Neutrino Astronomy

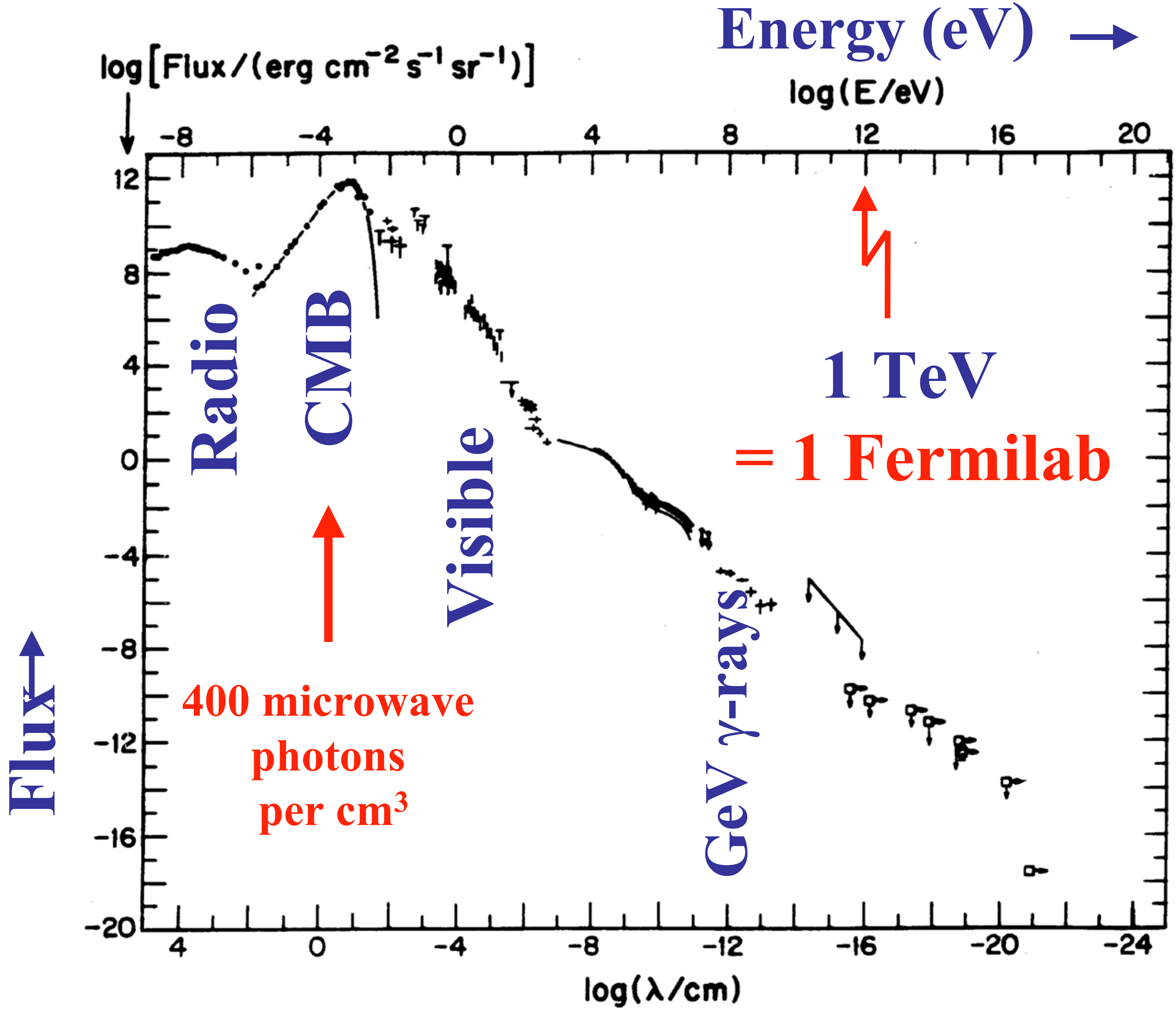
ν astronomy

- ν astronomy requires kilometer-scale detectors

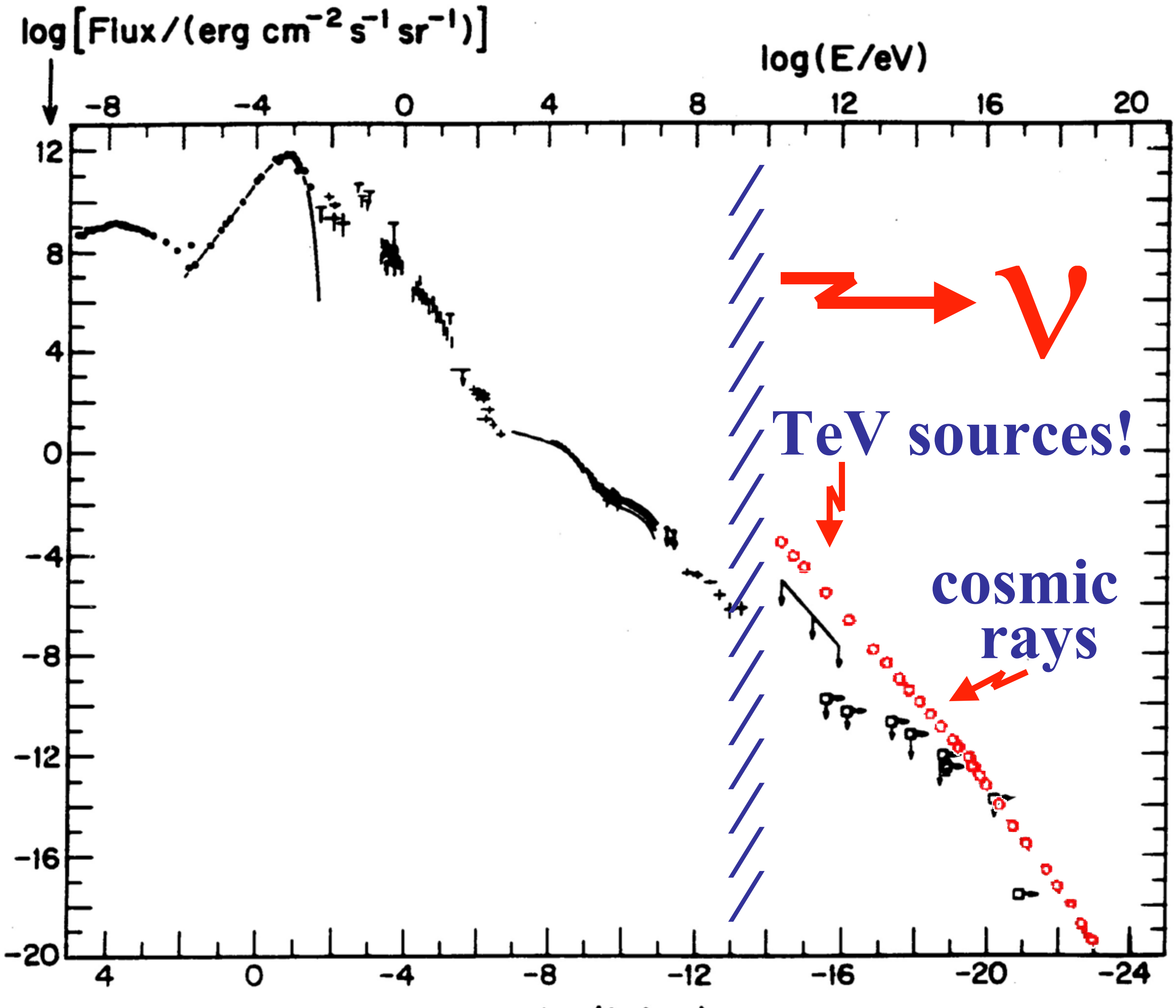
- IceCube/NEMO: kilometer-scale neutrino observatories

- Super- EeV detectors: RICE, ANITA, EUSO

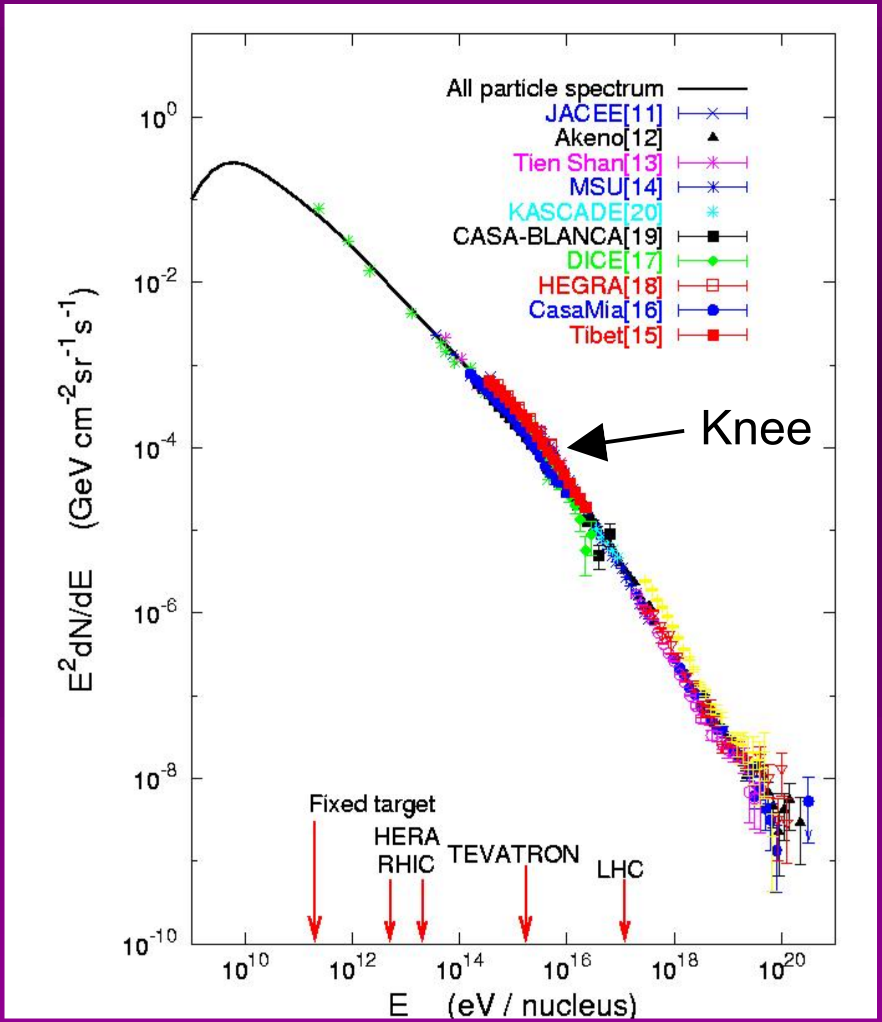
f. halzen
http://pheno.physics.wisc.edu/~halzen/
http://icecube.wisc.edu/

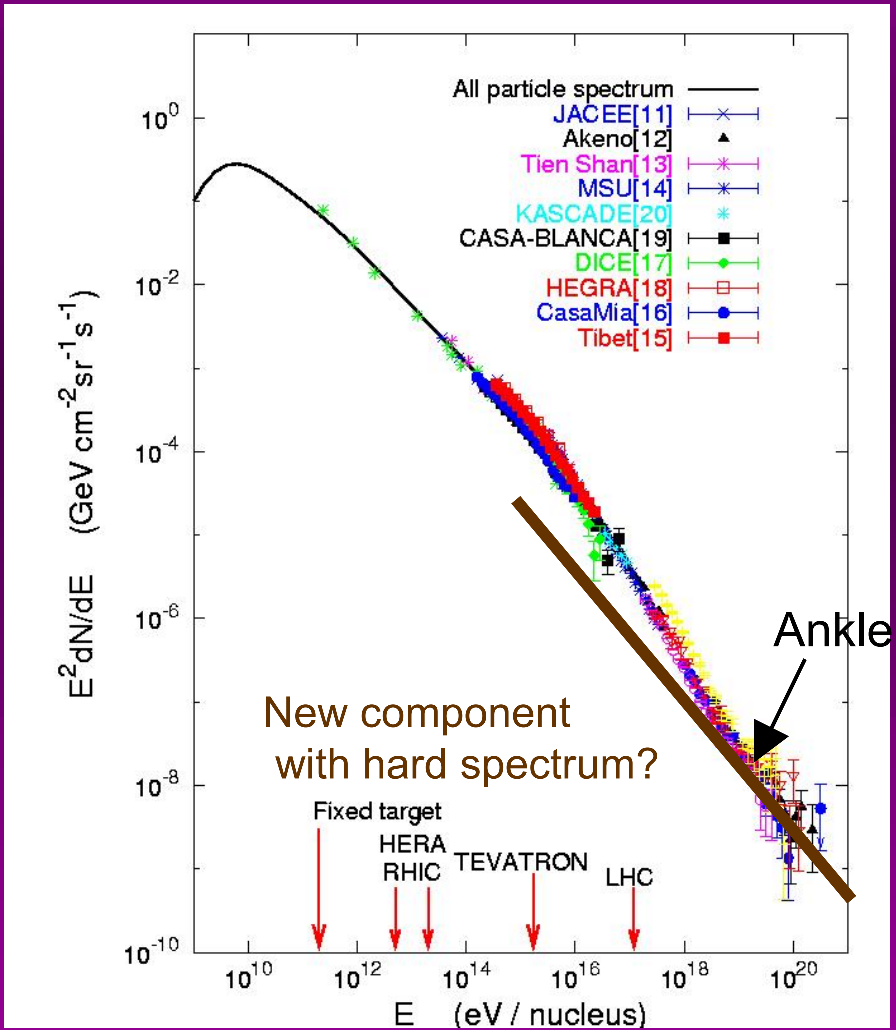


Energy (eV) →
log[Flux/(erg cm⁻² s⁻¹ sr⁻¹)]
log(E/eV)
-8 -4 0 4 8 12 16 20
12 8 4 0 -4 -8 -12 -16 -20
Radio
CMB
Visible
GeV γ-rays
1 TeV
= 1 Fermilab
400 microwave
photons
per cm3
Flux
4 0 -4 -8 -12 -16 -20 -24
log(λ/cm)


log[Flux/(erg cm^{-2} s^{-1} sr^{-1})]
log(E/eV)
log(λ/cm)
ν
TeV sources!
cosmic rays

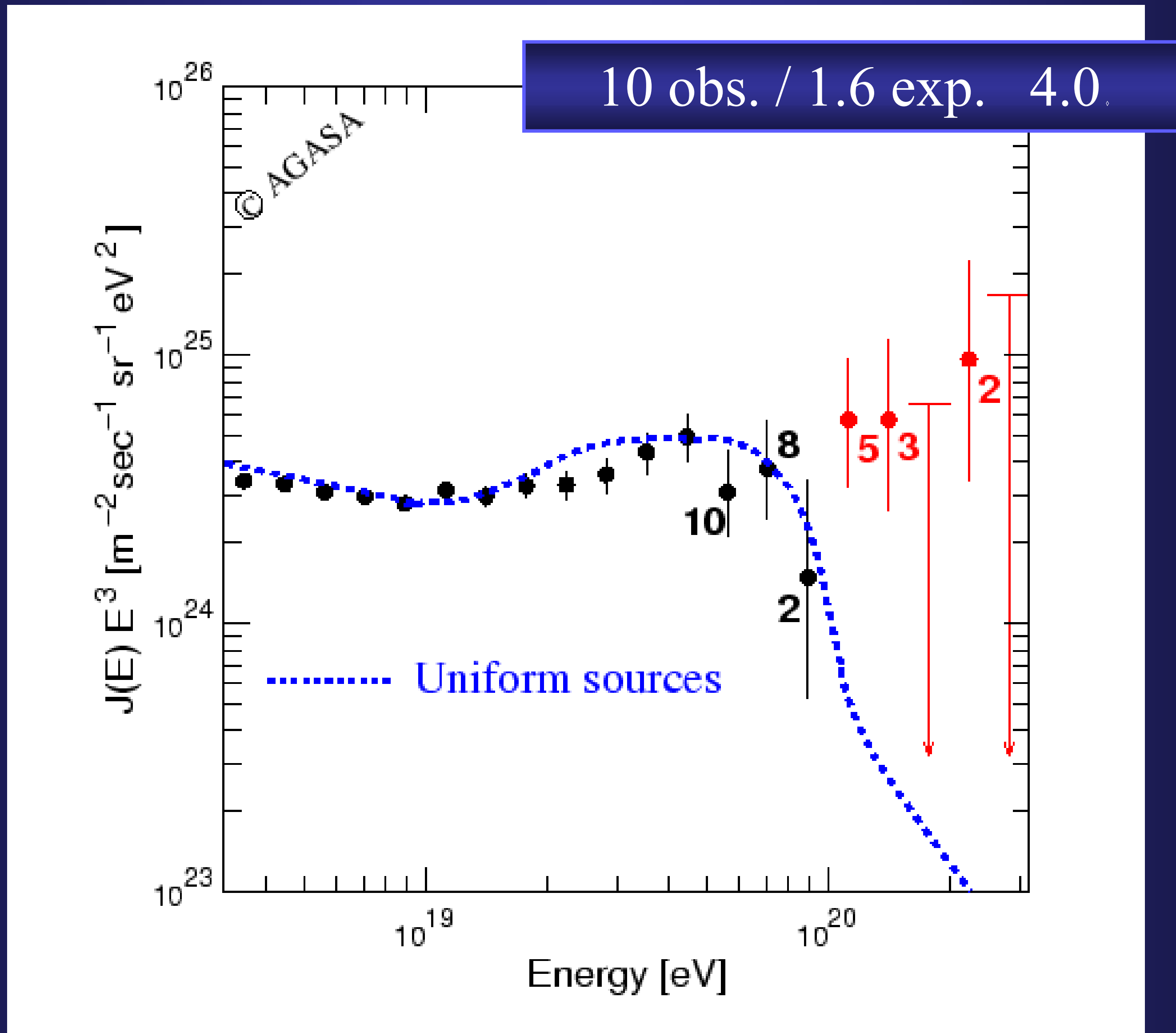
Galactic and Extragalactic Cosmic Rays





the extra-galactic component of the cosmic rays

Energy Spectrum by AGASA (< 45)



Interaction length of protons in microwave background

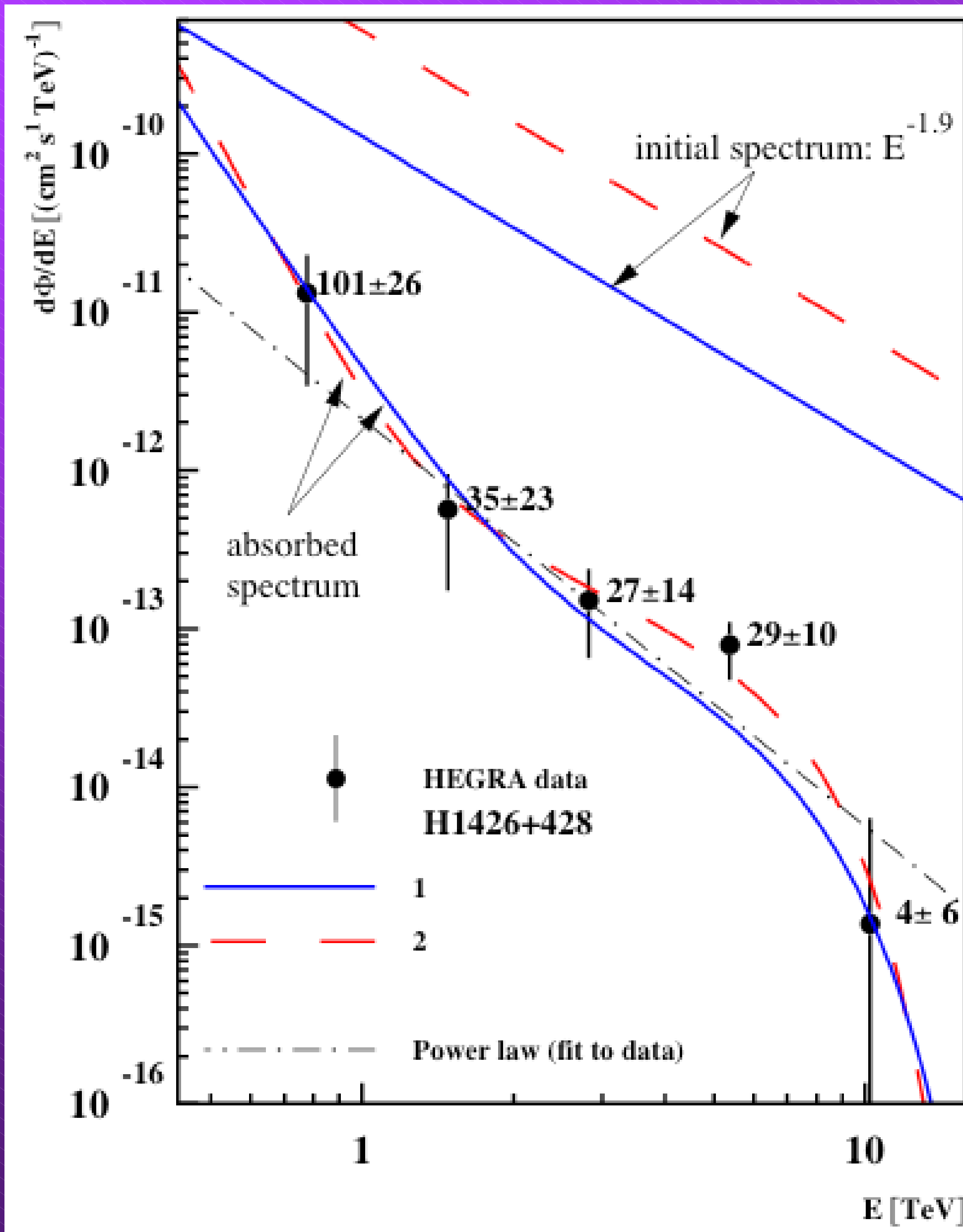
$$p + \gamma_{CMB} \longrightarrow \pi + N$$

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

$$\cong \mathbf{10\ Mpc}$$

GZK cutoff above ~ 50 EeV

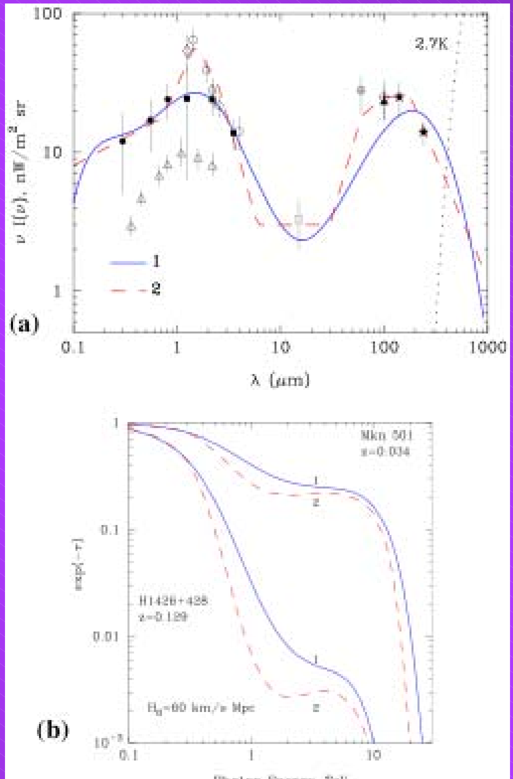
HEGRA: blazar at z=0.13



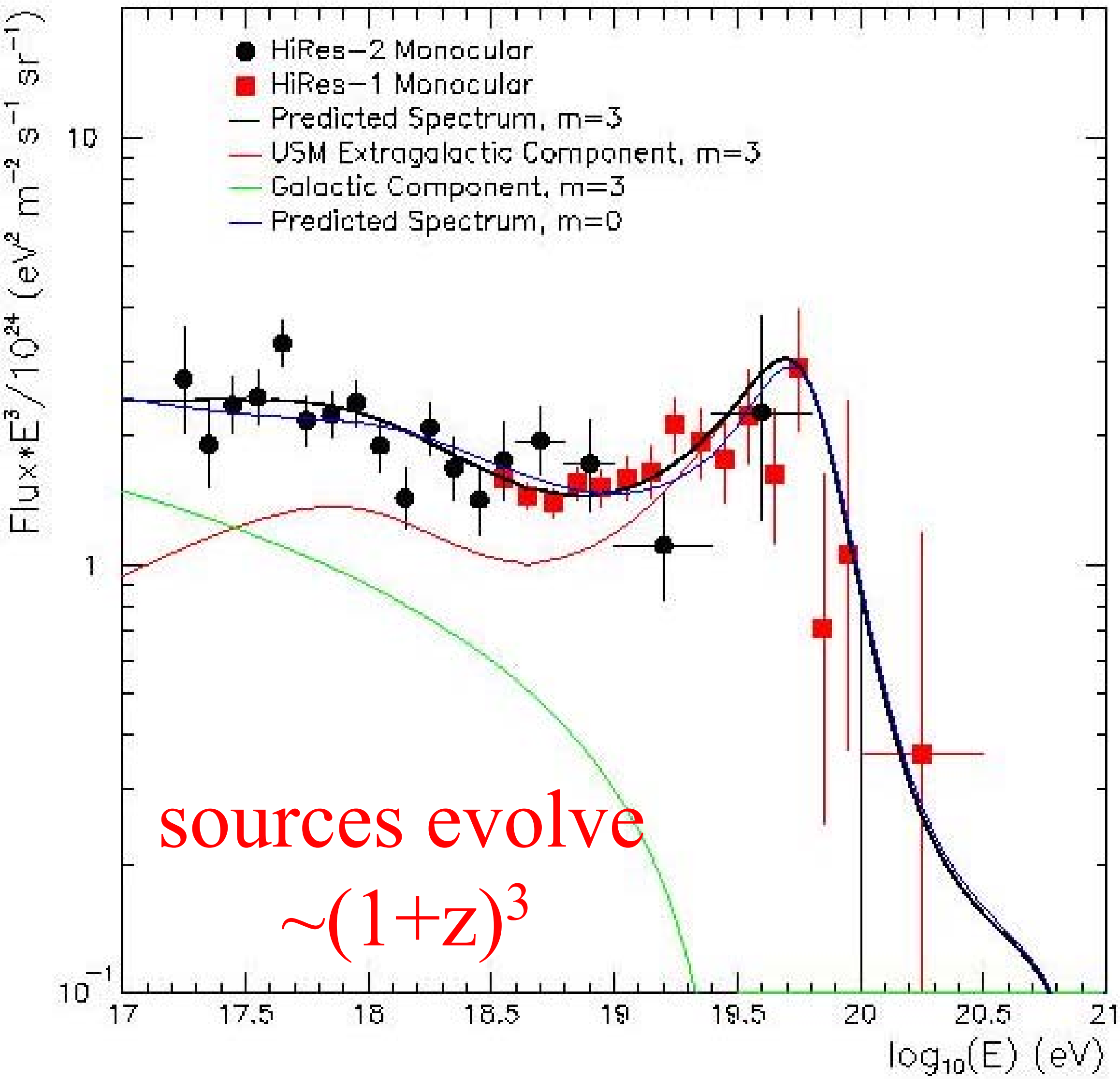
absorption on IR

$\gamma + \gamma \rightarrow e^{+} + e^{-}$

relativity works!



Generic Spectrum with Cosmological Evolution



Models of Cosmic Rays

Bottom up

- Jets of AGN
- GRB fireballs
- 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 γ-showers

Disfavored!

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

10^{24} eV = 10^{15} GeV $\simeq M_{GUT}$

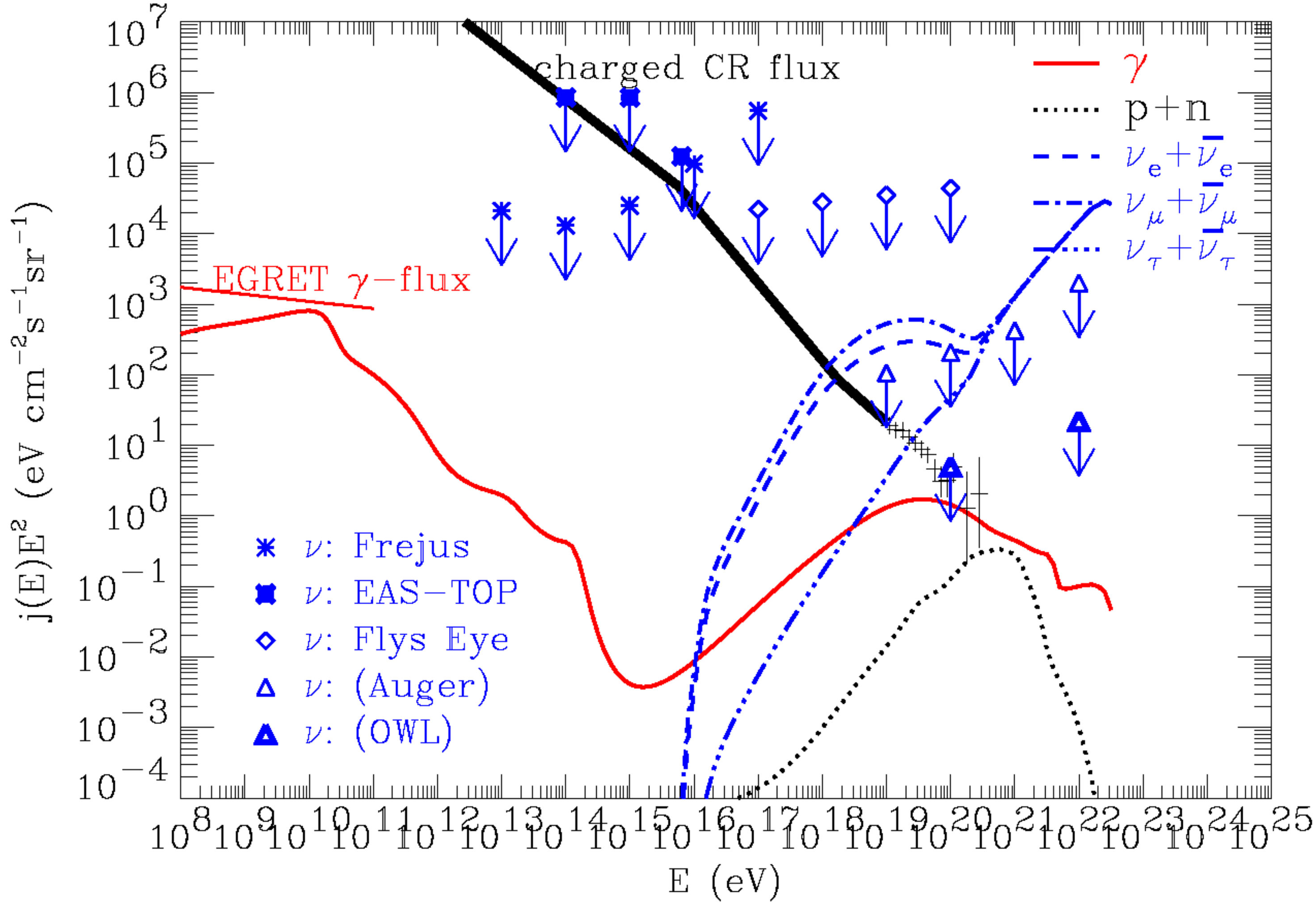
are cosmic rays the decay product of

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

Top. Def. → X,Y → W,Z quark + lept

$\gamma \gg p \quad \nu \gg \gamma$

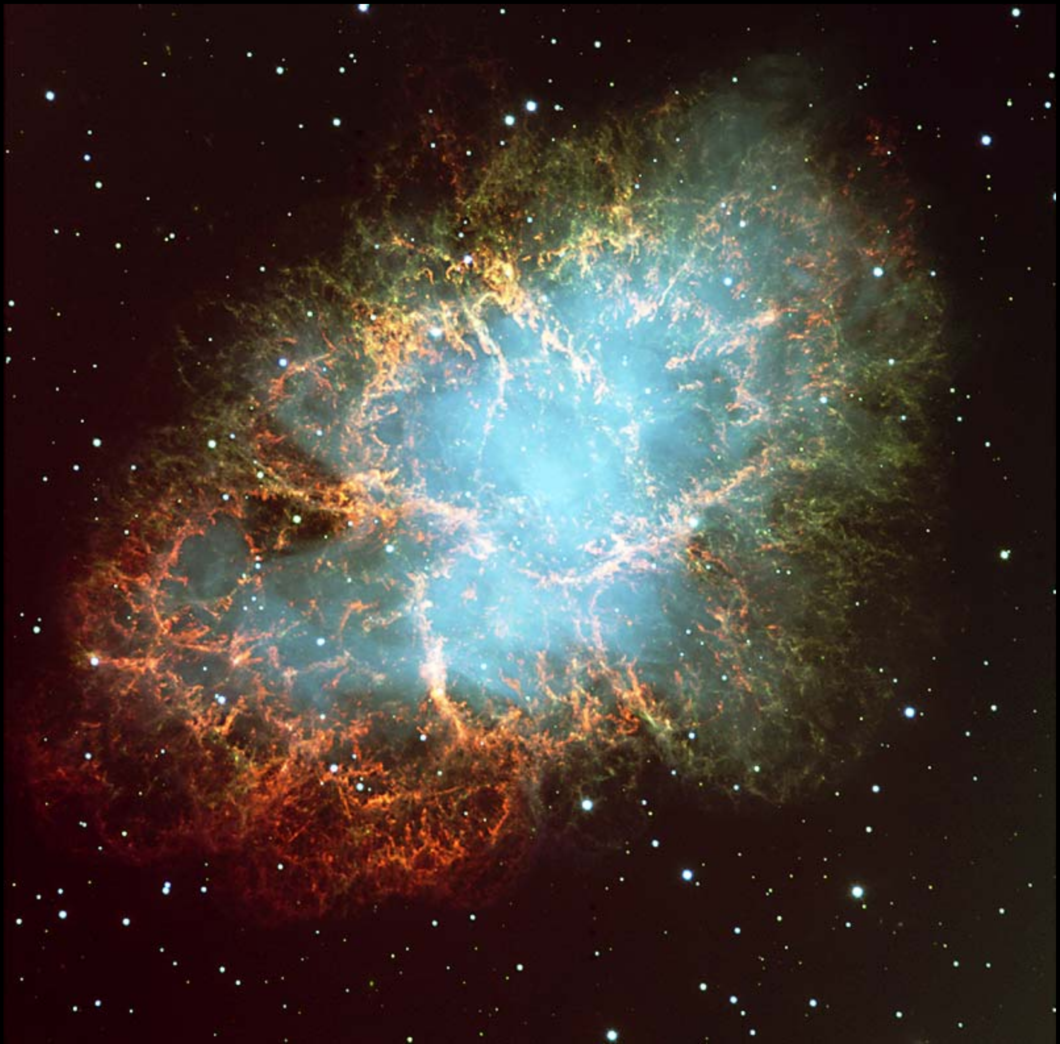
- top-down spectrum
- hierarchy: *neutrinos>>gammas>>protons*



normalizing the observed cosmic rays to protons (fatally) increases the predicted neutrino fluxes

the galactic component of the cosmic rays

Supernova shocks expanding in interstellar medium



Crab nebula

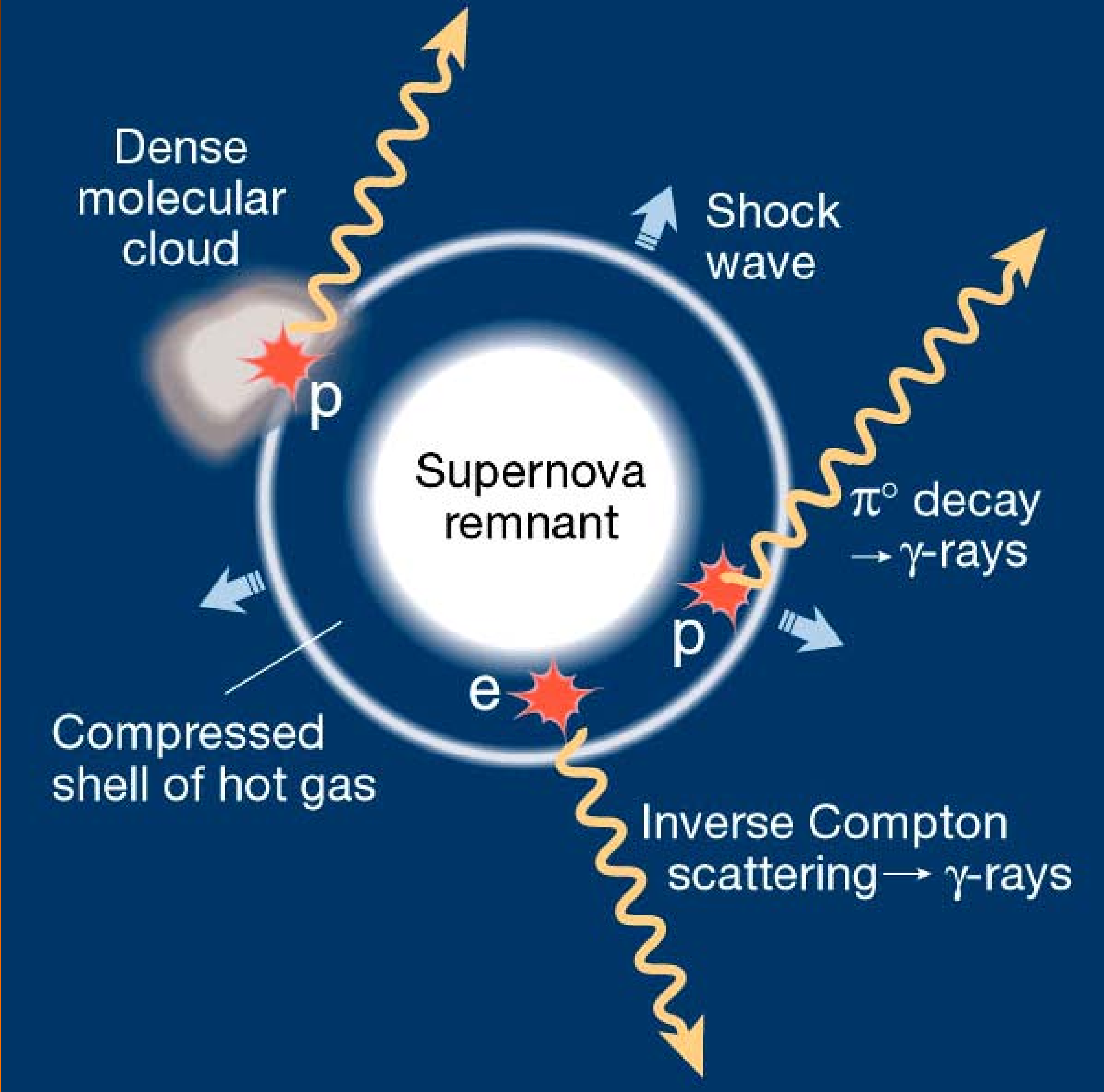
Cosmic accelerators? Pion production? Cygnus is Back

- HEGRA: unidentified TeV source in Cygnus -- no counterpart
- Extended source Cygnus OB2: 2600 young massive stars (~ $10^5 M_{sun}$)
- Interacting winds from thousands of young, massive stars with 0.1% conversion to protons?
- Time correlated, close-by SNR?
- Limits on electrons from radio and X-rays

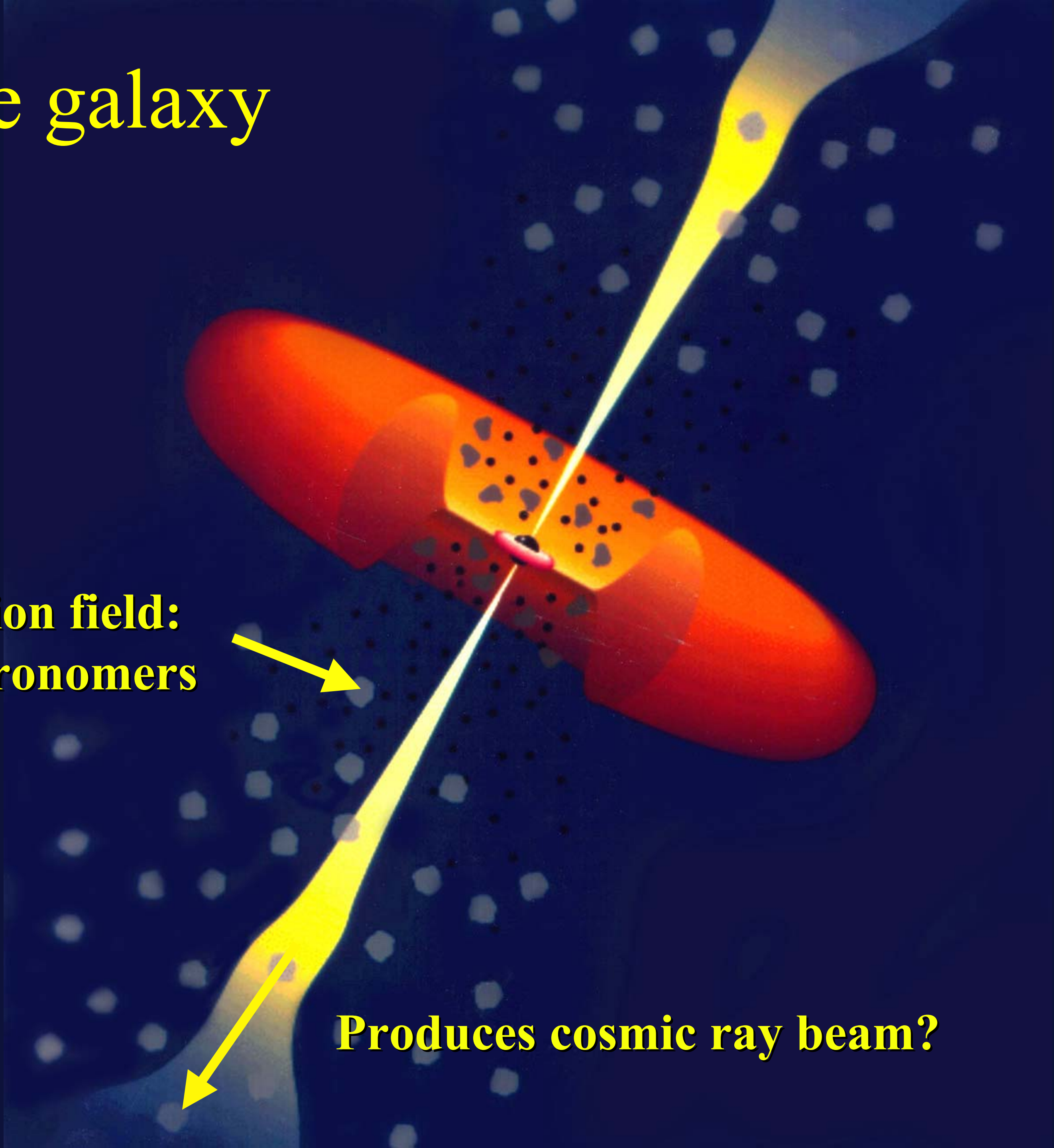
Cosmic accelerators? Pion production?
Cygnus is Back

- Highest fluctuation in the Kiel and AGASA cosmic ray sky: neutron, γ ?
- Mean-free path of 10^{17} eV neutron is 1.7 kpc.
- Photons above ~1 PeV absorption maximum on the microwave back-ground?

Galactic Beam Dump



active galaxy



**Radiation field:
Ask astronomers**

Produces cosmic ray beam?

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

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

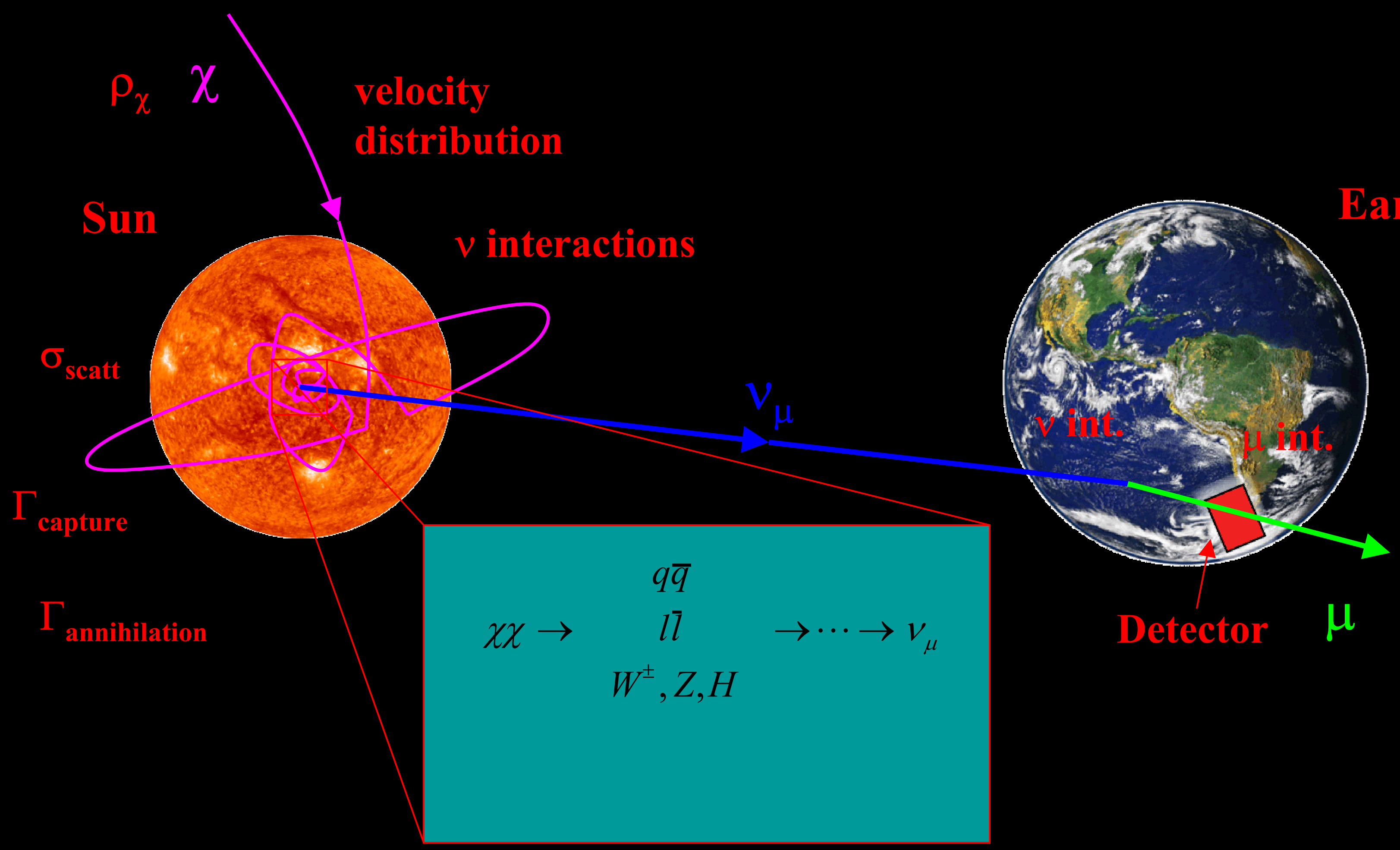
the science: a sampler

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

- **Dark matter**

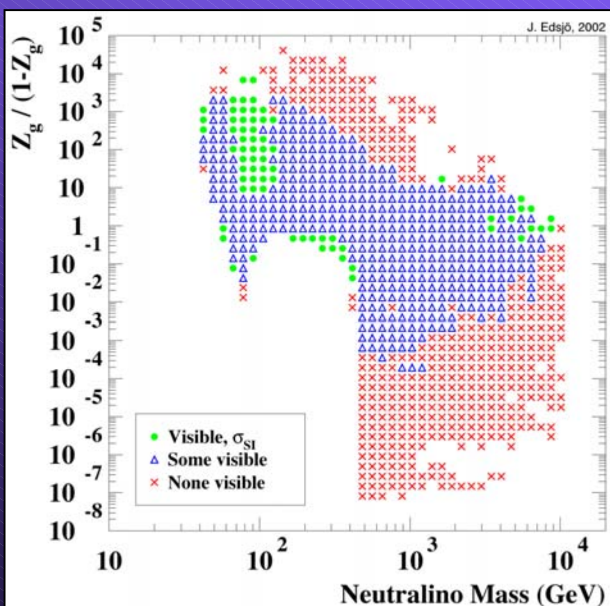
- **Higher compact dimensions…**

Neutralino capture and annihilation

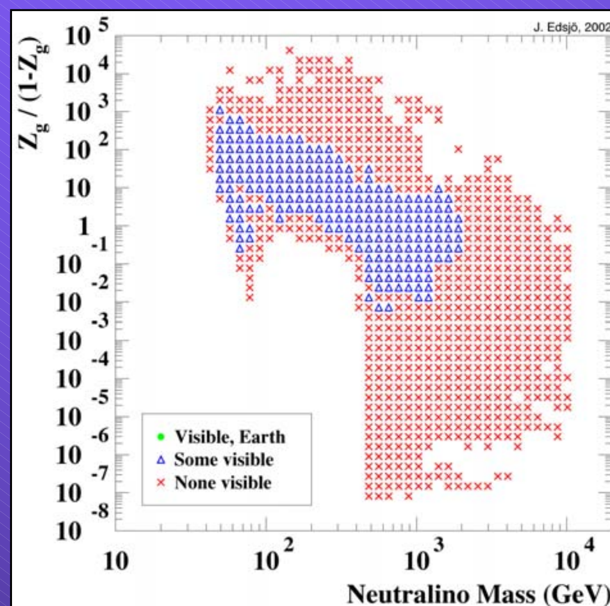


MSSM parameter space
Future probed regions I

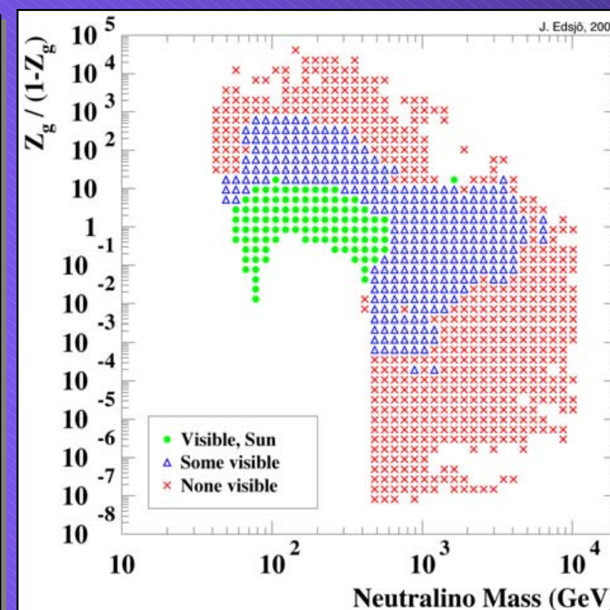
Direct detection
Genius/Cresst



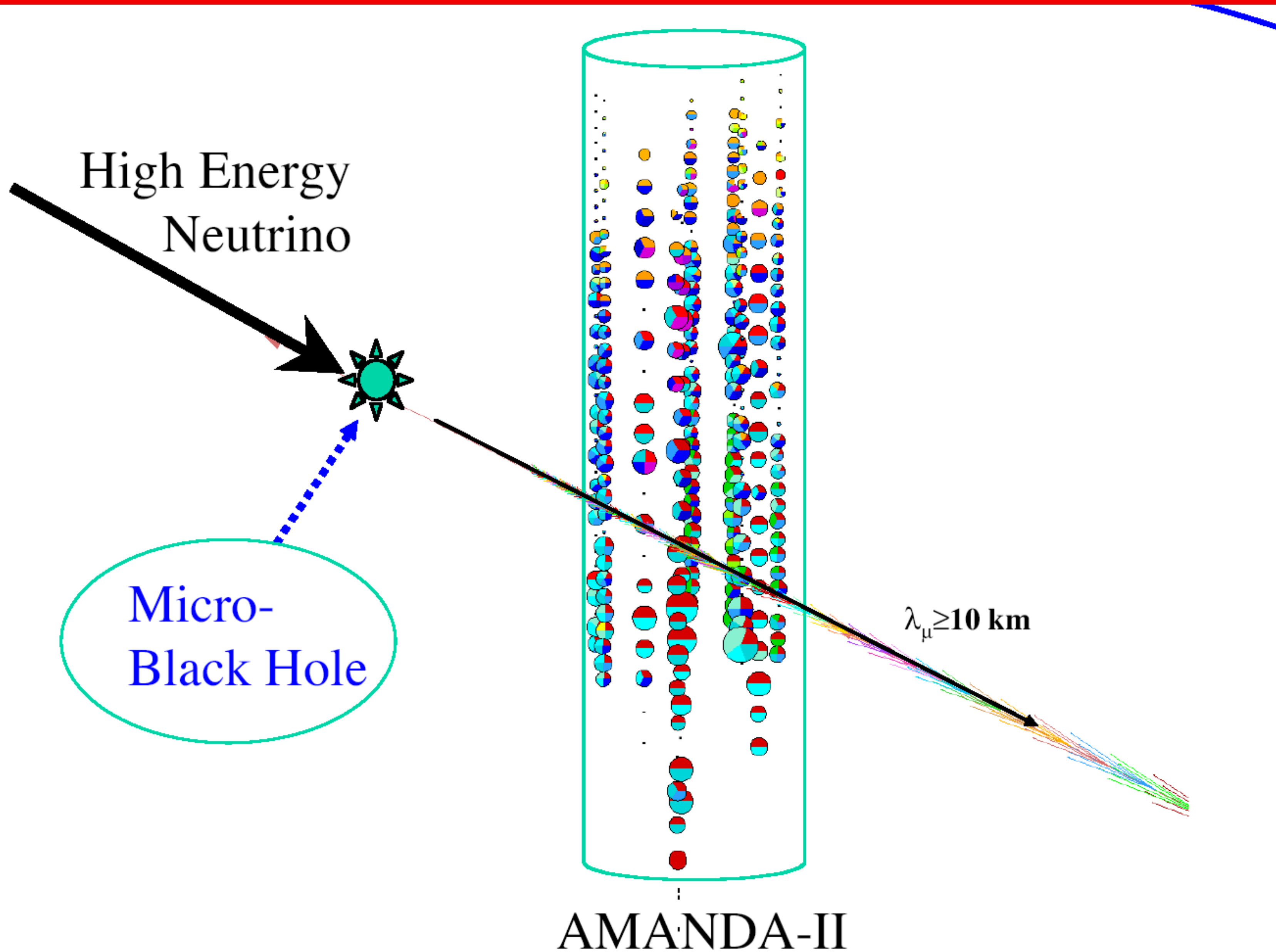
Earth, km^3



Sun, km^3

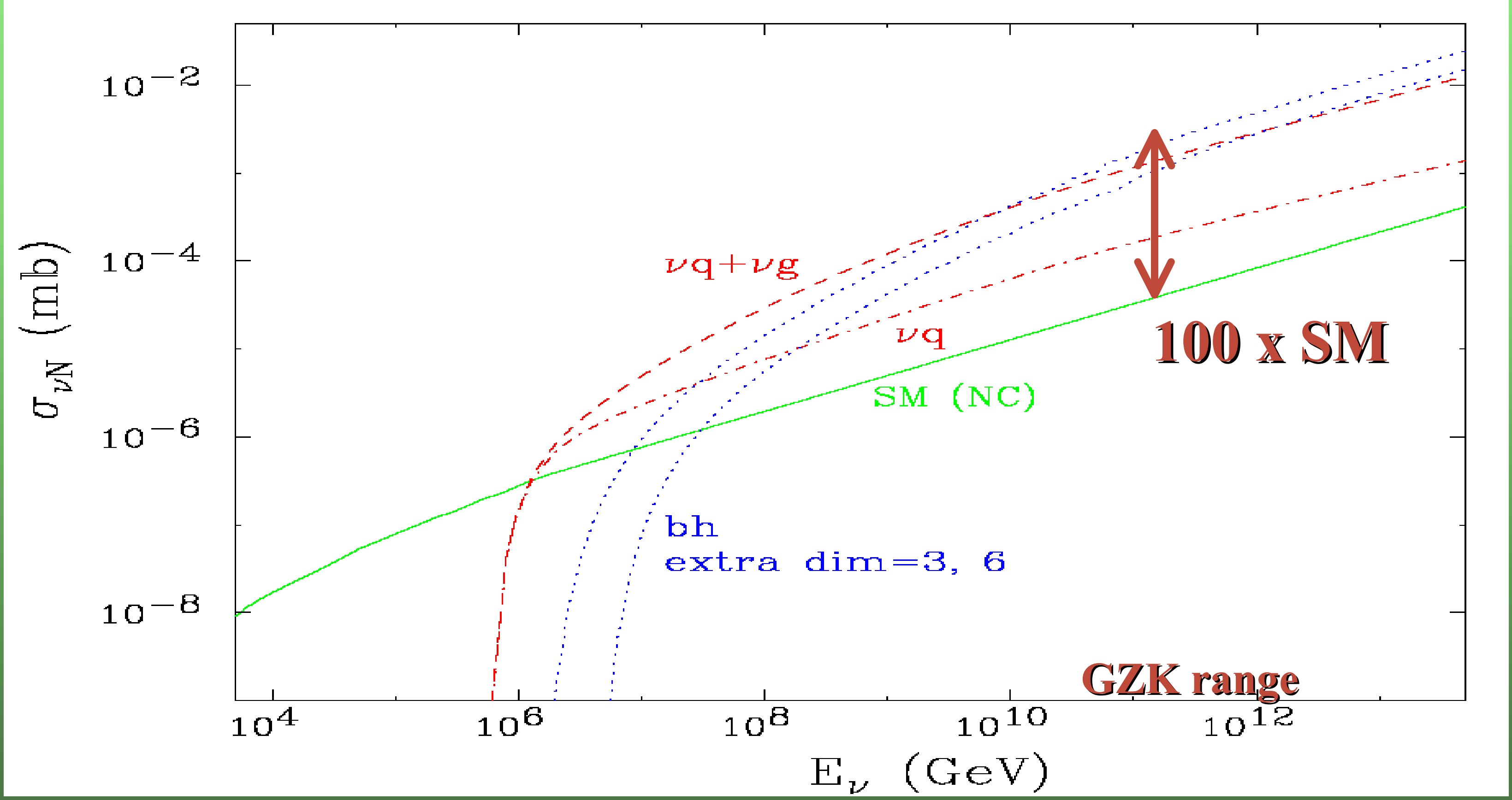


IceCube



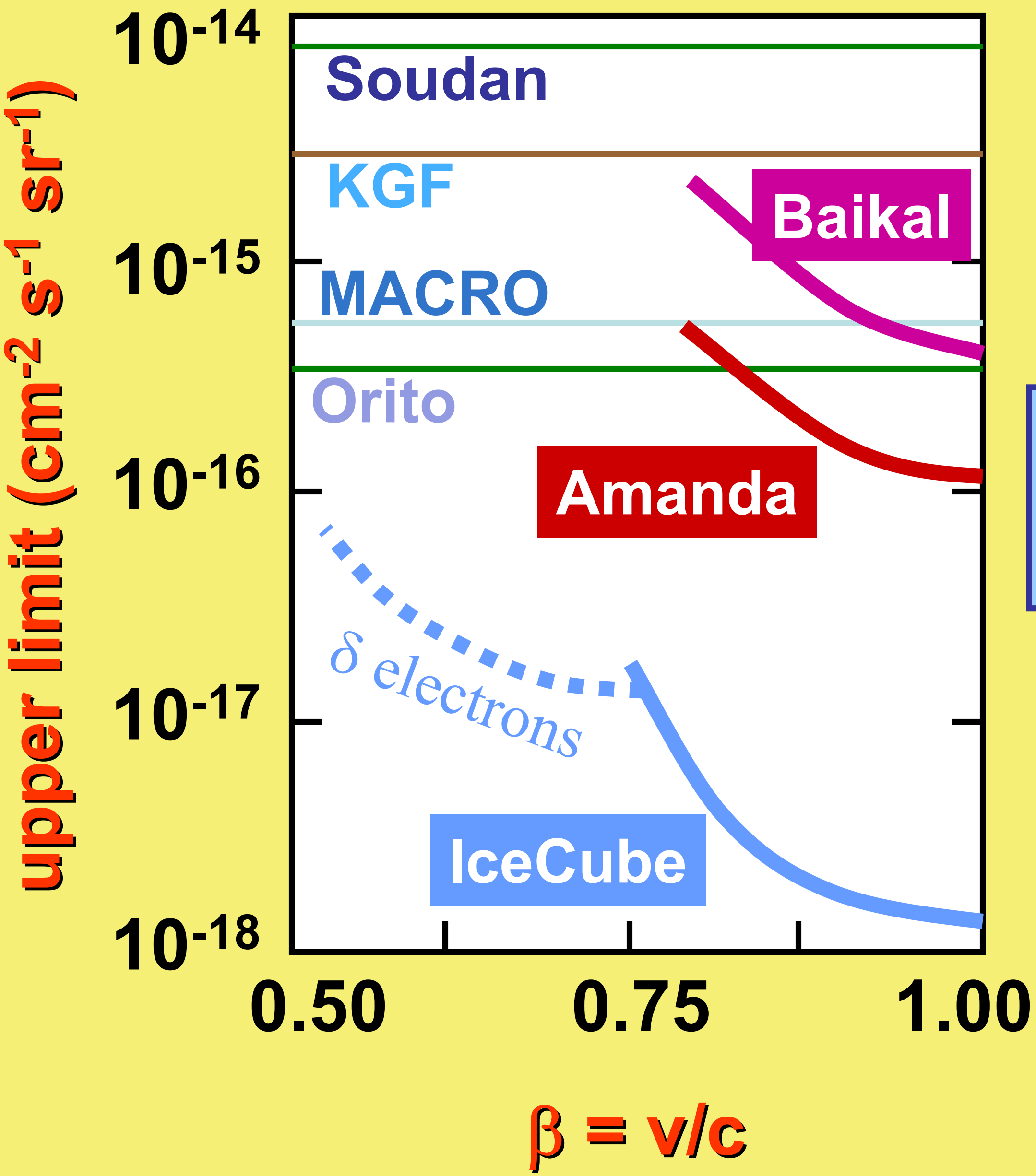
High Energy
Neutrino
Micro-
Black Hole
$\lambda_\mu \geq 10$ km
AMANDA-II

Neutrino Astronomy Explores Higher Dimensions



TeV-scale gravity increases PeV ν-cross section

Relativistic Magnetic Monopoles



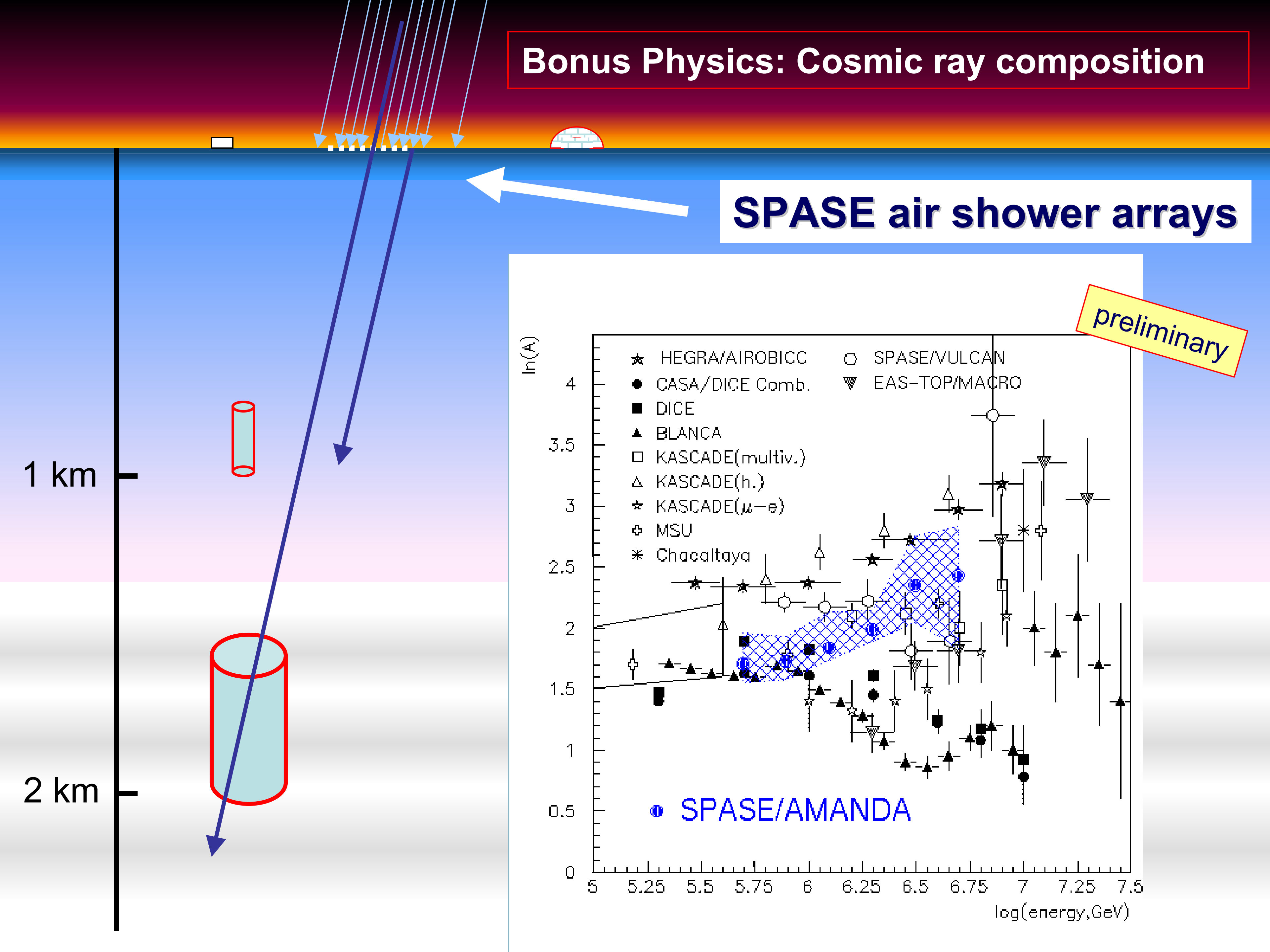
Cherenkov light output $\propto$ $n^2 \cdot (g/e)^2$

$n = 1.33$

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

≈ 8300

Bonus Physics: Cosmic ray composition



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

distance	ν luminosity	example
4000 Mpc	10^{47} erg/s	agn
4000 Mpc	10^{53} erg/10s	grb
100 Mpc	$5\ 10^{43}$ erg/s	Markarians
8 Kpc	$4\ 10^{35}$ erg/s	pulsars, micro-quasar…

Detection Probability:

$$N_{events} \sim \frac{L_\nu}{E_\nu} P_{\nu \to \mu} \text{ Area Time}$$

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

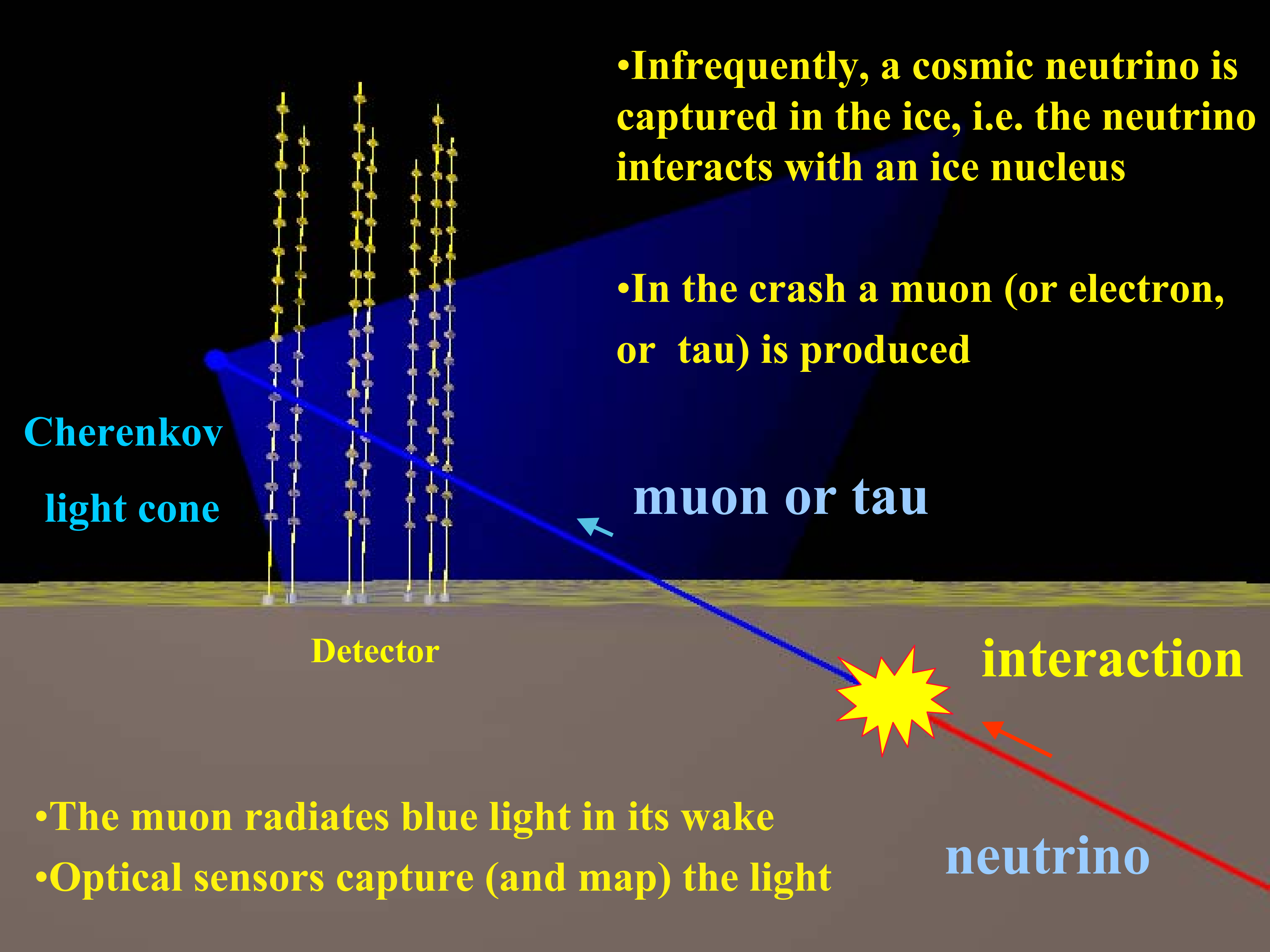
$\sim 10^{-4}$ for 100 TeV neutrinos

$\frac{L_\nu}{E_\nu}$ ↓

Neutrino flux required to observe N events:

$$L_\nu = \frac{5\times10^{-12}\,\frac{\text{erg}}{\text{cm}^2\text{s}}}{\text{Area (km2) Time (yr)}} N_{events}\,(4\pi d^2)$$

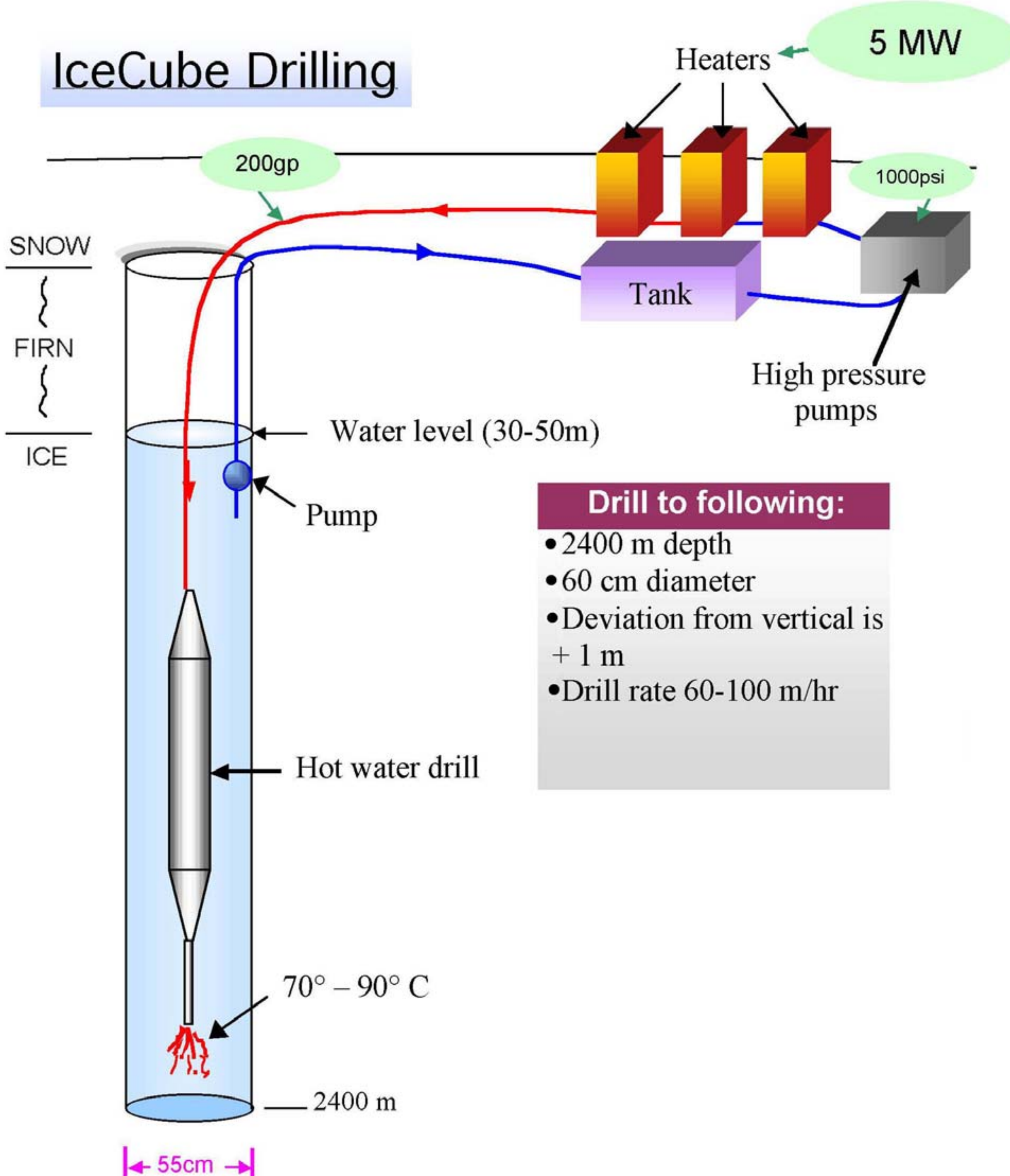
first-generation neutrino telescopes


•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
Cherenkov light cone
muon or tau
Detector
interaction
neutrino
•The muon radiates blue light in its wake
•Optical sensors capture (and map) the light

Building AMANDA

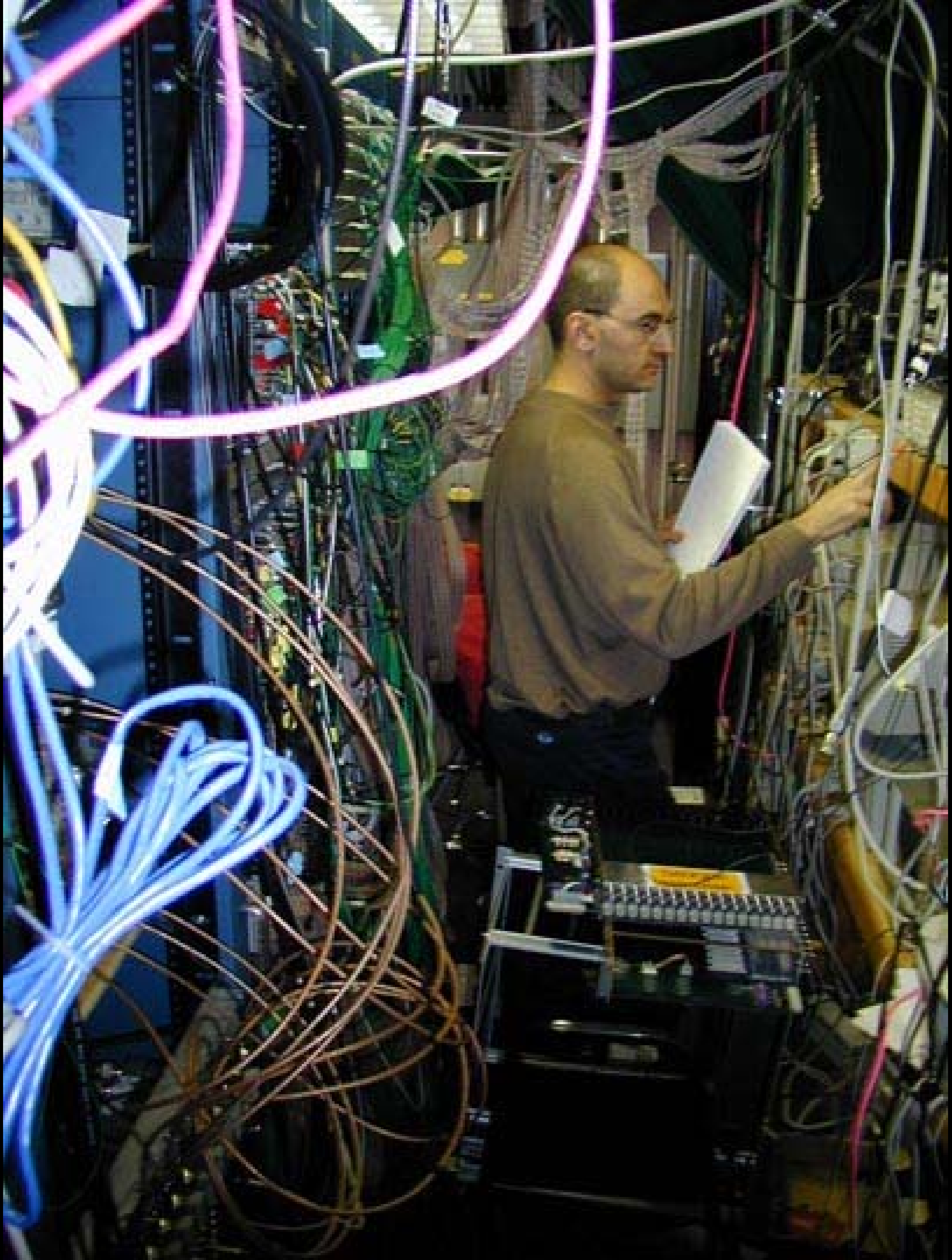

(c) 2002 Jonathban Berry

IceCube Drilling



Drill to following:

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

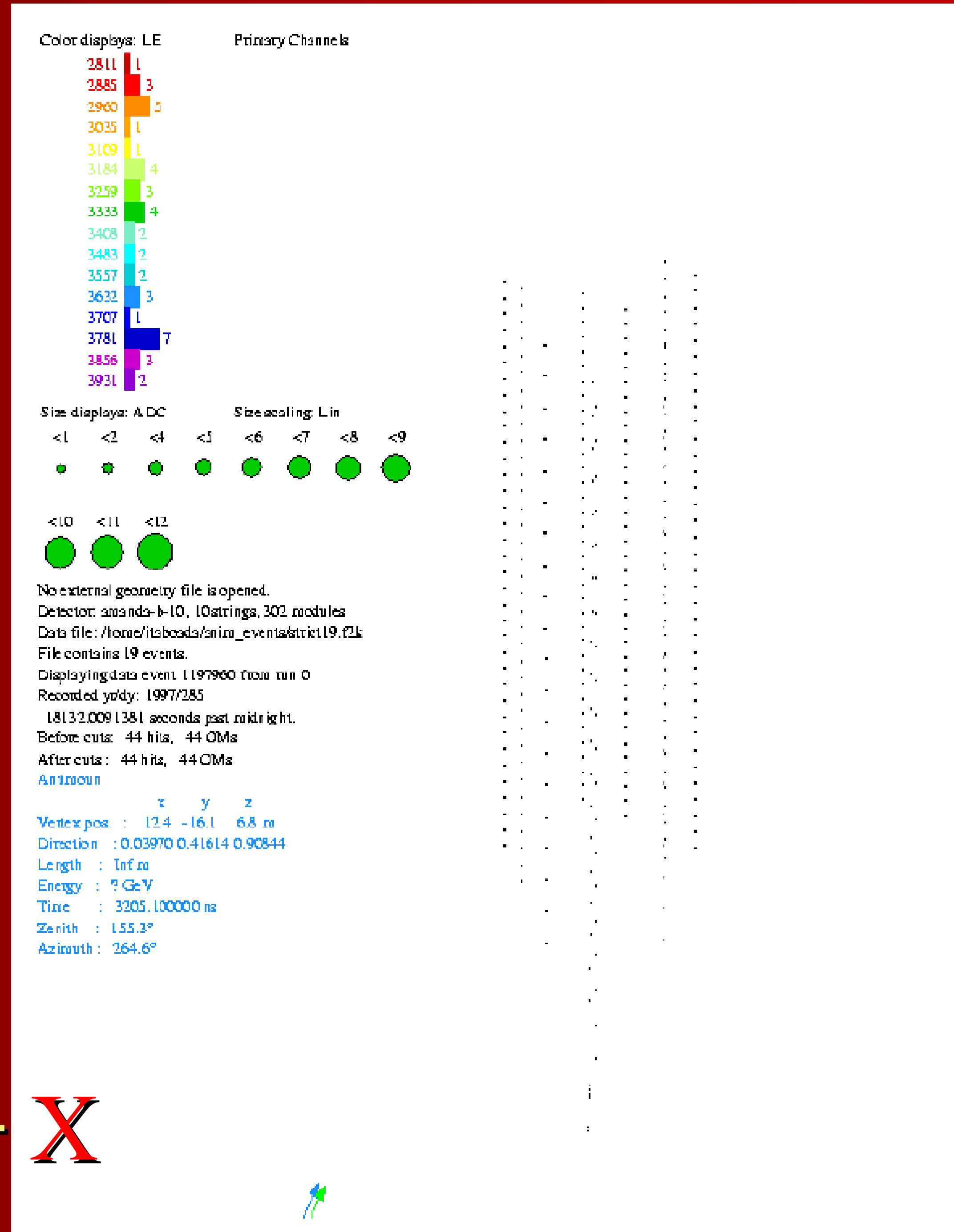


AMANDA Event Signatures: Muons

CC muon neutrino Interaction

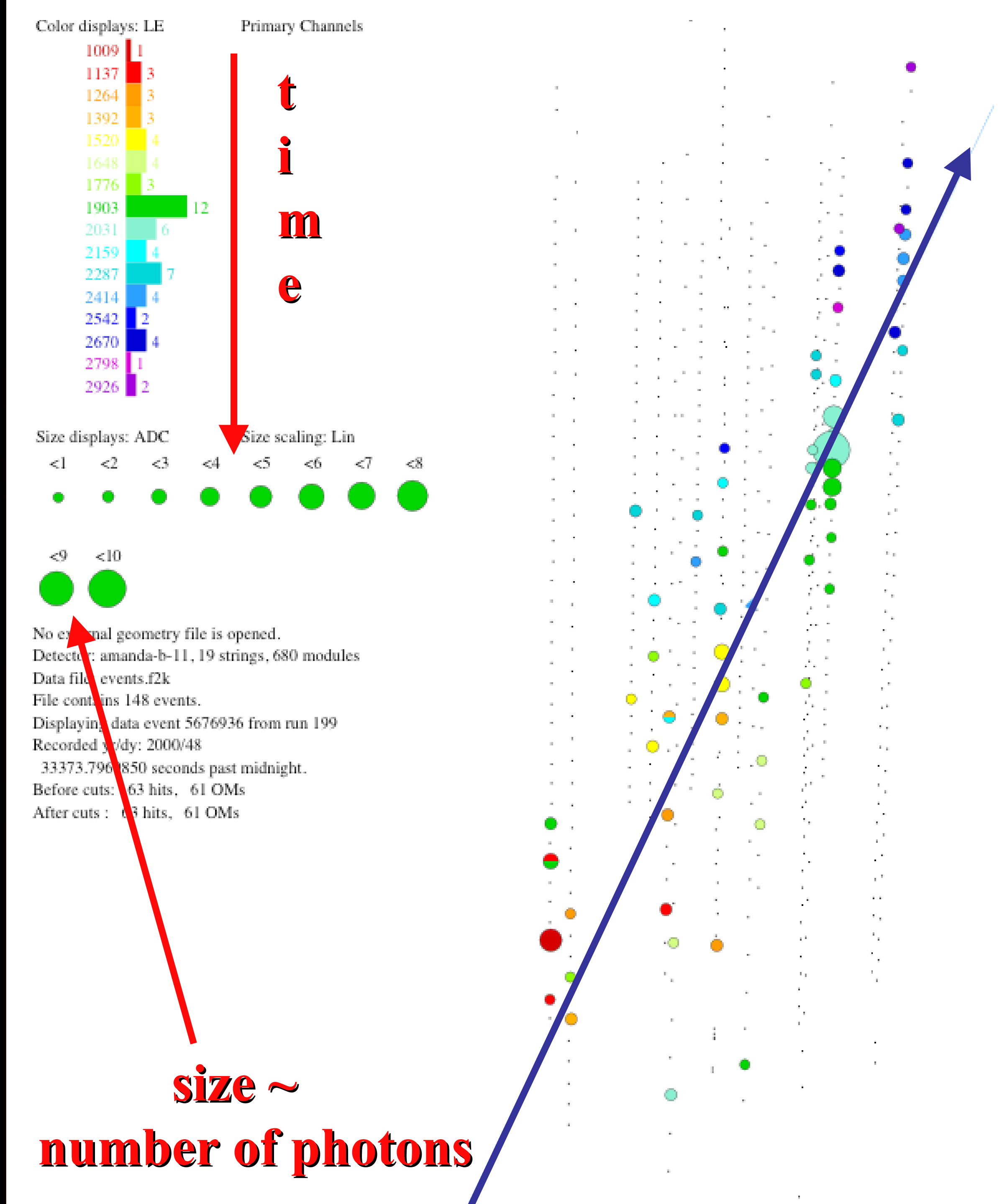
→ track

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



AMANDA II

- upgoing muon
- 61 modules



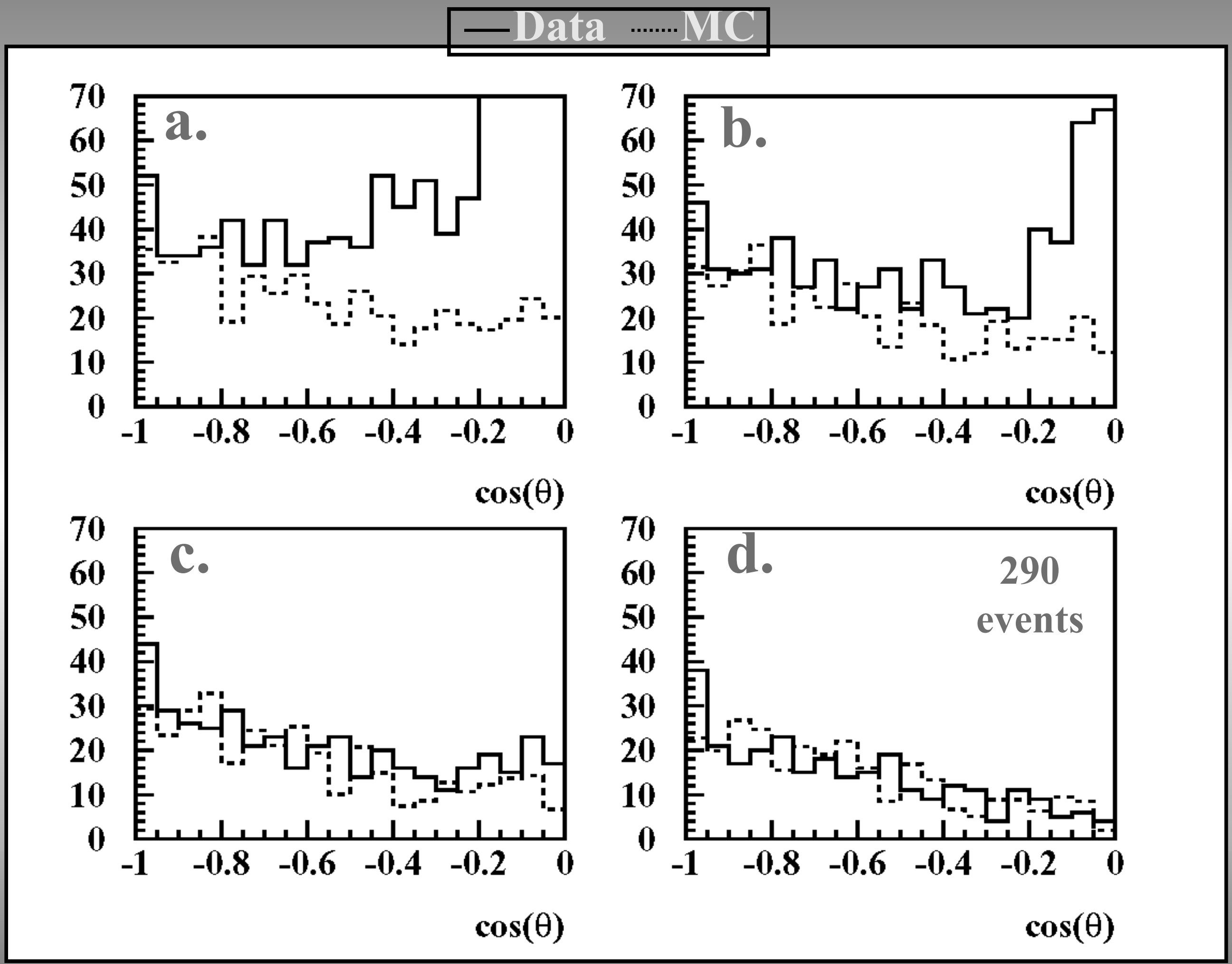
4~5 neutrinos/day on-line

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

2 cuts only!

4 nus per day

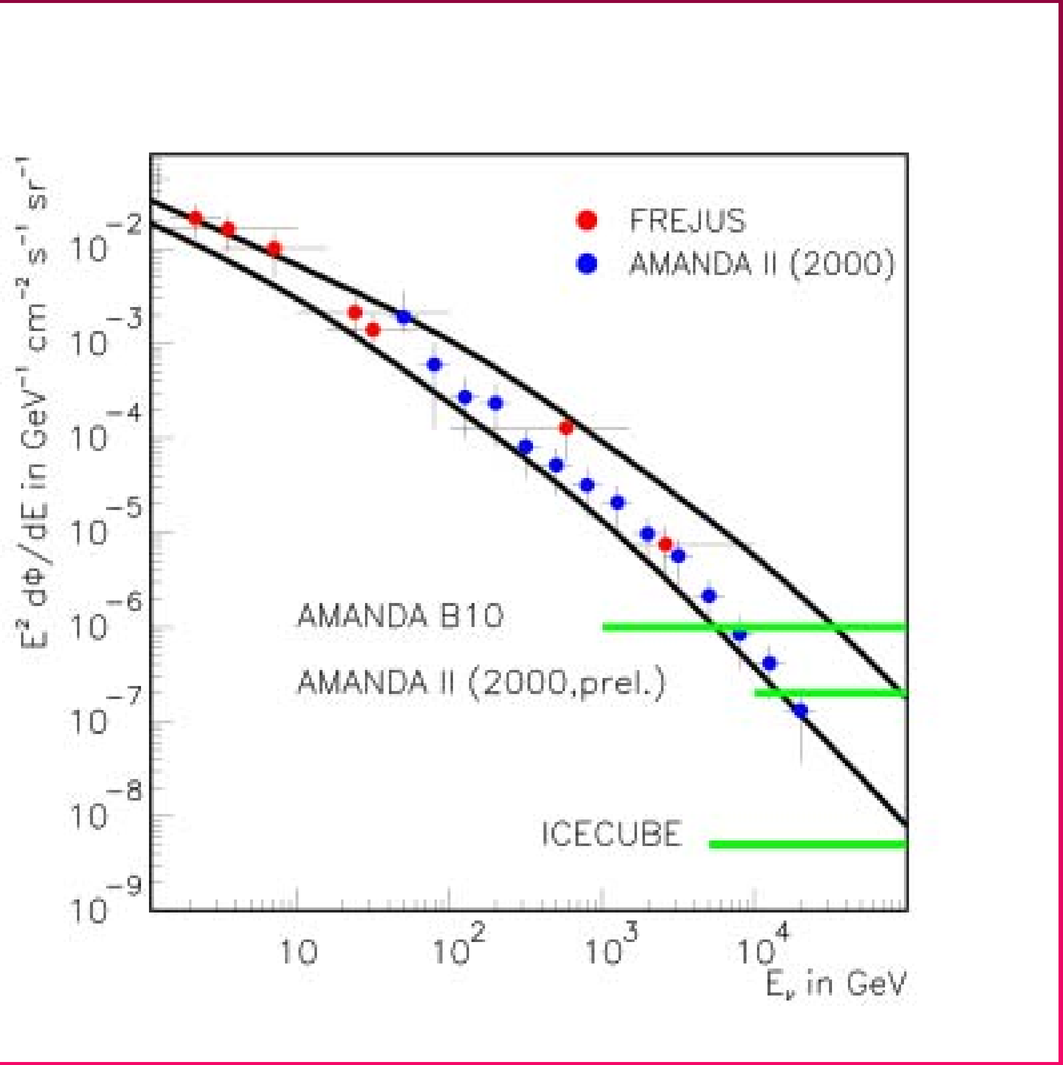


Gradual tightening of cuts extracts atm. ν signal

Reconstruction Handles

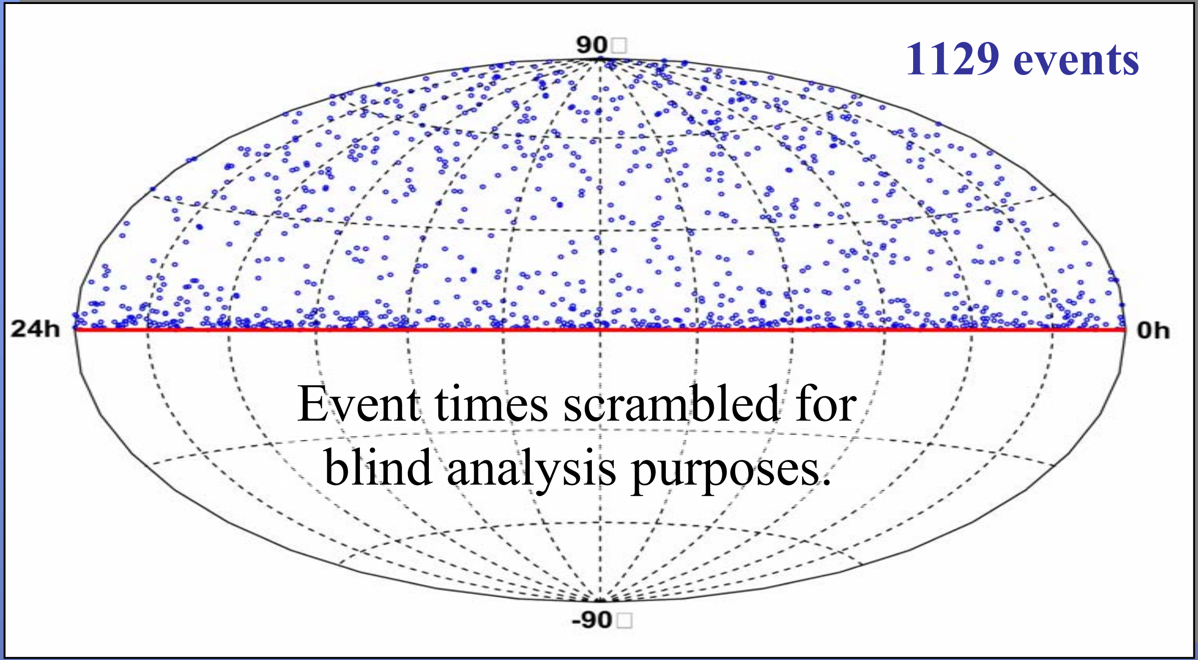
Signature	Signal /background
Diffuse flux	$\sim 10^{-8}$
Point source	$>10^{-6}$
Gamma ray burst	$>10^{-4}$

AMANDA 2000 Neutrino Flux



Point Sources Amanda II (2000)

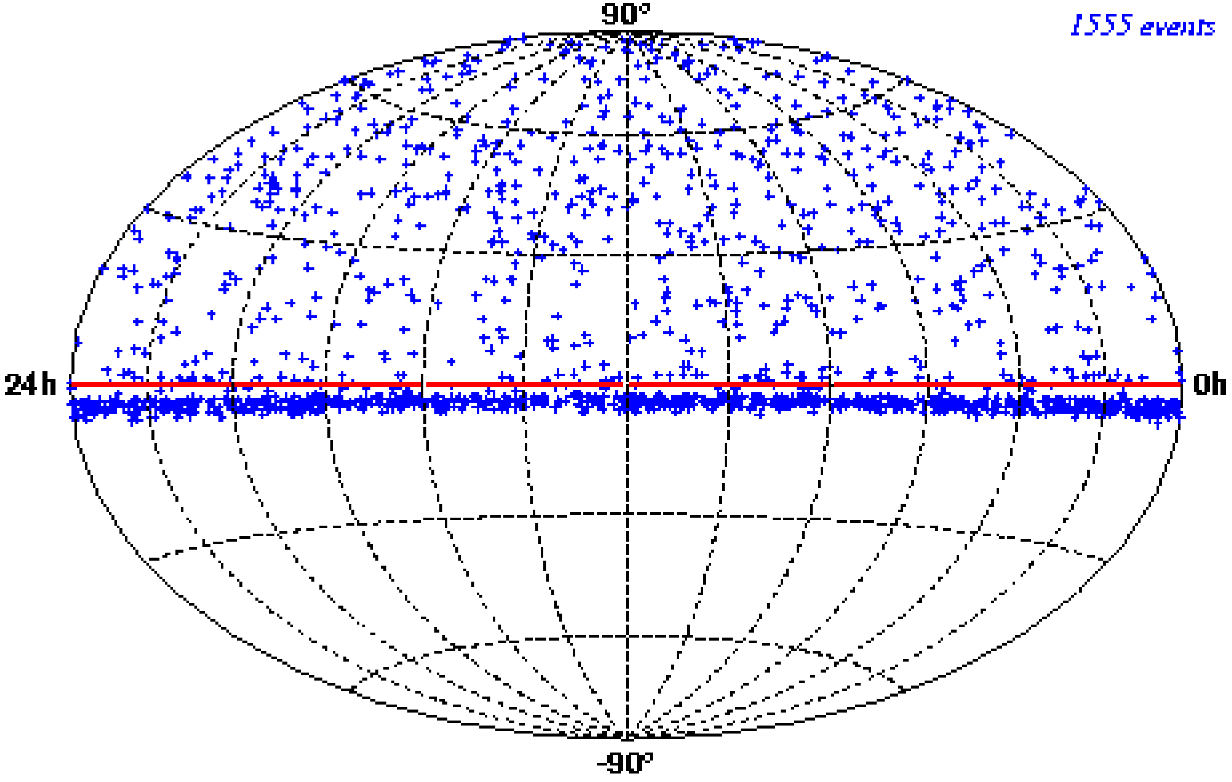
- Improved coverage near horizon
- Sensitivities calculated using background levels predicted from data
- close to "$\nu/\gamma \sim 1$ sensitivity" for some sources



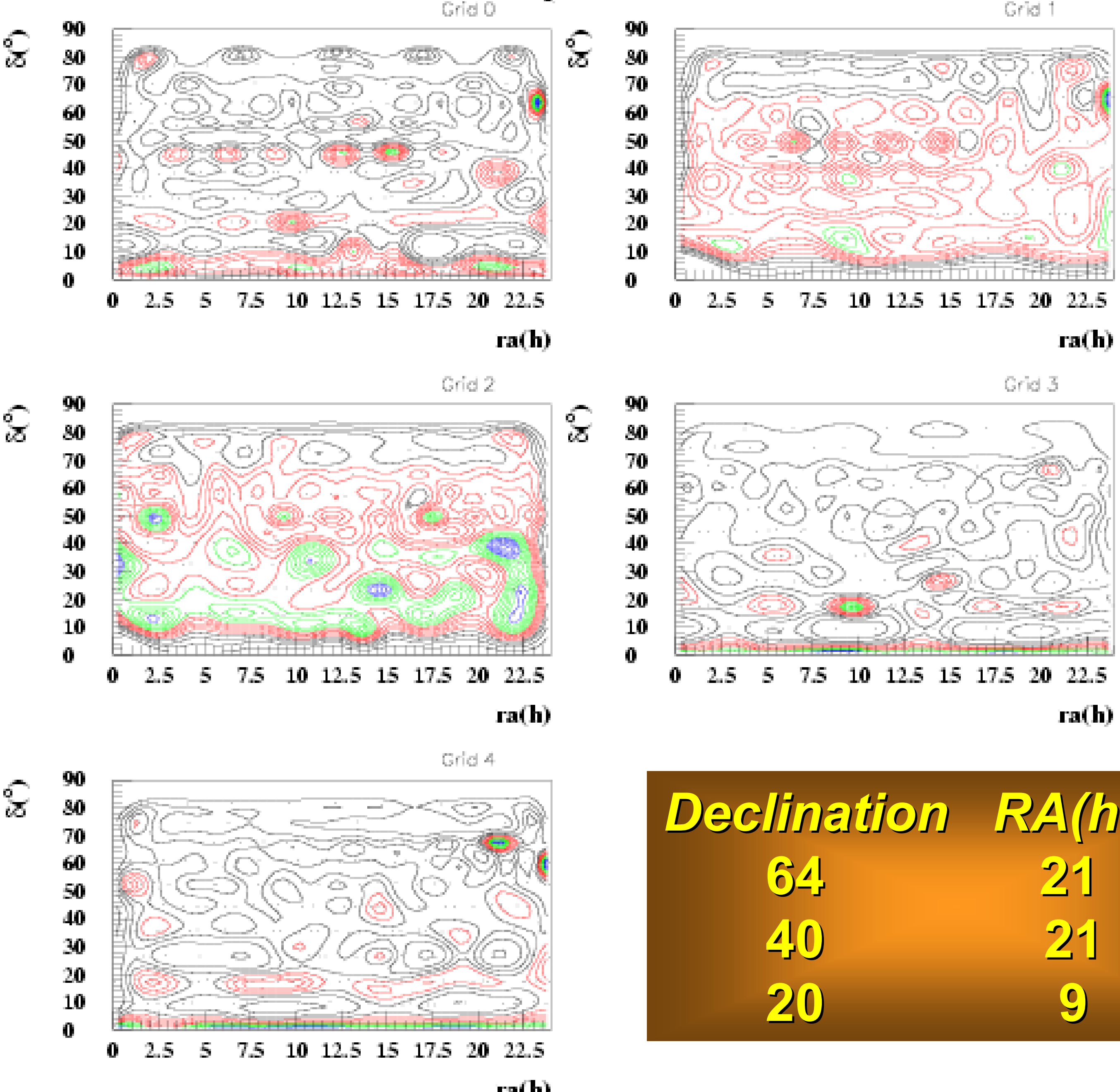
Source\Sensitivity	muon ($\times 10^{-15}$ cm^{-2} s^{-1})	ν (10^{-8} $GeVcm^{-2}$ s^{-1})
Markarian 421	0.5	3.1
Markarian 501	0.6	1.6
Crab	0.4	2.1
Cas-A	0.15	1.0
SS 433	0.15	0.6
Cygnus X-3	0.6	3.1

PRELIMINARY

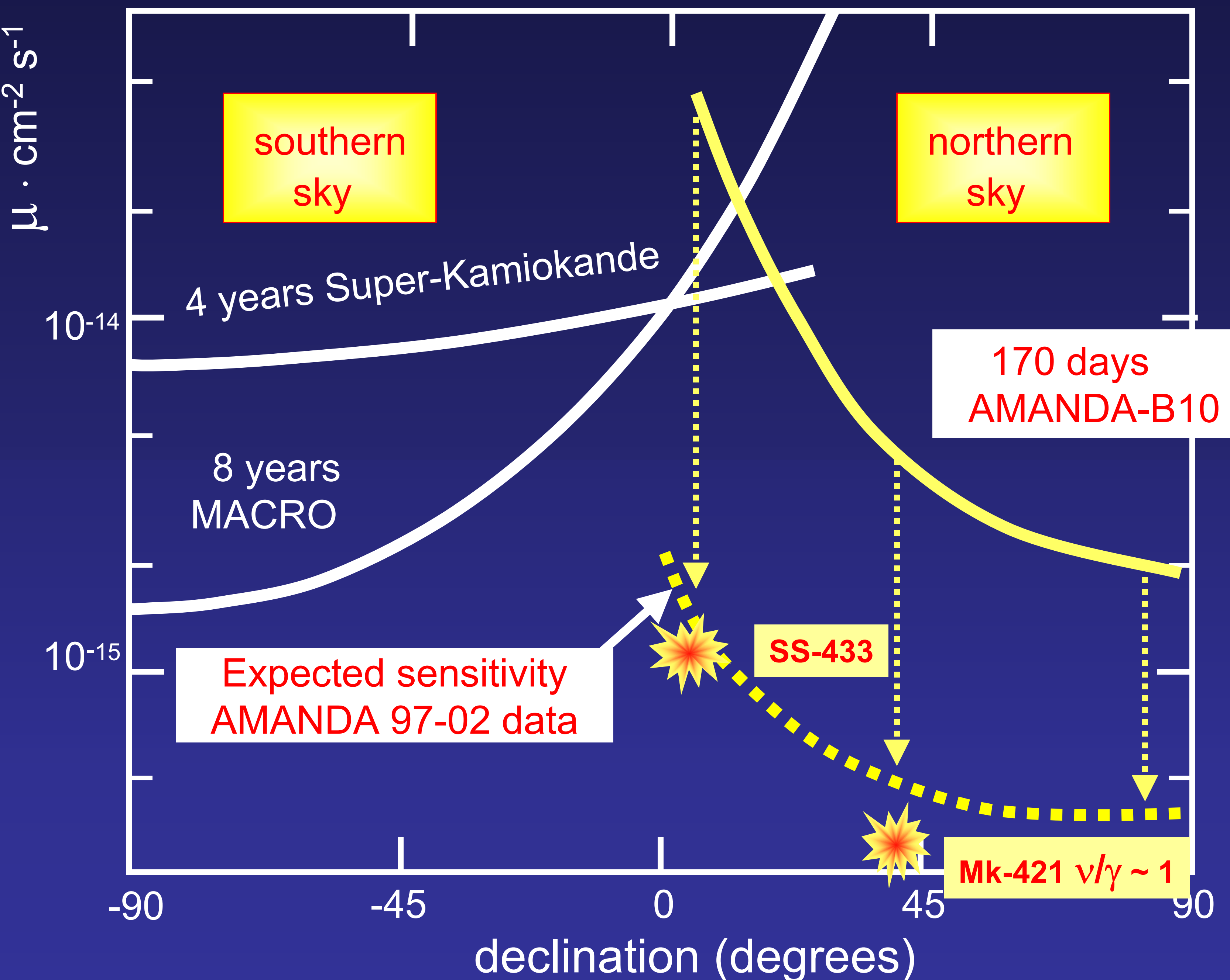
AMANDA II 2000



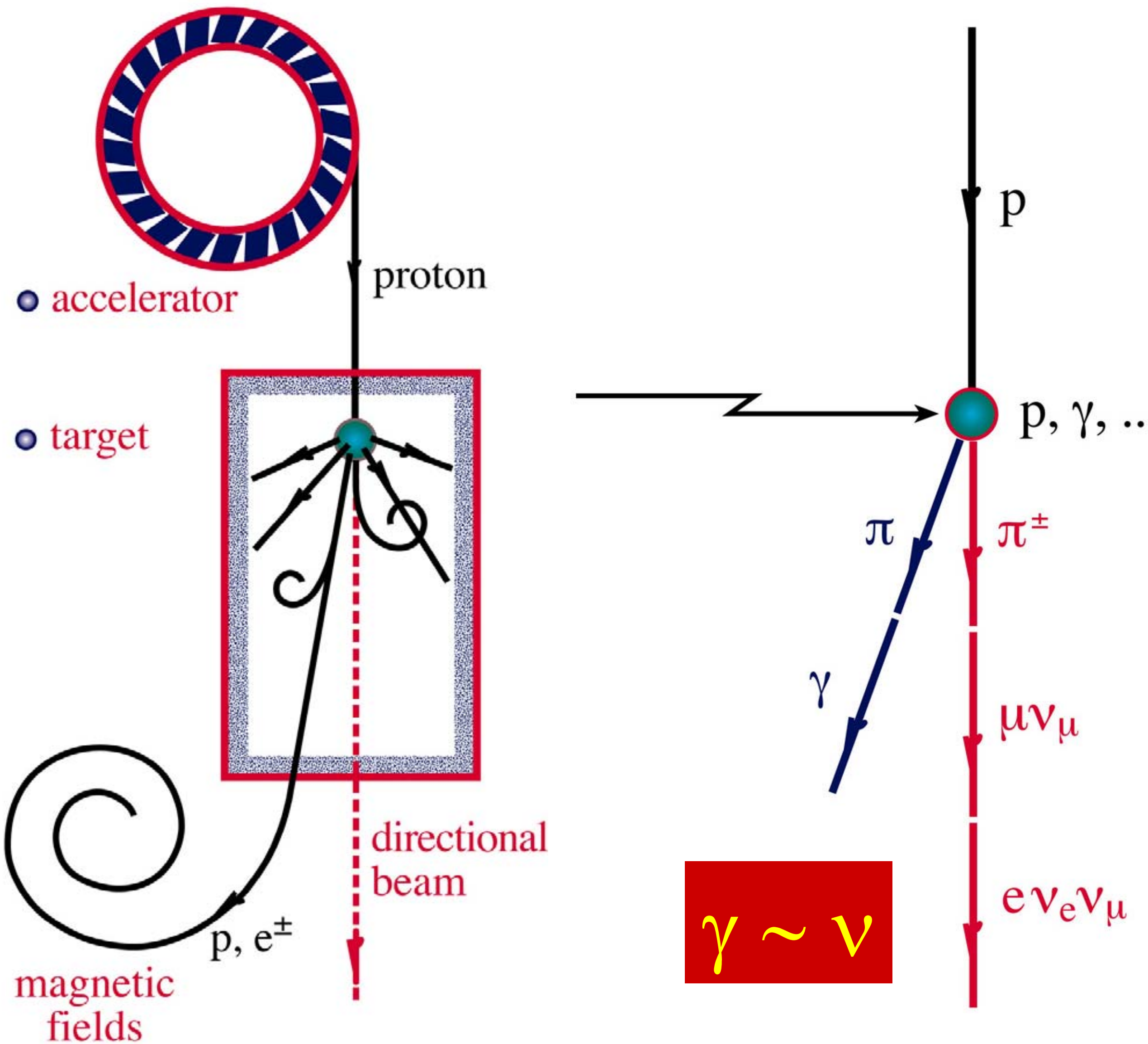
Final Exp Data (above 0°)



Declination	RA(hours)
64	21
40	21
20	9

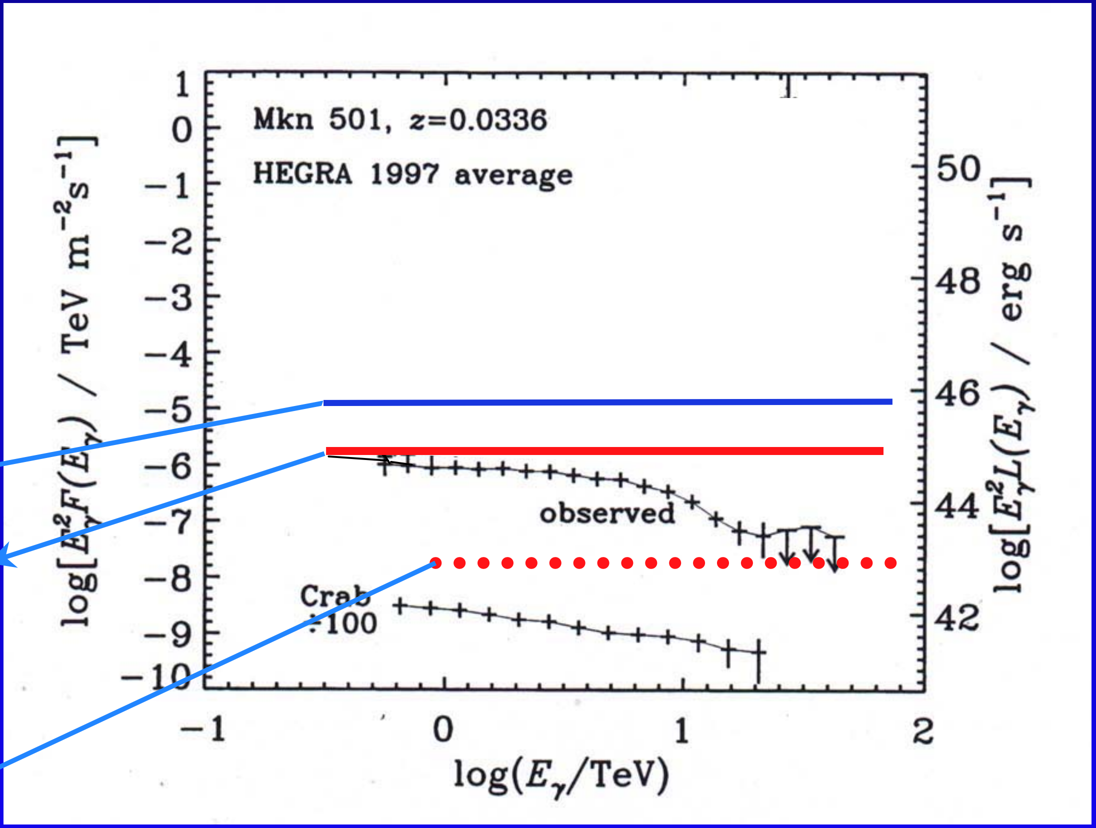

μ · cm-2 s-1
southern sky
northern sky
4 years Super-Kamiokande
10-14
10-15
170 days AMANDA-B10
8 years MACRO
SS-433
Expected sensitivity AMANDA 97-02 data
Mk-421 ν/γ ~ 1
-90
-45
0
45
90
declination (degrees)

NEUTRINO BEAMS: HEAVEN & EARTH



compare AMANDA ν sensitivity Mrk 501 gamma ray flux

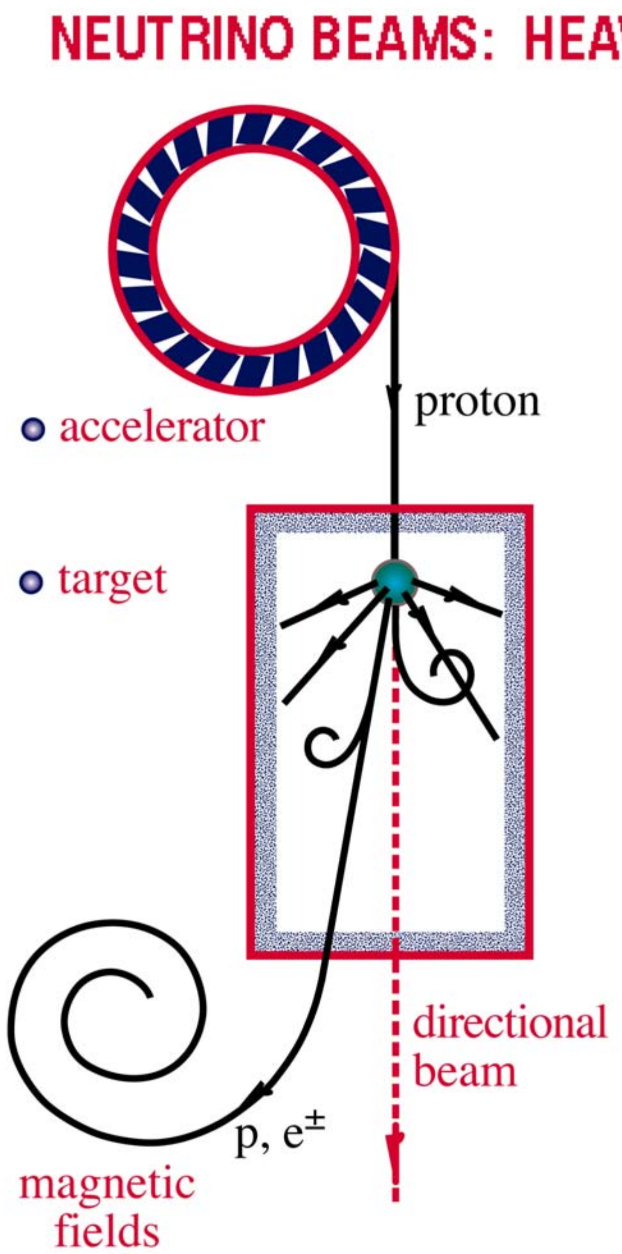
field of view: continuous 24 h x 2 π sr
(northern sky)



AMANDA B10

AMANDA II 2000 PRELIMINARY

Sensitivity of 3 years of IceCube



black hole

radiation enveloping black hole

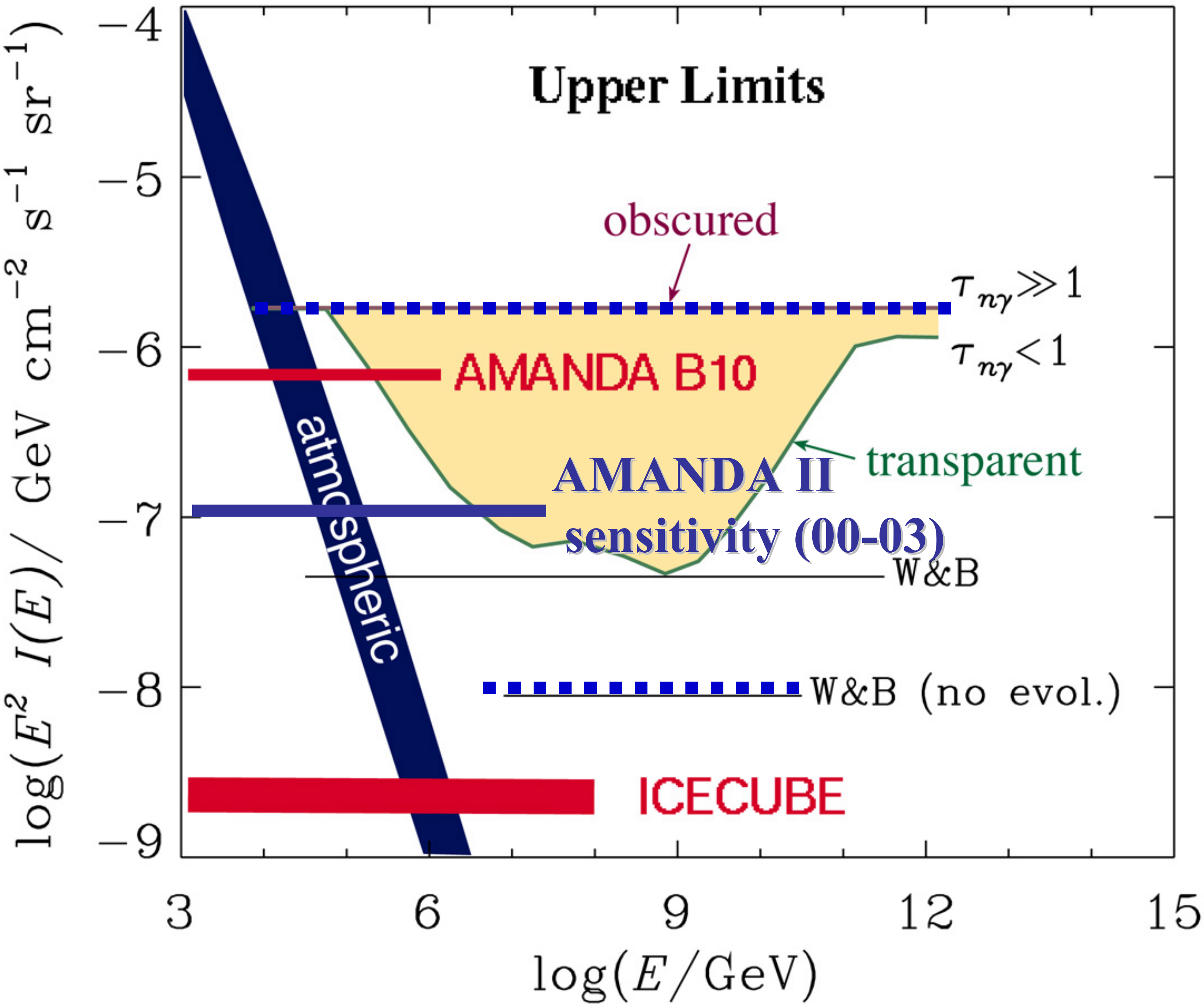
$p + \gamma \to n + \pi^+$

~ cosmic ray + neutrino

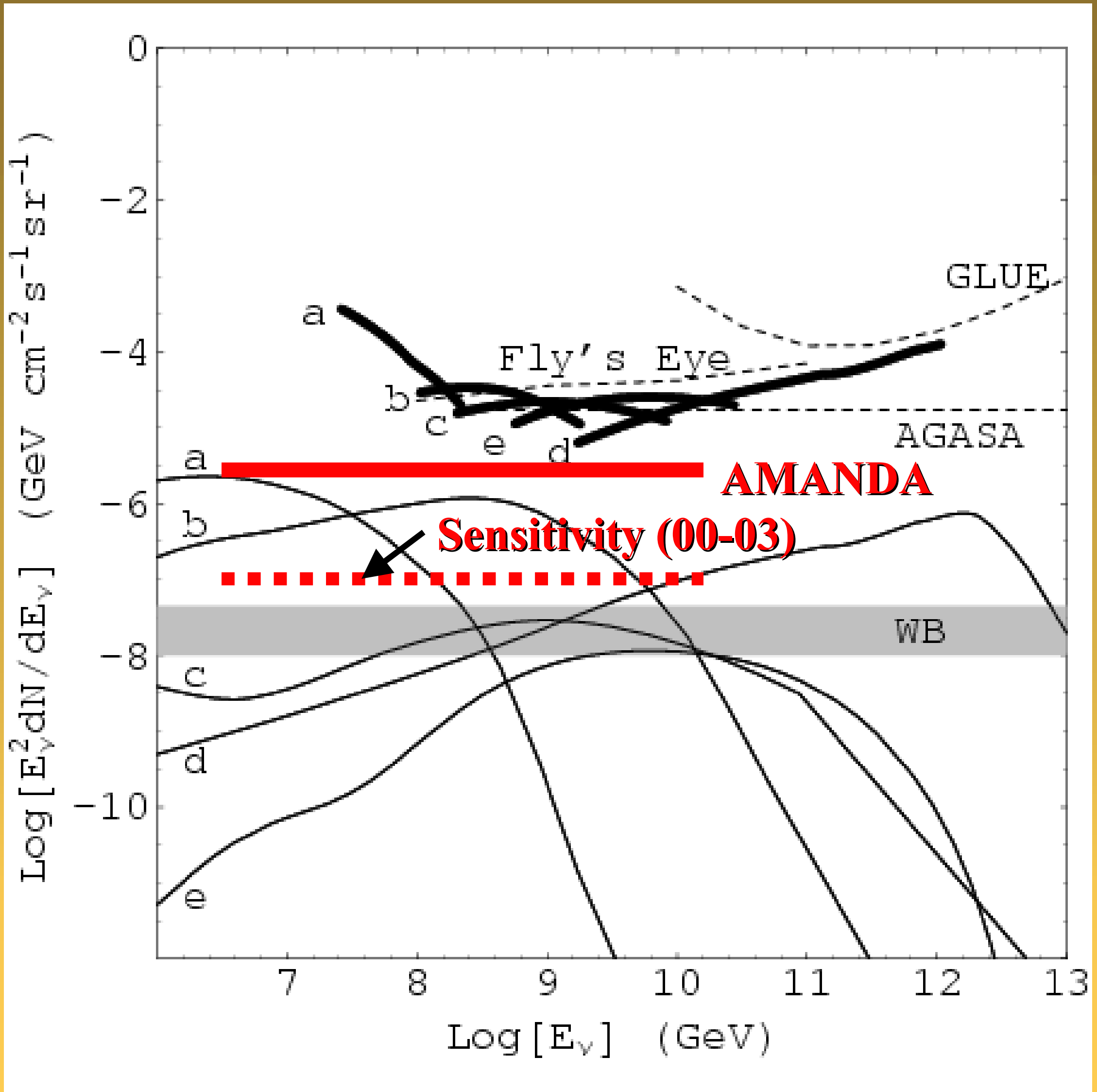
$\to p + \pi^0$

~ cosmic ray + gamma

neutrinos associated with the source of the cosmic rays?



diffuse EHE neutrino flux limits

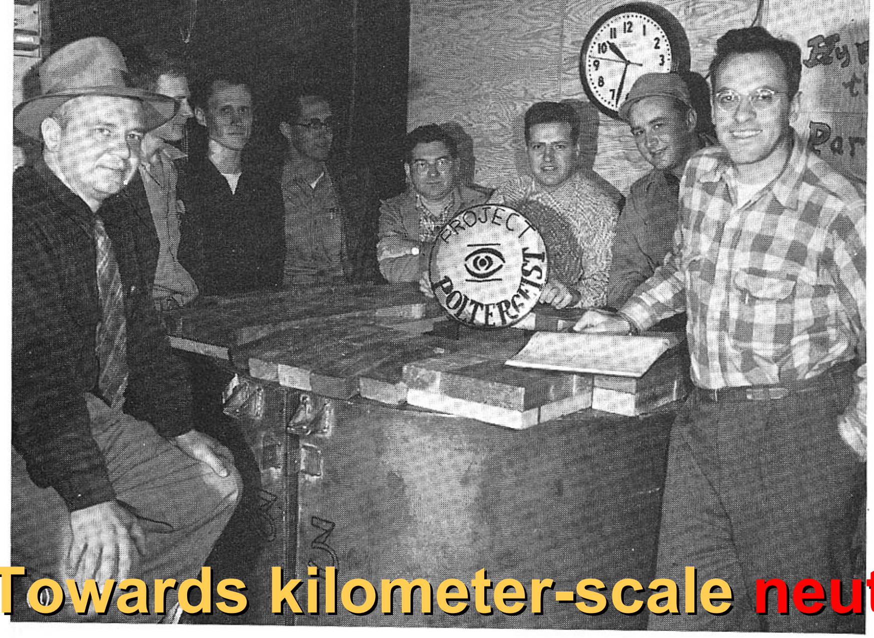


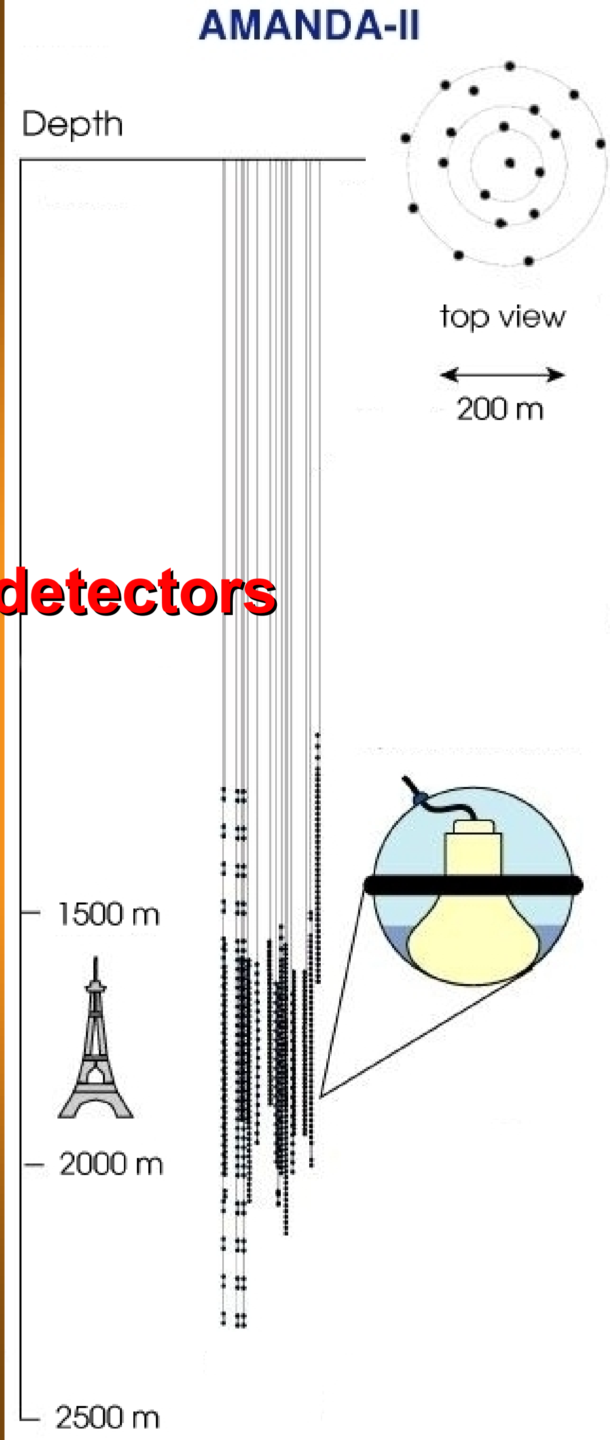
- Stecker & Salamon (AGN)
- Protheroe (AGN)
- Mannheim (AGN)
- Protheroe & Stanev (TD)
- Engel, Seckel & Stanev

Ranges are central 80%

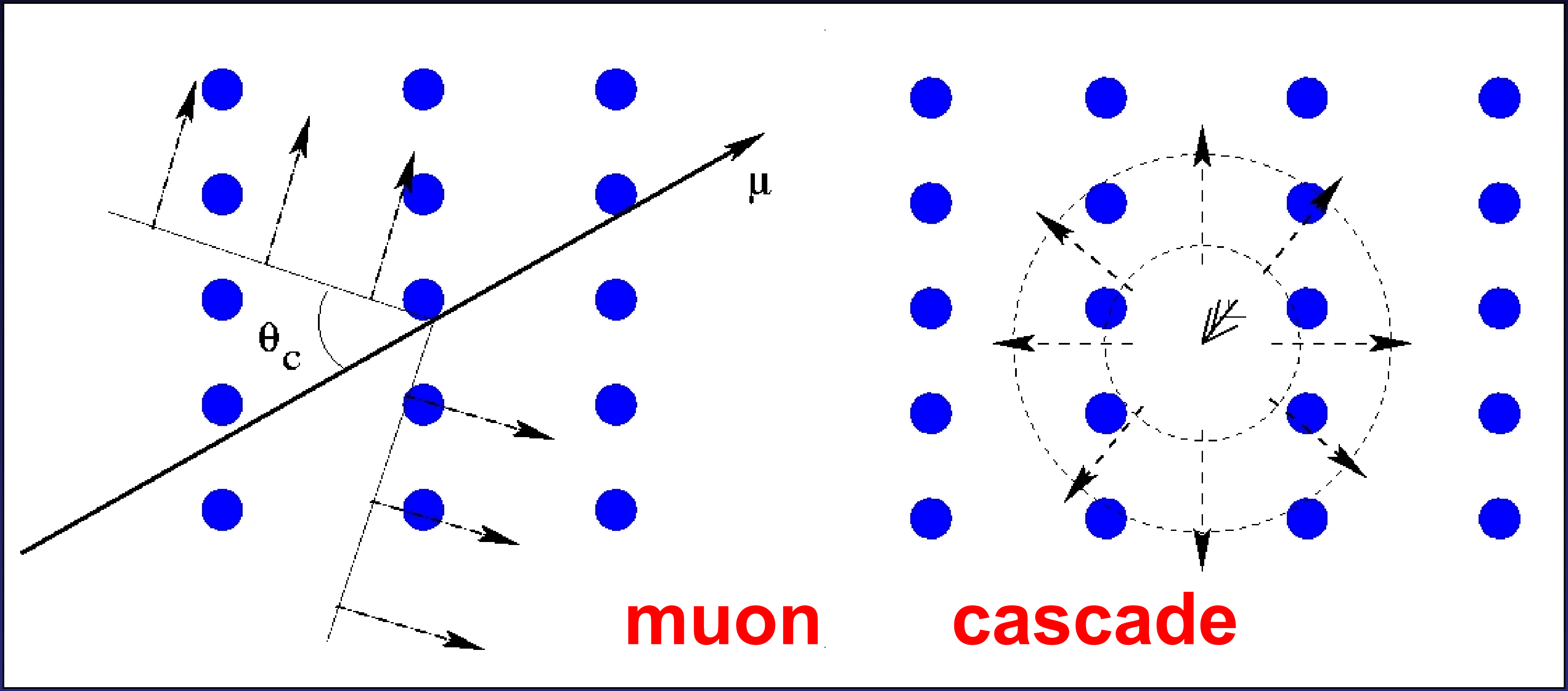
kilometer-scale neutrino observatories

Towards kilometer-scale neutrino detectors





Cherenkov light from muons and cascades



Reconstruction

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

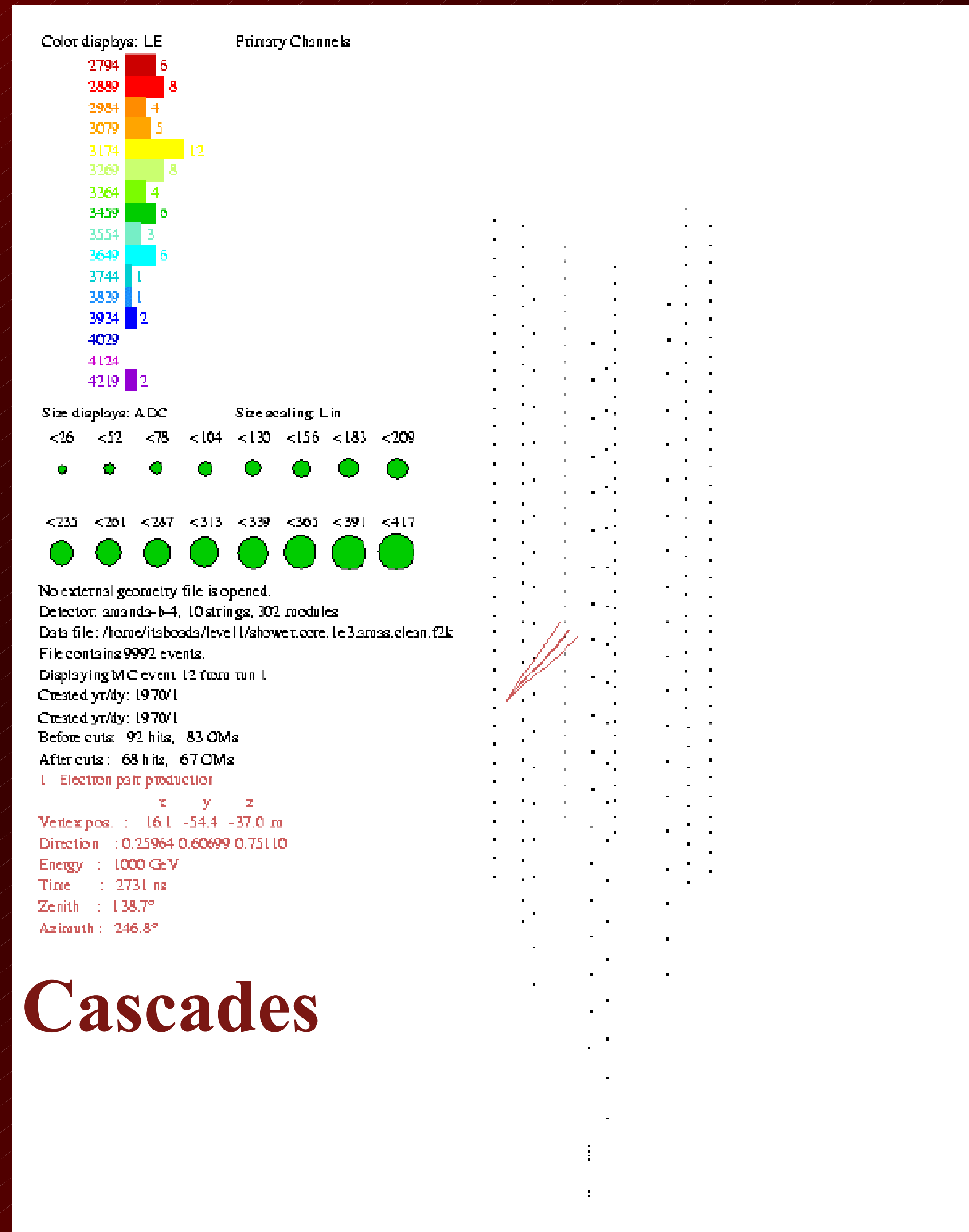
AMANDA Event Signatures: Cascades

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

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

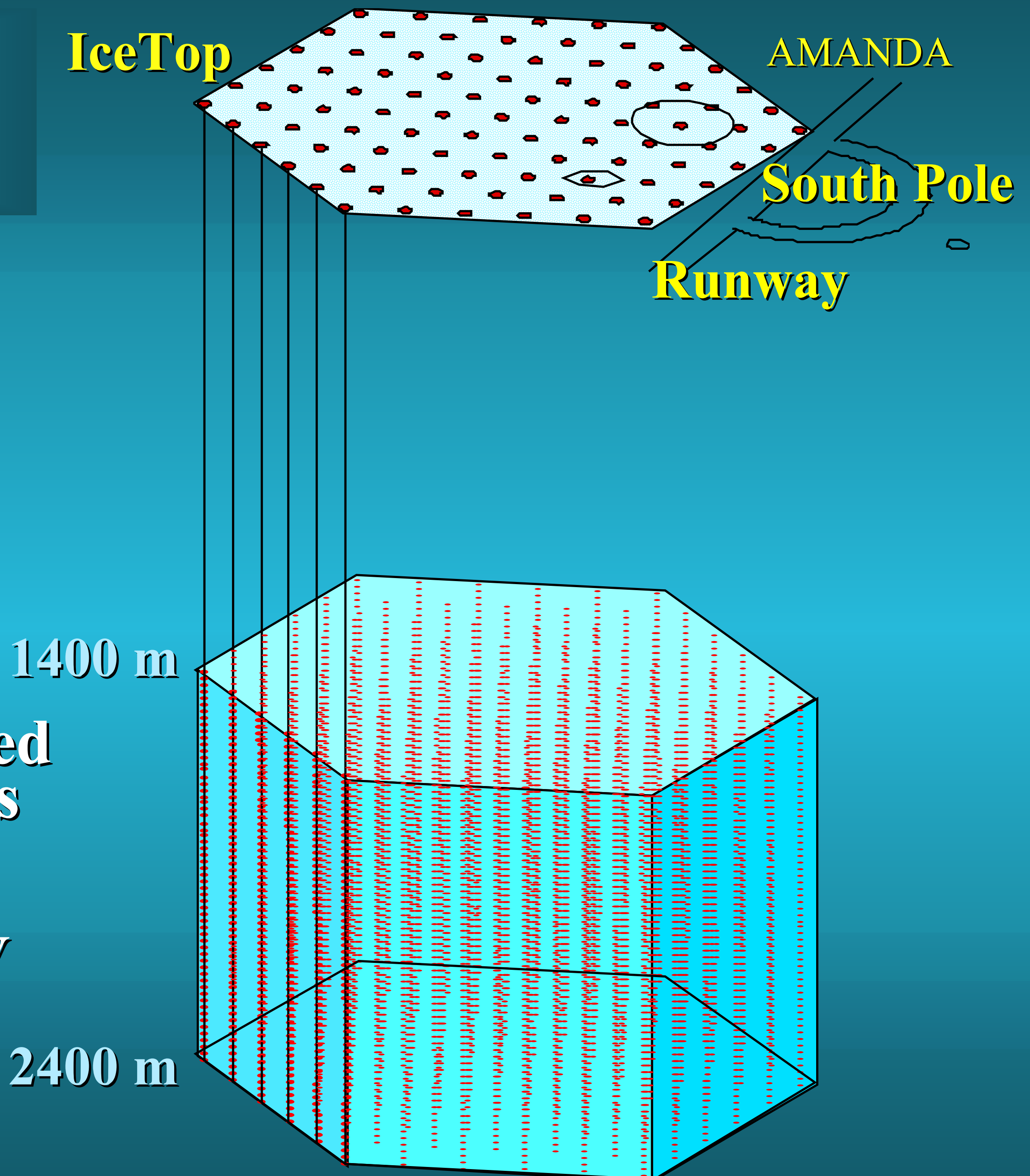
- **NC neutrino interaction:**

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



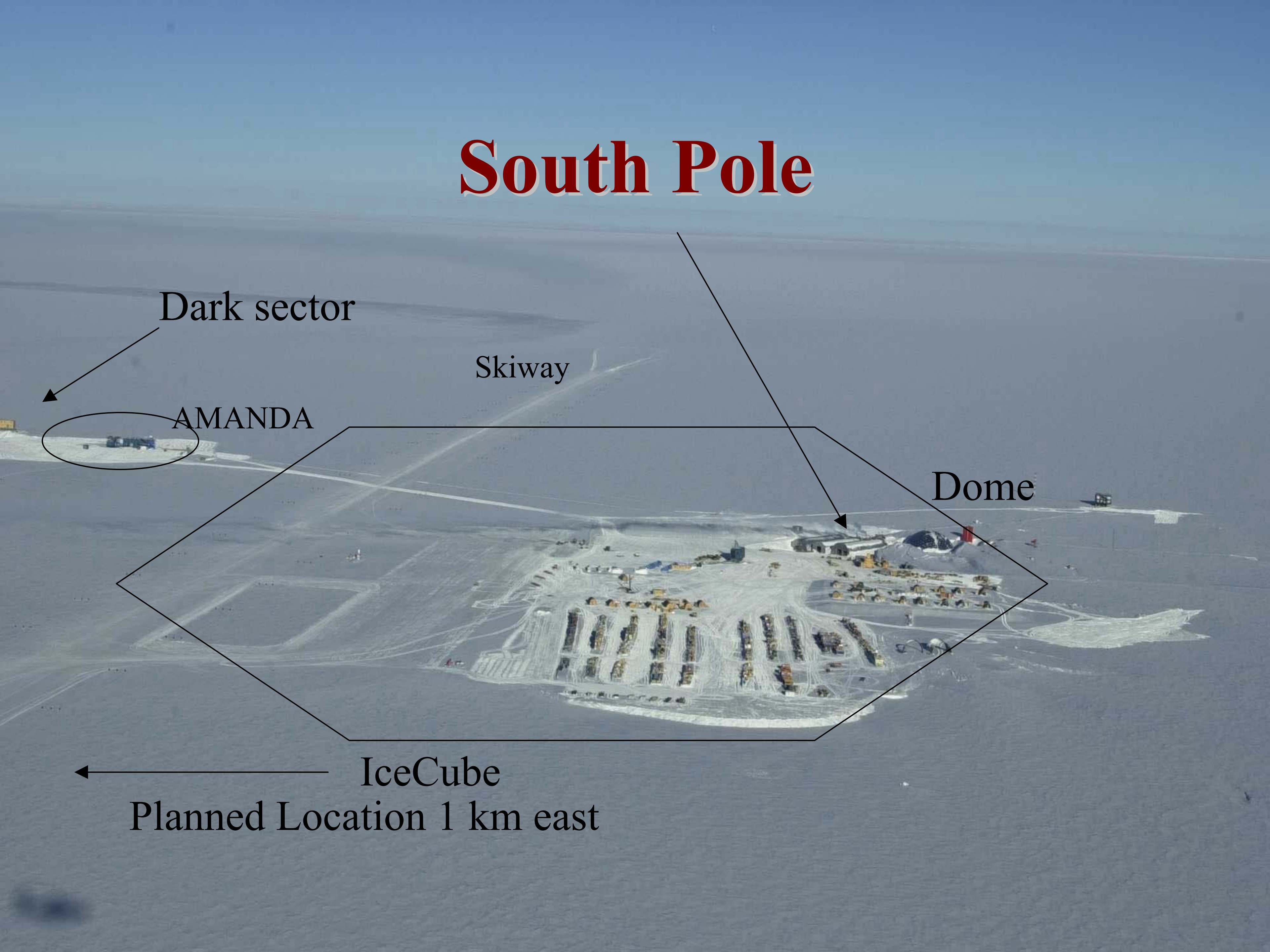
IceCube

- 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

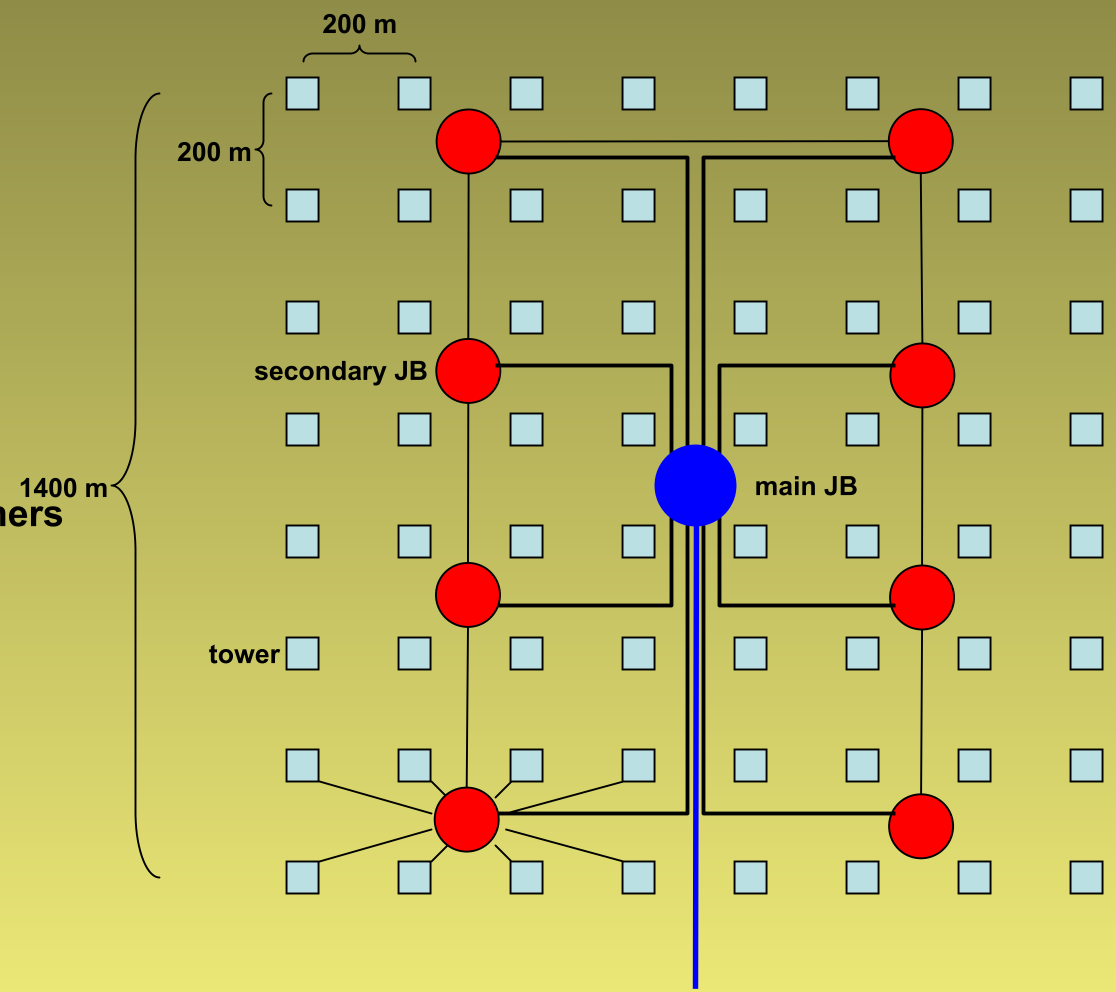

Dark sector
Skiway
AMANDA
Dome
IceCube
Planned Location 1 km east

South Pole

NEMO

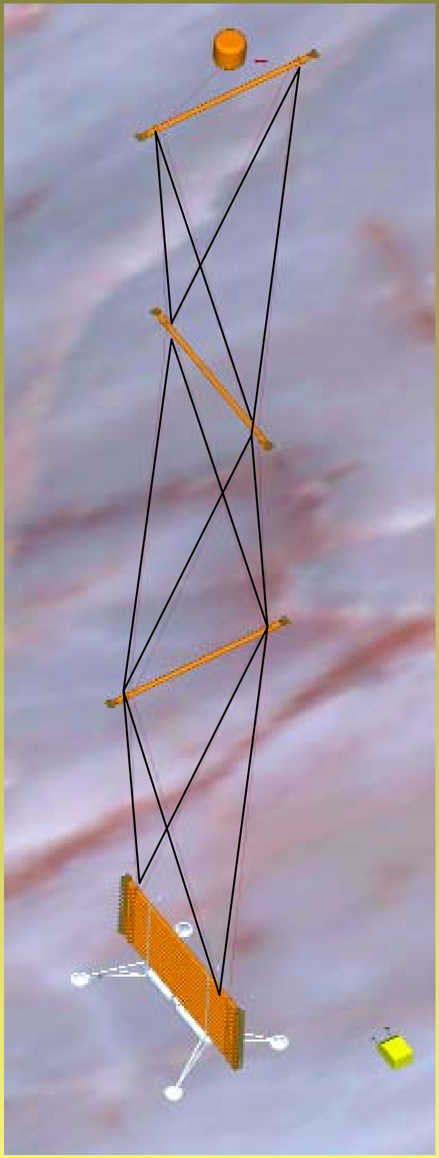
Actual proposal of general layout for Km^3 detector

- 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



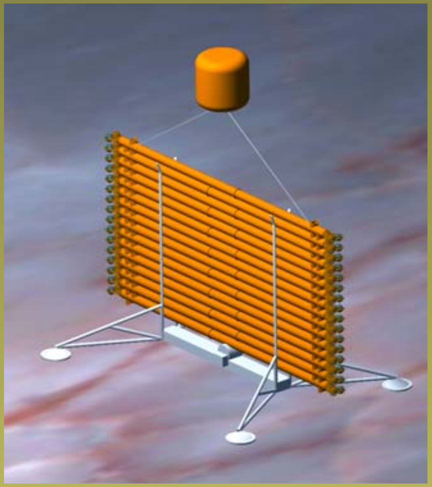
main electro optical cable
- 48 optical fibers
- 3 or 4 electrical conductors

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.



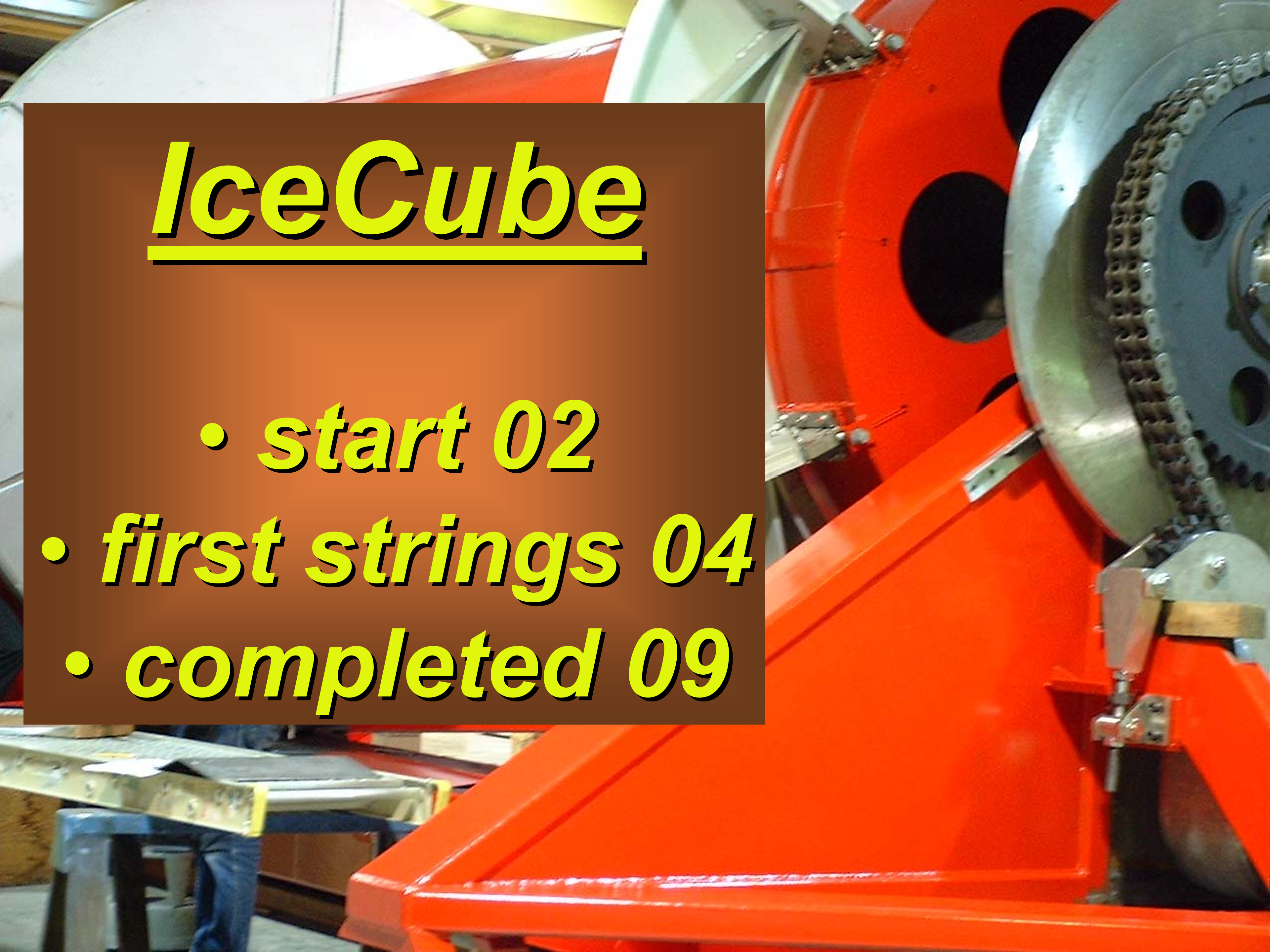
The mechanical stresses on the rigid part of the structure are:

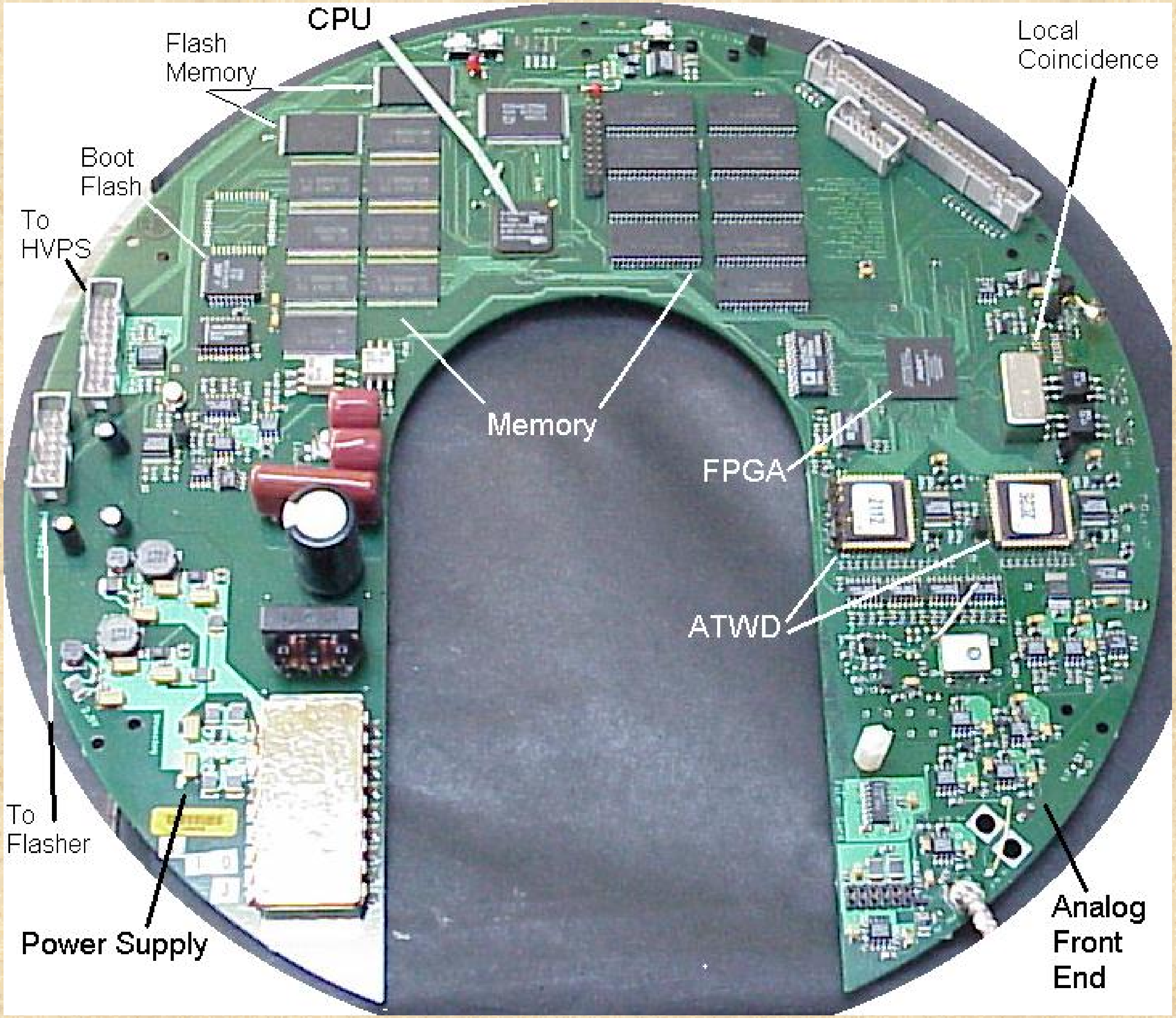
• a bending due to the weight of the spheres when it is out of the sea water;

• an axial load during the useful life due to the draught of the upper buoy.

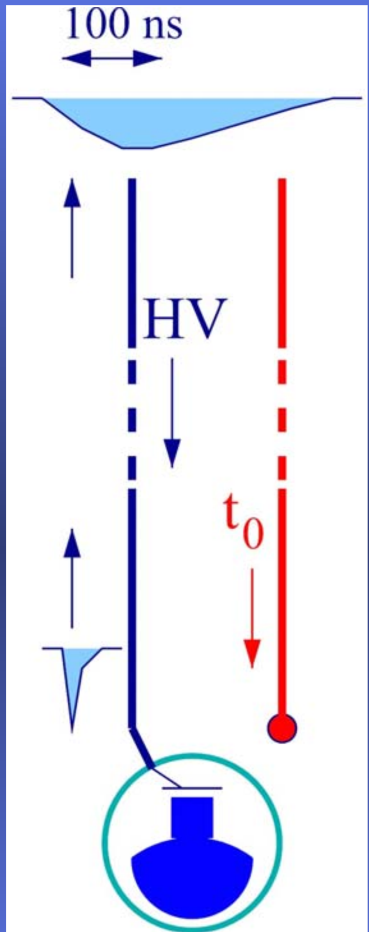
The electro optical cables can be easily fixed on the ropes.

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

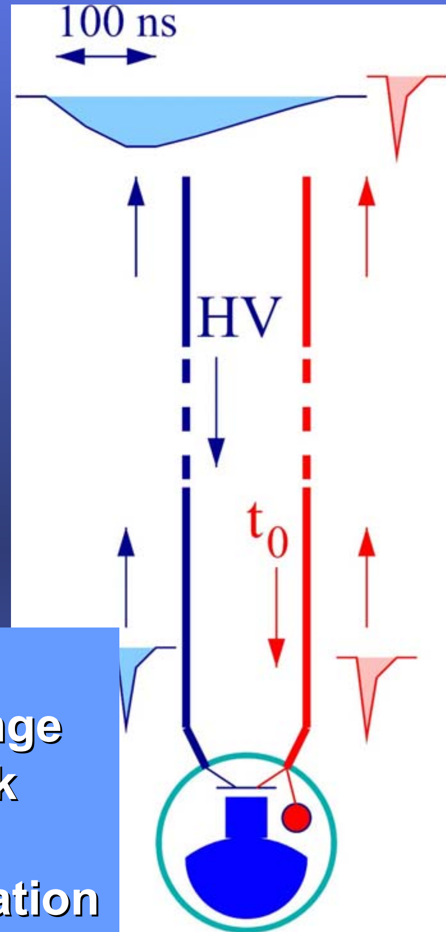

IceCube
• start 02
• first strings 04
• completed 09


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

Evolution of read-out strategy

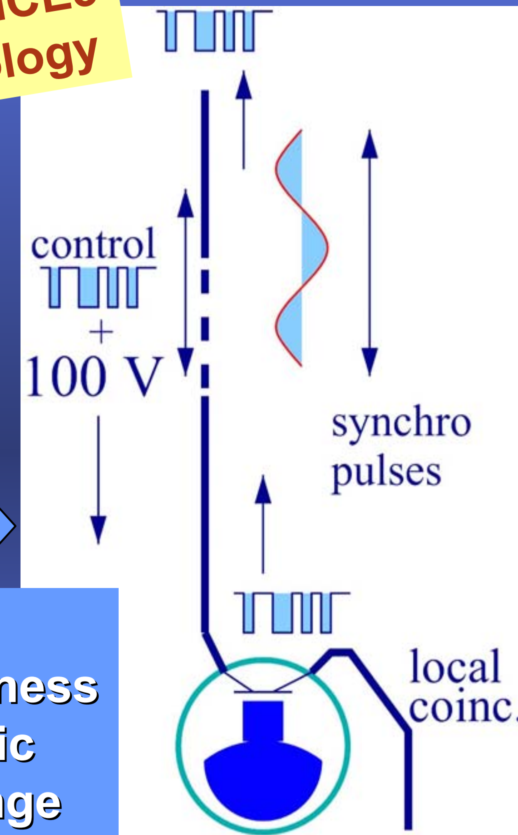


- timing
- dyn. range
- no x-talk
- easy calibration



Test of ICE3 technology

- cost
- robustness
- dynamic range



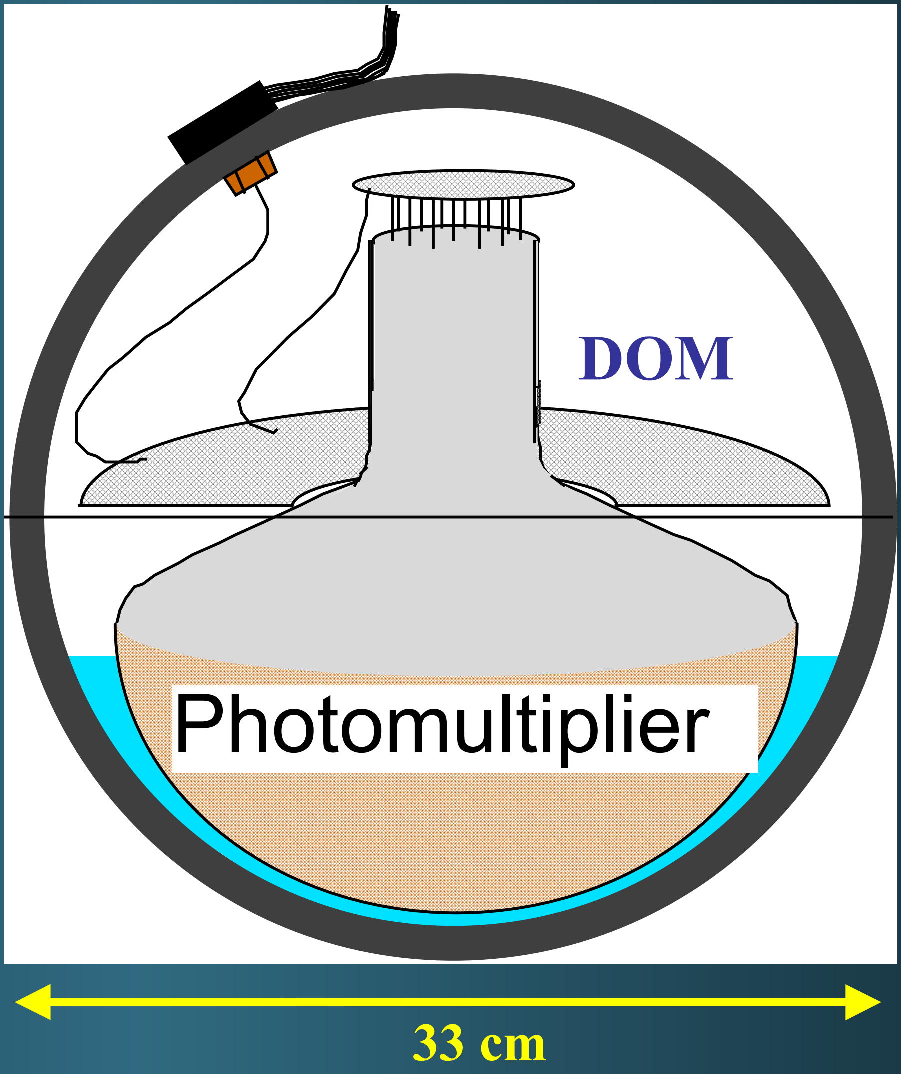
<u>01/02 - 03/04</u>: Equipping all Amanda channels with FADCs to get full waveform information (IceCube compatibility)

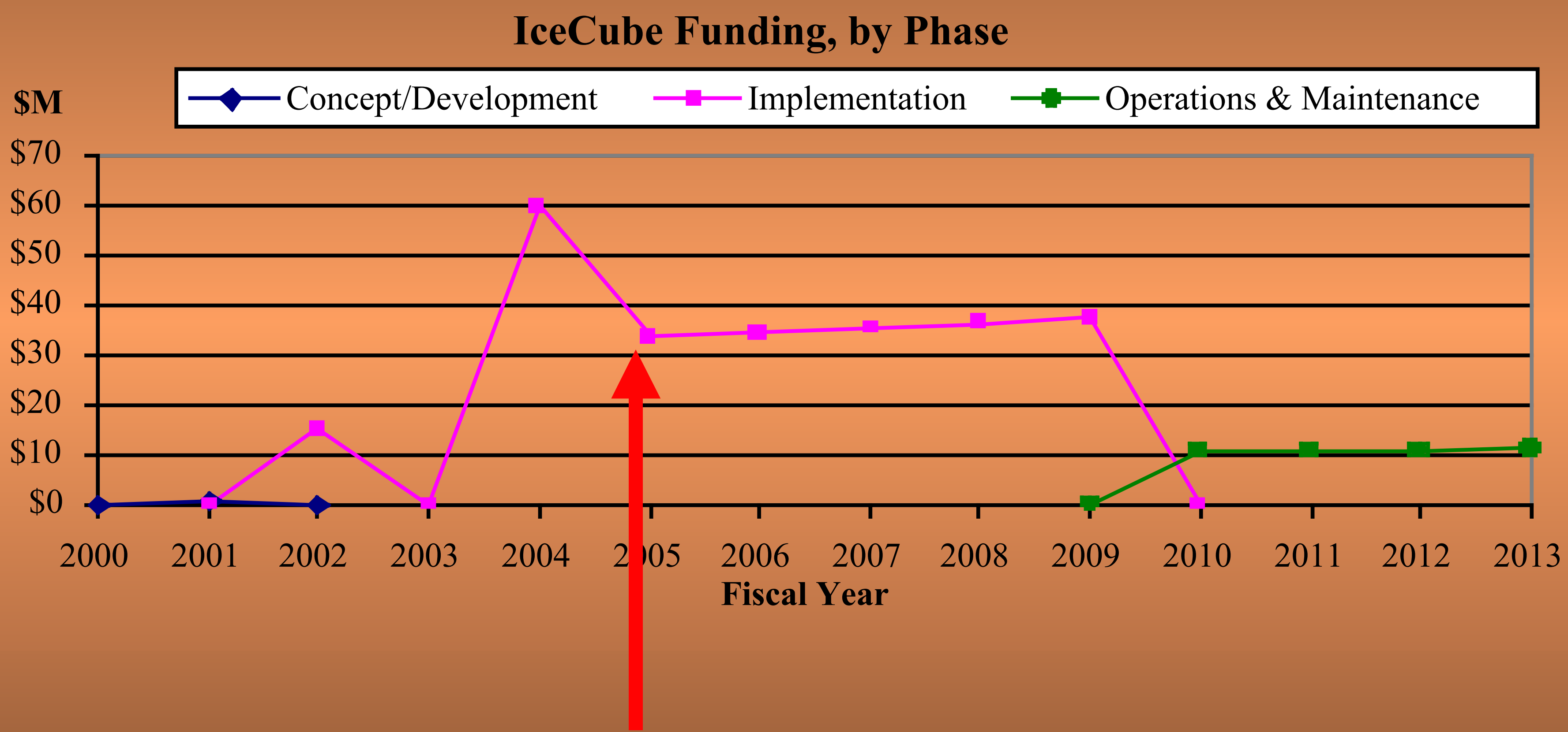
→ better reconstruction, particularly cascades and high energy tracks

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)**





first 8 strings

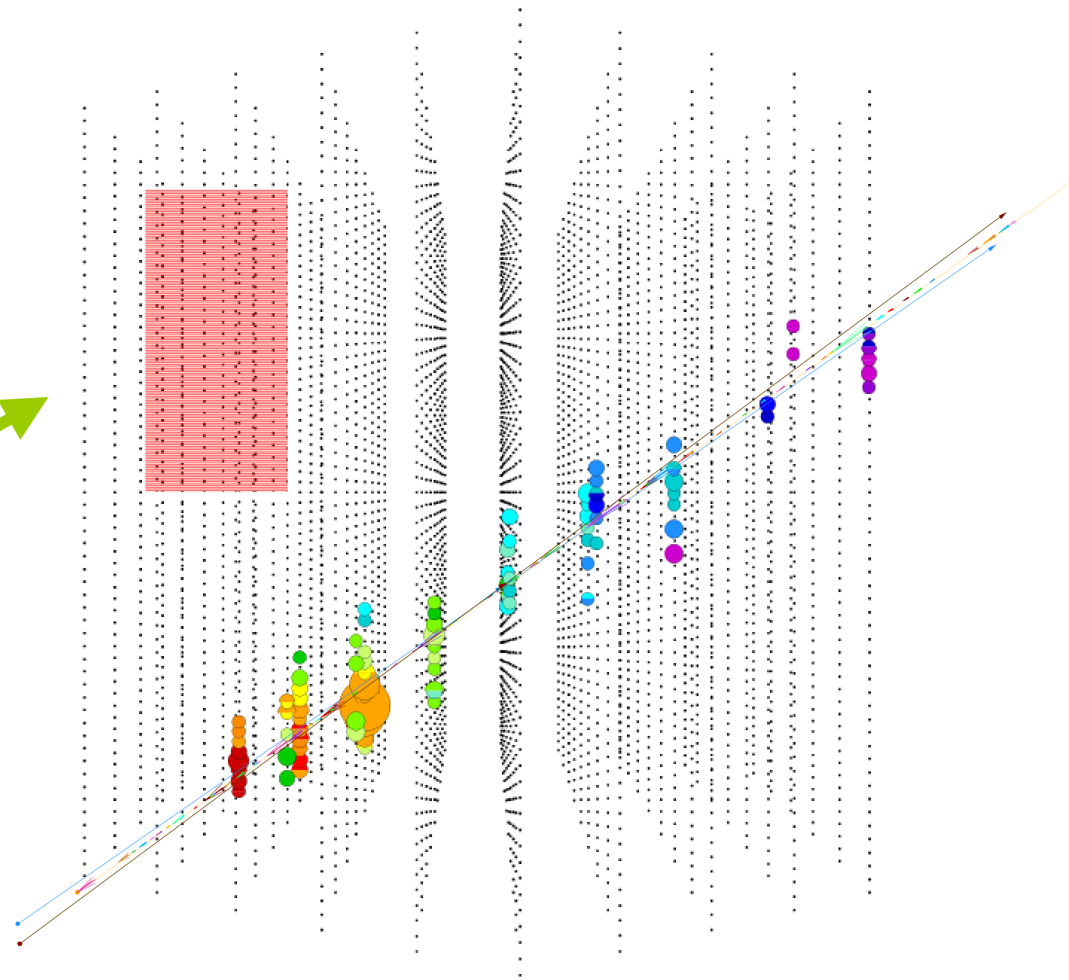
IceCube has been designed as a discovery instrument with improved:

- 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)

μ-event in IceCube

300 atmospheric neutrinos per day

AMANDA II

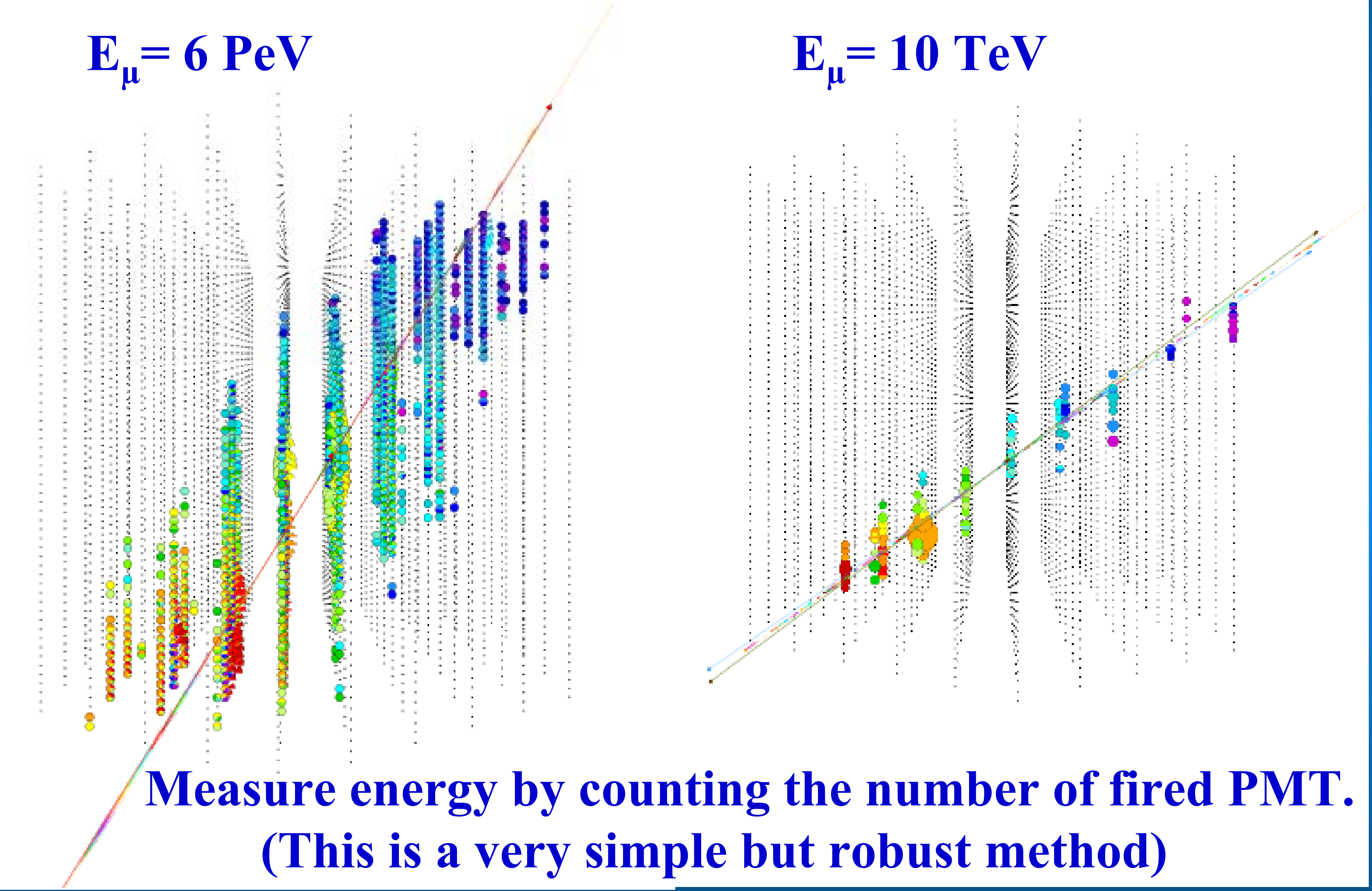


IceCube:

-> Larger telescope

-> Superior detector

Muon Events



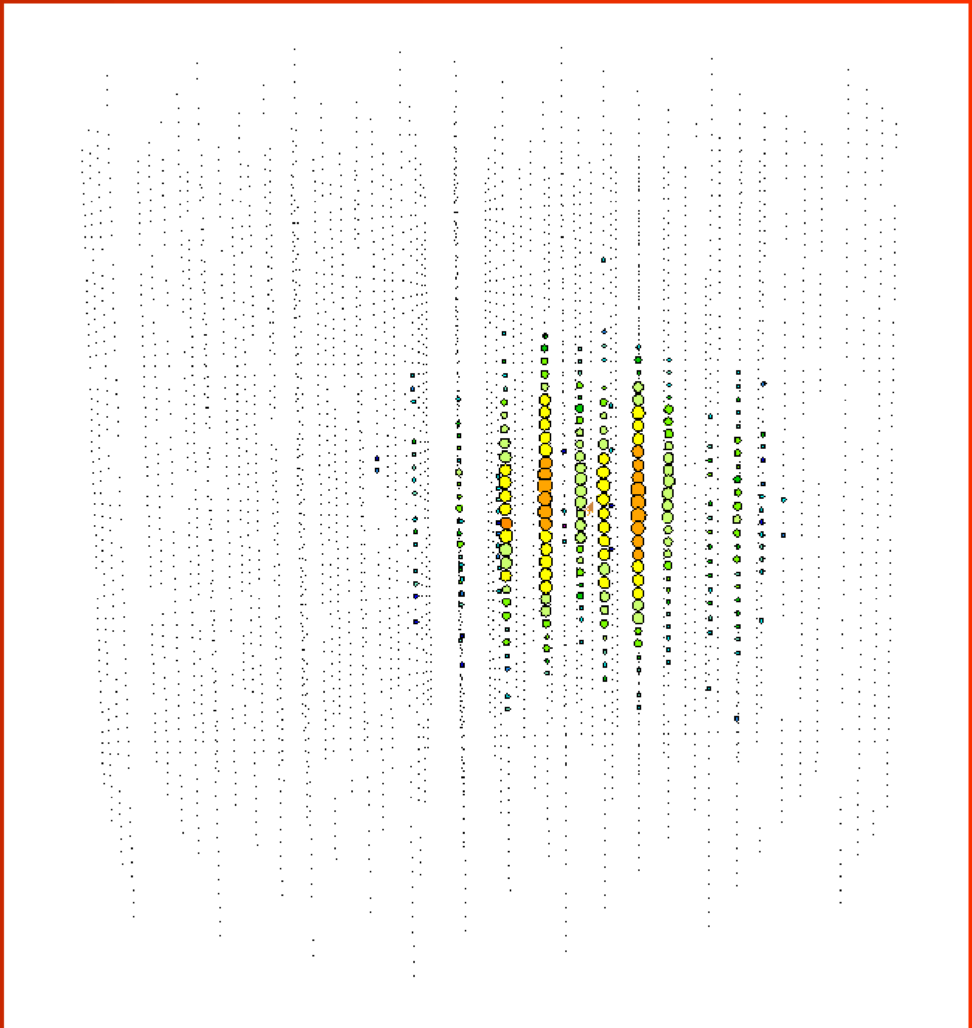
Measure energy by counting the number of fired PMT.
(This is a very simple but robust method)

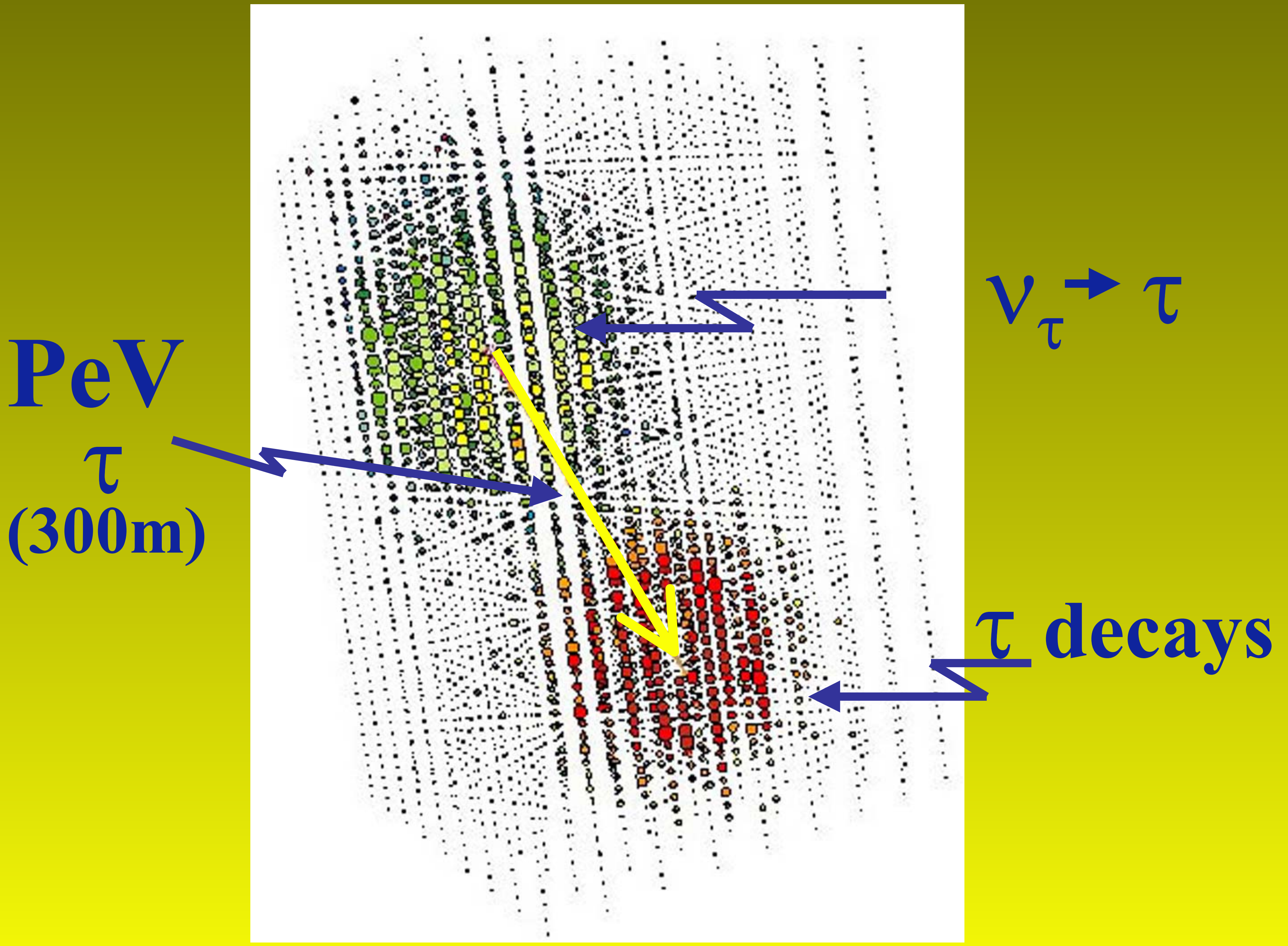
Cascade event

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

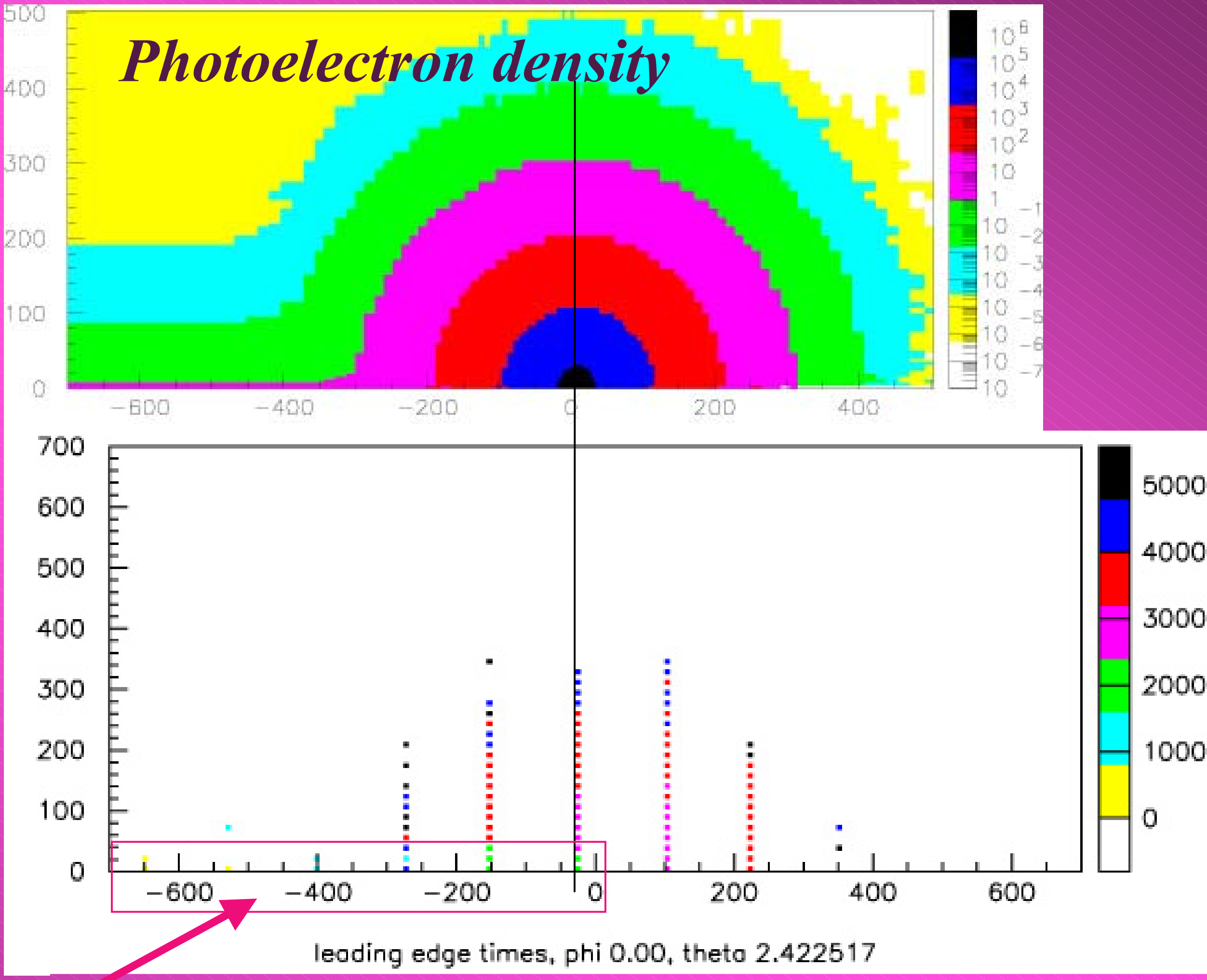
Energy = 375 TeV




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

ν_τ at E > PeV: Partially contained

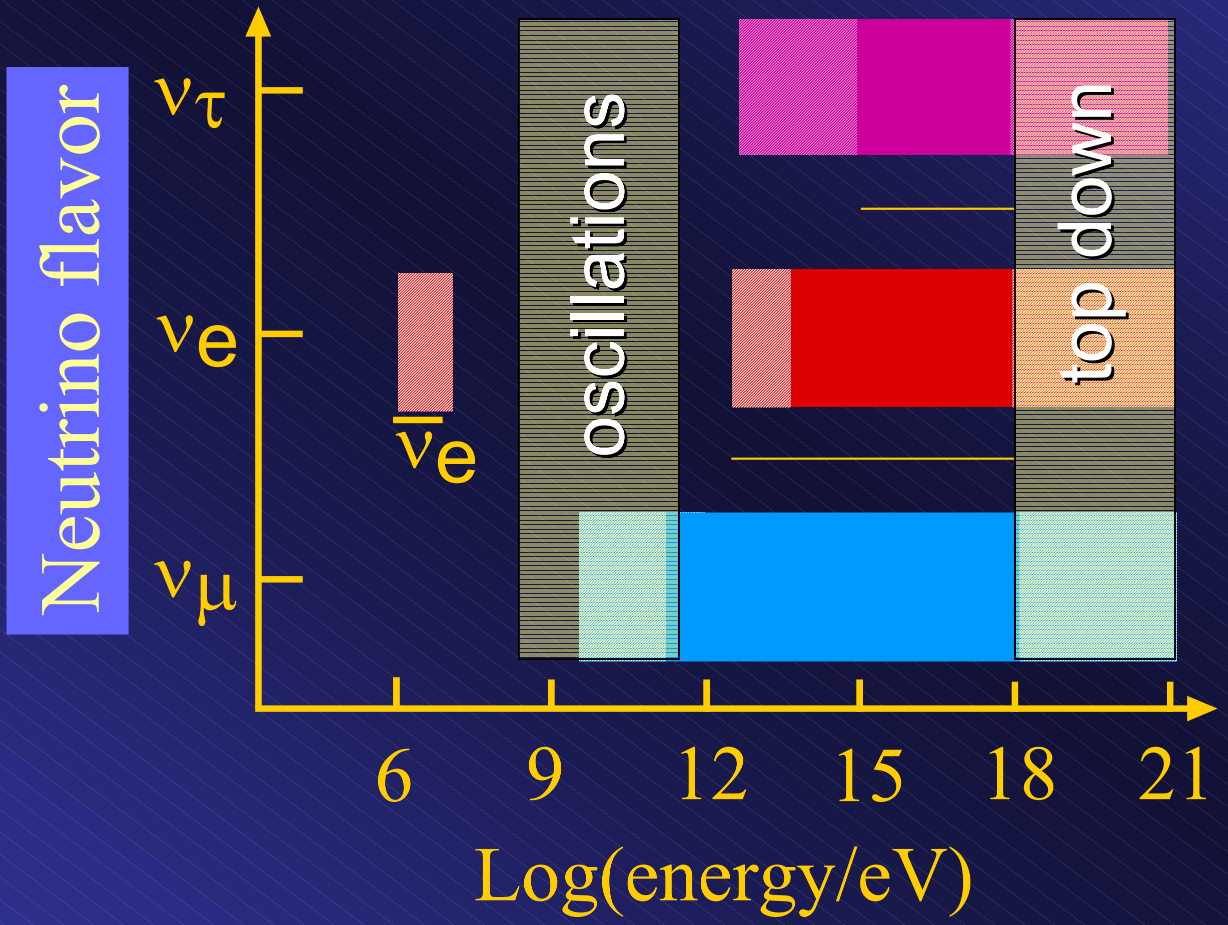
- The incoming tau radiates little light.
- The energy of the second cascade can be measured with high precision.
- Signature: Relatively low energy loss incoming track: would be much brighter than the tau (compare to the PeV muon event shown before)



Result: high effective Volume, only second bang needs to be seen in Ice3

10-20 OM early hits measuring the incoming τ-track

Neutrino ID (solid)
Energy and angle (shaded)

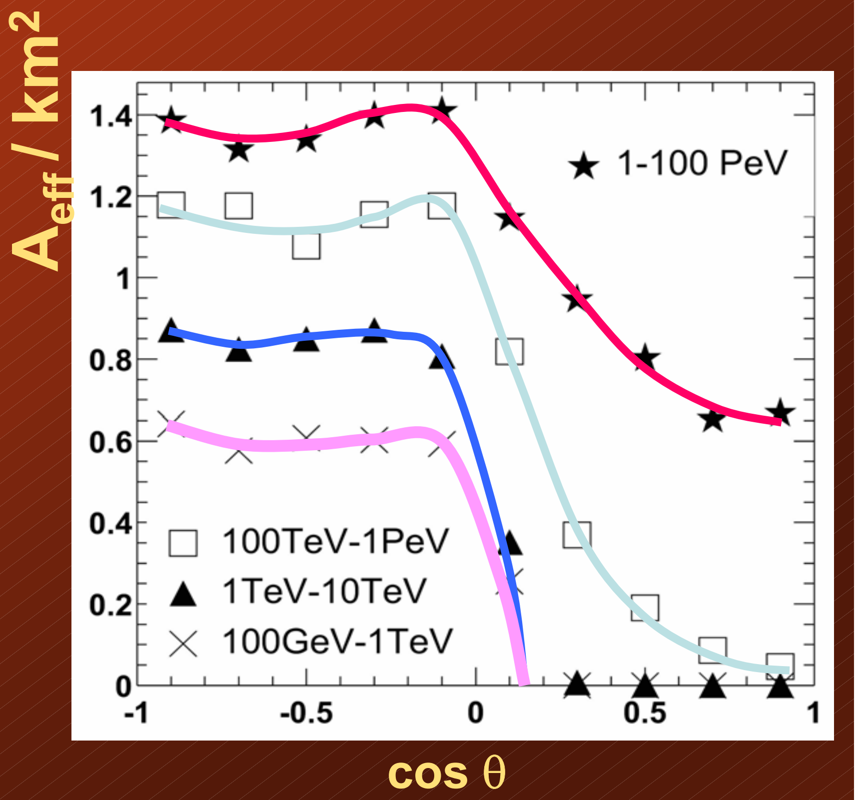


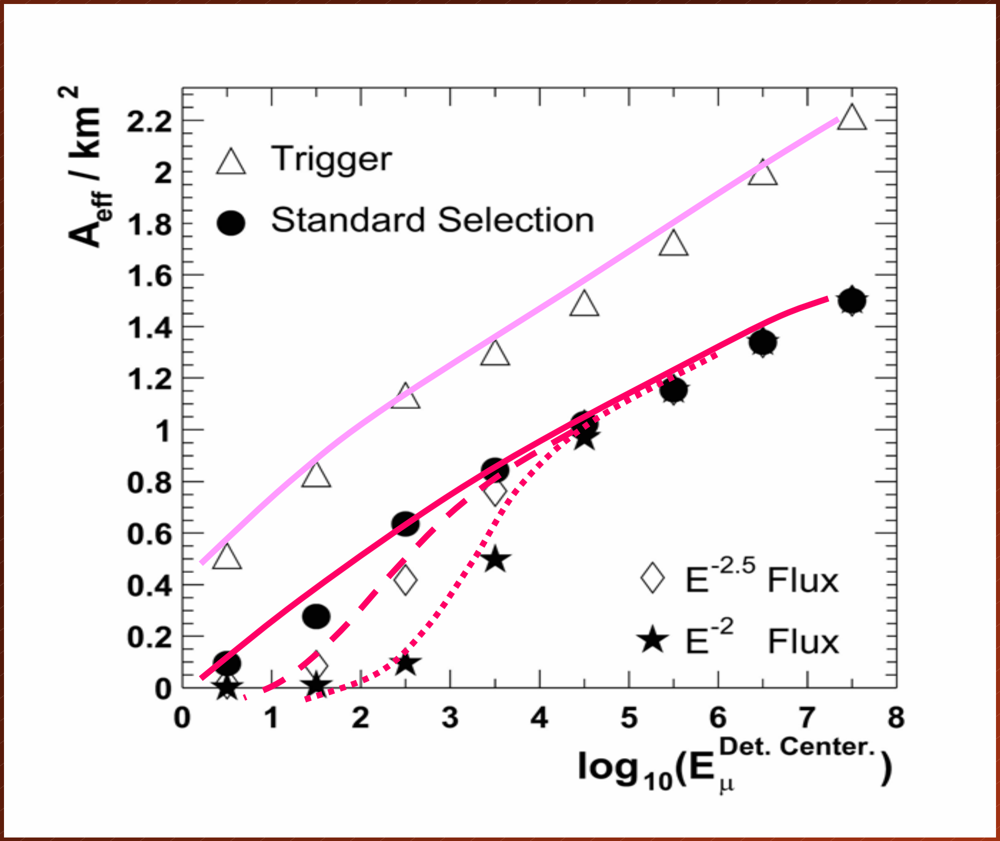
- Filled area: particle id, direction, energy
- Shaded area: energy only

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

Effective area of IceCube

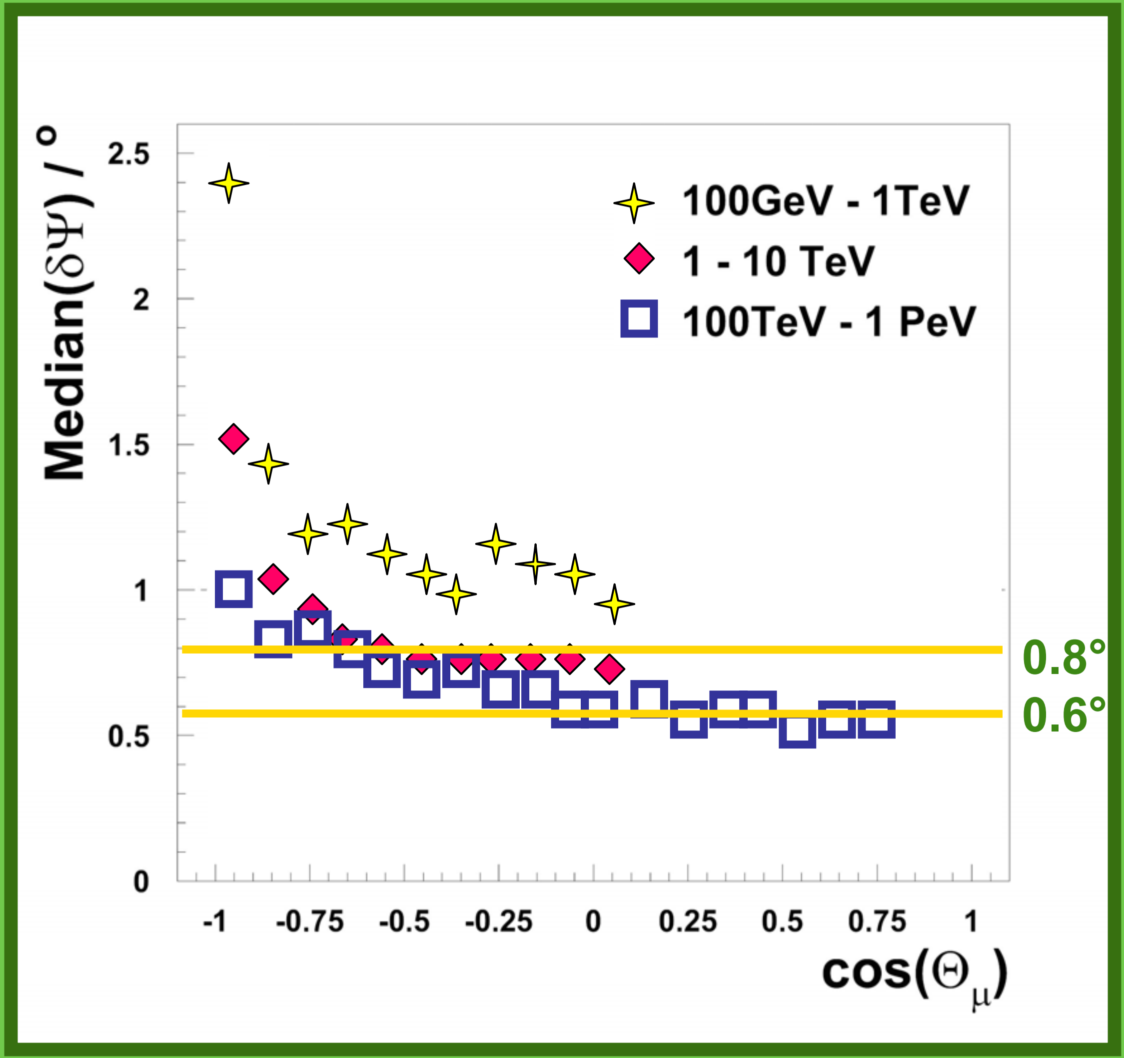




Effective area vs. zenith angle (downgoing muons rejected)

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

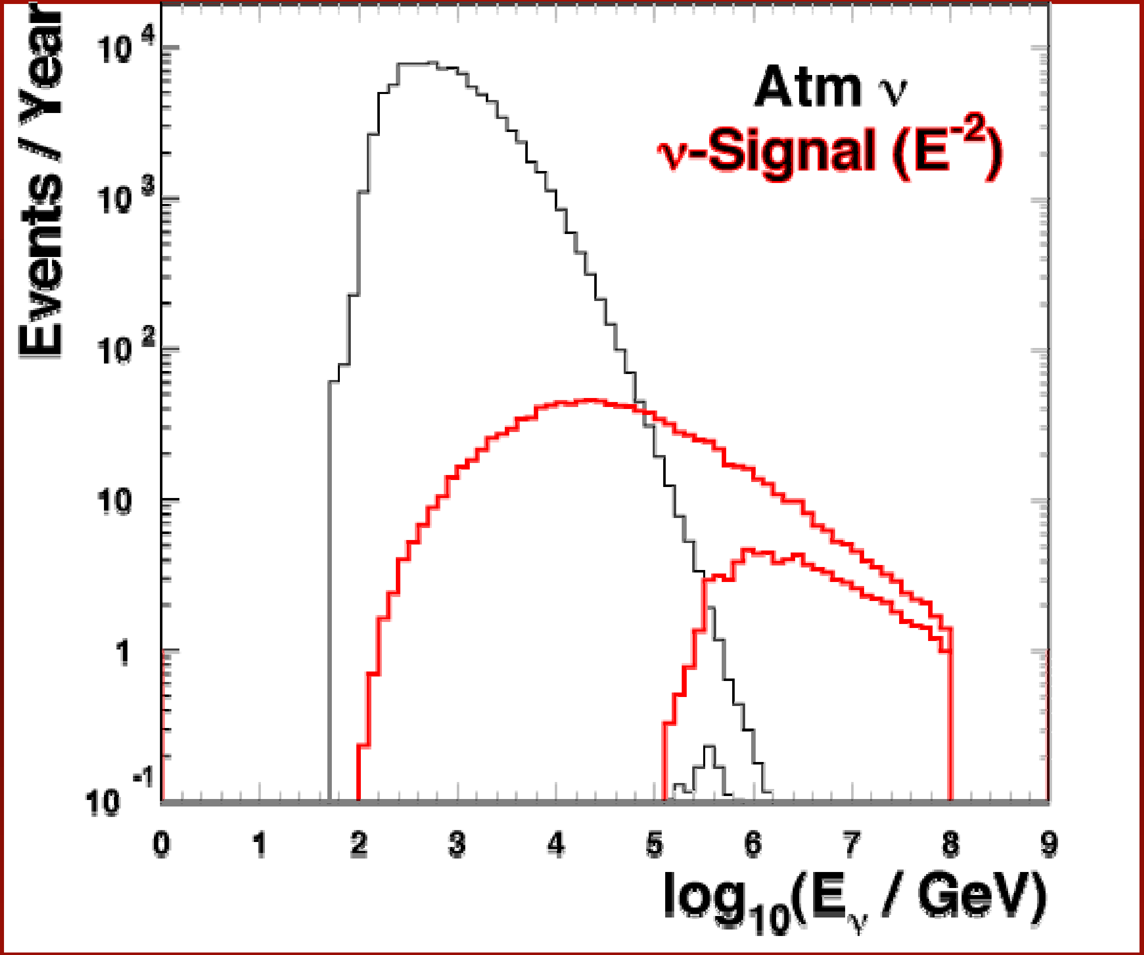
Angular resolution as a function of zenith angle



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

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

Event rates before and after energy cut

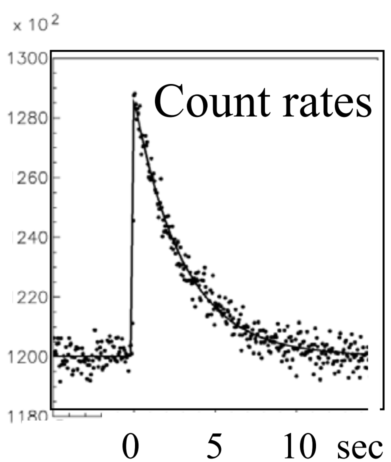


Note: **300,000** atmospheric neutrinos per year (TeV range)

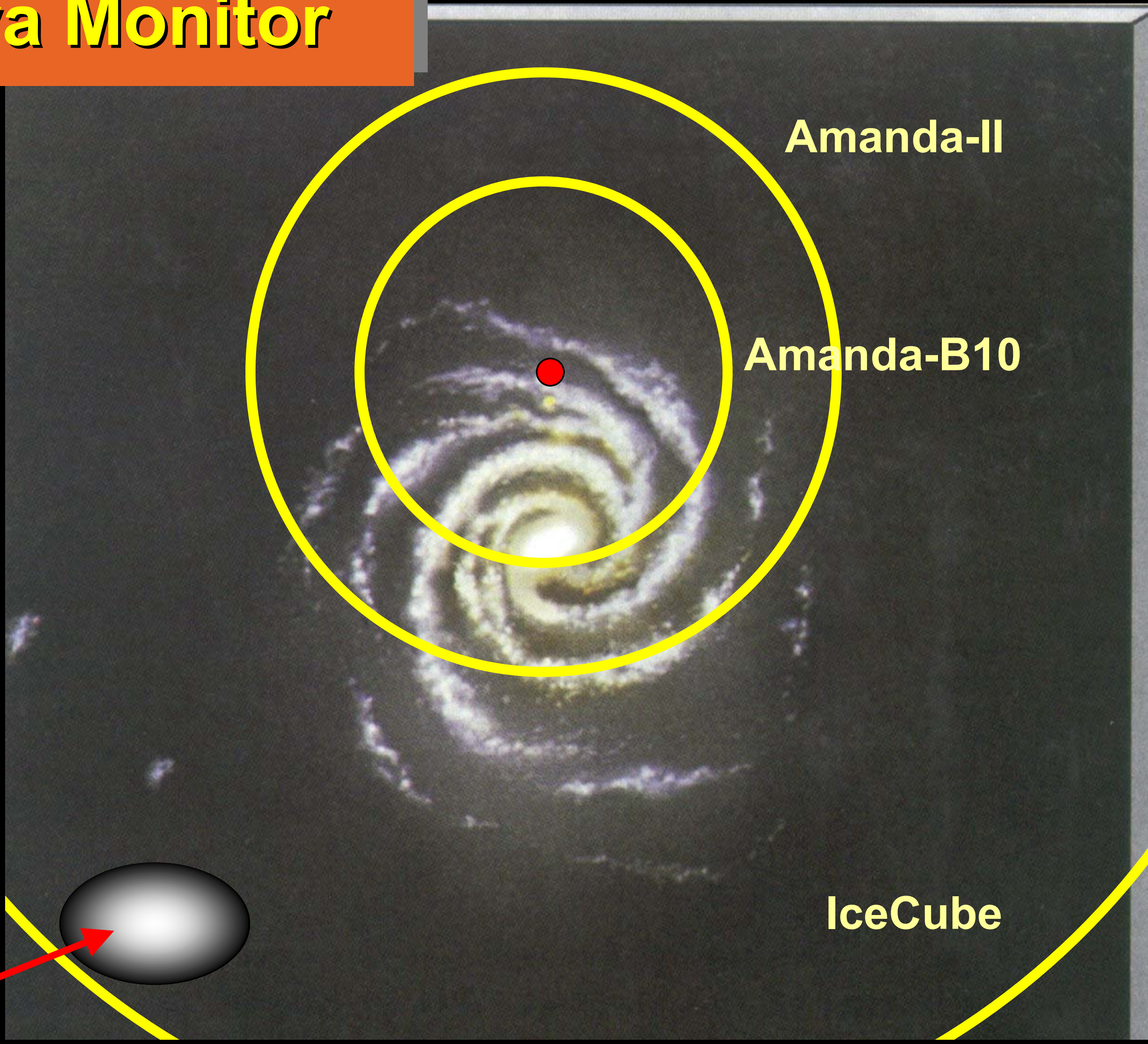
Supernova Monitor

B10:
60% of Galaxy

A-II:
95% of Galaxy



IceCube:
up to LMC



The IceCube Collaboration

Institutions: 11 US and 10 European institutions and 1 Japanese university
(most of them are also AMANDA member institutions)

- 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

super-EeV detectors

Event Rates

	volume	eff. area	threshold
• OWL	10^{13} ton	10^6 km^2	$3x10^{19}$ eV
• IceCube	10^9 ton	1km^2	10^{15} eV*

Events per year

		TD	Z_{burst}	$p_{+}\gamma_{2.7}$
• OWL	ν_e	16	9	5
• Ice Cube	ν_μ	11	30	1.5

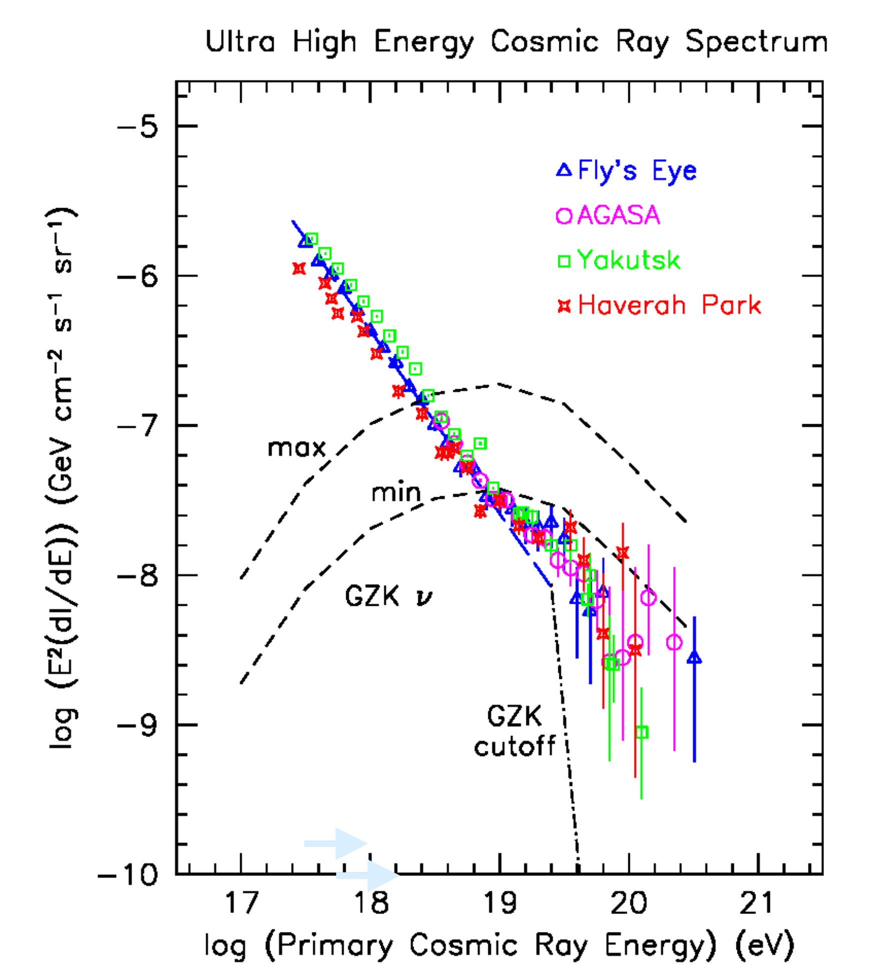
Cline, Stecker astroph 0003459

Alvarez-Muniz astroph 0007329

Warning: models identical?

*actual threshold ~100GeV, > 1 PeV no atmospheric ν background

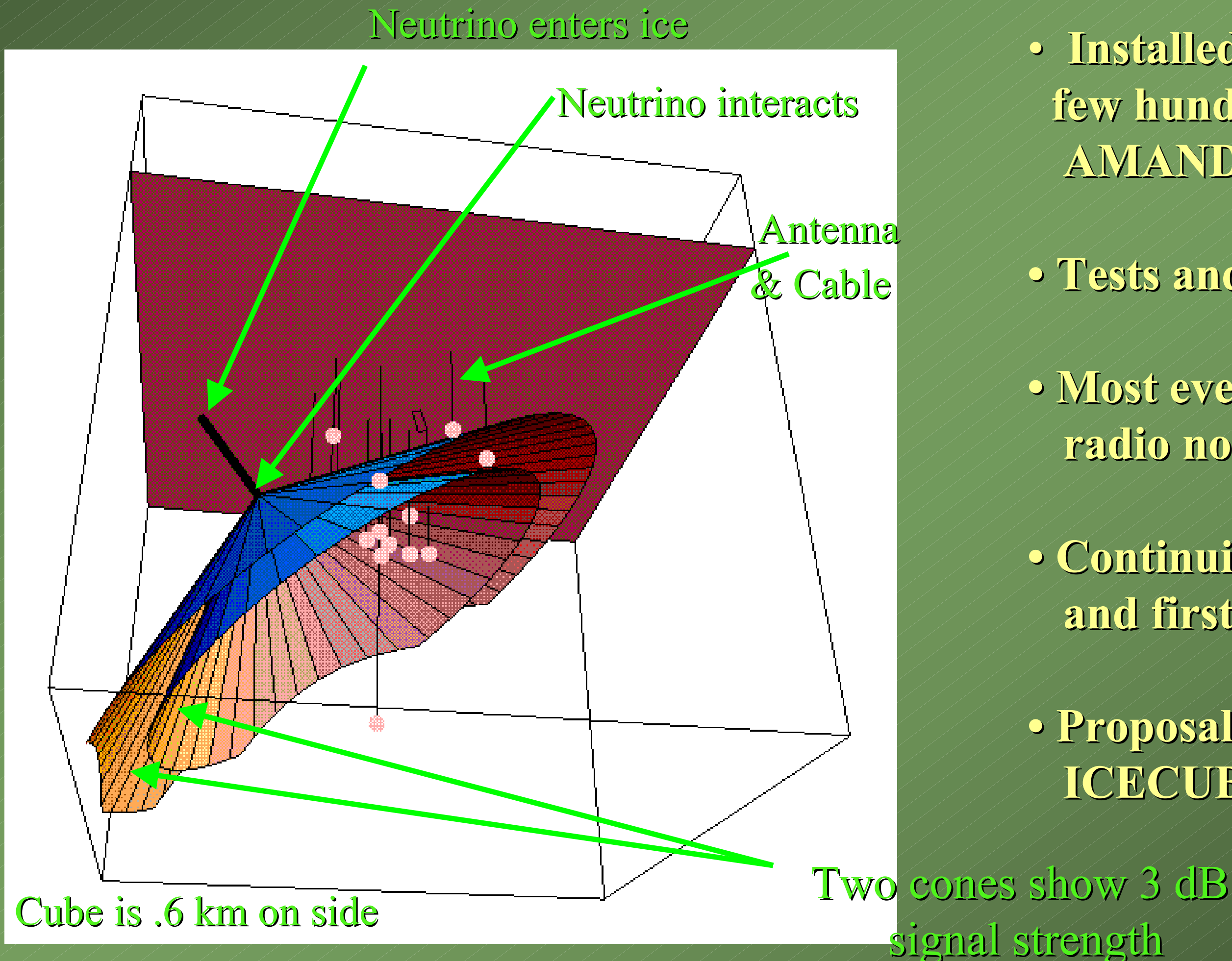
GZK Cosmic Rays & Neutrinos



- cosmogenic neutrinos are guaranteed
- fluxes may be larger for some models, such as topological defects

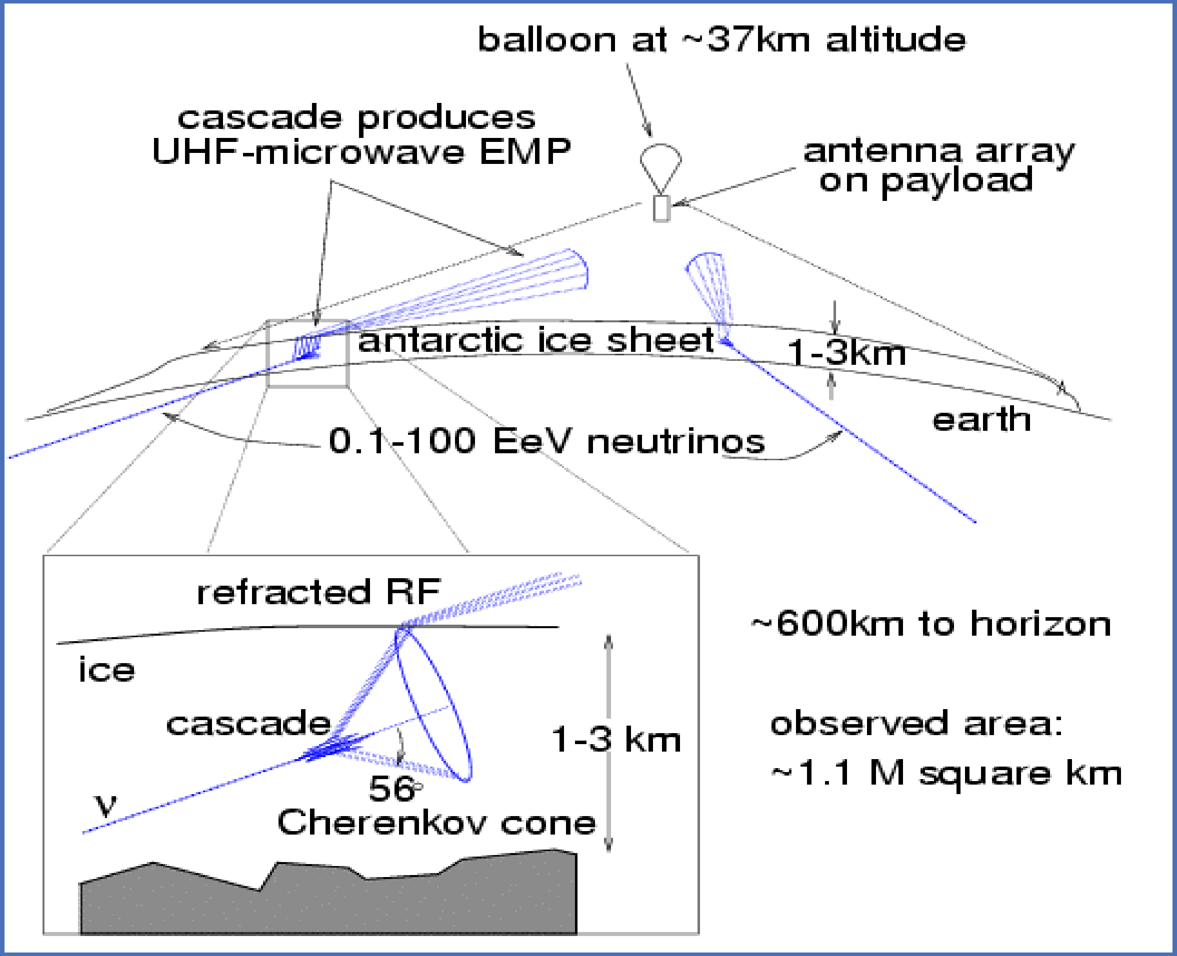
$$p + \gamma_{CMB} \rightarrow \pi + n$$

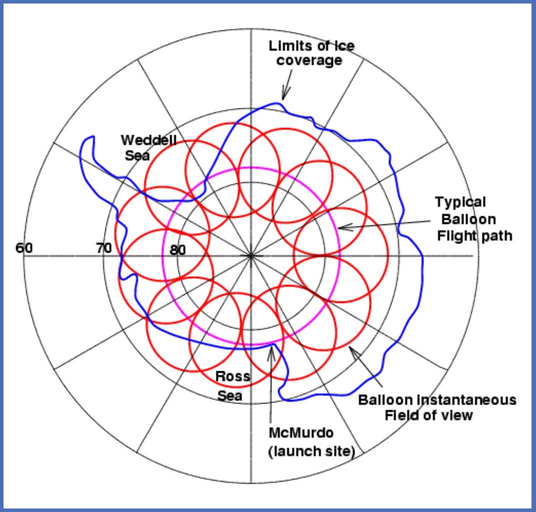
RICE
Radio Detection in South Pole Ice



- **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**

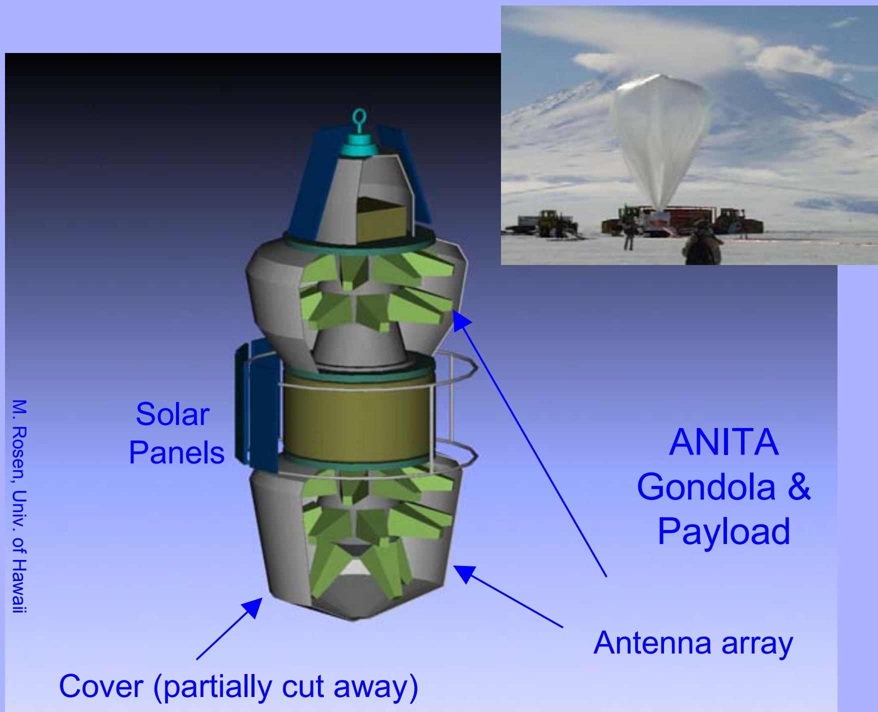
ANITA
Radio from EeV ν's in Polar Ice





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

Antarctic Impulsive Transient Antenna (ANITA)

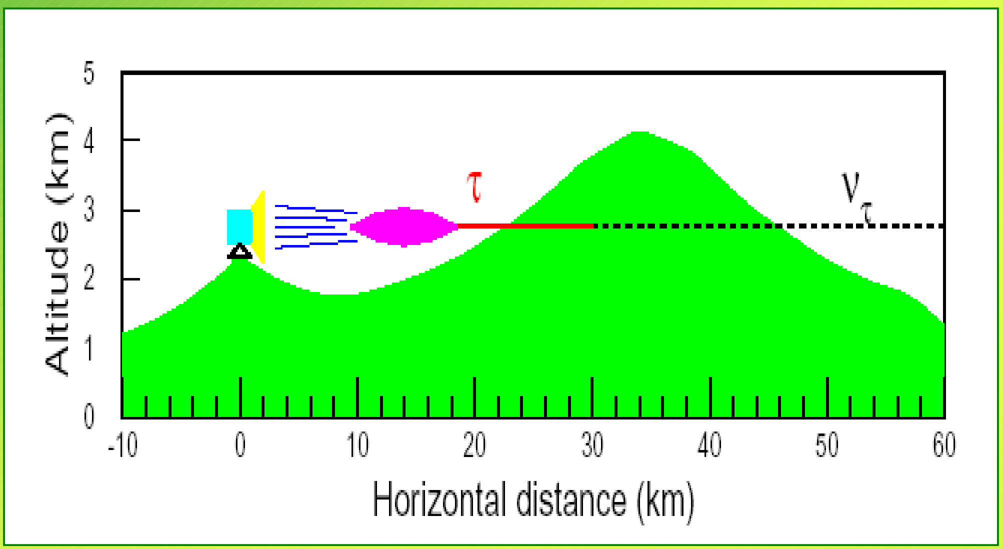


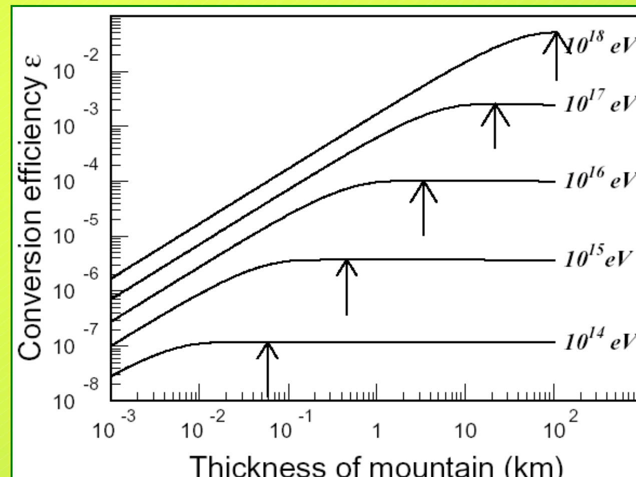
- ANITA Goal: Pathfinding mission for GZK neutrinos
- NASA SR&T start expected this October, launch in 2006

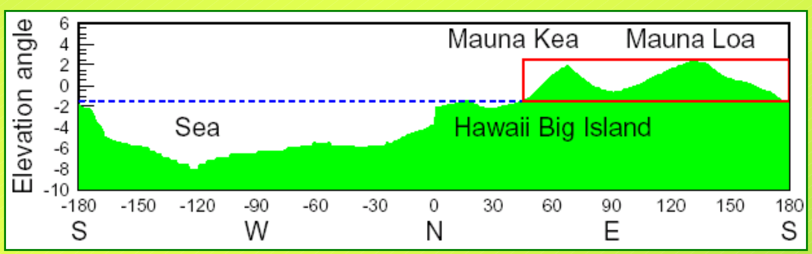
TauWatch

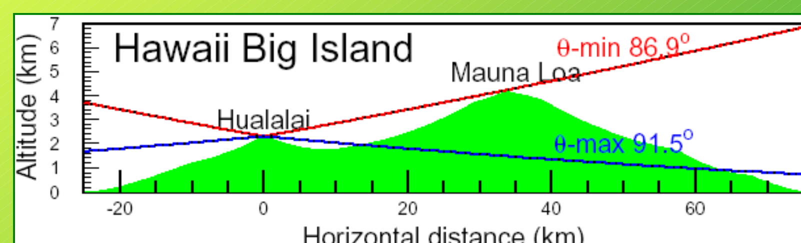
Using Mountains to Convert ?$_{t}$

3/02 Workshop in Taiwan, see http://hep1.phys.ntu.edu.tw/vhetnw





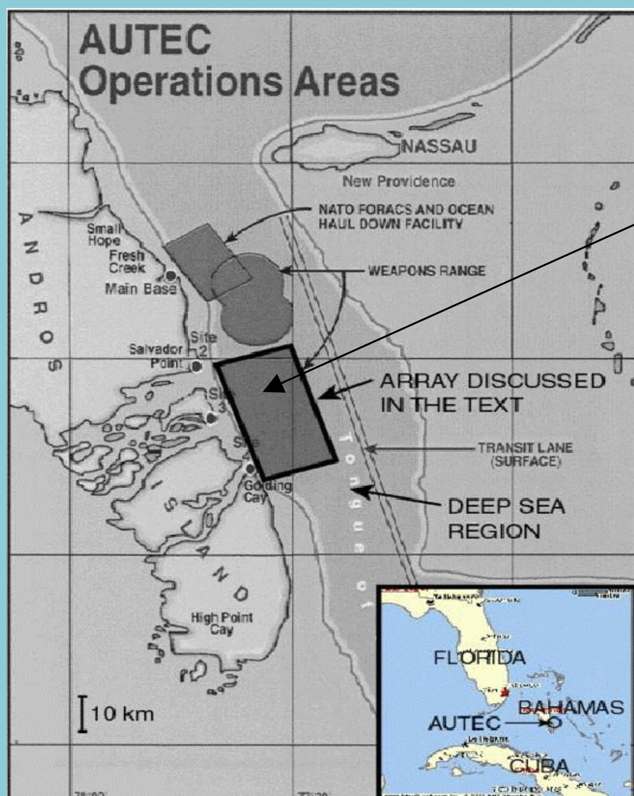


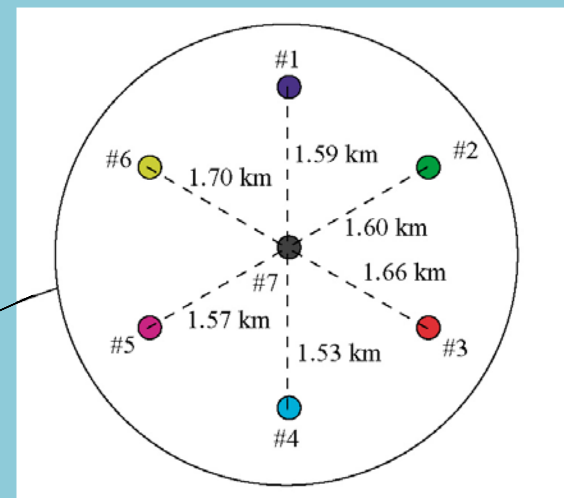


Ocean Acoustic Detection

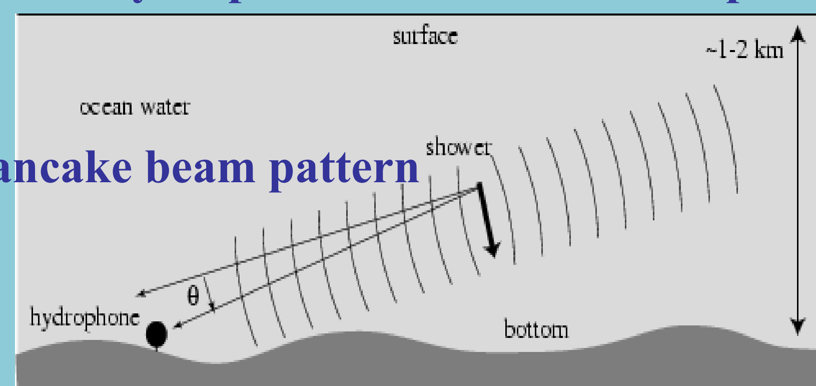
New Stanford Effort using US Navy Array

US Navy acoustic tracking range in Tongue of the Ocean, Atlantic





Hydrophones 1550-1600 m deep



pancake beam pattern

G.Gratta, atro-ph/0104033

conclusions

- nu astronomy reached ~ 0.1 km^2year
- will reach km-scale in < 5 years
- > 300,000 atmospheric events per year
- EeV detectors over similar time scale
- if history repeats, I did not tell you about the science