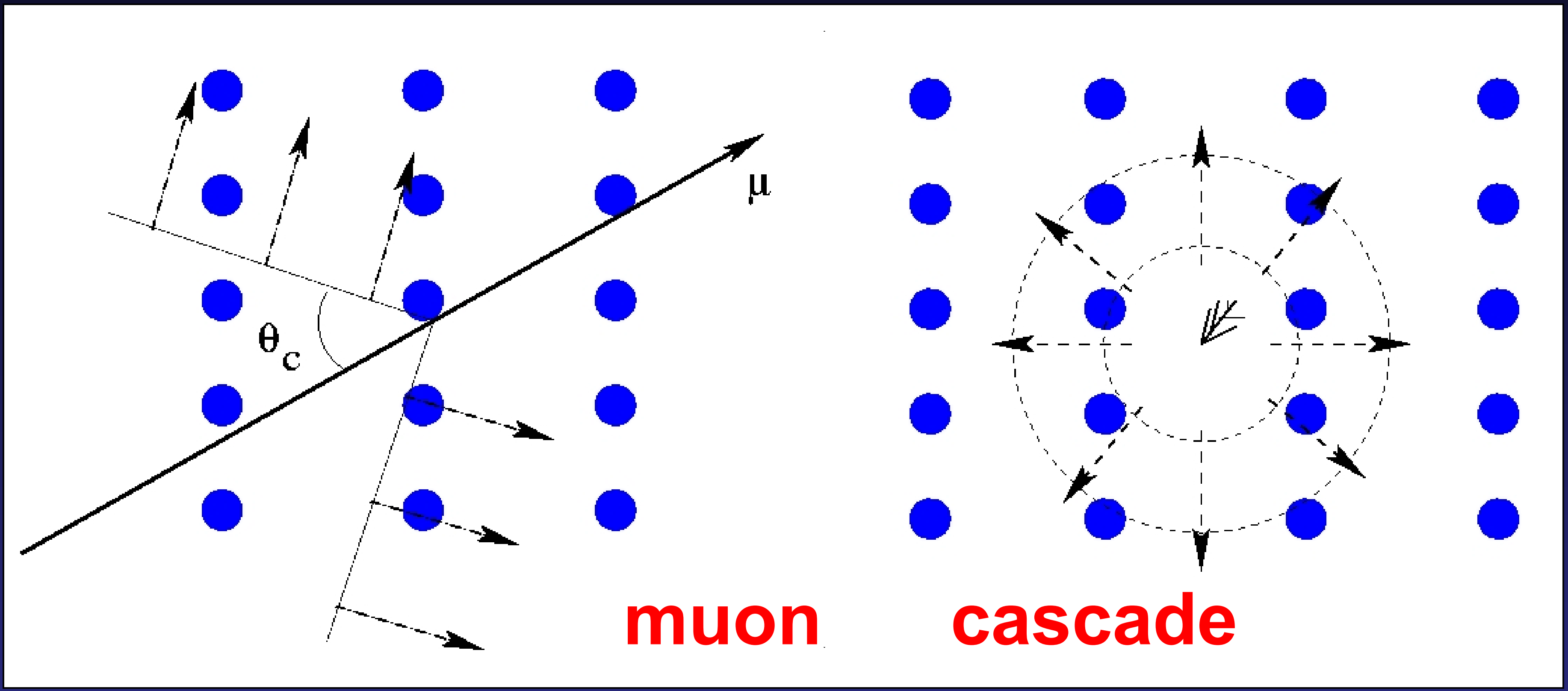
IceCube: A Kilometer-Scale Neutrino Observatory

- Uses neutrinos as cosmic messengers at energies where the universe becomes opaque to light
- Detects neutrinos of energies from 10^7 eV (bursts) to 10^{21} eV
- Will extend the distances accessible to neutrino astronomy by five orders of magnitude
- Black hole diagnostics with neutrinos
- Its kilometer scale is dictated by observed gamma ray and cosmic ray fluxes

IceCube: Concept

Cherenkov light from muons and cascades



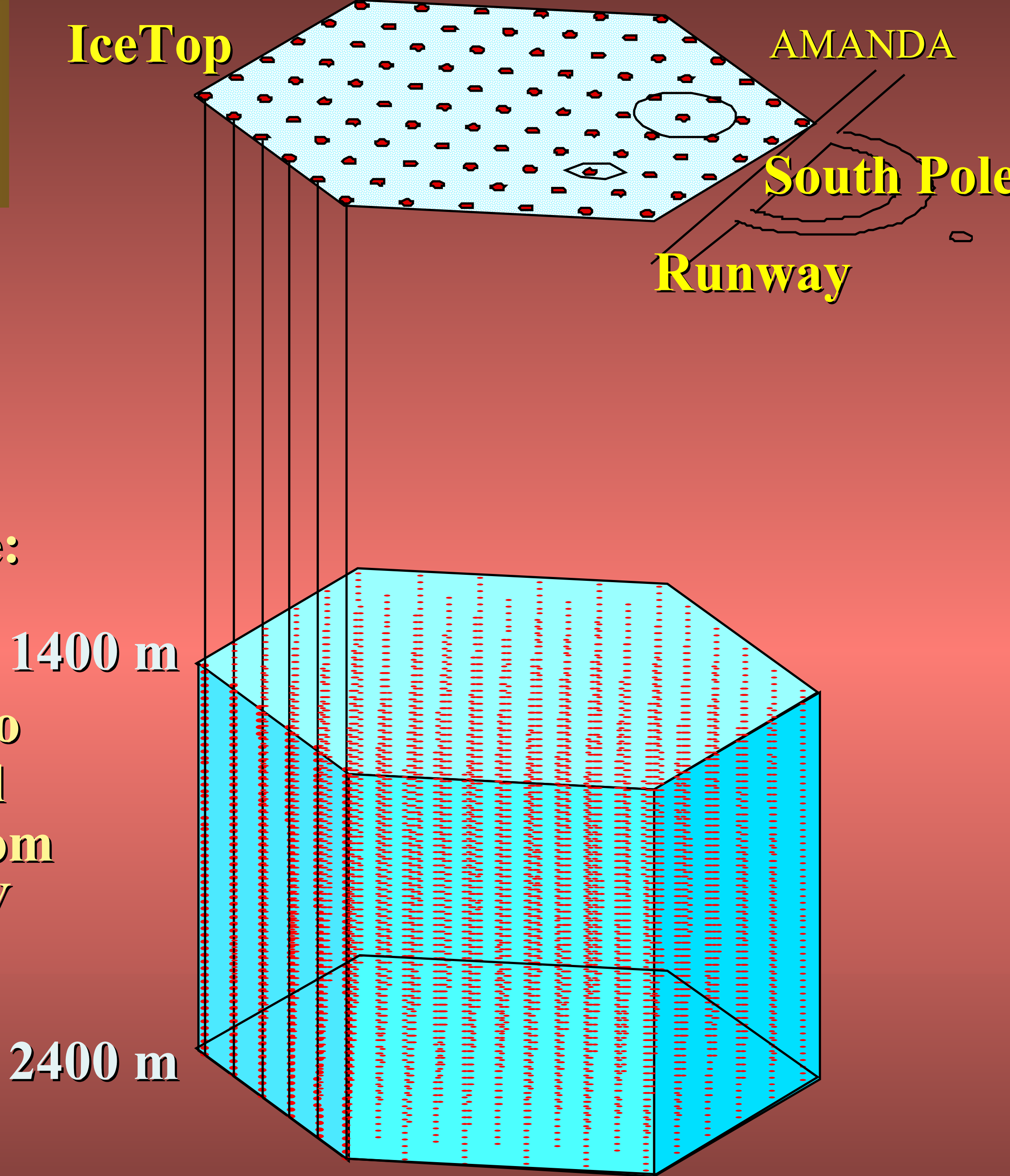
Reconstruction

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

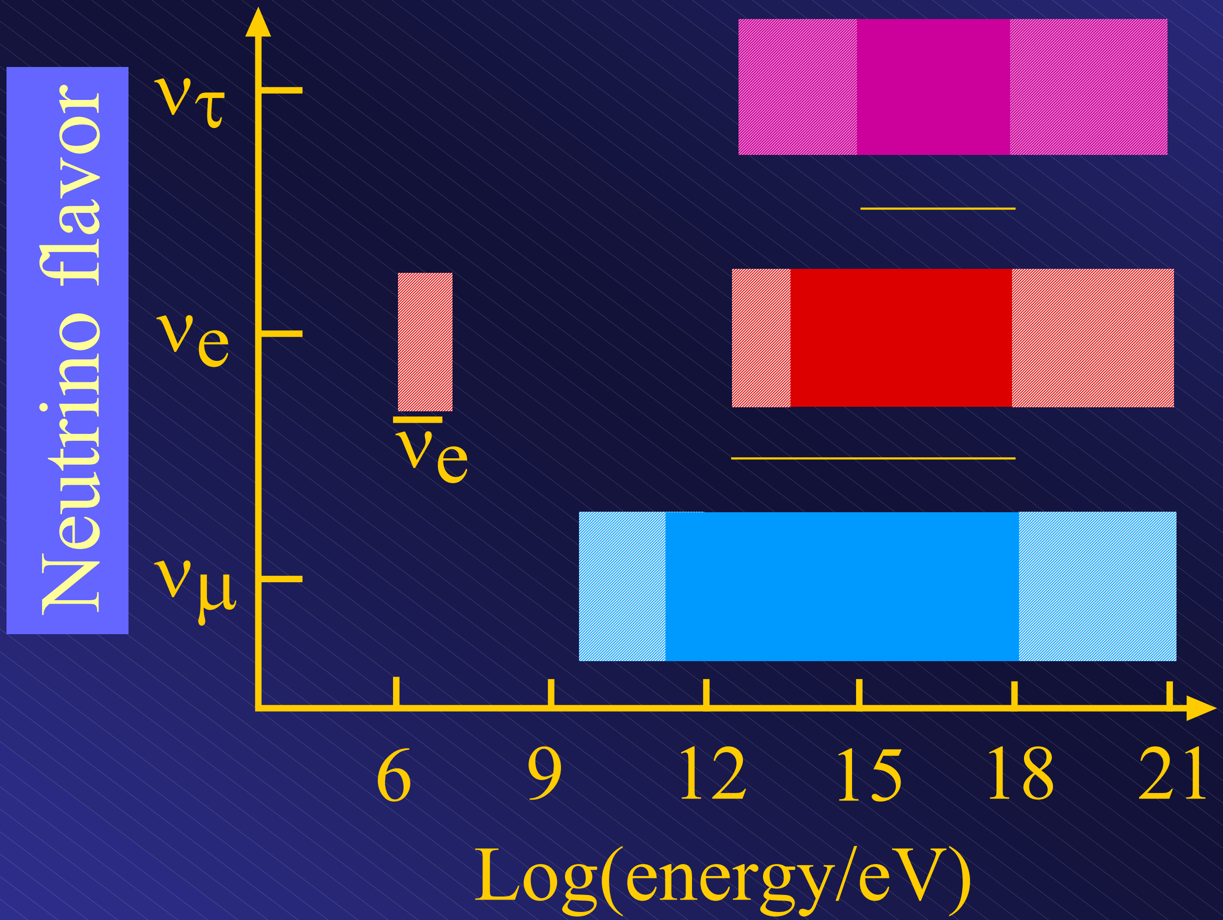
Building AMANDA: The Optical Module and the String

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**



Neutrino ID (solid)
Energy and angle (shaded)



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

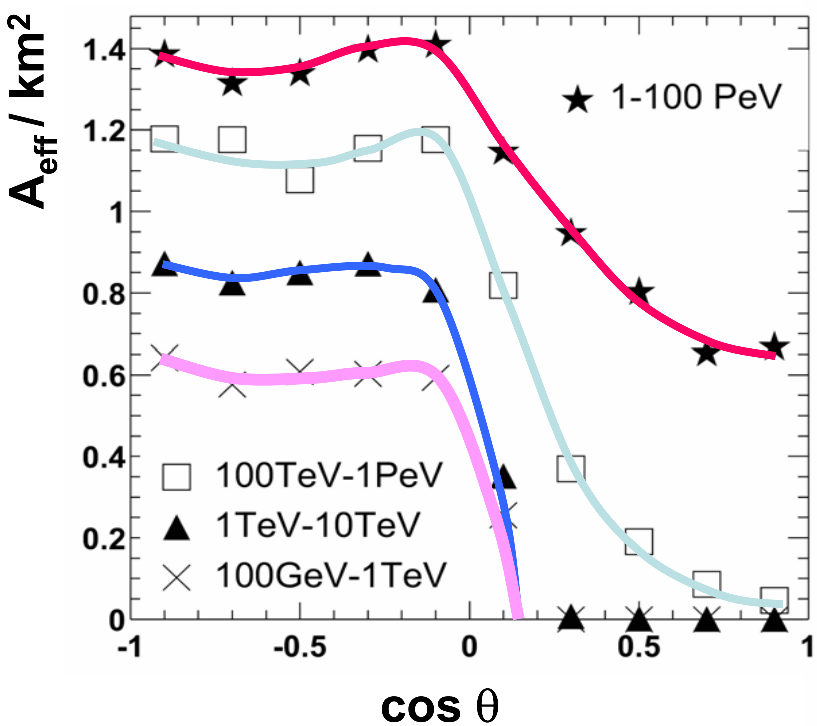
Enhanced role of tau neutrinos:

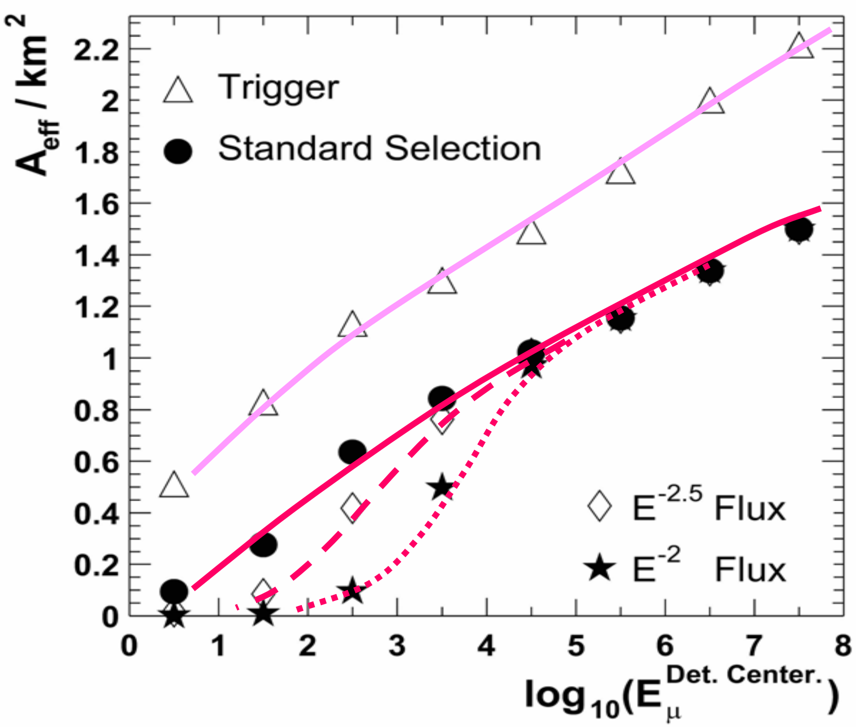
- Cosmic beam: $\nu_e = \nu_\mu = \nu_\tau$ because of oscillations
- ν_τ not absorbed by the Earth (regeneration)
- Pile-Up near 1 PeV where ideal sensitivity

IceCube has been designed as a discovery instrument with improved:

- telescope area (> 1km2 after all cuts)
- detection volume (> 1km3 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)

Effective area of IceCube

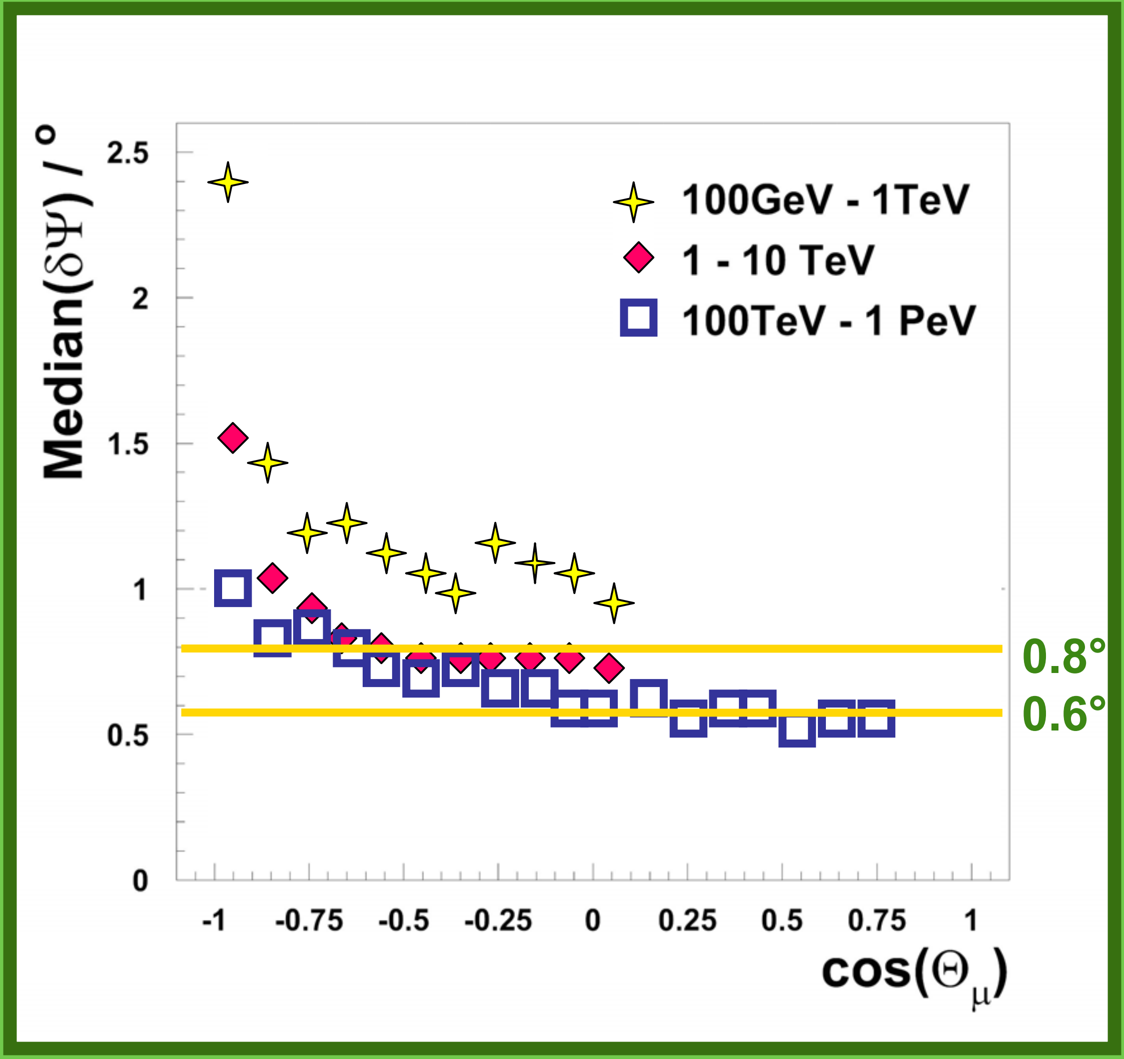




Effective area vs. zenith angle (downgoing muons rejected)

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

AMANDA: Proof of Concept

- Uses transparent ice as a particle detector: 4 daily nus in real time
- IceCube simulations based on simulations supported by AMANDA data

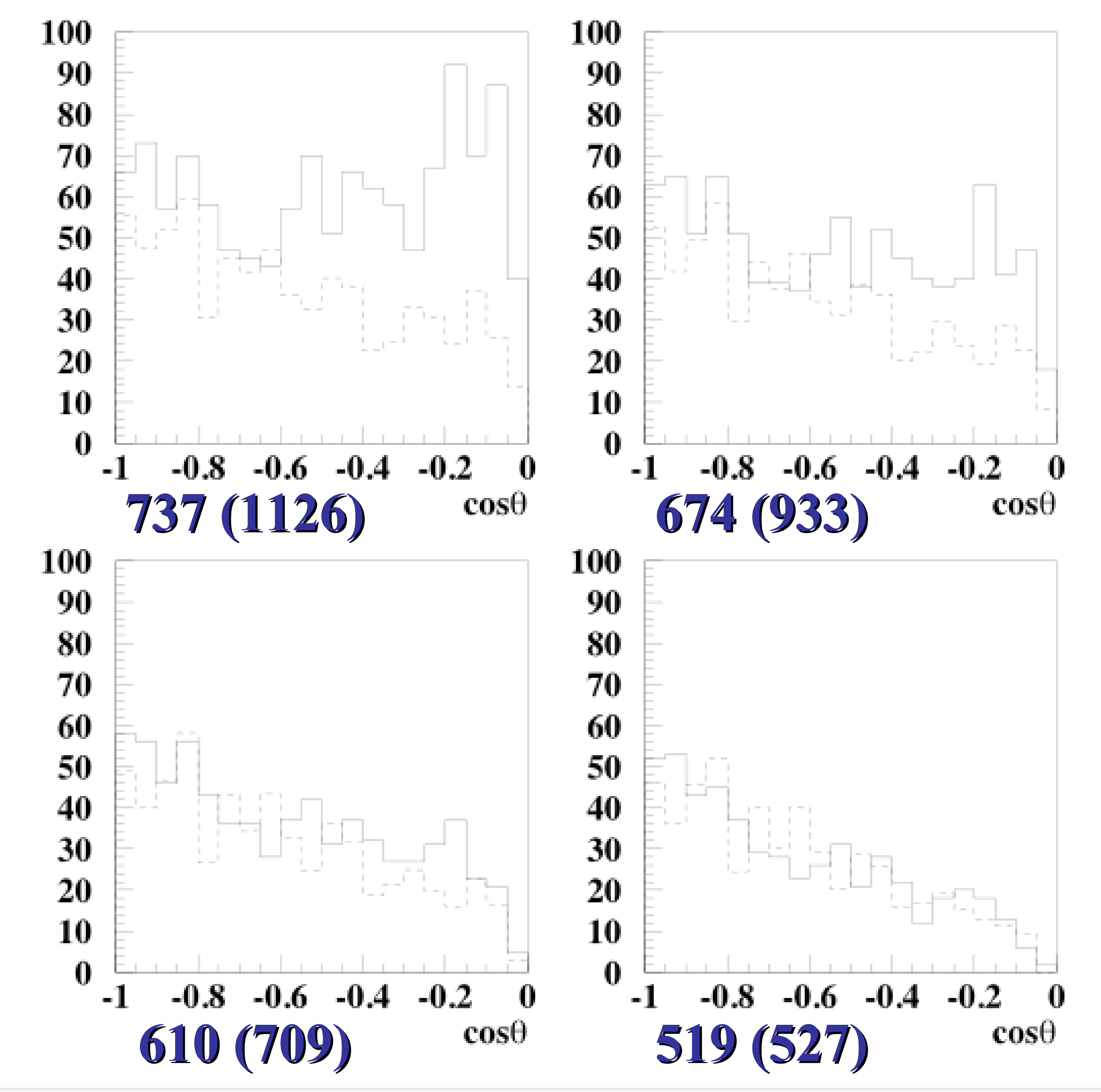
AMANDA II

Tighten Cuts on:

- Likelihood
- Length
- Smoothness
- Direct Hits

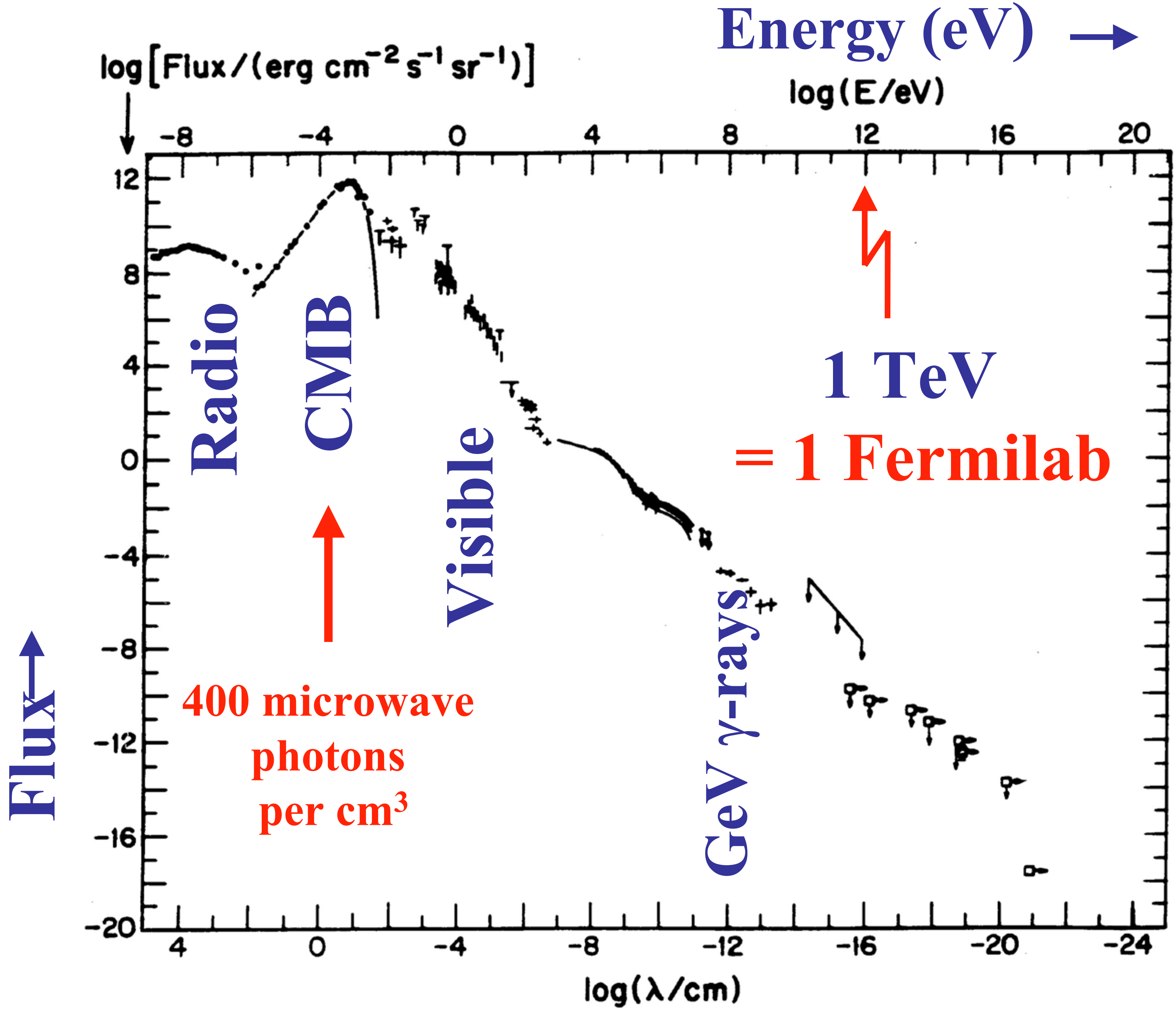
With appropriate cuts signal MC and data match

Neutrino events (Simulation)

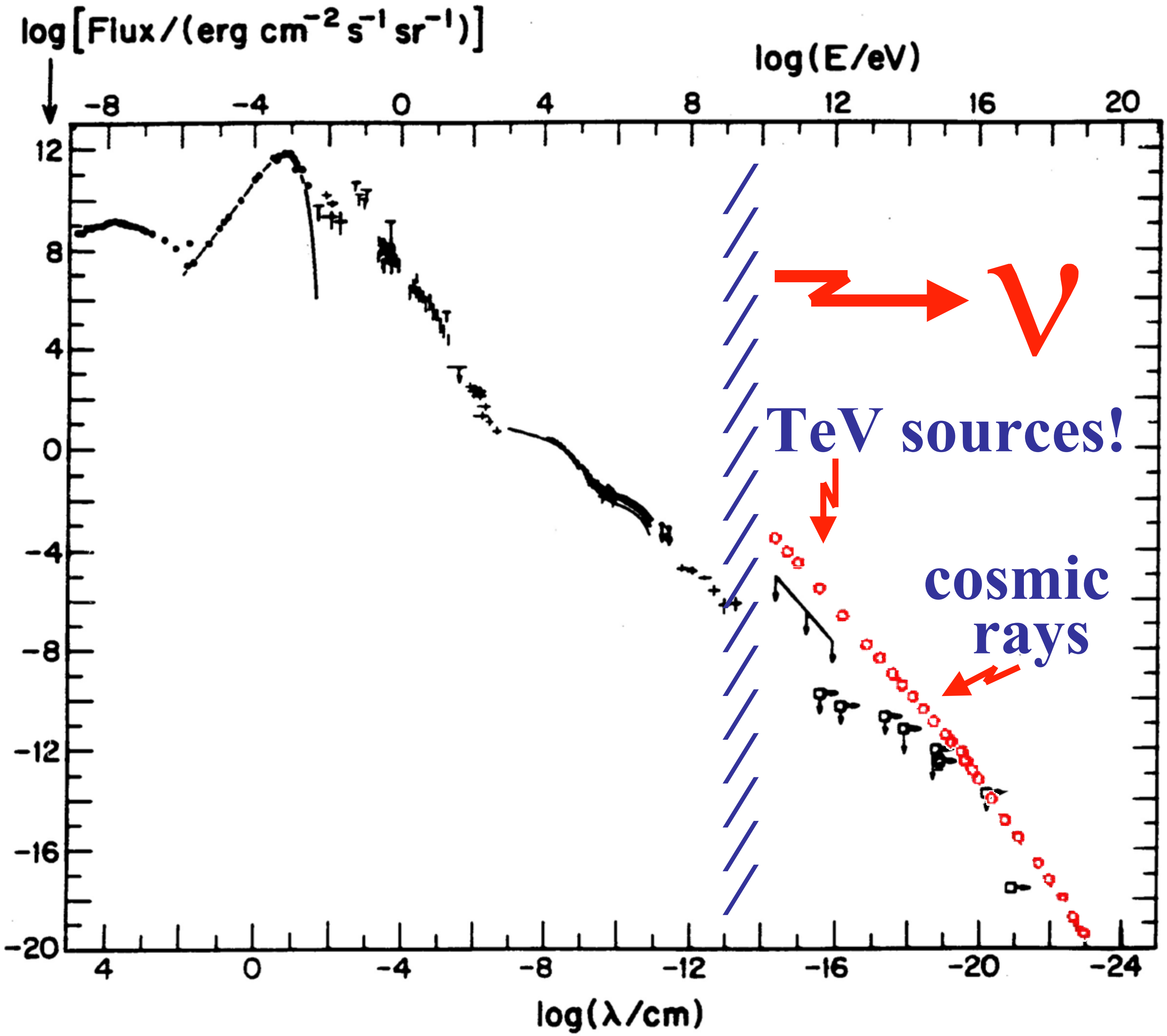


IceCube: Science

- Why neutrino astronomy?
- Why 1 kilometer cubed detector or kilometer squared telescope area?



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

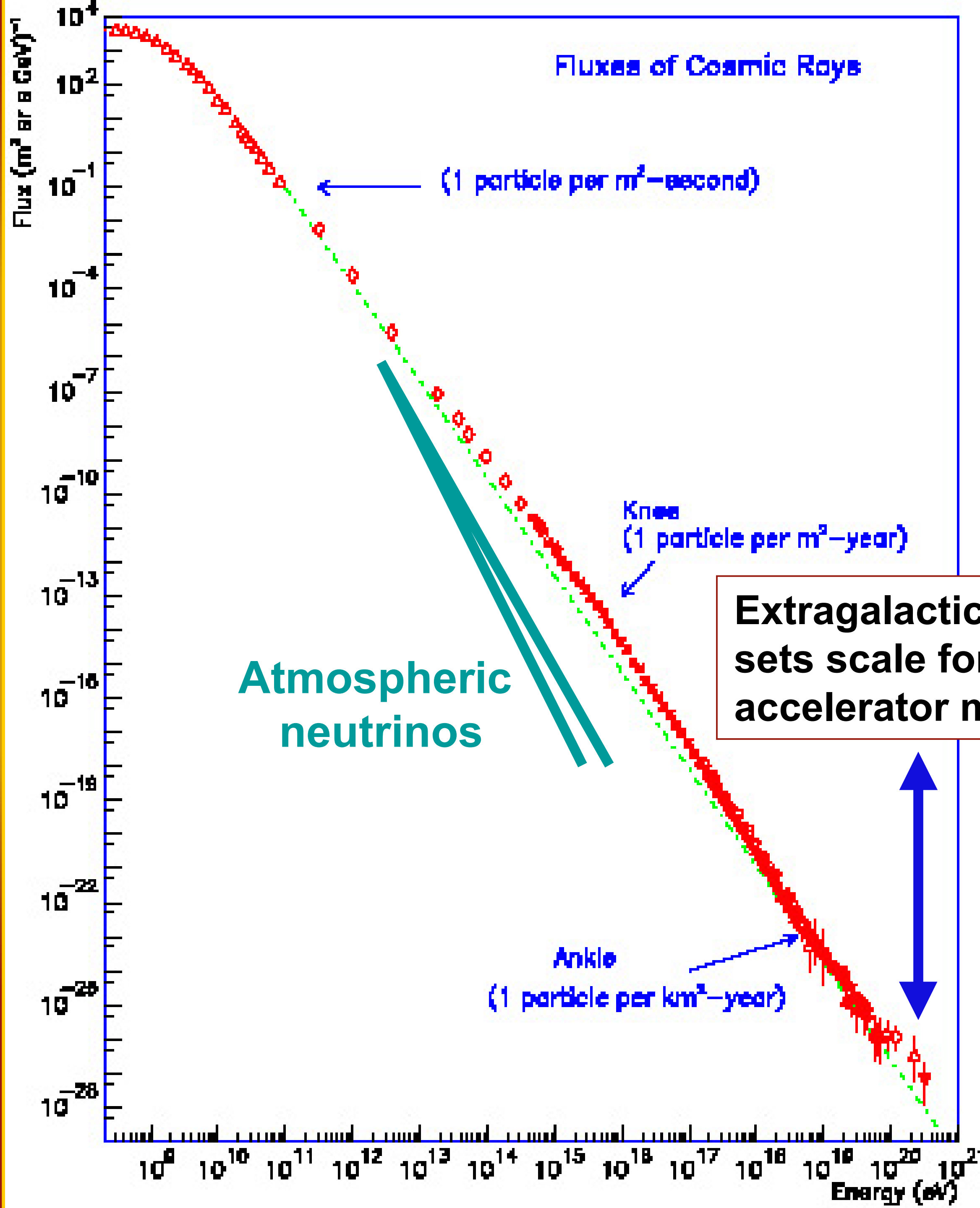


log[Flux/(erg cm^{-2} s^{-1} sr^{-1})]
log(E/eV)
-8
-4
0
4
8
12
16
20
12
8
4
0
-4
-8
-12
-16
-20
4
0
-4
-8
-12
-16
-20
-24
log(λ/cm)
ν
TeV sources!
cosmic rays

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

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

Cosmic Ray spectrum



Extragalactic flux sets scale for many accelerator models

Acceleration to 10^{21}eV?

~10^2 Joules

~ 0.01 M_{GUT}

dense regions with exceptional gravitational force creating relativistic flows of charged particles, e.g.

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

Cosmic Accelerators

$$\boxed{E \sim \Gamma c B R}$$

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

magnetic field

energy

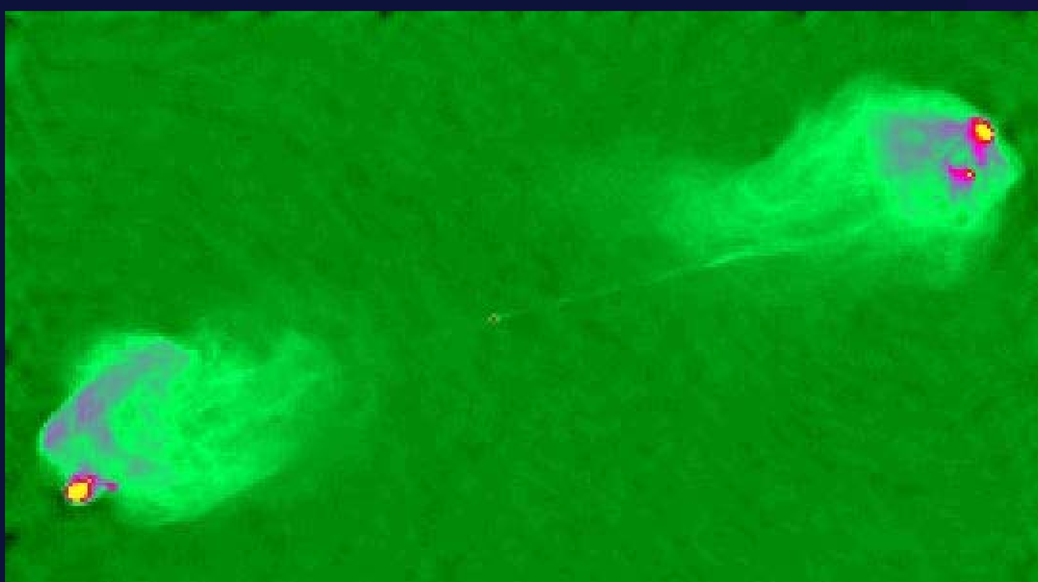
$$\boxed{E \sim \Gamma B M}$$

boost factor

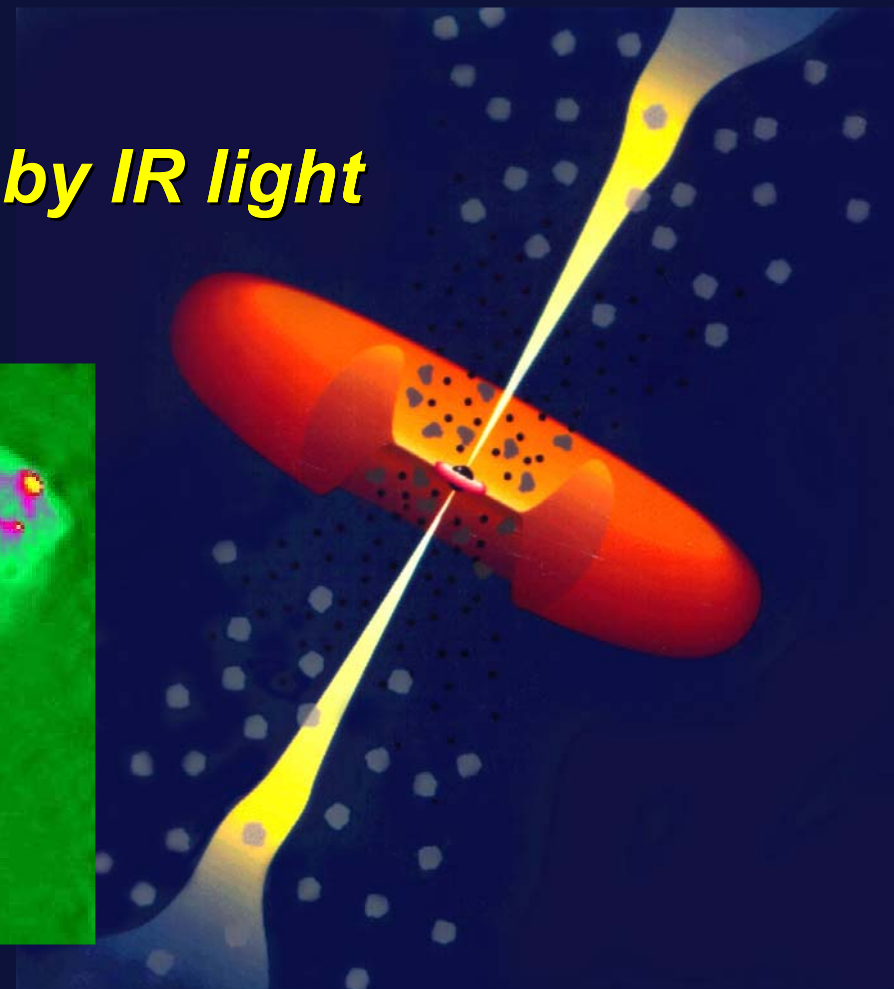
mass

Active Galaxies: Jets

20 TeV gamma rays
Higher energies obscured by IR light



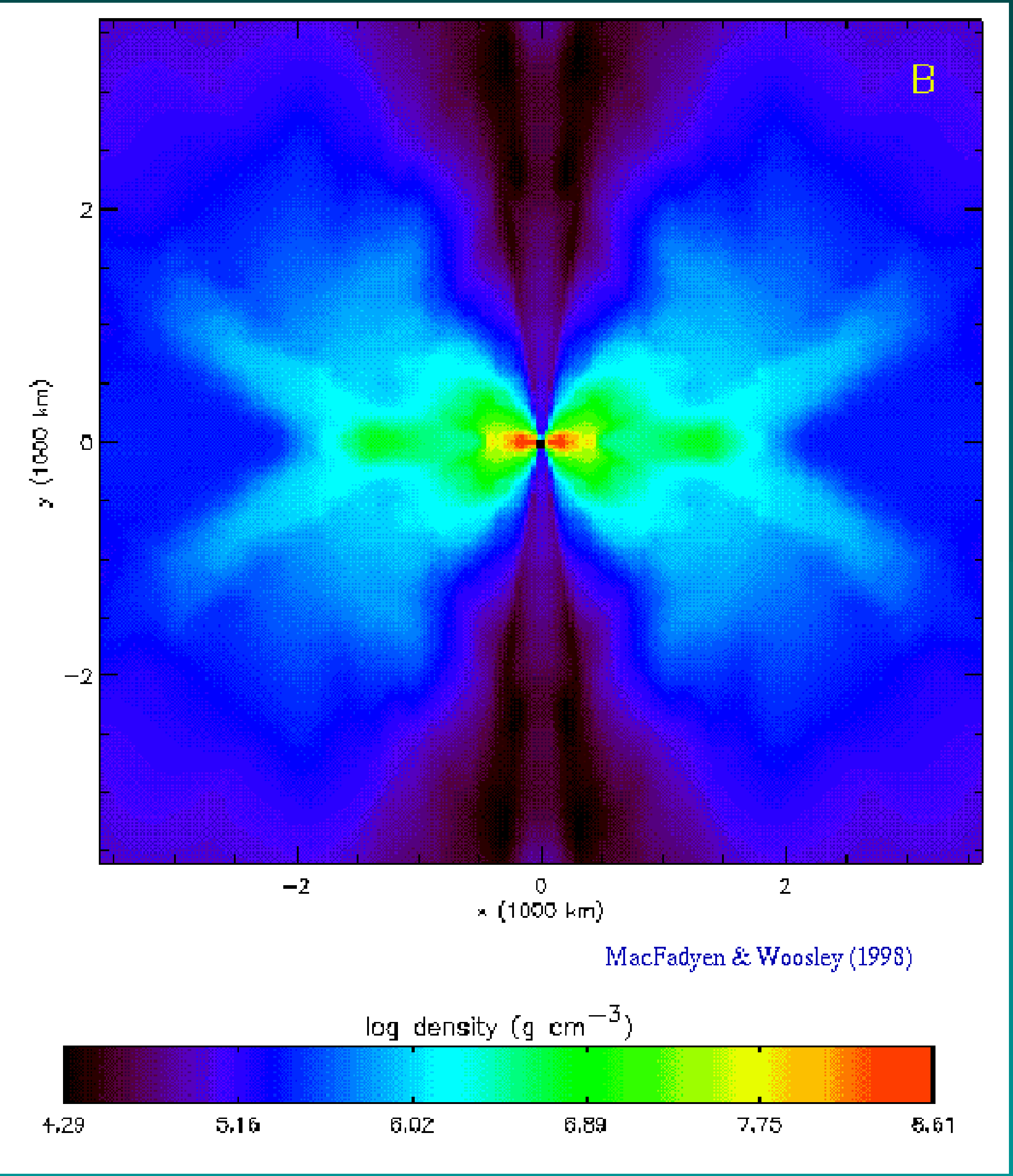
VLA image of Cygnus A



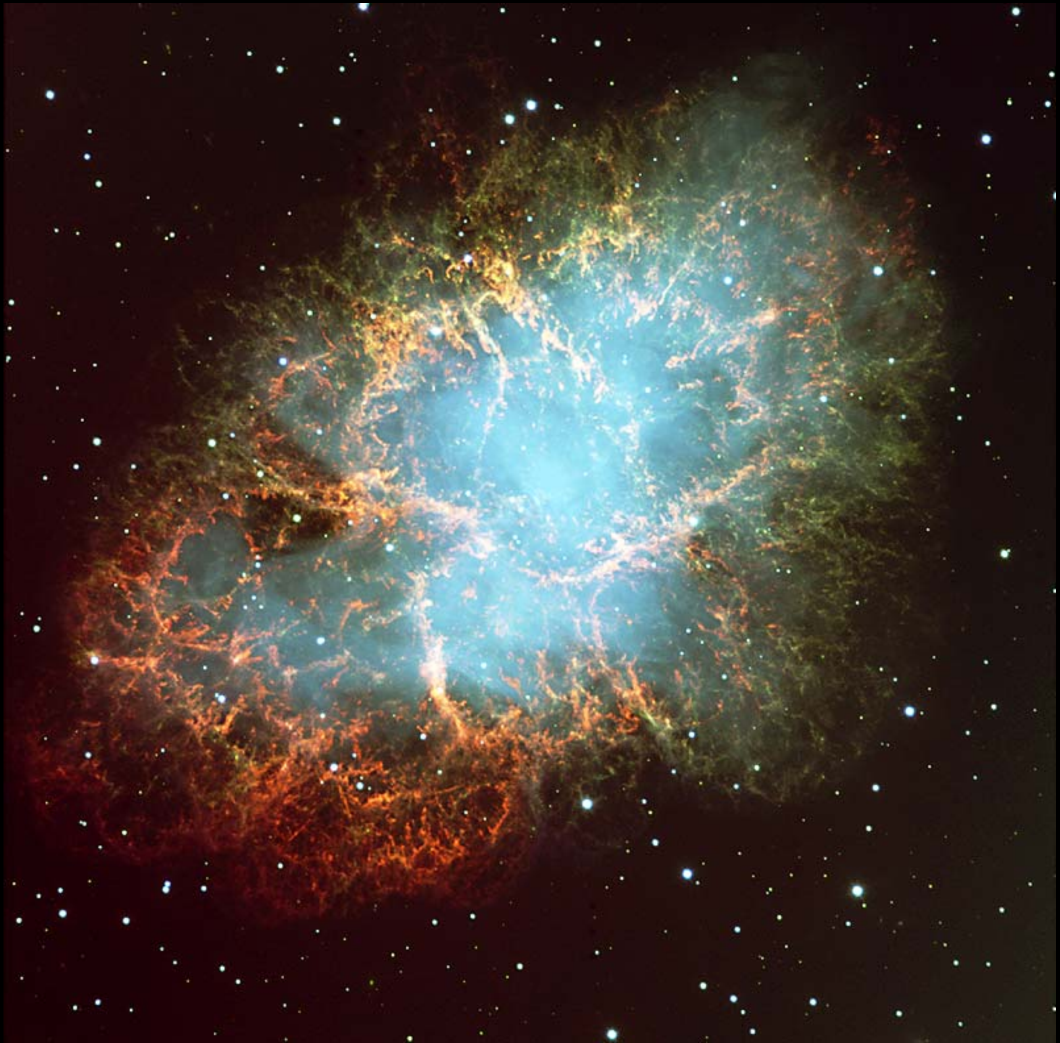
Gamma Ray Burst

- Photons and protons coexist in internal shocks

- External shocks



Supernova shocks expanding in interstellar medium



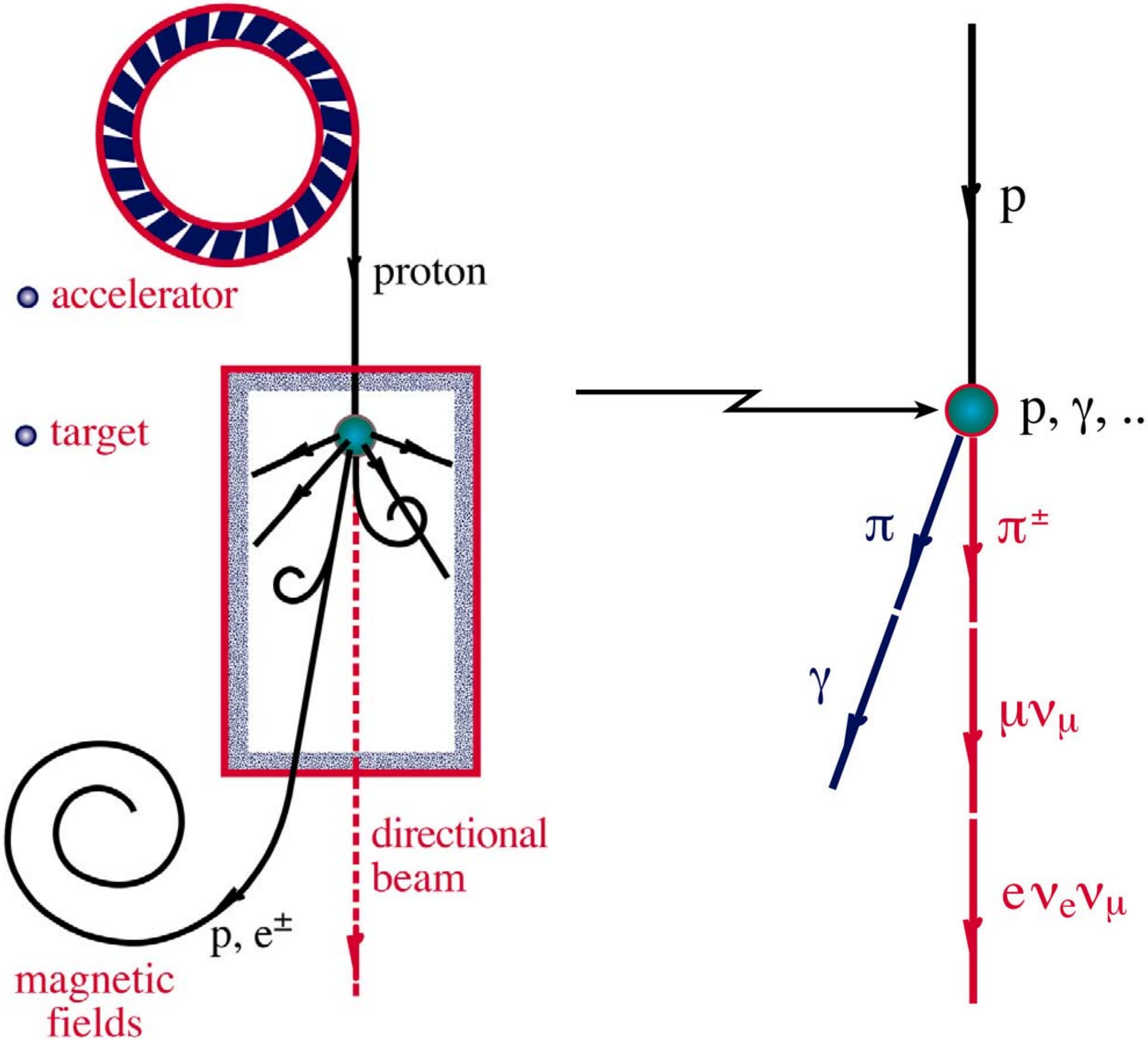
Crab nebula

The Oldest Problem in Astronomy:

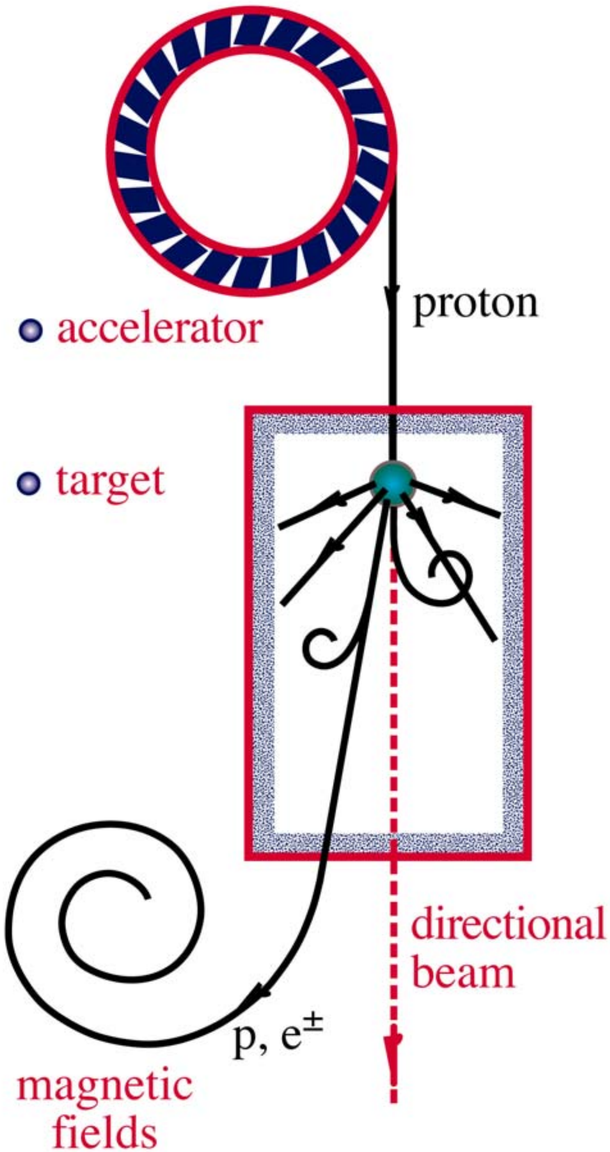
- No accelerator
- No particle candidate (worse than dark matter!)
- Not photons (excludes extravagant particle physics ideas)

Neutrino Astronomy to the Rescue?

NEUTRINO BEAMS: HEAVEN & EARTH



NEUTRINO BEAMS: HEAVEN & EARTH



→ black hole

→ radiation enveloping black hole

Irrespective of the cosmic-ray sources, some fraction will produce pions (and neutrinos) as they escape from the acceleration site

- through hadronic collisions with gas
- through photoproduction with ambient photons

Cosmic rays interact with interstellar light/matter even if they escape the source

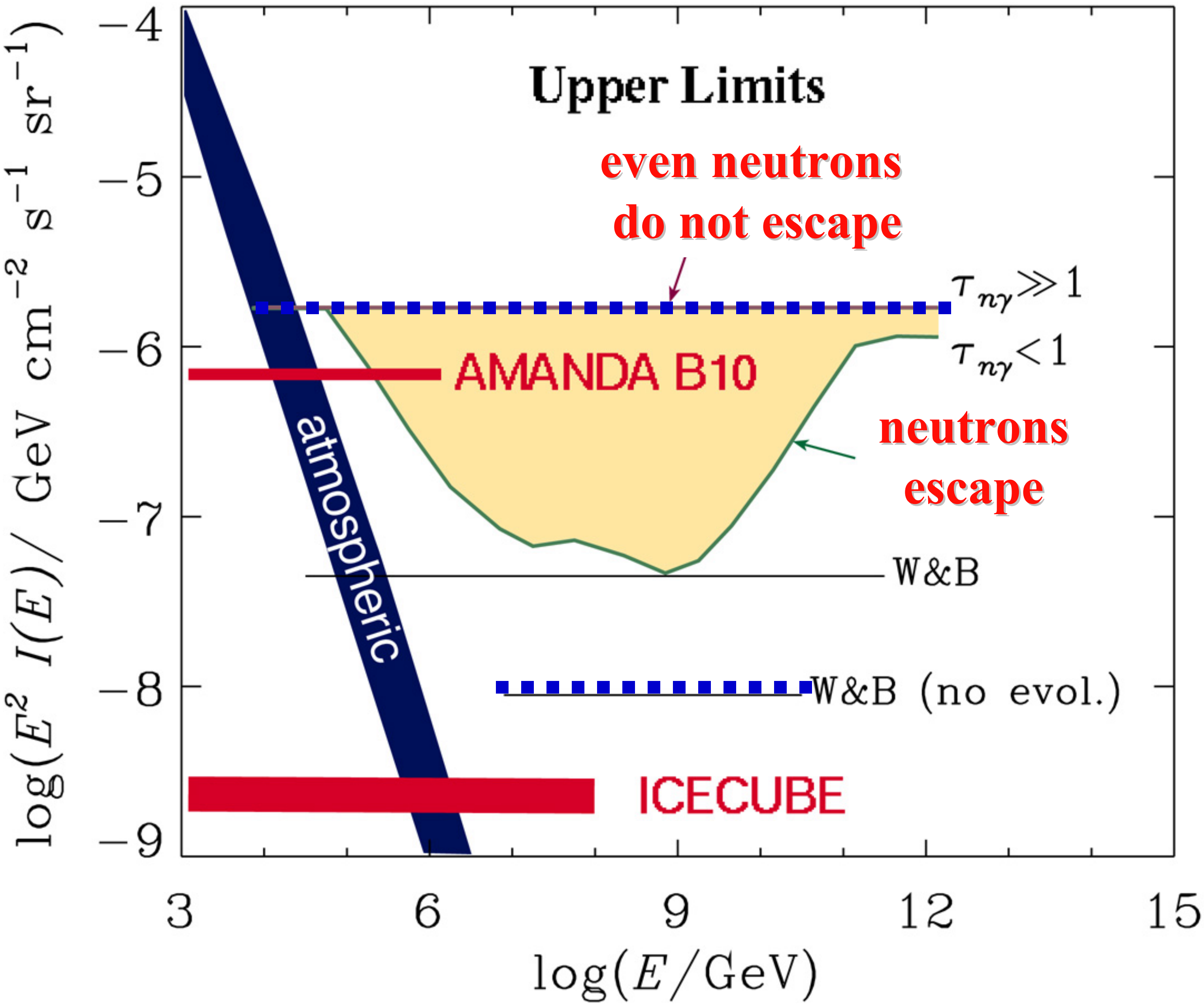
Sources:

- Transparent:

  protons (EeV cosmic-rays) ~ photons (TeV point sources) ~neutrinos
- Obscured sources
- Hidden sources

Unlike gammas, neutrinos provide unambiguous evidence for cosmic ray acceleration!

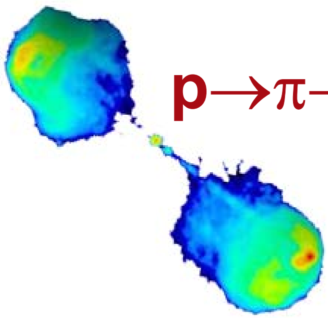
neutrinos associated with the source of the cosmic rays?



Energetics of sources yielding 10 detected events in 1 kilometer squared

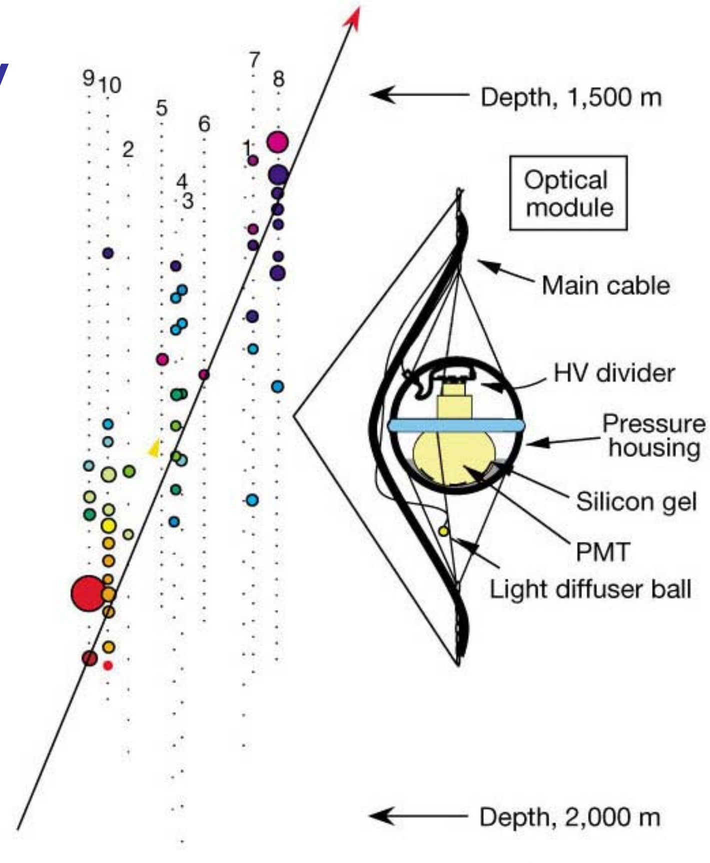
distance	Flux_{nu} >	example
4000 Mpc	10^{47} erg/s	agn
4000 Mpc	10^{52} erg/100s	grb
100 Mpc	$5\ 10^{43}$ erg/s	Markarians
8 Kpc	$4\ 10^{35}$ erg/s	pulsars, micro-quasar…

Detection principle

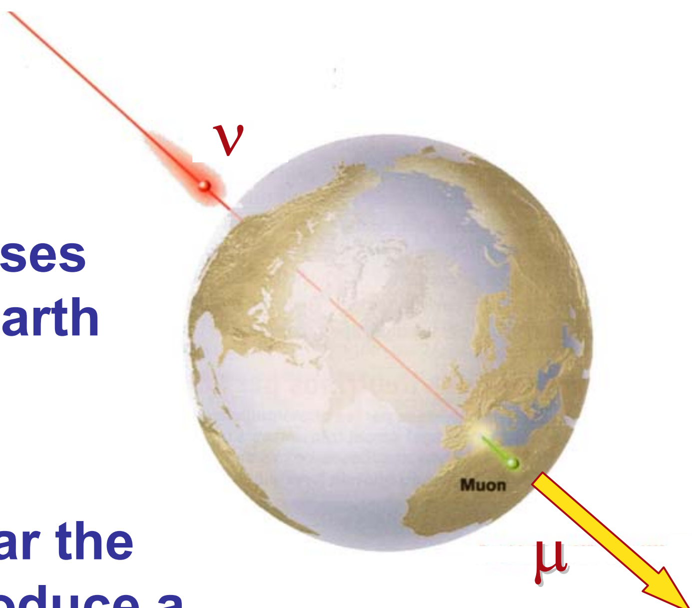


$p \rightarrow \pi \rightarrow \mu \rightarrow \nu$

μ Cherenkov light is observed



Neutrino passes through the earth



Interacts near the detector to produce a muon

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

Detection Probability:

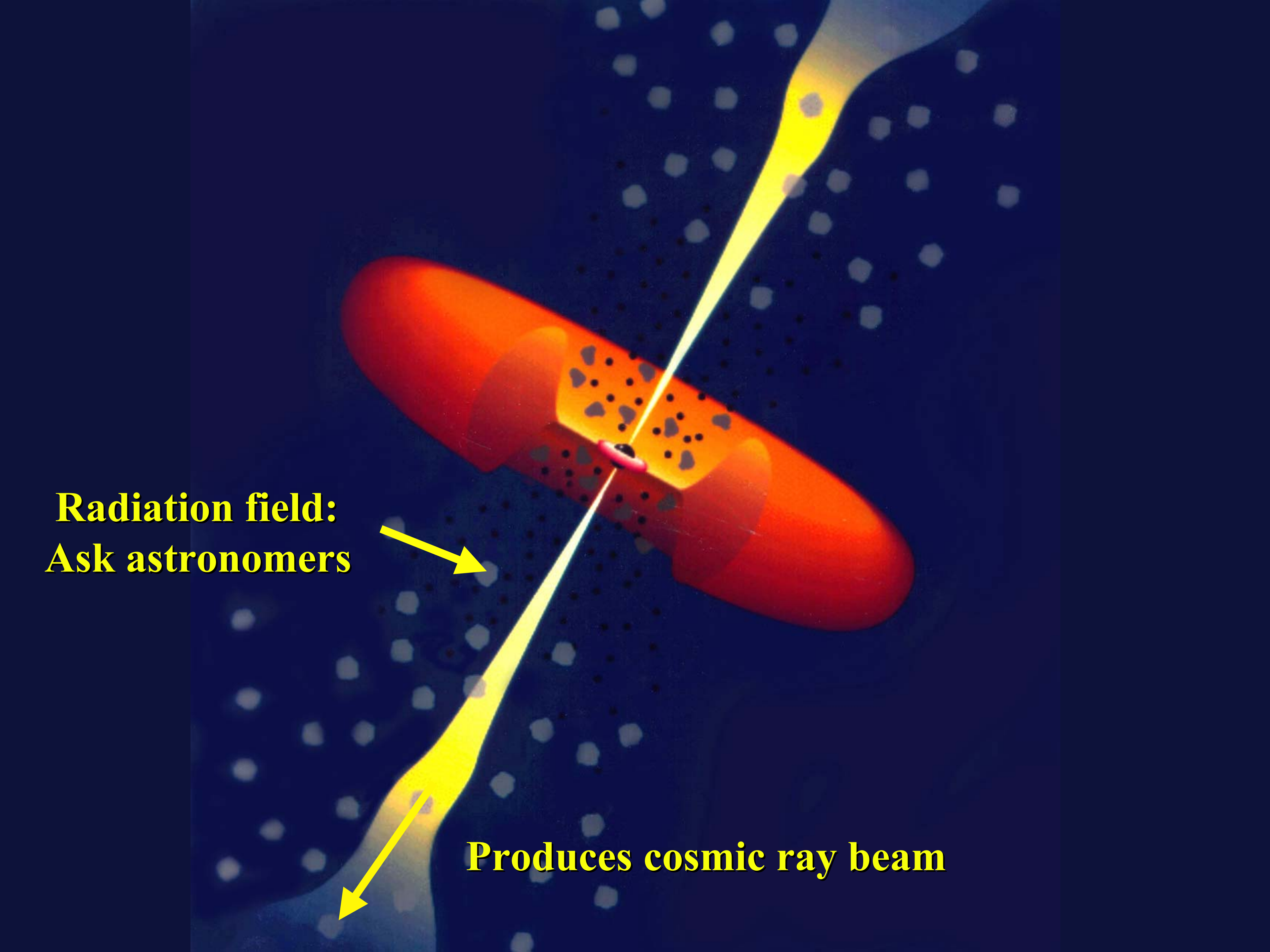
$$N_{events} \sim \frac{\Phi_\nu}{E_\nu} \, P_{\nu \to \mu} \quad \text{Area Time}$$

$$P_{\nu \to \mu} \to n_{target} \, \sigma_\nu \, \text{Range}_\mu$$

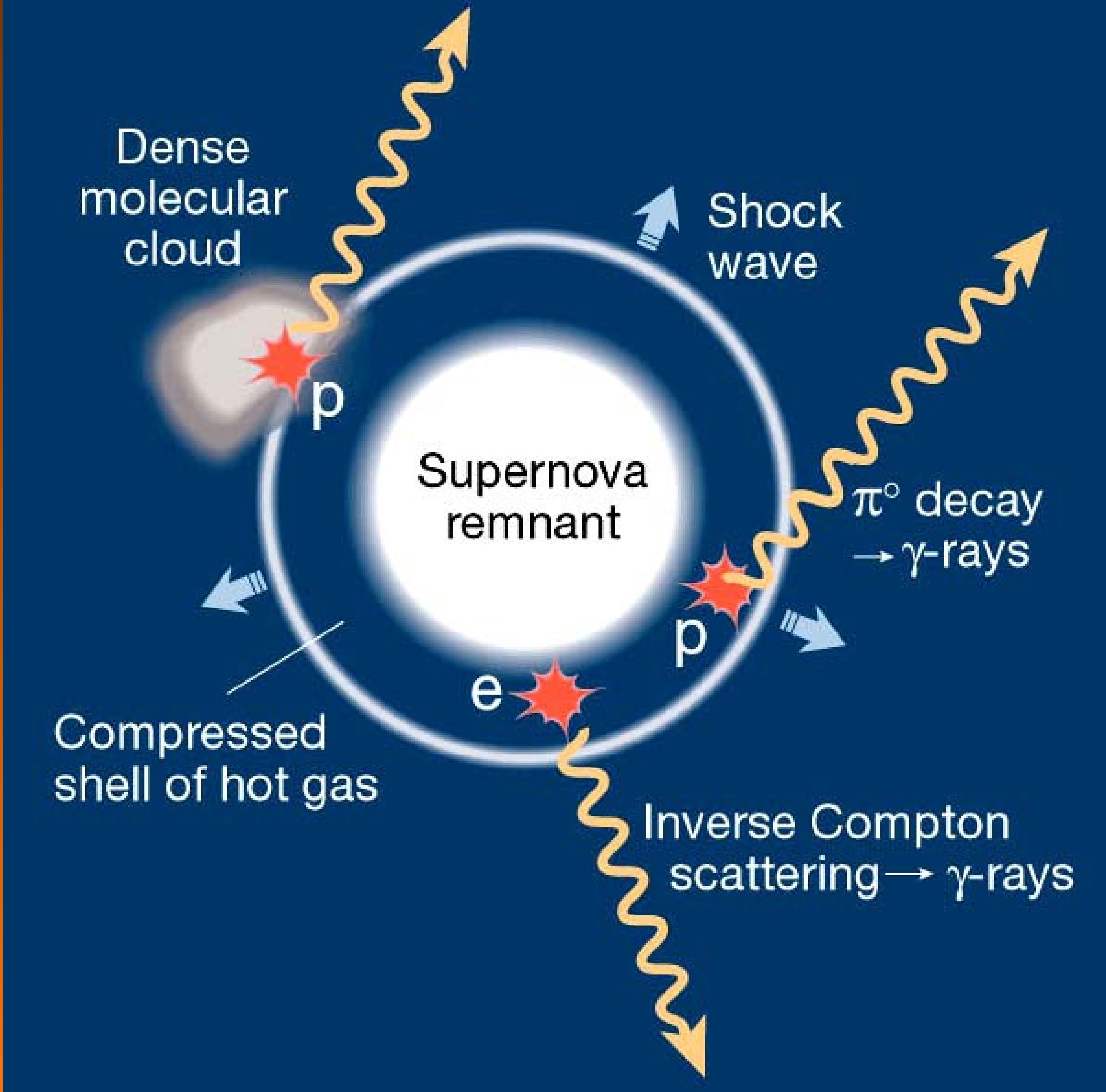
$\sim 10^{-4}$ for 100 TeV neutrinos

Neutrino flux required to observe N events:

$$\Phi_\nu = \frac{5\text{x}10^{-12} \, \frac{\text{erg}}{\text{cm}^2/\text{s}}}{\text{Area (km2) Time (yr)}} N_{events}$$


Radiation field:
Ask astronomers
Produces cosmic ray beam

Galactic Beam Dump



Modeling yields the same conclusion:

- ***Line-emitting quasars such as 3C279***

  Beam: blazar jet with equal power in electrons and protons

  Target: external quasi-isotropic radiation

- ***Supernova remnants such as RX 1713.7-3946 (?)***

  Beam: shock propagating in interstellar medium

  Target: molecular cloud

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

Greatest Marriage of Astronomy and Physics

- **Astronomy: new window on the Universe!**

  "You can see a lot by looking"

- **Physics:**

  search for dark matter

  search for topological defects and cosmological remnants

  search for monopoles

  measure the high-energy neutrino cross section

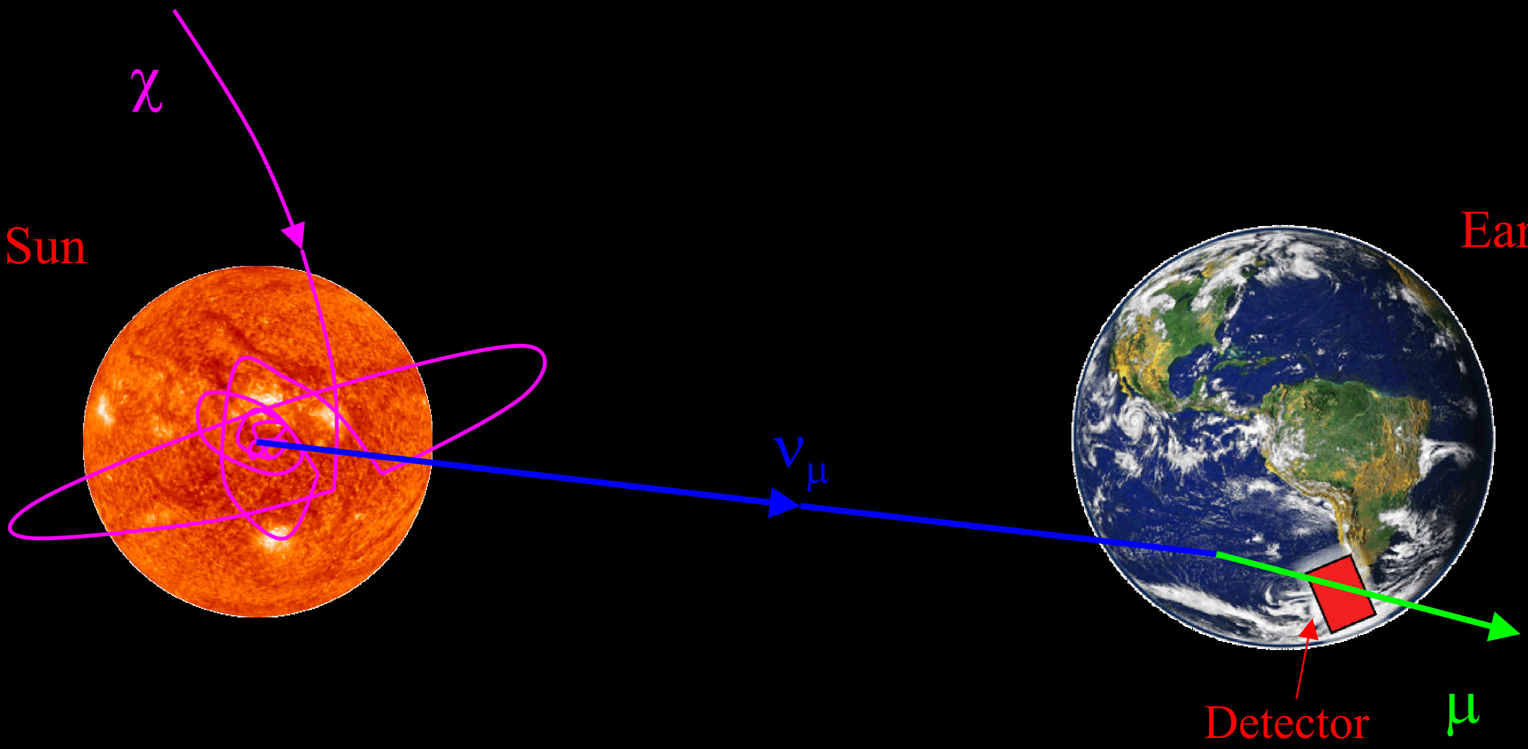
  (TeV-scale gravity?)

  cosmic ray physics: 150 atmospheric nus/day

  array with EeV sensitivity

  test special and general relativity with new precision

WIMP capture and annihilation

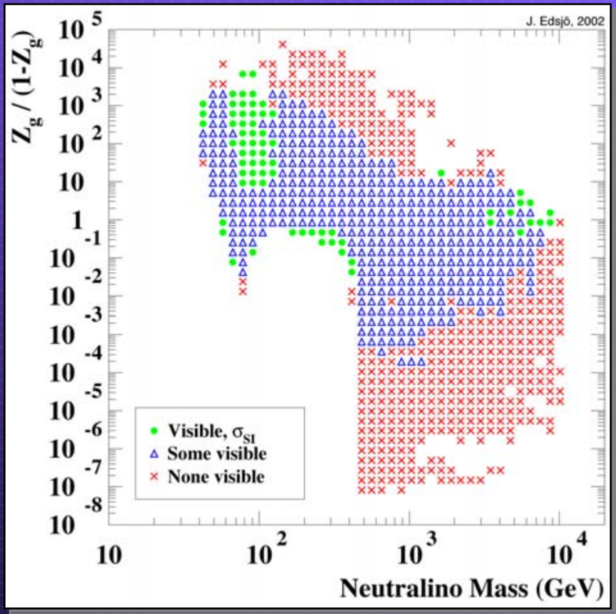


Silk, Olive and Srednicki, '85
Gaisser, Steigman & Tilav, '86

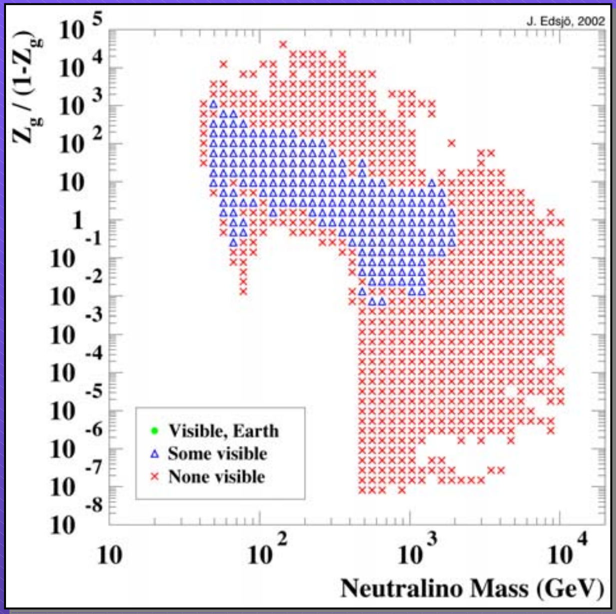
Freese, '86; Krauss, Srednicki & Wilczek, '86
Gaisser, Steigman & Tilav, '86

MSSM parameter space: Future probed regions

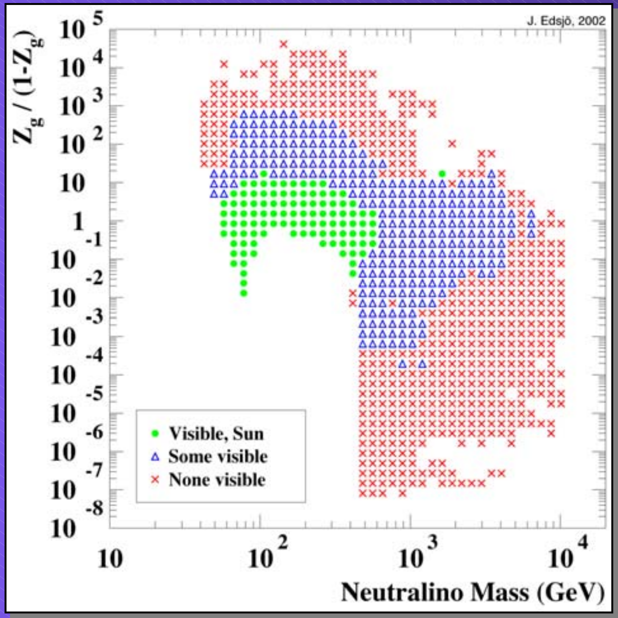
Direct detection e.g. Genius



Earth, km^3



Sun, km^3

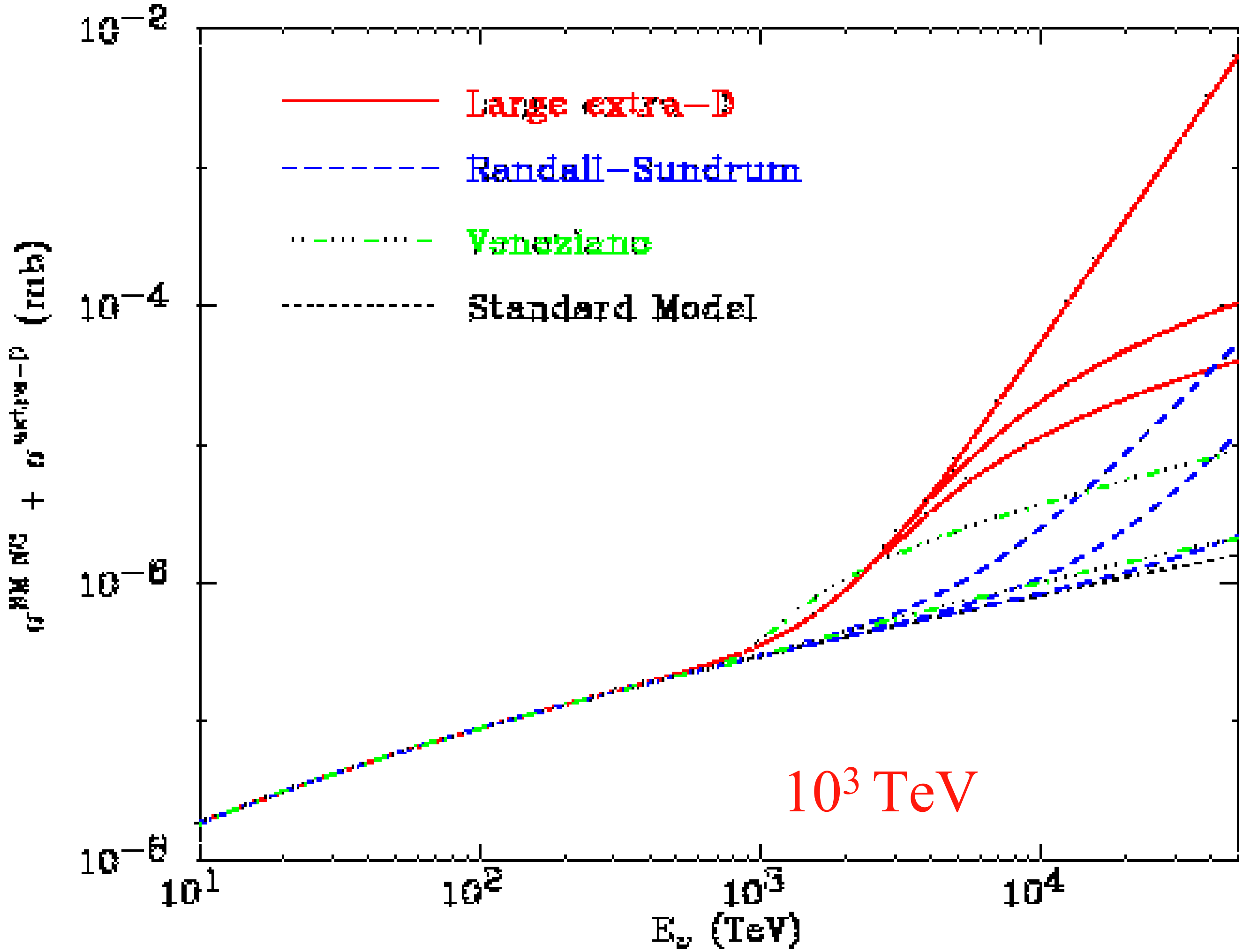


IceCube

The End

Illustration by Guy Billout

TeV-Scale Gravity Modifies PeV Neutrino Cross Sections!

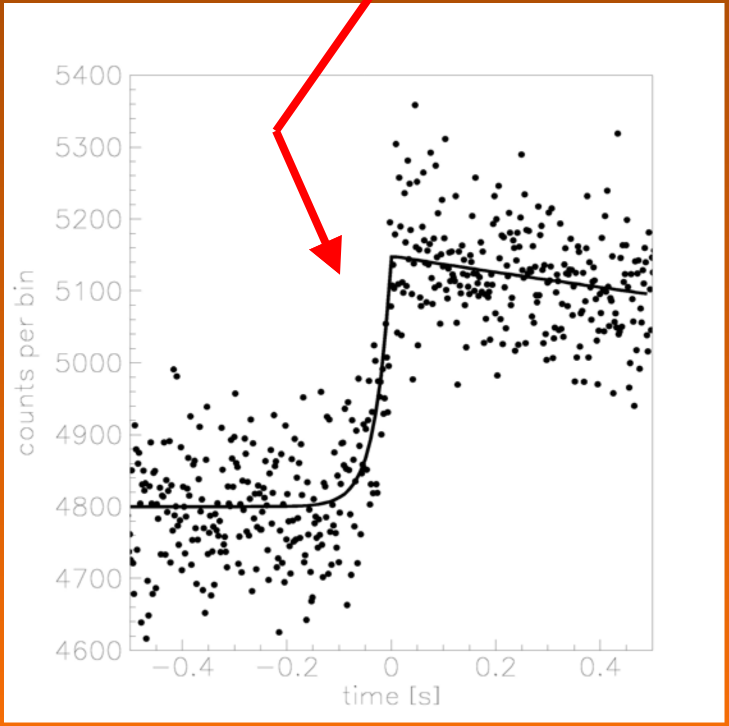


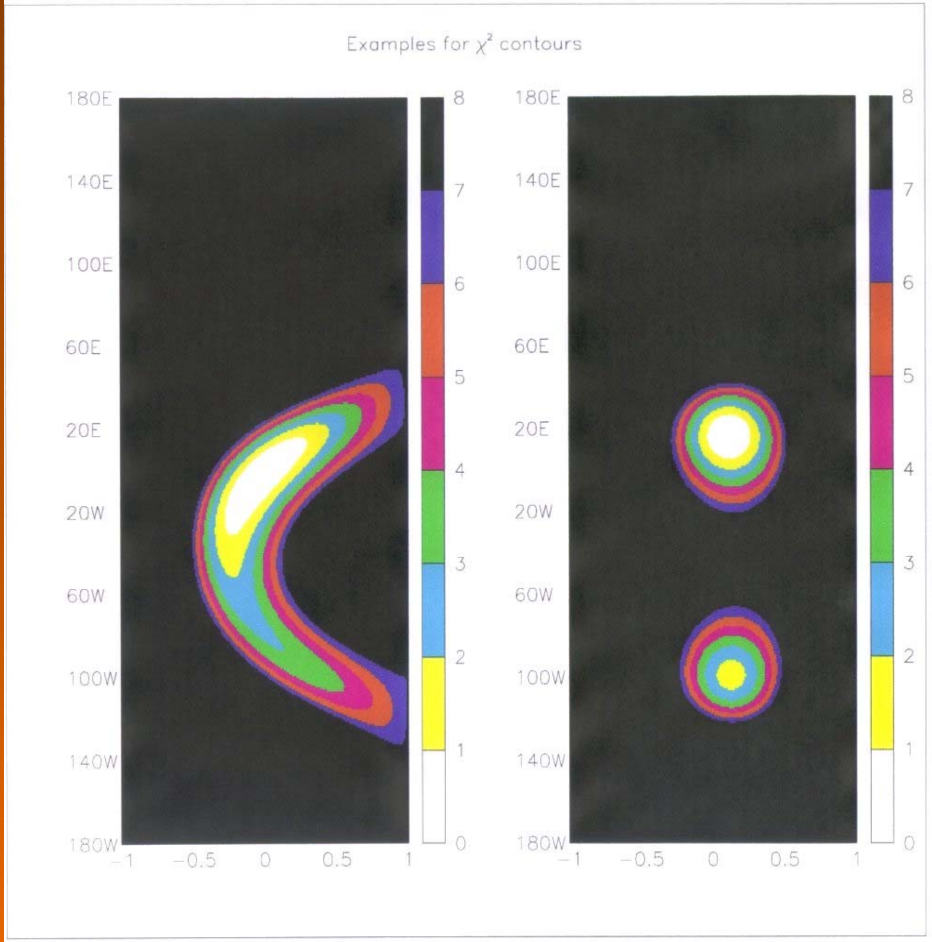
Supernova Triangulation ?

Record increase in average countig rate of all PMs with msec accuracy.

***Δt* (Amanda-II) = 14 msec**
***Δt* (IceCube) = 3 msec**

(model dependent!)





χ^2 contours of reconstructed SN direction.

Left: Amanda-II. Right: IceCube

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

- Search for vacuum oscillations ($\nu_\mu \rightarrow \nu_\tau$):

  $\Delta m^2 \gtrsim 10^{-17}\ \mathrm{eV}^2$

- Test weak equivalence principle: 10^{-6}

- Test $\dfrac{C_{photon} - C_\nu}{C_\nu}$: 10^{-16}

New Window on Universe?

Expect Surprises

Telescope	User	date	Intended Use	Actual use
Optical	Galileo	1608	Navigation	Moons of Jupiter
Optical	Hubble	1929	Nebulae	Expanding Universe
Radio	Jansky	1932	Noise	Radio galaxies
Micro-wave	Penzias, Wilson	1965	Radio-galaxies, noise	3K cosmic background
X-ray	Giacconi …	1965	Sun, moon	neutron stars accreting binaries
Radio	Hewish, Bell	1967	Ionosphere	Pulsars
γ-rays	military	1960?	Thermonuclear explosions	Gamma ray bursts

$E \sim \Gamma\, B\, M$

$E > 10^{19}$ eV ?

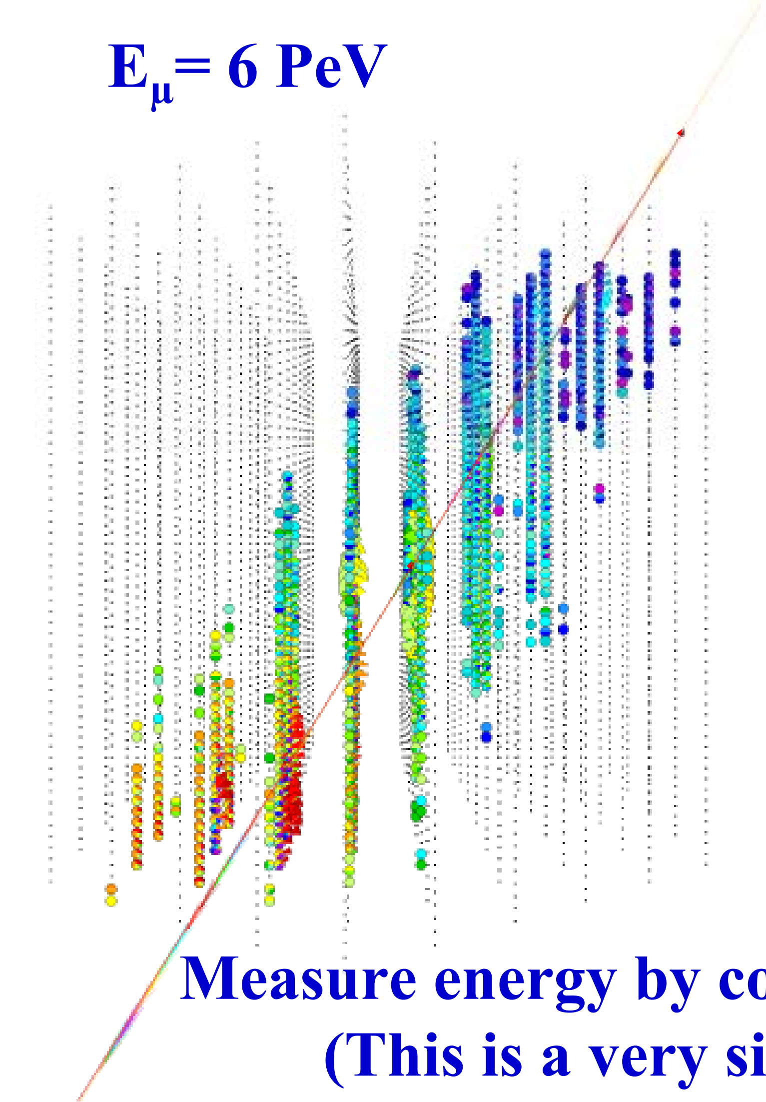
- quasars $\Gamma \cong 1$ $B \cong 10^{3}$G $M \cong 10^{9} M_{sun}$
- blasars $\gtrsim 10$
- neutron stars $\Gamma \cong 1$ $B \cong 10^{12}$G $M \cong M_{sun}$

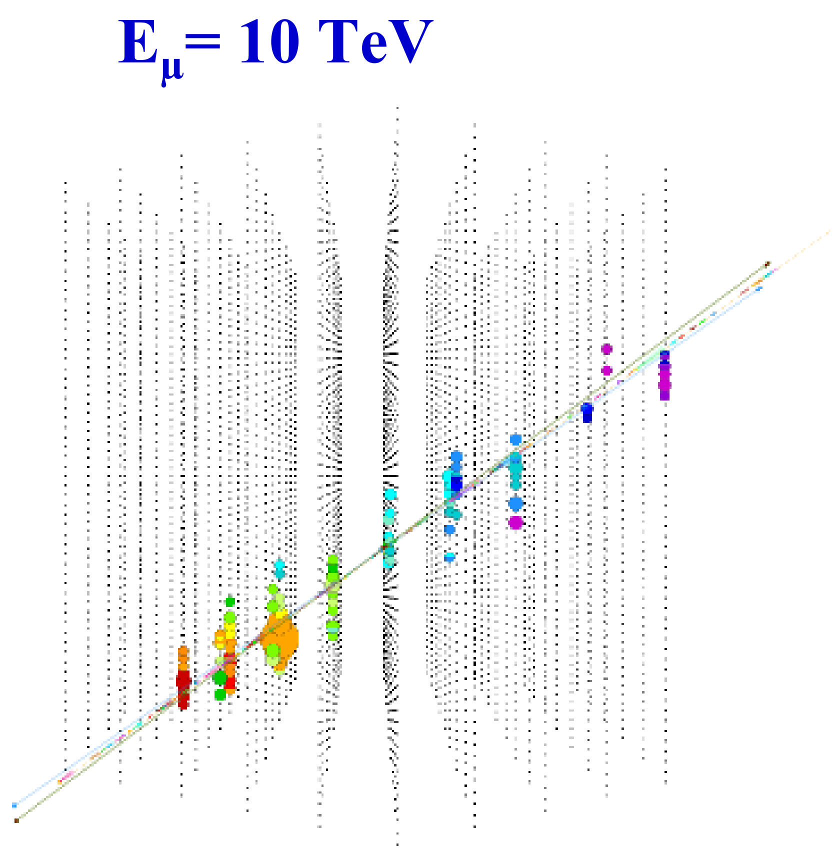
  black holes

  ⋮
- grb $\gtrsim 10^{2}$

emit highest energy γ's!

Muon Events



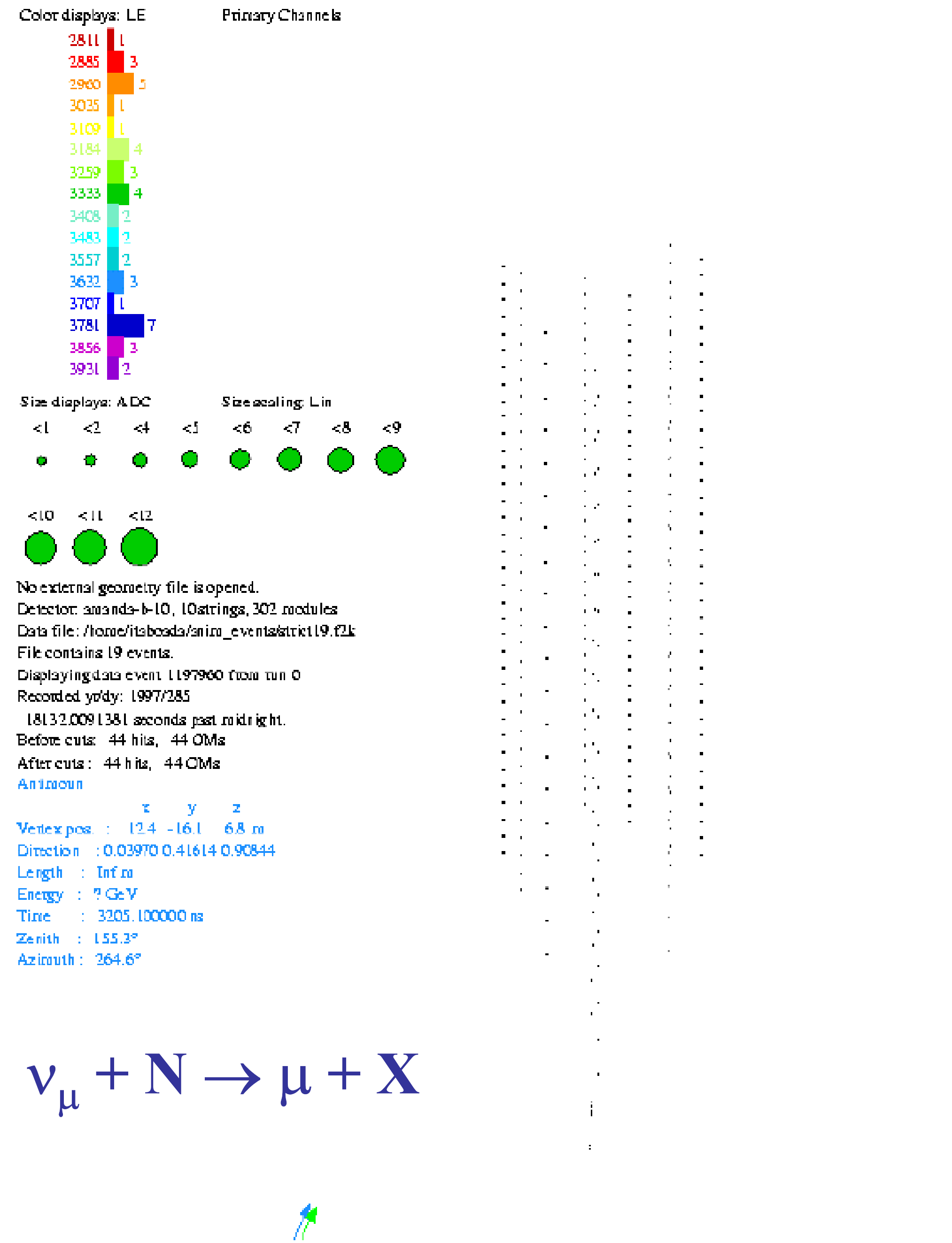


Measure energy by counting the number of fired PMT.
(This is a very simple but robust method)

AMANDA Event Signatures: Muons

CC muon-neutrino interactions

→ Muon tracks



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

AMANDA Event Signatures: “Cascades”

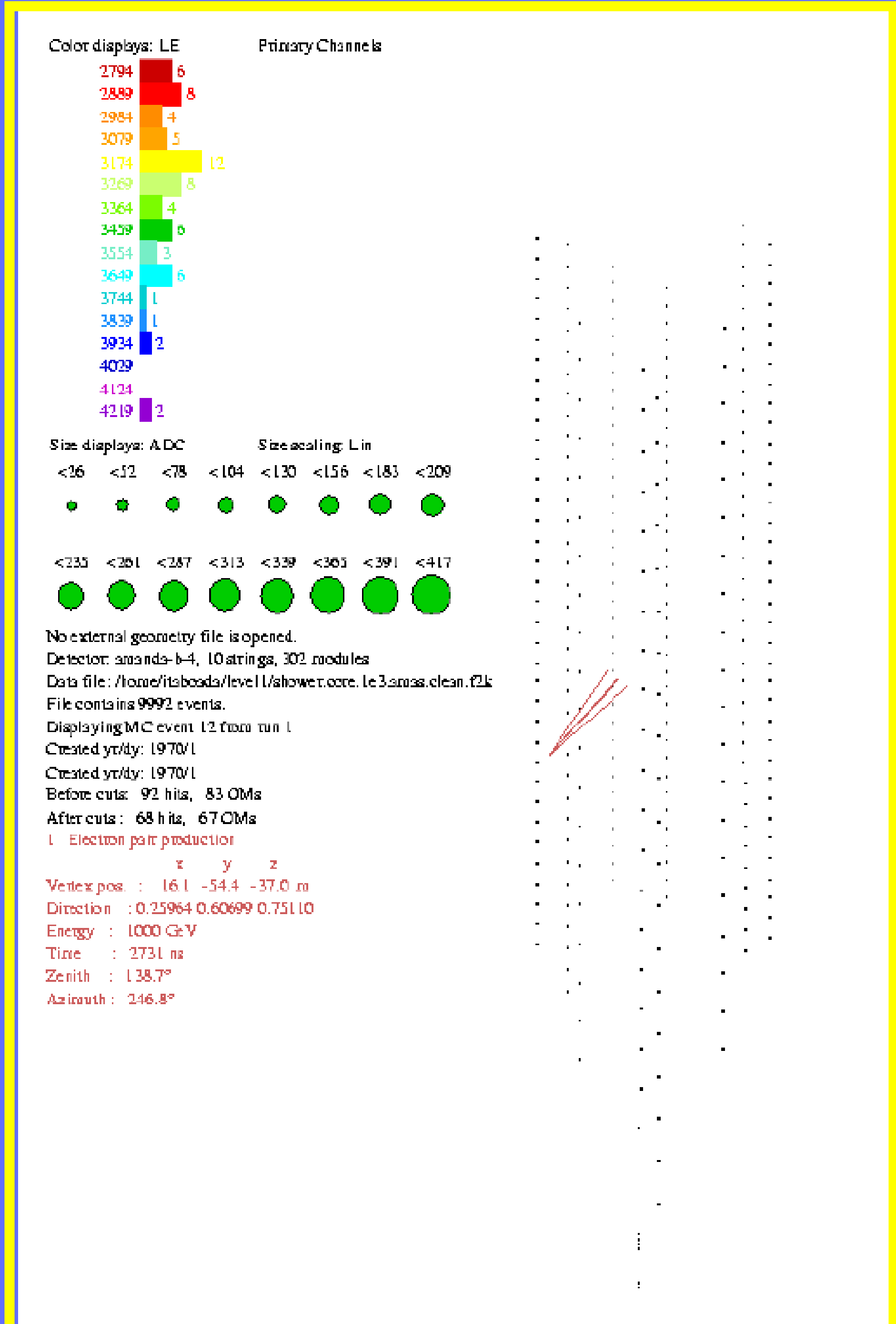
- CC electron and tau neutrino interactions:

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

- NC neutrino interactions:

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

} Cascades

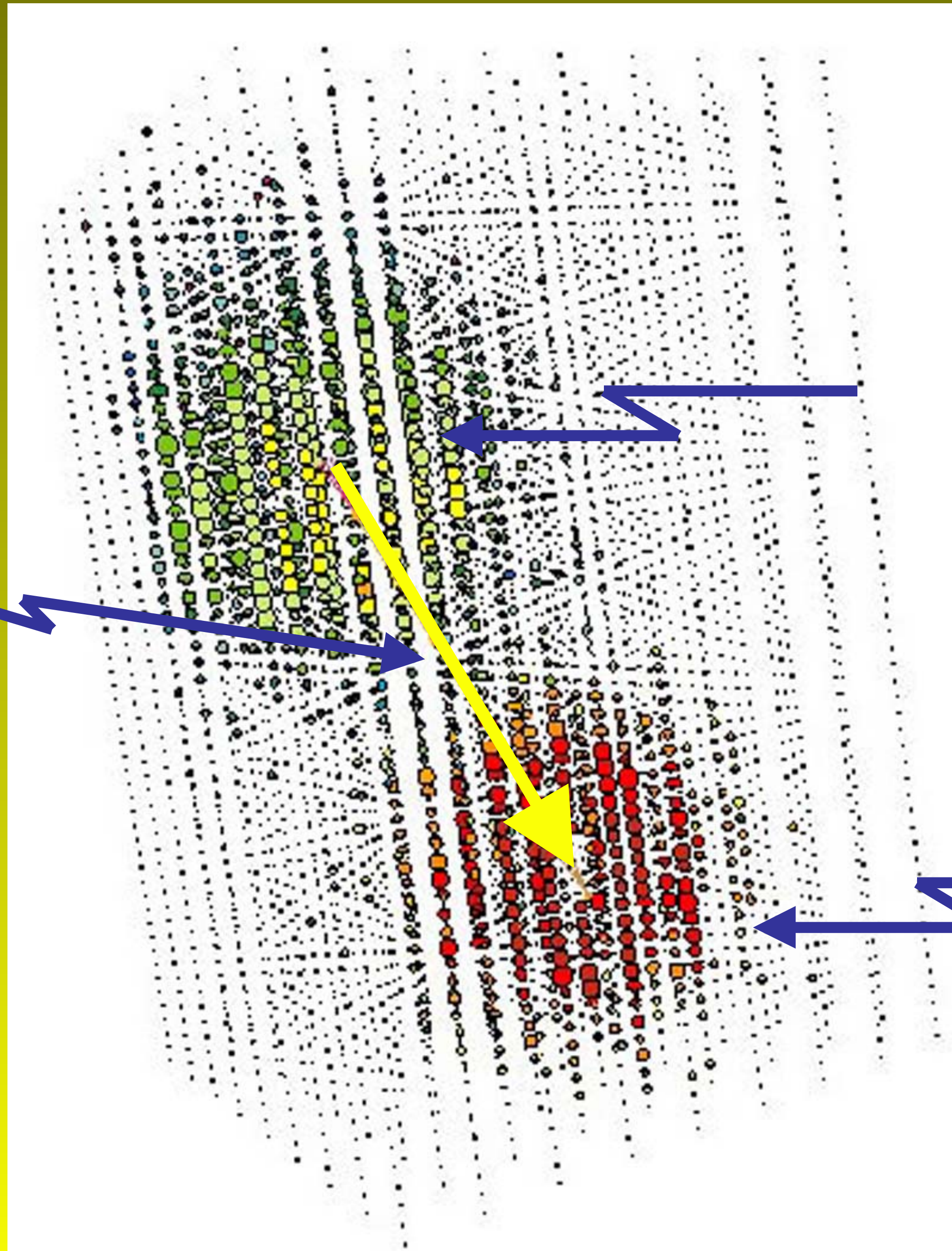


$\nu_\tau \rightarrow \tau$

PeV

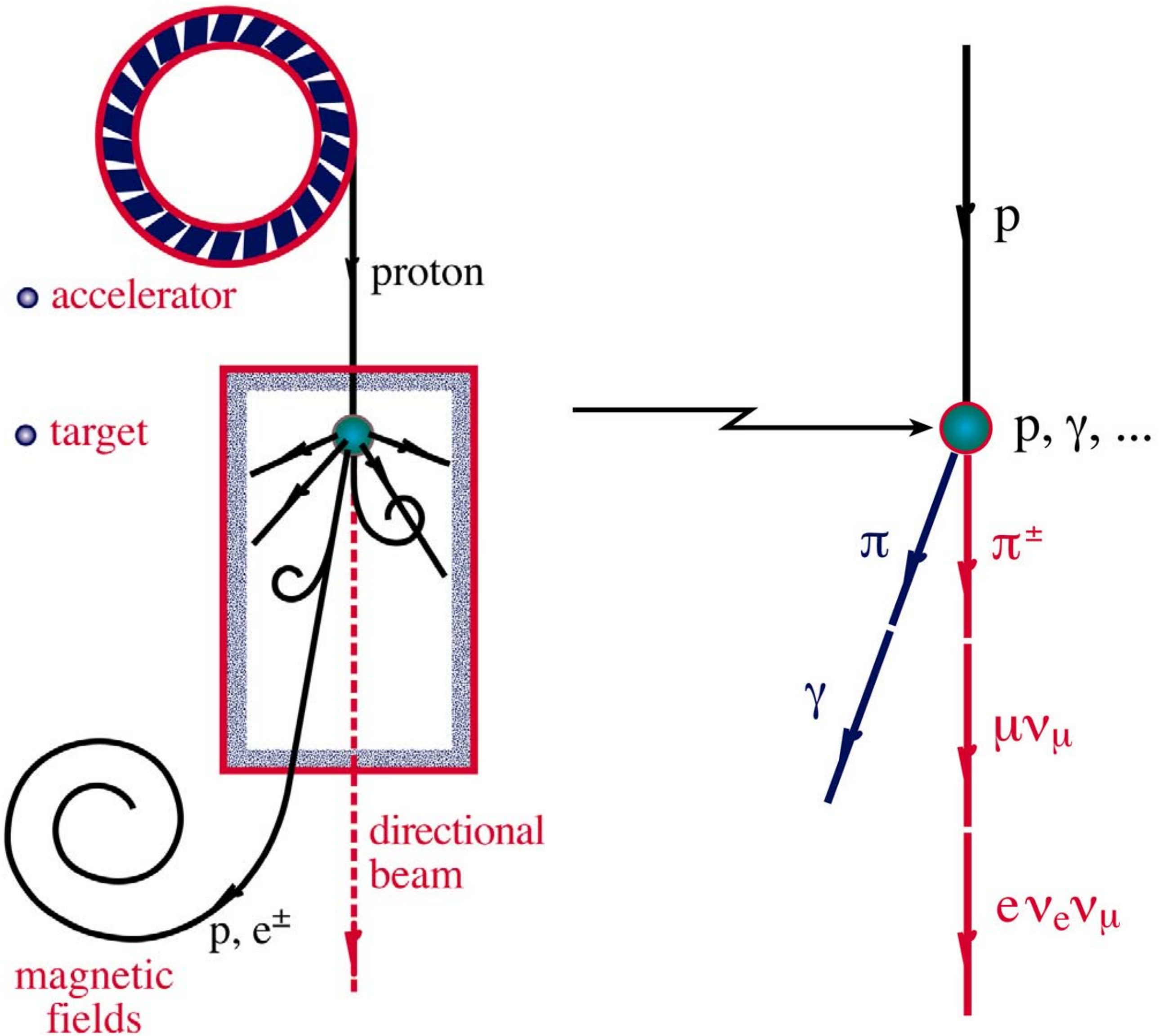
τ

(300m)



τ **decays**

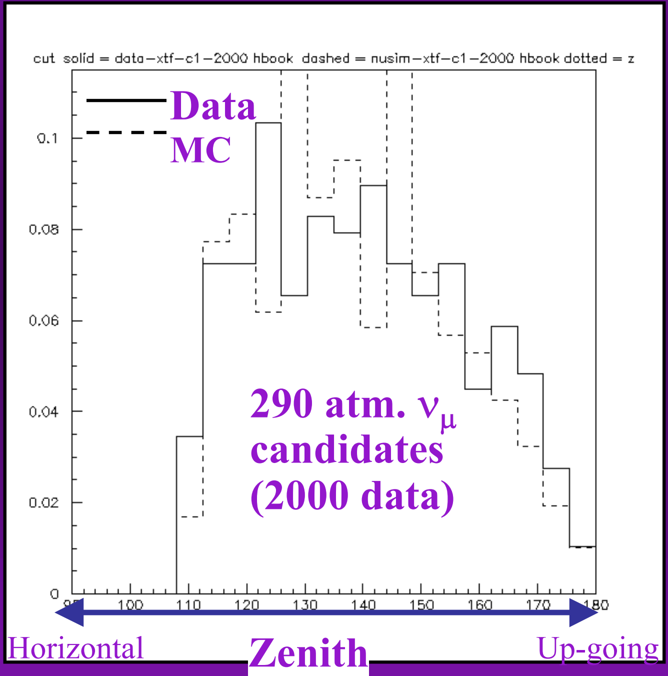
NEUTRINO BEAMS: HEAVEN & EARTH



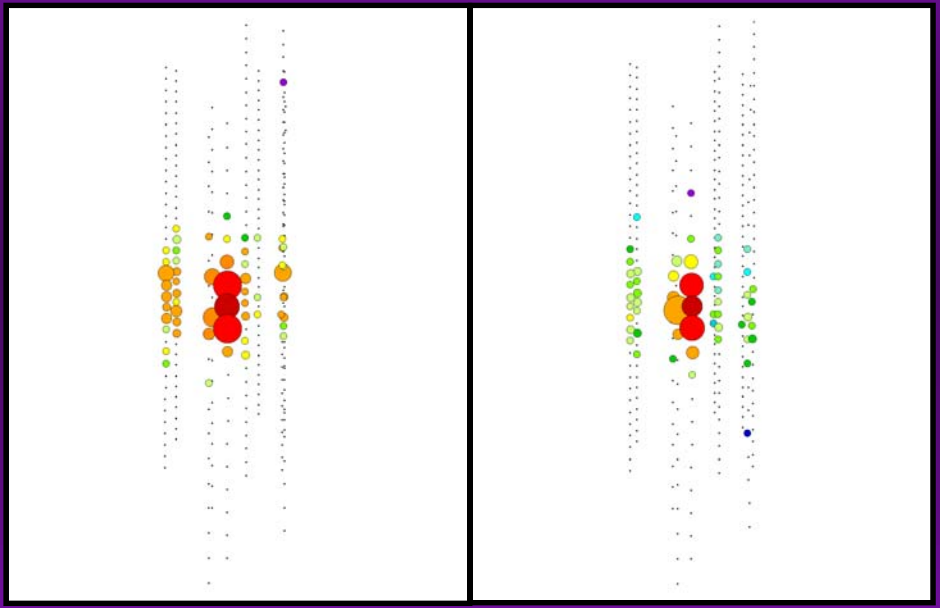
transparent dump: one cosmic ray for one gamma for one neutrino

AMANDA Is Working Well: 4 nus per day!

- Sensitivity to up-going muons demonstrated with CC atm. ν_μ interactions:

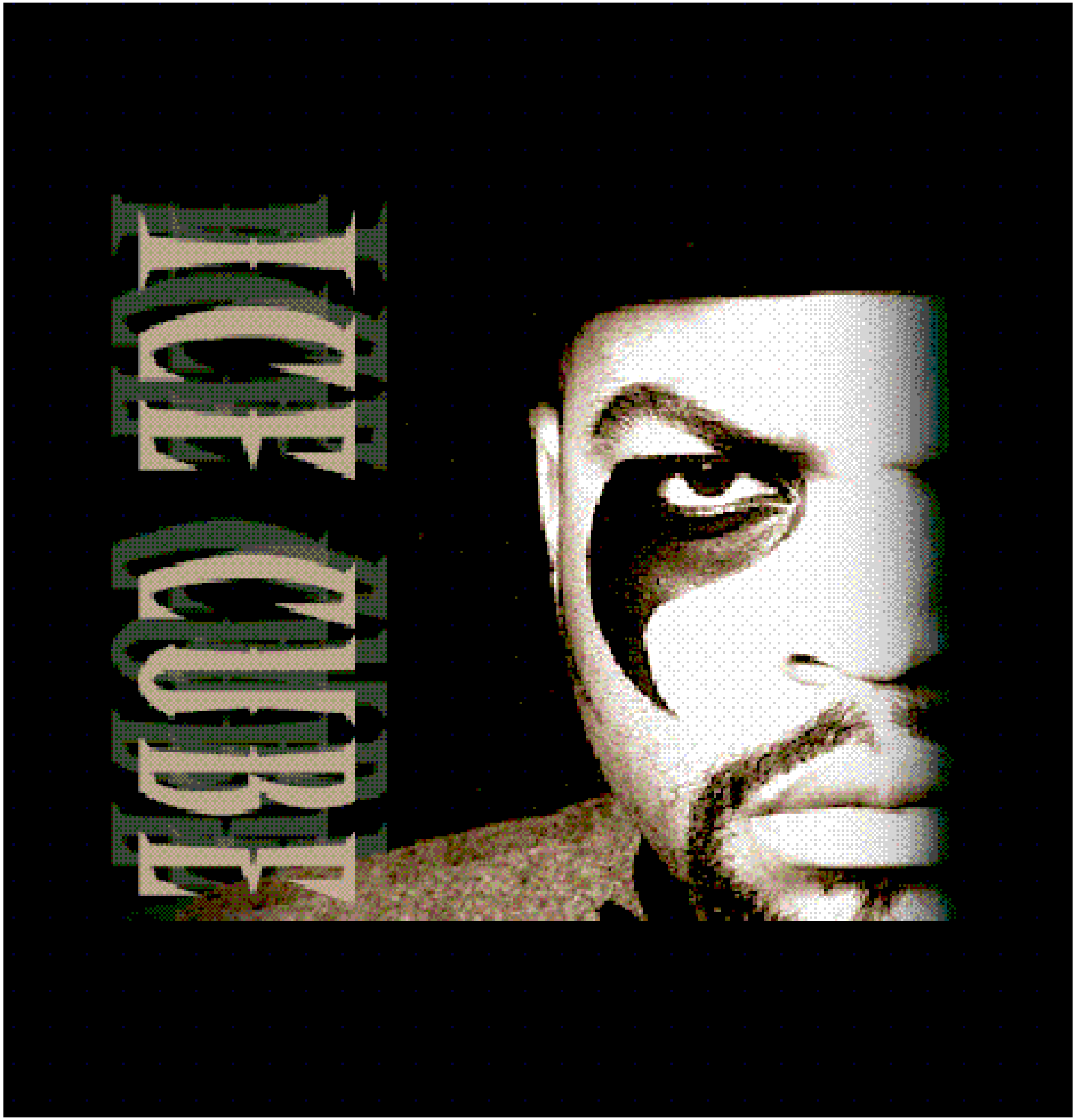


- Sensitivity to cascades demonstrated with *in-situ* sources (see figs.) & down-going muon brems.



In-situ light source   Simulated light source

- AMANDA also works well with *SPASE*:
  - Calibrate AMANDA angular response
  - Do cosmic ray composition studies.


ICE CUBE