IceCube

Searches for astrophysical sources of neutrinos

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Lake Louise Winter Institute

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LMU Excellence Cluster Universe

Technische Universität München

Outline

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- Cosmic Rays & Multi-Messenger Astronomy
- IceCube Neutrino Observatory
- Astrophysical neutrinos
  - Observed diffuse signal
  - Searches for neutrino point sources
- Summary

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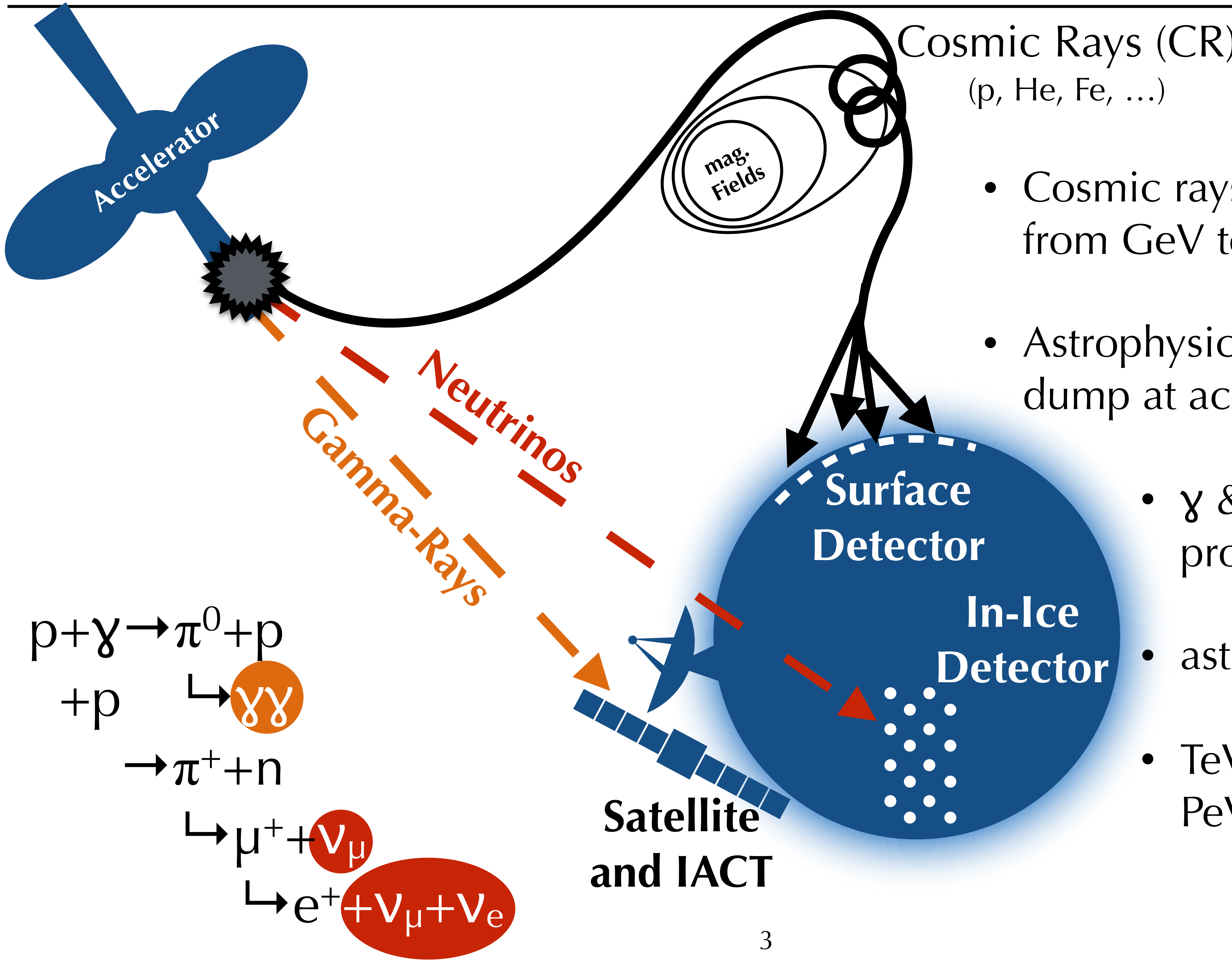
Cosmic Rays



- Cosmic rays observed from GeV to 10^{20}eV
- Astrophysical beam dump at acceleration site
  - γ & ν production
  - astronomy
  - TeV γ & ν from PeV cosmic rays

IceCube Detector Completion Dec. 2010
after 5 years of construction
IceCube operational since first deployment season

IceCube

Cubic km^3
neutrino & CR physics

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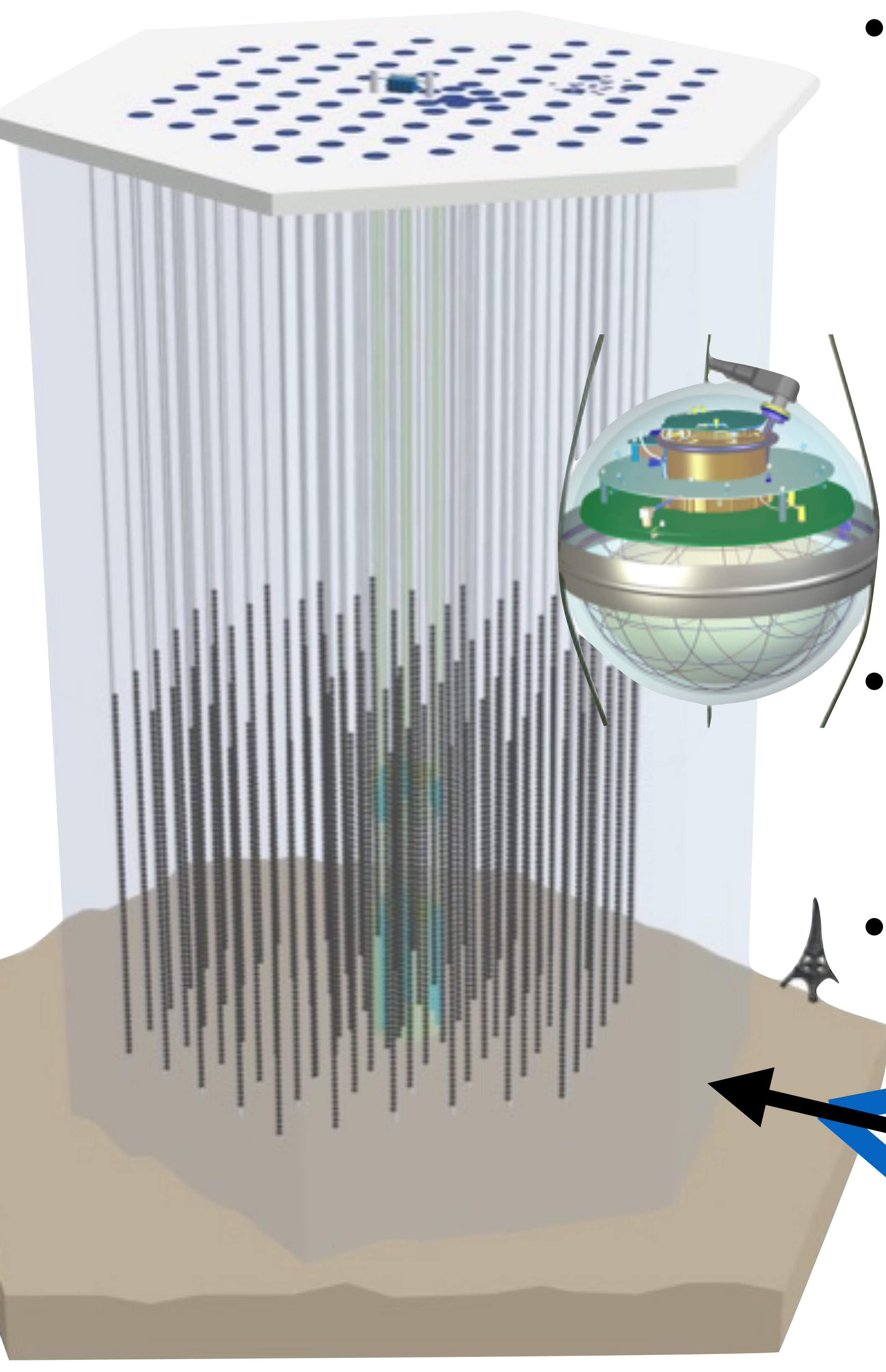
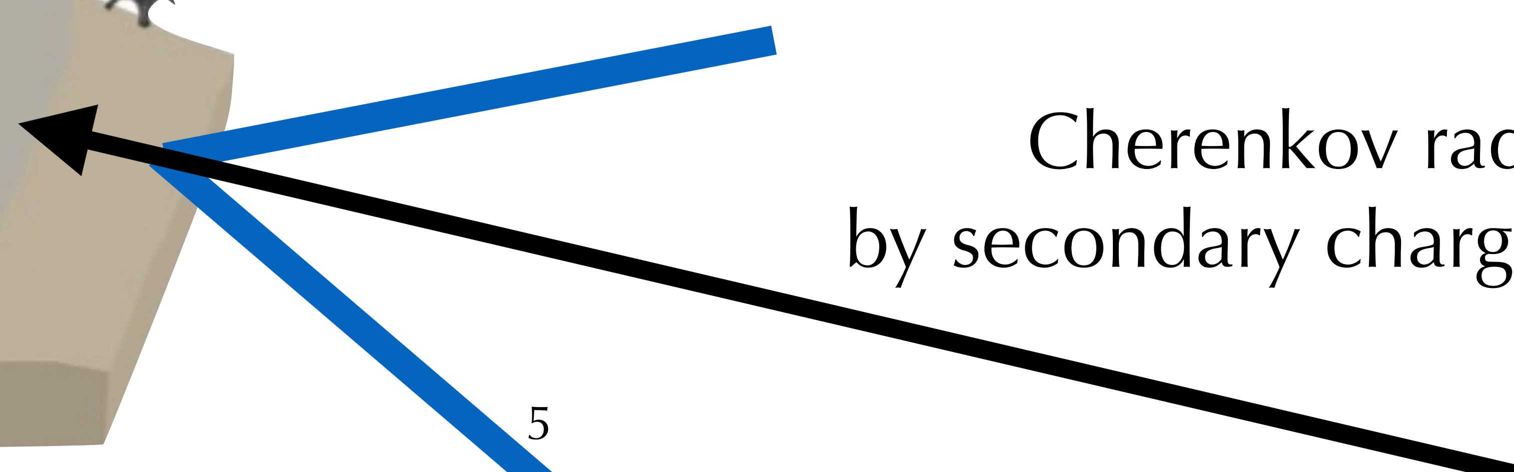


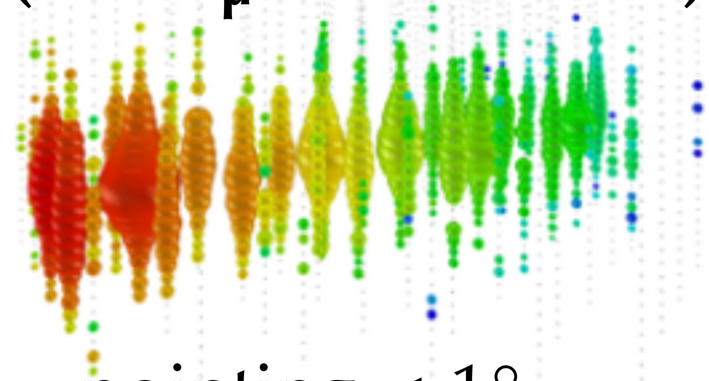
- 1km^3 instrumented volume
  - 5160 Digital Optical Modules (DOM)
  - 86 strings with each 60 DOMs
  - ν-energy threshold of ~100GeV
- Located at the South Pole at 1.5-2.5km depth
- Very stable operation: 97.2% *clean* uptime



Cherenkov radiation
by secondary charged particles

Neutrino signatures

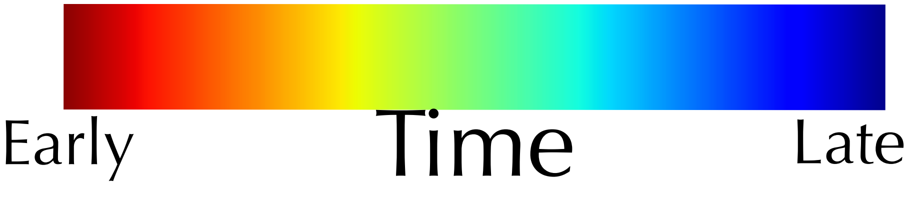
μ-Tracks
(CC ν_μ interaction)



- pointing < 1°

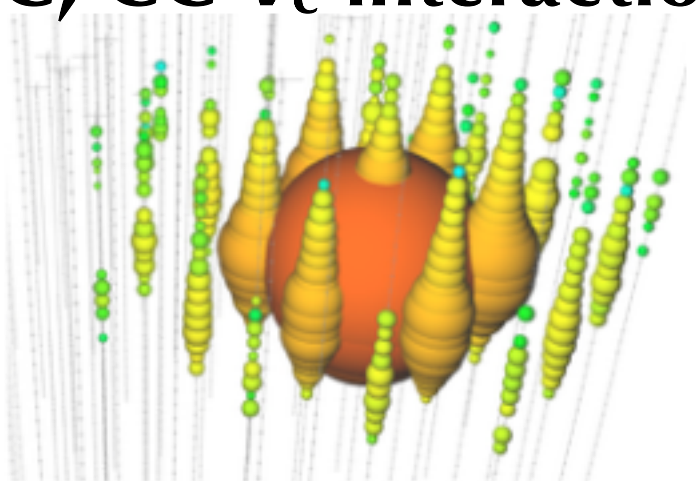
- Energy resolution factor of 2

- enter IceCube from far outside



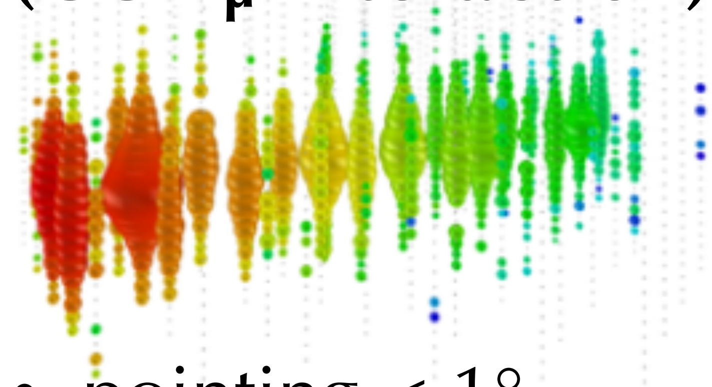
Neutrino signatures

Cascades / Shower
(NC, CC ν_e interaction)



- Energy deposited in detector
- 15% resolution in energy
- pointing ~ 10°

μ-Tracks
(CC ν_μ interaction)



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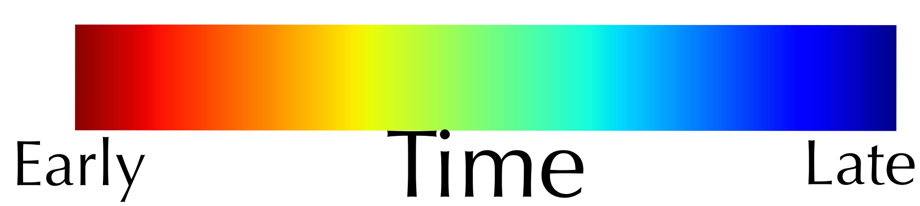

Neutrino signatures

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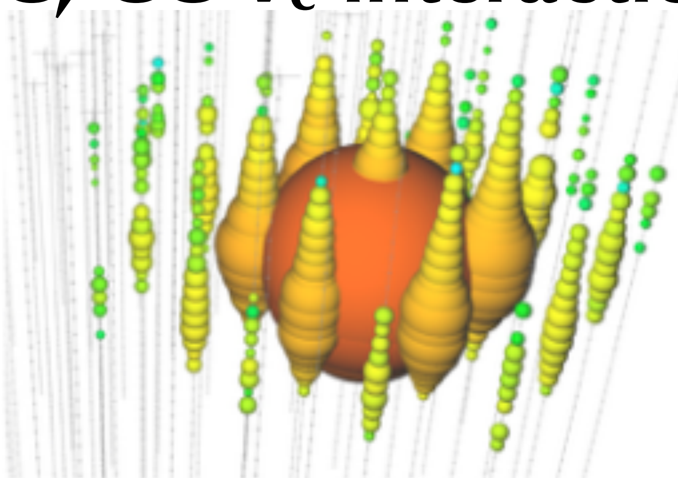
Cascades / Shower (NC, CC ν_e interaction)



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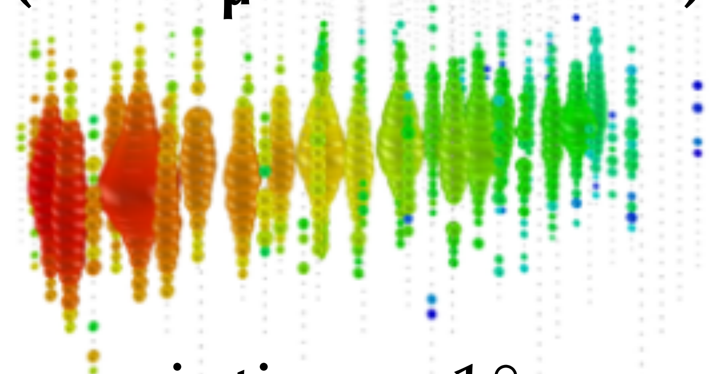

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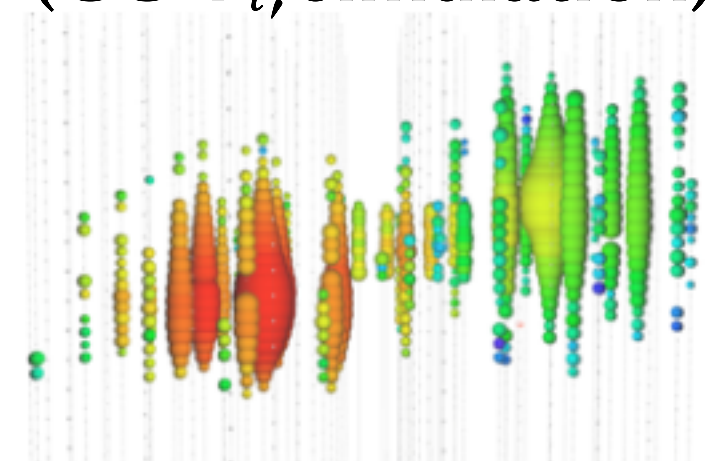
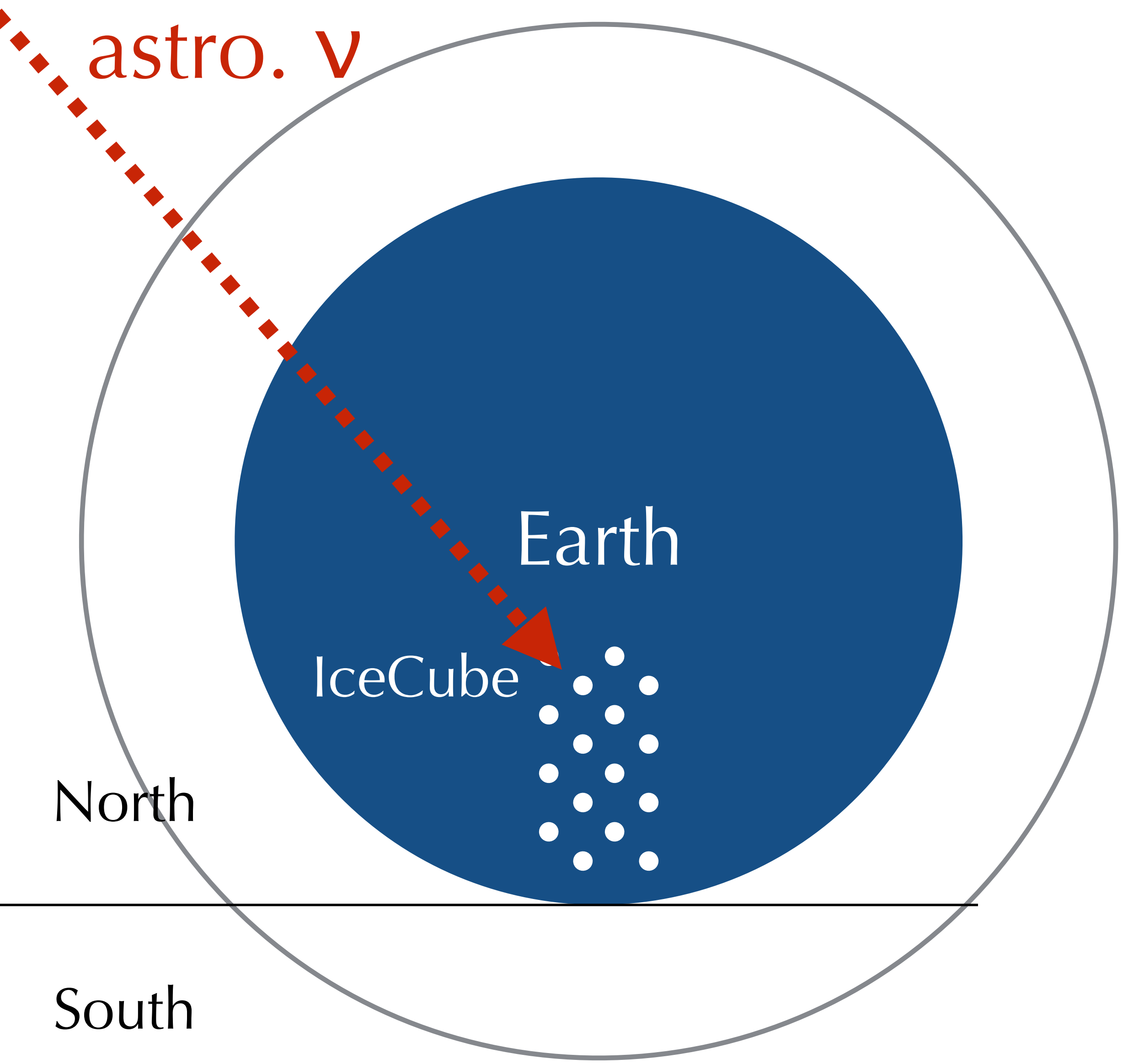
Double Bang (CC ν_τ, simulation)



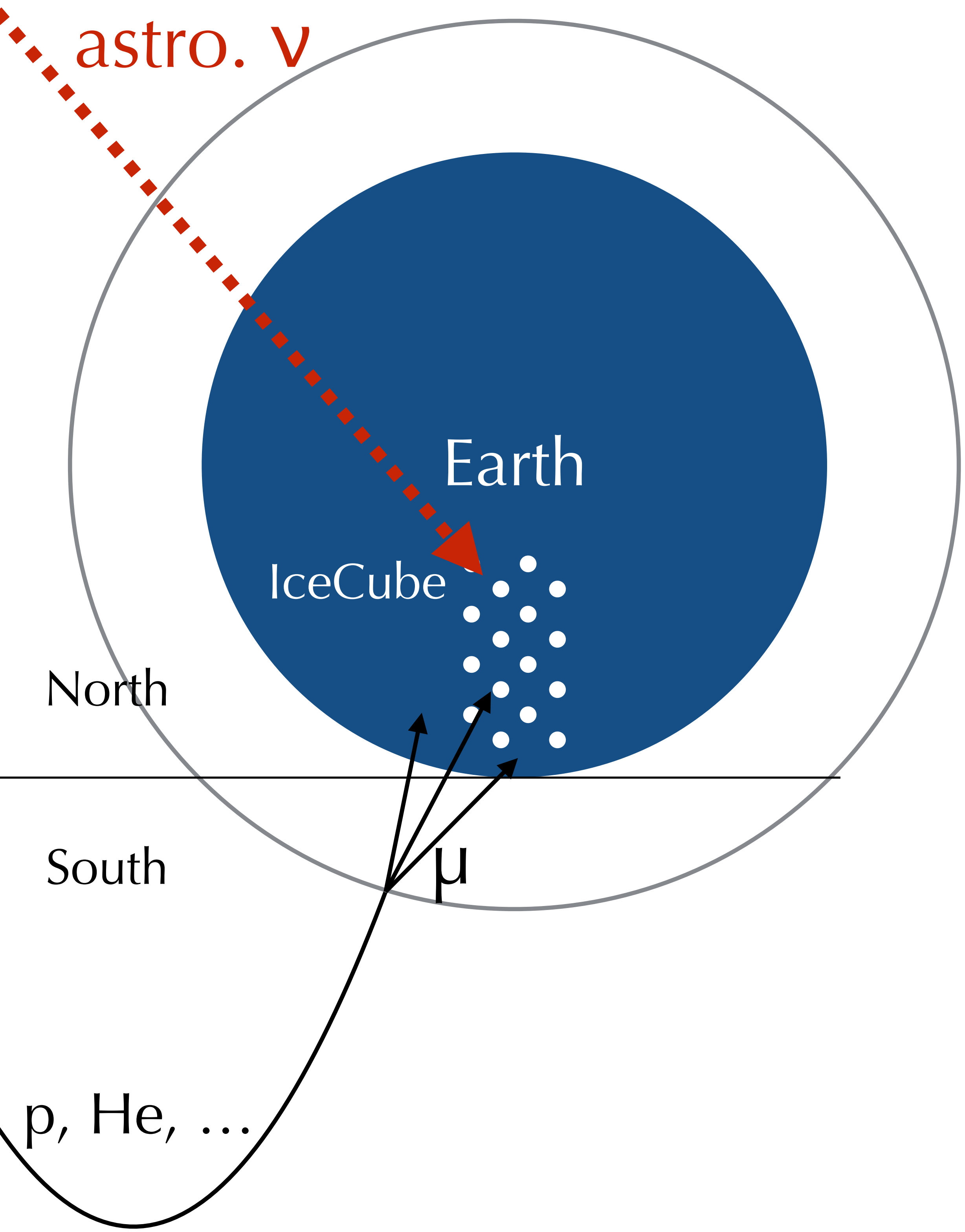
- τ-decay to π/K produces second cascade
- No observation yet
- Clear identifier for astrophysical neutrinos
- Decay length: 50m/PeV

Backgrounds



- Cosmic rays induce atmospheric air-showers

Backgrounds



- Cosmic rays induce atmospheric air-showers
- Muons penetrate IceCube from above
  - Trigger detector at ~2.5kHz
  - Energy spectrum ~$E^{-2.7}$

Backgrounds

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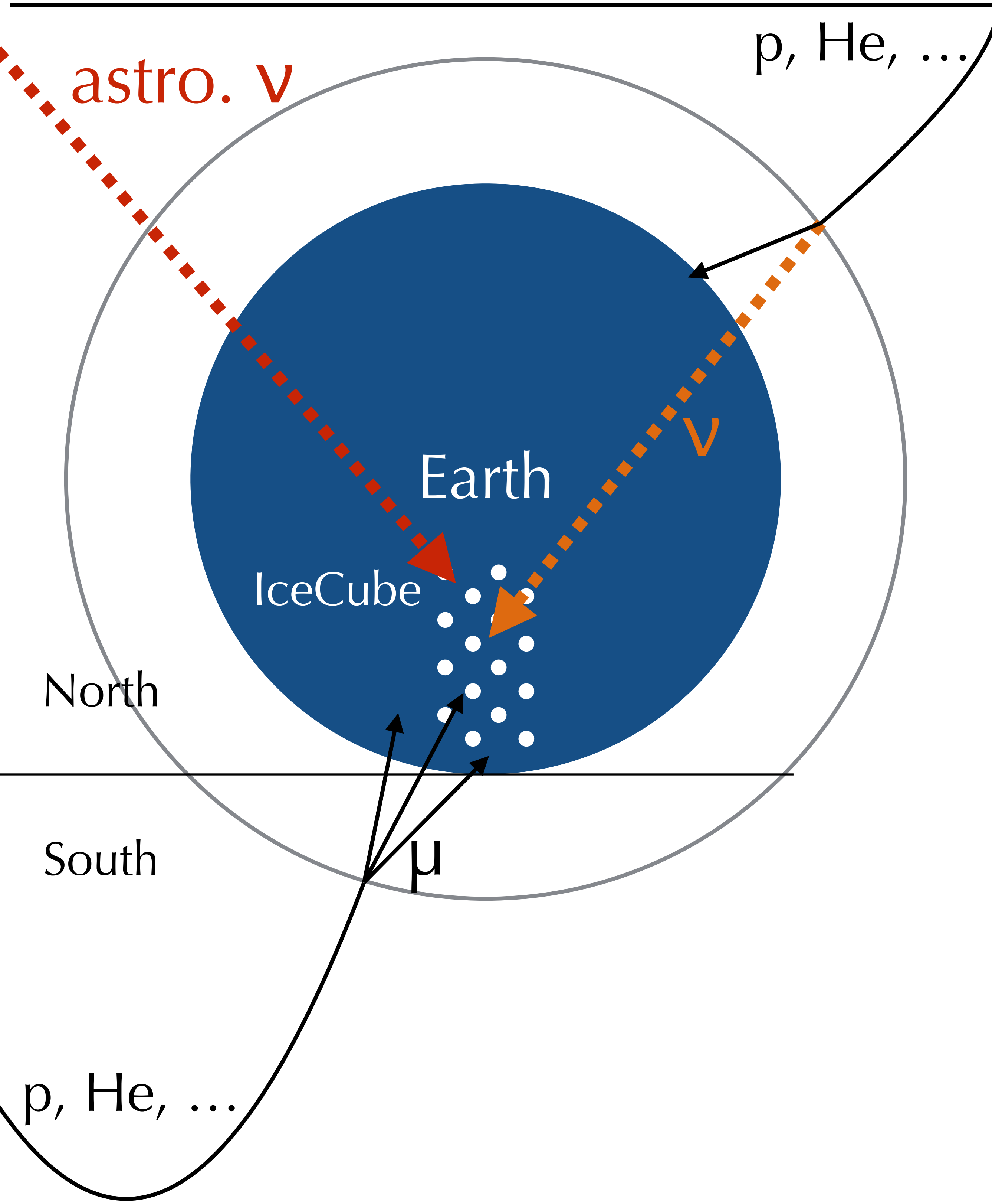

- Cosmic rays induce atmospheric air-showers
- Muons penetrate IceCube from above
  - Trigger detector at ~2.5kHz
  - Energy spectrum $\sim E^{-2.7}$
- Neutrinos are not absorbed by Earth shield (North)
  - Soft energy spectrum $\sim E^{-3.7}$
  - Other exciting physics possible with atm. ν: Oscillations, non-std. interactions…

Neutrino Selection

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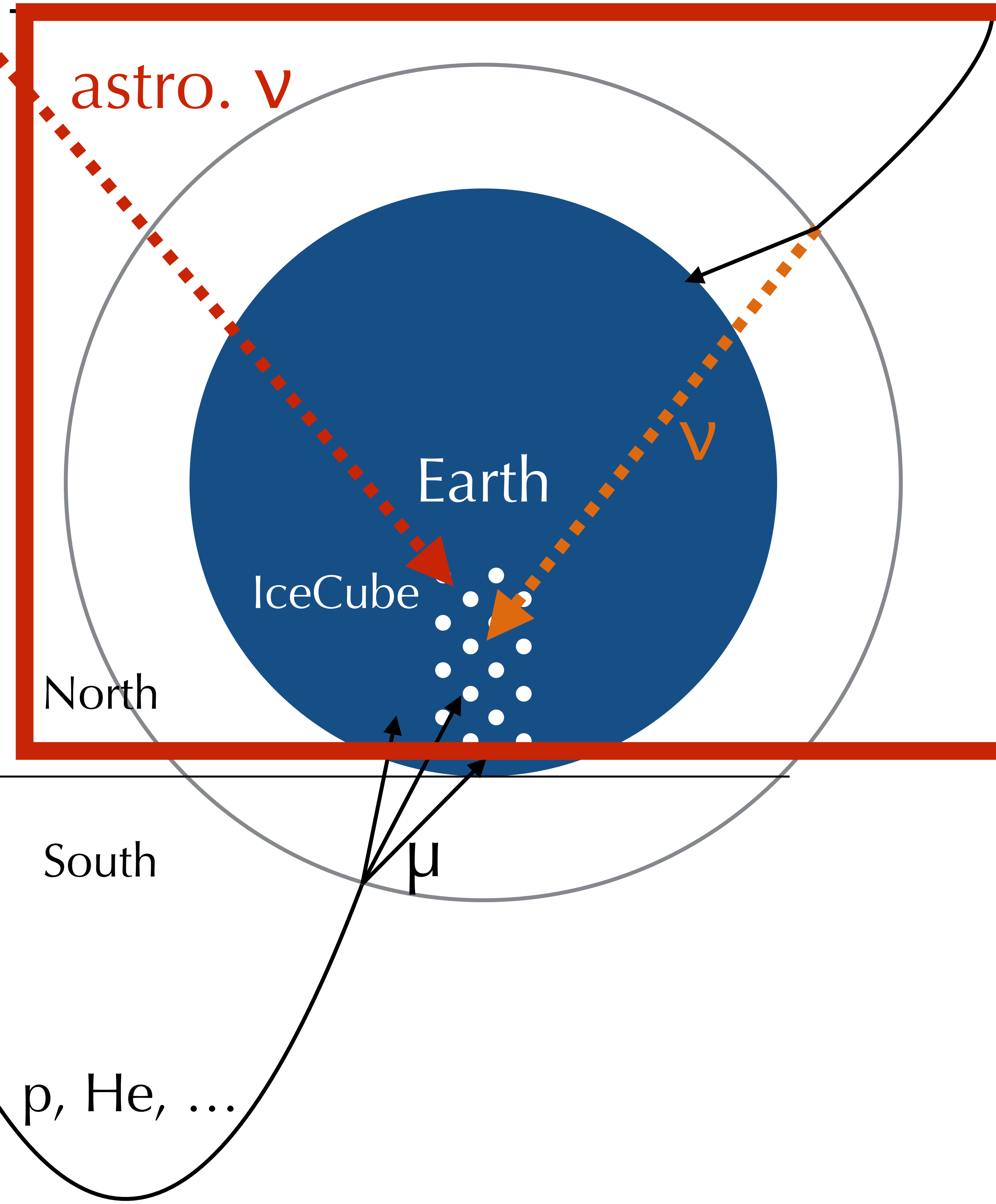

- up-going charged particles originate from neutrinos!
- select well reconstructed neutrinos → tracks
- Large detection volume, dominated by atm. ν at low energies
- Astrophysical signal > 100TeV, absorption in Earth at highest energies

Neutrino Selection

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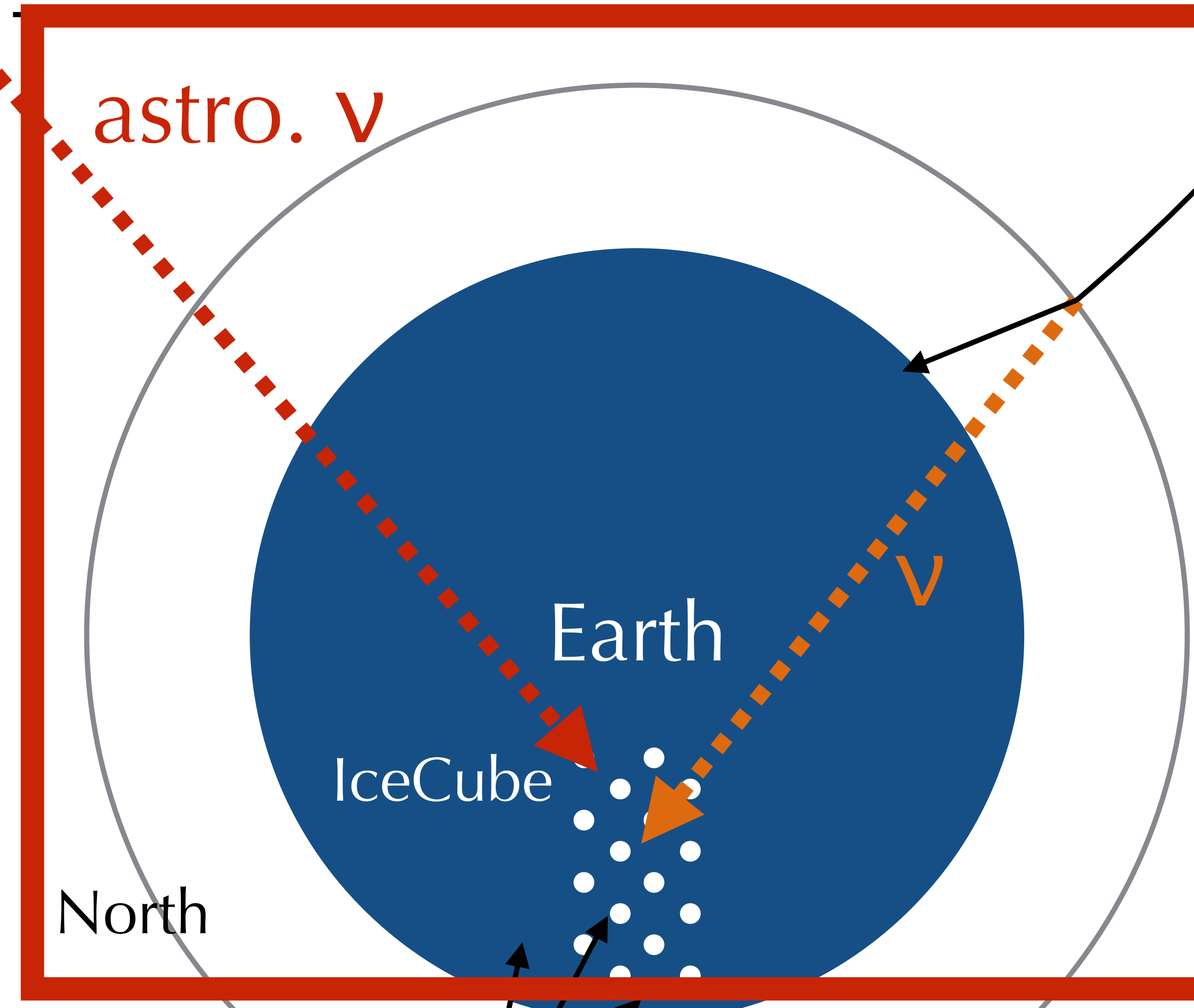

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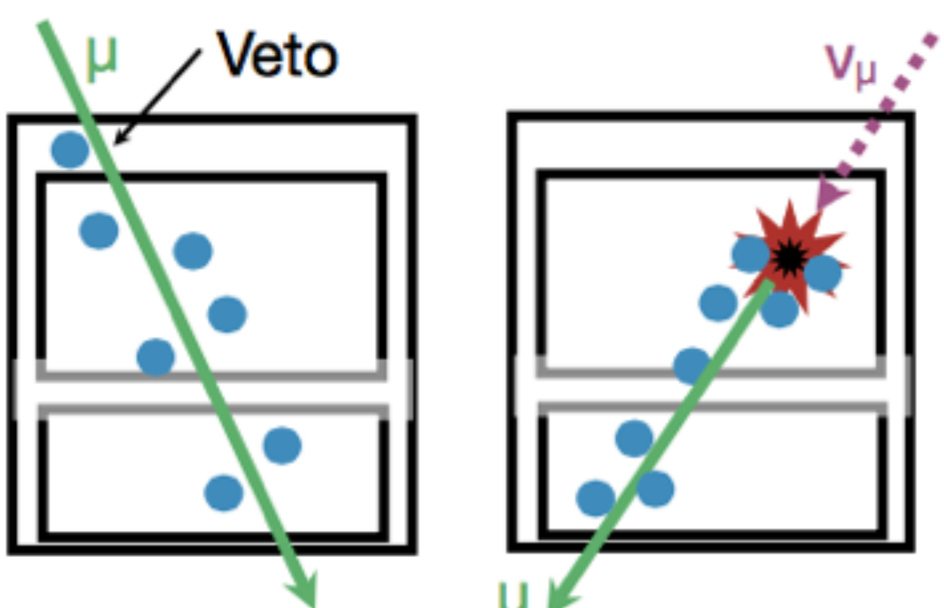

- South: Veto incoming atm. muons
- Starting events are neutrinos
- Reduced detector volume

- Astrophysical signal > 10-100TeV
- Through-going muon neutrinos only at very highest energies: >PeV

Astrophysical Neutrinos

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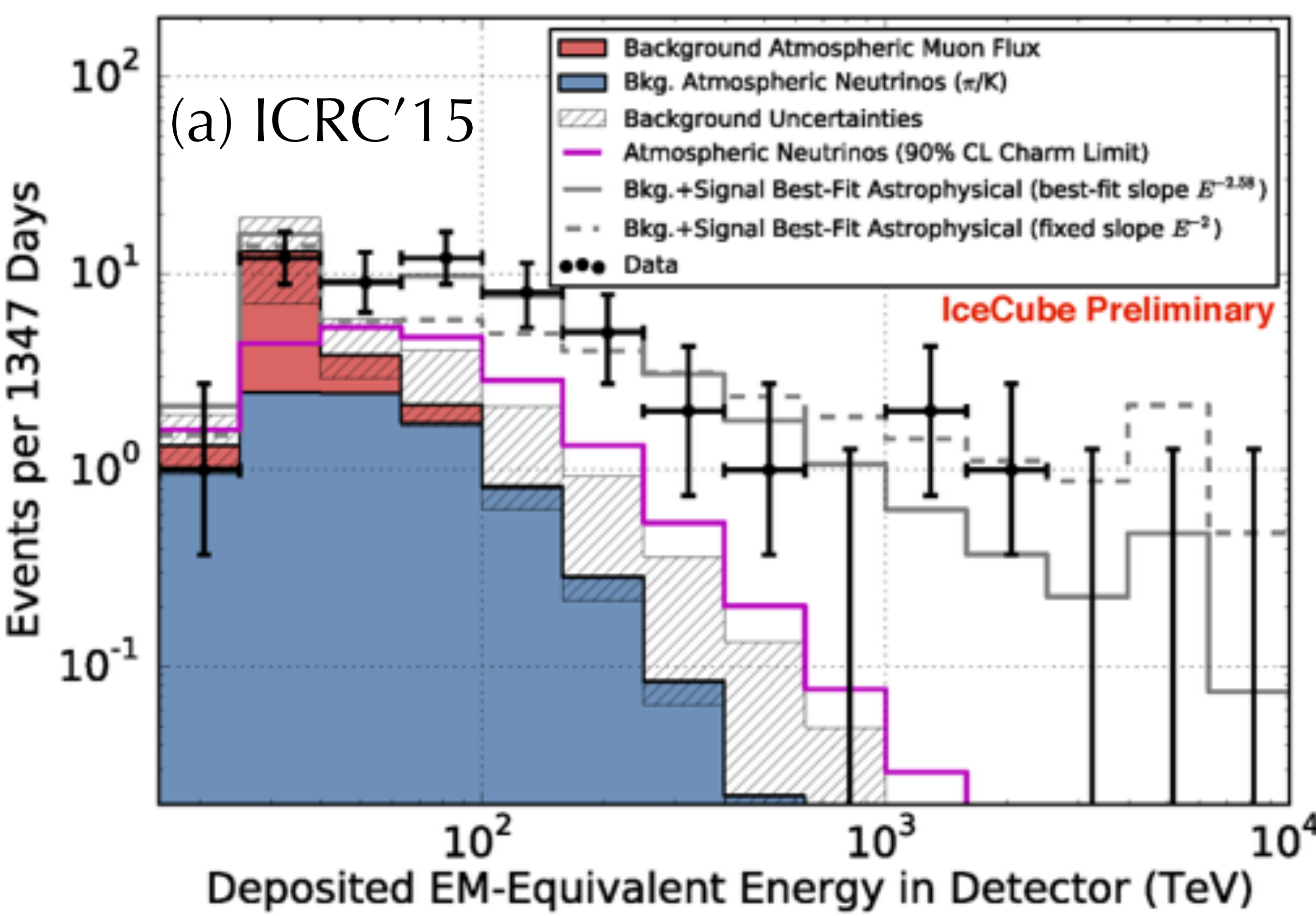
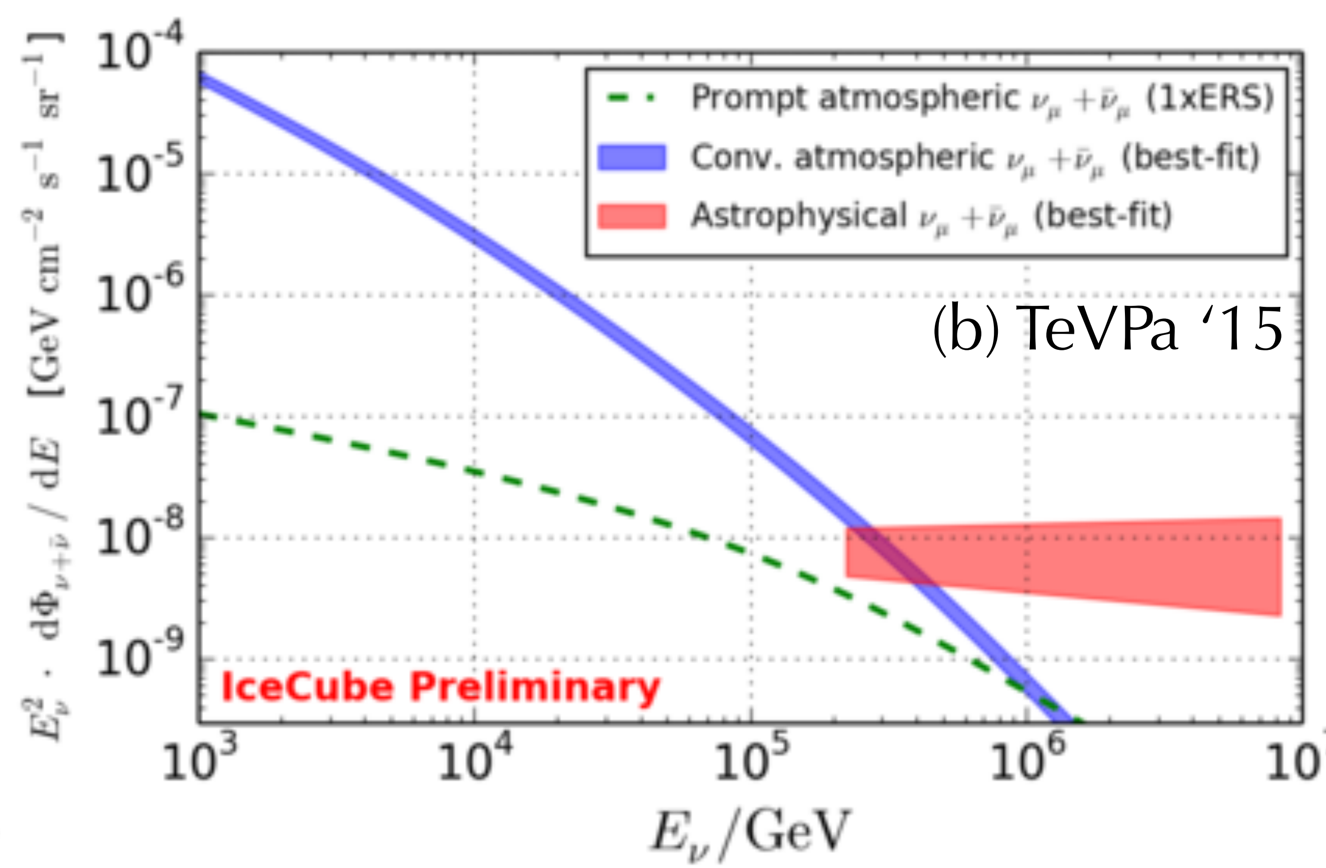
- Observation of an integrated *diffuse* flux of ν

  (a) All-flavour all-sky high-energy starting events (HESE): **53 events**

  (b) Up-going ν_μ: highest energy ν ever observed: 2.6±0.3 PeV deposited energy

- Consistent with isotropic power-law with spectral index E^{-2} and $E^{-2.5}$

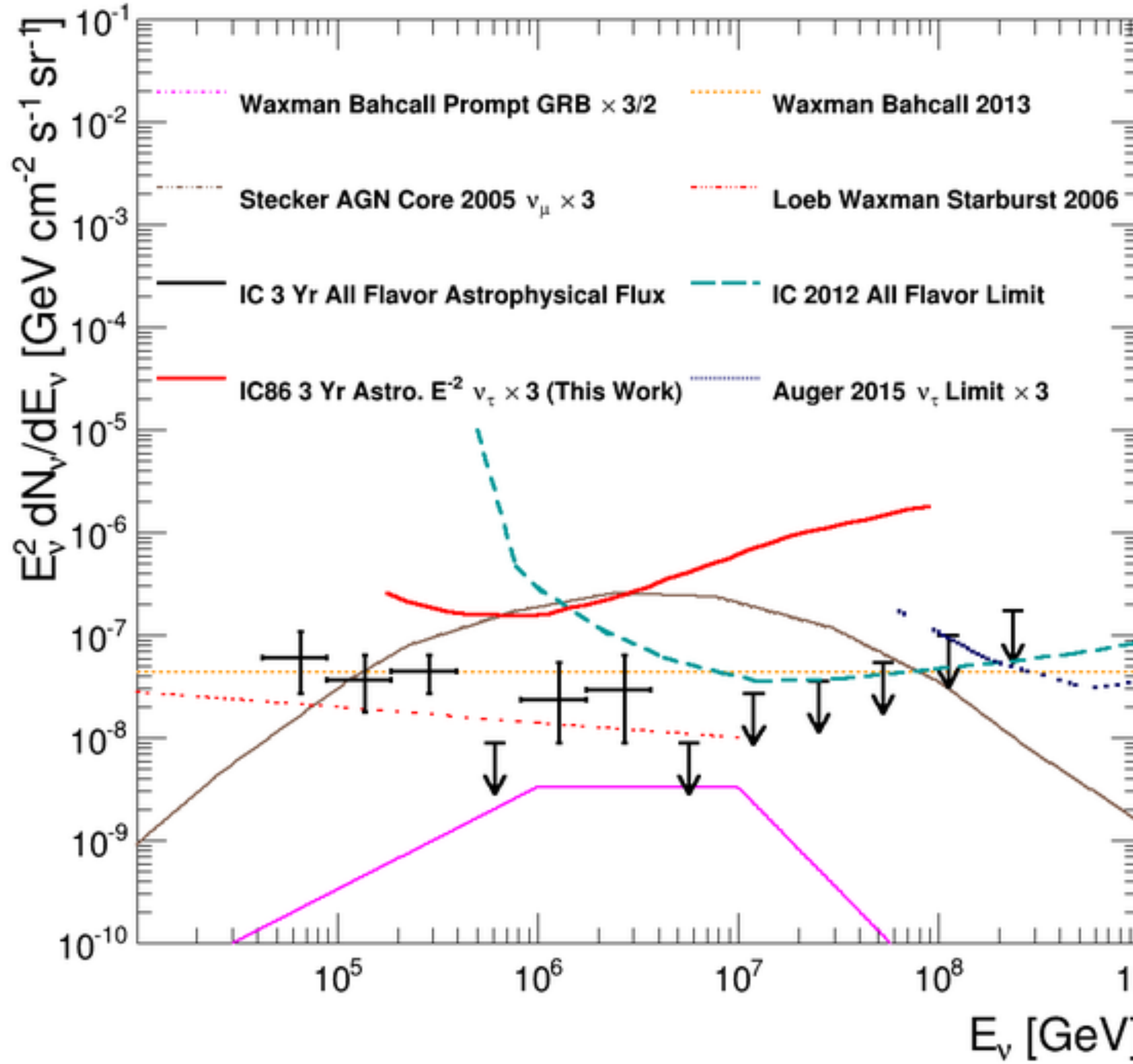




Putting it all together

- Observation of astroph. ν flux
  - All-flavour (starting events)
  - muon type (up-going tracks)
- No sign of cosmogenic neutrinos
- Dedicated ν_τ searches sensitivity above observed signal

PRD 93.022001



Neutrino Sources

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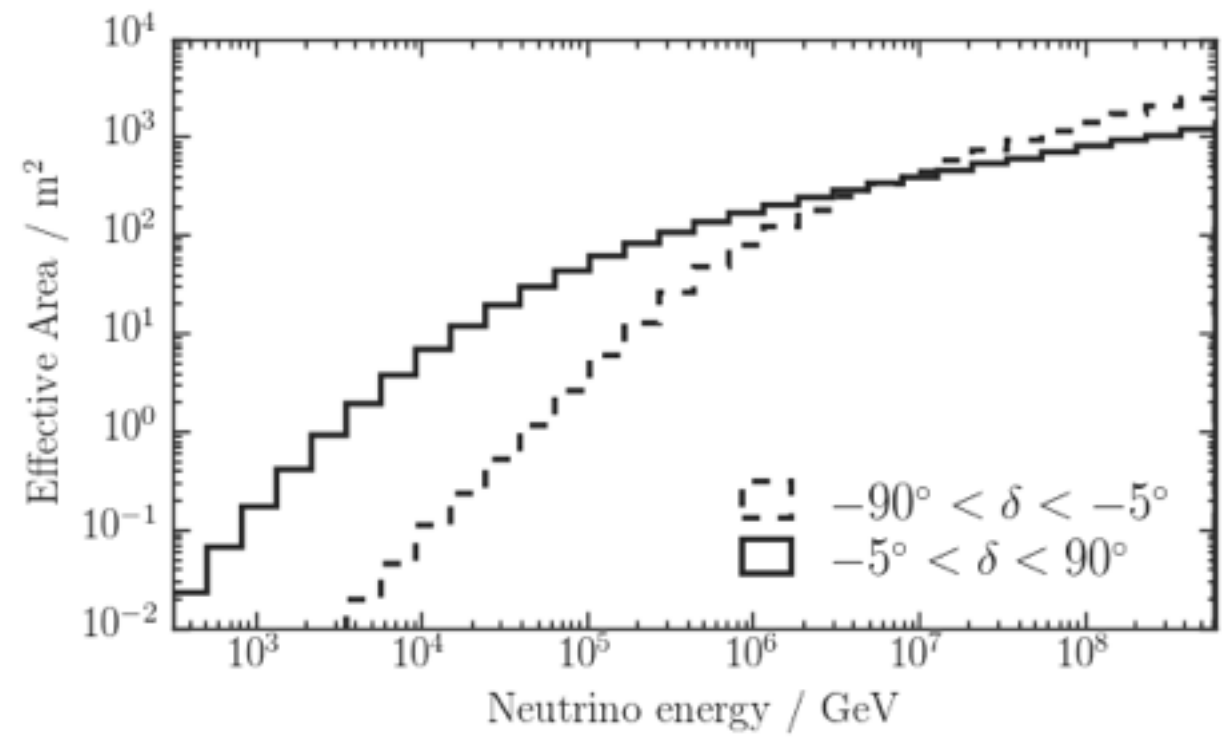
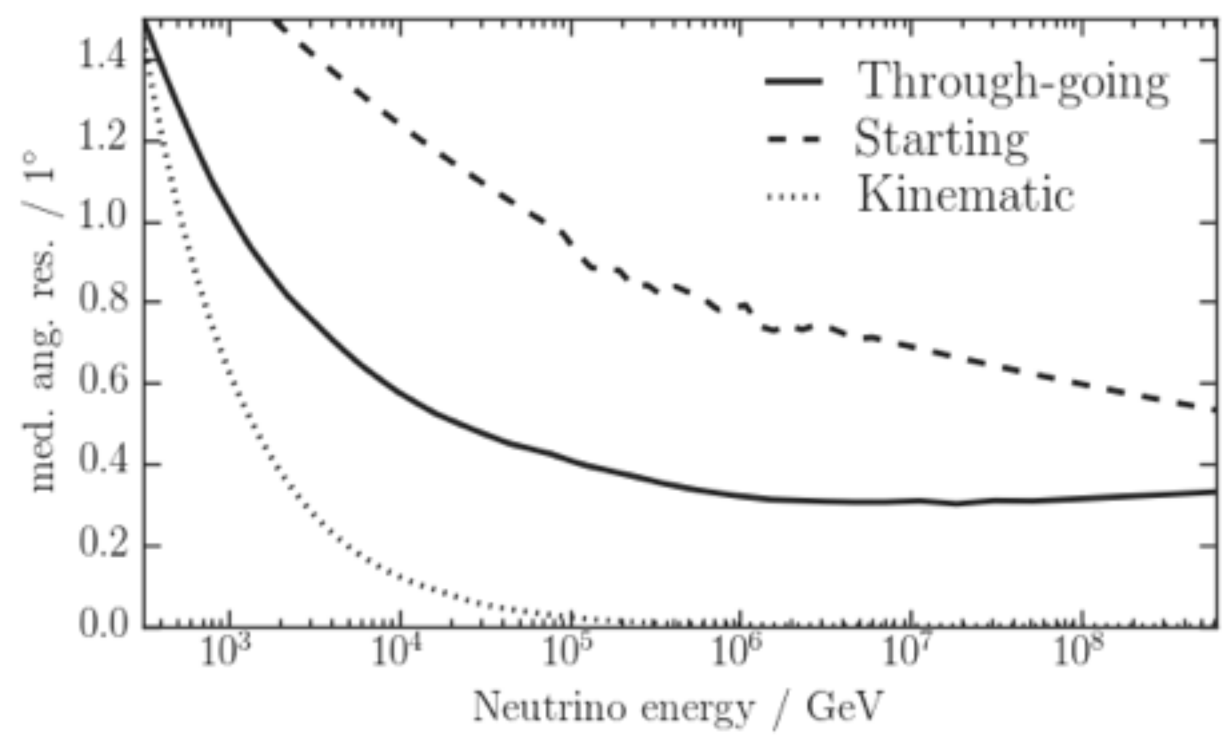
- *Where* do the neutrinos come from?
    - Galactic: diffuse emission, SNR, PWN, …
    - Extragalactic: AGN, UHE Cosmic Rays, GRB, …
- Use track-like events
    - ✓ Large collection volume
    - ✓ Good angular resolution (< 1°)
- Search for clustering of events in *full* sky
- 7 years of data available (2008 - 2015)
    - 700,000+ events used in analysis

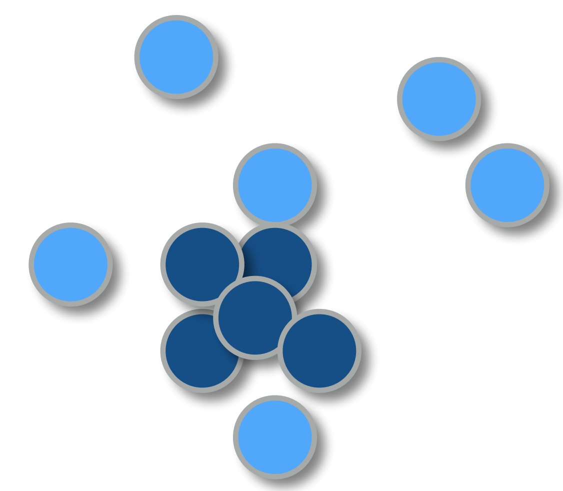




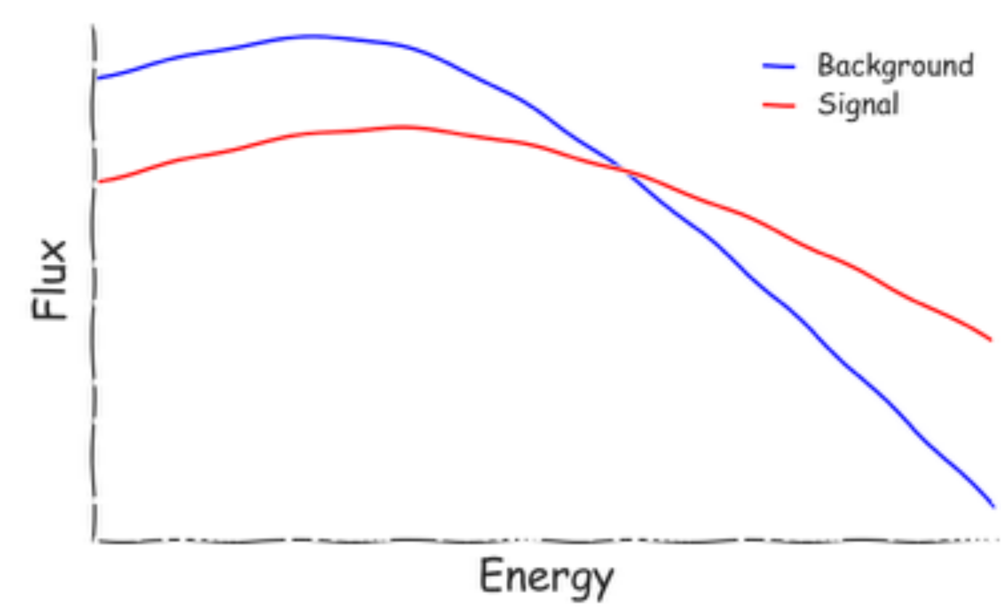
Point Source Search Method

$$\mathcal{L} = \prod_i \left(\frac{n_s}{N} \mathcal{S}\left(\Delta\Psi_i, \sigma_i, E_i; \gamma\right) + \left(1 - \frac{n_s}{N}\right) \mathcal{B}\left(\delta_i, E_i\right) \right)$$

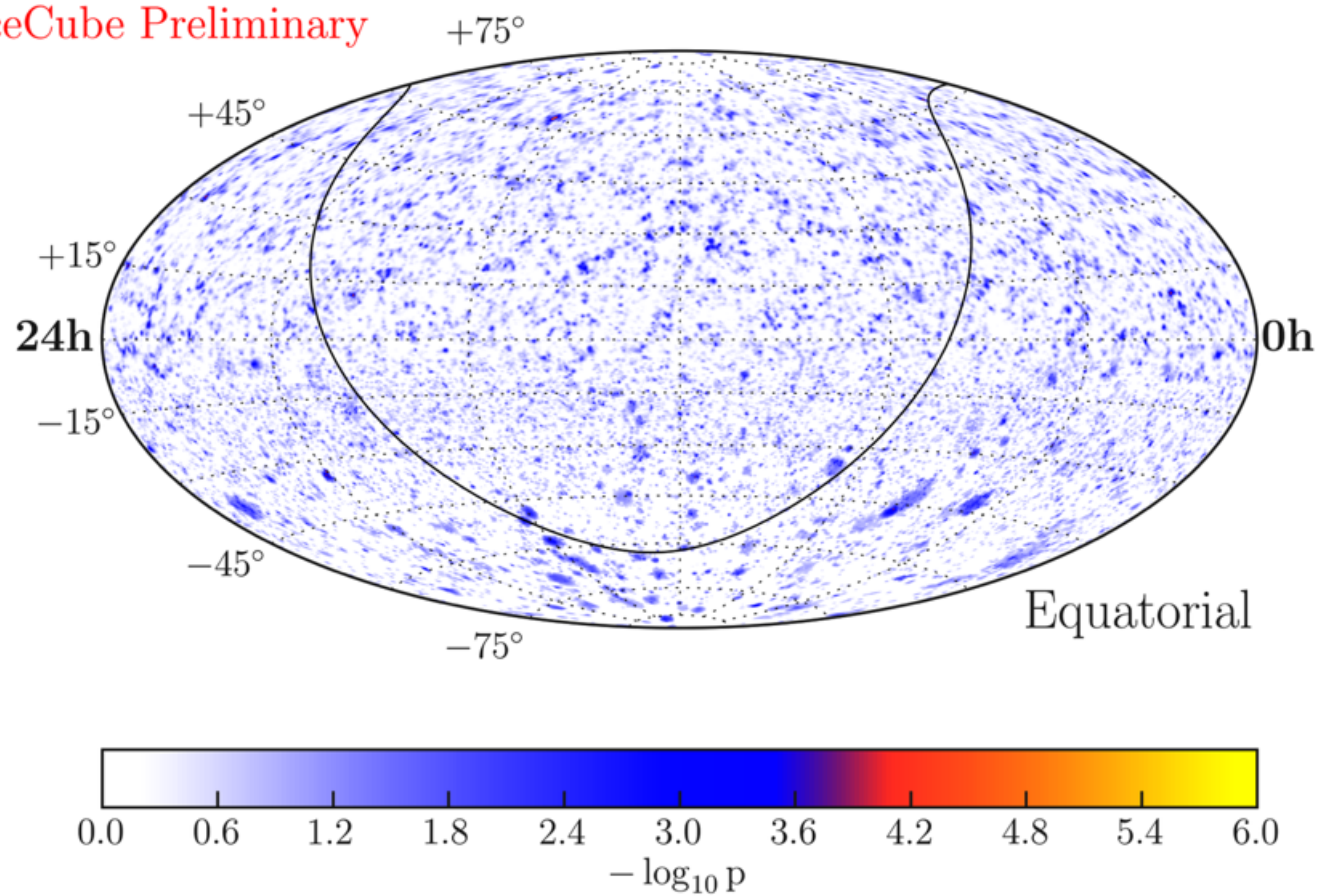
- Use unbinned clustering likelihood to search for steady sources



- Signal S: Gaussian clustering around source location
- Background B: Distributed homogeneously around source
- Energy: Signal at higher energies ($\sim E^{-2}$) than background ($\sim E^{-3.7}$)
  - Fit for spectral index ɣ



New Point Source Results



North
atm. ν

South
atm. μ

New Point Source Results

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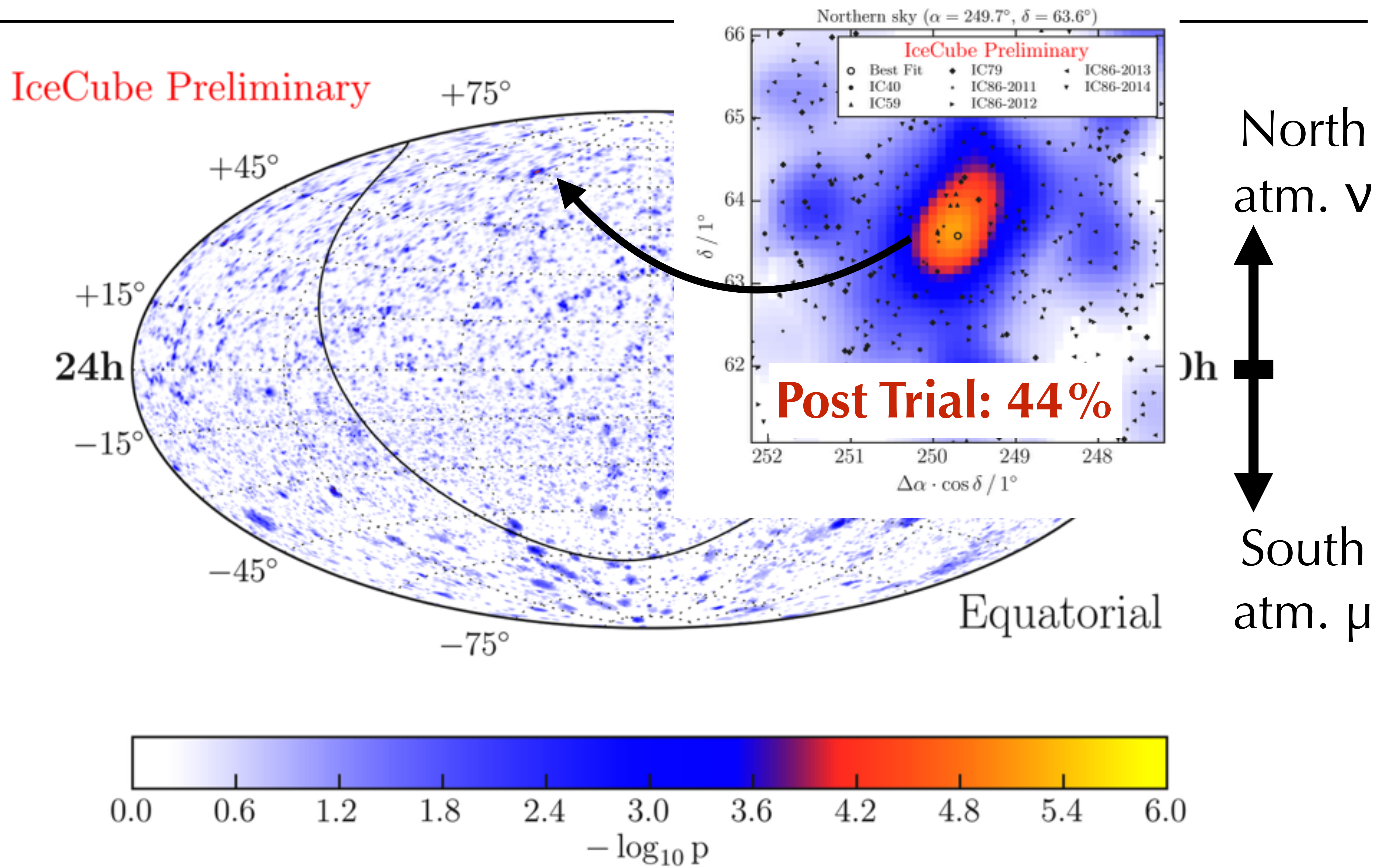

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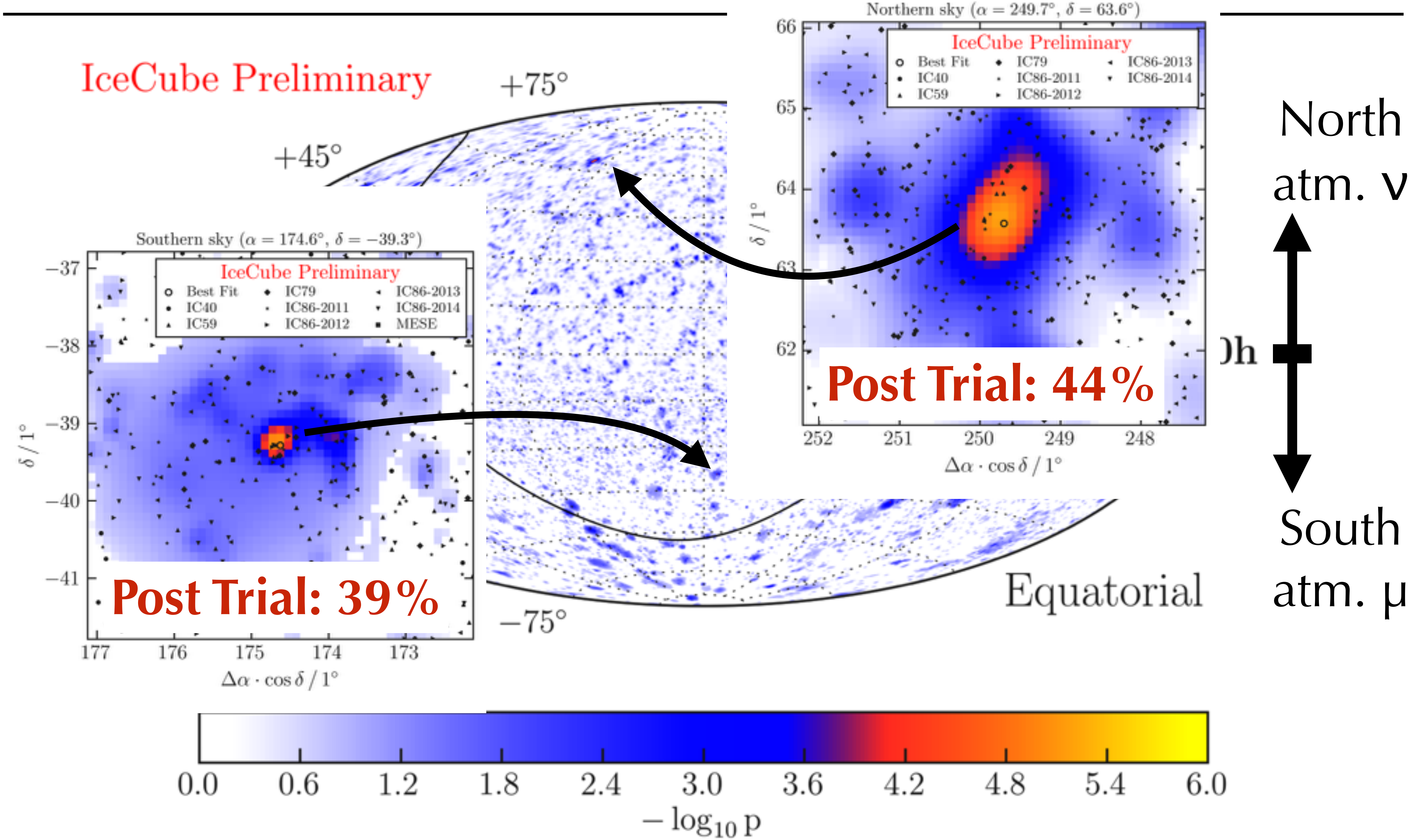

Point Source Constraints

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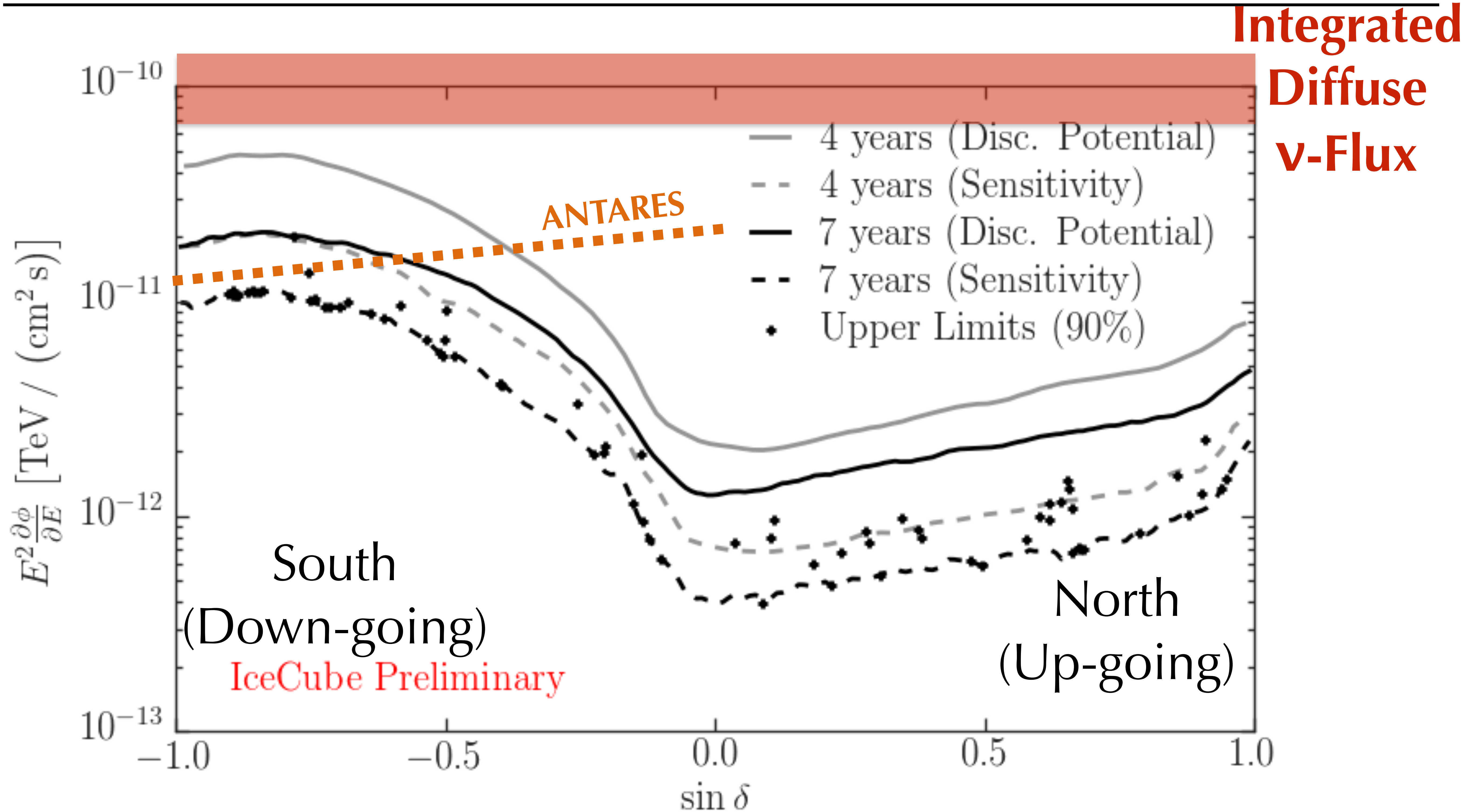

ANTARES: Astrophys.J. 786 (2014) L5
South: ANTARES probes energy regions below IceCube'

Point Source Constraints

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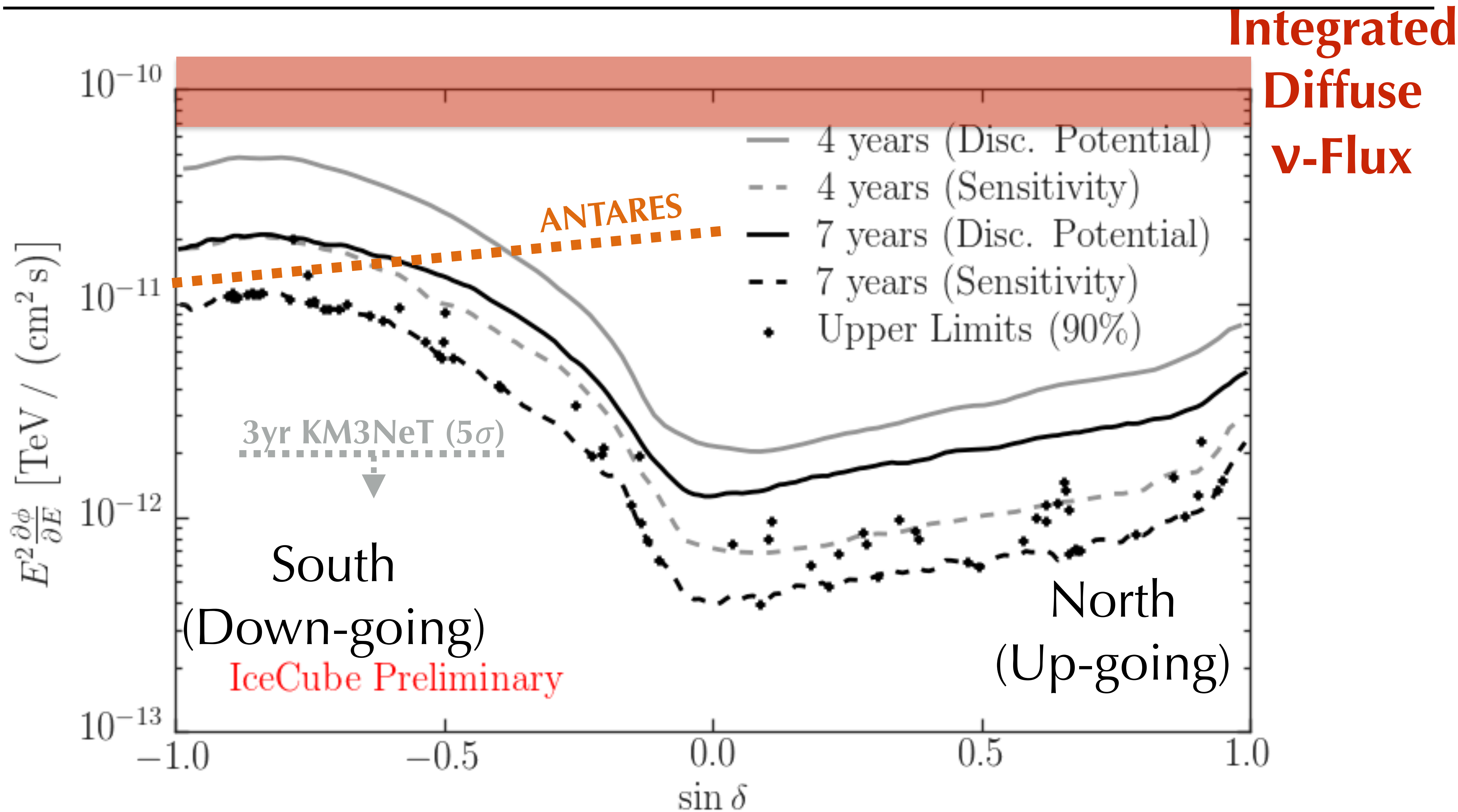

ANTARES: Astrophys.J. 786 (2014) L5
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γ-Ray Sources

PWN

AGN, FSRQ

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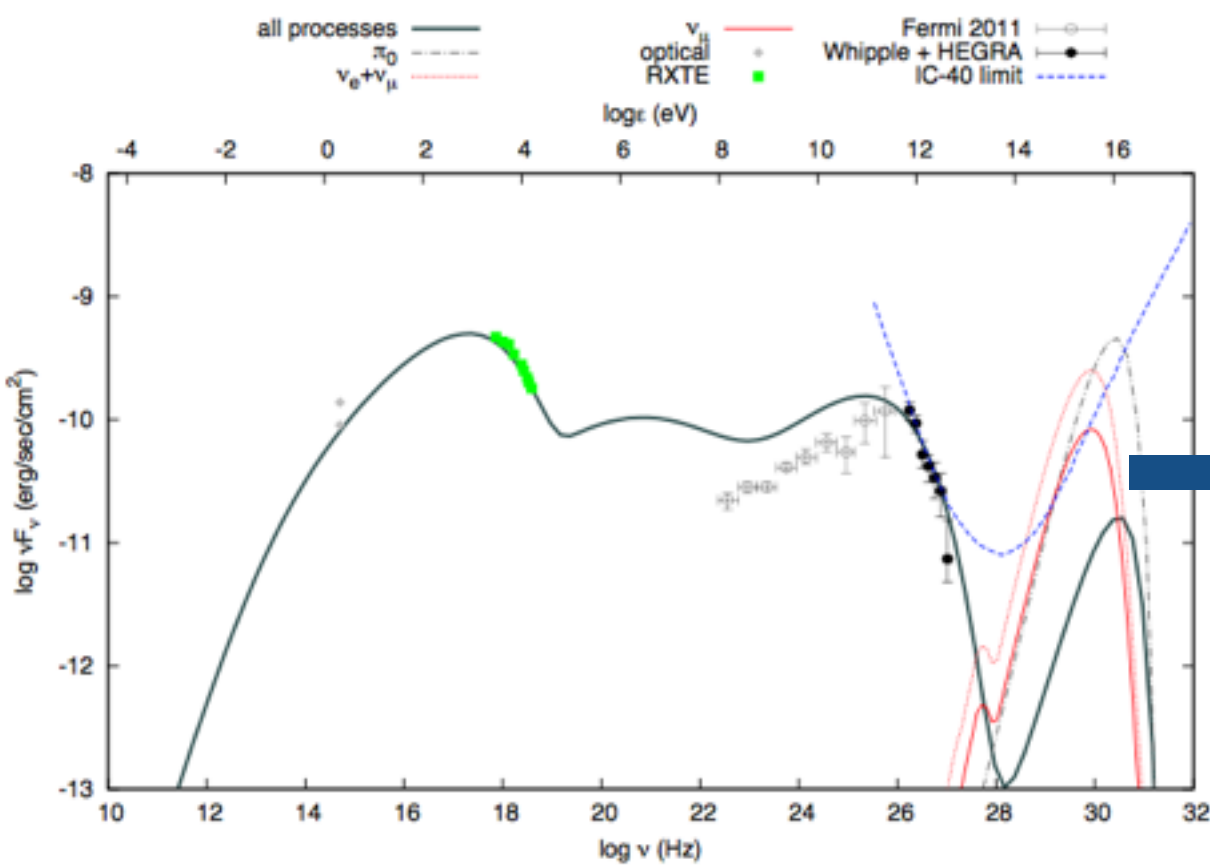
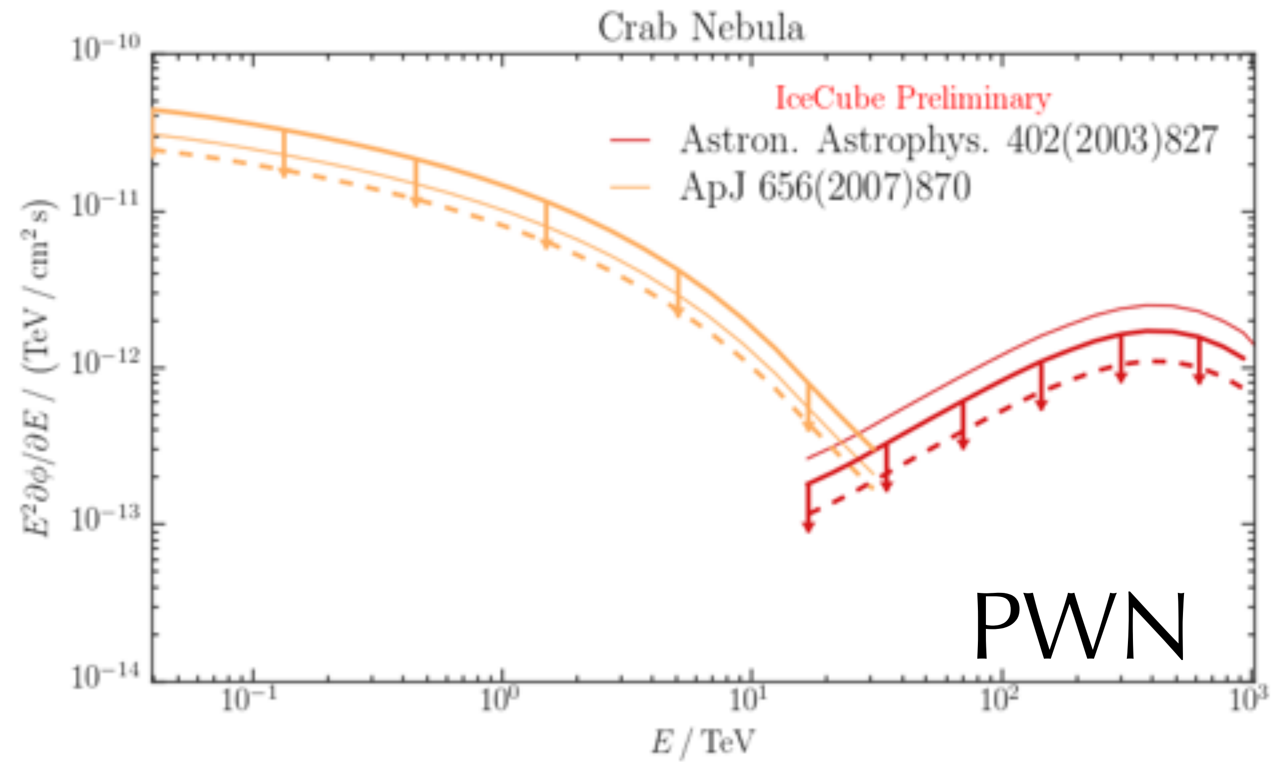
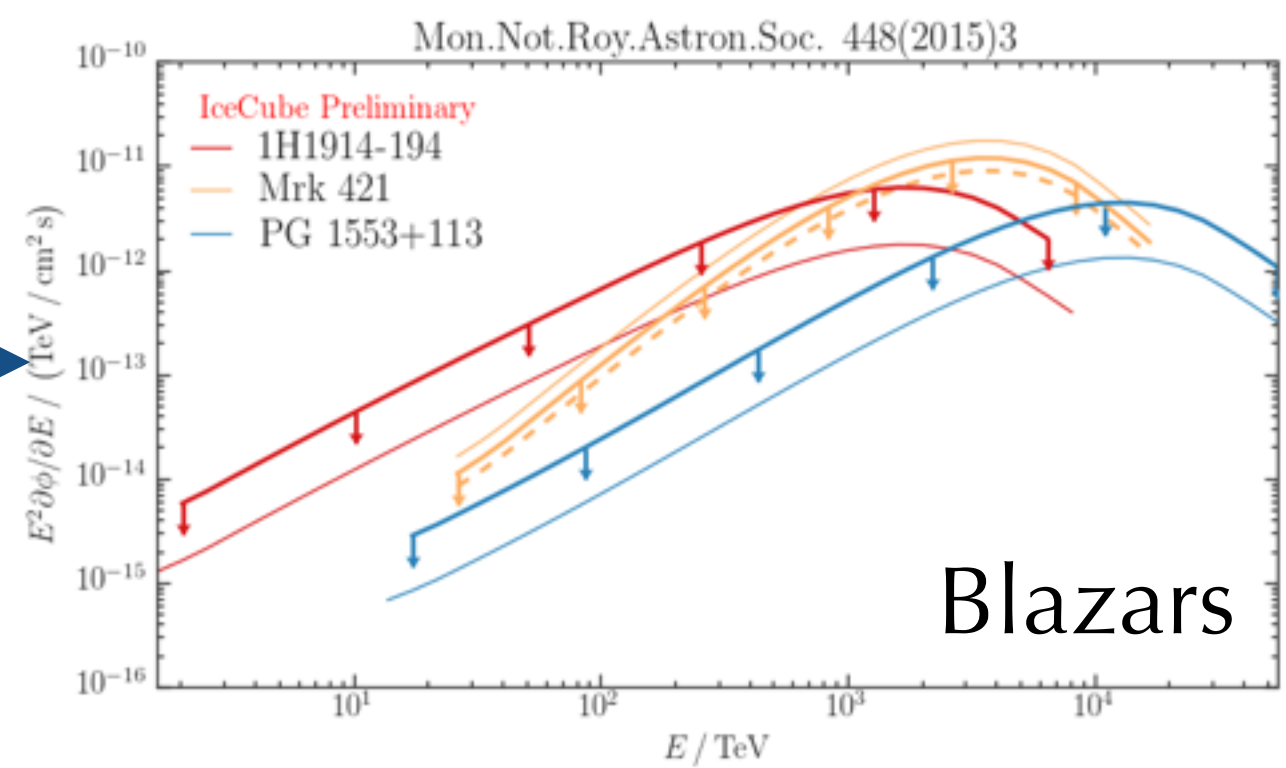
- Probe γ-ray sources for neutrino emission
  - Convert γ-flux to ν's assuming that they originate from π^0 & $\pi^{\pm}$
  - MC modelling of pp/pγ interactions
- IceCube puts limits in reach of models







Mon.Not.Roy.Astron.Soc. 448 (2015) 3, 2412-2429

Conclusion

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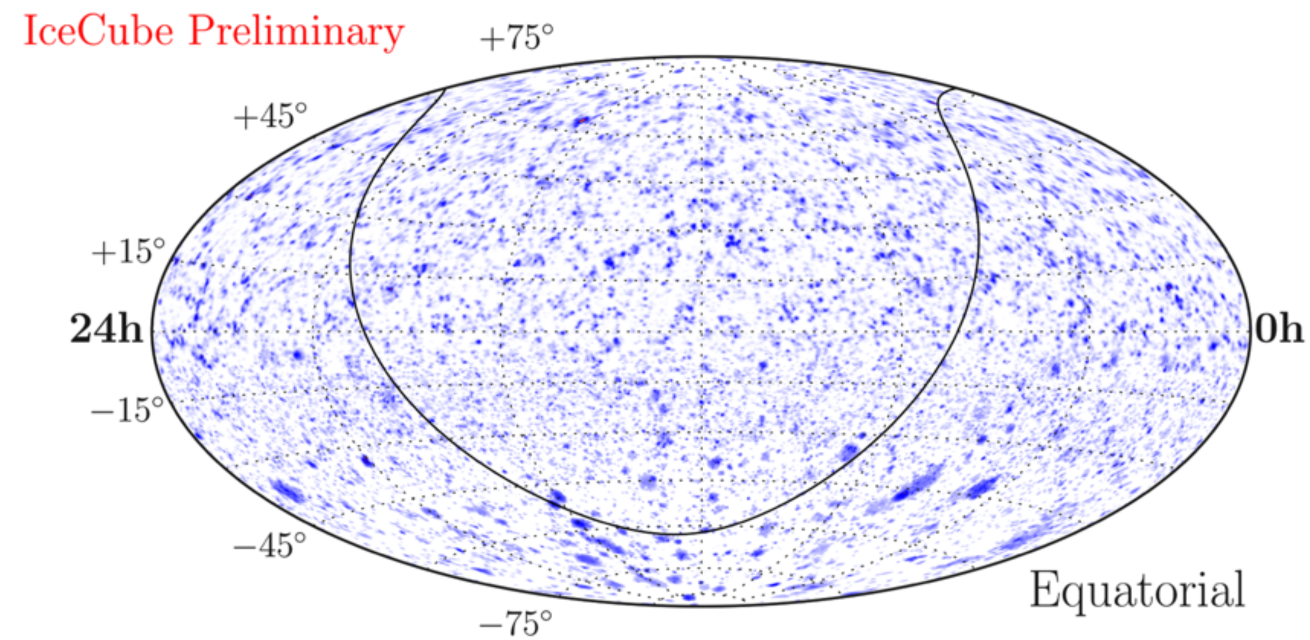
- IceCube found first evidence of astrophysical high-energy neutrinos
  - Consistent with isotropic distribution / full sky of all flavours
  - Statistics and angular resolution limits the identification of the origin
- Searches for point sources compatible with atm. background
  - Lots of other exciting physics



- Galactic emission
- Time-dependent
- Stacking
- Autocorrelation
- …

- Dark Matter
- Oscillations
- CR anisotropy
- Magnetic Monopoles
- GRB
- …

+ Multi Messenger (Gravitational Waves)

The IceCube Collaboration

Funding Agencies

- Fonds de la Recherche Scientifique (FRS-FNRS)
- Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
- Federal Ministry of Education & Research (BMBF)
- German Research Foundation (DFG)
- Deutsches Elektronen-Synchrotron (DESY)
- Japan Society for the Promotion of Science (JSPS)
- Knut and Alice Wallenberg Foundation
- Swedish Polar Research Secretariat
- The Swedish Research Council (VR)
- University of Wisconsin Alumni Research Foundation (WARF)
- US National Science Foundation (NSF)

IceCube-Gen2

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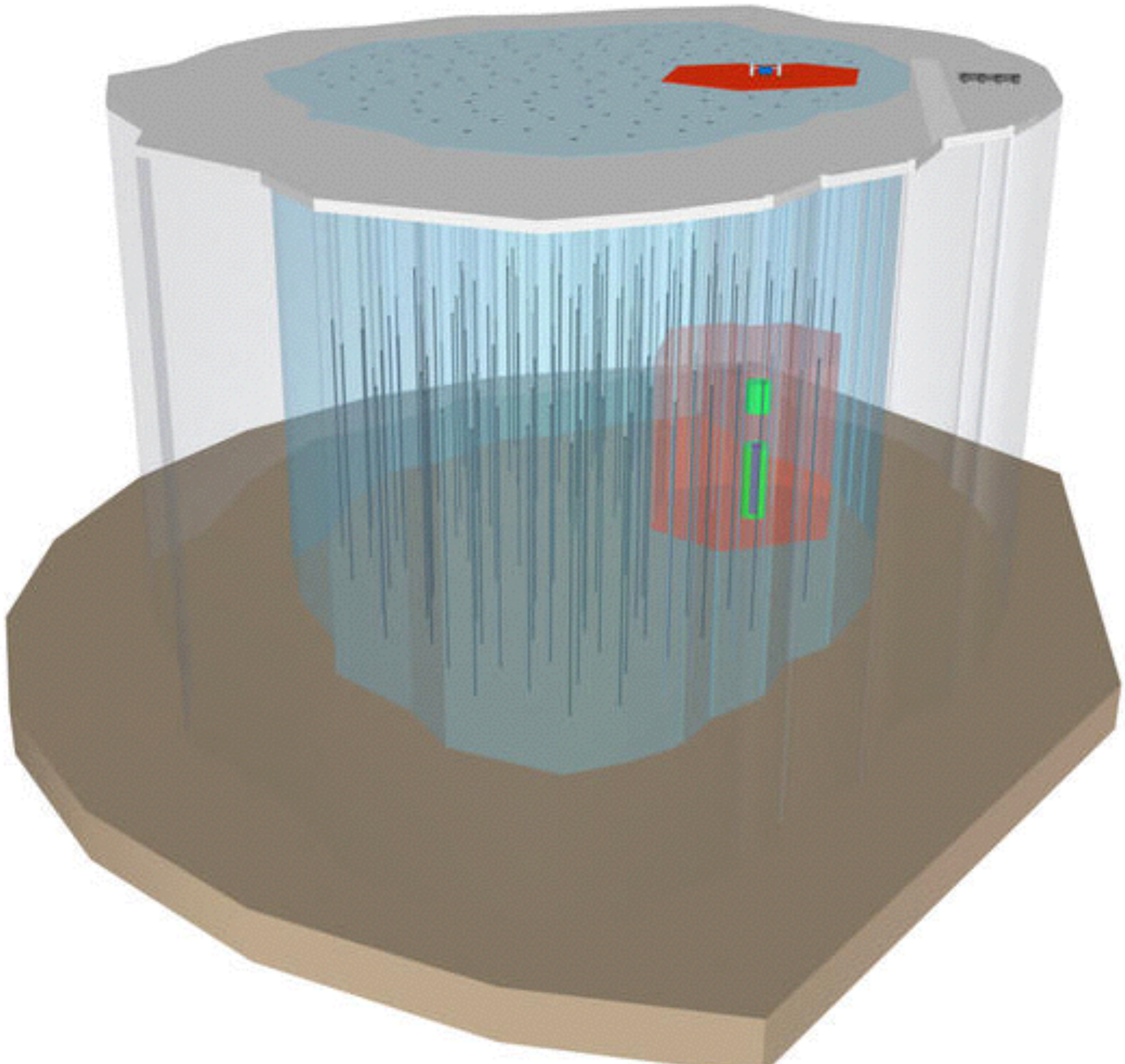

Gamma-ray bursts

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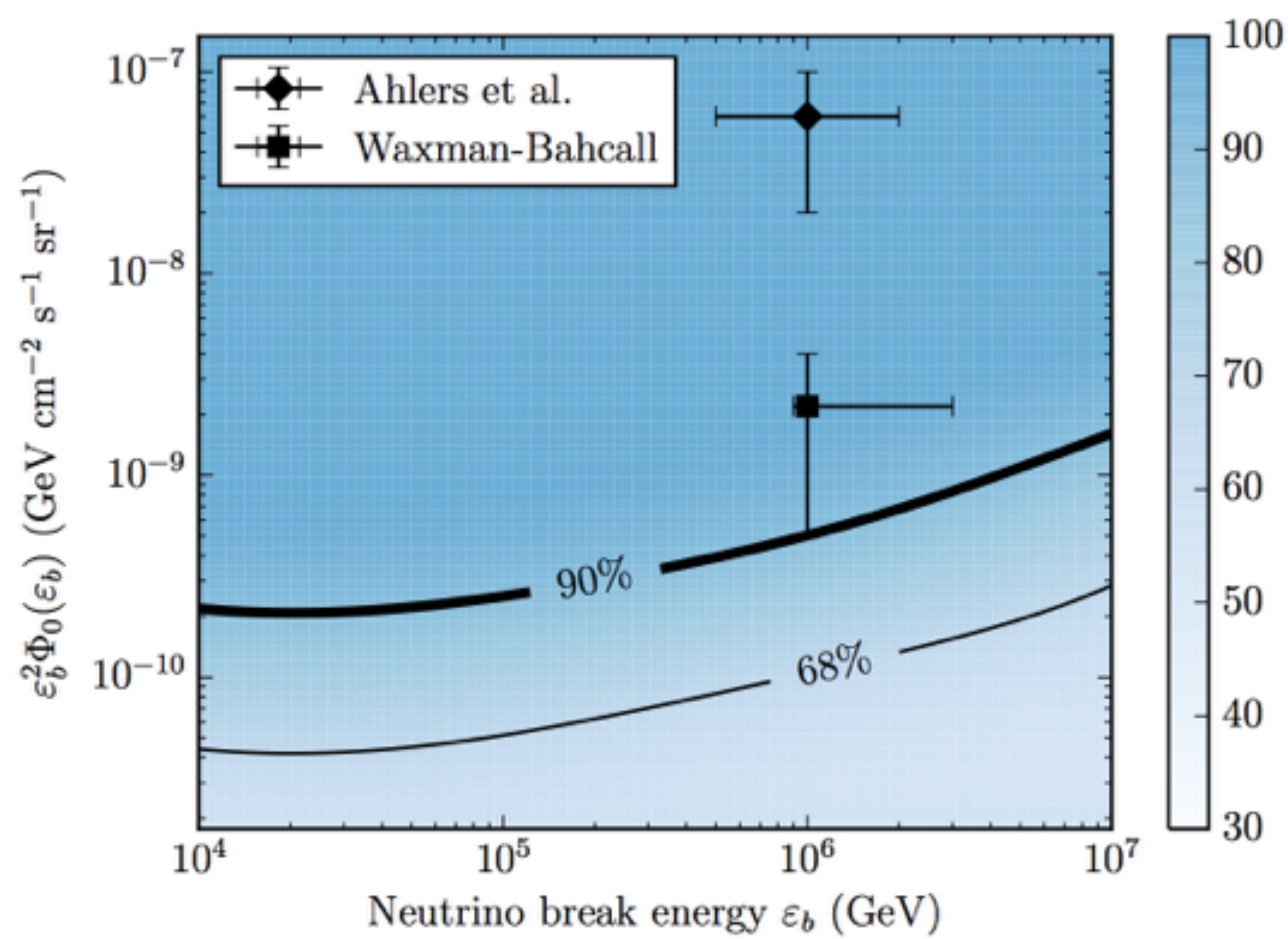
ApJ 805, L5 (2015)

- 1 ν in coincidence with GRB (506 GRBs in total)
  - neutrino probably atmospheric background
- <1% of astro. ν flux can come from prompt GRB ν
- absence of prompt ν disfavours GRB as candidate of accelerators of UHECR

Ahlers: neutrons escape GRB fireball
Waxman-Bahcall: protons escape



ν Oscillations with IceCube-DeepCore

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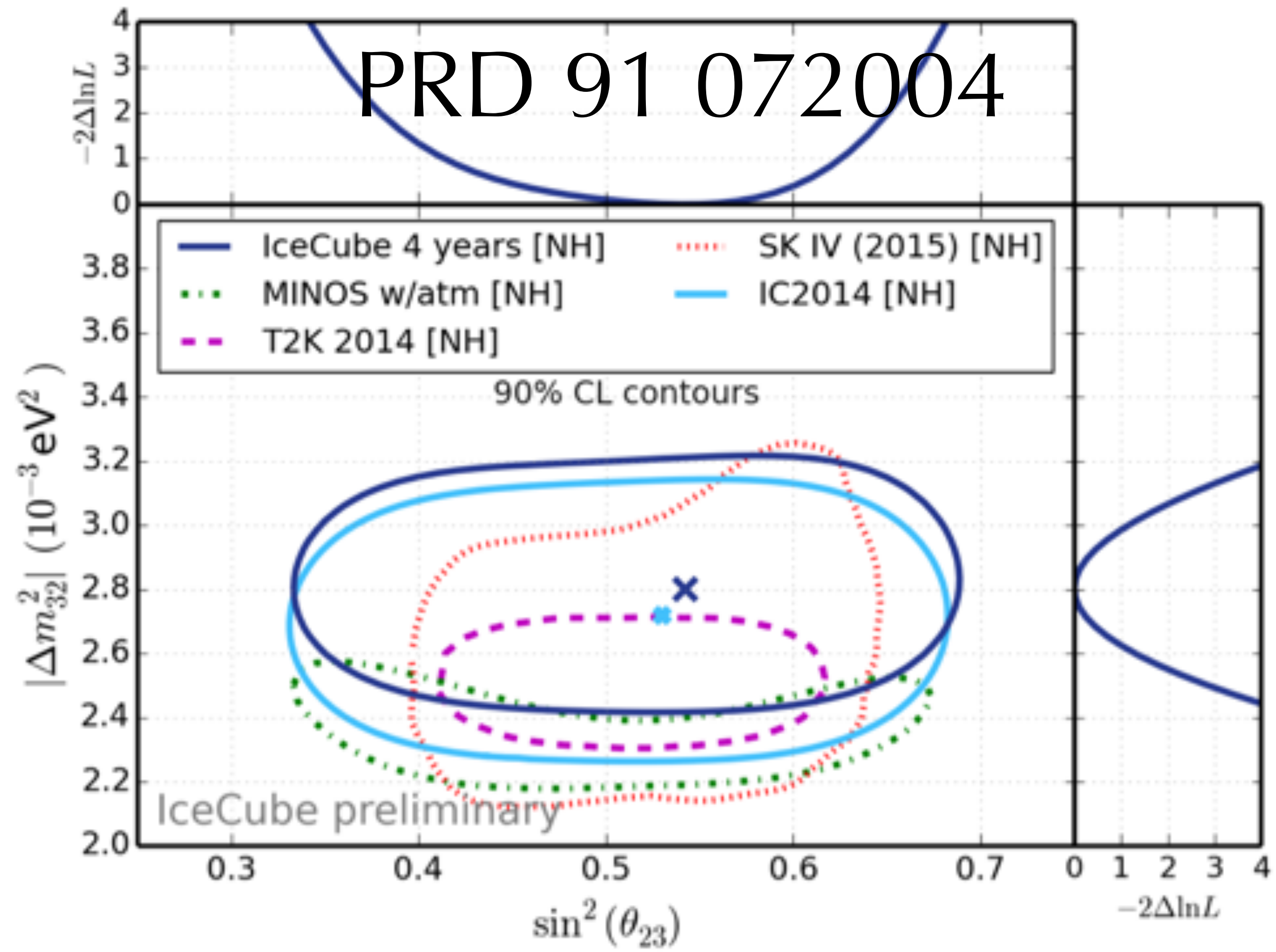
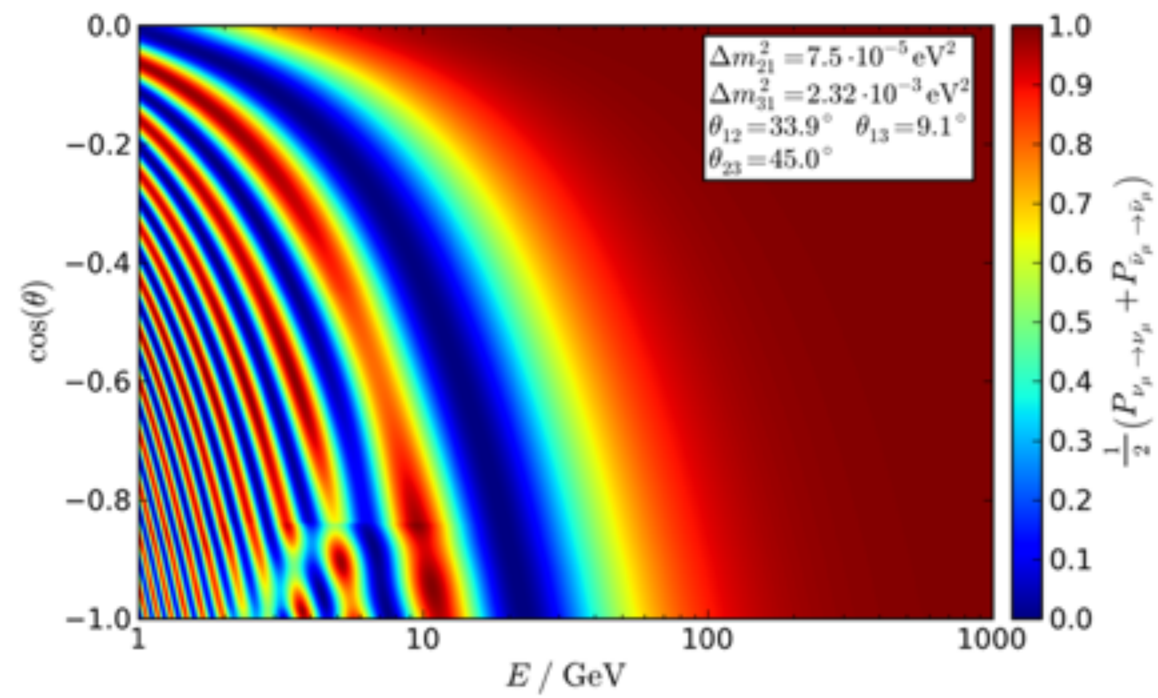
- Low-energy extension DeepCore accesses energies down to 10GeV
  - 8 strings in the center of IceCube (clearest ice)
  - IceCube works as active shield
  - Atm. ν_μ oscillation minimum visible at ~25GeV
- Use atm. ν to measure neutrino oscillations
- Search for non-std. interactions possible as well
- Sterile neutrinos could produce similar signatures at TeV energies





Dark Matter / WIMPs

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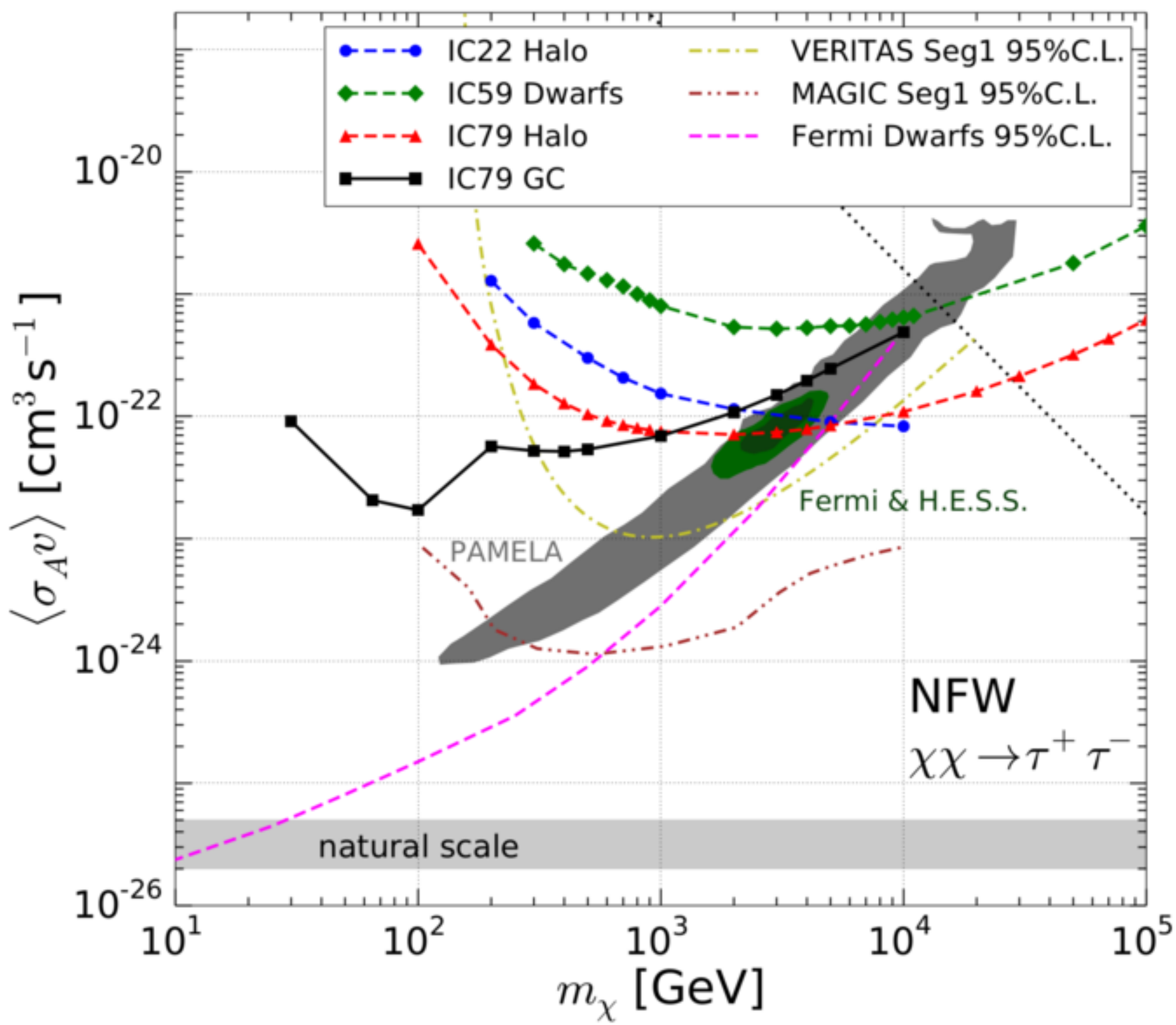
- Search for DM annihilation into neutrinos
  - direct **χχ**→νν or via W, b, τ
  - DM capture in Sun/Earth
  - Galactic center
  - Galactic halo
  - Galaxy clusters



Cosmic Ray Anisotropy

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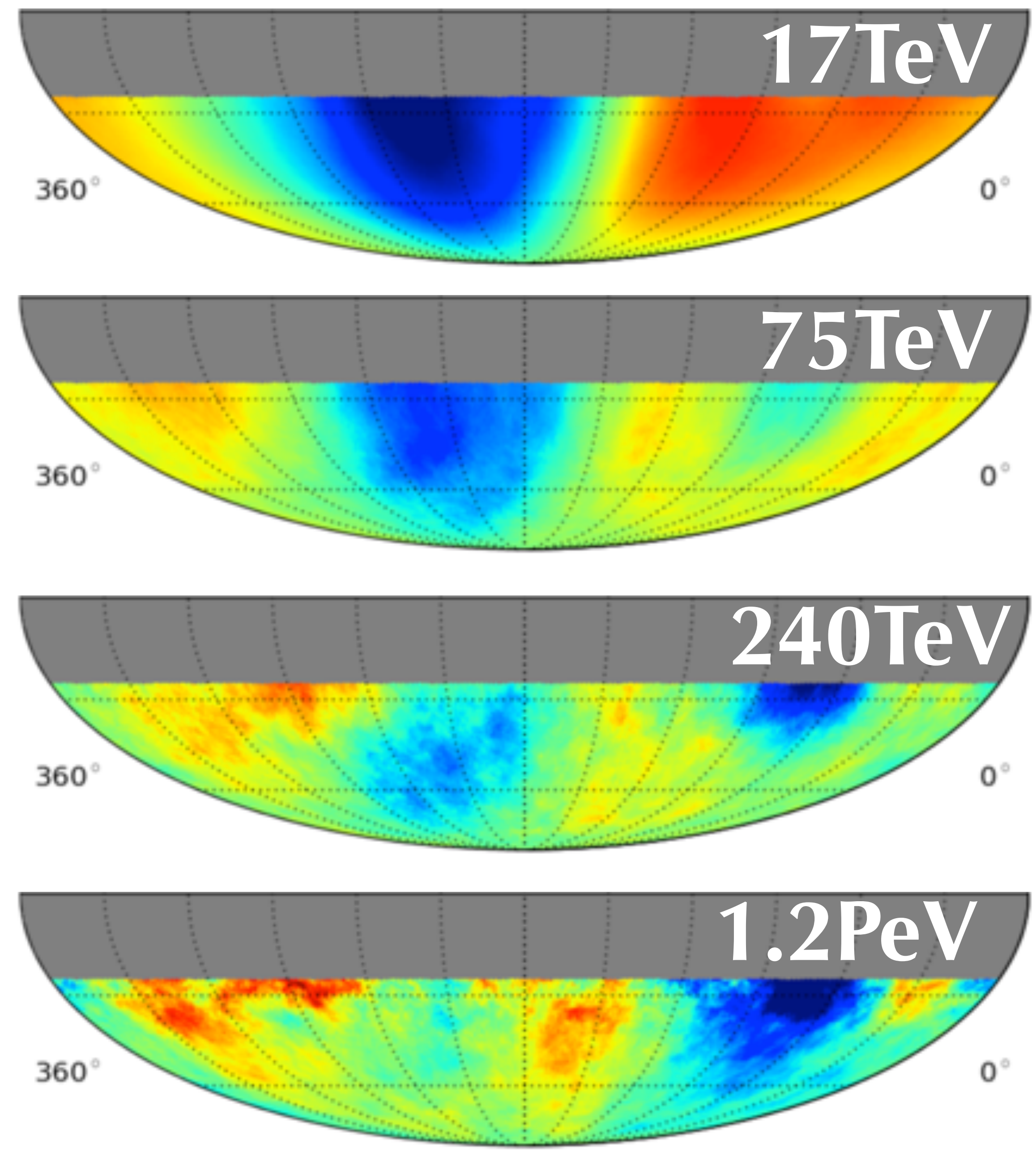
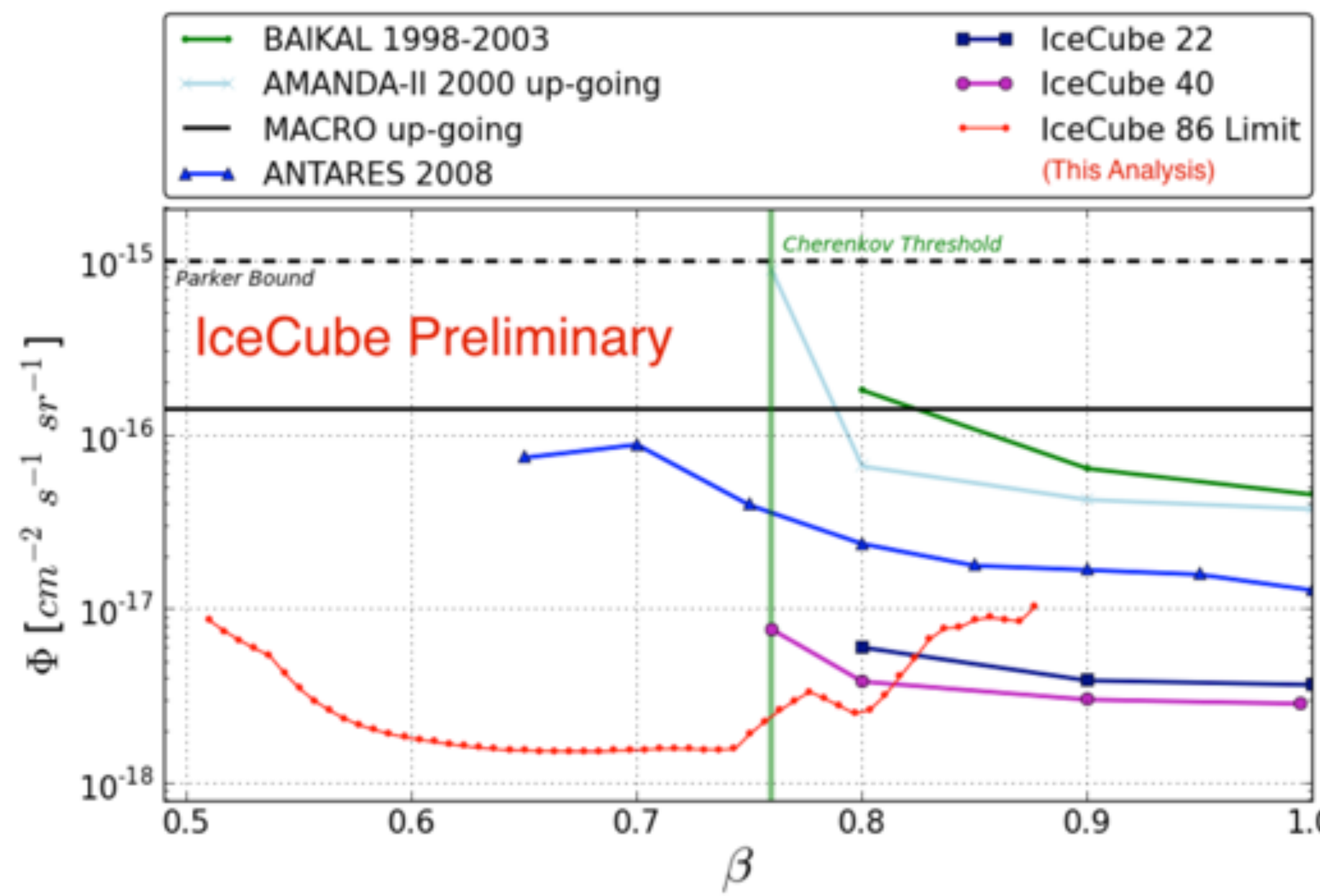
- Cosmic Ray anisotropy
- IceCube and surface array IceTop
- 318 *billion* atm. μ
- Observation of anisotropy in cosmic ray arrival direction in Southern sky



Magnetic Monopoles

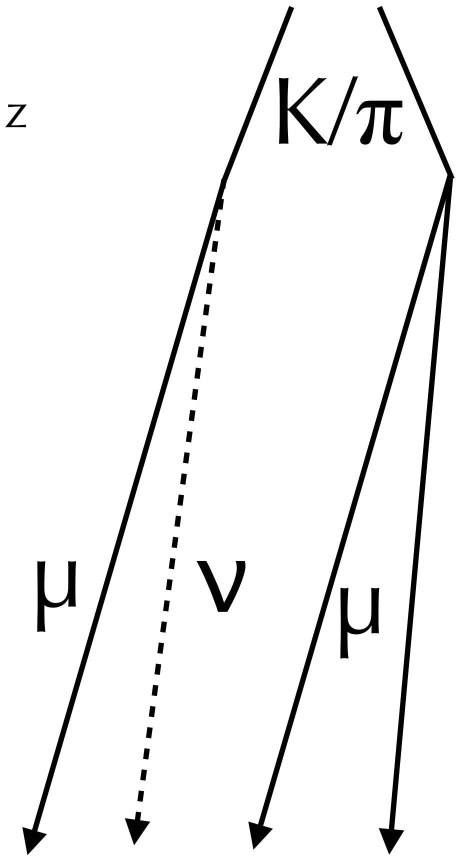
- Search for GUT magnetic monopoles
  - Light emission along path (Cherenkov and induced proton decay)
  - Velocities significantly slower than speed of light

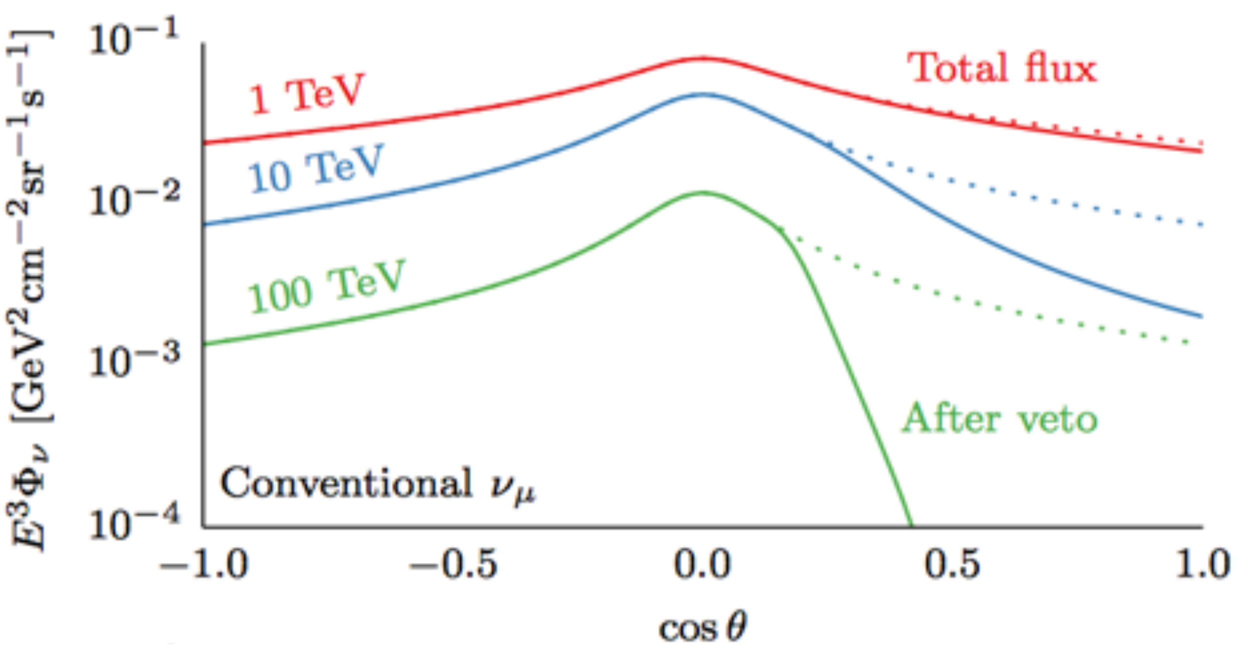


Atmospheric Self-Veto

Schönert, Gaisser, Resconi, Schulz
Phys.Rev.D79, 043009 (2009)

Gaisser, Jero, Karle, van Santen
Phys.Rev.D90, 023009 (2014)





- Incoming μ are most likely atmospheric events
- Use outer detector layer to identify incoming events
- Atmospheric ν are accompanied by μ of the same shower
- Veto reduces both atm. μ and atm. ν component

Atmospheric Self-Veto

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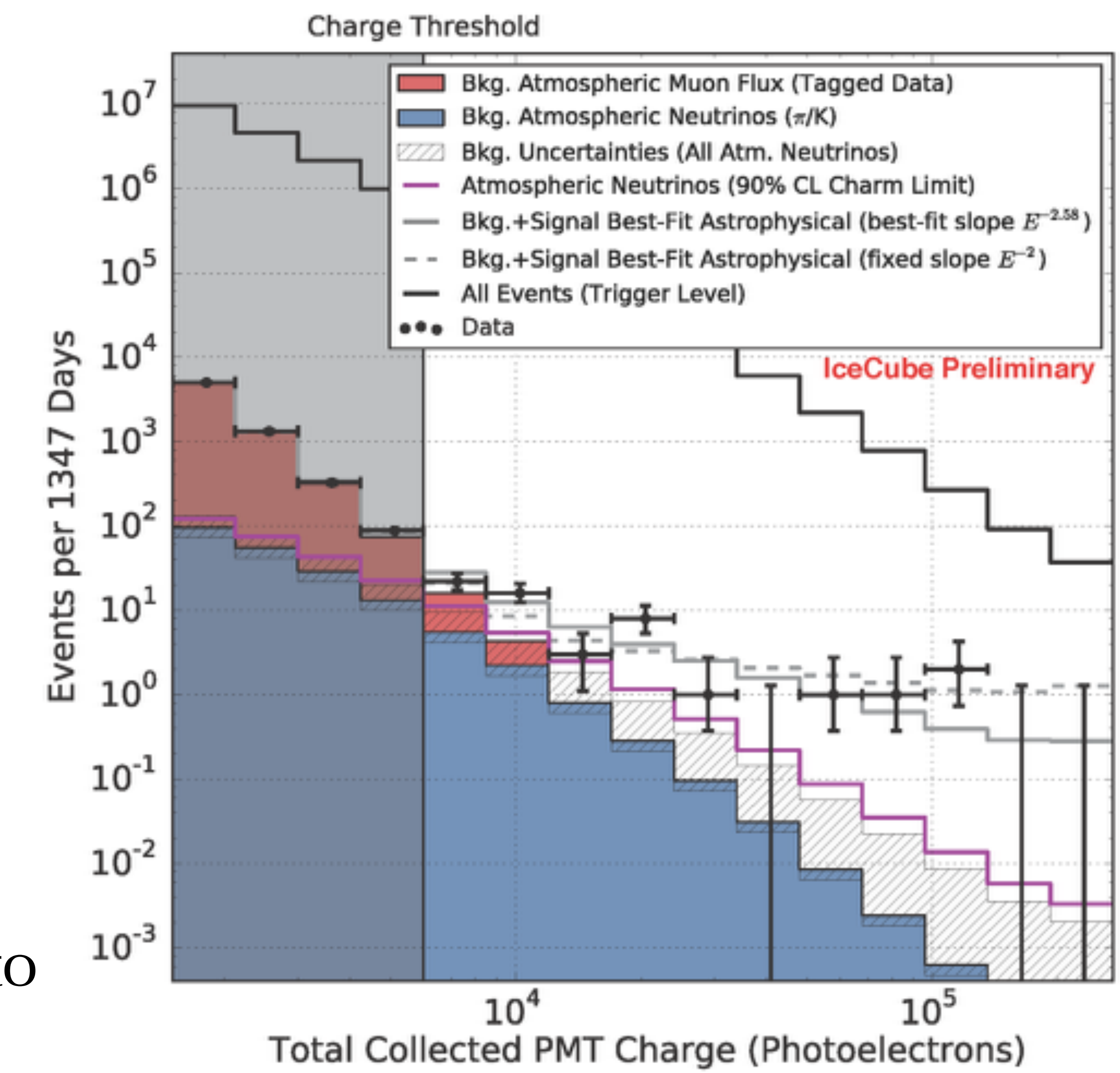
- Verify veto capabilities with experimental data
- Outer layer of DOMs is used as active veto
- Tag & Probe
- Use the second layer inside of the veto to identify incoming μ
- Check how many are correctly veto
- Very good agreement with MC, experimental constraint on μ contamination



Moon Shadow

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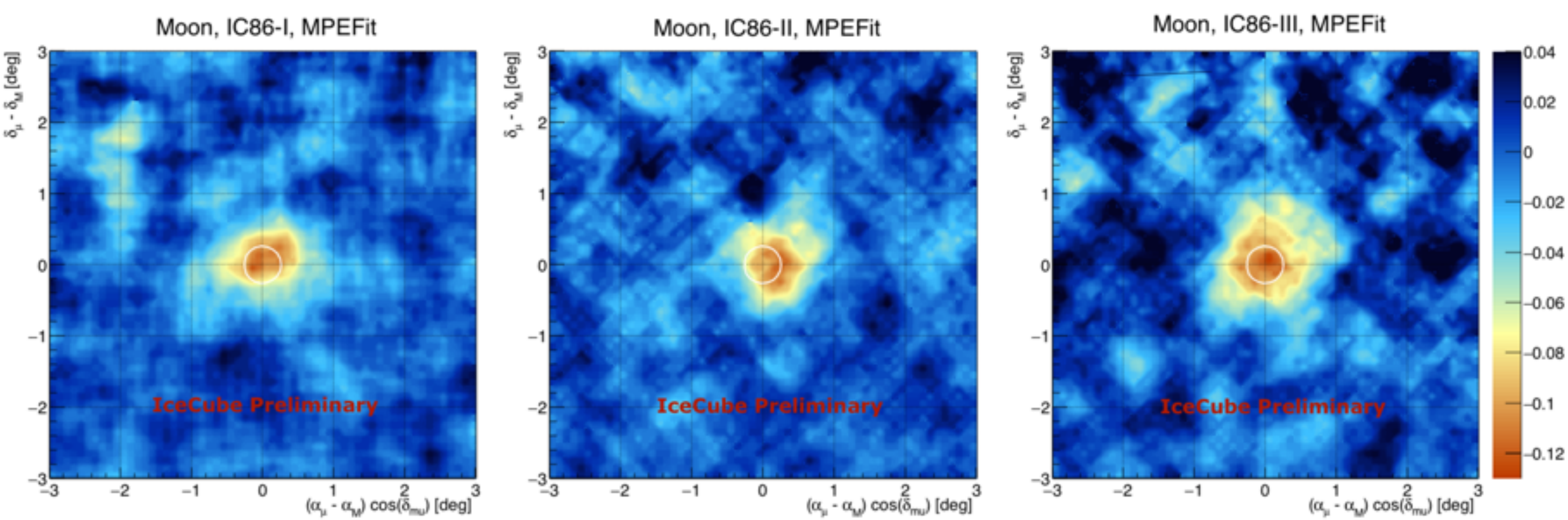
- Use Moon shadowing of cosmic rays to calibrate and verify angular reconstruction
  - Look for lack of muons from position of the Moon
  - Size of the Moon ~0.5°



South Pole Ice

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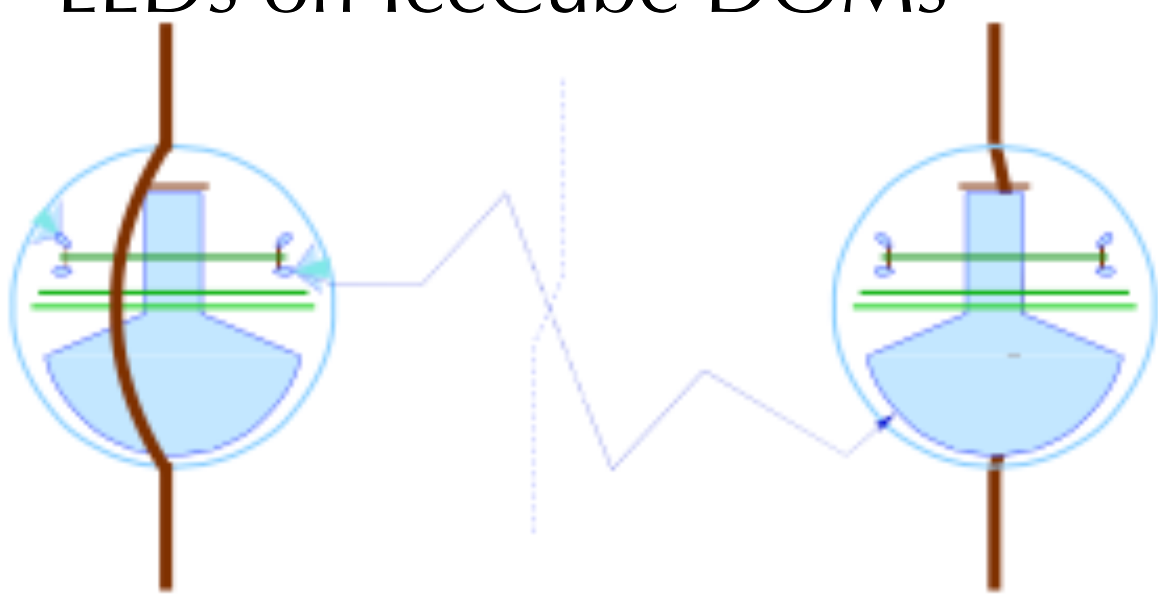
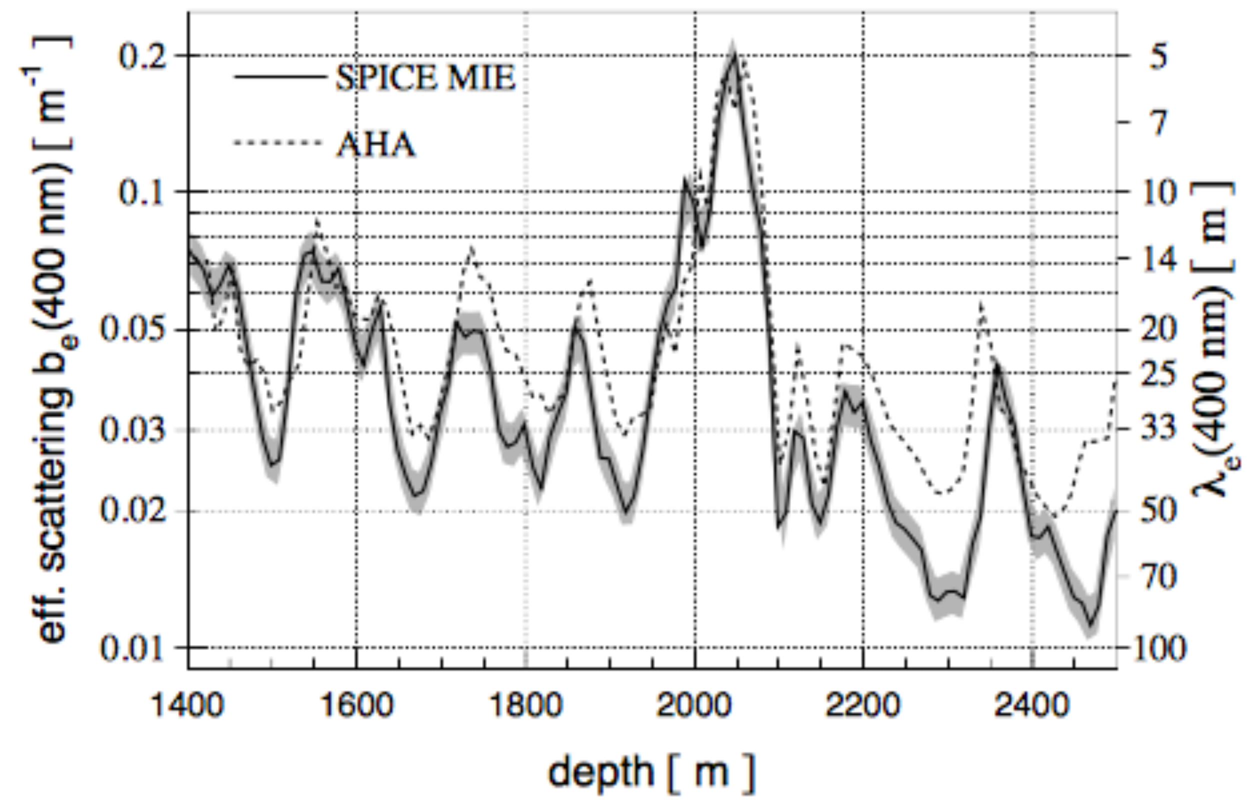
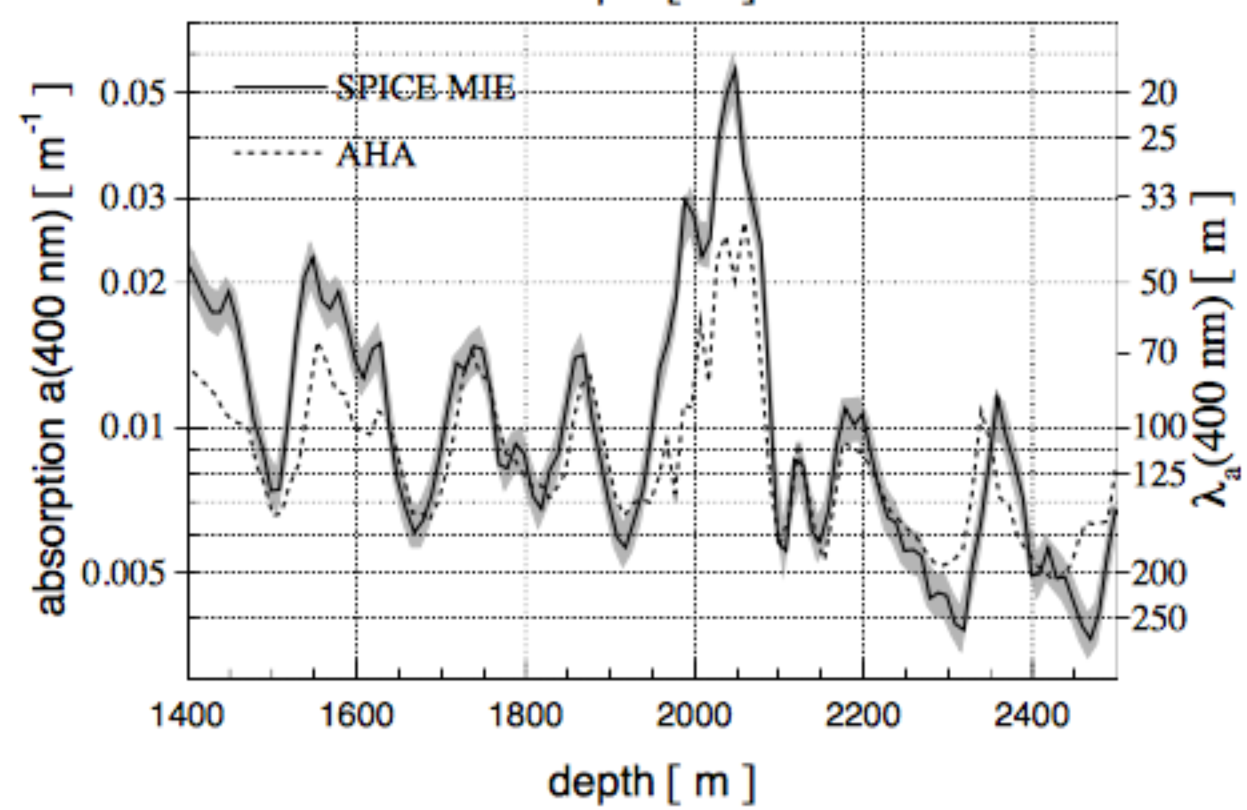
- Very clear Ice at the South Pole
  - Very large absorption length
  - Scattering due to dust
- Layer of dust at 2km depth inside of IceCube
- Dedicated Ice modelling using LEDs on IceCube DOMs



Nucl.Instrum.Meth. A711 (2013) 73-89





Astrophysical Neutrino Signal

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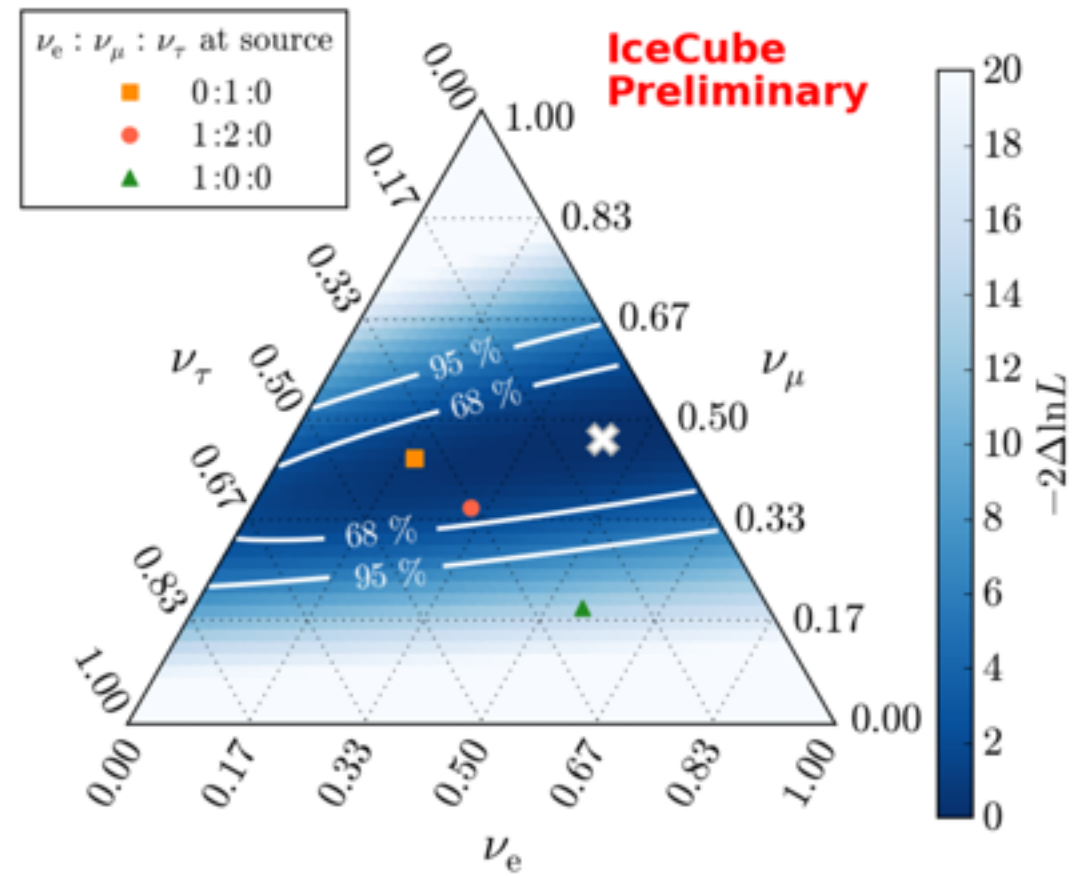
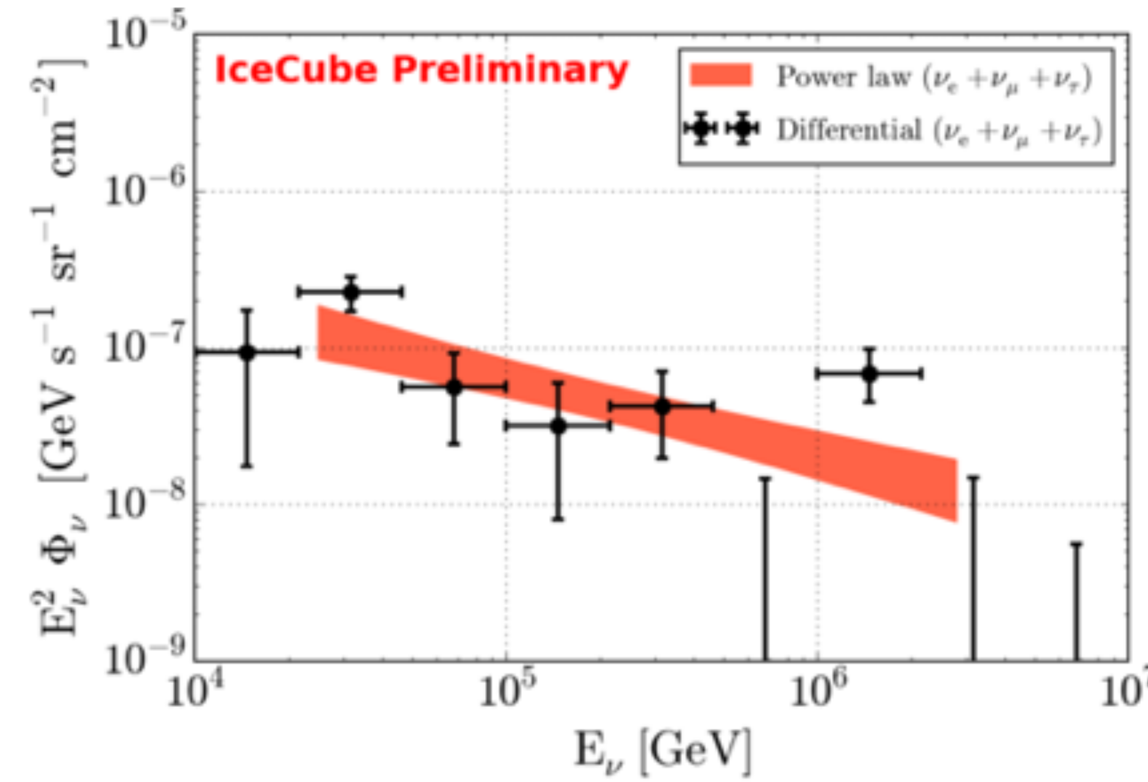
- Astrophysical ν's observed by independent observations
    - Starting Events (all-flavour)
    - Through- & up-going μ (ν_μ)
- Consistent with uniform (1:1:1) flavour composition





Point Sources: Accessible Energies

Stefan Coenders
Lake Louise
2016-02-12

- Strong energy dependence with energy
- North
  - Low energies (TeV) accessible
  - Absorption at high energies
- South
  - High energy threshold (PeV) due to large μ background
  - Starting events reduce energy threshold from PeV to 100-300 TeV
  - ANTARES sensitive below 100 TeV in South