Astroparticle physics with IceCube

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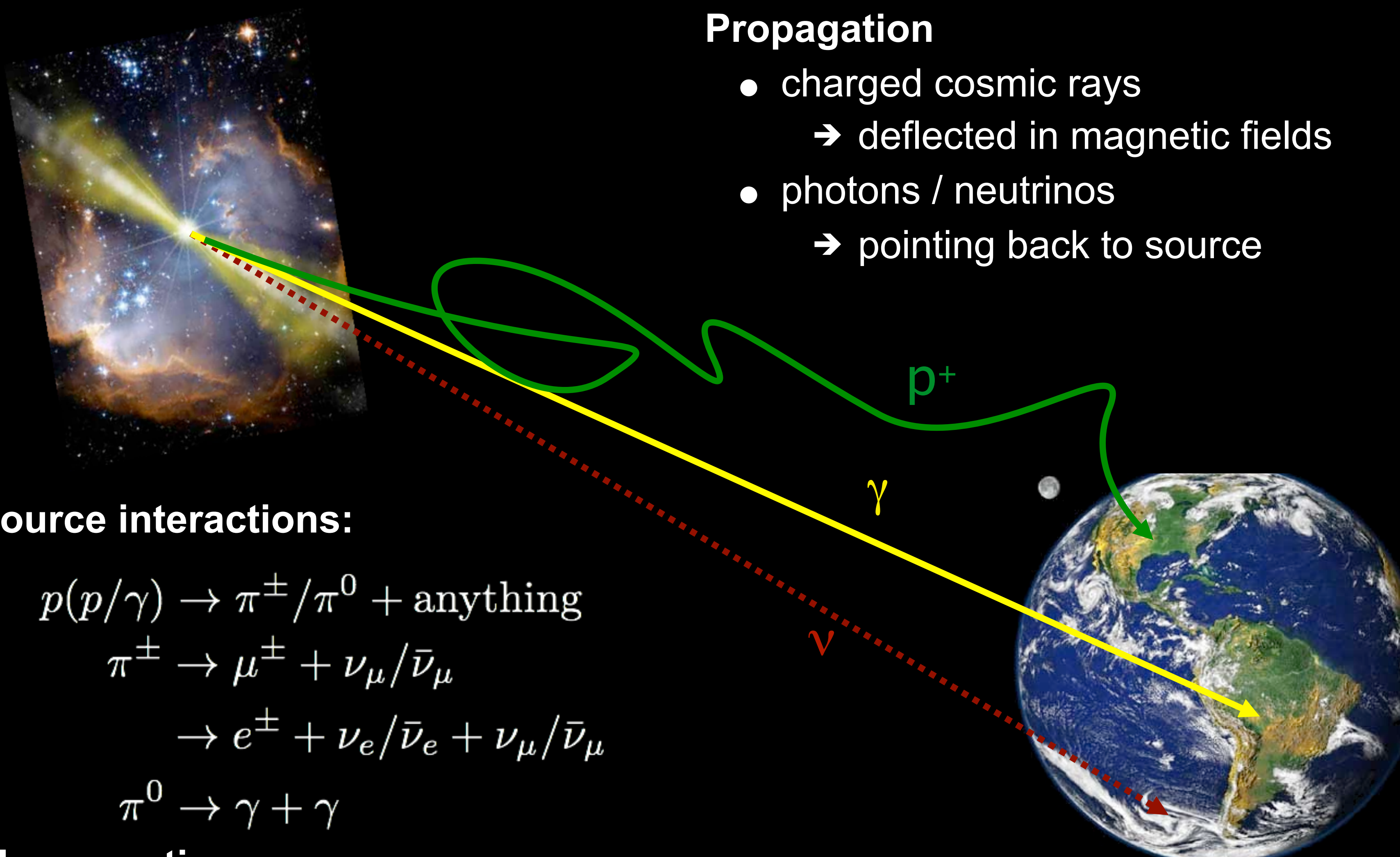
Dresden

7. März 2013

The cosmic ray – gamma – neutrino link



Propagation

- charged cosmic rays
  - ➔ deflected in magnetic fields
- photons / neutrinos
  - ➔ pointing back to source

Source interactions:

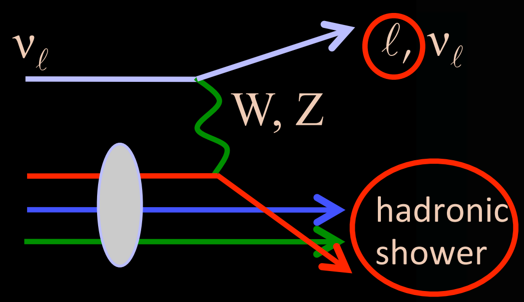
$$
\begin{aligned}
p(p/\gamma) &\rightarrow \pi^{\pm}/\pi^{0} + \text{anything} \\
\pi^{\pm} &\rightarrow \mu^{\pm} + \nu_{\mu}/\bar{\nu}_{\mu} \\
&\rightarrow e^{\pm} + \nu_{e}/\bar{\nu}_{e} + \nu_{\mu}/\bar{\nu}_{\mu} \\
\pi^{0} &\rightarrow \gamma + \gamma
\end{aligned}
$$

Flavour ratio

- 1:2:0 ➔ 1:1:1 smoothed out by oscillations

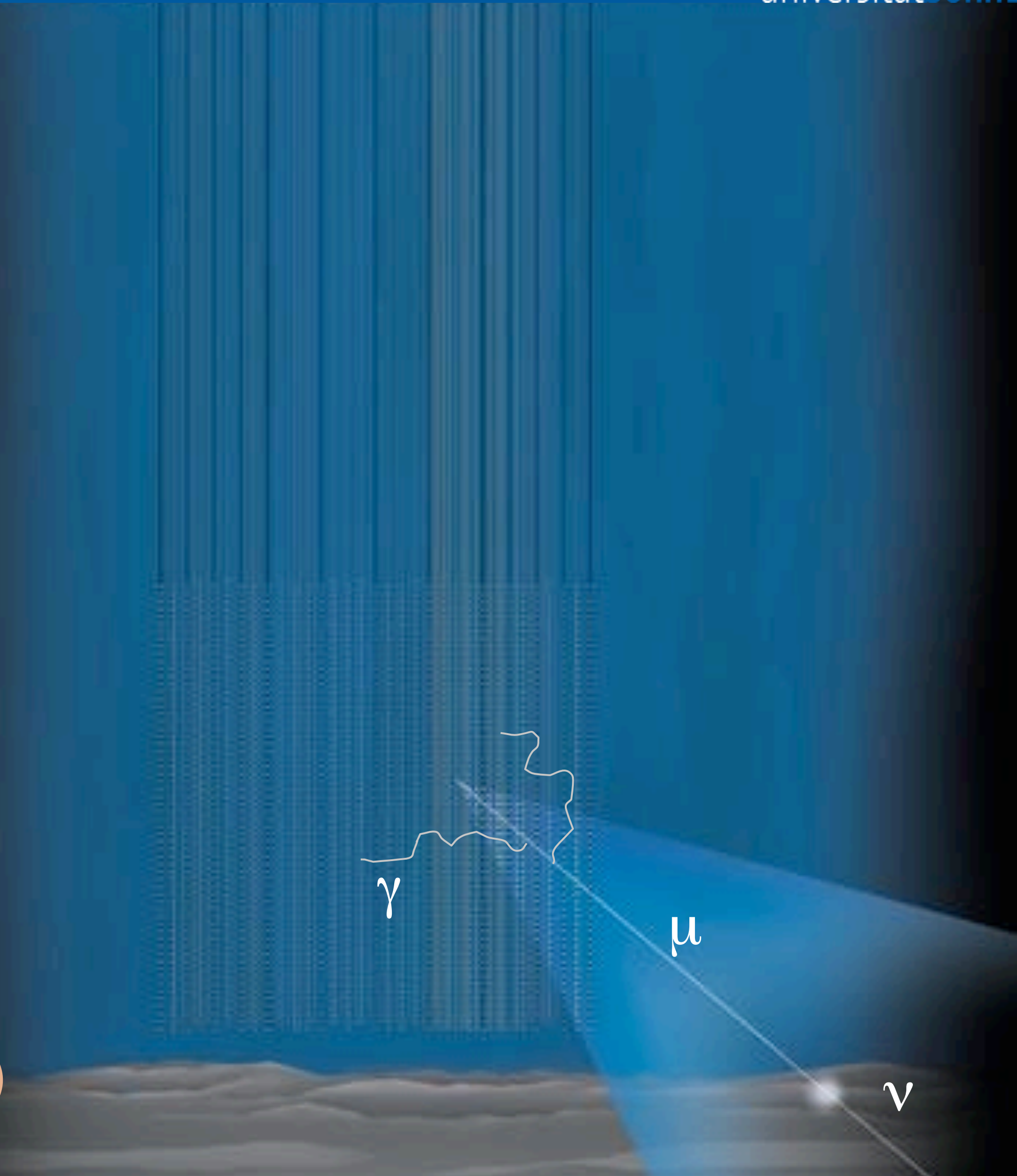
Neutrino detection principle

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

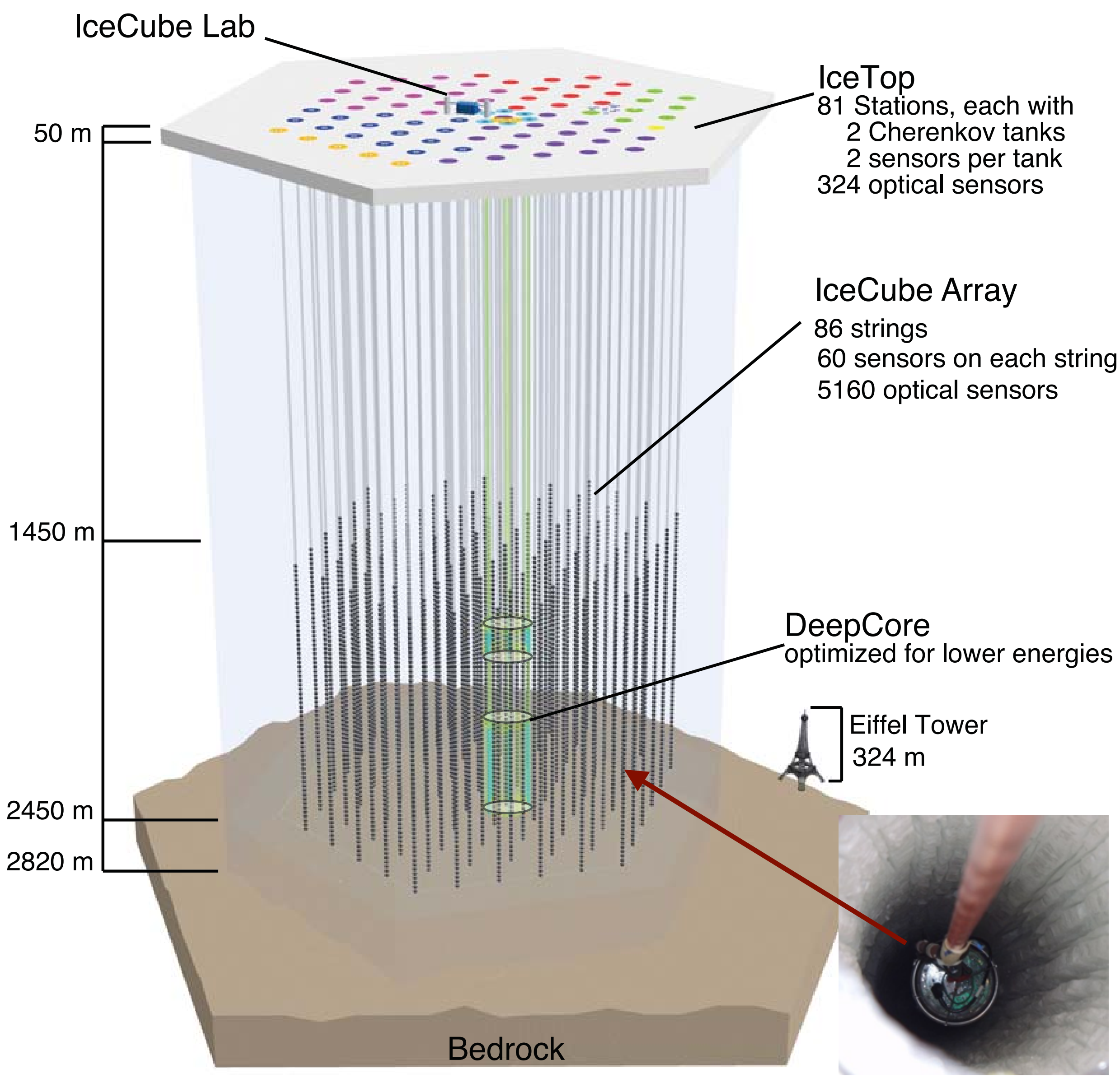


Need a huge volume (km^3) of an optically transparent detector material

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



The IceCube observatory



Deployment

- 04/05 1 string (IC01)
- 05/06 9 strings (IC09)
- 06/07 22 strings (IC22)
- 07/08 40 strings (IC40)
- 08/09 59 strings (IC59)
- 09/10 79 strings (IC59) (including DeepCore)
- 10/11 86 strings (IC86)

Dec, 2010

➔ installation completed

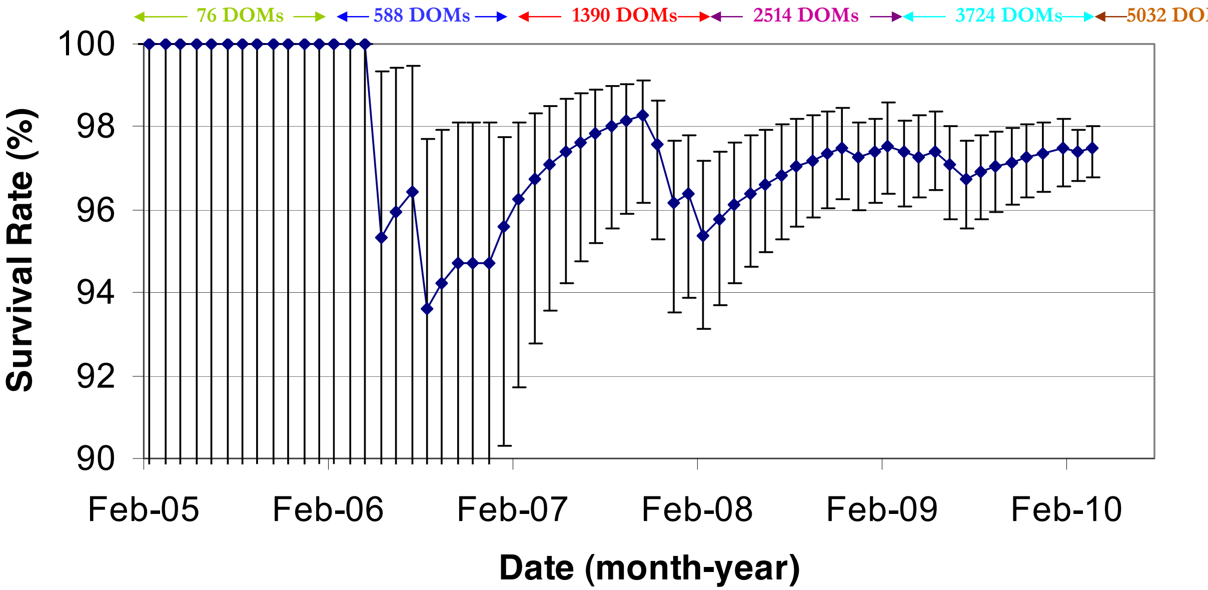
May, 2011

➔ operation of IC86 array

Performance

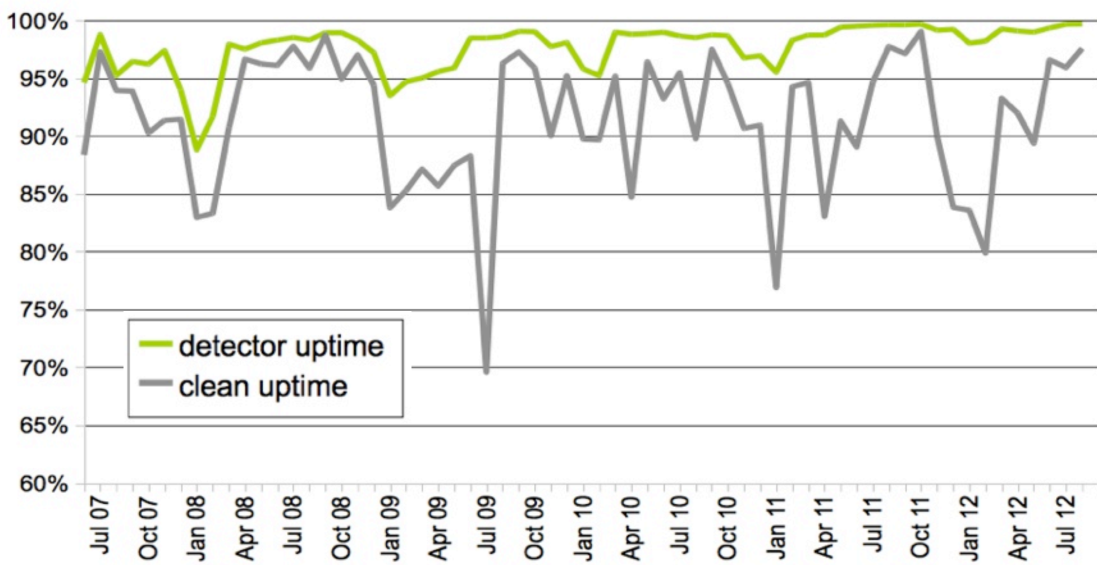
Installation

- 5484 optical modules installed
  - ➔ 128 DOMs failed (during installation)
  - ➔ 50% fixed again
- expected statistical lifetime
  - ➔ 14.000 years



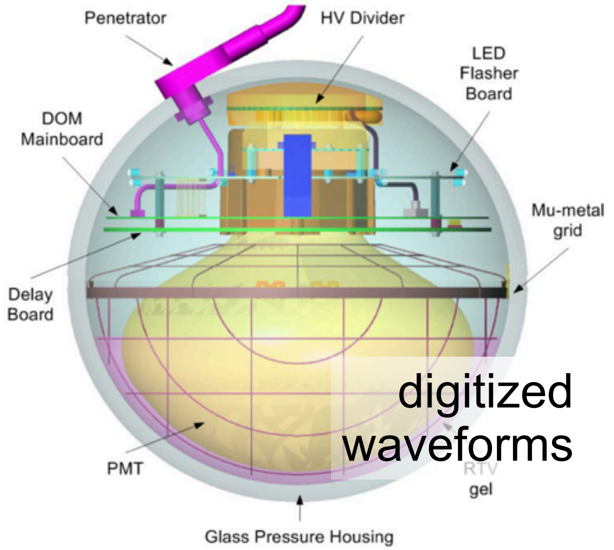
Data-taking

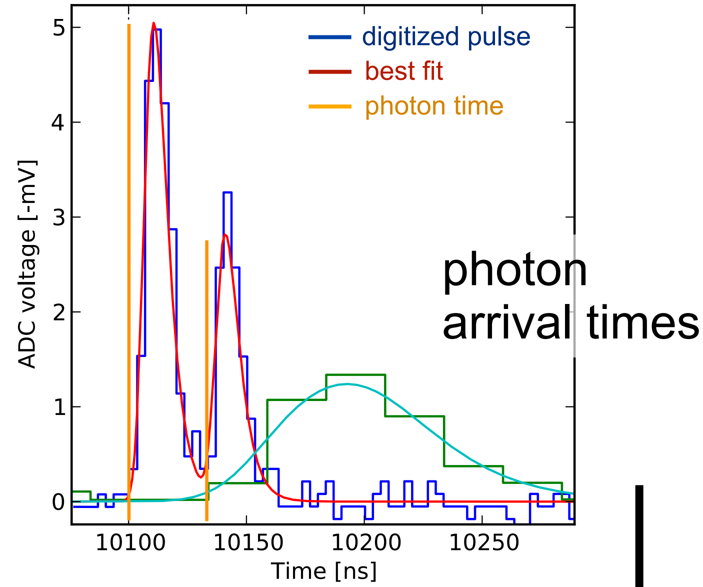
- average detector uptime
  - ➔ 98% over 5 years
- used for data analysis
  - ➔ 91% over 5 years

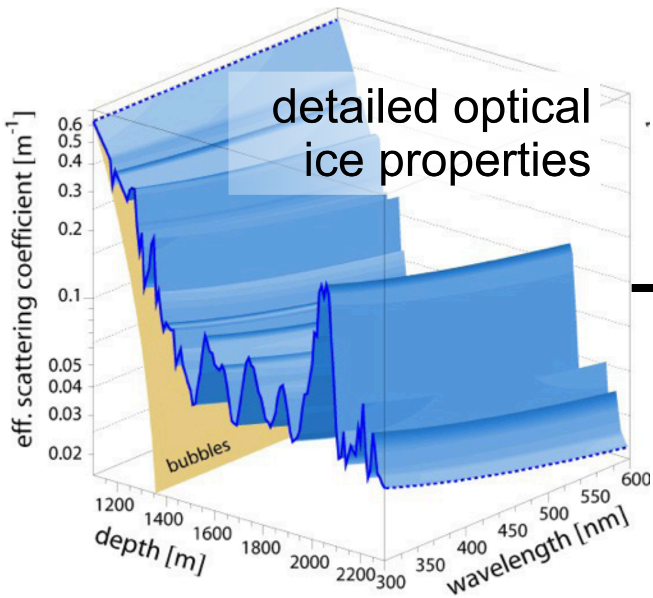


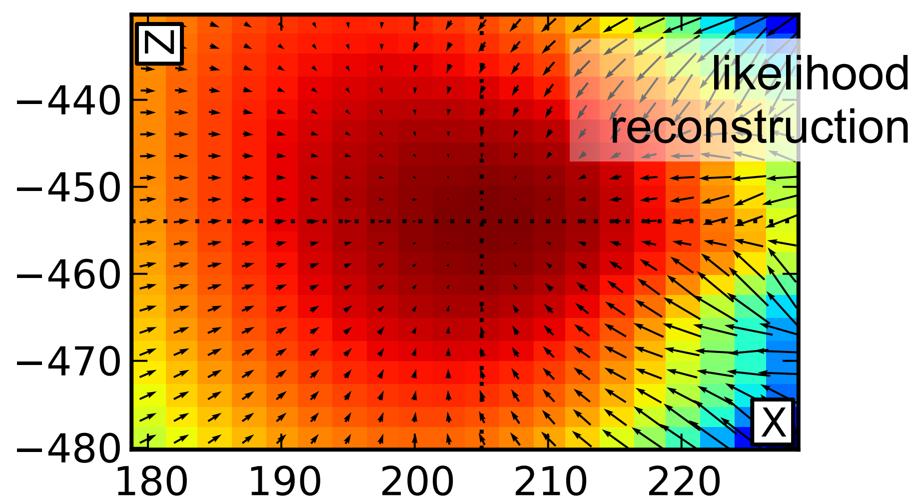
Very stable operation!

Detection method

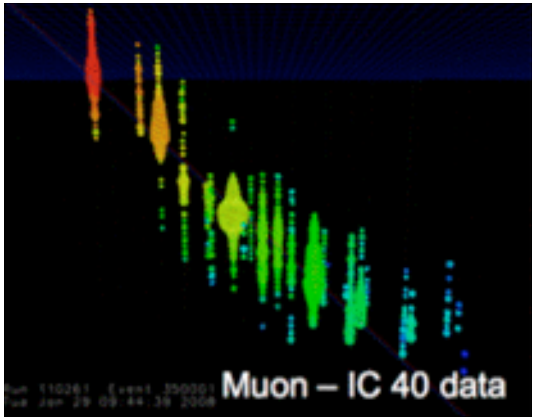








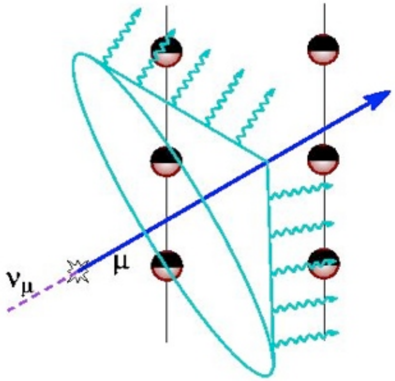
Event signatures

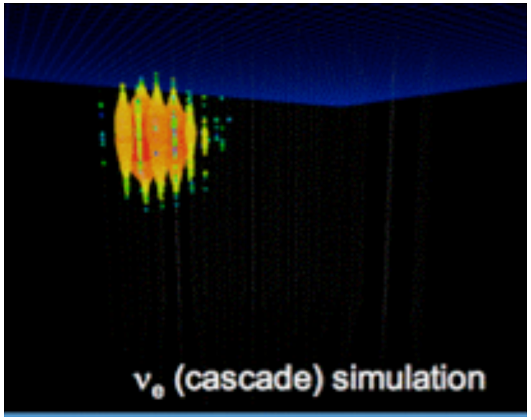


Tracks

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

- pointing resolution
  $\sigma_\Psi \sim 1^\circ$



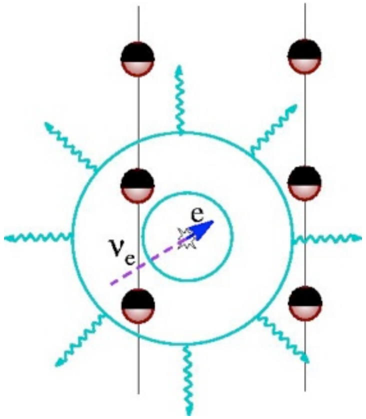


Cascades

$\nu_e + N \rightarrow e + X$

$\nu_f + N \rightarrow \nu_f + X$

- energy resolution
  $\sigma_E \sim 0.1 \log_{10}(E)$

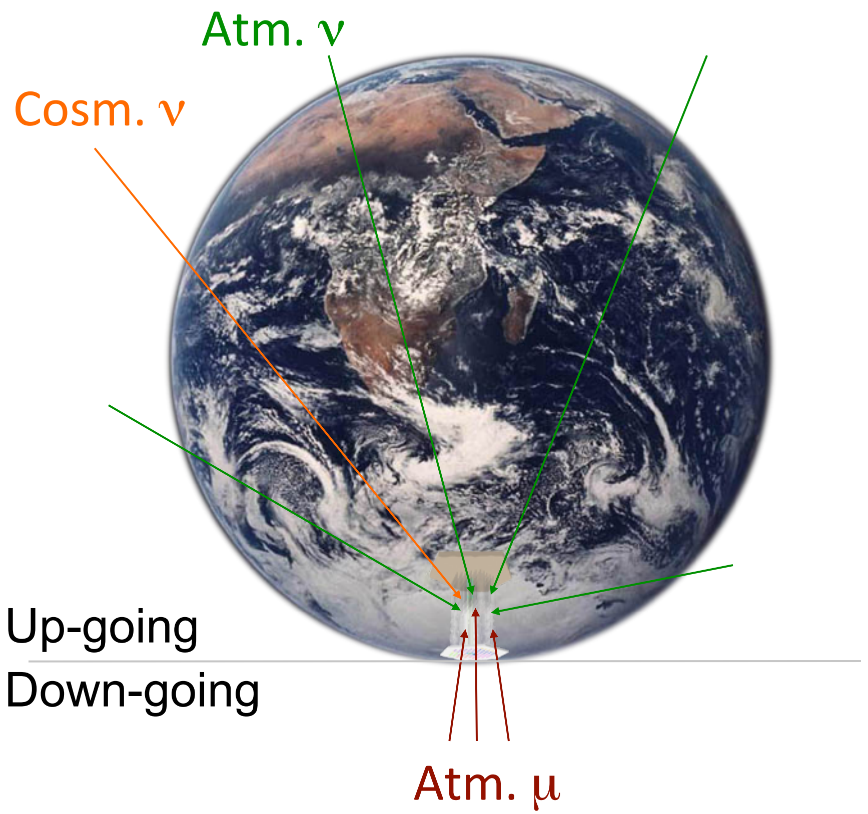


As well as...

- muon bundles (cosmic rays)
- double-bang (ν_τ)
- exotic states (monopoles,…)

not covered in this talk

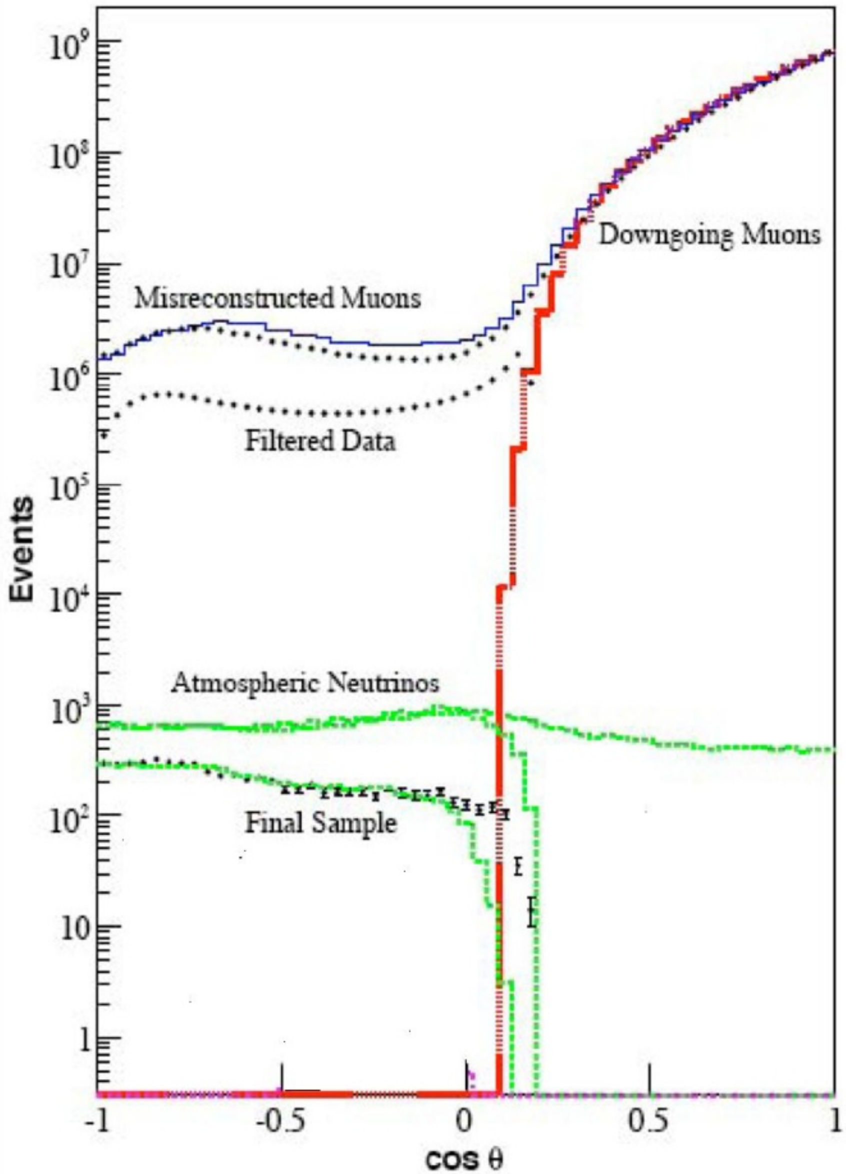
Background



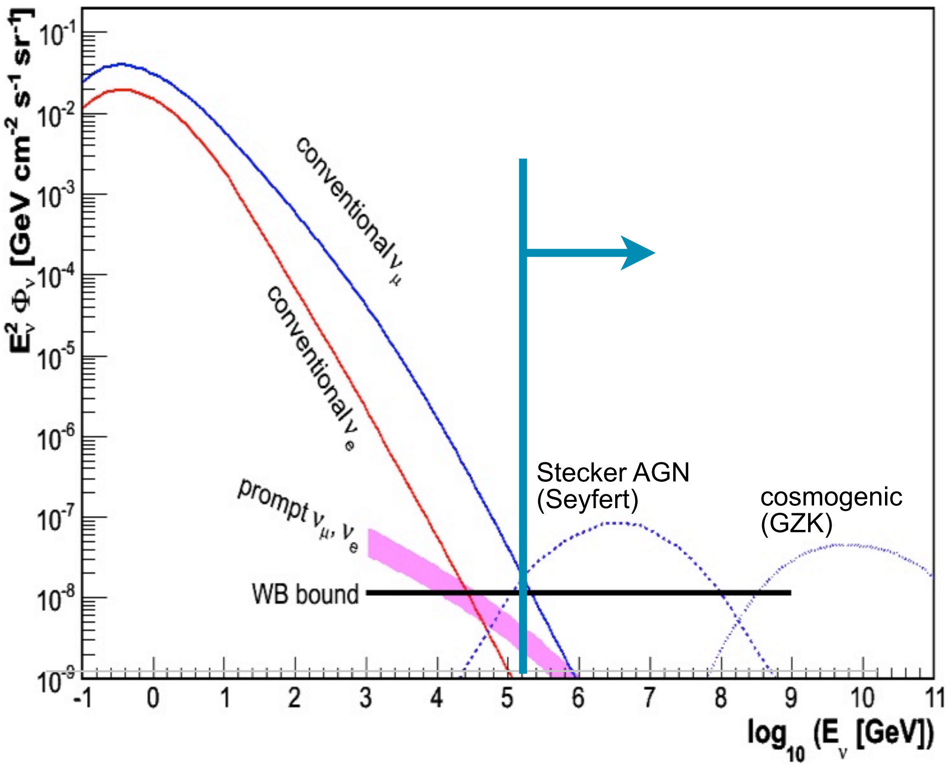
Rates

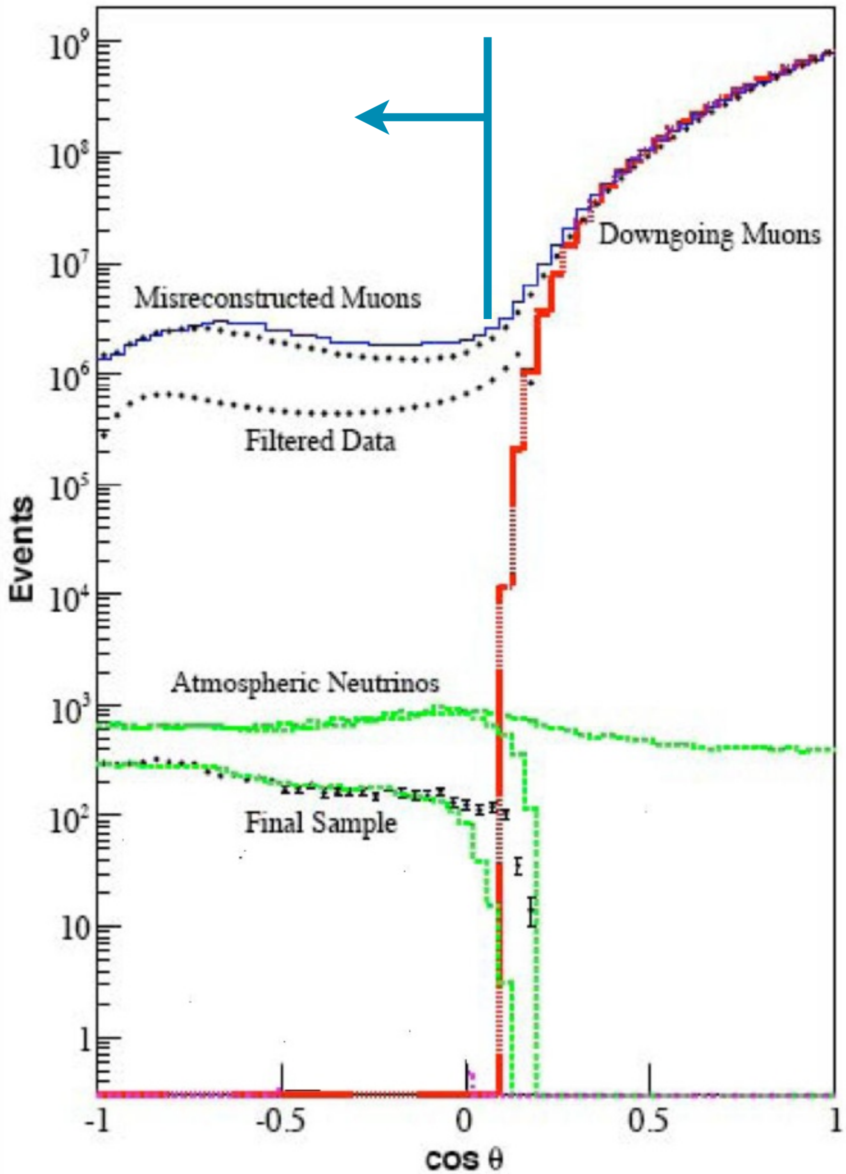
- atm. μ: 2800 per second
- atm. ν: 0.1 per minute

➔ need >10^6 background rejection!



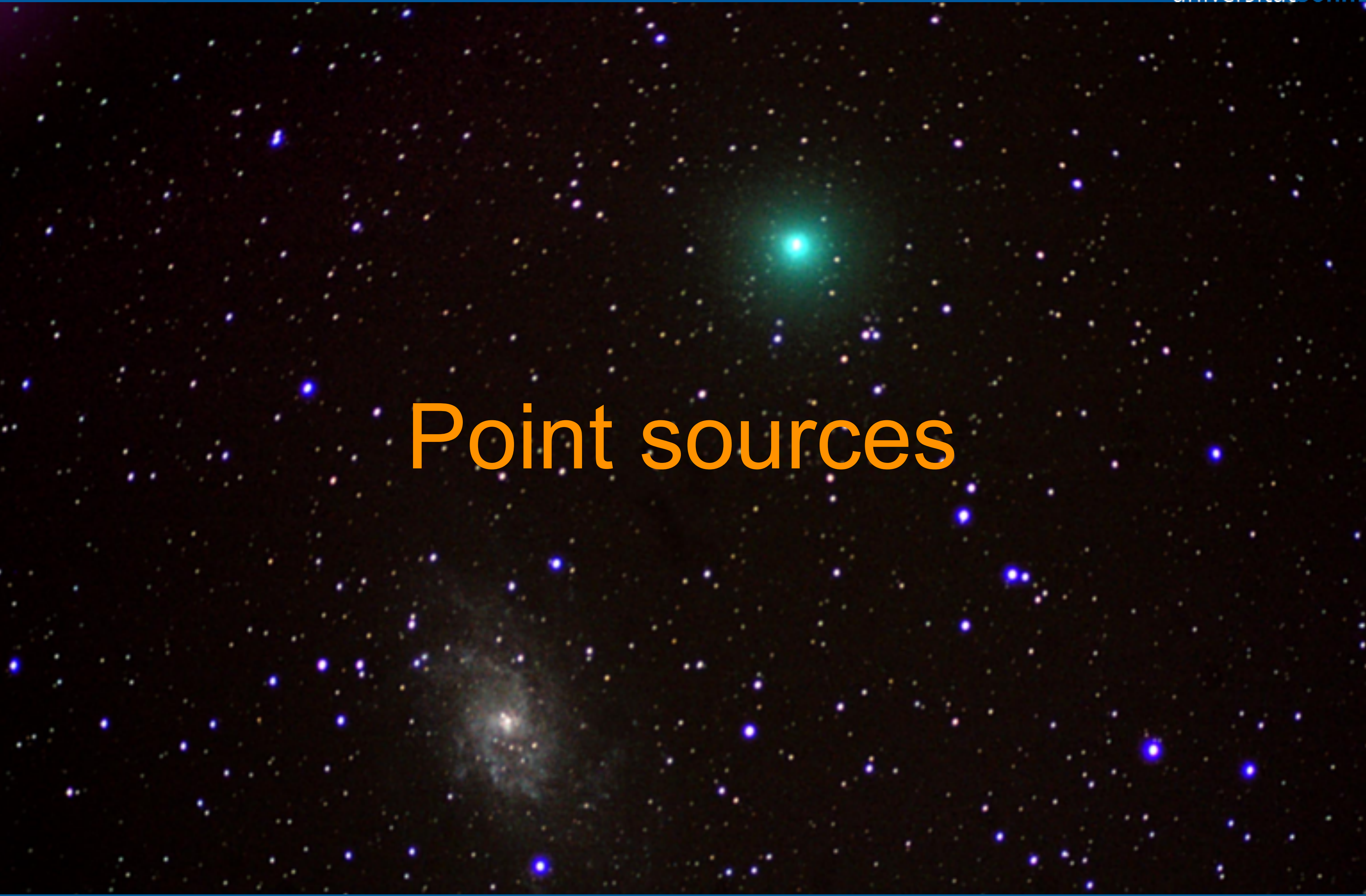
Background



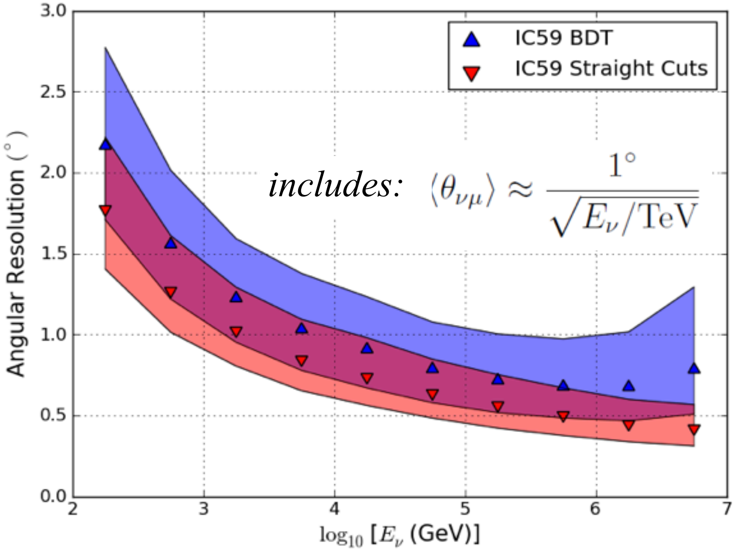


Background rejection

- event direction
  - ➔zenith angle, multiplets
- energy
  - ➔atmospheric fluxes ~ $E^{-2.7}$
- time ➔ multiplets

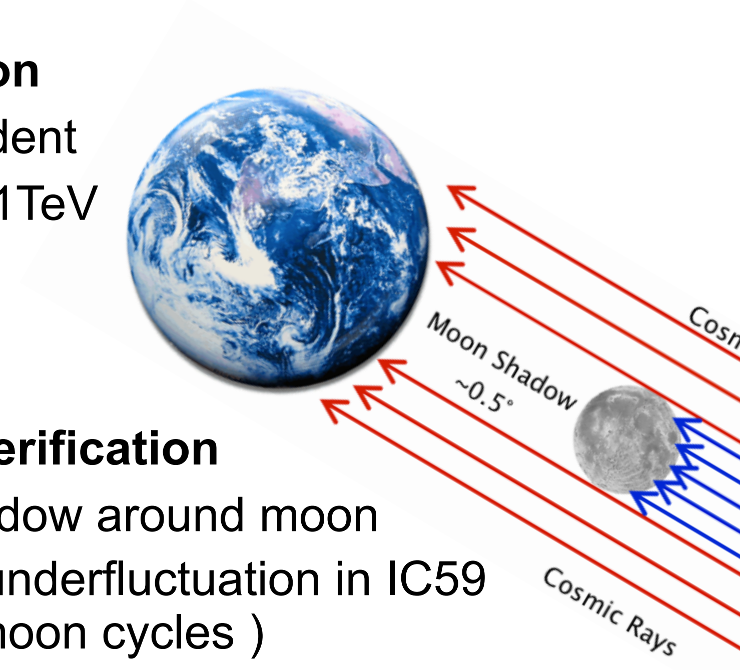

Point sources

ν_μ energy and pointing resolution



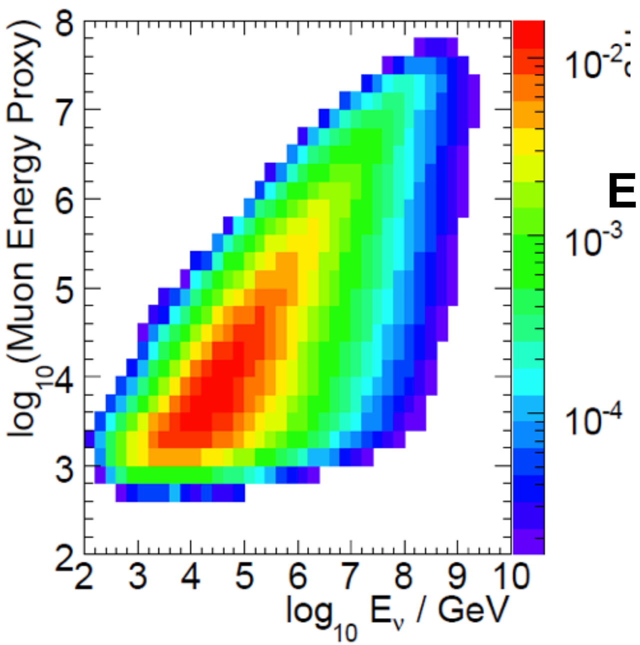
Pointing resolution

- energy dependent
  - → $\sigma(\theta_\nu) \approx 1^\circ$ at 1TeV



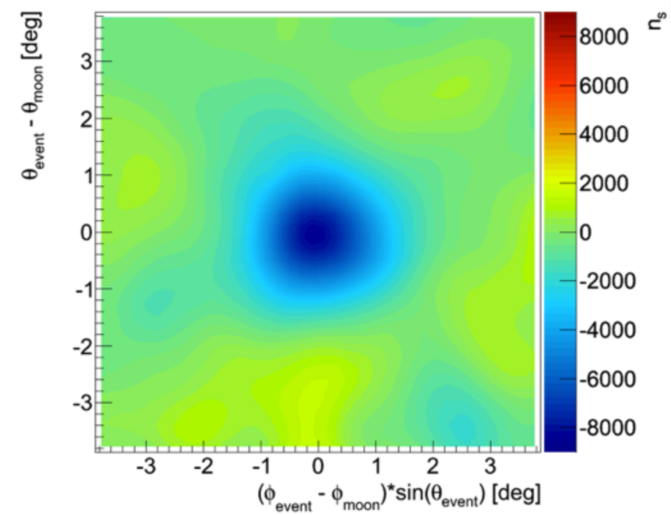
Pointing verification

- ±4° window around moon
  - → 13σ underfluctuation in IC59 (14 moon cycles)



Energy resolution

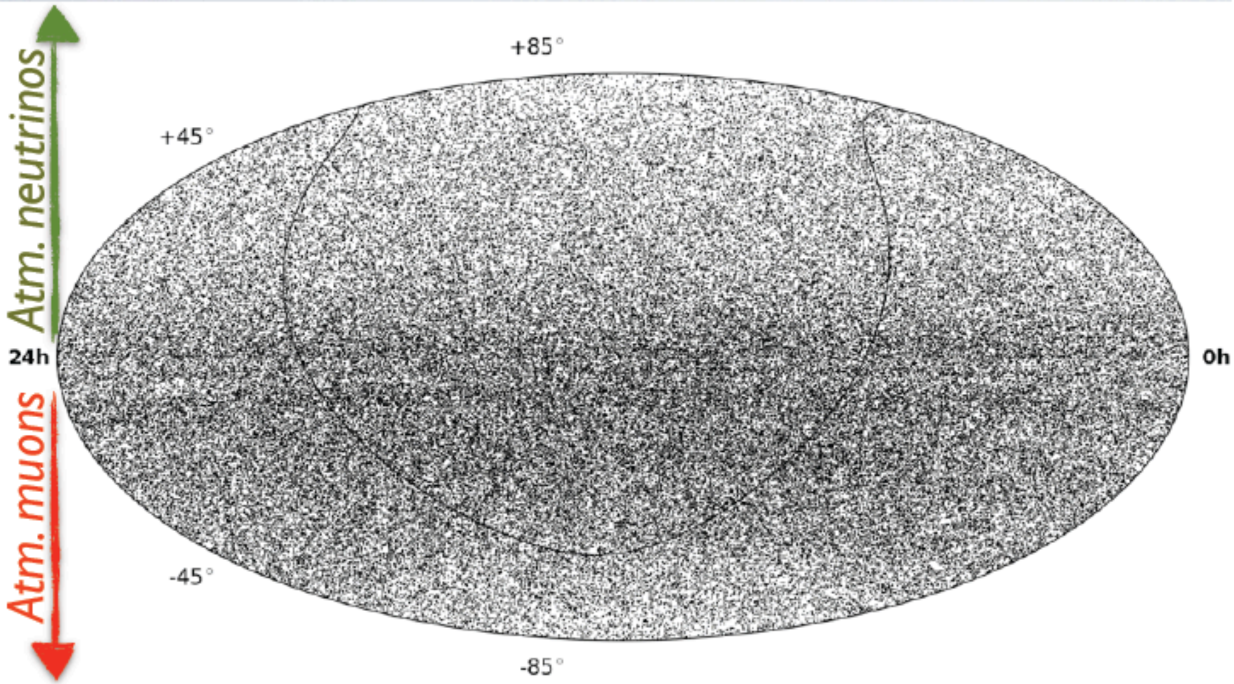
- estimated from dE/dx of muons
- dominated by stochastic losses
  - → $\sigma(E_\mu) \approx 0.3 \log_{10}(E_\mu)$

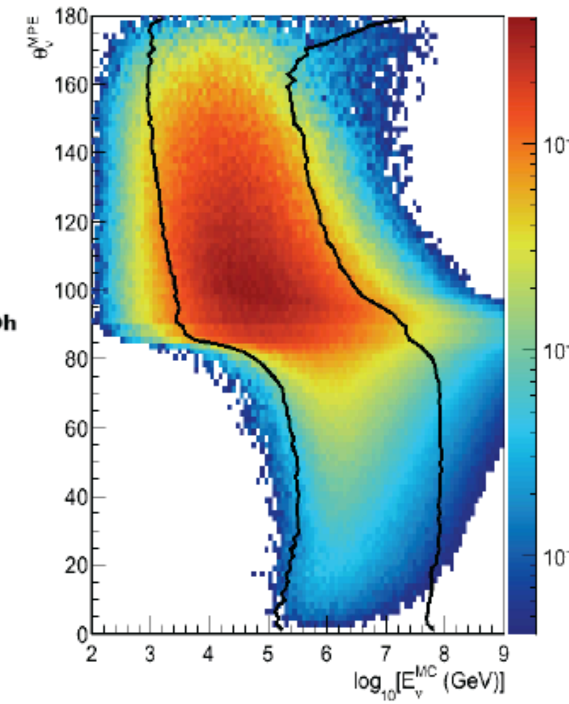


Point source searches

Dataset

- lifetime 1039 days
  (IC40+IC59+IC79)
- 108,317 up-going
- 146,018 down-going





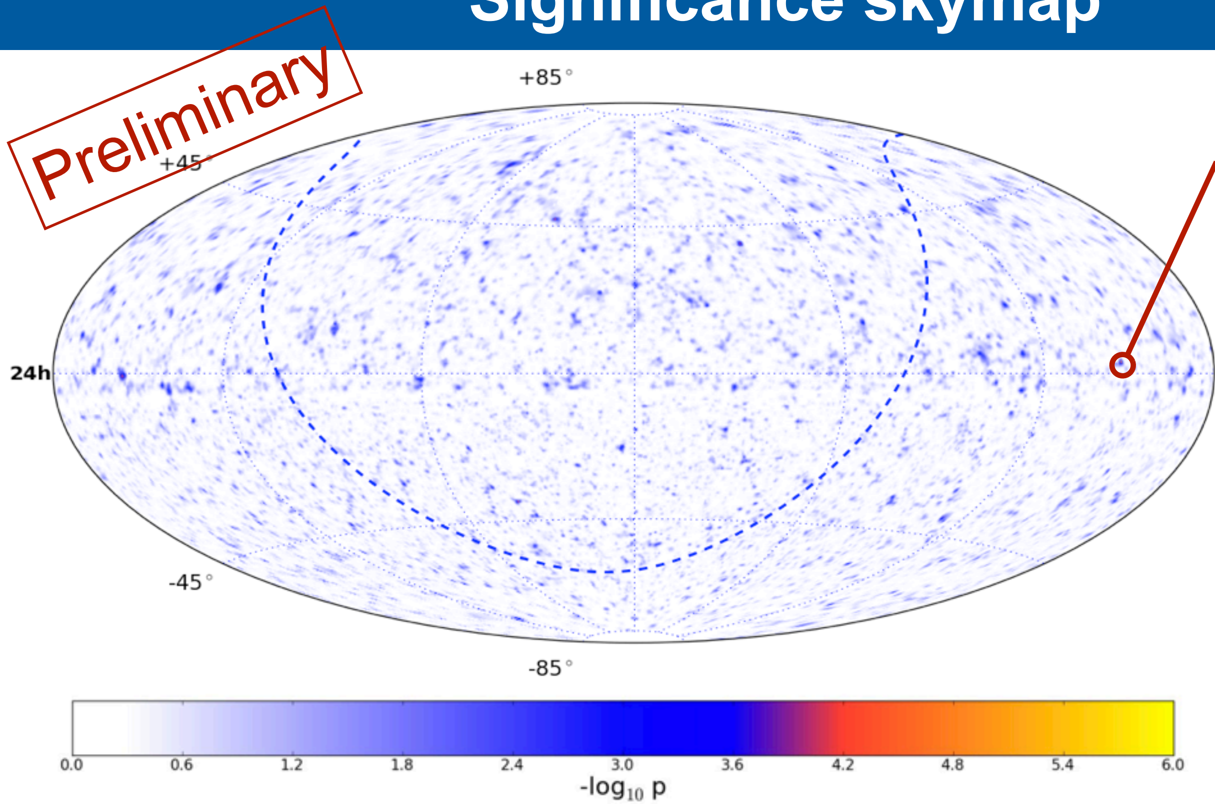
Likelihood analysis

- signal term: angular and energy pdf

$$\mathcal{S}_i = \frac{1}{2\pi{\sigma_i}^2} e^{-{r_i}^2/2{\sigma_i}^2} \cdot P(E_i|\gamma)$$

- background term
  → pdf from data in zenith band

Significance skymap



Hottest spot

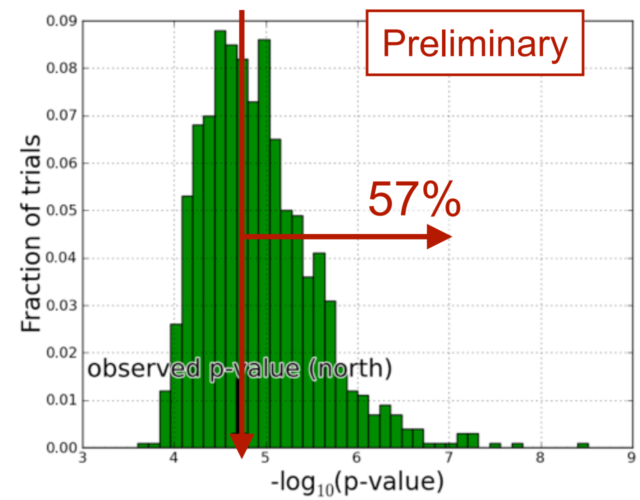
- RA: 34.25°
- DEC: 2.75°
- $-\log_{10}(p) = 4.707$
- $n_s = 23.07$, $\gamma = 2.35$

  ➔ no close-by candidates

Right ascension scrambling

- 2000 random datasets

  ➔ 57% have equal or larger max. p-value



Likelihood term

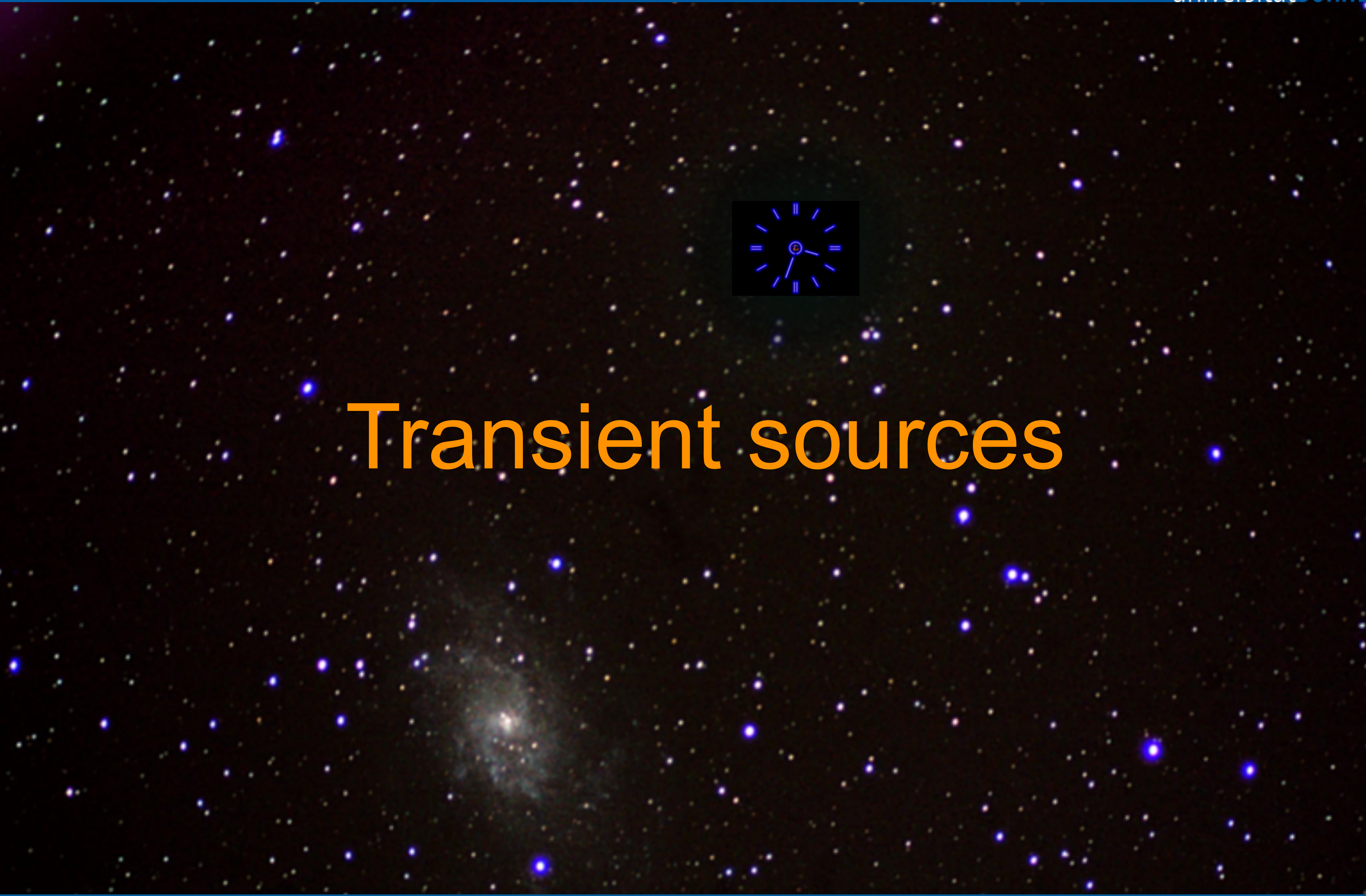
$$\mathcal{L}(n_s, \gamma) = \prod_{i=1}^{N} \left(\frac{n_s}{N} \mathcal{S}_i(\gamma) + (1 - \frac{n_s}{N}) \mathcal{B}_i \right)$$

Test statistics

$$\log \lambda = \left(\frac{\mathcal{L}(\hat{\gamma}, \hat{n_s})}{\mathcal{L}(n_s = 0)} \right)$$

chosen to maximize likelihood

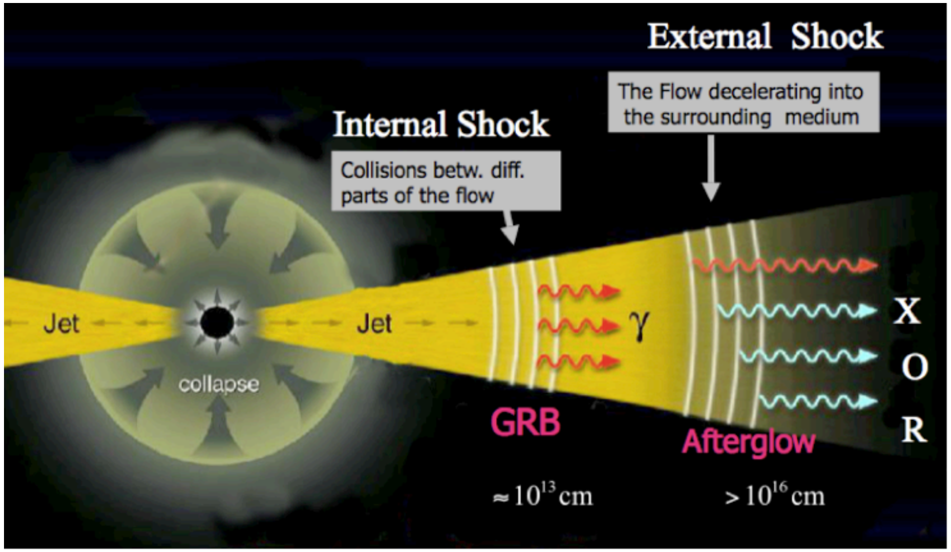
Transient sources



Gamma ray bursts

Fireball model (long GRBs)

- collapse of massive star
- ultra-relativistic jets
- shock front collision
  - ➔ PeV neutrino emission
- total energy release ~10^{52} ergs
  - ➔ good candidate for extragalactic cosmic ray flux

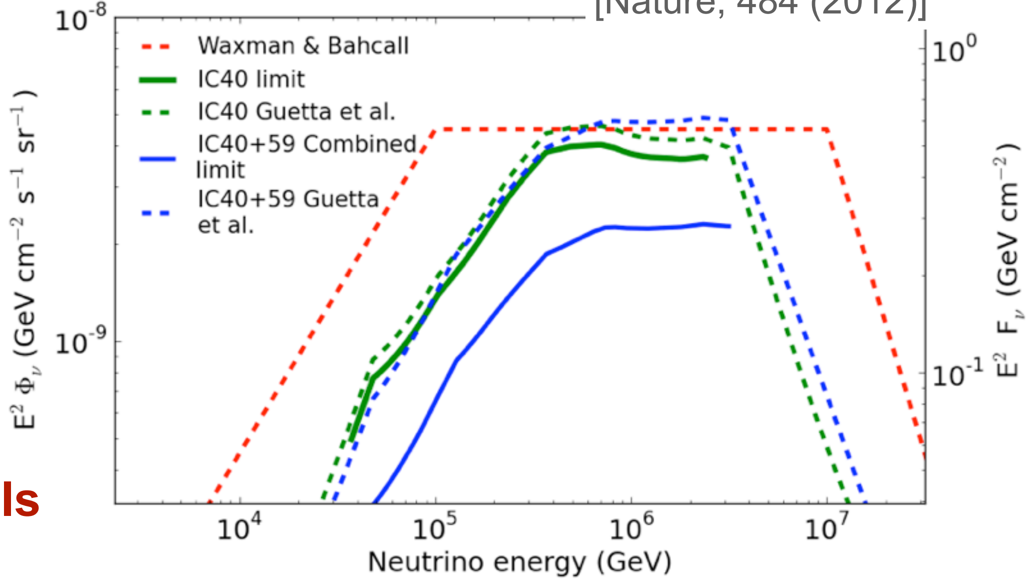


IceCube GRB analysis

- 215 GRBs from GCN
- coincidence analysis
  - ➔ time window ($\Delta T \approx 0.1$-100s)
  - ➔ direction ($\Delta\Psi_{IceCube} \approx 1°$)
- per-alert emission model
  - 5.2 events expected
  - **no** events observed

➔ starting to constrain GRB models

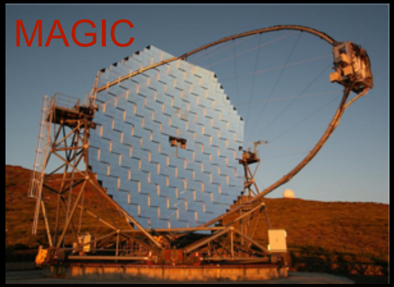
[Nature, 484 (2012)]

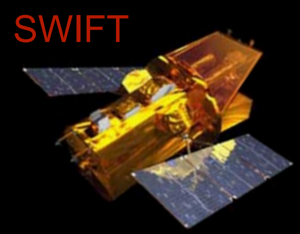


Follow-up program

Idea

- trigger follow-up observation by neutrinos in IceCube
  ➔ online neutrino analysis



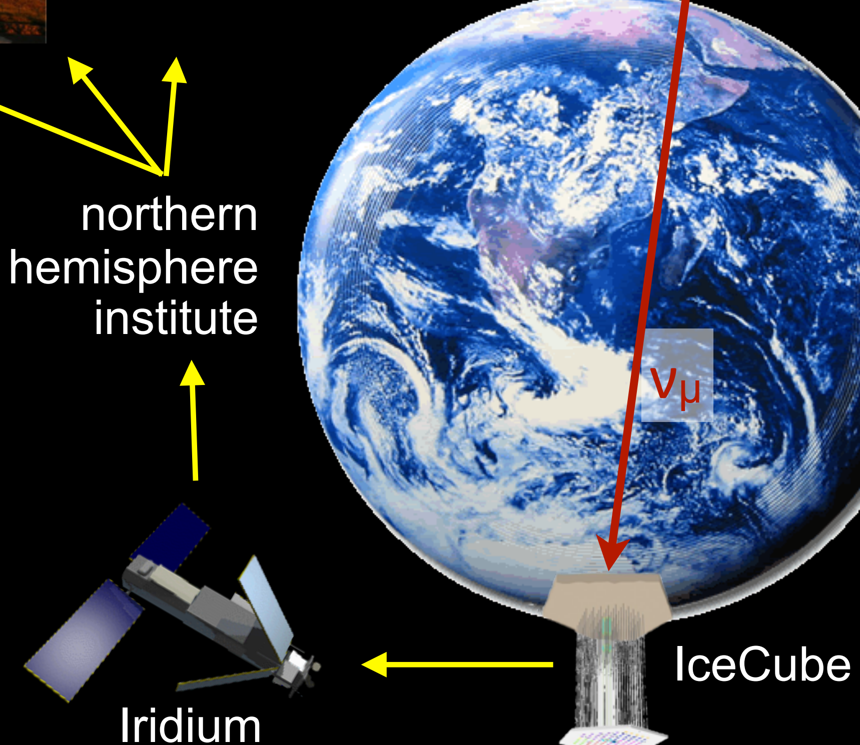


Online alerts

- multiplet trigger
  $N_\nu \geq 2$, $\Delta\Psi \geq 4°$, $\Delta t \leq 100$s separation
  ➔ likelihood analysis

Follow-up program

- optical: ROTSE, PTF
  ➔ first results
- X-rays: SWIFT
- γ-rays: MAGIC, VERITAS



IceCube online neutrino filter

Neutrino multiplets

	N_ν	Measured	Expected
IC 40	2	15	8.53
	3	0	0.003
IC 59	2	19	15.66
	3	0	0.004
IC79	2	32	42.5
	3	0	0.012
IC86	2	24	19.59
	3	0	0.005

Trigger
~3000 Hz

general muon filter

Level 1
~30 Hz

high-quality up-going events

Level 2
~3 Hz

neutrino selection

Level 3
~2 mHz

90% atmospheric neutrinos

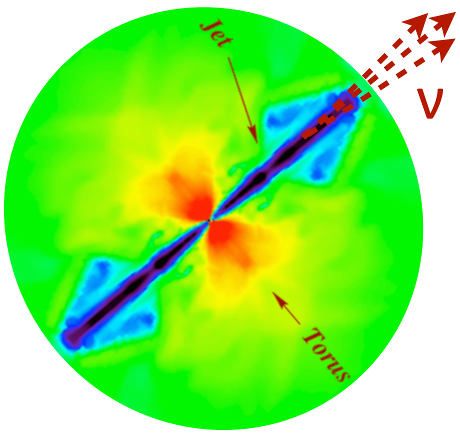
Latency

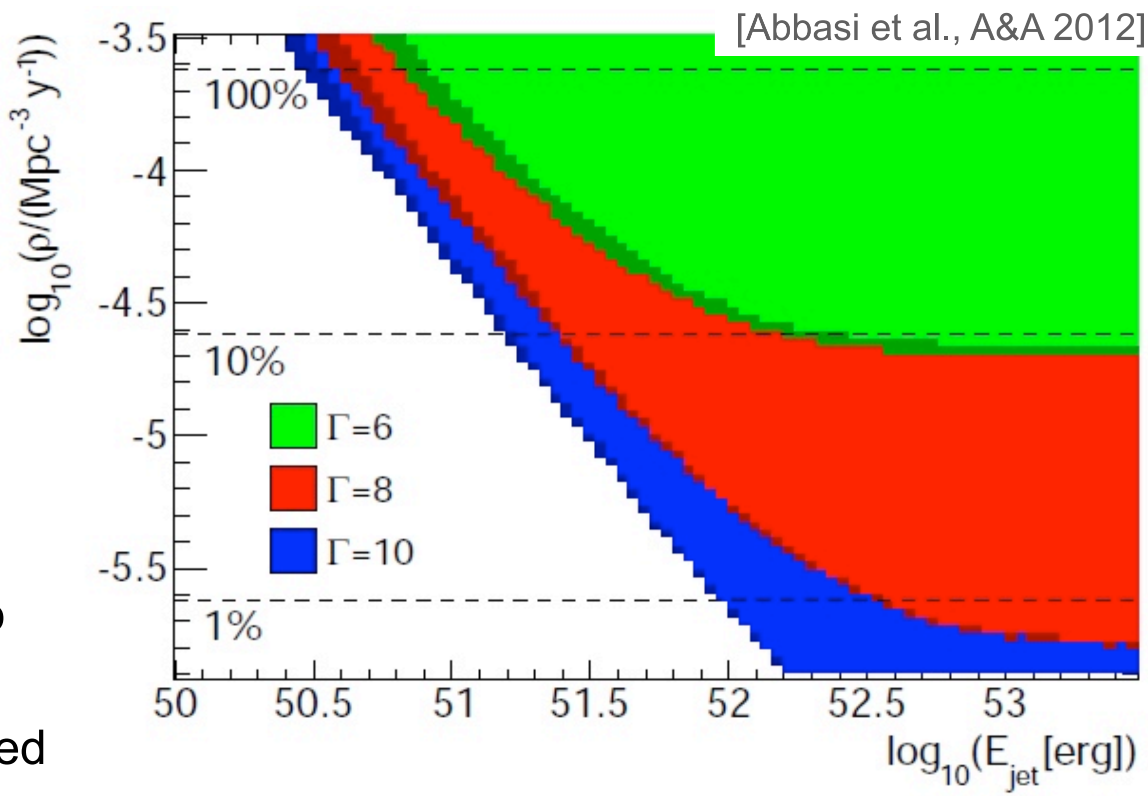
- 5 minutes

universitätbonn

Supernova jet model

- Are there GRB – like jets in core-collapse SNe?
  [Ando & Beacom (PRL 95/2005)]





First year of optical follow-up

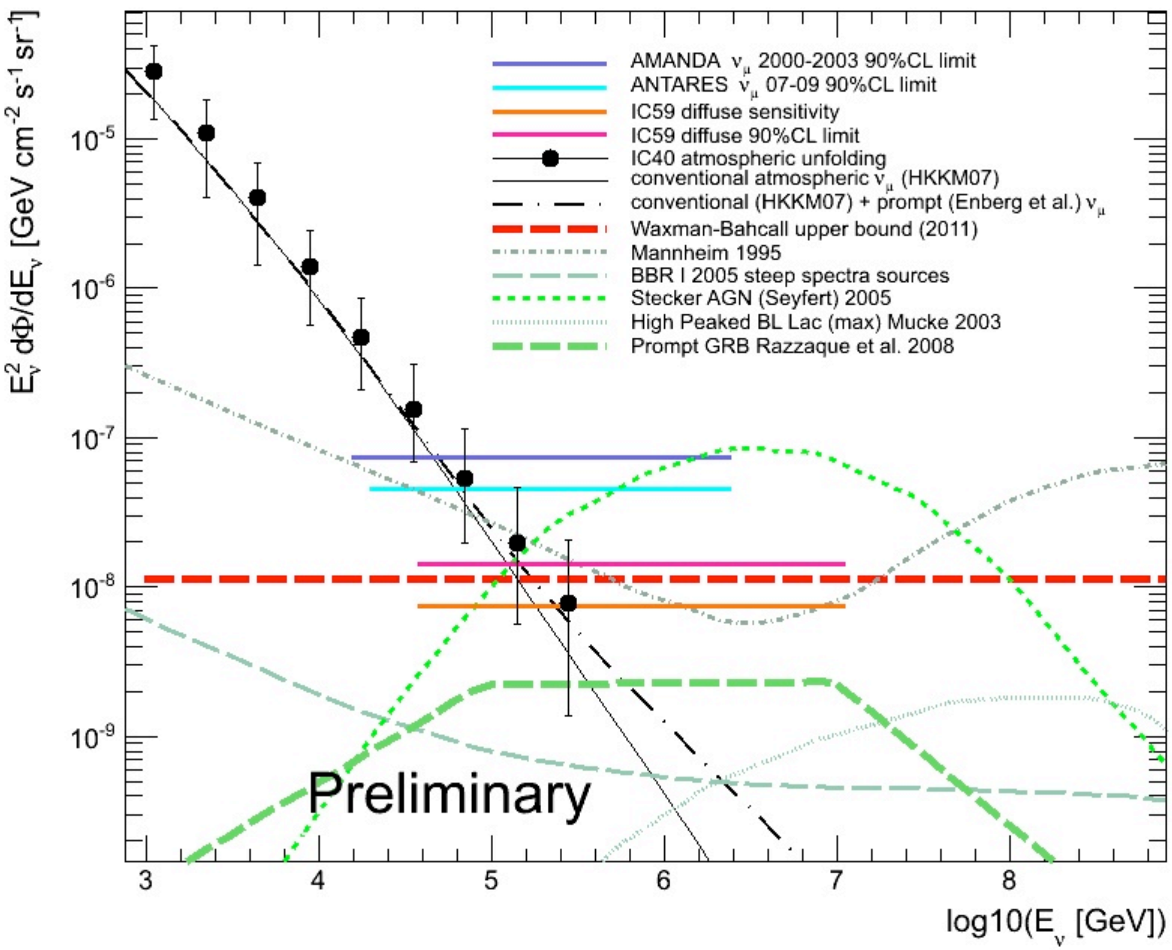
- 34 alerts send to ROTSE
- 0 SN counterparts observed

First limit on jets in CCSNe

➔less than 4.2% of CCSNe have a GRB-like jet with Γ ≥ 10

Diffuse sources

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



➔ can we improve beyond this?

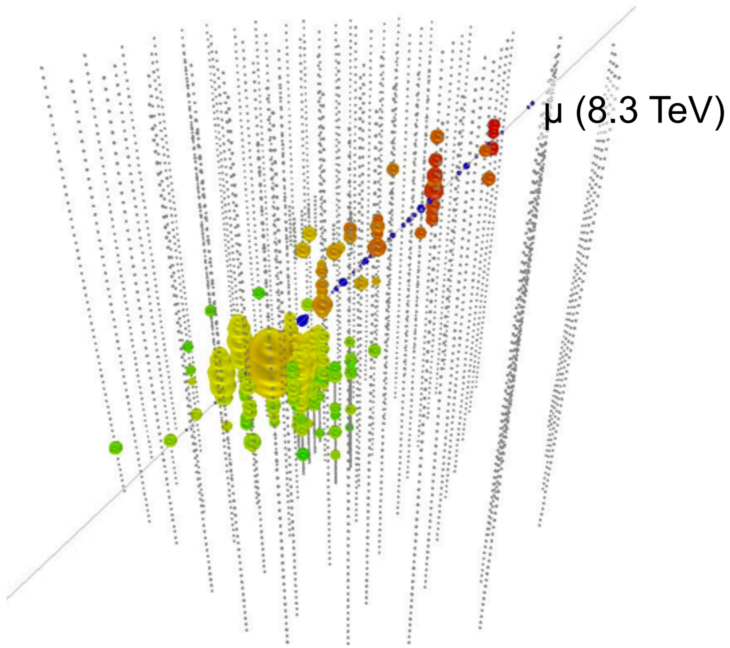
Diffuse ν_e searches

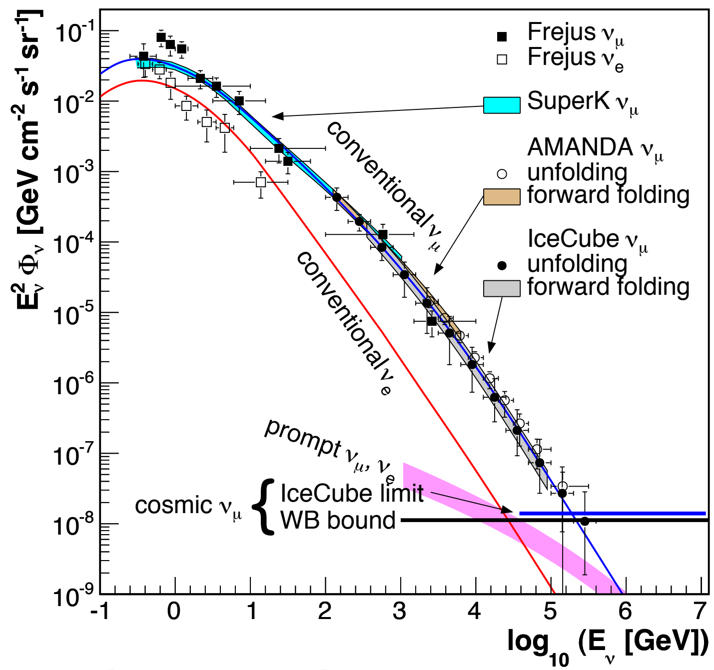
Advantages

- good energy reconstruction
- significantly less background
  - ➔ no atmospheric $e^{\pm}$
  - ➔ less atmospheric ν_e

Challenges

- stochastic energy loss from atm. μ
- limited directional reconstruction





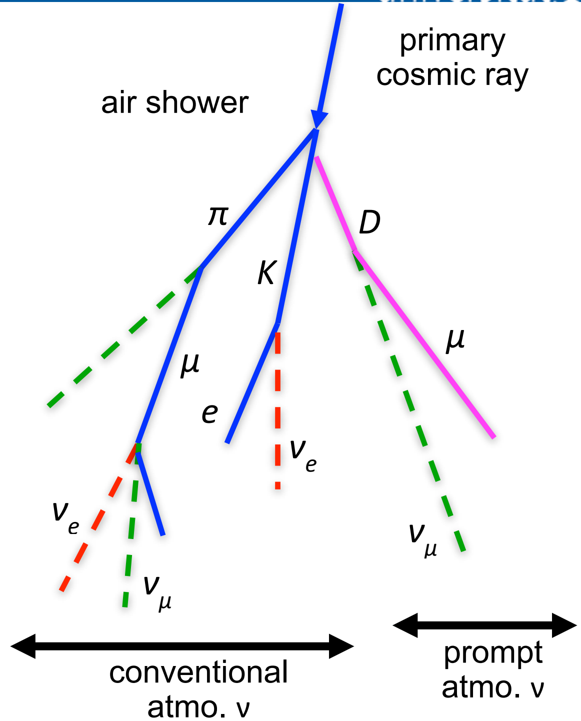
Analysis strategies

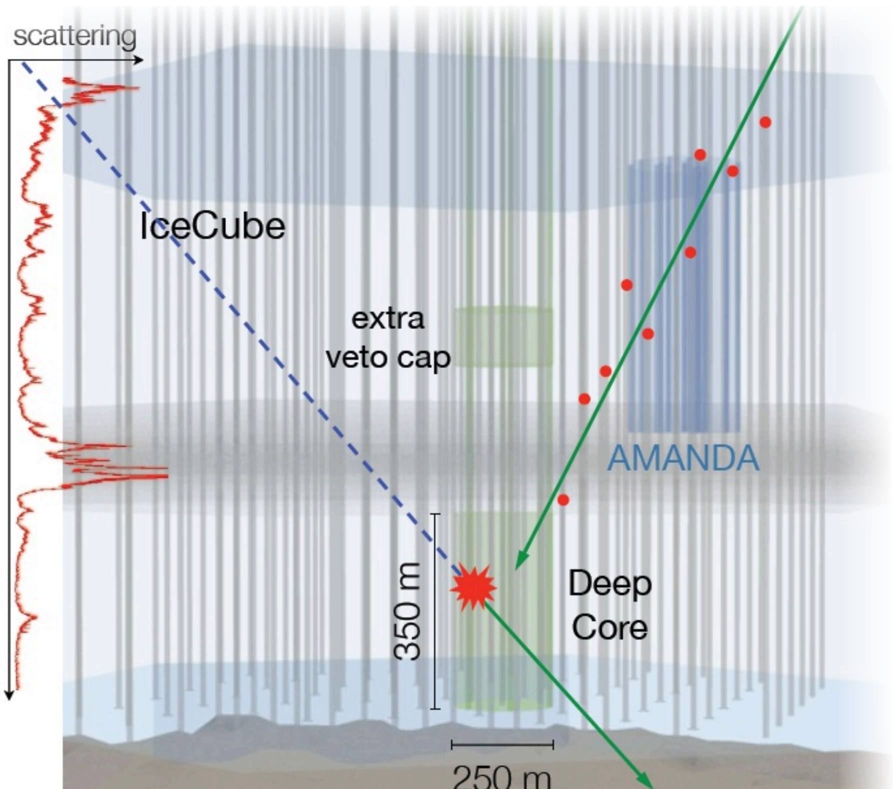
- low energies
  - ➔ **veto** around DeepCore
- middle energies
  - ➔ signature / **quality** cuts
- highest energies
  - ➔ only cut on **energy**

Low-energy cascades

Atmospheric electron neutrinos

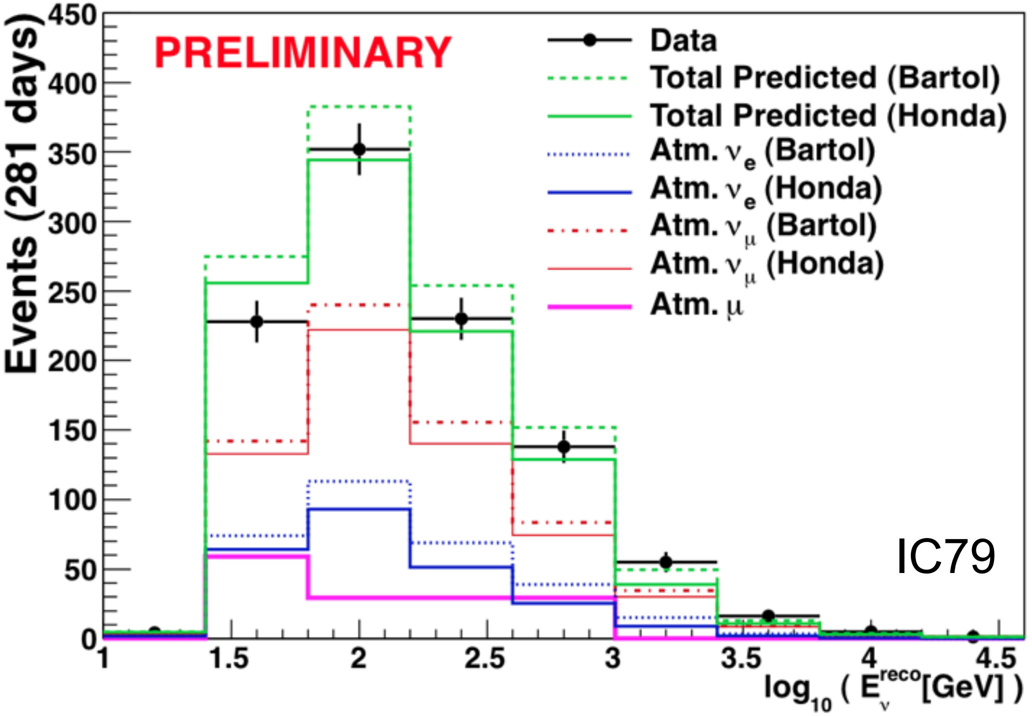
- conventional flux
  - ν_e-flux = ~10^{-2} ν_μ-flux
- prompt flux
  - decay of charmed mesons (e.g $D^{\pm}$,D_0,Λ_c)
  - ➔ probe hadronic interaction models

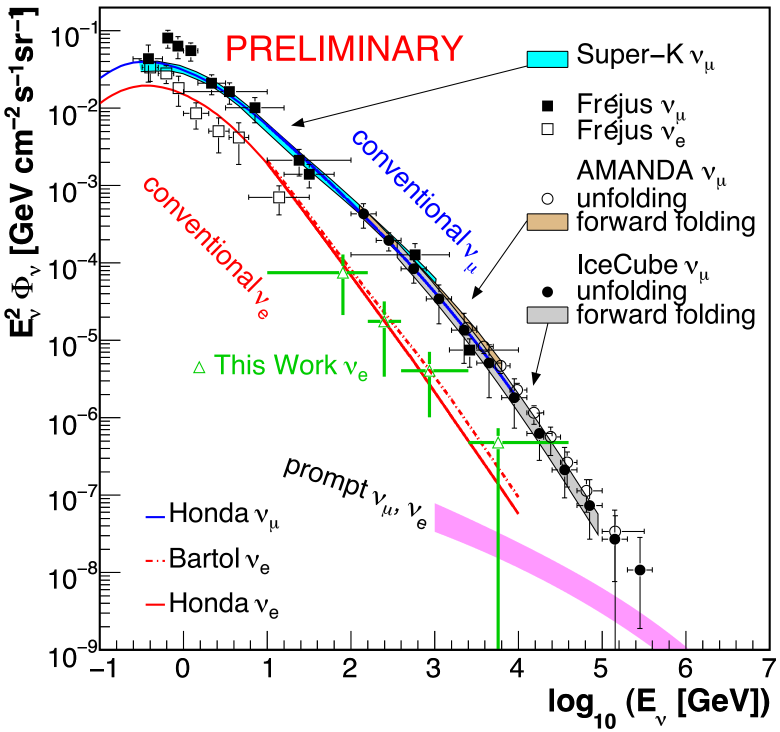




Analysis strategy

- DeepCore
  - ➔ denser module spacing
  - ➔ lower trigger threshold
  - ➔ in clearest part of the ice
- IceCube
  - ➔ use as surrounding veto for atm. μ





First observation of ν_e

- statistically significant (1029 evts, ~50% sig, ~50% bgd)
- substantial backgrounds remaining
  - ➔ not (yet) able to discriminate flux models
  - ➔ not (yet) sensitive to prompt atm. neutrino flux

Medium energy cascades

Analysis strategy

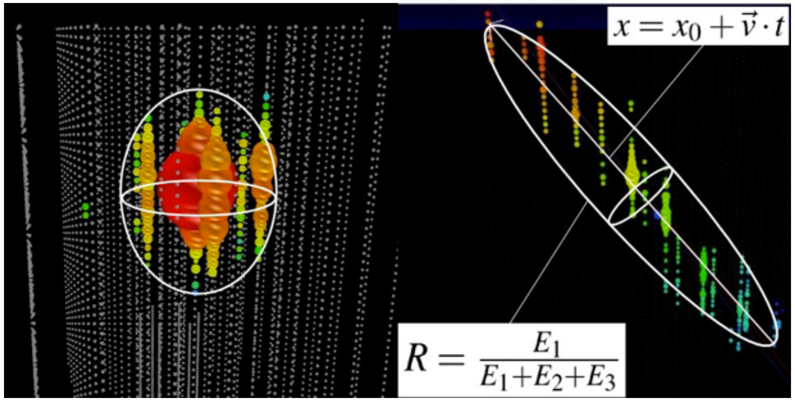
- select “cascade-like” events

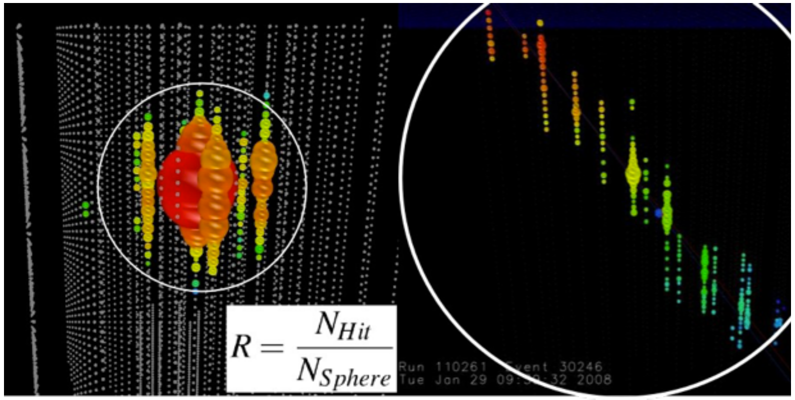
Quality parameters

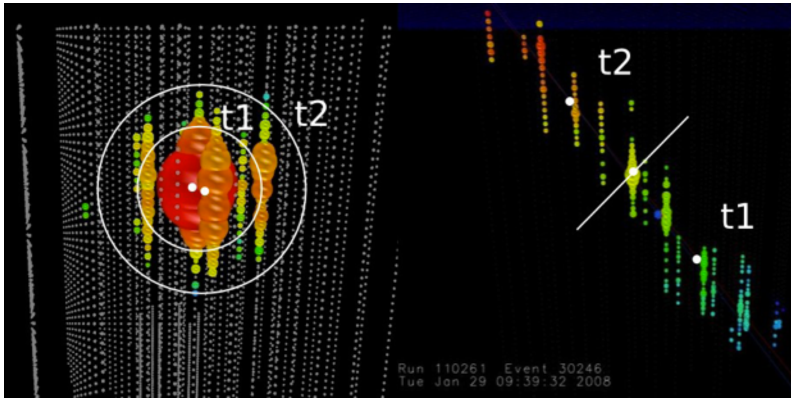
- tensor of inertia
  ➔ round vs. elongated
- fill ratio
  ➔ hits everywhere where expected
- vertex stability
  ➔ early and late hits from same origin
- …

Final selection

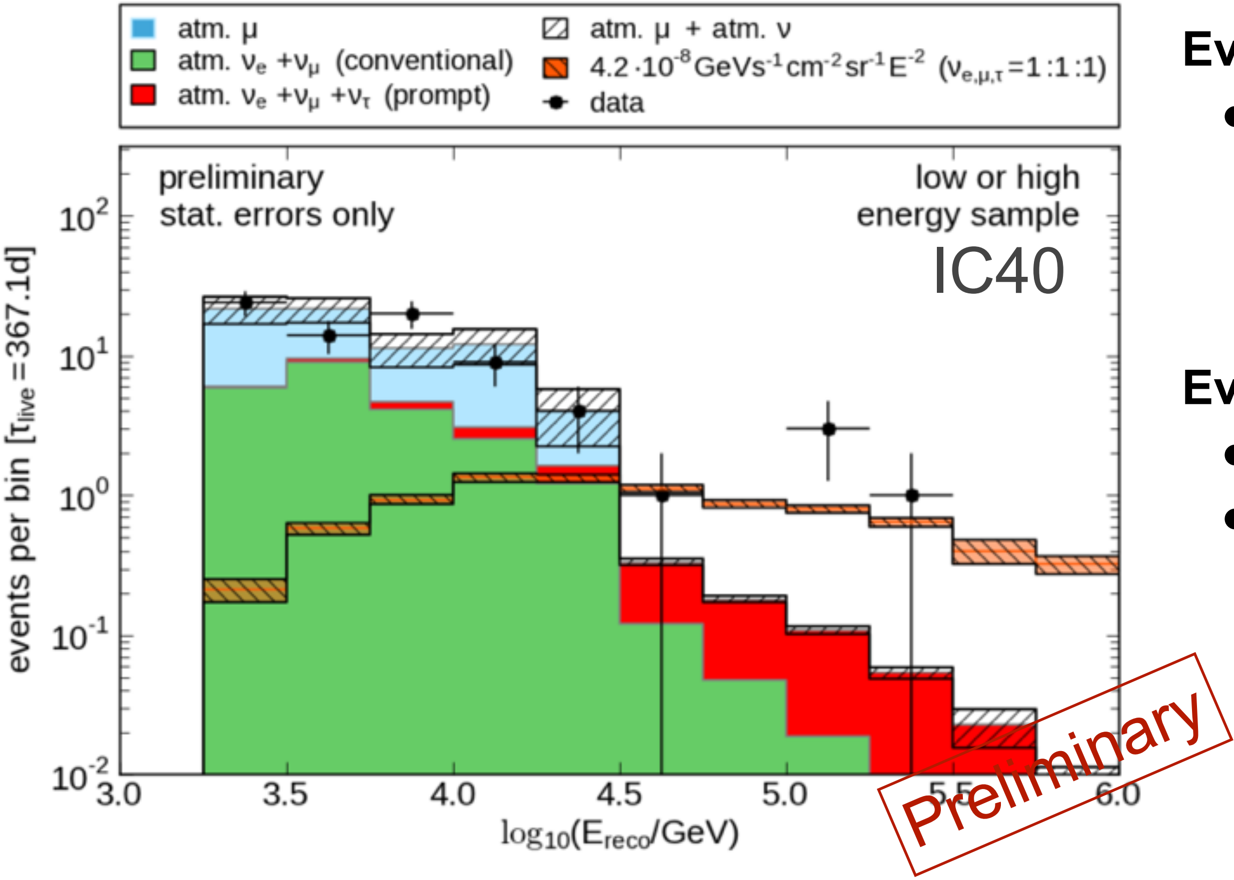
- Boosted decision tree
  ➔ separately optimized for two different energy regions







Search for neutrino-induced cascades

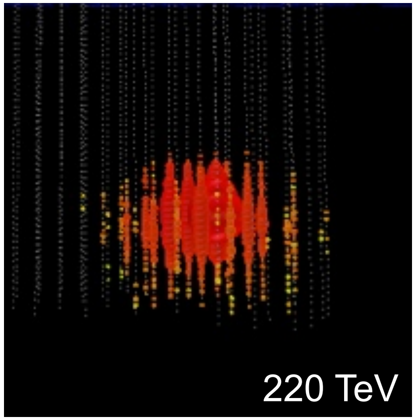


Events E ≤ 100 TeV

- consistent with expectations
  - ➔ conventional $\nu_{e}+\nu_{\mu}$
  - ➔ atmospheric μ

Events E ≥ 100 TeV

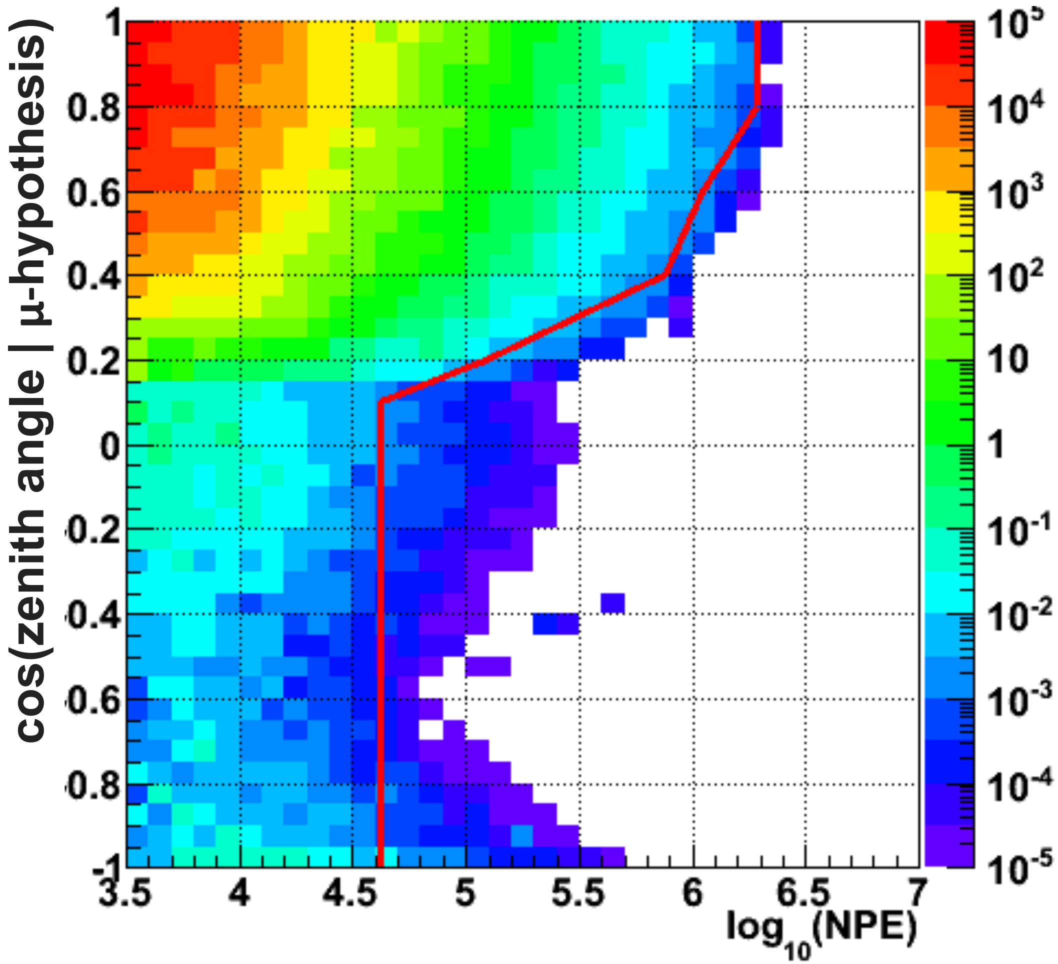
- observed: 3(+1) events
- expected: 0.36 events
  - ➔ significance: 2.75σ



Interpretation

- statistical fluctuation ?
- enhanced prompt flux ??
- astrophysical neutrinos ???

Highest energy diffuse search



Analysis strategy

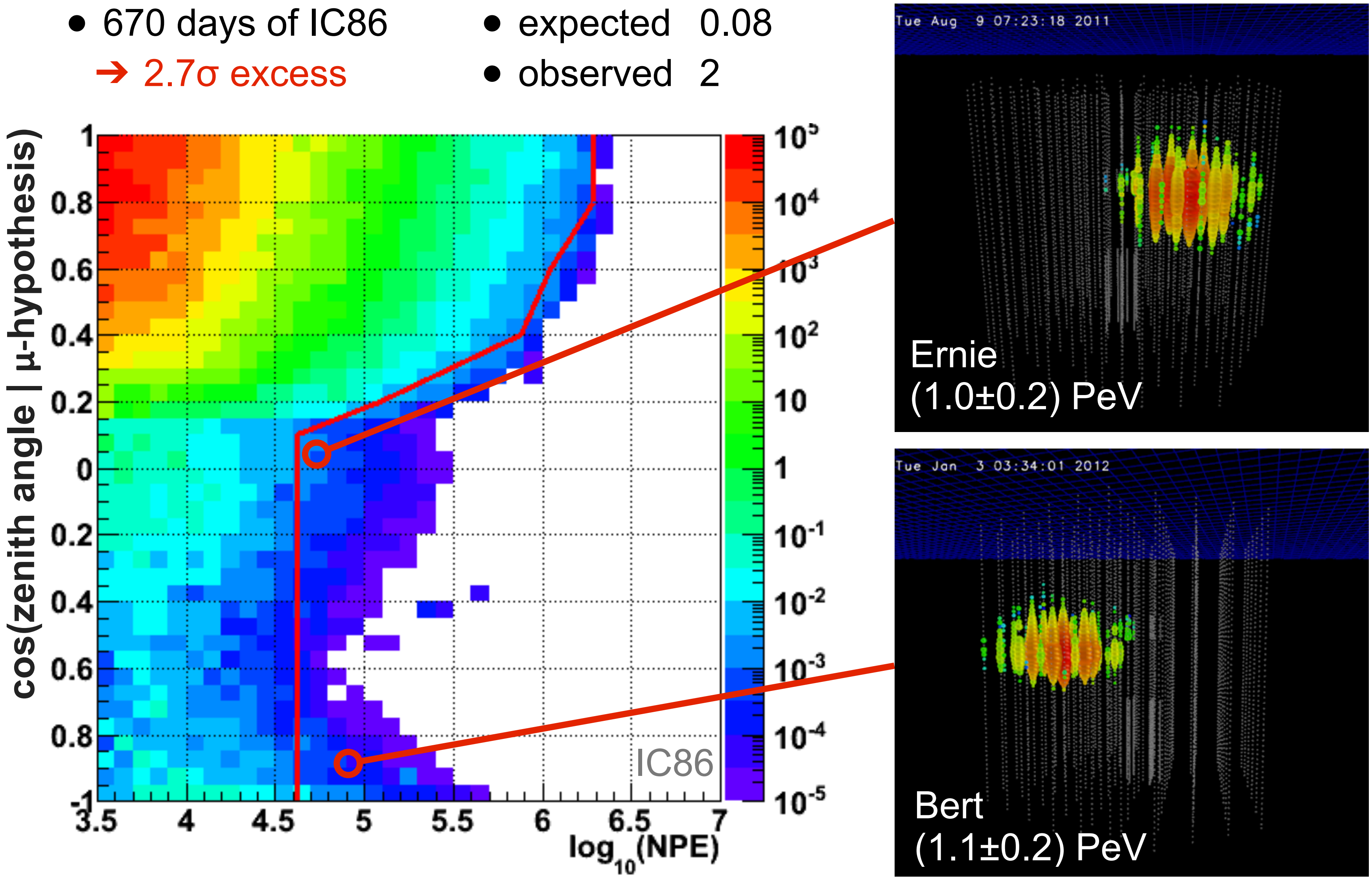
- only cut on energy-sensitive parameter
  - ➔ NPE = number of photo-electrons
- zenith angle dependent
  - ➔ lower threshold for *up-going* tracks
- mostly ignore event shape
  - ➔ sensitive to $\nu_e+\nu_\mu+\nu_\tau$

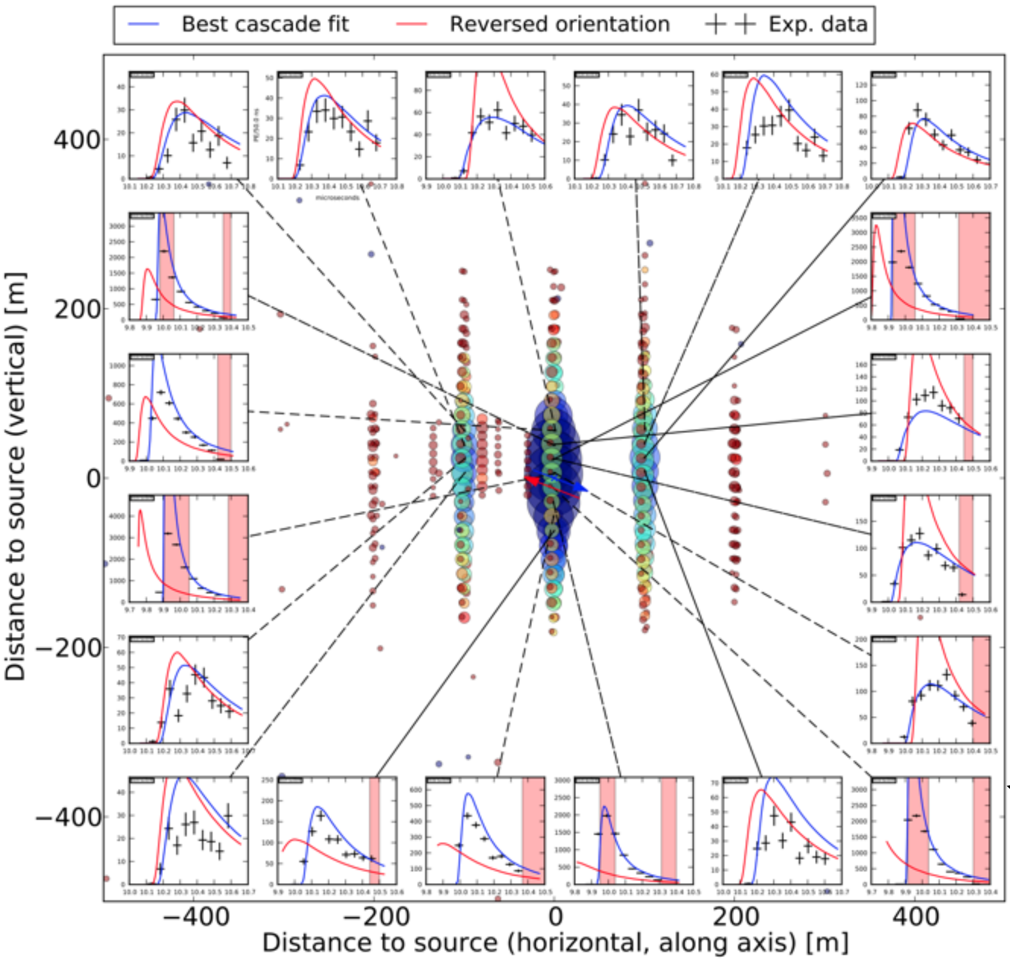
EHE diffuse search – results

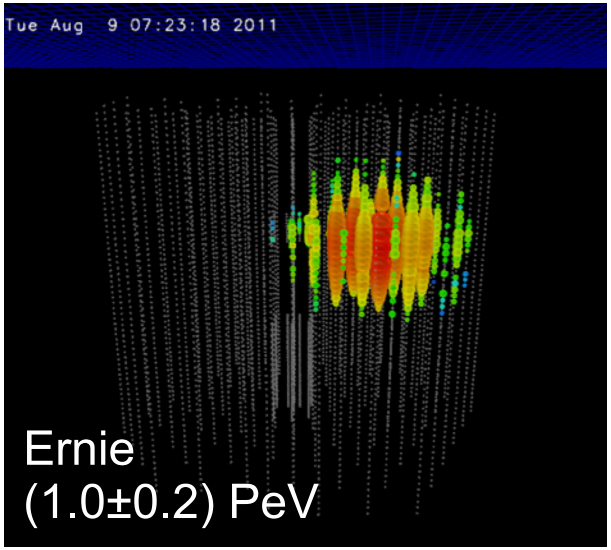
Dataset
- 670 days of IC86

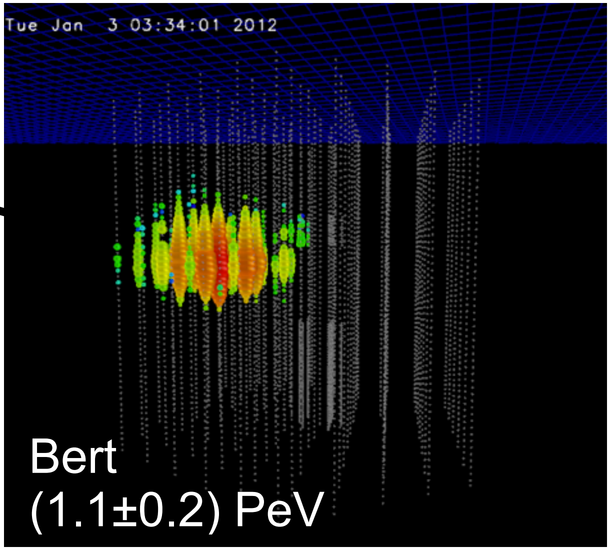
➔ 2.7σ excess

Events
- expected 0.08
- observed 2



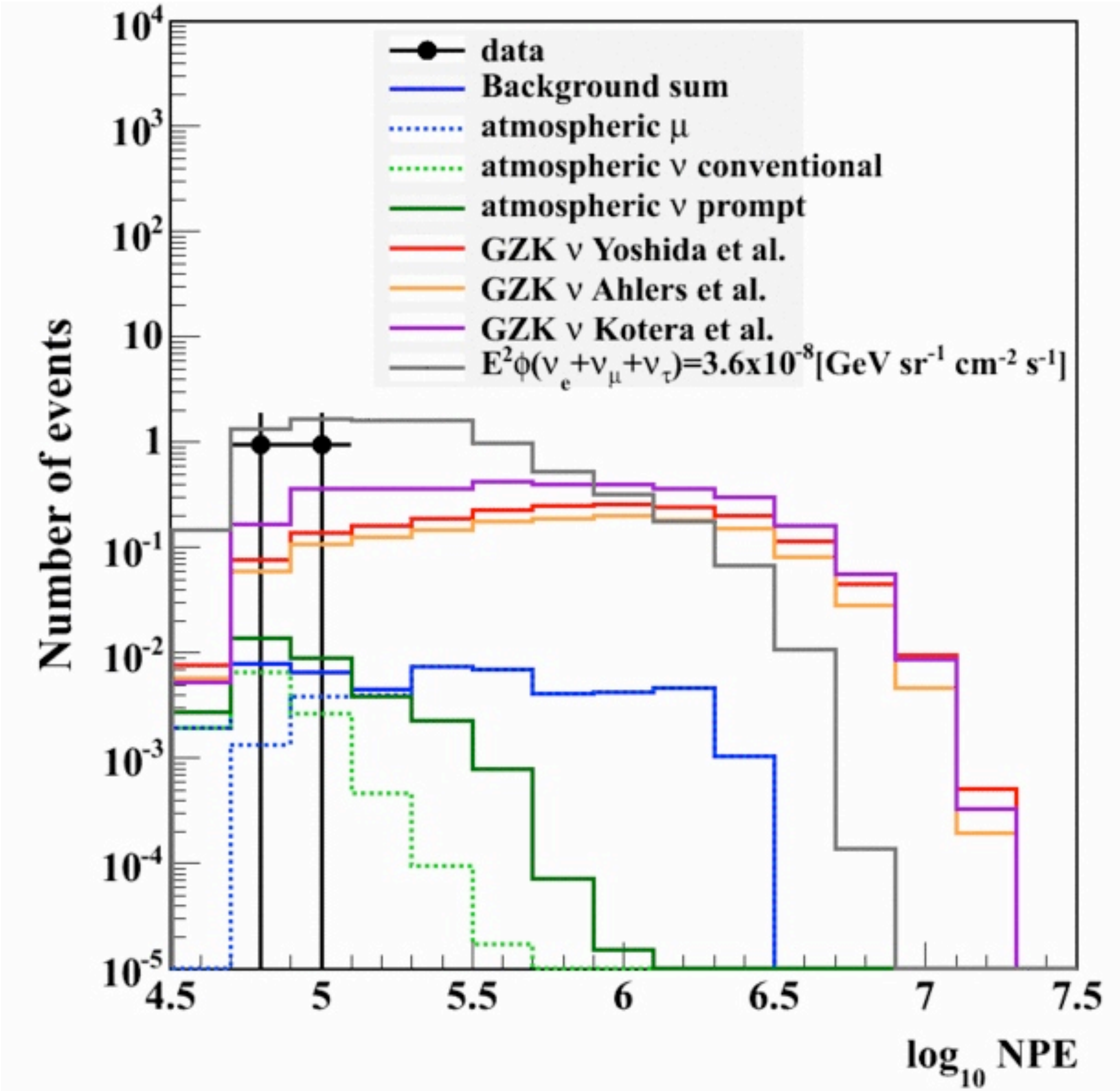






Detailed inspection

- indication that both events are down-going



Interpretation?

- above prompt expectation
- below Glashow resonance energy

  $\nu_e + e^\pm \rightarrow W^\pm$
- too low in energy for GZK models
- spectrum not very hard

  ➔ for E^{-2} expect

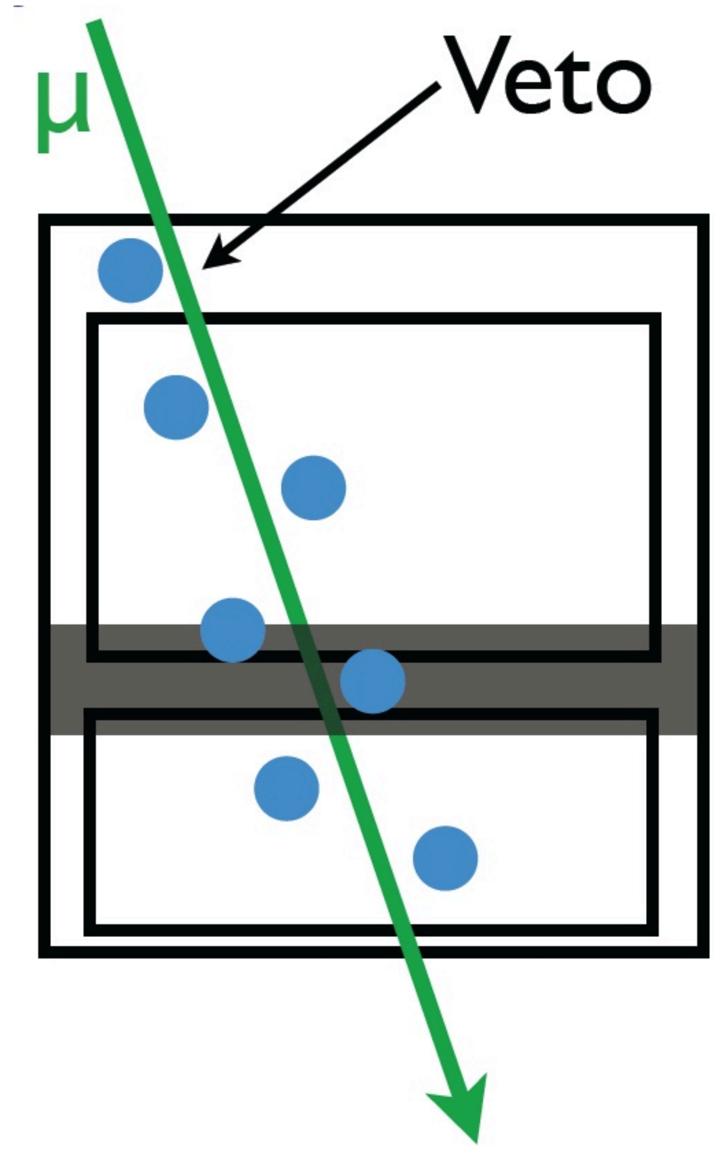
  8-9 events

Future searches

Combine advantages

- Explicit contained search (as for low energies)
  ➔ atmospheric muon veto
- Sensitive to all flavours
- Optimized for 1PeV region
  ➔ factor 3 gain in sensitivity

Stay tuned for results!



Summary

Point-Sources

- strict upper limits on steady sources
- limit on transient sources start to rule out models

→ enhance transient search with follow-ups

Diffuse flux

- first measurement of conventional ν_e flux
- small excess of cascade-like events in 0.1-1 PeV range

→ two independent analyses

→ we may be on the verge of discovery

IceCube will open a new window to the universe!