High Energy Neutrino Astronomy

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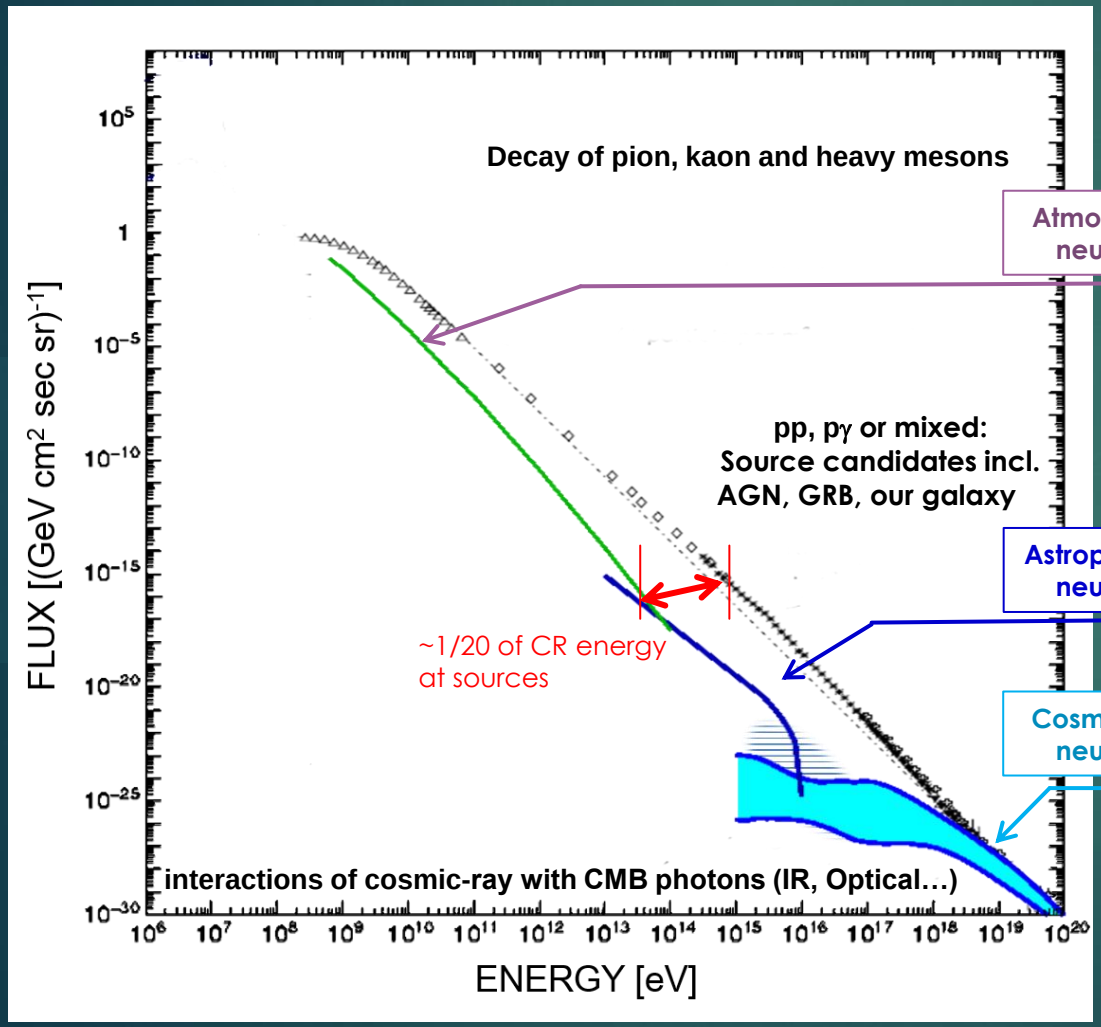
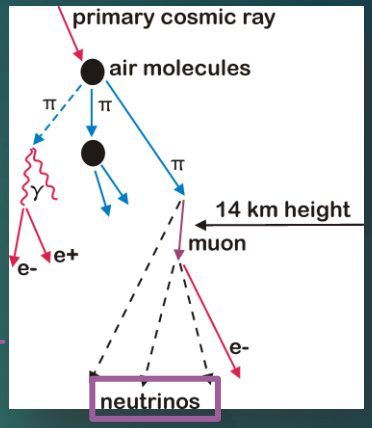
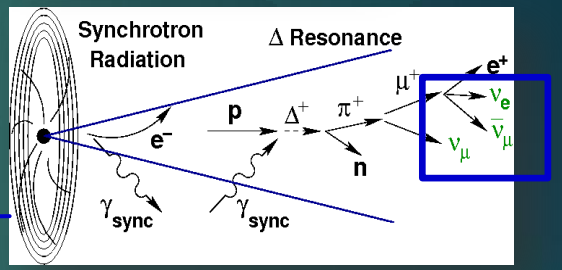
Outline

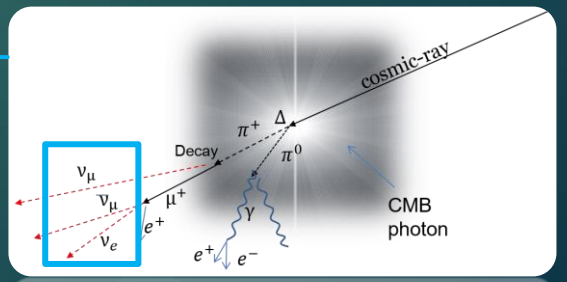
- Introduction
- Diffuse neutrinos
- Neutrino point sources
- Searches for higher energy neutrino components
- What's the next?

High energy neutrinos





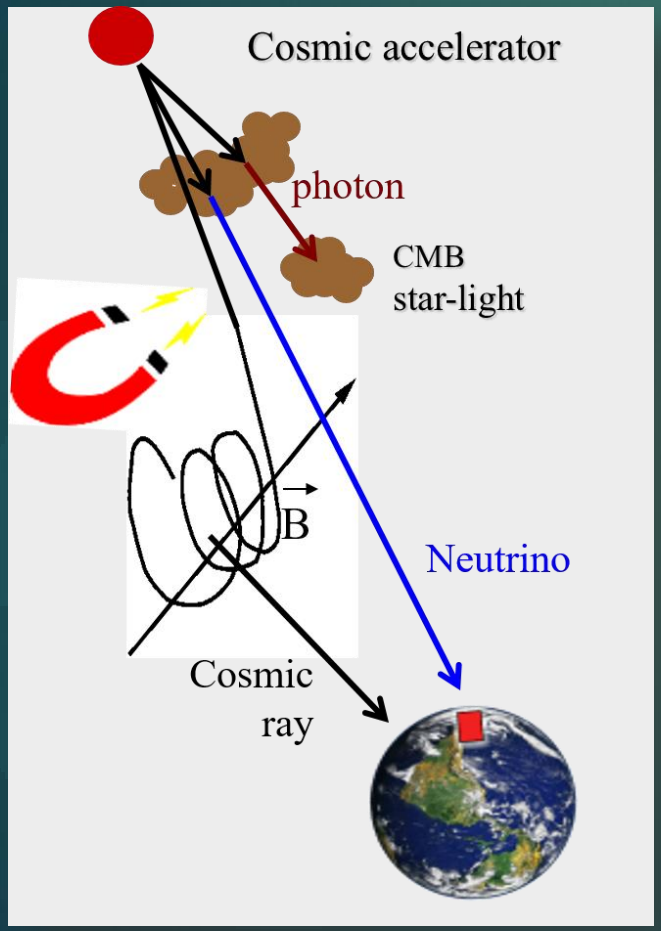


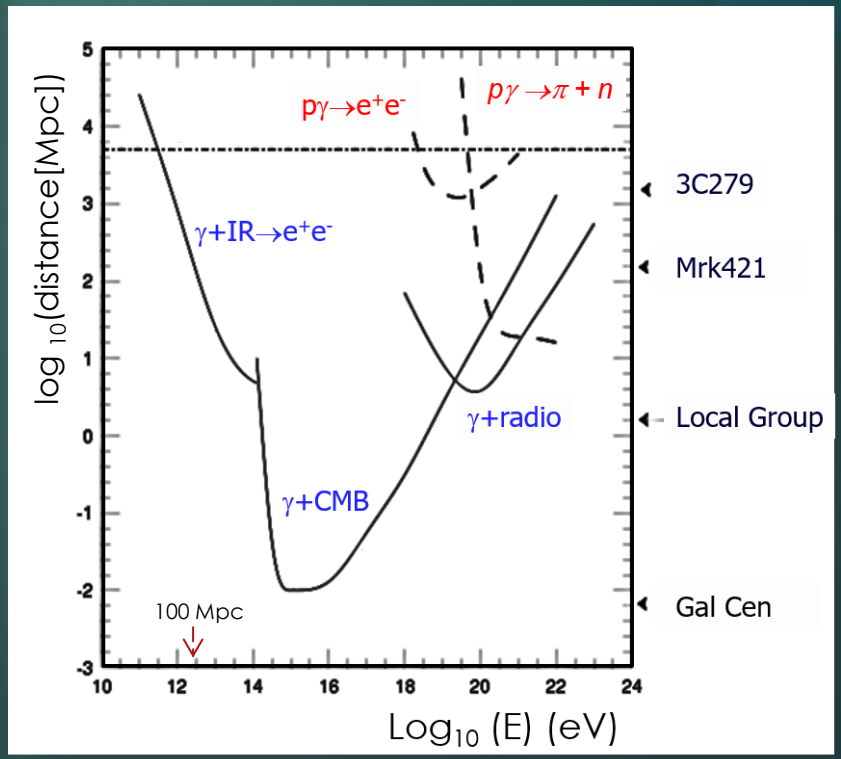


Neutrino as a cosmic messenger

Weak interaction during "propagation"

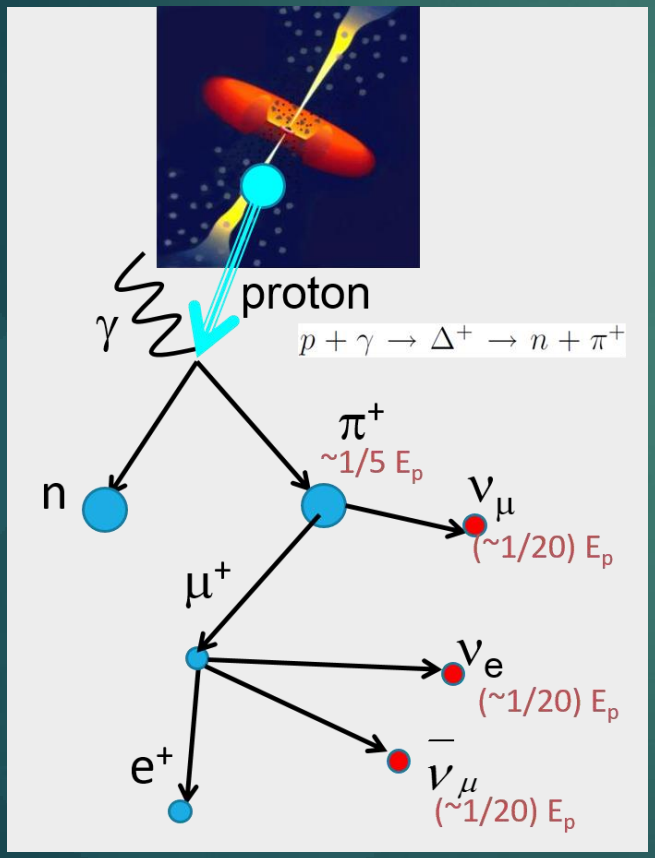
- **Penetration power**
- **Pointing capability**





Making neutrinos

Simple hadronic "creation"



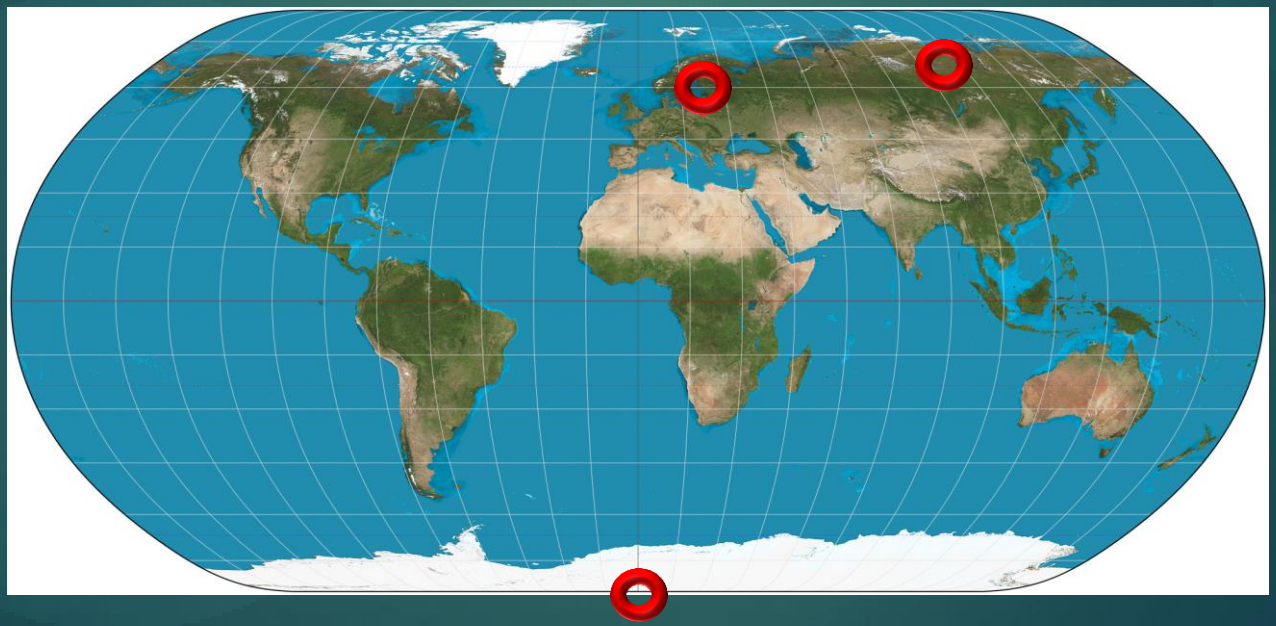
- **Simple modeling ingredients**
  - pp or pγ interaction
  - cosmic-ray and target spectra in source
- **Accompanying partners**
  - gamma-ray from neutral pions
  - Parent cosmic-rays
  - Multi-messenger !

$$E_\nu \approx \frac{1}{20} E_P \approx \frac{1}{2} E_\gamma$$

Neutrino detectors

Neutrino Telescopes need to be large

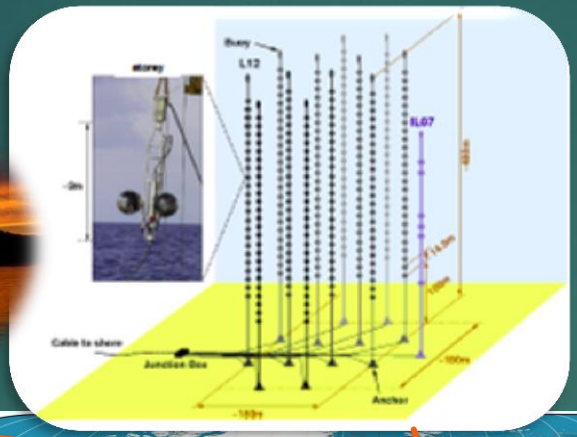
- Benchmark 1km^3 scale for a few neutrino events/year expected from CR observation
  - Natural photon-transparent materials as Cherenkov medium and neutrino beam dumping



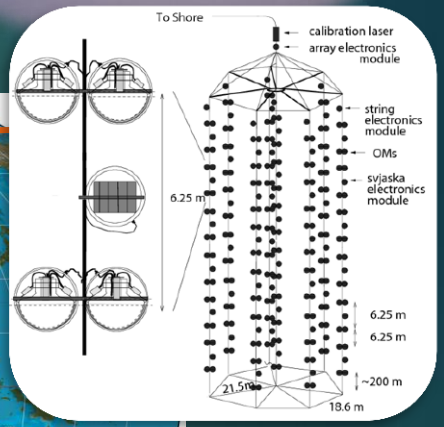
Neutrino detectors

Thursday 29th Neutrino parallel: ANTARES results By R. Gracia Ruiz

ANTARES



BAIKAL-NT200



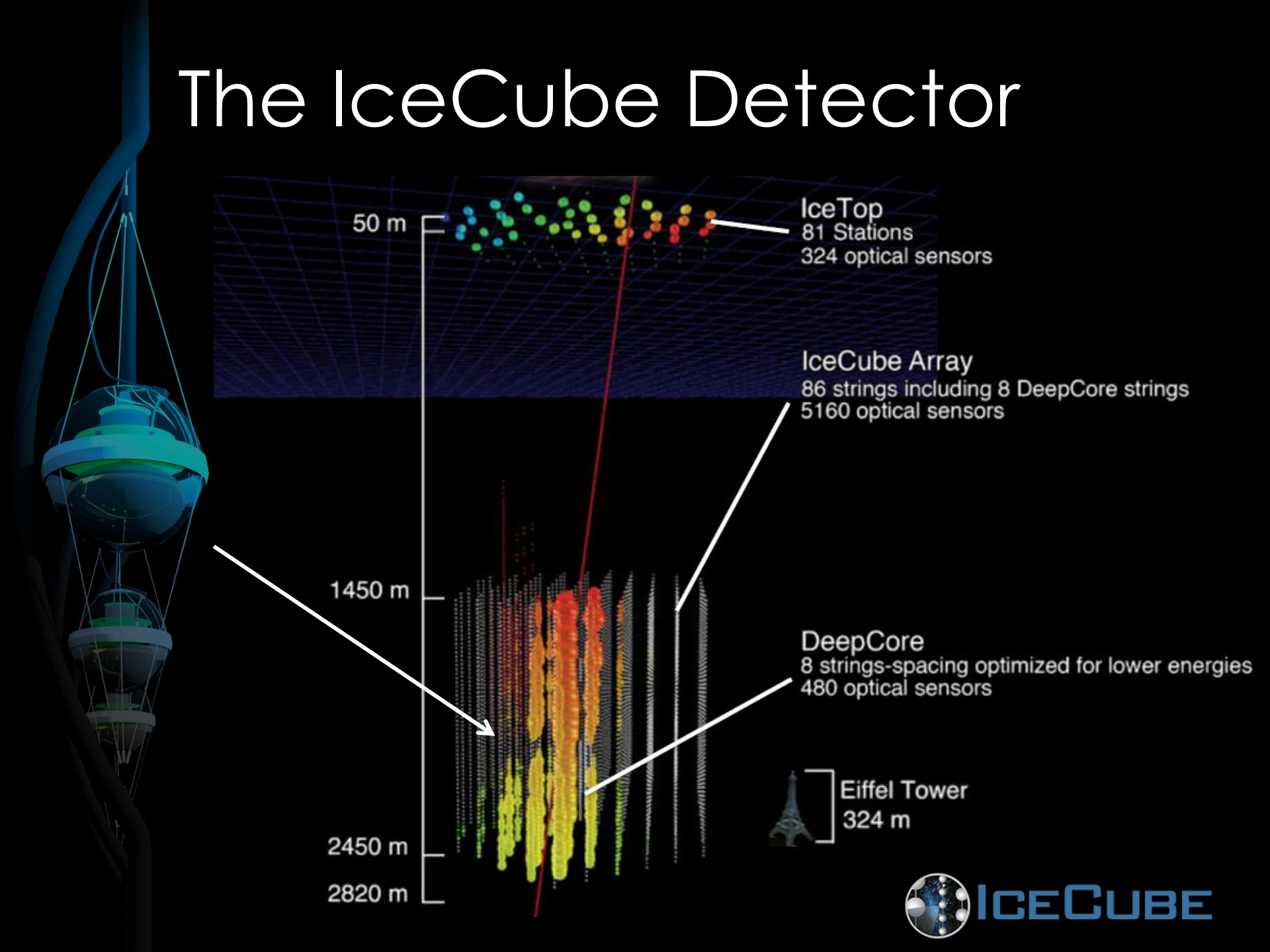
IceCube

BAIKAL-NT200 (8strings 192 PMTs) 1/2000km^3

ANTARES (12lines 882PMTs) 1/100km^3

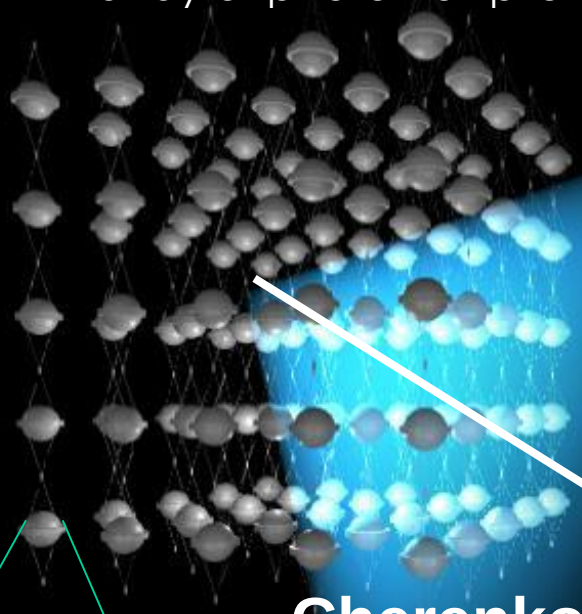
IceCube (86lines 5160PMTs) 1km^3

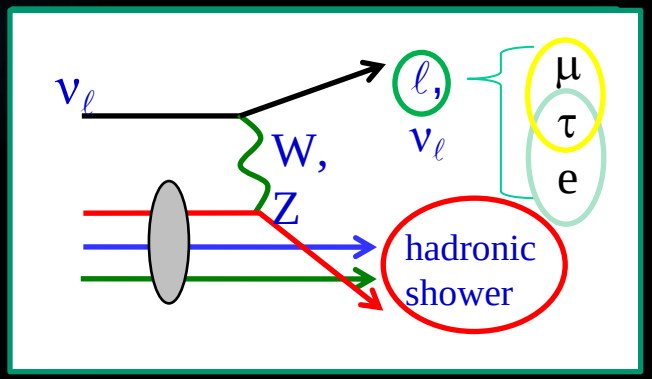
The IceCube Detector



Detection Principle

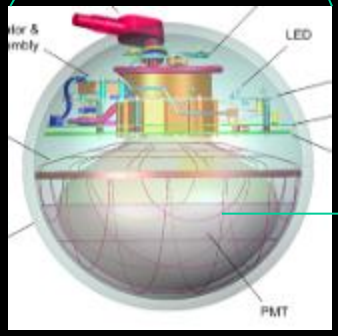
An array of photomultiplier tubes + Dark and transparent material

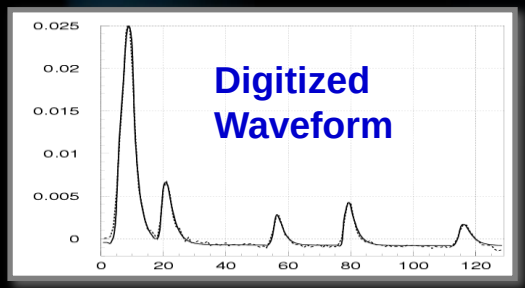




Cherenkov light

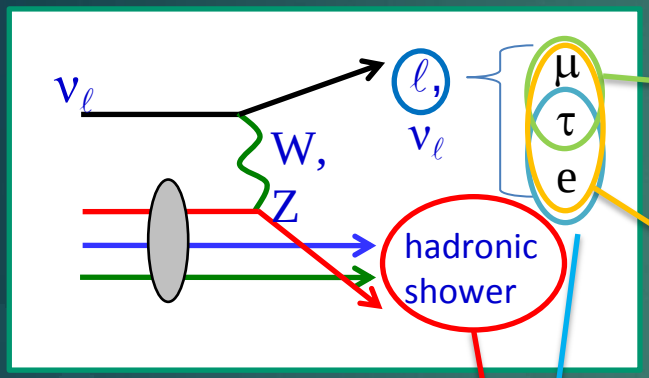
Charged Particles

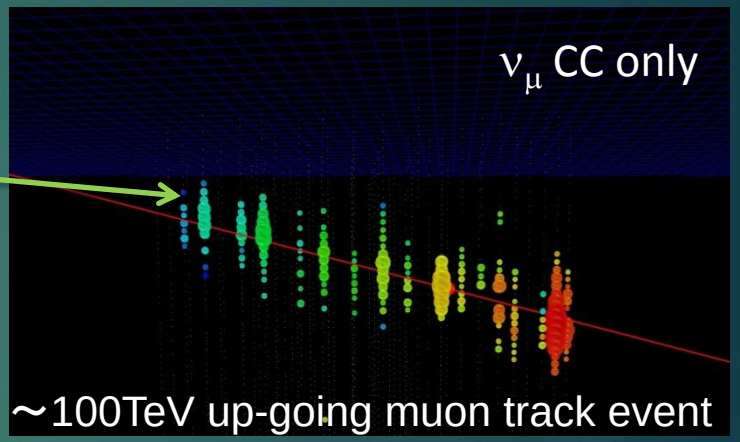




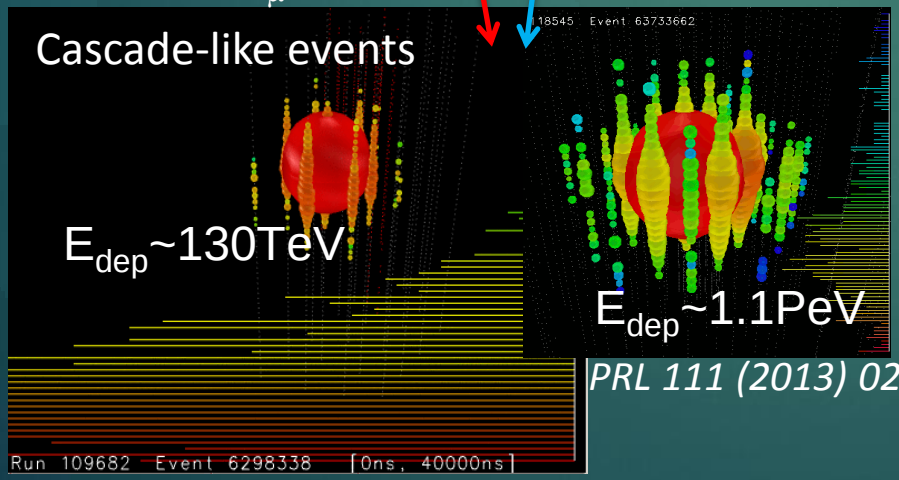
ν

High energy neutrino detection channels





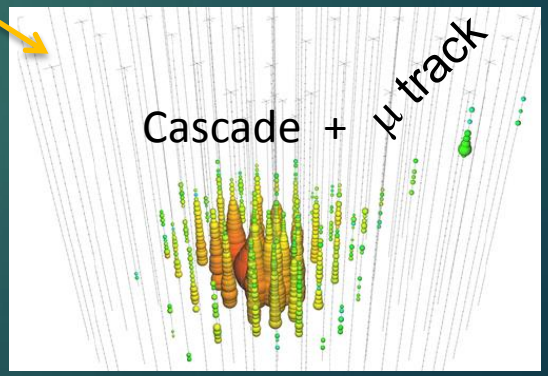
All except ν_μ CC



PRL 111 (2013) 021103

Phys. Rev. D 84, 072001 (2011)

Starting event inside detector sensitive to all flavor CC/NC



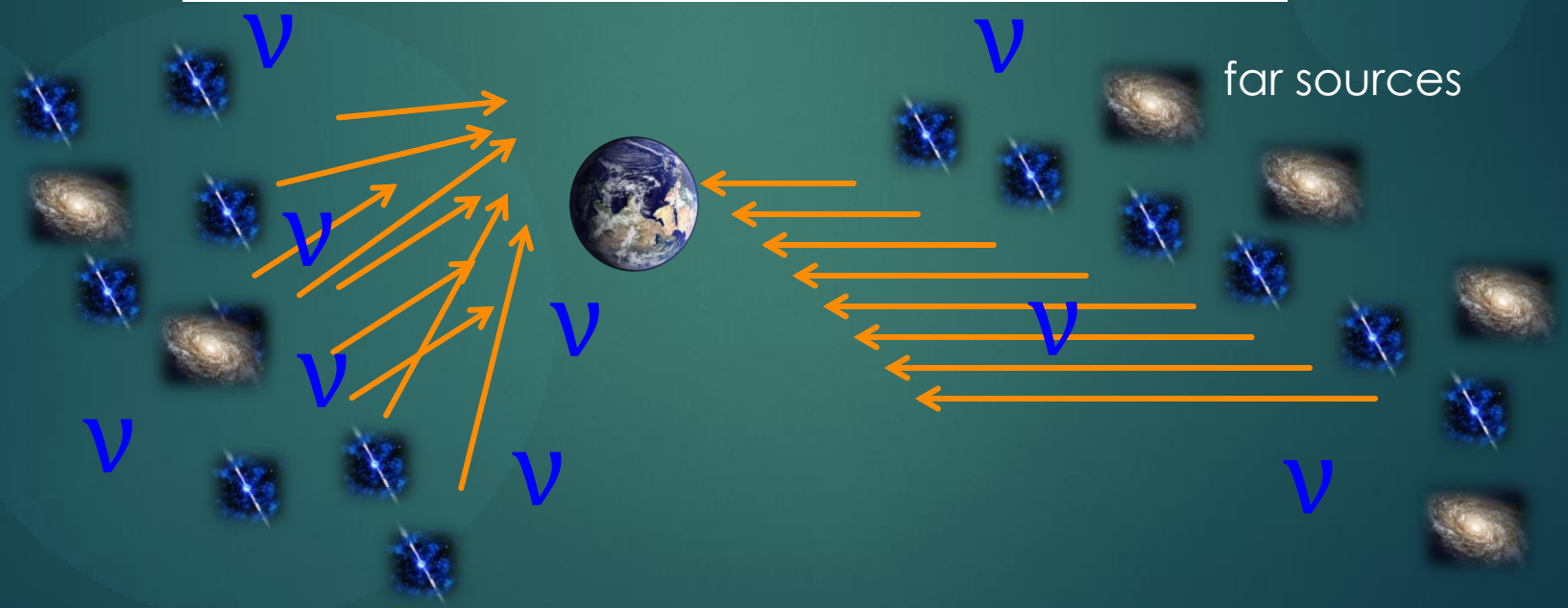
Science 22 Vol. 342 (2013)
PRL 113, 101101 (2014)

Diffuse neutrino spectra

Diffuse neutrino flux: Powerful tool to search abandant sources

- Accumulate neutrinos from many sources even at very far Universe, or very weak. Different direction or timing, and of different types
- Diffuse flux give hints to build a better point source observation strategy

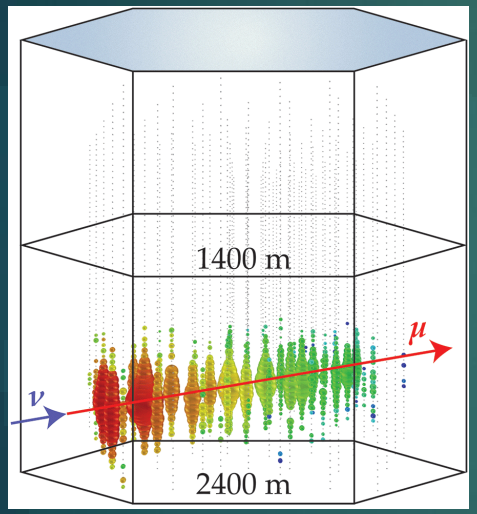
$$\phi_{\rm diffuse}\,(E|L,z) = \int\int\int \phi_{\rm single}\,(E|L,z)\,\frac{d^2n(L,z)}{dz\,dL}dz\,dL\,d\Omega$$



Thursday 29th Neutrino parallel: IceCube Diffuse flux By J. Van Santen

Upward-going muon channel

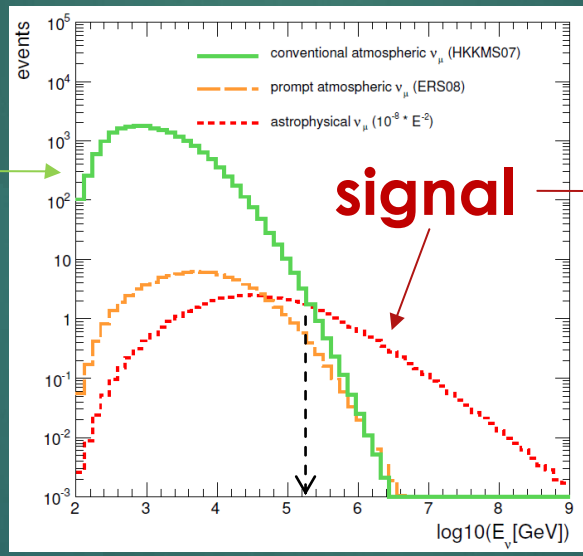
Select well reconstructed upward going tracks



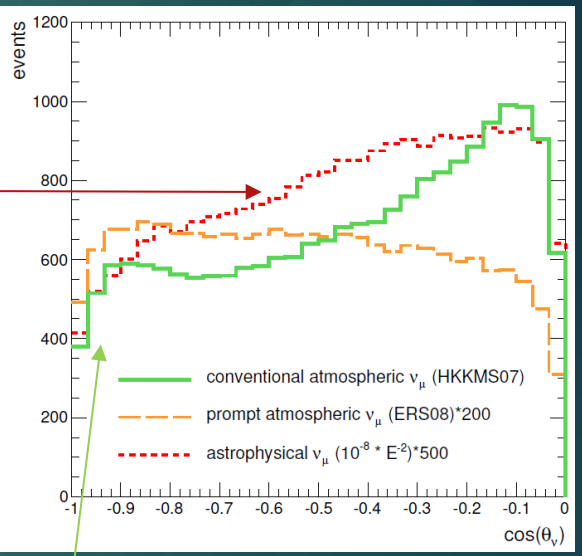
Physics 7, 88 (2014)

MC expectations

Energy



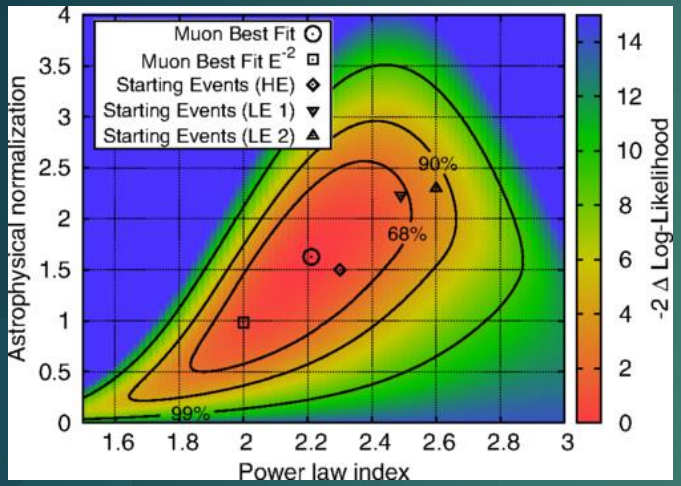
Direction

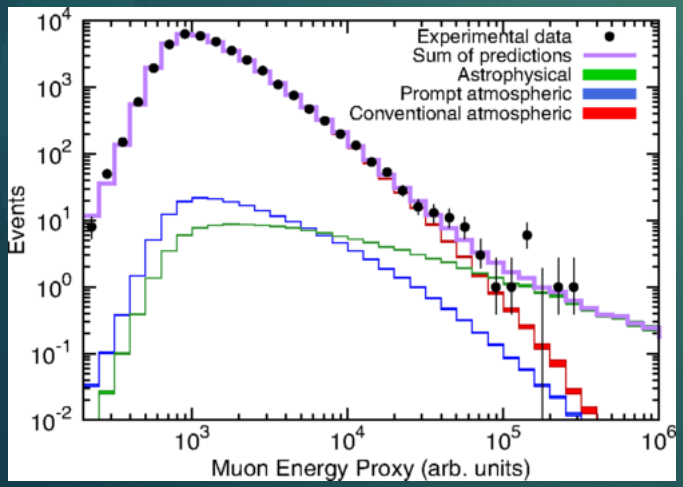


- high statistics atmospheric ν well confined from data
- Dominate over astronomical ν signal upto ~100 TeV

Upward-going muon channel

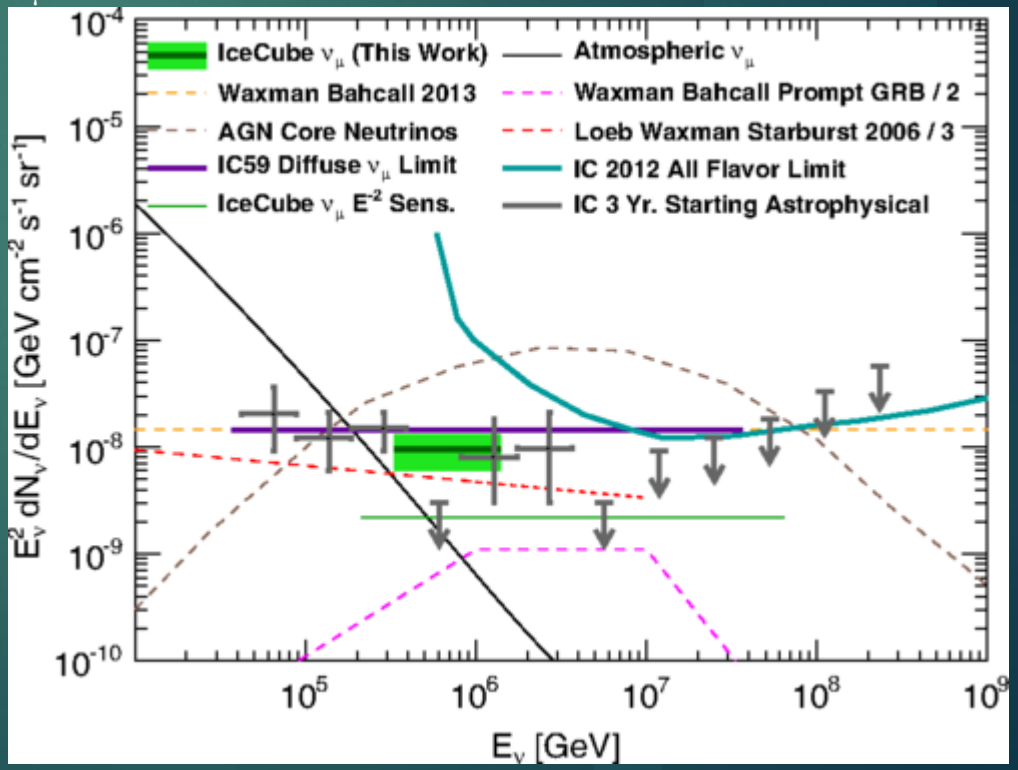
Data:2010-2012 (2 years) fit results Phys. Rev. Lett. 115, 081102 (2015)





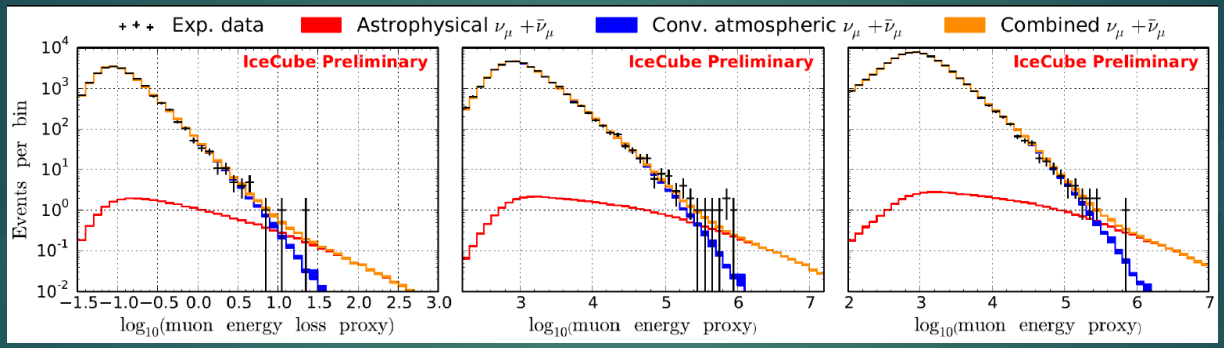
- 35000 events of 2 year sample 99.9% muon neutrino purity
- 3.7σ evidence of astrophysical flux

ν_μ flux



Updates on up-muon analysis

1. Previously separately analyzed 2009-2010 data and 2010-2012 2 year data are combined (ICRC2015)



2. Then 3 more years of the full IceCube are added (results at this conference)

Thursday 29th Neutrino parallel session talk By S. Schoenen

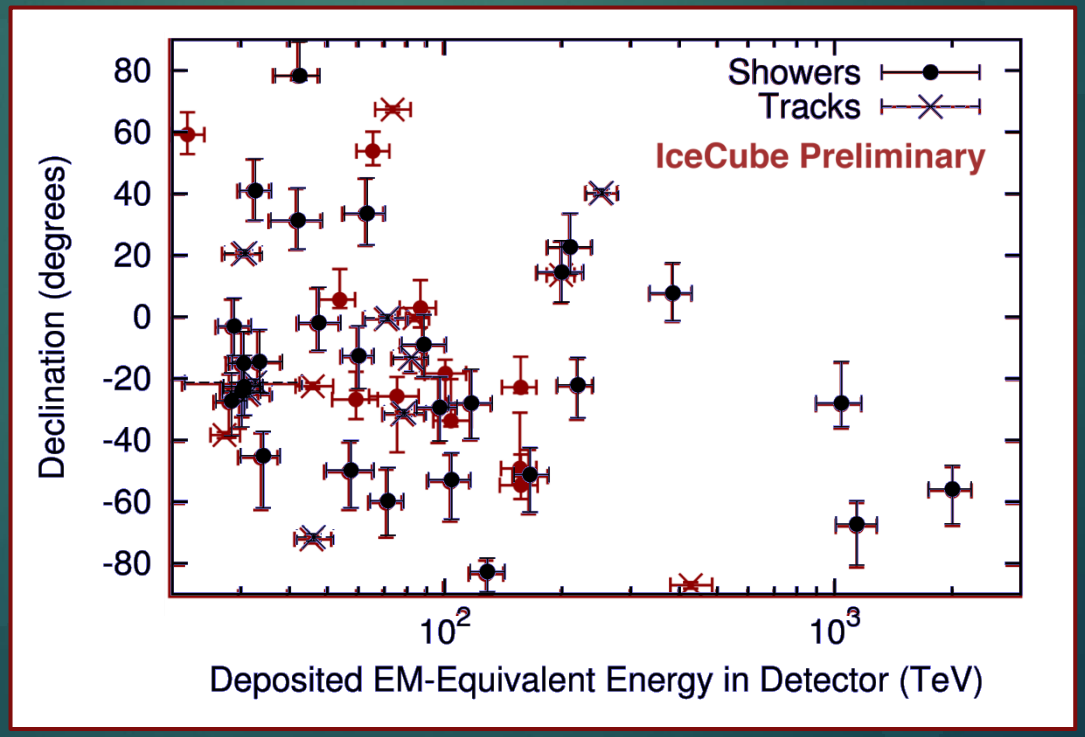
Highlights:

- Glowing significance: 1.8σ(1y) →3.7σ(2y) →4.3σ(3y) →5.9σ(6y)
- Consistent level of fluxes with reduced error
- Highest neutrino energy event (2.6±0.3 PeV energy deposit)

Starting event channel

- Use outer layer of IceCube detector as muon veto
  - Updated from previous publication (3 year sample, PRL 113, 101101) with additional one year of data

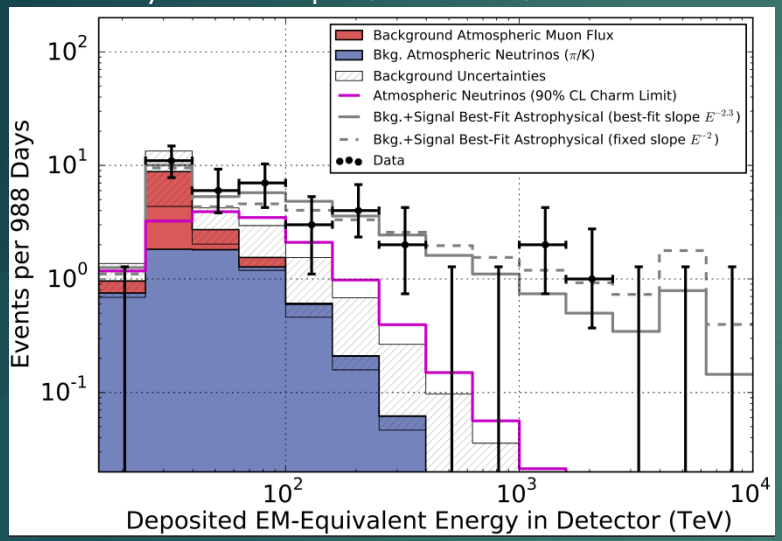
- Glowing significance: 4.1σ(2y) →5.7σ(3y) →6.5σ(4y)
- Increasing number of events: 28(2y) →36+1(3y) →53+1(4y)
- No new over PeV event

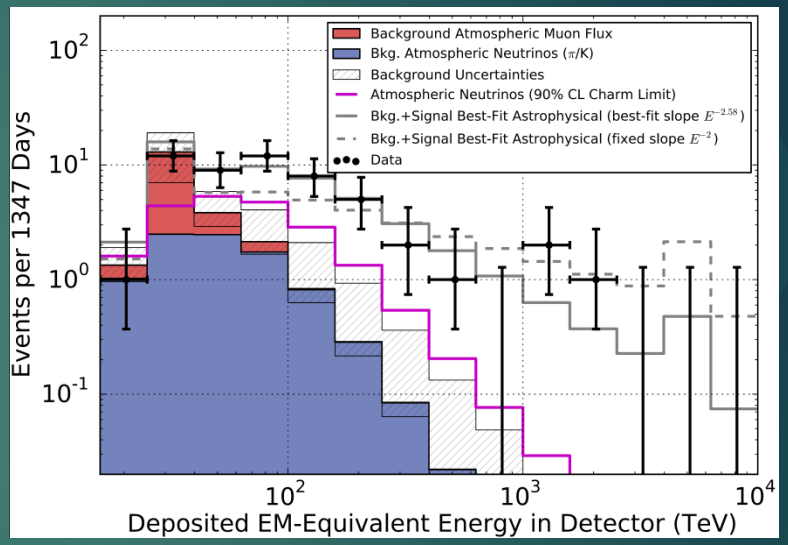


Starting event channel

Compared to the previous publication (Phys. Rev. Lett. 113, 101101), a softer spectra preferred while consistent within error

3 year sample, PRL 113, 101101

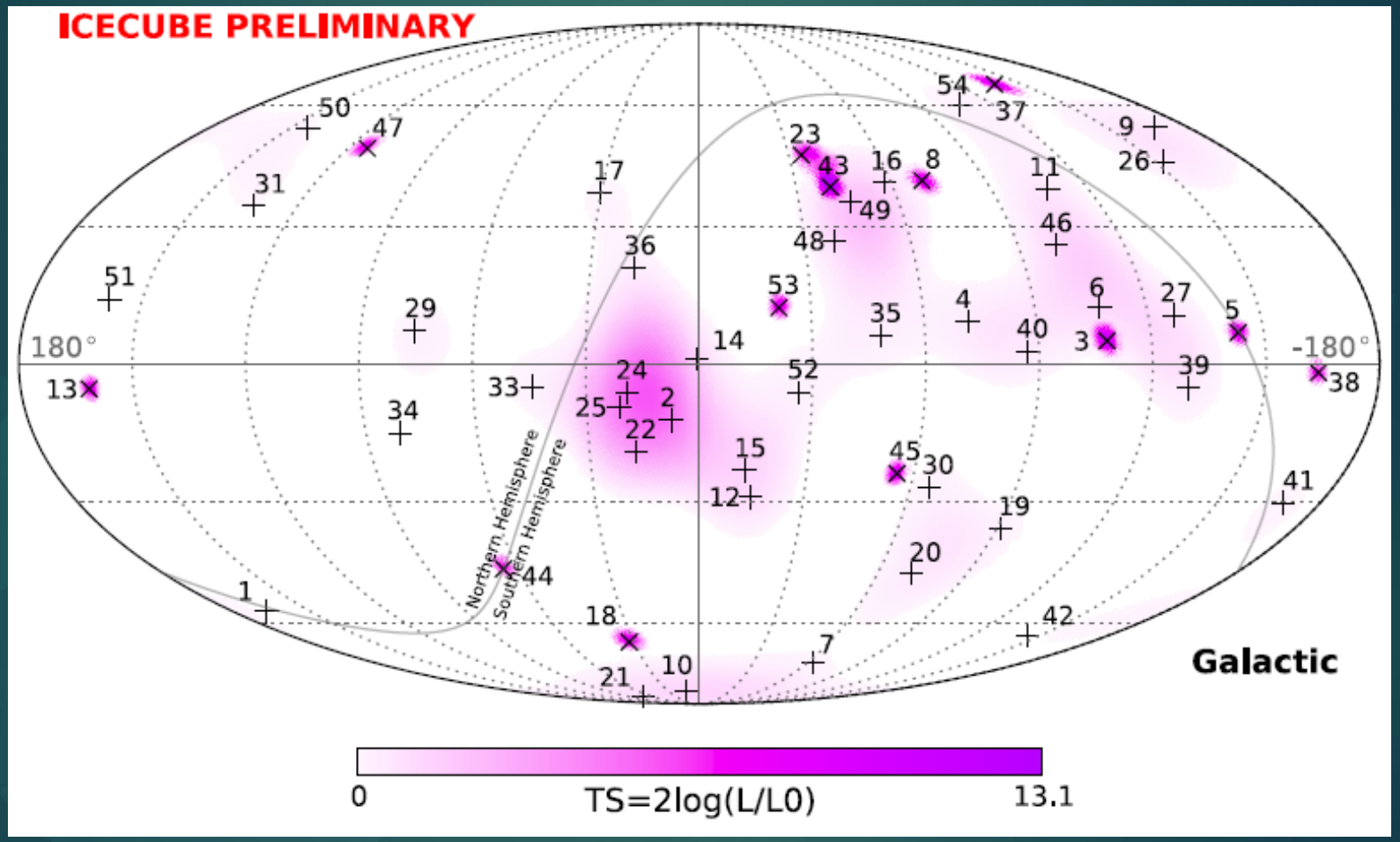




- Best fit spectral index was 2.30±0.3 (3y) and now 2.58±0.25 (4y)
- Energy threshold ~60GeV
  - Lower energy extension of analysis down to 1TeV! PRD 91 022001(2014)

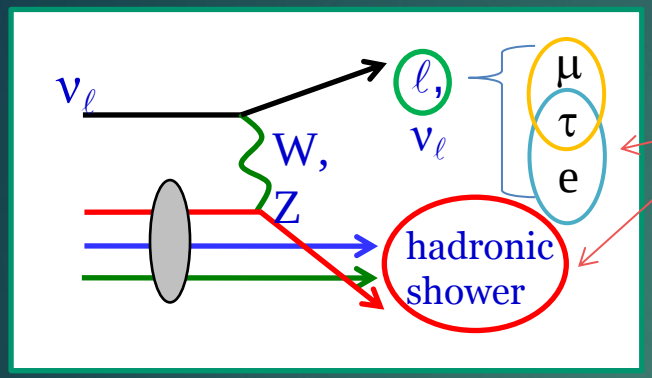
Thursday 29th Neutrino parallel: IceCube Diffuse flux By J. Van Santen

No clustering observed

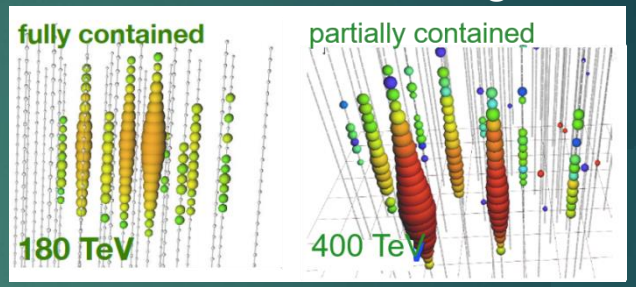


The most significant cluster p-value 58% with all events, 44% with shower events

Cascade channel



produces cascade-like signatures



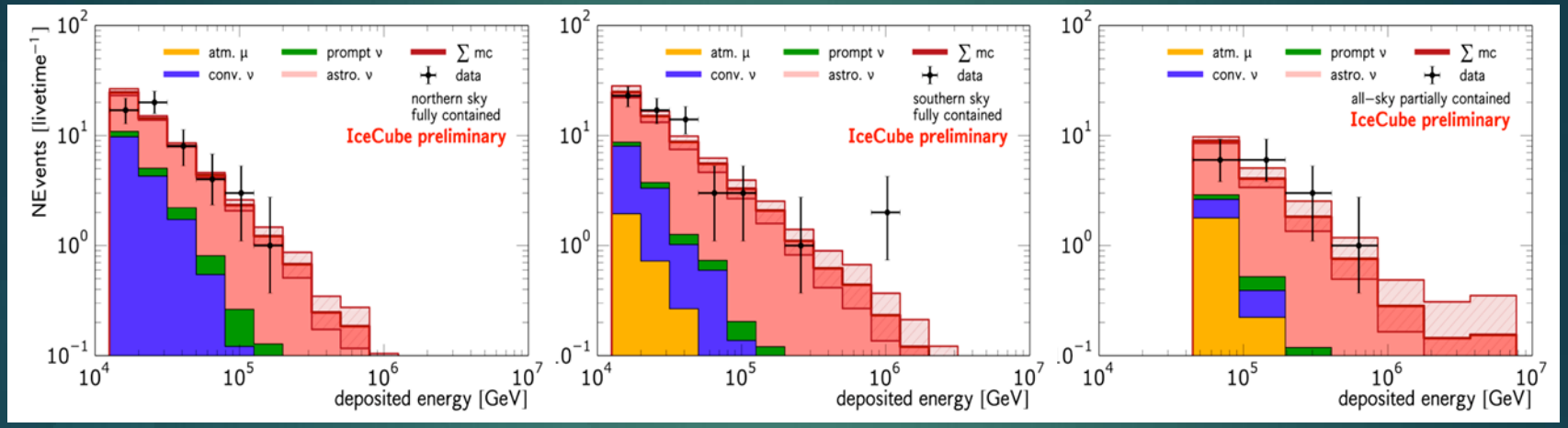
topological selection of cascade events

Cascade channel is complementary to upward muon channel

- Good energy resolution of ~10%
  - log(E)~0.3 for muon energy deposit to muon neutrino energy
- Directional resolution is ~10°
  - ~0.5° for muons
- Less atmospheric neutrino background
  - atm muons reach to ground before decaying
  - turn over energy from BG to signal is lower; sensitive to lower energy region (10TeV – 100TeV)
    - upward muon analysis sensitive above ~100TeV
- Sensitive to full sky

2 year cascade analysis

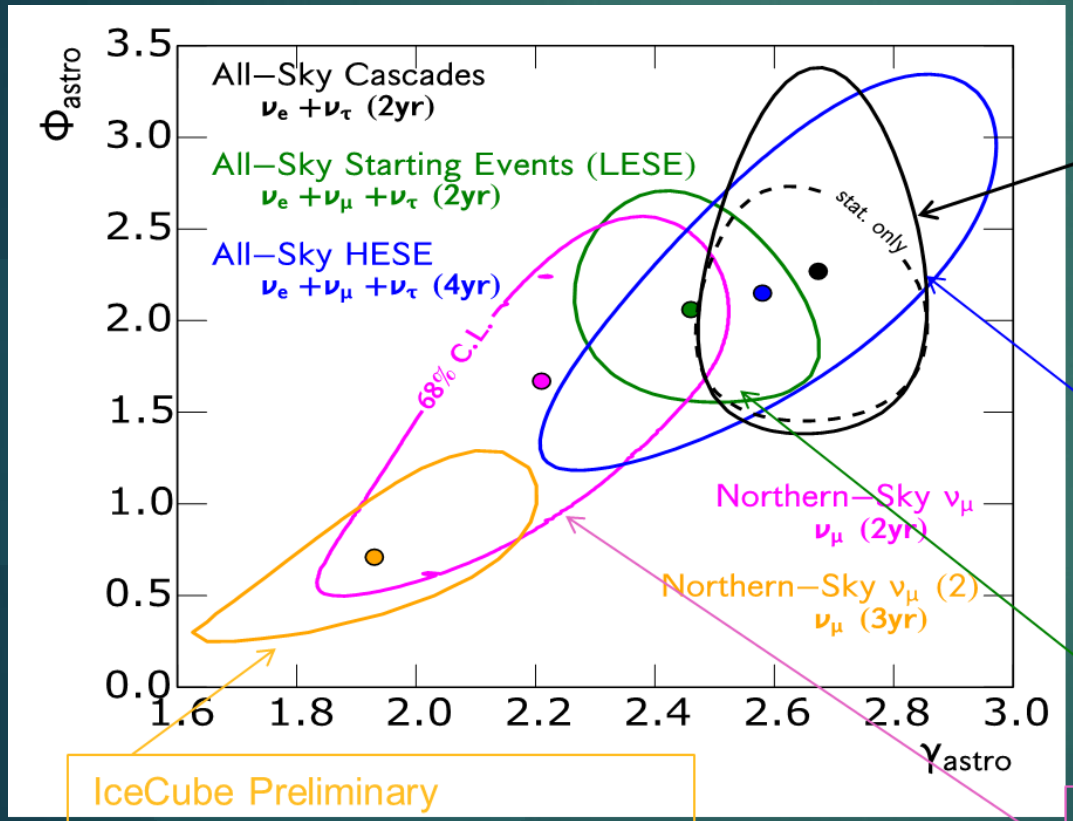
Data:2010-2012 (2 years) fit results



- Observed 172 events (energies 10 TeV – 1 PeV)
  60% are not overlapping with the other channel
- BG only ohpothesis is rejected at 4.7σ
- Best fit spectral index (soft) $\gamma = 2.67^{+0.12}_{-0.13}$

A best fit flux comparison

- Results are consistent
- Keep eye on the insignificant 2σ level of tension between cascade and upward muon analysis



IceCube Preliminary
2y Cascades
ICRC2015

IceCube Preliminary
4 year HESE
All flavor ($\nu_e + \nu_\mu + \nu_\tau$)
ICRC2015

PRD 91, 022001 (2015)
($\nu_e + \nu_\mu + \nu_\tau$) 2year

IceCube Preliminary
ν_μ (Northern Sky only) 3year
ICRC2015 to be updated

PRL 115 (2015) 8, 081102
ν_μ (Northern Sky only) 2year

What abut their sources?

Neutrino point source search

How to improve point source sensitivity

- Livetime, detector size (cross section of detector in the direction to the object)
  - sqrt(N)
- Angular resolution
  - linear
- Background veto
  - Down BG: atm muons, UP BG: atm nu
  - Surface veto can reduce down muon BG from Southern sky for IceCube

Monday 26th Neutrino parallel: KM3NeT By V. Van Elewyck

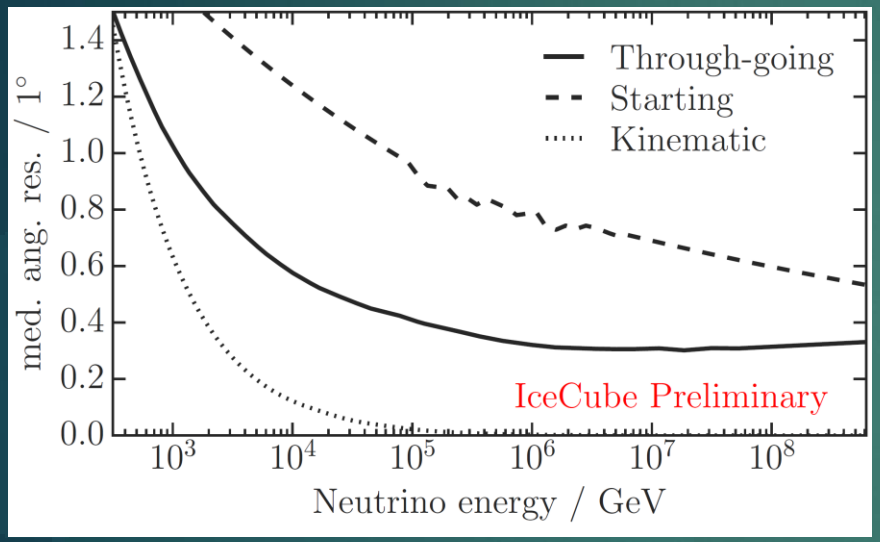
Friday 30th Plenary: The next generation neutrino telescopes By J. Kelley

Monday 26th Neutrino parallel: astrophysical neutrino search with IceCube surface veto By D. Tosi

- Stacking of the "right" class of object
  - Hints from diffuse neutrinos, point source upperlimits and gamma-ray observations
- Multimessenger
  - Trigger telescopes by neutrino for transient sources

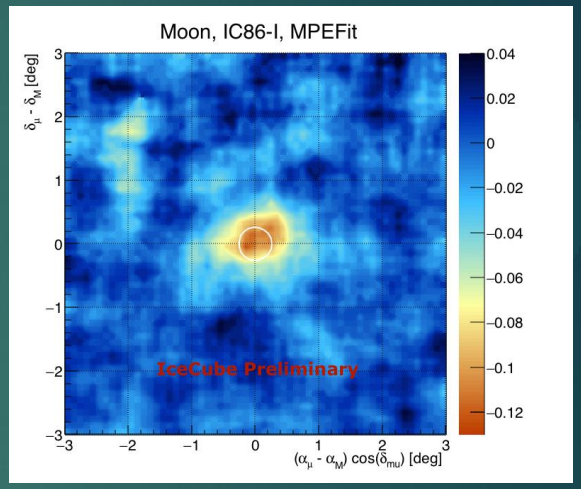
Point source search

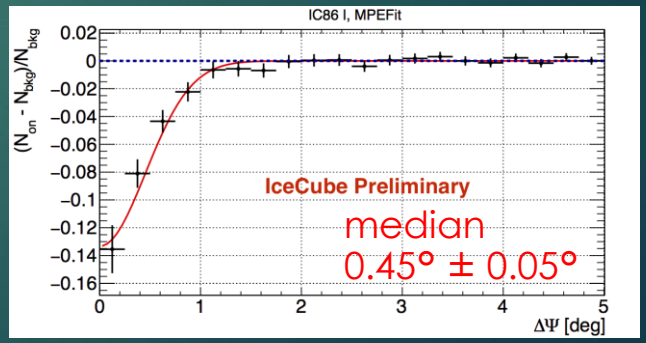
- Important factors
  - muon track angular resolution



  - source position in the sky
    - Southern sky: High energy atm muon BG (Signal PeV-EeV)
    - Northern sky: Atm neutrino BG (signal TeV-PeV)

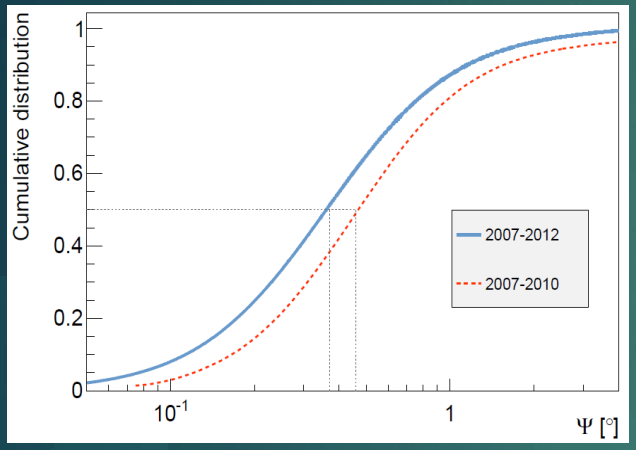
Moon shadow of cosmic ray muons using one year of data
(cosmic-ray primaries get absorbed in moon)

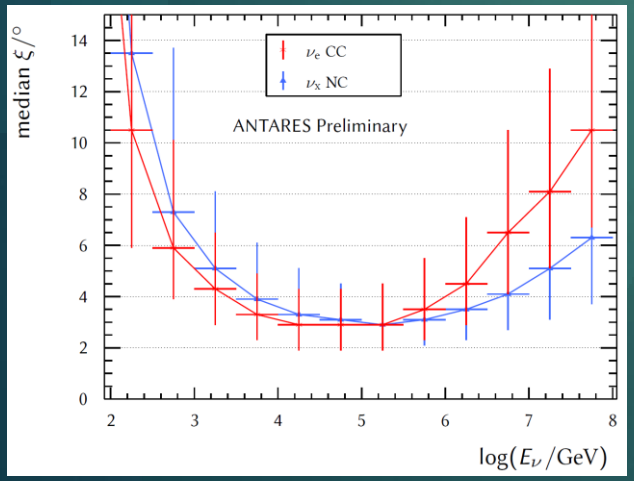




ANTARES in Sea water

Water:
Shorter light absorption length
Less light scattering





- Important factors
  - muon track angular resolution
  - cascade angular resolution
  - source positions in the sky
    - lower energy threshold for galactic sources

Tracks

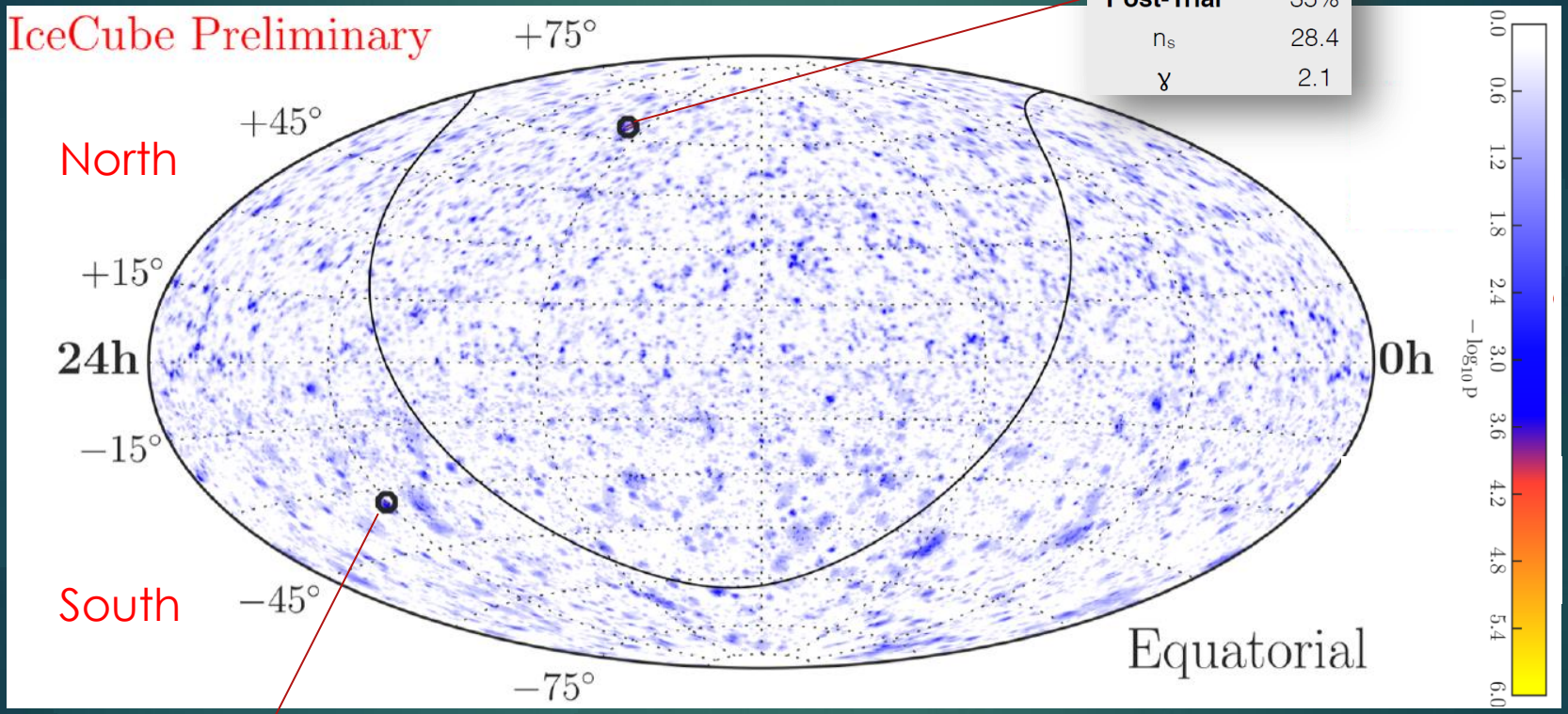
- 0.4° ± 0.1° median resolution

Cascades

- ~3° median resolution

IceCube cascades (Median angle 8~10°)

IceCube point source with 6 years of sample



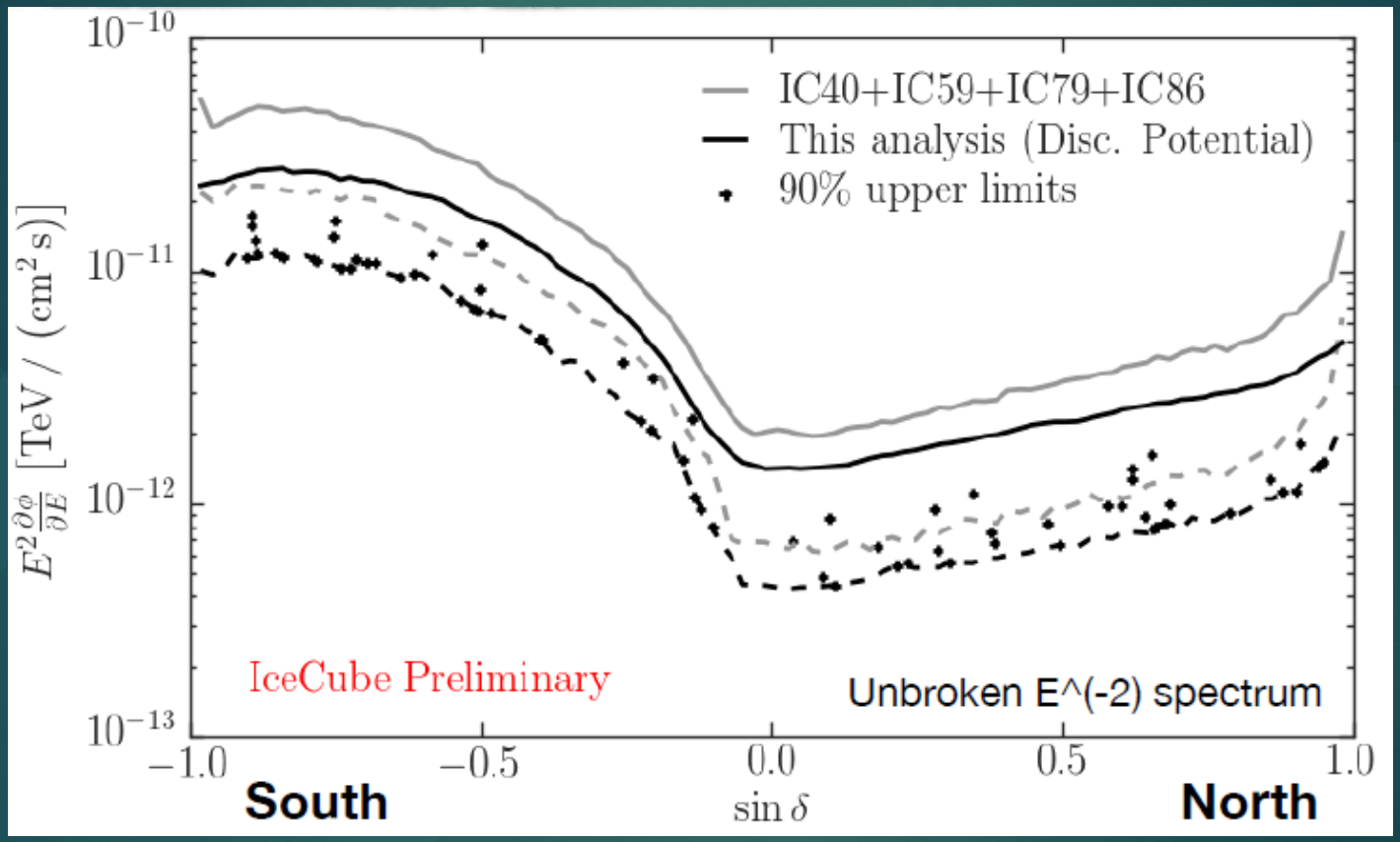
North	
$-\log_{10}(p)$	5.51
Post-Trial	35%
n_s	28.4
γ	2.1

South	
$-\log_{10}(p)$	4.74
Post-Trial	87%
n_s	19.4
γ	2.3

Full sky scan

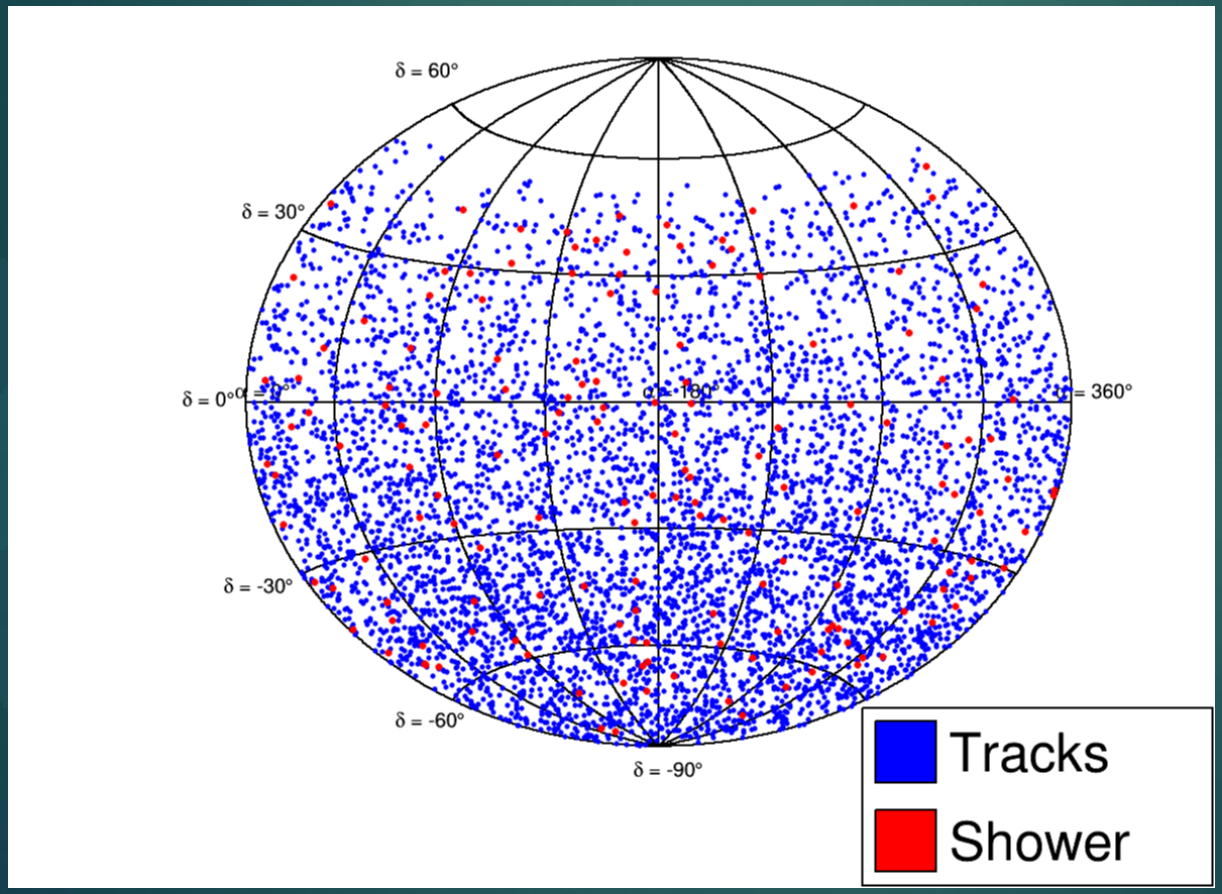
- No significant clustering observed

Upperlimits from 6 year point source search



Northern sky upperlimits (<10^9 GeV cm^{-2} s^{-1})
Southern sky upperlimits (<10^8 GeV cm^{-2} s^{-1})

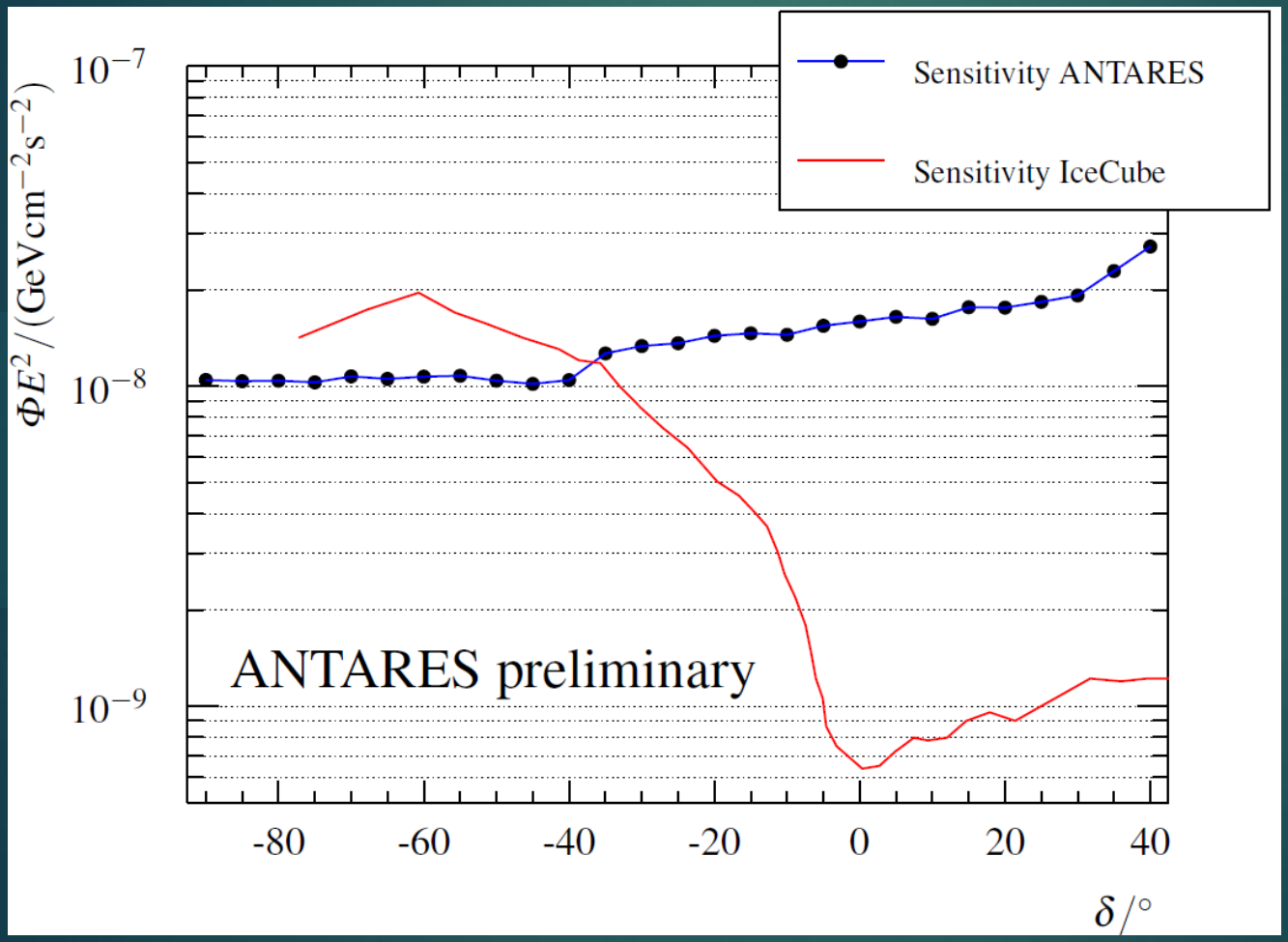
Antares point source update with cascade



Most significant cluster at
α =-48.3°
δ = -64.6°

p-value is 18.5%

Upperlimit from Antares track+cascade PS search



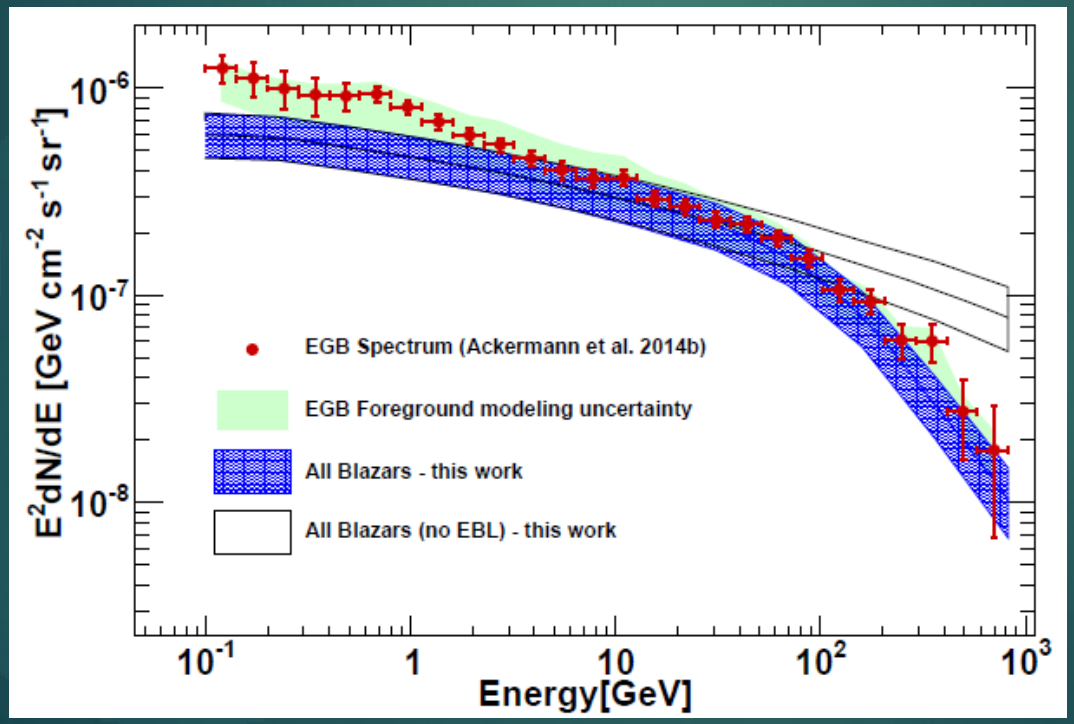
<10^8 GeV cm^{-2} s^{-1} in the Southern sky

~30% improvement from track only

Stacking source analysis

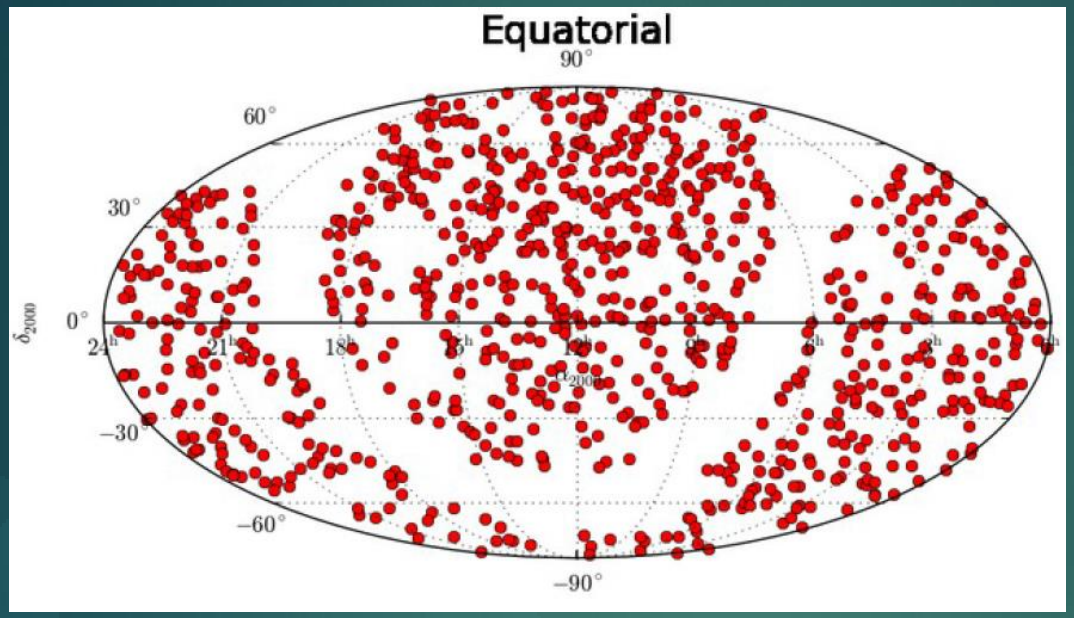
Motivation

- Do FERMI-LAT blazars all or certain sub population contribute to the diffuse signal?



arXiv:1501.05301

The cumulative neutrino flux from FERMI-LAT blazar populations



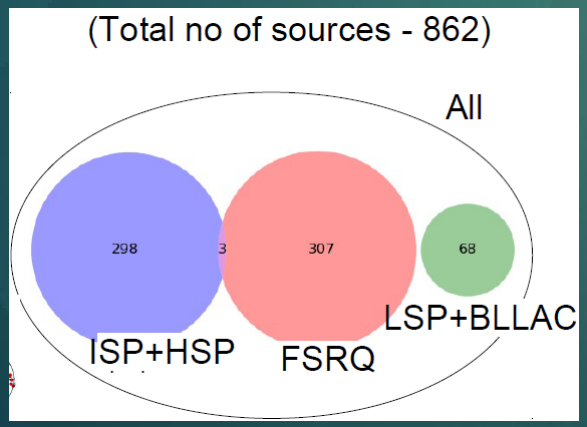
arxiv:1502.03104

Northern sky:

$TeV < E_\nu < PeV$

Southern sky:

$E_\nu > PeV$



simple modeling

All sources are equal

$$\left(w_{model,j}=1\right)$$

or

$$\nu_{lum.} \propto \gamma_{lum.}$$

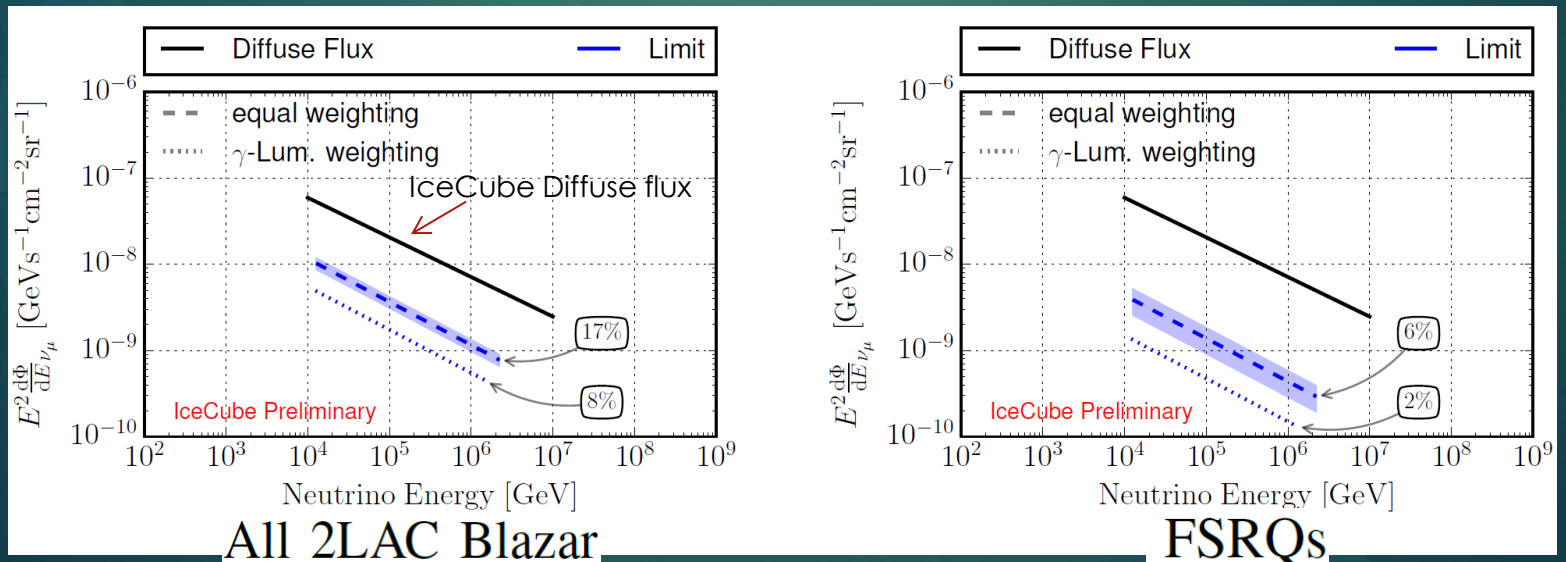
$$\left(w_{model,j} \propto \gamma_{lum.,j}\right)$$

FERMI blazar stacking results

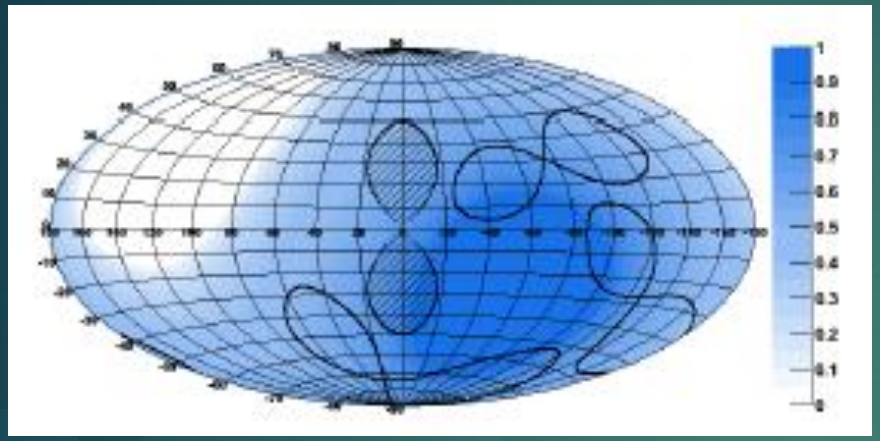
	p-values		
	$w_{source} \propto F_\gamma$	$w_{source} = 1$	No. of sources
All 2LAC Blazars	36 %	6 %	862
FSRQs	34 %	34 %	310
LSPs	36 %	28 %	308
ISP/HSPs	>50 %	11 %	301
LSP-BLLACs	13 %	7 %	62

- No significant excess
- The smallest p-value is 6% for the "All 2LAC Blazar"

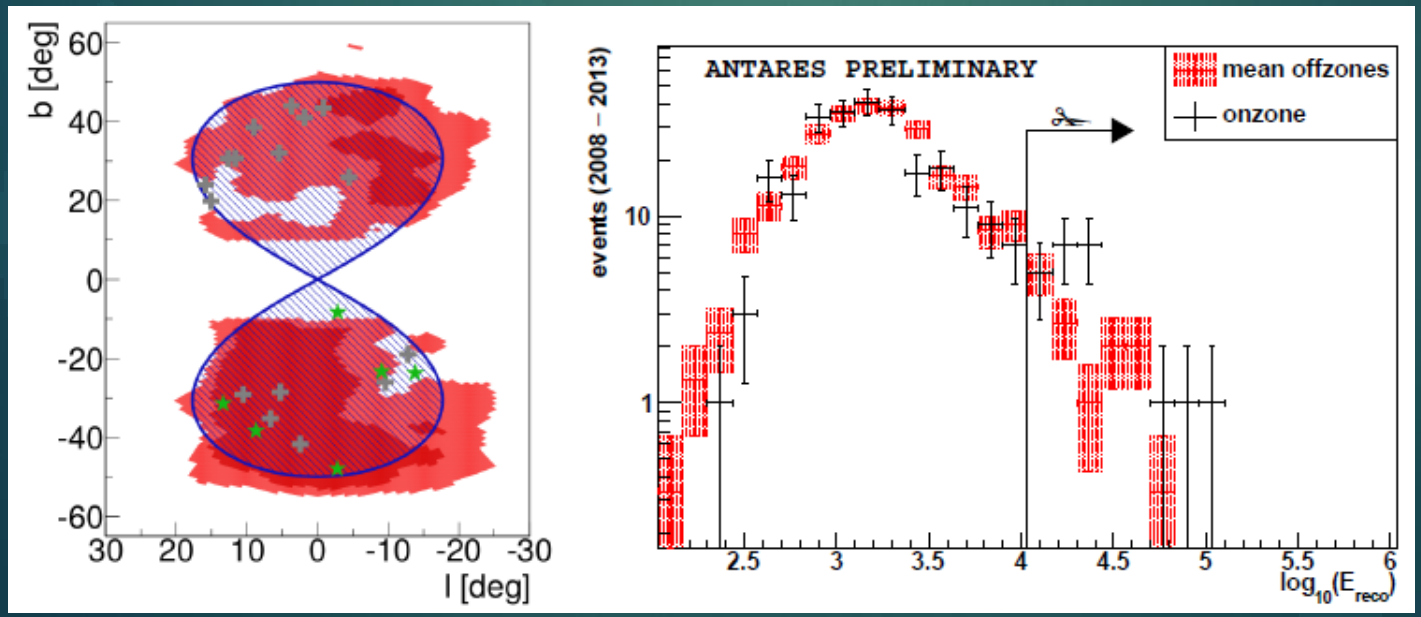
Upperlimits on diffuse flux contribution assuming parameterization in ApJ 720:435 (2010)



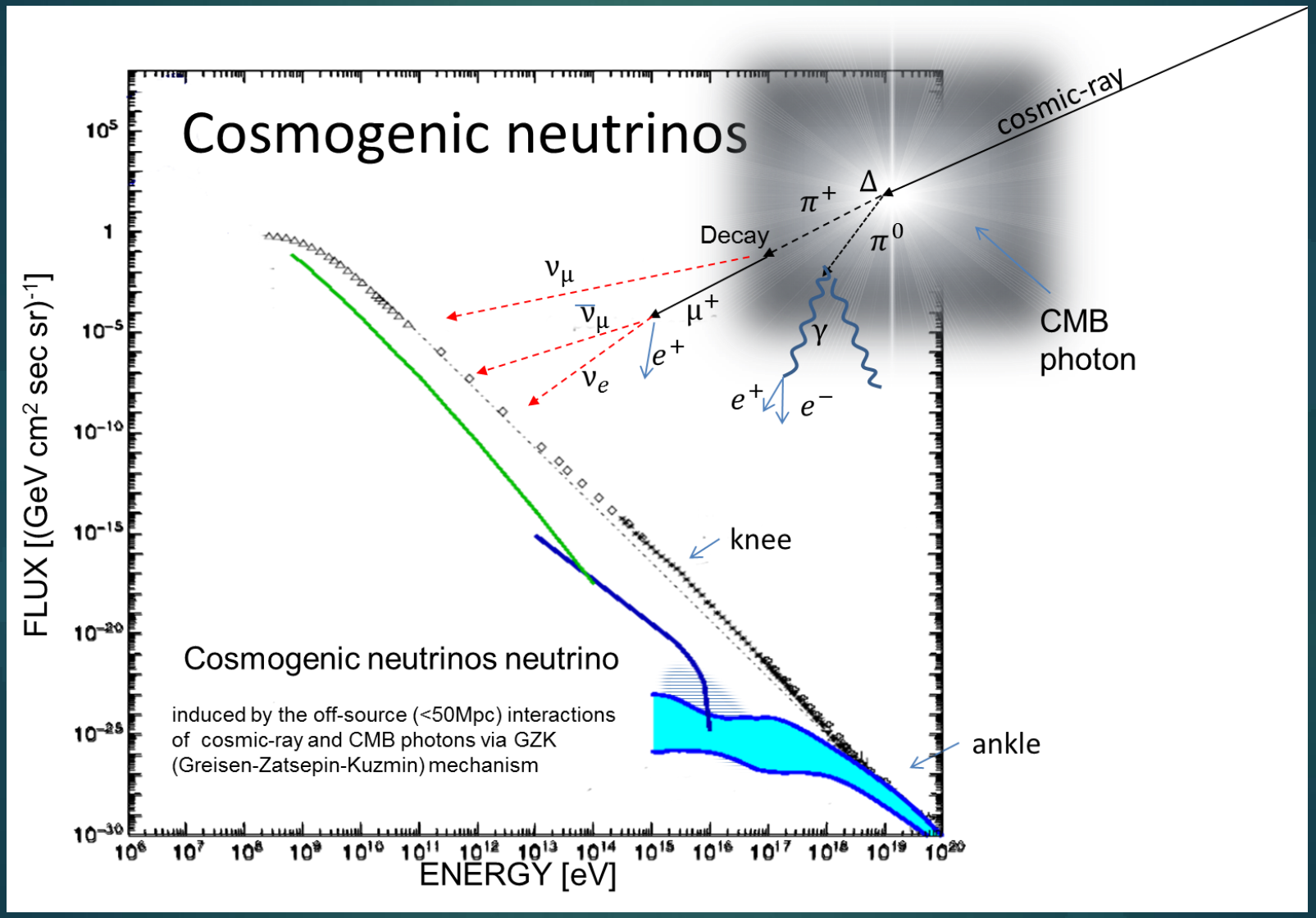
Search for Neutrino fluxes from the Fermi Bubble



- In the previous 4 year analysis, average 11 bg and 16 found (1.4σ)
- Additional year sample combined, average 13 bg and 22 found (1.9σ)



Flux above 10 PeV

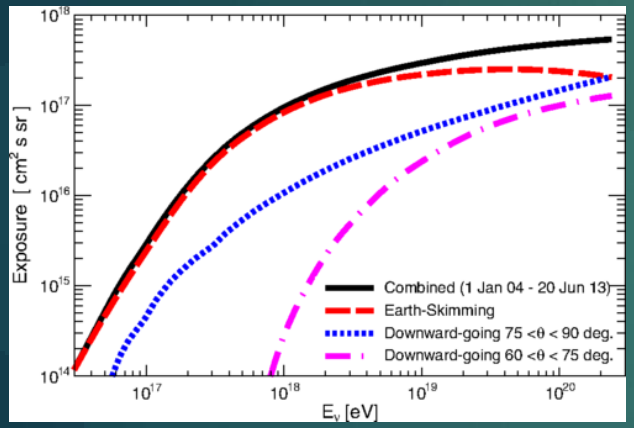


Cosmogenic neutrino search by air shower detector

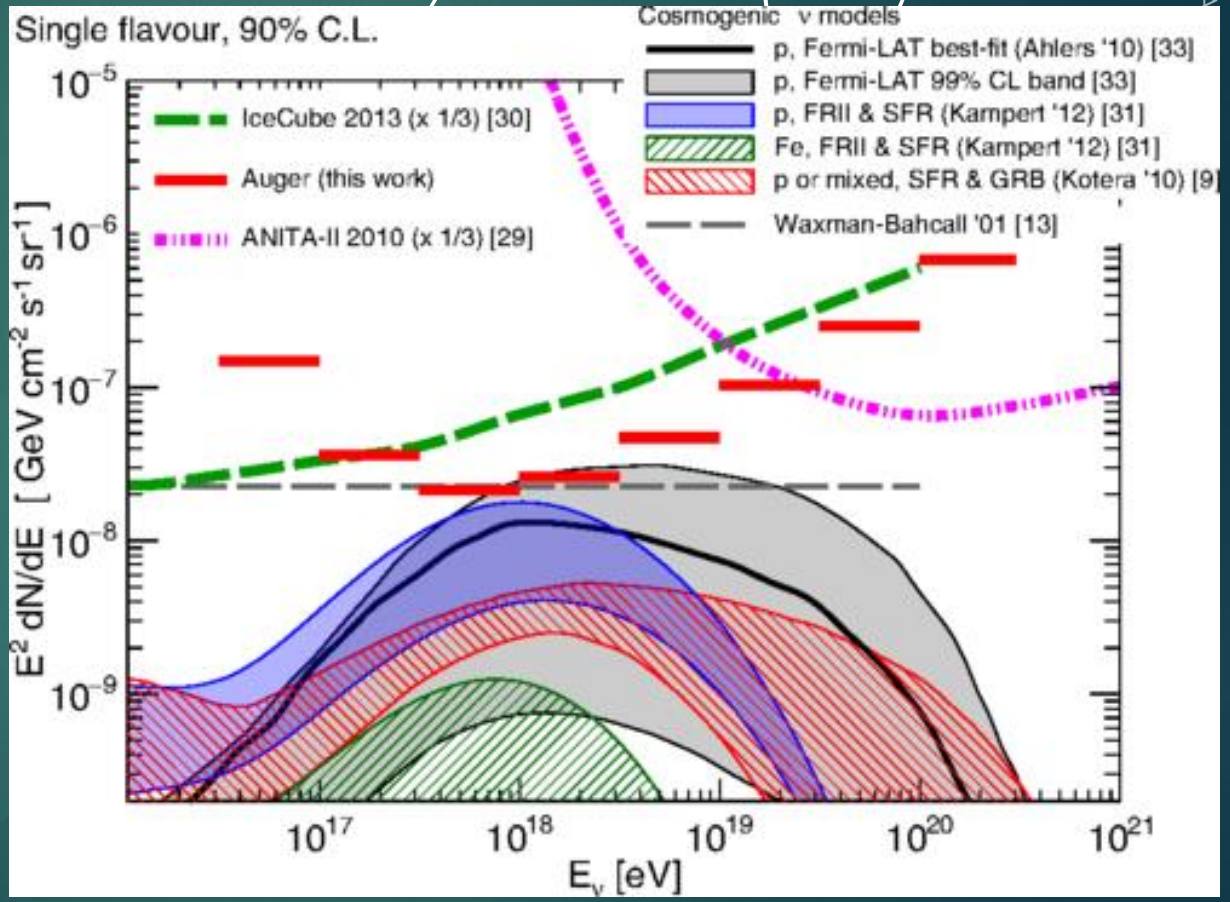
Phys. Rev. D 91 (2015) 092008

PIERRE AUGER OBSERVATORY

Exposure



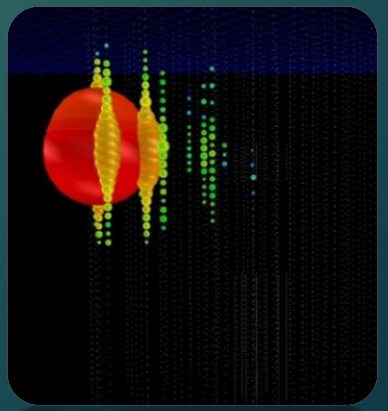
January 2004-June 2013



Extremely high energy ν search with IceCube

EHE neutrino search with IceCube have been updated with 6 years of IceCube sample (April, 2008-May, 2014) Effective livetime of 2014 days

- Updated 7 year results soon to come
- Multi-channel analysis looking for any type of events with a large energy deposit
- One partially contained upward-going cascade observed in Nov 16, 2012 data
  - Preliminary estimate of energy deposit: 770 TeV (NPE=74300)
  - Vertex position close to the outer most layer of optical sensors
  - **Atmospheric origin rejected at 99.3%CL**
  - **Inconsistent with GZK ν at 99.2%CL**

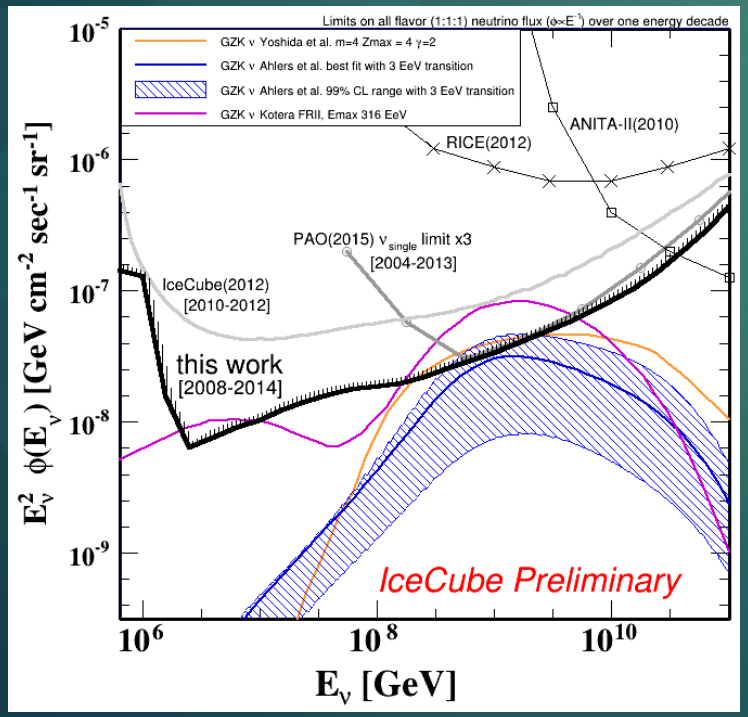


Tight upperlimits on GZK models are placed and constrains the UHE cosmic-ray sources!

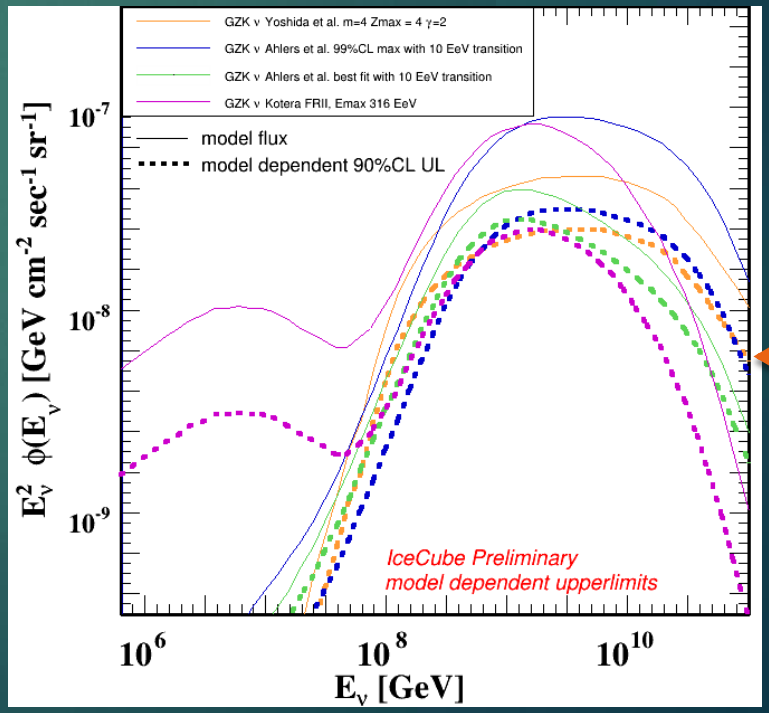
GZK model dependent and independent upperlimits

6 year model hypothesis tests including the 1 event observation			*90%CL
Models	**event rates /livetime**	**p-values**	**Model dependent UL***
Ahlers Fermi max fit (10EeV transition)	8.6 events	0.05%	0.35 times model flux
Ahlers Fermi best fit (10EeV transition)	4.2 events	3%	0.7 times model flux
Kotera FRII dip model	11.7 events	0.002%	0.3 times model flux
Kotera SFR dip model	2.8 events	16.6%	1.2 times model flux

quasi-differential upperlimits



model dependent upperlimits



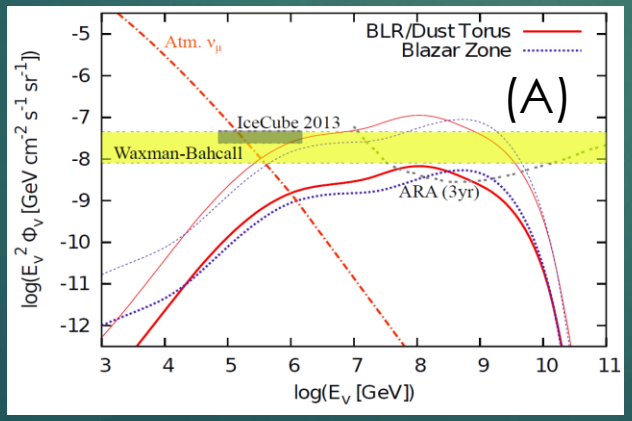
Constraints on high energy astrophysical sources

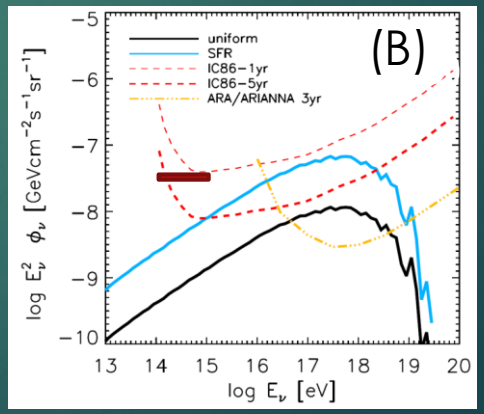
- There are not only of cosmogenic origin, extragalactic objects such as AGNs can produce neutrinos above >10PeV

Model hypothesis tests including the 2 events observation

Models	event rates /livetime	p-values	Model dependent UL 90%CL
astroMuraseAGN2_0(A)	12.3 events	<0.1%	0.3 times model flux
astroMuraseAGN2_3(A)	0.61 events	90%	5.8 times model flux
astroKePulsarSFR(B)	21.2 events	<0.1%	0.2 times model flux
astroKePulsarUniform(B)	3.6 events	7.9%	1.0 times model flux

- These models describing current IceCube flux are strongly constrained
- Still possible origin for high energy low level new components



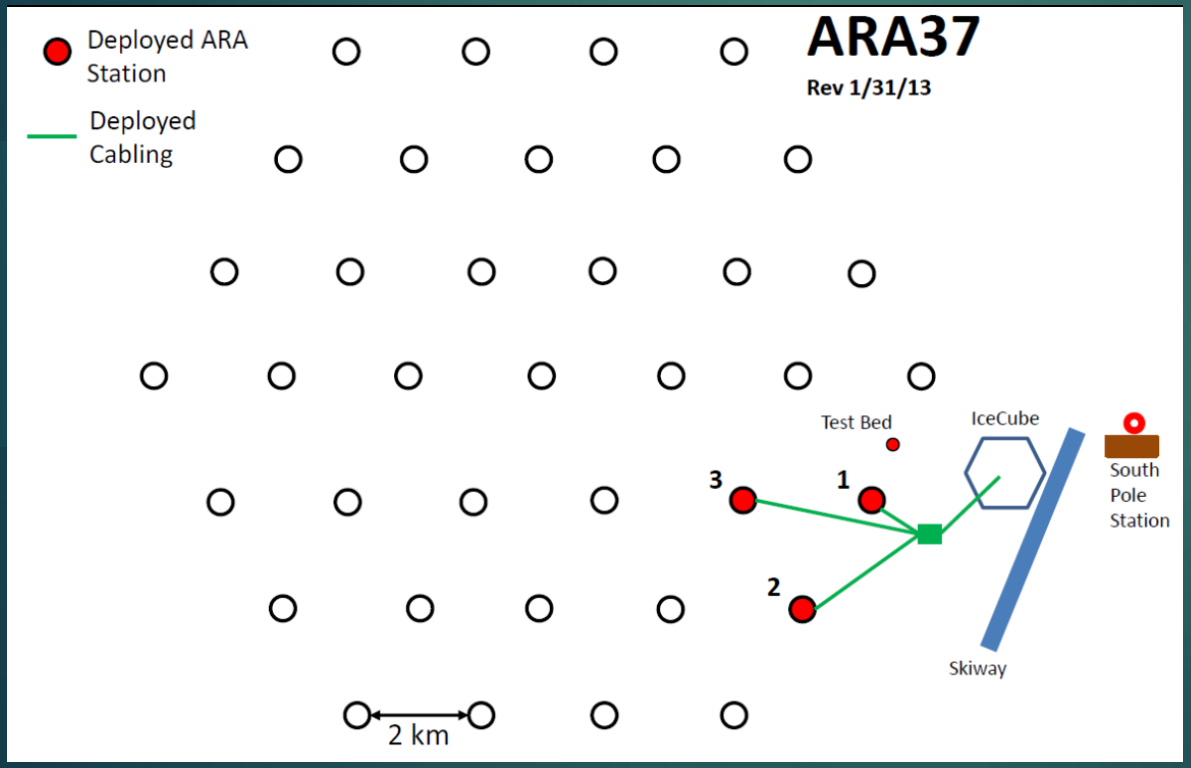


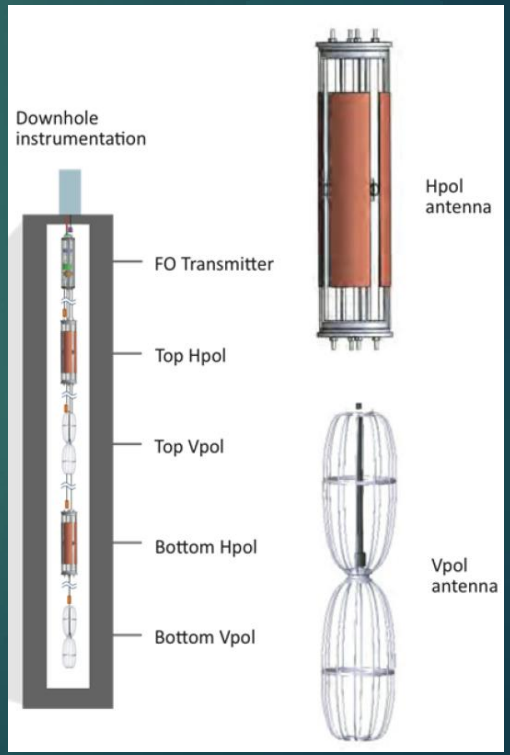
(A)Diffuse neutrino intensity from the inner jets of active galactic nuclei: Impacts of external photon fields and the blazar K. Murase et al. Phys Rev D 90 023007 (2014) (B)Testing the newborn pulsar origin of ultrahigh energy cosmic rays with EeV neutrinos Ke Fang, Kumiko Kotera, Kohta Murase, and Angela V. Olinto Phys Rev D 90 103005 (2014)

Cherenkov radio detection of neutrinos

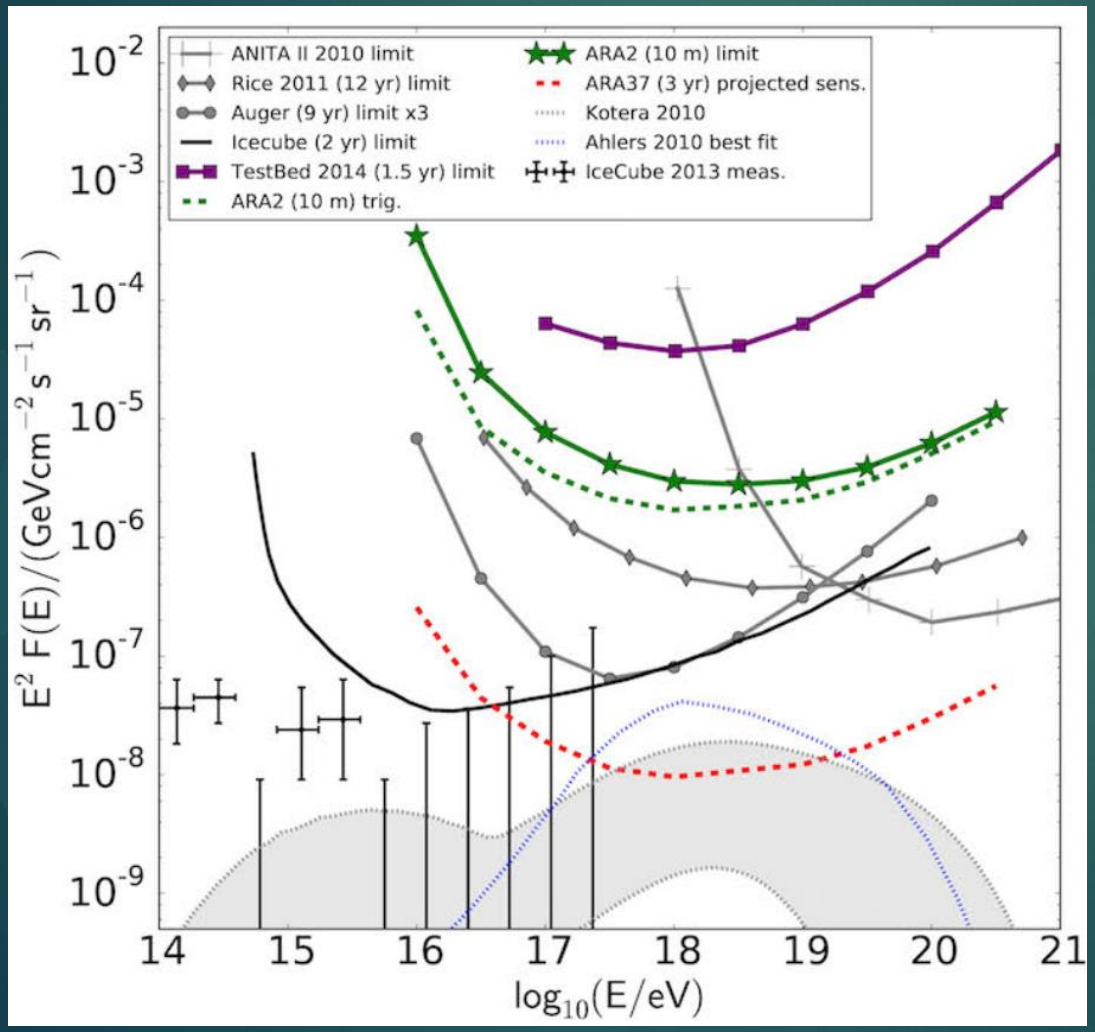
The Askaryan Radio Array (ARA) detector

Monday 26th Neutrino parallel: Results and prospects from ARA By M. Duvernois
Monday 26th Neutrino parallel: ARA detector calibration By R. Gaior





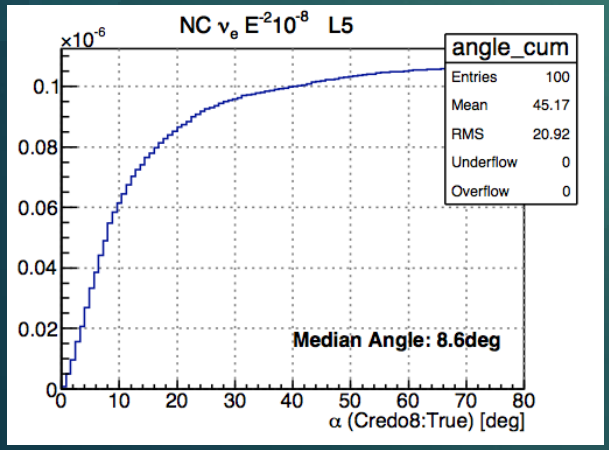
Upperlimits from the first partial ARA detector

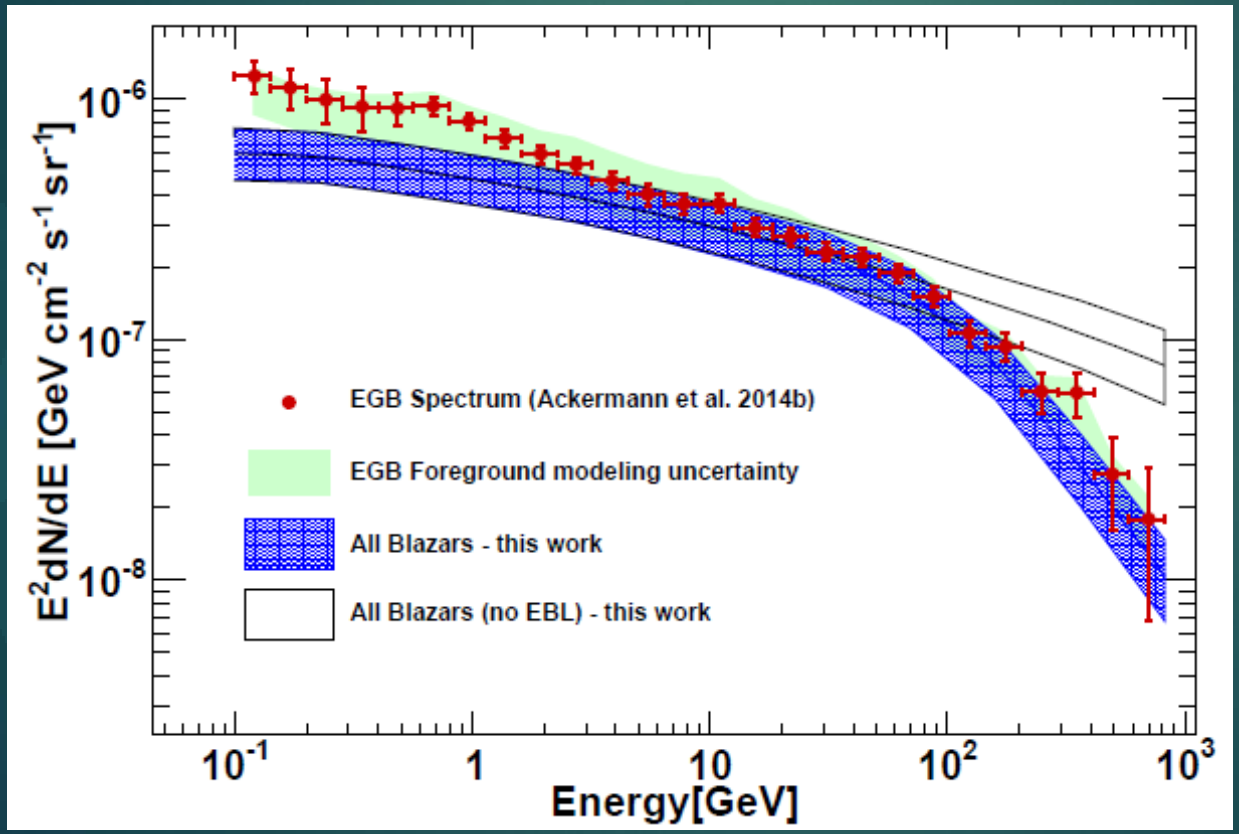


- Working as expected!

Summary

- We have observed cosmic-neutrino flux (spectral index varies -2.7 ~ -2.2)
  - Is tension between different analysis hint of energy threshold dependence? 100TeV-PeV flux softer below ~50TeV
- Upperlimits
  - Northern sky PS upperlimits ($<10^9$ GeV cm^{-2} s^{-1}), Southern sky ($<10^8$ GeV cm^{-2} s^{-1})
  - Blazer (sub components, all)
  - Galactic components (<50%, Ahlers etal arXiv:1505.03156)
    - Stay tuned for Fermi Bubble
  - GRB: No more than 1% GRB prompt contribution to IceCube diffuse flux (IceCube: ApJ 805 L5 2015)
  - AGN models to produce >10PeV neutrinos
- Extragalactic diffuse gamma-ray
  - Small room for neutrino objects (Soft neutrino spectra below ~50TeV)
  - Not p-p neutrinos?
  - Non-blazer, non-GRB $p\gamma$ sources?
- Good potential multi-wavelength follow up of the IceCube events (especially transit)
- Cosmogenic neutrinos must be there for some level
  - If not pure proton, radio detector is needed for iron/mixed composition


NC ν_e $E^{-2}10^{-8}$ L5
$\times 10^{-6}$
angle_cum
Entries 100
Mean 45.17
RMS 20.92
Underflow 0
Overflow 0
Median Angle: 8.6deg
0.1
0.08
0.06
0.04
0.02
0
0 10 20 30 40 50 60 70 80
α (Credo8:True) [deg]


E^2dN/dE [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
EGB Spectrum (Ackermann et al. 2014b)
EGB Foreground modeling uncertainty
All Blazars - this work
All Blazars (no EBL) - this work
10^{-1}
1
10
10^2
10^3
Energy[GeV]