ν astronomy

- ν astronomy requires kilometer-scale detectors
- IceCube: a kilometer-scale neutrino observatory
- AMANDA: proof of concept and first science

f. halzen
http://pheno.physics.wisc.edu/~halzen/
http://icecube.wisc.edu/

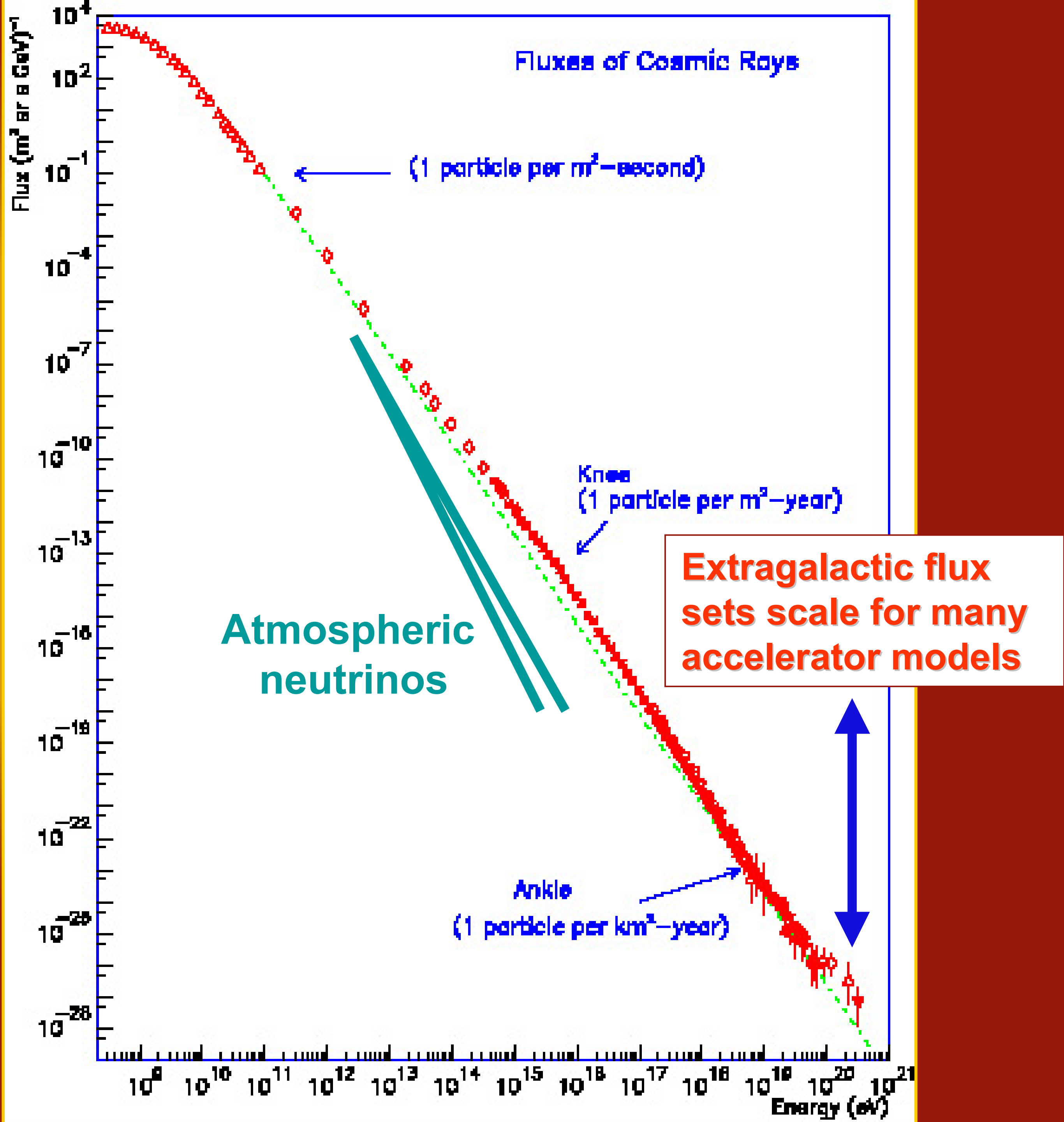
the science: a sampler

- **Source(s) of cosmic rays**:
  gamma-ray bursts, active galaxies,
  cosmological remnants…?

- **Dark matter**

- **More**

Cosmic Ray spectrum



With 10^3 TeV energy, photons do not reach us from the edge of our galaxy because of their small mean free path in the microwave background.

$$\gamma + \gamma_{CMB} \longrightarrow e^+ + e^-$$

Acceleration to 10^{21} eV?

~10^2 Joules

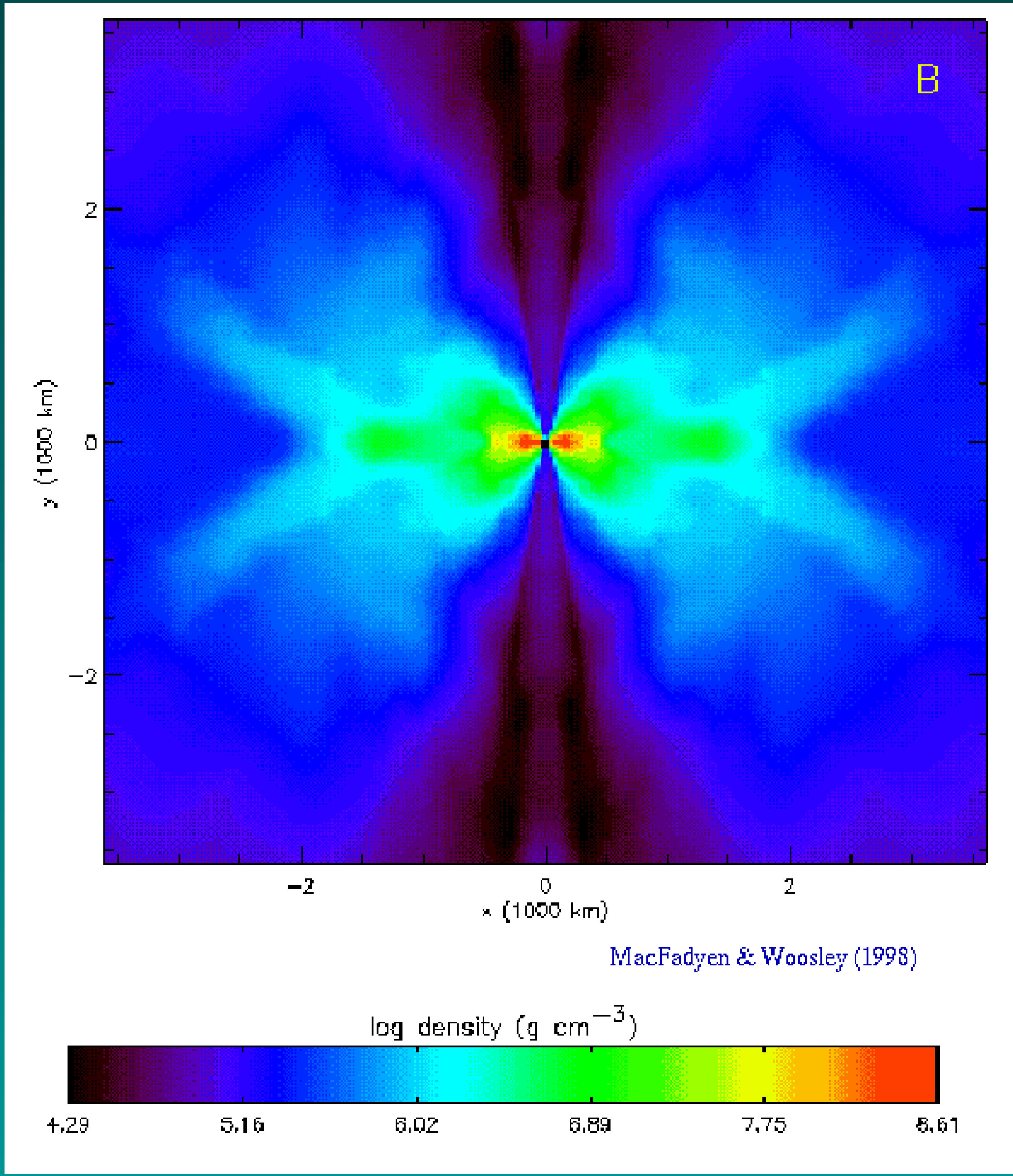
~ 0.01 M_{GUT}

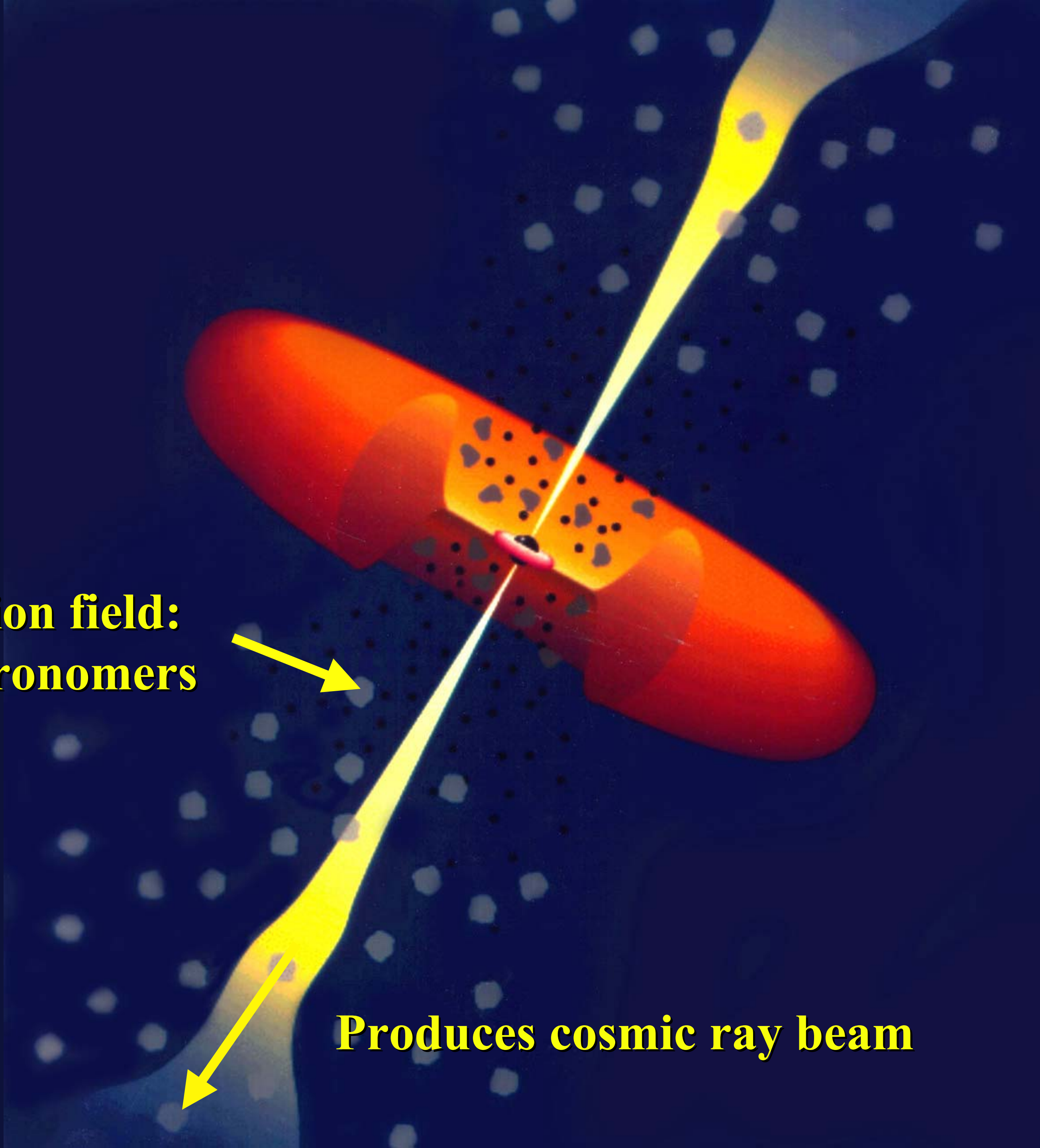
dense regions with exceptional gravitational force creating relativistic flows of charged particles, e.g.

- **coalescing black holes/neutron stars**
- **dense cores of exploding stars**
- **supermassive black holes**

Gamma Ray Burst

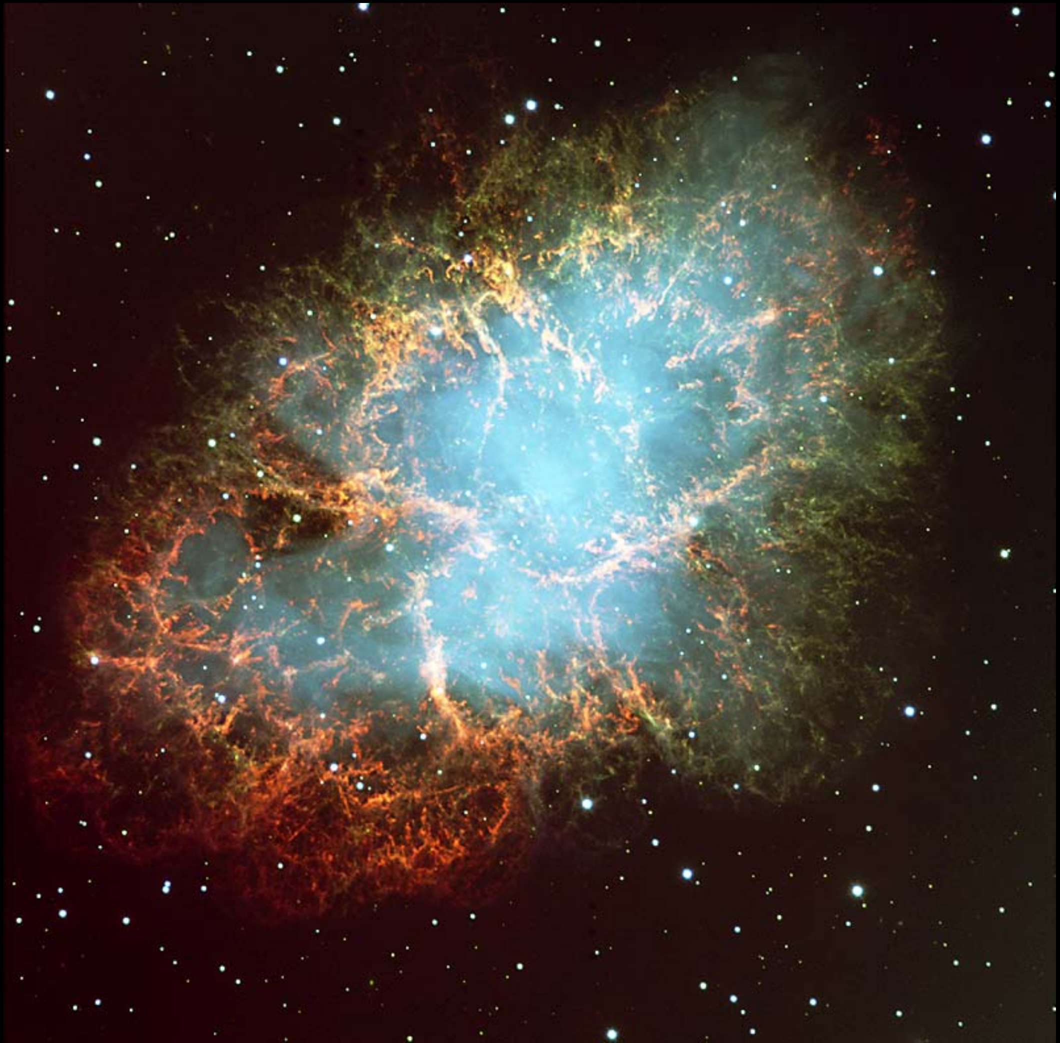
- Photons and protons coexist in internal shocks resulting in pion and neutrino production
- External shocks also



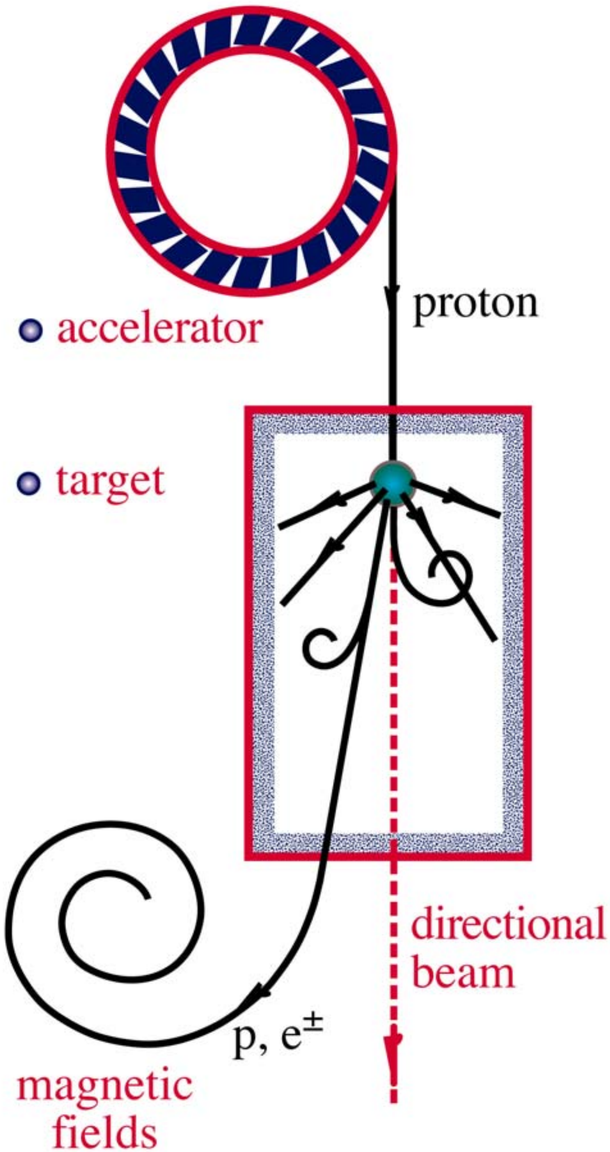

Radiation field:
Ask astronomers
Produces cosmic ray beam

Supernova shocks expanding in interstellar medium

Crab nebula



NEUTRINO BEAMS: HEAVEN & EARTH



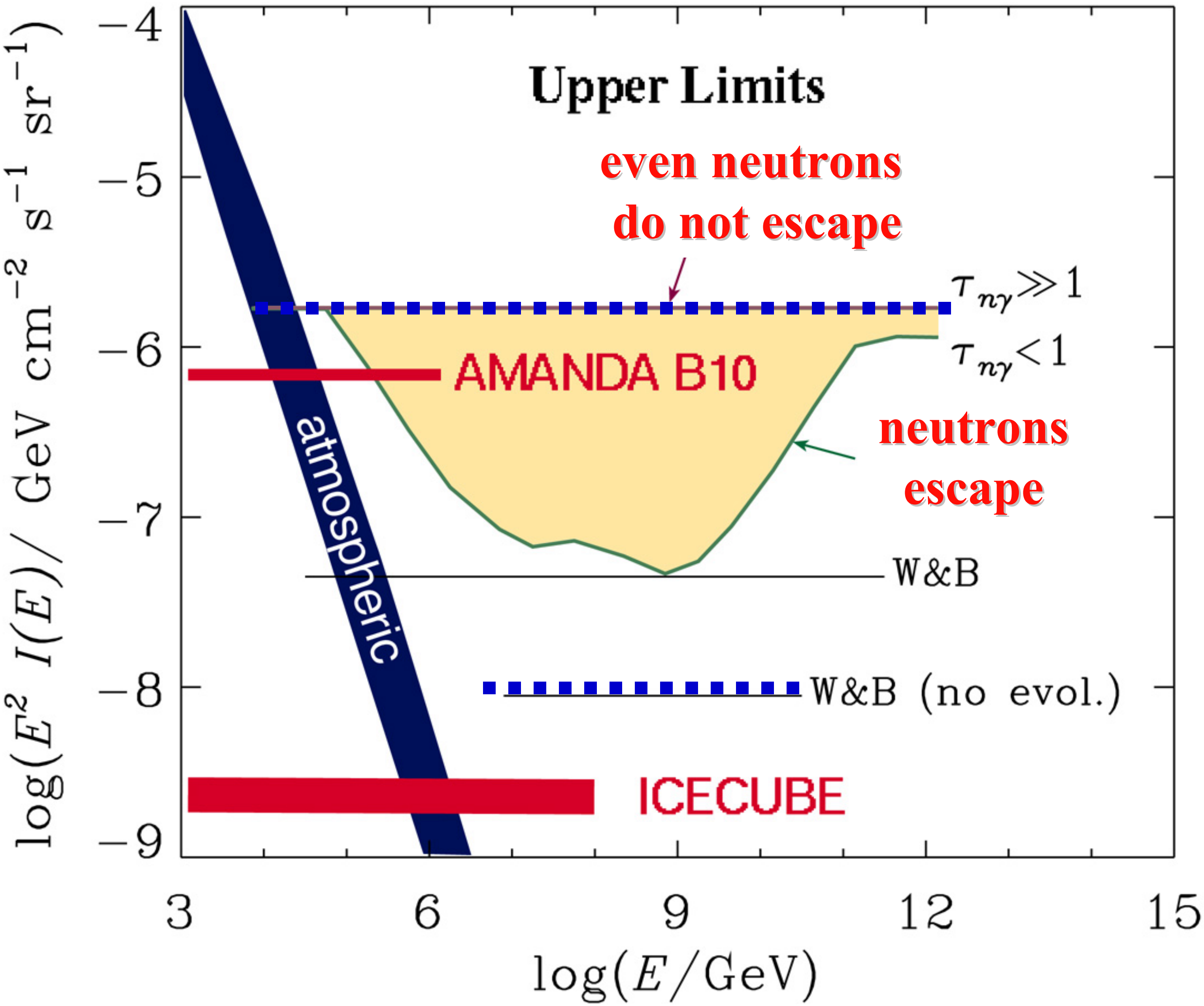
→ black hole

→ radiation enveloping black hole

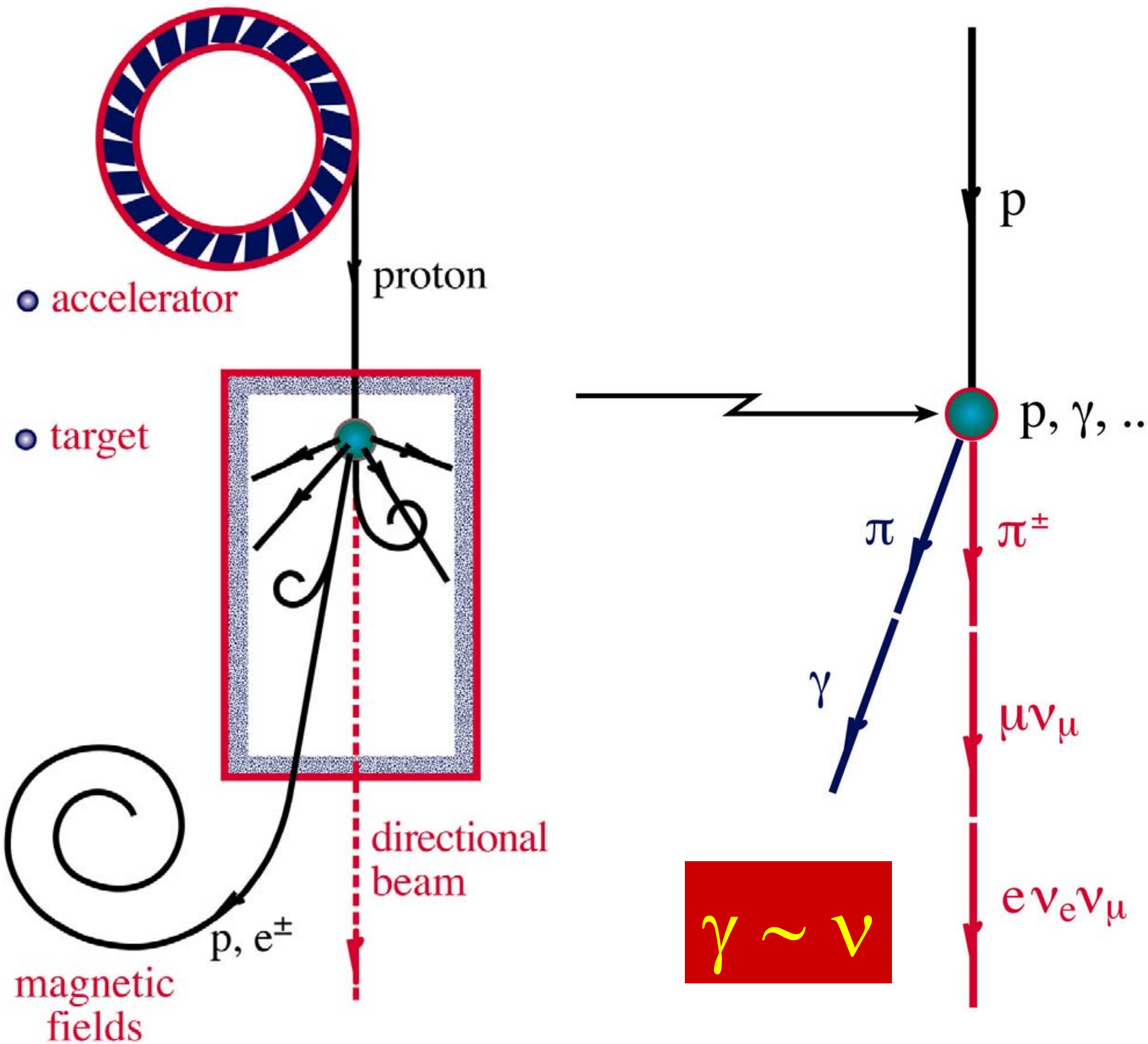
$p + \gamma \rightarrow n + \pi^{+}$

~ cosmic ray + neutrino

neutrinos associated with the source of the cosmic rays?

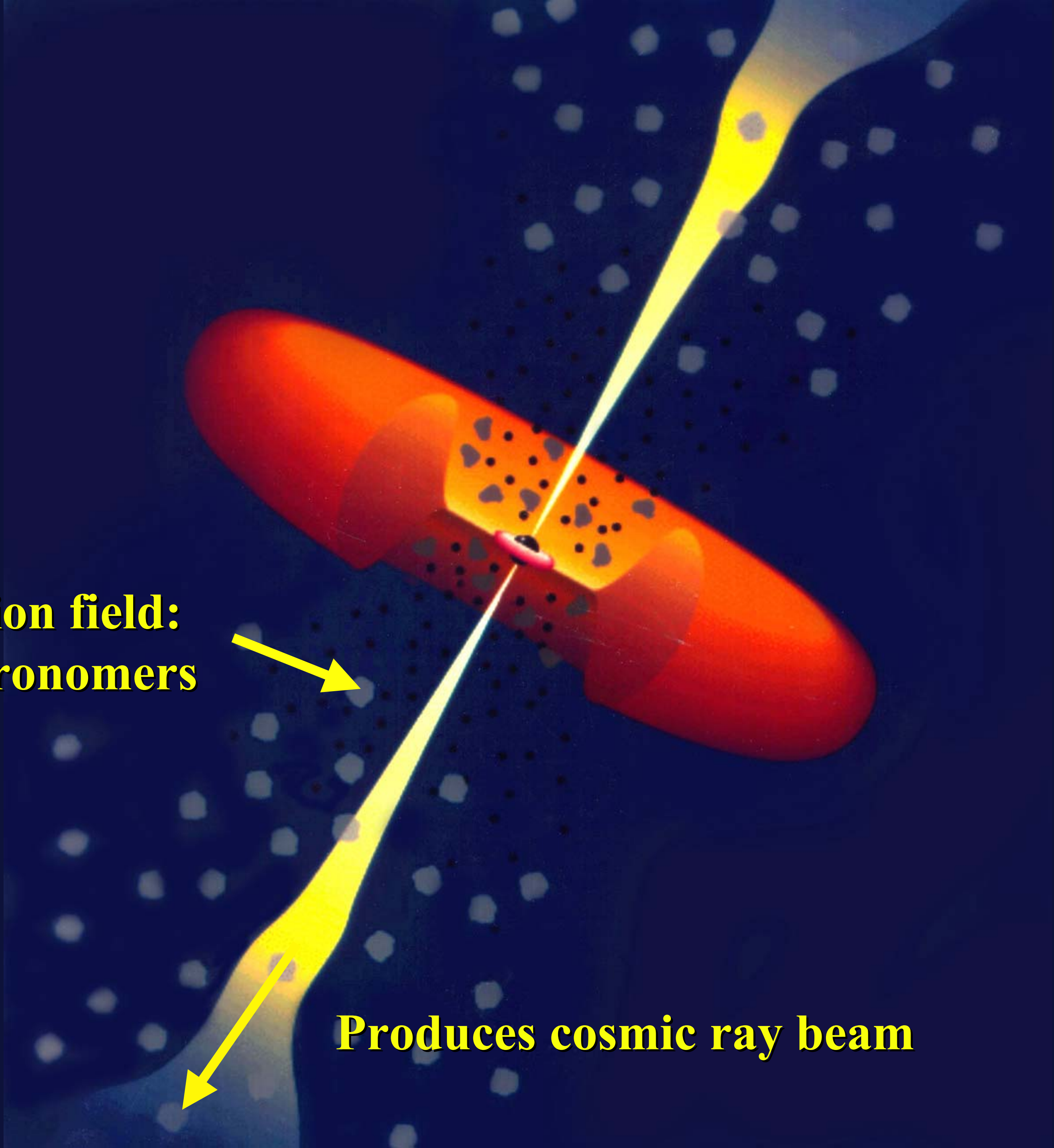


NEUTRINO BEAMS: HEAVEN & EARTH

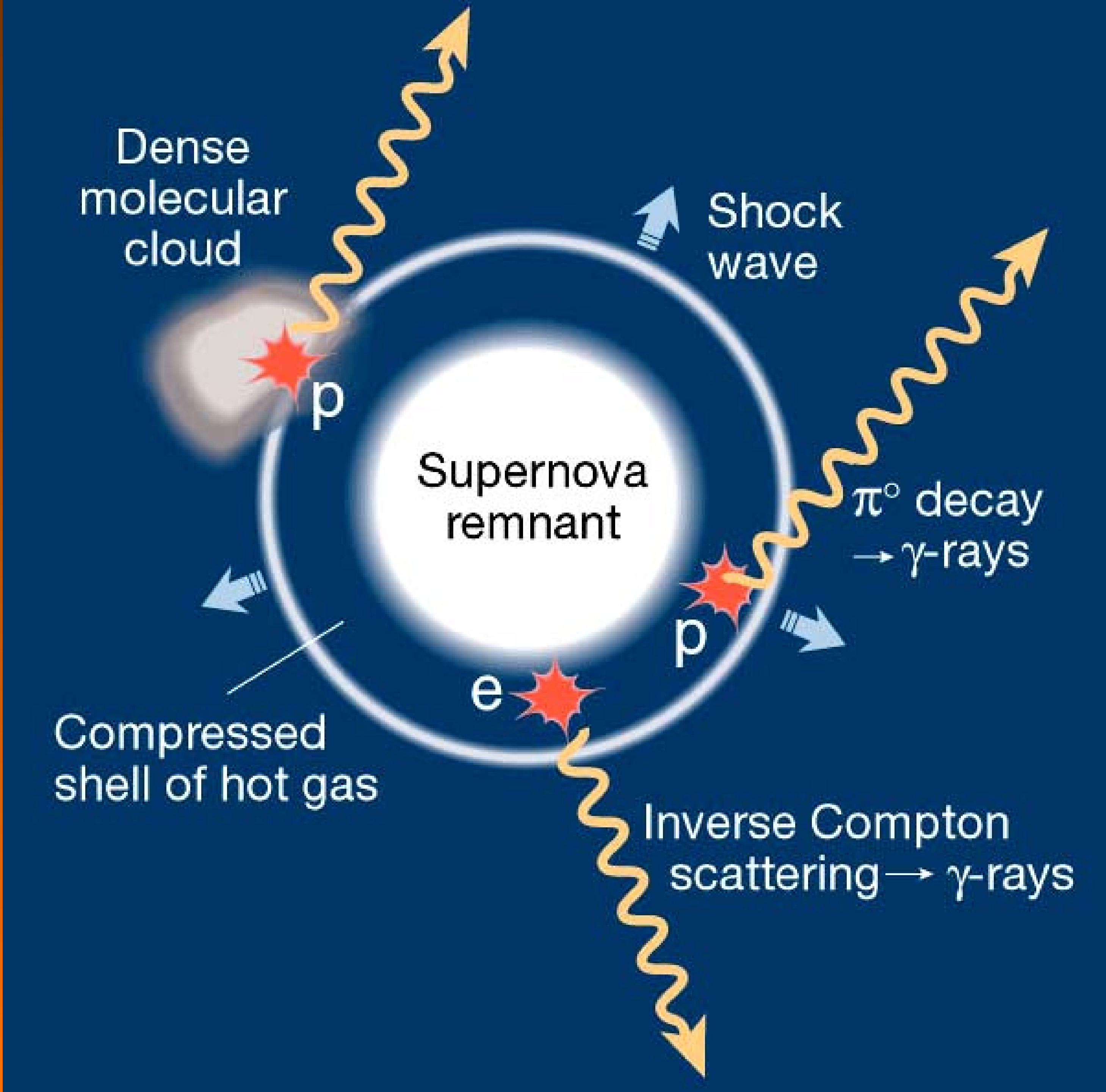


Energetics of sources yielding 10 events per year in 1 kilometer squared

distance	Lum_ν >	example
4000 Mpc	10^{47} erg/s	agn
4000 Mpc	10^{52} erg/100s	grb
100 Mpc	5 10^{43} erg/s	Markarians
8 Kpc	4 10^{35} erg/s	pulsars, micro-quasar…


Radiation field:
Ask astronomers
Produces cosmic ray beam

Galactic Beam Dump



Modeling yields the same conclusion:

- *Line-emitting quasars such as 3C279*

  Beam: blazar jet with equal power in electrons and protons

  Target: external quasi-isotropic radiation

- *Supernova remnants such as RX 1713.7-3946 (?)*

  Beam: shock propagating in interstellar medium

  Target: molecular cloud

$$N_{events} \sim 10 \ \ km^{-2} \ year^{-1}$$

Irrespective of the cosmic-ray sources, some fraction will produce pions (and neutrinos) as they escape from the acceleration site

- **through hadronic collisions with gas**
- **through photoproduction with ambient photons**

Cosmic rays interact with interstellar light/matter even if they escape the source

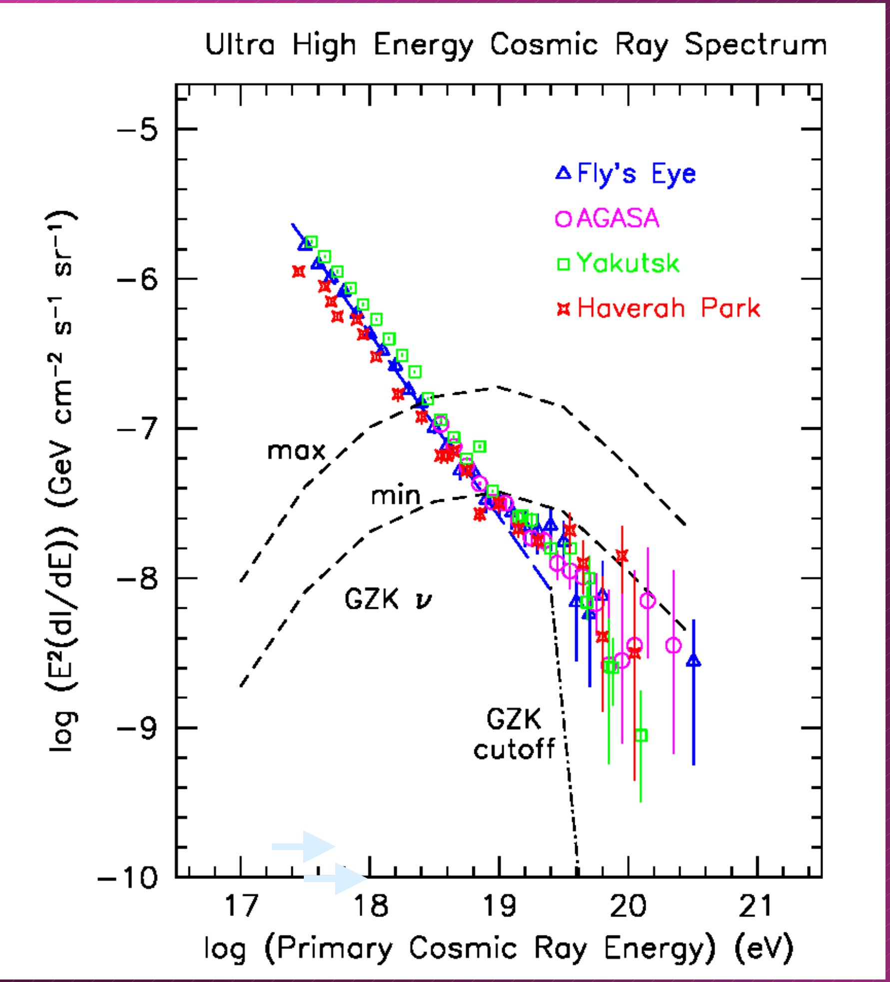
Sources:

- **Transparent:**

  protons (EeV cosmic-rays) ~ photons (TeV point sources) ~neutrinos
- **Obscured sources**
- **Hidden sources**

Unlike gammas, neutrinos provide unambiguous evidence for cosmic ray acceleration!

GZK Cosmic Rays & Neutrinos



- Cosmogenic Neutrinos are Guaranteed if primaries Nucleons.
- May be much larger fluxes, for some models, such as topological defects

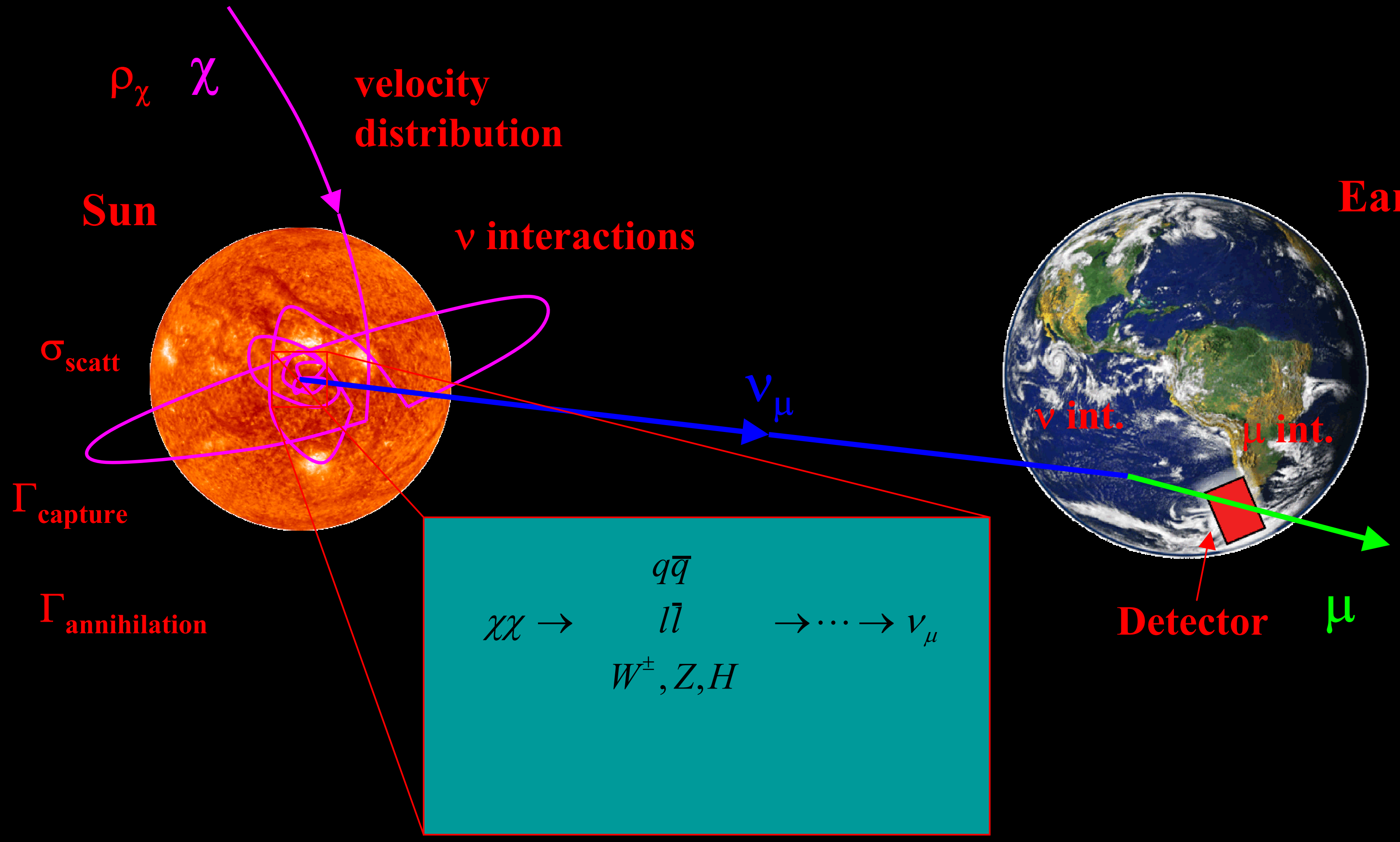
$$p + \gamma_{CMB} \rightarrow \pi + \ldots$$

the science: a sampler

- **Source(s) of cosmic rays**:
  gamma-ray bursts, active galaxies,
  cosmological remnants…?

- **Dark matter**

Neutralino capture and annihilation



The MSSM – general

- The Lightest Supersymmetric Particle (LSP): usually the neutralino. If R-parity is conserved, it is stable.

- The Neutralino – χ

$$\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}^3 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0$$

- Gaugino fraction

$$Z_g = |N_{11}|^2 + |N_{12}|^2$$

1. Select MSSM parameters
2. Calculate masses, etc
3. Check accelerator constraints
4. Calculate relic density
5. $0.05 < \Omega_\chi h^2 < 0.5$?
6. Calculate fluxes, rates,...

Calculation done with

DarkSUSY

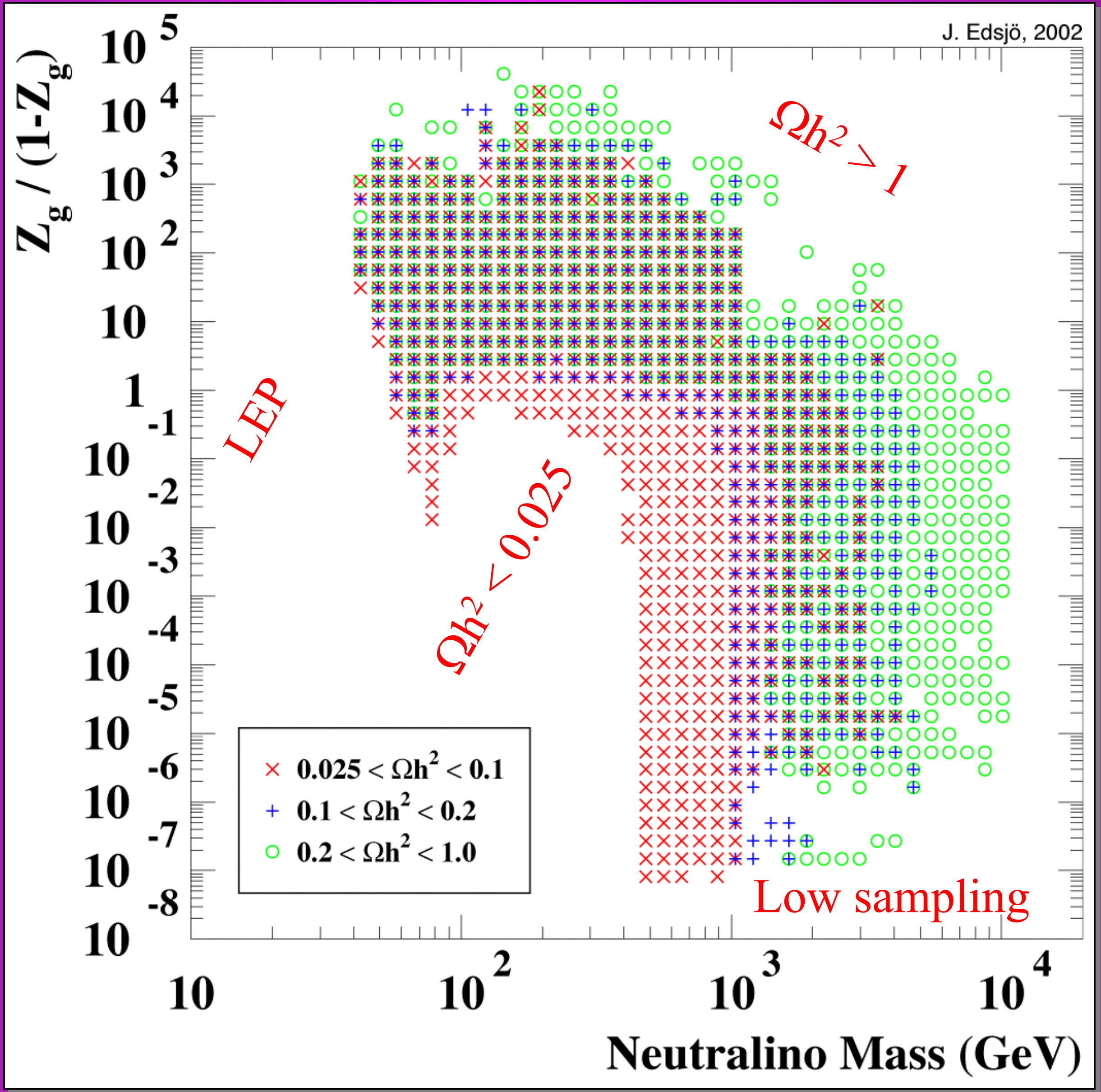
http://www.physto.se/~edsjo/darksusy/

The m_χ-Z_g parameter space

Gauginos

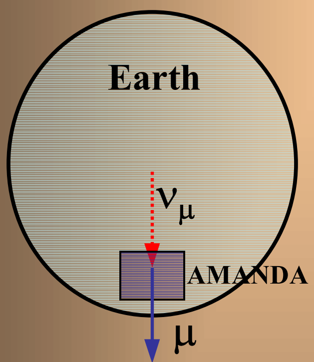
Mixed

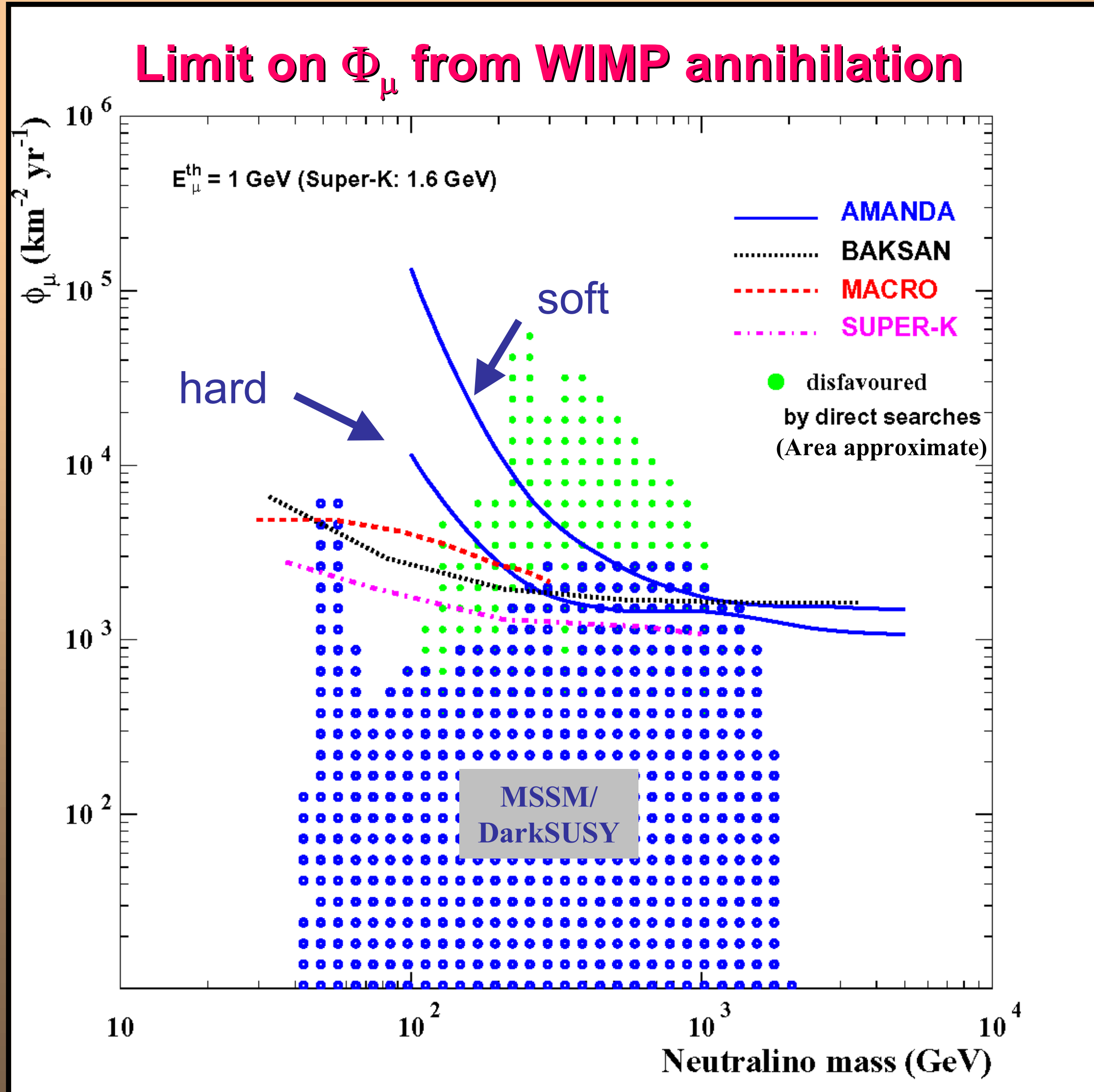
Higgsinos



WIMP Search

WIMP annihilation at Earth's center

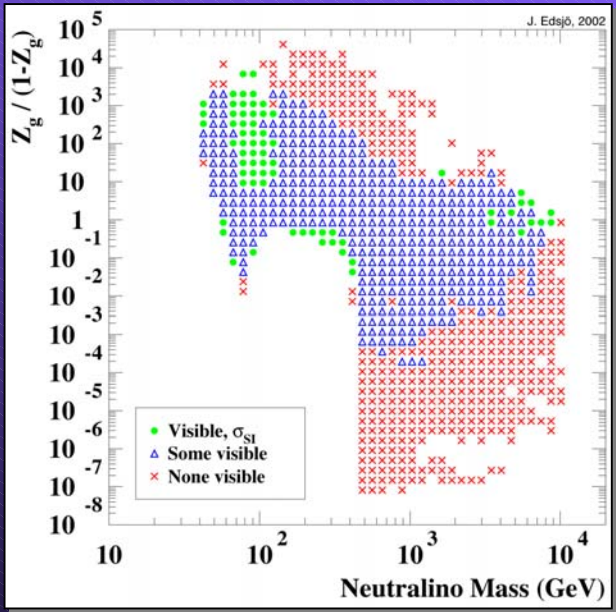




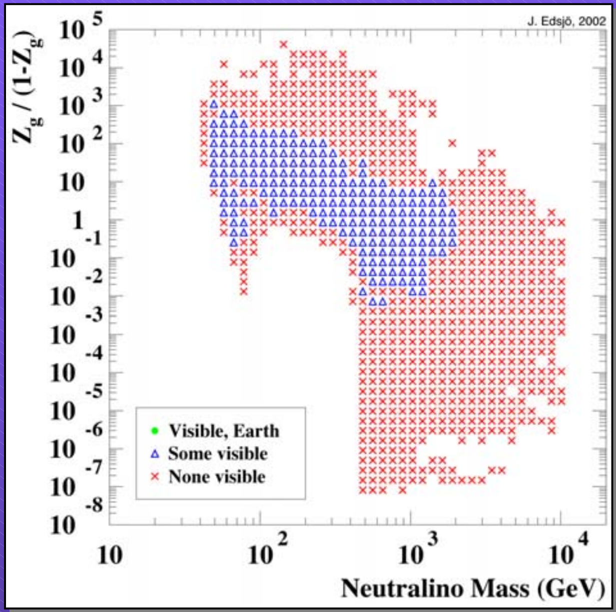
astro-ph/0202370, to appear in PRD

MSSM parameter space
Future probed regions I

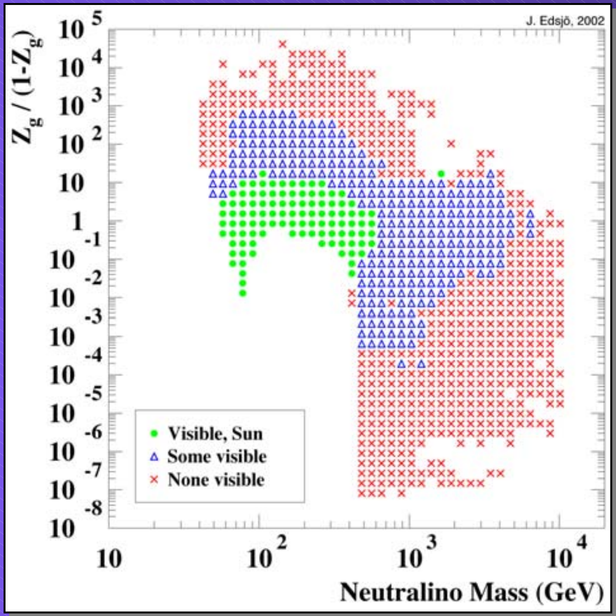
Direct detection
Genius/Cresst



Earth, km^3



Sun, km^3



IceCube

the science: a sampler

- **Source(s) of cosmic rays**:
  gamma-ray bursts, active galaxies,
  cosmological remnants…?

- **Dark matter**

- **More**

Why is Searching for ν's from GRBs of Interest?

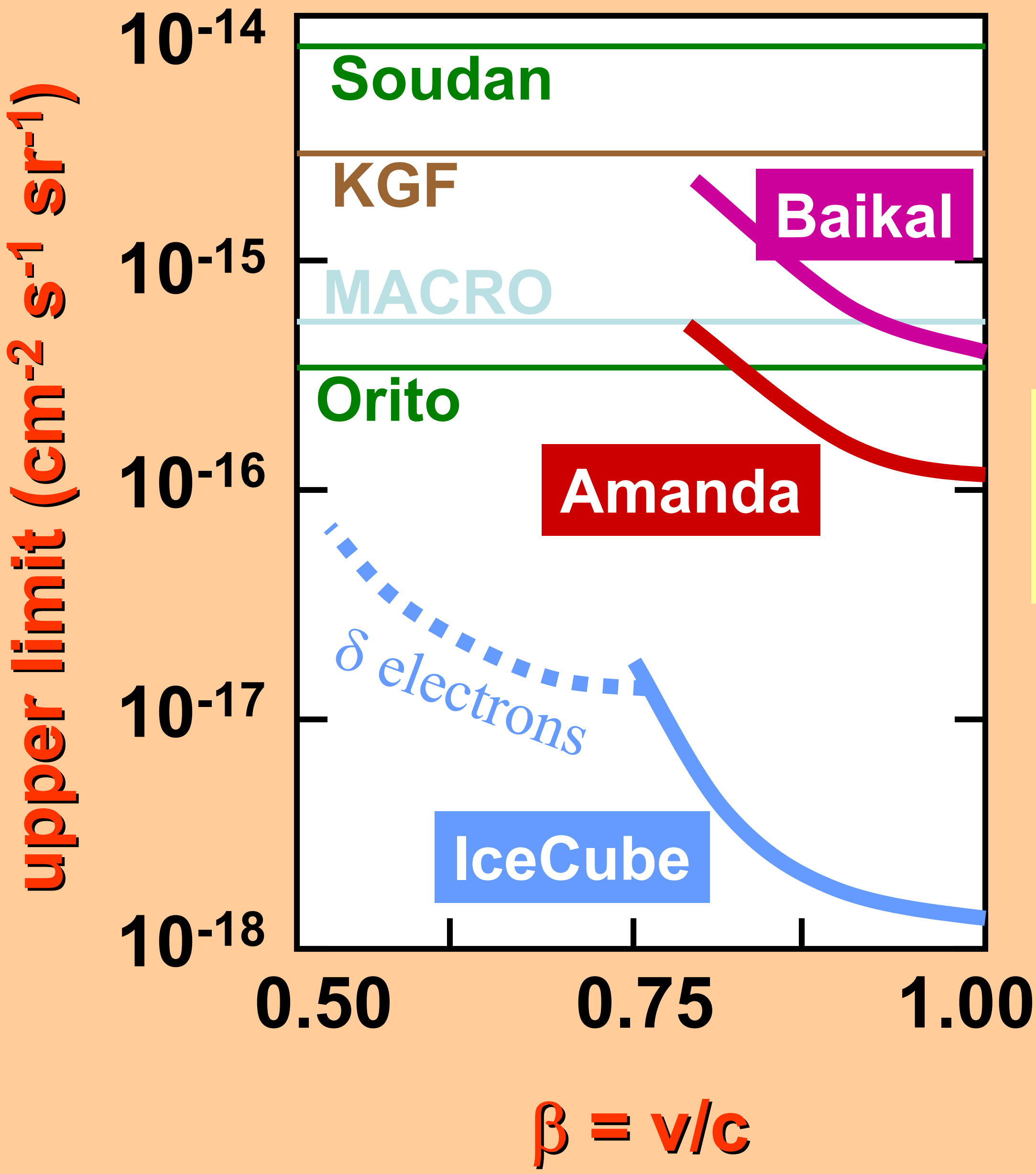
- Search for vacuum oscillations ($\nu_\mu \rightarrow \nu_\tau$):

  $\Delta m^2 \gtrsim 10^{-17}\ \mathrm{eV}^2$

- Test weak equivalence principle: 10-6

- Test $\dfrac{C_{photon} - C_\nu}{C_\nu}$: 10-16

Relativistic Magnetic Monopoles



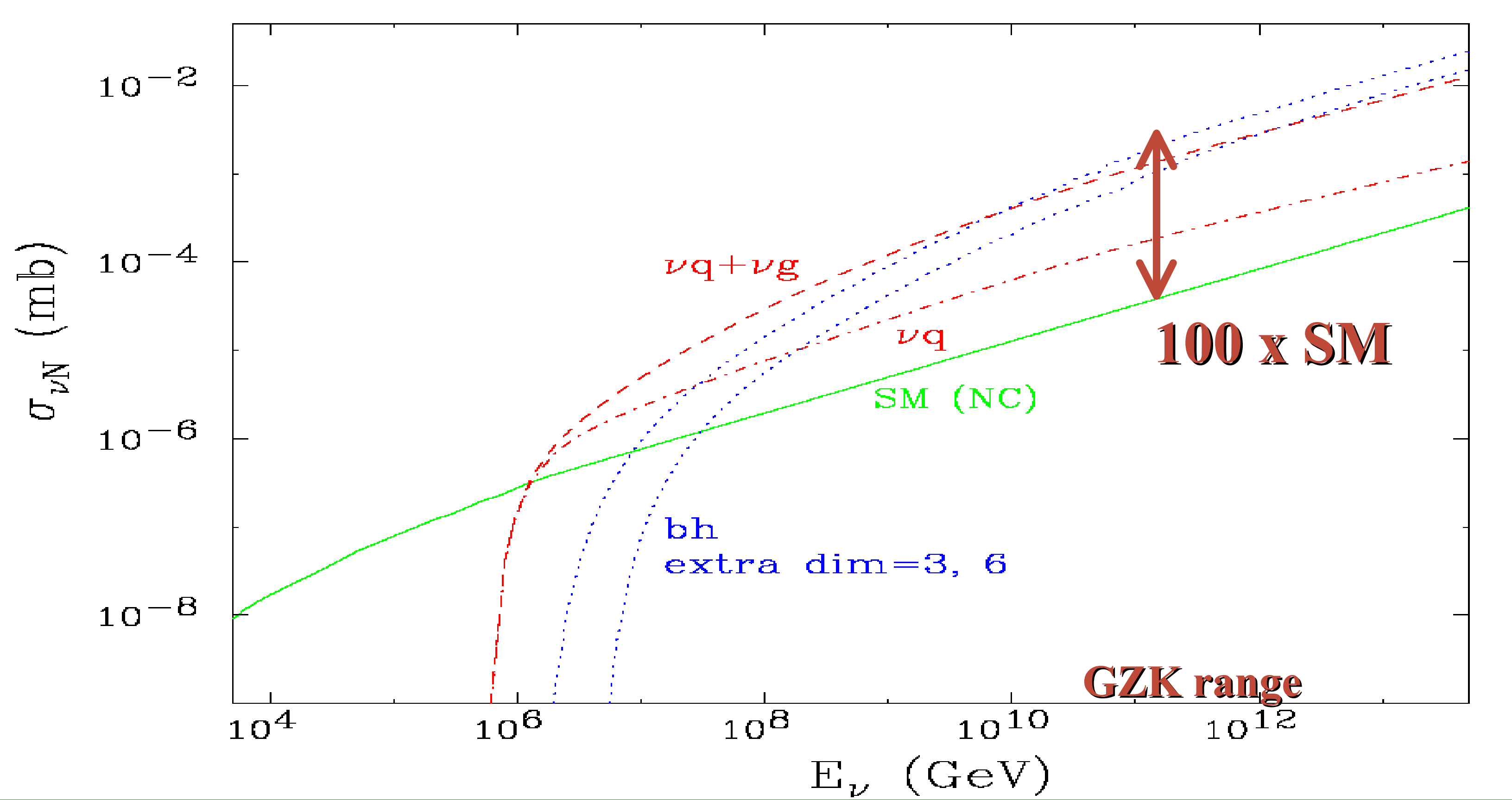
Cherenkov light output $\propto$ $n^2 \cdot (g/e)^2$

$n = 1.33$

$(g/e) = {}^{137}/_{2}$

≈ 8300

Neutrino Astronomy Explores Higher Dimensions

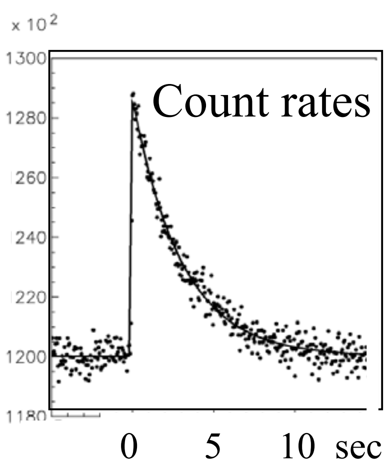


TeV-scale gravity increases PeV ν-cross section

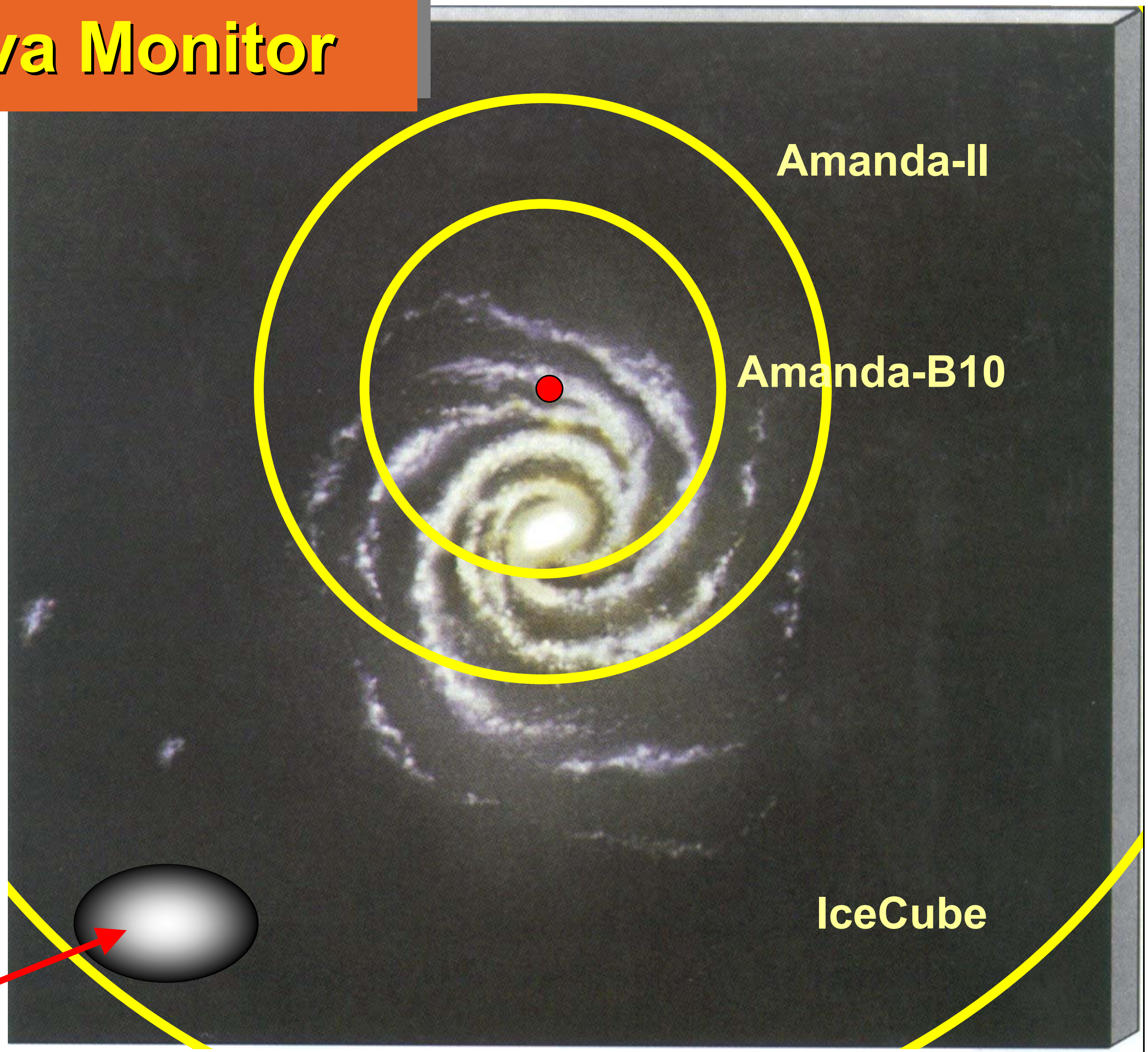
Supernova Monitor

B10:
60% of Galaxy

A-II:
95% of Galaxy



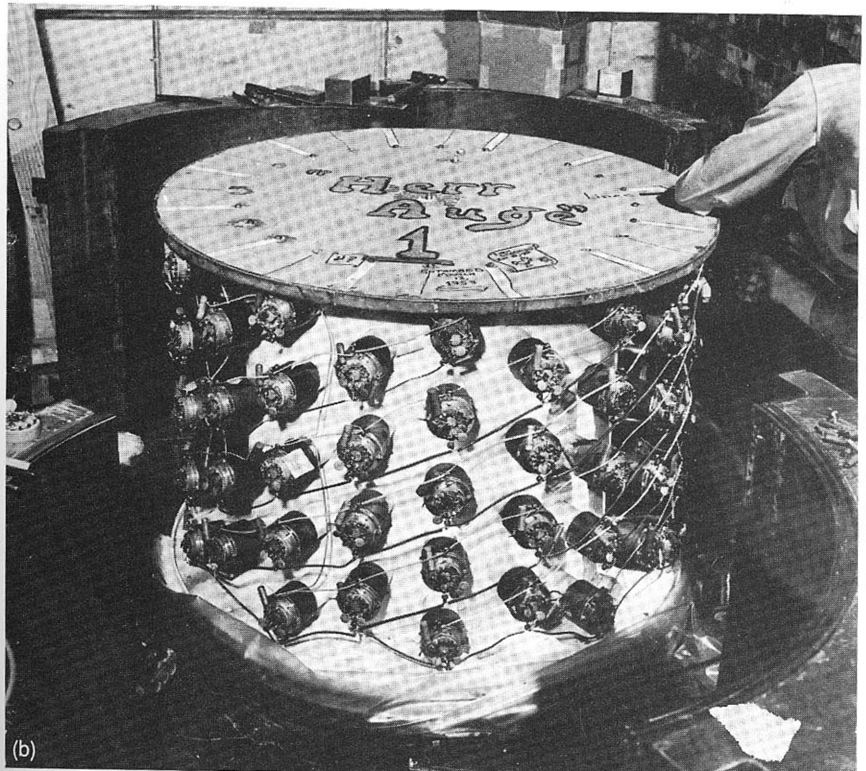
IceCube:
up to LMC



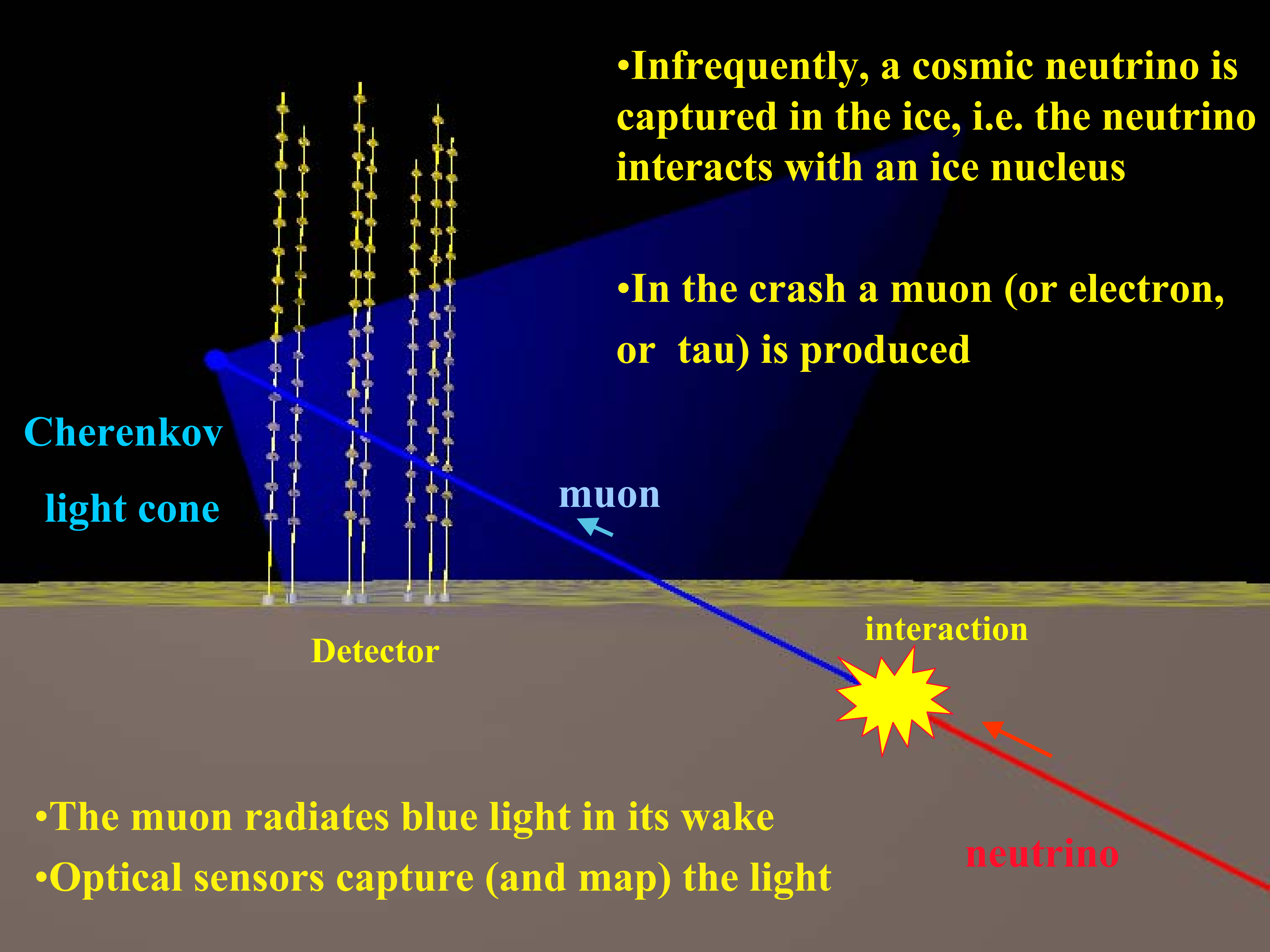
Kilometer-scale neutrino detectors?

How?

(a)



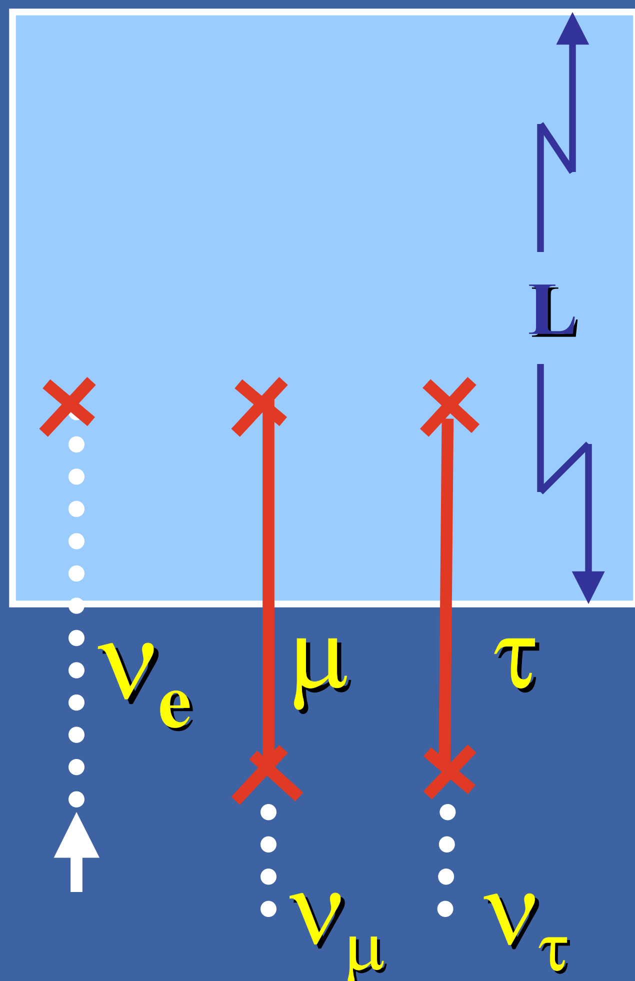
(b)


•Infrequently, a cosmic neutrino is captured in the ice, i.e. the neutrino interacts with an ice nucleus
•In the crash a muon (or electron, or tau) is produced
Cherenkov light cone
muon
Detector
interaction
•The muon radiates blue light in its wake
•Optical sensors capture (and map) the light
neutrino

Neutrino Detection Probability

neutrino survives

$$e^{-\frac{L}{\lambda_\nu}}$$



neutrino detected

$$1 - e^{-\frac{L}{\lambda_\nu}}$$

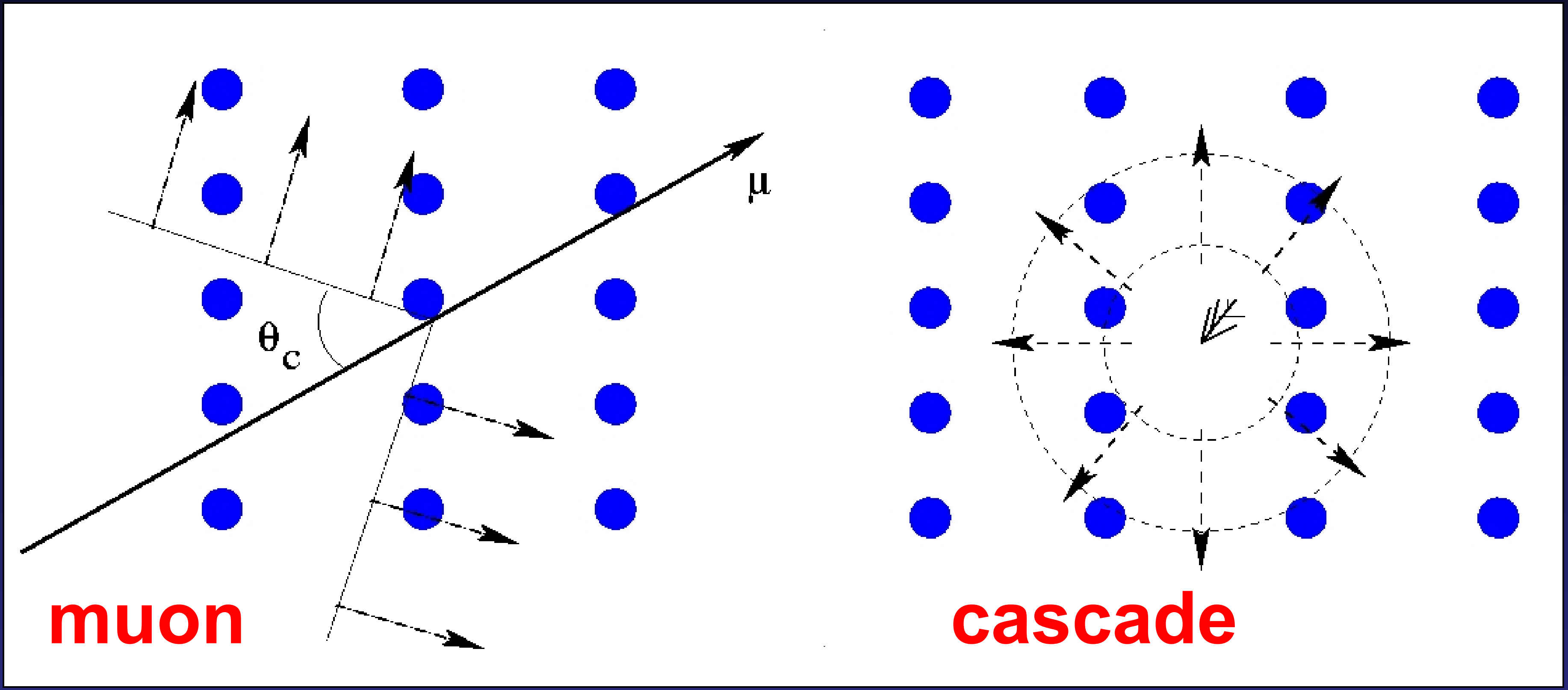
$$\simeq \frac{L}{\lambda_\nu}$$

$$\sim L\,\sigma_\nu$$

for ν_μ : $L \rightarrow R_\mu\ [E_\mu = (1 - y)\ E_\nu]$

for ν_τ : $L \rightarrow \frac{E_\tau}{m_\tau}\ c\ \tau_\tau$

Cherenkov light from muons and cascades



Reconstruction

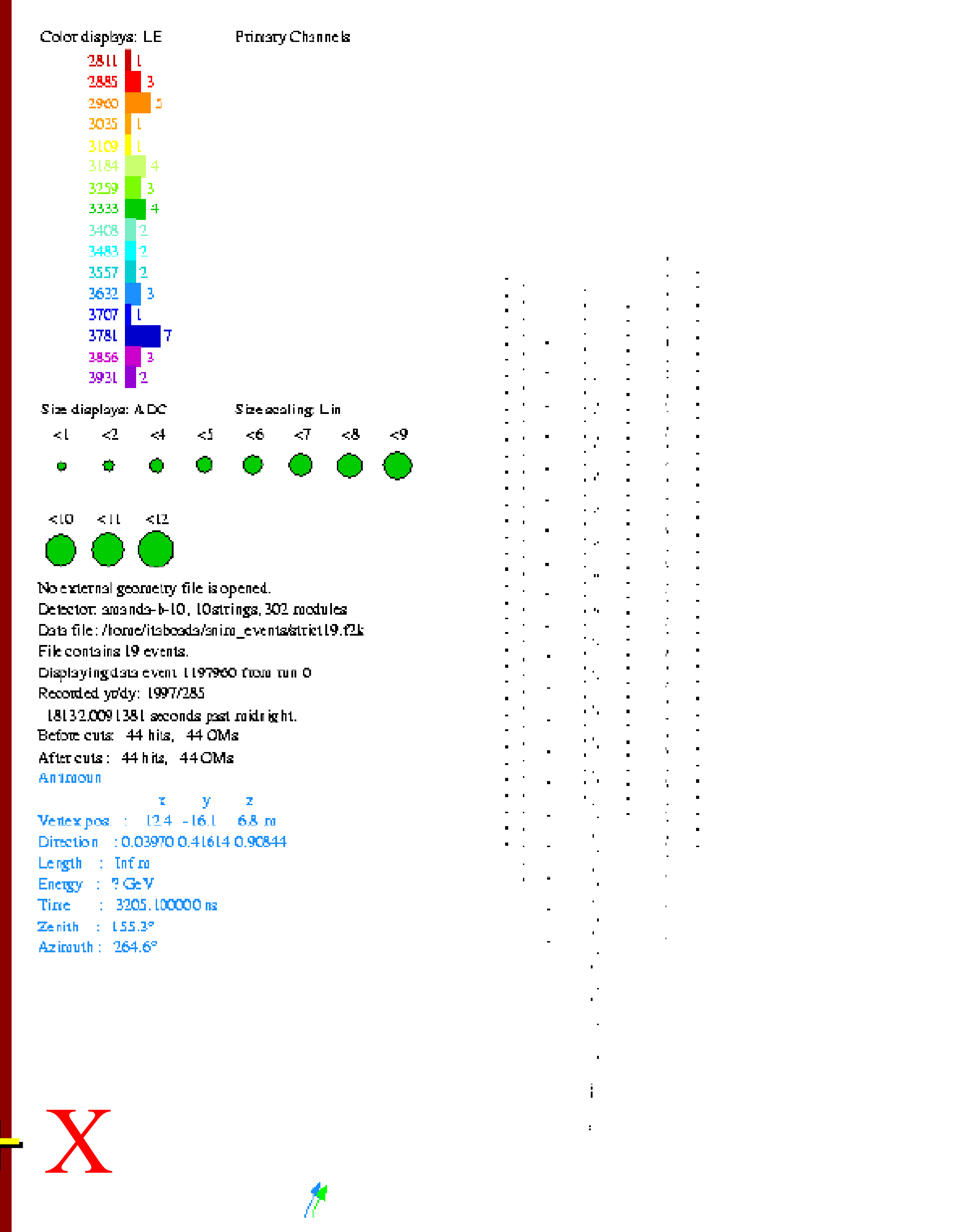
- Maximum likelihood method
- Use expected time profiles of photon flight times

AMANDA Event Signatures: Muons

CC muon neutrino Interaction

→ track

$$\nu_\mu + N \rightarrow \mu + X$$



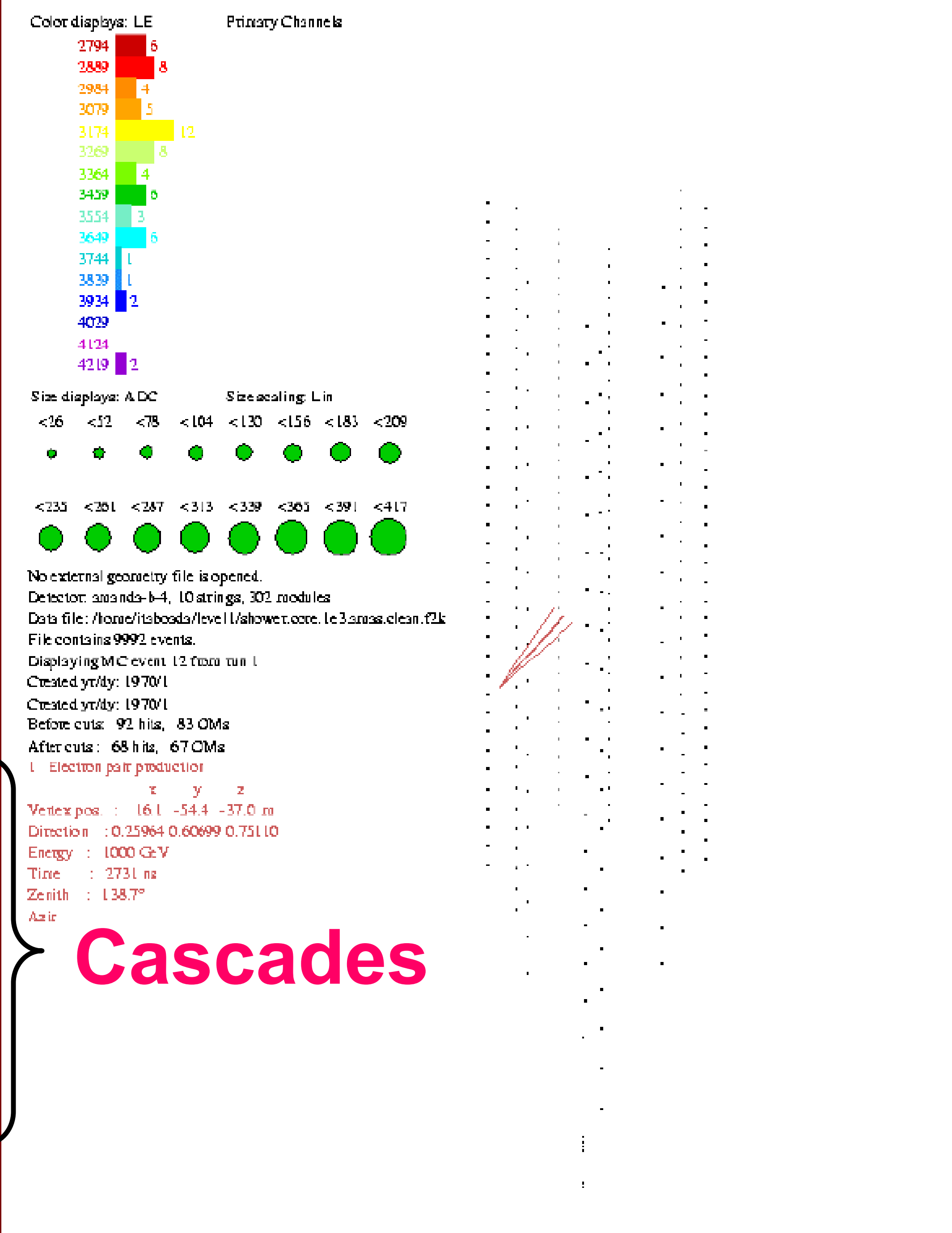
AMANDA Event Signatures: Cascades

- **CC electron and tau neutrino interaction:**

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

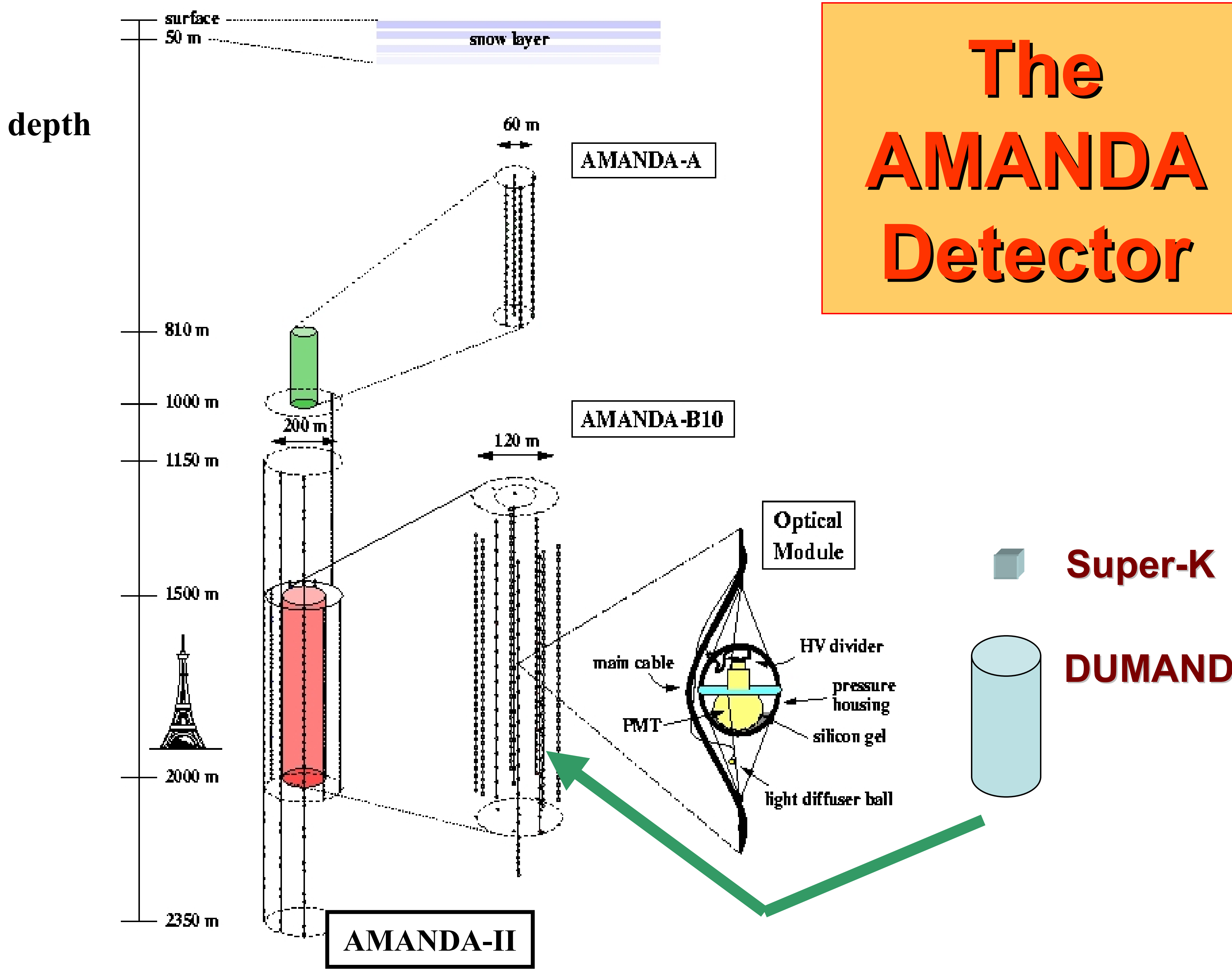
- **NC neutrino interaction:**

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

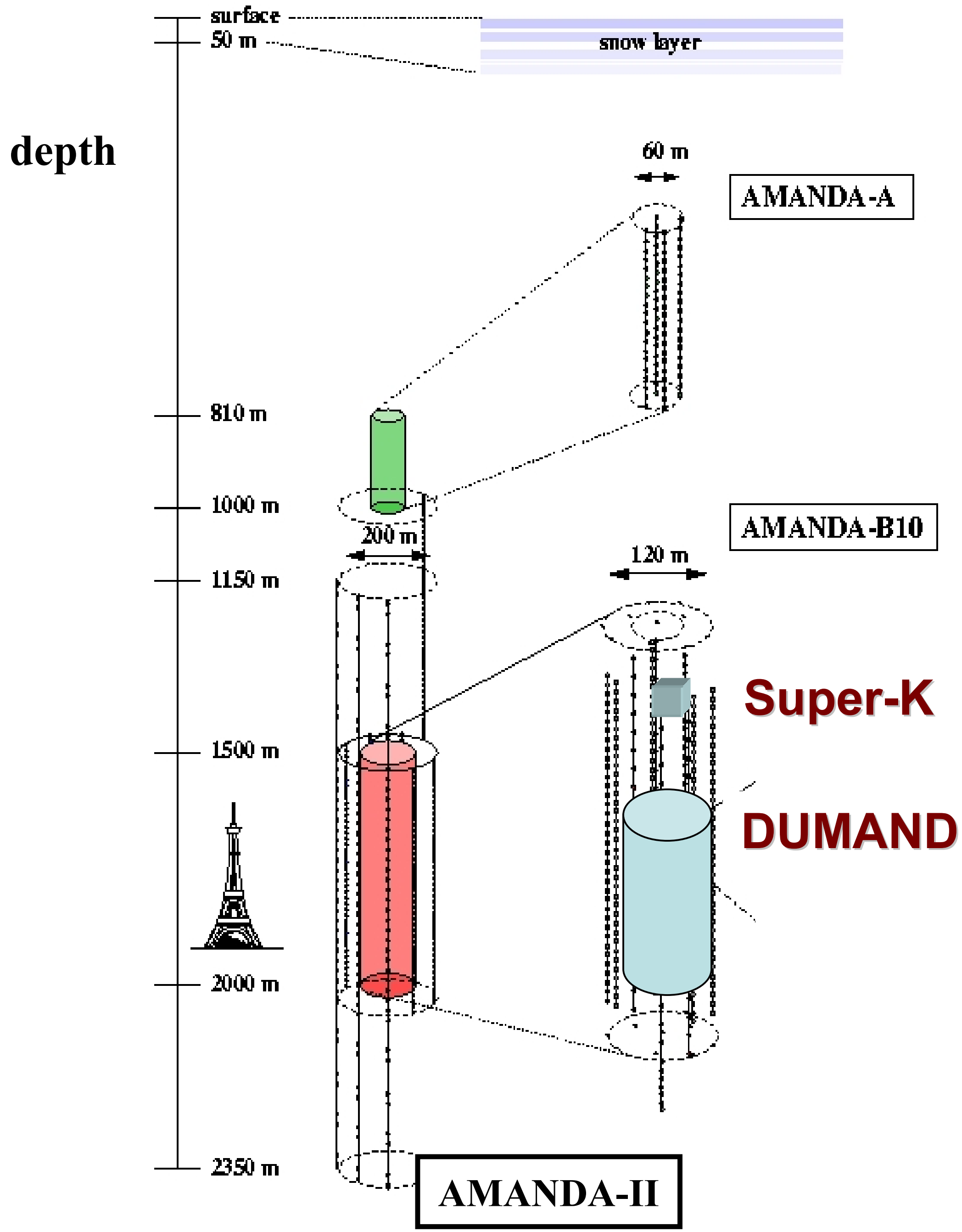


Cascades

The AMANDA Detector

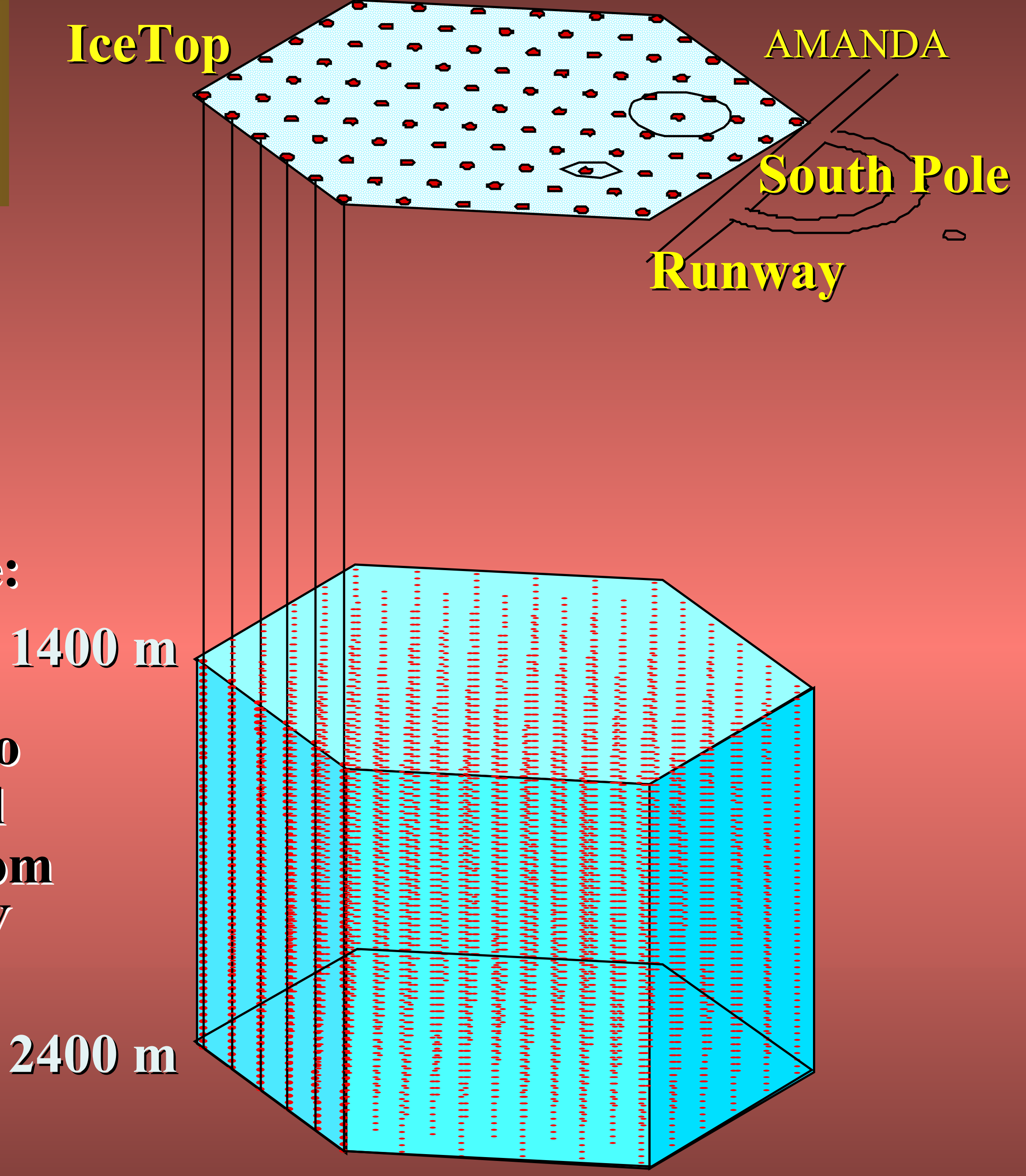


The AMANDA Detector



IceCube

- **80 Strings**
- **4800 PMT**
- **Instrumented volume: 1 km3 (1 Gton)**
- **IceCube is designed to detect neutrinos of all flavors at energies from 10^7 eV (SN) to 10^{20} eV**




South Pole

South Pole


Dark sector
Skiway
AMANDA
Dome
IceCube
Planned Location 1 km east

South Pole

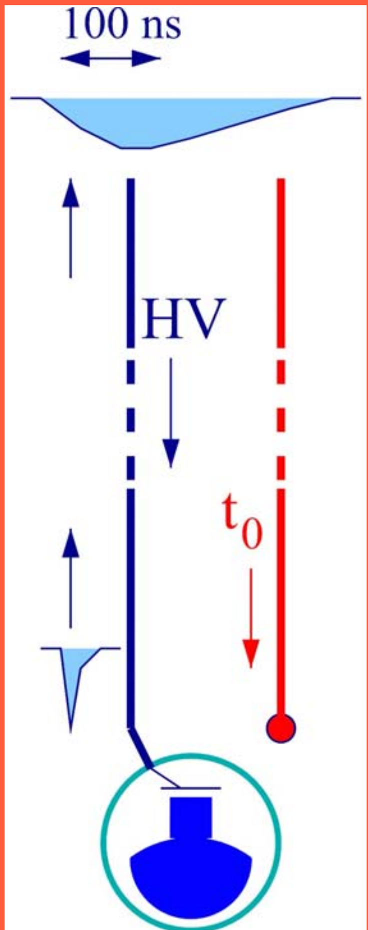
Building AMANDA

Drilling Holes with Hot Water

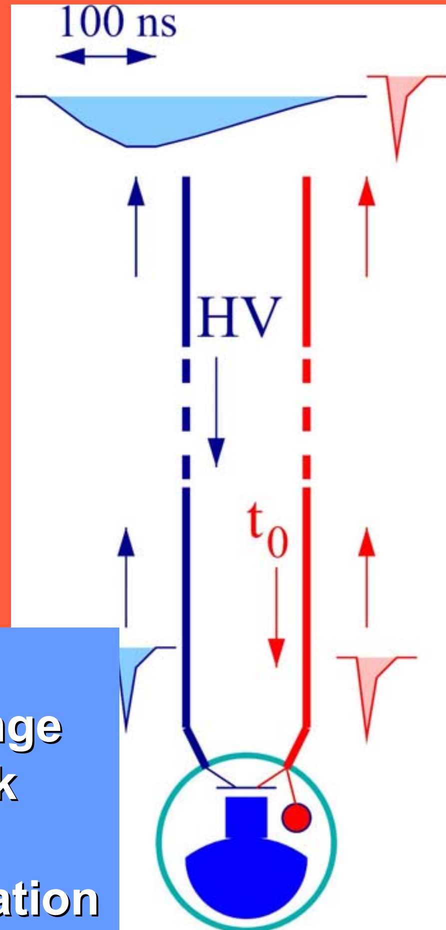
The Optical Module

Building AMANDA: The Optical Module and the String

Evolution of read-out strategy

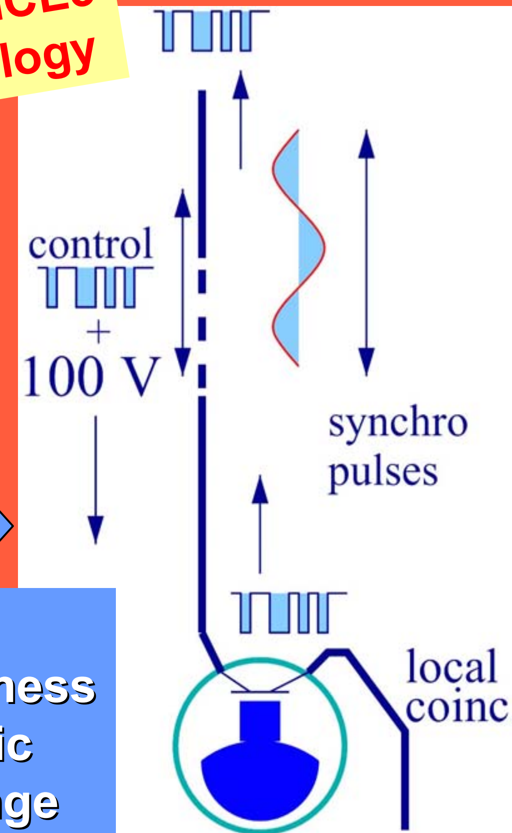


- timing
- dyn. range
- no x-talk
- easy calibration



Test of ICE3 technology

- cost
- robustness
- dynamic range



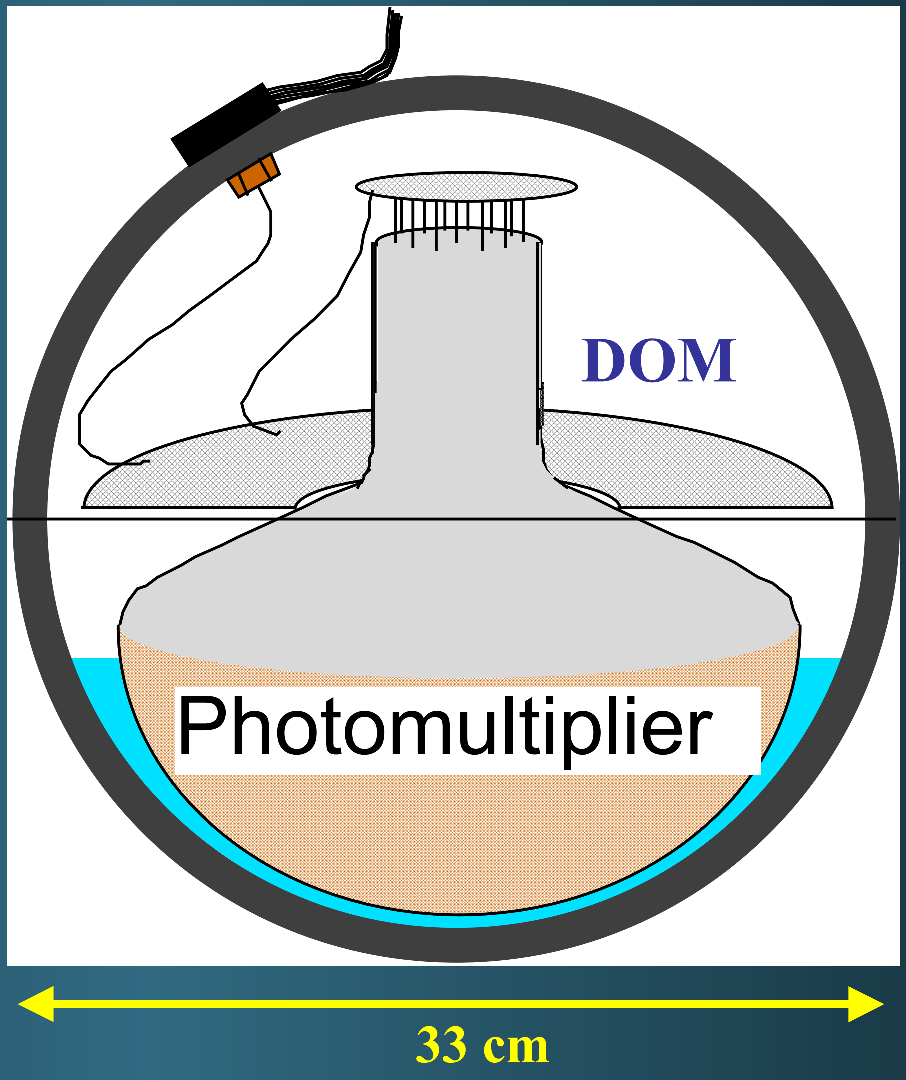
<u>01/02 - 03/04</u>: Equipping all Amanda channels with FADCs to get full waveform information (IceCube compatibility)

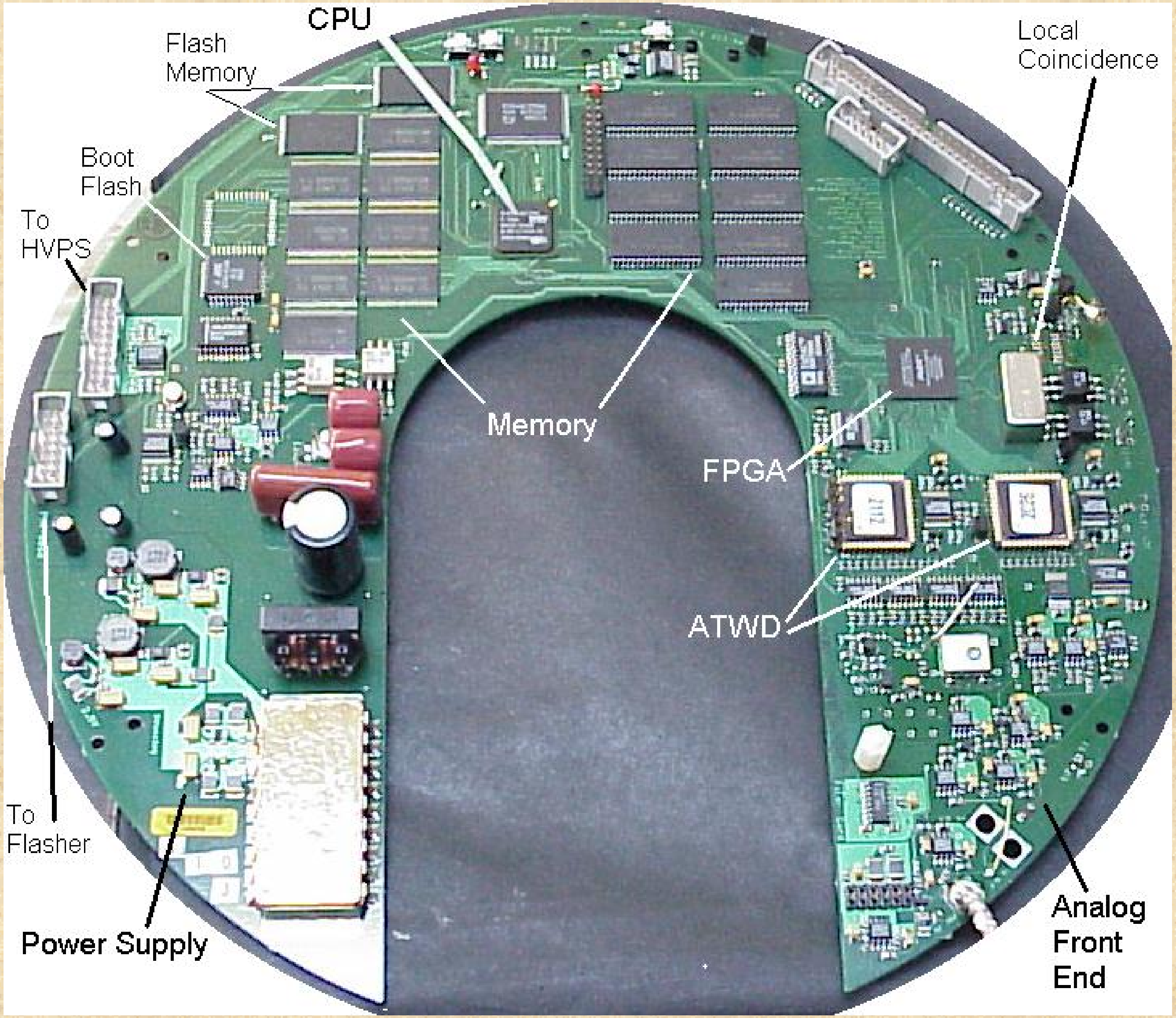
→ better reconstruction, particularly cascades and high energy tracks

DAQ design: Digital Optical Module - PMT pulses are digitized in the Ice

Design parameters:

- **Time resolution: < 5 ns rms**
- **Waveform capture:**
  >250 MHz for first 500 ns
  ~ 40 MHz for 5000 ns
- **Dynamic Range:**
  > 200 PE / 15 ns
  > 2000 PE / 5000 ns
- **Dead-time: < 1%**
- **OM noise rate: < 500 Hz (^{40}K in glass sphere)**

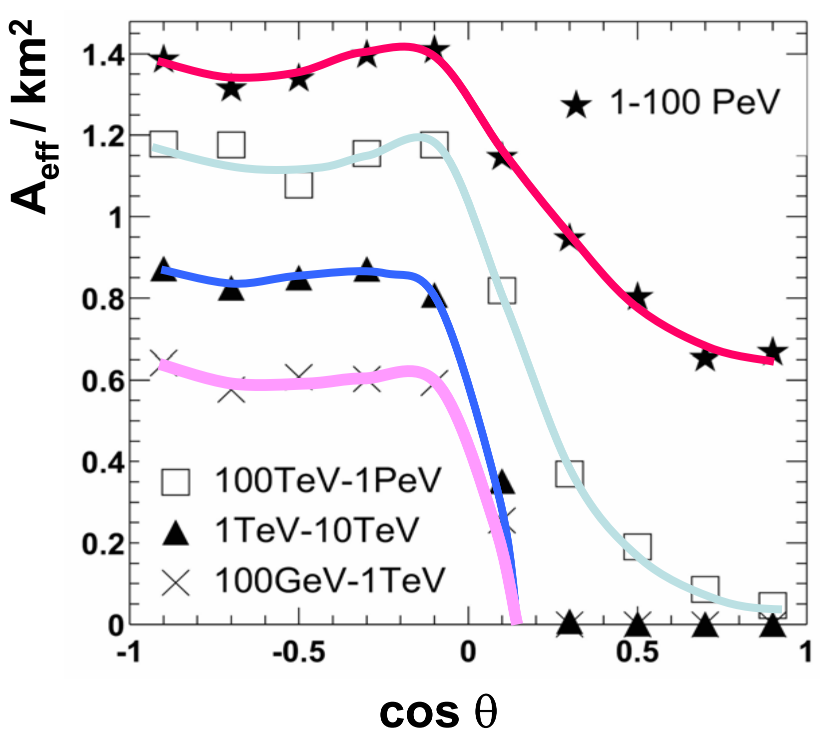


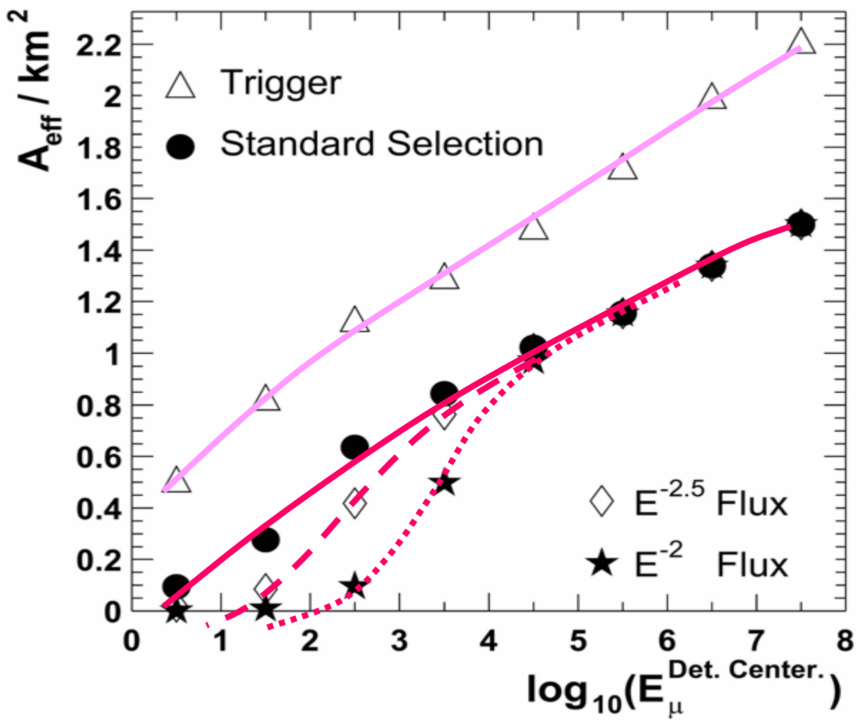

CPU
Flash Memory
Boot Flash
To HVPS
Local Coincidence
Memory
FPGA
ATWD
To Flasher
Power Supply
Analog Front End

IceCube has been designed as a discovery instrument with improved:

- telescope area (> 1km2 after all cuts)
- detection volume (> 1km3 after all cuts)
- energy measurement:
  secondary muons (< 0.3 in ln E) and
  electromagnetic showers (< 20% in E)
- identification of neutrino flavor
- Sub-degree angular resolution
  (< unavoidable neutrino-muon misalignment)

Effective area of IceCube

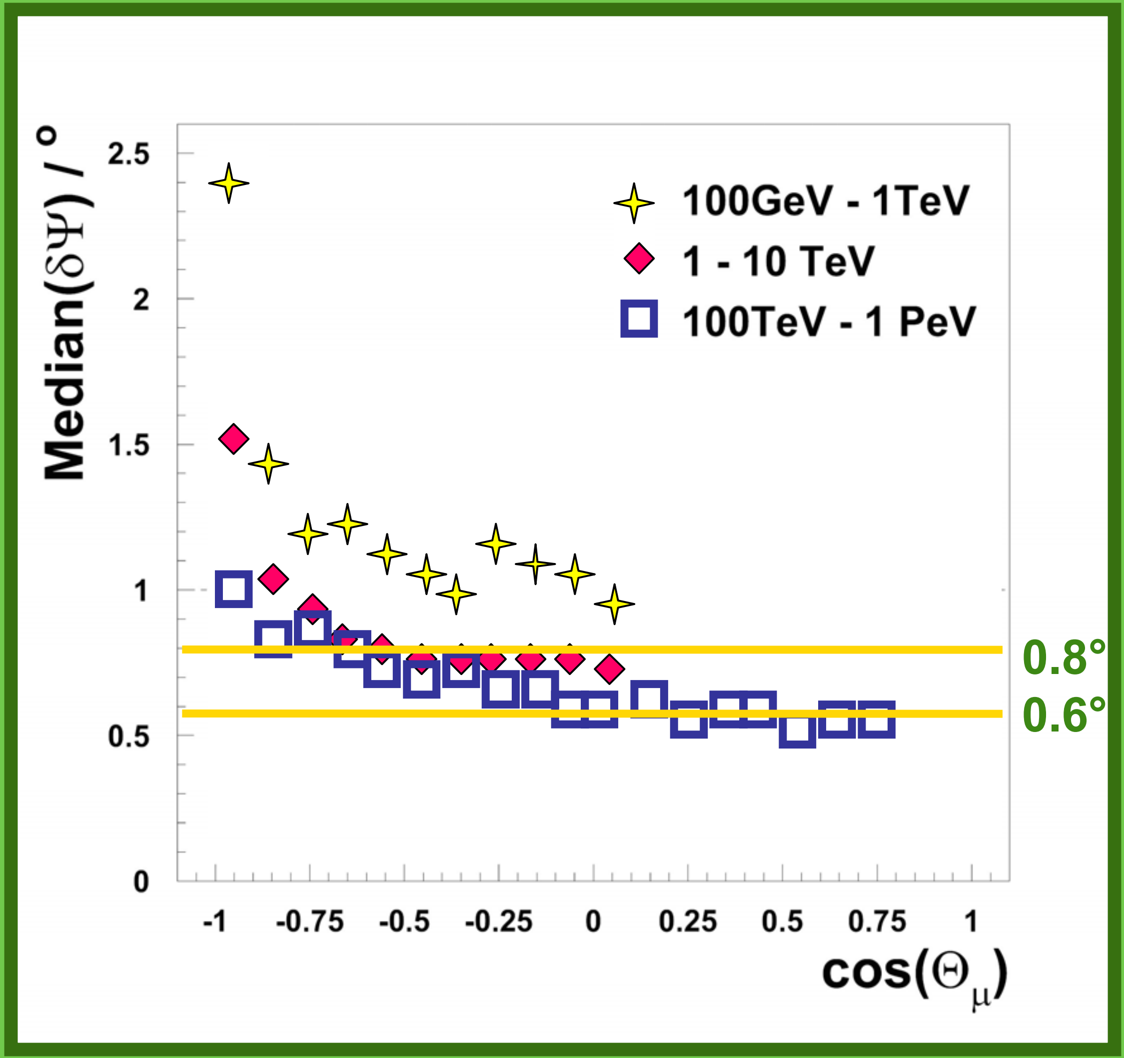




Effective area vs. zenith angle (downgoing muons rejected)

Effective area vs. muon energy (trigger, atm μ, pointing cuts)

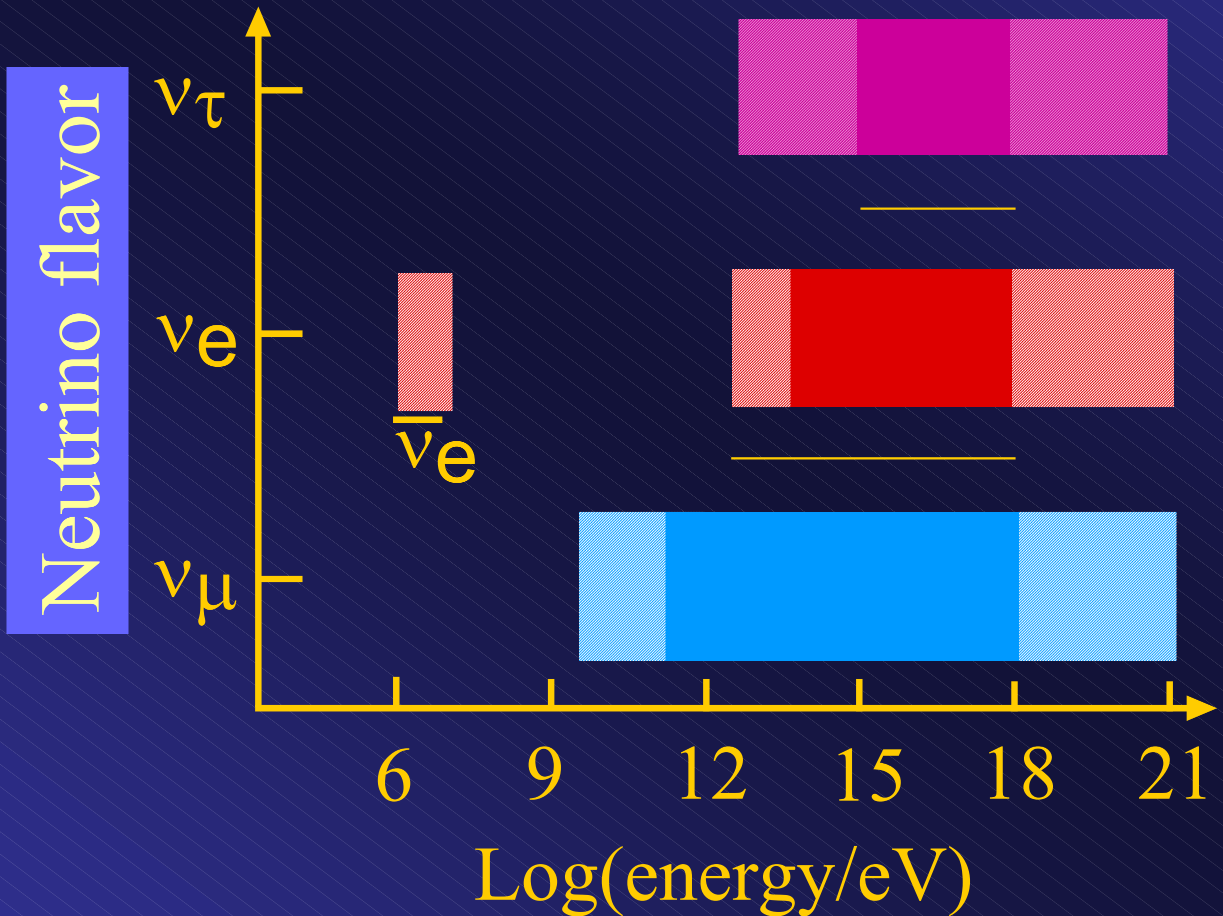
Angular resolution as a function of zenith angle



Waveform information not used. Will improve resolution for high energies !

→ above 1 TeV, resolution ~ 0.6 - 0.8 degrees for most zenith angles

Neutrino ID (solid)
Energy and angle (shaded)



- Filled area: particle id, direction, energy
- Shaded area: energy only

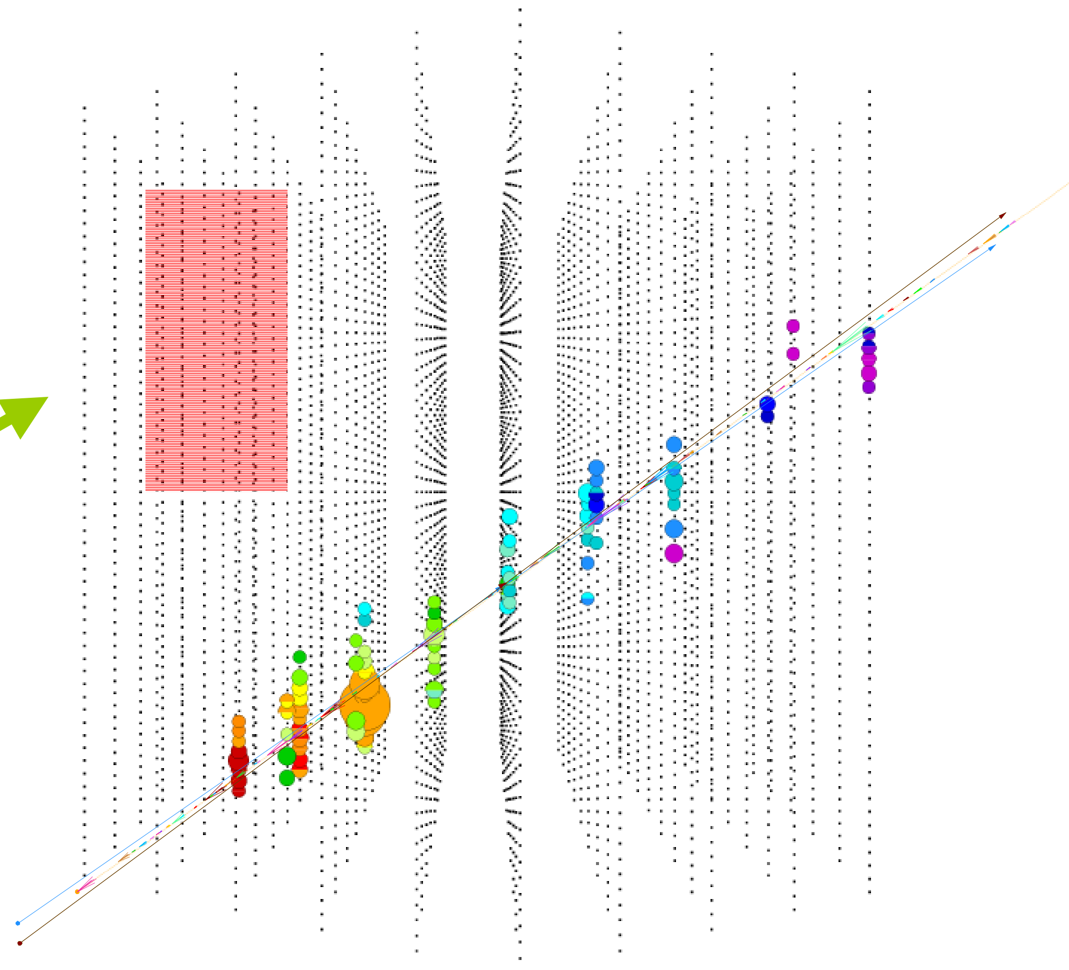
Enhanced role of tau neutrinos:

- Cosmic beam: $\nu_e = \nu_\mu = \nu_\tau$ because of oscillations
- ν_τ not absorbed by the Earth (regeneration)
- Pile-Up near 1 PeV where ideal sensitivity

μ-event in IceCube

300 atmospheric neutrinos per day

AMANDA II



1 km

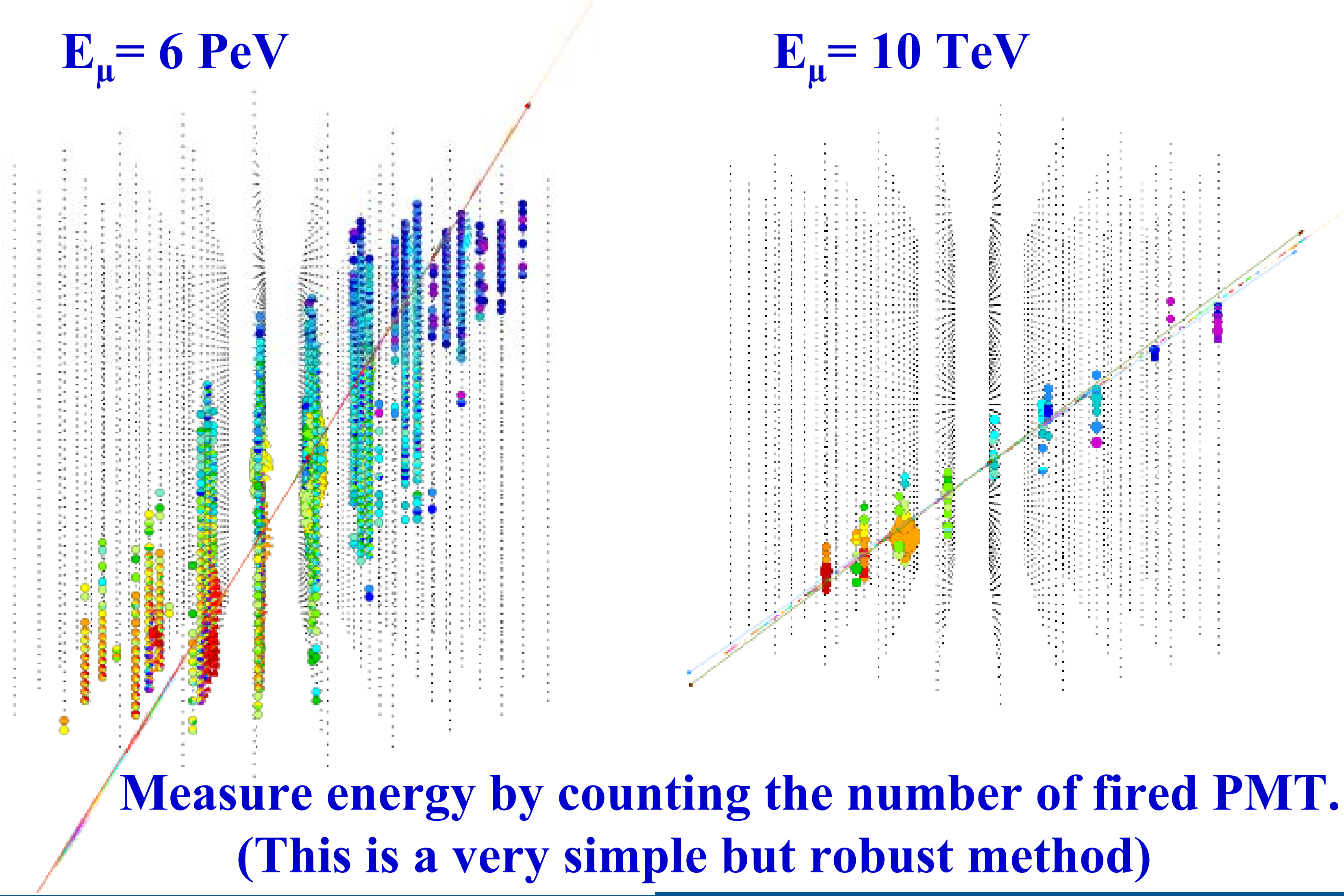
IceCube:

-> Larger telescope

-> Superior detector

Muon Events

E_μ= 6 PeV E_μ= 10 TeV



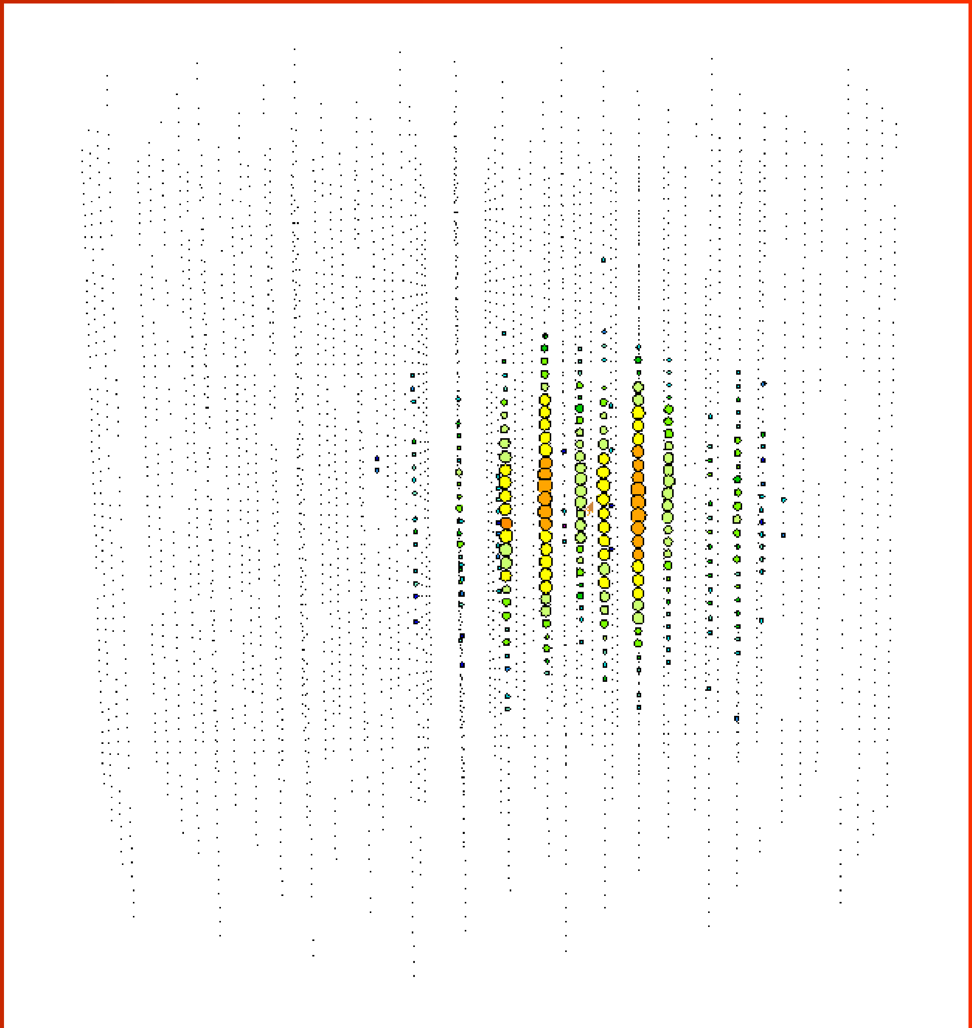
Measure energy by counting the number of fired PMT.
(This is a very simple but robust method)

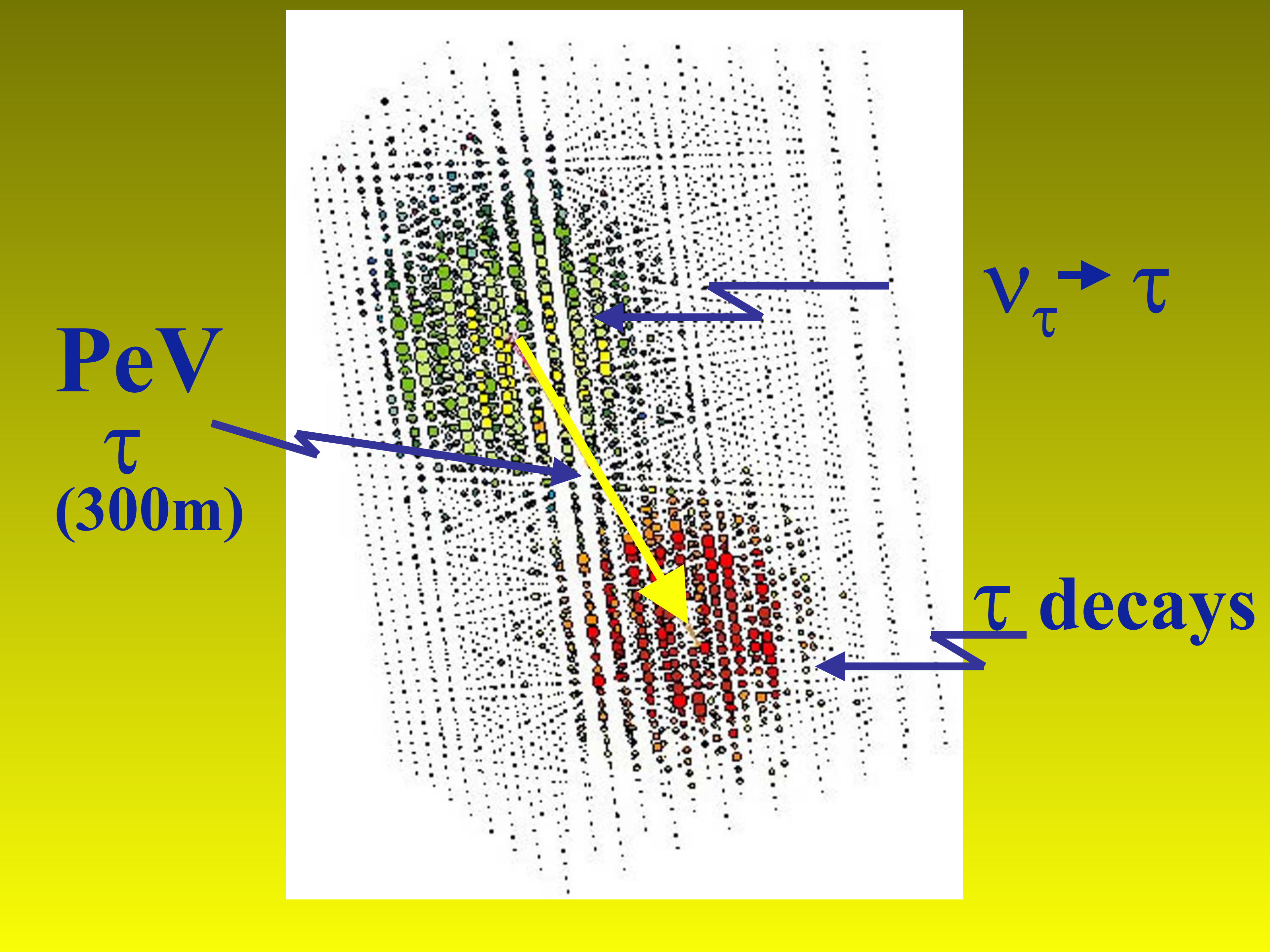
Cascade event

ν_e + N --> e- + X

- the length of the e^- cascade is small compared to the spacing of sensors.
- roughly spherical density distribution of light.
- 1 PeV " 500 m diameter, additional 100 m per decade of energy
- linear energy resolution

Energy = 375 TeV



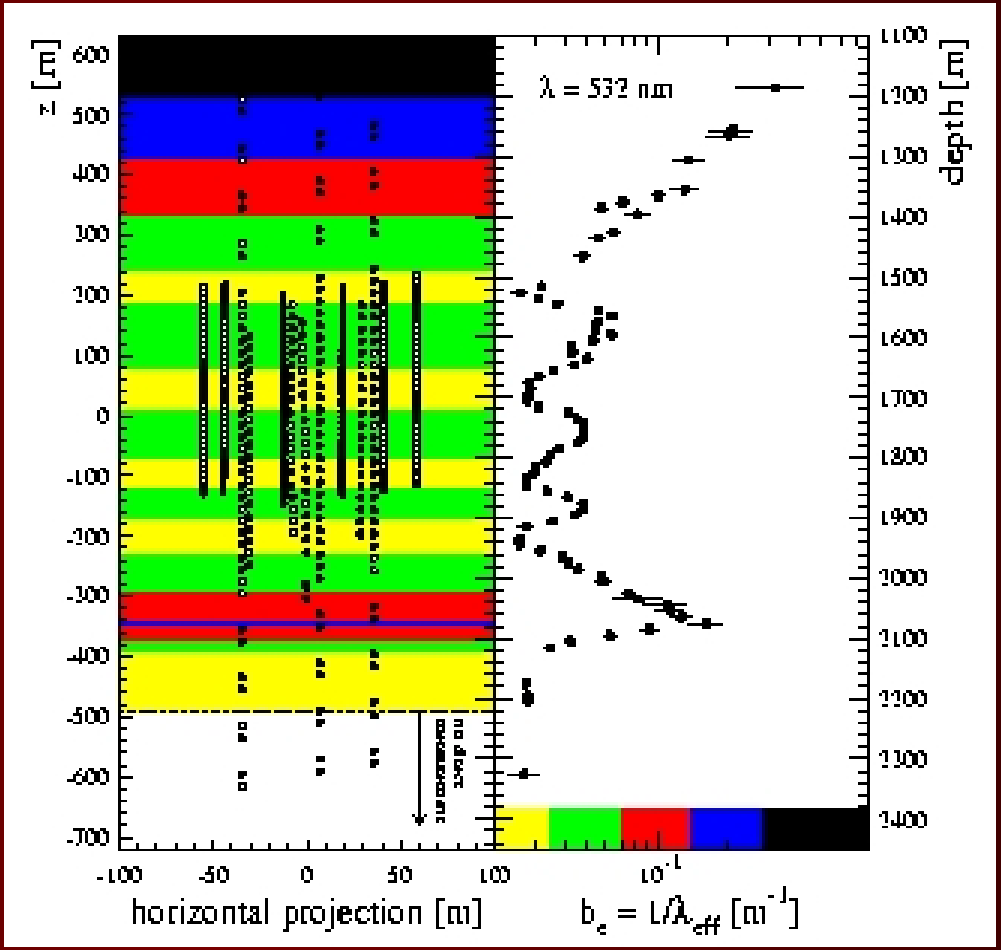

$\nu_\tau \rightarrow \tau$
PeV
τ
(300m)
τ decays

AMANDA: Proof of Concept

- since 1992 we have deployed 24 strings with more than 750 photon detectors (basically 8-inch photomultipliers).
- R&D detector for proof of concept: 375 times SuperK instrumented volume with 1.5% the total photocathode area.
- IceCube: 45 times AMANDA II instrumented volume with 7 times the total photocathode area.

Ice Properties

- Most challenging initial problems now understood using *in situ* lasers and LEDs
  - Disappearance of bubbles
  - Mapping of dust layers
- $\lambda_{scatter}$: 15 m - 45 m
- $\lambda_{absorption}$:
  90m - 240 m

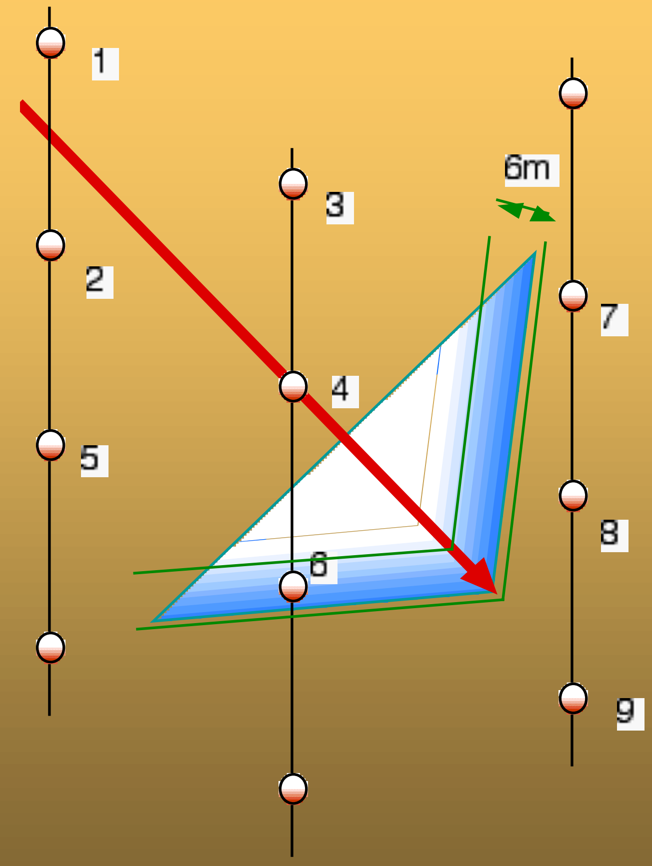


Understanding Ice and Calibrating AMANDA

- ***In situ* light sources**
  - Ice properties
  - Relative PMT timing, gain
  - Response to electromagnetic showers
  - crosstalk
- ***Downgoing cosmic-ray muons***
  - Relative PMT timing, gain
- ***AMANDA-SPASE coincidences***
  - Directionality
  - Ice properties
- ***Atmospheric neutrinos***
  - Full detector response

Event reconstruction

- Maximum Likelihood method
- Take into account time profiles of expected photon flight times
- Bayesian approach - use prior knowledge of expected backgrounds and signals



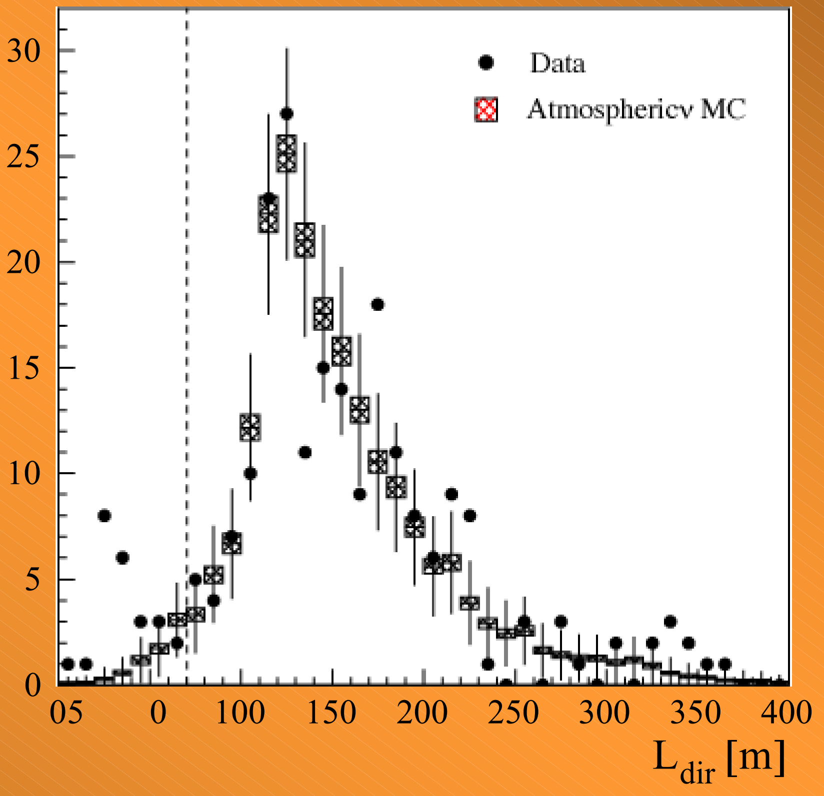
Atmospheric muons and neutrinos

- Atm. Neutrinos (ν_μ): 60/day
- Atm. Muons: $8.6*10^6$/day

Lifetime: 135 days		
	Observed Data	Pred. Neutrinos
Triggered	1,200,000,000	4574
Reconstructed upgoing	5000	571
Pass Cuts (Q " 7)	204	273

Quality parameters: Example 1: The track length

- **Short track length = more likely to be background**



Quality Parameters

- **Likelihood**
- **Zenith angle mismatch between two types of fits.**
- **Sphericity of Hits (Brem?)**
- **Track Length (is an energy cut, too)**
- **Smoothness of hits along the track**
- **Number of unscattered photons**

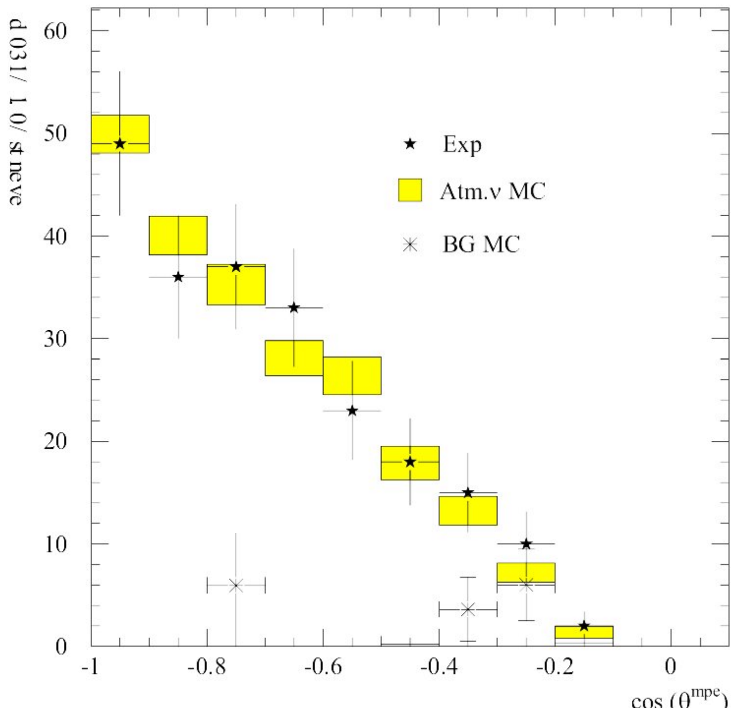
- **Combine 6 to a single event quality parameter.**
- **Only 3 for completed detector!**

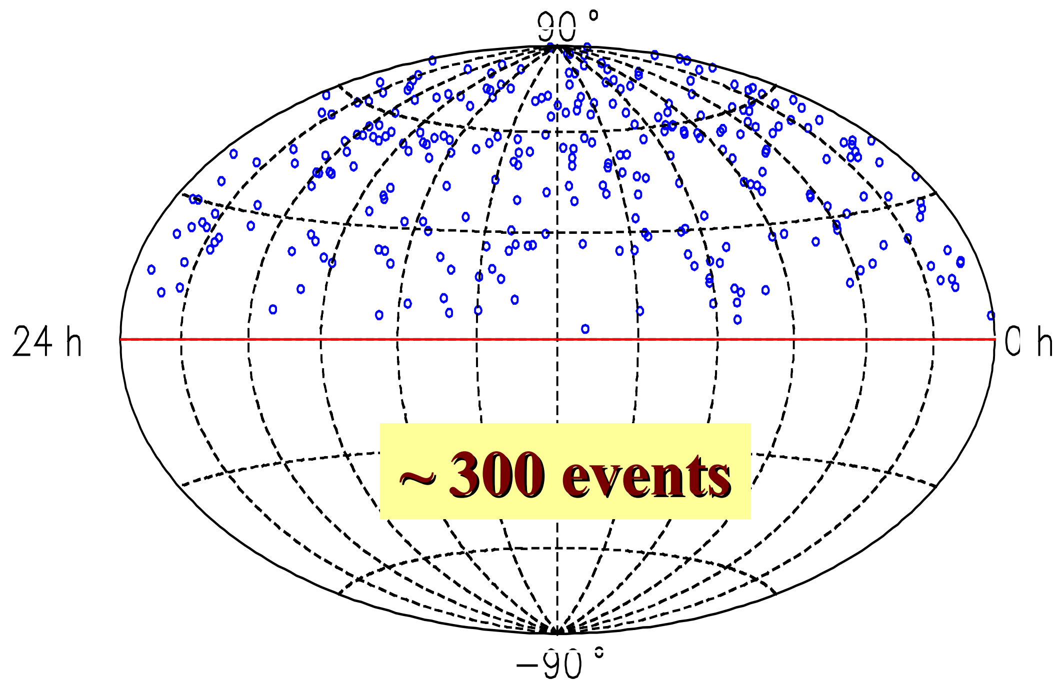
Atmospheric muons and neutrinos

- Atm. Neutrinos (ν_μ): 60/day
- Atm. Muons: $8.6*10^6$/day

Lifetime: 135 days		
	Observed Data	Pred. Neutrinos
Triggered	1,200,000,000	4574
Reconstructed upgoing	5000	571
Pass Cuts (Q " 7)	204	273

Atmospheric Neutrinos, 97 data





vertically up

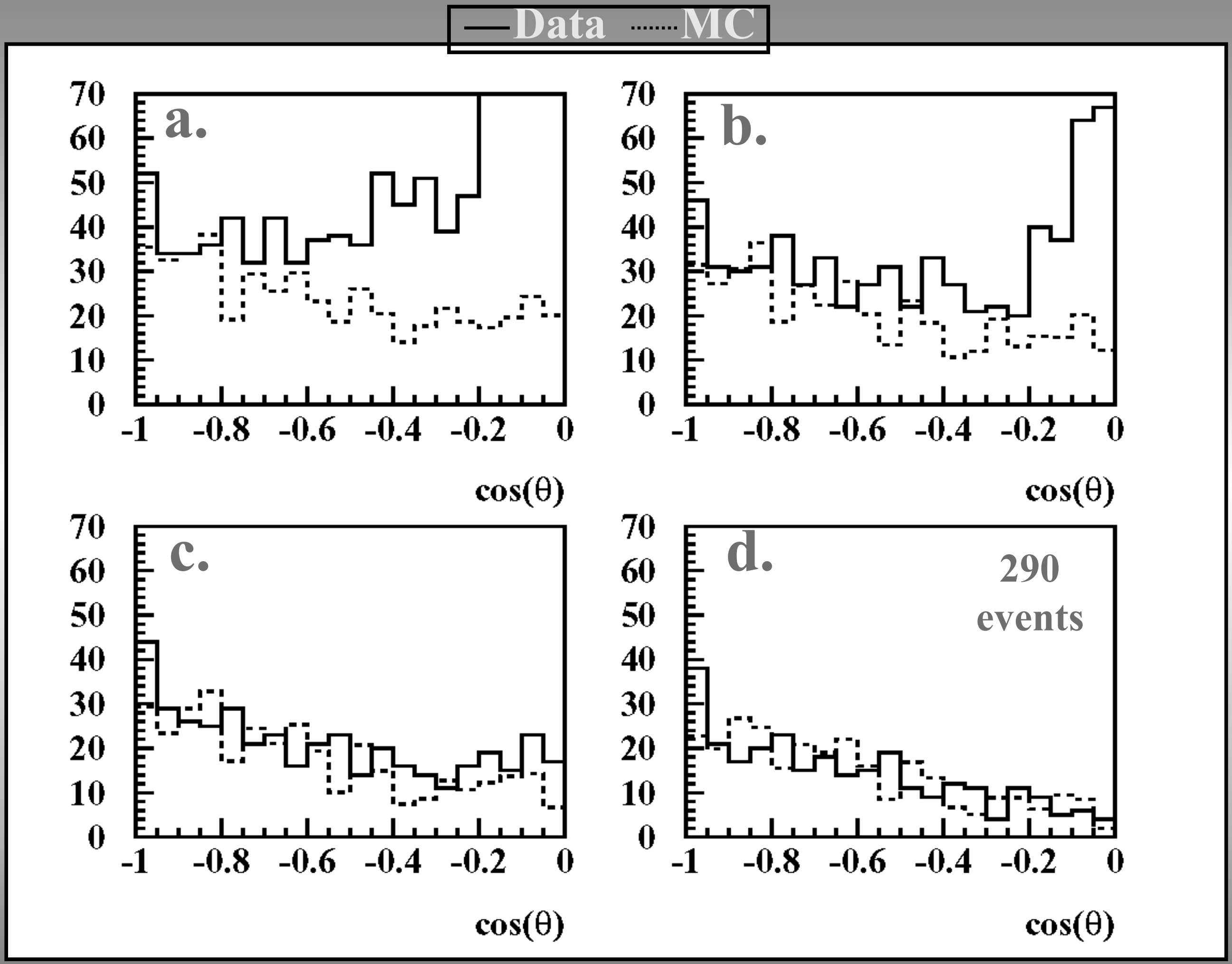
horizontally

AMANDA II: Atmospheric ν's as Test Beam

- **Selection Criteria:**
  - (N_{hit} < 50 only)
  - Zenith > 110°
  - High fit quality
  - Uniform light deposition along track
- **Excellent shape agreement!**
  - Less work to obtain than with A-B10

3 cuts only!

4 nus per day



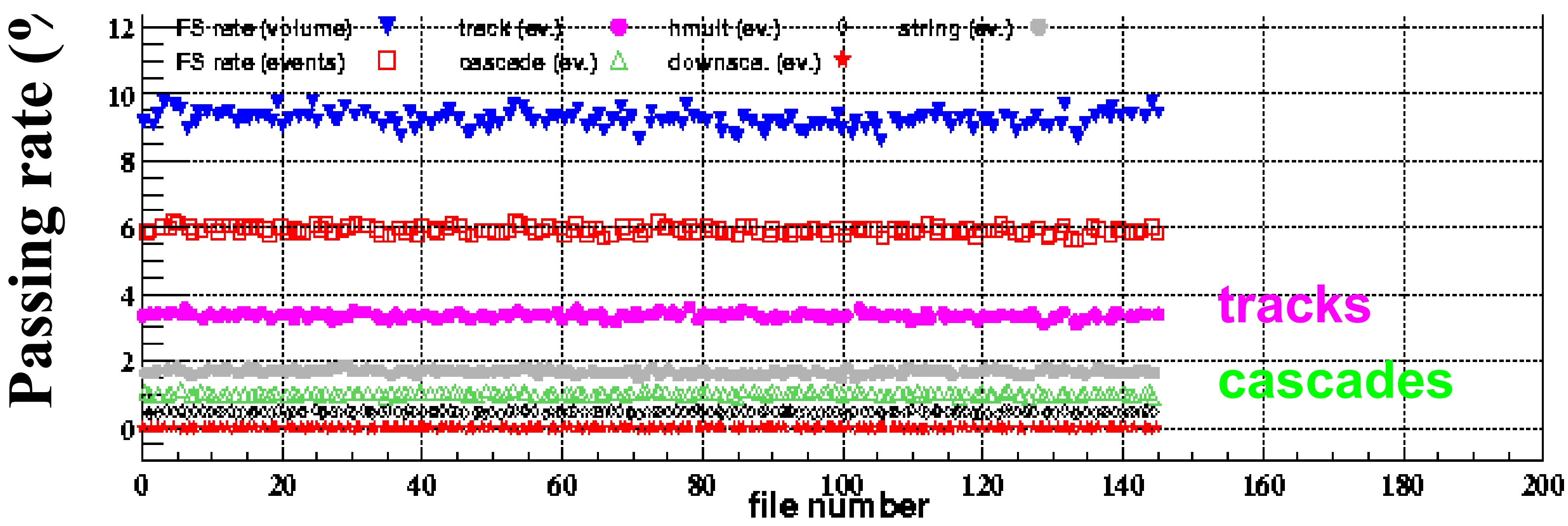
Gradual tightening of cuts extracts atm. ν signal

2002 real time analysis at Pole

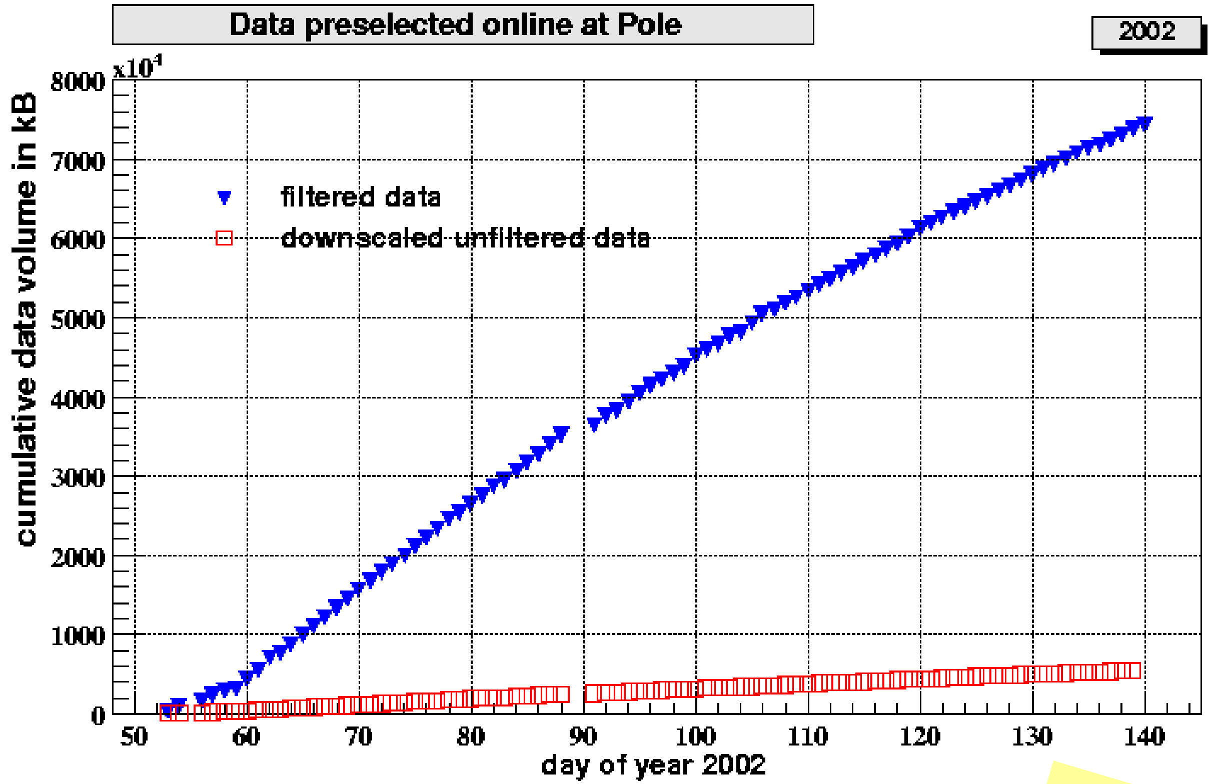
On line reconstruction and filtering with 2 high end PCs at SP

→ **2 % minimum bias**
→ **upward tracks**
→ **cascades**
→ **high multiplicities**
→ **string trigger**
→ **Spase-Amanda**

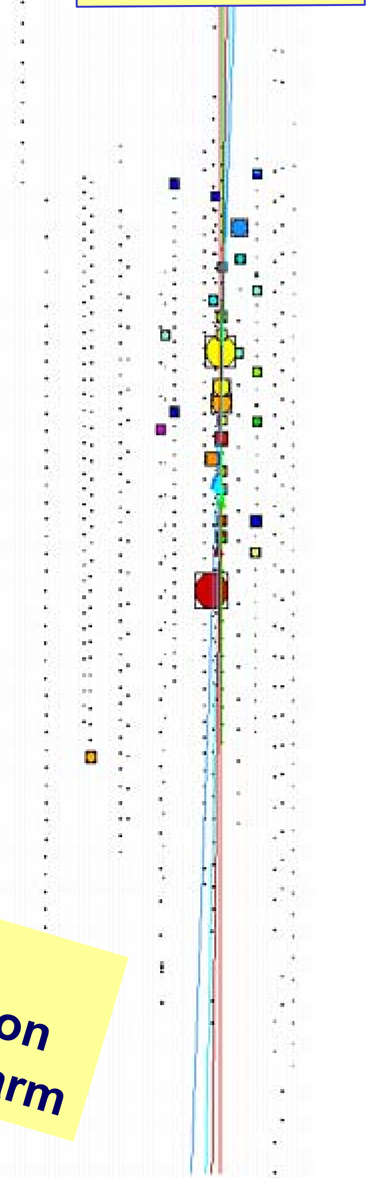
Friday, 14 June, 2002



2002 real time analysis



ν event
June 14



Daily transmission ~ 1 GB via satellite
Full data to tape (available next polar summer)
Monitoring shifts in home labs

From 02/03:
Iridium connection
for supernova alarm

Summary on Technology

- Over 5 years, Amanda has evolved into a 30.000 m^2 neutrino telescope
- Construction and improvement hand in hand
- Developed and tested IceCube technology
- Detailed measurement of ice down to 2.4 km
- Clear record in performance, reliability, time schedule and cost
- We know that we can build a km3 telescope

AMANDA

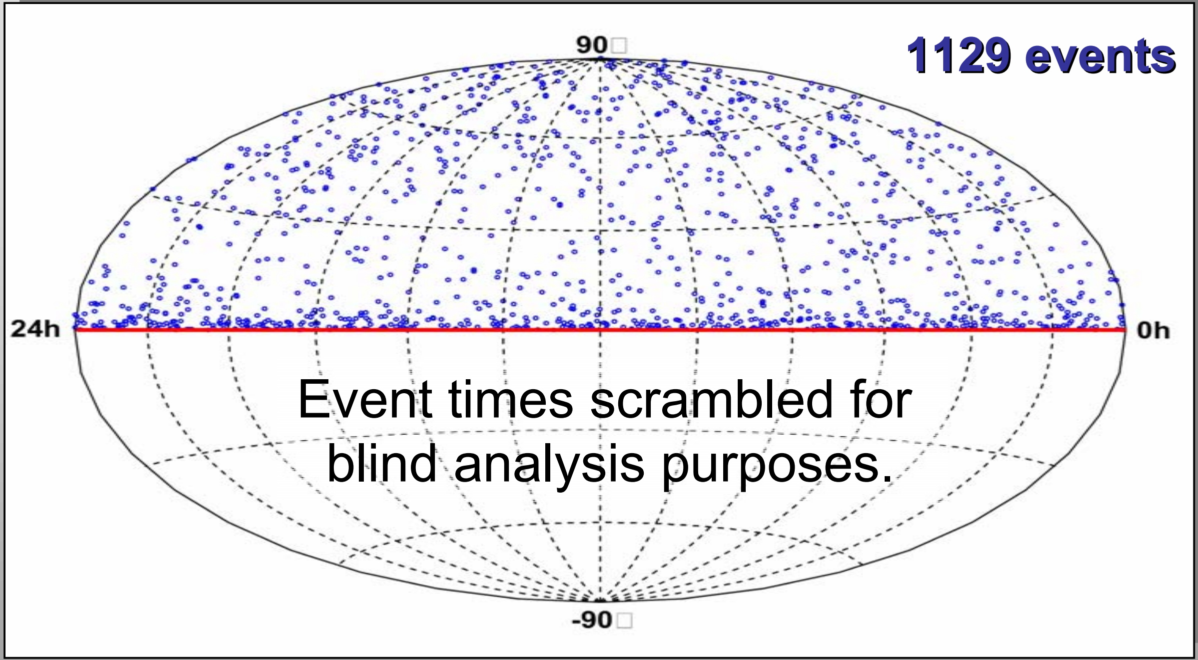
Initial physics results and first Amanda-II data

Reconstruction Handles

	up/down	energy	source direction	time
Atmospheric ν_μ	x			
Diffuse ν, EHE events	x	x		
Point Sources: AGN,WIMPs	x	x	x	
GRBs	x	x	x	x

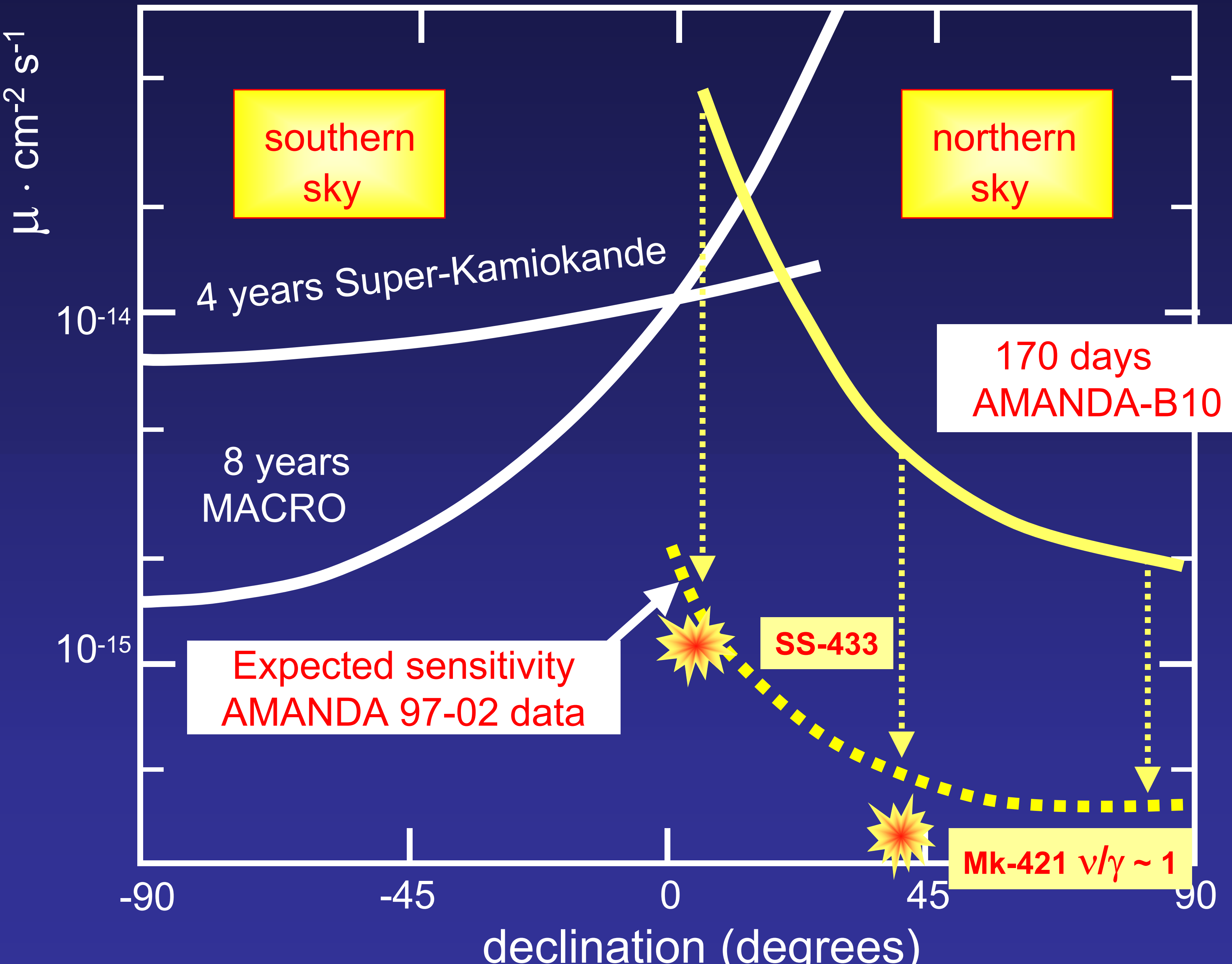
Point Sources Amanda II (2000)

- **Improved coverage near horizon**
- **Sensitivities calculated using background levels predicted from data**
- **close to "ν/γ ~ 1 sensitivity" for some sources**



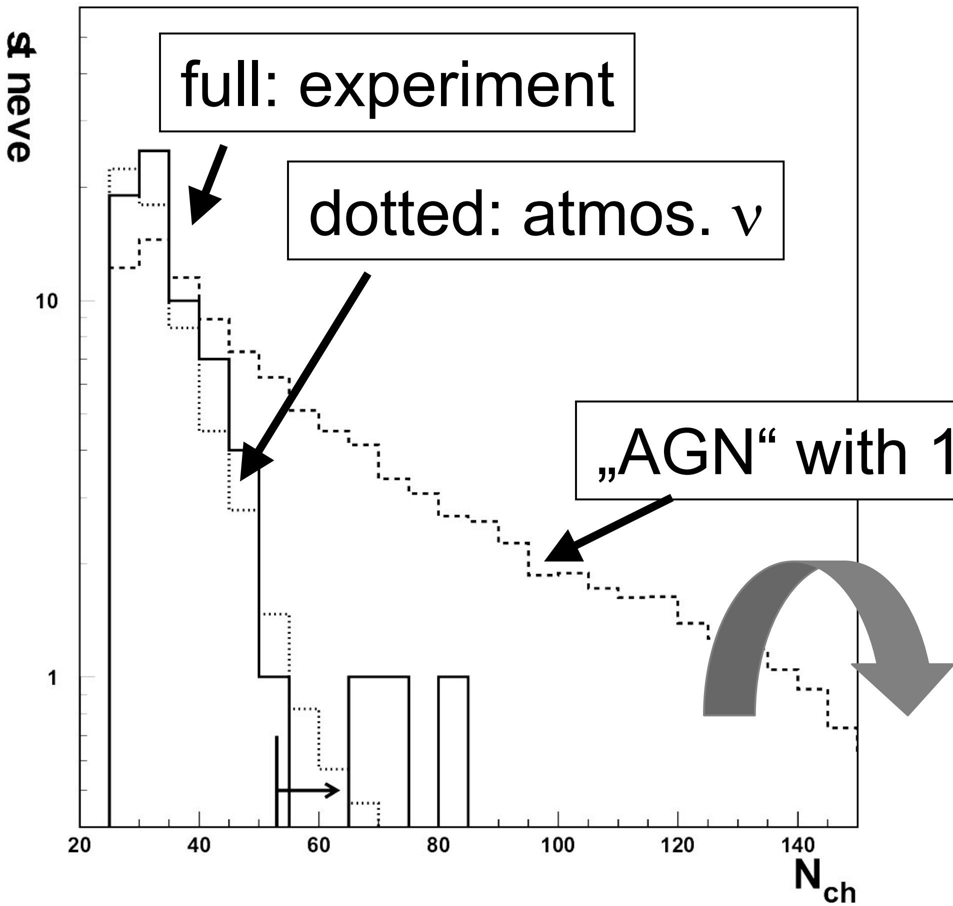
Source\Sensitivity	muon ($\times 10^{-15}$ cm^{-2} s^{-1})	ν($\times 10^{-8}$ cm^{-2} s^{-1})
Markarian 421	1.8	1.1
Markarian 501	1.8	1.1
Crab	2.7	1.3
Cass. A	1.6	1.2
SS433	5.9	2.4
Cyg. X-3	1.7	1.1

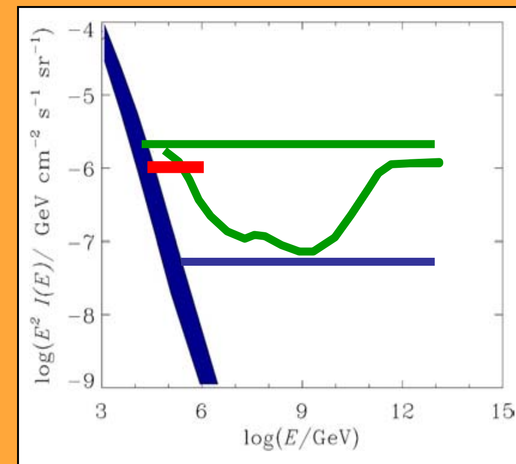
PRELIMINARY



$\mu \cdot cm^{-2}\, s^{-1}$
10^{-14}
10^{-15}
southern sky
northern sky
4 years Super-Kamiokande
8 years MACRO
170 days AMANDA-B10
Expected sensitivity AMANDA 97-02 data
SS-433
Mk-421 $\nu/\gamma \sim 1$
-90
-45
0
45
90
declination (degrees)

Upper Limit on the diffuse flux of h.e. upward muon neutrinos





$E^2 \Phi$

$< 0.9 \cdot 10^{-6}$ GeV^{-1} cm^{-2} s^{-1} sr^{-1}

Search for diffuse ν-flux in IceCube

Method:

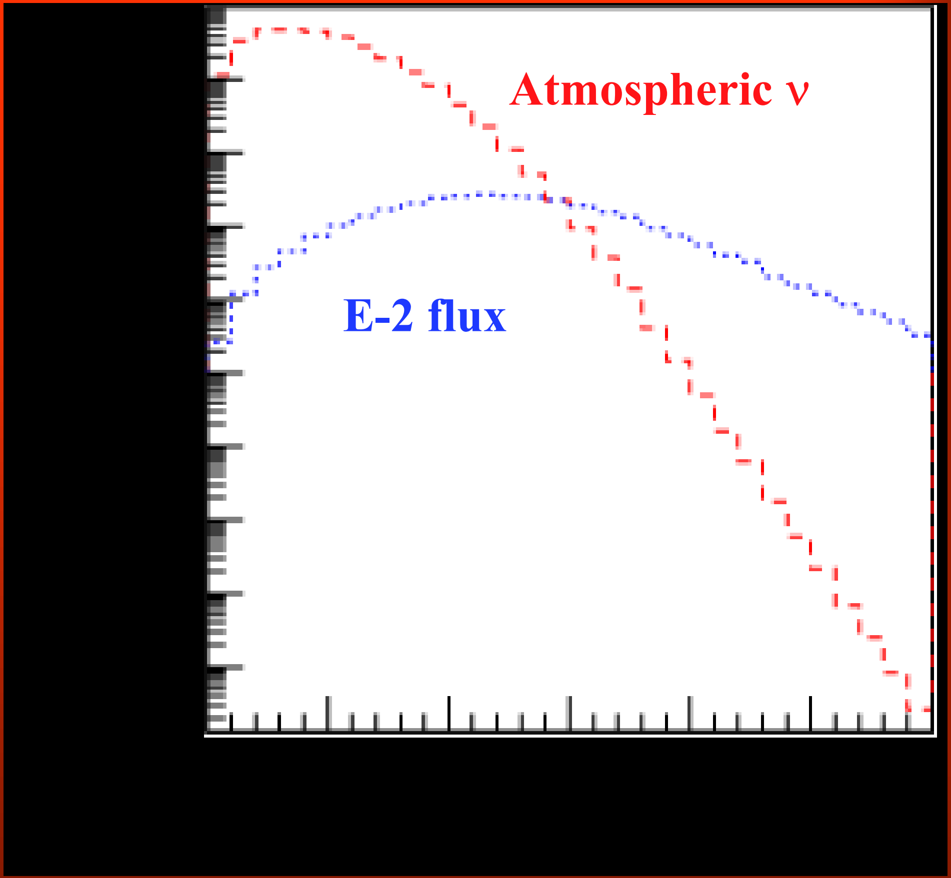
- Assume a diffuse neutrino flux at the current AMANDA limit:
  $dN/dE = 10^{-6} * E^{-2}/(cm^2\ sec\ GeV\ sr)$

→11,500 events /year

- The background is the atmospheric neutrino flux (after quality cuts):

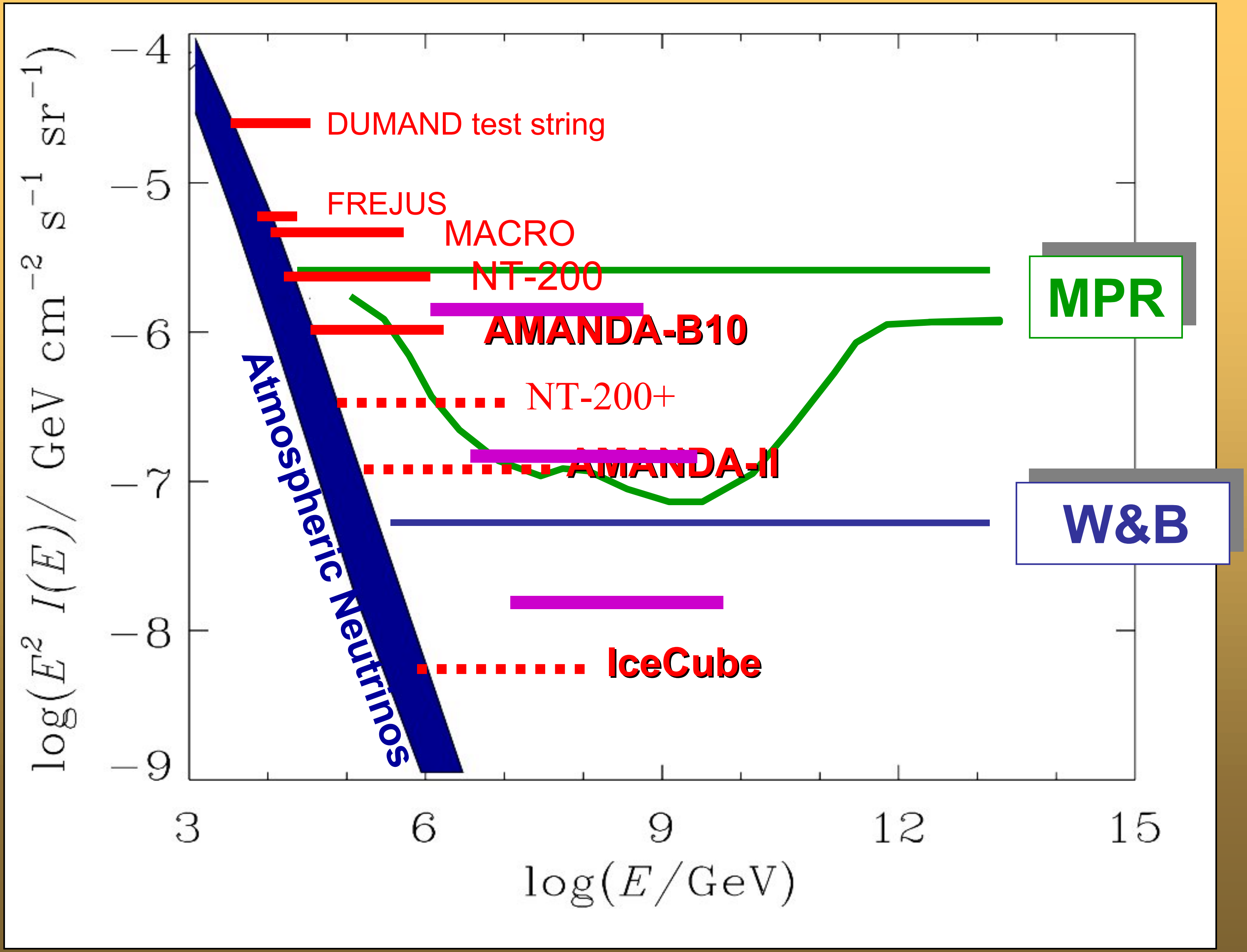
→100,000 atmospheric ν / year

~ 300 ν per day!



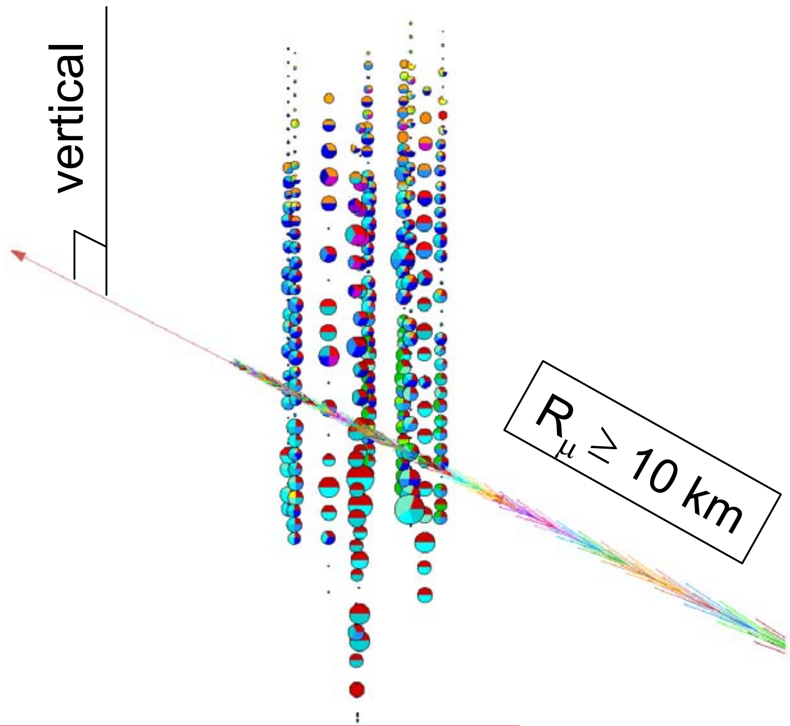
number of events vs neutrino energy

Diffuse fluxes: theoretical bounds and experimental limits



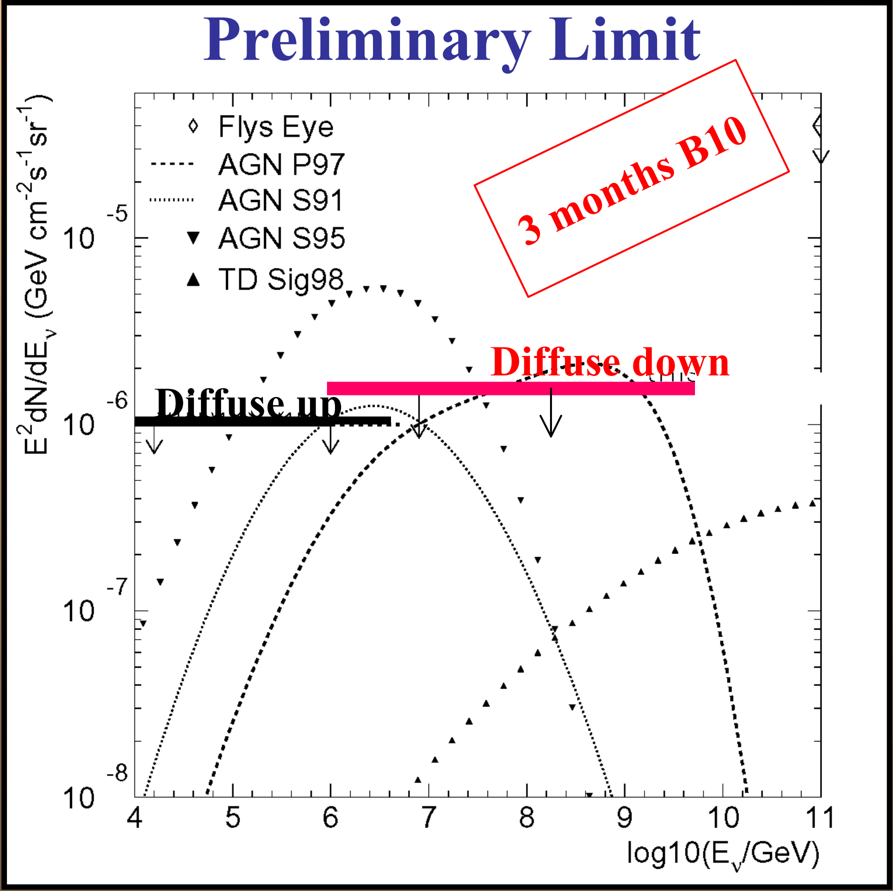
EHE ($E \geq 10^{16}$ eV) Search

EHE events very bright; many PMTs detect multiple photons

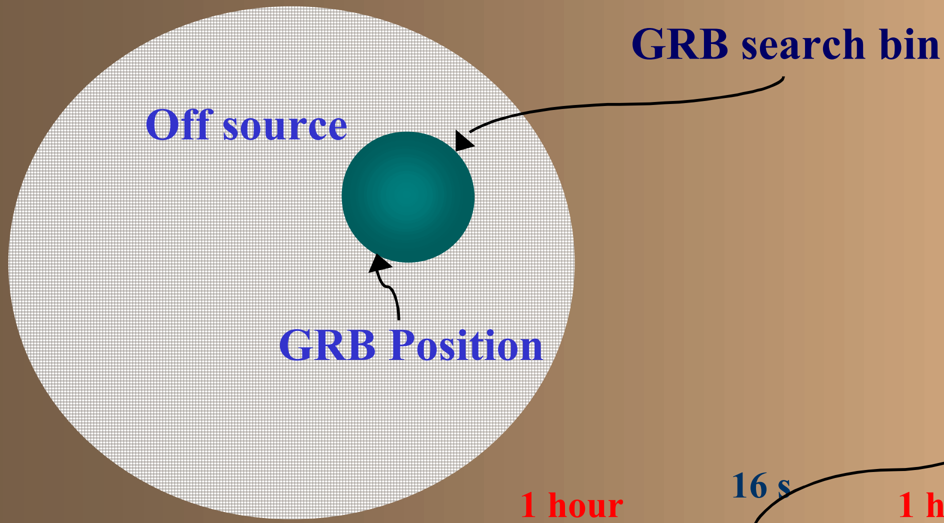


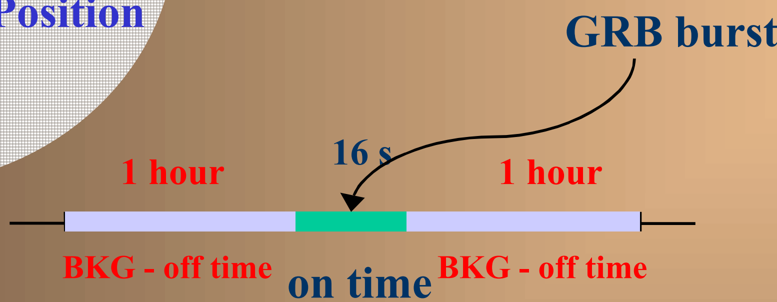
Expect most events near horizon

Main background: muon "bundles"
-> comparable N_{PMT} but less photons



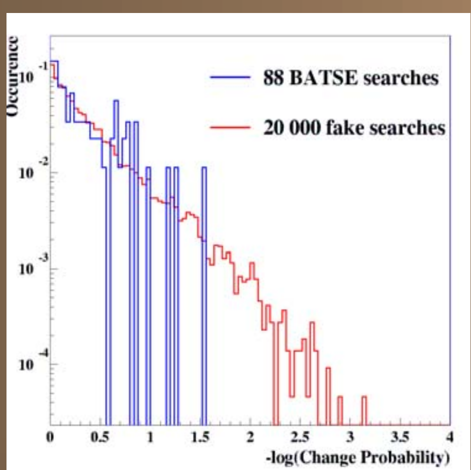
Correlations to GRB

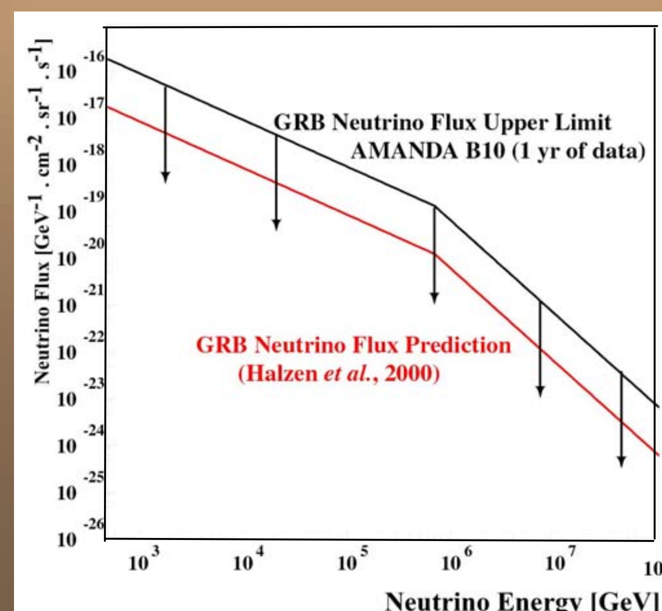




Background cuts can be loosened considerably → high signal efficiency

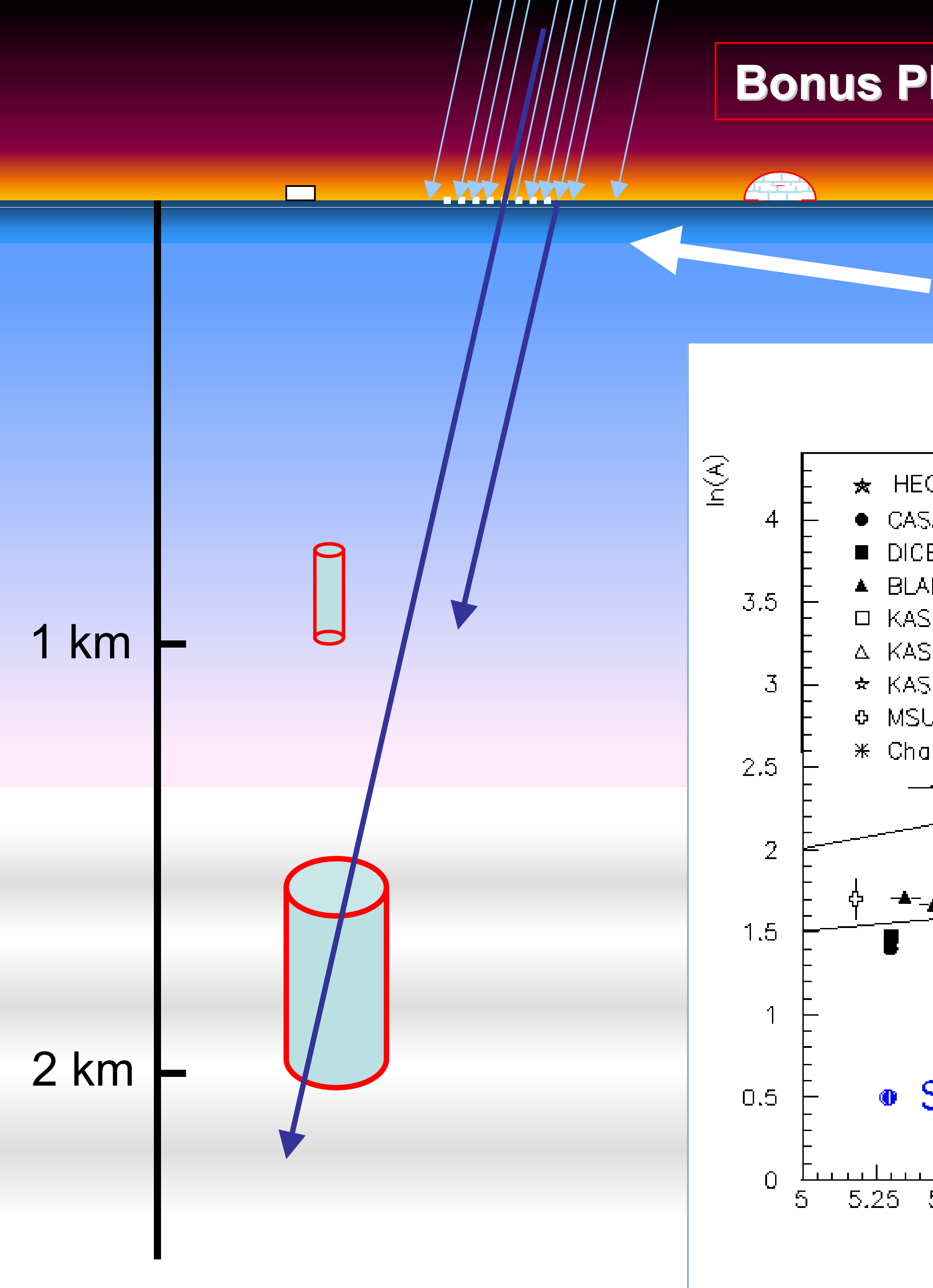
88 BATSE bursts in 1997



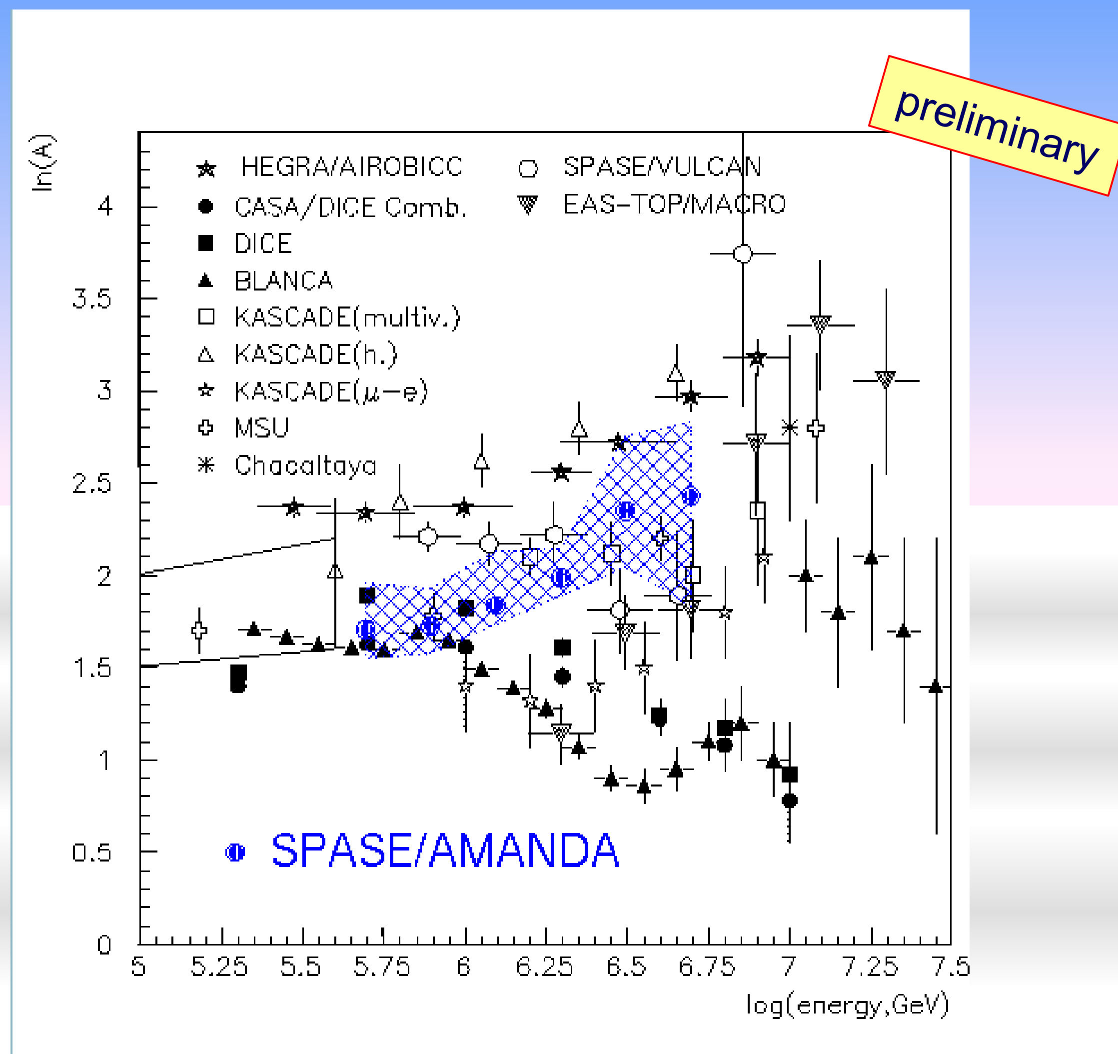


Combined data give sensitivity ~ prediction!

Bonus Physics: Cosmic ray composition



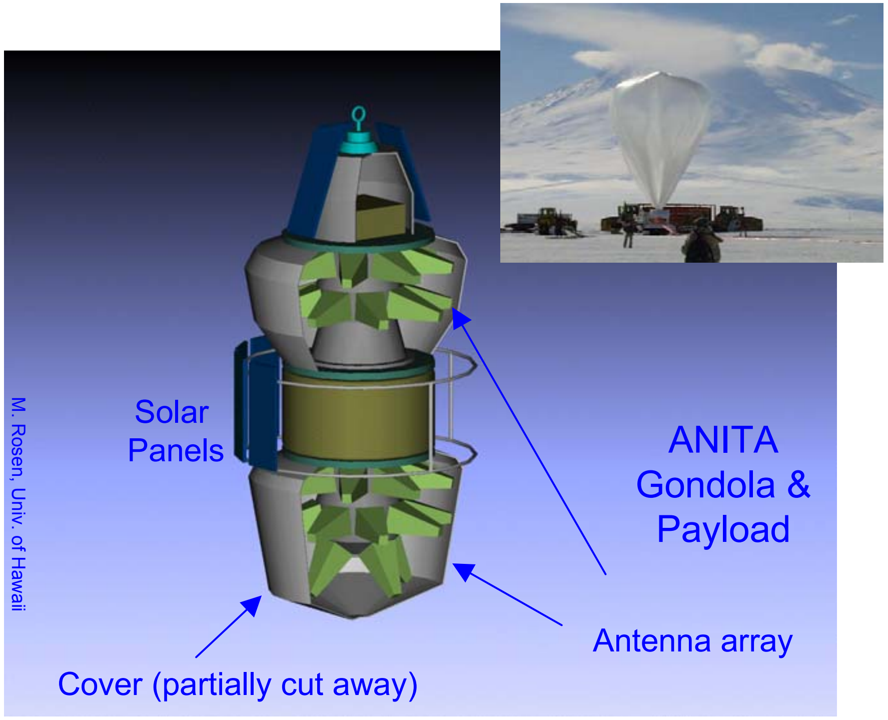
SPASE air shower arrays



conclusions

- AMANDA collected > 3,000 ν's
- > 300,000 per year from IceCube
- supernova watch for 100 years
- if history repeats, I did not tell you about IceCube science
- “ you can see a lot by looking “

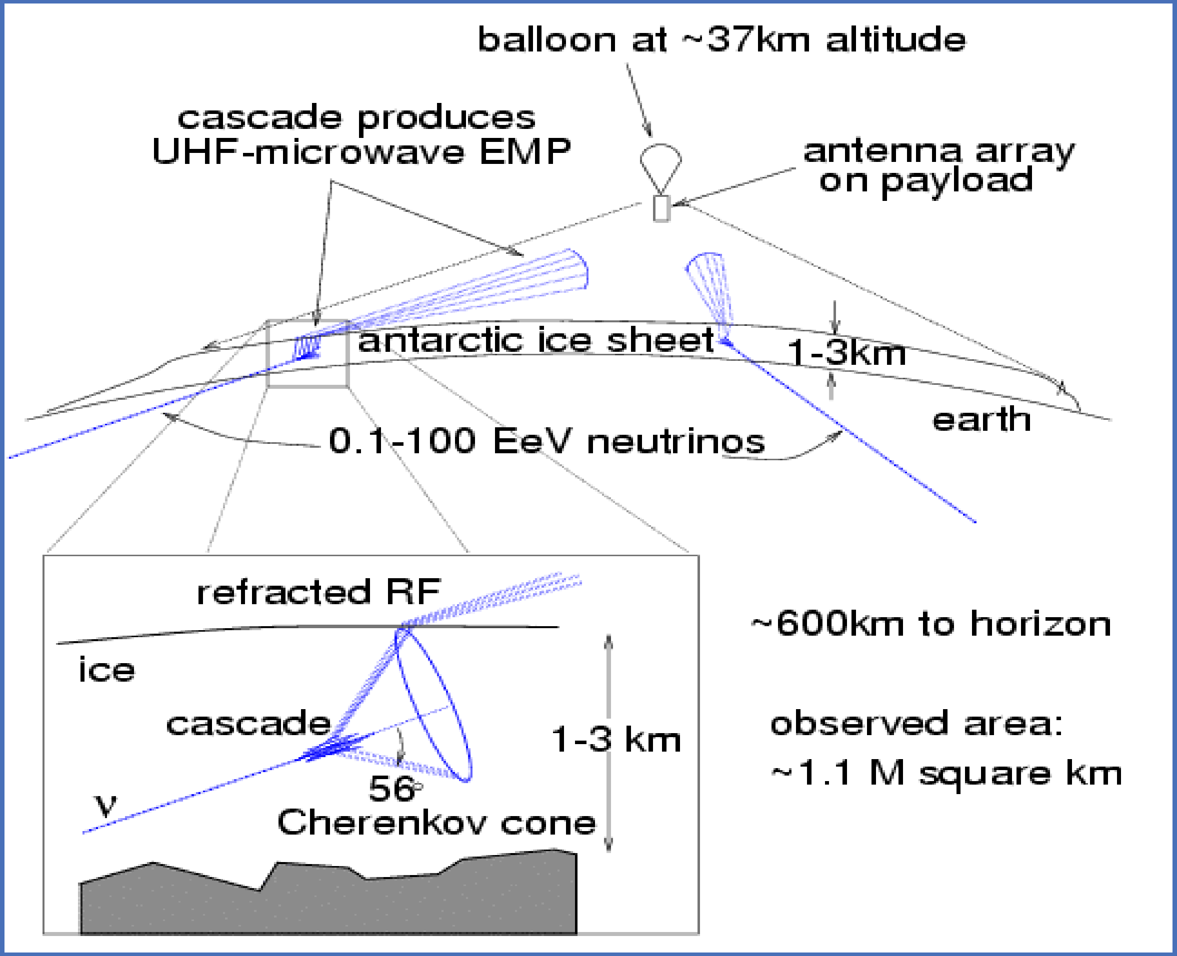
Antarctic Impulsive Transient Antenna (ANITA)

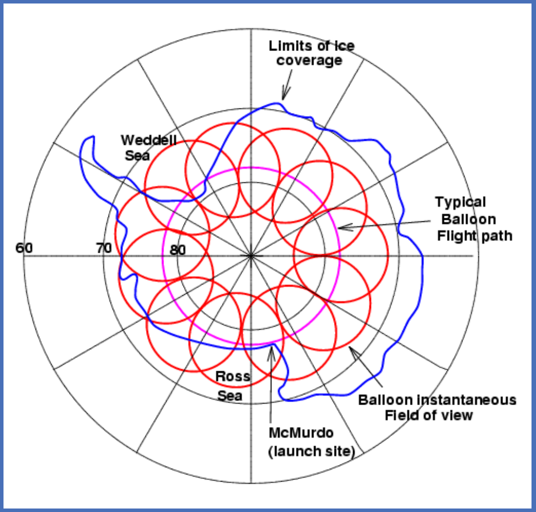


- ANITA Goal: Pathfinding mission for GZK neutrinos
- NASA SR&T start expected this October, launch in 2006

ANITA

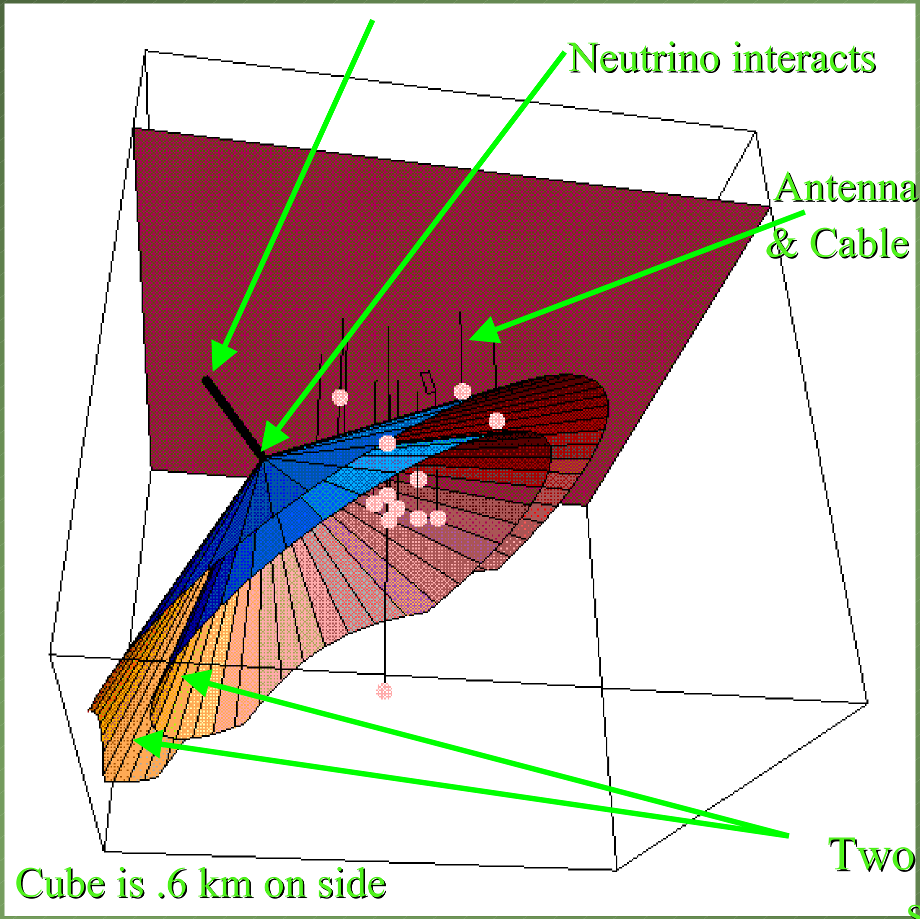
Radio from EeV ν's in Polar Ice



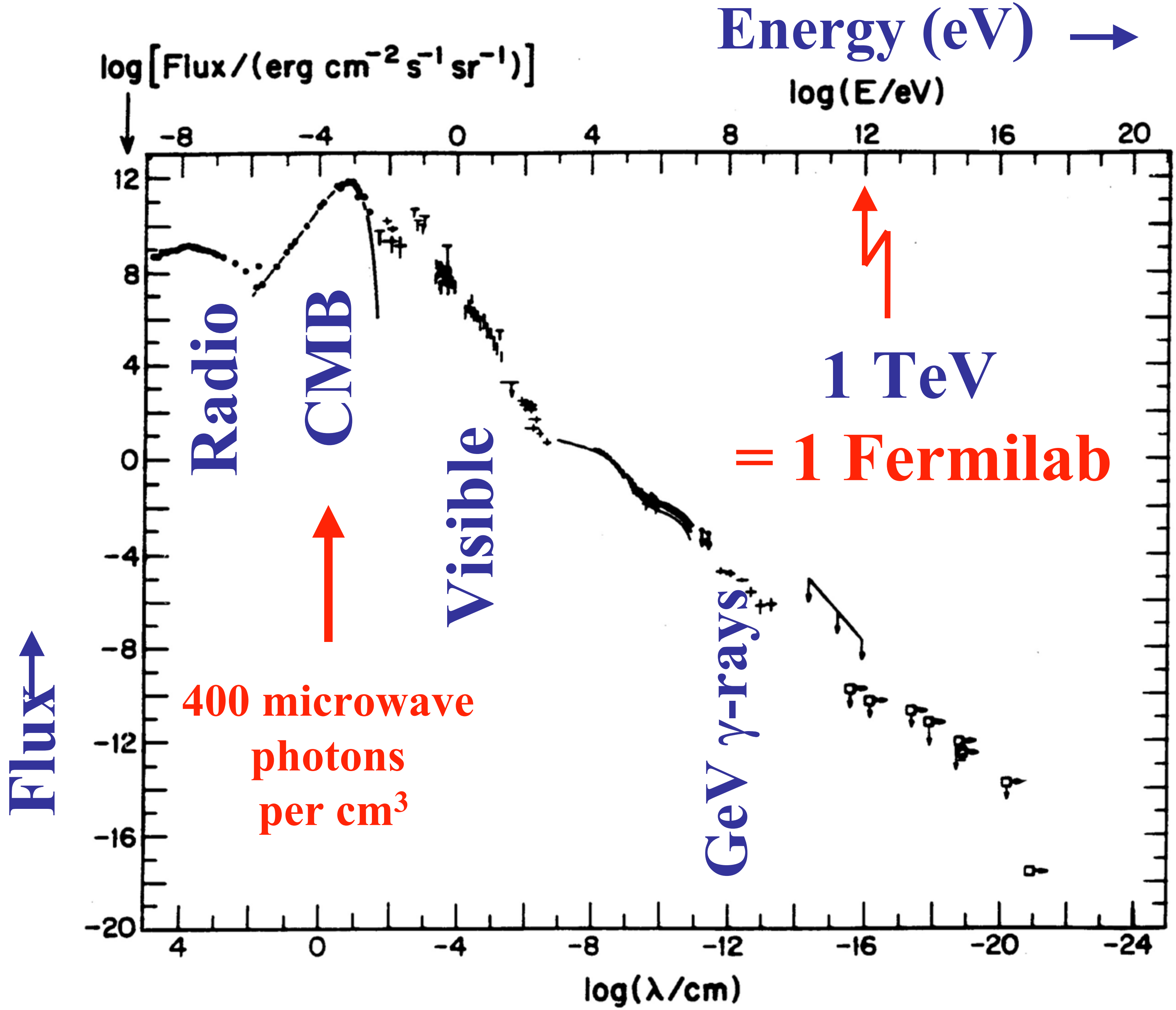


- Antarctic Ice at f<1GHz, T<-20C
- largest homogenous, RF-transmissive solid mass in the world

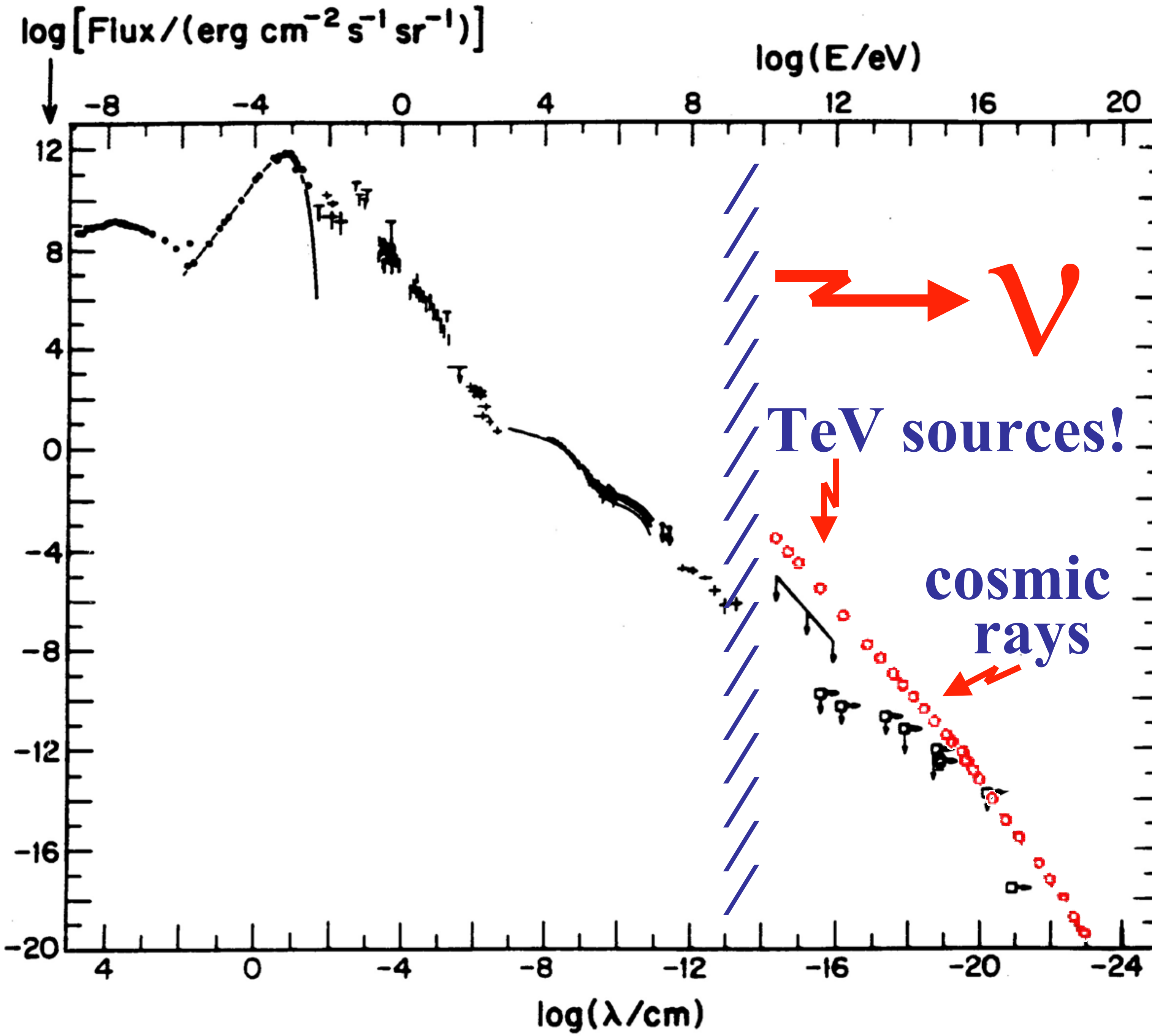
RICE
Radio Detection in South Pole Ice



- Installed ~15 antennas few hundred m depth with AMANDA strings.
- Tests and data since 1996.
- Most events due to local radio noise, few candidates.
- Continuing to take data, and first limits prepared.
- Proposal to Piggyback with ICECUBE

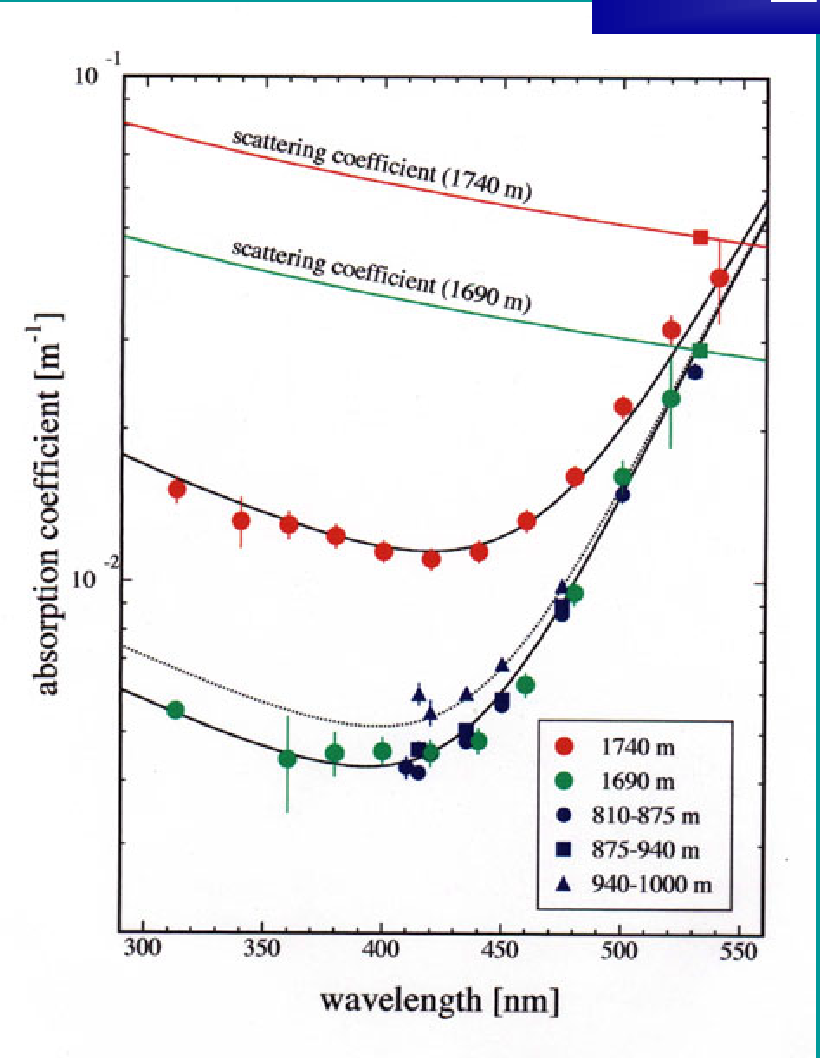


Energy (eV)
log[Flux/(erg cm^{-2} s^{-1} sr^{-1})]
log(E/eV)
-8
-4
0
4
8
12
16
20
12
8
4
0
-4
-8
-12
-16
-20
Radio
CMB
Visible
GeV γ-rays
1 TeV
= 1 Fermilab
400 microwave
photons
per cm^3
Flux
4
0
-4
-8
-12
-16
-20
-24
log(λ/cm)



log [Flux/(erg cm^{-2} s^{-1} sr^{-1})]
log(E/eV)
-8
-4
0
4
8
12
16
20
12
8
4
0
-4
-8
-12
-16
-20
4
0
-4
-8
-12
-16
-20
-24
log(λ/cm)
ν
TeV sources!
cosmic rays

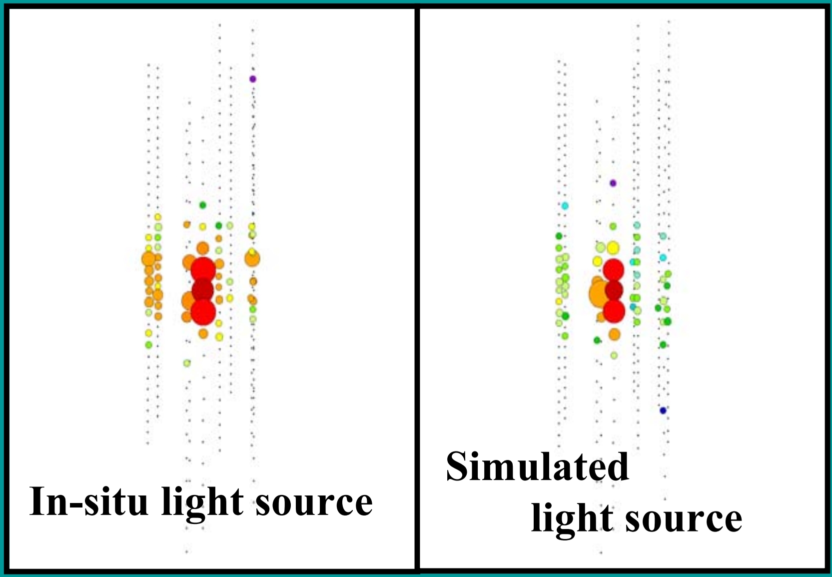
Examples

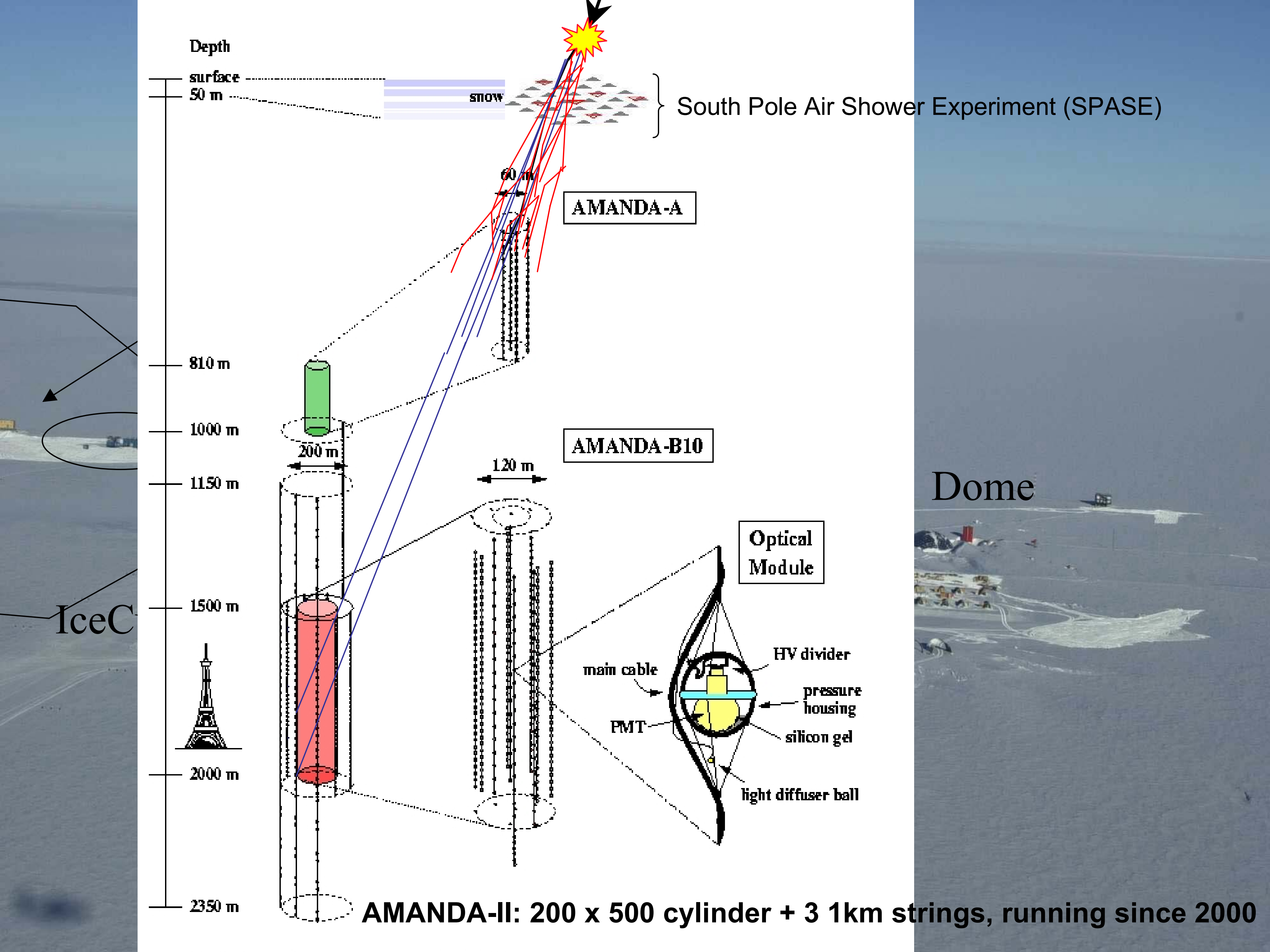


Detailed measurement of optical properties

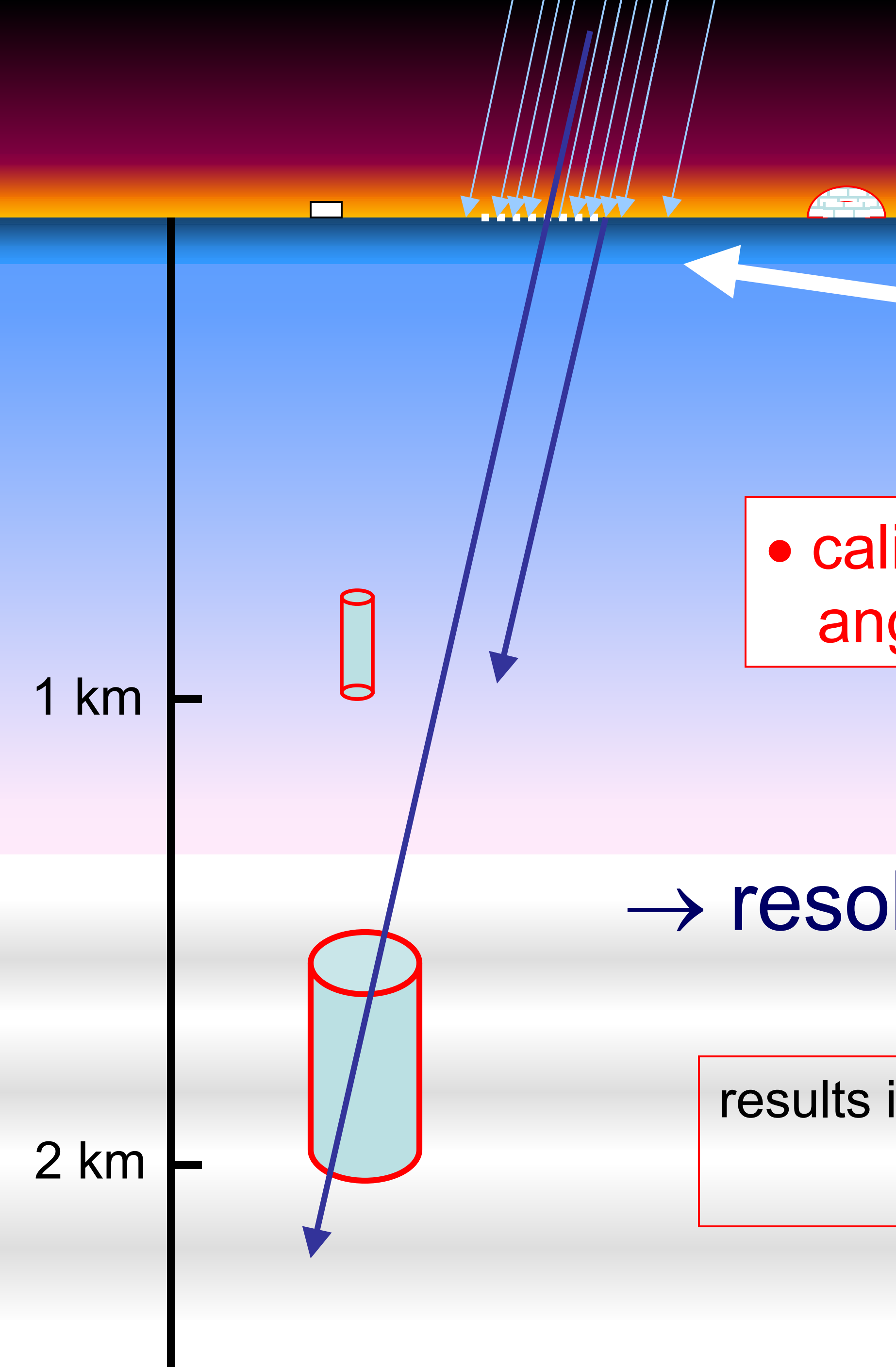
- low absorption
  (in particular in UV !!)
- scattering dominates absorption
- mapping of dust layers

Sensitivity to cascades demonstrated with *in-situ* sources & down-going muon brems.




Depth
surface
50 m
snow
South Pole Air Shower Experiment (SPASE)
60 m
AMANDA-A
810 m
1000 m
200 m
AMANDA-B10
120 m
1150 m
Dome
Optical
Module
IceC
1500 m
HV divider
main cable
pressure
housing
PMT
silicon gel
light diffuser ball
2000 m
2350 m
AMANDA-II: 200 x 500 cylinder + 3 1km strings, running since 2000

Unique:



SPASE air shower arrays

- calibration of AMANDA angular resolution and pointing !

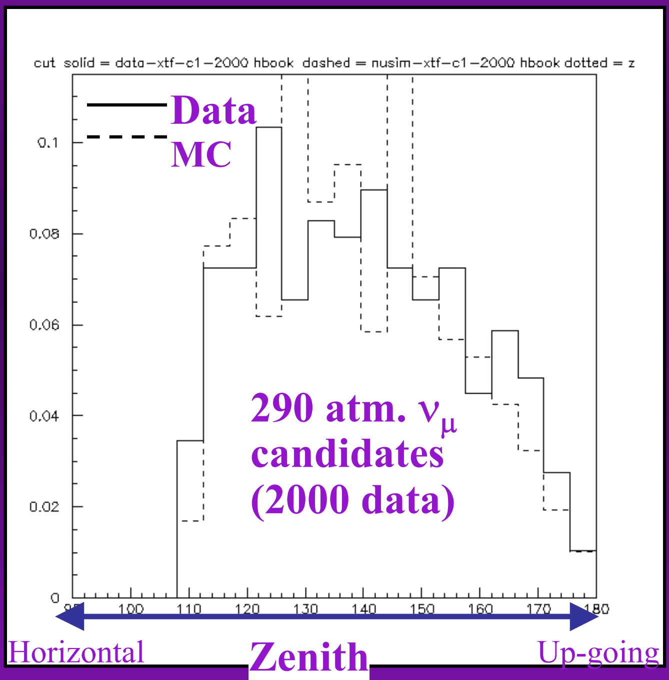
→ resolution Amanda-B10 ~ 3.5°

results in ~ 3° for upward moving muons

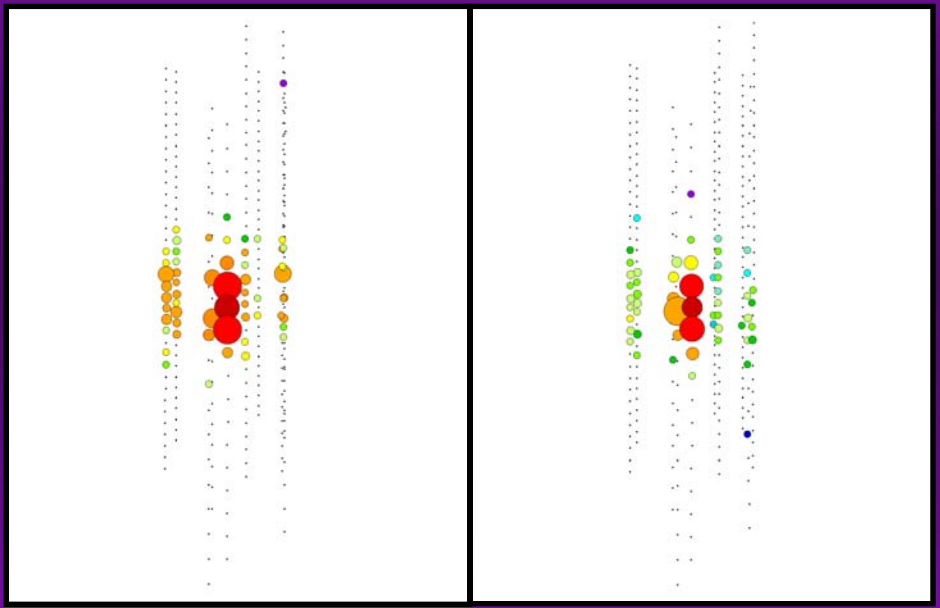
(Amanda-II: < 2°)

AMANDA Is Working Well: 4 nus per day!

- Sensitivity to up-going muons demonstrated with CC atm. ν_μ interactions:



- Sensitivity to cascades demonstrated with *in-situ* sources (see figs.) & down-going muon brems.

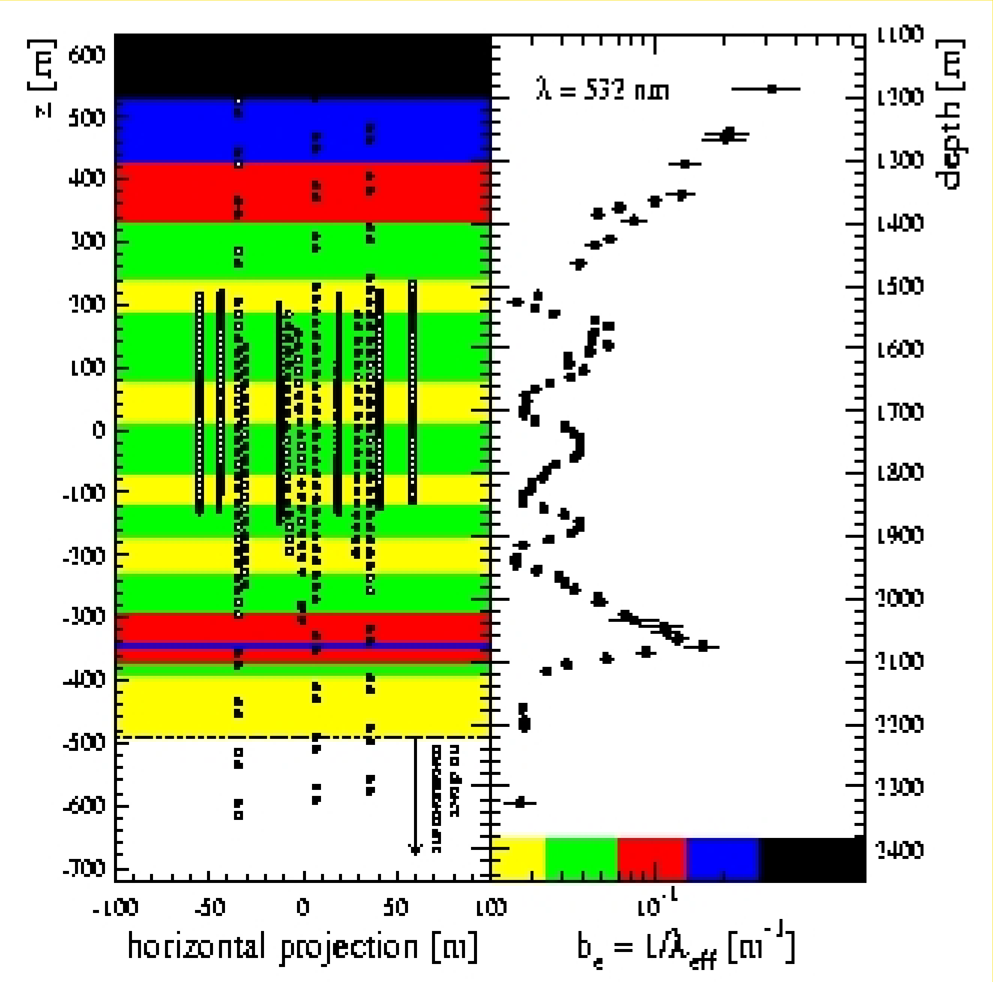


In-situ light source   Simulated light source

- AMANDA also works well with *SPASE*:
  - Calibrate AMANDA angular response
  - Do cosmic ray composition studies.

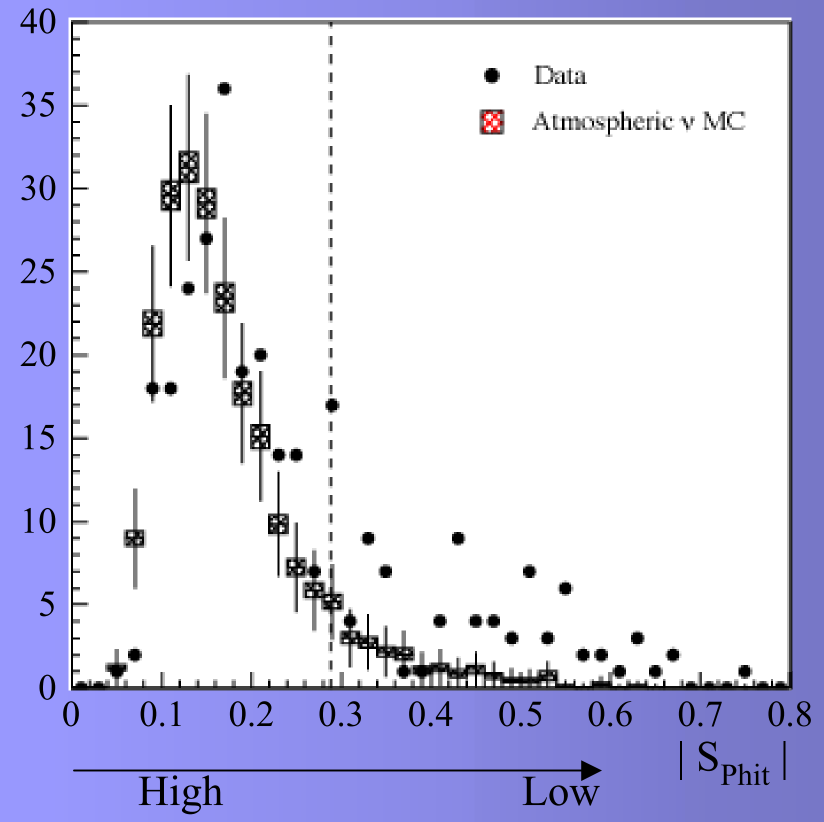
Ice Properties

- Most challenging initial problem, now essentially fully understood using in situ laser light sources
  - Bubble presence vs. depth
  - Dust layers
  - Drill-hole bubbles
- Fully simulated in the Monte Carlo



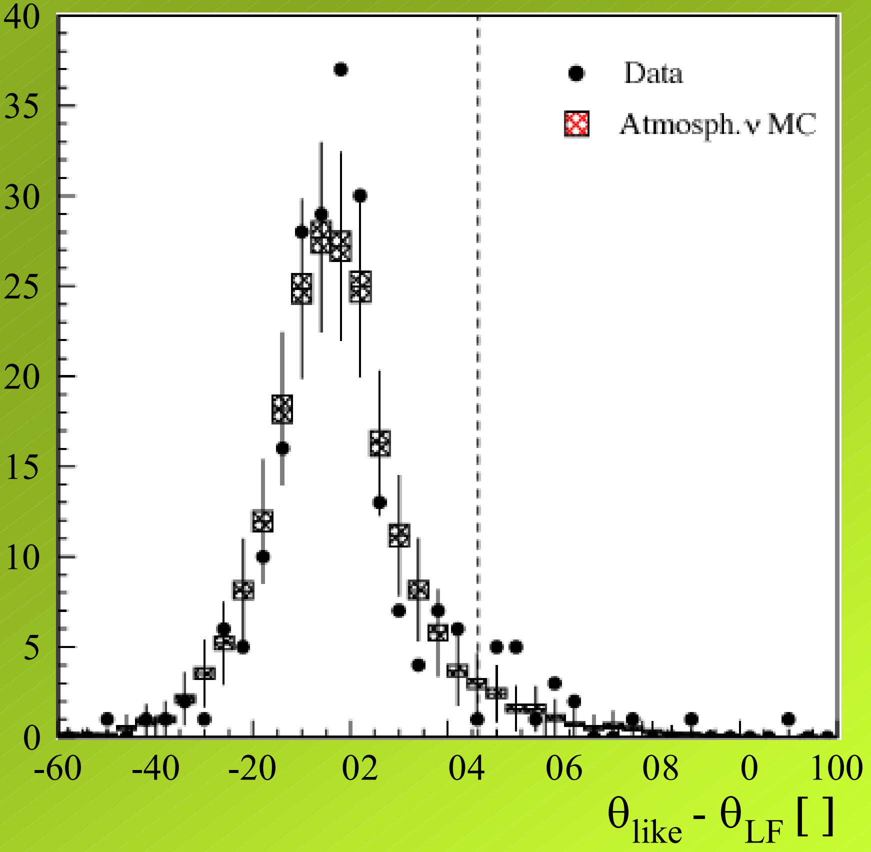
Quality parameters: Example 2: The smoothness

- **The smoothness is a measure of how regular the photon density is distributed along the track.**
- **A well reconstructed muon track is more likely to have a high smoothness.**

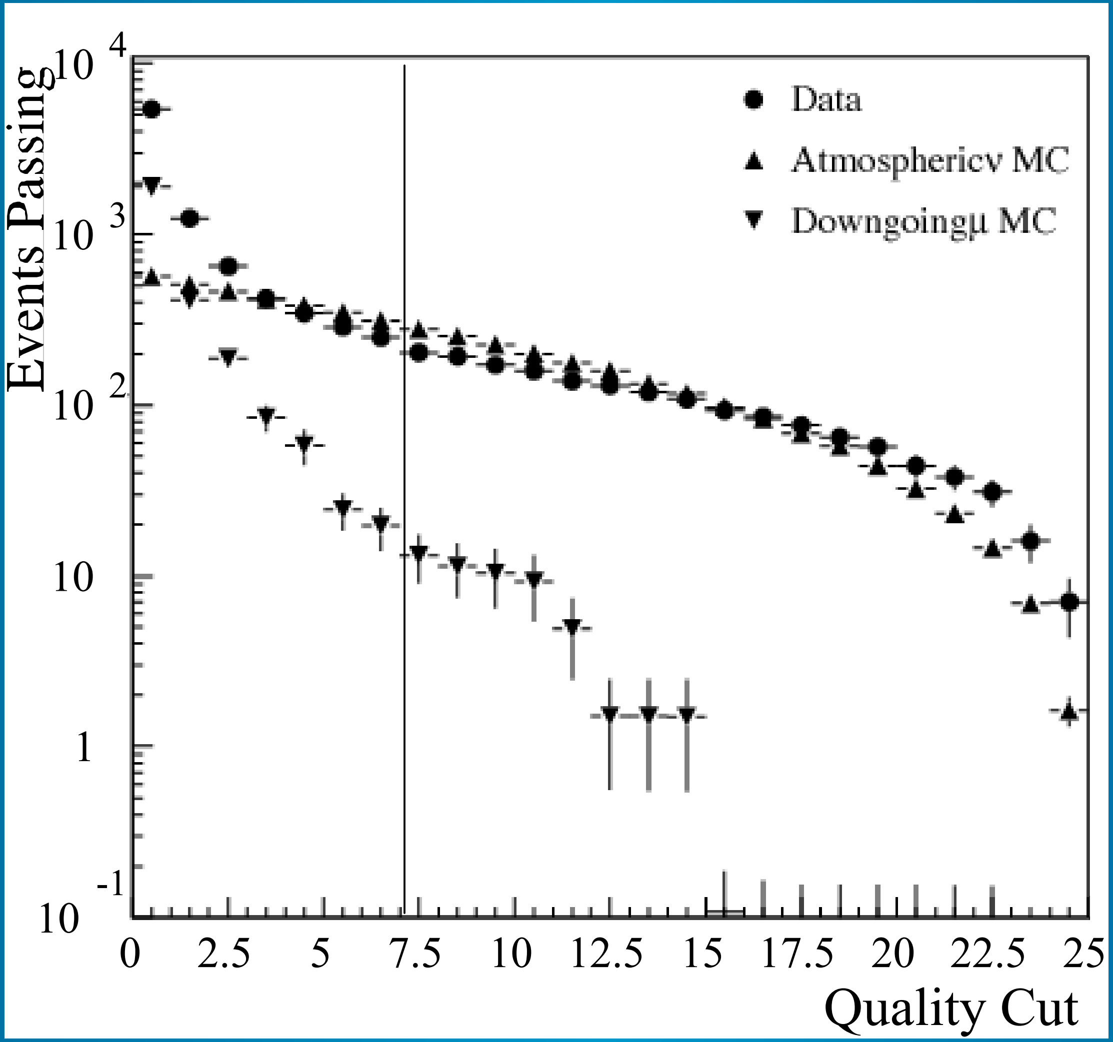


Quality parameters: Example 3: The angular difference between 2 fits

- **A well reconstructed event has better agreement between a simple fit and a full likelihood reconstruction.**

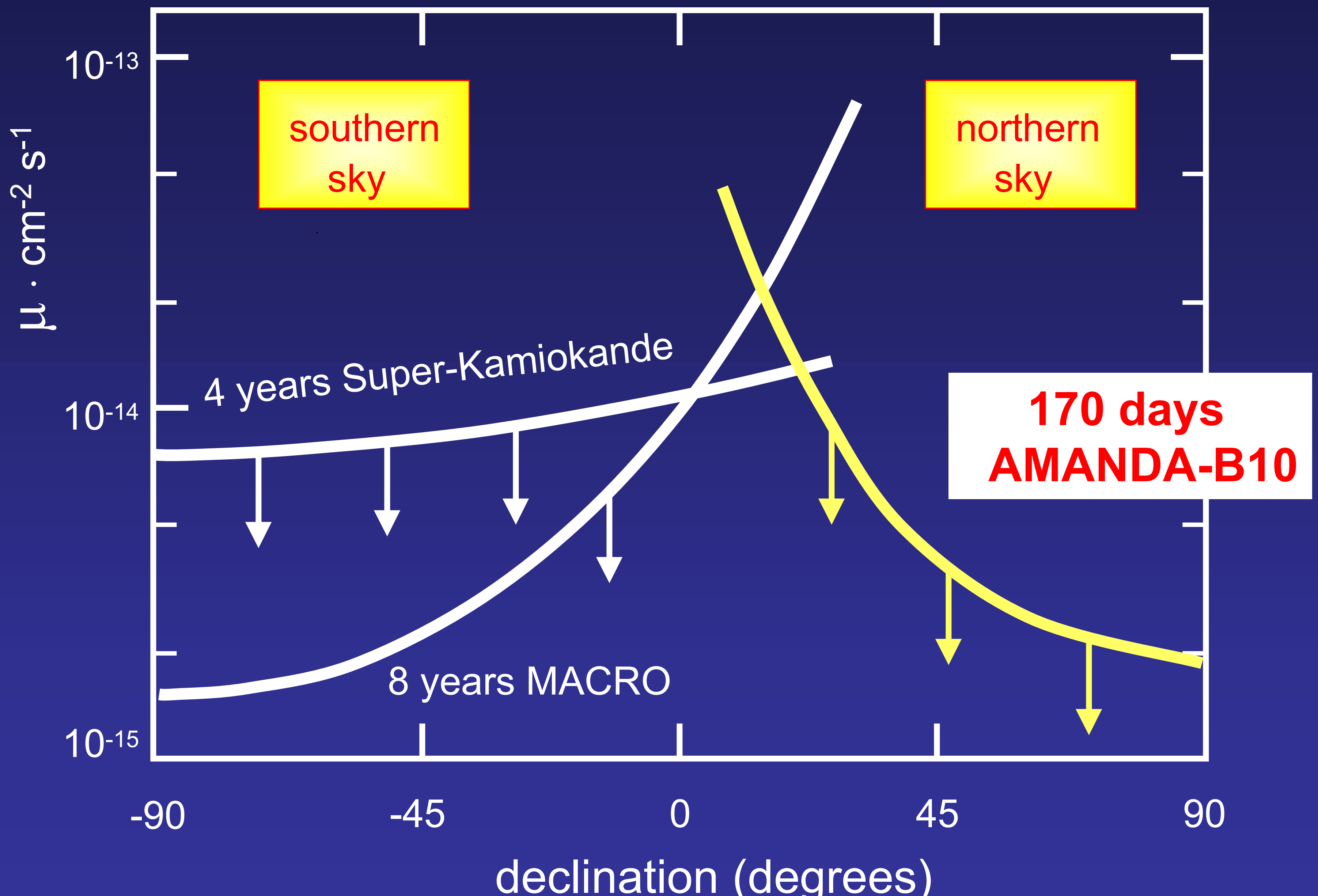


Quality cut



Events Passing
10^4
10^3
10^2
10
1
10^-1
0
2.5
5
7.5
10
12.5
15
17.5
20
22.5
25
Quality Cut
Data
Atmosphericν MC
Downgoingμ MC

Search for point sources 97



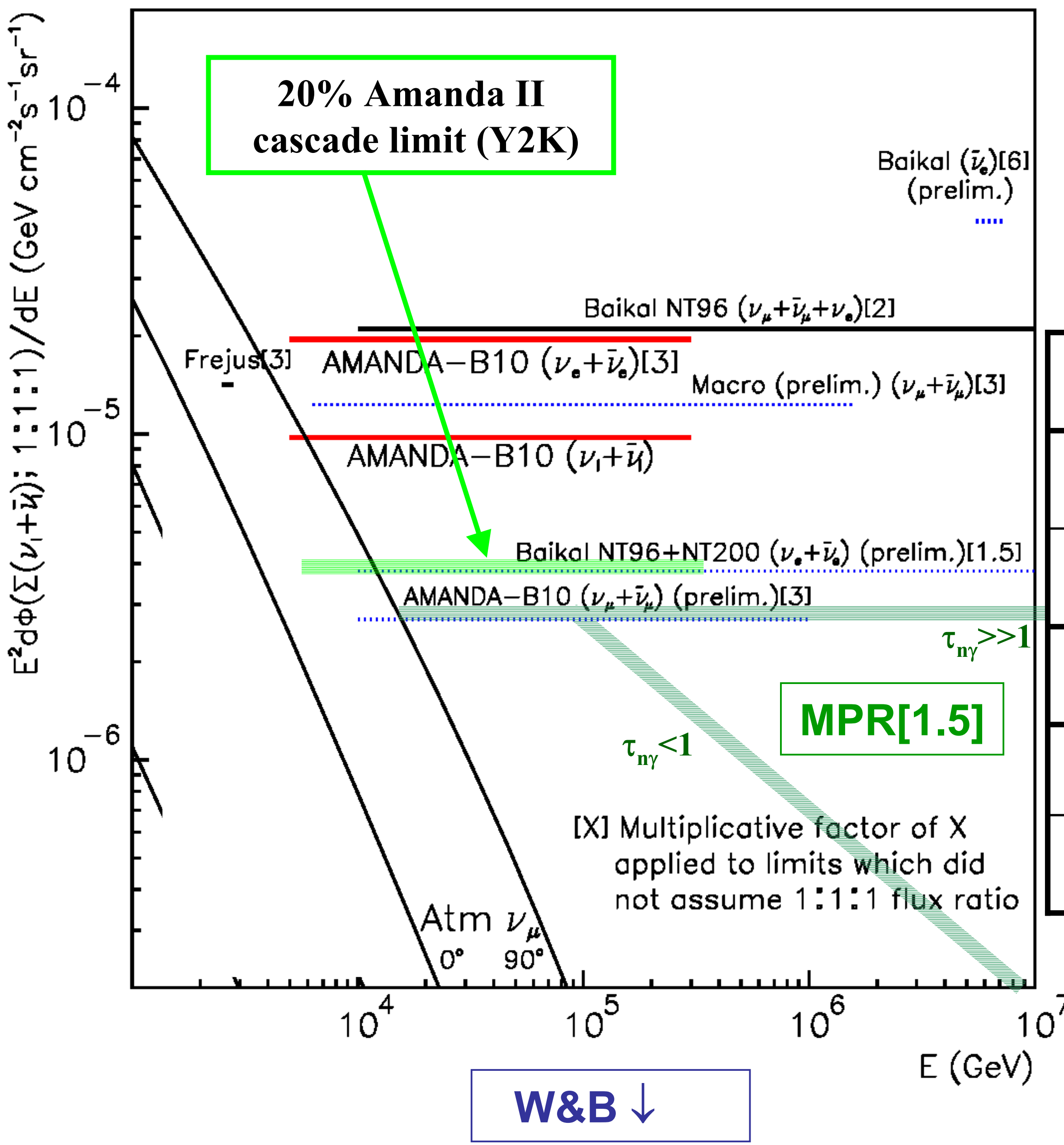
EM & Hadronic Showers: "Cascades"

- **Motivations for searching for cascades:**
  - oscillations: $\nu_\mu \rightarrow \nu_{e,\tau}$
  - better E_ν measurement
  - less cosmic-ray background
  - contained events give sensitivity over 4π
  - easier to calibrate
  - Glashow resonance
  - at E > 100 TeV, only ν_τ can penetrate the Earth

- **Drawbacks:**
  - effective volume smaller than for ν_μ
  - angular resolution worse than for tracks

Analysis gets easier and more competitive with muons as detector grows in size.
Amanda-B → Amanda-II

Cascade limits



Astrophysical ν's	*Predicted* events in 100% of 2000 data
$\Phi_{\nu_e+\nu_e} = 10^{-6}\ E^{-2}$ GeV cm^{-2} s^{-1}	5.5
$\Phi_{\nu_\tau+\nu_\tau} = 10^{-6}\ E^{-2}$ GeV cm^{-2} s^{-1}	3.2
Atmospheric ν's	***Predicted* events in 100% of 2000 data**
ν_e (CC), $\nu_e+\nu_\mu$ (NC)	0.15
Prompt charm (RQPM)	0.50

Detection Probability:

$$N_{events} \sim \frac{\Phi_\nu}{E_\nu} P_{\nu \rightarrow \mu} \text{ Area Time}$$

$$P_{\nu \rightarrow \mu} \rightarrow n_{target}\, \sigma_\nu\, Range_\mu$$

$\sim 10^{-4}$ for 100 TeV neutrinos

Neutrino flux required to observe N events:

$$\Phi_\nu = \frac{5\text{x}10^{-12}\ \frac{\text{erg}}{\text{cm}^2/\text{s}}}{\text{Area (km2) Time (yr)}} N_{events}$$

Neutrinos from GRBs