Neutrino Observations of TeV Objects

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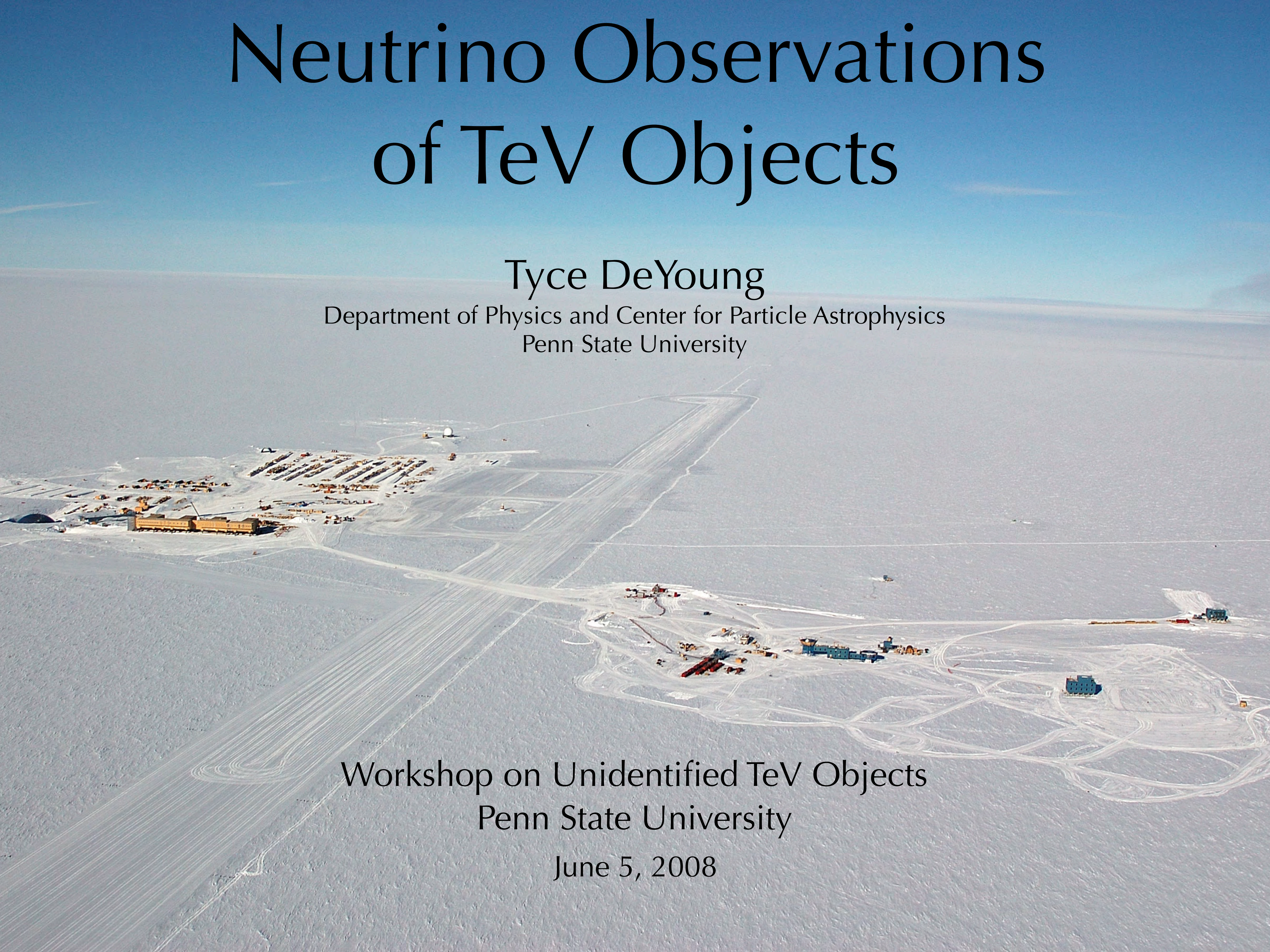


Workshop on Unidentified TeV Objects
Penn State University
June 5, 2008

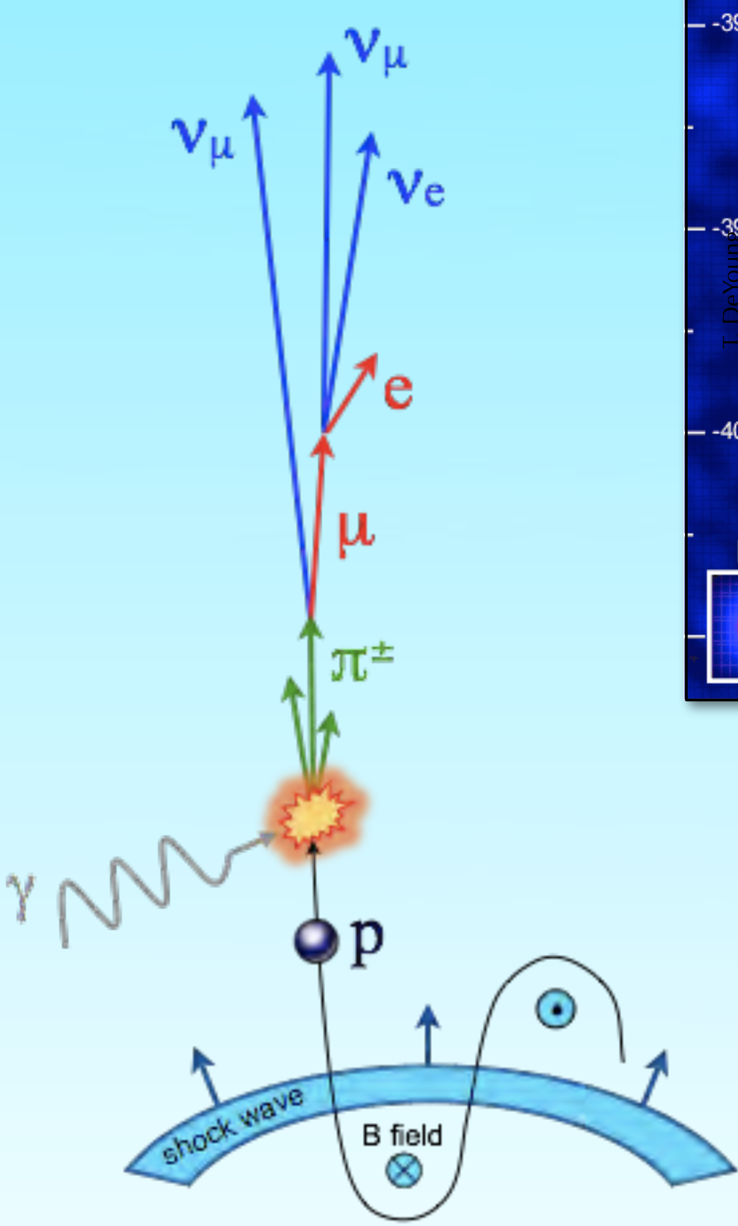
IceCube

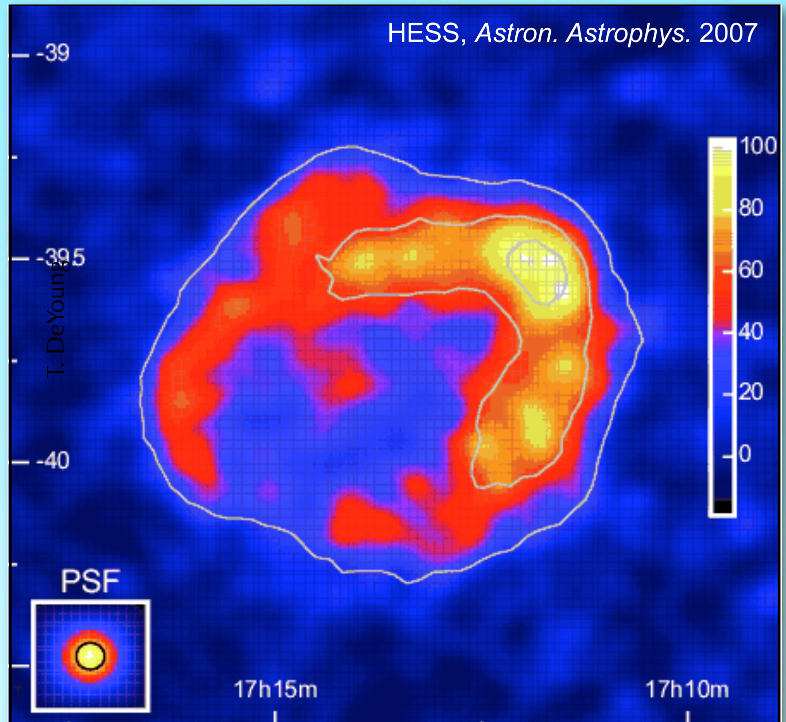
Outline

- Neutrino Astronomy
- Current State of the Art:
  AMANDA Point Source Search (2000–07)
- (Near) Future Work
  - Multimessenger Observations
  - Deep Core and Galactic Objects

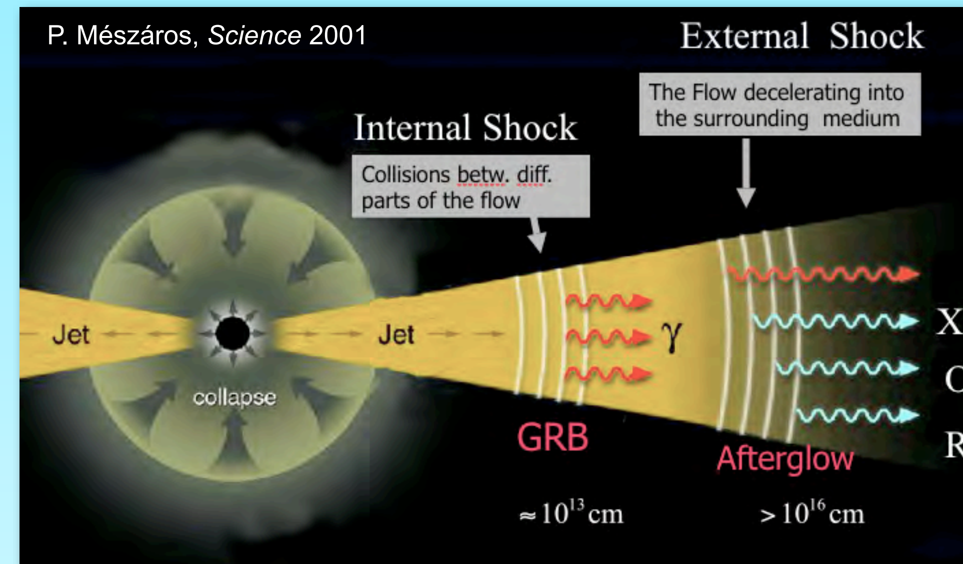
Neutrino Emission

IceCube

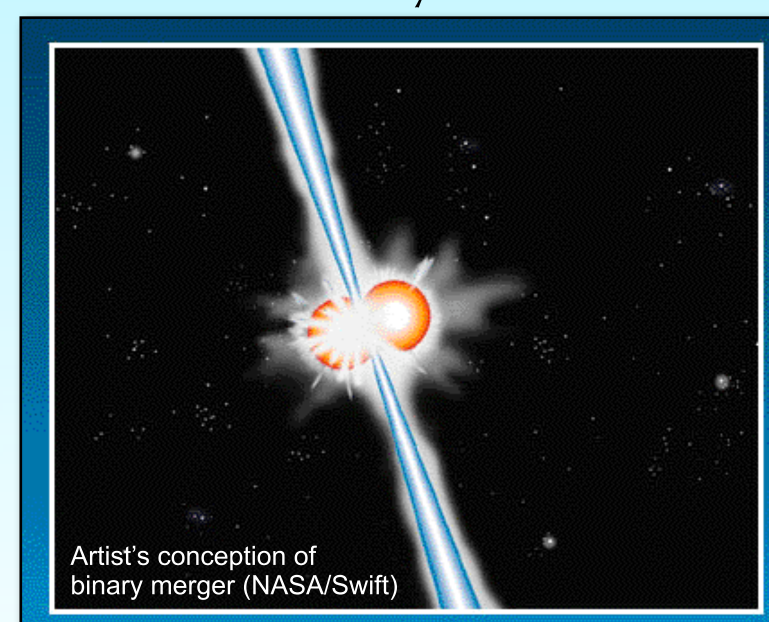


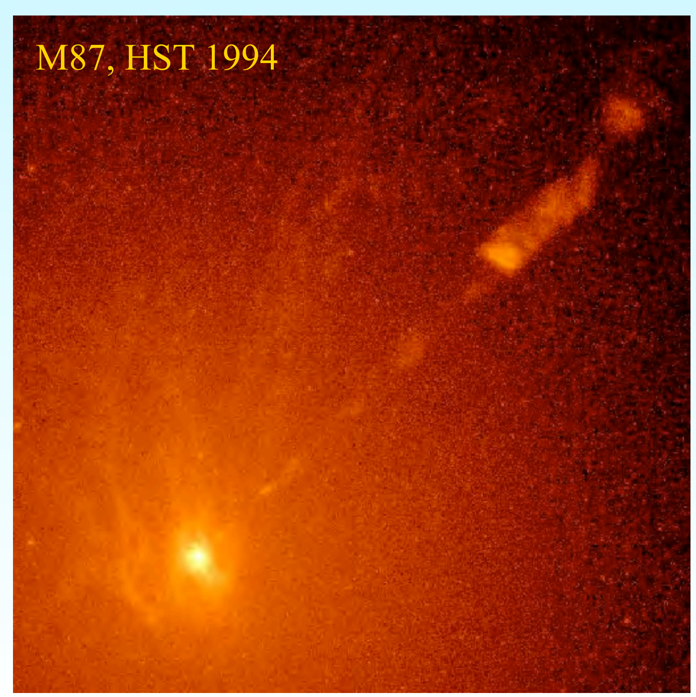


Supernova Remnants



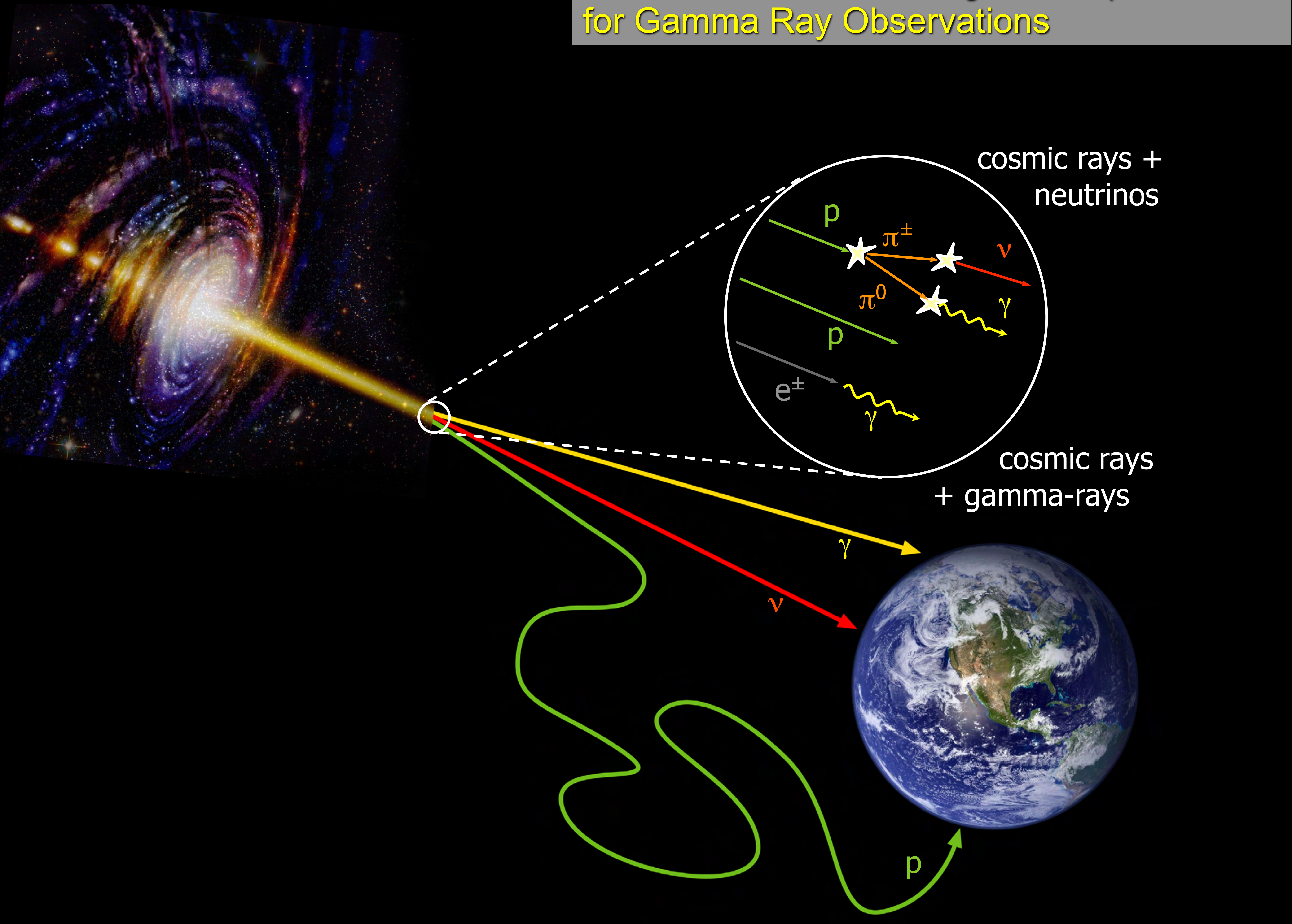
Gamma Ray Bursts





Active Galactic Nuclei

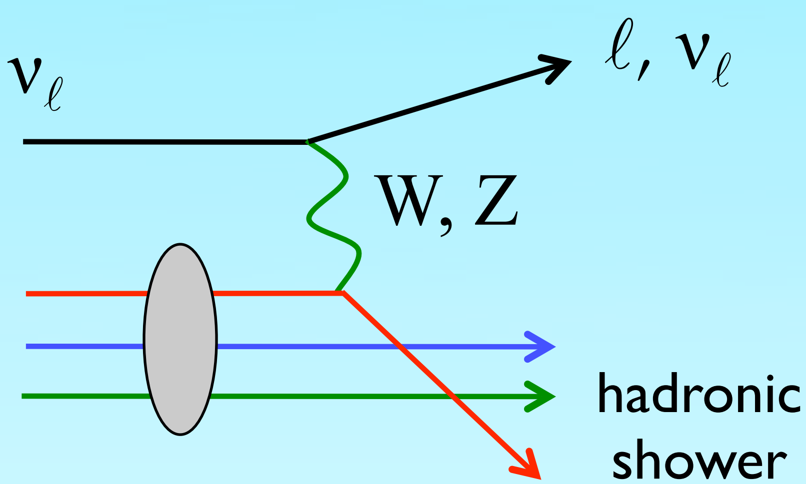
Hadronic and Electromagnetic Explanations for Gamma Ray Observations



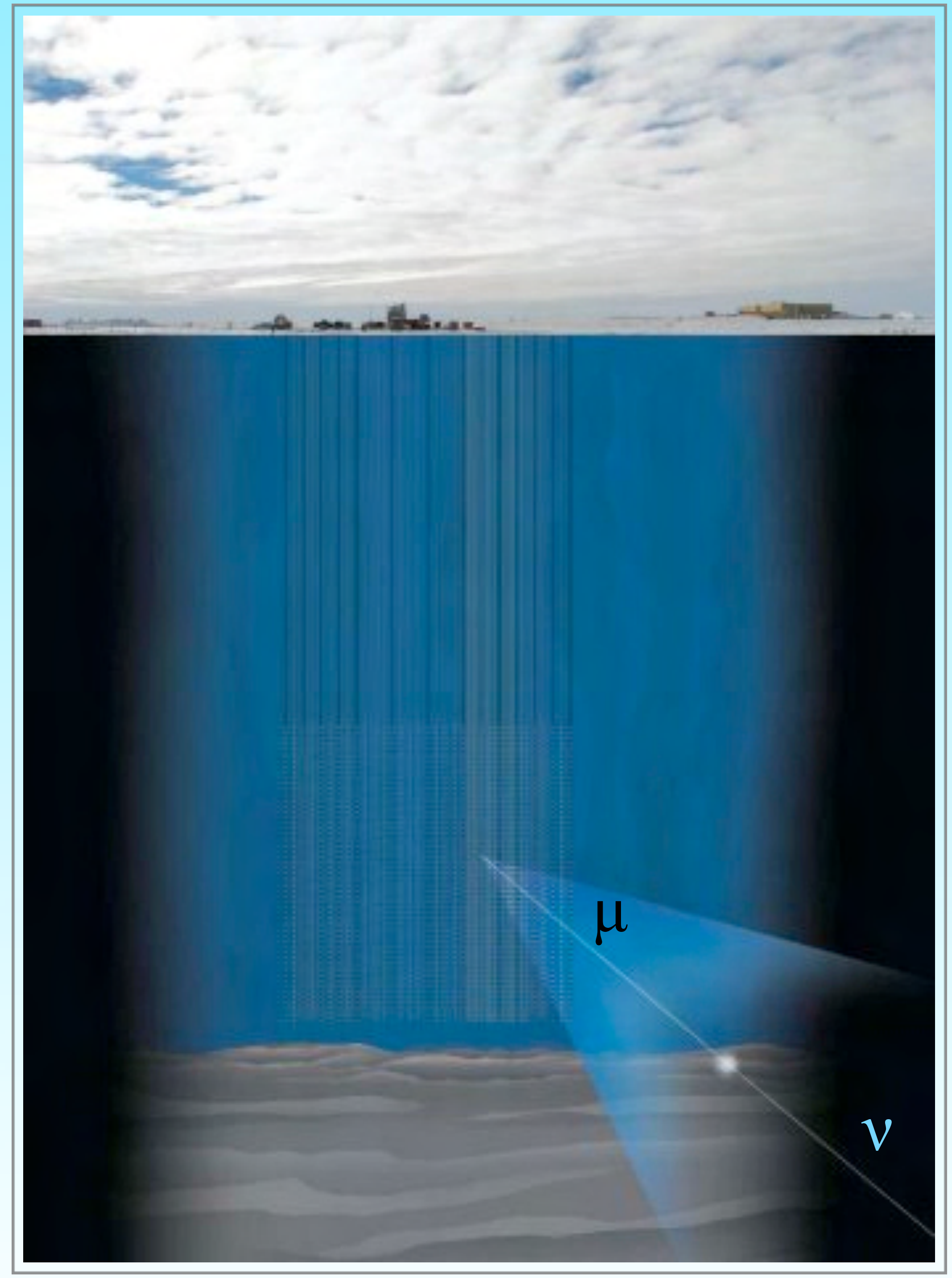
Neutrino Telescopes

IceCube

- Neutrinos interact in or near the detector



  - $\mathcal{O}$(km) muons from ν_μ (CC)
  - $\mathcal{O}$(10 m) particle cascades from ν_e, low energy ν_τ, and NC interactions
  - Cherenkov radiation detected by optical sensors



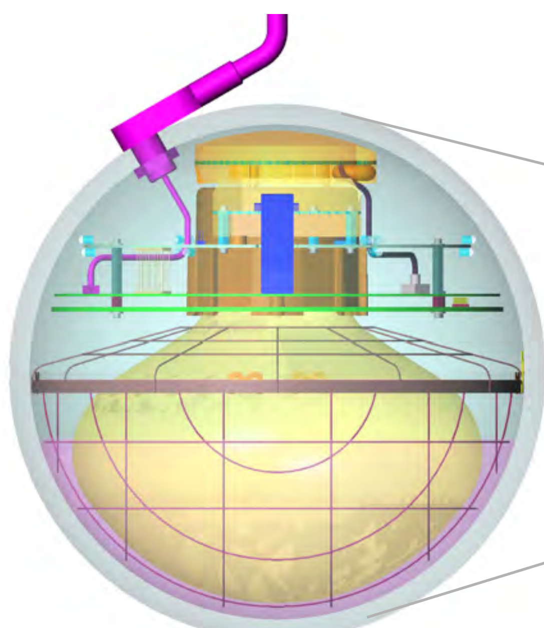
IceCube

4800 DOMs on 80 strings

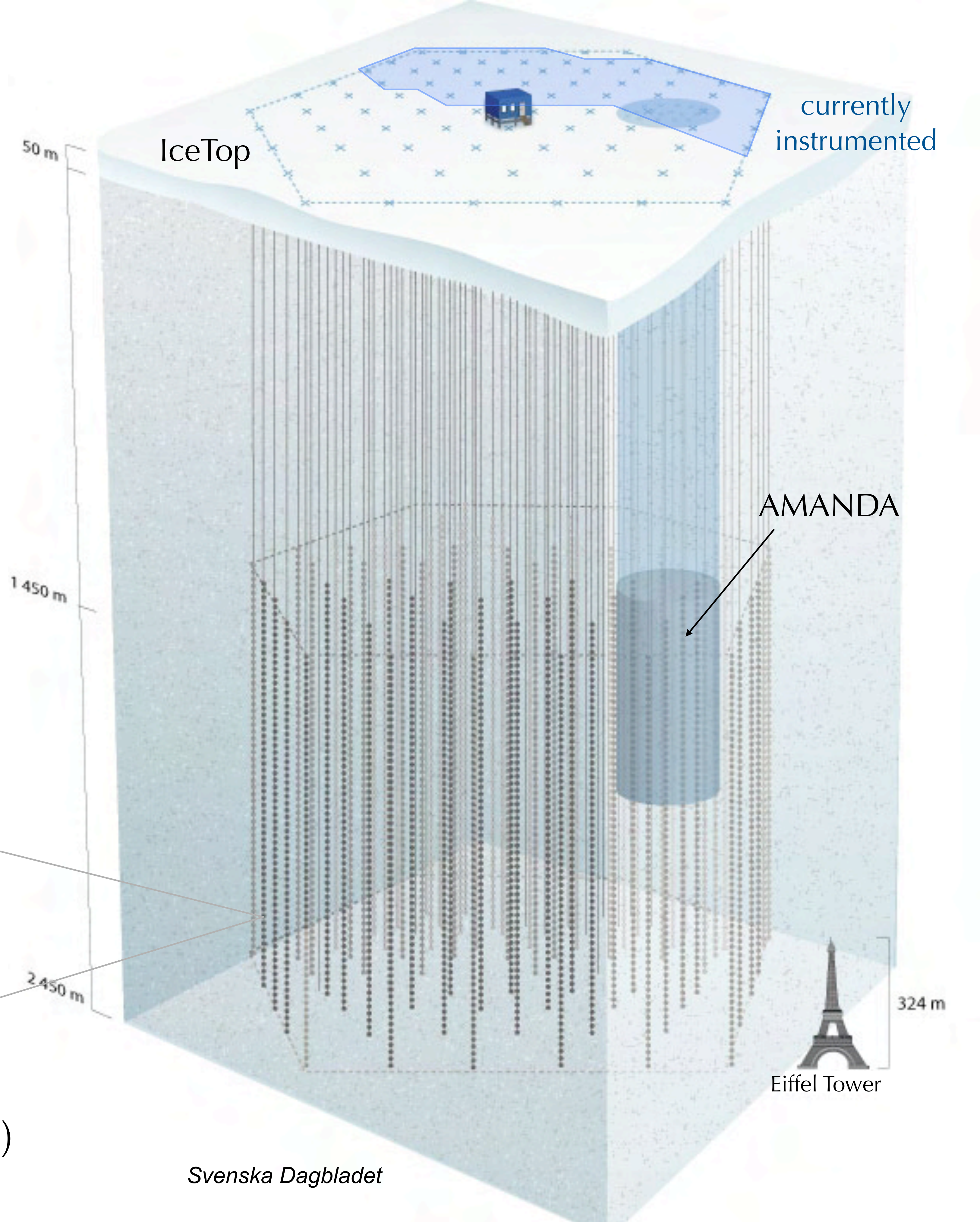
160 Ice-Cherenkov tank surface array (IceTop)

Surrounds existing AMANDA detector (677 OMs)

40 strings deployed in 4 construction seasons

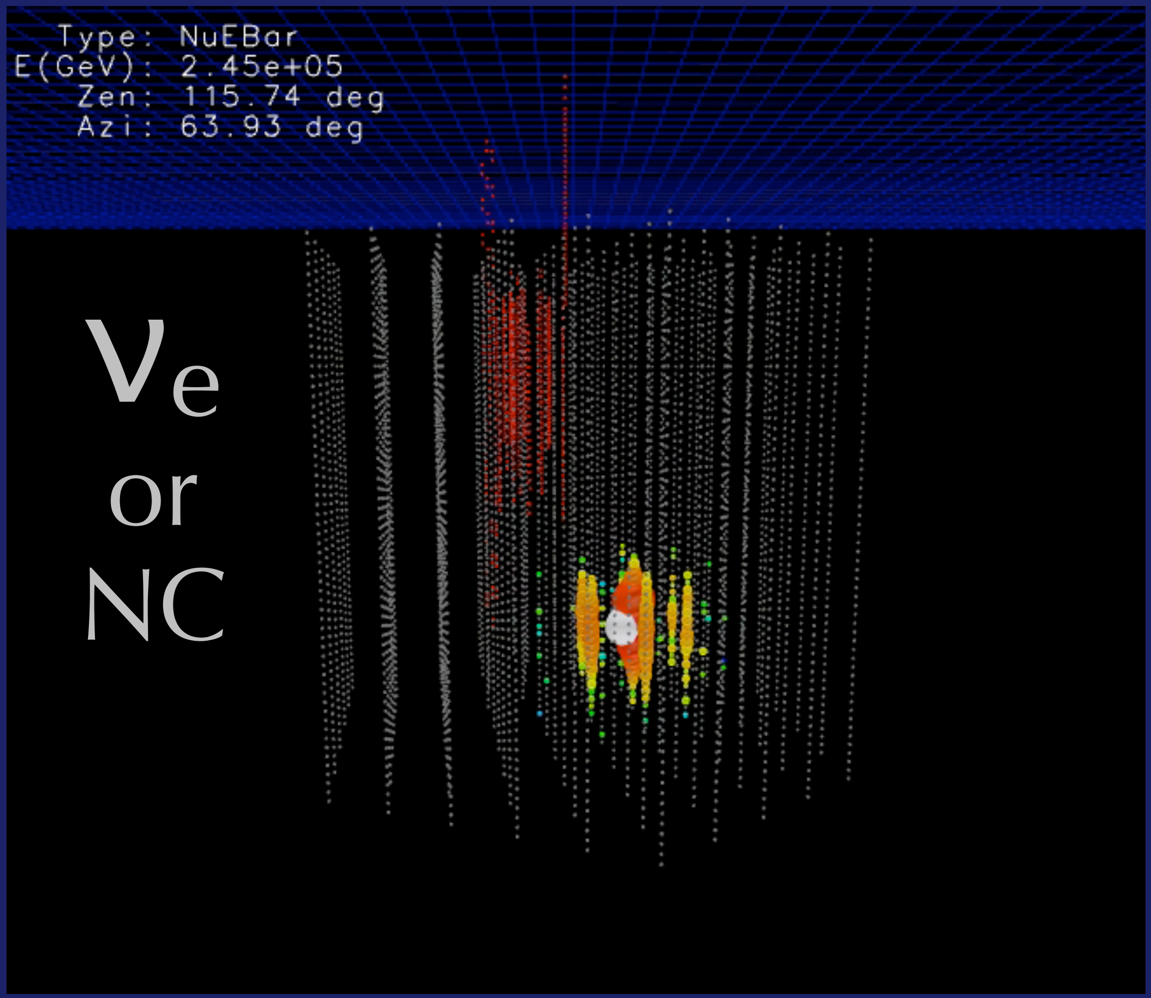


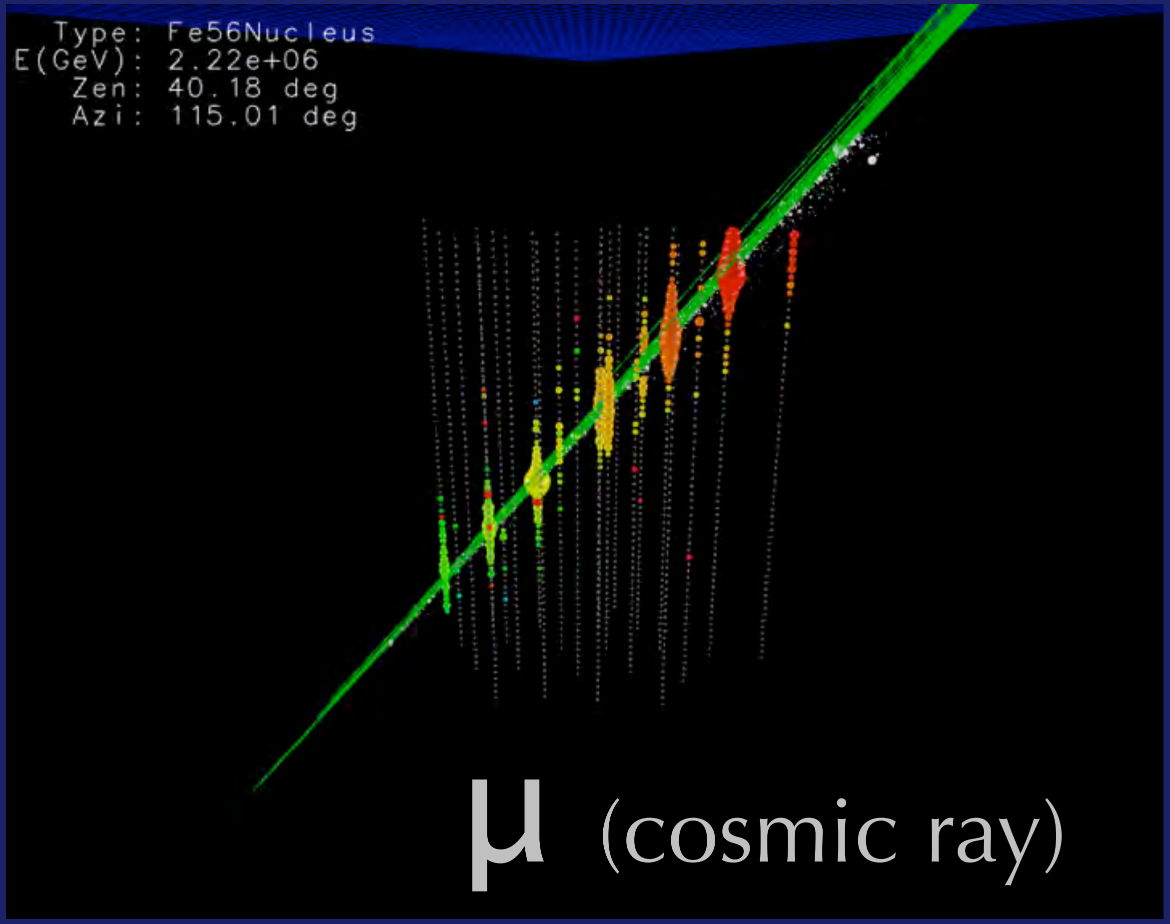
Digital Optical Module (DOM)

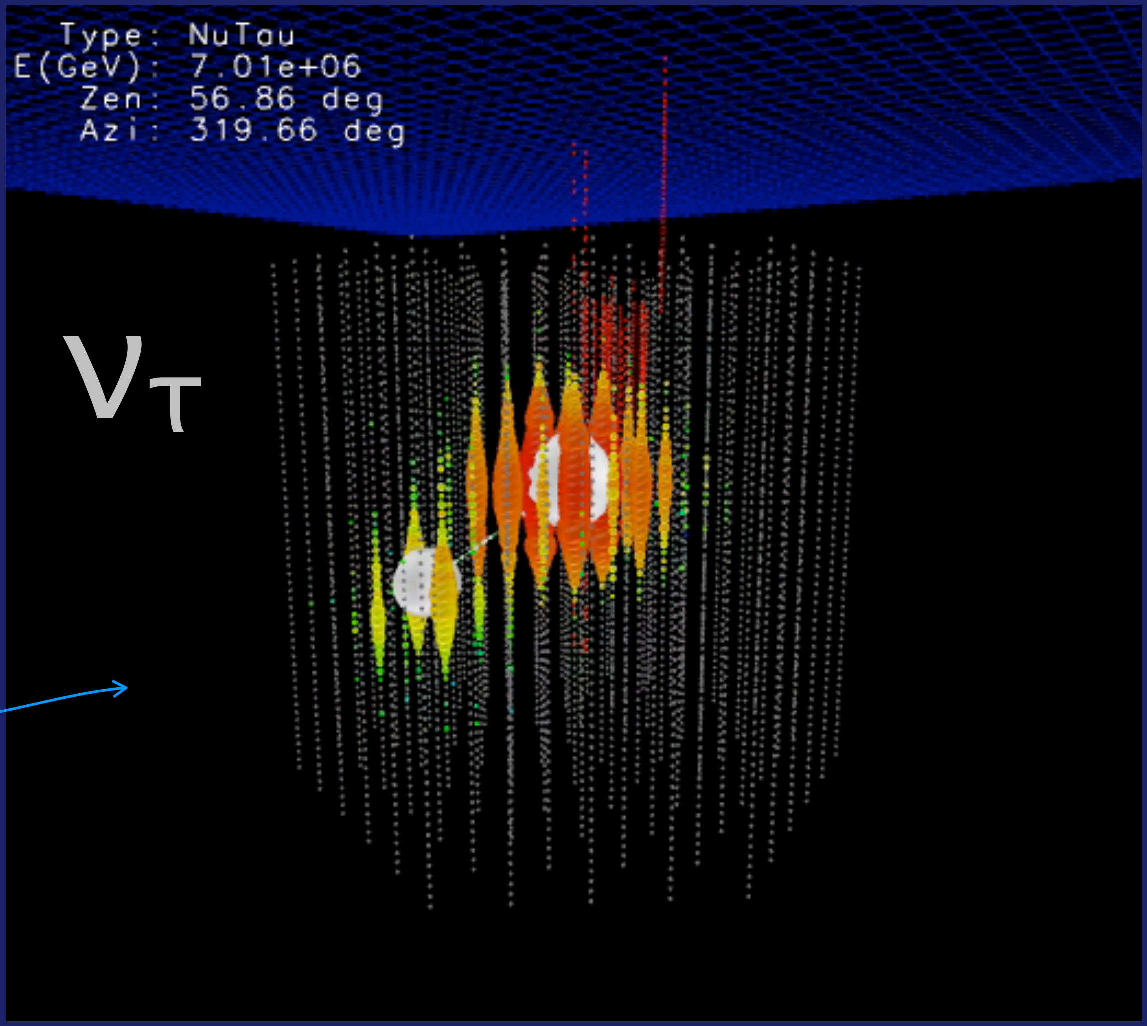


Svenska Dagbladet

Flavor Identification



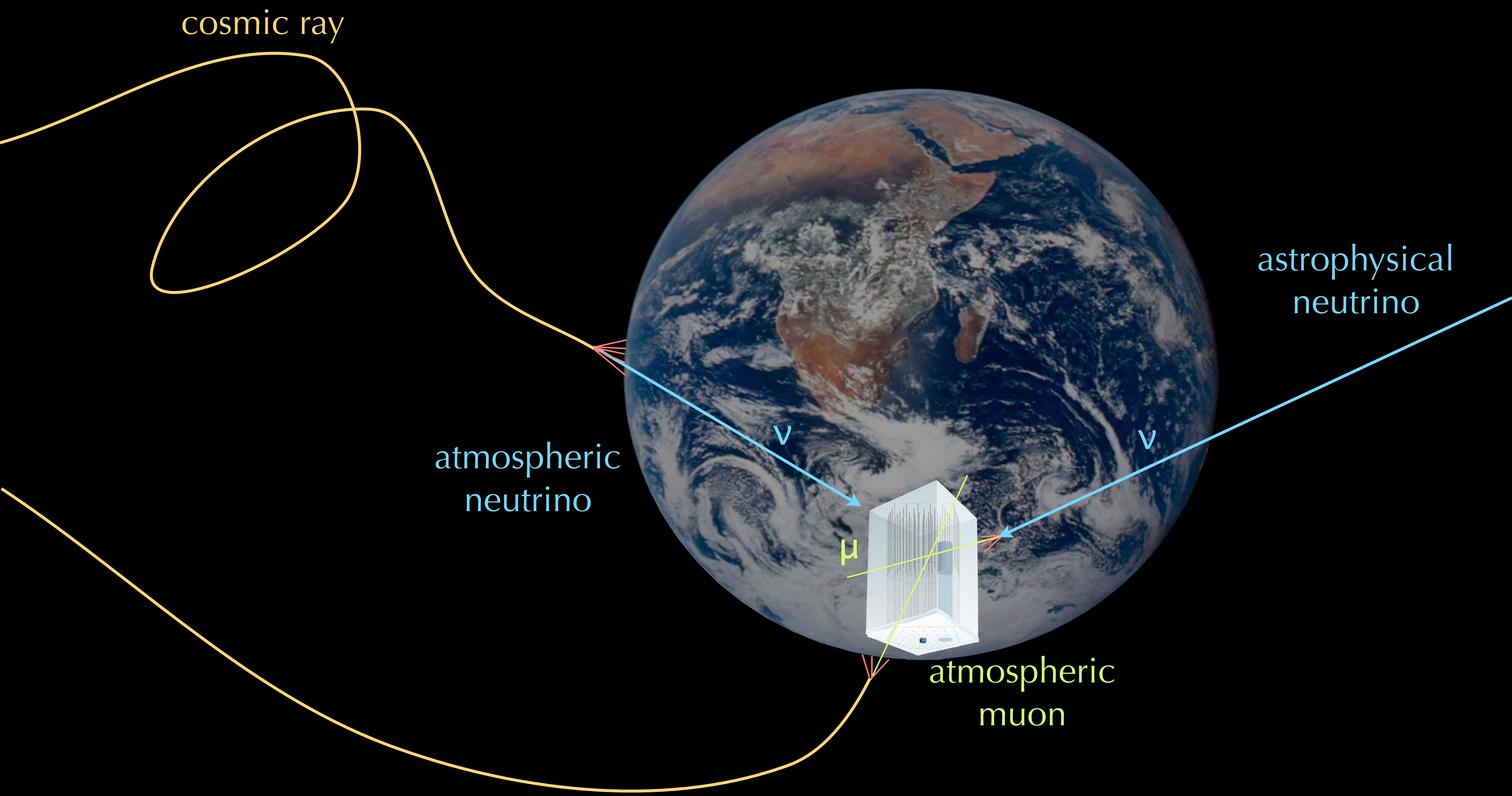




"Double Bang":

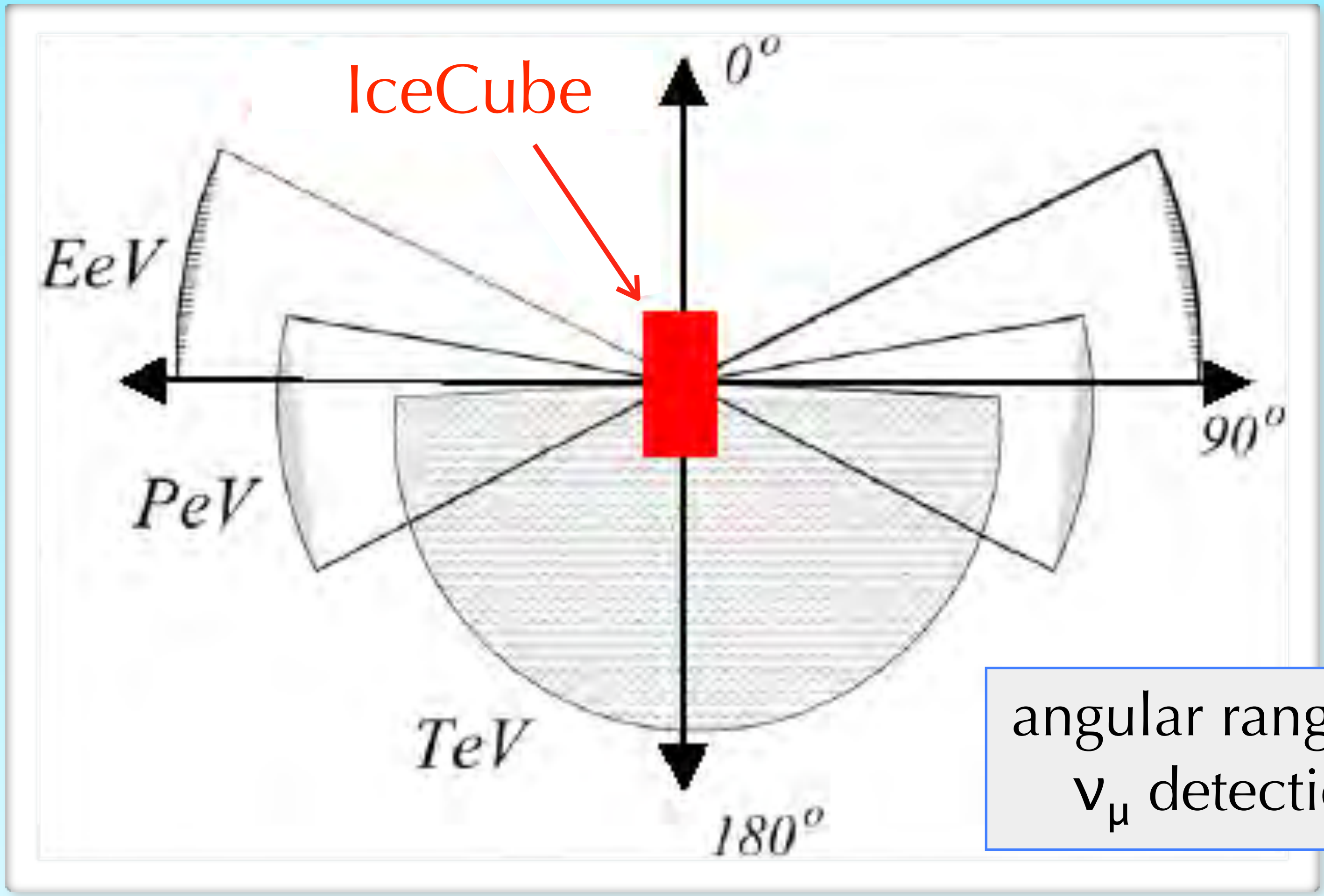
One of several tau signatures : lollipop, inverted lollipop, etc...

Signals and Backgrounds



Muon Field of View

- TeV: look down to avoid atmospheric muons
- PeV: Earth opaque, look horizontally
- EeV: Can look above horizon – atmospherics have softer spectrum



angular range for ν_μ detection

Cascades: 4π, except for absorption at high energies (with muons vetoed!)

IceCube

AMANDA-II Data Set

1996

1997

1998

1999

AMANDA-B operations
results from 4 string, 10 string
and 13 string phases

AMANDA-II complete

2000

2001

2002

2003

2004

2005

2006

Phys.Rev.Lett.92:071102 **2004**

Phys.Rev.D71:077102 **2005**

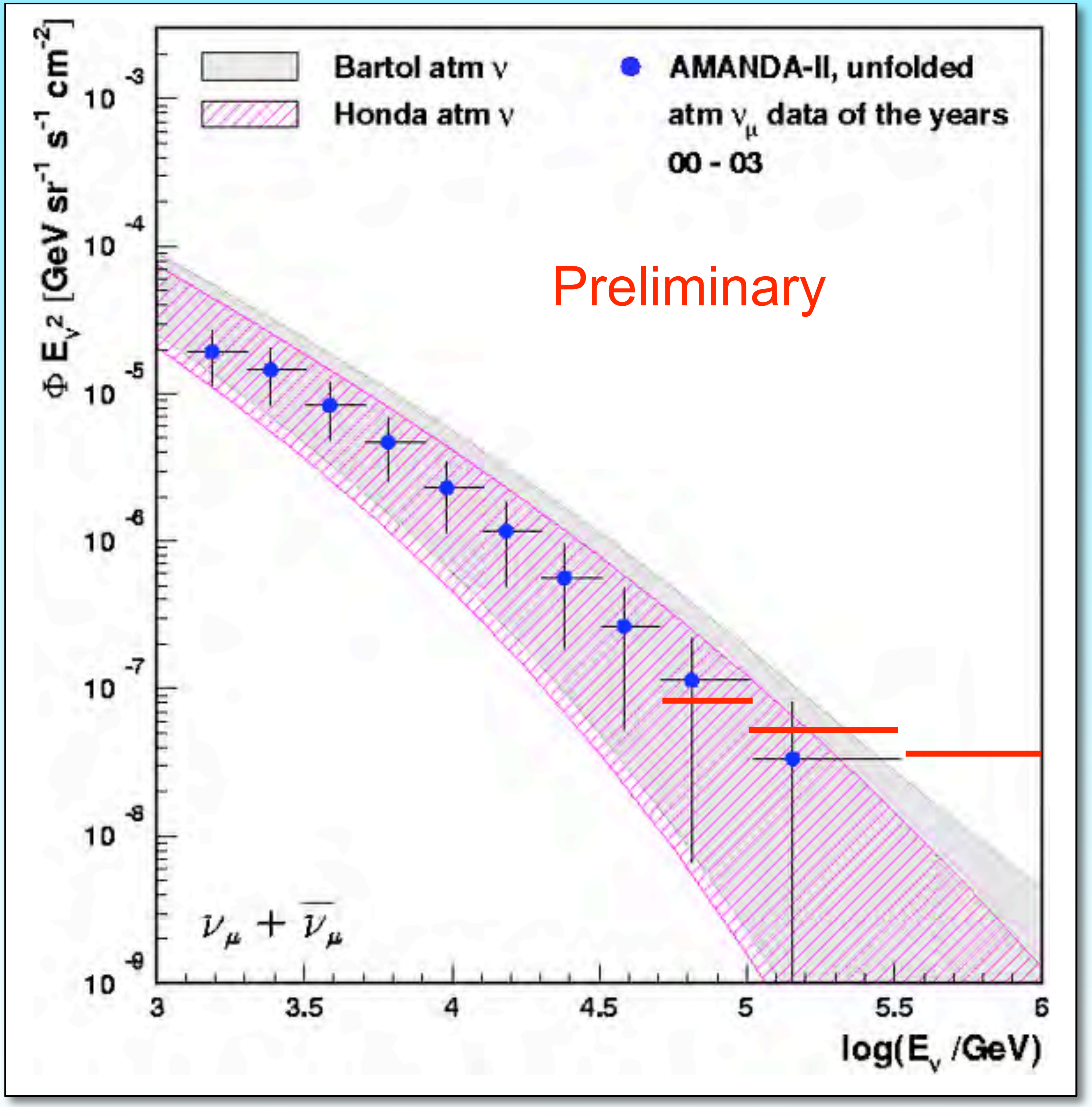
Phys.Rev.D75:102001 **2007**

Original DAQ decommissioned
AMANDA integrated into IceCube

Year	Livetime
2000	197 d
2001	193 d
2002	204 d
2003	213 d
2004	194 d
2005	199.3 d
2006	187 d
Total	**3.8 yr**

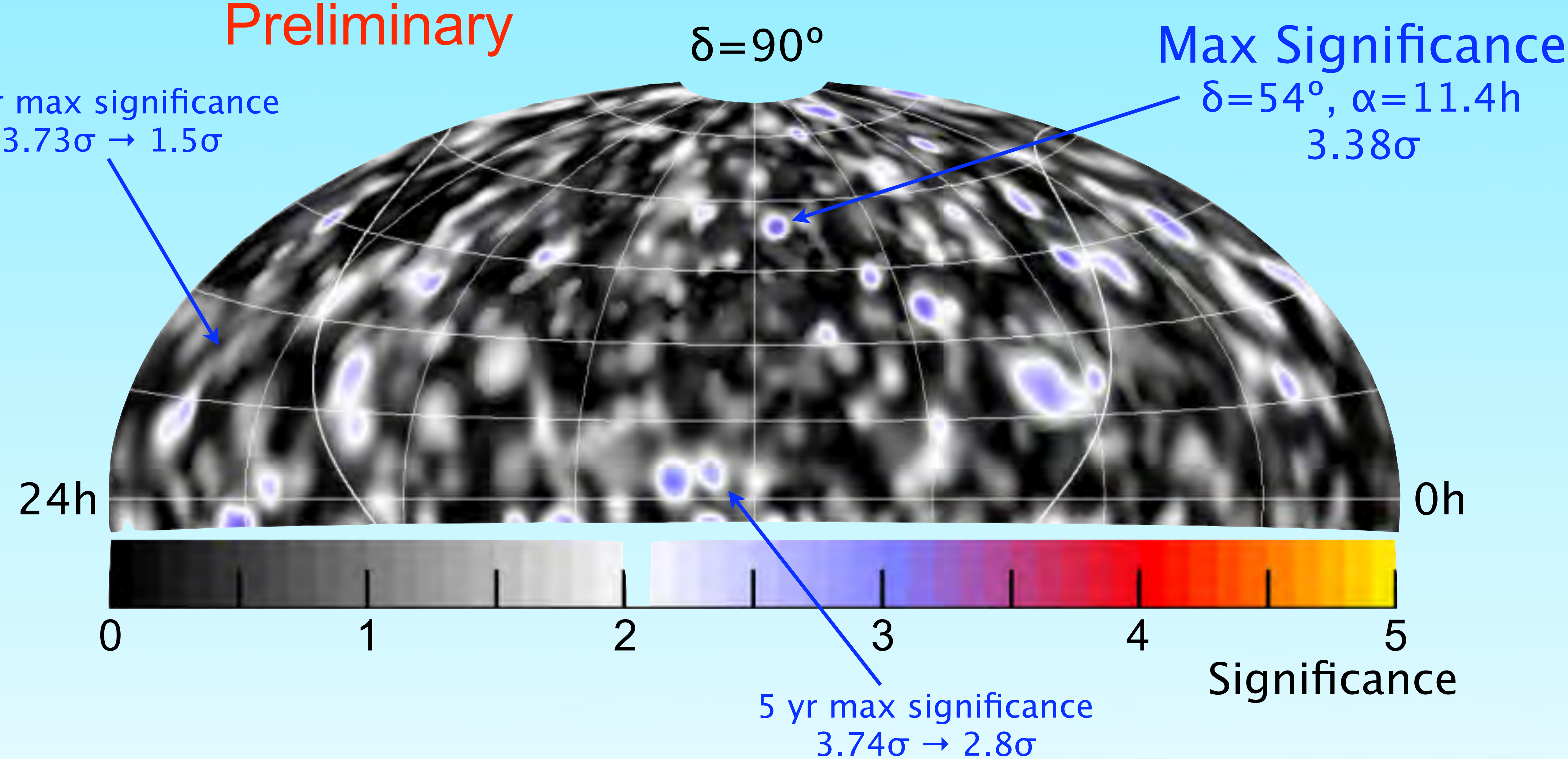
Atmospheric Neutrinos

- Statistical unfolding of atmospheric muon neutrino spectrum
  - Based on observed muon energies at detector
- Consistent with theoretical models
- Limit placed on possible high energy component
  - Would appear as excess above expected atmospheric flux



IceCube

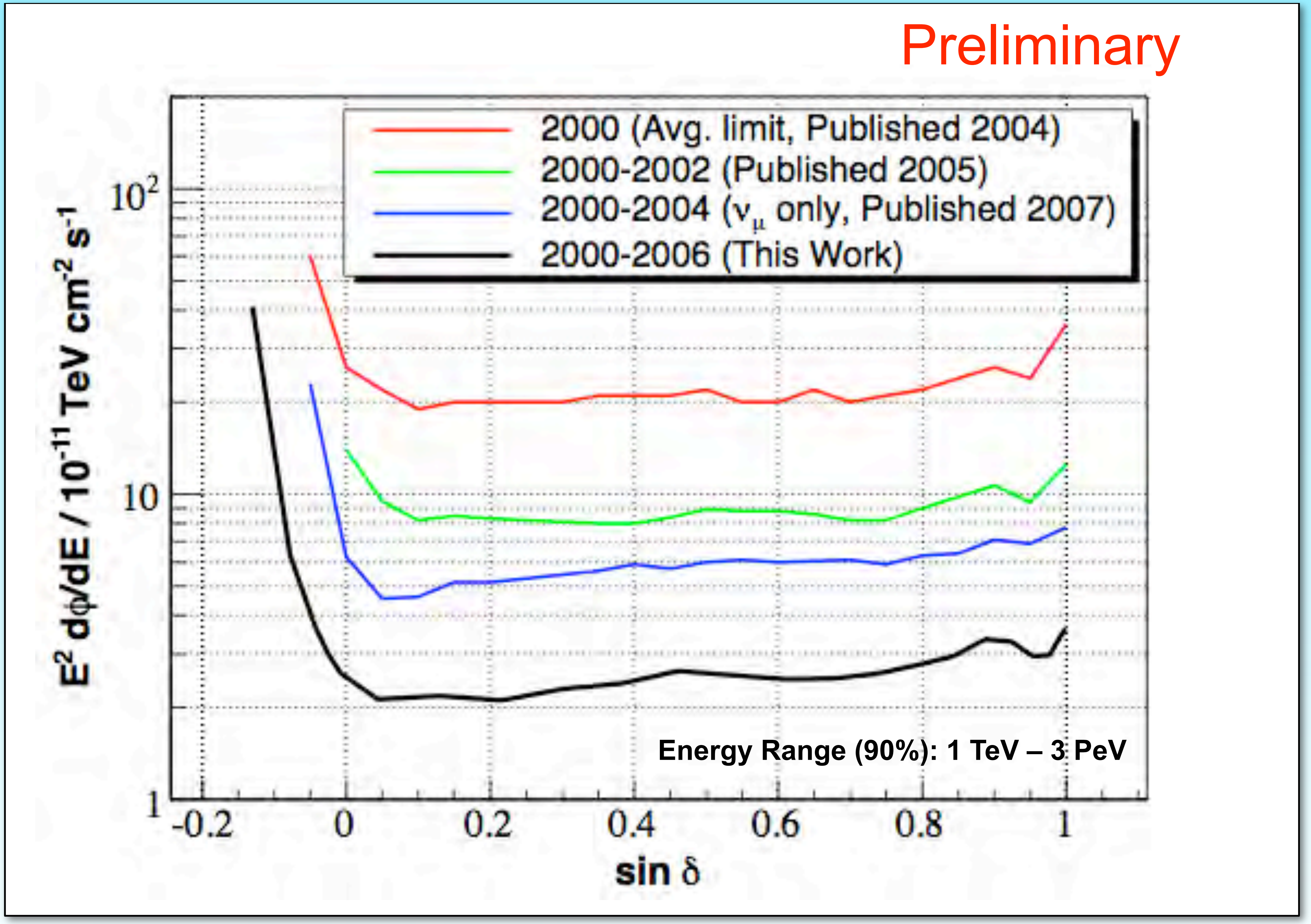
Full Sky Source Search



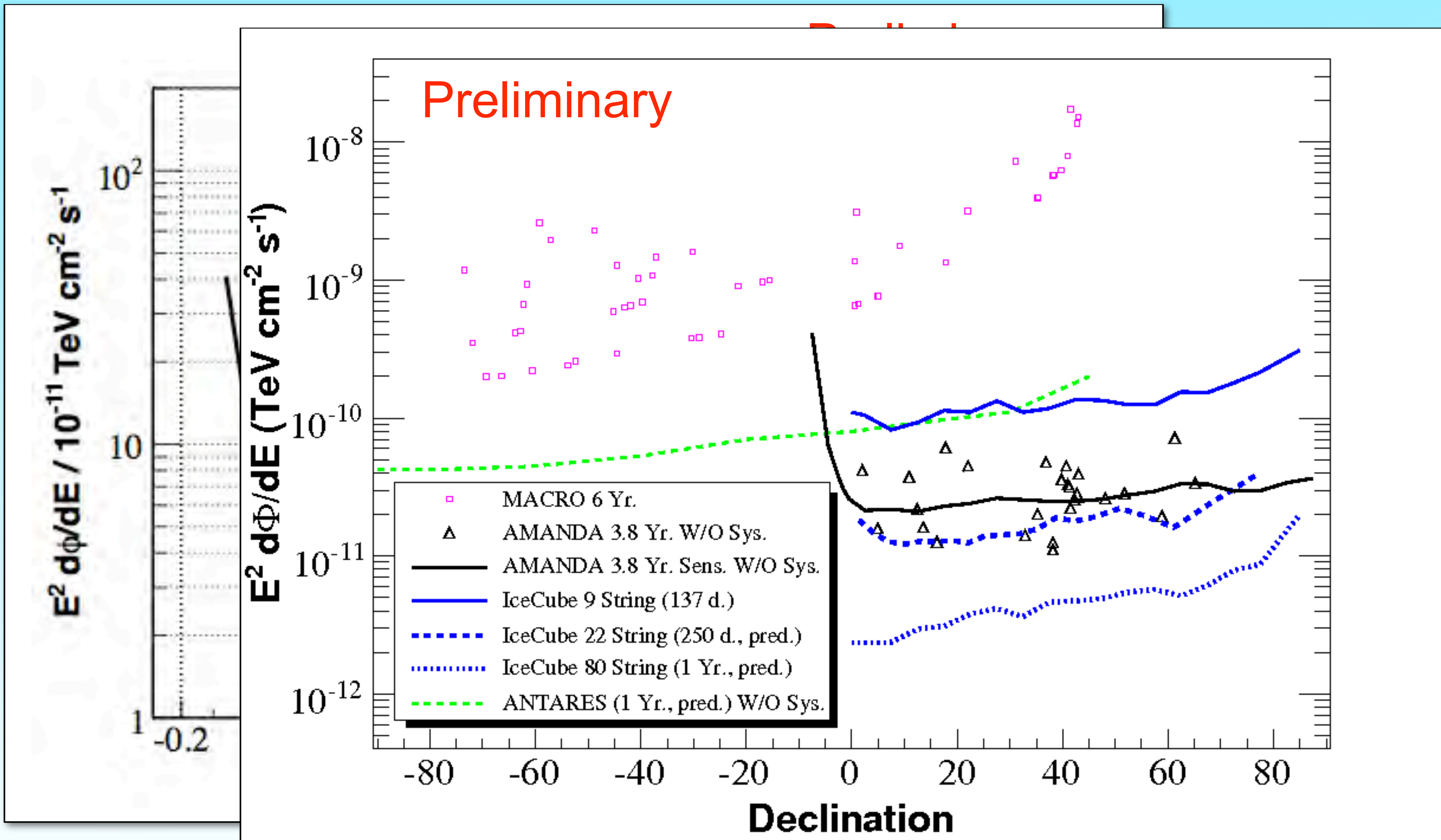
– All significances pre-trials

– 95 of 100 background maps (data randomized in RA) have a point with significance ≥ 3.38σ

Sensitivity



Sensitivity



Effective Area and Energy

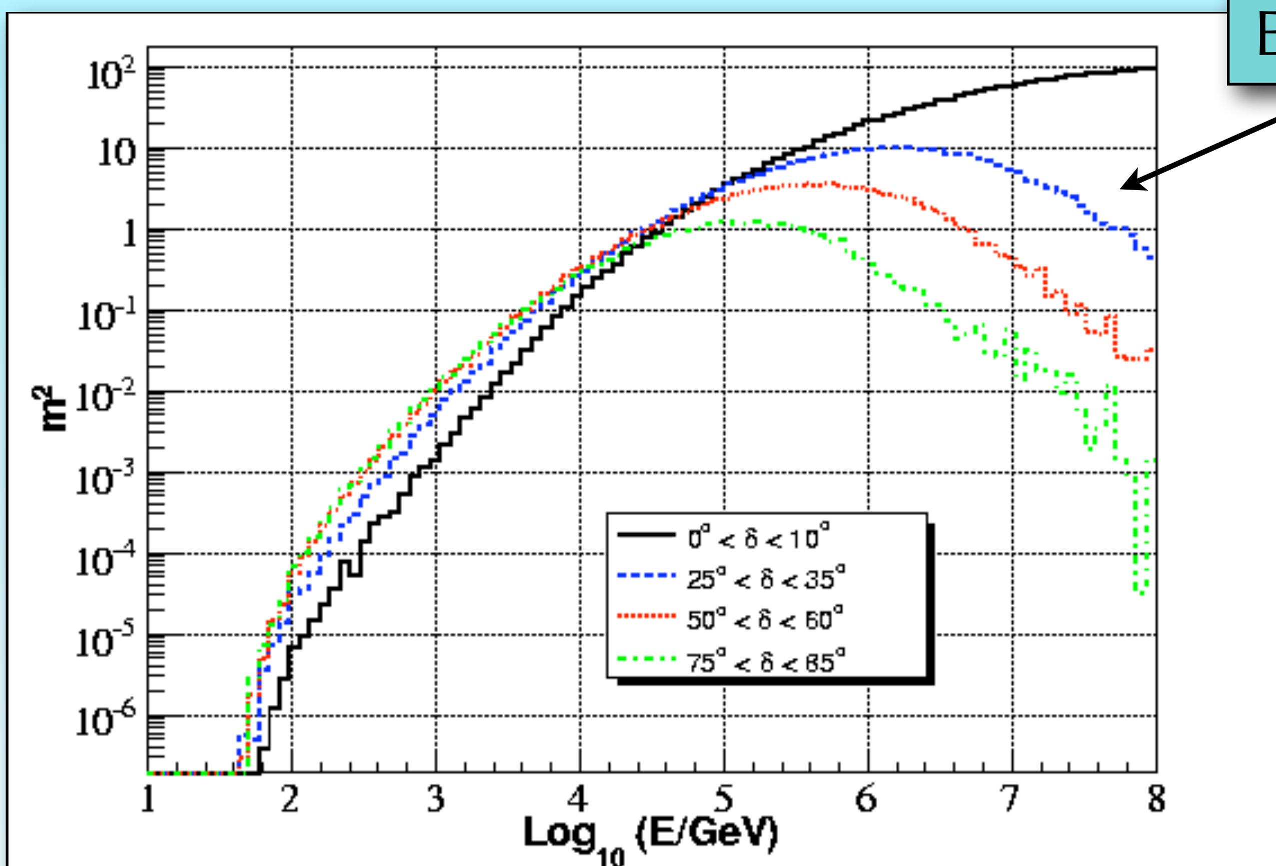
IceCube

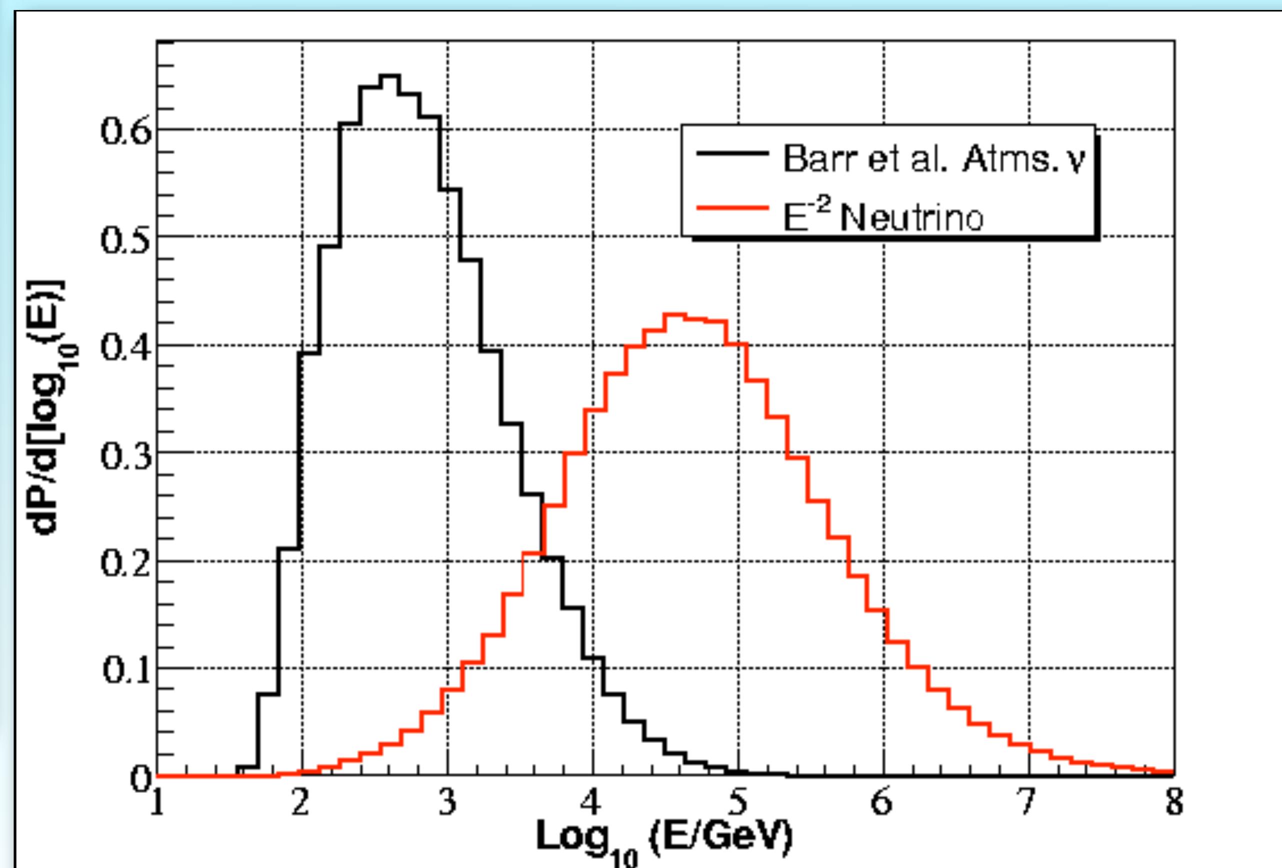
- Energy response shifted to higher energies than for gamma rays

$$\left.\begin{aligned} R_\mu &\propto E_\mu \\ \sigma_{\nu N} &\propto E_\nu \end{aligned}\right\} \text{at low energies}$$

AMANDA-II analysis: IceCube will be 10-20x bigger

Earth opacity





Source Catalog Search

- List of 26 sources selected *a priori*

Preliminary

Source	μ_{90}	P-value
Crab Nebula	4.47	0.10
MGRO J2019+37	4.75	0.077
Mkn 421	1.26	0.82
Mkn 501	3.56	0.22
LS I +61 303	7.21	0.033
Geminga	6.07	0.0086
1ES 1959+650	3.38	0.44
M87	2.18	0.43
Cyg X-1	2.00	0.57

probability of $p \leq 0.0086$ for
at least one of 26 sources is 20%

90% C.L. limits of
$E^2\Phi < \mu_{90} \times 10^{-11}$ TeV cm^{-2} s^{-1}

Upward fluctuations:
LS I +61 303
Geminga
MGRO J2019+37

Downward fluctuations:
Mkn 421

High Energy Neutrino Source Fluxes

$$\frac{N_\mu(E_\mu^{\min},\theta)}{AT} = \int_{E_\mu^{\min}}^{E_\nu} dE_\nu\, \Phi_\nu(E_\nu,\theta) \cdot P_{\nu\mu}(E_\nu, E_\mu^{\min}) \cdot e^{-\sigma_{tot}(E_\nu) N_A Z(\theta)}$$

Neutrino flux

Probability to produce a detectable muon ($E_\mu > E_{min}$)

Earth transparency

Expected events in a **1 km²** Cherenkov neutrino telescope

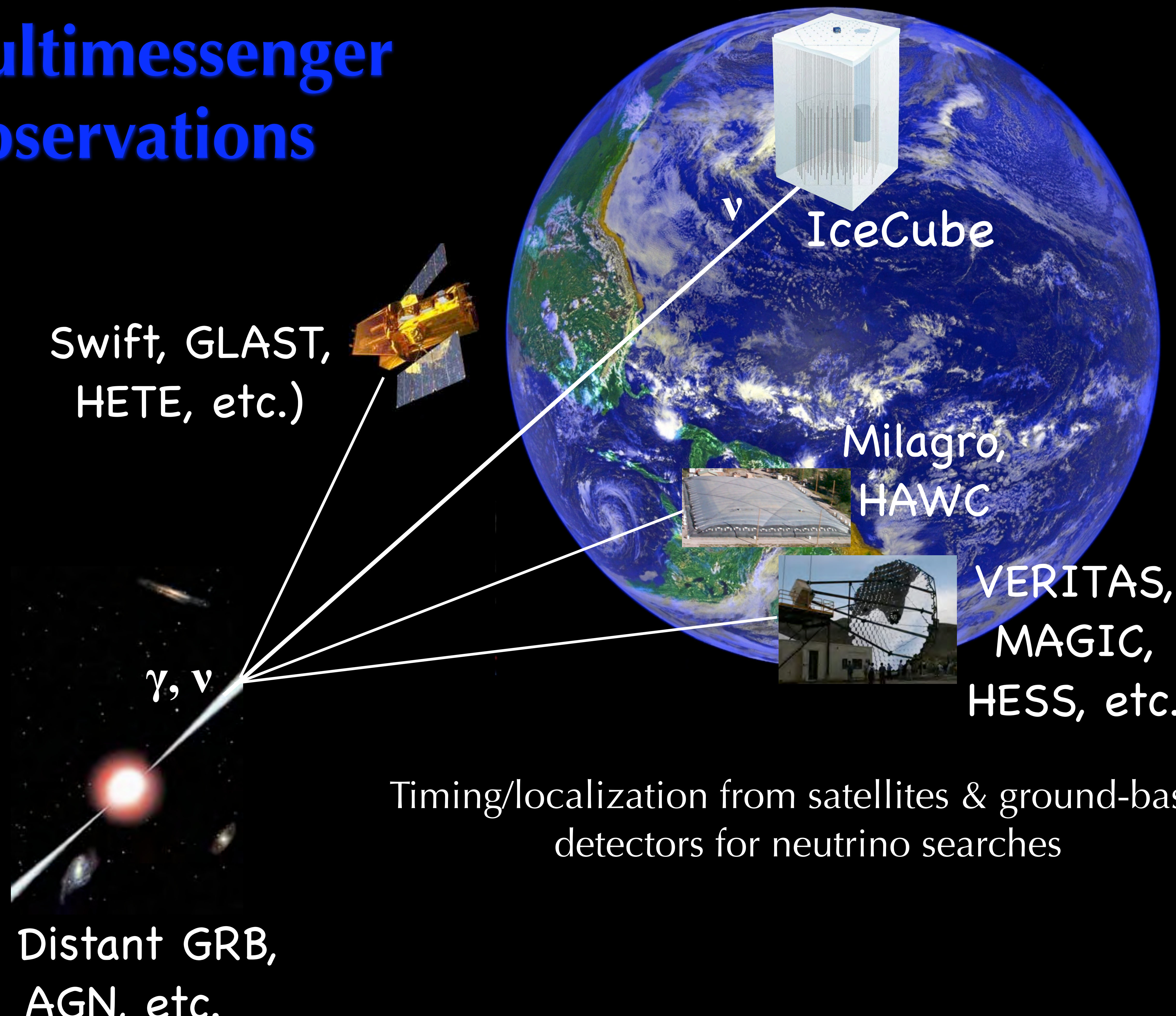
Diffuse fluxes

GZK neutrinos	0.5 / year
GRB *(Waxman)*	50 / year
AGN (thin) *(Mannheim)*	few / year
(thick)	>100 / year

Point-like sources

GRB (030329) *(Waxman)*	1-10 / burst
AGN (3C279) *(Dermer)*	few / year
Galactic SNR (RXJ1713, Vela) *(Aharonian, Vissani)*	few / year
Galactic Microquasar *(Distefano, Aharonian et al.)*	1-100 / year
Auger sources *(Halzen, O'Murchadha)*	5 – 0.03 / year
Milagro source (MGRO J1908+06) *(Halzen et al.)*	0.5 / year

Multimessenger Observations



Timing/localization from satellites & ground-based detectors for neutrino searches

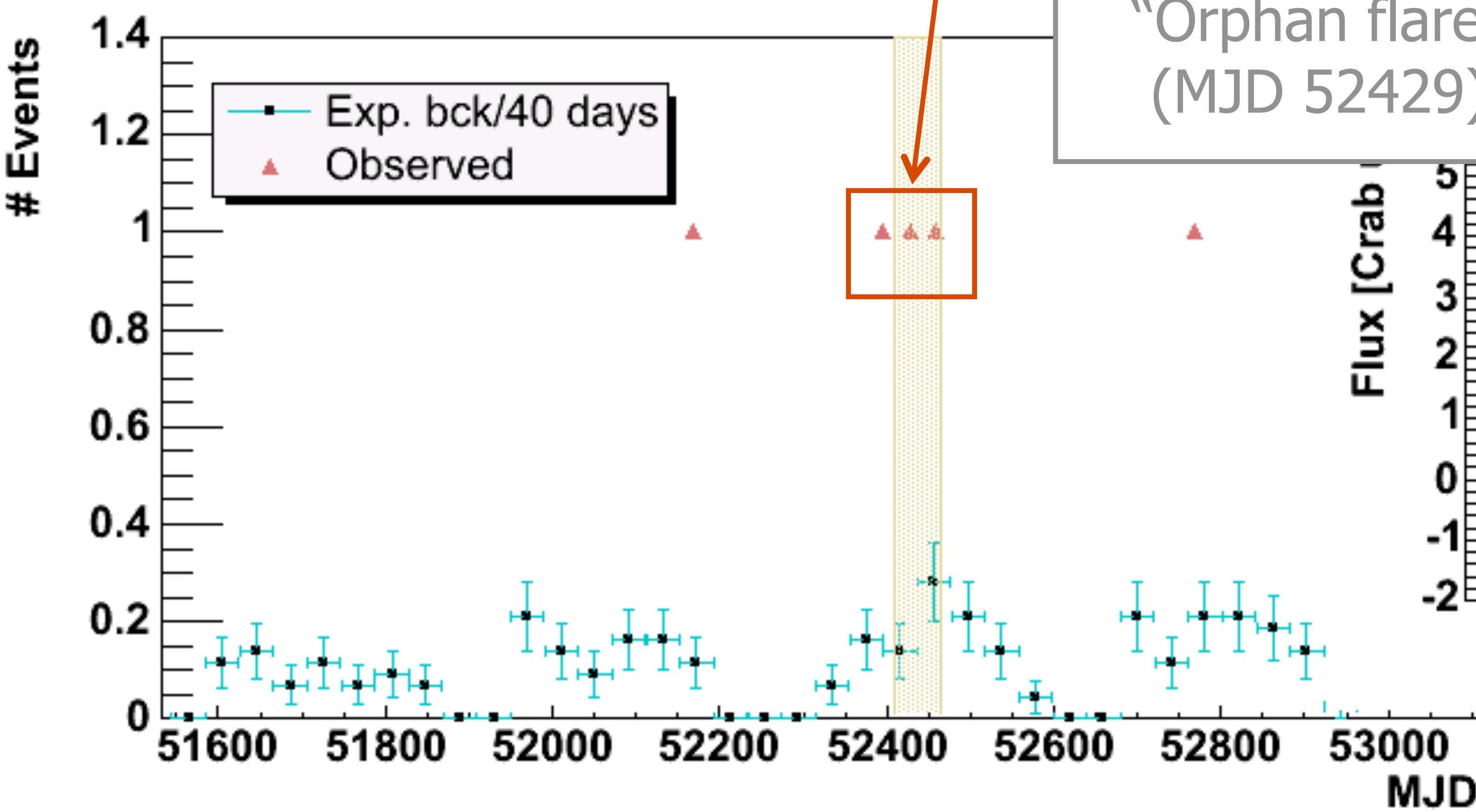
Observations in the direction of 1ES 1959+650

AMANDA

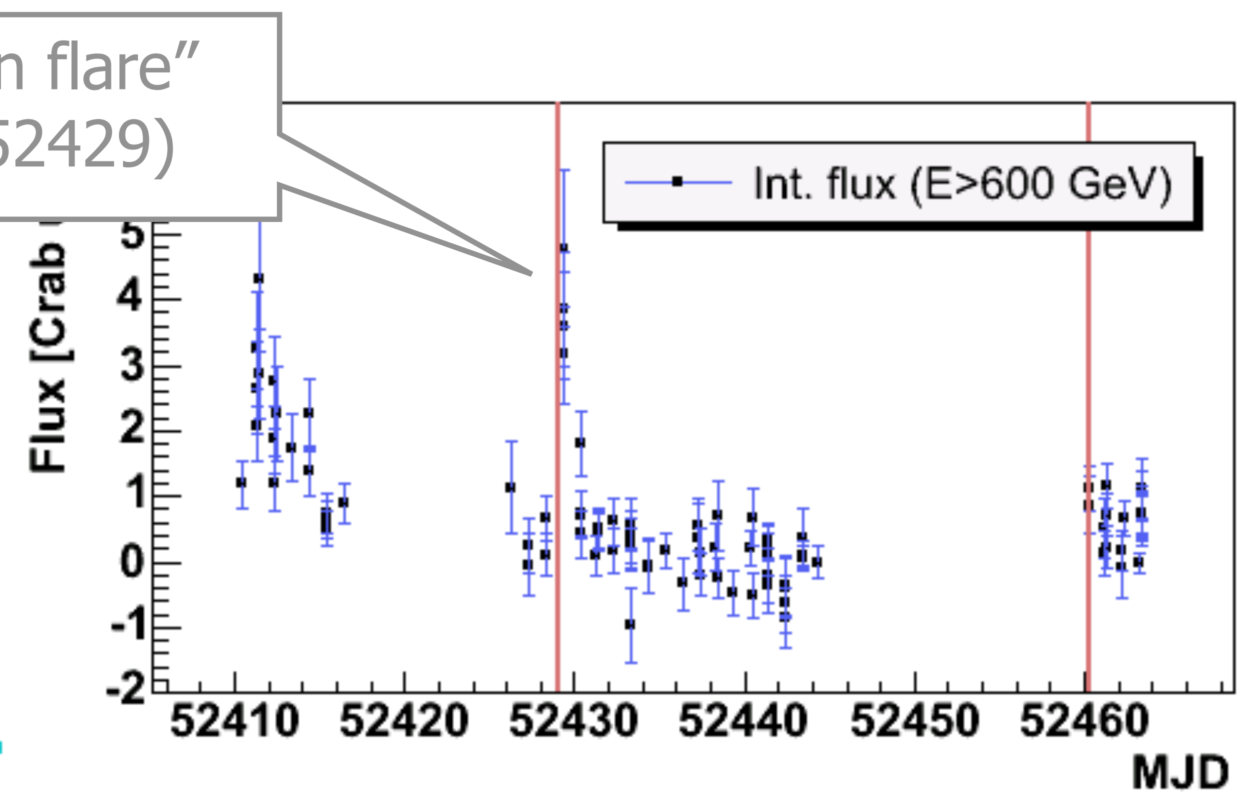
An interesting coincidence with a gamma ray flare:

3.7 atmospheric neutrino events expected between 2000 and 2003.

5 events observed, incl. 3 in 66 days in 2002, during active period of source



AMANDA events within 2.25° of the direction of 1ES 1959+650



Whipple light curve [Holder et al 2003]

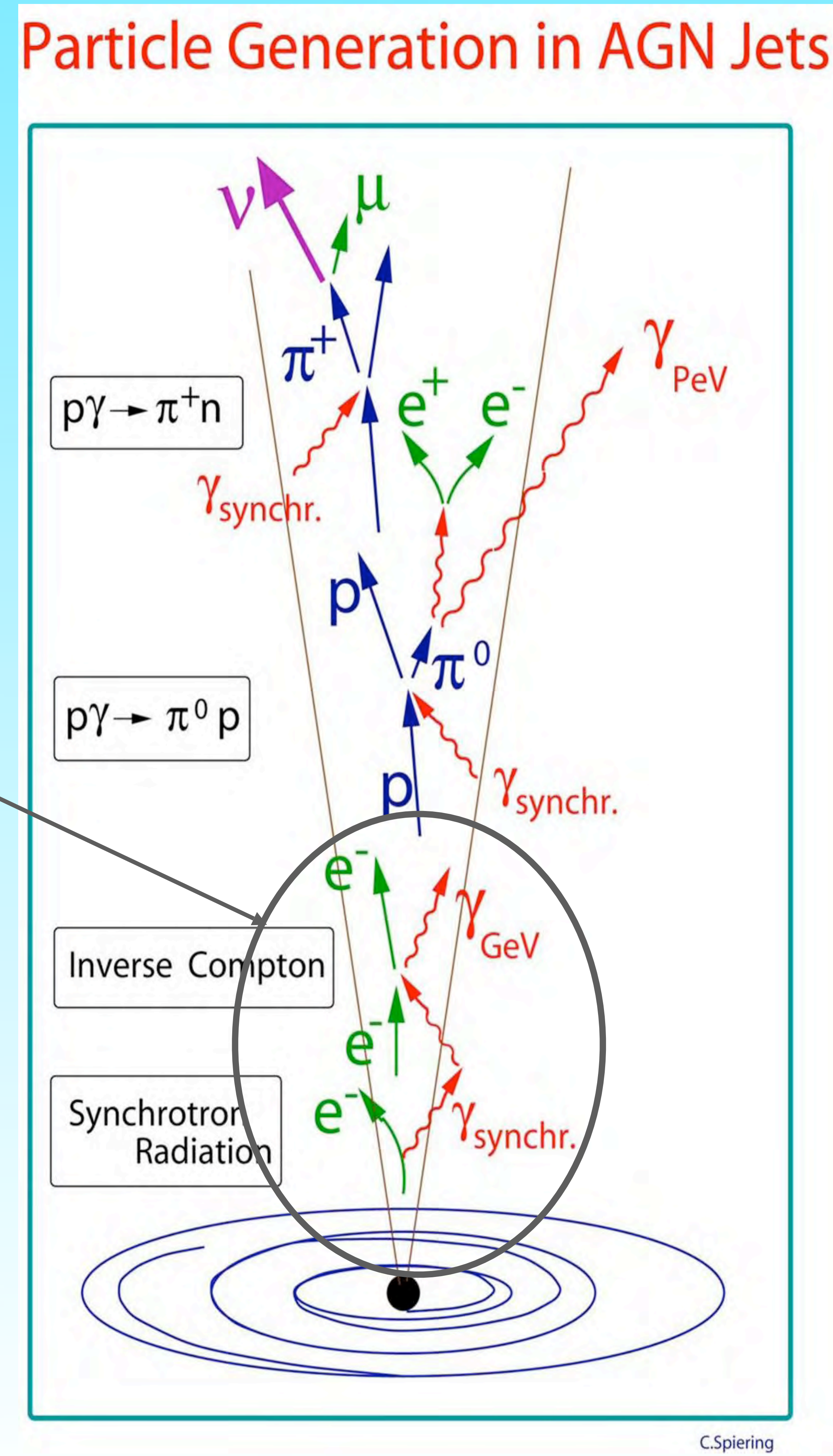
Orphan Flares

IceCube

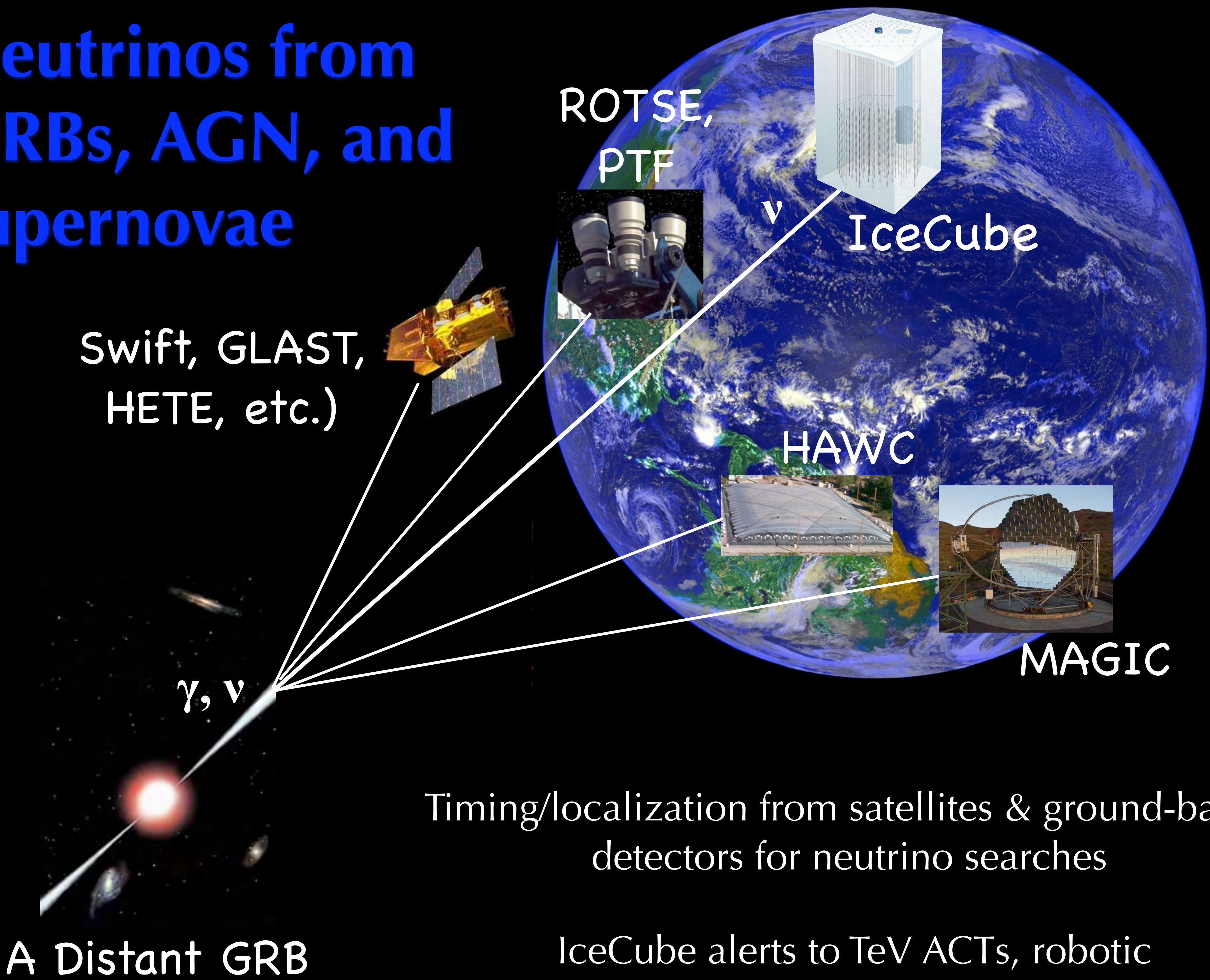
- Seem to suggest acceleration of hadrons
  - But not impossible in EM scenarios

In electromagnetic acceleration scenarios, the X-ray synchrotron photons are the seeds for the gamma rays

- Only observed serendipitously with current instruments
  - Are these common? Only specific objects? Spectral clues?
  - Need a wide field-of-view TeV gamma ray telescope



Neutrinos from GRBs, AGN, and supernovae



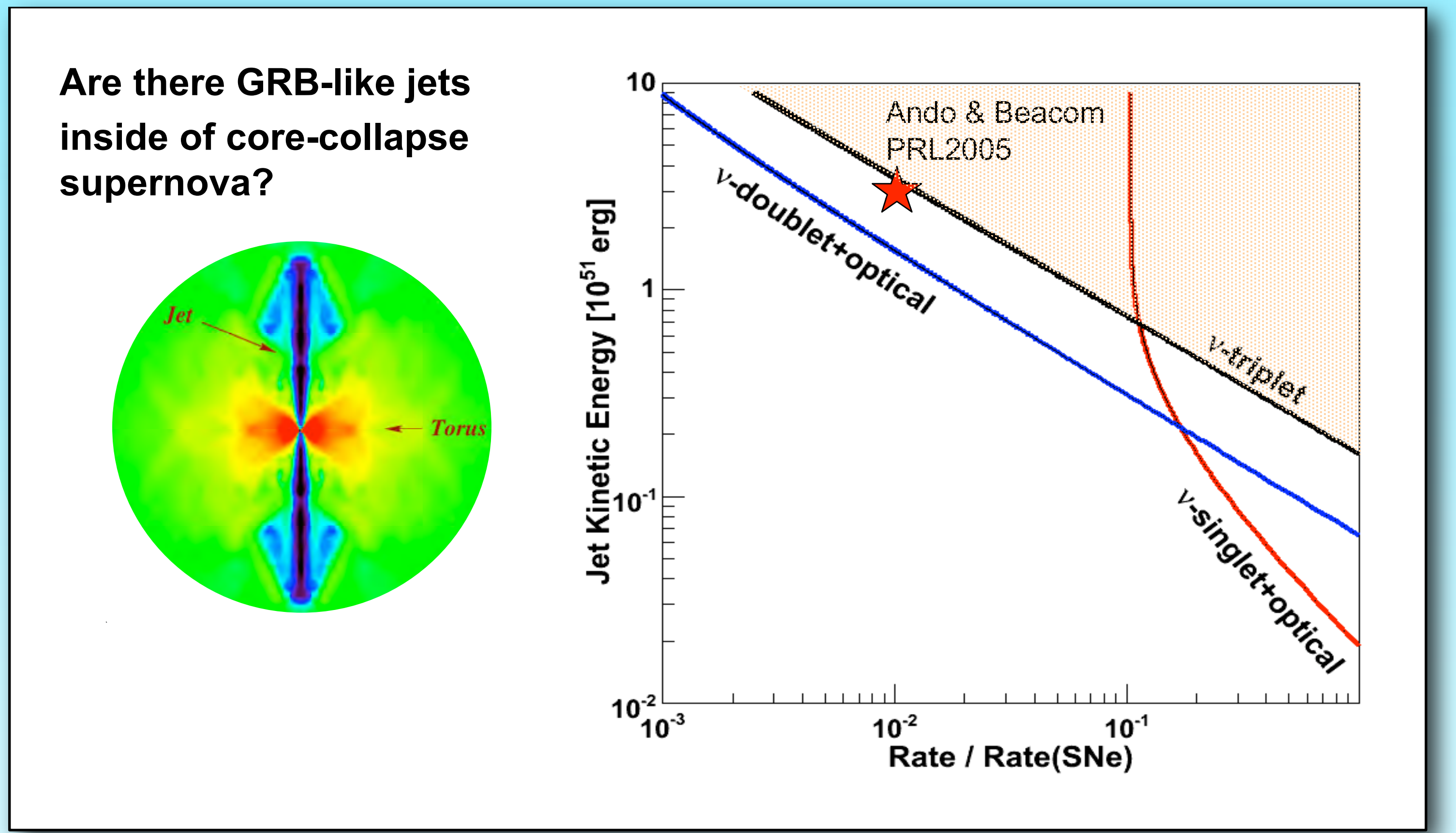
Timing/localization from satellites & ground-based detectors for neutrino searches

IceCube alerts to TeV ACTs, robotic optical telescopes?

Neutrino-Triggered ToO's

IceCube

- Search for "choked" jets inside supernovae *(Mészáros & Waxman)*
- Up to 30 events in 10 s for a SN at 10 Mpc *(Ando & Beacom)*
- Look for correlated neutrino events in IceCube, then follow up with robotic optical telescopes looking for supernovae *(Kowalski & Mohr)*



- Expect ~10 neutrino doublets (w/in 2°-3°) and ~10 high energy neutrinos (E_{μ} > 100 TeV) per year

Galactic Sources?

IceCube

- If cosmic ray muons can be beaten down below the atmospheric neutrino background, can look up at the Southern sky and Galactic center region
  - Demand events with ν-N interaction vertex contained in detector
  - ***Rough*** estimate of fraction of starting tracks:

$$\epsilon(E) \sim \frac{L_{detector}}{R_\mu(E)} \simeq \frac{1\ \mathrm{km}}{\frac{1}{b}\ln\left(\frac{bE}{a}+1\right)}$$

where

$$-dE_\mu/dx \simeq a + b\,E_\mu$$

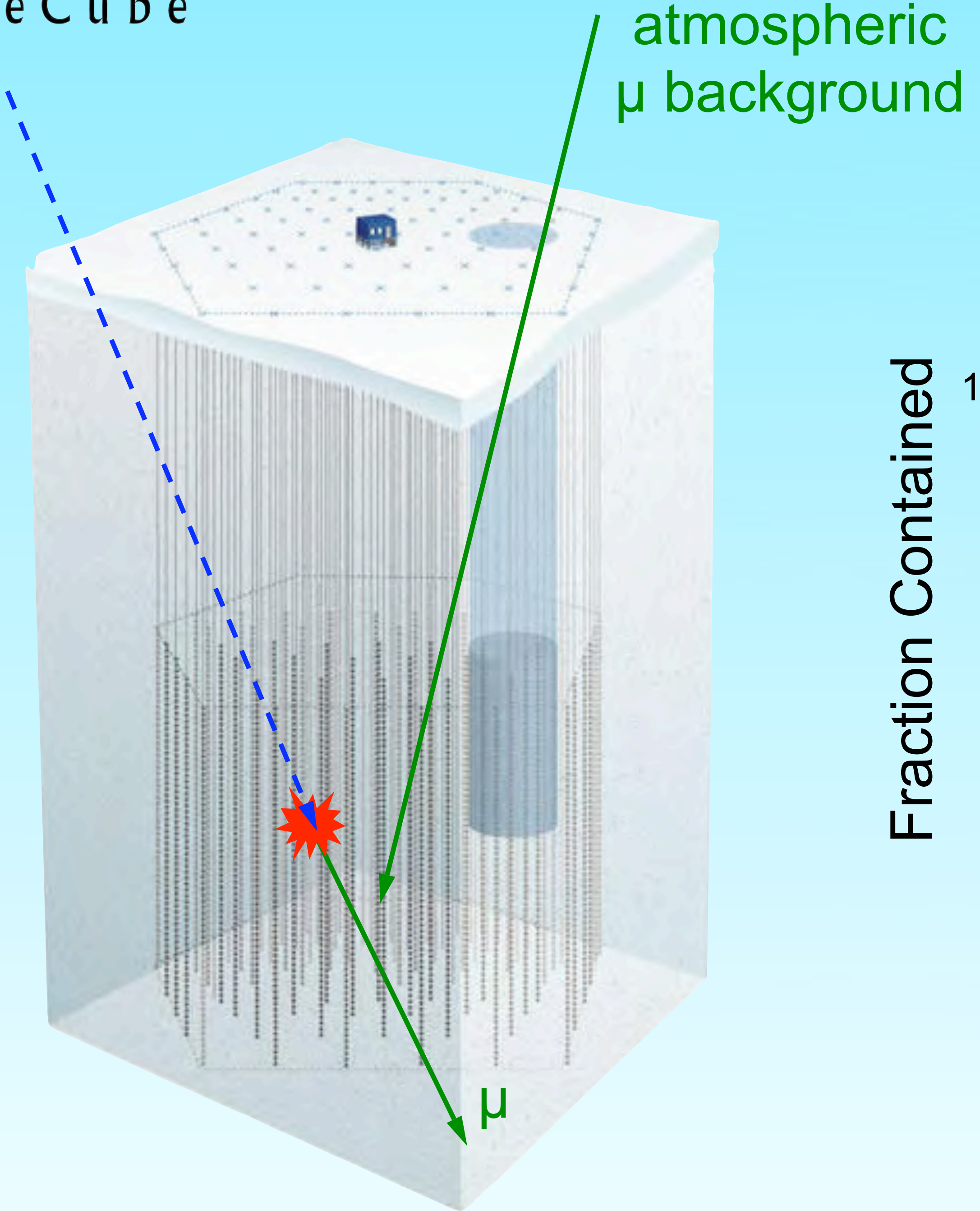
$$a \simeq 0.2\ \mathrm{GeV/m}$$

$$b \simeq 3.4 \times 10^{-4}\ \mathrm{m}^{-1}$$

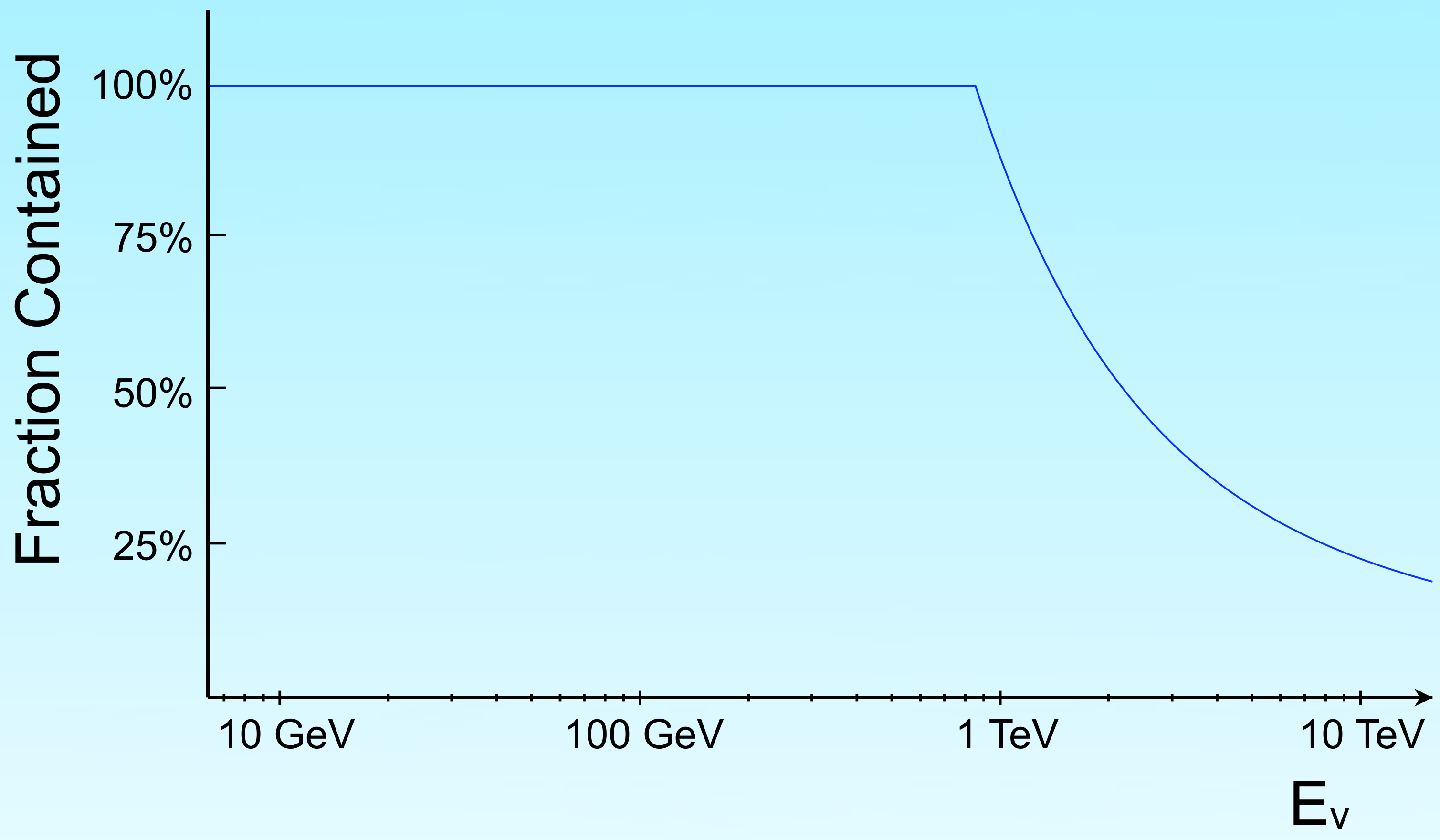
also account for

$\langle y \rangle \sim 0.42$ at low E (average over ν, $\bar{\nu}$)

Galactic Sources?



Initial analysis underway at PSU (with AMANDA+IceCube): C. H. Ha

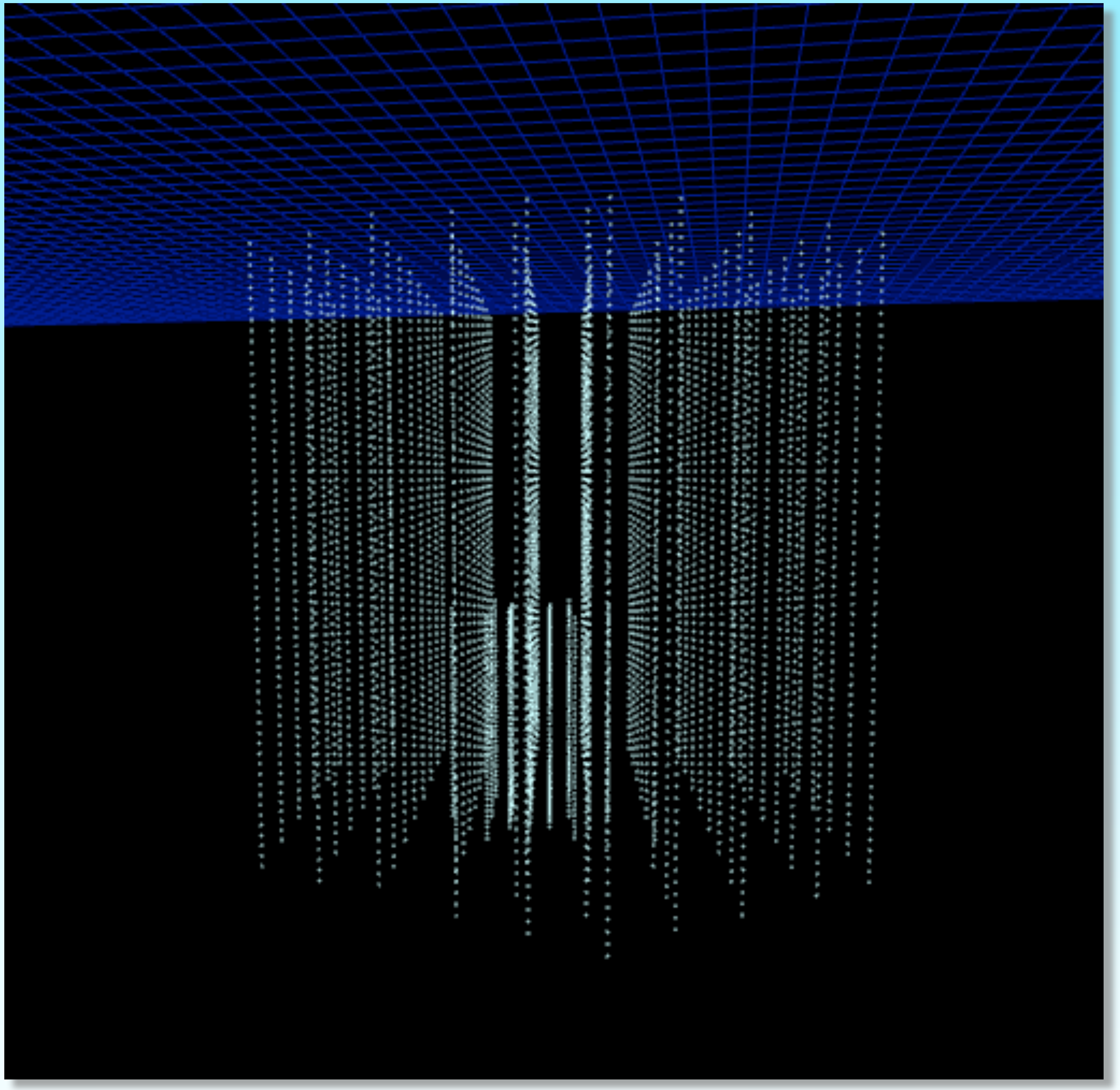


- Most events below $E_\nu \approx 1$ TeV are contained
  - Some events up to ~10 TeV (comparable to typical analysis efficiency)

IceCube Deep Core

IceCube

- Extend IceCube sensitivity to neutrinos with energies below a few hundred GeV
  - Six strings with 60 high-QE PMTs each
  - Use very clear ice at bottom of IceCube (λ_{att} ~ 40-50 m, cf. 20 m)
  - IceCube active veto
    - Reduce cosmic ray muons to atm. ν level (factor 10^{-6})



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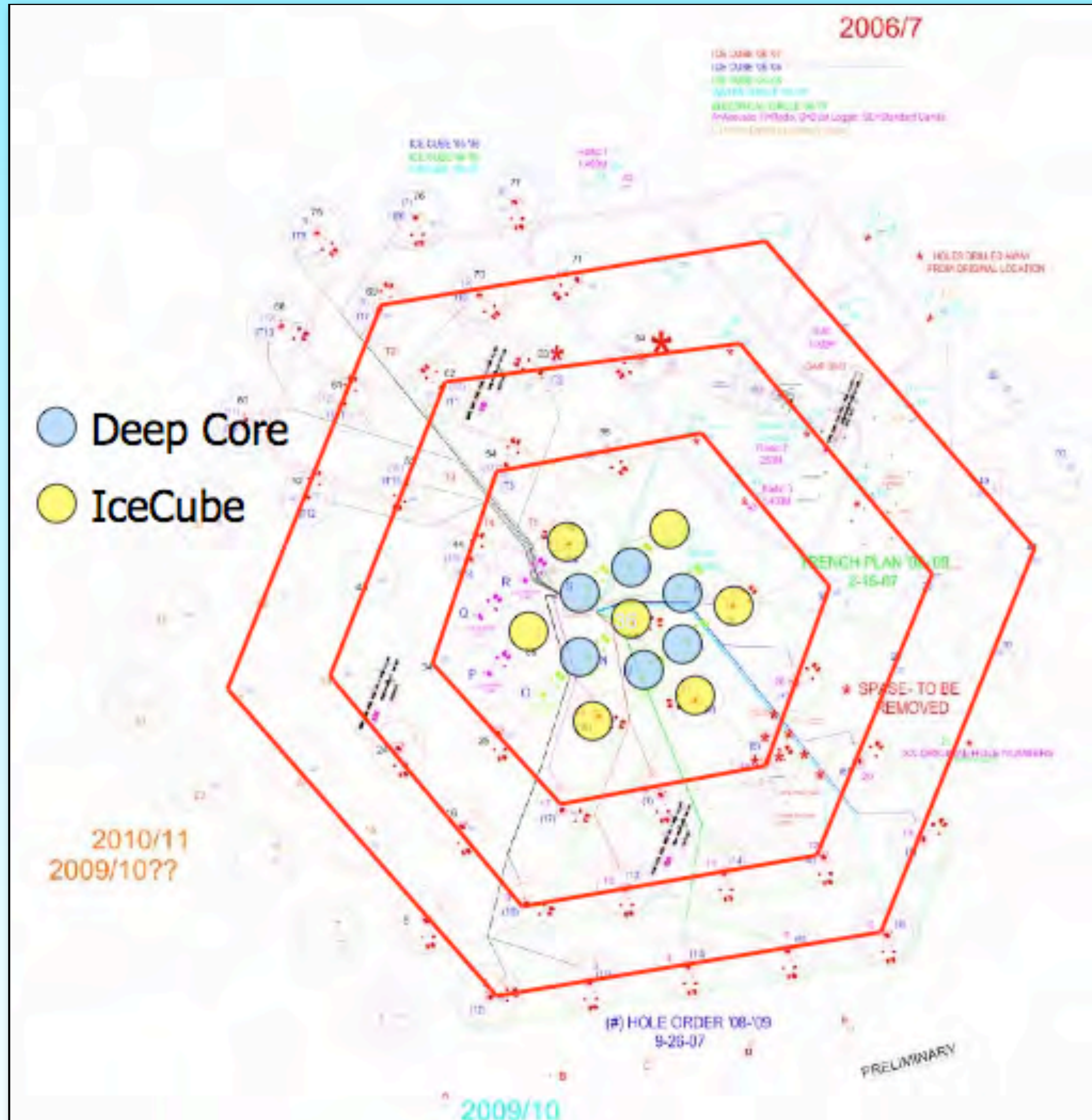

IceCube Deep Core

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  with energ
  few hundr
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    (λ_{att} ~ 40-
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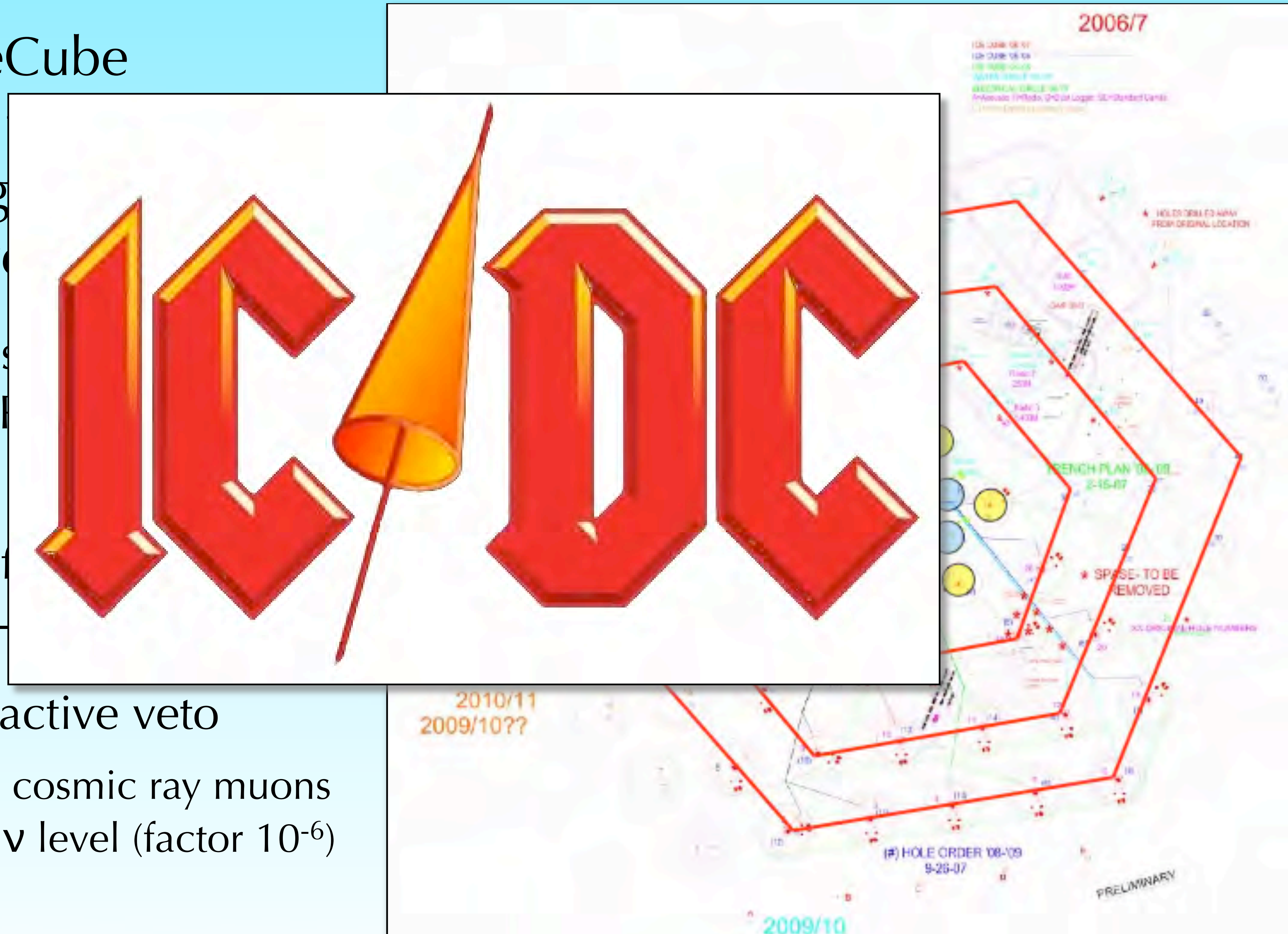
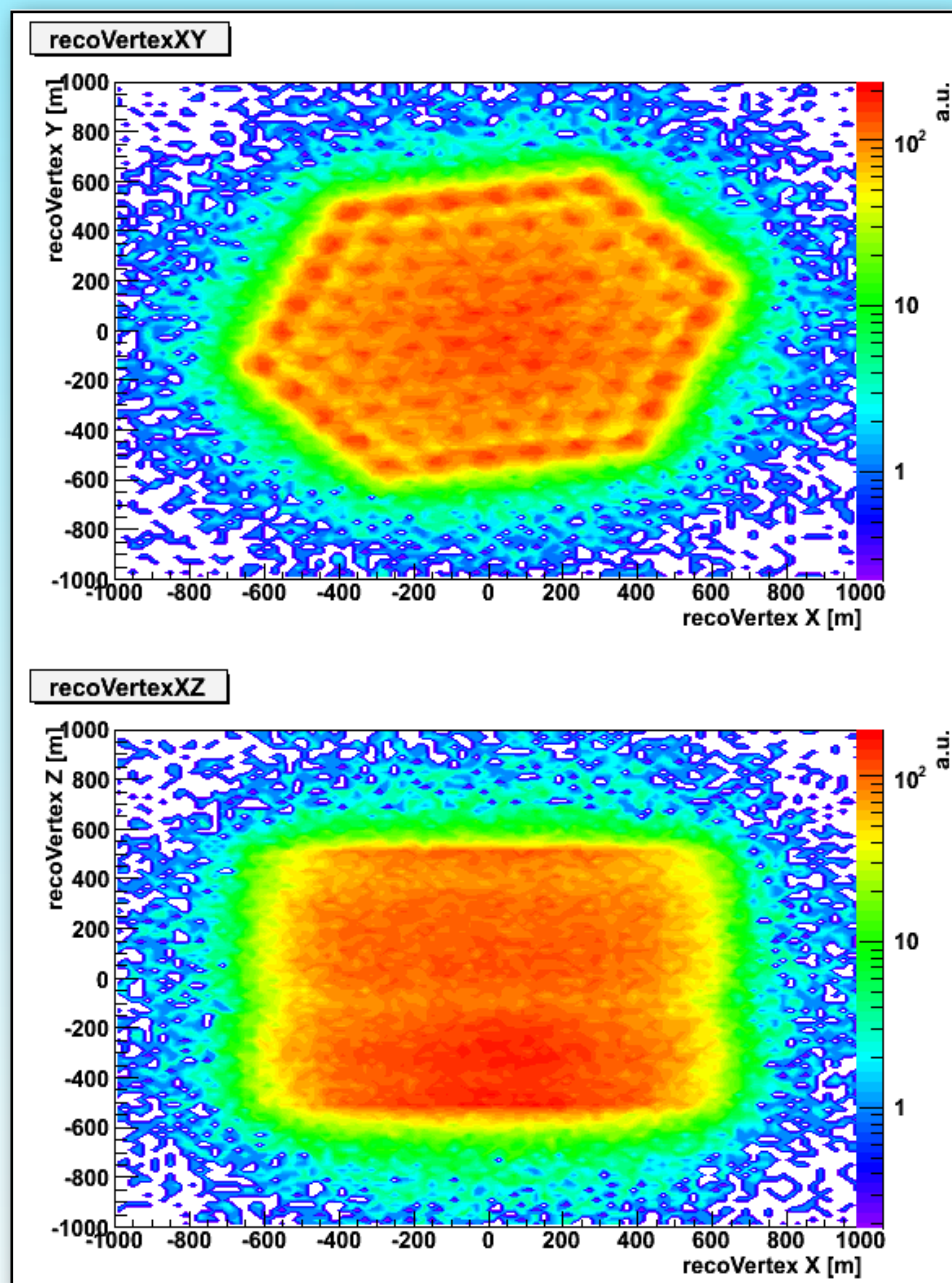


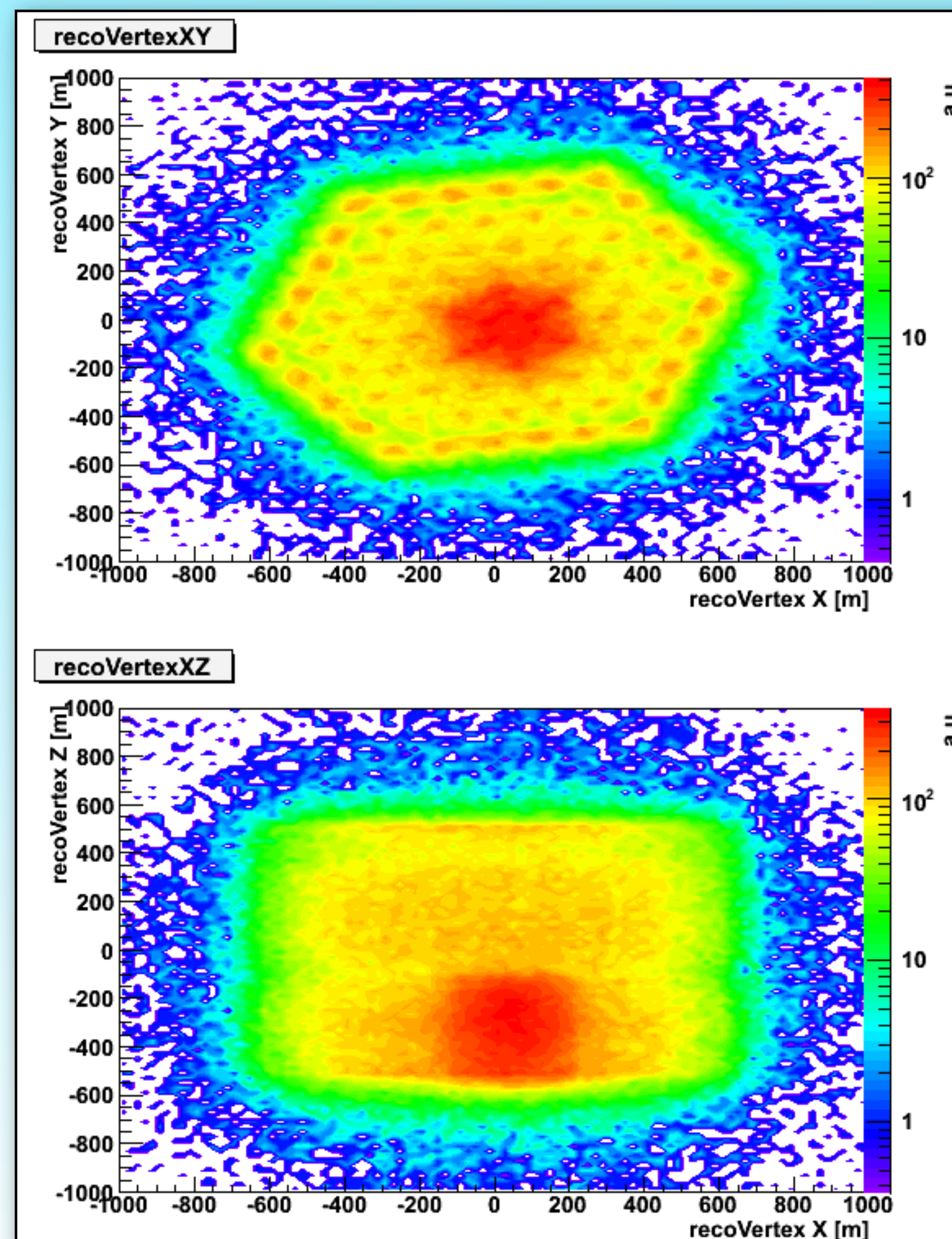
Deep Core

IceCube

IceCube Baseline



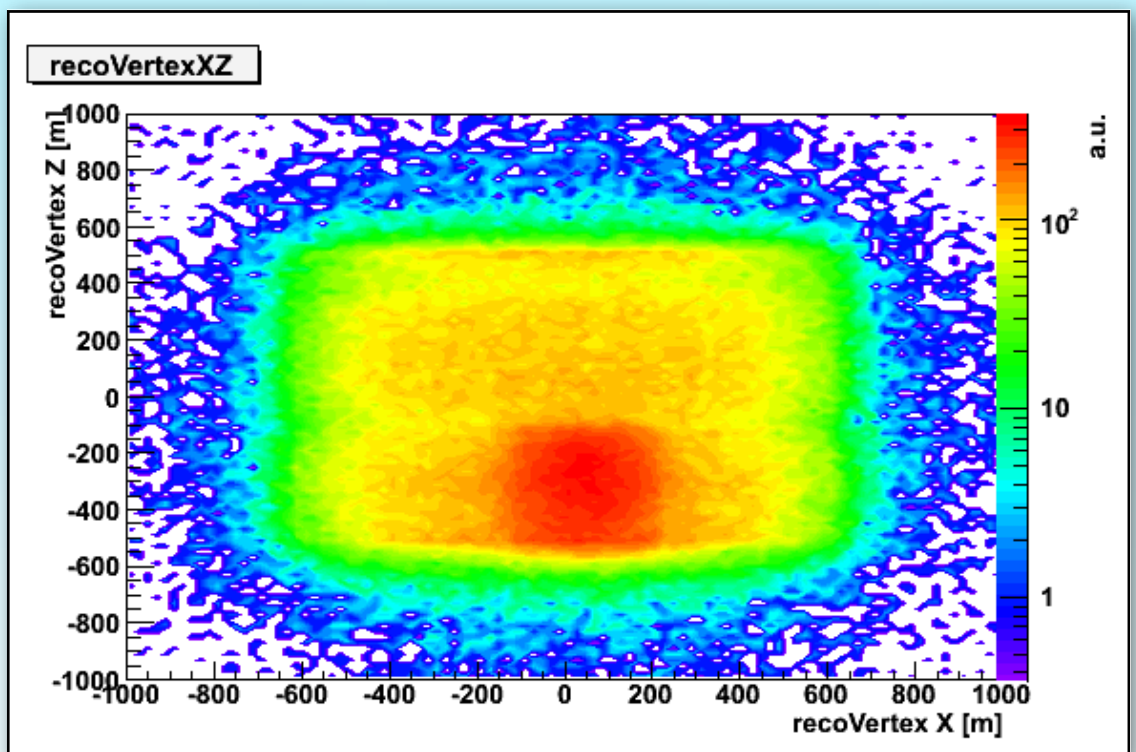
Including Deep Core
(renormalized)

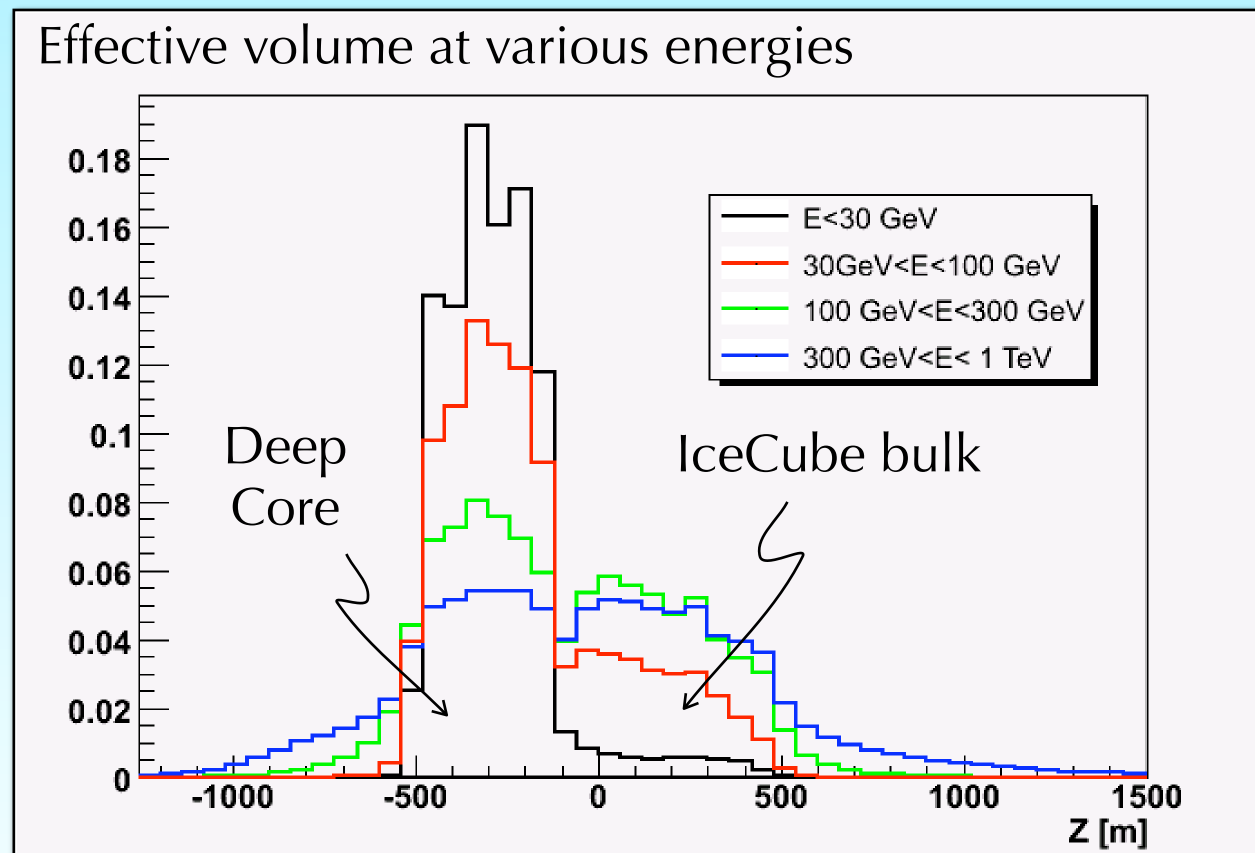


νN vertex positions for simulated ν_μ on E^{-2} from 5 GeV–50 TeV

Low Energy with Deep Core

- Large increase in effective volume for $E_\nu < 100$ GeV
  - WIMPs, southern sky, atmospheric neutrino oscillations
  - Threshold down to 10-20 GeV





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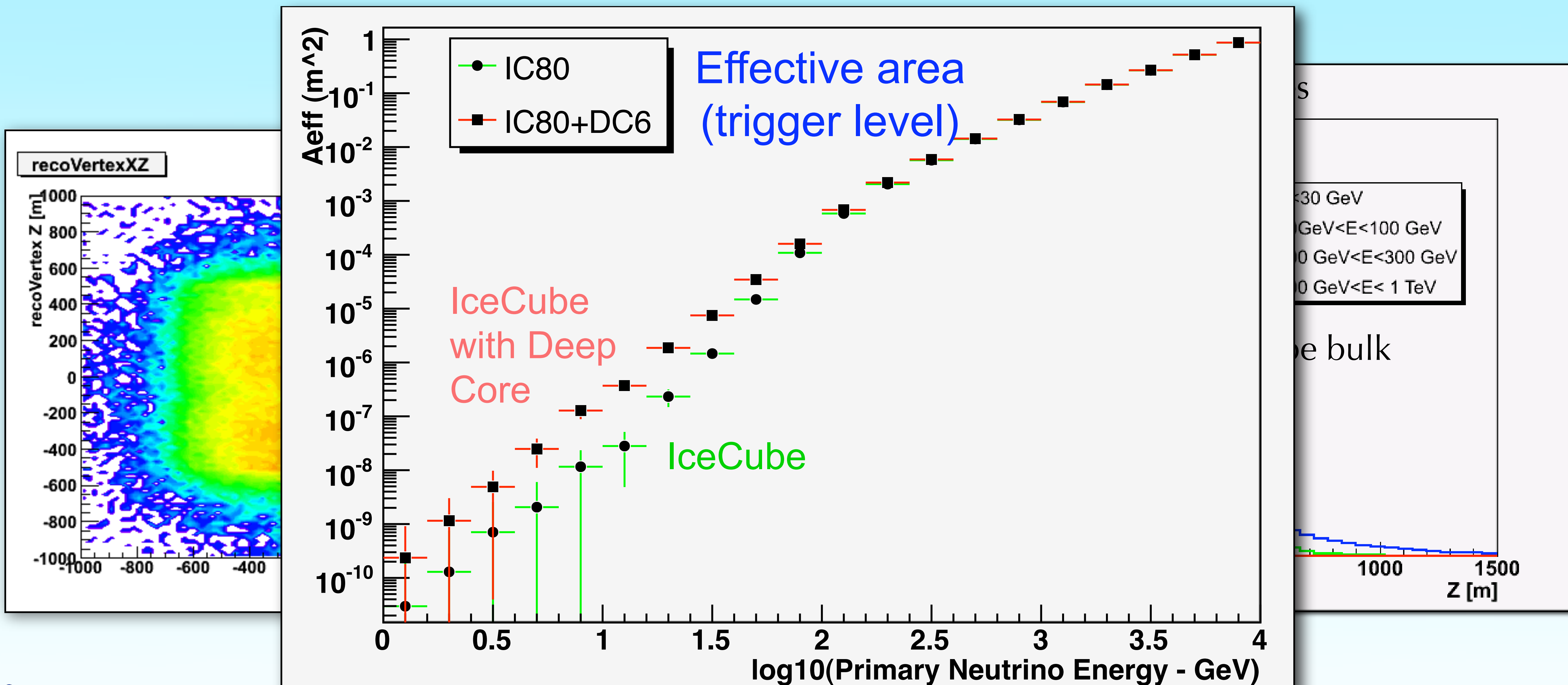

Conclusions

- No neutrino sources yet
- Rapid increases in sensitivity in next few years
- Multimessenger observations can give a large advantage
  - IceCube analysis tailored to published X-ray, gamma ray observations
  - IceCube-triggered ToO's
- Deep Core coming – open up the southern sky?