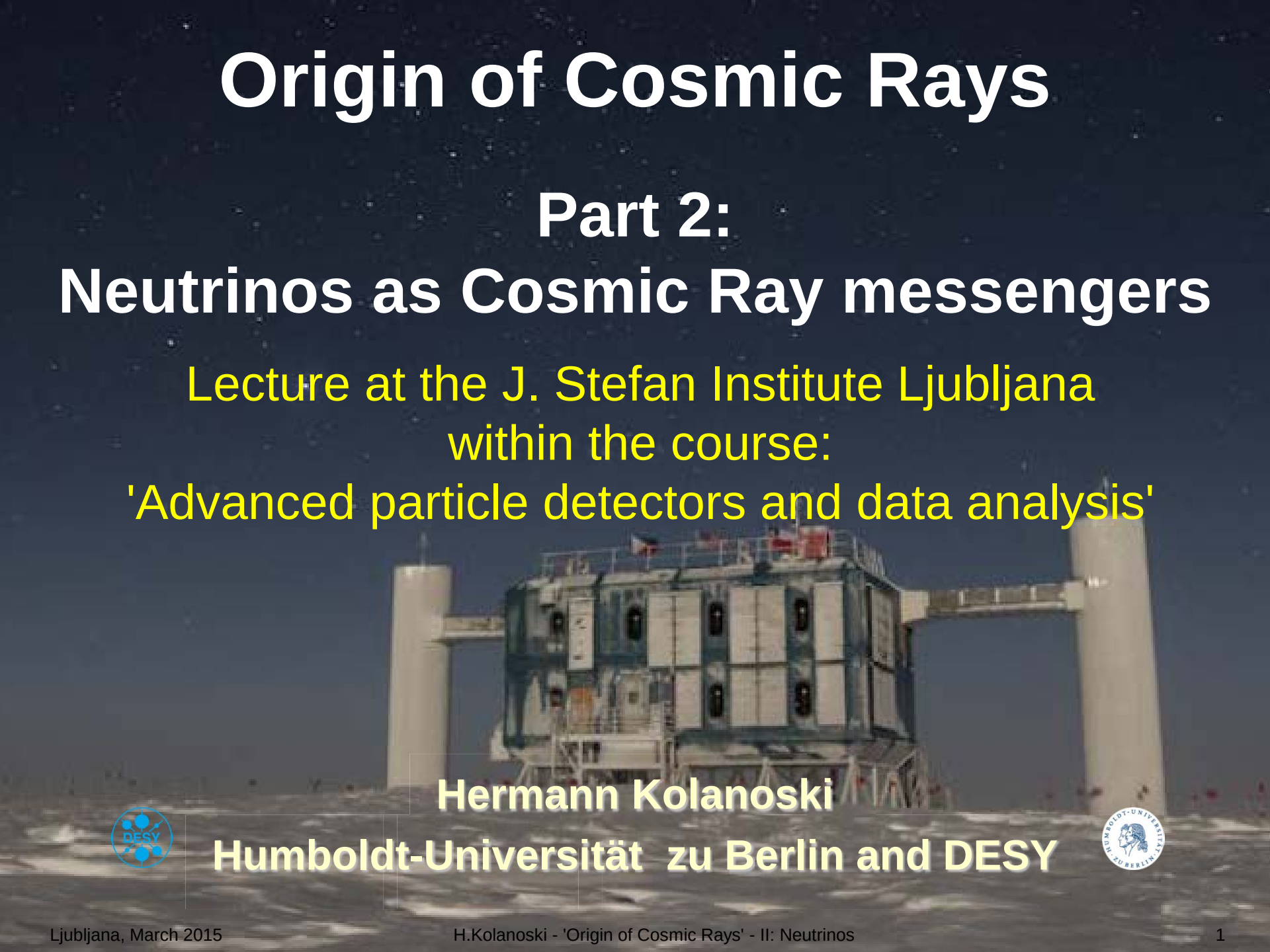
Origin of Cosmic Rays

Part 2:
Neutrinos as Cosmic Ray messengers

Lecture at the J. Stefan Institute Ljubljana
within the course:
'Advanced particle detectors and data analysis'

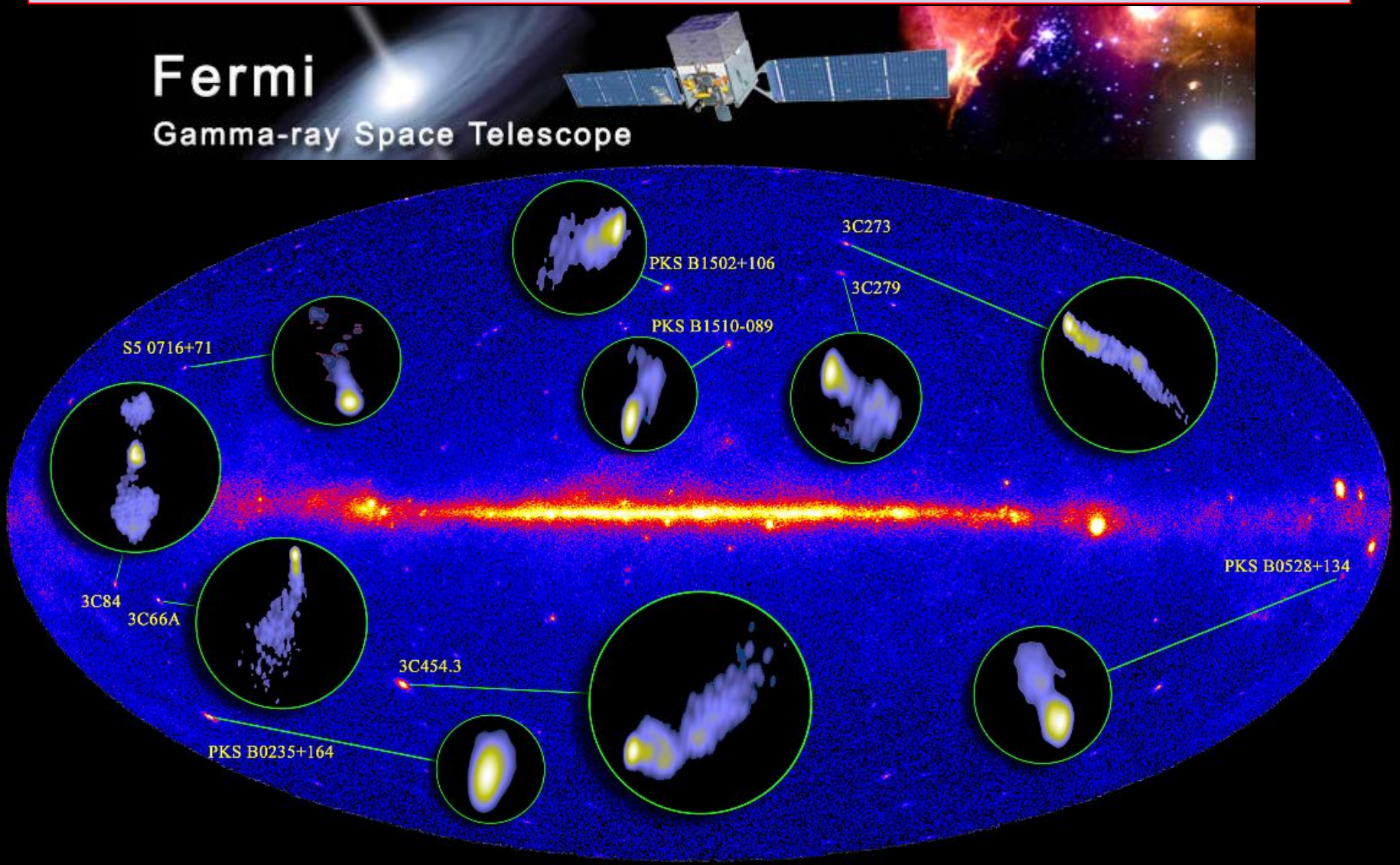


Hermann Kolanoski
Humboldt-Universität zu Berlin and DESY

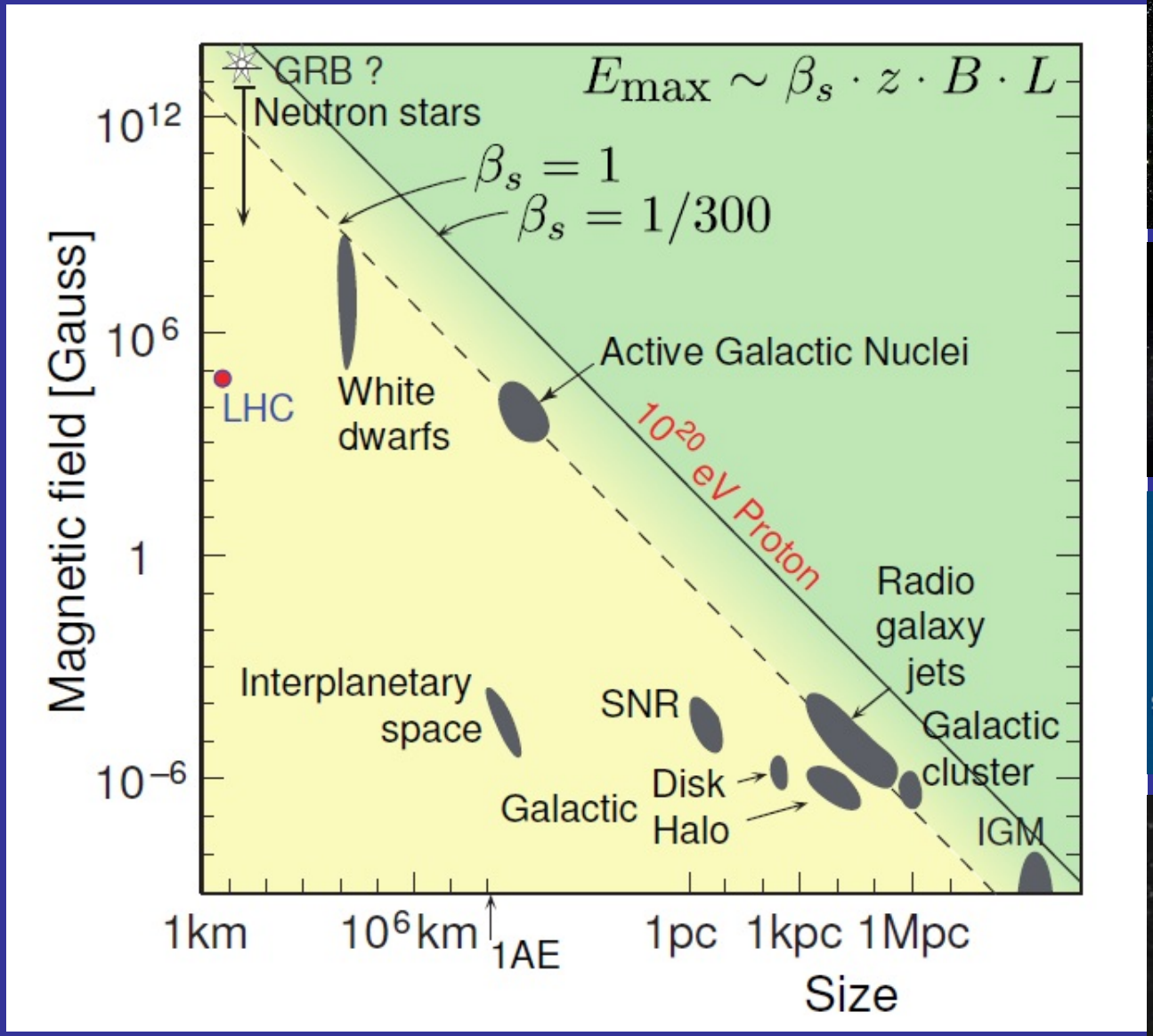
What I want to tell you:

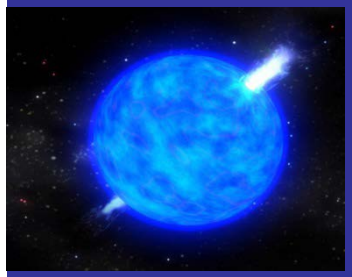
- Candidates for cosmic ray accelerators
- Neutrinos as messengers for CR sources
- HE Neutrino telescopes
- Neutrino detection
- Point source searches
- EHE neutrinos and the Muppet Show
- Cosmic signals from contained events

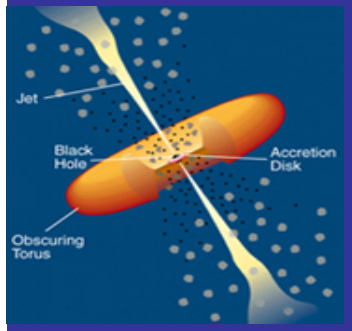
The „non-thermal Universe“



Where could particles possibly be accelerated? Hillas diagram

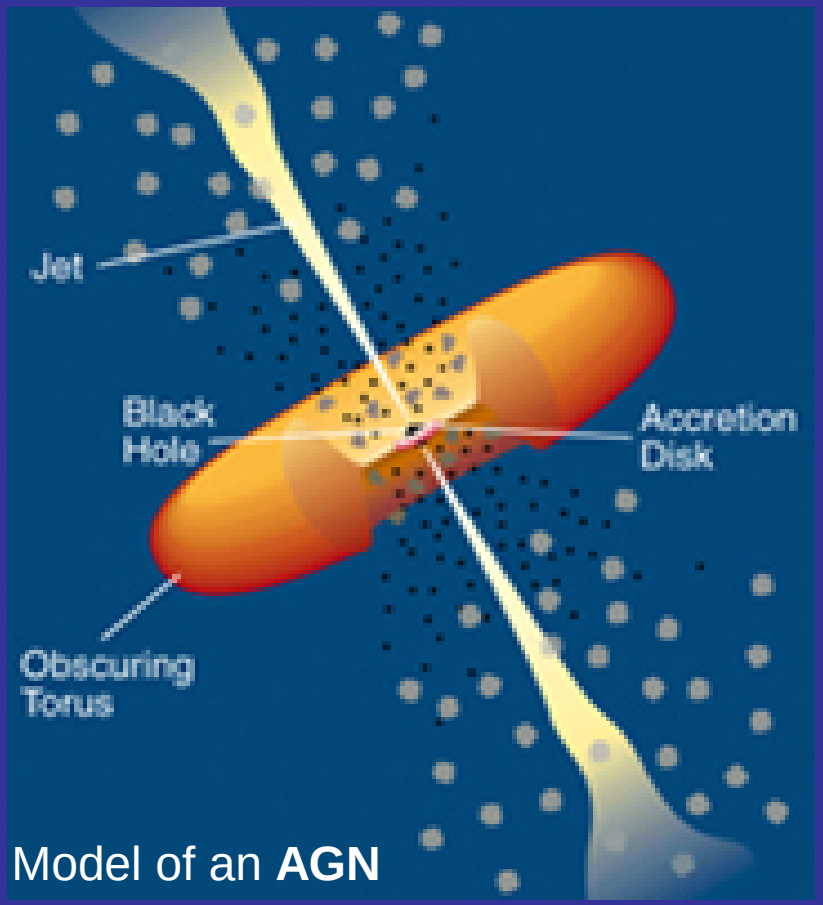






Active Galactic Nuclei

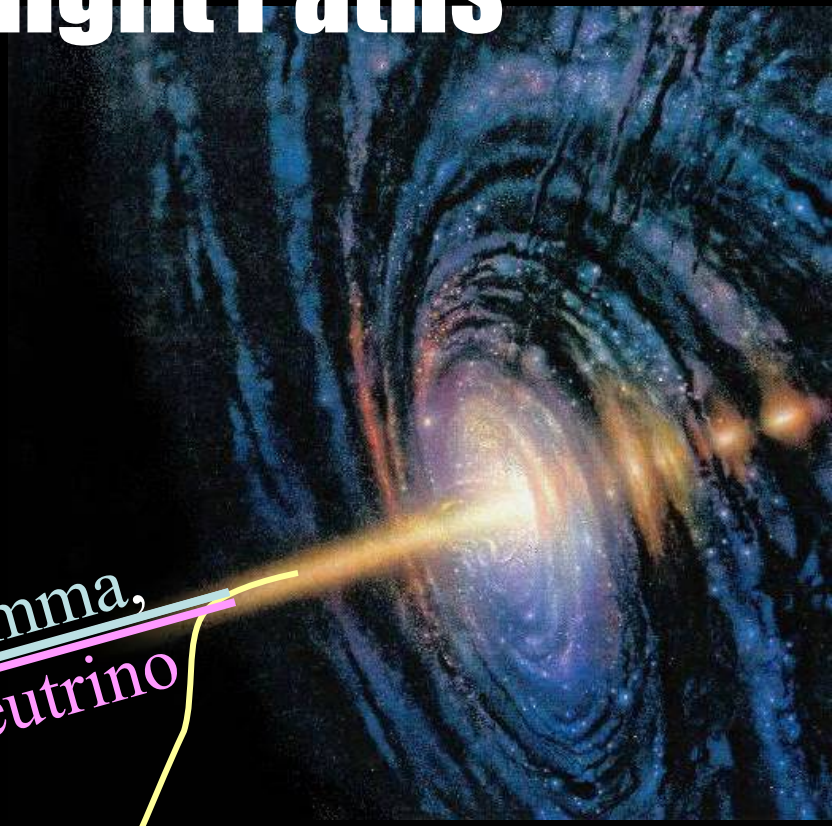
Hubble Heritage Picture of M87

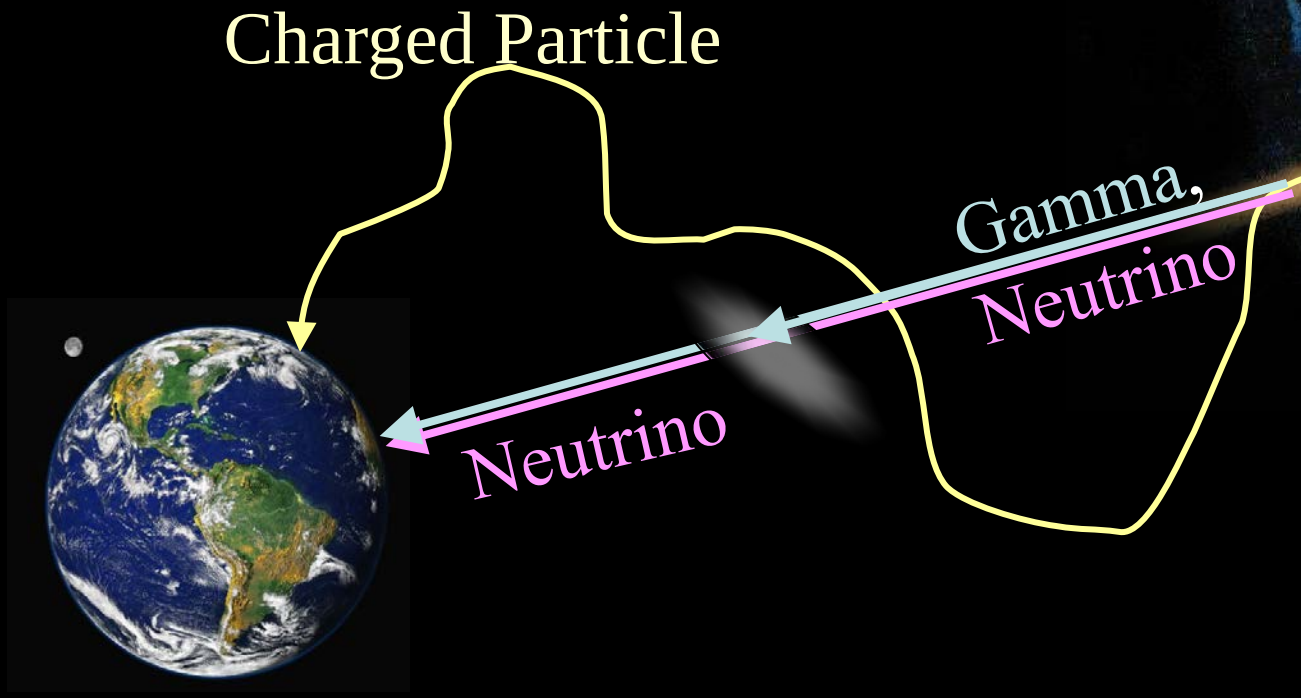


Model of an **AGN**

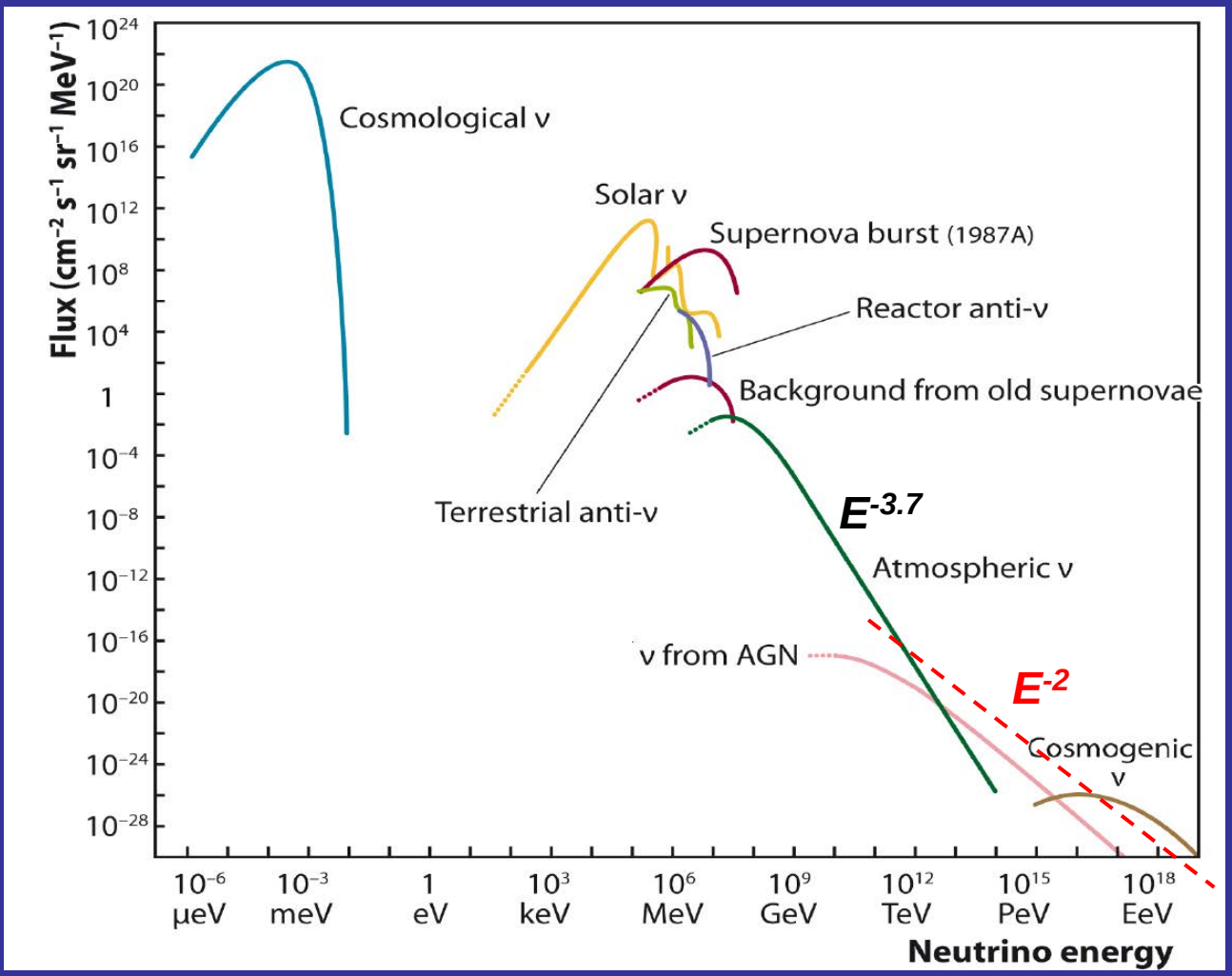
Origin of the HE cosmic radiation?

Twisted and Straight Paths





Neutrino fluxes



Cosmic neutrinos should have a hard spectrum

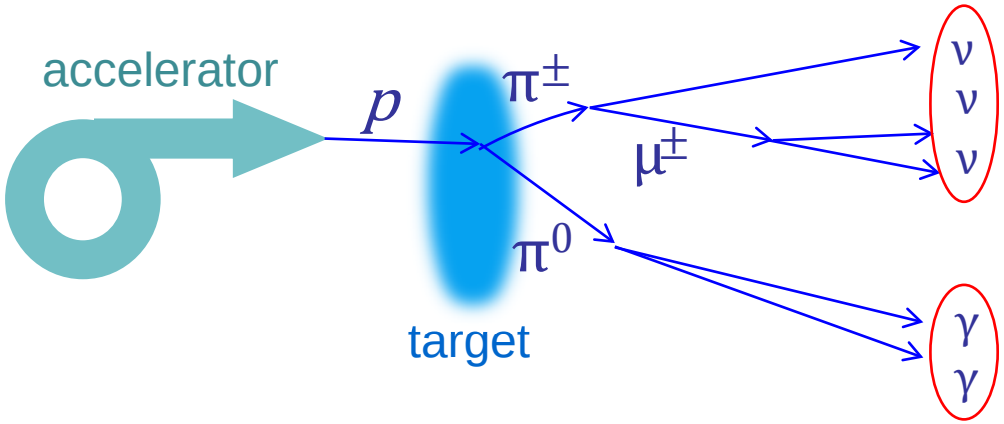
$F \sim E^{-2}$

atmospheric ν

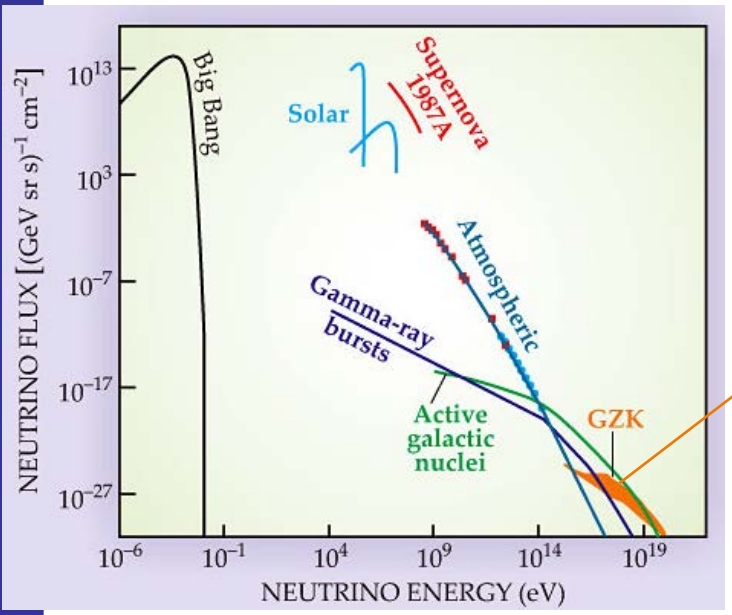
$F \sim E^{-3.7}$

Cosmic Rays, Gammas and Neutrinos

CR – ν – γ connection



the **γ – ν** connection for hadron accelerators



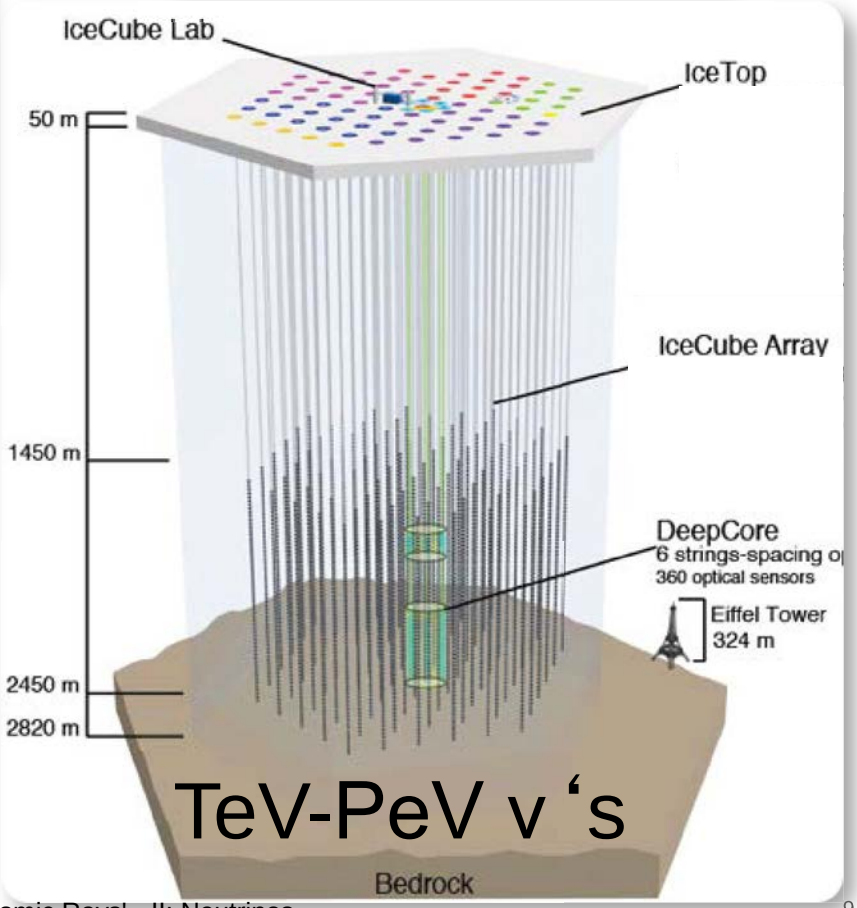
GZK ν's:

$$\gamma_{cmb}\, p \rightarrow \Delta^{+} \rightarrow \begin{matrix} n\,\pi^{+} \rightarrow n\,\mu\nu \\ p\,\pi^{0} \rightarrow p\,\gamma\gamma \end{matrix}$$

CMB 2.7 K → threshold $E_p \approx 4\times10^{19}$ eV

Three Pillars of HE-Astroparticle Physics

- Cosmic Rays
- GeV-TeV γ ‘s
- TeV-PeV ν ‘s



How to detect cosmic high energy neutrinos?

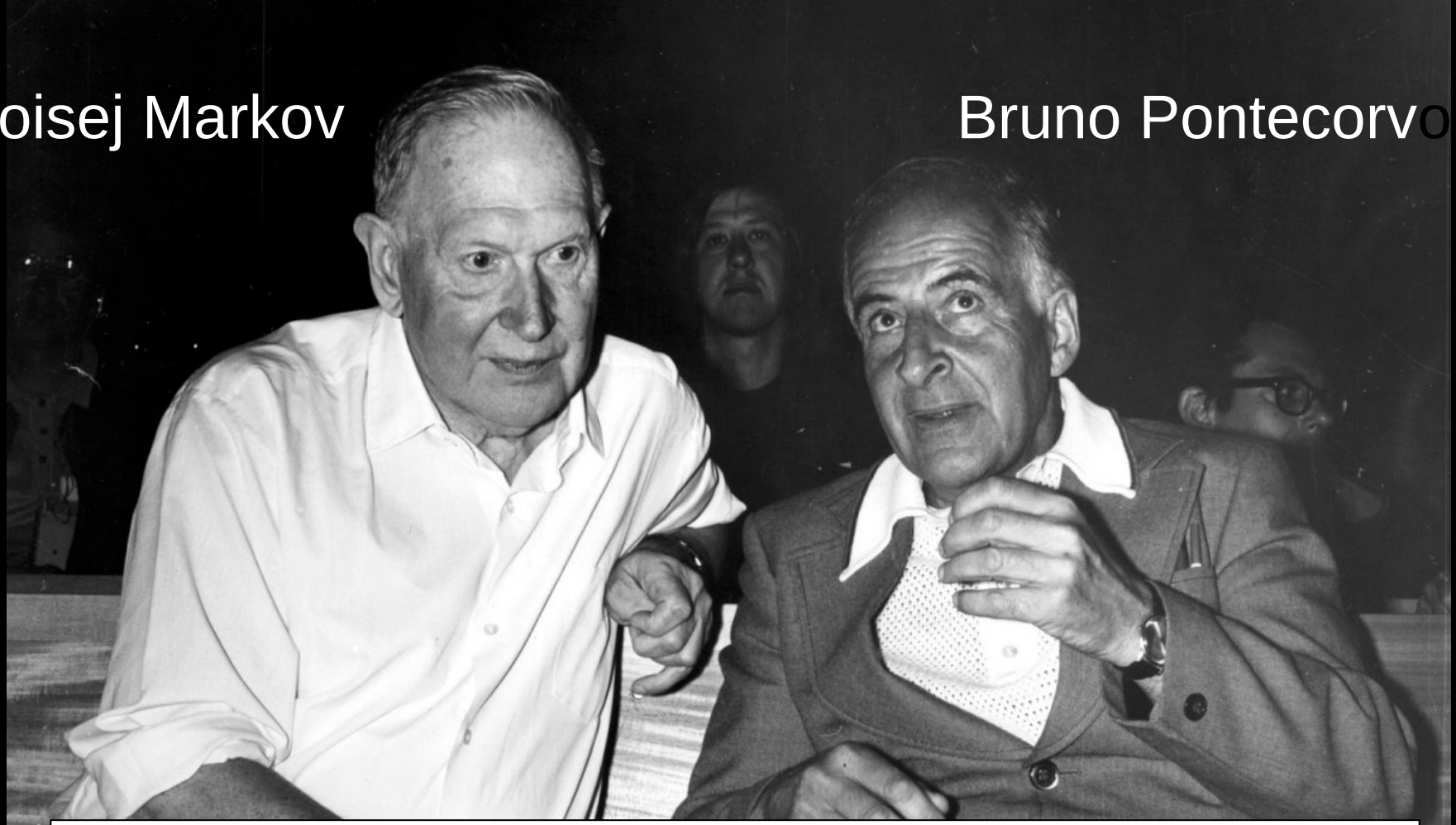
quite difficult

Absorption small → detection probability small

Need something

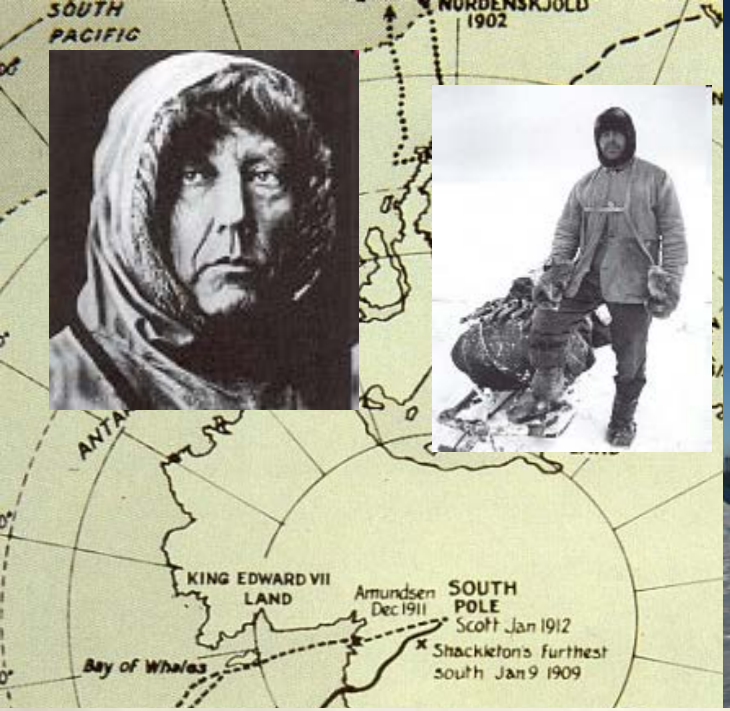
- **large**
- **transparent**

⇒ **water** or **ice**



М.Марков, **1960**:

„We propose to install **detectors deep in a lake or in the sea** and to determine the direction of charged particles with the help of **Cherenkov radiation**.“


SOUTH PACIFIC
NORDENSKJOLD 1902
ANTA
KING EDWARD VII LAND
Amundsen Dec 1911
SOUTH POLE
Scott Jan 1912
Shackletons furthest south Jan 9 1909
Bay of Whales

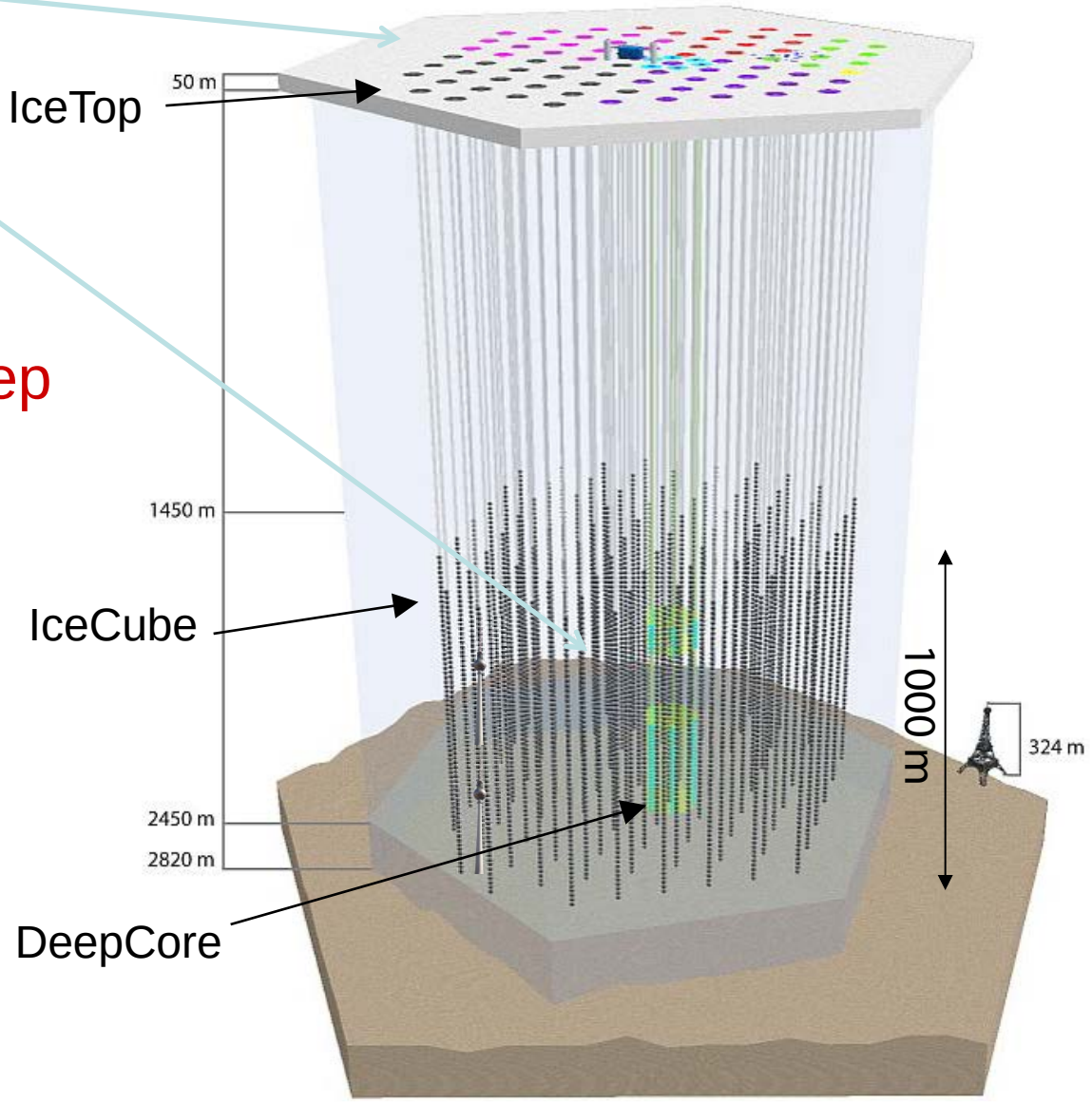

GEOGRAPHIC SOUTH POLE
ROALD AMUNDSEN
ROBERT F. SCOTT

IceCube

air shower array

gigaton-scale
neutrino telescope

- 86 Strings, 2450 m deep
- 5160 Optical Modules
- Instrumented: 1 km^3
- IceTop: 1 km^2
- Installation: 2005-2011



DOM – Digital Optical Module

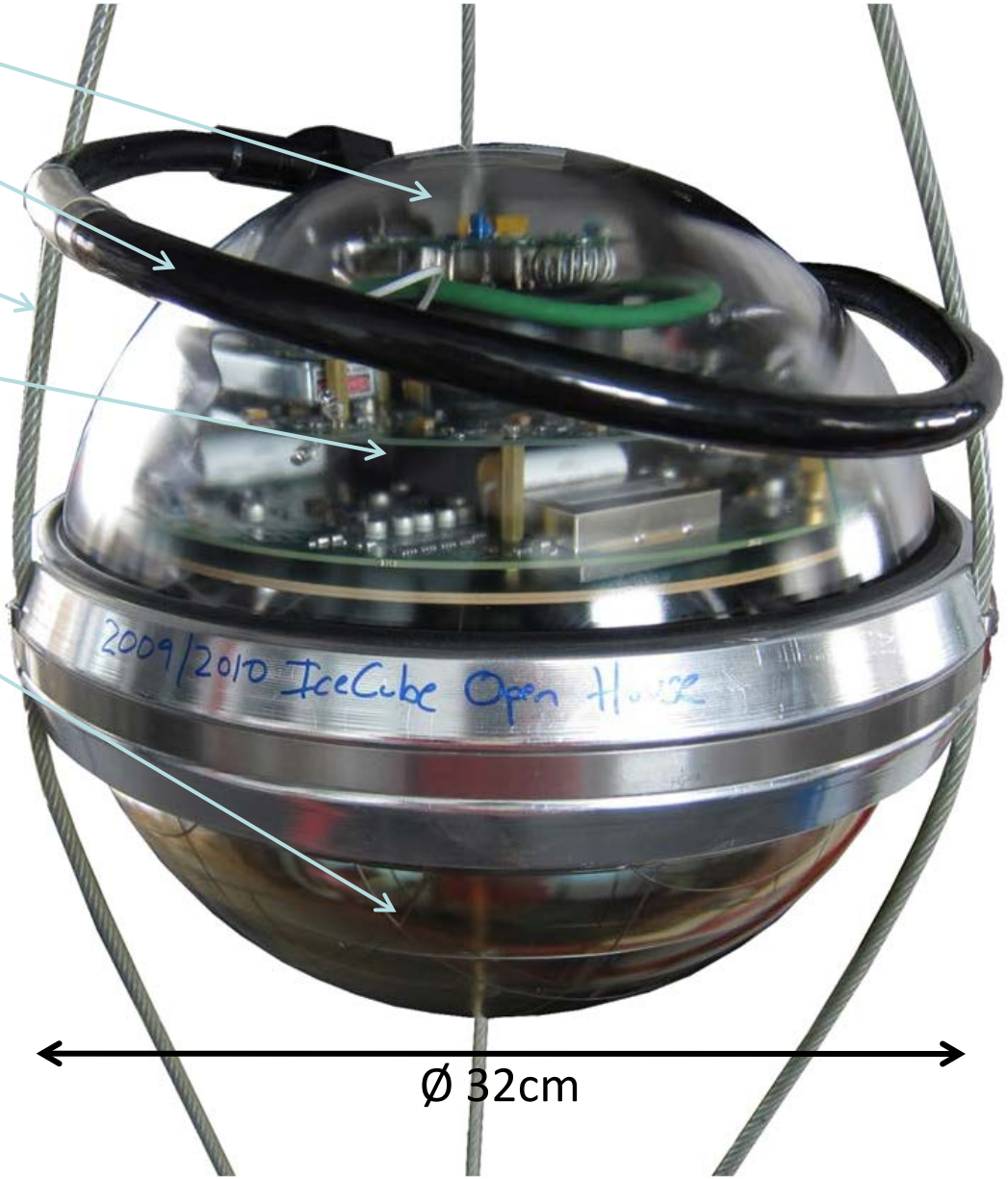
pressure glas sphere

junction cable

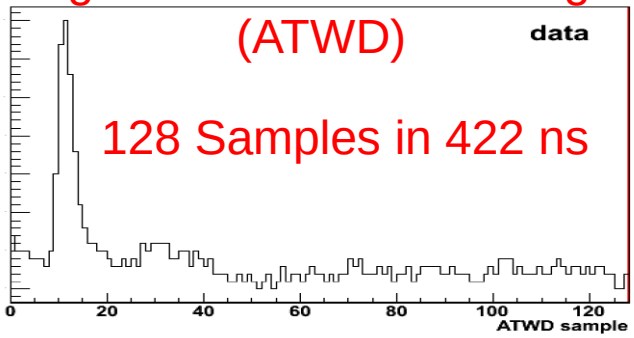
harness

elektronics:
high voltage,
digitalization,
data transfer

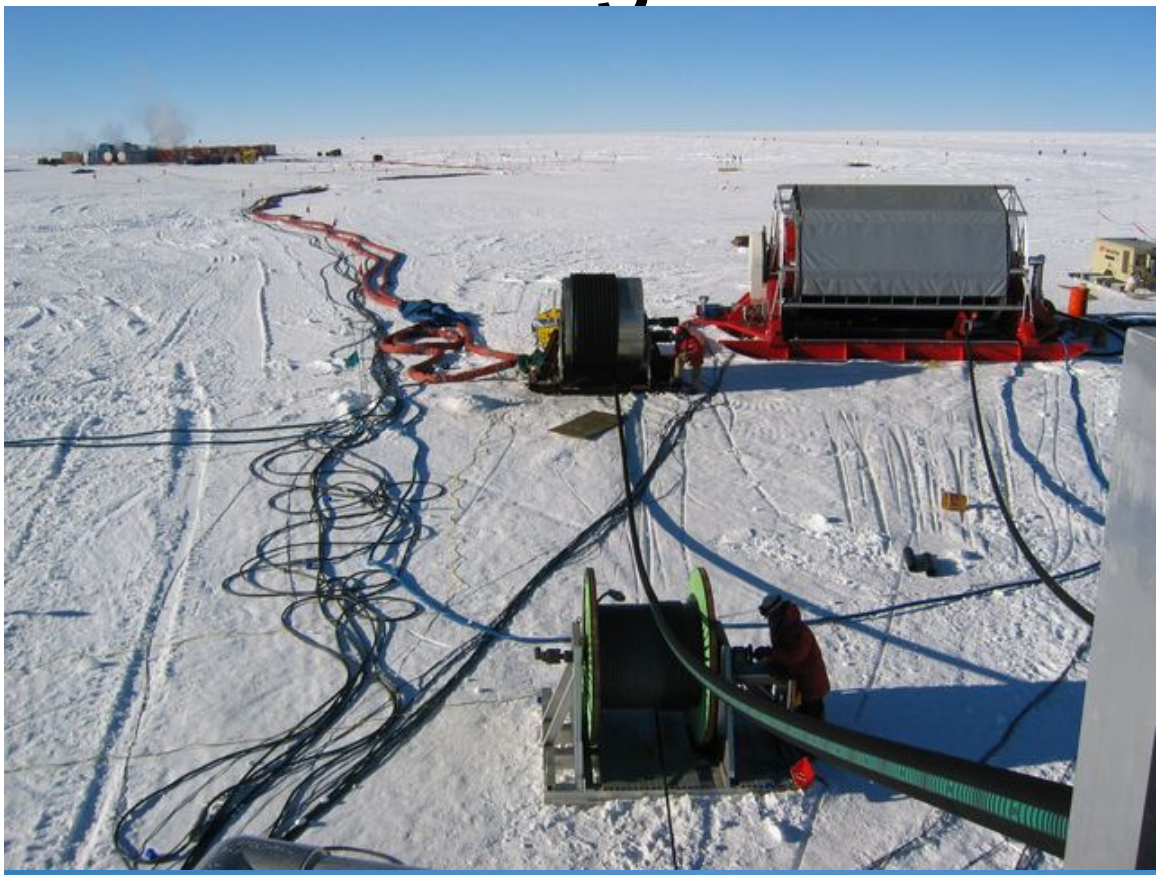
photomultiplier = light sensor

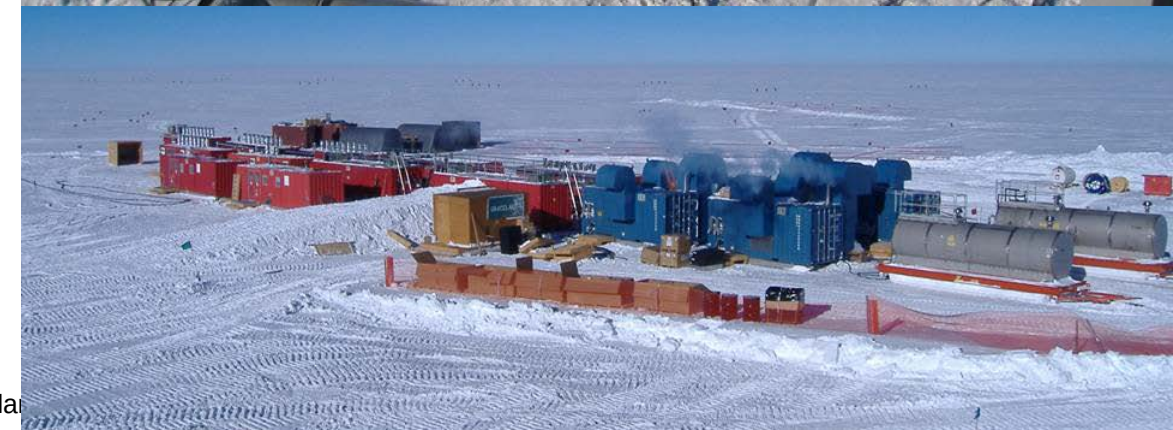


analog transient waveform digitizer (ATWD)



Hot Water Drilling



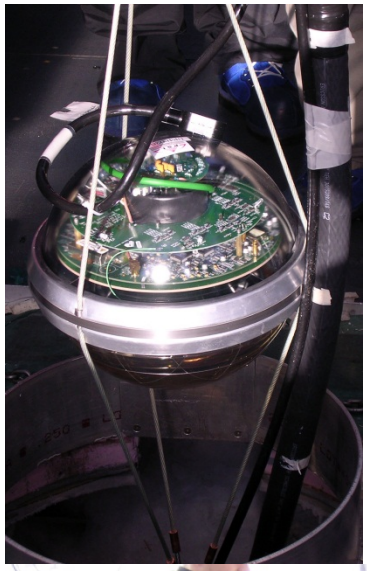


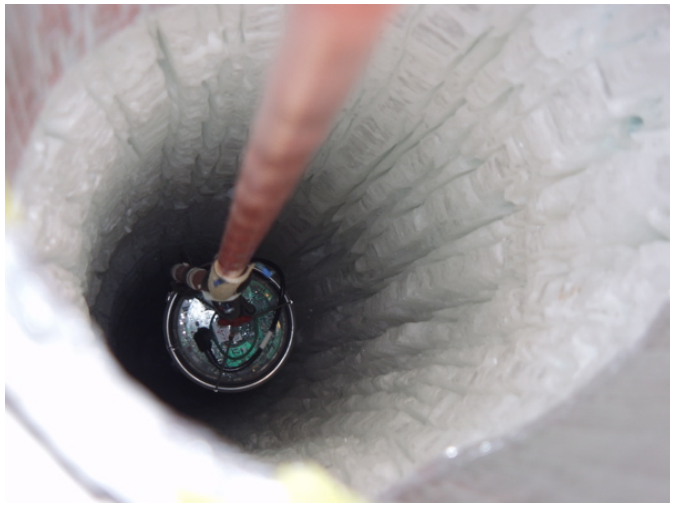
IceCube EHWD operation:

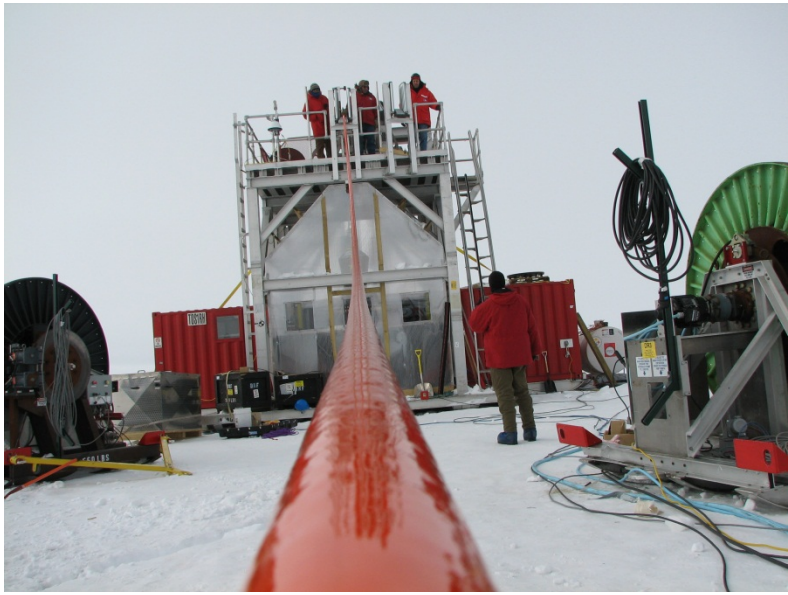
entire drill camp setup, including generators, heater plants, fuel systems, and support workshops.

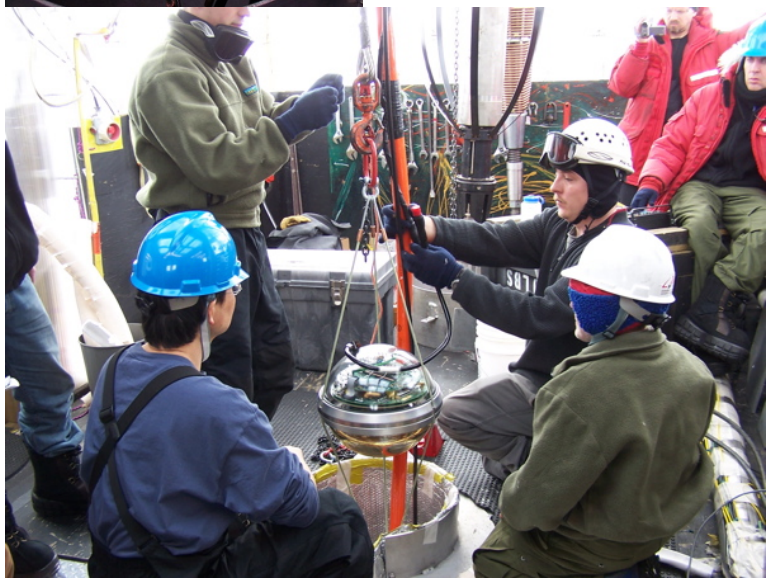
2 drill towers connect to central plants and leapfrog over holes.

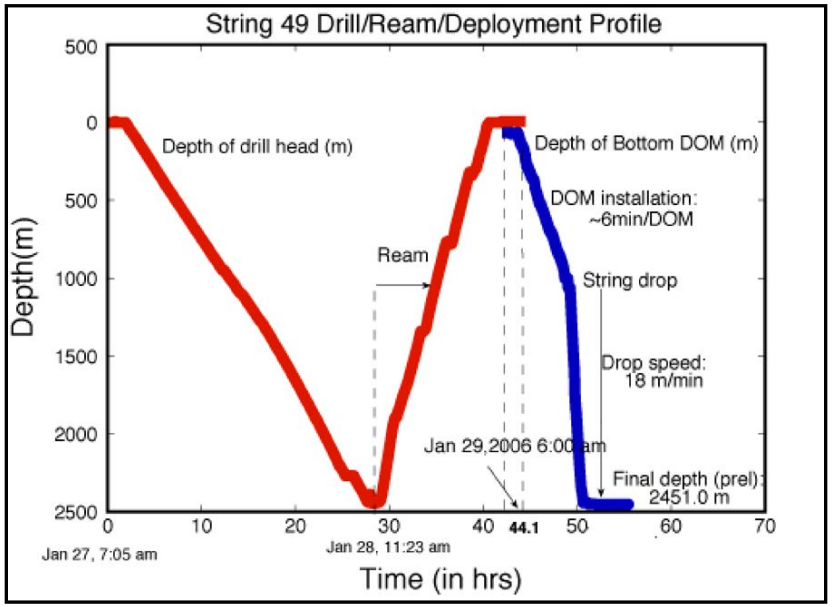
Deployment





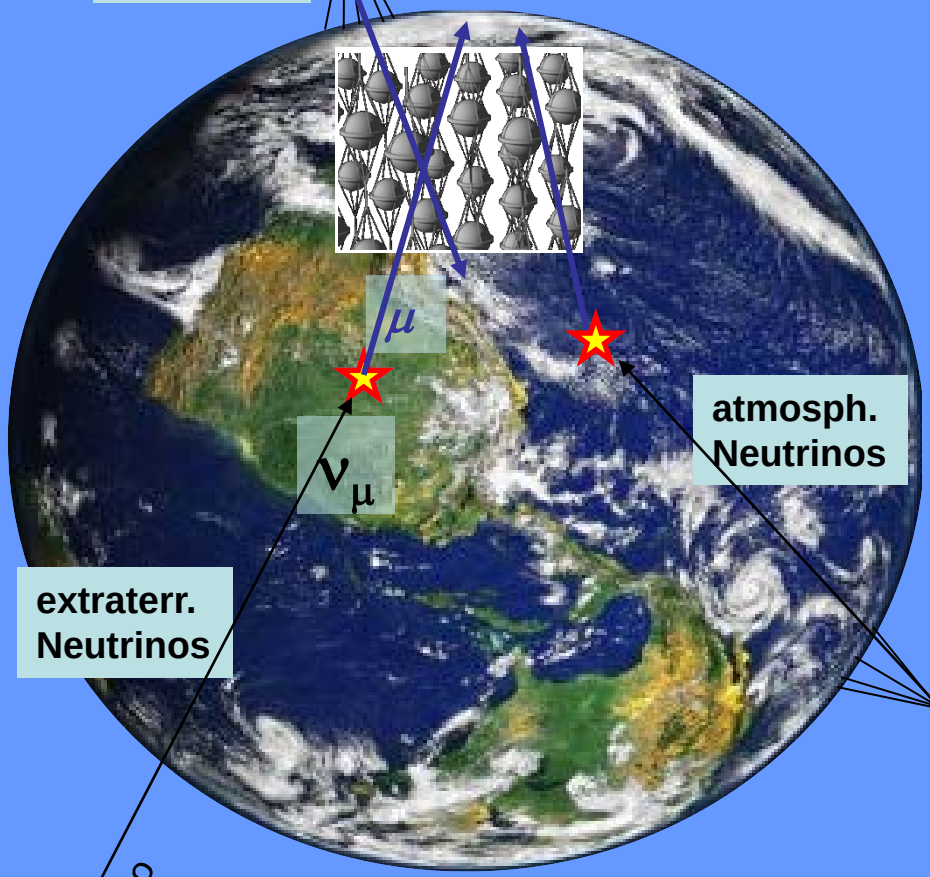






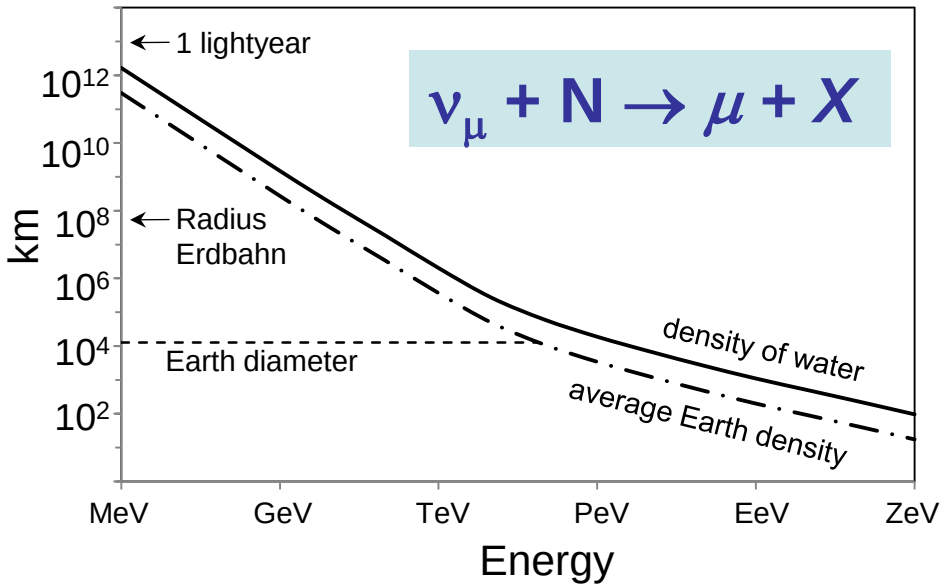
99% of DOMs survive deployment and freeze-in

Detection of High Energy Neutrinos



Earth as filter

mean free path



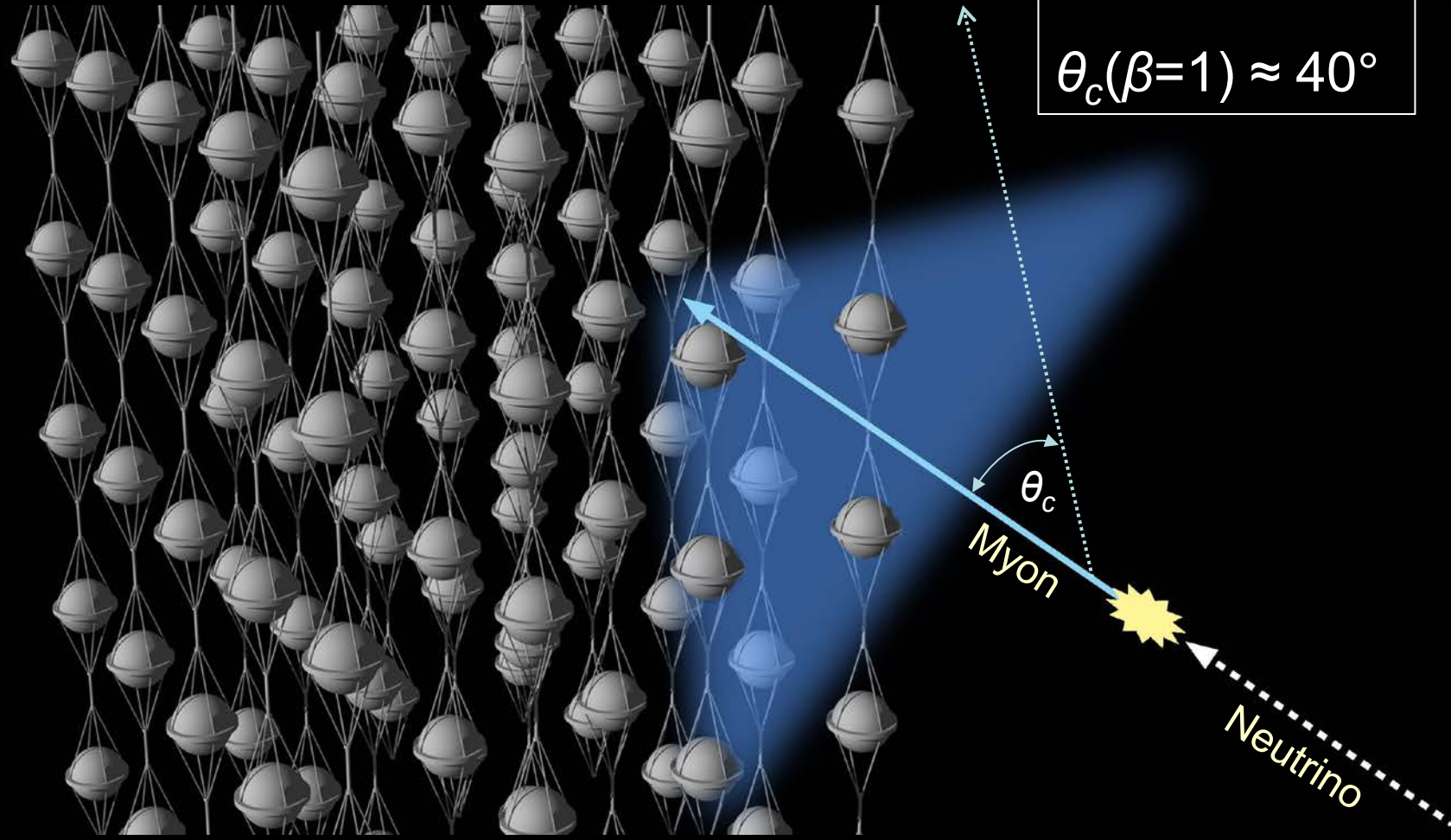
even for neutrinos the Earth becomes opaque above about 1 PeV

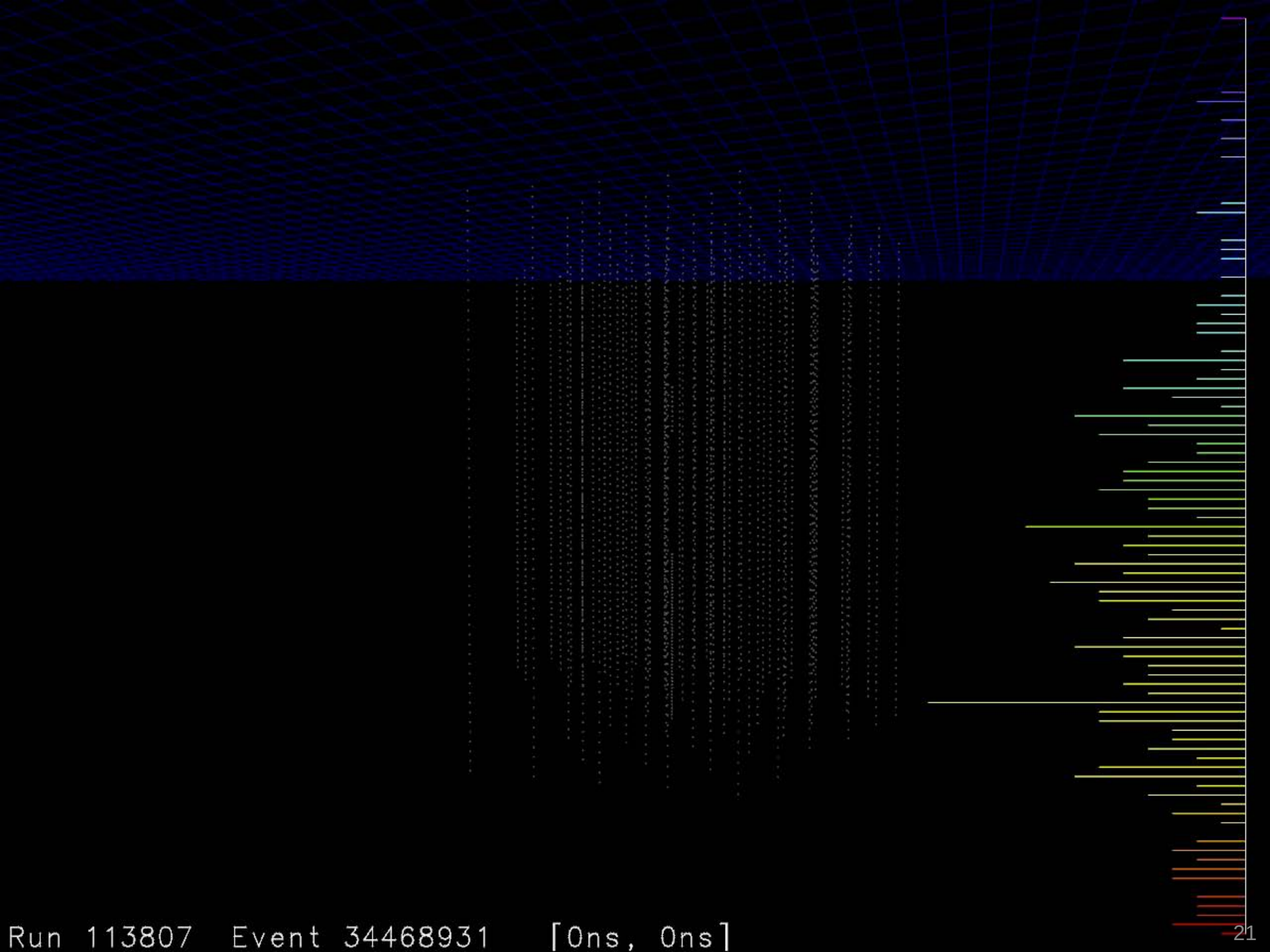
⇒ look **upward** – atm. background becomes less

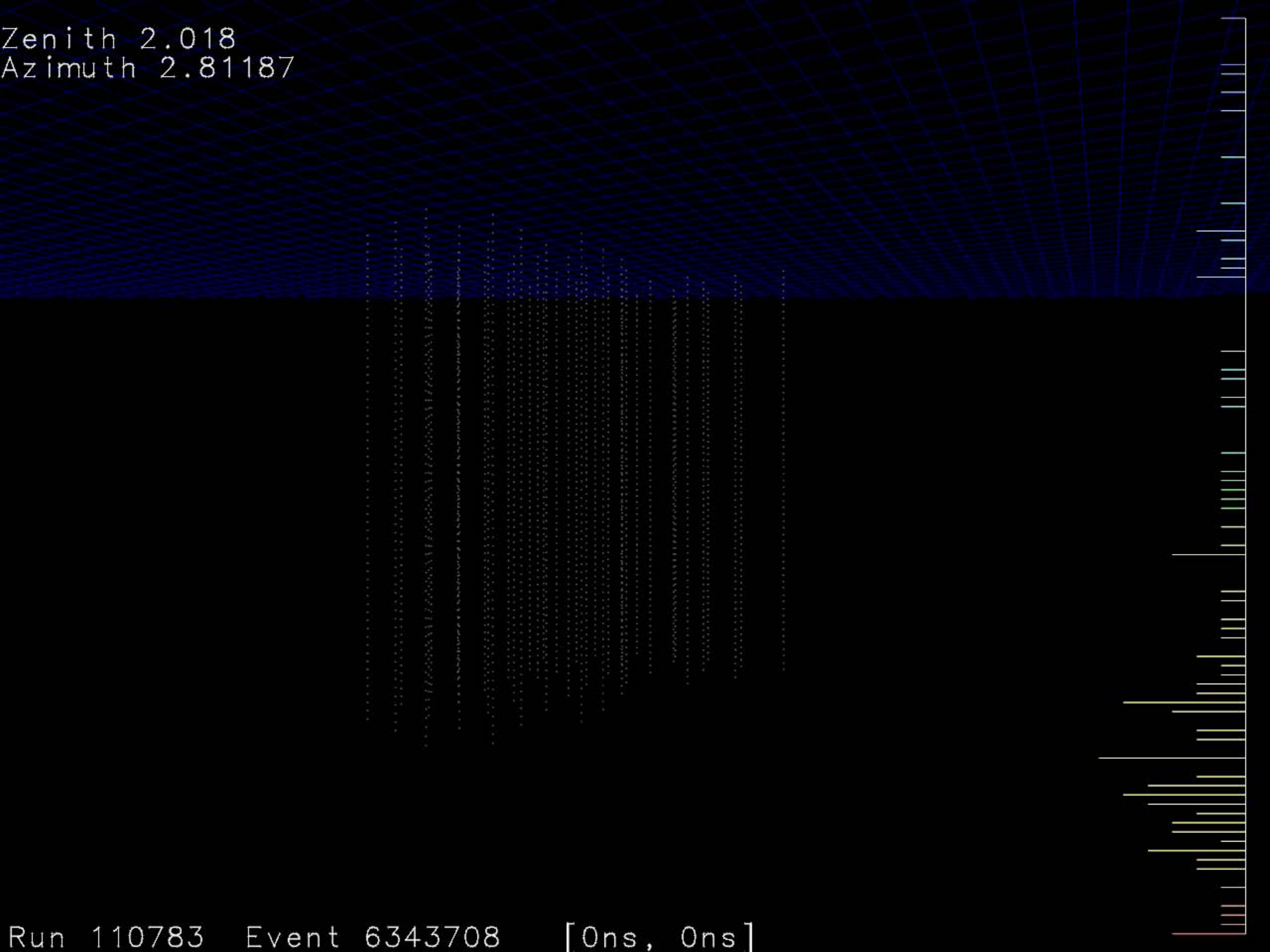
Detection of a Neutrino

$\cos \theta_c = (\beta n)^{-1}$

$\theta_c(\beta=1) \approx 40°$

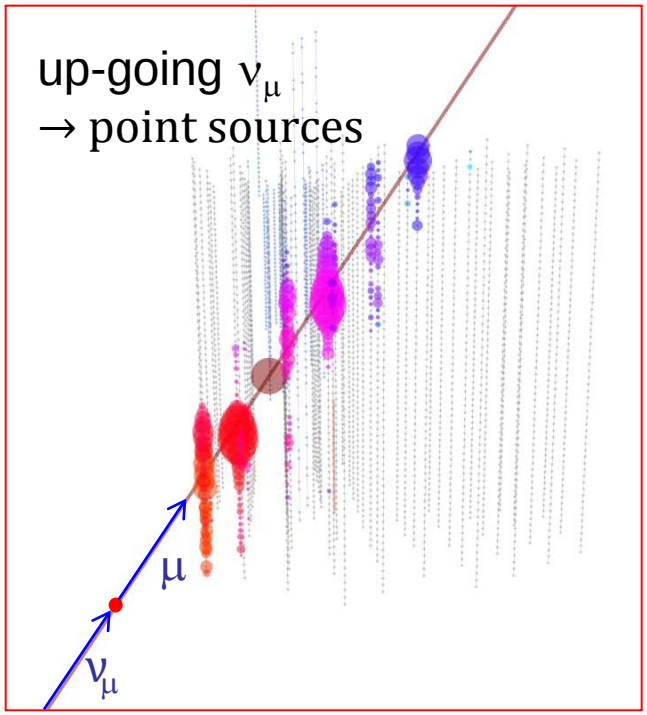


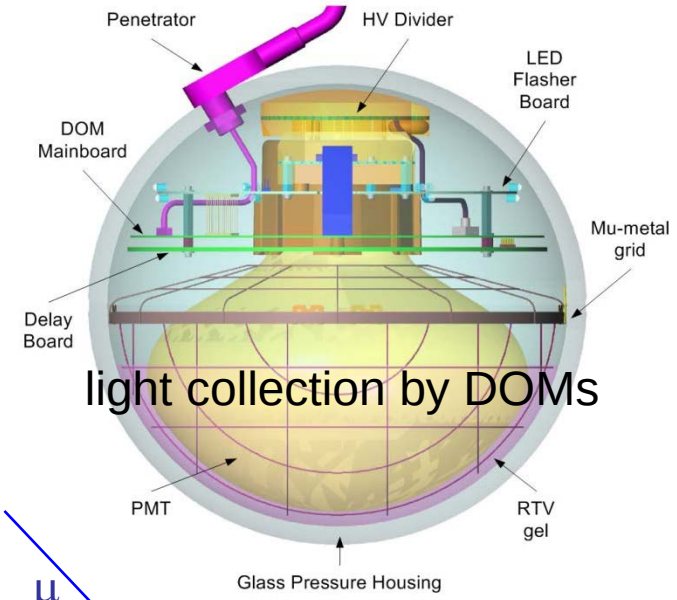

Run 113807 Event 34468931 [0ns, 0ns]


Zenith 2.018
Azimuth 2.81187
Run 110783 Event 6343708 [0ns, 0ns]

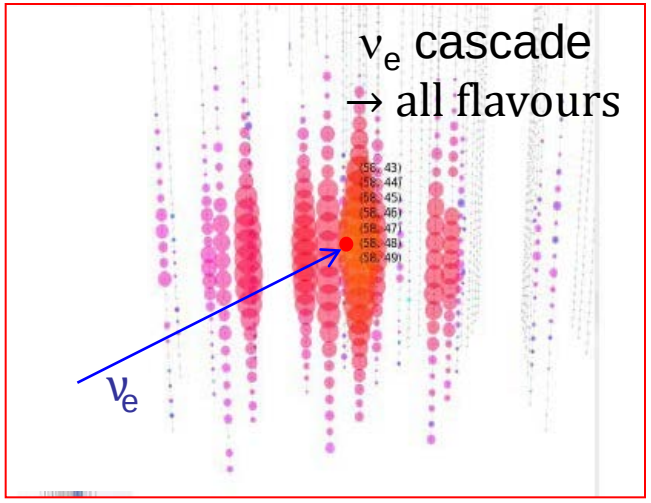
Particle Signatures

up-going ν_μ
→ point sources



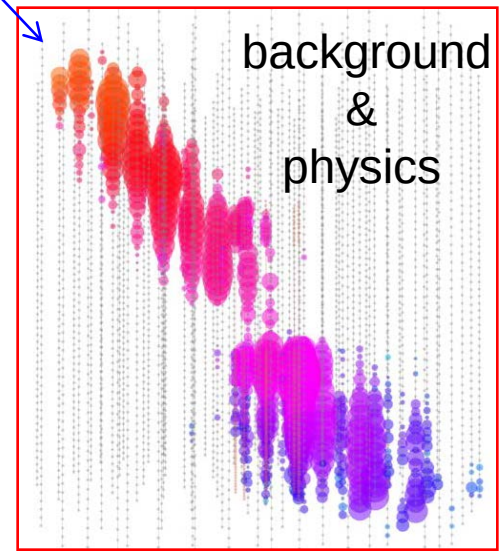


light collection by DOMs

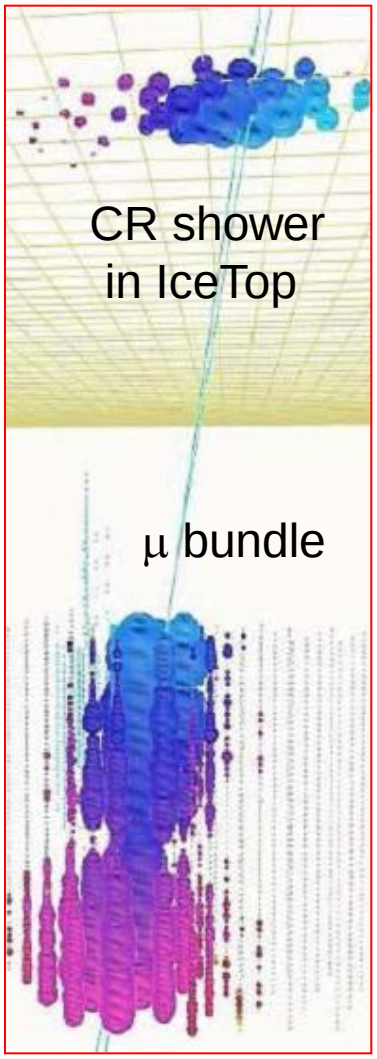


ν_e cascade
→ all flavours

μ



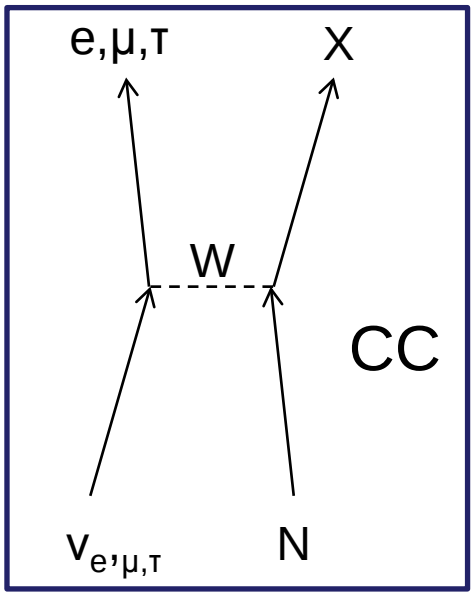
background
&
physics

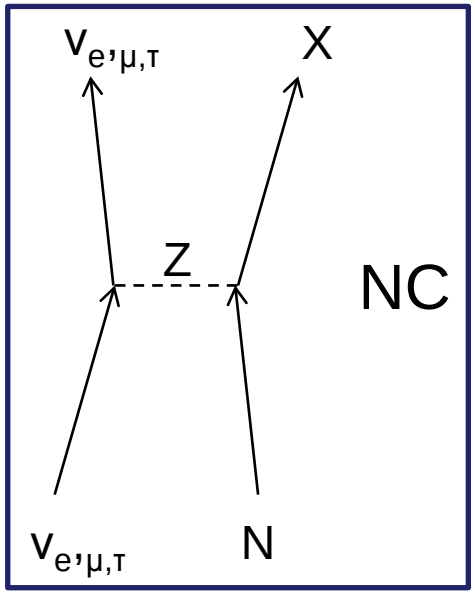


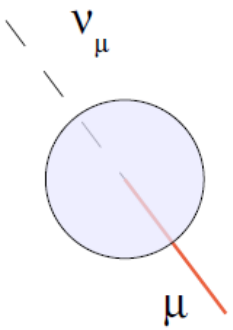
CR shower
in IceTop

μ bundle

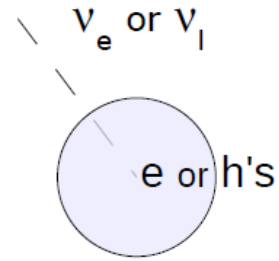
Neutrino Signals in IceCube



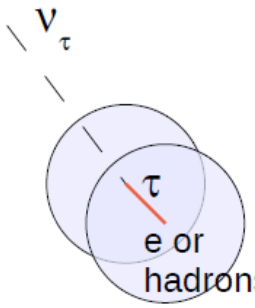




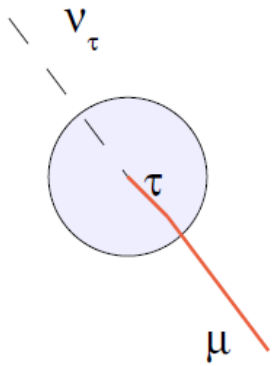
Cascade and track
(ν_μ CC interaction)



EM cascade
(ν_e CC interaction)
or hadron cascade
(NC interaction, all flavors)

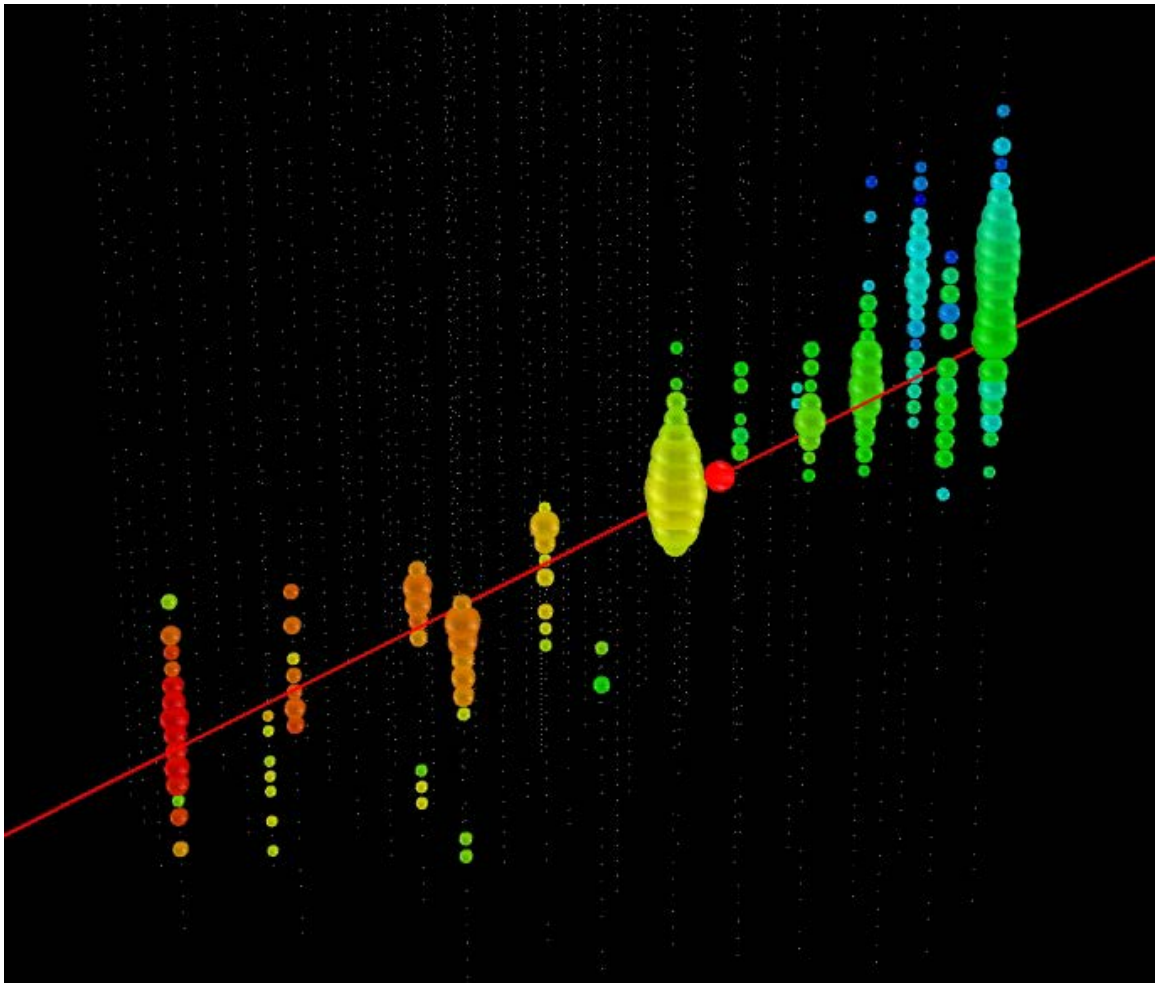


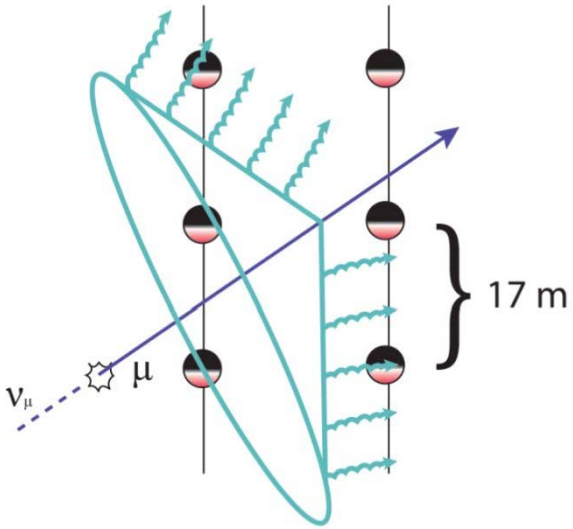
Two cascades and a track
(ν_τ CC interaction)



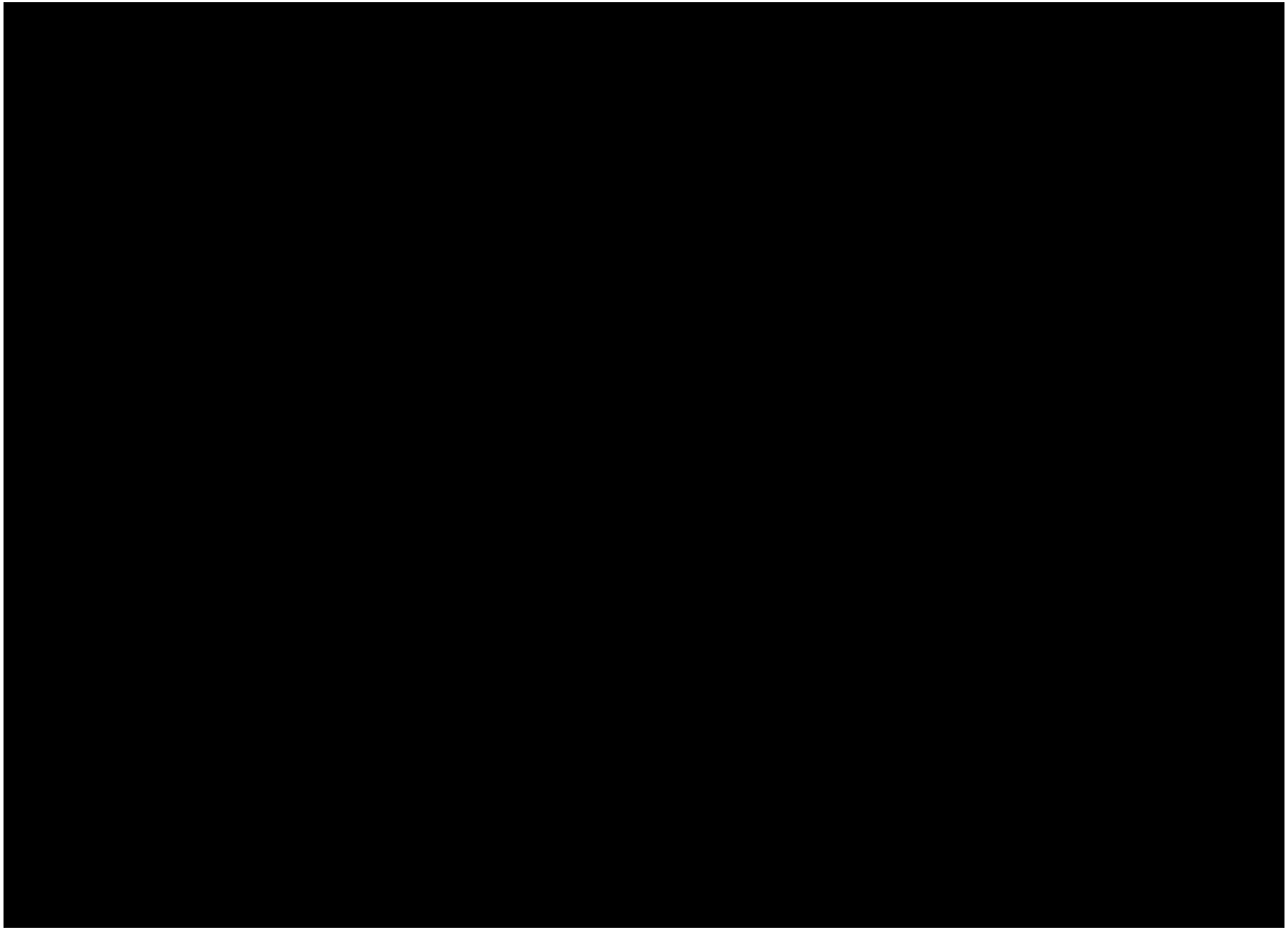
Cascade and track
(ν_τ CC interaction)

Neutrino induced muon tracks.





- Only ν_μ CC interactions
- Angular resolution: < 1˚
- Energy measurement: **only dE/dx**
  - μ might have lost significant fraction of energy before entering the detector
- Effective volume **larger** than instrumented volume



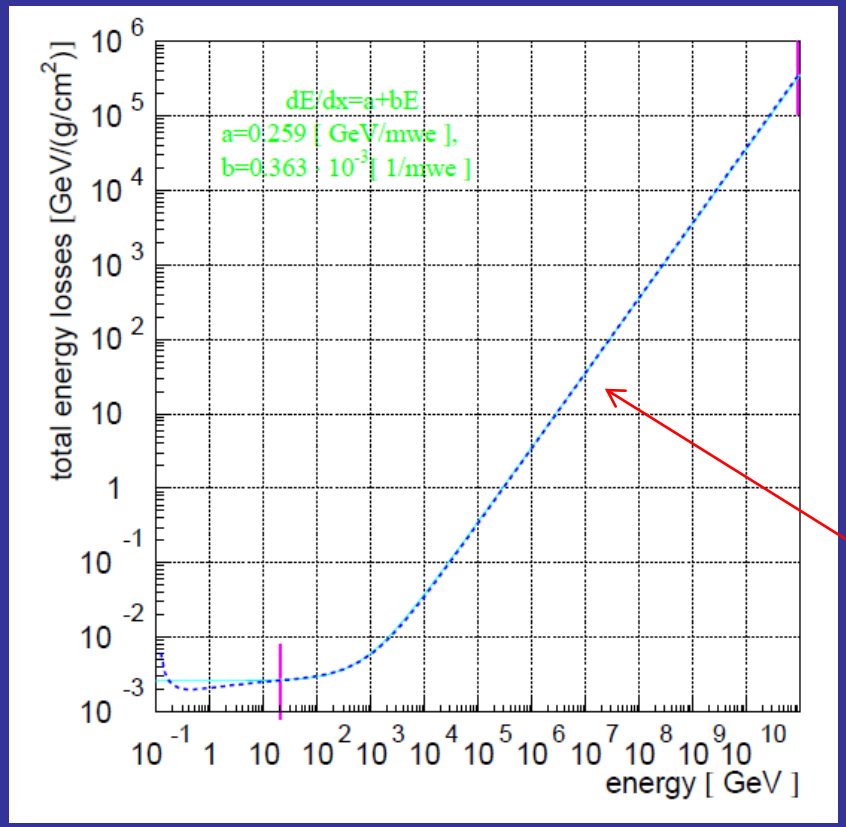
Muon Energy Loss

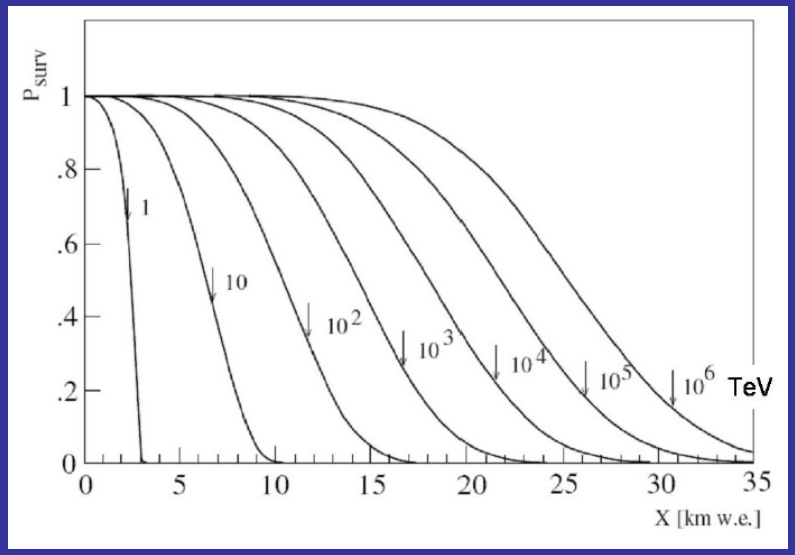
$$-\frac{dE}{dx} = a(E) + b(E)\,E$$

$b(E)E$ = stochastic losses due to bremsstrahlung

$$a(E_k^\mu) = b(E_k^\mu)\,E_k^\mu$$

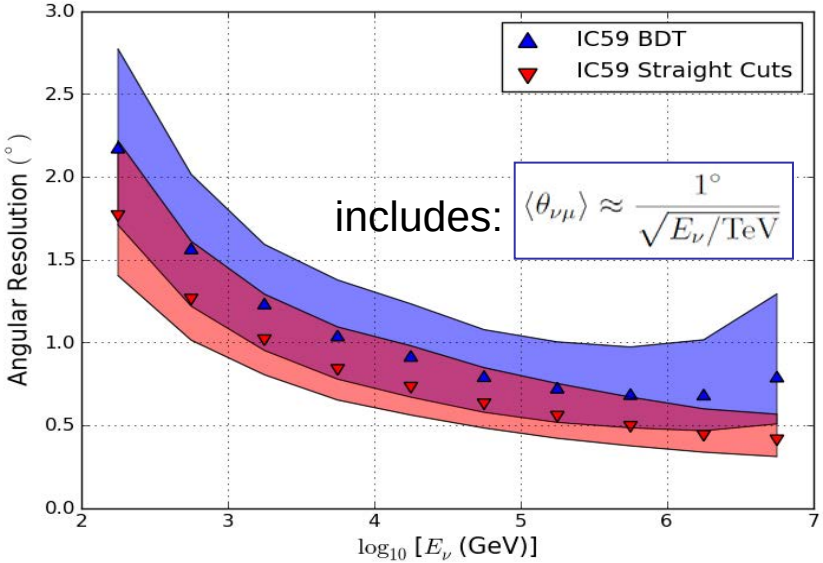
critical energy





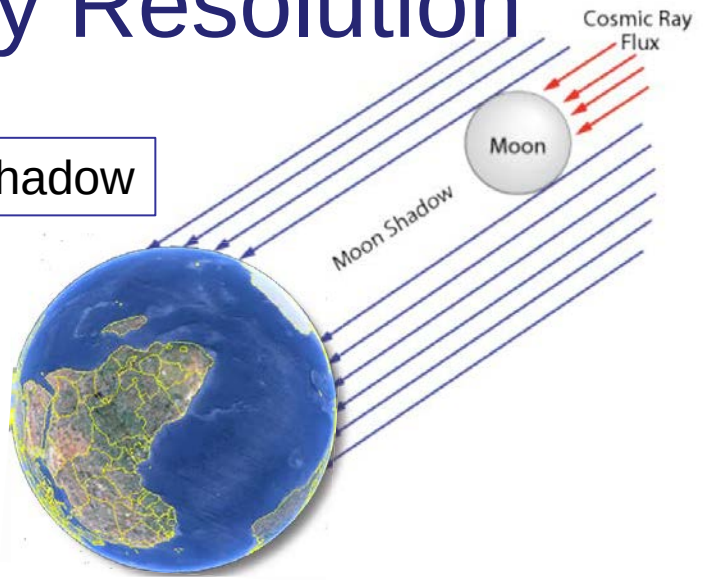
~E → allows energy reconstruction of muons, not of the neutrinos!

ν_μ Angular and Energy Resolution

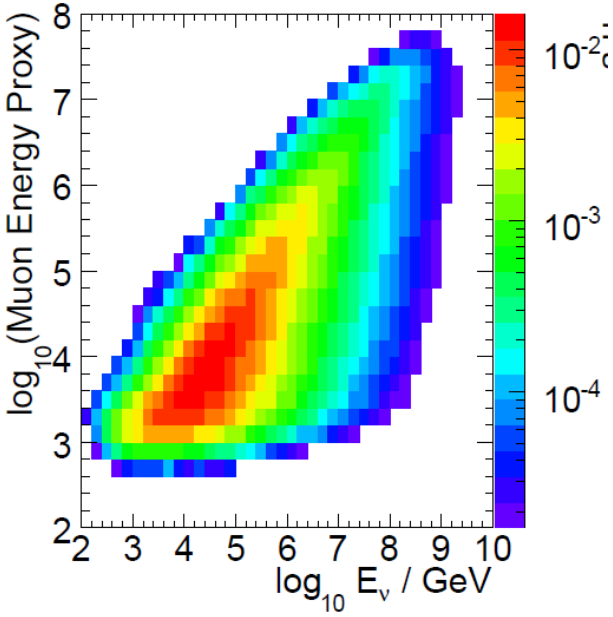


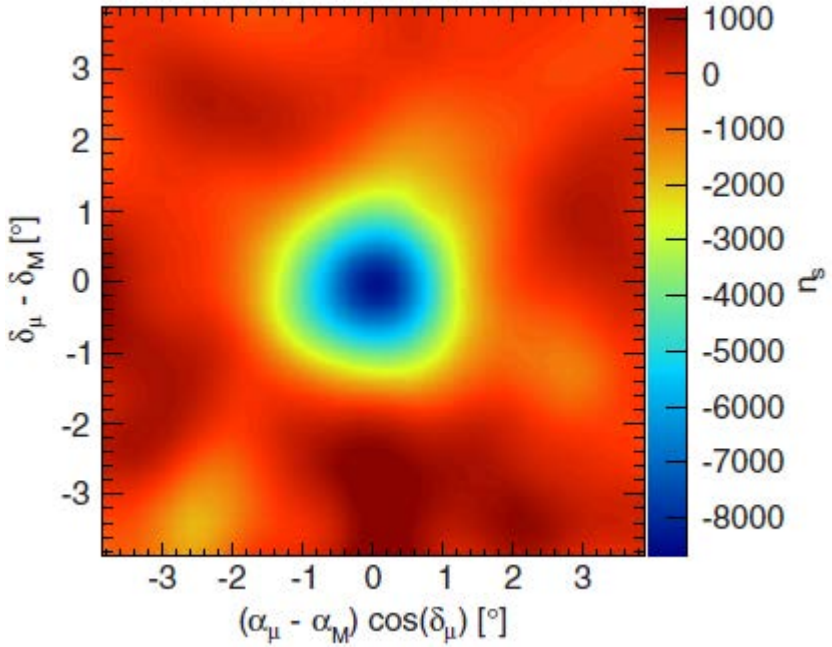
includes: $\langle \theta_{\nu\mu} \rangle \approx \frac{1^\circ}{\sqrt{E_\nu / \mathrm{TeV}}}$

Moon shadow

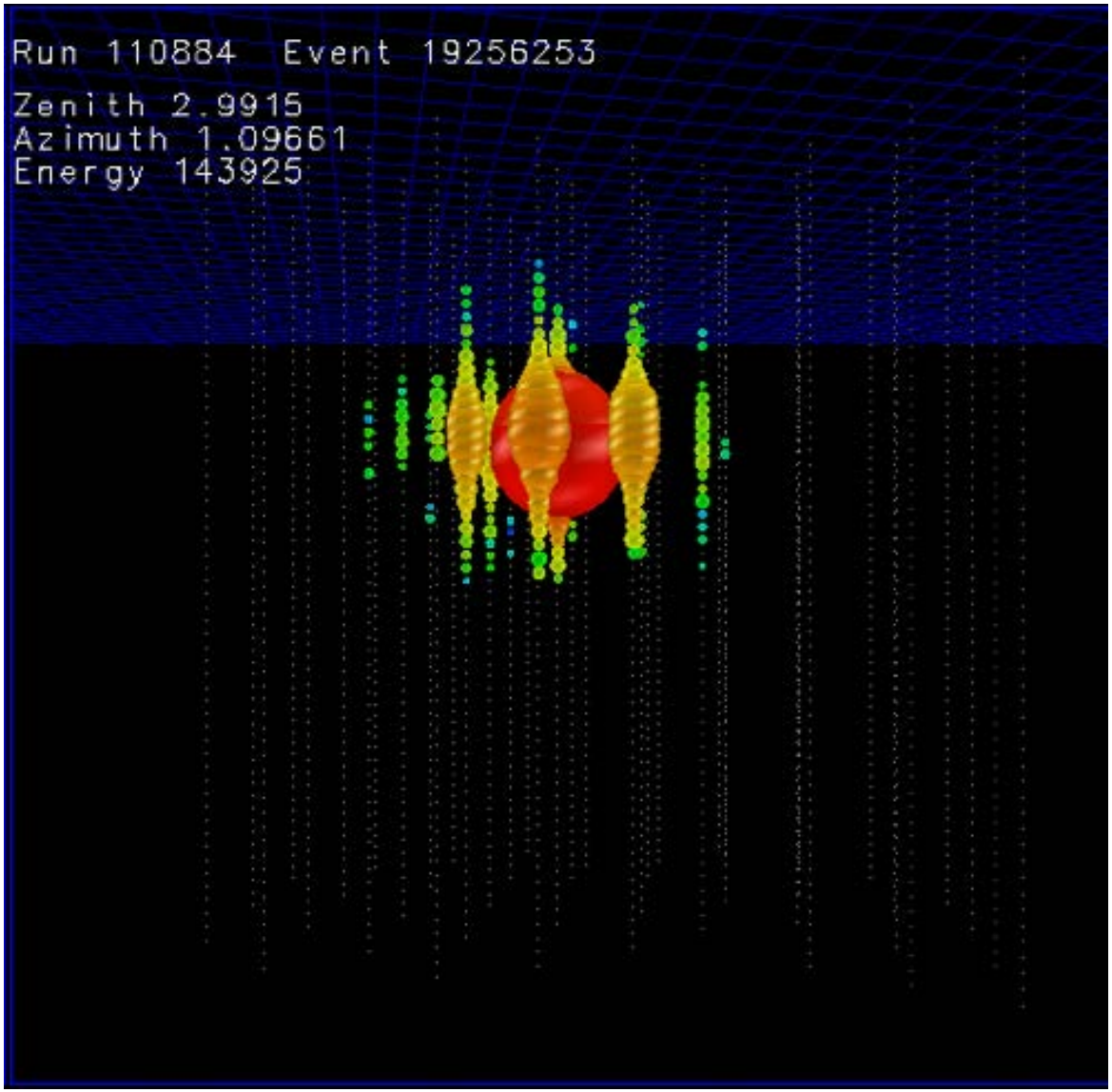


ν_μ energy estimated from dE/dx of muon (bremsstr.)

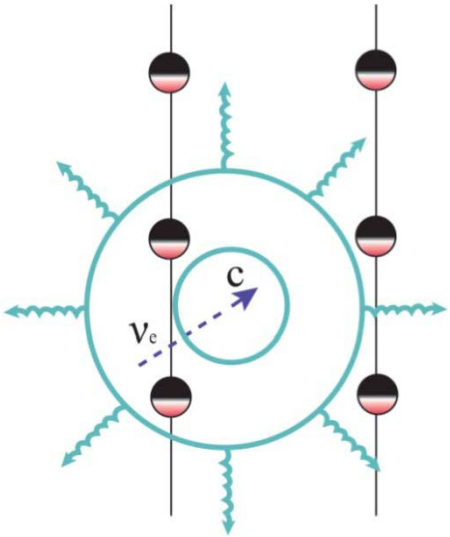




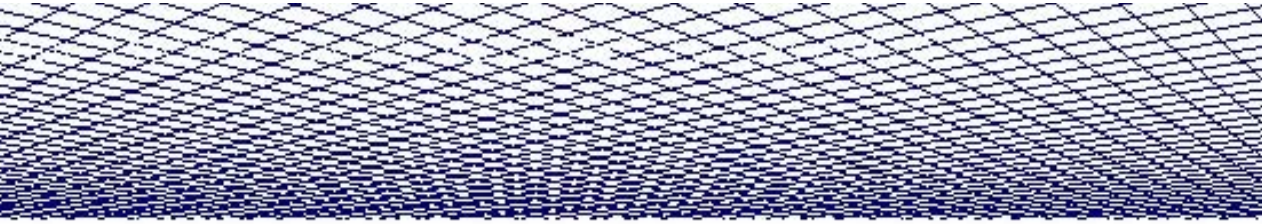
Shower-Type Event (Cascade)

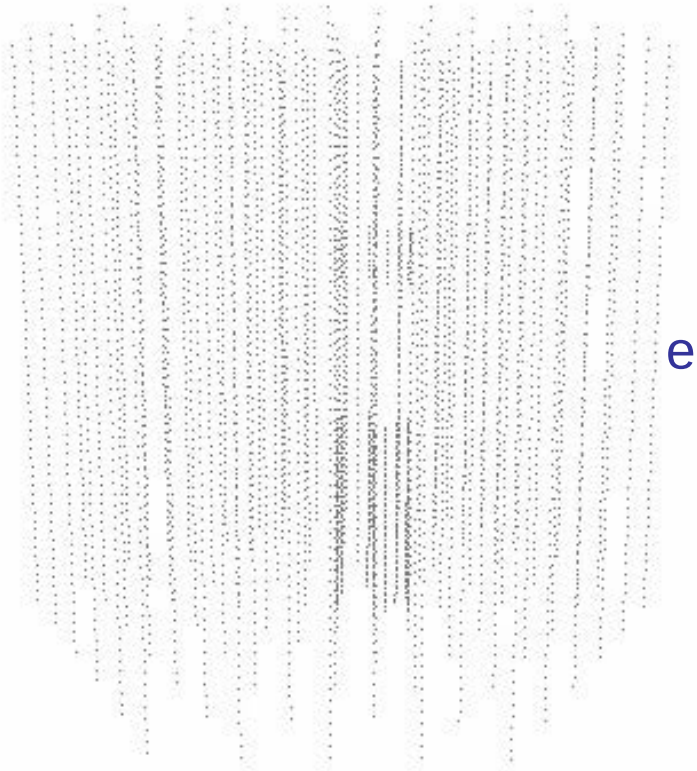


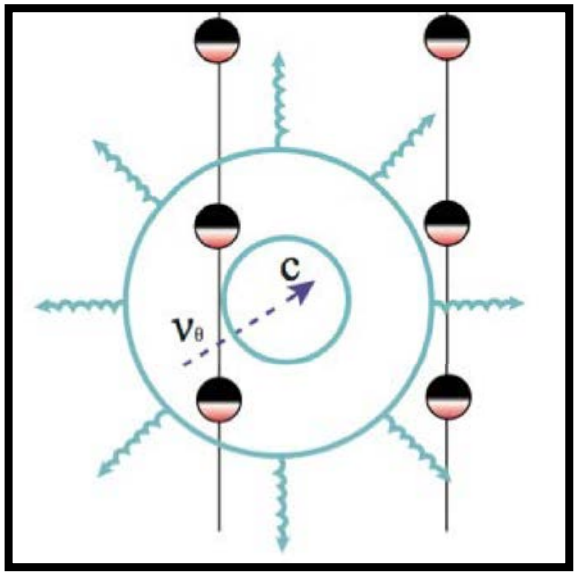
- $\nu_e + \nu_\mu$ NC + ν_τ interactions
- Angular resolution: ≥10˚
- Energy resolution: 15%
- Effective volume **smaller** than instrumented volume



Cascade Events



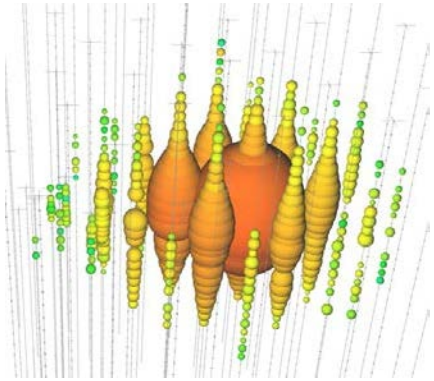




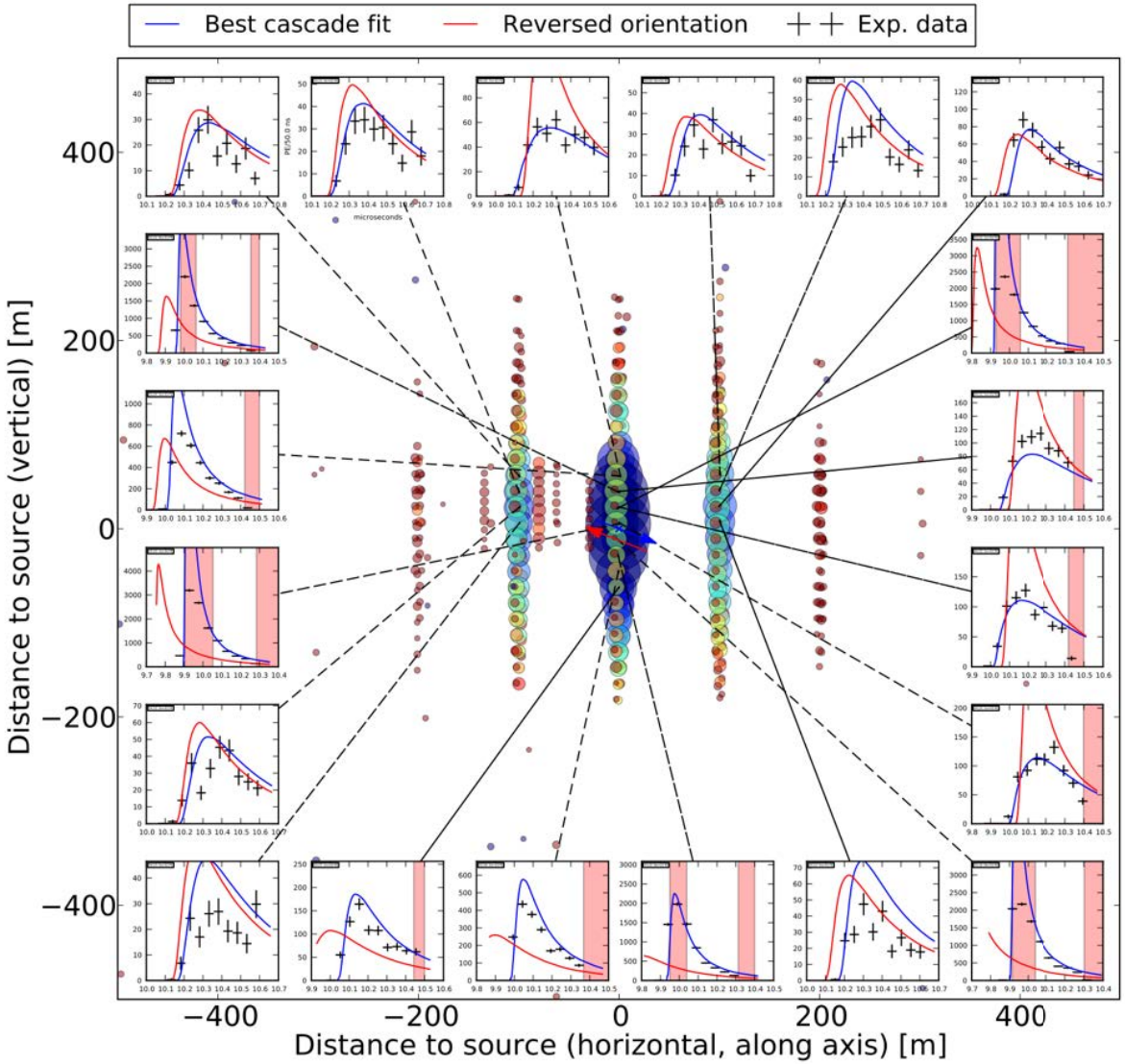
electron neutrinos produce electrons which deposit there energy locally

spherical signal growth

Angular & energy resolution for shower-type events.

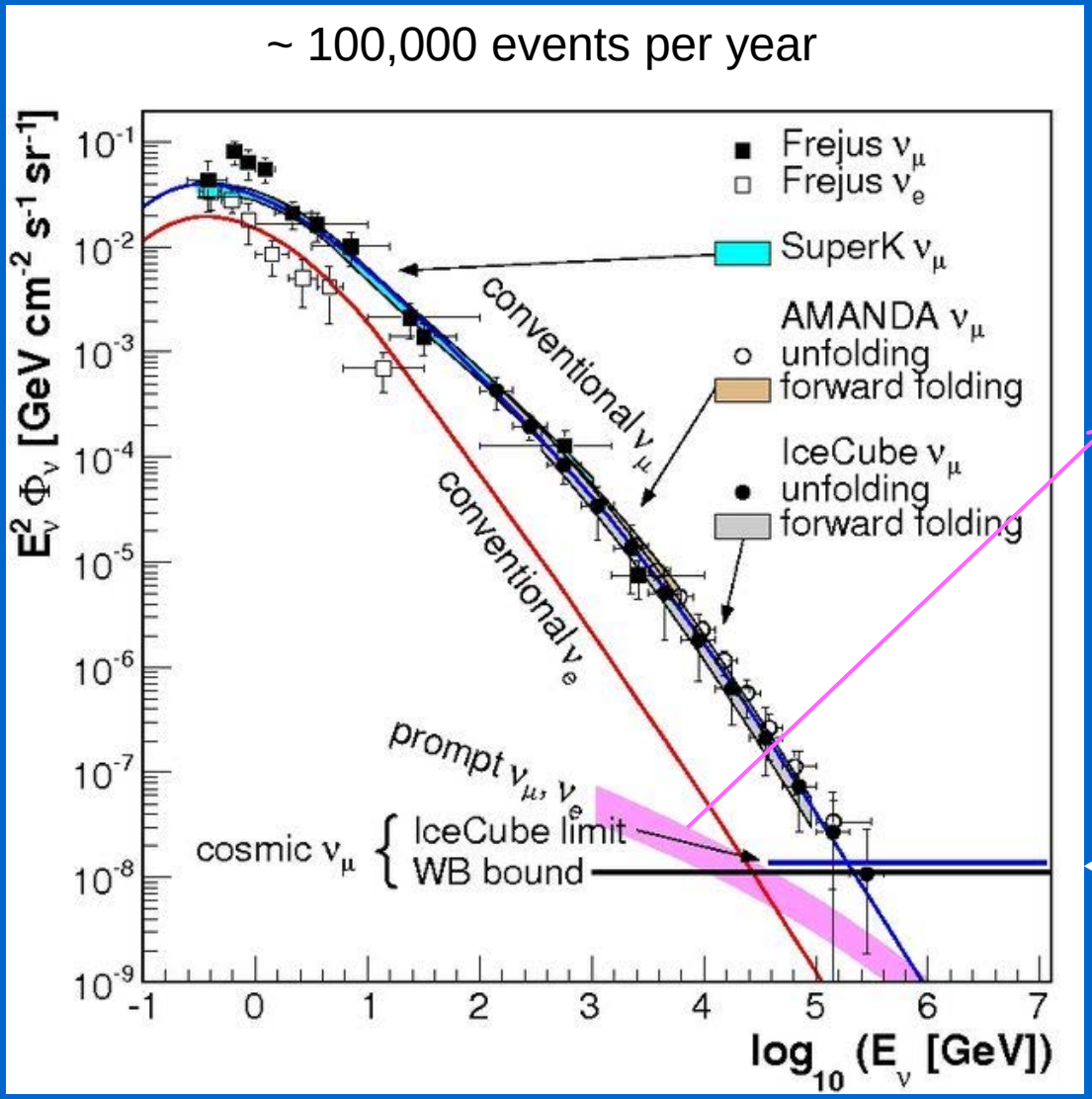


- Full likelihood reconstruction of observed waveforms.
- ~15% energy resolution.
- ≳ 10º angular resolution.
- Calibrated by artificial light sources and CR air shower mons.



Search for Diffuse Astrophysical Neutrino Flux Background: Atmospheric Neutrinos

~ 100,000 events per year



"prompt" ν's:

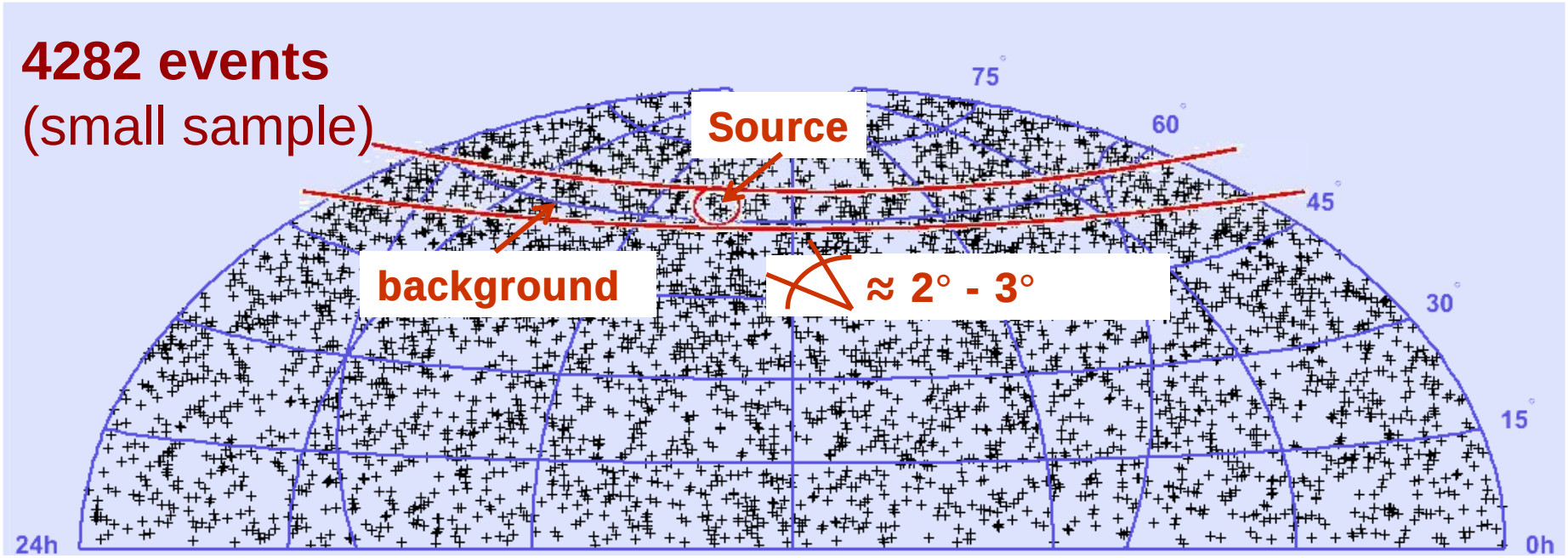
from (semi-) leptonic decays of heavy hadrons (mainly charm).

Flatter spectrum than "conventional" ν's
$\Rightarrow$ large uncertainty for astro-ν's

IceCube has now constrained to ~ ERS model (Enberg et al.)

E^{-2} astrophysical?

Search for Pointsources: The Method



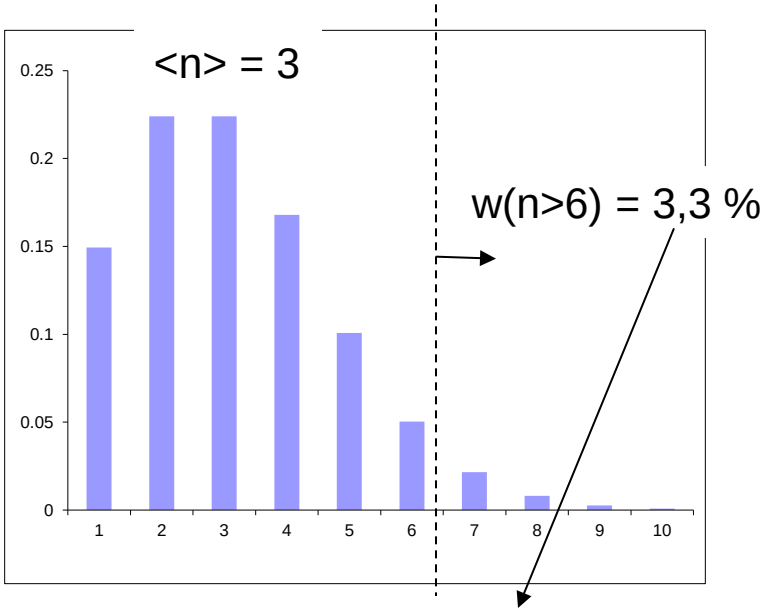
- background: atmospheric ν
- Search for event excess within **2° - 3°**
  - **somewhere in the Northern sky**
  - **from list of candidate sources**

The Statistics Problem

If you serach long enough we will for sure get an exces at some point

"I only believe in statistics
that I doctored myself"

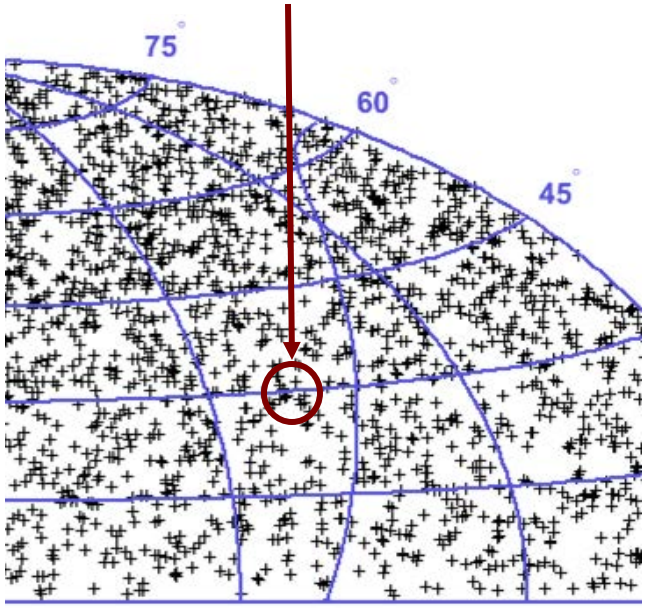
Winston Churchill



Already for about 30 search windows the probability to see 7 or more events in any window is about 60% for background only.

Example:

Expect 3 events background in a search window, but see 7. How significant is this?

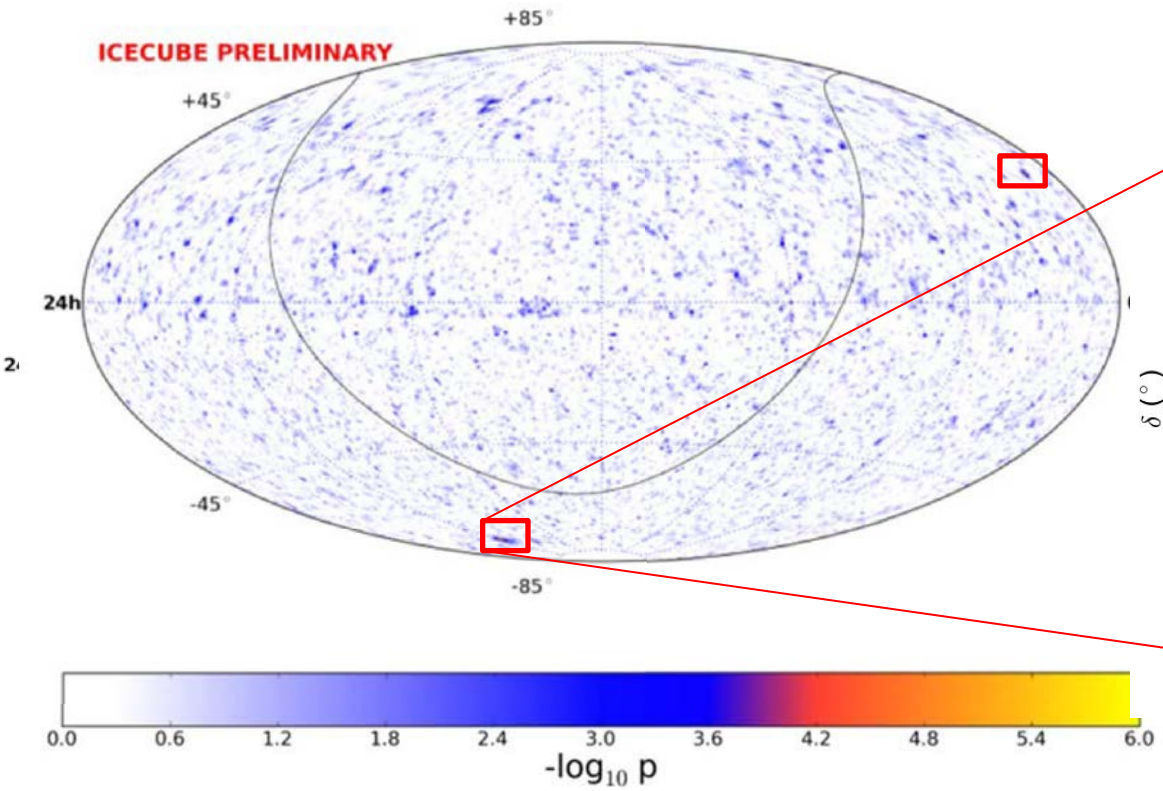


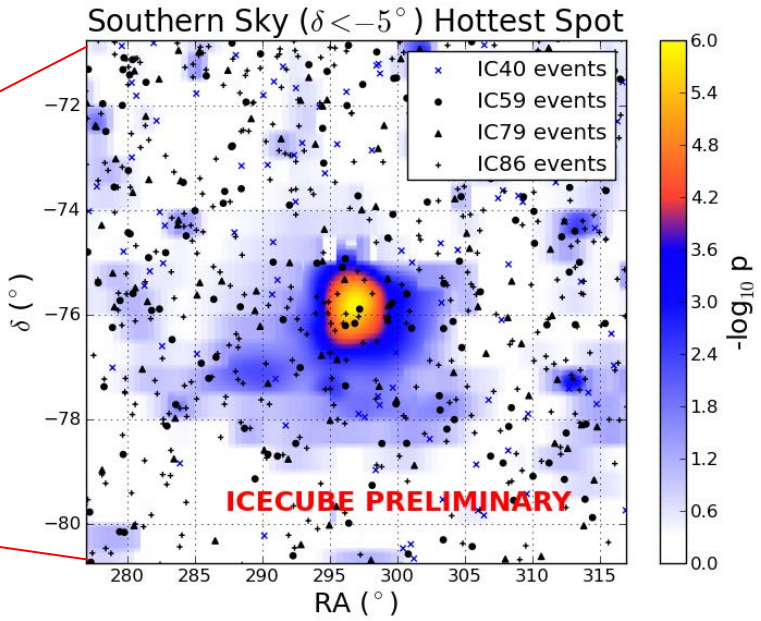
Significance is determined by ~10000-fold

simulation of measurement

Point Source Search 2008-2011

IC86+79+59+49





The 4-year skymap:

No significant signal

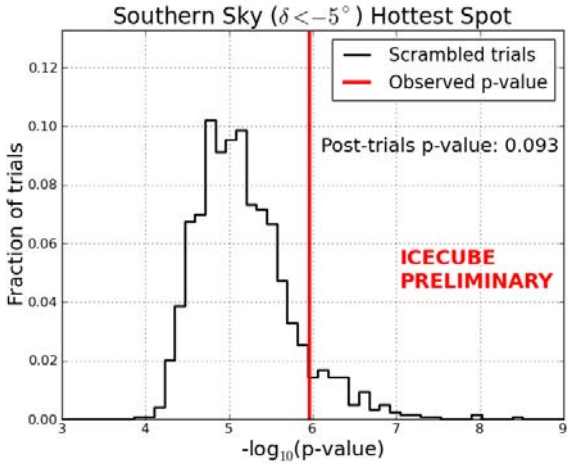
Hottest spot in South:

-log10(p) = 5.95

Ra: 296.95 Dec: -75.75

Ns: 16.16 Gamma: 2.34

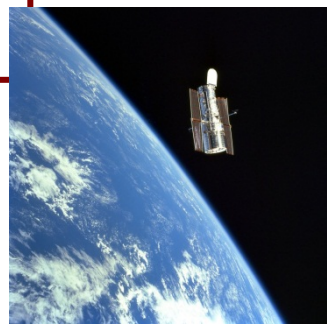
p-value ~9.3% (post trial)

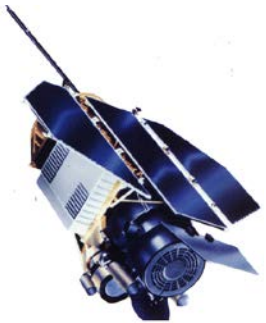


Improving Statistical Significance

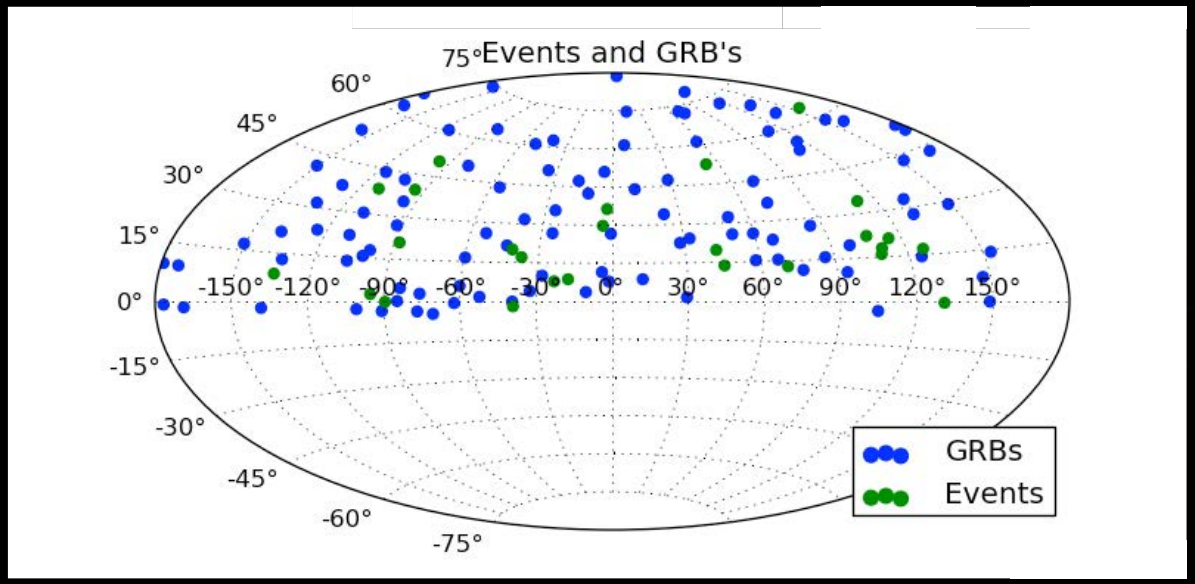
- pre-defined source positions
- pre-defined time-window
- „stacking“ of pre-defined sources

„Pre-Definition“ with **„multi-messenger“** information of optical, gamma, X-ray, radio telescopes …

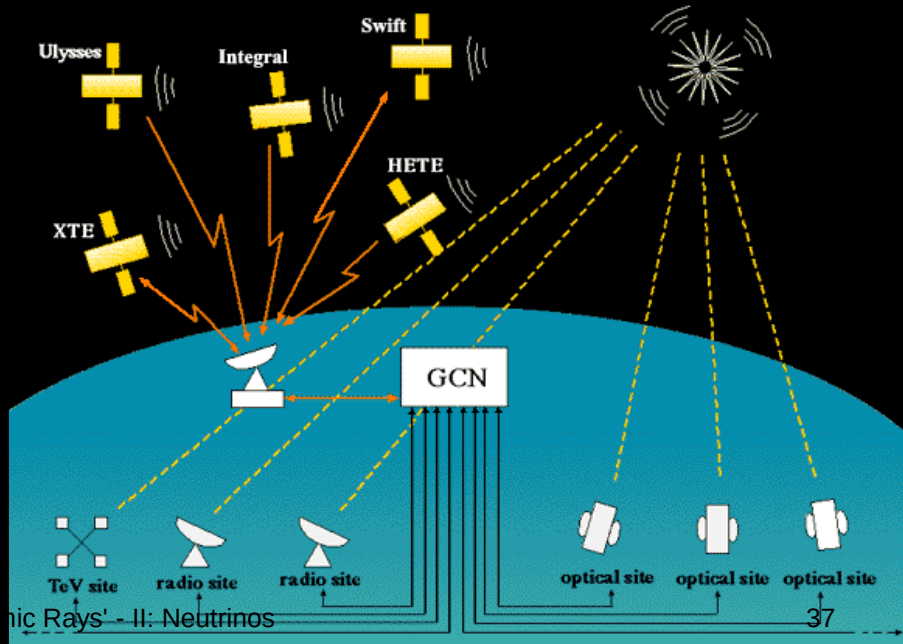




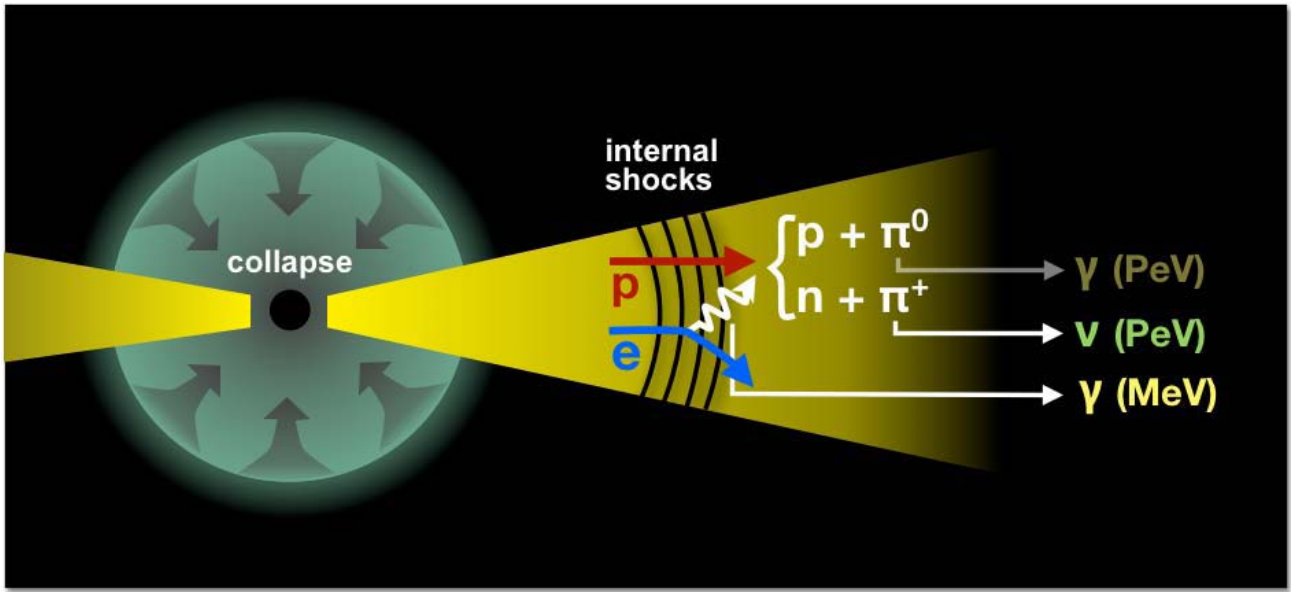
Gamma-ray bursts



Search for neutrinos which are in time and direction consistent with GRB



GRB Model

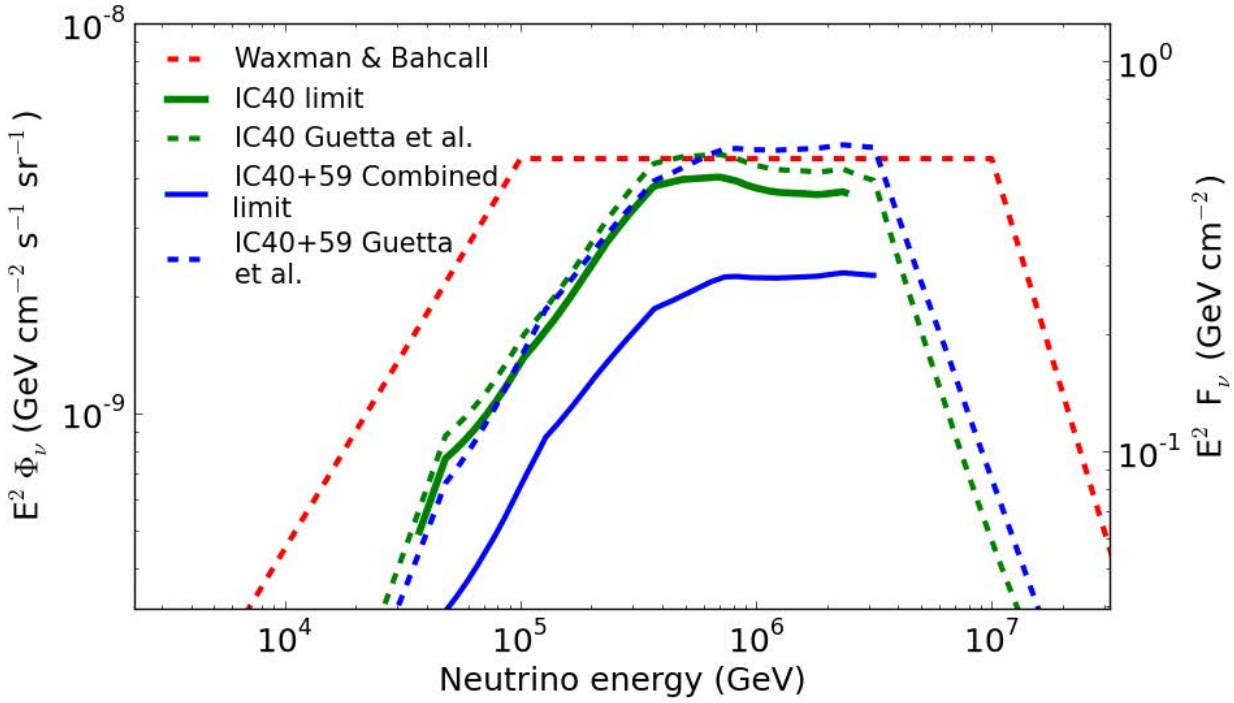


- Gamma Ray Bursts (GRBs) release $\sim 10^{51} - 10^{54}$ erg $\times\, \Omega/4\pi$ where Ω is the solid angle of beamed emission.
- If nucleons are present and accelerated with similar efficiency to electrons, then GRBs could account for the observed ultra high energy cosmic rays.
- If nucleons present, interactions with γ will yield neutrinos, for example via:

$$p + \gamma \to \Delta^+ \to n + \pi^+; \qquad \pi^+ \to \mu^+ + \nu_\mu; \qquad \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu.$$

- Therefore, observation of GRB-neutrino coincidence would lend support to the hypothesis that GRBs produce high energy cosmic rays.

Are GRBs the main sources of Cosmic Rays?



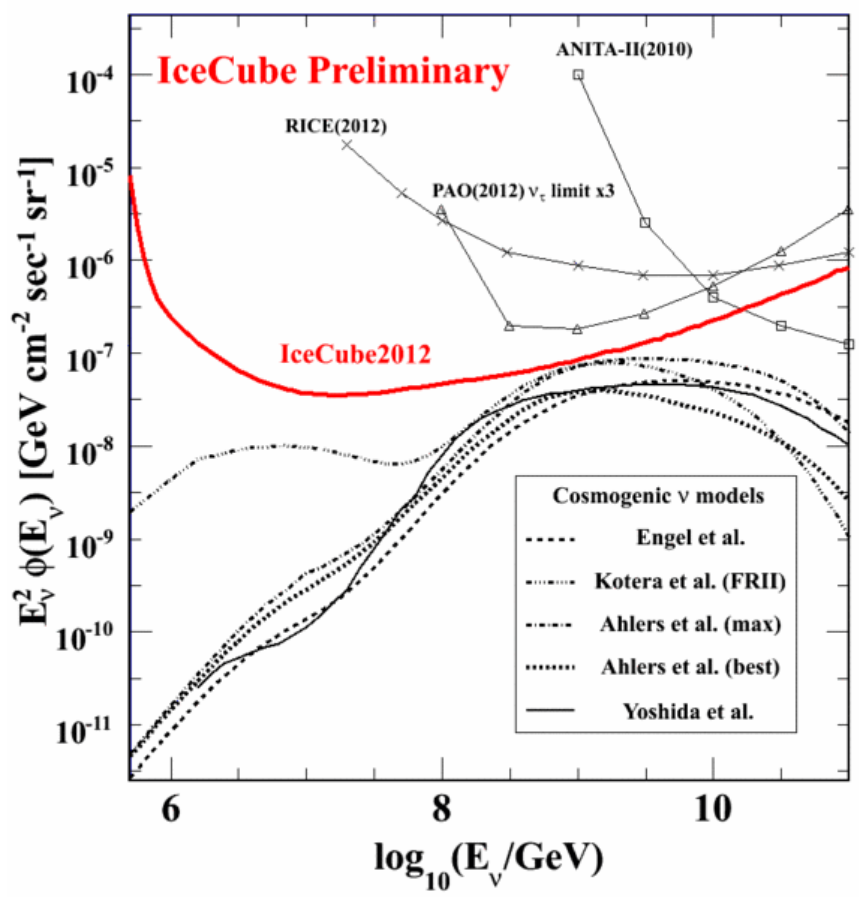
225 GRB ... no coincidences observed

Standard Fireball Models excluded [Nature 484 (2012) 351]

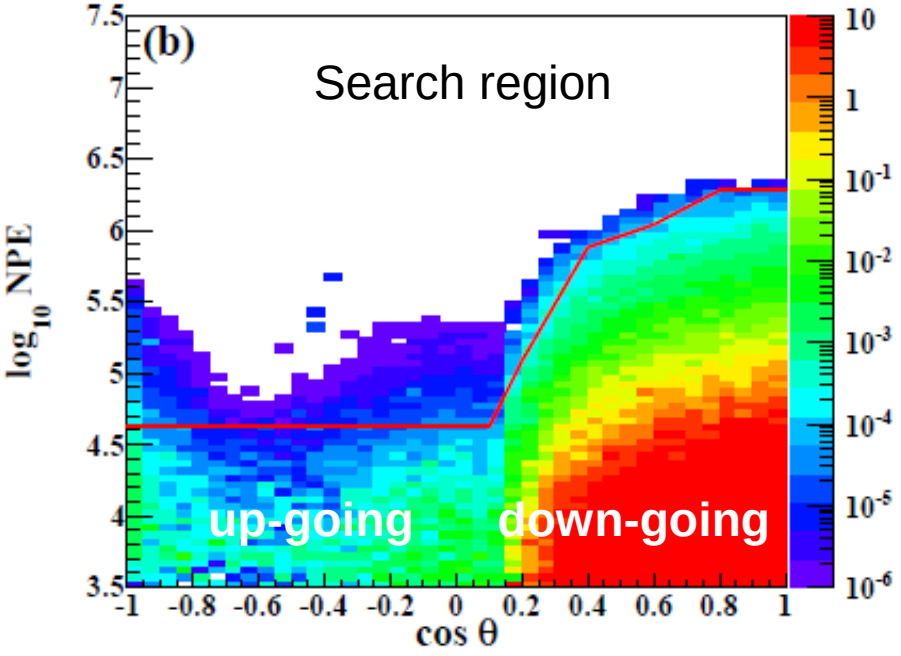
EHE Neutrinos

(extremly high energy)

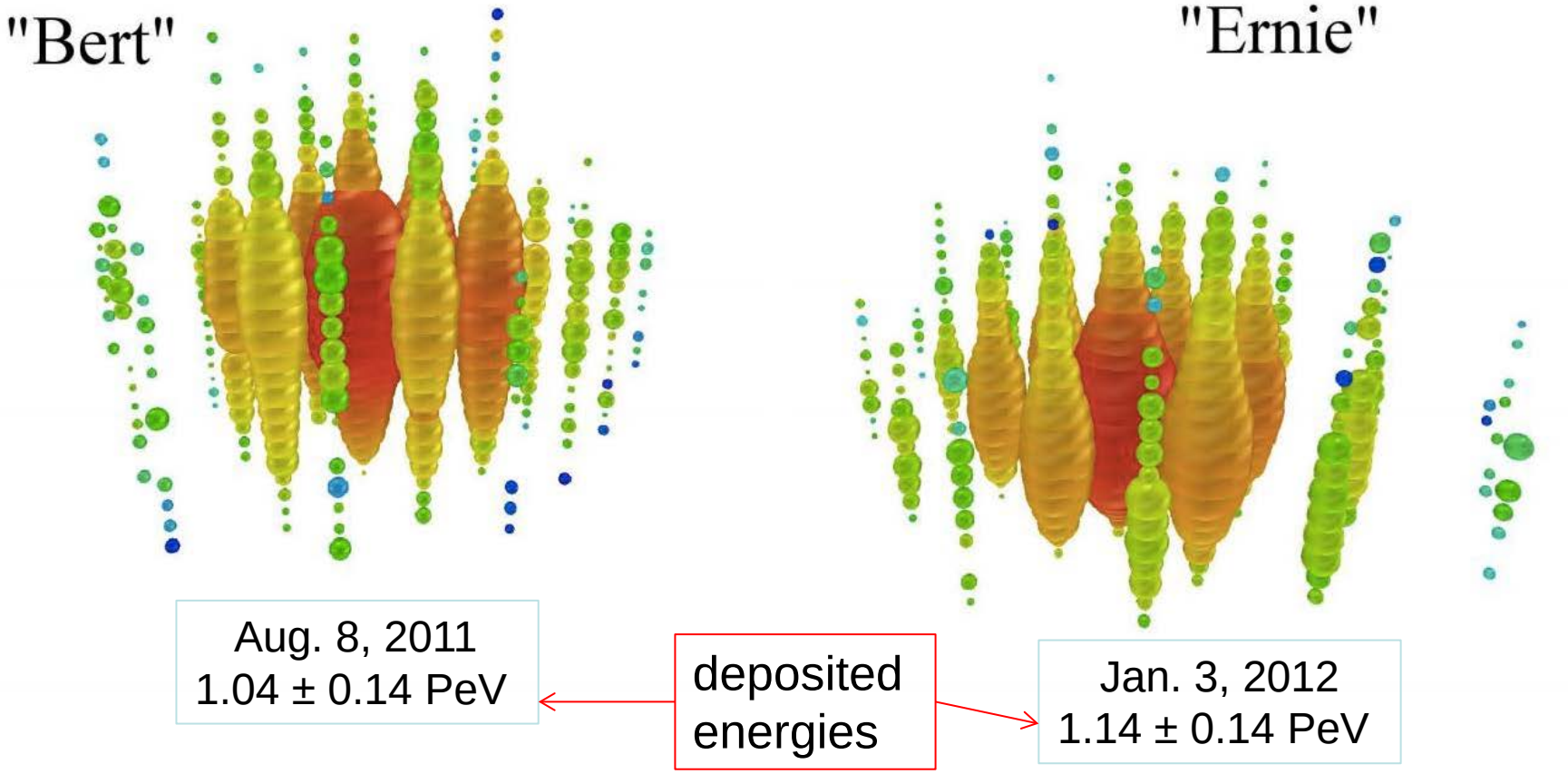
GZK $\gamma_{cmb}\, p \rightarrow \Delta^{+} \rightarrow \begin{matrix} n\,\pi^{+} & \rightarrow n\,\mu\nu \\ p\,\pi^{0} & \rightarrow p\,\gamma\gamma \end{matrix}$ threshold ~ 5×10^{19} eV



Search for high
number of C-photons = NPE

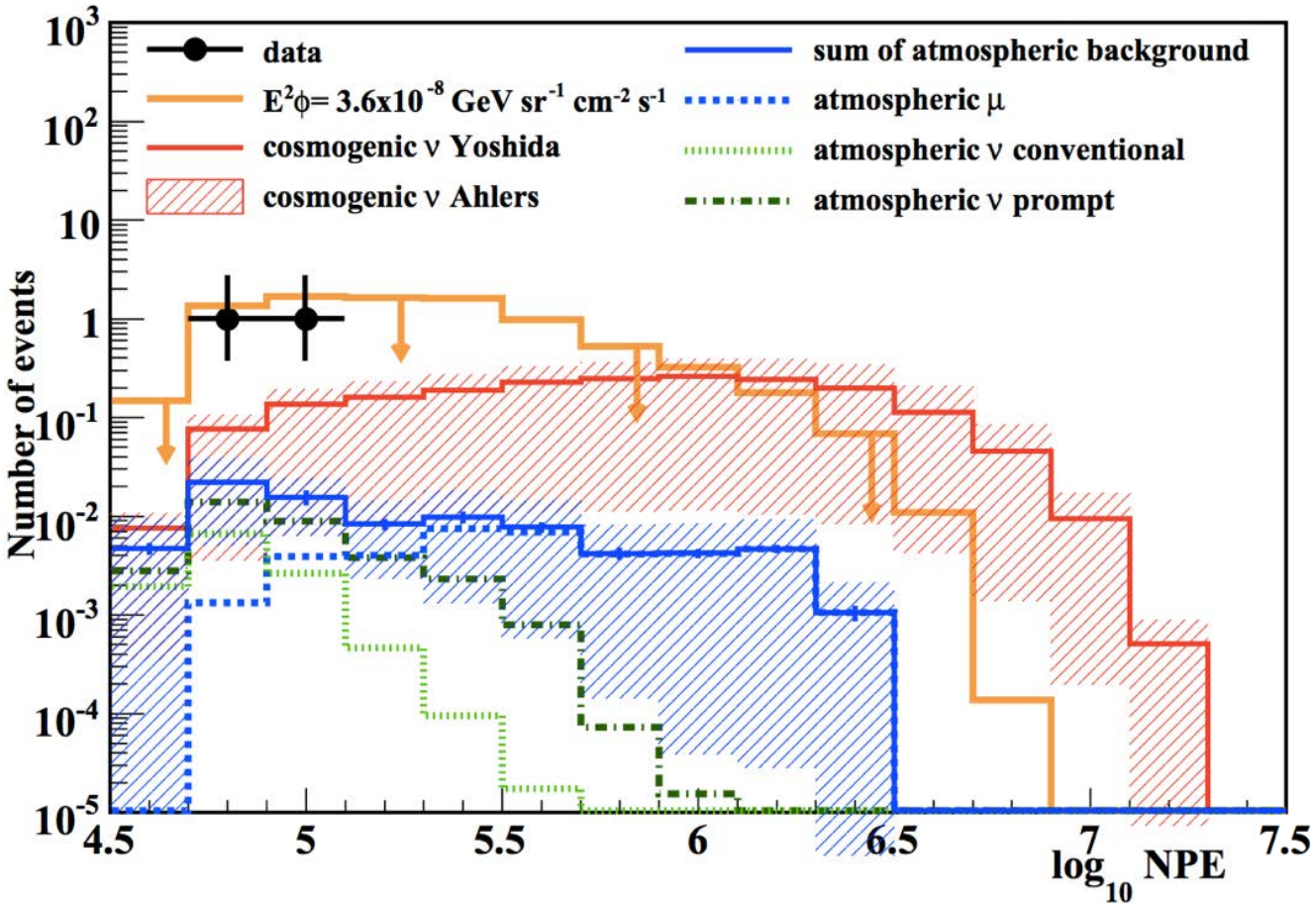


Search for cosmogenic neutrinos with 2010-2012 data.



- Two shower type events found in 616 days of IceCube observations.
- Neutrino energies could be higher than deposited energies, if neutral current interaction.

Search for cosmogenic neutrinos with 2010-2012 data.

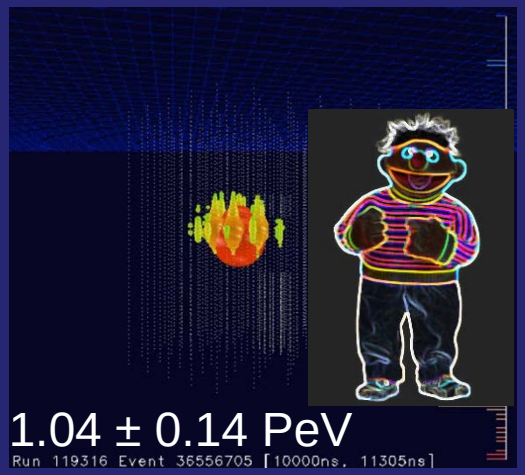


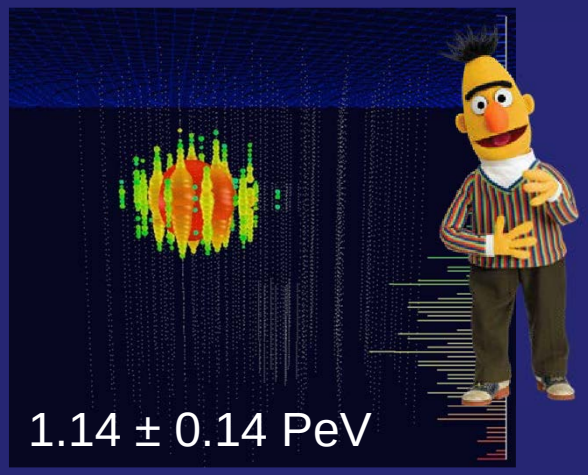
> Search targeted for multi-PeV to EeV events expected from cosmogenic neutrinos.

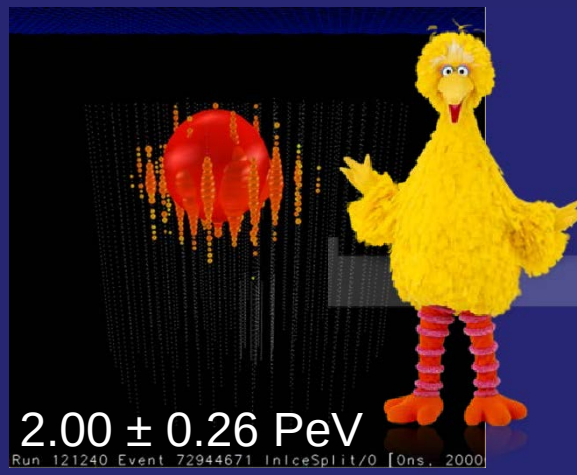
> PeV events found at the brightness threshold for this analysis.

> 2.8σ above expectations from atmospheric background.

The Muppet Show







A theoreticians view (Francis Halzen, IceCube PI) :

A detection of 1 neutrino is interesting …

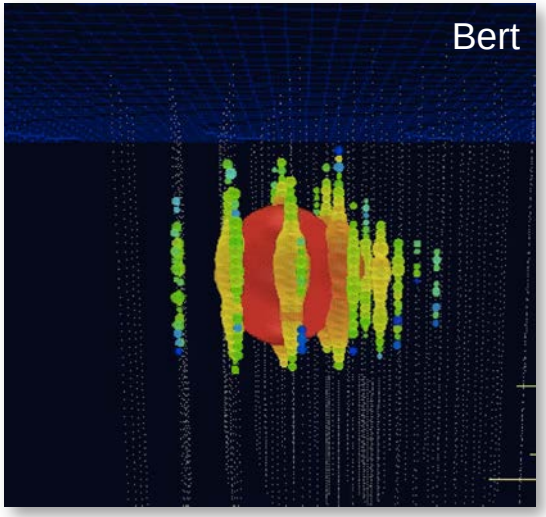
2 is evidence …

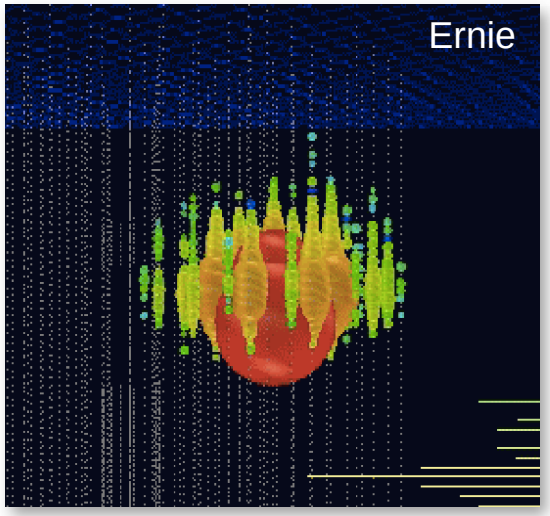
… and 3 is a spectrum!

Things we wanted to learn

- Isolated events or tail of spectrum?
- Spectral slope/cutoff
- Flavor composition (ratio tracks/cascades)
- Where do they come from?
- Astrophysical or air-shower physics (e.g. charm)?

→ Needed more statistics to answer all of these

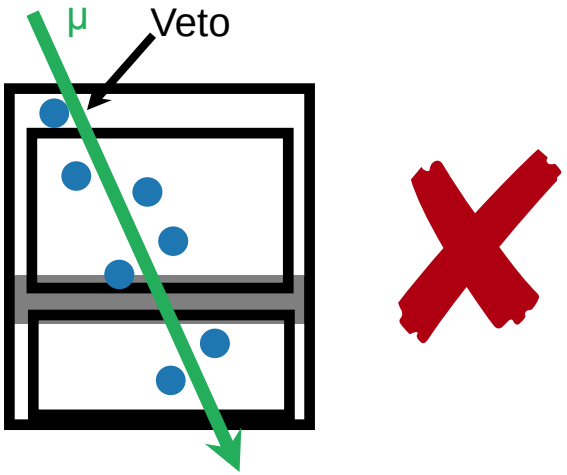


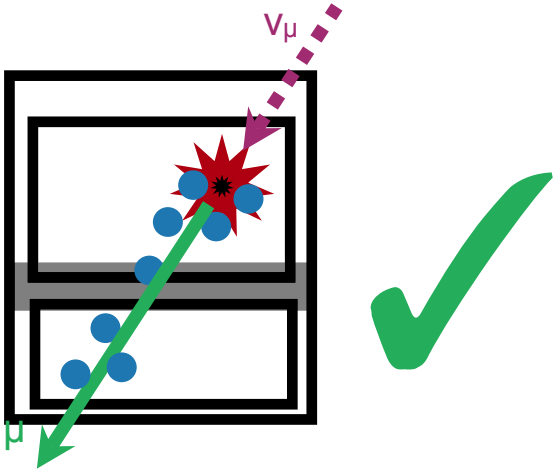


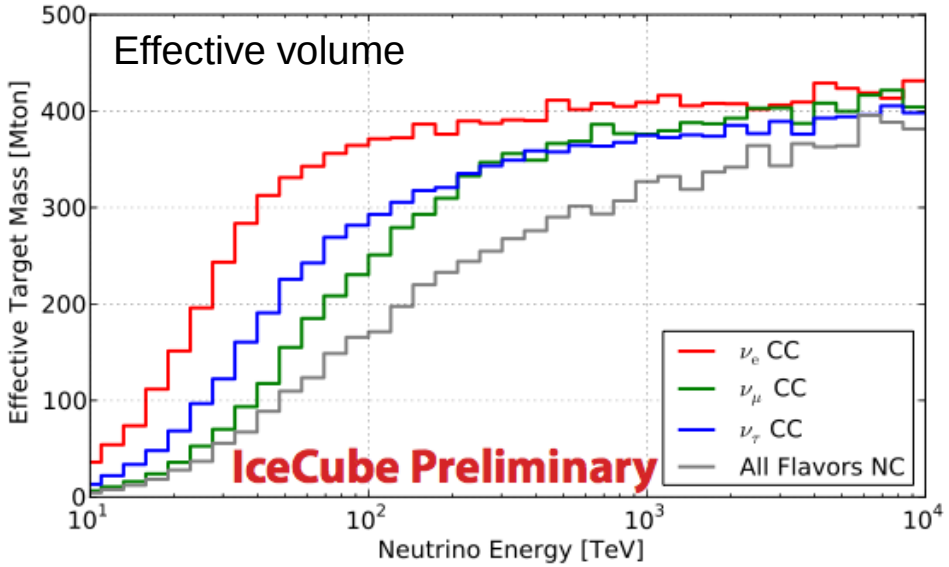
Search for contained and semi-contained events.

- Designed to find contained events below the energy threshold of the “Bert-and-Ernie” analysis
  - same dataset
  - 662 days of livetime

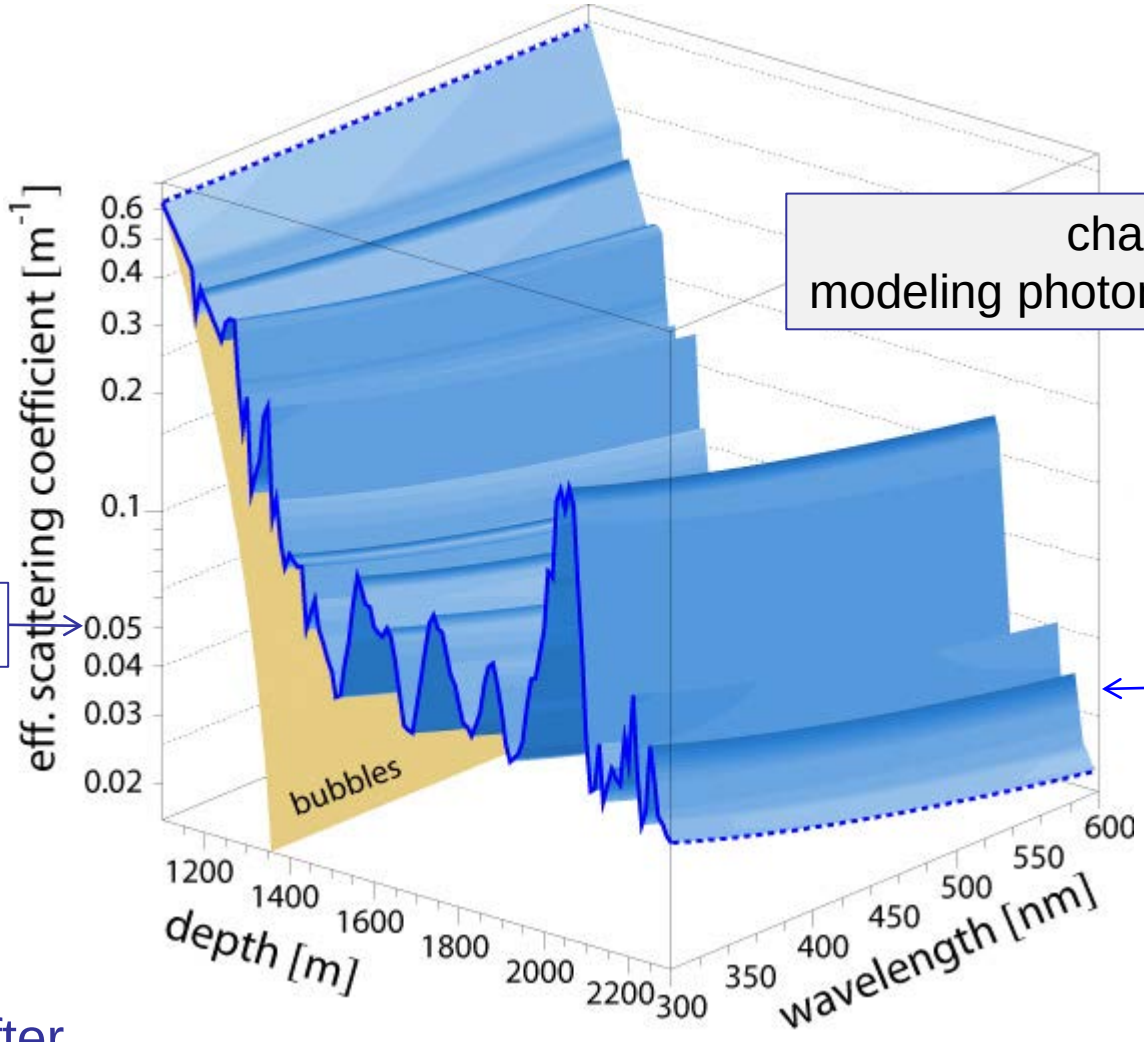
- Use outer IceCube layers as incoming track veto
  - Additional atmospheric muon veto
  - Sensitive to all flavors in region above ~ 60TeV
  - Muon background can be estimated from data







Ice Properties



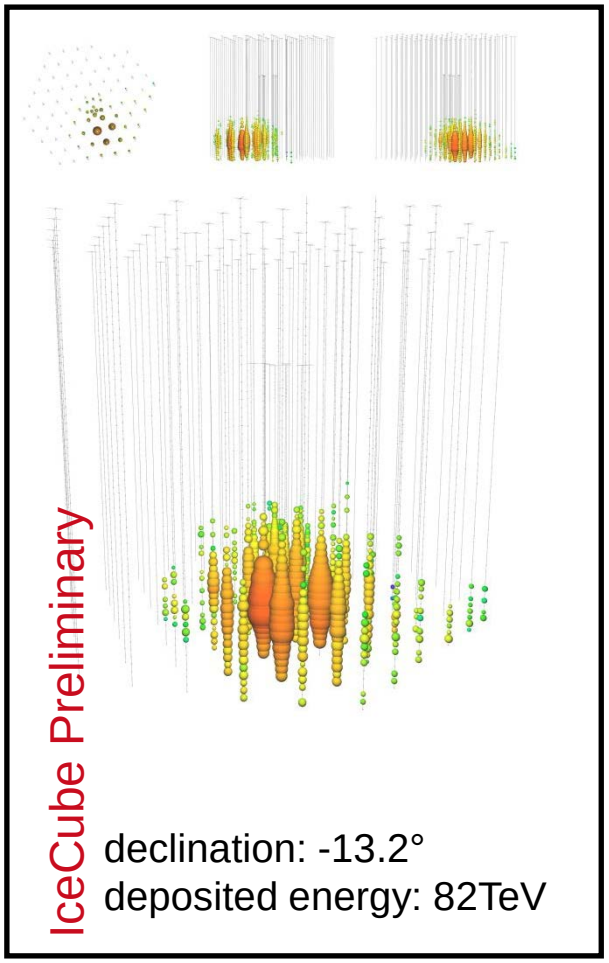
challenge:
modeling photon propagation in ice

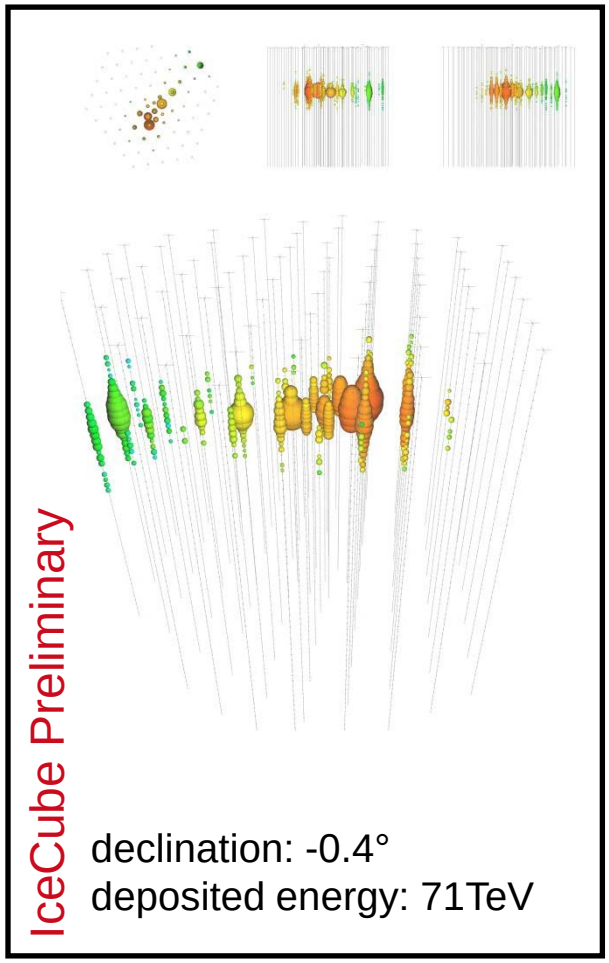
λ_{eff} = 20 m

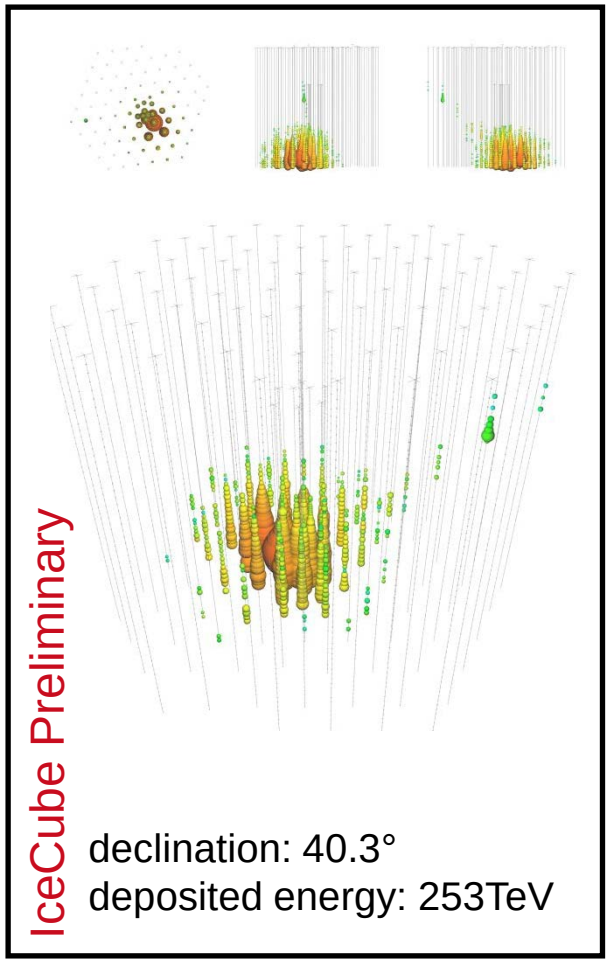
DeepCore

λ_{eff} length after
which light is isotropic

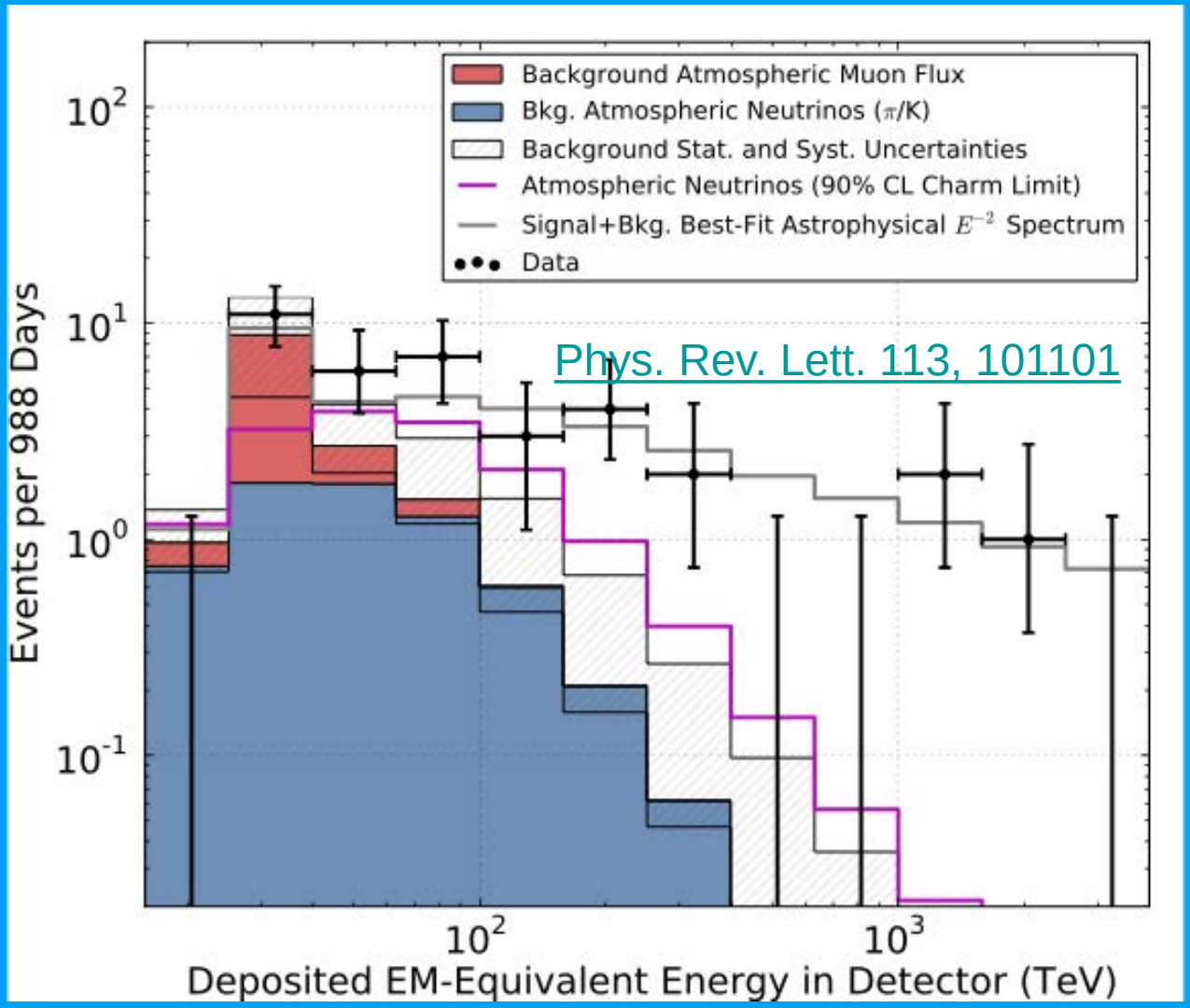
Some example events







Excess of HE Starting Tracks

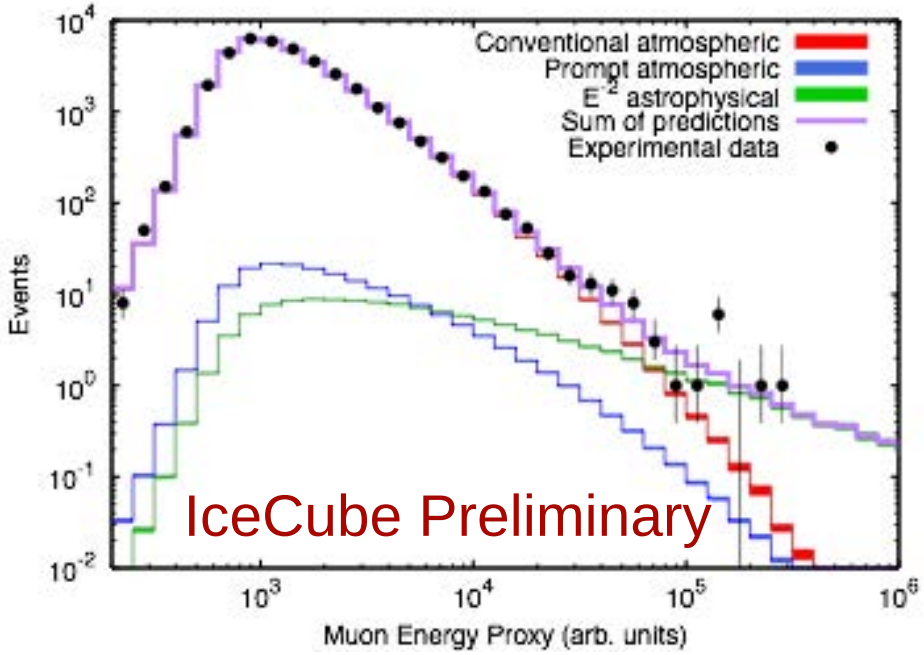


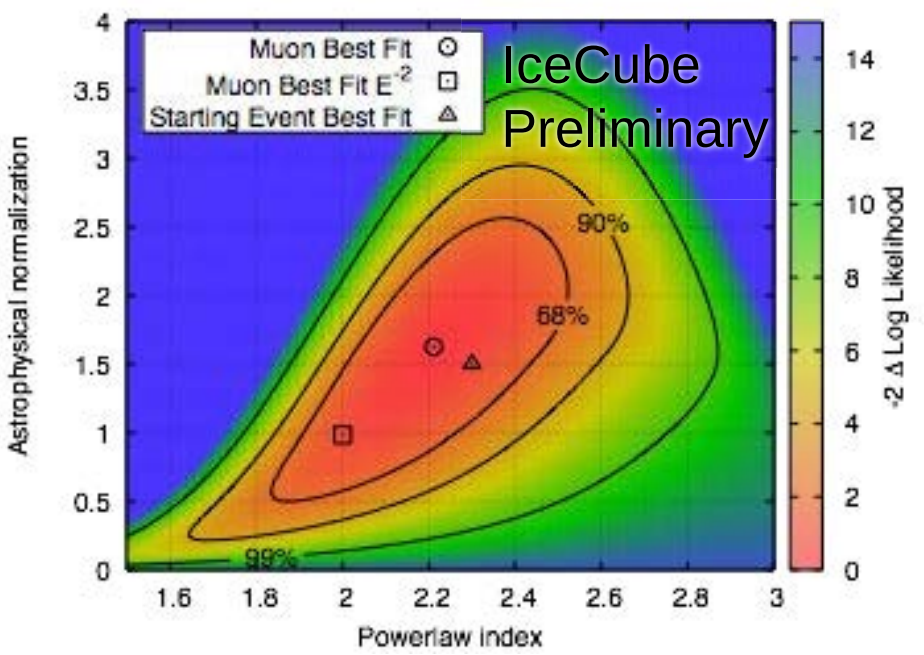
Significance about 5.7 σ

First observation of astrophysical flux of high energy neutrinos

Starting events depositing >60 TeV using 3 years of data, events up to ~2 PeV

Northern Sky Through-going Events





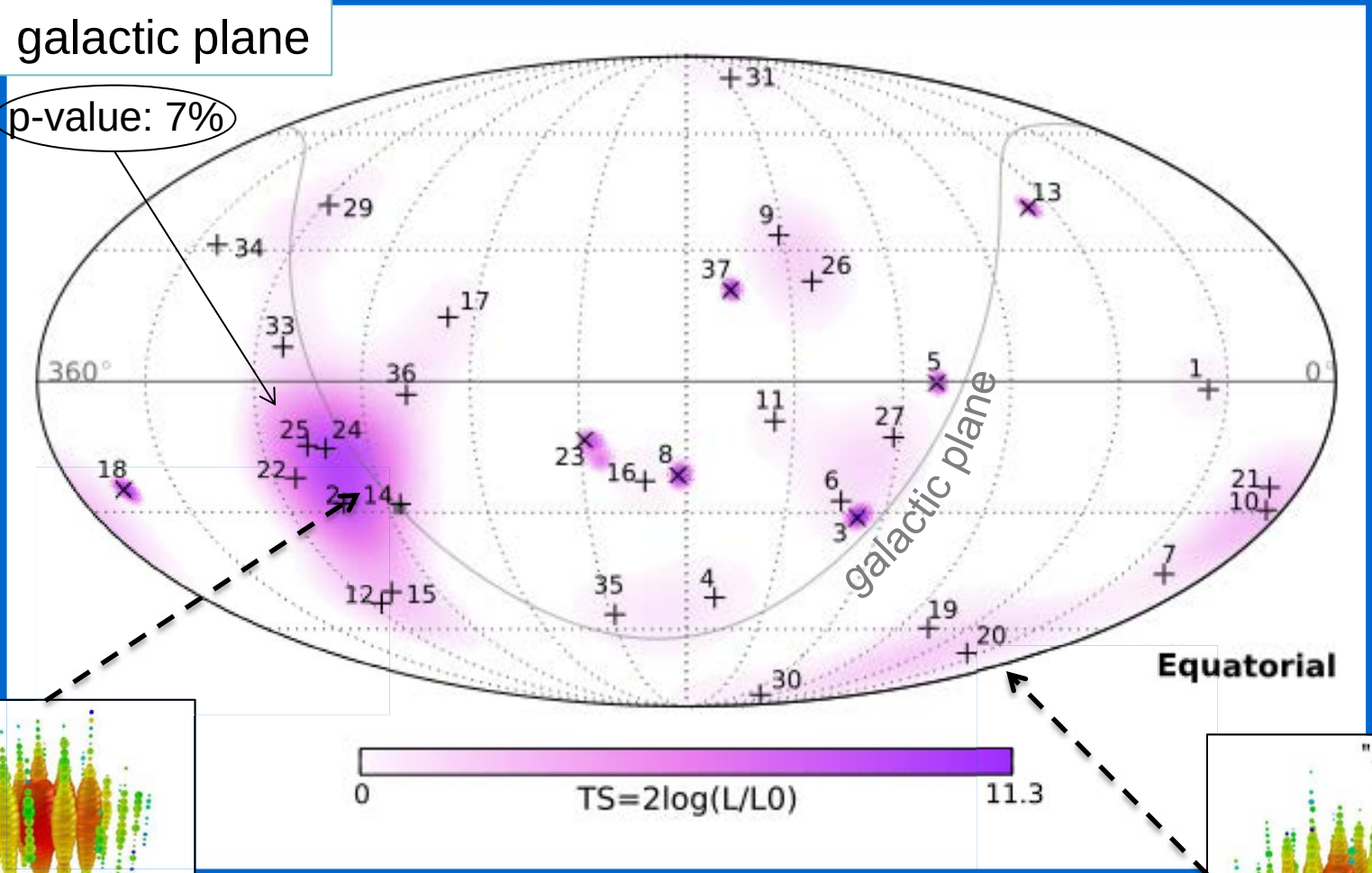
- (Paper in internal review) Analysis of through-going events from the northern sky using 2 years of data—ν_μ charged current only, >1 TeV
- Excess over atmospheric background of 3.7σ
- Signal looks similar in different channels and different parts of the sky

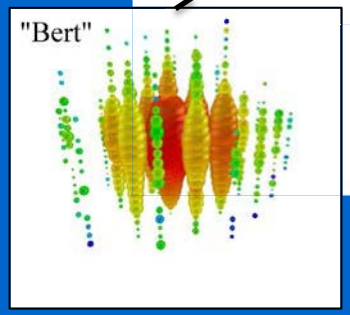
Skymap

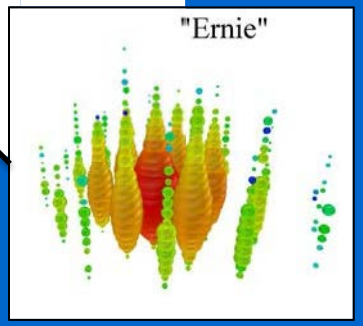
no significant correlation with galactic plane

p-value: 7%

equatorial coordinates

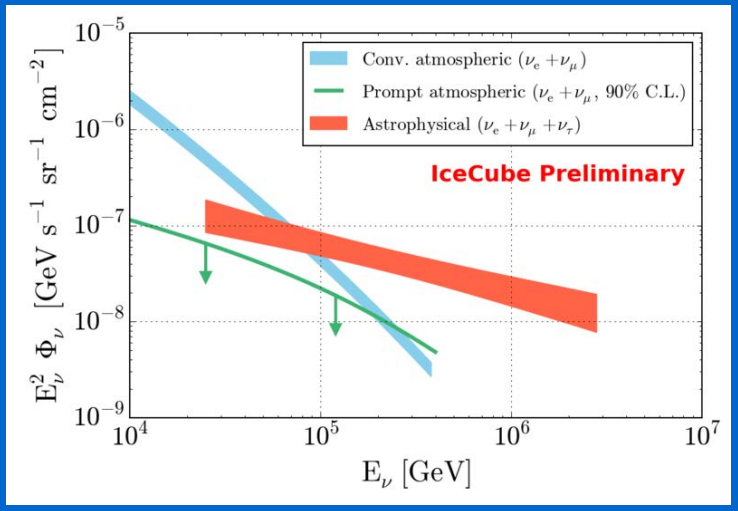


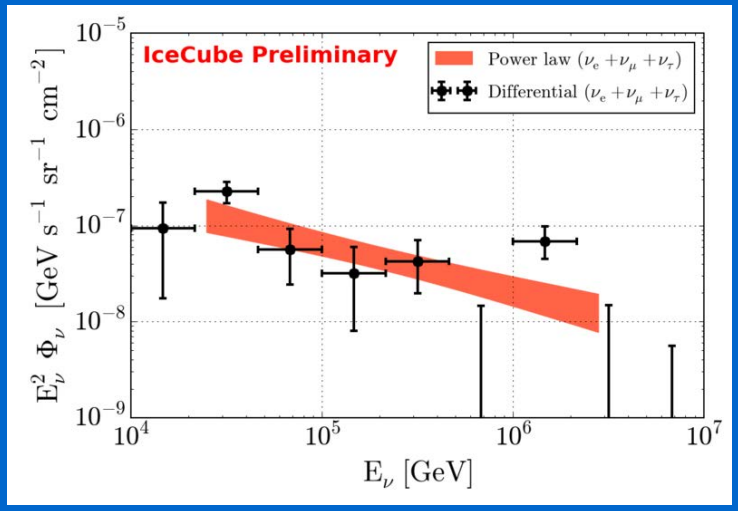


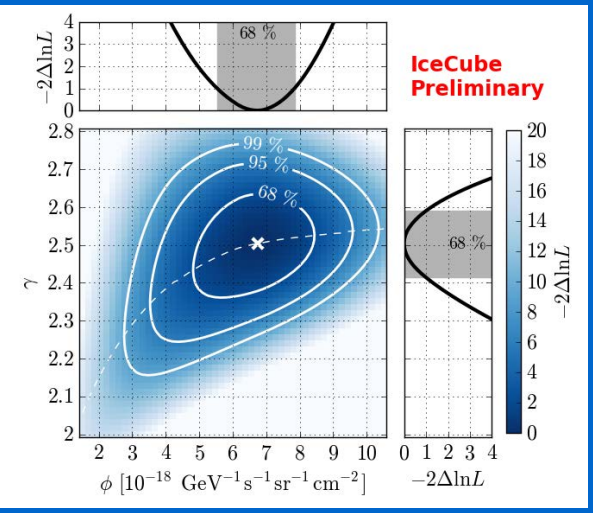


Global Fit to 6 Different Measurements

Simplest model: flux $\Phi_\nu = \phi \cdot \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-\gamma}$ and flavor ratio $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$







Results:

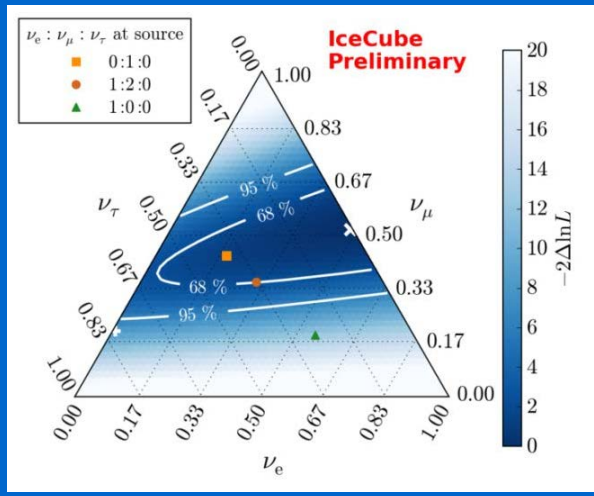
$$\gamma = 2.50 \pm 0.09$$

$$\phi = \left(6.7^{+1.1}_{-1.2}\right) \cdot 10^{-18}\,\mathrm{GeV^{-1}s^{-1}sr^{-1}cm^{-2}}$$

Flavor ratio compatible with

$$\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$$

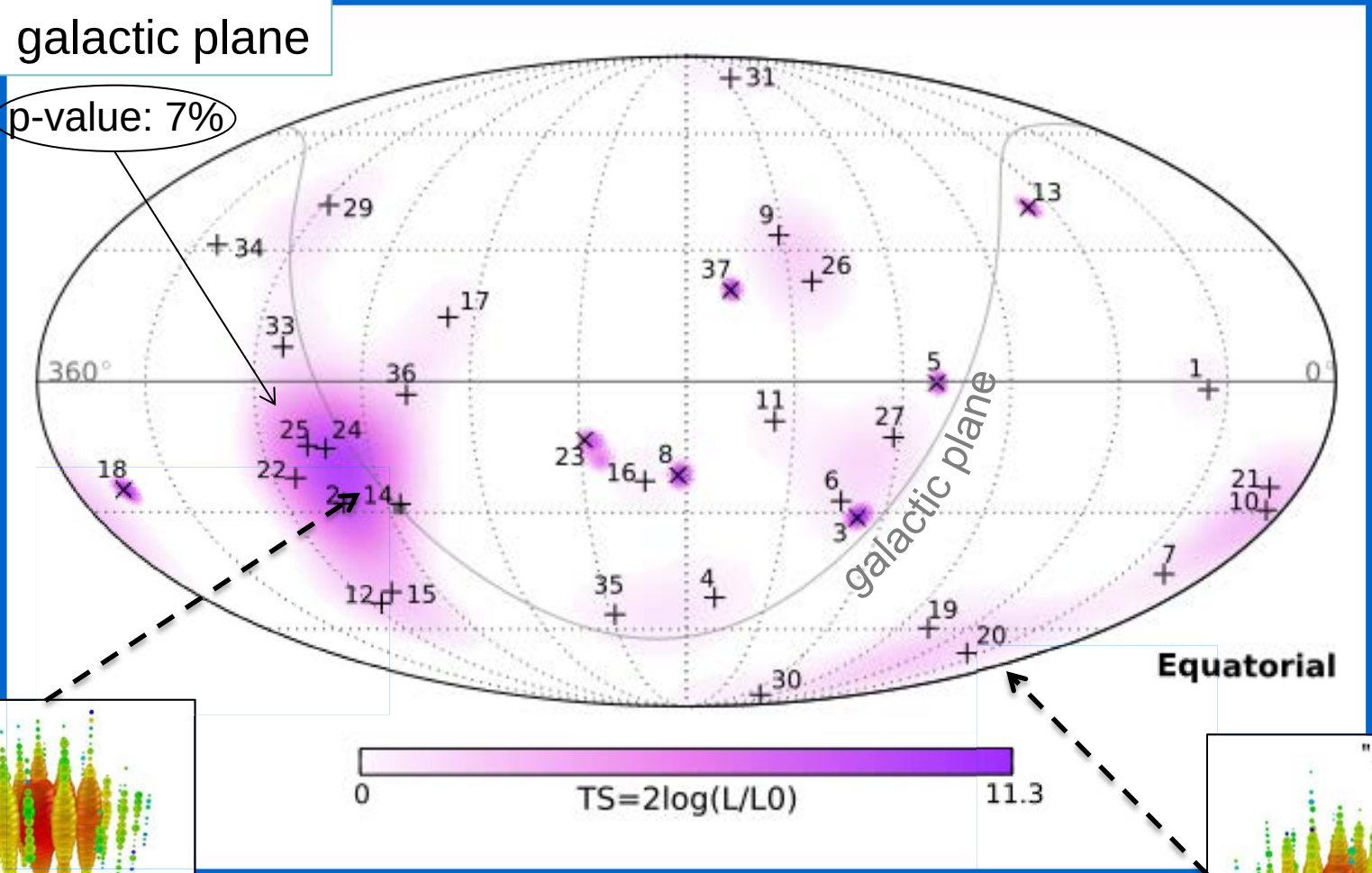
„prompt“ < 2 × ERS

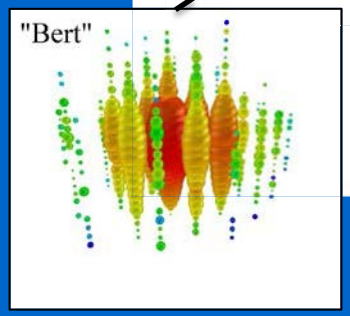


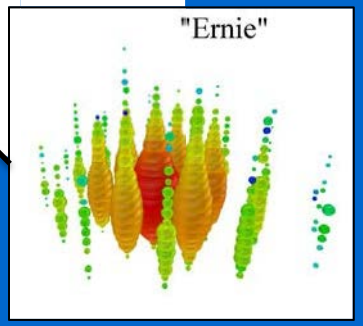
Skymap

no significant correlation with galactic plane

p-value: 7%

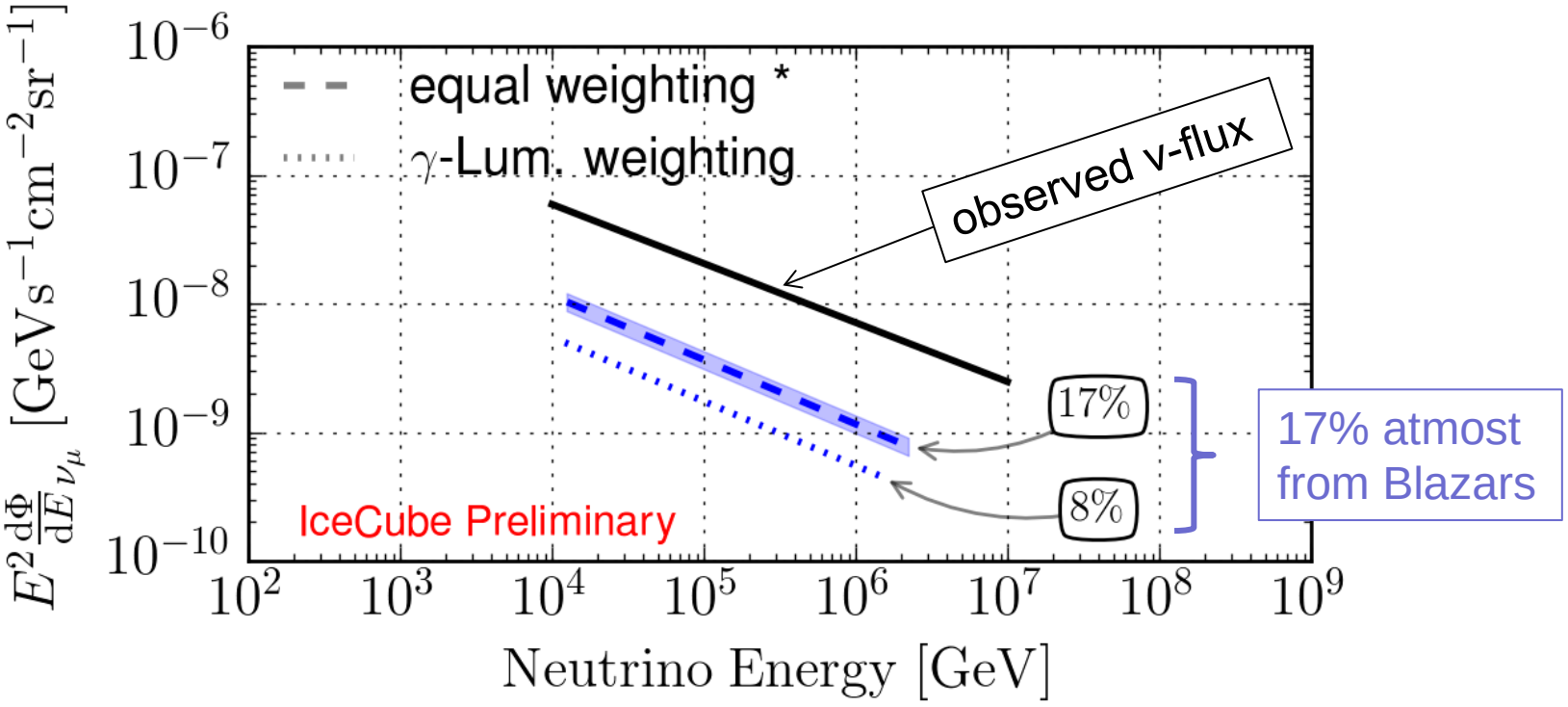






Blazars or GRB as Sources?

Compare directions of the high energy ν_μ
with directions of Blazars observed by
Fermi Satellite at high γ luminosity



17% atmost from Blazars

Even more stringent for GRB:
from analysis of 506 GRBs in four years it was found that no more than 1% of the high energy neutrinos could come from GRB

1% atmost from GRBs


The End