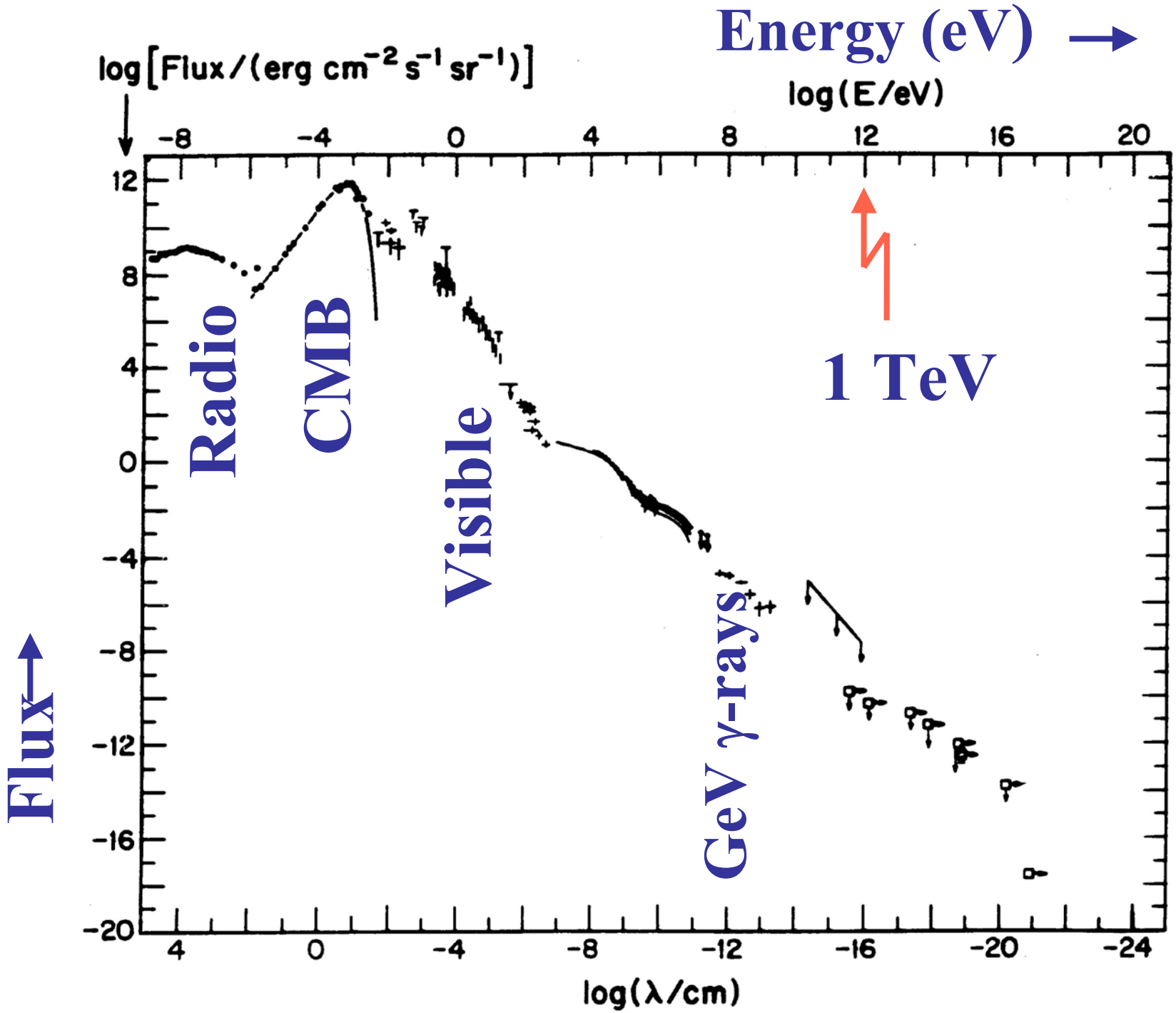
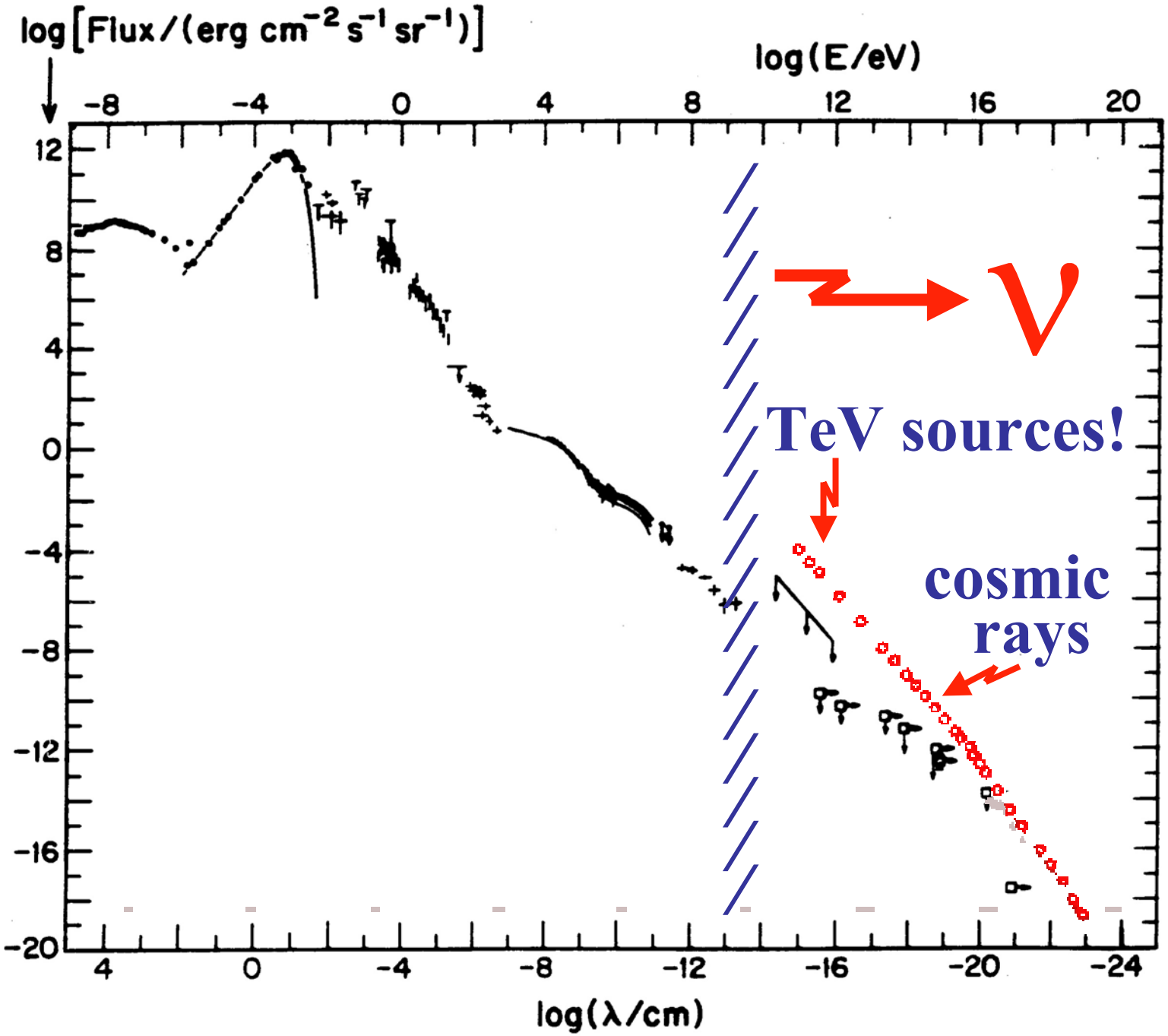
WIN 02
Francis Halzen

- **the sky** > 10 GeV photon energy
  < 10^{-14} cm wavelength
- **> 10^8 TeV particles exist**
  Fly's Eye/Hires
- **they should not**
- **more/better data**
  - → arrays of air Cherenkov telescopes
  - → 10^4 km^2 air shower arrays
  - → ~ km^3 neutrino detectors

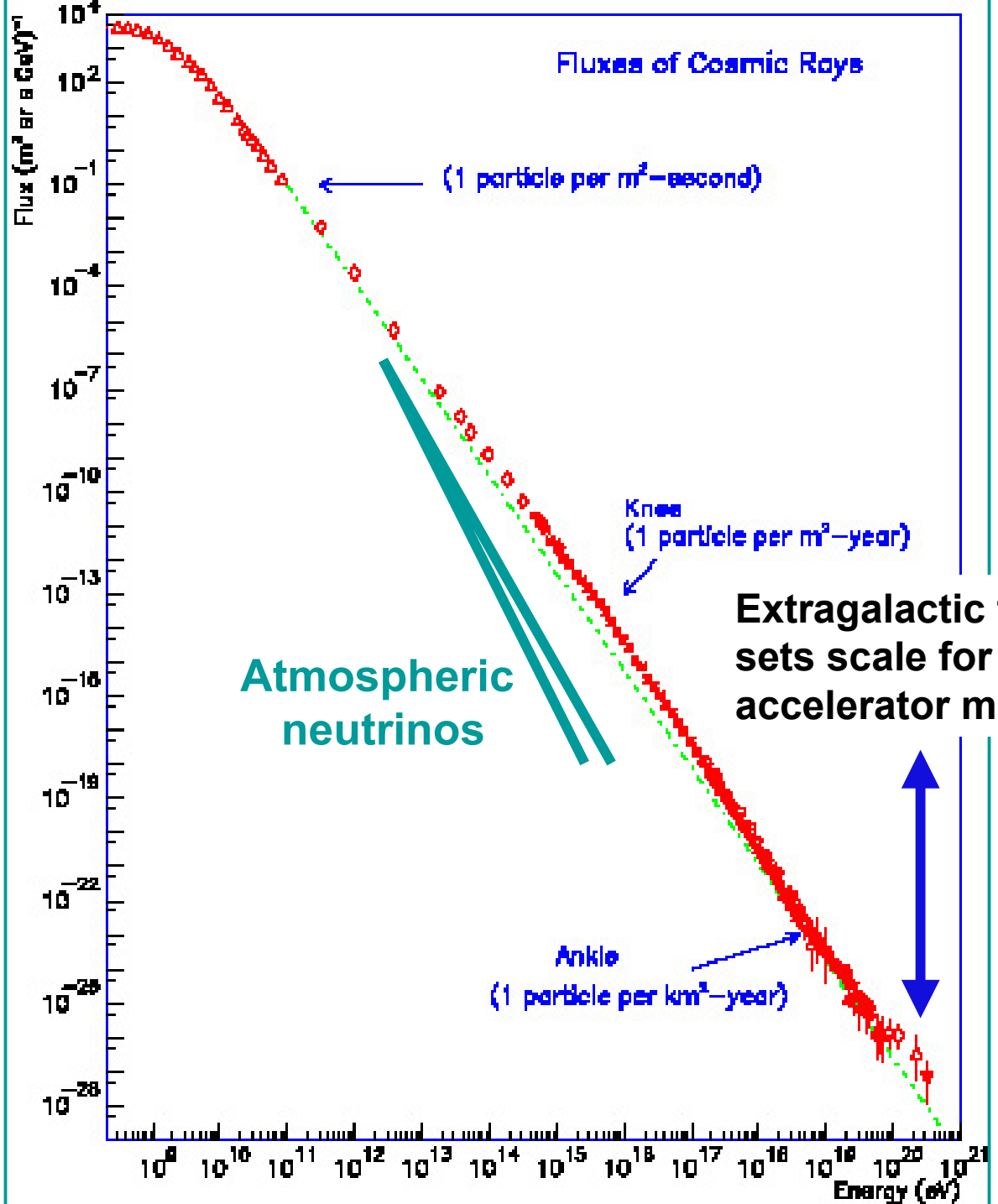

Energy (eV) →
log[Flux/(erg cm⁻² s⁻¹ sr⁻¹)]
log(E/eV)
-8
-4
0
4
8
12
16
20
12
8
4
0
-4
-8
-12
-16
-20
Radio
CMB
Visible
GeV γ-rays
1 TeV
Flux→
4
0
-4
-8
-12
-16
-20
-24
log(λ/cm)

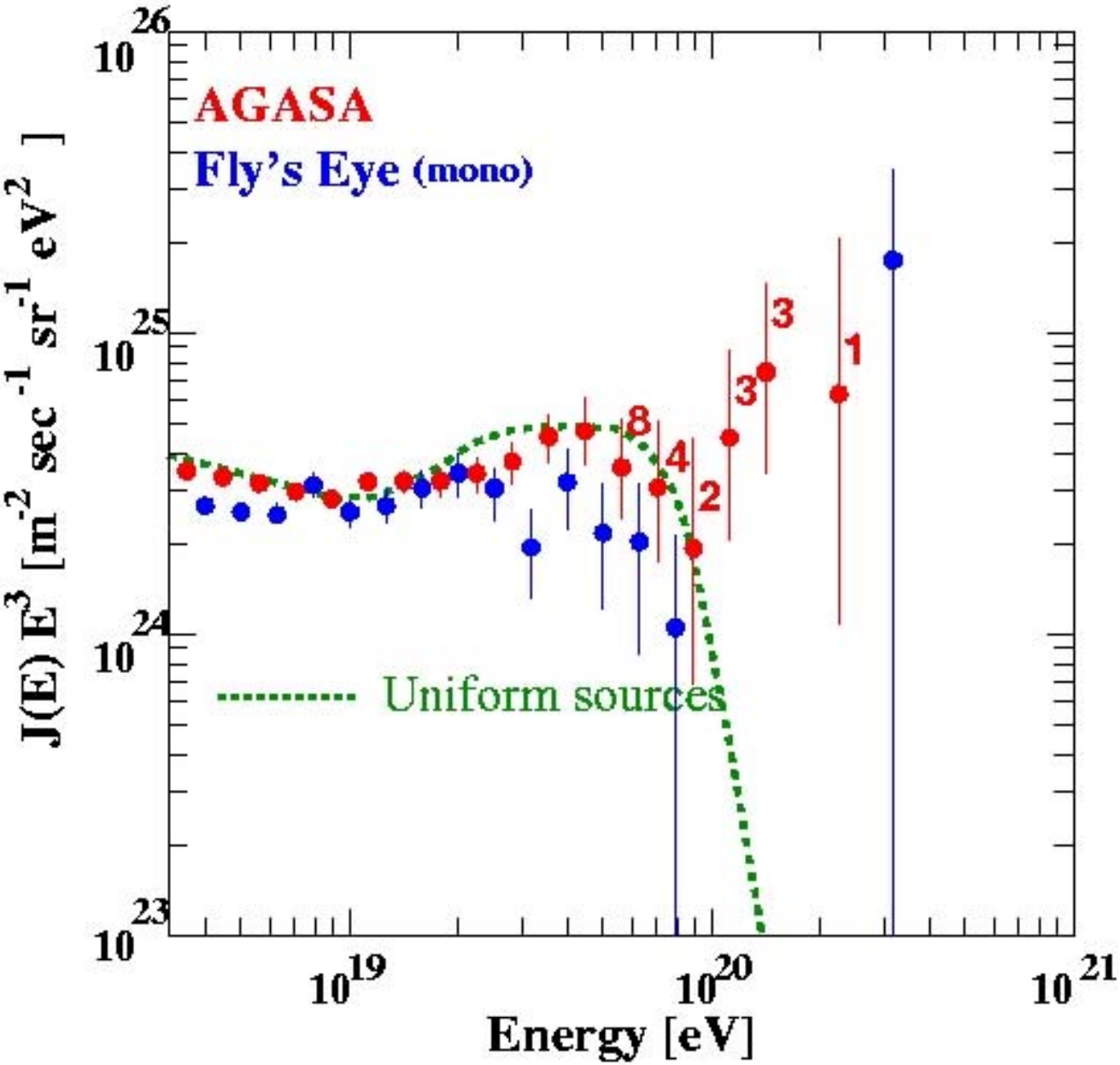
With 10^3 TeV energy, photons do not reach us from the edge of our galaxy because of their small mean free path in the microwave background.

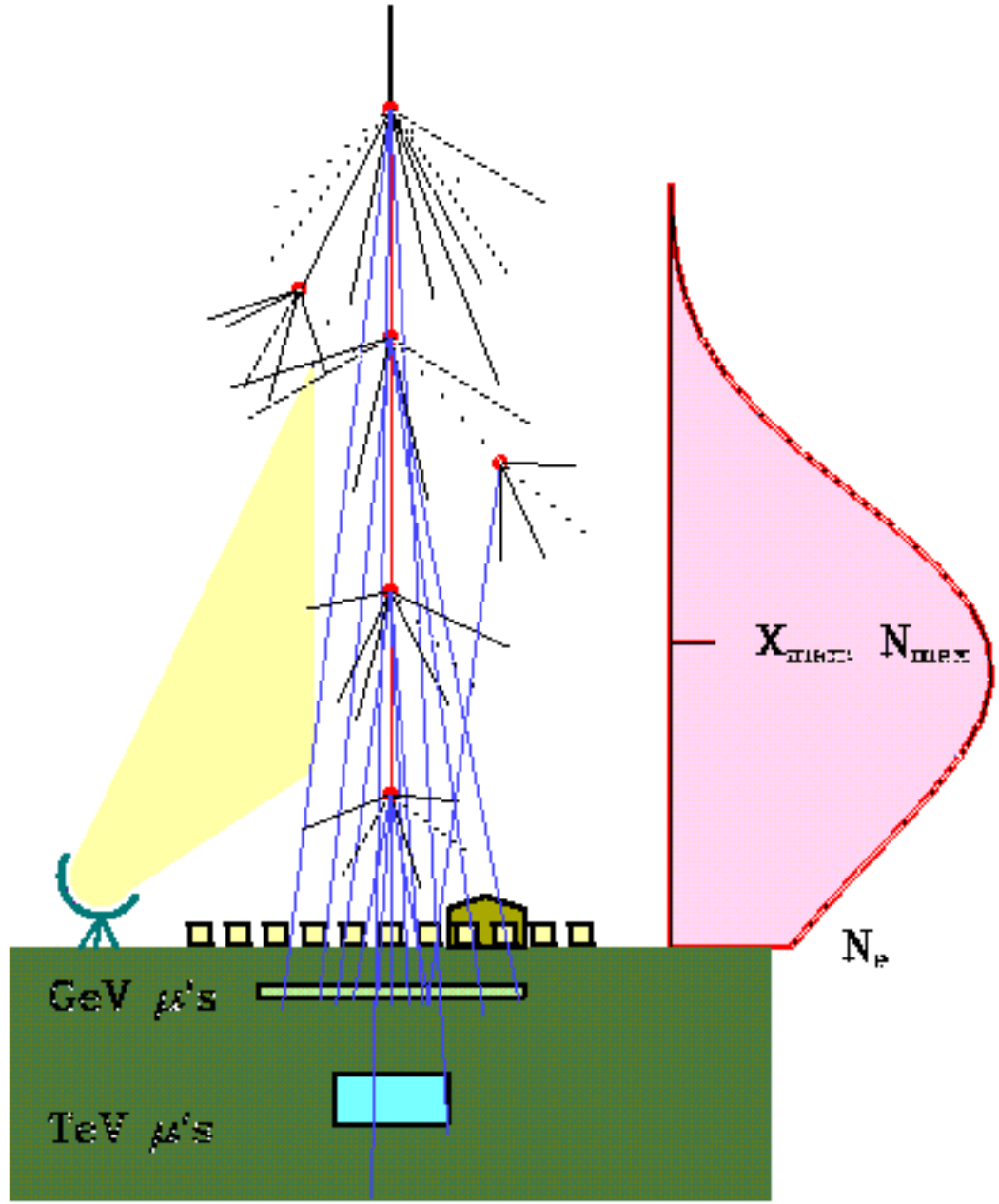
$$\gamma + \gamma_{CMB} \longrightarrow e^+ + e^-$$


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
ν
TeV sources!
cosmic rays
4
0
-4
-8
-12
-16
-20
-24
log(λ/cm)

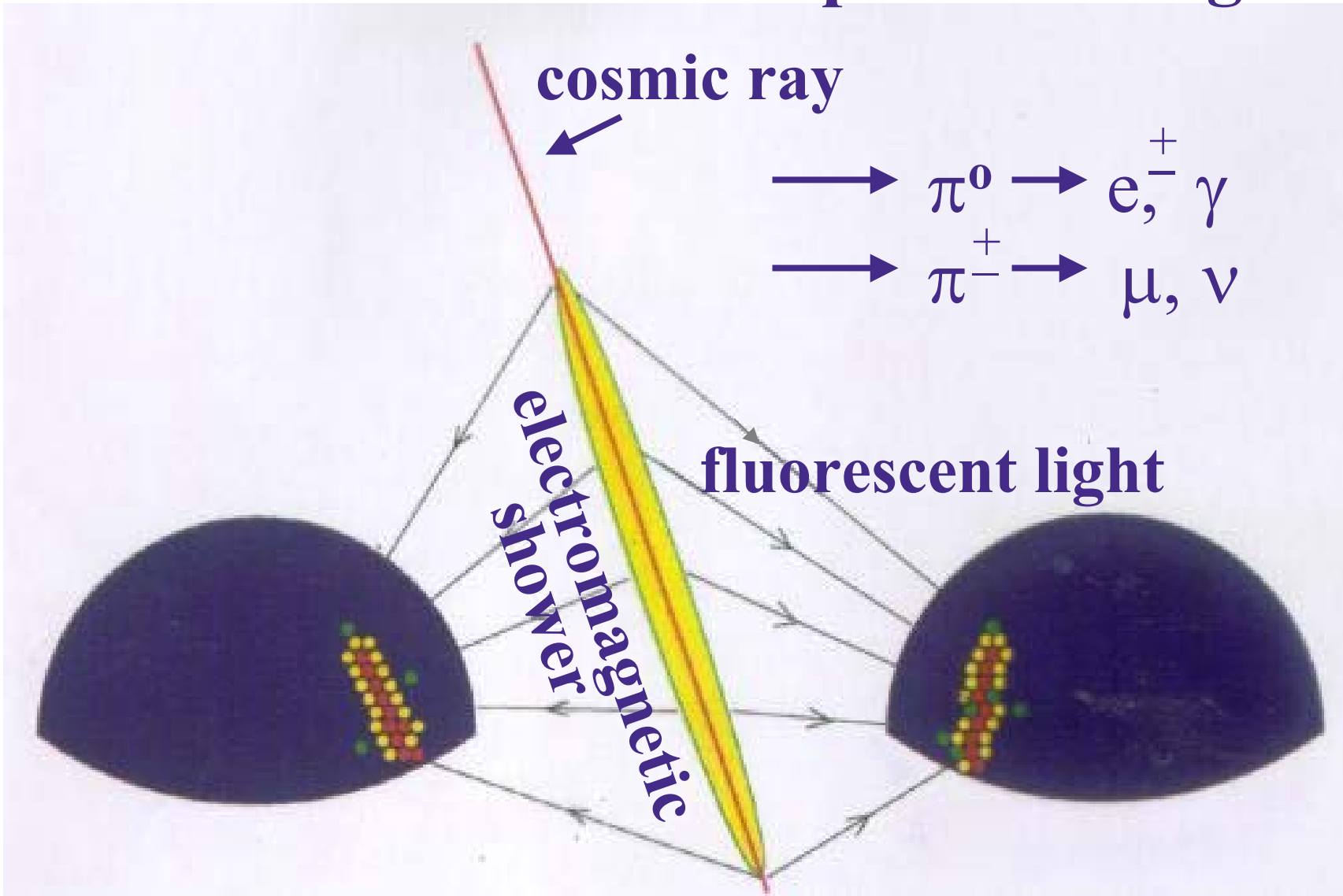
Cosmic Ray spectrum

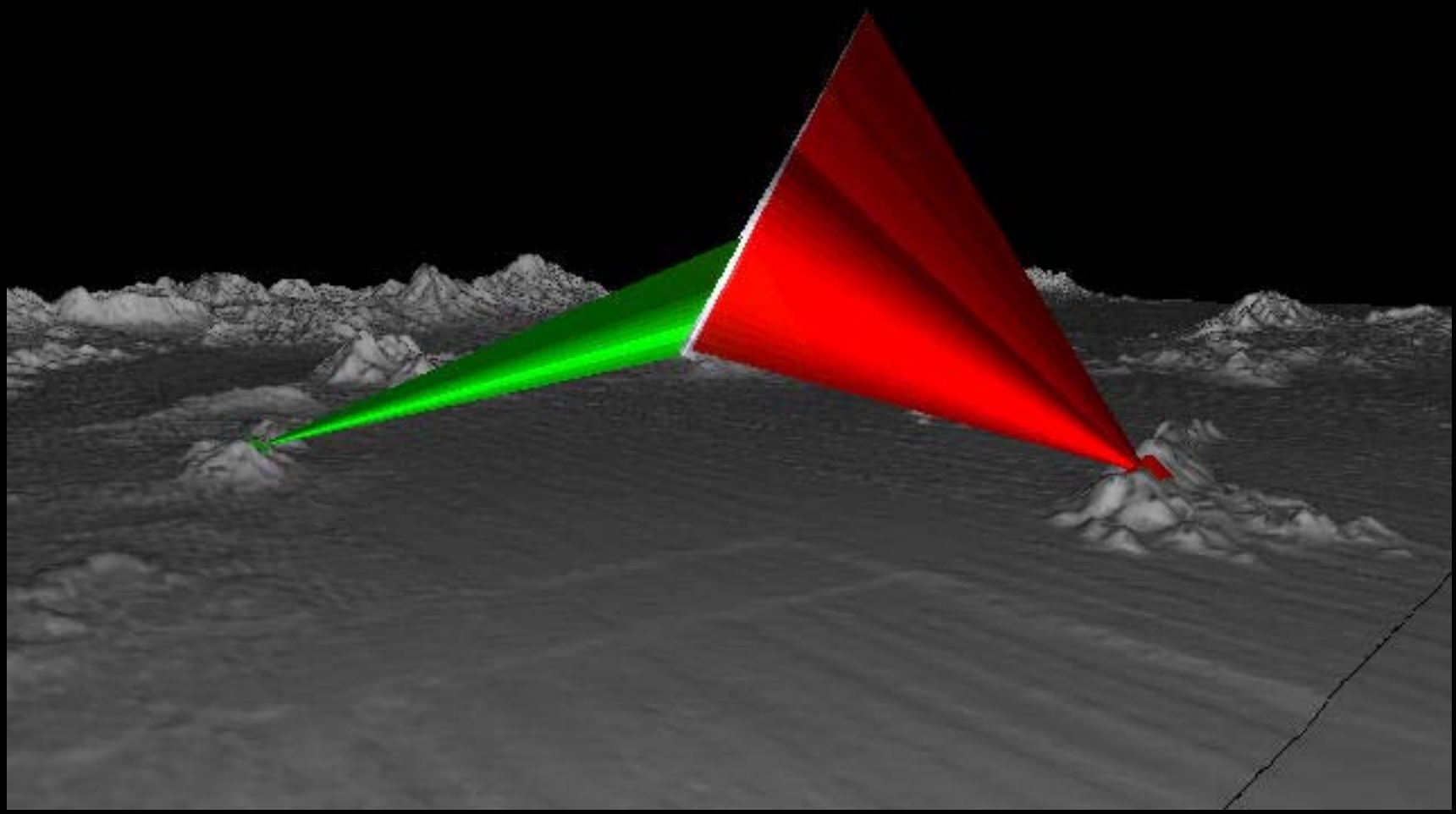


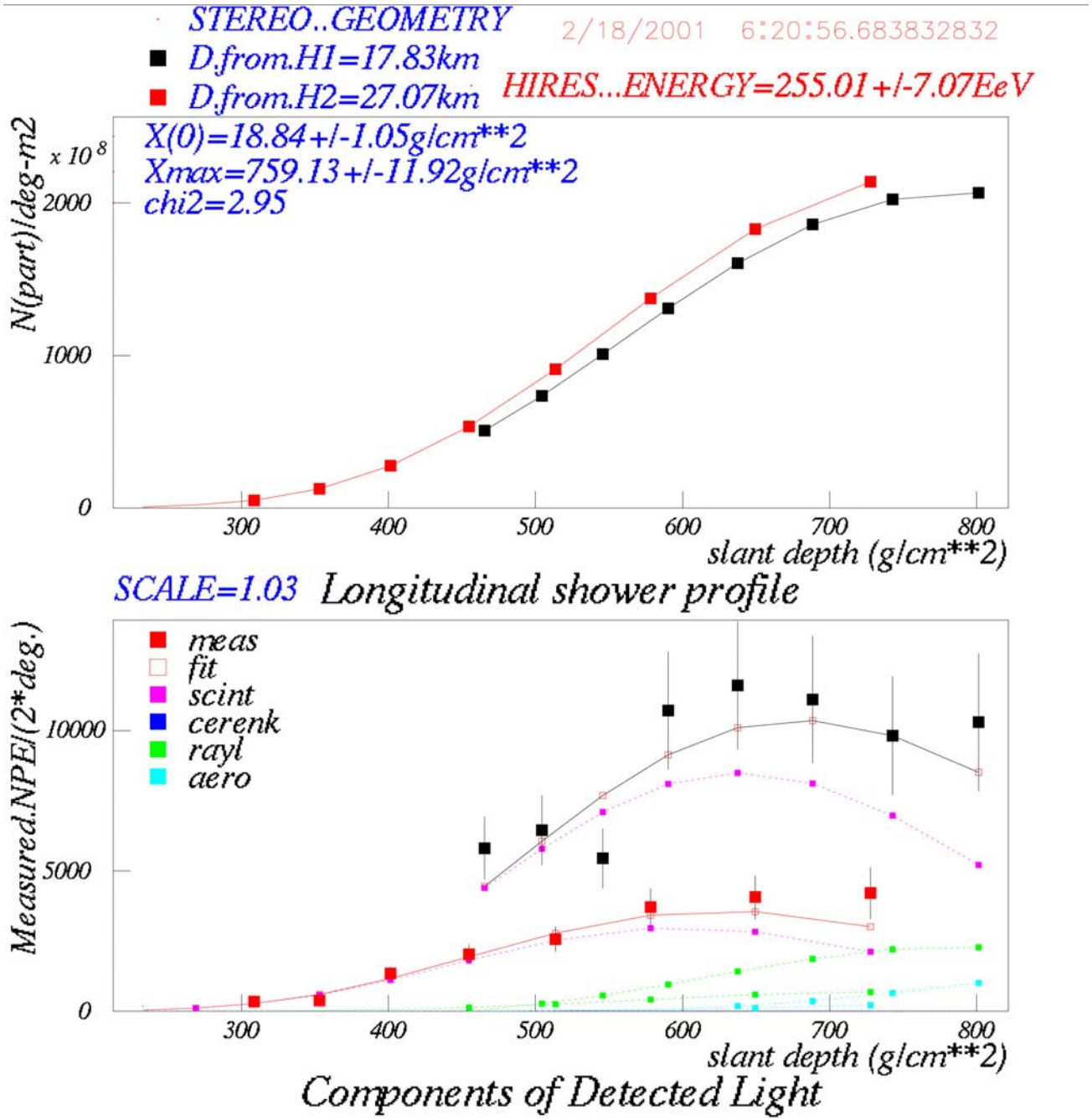

AGASA
Fly's Eye (mono)
Uniform sources
8
4
2
3
3
1
10^{26}
10^{25}
10^{24}
10^{23}
10^{19}
10^{20}
10^{21}
J(E) E^3 [m^{-2} sec^{-1} sr^{-1} eV^2]
Energy [eV]


X_{max} N_{max}
N_e
GeV μ's
TeV μ's

fluorescence from atmospheric nitrogen






STEREO..GEOMETRY
2/18/2001 6:20:56.683832832
D.from.H1=17.83km
D.from.H2=27.07km
HIRES...ENERGY=255.01+/-7.07EeV
X(0)=18.84+/-1.05g/cm**2
Xmax=759.13+/-11.92g/cm**2
chi2=2.95
x 10^8
N(part)/deg-m2
2000
1000
0
300
400
500
600
700
800
slant depth (g/cm**2)
SCALE=1.03
Longitudinal shower profile
meas
fit
scint
cerenk
rayl
aero
Measured.NPE/(2*deg.)
10000
5000
0
300
400
500
600
700
800
slant depth (g/cm**2)
Components of Detected Light

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.

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

Cosmic Accelerators

$$E \sim \Gamma c B R$$

$$R \sim GM/c^2$$

energy

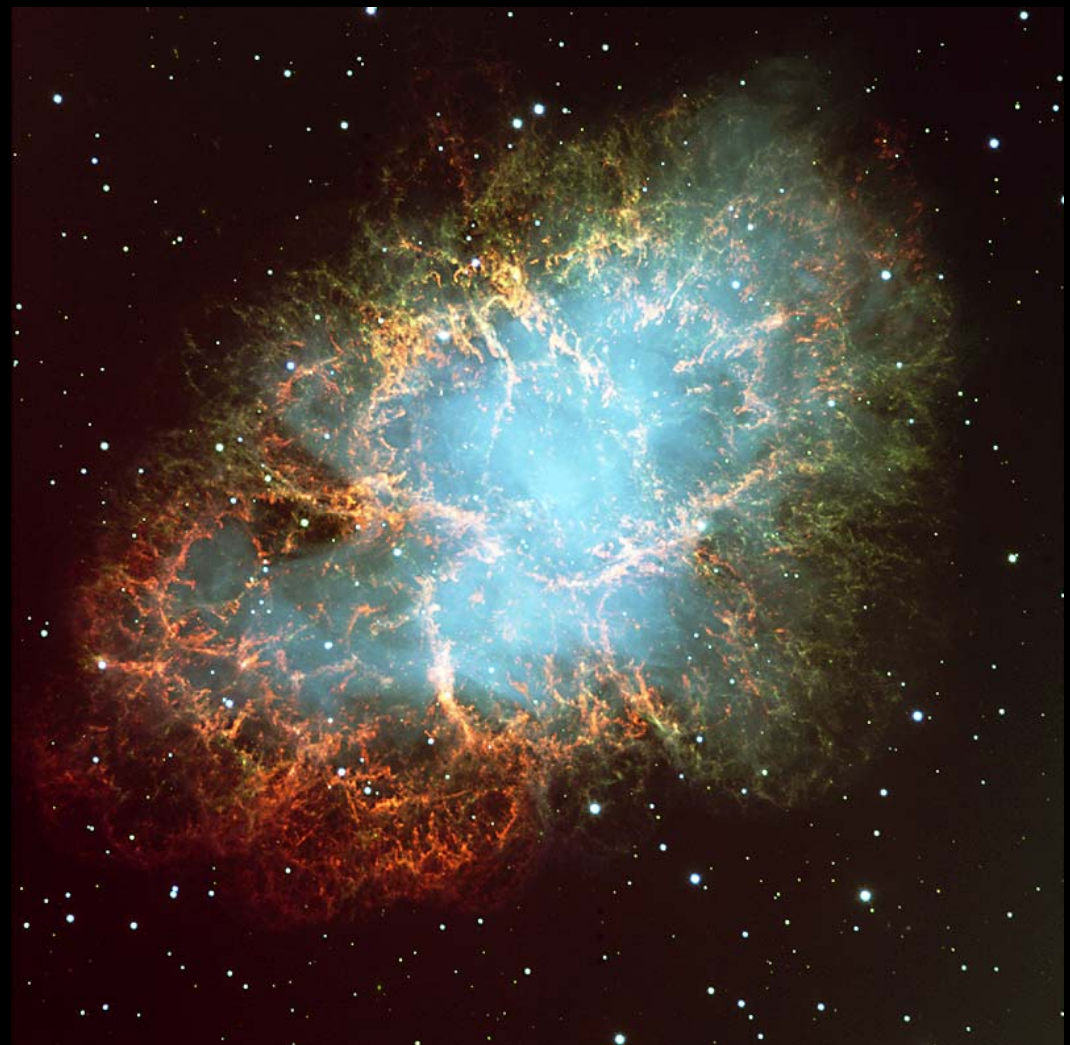
magnetic field

$$E \sim \Gamma B M$$

boost factor

mass

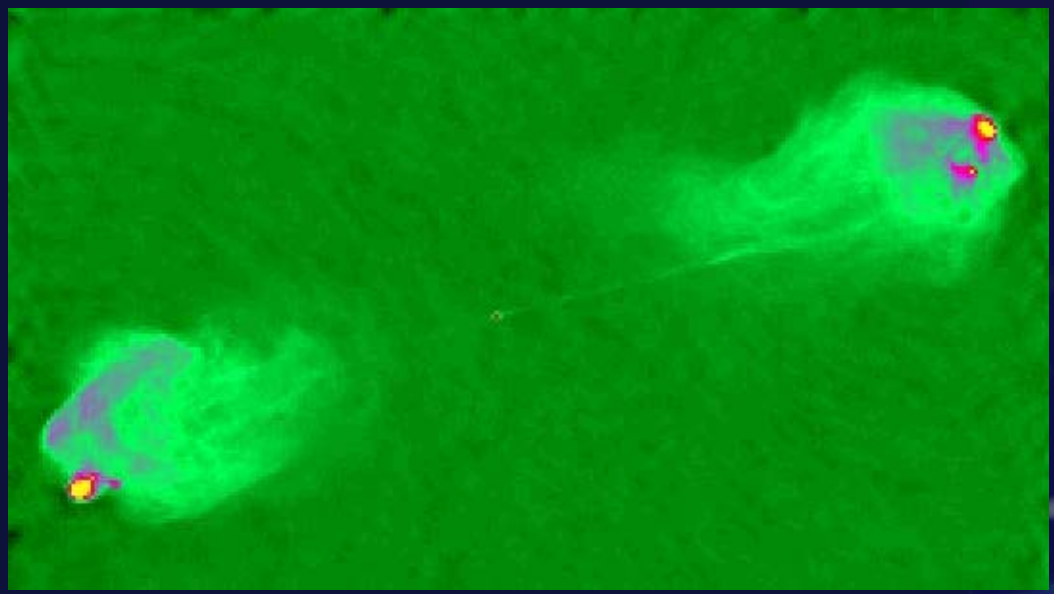
Supernova shocks expanding in interstellar medium



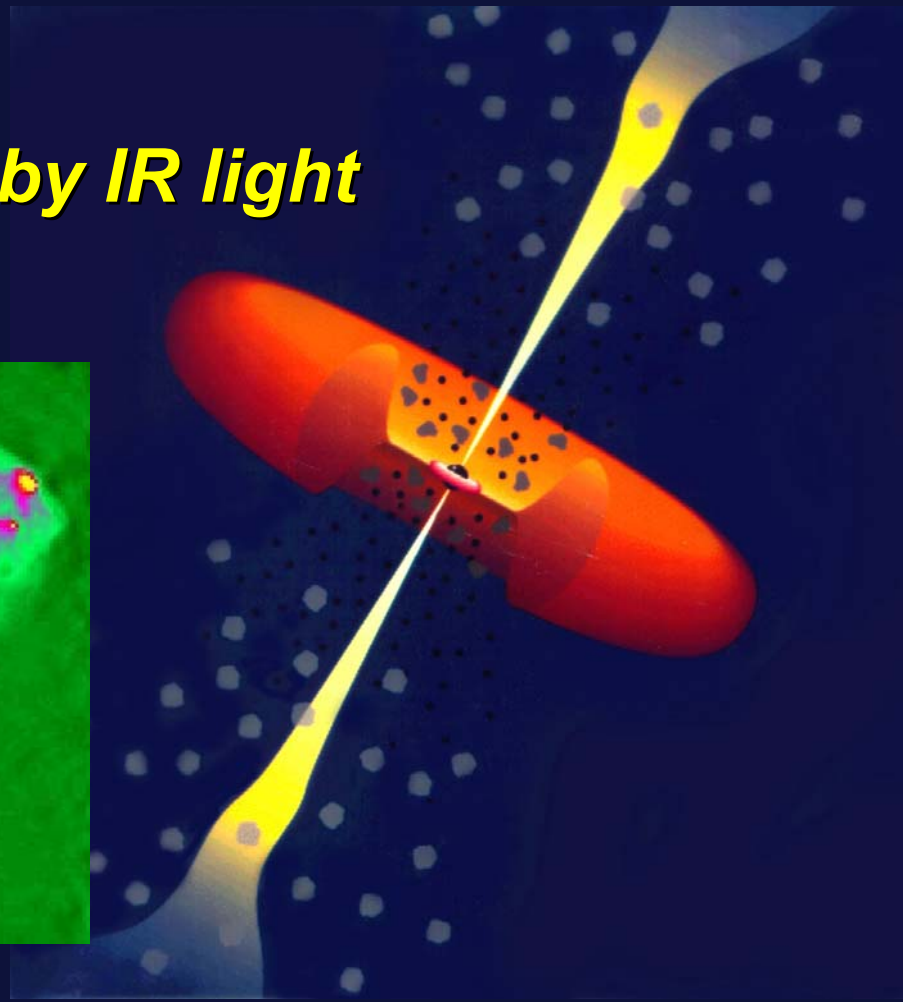
Crab nebula

Active Galaxies: Jets

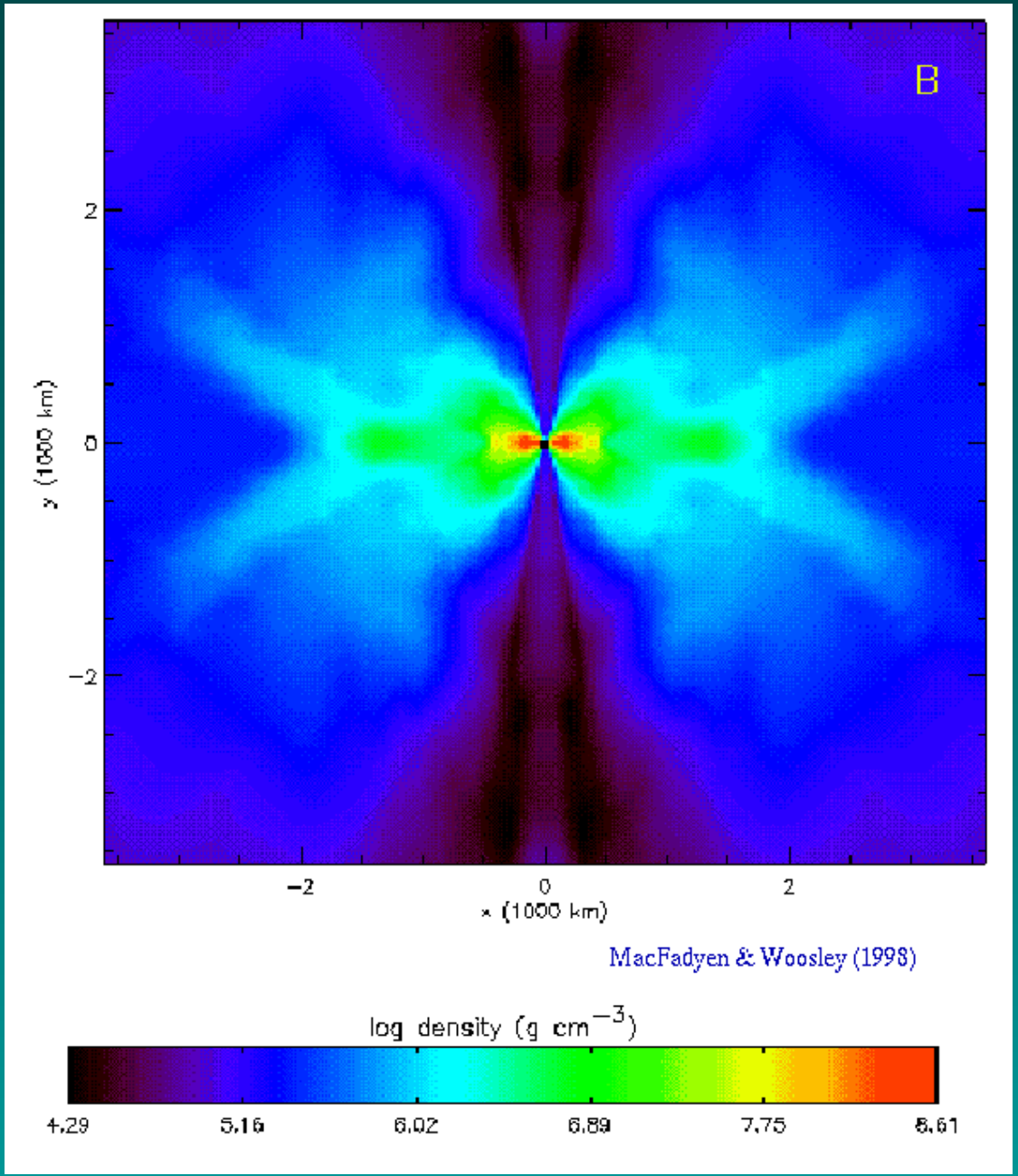
20 TeV gamma rays
Higher energies obscured by IR light



VLA image of Cygnus A



Gamma Ray Burst



$E \sim \Gamma B M$

$E > 10^{19}$ eV ?

- quasars $\Gamma \cong 1$ $B \cong 10^3$G $M \cong 10^9 M_{sun}$
- blasars $\gtrsim 10$
- neutron stars $\Gamma \cong 1$ $B \cong 10^{12}$G $M \cong M_{sun}$
  black holes
  :
- grb $\gtrsim$ 10^2

emit highest energy γ's!

Particles > 10^{20} eV ?

- **not protons**

  cannot reach us from cosmic accelerators

  $\lambda_{int} < 50$ Mpc

  no diffusion in magnetic fields

  doublets, triplet

- **not photons**

  $\gamma + B_{earth} \rightarrow e^+ + e^-$ not seen

  showers not muon-poor

- **not neutrinos**

  $\sigma_{\nu p} \cong 10^{-5} \sigma_{pp}$ ⇒ no <u>air</u> showers

Interaction length of protons in microwave background

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

$$\lambda_{\gamma p} = \left(\square\, n_{CMB}\, \sigma_{p+\gamma_{CMB}} \right)^{-1}$$

$$\cong 10 \text{ Mpc}$$

GZK cutoff

Particles > 10^{20} eV ?

new astrophysics?

- **not protons**

  cannot reach us from cosmic accelerators

  $\lambda_{int} < 50$ Mpc

  no diffusion in magnetic fields

  doublets, triplet

trouble for top-down scenarios

- **not photons**

  $\gamma + B_{earth}$ $e^+ + e^-$ not seen

  showers not muon-poor

- **not neutrinos**

  $\sigma_{\nu p} \cong 10^{-5}\ \sigma_{pp}$ → □□□□□no air showers

$\sigma_{\nu p} \cong \sigma_{pp}$ with TeV - gravity unitarity?

10^{24} eV = 10^{15} GeV ≃ M_{GUT}

are cosmic rays the decay product of

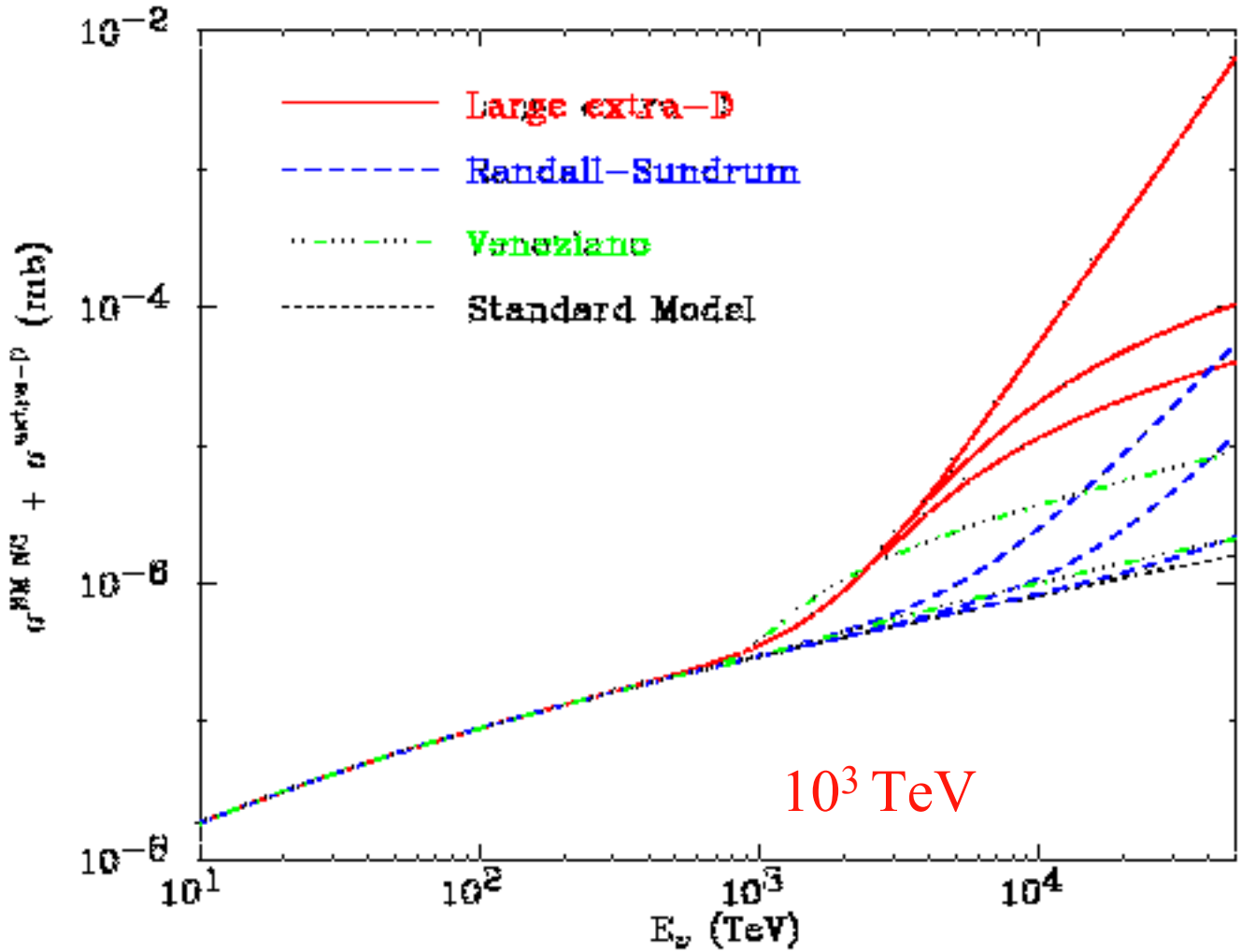
- **topological defects?**
  (vibrating string, annihilating monopoles)
- **heavy relics?**

Top. Def. → X,Y → W,Z → quark + lept

γ >> p ν >> γ

- top-down spectrum
- hierarchy $\nu\nu$ >> $\gamma\gamma$ >> p

TeV-Scale Gravity Modifies PeV Neutrino Cross Sections!

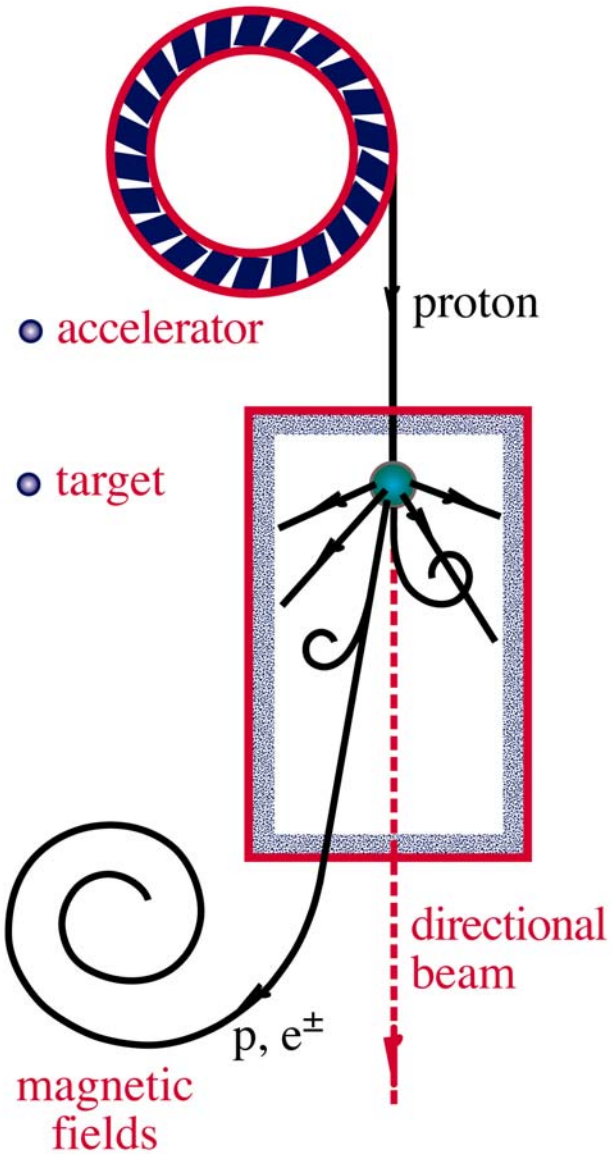


The Oldest Problem in Astronomy:

- No accelerator
- No particle candidate (worse than dark matter!)
- Not photons (excludes extravagant particle physics ideas)

What Now?

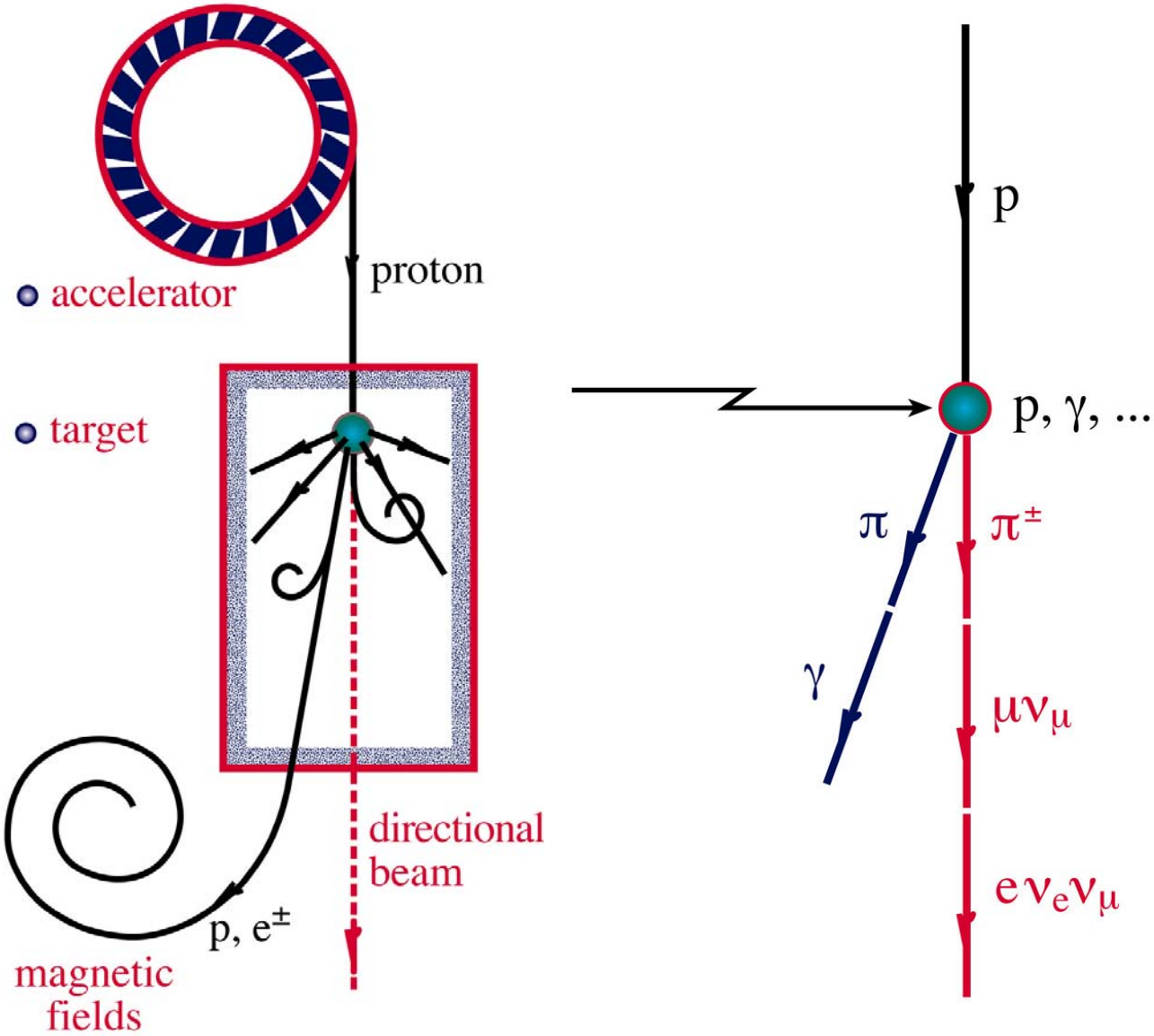
NEUTRINO BEAMS: HEAVEN & EARTH



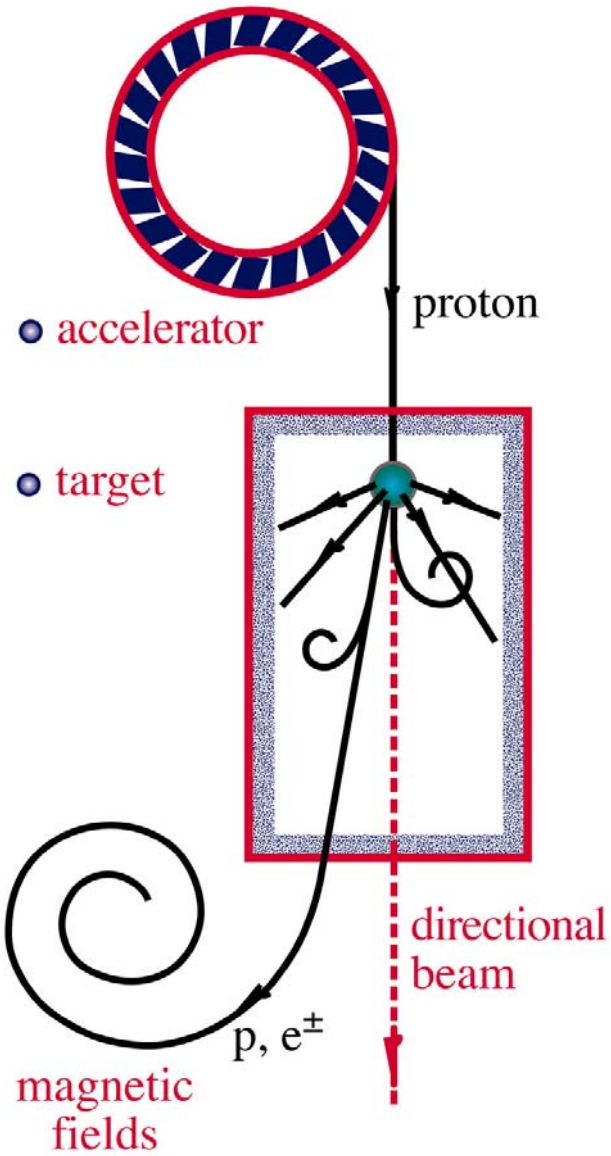
→ black hole

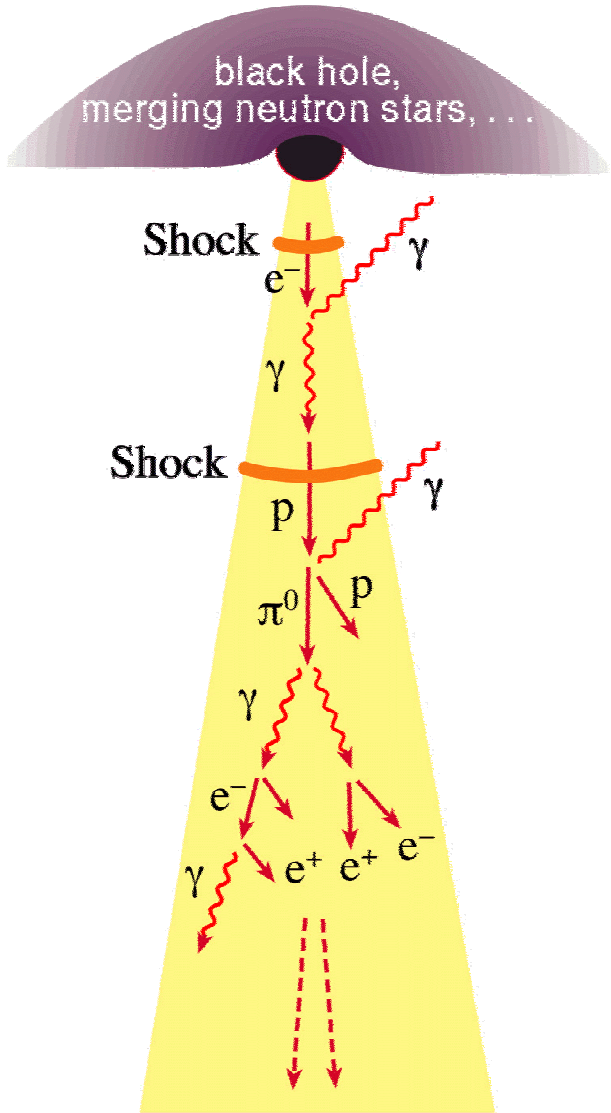
→ radiation enveloping black hole

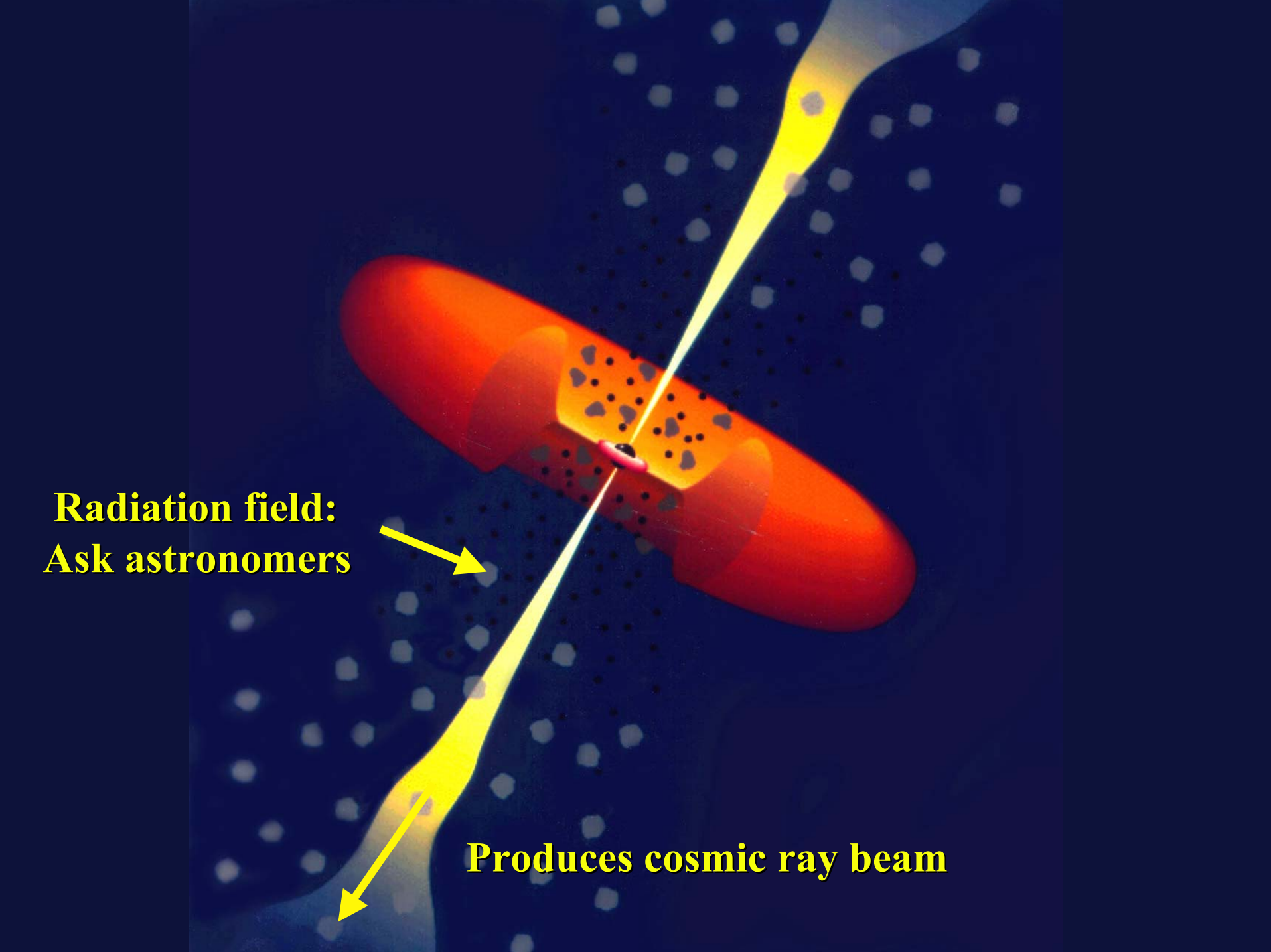
NEUTRINO BEAMS: HEAVEN & EARTH



NEUTRINO BEAMS: HEAVEN & EARTH






Radiation field:
Ask astronomers
Produces cosmic ray beam

cosmic ray puzzle

protons

~ 10^4 km^2 air shower arrays

e.g.
- Hi Res, Auger, Airwatch, OWL, TA…

also

TeV γ - rays

- atmospheric Cherenkov
- space-based

- Veritas, Hess, Magic …
- GLAST…

- short-wavelength study of supernova remnants and galaxies

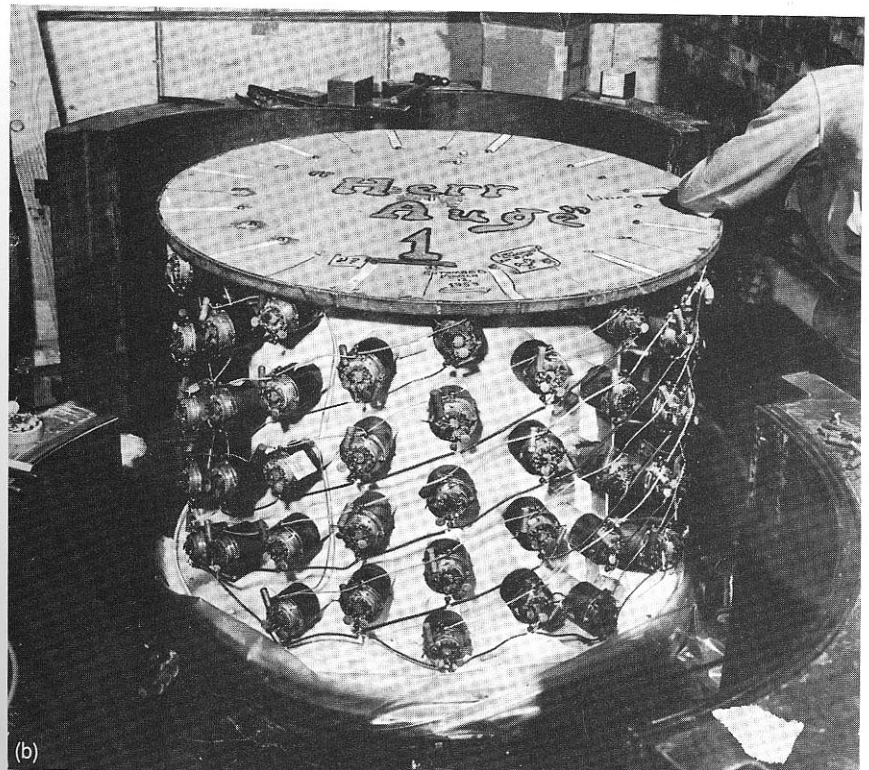
neutrinos

~ 1 km^3 high energy detectors

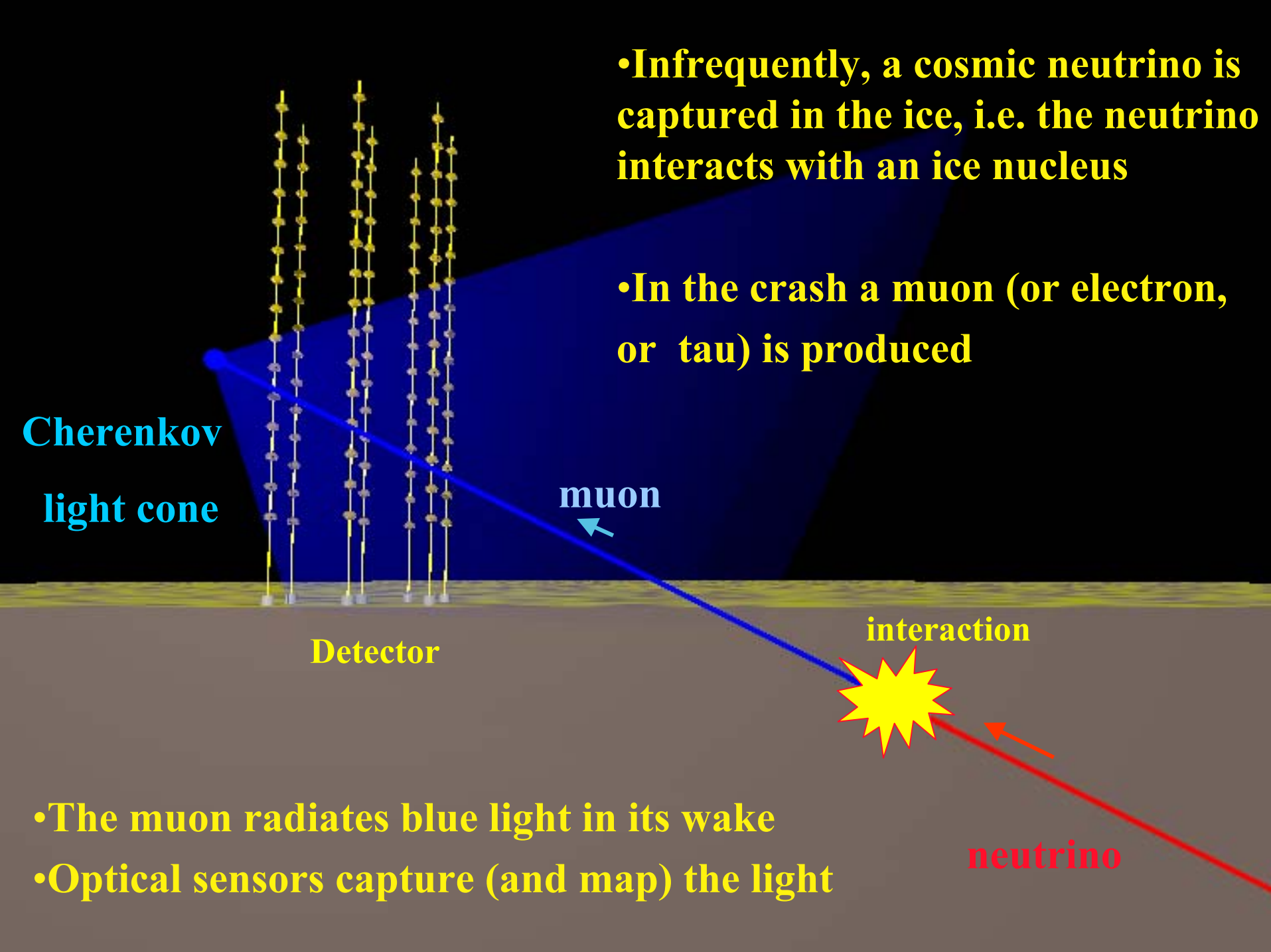
- AMANDA / Ice Cube Antares, Nestor, NEMO

- particle physics and cosmology
- dark matter search
- discovery

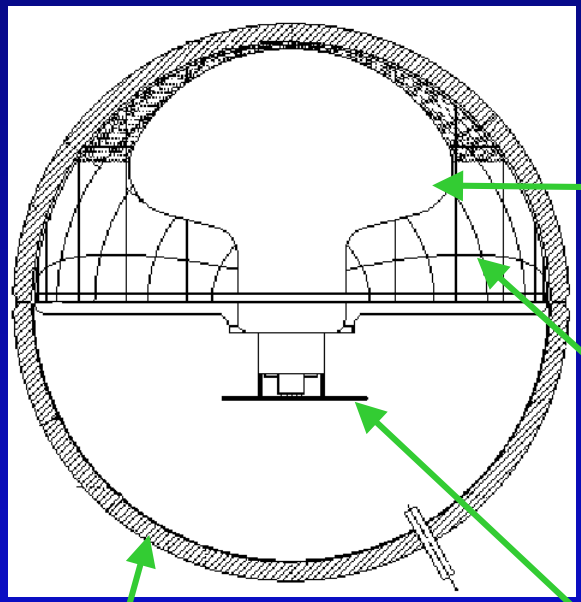
(a)



(b)

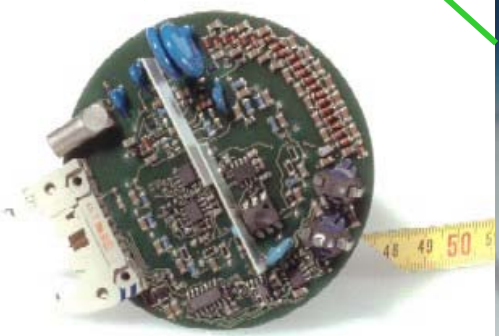

•Infrequently, a cosmic neutrino is captured in the ice, i.e. the neutrino interacts with an ice nucleus
•In the crash a muon (or electron, or tau) is produced
Cherenkov light cone
muon
Detector
interaction
neutrino
•The muon radiates blue light in its wake
•Optical sensors capture (and map) the light

Optical Module



Photomultiplier: 10 inch Hamamatsu

Active PMT base

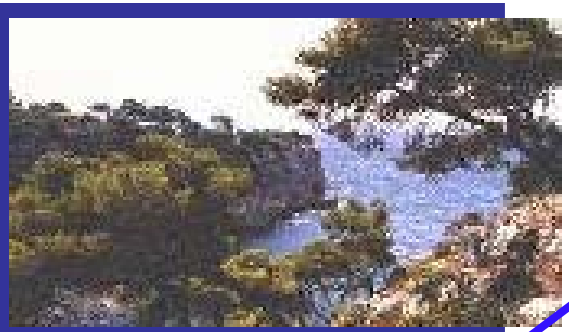


Glass sphere: Nautillus

Mu metal magnetic shield

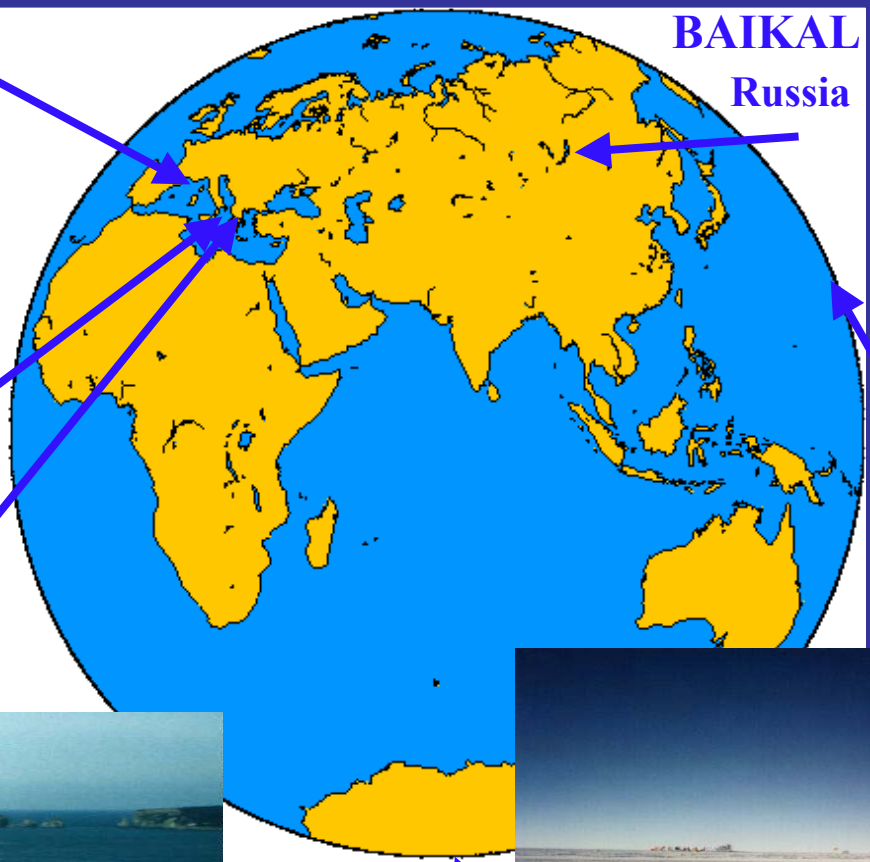
Optical Cherenkov Neutrino Telescope Projects

ANTARES
La-Seyne-sur-Mer, France



NEMO
Catania, Italy

NESTOR
Pylos, Greece

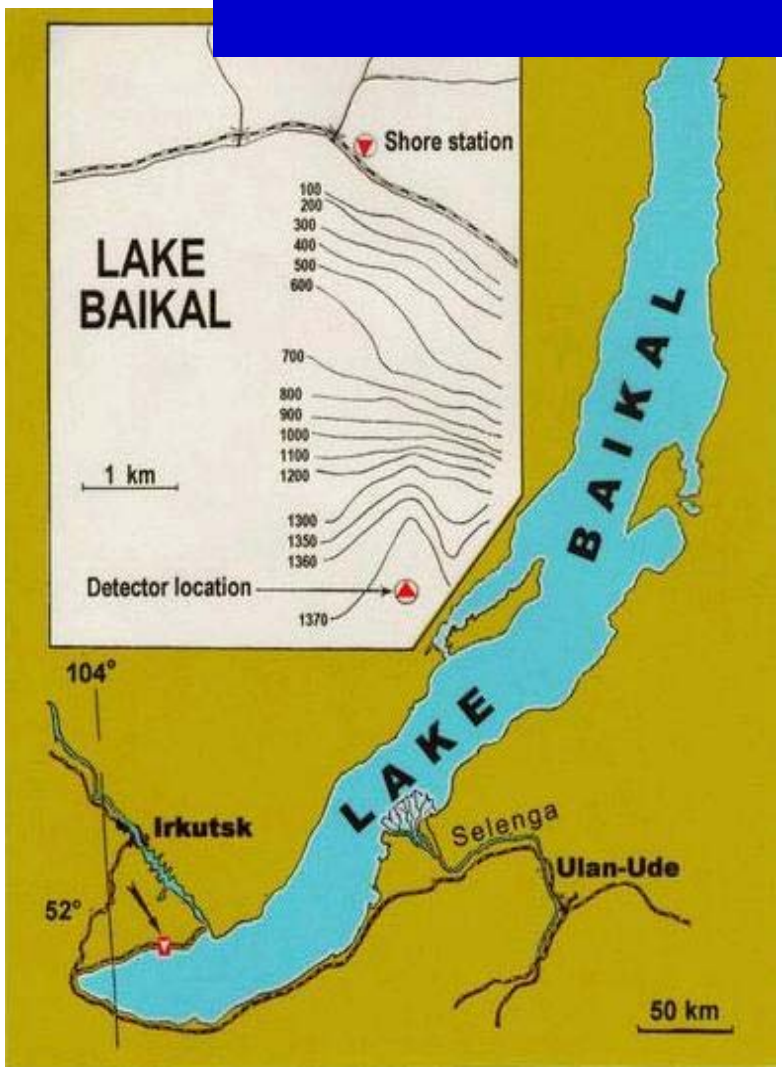


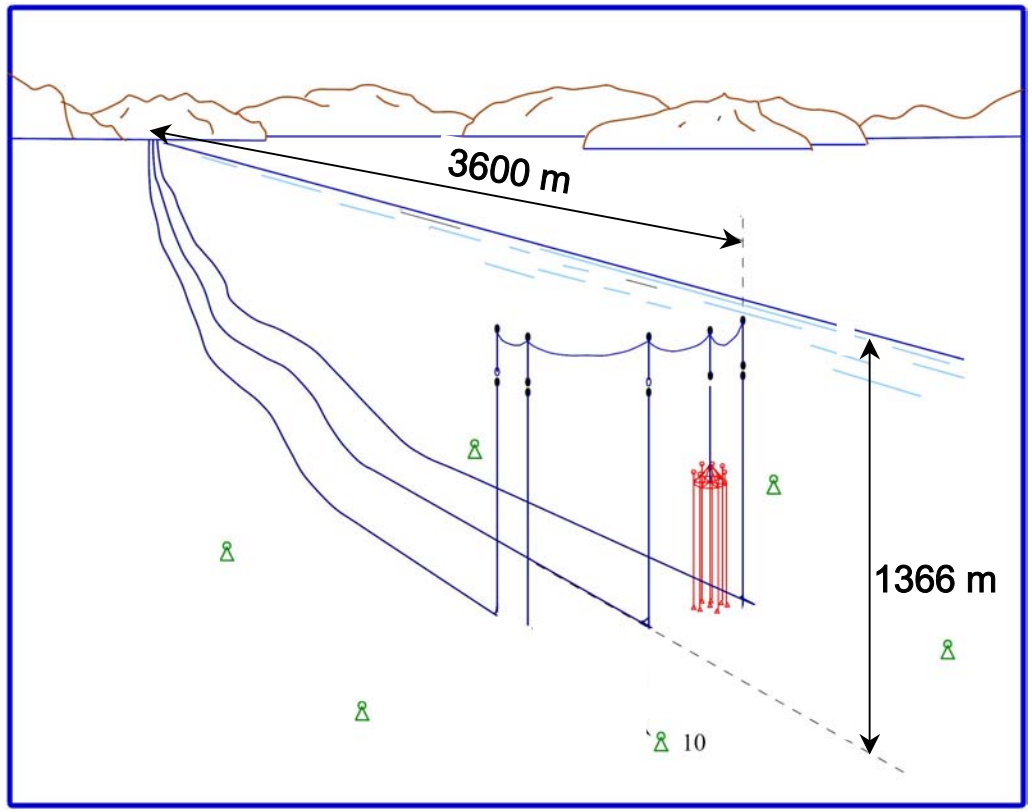
BAIKAL
Russia

DUMAND
Hawaii
(cancelled 1995)

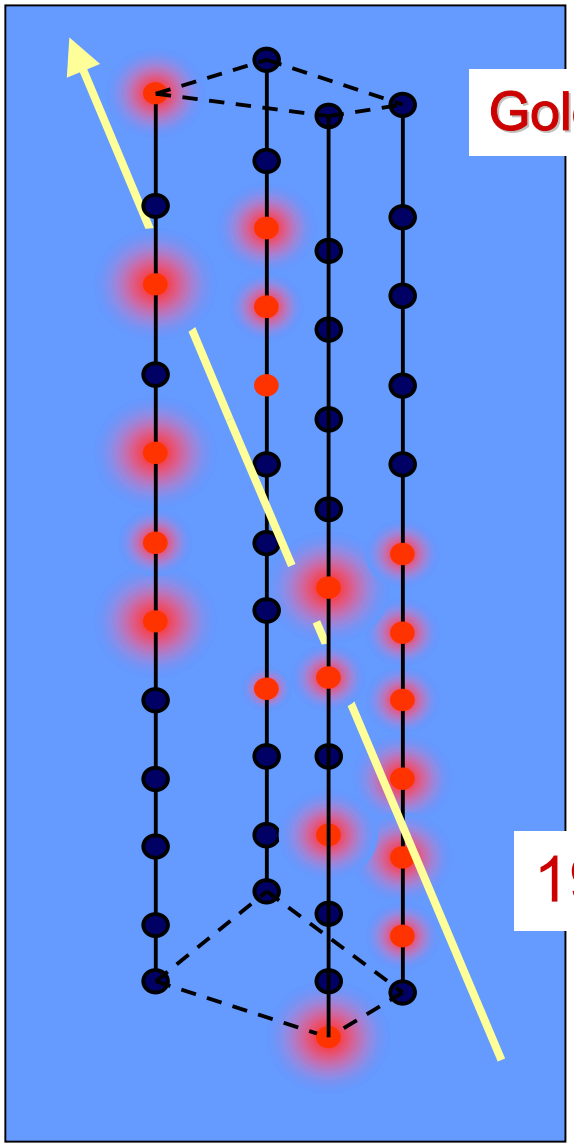
AMANDA, South Pole, Antarctica

Lake Baikal, NT-200: The Site





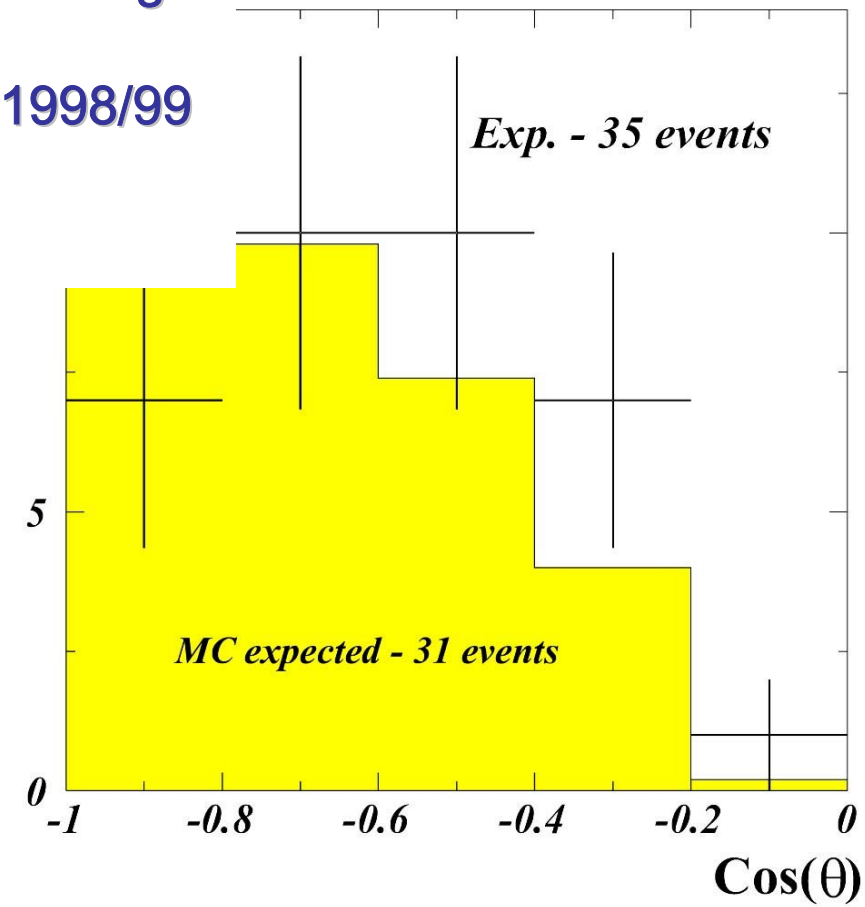
Lake Baikal: atmospheric neutrinos



Gold plated neutrino event, 4-string stage (1996)

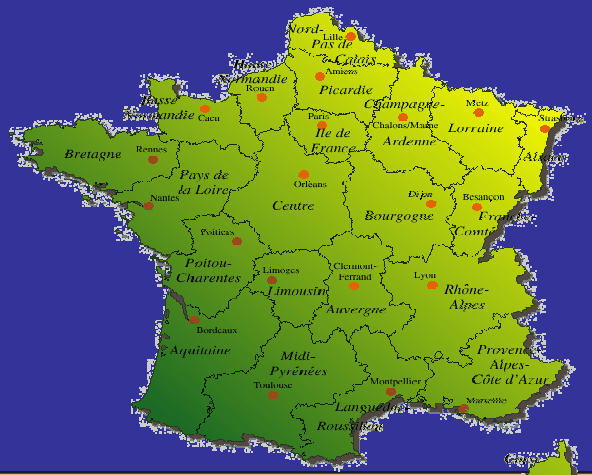
19 hits

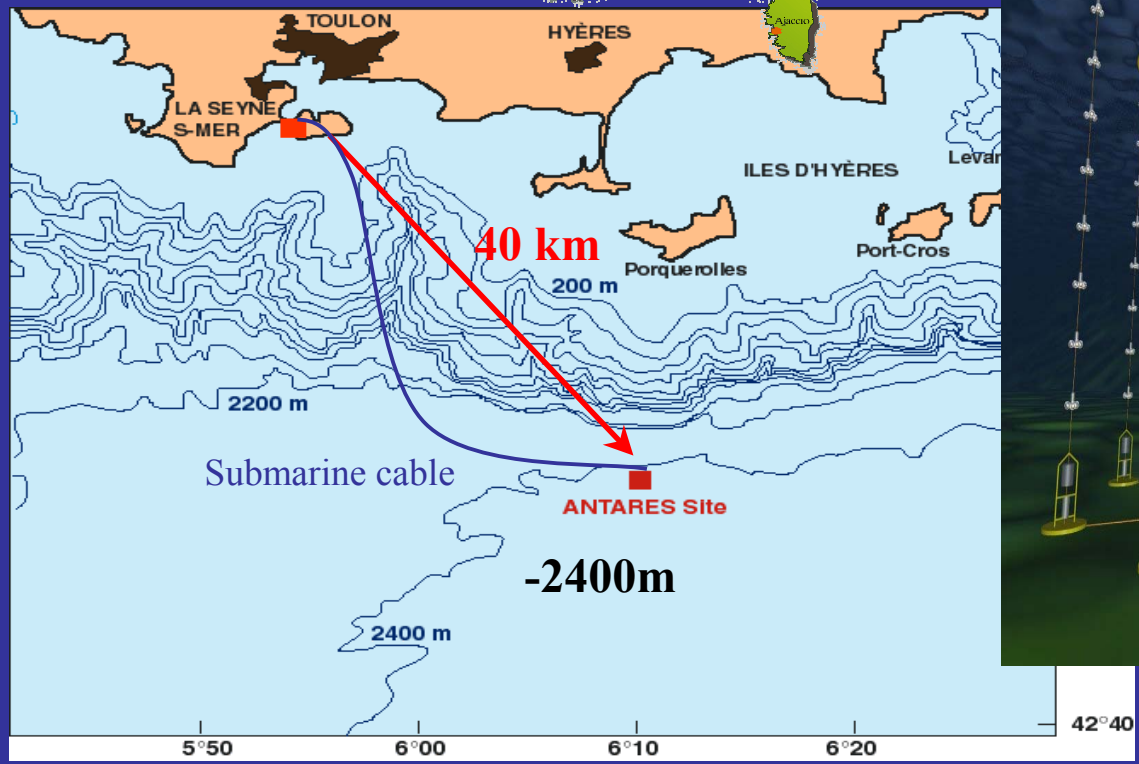
NT-200: zenith angle distribution
234 days in 1998/99

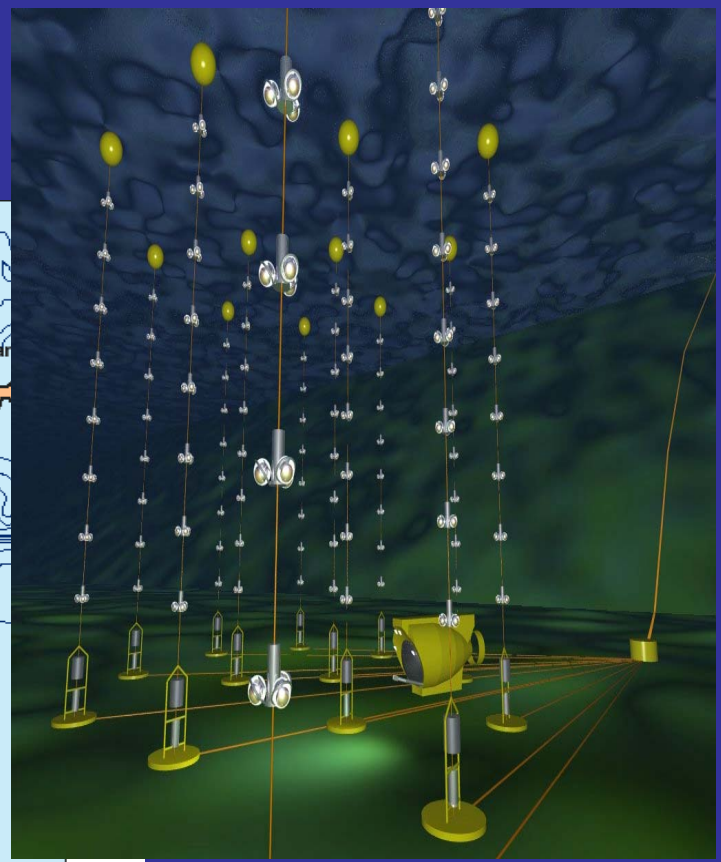


ANTARES SITE

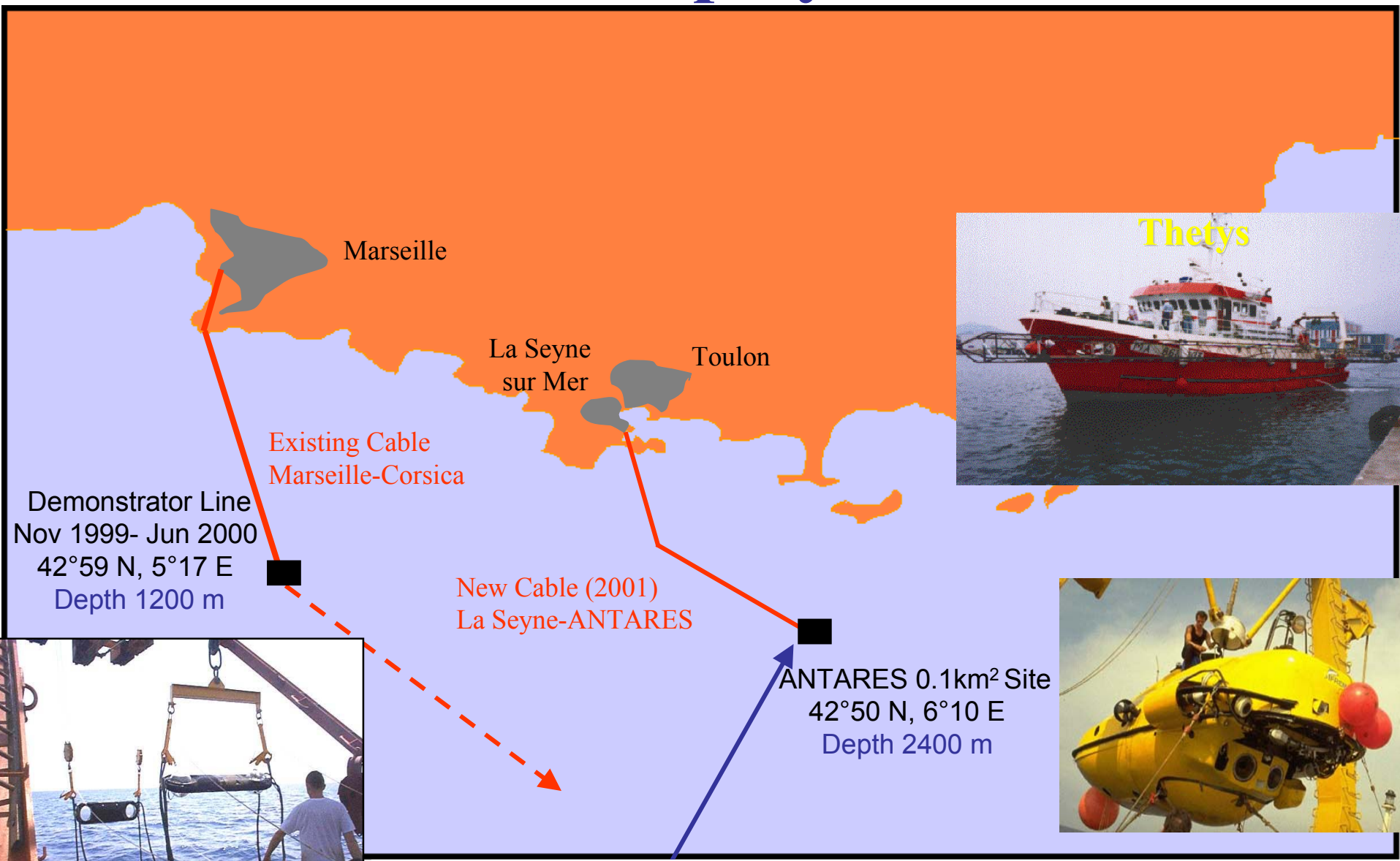
40Km SE Toulon
Depth 2400m
Shore Base
La Seyne-sur-Mer







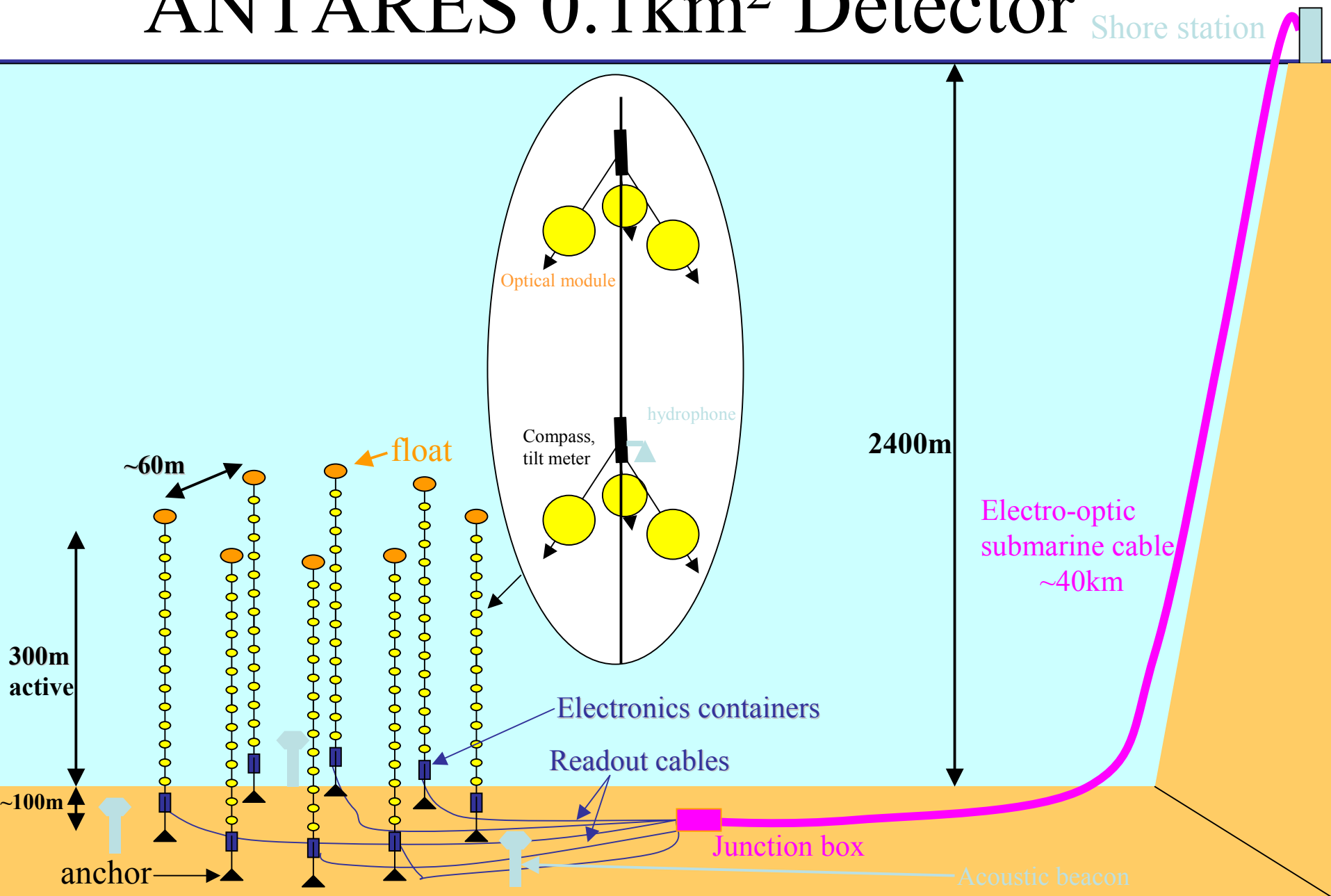
ANTARES Deployment Sites

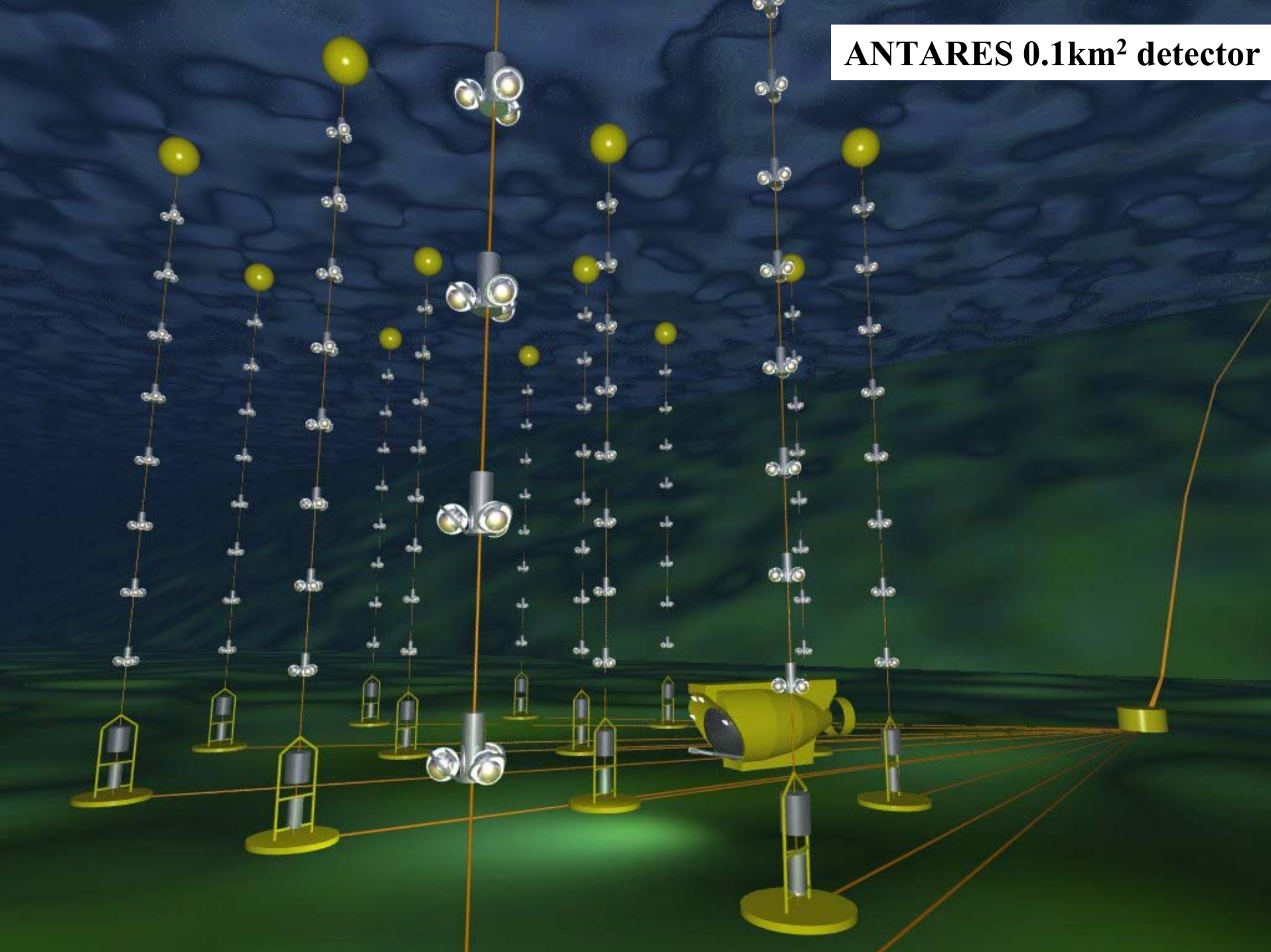


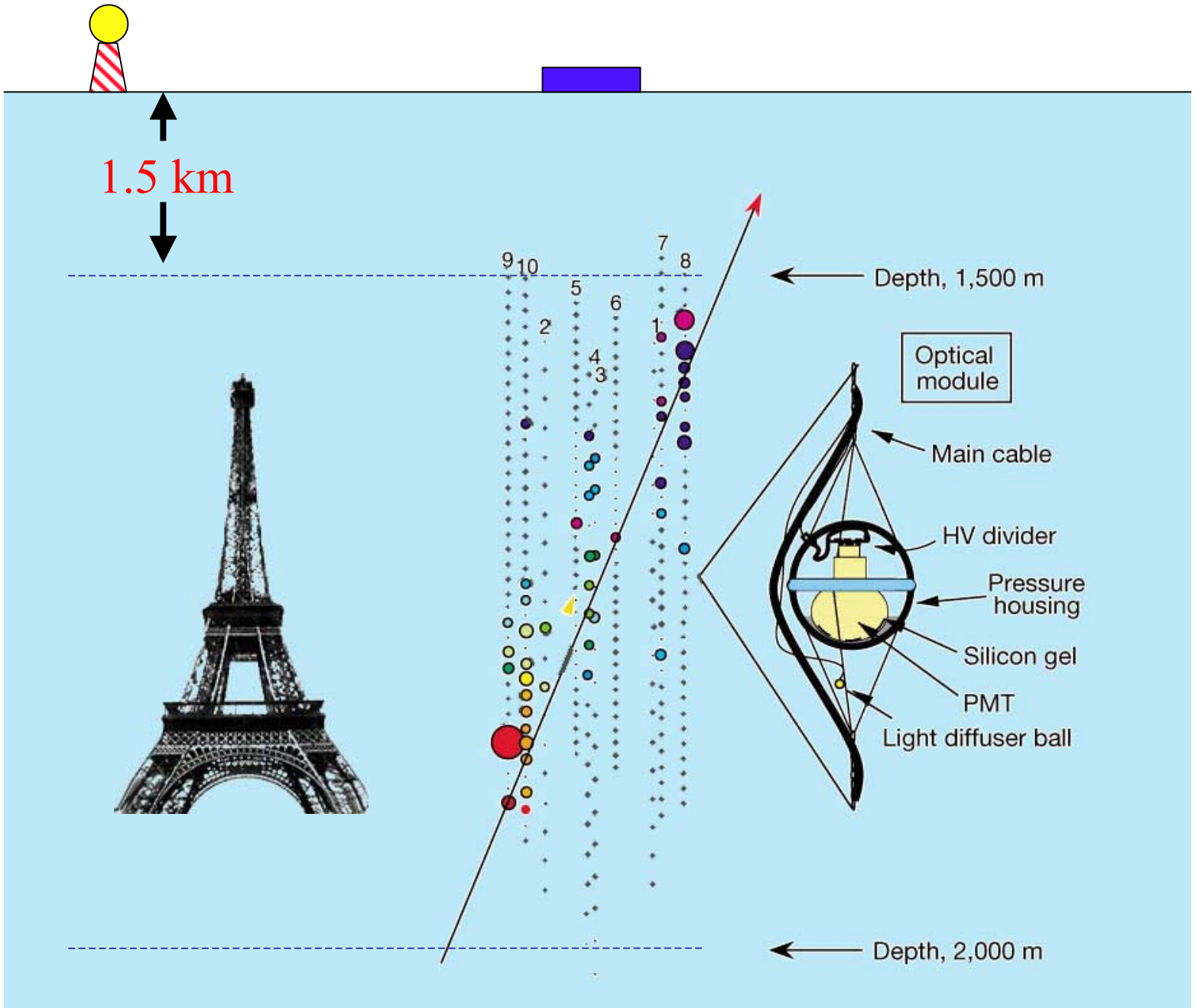
~ 40 deployments and recoveries of test lines for site exploration

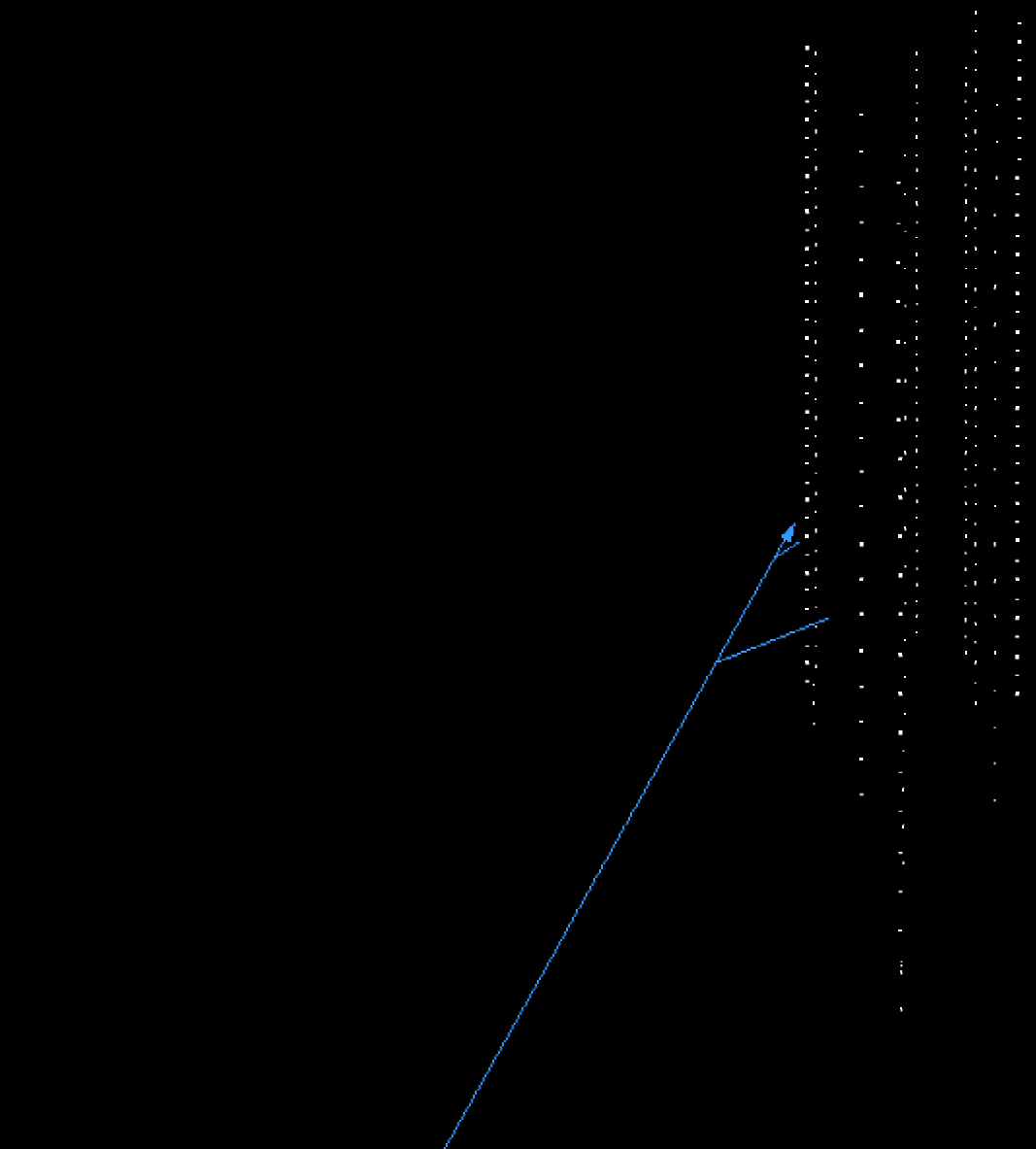
0.1 km² Detector with 900 Optical Modules , deployment 2002- 200

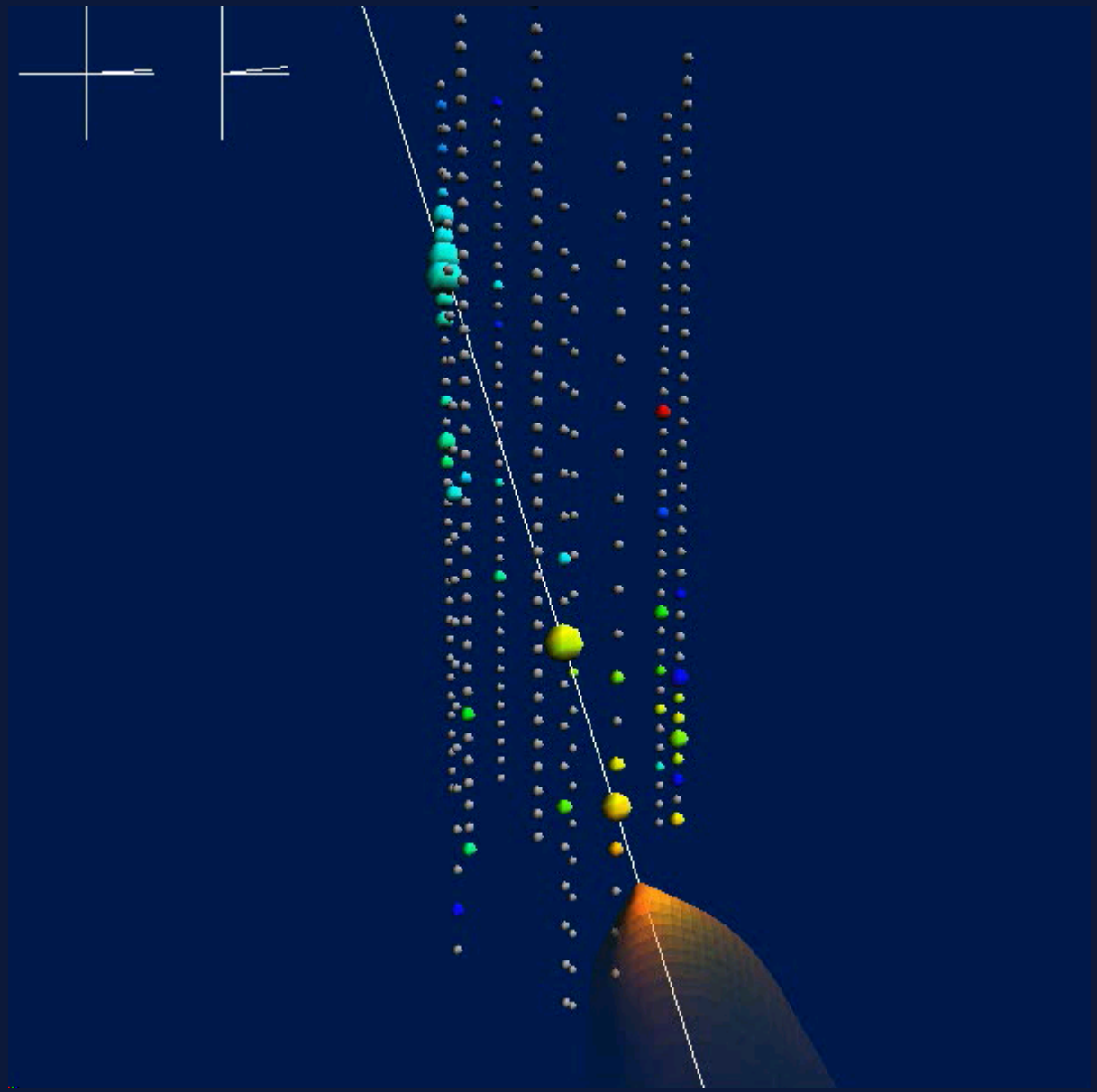
ANTARES 0.1km^2 Detector




ANTARES 0.1km² detector


1.5 km
9
10
2
5
6
4
3
7
1
8
Depth, 1,500 m
Optical module
Main cable
HV divider
Pressure housing
Silicon gel
PMT
Light diffuser ball
Depth, 2,000 m

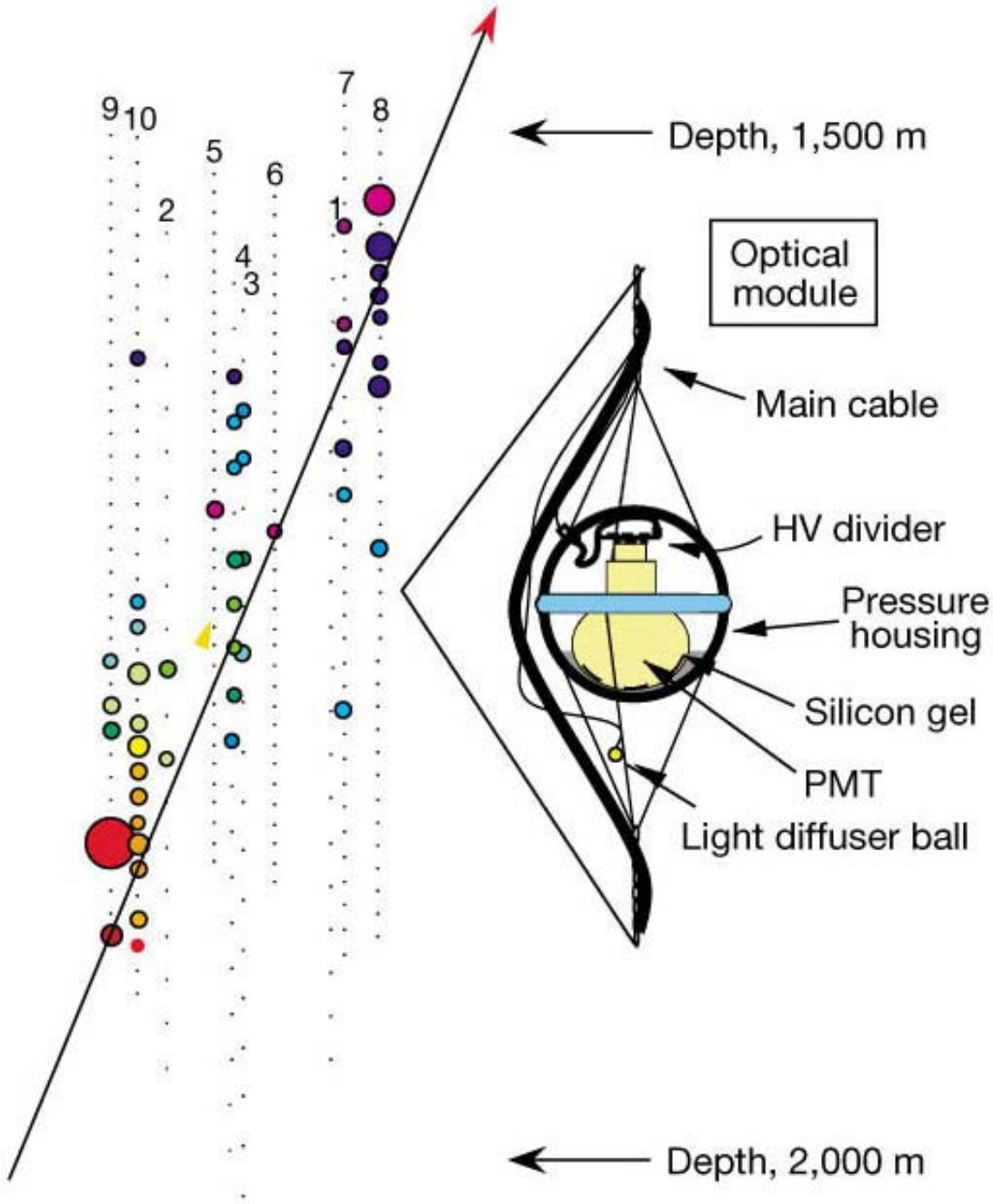


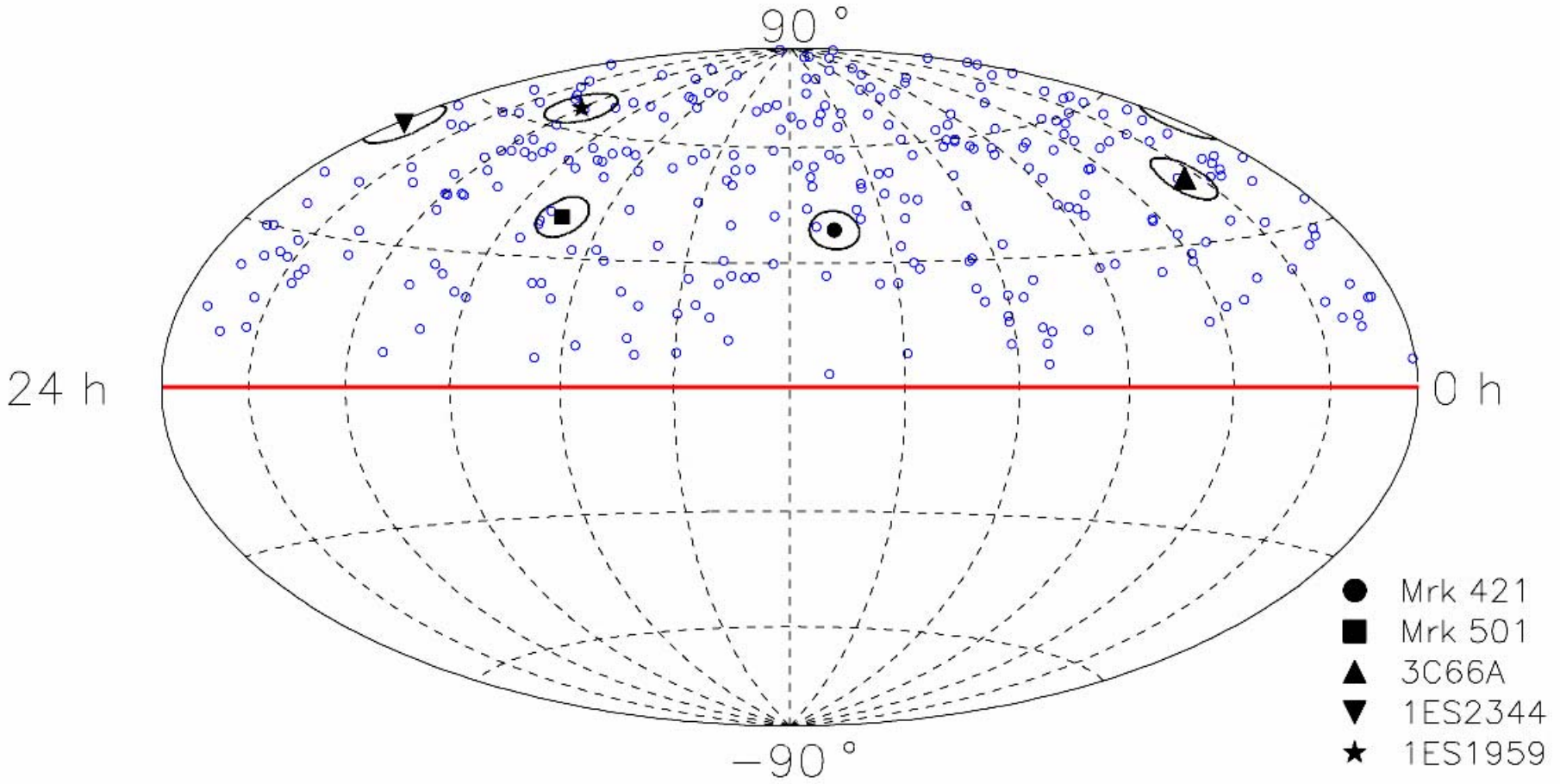



S. AIR FORCE
0491


Amundsen-Scott South Pole Station
South Pole

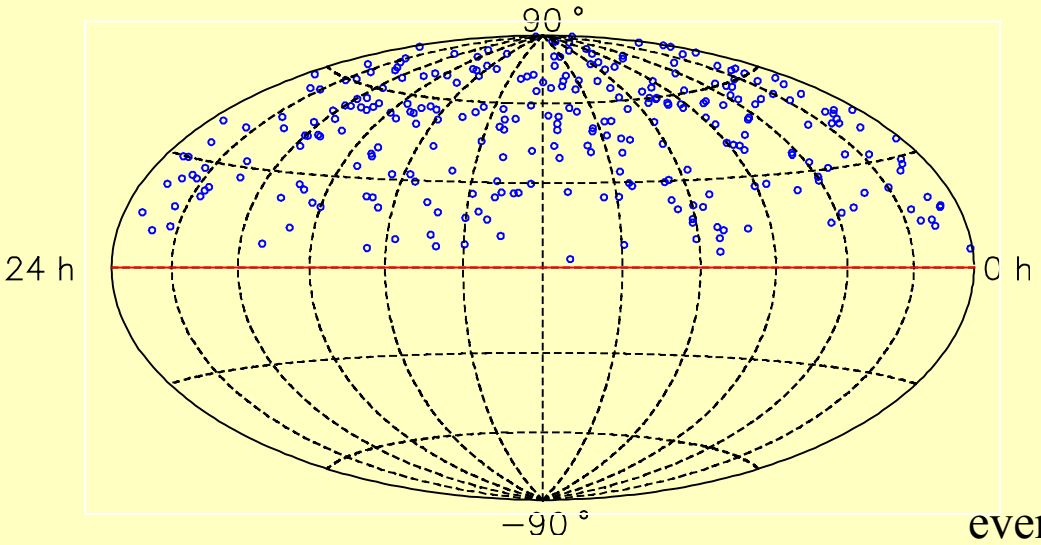

The Counting House

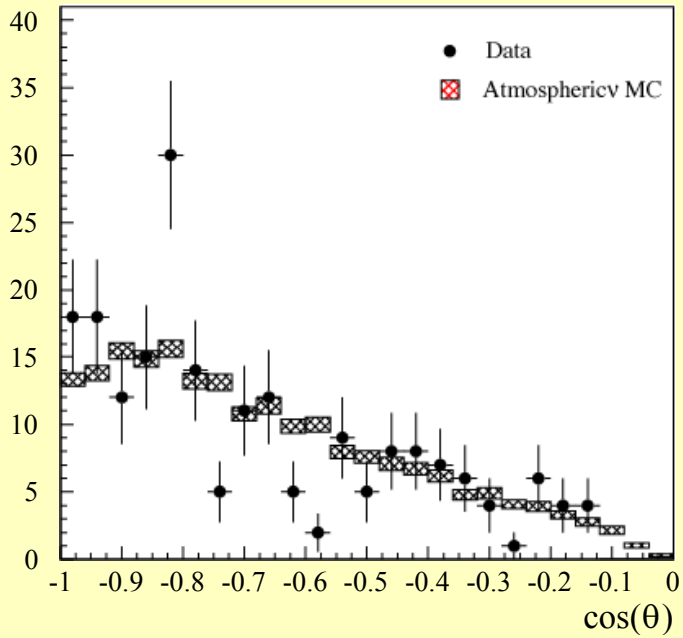

9
10
2
5
6
7
8
1
4
3
Depth, 1,500 m
Optical module
Main cable
HV divider
Pressure housing
Silicon gel
PMT
Light diffuser ball
Depth, 2,000 m



AMANDA NEUTRINO SKY

Neutrino sky seen by AMANDA





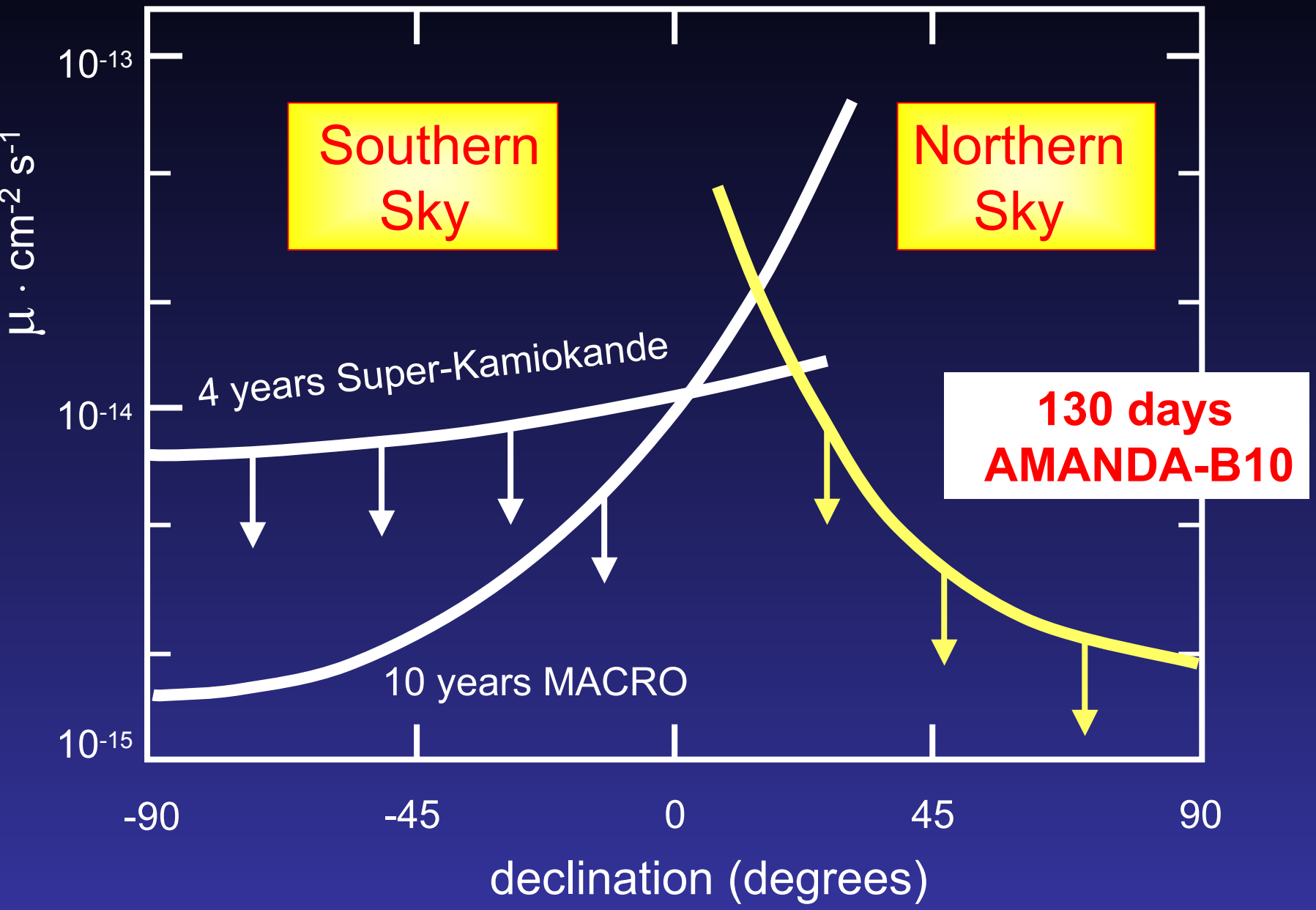
Cos(θ)

- **Monte Carlo methods verified on data**
- **~ 300 neutrinos from 130 days of B-10 operation** (Nature 410, 441, 2001)

Atmospheric Muons and Neutrinos

Lifetime: 135 days		
	Observed Data	Predicted Neutrinos
Triggered	1,200,000,000	4574
Reconstructed upgoing	5000	571
Pass Quality Cuts ($Q \geq 7$)	204	273

Upper limits to the muon flux from point sources



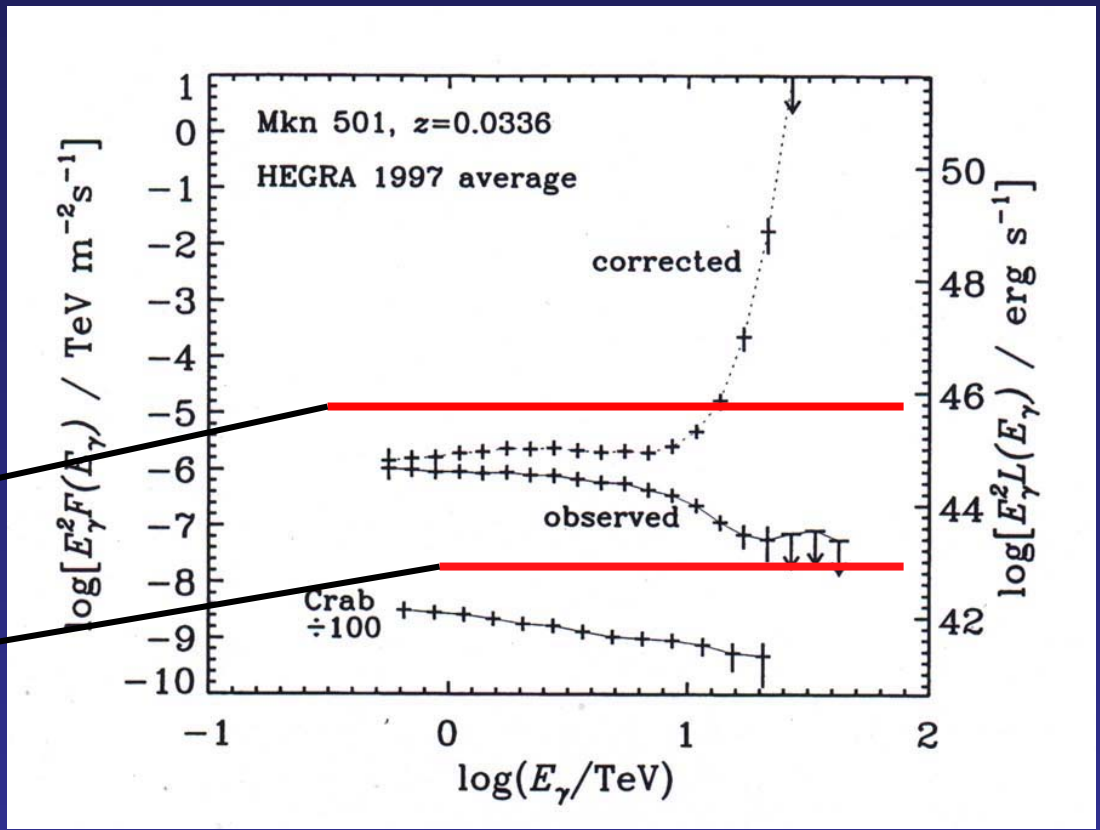
Compare to Mrk 501 gamma rays

Field of view:Continuous 2 π ster !

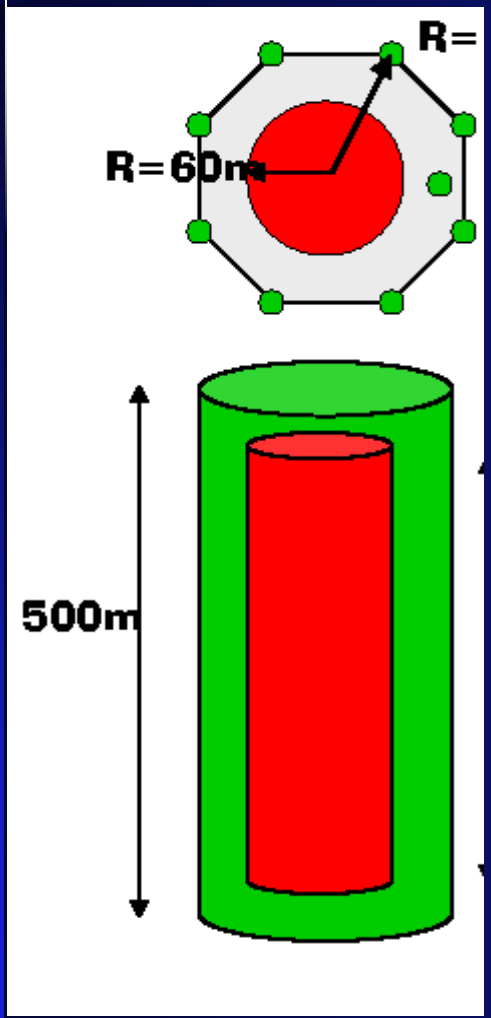
AMANDA limit

B10 1year only

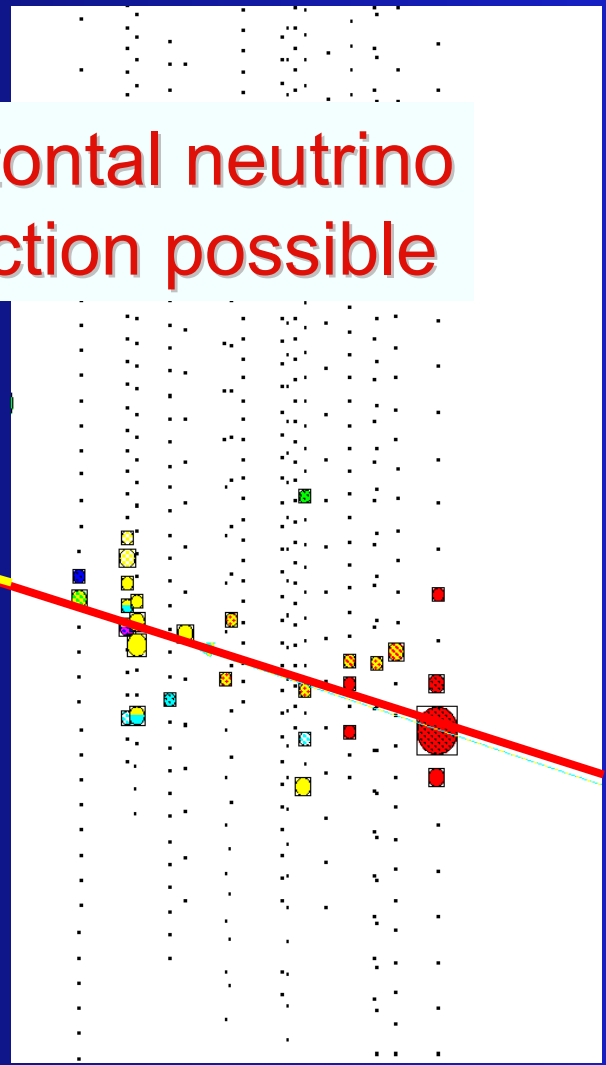
Sensitivity of 3 years of IceCube



AMANDA II - the full detector

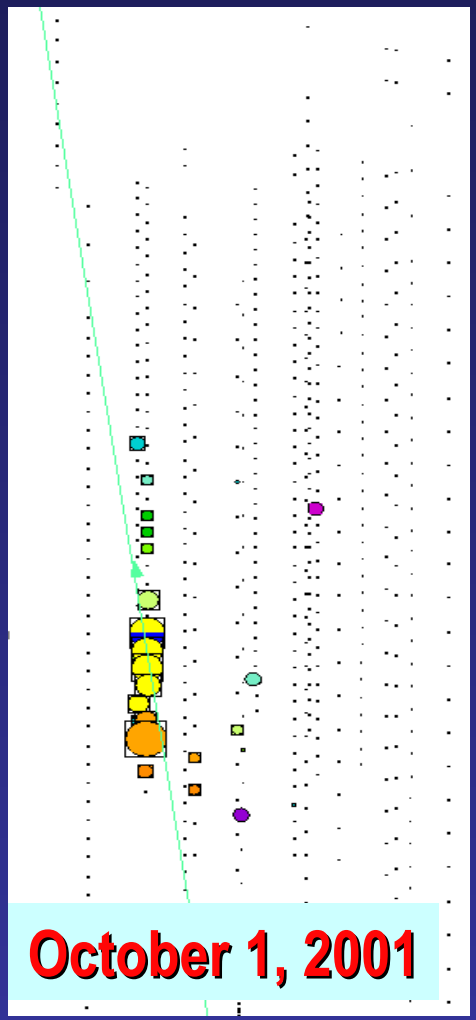


horizontal neutrino detection possible

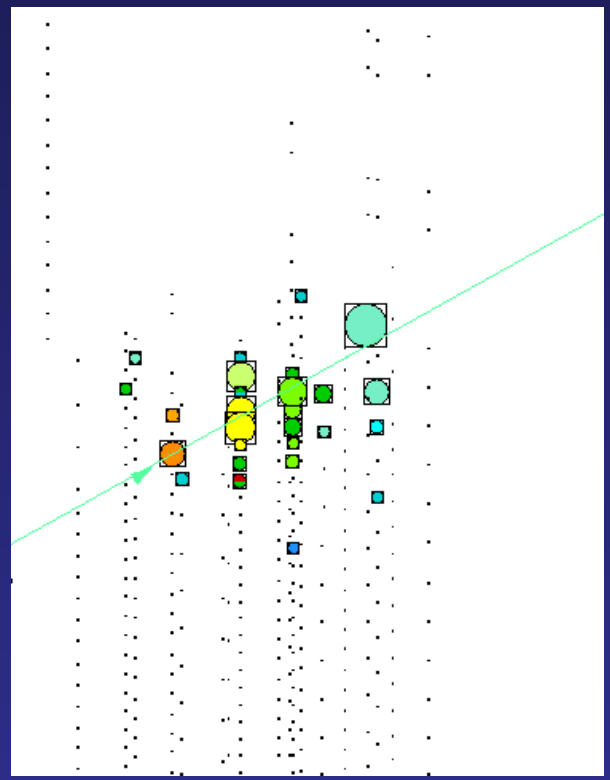


...online 2001 analysis

2 recent events:

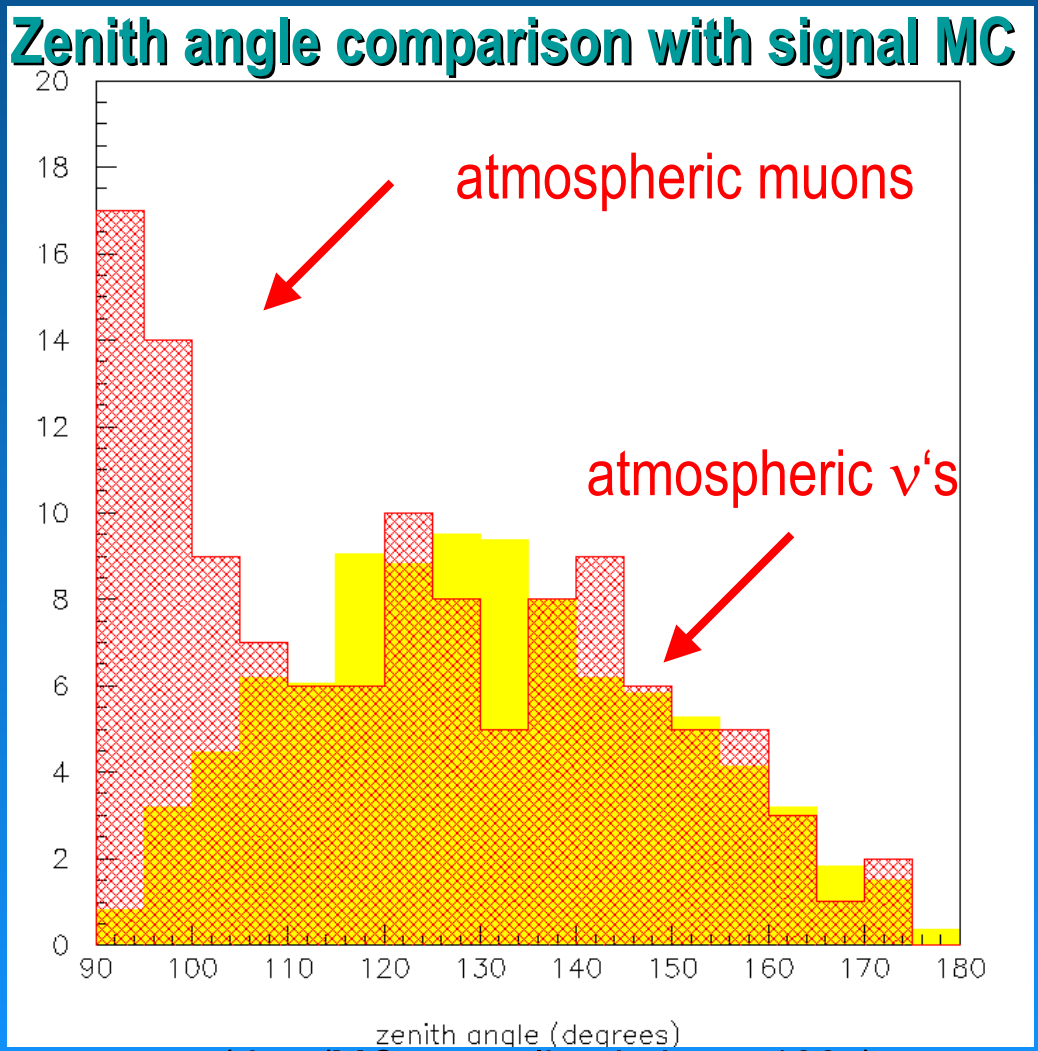


October 1, 2001



October 10, 2001

...online 2001 analysis



(data/MC normalized above 100°)

- real-time filtering at Pole
- real-time processing (Mainz)

Left plot:

- 20 days (Sept/Oct 2001)
- 90 ν–candidates above 100°

4.5 ν–candidates / day

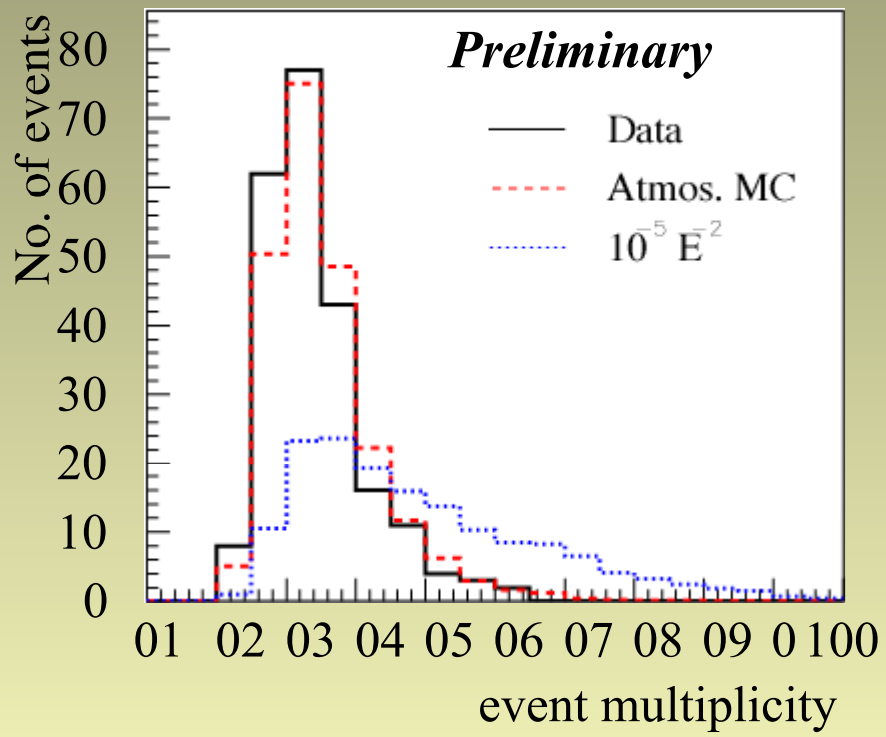
AMANDA: Proof of Concept

- 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.

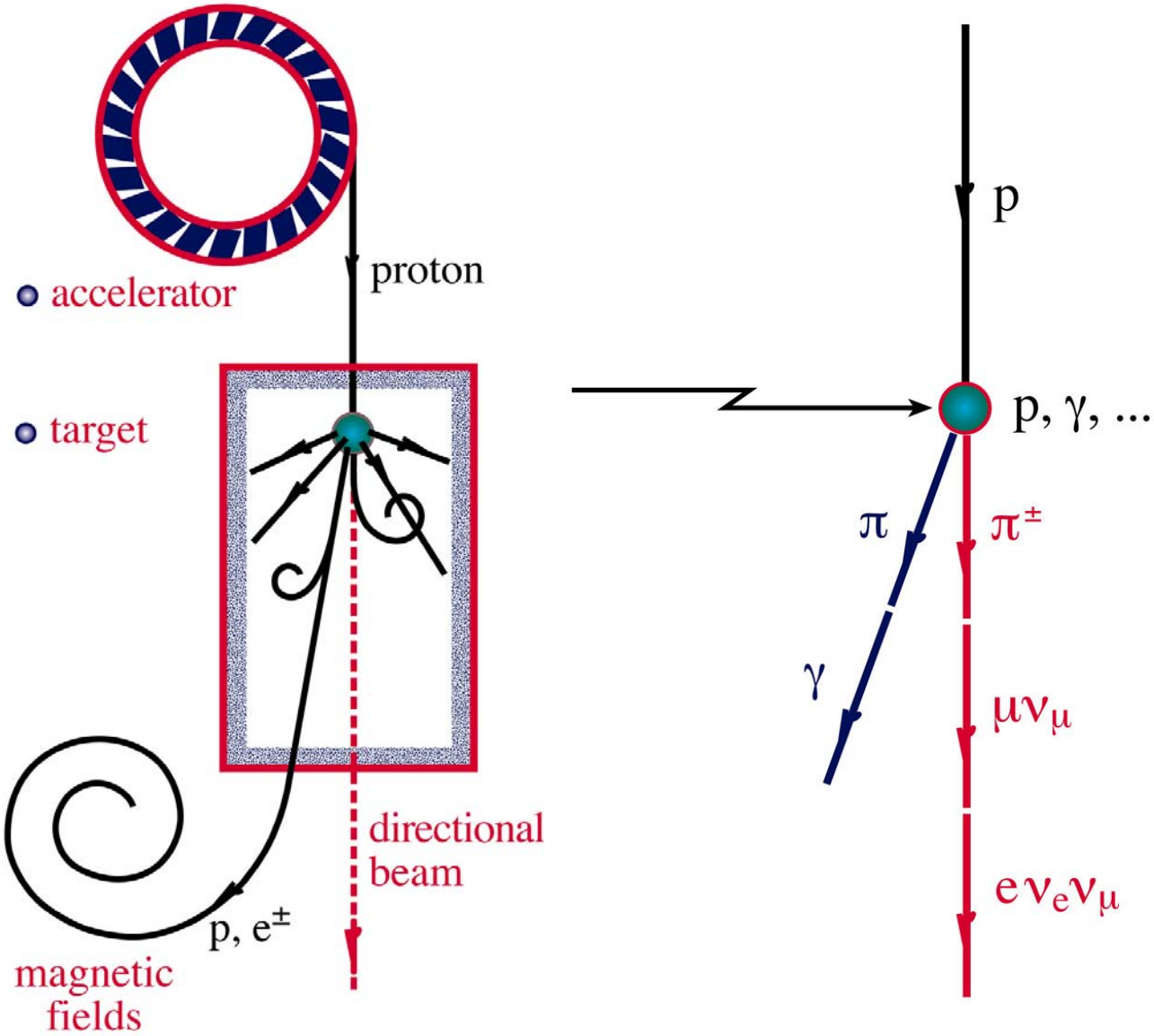
Search for a diffuse ν-flux of astrophysical sources

Method:

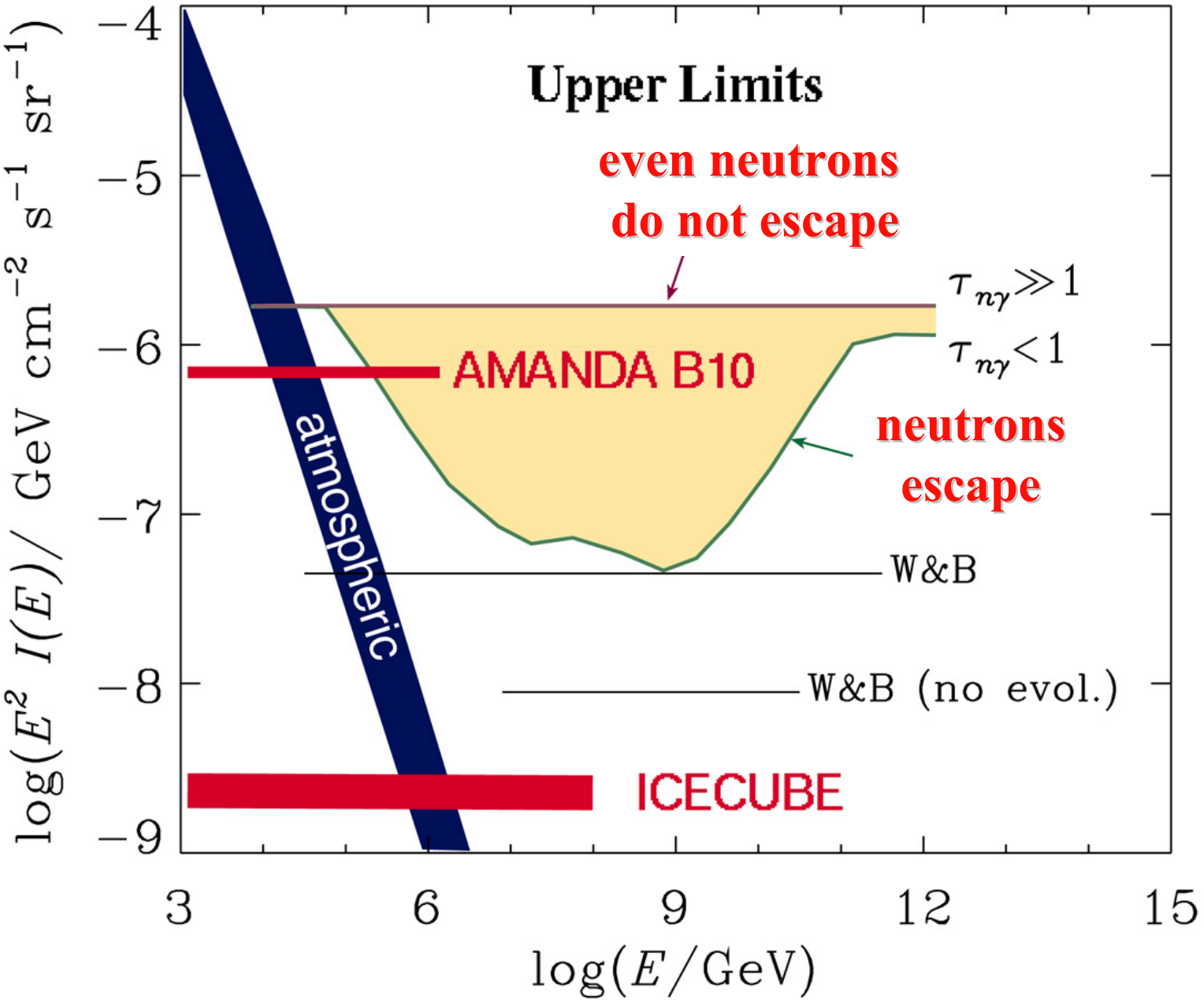
- Assume a diffuse neutrino flux (Hypothesis), e.g.:
  $dN/dE = 10^{-5} * E^{-2} / (cm^2\ sec\ GeV)$
- The background is the atmospheric neutrino flux (after quality cuts): ≈ **200 events**
- Apply energy cut.



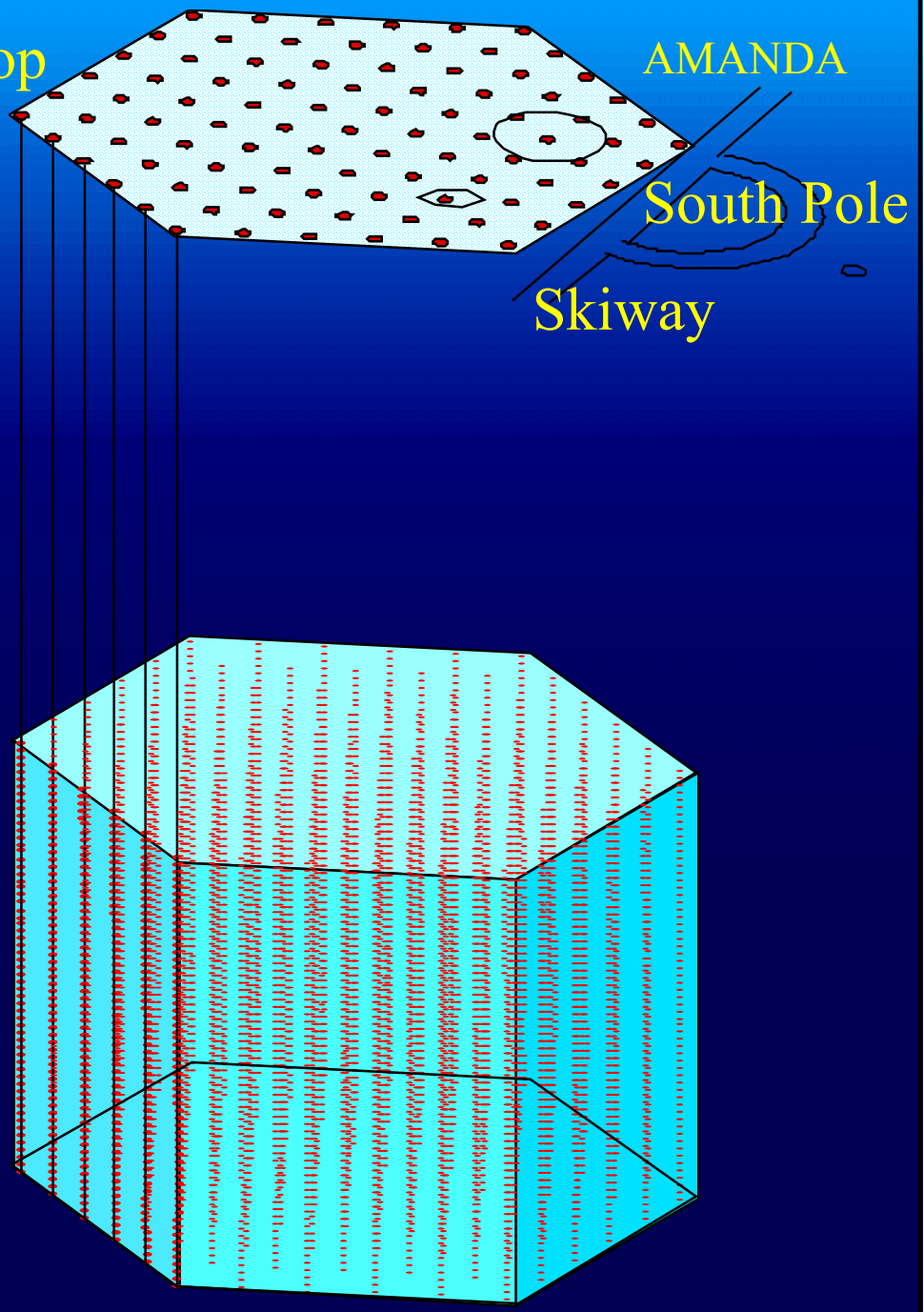
NEUTRINO BEAMS: HEAVEN & EARTH



neutrinos associates with the source of the cosmic rays?

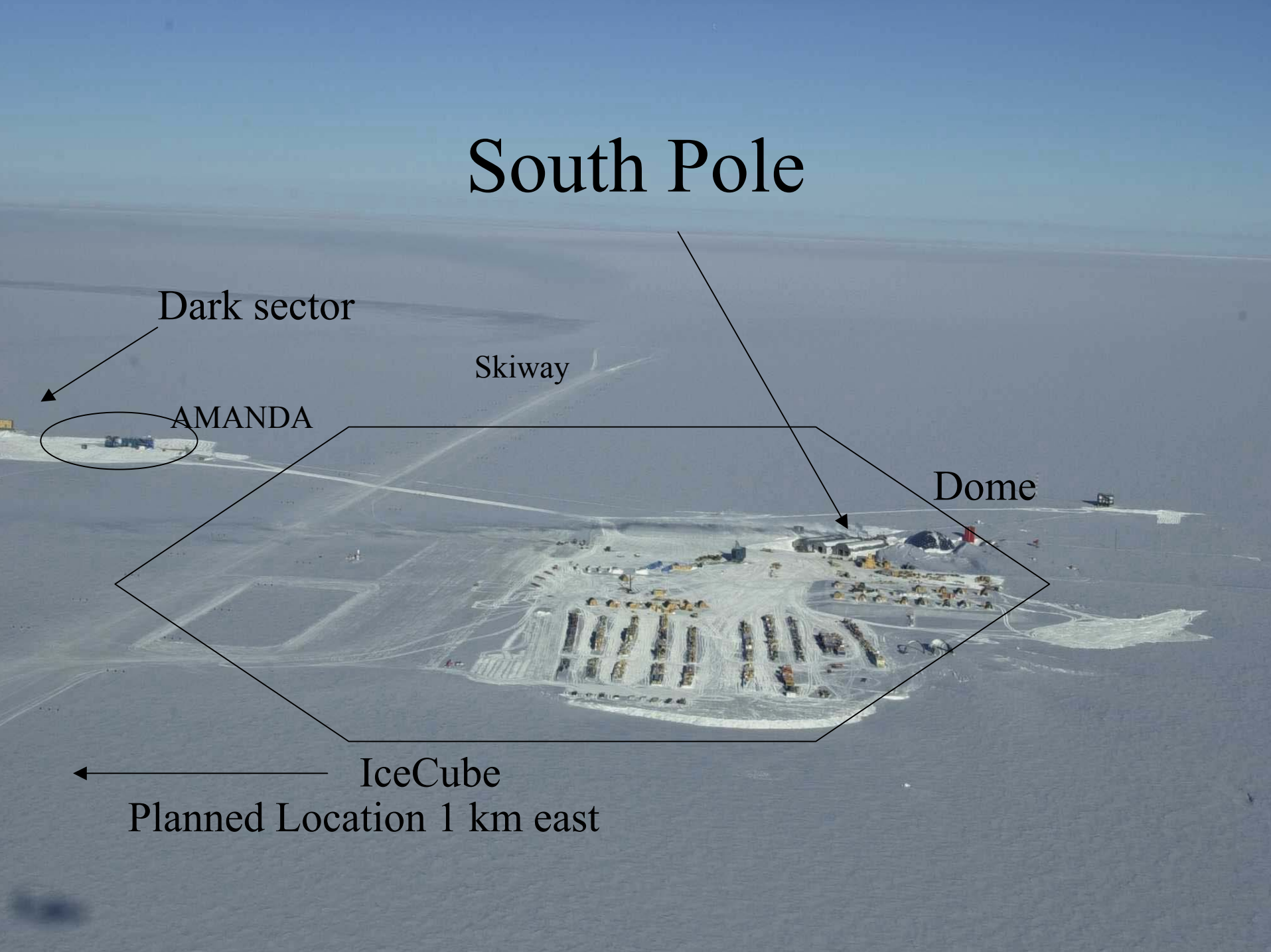


IceCube



- **80 Strings**
- **4800 PMT**
- **Instrumented volume: 1 km3 (1 Gt)**
- **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
Dark sector
Skiway
AMANDA
Dome
IceCube

μ-event in IceCube

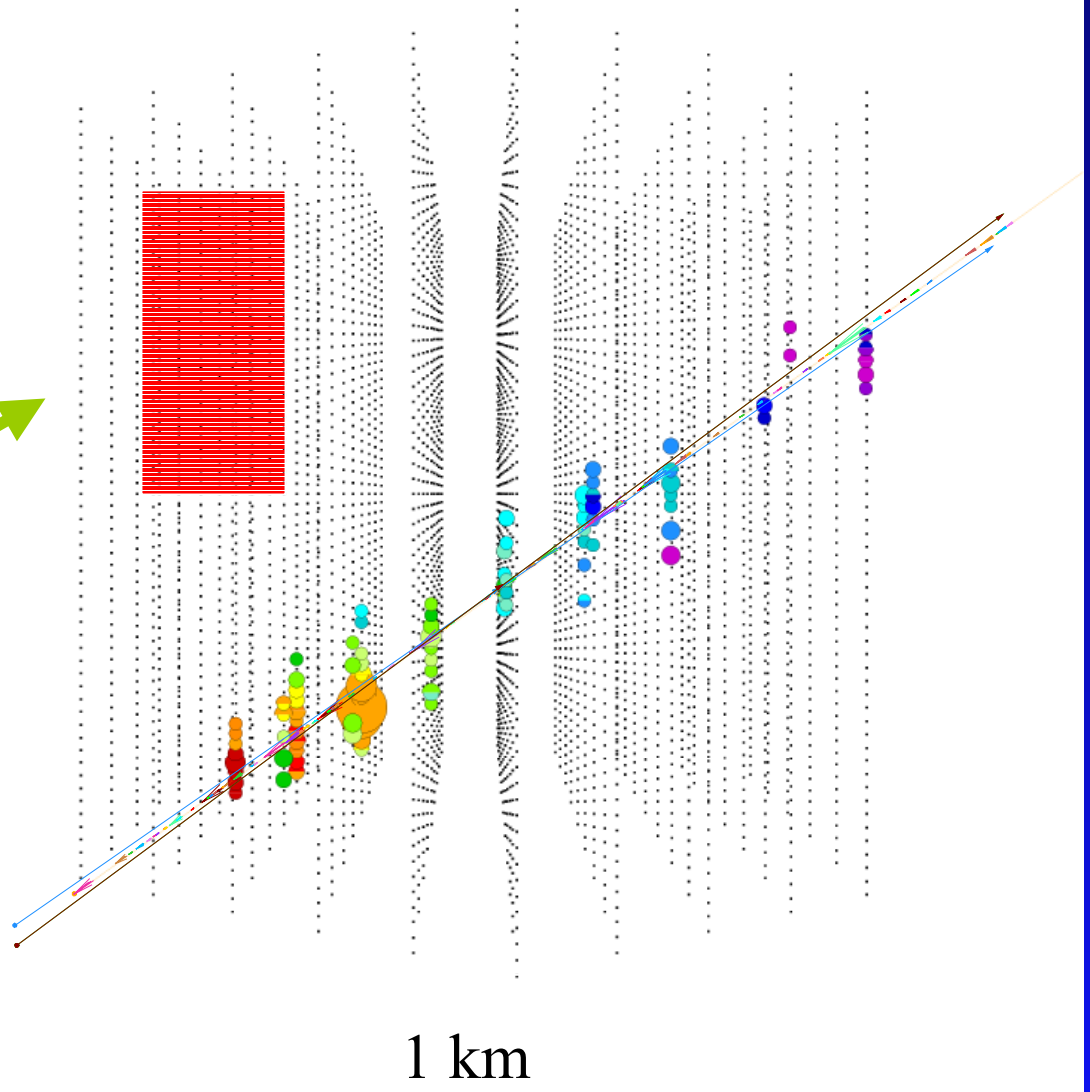
300 atmospheric neutrinos per day

AMANDA II

IceCube:

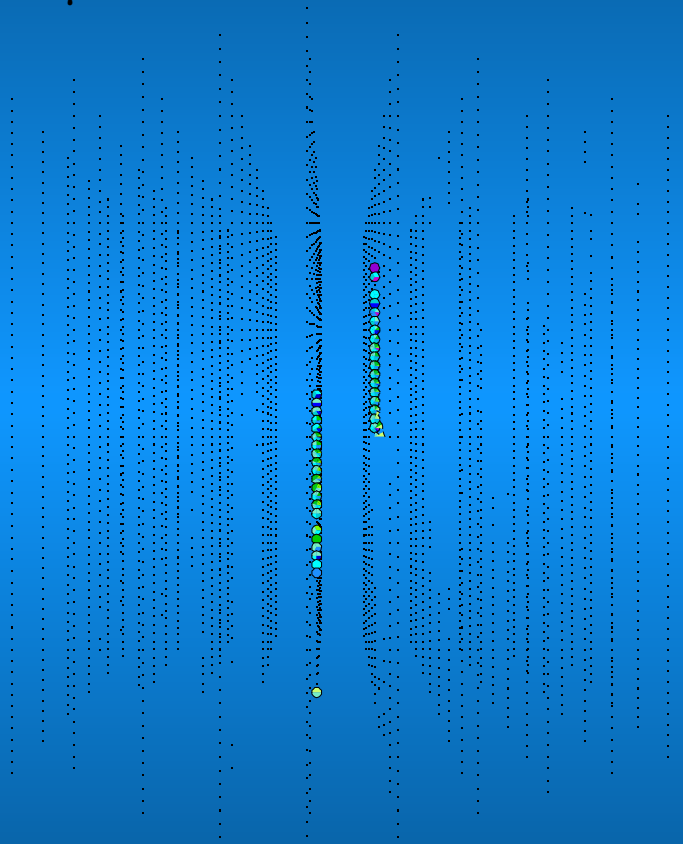
--> Larger telescope

--> Superior detector

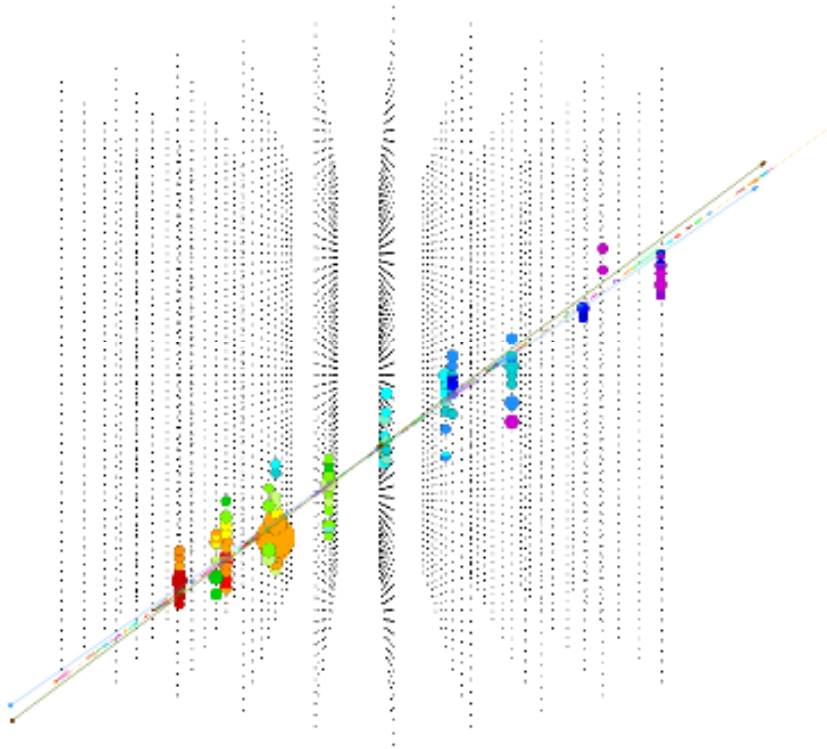


Muon Events

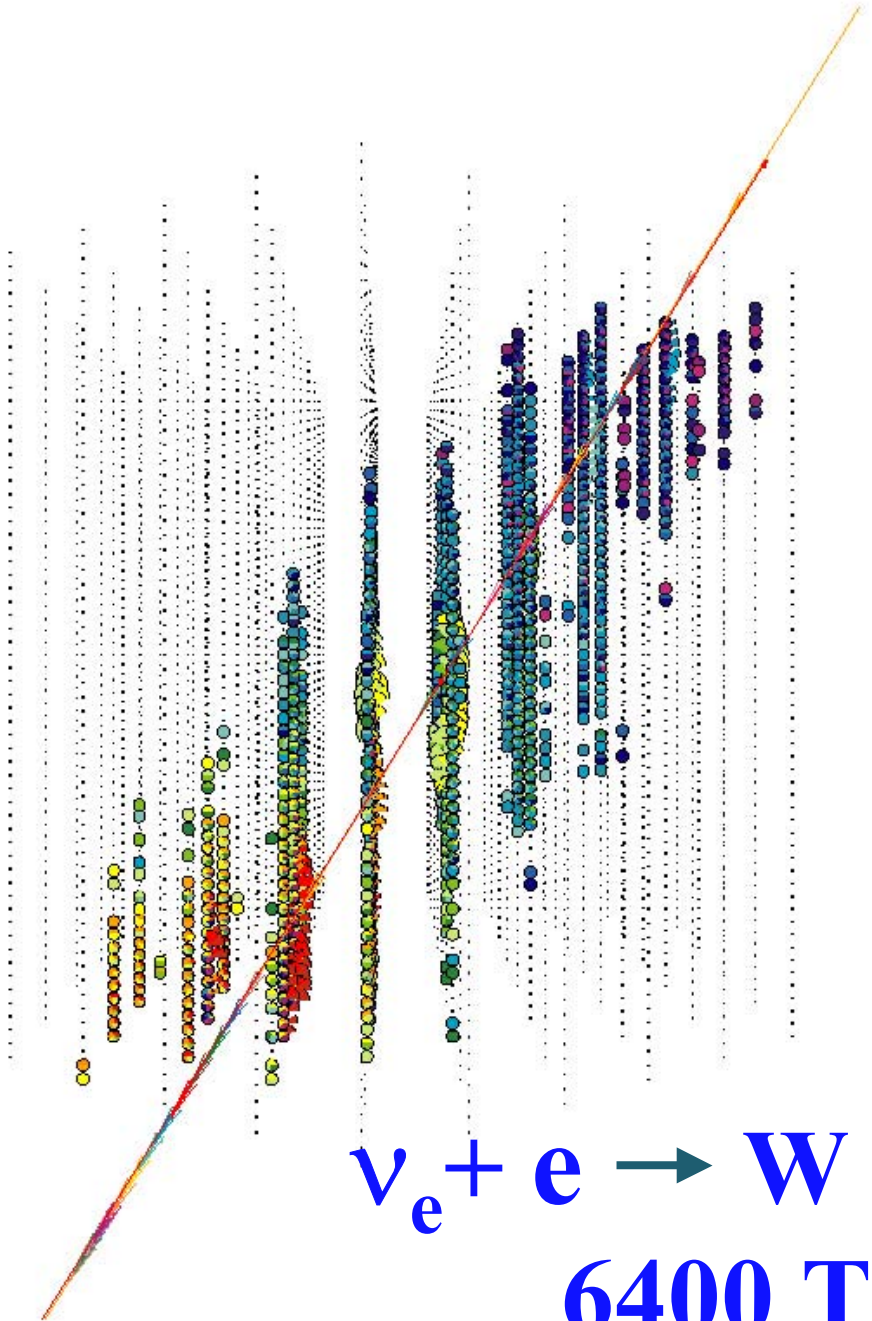
E_μ= 6 PeV



E_μ= 10 TeV



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



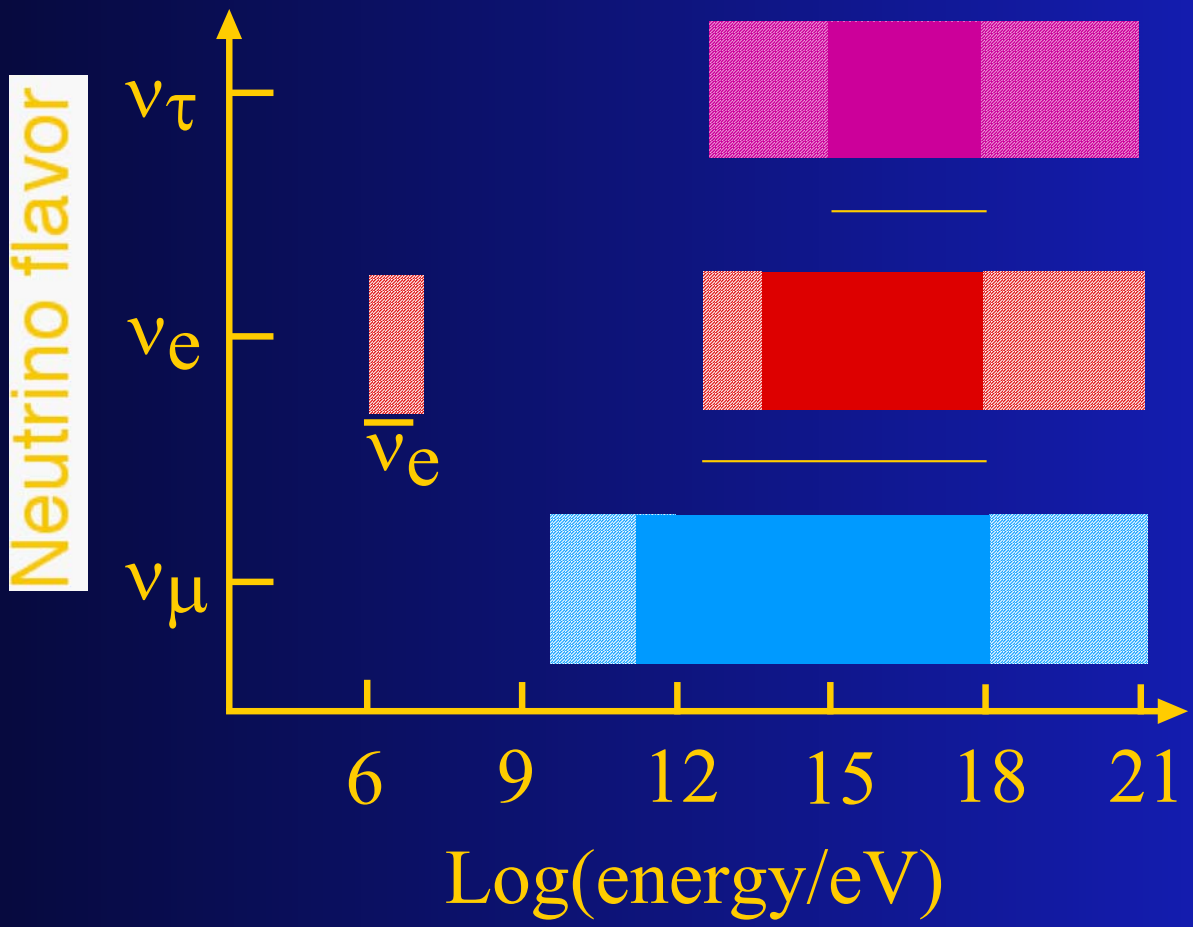
$\nu_e + e \rightarrow W \rightarrow \mu + \nu_\mu$

6400 TeV

Enhanced role of tau neutrinos because of SNO discovery

- 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

Neutrino ID (solid) Energy and angle (shaded)

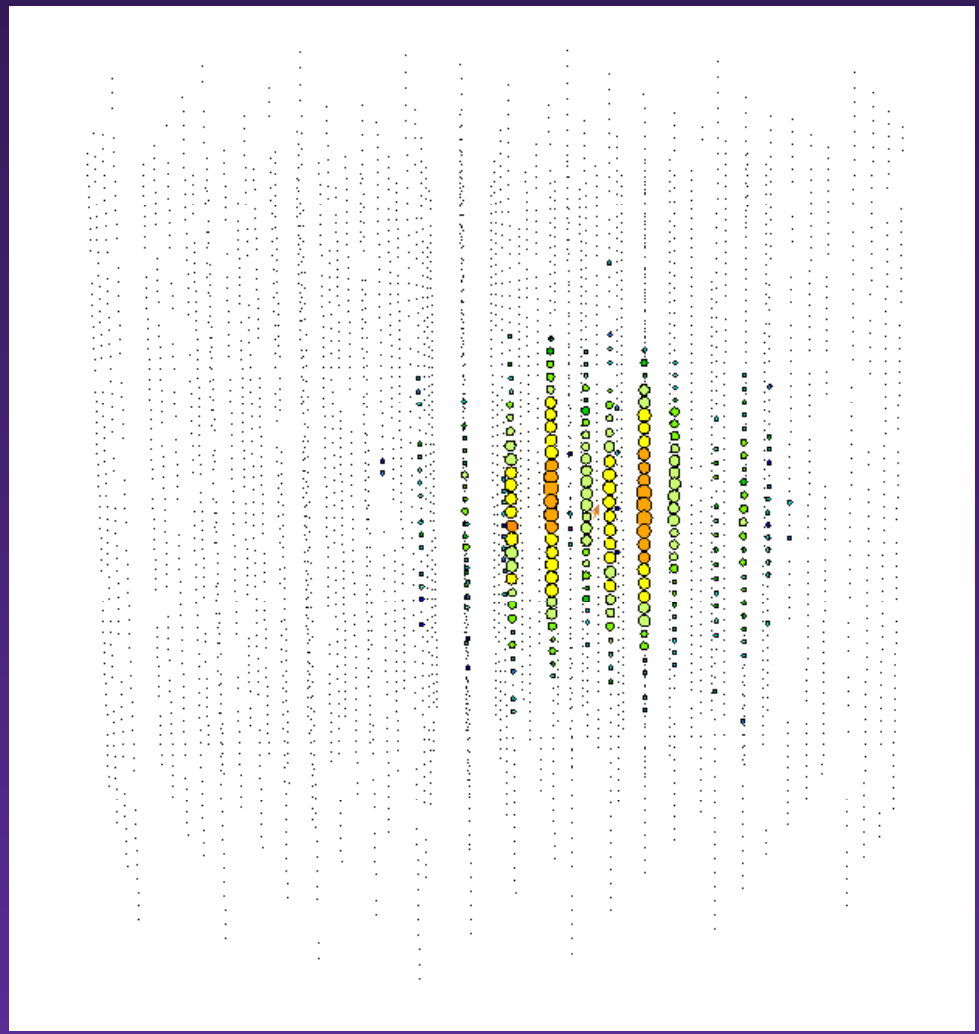


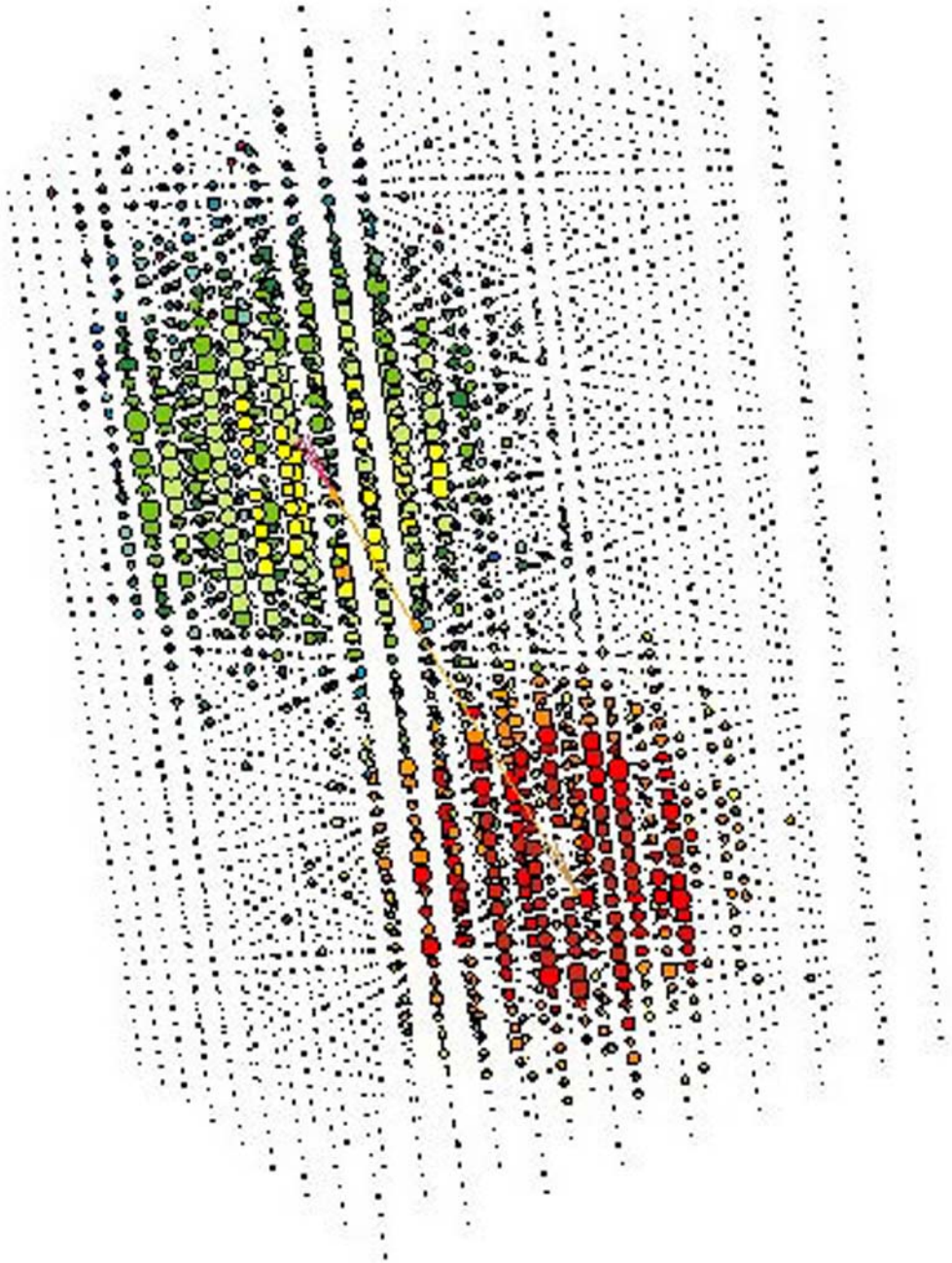
Cascade event

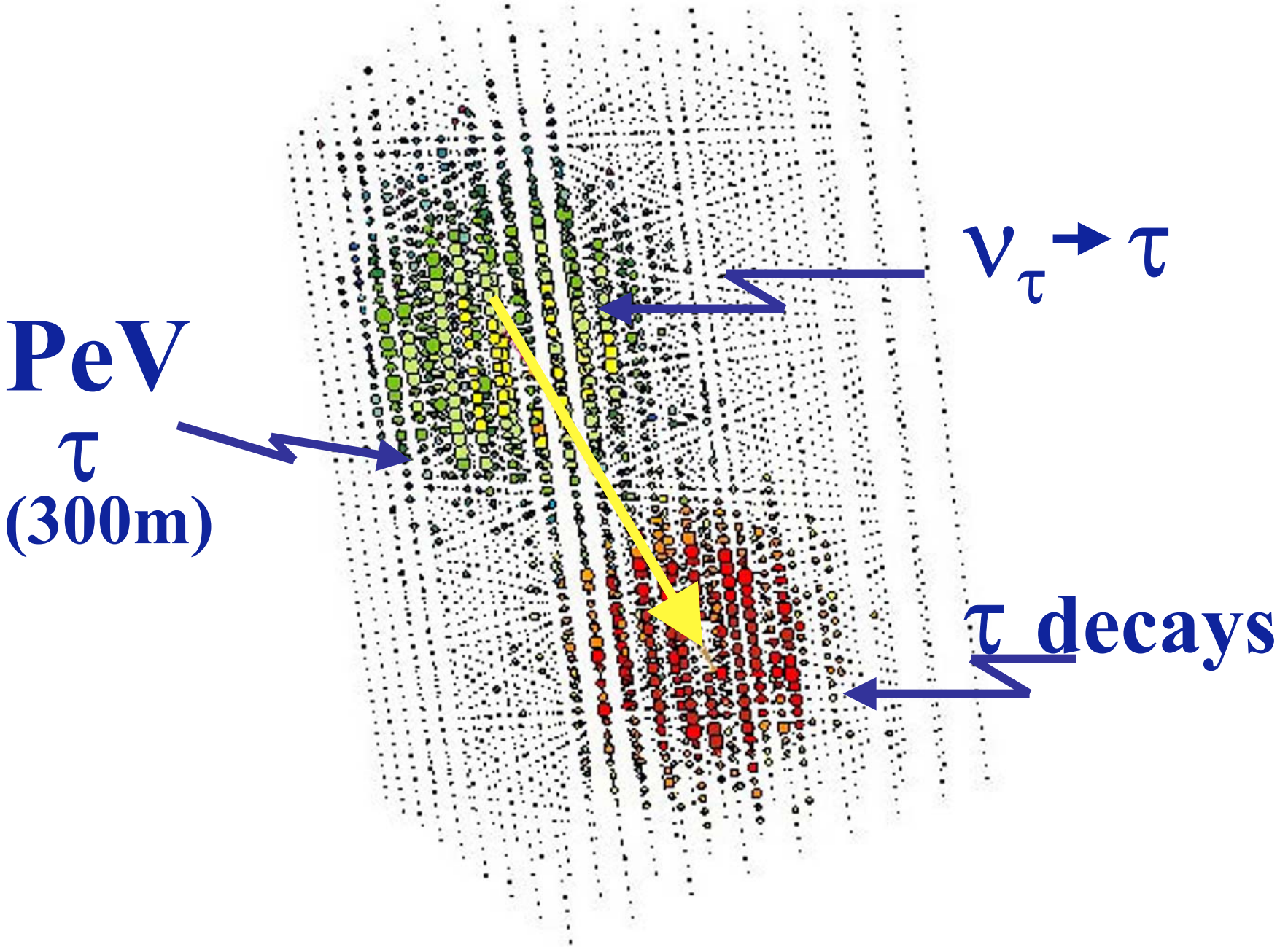
Energy = 375 TeV

$\nu_e + N \rightarrow e^- + X$

- The length of the actual cascade, ≈ 10 m, is small compared to the spacing of sensors
- roughly spherical density distribution of light
- 1 PeV ≈ 500 m diameter
- Local energy deposition = good energy resolution of neutrino energy

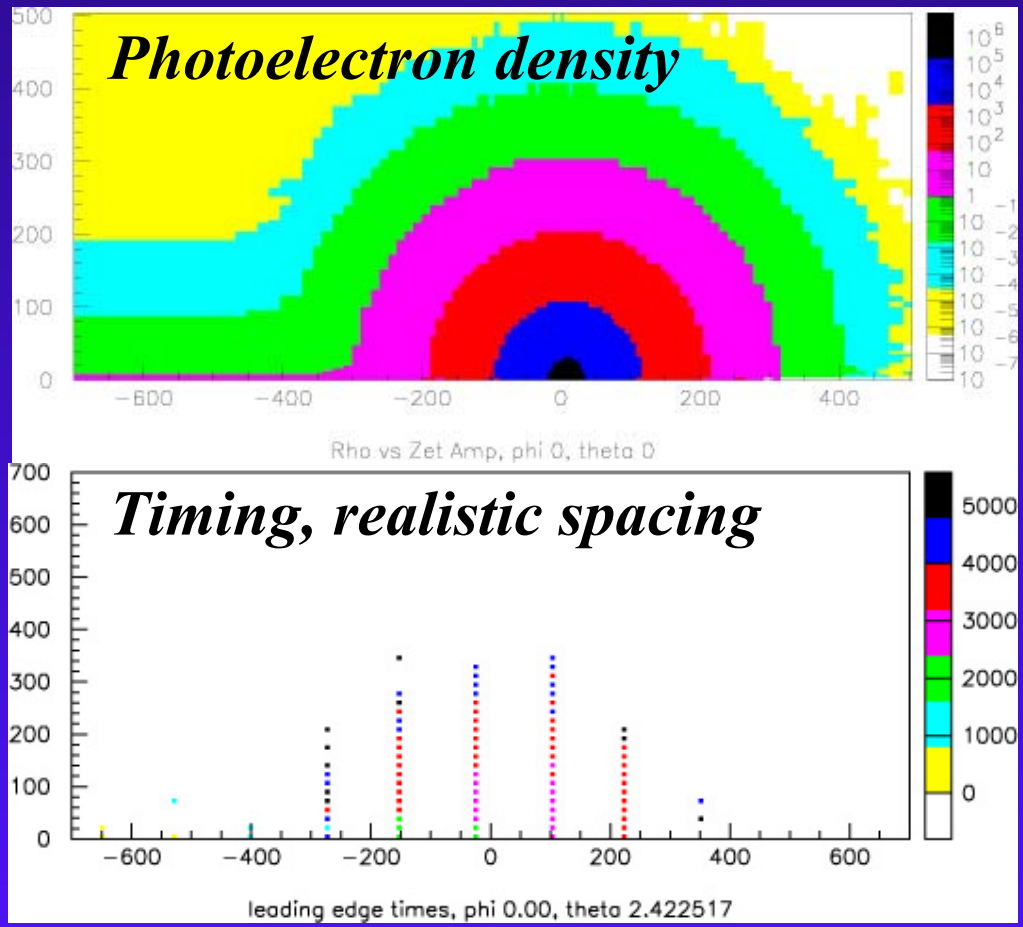





PeV
τ
(300m)
$\nu_\tau \rightarrow \tau$
τ decays

ν_τ at E>PeV: Partially contained

- The incoming tau radiates little light.
- The energy of the second bang can be measured with high precision.
- Clear signature
- Muon Brem would be much brighter than the tau (compare to the PeV muon event shown before)



Result:
high effective volume;
only second bang seen in Ice3

SUMMARY

- **the sky** > 10 GeV photon energy
  < 10^{-14} cm wavelength
- **> 10^{8} TeV particles exist**
  Fly's Eye/Hires
- **they should not**
- **more/better data**
  - → arrays of air Cherenkov telescopes
  - → 10^{4} km^{2} air shower arrays
  - → ~ km^{3} neutrino detectors

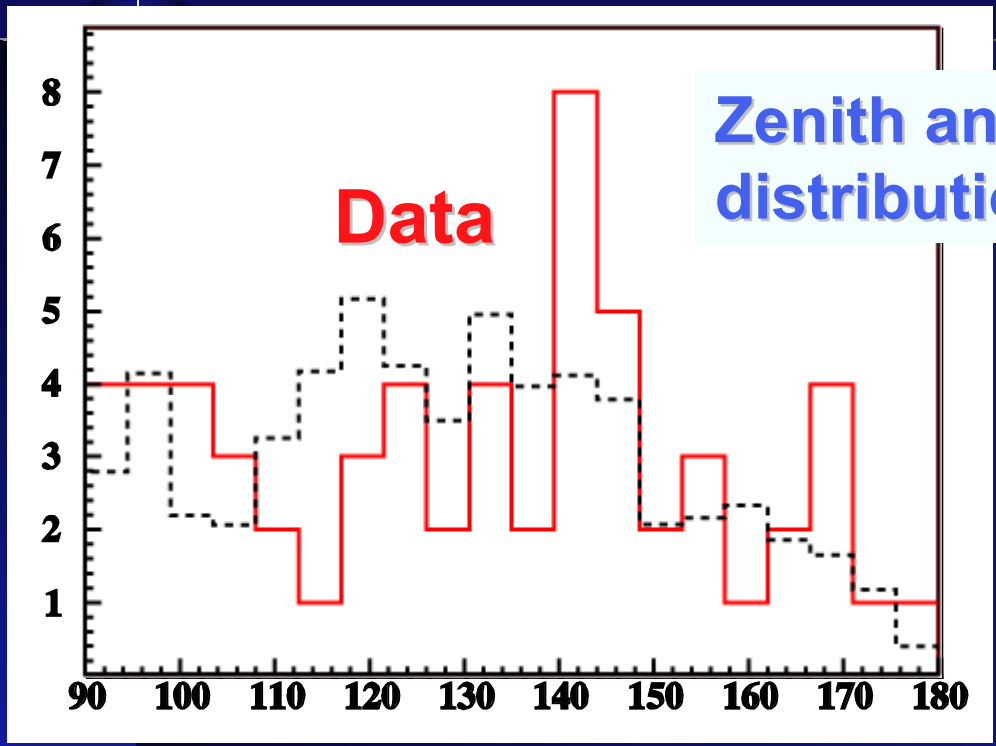
Illustration by Guy Billout

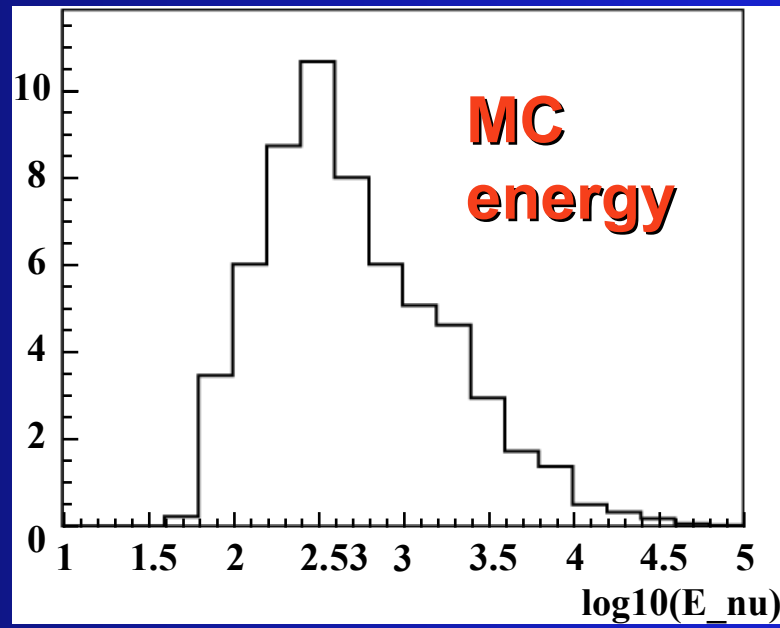
The End

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

- Search for vacuum oscillations ($\nu_\mu \rightarrow \nu_\tau$):
  $\Delta m^2 \gtrsim 10^{-17}\ eV^2$
- Test weak equivalence principle: 10^{-6}
- Test $\dfrac{C_{photon} - C_\nu}{C_\nu}$: 10^{-16}

AMANDA II first look (16 days)





- up to now 10% of 2000 data analysed
- after cuts about 5 ν_μ per day
- cut efficiency improved from AMANDA B10 by 3-5

Average energy ~ 0.3 TeV

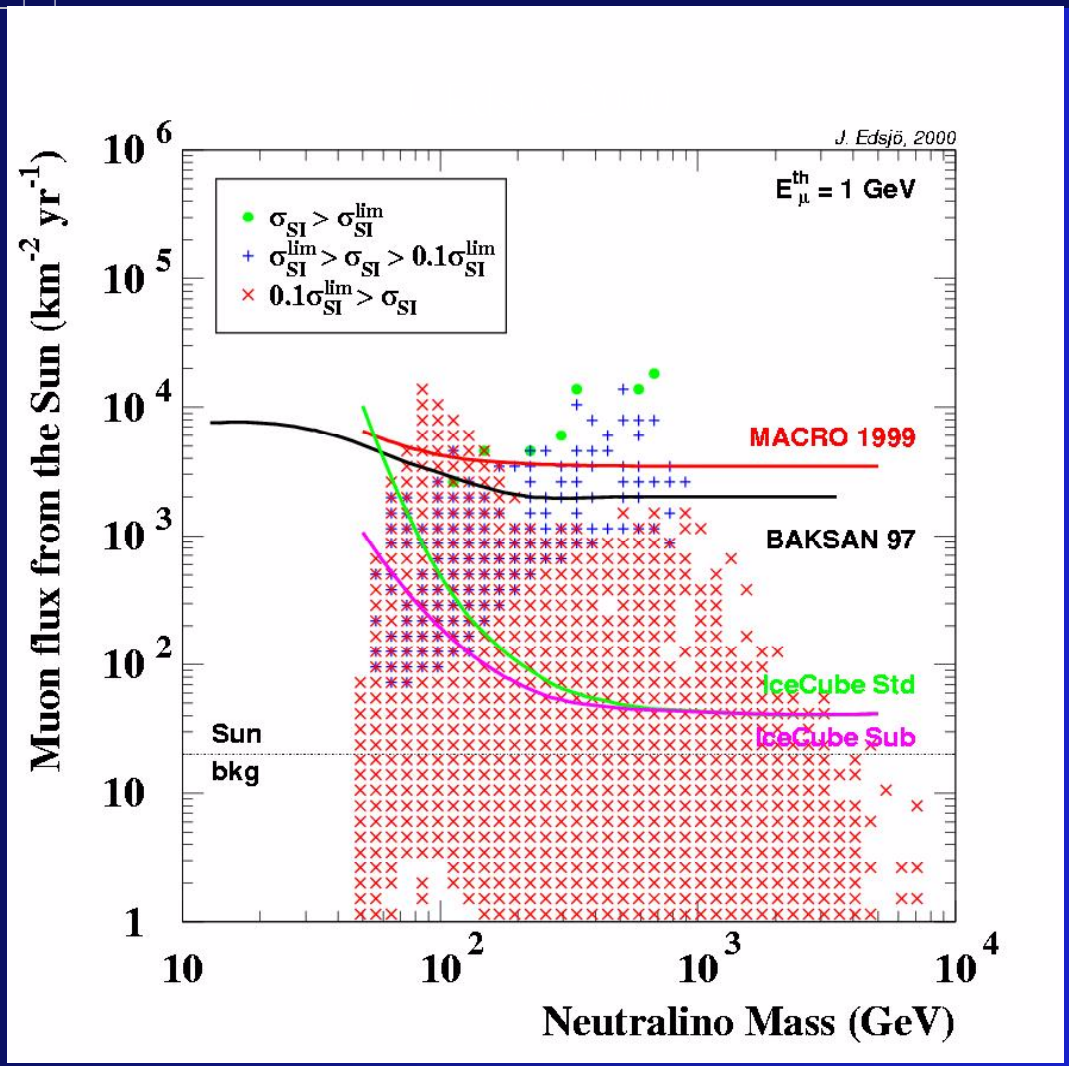
Forthcoming AGASA Results

- The highest energy cosmic rays do come from point sources: 5 sigma correlation between directions of pairs of particles. Birth of proton astronomy!
- Are the highest energy cosmic rays Fe?

  → GKZ cutoff at ~2 10^{20} eV ?

WIMPs from the Sun with IceCube

- Ice^3 will significantly improve the sensitivity.
- Sensitivity comparable to GENIUS,…

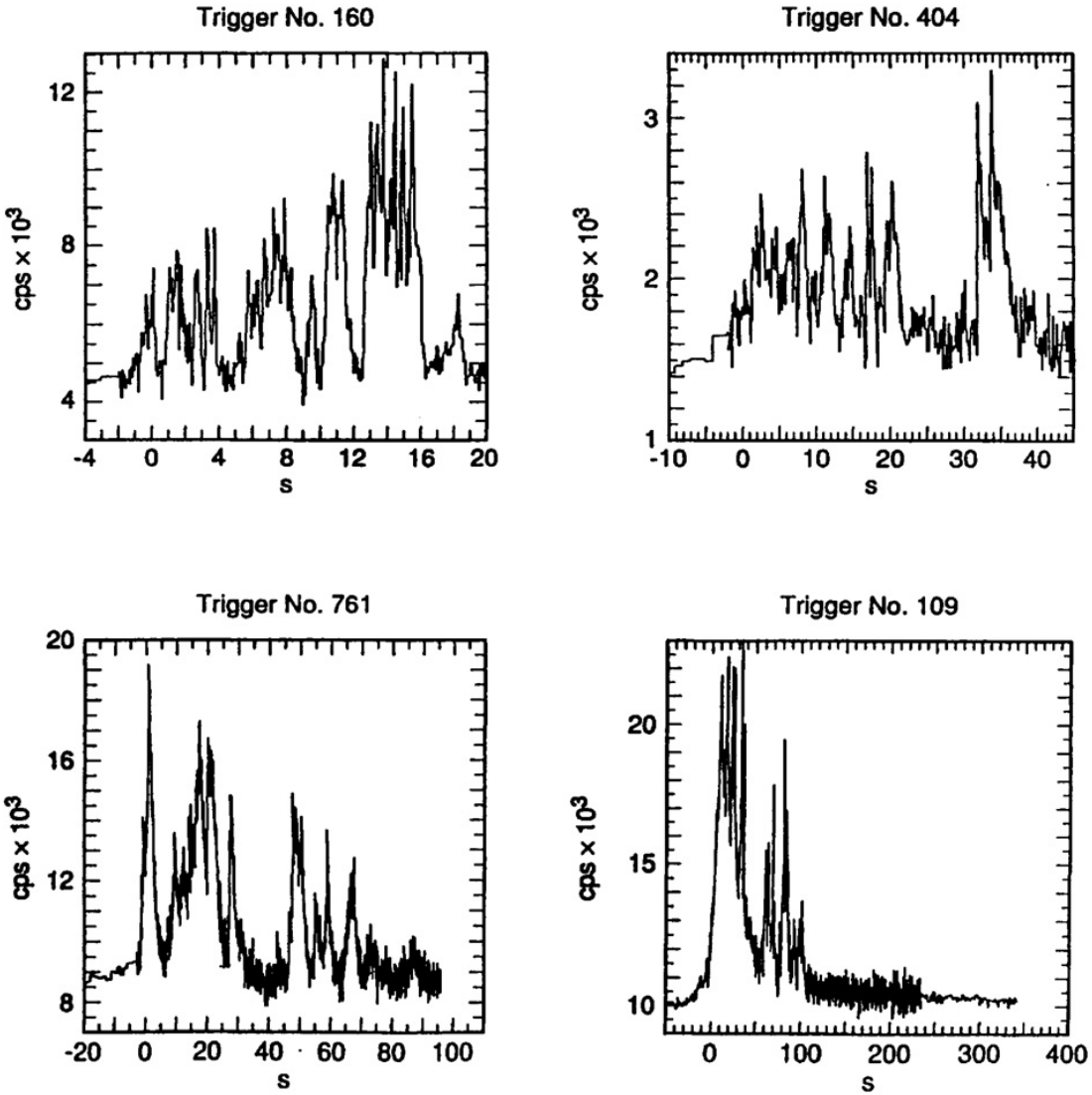


The IceCube Collaboration

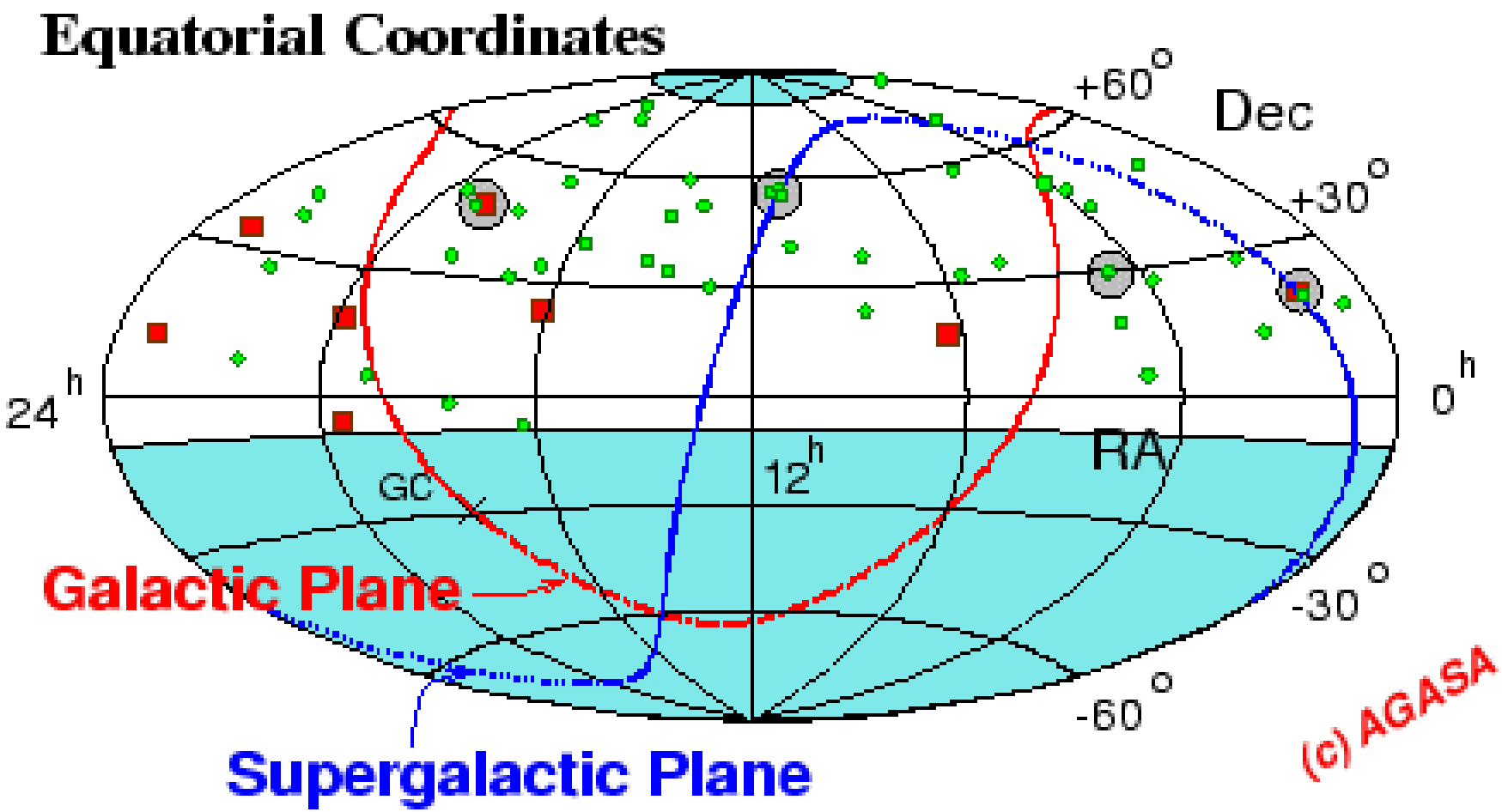
Institutions: 11 US and 9 European institutions
(most of them are also AMANDA member institutions)

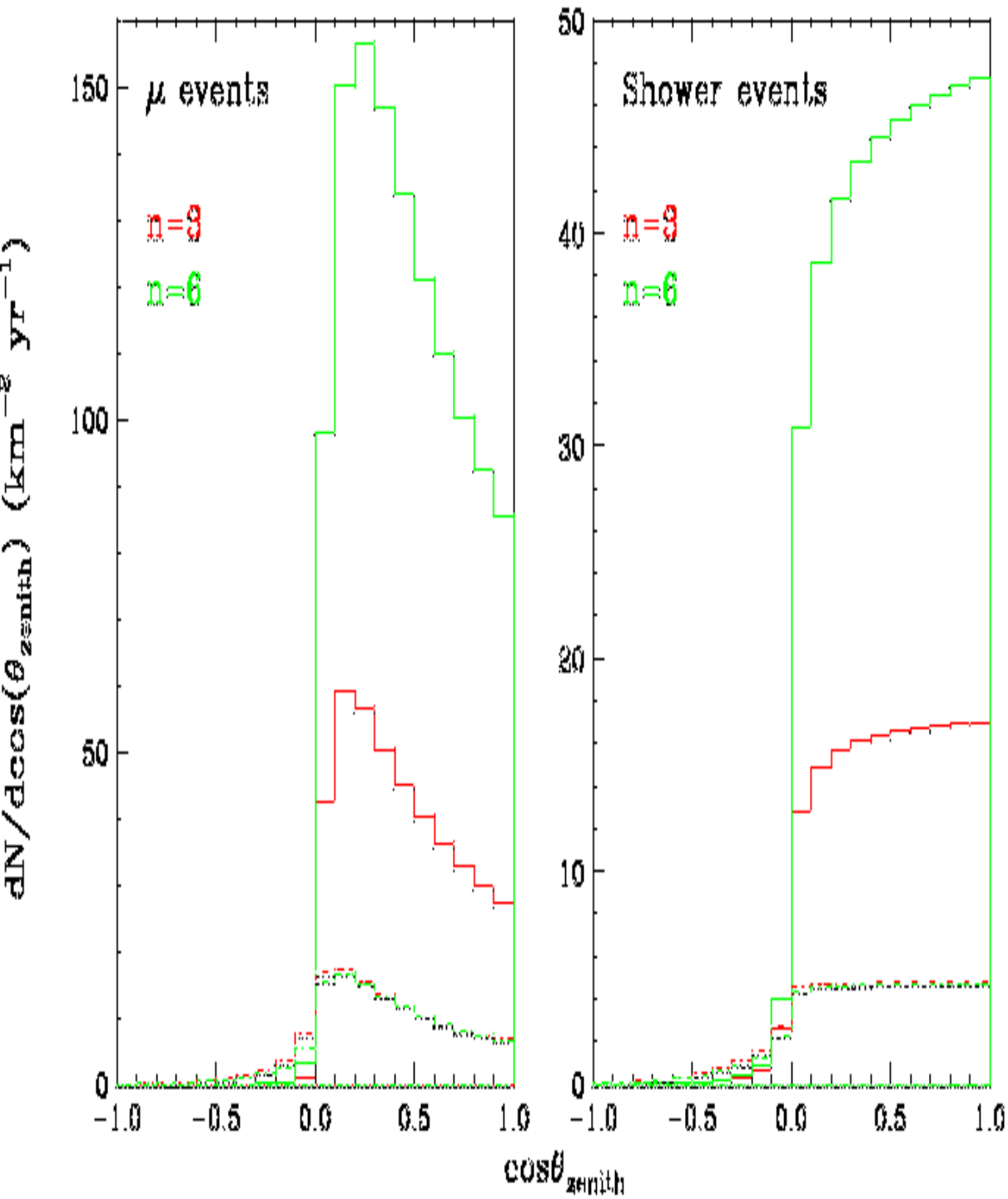
1. Bartol Research Institute, University of Delaware
2. BUGH Wuppertal, Germany
3. Universite Libre de Bruxelles, Brussels, Belgium
4. CTSPS, Clark-Atlanta University, Atlanta USA
5. DESY-Zeuthen, Zeuthen, Germany
6. Institute for Advanced Study, Princeton, USA
7. Dept. of Technology, Kalmar University, Kalmar, Sweden
8. Lawrence Berkeley National Laboratory, Berkeley, USA
9. Department of Physics, Southern University and A\&M College, Baton Rouge, LA, USA
10. Dept. of Physics, UC Berkeley, USA
11. Institute of Physics, University of Mainz, Mainz, Germany
12. Dept. of Physics, University of Maryland, USA
13. University of Mons-Hainaut, Mons, Belgium
14. Dept. of Physics and Astronomy, University of Pennsylvania, Philadelphia, USA
15. Dept. of Astronomy, Dept. of Physics, SSEC, PSL, University of Wisconsin, Madison, USA
16. Physics Department, University of Wisconsin, River Falls, USA
17. Division of High Energy Physics, Uppsala University, Uppsala, Sweden
18. Fysikum, Stockholm University, Stockholm, Sweden
19. University of Alabama, Tuscaloosa, USA
20. Vrije Universiteit Brussel, Brussel, Belgium

Examples of gamma-ray bursts with extremely complex temporal structures



seconds ►


Equatorial Coordinates
+60°
Dec
+30°
24h
0h
RA
12h
GC
-30°
-60°
Galactic Plane
Supergalactic Plane
(c) AGASA

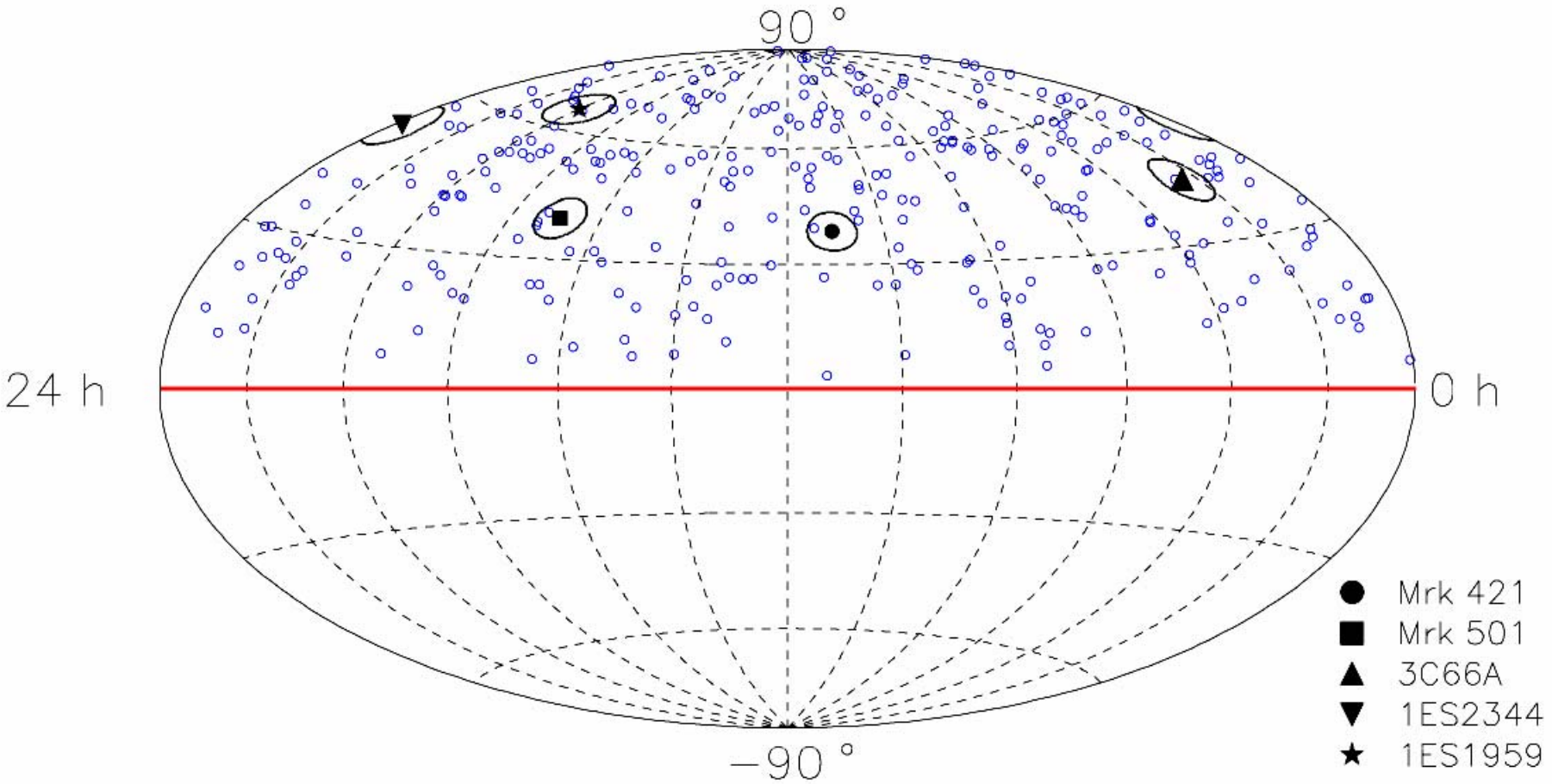

WB bound. Solid=BH, Dashes=SM
μ events
n=3
n=6
Shower events
n=3
n=6
150
100
50
0
50
40
30
20
10
0
-1.0
-0.5
0.0
0.5
1.0
dN/dcos(θzenith) (km-2 yr-1)
cosθzenith

Telescope = Earth's Atmosphere

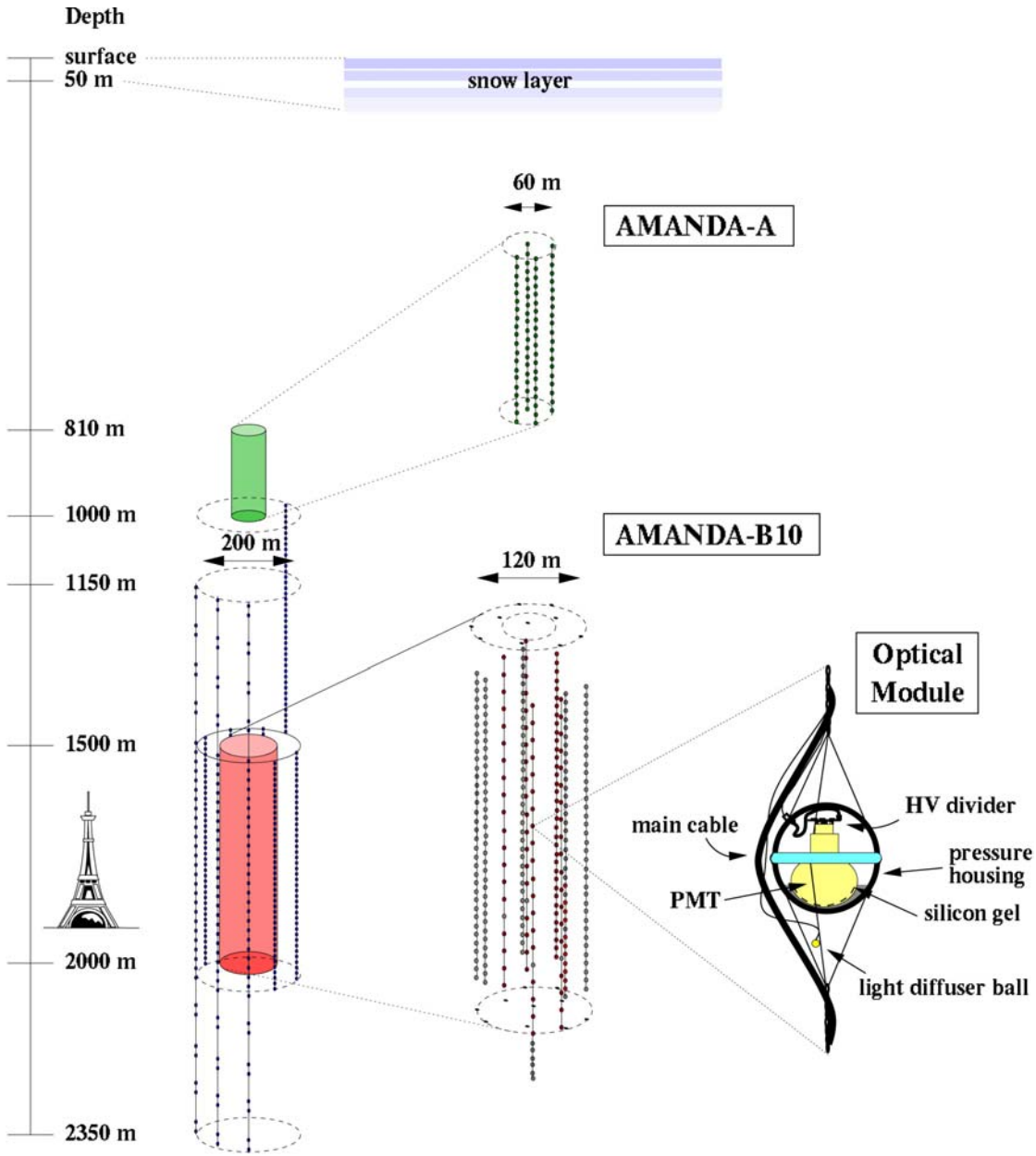
Particle initiates electromagnetic + hadronic cascade detected by:

- **Electron/photon shower**
- **Muon component**
- **Cerenkov radiation**
- **Nitrogen fluorescence**
- **Neutrinos**

Neutrino sky seen by AMANDA




SMITH

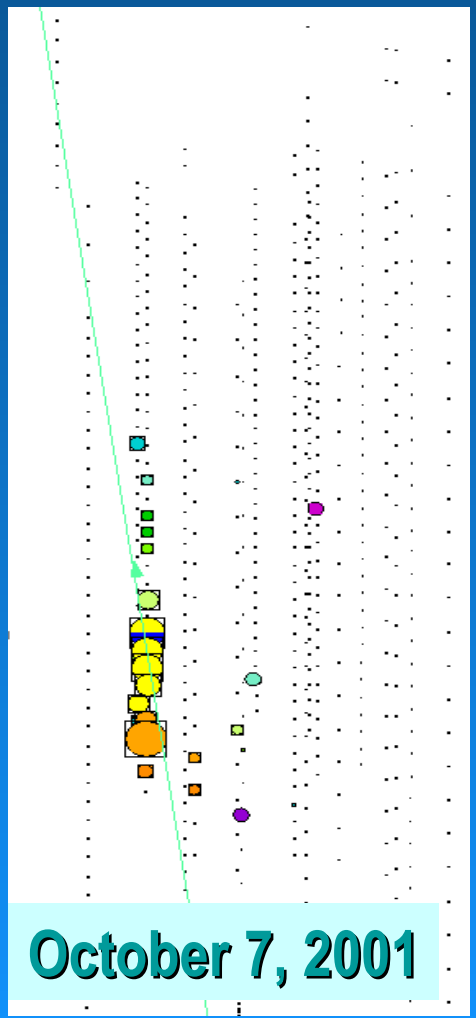


AMANDA as of 2000
Eiffel Tower as comparison
(true scaling)

zoomed in on
AMANDA-A (top)
AMANDA-B10 (bottom)

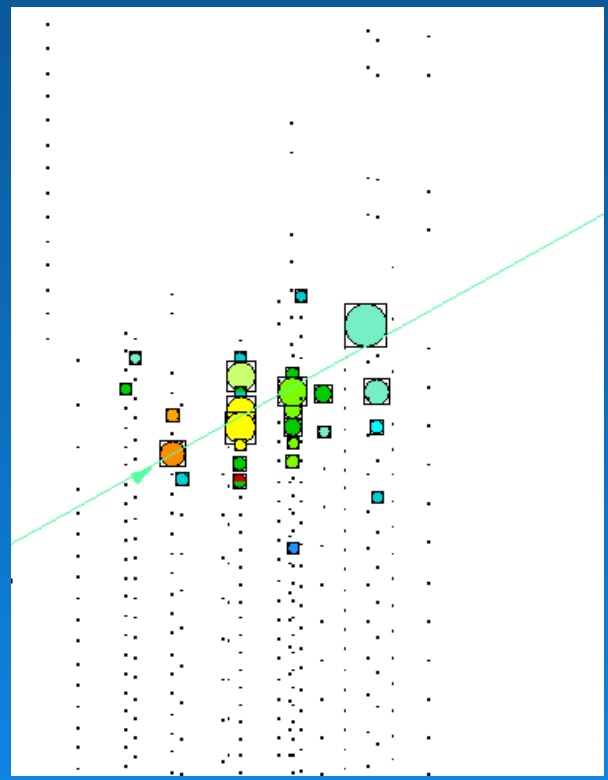
zoomed in on one
optical module (OM)

...online 2001 analysis



October 7, 2001

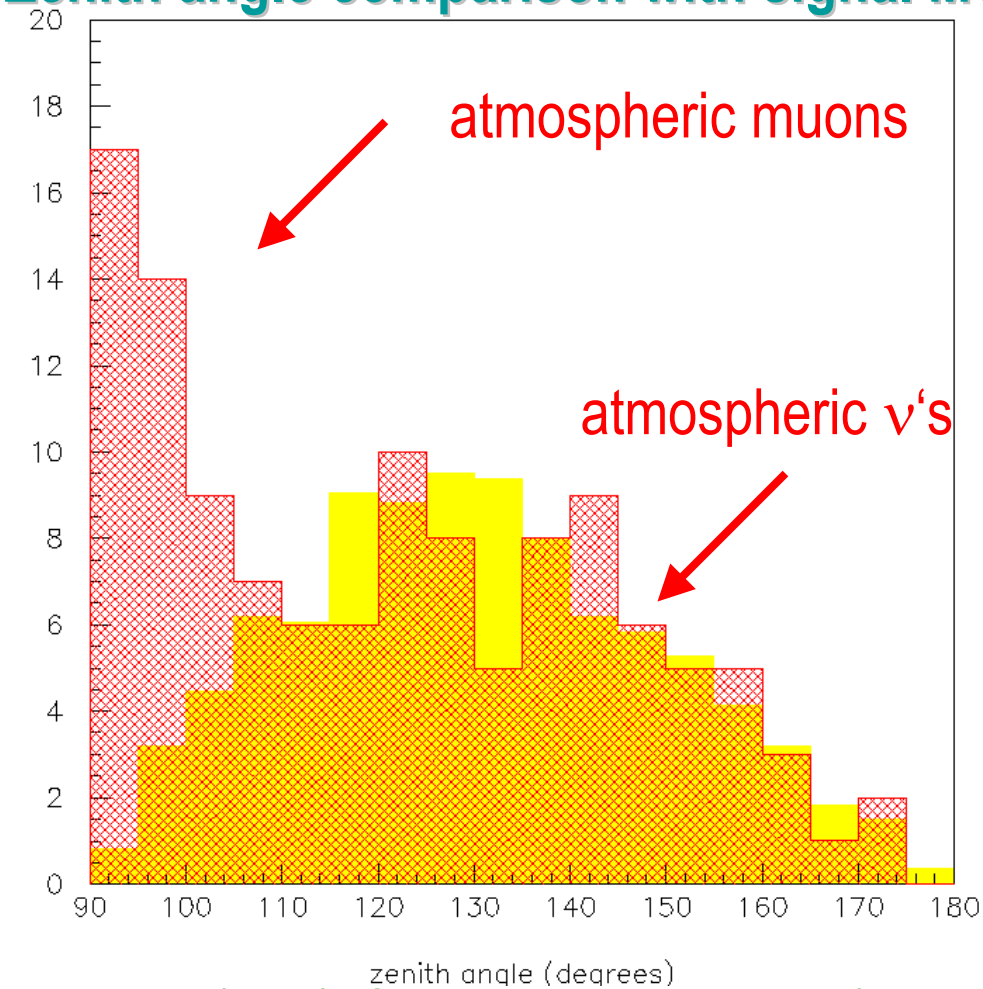
2 recent events



October 10, 2001

...online 2001 analysis

Zenith angle comparison with signal MC



(data/MC normalized above 100°)

- real-time filtering at Pole
- real-time processing (Mainz)

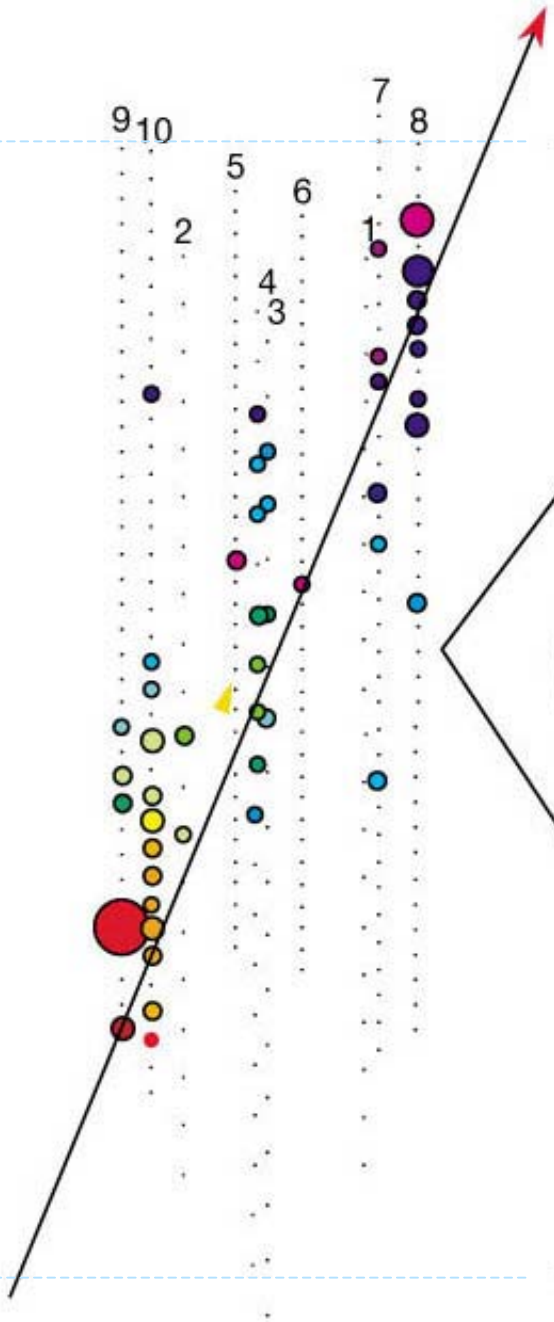
Left plot:

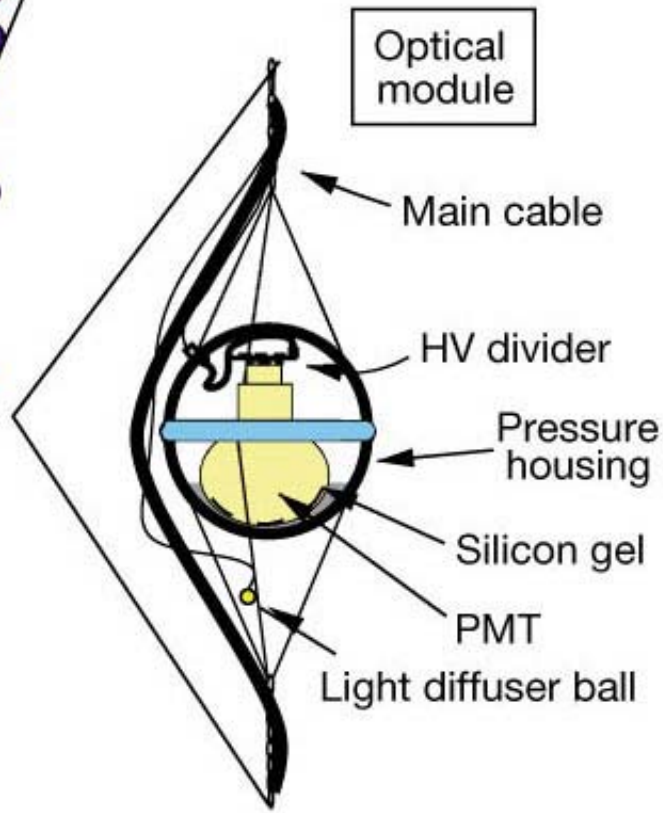
- 20 days (Sept/Oct 2001)
- 90 ν–candidates above 100°

4.5 ν–candidates / day

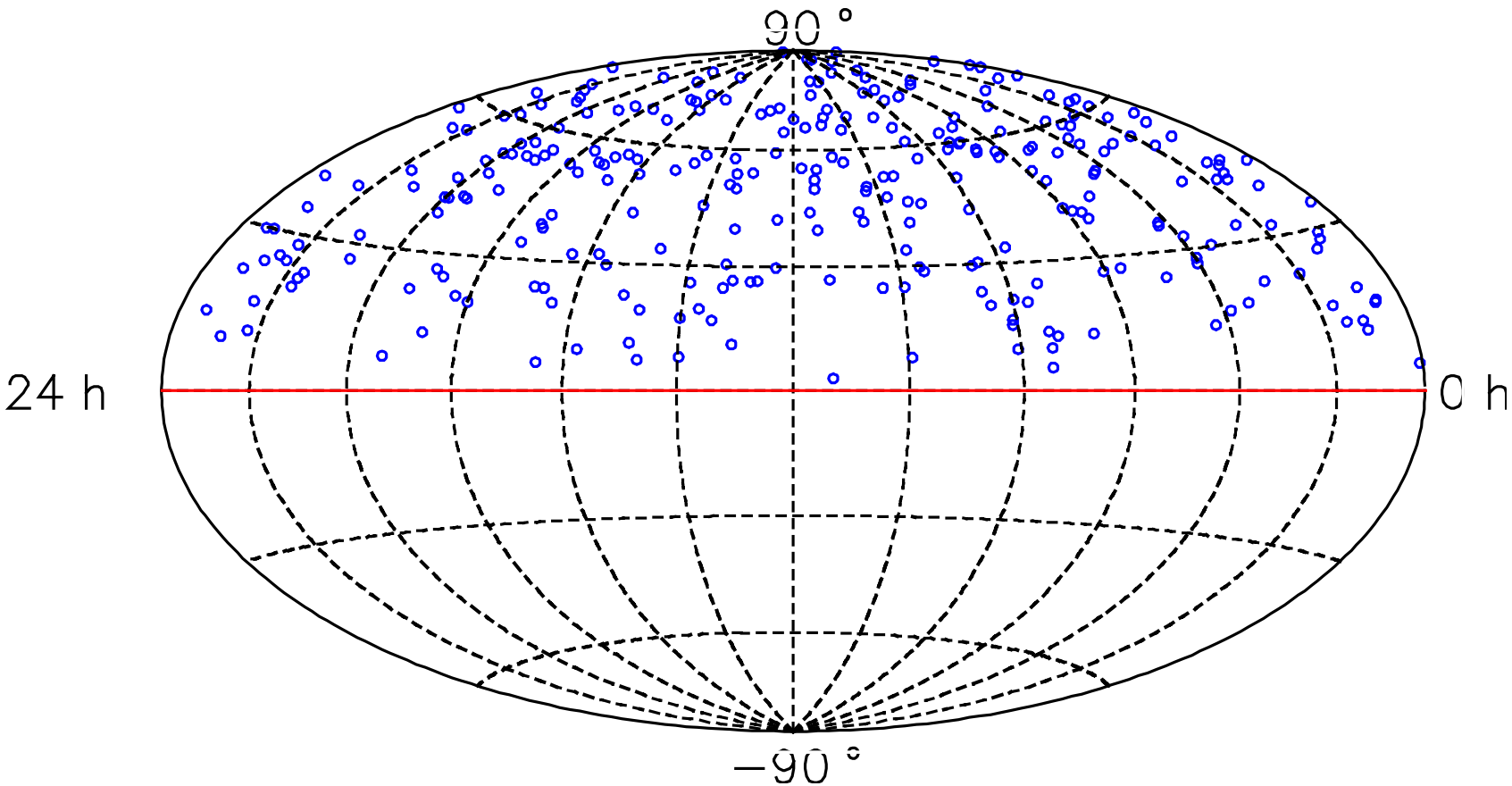
Two Puzzles or One?

- Gamma ray bursts
- Source of the highest energy cosmic rays


9
10
2
5
6
7
8
1
4
3
Depth, 1,500 m
Depth, 2,000 m


Optical module
Main cable
HV divider
Pressure housing
Silicon gel
PMT
Light diffuser ball

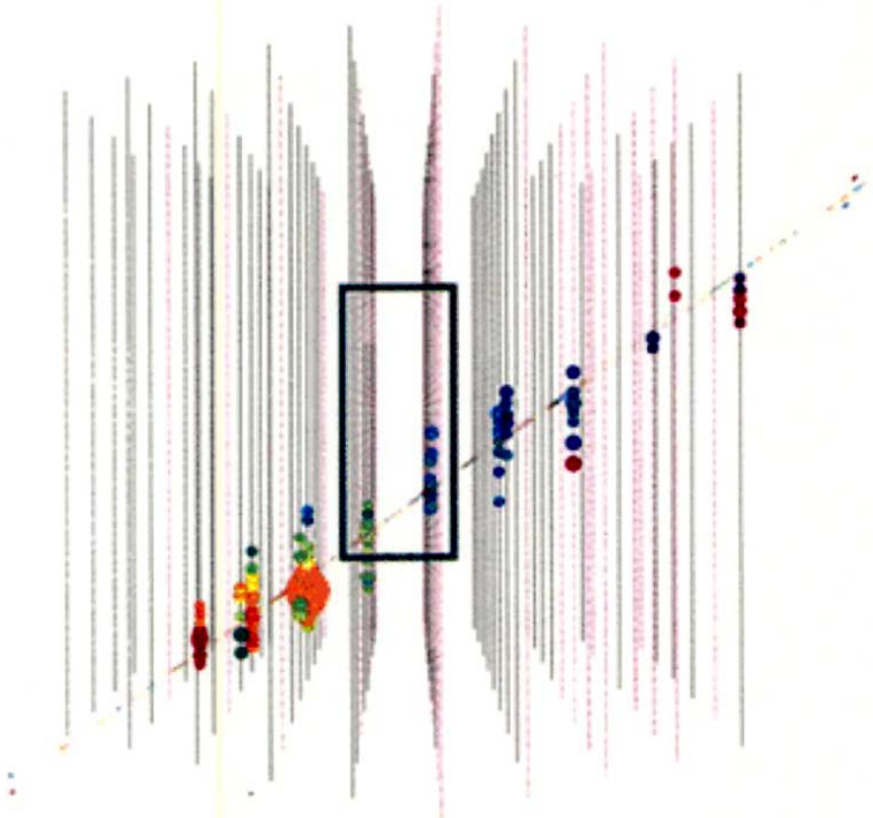
Neutrino sky seen by AMANDA



AMANDA: Proof of Concept

- 80 modules: first nus, Astropart. Phys. 13, 1, 2000
- 302 modules: 97 atmospheric neutrino analysis published; 98, 99 data analysis in progress (1-2 neutrinos per day).
- 677 modules: 01, 02 data analysis in progress (>5 neutrino events per day despite higher threshold)--**scaling of detector verified!**
- Daily nus: extract neutrinos from daily satellite transmissions.

Amanda ⇒ Ice Cube



Amanda-B10

302 OMs

200 ν_{atm} in

130 days

Ice Cube

5000 OMs

250 ν_{atm} per day

Profile of Gamma Ray Bursts

- Total energy: one solar mass
- Photon energy: 0.1 MeV to TeV
- Duration: 0.1 secs -- 20 min
- Several per day
- Brightest object in the sky
- Complicated temporal structure:

  no ‘typical’ burst profile