Neutrino Astronomy at the South Pole

Latest results from IceCube

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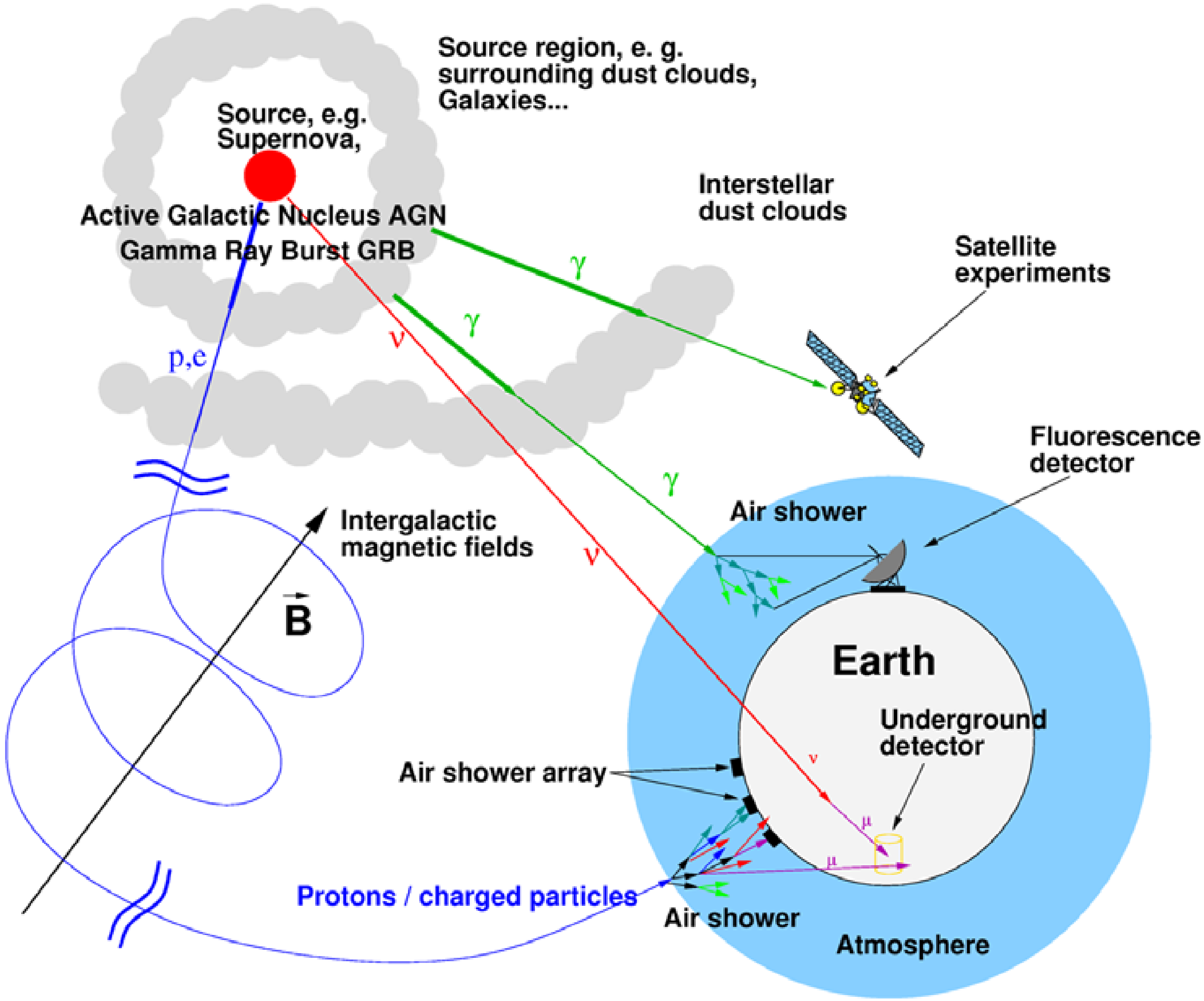
UC Berkeley

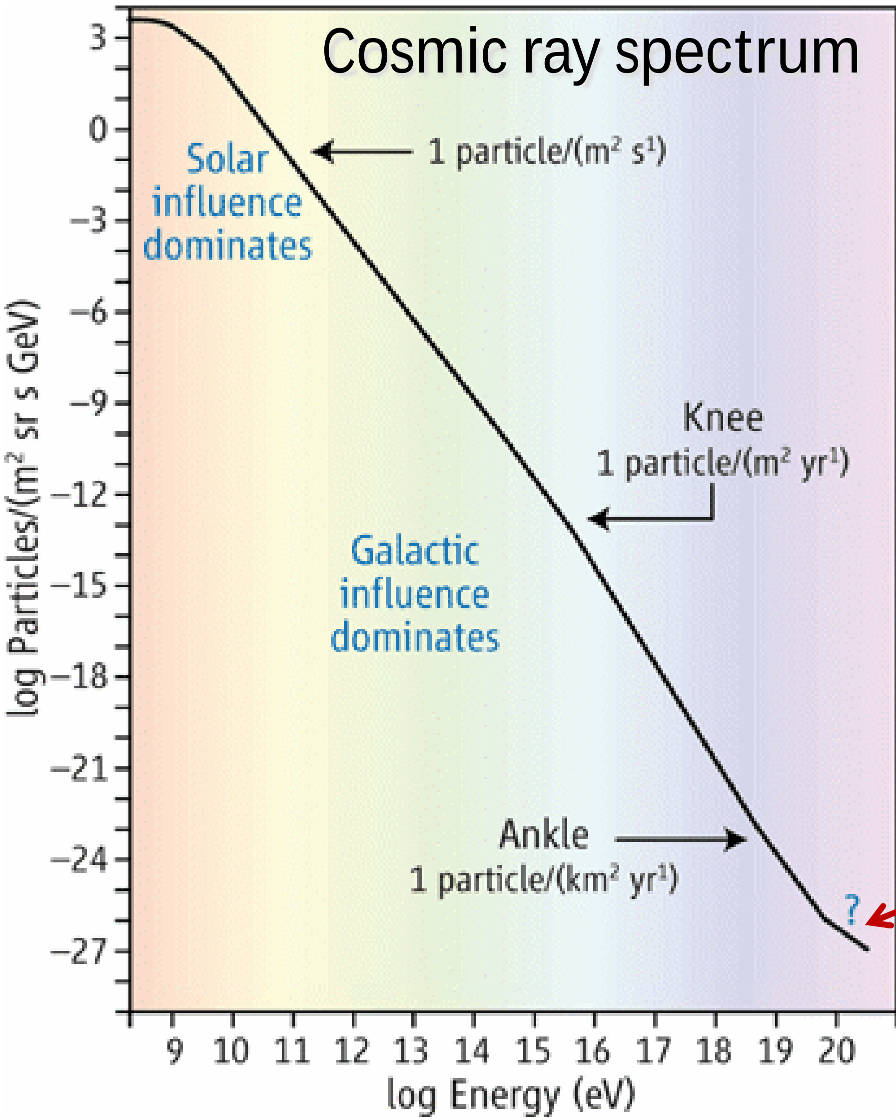
SLAC Summer Institute

August 3, 2011

Neutrinos as Cosmic Messengers



Neutrinos and the Origin of Cosmic Rays



Galactic: SN remnants

Extragalactic:
AGNs / GRBs / Other

We expect high-energy neutrinos from the same sources:

$p + p \rightarrow \pi + \ldots \rightarrow \nu + \ldots$ or

$p + \gamma_{CMB} \rightarrow \Delta \rightarrow \pi + n \rightarrow \nu + \ldots$

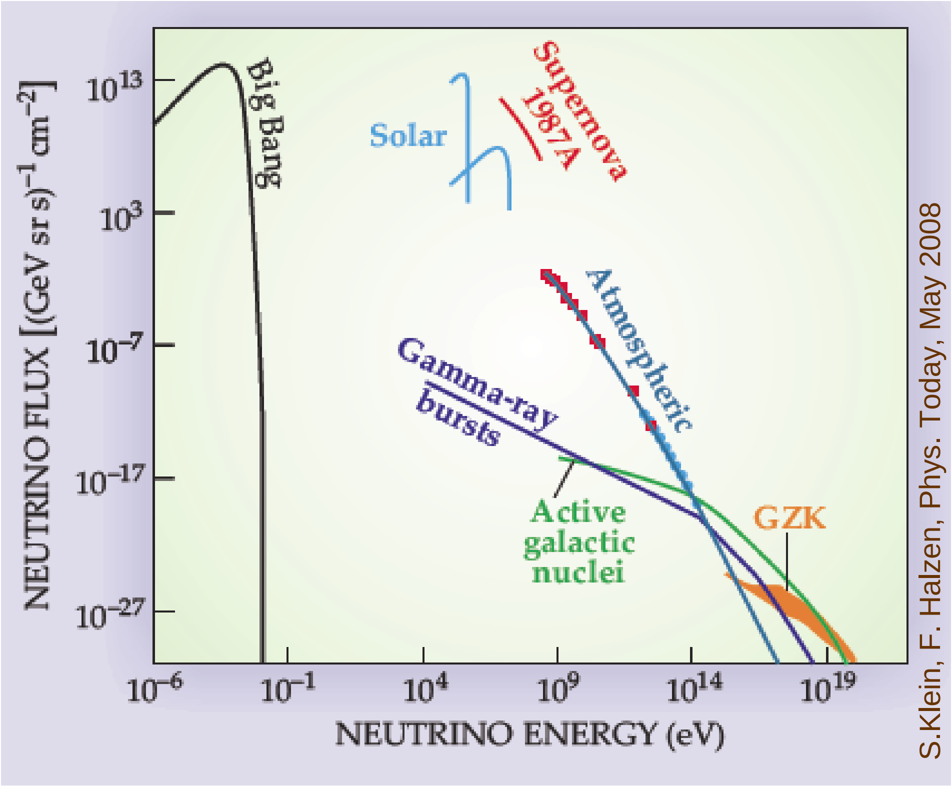
$E_p > 6 \times 10^{19} eV$ GZK cutoff

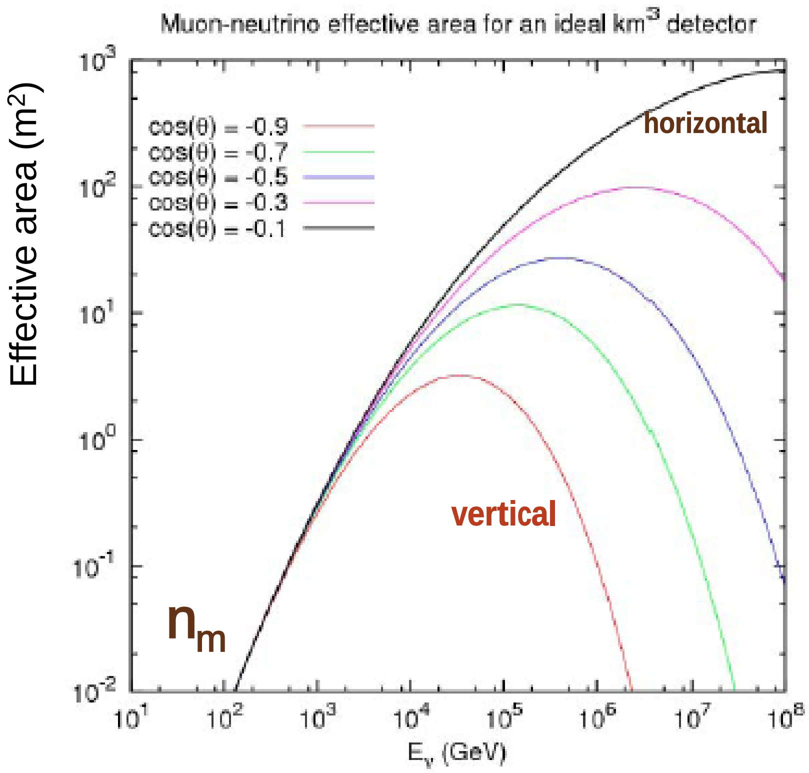
Greisen, Zatsepin, and Kuzmin (1966)

GZK neutrinos are “guaranteed”

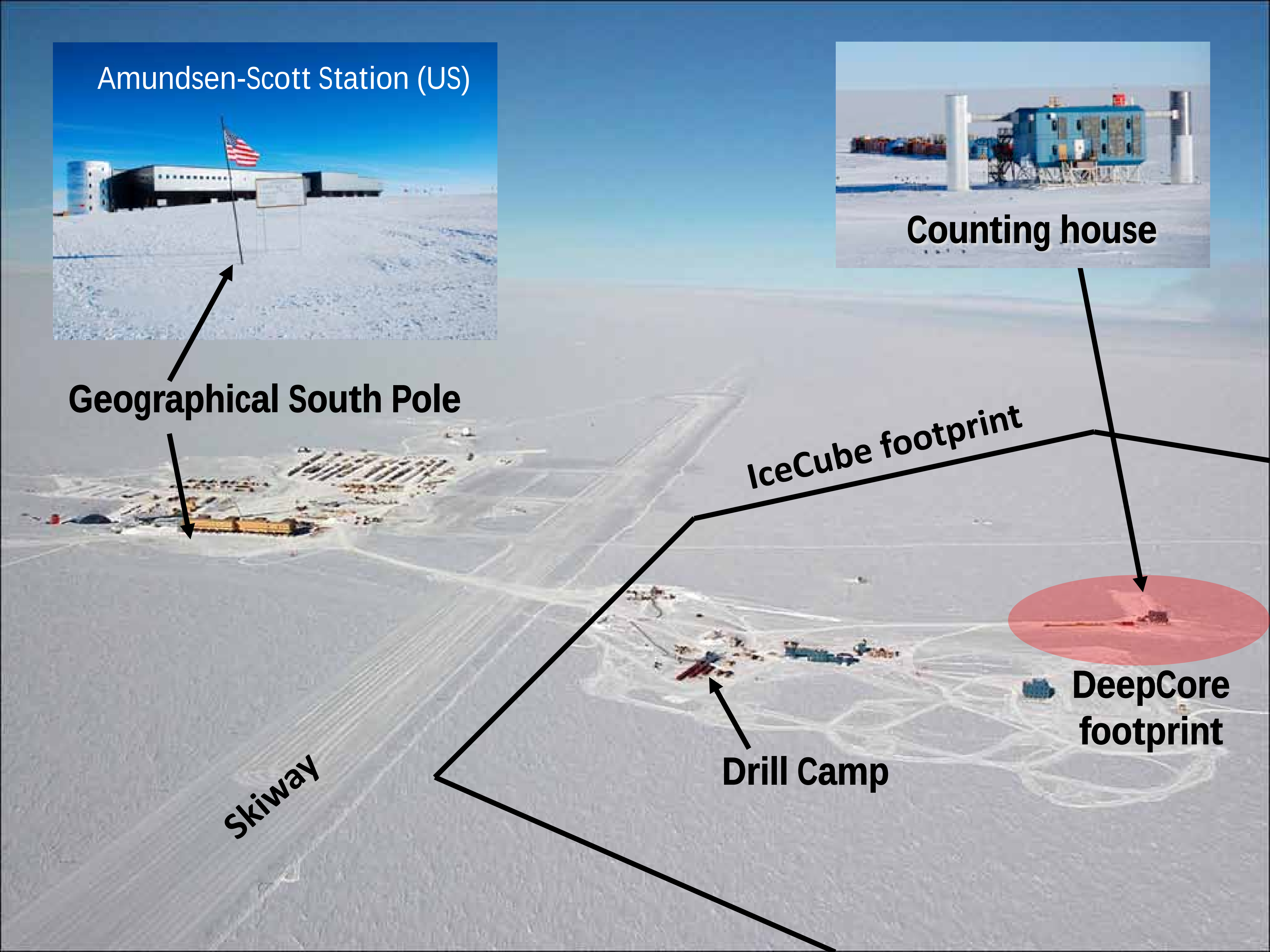
Size matters: need for a km^3 neutrino detector

Rate = Neutrino flux x Neutrino Effective Area
= Neutrino flux x Neutrino Cross Section x Absorption in Earth
x Size of detector x (Range of muon for n_m)



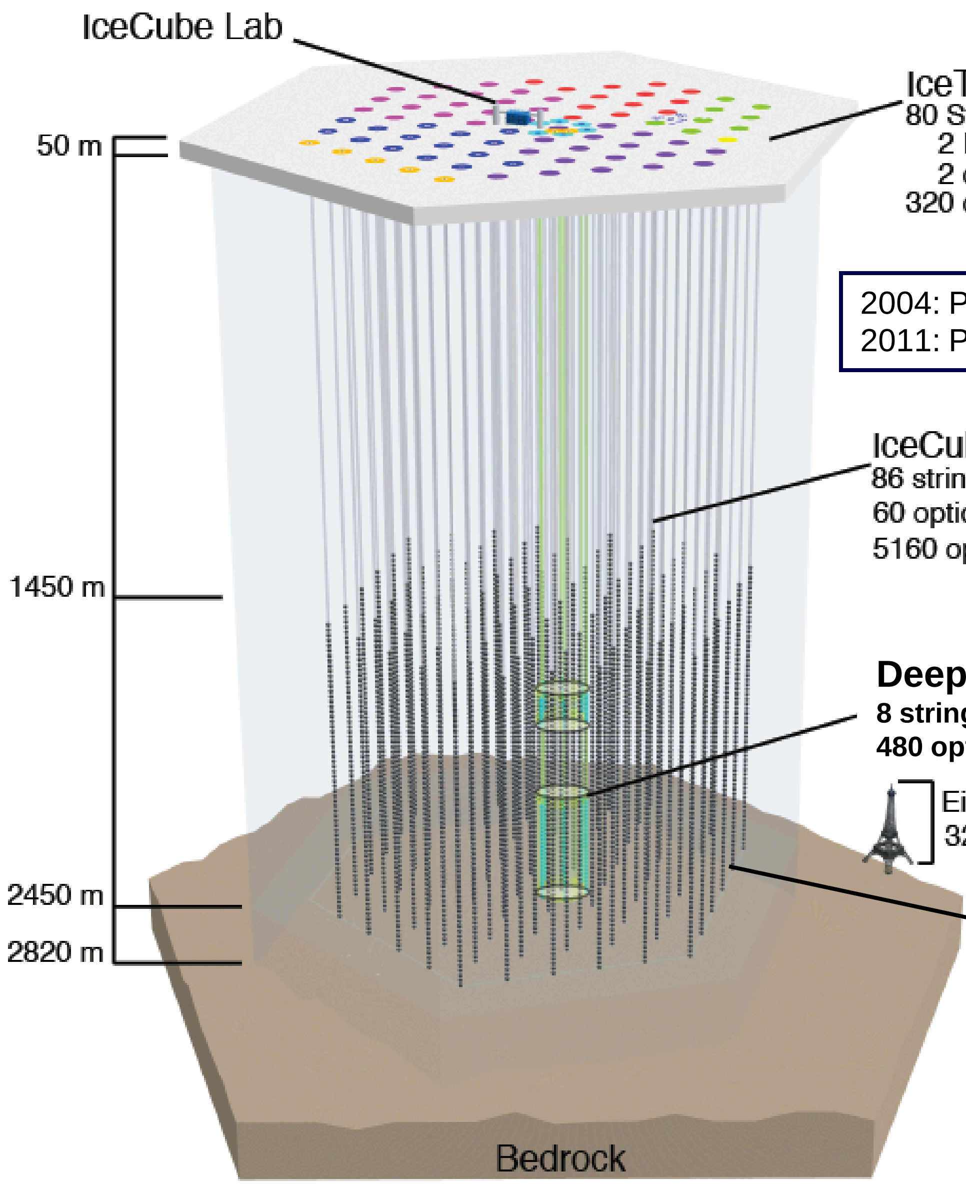


Expected GZK neutrino rates in 1 km^3 detector: ~ 1 per year


Amundsen-Scott Station (US)
Counting house
Geographical South Pole
IceCube footprint
DeepCore
footprint
Drill Camp
Skiway

The IceCube Neutrino Observatory

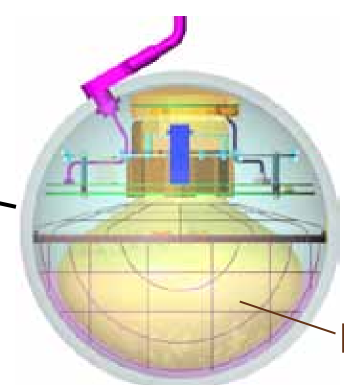
Completed: Dec 2010



2004: Project Start	1 string
2011: Project completion	86 strings

Configuration chronology

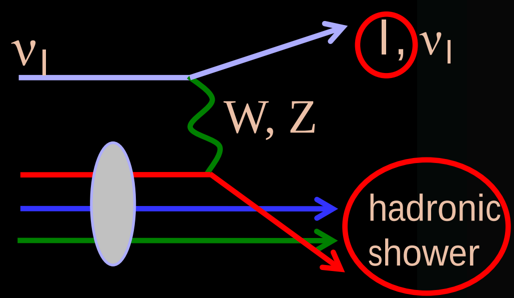
2006: IC9
2007: IC22
2008: IC40
2009: IC59
2010: IC79
2011: IC86



Digital Optical Module (DOM)

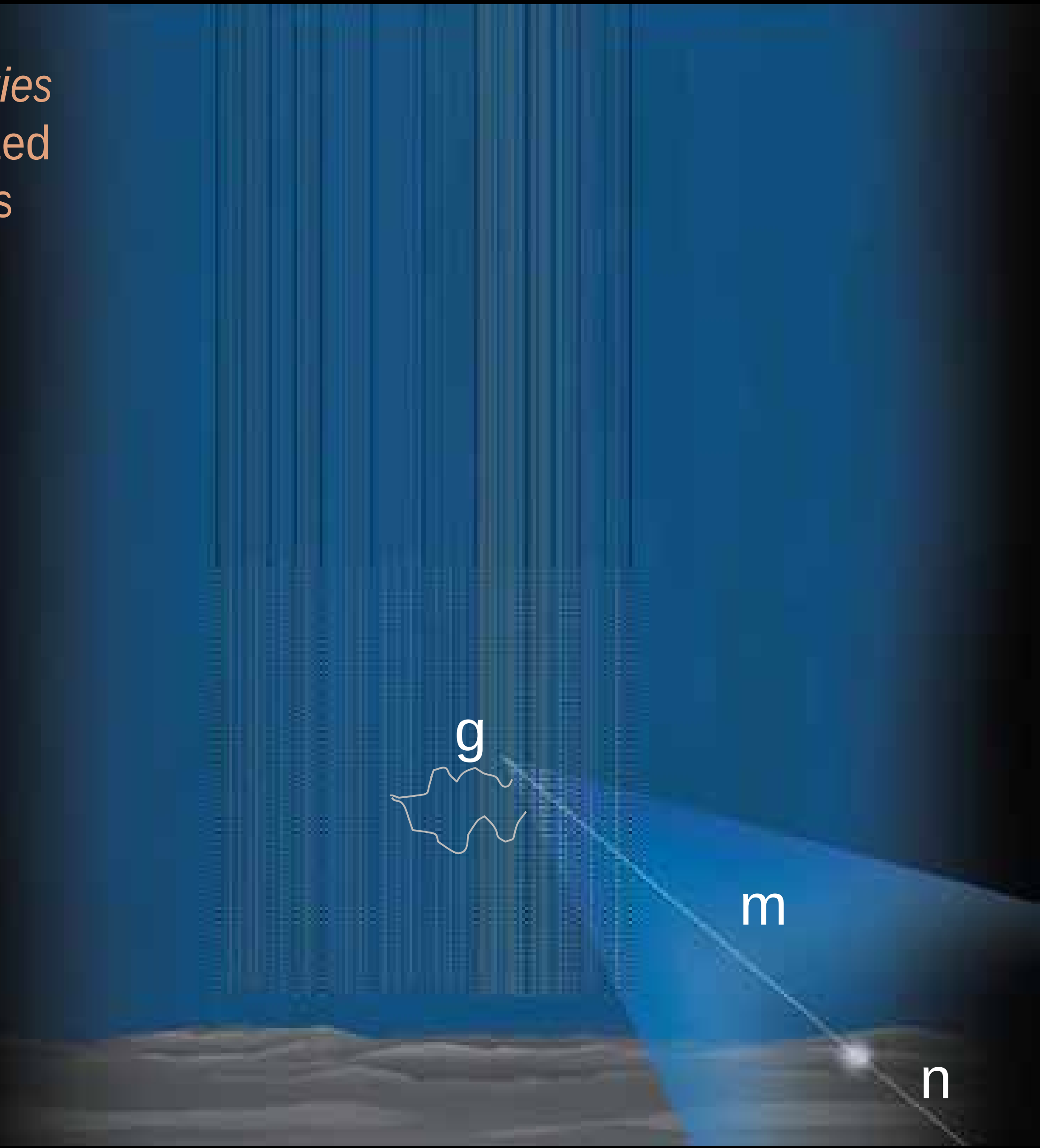
Neutrino Detection Principle

Observe the charged *secondaries* via Cherenkov radiation detected by a 3D array of optical sensors

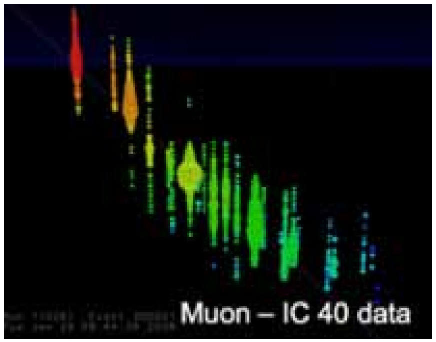


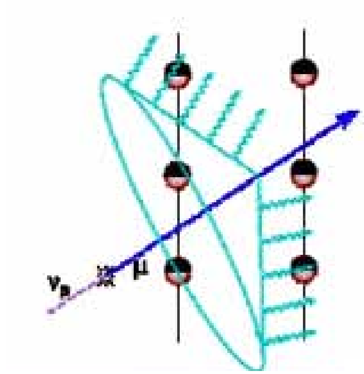
Need a huge volume (km^3) of an optically transparent detector material

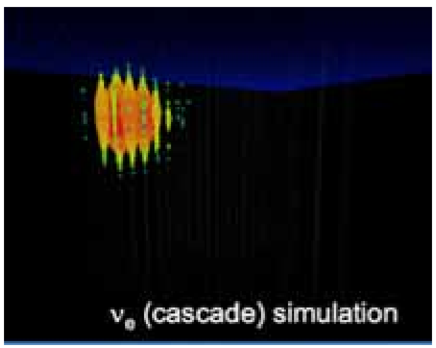
Antarctic ice is the most transparent natural solid known (absorption lengths up 200 m)

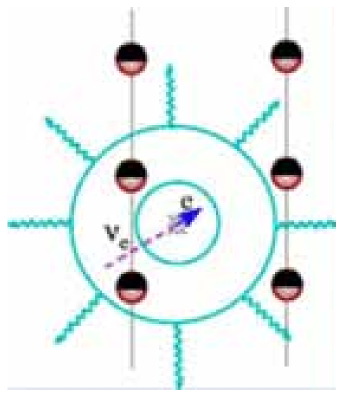


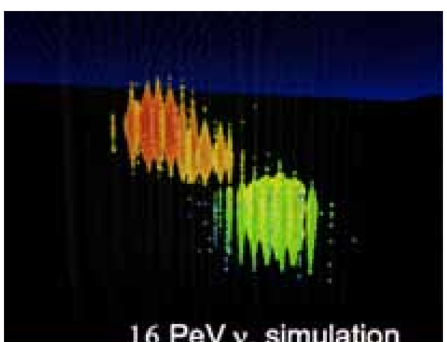
Neutrino Event Signatures











Tracks

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

§ pointing resolution ~1°

Cascades

§ e-m and hadronic cascades

$$\nu_{e(\tau)} + N \rightarrow e(\tau) + X$$
$$\nu_f + N \rightarrow \nu_f + X \quad f = e, \mu, \tau$$

§ energy resolution 10% in log(E)

Composites

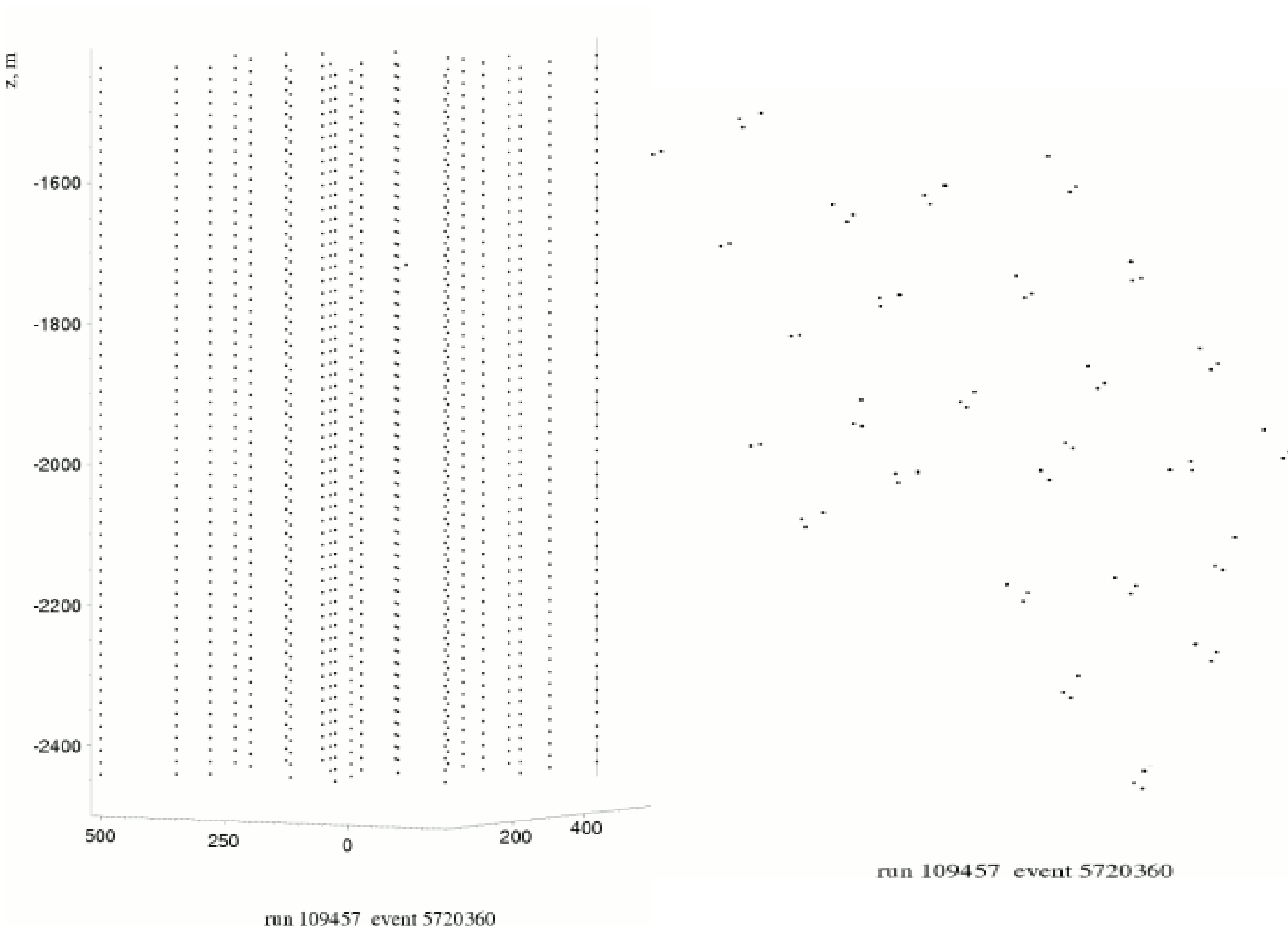
§ starting tracks

§ tau double bangs

§ good directional and energy resolution

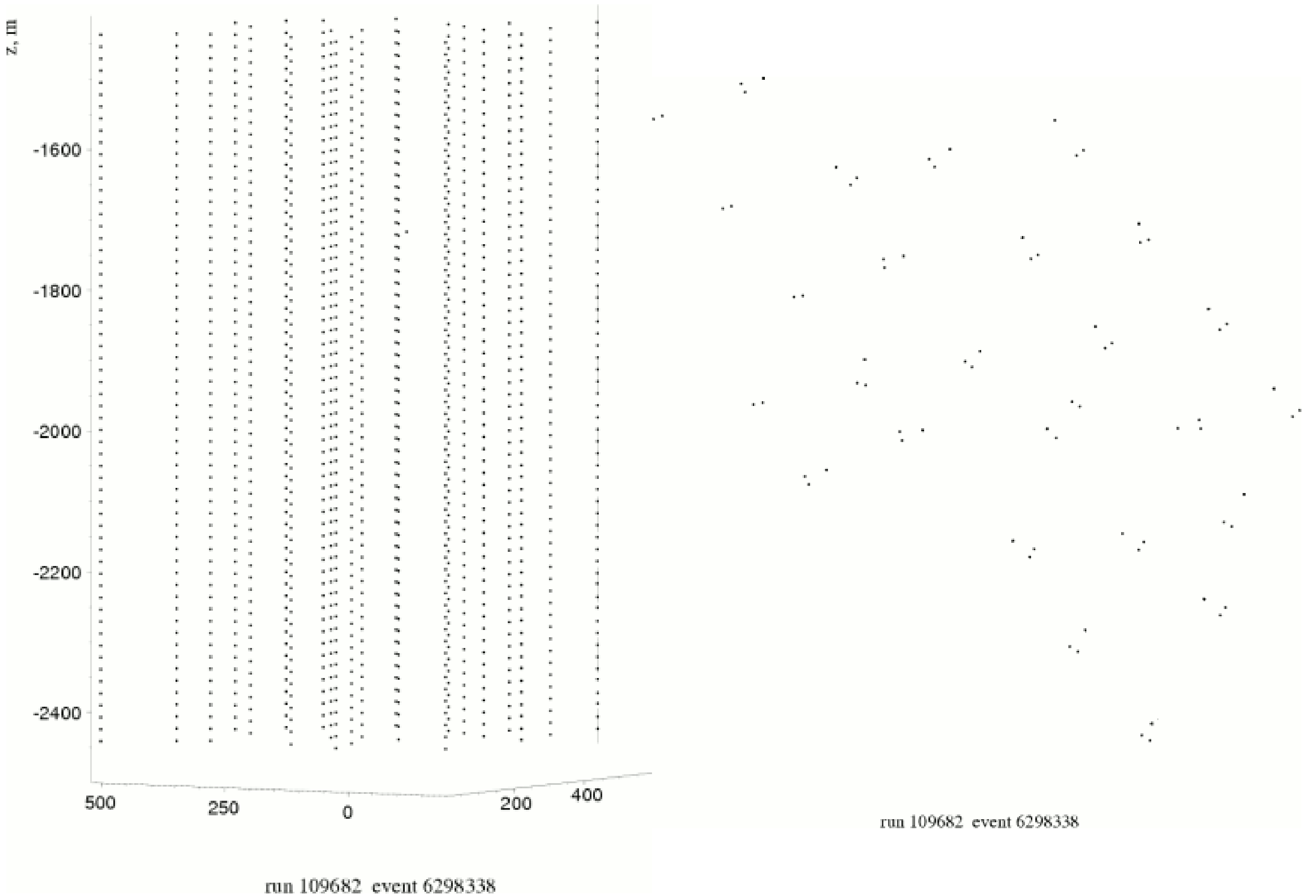
Up-going muon: signature of n_m event

IC22



Cascade candidate: signature of n_e event **IC22**

Reconstructed energy = 134 TeV

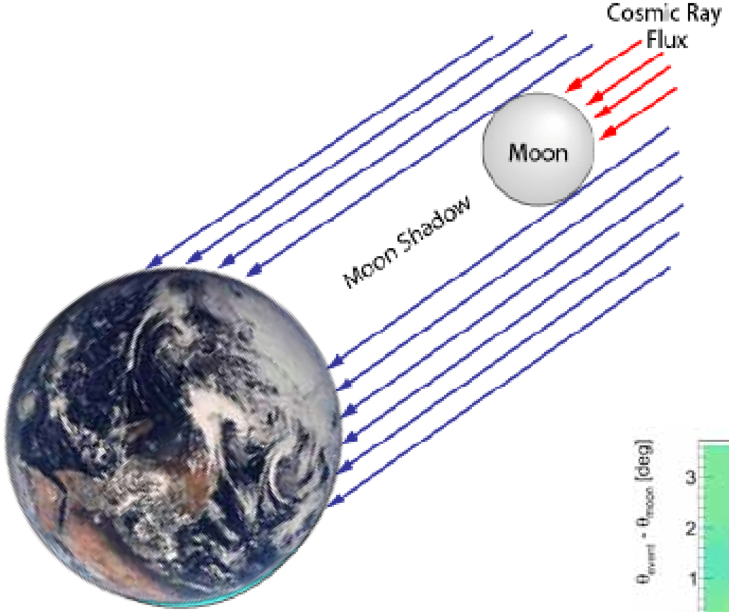


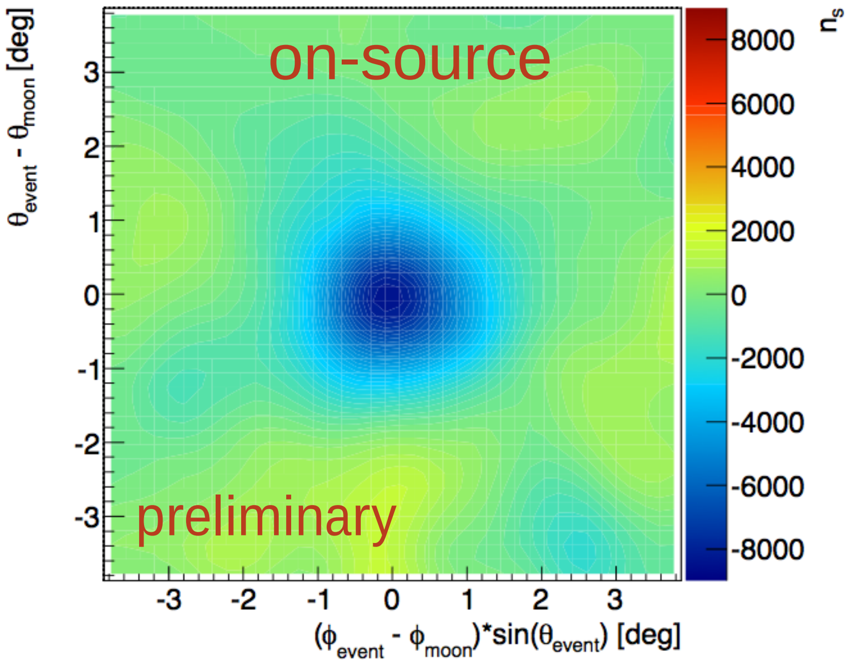
arXiv: 1101.1692

In the Shadow of the Moon

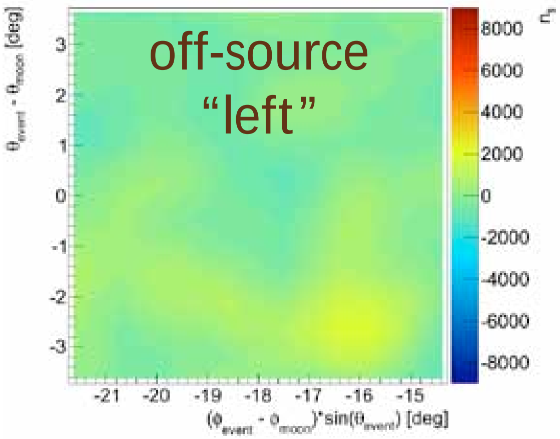
IC59

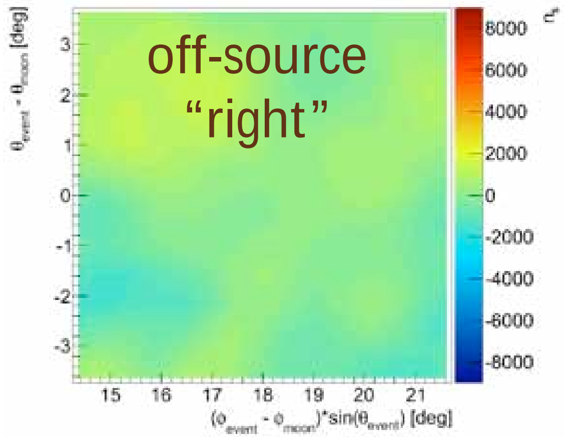
Cosmic rays blocked by the moon cause point-like deficit in angular distribution of down-going muons in the detector





Moon shadow seen with ~10s
Systematic pointing error < 0.1º
Verification of PSF for track reco.





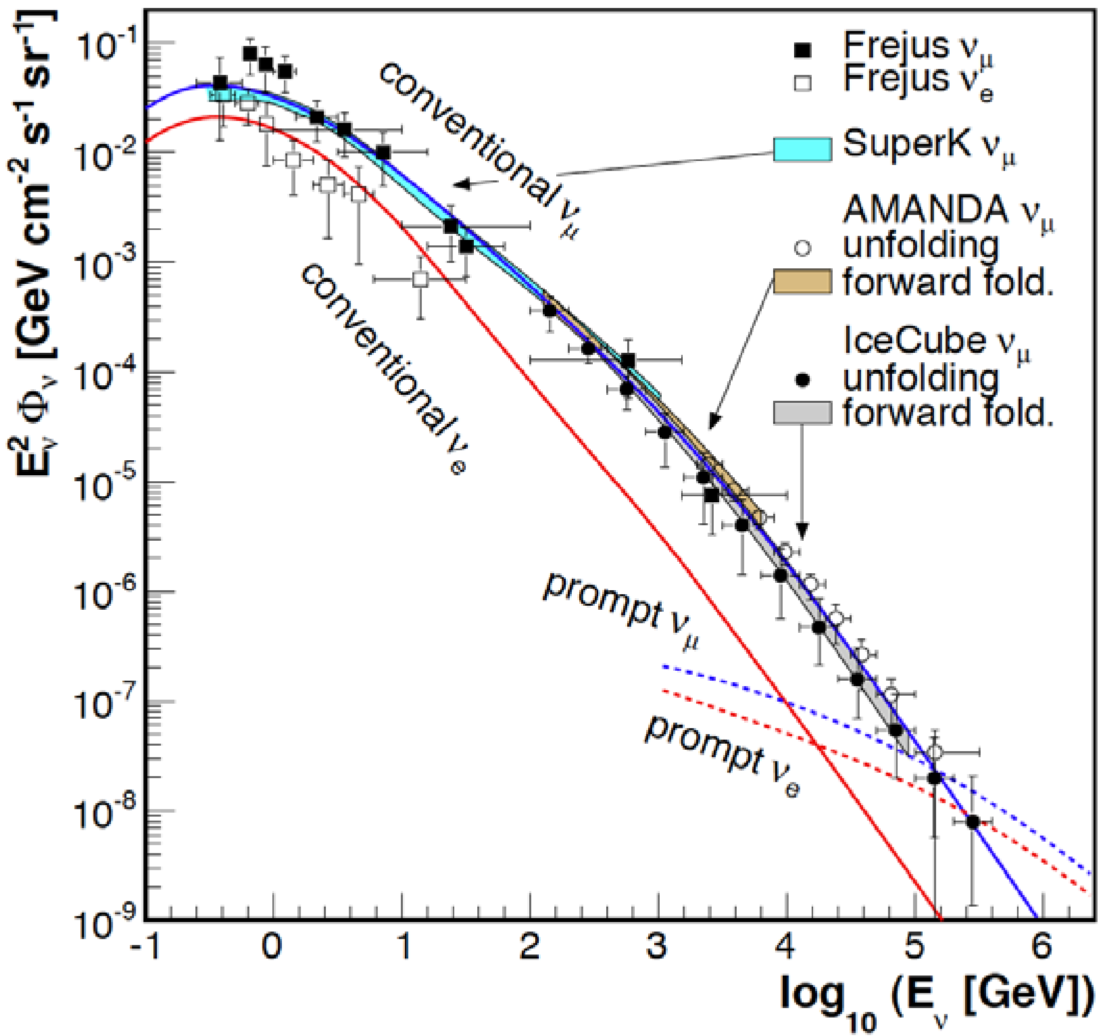
Need high statistics and good angular resolution!

Atmospheric Neutrinos

IC40

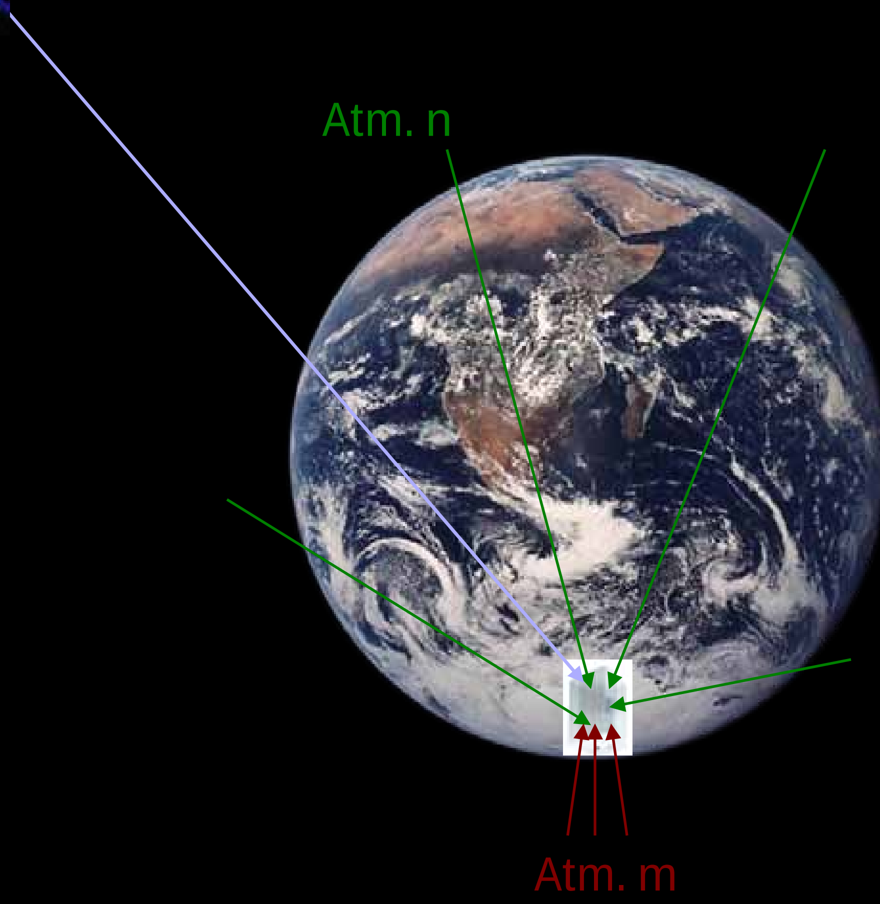
IceCube ν_μ spectrum up to 400 TeV

Phys. Rev. D83 (2011) 012001



Search for Neutrino Point Sources

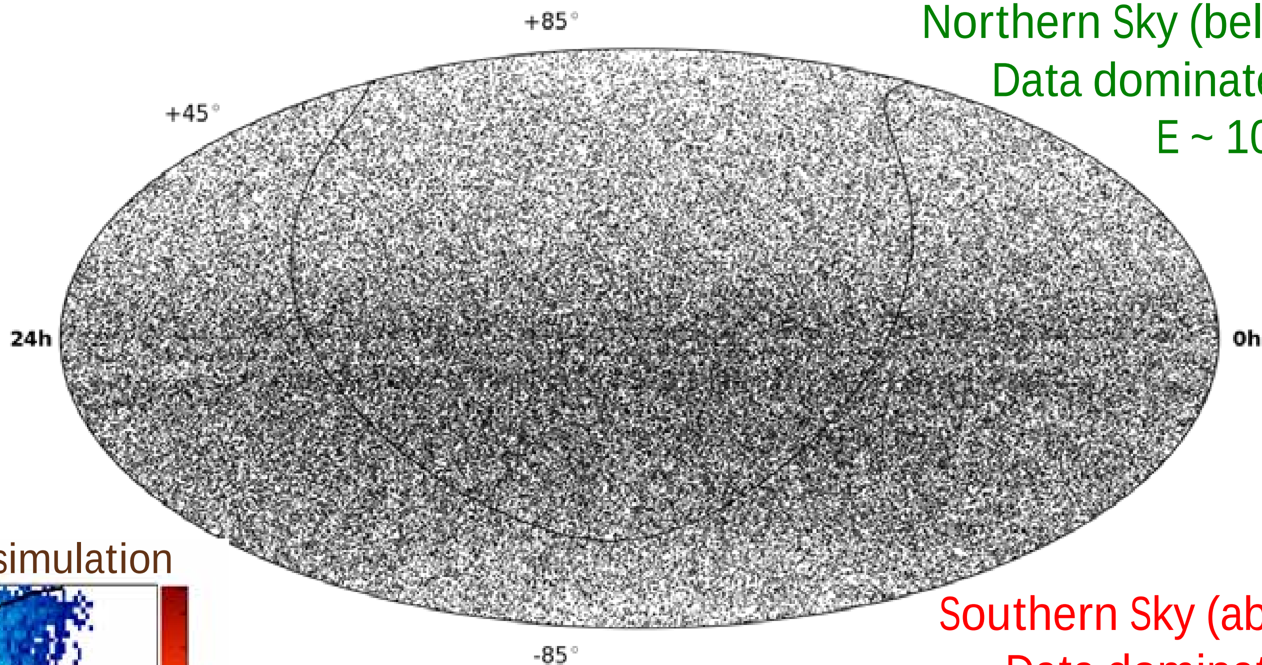
Search for an excess of astrophysical neutrinos from a common direction over a background of atmospheric neutrinos



All-Sky Point Source Search

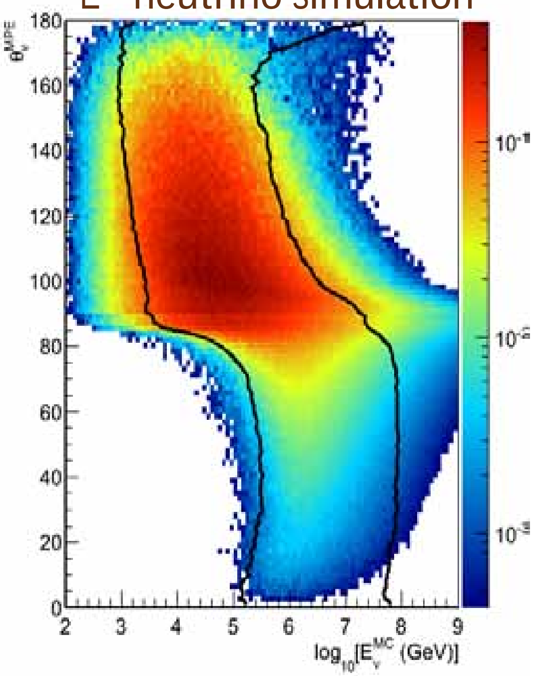
IC40+IC59

Northern Sky (below the horizon)
Data dominated by atmos. n's
E ~ 10's - 100's of TeV



Southern Sky (above the horizon)
Data dominated by atmos. m's
E > PeV, increasing with angle

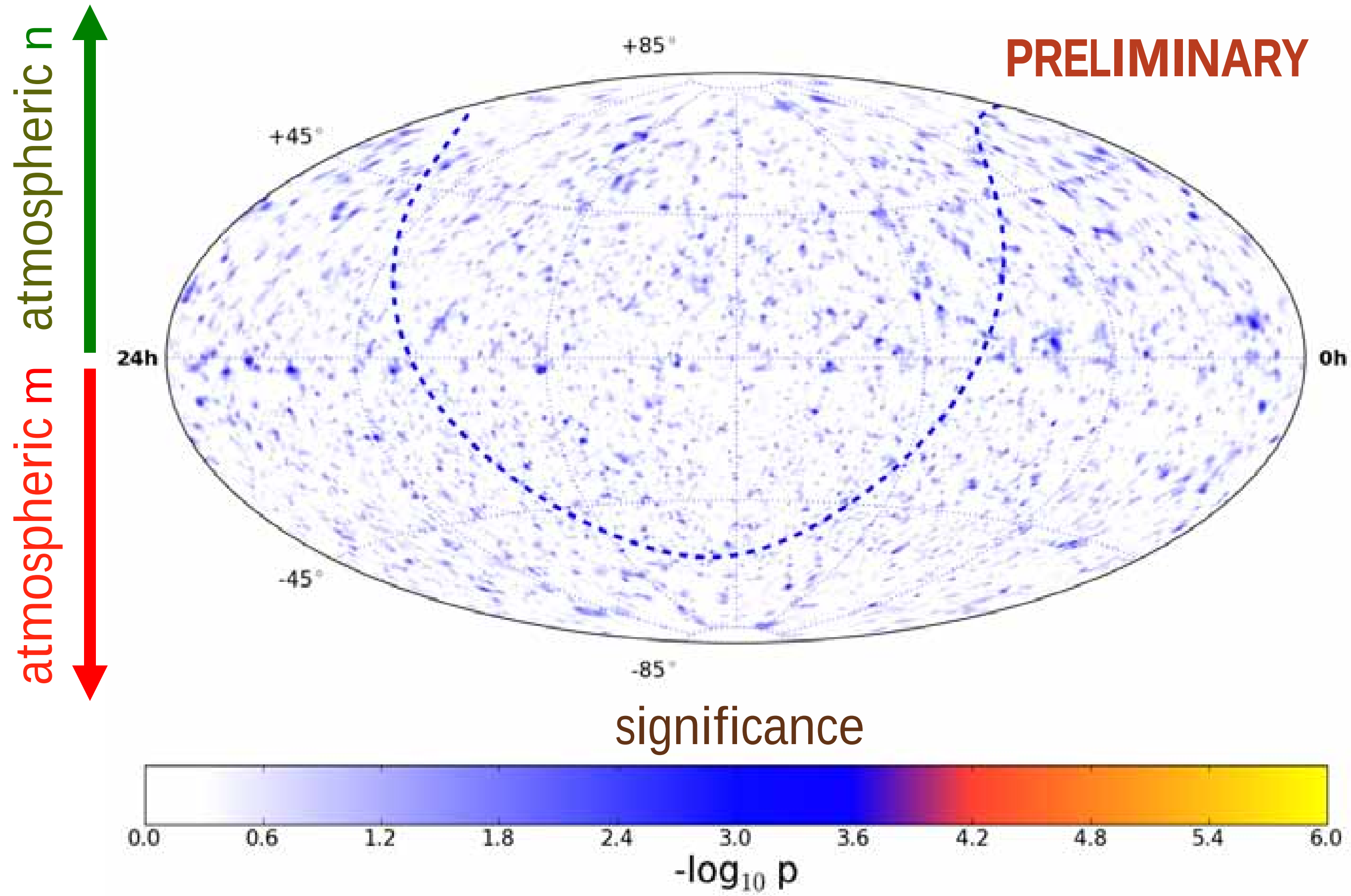
E^{-2} neutrino simulation



More than 107,000 events:
43,339 upgoing + 64,230 downgoing
Livetime: 348 days (IC59) + 375 days (IC40)

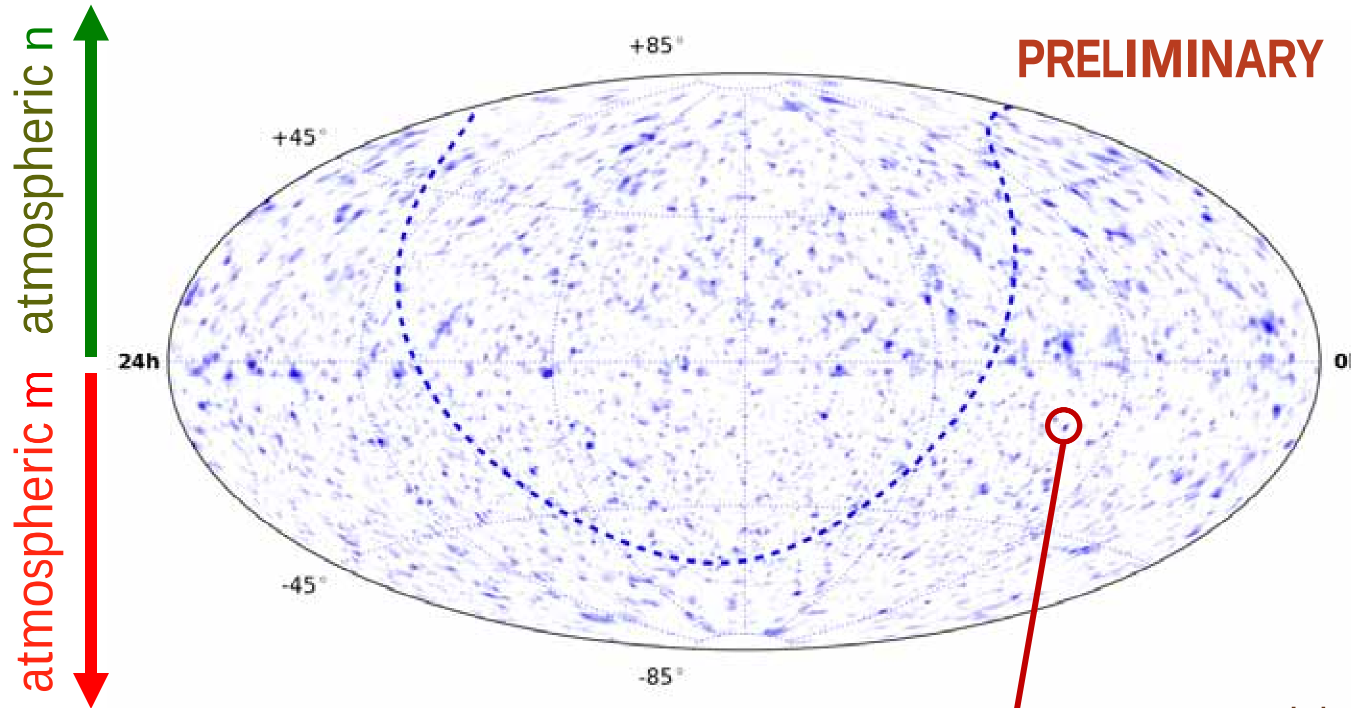
All-Sky Point Source Search

IC40+IC59



All-Sky Point Source Search

IC40+IC59



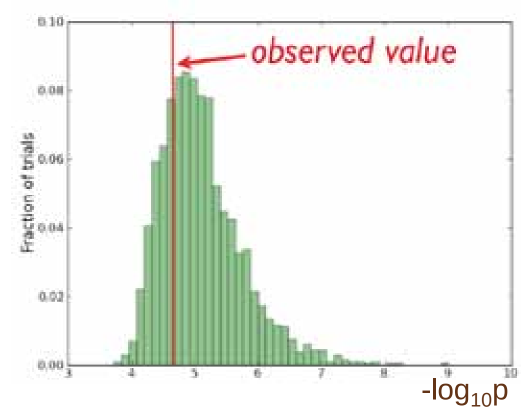
significance

Hottest spot

(Ra=75.45, Dec=-18.15)

$-\log_{10}p = 4.65$
$nSrc_{best} = 18.3$
$g_{best} = 3.9$

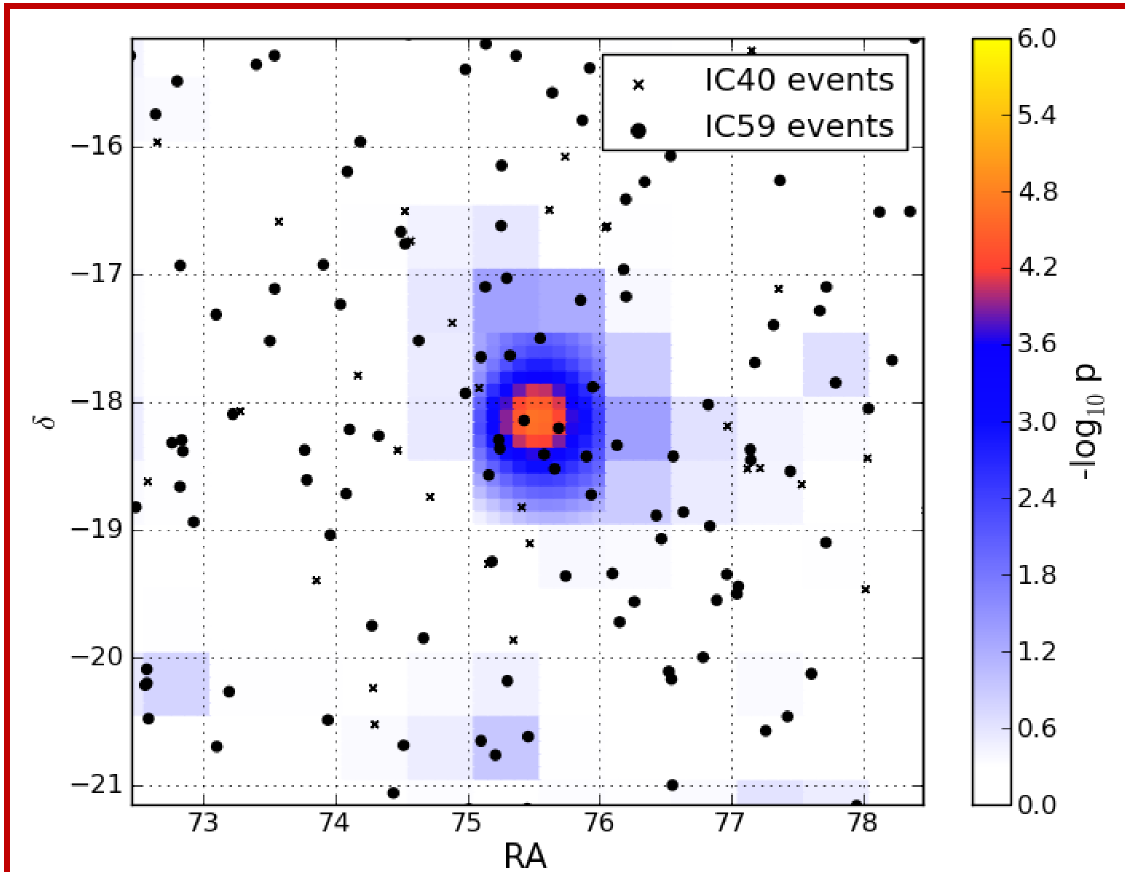
Highest significance in azimuthally scrambled skymaps (2000 trials)

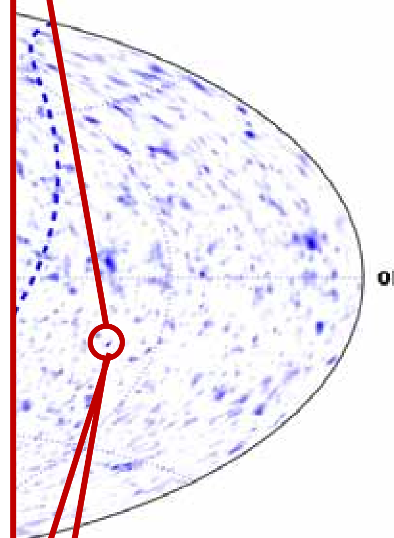


Not significant: 74.2% of trials have significance ≥ hottest spot

IC40+IC59

PRELIMINARY





Hottest spot

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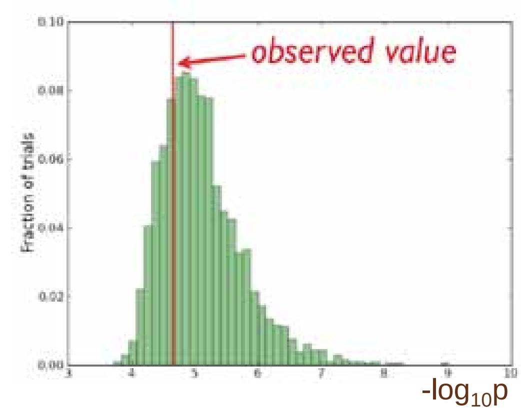
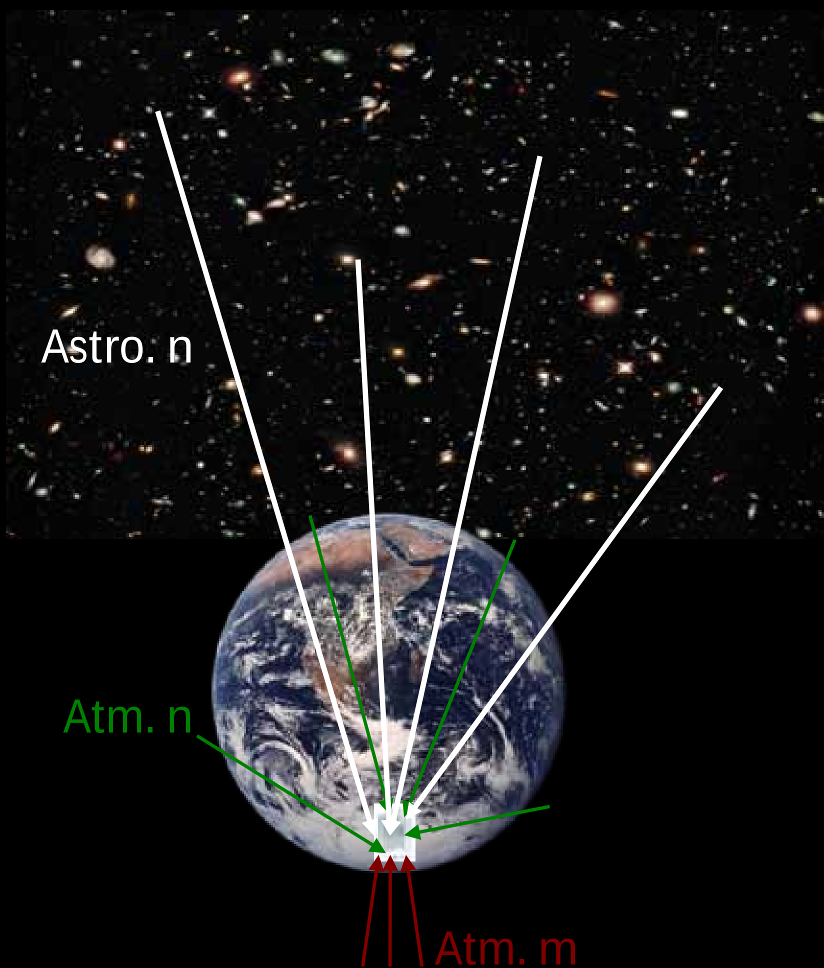


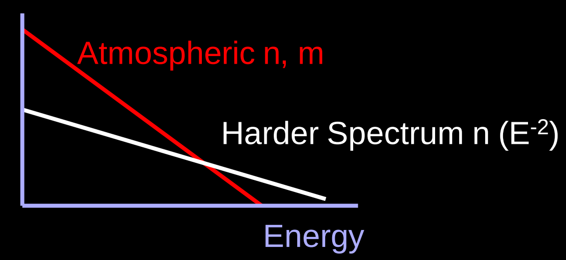
Not significant: 74.2% of trials have significance ≥ hottest spot

Searches for a Diffuse Neutrino Flux

Diffuse Flux = effective sum from all (unresolved) extraterrestrial sources (e.g., AGNs)
Possibility to observe diffuse signal even if flux from any individual source is too weak for detection as a point source



Search for excess of astrophysical neutrinos with a harder spectrum than background atmospheric neutrinos



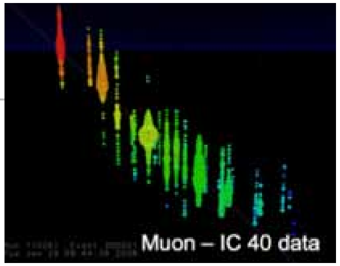
Advantage over point source search:
  can detect weaker fluxes

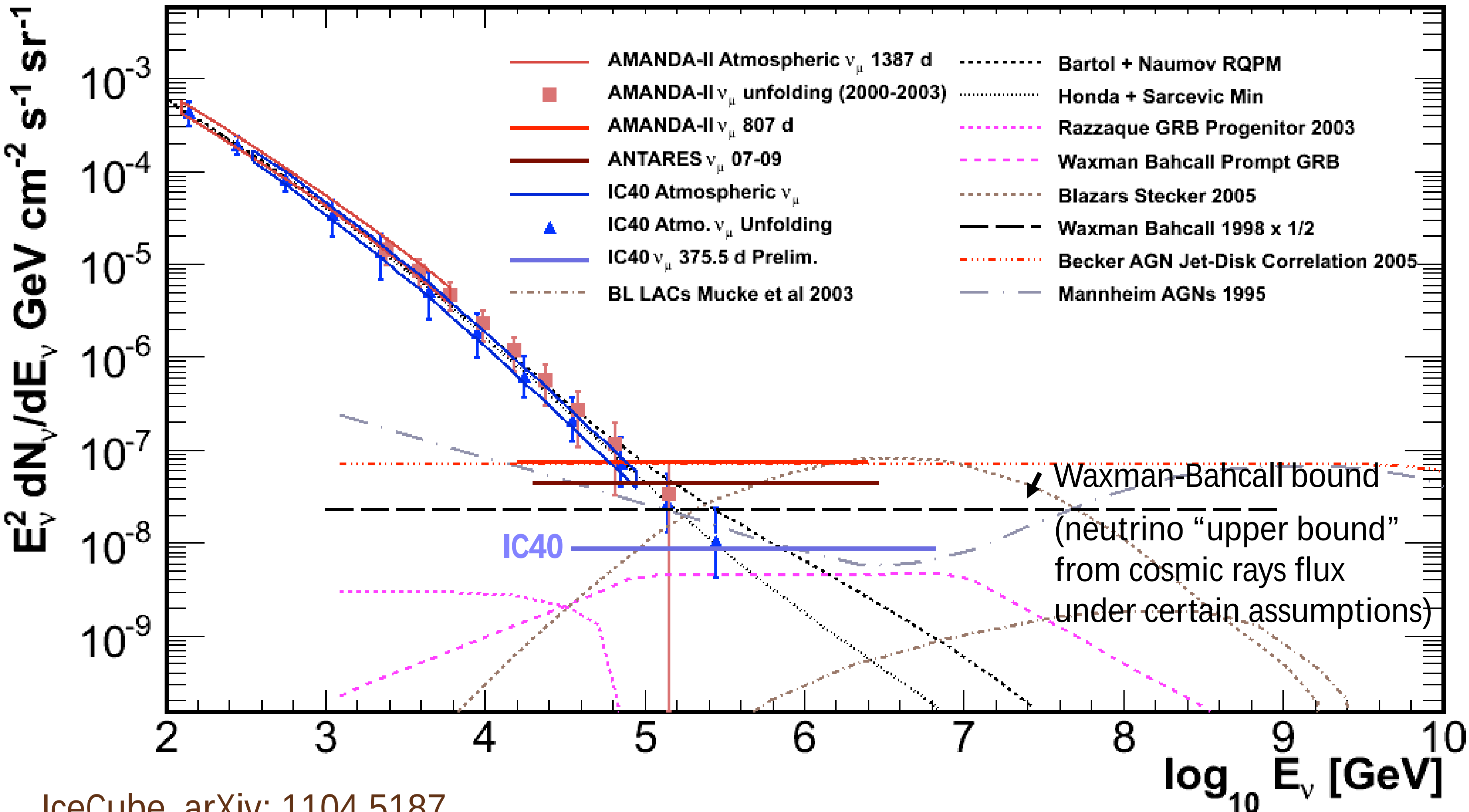
Disadvantages:
  high background
  must simulate background precisely

Sensitive to all three neutrino flavors

Limits on a diffuse muon neutrino flux

Experimental upper limits on the diffuse flux of muon neutrinos from sources with F ~ E^{-2} energy spectrum

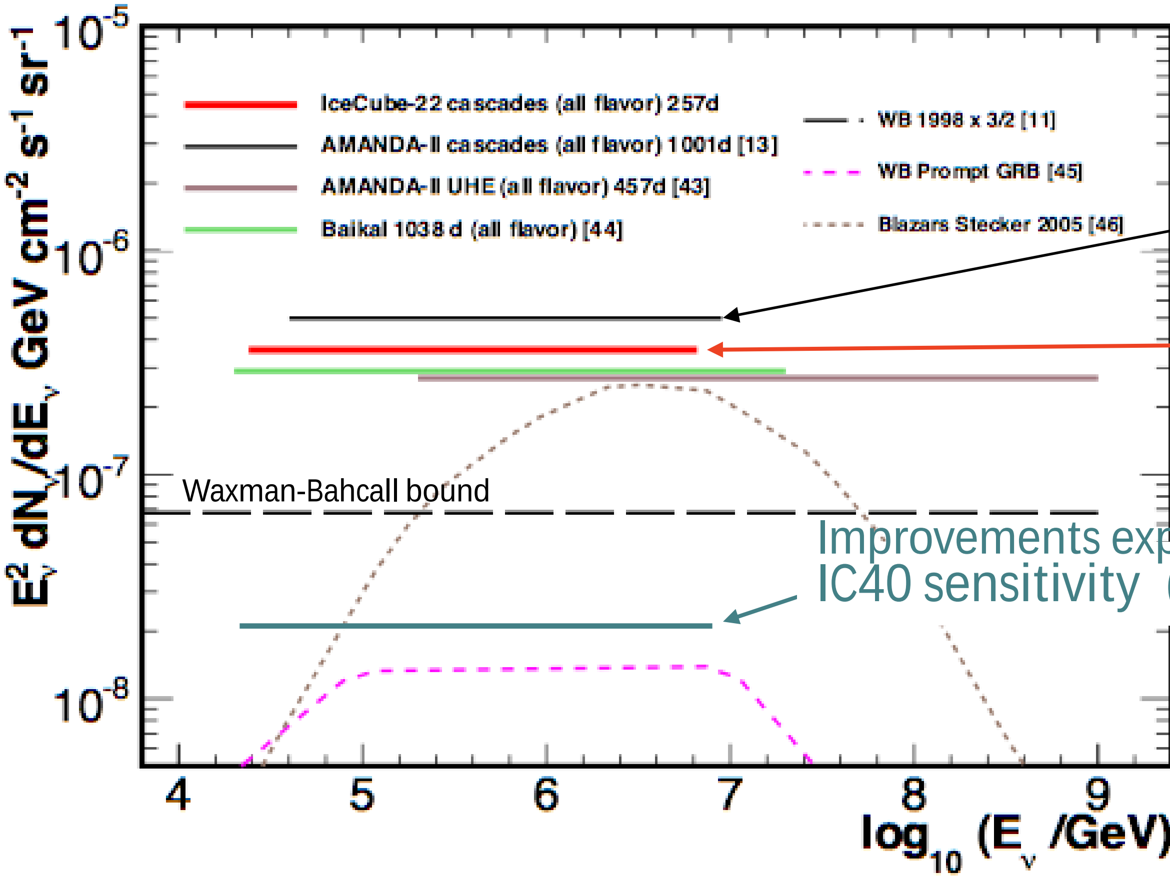


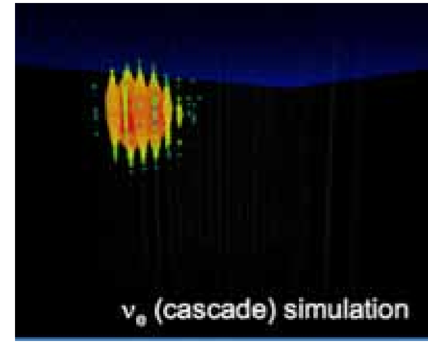


IceCube, arXiv: 1104.5187

Limits on a diffuse neutrino flux: cascades

Experimental upper limits on the diffuse flux of neutrinos from sources with F ~ E^{-2} energy spectrum





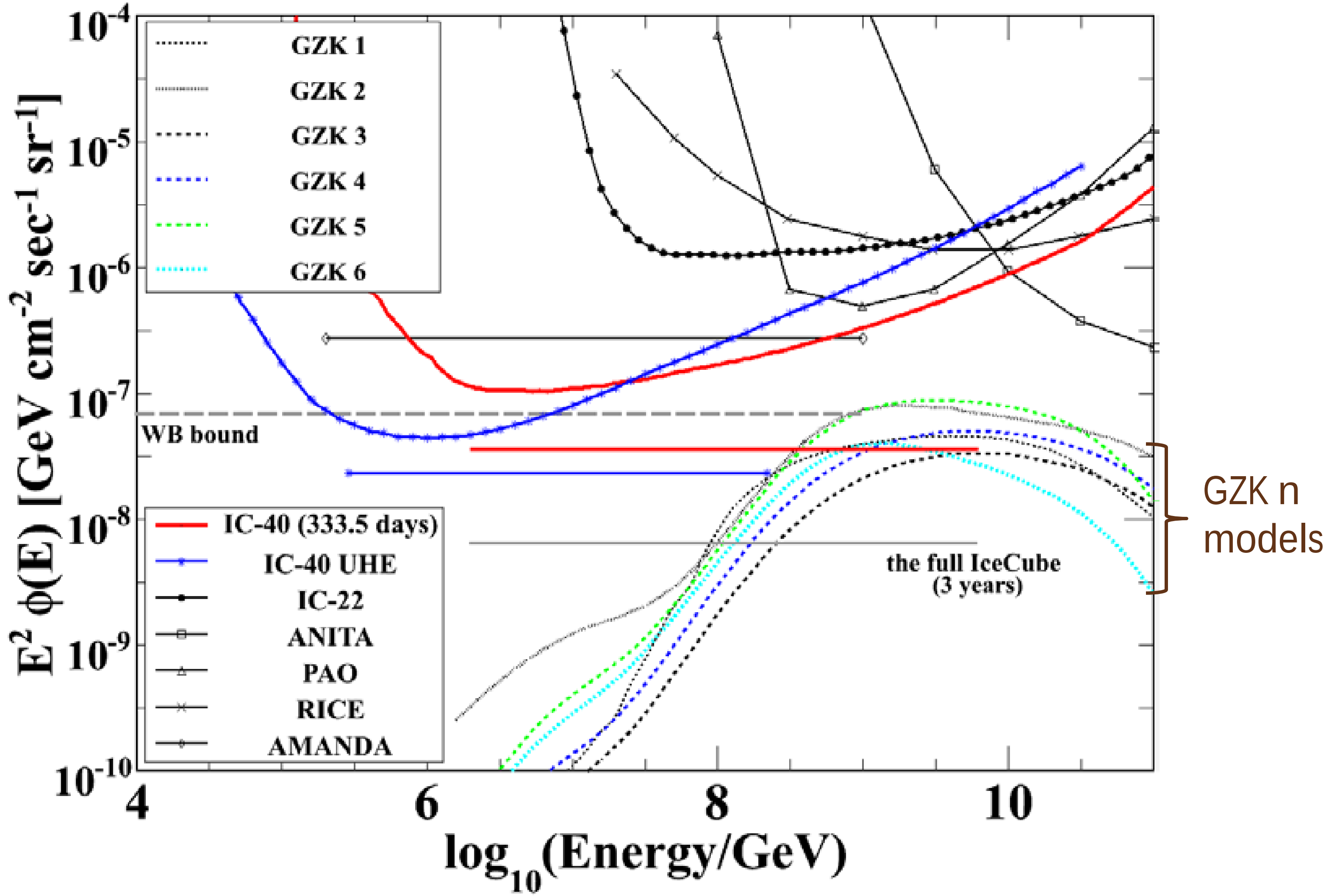
AMANDA (1001d)
Astropart. Phys. 34 (2011) 420

IC22 (257d)
arXiv: 1101.1692

Improvements expected with a larger detector
IC40 sensitivity (337d)

Extremely High-Energy Cosmic Neutrino Fluxes

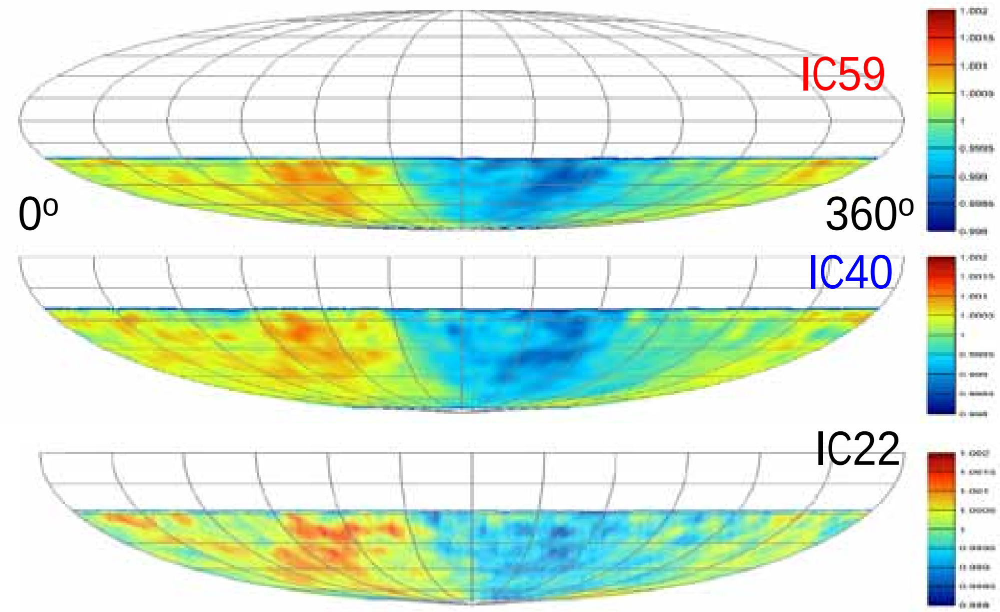
Phys. Rev. D83 (2011) 092003

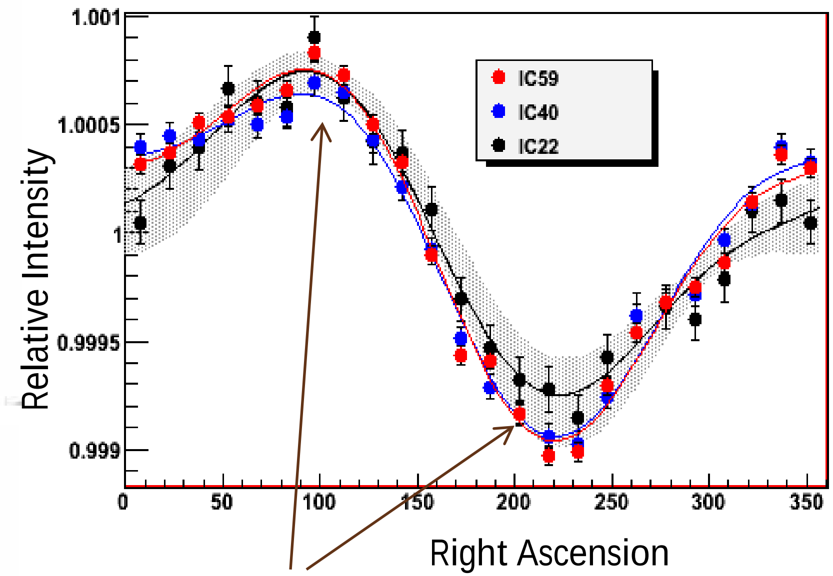


The world's best all-flavor n upper limits to date from 10^6 to 10^{10} GeV

Cosmic Ray Anisotropy

Observation of **anisotropy** in the arrival directions of cosmic rays



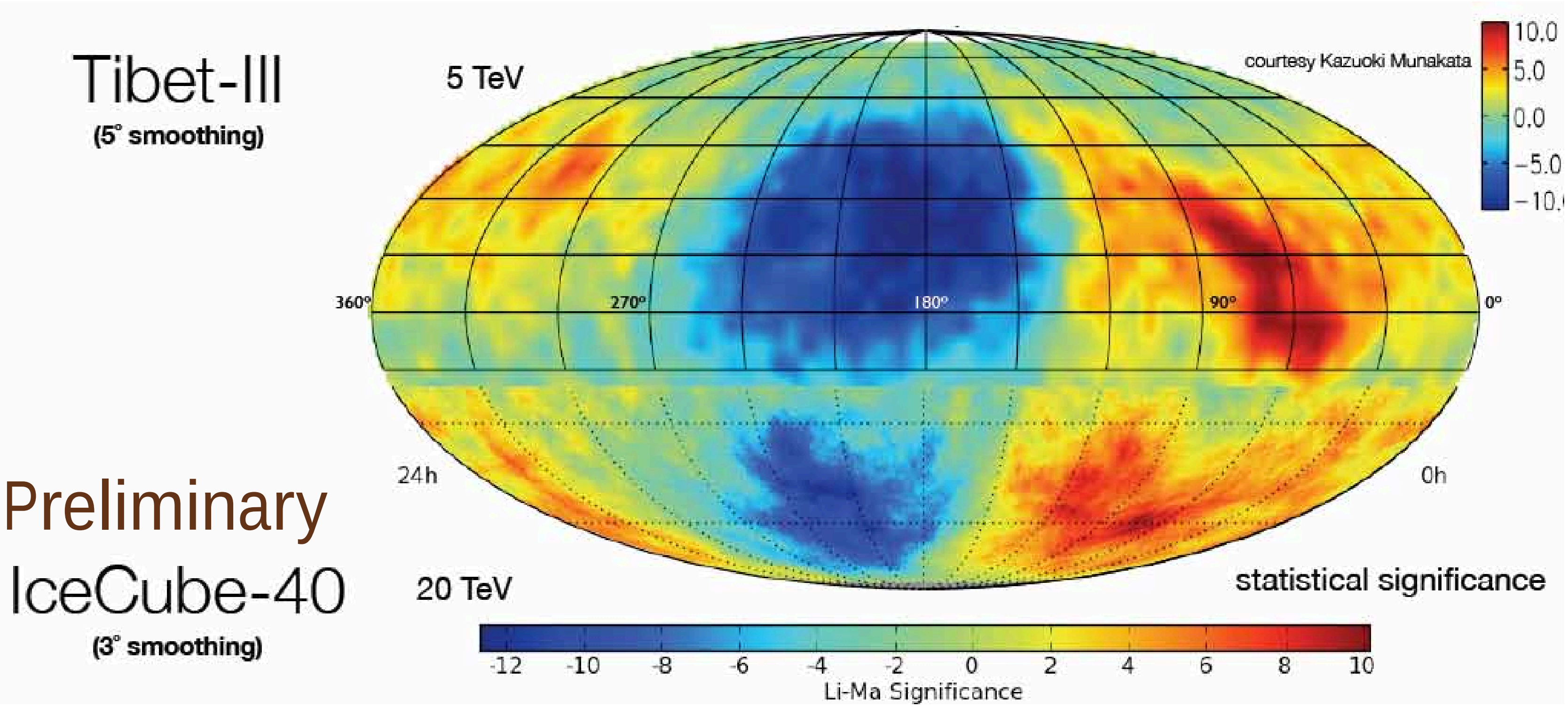


not 180° between min/max → not a dipole

Year	Rate (Hz)	LiveTime	CR Median Energy	Median Angular Resolution	Events
2007 (IC22)	240	~226 days	~19 TeV	3°	$4 \cdot 10^9$
2008 (IC40)	780	~324 days	~19 TeV	3°	$1.9 \cdot 10^{10}$
2009 (IC59)	1200	~324 days	~19 TeV	3°	$3.3 \cdot 10^{10}$

Cosmic Ray Anisotropy

Anisotropy seen in Southern Sky by IceCube is continuation of anisotropy seen in Northern Sky



Cause of anisotropy not known. Speculations include:

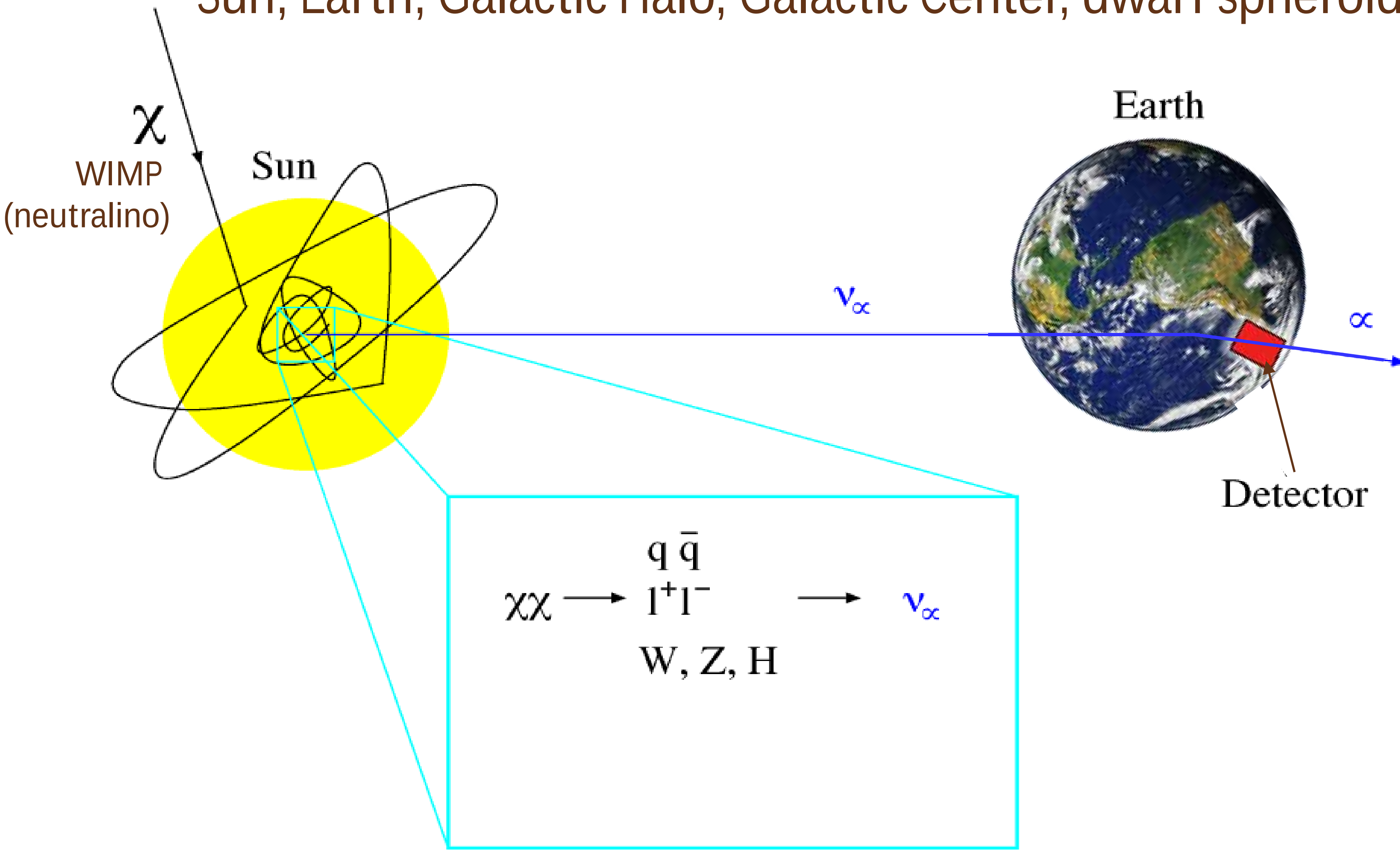
- Isolated nearby and recent SNR (unlikely)
- Configuration of magnetic fields in or near solar system
- Compton-Getting effect (not consistent with data)

Further studies of anisotropy vs energy, angular scale, time variability, spectral properties, ...

Indirect Dark Matter Searches

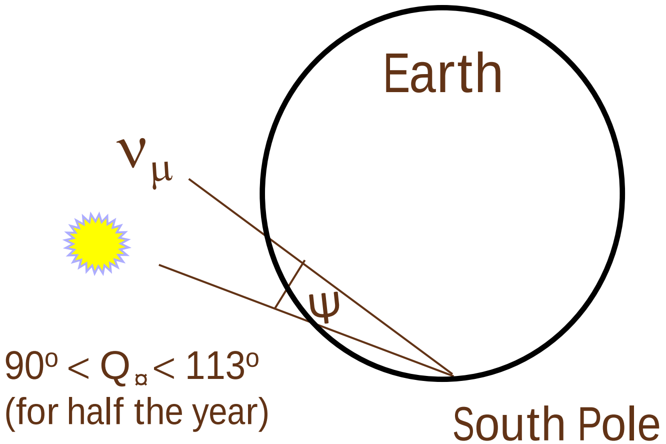
Search for neutrinos from objects where Dark Matter can have accumulated gravitationally over the evolution of the Universe:

Sun, Earth, Galactic Halo, Galactic Center, dwarf spheroids…

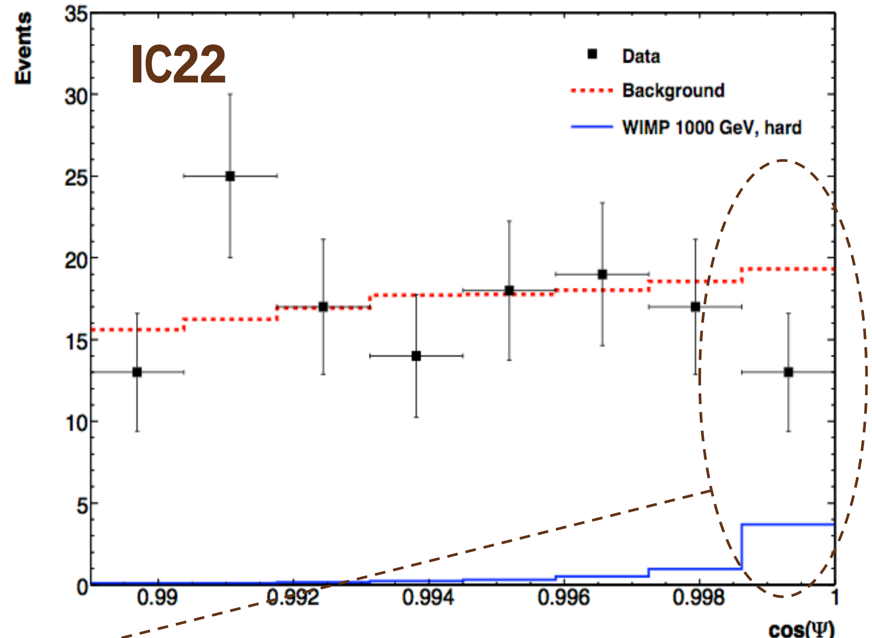


Indirect Dark Matter Search: Solar WIMPs

Data collected when the Sun is below the horizon at South Pole



Phys. Rev. Lett. 102 (2009) 201302



No excess of events from the Sun, observation consistent with the expected background

⇒ upper limit on the number of signal events at 90% CL : μ_s

⇒ 90% CL limit on the neutrino to muon conversion rate: $\Gamma_{\nu\rightarrow\mu} = \frac{\mu_s}{V_{eff} \times T}$

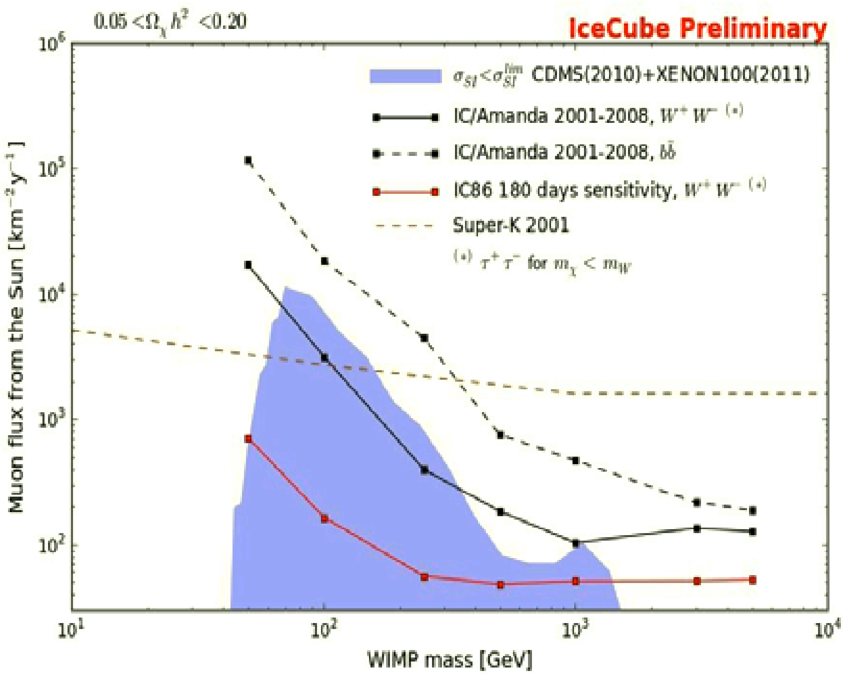
⇒ 90% CL limit on the neutralino annihilation rate in the Sun: $\Gamma_A = \kappa^{-1}(\chi) \times \Gamma_{\nu\rightarrow\mu}$

Indirect Dark Matter Search: Solar WIMPs

IceCube/AMANDA results from 1065 days of livetime between 2001-2008

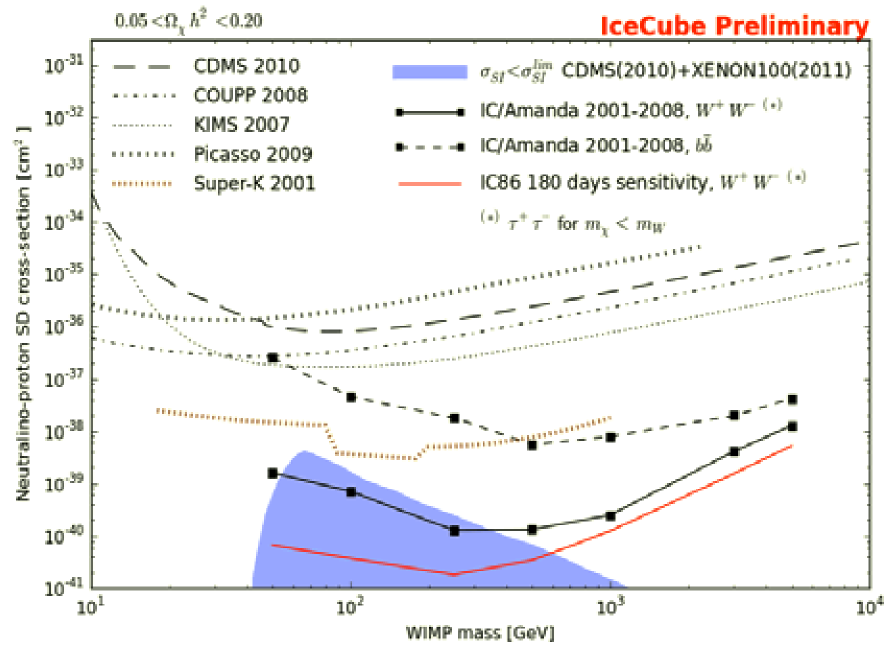
90% CL **muon flux limit** from the Sun

(compared to MSSM scans)



90% CL **neutralino-p Xsection** limit

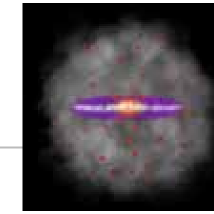
(compared to MSSM scans)



$$\Phi\mu \rightarrow \Gamma_A \rightarrow C_c \rightarrow \sigma_{Xp}$$

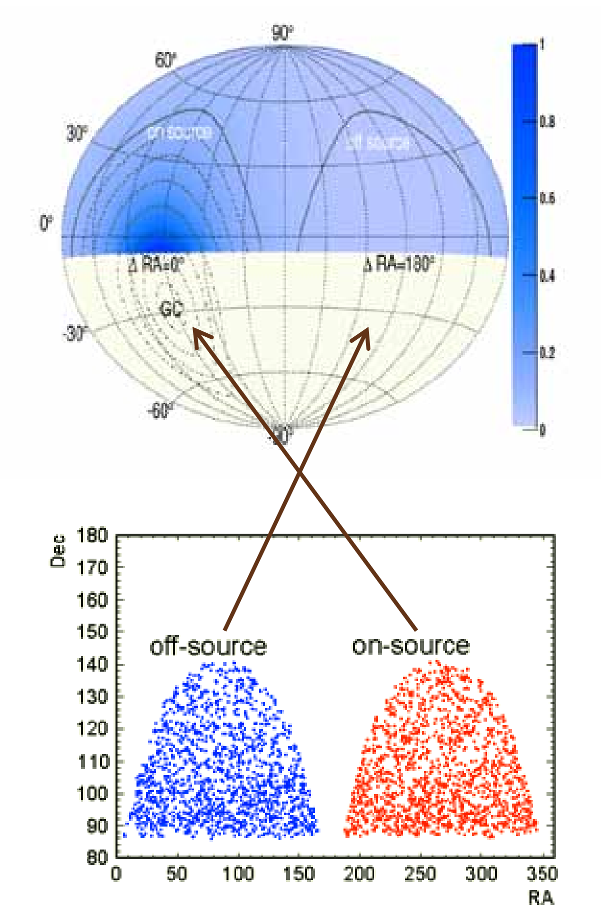
(particle physics and solar model)

Indirect Dark Matter Search: Galactic Halo



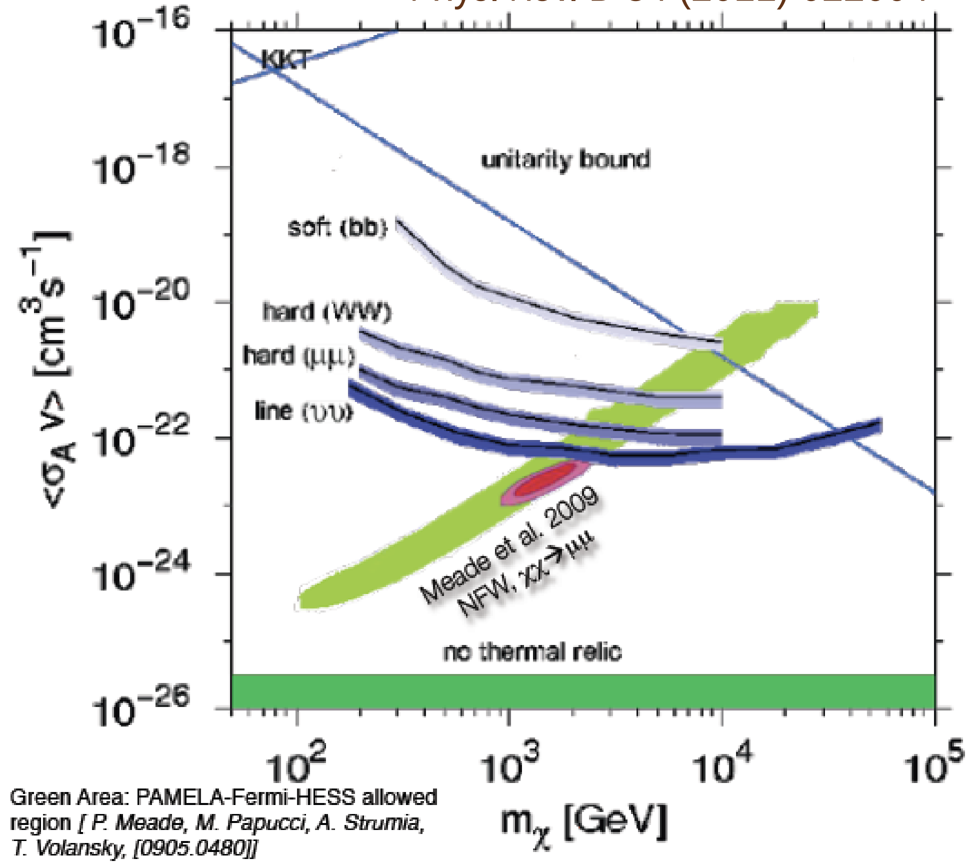
IC22 (275 days)

Expected relative neutrino flux from DM self-annihilation in GH



neutrino candidates

Phys. Rev. D 84 (2011) 022004



No observed excess over background

Summary

IceCube Neutrino Observatory completed

- The era of km^3 neutrino astronomy has begun
- Physics run with complete detector started in May, 2011

100,000+ high-energy neutrinos on the books

No astrophysical neutrino sources detected yet

Increased sensitivity at lower energies with DeepCore

Lots of physics to come:

cosmic ray spectrum · cosmic ray composition · cosmic ray anisotropies · atmospheric neutrinos (prompt component, oscillations, effects of quantum gravity, sterile neutrinos, …) · neutrino point sources · gamma ray bursts · GZK neutrinos · multimessenger approaches · diffuse n fluxes · dark matter · magnetic monopoles · supernova bursts · shadow of the moon · atmospheric physics · glaciology · climatology · new technologies for highest energies (radio, acoustics)

The IceCube Collaboration

http://icecube.wisc.edu

36 institutions, ~250 members

Canada
University of Alberta

US
Bartol Research Institute, Delaware
Pennsylvania State University
University of California - Berkeley
University of California - Irvine
Clark-Atlanta University
University of Maryland
University of Wisconsin - Madison
University of Wisconsin - River Falls
Lawrence Berkeley National Lab.
University of Kansas
Southern University, Baton Rouge
University of Alaska, Anchorage
University of Alabama, Tuscaloosa
Georgia Tech
Ohio State University

Barbados
University of West Indies

Sweden
Uppsala Universitet
Stockholms Universitet

UK
Oxford University

Germany
Universität Mainz
DESY-Zeuthen
Universität Dortmund
Universität Wuppertal
Humboldt-Universität zu Berlin
MPI Heidelberg
RWTH Aachen
Universität Bonn
Ruhr-Universität Bochum

Japan
Chiba University

Belgium
Université Libre de Bruxelles
Vrije Universiteit Brussel
Universiteit Gent
Université de Mons-Hainaut

Switzerland
EPFL, Lausanne

New Zealand
University of Canterbury

ANTARCTICA
Amundsen-Scott Station