Exploring the Universe with Neutrinos

Nick van Eijndhoven

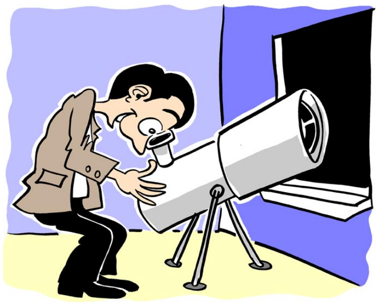
nick@icecube.wisc.edu http://www.iihe.ac.be

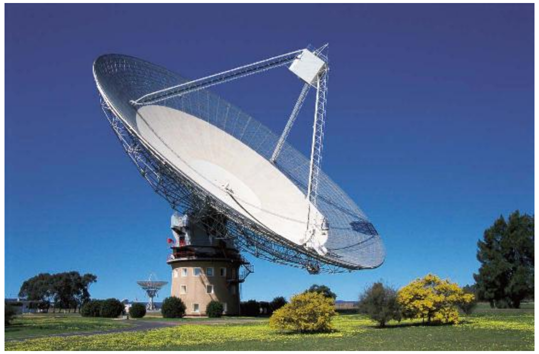
Vrije Universiteit Brussel - IIHE(ULB-VUB)
Pleinlaan 2, B-1050 Brussel, Belgium

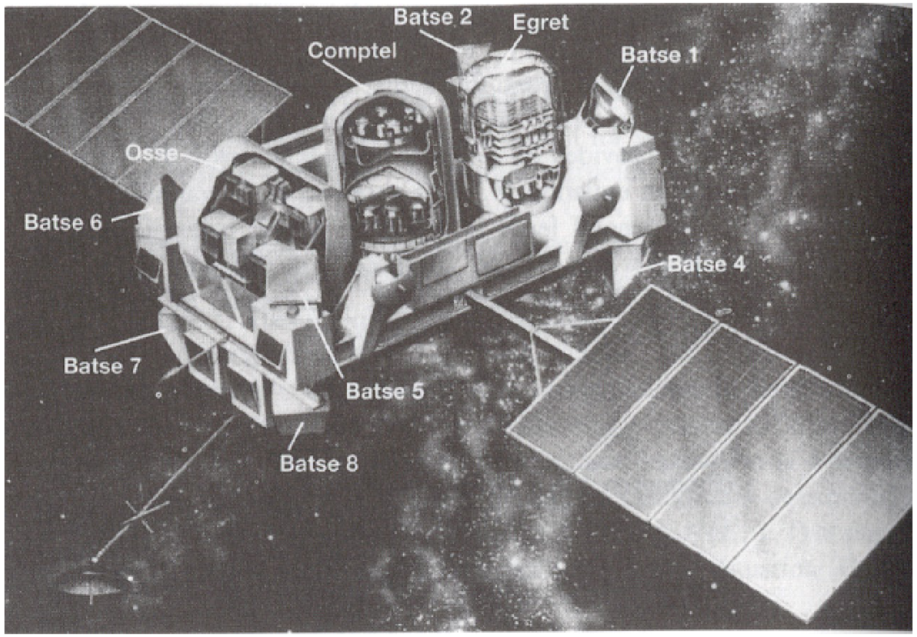
Overview

Why Neutrinos ?	1
Neutrino Telescopes	6
Hunting for Cosmic Neutrino Sources	9
Diffuse Neutrino Flux	13
Outlook	20

Investigating the Universe with electromagnetic radiation







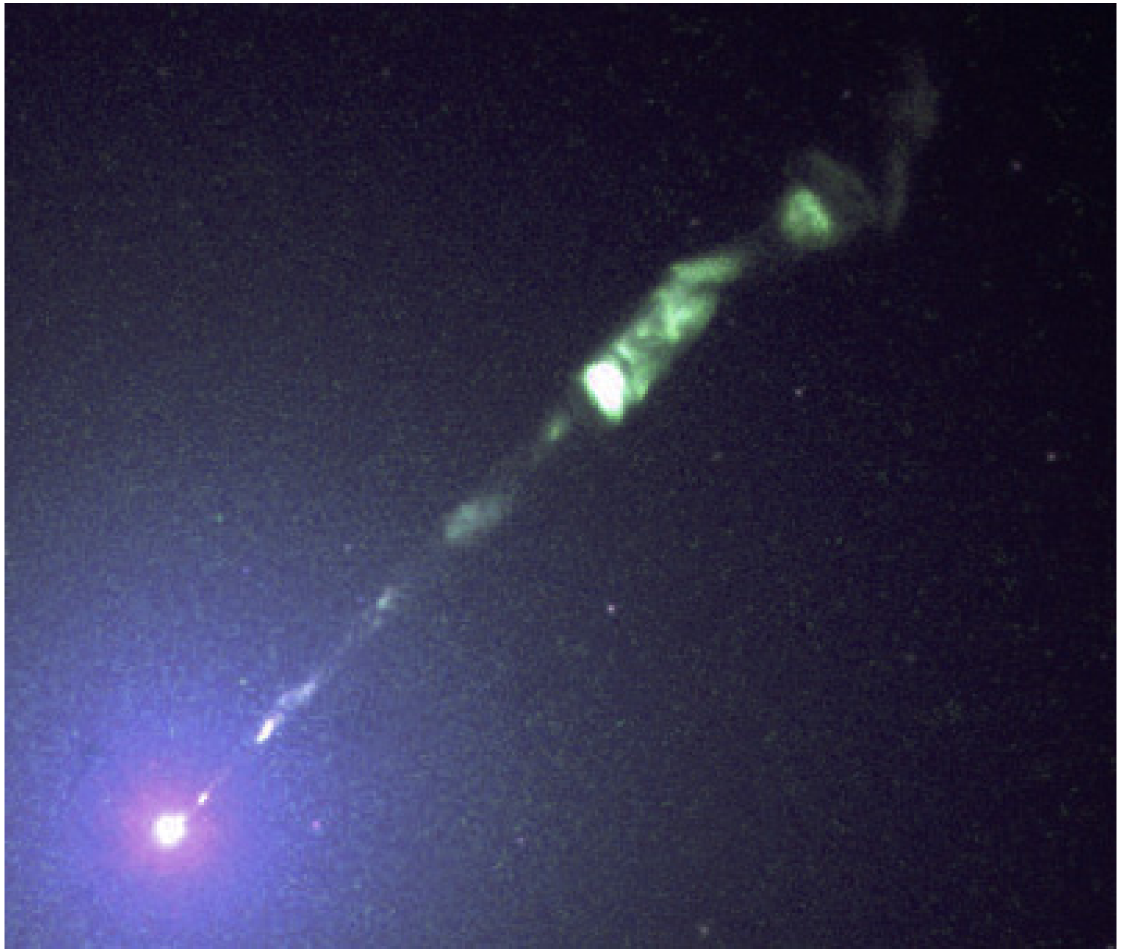
Credit NASA

Observations at different wavelengths

- Various new discoveries (pulsars)
- Better insight in (astro)physical processes
- Rather complete view on the large picture of the Universe

Why Neutrinos ?

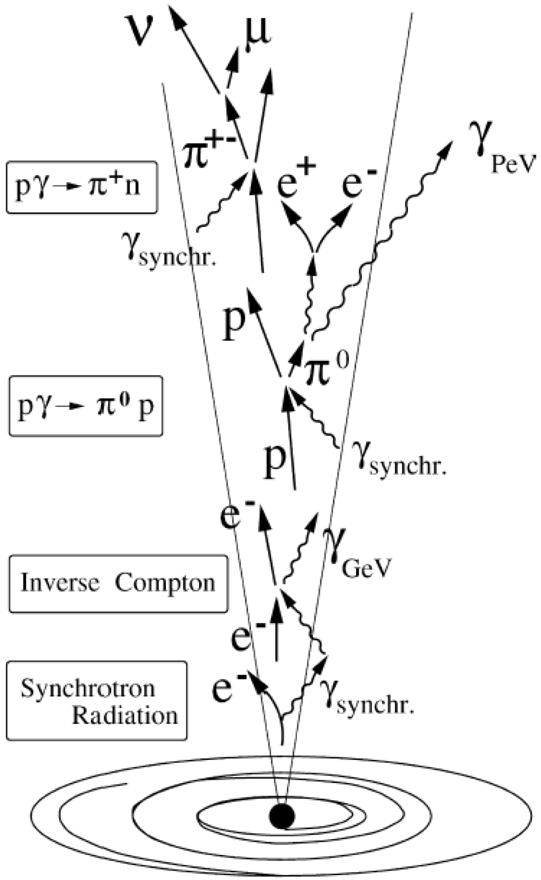
Observed jet signature (M87)



Credit NASA

Acceleration in shock waves

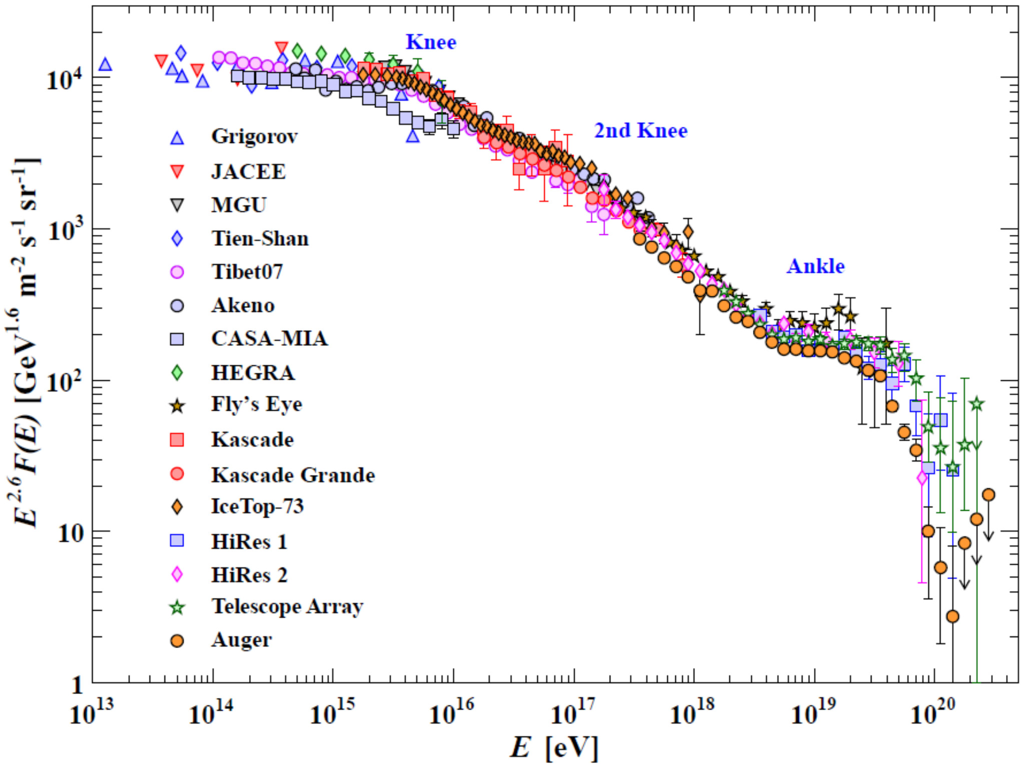
Processes in the jet



Credit C. Spiering

High-energy γ, nuclei and ν

The $E^{2.6}$ scaled Cosmic Ray flux



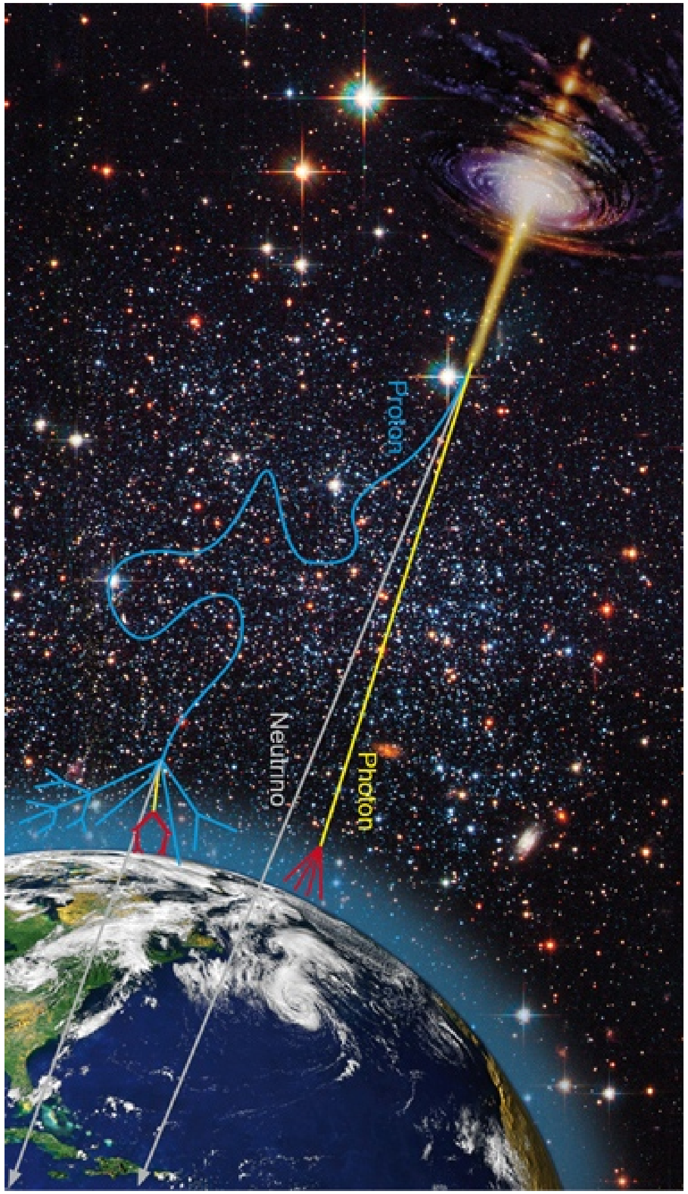
Credit PDG 2014

- Spectral features (knee, ankle)

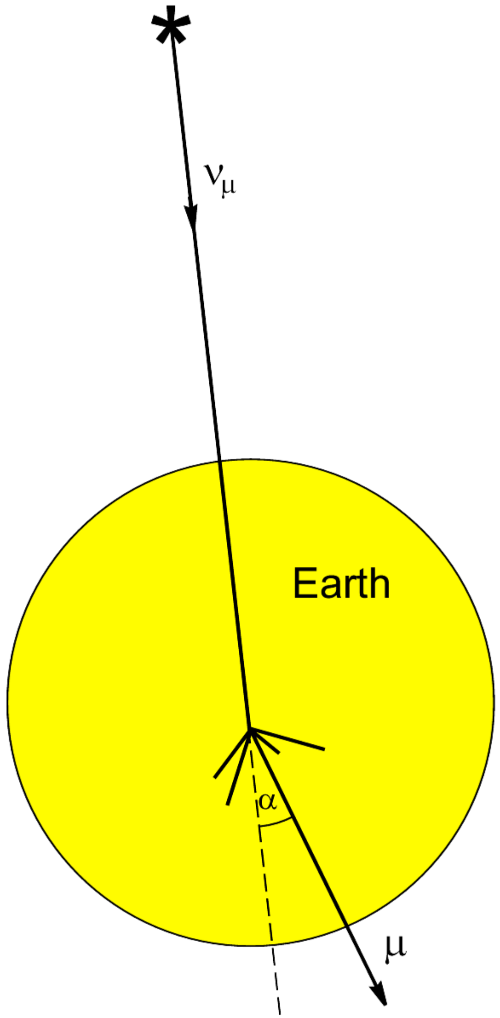
  E limits of cosmic accelerators ?

  Onset of extra-galactic component ?

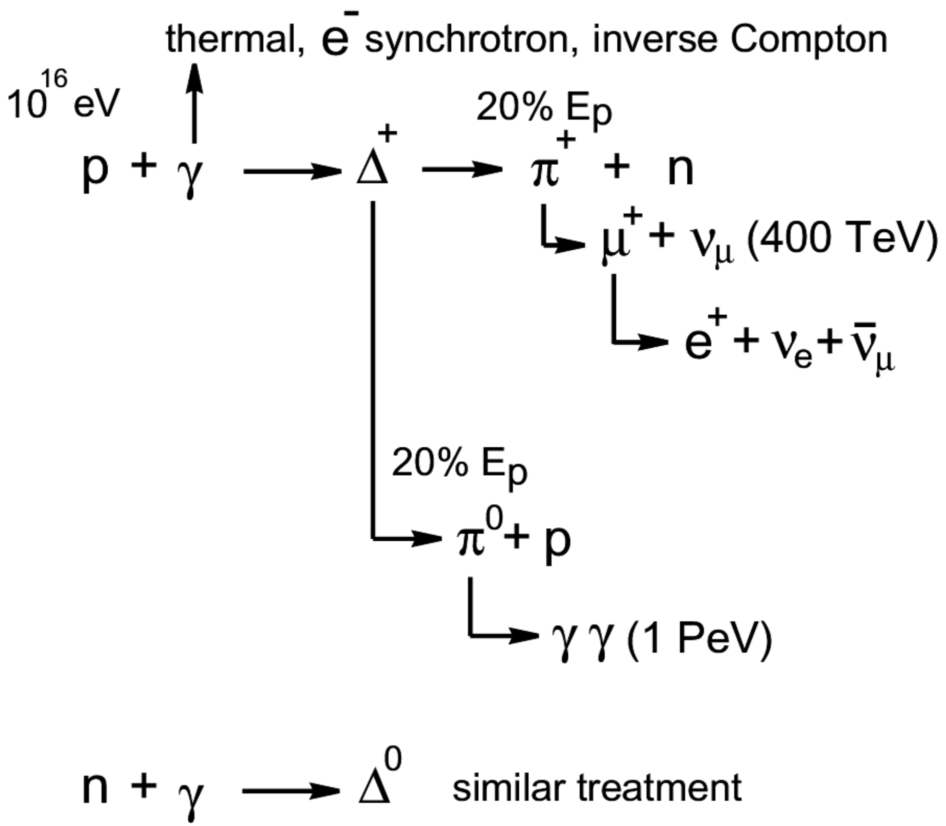
  Do we observe the GZK cut-off ?
- Sources ? (SNe, GRBs, AGN, ...)



Neutrino detection principle



Neutrino production mechanism



- Δ prod. threshold : $E_\gamma \geq 10$ eV (UV photons)

- **Waxmann-Bahcall** (PRL 78 (1997) 2292)

  High-E p diffuse out of the shocks

  Observed CR $\rightarrow$ lower limit on p flux

  Fraction of p used for ν production ?

- **M. Ahlers et al.** (APP 35 (2011) 87)

  Protons trapped, neutrons escape

  CR observations provide the n flux

  Direct relation CR $\leftrightarrow$ ν flux

- **Generic broken powerlaw ν spectrum**

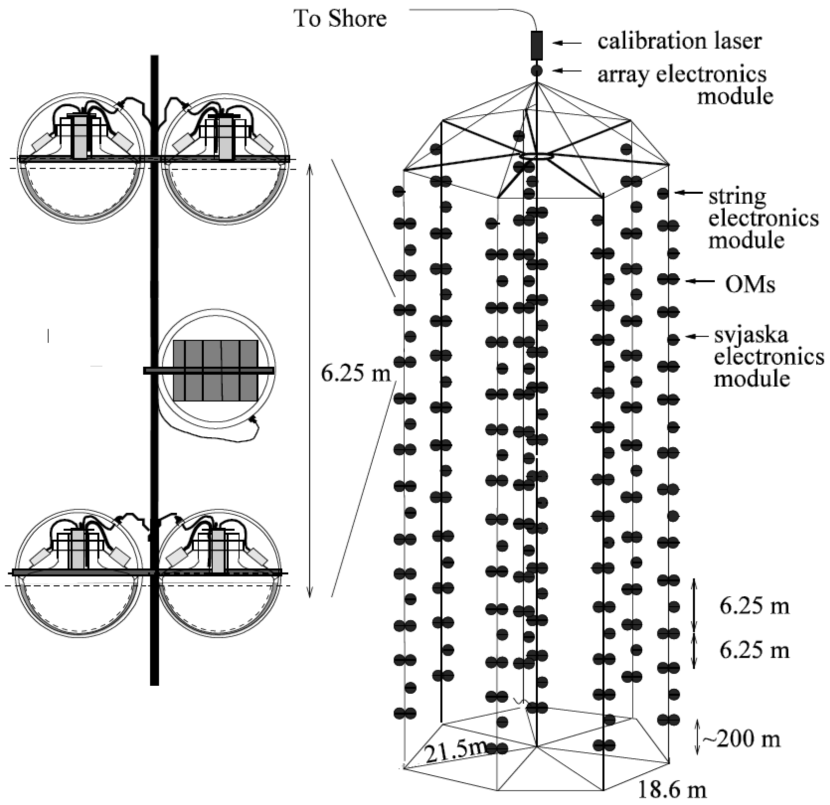
$$\Phi_\nu(E) \sim \begin{cases} E^{-1}\epsilon_b^{-1} & (E < \epsilon_b) \\ E^{-2} & (\epsilon_b \leq E \leq 10\epsilon_b) \\ E^{-4}(10\epsilon_b)^2 & (E > 10\epsilon_b) \end{cases}$$

with $\epsilon_b \approx 1$ PeV (JCAP 0903 (2009) 020)

∗ Let's search for high-E ν sources

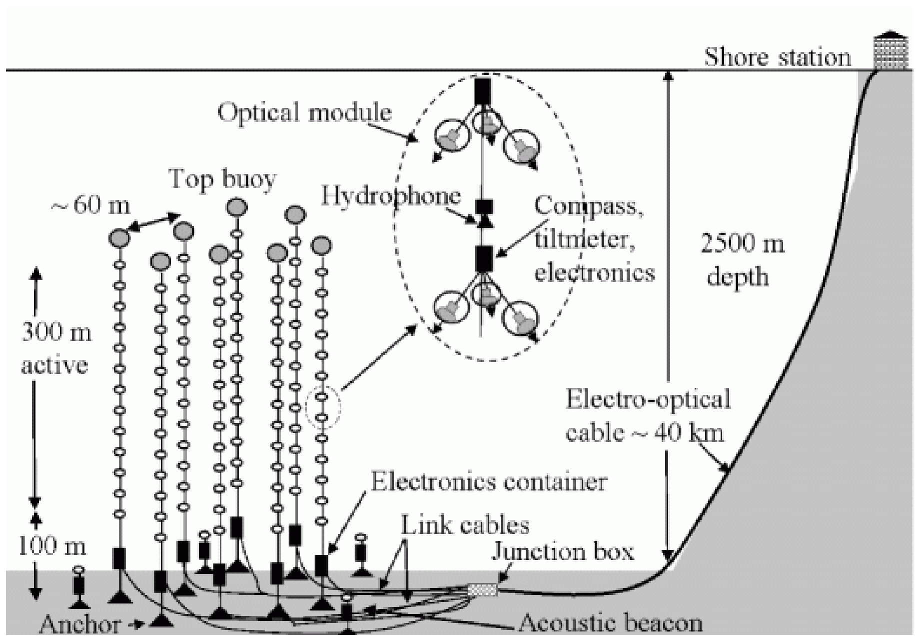
Underwater Neutrino Detectors

Lake Baikal (Russia) : Baikal-NT200



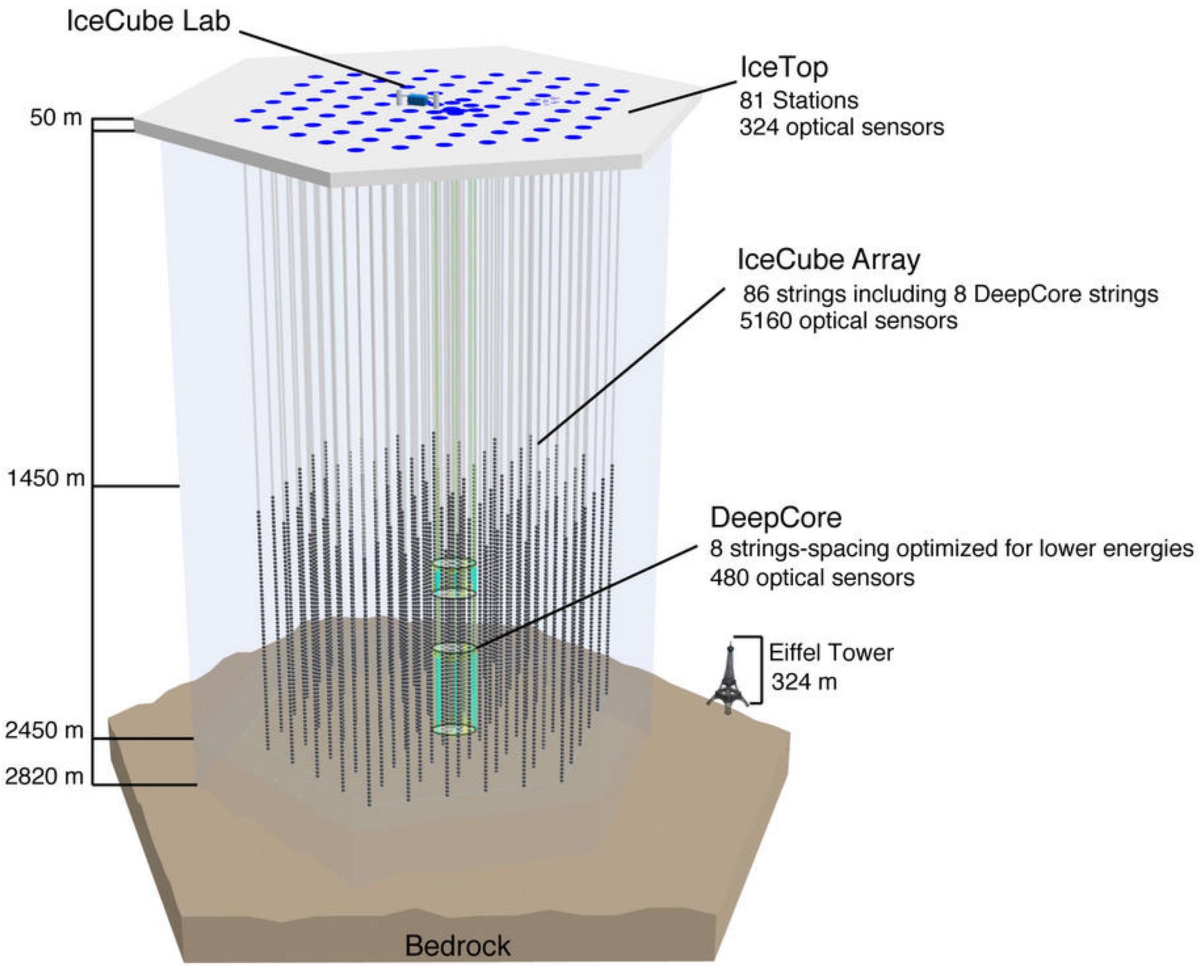
8 strings, 192 optical sensors
Instrumented volume $\sim 10^{-4}$ km^3

Mediterranean : Antares



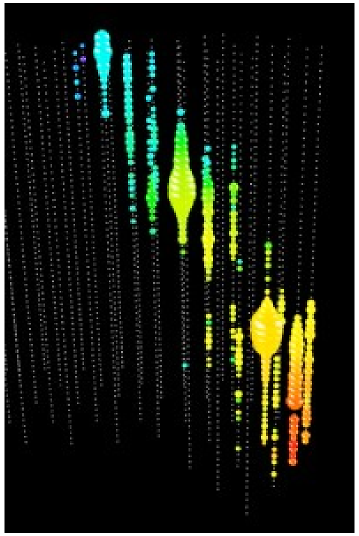
12 strings, 900 optical sensors
Instrumented volume ~ 0.03 km^3

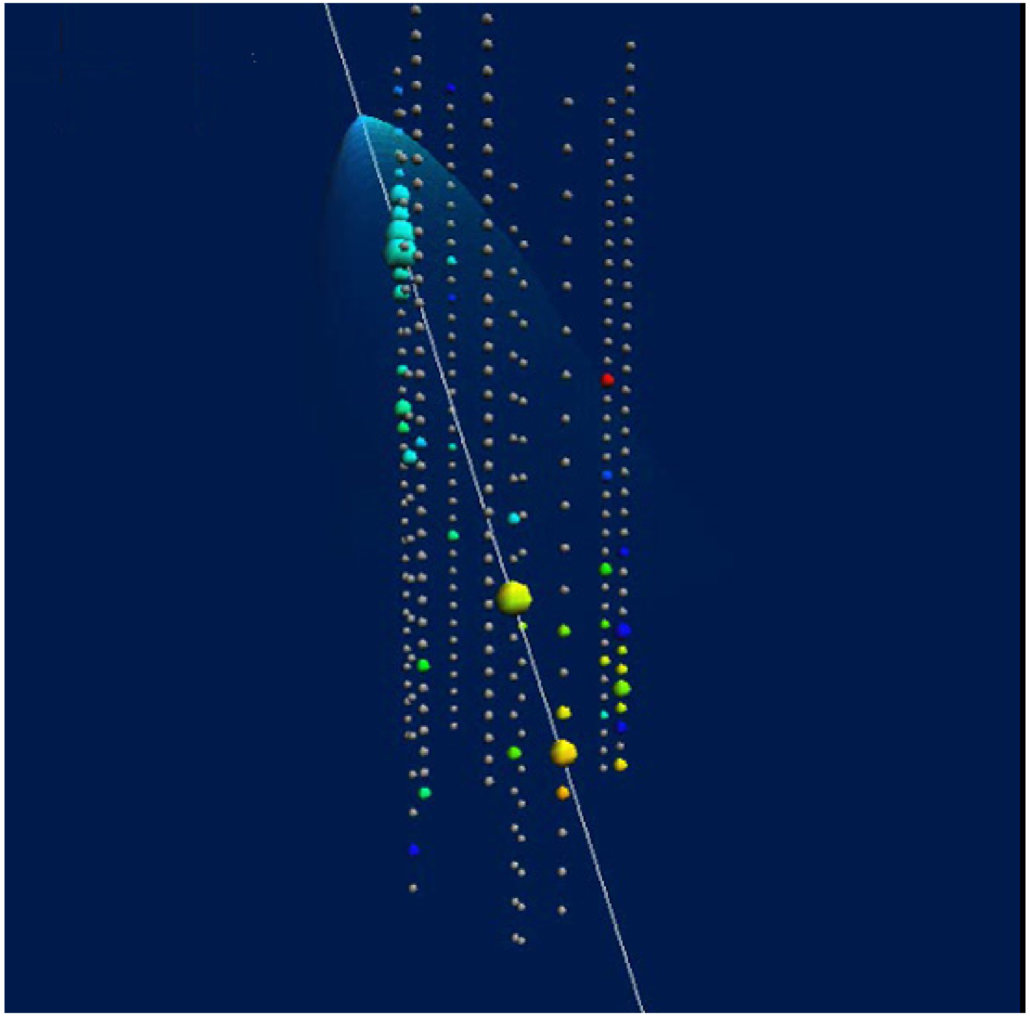
The IceCube Neutrino Observatory at the South Pole



86 strings, 5160 optical sensors, instrumented volume $\sim 1\ \mathrm{km}^3$

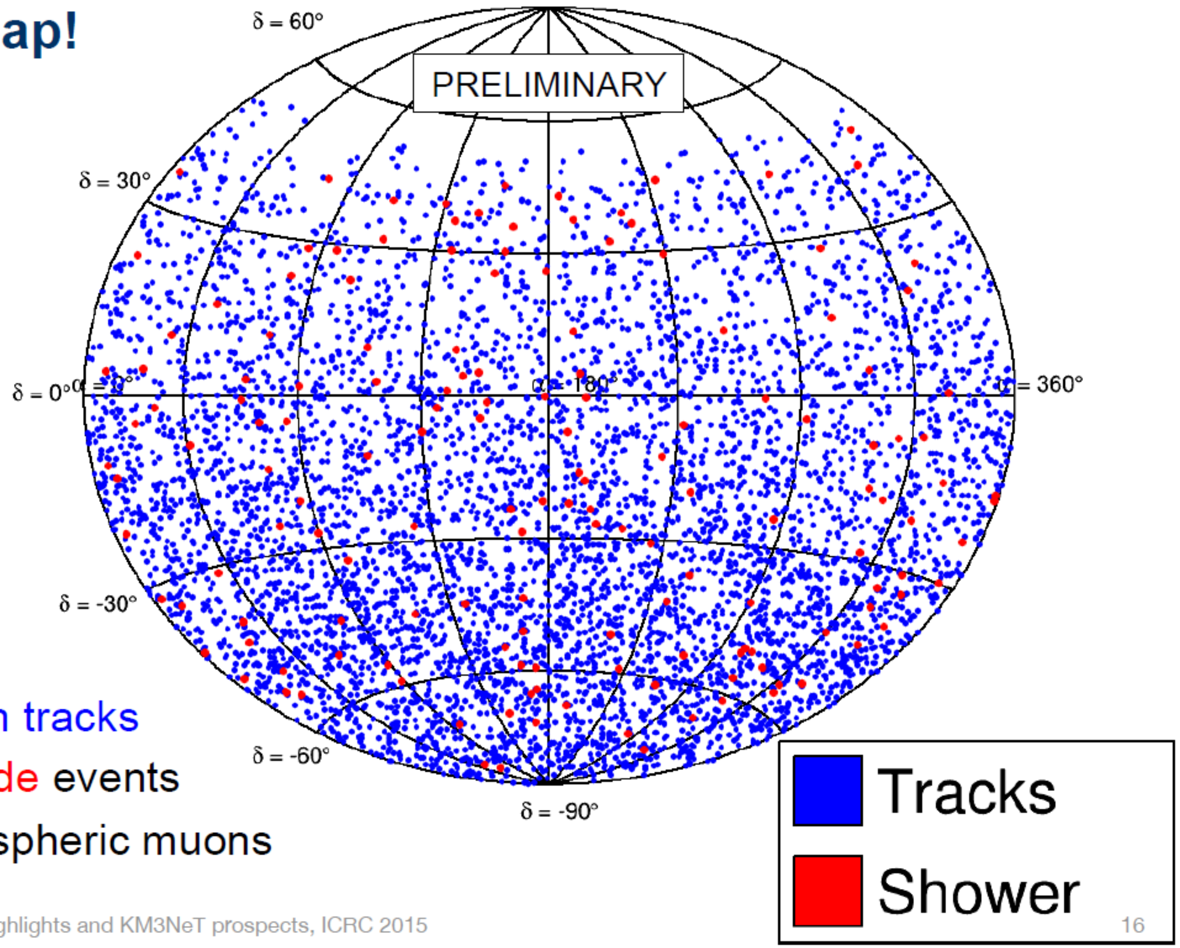
The detection principle





Antares 5-years skymap (C. James, ICRC2015)

New skymap!

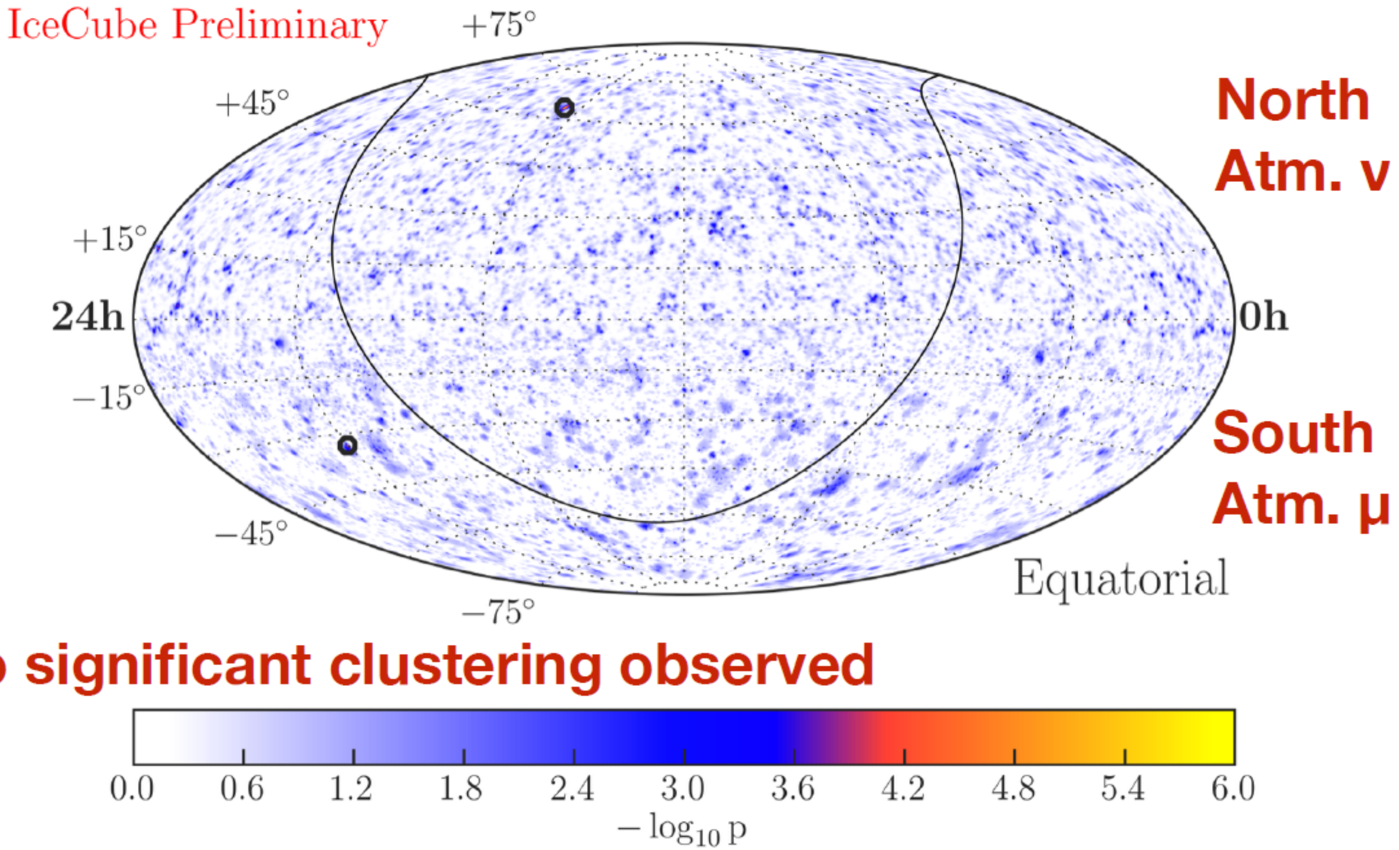


- 6261 muon tracks
- 156 cascade events
- 10% atmospheric muons

C.W. James, ANTARES highlights and KM3NeT prospects, ICRC 2015 16

No significant clustering found

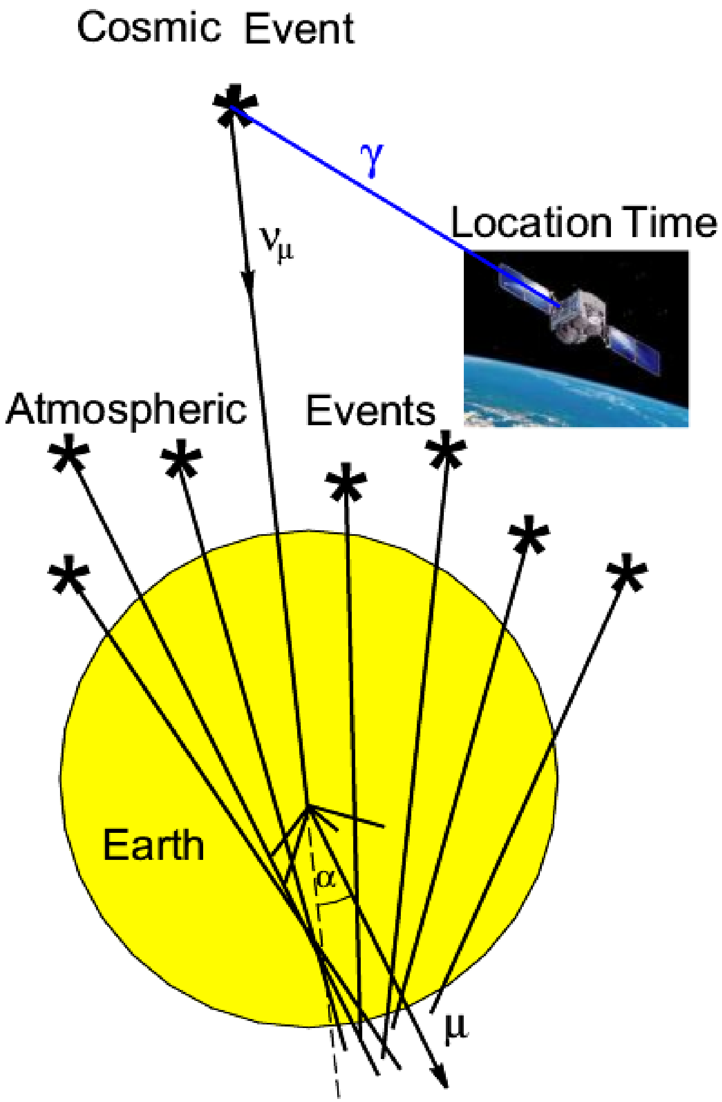
IceCube 6-years skymap (∼600'000 events) (S. Coenders, ICRC2015)



Hot spot North : $\alpha =$ **16h 38m 24s** $\delta = 63.6°$ **P-value** $= 1.78 \cdot 10^{-6}$

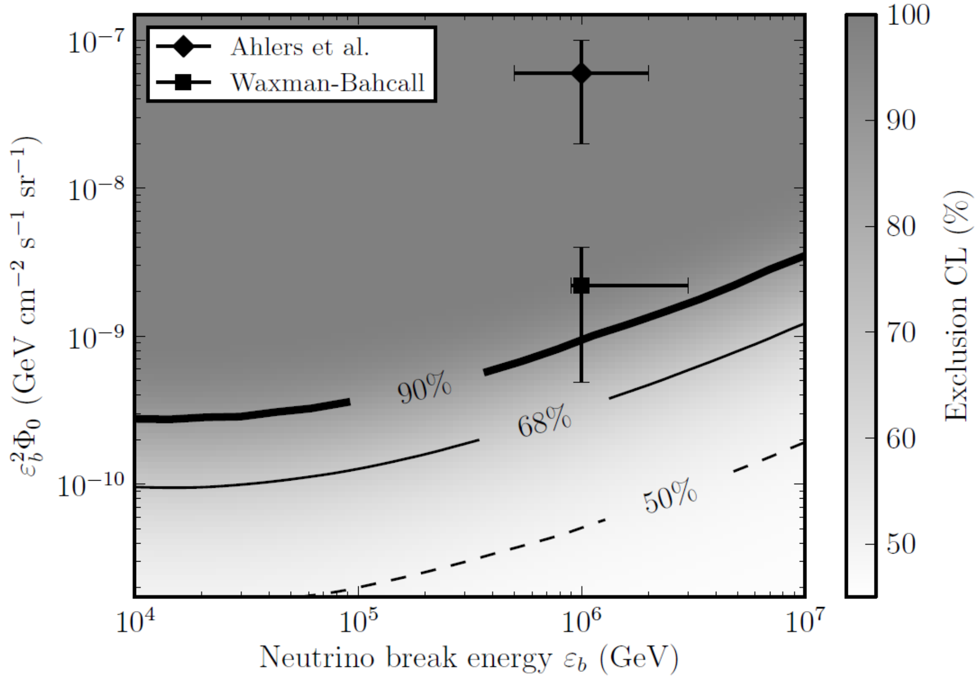
Hot spot South : $\alpha =$ **20h 01m 36s** $\delta = -33.2°$ **P-value** $= 1.82 \cdot 10^{-5}$

Randomised α **data sets** $\rightarrow$ **post-trial P-values : 0.35 (North) and 0.87 (South)**



IceCube GRB prompt ν flux limit

(ApJ Let. 805 (2015) L5)



GRBs not the (only) UHECR sources

Or : ν prod. lower than expected

Or : ν prod. outside prompt phase

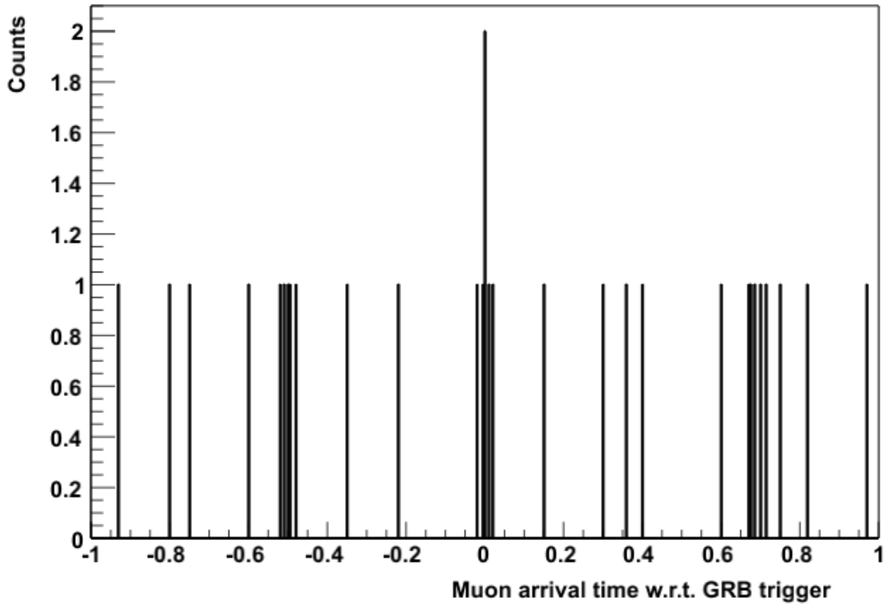
IceCube search for GRB ν's outside prompt phase (M. Casier et al. ICRC2015)

- Fixed time window around each GRB

  Record μ arrival times

  Stack the GRB time windows

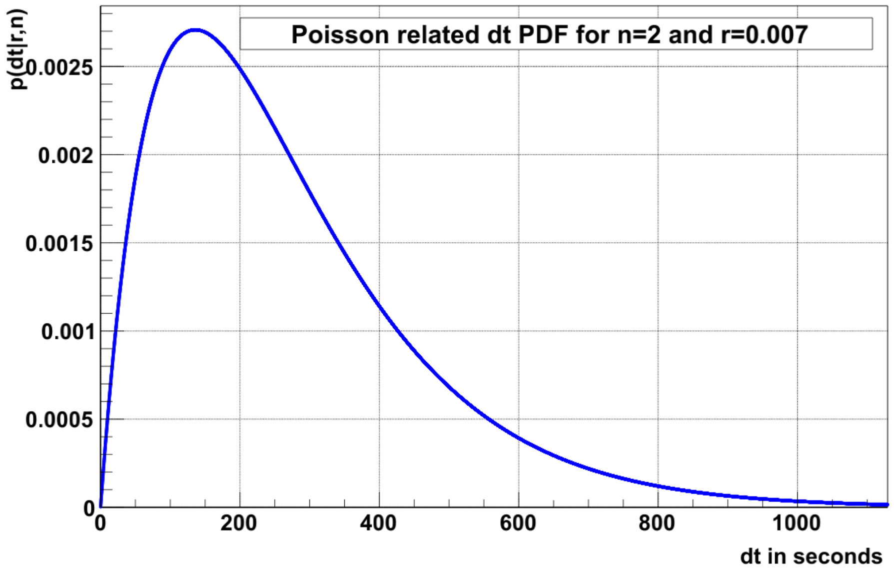
Example plot



Study μ arrival time profile

- Bkg : $p(n|r,dt)$ =Poisson pdf

  $\rightarrow$ Bkg : $p(dt|r,n)$ =Erlang pdf



Promising for short (< 2 sec.) GRBs

Long GRBs : Core collapse

Short GRBs : Mergers (NS-NS/BH)

Diffuse Neutrino Flux

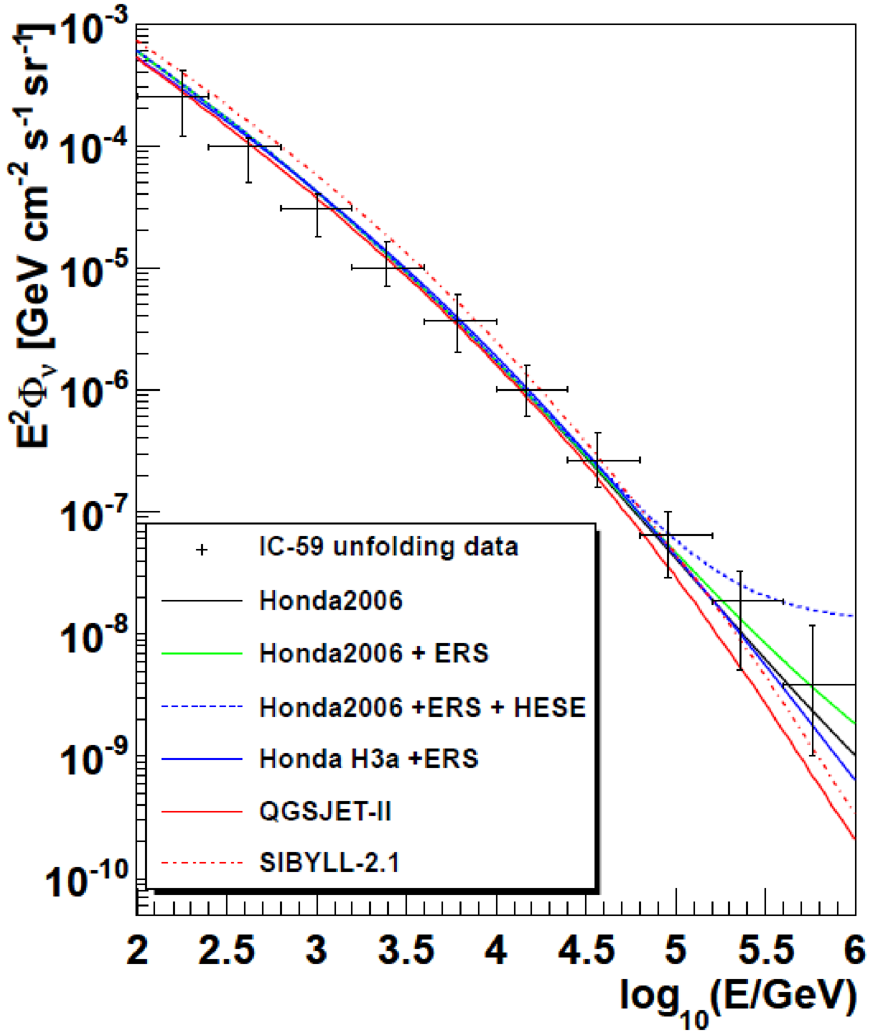
- Many point sources : diffuse ν flux
  Expected flux $\sim E^{-2}$
  (Fermi shock acceleration)
  Observed in TeV photons
- CR primaries : flux $\sim E^{-2.7}$
  $\longrightarrow$ Calculate atm. ν E-spectrum
- ν det. observe atm. ν spectrum
  Validate calculated spectrum

∗ PDF for atm. ν E-spectrum

- Very high E : Nearly atm. bkg free
  0.1 atm. ν km^{-3} year^{-1} at 1 PeV
  VHE events might prove cosmic ν

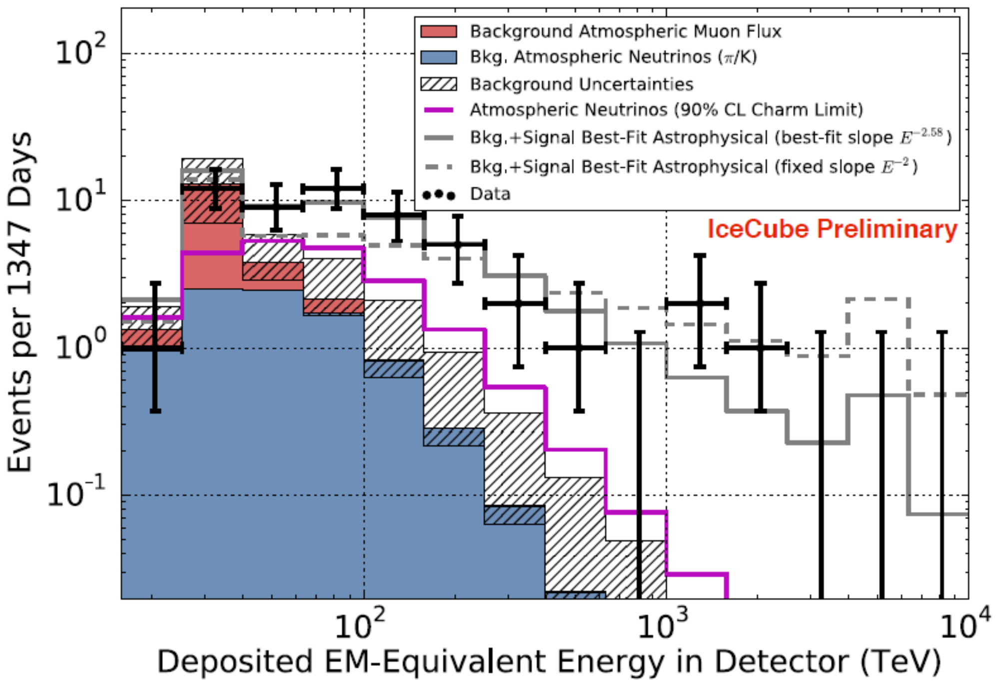
IceCube atmospheric ν spectrum

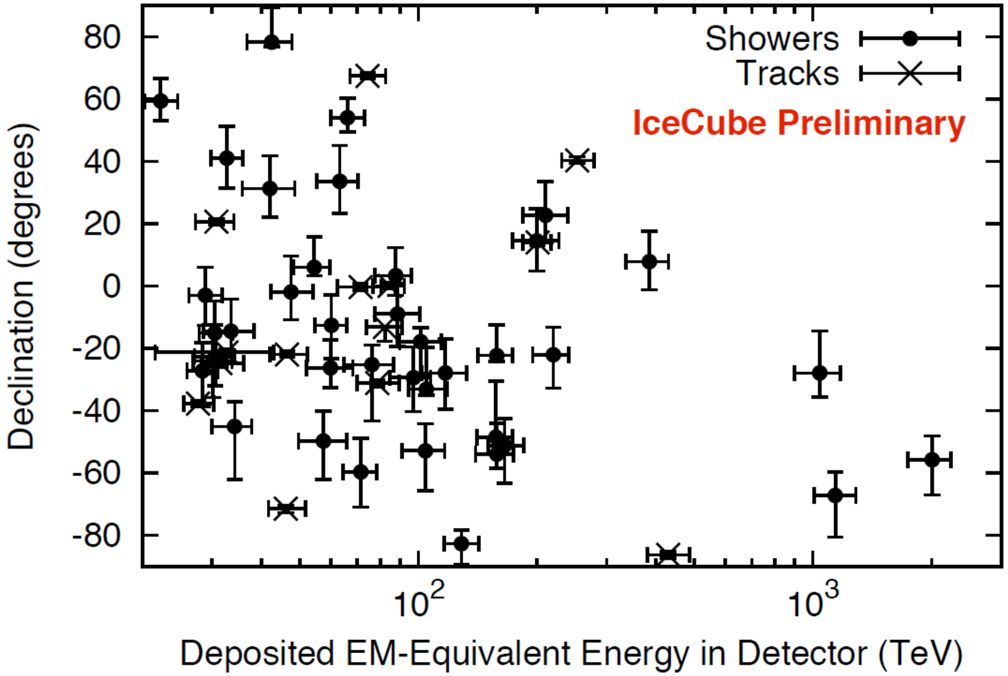
(Eur. Phys. J. C75 (2015) 116)



IceCube observed 54 High-Energy Starting Events (HESE) (C. Kopper, ICRC2015)

39 Showers 15 Tracks



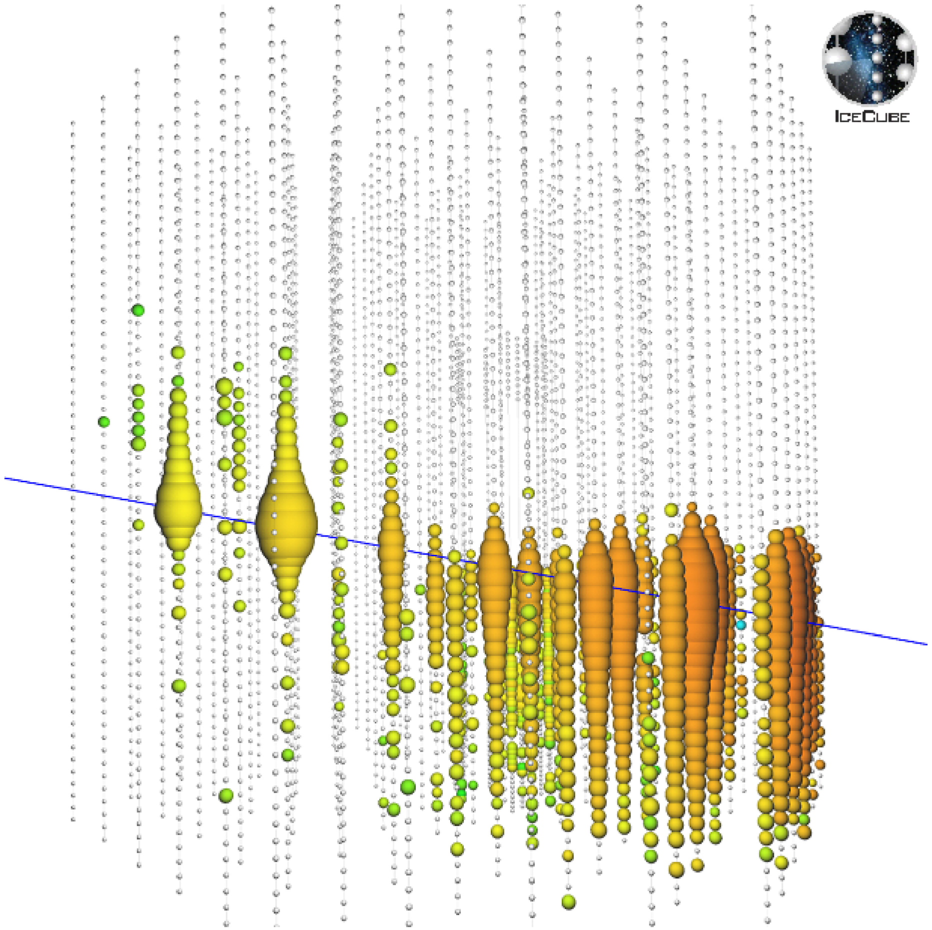


Evidence (6.5σ) for cosmic high-energy neutrinos

Energy spectrum not a single power law ?
Where are the multi-PeV events ?

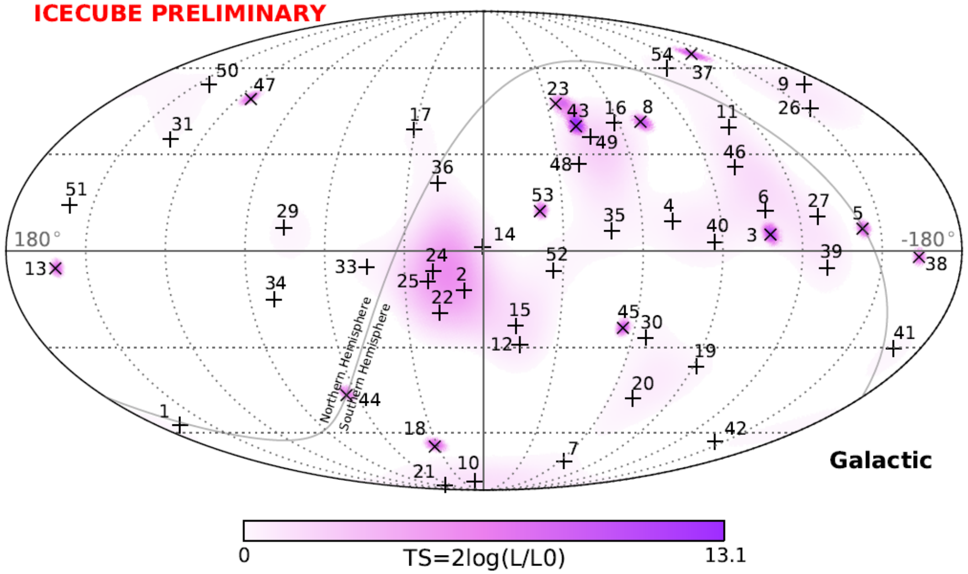
Recent IceCube observation of a very energetic through-going muon

α : 7h 21m 22s $\quad \delta$: 11.5° (L. Rädel, ICRC2015)



Deposited energy 2.6 ± 0.3 PeV $\rightarrow E_\mu = 4 - 5$ PeV $\rightarrow E_\nu > 5$ PeV

Source directions of the HESE events



No evidence for point source(s)

- Need more statistics
- Better resolution on showers helps

  Lower E tracks in the North ?

Antares follow up study (A&A 576 (2015) L8)

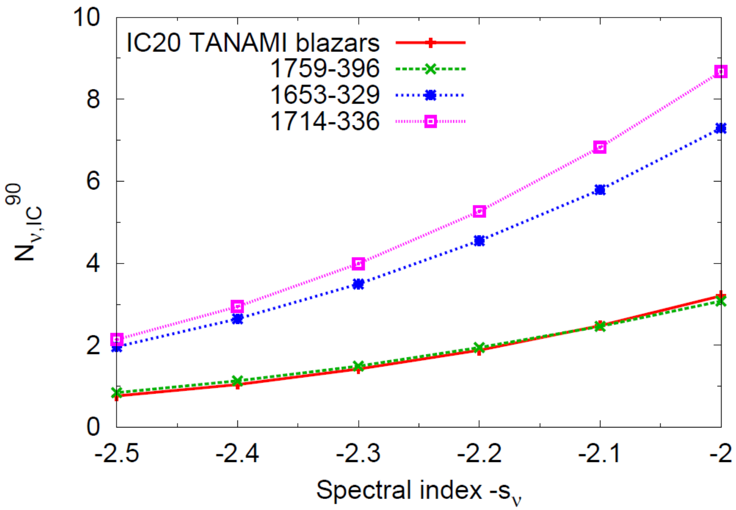
- TANAMI : Blazars 3@IC14 3@IC20
- Antares performed a track analysis

∗ No events observed at IC20

∗ 2 events at IC14 (from 2 Blazars)

Compatible with bkg → set limits

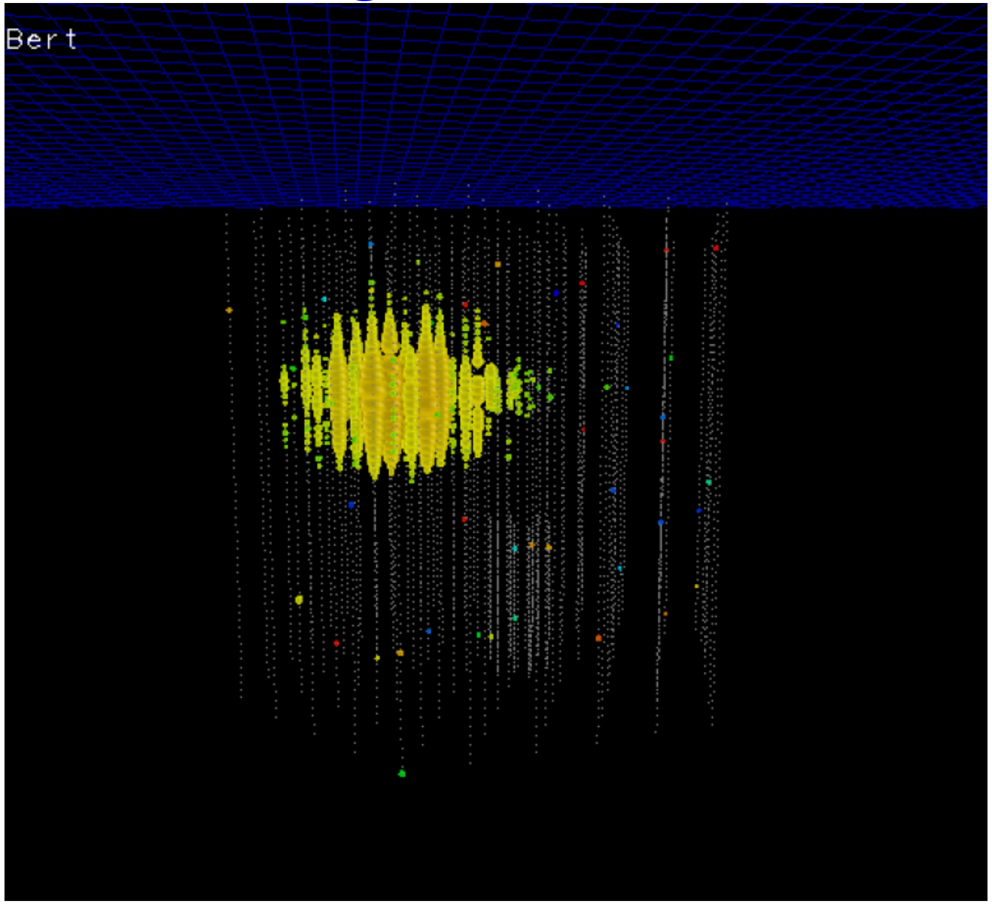
Max. # of IC events per Blazar



No (dis)proof of Blazar origin

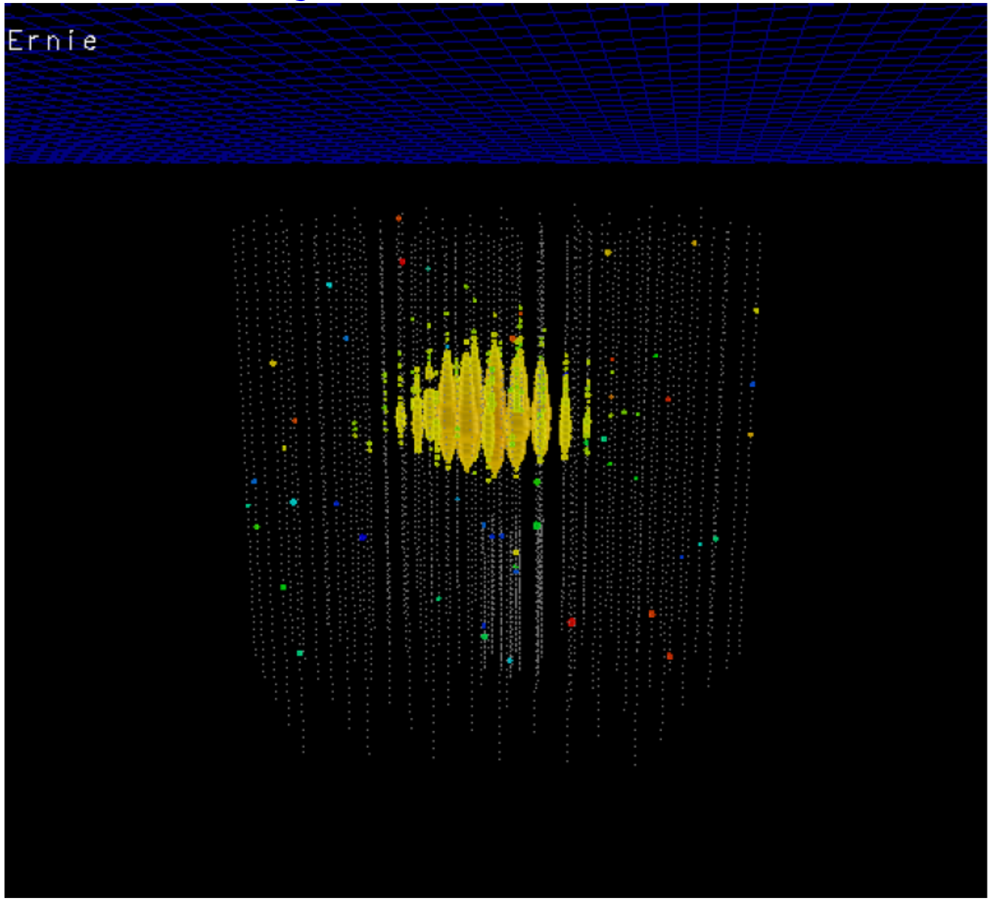
Diffuse Neutrino Flux

Tue 09-aug-2011 07:23:18 UTC



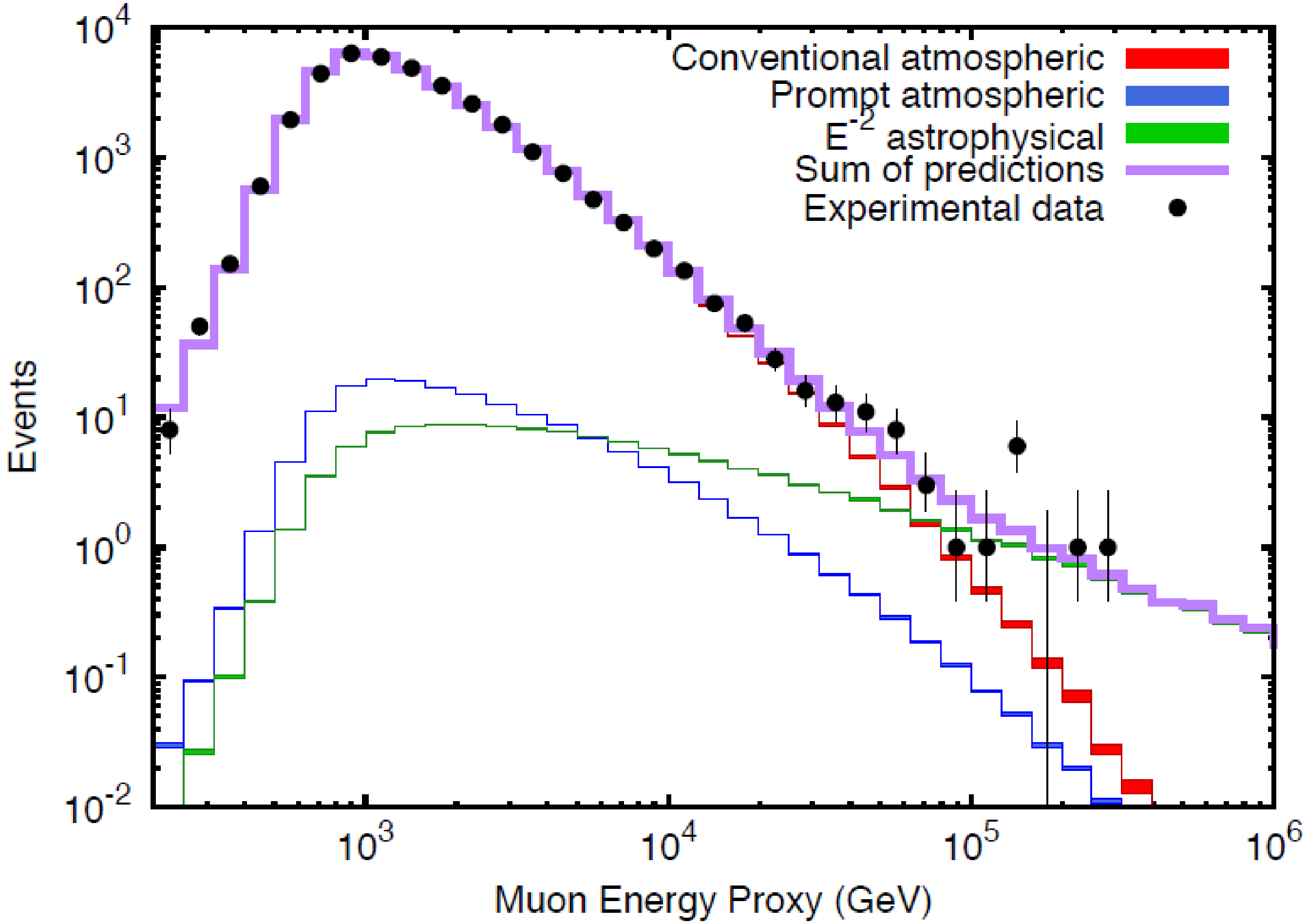
1.04 ± 0.14 PeV
(IceCube HESE event no. 14)

Tue 03-jan-2012 03:34:01 UTC



1.14 ± 0.14 PeV
(IceCube HESE event no. 20)

IceCube Northern (=upgoing) diffuse μ analysis (arXiv:1507.04005)



Evidence ($\sim 4\sigma$) for an astrophysical component

Search for $\nu-$UHECR correlations (G. Golup, ICRC2015)

- IceCube-Auger-TA combined effort
- Cross correlation analysis

  IceCube cosmic ν candidates (39 cascades, 16 tracks)

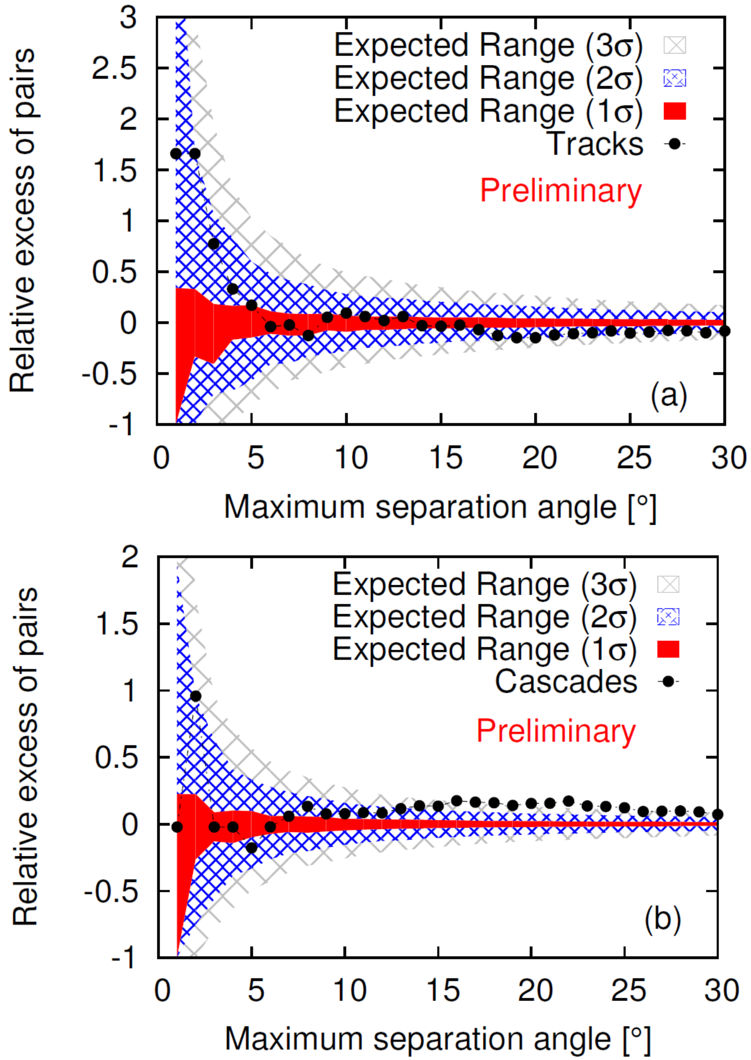
  10 years of Auger data (231 UHECR)

  6 years of TA data (87 UHECR)
- Neutrinos $\equiv$ source directions
- Ang. separation of $\nu-$UHECR pairs
- Look for excess w.r.t. isotropic distr.

  $[N_{pair}(\alpha)/ < N_{pair}^{iso}(\alpha) >] - 1$
- Most significant deviations

  Tracks : 2° P-value=0.34

  Cascades : 22° P-value=$5 \cdot 10^{-4}$



Outlook

- Neutrino telescopes are providing high quality data
- IceCube has started to yield ground breaking results

  We have witnessed the birth of Neutrino Astronomy

  High-energy cosmic neutrinos observed for the first time in history

  No sources could be identified yet
- Observations guide us towards detector upgrades

  Clear advantage to have complementary detectors at both hemispheres

  More cosmic neutrino data needed $\rightarrow$ Larger detector volume
  - Extension of IceCube ($\sim 10\ \mathrm{km}^3$) foreseen (IceCube-Gen2)
  - Gigaton Volume Detector ($\sim 1.5\ \mathrm{km}^3$) under construction in Lake Baikal
  - KM3Net planned in the Mediterranean ($\sim 1\ \mathrm{km}^3$)
- Going to the highest energies $\rightarrow$ GZK neutrinos

  Proof to establish the GZK effect or "just" max. E of cosmic accelerators

  Extremely low flux $\rightarrow$ New techniques needed (Radio detection)

Radio detection in ice

- **Long (∼1 km) attenuation length**

  Cover large (>100 km^2) area

- **Detect events $> 10^{17}$ eV**

  Askaryan Radio Array (ARA)
  (South Pole, next to IceCube)

  Arianna detector (Ross Ice Shelf)

- **GZK ν : Proof of GZK effect**

  or : Insight in UHECR composition

- **Radar reflections from shower plasma**

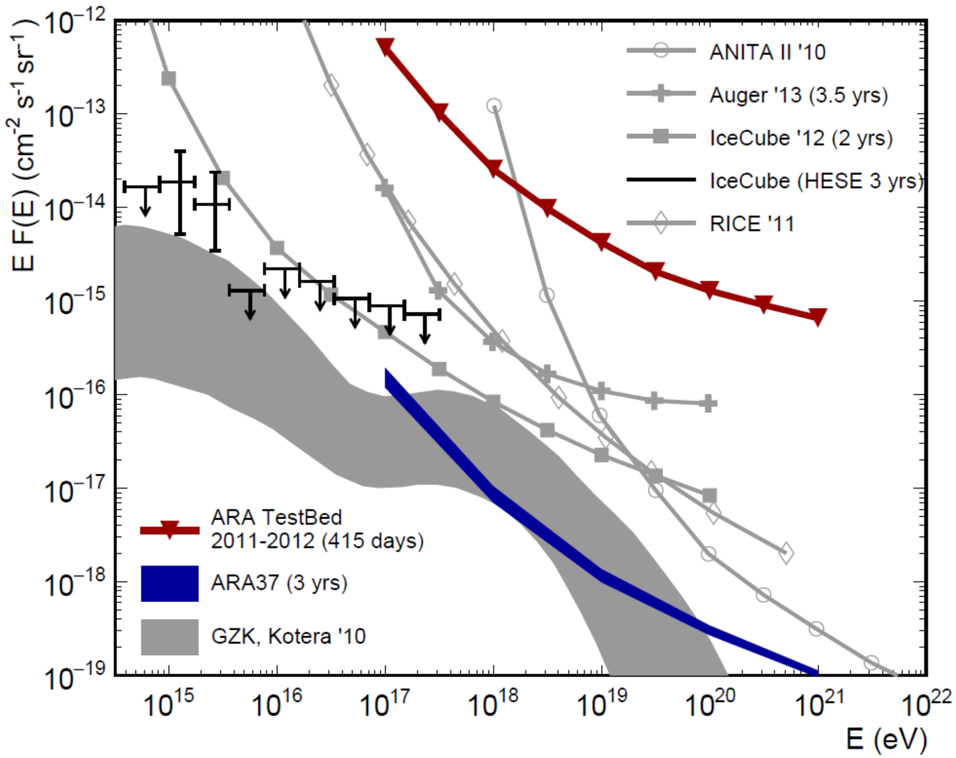
∗ **This is a new idea**

  Works also at energies below 10^{17} eV

  Fill E gap between IceCube and ARA

The GZK neutrino landscape

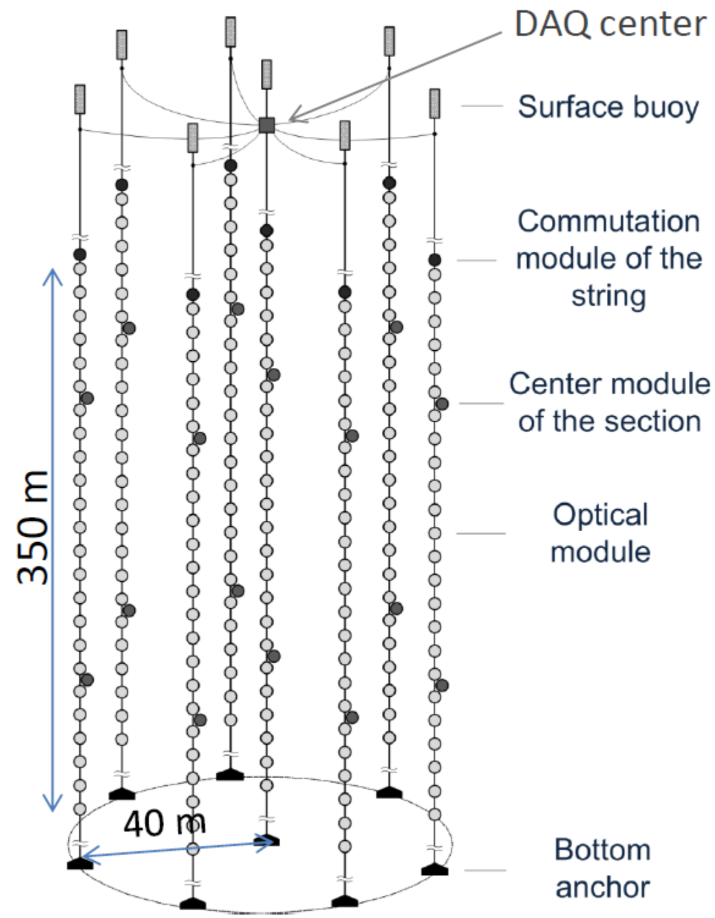
arXiv:1412.5106



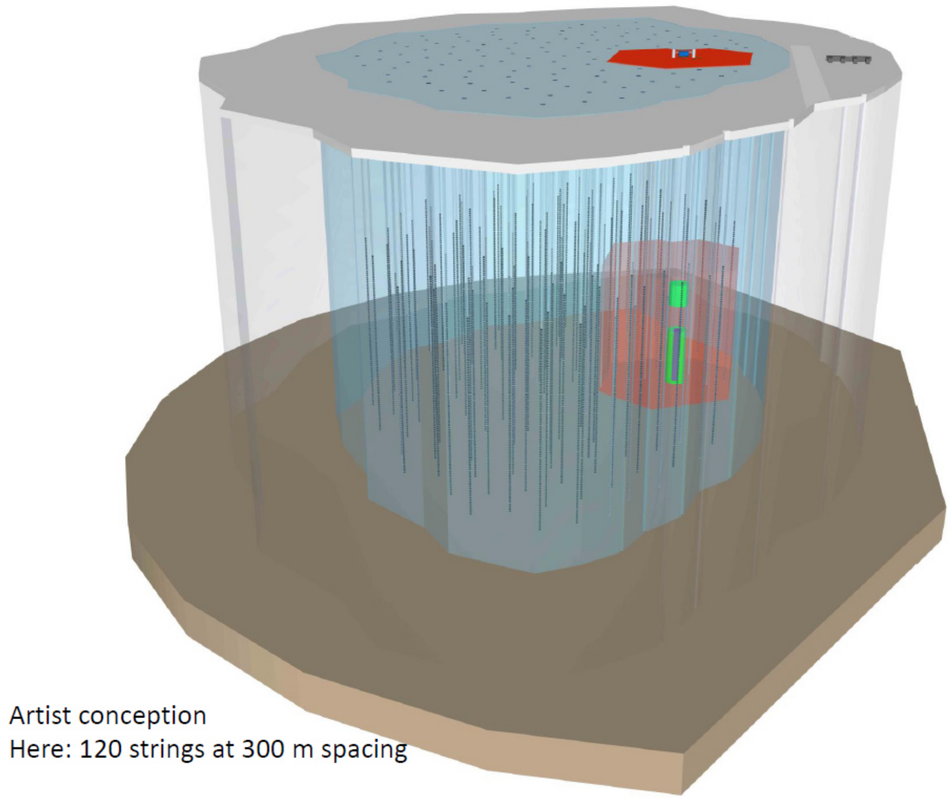
The ∼20 cluster Gigaton Volume Detector (GVD) in Lake Baikal (S. Bair, ICRC2015)

The first cluster is completed in April 2015

- 192 OMs at 8 strings
  - 24 OMs per string with 15 m spacing
  - depth 950 - 1300 m
  - 40 m between strings (60 m projected)
- Cluster DAQ center (30 m below surface)
  - Trigger, power, data transfer systems of the cluster
- Electro-optical cable to shore
- Acoustic positioning system (4 beacons on each string)
- Calibration light beacon (LEDs)
  - Interstring time calibration

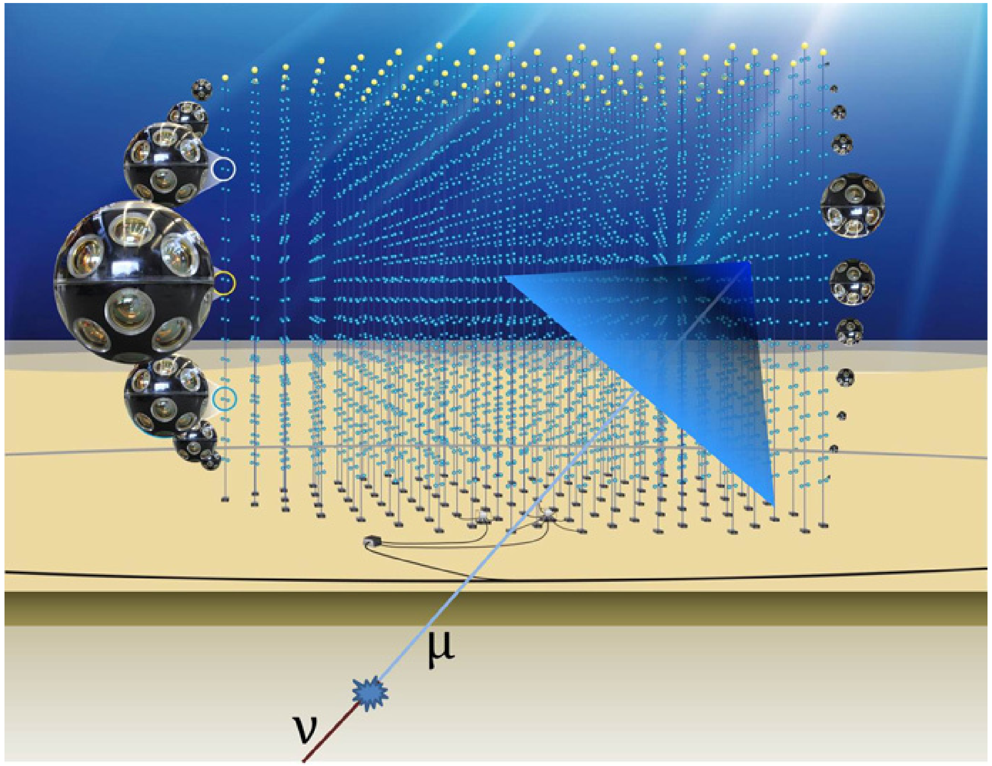


The IceCube-Gen2 detector extension



Also radio components foreseen

The KM3Net project



Multi-PMT optical module concept

Backup slides

IceCube search for a diffuse Very High-Energy (VHE) neutrino flux

- **Use event start veto criteria → remove atm. bkg μ and ν (showers)**
  Guarantees (contained) ν events and allows reduced E cut → 4π