Searches for point-like sources of high-energy neutrinos with the AMANDA-II detector

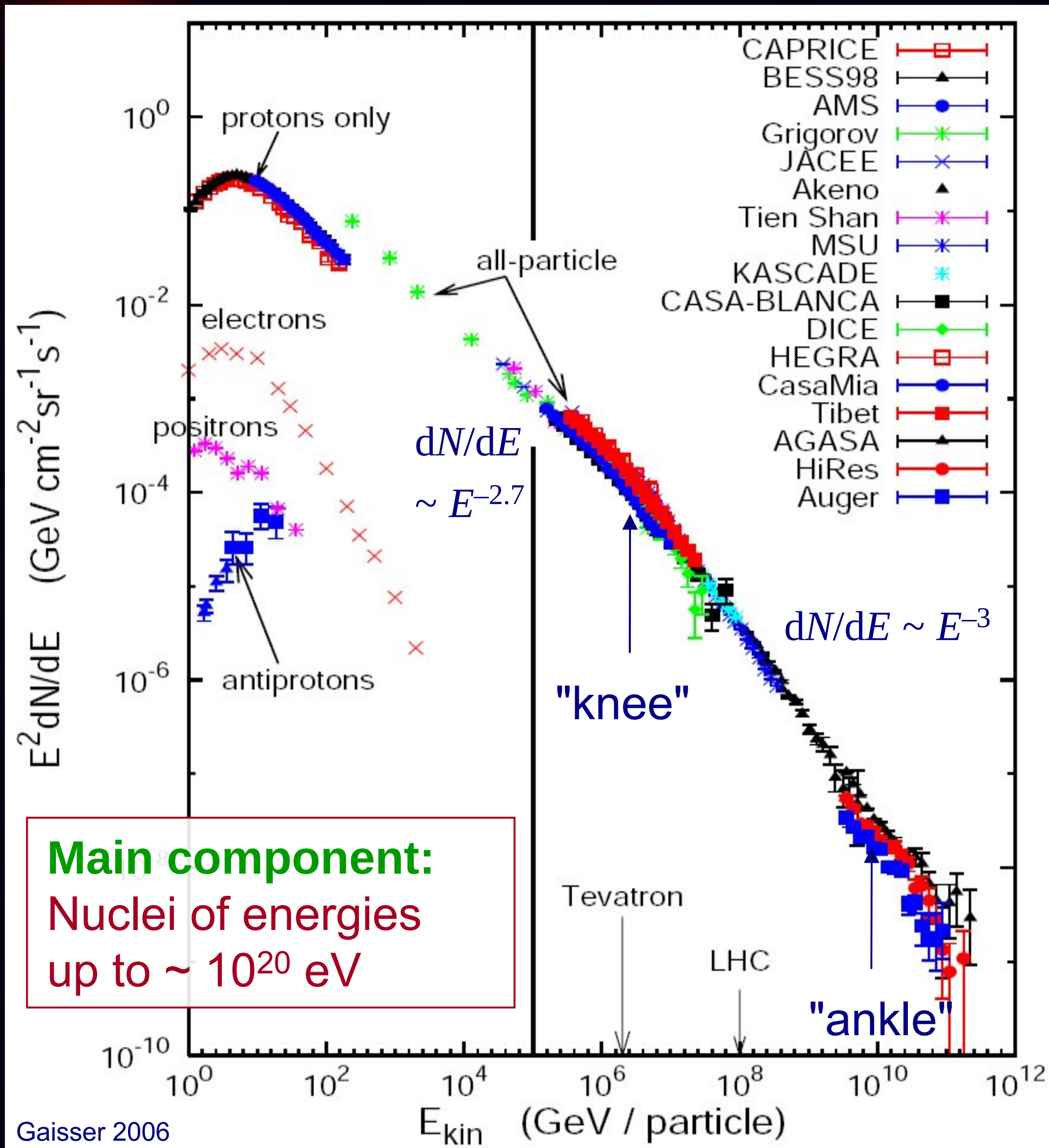
Markus Ackermann
IceCube collaboration

Markus.Ackermann@desy.de
DESY

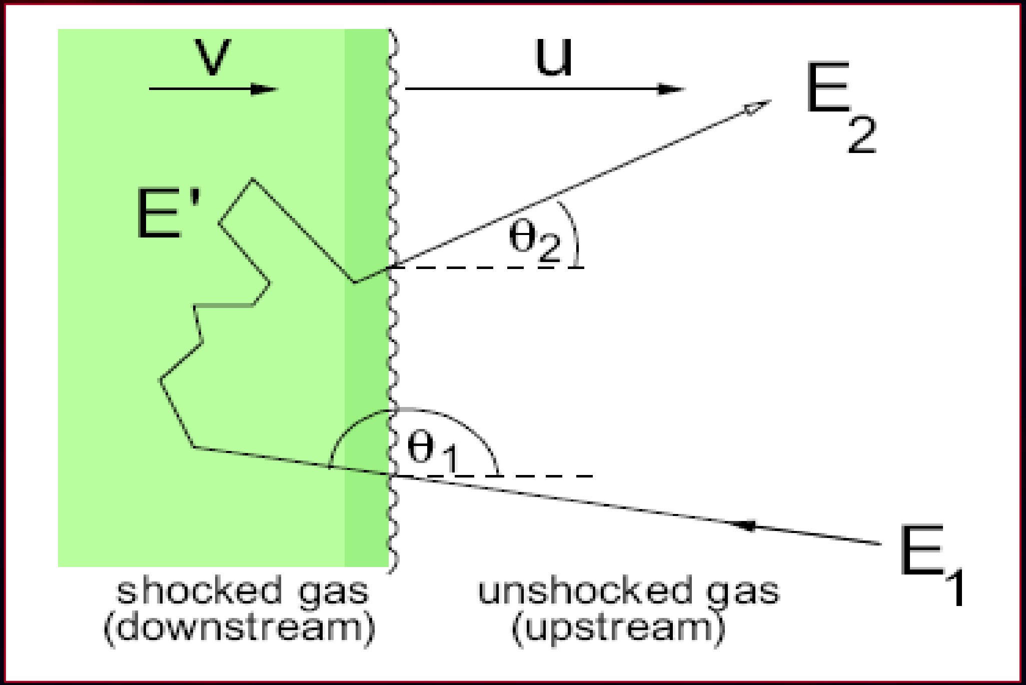
http://icecube.wisc.edu

I Motivation

Cosmic rays

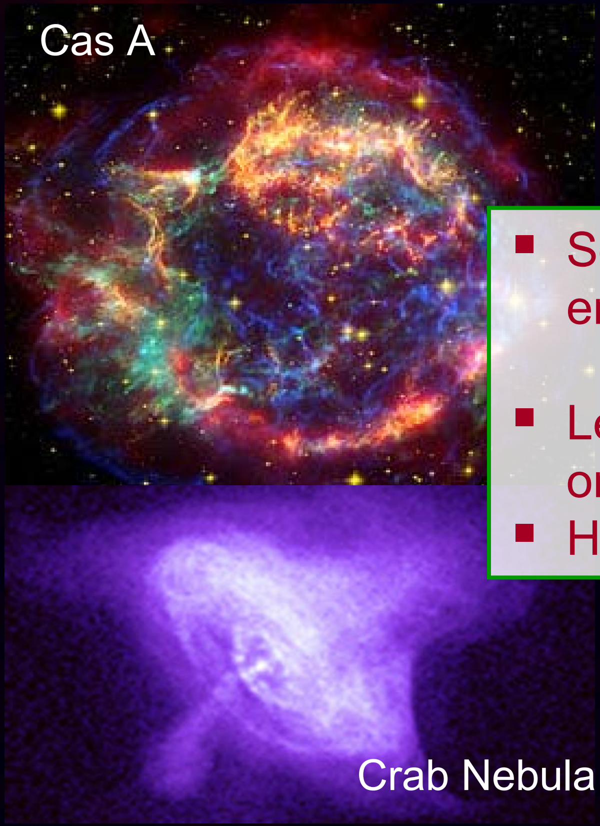


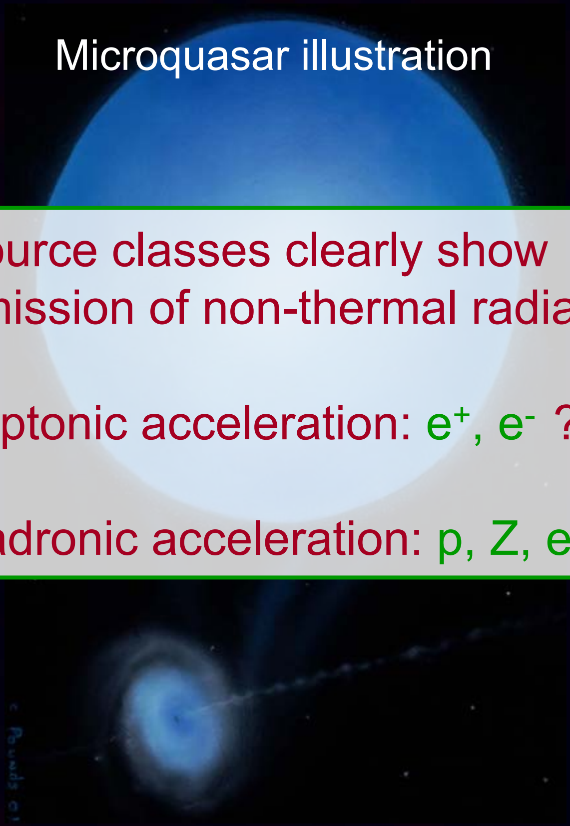
- Discovered 1912
- Spectrum and (low energy) composition well known.
- The origin of the high-energy cosmic rays is still unresolved.
- „Bottom-up“ and „top-down“ scenarios for production.



- Acceleration in relativistic shocks (first order Fermi acceleration)
- Energy gain: $\Delta E = E_2 - E_1 \sim \beta$
- Expected energy spectrum: $\Phi \sim E^{-2 \ldots -2.3}$
- Compatible with cosmic ray spectrum: $\Phi \sim E^{-2.7}$
  (if propagation losses are taken into account)

Potential sources of high-energy cosmic rays

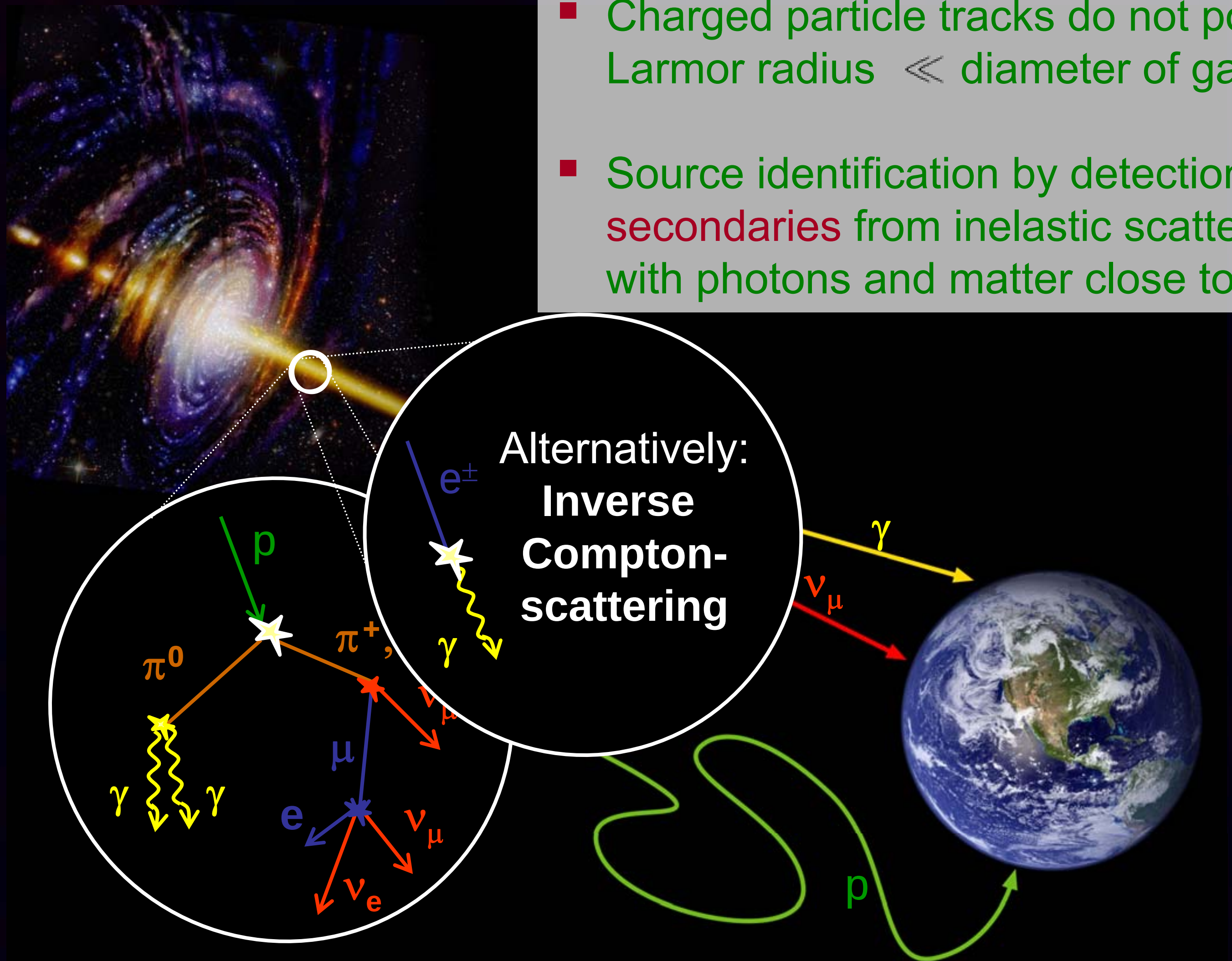




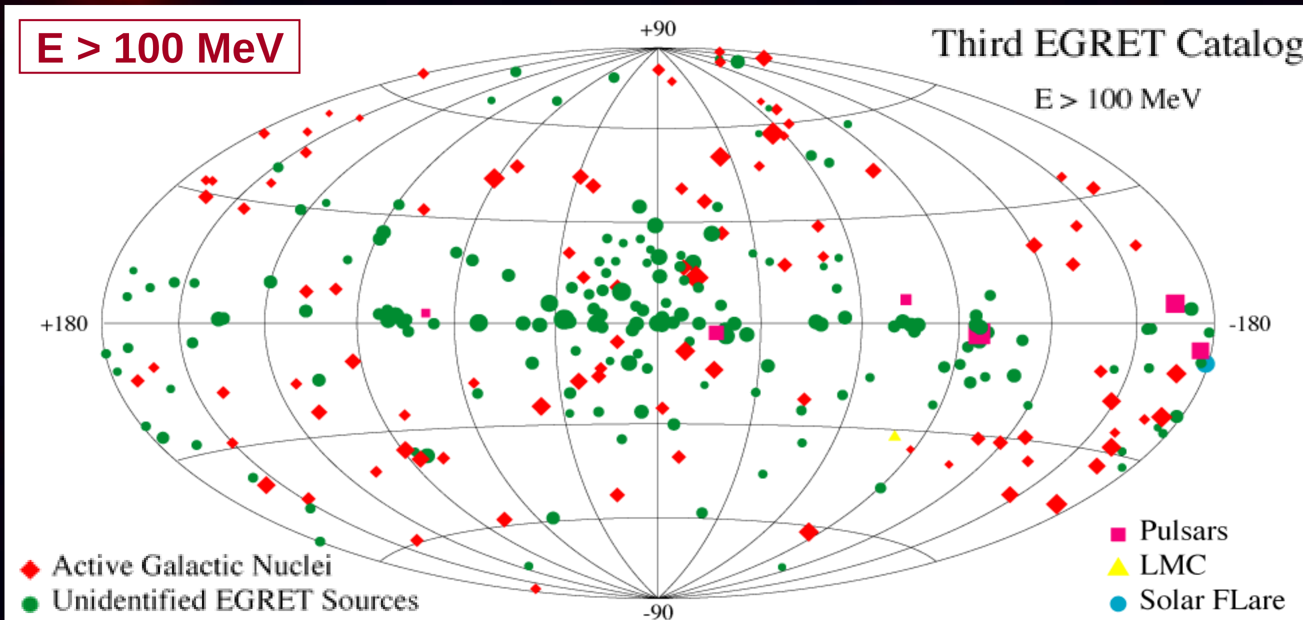
- Source classes clearly show emission of non-thermal radiation
- Leptonic acceleration: e^+, e^- ?
  or
- Hadronic acceleration: p, Z, e^- ?

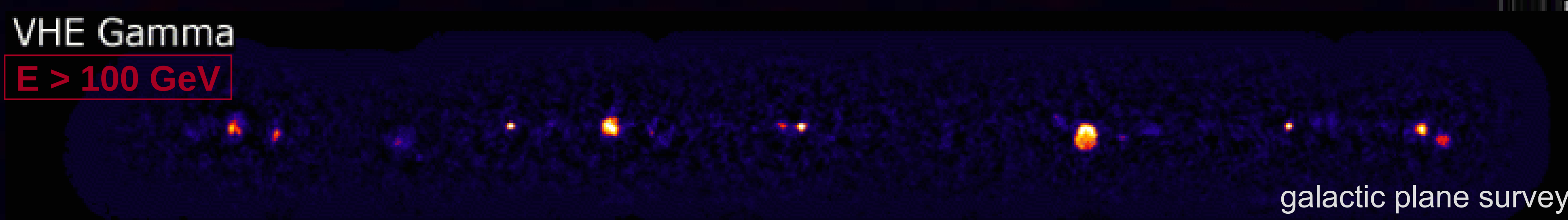
Supernova remnants Pulsar wind nebulae	X-ray binaries	Active galactic nuclei (AGN)
galactic		extra-galactic

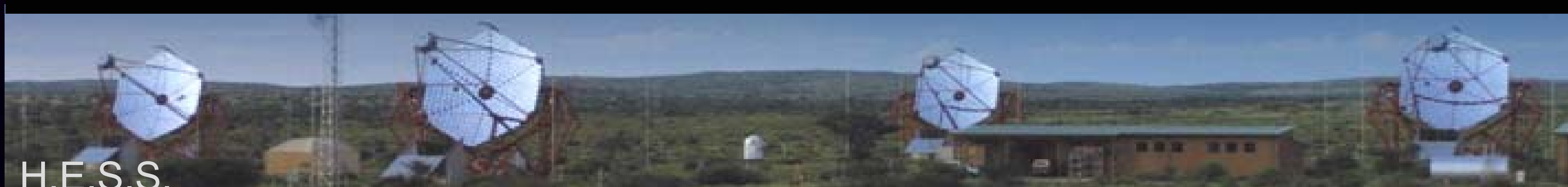
- Charged particle tracks do not point to their source: Larmor radius $\ll$ diameter of galaxy
- Source identification by detection of uncharged secondaries from inelastic scattering of cosmic rays with photons and matter close to their source



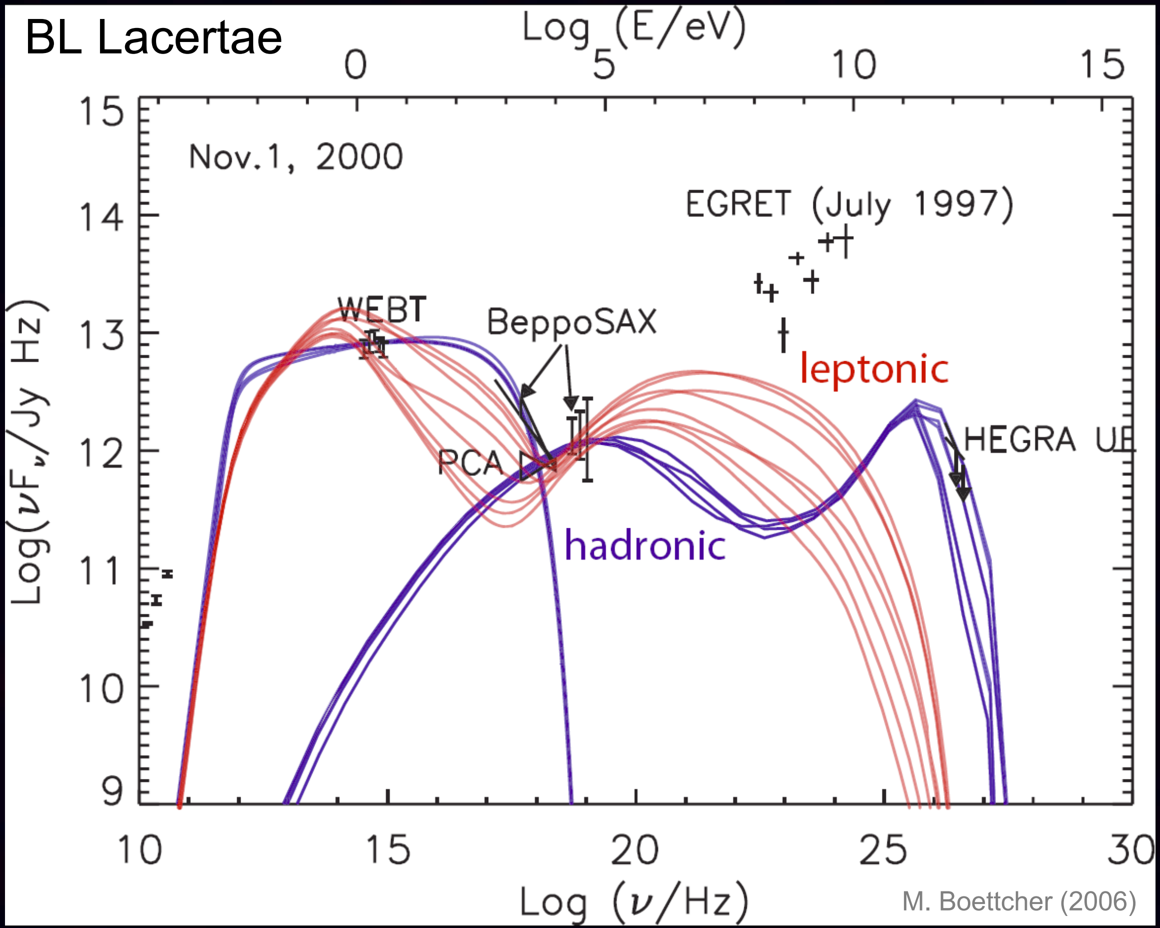
Observations of high energy gamma ray sources







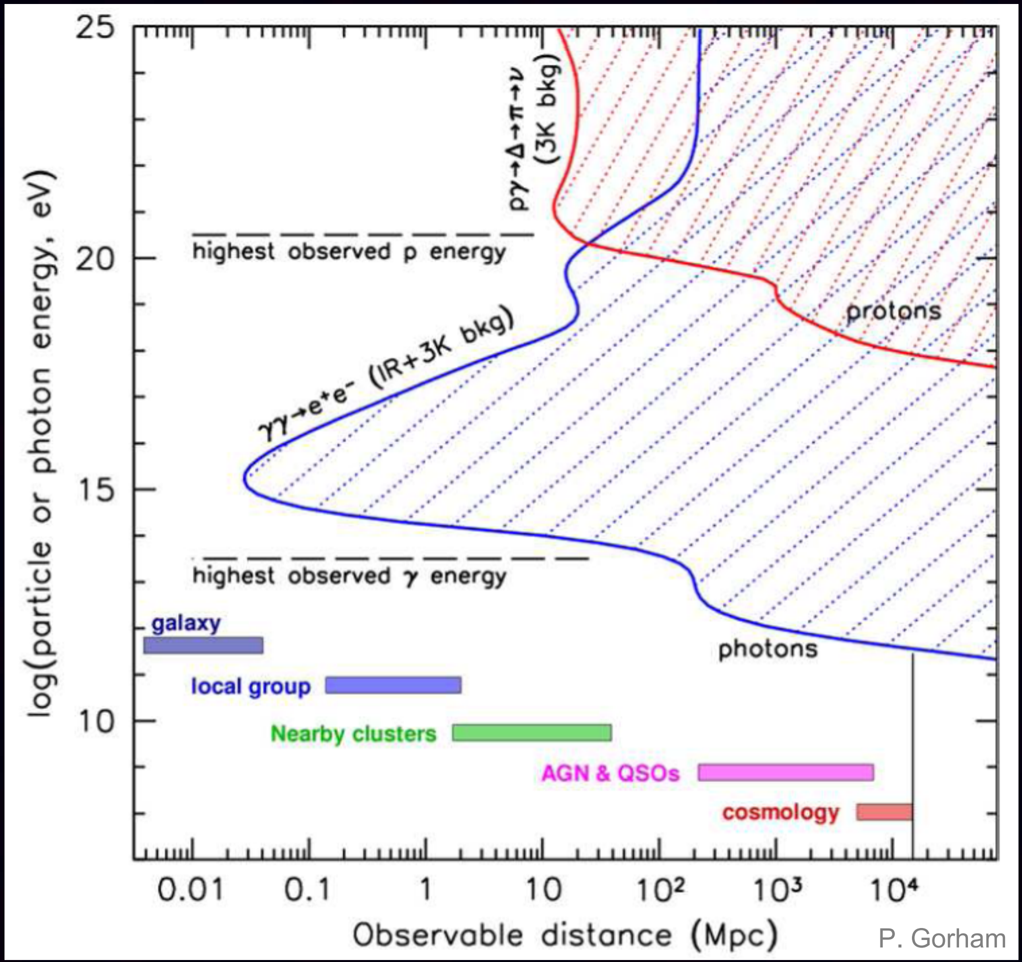
Gamma-ray vs. neutrino signal



γ Multi-wavelength observation + spectral modelling necessary to distinguish hadronic & leptonic acceleration processes.

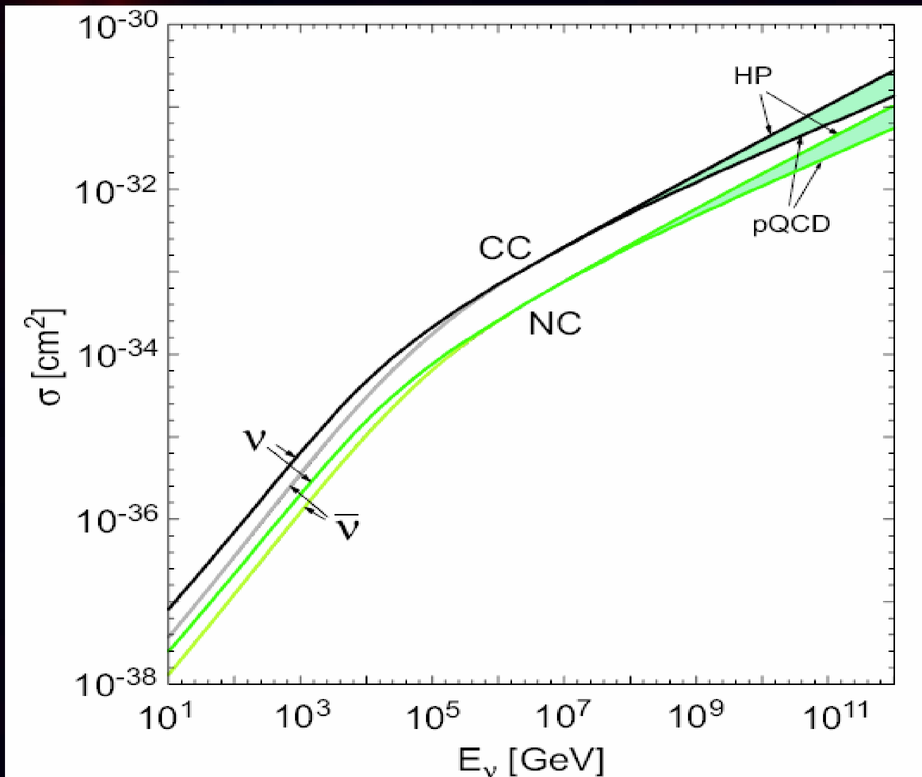
ν Signal unambiguous indicator for hadronic acceleration.

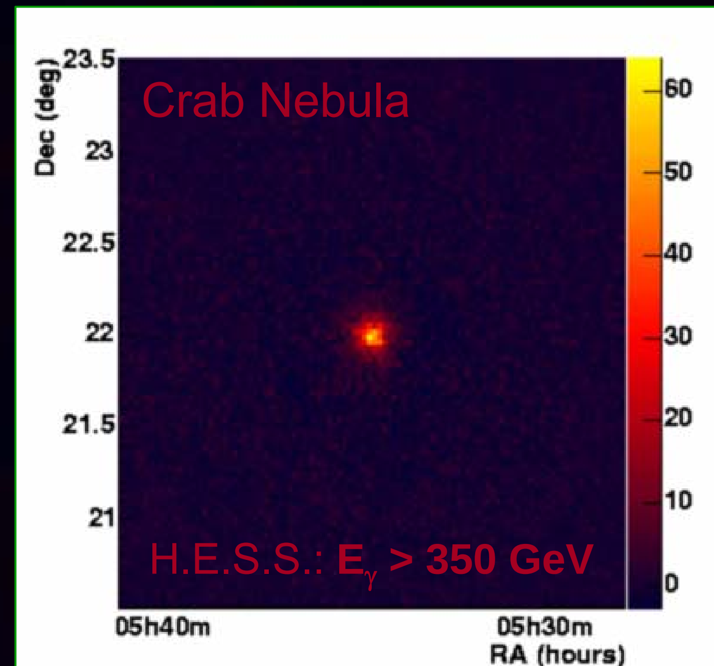
Gamma-ray vs. neutrino detection



γ Universe partly opaque for gamma-rays. Opaqueness increasing with energy.

ν Universe is transparent for neutrinos up to the highest energies.





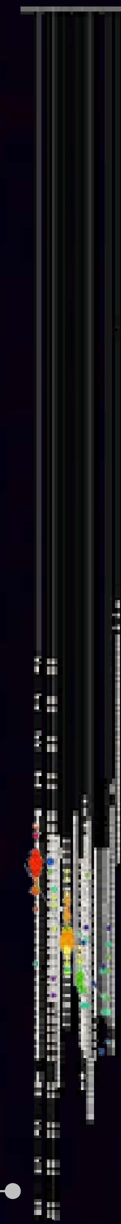
ν Small cross section of neutrino-nucleon scattering demands for detectors with huge target volume

O(10) ν_μ / year (E_ν > 1TeV) expected in a km^3-sized neutrino detector.
(If γ-rays from π_0-decay)

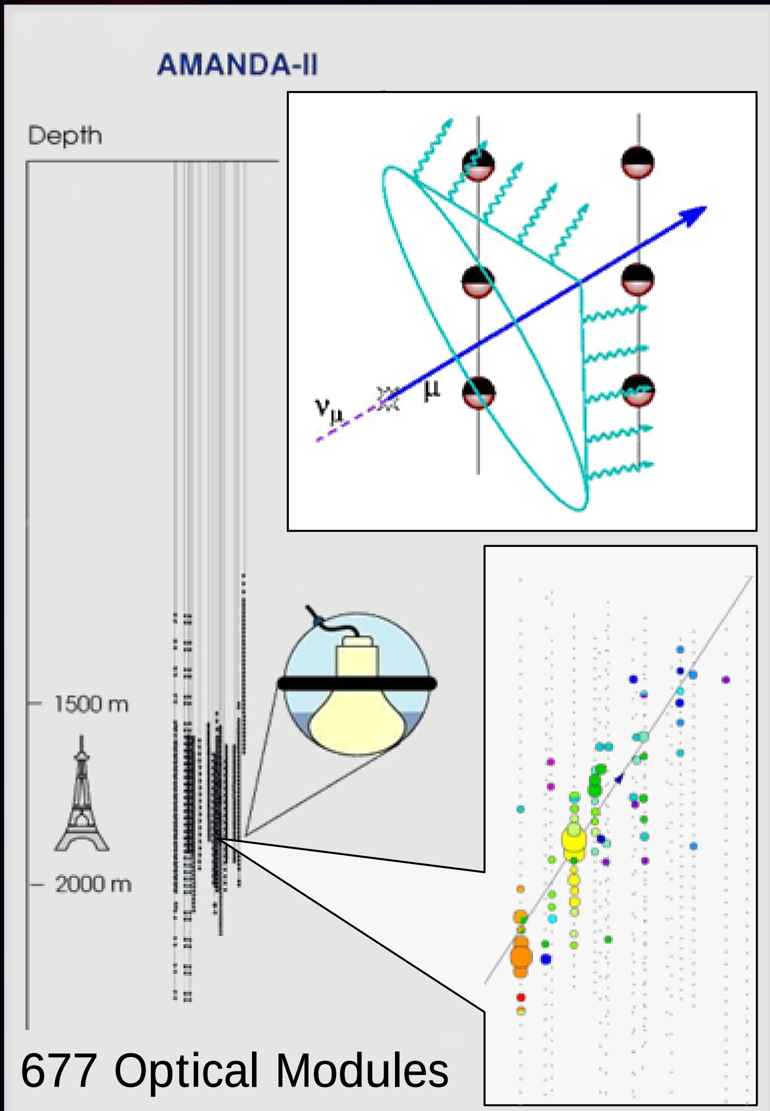
Guetta and Amato, astro-ph/0209537

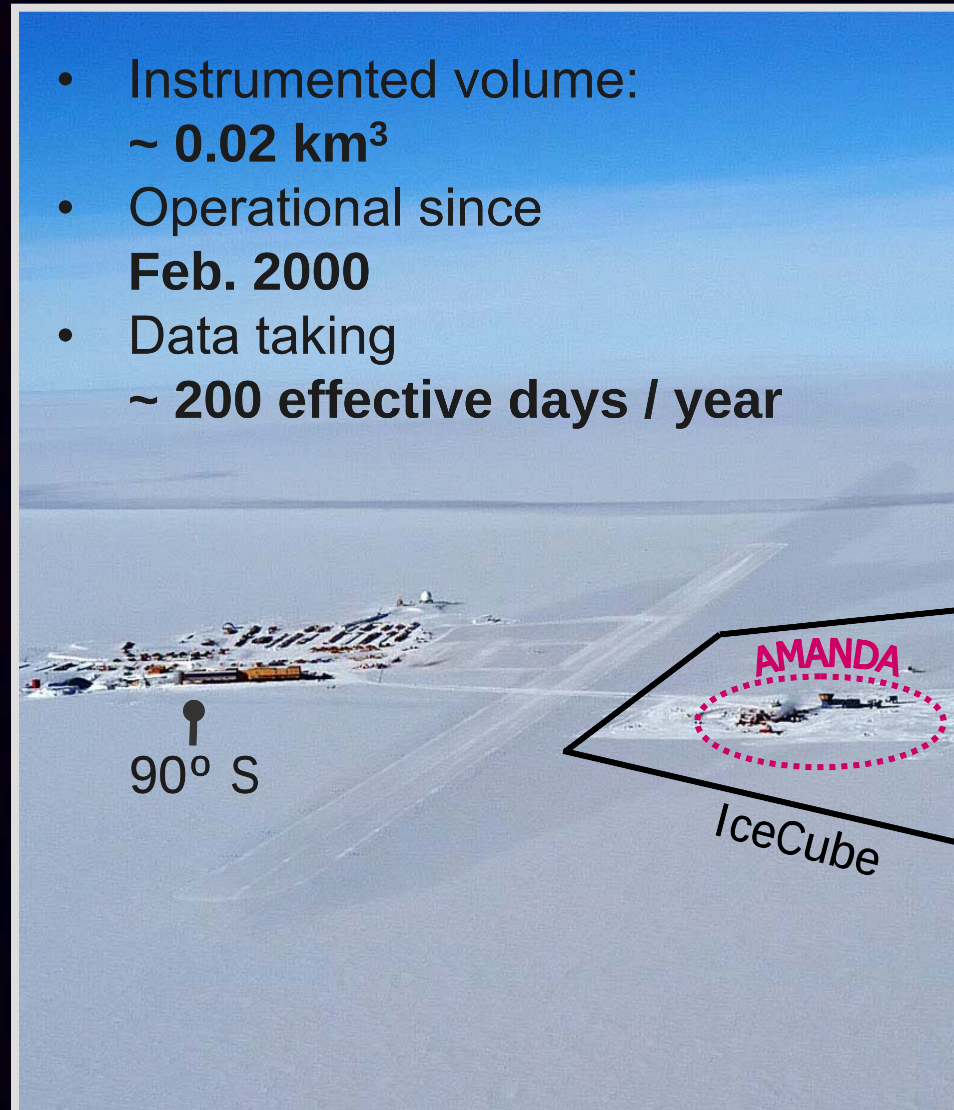
Kappes et al., astro-ph/0607286

II The AMANDA-II Neutrino detector

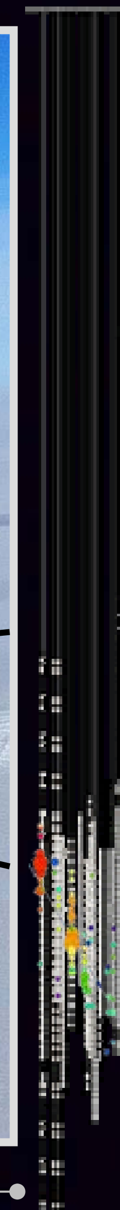


The AMANDA-II neutrino detector

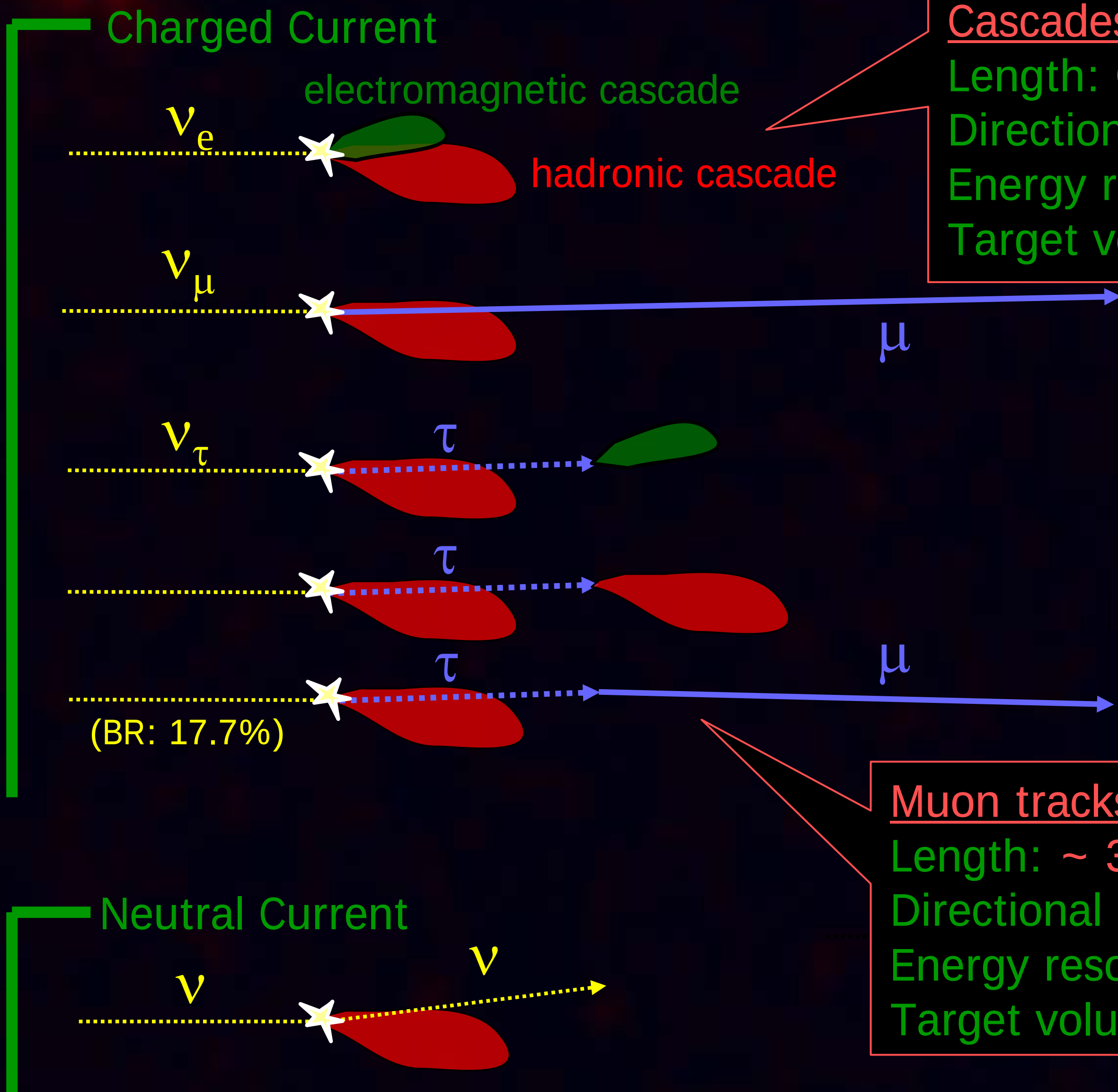




- Instrumented volume: **~ 0.02 km³**
- Operational since **Feb. 2000**
- Data taking **~ 200 effective days / year**



Signatures of neutrino interactions in ice

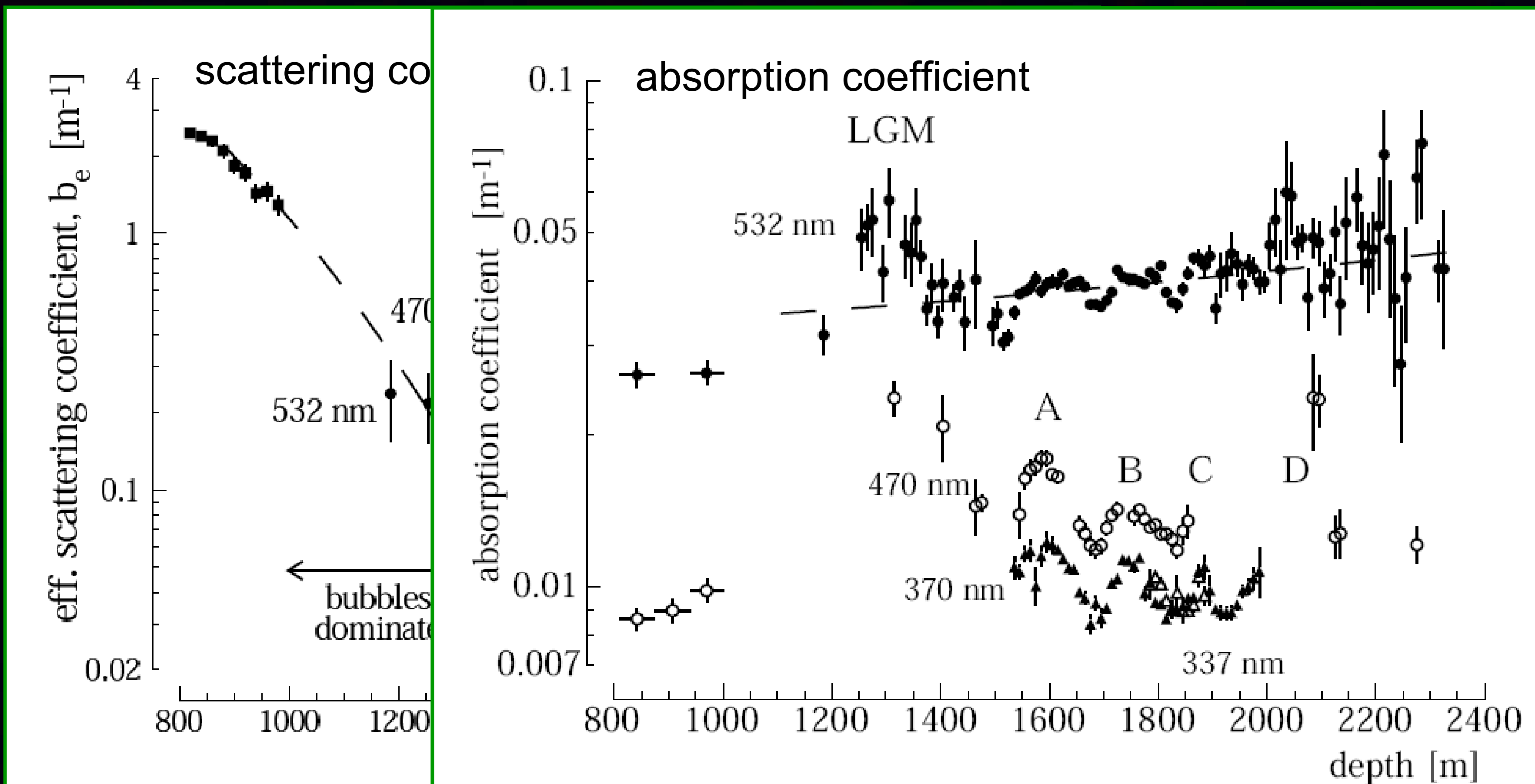


Cascades:
Length: O(10m) → „point-like“
Directional resolution: ± 30°
Energy resolution: ± 0.1 (log E)
Target volume: low

Muon tracks:
Length: ~ 3km @ 1TeV
Directional resolution: ± 2°
Energy resolution: ± 0.4 (log E)
Target volume: high

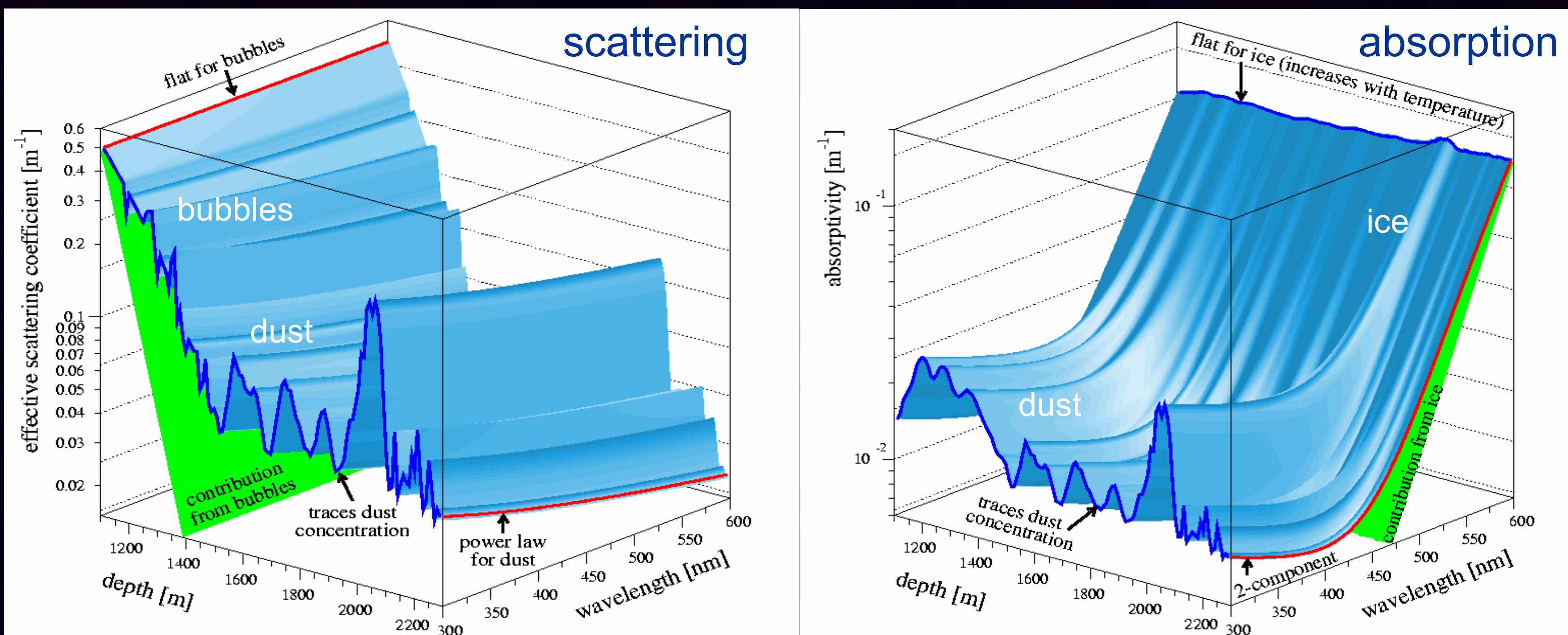
The South Pole challenge

- Use of a natural target material
- Optical properties of glacial ice are very inhomogeneous
- Require extensive measurements, modelling and simulation



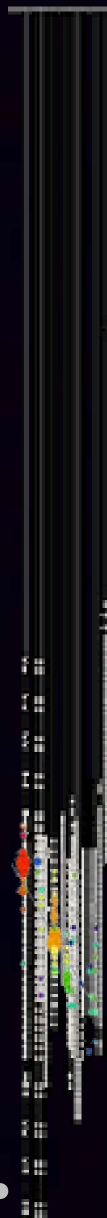
The South Pole challenge

- 2-dimensional ice model was developed for simulation
- Just recently implemented in the simulation chain (due to CPU constraints)

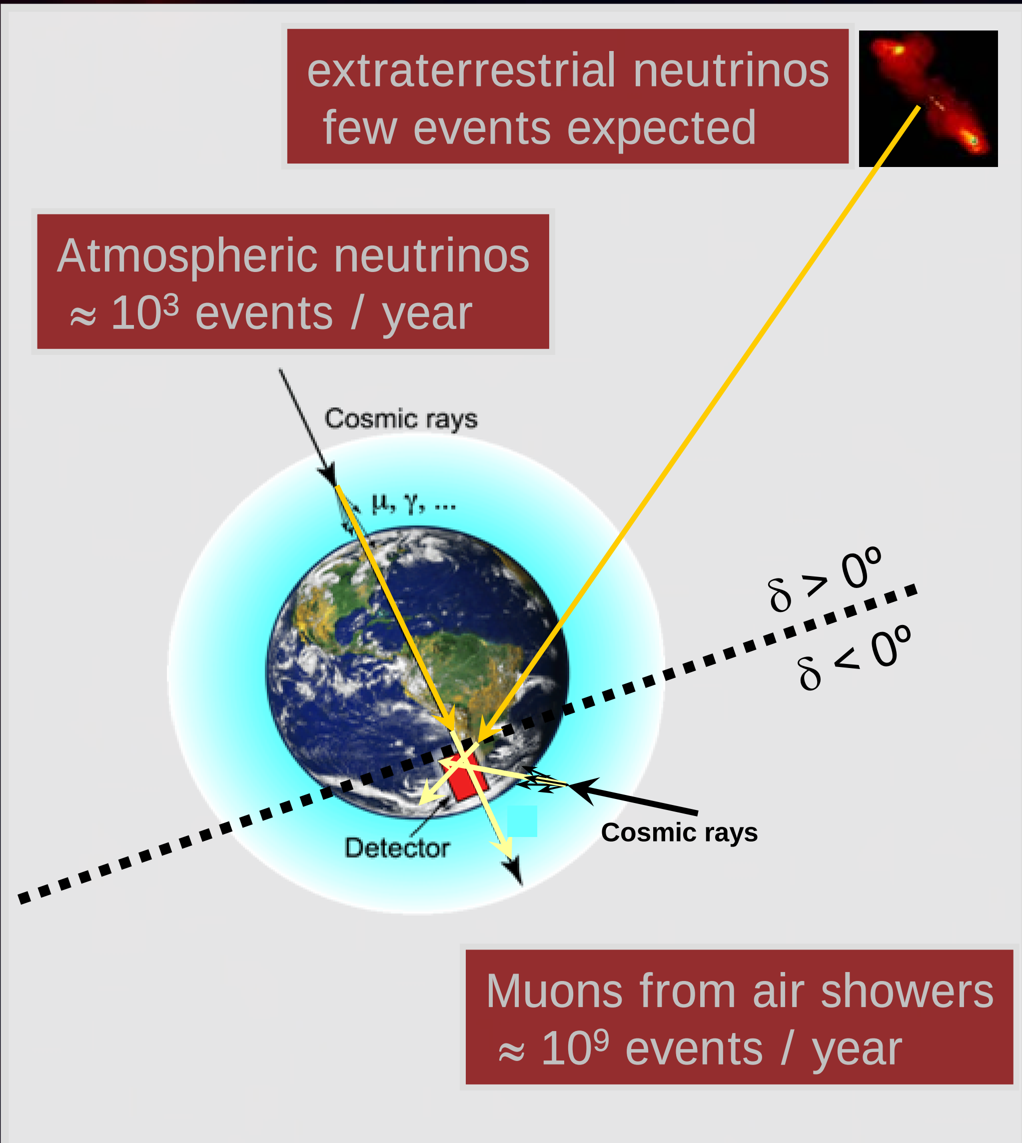


AMANDA-II physics program

- Search for point sources of astrophysical neutrinos
  - Time integrated searches
  - Searches for time variable sources
  - Gamma-Ray Bursts
- Search for a diffuse cosmic neutrino flux
  - Muon neutrinos
  - Cascades (all neutrino flavors)
  - Ultra high energy analysis
  - Galactic plane
- Search for neutrinos from WIMP annihilation
- other topics: Atmospheric muons & neutrinos, cosmic ray composition, gamma-ray astronomy with muons, supernova searches, exotic particles



Neutrino event selection (point source search)

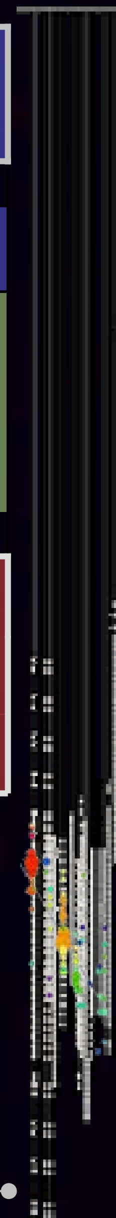


2000-2004 data set	1001 effective days

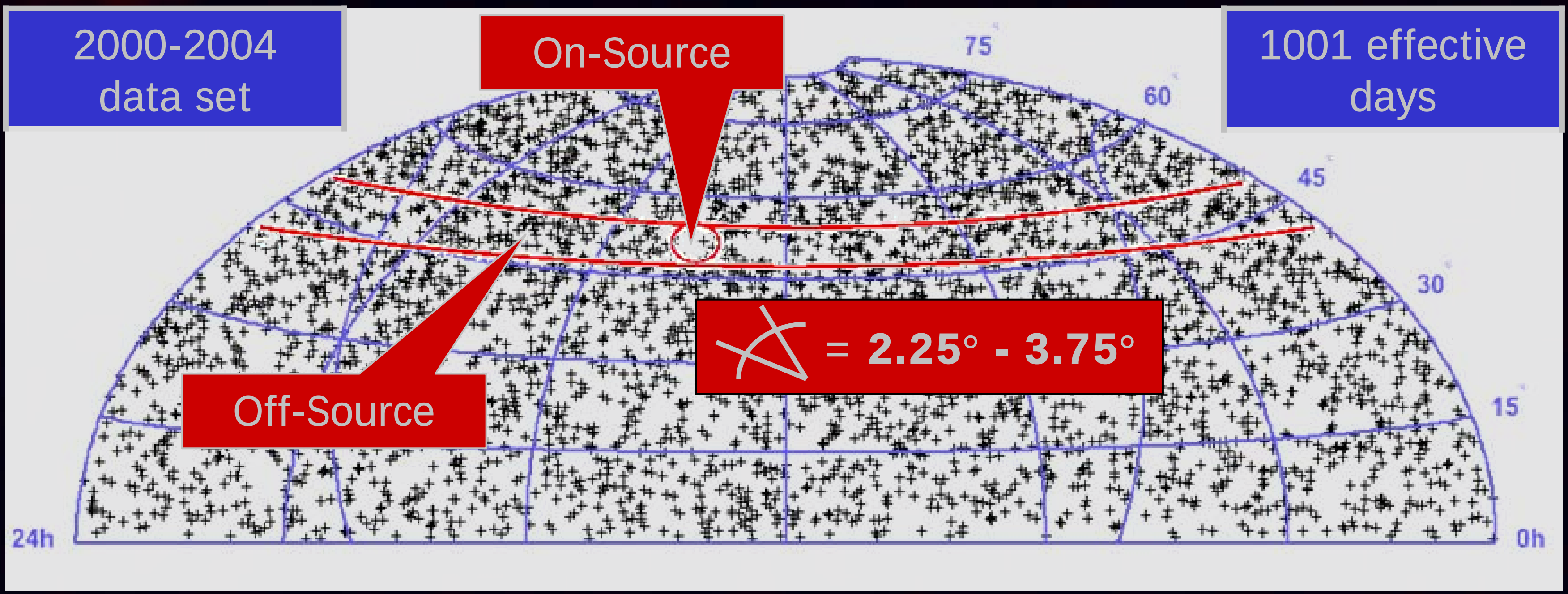
Event selection	R_{evt}	$R_{atm-\nu}$
Triggered events	100%	100%
Directional cuts	0.11 %	87%
Topological cuts	5 10^{-5} %	35%

	N_{evt}
Final neutrino sample	**4282**
Atm-ν simulation	**3627 - 4912**

- „Blind“ event selection to avoid statistical biases
- Selection optimized for hard and soft spectra



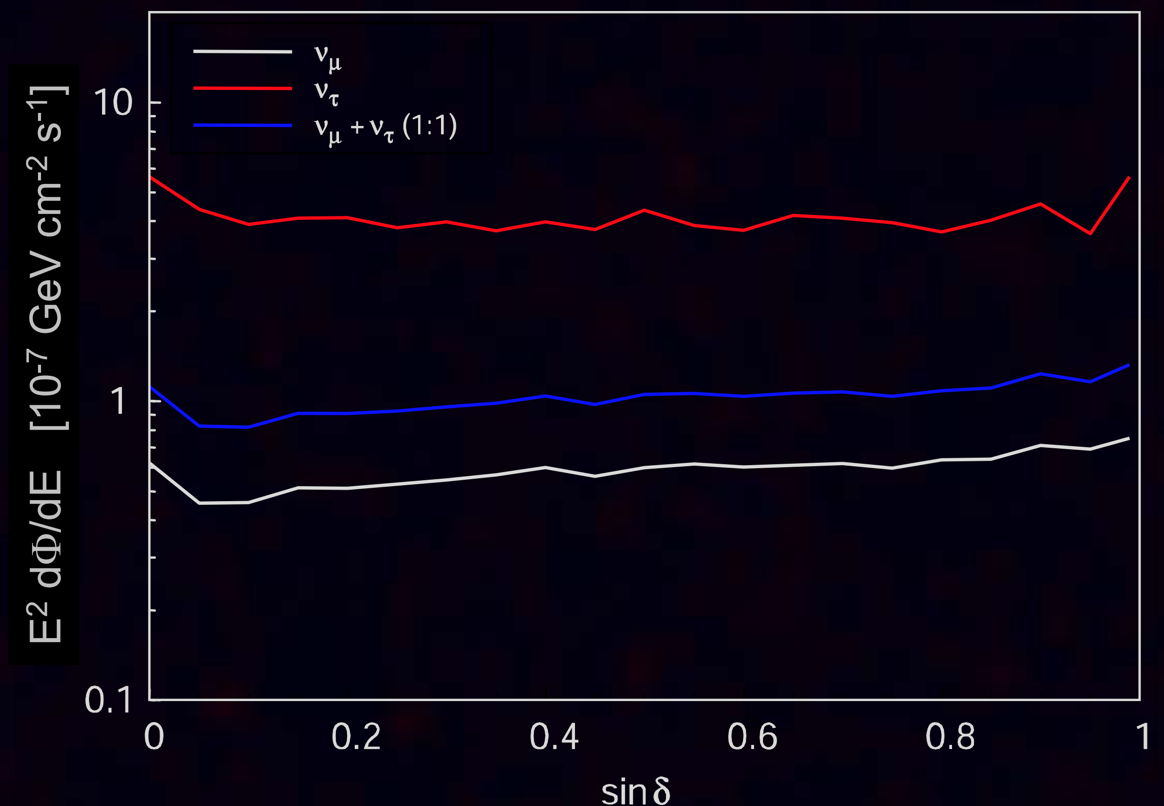
Search for point sources



- Search for signal from candidate sources
- Scan of full northern sky
- Dedicated searches for variable sources
- Flux upper limits set if no signal is seen

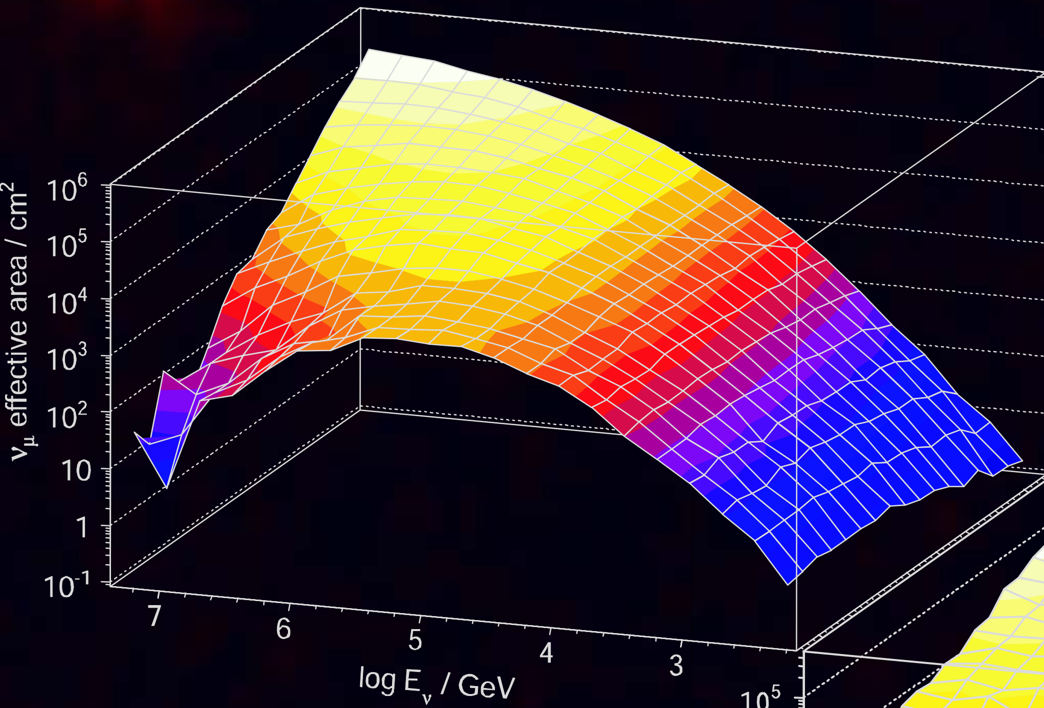
Sensitivity

- Sensitivity (limit setting capability) to neutrino flux $d\Phi/dE \sim E^{-2}$
- Contribution of ν_τ to sensitivity 10-16% (declination dependent)
- $\nu_\mu + \nu_\tau$ is the strongest limit on the neutrino flux for a $\nu_\mu:\nu_\tau$ = 1:1 flavor ratio

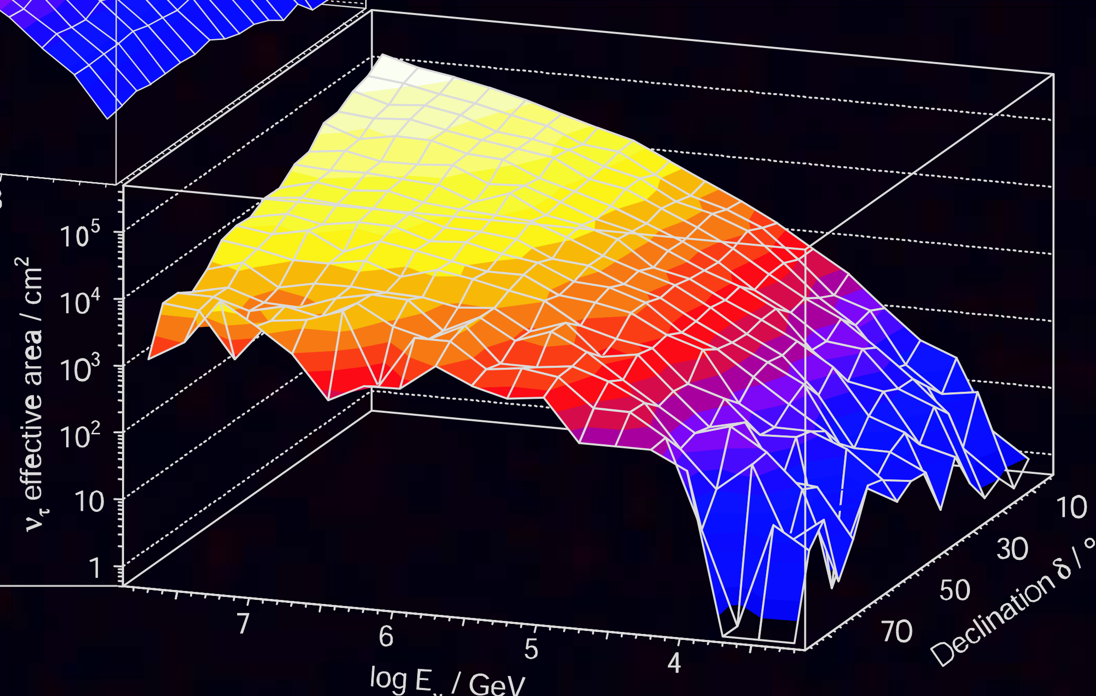


Neutrino effective areas

muon neutrinos

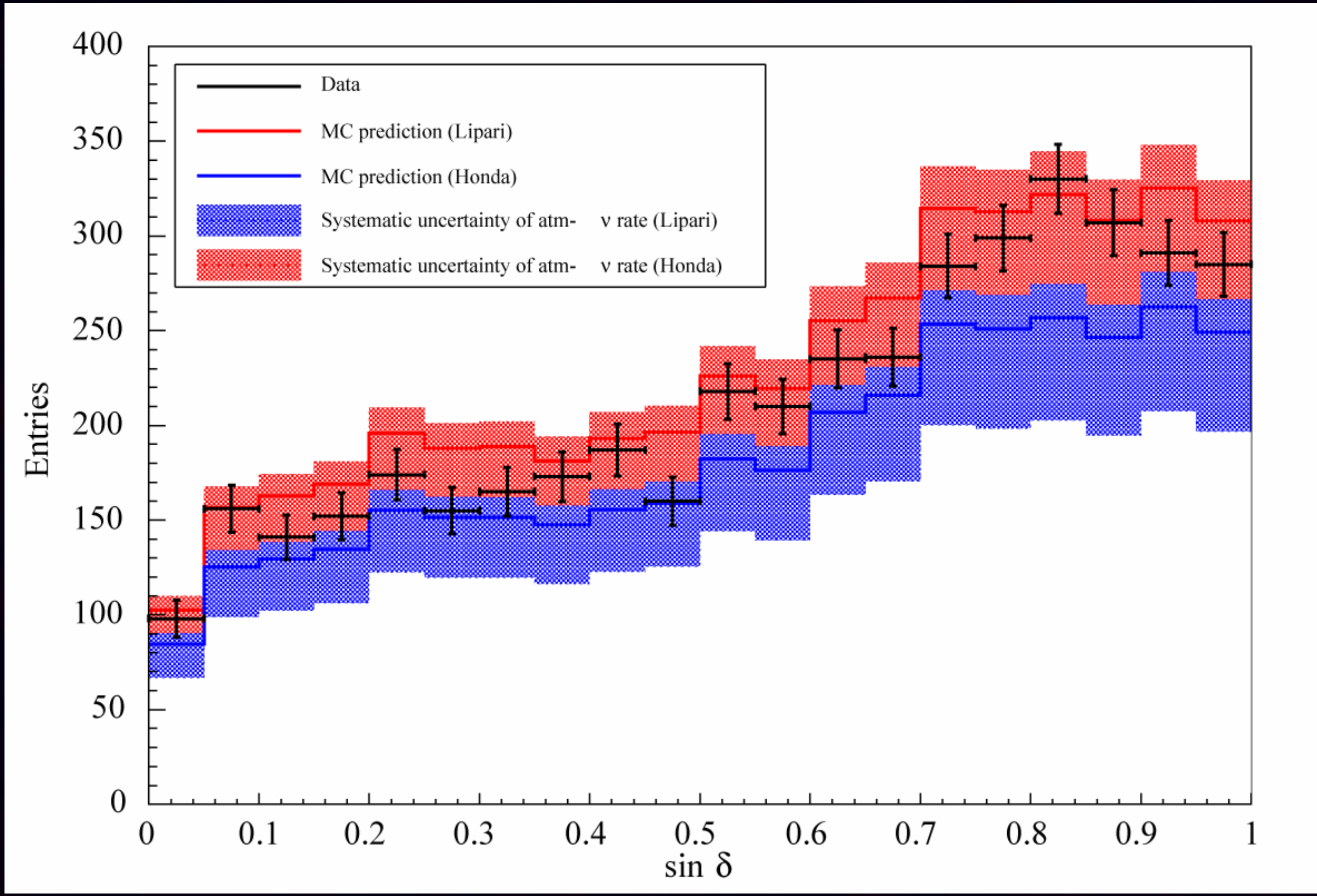


tau neutrinos via
$\nu_\tau \rightarrow \tau \rightarrow \mu + \nu_\tau + \overline{\nu_\mu}$
(17.7 %)



Final neutrino sample

- Zenith distribution of events in the point source sample
- Predictions from atmospheric neutrino simulation is shown with its (experimental) systematic error interval



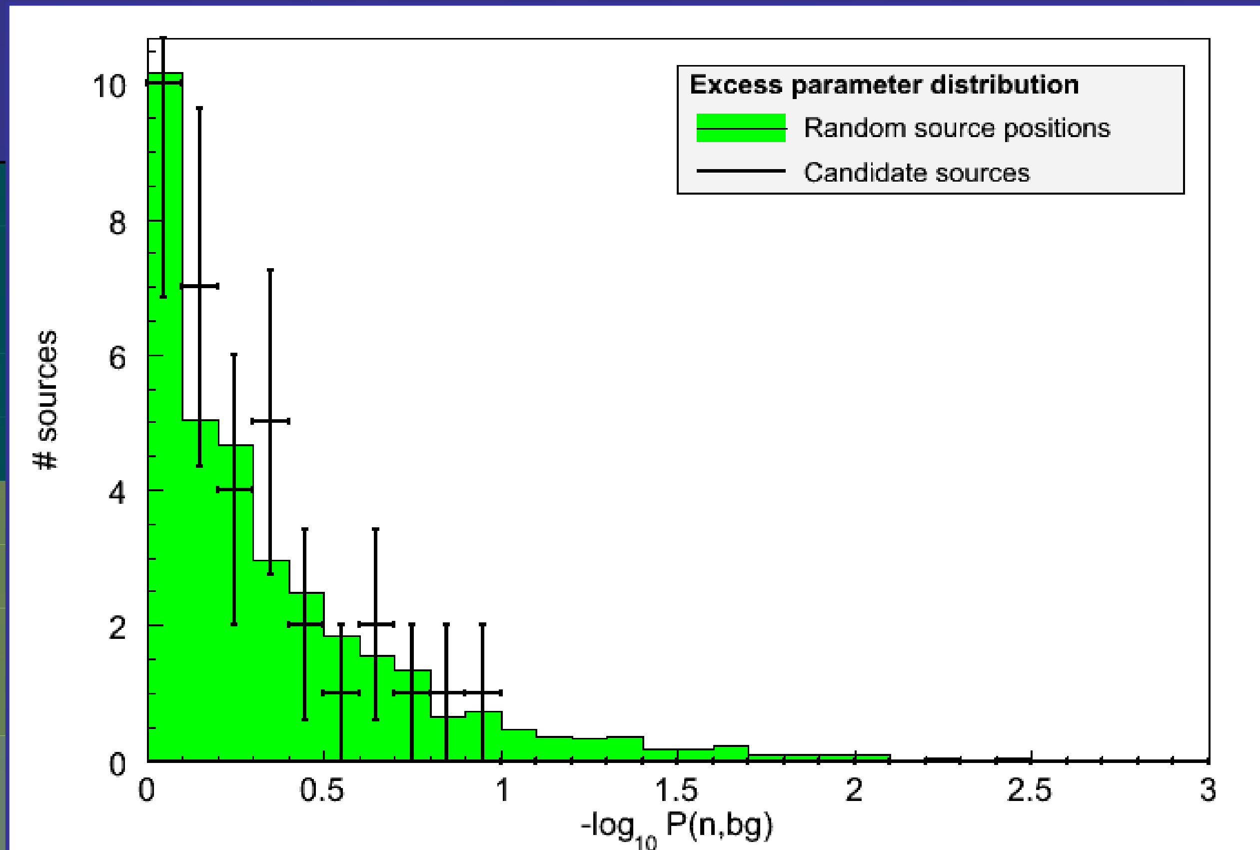
Systematic uncertainties

- Main contributions the systematic error are (point source analysis)
  - average OM efficiency (~ 10%)
  - rock density (up to 7%)
  - detector simulation inaccuracies (~ 7 %)
- Total systematic uncertainty on the signal efficiency
  - E^{-2} spectrum: +10 / -15 %
  - E^{-3} spectrum: +5 / -20 %
  - atmos. spectrum: +5 / -25 %
- Included in the limit calculation

III Results from the point source search

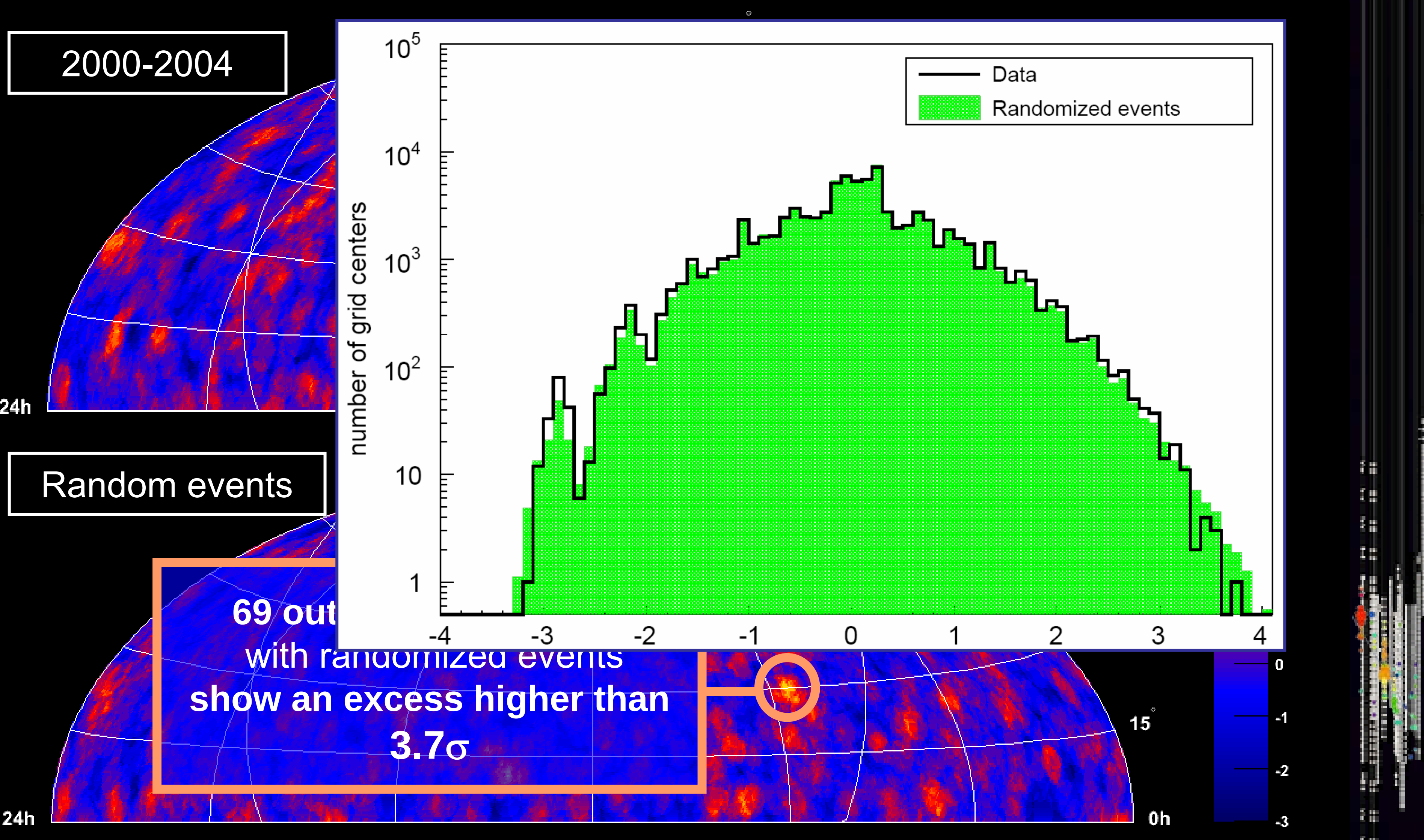
Results I: Candidate sources

	Source	Events observed/	Excess	Flux upper limit (15% sys, 7% stat)
AGN	Markarian 421			
	Markarian 501			
	1ES1959+650			
	M87			
	3C273			
Microquasar	SS433			
	LSI +61 303			
	Cygnus X-1			
	Cygnus X-3			
SNR	Cassiopeia A			
	Crab Nebula			

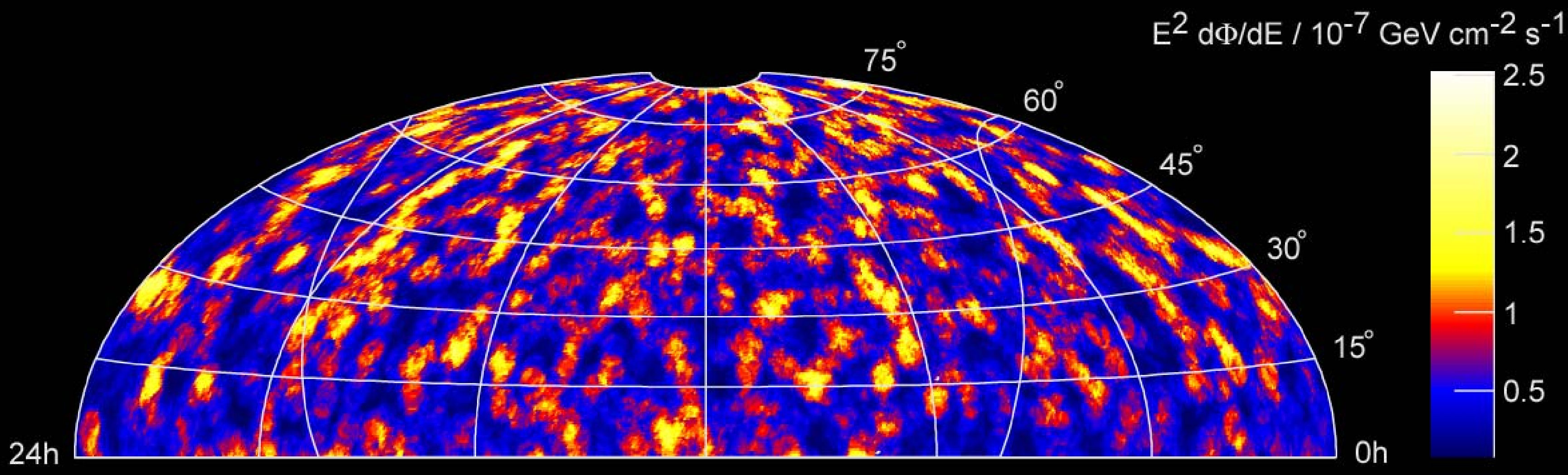


- 32 sources in candidate list
- No significant excess, no indication for a neutrino source
- Systematic error of 15% on signal prediction included in limits

Results II: Grid search



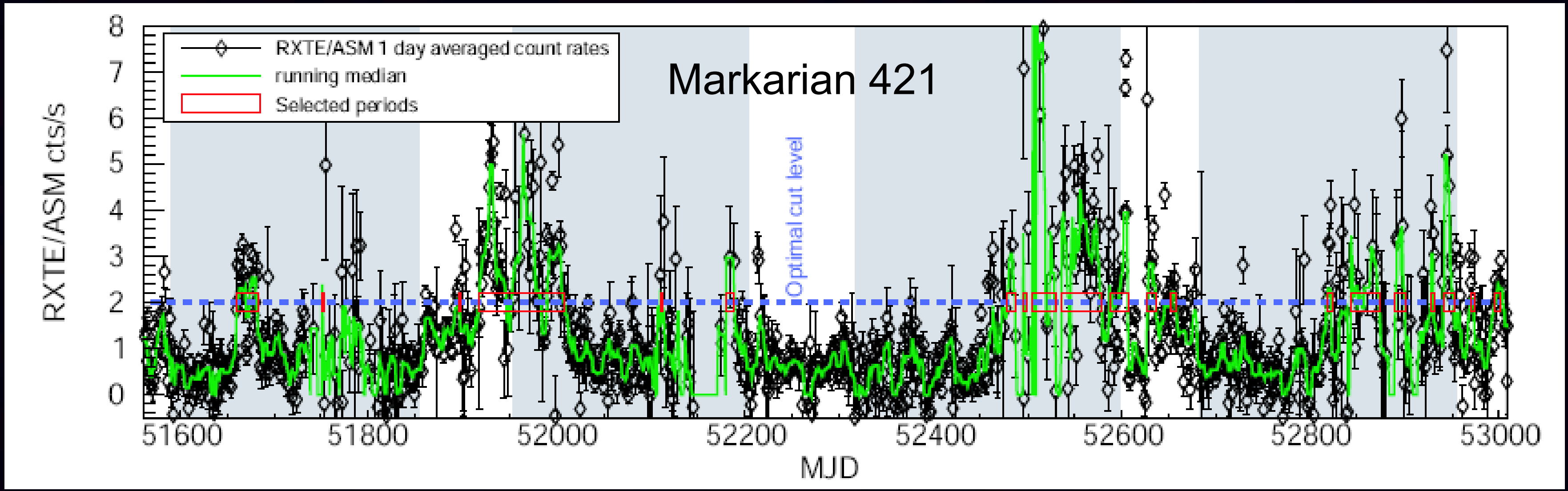
Limit map



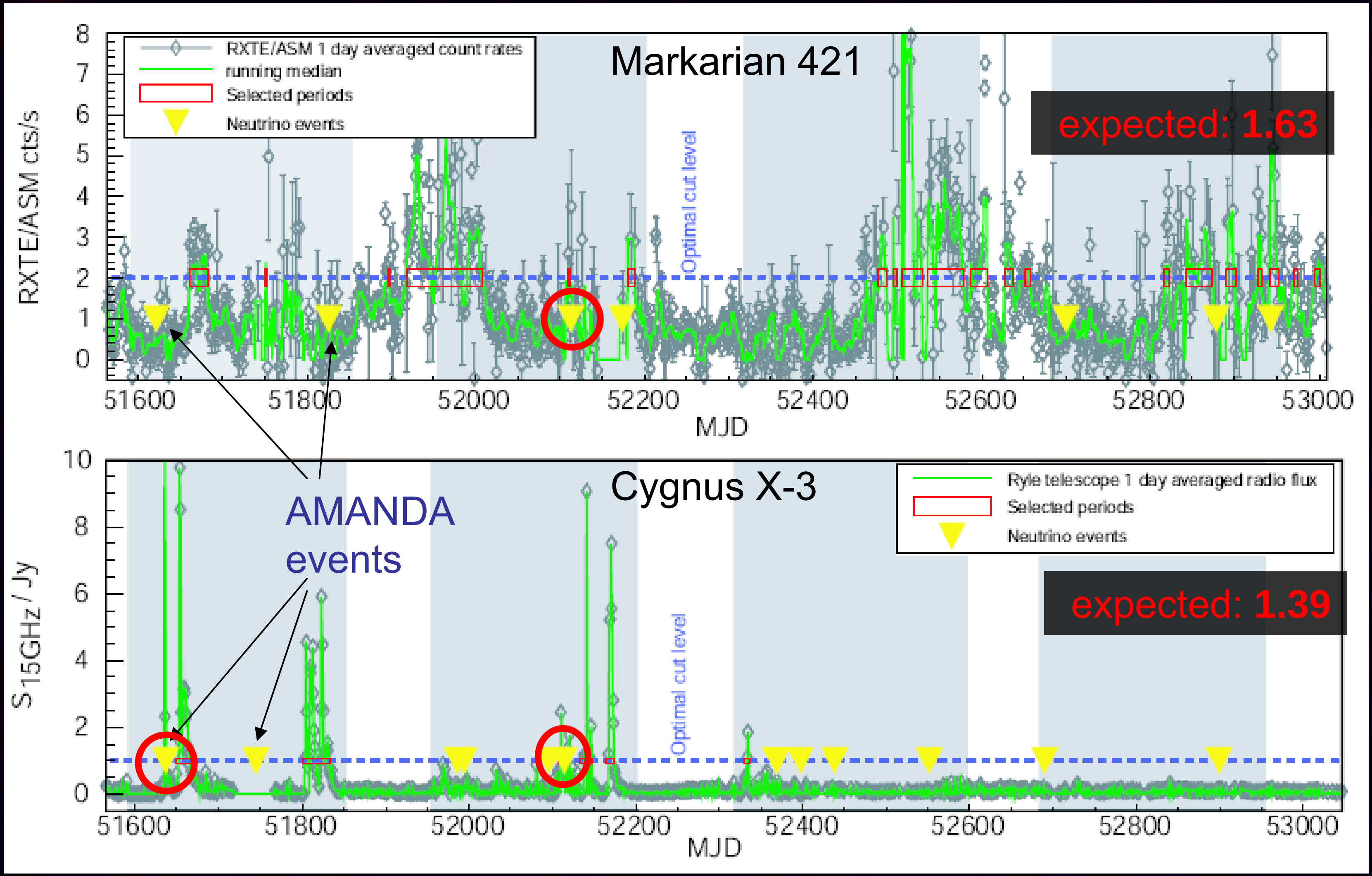
- 90% confidence level flux upper limits for the northern hemisphere in 0.5 deg bins (15% systematic error included)

Search for neutrinos in active phases of variable sources

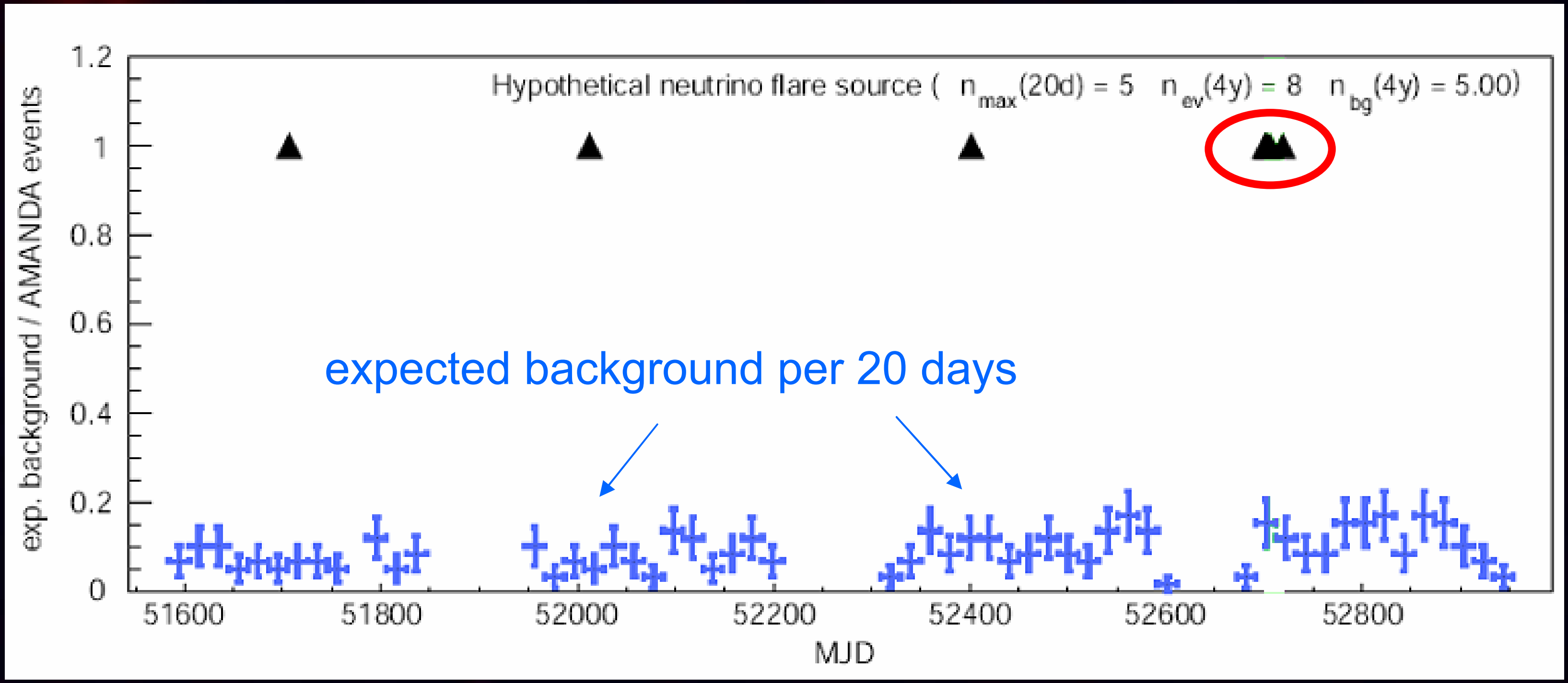
- Time-integrated search not optimal if neutrino emission of a source is variable.
- Hypothesis: electromagnetic and neutrino emission are correlated (naturally expected for neutrino / high-energy gamma-ray emission).
- Selection of time periods of high electromagnetic source activity to improve signal-to-noise ratio.
- Continuous monitoring of source activity necessary → X-ray / radio data used for period selection.
- 3 Sources investigated: Markarian 421, 1ES1959+650 and Cygnus X-3



Search in predefined time windows

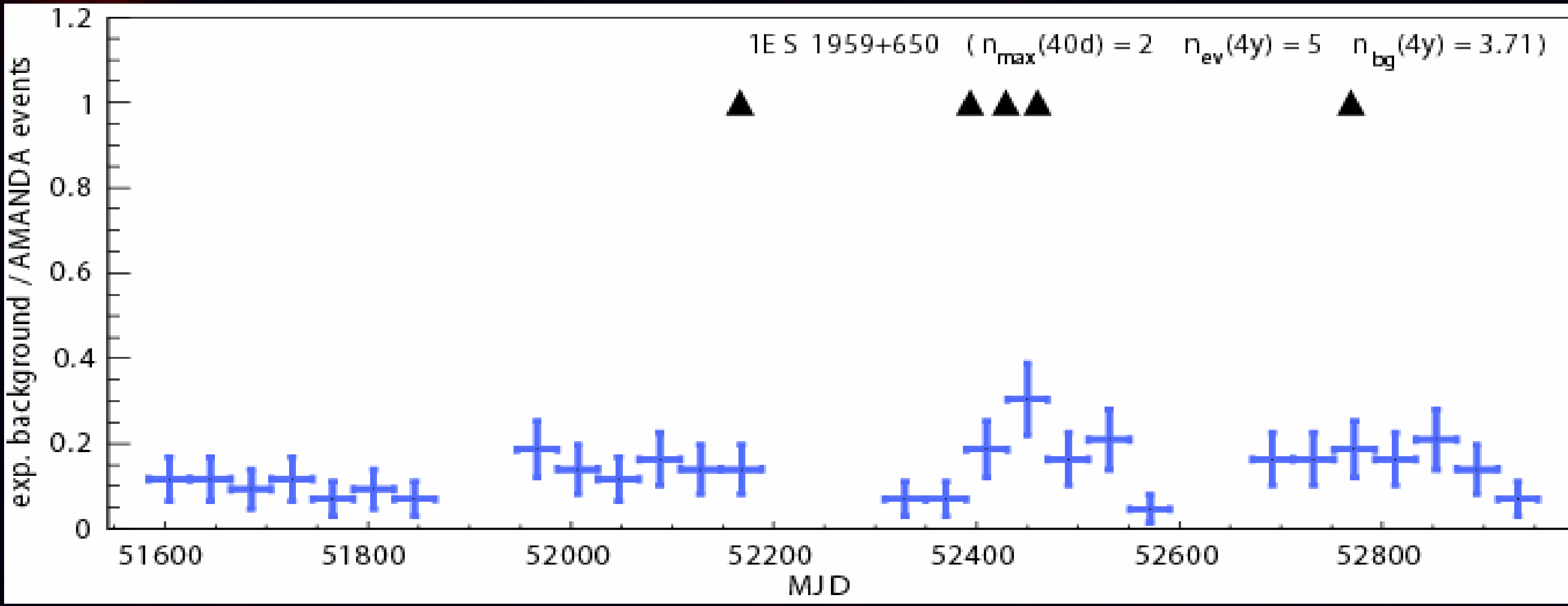


Search for neutrino flares



- Search for excess of events in short time window.
- 12 potentially variable sources investigated.
- Search with sliding time window of 20 days (galactic sources) / 40 days (extra-galactic sources) duration.
- No significant excess of events found.

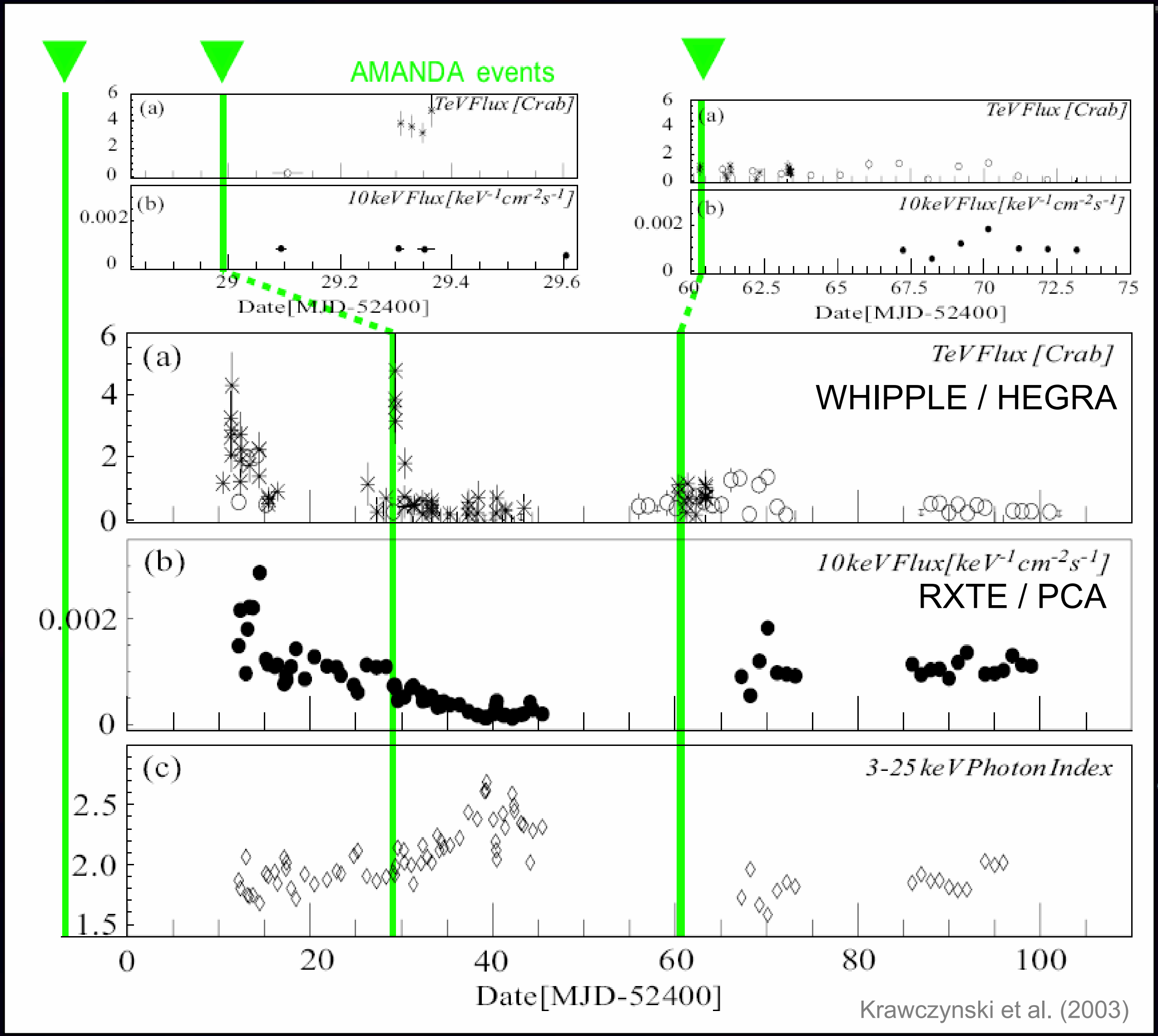
Neutrinos from the direction of 1ES 1959+650



- 3 neutrinos in 66 days.
- In overlap with the only observed period of strong gamma-ray flares of this source.
- Only affirmed observation of an "orphan flare" (gamma-ray and x-ray intensity not correlated)

Neutrinos from the direction of 1ES 1959+650

- Event at MJD 52429.0 at the day of the „orphan flare"
- Event at MJD 52460.3 in coincidence with smaller flare
- „A posteriori" observation. Assignment of a significance not possible.



Target of opportunity test run with MAGIC IACT (Sep - Dec 2006)

- Trigger γ-ray observations by neutrinos
- Neutrino events selected by AMANDA on-line filtering ($\Delta t \approx 1h$)
- Alert sent to MAGIC if neutrinos are from the directions of predefined source candidates
- MAGIC observation, if source visible within 24 hours after the neutrino arrival
- 5 alerts sent, 1 MAGIC observation.

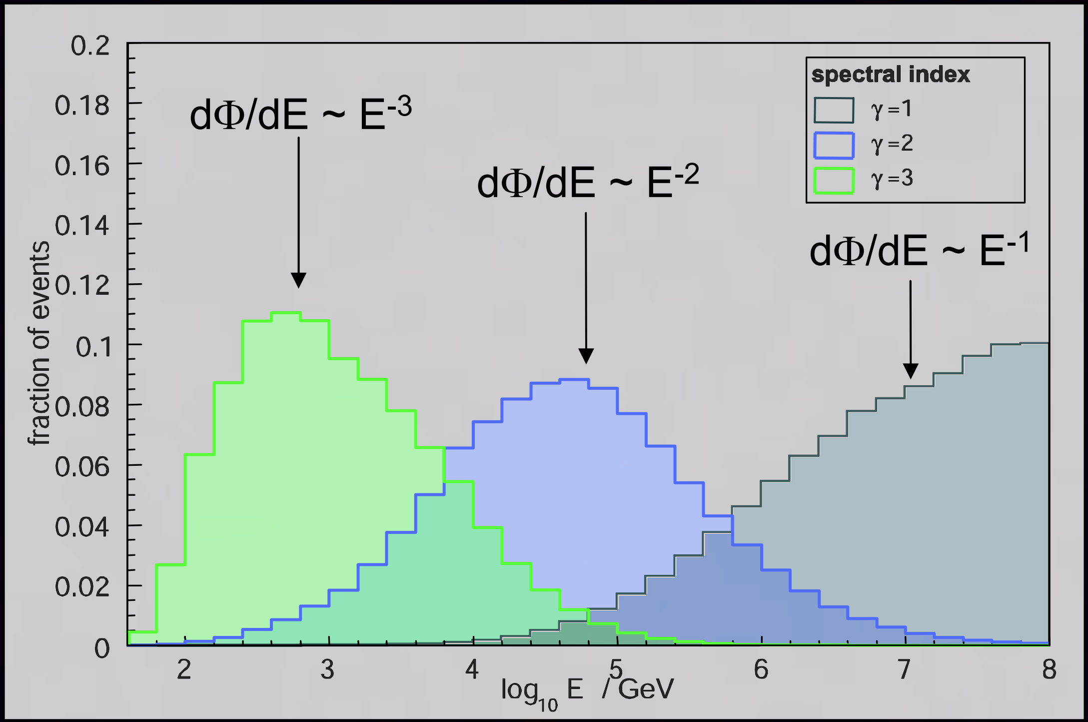
MAGIC telescope, La Palma

- Results will be exchanged and compared to pre-determined thresholds for γ-ray flux.
- Neutrino events by themselves are consistent with prel. background estimates.

IV Interpretation of flux limits

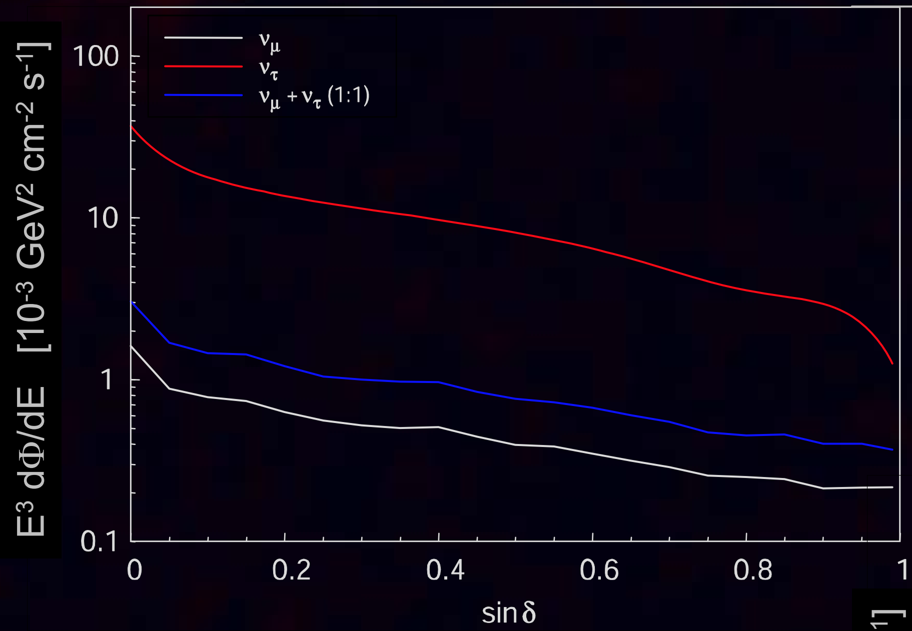
Comparison to selected models

- Specific theoretical models for neutrino emission from a single source rarely show a pure E^{-2} spectrum
- Variation of the spectral index between γ=1 and γ=3 shifts the peak energy of the detected neutrinos by 6 orders of magnitude

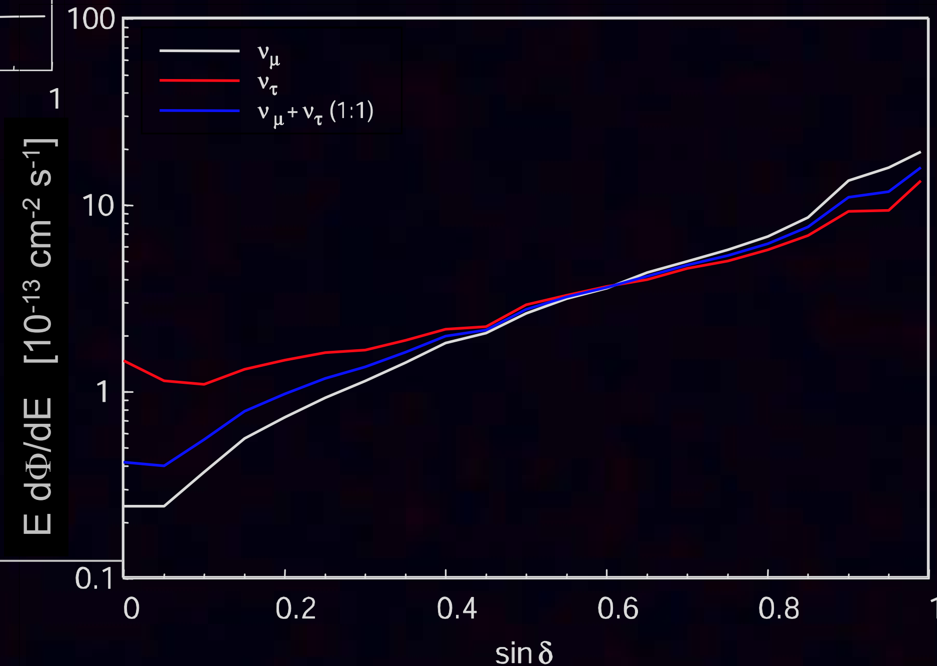


- Specific limits have to be calculated for the sources/spectra modelled based on the effective area of AMANDA-II

Sensitivity to different spectra



Sensitivity to dΦ/dE ~ E^{-3} :
Declination dependence from detector efficiency



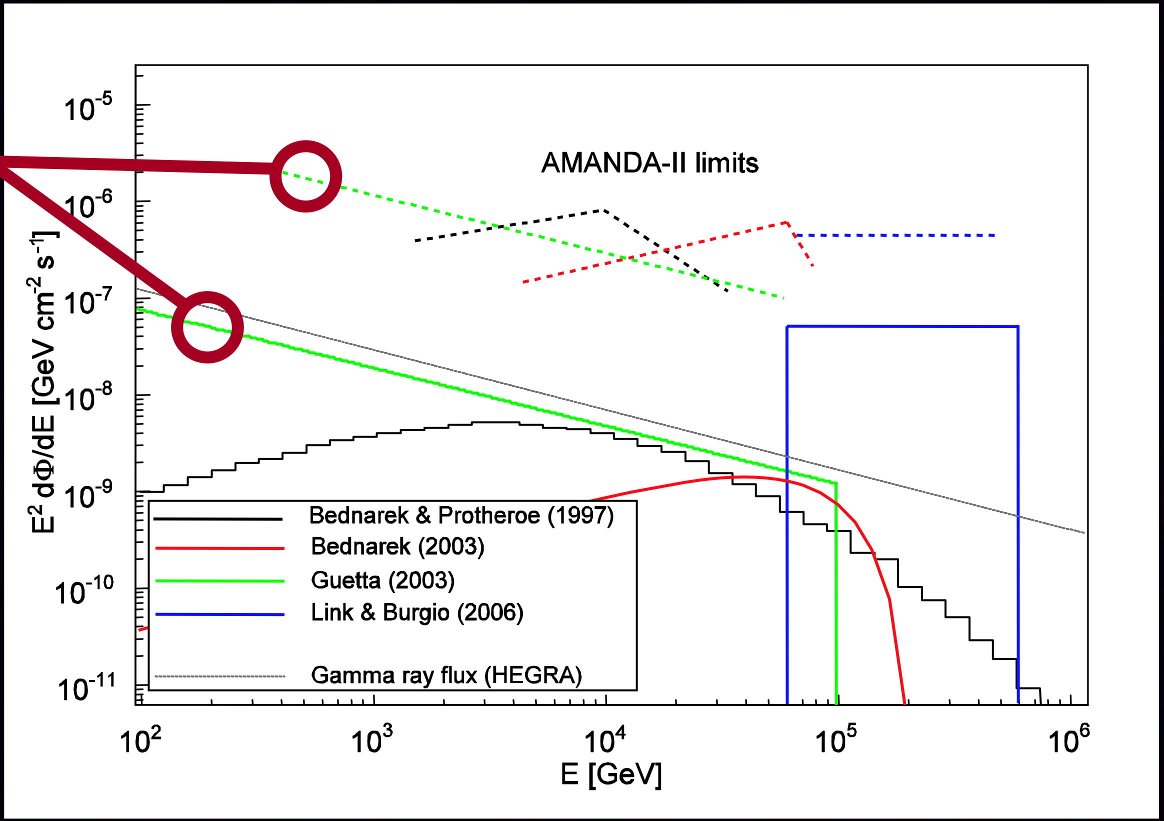
Sensitivity to dΦ/dE ~ E^{-1} :
Declination dependence due to neutrino absorption

Crab nebula

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

Flux limits and predictions shown correspond to $\nu_\mu+\nu_\tau$ flux on earth for a flavor ratio of $\nu_\mu:\nu_\tau$ = 1:1

Crab nebula	
$N_{observed}$	10
$N_{background}$	6.74
Event upper limit (90% CL)	10.1



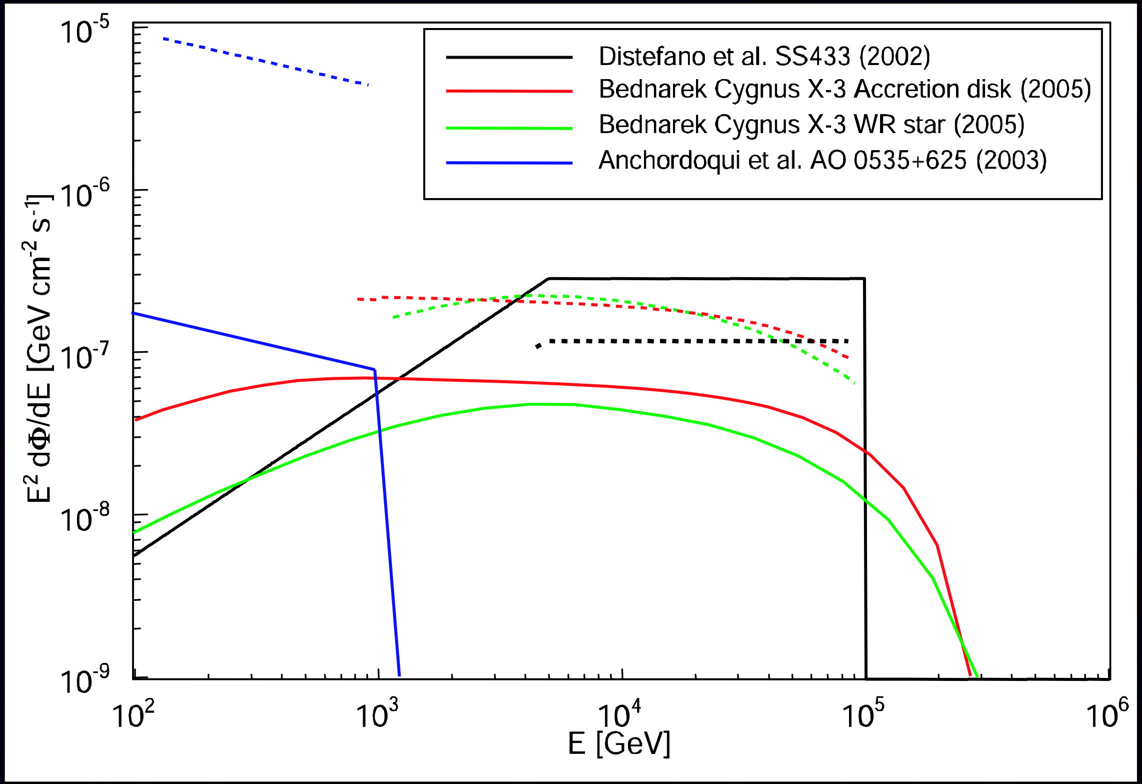
X-ray binaries

- Distefano et al.: pγ-interaction in the jet with int. and ext. photons ($N_{\nu,exp}$=7.8 for SS 433)
- Bednarek: pp-interaction in WR star and accretion disk after photo-dissoziation of heavy nuclei in the jet ($N_{\nu,exp}$=2.1 / 1.4 for Cygnus X-3)
- Anchordoqui et al.: Protons accelerated in electrostatic gap interact in accretion disk ($N_{\nu,exp}$=0.12 for AO 0535+625)

SS433	
N_{obs} / N_{bg}	4 / 6.14
Event upper limit (90% CL)	3.1

Cygnus X-3	
N_{obs} / N_{bg}	7 / 6.48
Event upper limit (90% CL)	6.4

AO 0535+625	
N_{obs} / N_{bg}	7 / 6.48
Event upper limit (90% CL)	6.4



EGRET Blazars

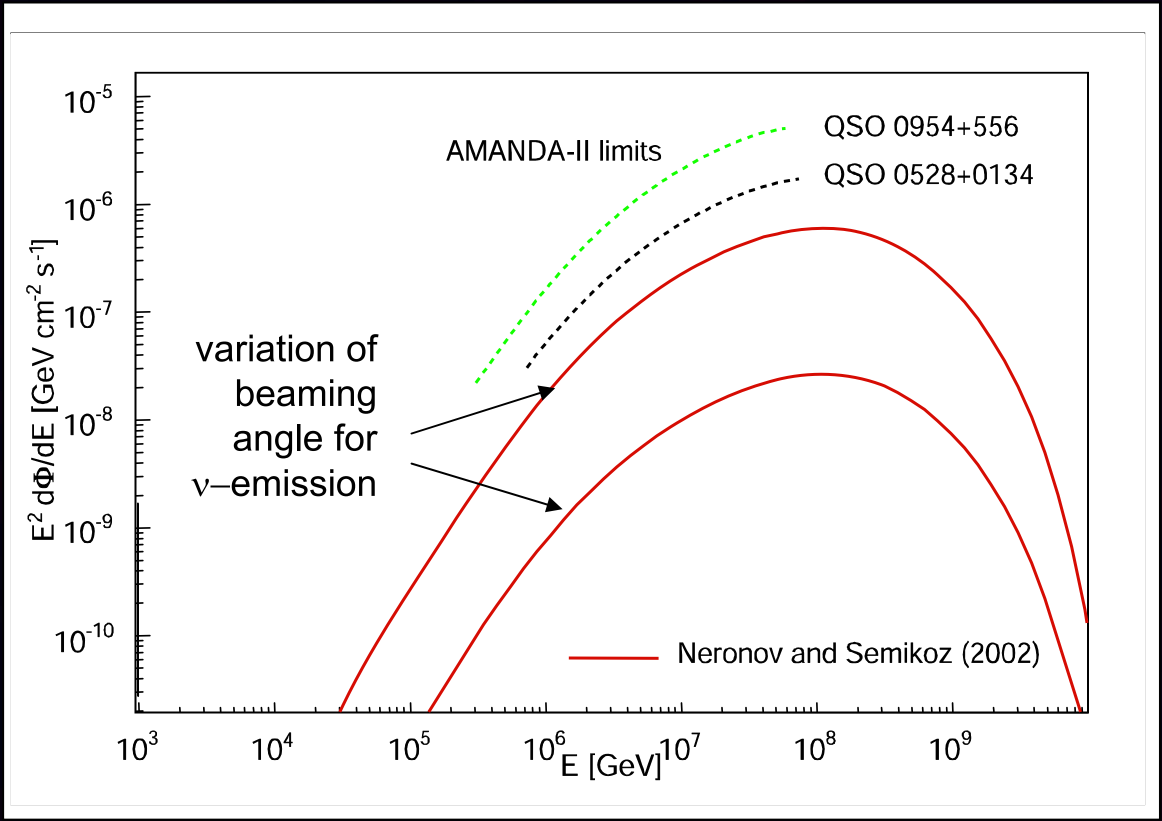
- Neronov and Semikoz: Model for "typical GeV loud Blazar", pγ-interaction in the AGN core

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

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

QSO 0528+0134	
N_{obs} / N_{bg}	4 / 6.08
Event upper limit (90% CL)	3.2

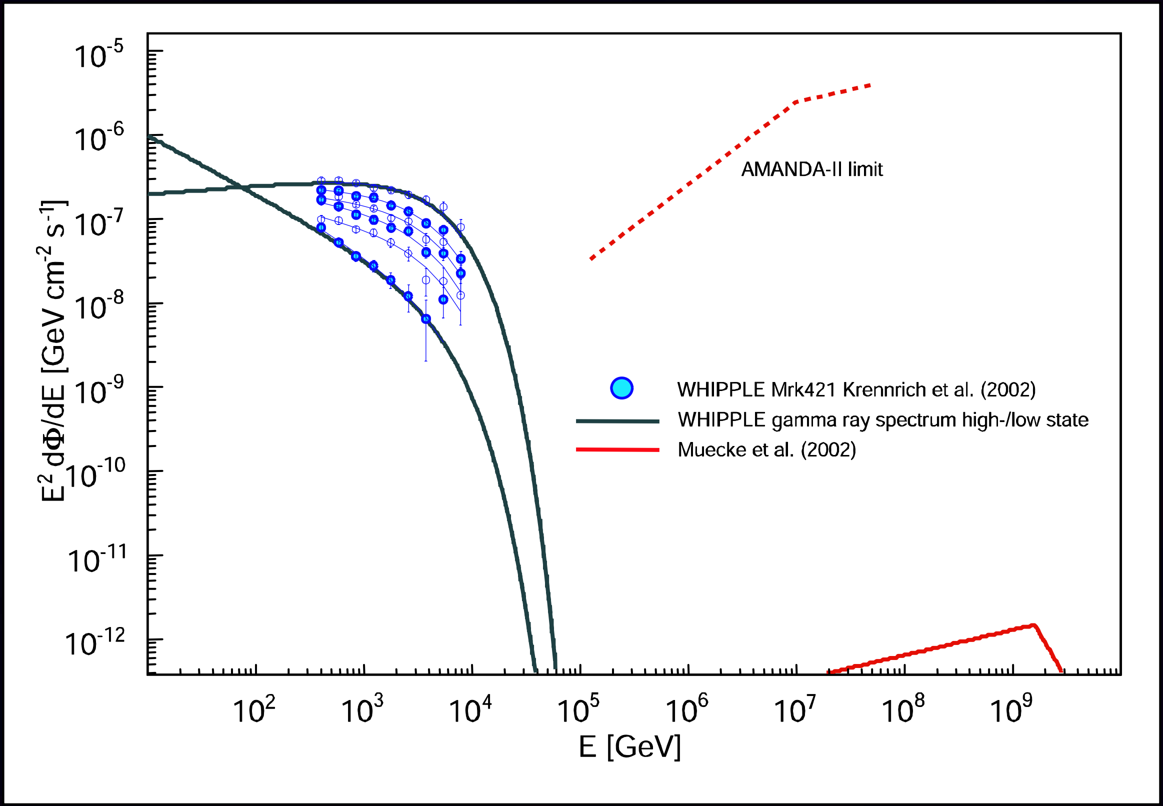
QSO 0954+556	
N_{obs} / N_{bg}	2 / 6.26
Event upper limit (90% CL)	1.4



Markarian 421

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

Markarian 421	
$N_{observed}$	6
$N_{background}$	7.37
Event upper limit (90% CL)	4.1

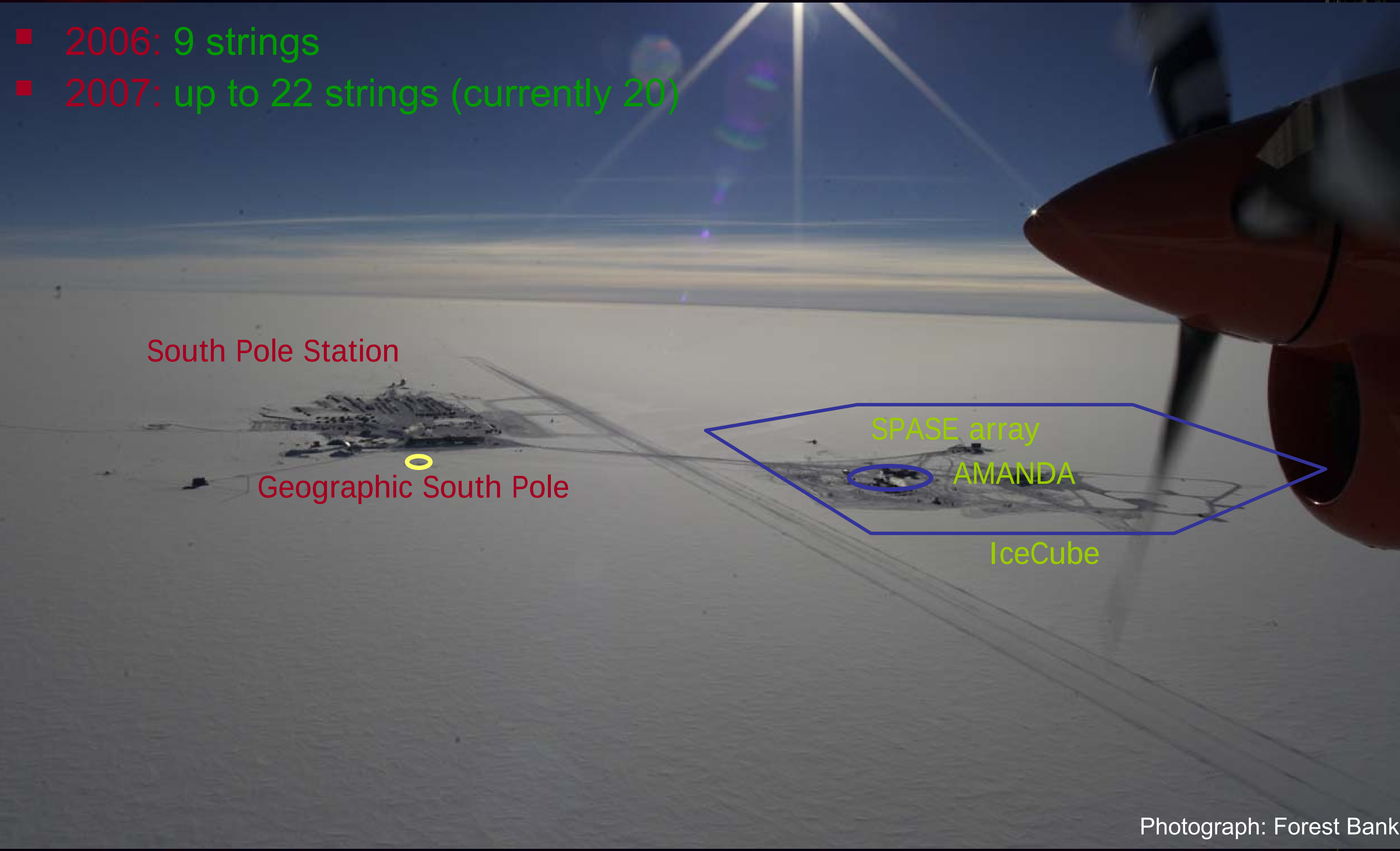


Summary....

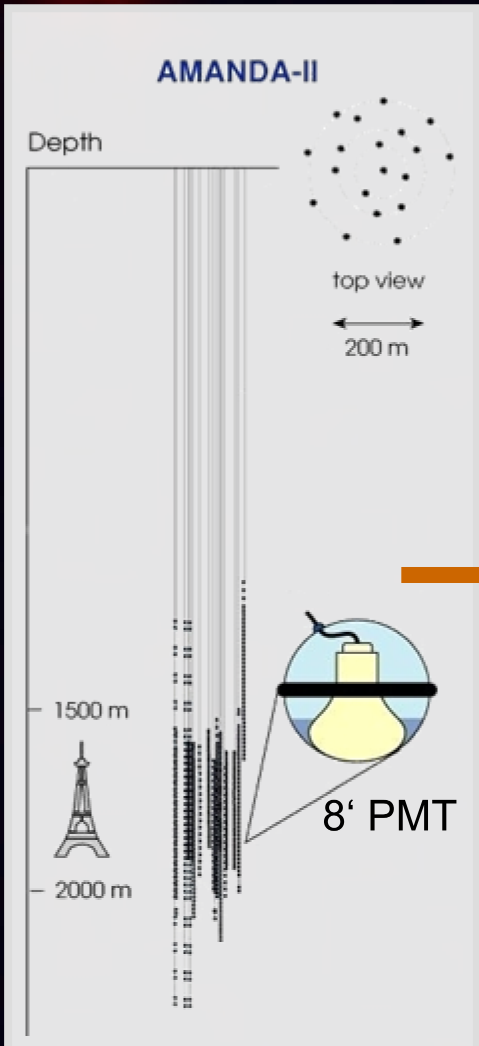
- 5 years of data (1001 effective days) of the AMANDA-II detector have been analyzed for a signal from neutrino point sources.
- No statistically significant source of neutrinos has been found so far.
- A dedicated analysis for variable sources has been performed also with negative result.
- An interesting coincidence between a gamma-ray flare and the arrival time of neutrinos has been found for the Blazar 1ES 1959+650
- The analysis provides the most stringent limits on neutrino fluxes from point sources on the northern hemisphere.
- Current models of neutrino emission from Microquasars can be constrained by the results.

… and Outlook: IceCube

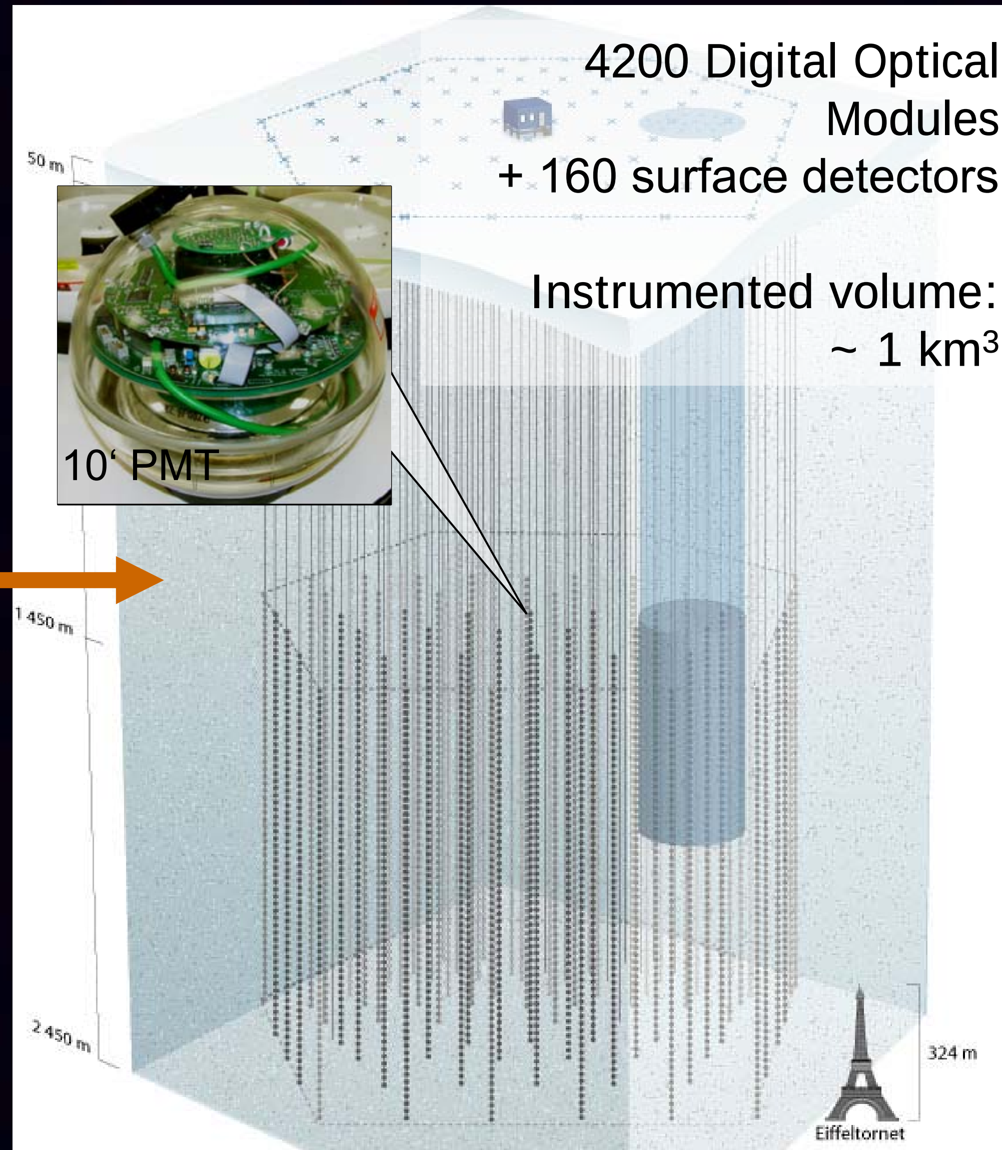
- 2006: 9 strings
- 2007: up to 22 strings (currently 20)



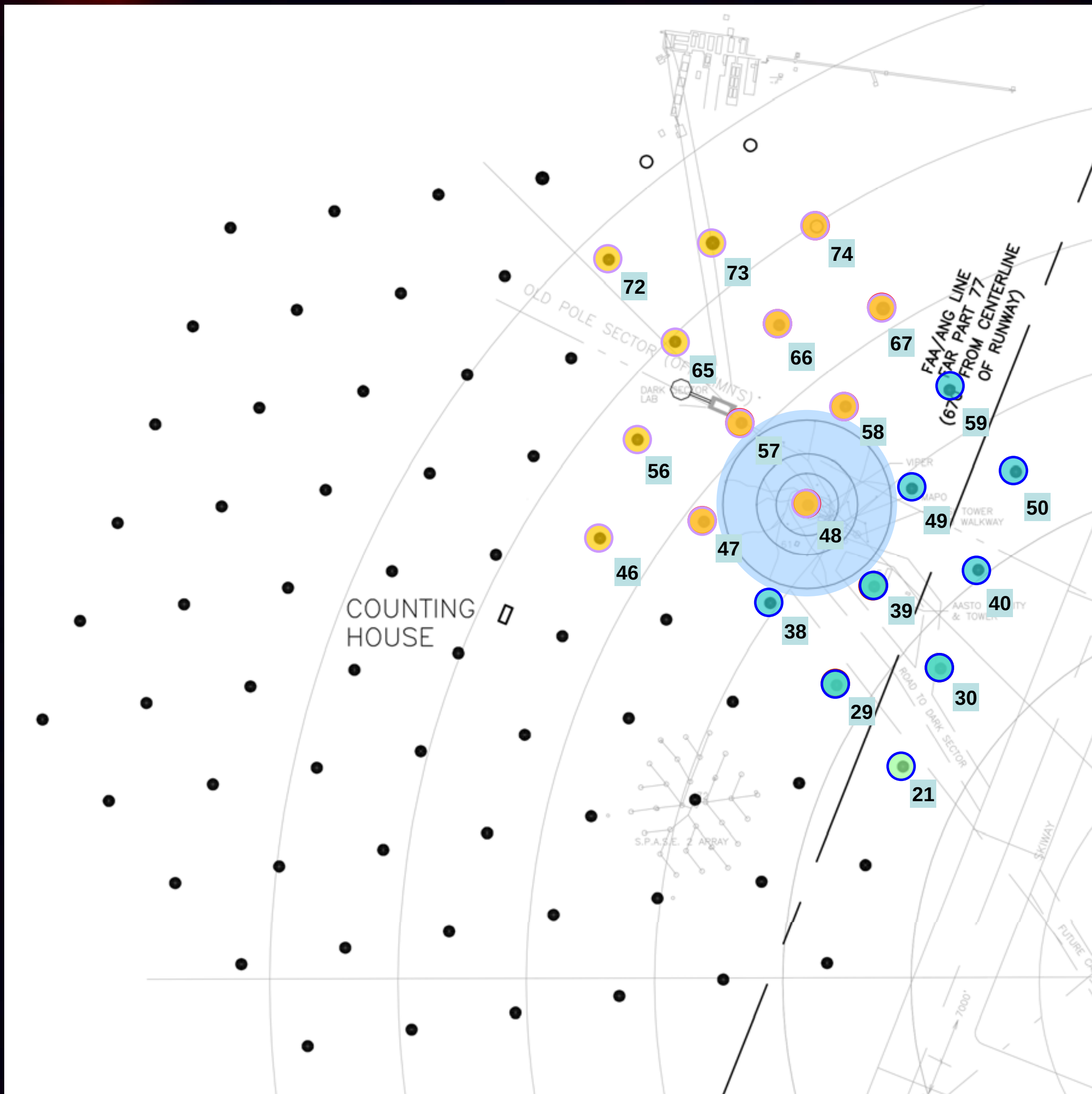
From AMANDA to IceCube

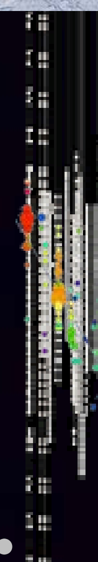


677 Optical Modules



Deployment status

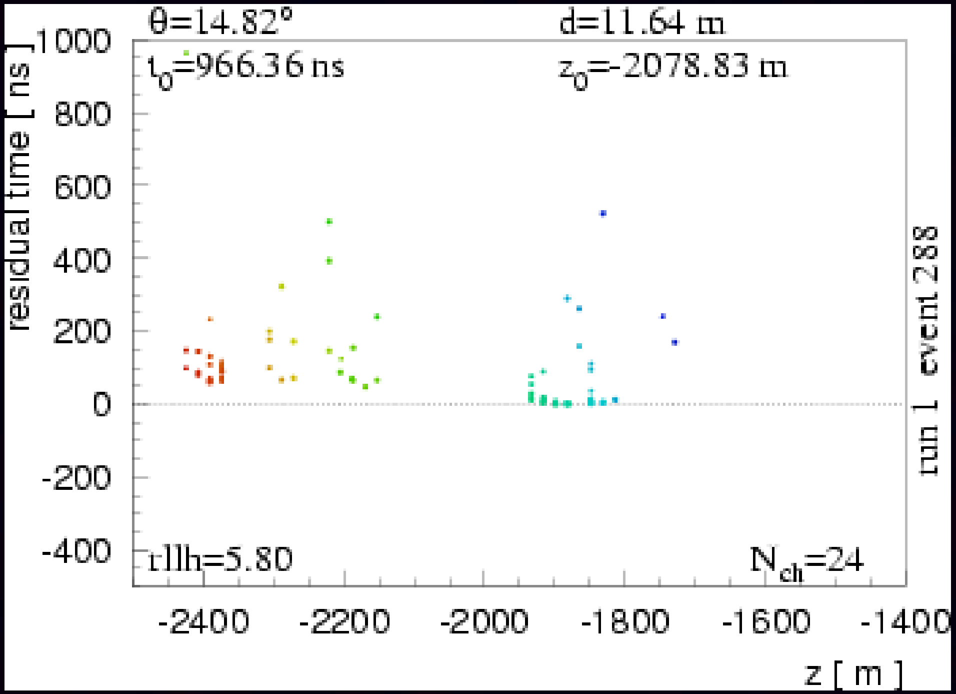


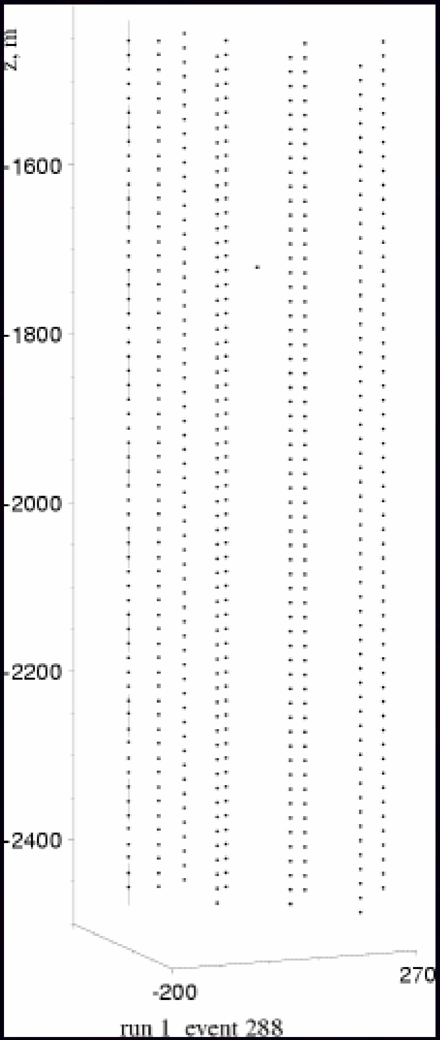


- Currently 20 strings deployed,
- 21-22 expected after end of deployment season

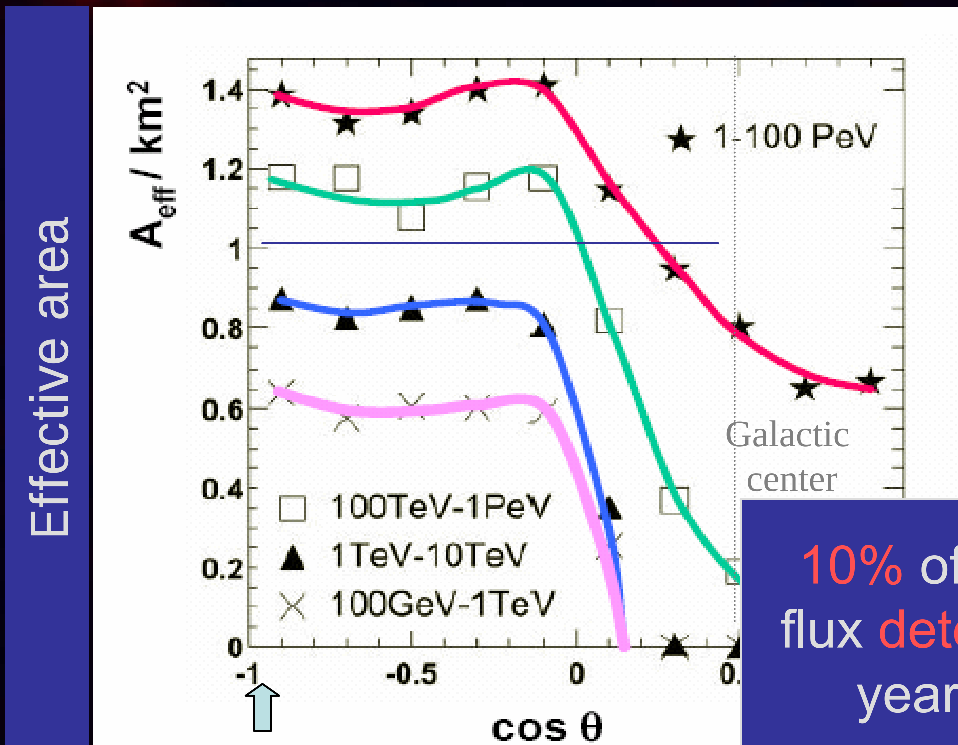
Neutrino candidate in IceCube-9

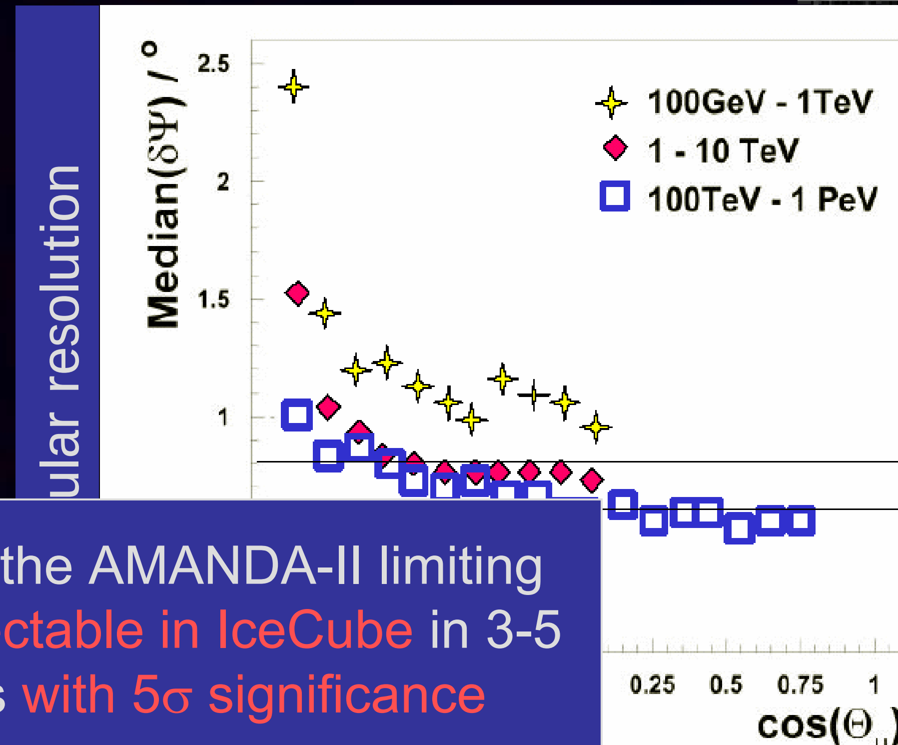
- Candidate event for a neutrino-induced muon in IceCube-9
- First physics analyses are under way





Expected IceCube performance



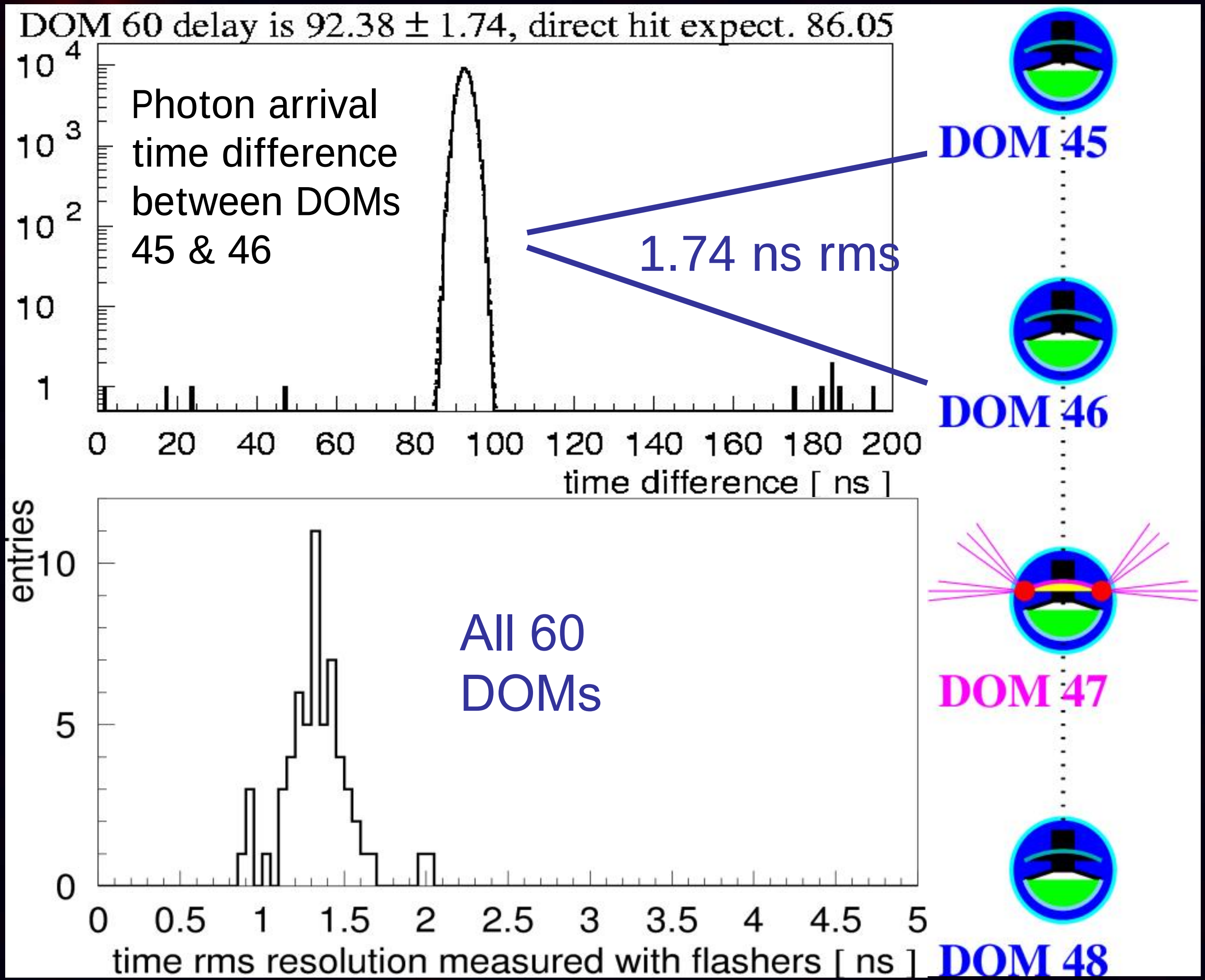


10% of the AMANDA-II limiting flux detectable in IceCube in 3-5 years with 5σ significance

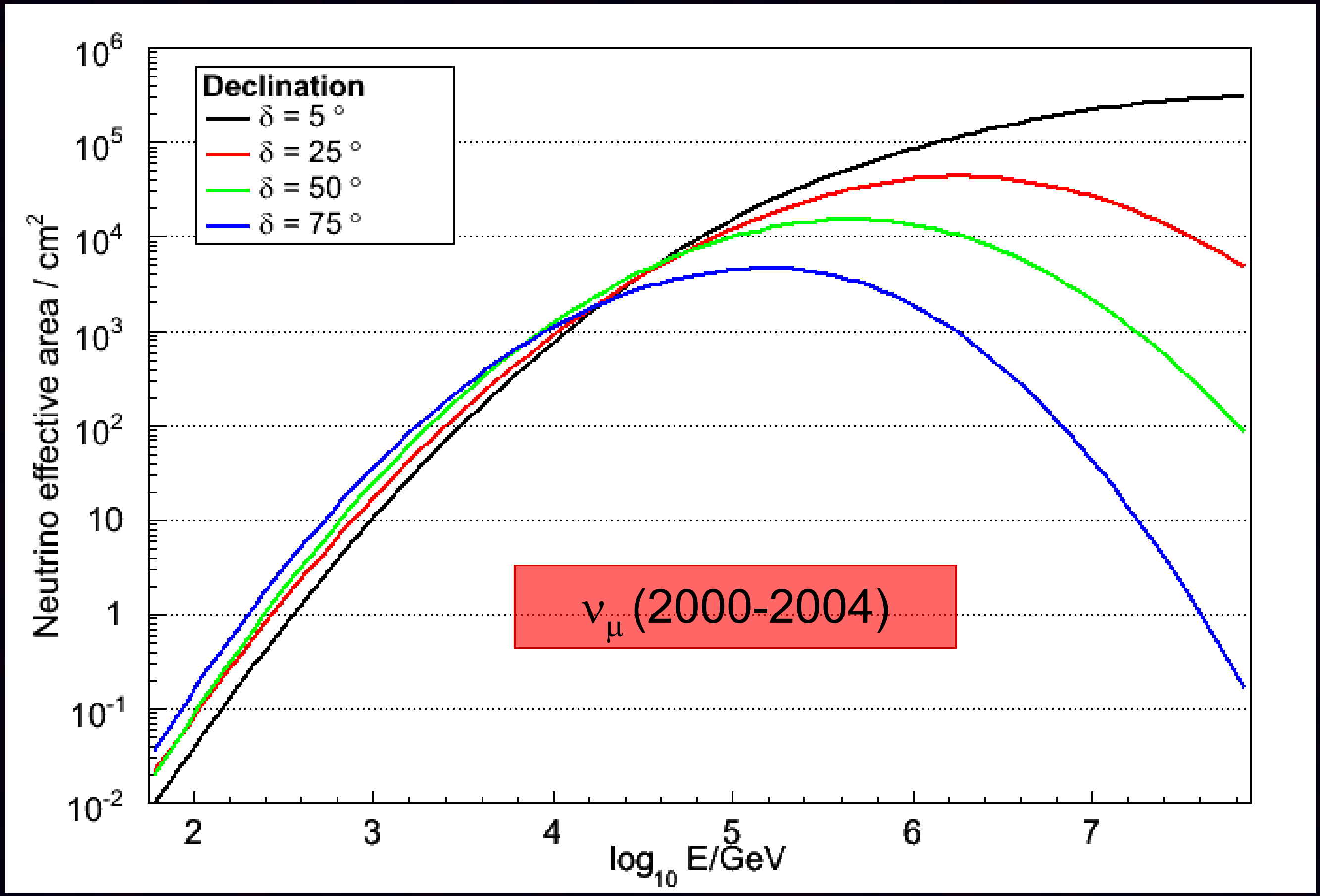
Years	Diffuse neutrino flux [GeV cm^{-2} s^{-1} sr^{-1}]		Point Sources [GeV cm^{-2} s^{-1}]	
	exp. Sensitivity (90% CL)	exp. Detection threshold (5σ)	exp. Sensitivity (90% CL)	exp. Detection threshold (5σ)
1	8.1×10^{-9}	2.6×10^{-8}	5.5×10^{-9}	1.7×10^{-8}
3	4.2×10^{-9}	1.2×10^{-8}	2.4×10^{-9}	7.2×10^{-9}
5	3.2×10^{-9}	9.9×10^{-9}	1.7×10^{-9}	4.9×10^{-9}

BACKUP SLIDES

IceCube verification: Time calibration



Neutrino effective area

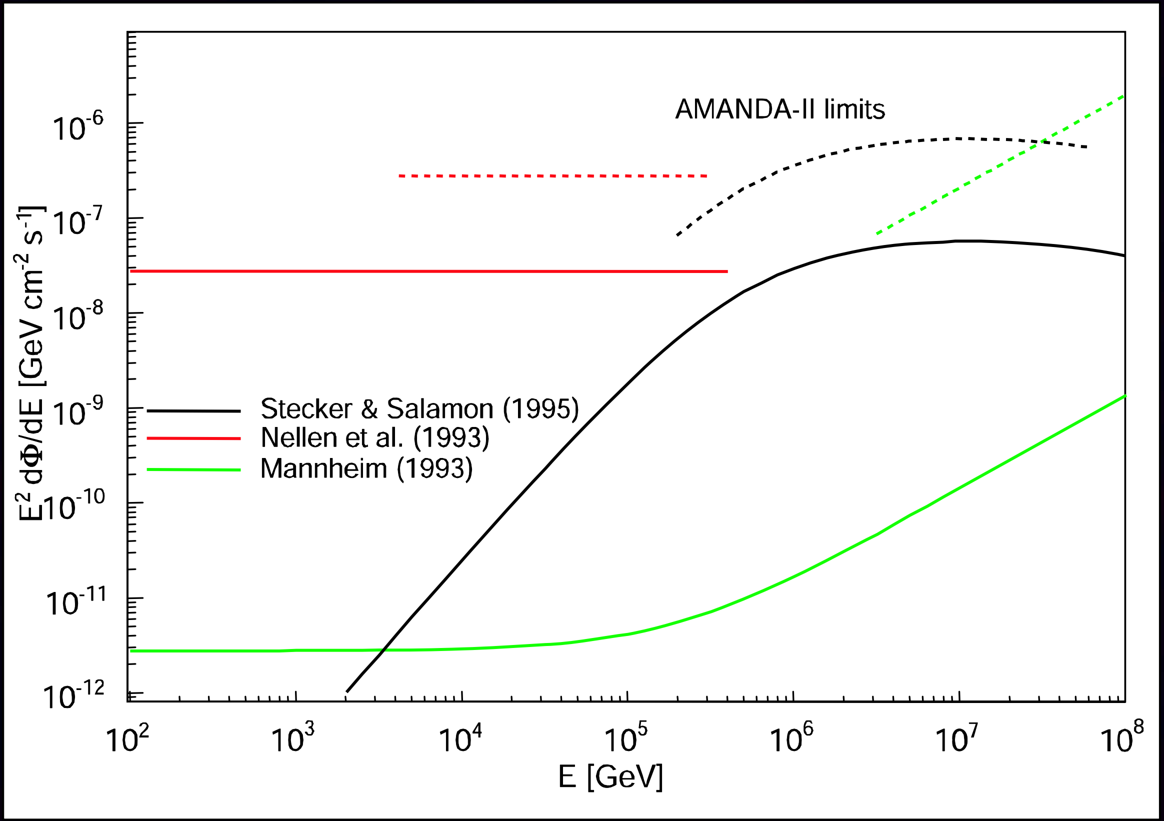


3C273

- Nellen et al.: pp interaction in AGN core **($N_{\nu,exp}$ = 0.86)**
- Stecker and Salamon: pγ interaction in AGN core **($N_{\nu,exp}$ = 0.81)**
- Mannheim: pp and pγ interaction in the Blazar jet **($N_{\nu,exp}$ = 0.01)**

Diffuse flux predicitons from Nellen et al. and Stecker and Salamon already excluded by AMANDA-II limits

3C273	
$N_{observed}$	8
$N_{background}$	4.72
Event upper limit (90% CL)	9.6



Source stacking analysis

- Search for an excess of events from several sources combined
- AGNs grouped in classes of potential high energy neutrino sources
- Assumption: neutrino flux is linearly correlated with luminosity

Source class	N_{src}	Flux
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

Flux upper limit in units of 10^{-7} GeV $cm^{-2}s^{-1}$ for differential flux $d\Phi/dE \sim E^{-2}$

A. Gross, Ph.D thesis, University of Dortmund
Achtenberg et al., “On the selection of AGN ...”, Accepted by Astropart. Phys.