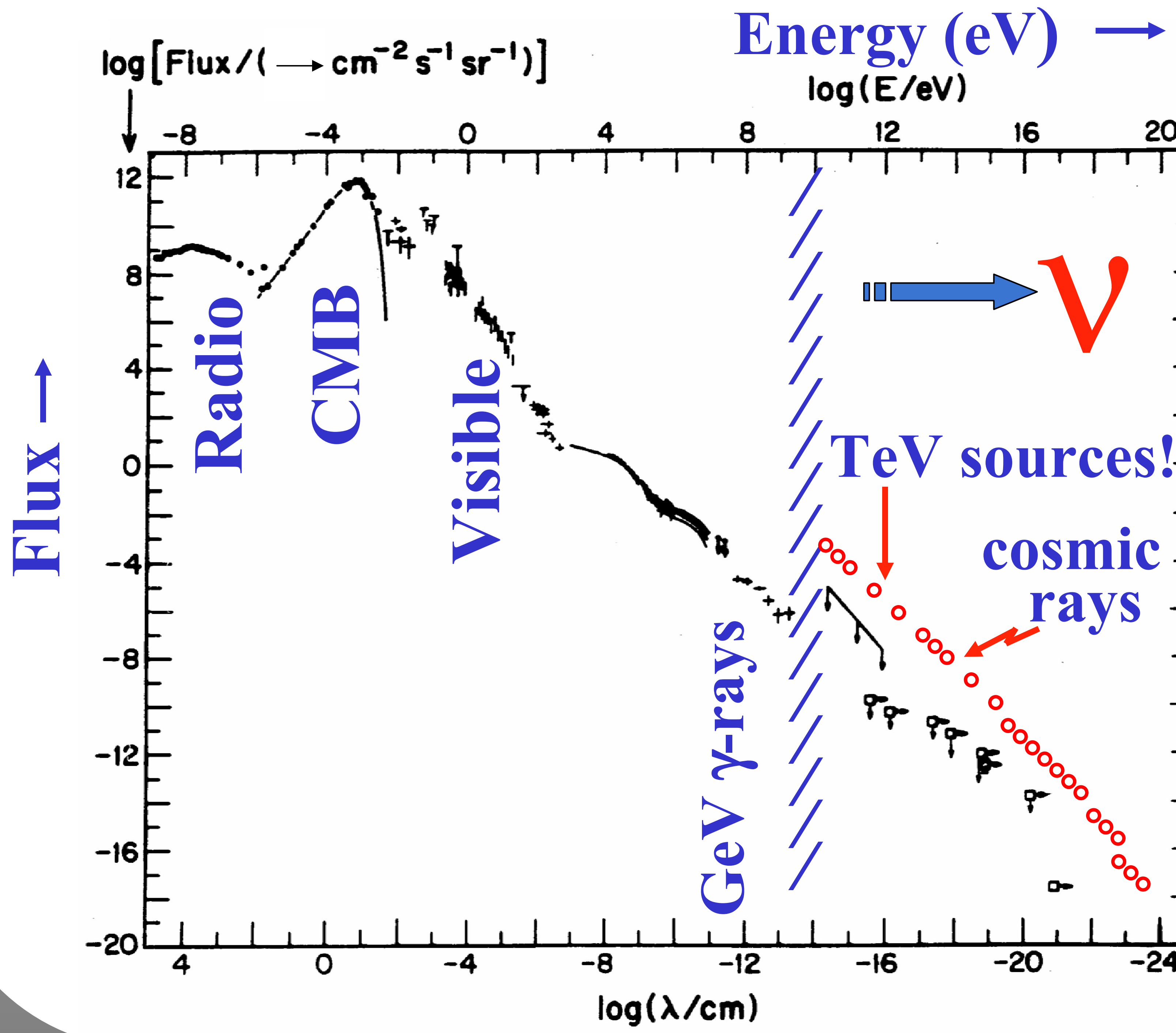
Francis Halzen
University of Wisconsin
http://icecube.wisc.edu

The real voyage is not to travel to new landscapes, but to see with new eyes. . .

Marcel Proust



Energy (eV) →
log[Flux/(→ cm^-2 s^-1 sr^-1)]
log(E/eV)
Flux →
Radio
CMB
Visible
GeV γ-rays
TeV sources!
cosmic rays
ν
log(λ/cm)

Multi-Messenger Astronomy

protons, γ-rays, neutrinos, gravitational waves as probes of the high-energy Universe

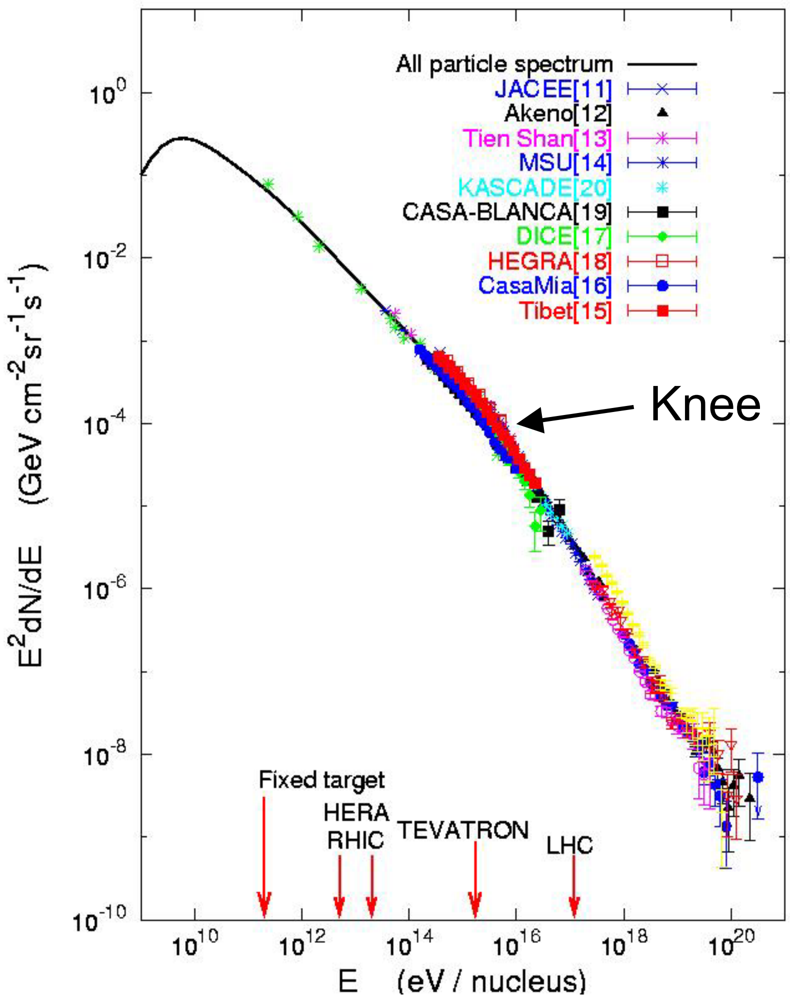
1. protons: directions scrambled by magnetic fields
2. γ-rays : straight-line propagation but reprocessed in the sources, extragalactic backgrounds absorb $E\gamma > \text{TeV}$
3. neutrinos: straight-line propagation, unabsorbed, but difficult to detect

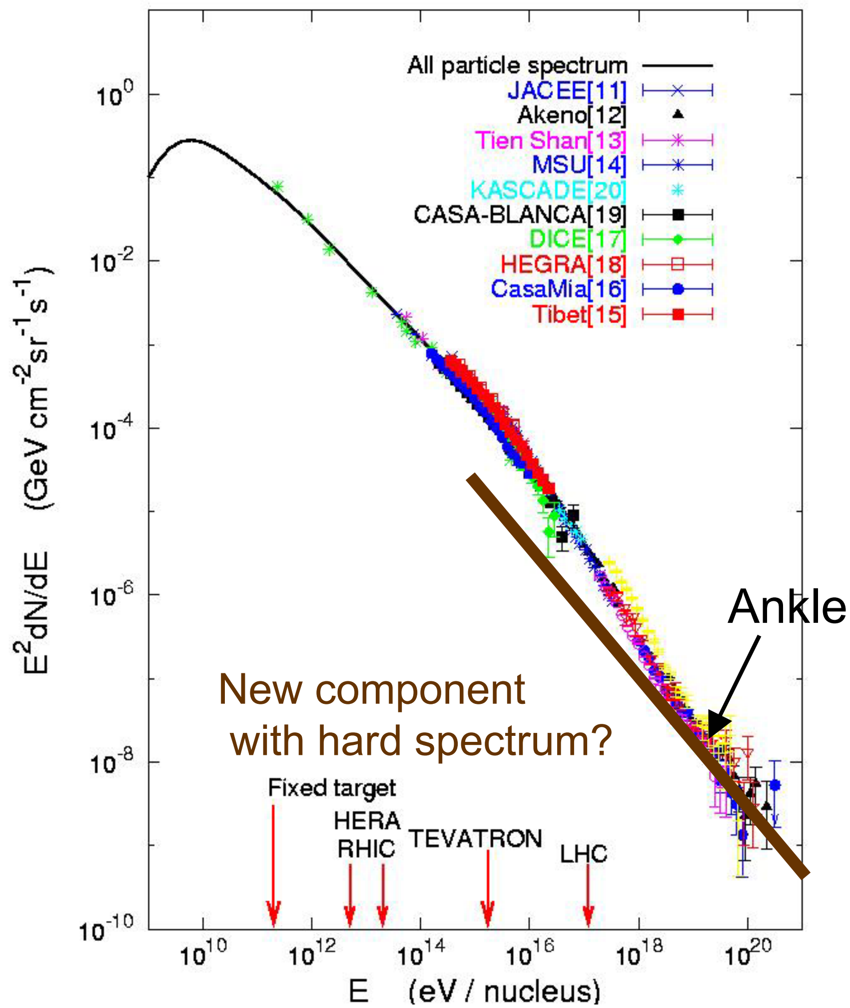
ν astronomy

- **ν astronomy requires kilometer-scale detectors**
- **AMANDA: proof of concept**
- **IceCube: a kilometer-scale ν observatory**

cosmic neutrinos associated with cosmic rays

Galactic and Extragalactic Cosmic Rays





>>> energy in extra-galactic cosmic rays:

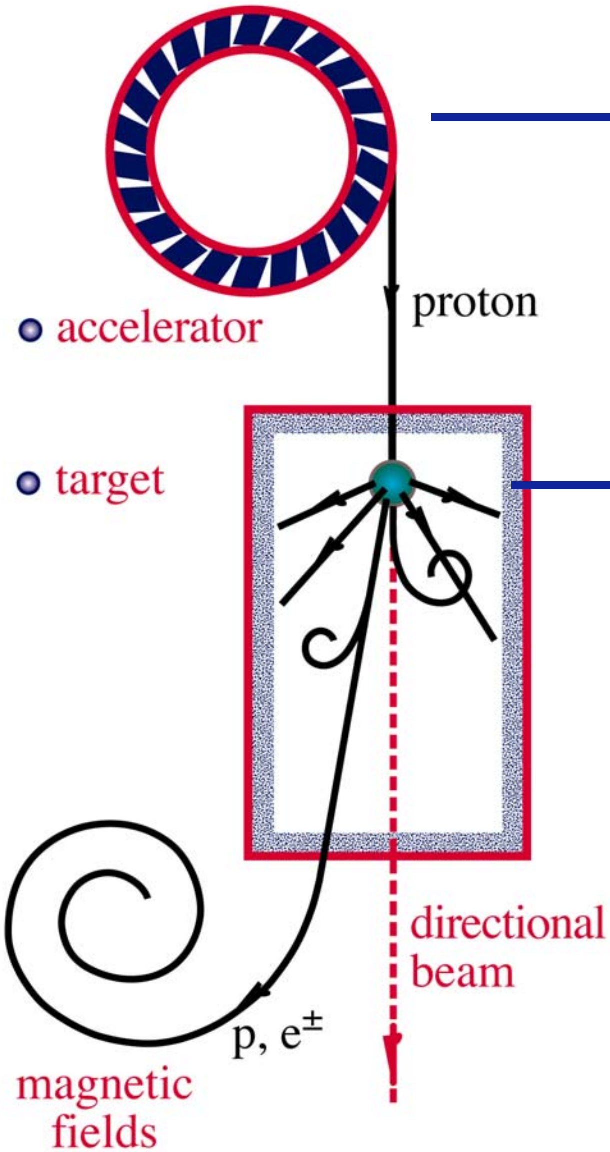
~ $3x10^{-19}$ erg/cm^3 or
~ 10^{44} erg/yr per $(Mpc)^3$ for 10^{10} years

$3x10^{39}$ erg/s per galaxy
$3x10^{44}$ erg/s per active galaxy
$2x10^{52}$ erg per gamma ray burst

>>> energy in cosmic rays ~ equal to the energy in light !

1 TeV = 1.6 erg

Neutrino Beams: Heaven & Earth



Black Hole

Radiation Enveloping Black Hole

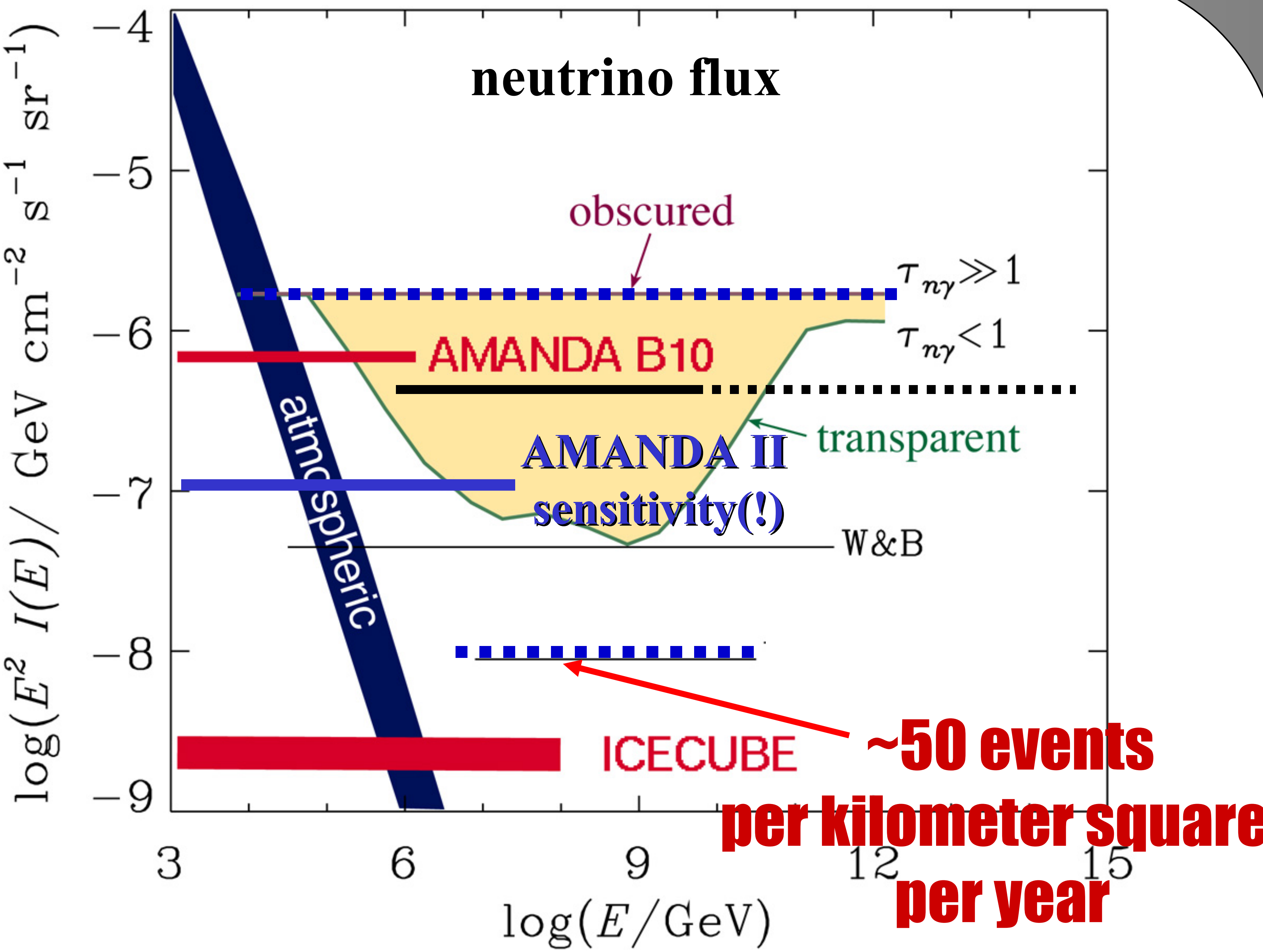
$p + \gamma -> n + \pi^+$

~ cosmic ray + neutrino

$-> p + \pi^0$

~ cosmic ray + gamma

Neutrinos Associated With the Source of the Cosmic Rays?



why km^2 telescope area ?

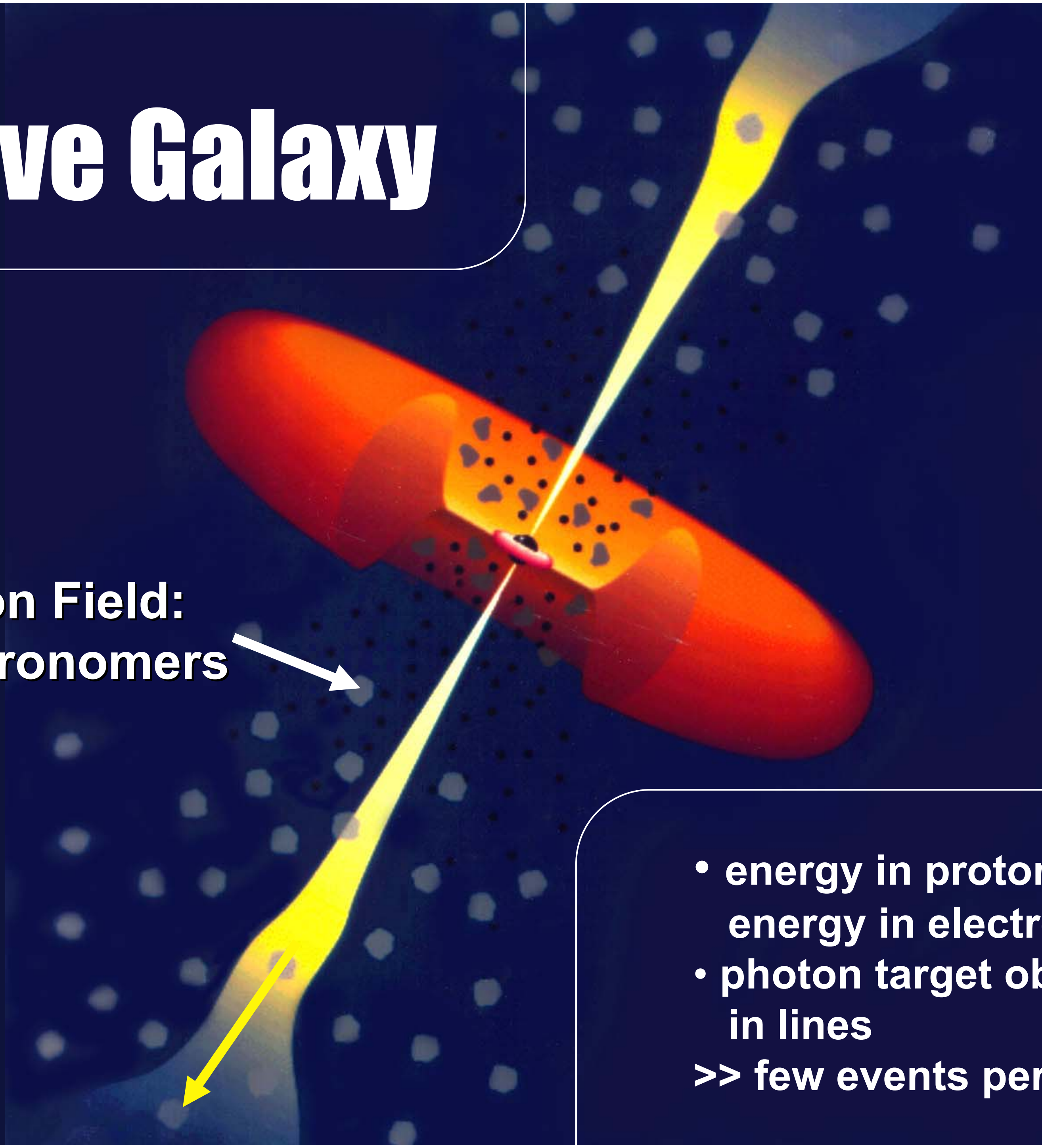
• neutrinos associated with the observed sources of cosmic rays (and gamma rays)

• models of cosmic ray accelerators: an example

• “guaranteed" cosmic neutrino fluxes

→ cosmic ray interactions with CMBR
→ cosmic ray interactions in galactic plane, in galaxy clusters, in the sun
→ decaying EeV neutrons
→ gamma ray burst
→ RXJ 1713 !!!

Active Galaxy

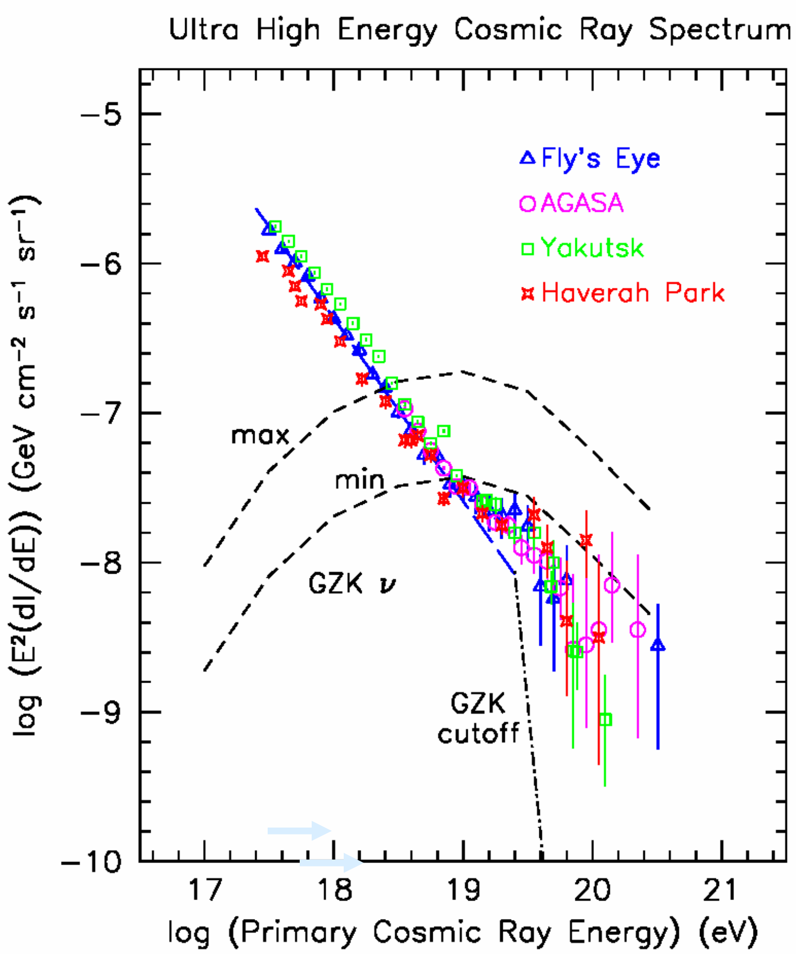


Radiation Field:
Ask Astronomers

- energy in protons ~ energy in electrons
- photon target observed in lines

>> few events per year km^2

GZK Cosmic Rays & Neutrinos

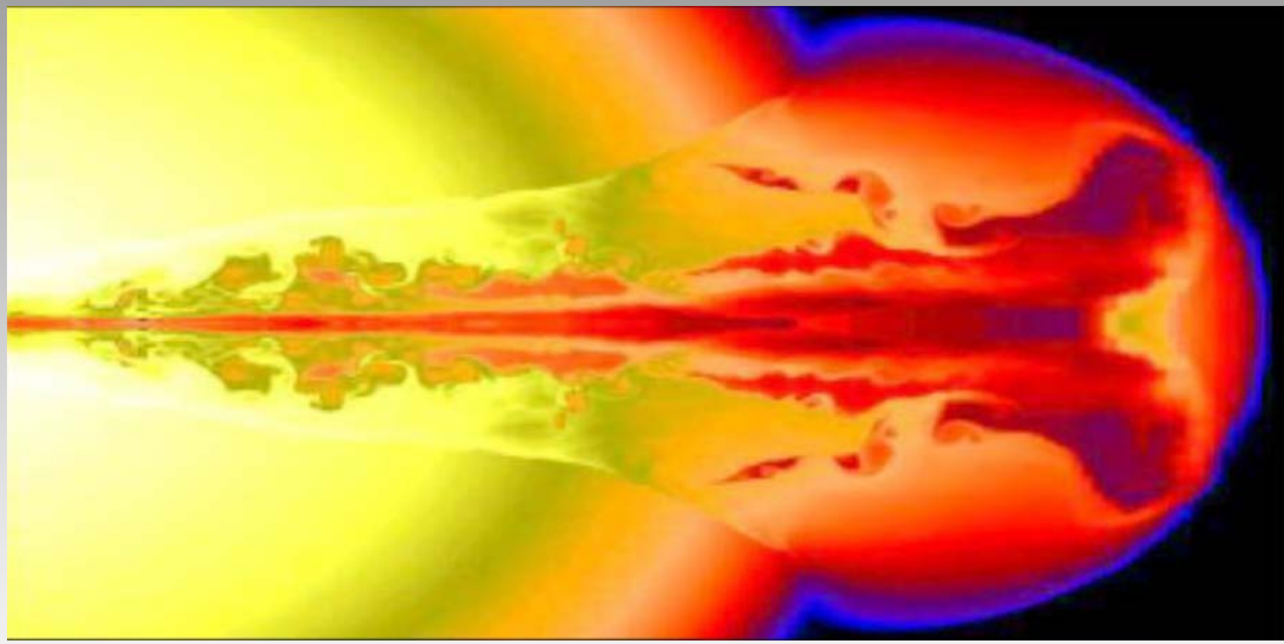


- cosmogenic neutrinos are "guaranteed"
- 0.1– few events per year in IceCube

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

Gamma Ray Bursts

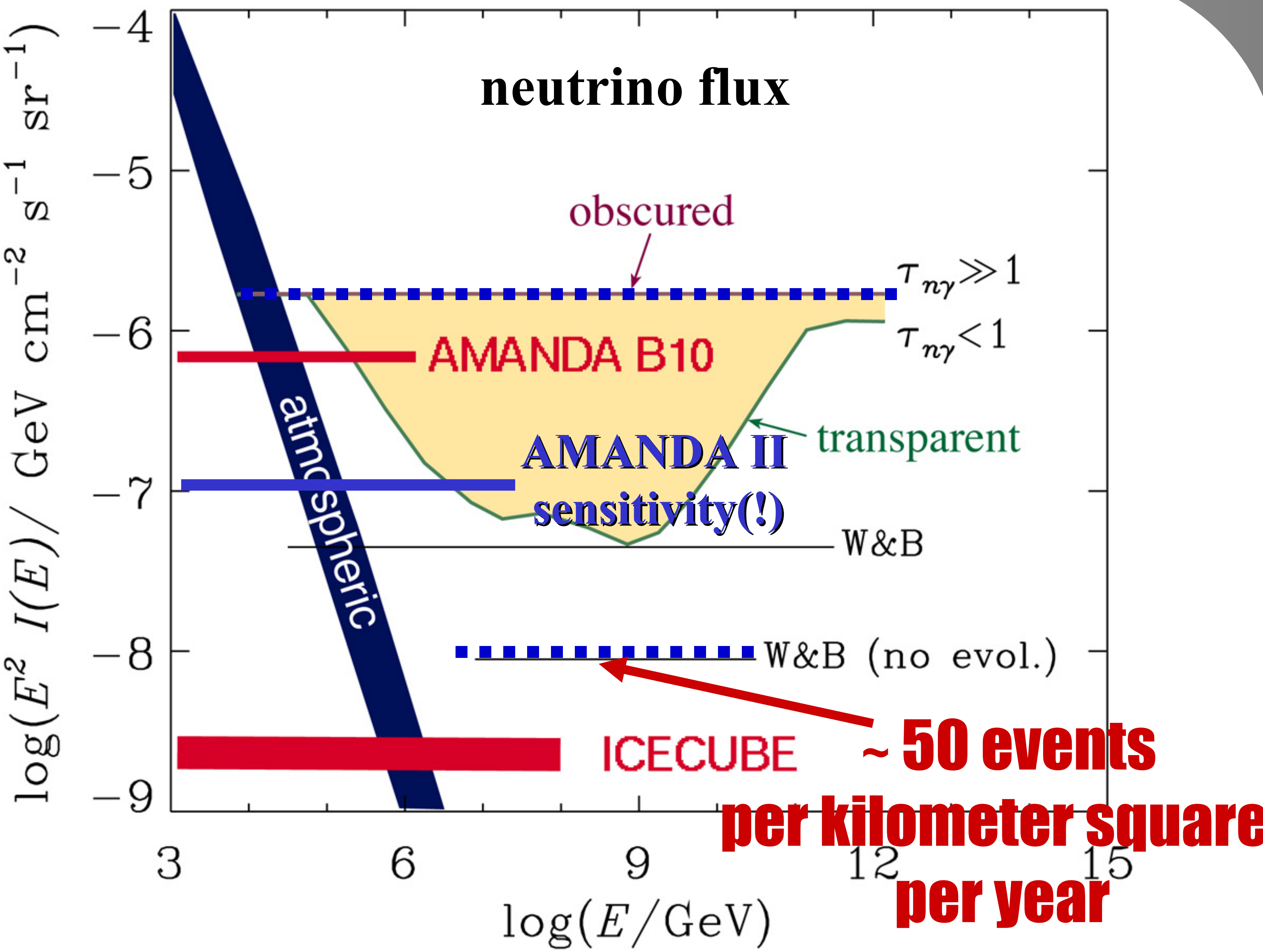
Fireball: Rapidly expanding collimated ball of photons, electrons and positrons becoming optically thin during expansion



Shocks: external collisions with interstellar material (**e.g. remnant—guaranteed TeV neutrinos**!!!) or internal collisions when slower material is overtaken by faster in the fireball.

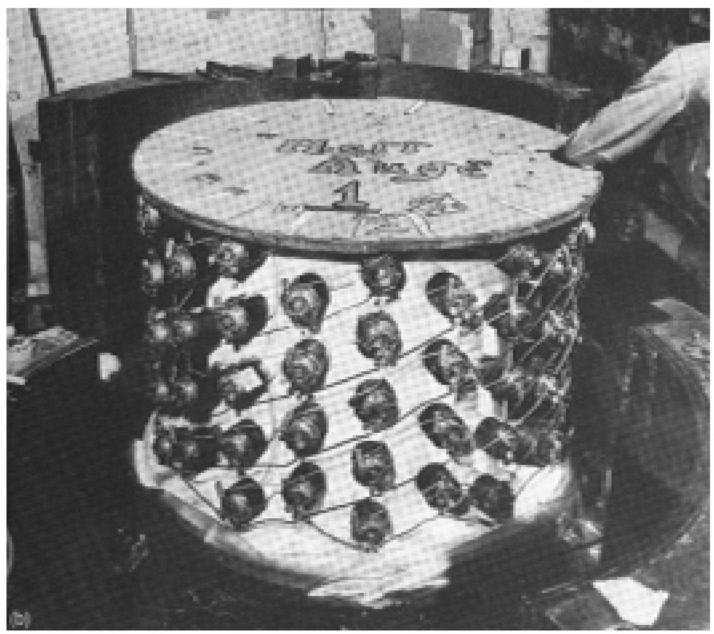
Protons and photons coexist in the fireball

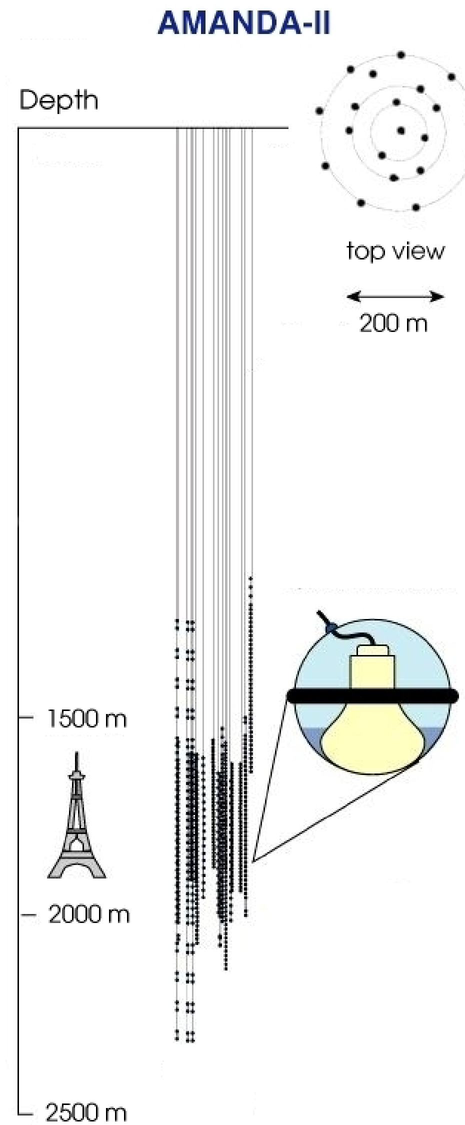
Models of Cosmic Ray Accelerators: Same Conclusion !

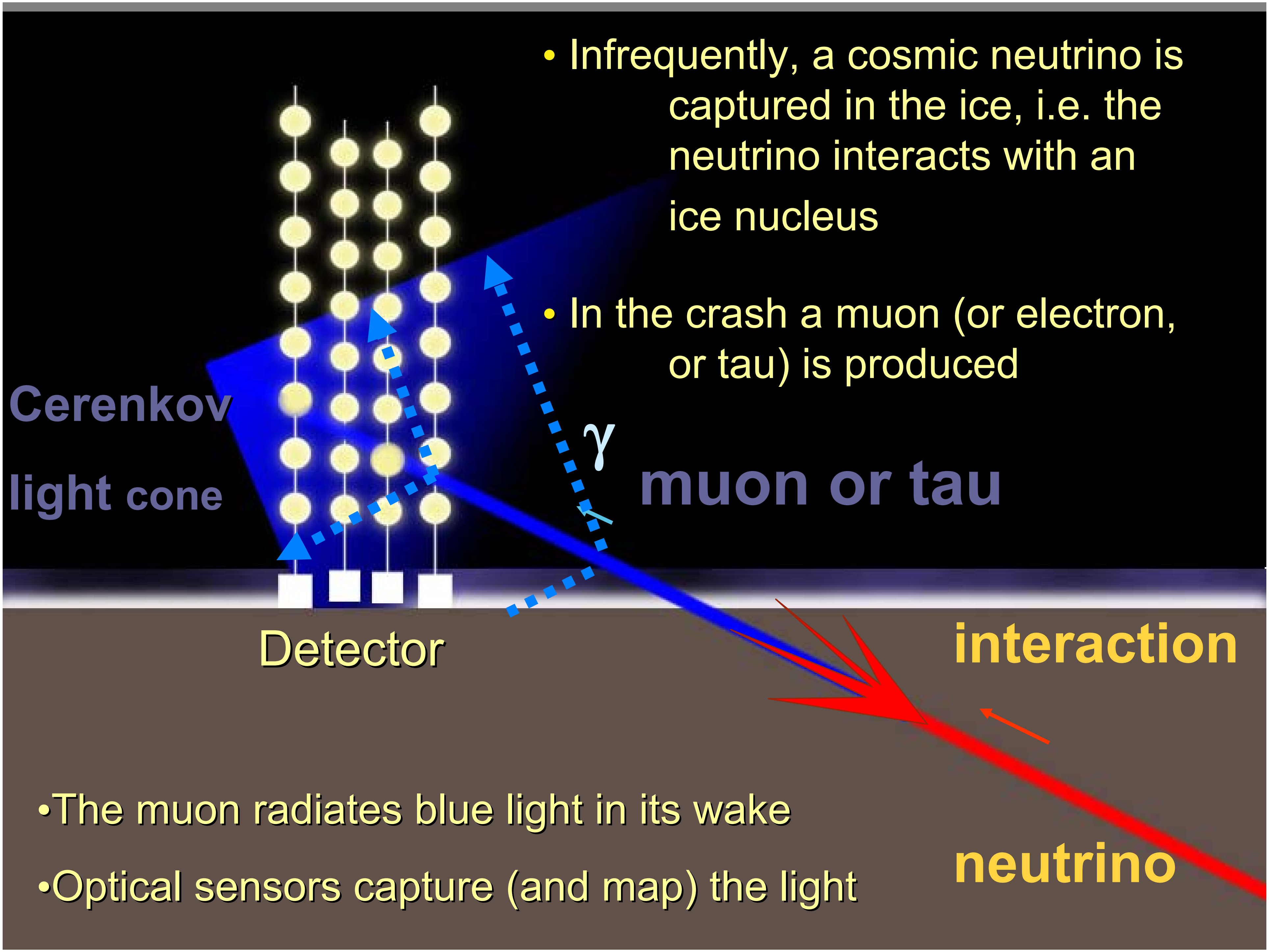


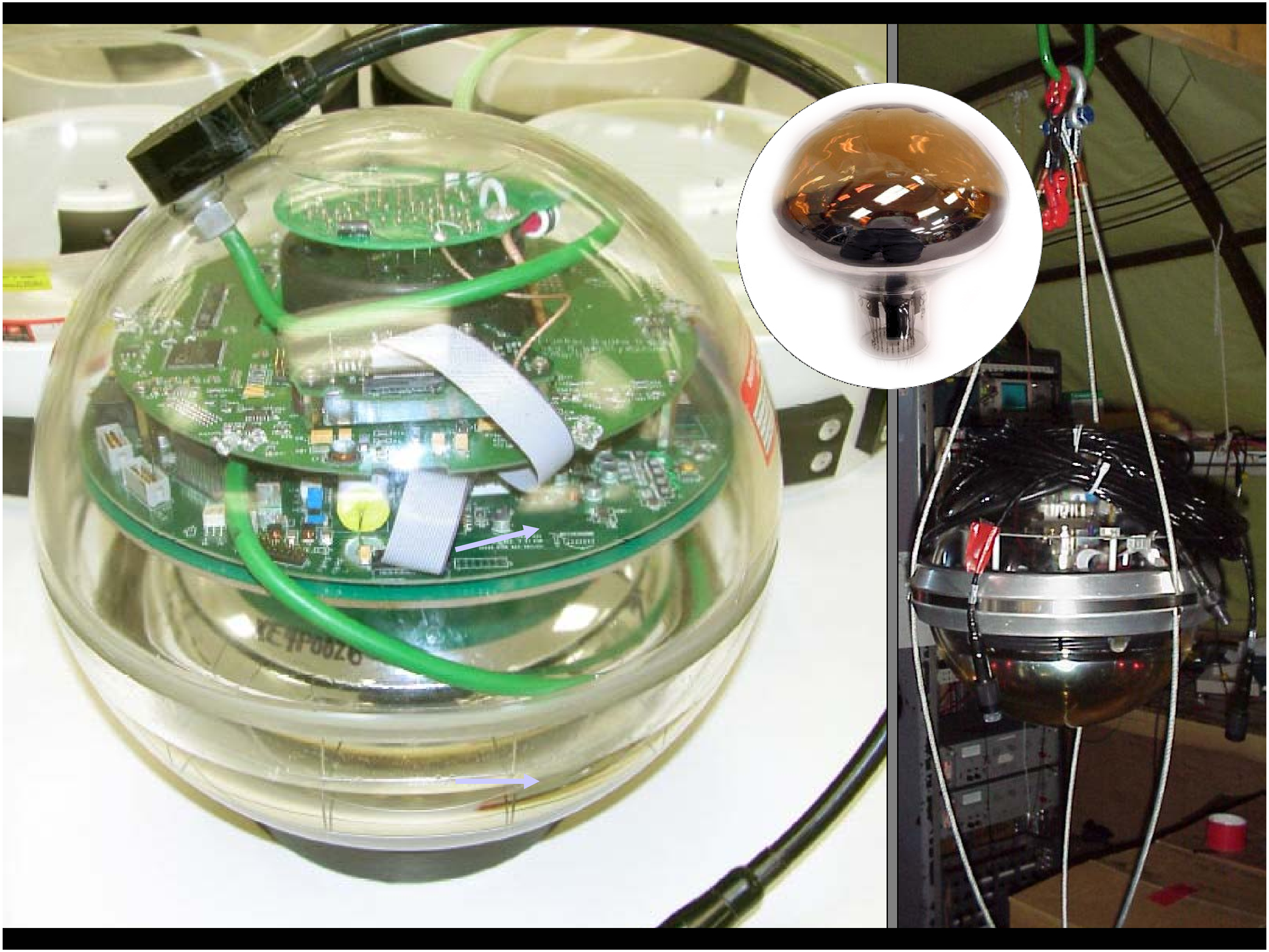
First-Generation Neutrino Telescopes

Requires Kilometer-Scale Neutrino Detectors

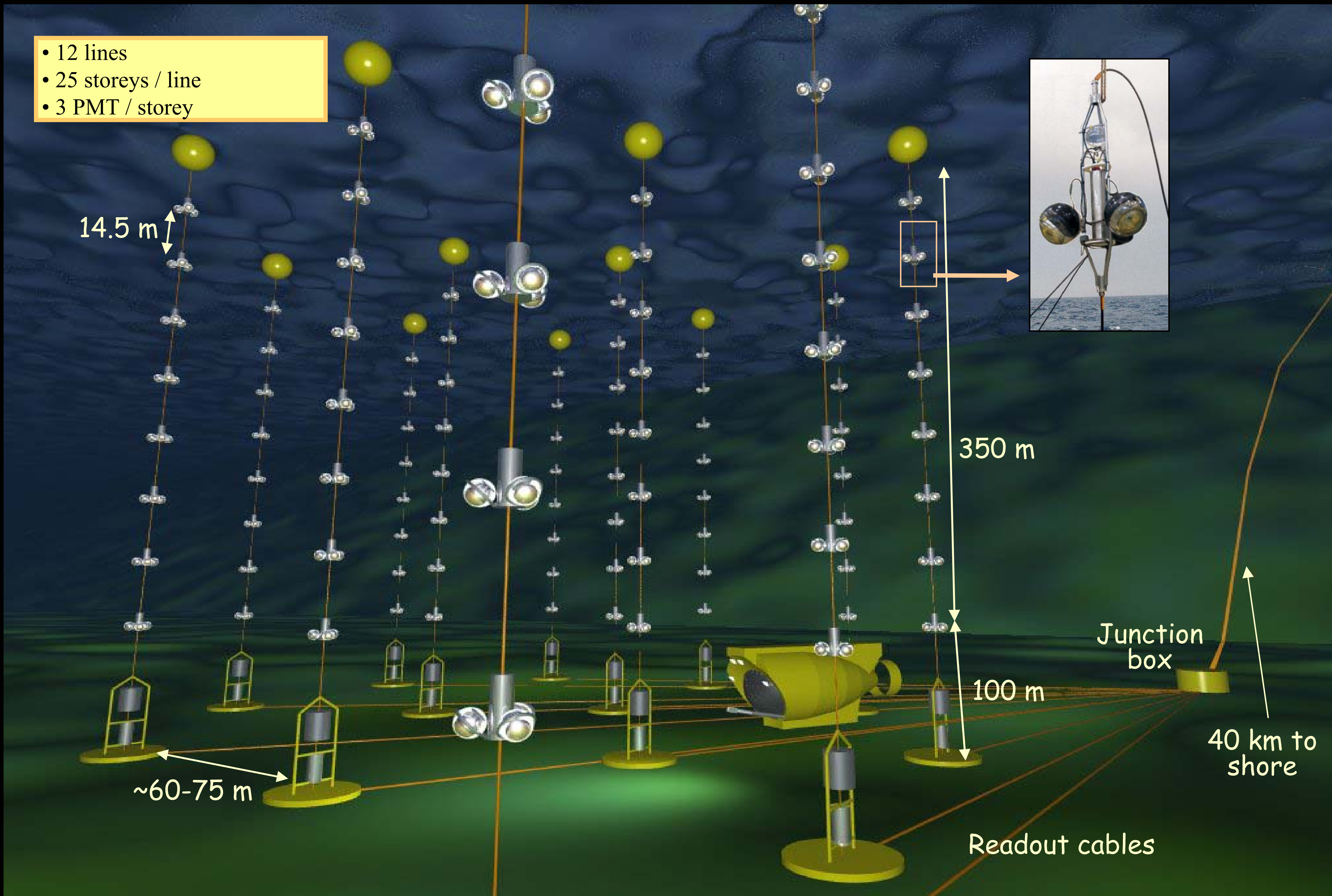





• Infrequently, a cosmic neutrino is captured in the ice, i.e. the neutrino interacts with an ice nucleus
• In the crash a muon (or electron, or tau) is produced
Cerenkov light cone
γ
muon or tau
Detector
interaction
neutrino
•The muon radiates blue light in its wake
•Optical sensors capture (and map)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



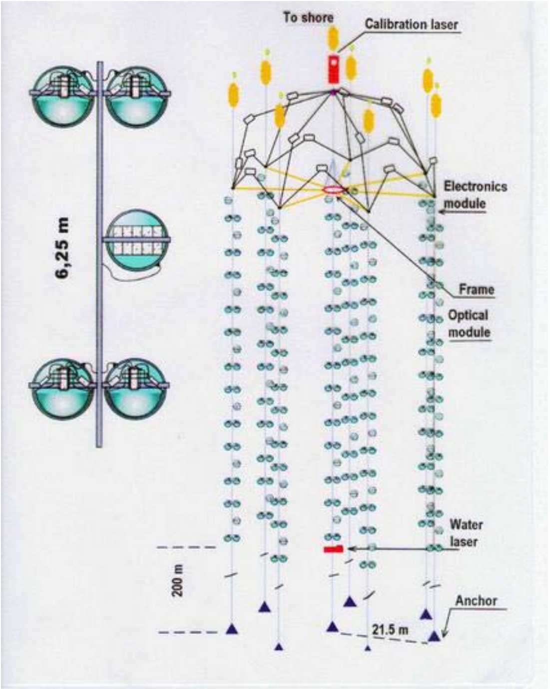
ANTARES



• 12 lines
• 25 storeys / line
• 3 PMT / storey
14.5 m
350 m
100 m
Junction box
40 km to shore
~60-75 m
Readout cables

Northern hemisphere detectors

Baikal NT200

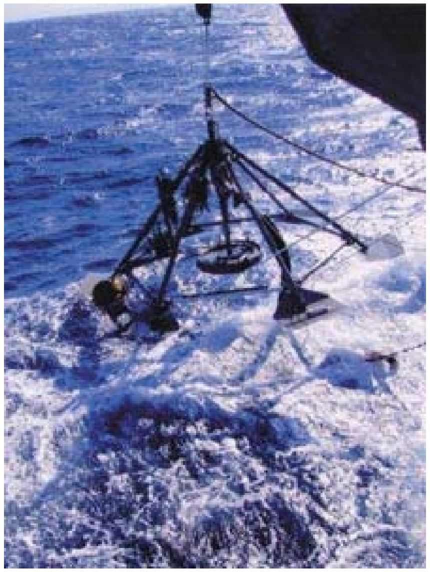


1100 m deep
data taking since 1998
new: 3 distant strings

Antares

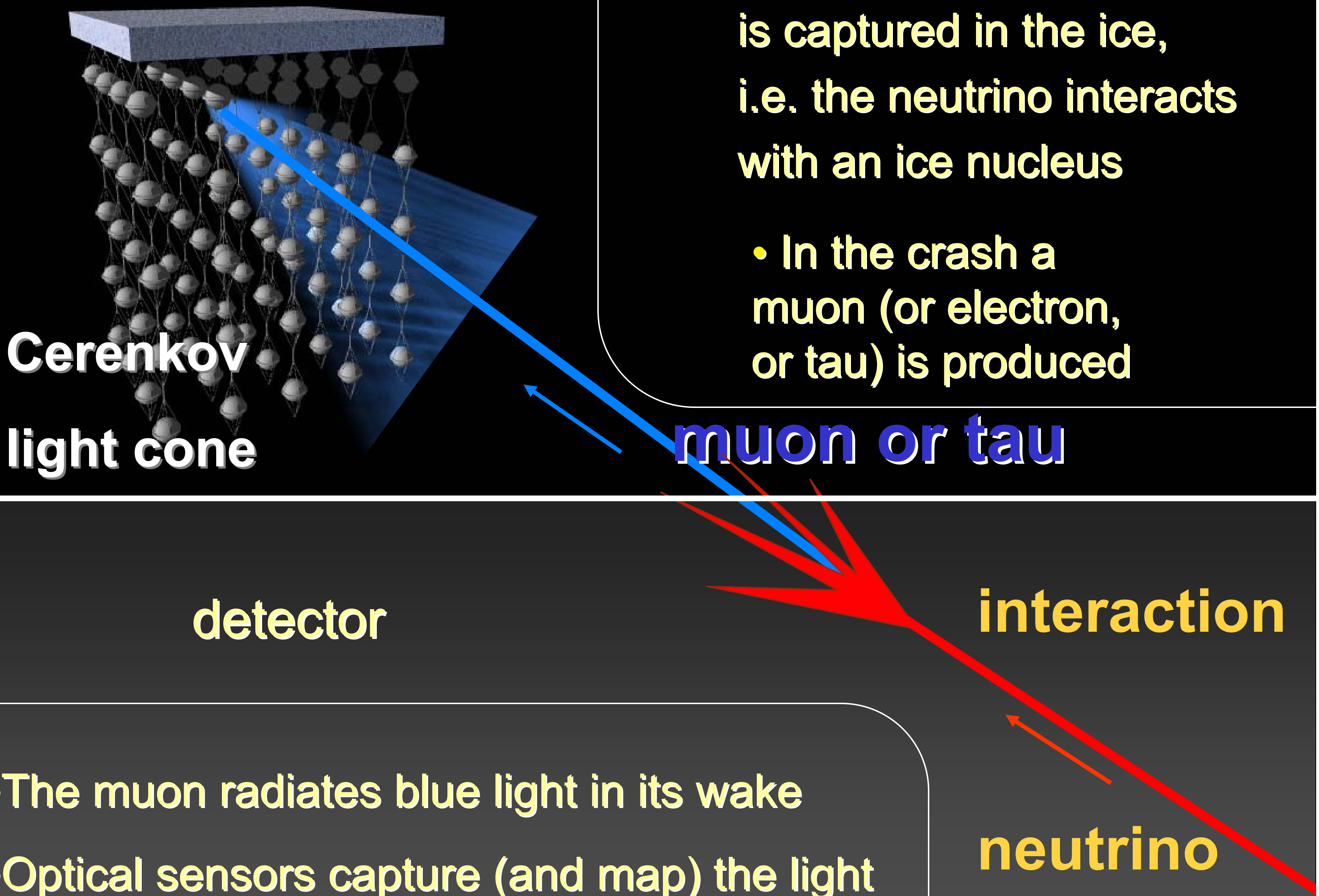
March 17, 2003
2 strings connected
2400 m deep
completion: start 2006

Nestor

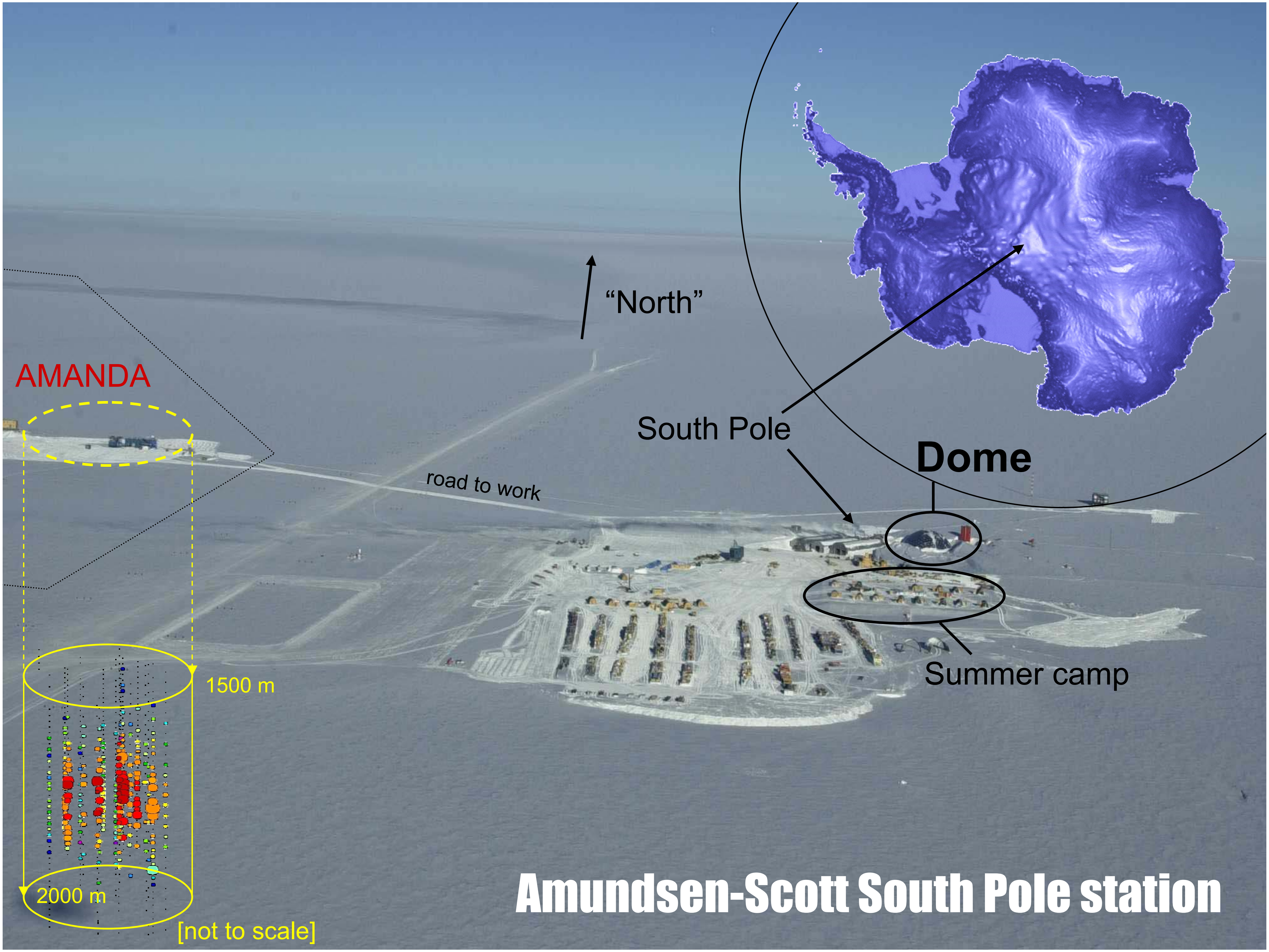


March 29, 2003
1 of 12 floors deployed
4000 m deep
completion: 2006

- 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



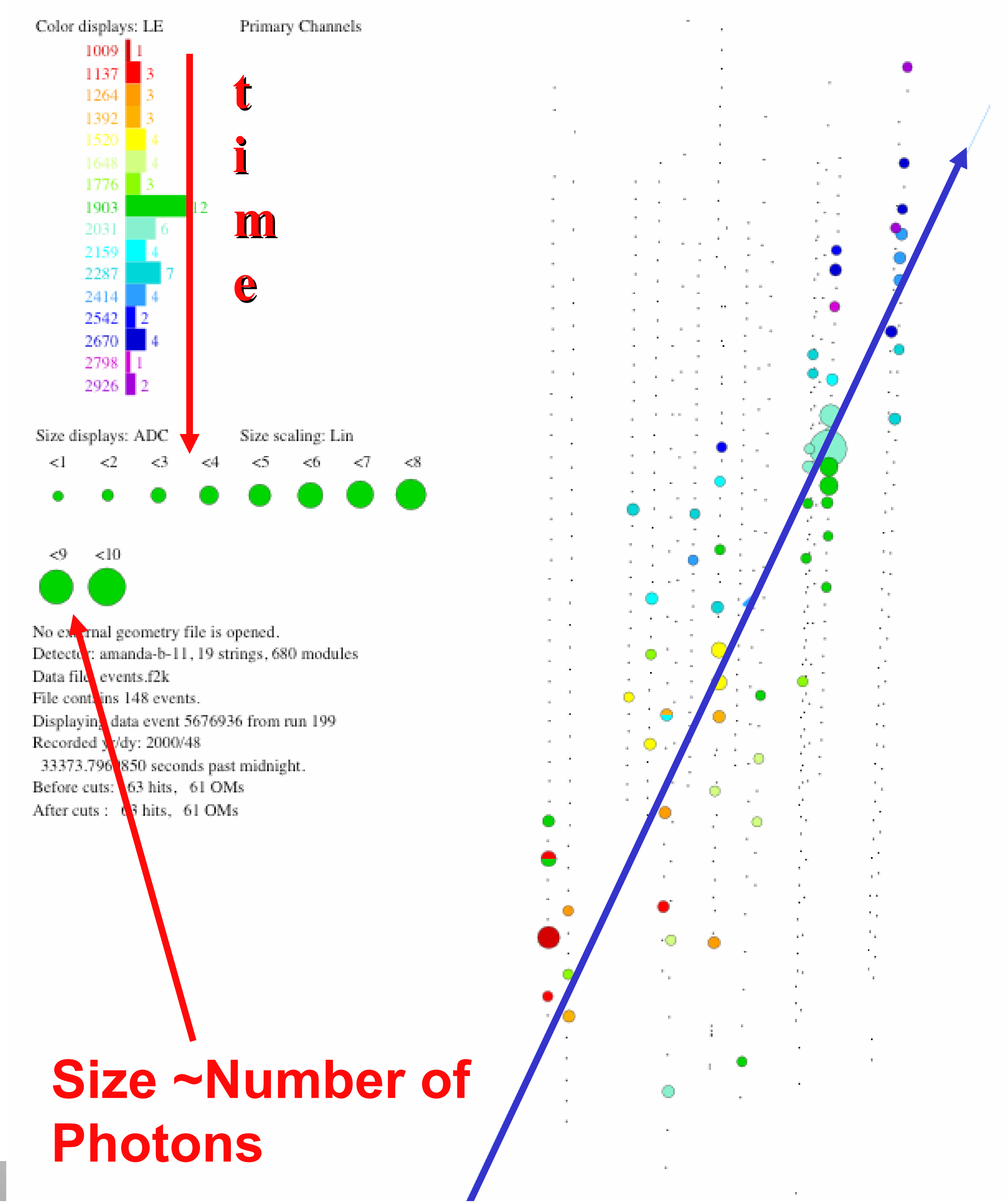
- The muon radiates blue light in its wake
- Optical sensors capture (and map) the light



"North"
AMANDA
South Pole
Dome
road to work
1500 m
2000 m
[not to scale]
Summer camp
Amundsen-Scott South Pole station

AMANDA II

- up-going muon
- 61 modules hit

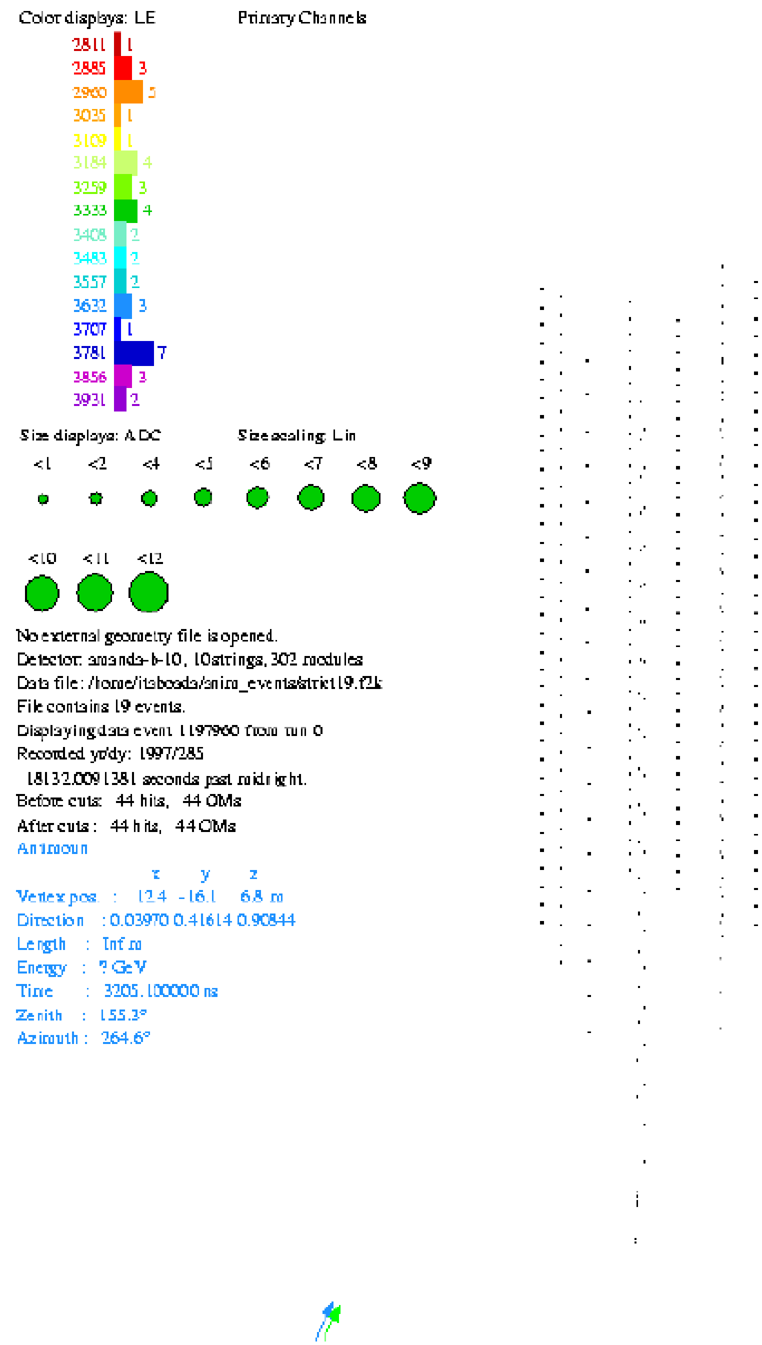


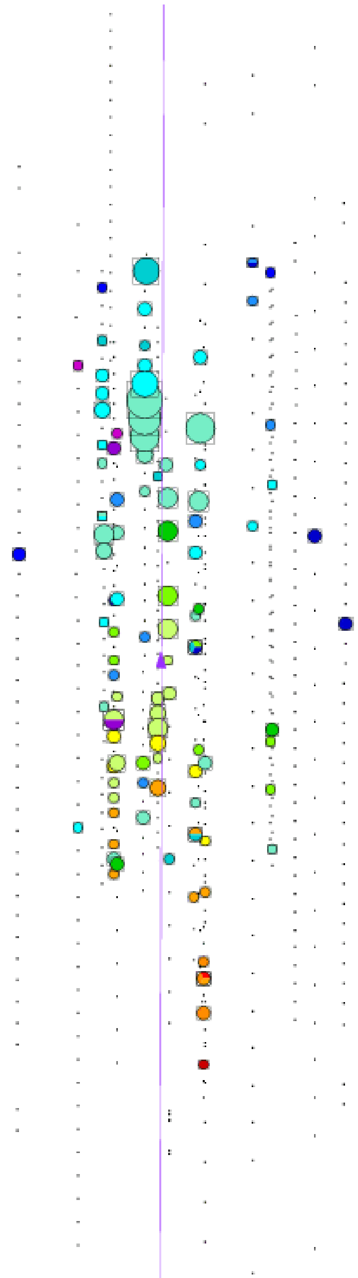
> 7 neutrinos/day on-line

AMANDA Event Signature: Muon

***CC* muon neutrino interaction**
→ track

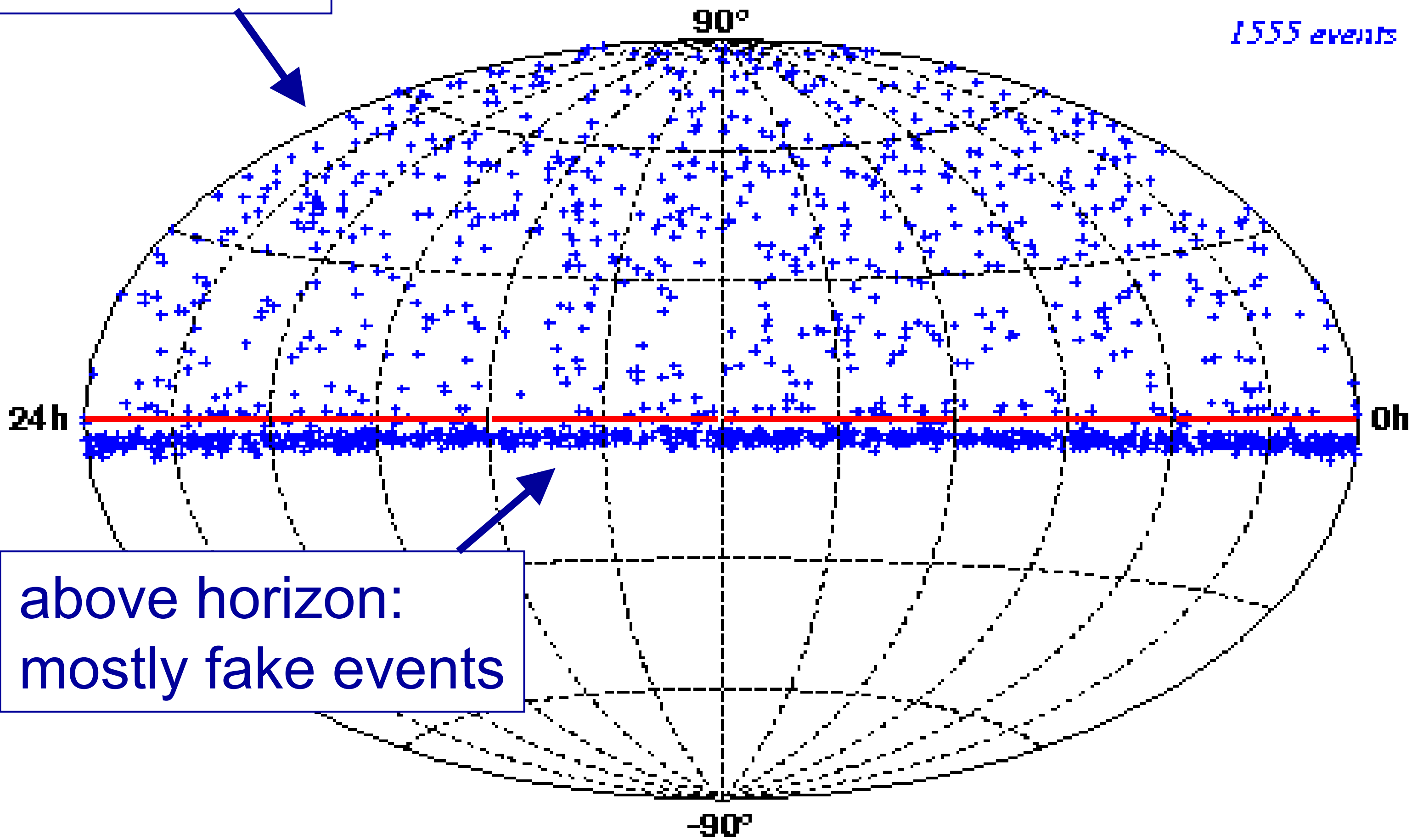
$$\nu_\mu + N \rightarrow \mu + X$$





Skyplot Amanda-II, 2000

697 events below horizon



above horizon: mostly fake events

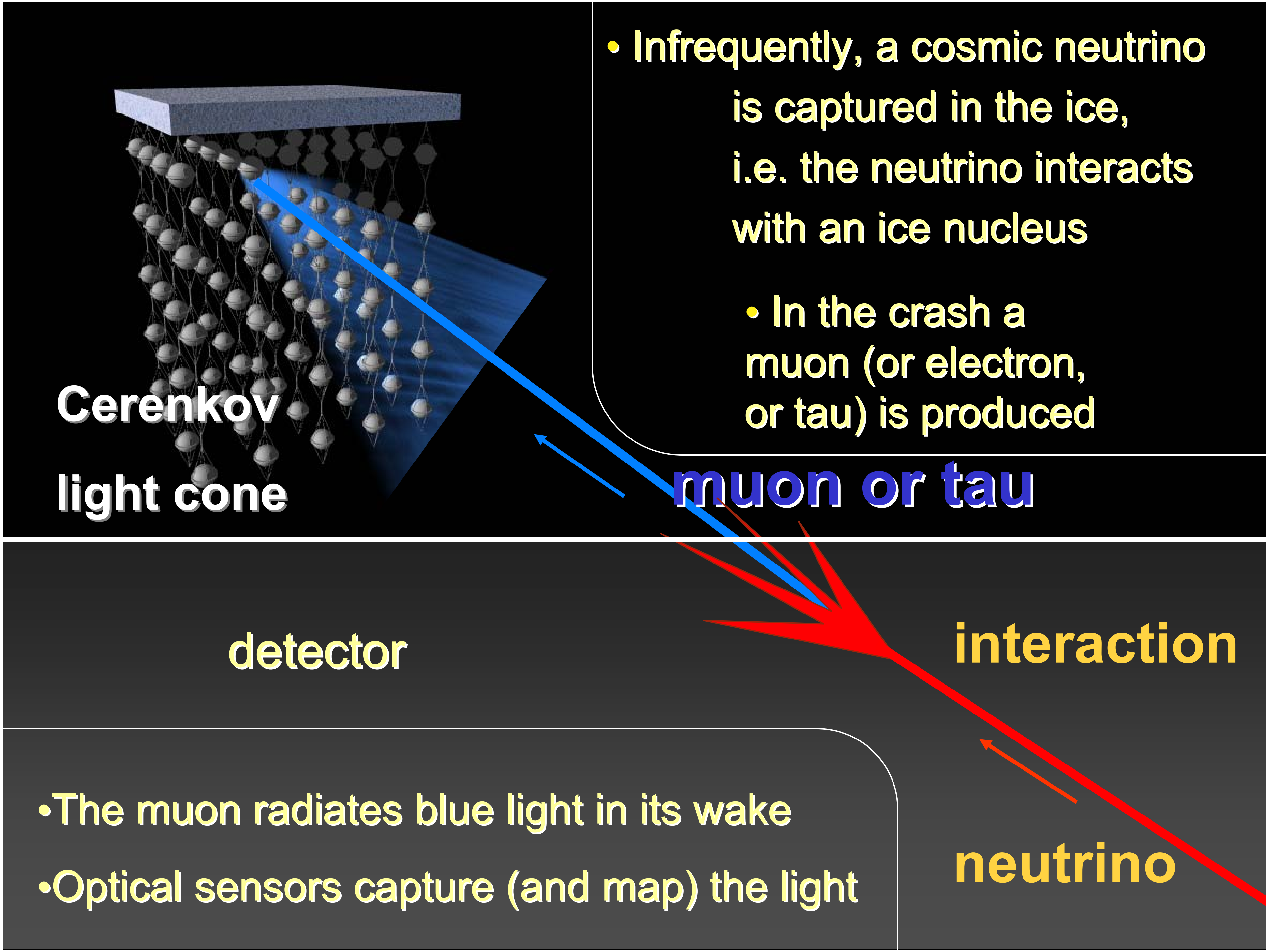
Detection of $\phi_\nu(E_\nu)$

$$dN/dE = A_\nu \, \phi_\nu$$

$$= \{P_{earth} \, P_\mu \, A_\mu\} \, \phi_\nu$$

with $P_\mu = n \, R_\mu \, \sigma_\nu \sim 10^{-6} \, E_{Tev}$

$$A_\nu = P_{earth} \, P_\mu \, A_\mu$$

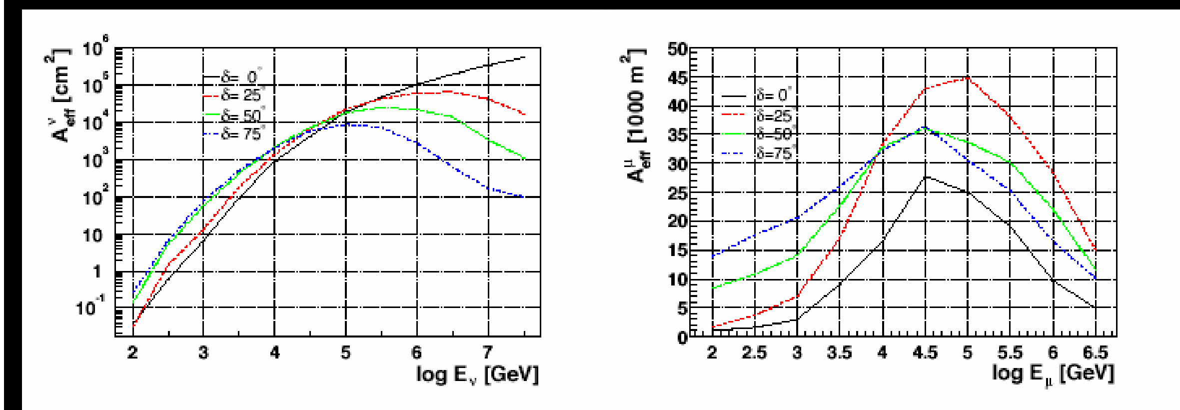

• Infrequently, a cosmic neutrino is captured in the ice, i.e. the neutrino interacts with an ice nucleus
• In the crash a muon (or electron, or tau) is produced
Cerenkov light cone
muon or tau
detector
interaction
neutrino
•The muon radiates blue light in its wake
•Optical sensors capture (and map)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

at TeV energy

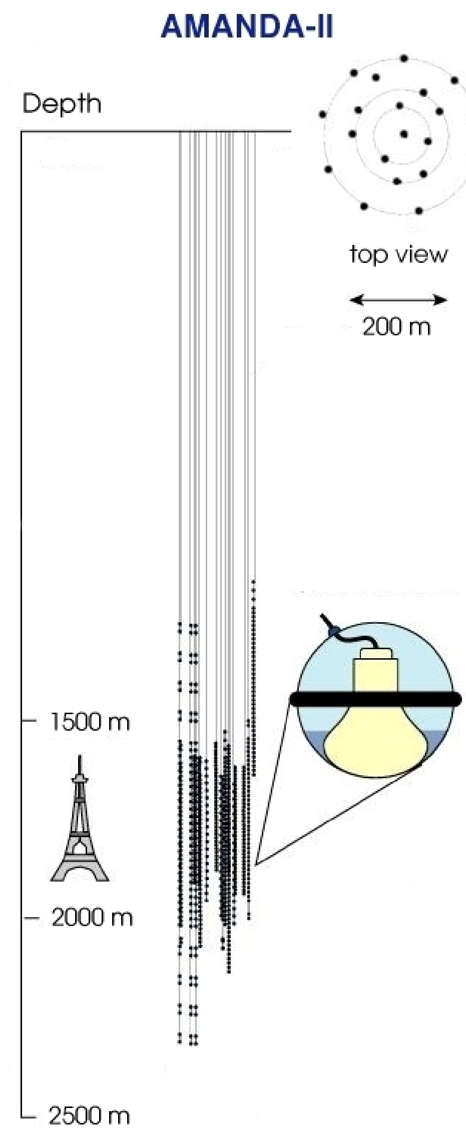
Neutrino area: 10~100 cm^2

Muon area: ~ 10,000 m^2

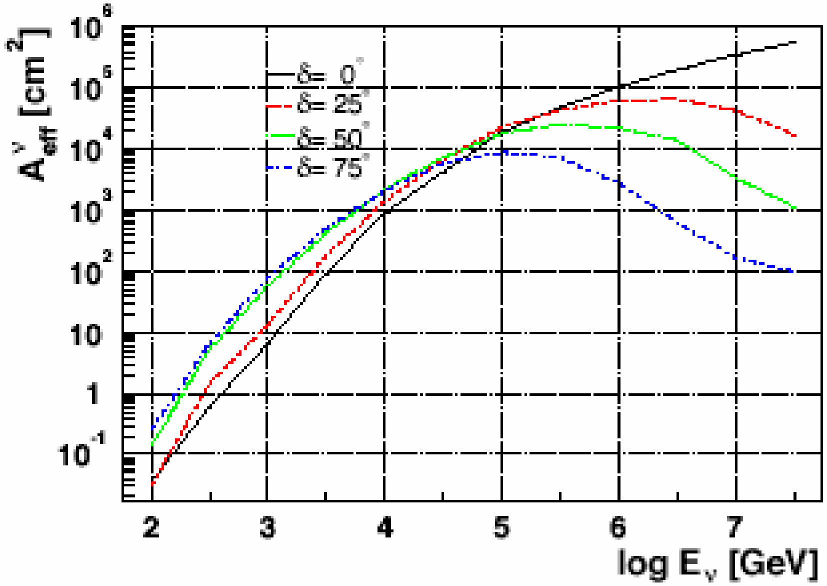
(geometric area 0.03—0.1 km^2)

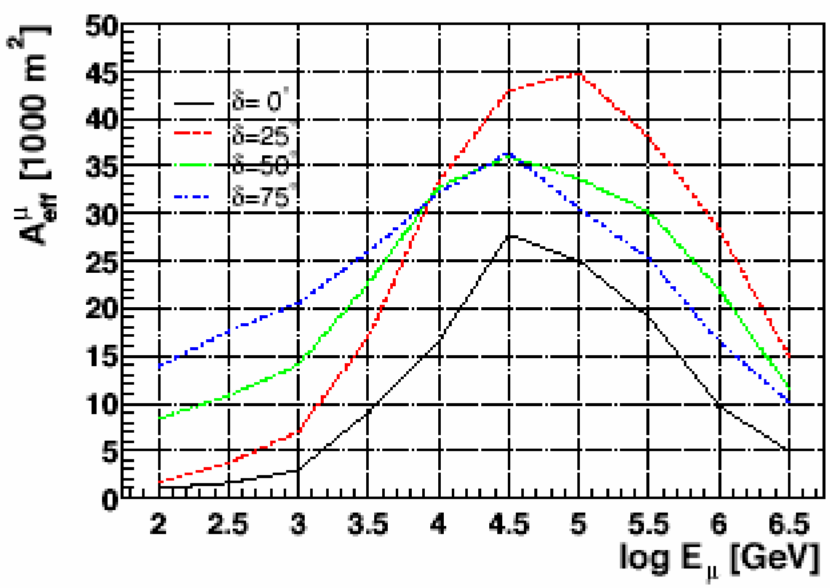


The AMANDA Detector



AMANDA effective area

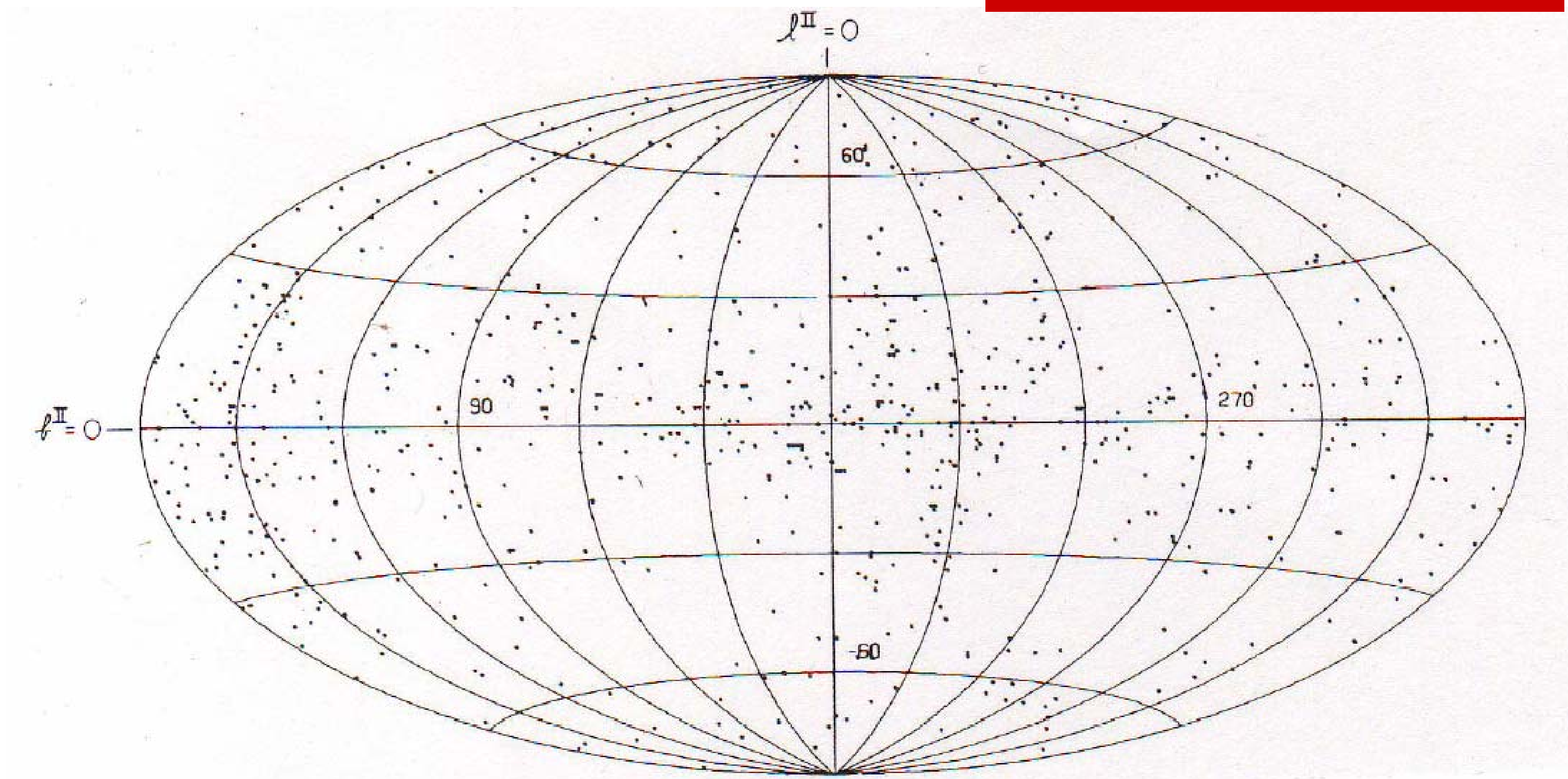




1968 OSO-3 (Kraushaar et al. 1972)

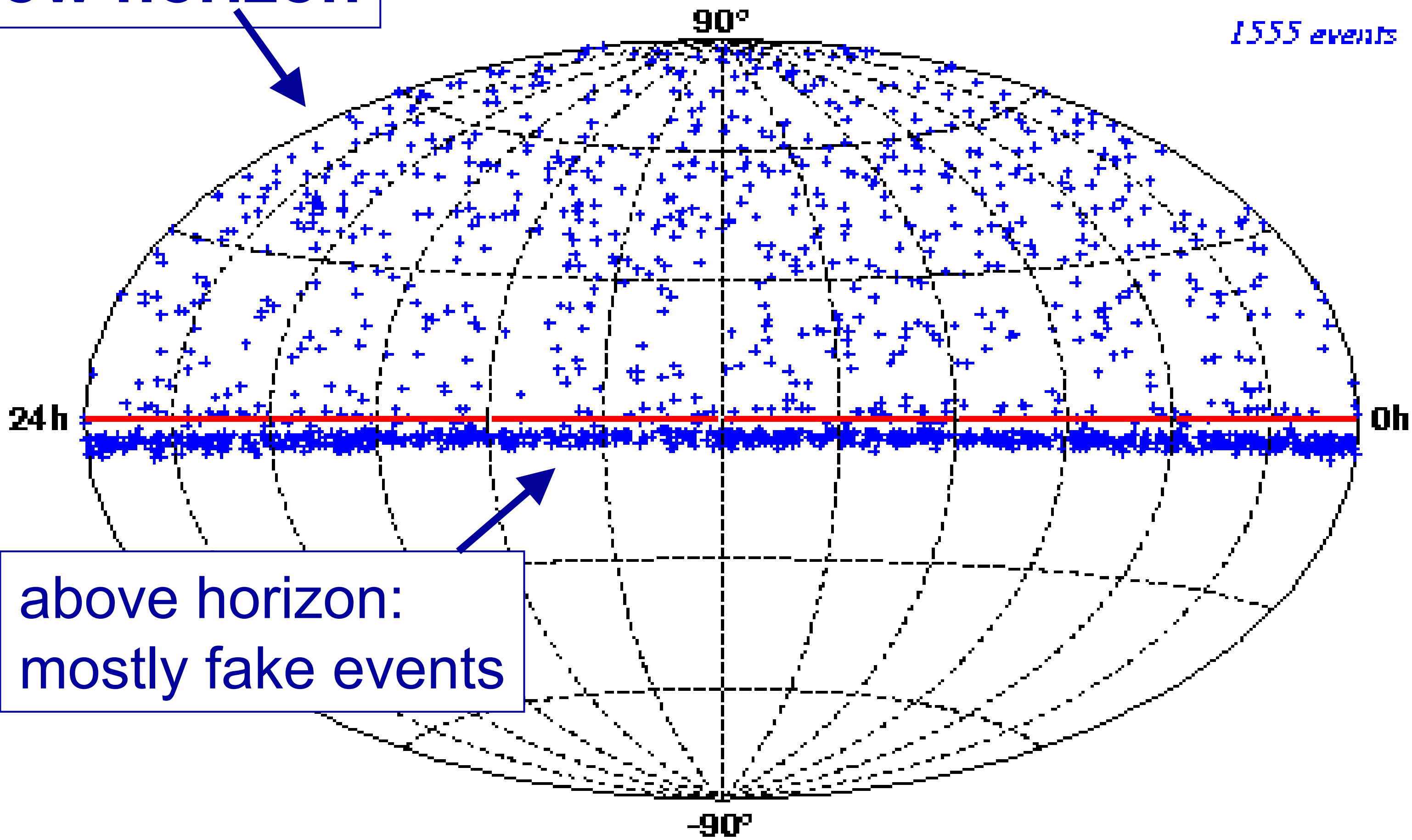
- effective area 4 cm^2
- 600 photons

sources seen in next mission! SAS-2 100 cm^2



Skyplot Amanda-II, 2000

697 events below horizon

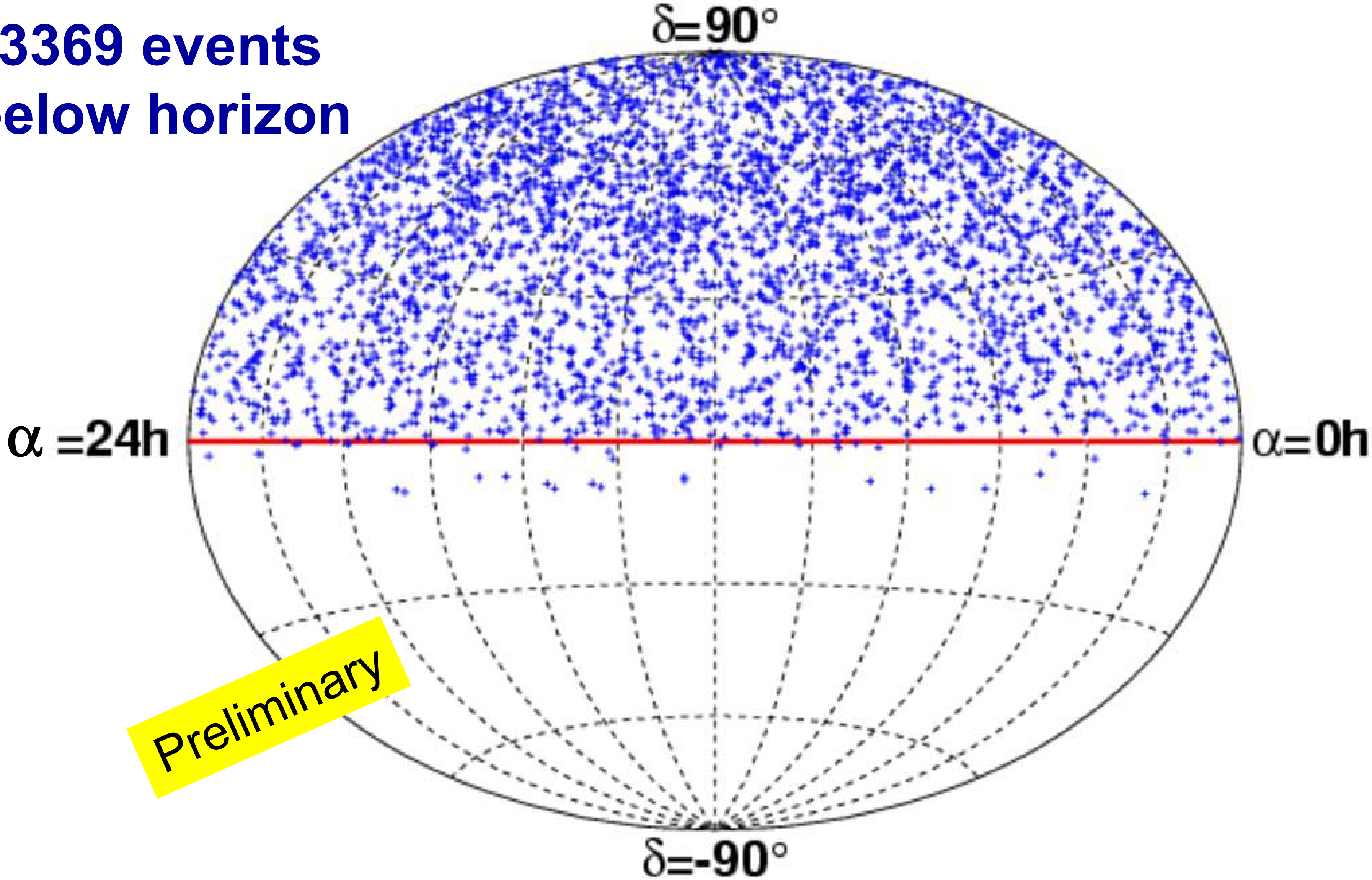


above horizon:
mostly fake events

AMANDA skyplot 2000-2003

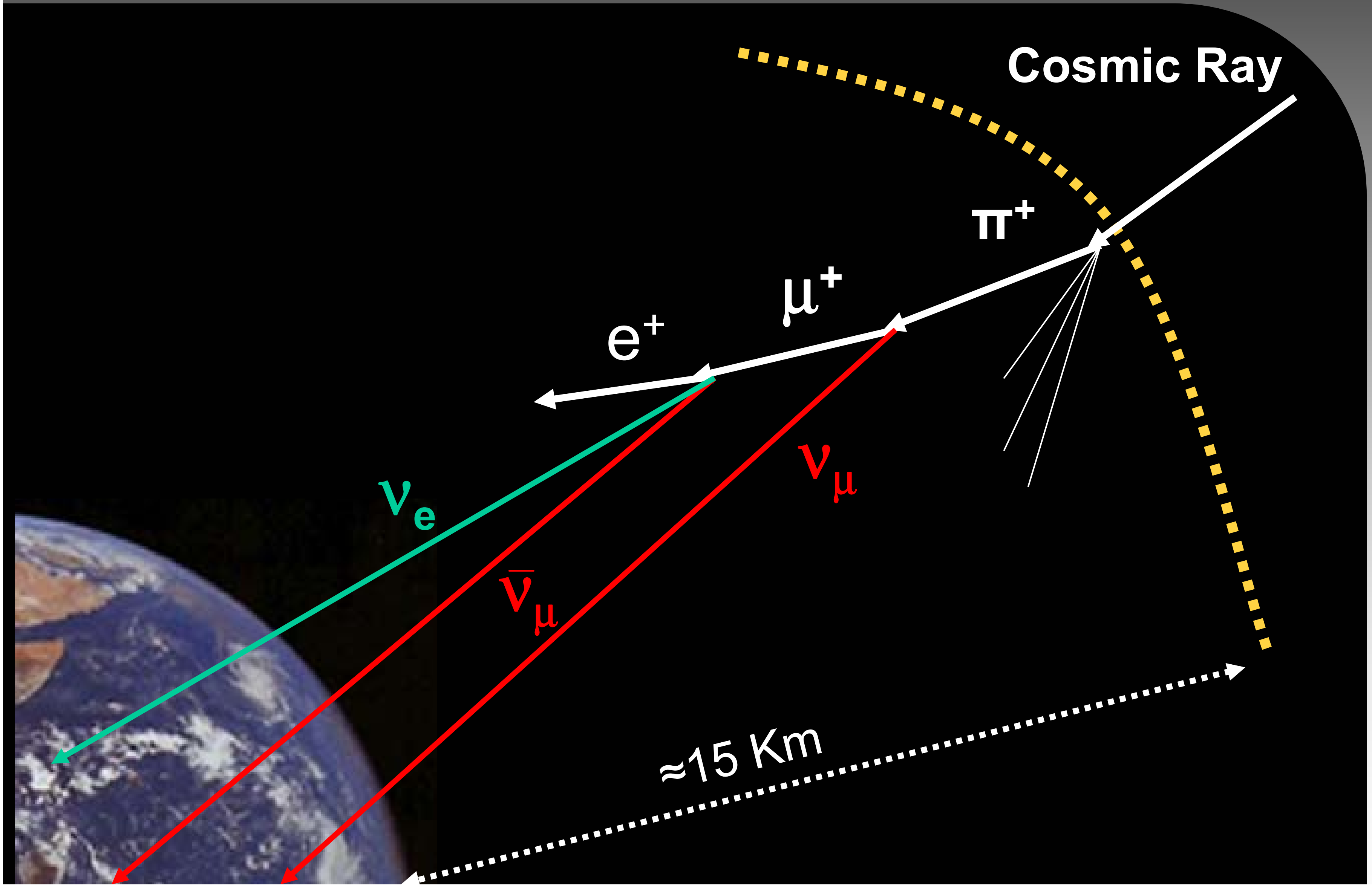
optimized for best sensitivity to E^{-3} – E^{-2} sources

3369 events below horizon

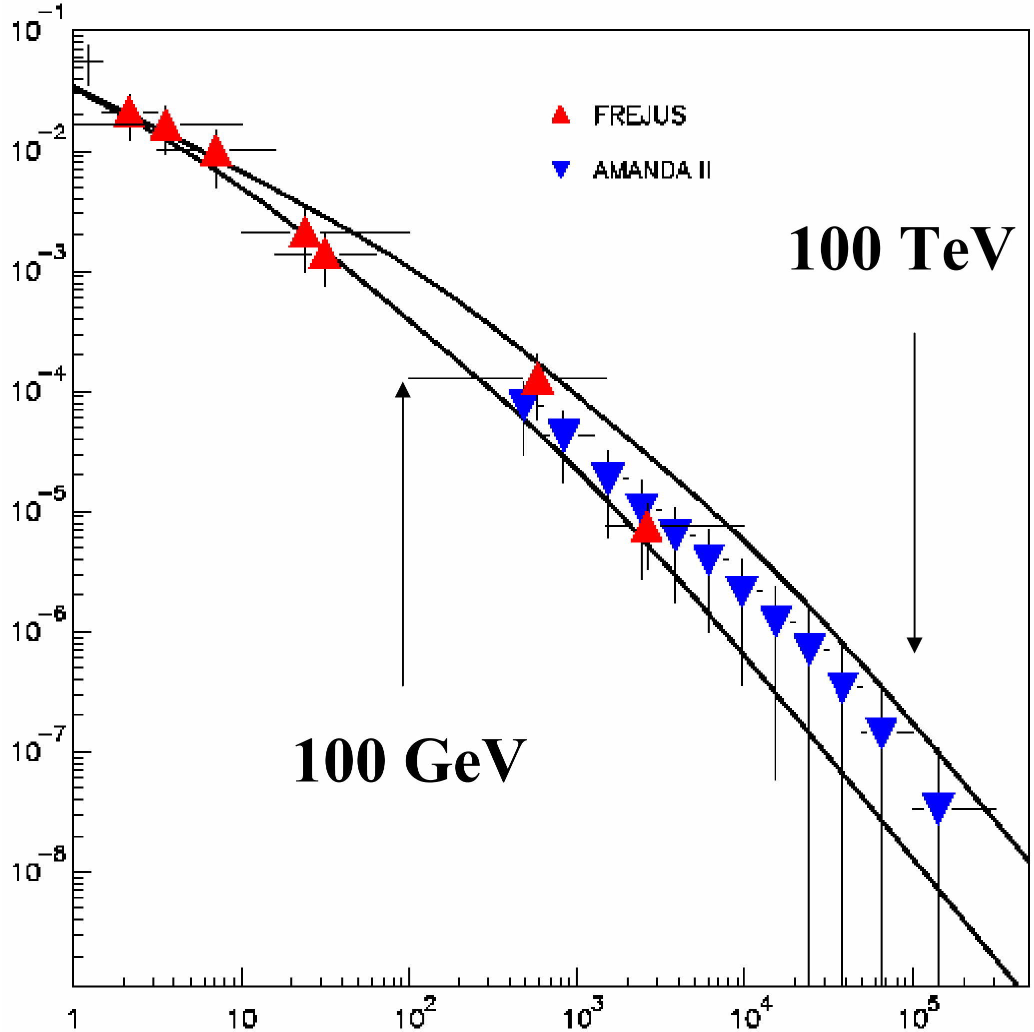


AMANDA: proof of concept

Atmospheric Neutrinos



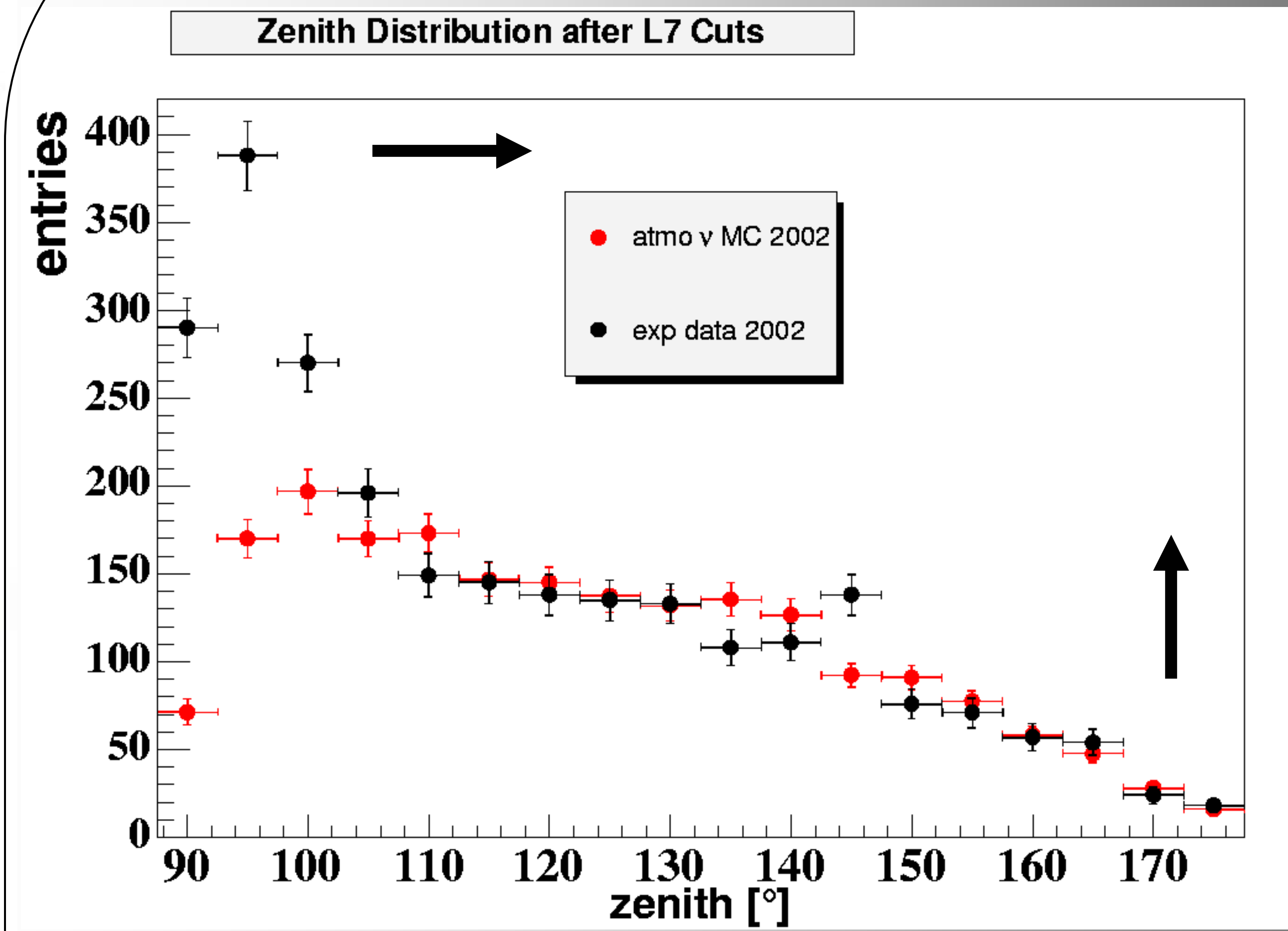
Atmospheric ν 's as Test Beam



Neutrino Energy in GeV

Optimized 2002 analysis

zenith distribution

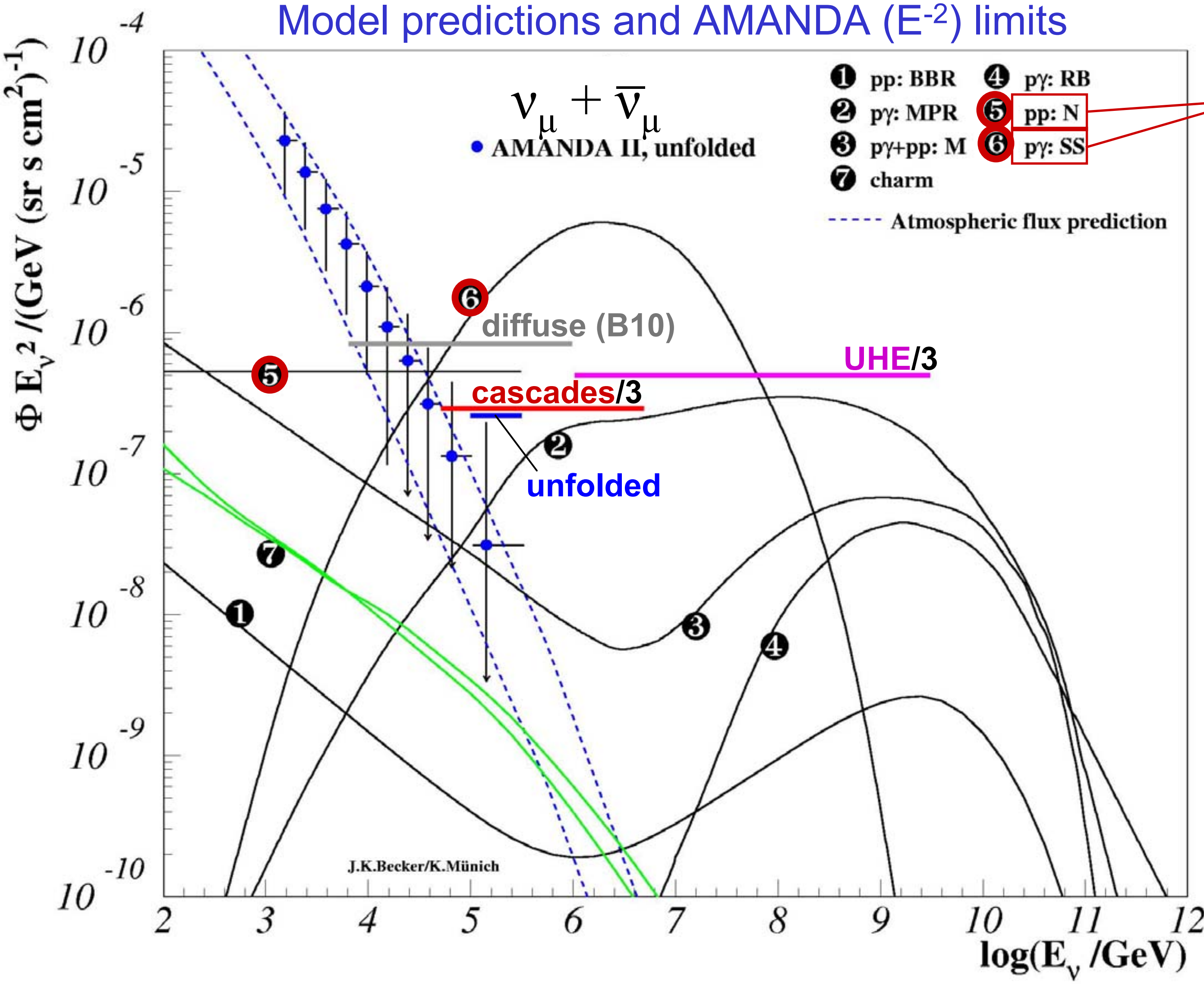


	data	atmo
>110°	1272	1322
<110°	1232	694
>90°	2504	**2017**

normalization not final yet, assumed life-time is 208 days

Diffuse muon neutrino fluxes

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



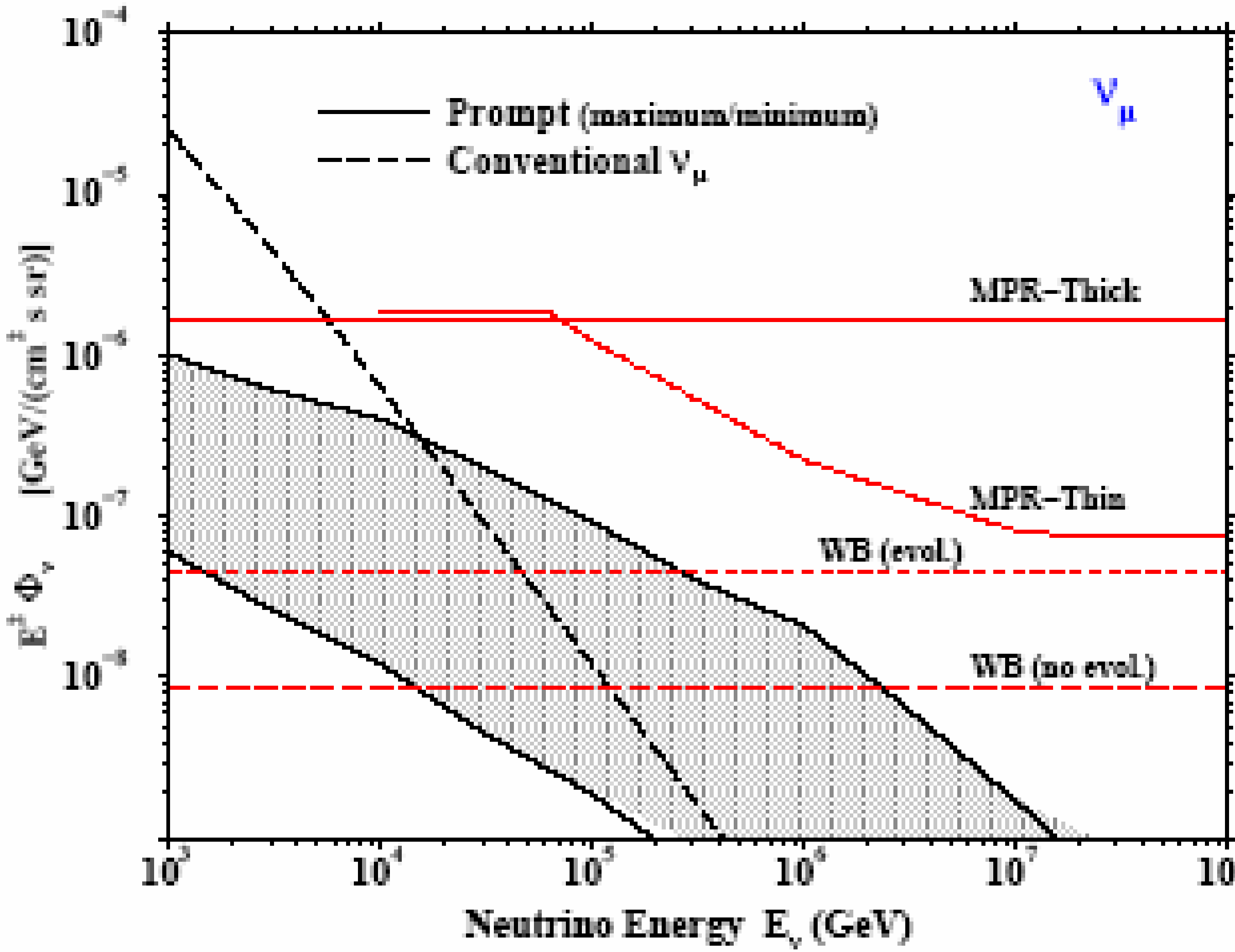
Excluded predictions

Integral limits (cover 90% of final energy spectrum):

- diffuse (B10)
- cascades
- UHE

Quasi-differential limit:

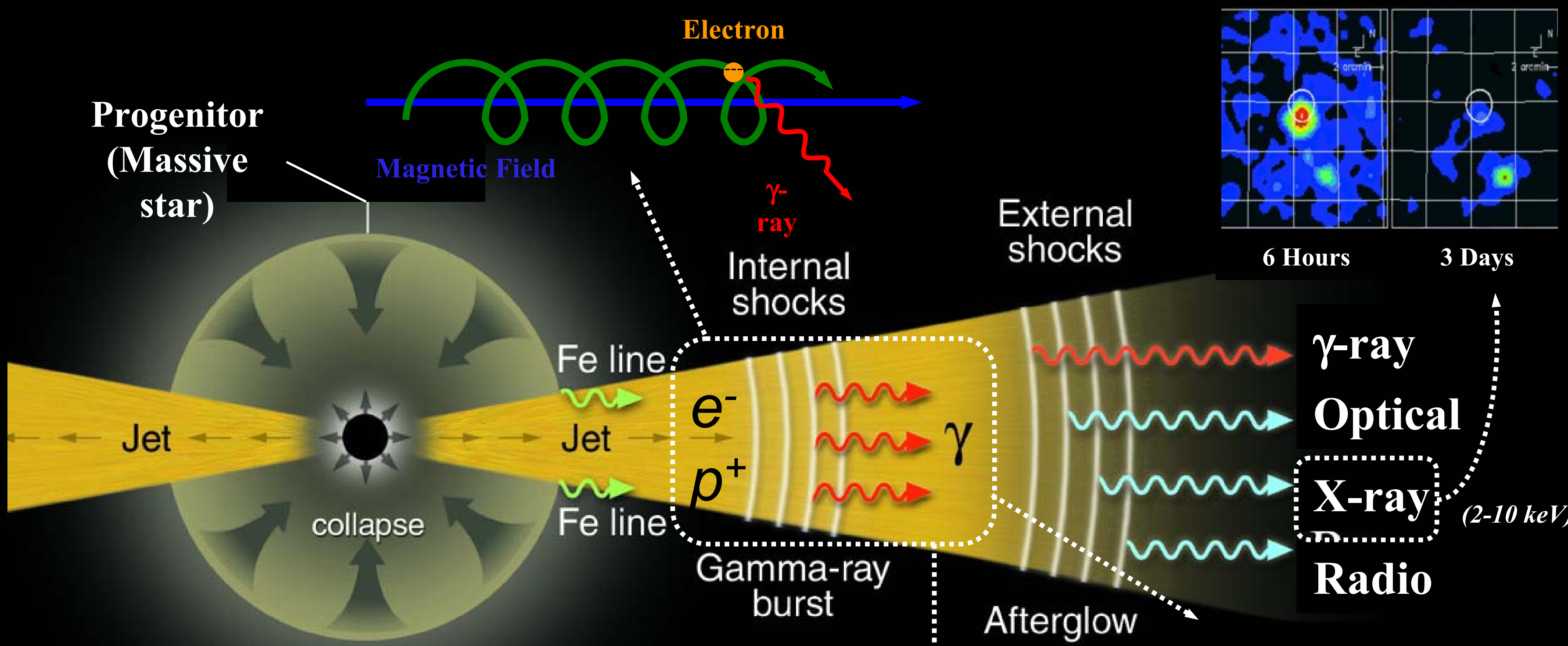
- unfolded



Prompt (maximum/minimum)
Conventional ν_μ
ν_μ
MPR−Thick
MPR−Thin
WB (evol.)
WB (no evol.)
E² Φ_ν [GeV/(cm² s sr)]
Neutrino Energy E_ν (GeV)

Astronomy

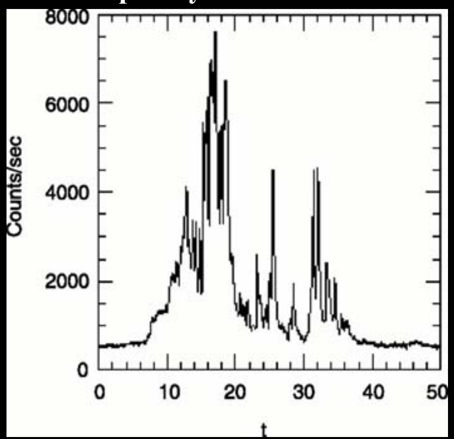
Fireball Phenomenology & The Gamma-Ray Burst (GRB) Neutrino Connection



$E \cong 10^{51} - 10^{54}$ ergs

$$p^{+} + \gamma \rightarrow \Delta^{+} \rightarrow (n) + \pi^{+} \rightarrow \nu_{\mu} + \mu^{+} \rightarrow \nu_{\mu} + e^{+} + \nu_{e} + \bar{\nu}_{\mu}$$

Shock variability is reflected in the complexity of the GRB time



over 500 GRB searched!

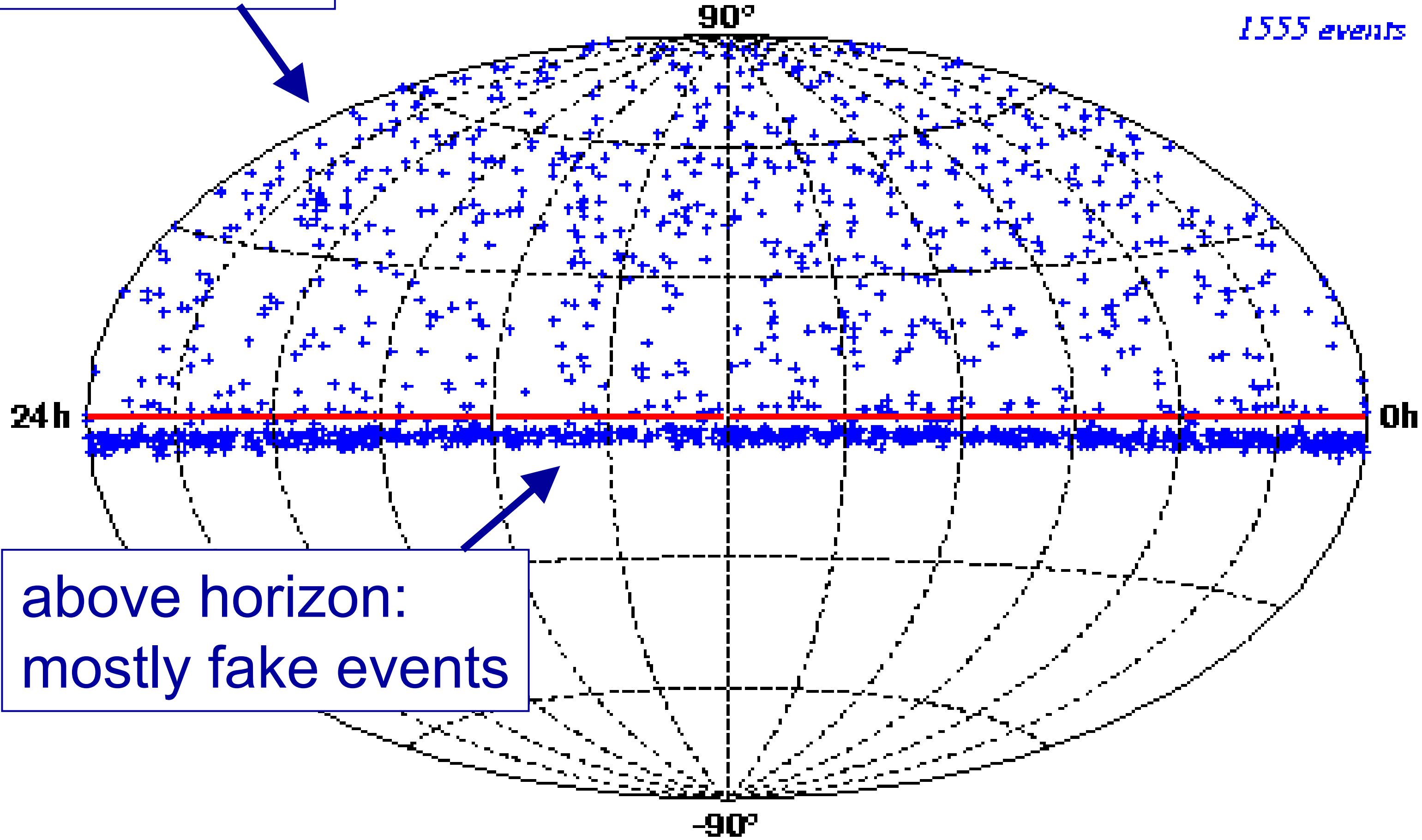
$R < 10^{8}$ cm

$R \leq 10^{14}$ cm, $T \cong 3 \times 10^{3}$ seconds

$R \leq 10^{18}$ cm, $T \cong 3 \times 10^{16}$ seconds

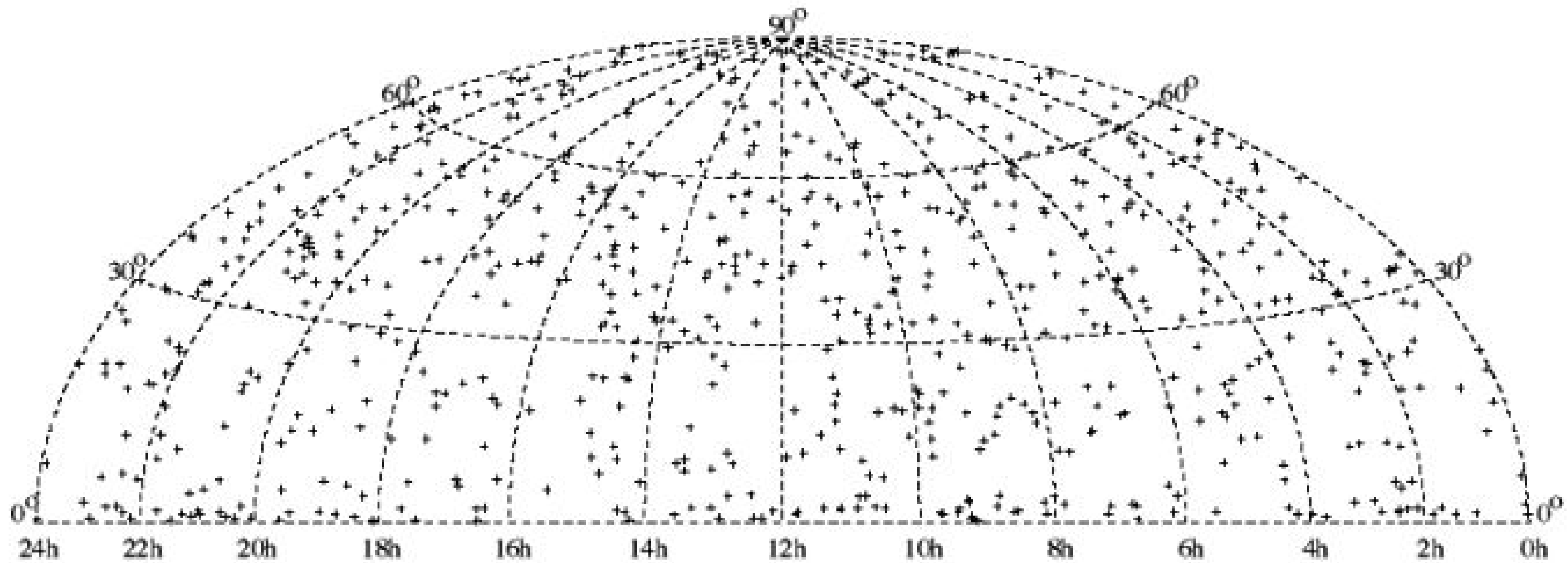
Skyplot Amanda-II, 2000

697 events
below horizon

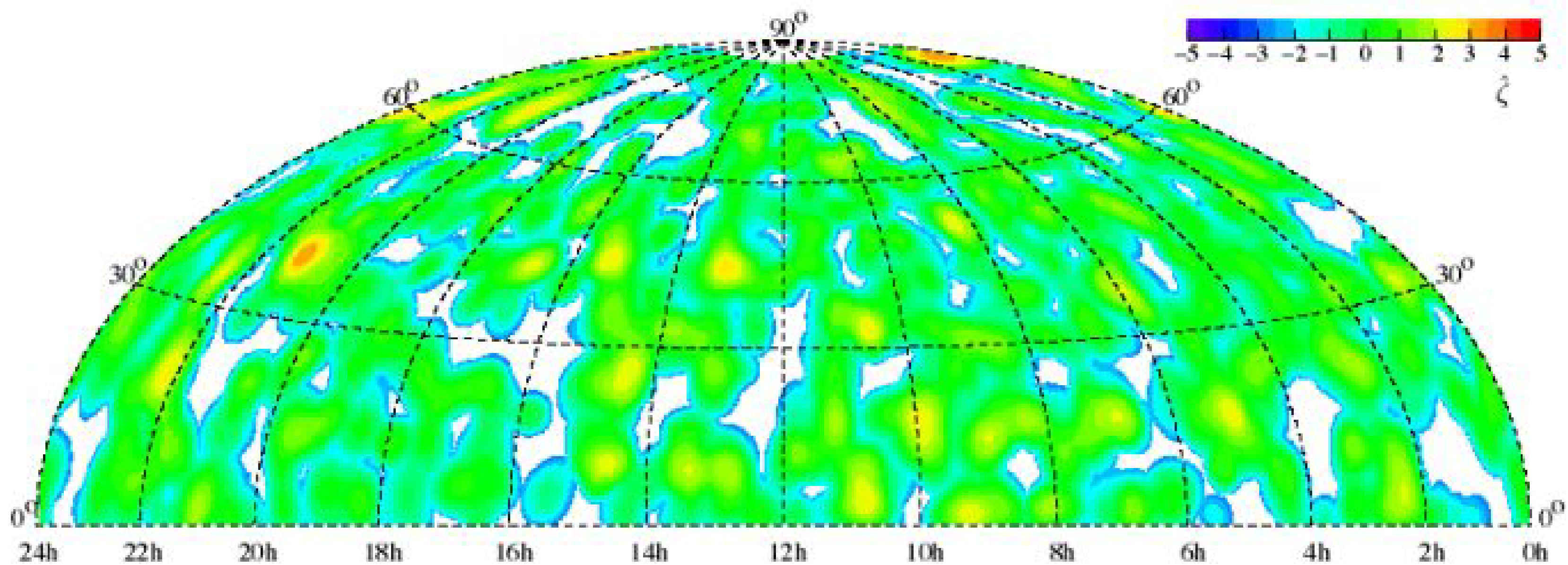


above horizon:
mostly fake events

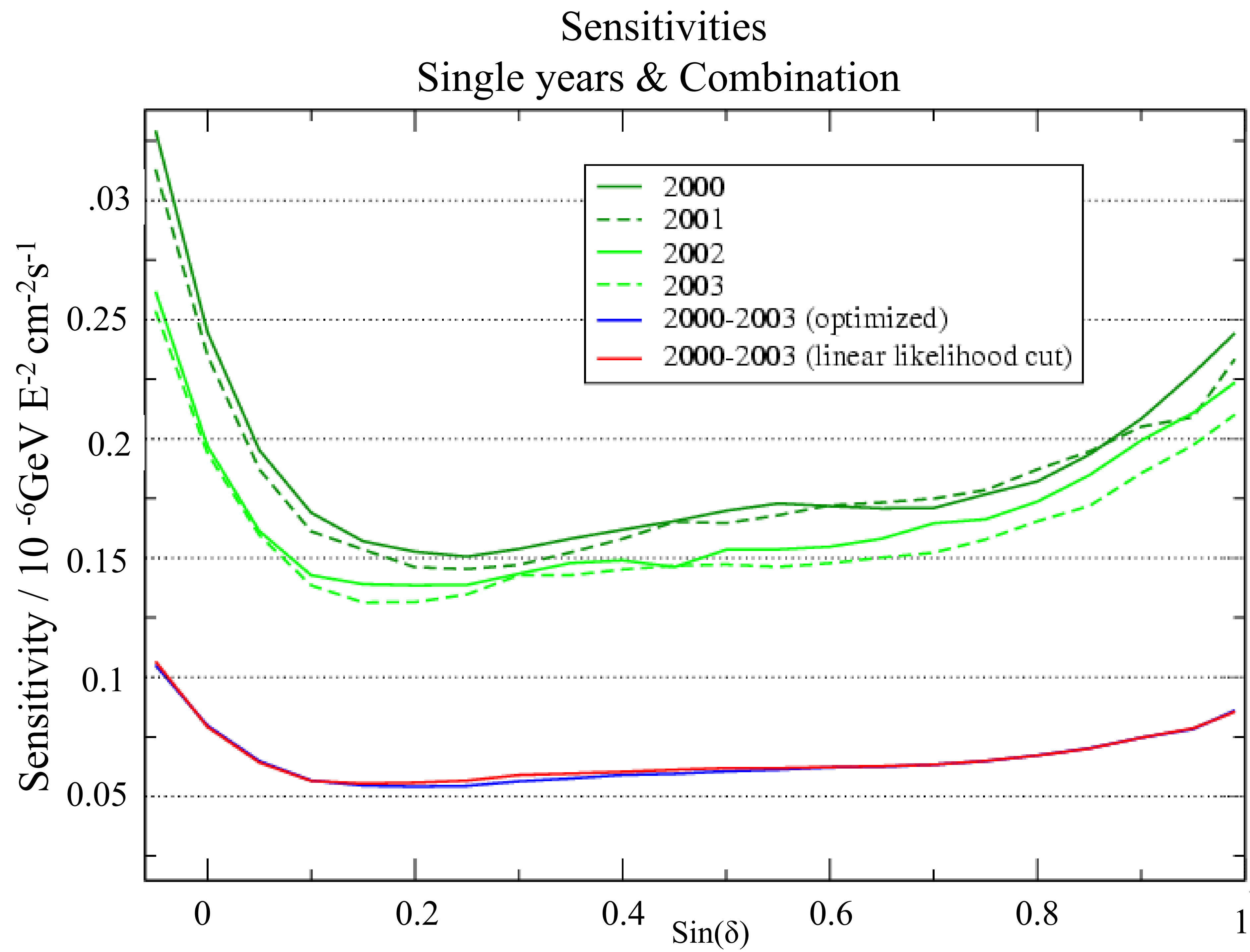
AMANDA 2000

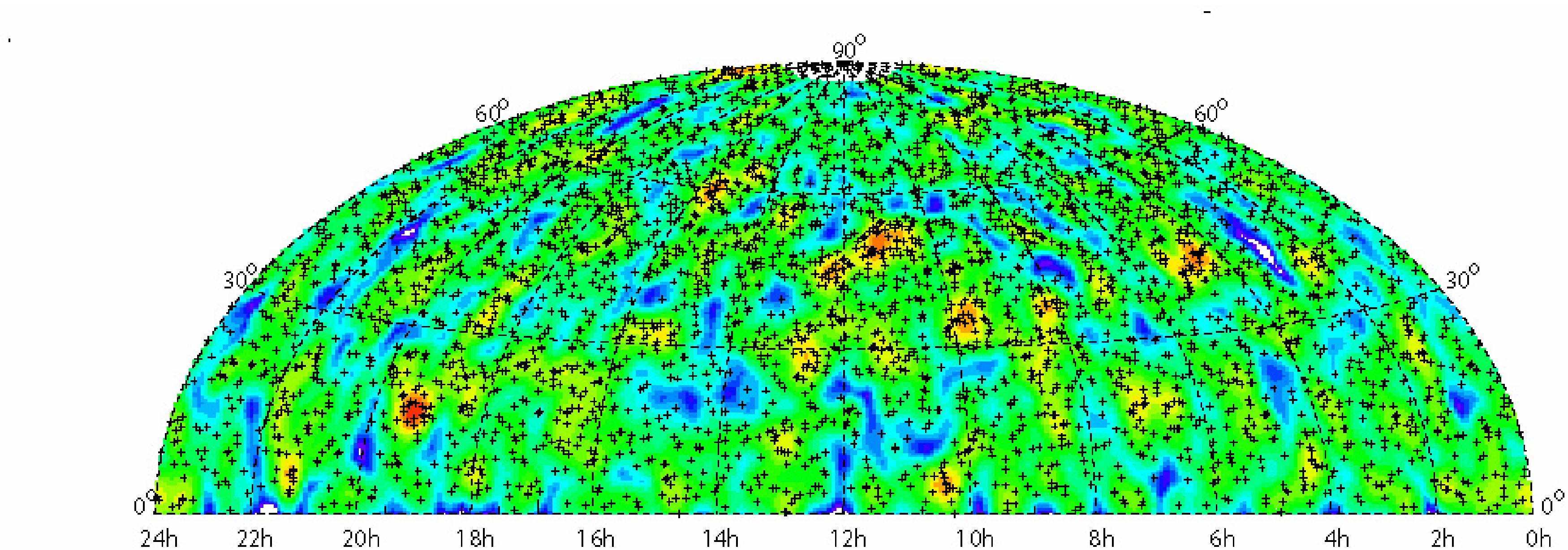


90°
60°
60°
30°
30°
0°
0°
24h
22h
20h
18h
16h
14h
12h
10h
8h
6h
4h
2h
0h

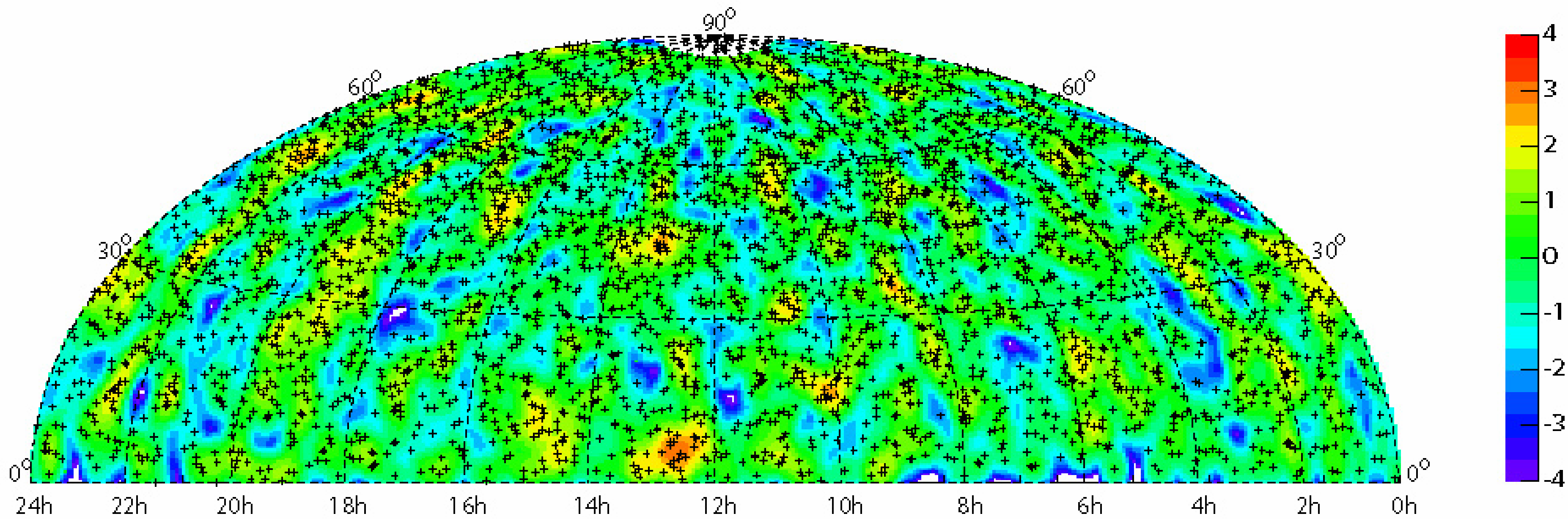


90°
-5 -4 -3 -2 -1 0 1 2 3 4 5
ζ
60°
60°
30°
30°
0°
0°
24h
22h
20h
18h
16h
14h
12h
10h
8h
6h
4h
2h
0h

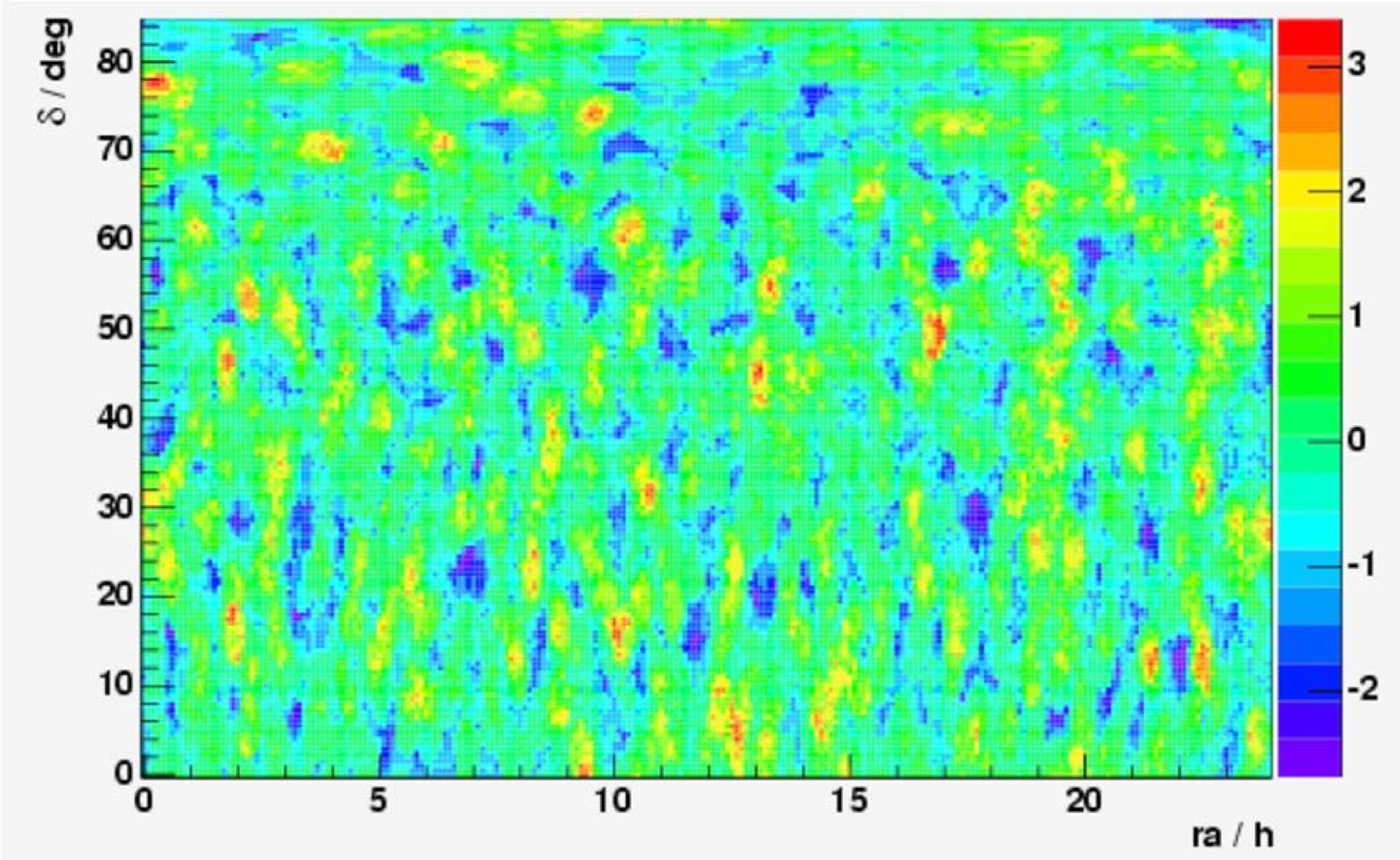

Sensitivities
Single years & Combination
2000
2001
2002
2003
2000-2003 (optimized)
2000-2003 (linear likelihood cut)
Sensitivity / 10 -6GeV E-2 cm-2s-1
.03
0.25
0.2
0.15
0.1
0.05
0
0.2
0.4
0.6
0.8
1
Sin(δ)

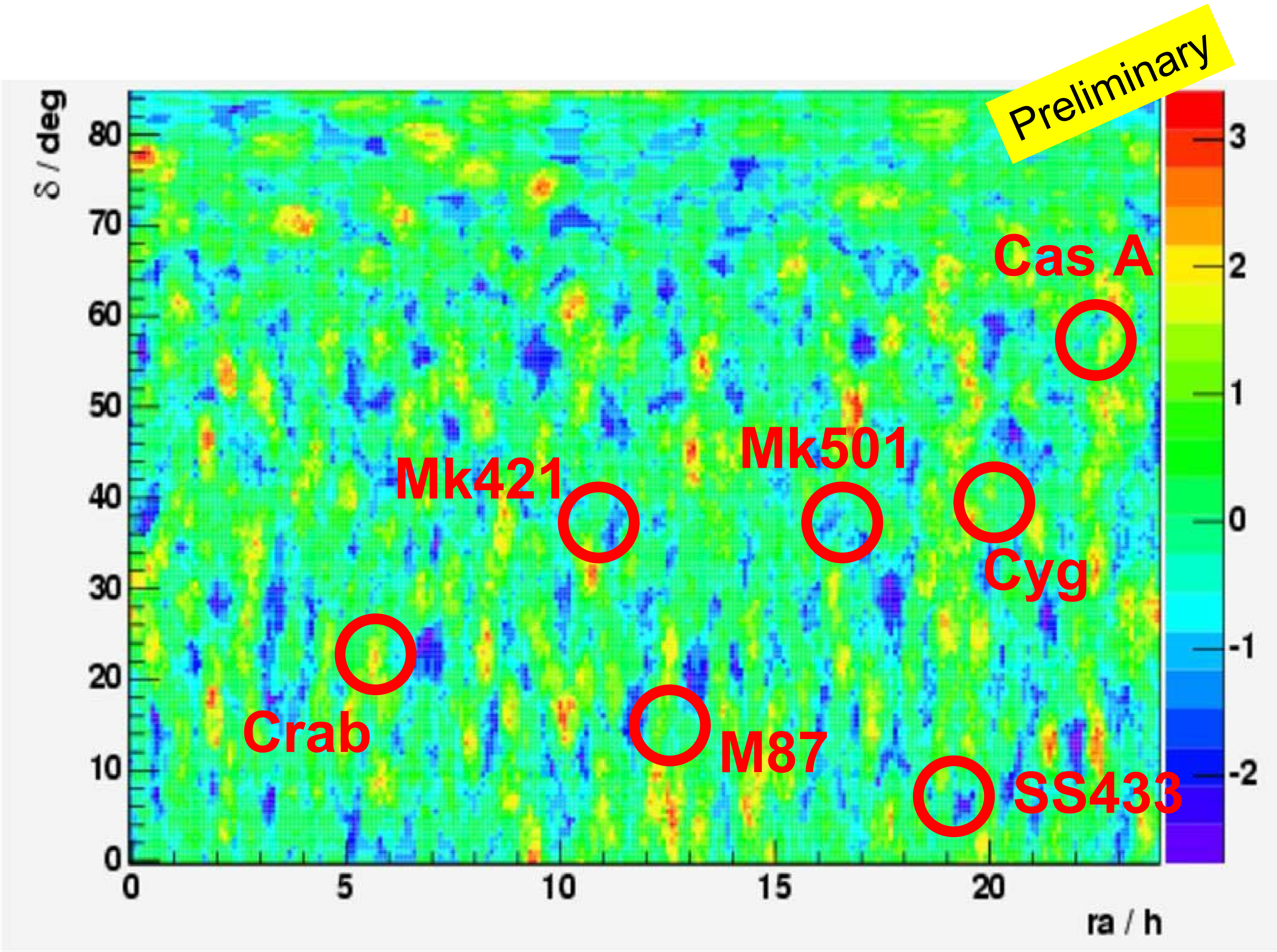


2000-03: scrambled (top) and unblinded (bottom)



Significance map for 2000-2003




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

90% C.L. upper limits (in units of $10^{-8}cm^{-2}s^{-1}$) for selected sources for an E^{-2} spectral shape integrated above E_ν=10 GeV

Source	Declination	1997	2000		2000+2001	
		Φ_ν^{limit}	Φ_ν^{limit}	N_{obs} / N_{bgr}	Φ_ν^{limit}	N_{obs} / N_{bgr}
SS433	5.0°	-	0.7	**0 / 2.38**	2.3	**1 / 1.69**
M87	12.4°	17.0	1.0	**0 / 0.95**	3.8	**2 / 1.10**
Crab	22.0°	4.2	2.4	**2 / 1.76**	4.2	**3 / 1.10**
Mkn 421	38.2°	11.2	3.5	**3 / 1.50**	1.5	**0 / 0.65**
Mkn 501	39.8°	9.5	1.8	**1 / 1.57**	1.4	**0 / 0.69**
Cyg. X-3	41.0°	4.9	3.5	**3 / 1.69**	1.5	**0 / 0.67**
Cas. A	58.8°	9.8	1.2	**0 / 1.01**	4.7	**2 / 1.03**

PRELIMINARY

Selected Source Analysis

Stacking Source Analysis

Galactic Plane

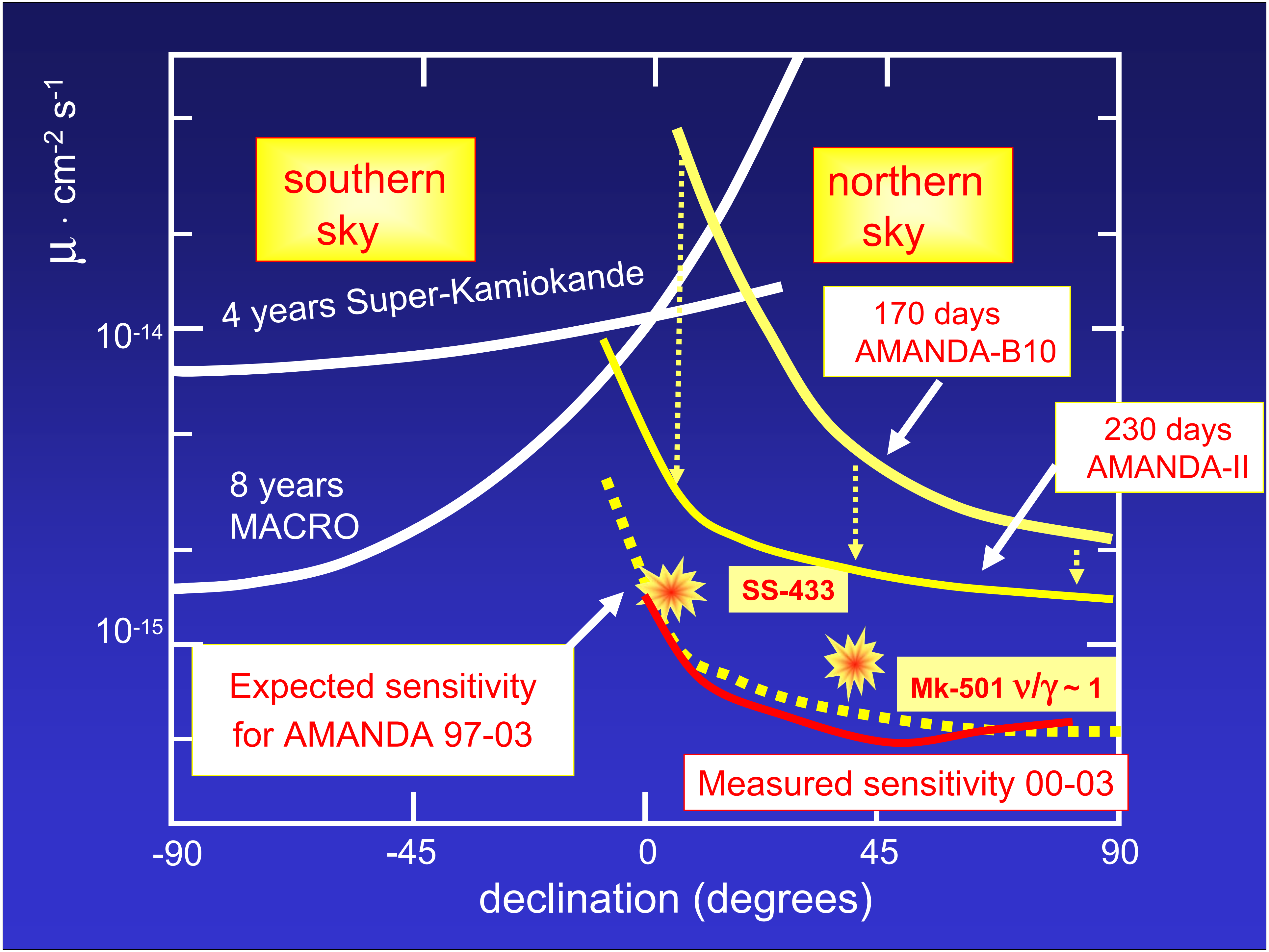
Transient Sources

Burst Search

Correlation Analysis

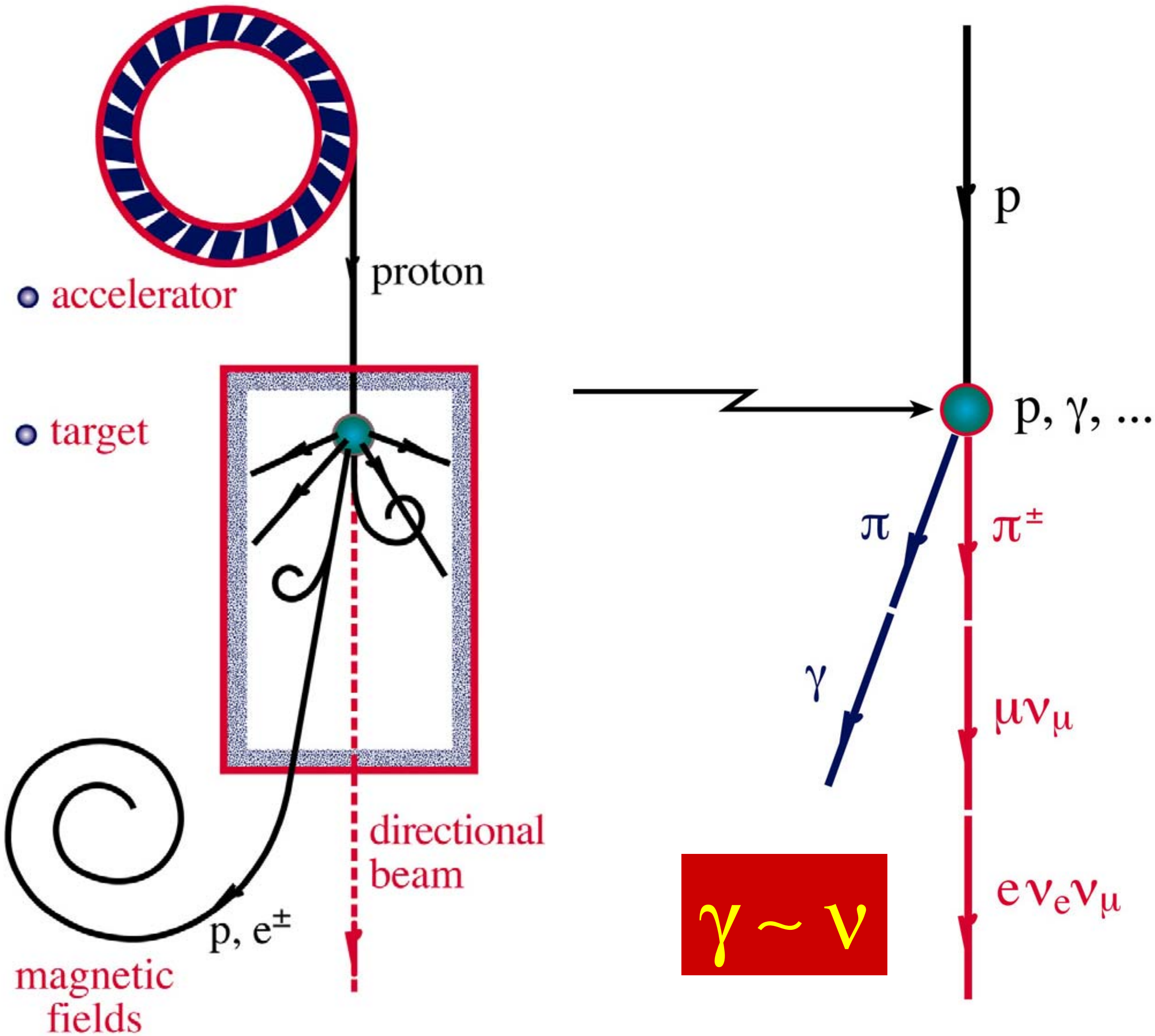
Multi-Pole Analysis

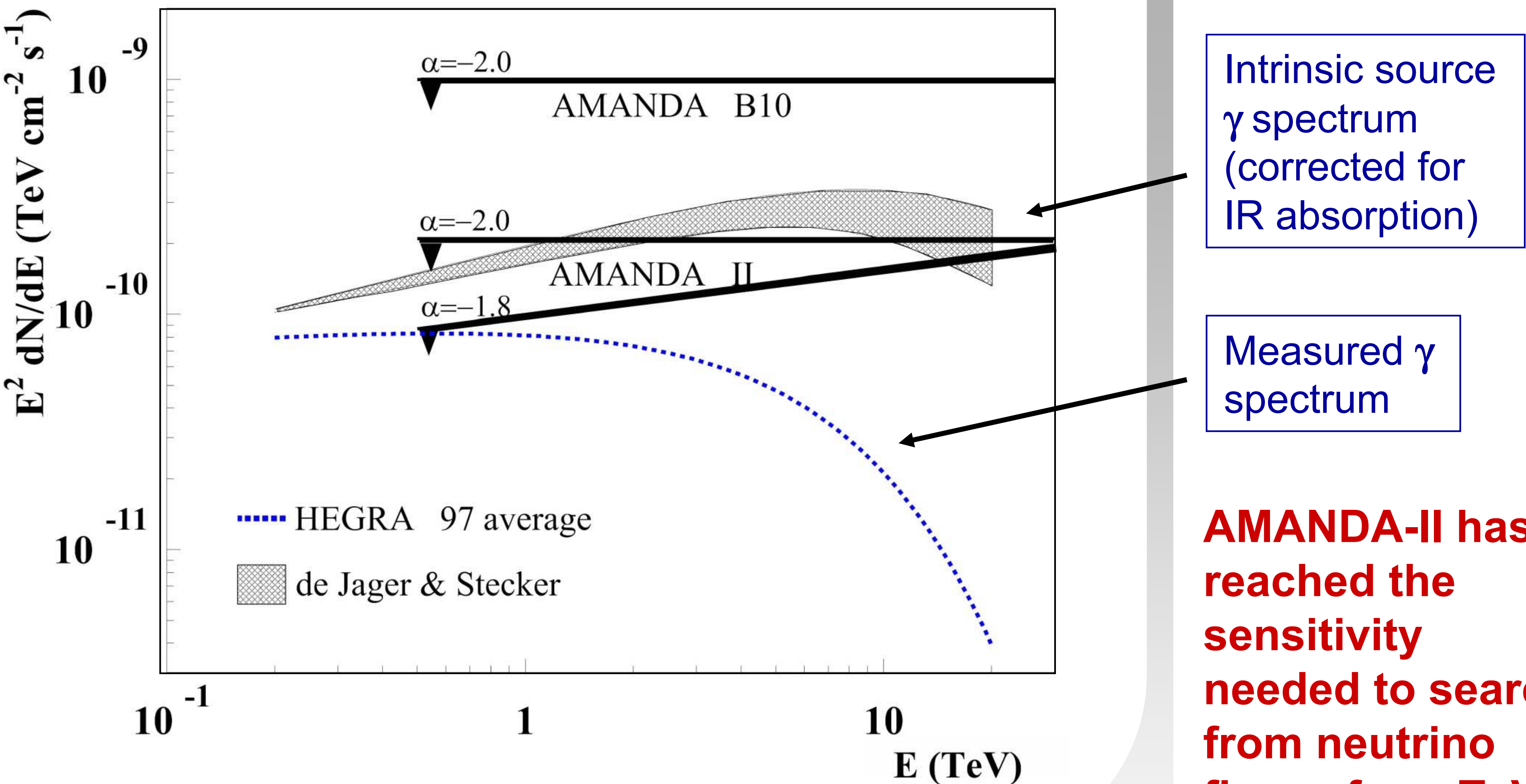
Lower energy threshold
(optimize to steeper spectra)



μ · cm-2 s-1
southern sky
northern sky
4 years Super-Kamiokande
170 days AMANDA-B10
230 days AMANDA-II
8 years MACRO
SS-433
Mk-501 ν/γ ~ 1
Expected sensitivity for AMANDA 97-03
Measured sensitivity 00-03
10-14
10-15
-90
-45
0
45
90
declination (degrees)

Neutrino Beams: Heaven & Earth





AMANDA-II has reached the sensitivity needed to search from neutrino fluxes from TeV gamma sources of similar strength to the instrinsic gamma flux. This Plot 2000 data only!

AMANDA average flux limit for two assumed spectral indices α, compared to the average gamma flux of **Markarian 501** as observed in 1997 by HEGRA.

γ-rays from π^0 decay discovered

$$E_\nu N_\nu (E_\nu) = \varepsilon E_\gamma N_\gamma (E_\gamma)$$

$$1 < \varepsilon < \infty$$

transparent source

$\pi^0 = \pi^+ = \pi^-$

accelerator beam dump (hidden source)

ν flux predicted

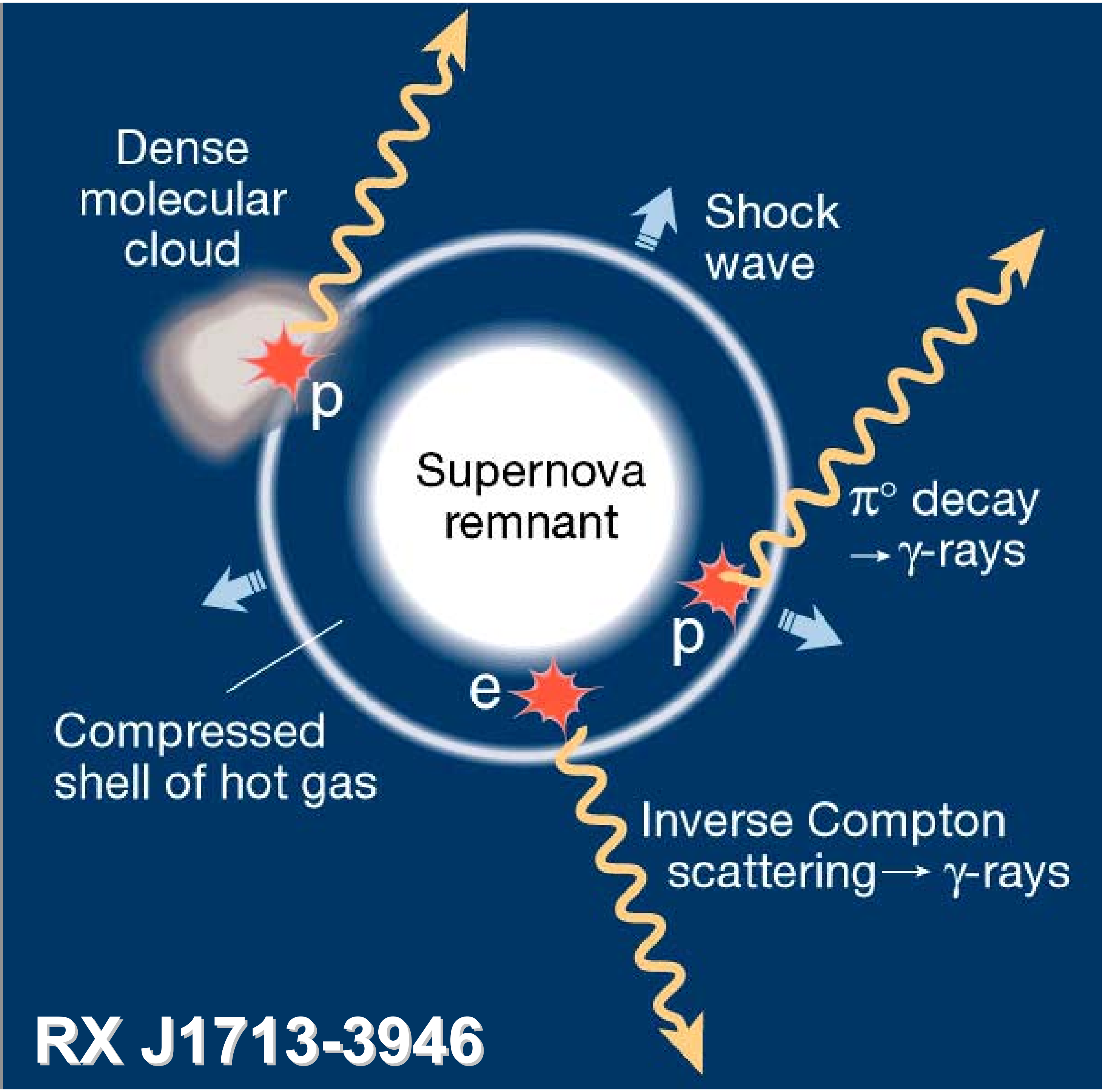
~40 per km2 per year

observed γ-ray flux

RX J1713-3946 (galactic center)

(Hess/ Cangaroo)

Supernova Beam Dump



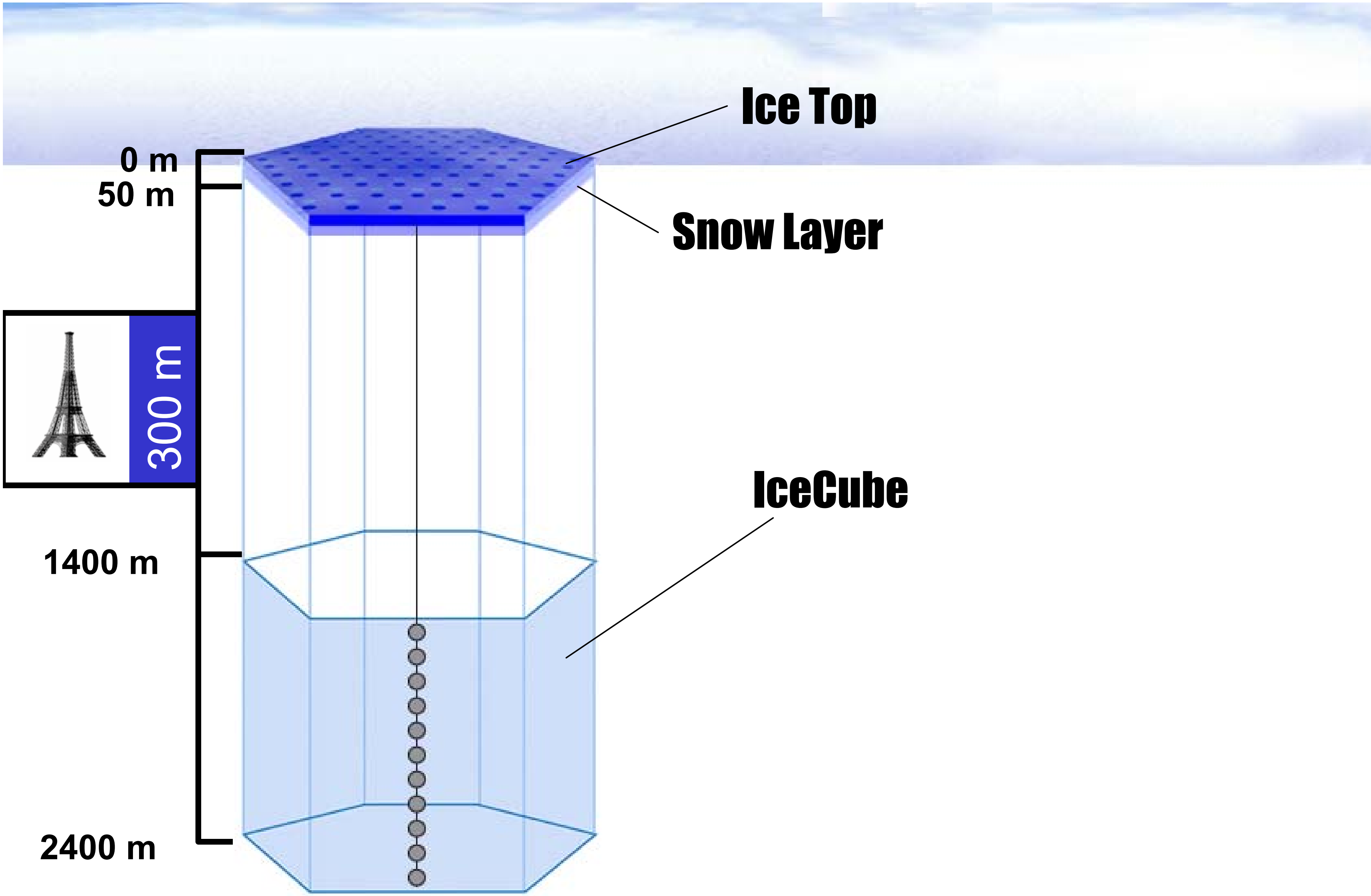
…leaving the 3 σ club

	IceCube	AMANDA-II**	ANTARES
# OF PMTS	4800/10 INCH	600/8 INCH	900/10 INCH
point source sensitivity (ν_μ per year)	10^{-17} cm^{-2} s^{-1}	1.6 10^{-15} cm^{-2} s^{-1} weakly dependent on declination	0.4--5 x 10^{-15} cm^{-2} s^{-1} depending on declination
diffuse limit* (ν_μ per year)	10^{-9} GeV cm^{-2} s^{-1} sr^{-1}	10^{-7} GeV cm^{-2} s^{-1} sr^{-1}	0.8 x 10^{-7} GeV cm^{-2} s^{-1} sr^{-1}

* depends on assumption for background from atmospheric neutrinos from charm
** includes systematic errors

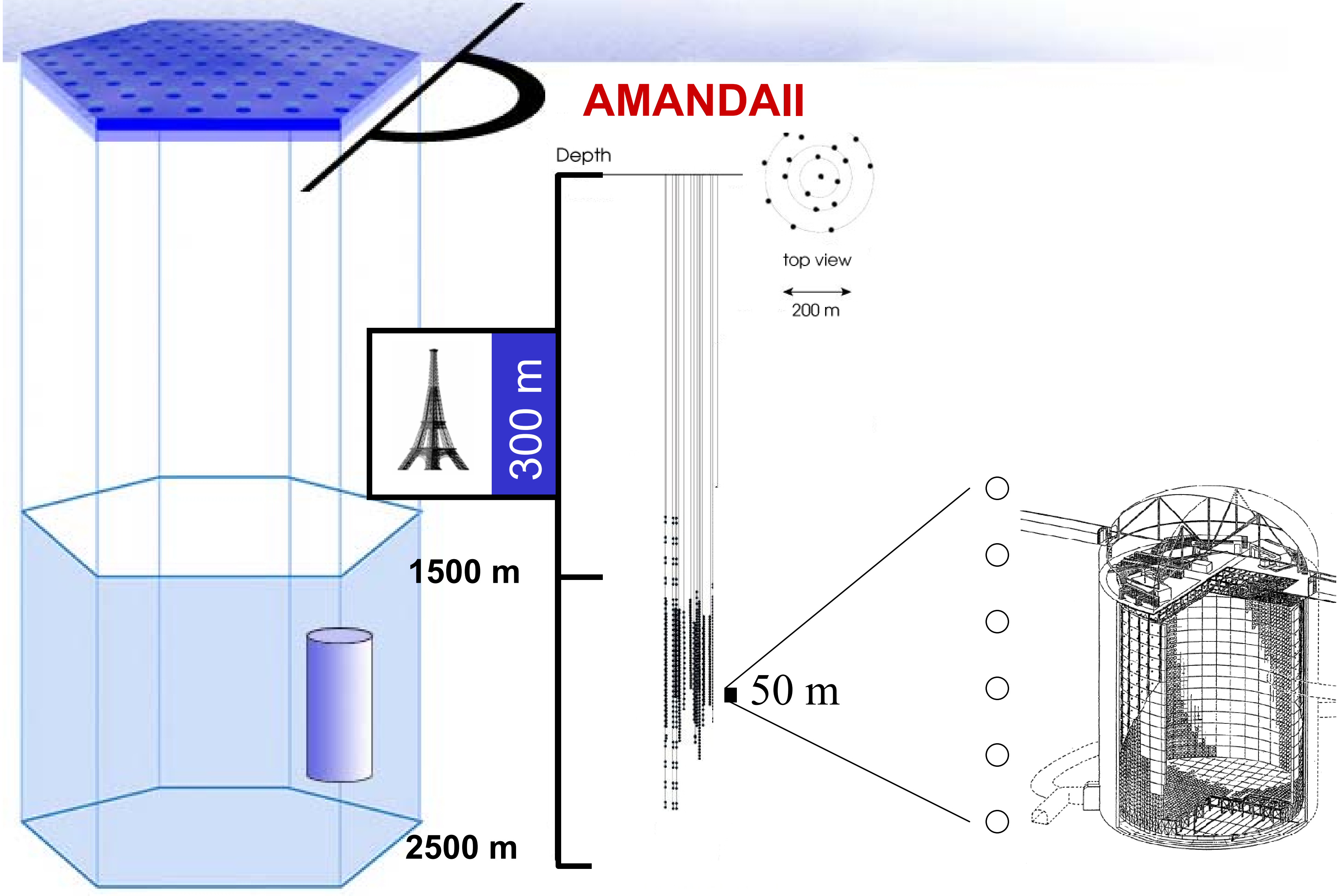
Water or Ice ?

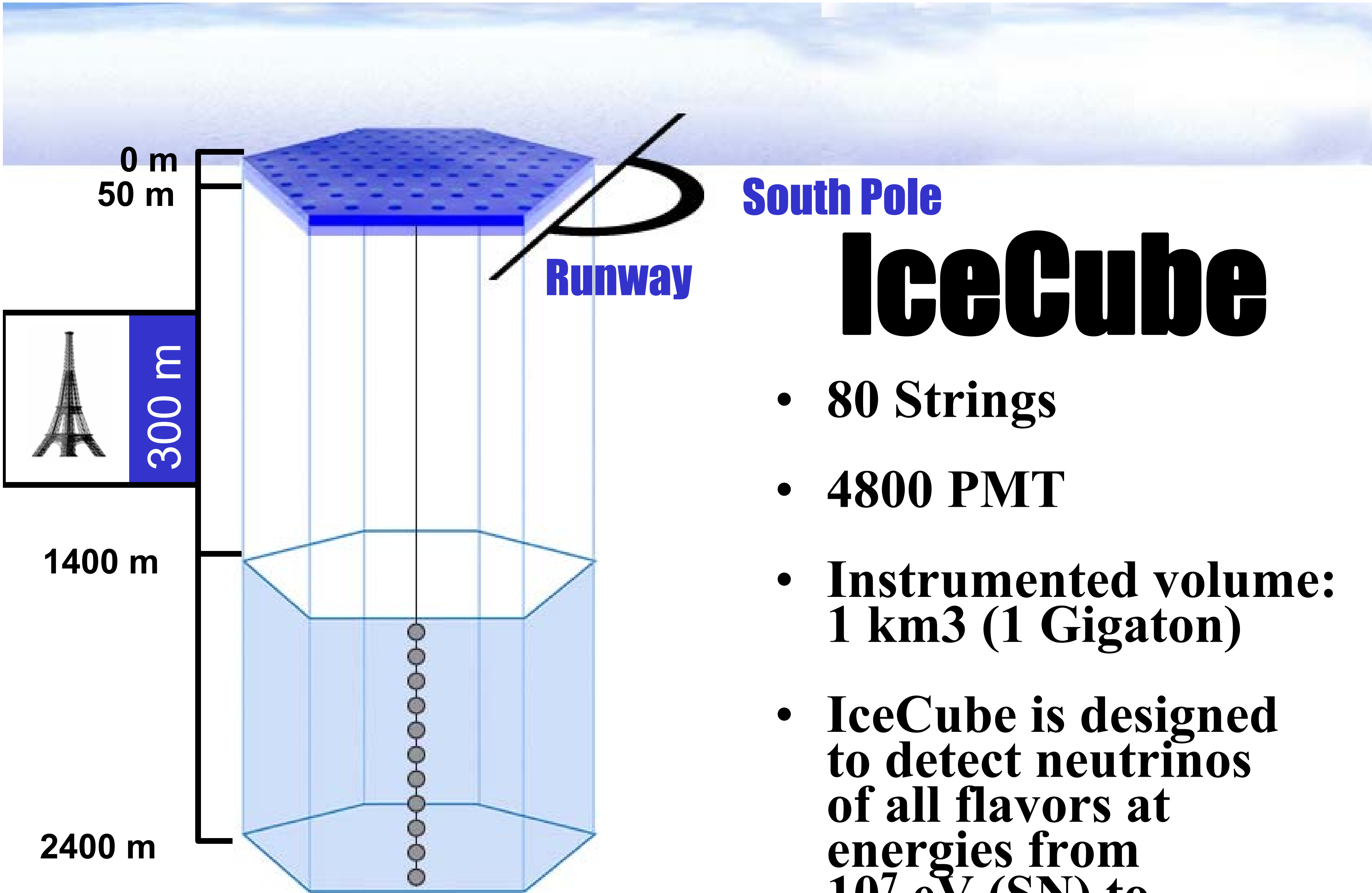
Kilometer-Scale Neutrino Telescopes



Ice Top
0 m
50 m
Snow Layer
300 m
IceCube
1400 m
2400 m

Size Perspective

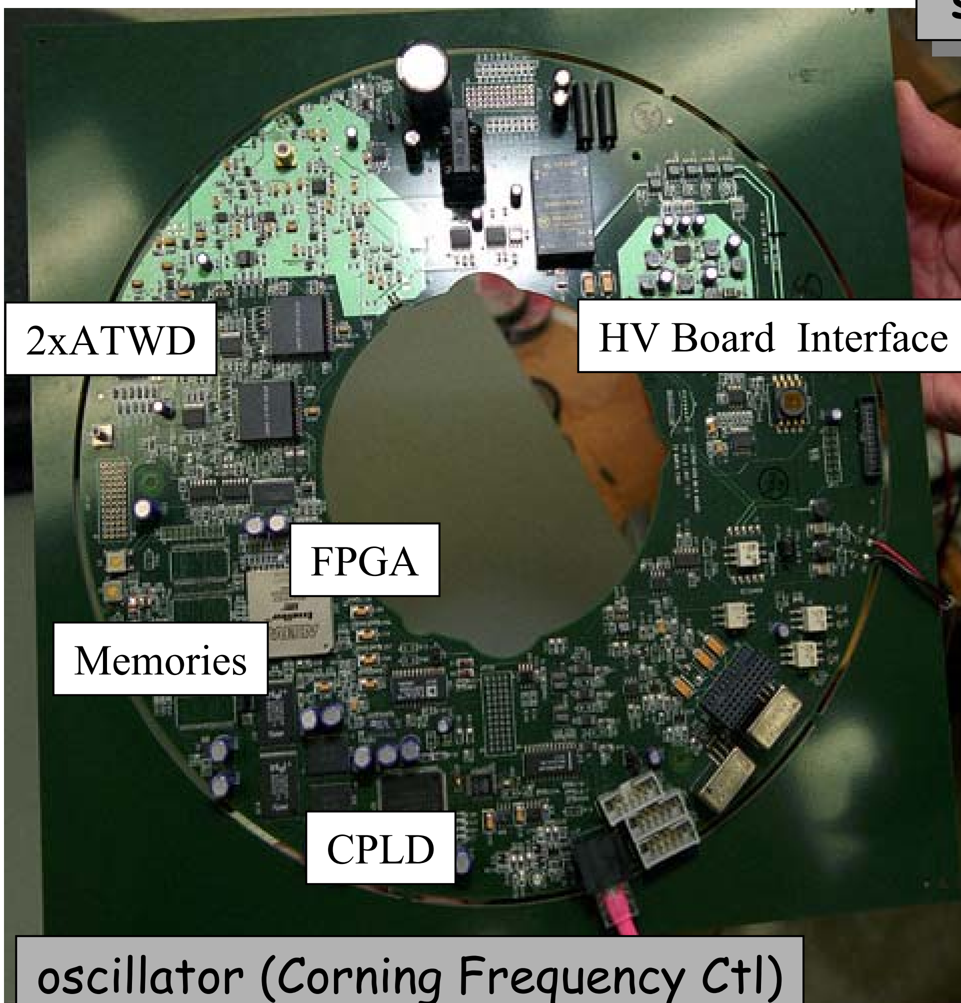




IceCube

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

DOM Mainboard



▪ 2 four-channel ATWDs
Analog Transient Waveform Digitizers
low-power ASICs
recording at 300 MHz over first 0.5μs
signal complexity at the start of event

▪ fast ADC
recording at 40 MHz over 5 μs
event duration in ice

▪ Dead time < 1%

Dynamic range
- 200 p.e./15 ns
- 2000 p.e./5 μs
energy measurement (TeV – PeV)

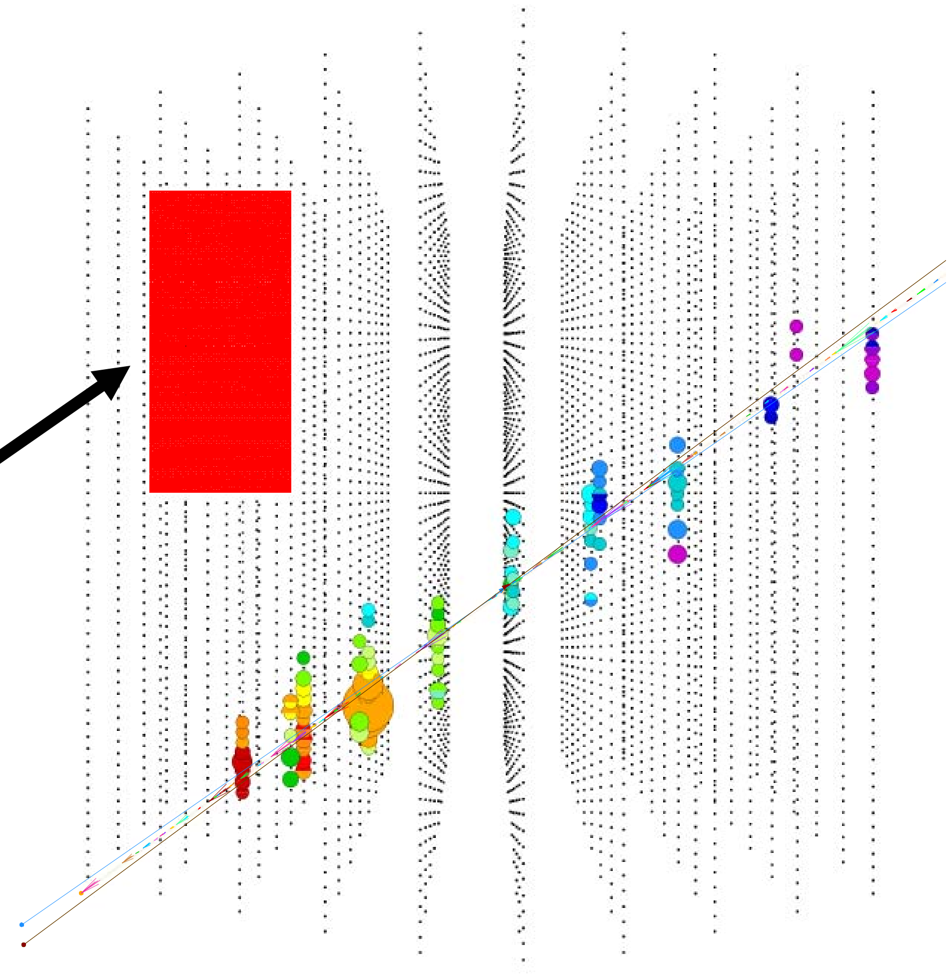
oscillator (Corning Frequency Ctl)
running at 20 MHz
maintains $\delta f/f < 2 \times 10^{-10}$

▪ FPGA (Excalibur/Altera)
reads out the ATWD
handles communications
time stamps events
system time stamp resolution
7 ns wrt master clock

μ-event in IceCube

300 atmospheric neutrinos per day

AMANDA II

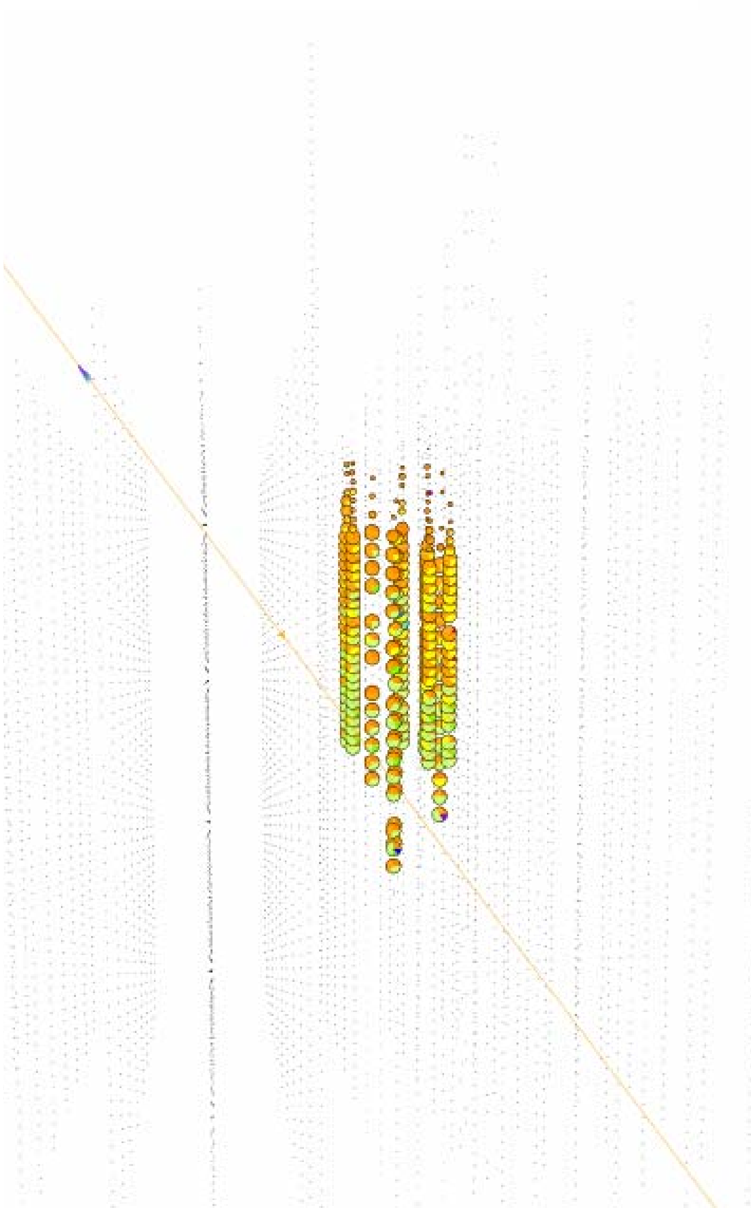


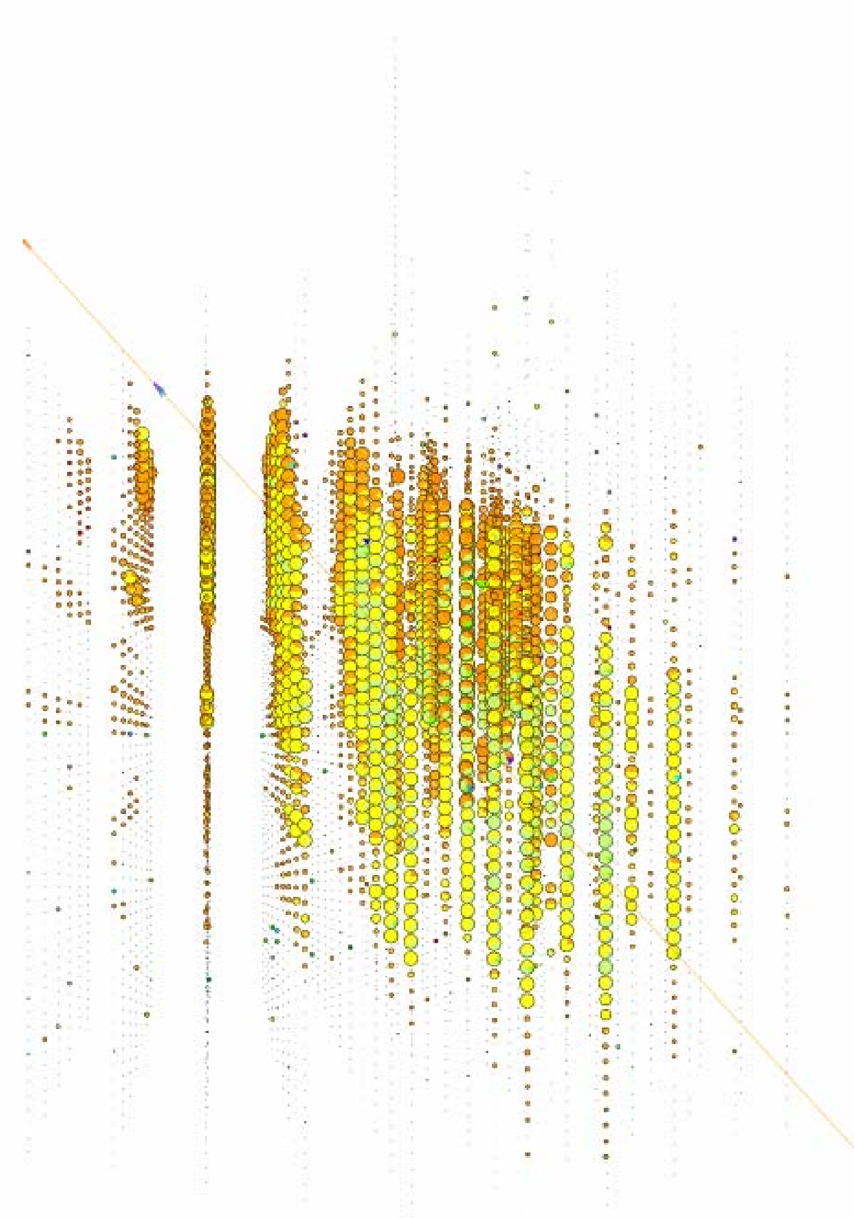
1 km

IceCube:

Larger Telescope
Superior Detector

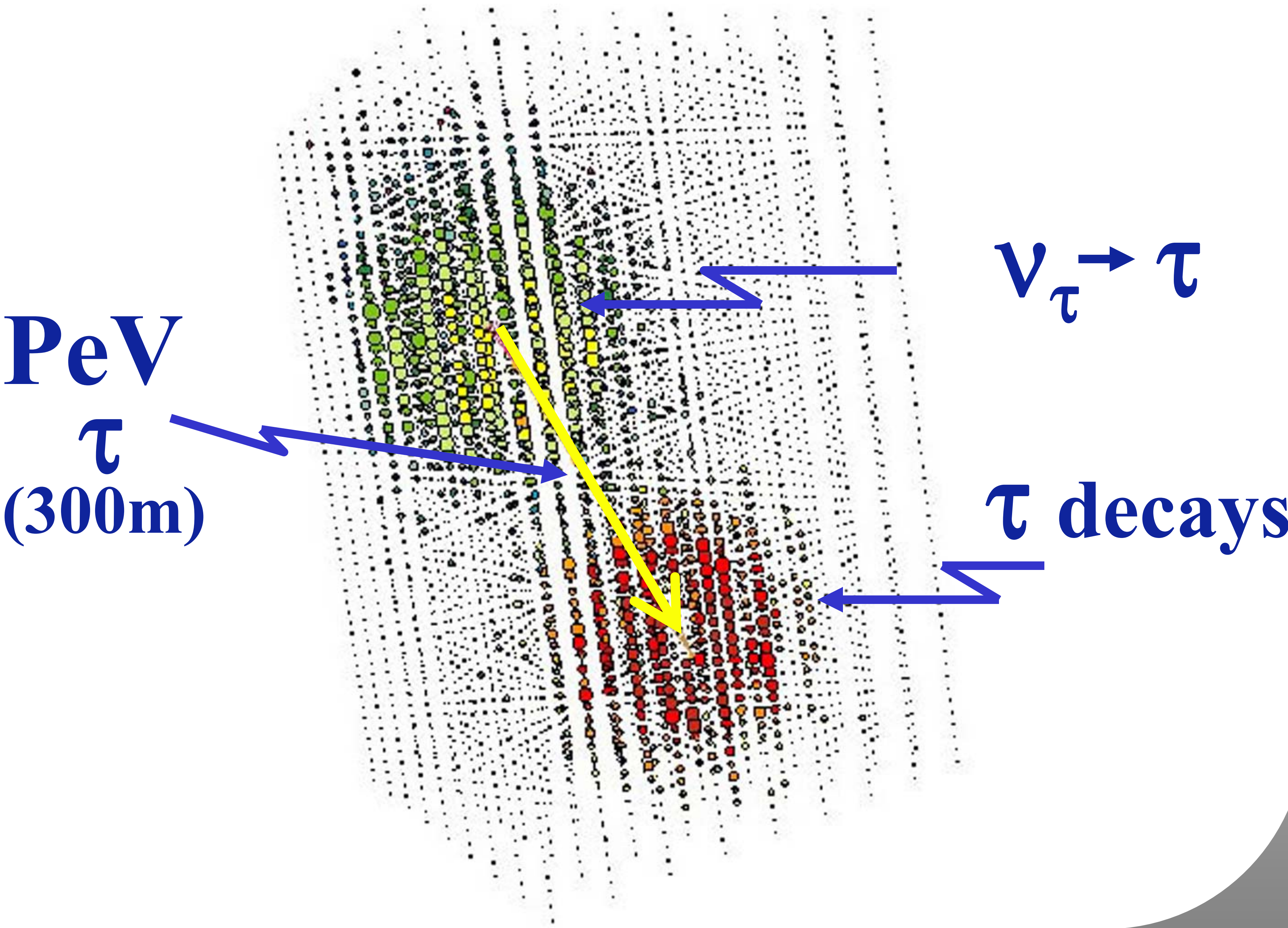
2 x 10^19 eV event in AMANDA and IceCube



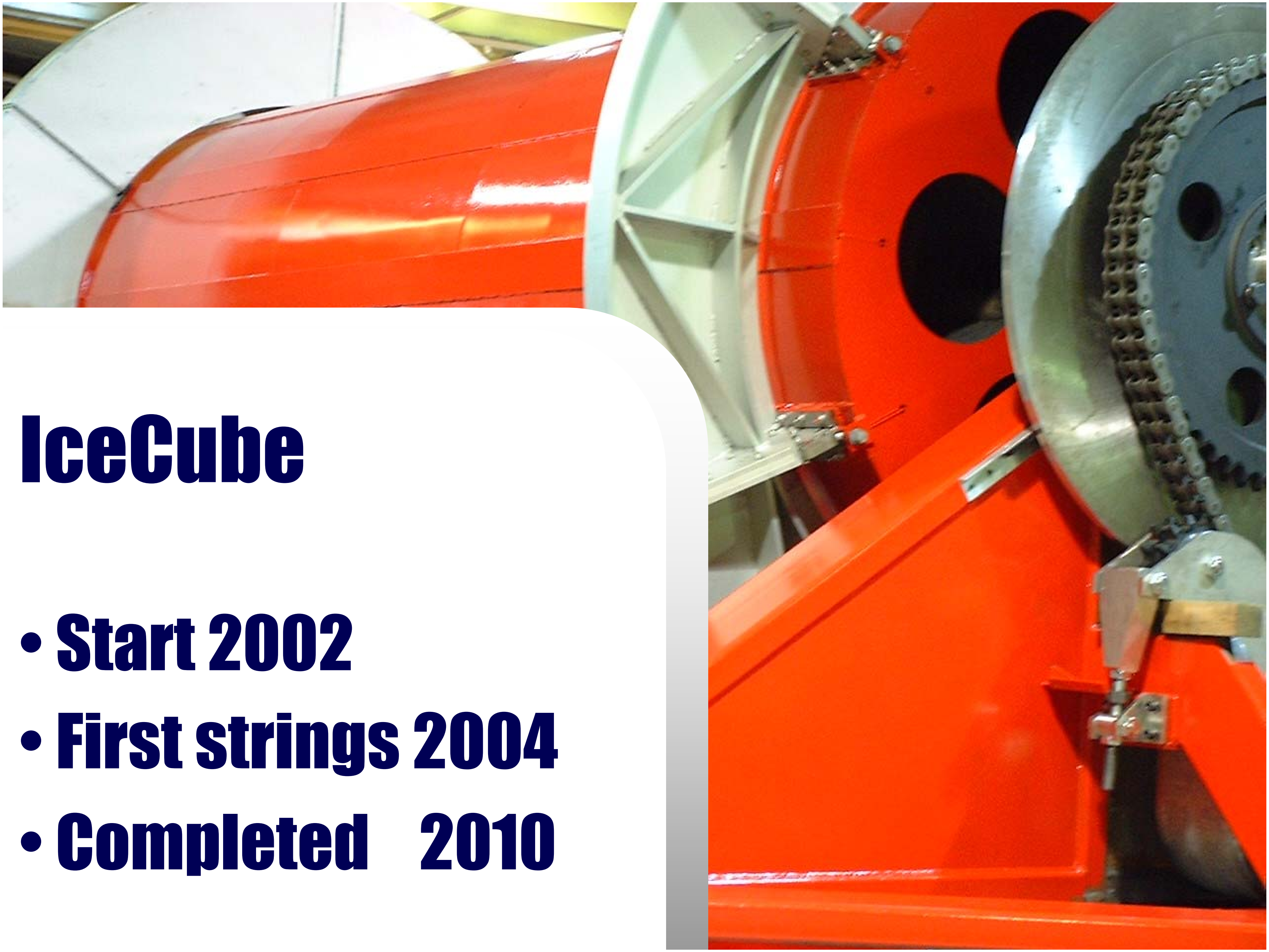


enhanced role of tau neutrinos:

- 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

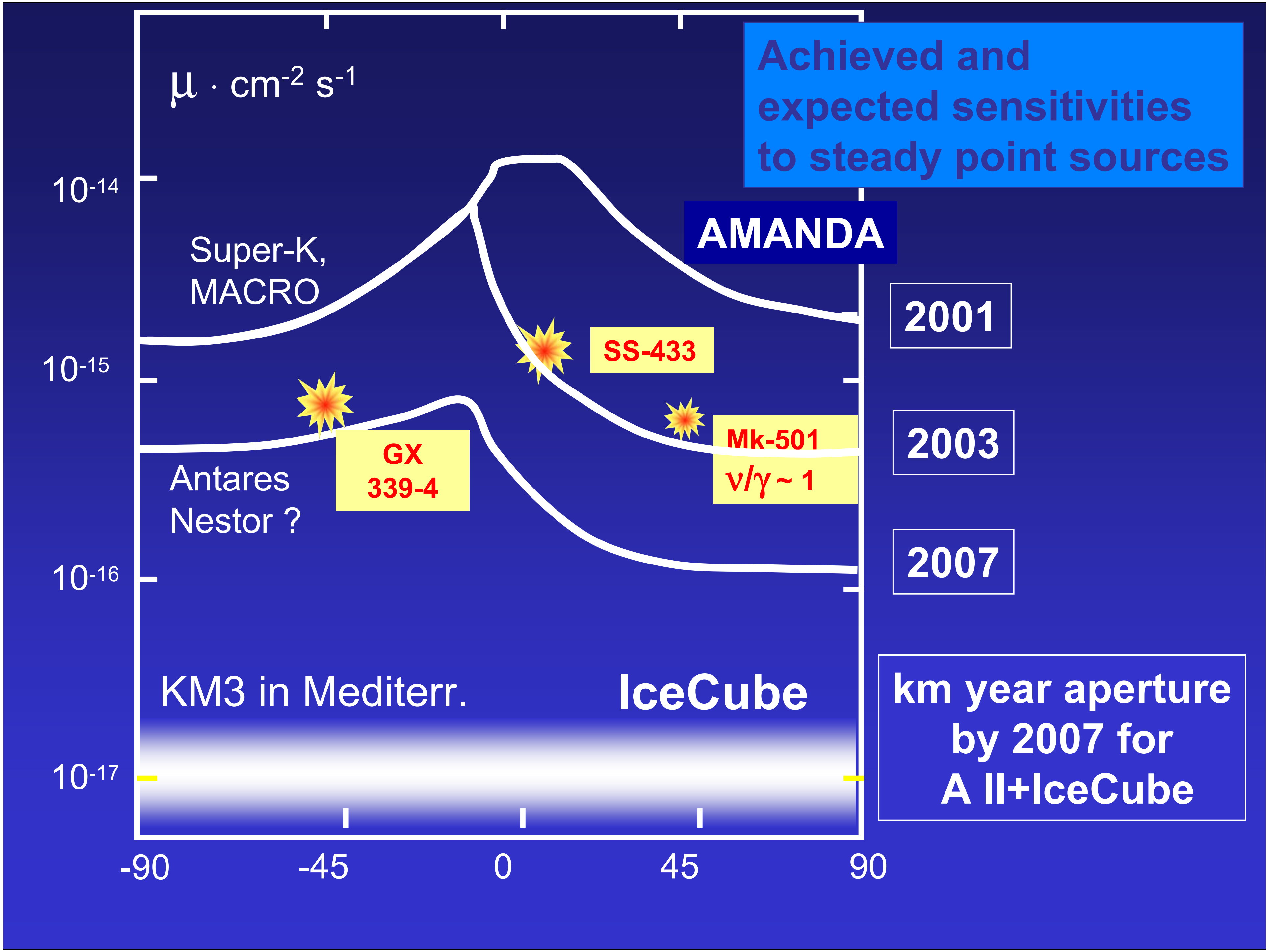


PeV
τ
(300m)
$\nu_\tau \rightarrow \tau$
τ decays



IceCube

- Start 2002
- First strings 2004
- Completed   2010



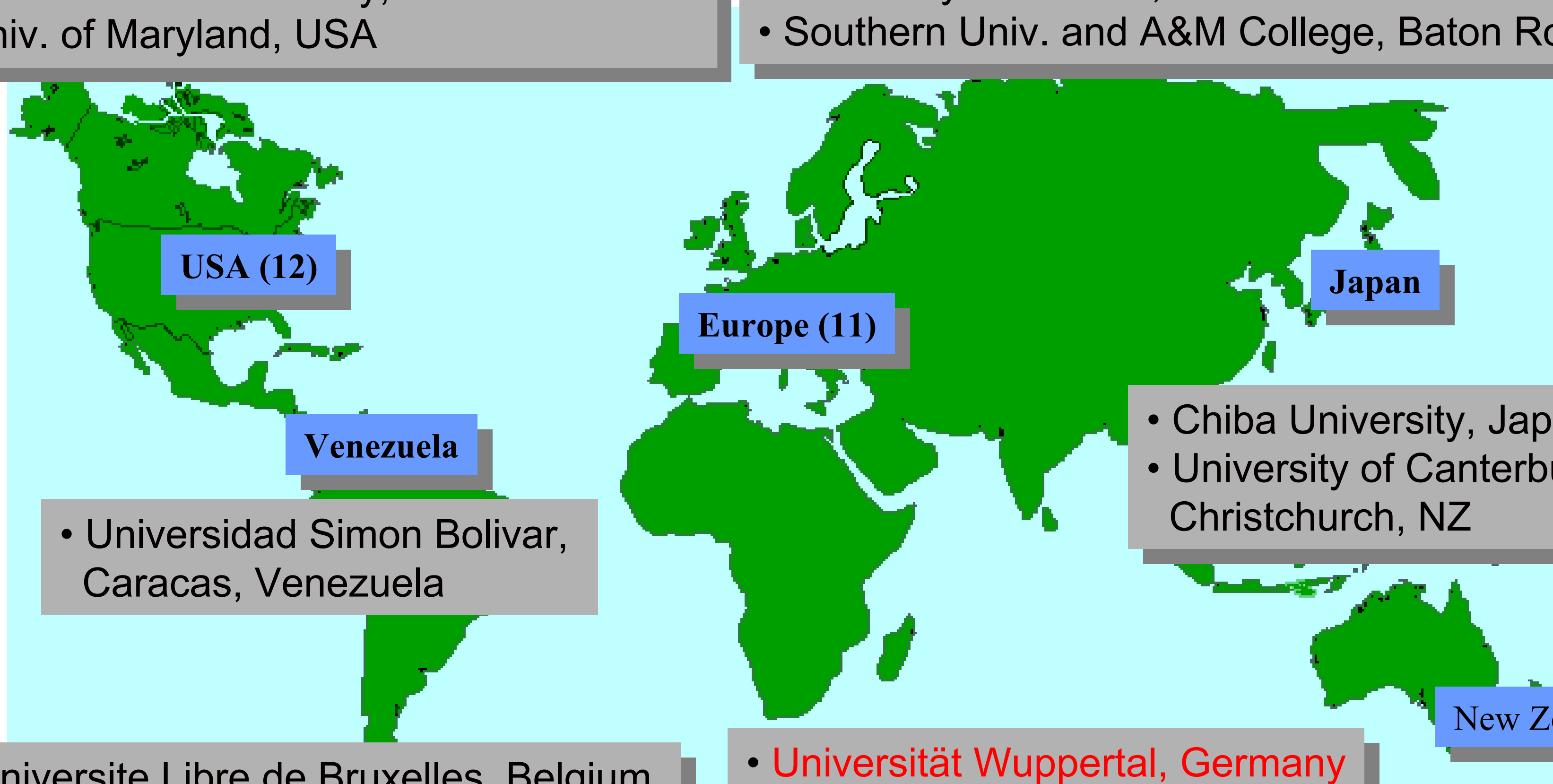
Achieved and expected sensitivities to steady point sources
μ · cm-2 s-1
10-14
10-15
10-16
10-17
Super-K, MACRO
Antares Nestor ?
KM3 in Mediterr.
IceCube
AMANDA
SS-433
GX 339-4
Mk-501
ν/γ ~ 1
2001
2003
2007
km year aperture by 2007 for A II+IceCube
-90
-45
0
45
90

conclusions

- AMANDA collected > 5,000 ν's
- ~ 10 (7) more every day on-line
- neutrino sensitivity has reached ν = γ
- > 300,000 per year from IceCube
- from 1 Crab to < 0.01 Crab sensitivity

- Bartol Research Institute, Delaware, USA
- Univ. of Alabama, USA
- Pennsylvania State University, USA
- UC Berkeley, USA
- Clark-Atlanta University, USA
- Univ. of Maryland, USA

- IAS, Princeton, USA
- University of Wisconsin-Madison, USA
- University of Wisconsin-River Falls, USA
- LBNL, Berkeley, USA
- University of Kansas, USA
- Southern Univ. and A&M College, Baton Rouge



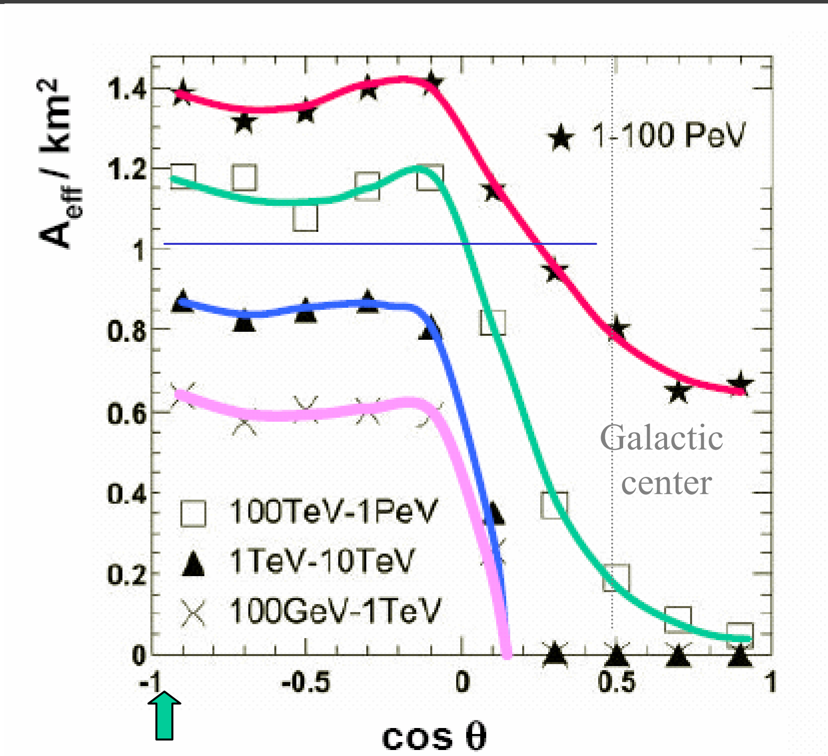
- Chiba University, Japan
- University of Canterbury, Christchurch, NZ

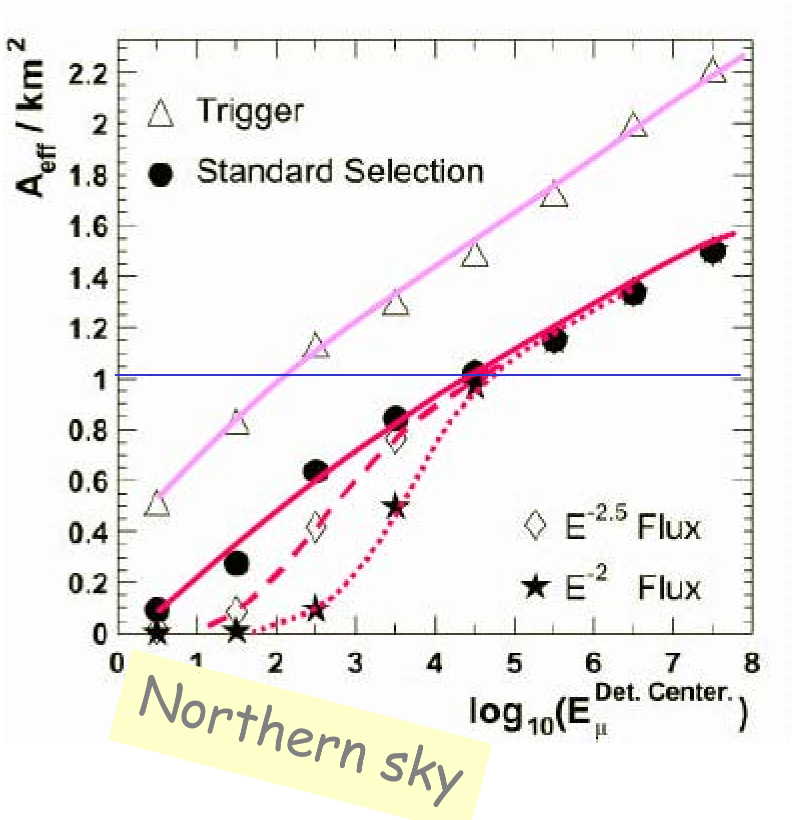
- Universidad Simon Bolivar, Caracas, Venezuela

- Universite Libre de Bruxelles, Belgium
- Vrije Universiteit Brussel, Belgium
- Université de Mons-Hainaut, Belgium
- Universität Mainz, Germany
- DESY-Zeuthen, Germany

- Universität Wuppertal, Germany
- Uppsala University, Sweden
- Stockholm university, Sweden
- Imperial College, London, UK
- University of Oxford, UK
- NIKHEF, Utrecht, Netherlands

IceCube effective area for muons



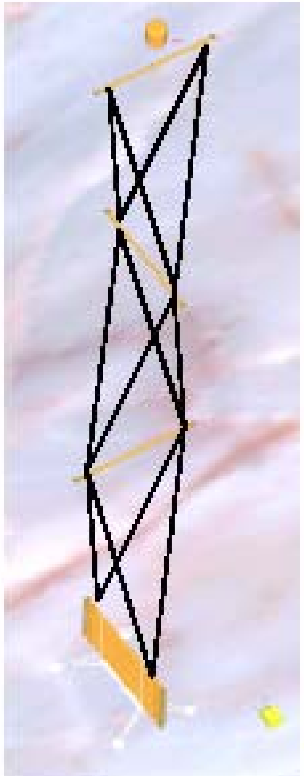


- after quality cuts and
  atm μ reduction by ~10^6
- averaged over E^{-2} spectrum

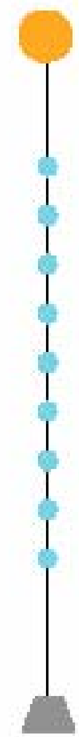
- at trigger level
- after quality cuts and atm m red.
- after additional energy cuts
  optimized for point source search

For E > 1 TeV, $A_{eff} > A_{geom}$ → **non-contained events**

Comparison of different km3 architectures



Simulations have been performed with the ANTARES simulation package



Tower architecture (5832 OM)

18 storey towers with 4 OM per storey
20 m storey length
40 m spacing between storeys
81 towers arranged in a 9x9 square lattice
140 m spacing between towers
≈ 0.9 km3 instrumented volume

Lattice architecture (5600 OM)

Strings with 58 downlooking OM spaced by 16 m
100 strings arranged in a 10x10 lattice
125 m spacing between string
≈ 1.2 km3 instrumented volume

Comparison of string and tower geometries

- Up-going muons with E^{-1} spectrum
- 60 kHz background
- Reconstruction + Quality Cuts

● Nemo20m 140 (5832 OM)
● Lattice 125 16 (5600 OM)