Data Analysis in IceCube: Implications for GW Coincidence Searches

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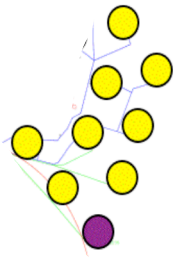
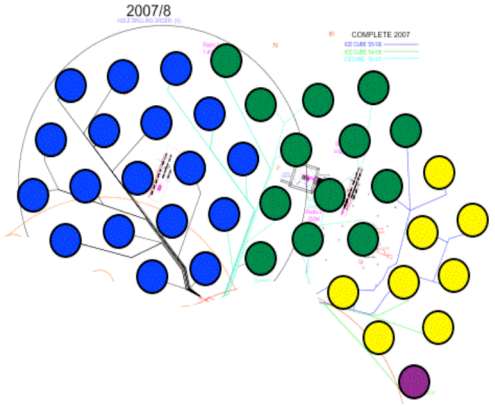
GW+HEN Workshop, Paris
May 20, 2009

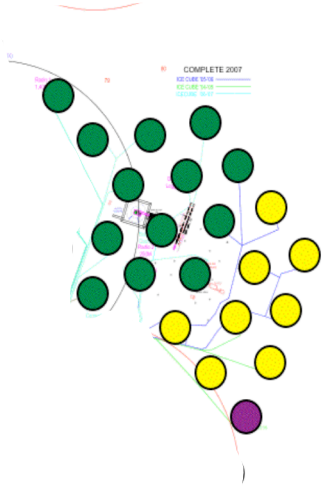
Brief History of IceCube: Four Seasons 2006-9



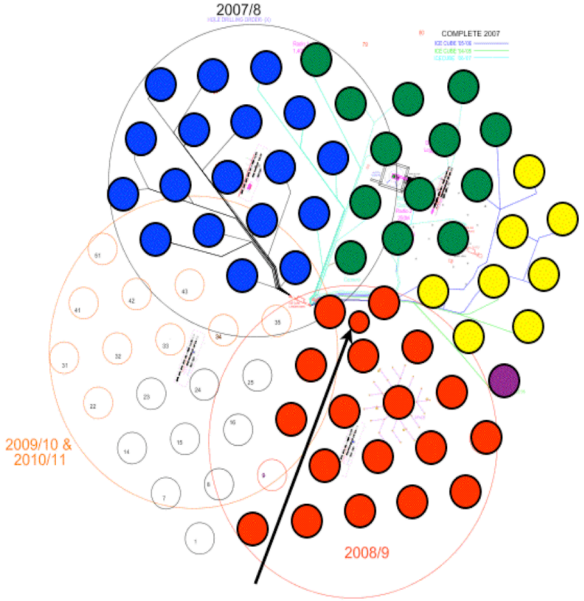
IceCube-9: “Naked-Eye” GRB



IceCube-40: analysis starting now

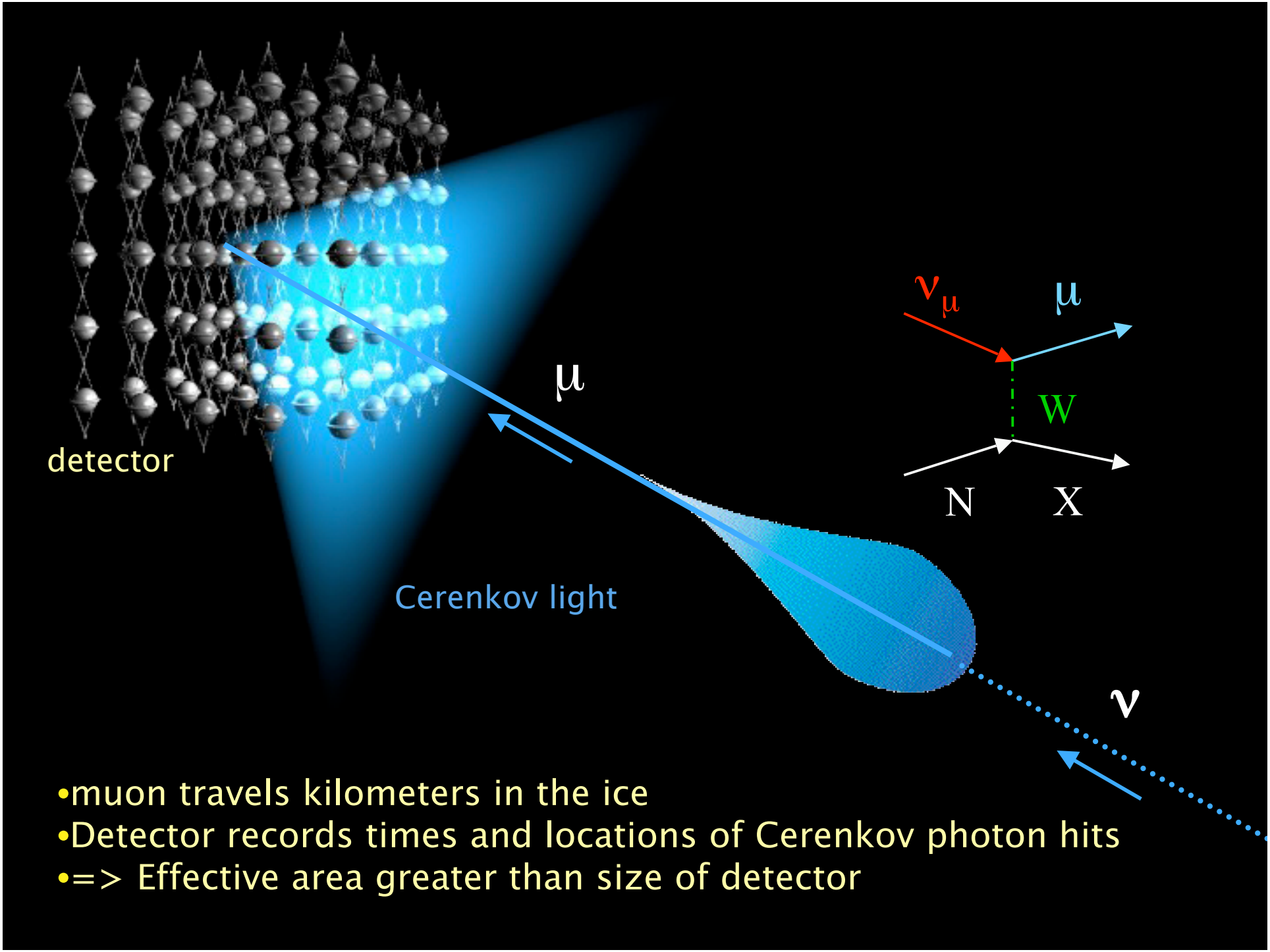


IceCube-22: current point source results

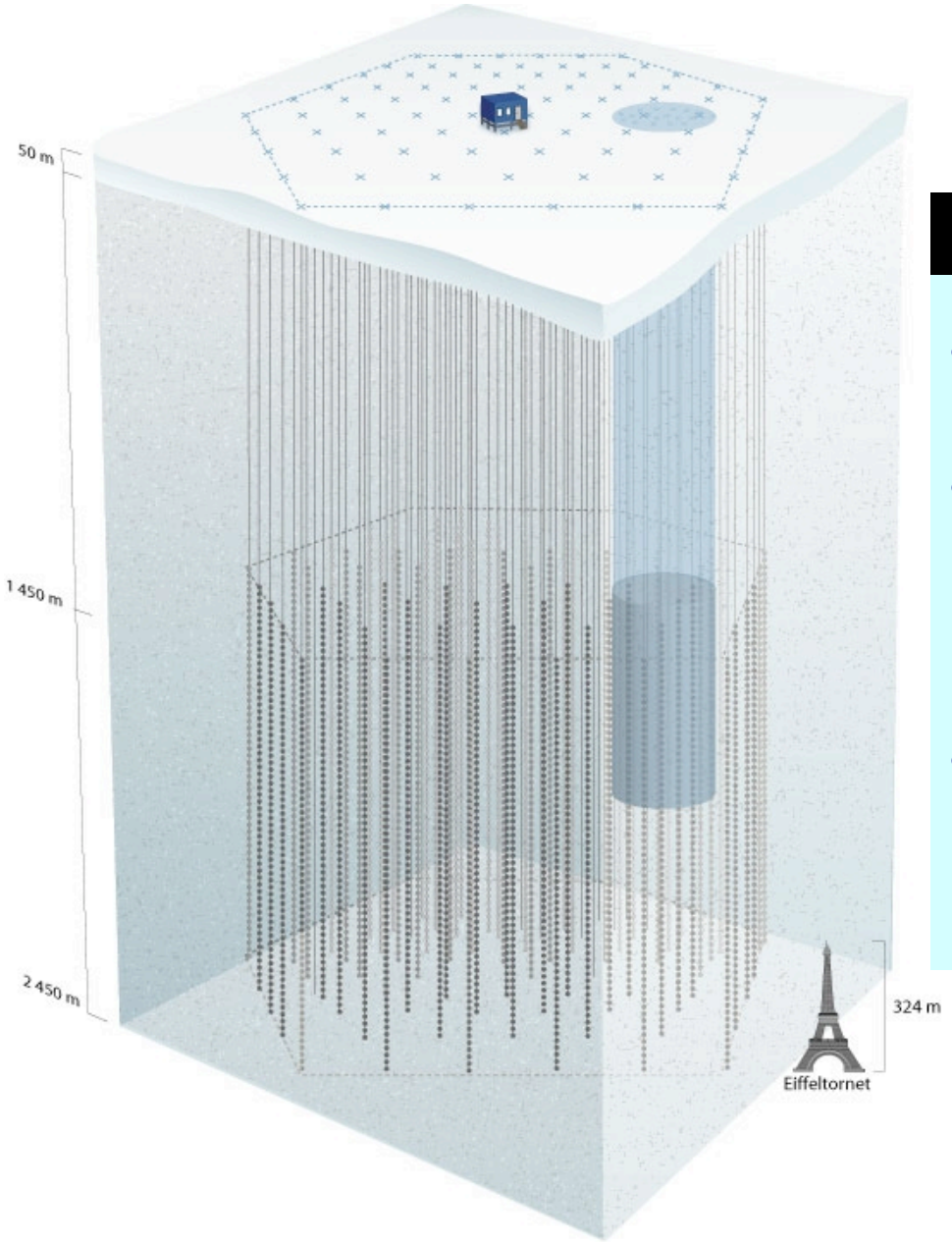


1st DeepCore string

IceCube-59: data-taking starting now


detector
μ
Cerenkov light
ν_μ
μ
W
N
X
ν
•muon travels kilometers in the ice
•Detector records times and locations of Cerenkov photon hits
•=> Effective area greater than size of detector

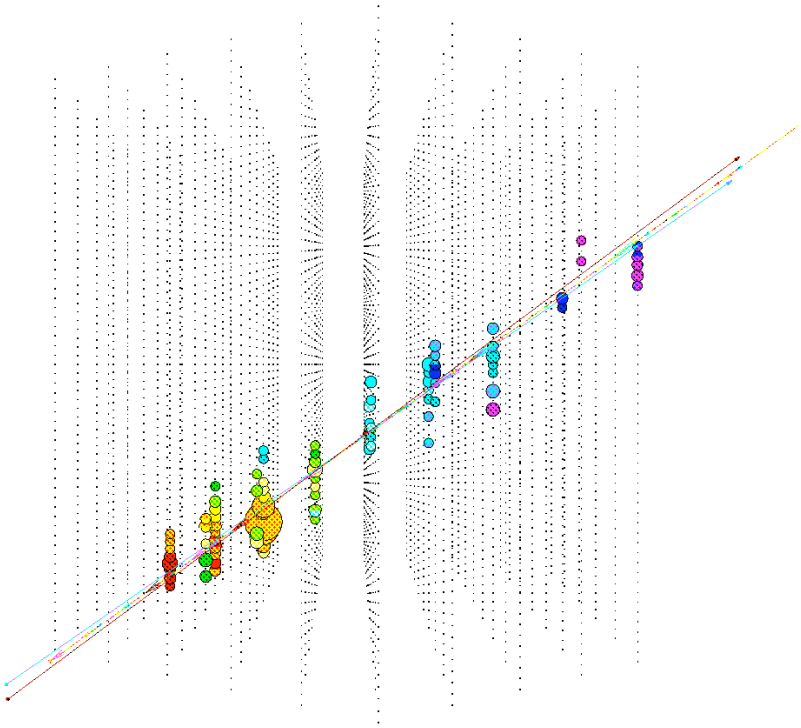
The IceCube Detector Array



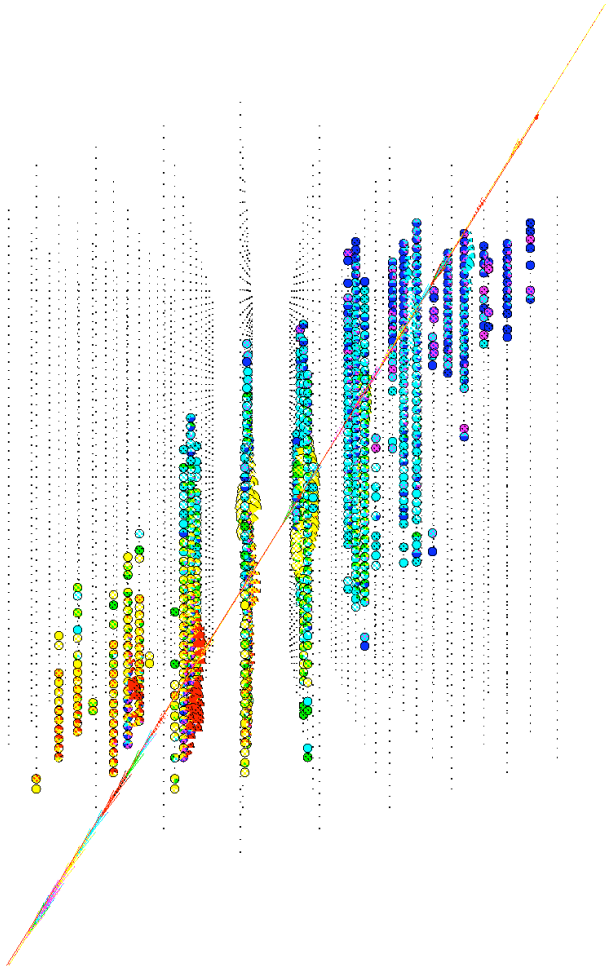
Design Overview

- 1 km^3 -- 1 Gton instrumented volume
- 80 strings
  - 1.5 km - 2.5 km deep
  - 125 m spacing between strings
- 60 Optical Modules per string
  - 17 m vertical spacing between modules

ν_μ Detection in IceCube



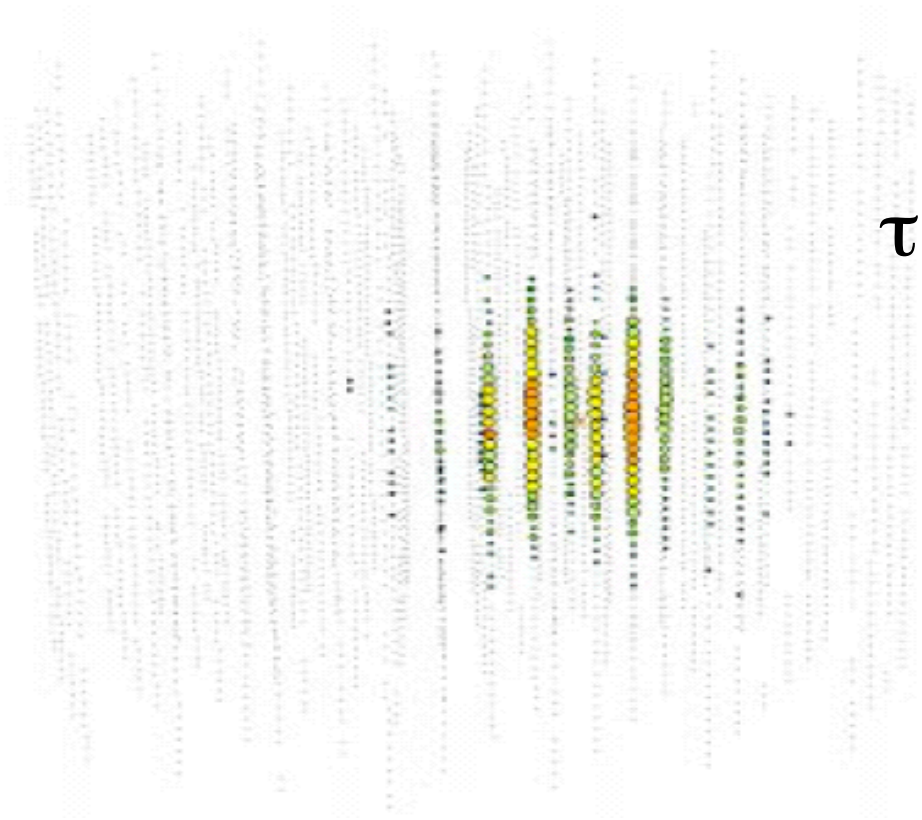
E = 6 TeV



E = 6400 TeV

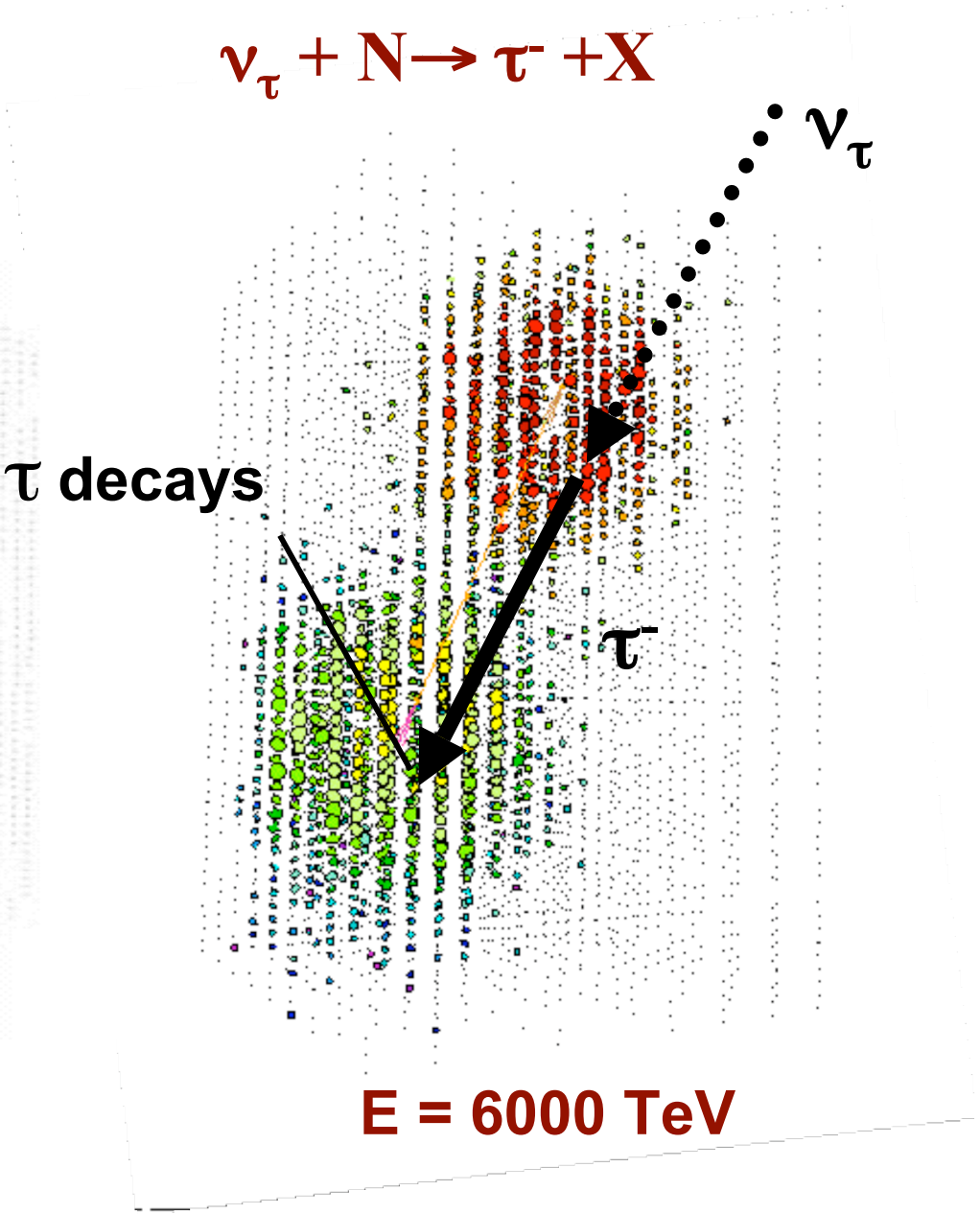
ν_e and ν_τ cascade detection in IceCube

$\nu_e + N \rightarrow e^- + X$



E = 375 TeV

$\nu_\tau + N \rightarrow \tau^- + X$



E = 6000 TeV

Event Triggers

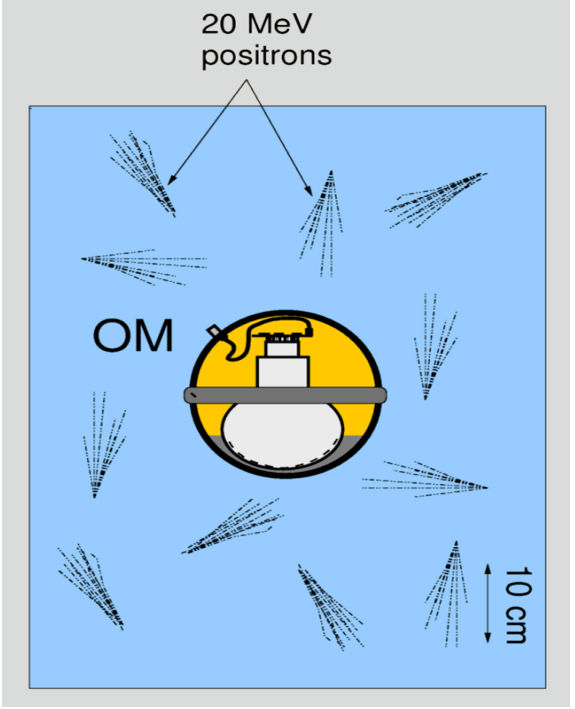
- Waveforms are recorded when nearest or next-to-nearest DOMs fire within ± 1 microsecond (local coincidence)

- **Event trigger** occurs when at least 8 DOMs record waveforms within 5 microseconds.

This trigger primarily sensitive to cherenkov light emitted by e.g. >100GeV muon passing through ice

Sensitivity to ~ MeV neutrinos from supernova is via a separate DAQ...

Supernova MeV Neutrino Detection in IceCube



Bursts of low-energy (MeV) neutrinos
from core collapse supernovae

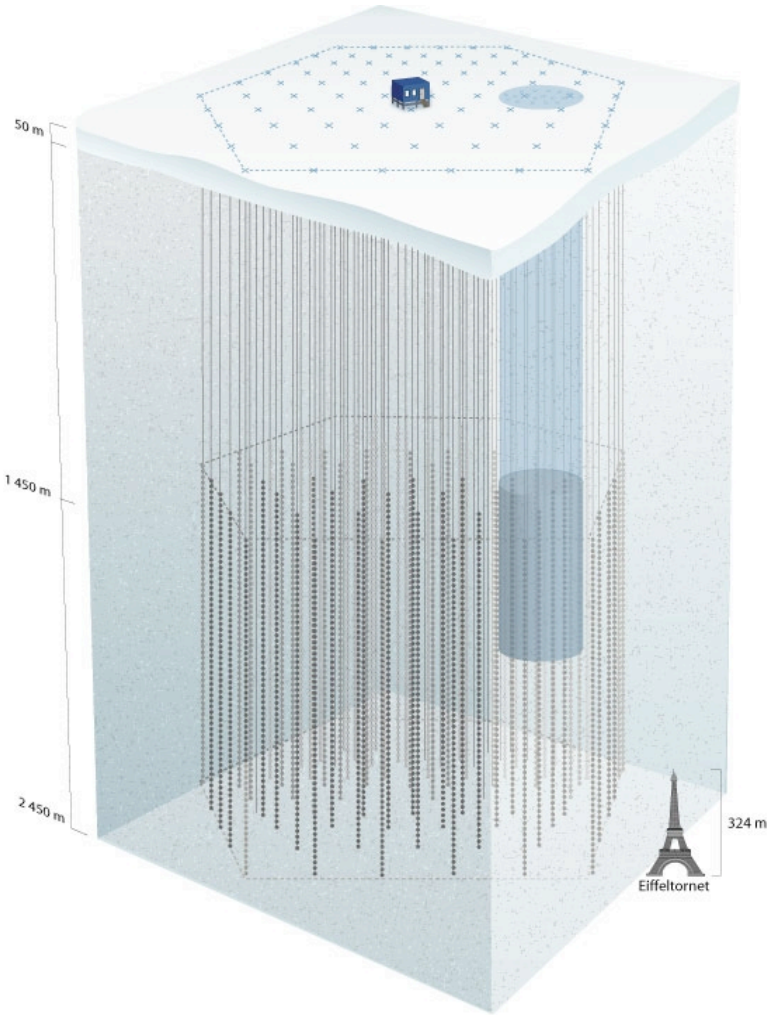
Neutrinos interact in the ice:

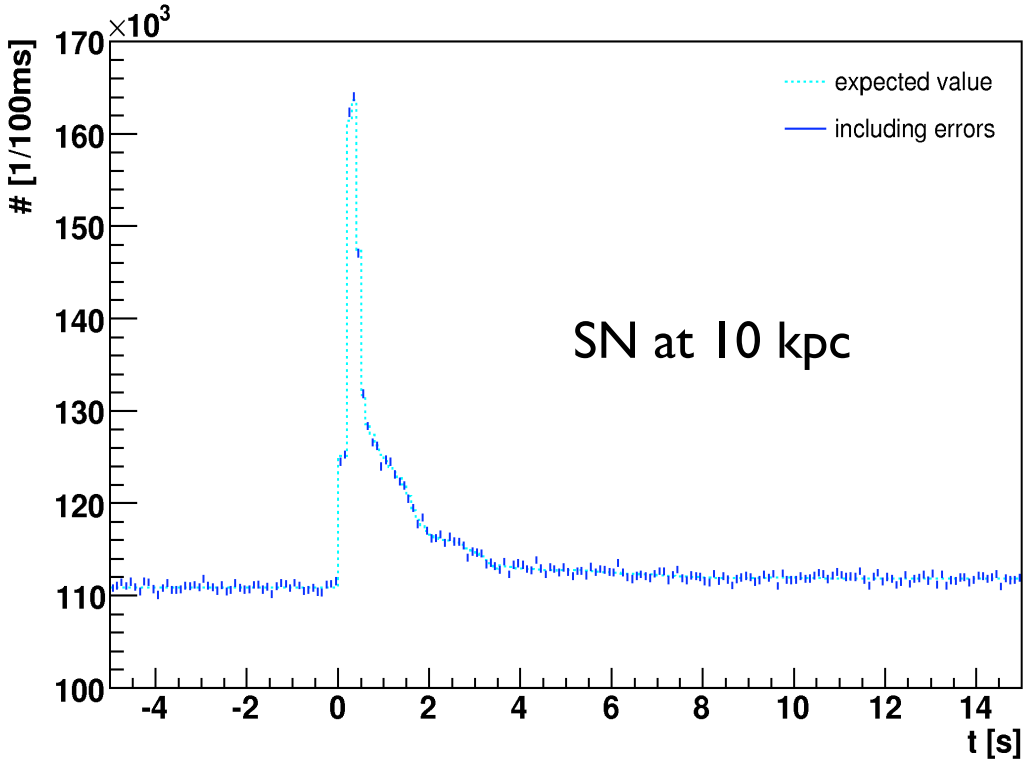
$$\bar{\nu}_e + p \rightarrow n + e^+$$

The produced positron is emitted almost isotropically

Short paths of MeV positrons do not create detectable "tracks." But they increase the **noise rate**.

IceCube as MeV SN ν detector



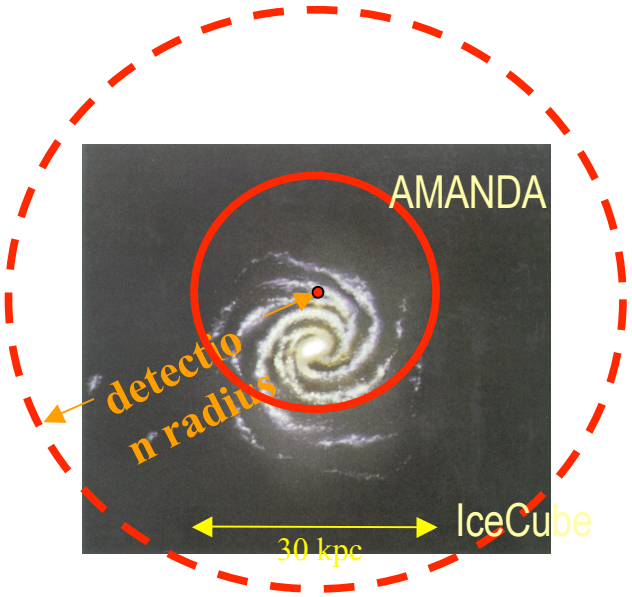


Detection via increase of the dark noise rate globally throughout detector

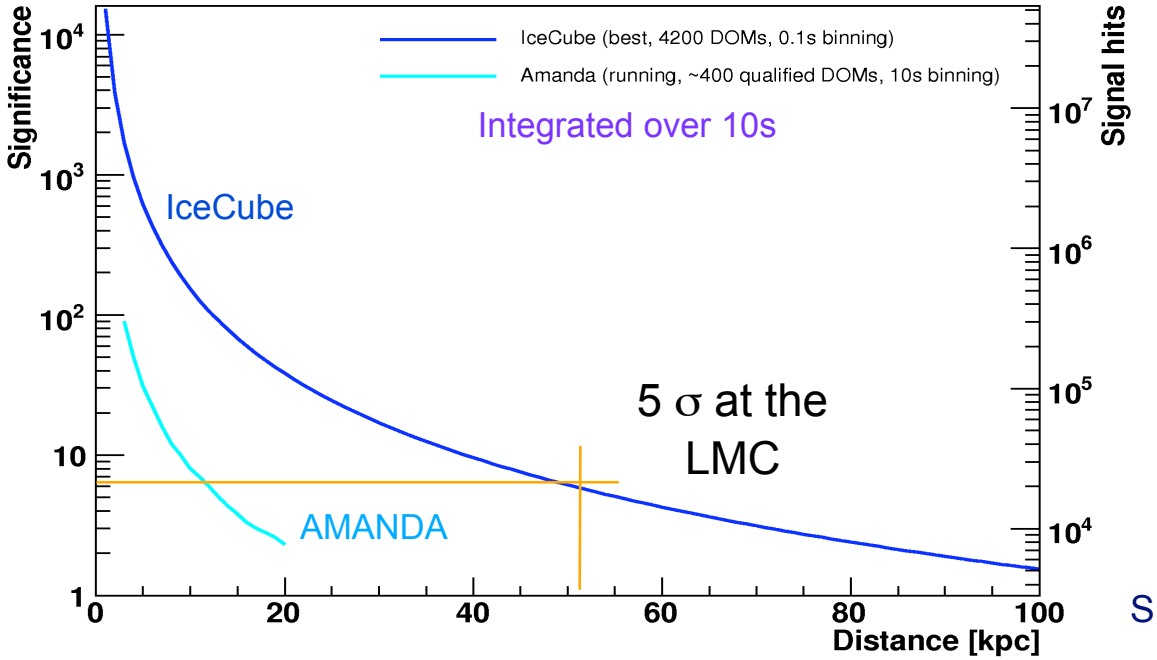
No directionality, but excellent time resolution and high significance signal

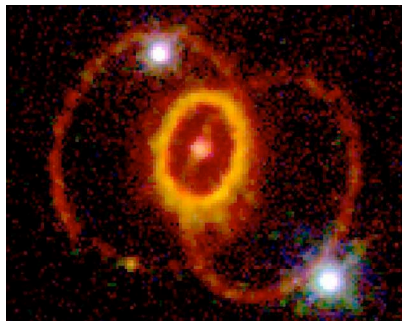
Supernova Neutrino Search

Participate in SNEWS (SuperNova Early Warning System): a collaborative effort among Super-K, SNO, LVD, KamLAND, IceCube, BooNE and gravitational wave experiments



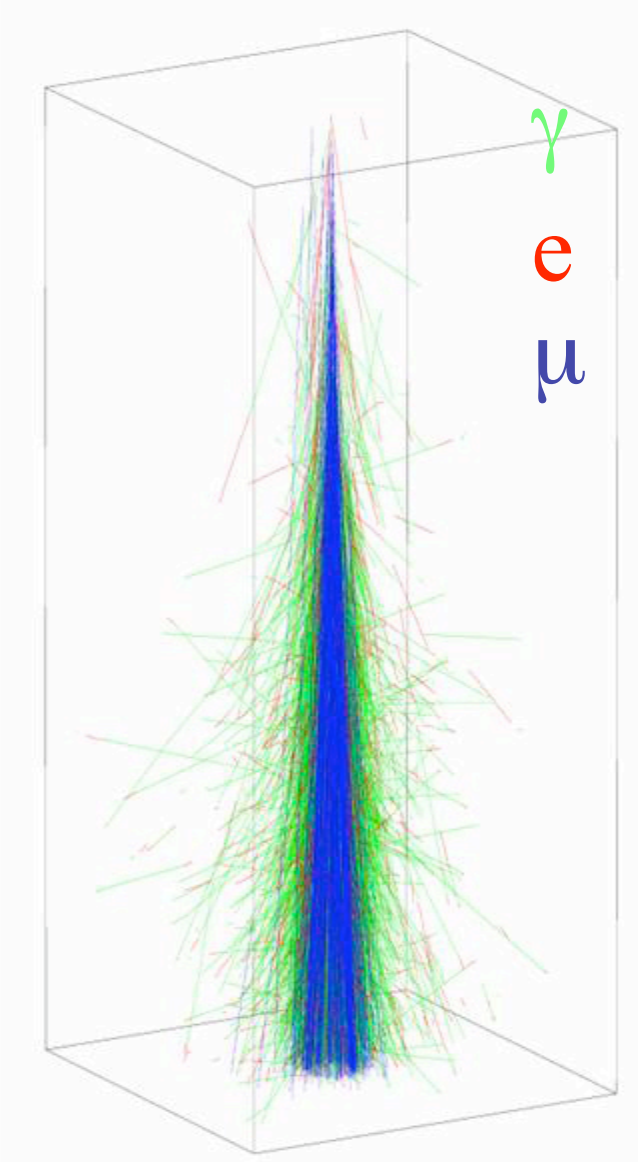
- **AMANDA saw 90% of the galaxy**
- **IceCube will see out to the LMC (~50 kpc)**

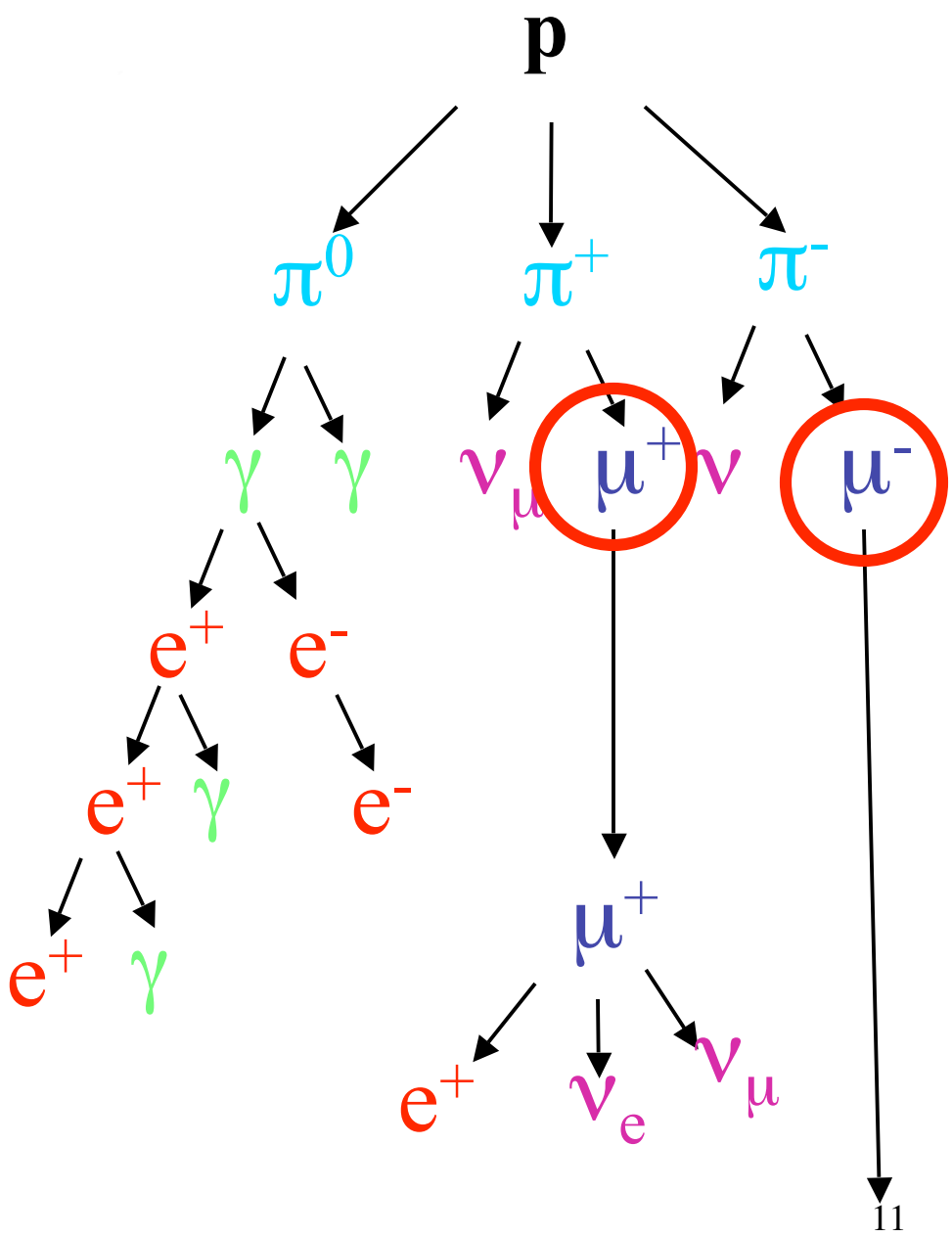




SN 1987A in Large Magellanic Cloud

Backgrounds: **Atmospheric muons** from cosmic-ray showers





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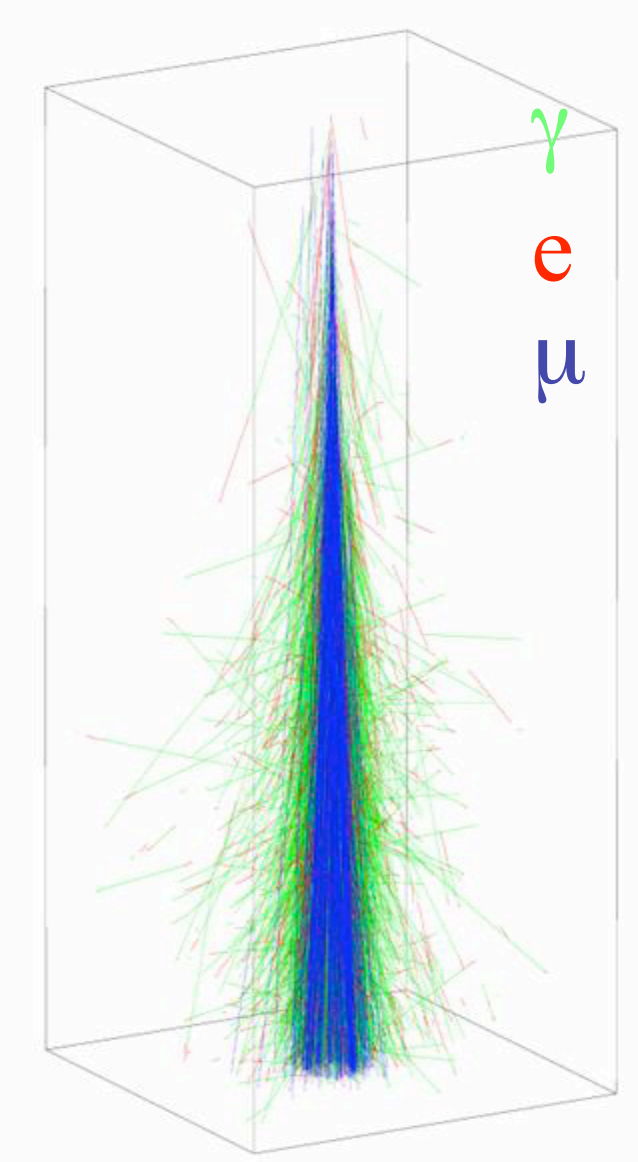
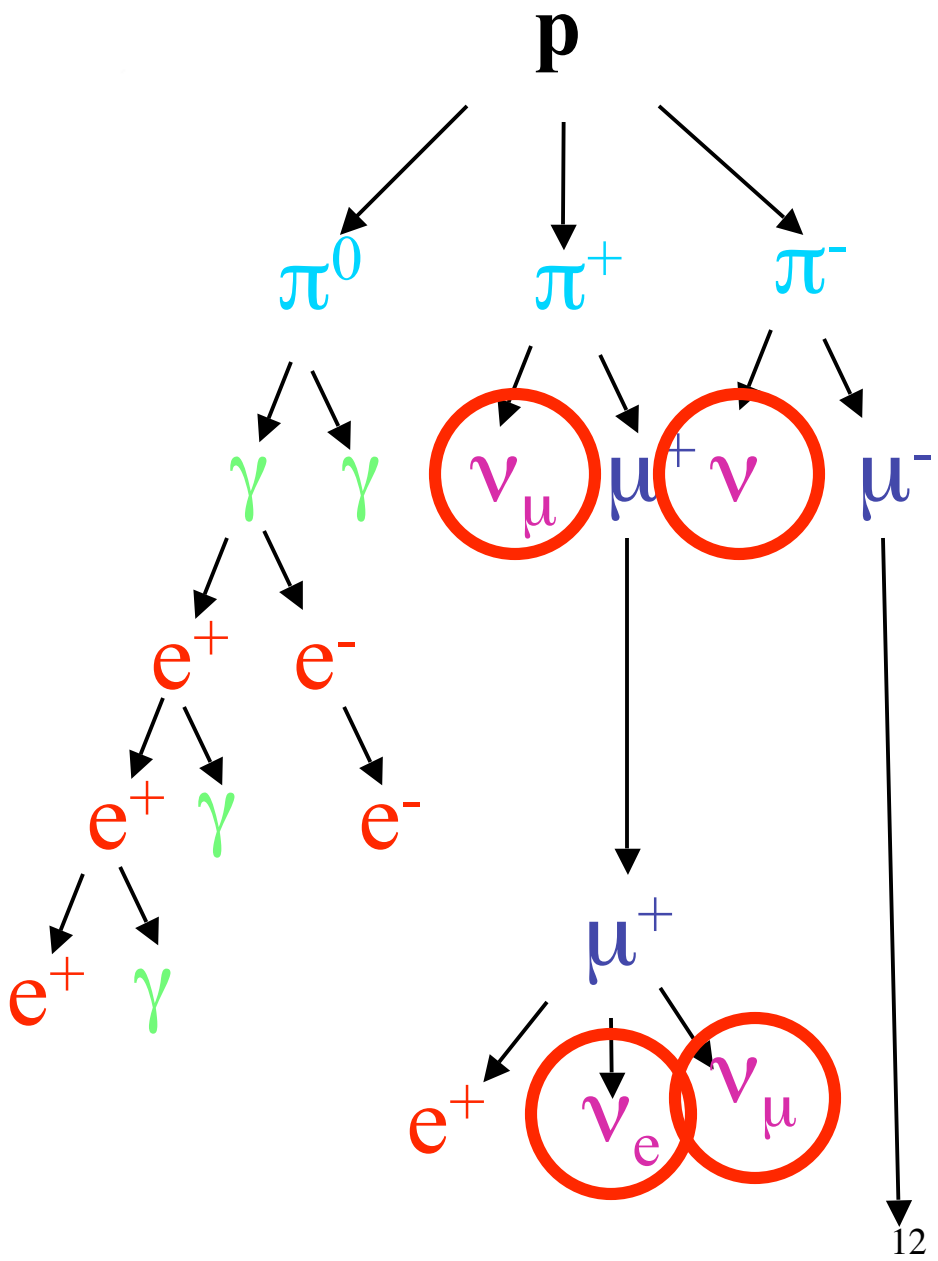
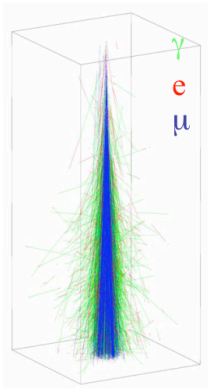
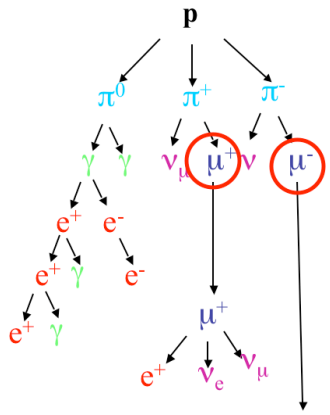
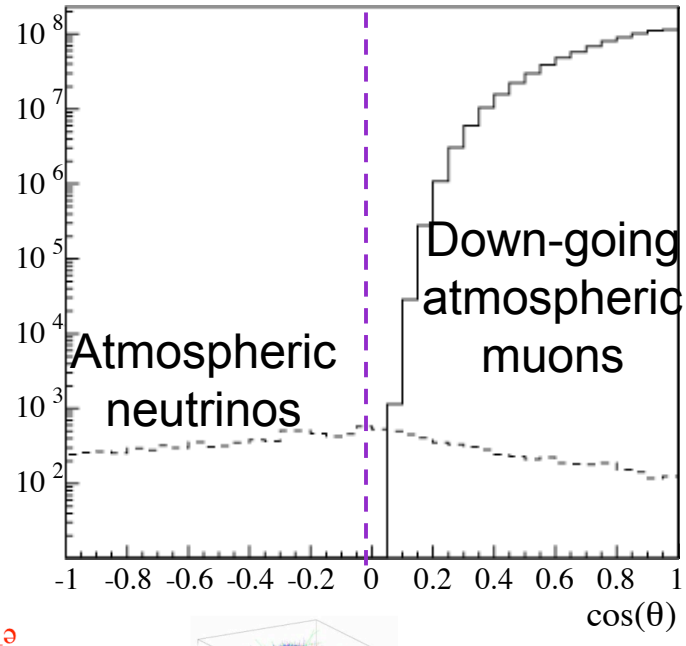


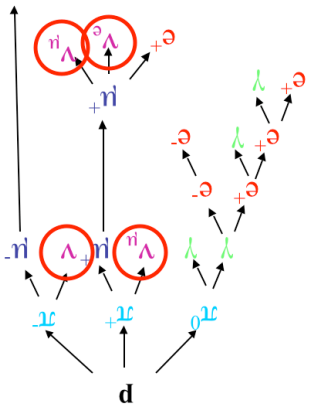


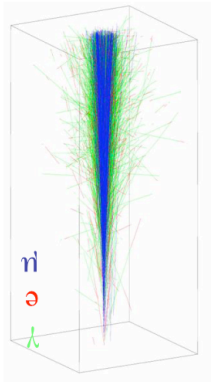
Backgrounds











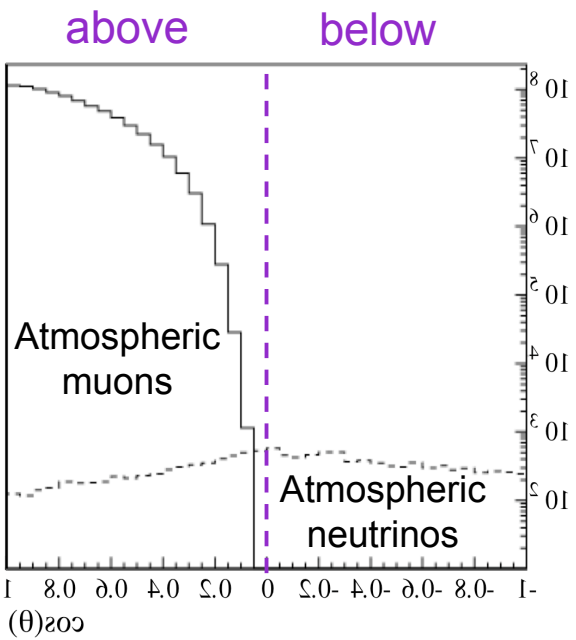
Atmospheric muons dominate down-going trigger rate

Atmospheric neutrinos (detected via induced muon) can arrive from any direction

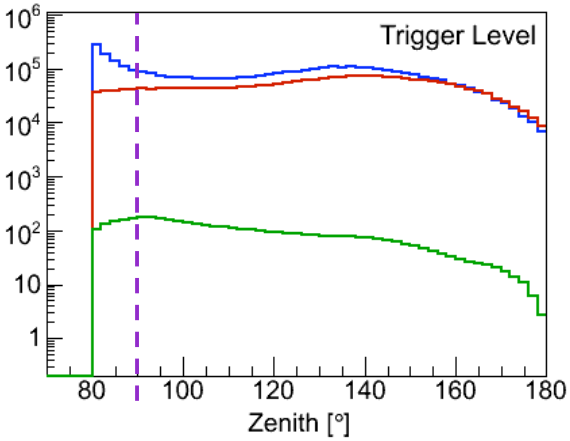
Earth filters out everything but neutrinos in up-going direction

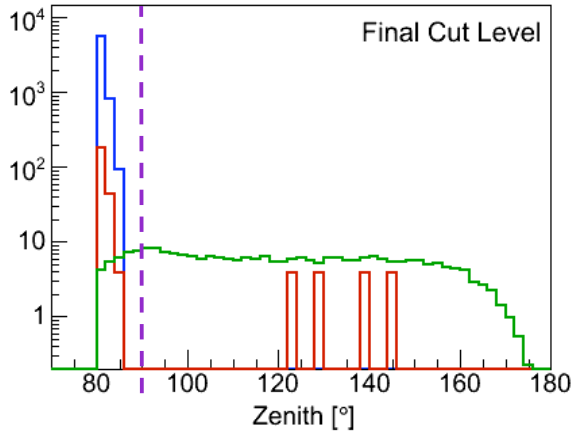
Background

True Zenith Angle

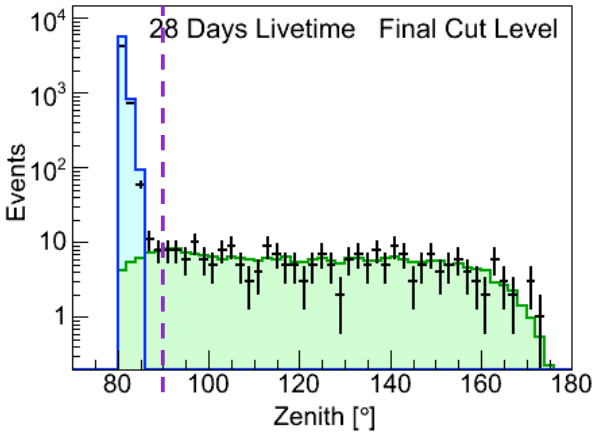


Reconstructed Zenith Angle





- Downgoing muons
- Coincident muons
- Atmospheric nu's
- Data (22-string IceCube)



High quality cuts (quality of track fit, angular error, comparison to forced-down-going best-fit track) remove most mis-reconstructed events. In up-going direction, only atmospheric neutrinos remain.

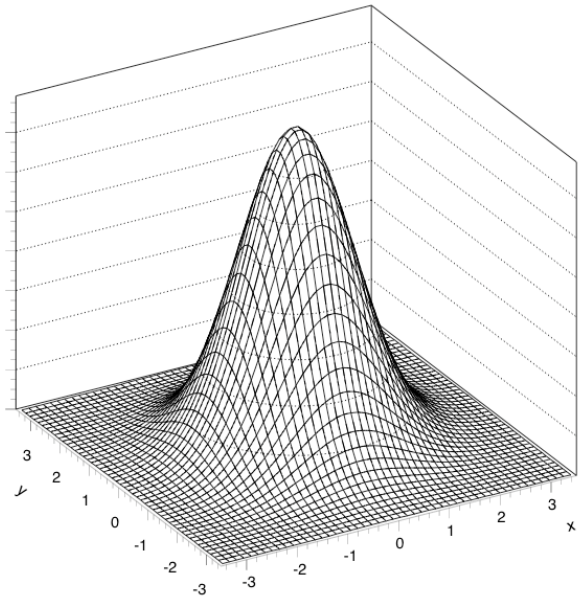
Atmos. neutrinos are "irreducible" background to astrophysical neutrino searches. But they are good calibration**: verify event reconstruction and neutrino detection**.

Maximum Likelihood Analysis Point Source Search

Basic Ingredient is a PDF for each event which is weighted sum of a signal PDF and background PDF for the event :

$$\mathcal{L}(n_s) = \prod_{i=1}^{N} \left(\frac{n_s}{N} \mathcal{S}_i + \left(1 - \frac{n_s}{N}\right) \mathcal{B}_i \right)$$

PDFs can be constructed from as many parameters as useful to separate signal and background, e.g. the point spread function for each event describes probability to come from nearby source coordinate:



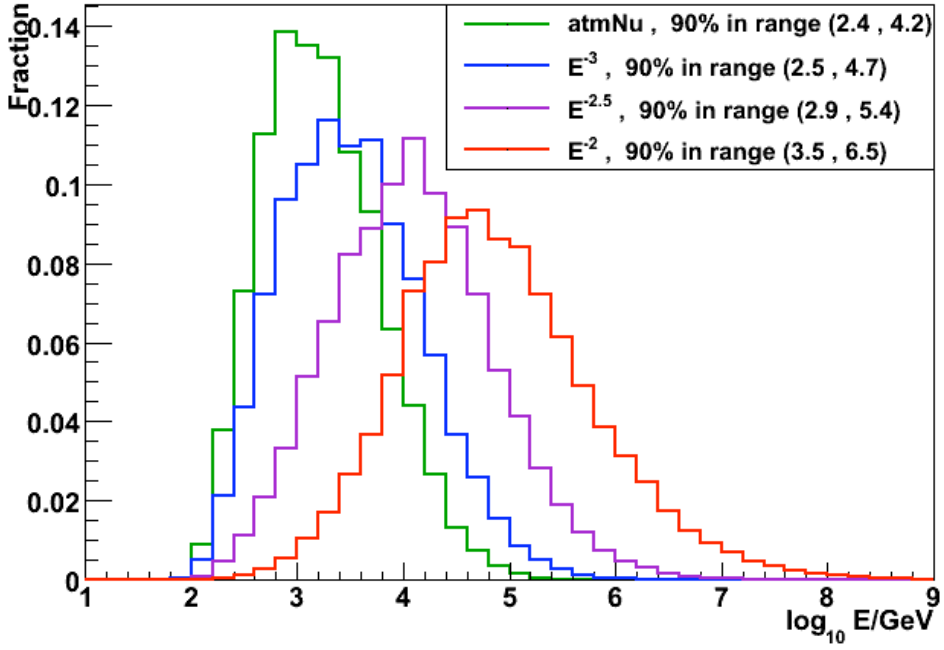
$$\mathcal{S}_i = \frac{1}{2\pi {\sigma_i}^2} e^{-{r_i}^2/2{\sigma_i}^2}$$

and the background PDF depends only on zenith angle distribution of data:

$$\mathcal{B}_i = B_{\text{zen}} \,.$$

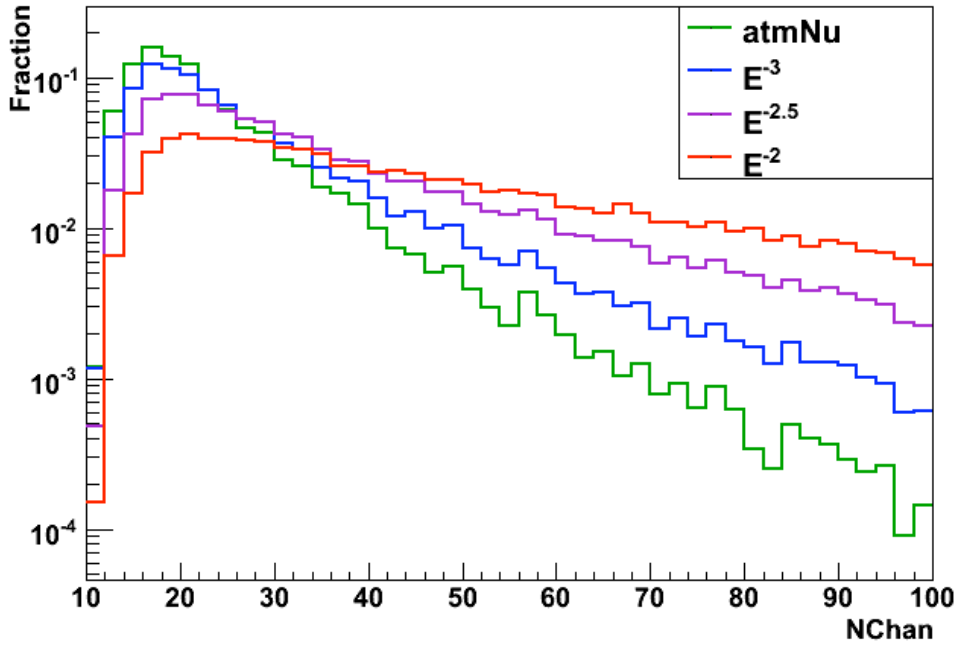
Energy as Signal / Background Separator

Primary neutrino energy distribution for atmospheric neutrinos and different source spectra



Number of hit optical modules ("NChannel") is basic estimator of induced-muon energy

- **lower-bound estimator of primary energy,** since high energy neutrino interaction may occur ~ kms before induced muon reaches detector



Maximum Likelihood Analysis Point Source Search

- Now, want to add energy term to the Likelihood function, to weight higher energy events with greater significance:

$$\mathcal{L}(n_s) = \prod_{i=1}^{N} \left(\frac{n_s}{N} \mathcal{S}_i + \left(1 - \frac{n_s}{N}\right) \mathcal{B}_i \right)$$

$$\mathcal{S}_i = \frac{1}{2\pi {\sigma_i}^2} e^{-{r_i}^2/2{\sigma_i}^2}$$

$$\mathcal{B}_i = B_{\text{zen}}$$

Maximum Likelihood Analysis Point Source Search

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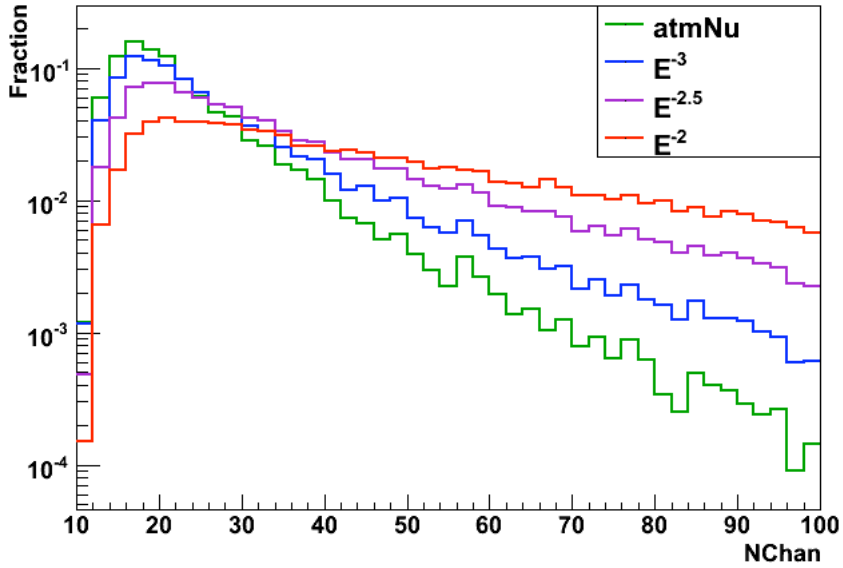
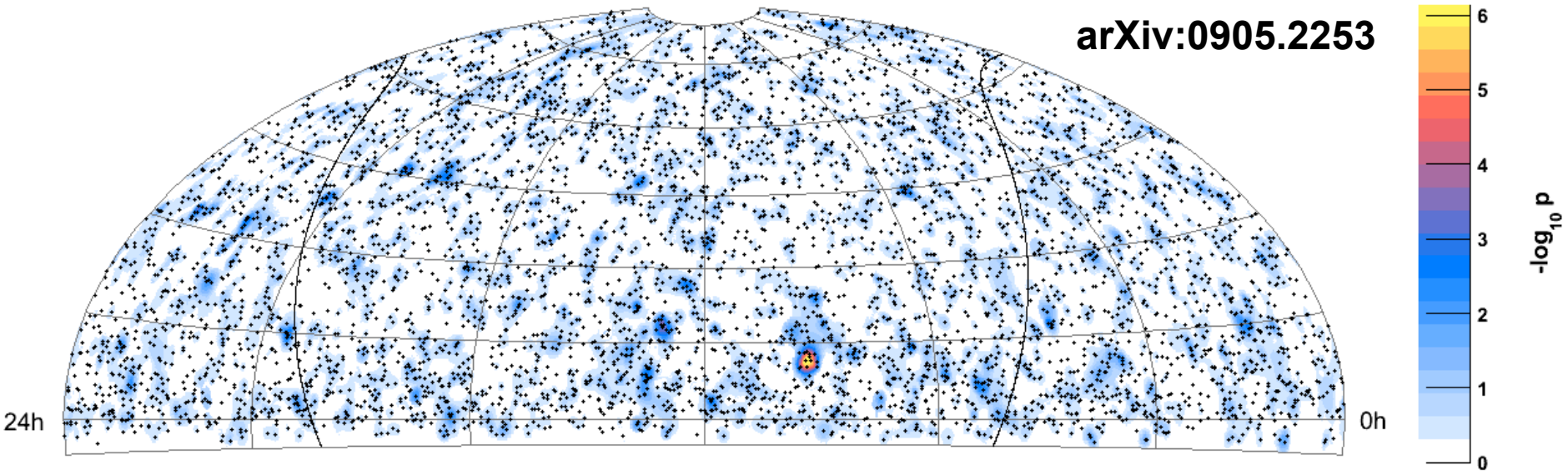
$$\mathcal{S}_i = \frac{1}{2\pi {\sigma_i}^2} e^{-{r_i}^2/2{\sigma_i}^2} \cdot P(E_i|\gamma)$$

$$\mathcal{B}_i = B_{\text{zen}} \cdot P_{\text{atm}}(E_i)$$



Results: IceCube-22 All Sky Search



Hottest spot found at r.a. 153º , dec. 11º

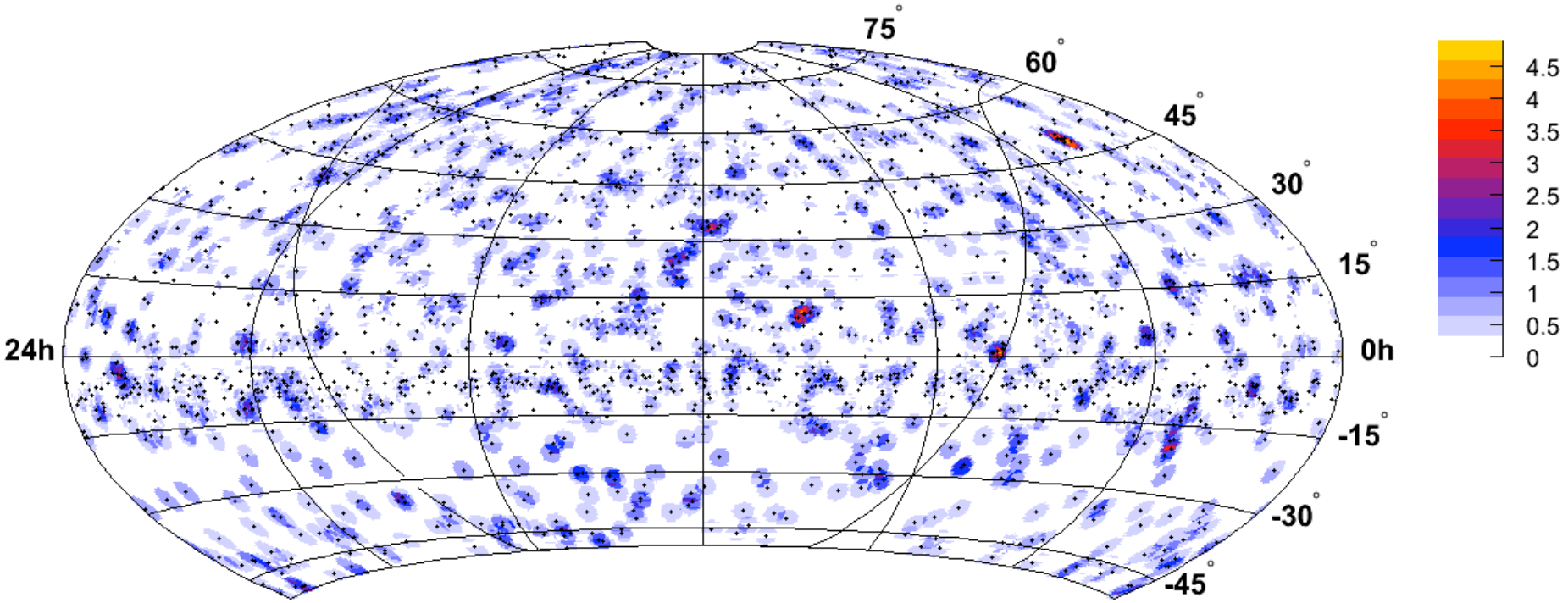
est. nSrcEvents = 7.7 est. gamma index = 1.65

max. llhRatio = 13.4
est. pre-trial p-value: $-\log_{10}(p)$: 6.14 (4.8 sigma)

Post-trials p-value of analysis is ~ 1.34% (2.2 sigma).
Not significant.

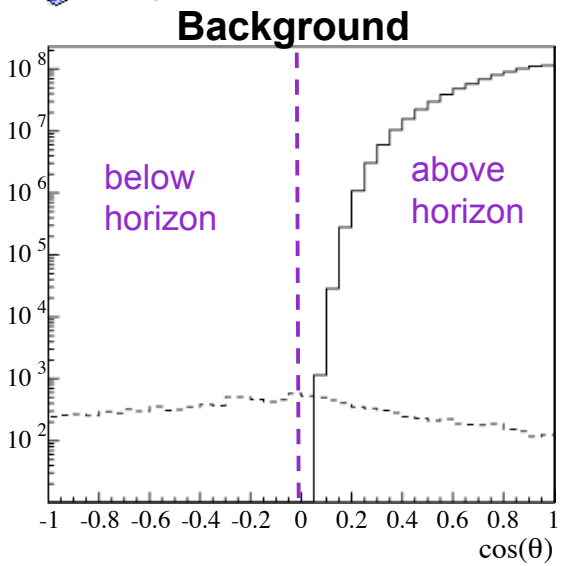
Part II: New Techniques and New Designs

UHE Analysis: Extension to Southern Sky in IC-22

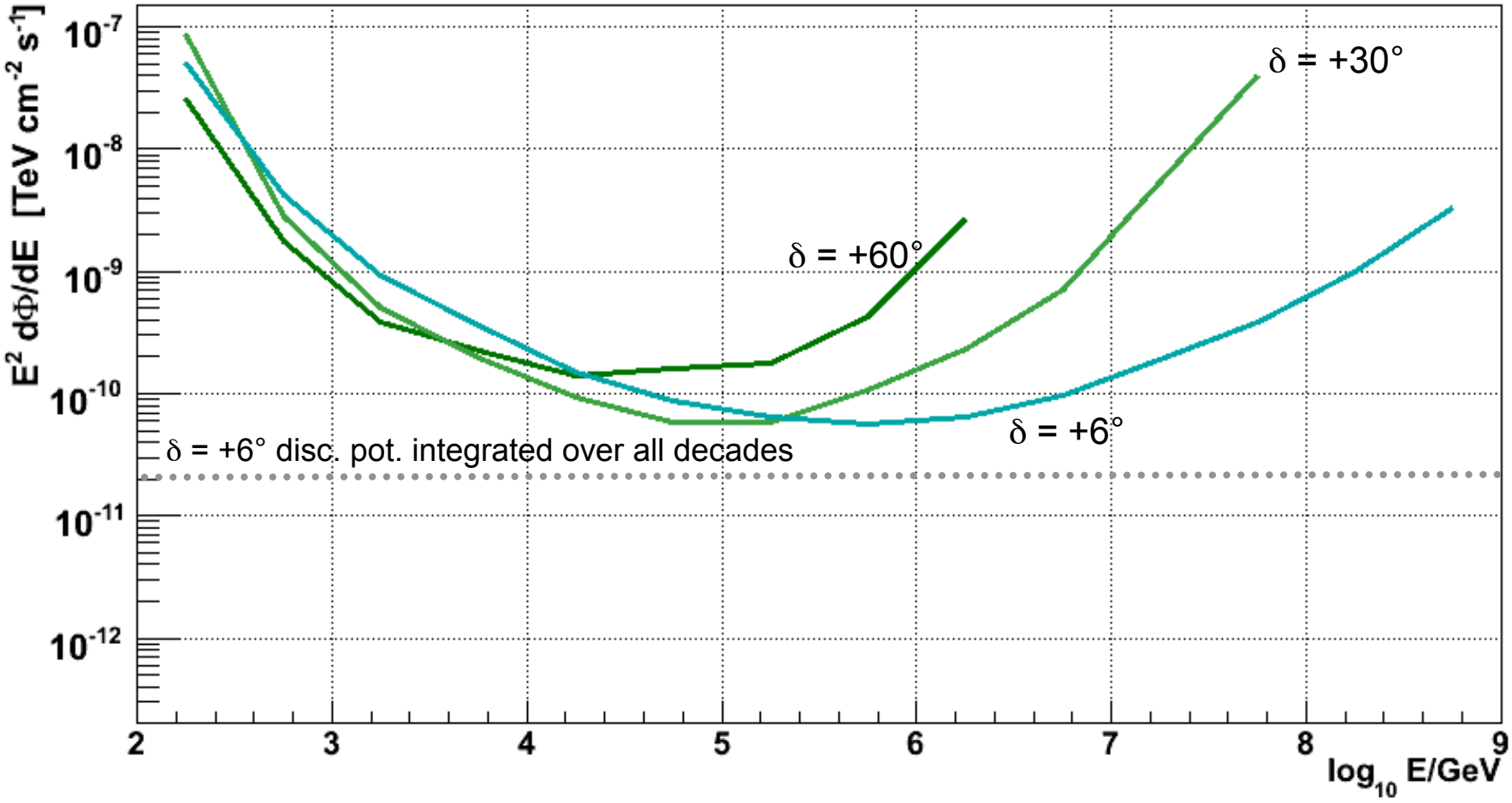


Recall: extreme background of cosmic ray muons when looking "up". But for energies above PeV, muon background also becomes manageable.

Sensitivity to hard $E^{-1.5}$ spectrum is comparable above and below horizon.

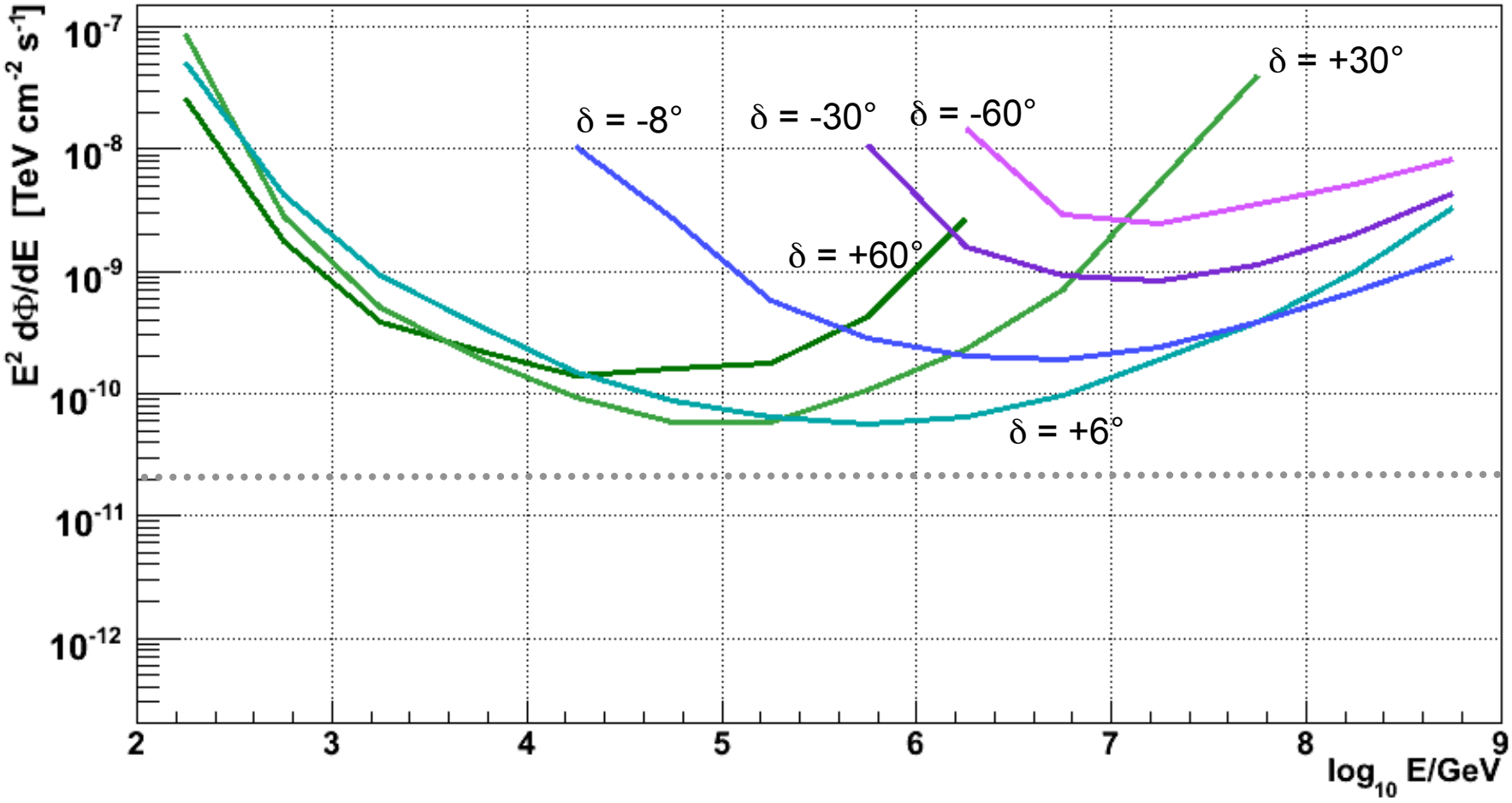


Discovery Potential for E^{-2} signal injected in 1/2 decades of energy



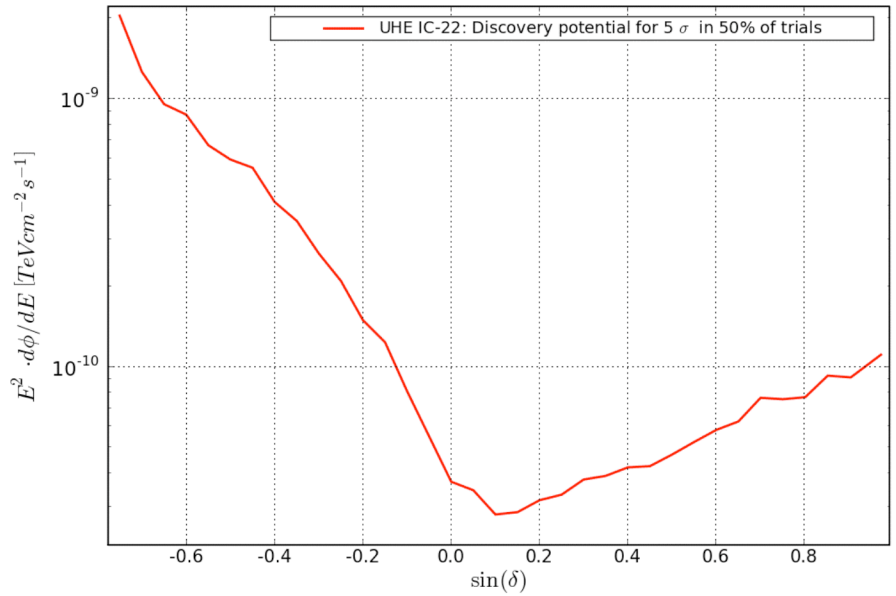
- preliminary IC40 Differential 5σ Discovery Potentials
  - Northern Sky

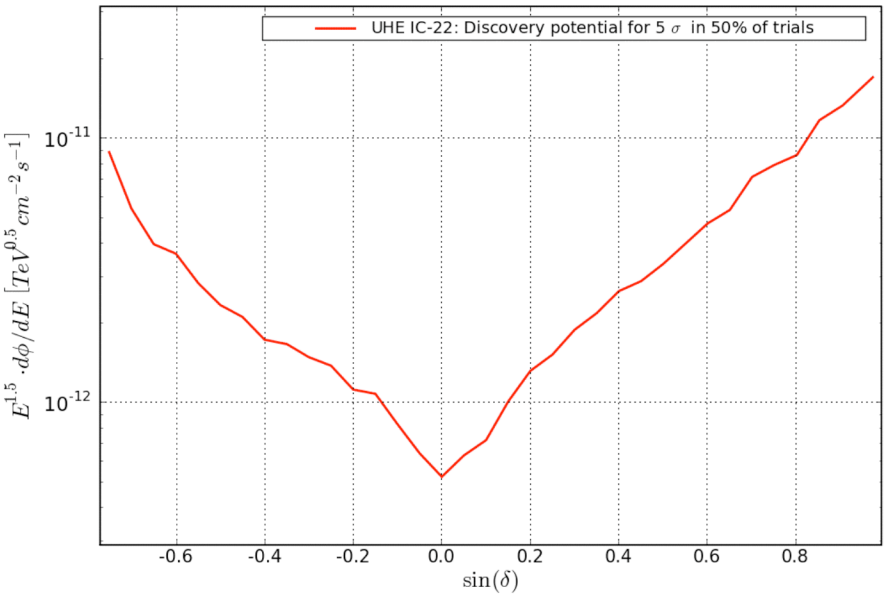
Discovery Potential for E^{-2} signal injected in 1/2 decades of energy



- preliminary IC40 Differential 5σ Discovery Potentials
  - Northern and Southern Sky

IC-22 Discovery Potential vs sin(declination)





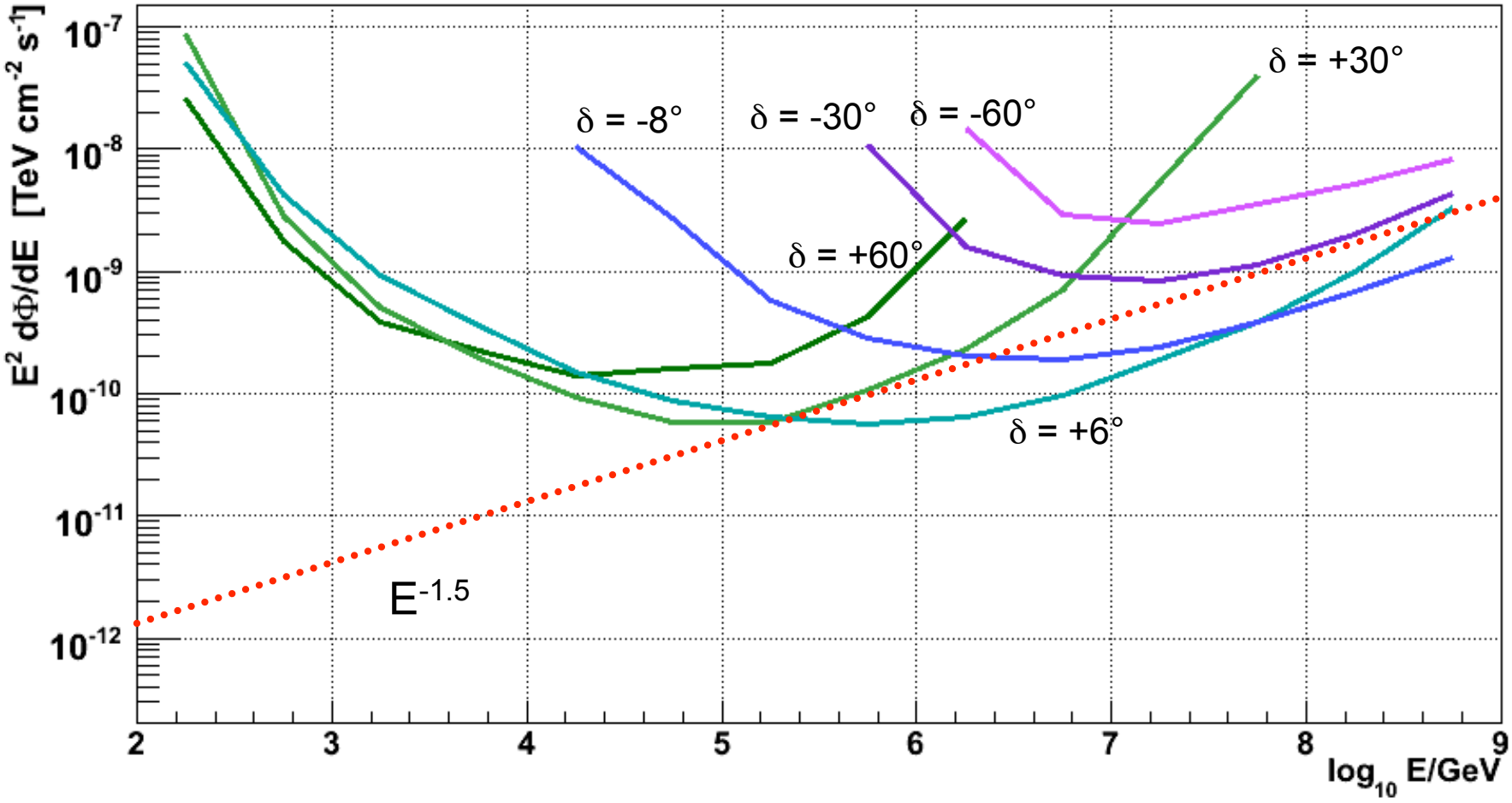
E^{-2}

Above Horizon Below Horizon

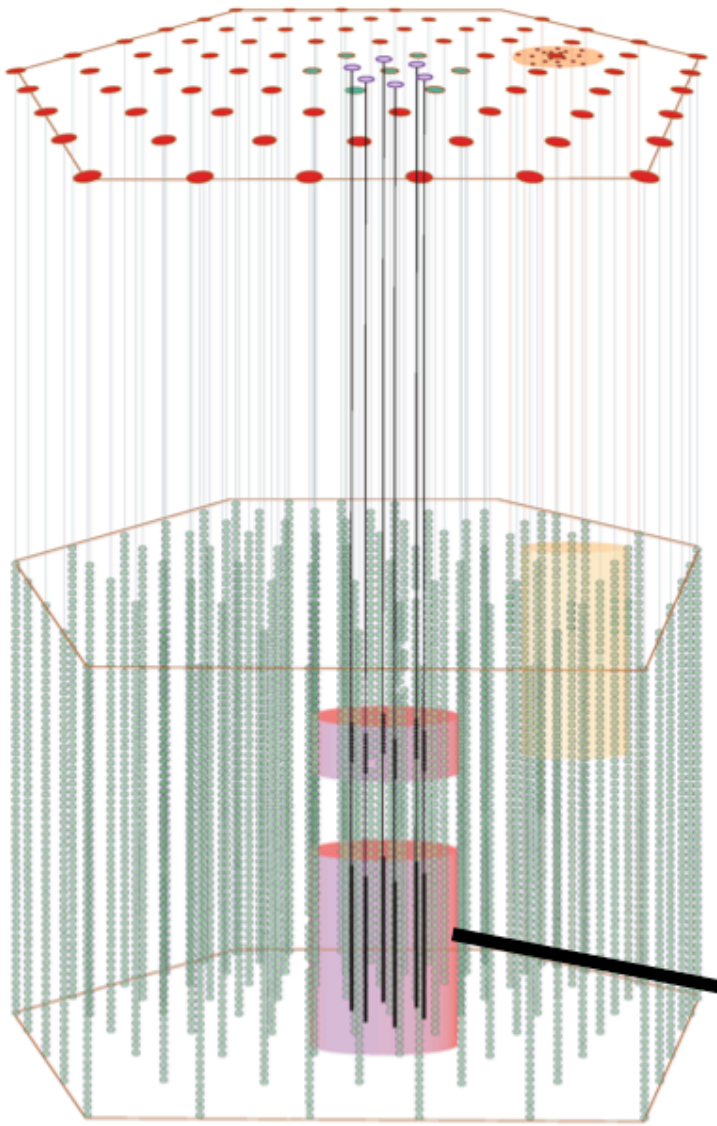
$E^{-1.5}$

Above Horizon Below Horizon

Discovery Potential for E^{-2} signal injected in 1/2 decades of energy



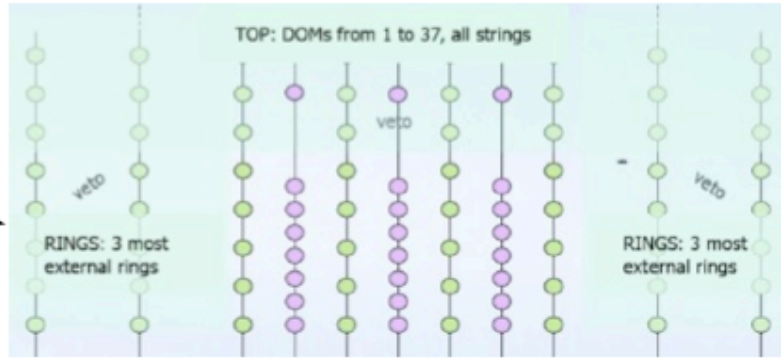
Low Energy Extension: DeepCore



- Aim: lower energy threshold through a denser core in the center of the IceCube array

- 6 additional strings of 60 high quantum efficiency PMTs

- denser instrumentation, 7 m DOM vertical spacing (17m in IceCube), 72 m inter string spacing (125m in IceCube)

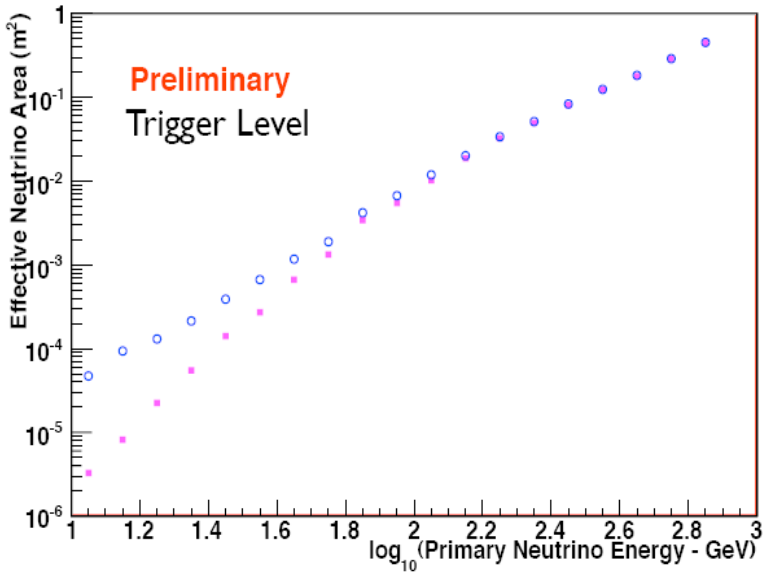


Low Energy Extension: DeepCore

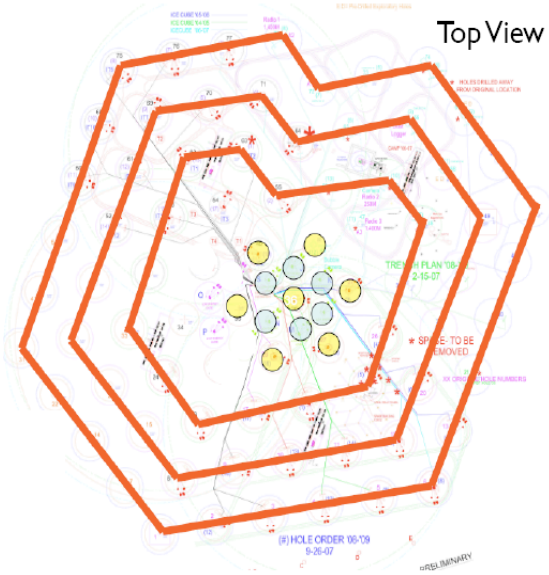
- full sky sensitivity using IceCube surrounding strings as a veto

→ access to southern hemisphere, galactic center and all-year Sun visibility

- preliminary studies show 10^4 background rejection with 98% signal efficiency possible

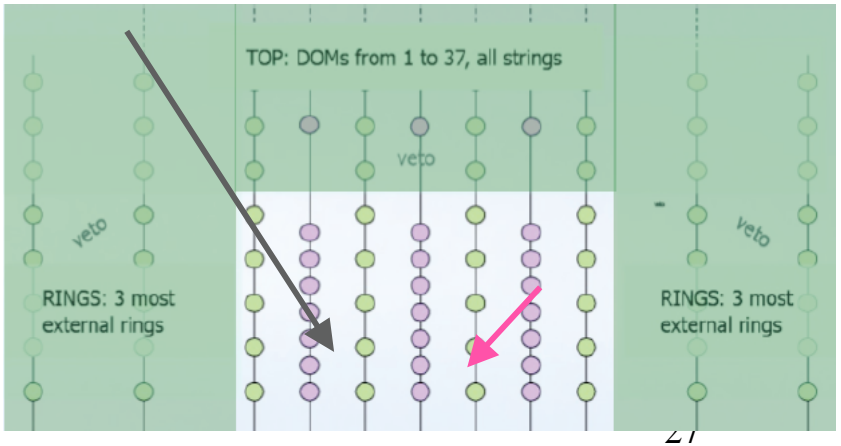


- 375 m thick detector veto - three complete IceCube DOM layers surround DeepCore.

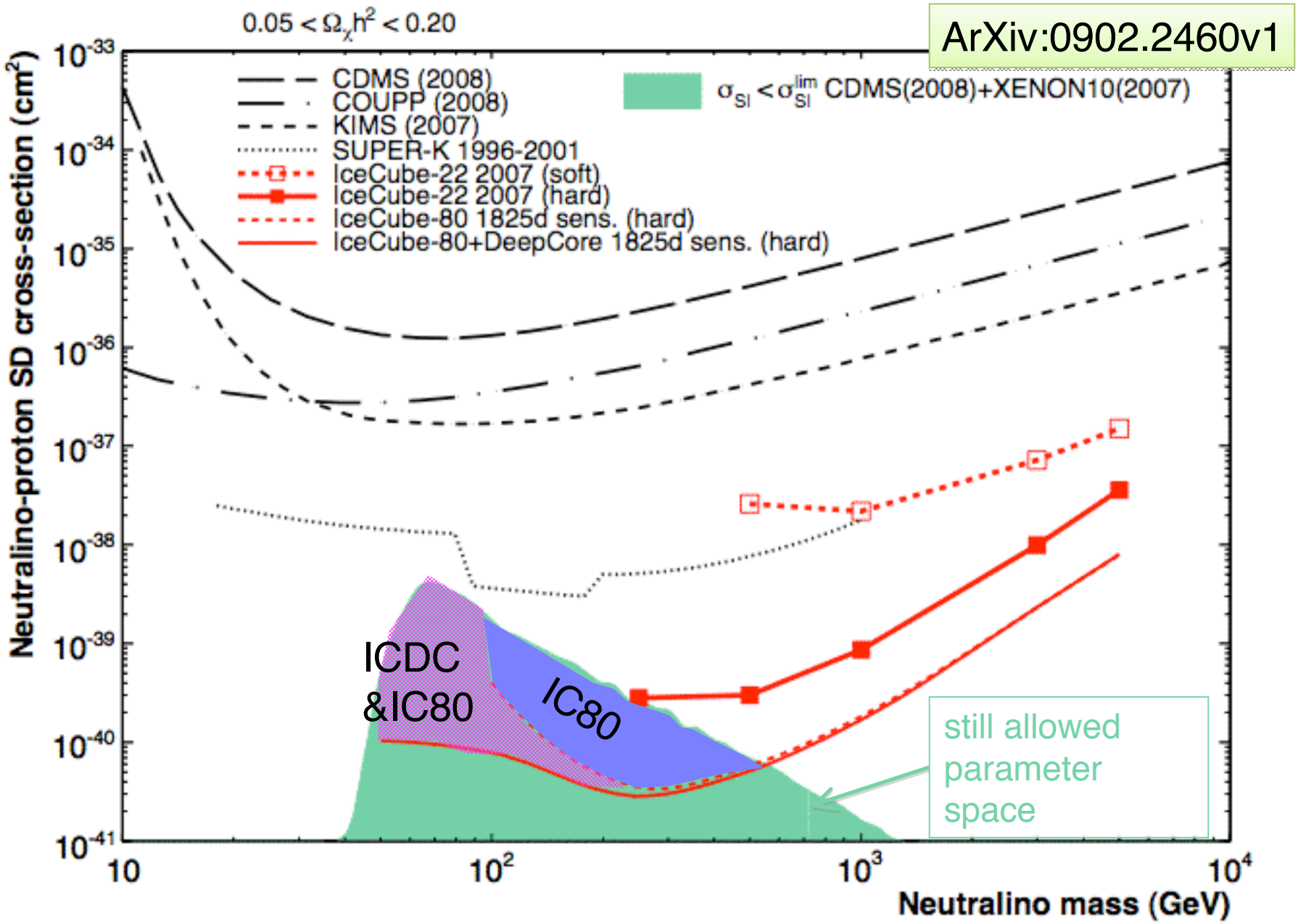


Deep Core

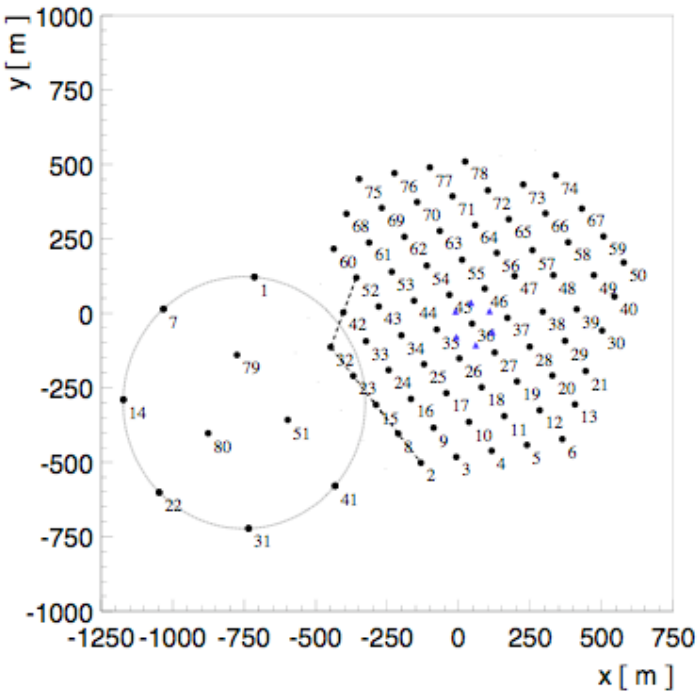
IceCube



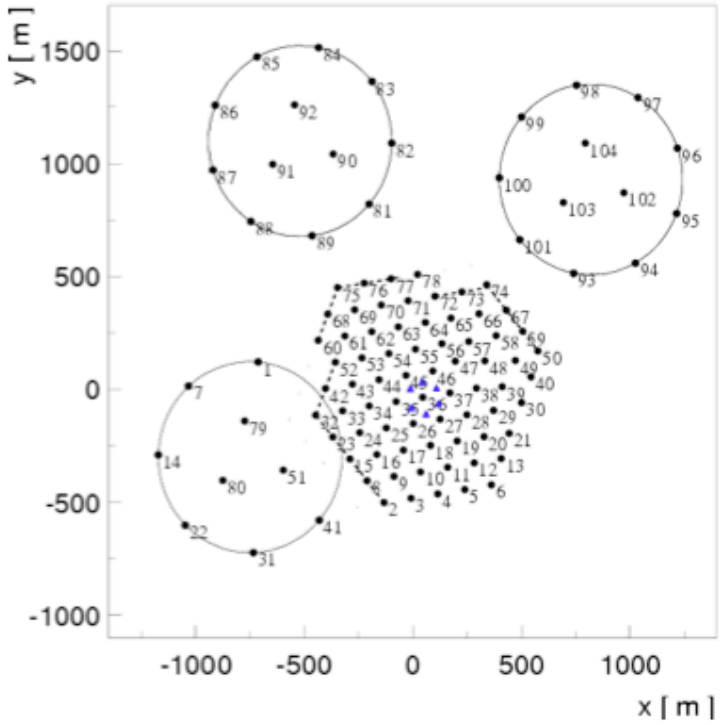
IceCube + DeepCore 5-Year Sensitivity



Proposed High Energy Extensions of IceCube



Reach baseline performance at 10 TeV, up to 30% increase in performance at 3 PeV.



Scenario for 110 strings: 2 additional rings of 12 strings, 48 DOMs/string

Summary

Event reconstruction and background rejection tools (many developed in AMANDA) working well

Signal / Background amplification via analysis (energy-weighted maximum likelihood) rather than via cuts, enhances sensitivity to hard spectra while retaining sensitive to soft spectra

Extension of steady point source searches to UHE energies above the horizon demonstrated in IC-22, will be extended to whole sky (-85 to +85 declination) in IC-40

Deep-Core (first string deployed) and use of outer IceCube layers as veto will extend reach to lower energies ~100 GeV, both above and below horizon

Possible re-configuring of final strings may begin a High Energy Extension, eventually doubling effective area above PeV.