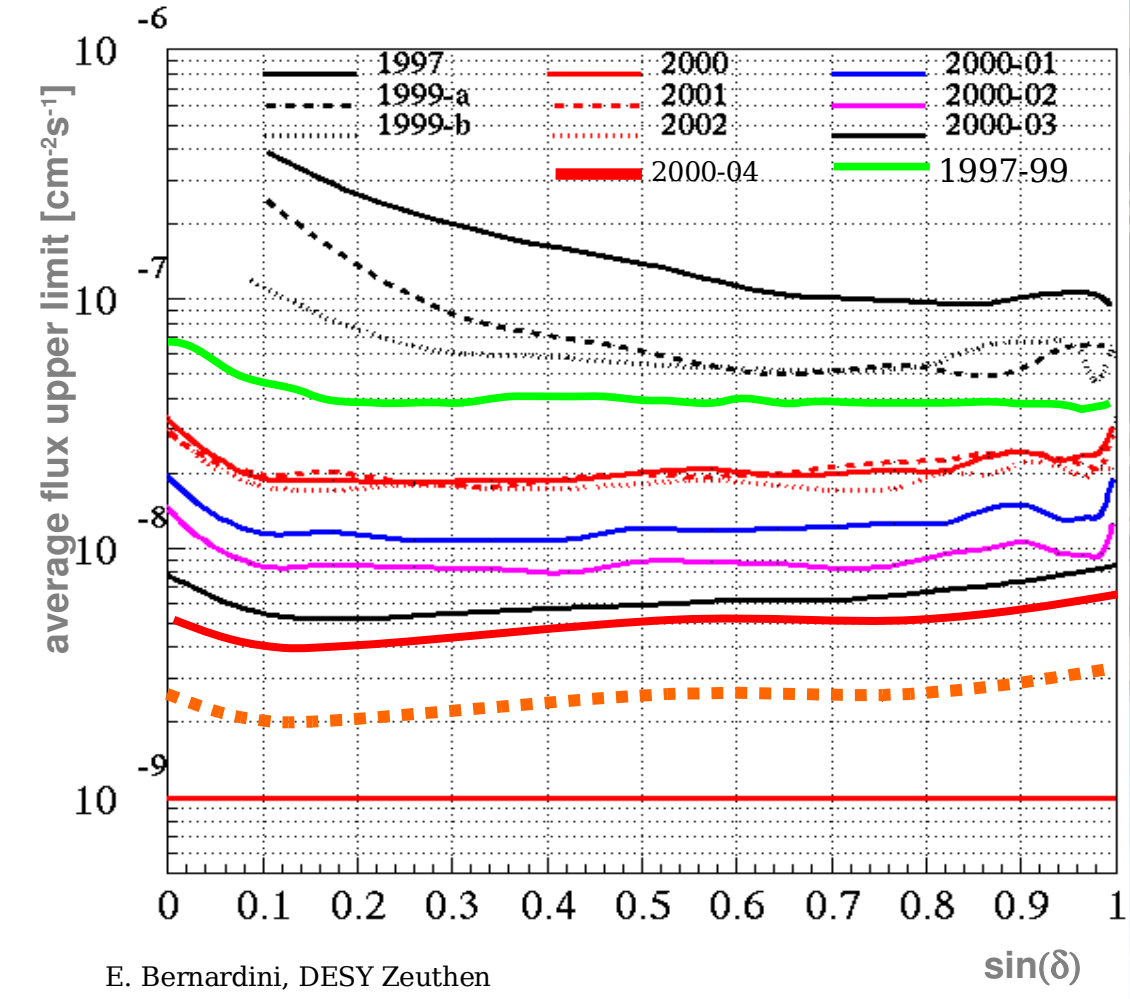
Source	time frame	Number of pairs	Probability
Markarian 421	40 days	0	Close to 1
1ES1959+650	40 days	1	0.34
3EG J1227+4302	40 days	1	0.43
3EG J0450+1105	40 days	1	0.47
QSO 0235+164	40 days	1	0.52
QSO 0528+134	40 days	0	Close to 1
Cygnus X-3	20 days	0	Close to 1
Cygnus X-1	20 days	0	Close to 1
GRS 1915+105	20 days	1	0.32
GRO J0422+32	20 days	0	Close to 1
3EG J1828+1928	20 days	0	Close to 1
3EG J1928+1733	20 days	1	0.35



IceCube/MAGIC Target of Opportunity

- Coincidence of neutrino events in IceCube with heightened VHE gamma emission
- 5 Sources (3 Blazars, 2 Microquasars)
- Thresholds chosen to have 2-3 “alerts” per month
- Initiative of the DESY-Zeuthen Group (E. Bernardini)
- Test run finished, regular run may commence soon

Point Source Summary



AMANDA-B10 (first analyses)

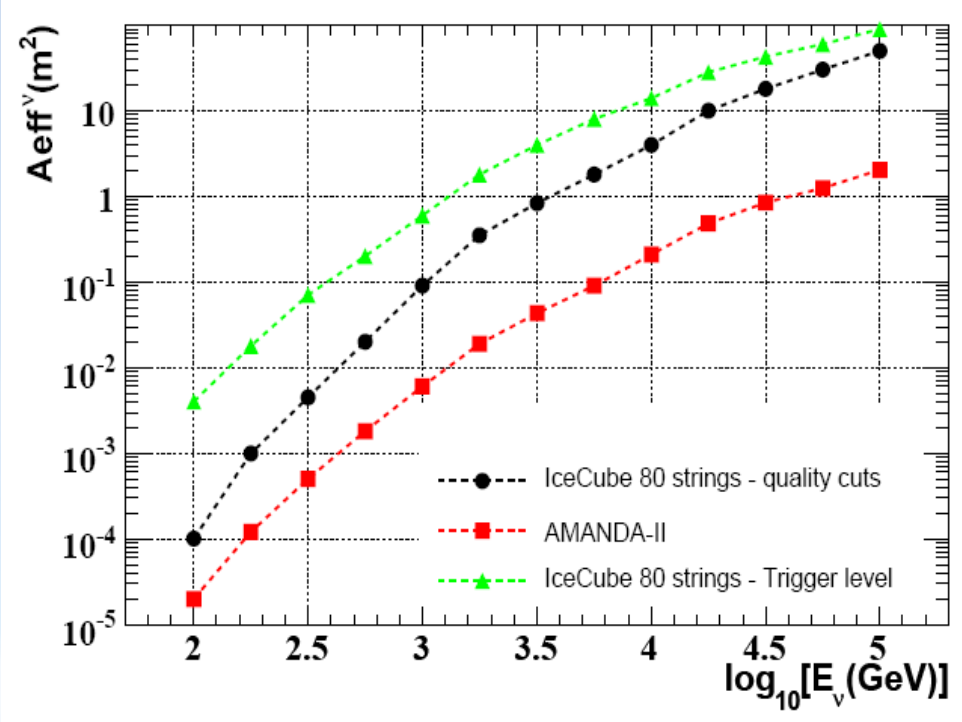
B-10 Combined

AMANDA-II

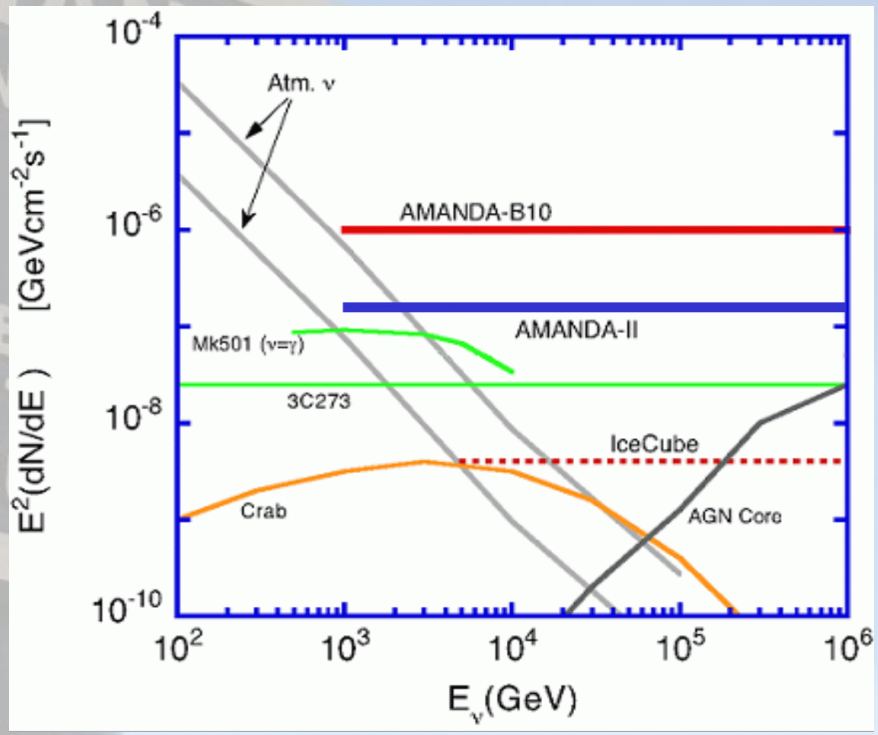
AMANDA Total (Estimate)

6 Months 80-String IceCube (Estimate)

On to IceCube!

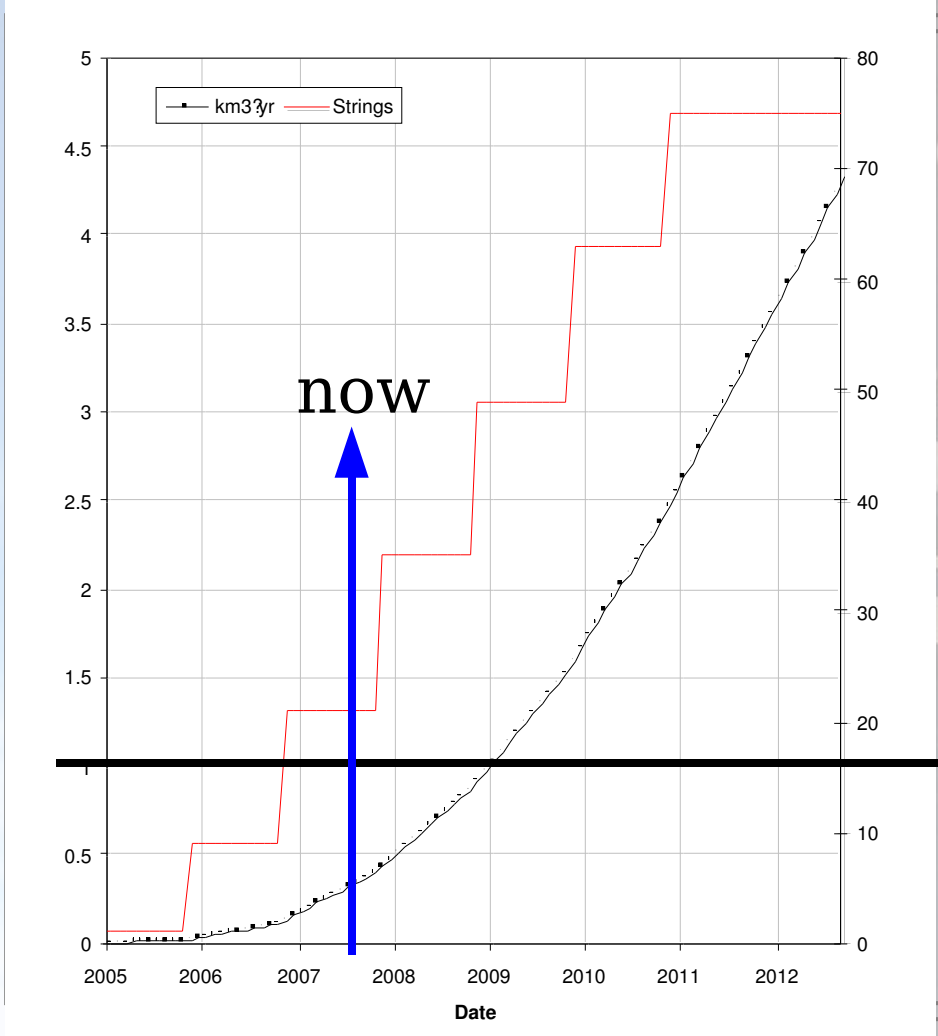


Effective Area



Flux Limit

Integrated Exposure

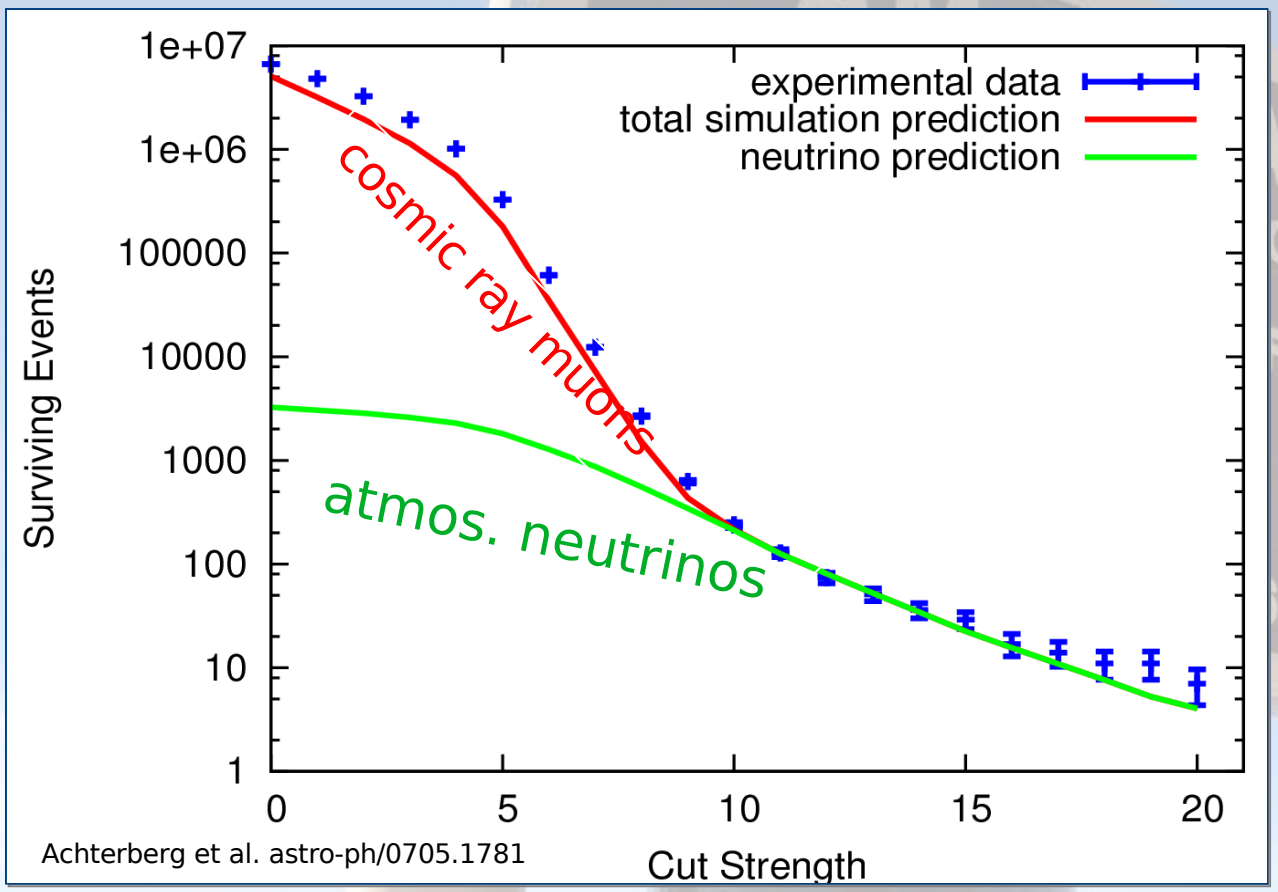


Cumulative values

Construction finished by 2011

1 km^3 year by 2009

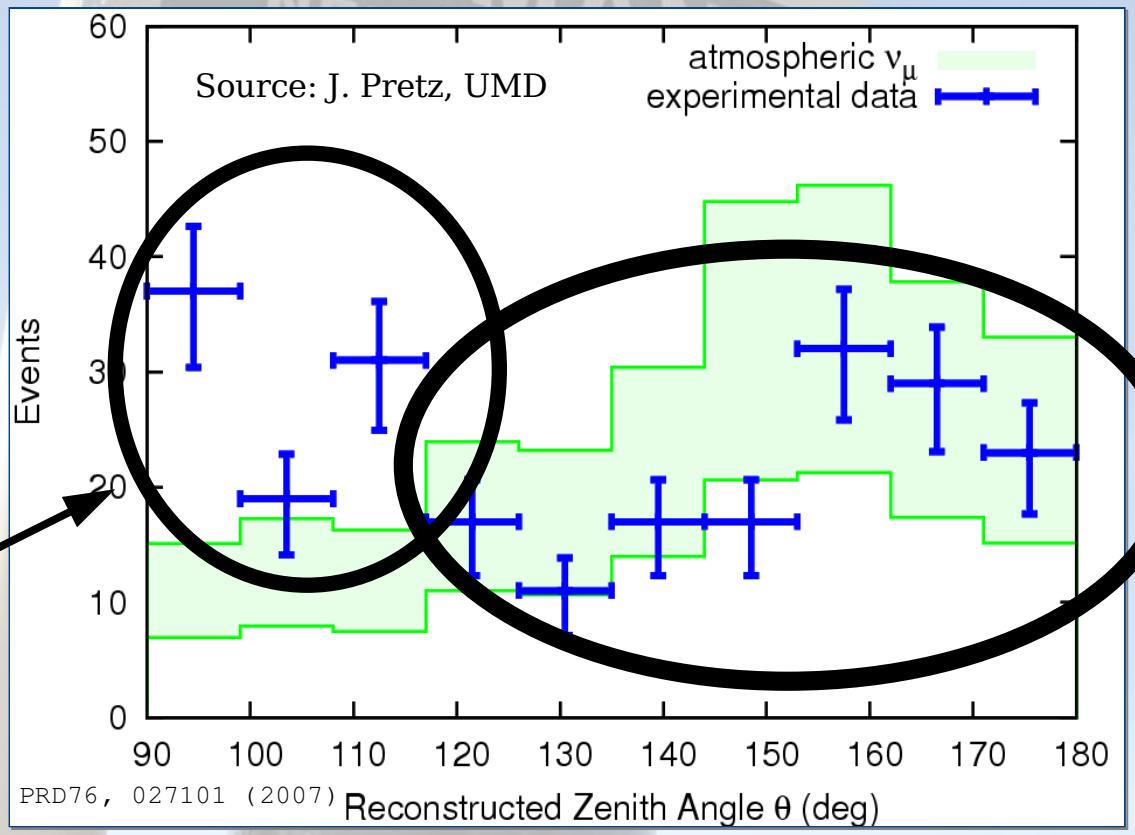
IceCube (9-string)



First IceCube analyses:

- Point Sources
- Atm. Neutrinos

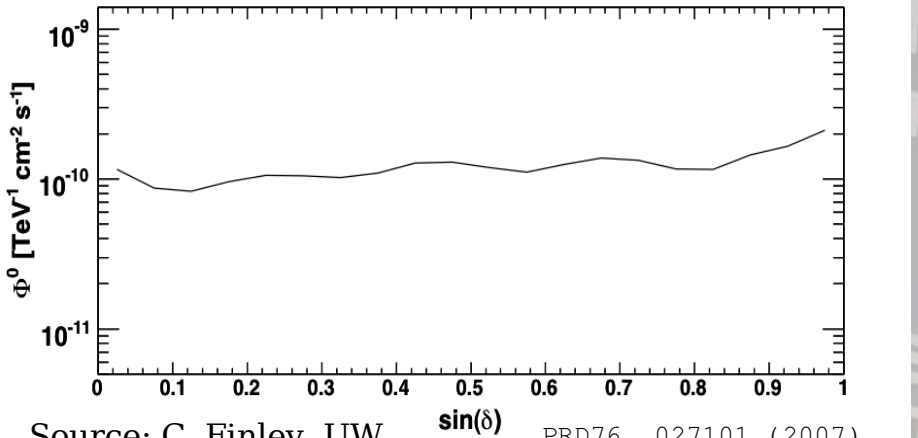
Atmospheric Neutrinos



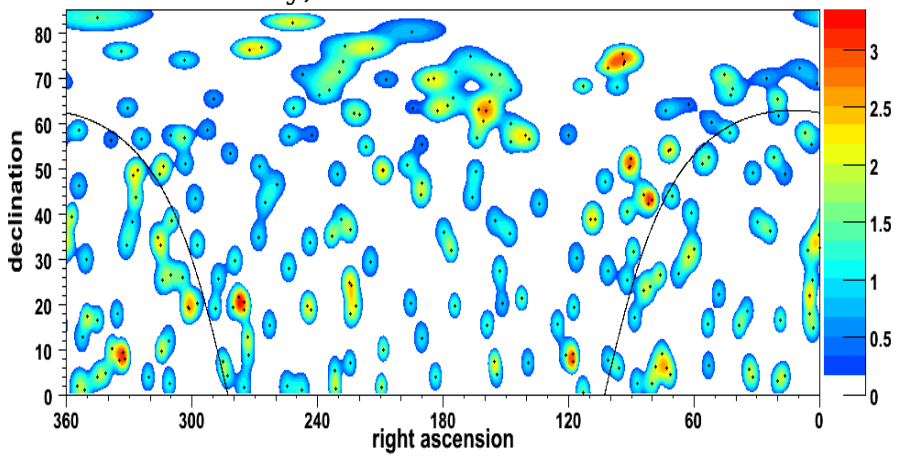
Residual muons near horizon

Agreement with simulation

Point Source Search



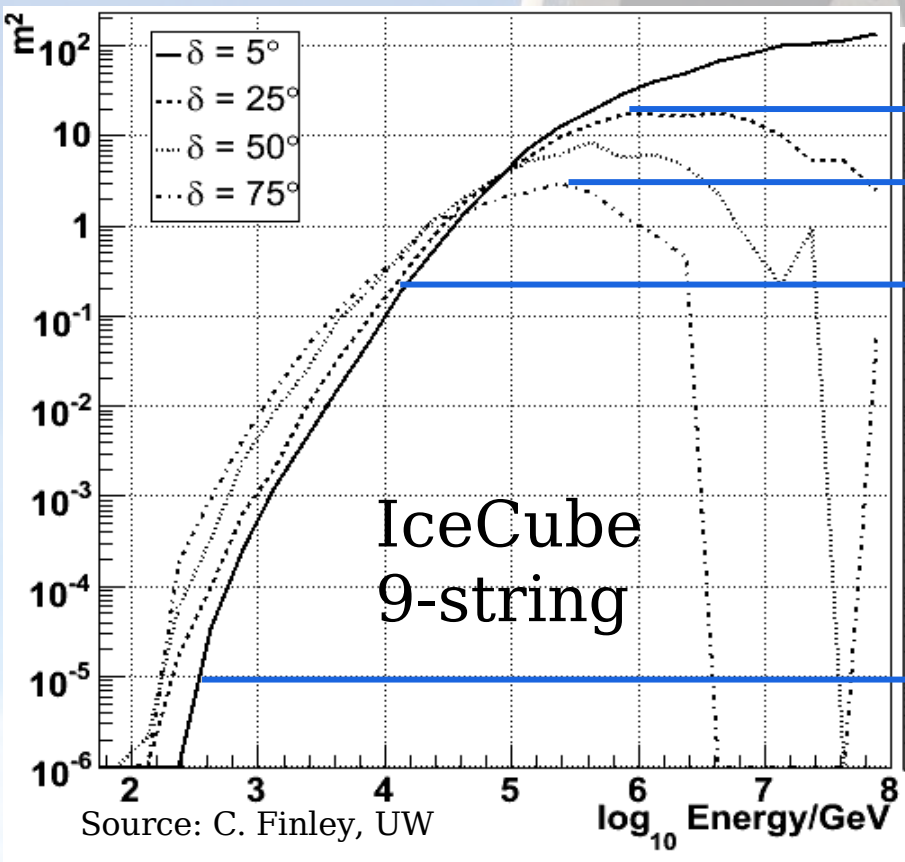
Source: C. Finley, UW PRD76, 027101 (2007)



Flux limit: 1 year IceCube 9-string about same as 1 year AMANDA

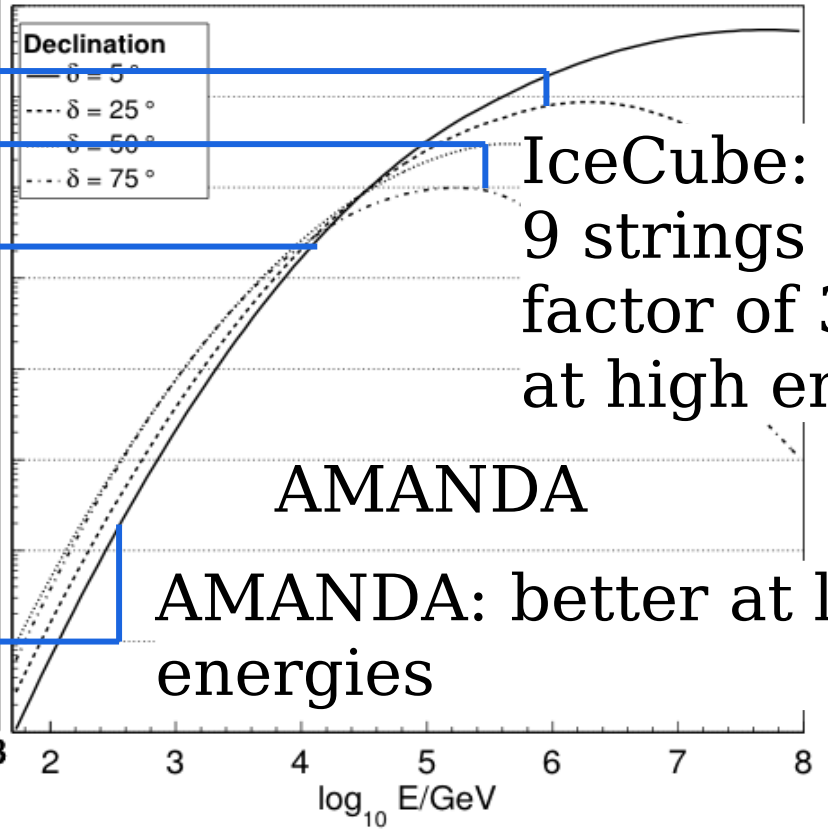
60% of random skies have higher maximum significance

Effective Area Comparison



IceCube 9-string

Source: C. Finley, UW



AMANDA

IceCube: 9 strings already factor of 3 better at high energies!

AMANDA: better at low energies

What Else?

- CR composition
- Charm Physics
- EHE/UHE
- GZK neutrinos
- Kaluza-Klein DM
- Neutrino oscillations
- Lorentz invariance
- Extra dimensions
- Magnetic monopoles
- SN monitoring
- …

Conclusion

- No confirmed (extraterrestrial) sources yet
- But we are working on it!