Neutrino Astronomy

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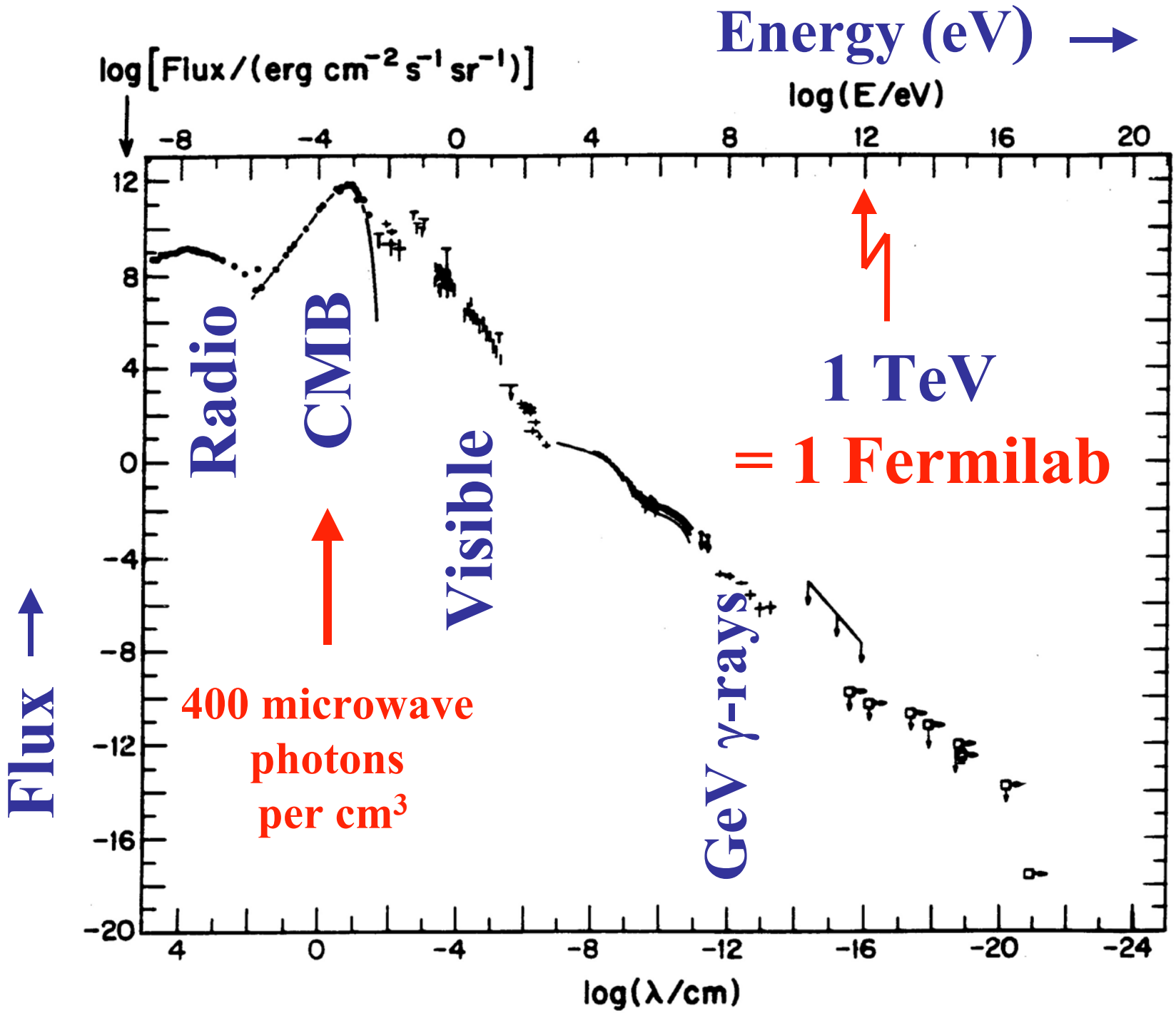
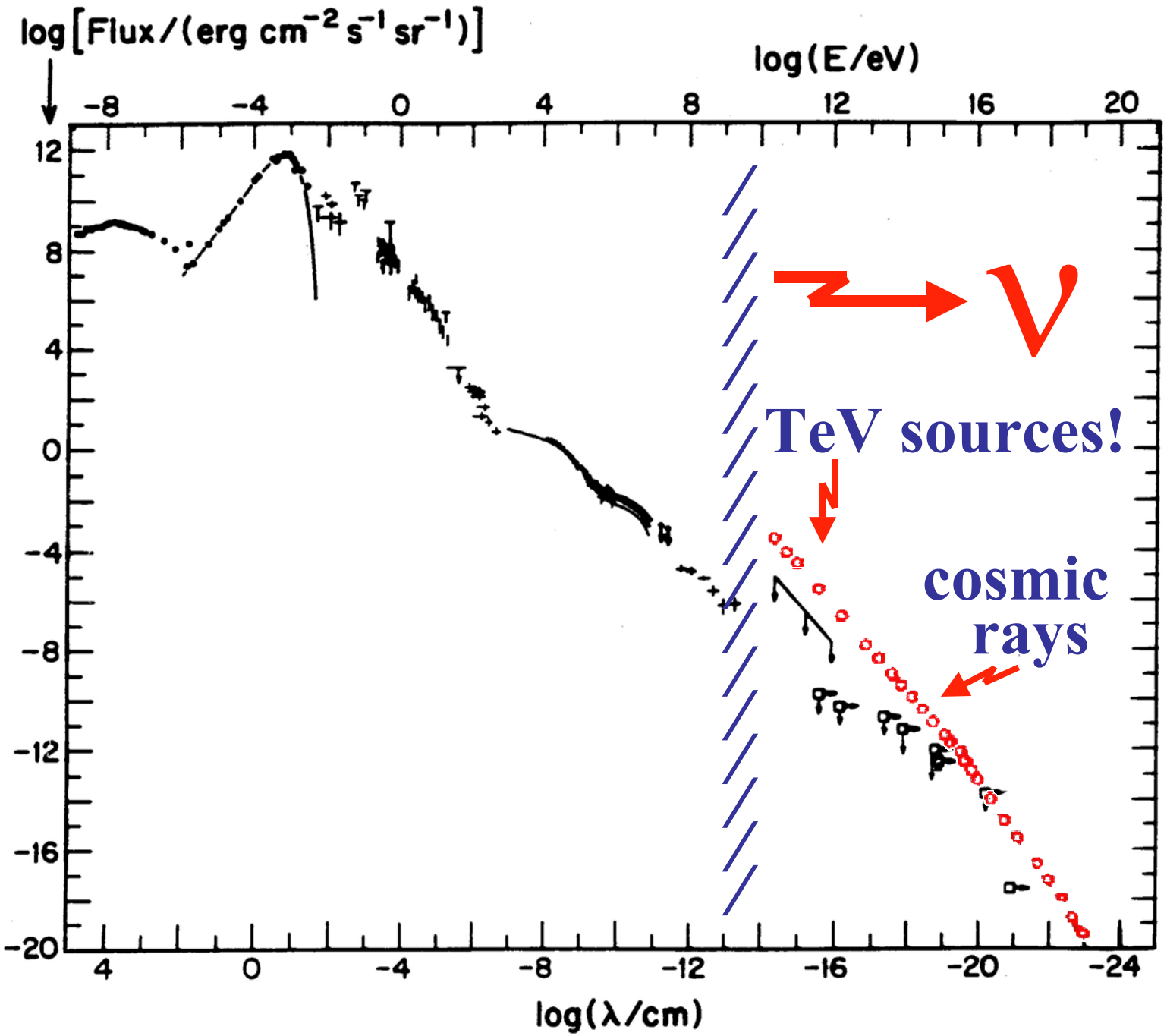
ν astronomy

- **ν astronomy requires kilometer-scale detectors**

- **Proof of concept: AMANDA reaches ~ 0.1 km^2 year**

- **Baikal, ANTARES, NESTOR, RICE…**
  → IceCube, ANITA, NEMO…


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 cm³
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

Multi-Messenger Astronomy

Protons, γ-rays, neutrinos, [gravitational waves] as probes of the high-energy Universe

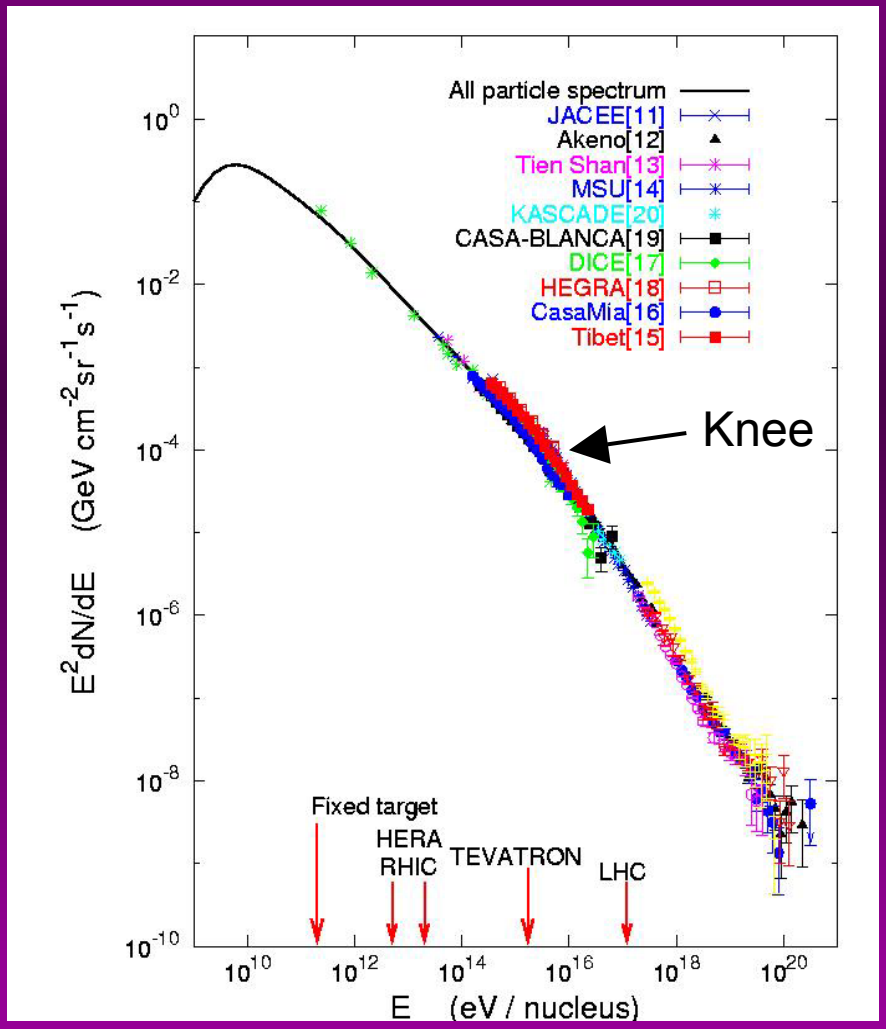
1. Protons: directions scrambled by magnetic fields

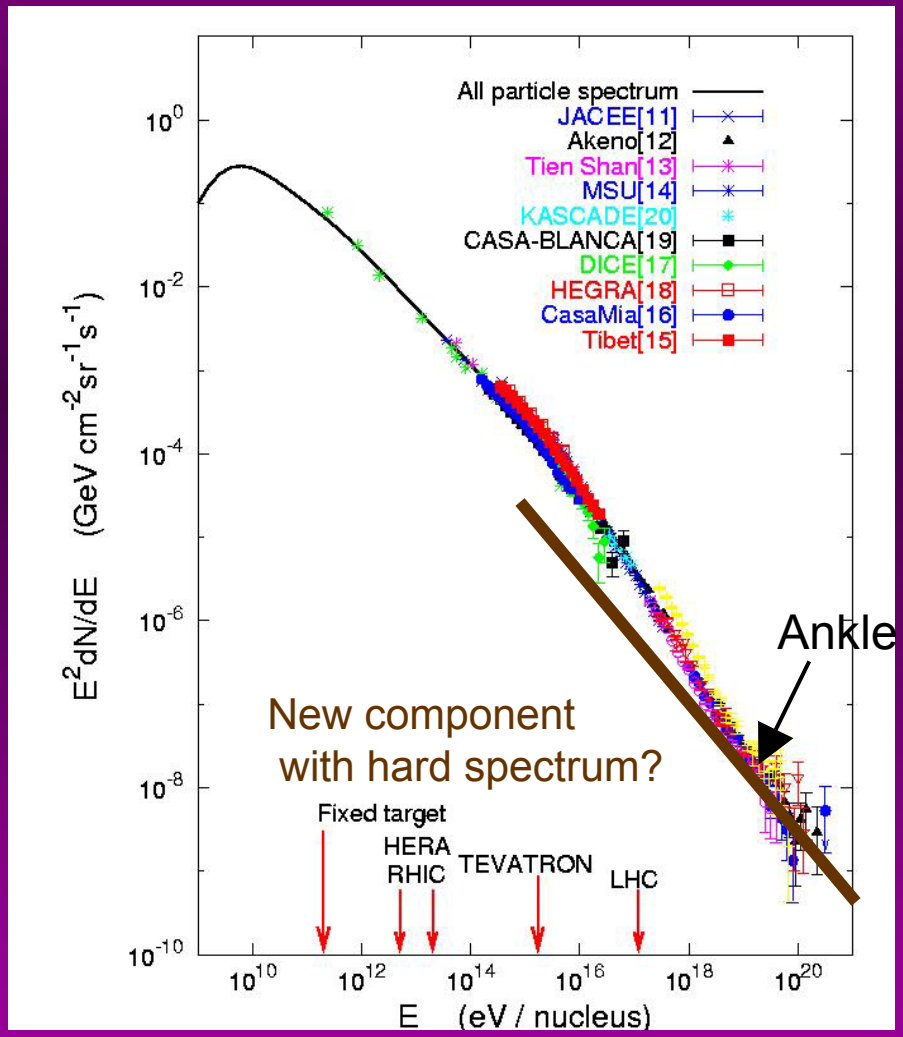
2. **γ-rays** : straight-line propagation but
   reprocessed in the sources
   extragalactic backgrounds absorb Eγ > TeV

3. **Neutrinos**: straight-line propagation,
   unabsorbed, but difficult to detect

cosmic neutrinos associated with cosmic rays

Galactic and Extragalactic Cosmic Rays





Energy in extra-galactic cosmic rays ~ 3×10^{-19} erg/cm^3 or 10^{44} erg/yr per (Mpc)^3 for 10^{10} years

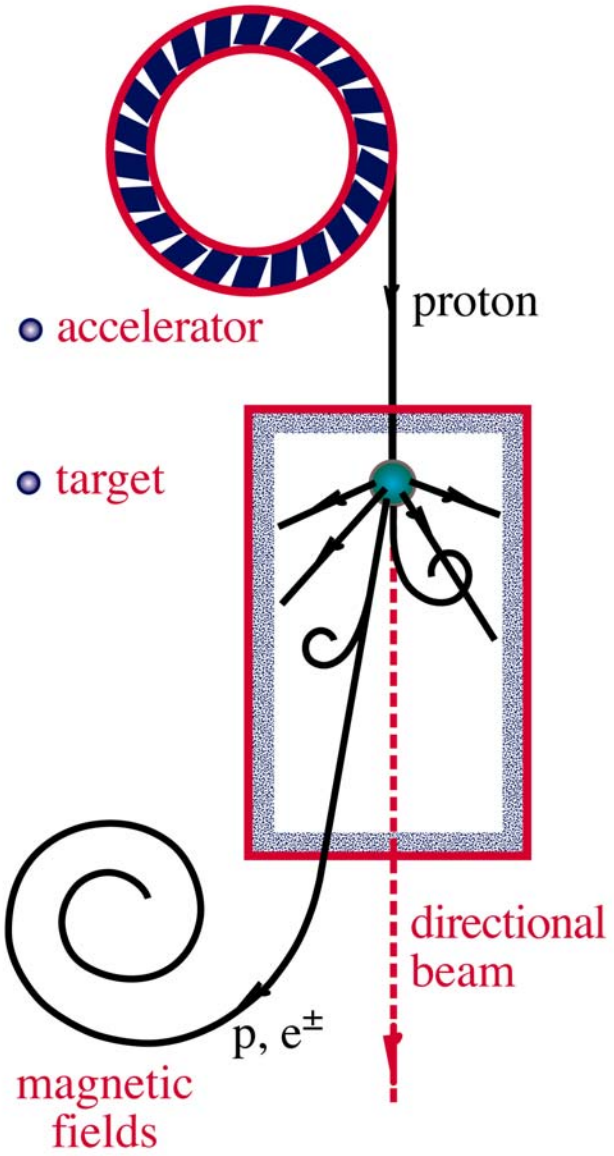
3×10^{39} erg/s per galaxy

3×10^{44} erg/s per active galaxy

2×10^{52} erg per gamma ray burst

1 TeV = 1.6 erg

NEUTRINO BEAMS: HEAVEN & EARTH



→ black hole

→ radiation enveloping black hole

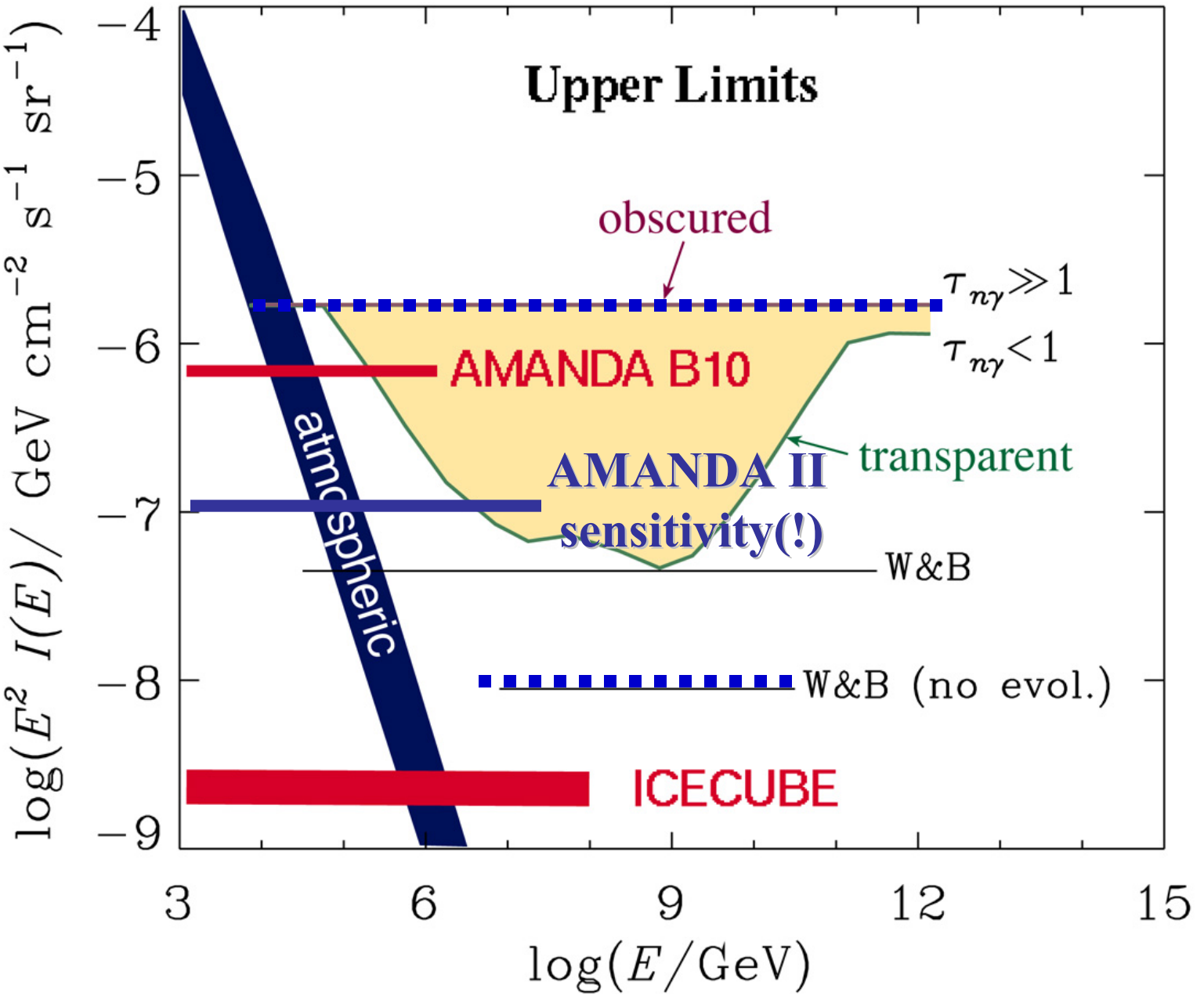
$p + \gamma \rightarrow n + \pi^+$

~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

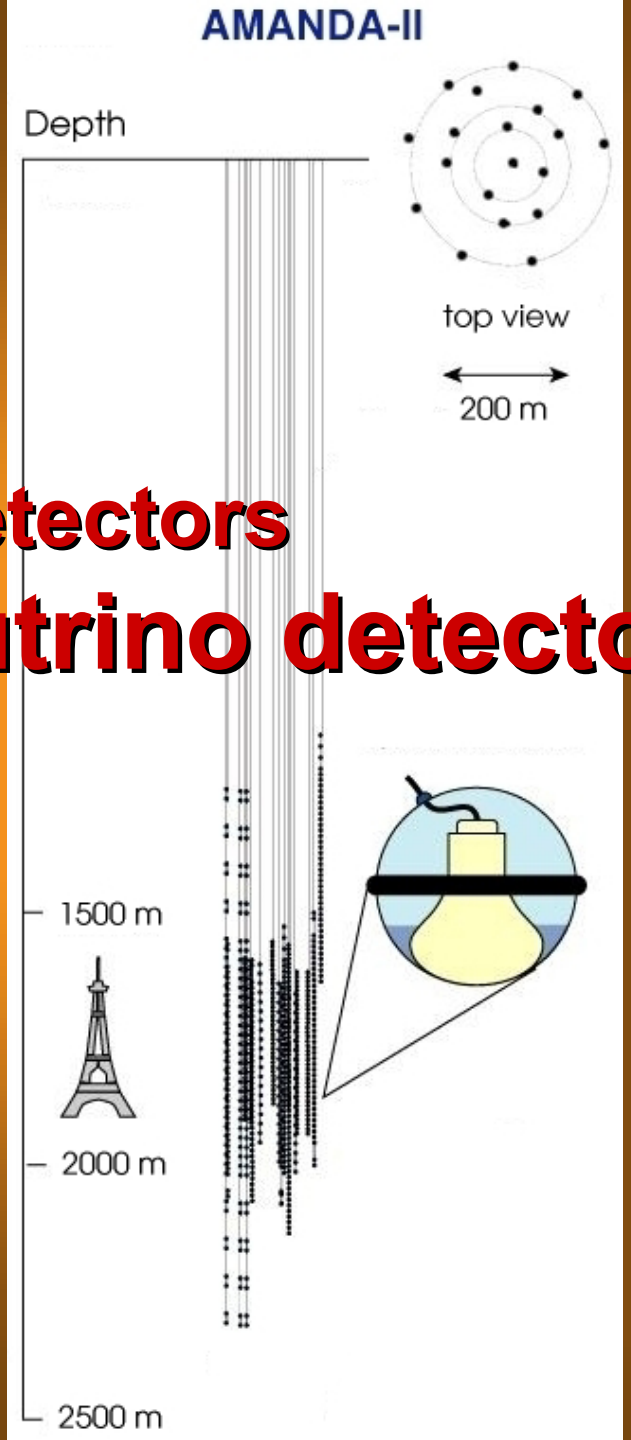
~ cosmic ray + gamma

neutrinos associated with the source of the cosmic rays?



Requires kilometer-scale detectors

neutrino detectors



Alternatively. . . Models of Cosmic Rays

Bottom up

- GRB fireballs
- Jets in active galaxies
- Accretion shocks in galaxy clusters
- Galaxy mergers
- Young supernova remnants
- Pulsars, Magnetars
- Mini-quasars
- …

• Observed showers either protons (or nuclei)

Top-down

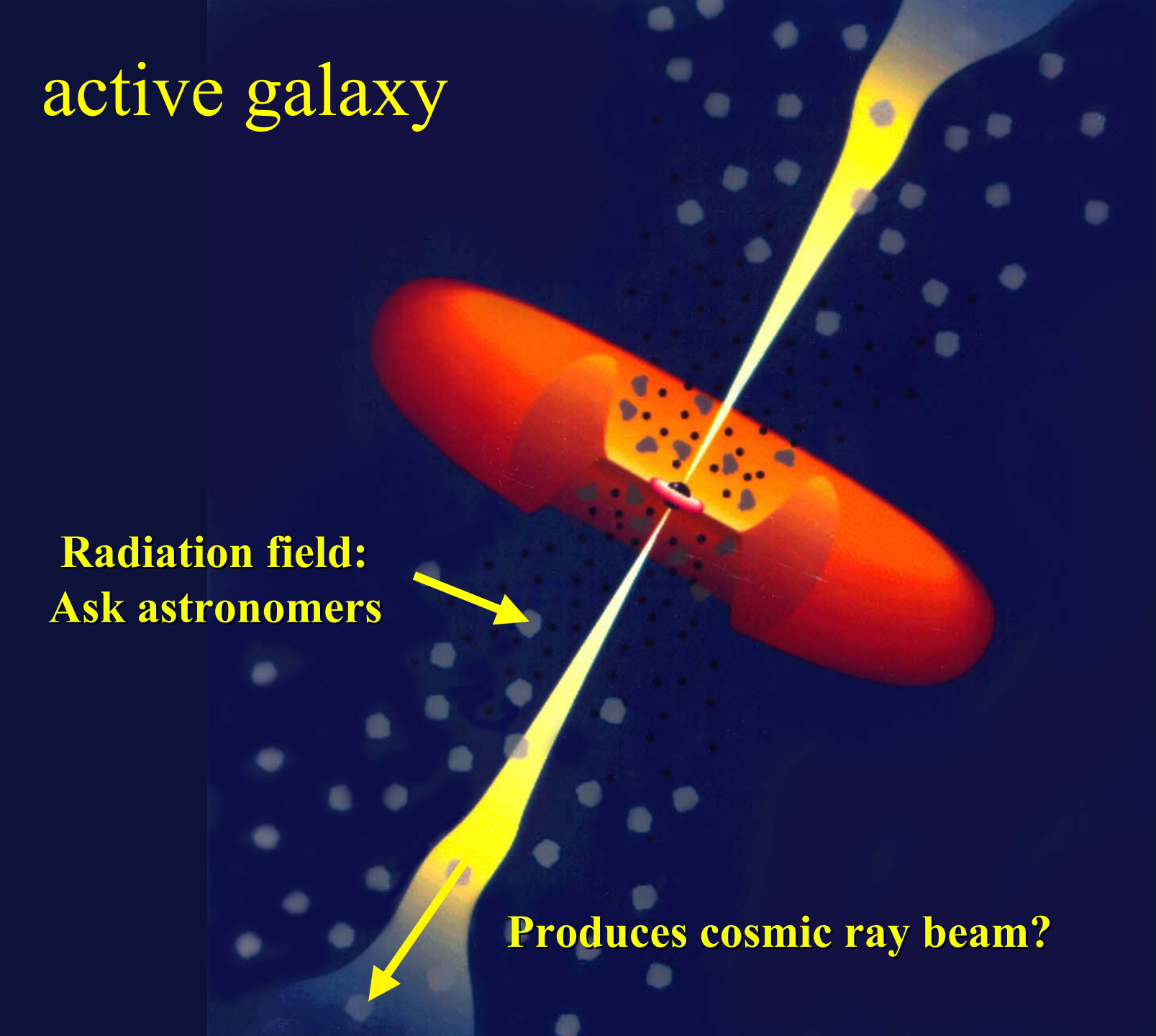
- Radiation from topological defects
- Decays of massive relic particles in Galactic halo
- Resonant neutrino interactions on relic ν's (Z-bursts)

• Mostly pions (neutrinos, photons, not protons)

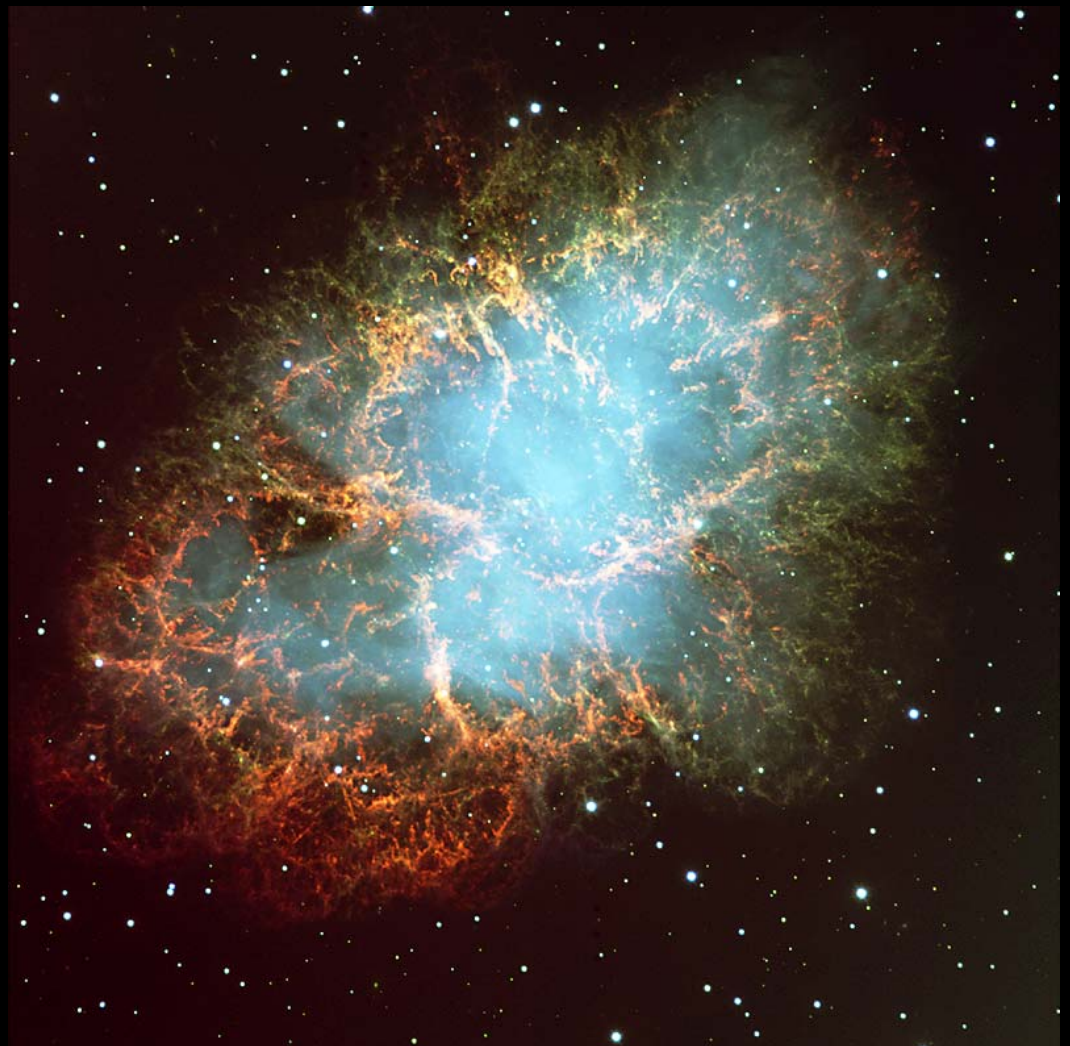
Disfavored!

- **Highest energy cosmic rays are not gamma rays**
- **Overproduce TeV-neutrinos**

active galaxy

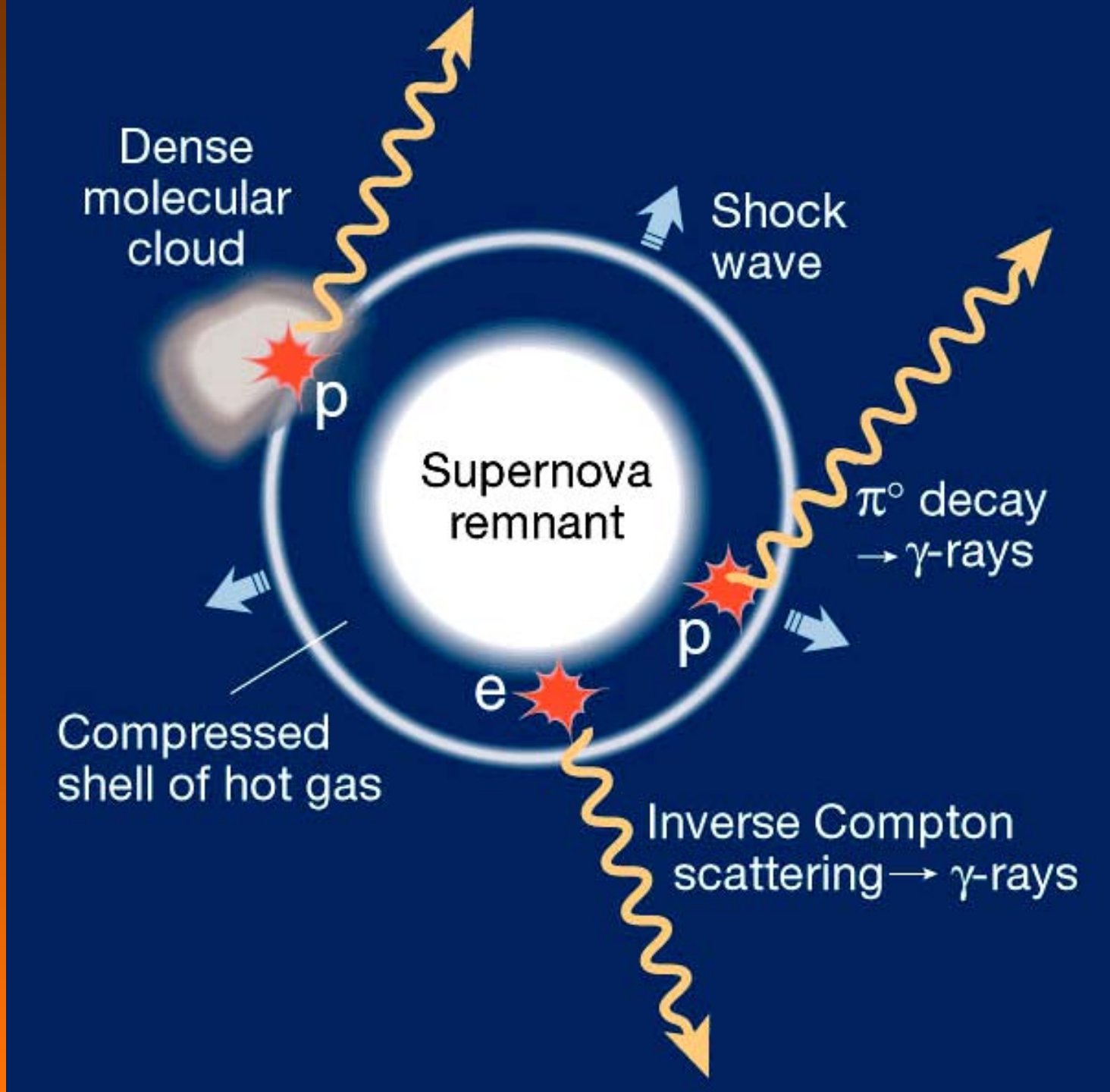


Supernova shocks expanding in interstellar medium



Crab nebula

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 in interstellar medium
  Target: molecular cloud

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

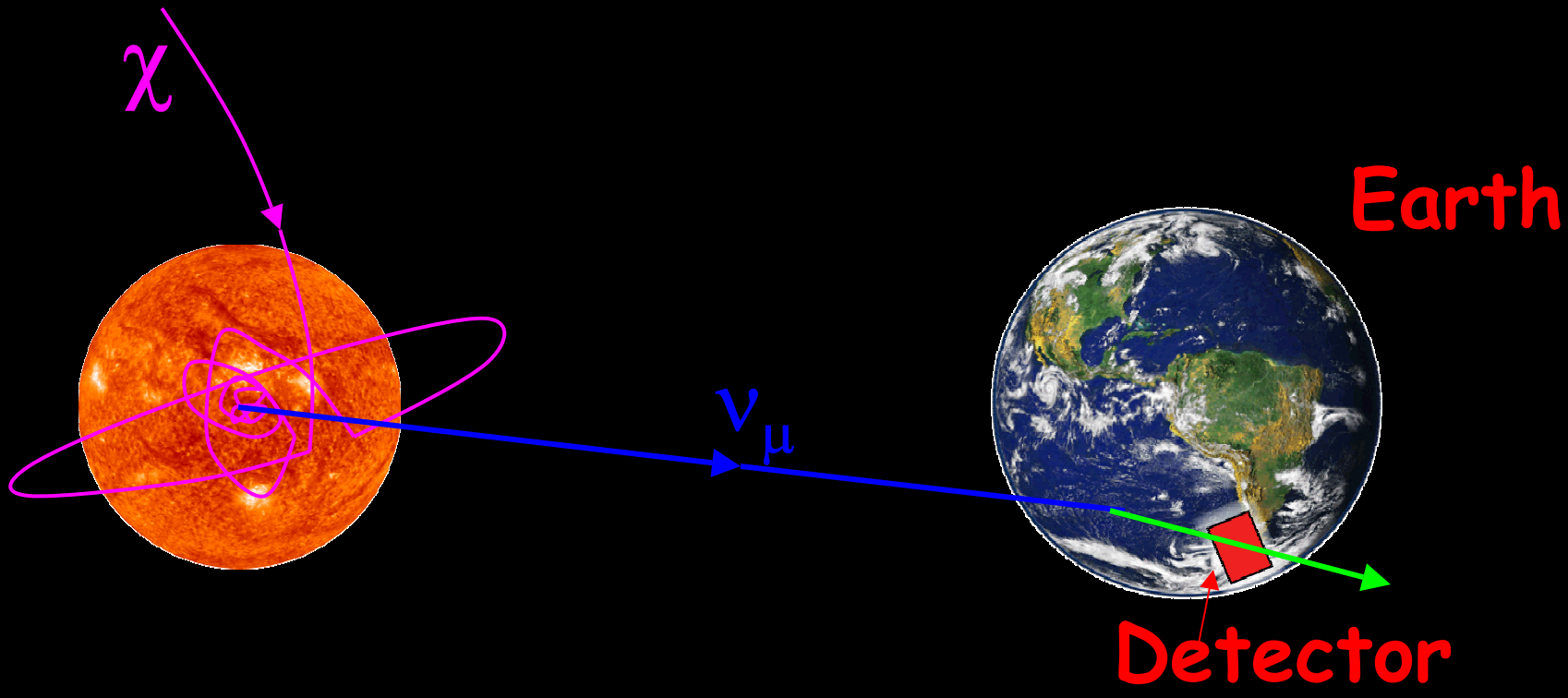
the science: a sampler

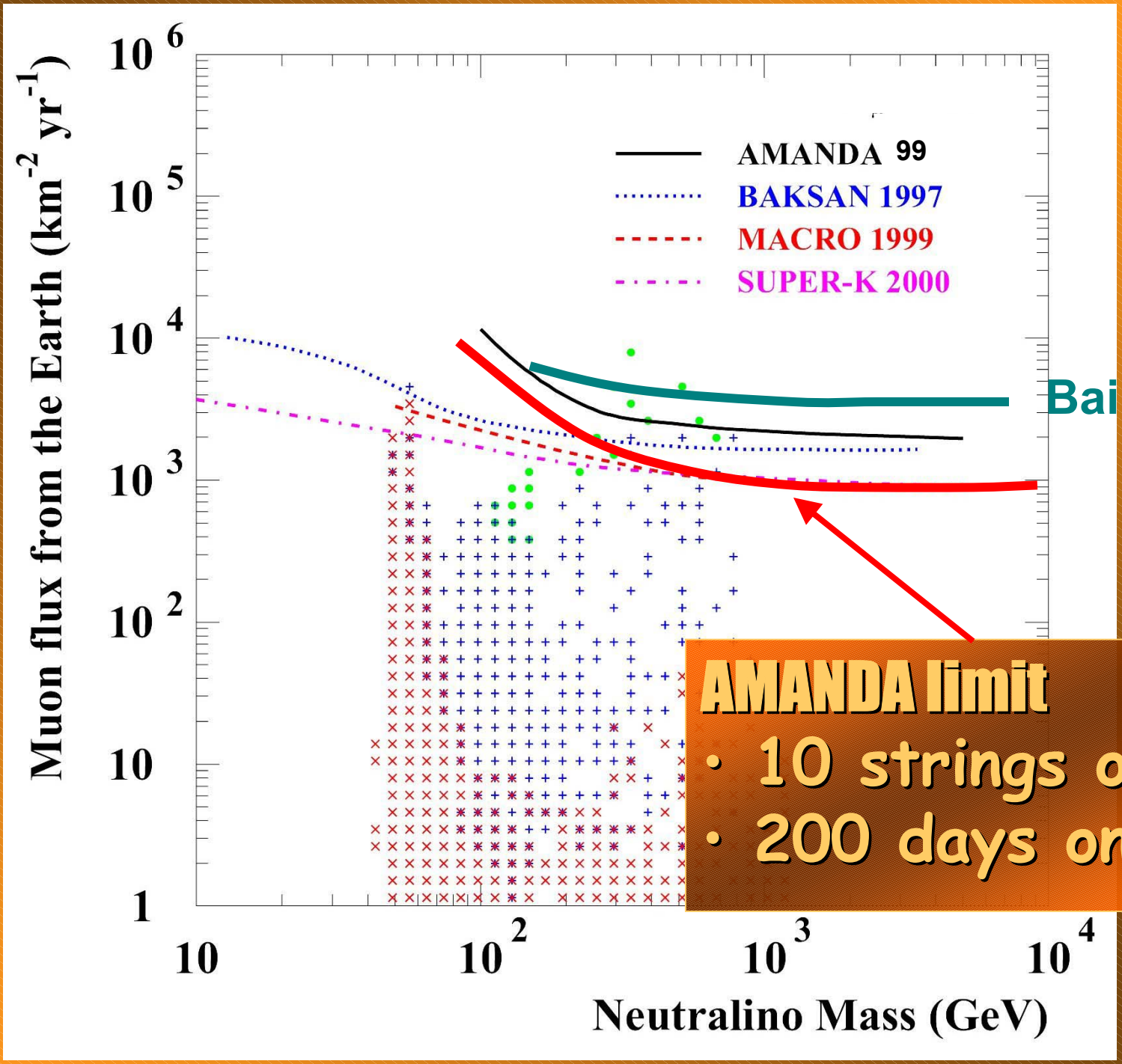
- **Source(s) of cosmic rays**:
  gamma-ray bursts, active galaxies,
  cosmological remnants…?

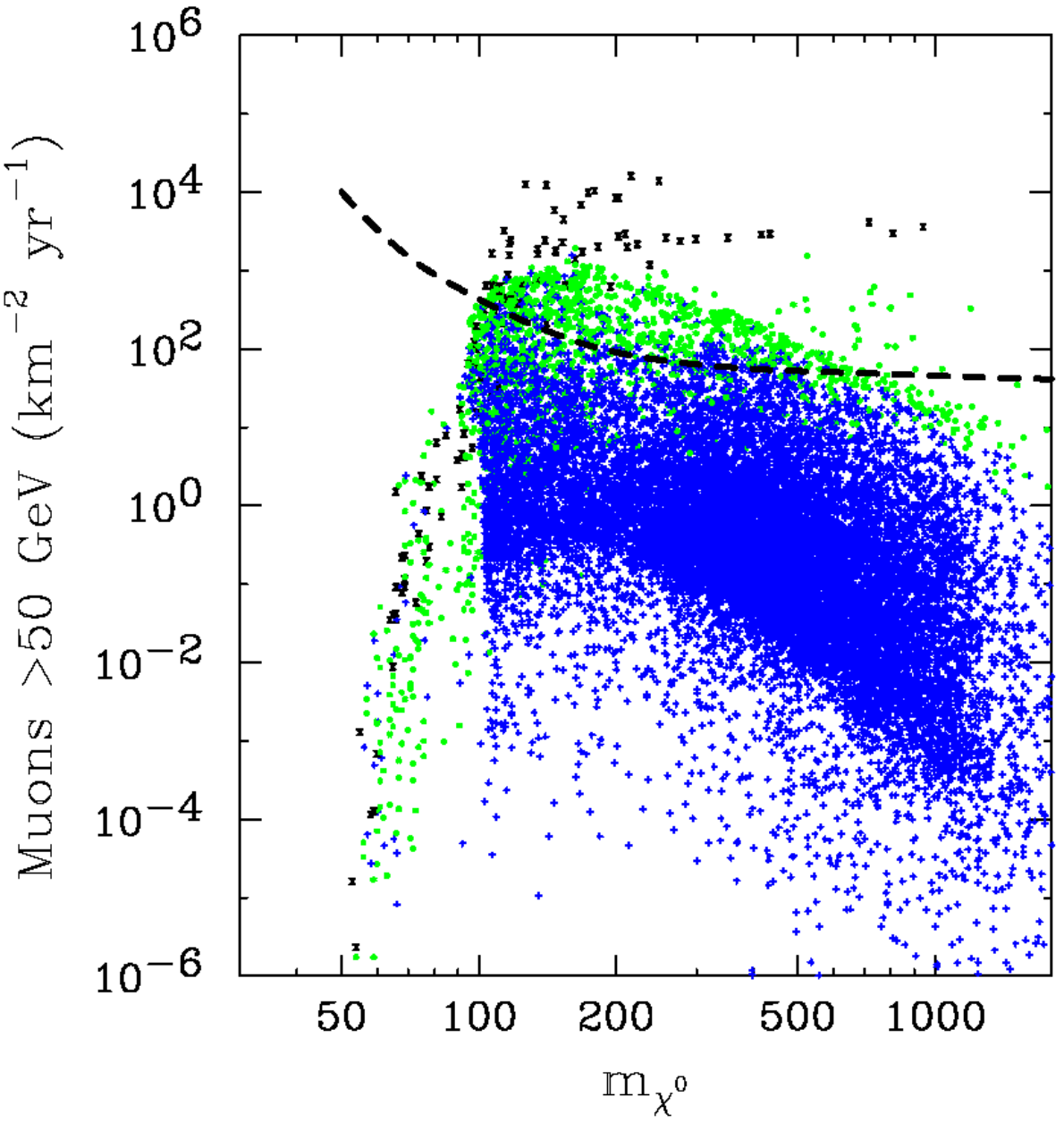
- **Dark matter**

- **Higher compact dimensions…**

WIMP capture and annihilation




Muon flux from the Earth (km^{-2} yr^{-1})
10^6
10^5
10^4
10^3
10^2
10
1
10
10^2
10^3
10^4
Neutralino Mass (GeV)
AMANDA 99
BAKSAN 1997
MACRO 1999
SUPER-K 2000
Baikal
AMANDA limit
• 10 strings only
• 200 days only



IceCube

vs

Direct Detection

(Zeppelin4/Genius)

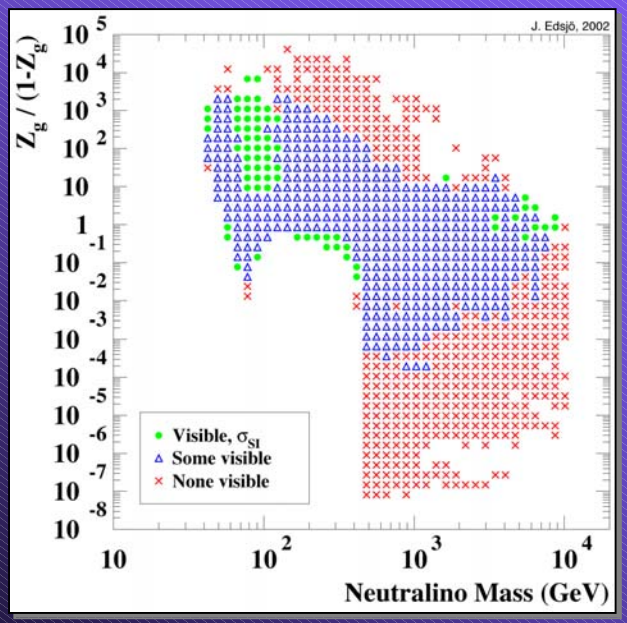
Black: out
Green: yes
Blue: no

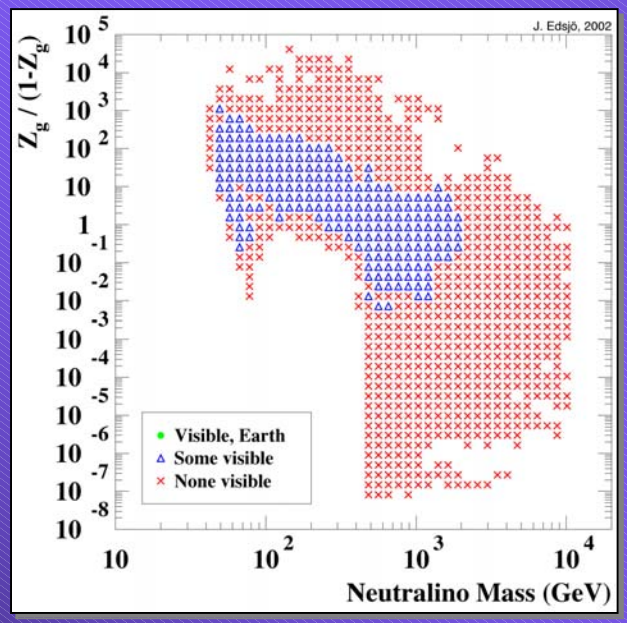
MSSM parameter space
Future probed regions I

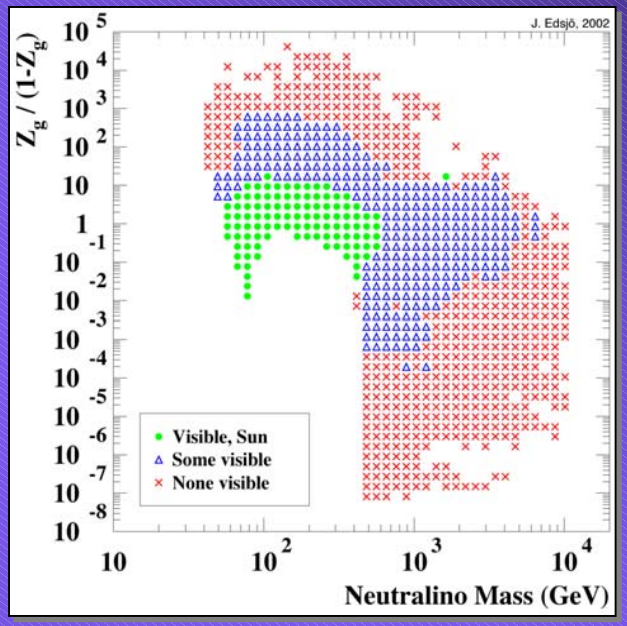
Direct detection
Genius/Cresst

Earth, km^3

Sun, km^3

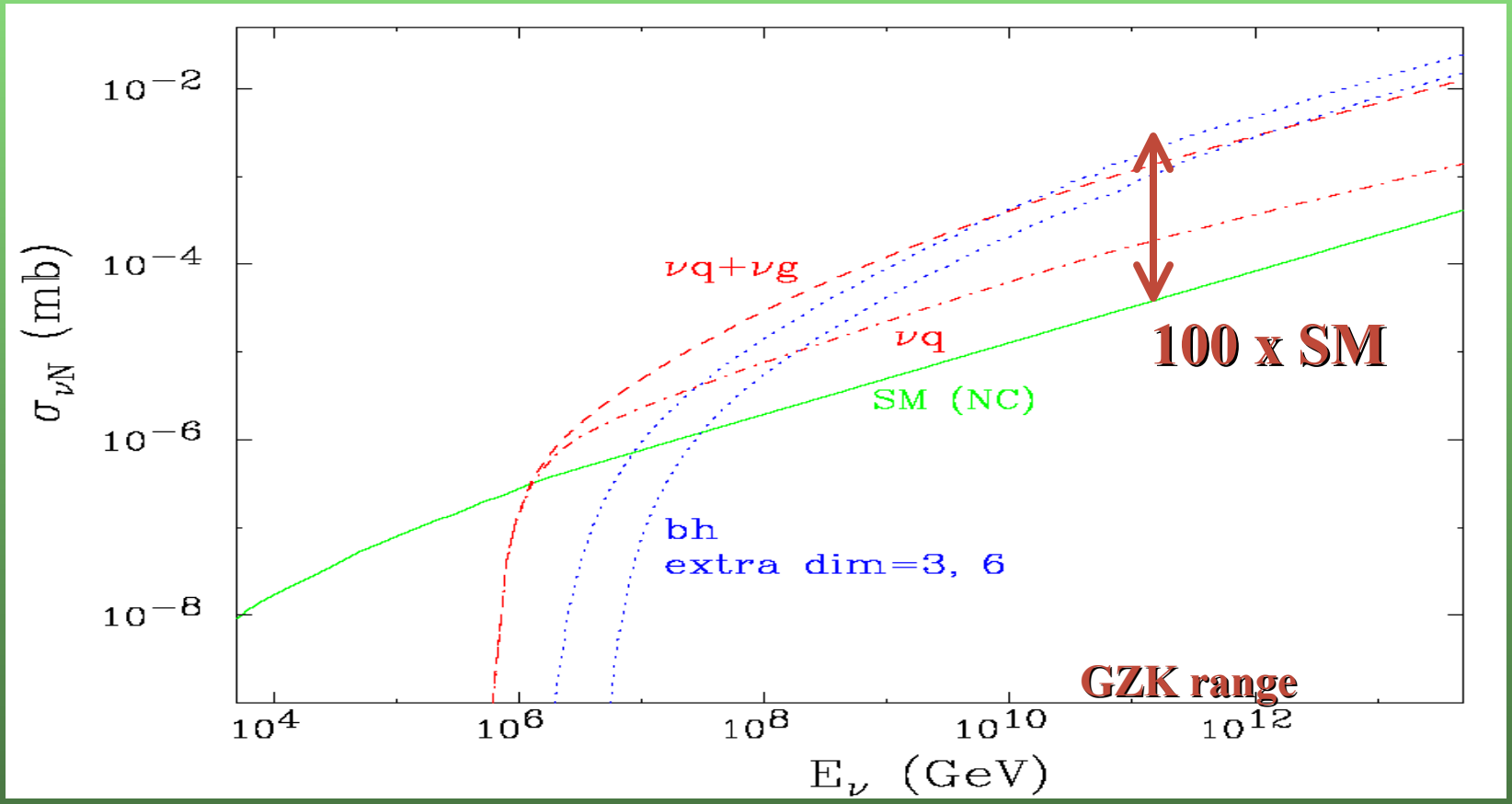




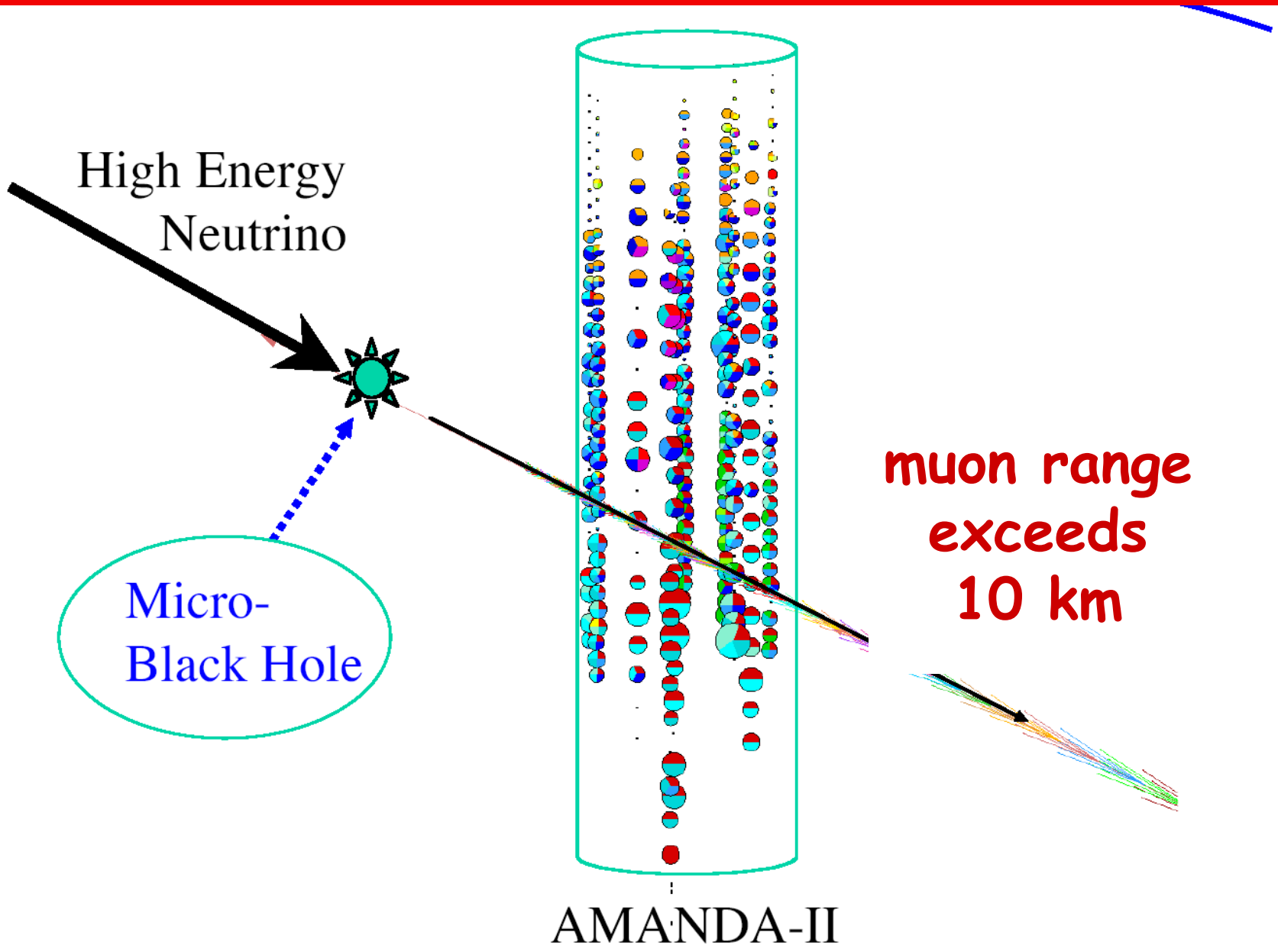


IceCube

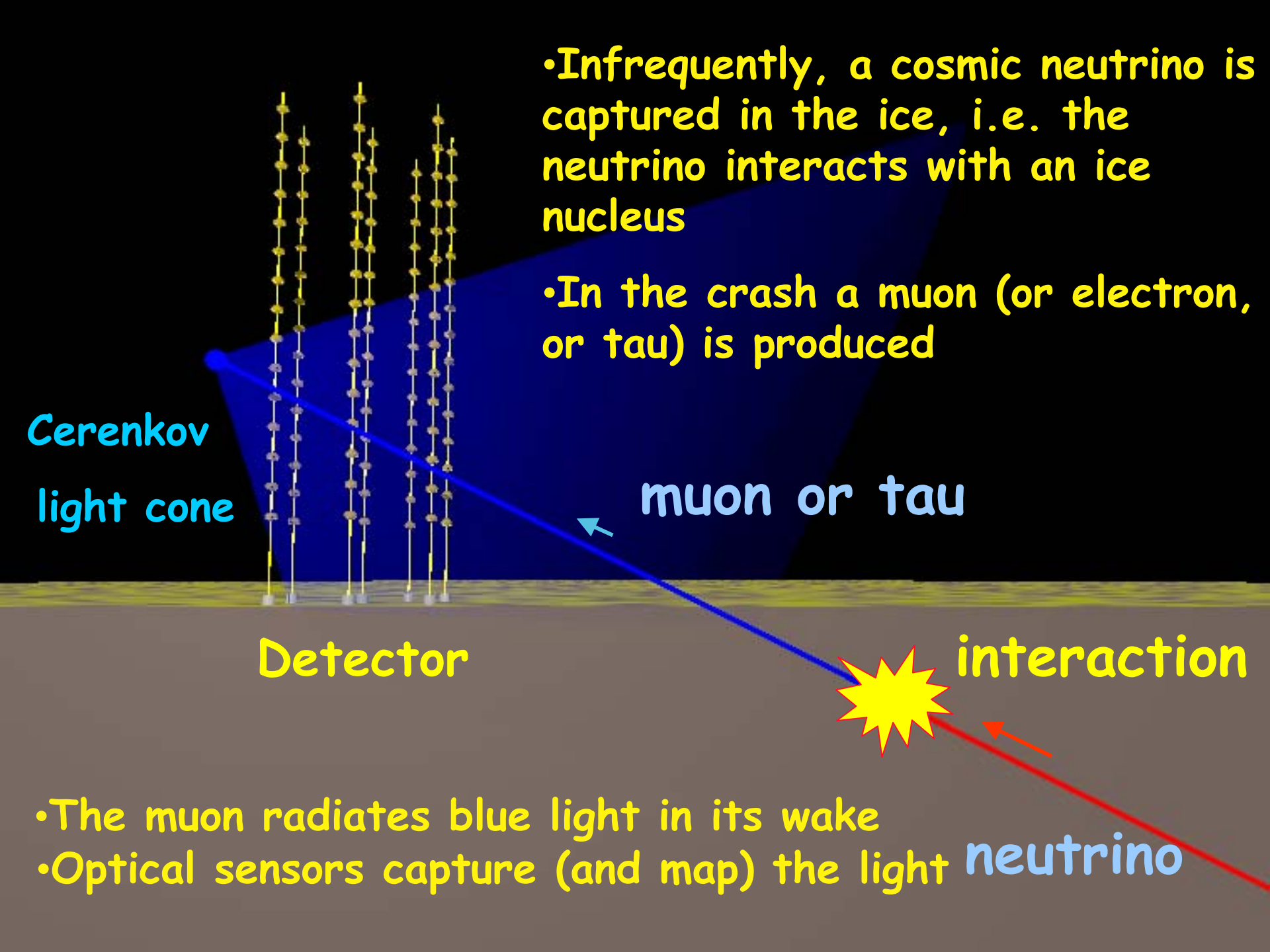
Neutrino Astronomy Explores Higher Dimensions



TeV-scale gravity increases PeV ν-cross section


High Energy
Neutrino
Micro-
Black Hole
muon range
exceeds
10 km
AMANDA-II

first-generation neutrino telescopes

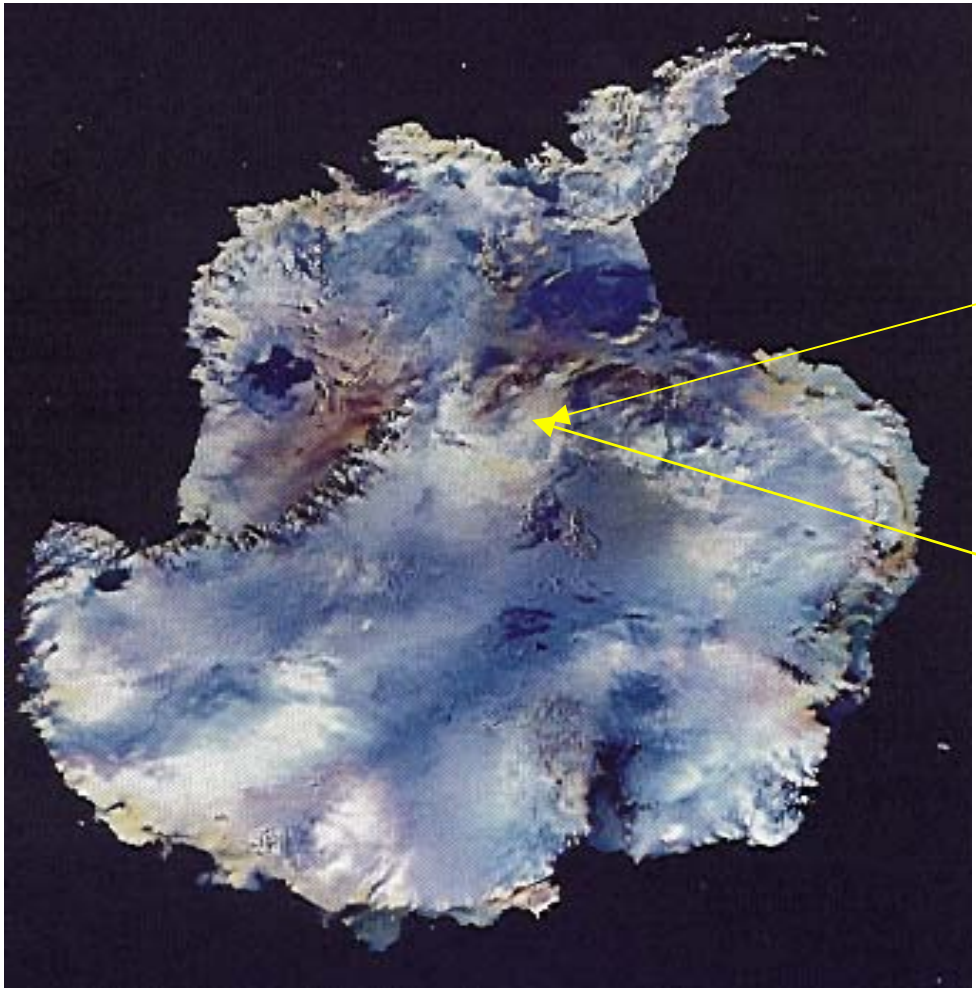

•Infrequently, a cosmic neutrino is captured in the ice, i.e. the neutrino interacts with an ice nucleus
•In the crash a muon (or electron, or tau) is produced
Cerenkov
light cone
muon or tau
Detector
interaction
•The muon radiates blue light in its wake
•Optical sensors capture (and map) the light
neutrino

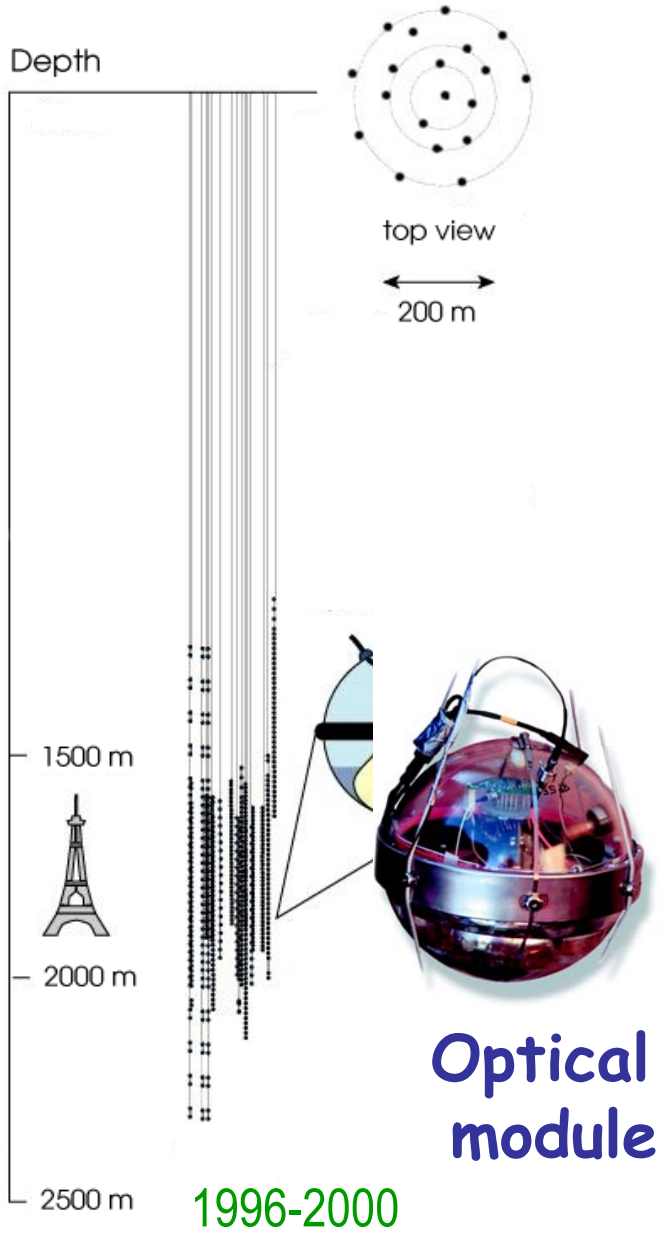
Optical Module

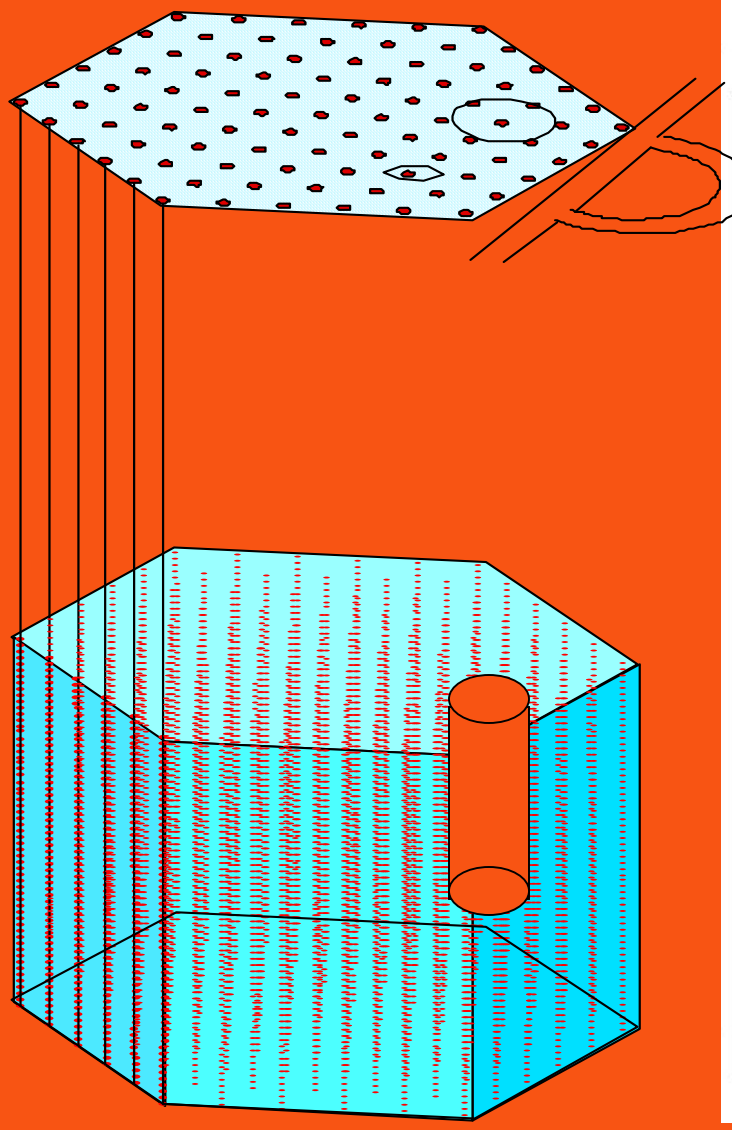

South Pole
AMANDA– 1 mile deep

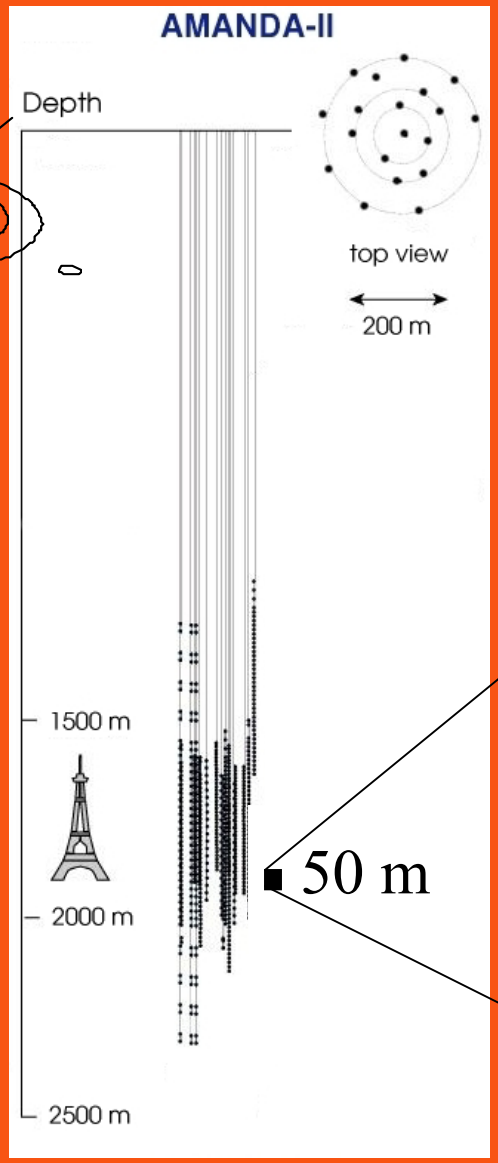
AMANDA II

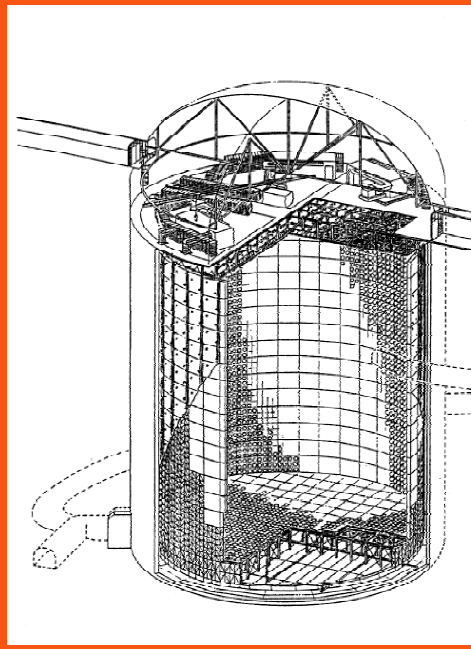
Amundsen-Scott Station South Pole











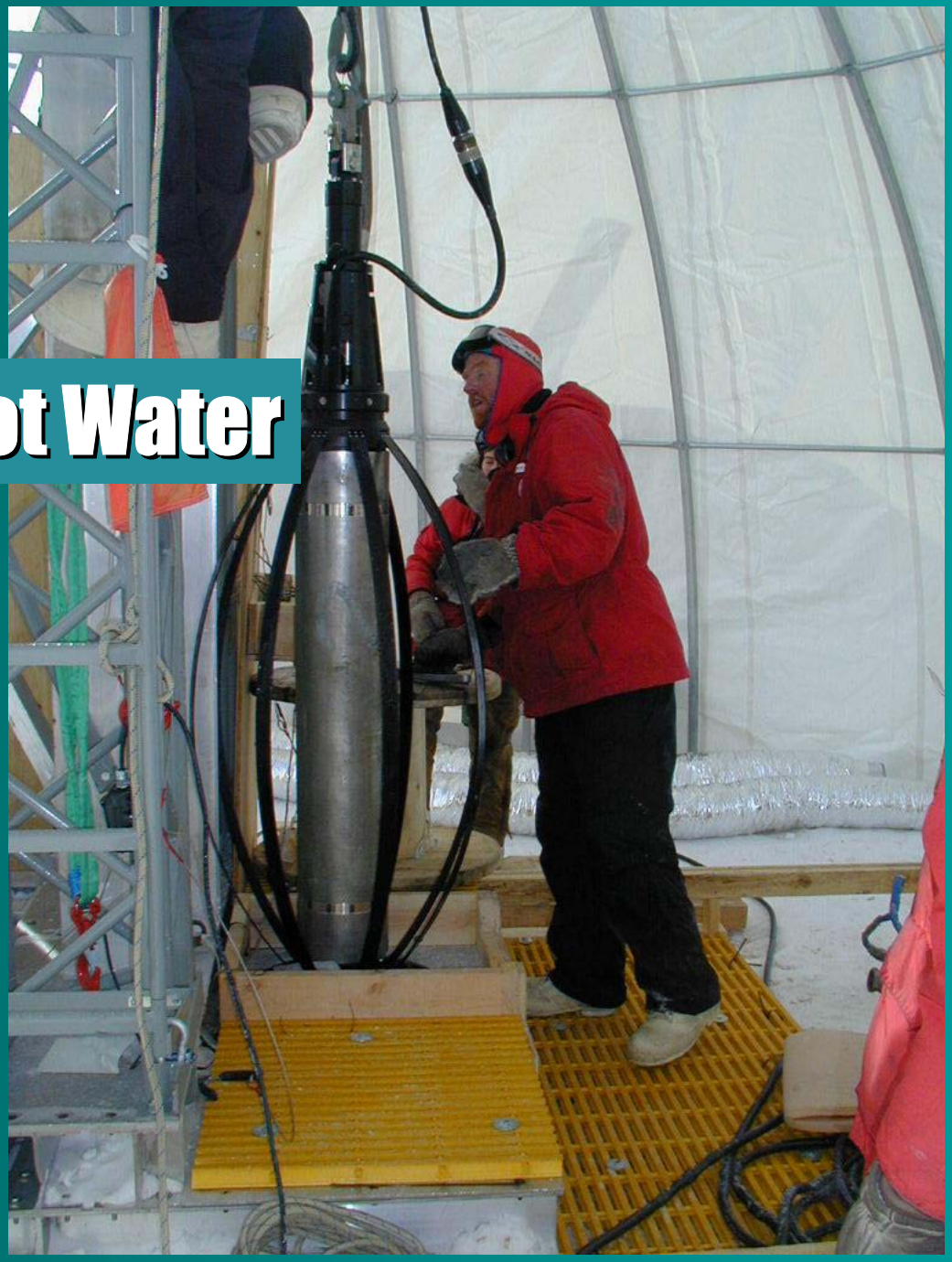
Size perspective

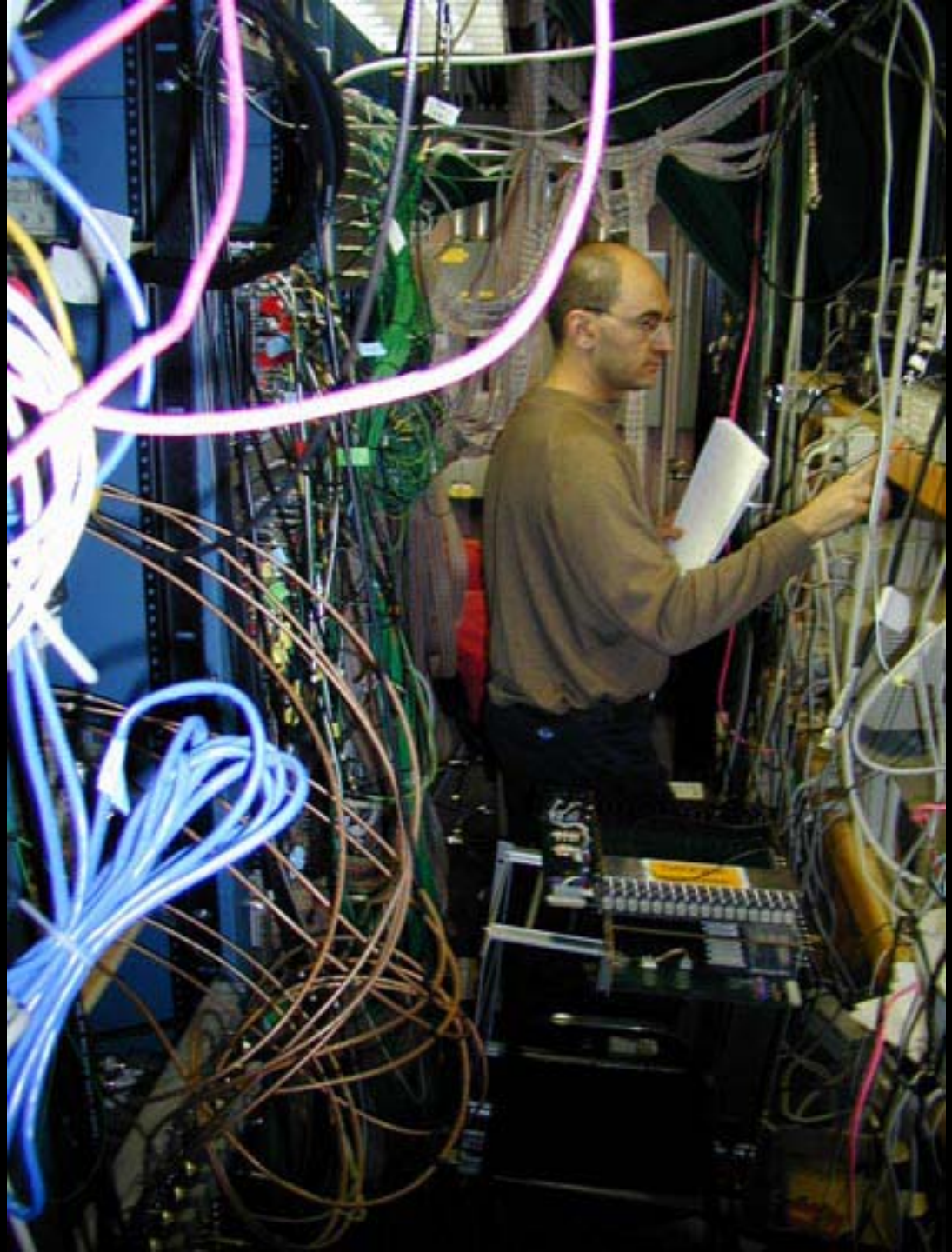

Logistics simple!

Building AMANDA

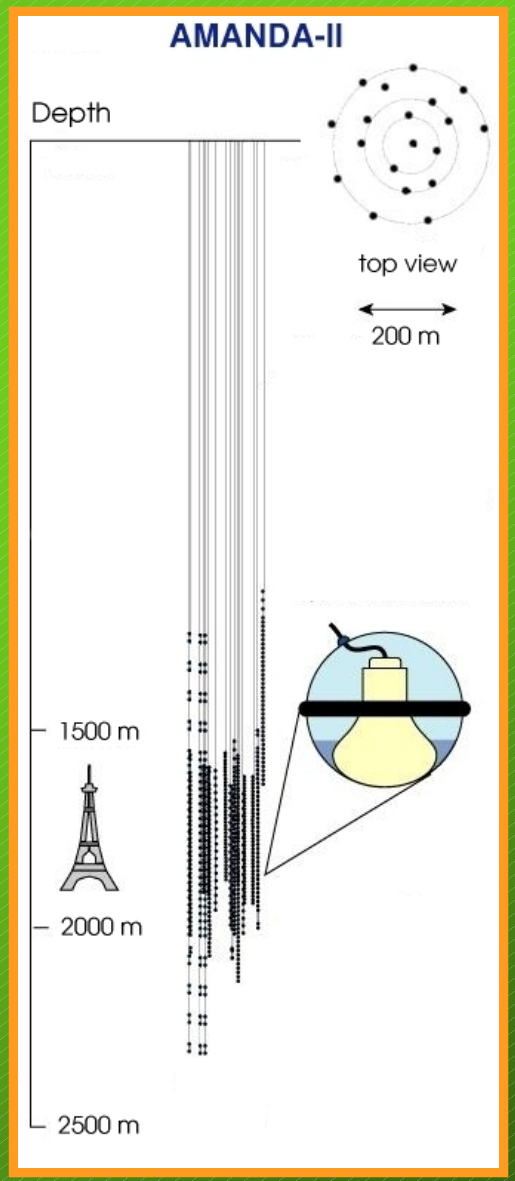
Drilling Holes with Hot Water

The Optical Module





- Construction began in 1995 (4 strings)
- AMANDA-II completed in 2000 (19 strings total)
- 677 optical modules
- 200 m across
- ~500 m tall (most densely instrumented volume)

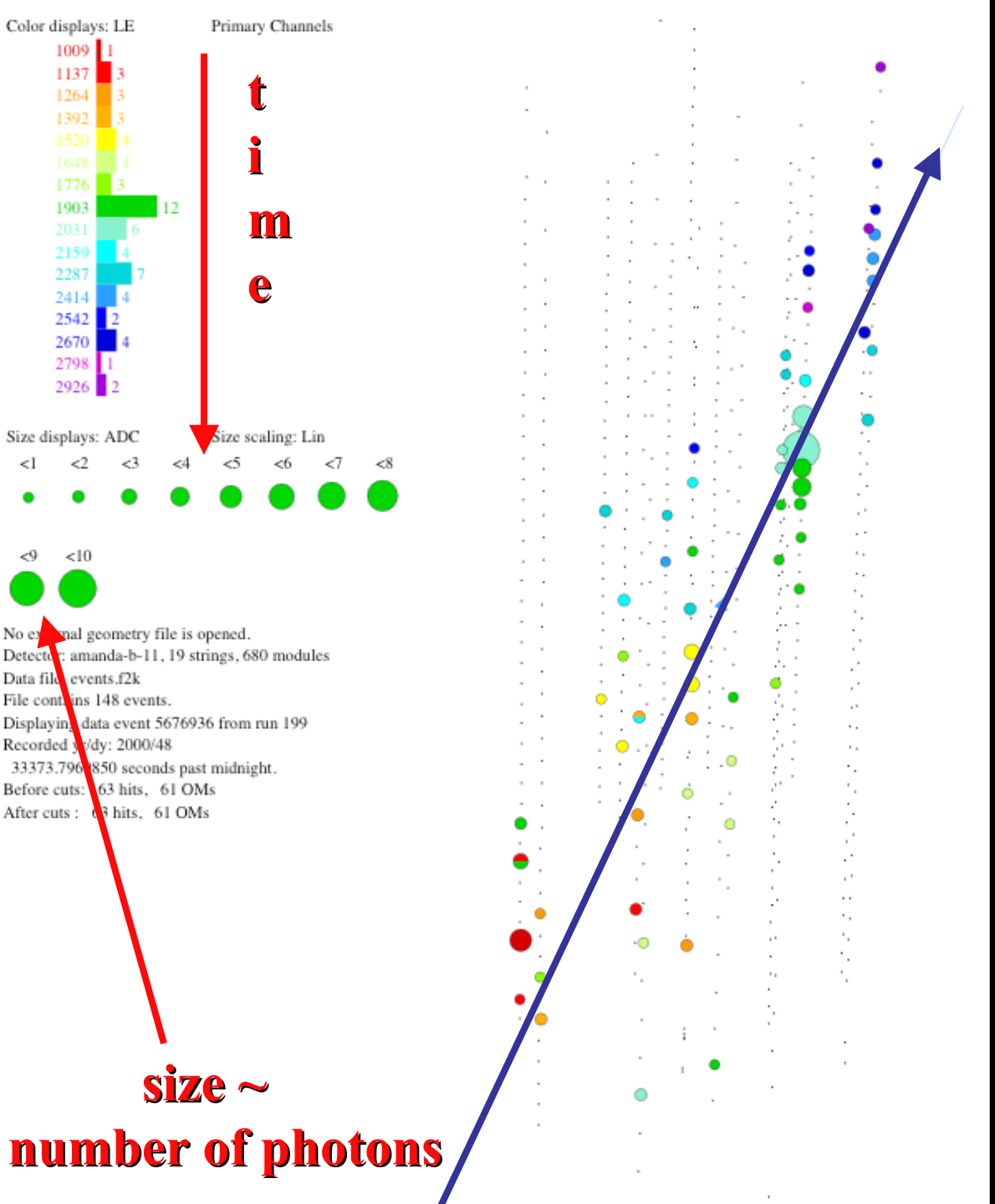


The AMANDA detector

AMANDA II

- up-going muon
- 61 modules hit

> 4 neutrinos/day on-line

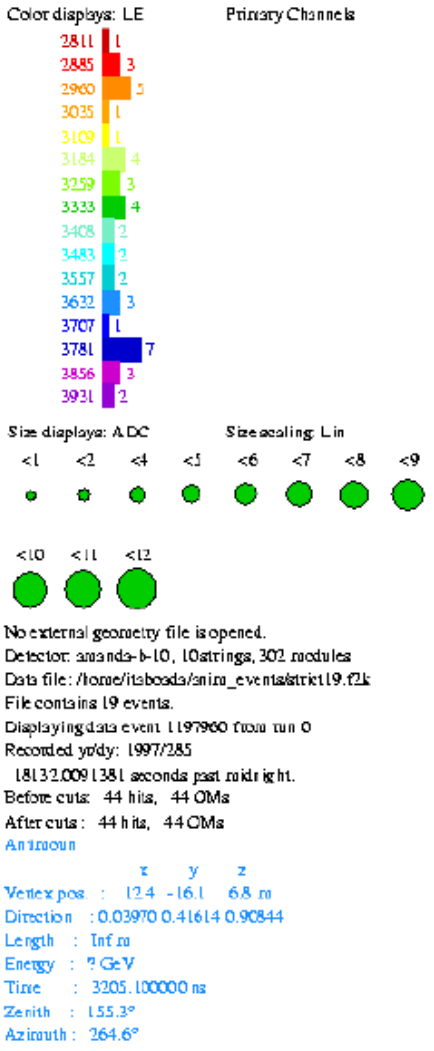


AMANDA Event Signature: Muon

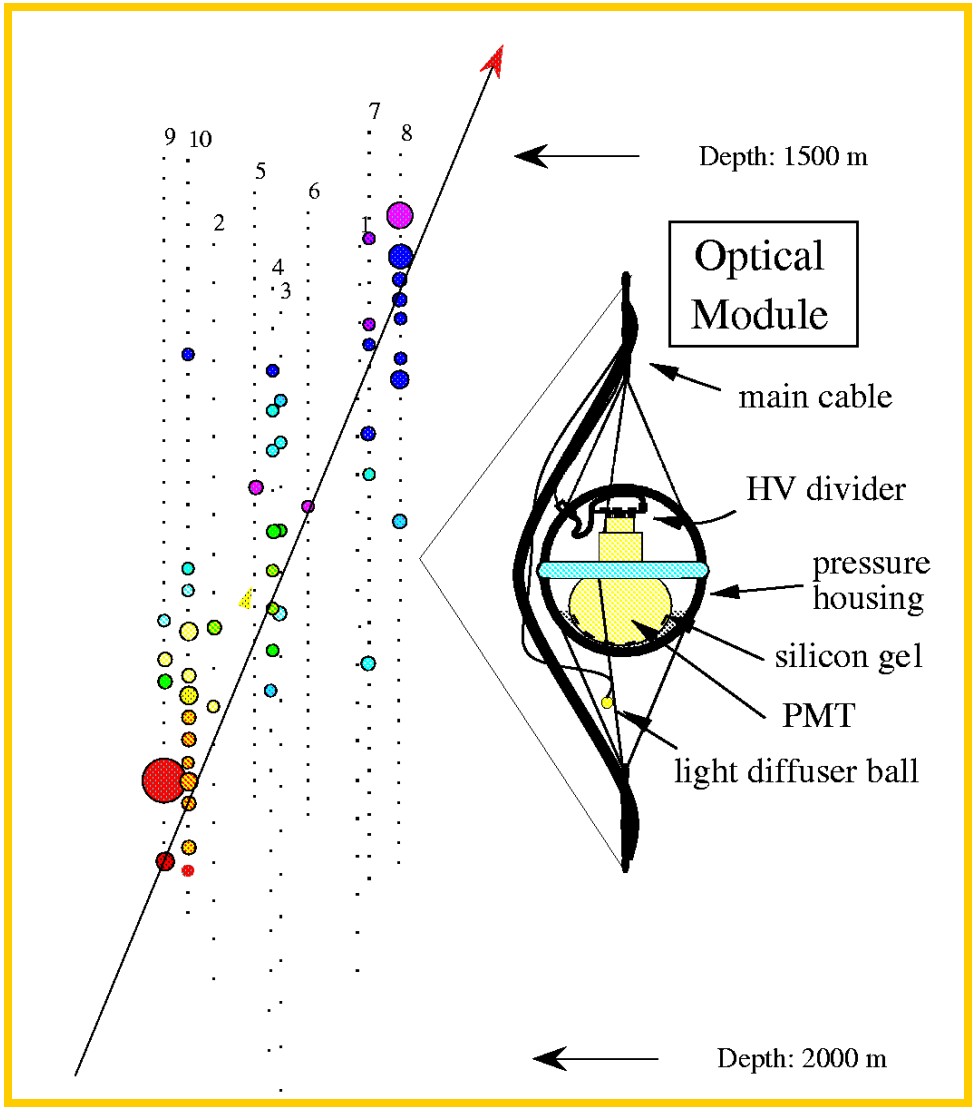
CC muon neutrino interaction

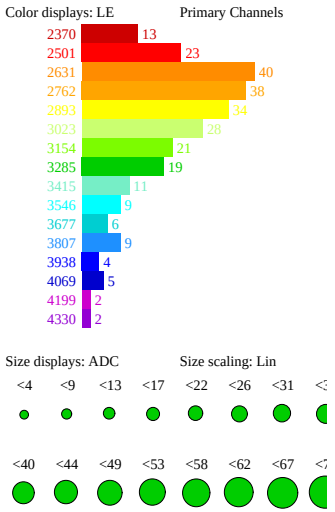
→ track

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



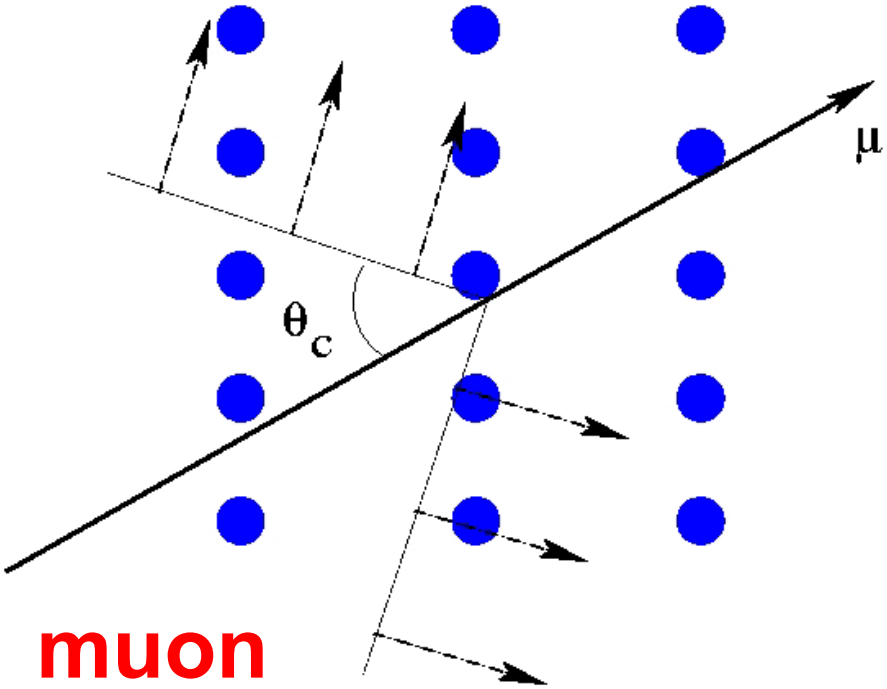
two events



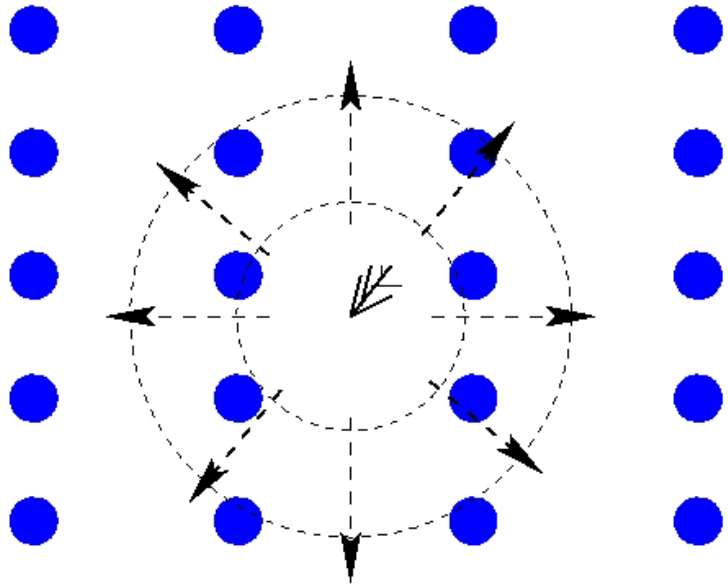


200 TeV ν_e

Cherenkov light from muons and cascades



muon

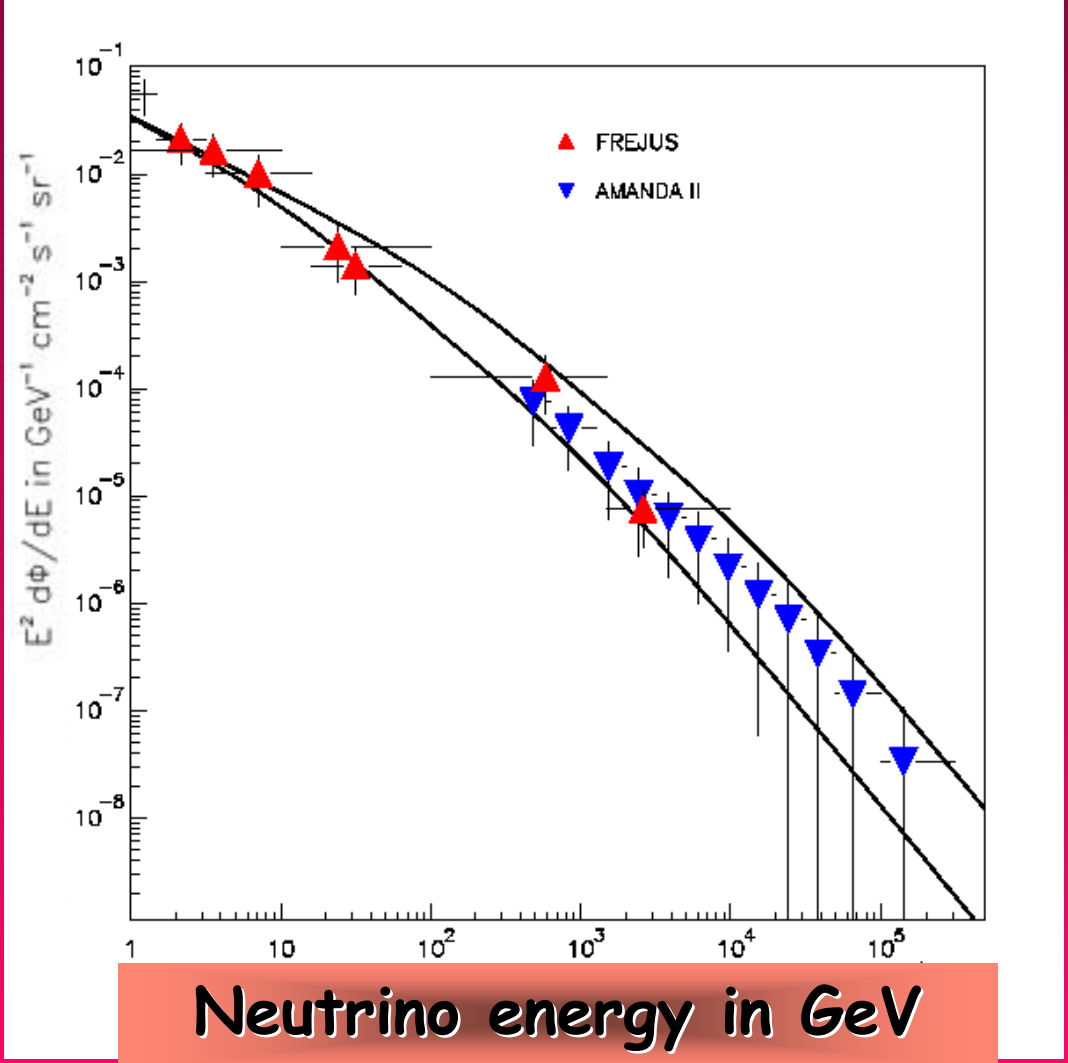


cascade: e or τ

Reconstruction

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

Atmospheric ν 's as Test Beam



Atmospheric ν 's as Test Beam

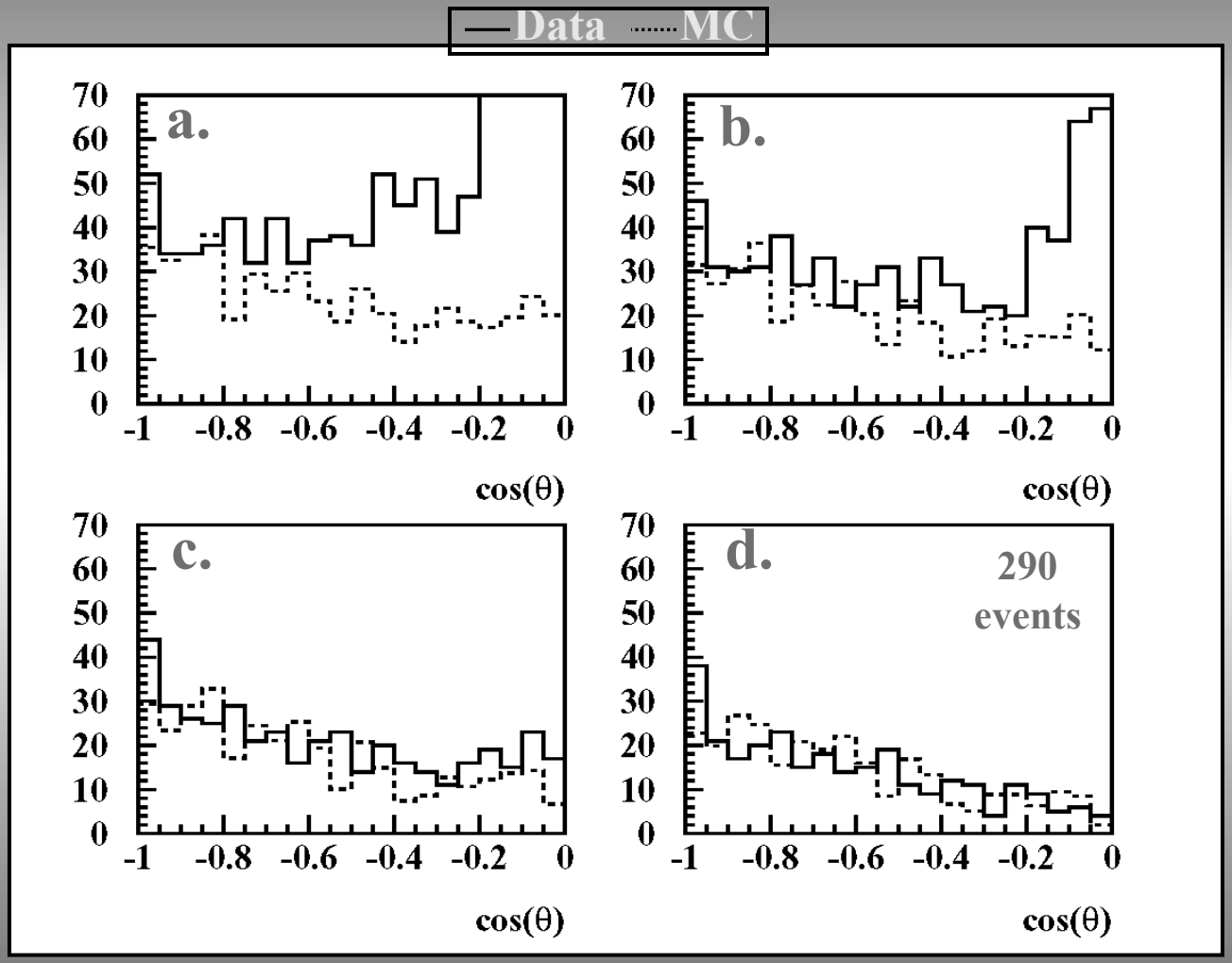
Selection Criteria:

- (N_{hit} < 50 only)
- Zenith > 110°

- High fit quality
- Uniform light deposition along track

2 cuts only!

4 nus per day

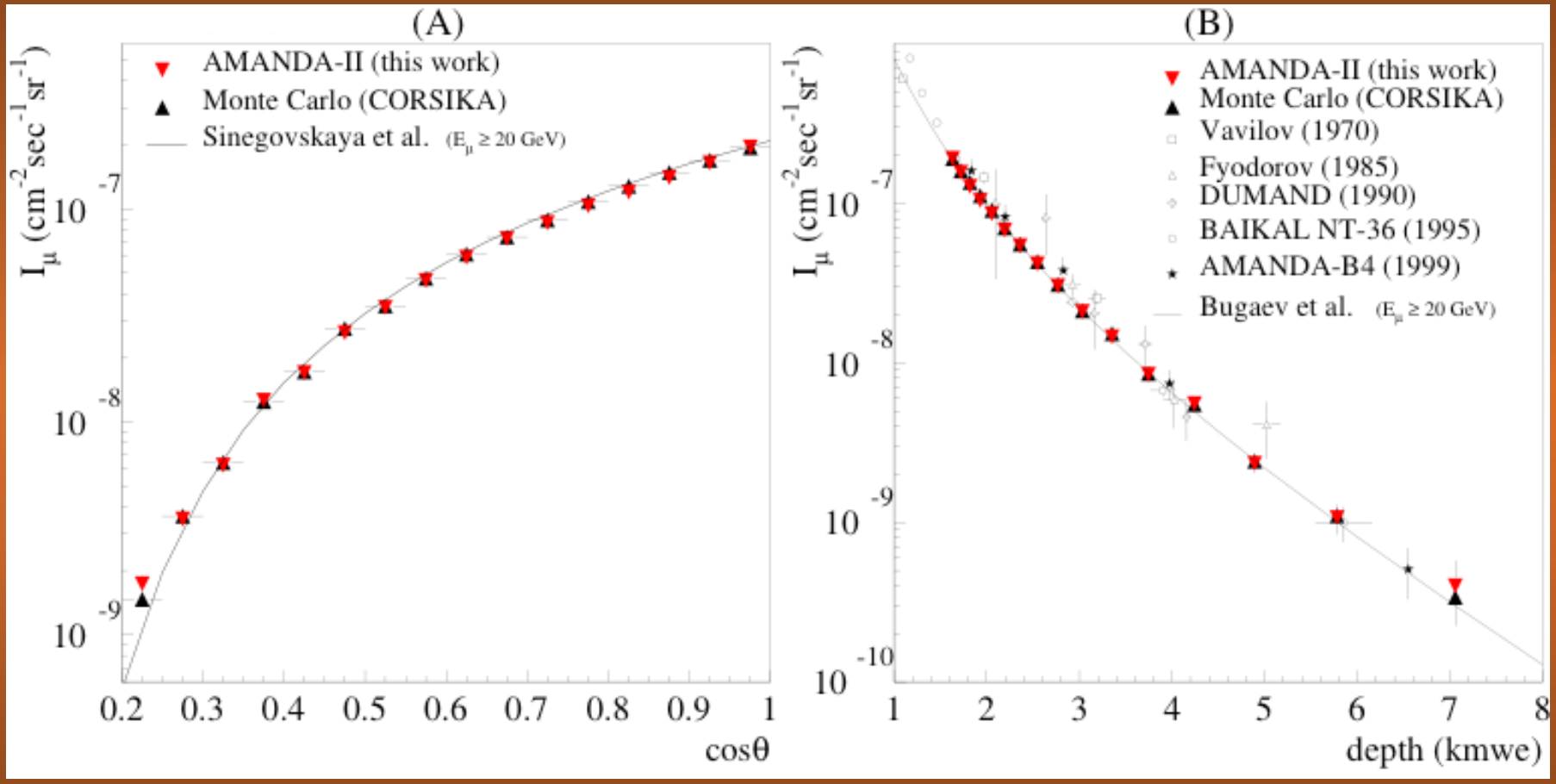


tightening of cuts extracts atm. ν signal

required background rejection

Signature	neutrino signal / cosmic muon bkg
Diffuse flux	$\sim 10^{-8}$
Point source	$> 10^{-6}$
Gamma ray burst	$> 10^{-4}$

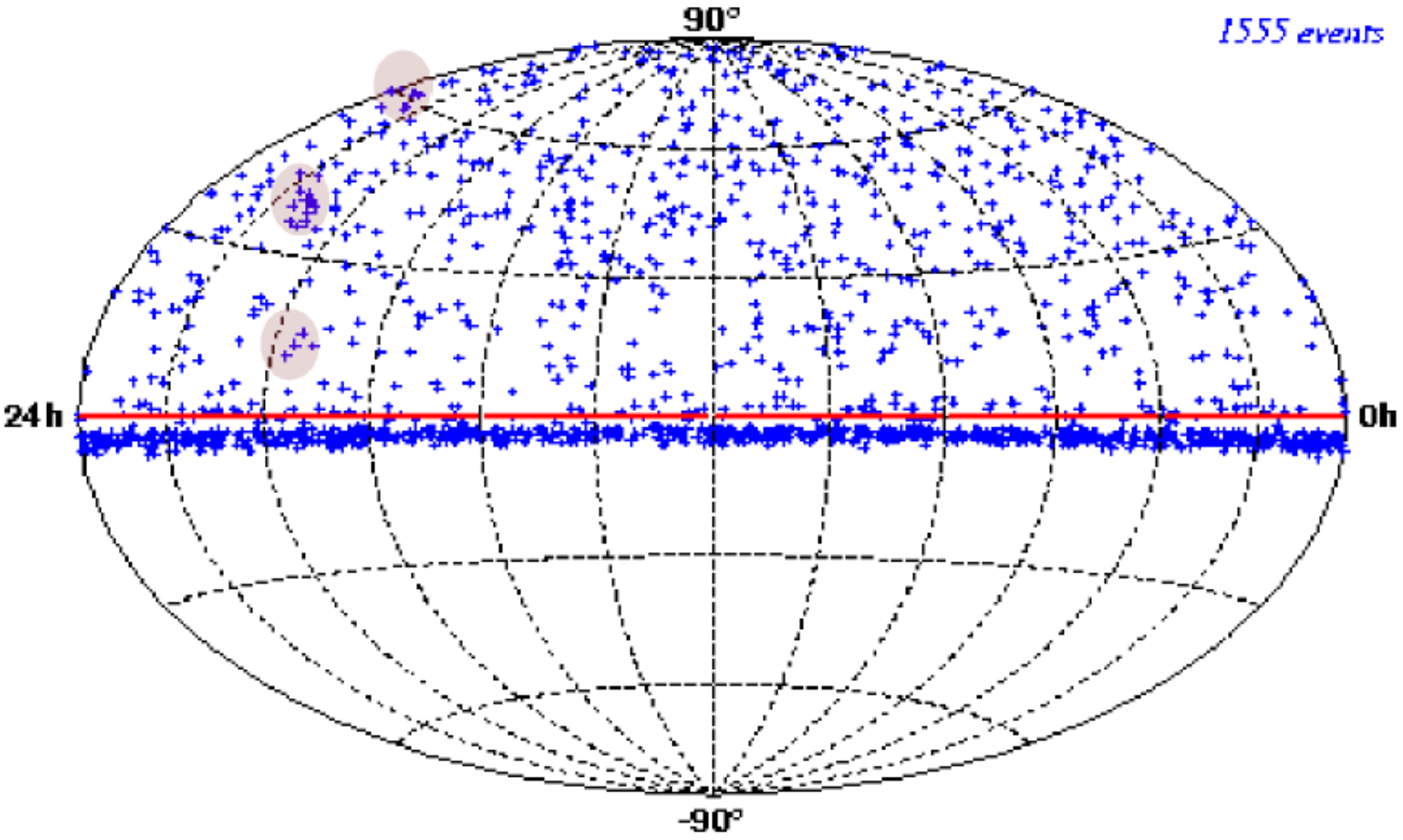
down-going muon flux

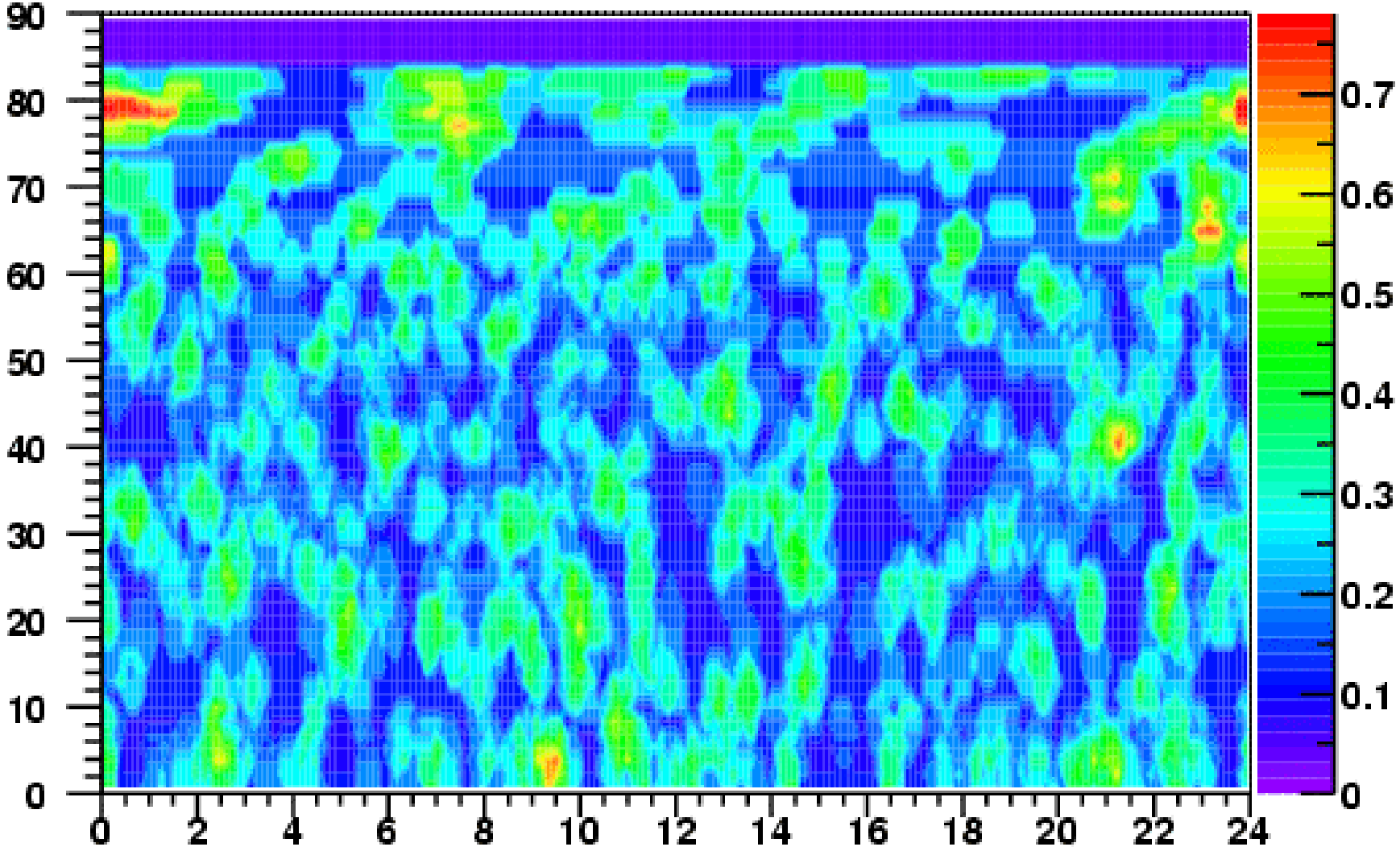


zenith angle

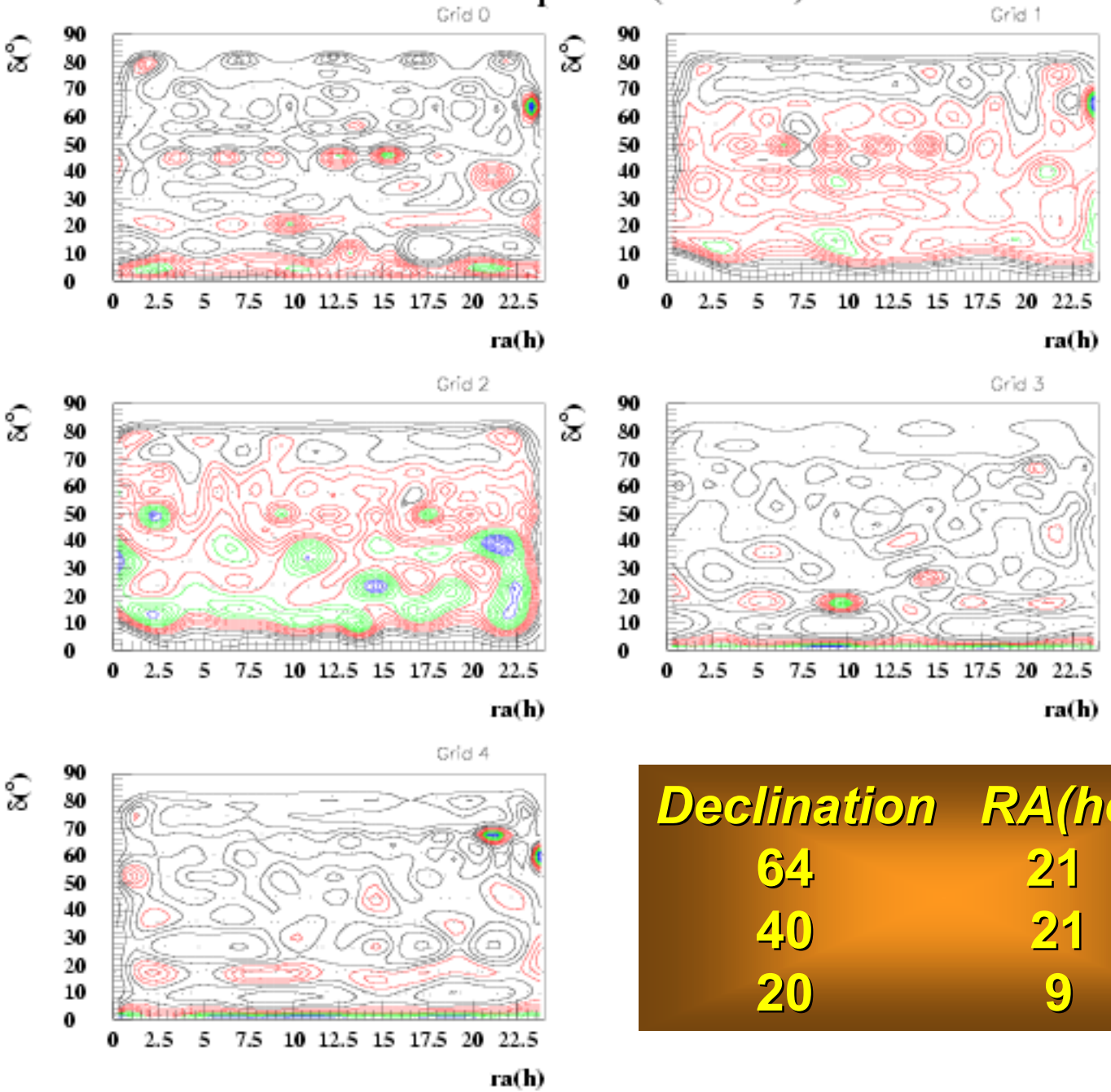
depth

AMANDA II 2000




90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
16
18
20
22
24
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

Final Exp Data (above 0°)

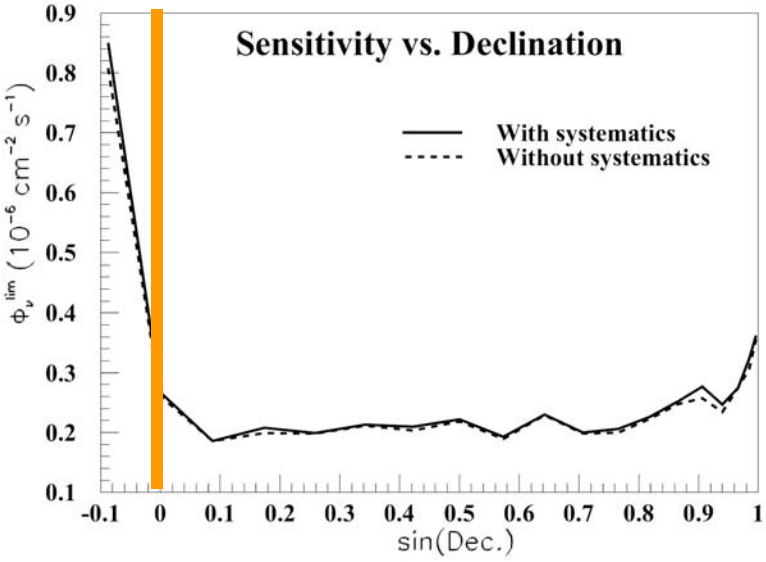


Declination	RA(hours)
64	21
40	21
20	9

selected point source flux limits

sensitivity ≈ flat above horizon - 4 times better than B10 ¶!

PRELIMINARY

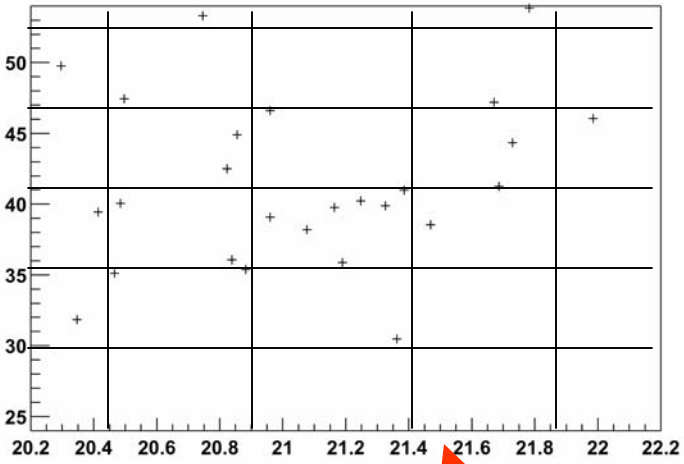


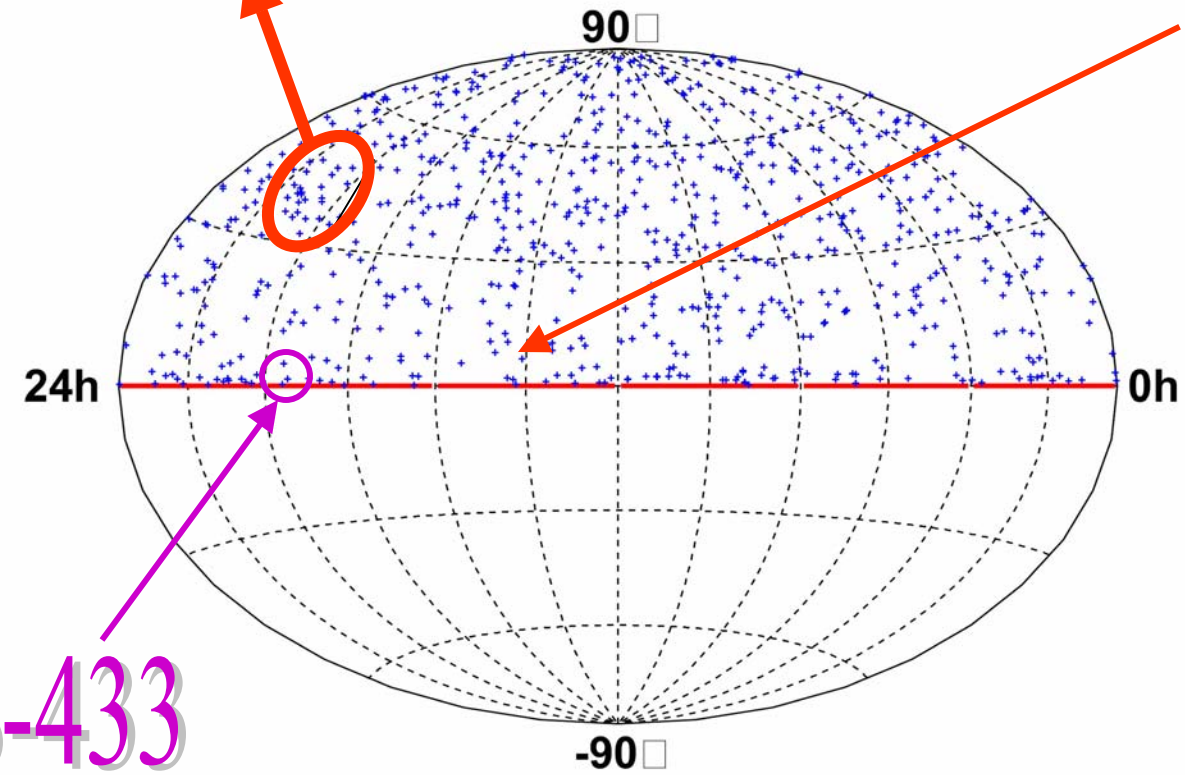
declination averaged sensitivity:
$\Phi_\nu^{lim} \approx 0.23 \cdot 10^{-7}$ cm^{-2}s^{-1} @90%

Sources	declination	1997 ¶	2000
SS433	5.0°	-	0.7
M87	12.4°	17.0	1.0
Crab	22.0°	4.2	2.4
Mkn 421	38.2°	11.2	3.5
Mkn 501	39.8°	9.5	1.8
Cyg. X-3	41.0°	4.9	3.5
Cas. A	58.8°	9.8	1.2

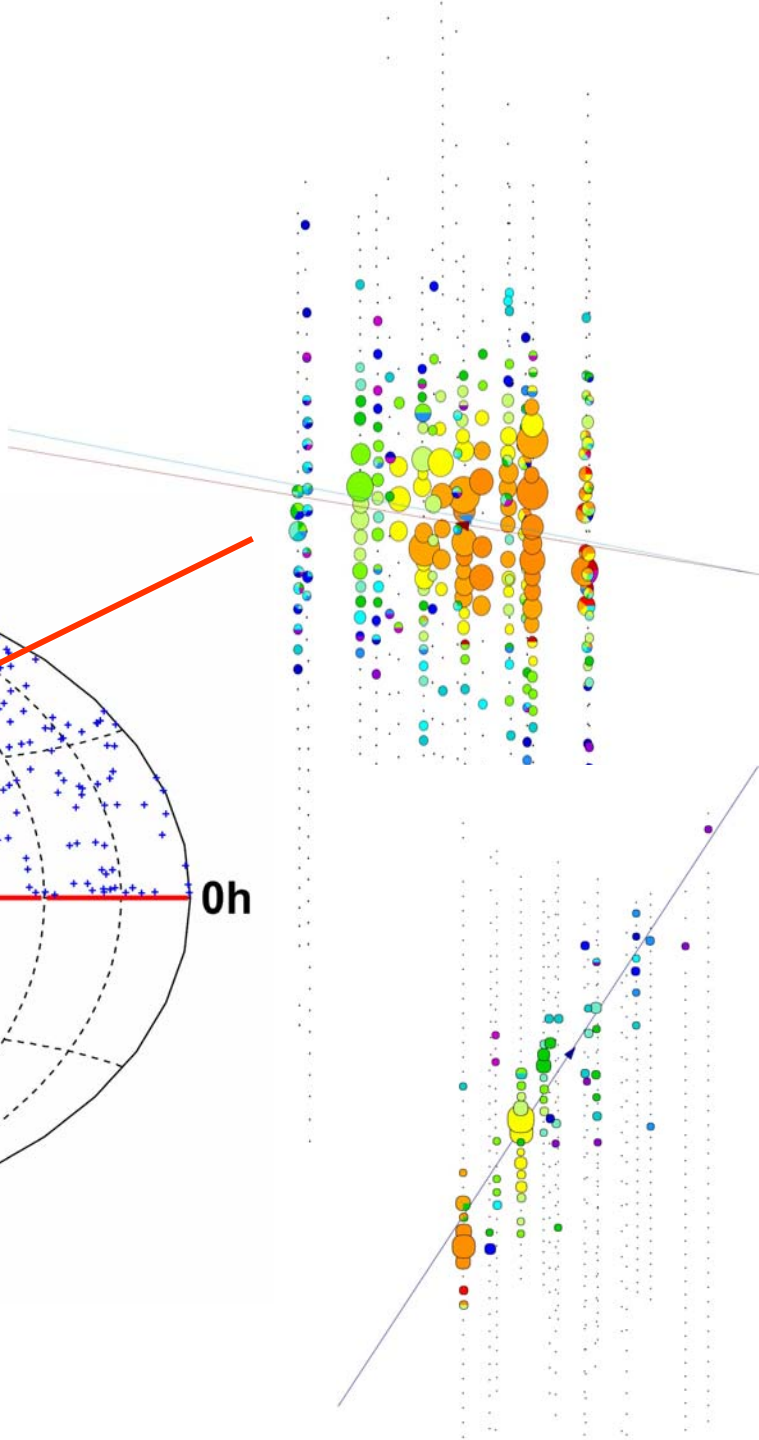
upper limits @ 90% CL in units of 10^{-8}cm^{-2}s^{-1}

¶ published Ap. J, 582 (2003)

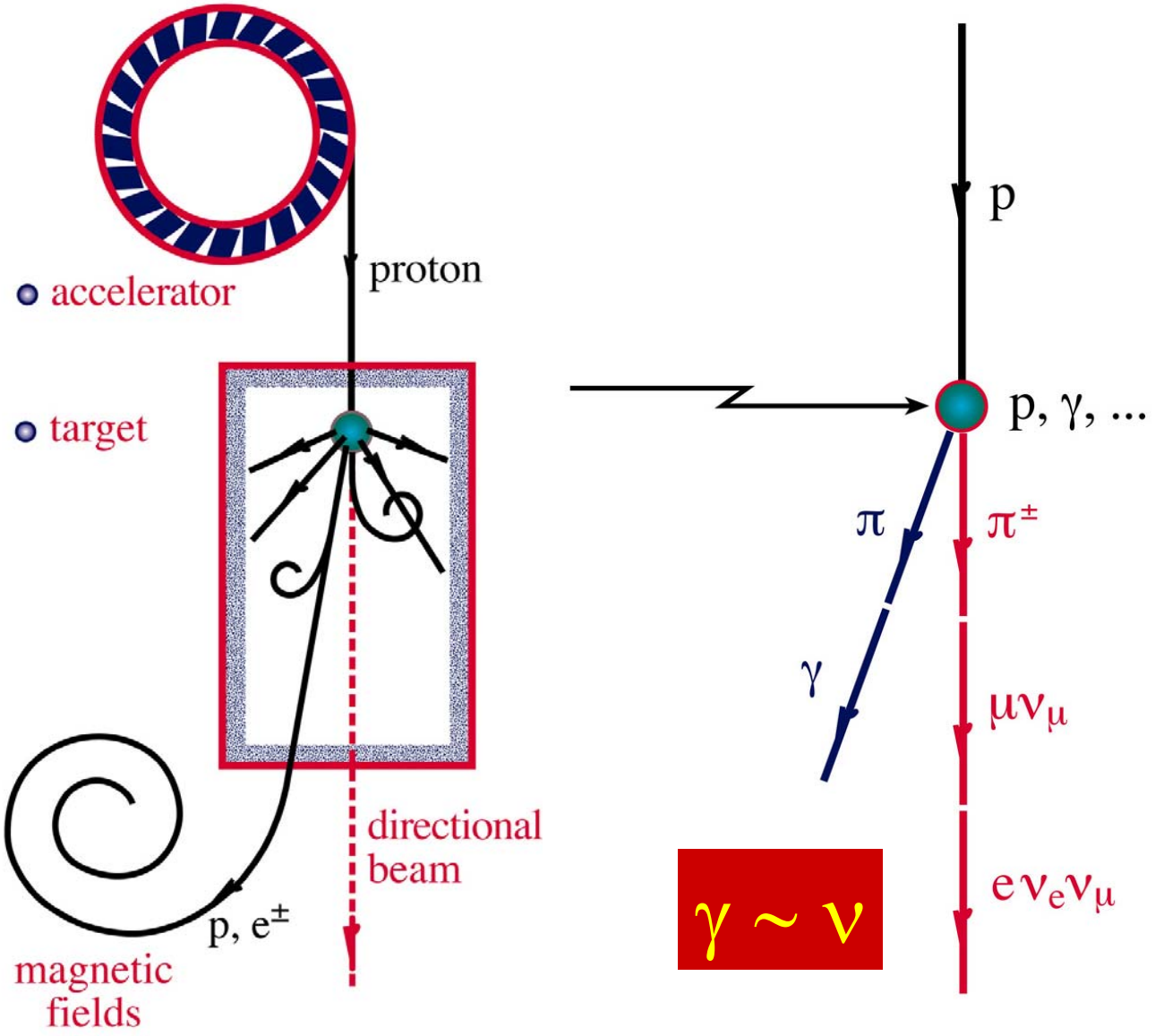

50
45
40
35
30
25
20.2
20.4
20.6
20.8
21
21.2
21.4
21.6
21.8
22
22.2

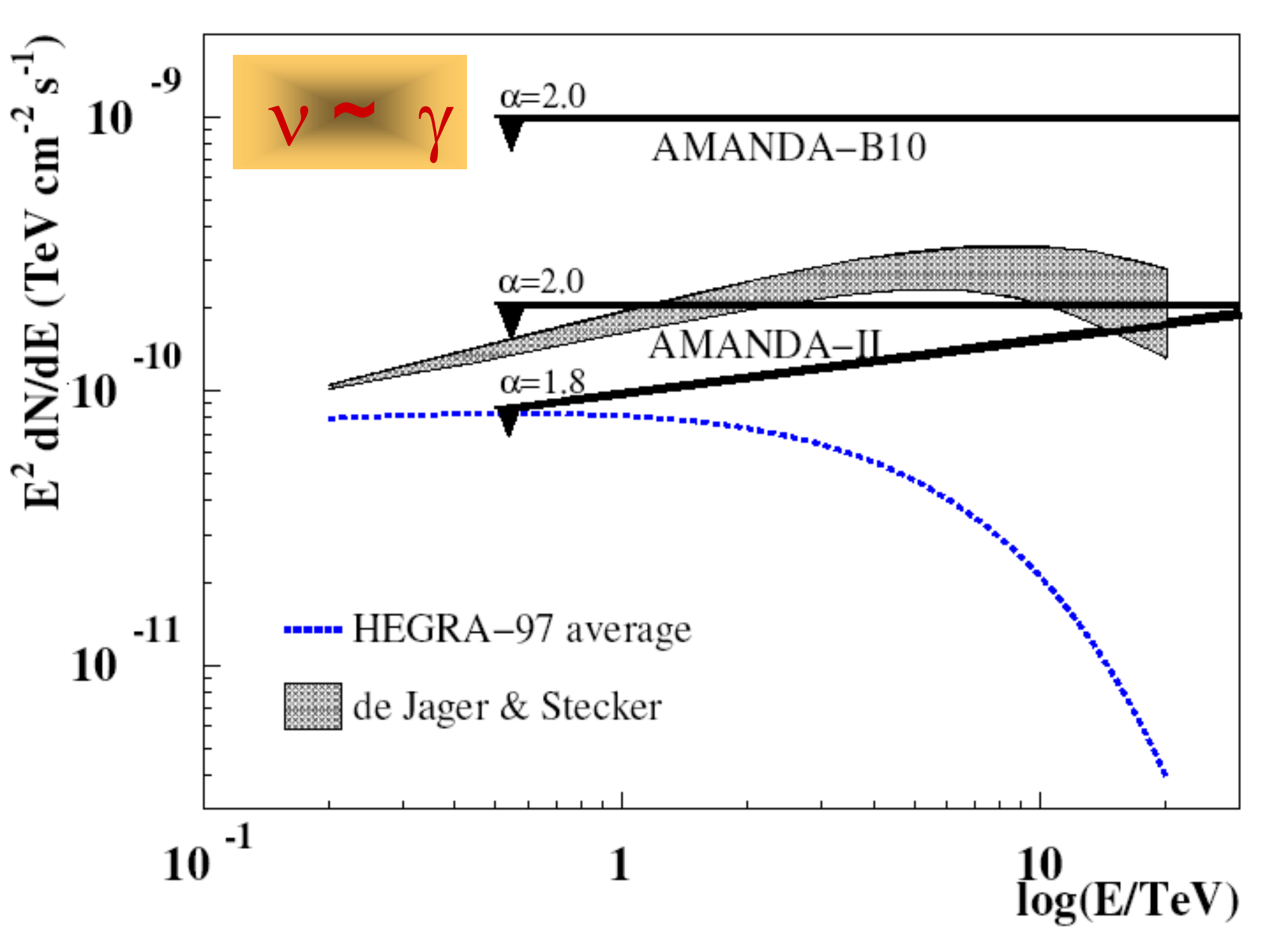

90°
24h
0h
-90°

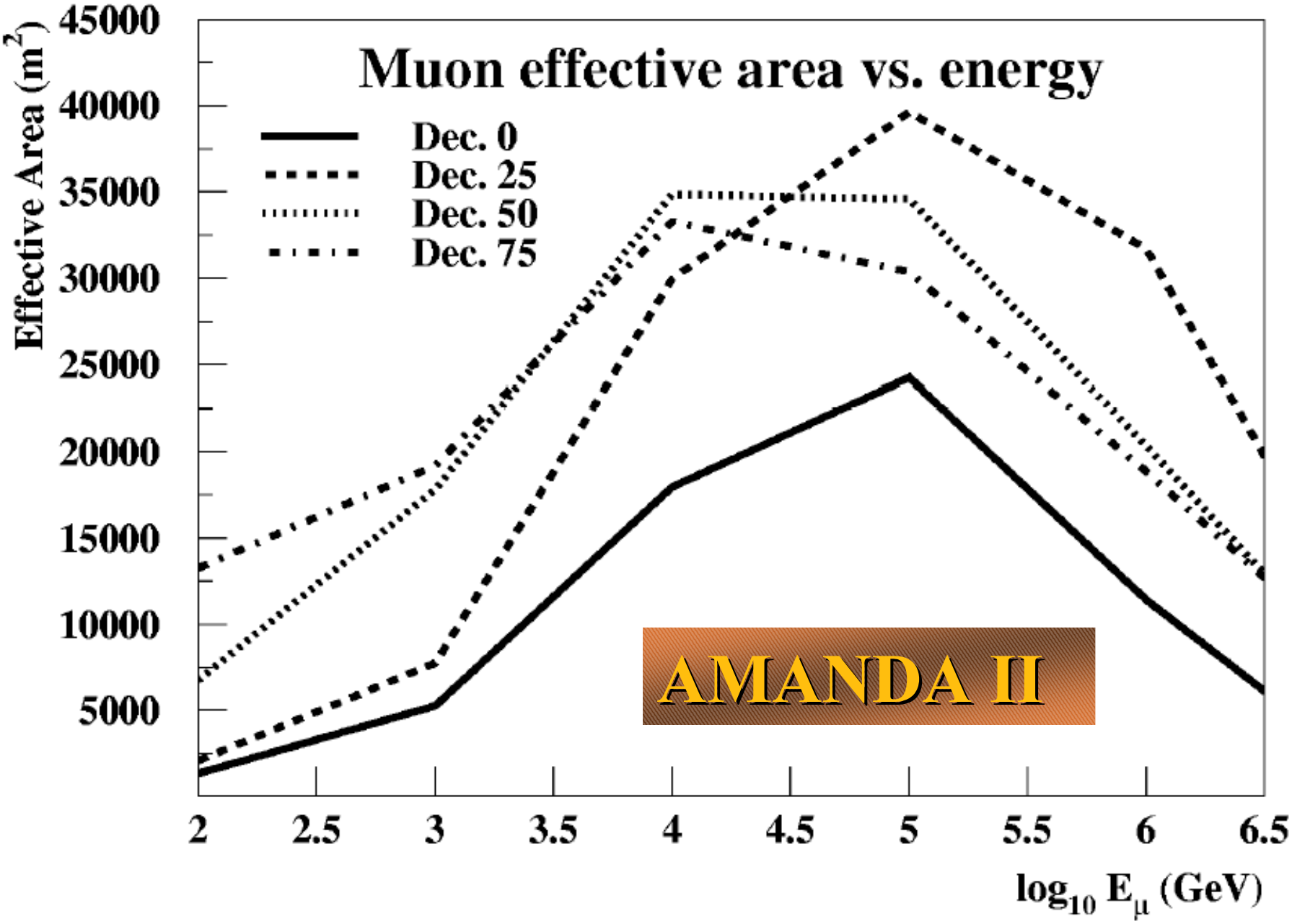
SS-433

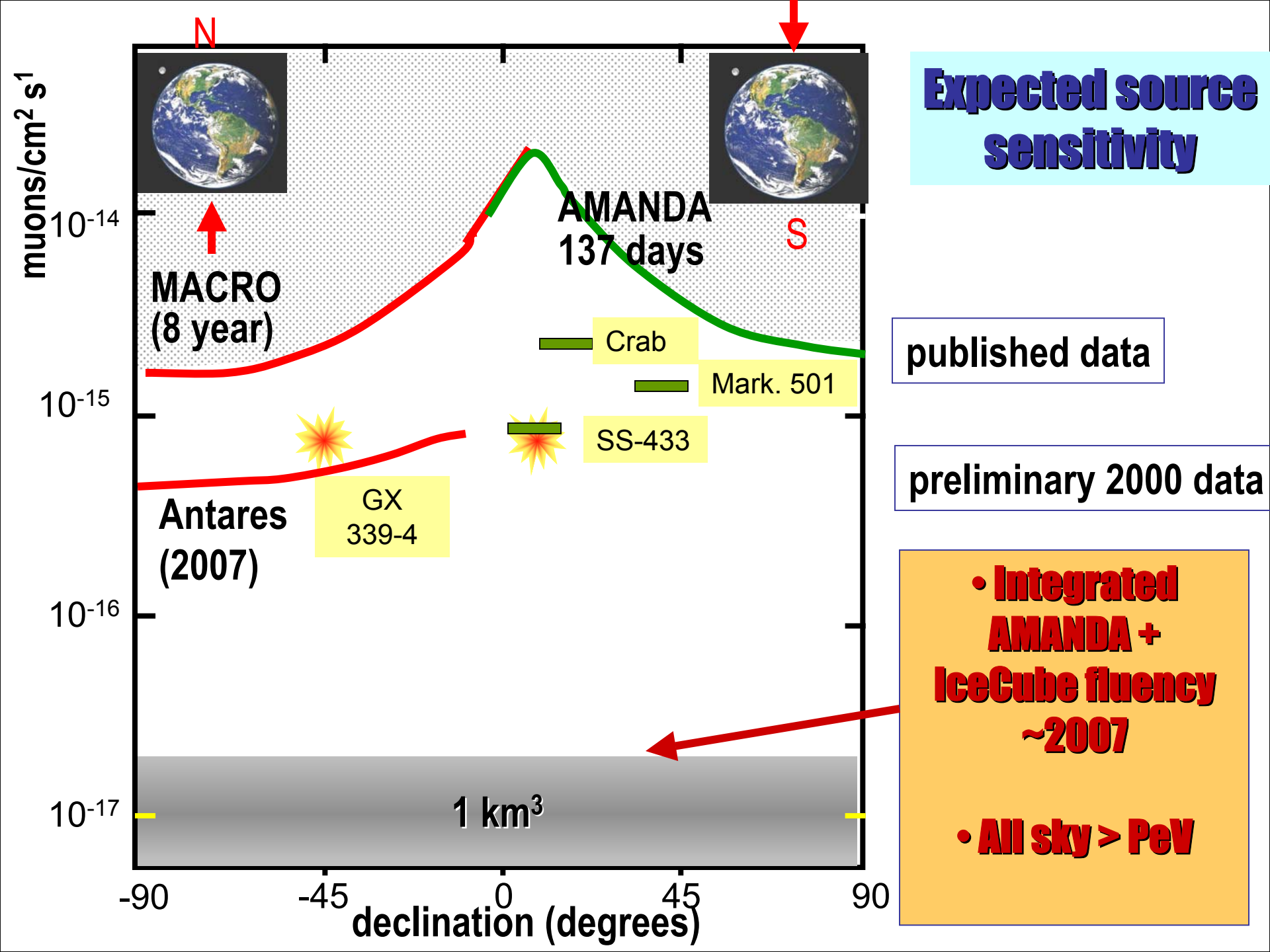


NEUTRINO BEAMS: HEAVEN & EARTH



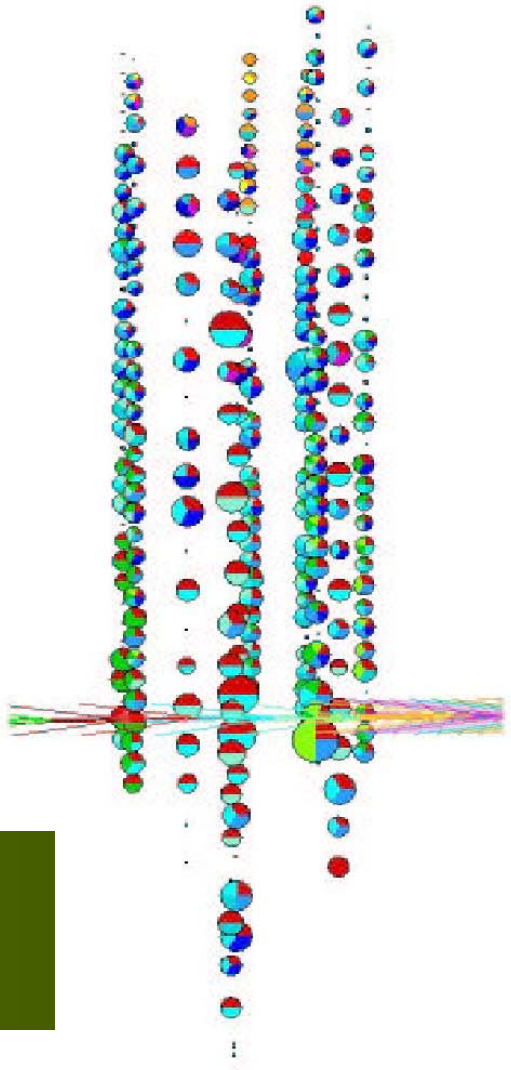

ν ~ γ
α=2.0
AMANDA–B10
α=2.0
AMANDA–II
α=1.8
HEGRA–97 average
de Jager & Stecker
E² dN/dE (TeV cm⁻² s⁻¹)
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹
1
10
log(E/TeV)


Muon effective area vs. energy
Dec. 0
Dec. 25
Dec. 50
Dec. 75
AMANDA II
Effective Area (m^2)
45000
40000
35000
30000
25000
20000
15000
10000
5000
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
log$_{10}$ E$_\mu$ (GeV)


N
S
muons/cm^2 s^1
10^{-14}
10^{-15}
10^{-16}
10^{-17}
MACRO
(8 year)
AMANDA
137 days
Crab
Mark. 501
SS-433
GX
339-4
Antares
(2007)
1 km^3
-90
-45
0
45
90
declination (degrees)
Expected source sensitivity
published data
preliminary 2000 data
• Integrated AMANDA + IceCube fluency ~2007
• All sky > PeV

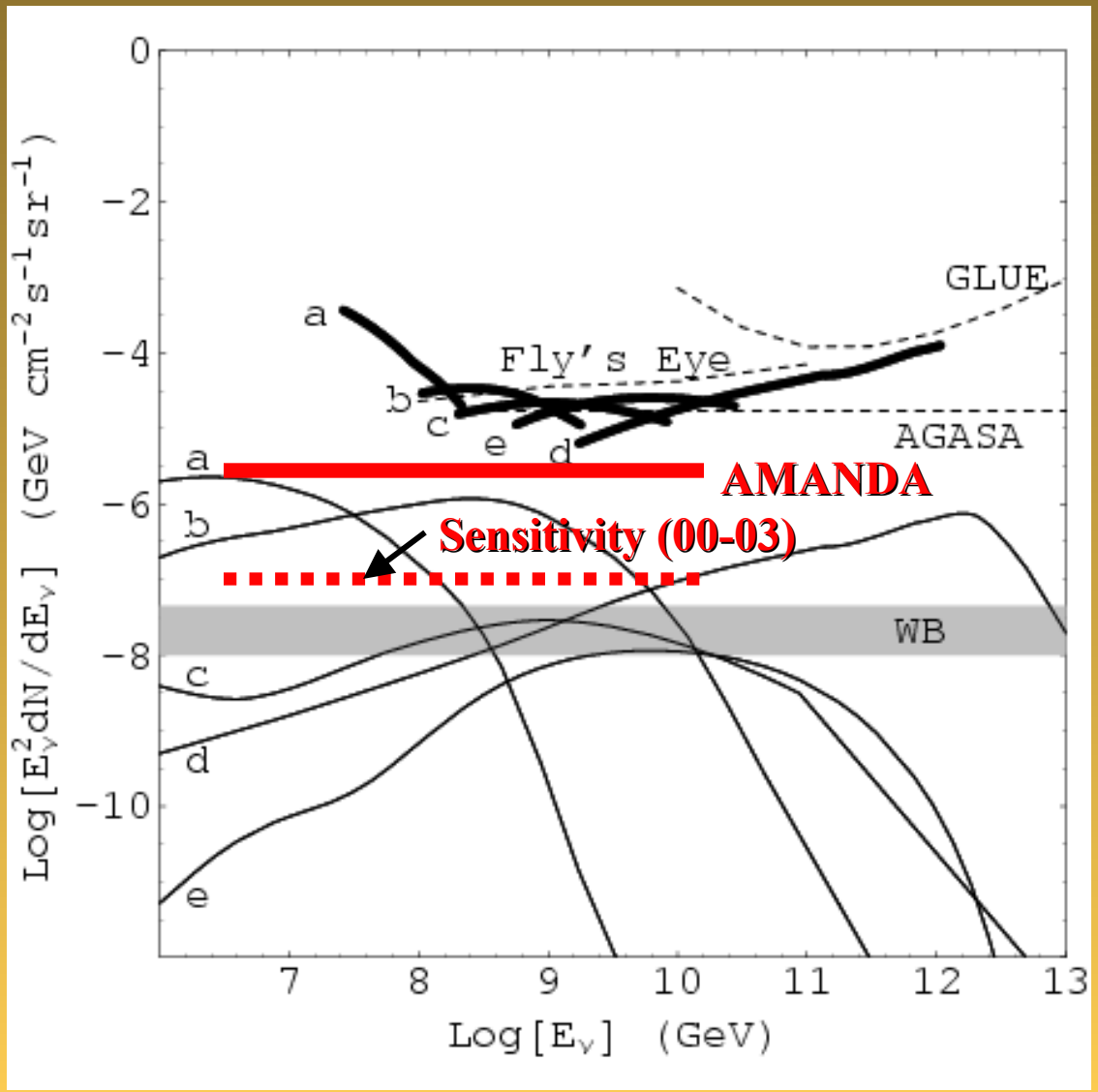
Ultra High Energy Neutrinos in AMANDA

- **Energy > 10 PeV**
- **All sky**
- **Large neutrino cross sections**
- **Large muon range (> 10 km)**



Competitive with radio, acoustic and air shower experiments

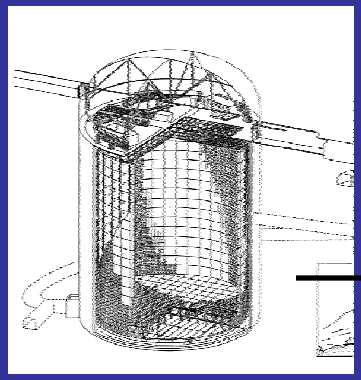
diffuse EHE neutrino flux limits

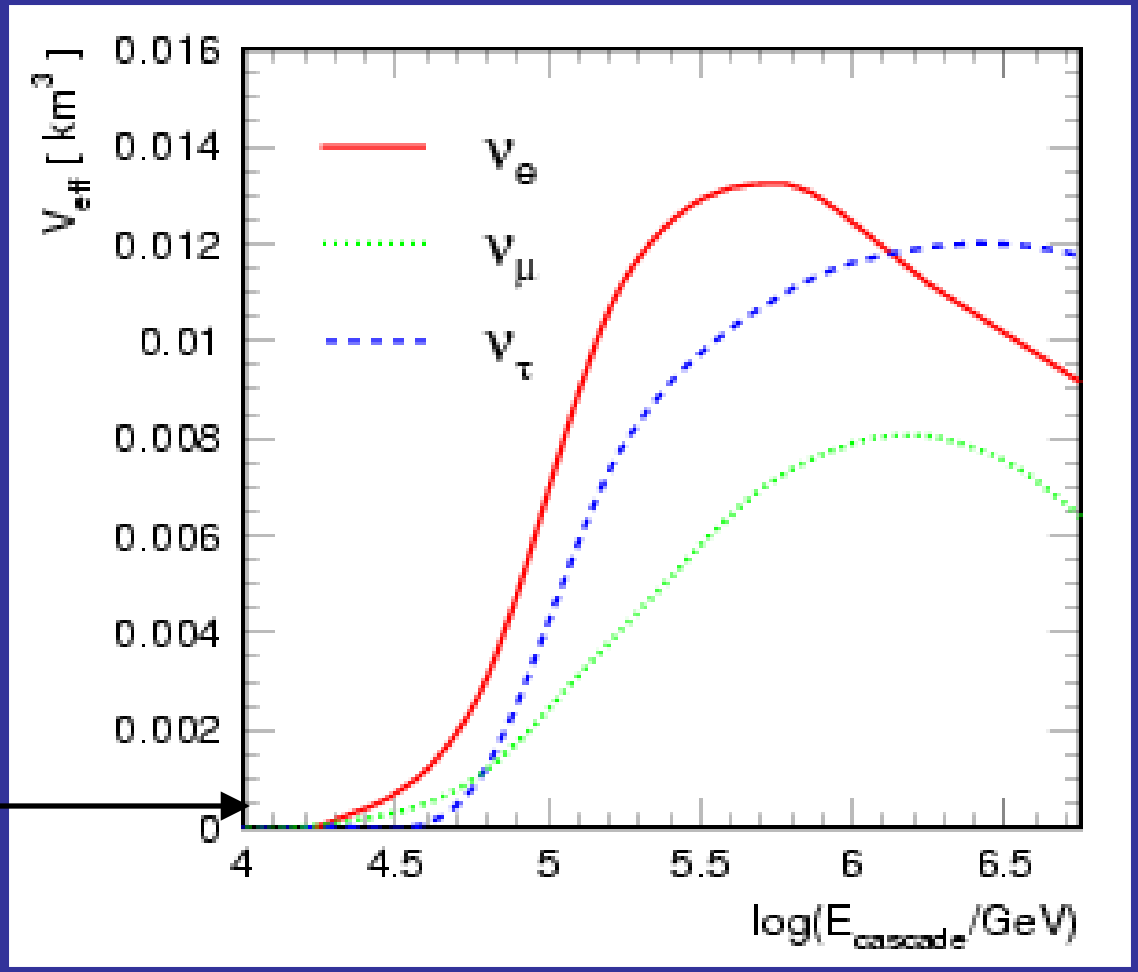


a) Stecker & Salamon (AGN)
b) Protheroe (AGN)
c) Mannheim (AGN)
d) Protheroe & Stanev (TD)
e) Engel, Seckel & Stanev

Ranges are central 80%

Effective Volume for ν_e, ν_μ and ν_τ

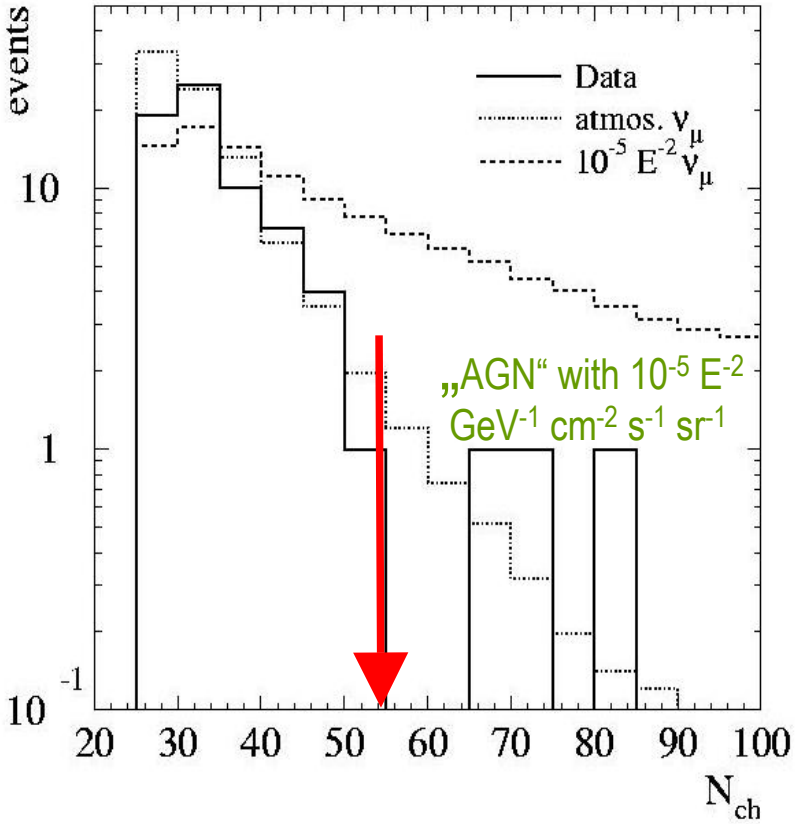




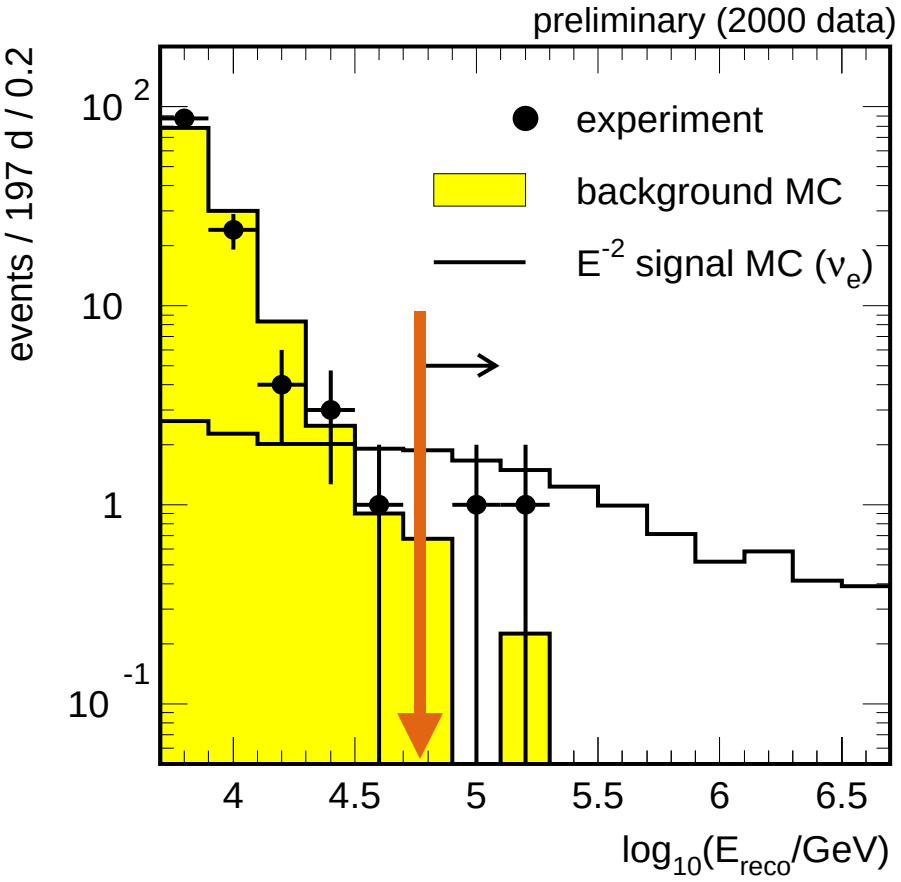
Excess of cosmic neutrinos?

.. for now use number of hit channels as energy variable ...

muon neutrinos (1997 B10-data)

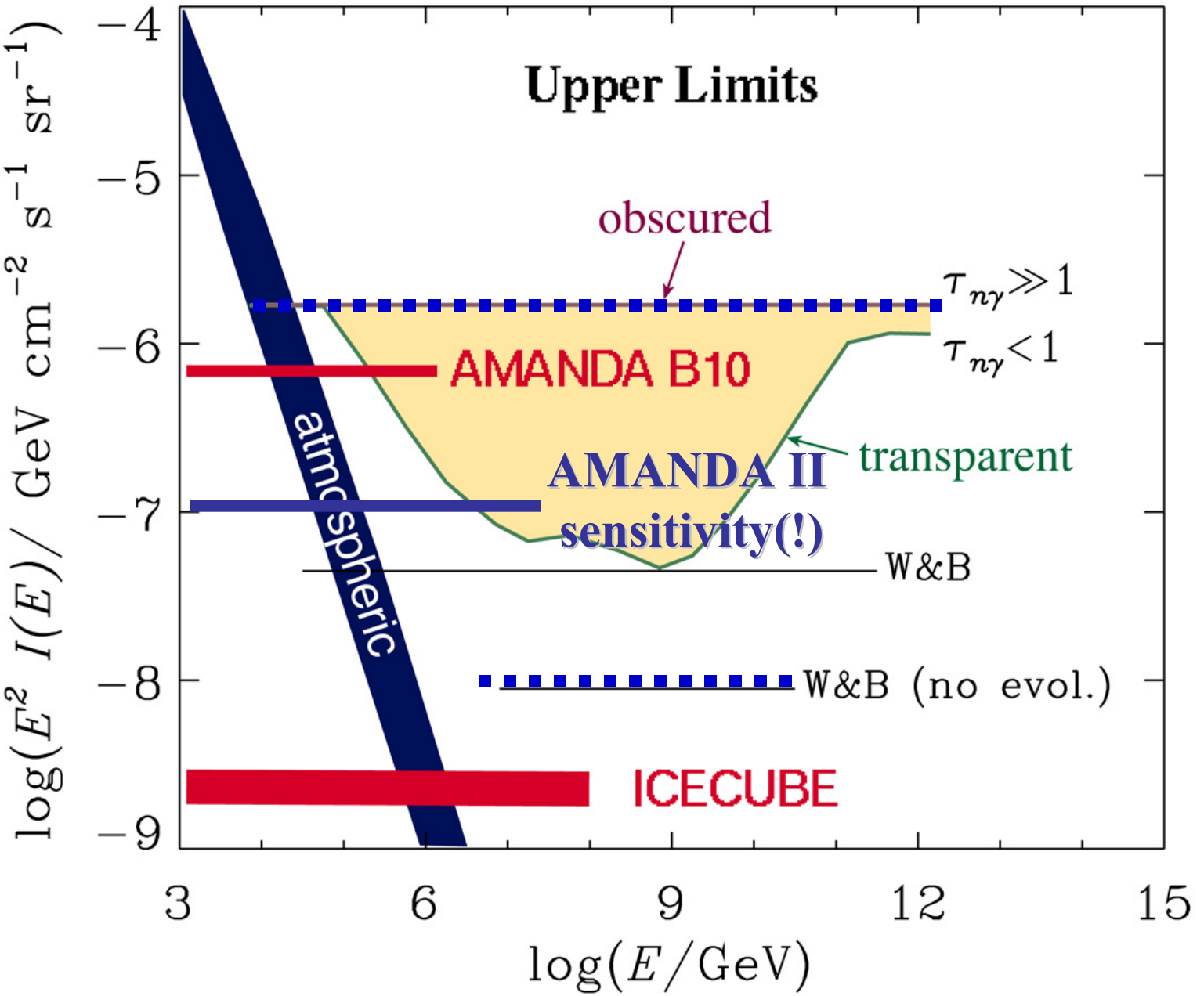


Electron + tau (2000 data)

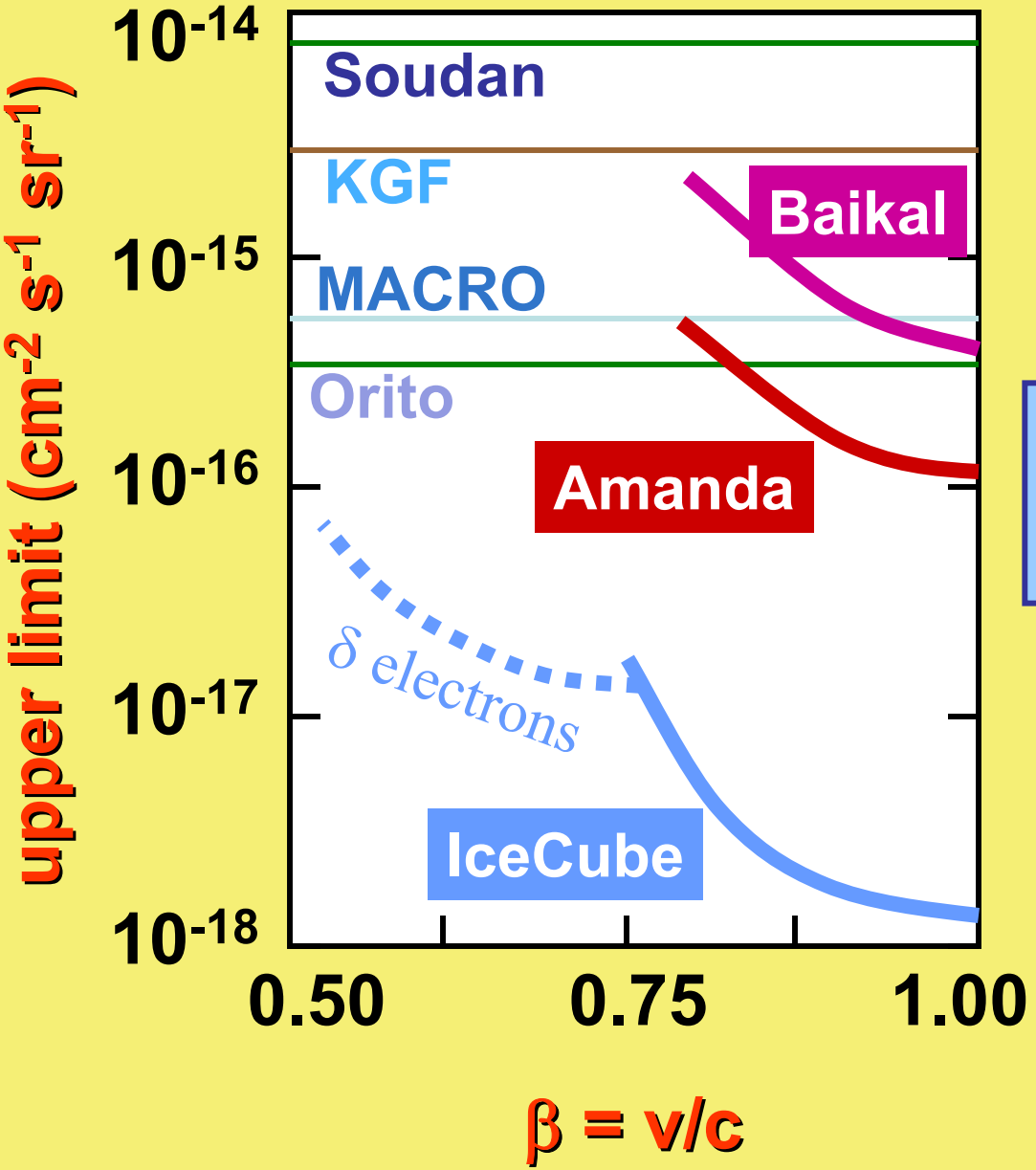


cuts determined by MC – blind analyses !

neutrinos associated with the source of the cosmic rays?



Relativistic Magnetic Monopoles



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

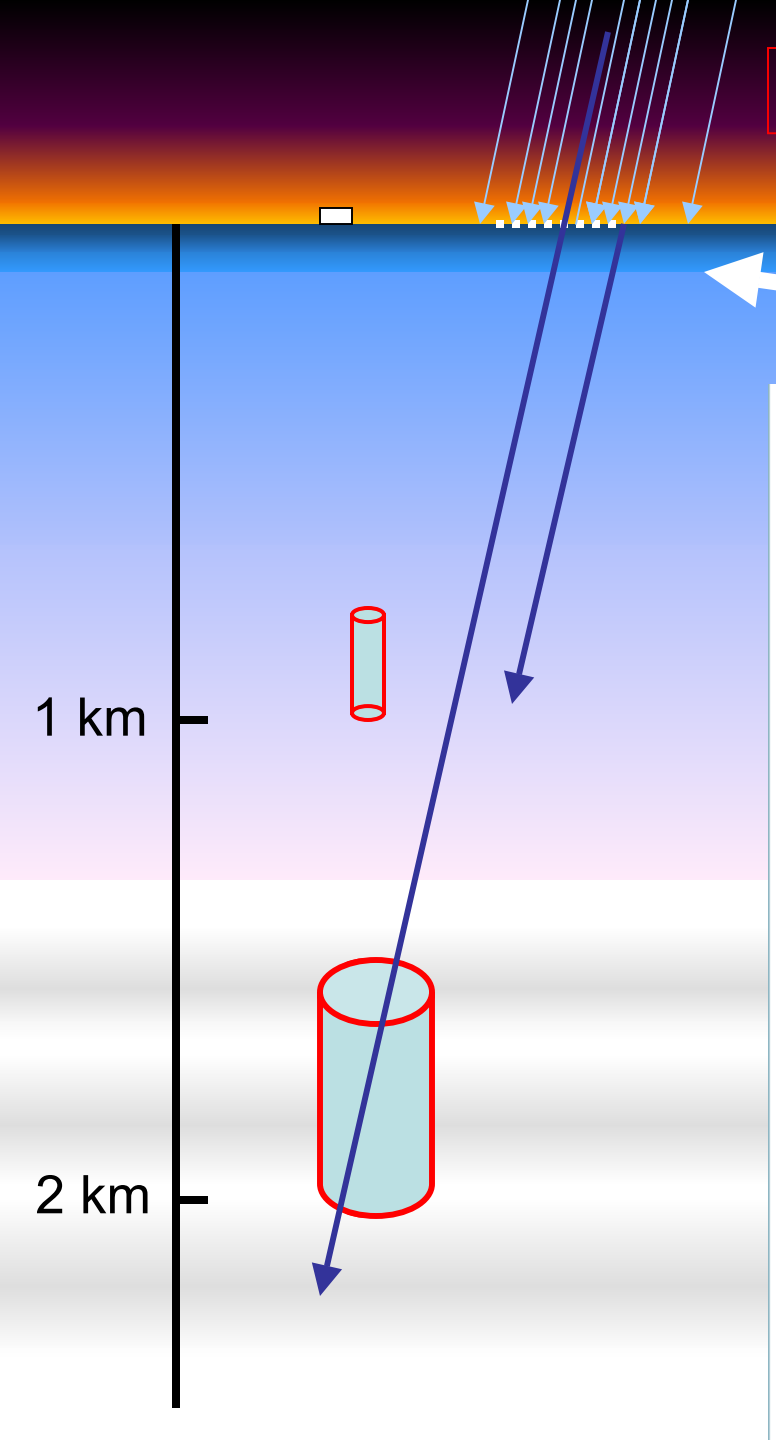
$n = 1.33$

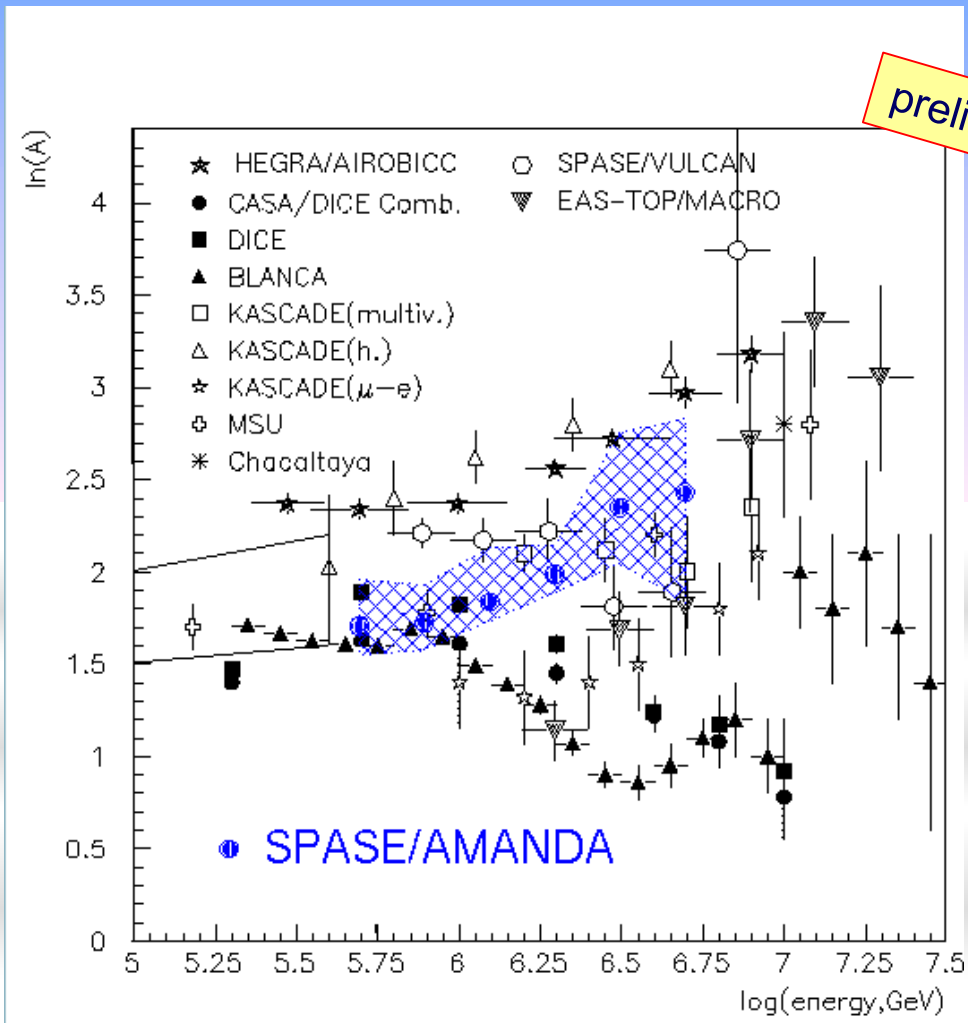
$(g/e) = 137/2$

≈ 8300

Bonus Physics: Cosmic ray composition

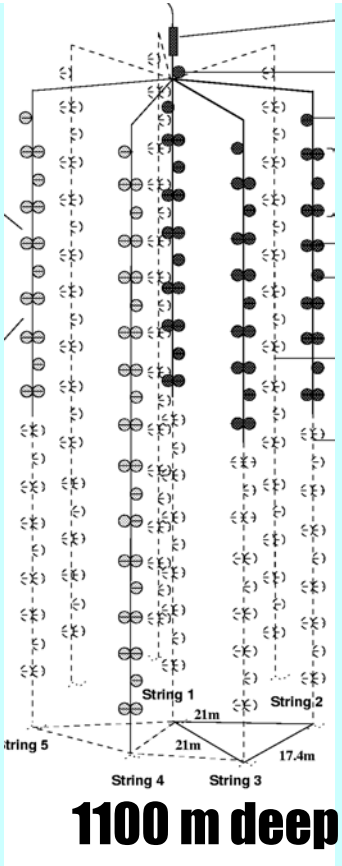
SPASE air shower arrays





Northern hemisphere detectors

Baikal NT200



1100 m deep

data taking since 1998

new: 3 distant strings

Antares

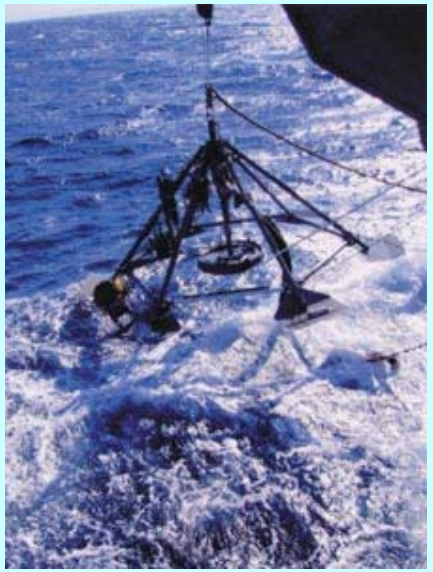
March 17, 2003

2 strings connected

2400 m deep

completion: start 2006

Nestor



March 29, 2003

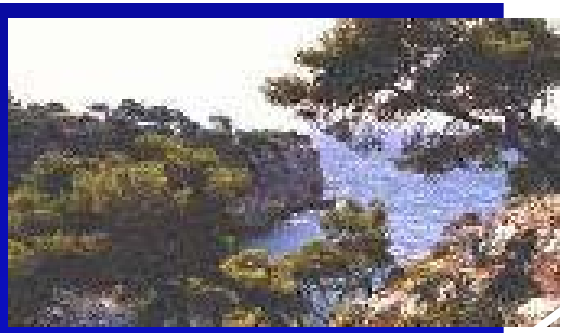
1 of 12 floors deployed

4000 m deep

completion:

Optical Cerenkov Neutrino Telescope Projects

ANTARES
La-Seyne-sur-Mer, France



NEMO
Catania, Italy

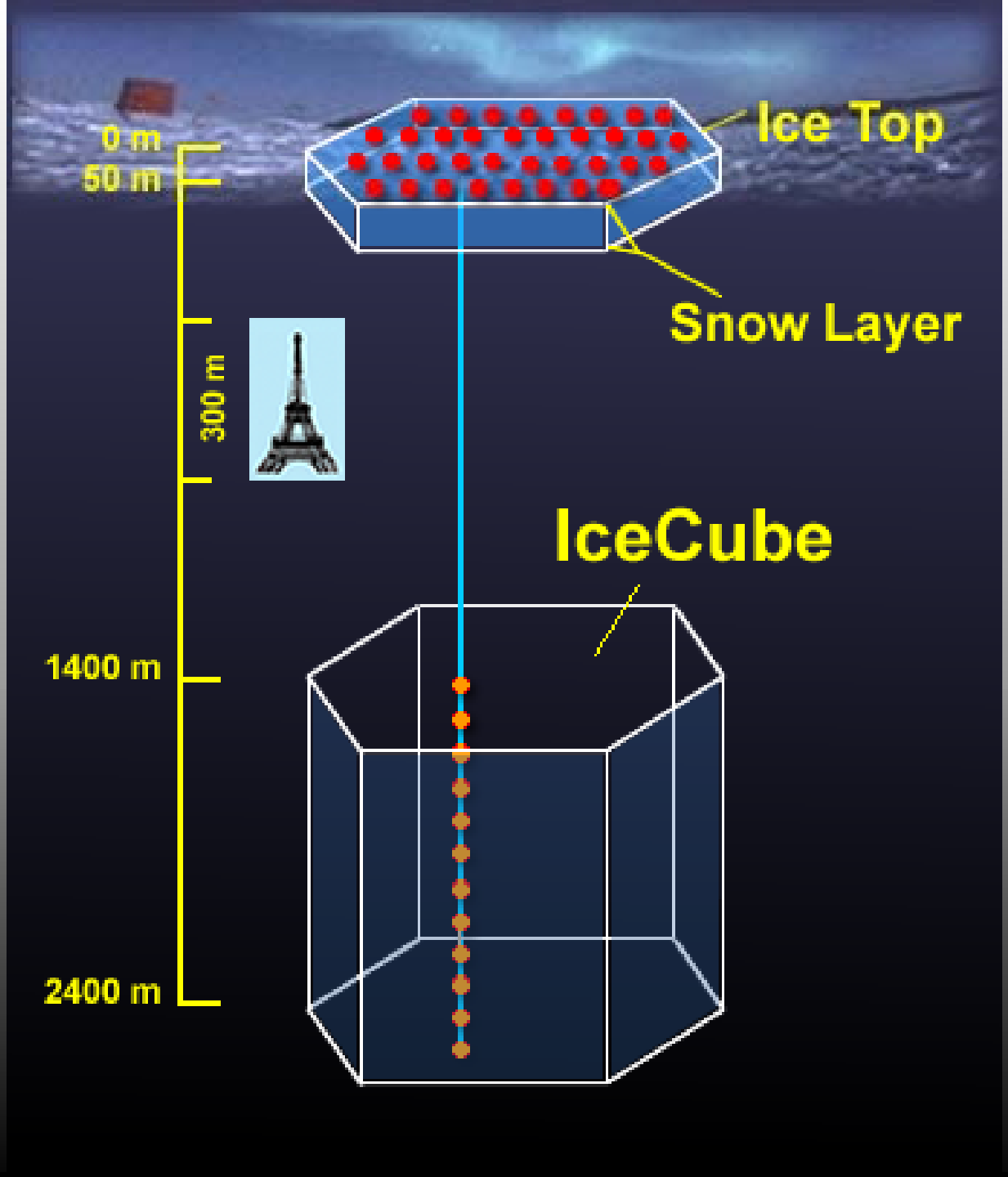
NESTOR
Pylos, Greece

BAIKAL
Russia

DUMAND
Hawaii
(cancelled 1995)

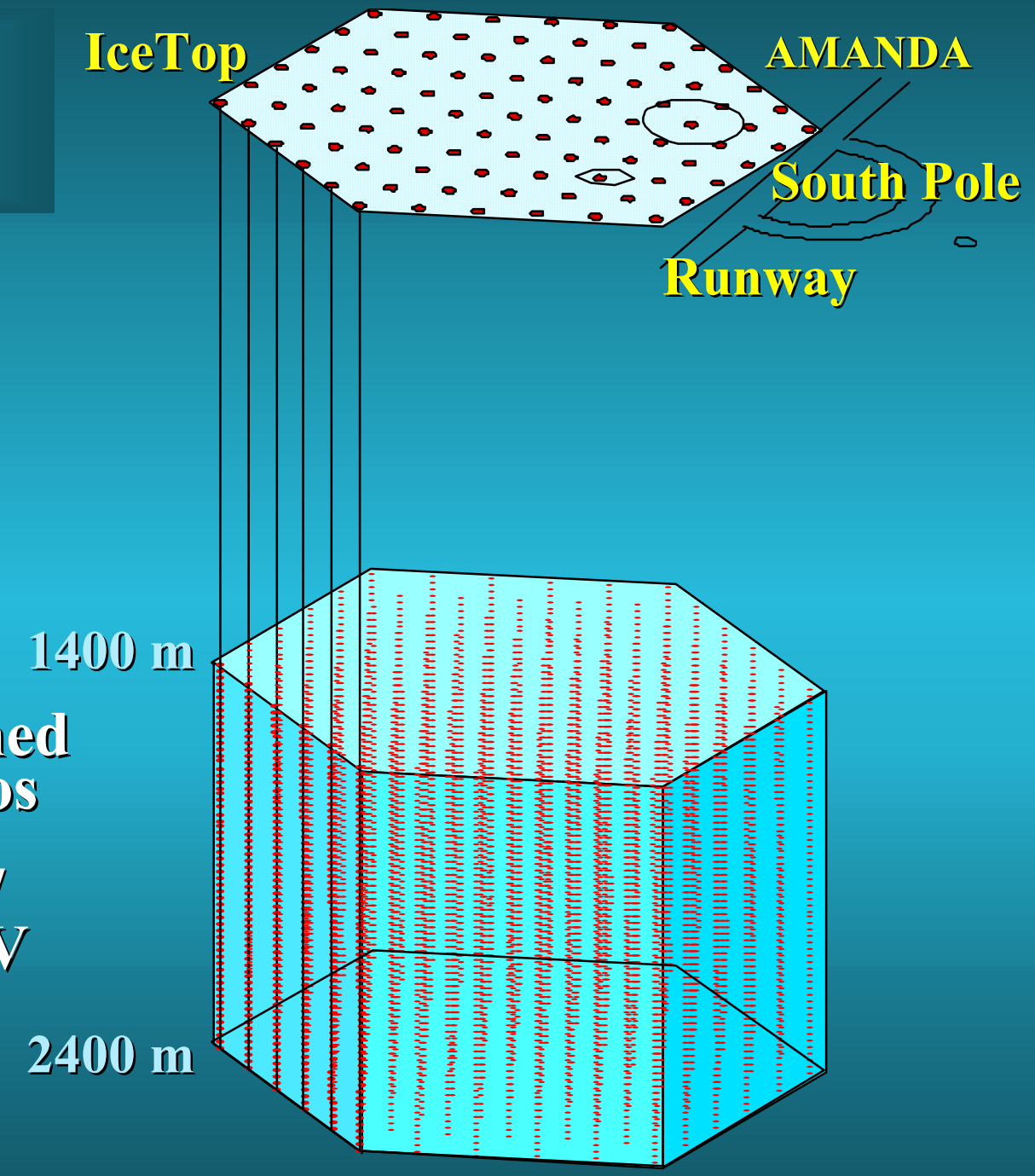
AMANDA, South Pole, Antarctica

kilometer-scale neutrino observatories

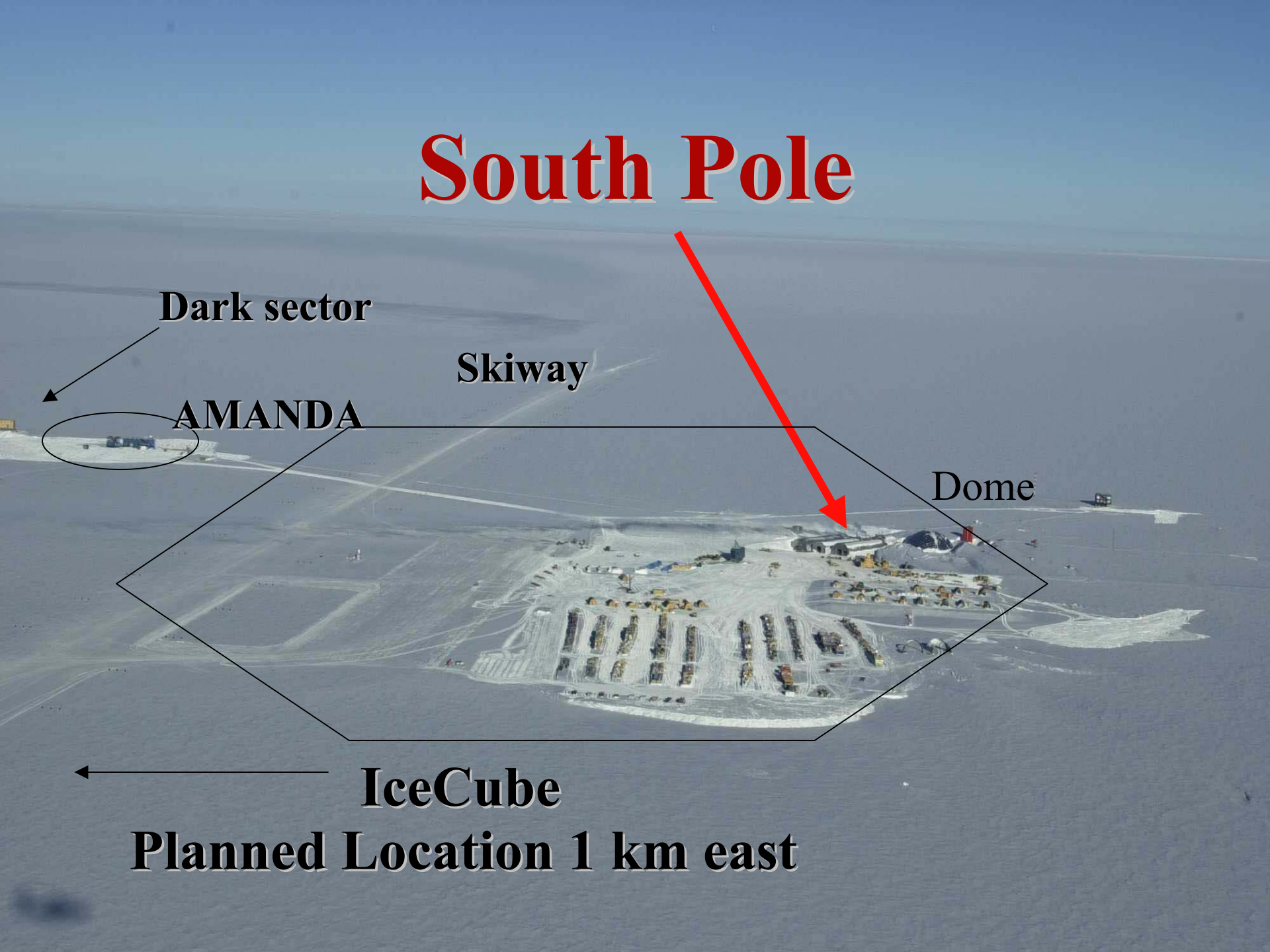

0 m
50 m
Ice Top
Snow Layer
300 m
IceCube
1400 m
2400 m

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



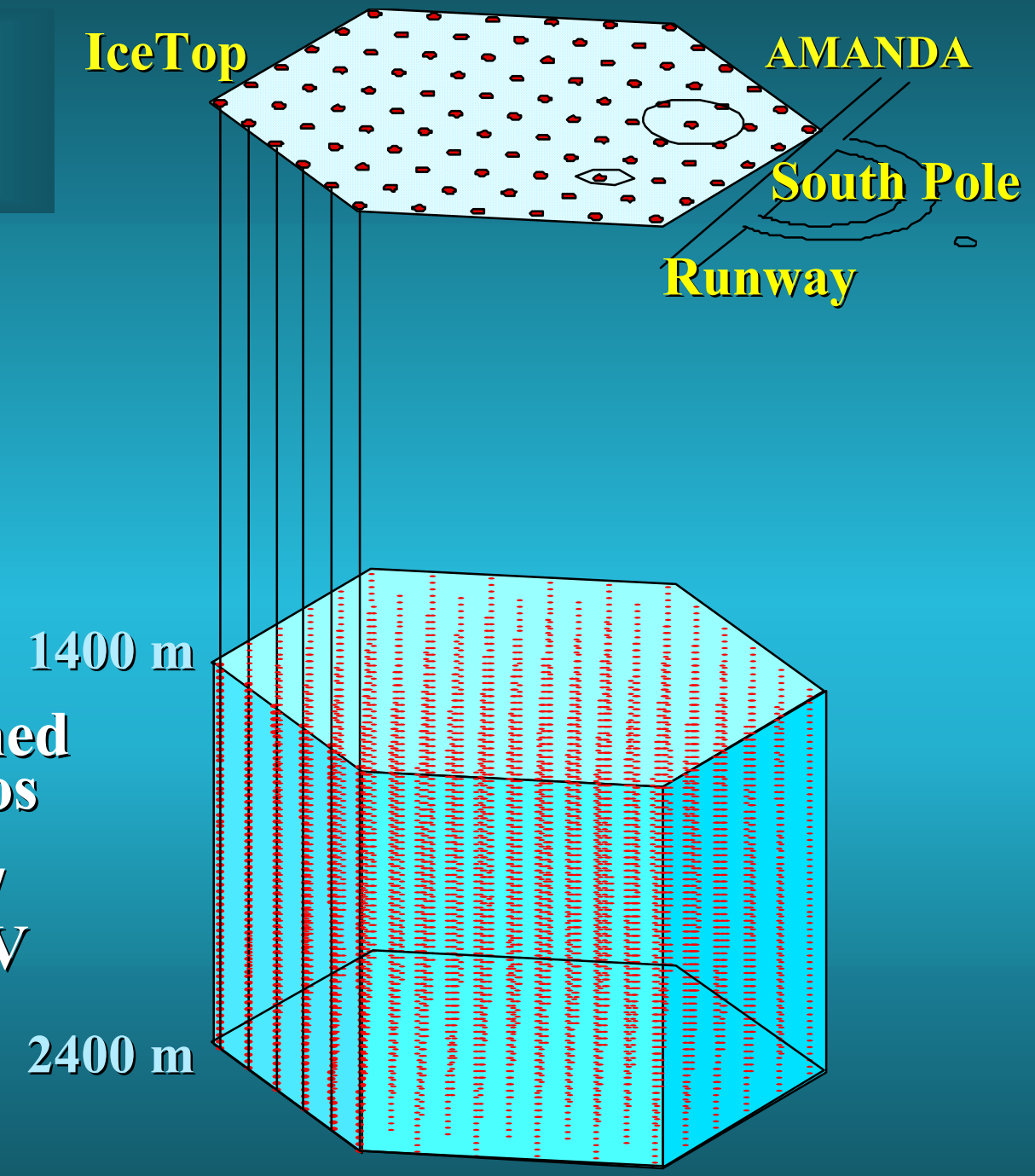

South Pole
AMANDA– 1 mile deep


South Pole
Dark sector
Skiway
AMANDA
Dome
IceCube
Planned Location 1 km east


South Pole
Dark sector
Skiway
AMANDA
Dome
IceCube

IceCube

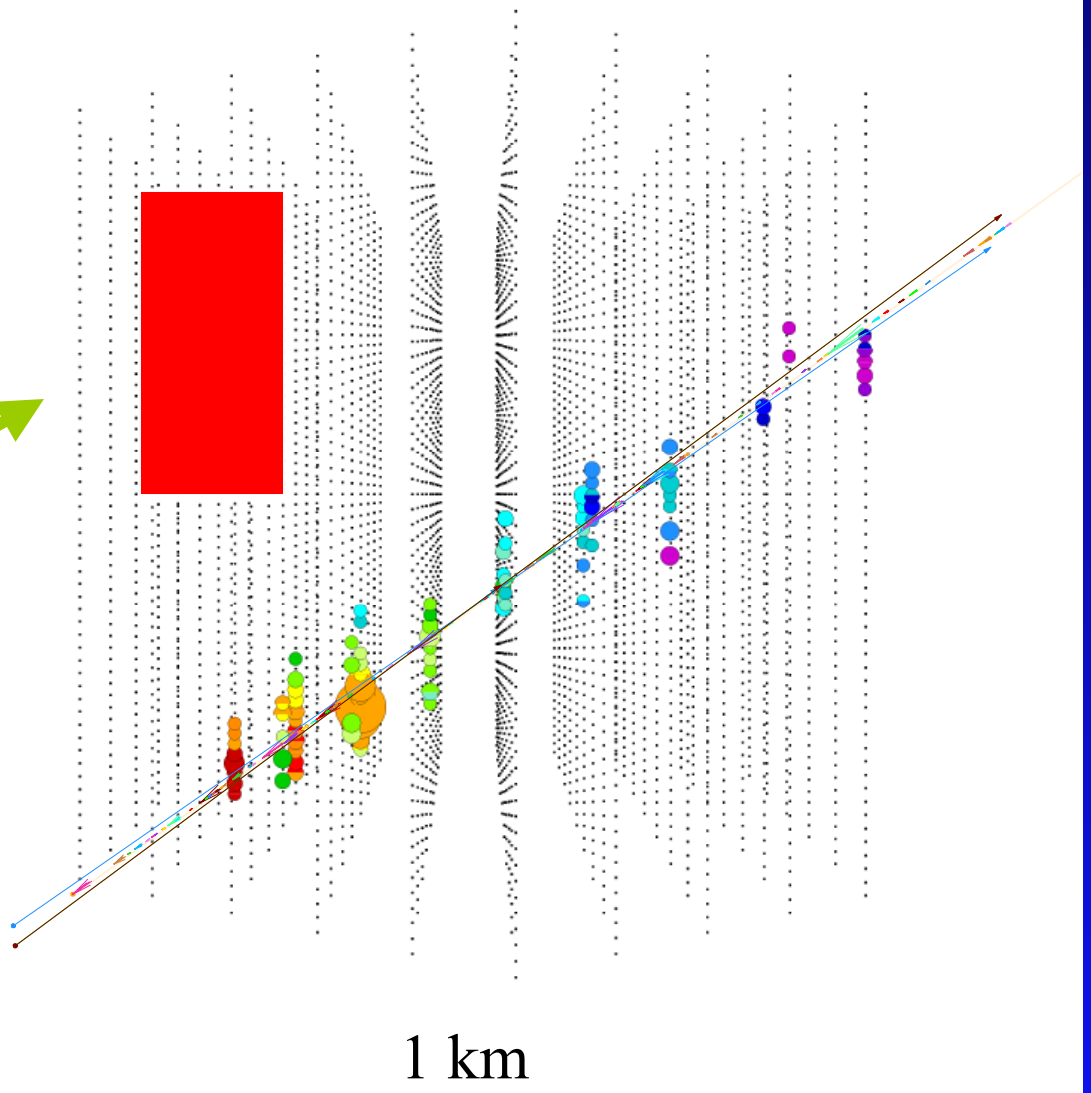
- 80 Strings
- 4800 PMT
- Instrumented volume: 1 km3 (1 Gton)
- IceCube is designed to detect neutrinos of all flavors at energies from 10^7 eV (SN) to 10^{20} eV



μ-event in IceCube

300 atmospheric neutrinos per day

AMANDA II



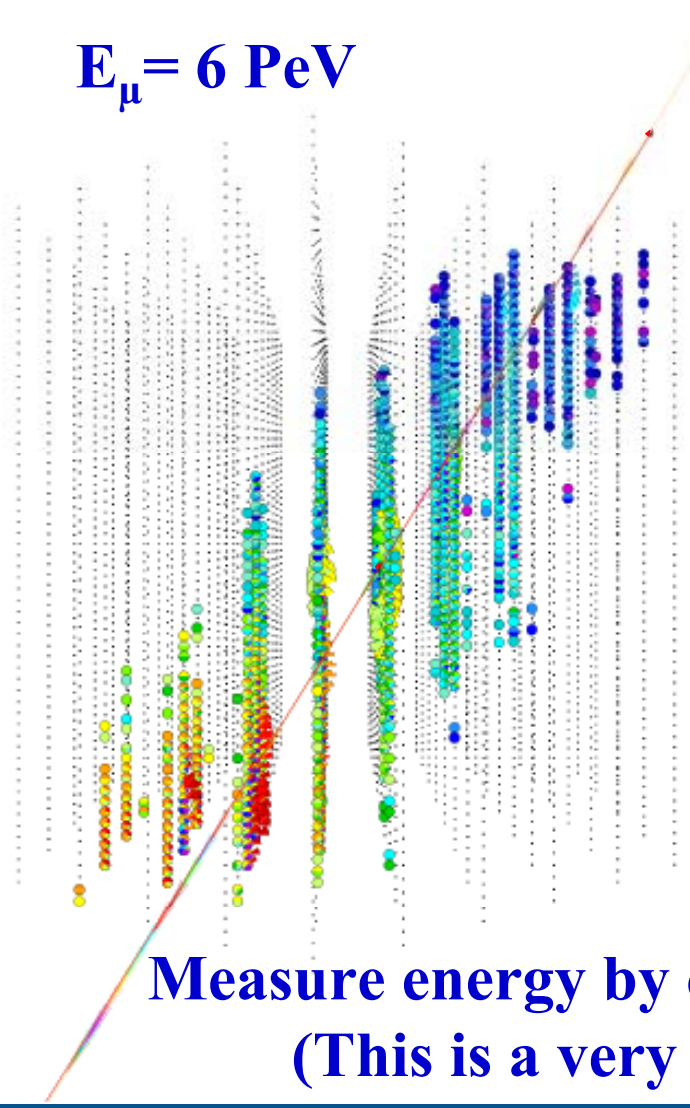
IceCube:

-> Larger telescope

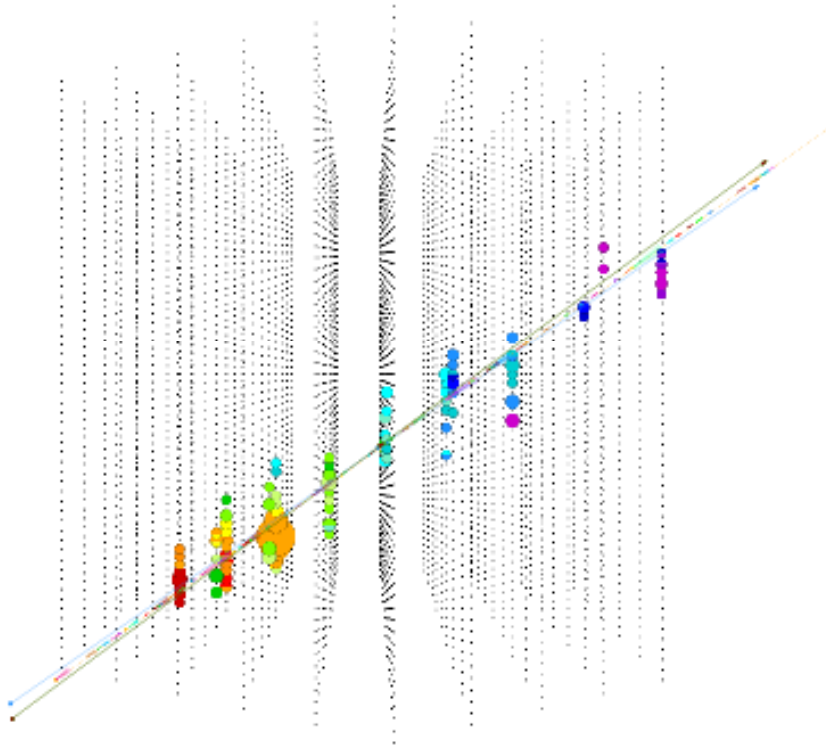
-> Superior detector

Muon Events

E_μ= 6 PeV



E_μ= 10 TeV



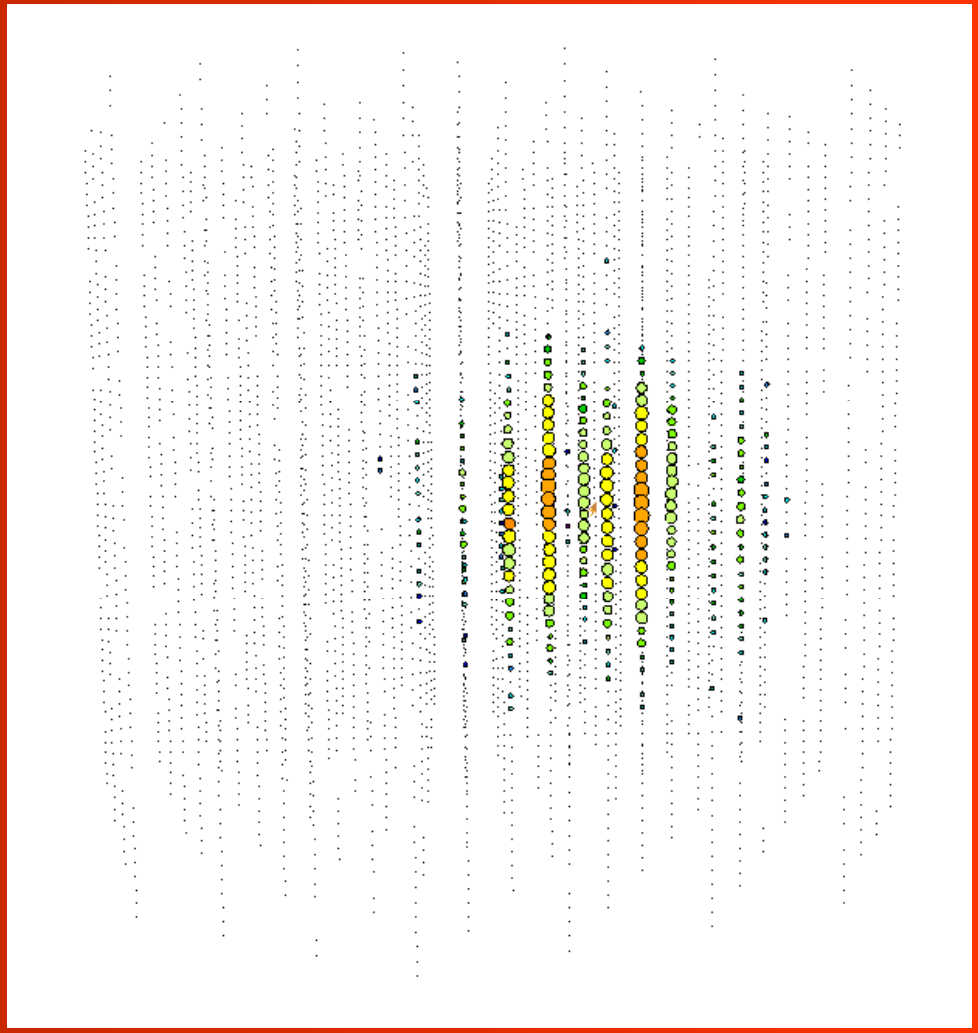
Measure energy by counting the number of fired PMT.
(This is a very simple but robust method)

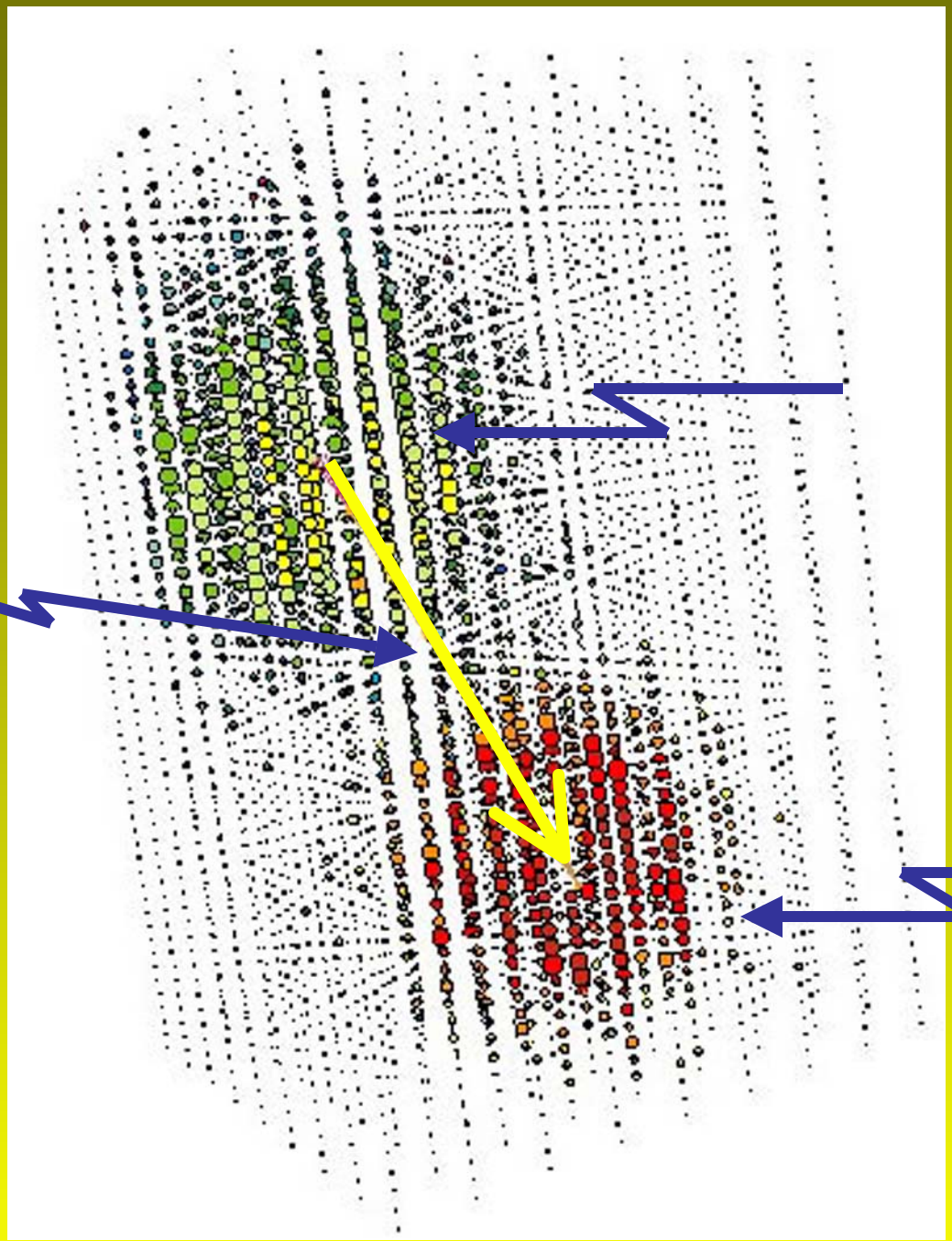
Cascade event

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

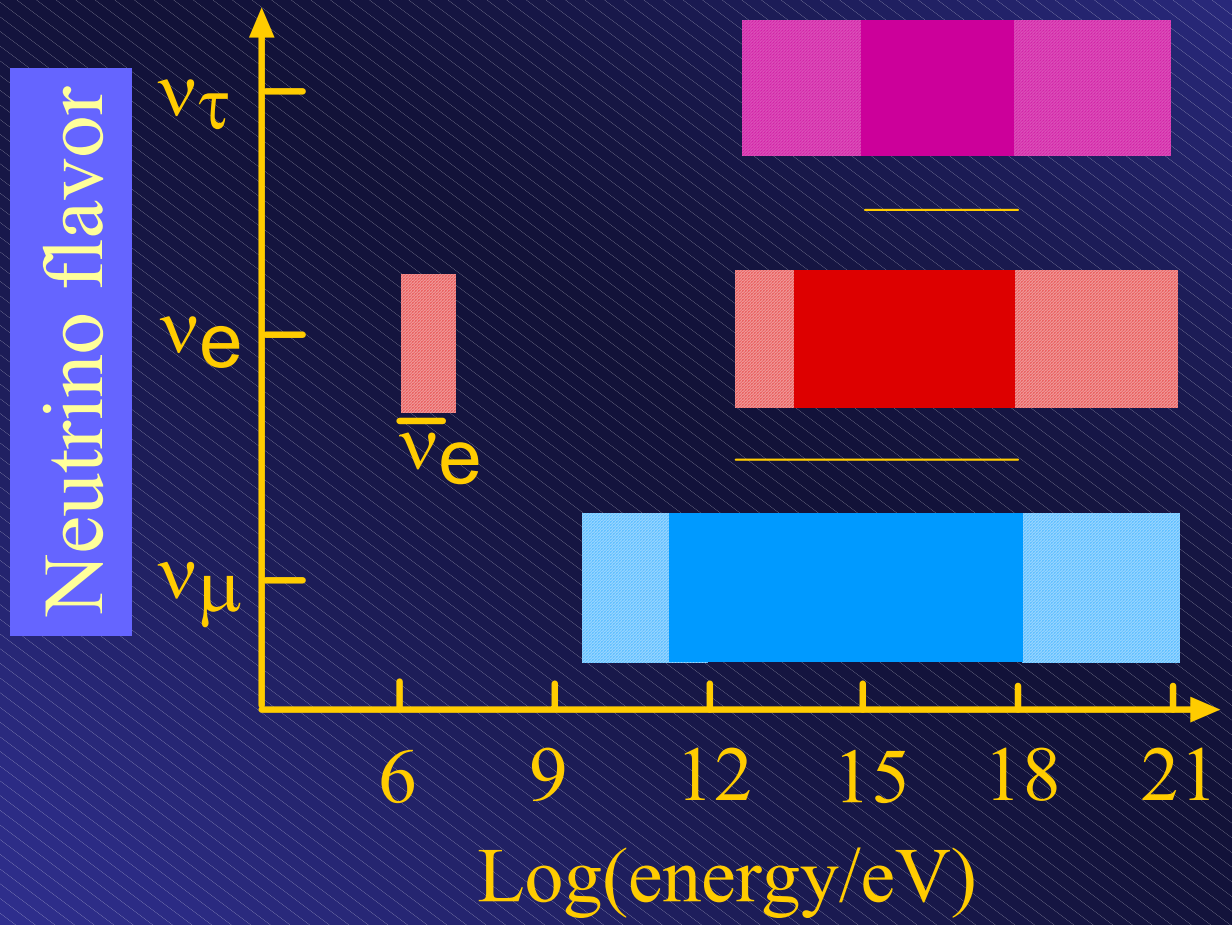
- the length of the e^- cascade is small compared to the spacing of sensors.
- roughly spherical density distribution of light.
- 1 PeV ≈ 500 m diameter, additional 100 m per decade of energy
- linear energy resolution

Energy = 375 TeV




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

Neutrino ID (solid)
Energy and angle (shaded)



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

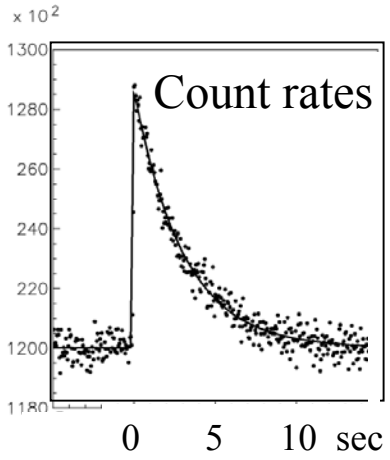
enhanced role of tau neutrinos:

- 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

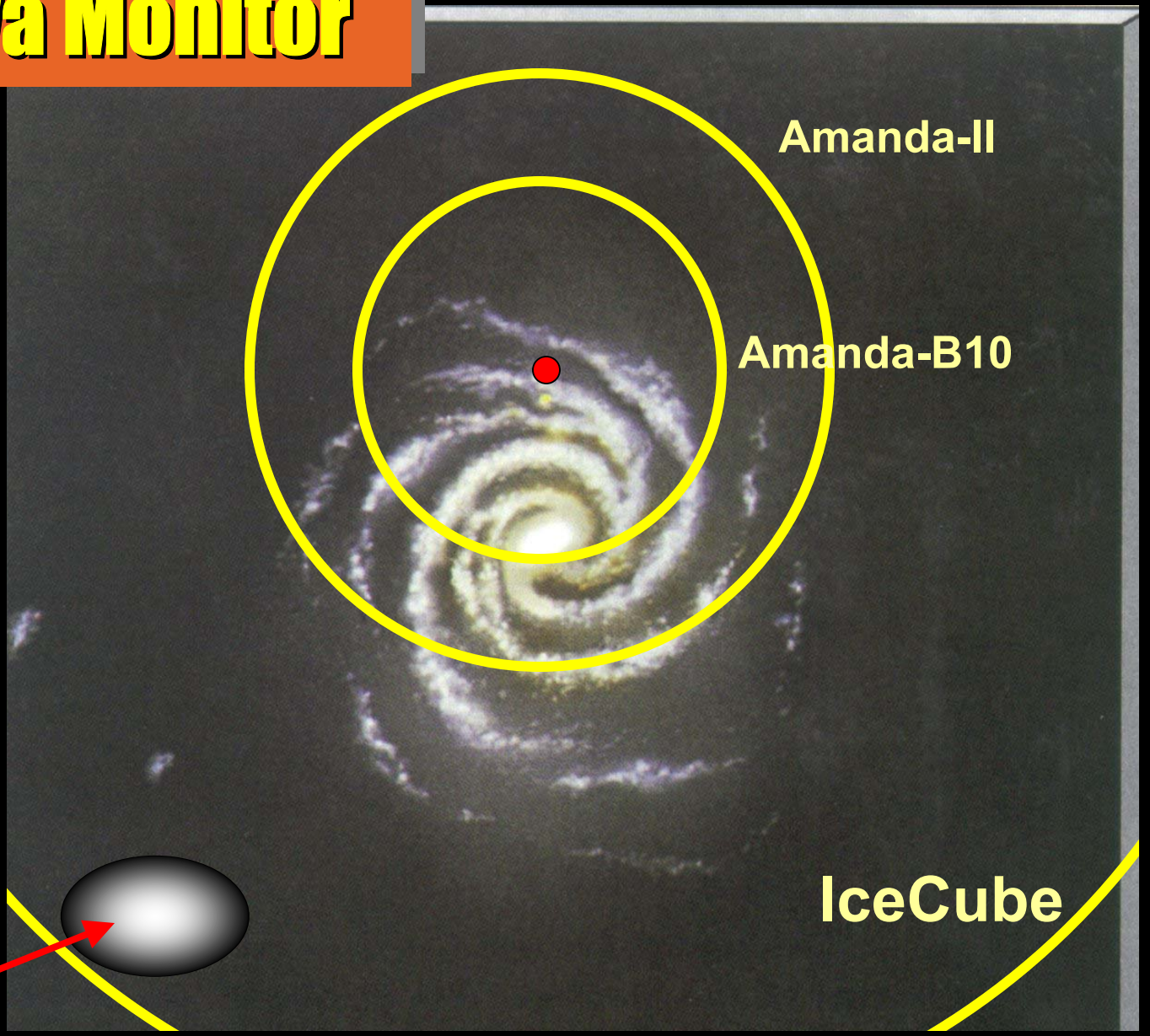
Supernova Monitor

B10:
60% of Galaxy

A-II:
95% of Galaxy



IceCube:
up to LMC



Raffelt astro-ph/0303210 !

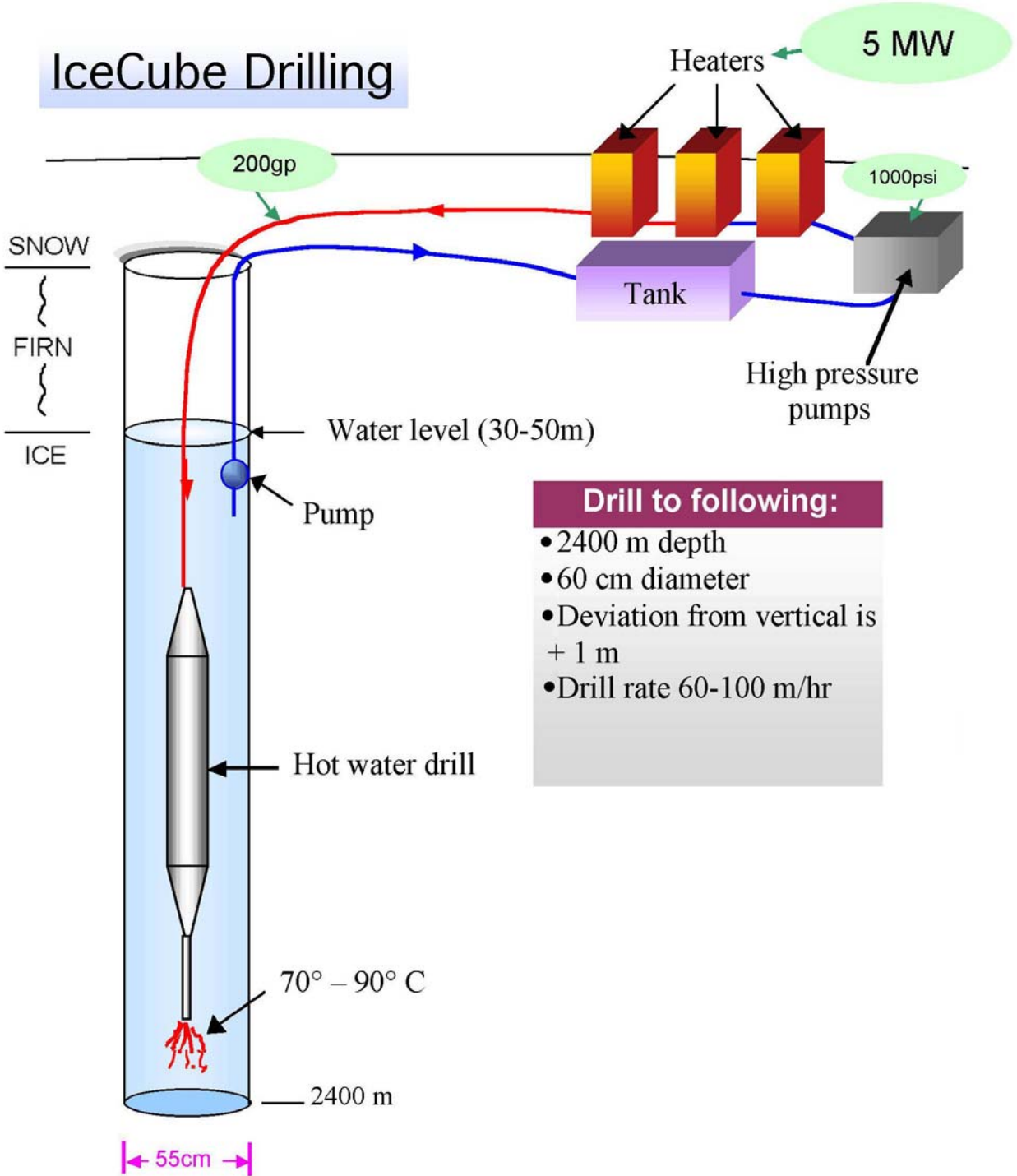
Enhanced role of tau neutrinos:

- 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

IceCube

- start 02
- first strings 04
- completed 09

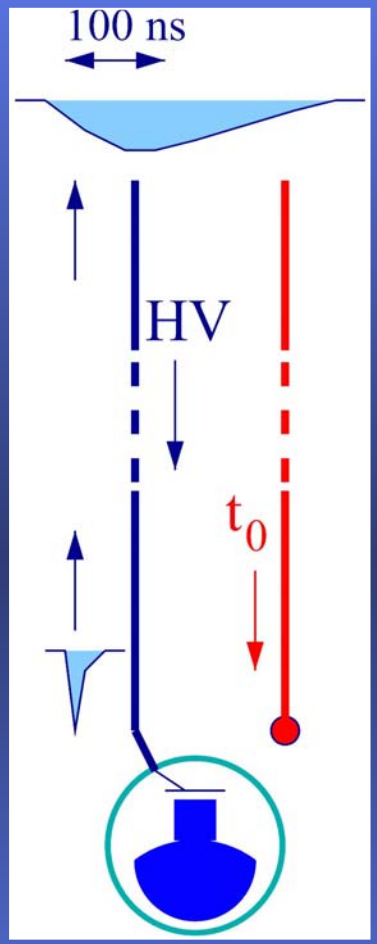
IceCube Drilling

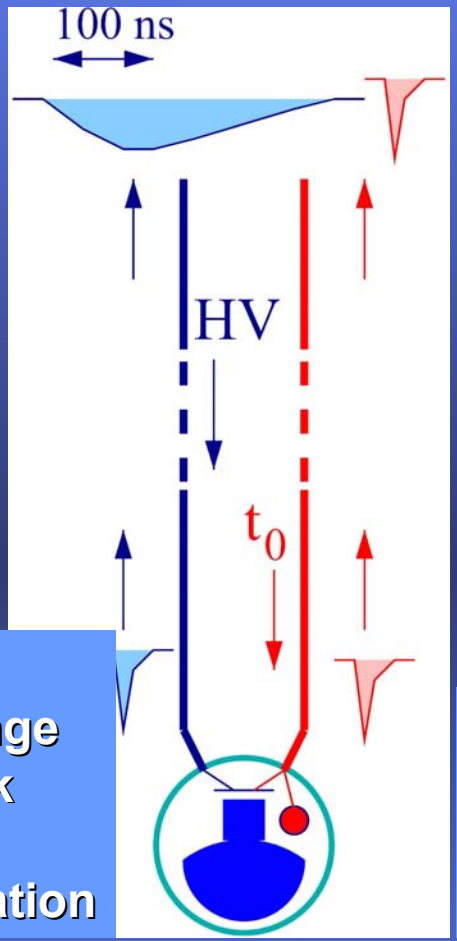


Drill to following:

- 2400 m depth
- 60 cm diameter
- Deviation from vertical is + 1 m
- Drill rate 60-100 m/hr

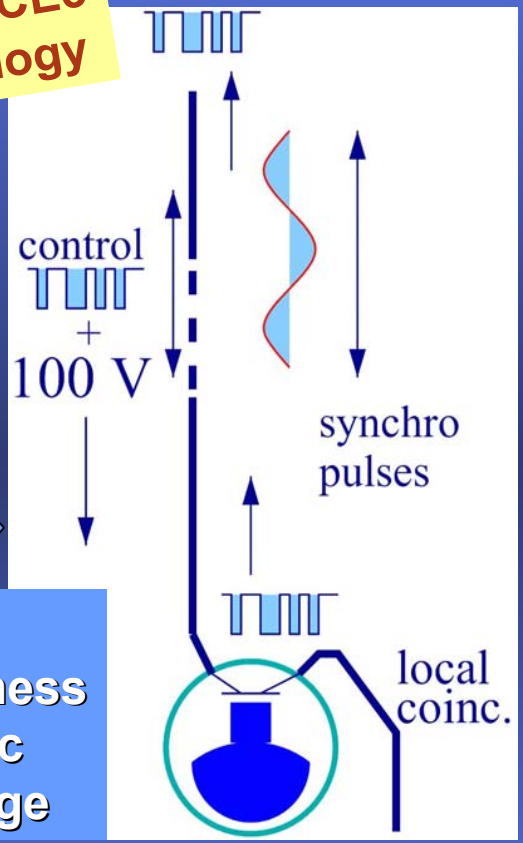
Evolution of read-out strategy





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

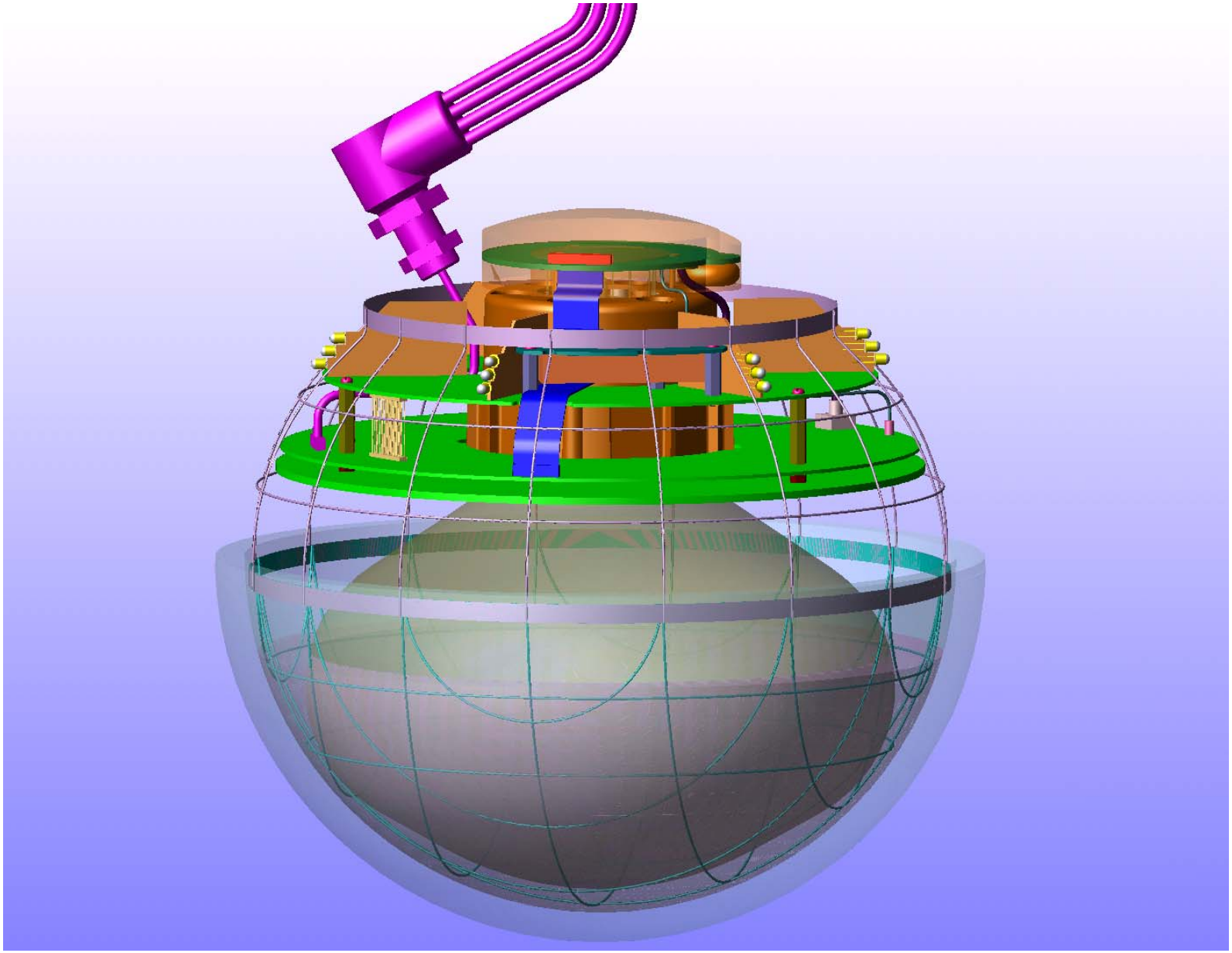
Test of ICE3 technology

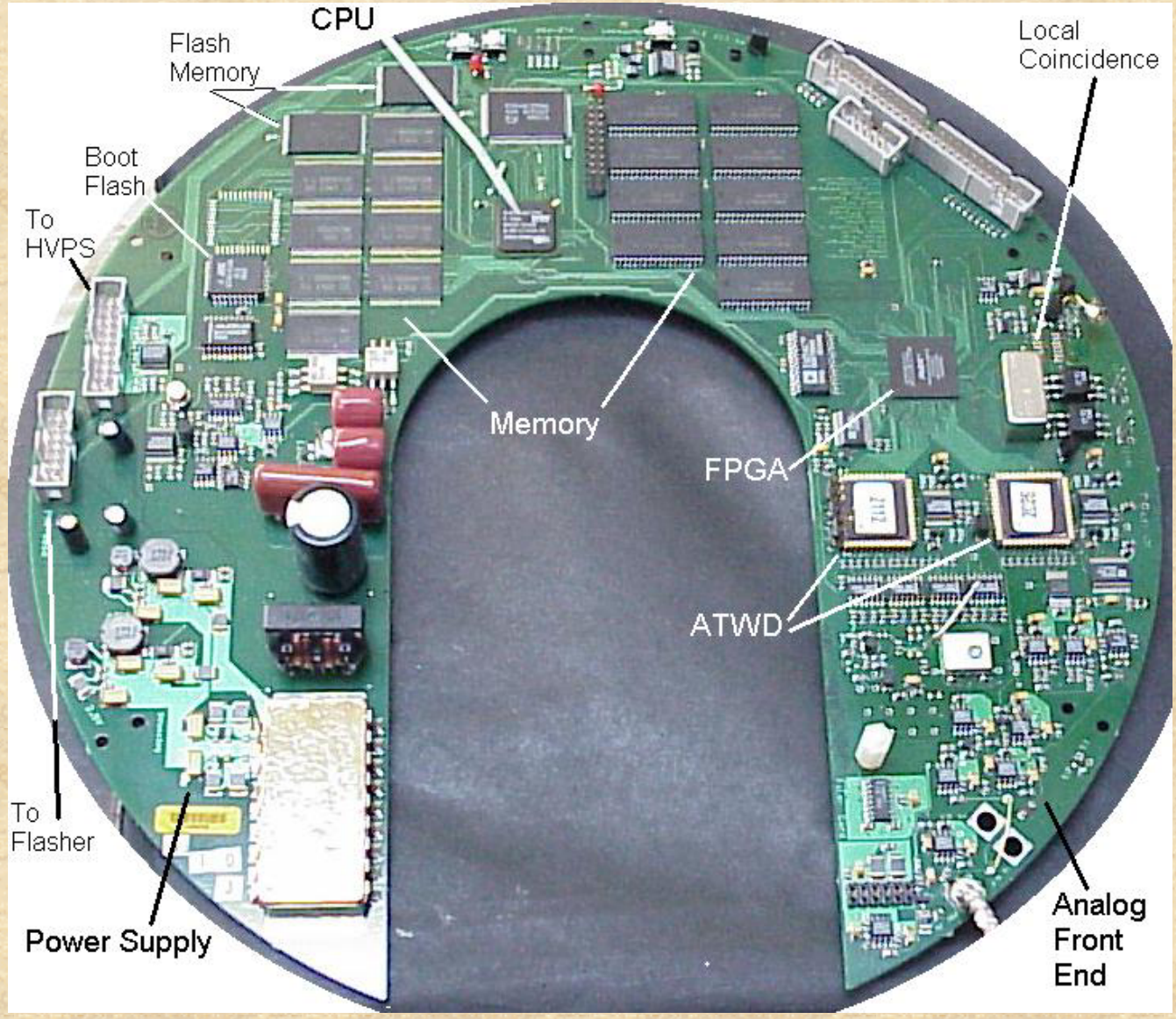


- cost
- robustness
- dynamic range

<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

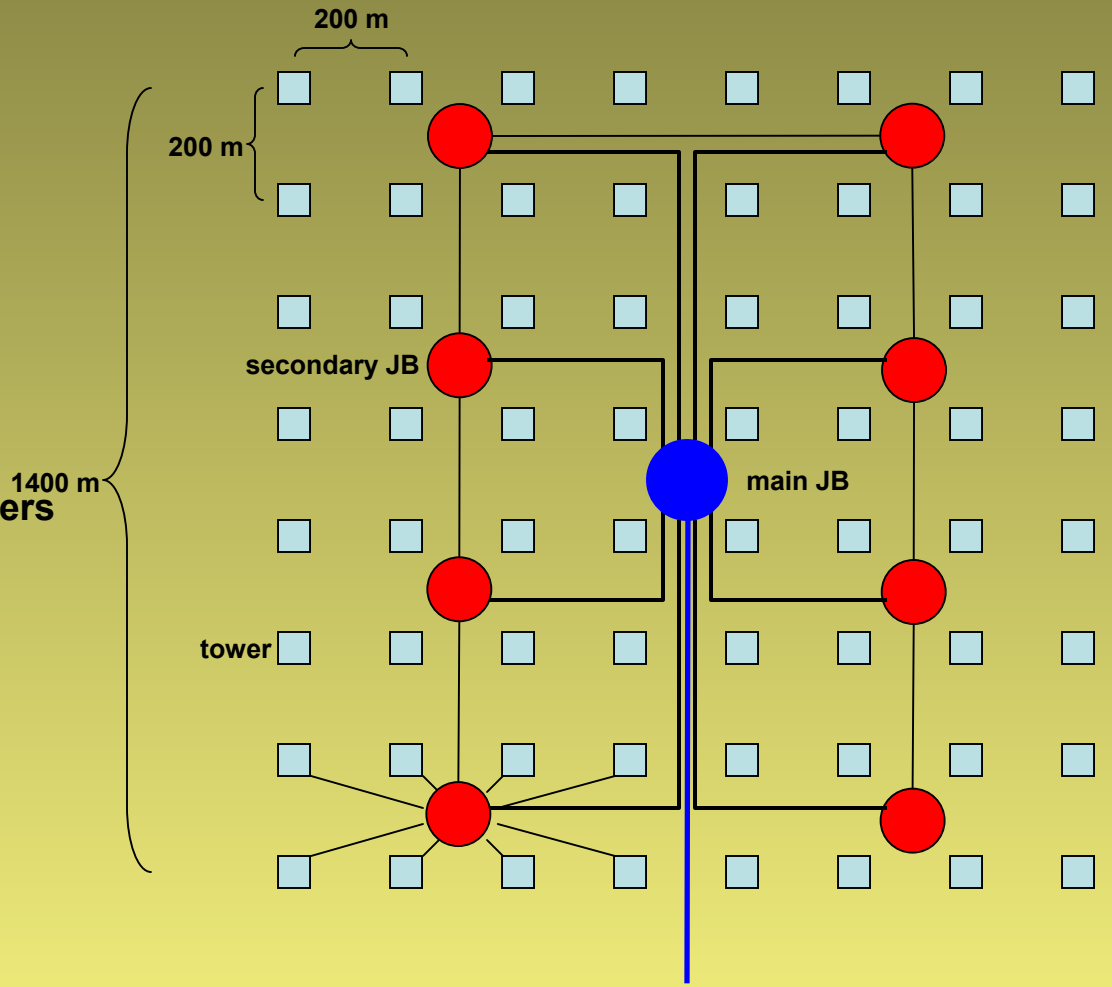



CPU
Flash Memory
Boot Flash
To HVPS
Memory
Local Coincidence
FPGA
ATWD
To Flasher
Power Supply
Analog Front End

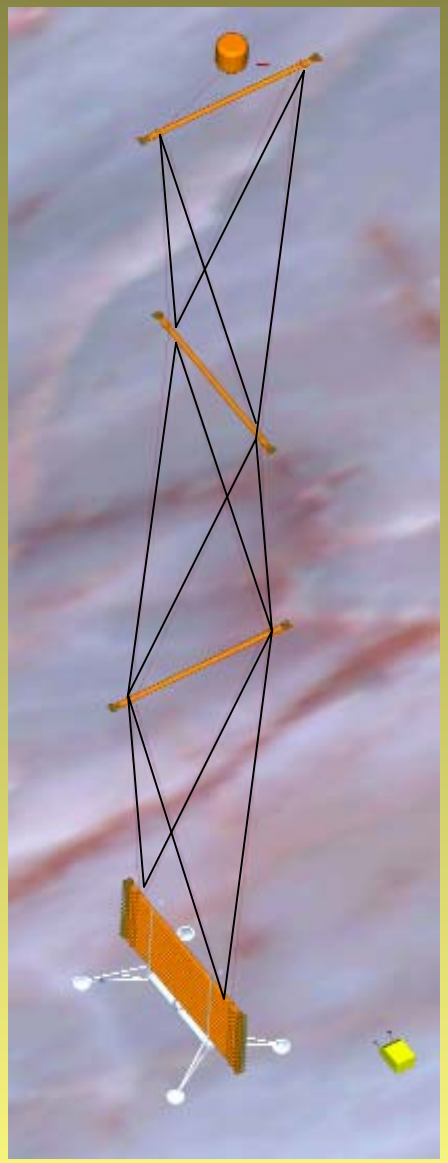
NEMO

Actual proposal of general layout for Km^3 detector

- n. 1 main Junction Box
- n. 8 secondary Junction Box
- n. 64 towers
- 200 m between each row and the others
- 200 m between each columns and the others
- 16 storeys for each tower
- 64 PMT for each tower
- 4096 PMT

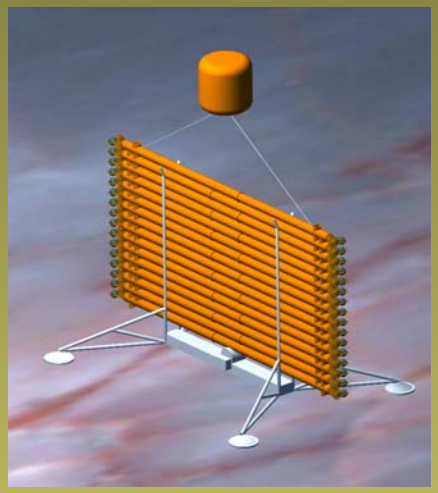


NEMO



The use of pipes to realize the storeys gives a very low resistance to the water flow.

The largest estimated movement of the upper part of the structure due to the currents are lower than 20m.



The mechanical stresses on the rigid part of the structure are:

- a bending due to the weight of the spheres when it is out of the sea water;
- an axial load during the useful life due to the draught of the upper buoy.

The electro optical cables can be easily fixed on the ropes.

During the deployment the main ropes can be kept in position on the pipes by means of small breakable ropes.

IceCube has been designed as a discovery instrument with improved:

- telescope area (> 1km^2 after all cuts)
- detection volume (> 1km^3 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)

AMANDA

- AMANDA collected > 3,000 ν's
- 4 more every day on-line
- neutrino sensitivity has reached $\nu = \gamma$
- > 300,000 per year from IceCube
- race for solving the CR puzzle is on!

The IceCube Collaboration

- Bartol Research Institute, University of Delaware
- BUGH Wuppertal, Germany
- Universite Libre de Bruxelles, Brussels, Belgium
- CTSPS, Clark-Atlanta University, Atlanta USA
- DESY-Zeuthen, Zeuthen, Germany
- Institute for Advanced Study, Princeton, USA
- Dept. of Technology, Kalmar University, Kalmar, Sweden
- Lawrence Berkeley National Laboratory, Berkeley, USA
- Department of Physics, Southern University and A\&M College, Baton Rouge, LA, USA
- Dept. of Physics, UC Berkeley, USA
- Institute of Physics, University of Mainz, Mainz, Germany
- Dept. of Physics, University of Maryland, USA
- University of Mons-Hainaut, Mons, Belgium
- Dept. of Physics and Astronomy, University of Pennsylvania, Philadelphia, USA
- Dept. of Astronomy, Dept. of Physics, SSEC, PSL, University of Wisconsin, Madison, USA
- Physics Department, University of Wisconsin, River Falls, USA
- Division of High Energy Physics, Uppsala University, Uppsala, Sweden
- Fysikum, Stockholm University, Stockholm, Sweden
- University of Alabama, Tusceloosa, USA
- Vrije Universiteit Brussel, Brussel, Belgium
- Chiba University, Japan
- Imperial College London, UK
- Utrecht University, Utrecht, The Netherlands
- Universidad Simon Bolivar, Caracas, Venezuela
- University of Canterbury, Christchurch, New Zealand