The latest results from the IceCube experiment

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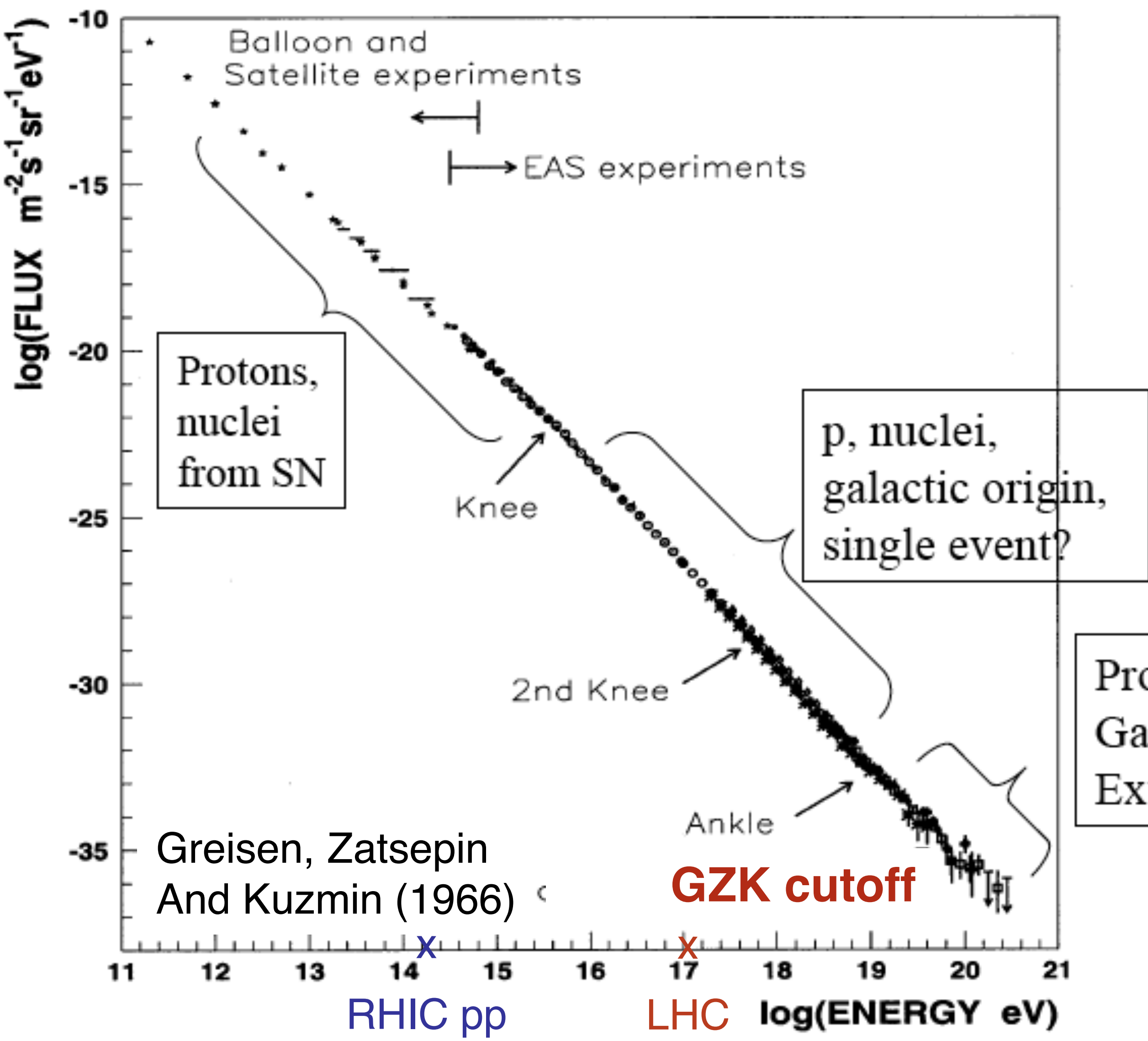
Outline:

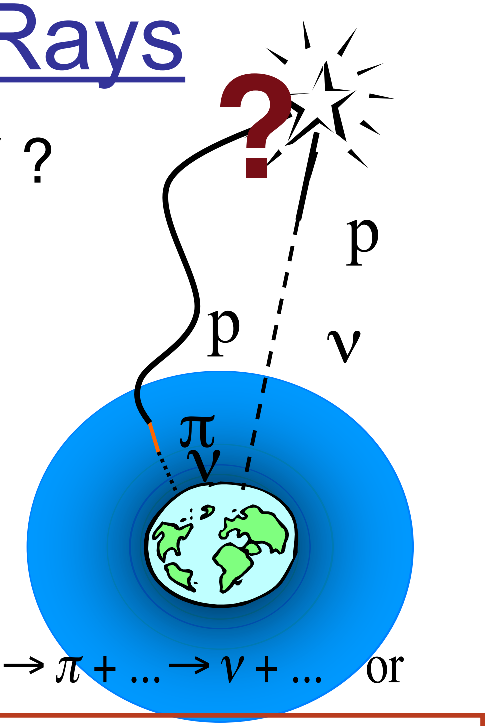
- Motivation why a km^3 scale detector?
- Detector description
- Latest (Selected) Results
- Summary

Neutrino Sources and Cosmic Rays

What is the origin of Cosmic Rays with E up to 10^{20} eV ?



Protons? Nuclei?
Gammas? Exotics?
Extra-galactic origin



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

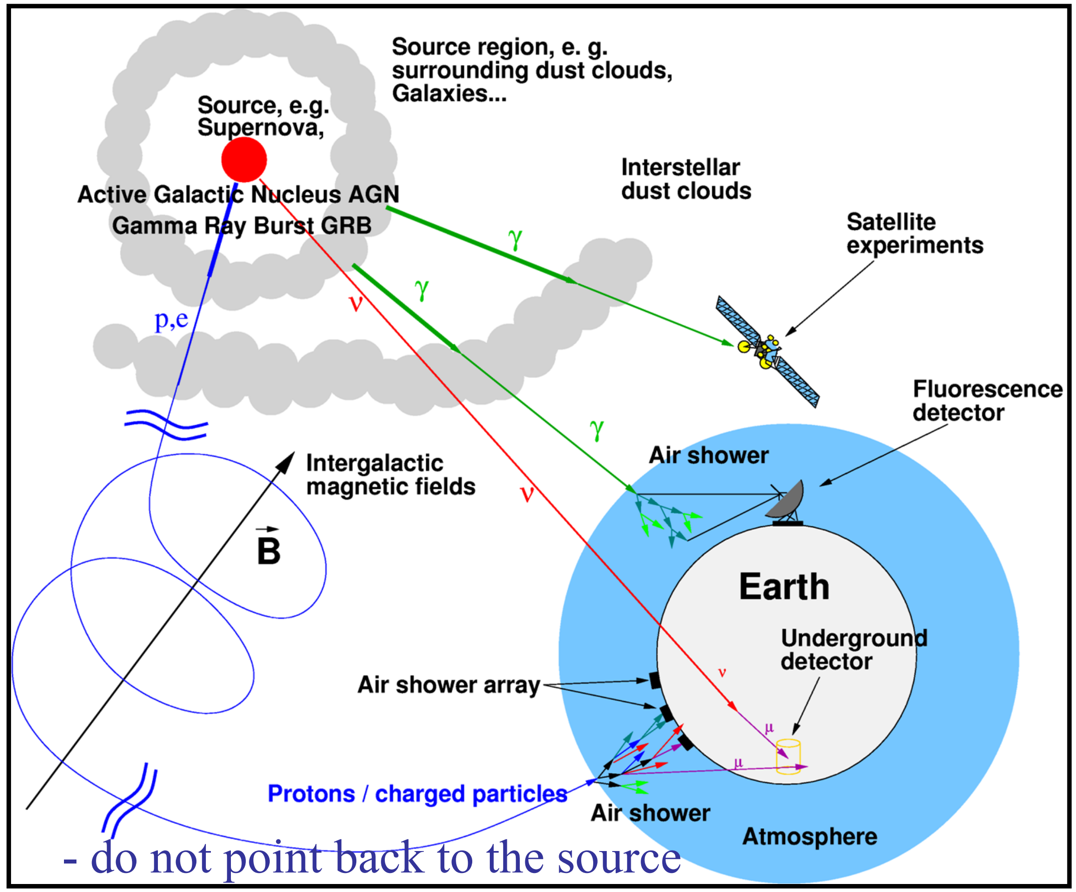
$p + \gamma_{CMB} \rightarrow \Delta \rightarrow \pi + n \rightarrow \nu + \ldots$

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

Neutrino Astronomy

Neutrinos as probes of the high-energy Universe

- Protons with $E_p < 10$ EeV directions scrambled by magnetic fields
- γ-rays: straight-line propagation but reprocessed in the sources; TeV γ–ray astronomy: many newly discovered (galactic and extragalactic sources)
- Neutrinos: straight-line propagation, unabsorbed, not GZK suppressed, will provide evidence of hadronic acceleration; but difficult to detect



Extraterrestrial high-energy neutrinos: discovery potential!

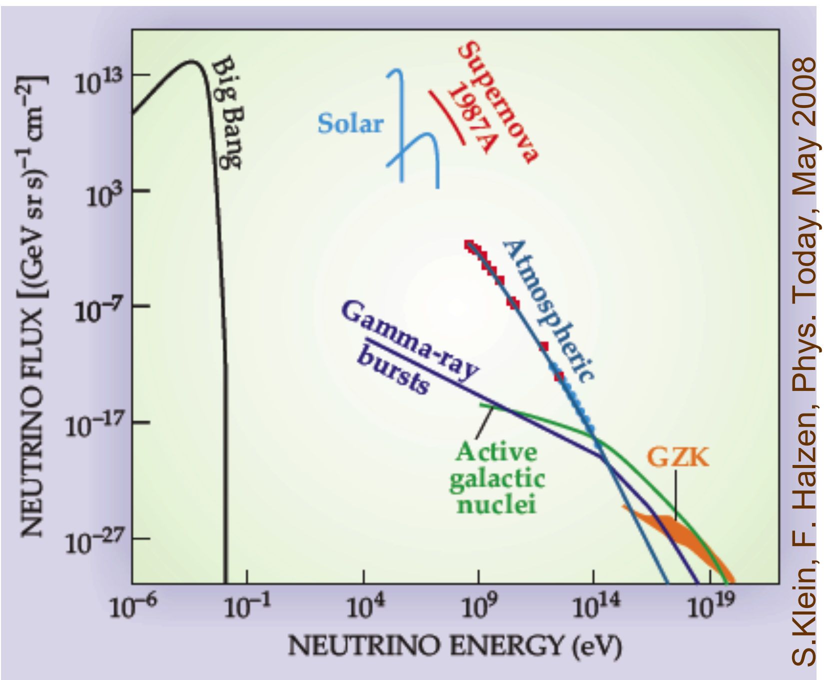
The only confirmed extraterrestrial low energy neutrino sources detected so far are the Sun and the supernova SN1987A

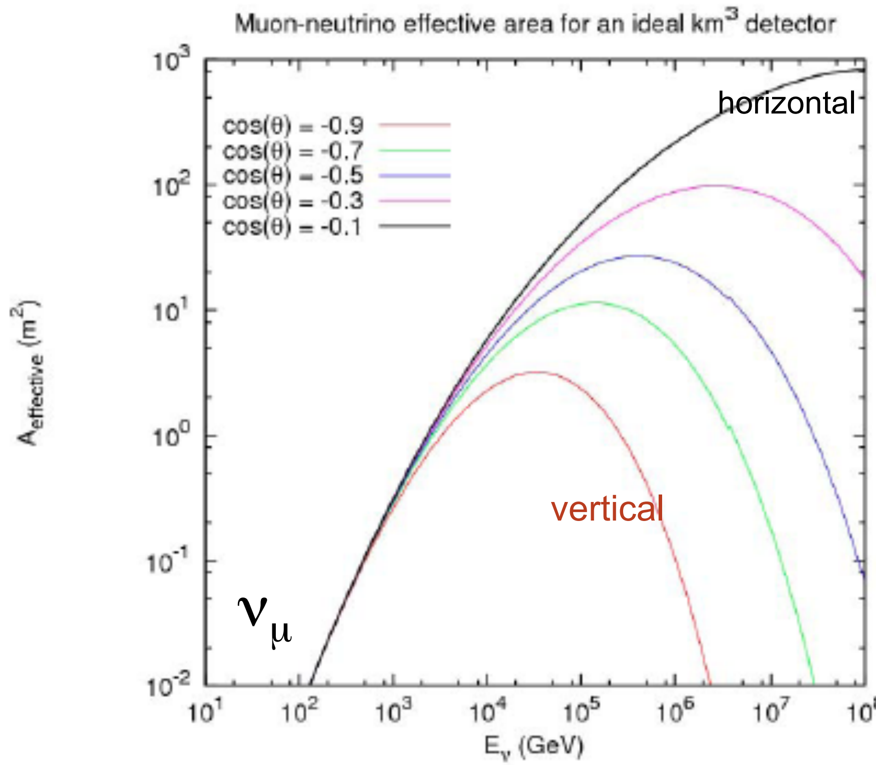
Need for a 1 km^3 Neutrino Detector

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 ν_μ)





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

IceCube

Science with IceCube

Main Goal: *Detect neutrinos of all flavors at energies from ~10^{10} eV to 10^{20} eV, and low energy ν's from supernovae*

Astronomy:

- Search for astrophysical neutrino ***point sources***
- Search for ***diffuse flux*** from all sources

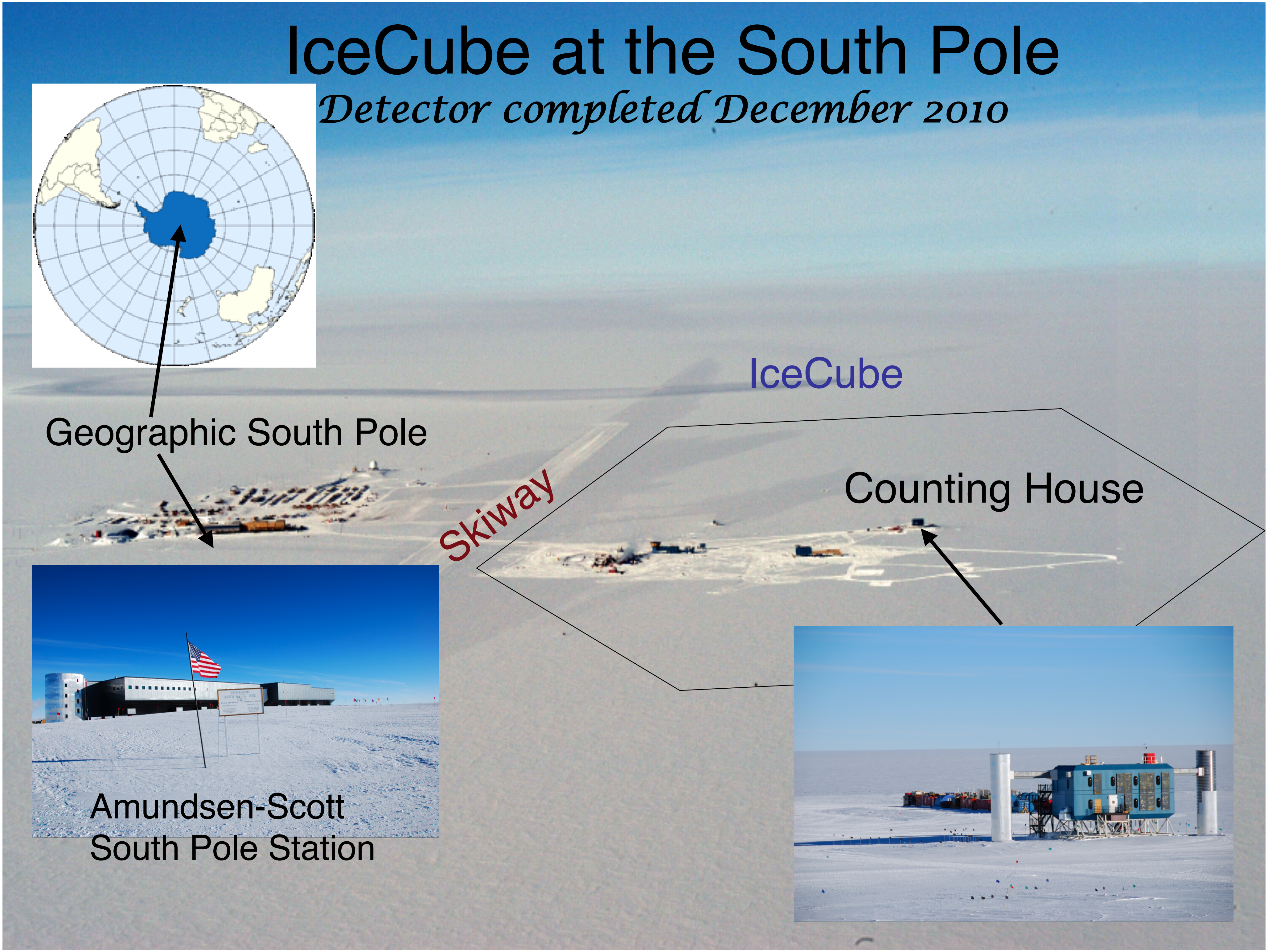
Physics Beyond Standard Model:

- Neutrino oscillations (Deep Core)
- Search for Dark Matter
- non-standard model neutrino interactions

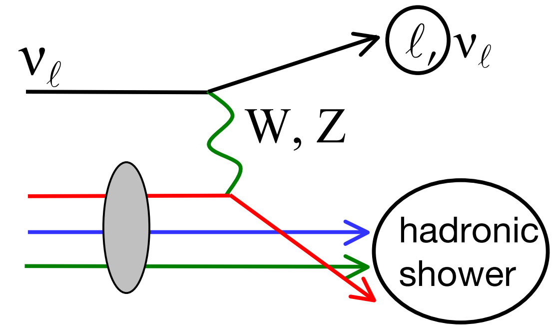
this talk

Cosmic Rays:

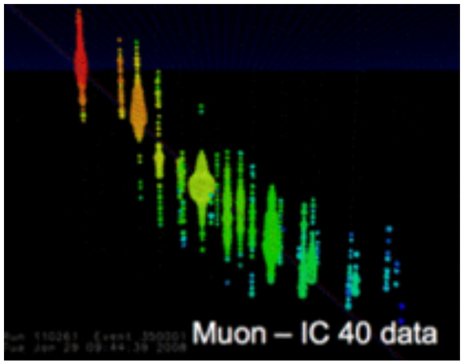
- Spectrum
- Composition
- Anisotropy

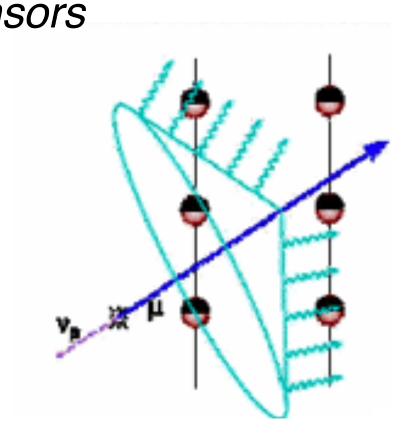

IceCube at the South Pole
Detector completed December 2010
IceCube
Geographic South Pole
Counting House
Skiway
Amundsen-Scott
South Pole Station

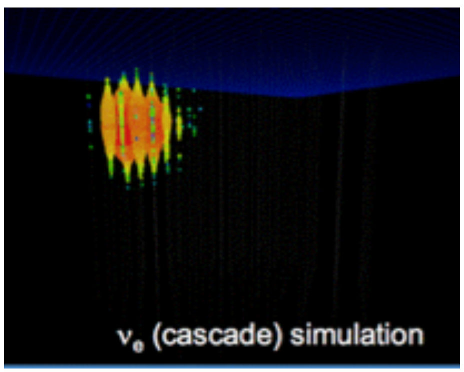
Neutrino Detection and Signatures

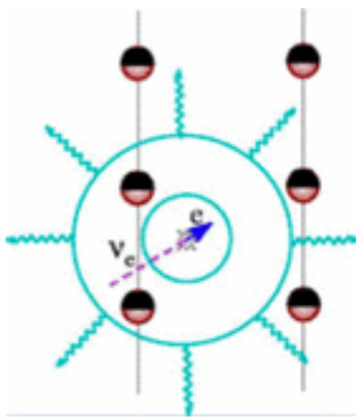


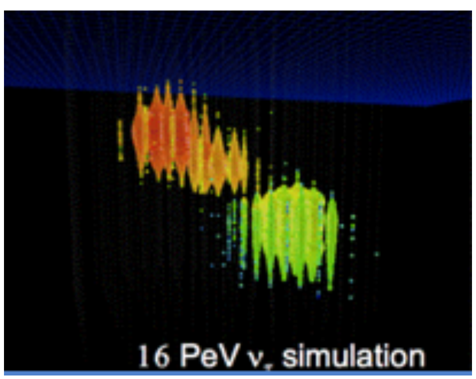
Observe the secondaries via Cherenkov radiation detected by a 3D array of optical sensors











Tracks:

- $\nu_\mu + N \rightarrow \mu + X$
- pointing resolution ~1°
- used for *point source and diffuse flux searches*

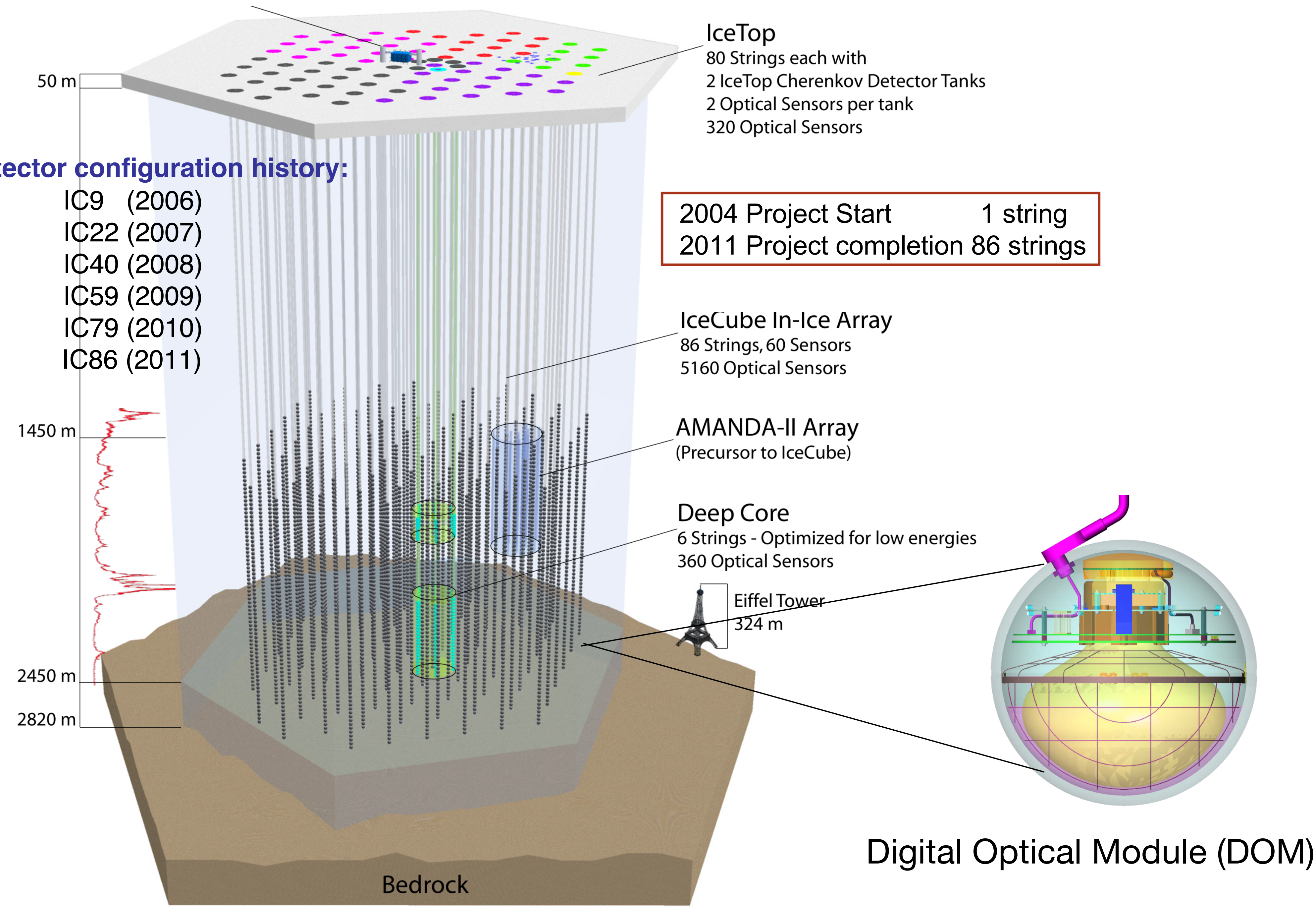
Cascades:

- 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)
- used for *diffuse flux searches*

Composites

- starting tracks
- tau double bangs
- good directional and energy resolution

IceCube Detector



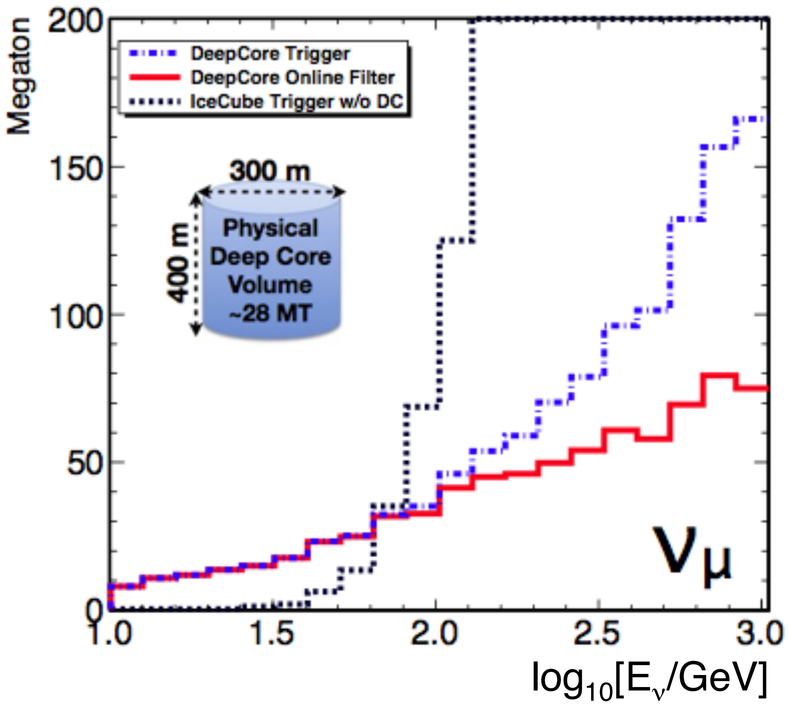
Detector configuration history:

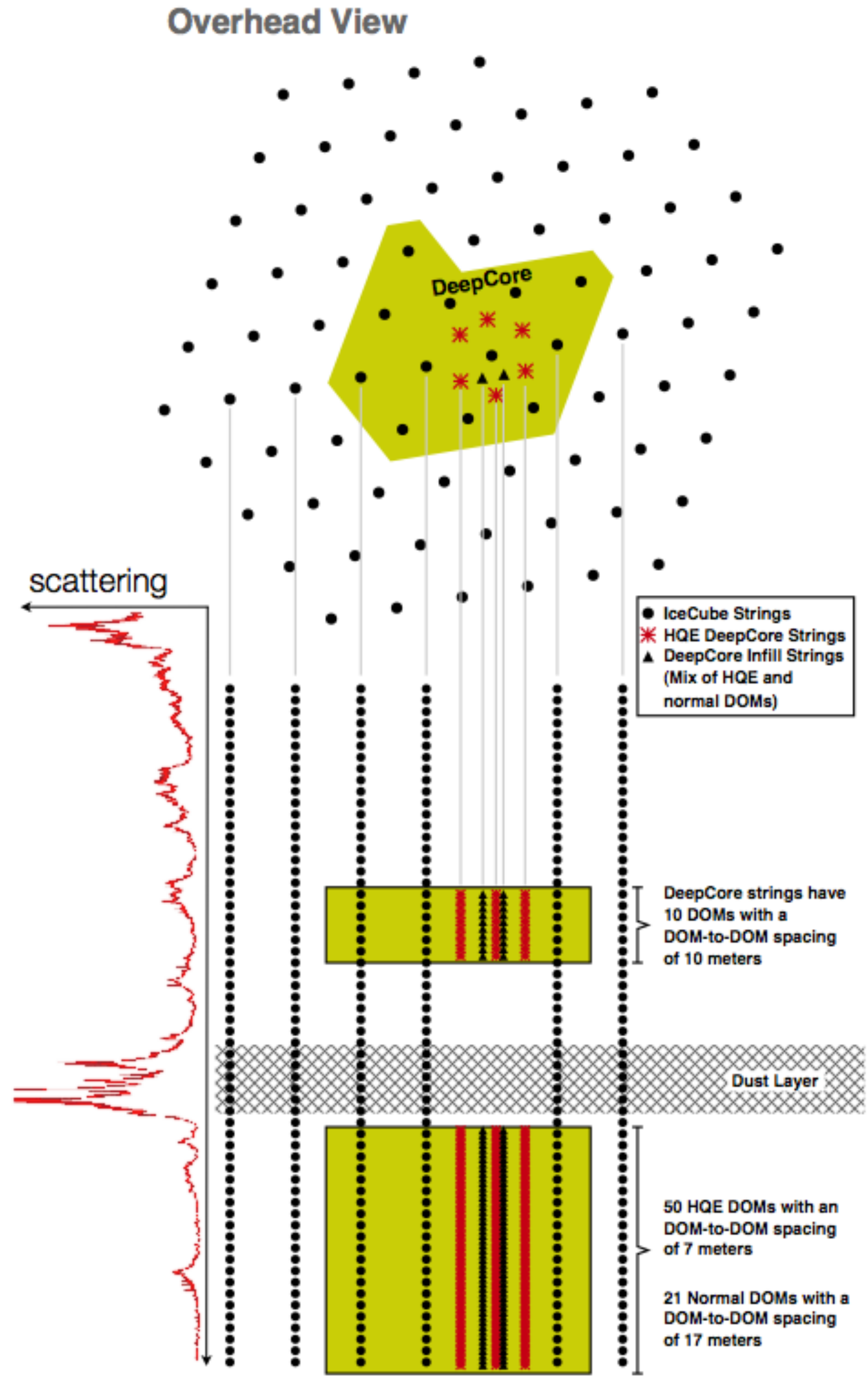
IC9 (2006)
IC22 (2007)
IC40 (2008)
IC59 (2009)
IC79 (2010)
IC86 (2011)

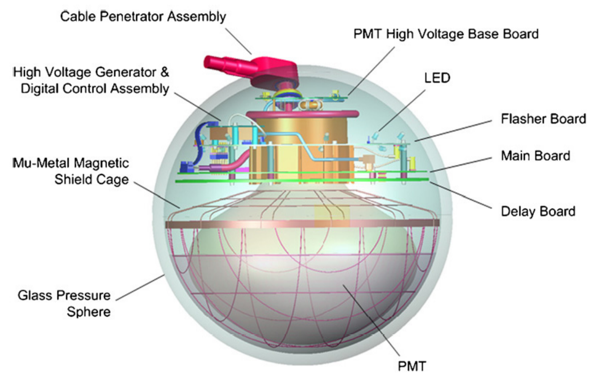
2004 Project Start	1 string
2011 Project completion	86 strings

Deep Core

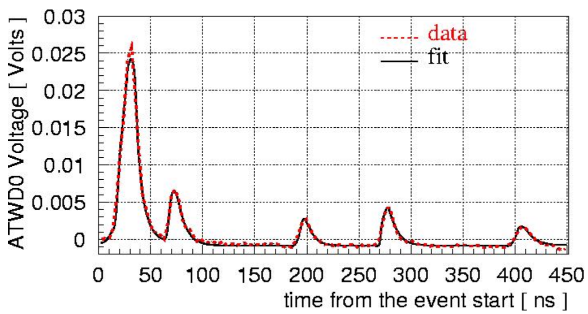
- Deployed in the deepest clearest ice:
  40 m scattering length && 140 m absorption length
- Densely populated strings
  72 m interstring and 7 m DOM spacing
- E_μ threshold 10 GeV
- Nearby IceCube strings used as veto







Digital Optical Module

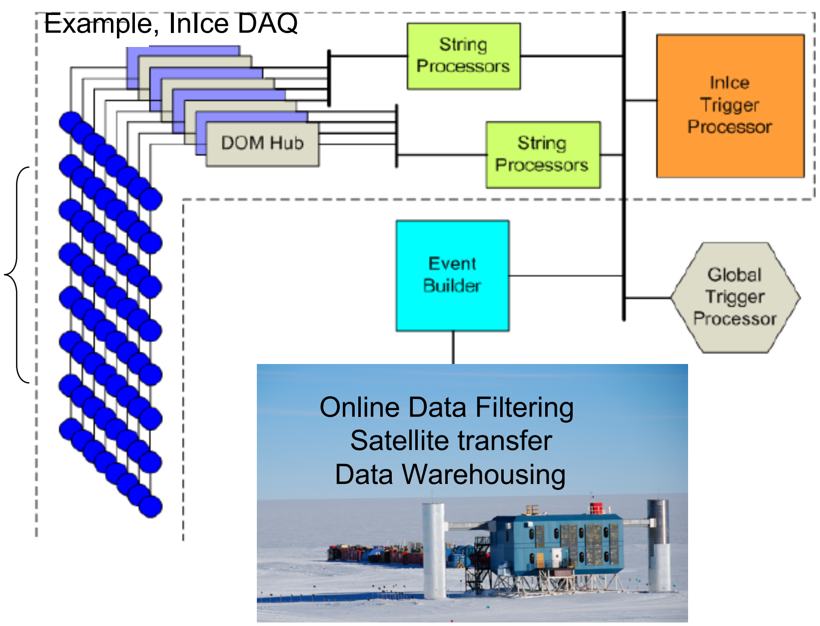


DOM+Main Board - a complete data acquisition system

- internal digitization (waveform digitizers) and time stamping the photonic output signals from the PMT
- wide dynamic range: from single p.e. to thousands p.e.
- performs PMT gain and time calibration
- power consumption 3W, deadtime < 1%, dark noise rate < 400 Hz

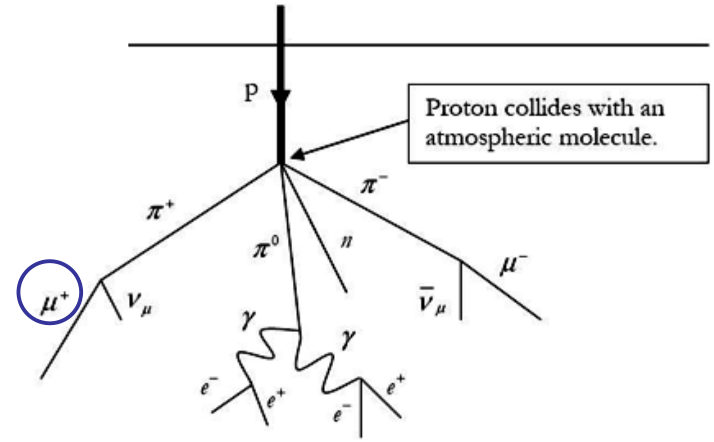
Triggering and Filtering

- Local coincidence communication between DOMs In ice
- Triggering on surface
- Physics <u>filtering</u> (simple reconstruction algorithms) on data sent to the North via satellite

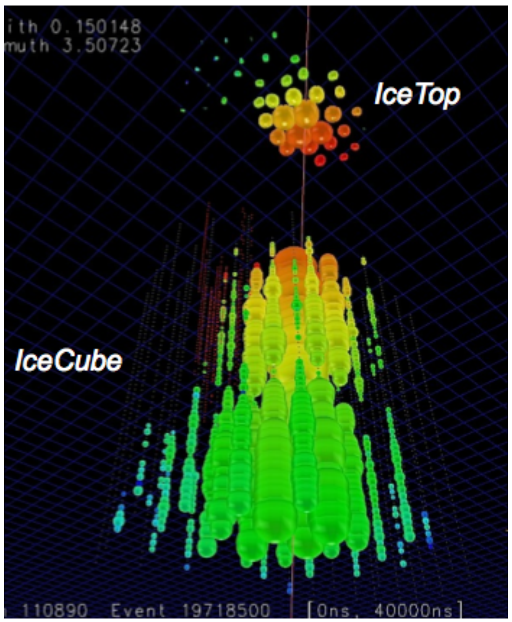


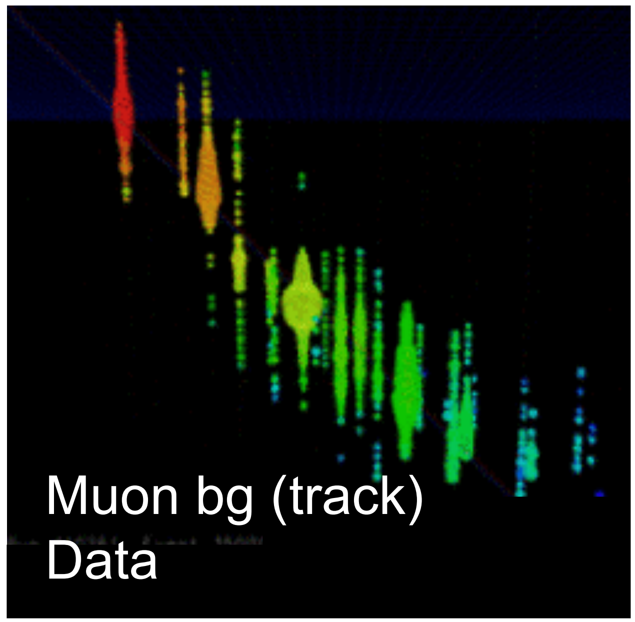
Trigger Rates:

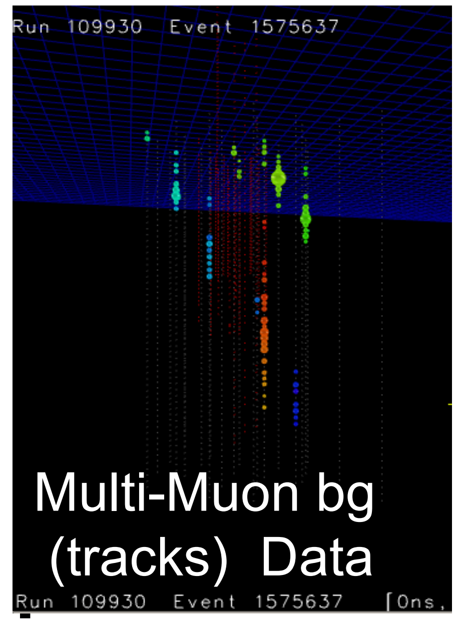
- IC22: CR rate is ~550 Hz
- IC40: ~1000 Hz
- IC86: ~2000 Hz   (complete detector)



High trigger rates due to Atmospheric μ Background



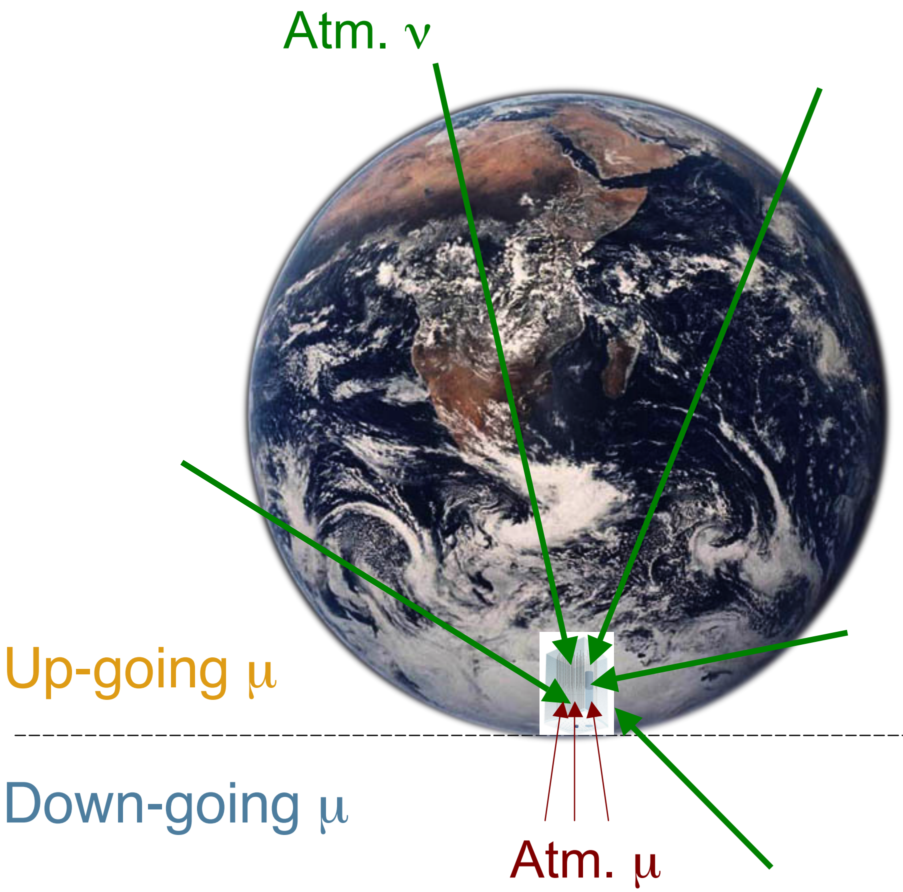


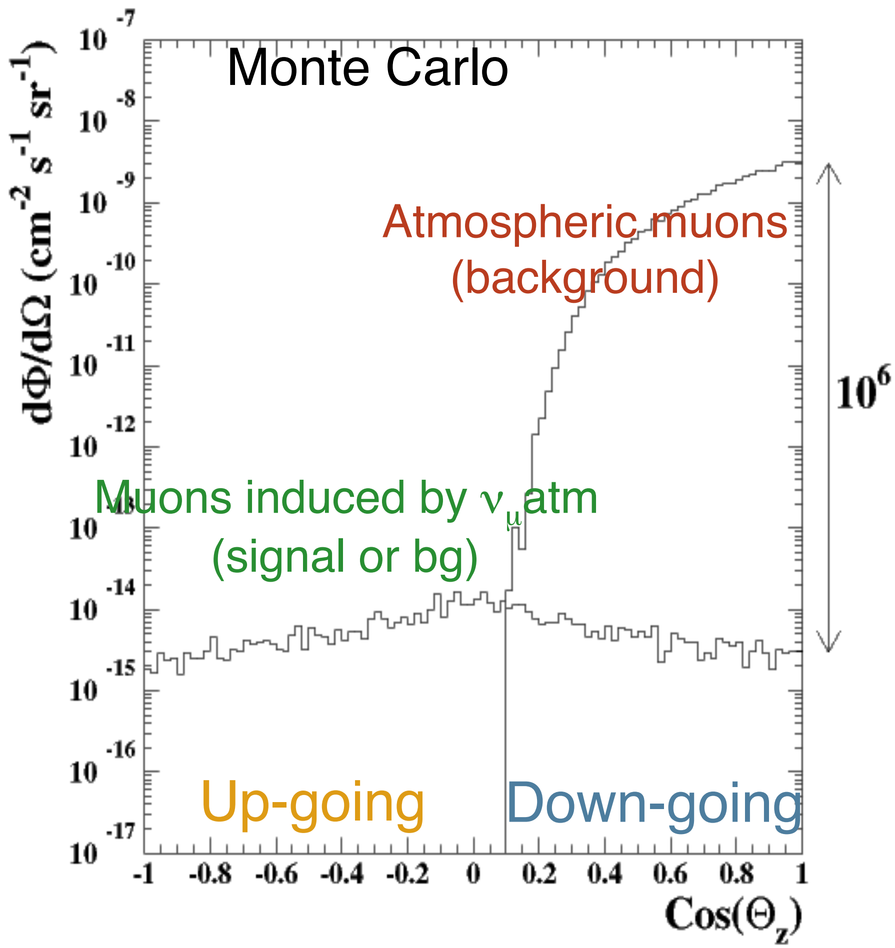


Main challenge: background rejection

The approach is filtering based on hit topology and online reconstruction

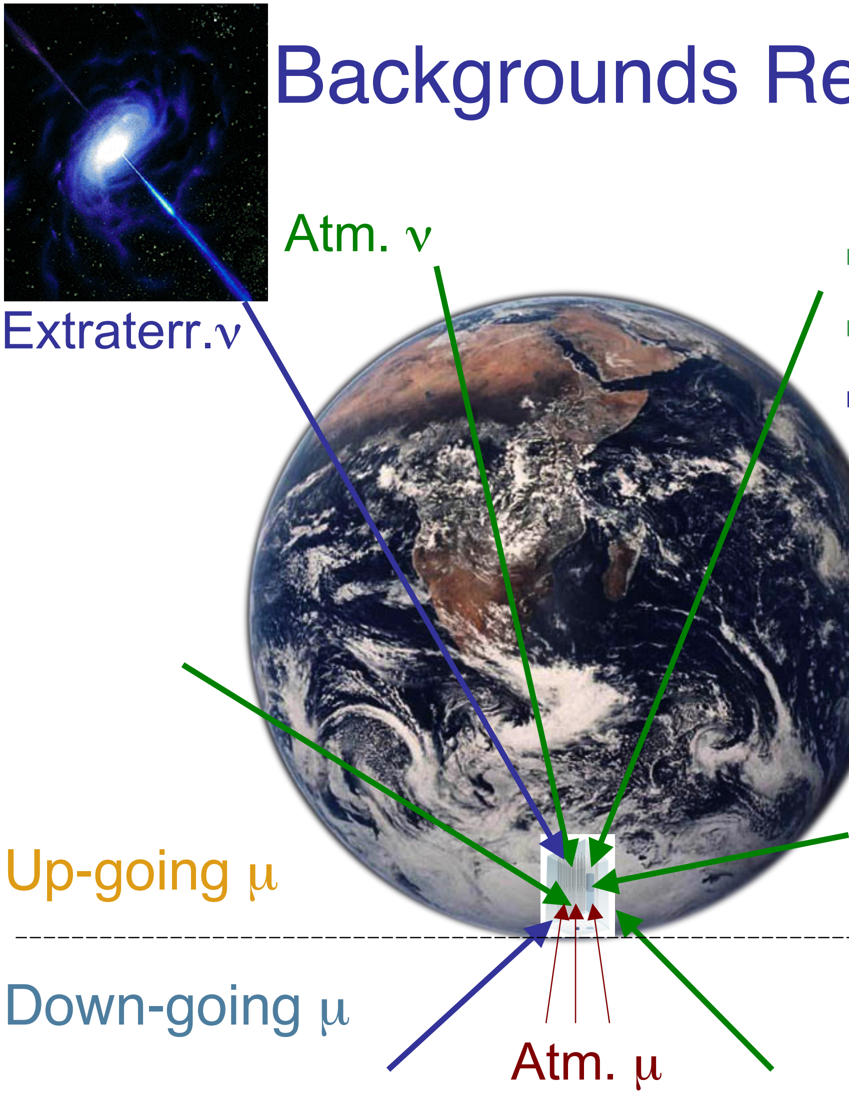
Backgrounds Rejection Methods (low energies)



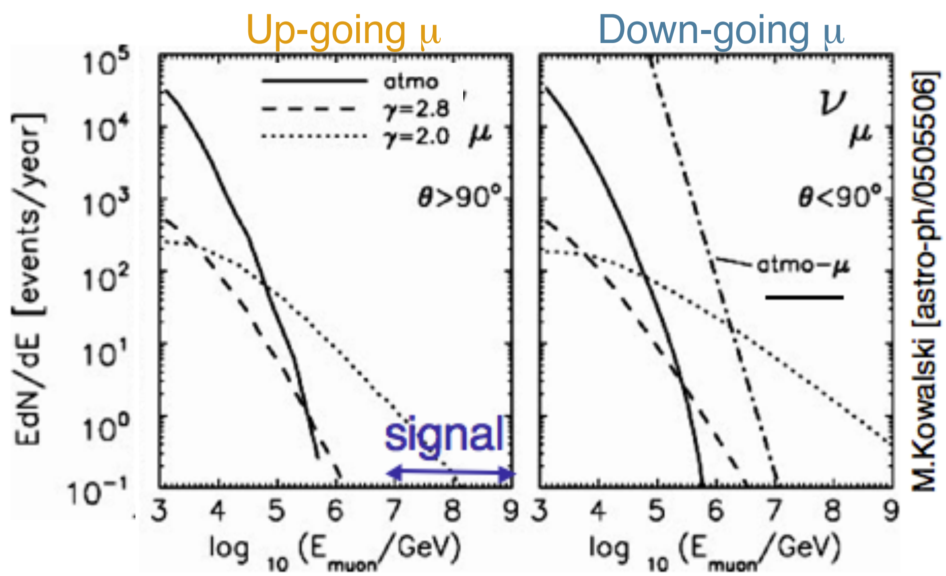


Reconstruct μ tracks and identify their origin (Cosmic Rays vs atm. ν_μ) by their direction

Backgrounds Rejection Methods (high energies)



- Atm. ν: $dN/dE \sim E^{-3.7}$ bg ν
- Prompt atm. ν: $dN/dE \sim E^{-2.8}$ bg ν
- Extraterrestrial ν: $dN/dE \sim E^{-2.0}$ (model) signal ν

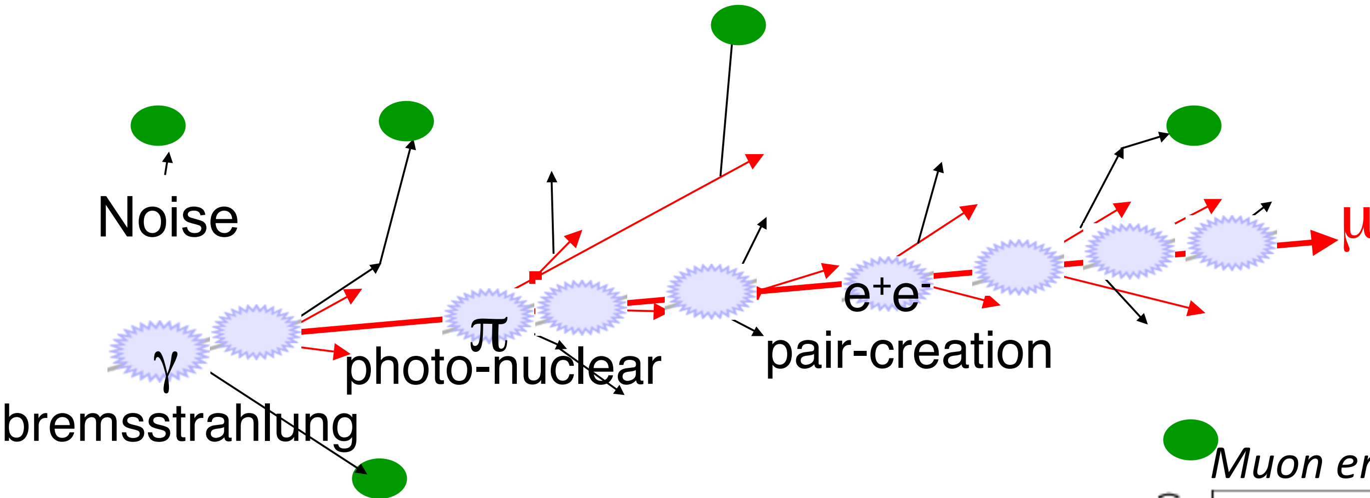


Distinguish signal vs bg atm. ν by their energy

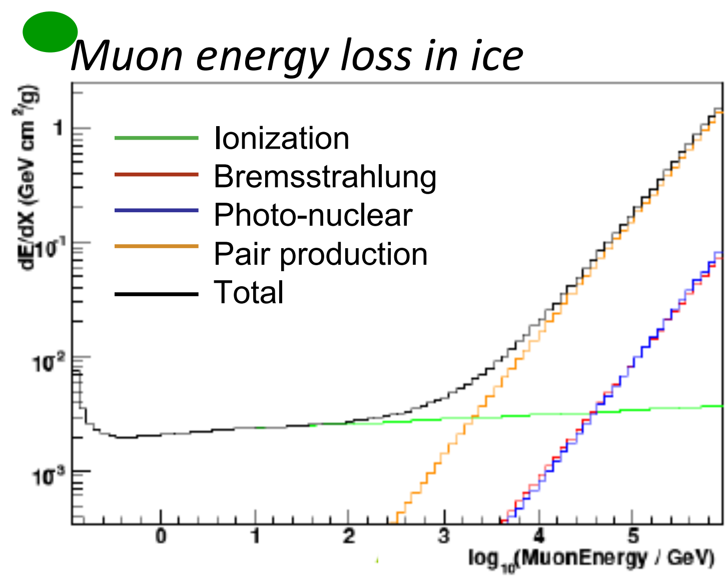
Particle (μ) Tracking

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

μ tracks lose energy by emitting γ, e^+e^- pairs and hadronic interactions



ice properties:
scattering λ_{sca}~20m@400 nm
absorption λ_{abs}~110m@400nm



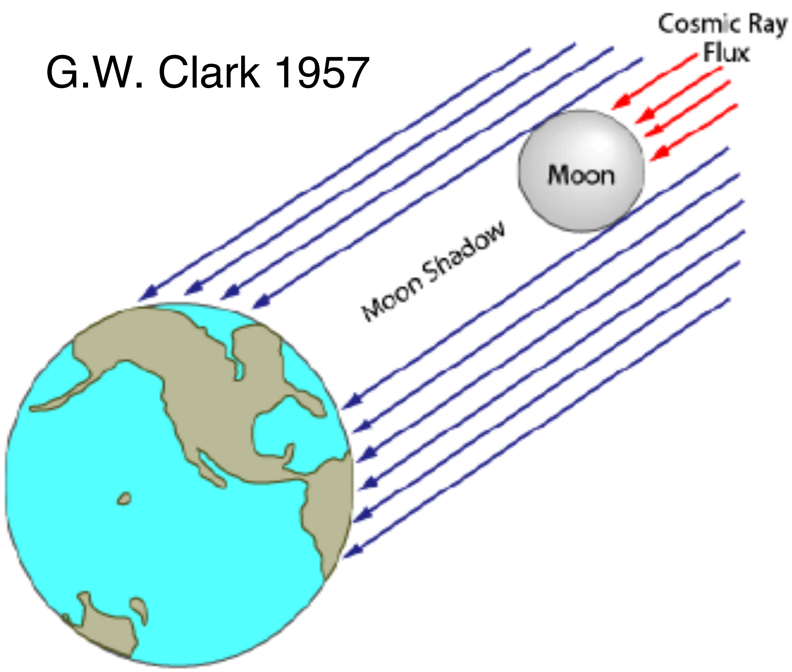
- Charged particles emit Cherenkov radiation
  $\theta = \cos^{-1}(1/n) = 41^0$
- Photons scatter (L ~ 25 m)
- Fraction ($<10^{-6}$) of photons observed in DOMs
- We measure points 0-30 meters from the μ track
- Angular resolution < 1^0

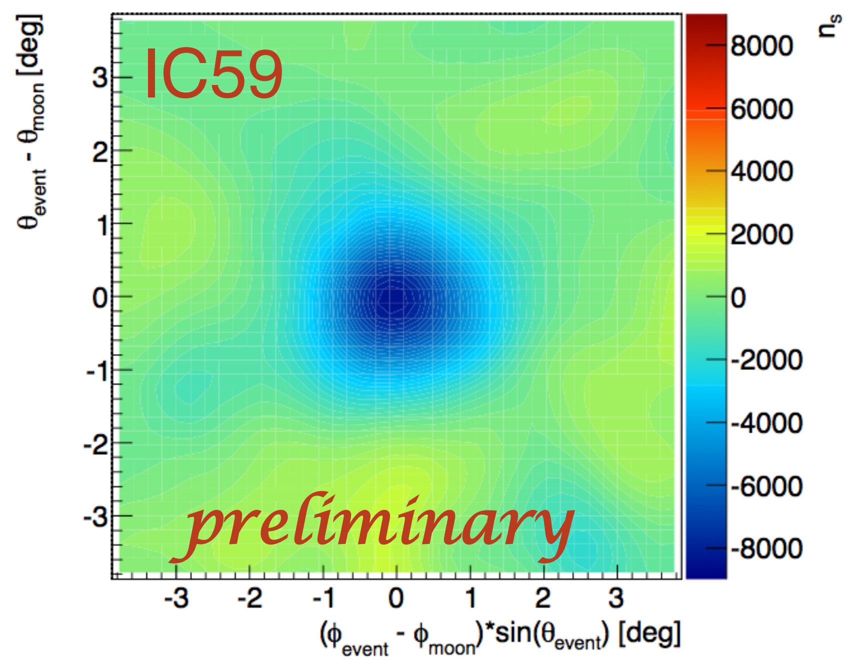
- E_μ<500 GeV (ionization dominant ~2 MeV/cm)
- E_μ>500 GeV (stochastic energy loss dominant)
- Muon energy measurement from dE/dx

Moon shadow observed in muons

Important verification of angular resolution and absolute pointing

G.W. Clark 1957



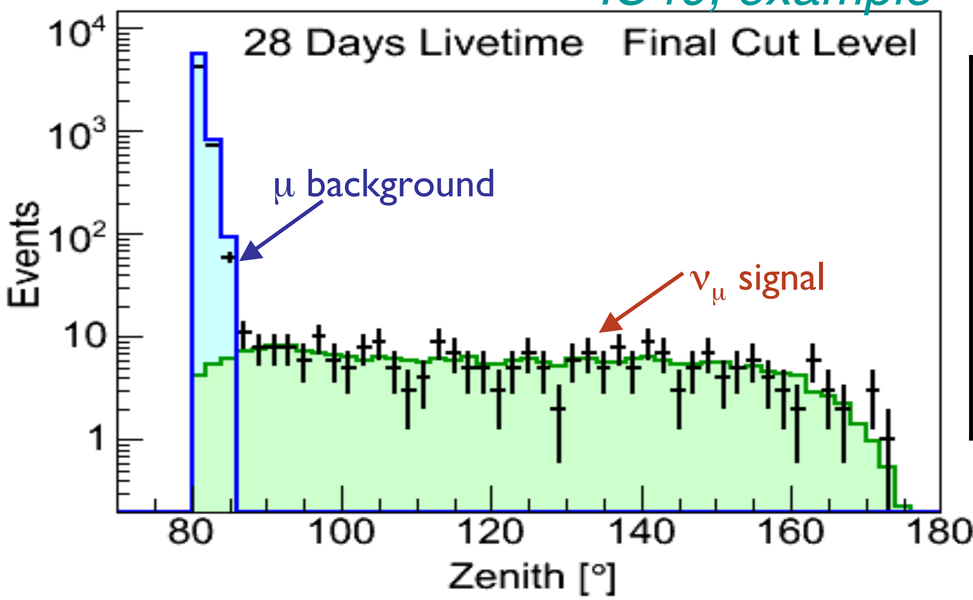


- Moon shadow seen with ~10σ
- Systematic pointing error less than 0.1°

Atmospheric muon neutrinos

High-purity atmospheric neutrino sample achieved after quality cuts

IC40, example

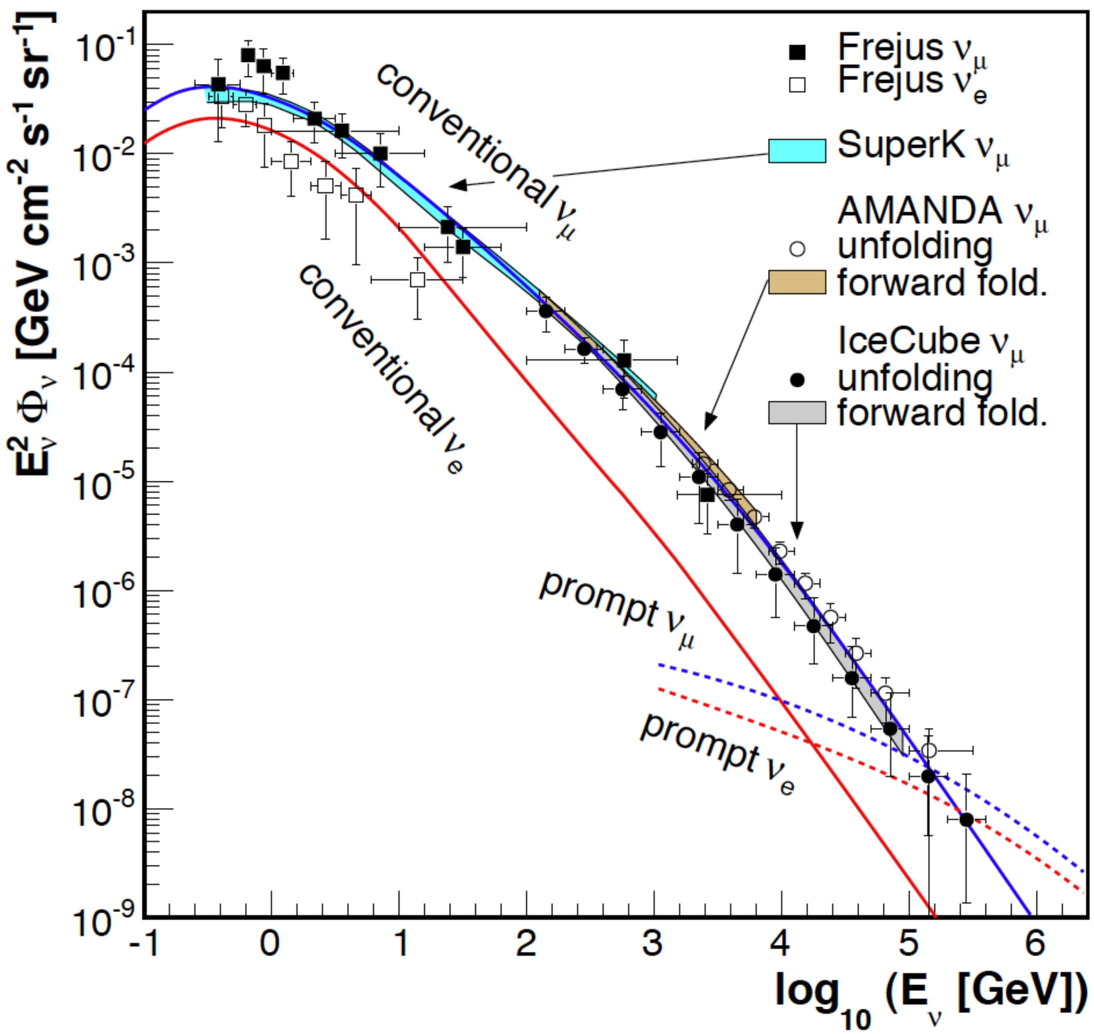


Strings	Year	Livetime	ν_μ rates
IC22	2007	275 days	28/day
IC40	2008	375 days	110/day
IC59	2009	360 days	160/day
IC79	2010	1 year	
IC86	**2011-**	**Since 05/13/2011**	**220/day***

*estimated

Atmospheric Neutrinos

- IC40: high statistics sample of HE (E>100 GeV) atm. ν_μ (13 000, 95% purity) and flux consistent with previous measurement in the overlap regio (Phys.Rev.D83:012001,2011)
- As detector size increases, this measurement can be extended up to > 1 PeV



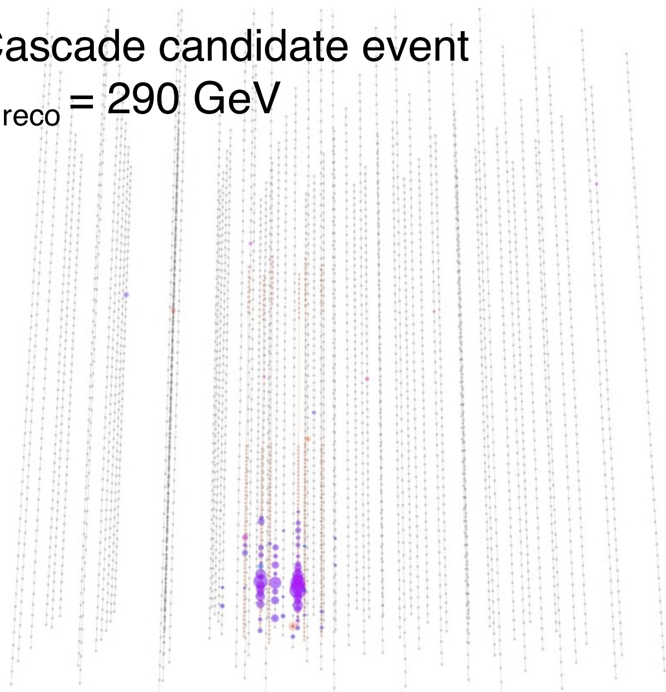
- IC59 statistics: 40 000 ν_μ, even bigger sample in IC79
- Use the HE sample (> 100 GeV and higher) to search for non-standard oscillations

No atmospheric ν_e observed so far by AMANDA and IceCube.

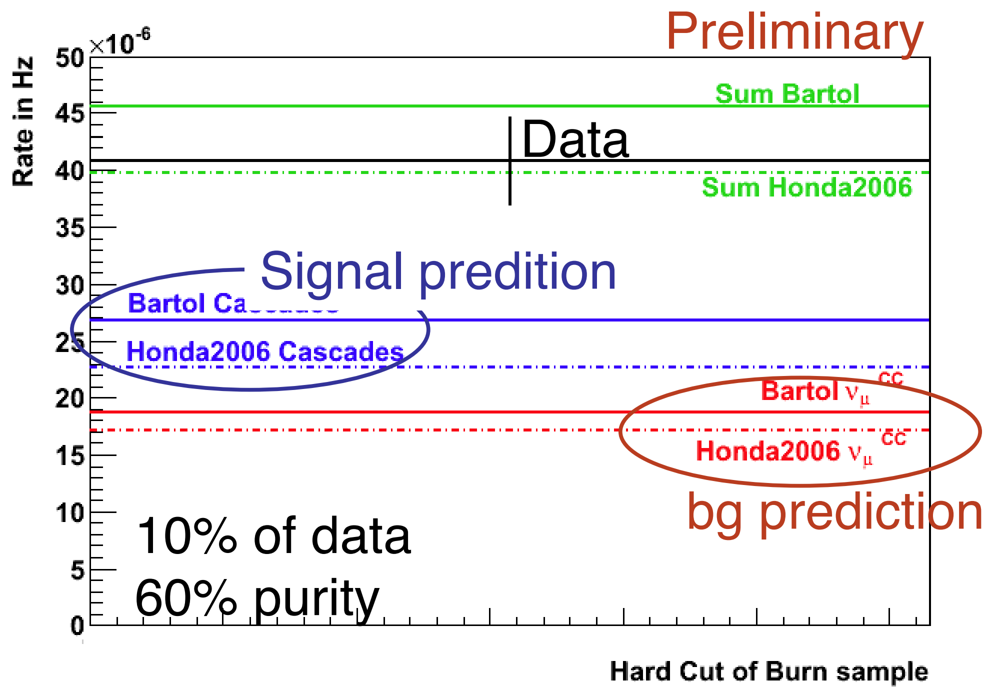
Deep Core: extension towards lower energies (higher ν_μ, ν_e rates): next slide

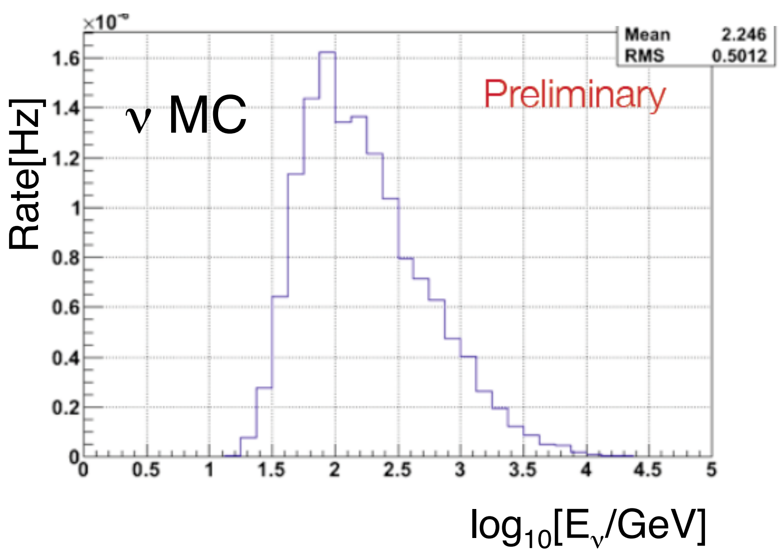
IC79 (IC73+Deep Core) Low Energy Cascades

Cascade candidate event
E_{reco} = 290 GeV



Run 116020, event 20788565 (06/06/2010)

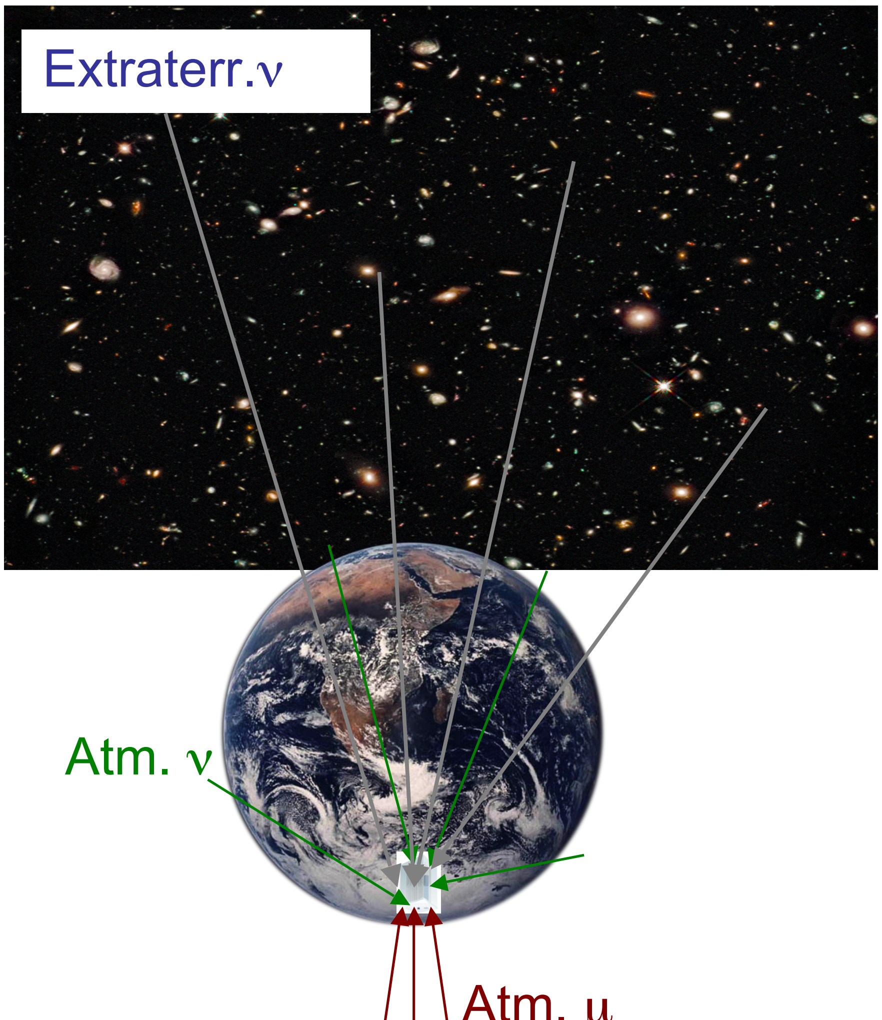




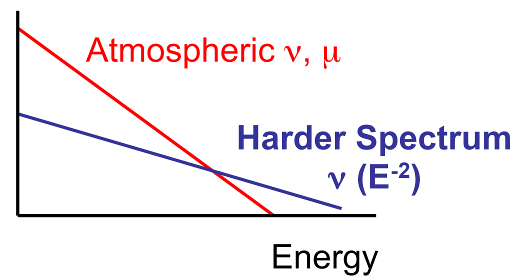
- Data rate (~4 events/day) agrees with atm. ν rate prediction
- $\frac{\text{MC Rate (signal cascades)}}{\text{MC Rate (background } \nu_\mu \text{ CC)}} \sim 1.5$

Search for Diffuse Neutrino Fluxes

Diffuse flux = effective sum from all (unresolved) extraterrestrial sources (e.g.AGNs)
Possibility to observe diffuse signal even if flux from an individual source is too small to be detected by point source techniques.



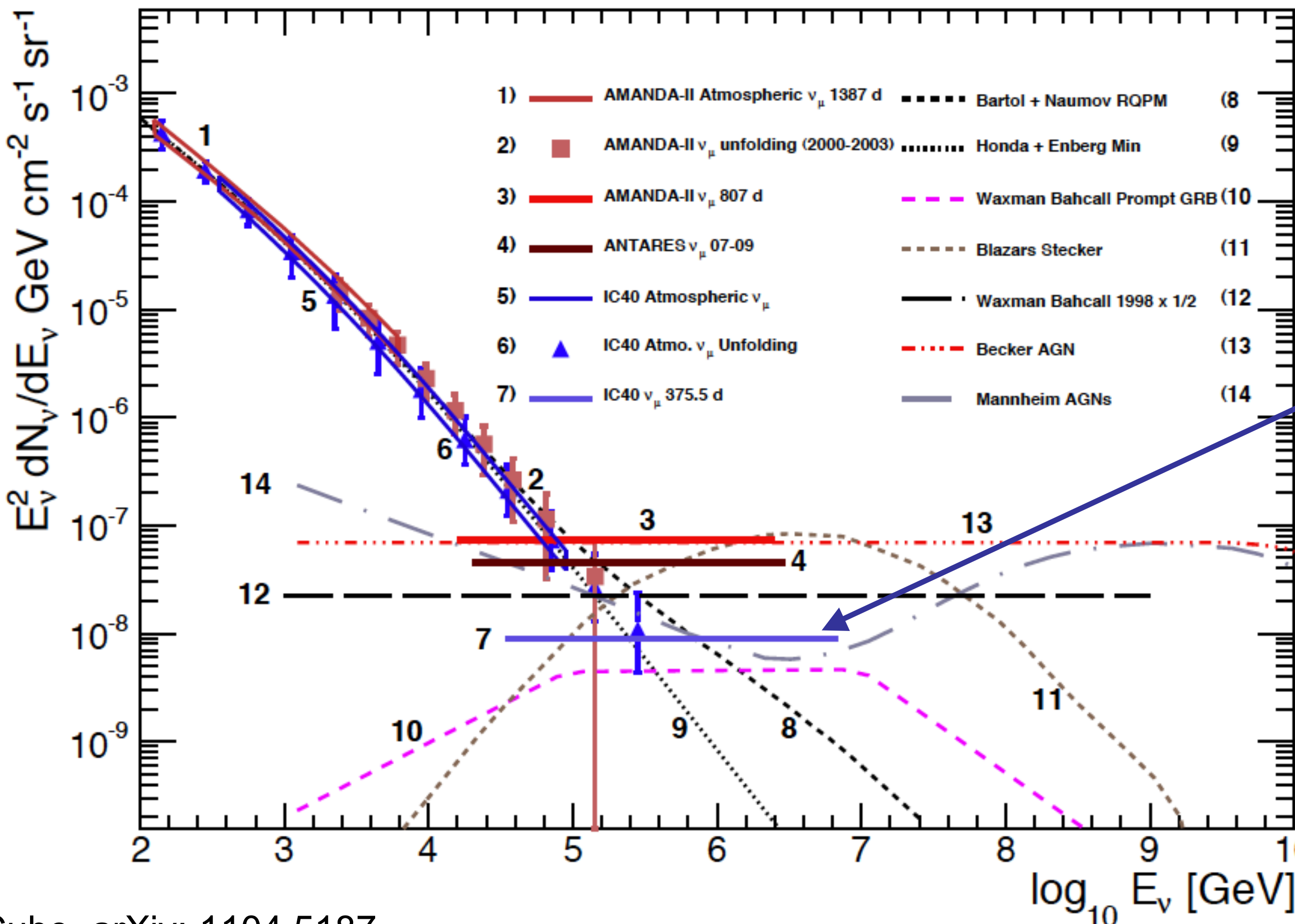
- Search for excess of astrophysical neutrinos with a harder spectrum than background atmospheric neutrinos



- Advantage over point source search: can detect weaker fluxes
- Disadvantage: high background
- Sensitive to all three flavors of neutrinos

IC40 <u>muon neutrino</u> diffuse flux limit

Experimental upper limits on the diffuse flux of neutrinos from sources with $\Phi \sim E^{-2}$ energy spectrum

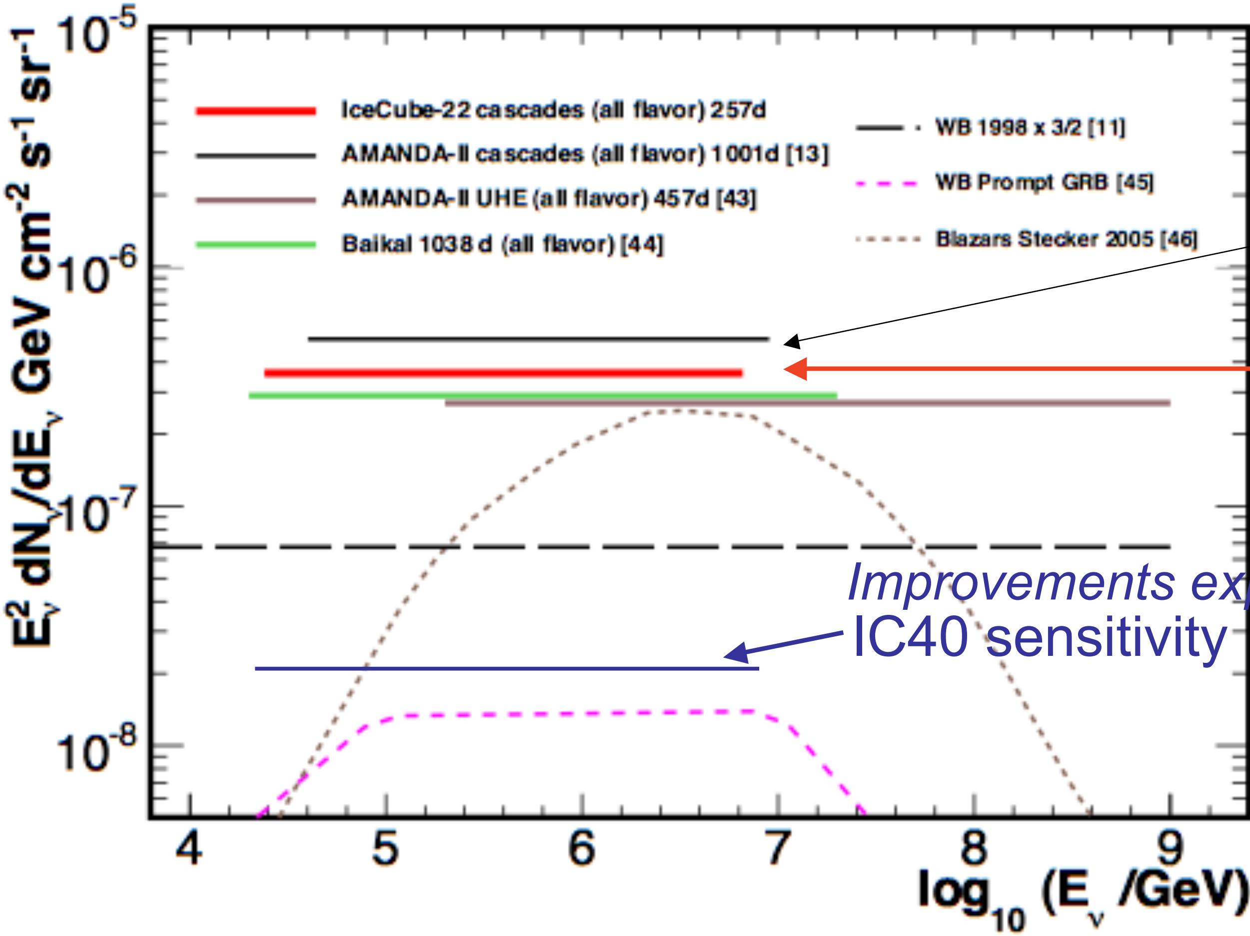


Below the Waxman - Bahcall bound

IceCube, arXiv: 1104.5187

IC22 Cascade diffuse flux limit

Experimental upper limits on the diffuse flux of neutrinos from sources with $\Phi \sim E^{-2}$ energy spectrum



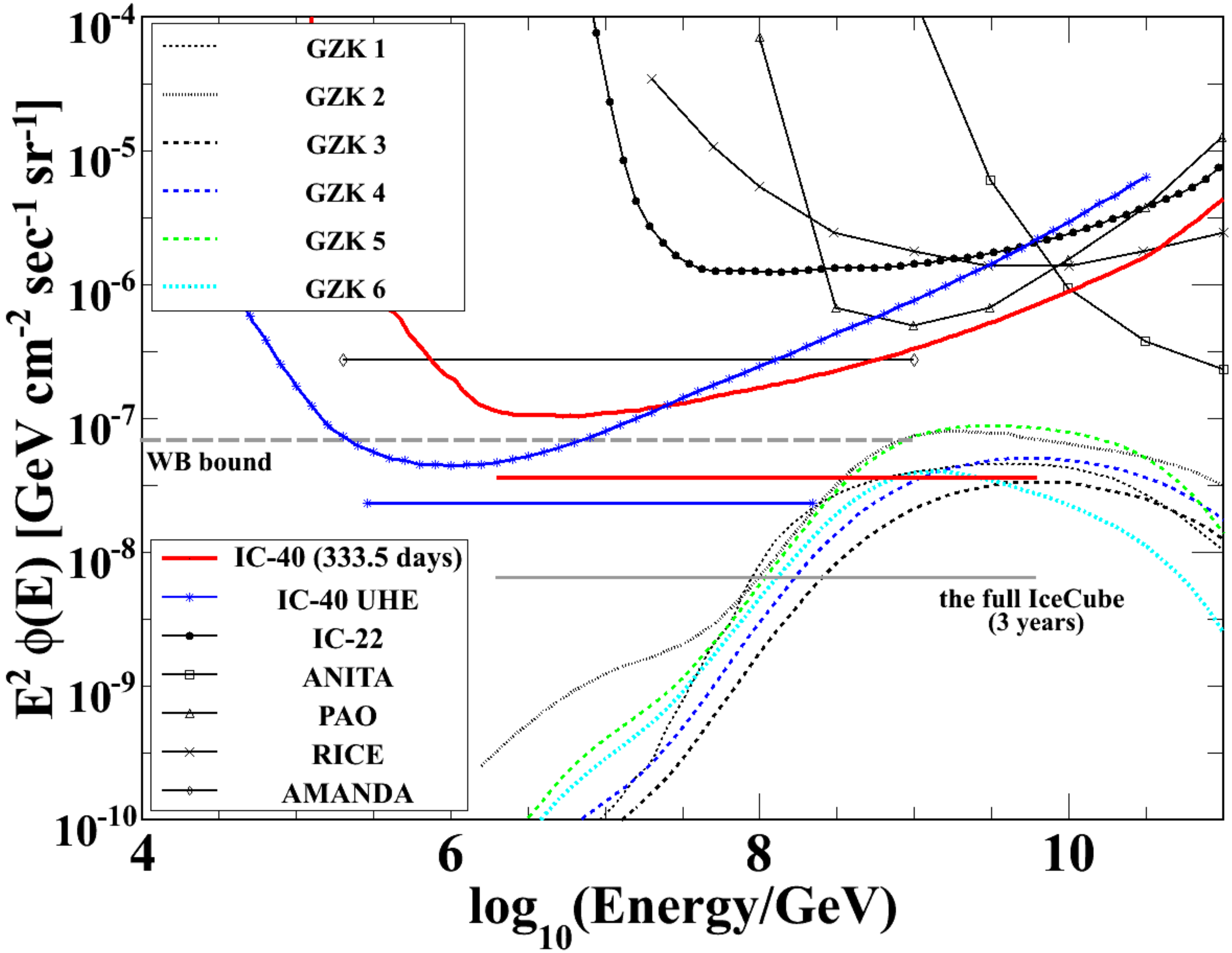
2000-2004 Amanda
Upper limit (1001d)
Phys.Rev.D (2010)

IC22 upper limit (257d)
arXiv: 1101.1692

Improvements expected with a bigger detector

IC40 sensitivity (337d)

IC40 Extremely High Energy Cosmic Neutrino Flux Limits

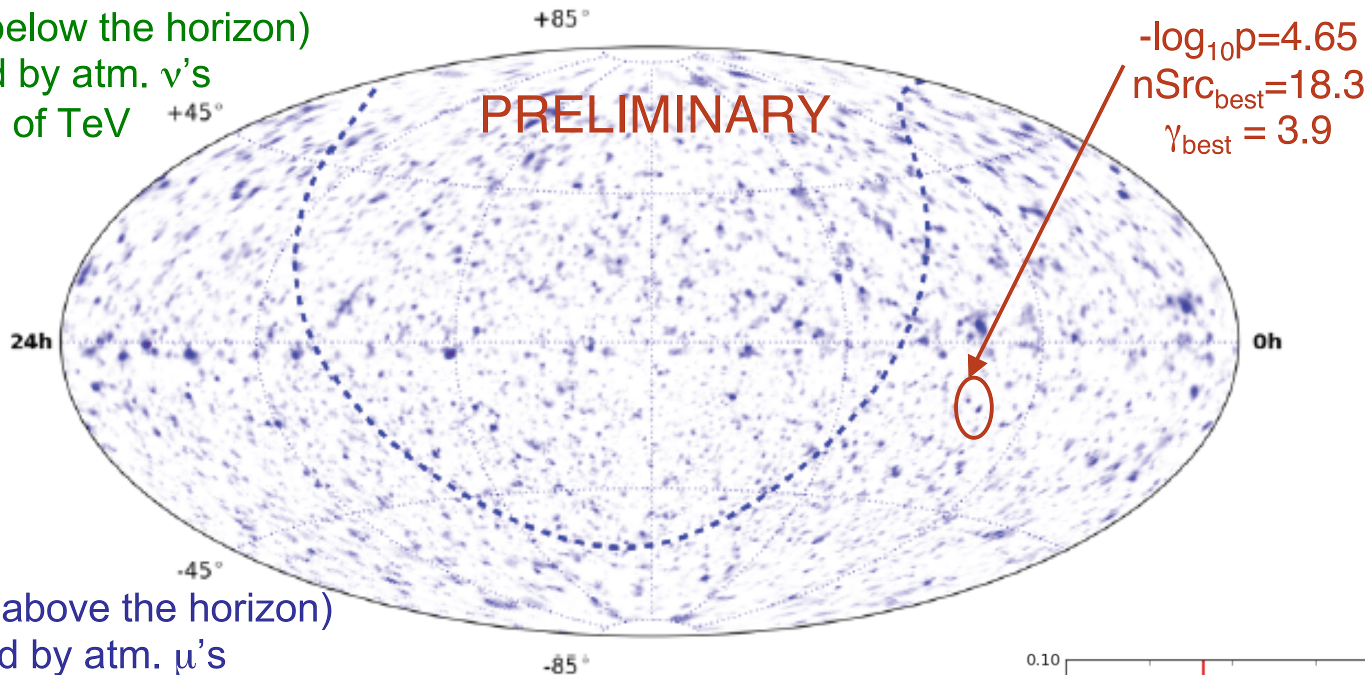


The world's best 3 flavor ν upper limits to date from ~10^6 to 10^{10} GeV

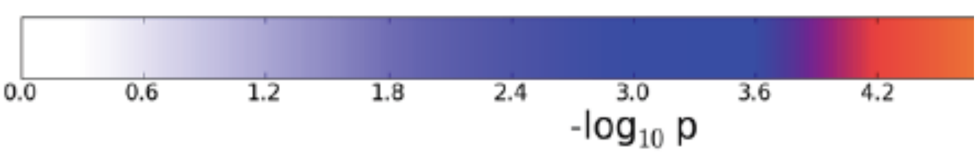
IC40+IC59 All Sky Point Source Search

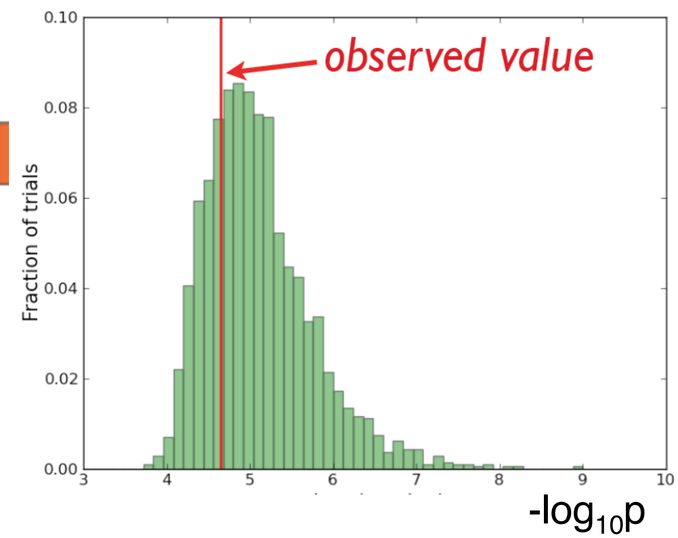
Search for excess of astrophysical neutrinos from a common direction over the background of atmospheric neutrinos

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



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





- 107,569 neutrino candidates (64,230 atm. μ from southern hemisphere)
- Hottest spot (Ra=75.45, Dec=-18.15) not significant:
  75.4% of trials have p-value value equal or lower than the observed one

Indirect Dark Matter searches

$\Omega_m \sim 24\%$, $\Omega_b \sim 4\%$

$\Omega_{DM} \sim 20\%$ non-baryonic and non-relativistic

(cold) DM currently favored candidate: WIMP

Look at objects where the DM particle can be gravitationaly trapped and annihilate: Sun, Earth and galactic halo

- MSSM CDM candidate: neutralino, χ
- UED CDM candidate: lightest Kaluza-Klein (LKK)

⟶ CDM annihilation and decay to neutrinos:

$$\tilde{\chi}\tilde{\chi} \to \left\{ \begin{array}{c} q\bar{q} \\ l\bar{l} \\ W^{\pm}, Z, H \end{array} \right\} \to \cdots \to \nu_\mu$$

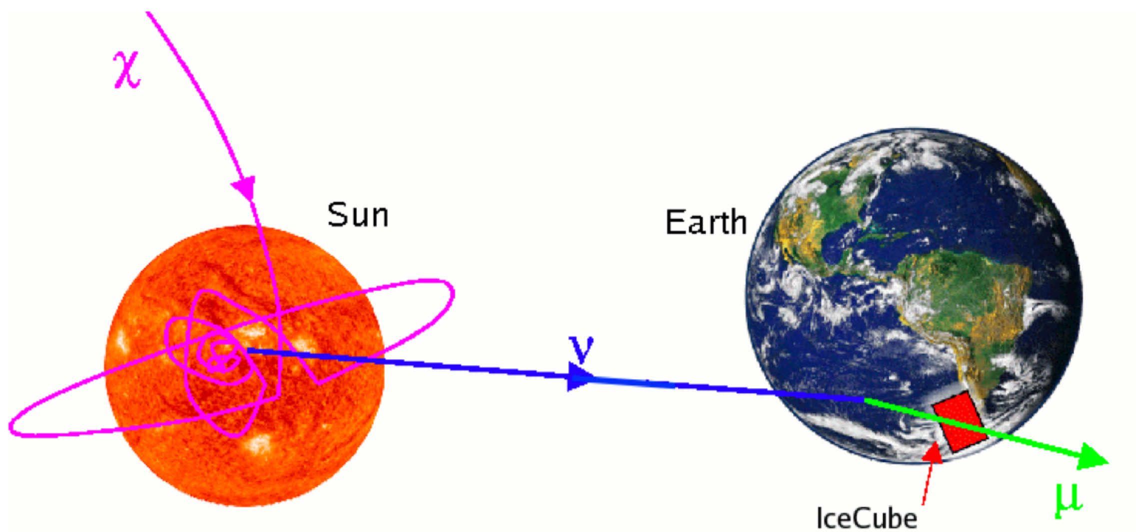
$$KK \to \nu\nu$$

<u>Signature:</u> neutrino excess from Sun,Earth or galactic halo direction
ν energy range: ~ 10 GeV to a few TeV

<u>Example:</u> WIMPs in Sun

$$\frac{dN}{dt} \sim C_c - C_A N^2 = C_c - 2\Gamma_A$$

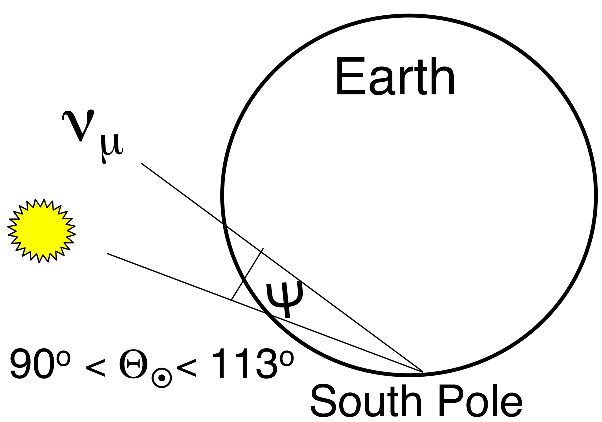
in equilibrium (dN/dt = 0)
capture rate ~ annihilation rate



Indirect Dark Matter searches: Solar WIMPs

90% CL limits on the spin-dependent (SD) and spin-independent (SI) χ-p cross sections assumming equilibrium between capture and annihilation:

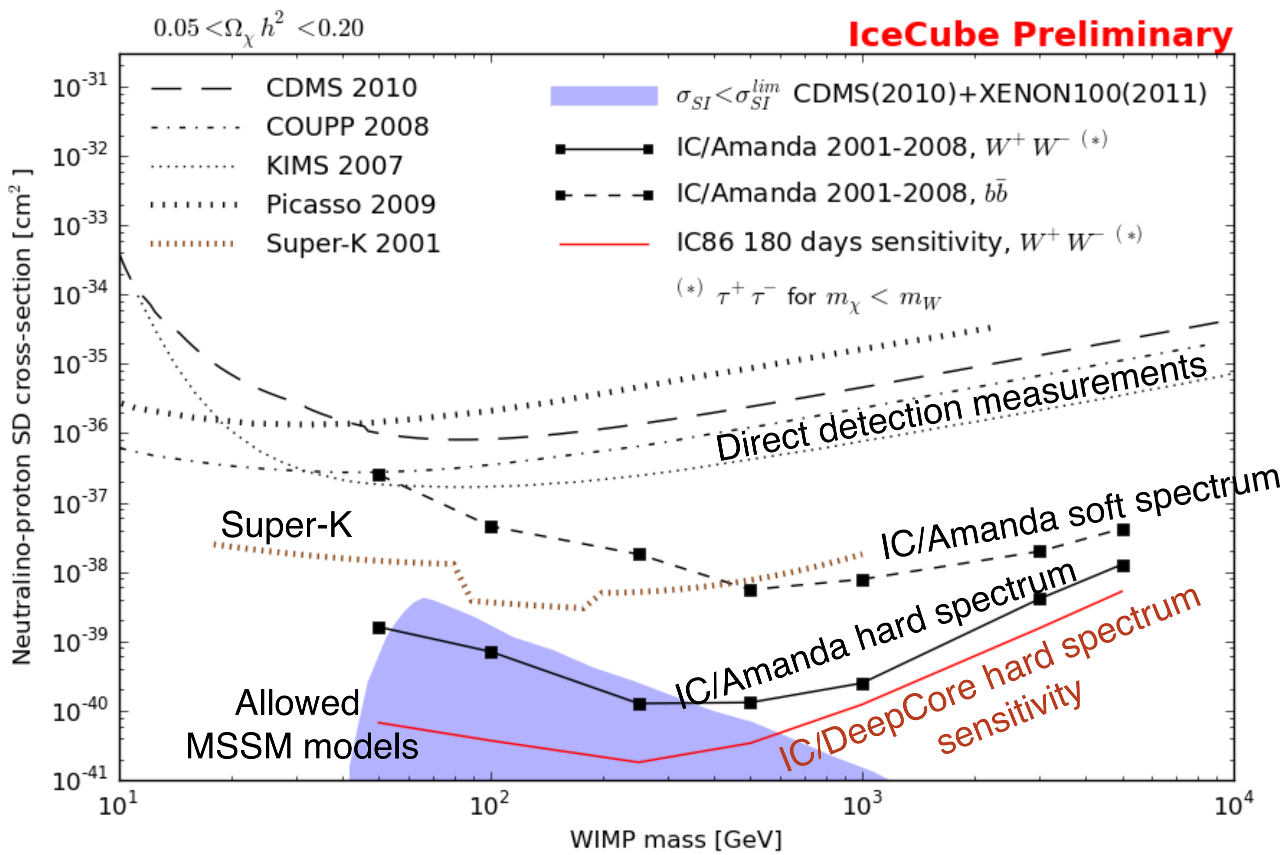
- $\sigma^{SI} = \lambda_{SI}(m_\chi)\Gamma_A$ and $\sigma^{SD} = 0$ ⇒ *constrained well by direct searches*
- $\sigma^{SI} = 0$ and $\sigma^{SD} = \lambda_{SD}(m_\chi)\Gamma_A$ ⇒ capture in the Sun dominated by σ^{SD} competitive limits by indirect searches



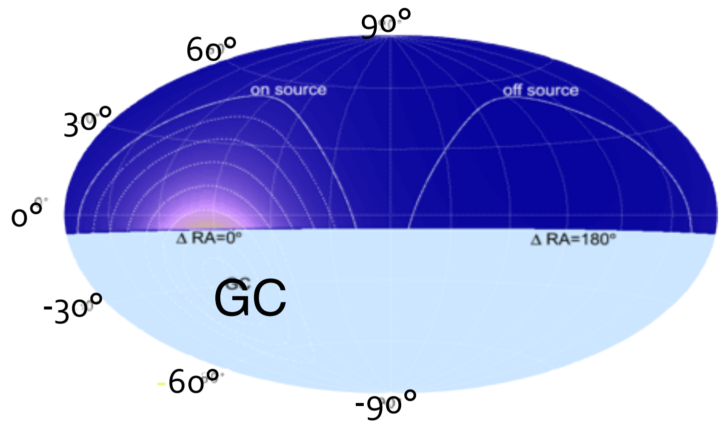
$$\Gamma_{\nu\to\mu} = \frac{\mu_s}{V_{eff} \times T}$$

$$\Gamma_A = \kappa^{-1}(\chi) \times \Gamma_{\nu\to\mu}$$

IC22+IC40+AMANDA combined results:



Dark Matter searches: Galactic Halo and Galactic Center



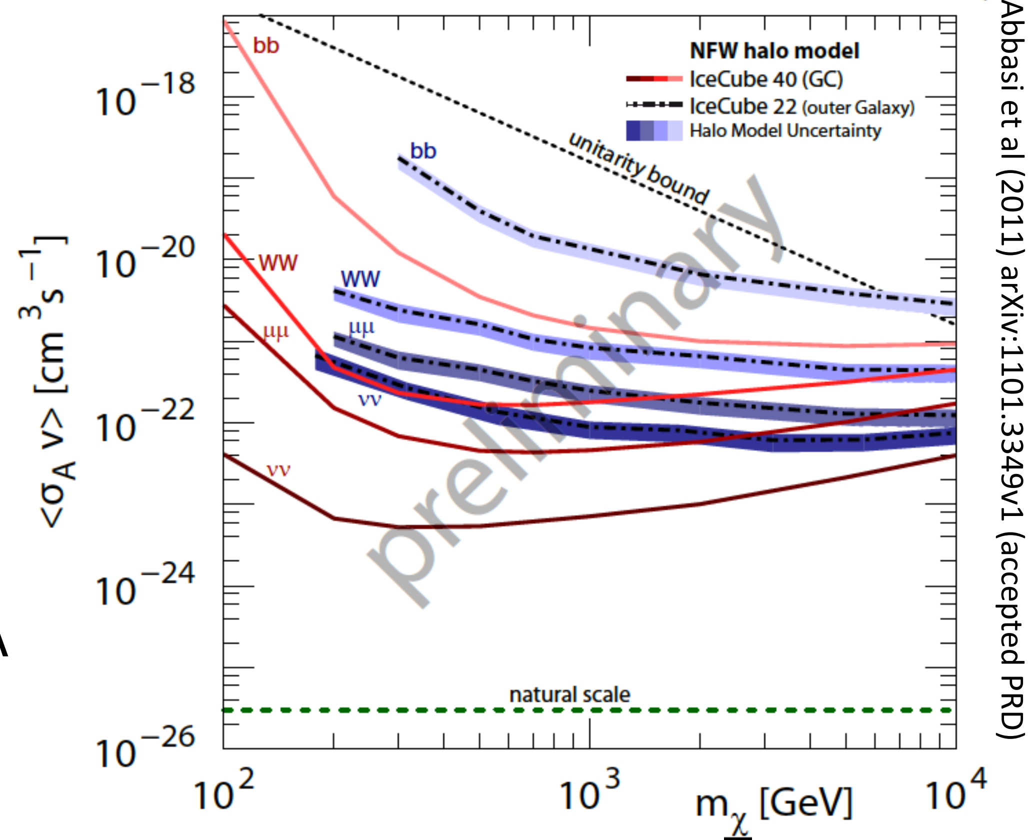
- Galactic Halo analysis searched for a neutrino anisotropy on the northern hemisphere
- Galactic Center analysis searched for an excess in down-going events in direction of the GC
- Observations in both analyses were consistent with background expectations

90% CL limits on the WIMP self-anhihilation cross section $<\sigma_A v>$ $(\chi\chi \rightarrow bb, WW, \mu\mu, \nu\nu)$

$$\frac{d\phi_\nu}{dE} = \frac{\langle\sigma_A v\rangle}{2} J(\psi) \frac{R_{sc}\rho_{sc}^2}{4\pi m_\chi^2} \frac{dN_\nu}{dE}$$

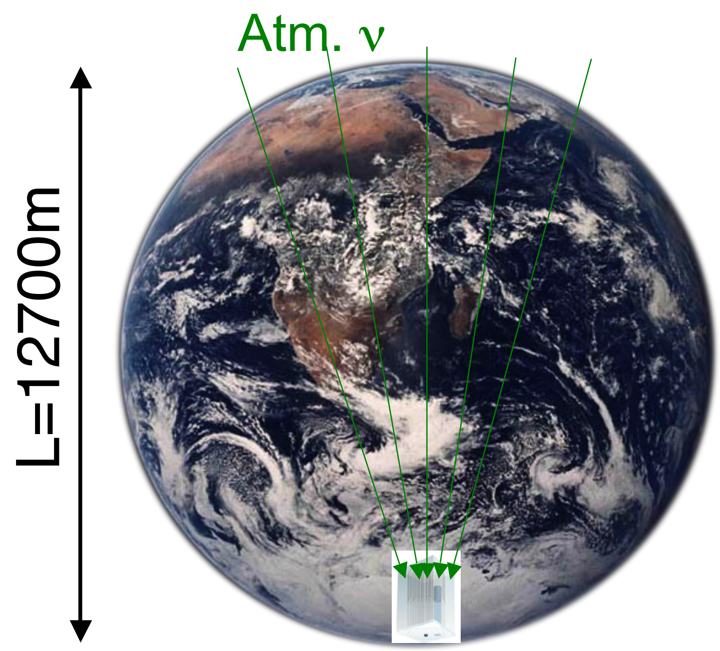
Measure — "2 WIMPs per annihilation" — Isotropic emission — SUSY Model

Results start to constrain WIMP models with large boost factors as motivated by PAMELA observations

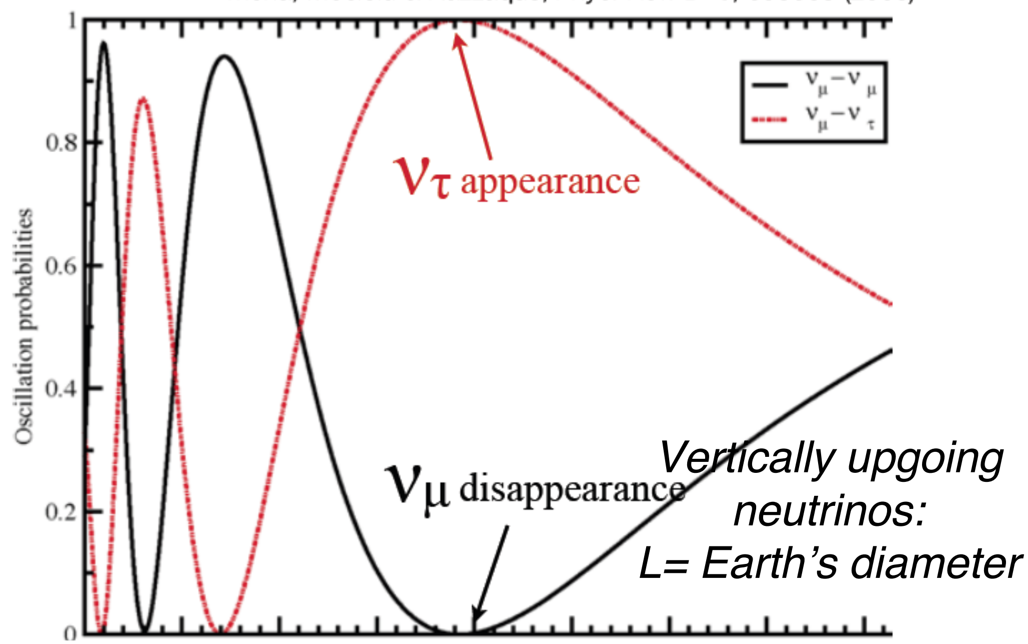


Abbasi et al (2011) arXiv:1101.3349v1 (accepted PRD)

Neutrino Oscillations with DeepCore

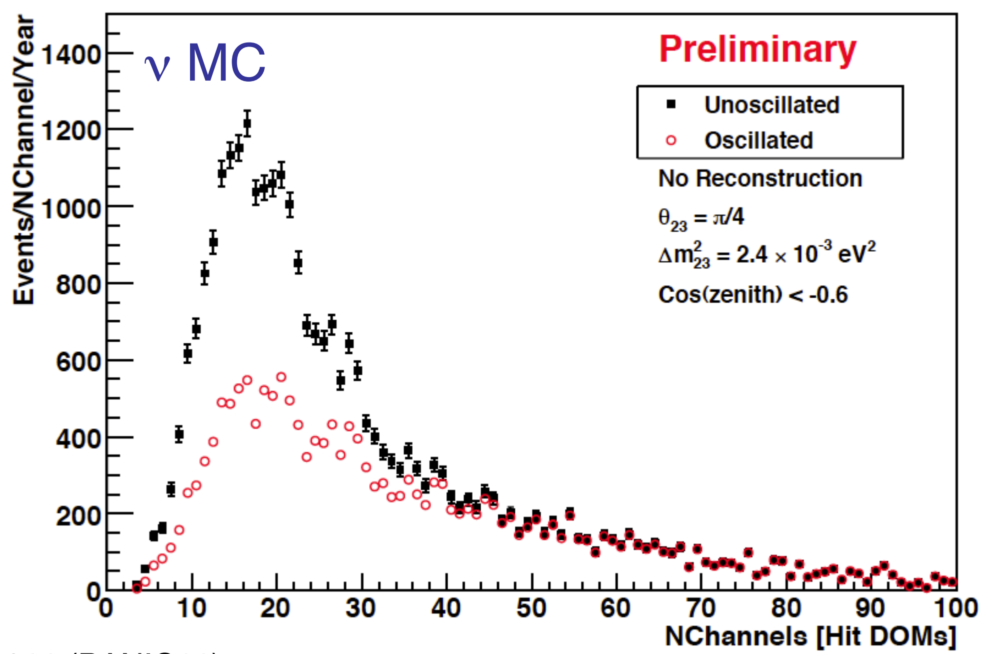


Mena, Mocioiu & Razzaque, *Phys. Rev.* D**78**, 093003 (2008)

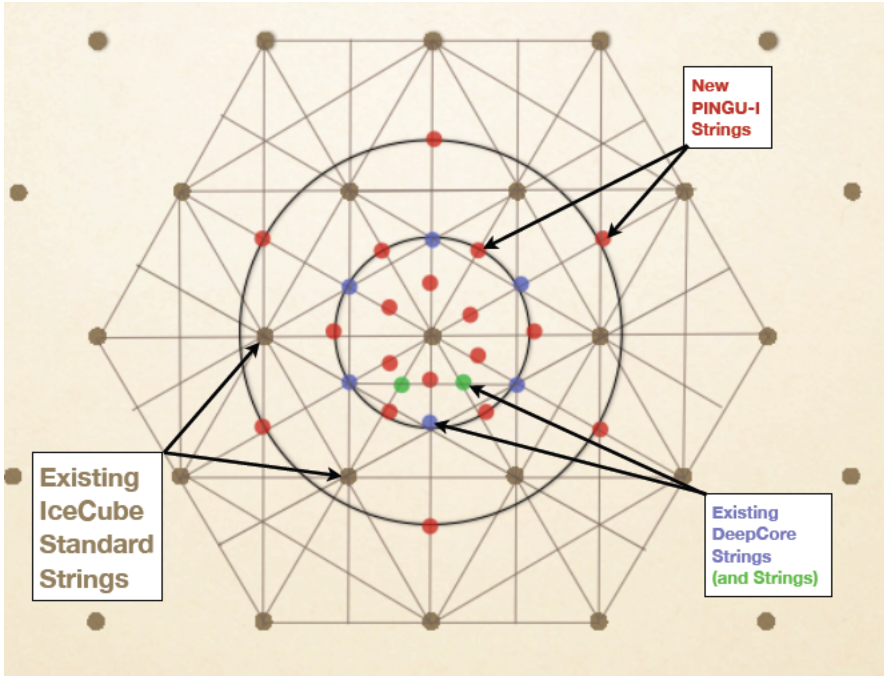


ν_μ disappearance MC

- 3-flavor oscillations
- signal simulation only
- lifetime= 1 year IC79



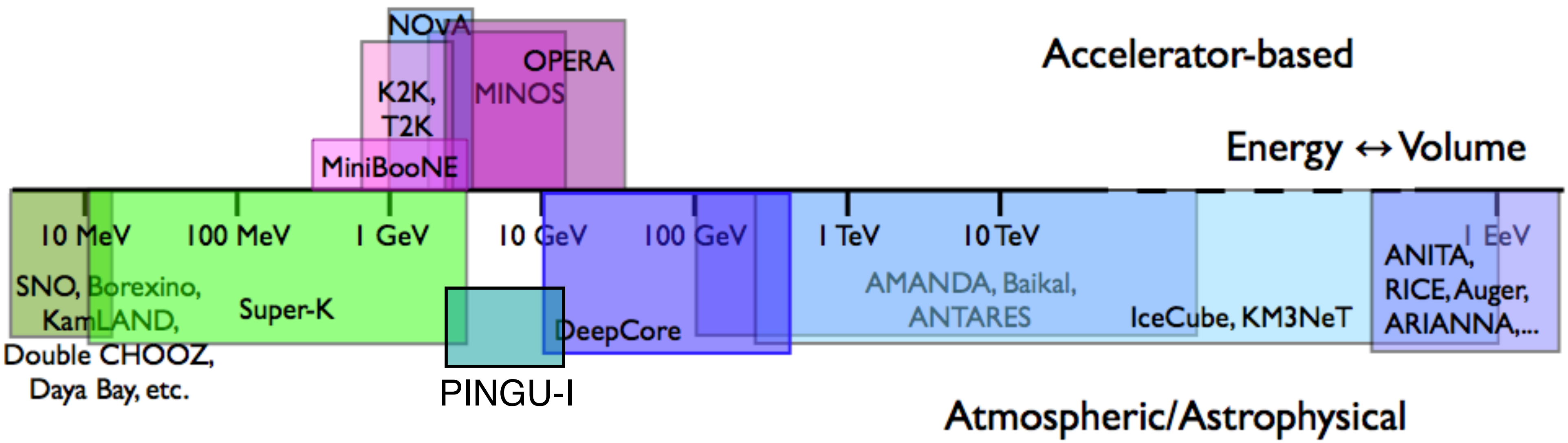
Phased IceCube Next Generation Upgrade (PINGU-I)



- 18 additional strings (~1000 DOMs) in the 30 MT Deep Core volume

- enhancement of capabilities at LE for:

✓ neutrino oscillations
✓ indirect searches for Dark Matter
✓ detecting ν from Supernovae



Summary

- IceCube detector completed construction in December 2010
  - IC86 run starts on May 13, 2011
  - the era of km^3 neutrino astronomy has begun

- Deep Core construction is complete
  - extends IceCube sensitivity down to ~ 10 GeV

- Selected initial results (partial detector configurations)
  - Atmospheric muon neutrinos: hundreds /day, energy spectra
  - Atmospheric neutrinos at low energies (Deep Core), cascade channel: a few/day
  - Ongoing searches for extraterrestrial neutrinos:
    point sources (ν_μ) , diffuse flux (all-flavor ν)

  No sources of high energy extraterrestrial neutrinos found as of today.
  The sensitivity increases with the detector size, the data taking and analyses techniques

Stay tuned!

THE ICECUBE COLLABORATION

http://icecube.wisc.edu

36 institutions, 250 members

Canada:
University of Alberta

USA:
Bartol Research Institute, Delaware
Pennsylvania State University
UC Berkeley
UC 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

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