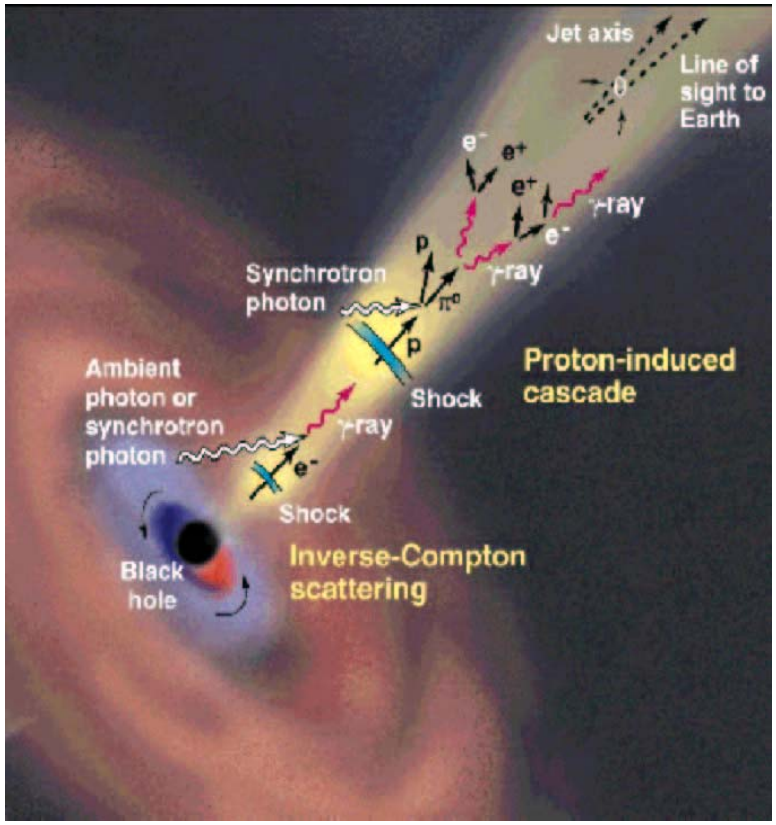
Astophysical Neutrinos

Shigeru Yoshida

Outline

- What we can learn from high energy ν
- Extremely High Energy ν Generation
  - Astrophysics
  - Particle Physics
- Cosmic ν detection status
  - EHE regime
  - PeV regime
  - Point Source

Physics motivation



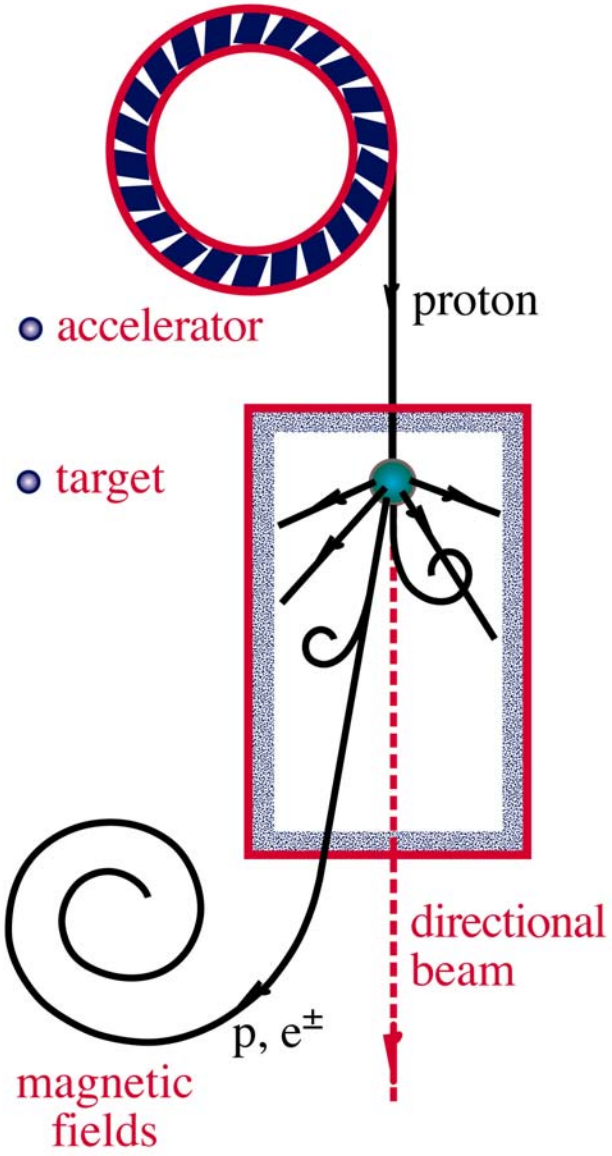
- origin and acceleration of cosmic rays
- understand cosmic cataclysms
- find new kind of objects?

- neutrino properties (ν_τ , cross sections ..)

- dark matter (neutralino annihilation)

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

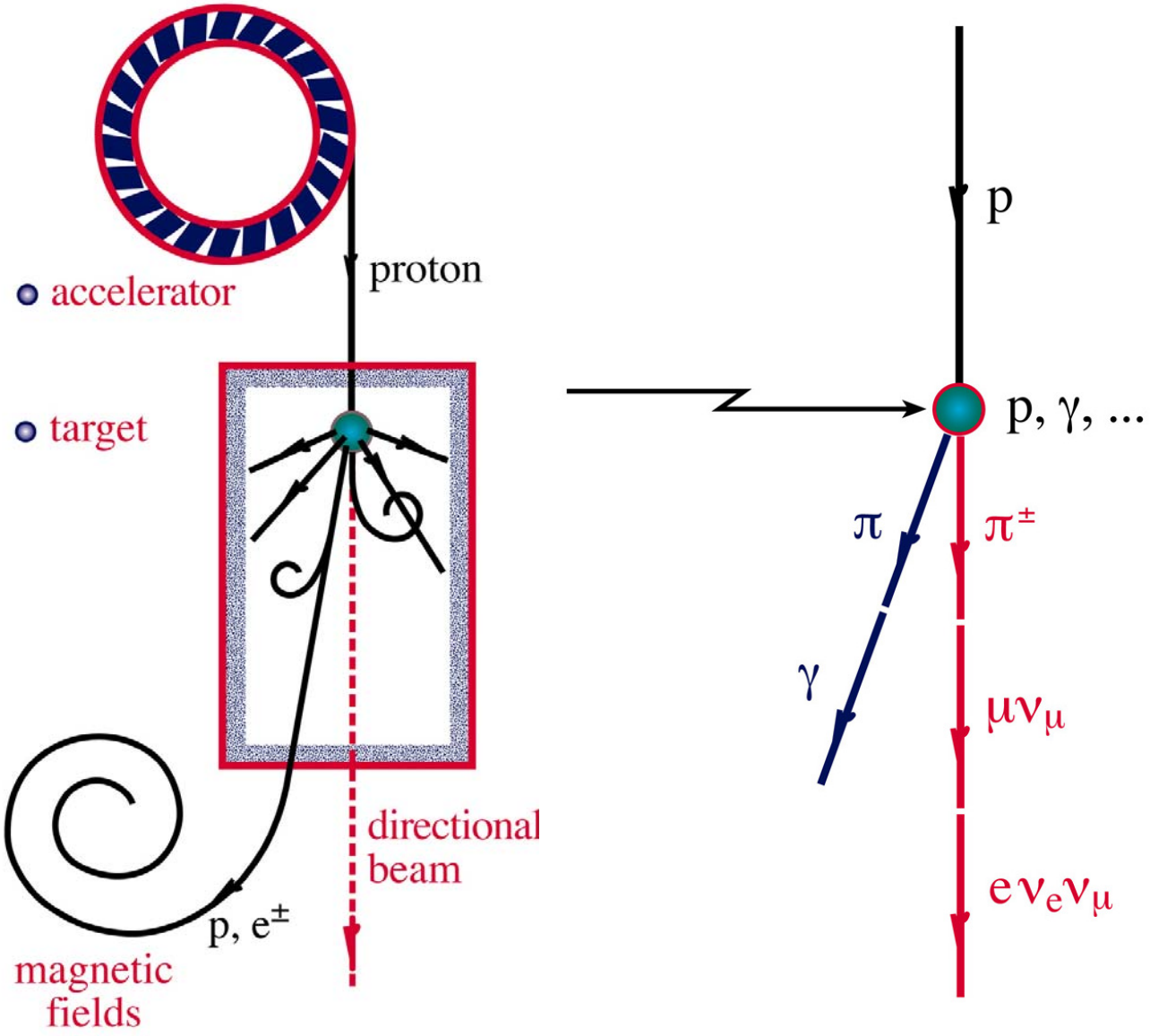
NEUTRINO BEAMS: HEAVEN & EARTH



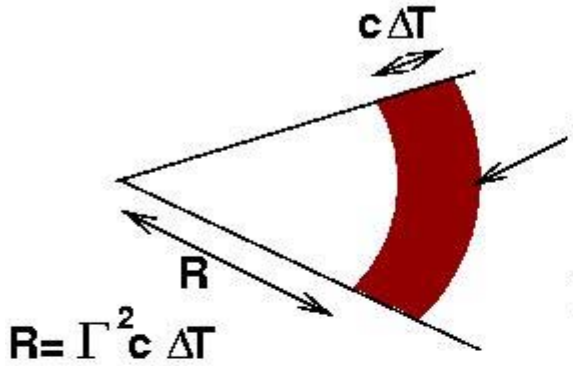
black hole

radiation enveloping black hole

NEUTRINO BEAMS: HEAVEN & EARTH



GRBs might be a solution.....



Lorents Factor of the plasma bulk
$\Gamma \sim 100\text{–}1000$

Observed MeVγ's Energy Density @ the shock rest frame $U_{rad} = \eta \dfrac{E_{total}}{4\pi R^2 \Gamma^2 c\, T_{GRB}}$

E_{total} : total energy of a GRB $\sim 10^{53}$ erg

η : Efficiency to the energy transfer to γ

Fraction of energies going into pions

$$f = \frac{t_{esc}}{t_{p\gamma}} \qquad t_{esc} = \Gamma \Delta T$$

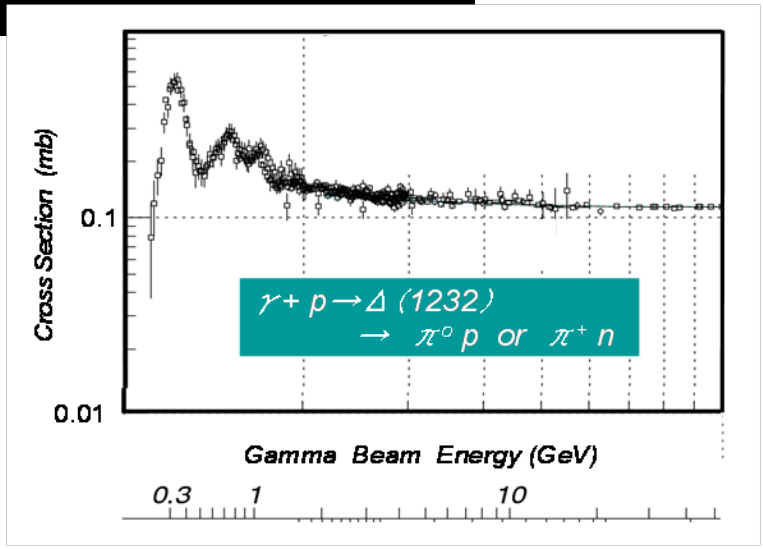
$$t_{p\gamma}^{-1} = \frac{U_{rad}}{c\, k_{break}} \sigma_{res} \frac{\Delta s}{s - m_p^2} \varepsilon \quad \text{@ the shock rest frame}$$

$$k_{break}^{obs} = \Gamma k_{break} \sim 1 \text{ MeV} \qquad \varepsilon \sim 0.2$$

$$f = 0.8 \left(\frac{\eta}{1.00}\right)\left(\frac{E_{total}}{10^{53}\text{erg}}\right)\left(\frac{\Gamma}{300}\right)^{-4}\left(\frac{\Delta T}{10\text{ ms}}\right)^{-1}\left(\frac{T_{GRB}}{10\text{ s}}\right)^{-1}\left(\frac{k_{break}^{obs}}{1\text{MeV}}\right)^{-1}$$

(E)HE ν generation needs target photons!

Δresonance in the photopion production



$E_p\ E_\gamma \sim 0.25\ \Gamma^2\ [GeV^2]$

$\Gamma \sim 300, E_\gamma \sim$ MeV ⟶ $E_p \sim 10^{16}$ eV ~ 10 PeV

$\Gamma \sim 300, E_\gamma \sim$ eV ⟶ $E_p > 10^{20}$ eV ~ 1 ZeV

$E_\gamma \sim$ eV ??

Proton-synchrotron model (Totani 1998)

Energy limit!

Life is not so easy...

Synchrotron cooling supresses the intensity? **Yes!!**

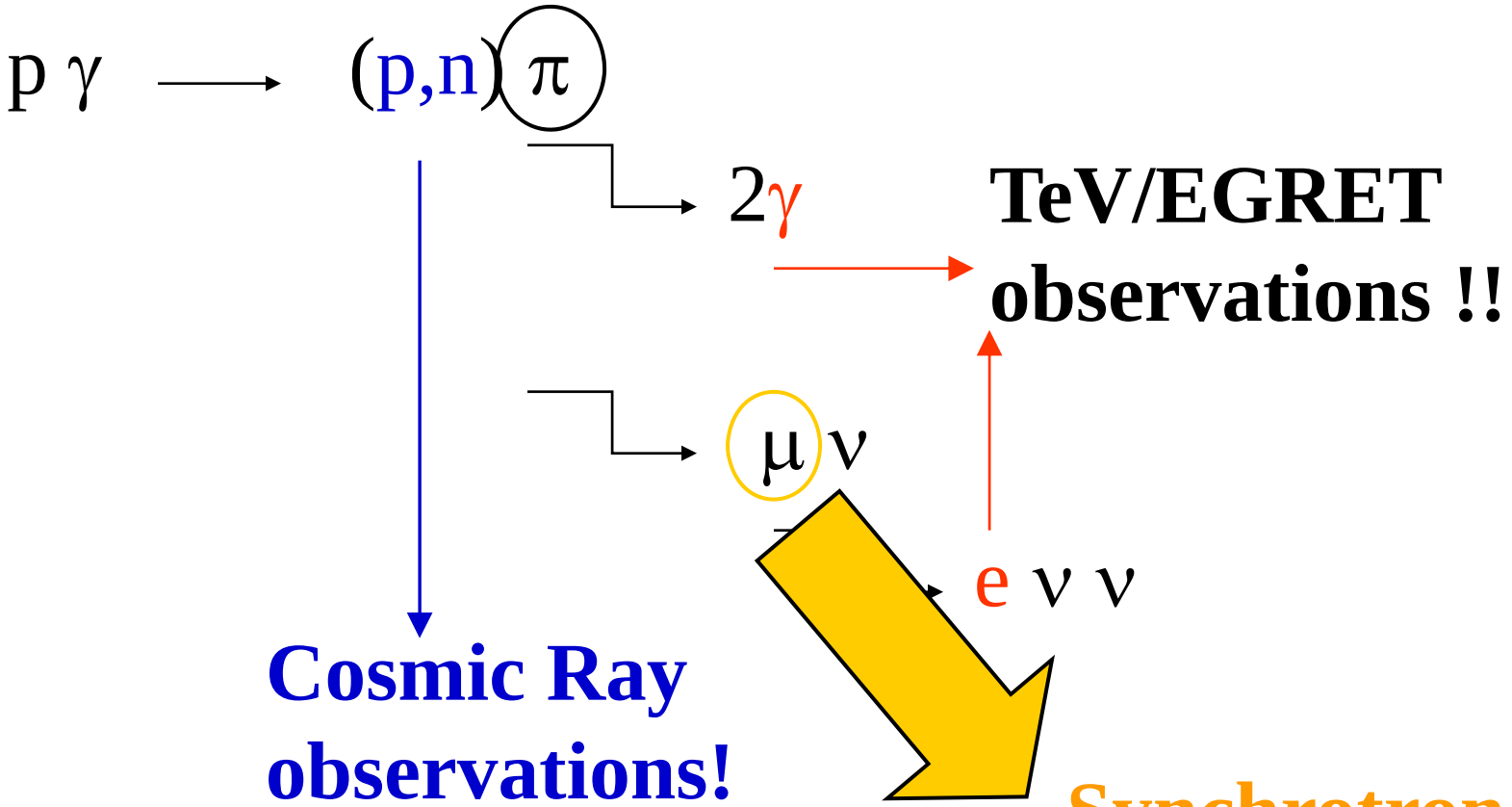
$$\varepsilon_{syn} = \frac{t_{syn}}{\tau} \qquad \tau = \tau_{rest}\left(\frac{E^{obs}}{m\Gamma}\right) \qquad t_{syn}^{-1} = \frac{4}{3} U_{mag} \sigma_t \frac{m_e^2}{m^3}\left(\frac{E^{obs}}{m\Gamma}\right)$$

$$U_{mag} = \xi_B U_{rad} \quad \text{(equipartition)}$$

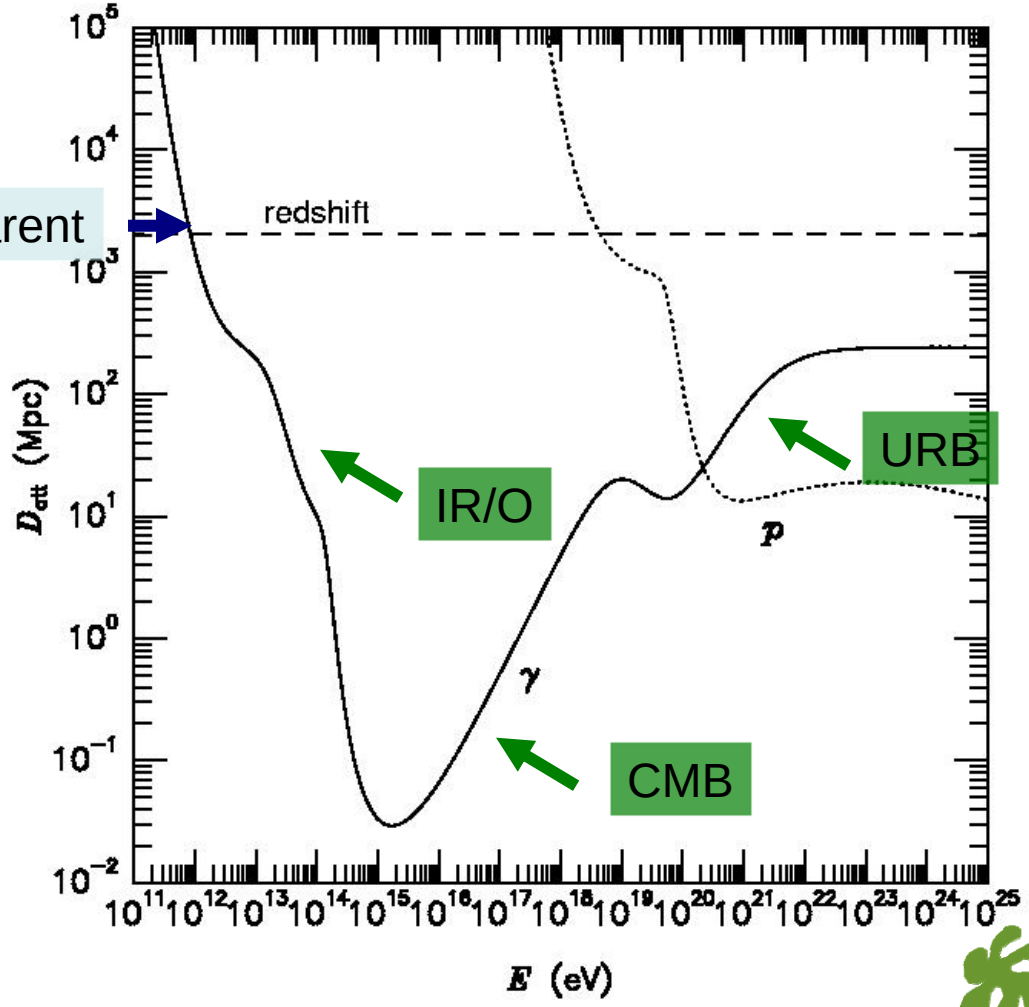
$$\varepsilon_{syn}^{\mu} = 2\times10^{-9}\left(\frac{E_{total}}{10^{56}\,erg}\right)^{-1}\left(\frac{\Gamma}{300}\right)^{8}\left(\frac{\Delta T}{10\,s}\right)^{3}\left(\frac{E\nu}{4\times10^{21}\,eV}\right)^{-2}\xi_B^{-1} \qquad \varepsilon_{syn}^{\pi} = 3.4\times10^{2}\,\varepsilon_{syn}^{\mu} \ll 1$$

$$\varepsilon_{syn} \sim 1 \longrightarrow E_{\nu} = 10^{19}\,eV\left(\frac{\Gamma}{300}\right)^{4} \sim E_{GZK}\ !!$$

You cannot expect too many ν!



(EHE) Photons in EBL

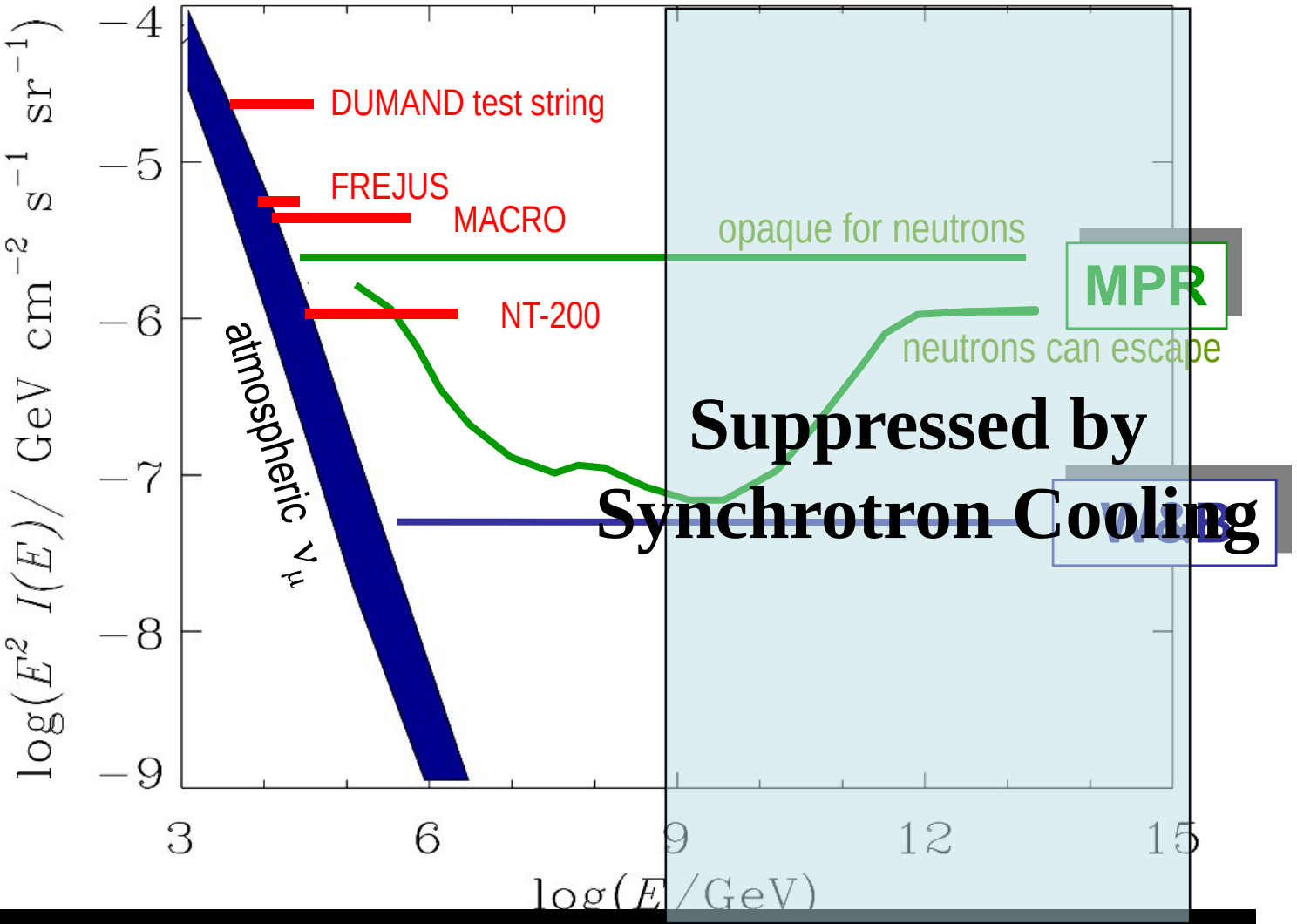


EM cascades lead to the diffuse γ-ray BG in the GeV range

Energy Conservation

$$E^2 \frac{dN}{dE}\Big|_{EHE} \mapsto E^2 \frac{dN}{dE}\Big|_{GeV}$$

Theoretical bounds



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

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

EHE(Extremely HE) ν

Synchrotron cooling of μ …
Production sites with low B

→ **Intergalactic space!!**

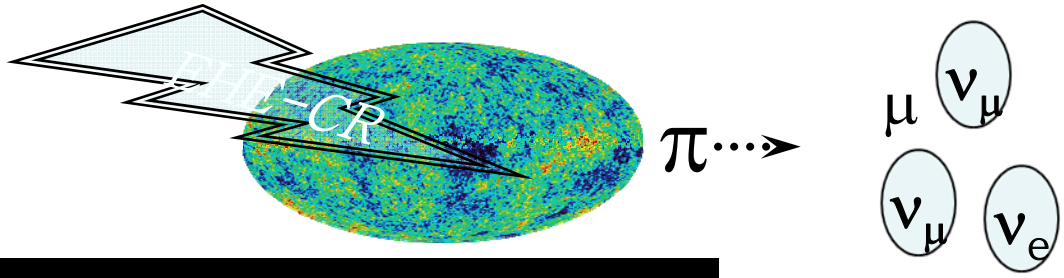
- **GZK Production**
- Z-burst
- Top Down Model --

Topological Defects/Super heavy Massive particles

GZK ν

$$p\gamma_{2.7K} \rightarrow \pi^{\pm} + X \rightarrow \mu^{\pm} + \nu \rightarrow e^{\pm} + \nu's$$

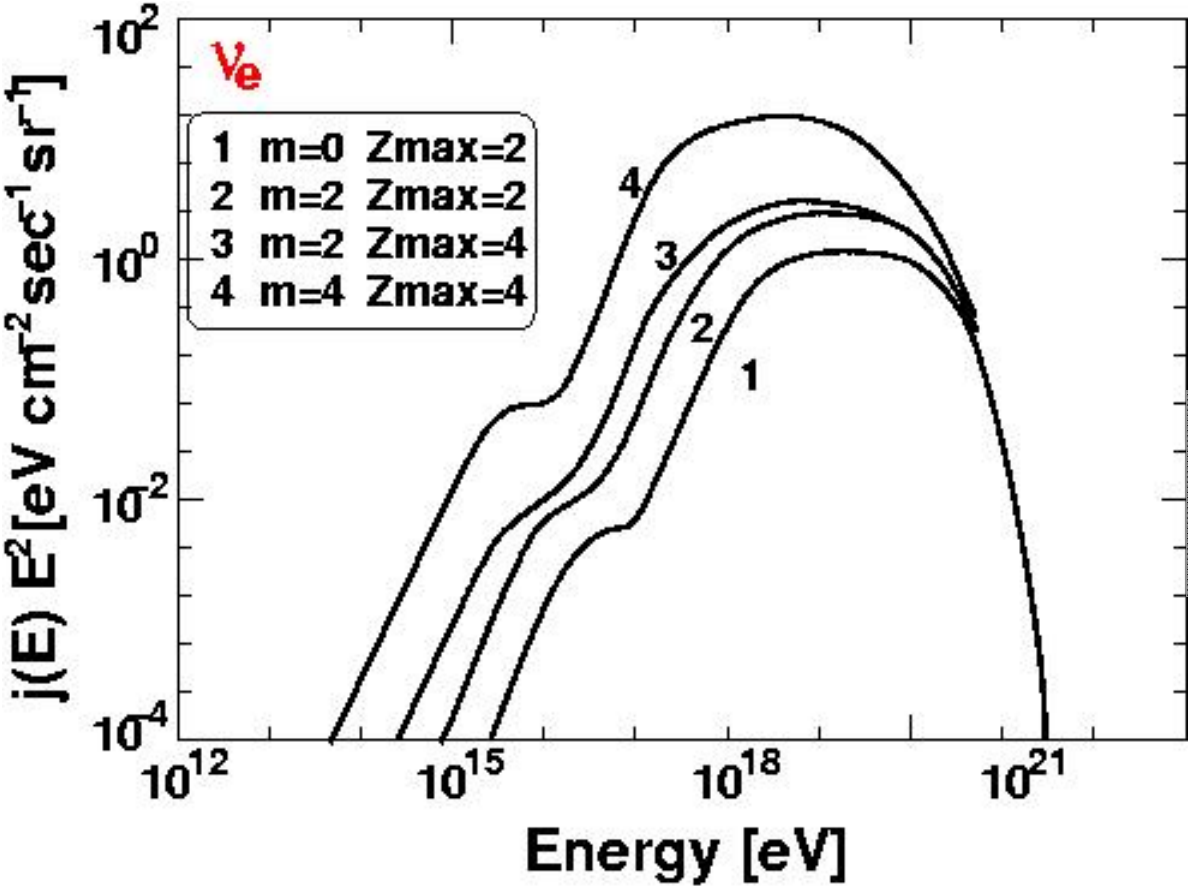
- The standard scenario



EHE cosmic-ray
induced neutrinos

The main energy range: Eν ~ 10^{9-10} GeV

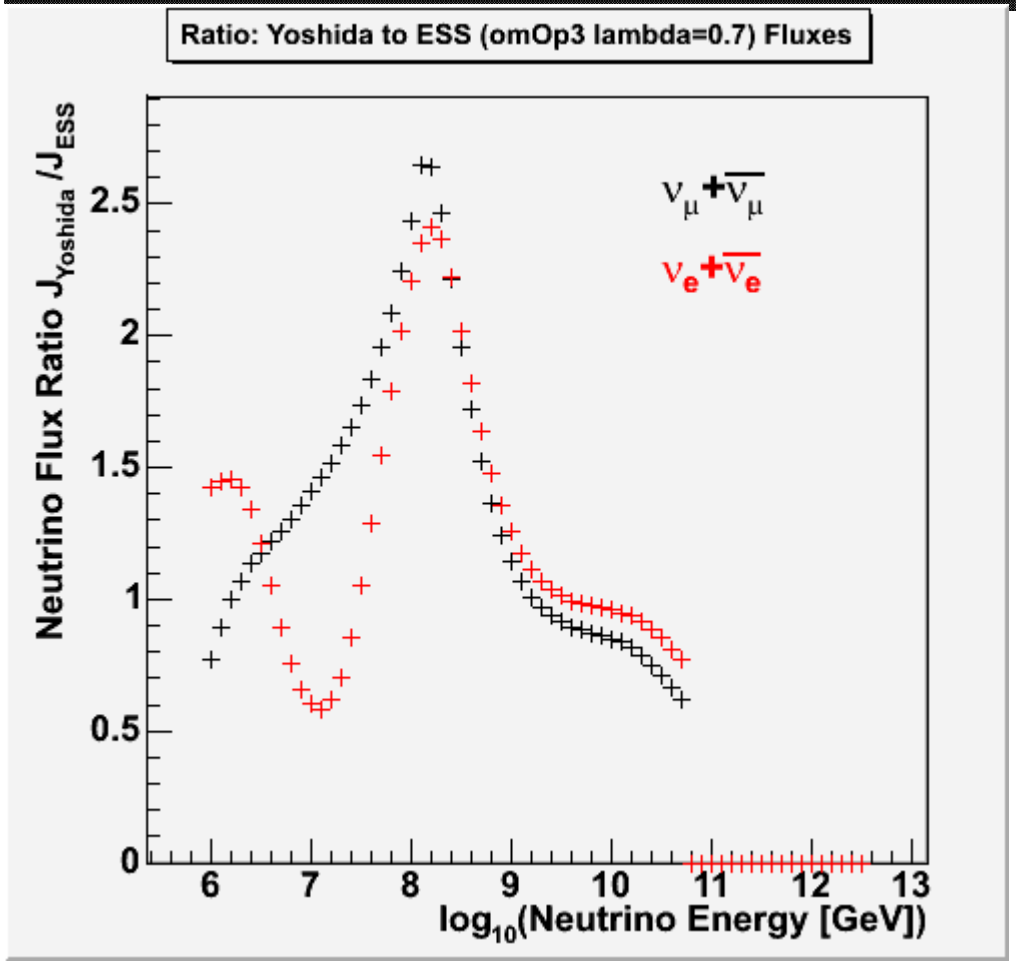
GZK ν



$$\int_0^{z^{max}} dz(1+z)^{m-\frac{5}{2}} J(E(1+z))$$

Yoshida, Teshima, Prog.Theo.Phys. 1993

GZK ν – it's robust



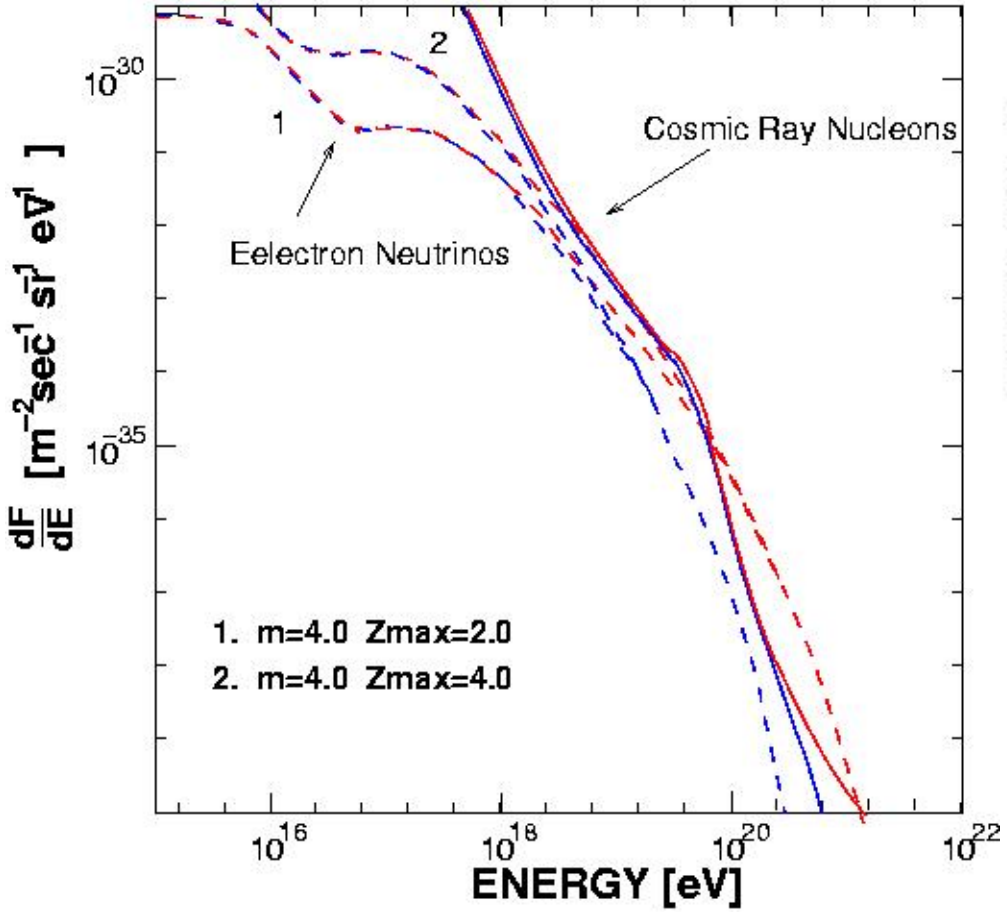
Yoshida, Teshima. 1993

Engel, Seckel, Stanev 2001

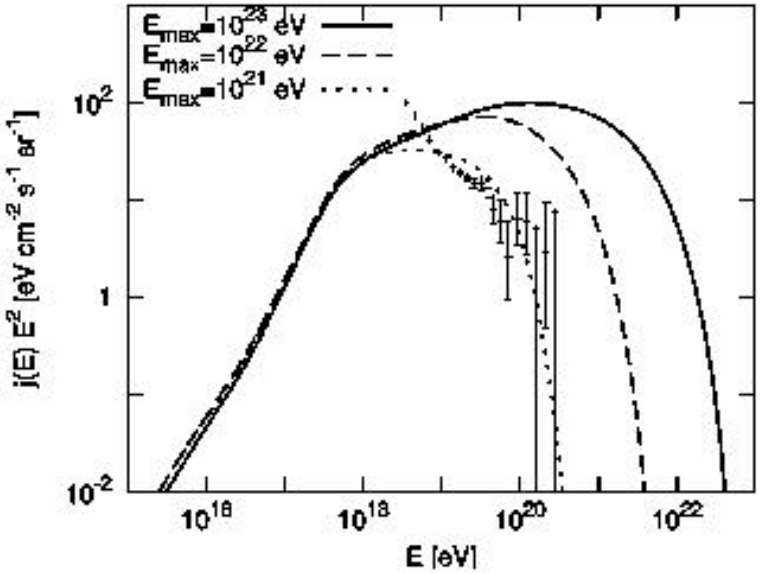
Compiled by A. Ishihara

GZK ν – parameter dependences

ENERGY SPECTRUM



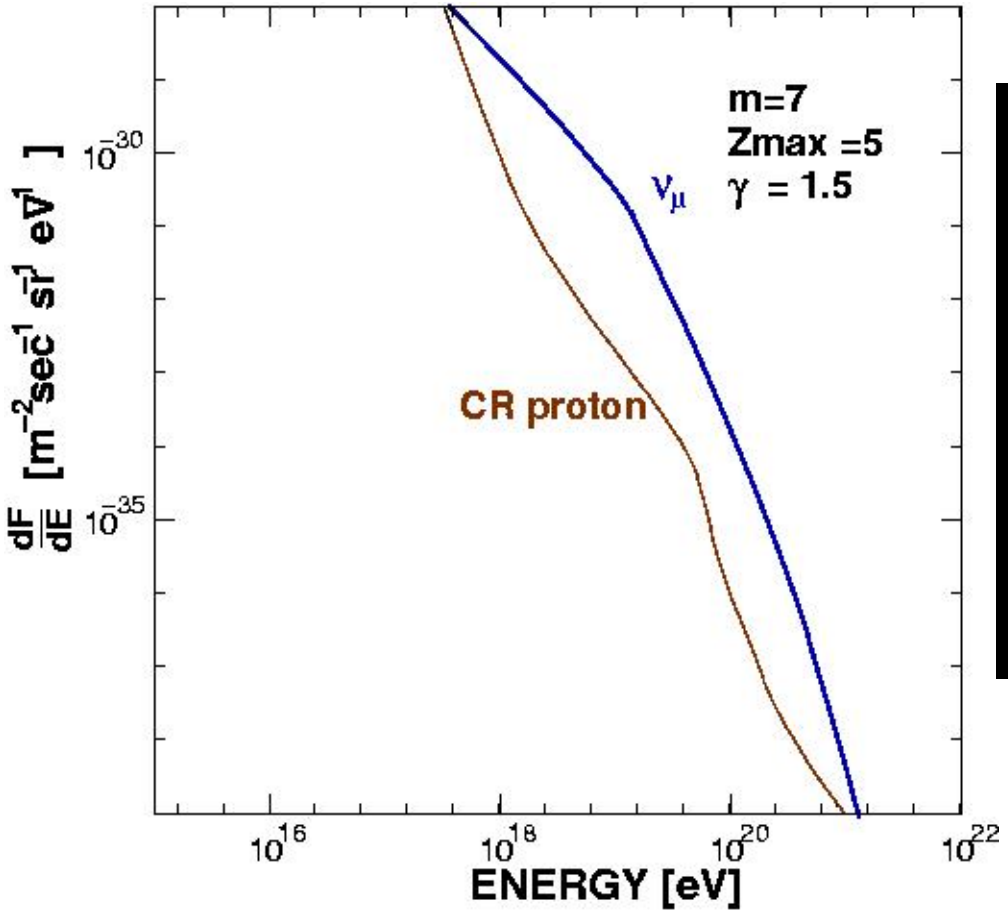
Yoshida, Teshima, Prog.Theo.Phys. 1993



Kalashev et al PRD 2002

E_{max}, $E^{-\alpha}$ → J(E>10 EeV)
m, Zmax → J(E<1EeV)

GZK ν – Strong Evolution case



Yoshida, Dai, Jui, Sommers ApJ 1997

Hard primary proton spectrum
+
strong evolution of sources

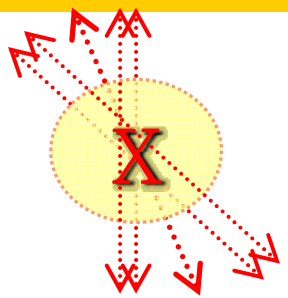
Unlikely case, but
- Flux >> Waxman.Bahcall
- GeV diffuse γ OK with EGRAT
- Reachable even by present detectors.

Top Down models don't die

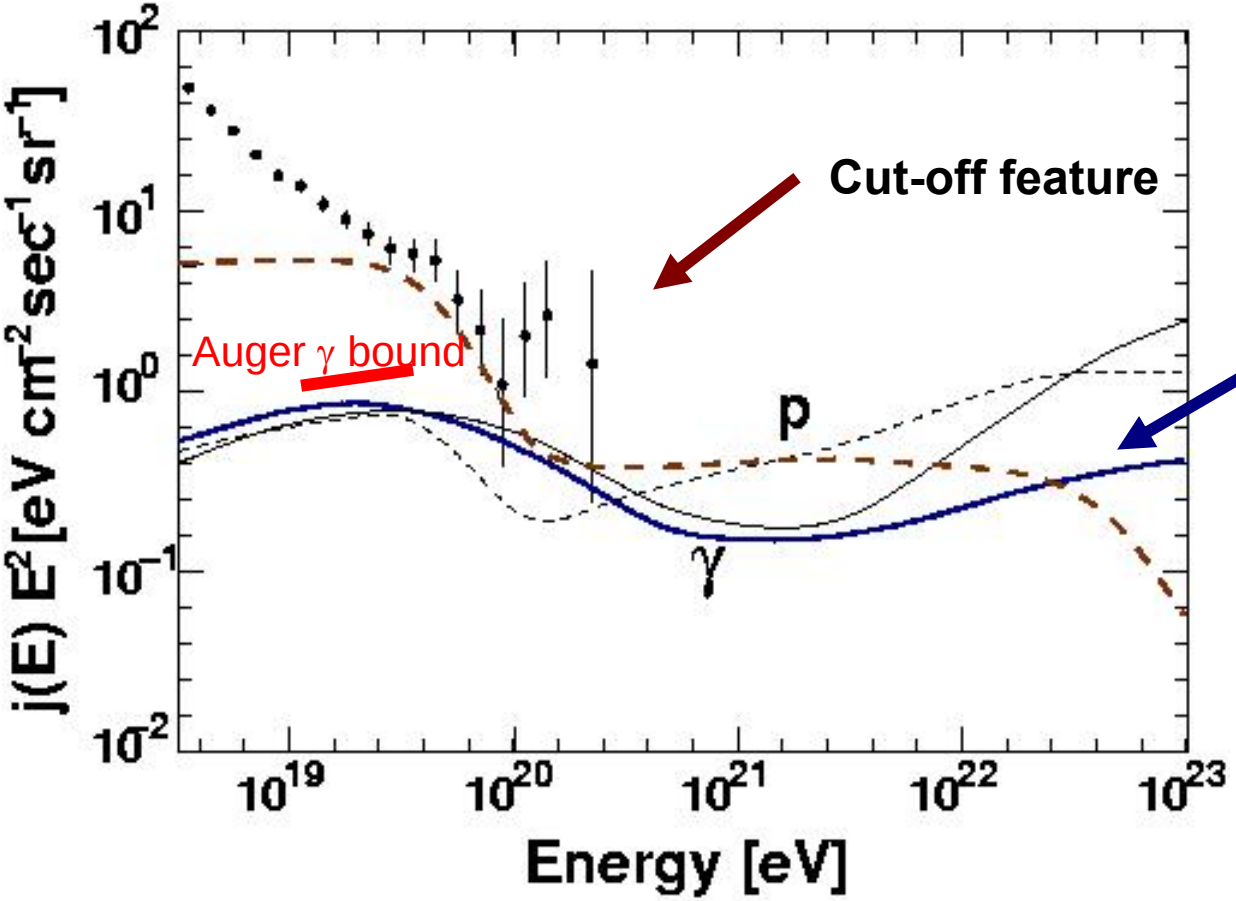
Beyond the Standard Model

Top-Down neutrinos
decays/interaction of massive particles
(topological defects, SUSY, micro black hole, …)

The main energy range: $E\nu \sim 10^{11-15}$ GeV



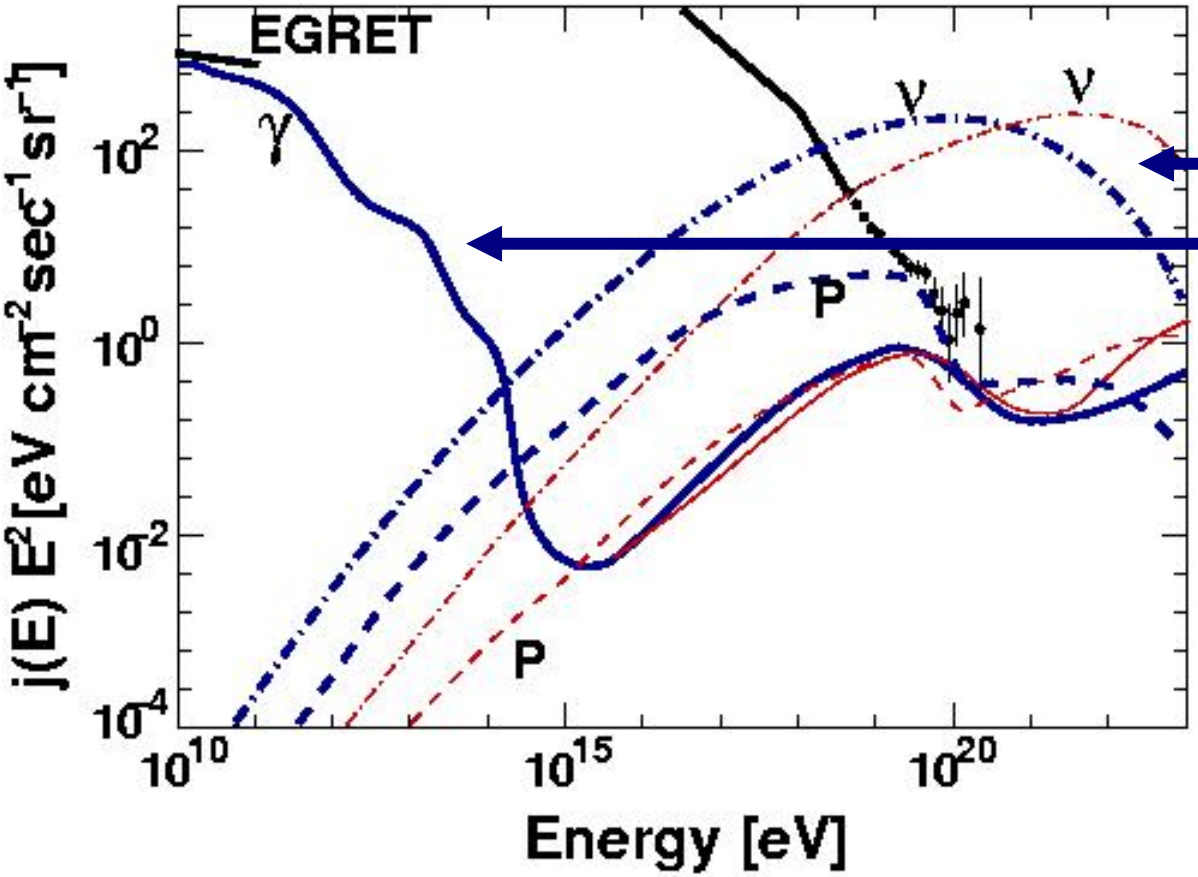
Top Down models don't die



γ suppressed
by (unknown) URB

Sigl, Lee, Bhattacharjee, Yoshida, PRD 1999

Top Down models don't die

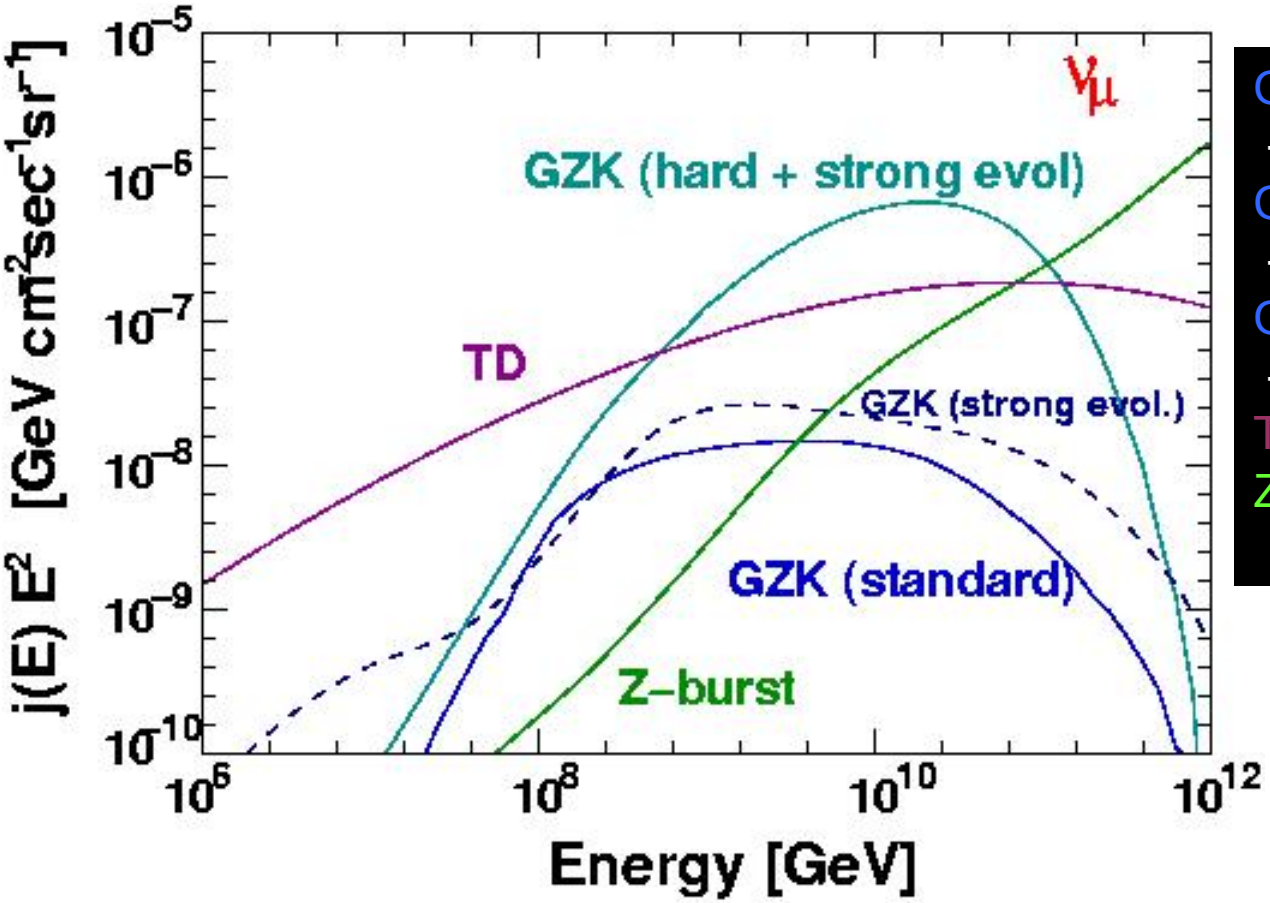


A bunch of ν

Recycling γ in 100 GeV region

Sigl, Lee, Bhattacharjee, Yoshida, PRD 1999

UHE/EHE ν fluxes



GZK (hard, high Emax)
- Kalashev et al 2002
GZK (strong evolution)
- ibid
GZK (standard)
- Yoshida Teshima 1993
TD - Sigl et al 1999
Zburst –
Yoshida et al 1998

Explore Particle Physics

ν Flux measurement

$$\text{Rate} = \text{V}\,\Omega\,\text{T} \otimes N_A\sigma \otimes \phi(\text{E}_\nu)\exp(-N_A\sigma\,\text{X})$$

- Detector+ Geometry
- Interaction
- Unknown FLUX
- Absorption

Explore Particle Physics

ν Cross Section measurement !!

$$\text{Rate} = \text{V}\,\Omega\,\text{T} \otimes N_A\sigma \otimes \phi(\text{E}_\nu)\exp(-N_A\sigma\,\text{X})$$

Detector+ Geometry

Interaction

GZK ν FLUX

Absorption

Kusenko, Weiler PRL. 2002

Downgoing events / Upgoing events

Tyler, Olinto, Sigl PRD. 2001

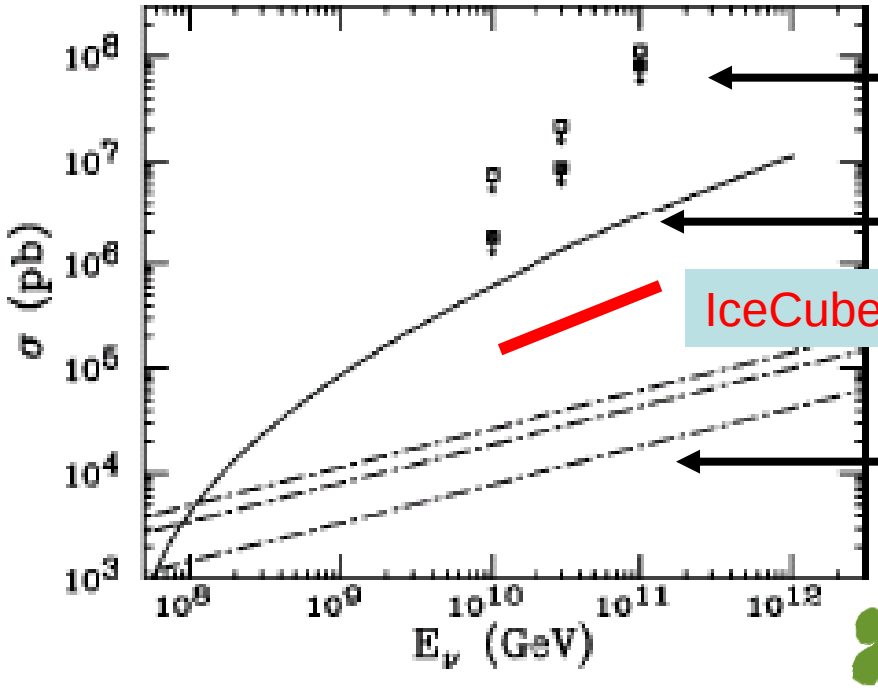
$$\sigma_{CC}(\text{E} \geq 10^9\ \text{GeV}) \leq\sim 10^{-29}\ \text{cm}^2$$

Explore Extra Dimension

Tyler, Olinto, Sigl PRD. 2001

$$\sigma \approx 10^{-28}\left(\frac{M_{4+n}}{1\mathrm{TeV}}\right)^{-4}\left(\frac{E_\nu}{10^{10}\,\mathrm{GeV}}\right)\mathrm{cm}^2$$

Anchordoqui, Feng et al PRD. 2002



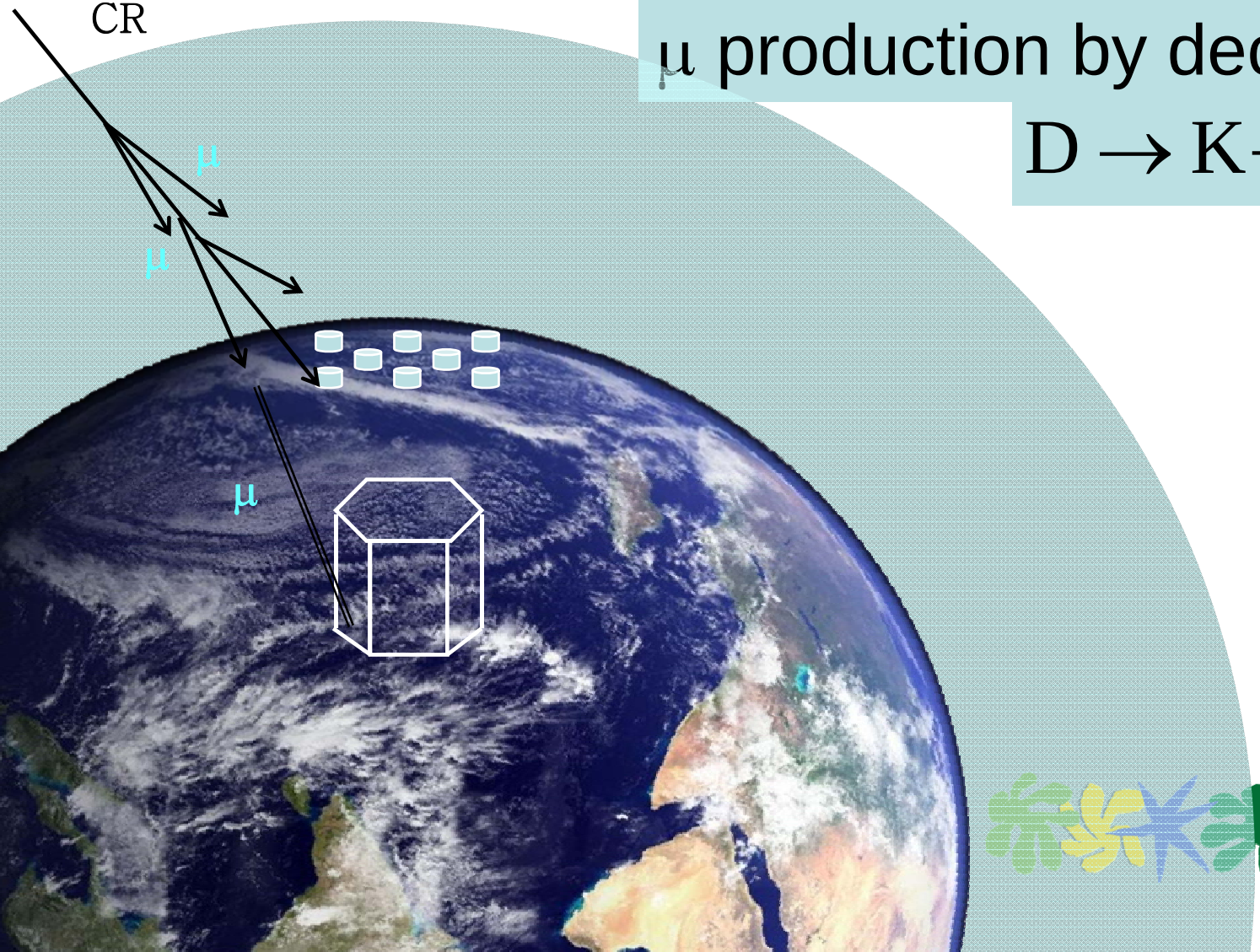
Model Independent limits

BH production limit

IceCube sensitivity

SM CC/NC σ

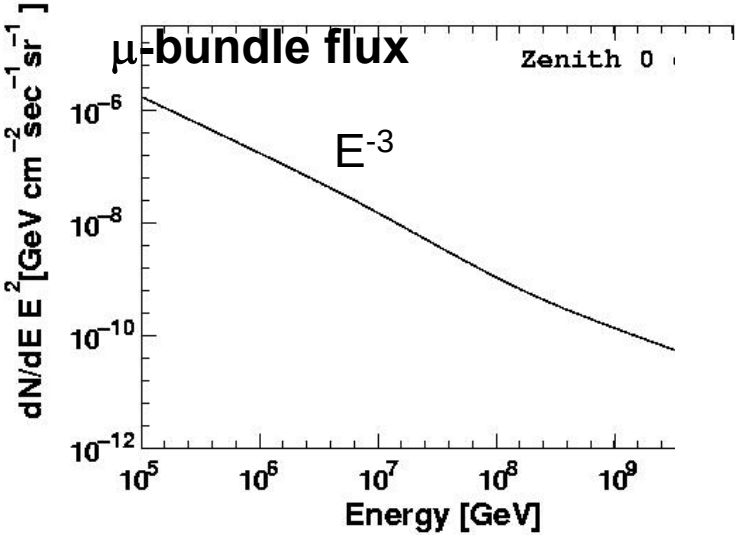
Explore Particle Physics



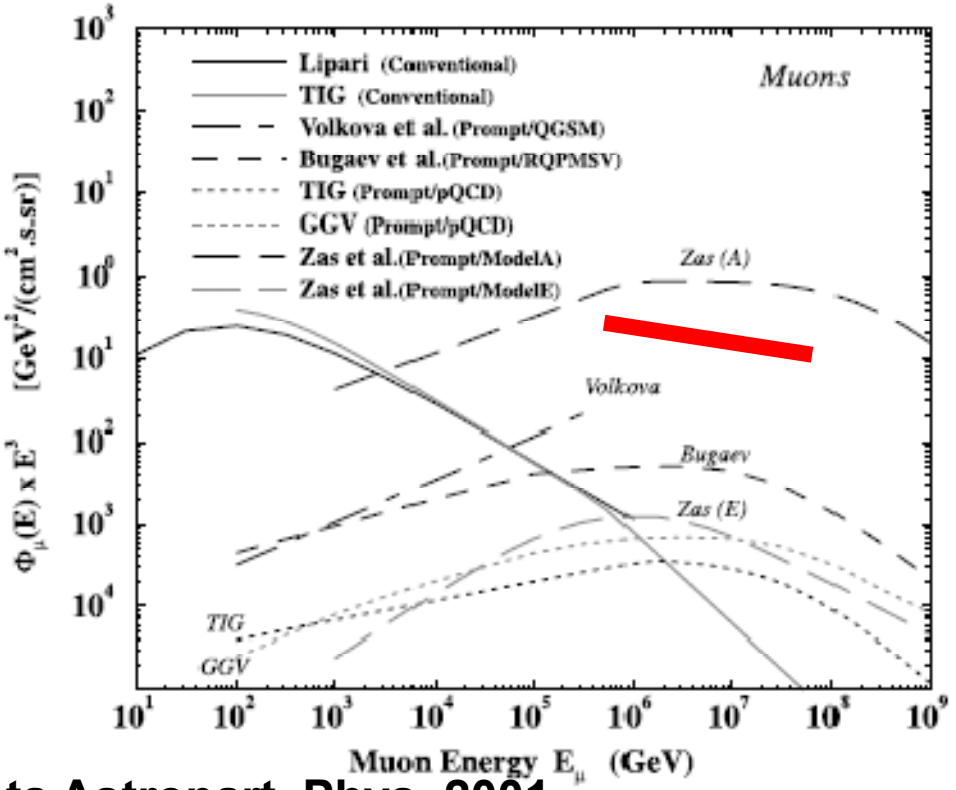
μ production by decay of D/Λ

$$D \rightarrow K + \mu + \nu$$

Explore Particle Physics

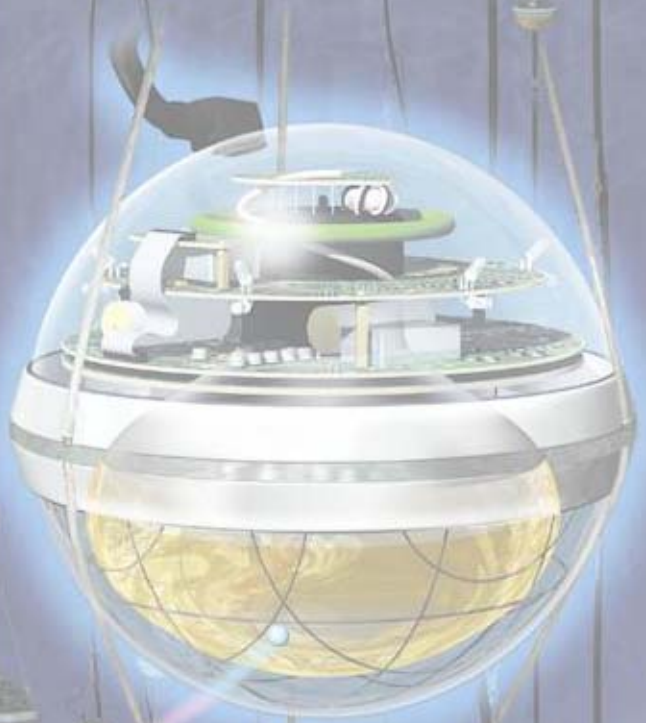


IceCube 2006 data suggestion



Costa Astropart. Phys. 2001

Neutrino Observation



Completed by 2011

The IceCube Observatory

~1 km

IceTop

AMANDA

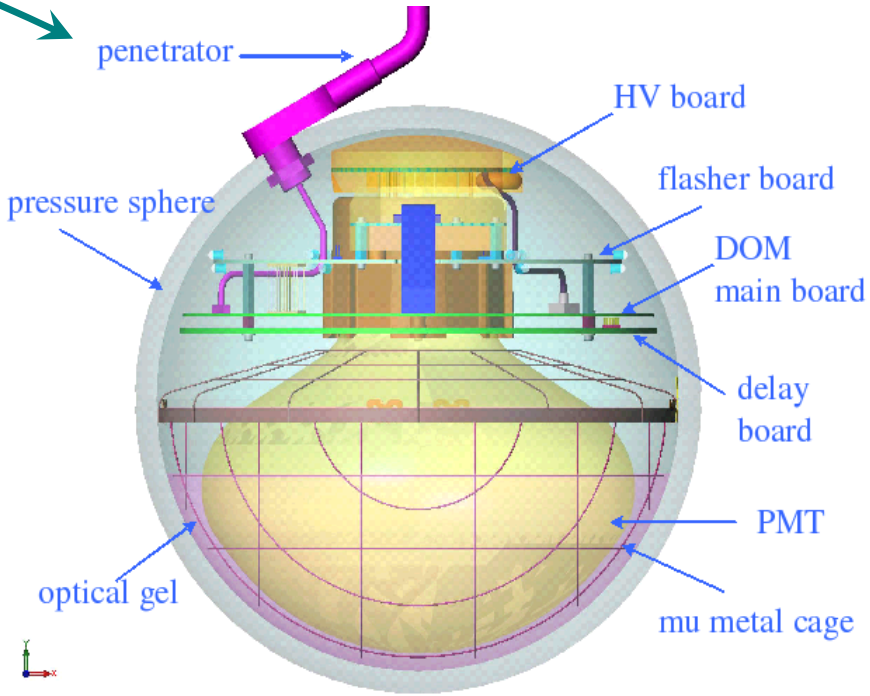
1450m

60 DOMs

2450m

324 m

Digital Optical Module

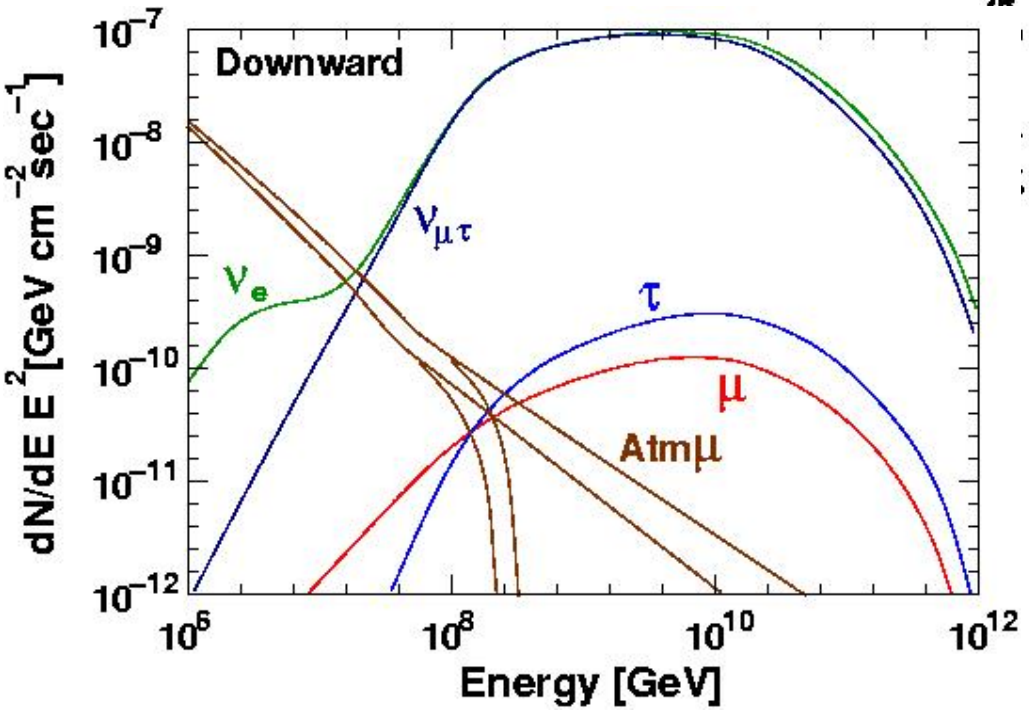


400ns/6.4μs time range

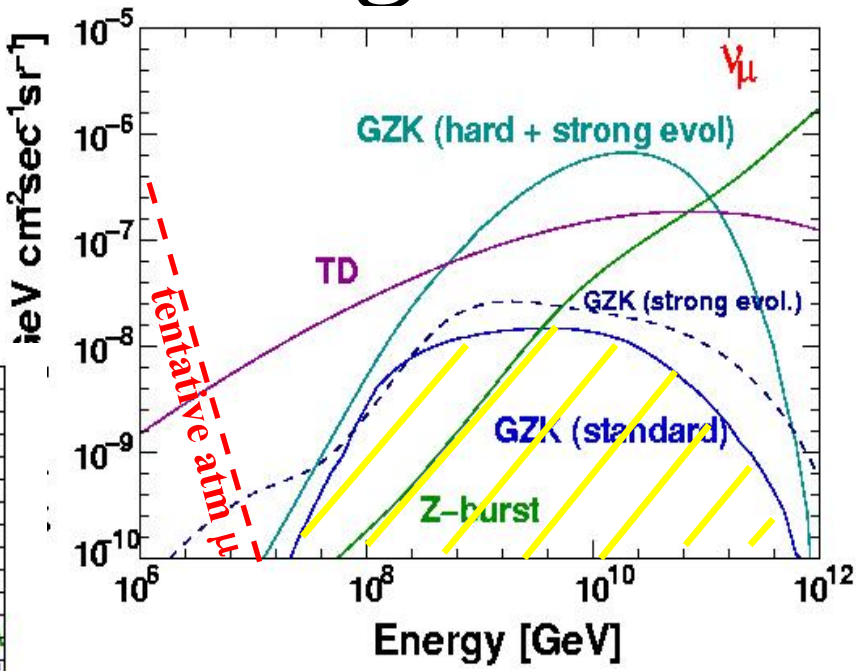
- 400 photoelectron/15ns
- measure individual photon arrival time
- 1~2ns time resolution

EHE Neutrino Underground

Fluxes at the IceCube depth



S. Yoshida et. al. (2004)
Phys. Rev. D 69 103004



<u>main signal</u>

GZK neutrino induced leptons

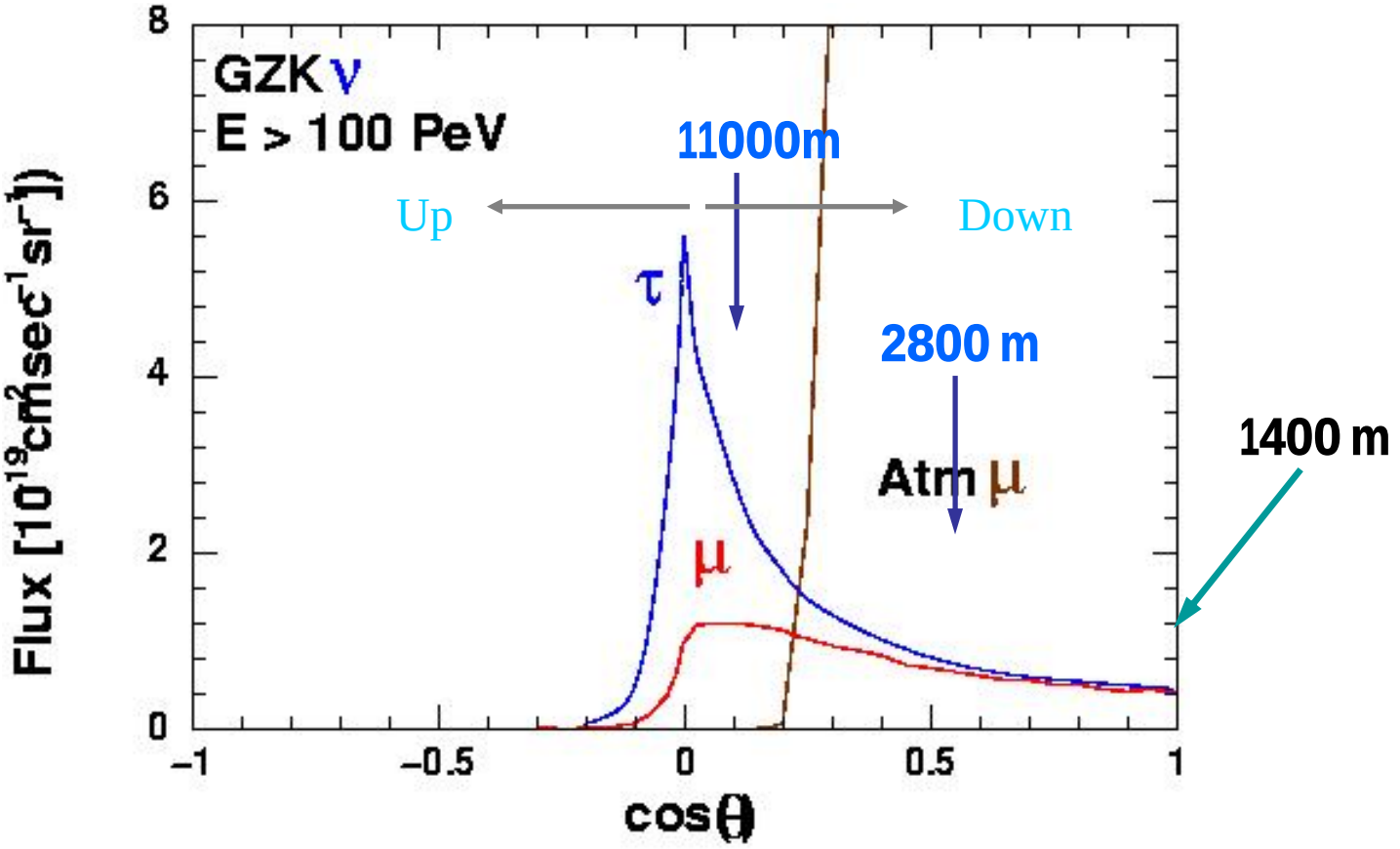
<u>background</u>

Atmospheric muon

$E_{GZK} >> E_{Atm\mu}$!!

Simple energy cut works!

And coming horizontally..

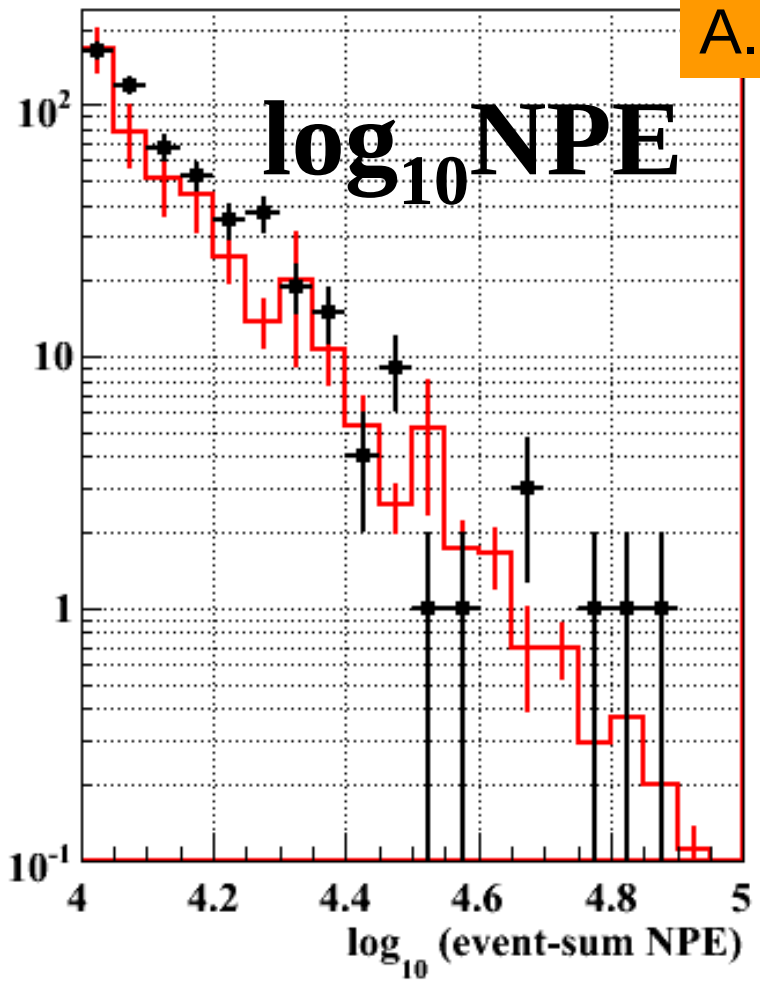


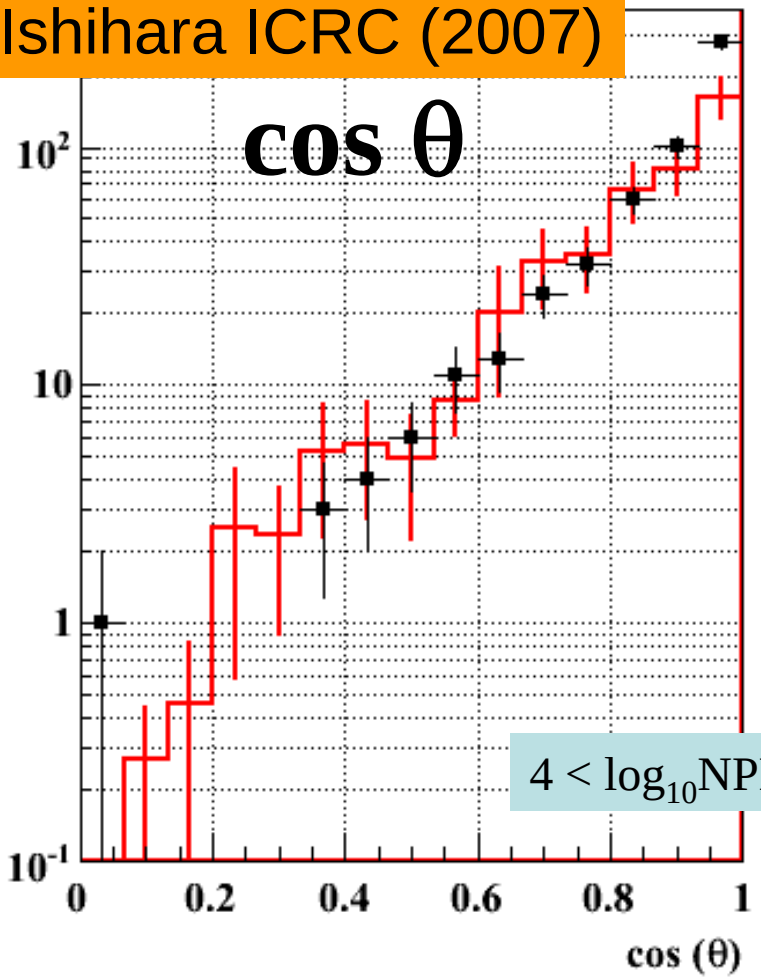
μ BG Data-MC comparison

Partial experimental data

atmospheric μ simulation model

A. Ishihara ICRC (2007)

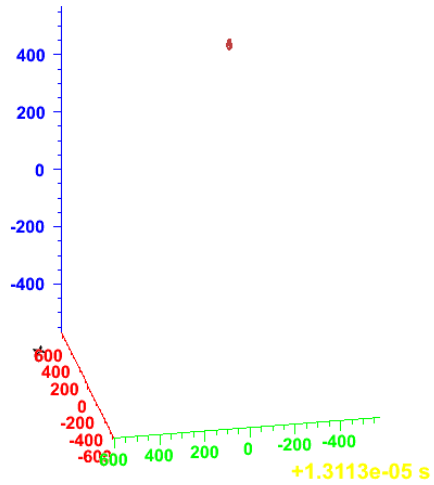


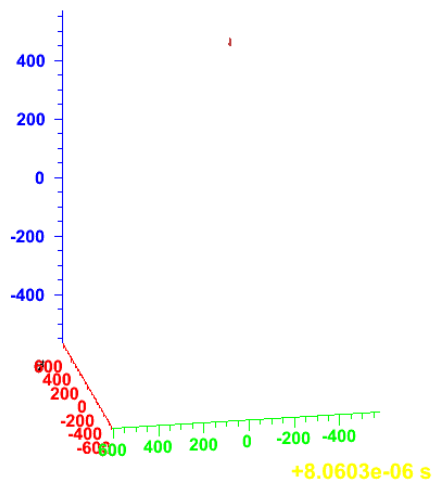


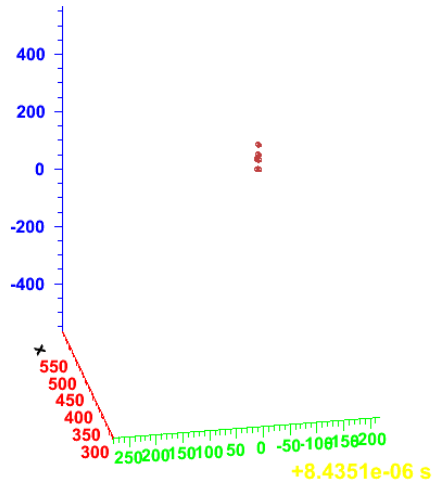
$4 < \log_{10}\mathrm{NPE} < 5$

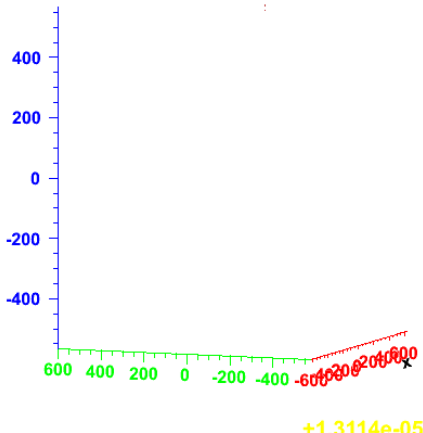
The 2006 9-string real data

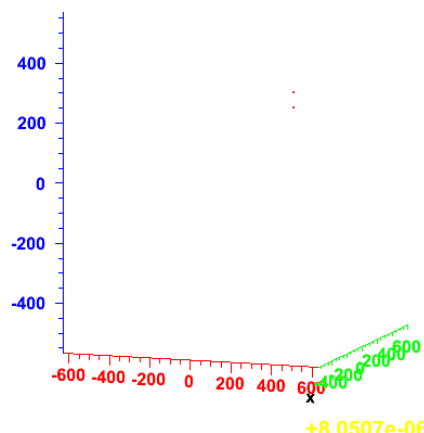
Example Bright Events







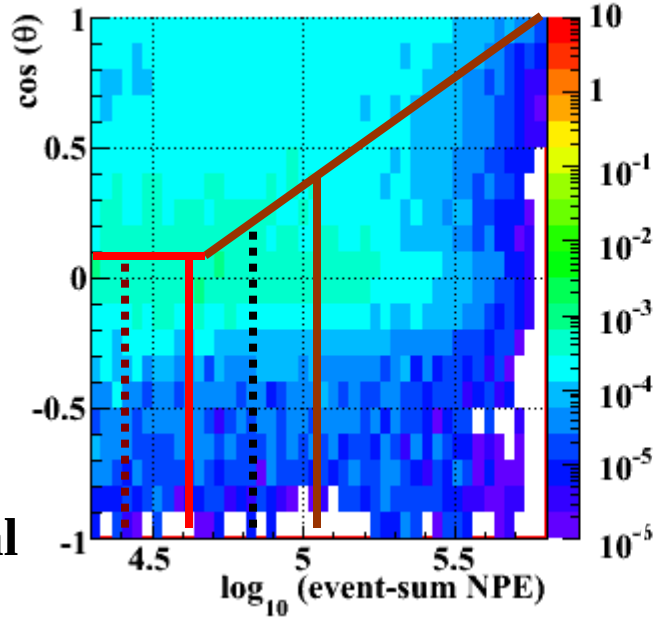


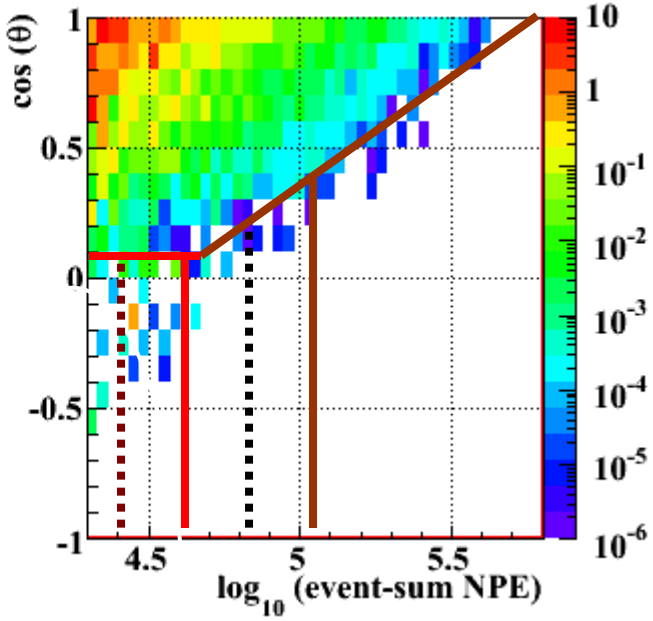


2007/9/4

Event Selection and Numbers

GZK signal





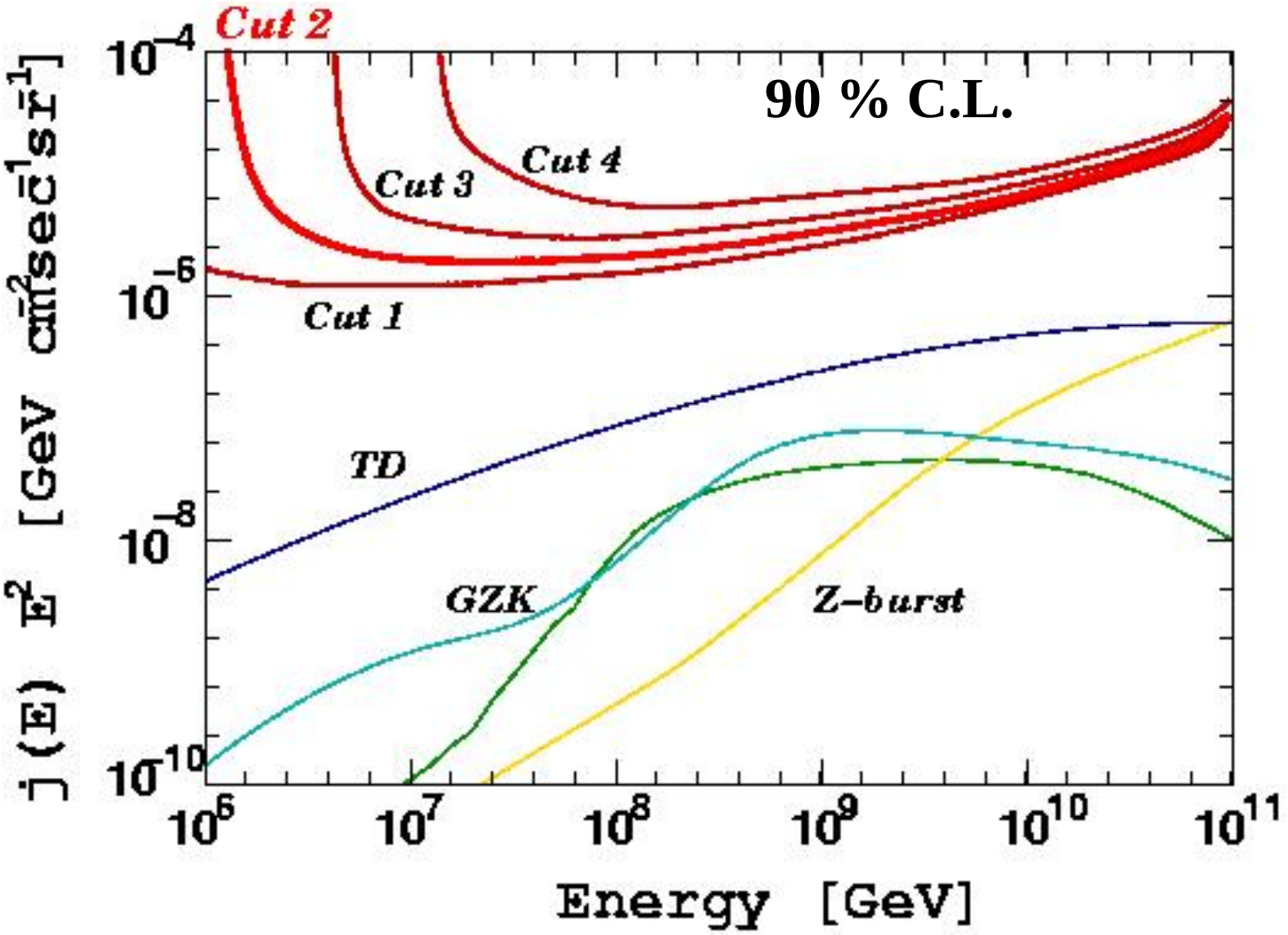
Atm. μ

Cut Level	GZK ν events $\nu_e+\nu_\mu+\nu_\tau$	Atmospheric μ model 1	Atmospheric μ model 2
1 (dotted brown)	0.055	0.003	0.006
2 (solid red)	0.046	$< 10^{-4}$	$< 10^{-4}$
3 (dotted black)	0.036	$< 10^{-4}$	$< 10^{-4}$
4 (solid brown)	0.024	$< 10^{-4}$	$< 10^{-4}$

A. Ishihara ICRC (2007)

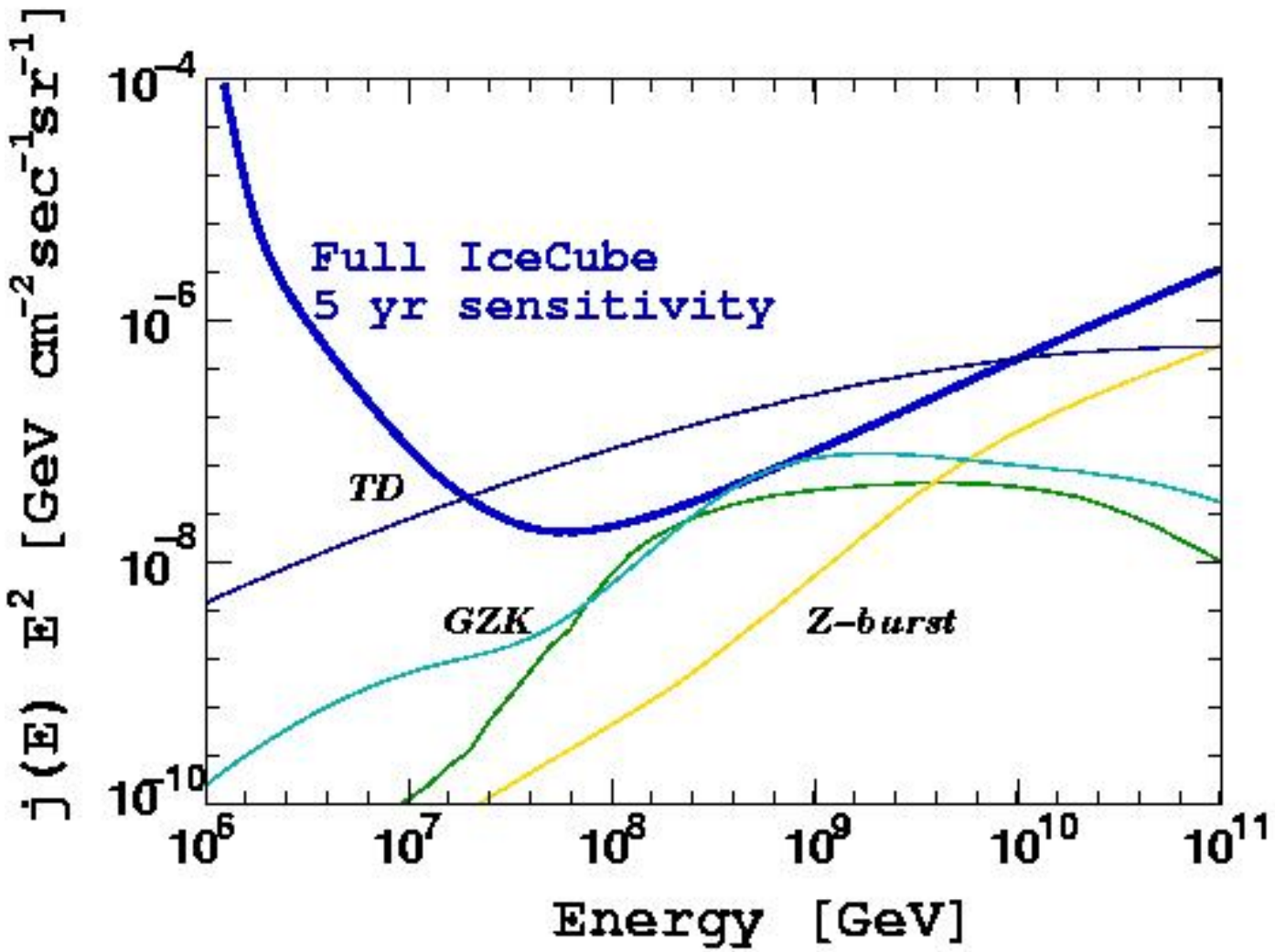
Upper bound of EHE flux

$E^2 \phi^{cut2}$ $(10^{6.5} < E < 10^{9.5}) \sim 10^{-6}$ [GeV cm^{-2} sr^{-1} sec^{-1}]



all ν flavors added assuming 1:1:1 ratio

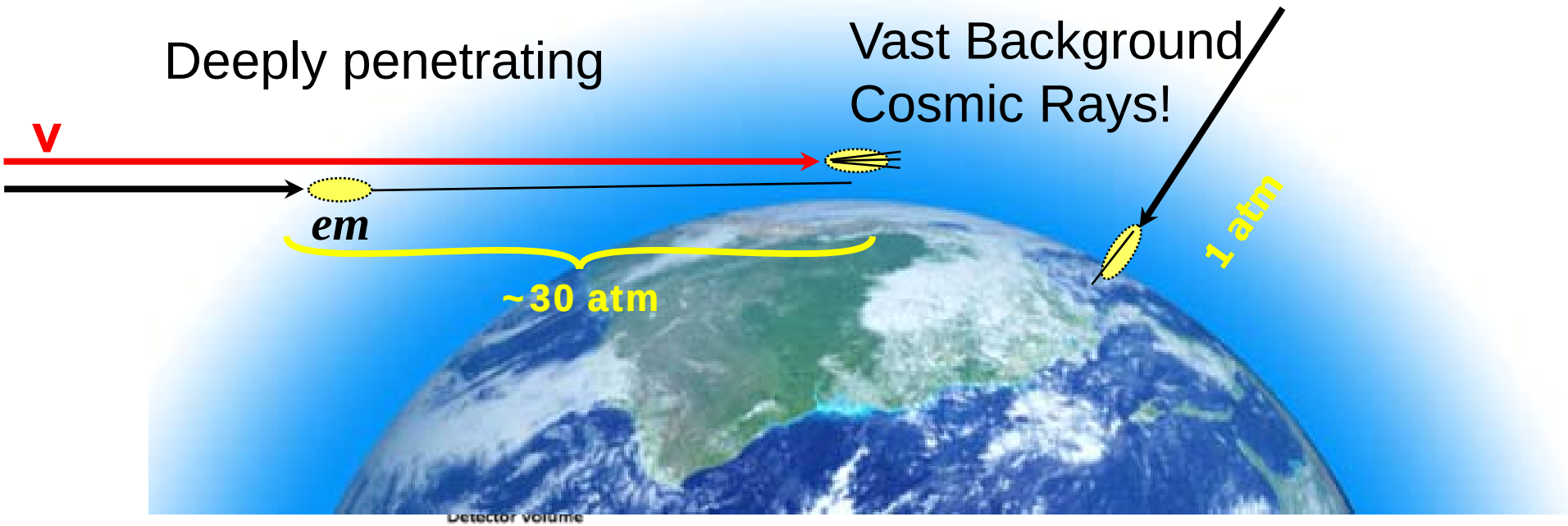
A “projected” sensitivity

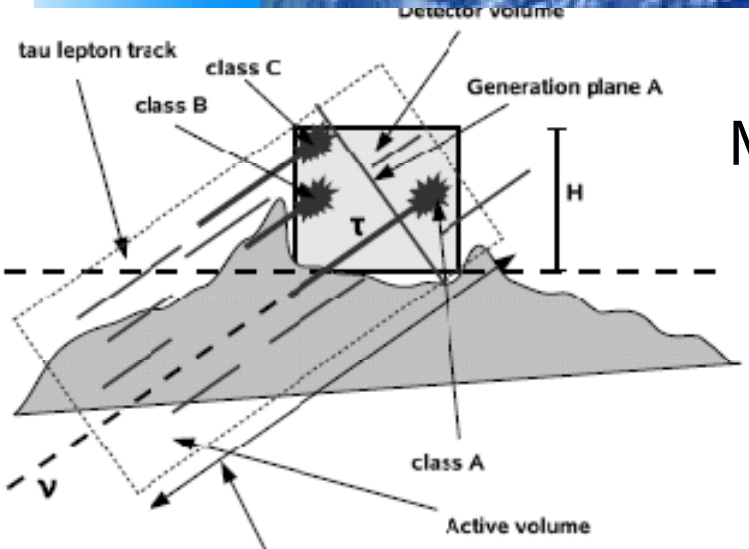


ν Search by the EAS detectors

Deeply penetrating

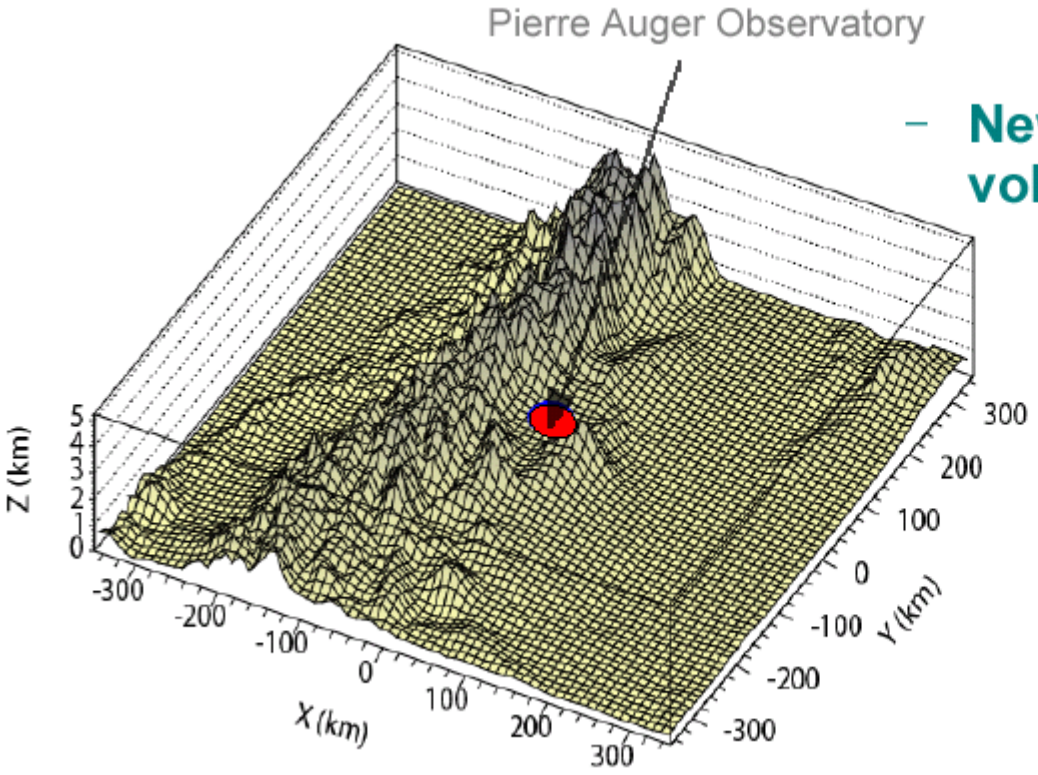
Vast Background
Cosmic Rays!



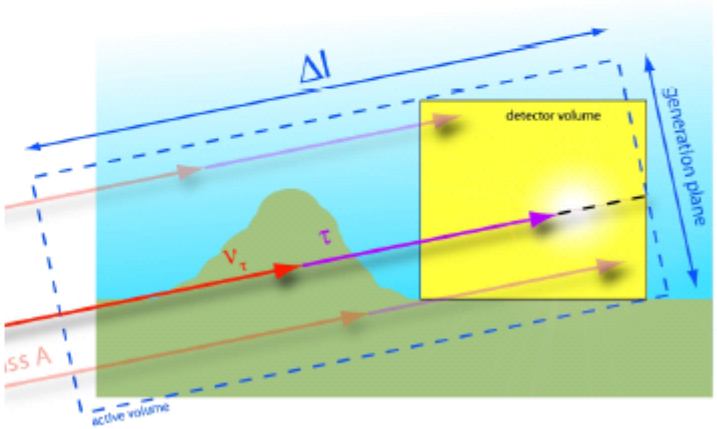


Mountain skimming

Auger

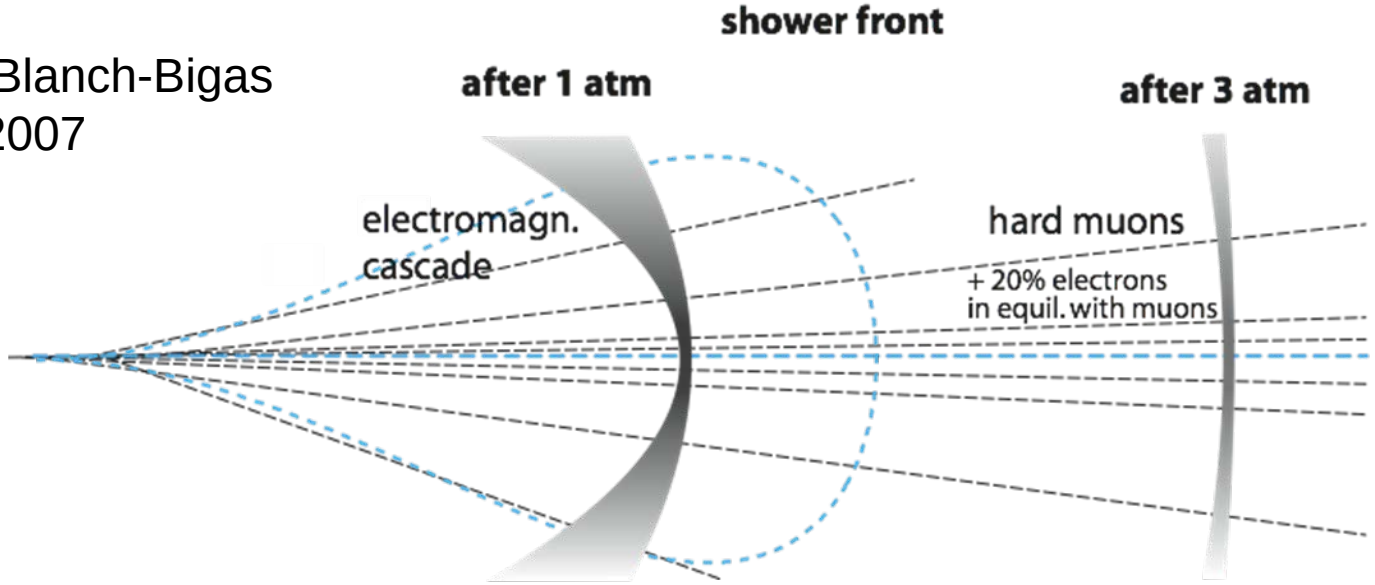


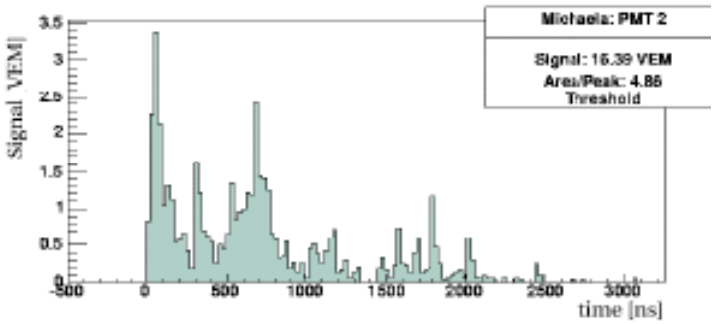
- **New definition of active volume**

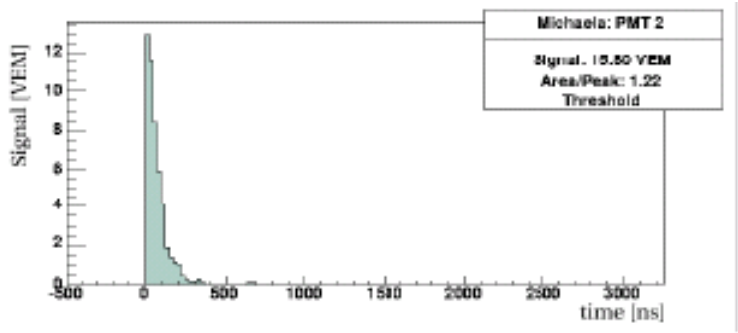


Auger

Oscar Blanch-Bigas
ICRC 2007





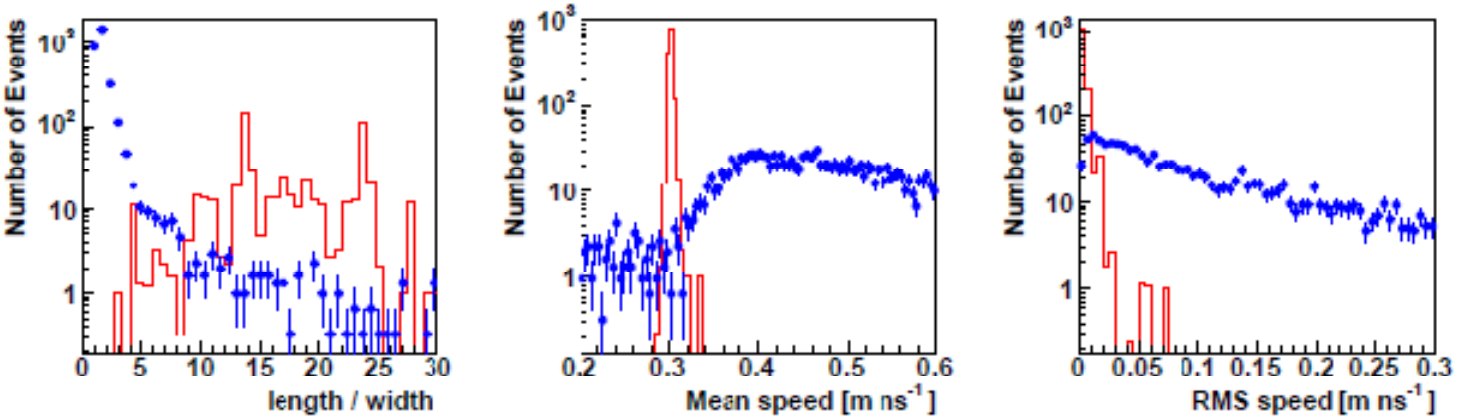


Select “young” showers

Oscar Blanch-Bigas
ICRC 2007

Then search for “horizontal” events

— ν MC
• Data



“0” events in the data survives the horizontal cuts

↓

Upper limit of ν_τ flux

HiRes

K. Martens et al
ICRC 2007/astro-ph07074417

1. search for horizontal events - low zenith (88.1 – 95.1 deg)
2. search for lower events in the atmosphere (R_p<20km)

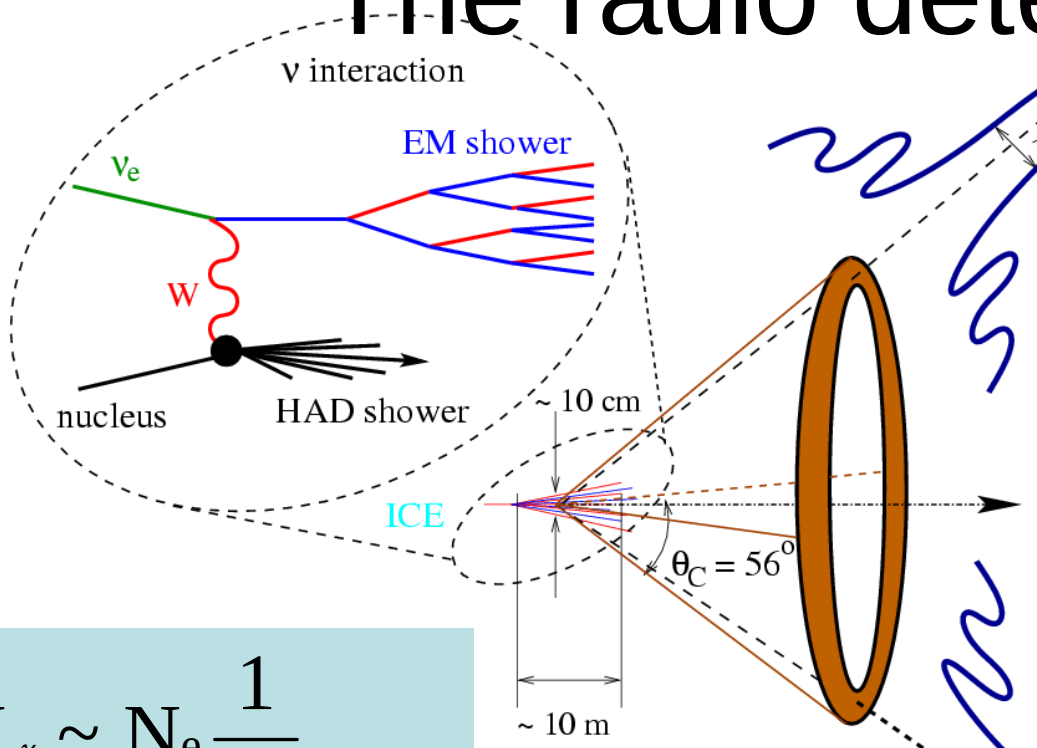
"134" events in the data survives the horizontal cuts

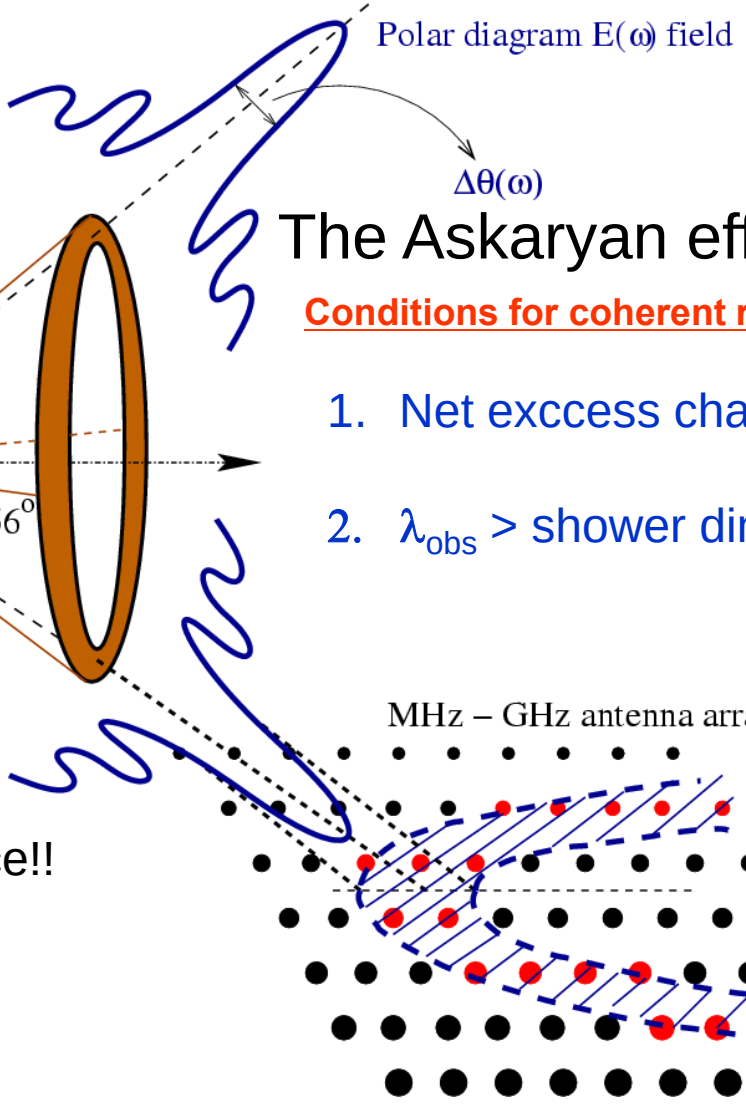
"Scattered" laser events off haze

↓

Upper limit of ν_τ flux

The radio detection





The Askaryan effect

Conditions for coherent radio emission

1. Net exccess charge
2. λ_{obs} > shower dimensions

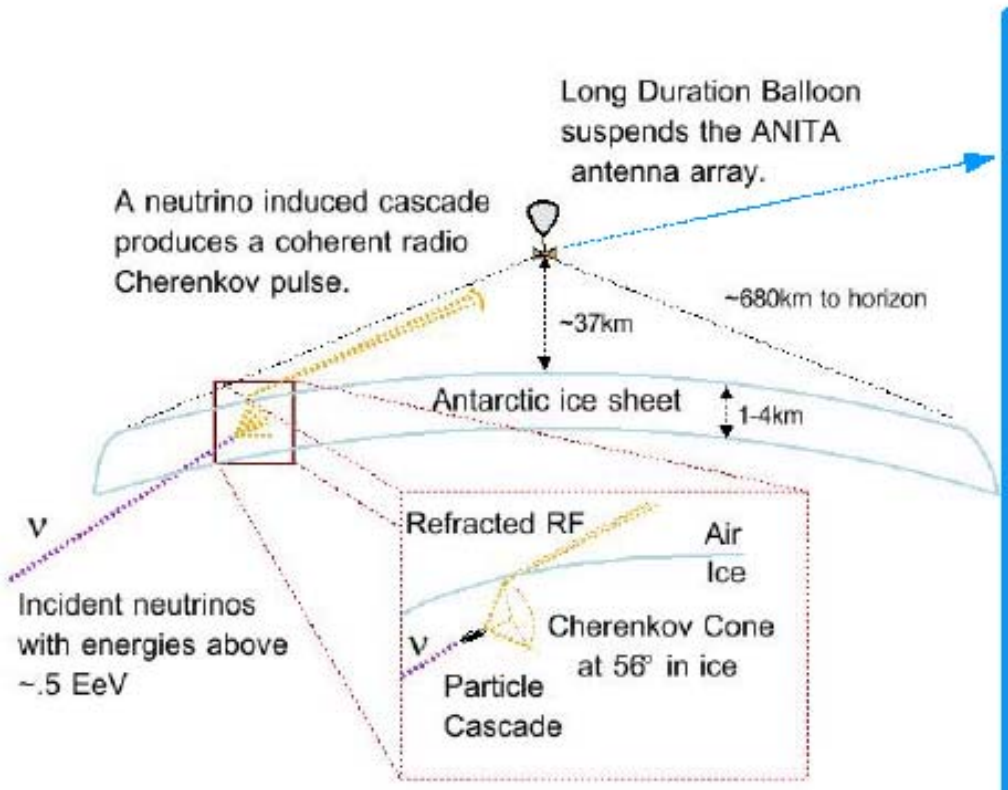
$$N_\gamma \sim N_e \frac{1}{\lambda^2}$$

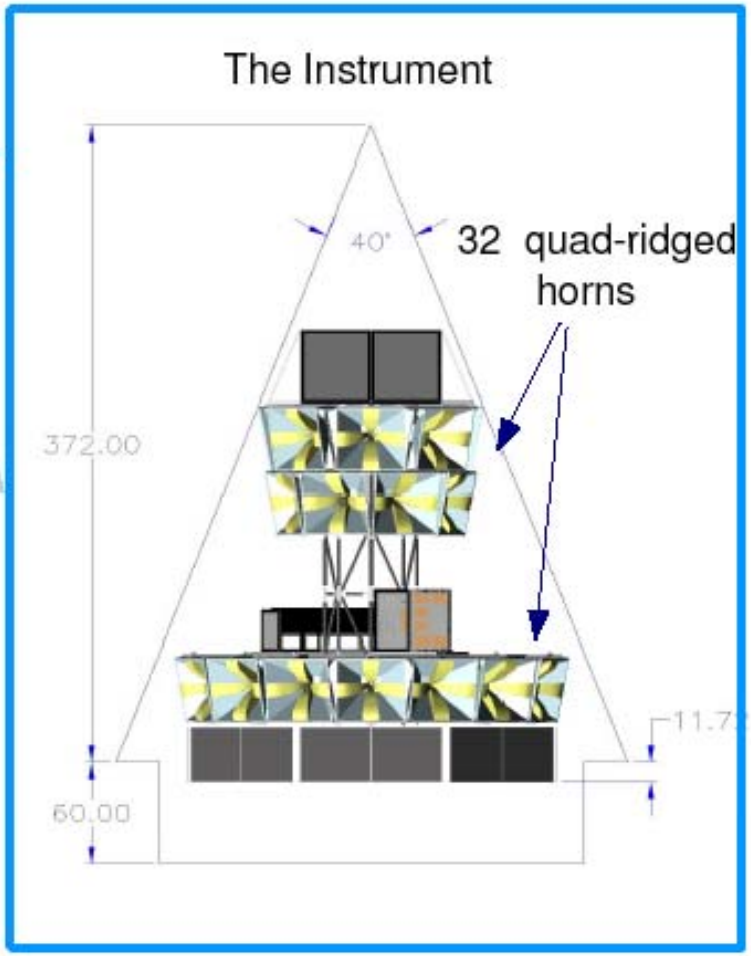
$$W \sim (N_e \Delta q)^2 \frac{1}{\lambda^2}$$

Coherence!!

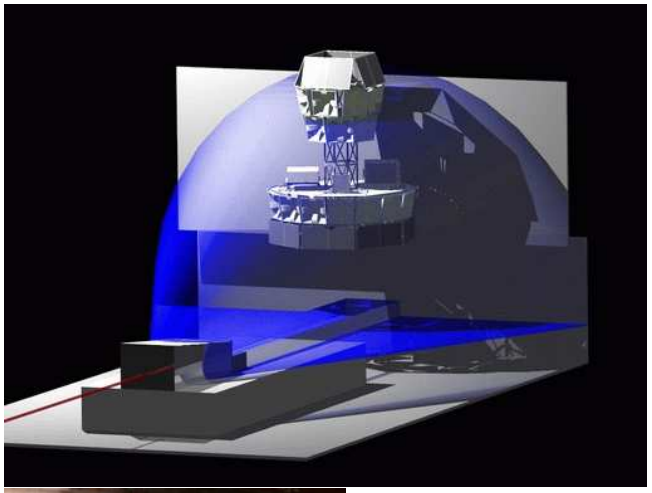
J. Alvarez–Muñiz & E. Zas (2005)

The ANITA Concept





Calibration of the Askaryan effect



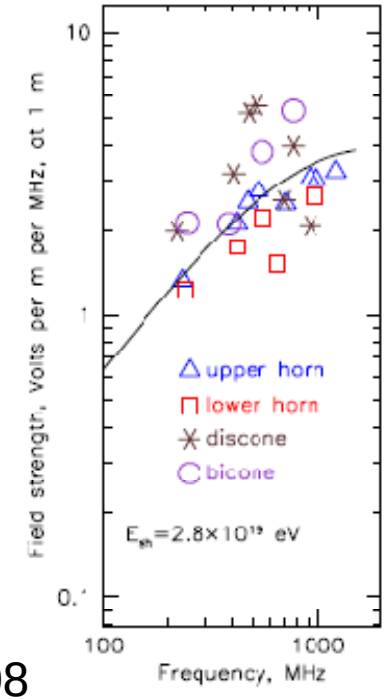
@SLAC 10^9 x 28.5 GeV e

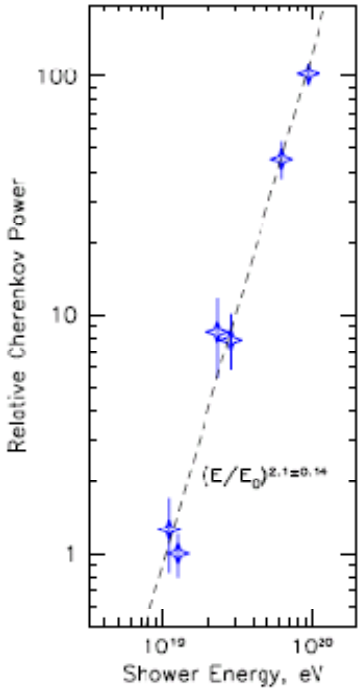
↓

$2x10^{10}$ e^+e^- in the target ice

↓

Anita instruments





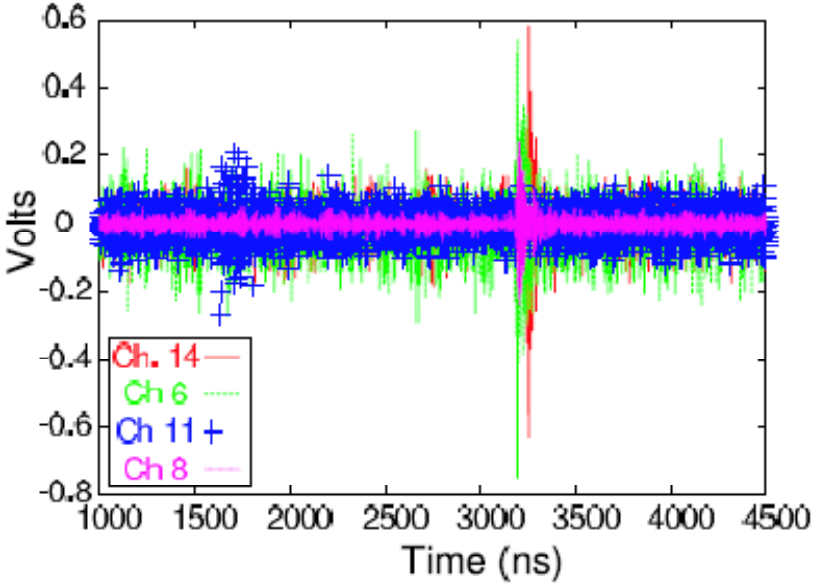
Gorham et al hep-ex/0611008

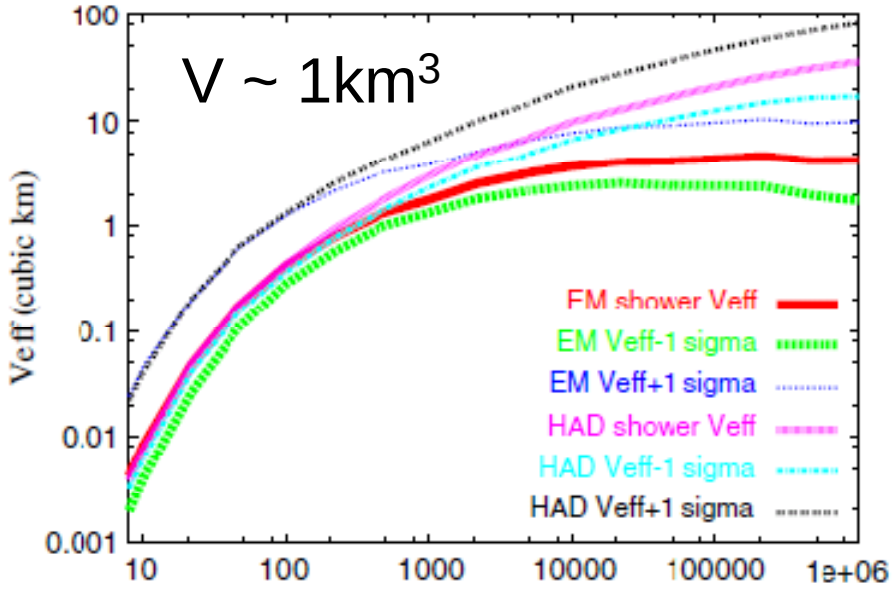
RICE

~ 300 MHz radio array
@ the south pole

BGs

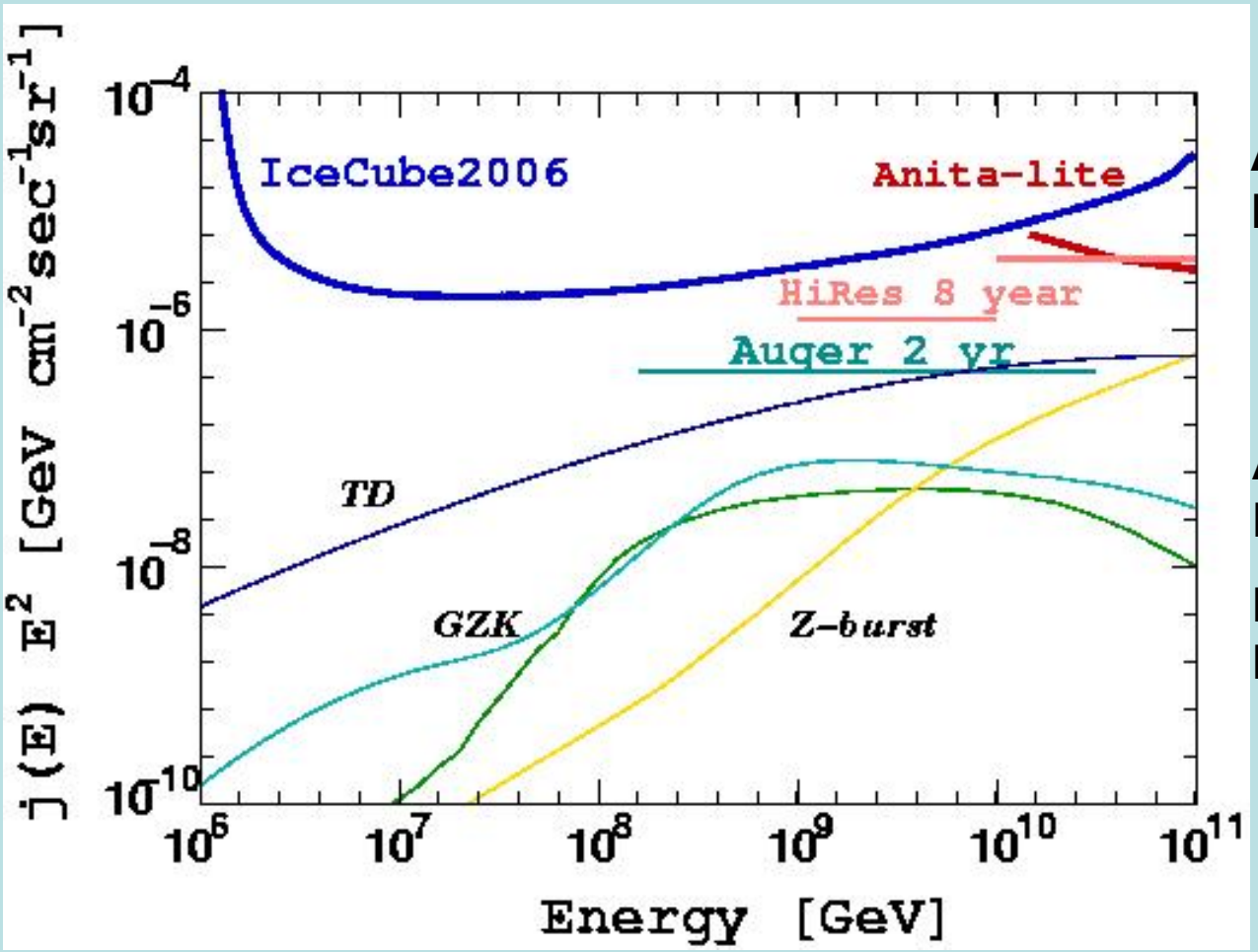
1. Continuous waveform background
2. Thermal noise
3. AMANDA PMTs (< 250 MHz)





7 years run → upper limit (PRD 2006)

2006 constraints



Anita
Barwick et al PRL 2006

HiRes
Martens astro-ph/0707

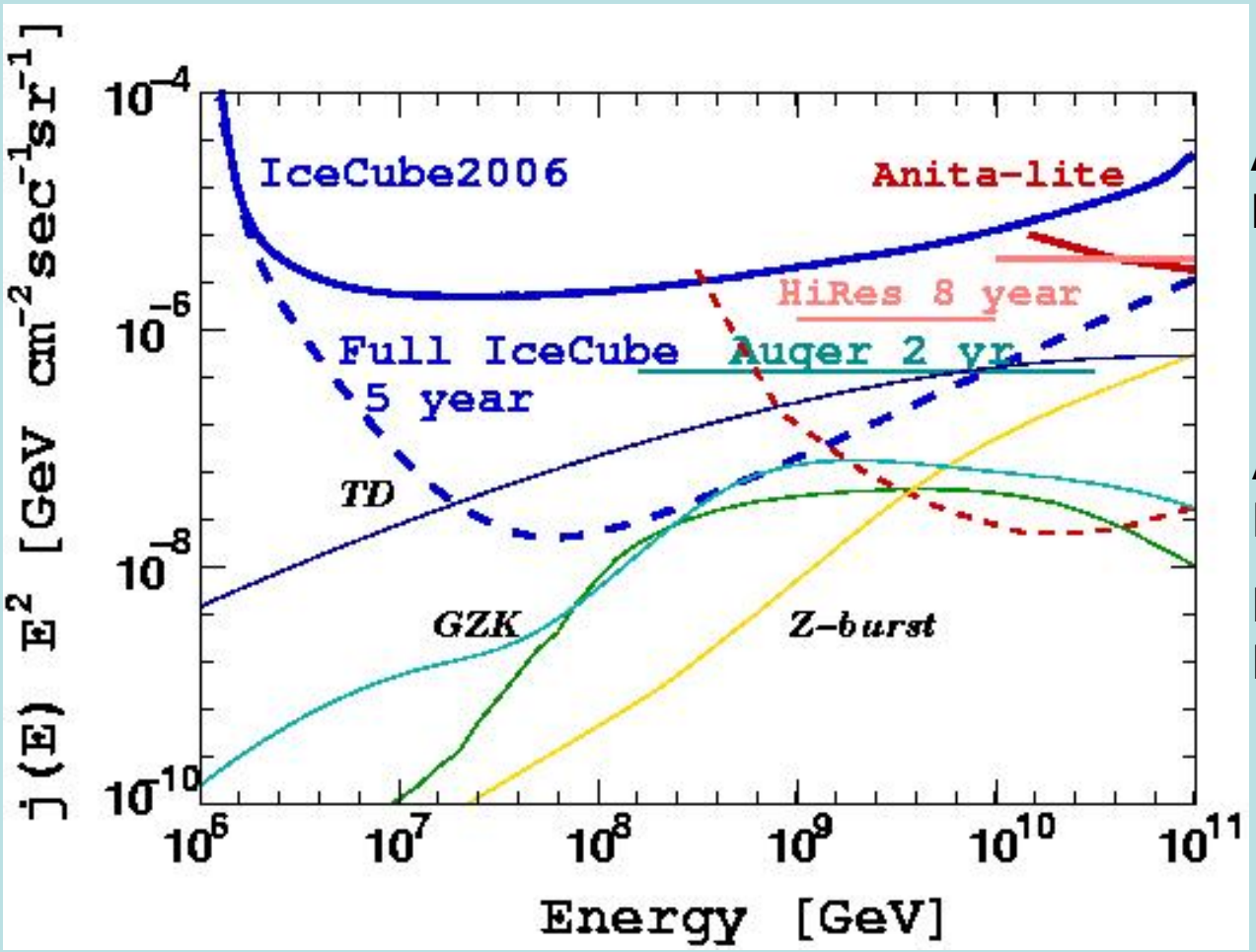
Auger
Bigas ICRC 2007

IceCube
Ishihara ICRC 2007

all ν flavors added assuming 1:1:1 ratio

Note: Auger/HiRes assumes ~E^{-2} !

Future…



Anita
Barwick et al PRL 2006

HiRes
Martens astro-ph/0707

Auger
Bigas ICRC 2007

IceCube
Ishihara ICRC 2007

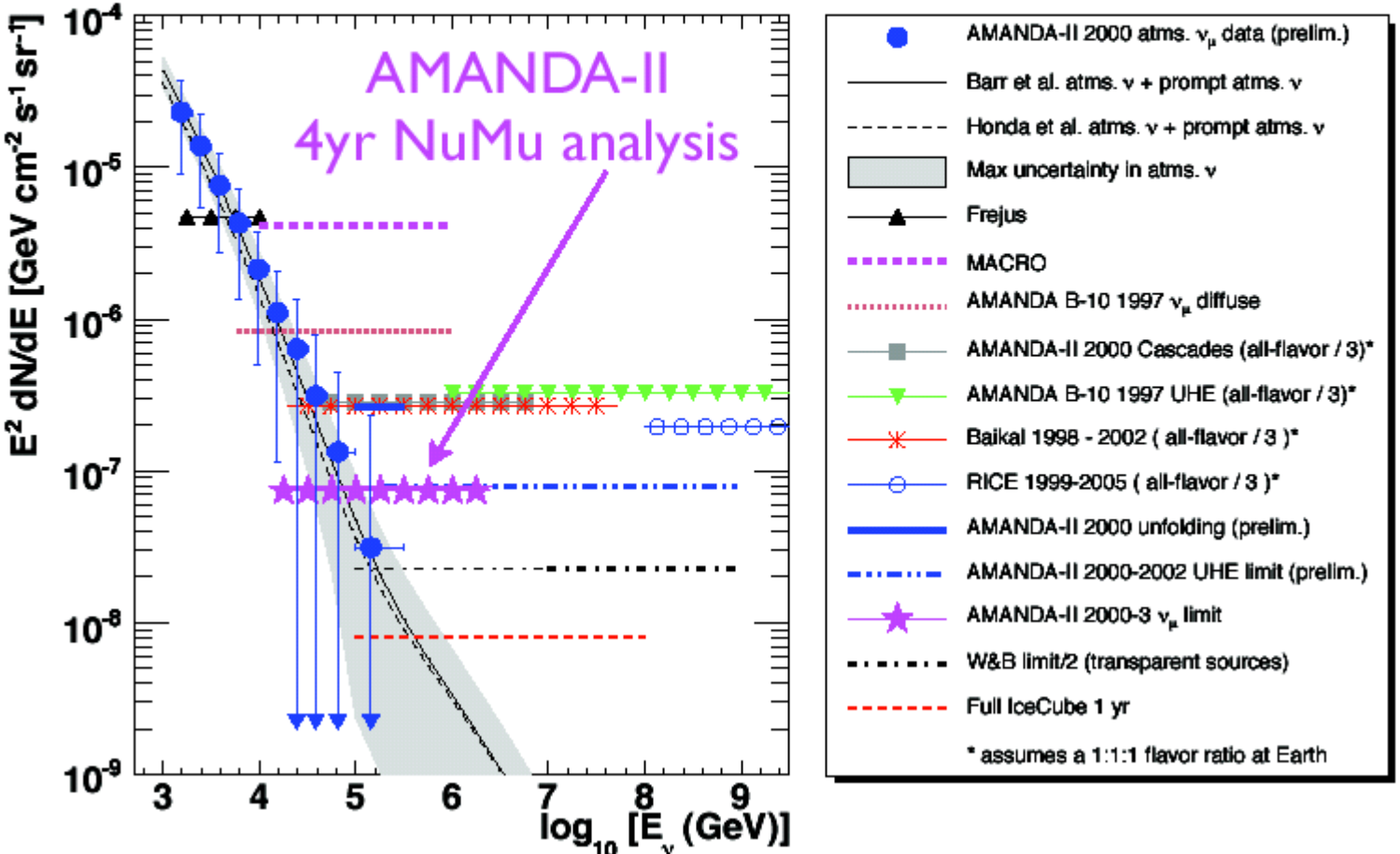
all ν flavors added assuming 1:1:1 ratio

Note: Auger/HiRes assumes ~E^{-2} !

Search for diffuse PeV ν

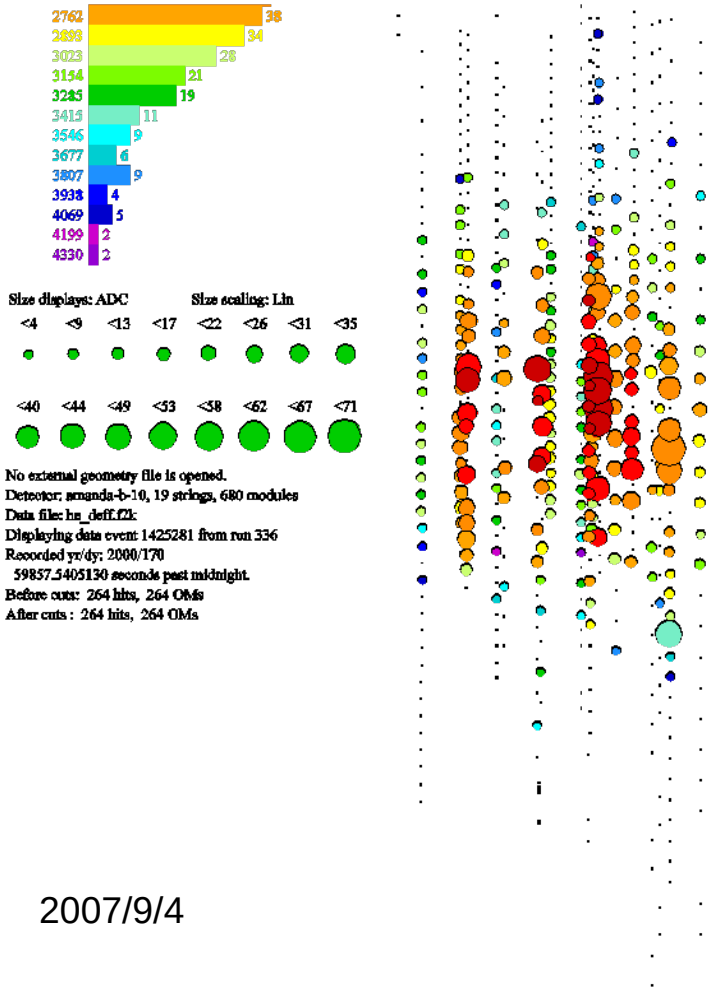
AMANDA-II 2000-2003 integrated analysis Gary Hill et al.

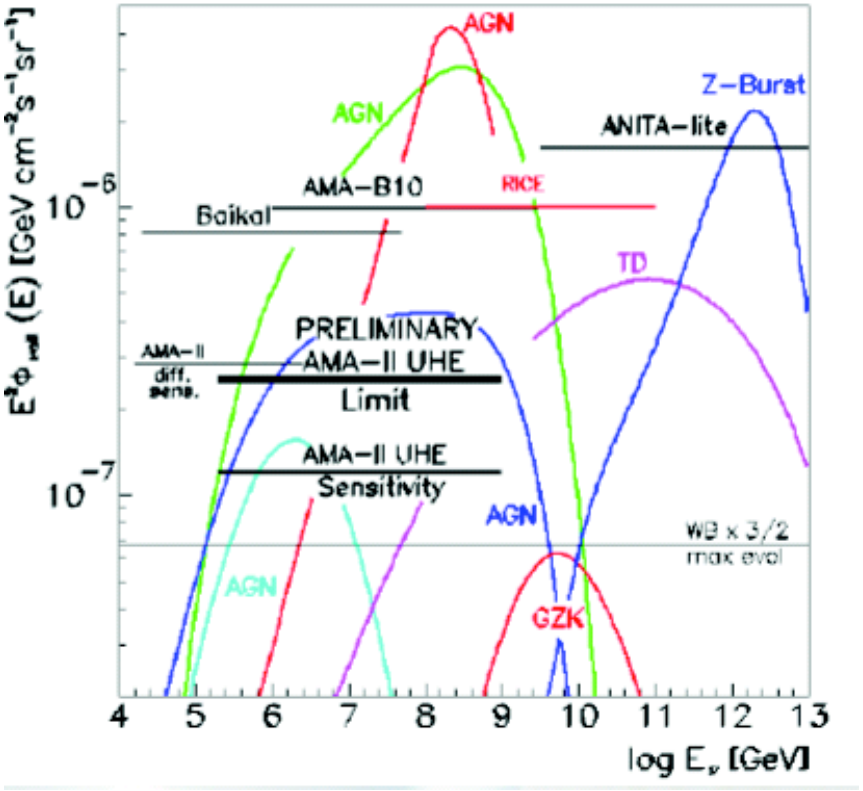
Upper Limit



Search for diffuse PeV ν

Cascade channel



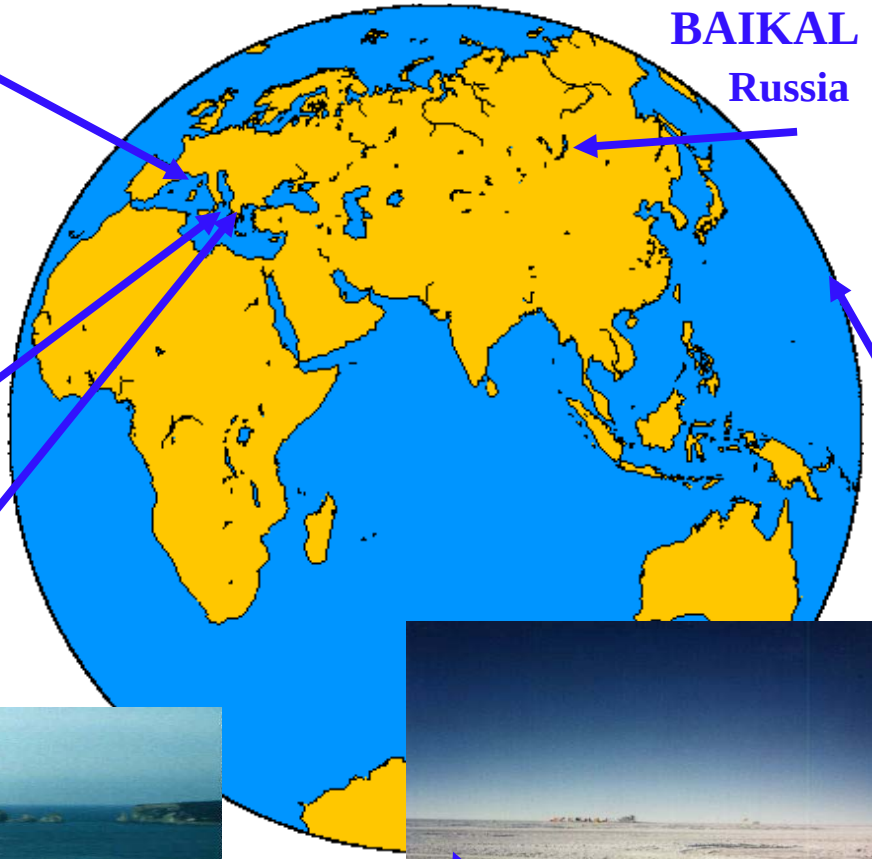


Optical Cherenkov Neutrino Telescope Projects

ANTARES
La-Seyne-sur-Mer, France

NEMO
Catania, Italy

NESTOR
Pylos, Greece



BAIKAL
Russia

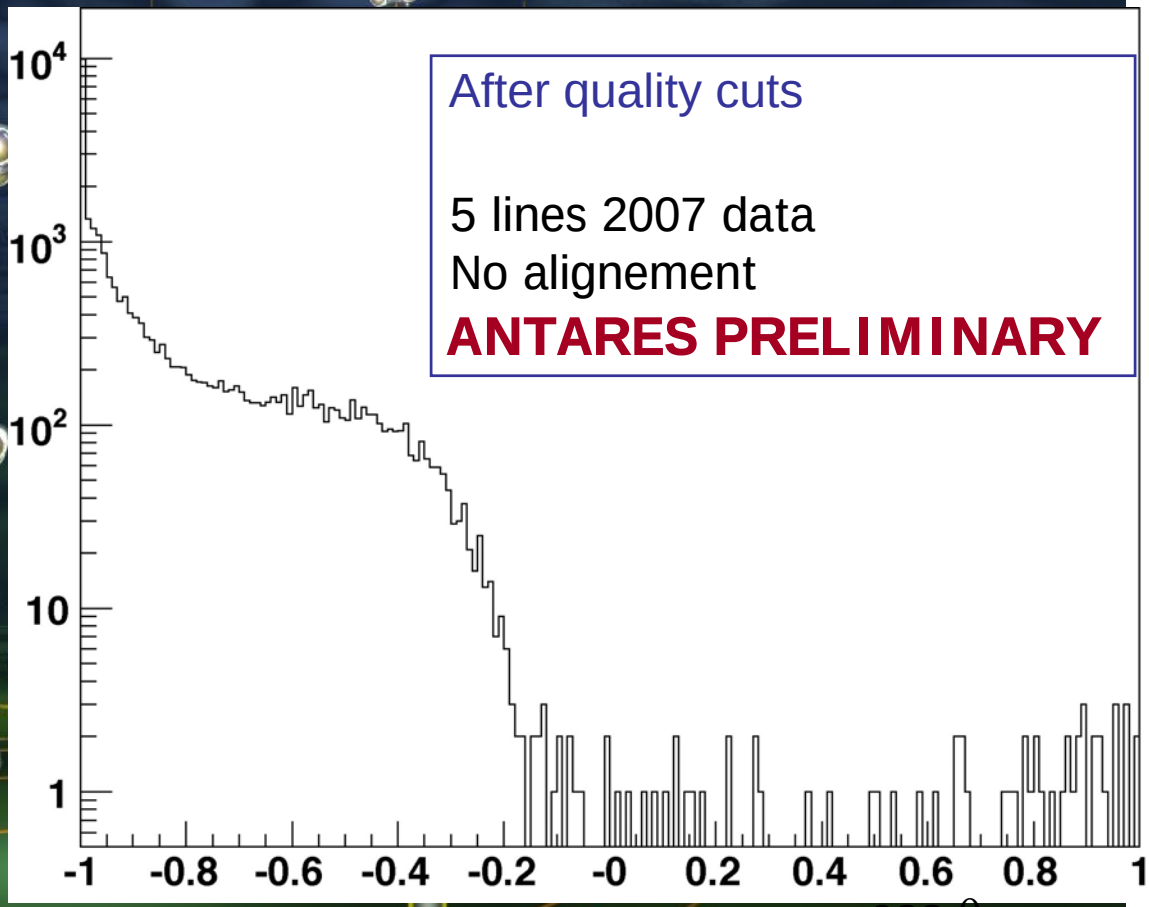
DUMAND
Hawaii
(cancelled 1995)

IceCube, South Pole, Antarctica

ANTARES

- 12 lines
- 25 storeys / line
- 3 PMT / storey

5 lines in operation →12 lines by 2008



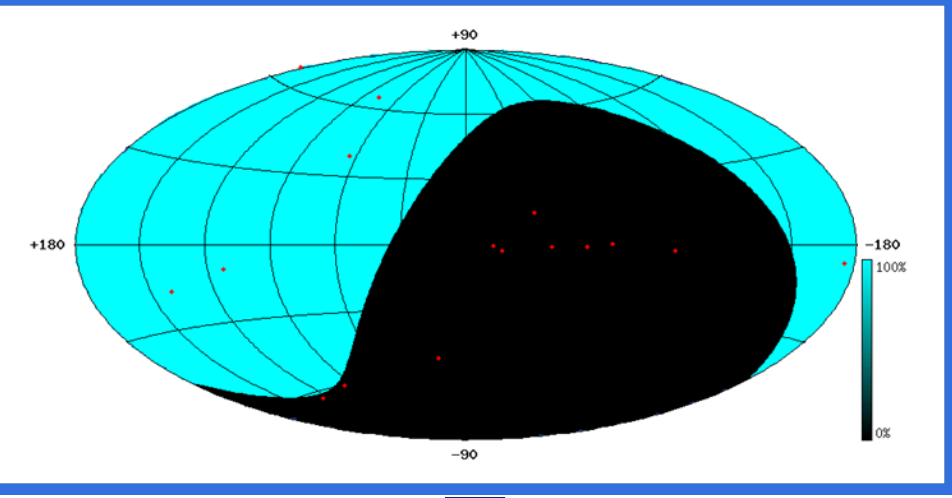
Km3 telescope in the north

- EU funded the joint activity for a European-scale Design Study for a km^3 ν-telescope in the Mediterranean Sea
  - KM3NeT: ANTARES-NEMO-NESTOR consortium

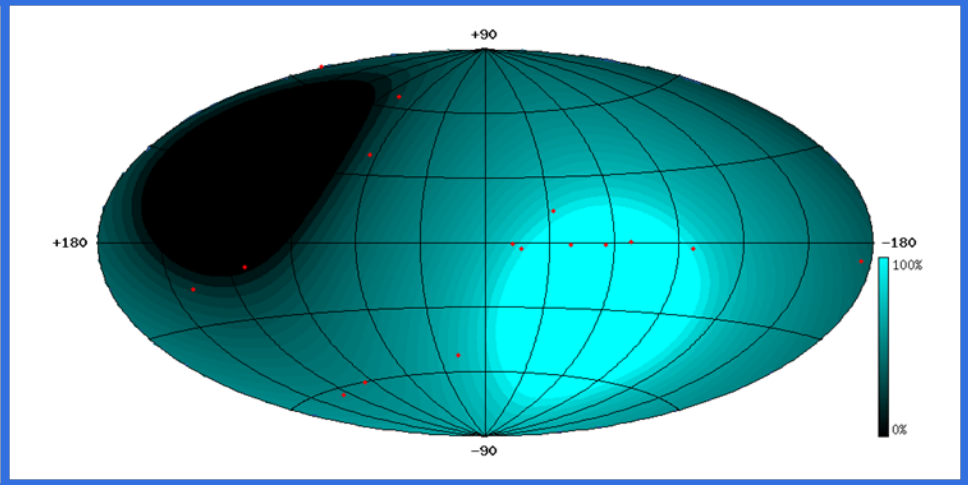
http://www.km3net.org/

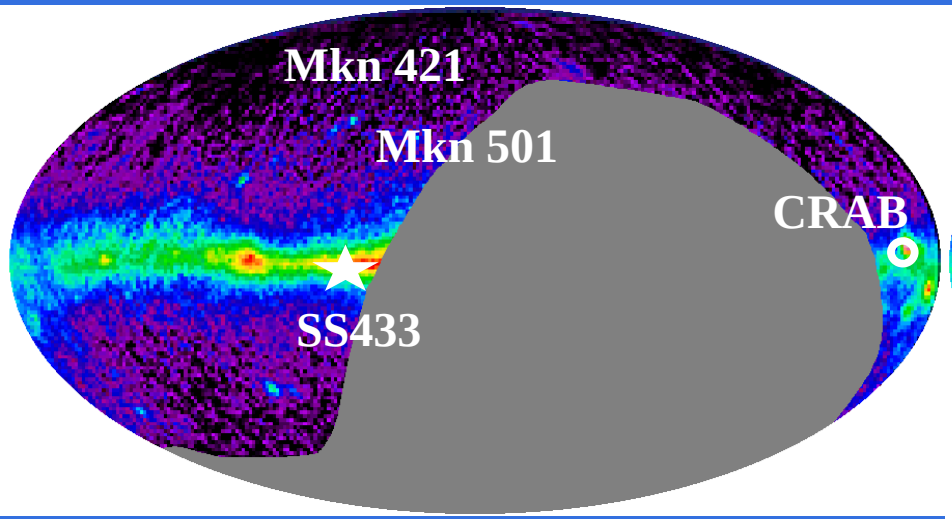
ν point source business

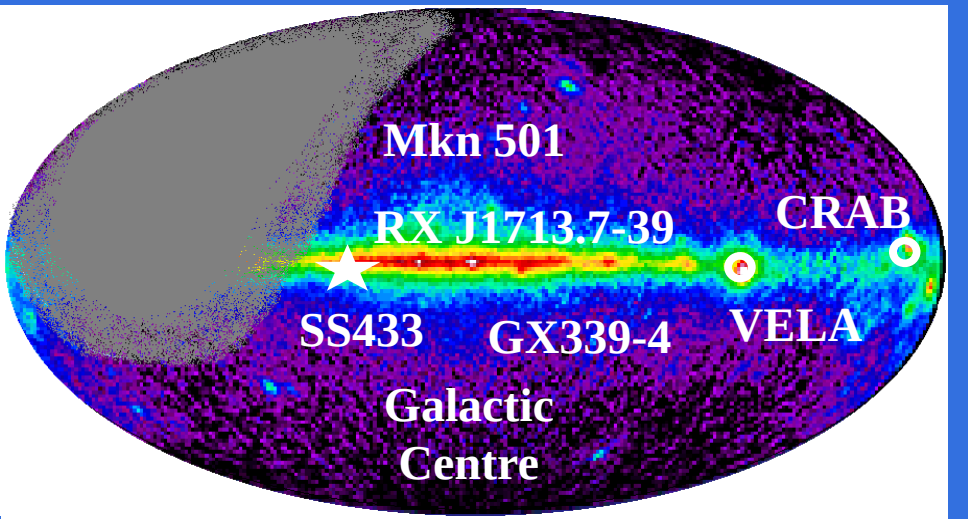
AMANDA (South Pole)



ANTARES (43° North)

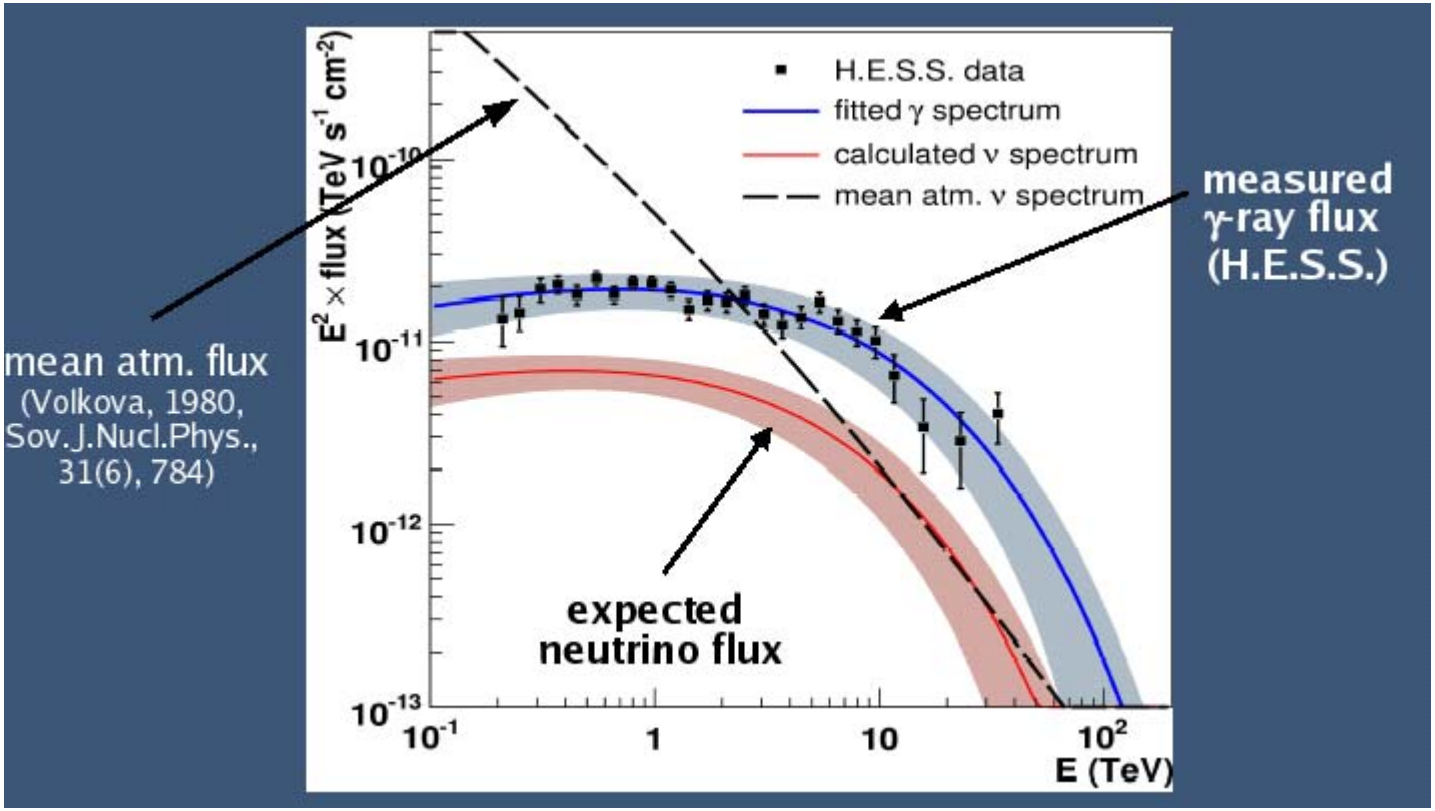






ν point source business

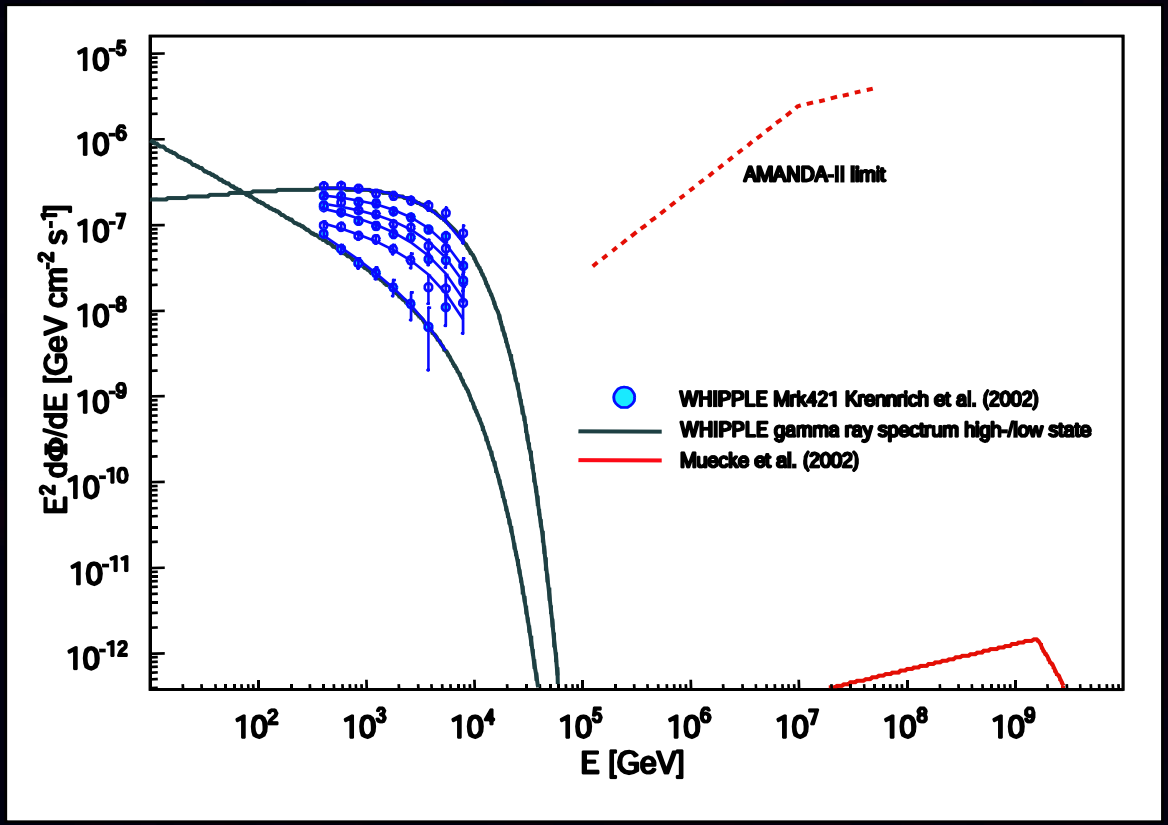
Galactic Point Source – RXJ1713-3946



Markarian 421

- Muecke et al.: Model of Markarian 421 as High frequency peaked BLLac in the Proton Synchrotron Blazar model **($N_{\nu,exp} \sim 0$)**

Markarian 421	
$N_{observed}$	6
$N_{background}$	7.37
Event upper limit (90% CL)	4.1



Summary

- Measurement of the high energy ν is the final resort to explore the Cosmic Ray Universe !
- Extremely High Energy ν detection will be realized within 10 years!

  Probe CR sources at cosmological distances

  Probe particle physics – extra dimensions!
- IceCube + ANTARES/NEMO etc covers the entire sky now.

Understanding of the EHE cosmic ray sky

Auger/TA find clusters?

Yes!

ID source by VHE γ

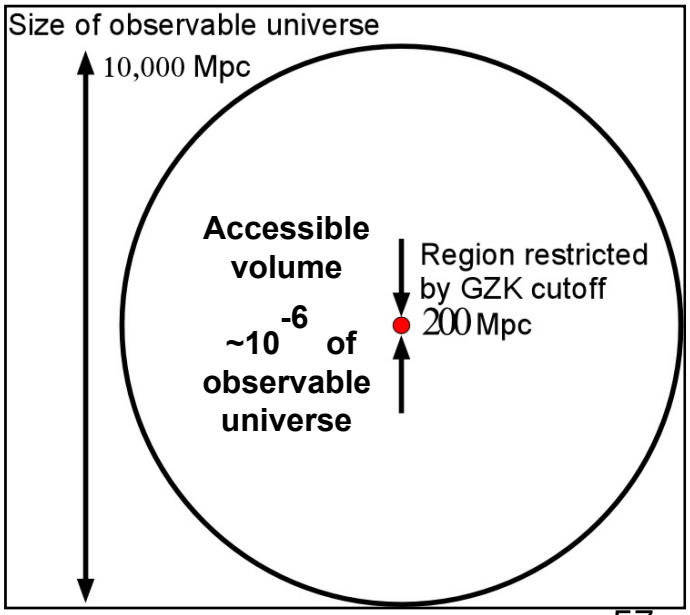
No ….

But just a local universe

Source Evolution
Max. Energy

ν

Penetration Power



Understanding of the TeV cosmic ray sky