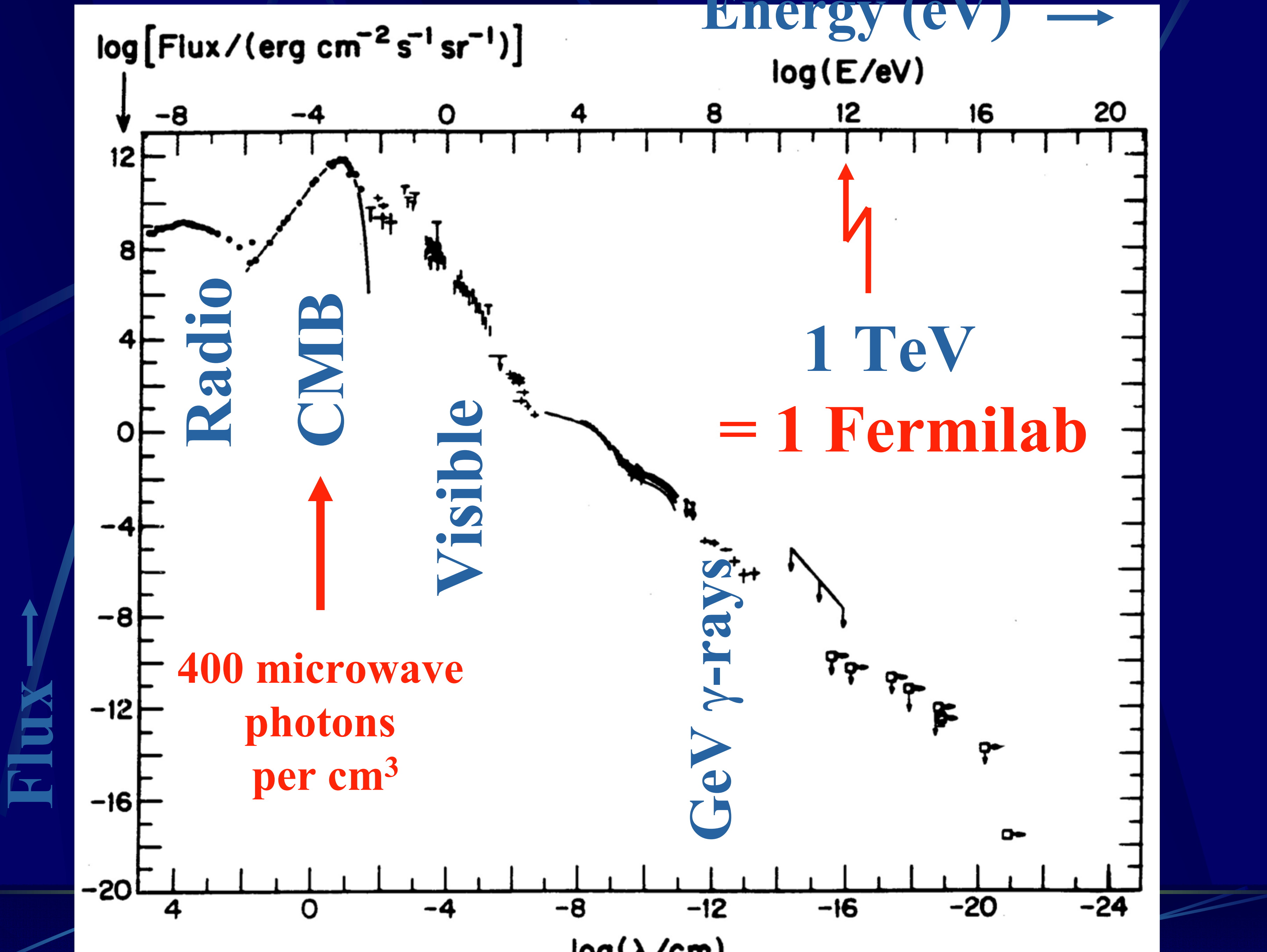
The AMANDA and IceCube

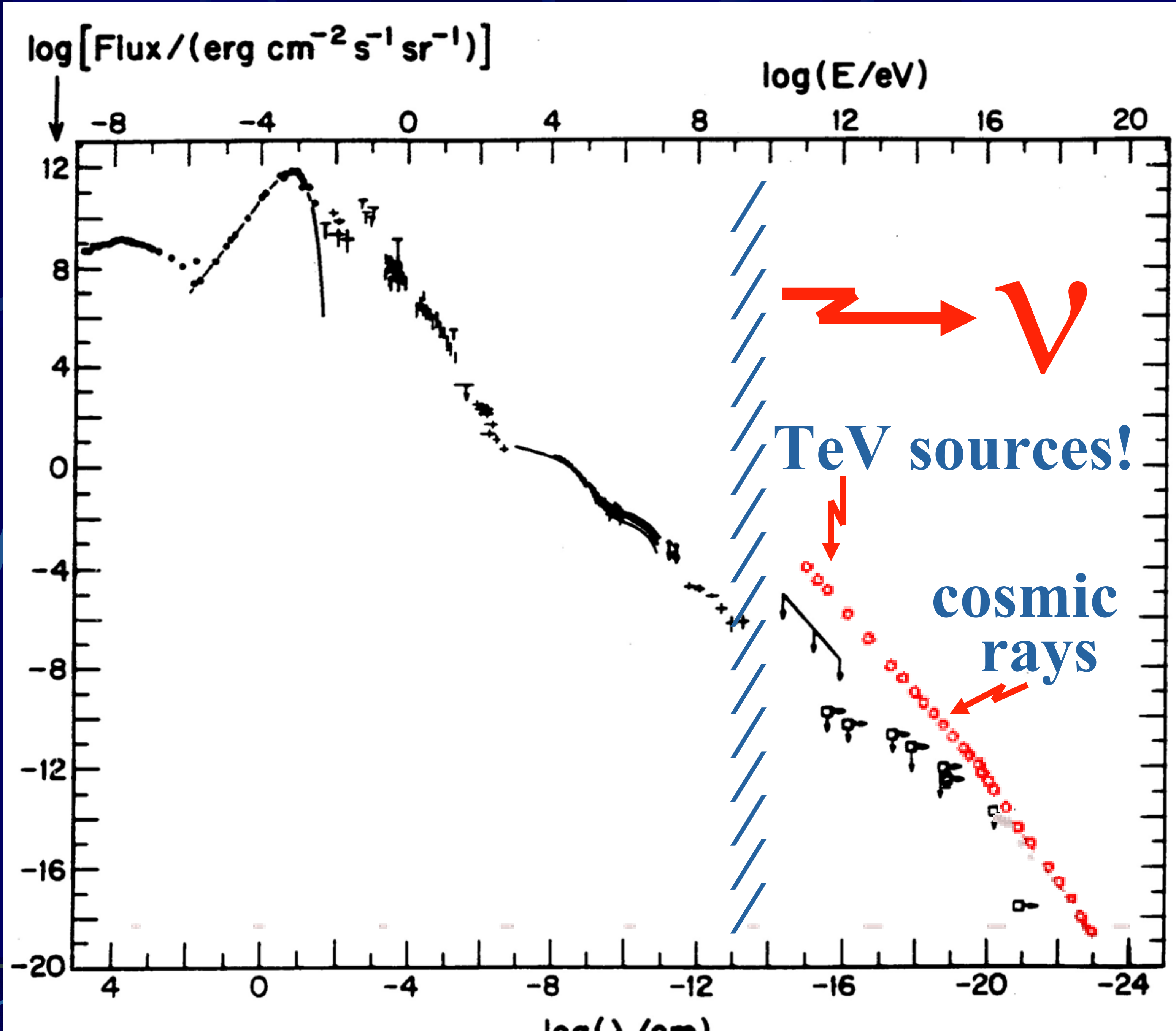
高エネルギーν天文学:宇宙探査の窓

- Physics Motivation
- AMANDA detector
- Recent Experimental Results
- IceCube Project overview and Status
- EHE Physics Example: Detection of GZK neutrinos

吉田　滋 (千葉大学理)

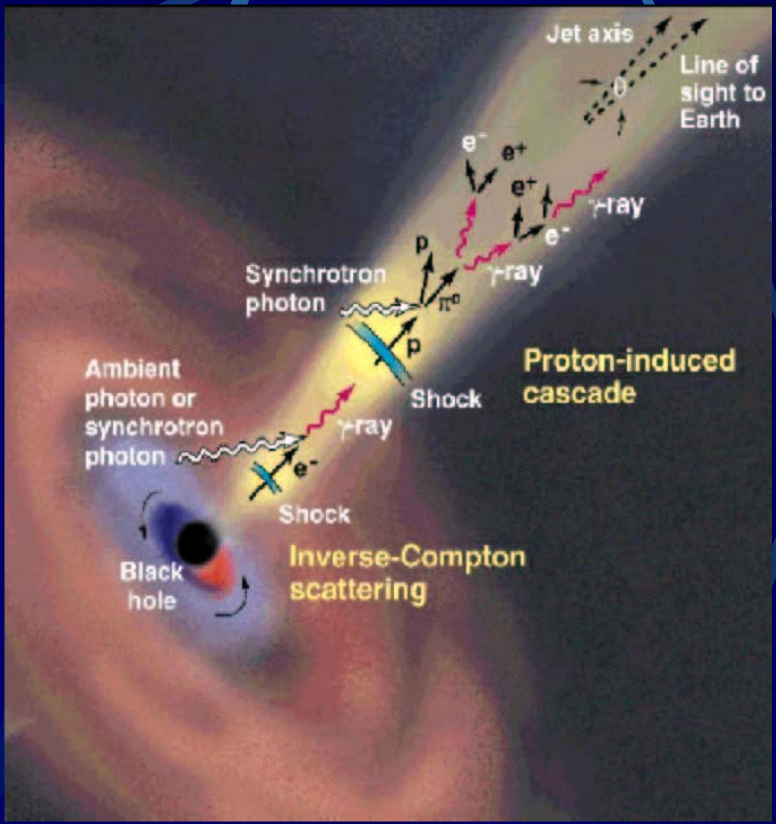


Energy (eV)
log[Flux/(erg cm-2 s-1 sr-1)]
log(E/eV)
-8
-4
0
4
8
12
16
20
12
8
4
0
-4
-8
-12
-16
-20
Radio
CMB
Visible
GeV γ-rays
1 TeV
= 1 Fermilab
400 microwave
photons
per cm3
Flux
4
0
-4
-8
-12
-16
-20
-24



log[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

Physics motivation



- origin and acceleration of cosmic rays
- understand cosmic cataclysms
- find new kind of objects?

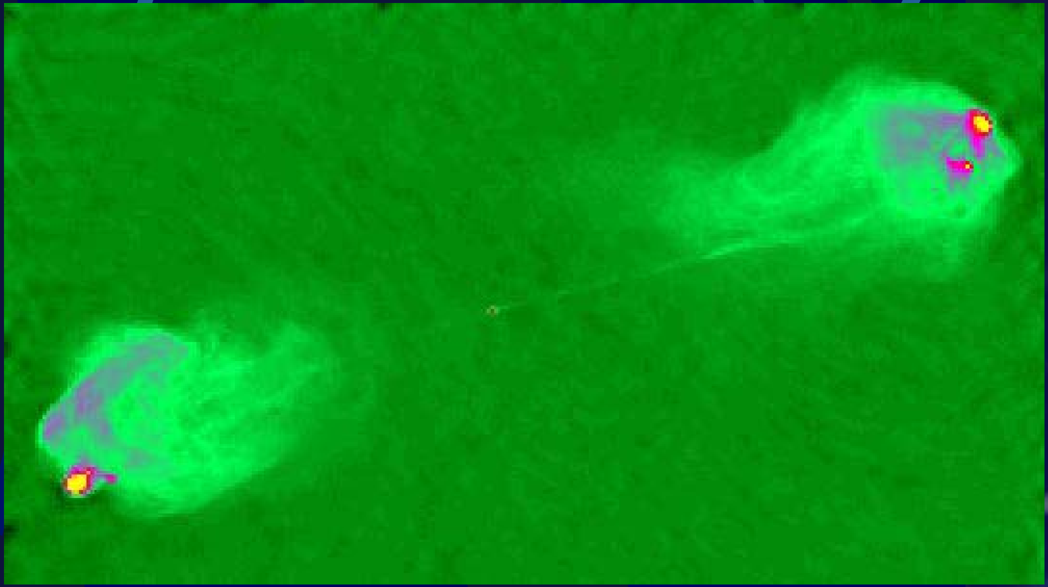
- neutrino properties (ν_τ , cross sections ..)

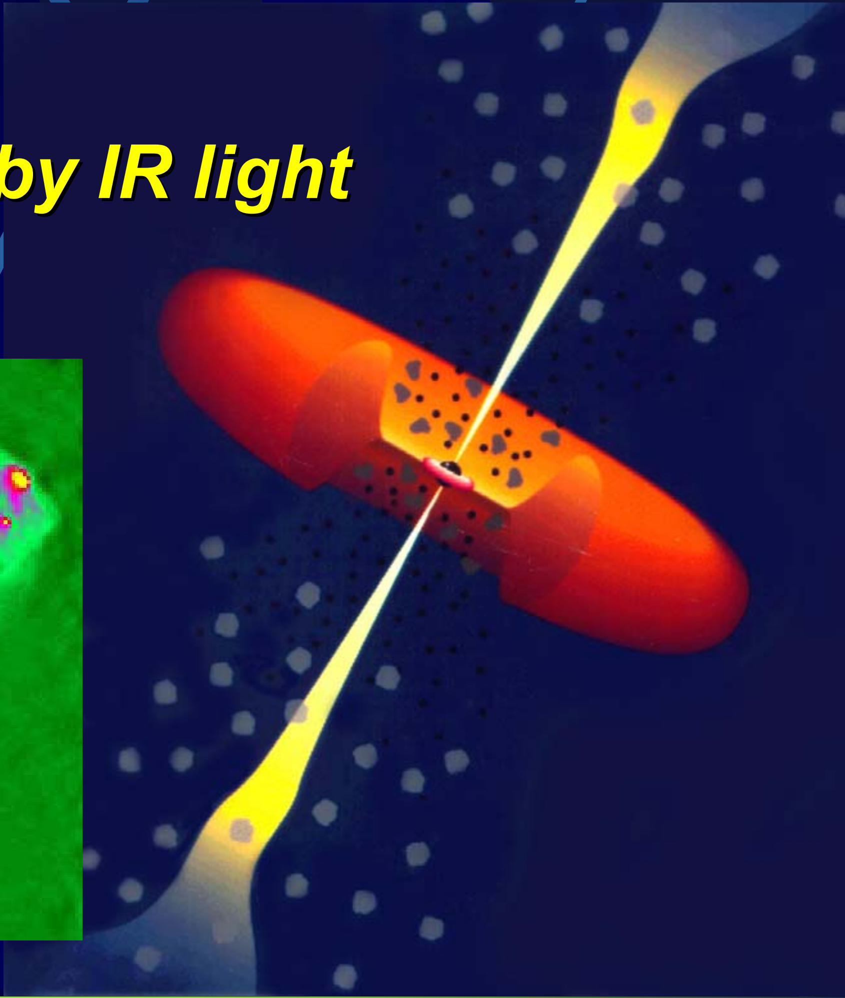
- dark matter (neutralino annihilation)

  - *tests of relativitiy ....*
  - *search for big bang relics ...*
  - *effects of extra dimension etc. ...*

Active Galaxies: Jets

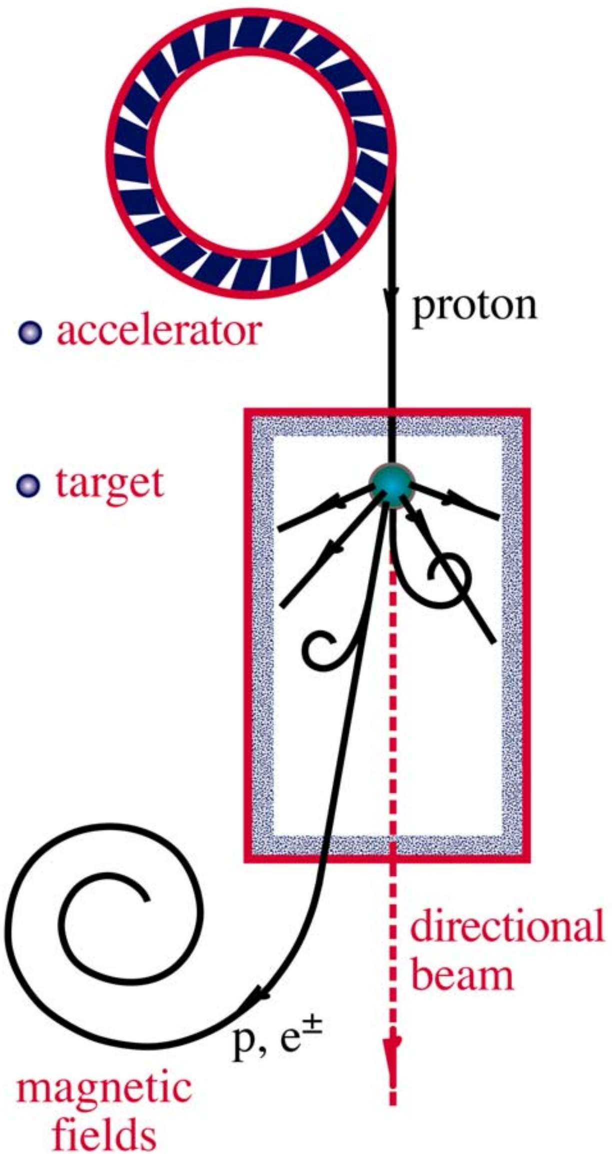
20 TeV gamma rays
Higher energies obscured by IR light





VLA image of Cygnus A

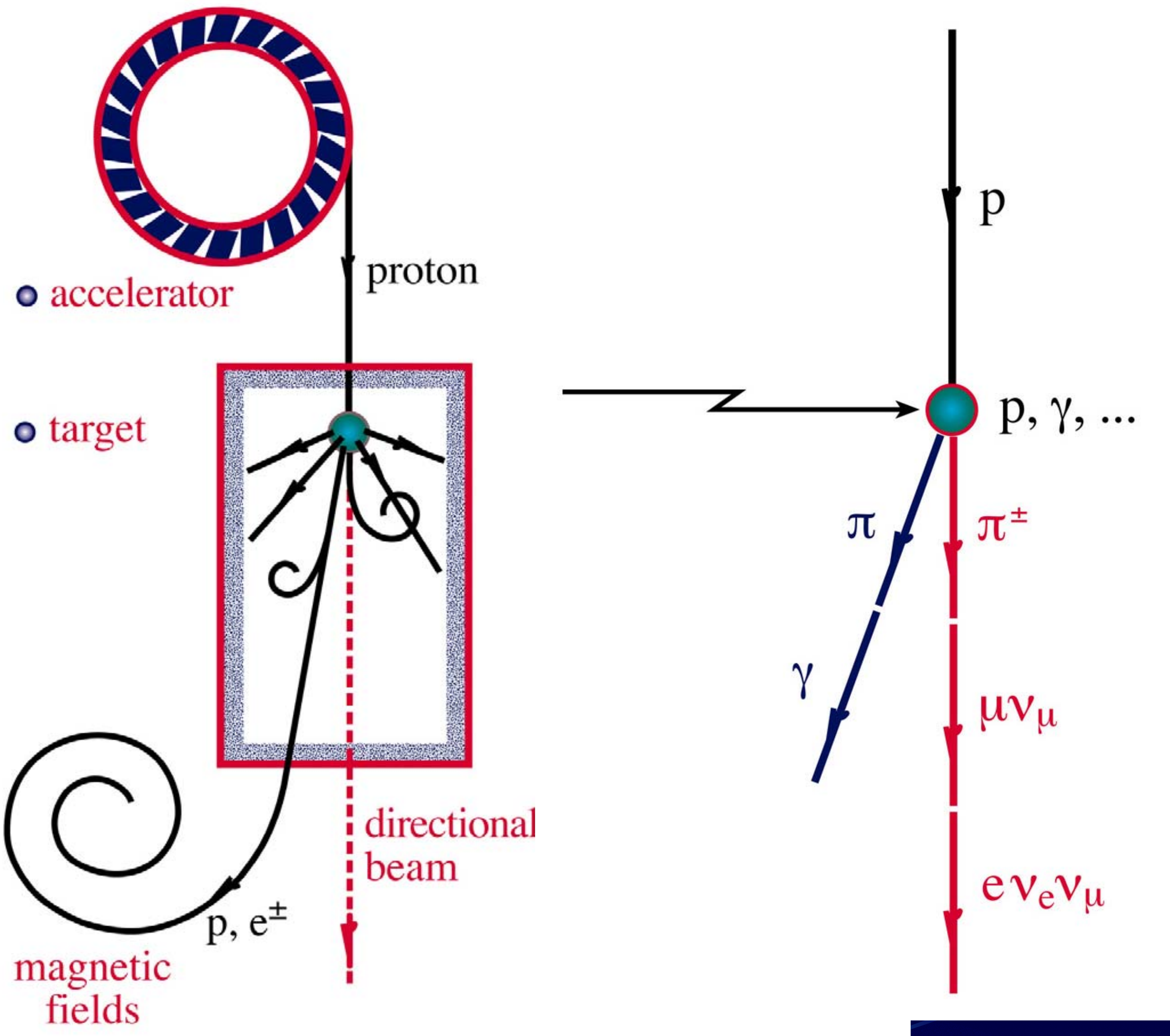
NEUTRINO BEAMS: HEAVEN & EARTH



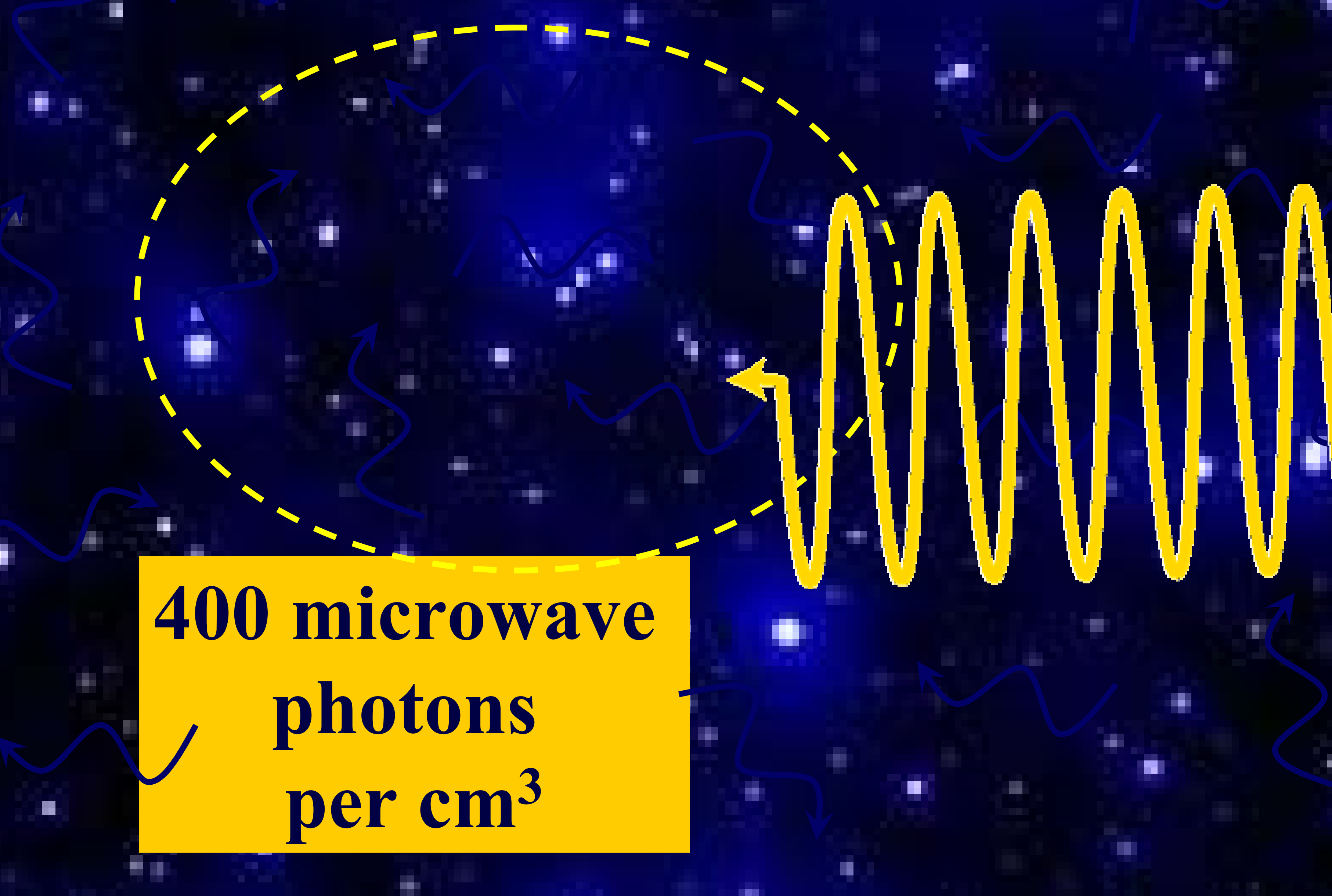
black hole

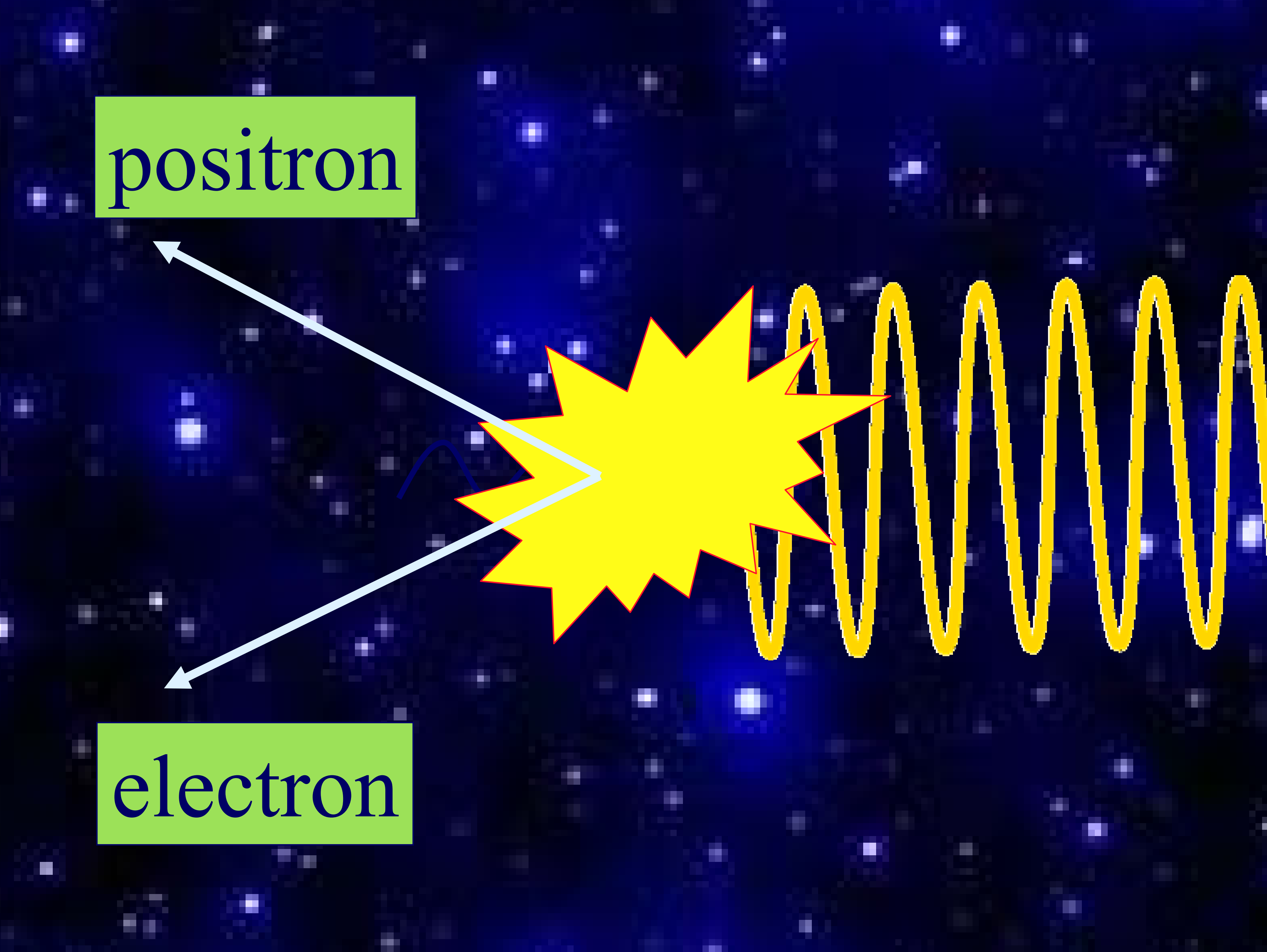
radiation enveloping black hole

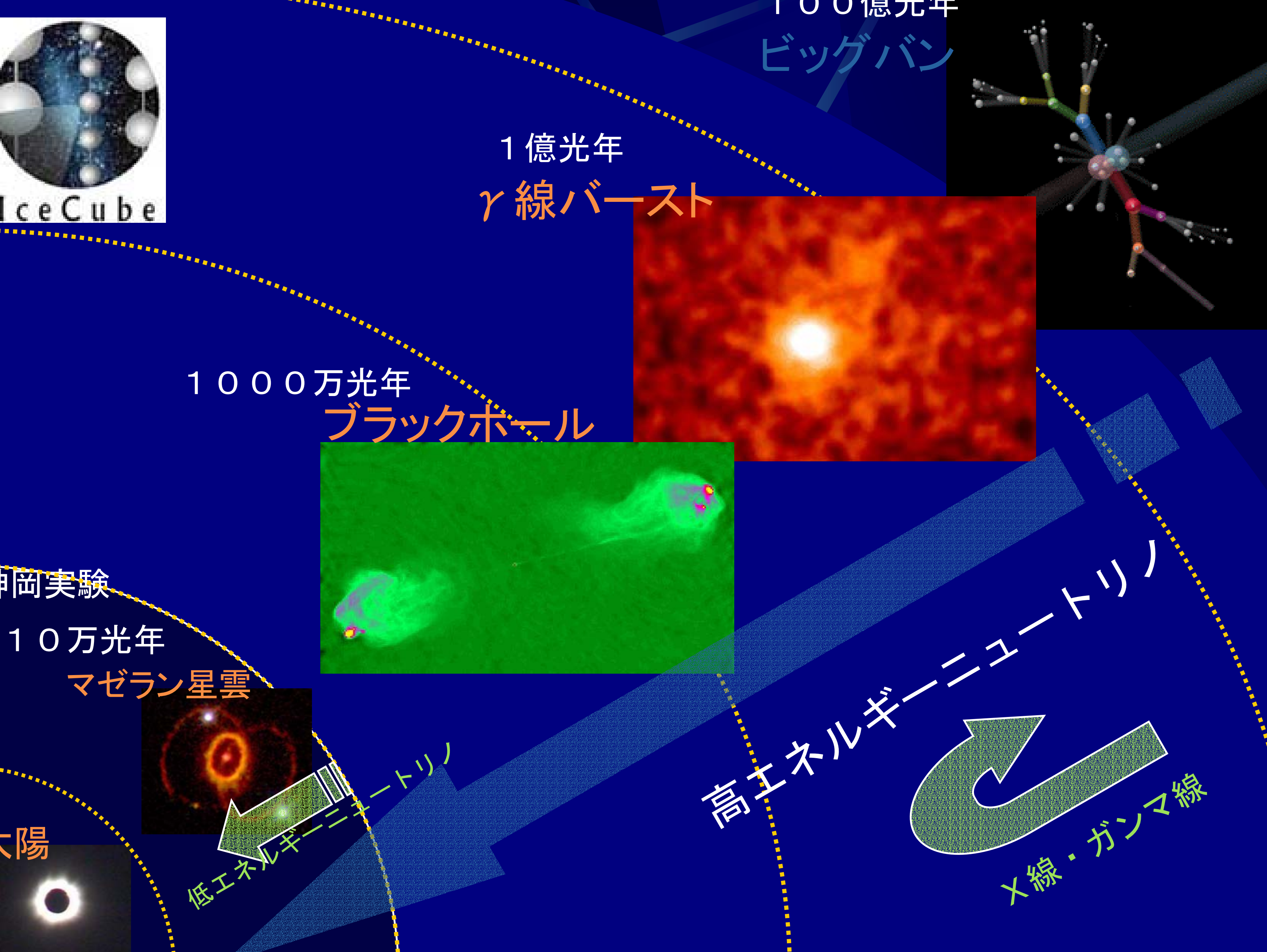
NEUTRINO BEAMS: HEAVEN & EARTH



The Universe

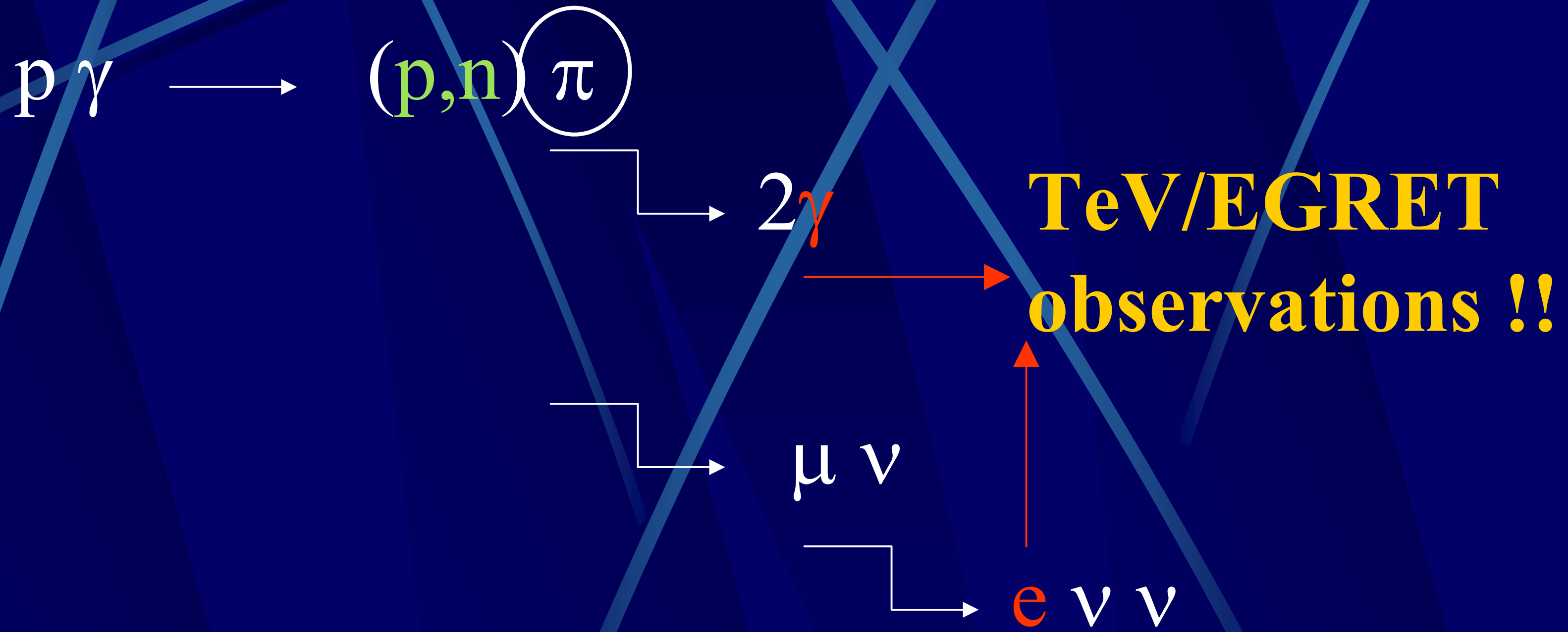



positron
electron



１００億光年
ビッグバン
IceCube
１億光年
γ線バースト
１０００万光年
ブラックホール
神岡実験
１０万光年
マゼラン星雲
太陽
低エネルギーニュートリノ
高エネルギーニュートリノ
X線・ガンマ線

You cannot expect too many ν!



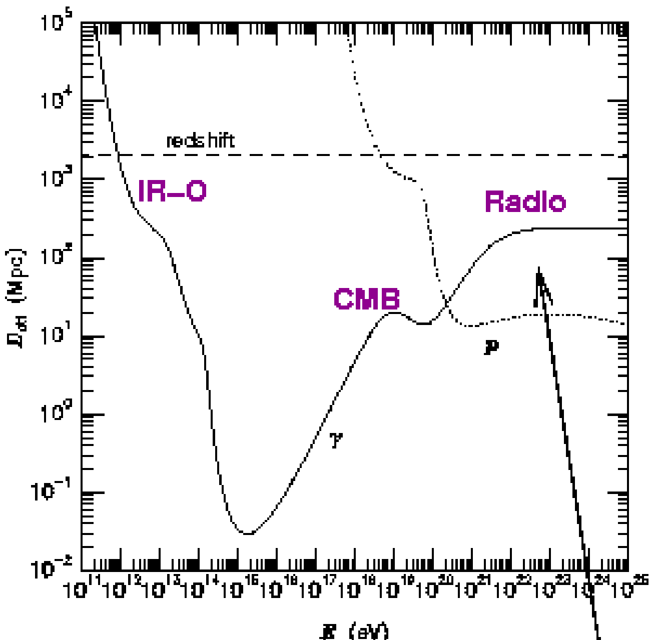
Downgrading

EM cascades recycle eγ energies to GeV

$\gamma\,\gamma_{rad} \longrightarrow ee \qquad E_{th} = \frac{m_{electron}}{E_{rad}} = 2.6 \times 10^{14} \left(\frac{E_{rad}}{10^{-3}\,eV} \right)^{-1} eV$

$e\,\gamma_{rad} \longrightarrow e\gamma$

$e\,B \longrightarrow e\,\gamma\,B$



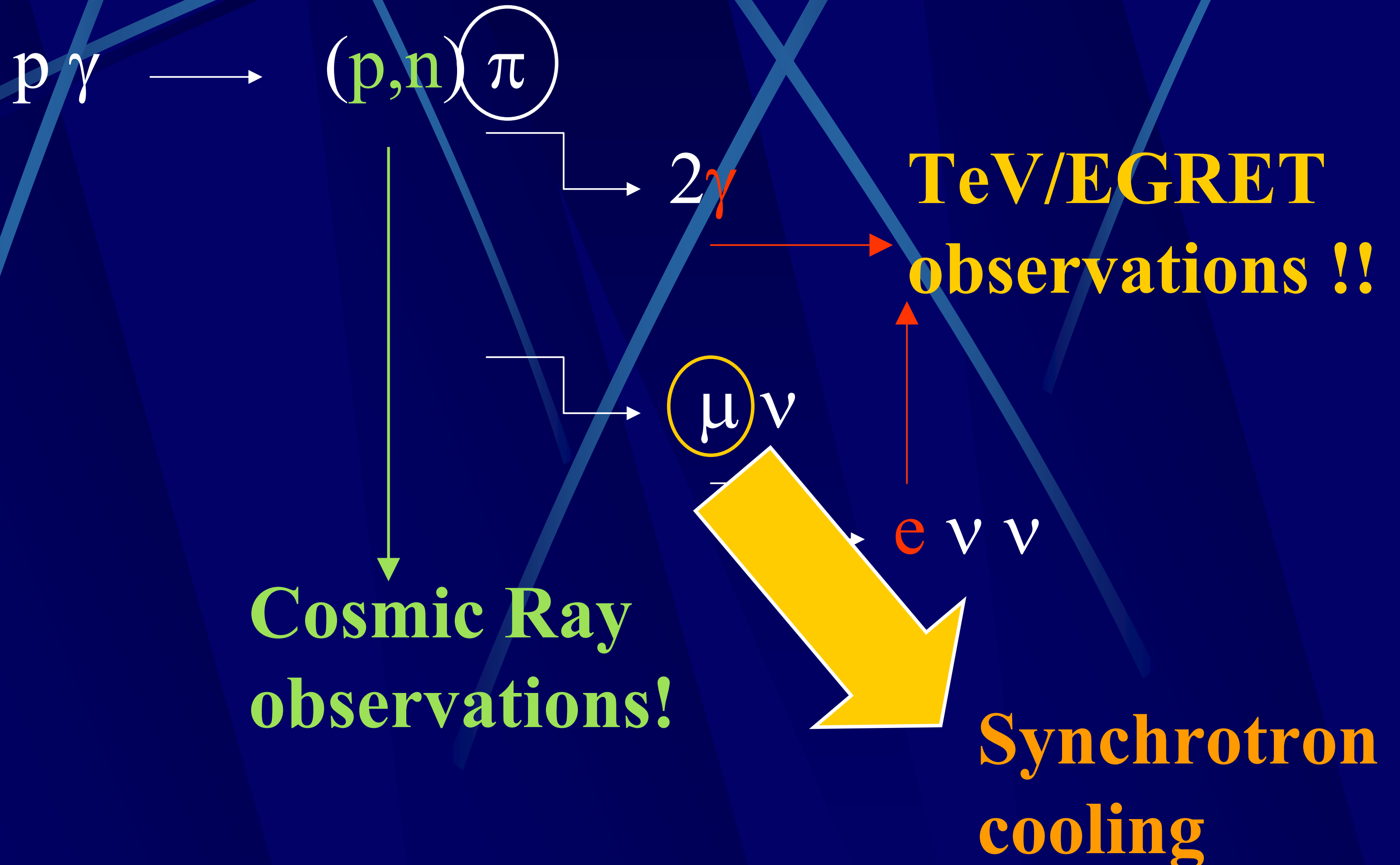
$$\frac{d\sigma}{d\eta} \sim \frac{2\pi m^2 r_e^2}{s} \left(\frac{1-\eta}{\eta} + \frac{\eta}{1-\eta} \right)$$

$$\eta = \frac{E_-}{E_\gamma}$$

$\longrightarrow$ "leading" particles carry most faction of the photon energy

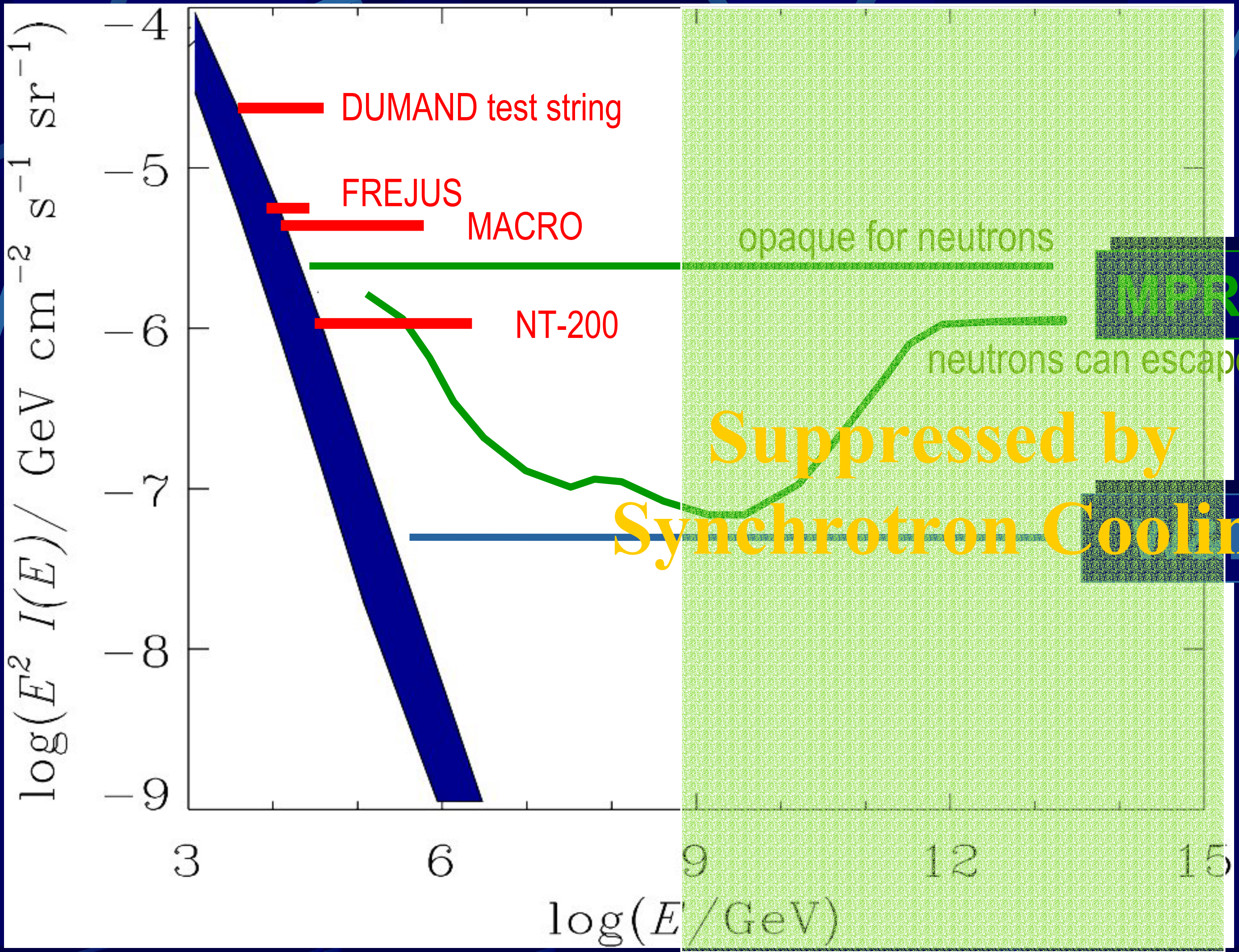
10 times larger then D_{proton}

You cannot expect too many ν!



You cannot expect too high energies

Theoretical bounds



annheim, Protheroe and Rachen (2000) – Waxman, Bahcall (1999)

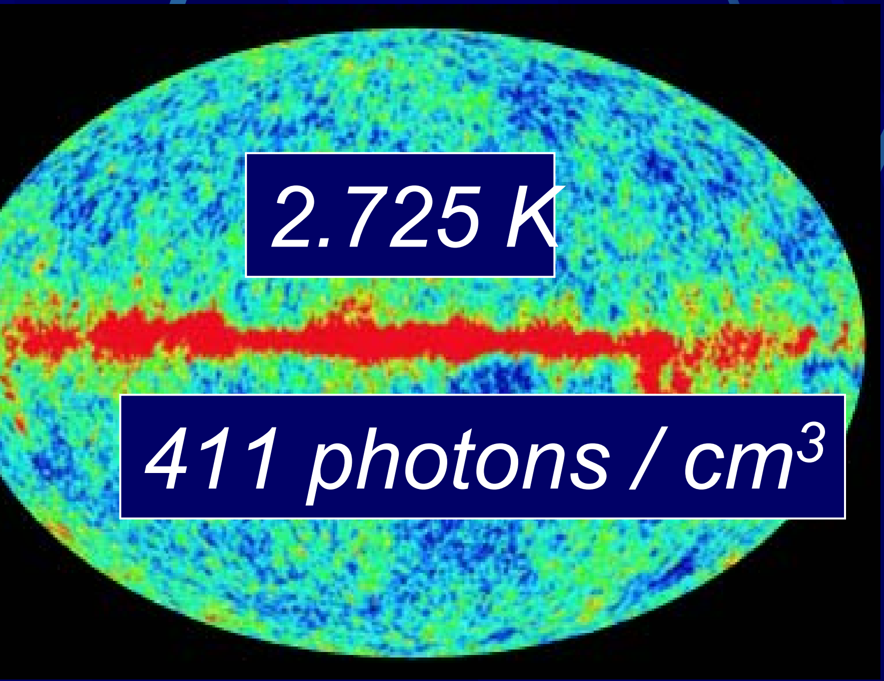
EHE(Extremely HE) ν

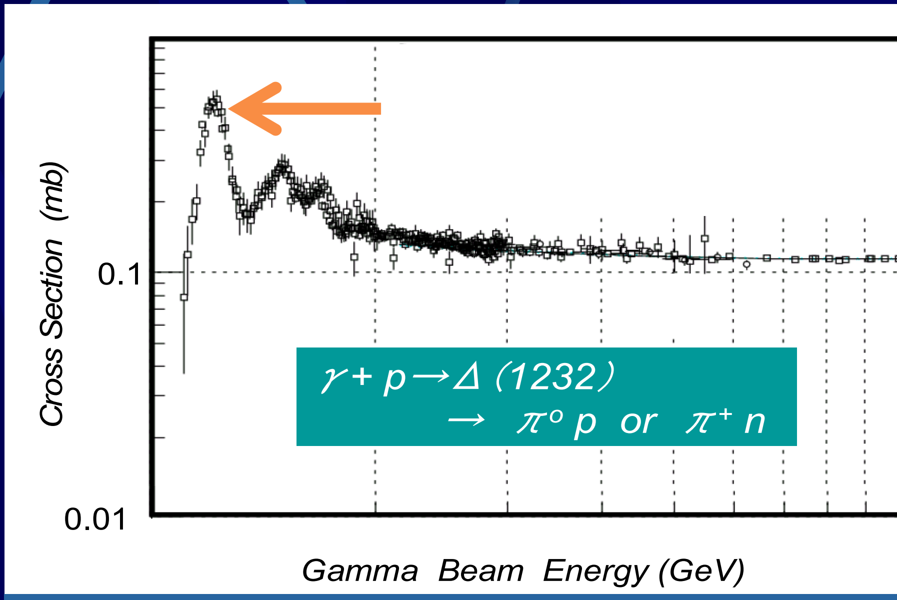
Synchrotron cooling of μ …
Production sites with low B

→ **Intergalactic space!!**

- **GZK Production**
- Z-burst
- Topological Defects/Super heavy Massive particle

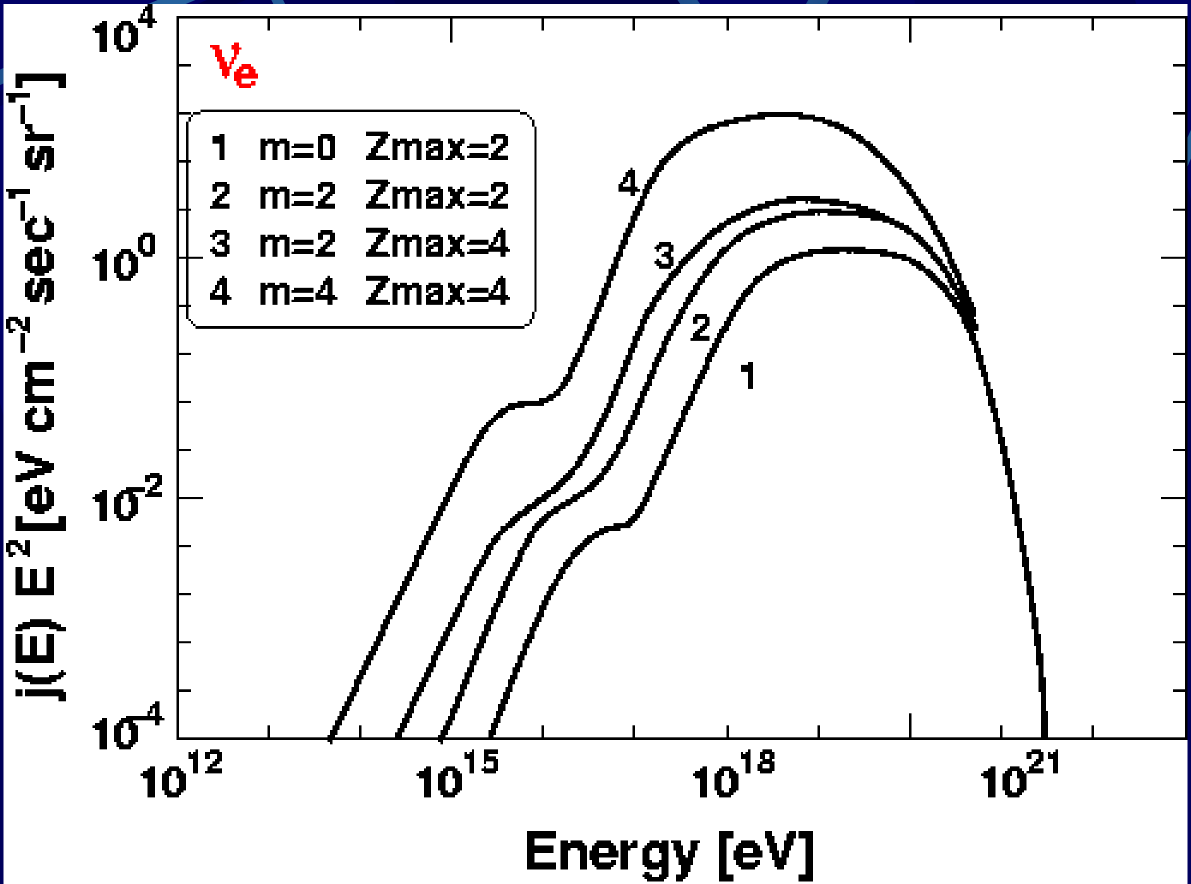
GZK Neutrino Production





→ Conventional Mechanism of EHE neutrinos!

GZK ν fluxes



Yoshida and Teshima 1993

Yoshida, Dai, Jui, Sommers 1997

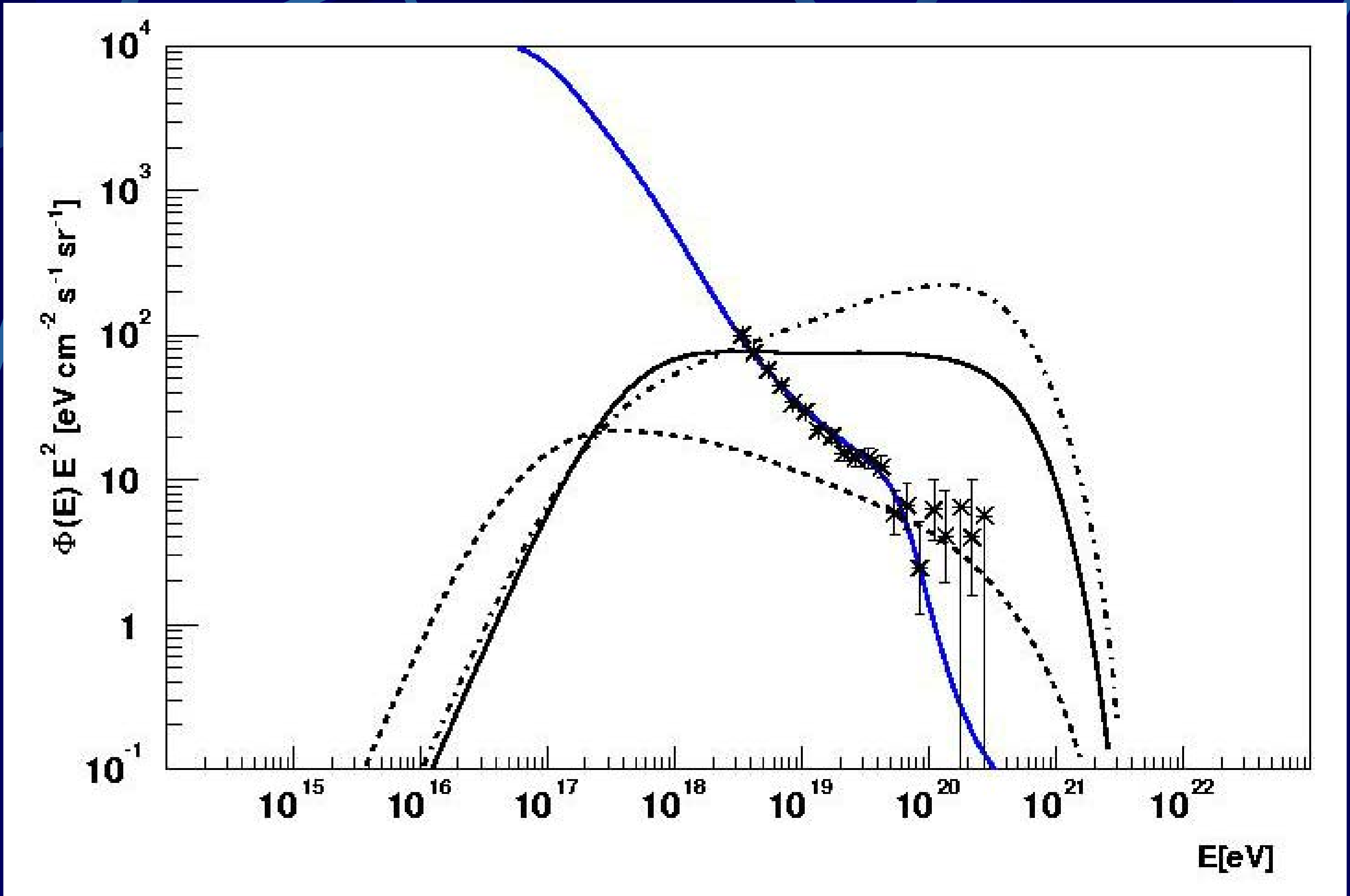
Parameters involved in calculation. Predicted fluxes.

Parameters	Orientative order of magnitude
γ spectral injection index	[1-3]
m activity evolution index	[3-5]
z_{max} z of formation of sources	[1-4]
Ω_M density of matter	[0.2-1]
H_o Hubble constant	[50-80 Km/s/Mpc]
B intergalactic magnetic field	[B≤1nG]
$\eta_L \rho_L / \eta_o \rho_o$ local enhancement	[?]
E_{max} maximum acceleration energy in source	[E_{max} >4 10^{20} eV]

(Diego González-Díaz, Ricardo Vázquez, Enrique Zas 200

Diego González-Díaz, Ricardo Vázquez, Enrique Zas 2003)

CR and ν fluxes for different models



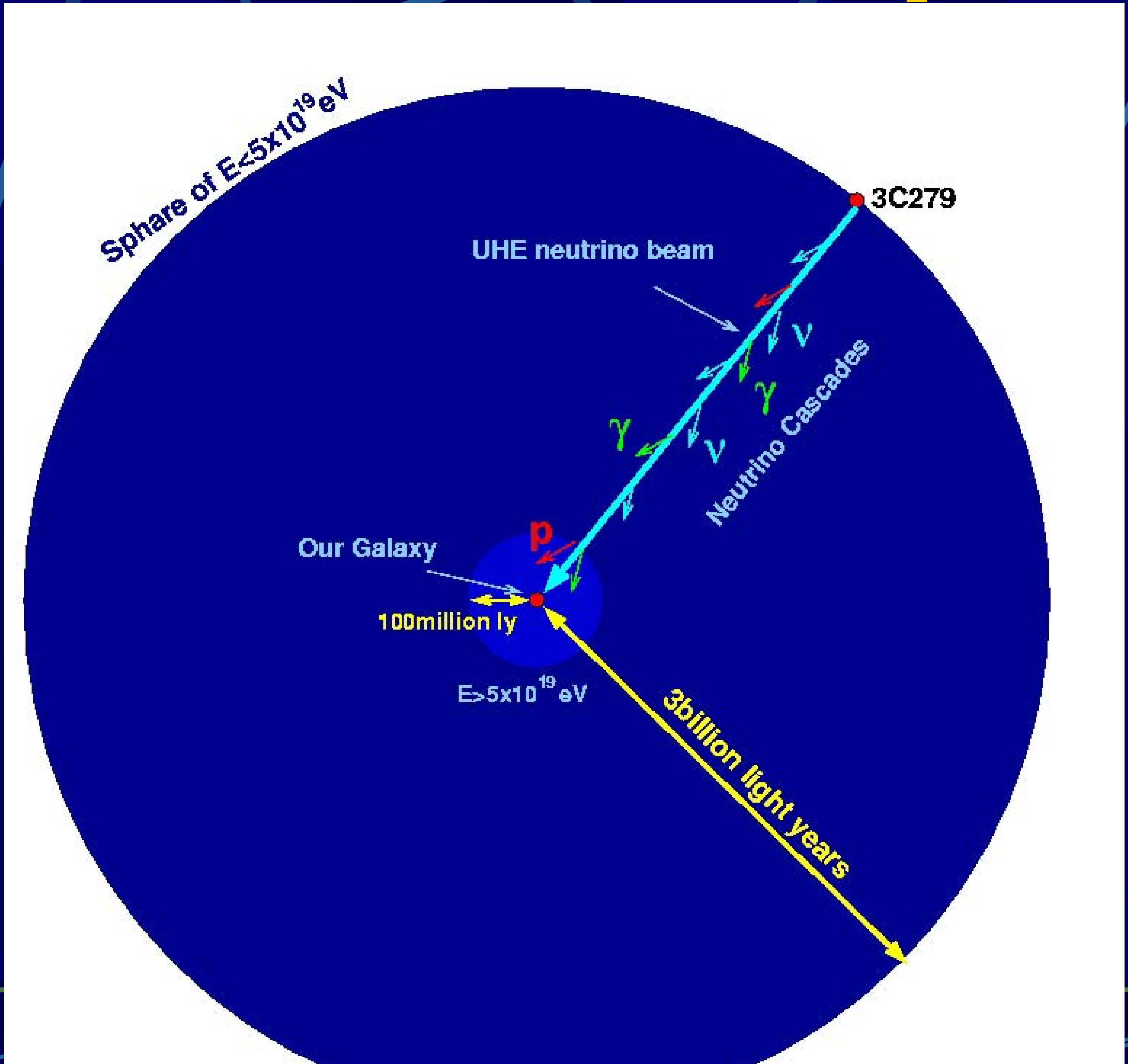
EHE Constraints by CR/γ

	"Cosmological" component	"Local" component
Distance	$\lambda_{RES}\,(1+z)^{-3}$	$L_{supercluster}$
Scale	~ 1 Gpc	~ 5 Gpc
Typical Energy Scale	10 GeV	100 EeV
Composition	γ	γ P
Observational Constraints	EGRET Diffuse γ	UHECR FLux

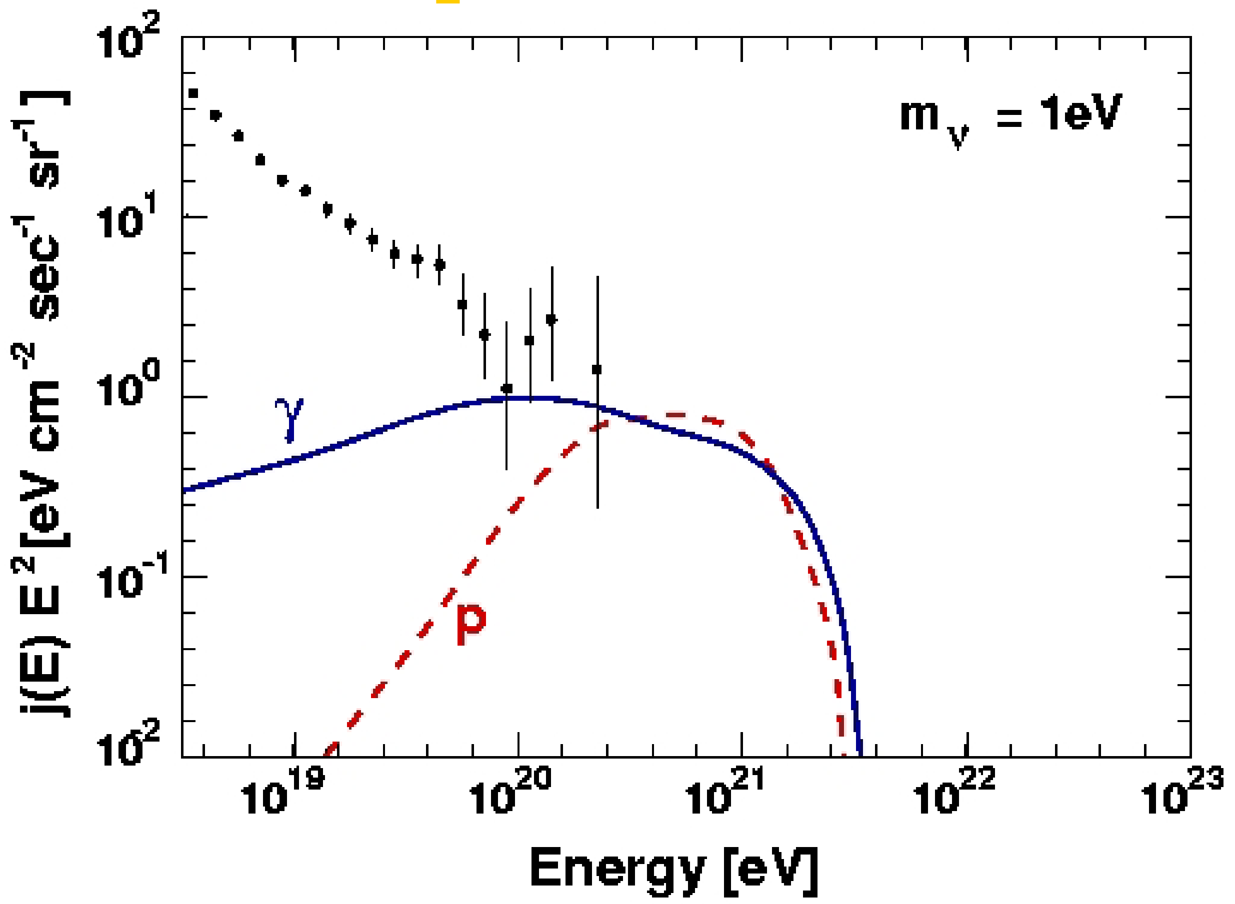
Deciding factors

- Source Evolution
- Extension of source distribution
- Local source enhancement?

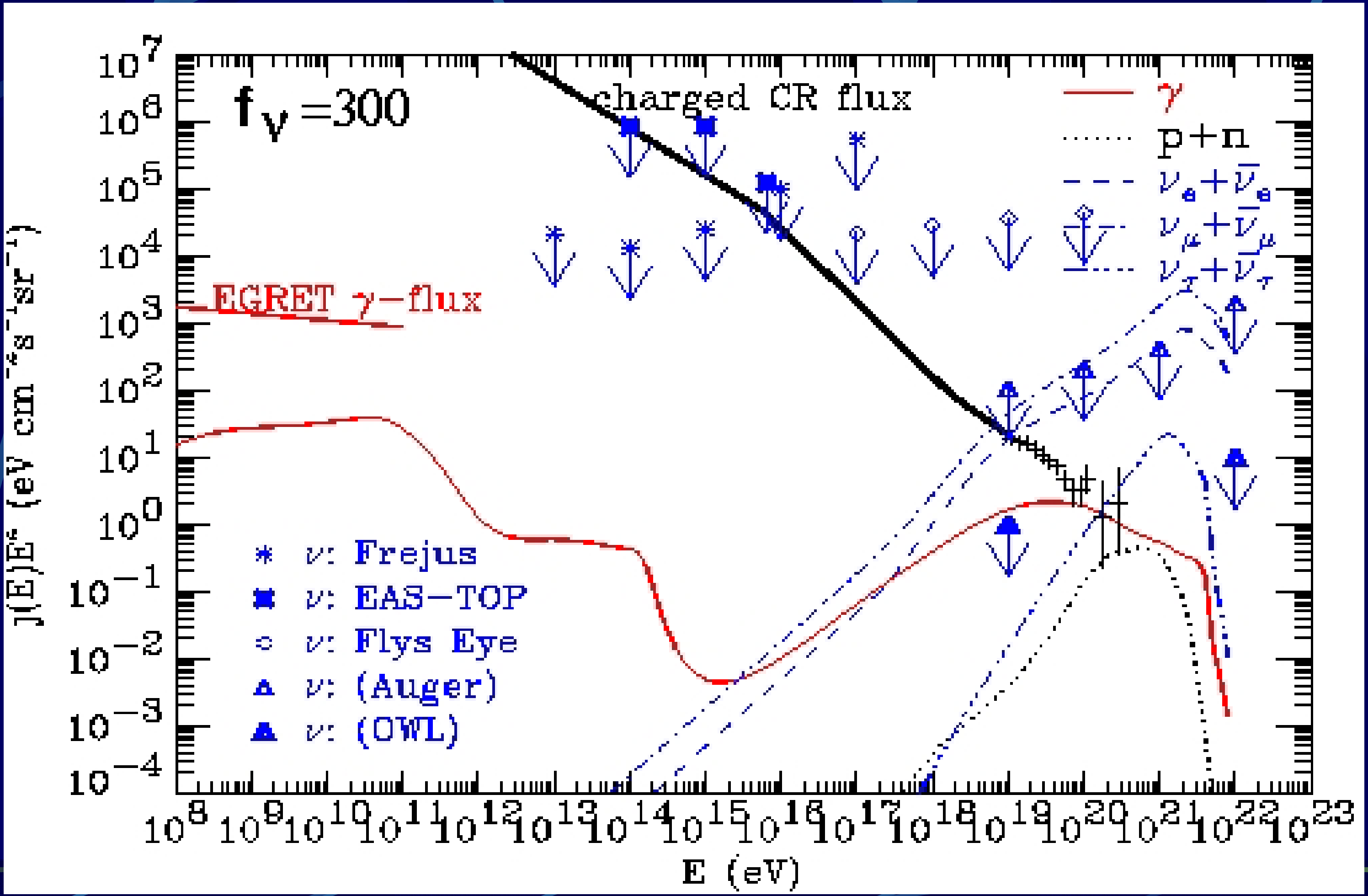
Z-bursts Concept



CRs extending to superEHEs!

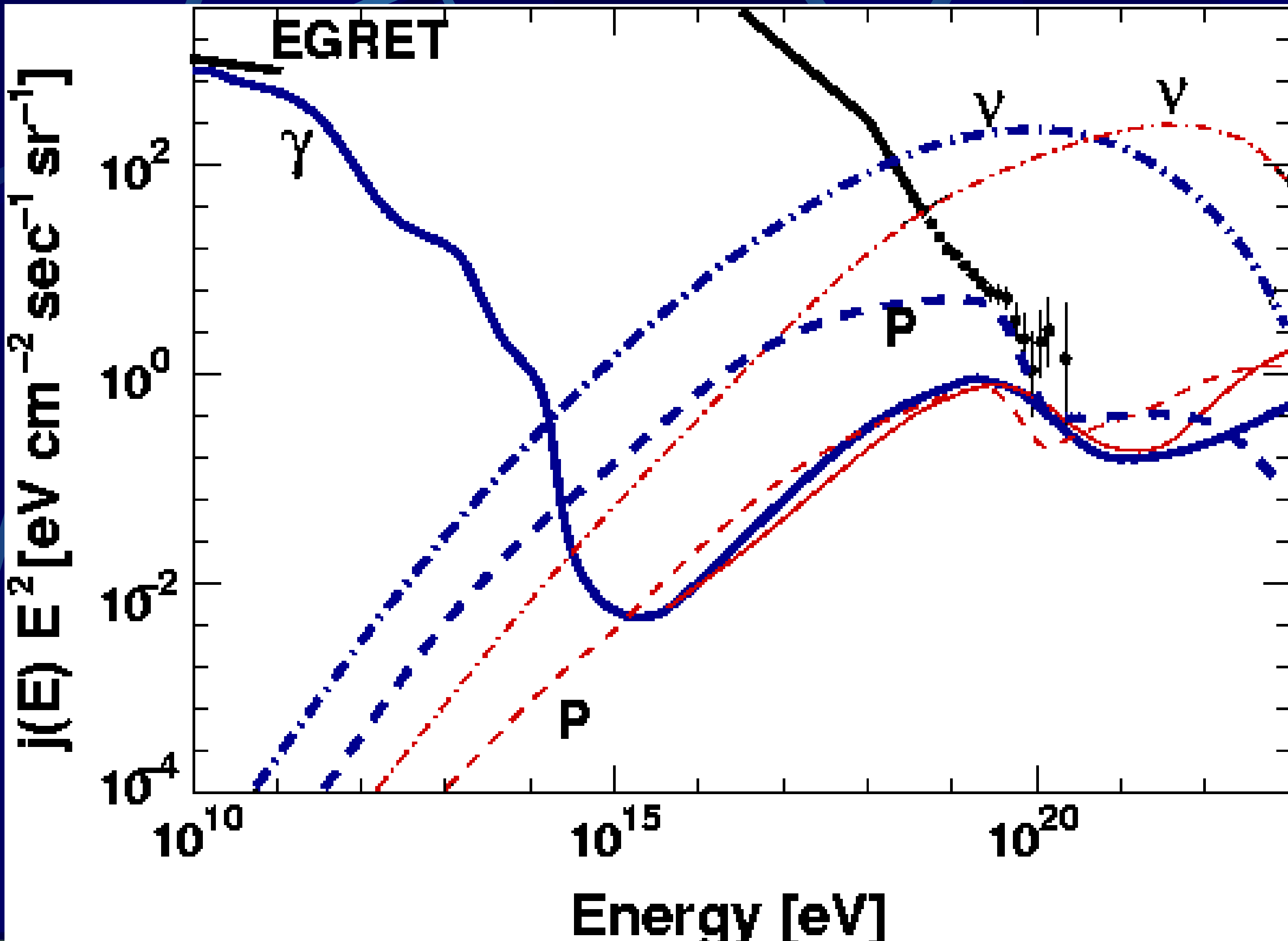


Z-burst constraints



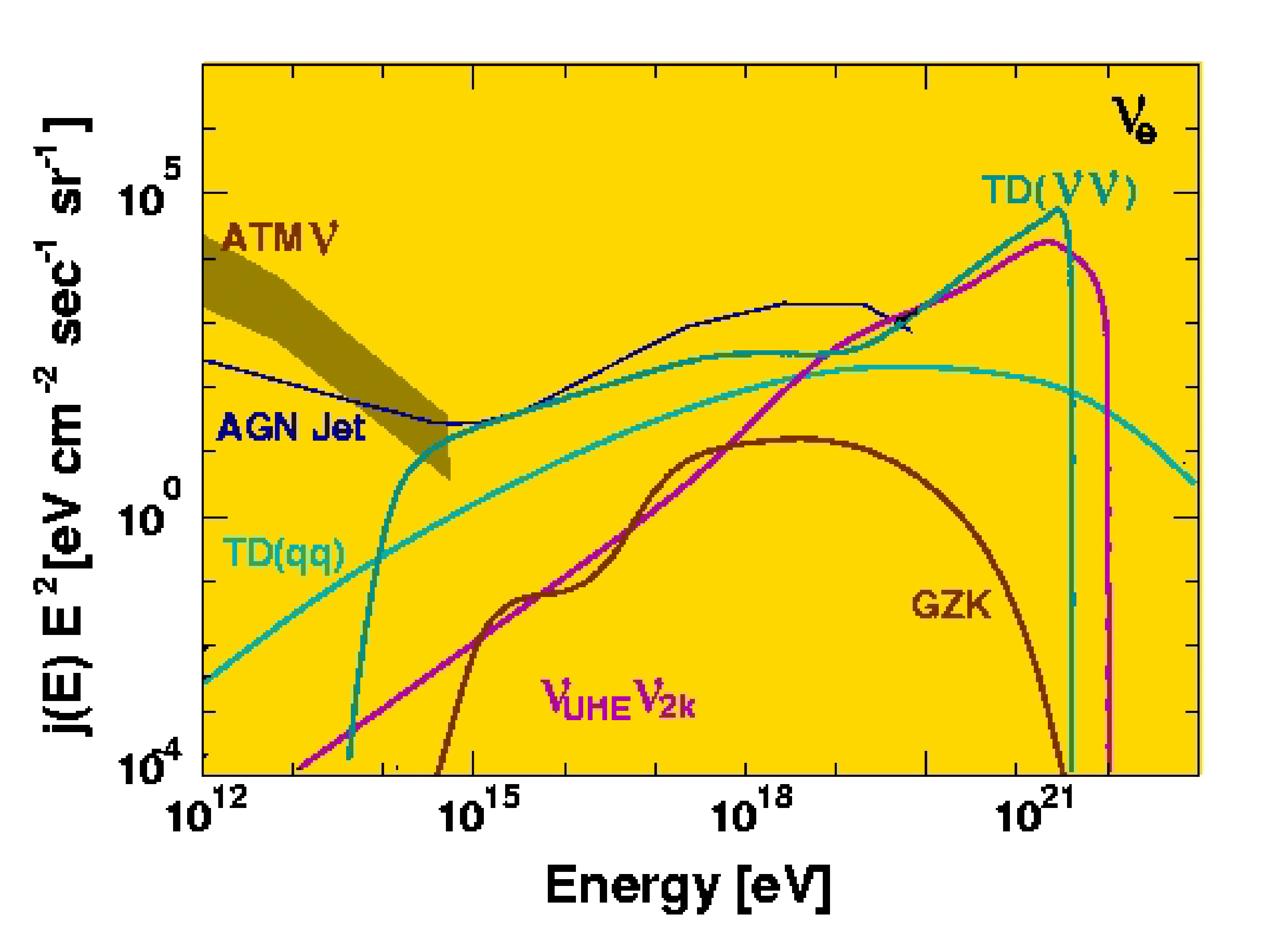
(Yoshida, Sigl, Lee 1998)

From Cosmic String?



Sigl, Lee, Bhattacharjee, Yoshida (1998)

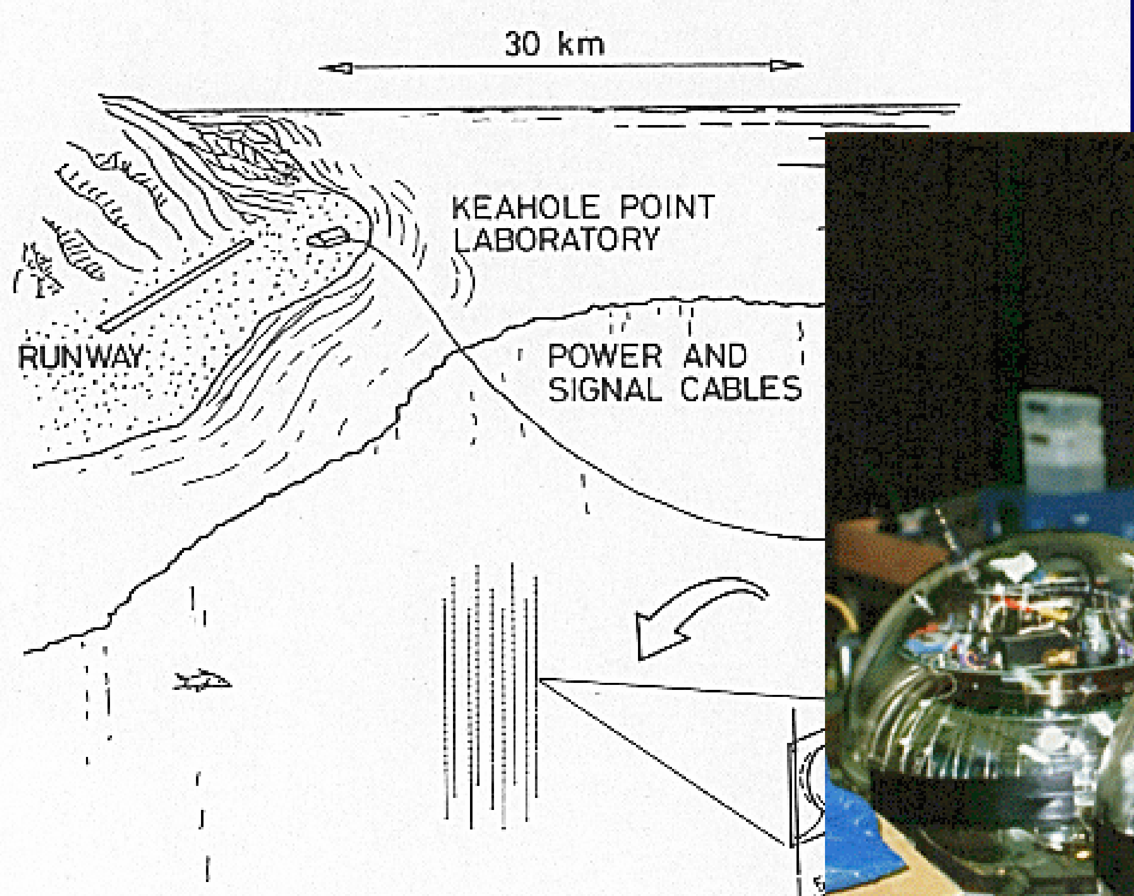
EHE Neutrino Fluxes



Shall we Dance?

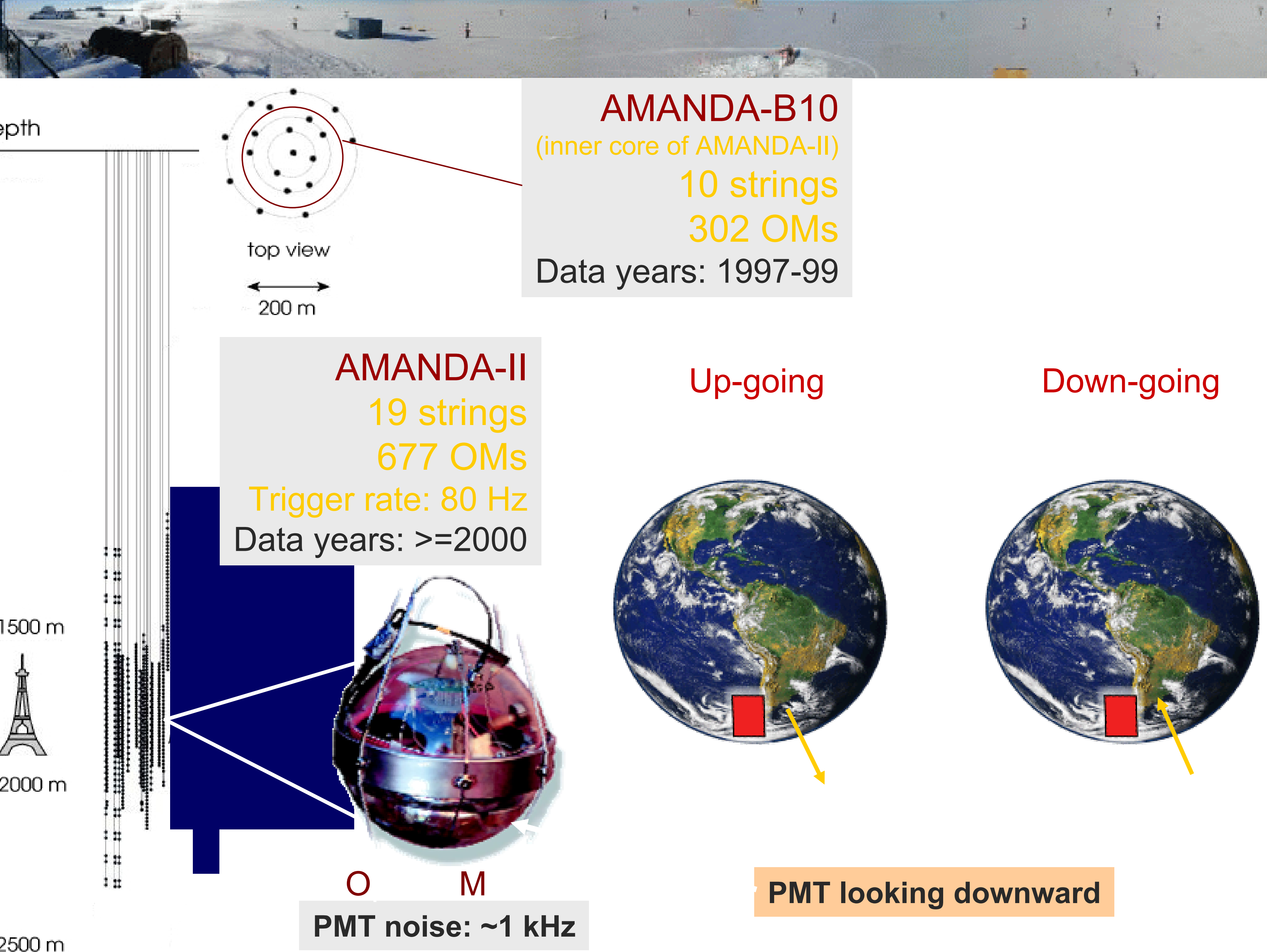
Historical lookback

- DUMAND (1987-1995)

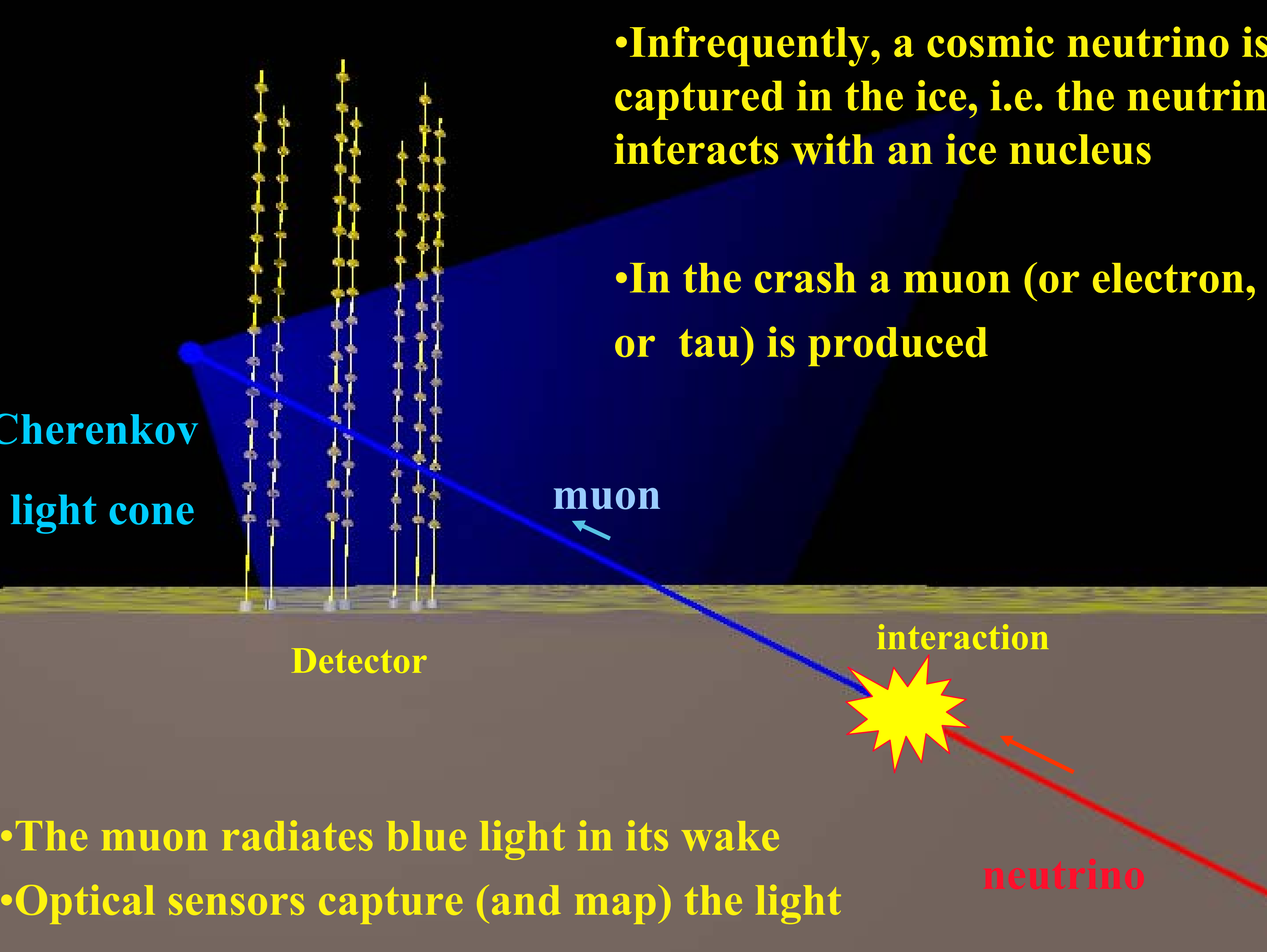


Where are we ?

South Pole
Dome
road to work
Summer camp
AMANDA
1500 m
2000 m
Amundsen-Scott South Pole Station

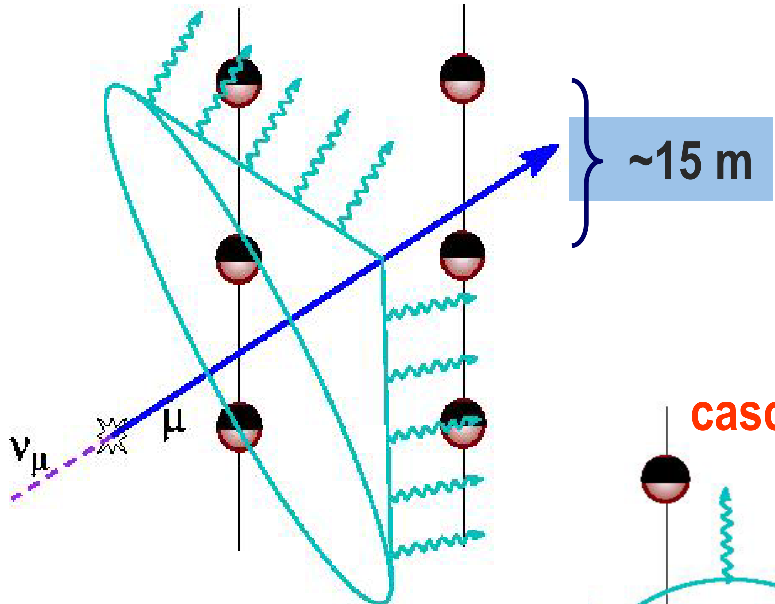


epth
top view
200 m
1500 m
2000 m
2500 m
AMANDA-B10
(inner core of AMANDA-II)
10 strings
302 OMs
Data years: 1997-99
AMANDA-II
19 strings
677 OMs
Trigger rate: 80 Hz
Data years: >=2000
O M
PMT noise: ~1 kHz
Up-going
Down-going
PMT looking downward

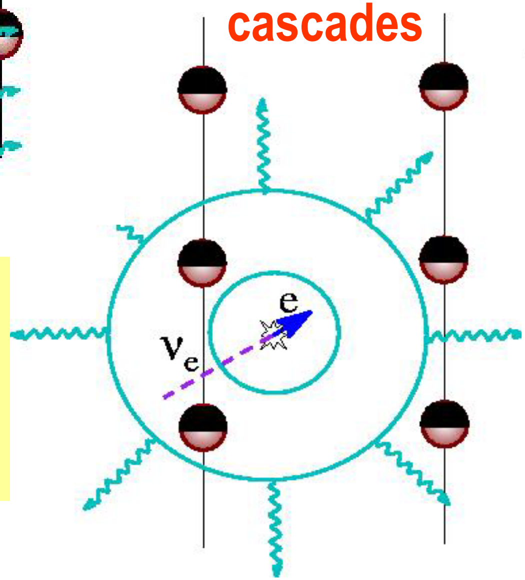

•Infrequently, a cosmic neutrino is
captured in the ice, i.e. the neutrin
interacts with an ice nucleus
•In the crash a muon (or electron,
or tau) is produced
Cherenkov
light cone
muon
Detector
interaction
neutrino
•The muon radiates blue light in its wake
•Optical sensors capture (and map) the light

Event detection in the ic

O(km) long μ tracks



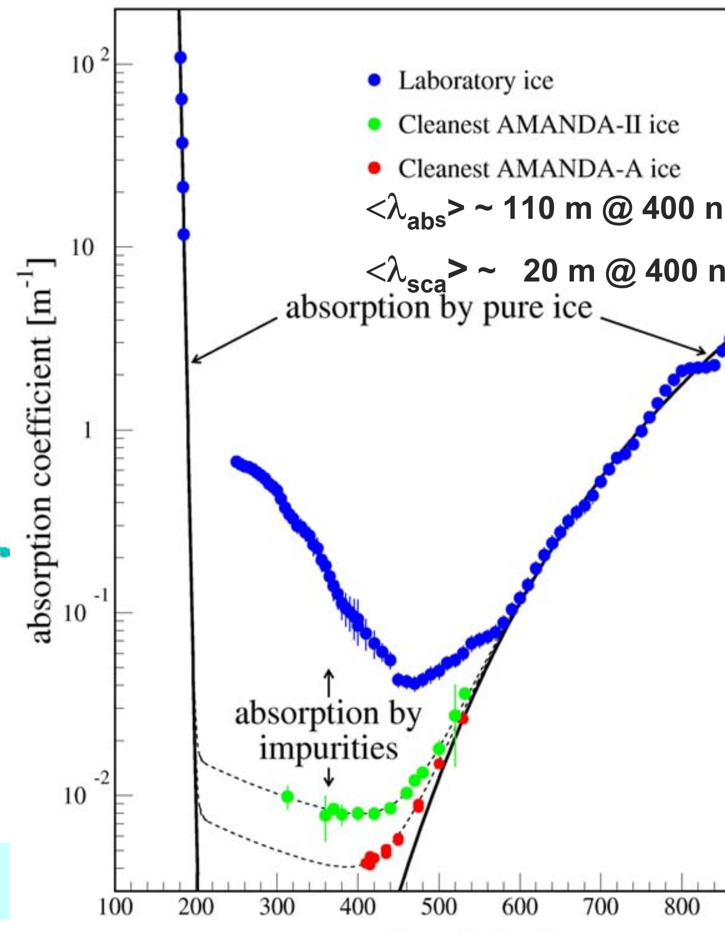
cascades



a neutrino telescope

$\Theta_{\mu\nu} \approx 0.65^o \cdot (E_\nu/TeV)^{-0.48}$
$(3TeV < E_\nu < 100TeV)$

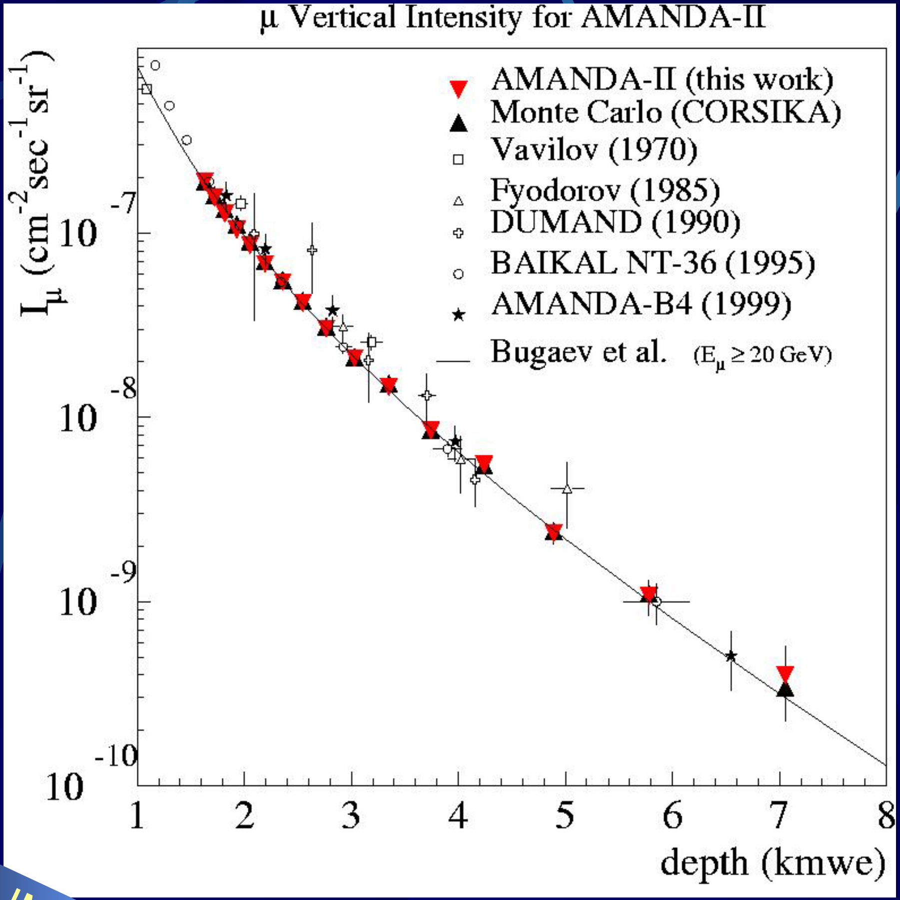
South Pole ice:
the most transparent natural medium ?



Longer absorption length → larger effective volume

Atmospheric muons in AMANDA-II

Atmospheric muons and neutrinos: AMANDA's test beams



much improved simulation

...but data 30% higher than MC ...

normalize to most vertical bin

Systematic errors:

- 10% scattering (20m @ 400nm)
  absorption (110m @ 400nm)
- 20% optical module sensitivity
- 10% refreezing of ice in hole

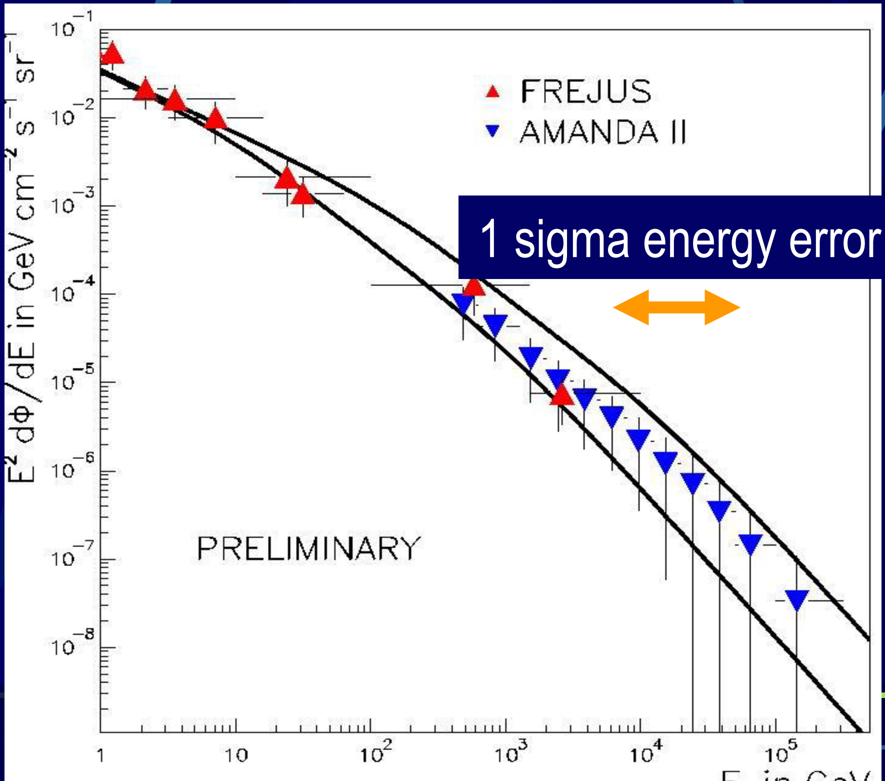
threshold energy ~ 40 GeV (zenith averaged)

Atmospheric ν's in AMANDA-II

PRELIMINARY

- neural network energy reconstruction
- regularized unfolding

measured atmospheric neutrino spectrum



- spectrum up to 100 TeV
- compatible with Frejus data

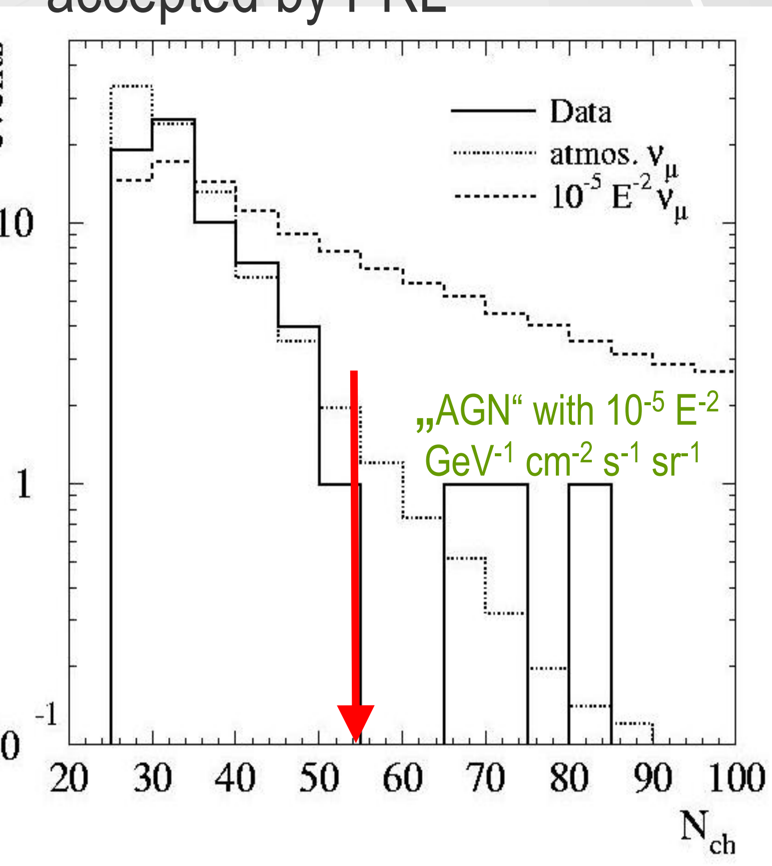
presently no sensitivity to LSND/Nunokawa prediction of dip structures between 0.4-3 TeV

In future, spectrum will be used to study excess due to cosmic ν's

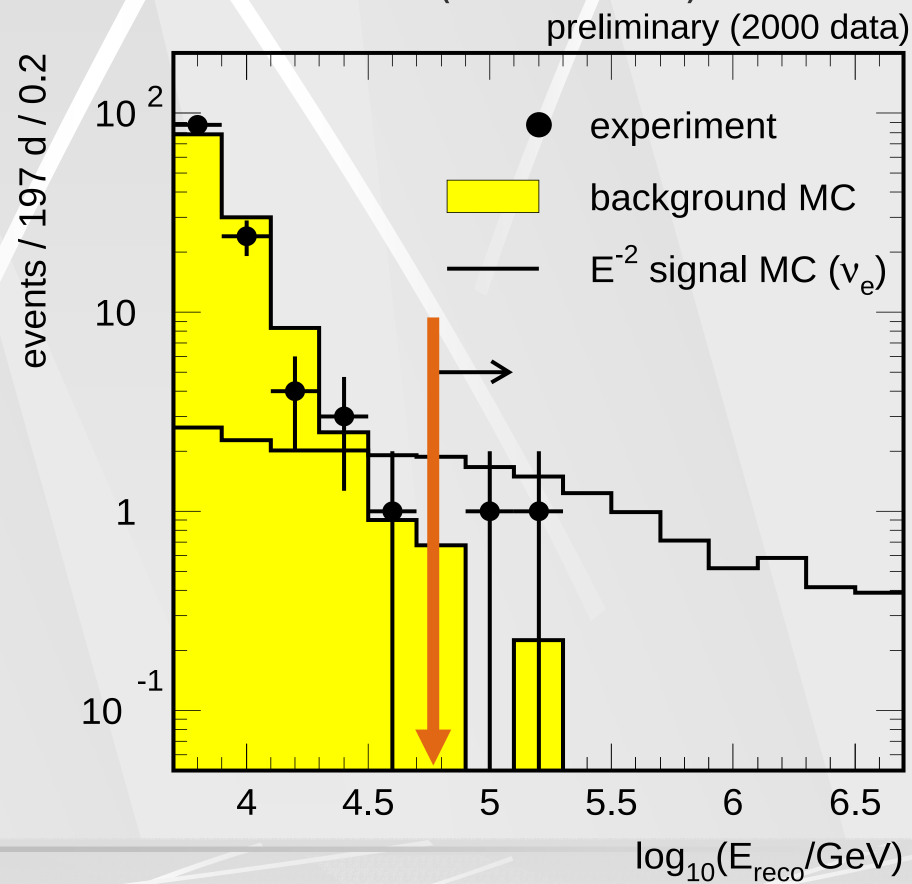
Excess of cosmic neutrinos? Not yet ...

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

muon neutrinos (1997 B10-data)
accepted by PRL



cascades (2000 data)



cuts determined by MC – blind analyses !

Diffuse flux muon neutrinos

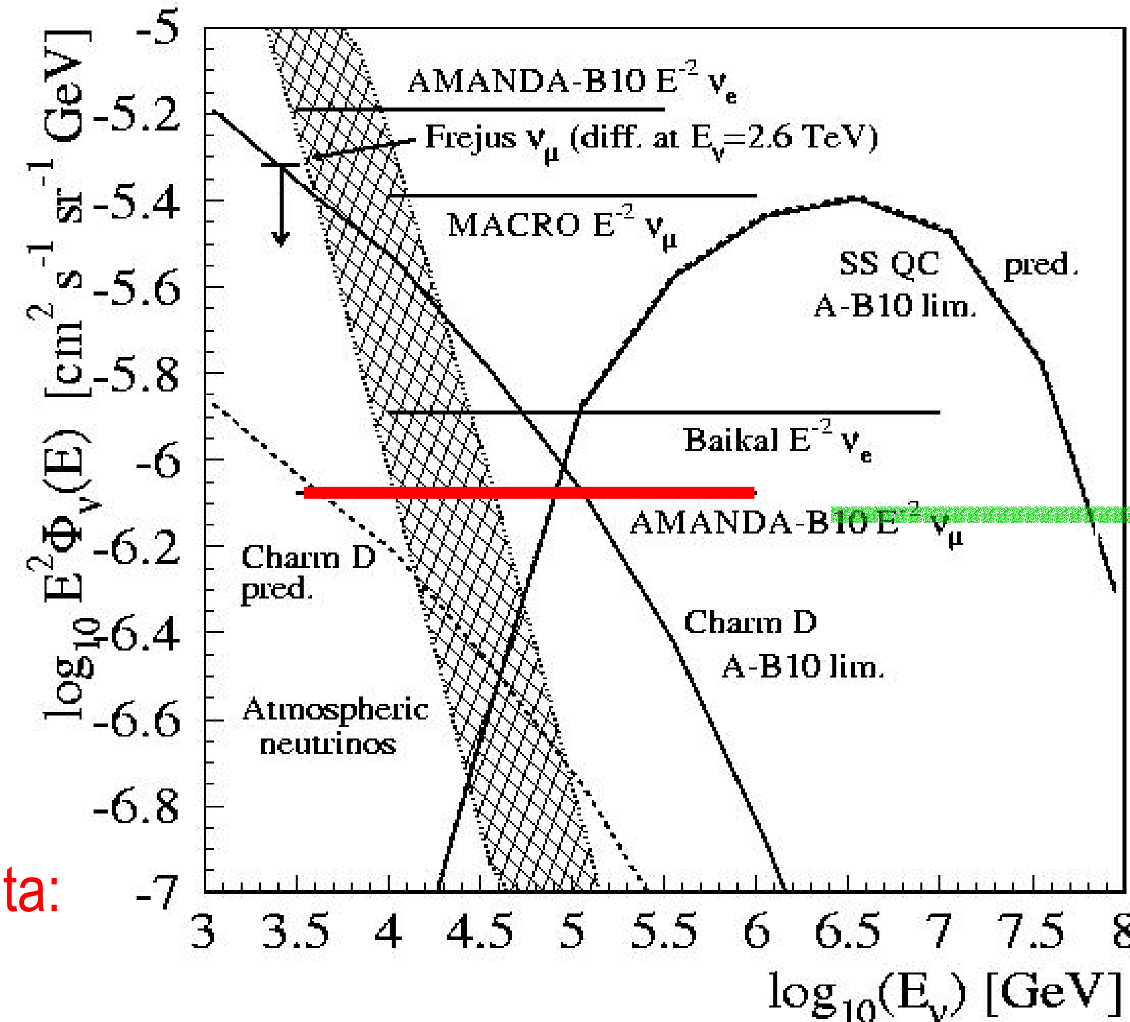
Note that limits depend on assumed energy spectrum ...

$3 \cdot 10^3 – 10^6$ GeV:

$E^2\,\Phi(E) < 8 \cdot 10^{-7}$ $GeV^{-1}\,cm^{-2}\,s^{-1}\,sr^{-1}$

$2.5 \cdot 10^6 – 5.6 \cdot 10^8$ GeV:

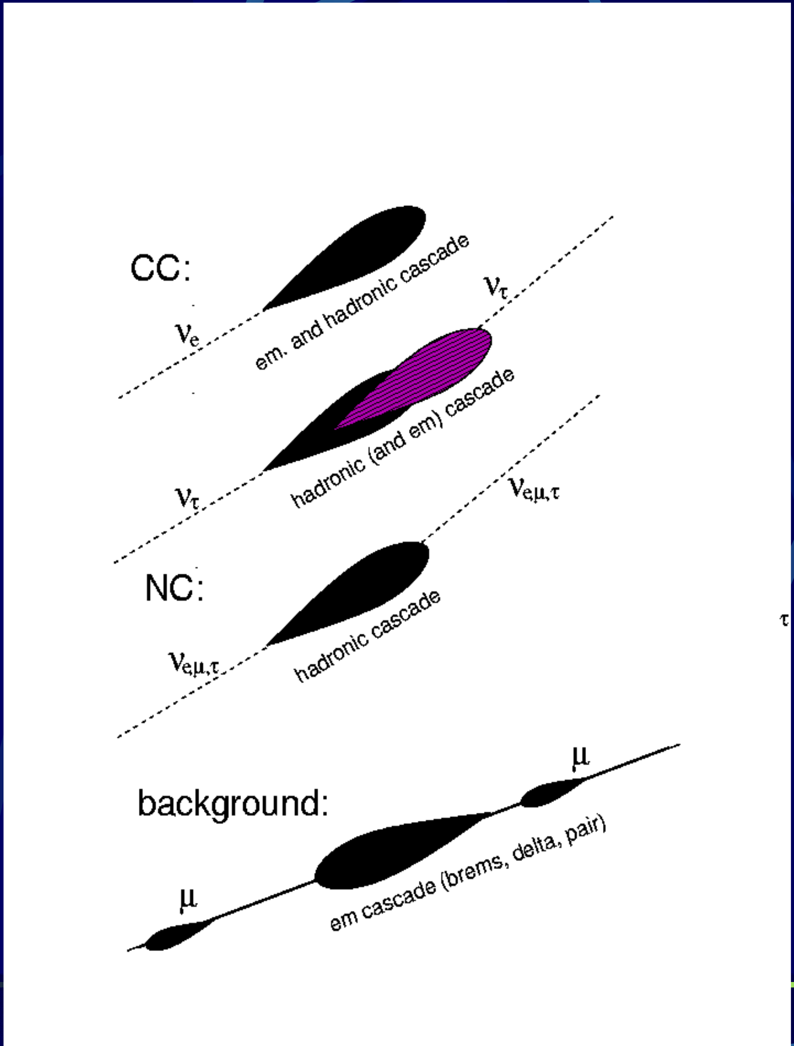
$E^2\,\Phi(E) < 7.2 \cdot 10^{-7}$ $GeV^{-1}\,cm^{-2}\,s^{-1}\,sr^{-1}$



Expected sensitivity 2000 data:

~ $3 \cdot 10^{-7}$ $GeV^{-1}\,cm^{-2}\,s^{-1}\,sr^{-1}$

Neutrino-Induced Cascades:



- Signature of ν_e and ν_τ are hadronic and electro-magnetic cascades.
- Neutral Current interactions of all neutrino flavors produce hadronic cascades
- Background consists of atmospheric muons, emitting energetic secondaries

Why search for Neutrino-Induced Cascades?

Advantages:

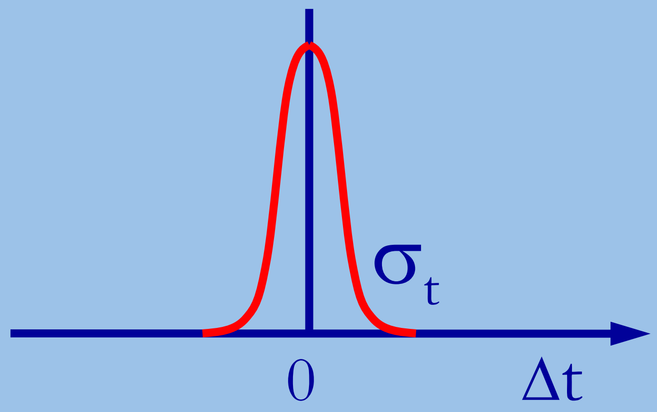
- Large Sensitivity for ν_e and ν_τ
- Local events, therefore better energy resolution
- Less intrinsic background of atmospheric muons & neutrinos
- Nearly 4 π sensitivity

Disadvantages:

- Less signal than in the muon channel due to very large muon range
- Worse angular resolution

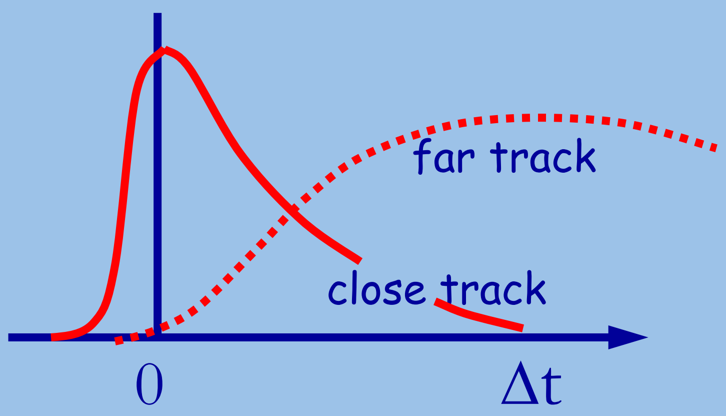
Reconstructing Cascades: Vertex Position

Without scattering



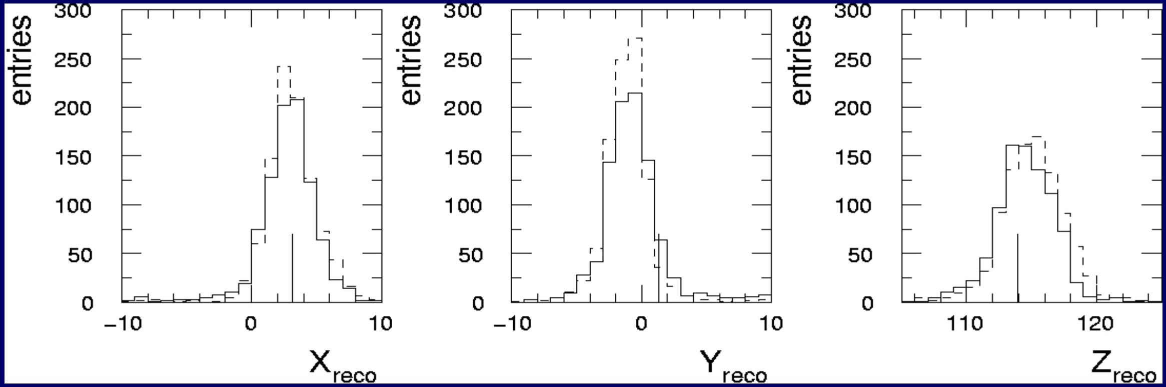
$$\chi^2 = \sum_{i=1}^{N} \frac{(t_i - t_{i0})^2}{\sigma_i^2}$$

With scattering



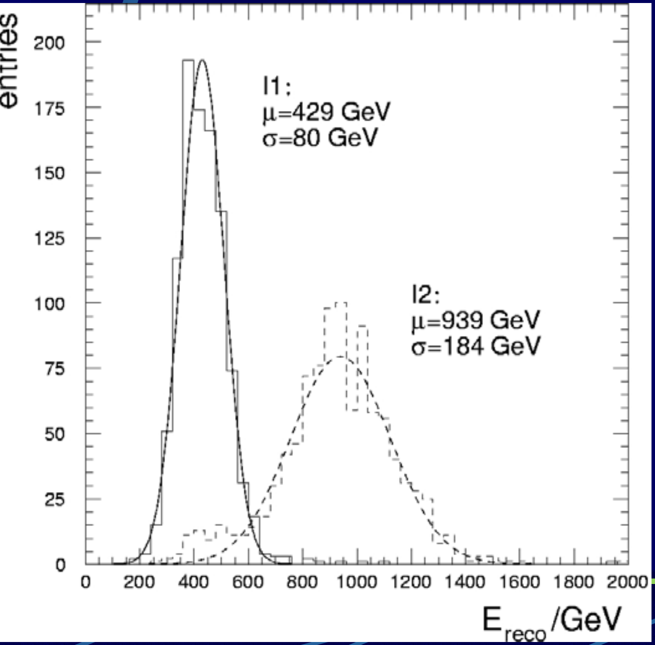
$$L = f(t_i, t_{i0}, \sigma_i, dist, \lambda_{abs}, \lambda_{scatt})$$

Testing Reconstruction with In-Situ Light Sources



Vertex reconstruction:

Reconstructing position of YAG laser light emitters (position known to ~ 1 m).



Energy reconstruction:

LEDs (UV 370 nm) run at different intensities.

Reconstructing energy of LED events (20 % resolution) .

Absolute intensity not known, but relative Intensities reconstructed correctly.

Energy Reconstruction

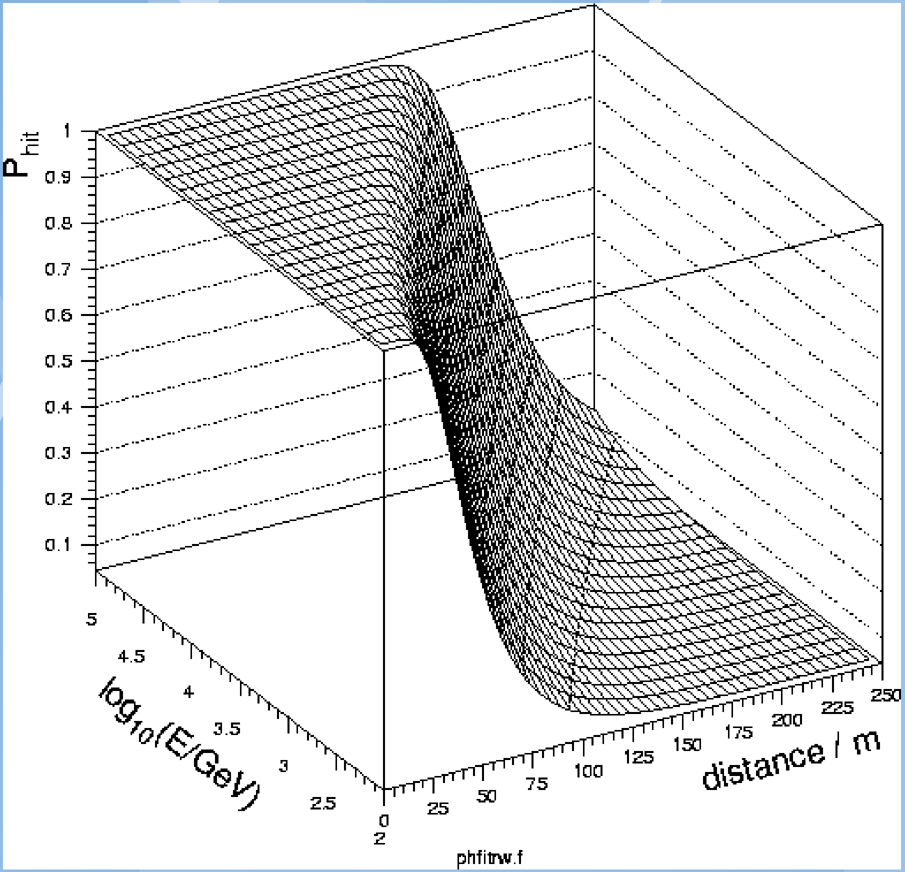
- Parameterization of hit-probability with MC. Function is *random walk* inspired:

$$P_{hit}(d,E) = 1 - e^{-\mu}$$

$$\mu = c \cdot E / d \cdot e^{-d/\lambda}$$

- Construction of Likelihood function:

$$L(E) = \prod^{allhits} P_{hit}(E) \prod^{nohits} (1 - P_{hit})$$

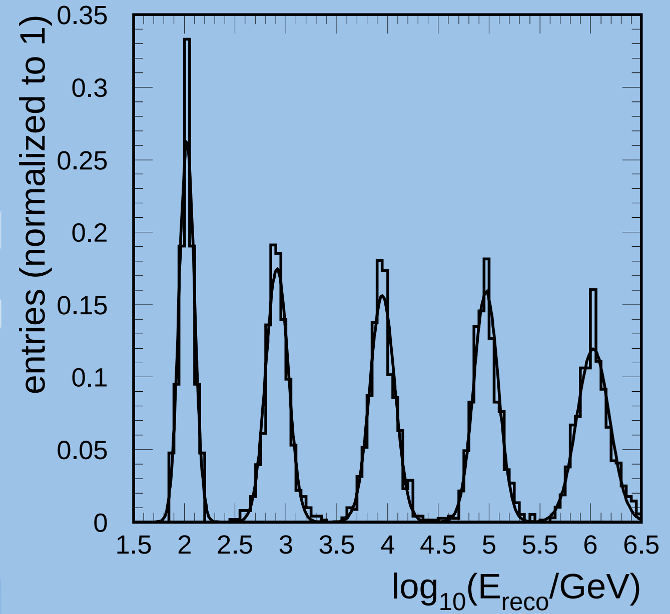


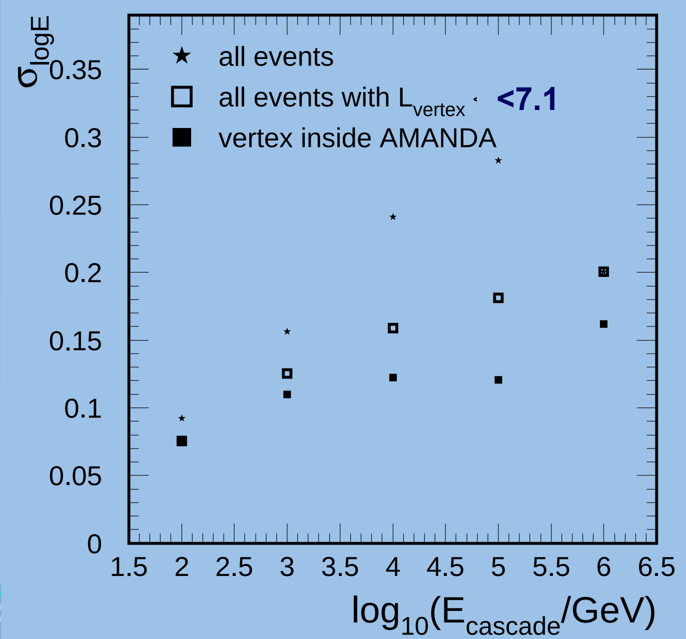
Resolution of Energy Reconstruction

- Reconstruction of EM cascades of energies: 10^2, 10^3, 10^4, 10^5, 10^6 GeV.

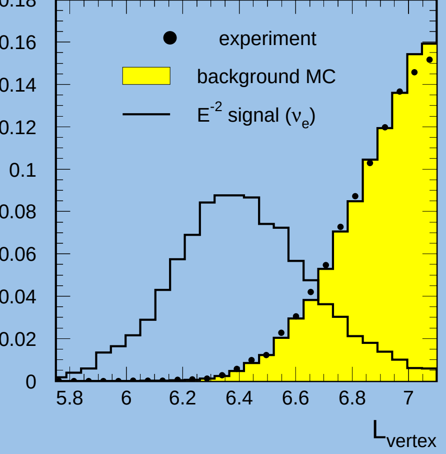
- Vertex within AMANDA II. (radius = 100m, height =200m) Vertex fitted with time-likelihood.

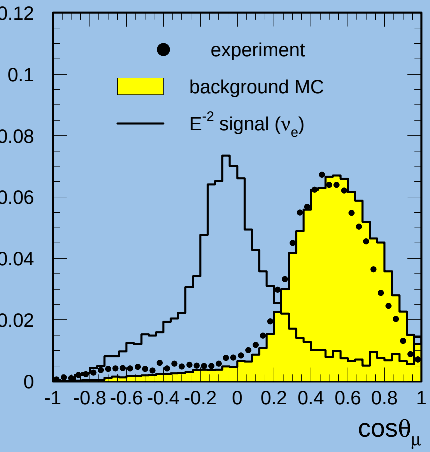
$$\sigma(\log E) < 0.2$$

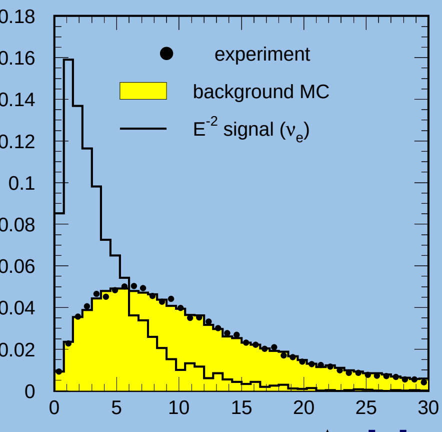




Final cut variable







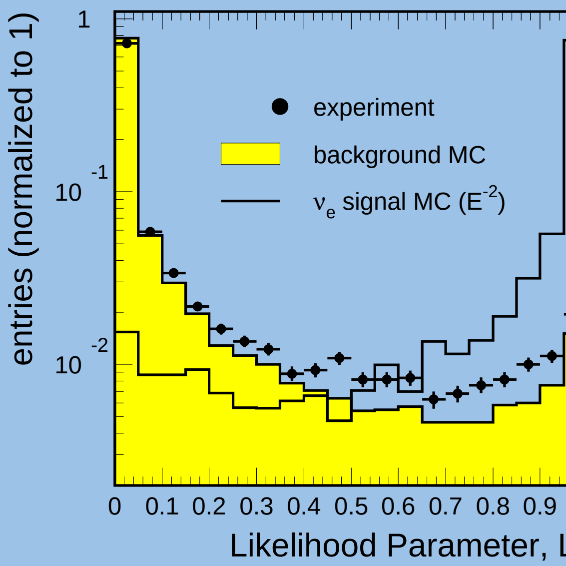
Variables merged into one

"Bayesian Discriminator"

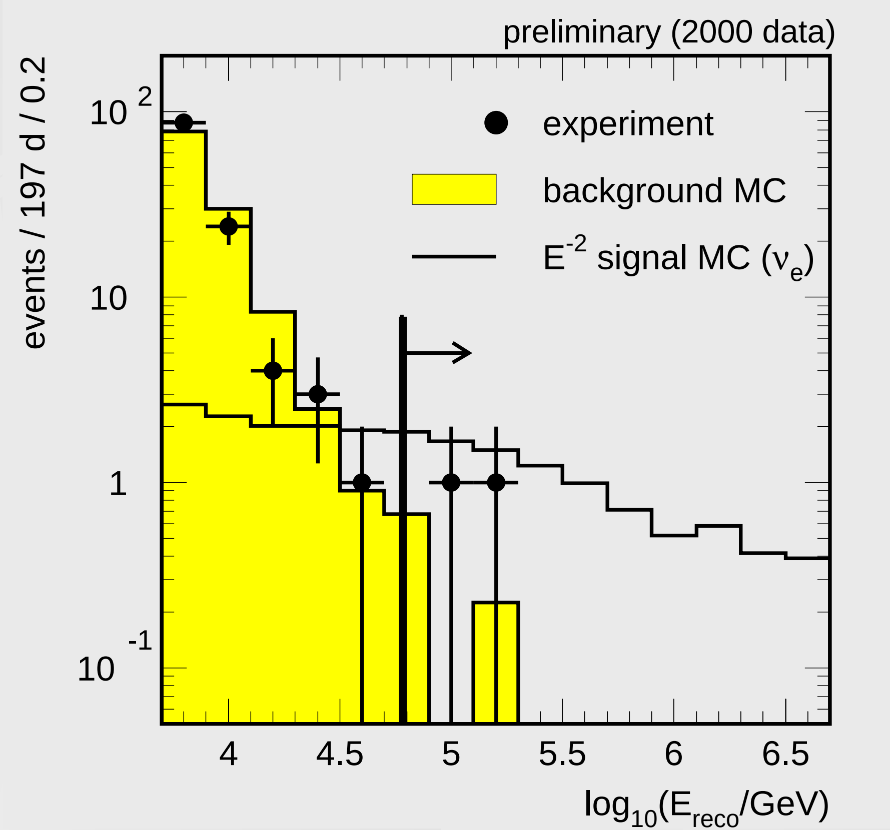
(thereby neglecting correl.)

$$P_{S/B} = \prod_i \frac{P^i_{S/B}}{P^i_S + P^i_B}$$

$$L_s = \frac{P_S}{P_S + P_B}$$



Final energy spectrum



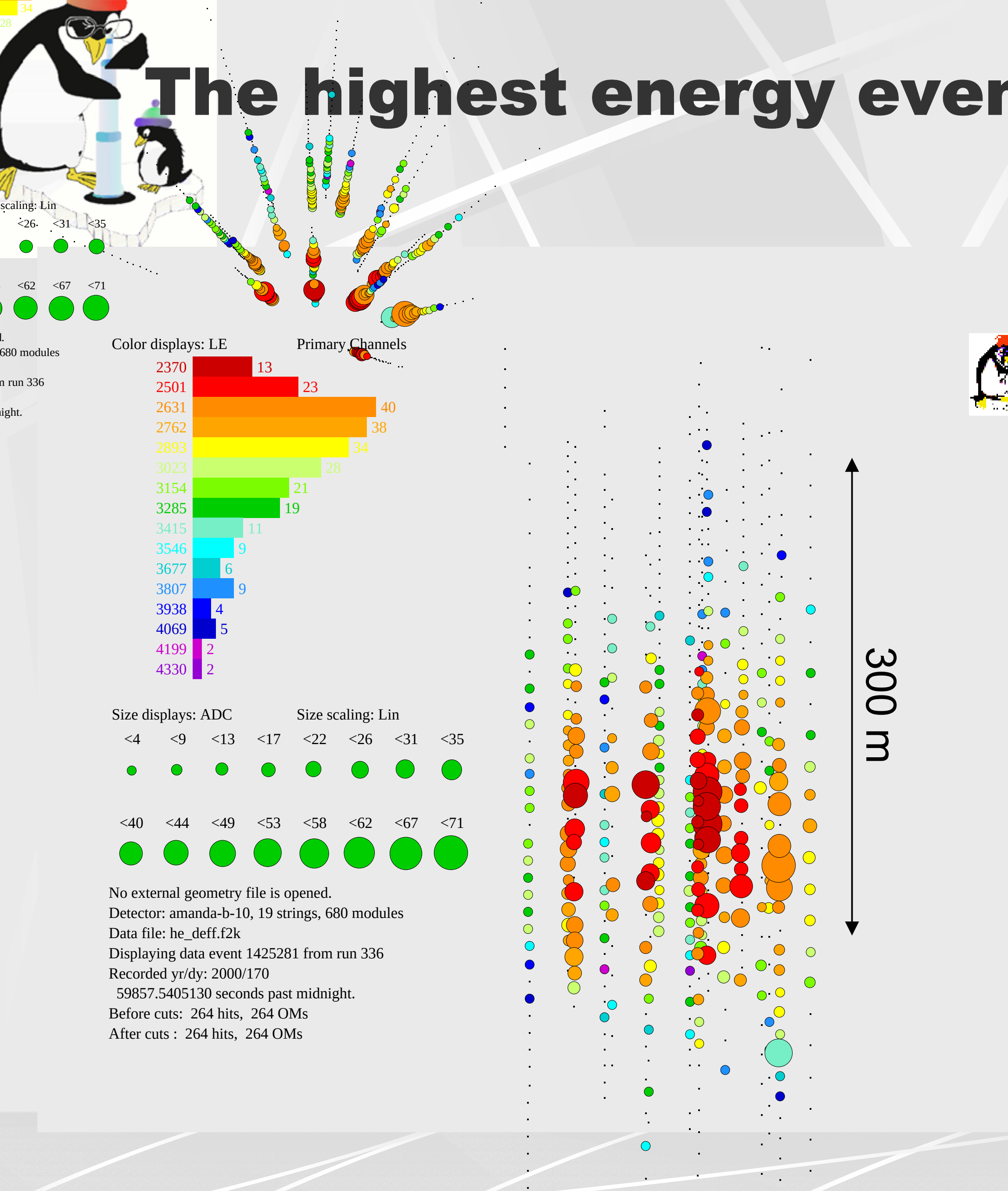
Energy cut chosen by MC

Optimization

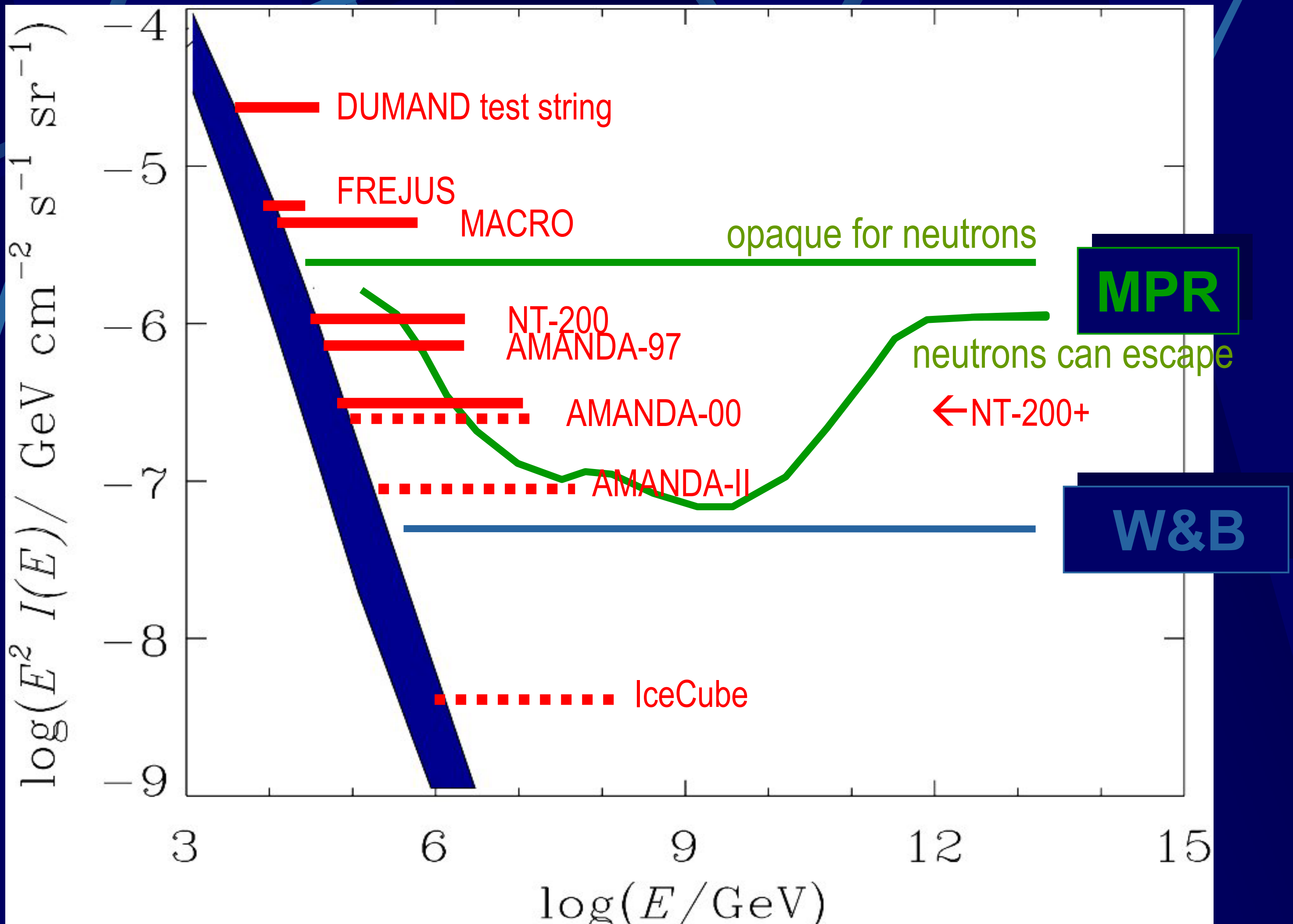
2 events passed all cuts

Background	Expectation
Atmospheric muons	**$0.45^{+0.5}_{-0.3}$**
Conventional atmospheric ν	**$0.05^{+0.05}_{-0.02}$**
Prompt charm ν	**0.015-0.7**
Sum (w/o charm)	**$0.50^{+0.5}_{-0.3}$**

The highest energy event (~200 TeV)



Theoretical bounds and future



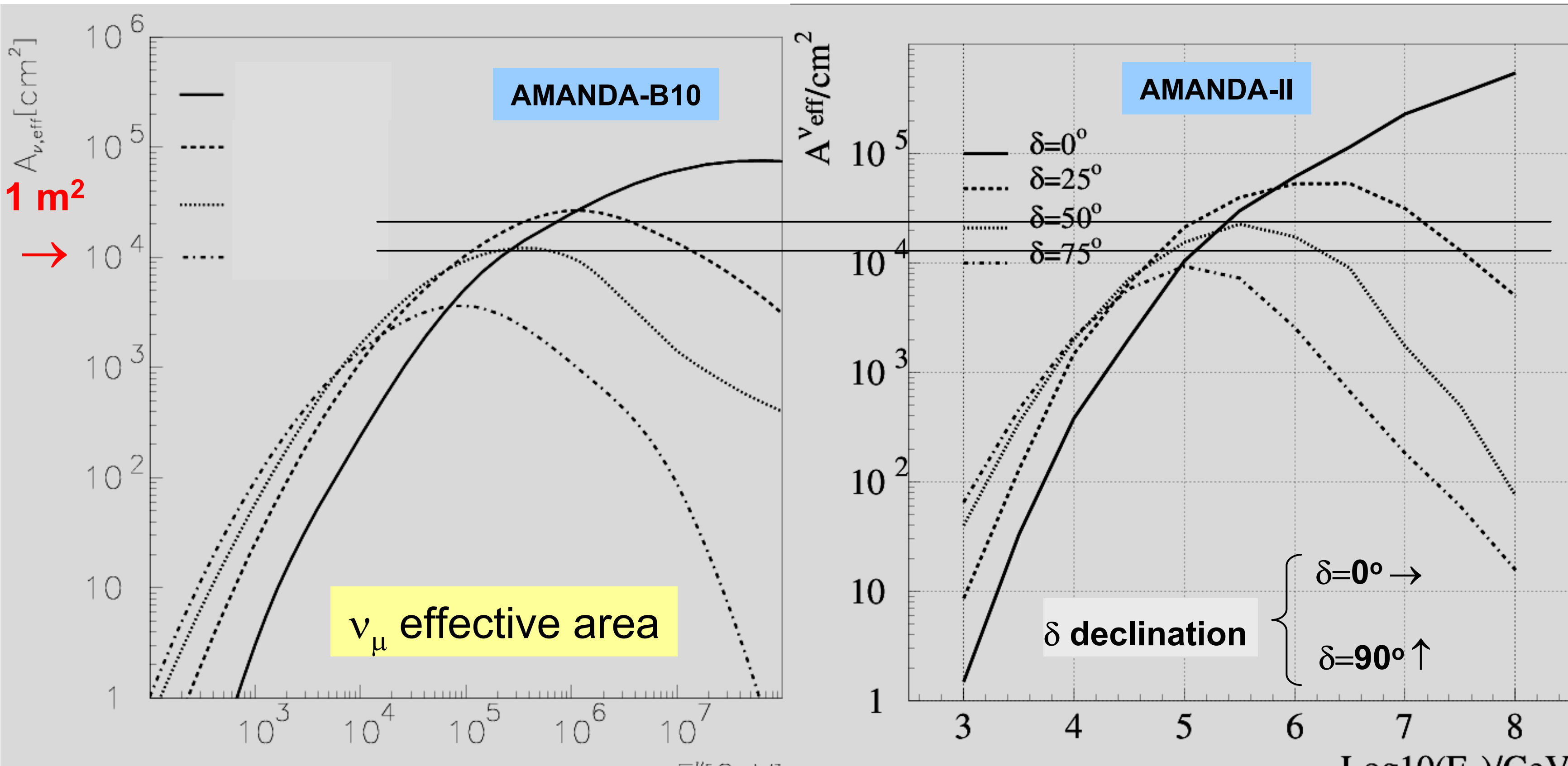
annheim, Protheroe and Rachen (2000) – Waxman, Bahcall (1999)

↙ derived from known limits on extragalactic protons + γ-ray flux

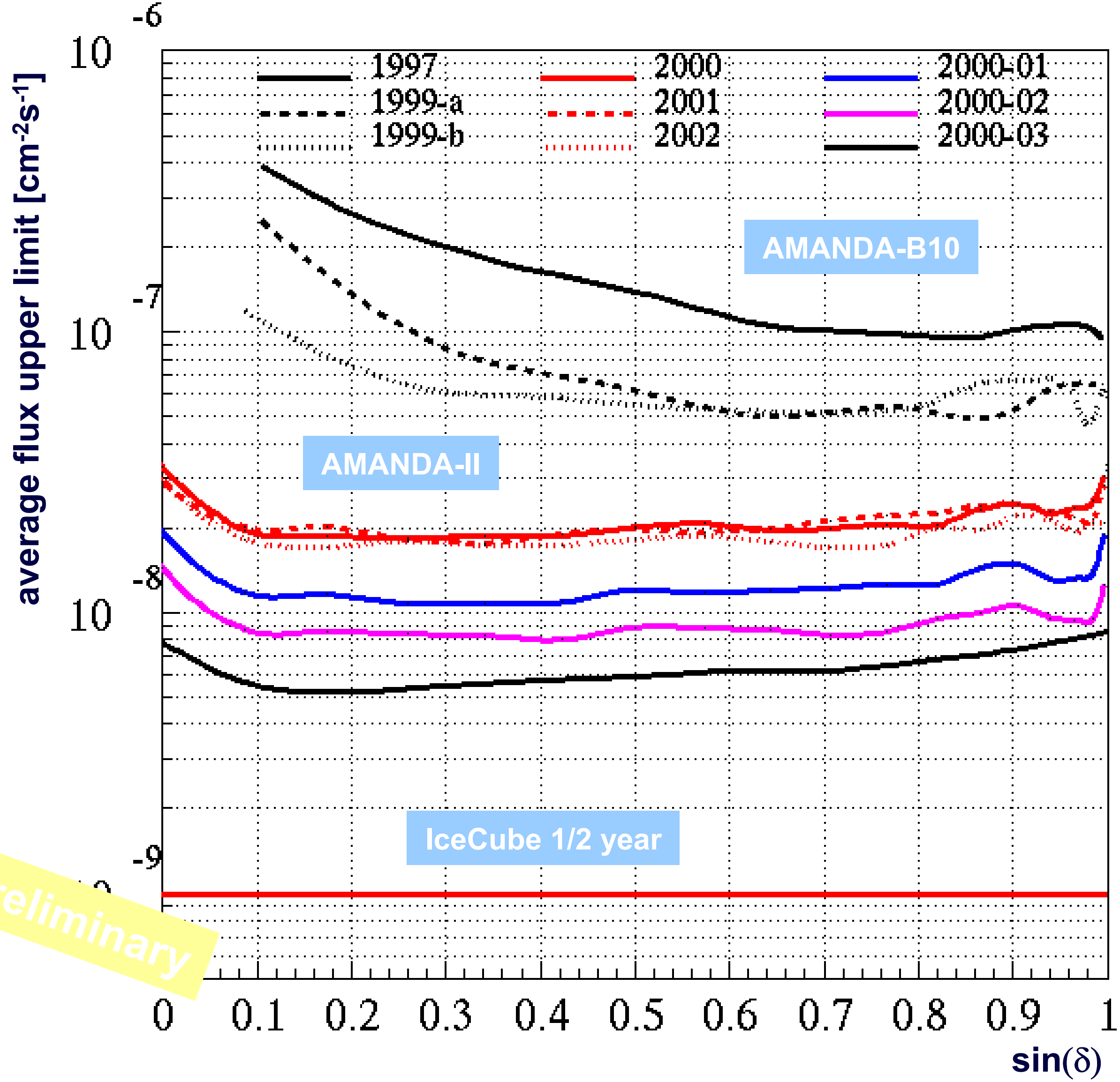
ν telescope : point source searc

Detection of ν_μ from discrete steady bright or close sources (AGN, …)

- cosmic ray μ background rejection
- good pointing resolution
- bin search optimization versus a given signal ($\propto E^{-2}$)



ν telescope : point source searc



Average upper limit = sensitivity
($\delta > 0^\circ$)
(integrated above 10 GeV, E^{-2} signal)

Sensitivity independent of direction

1997 : Ap.J. 583, 1040 (2003)

2000 : PRL 92, 071102 (2004)

IceCube : Astrop Phys 20, 507 (2004

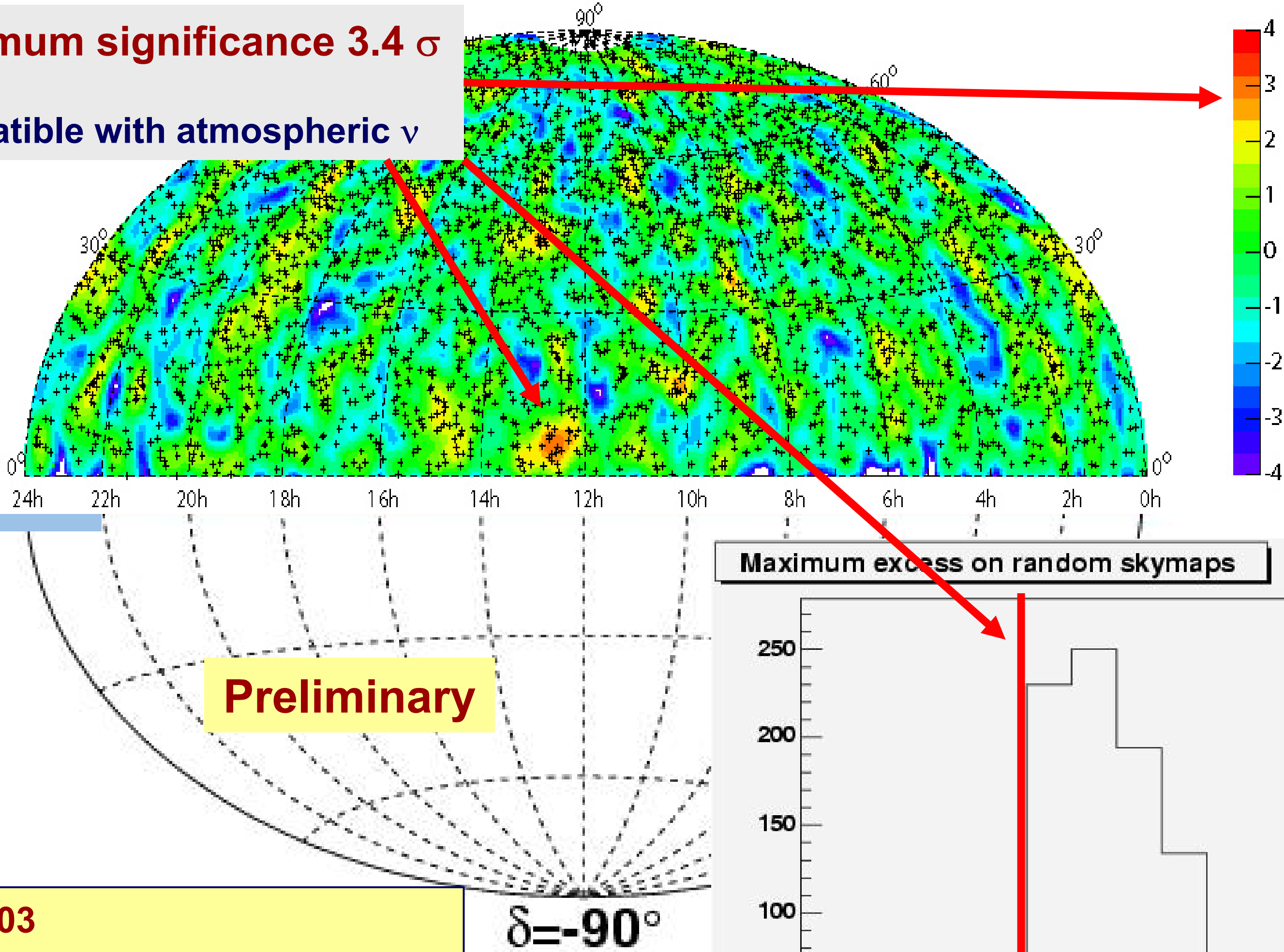
$\Phi_\nu^{lim} \approx 0.68 \cdot 10^{-8}\ cm^{-2}s^{-1}$

δ declination

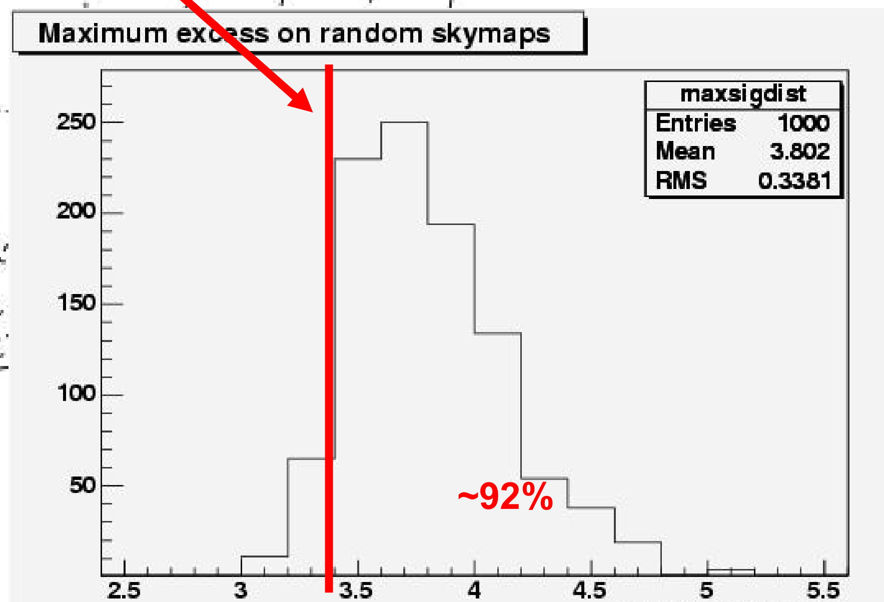
ν telescope : point source search

Maximum significance 3.4 σ

compatible with atmospheric ν



Preliminary



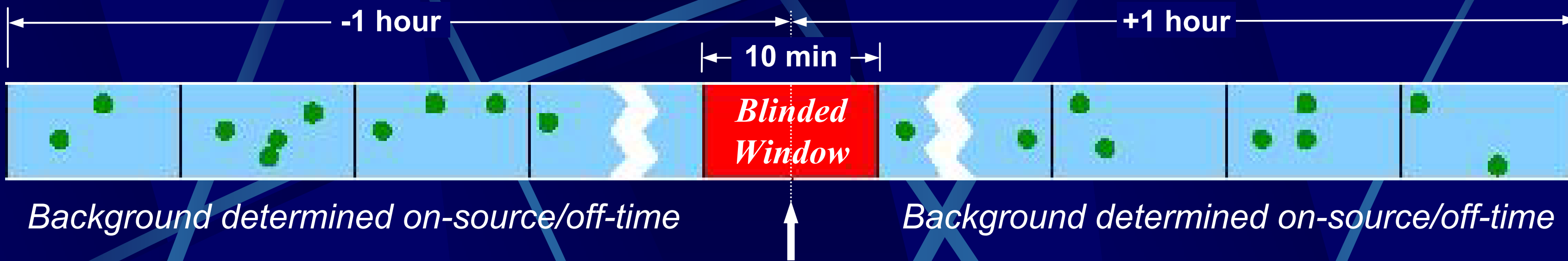
2000-2003

3369 ν from northern hemisphere

3438 ν expected from atmosphere

⇒ **also search for neutrinos from unresolved sources**

Search for ν_μ correlated with GRBs



Time of GRB
(Start of T_{90})

Low background analysis due to space and time coincidence!

PRELIMINARY

Year	Detector	N_{Bursts}	$N_{BG, Pred}$	N_{Obs}	Event U.L.
1997	B-10	78 (BT)	0.06	0	2.41
1998	B-10	94 (BT)	0.20	0	2.24
1999	B-10	96 (BT)	0.20	0	2.24
2000	A-II (2 analyses)	44 (BT)	0.83/0.40	0/0	1.72/2.05
97-00	B-10/A-II	312 (BT)	1.29	0	1.45
2000	A-II	24 (BNT)	0.24	0	2.19
2000	A-II	46 (New)	0.60	0	1.88
2000	A-II	114 (All)	1.24	0	1.47

(BT = BATSE Triggered BNT = BATSE Non-Triggered New = IPN & GUSBAD)

GRB catalogs:
BATSE, IPN3 & GUSBAD

Analysis is blind:
finalized off-source (± 5 min) with MC simulated signal

BG stability required within ± 1 hour

Muon effective area *(averaged over zenith angle)* ≈ 50,000 m² @ PeV

97-00 Flux Limit at Earth*: $E^2\Phi_\nu \leq 4\cdot10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

*For 312 bursts w/ WB Broken Power-Law Spectrum (E_{break} = 100 TeV, Γ_{Bulk} = 300)

WIMP annihilations in the center of Earth

Sensitivity to muon flux from neutralino annihilations in the center of the Earth:

$$\chi\chi \rightarrow q\bar{q}, l^+l^-, W, Z, H \rightarrow \nu_\mu$$

PRELIMINARY

Look for vertically upgoing tracks

NN optimized (on 20% data) to
- remove misreconstructed atm. μ
- suppress atmospheric ν
- maximize sensitivity to WIMP signal

Combine 3 years: 1997-99

Total livetime (80%): 422 days

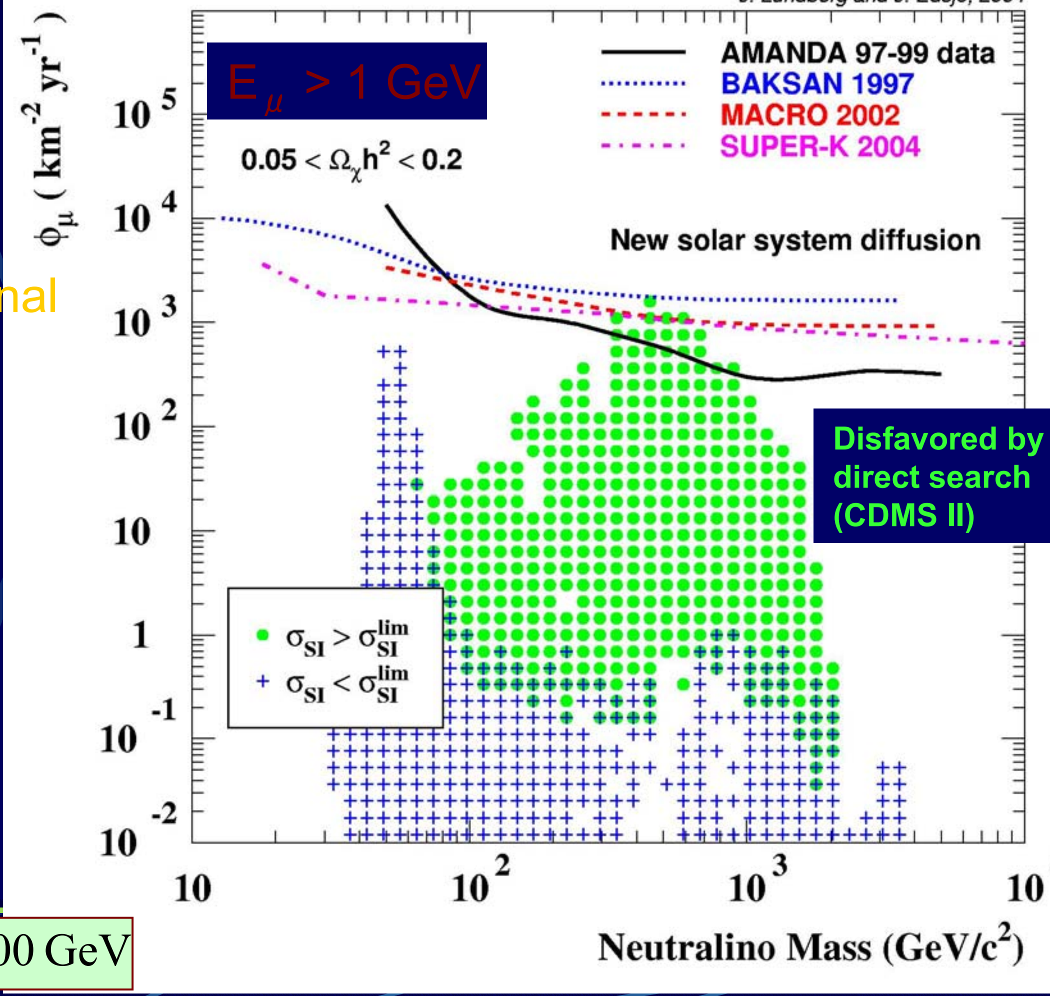
No WIMP signal found

Limit for "hardest" channel:

$$\chi\chi \rightarrow \tau^+\tau^- \rightarrow \nu_\mu \quad M_\chi = 50 \text{ GeV}$$

$$\chi\chi \rightarrow W^+W^- \rightarrow \nu_\mu \quad M_\chi = 100\text{-}5000 \text{ GeV}$$

Muon flux limits



WIMP annihilations in the Sun

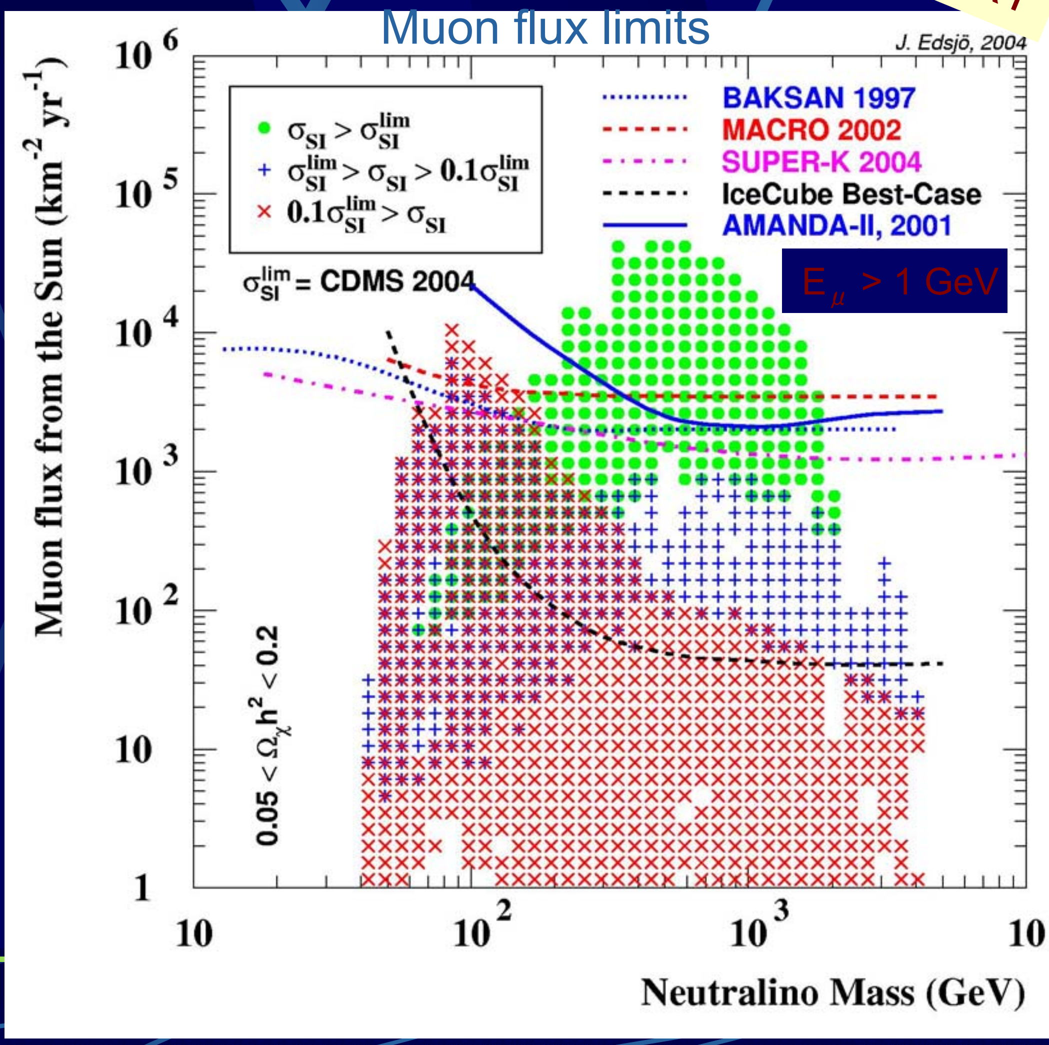
- ncreased capture rate due to addition of spin-dependent processes
- Sun is maximally 23° below horizon
- Search with AMANDA-II possible thanks to improved reconstruction capabilities for horizontal tracks
- Exclusion sensitivity from analyzing off-source bins

2001 data
0.39 years livetime

No WIMP signal found

Best *sensitivity* (considering livetime) of existing indirect searches using muons from the Sun/Earth

PRELIMINARY



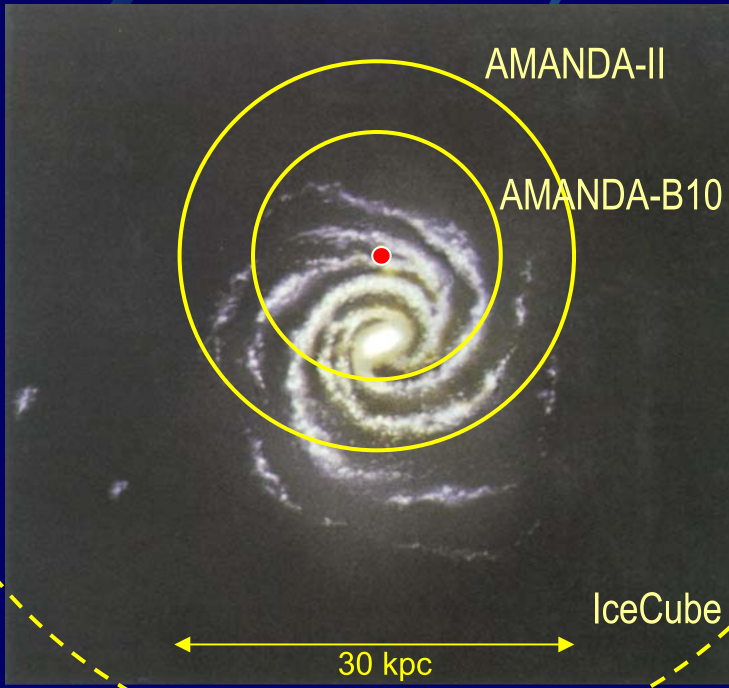
AMANDA as supernova monitor ~MeV

Bursts of low-energy (MeV) $\bar{\nu}_e$ from SN

- simultaneous increase of all PMT count rates (~10s)

Since 2003:

SNDAQ includes all AMANDA-II channels



Recent online analysis software upgrades

- can detect 90% of SN within 9.4 kpc
- less than 15 fakes/year

⇒ can contribute to SuperNova Early Warning System (with Super-K, SNO, Kamland, LVD, BooNE)

coverage

B10: 70% of Galaxy
A-II: 95% of Galaxy
IceCube: up to LMC

Analysis of 200X data in progress

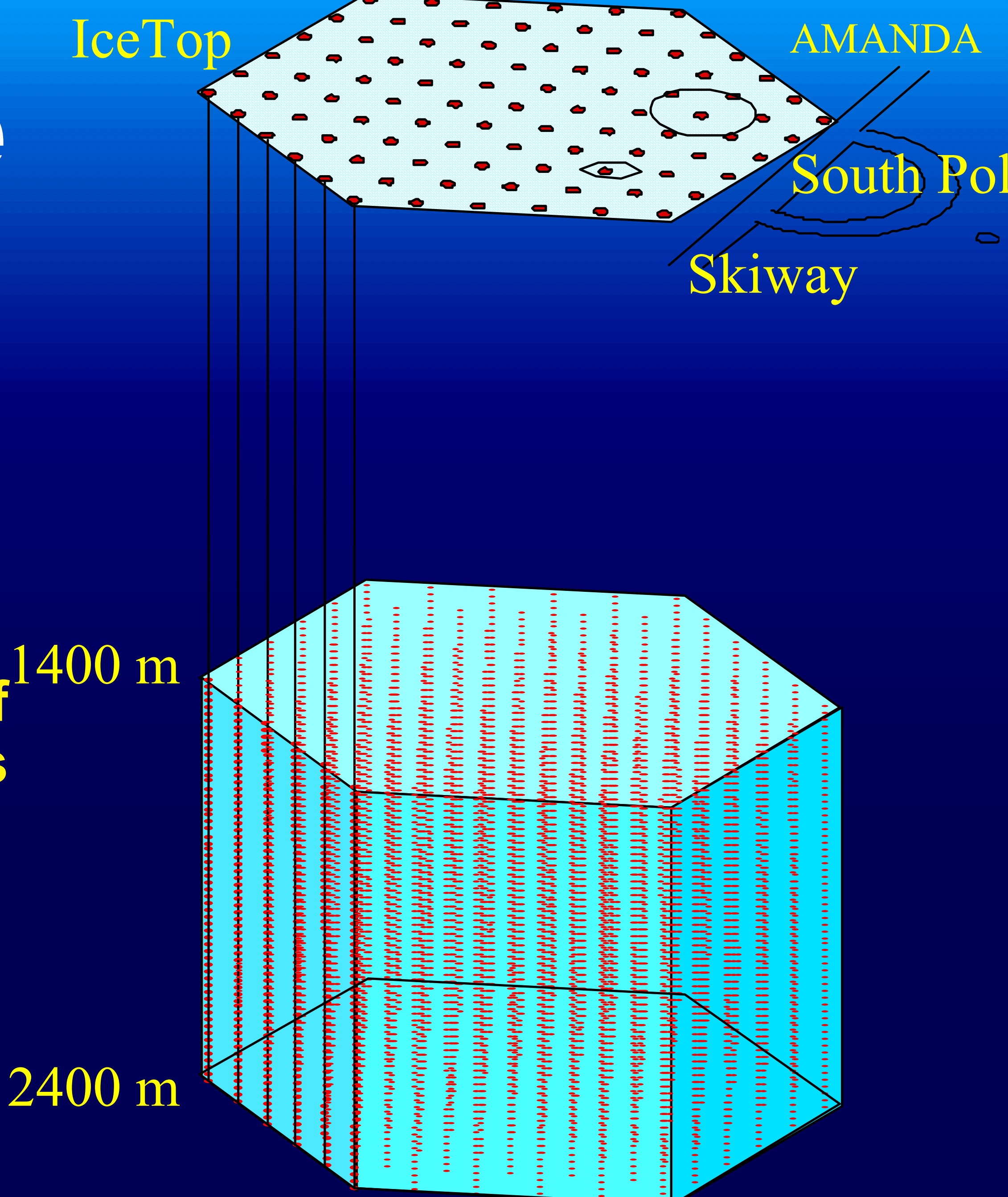
The IceCube Neutrino Telescope

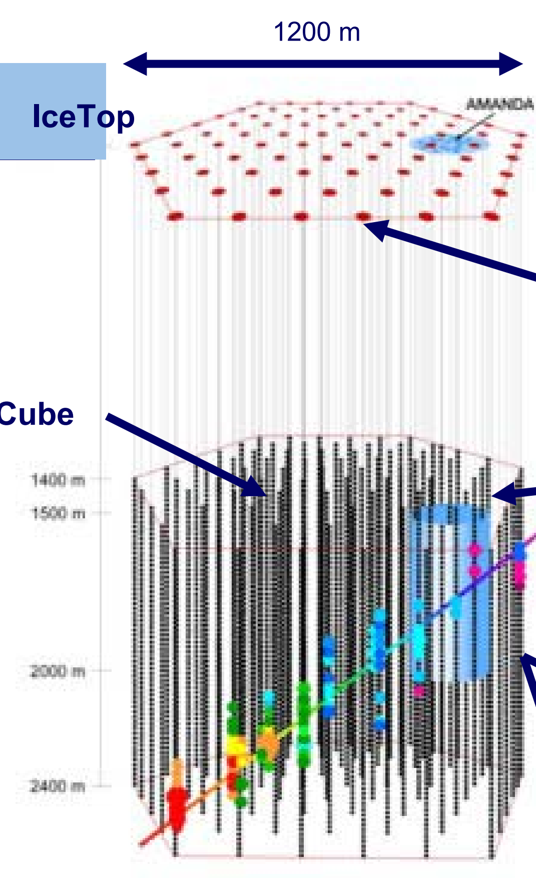
- Project overview and Status
- EHE Physics Example: Detection of GZK neutrinos


Bartol Research Inst, Univ of Delaware, USA
Pennsylvania State University, USA
University of Wisconsin-Madison, USA
University of Wisconsin-River Falls, USA
LBNL, Berkeley, USA
UC Berkeley, USA
UC Irvine, USA
Univ. of Alabama, USA
Clark-Atlanta University, USA
Univ. of Maryland, USA
IAS, Princeton, USA
University of Kansas, USA
Southern Univ. and A&M College, Baton Rouge
Chiba University, Japan
University of Canterbury, Christchurch, New Zealand
Universidad Simon Bolivar, Caracas,Venezuela
Université Libre de Bruxelles, Belgium
Vrije Universiteit Brussel, Belgium
Université de Mons-Hainaut, Belgium
Universität Mainz, Germany
DESY-Zeuthen, Germany
Universität Wuppertal, Germany
Uppsala Universitet, Sweden
Stockholm universitet, Sweden
Kalmar Universitet, Sweden
Imperial College, London, UK
University of Oxford, UK
Utrecht University, Utrecht, NL

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





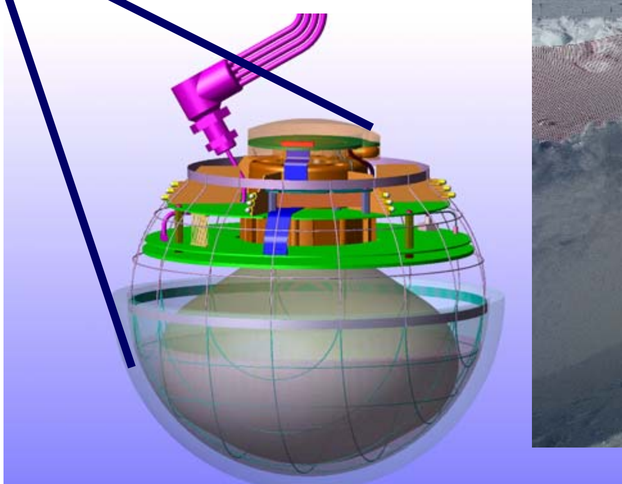
IceTop
160 tanks
frozen-water tanks
2 OMs / tank

First year deployment (Jan 2005
4 IceCube strings (240 OMs
8 IceTop Tanks (16 OMs

AMANDA

IceTop Tank deployed in 2004

IceCube
80 strings
60 OMs/string
17 m vertical spacing
25 m between strings

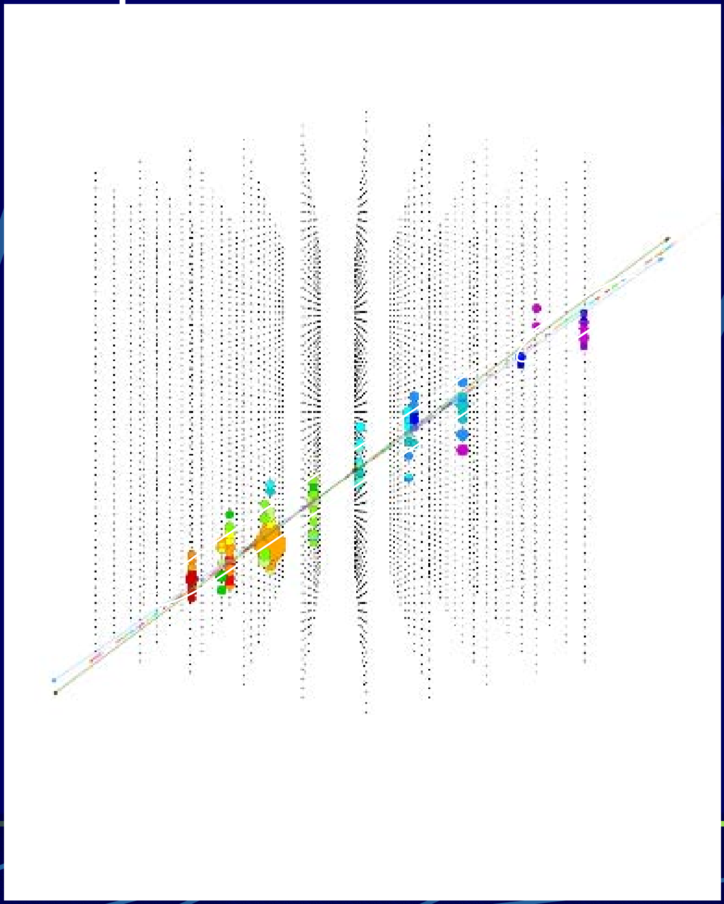


10" Hamamatsu R-7081

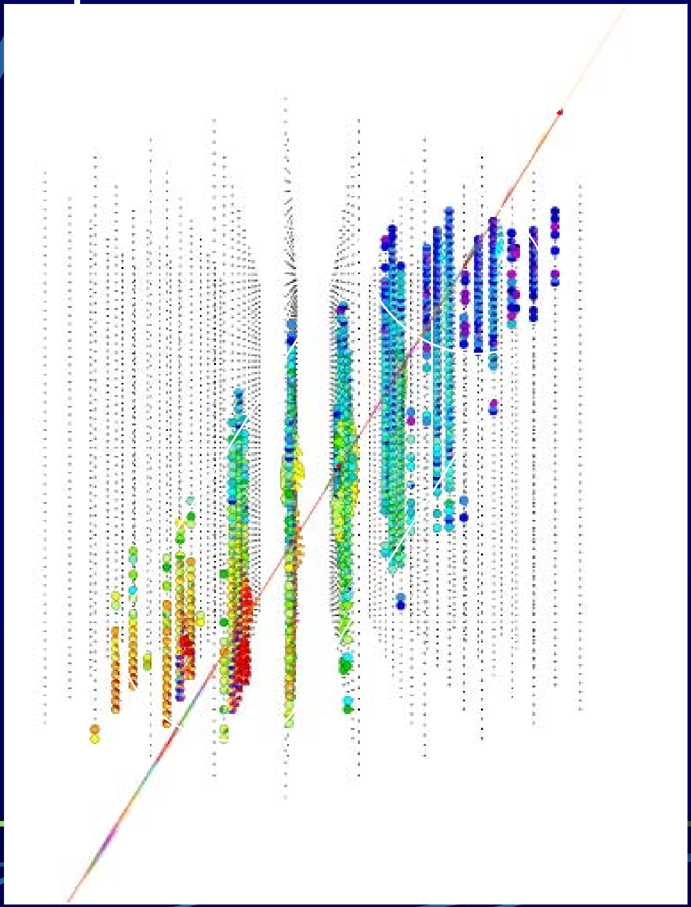
How EHE events look like

The typical light cylinder generated by a muon of 100 GeV is 20 m, 1PeV 400 m, 1EeV it is about 600 to 700 m.

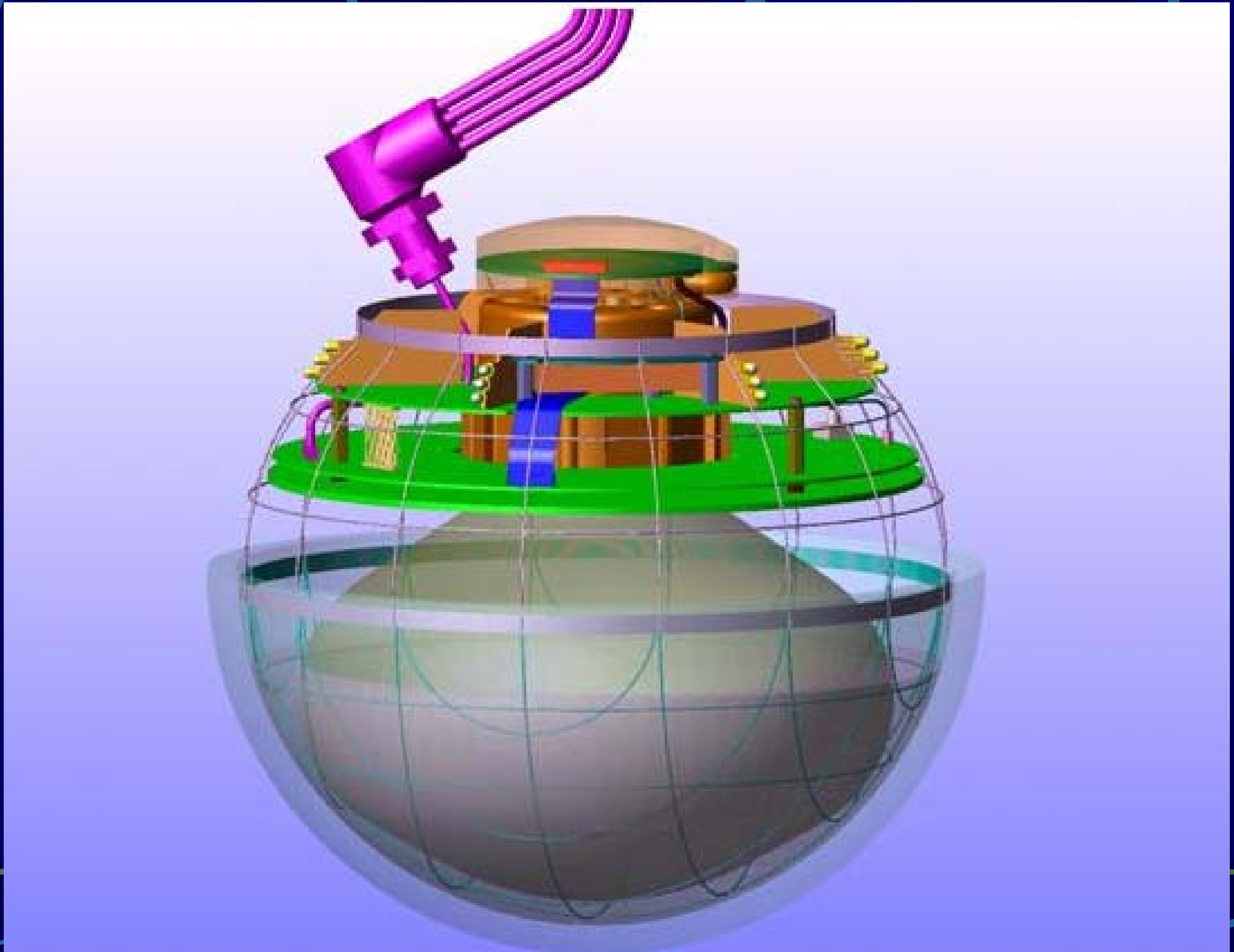
E_μ=10 TeV ≈ 90 hits



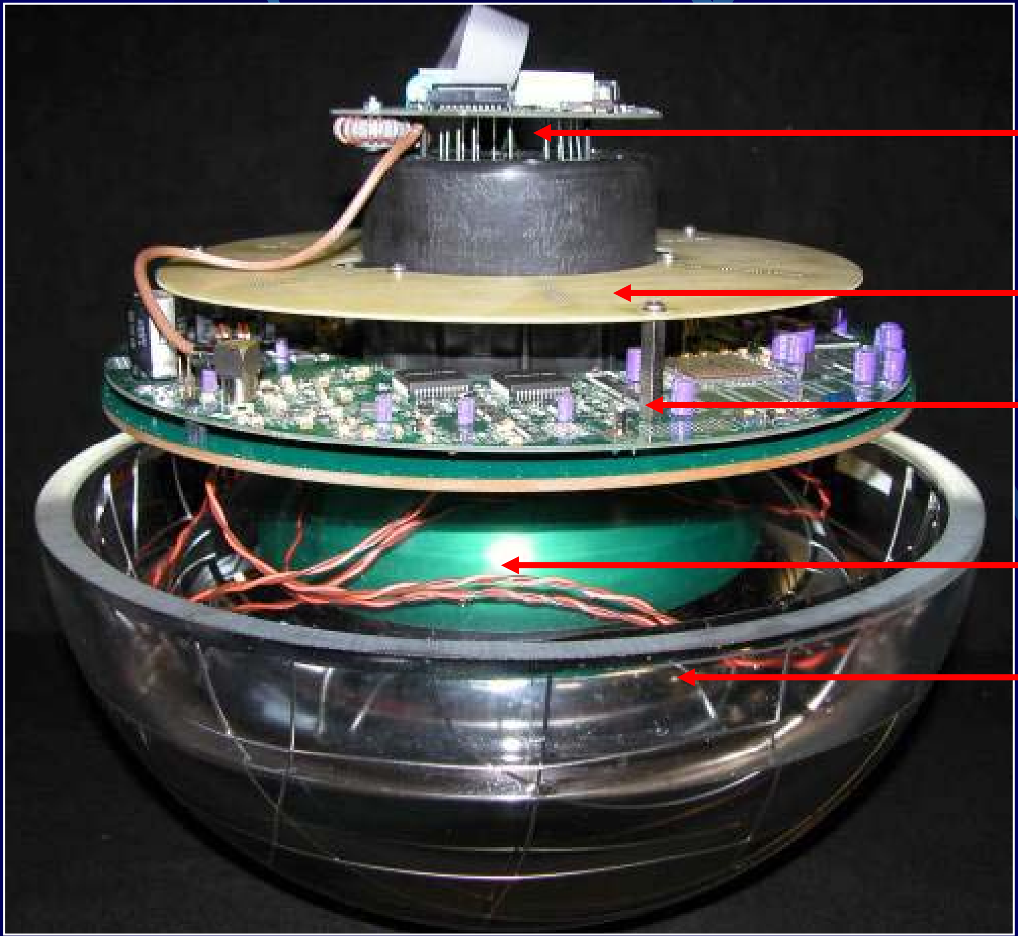
E_μ=6 PeV ≈ 1000 hits



DOM … a Key element in IceCube



Digital Optical Module (DOM)



HV Base

"Flasher Board"

Main Board (DOM-MB)

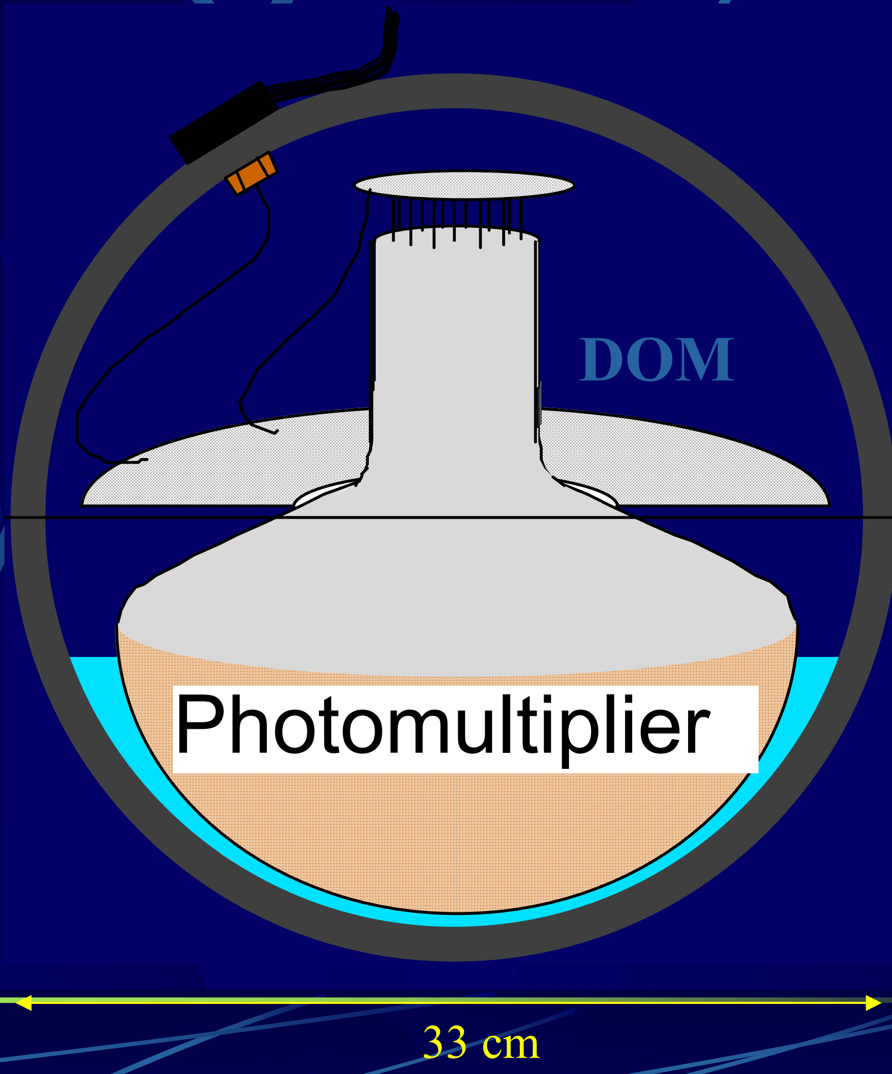
10" PMT

13" Glass (hemi)sphere

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

esign parameters:

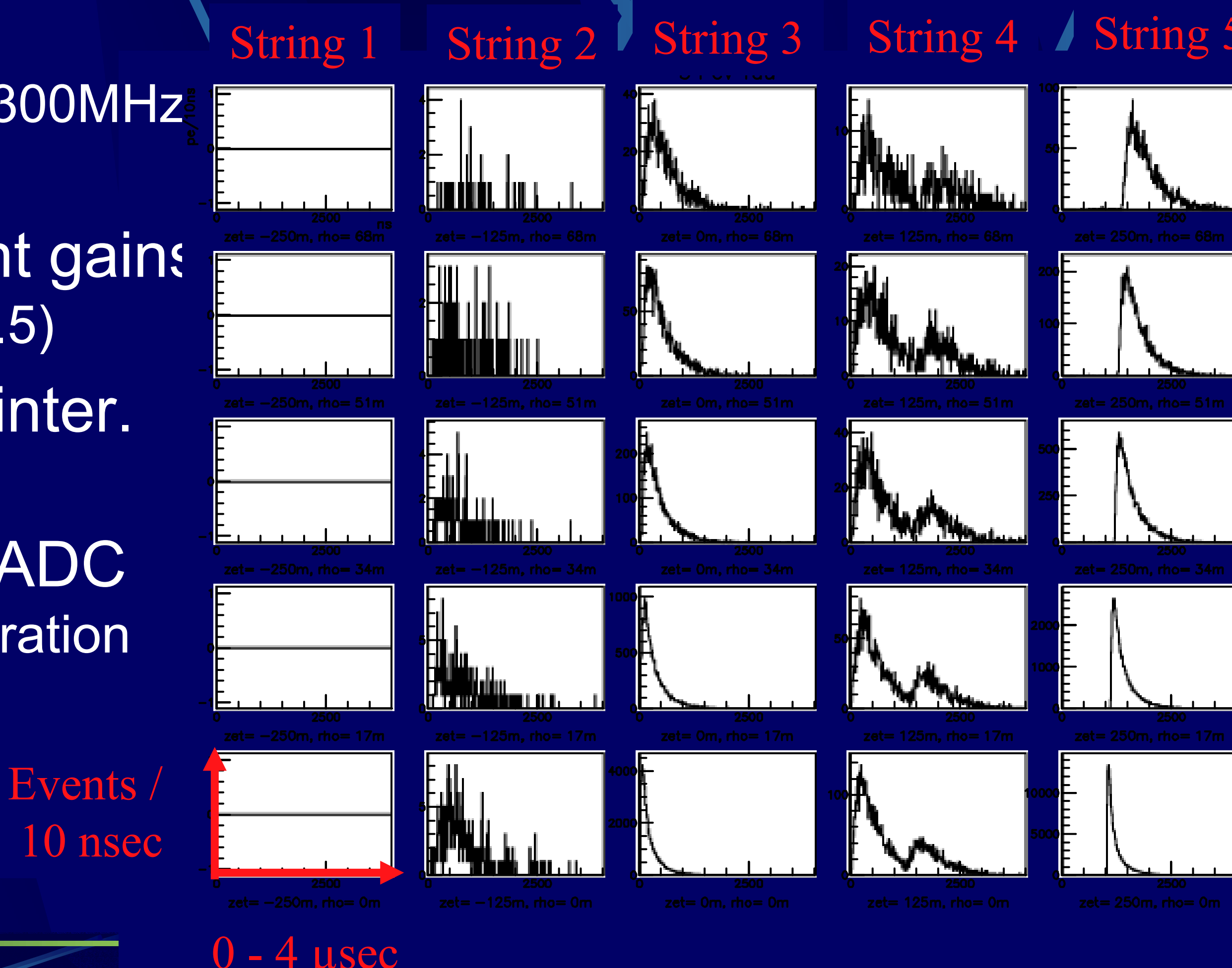
- Time resolution:≤ 5 nsec (system level)
- Dynamic range: 200 photoelectrons/15 nsec
- (Integrated dynamic range: > 2000 photoelectrons)
- (1.p.e. /10ns ~ 160μA 10^7G ~8mV 50 Ω) 4V saturation→500p.e.
- Digitization depth: 4 μsec.
- Noise rate in situ: ≤500 Hz
- Tube trig.rate by muons 20Hz



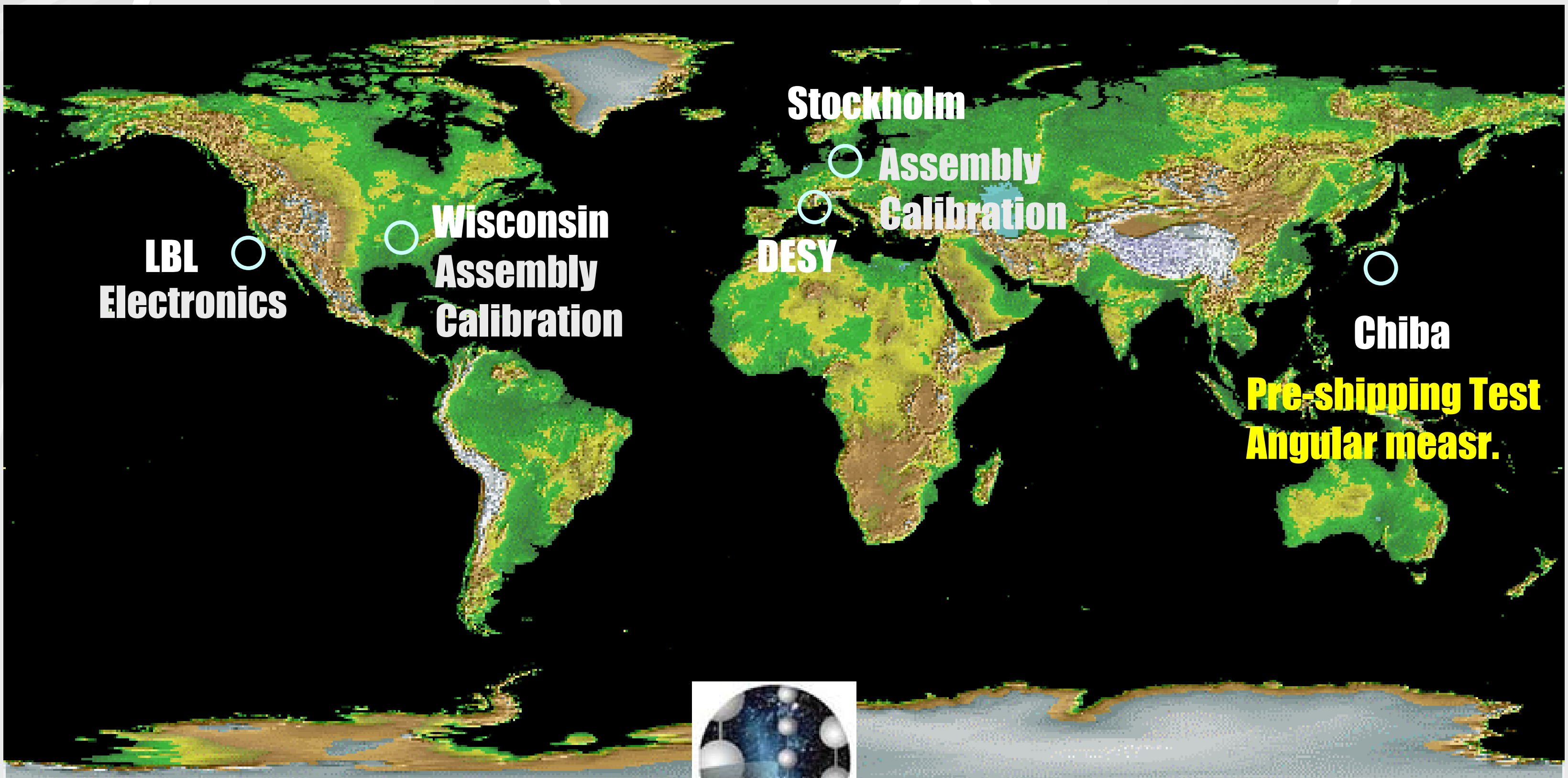
Capture Waveform information (MC)

$\nu\tau$
E=10 PeV

- ATWD 300MHz 14 bits.
- 3 different gains (x15 x3 x0.5)
- Capture inter. 426nsec
- 10 bits FADC for long duration pulse.



World-wide DOM collaboration



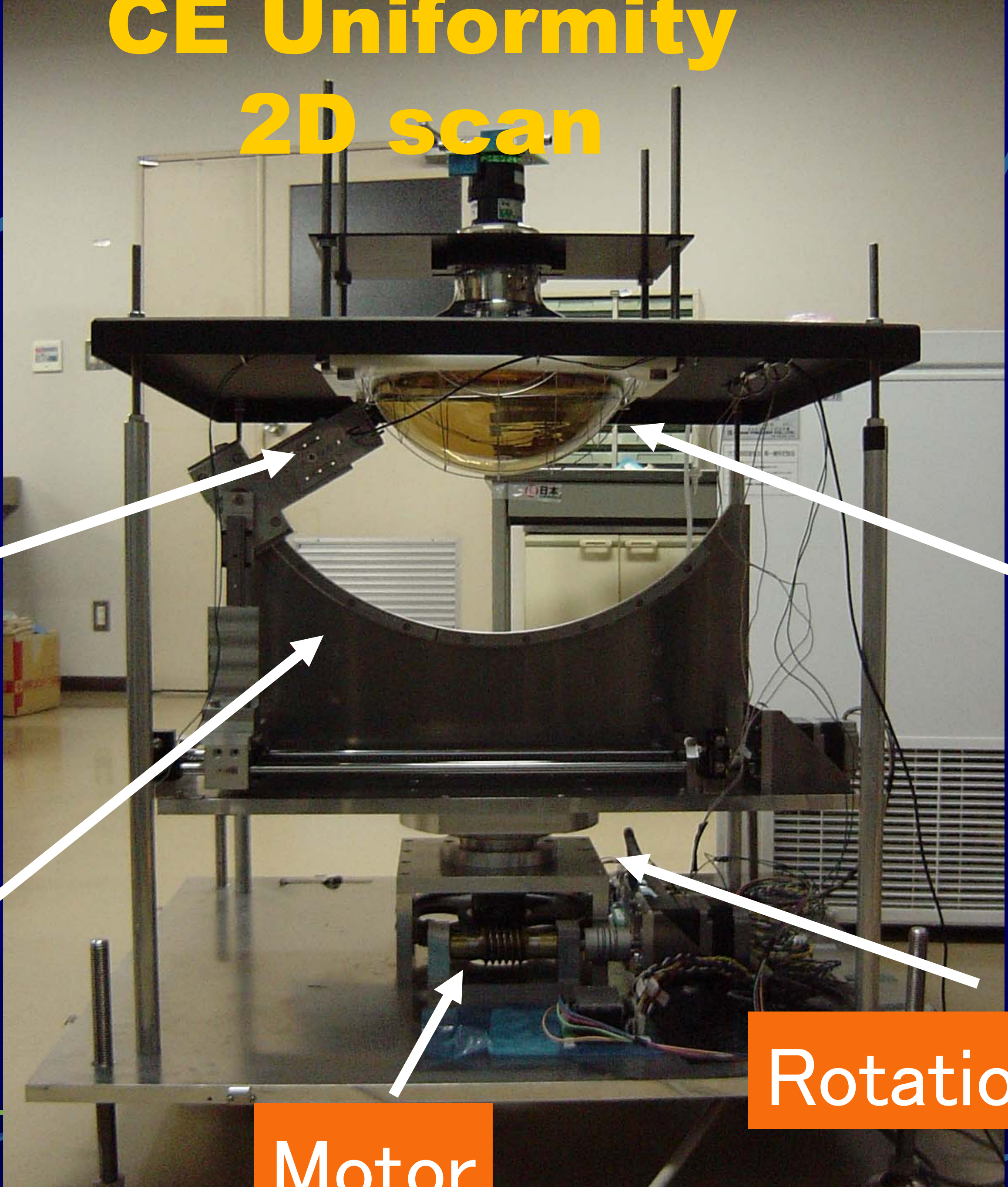
IceCube

Photomultiplier:
Hamamatsu R7081-02
(10", 10-stage, 1E+08 gain)

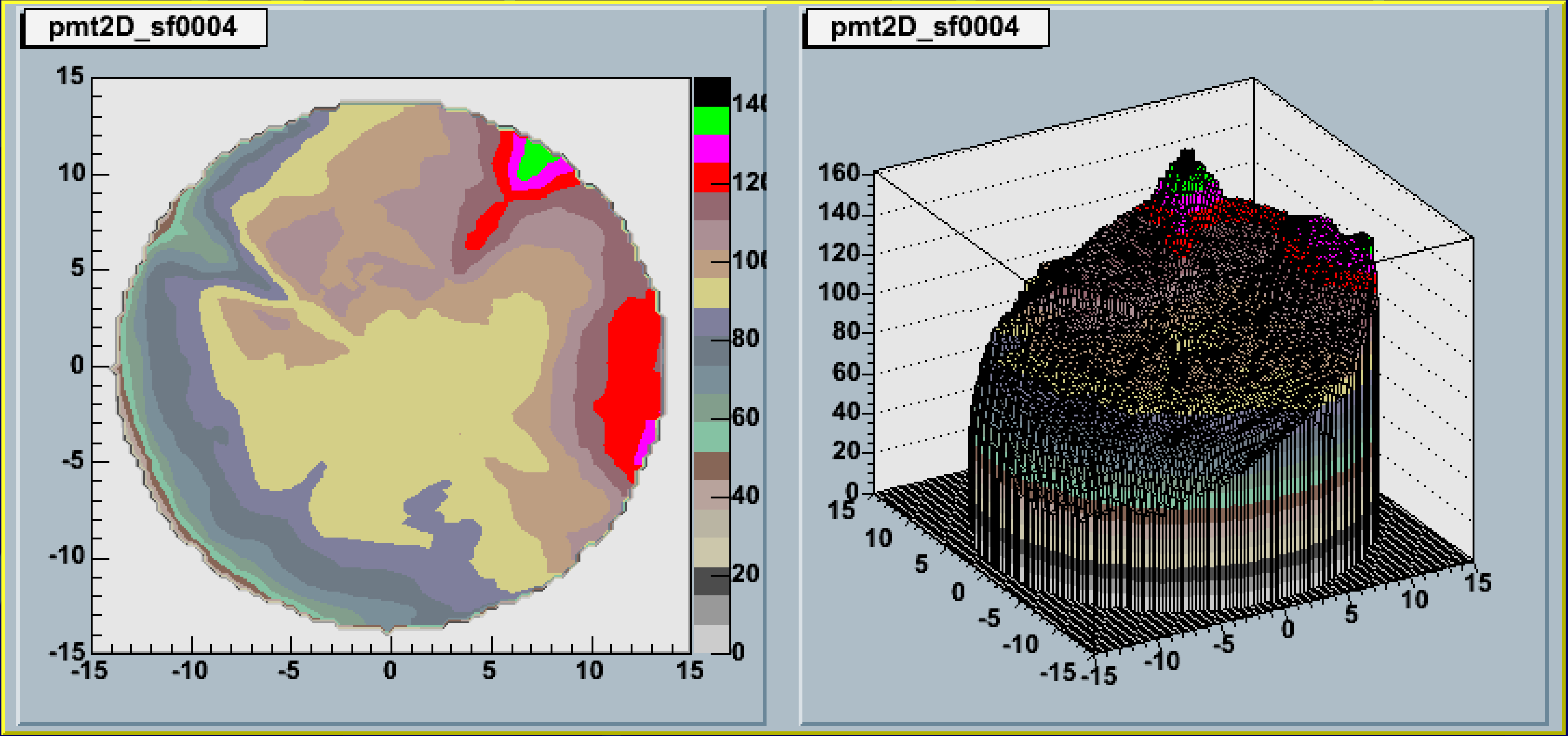
Selection criteria (@ -40 ° C)
- Noise < 300 Hz (SN, bandwidth)
- Gain > 5E7 at 2kV (nom. 1E7 + margin)
- P/V > 2.0 (Charge res.; *in-situ* gain calibration)

Notes:
- Only Hamamatsu PMT meets excellent low noise rates!
- Tested three flavors of R7081.

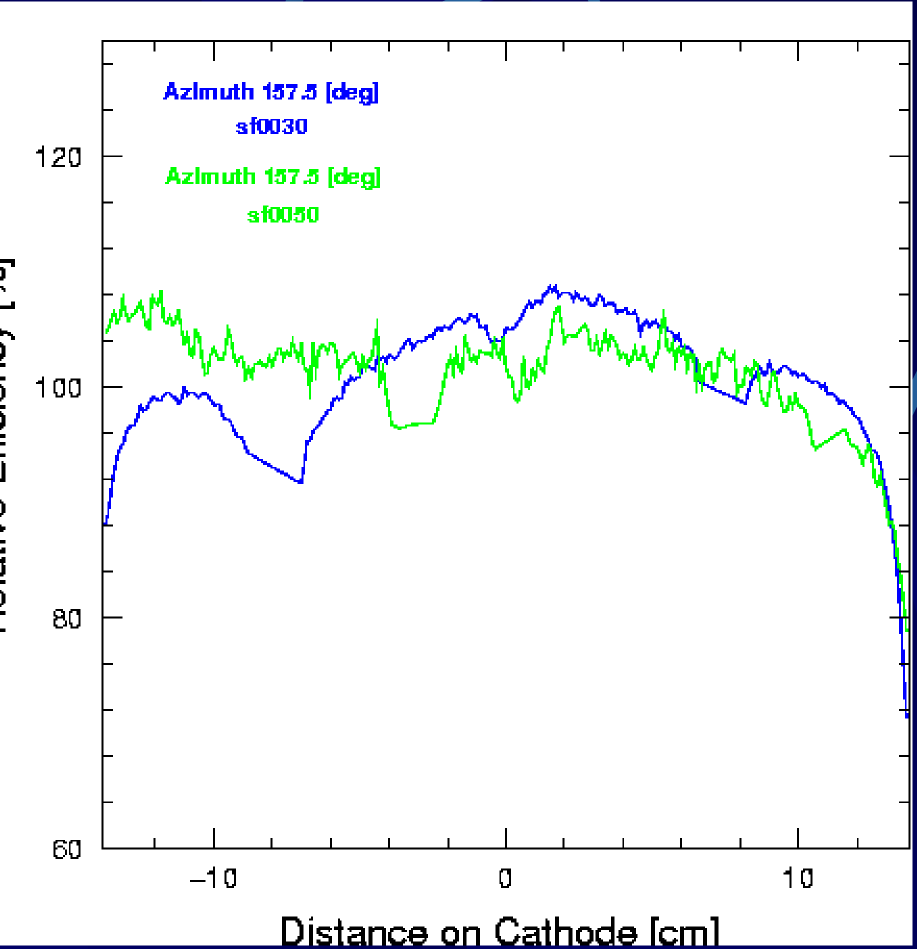
CE Uniformity
2D scan

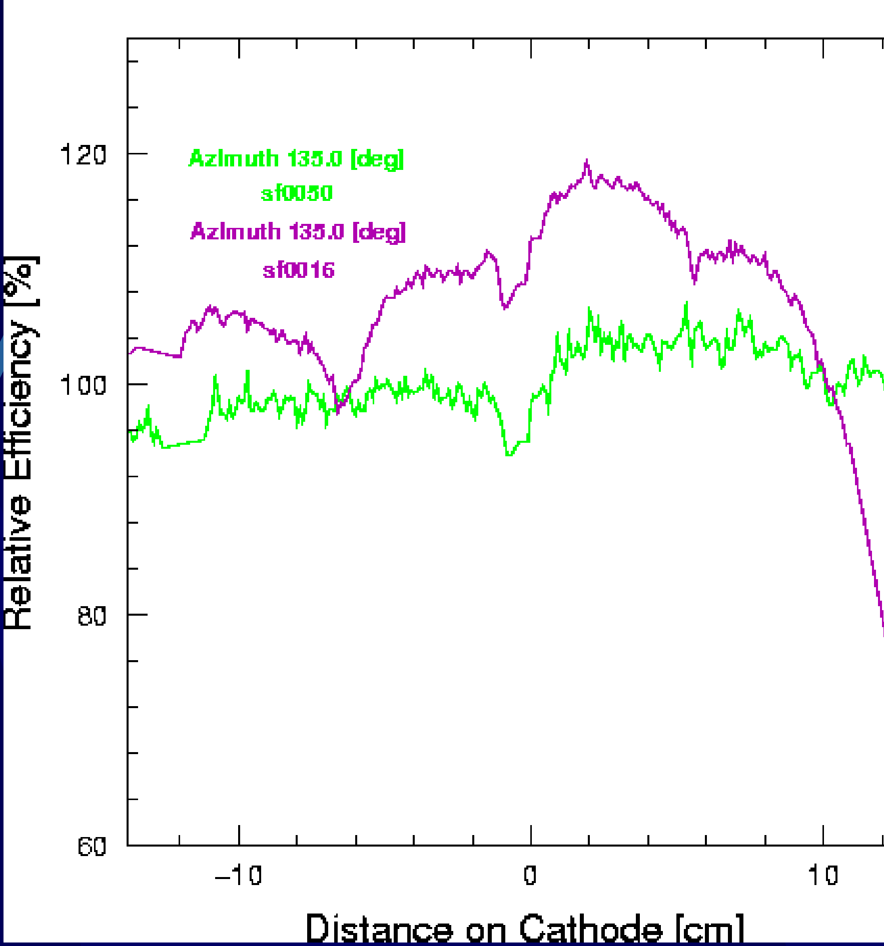


The Collection Efficiency: Lego plot



Example: The relative Collection Efficiency





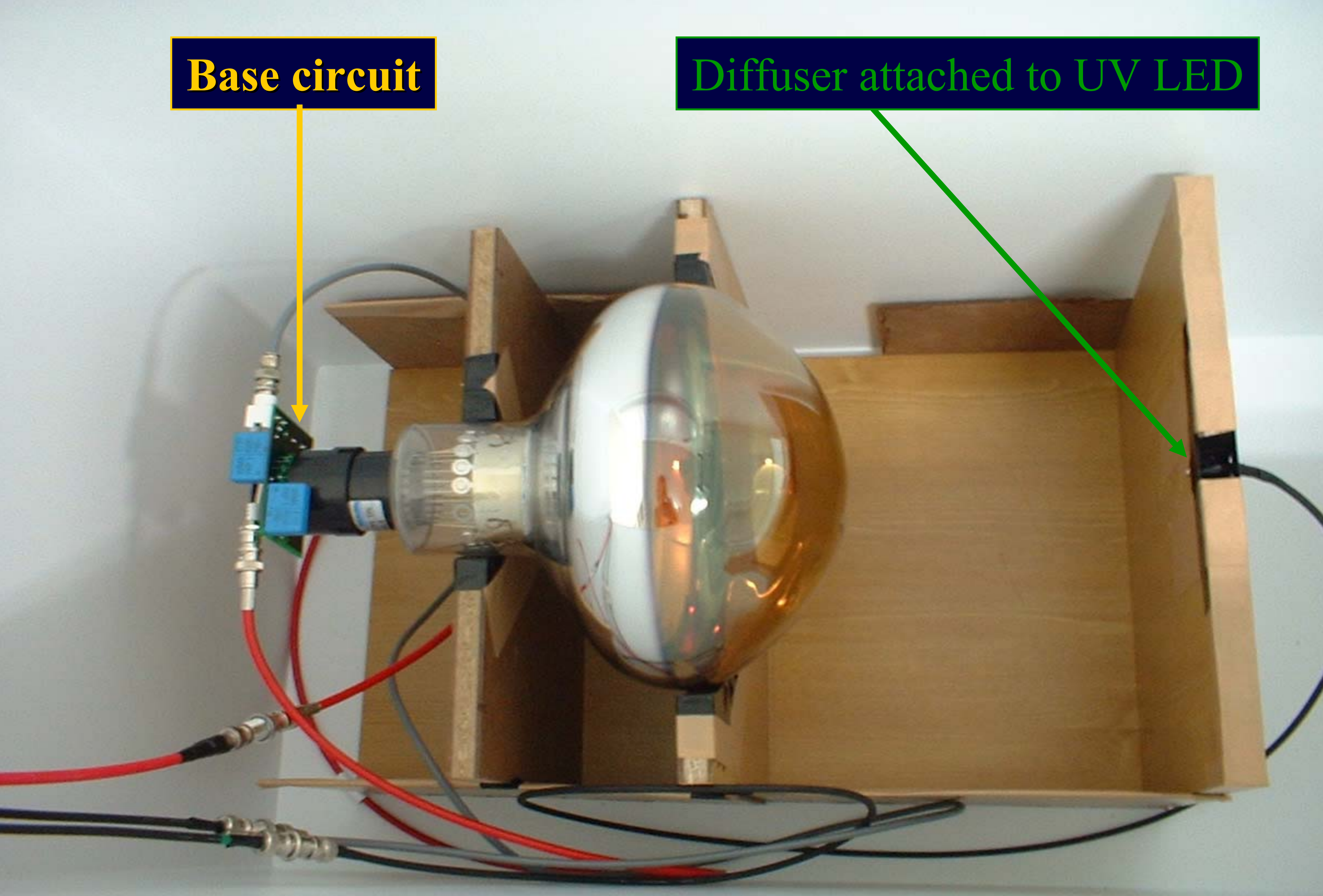
SF0030 vs SF0050 SF0016 vs SF0050

Charge Resolution/Waveform

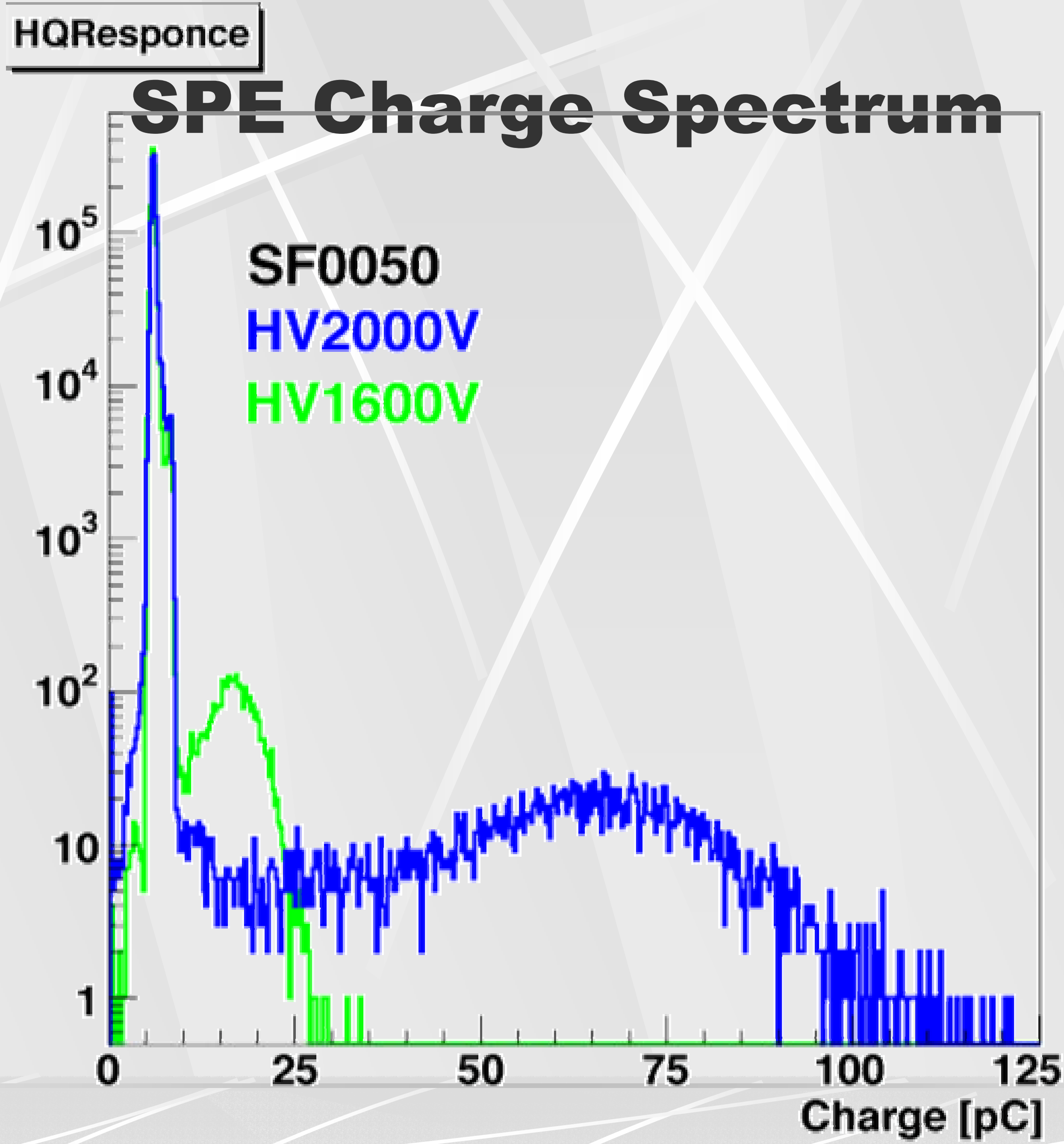
In the Freezer

Temp –**32**degree

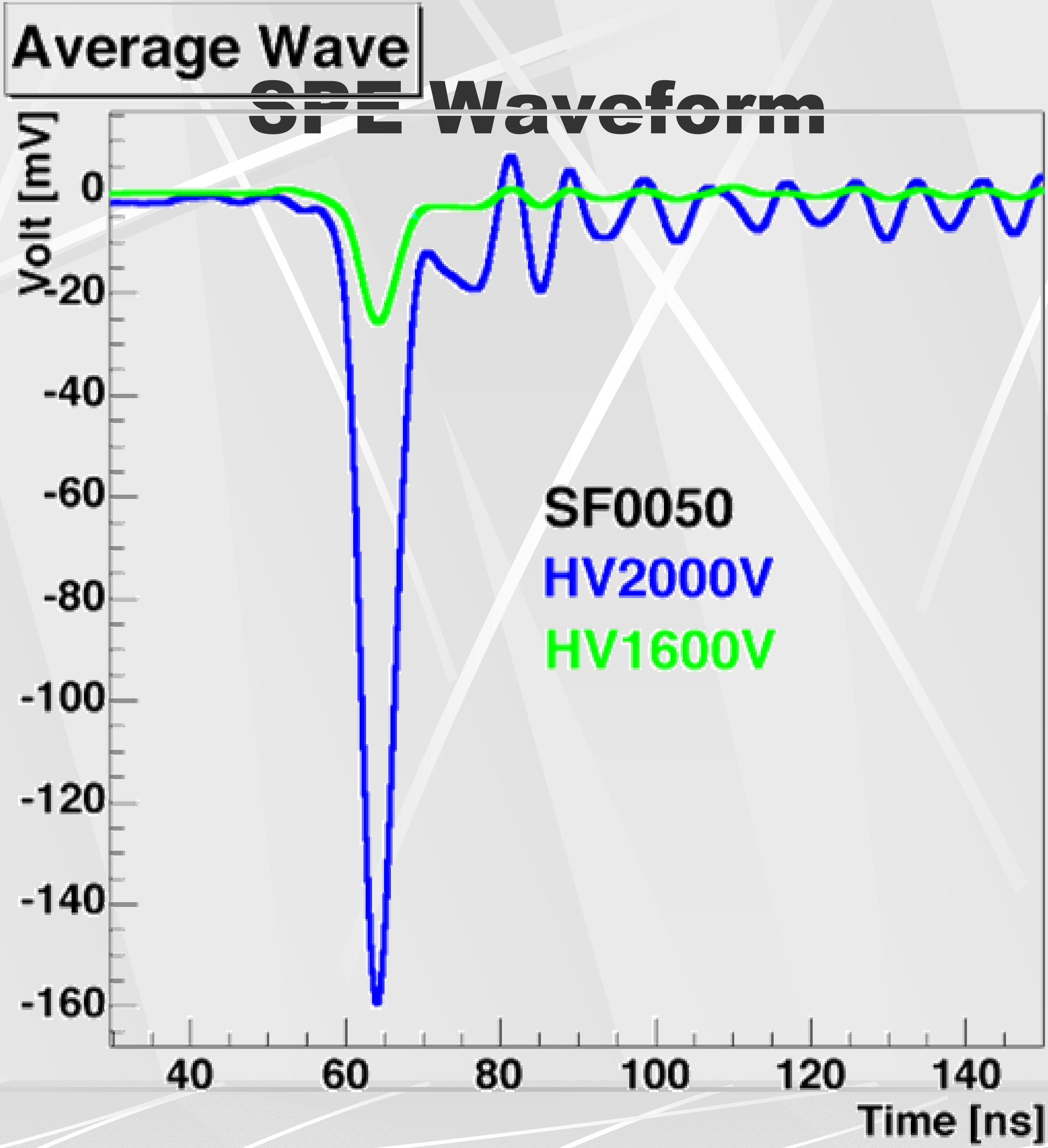
PMT Setting in the Freezer



SPE Charge Spectrum

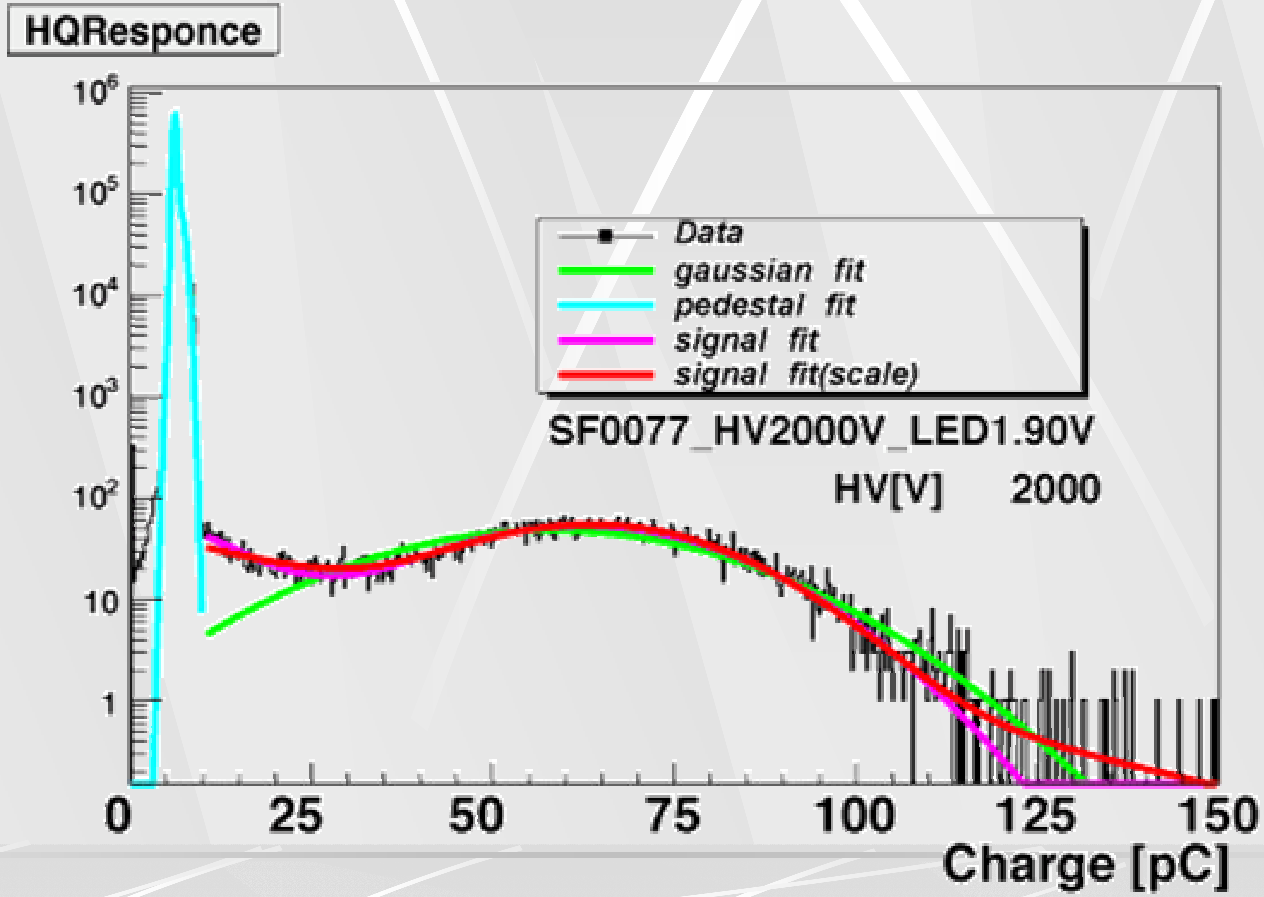


SPE Waveform

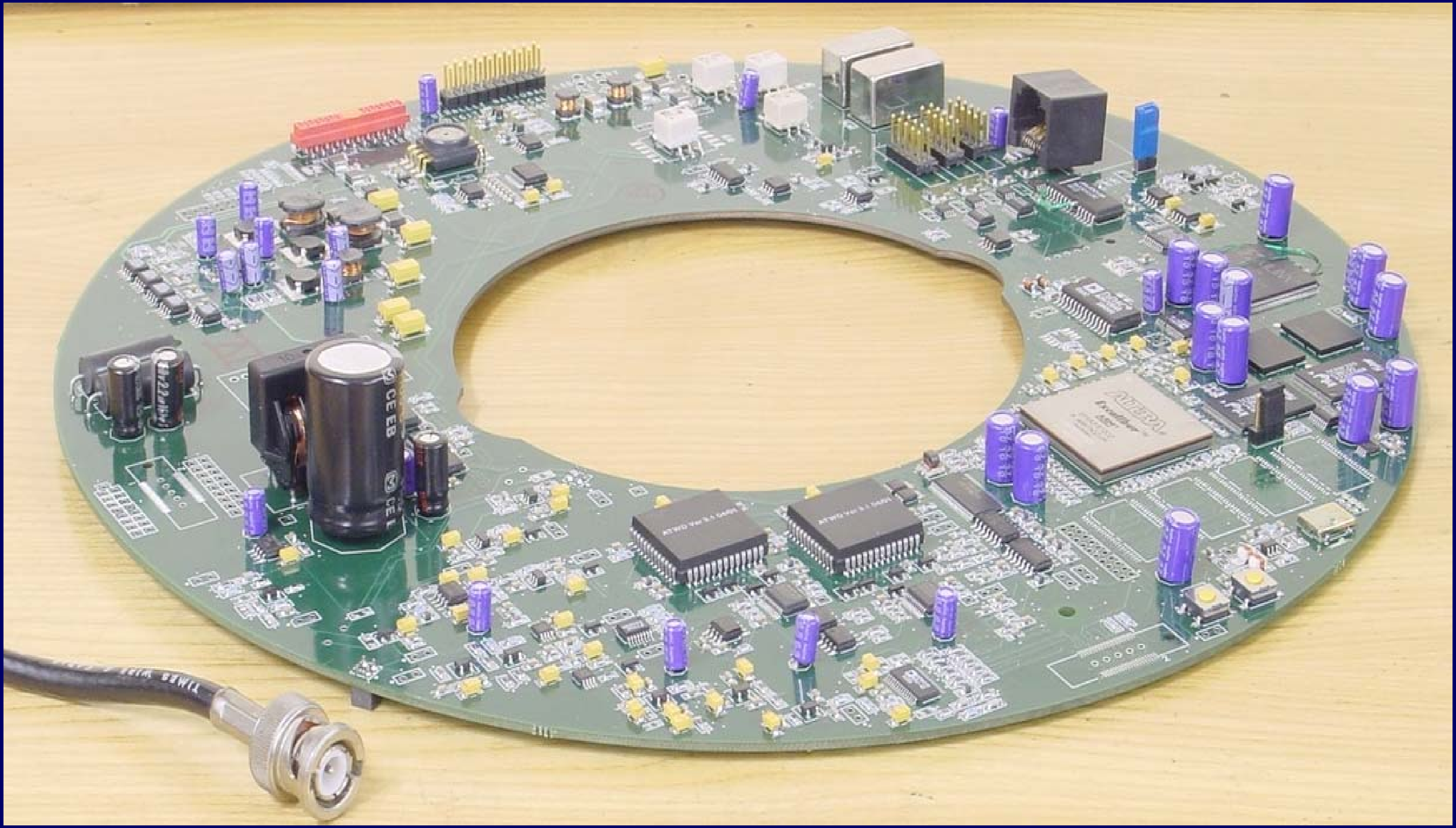


SPE Charge Response

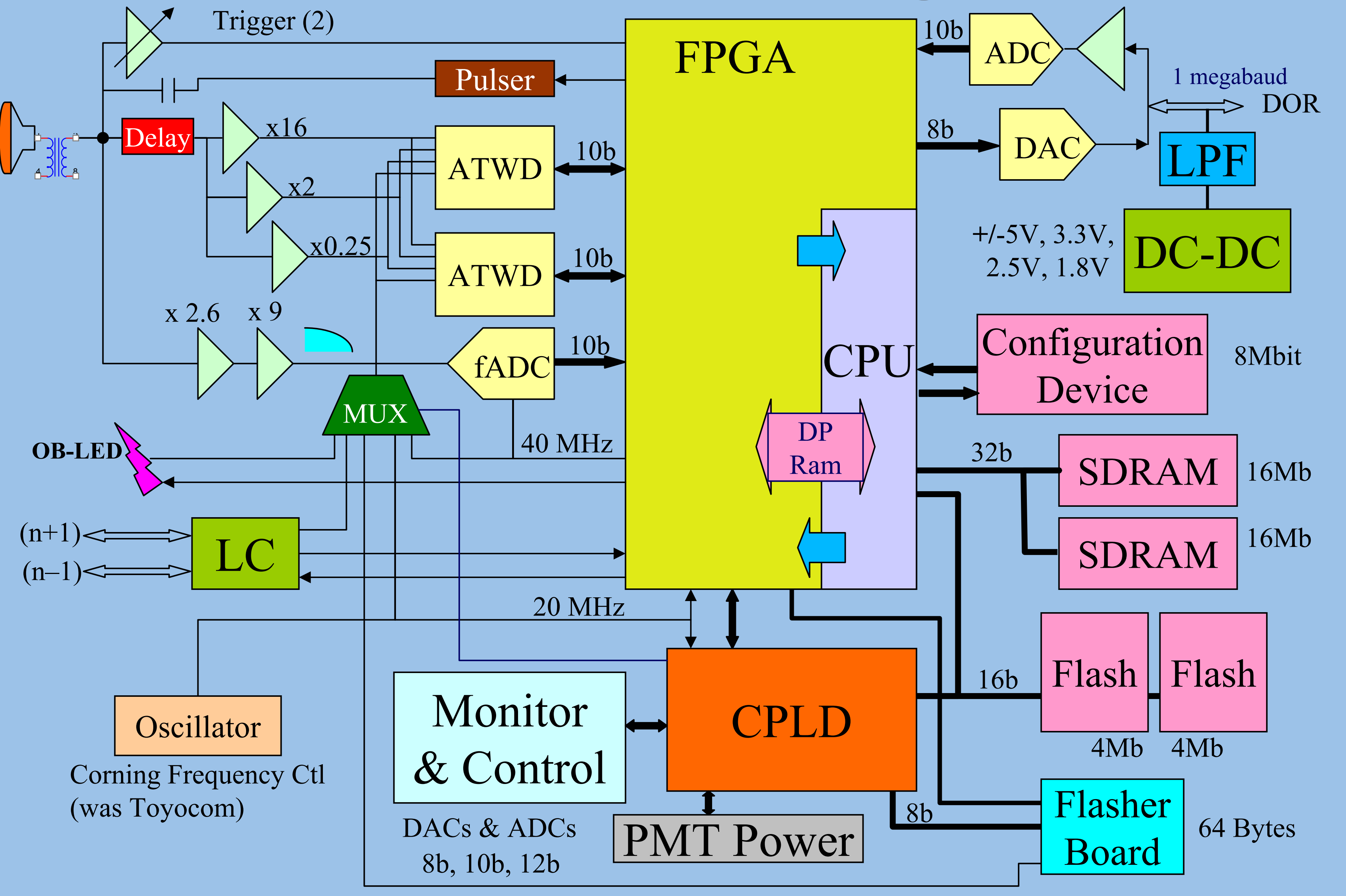
- $S_{spe}(q) \sim (1-P_e)\exp[-q/q_\tau] + P_e N_G(q-q_0/q_\sigma)$



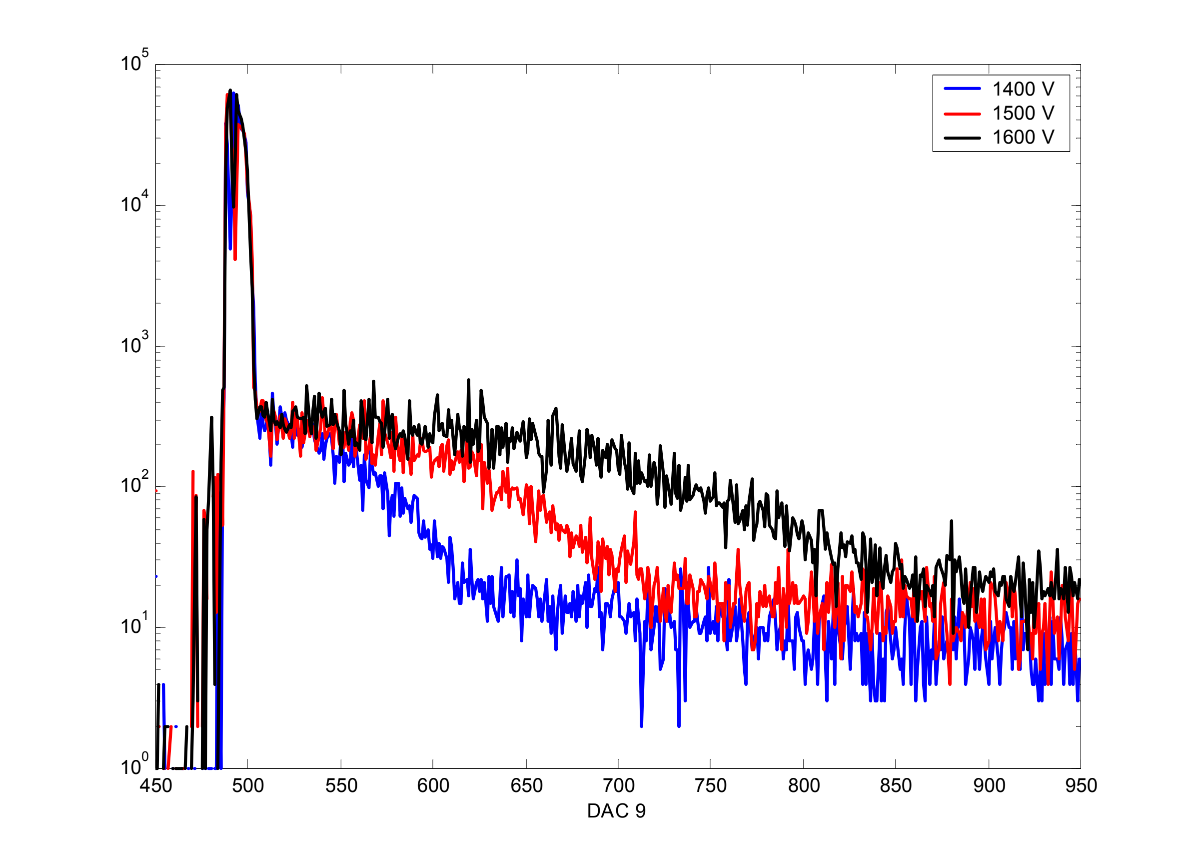
Digital Optical Module (DOM) Main Board Test Card



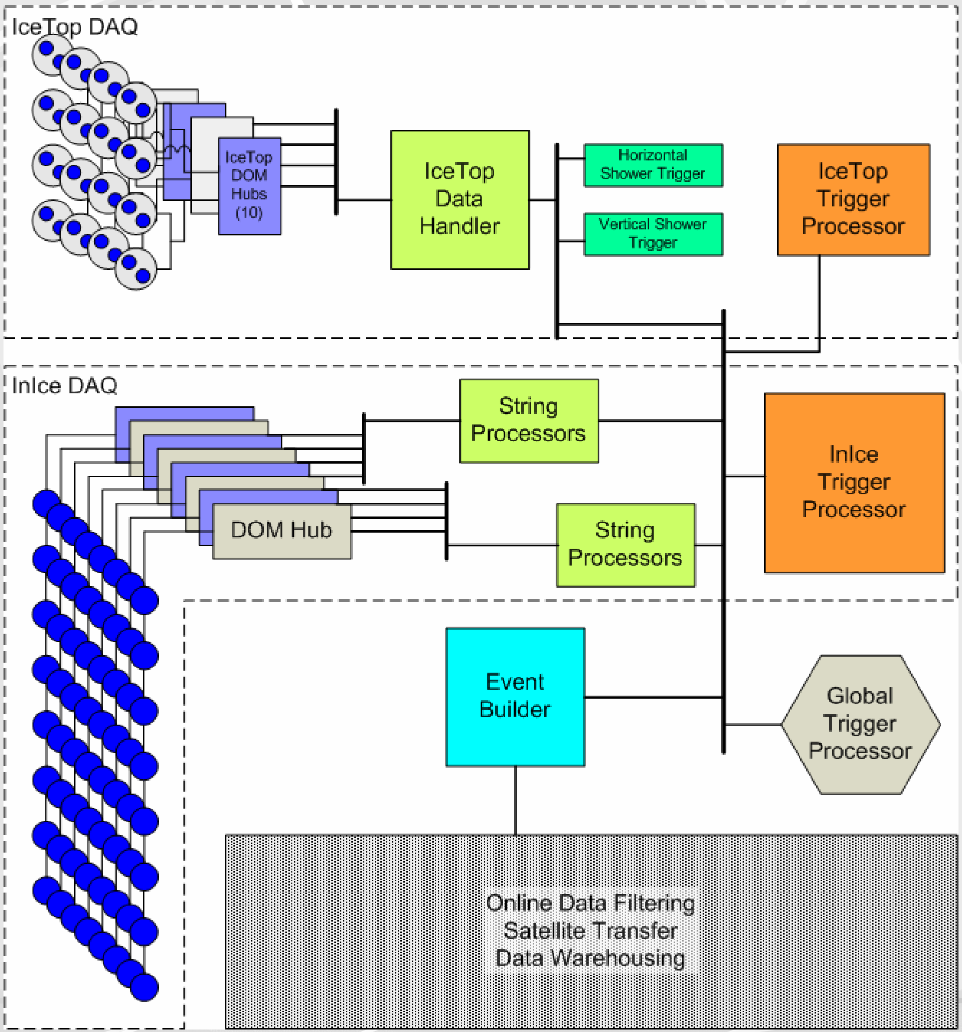
DOM MB Block diagram



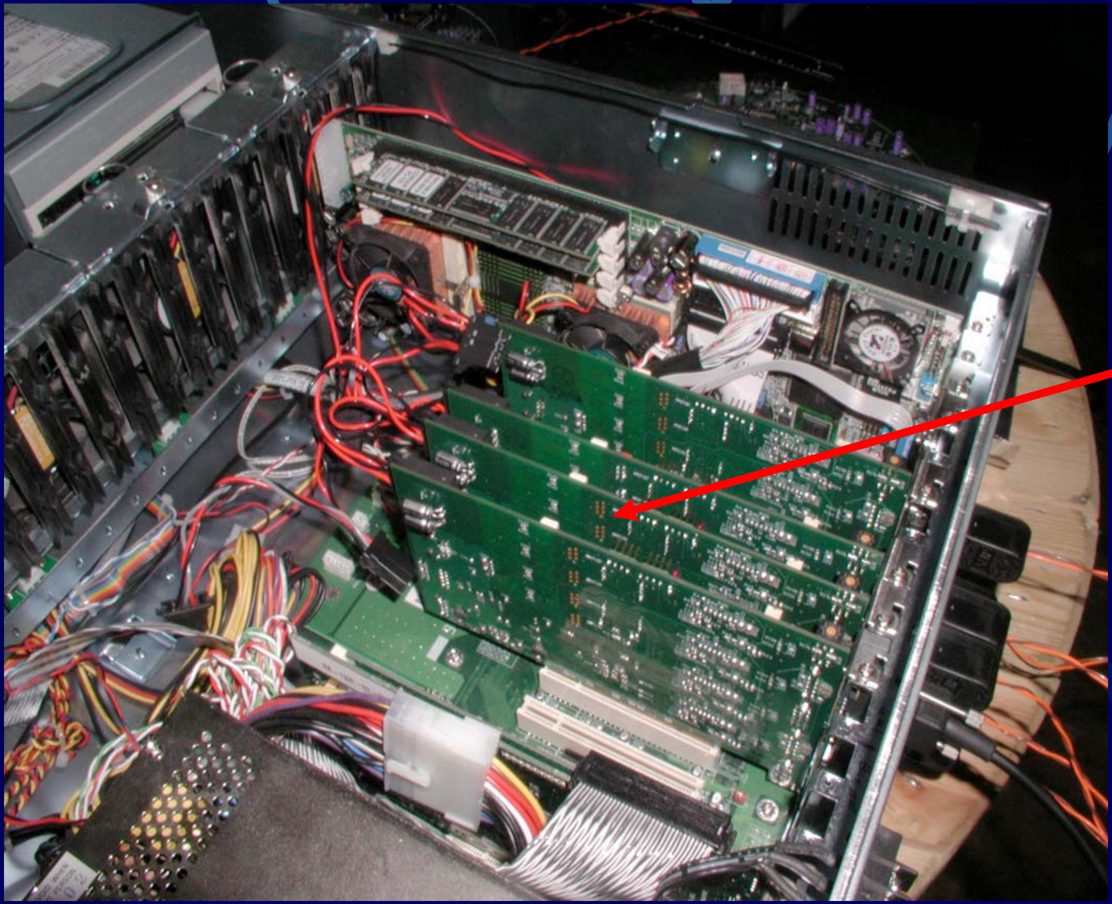
SPE Discriminator Scan – PMT Pulses Input (71DB)



DAQ Blocks…


IceTop DAQ
IceTop DOM Hubs (10)
IceTop Data Handler
Horizontal Shower Trigger
Vertical Shower Trigger
IceTop Trigger Processor
InIce DAQ
String Processors
String Processors
DOM Hub
InIce Trigger Processor
Event Builder
Global Trigger Processor
Online Data Filtering
Satellite Transfer
Data Warehousing

DOM Hub



DOM-Hub

DOR Cards
(8/DOM-Hub

Each DOR
card serves 8
DOMs

Local Coincidence (LC)

- Basic idea: reject PMT noise, reduce data
  - Philosophical debates continue!
- DOMs are connected to both neighbors
- "Coherence length" is programmable
- Three operational modes (in-ice):

None ⇒ all hits, all waveforms transmitted

Soft ⇒ all hits, waveforms only for non-isolated

Hard ⇒ non-isolated hits only

- Baseline mode is **soft** local coincidence

Expected Data Rates

- PMT noise rate of 1 kHz is expected
  - "Scintillation" of glass introduces correlations!
- Two DOMs/twisted pair ($, kg, flights,...)
- Rates/pair (bits/s) for coincidence mode
  (with zero suppression and compression)
  - **None**: 18 kbytes/s x 2 x 10 = ~400 kbits/s
  - **Soft**: 6-8 kbytes x 2 x 10 = ~160 kbits/s
  - **Hard**: <1 kbyte/s x 2 x 10 = ~20 kbits/s
- Demonstrated in the lab: 1 Mbit/s

Trigger Issues

- Low energy muons (Wimps,…) present the <u>most</u> <u>challenging</u> IceCube trigger condition:
  - Low multiplicity, relatively short, dim tracks
  - Array noise rate: ~ 25 counts/5 μs $\Rightarrow$ Can't use a simple multiplicity trigger *a la* Amanda
- Proposal: Require <u>at least one LC</u> to be present for <u>any</u> ***event trigger***. $\equiv$ 1 LC trigger

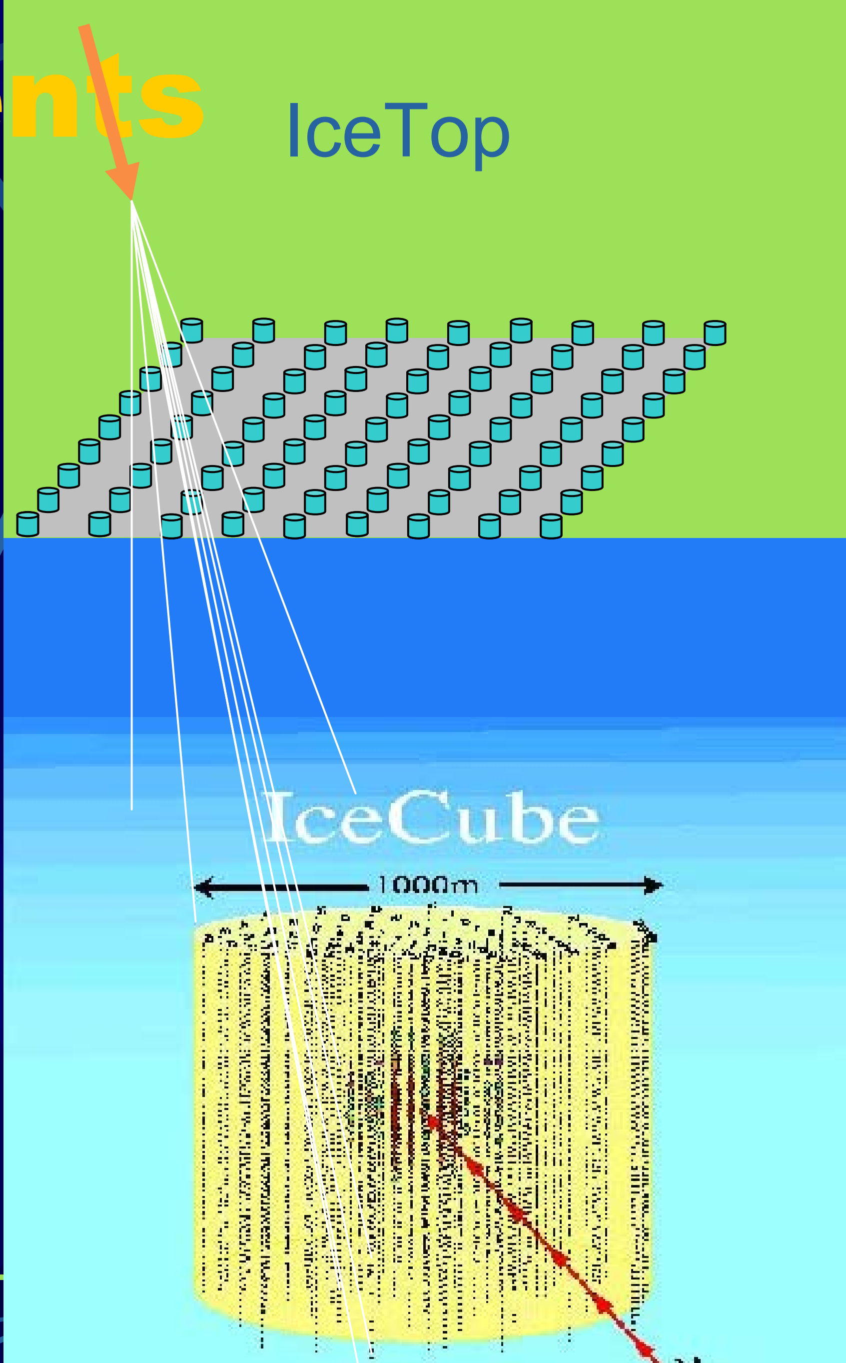
"1 LC Trigger"

- Perceived advantages:
  - Nearly the loosest trigger condition possible
    - "Any reconstructable event should have 1 LC."
  - Reduces raw data flow to ***global*** trigger: ~ 250
    - Array hit rate: 5000 x 1 kHz = 5000 kHz
    - Array 1LC trigger rate: = ~20 kHz
    - String processor looks for hits with LC tag
  - Global trigger needs to filter out "noise 1 LC":
    - Topology calculation reduces rate to < 1 kHz

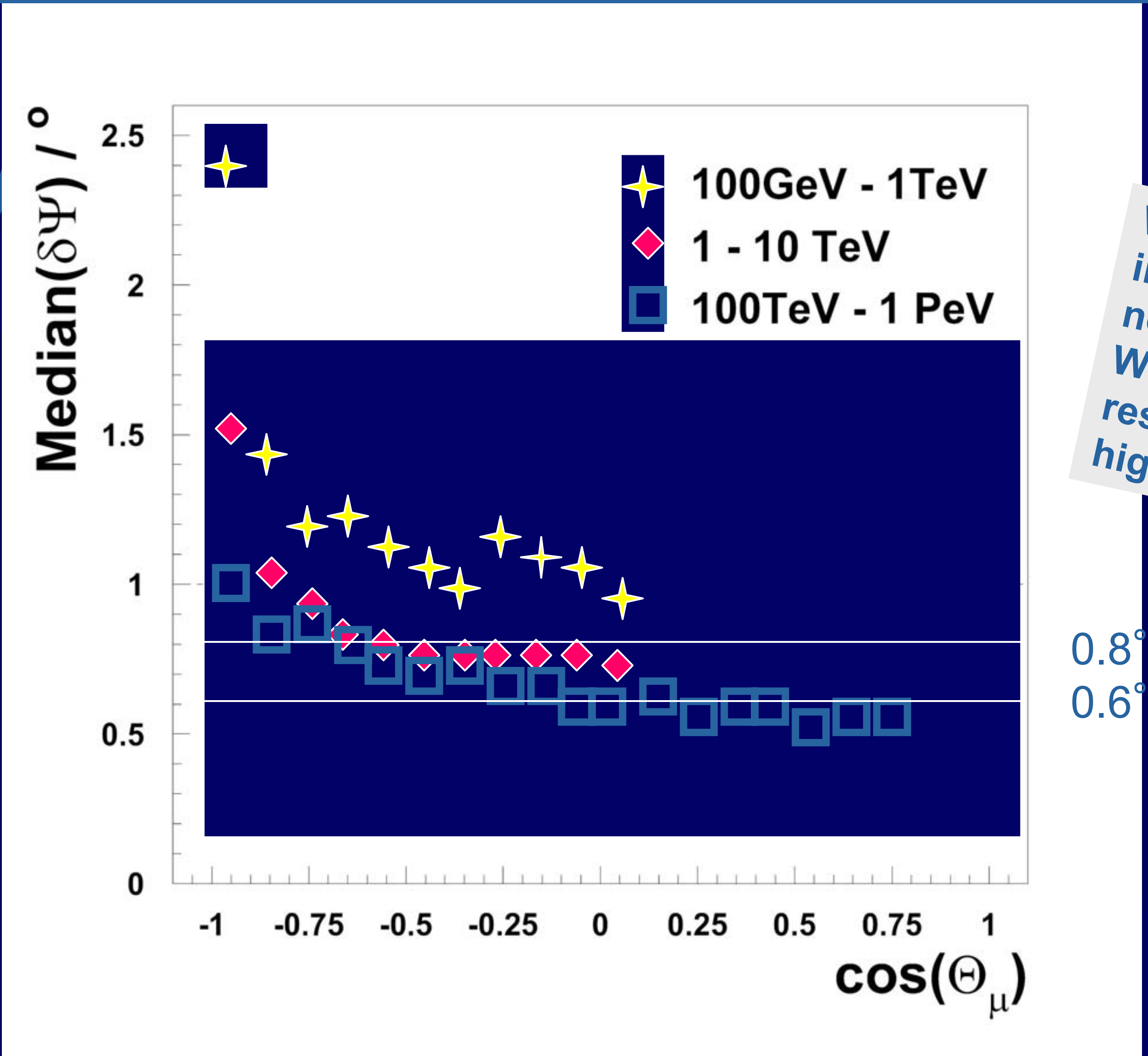
The big reel for the hotwater drill

Coincident events

- Energy range:
  - ~3 x 10^{14} -- 10^{18} eV
- Two functions
  - veto and calibration
  - cosmic-ray physics
  - few to thousands of muons per event
- Measure:
  - Shower size at surface
  - High energy muon component in ice
- Large solid angle
  - One IceTop station per hole
  - ~ 0.5 sr for C-R physics with “contained” trajectories
  - Larger aperture as veto



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 for

atmospheric ν

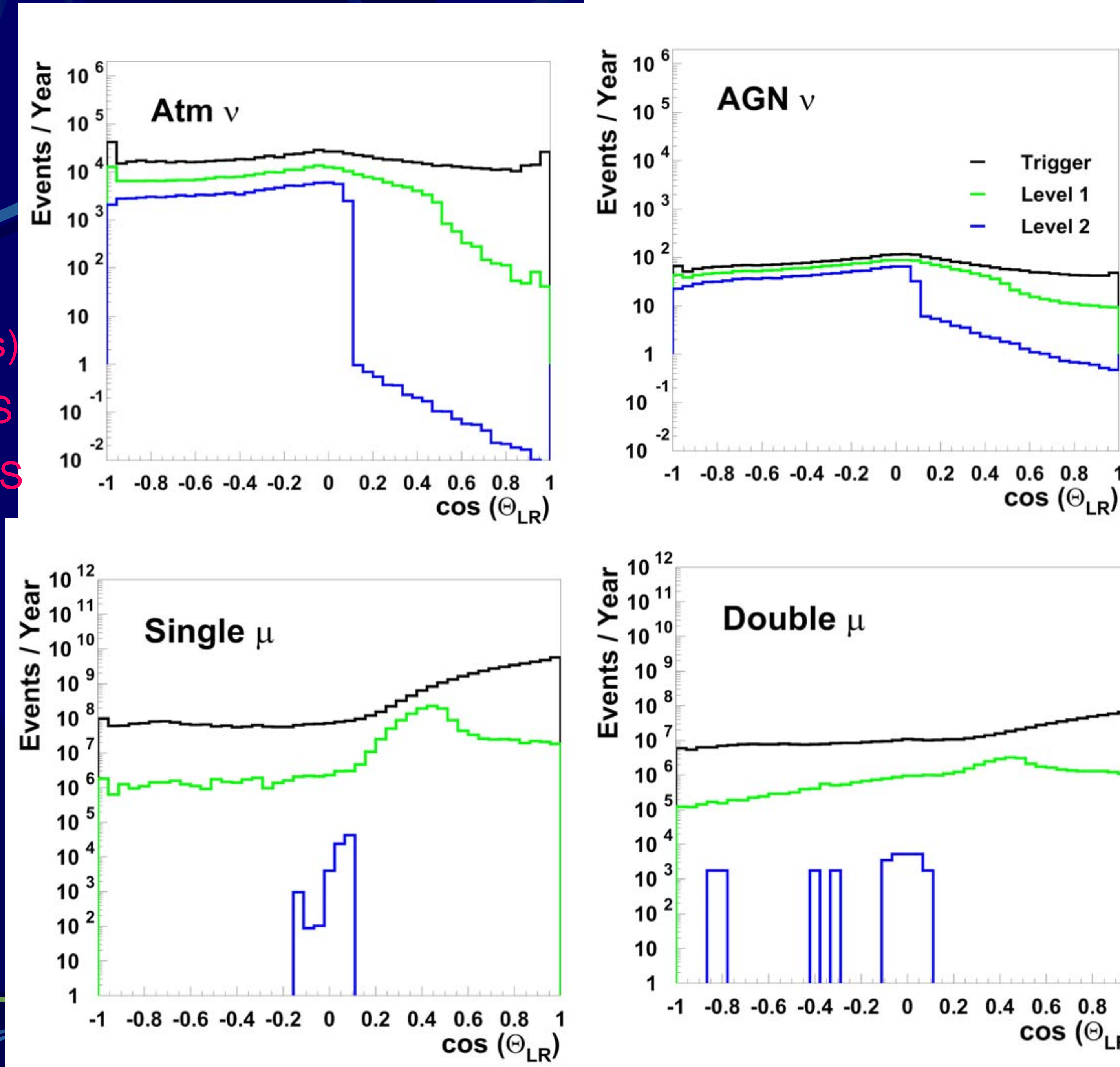
AGN ν (E^{-2} flux 10 times below MPR bound and present exp. limits)

atm. μ from 1 EAS

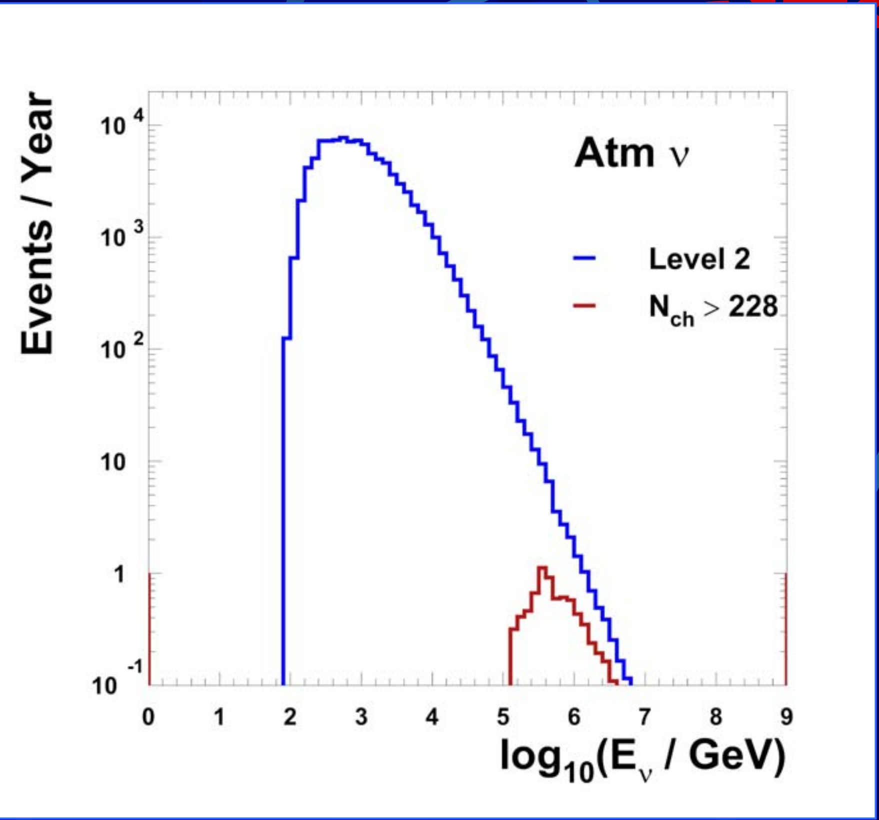
atm. μ from 2 EAS

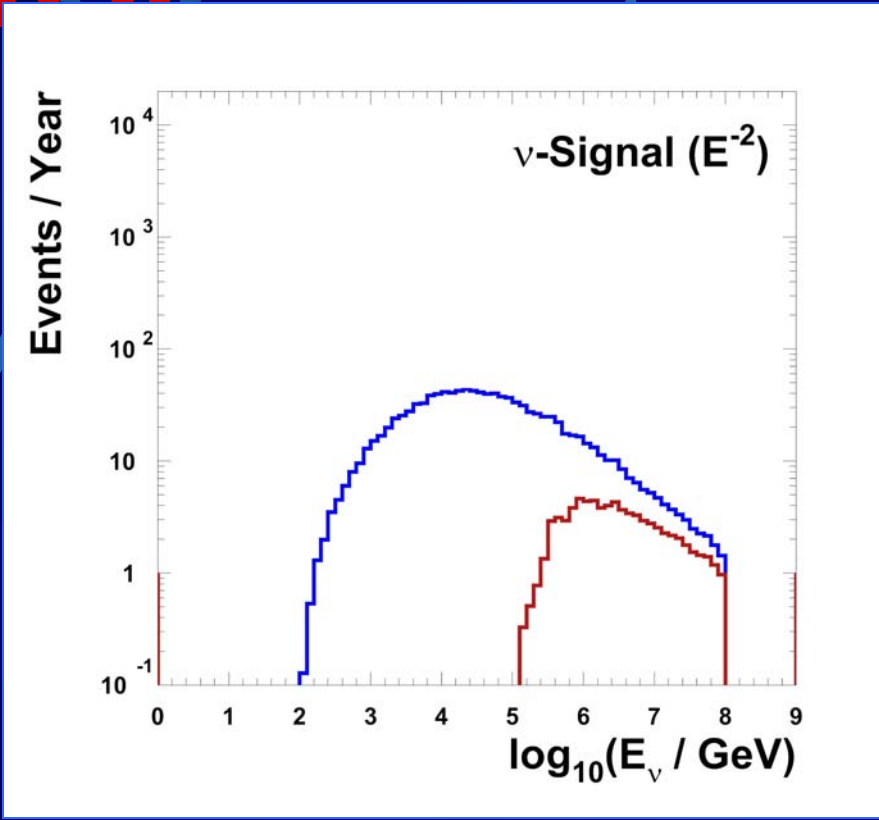
after trigger

after cuts to reject atm.μ background (Level 2)



Energy Spectrum Diffuse Search

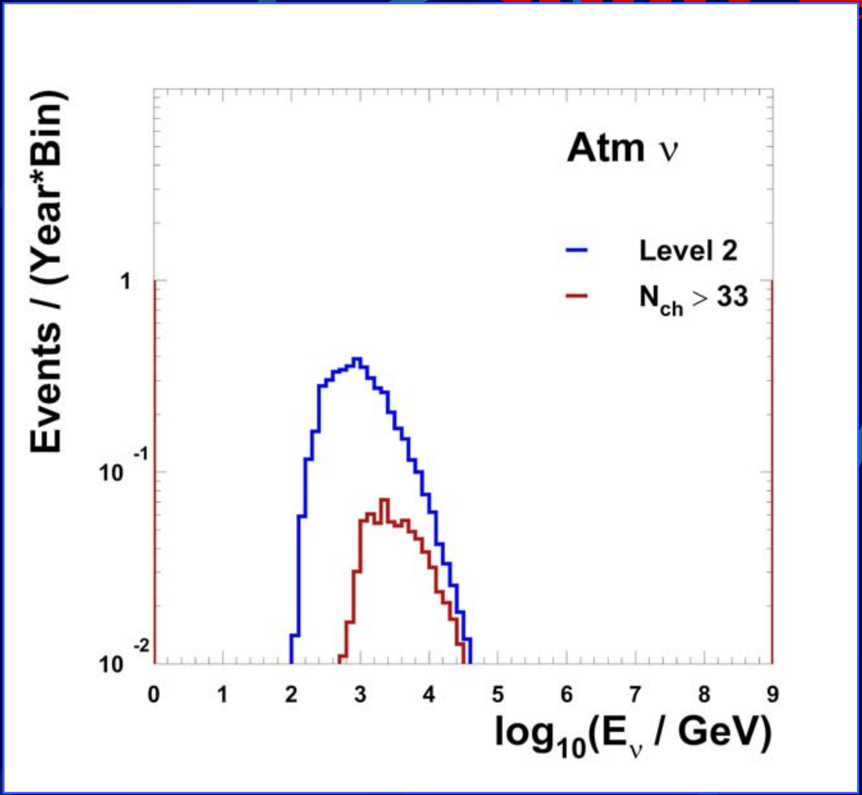


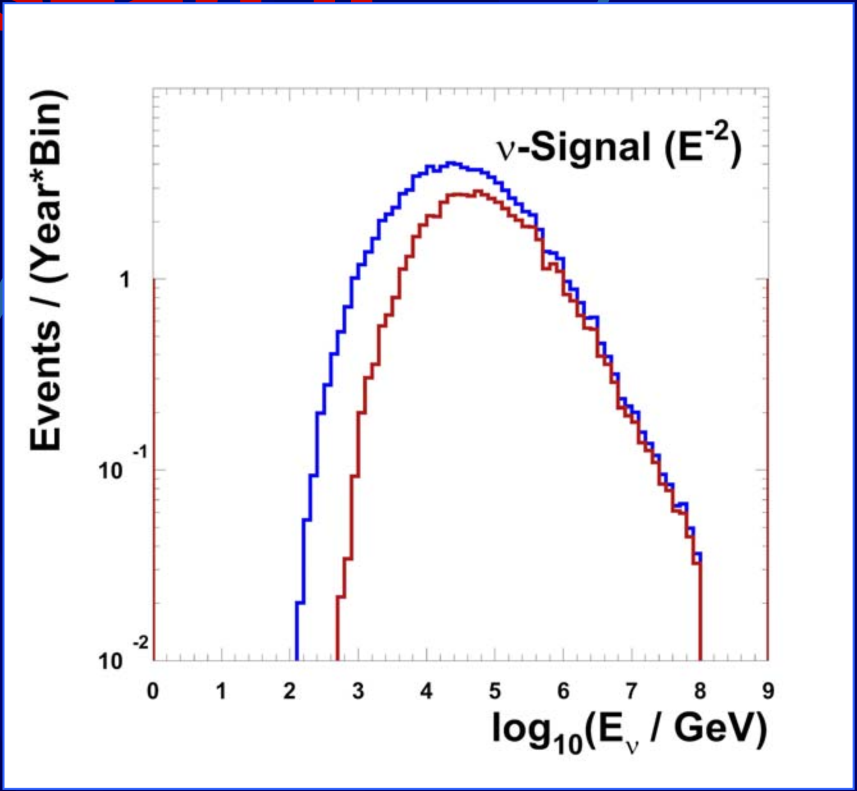


Blue: after downgoing muon rejection

Red: after cut on N_{hit} to get ultimate sensitivity

Energy Spectrum Point Source Search

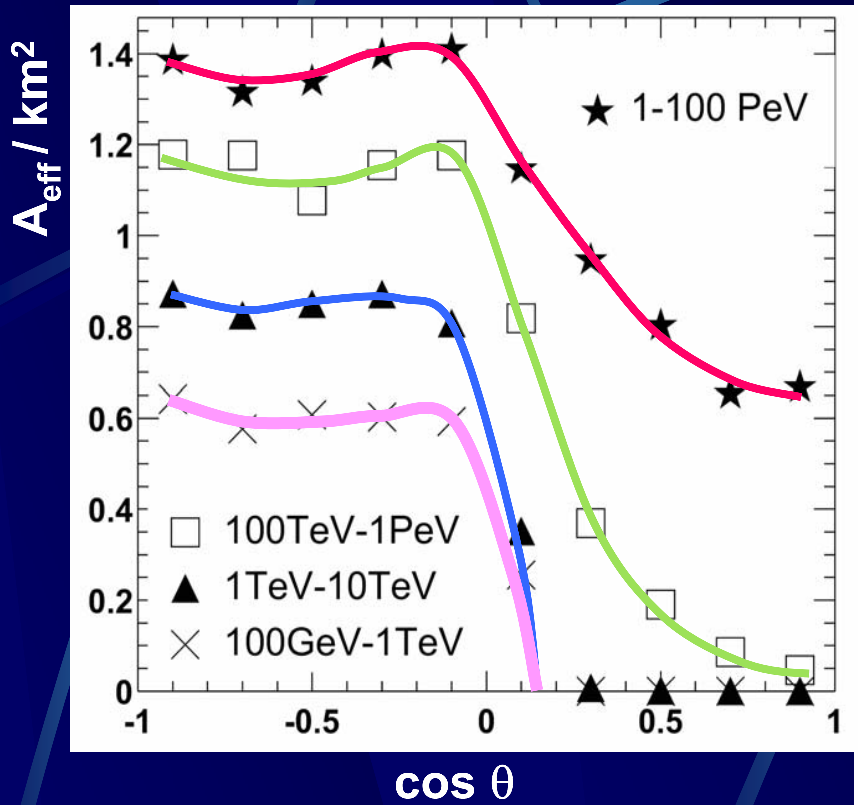


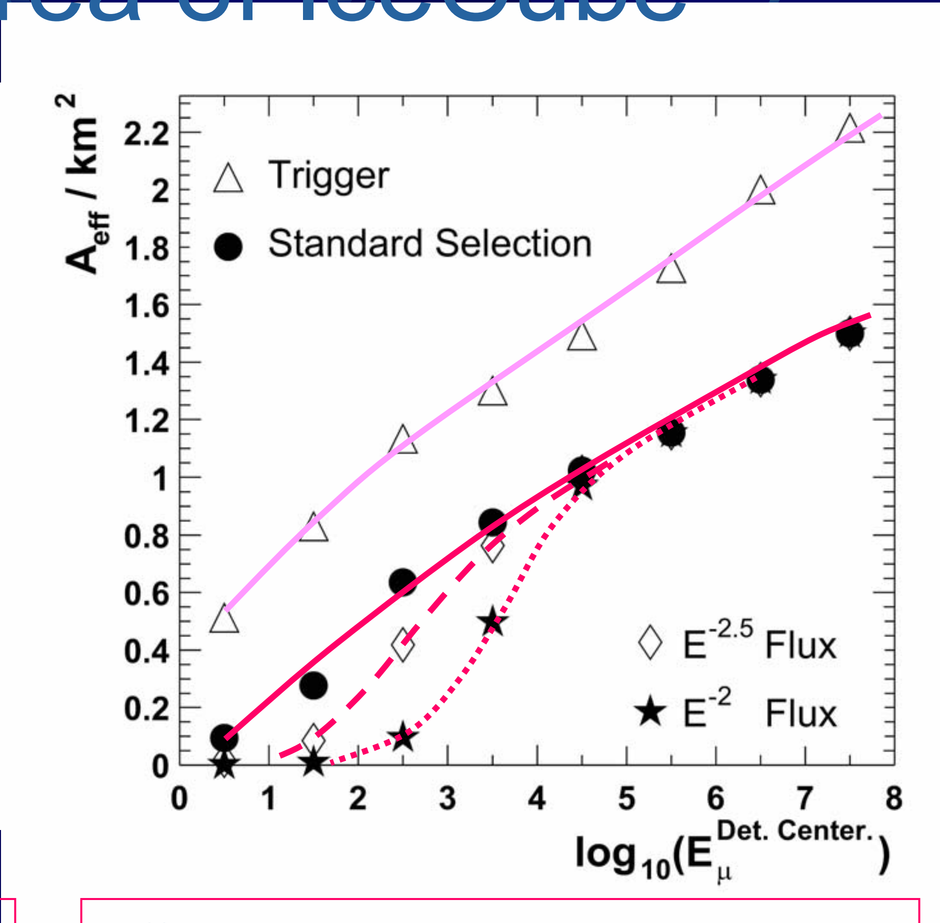


Blue: after downgoing muon rejection

Red: after cut on N_{hit} to get ultimate sensitivity

Effective area of IceCube





Effective area vs. zenith angle after rejection of background from downgoing atmospheric muons

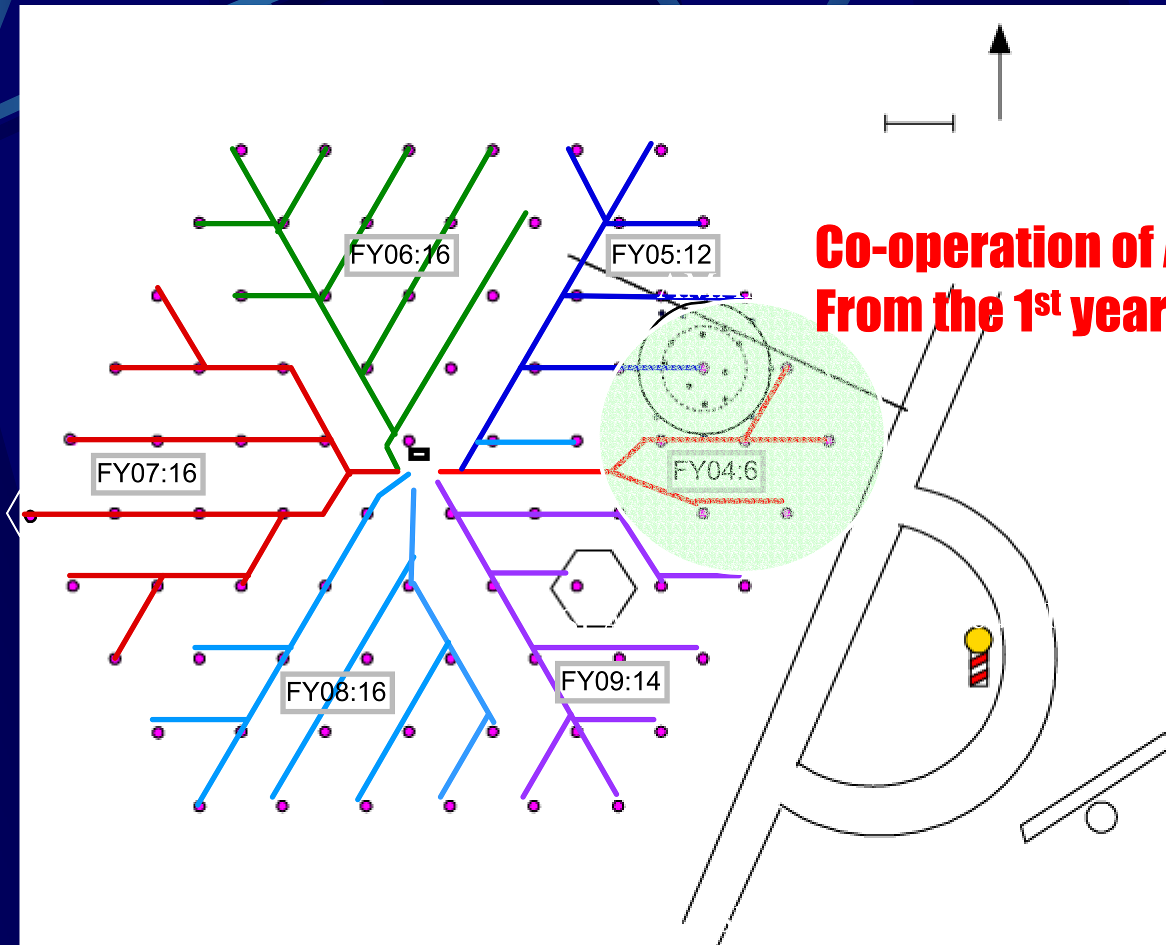
Effective area vs. muon energy
- after trigger
- after rejection of atm μ
- after cuts to get the ultimate sensitivity for point sources (optimized for 2 benchmark spectra)

In three years operation…

- $E^2 dN\nu/dE \sim 10^{-8}$ GeV/cm^2 s sr (diffuse)
- $E^2 dN\nu/dE \sim 7\times10^{-9}$ GeV/cm^2 s (Point source)
- 200 bursts in coincidence (GRBs – WB flux)

For 5σ detection

Construction: 11/2004-01/2009



Co-operation of AMANDA-IceCub
From the 1st year

Next season: Buildup of the Drill and IceTop prototypes

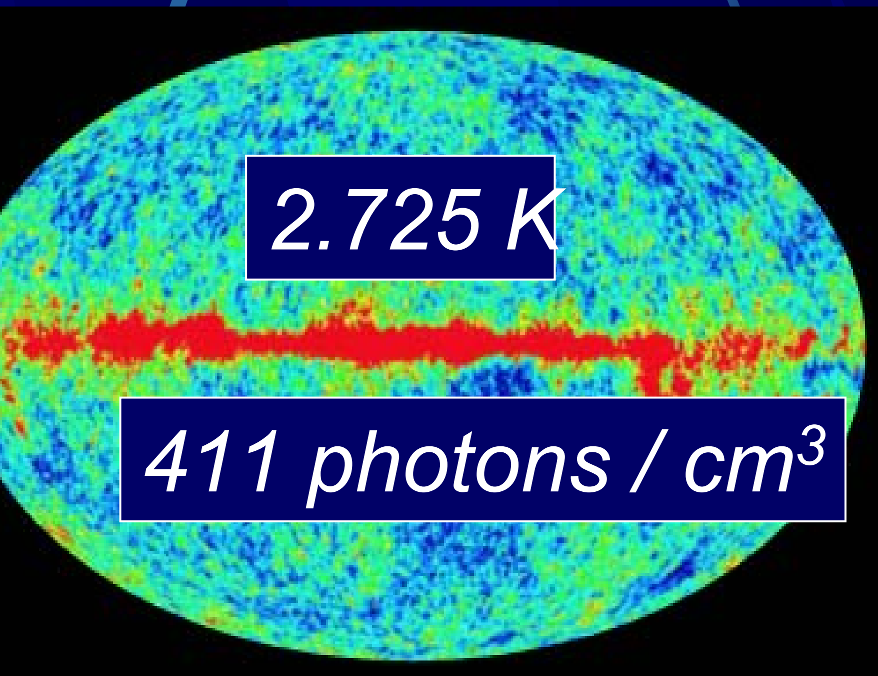
Project status

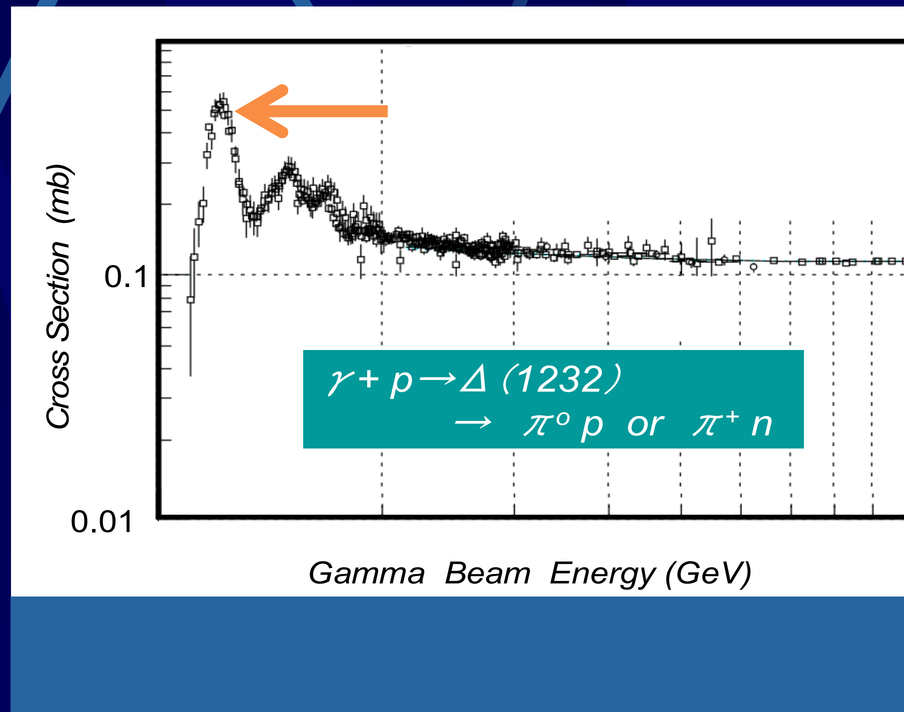
- Startup phase has been approved by the U.S. NSB and funds have been allocated.
- 100 DOMs are produced and being tested this year.
- Assembling of the drill/IceTop prototypes is carried out at the pole this season.
- Full Construction start in 04/05; takes 6 years to complete.
- Then 16 strings per season, increased rate may be possible.

GZK EHEν detection

- What is the GZK mechanism?
- EHE $\nu/\mu/\tau$ Propagation in the Earth
- Expected intensities at the IceCube depth
- Atmospheric μ – background
- Event rate

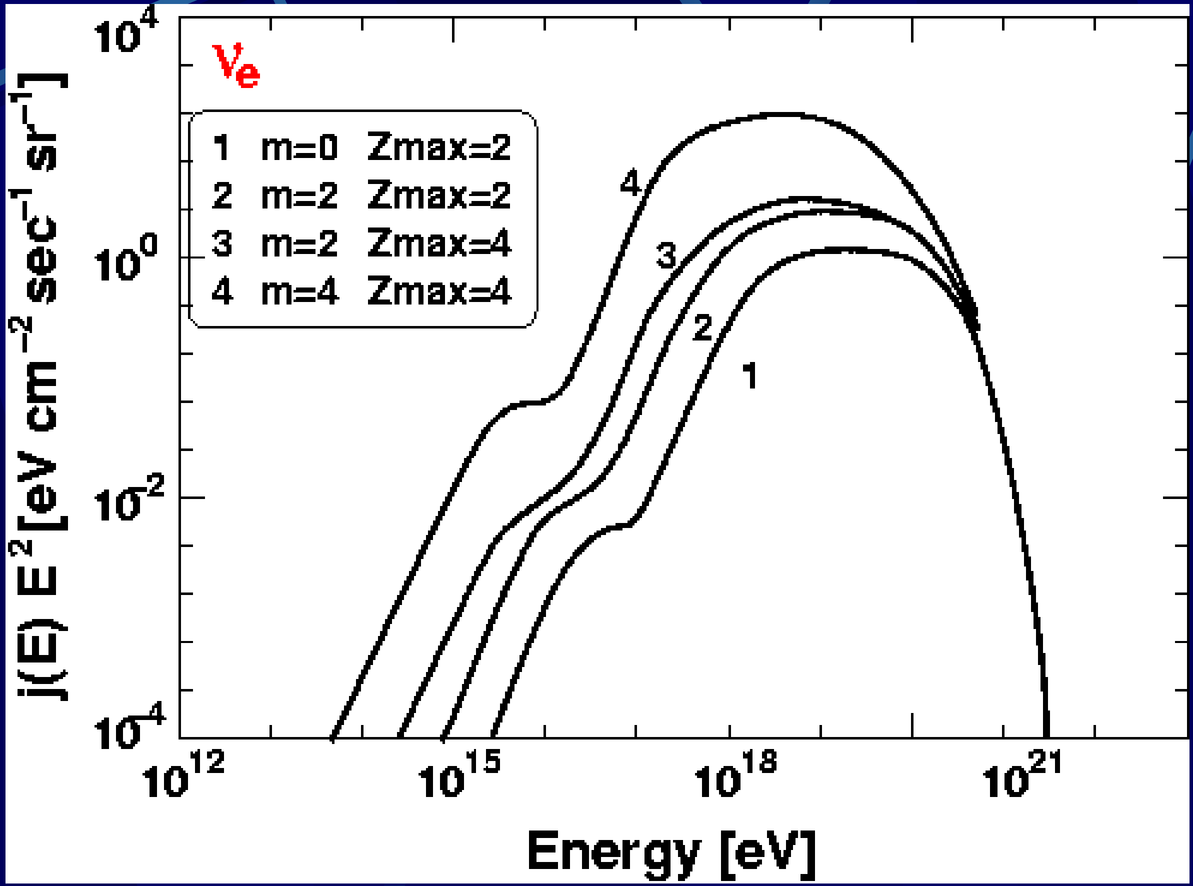
GZK Neutrino Production





→ Conventional Mechanism of EHE neutrinos!

Note: The oscillations convert ν_e, ν_μ to ν_e,ν_μ, ν_τ



Yoshida and Teshima 1993

Yoshida, Dai, Jui, Sommers 1997

UHE (EeV or even higher) Neutrino Events

Arriving Extremely Horizontally

- **Needs Detailed Estimation**
- **Limited Solid Angle Window**

$$(\sigma\rho N_A)^{-1} \sim 600\ (\sigma/10^{-32}\mathrm{cm}^2)^{-1}(\rho/2.6\mathrm{g\ cm}^{-3})^{-1}\ [\mathrm{km}]$$

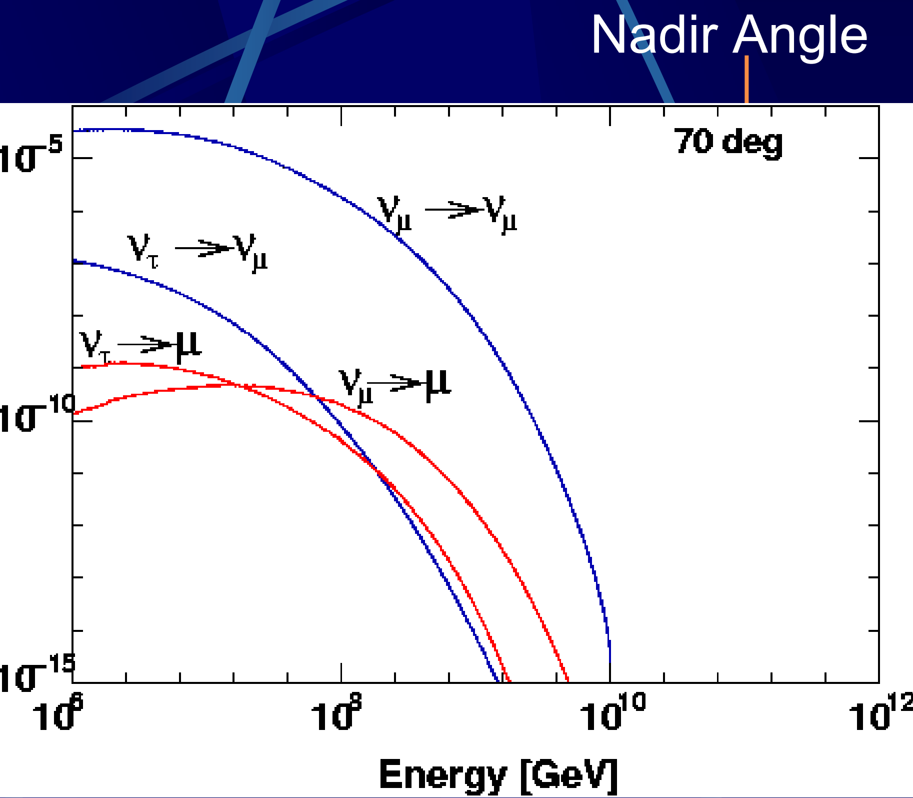
Involving the interactions generating electromagnetic/hadron cascades

$$\mu N \longrightarrow \mu X\ e^+e^-$$

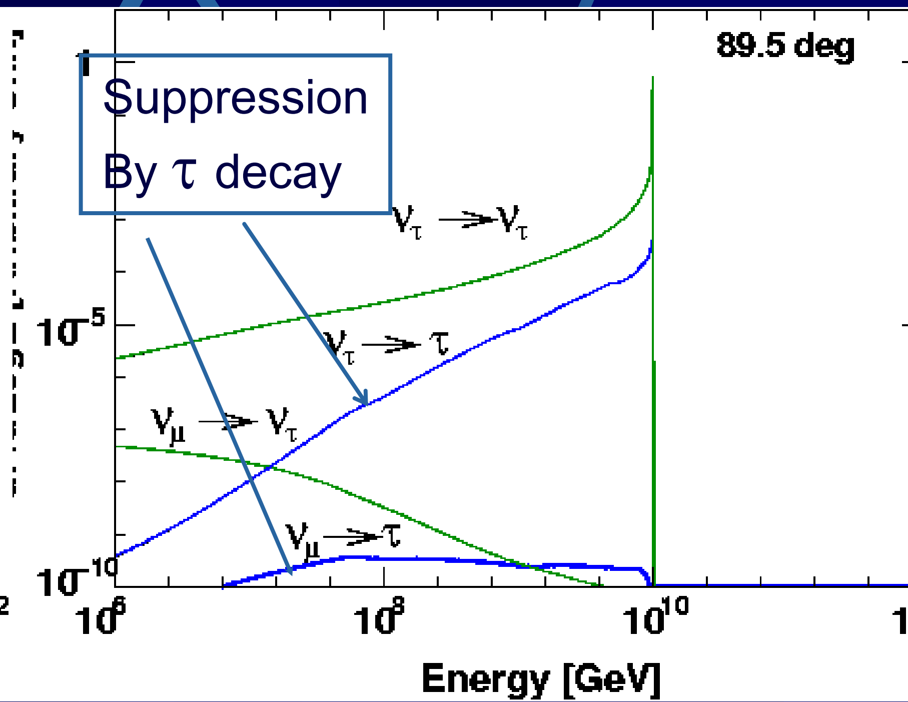
Products

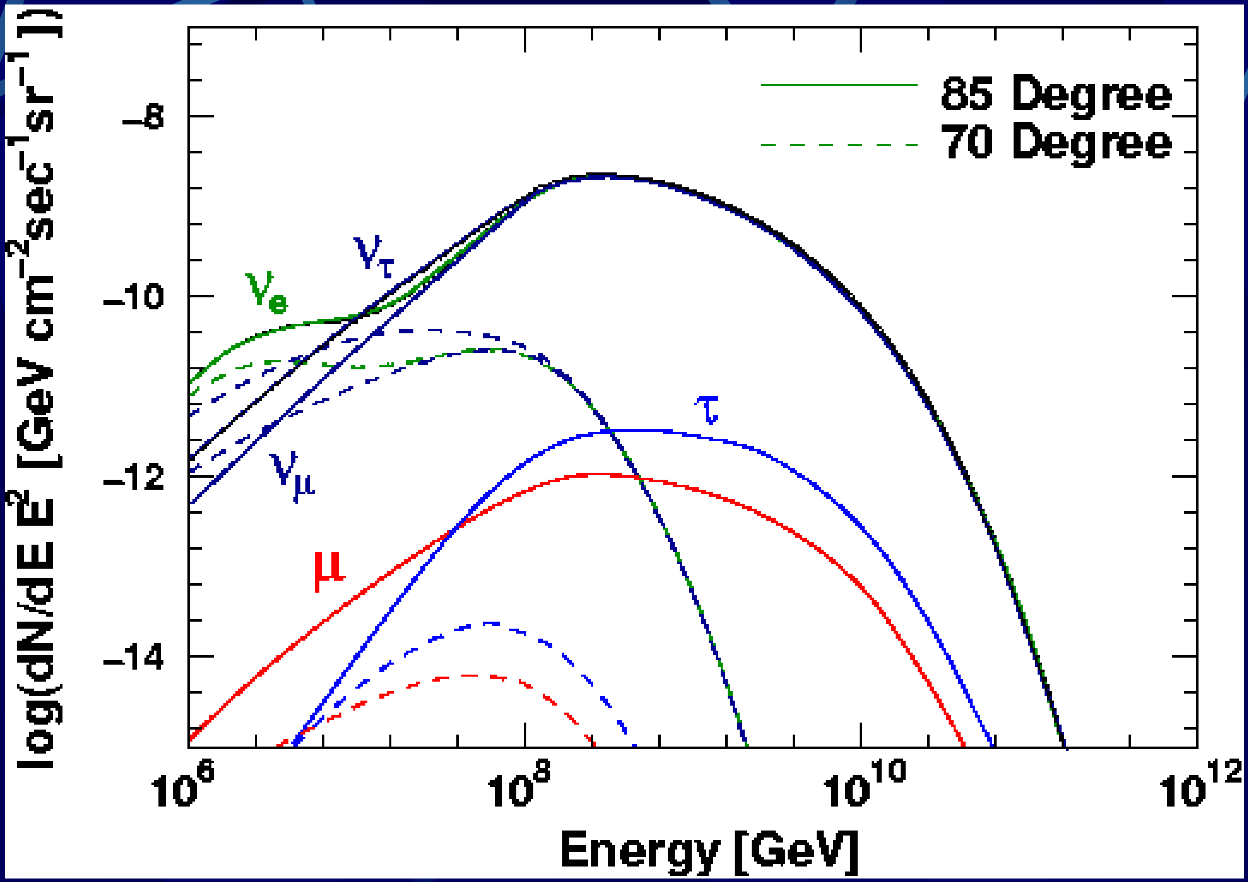
Incoming	ν_e	ν_μ	ν_τ	e/γ	μ	τ	π
ν_e				Weak			Weak
ν_μ					Weak		Weak
ν_τ						Weak	Weak
e/γ				Cascades			
μ	Decay	Decay Weak		Pair/decay Bremss	Pair	Pair	PhotoNucl.
τ	Decay	Decay	Decay Weak	Pair Bremss Decay	Decay Pair	Pair	Decay PhotoNucl.
π							Cascades

Muon(Neutrinos) from ν_μ ν_τ

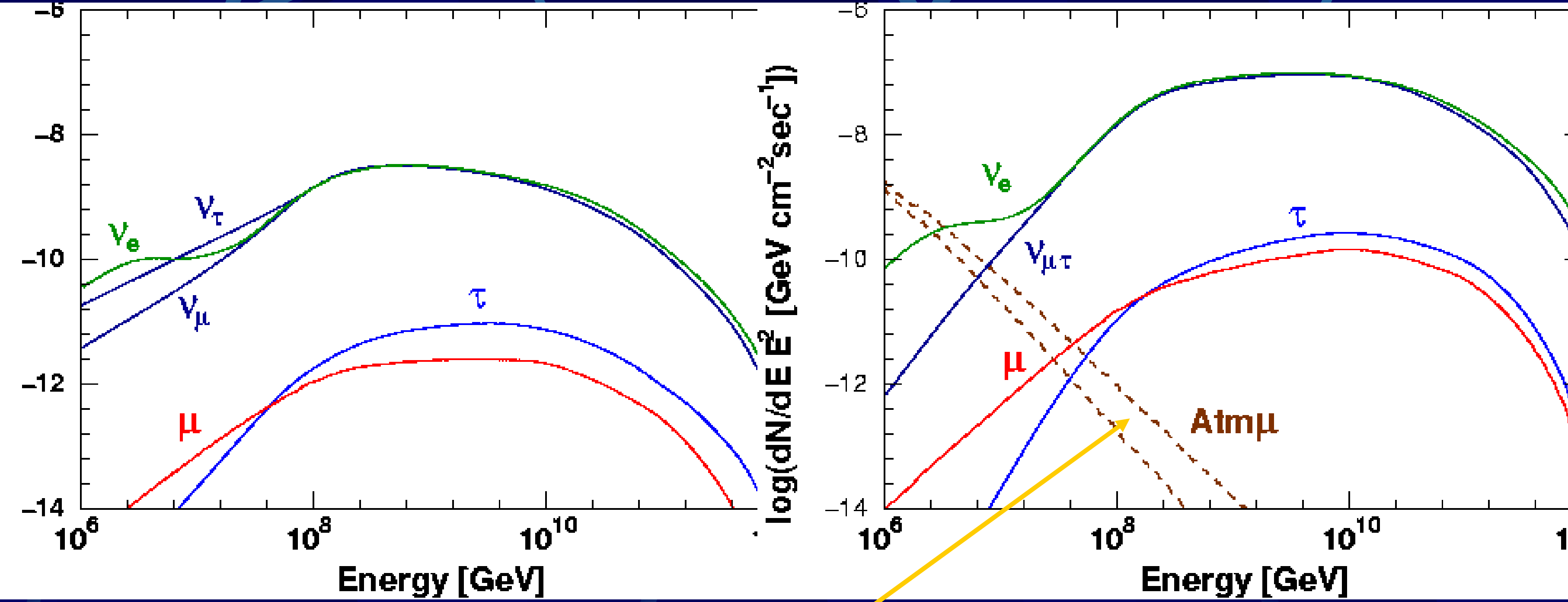


Tau(Neutrinos) from ν_μ ν_τ

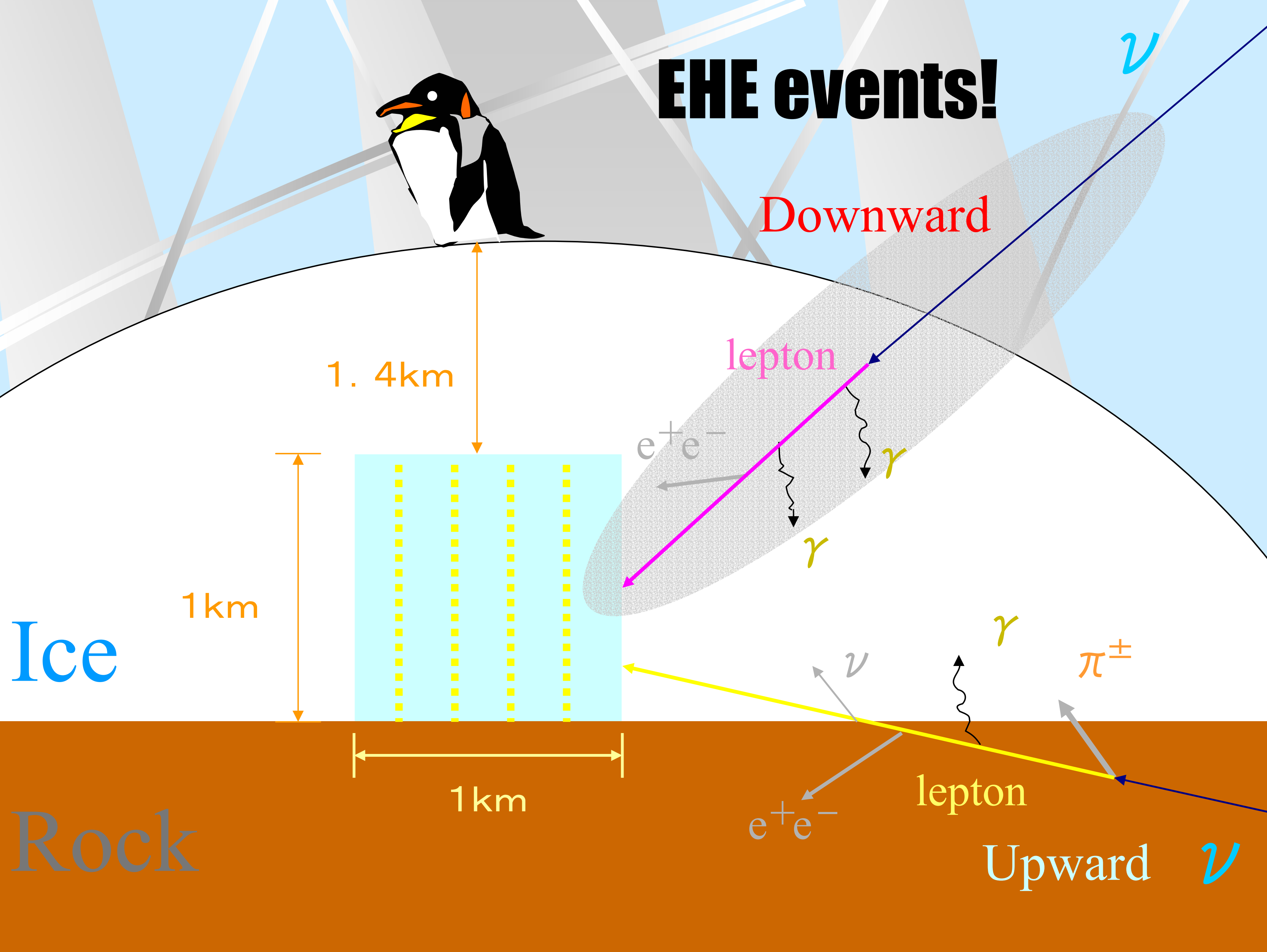



85 Degree
70 Degree
−8
−10
−12
−14
ν_e
ν_τ
ν_μ
τ
μ
10^6
10^8
10^{10}
10^{12}
Energy [GeV]
log(dN/dE E^2 [GeV cm^{-2}sec^{-1}sr^{-1}])

Upward-going　　　　Downward going!!



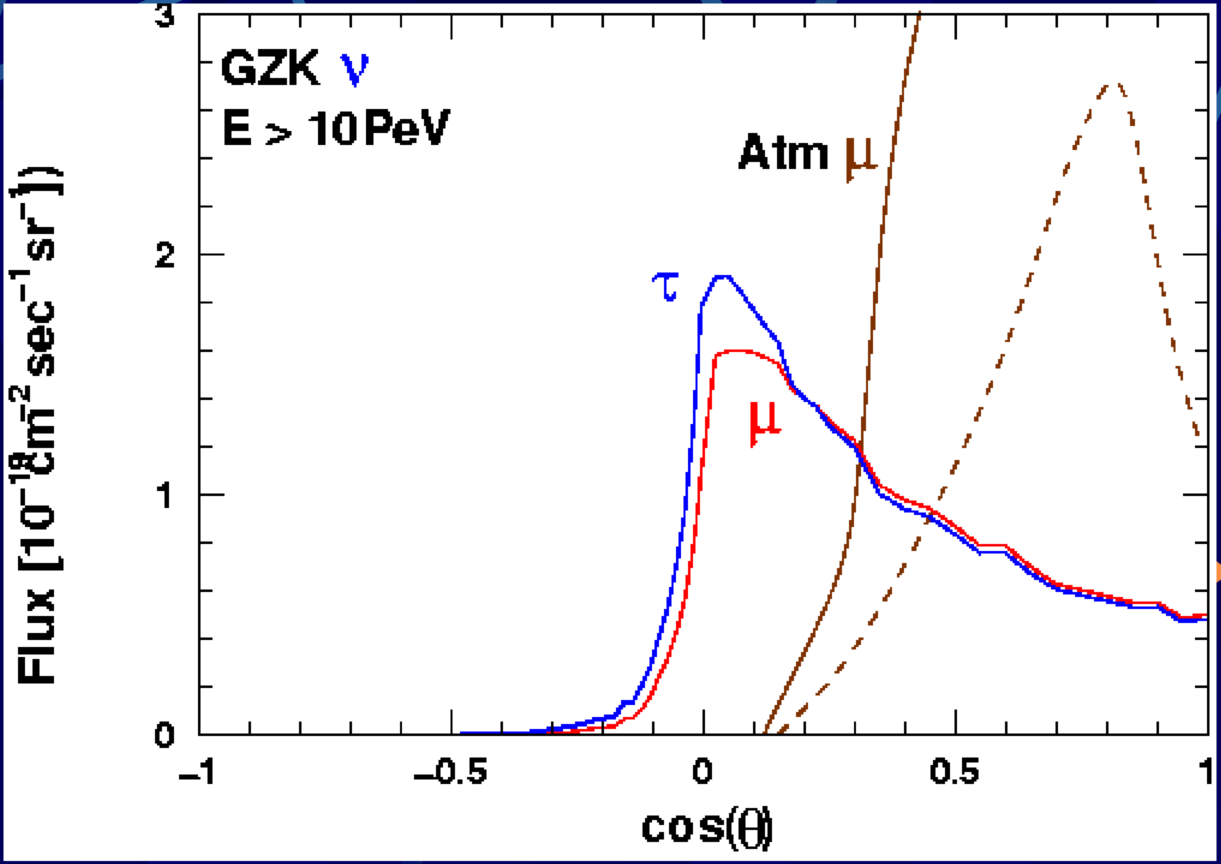
Atmospheric muon! – a major backgrond
But so steep spectrum



EHE events!
ν
Downward
lepton
1. 4km
e+e−
γ
γ
1km
Ice
γ
ν
π±
Rock
1km
e+e−
lepton
Upward
ν

Down-going events dominate...

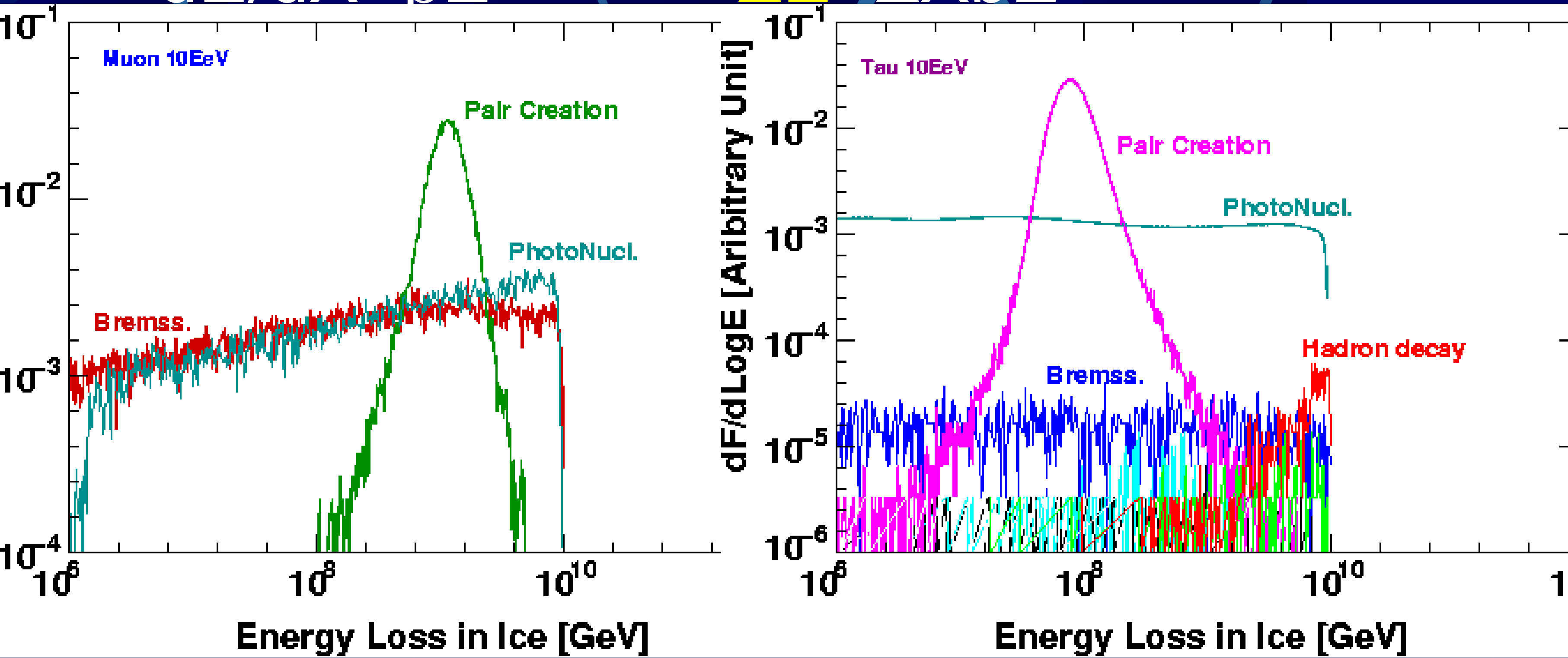
Atmospheric μ is strongly attenuated...



1400 m

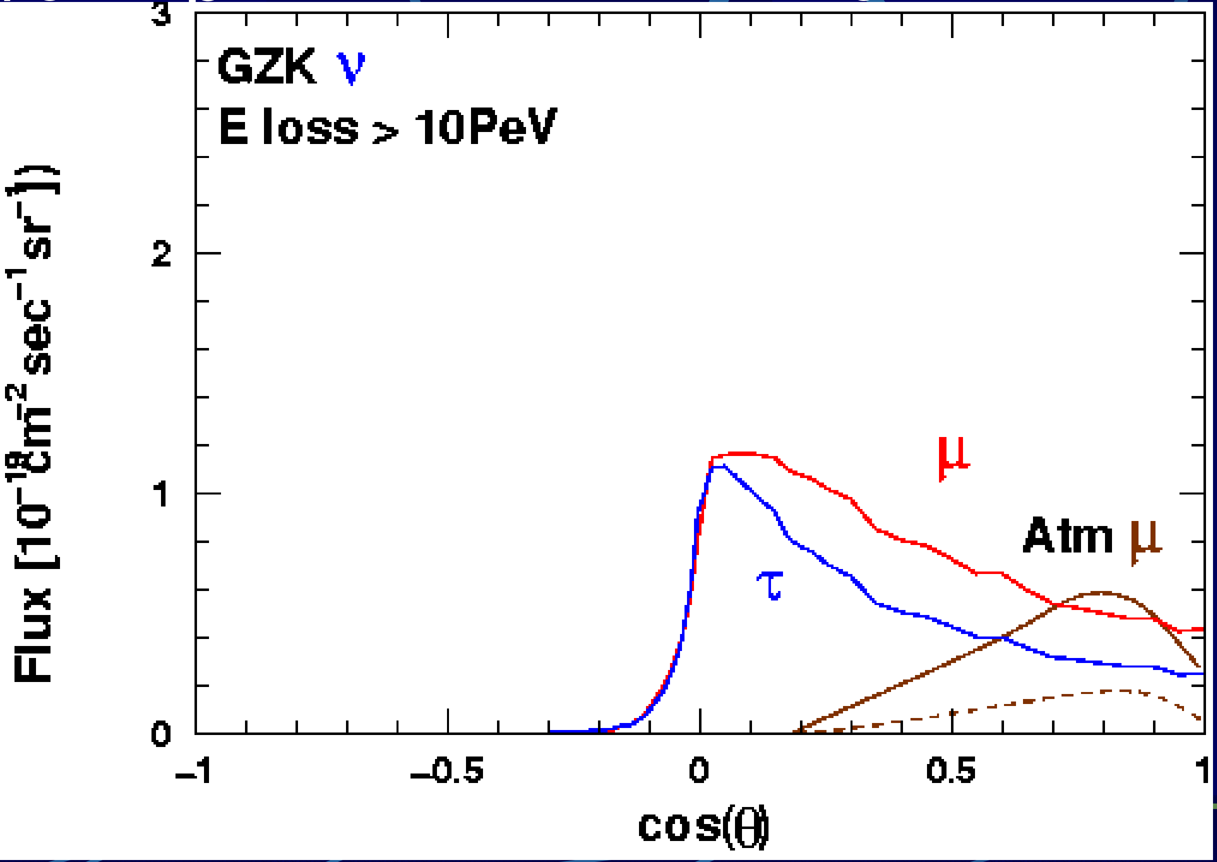
Flux as a function of energy deposit in km^3

- $dE/dX \sim \beta E \longrightarrow \Delta E \sim \Delta X b E$



Flux as a function of energy deposit in km³

- dE/dX~βE ⟶ ΔE~ΔXbE



Intensity of EHE μ and τ

[cm^{-2} sec^{-1}]

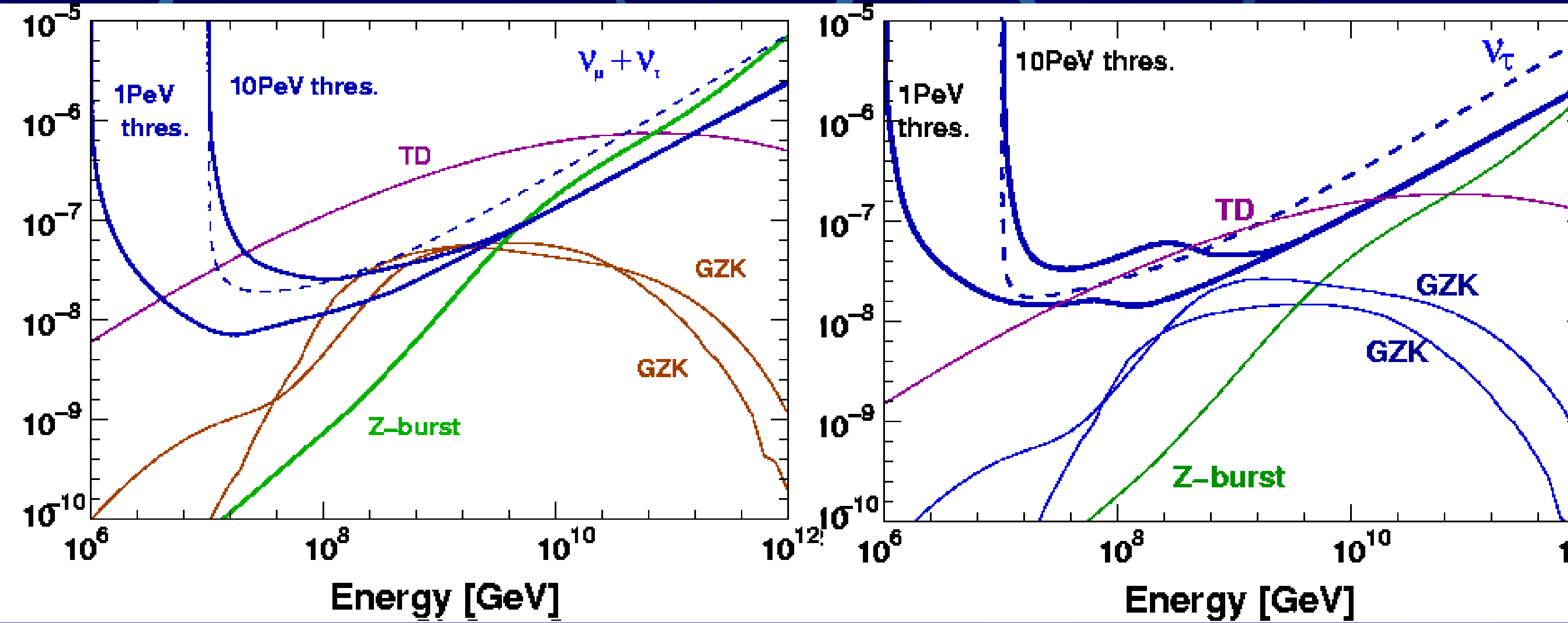
GZK m=4 Zmax=4		Iμ(E>10PeV)	Iτ(E>10PeV)	RATE [/yr/km^2]
Down		**5.90 10^{-19}**	**5.97 10^{-19}**	0.37
Up		3.91 10^{-20}	6.63 10^{-20}	0.03
		Iμ(E>10PeV) **Energy Deposit**	Iτ(E>10PeV) **Energy Deposit**	
Down		**4.75 10^{-19}**	**3.28 10^{-19}**	0.25
m=7 Zmax=5 **Down**		**7.21 10^{-17}**	**4.83 10^{-17}**	37.9
Atm μ		1.74 10^{-19}		0.05

IceCube EHE ν Sensitivity

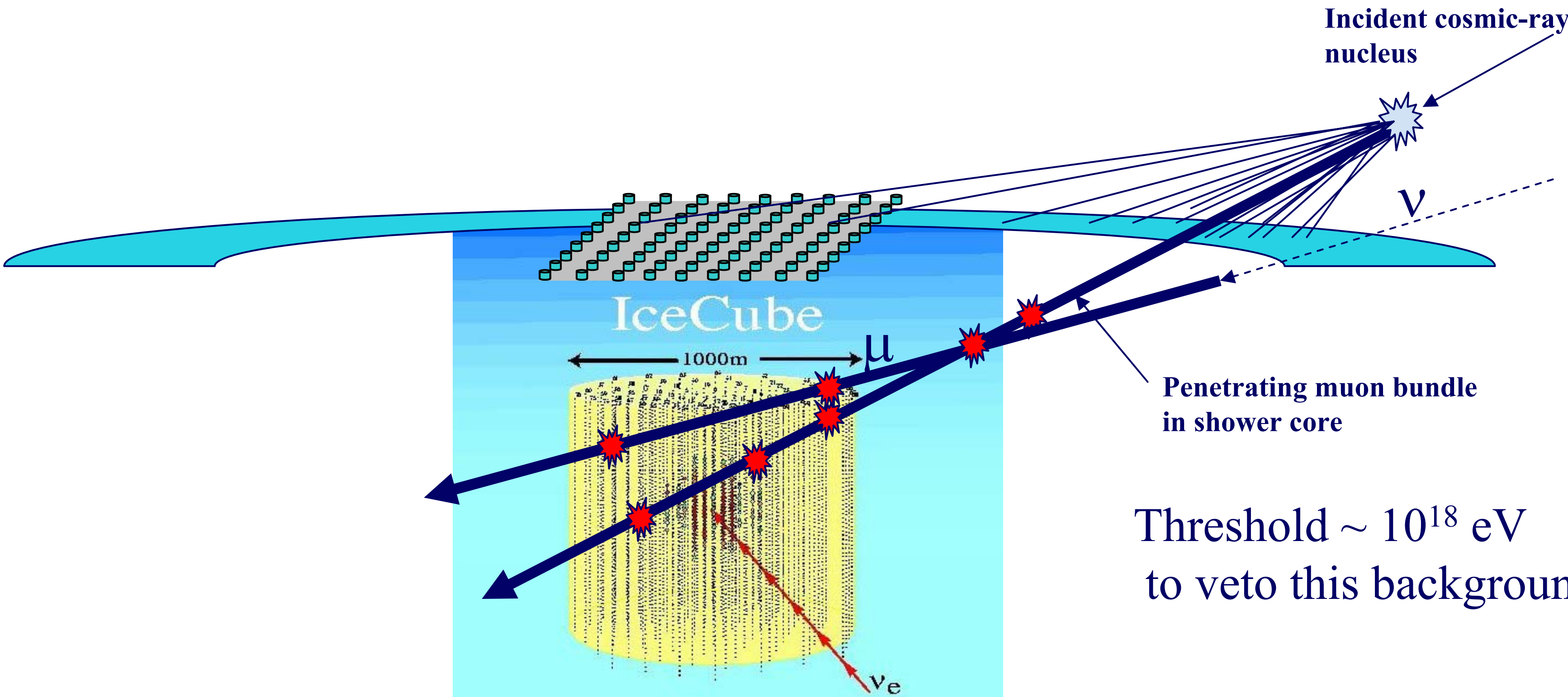
90% C.L. for 10 year observation

- Published in Phys. Rev. D

S.Yoshida, R.Ishibashi, H,Miyamoto, PRD 69 103004 (2004)



IceTop : EeV detectio



Threshold ~ 10^{18} eV
to veto this backgroun

Potential to reject this background for EeV neutrinos by detecting the fringe of coincident horizontal air shower in an array of water Cherenkov detectors (*cf.* Ave *et al*., PRL 85 (2000) 2244, analysis of Haverah Park)

back

IceCube summary

IceCube has great capability for TeV-PeV ν-induced muons taking advantage of long rang in the clear ice.

For EHE ν like the GZK....

/μ appeared in 10 PeV- EeV are our prime target on GZK ν detection.

1/1000 of primary ν intensity!

Downward τ and μ make main contributions in PeV -EeV

Energy Estimation would be a key for the bg reductio

Because atmospheric μ spectrum ~ $E^{-3.7}$

GZK ν is DETECTABLE by IceCube

0.3-40 events/year (BG 0.05 events/year)

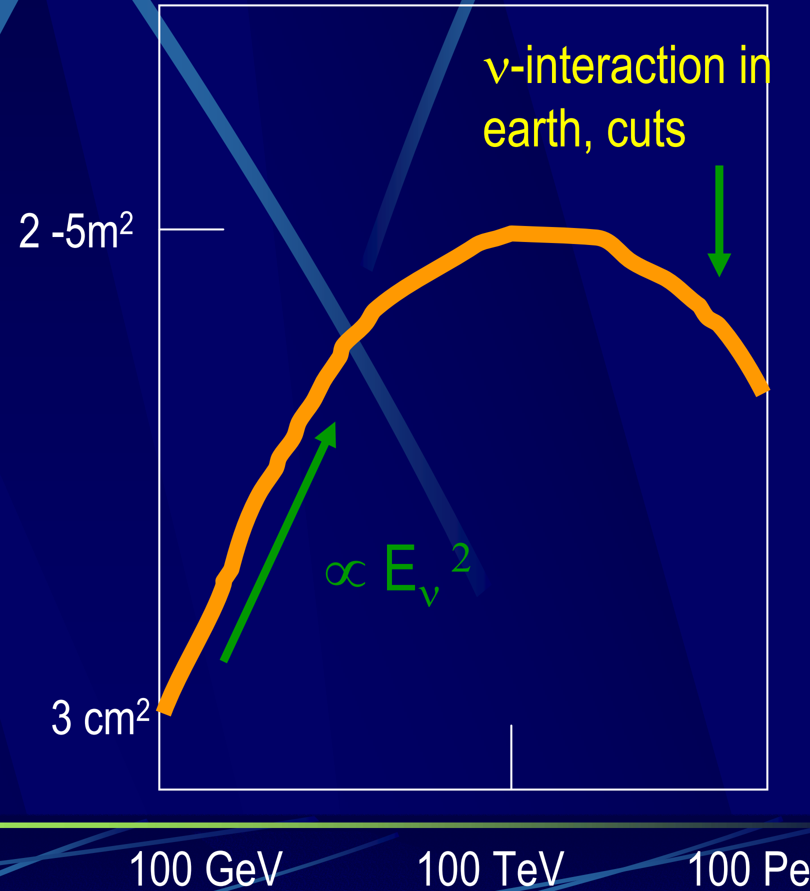
Backup slides

Detector capabilities

- **muons:**
  - directional error: 2.0 - 2.5°
  - energy resolution:¶ 0.3 – 0.4
  - coverage: **2**π
- **primary cosmic rays:** (+ SPASE)
  - energy resolution:¶ 0.07 – 0.10
- **„cascades“:** ($e^{\pm}$, $\tau^{\pm}$, neutral current)
  - zenith error: 30 - 40°
  - energy resolution:¶ 0.1 – 0.2
  - coverage: **4**π

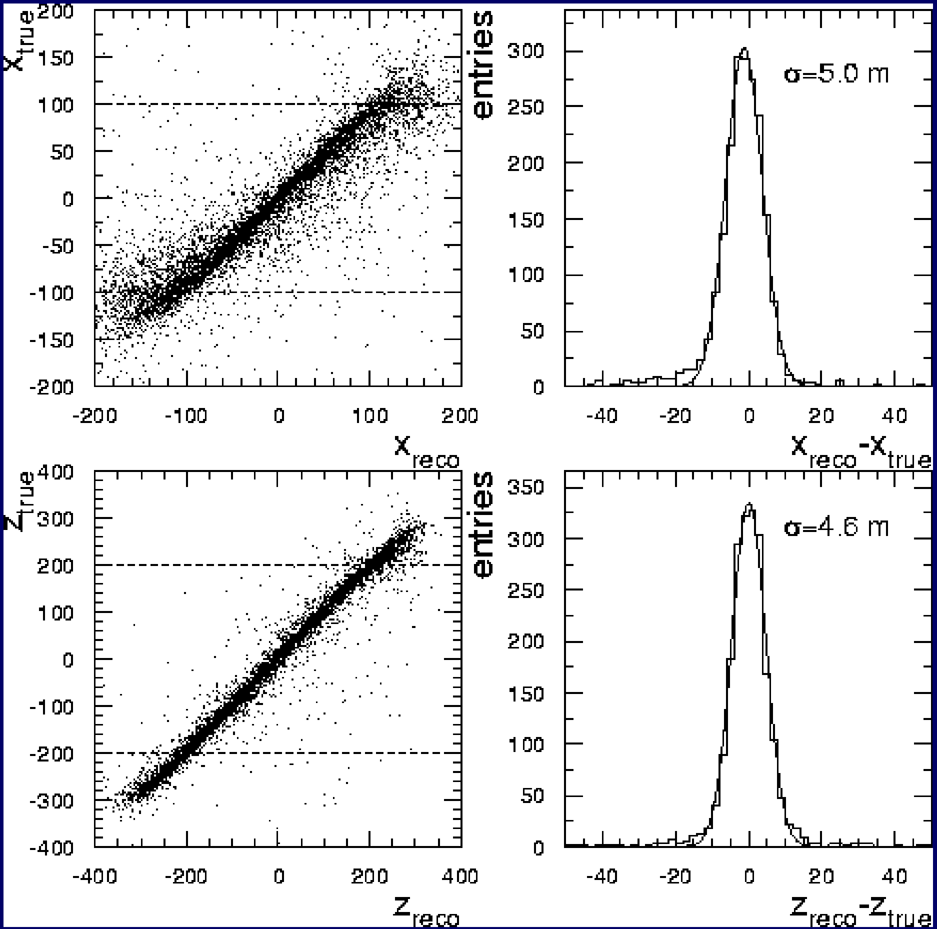
¶$\sigma[\log_{10}(E/TeV)]$

ν_μ effective area (schematic):



Vertex Resolution

Reconstruction of 1 TeV EM cascades which trigger AMANDA II

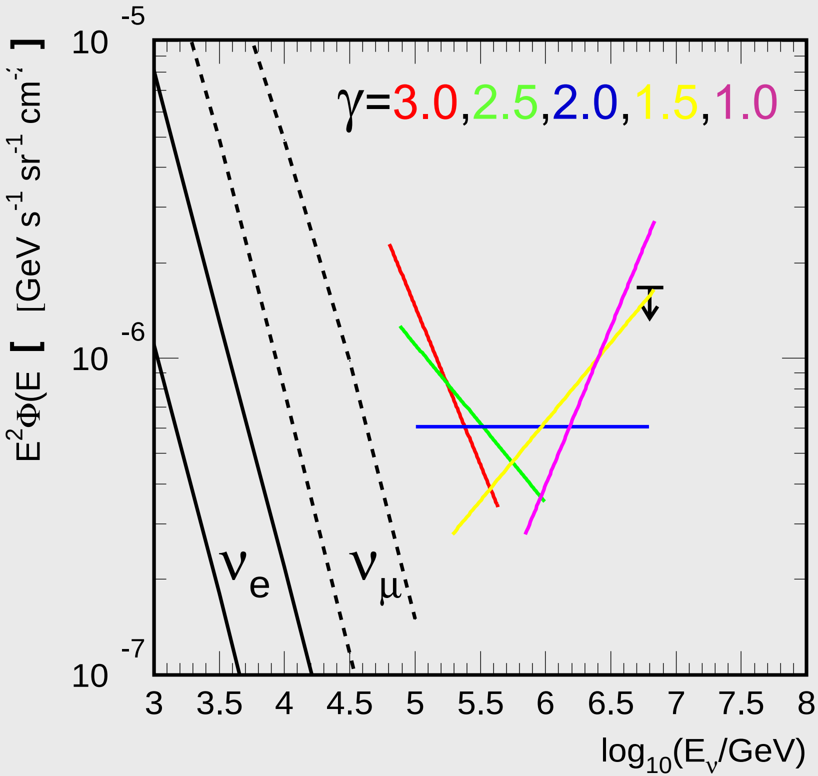


Vertex resolution of cascades in the detector:
(radius 100 m, height = 200 m)

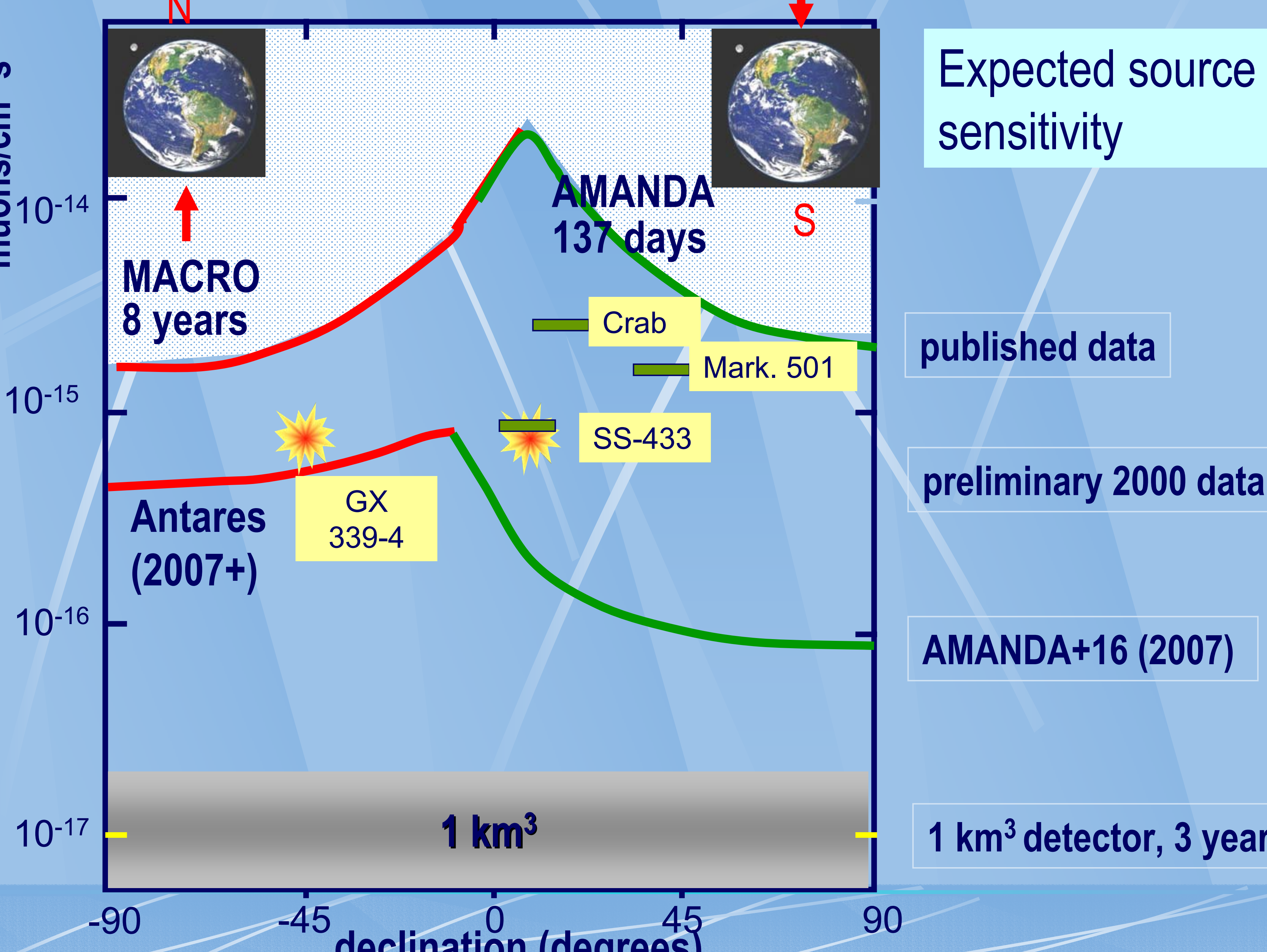
$\sigma \sim 5$ m

for x,y,z coordinates and large range of energies.

Upper limits on the diffuse flux



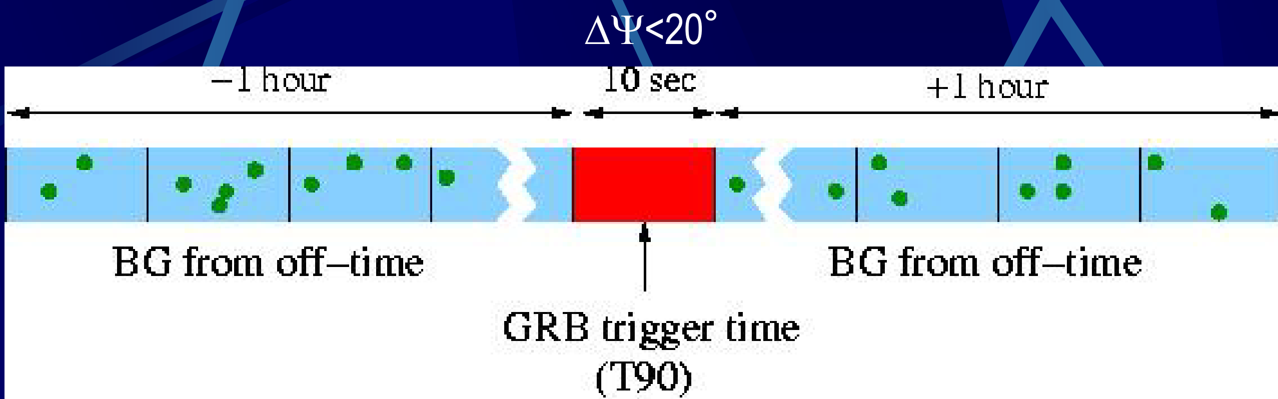
- $N_{obs}=2$; $N_{bg}=0.5^{+0.5}_{-0.3}$
- Upper bounds on the diffuse flux of astrophysical neutrinos (at 90% CL) for different assumed spectras: $\Phi(E) \sim E^{-\gamma}$; $\gamma=1-3$
- Limit on tau neutrinos 25 - 30 % worse than for electron neutrinos
- Glashow resonance at 6.3 PeV results in differential ν_e limit



Expected source sensitivity
MACRO
8 years
AMANDA
137 days
S
Crab
Mark. 501
SS-433
GX
339-4
Antares
(2007+)
1 km³
published data
preliminary 2000 data
AMANDA+16 (2007)
10-14
10-15
10-16
10-17
-90
-45
0
45
90
declination (degrees)

GRB ν search in AMANDA

Search for ν_μ candiates correlated with GRBs - background established from data



PRELIMINARY

Year	#GRB	bkg	observed
1997	78	0.10	0
1998	99	0.20	0
1999	96	0.20	0
2000	44	0.60	0
Total	317	1,30	0

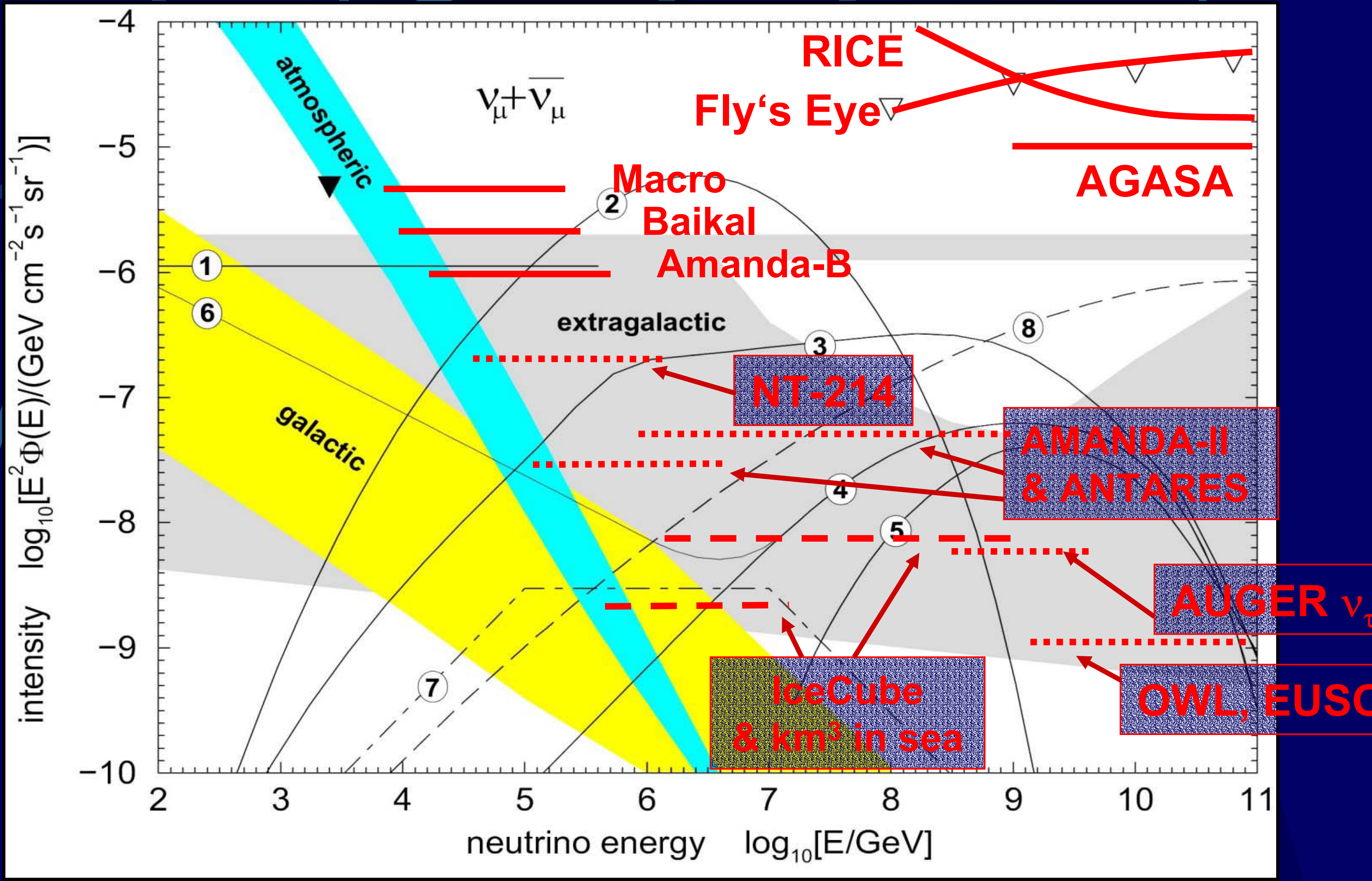
- 317 BATSE triggers (1997—2000)
- effective μ-area ≈ 50000 m^2

  low background due to space- time coincidence
- **No excess observed!**

  assuming WB spectrum 4 x 10^{-8}GeV/s/cm^2/sr

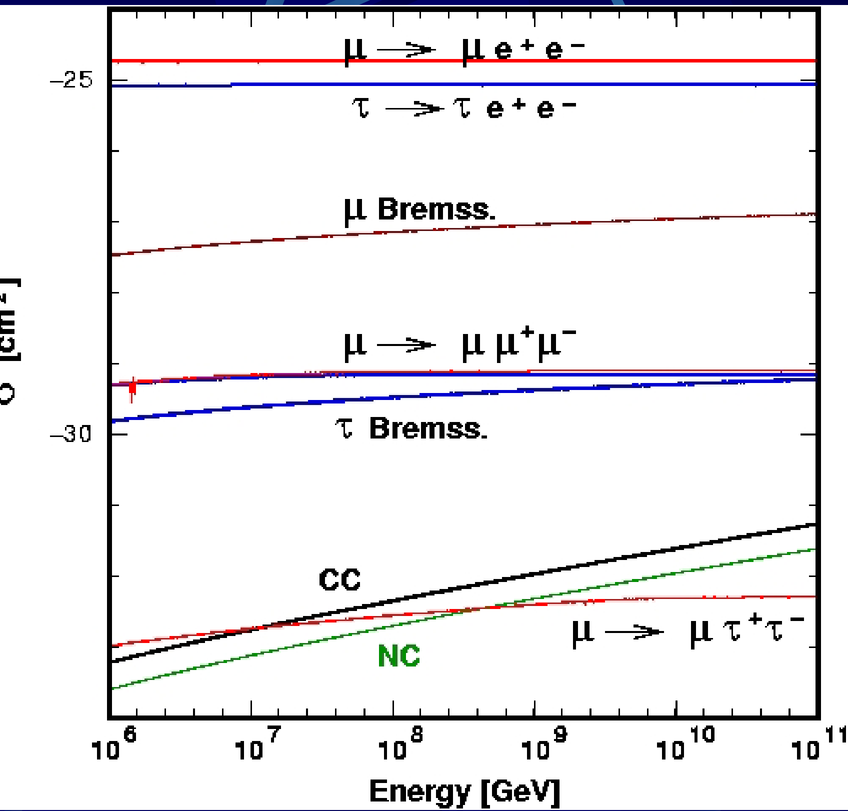
analysis continues with non-triggered BATSE and IPN3 data

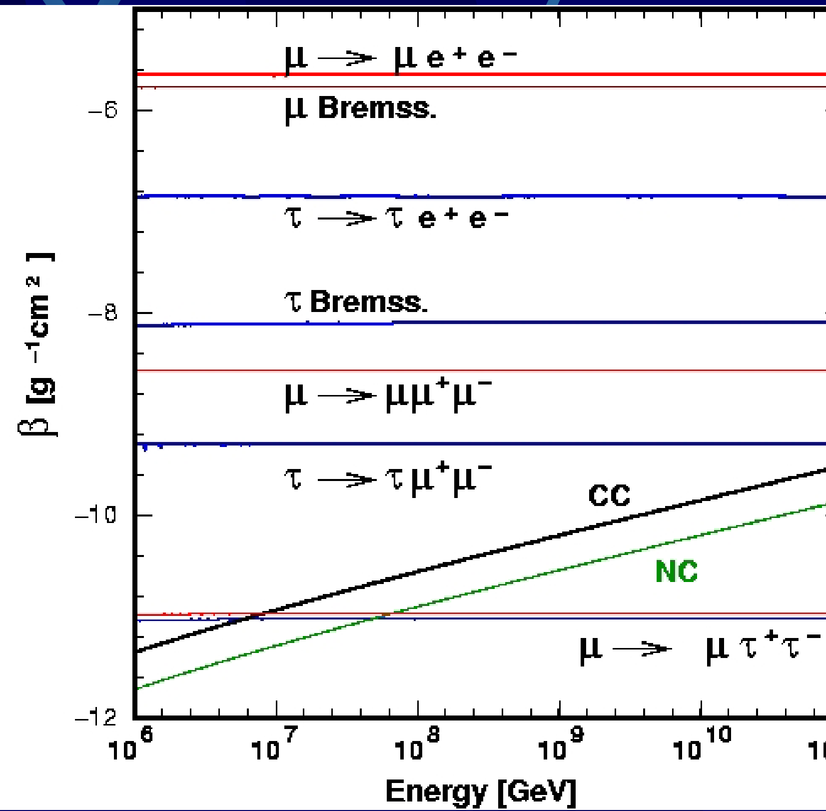
Grand Summary

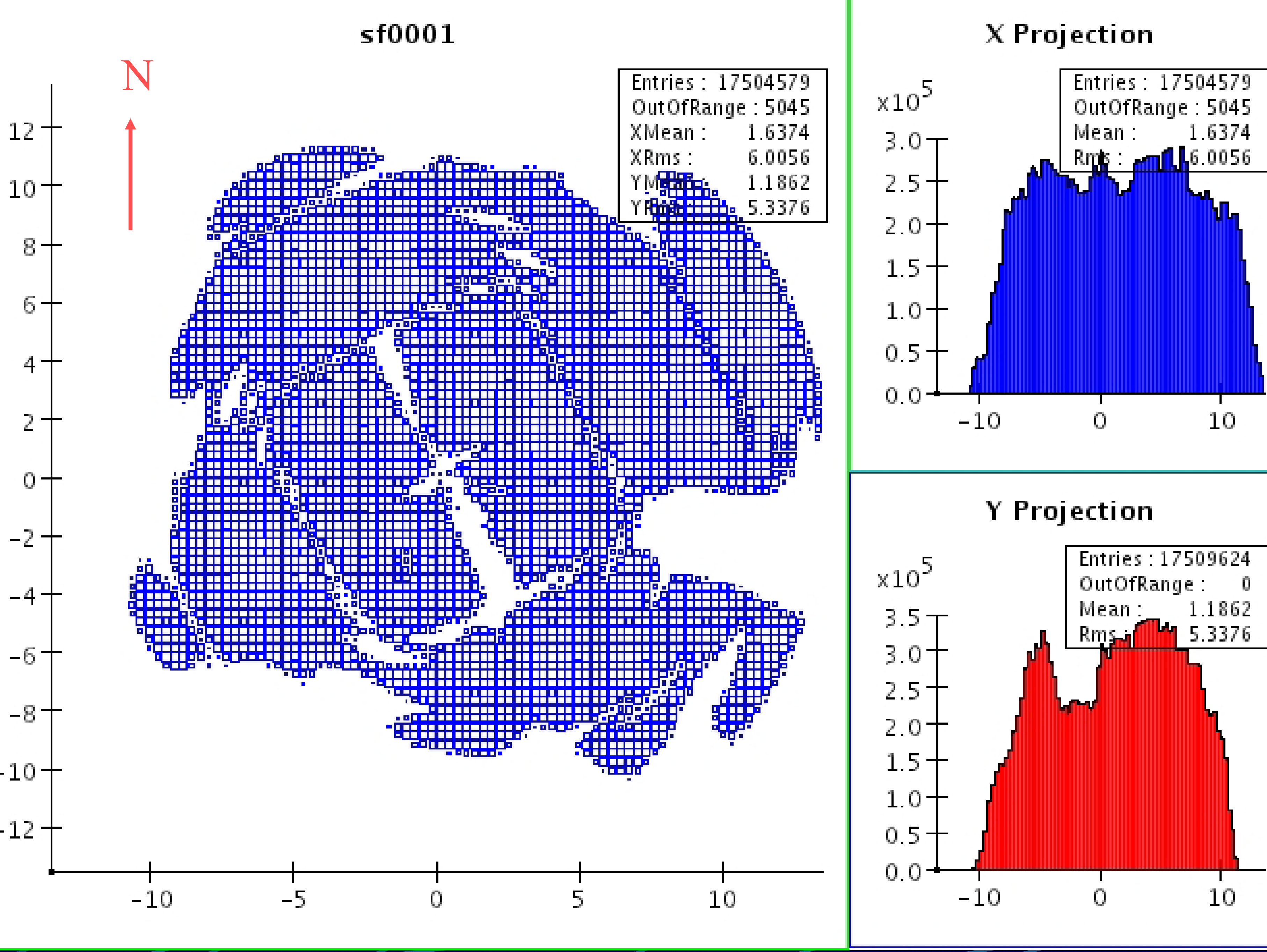


Courtesy: Learned & Mannheim; Spiering

τ/μ propagation in Earth







sf0001
N
Entries : 17504579
OutOfRange : 5045
XMean : 1.6374
XRms : 6.0056
1.1862
5.3376
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-10
-5
0
5
10
X Projection
x10^5
Entries : 17504579
OutOfRange : 5045
Mean : 1.6374
6.0056
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-10
0
10
Y Projection
x10^5
Entries : 17509624
OutOfRange : 0
Mean : 1.1862
5.3376
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-10
0
10