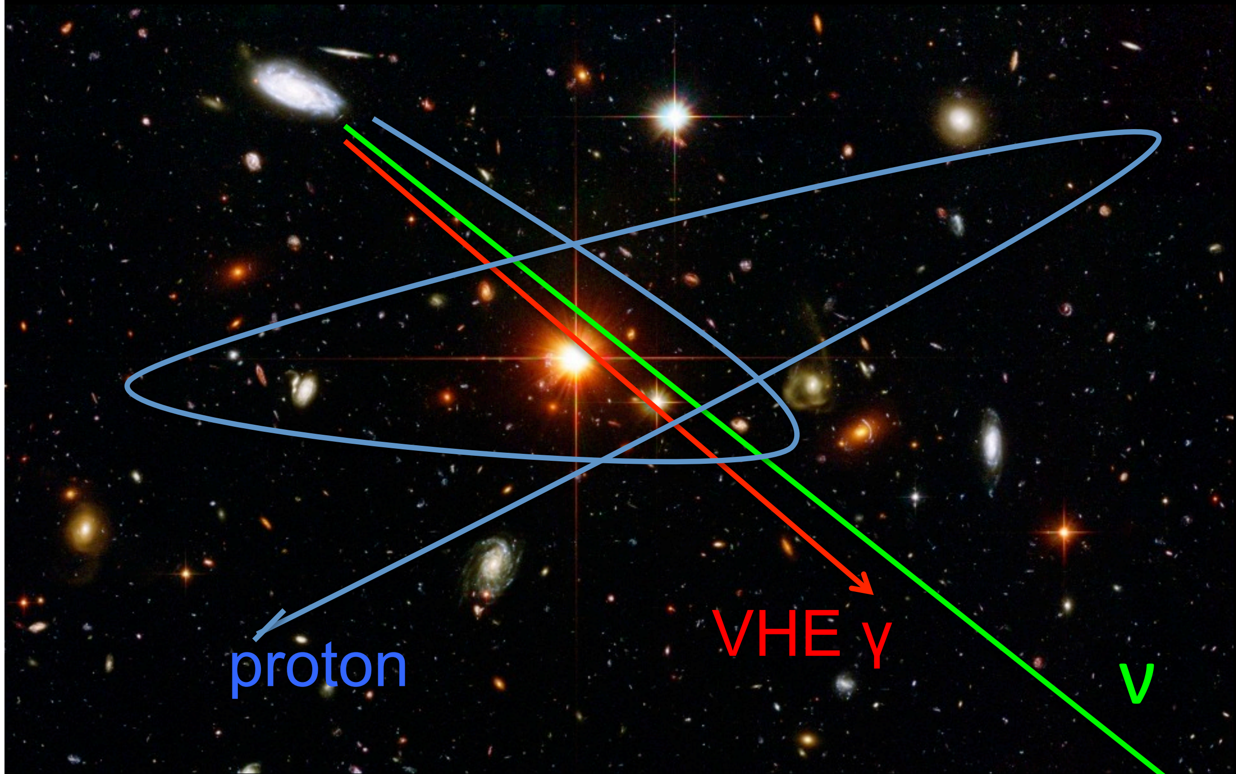
The latest IceCube results and the implications

K. Mase, Chiba Univ.
for the IceCube collaboration

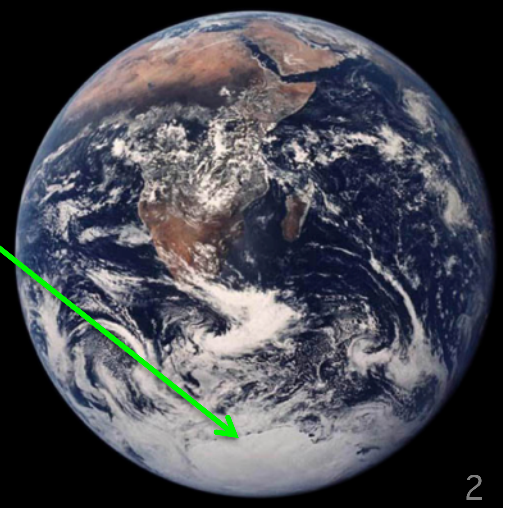
Neutrinos to elucidate cosmic ray origin



Neutrinos are rarely interacting particles

- Arrive straight to the Earth from the deep Universe
- Produced through hadronic interactions

  → **Cosmic ray origin**



Multi messengers

Neutrino production is closely related to production of **cosmic rays** and **gamma rays**

$$p + p\,(\gamma) \rightarrow \pi^{\pm} / \pi^{0} + anything$$

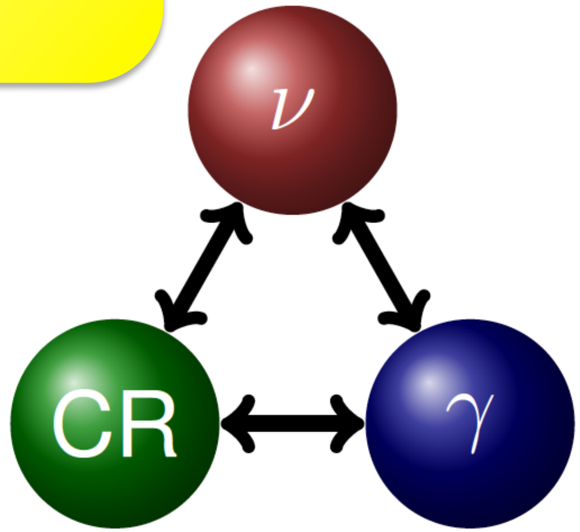
$$\pi^{+} \rightarrow \mu^{+} \nu_{\mu}$$

$$\mu^{+} \rightarrow e^{+} \nu_{e} \bar{\nu}_{\mu} \qquad E_{\nu_{\mu}} \approx E_{\nu_{e}} \approx E_{\bar{\nu}_{\mu}}$$

$$\pi^{0} \rightarrow 2\gamma$$

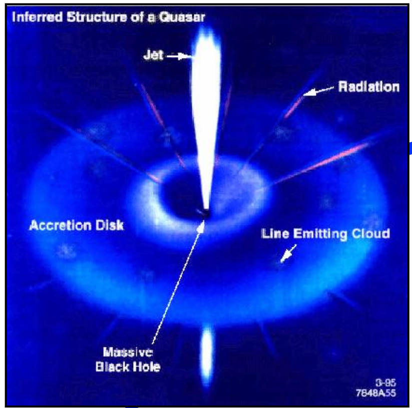
$$E_{\nu} \approx \frac{1}{20} E_{p} \qquad \because E_{\pi} \approx \frac{1}{5} E_{p}, E_{\nu} \approx \frac{1}{4} E_{\pi}$$

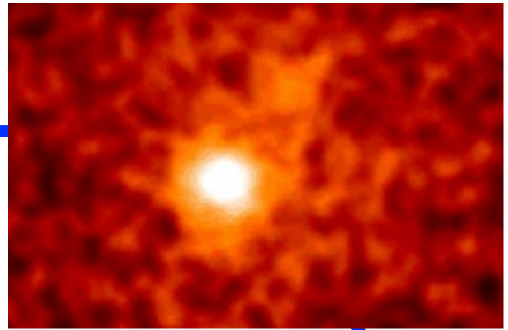
$$E_{\nu} \approx E_{\gamma}$$



©M. Ahlers

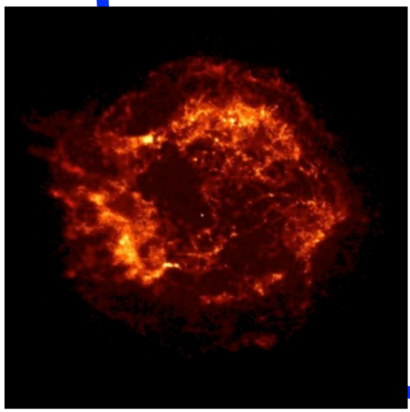
Exploring the universe with neutrinos

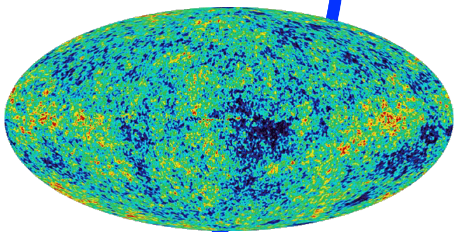


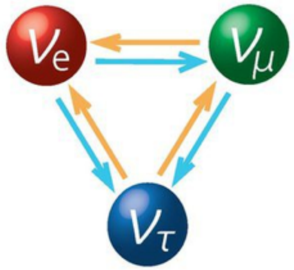


- GRBs
- AGNs

- Dark Matter
- Cosmic ray origin
- Particle physics





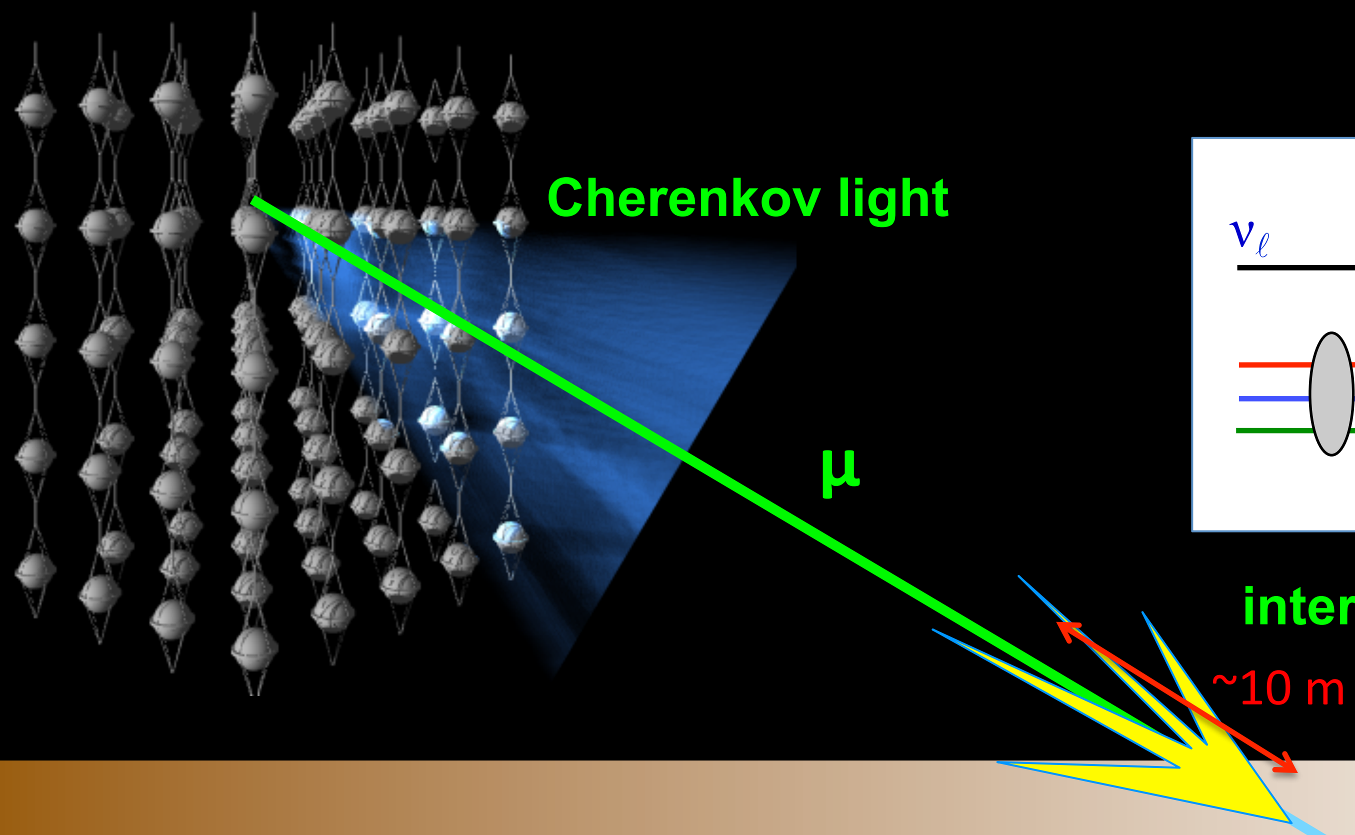


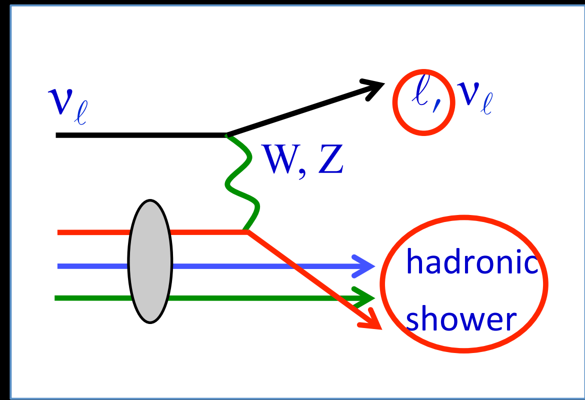
- Supernova
- Cosmogenic neutrinos

See A. Ishihara's talk

- Neutrino oscillation

How do we detect neutrinos?

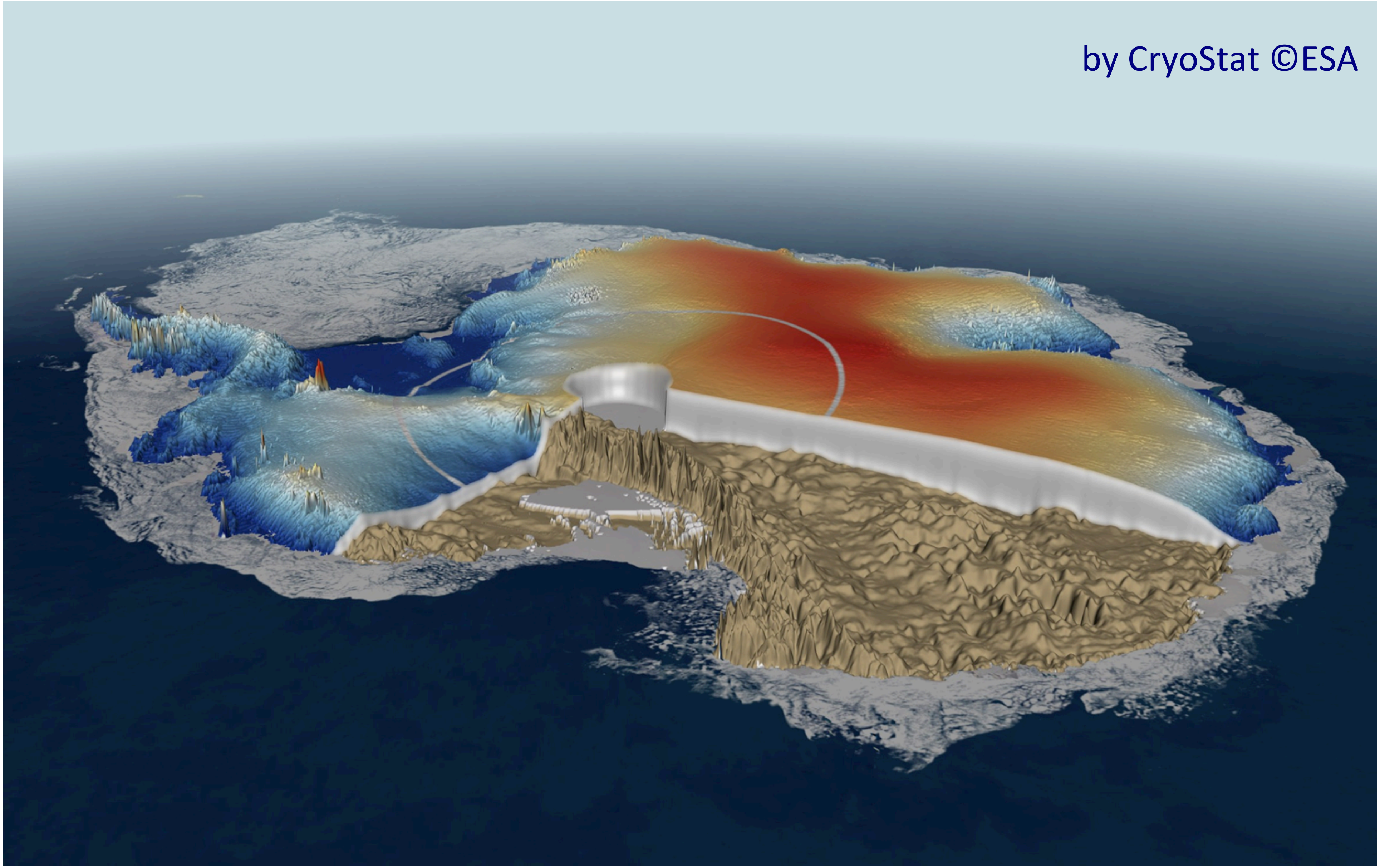




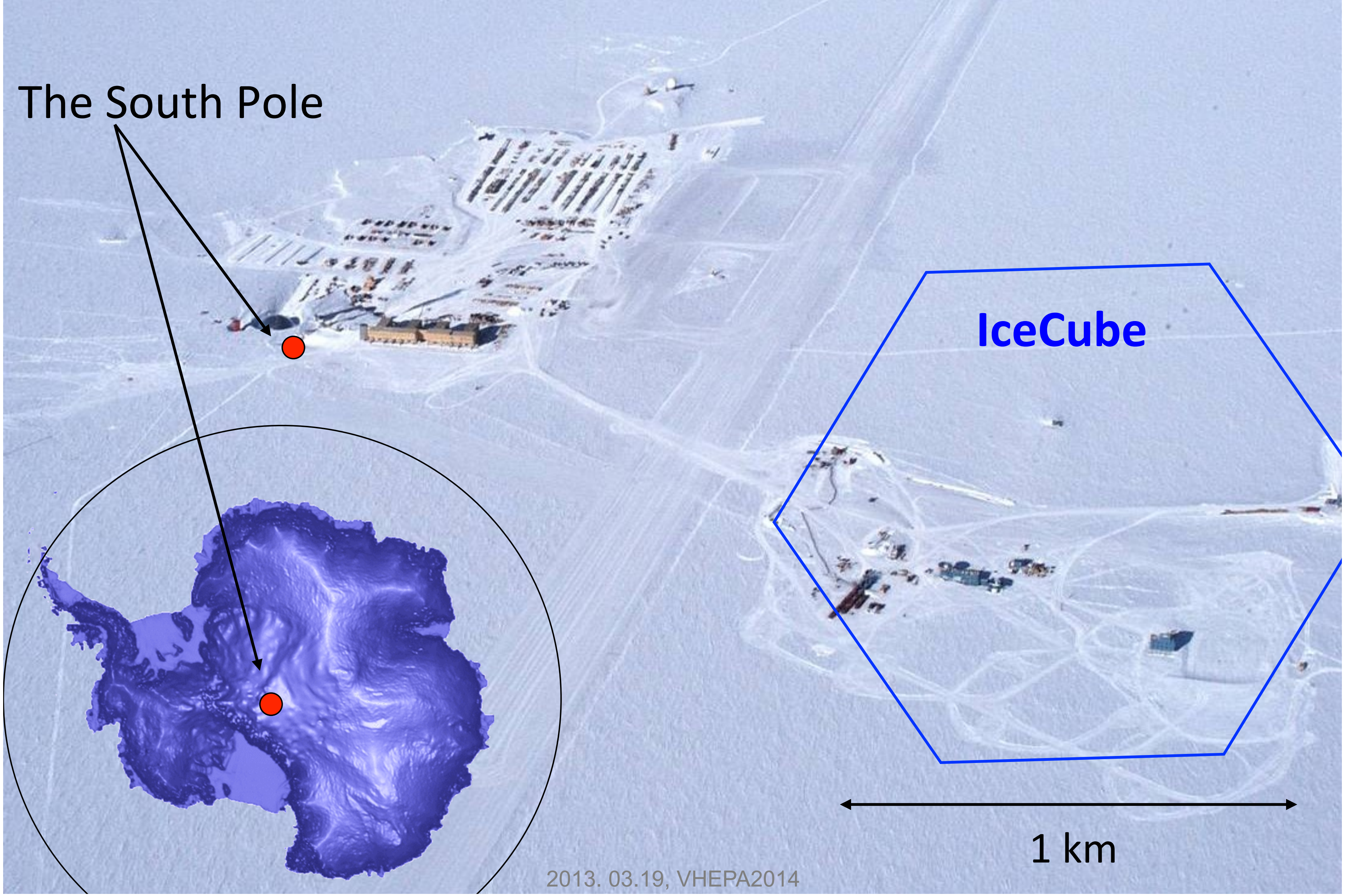
- Large volume for neutrinos to interact
- Transparent medium for light to propagate to photo-sensors

  → **Antarctica ice**

■ Part of our detector: Antarctica ice

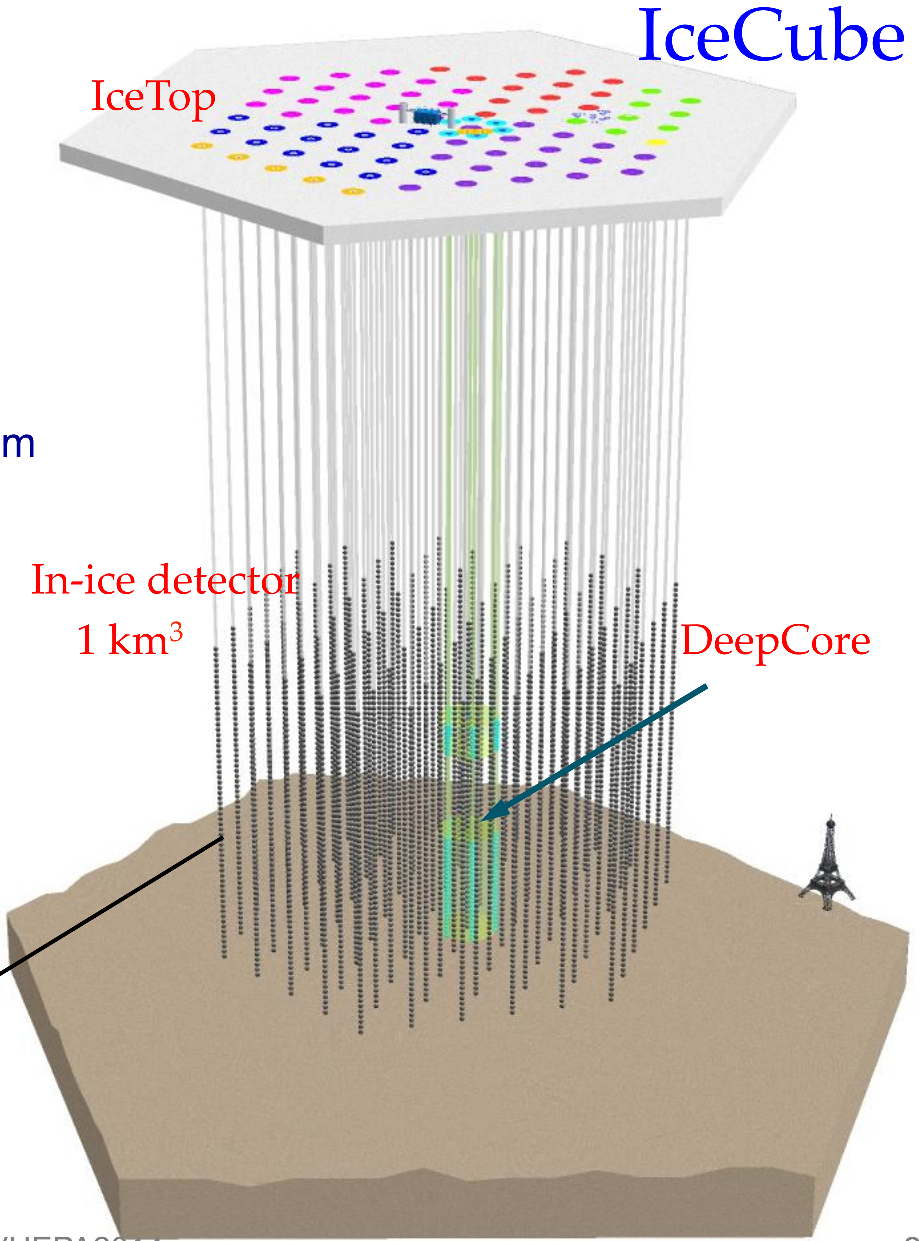


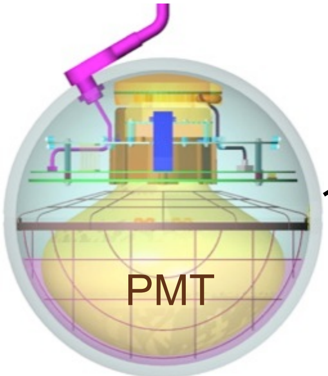
■ The IceCube detector at the South Pole



The IceCube detector

- Deployed in the Antarctica glacier
- In-ice + IceTop + DeepCore
- 86 strings (completed in 2010)
- ~ 5,000 photo-multiplier tubes (PMTs)
- Detector volume: ~ 1 km^3
- Detector spacing: horizontal 125m, vertical 17m
- ATWD 300MSPS
  3 different gains (x16, x2, x0.25)
- FADC for long duration pulse (6.4 μs)
- **Targets for cosmic high energy neutrinos**
  (mainly >~ 100 GeV)

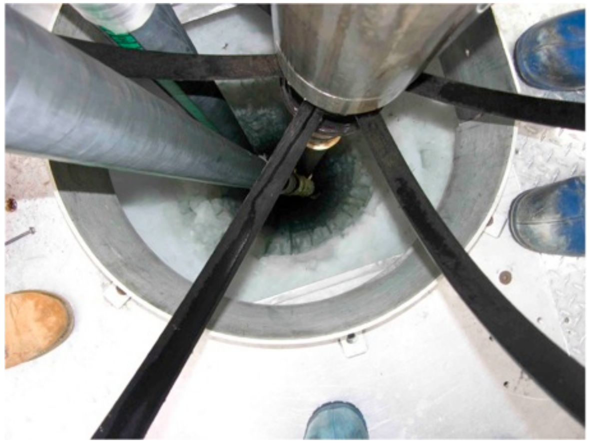




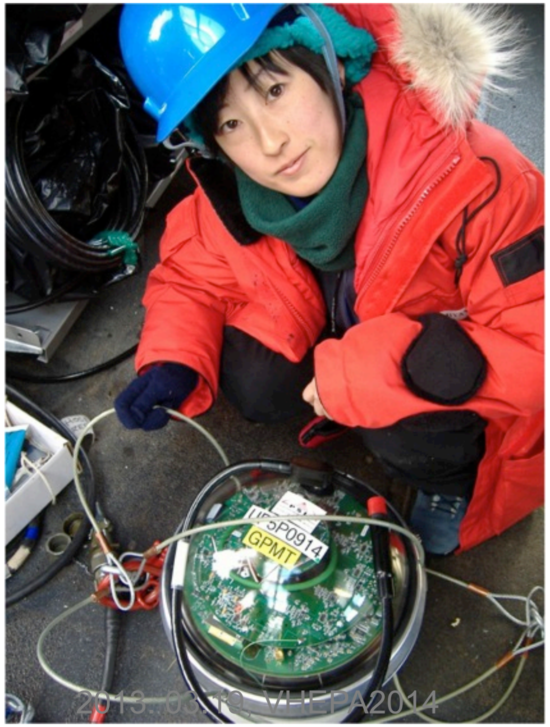
Digital Optical Module (DOM)

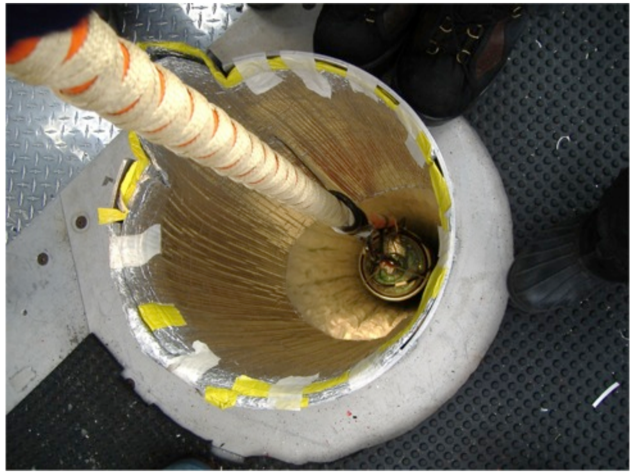
45 institutes and ~300 physicists

The deployment



Use hot water to make a hole

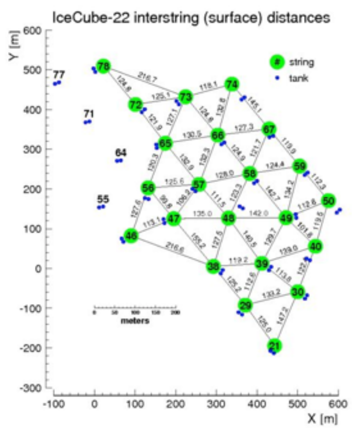




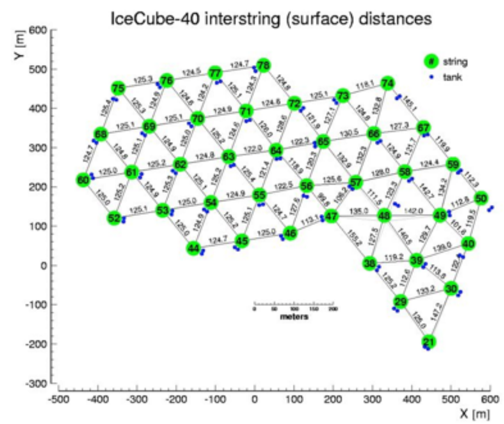
The construction

2004: project started
2006-2007: IC9
2007-2008: IC22
2008-2009: IC40
2009-2010: IC59
2010-2011: IC79
End of 2010: IceCube completed!
2011~: IC86

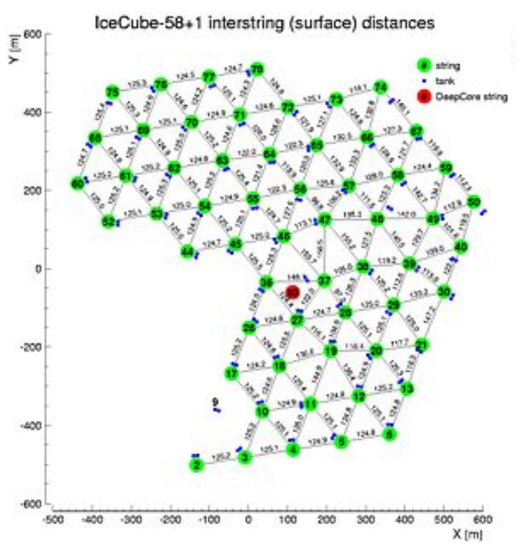
IC22 (2007-2008)



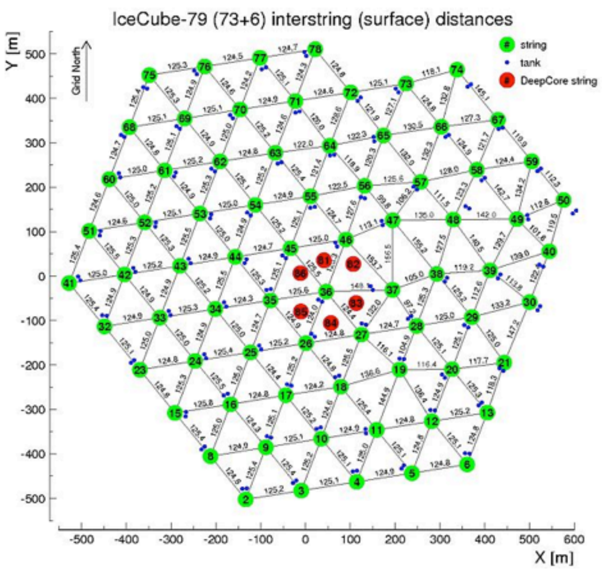
IC40 (2008-2009)



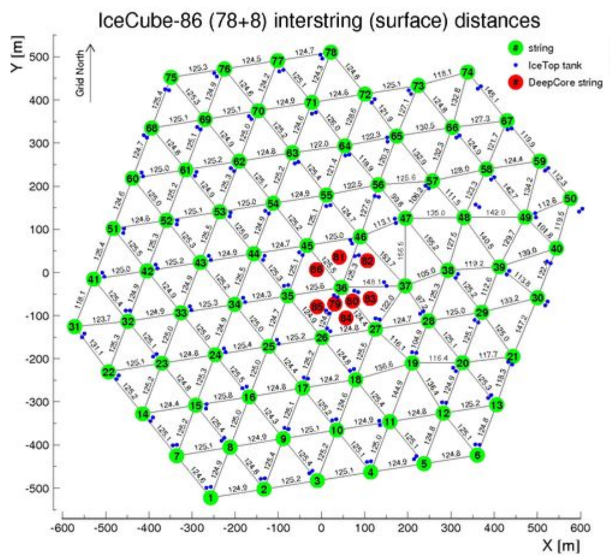
IC59 (2009-2010)



IC79 (2010-2011)



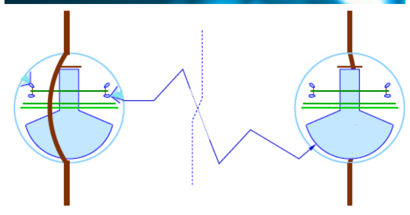
IC86 = complete IceCube (2011~)

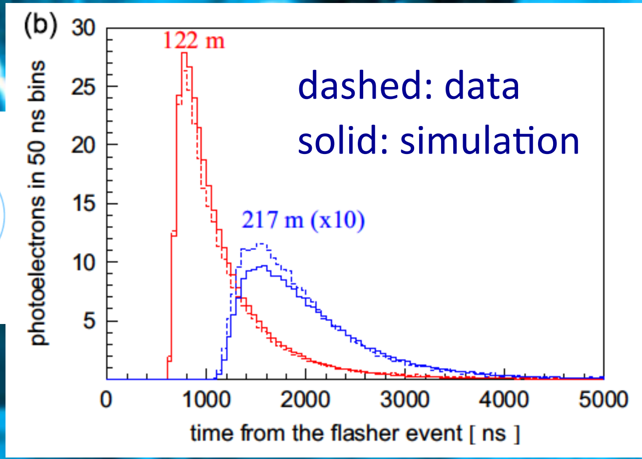


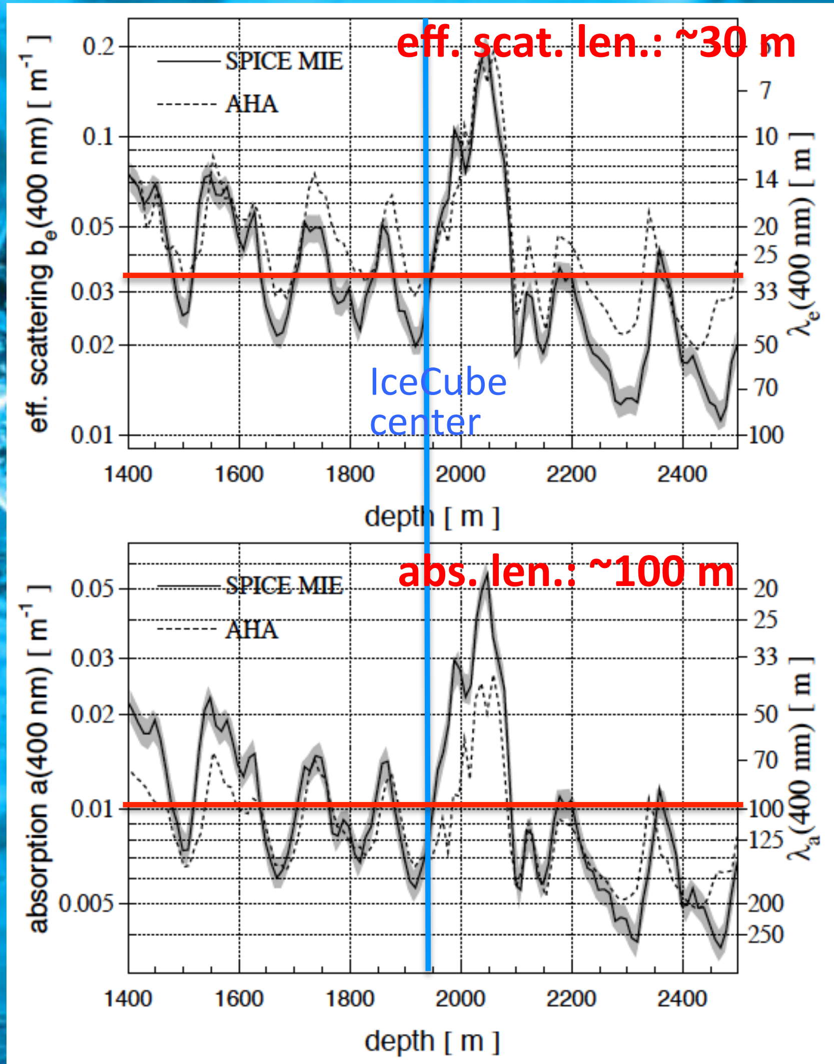
Calibration of our detector: ice

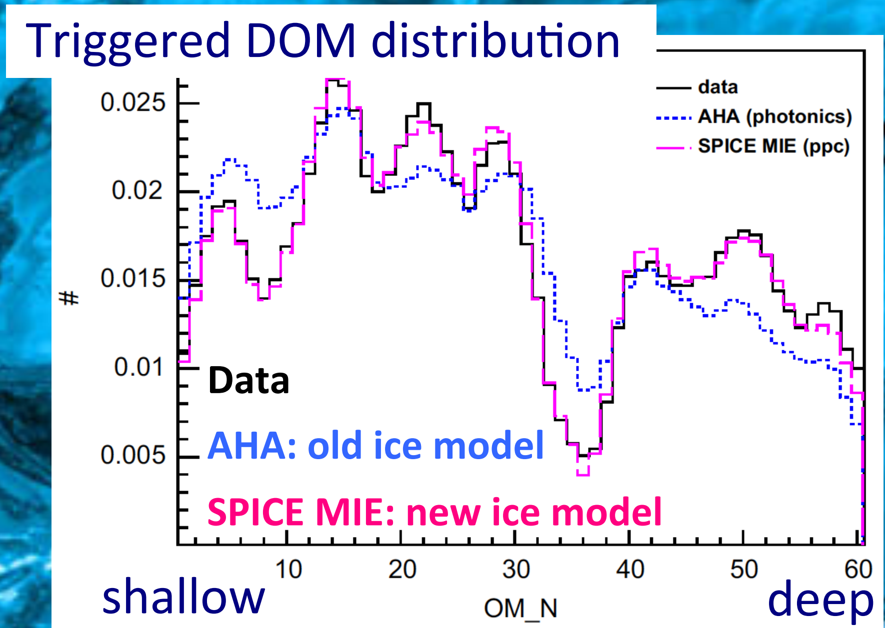
Ice properties calibrated by LEDs installed in DOMs

NIM A, 711, 73 (2013)





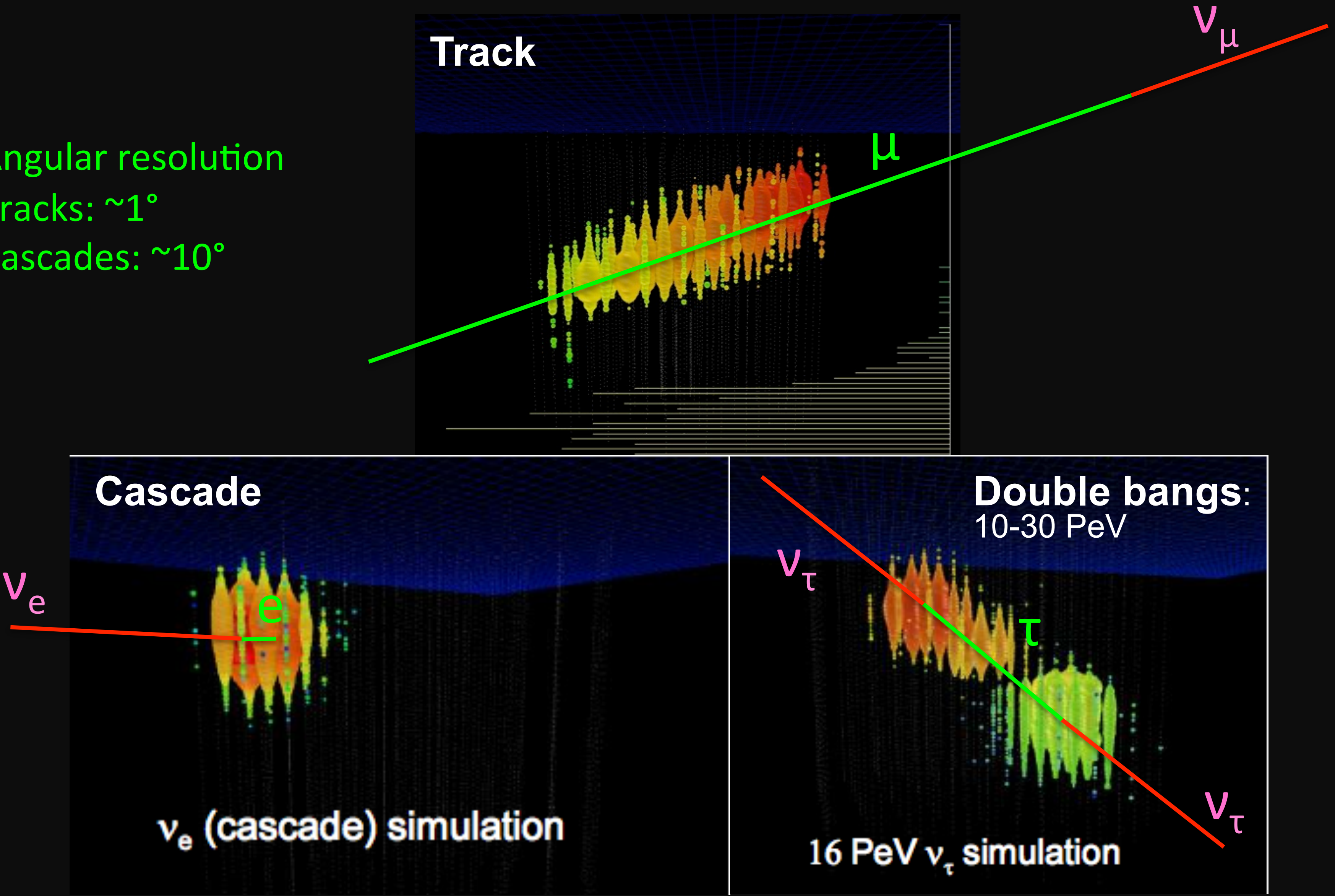




We understand the ice properties better!

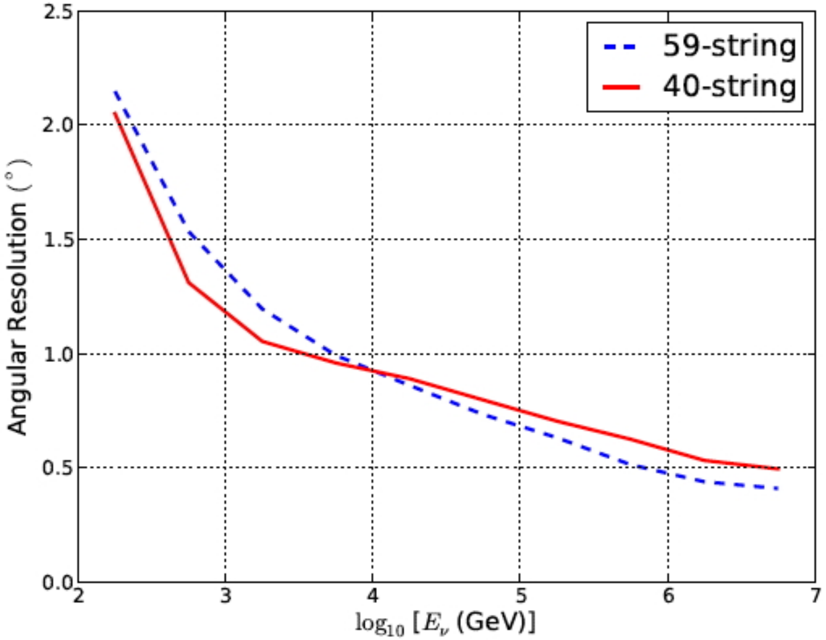
Particle identification

Angular resolution
Tracks: ~1°
Cascades: ~10°

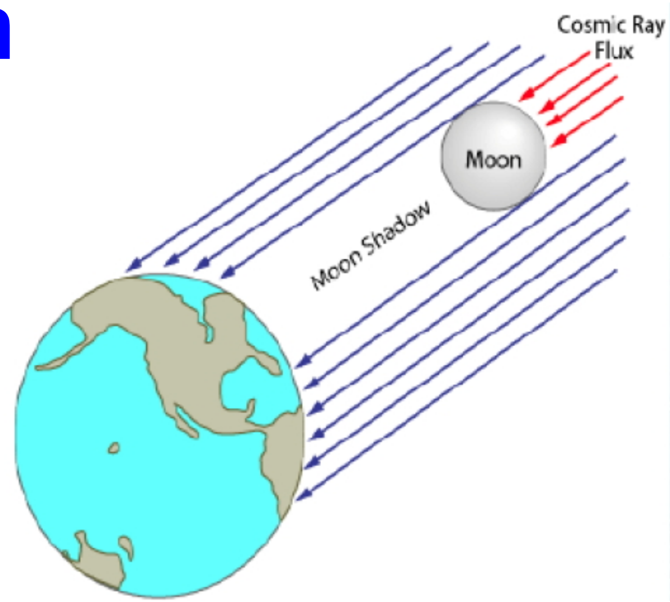


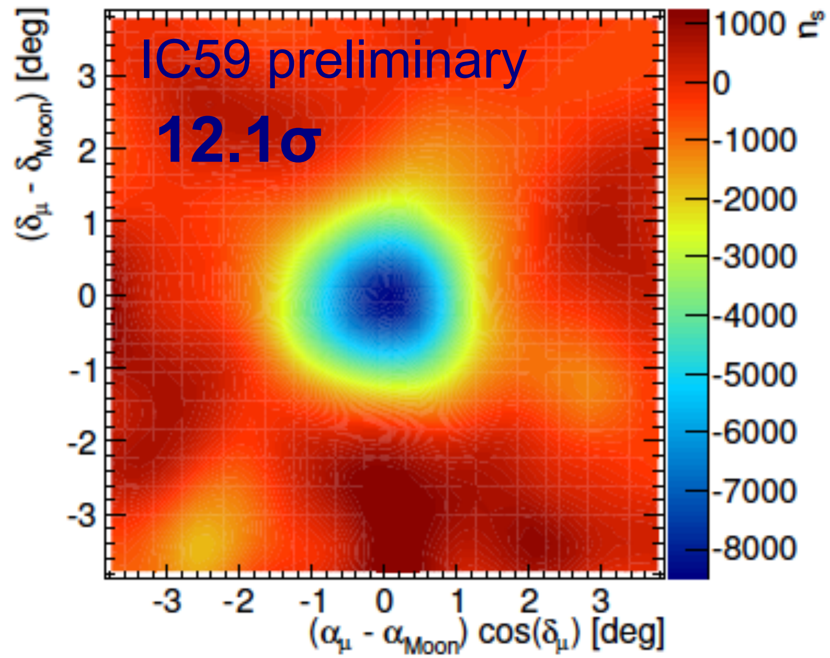
Note: neutral current events also generate cascades

The angular resolution



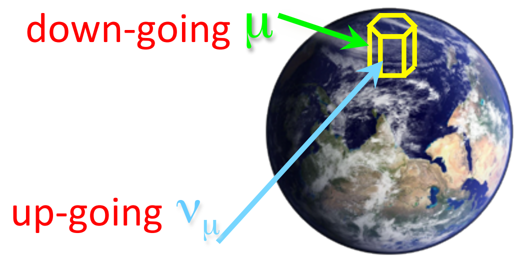
arXiv:1111.2741



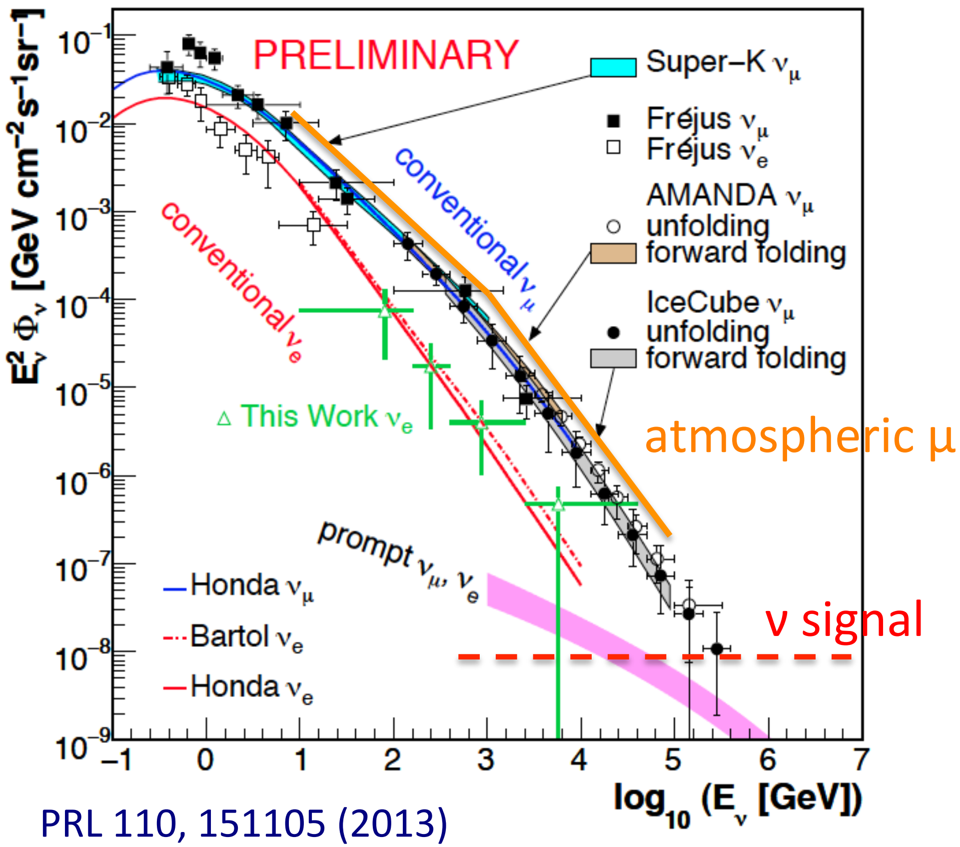


- Systematic angular shift < 0.2°
- Angular resolution < 1° (> 10 TeV)

Backgrounds

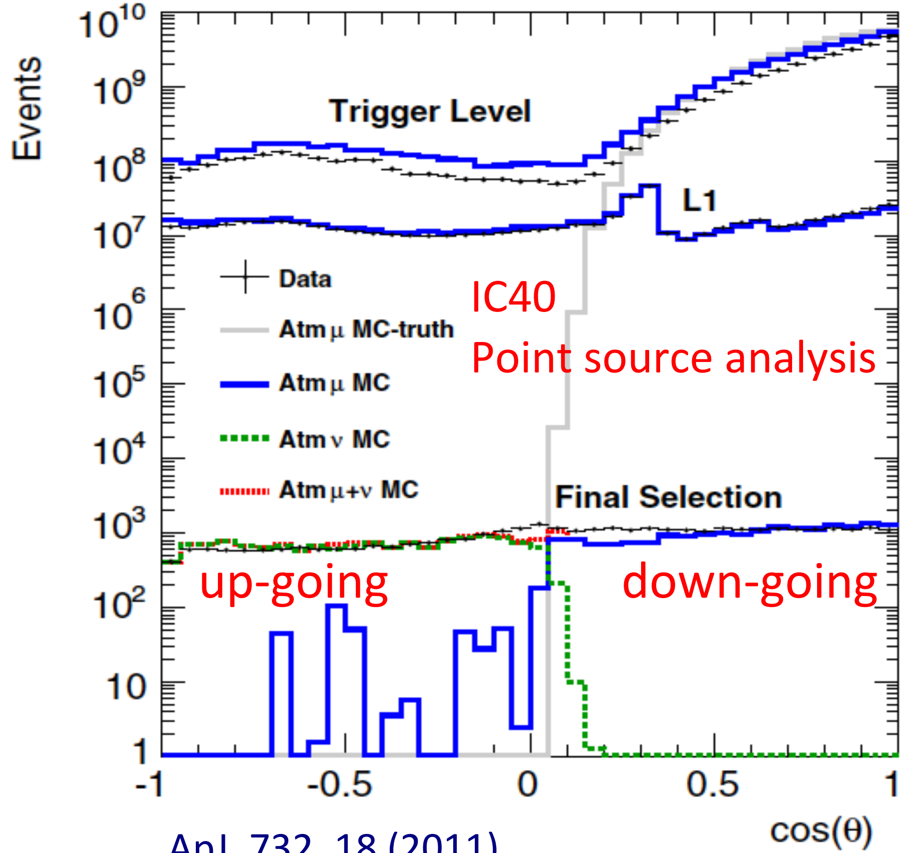


Energy spectra @ surface



PRL 110, 151105 (2013)

Zenith angle distribution @ detector



ApJ, 732, 18 (2011)

- Three main backgrounds: Atm μ, Atm ν, prompt ν (all CR originated)
- Essentially energy and zenith angle information used for signal searches

Point source search

Sensitive: > ~1 TeV

Search for muon neutrinos by using mainly the directions (energy info also used)

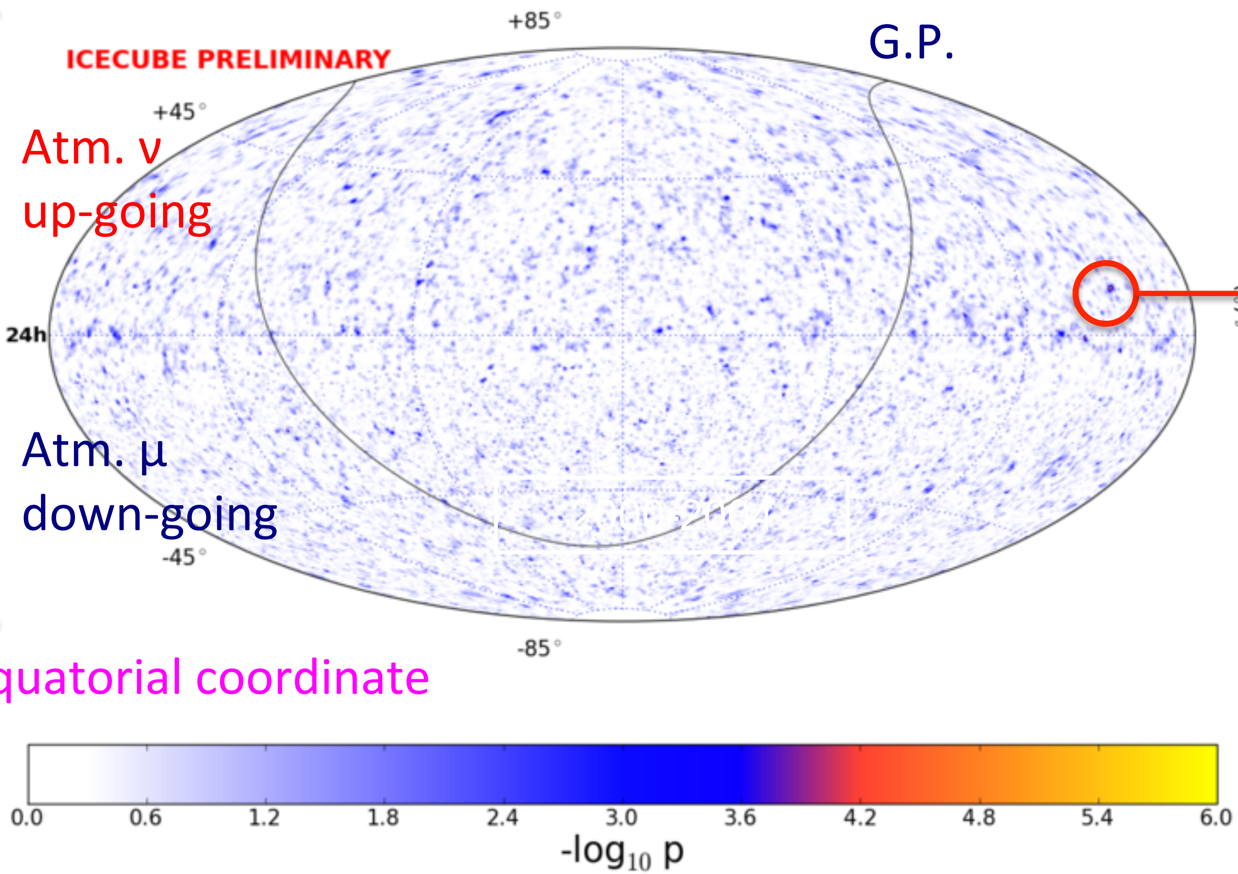
Test null hypothesis of no signal against one with signals

4-year data (IC40+IC59+IC79+IC86-I): 1371.7 days

178000 ν + 216000 μ

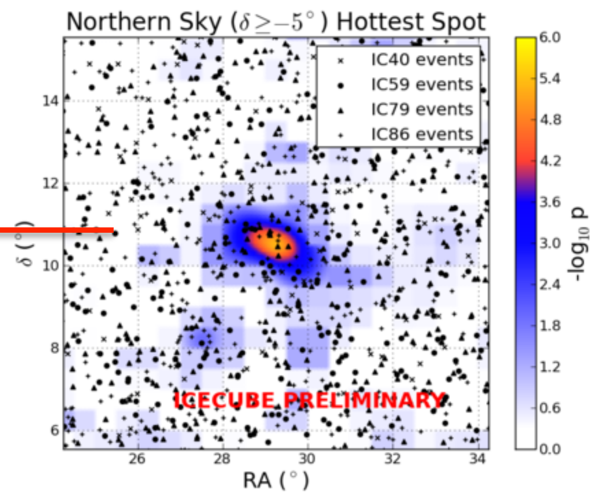
Atm. ν up-going

Atm. μ down-going



Equatorial coordinate

Hottest spot



post-trial after scrambling data

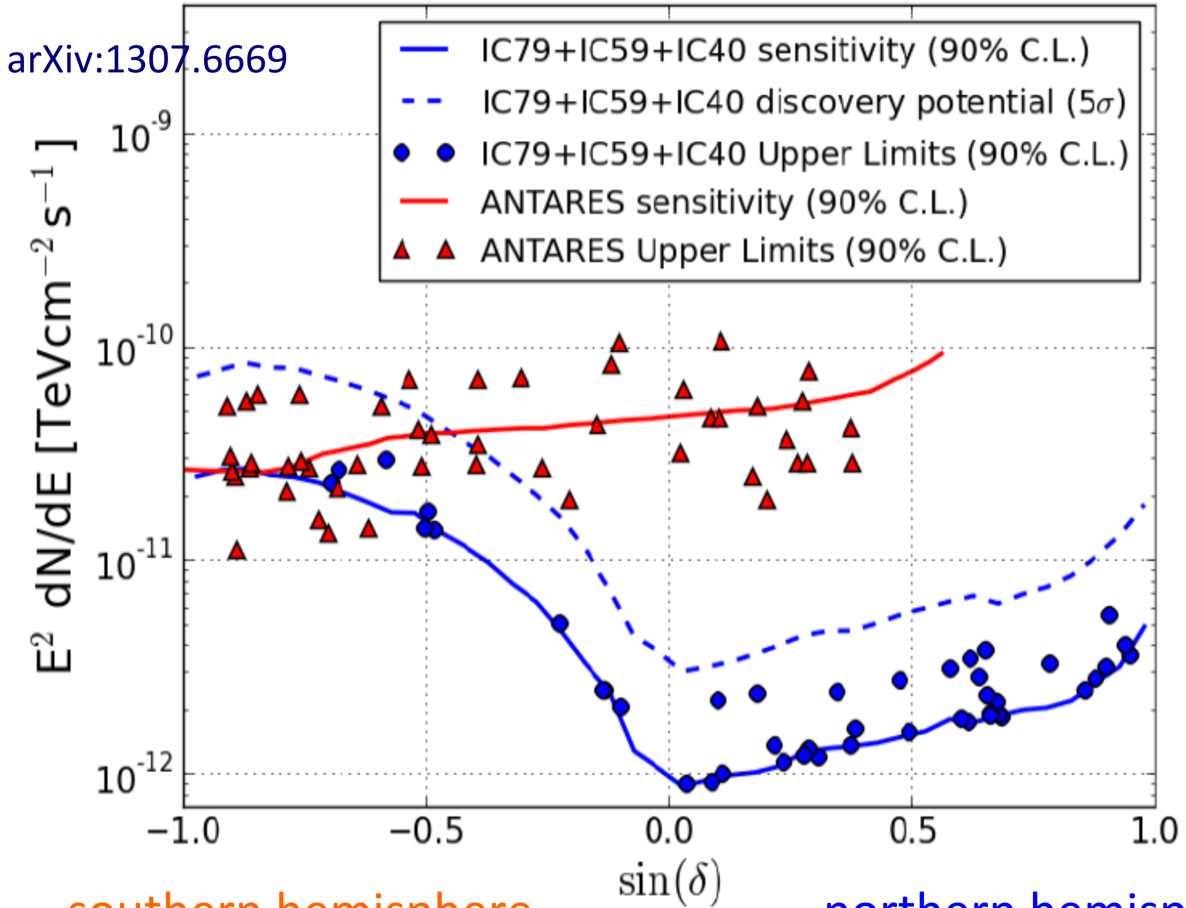
→ P-value: 22.6%

Not significant

Upper limit for selected sources

Most significant 44 sources are selected a priori to reduce the number of trials

The list was determined by a modeling producing neutrinos



southern hemisphere

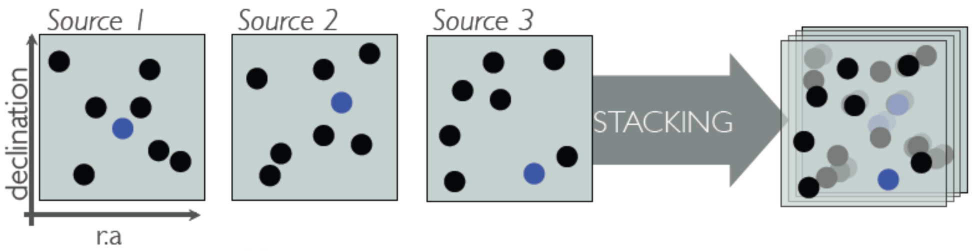
northern hemisphere

S5 0716+71	3C279
M82	QSO 2022-077
1ES 1959+650	PKS 1406-076
TYCHO	QSO 1730-130
LSI 303	Sgr A*
Cas A	PKS 1622-297
1ES 2344+514	PKS 2155-304
3C66A	PKS 1454-354
H 1426+428	Cen A
BL Lac	PKS 0537-441
NGC 1275	
Cyg OB2	
Cyg X-3	
Cyg A	
Mrk 501	
Mrk 421	
4C 38.41	
MGRO J2019+37	
Cyg X-1	
3C 123.0	
W Comae	
IC443	
Crab Nebula	
1ES 0229+200	
Geminga	
PKS 0235+164	
3C 454.3	
PKS 0528+134	
M87	
PKS 1502+106	
MGRO J1908+06	
HESS J0632+057	
SS433	
3C 273	

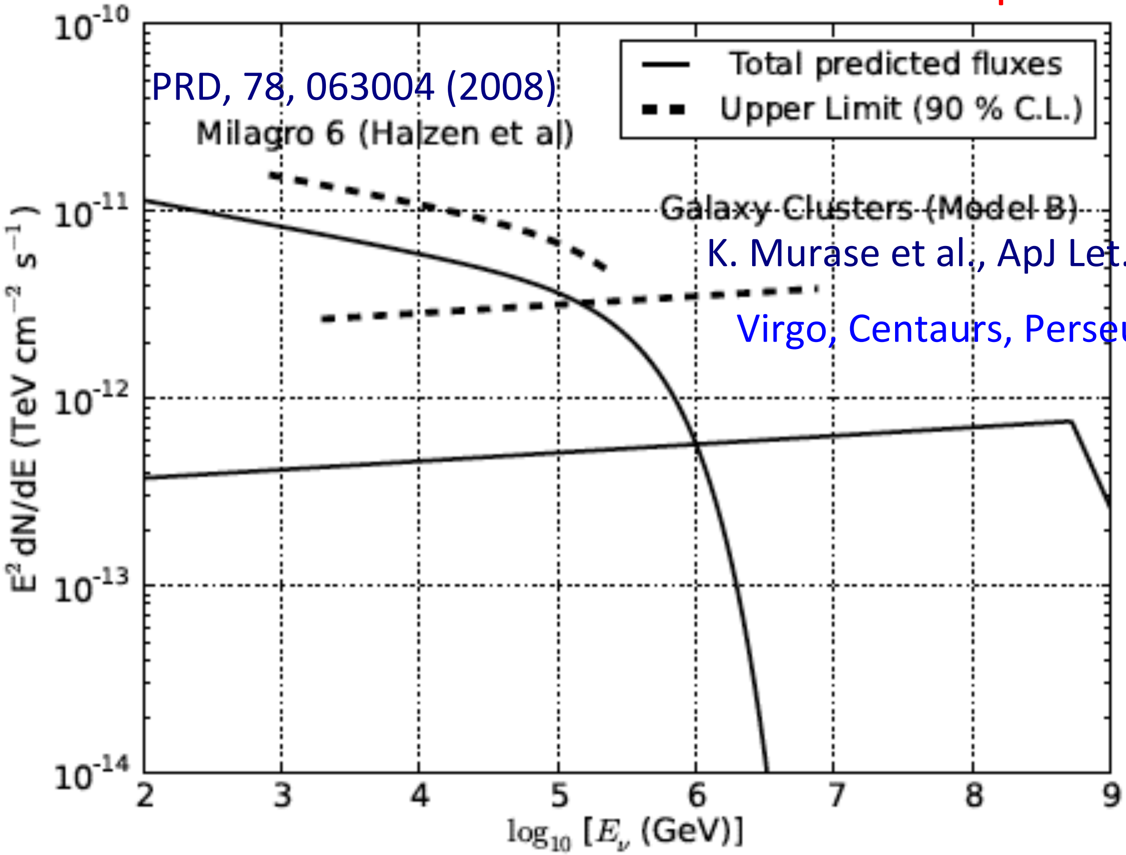
Stacking analysis

arXiv:1307.6669

Increase the ability by stacking a specific source class



Pp interactions



CRs generated inside virial radius of clusters

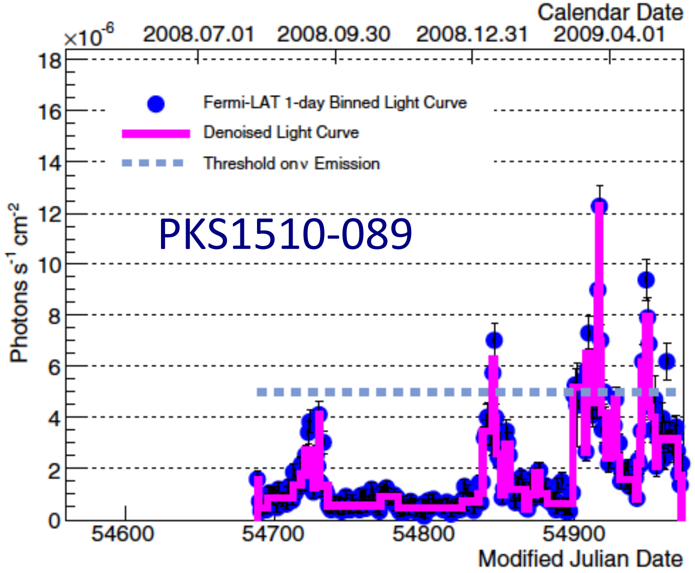
K. Murase et al., ApJ Let., 689, L105 (2008)

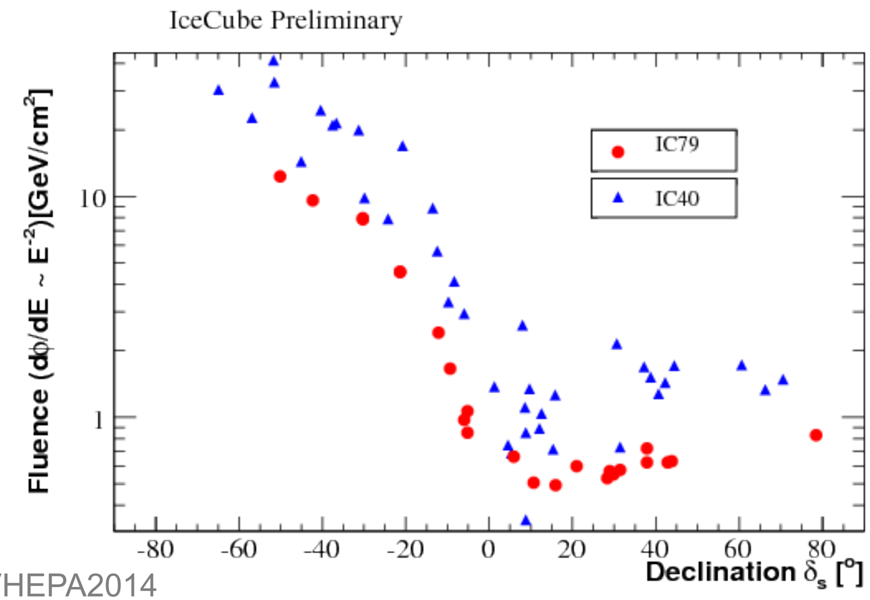
Virgo, Centaurs, Perseus, Coma, Ophiuchus

Close to model prediction

Search for neutrinos from AGN flares

- ✓ Use timing information of AGN flares to reduce background
- ✓ Fermi data used for selecting sources and the light curve
- ✓ Selected hard spectrum BL-Lacs, and FSRQs
- ✓ No significant signal was found

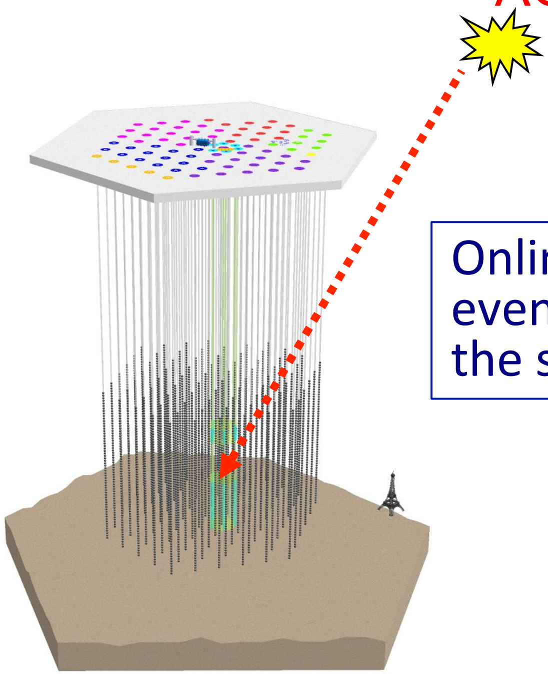




IceCube follow-up programs

- ✓ Send alerts to satellites/telescopes
- ✓ Multi messenger approach
- ✓ Few alerts per year

AGN/SN/GRB



Online neutrino event selection at the south pole

Alert

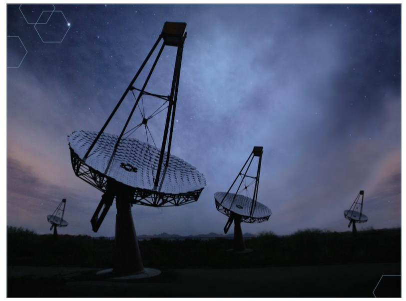
Swift (X-ray)

PTF (optical)

ROTE (optical)

MAGIC (γ-ray)

VERITAS (γ-ray)



EHE online alert is coming

Search for neutrinos from GRBs

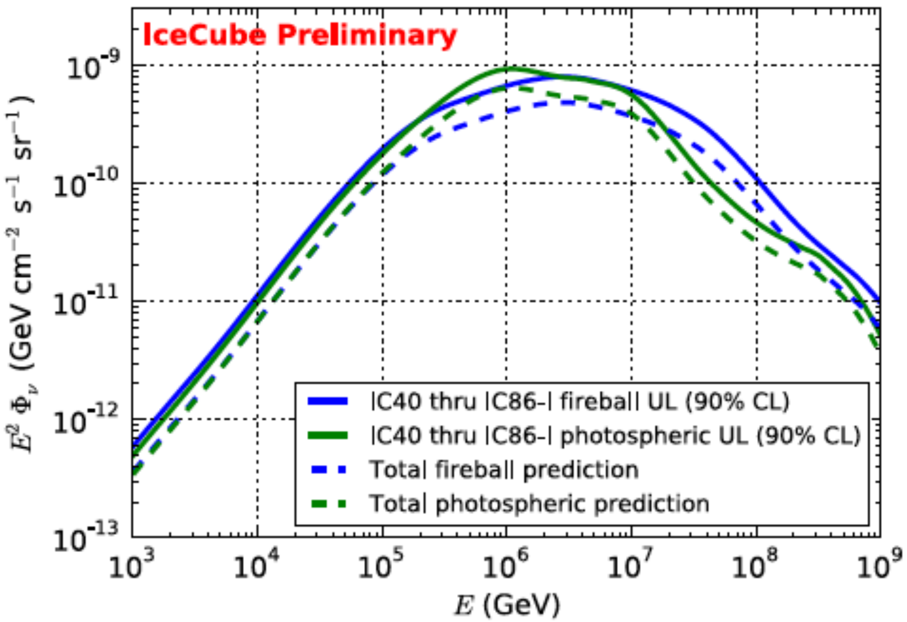
neutrino (ν_μ) searches by using the direction and the timing information of GRBs

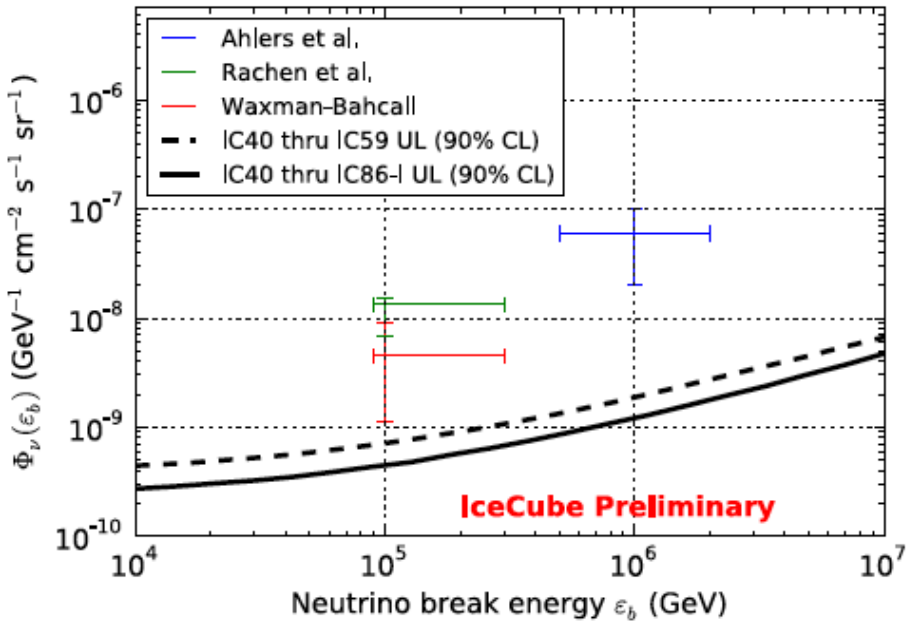
→ Very low backgrounds

arXiv: 1309.6979

4 year data (IC40+IC59+IC79+IC86-I) ~540 GRBs

No significant neutrino signal → limits





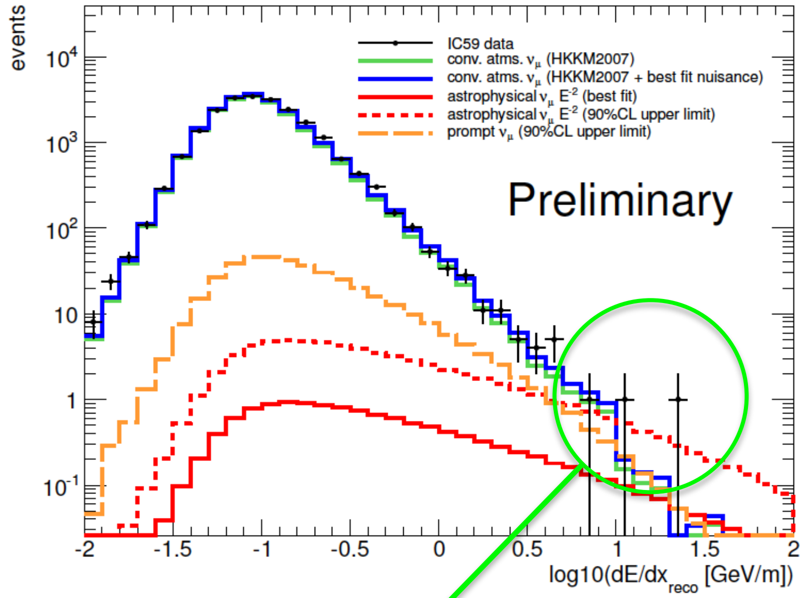
Either GRBs are not the main source for UHECRs

Or, theoretical models may need modifications

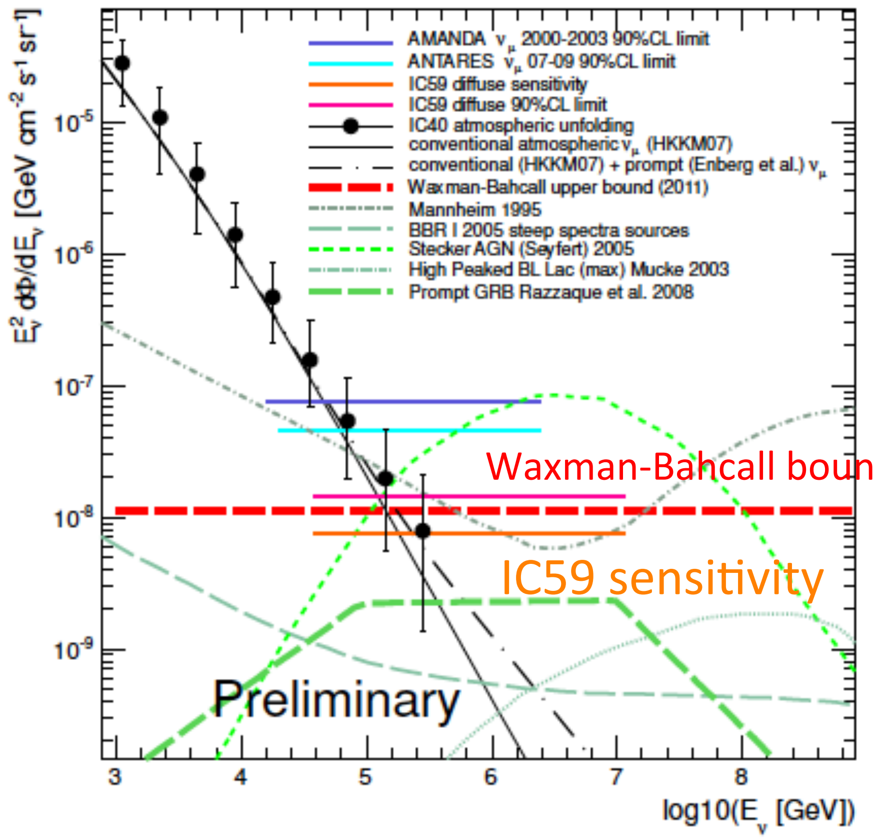
Diffuse neutrino search

Idea to integrate weak neutrino flux
Search for diffuse muon neutrinos by using mainly energy information
Signal slope is harder than background slope

arXiv:1302.0127



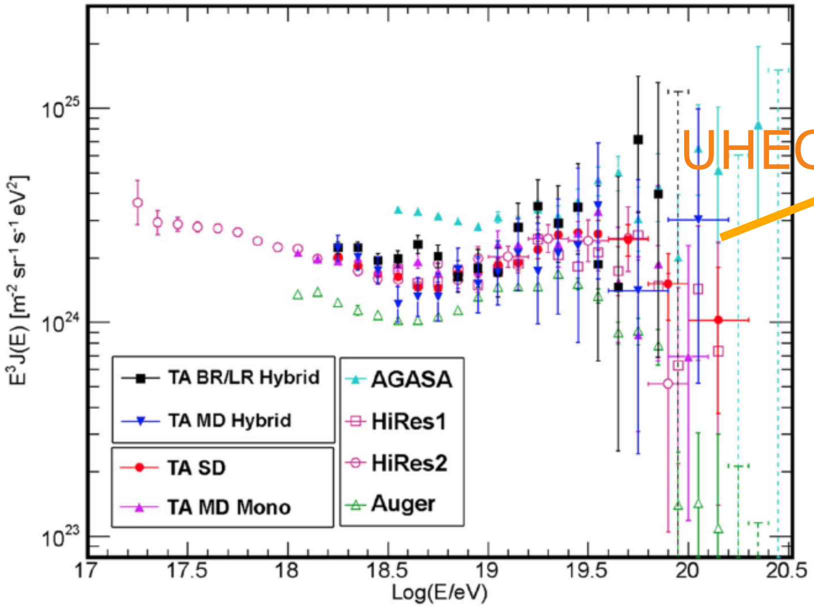
Sensitive: 30 TeV-10 PeV

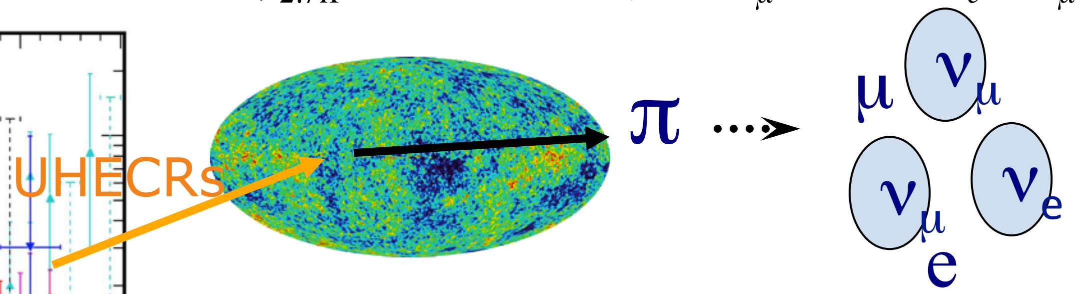


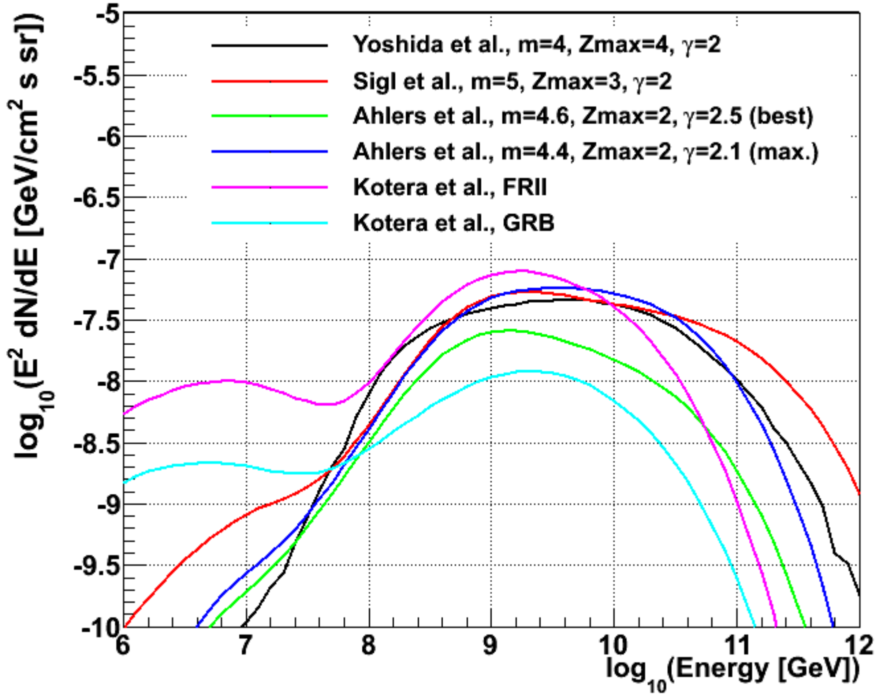
- Sensitivity is below Waxman-Bahcall bound
- Atmospheric neutrinos measured from 100 GeV - 300 TeV
  → Consistent with previous measurements

The extremely high energy (EHE) cosmogenic neutrino search

$$p\gamma_{2.7K} \rightarrow \pi^{+} + X \rightarrow \mu^{+} + \nu_{\mu} \rightarrow e^{+} + \nu_{e} + \overline{\nu_{\mu}} + \nu_{\mu}$$







Shed light on the UHECR origin

- ✧ Source position
- ✧ Composition (proton/iron)?
- ✧ Source evolution / when the UHECR generation started

All flavor sensitive, Energy > 1 PeV

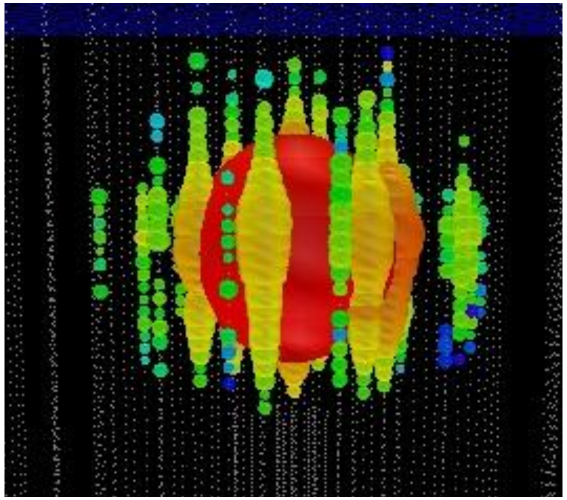
Two cascade like events found in 2011-2012 data

May, 2011 - May, 2012 (350.9 days), IC86 configuration

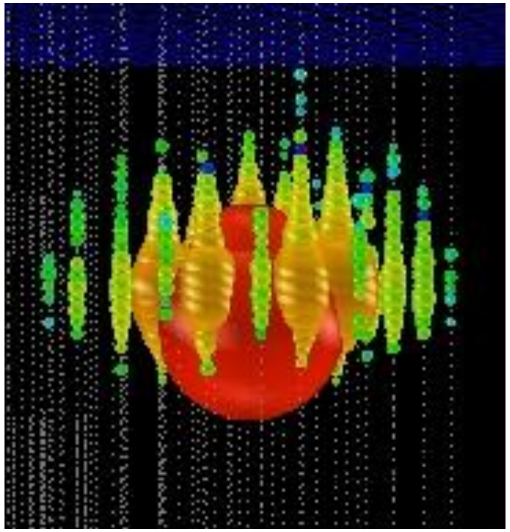
PRL 111, 021103 (2013)

Either CC interaction of ν_e or NC interaction of any flavor ν

"Bert"
Aug., 9th, 2011
Run 118545
-Event 63733662
NPE: 7.0×10^4
NDOM: 354
1.04±0.16 PeV



"Ernie"
Jan, 3rd, 2012
Run 119316
-Event 36556705
NPE: 9.6×10^4
NDOM: 312
1.14±0.17 PeV



	event rate in 615.9 days
Atmospheric muons	0.038 ± 0.004
conventional atmospheric neutrinos	0.012 ± 0.001
prompt neutrinos*	0.033 ± 0.001
total background	**0.082 ± 0.004**

* R. Enberg et al., PRD78, 043005 (2008)

Significance: 2.8σ

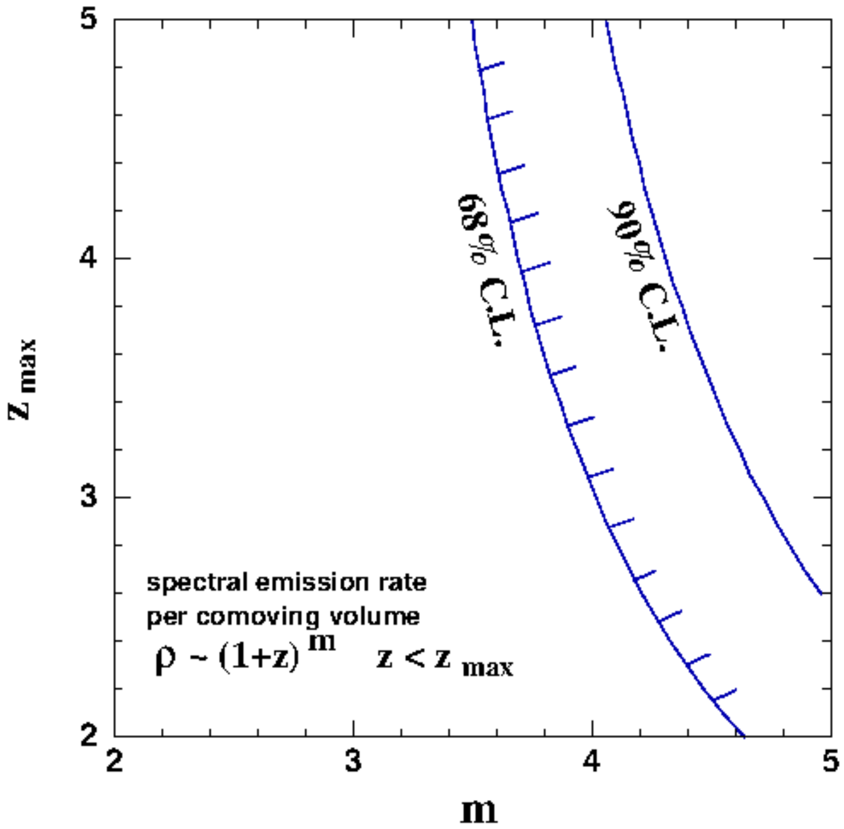
Highest energy neutrinos ever seen!

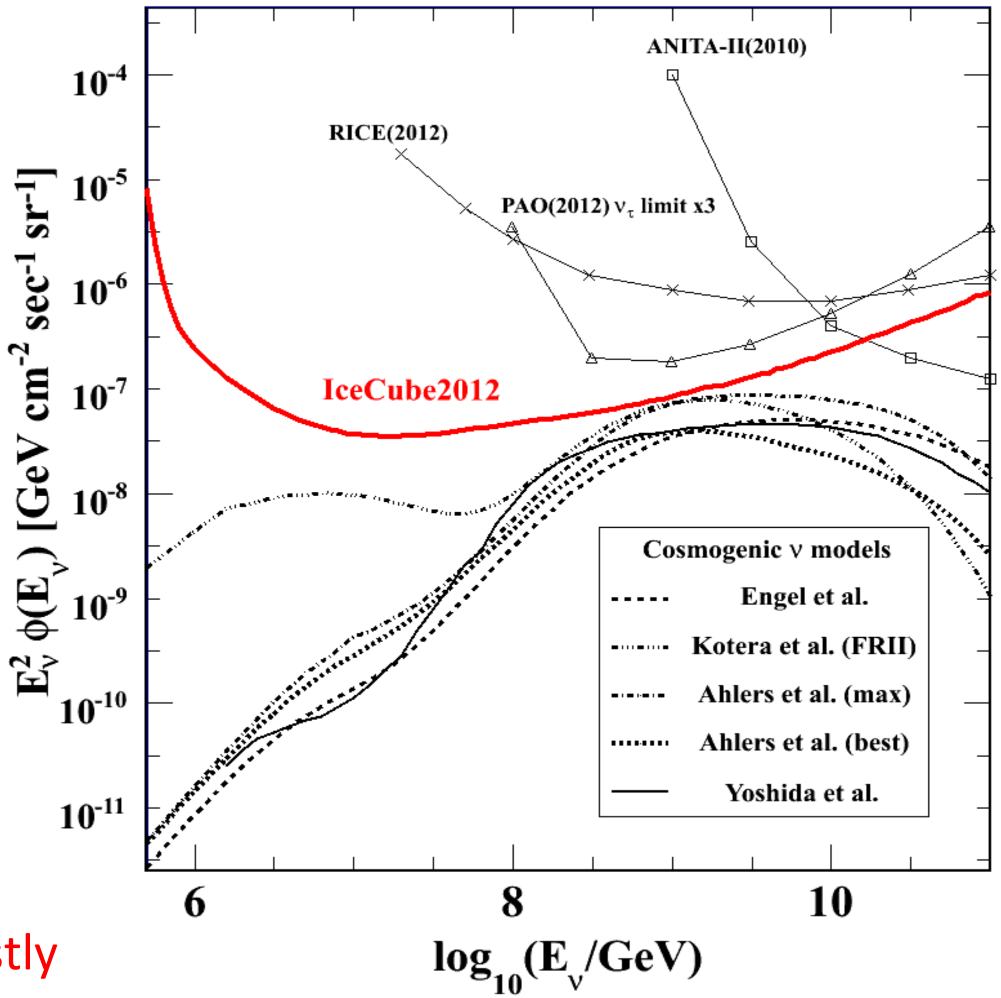
Limits

Energies of two PeV events are too low to be explained by cosmogenic neutrinos

No events observed above 100 PeV

PRD 88, 112008 (2013)



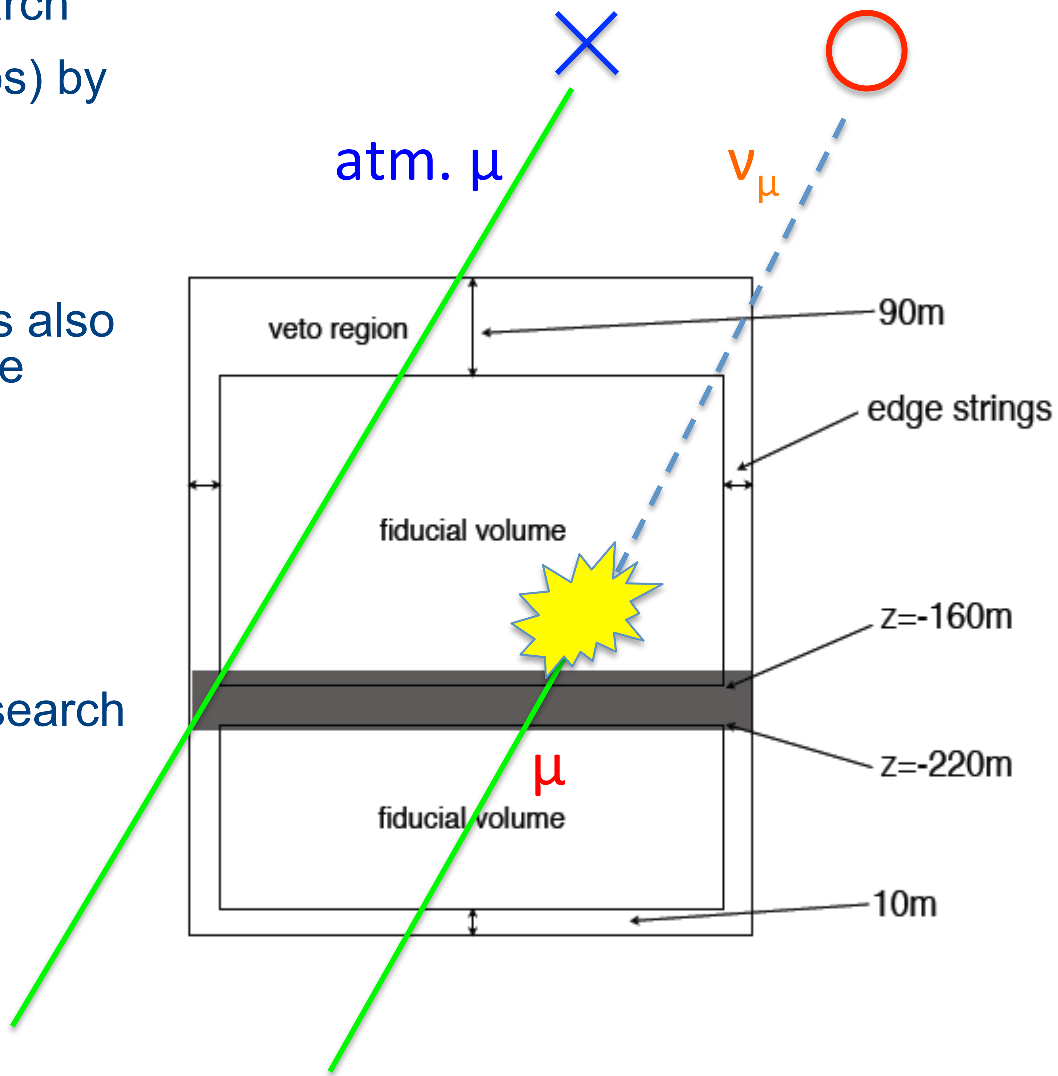


High evolution models (m>4) are mostly ruled out such as FR-II class of AGN

differential limit per one energy decade

High energy starting event search

- Follow-up of the EHE neutrino search
- Search contained events (neutrinos) by using outer layers as veto
- Atmospheric muon backgrounds reduced
- Atmospheric neutrino backgrounds also reduced as atmospheric muons are normally accompanied
- 420 Mton fiducial mass
- All flavor
- > 50 TeV
- 3 times better than EHE neutrino search @ 1 PeV



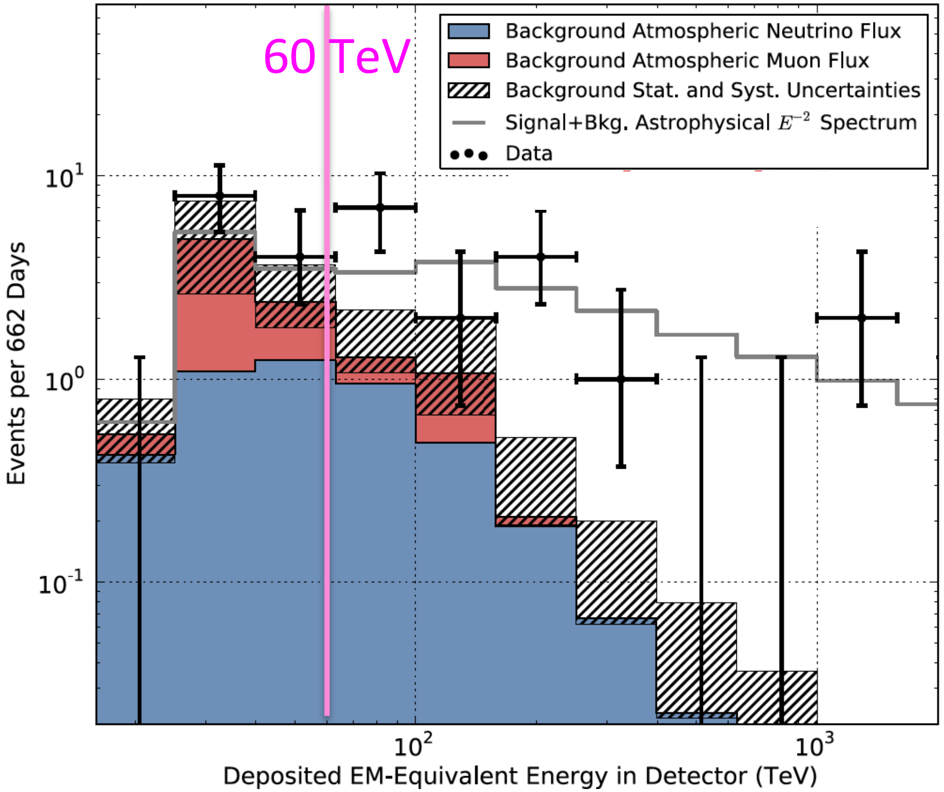
Deposited energy and zenith angle distributions

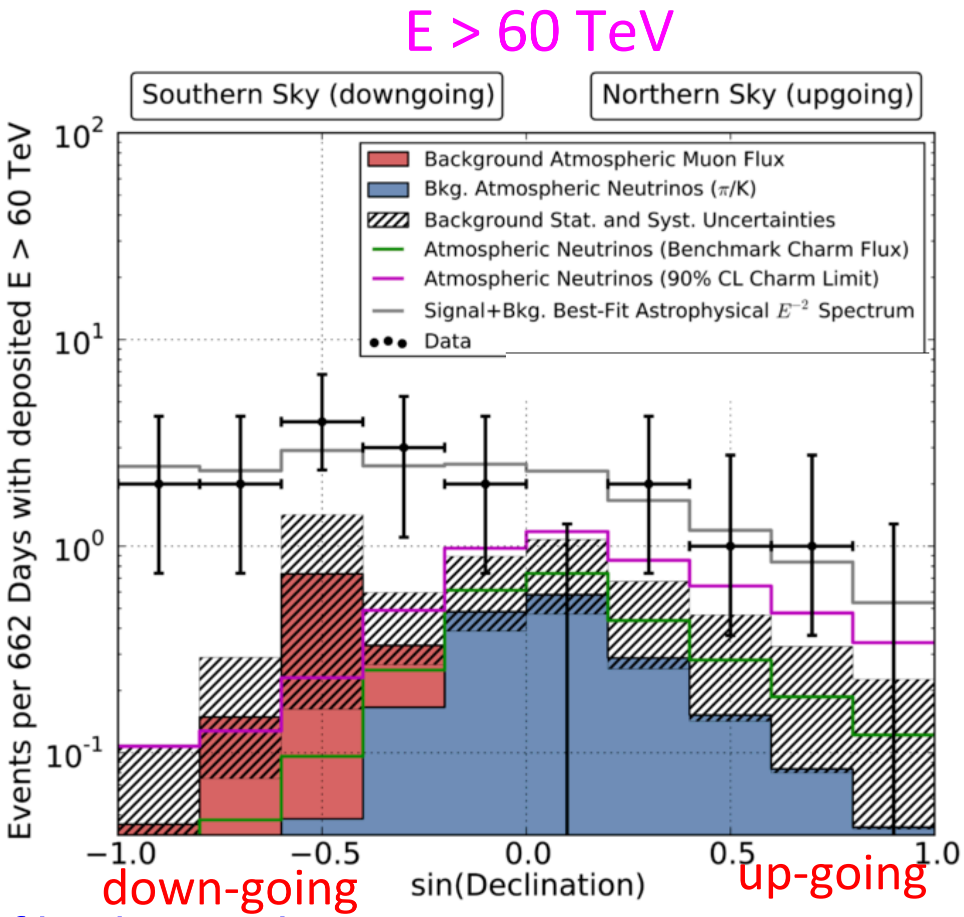
Other 26 events found! (19 cascades, 7 tracks) 2 year data

Significance: 4.1σ (26+2 events combined)

Science, 342, 1242856 (2013)

Expected BG: $10.6^{+5.0}_{-3.6}$





- Energy spectrum harder than that of backgrounds
- Best fit: $E^{-2.2\pm0.4}$
- $E^2\varphi = 3.6 \pm 1.2 \times 10^{-8}$ GeV/cm²/s/sr (3 flavors)

A. Ishihara will show 3yr results tomorrow

Sky map and the significance

Test null hypothesis against the most likely

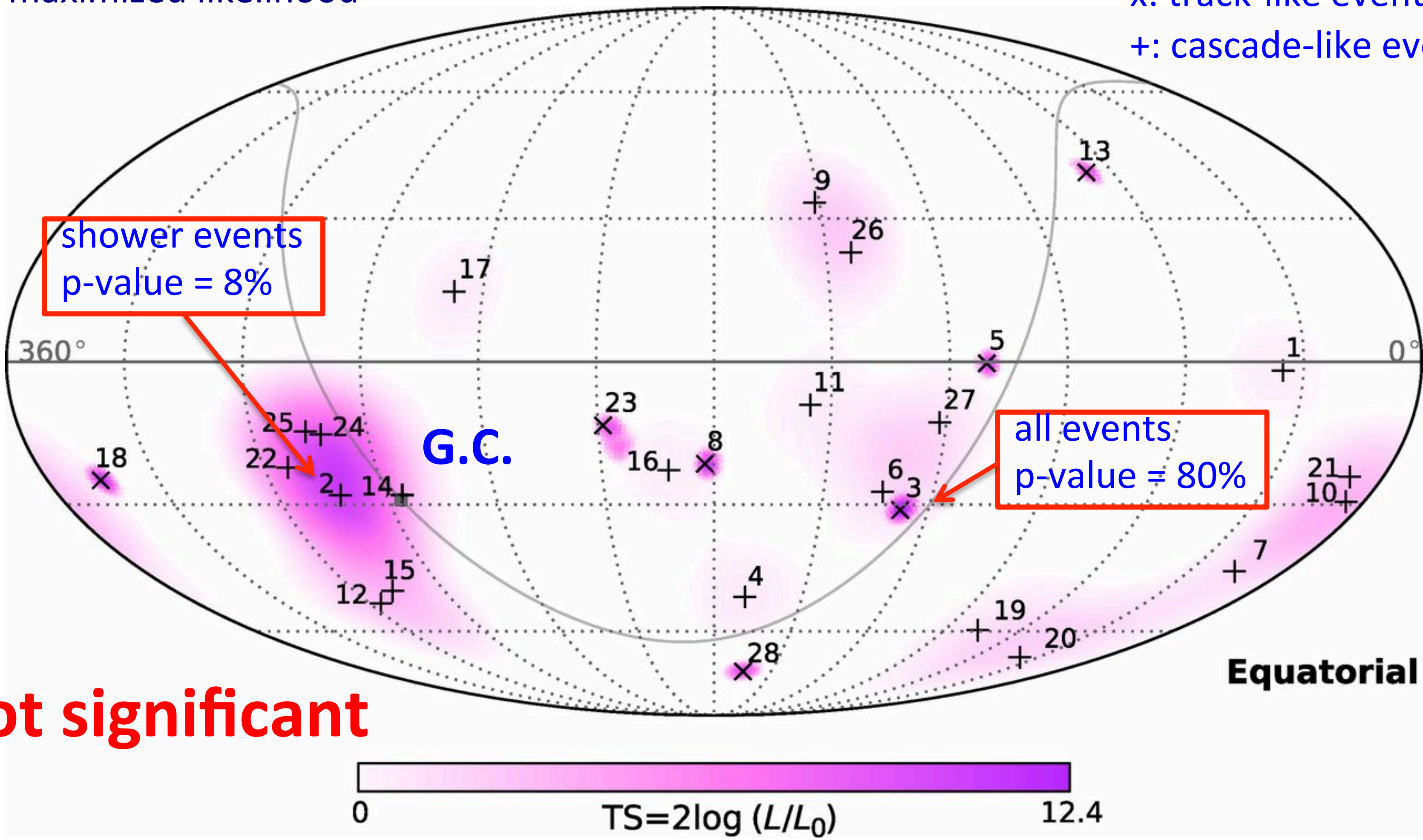
L0: null hypothesis

L: maximized likelihood

Science, 342, 1242856 (2013)

x: track-like events

+: cascade-like events



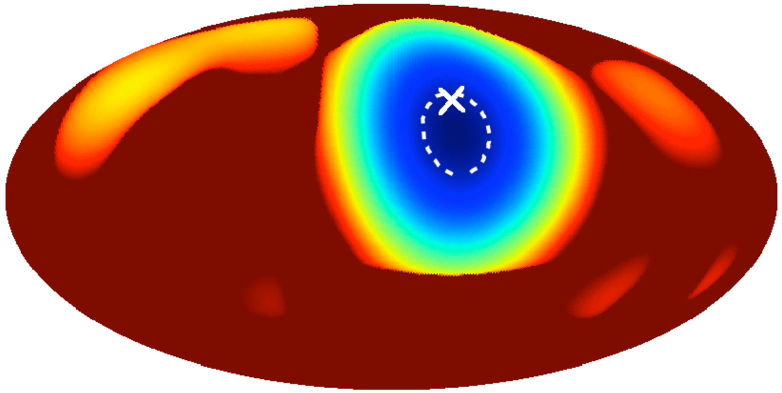
Not significant

HESE GRB correlation

- Investigated correlation between HESE events and GRBs
- Model independent (10s to 15 days)
- 568 GRBs
- “Best” time window: 80340 s (~ 22.3 hours)
- “Best” pre-trial p-value: 17%
- Post-trial p-value: 77%
- Not significant

Bert (1.04 PeV)
74.304 s after GRB
9.8 deg. apart

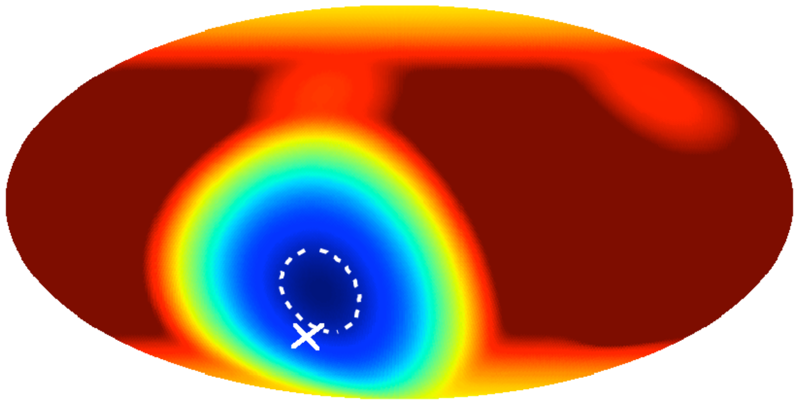
Spatial PDF



Preliminary

Oscar (63.2 TeV)
80.336 s after GRB
22.9 deg. apart

Spatial PDF



High energy extension

Increase the sensitivity at high energy (> 10 TeV)

IceCube (120 m): 1 km^2

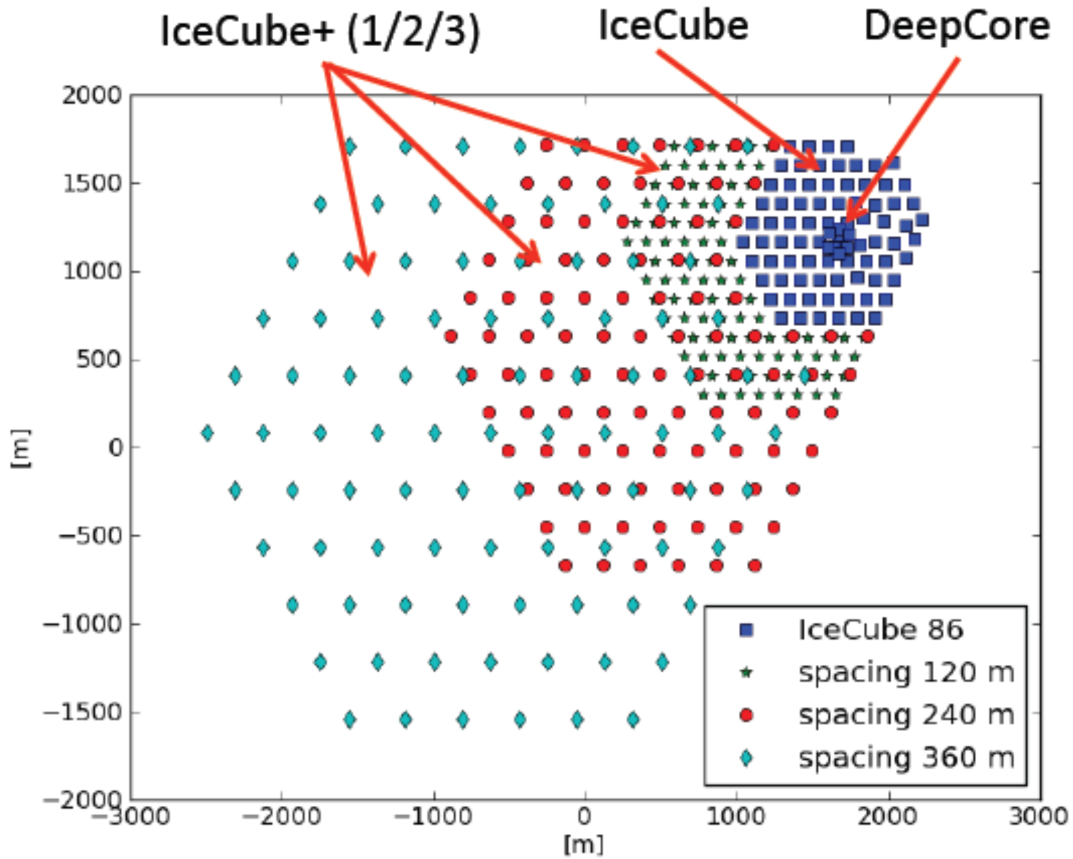
+HEX (120 m): 2.3 km^2

+HEX (240 m): 6.3 km^2

+HEX (360 m): 12.6 km^2

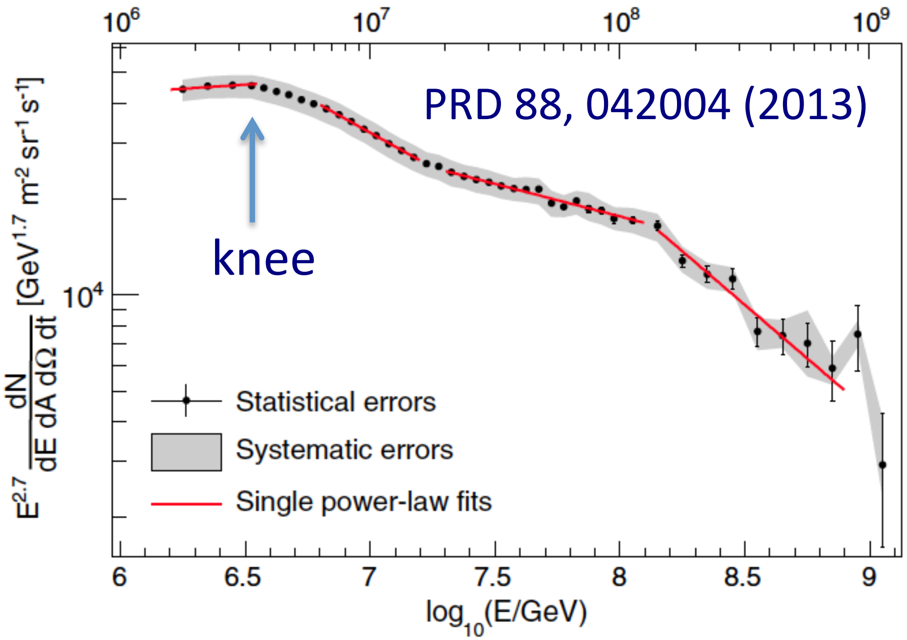
The optimization is on-going

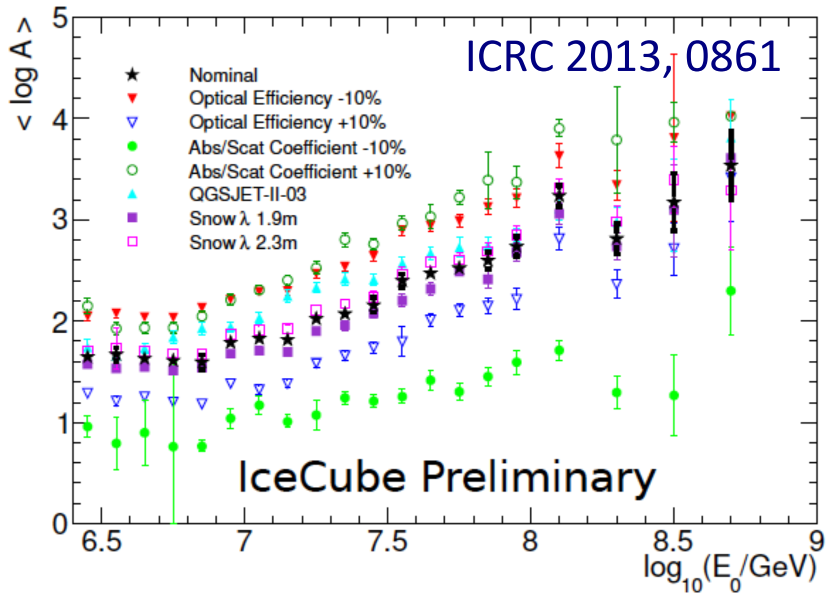
Additional idea to extend
surface tanks for veto



~100 new strings

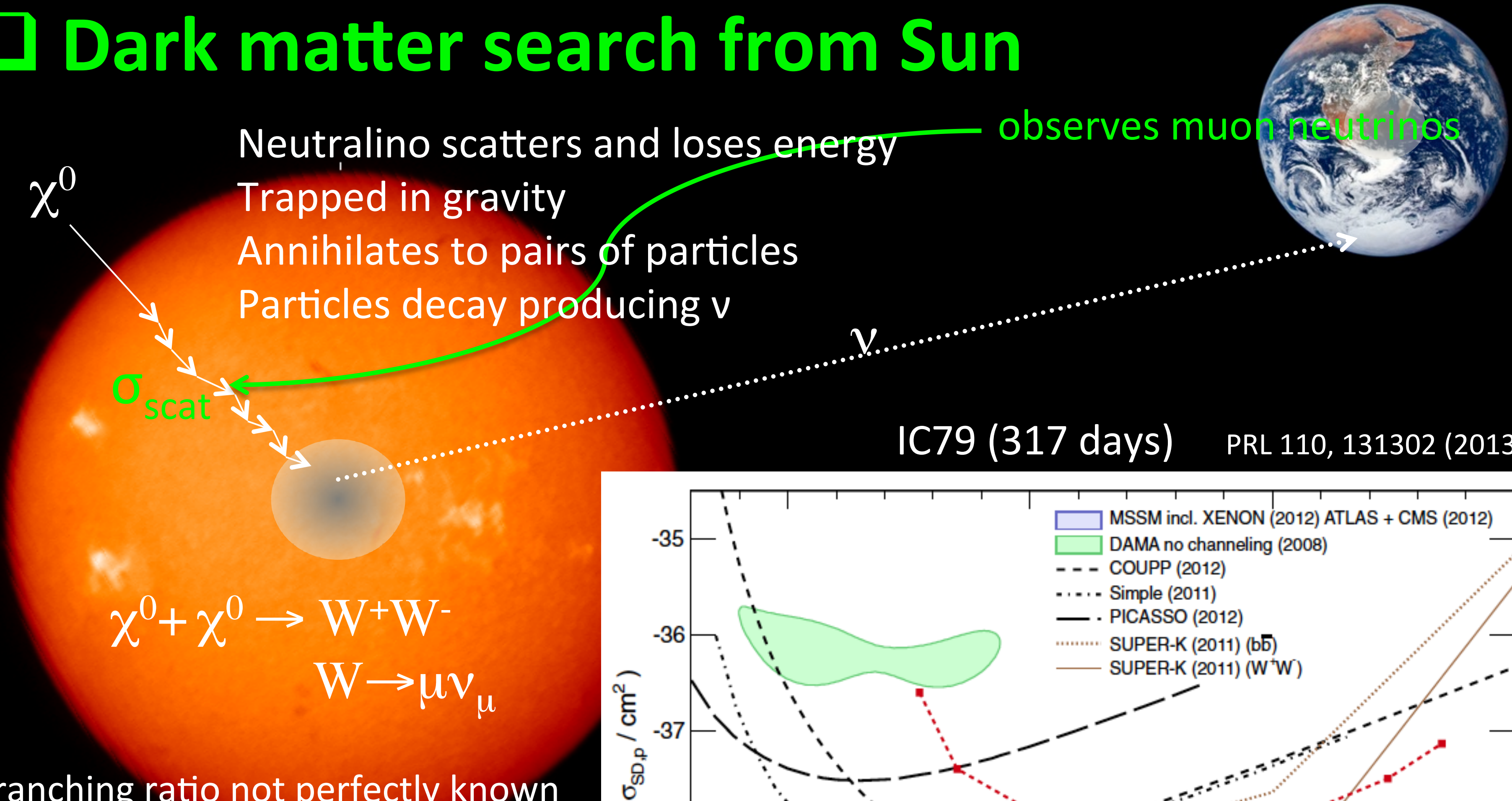
Cosmic ray measurements by IceTop





- 1 year cosmic ray energy spectrum measured by IceTop-73 configuration from 1.6 PeV to 1.3 EeV
- Precise measurement: uncertainty 12% above 10 PeV
- Consistent with other experiments
- 4 characteristic energy slopes found
- May indicate composition change
- Mass number increases with energy up to 100 PeV

❑ Dark matter search from Sun



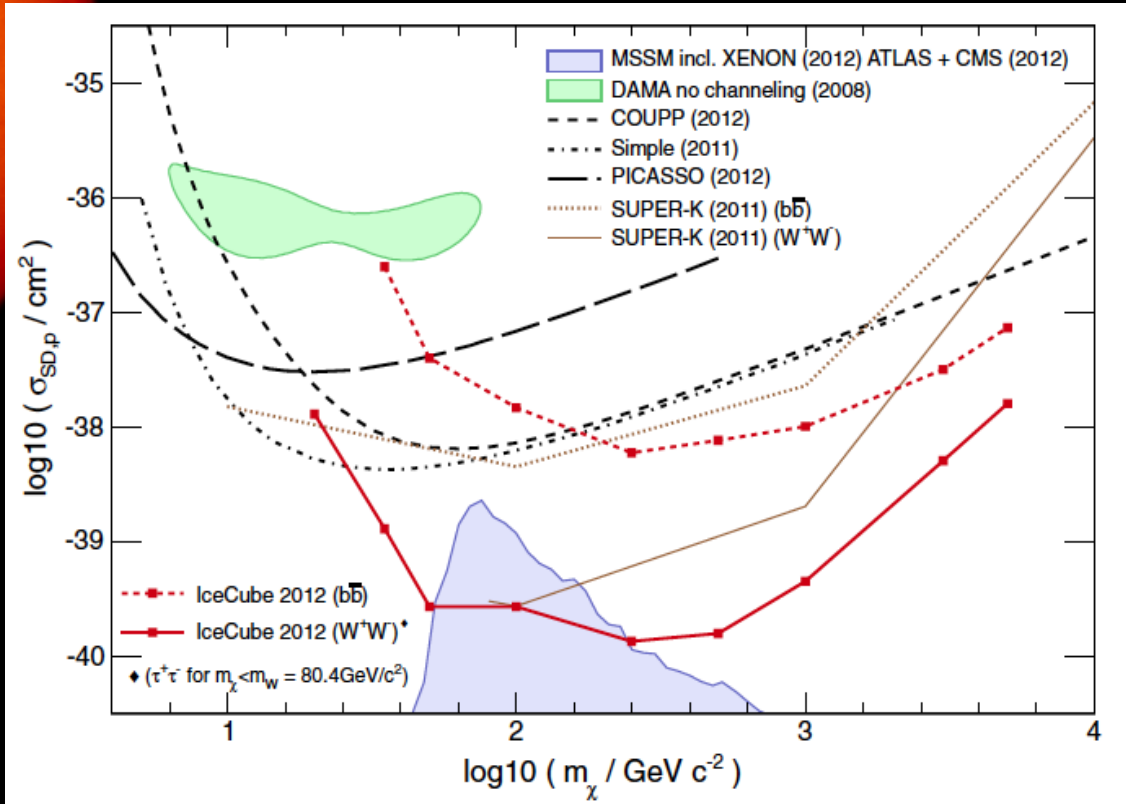
Neutralino scatters and loses energy
Trapped in gravity
Annihilates to pairs of particles
Particles decay producing ν

$\chi^0 + \chi^0 \rightarrow W^+W^-$
$W \rightarrow \mu\nu_\mu$

Branching ratio not perfectly known
$\chi^0 + \chi^0 \rightarrow W^+W^-$ (hard channel, typical)
$\chi^0 + \chi^0 \rightarrow b\bar{b}$ (soft channel, conservative)

χ^0: neutralino
Supersymetry particle
Mixture of super-partner of zino, photino, higgsino

IC79 (317 days) PRL 110, 131302 (2013)



❑ Dark matter search in the Milky Way

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

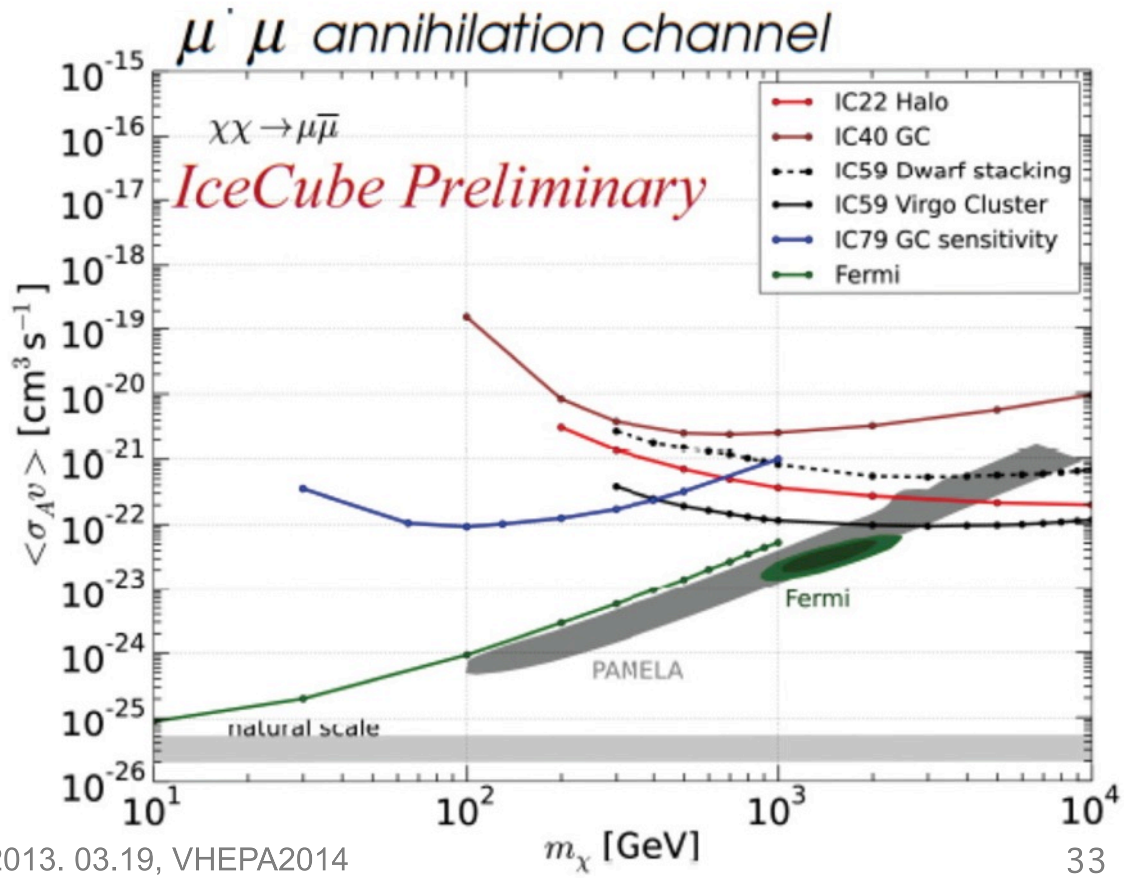
Dark matter density profile
(model dependent.
NFW model as benchmark.)

SUSY model (model dependent)

Measure of muon neutrinos

cross section to be constrained

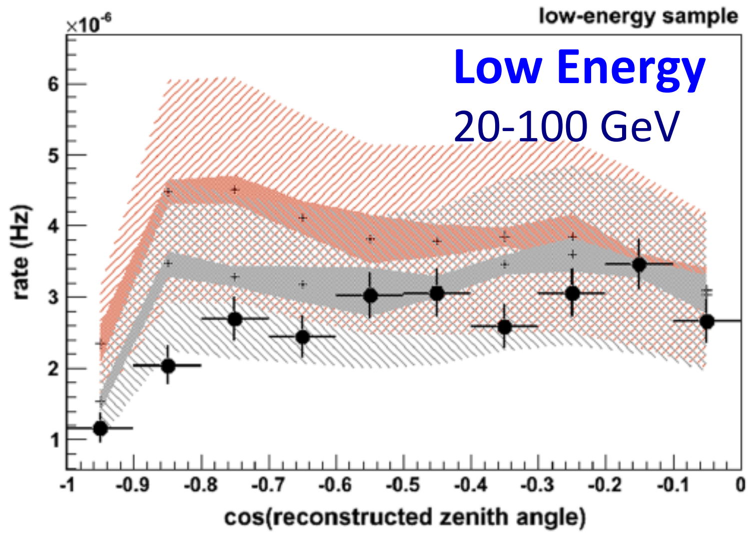
IC79 (320 days)
found no excess

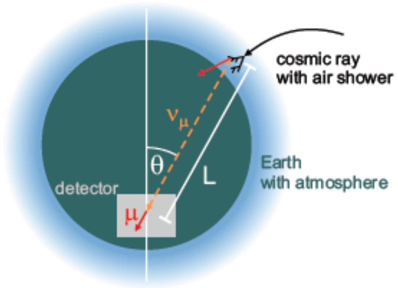


Atmospheric neutrino oscillation

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{23})\sin^2(1.27\Delta m_{32}^2 L/E)$$

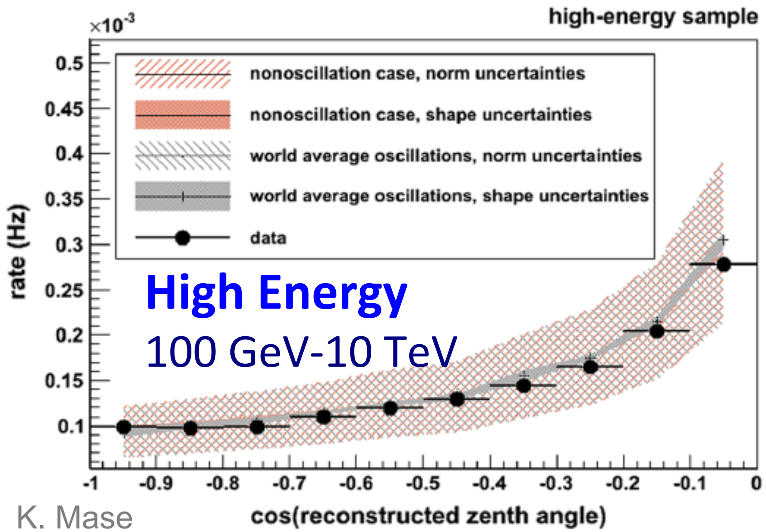
PRL, 111, 081801 (2013)

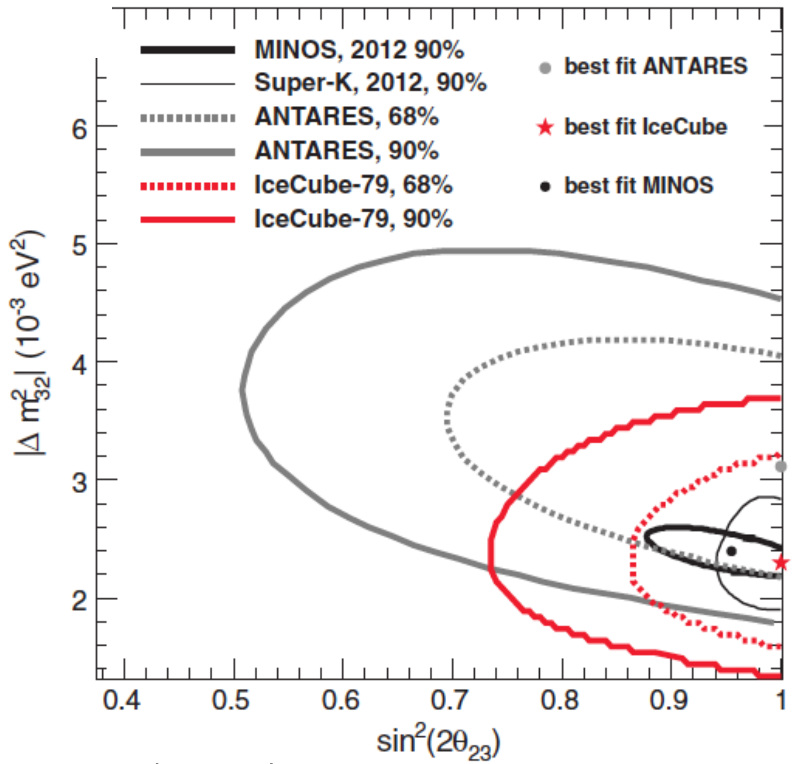




No oscillation scenario rejected by 5.6σ

IC79 (318.9 days)



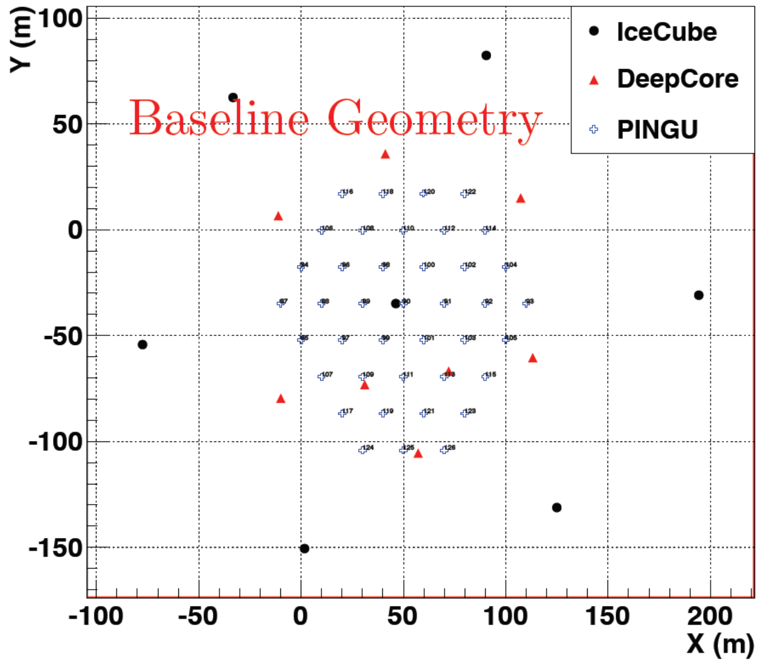


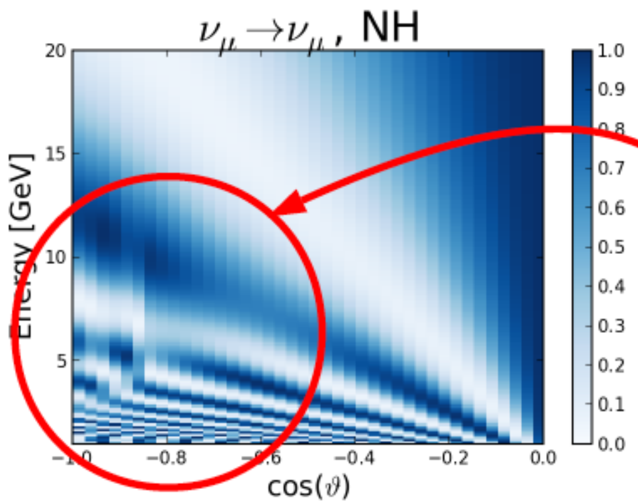
$$\left|\Delta m_{32}^2\right| = (2.3^{+0.6}_{-0.5}) \times 10^{-3}\ eV^2$$

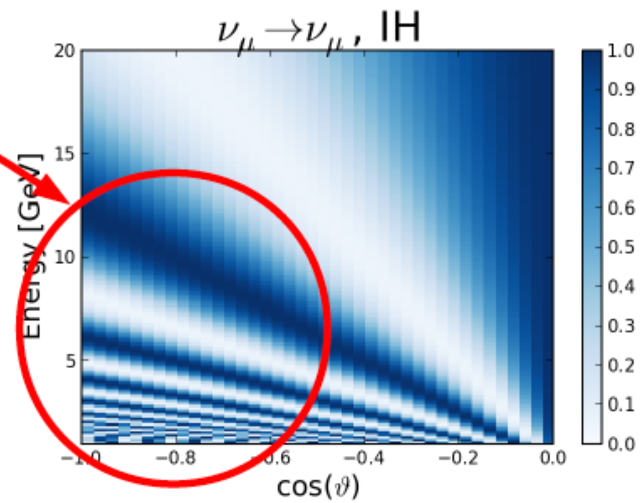
$$\sin^2(2\theta_{23}) > 0.93\ (68\%\ C.L.)$$

Precision IceCube Next Generation Upgrade (PINGU)

- High detector density (40 strings with 20 m spacing)
- Energy threshold: a few GeV
- Measures neutrino mass hierarchy
- Normal mass hierarchy with 3 sigma after 3.5 years
- Resolutions:
  ΔE ~ 20%, Δθ ~ 10° (depends on energy and flavor)







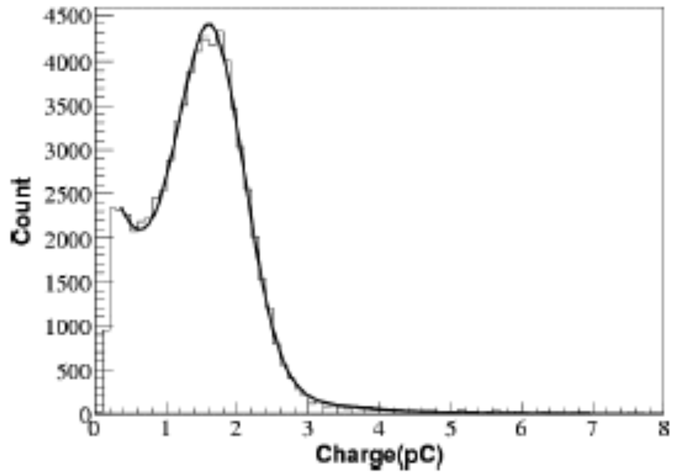
❑ Summary

- **IceCube completed end of 2010 and performing as expected**
- Two PeV neutrinos were observed (significance 2.8σ)
- 26 events observed by a follow-up search for high energy starting events (significance 4.1σ)
- **We have started to see something other than backgrounds!**
- **We do not know yet what they are**
- GRBs are probably not the main source of UHECRs, or the theoretical models need modifications
- FR-II types are not the UHECR source in case of proton composition
- Particle physics can be performed
- **More data are coming** (See A. Ishihara's talk tomorrow)

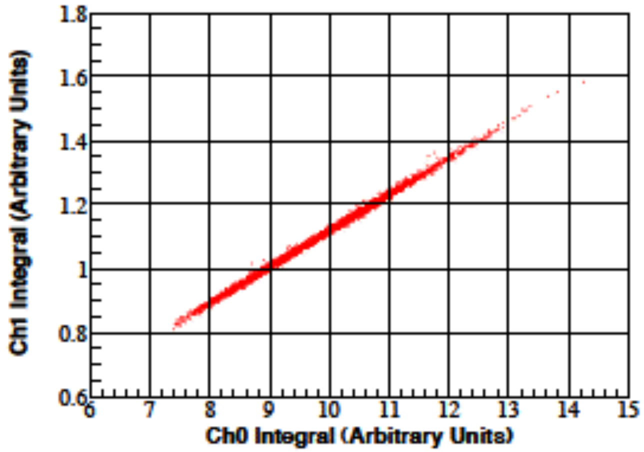
backups

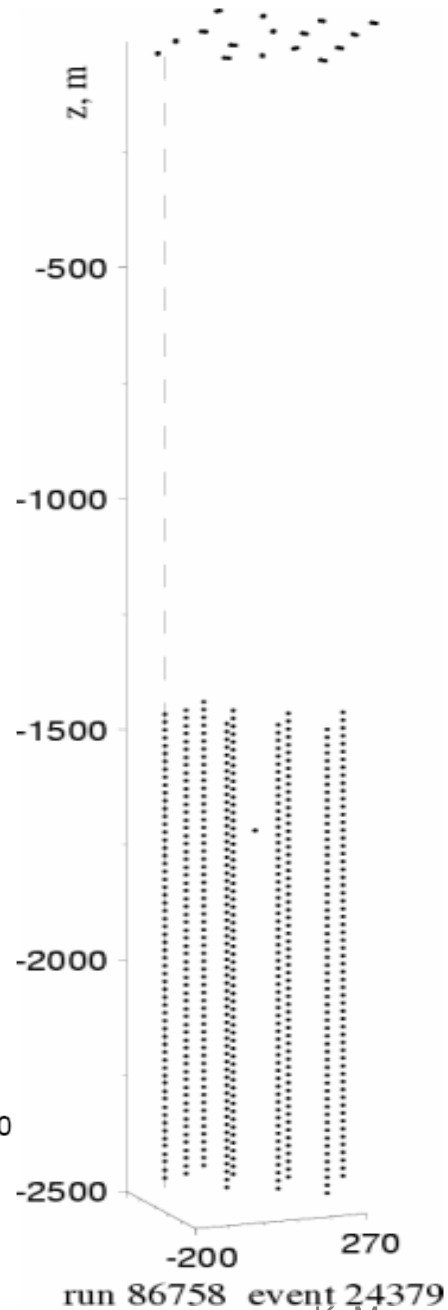
The detector performance check

1 p.e. distribution

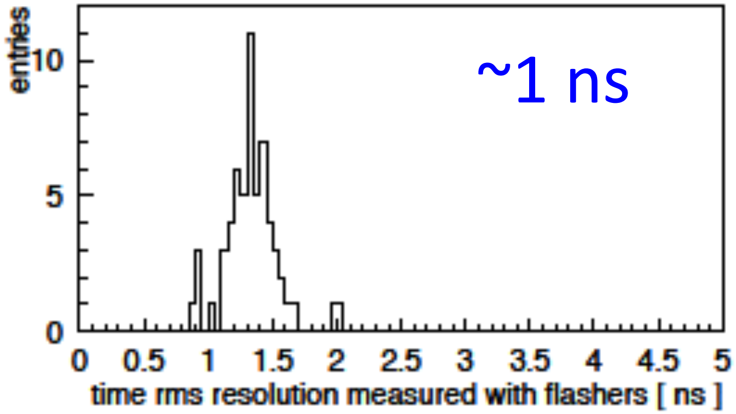


Gain check

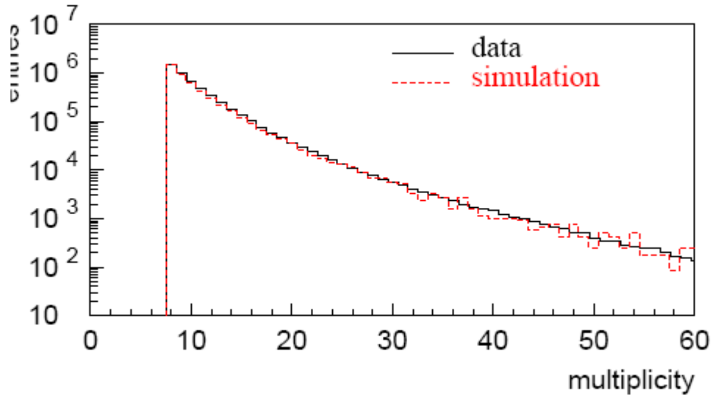




Time resolution



Multiplicity distribution



A. Achterberg et al., Astropart. Phys., 26, 3, 155-173 (2006)

Likelihood method translates events on the sky into p-values

Signal: Astrophysical neutrinos clustering in space
Background: Isotropic atmospheric neutrinos

Maximize the likelihood function:

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

Braun et. al., arXiv: 0801.1604

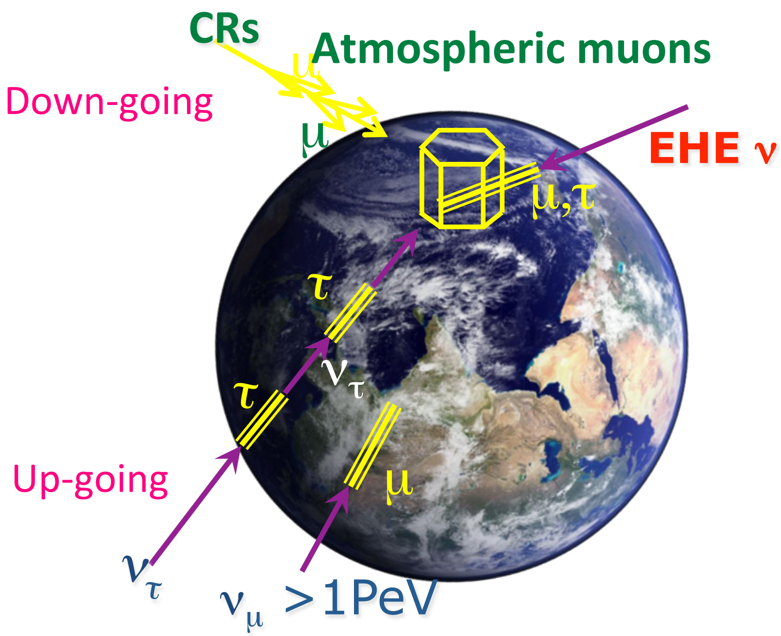
Test statistic:

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

Obtain **p-value** by comparing test statistic for real data to random trials from scrambled data

Fit for:
- $\mathbf{n_s}$, # of signal events
- **γ**, neutrino spectral index

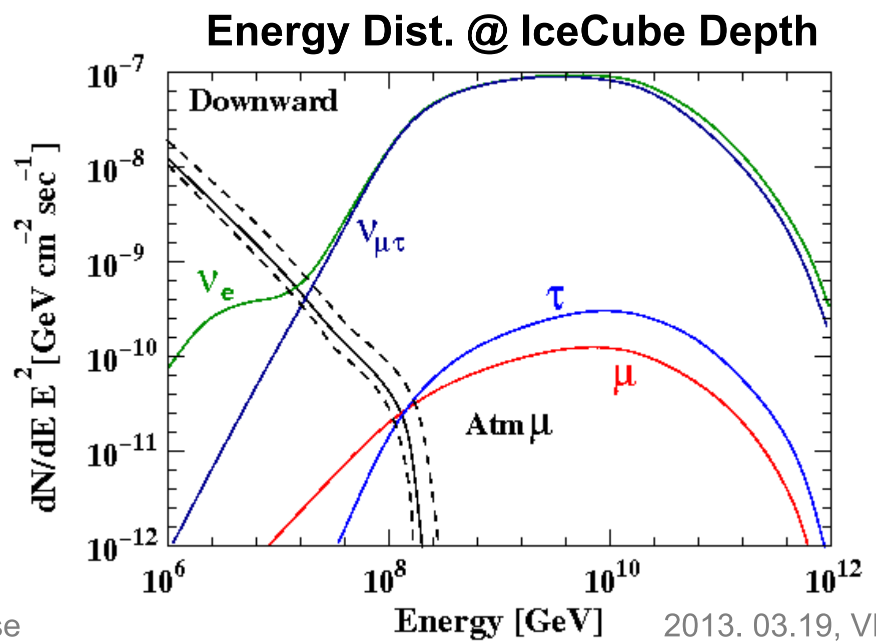
The detection principle

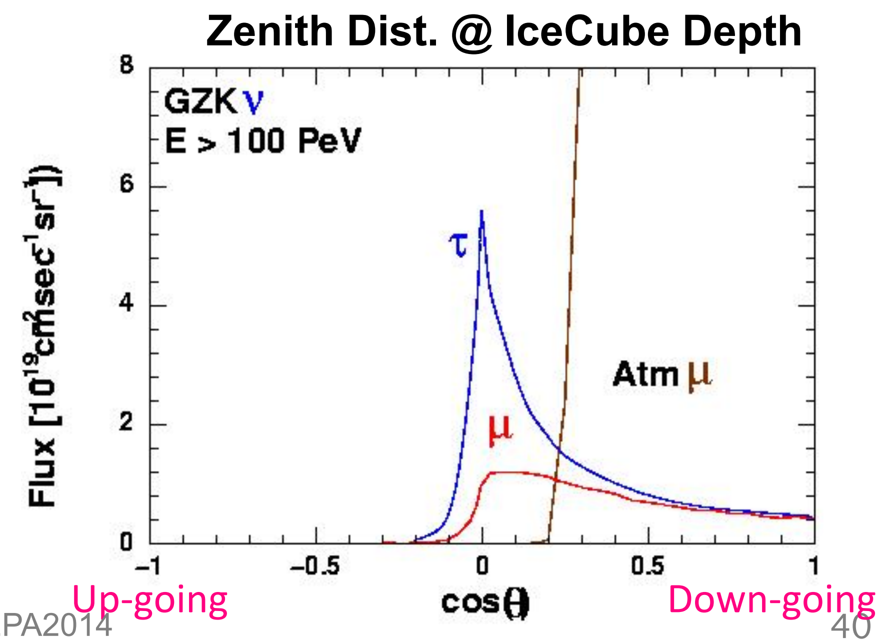


- **EHE neutrino signal (all flavor)**
  - Horizontal (opaque to the earth)
  - High energy (> 10^8 GeV)

- **Atmospheric muon background**
  - Down-going
  - Low energy (the energy spectrum is steep (~$E^{-3.7}$))

Yoshida et al PRD **69** 103004 (2004)



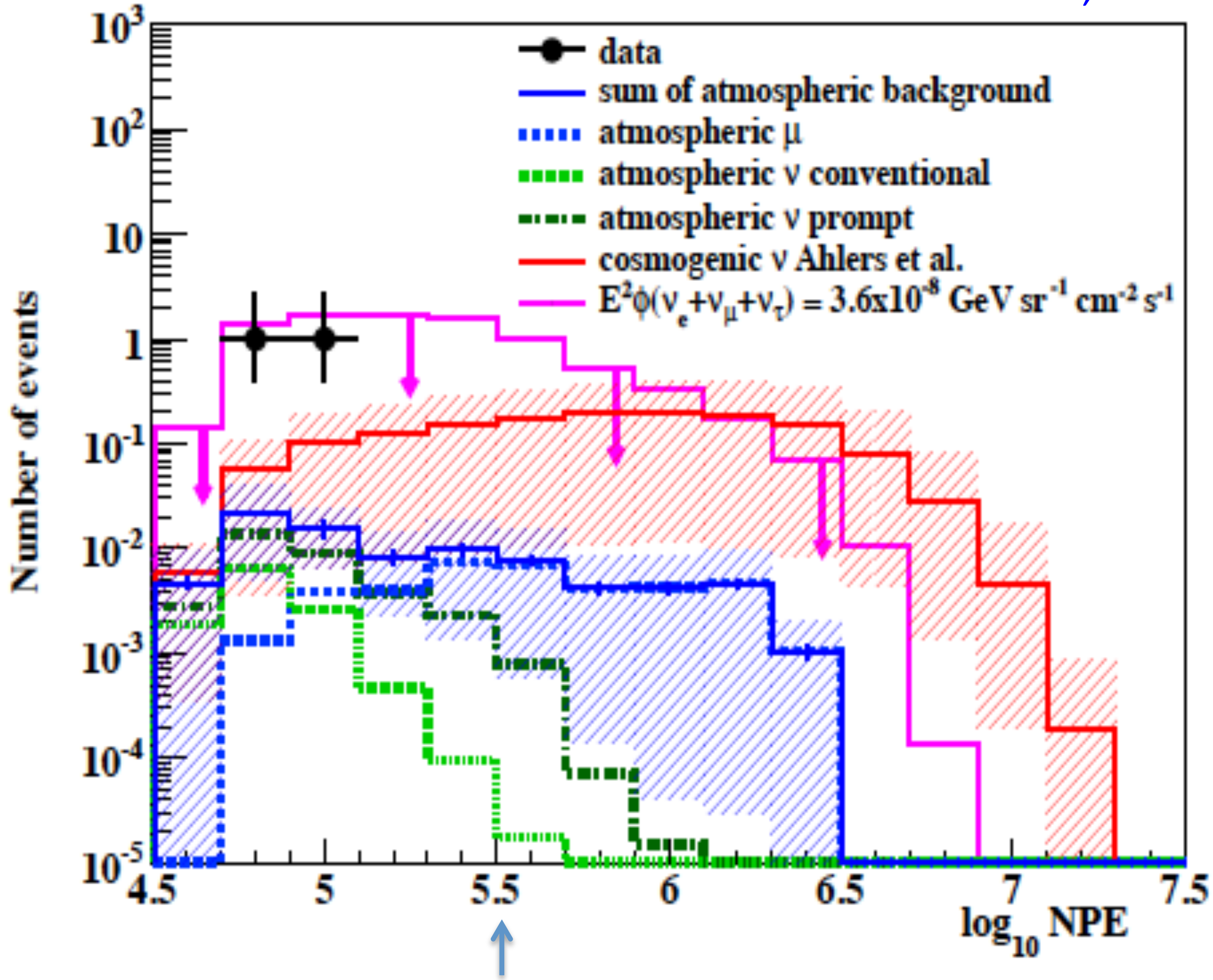


Bert visits Tokyo

NPE distribution at final level

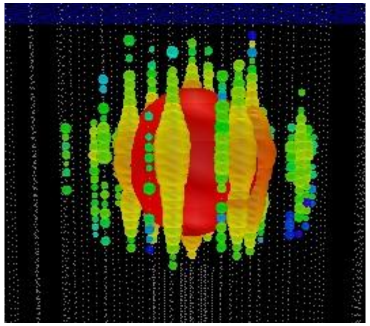
IC79/86 combined (615.9 days)

PRL 111, 021103 (2013)



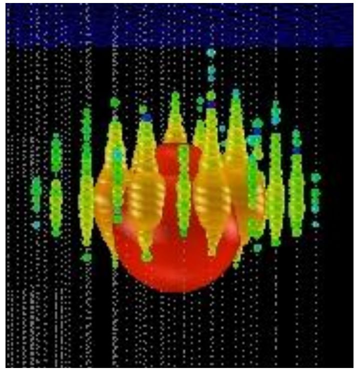
corresponds to ~10^8 GeV neutrinos at surface with a cosmogenic neutrino spectrum

The energy deposit reconstruction



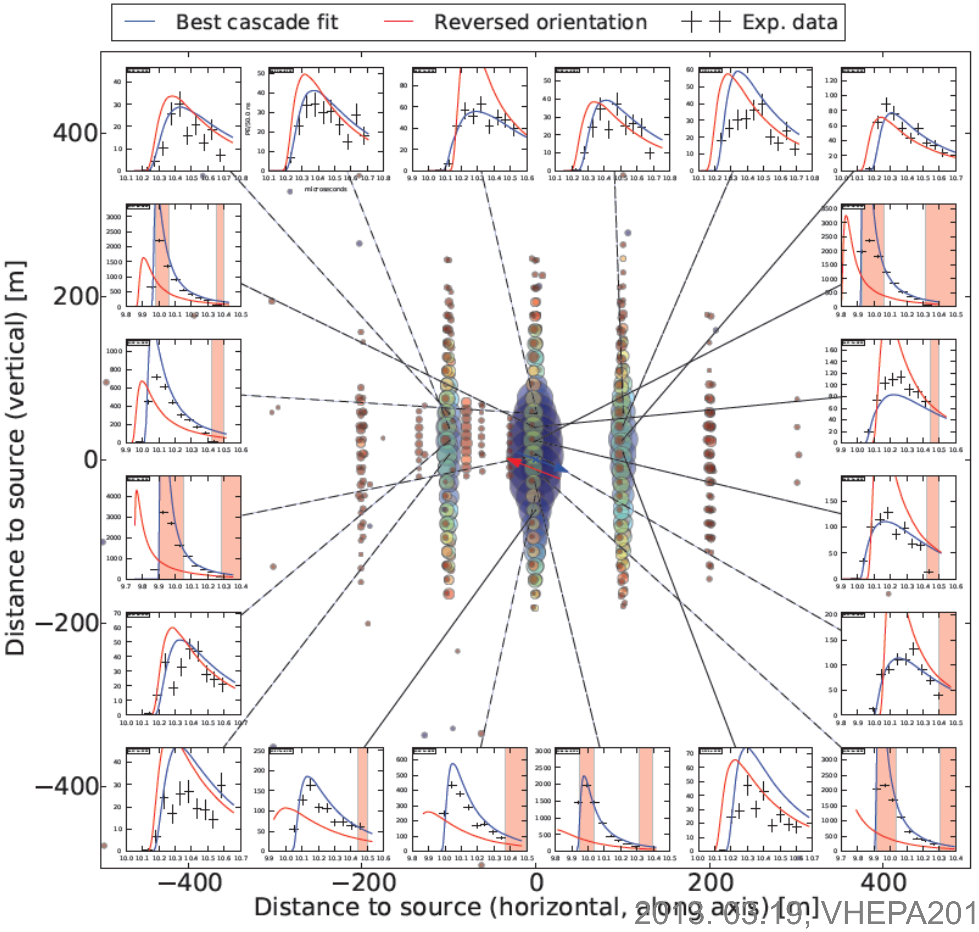
Aug. (“Bert”)

1.0±0.2 PeV



Jan. (“Ernie”)

1.1±0.2 PeV

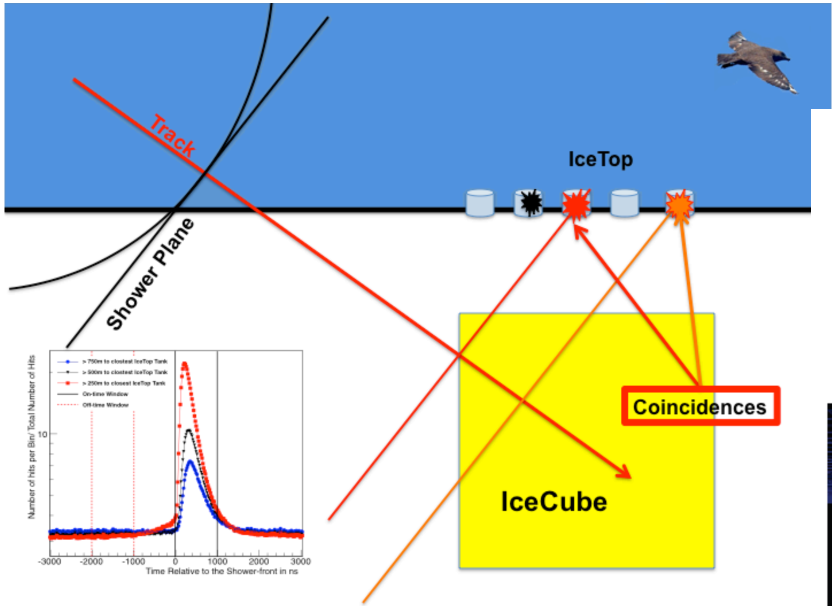


energy resolution for these specific events

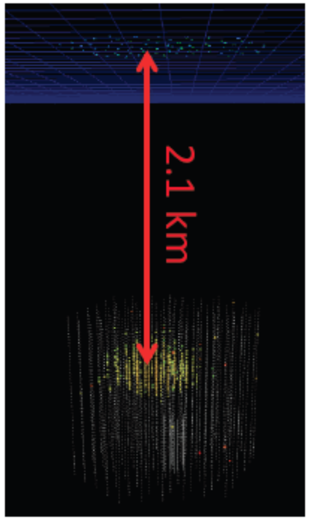
including systematics (ice + DOM eff.)

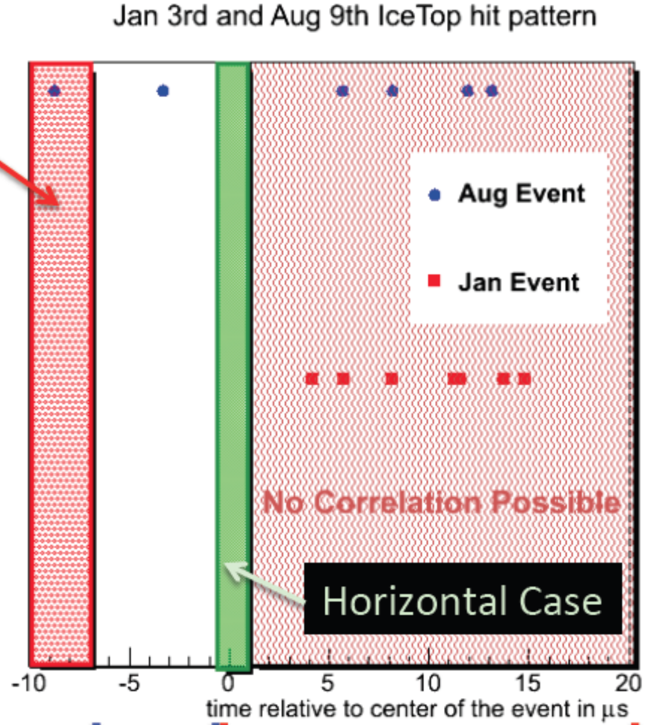
Preliminary

❑ IceTop (surface array) veto information



Geometrical not possible as Cascades 2 .1km deep





Before first Hit: Correlation possible

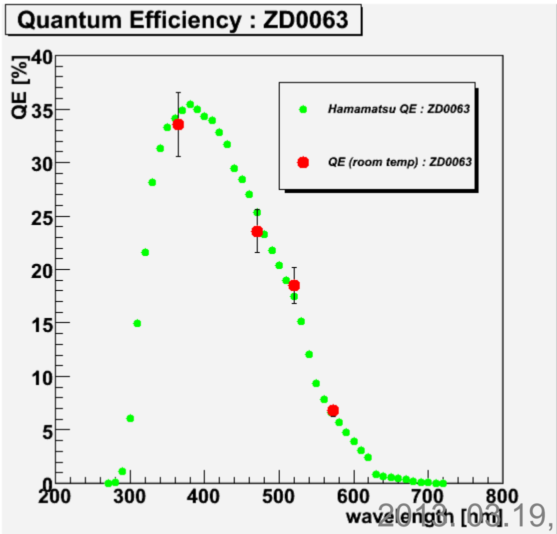
After the Event no Down-going correlation possible

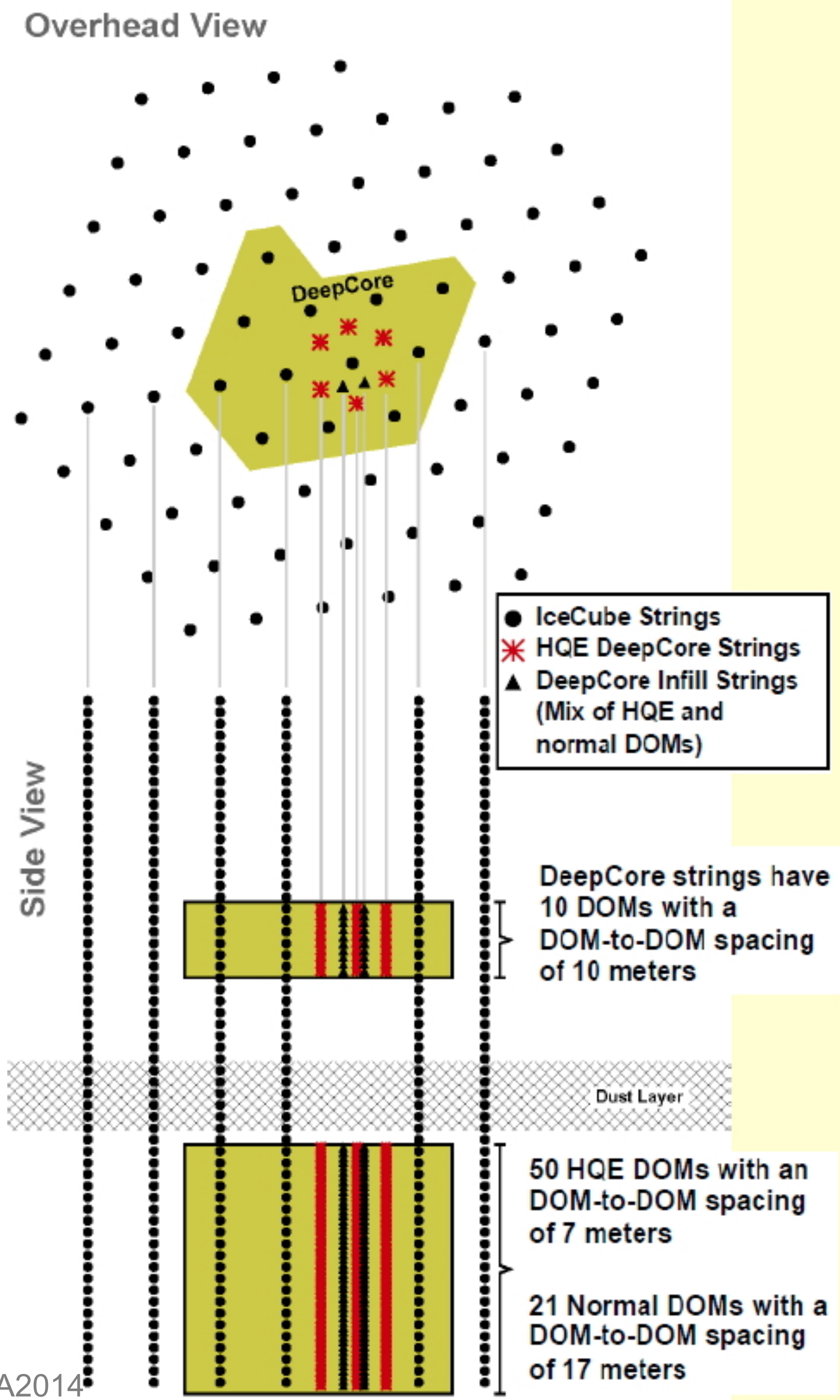
- IceTop veto information was checked
- hits search in allowed 8µs time window
- 0 and 1 hit observed again 2.1 hits expected

-> No CR shower

IceCube Deep Core

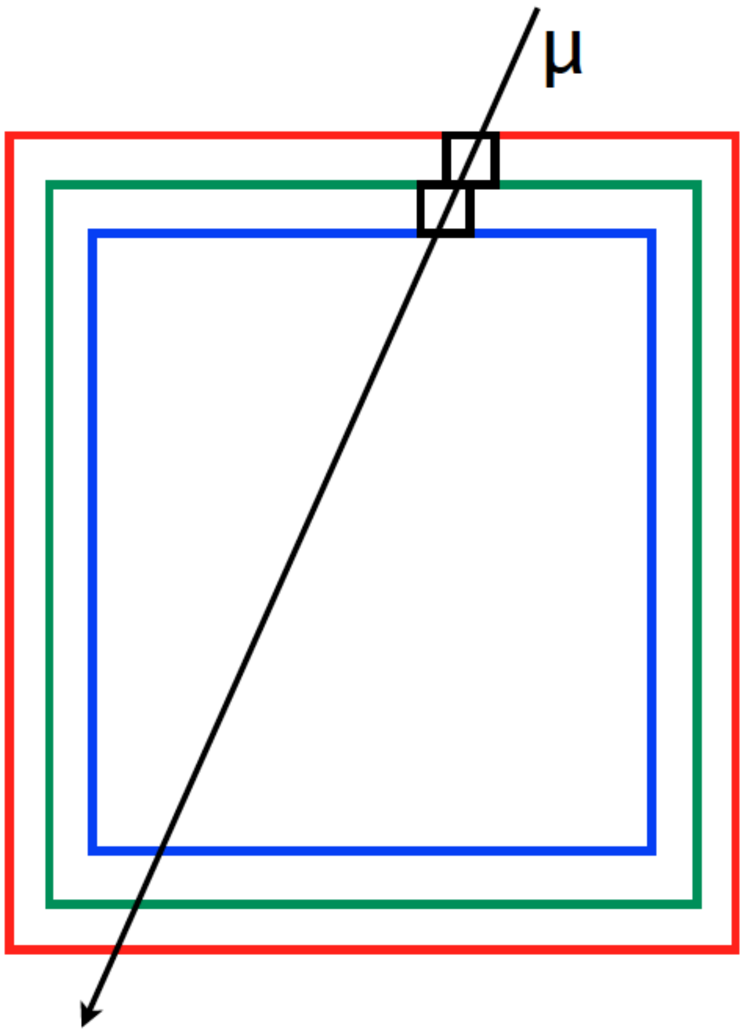
- Extend IceCube sensitivity to neutrinos with energies down to ~10 GeV
  - Six strings with 60 high-QE PMTs each (HAMAMATSU super bialkali)
  - Use very clear ice at bottom of IceCube





Atmospheric muon background

- Dominant down-going background
- Estimated by using data
- Second veto layer introduced
- veto power: at least 3 orders of magnitude
- Removes also 70% of down-going atmospheric neutrino background (southern sky)
- 3 muon events passed the inner layer → 6.0 ± 3.4 events / 2 years with geometrical volume correction

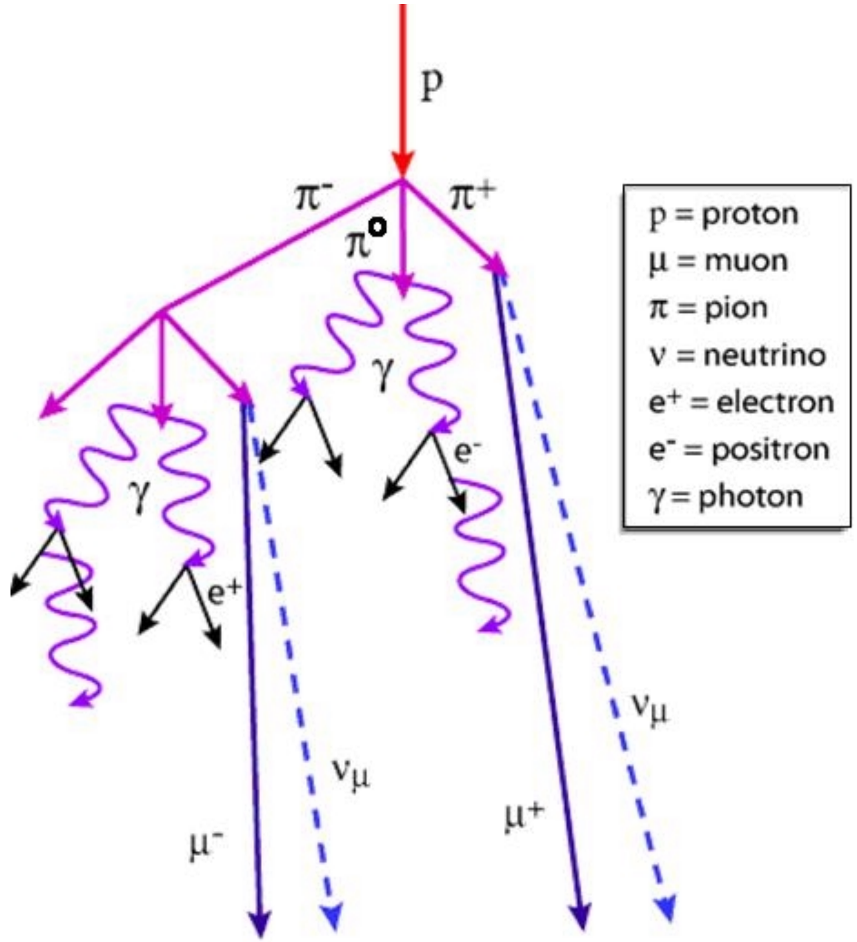


Atmospheric neutrino background

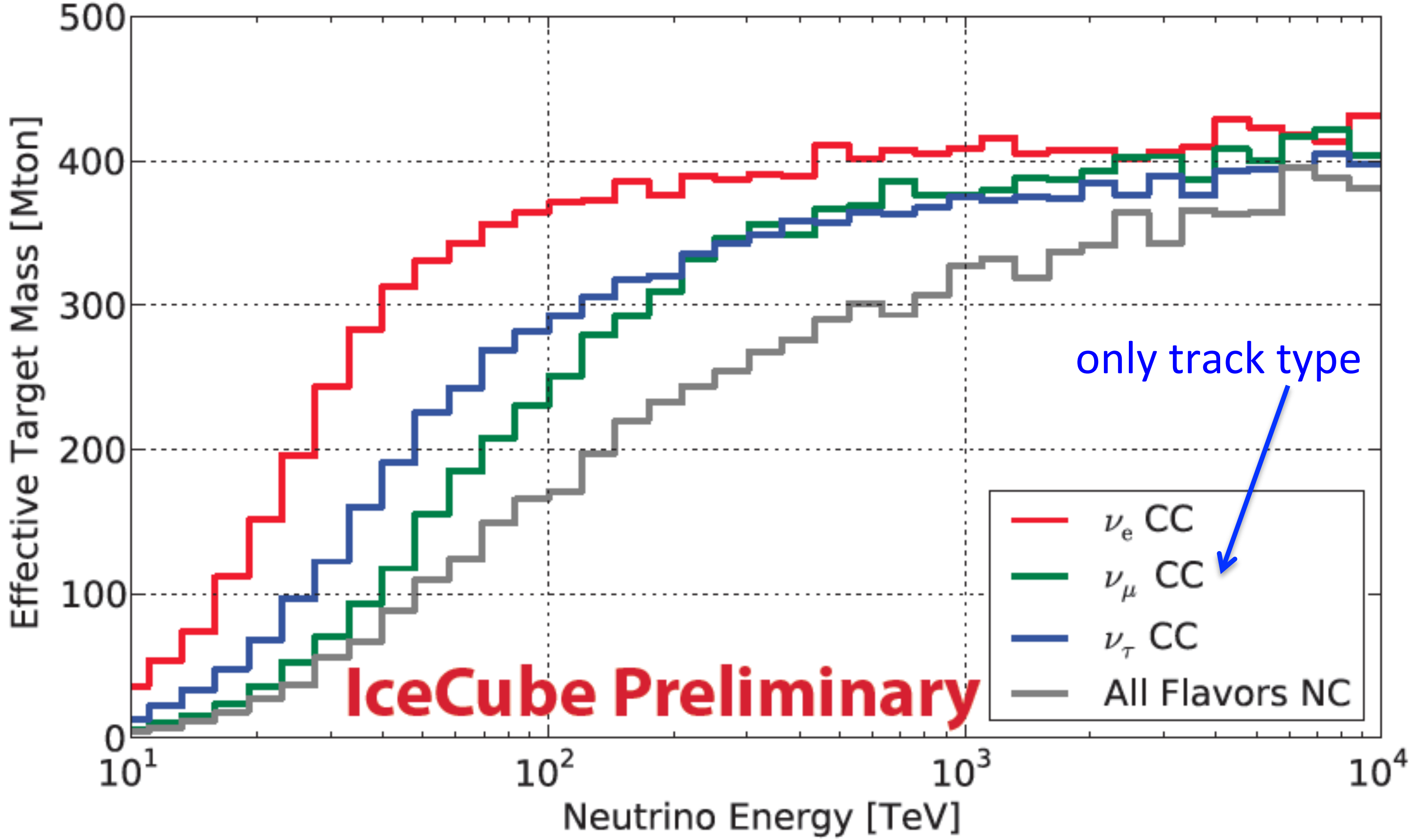
- Low rate at PeV energy (0.1 event/year)
- Reduced by 70% by the muon veto
- Uncertainty ~30% from CR composition and hadronic interaction
- Large uncertainty from unmeasured charm contribution Enberg et al. (2008) employed (NLO perturbative QCD)

  -> 3.4 events

- Estimated bg rate: 4.6$^{+3.7}_{-1.2}$ events / 2 years



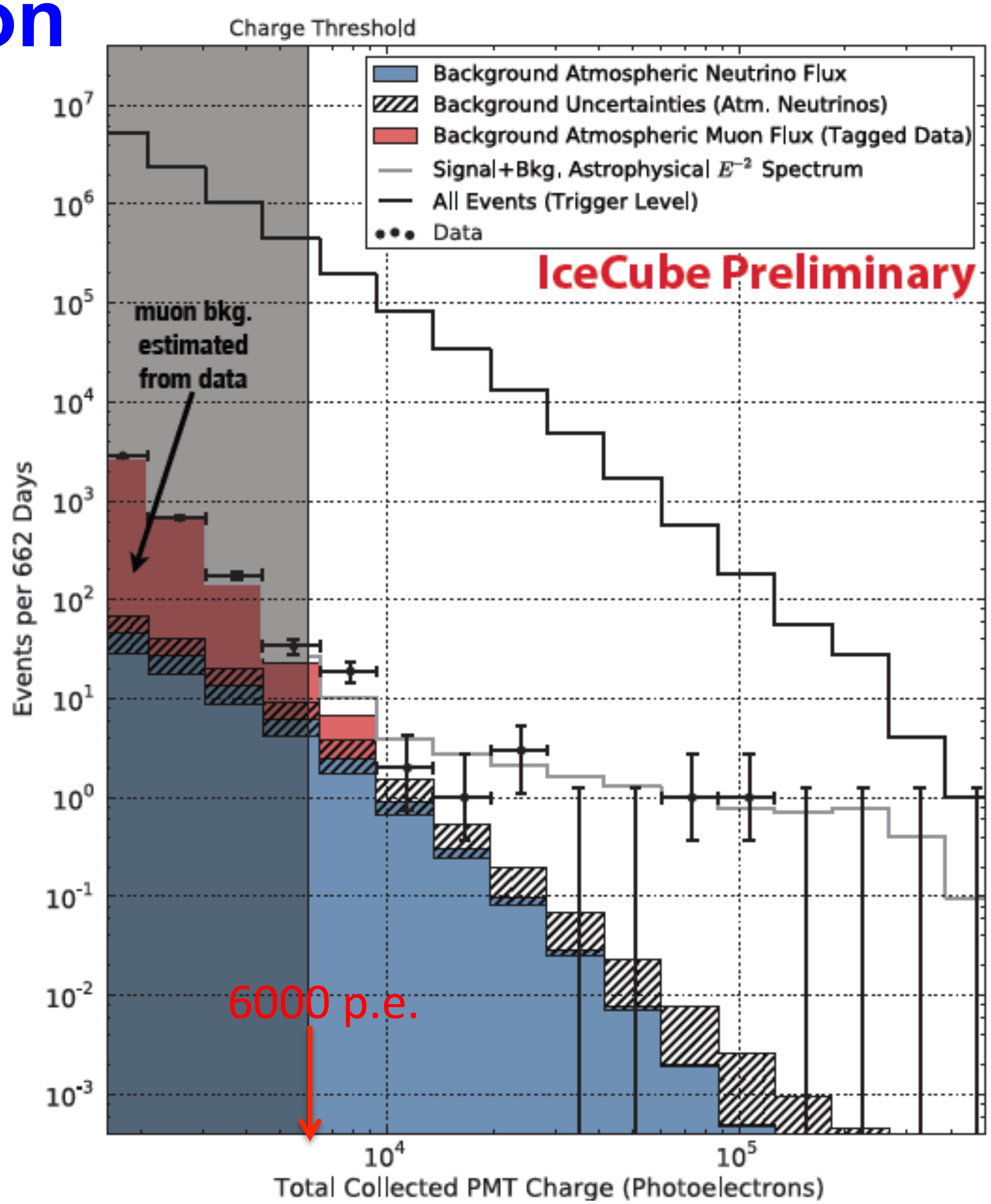
Effective volume



This analysis is more sensitive to cascade events

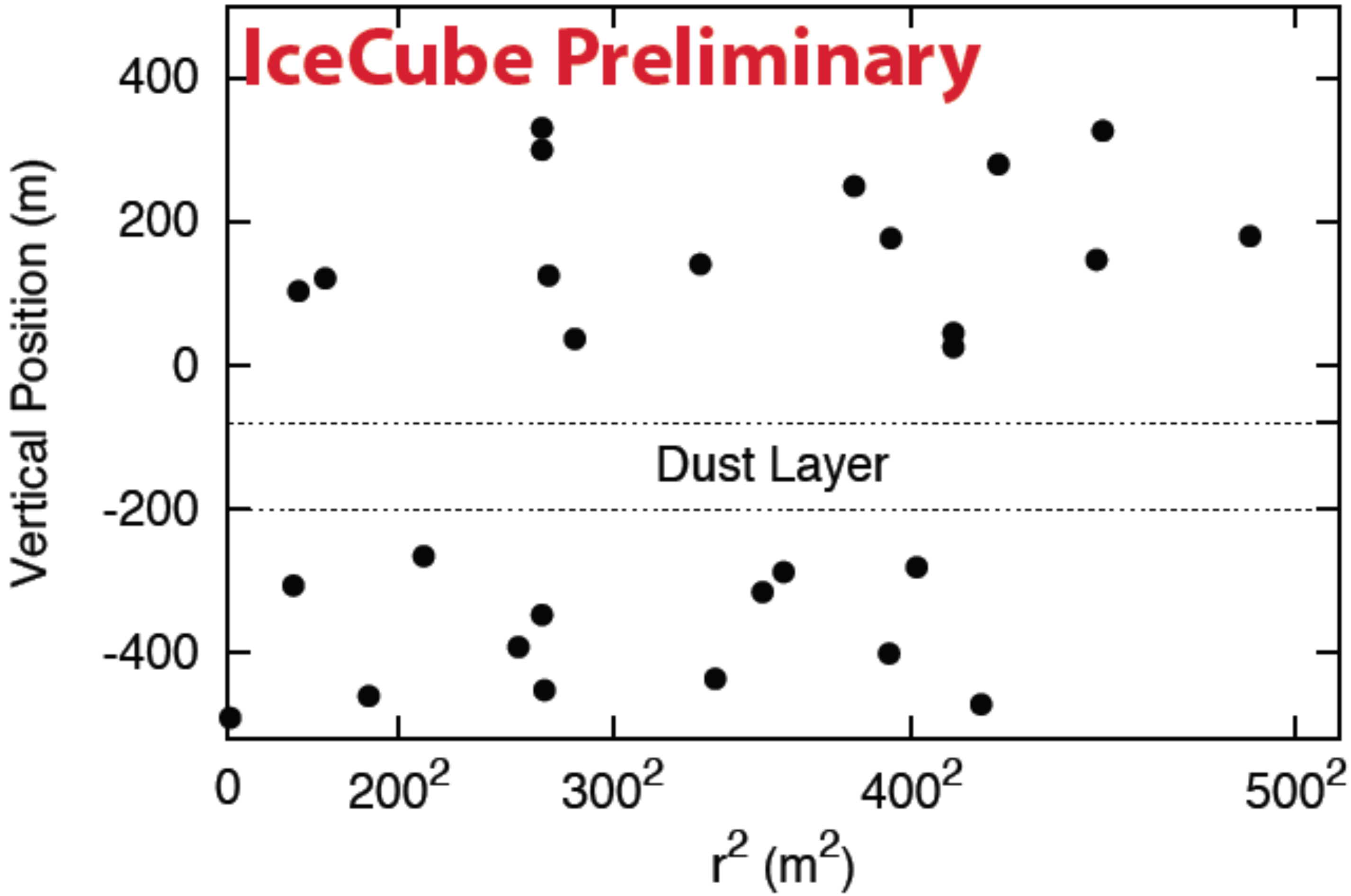
Charge distribution

- 28 events observed above selection criteria
- Total bg: $10.6^{+4.5}_{-3.9}$
- Significance: 3.3σ (HESE analysis alone wo two PeV events)
- Including EHE result (2.8 σ): 4.1σ
- A posteriori (including two PeV events): 4.8σ
- Atmospheric muons are largely reduced
- Data and MC agree well at low charge



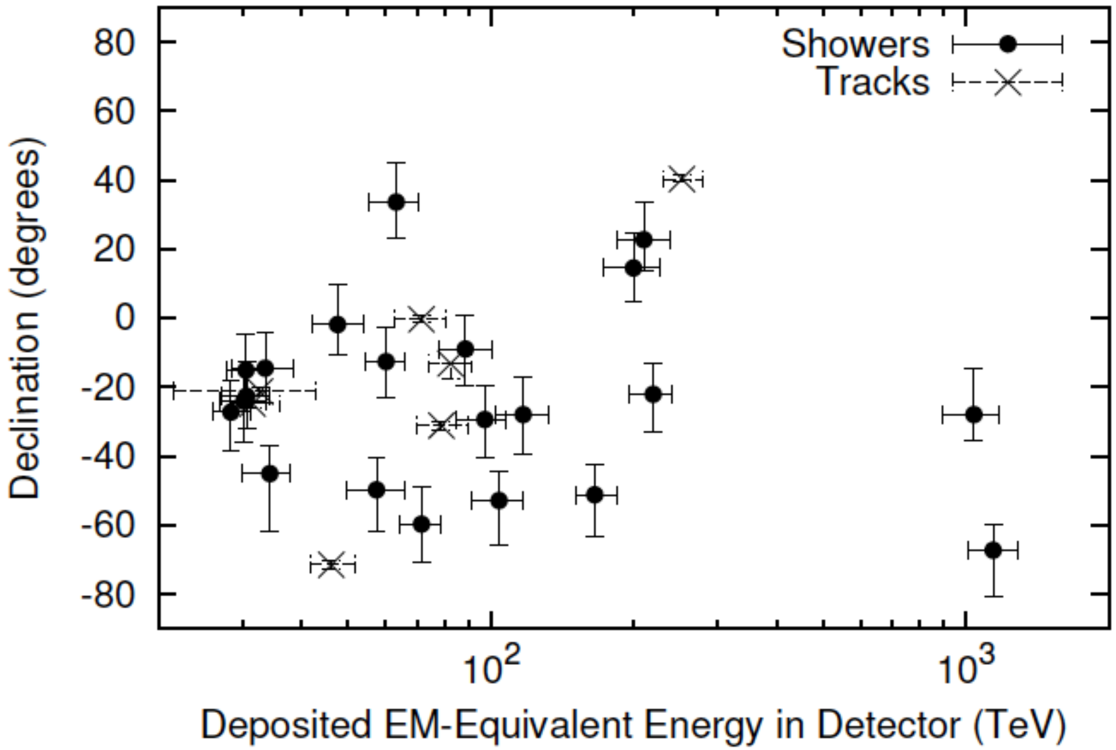
Coordinate of the first detected light

- Uniformly distributed

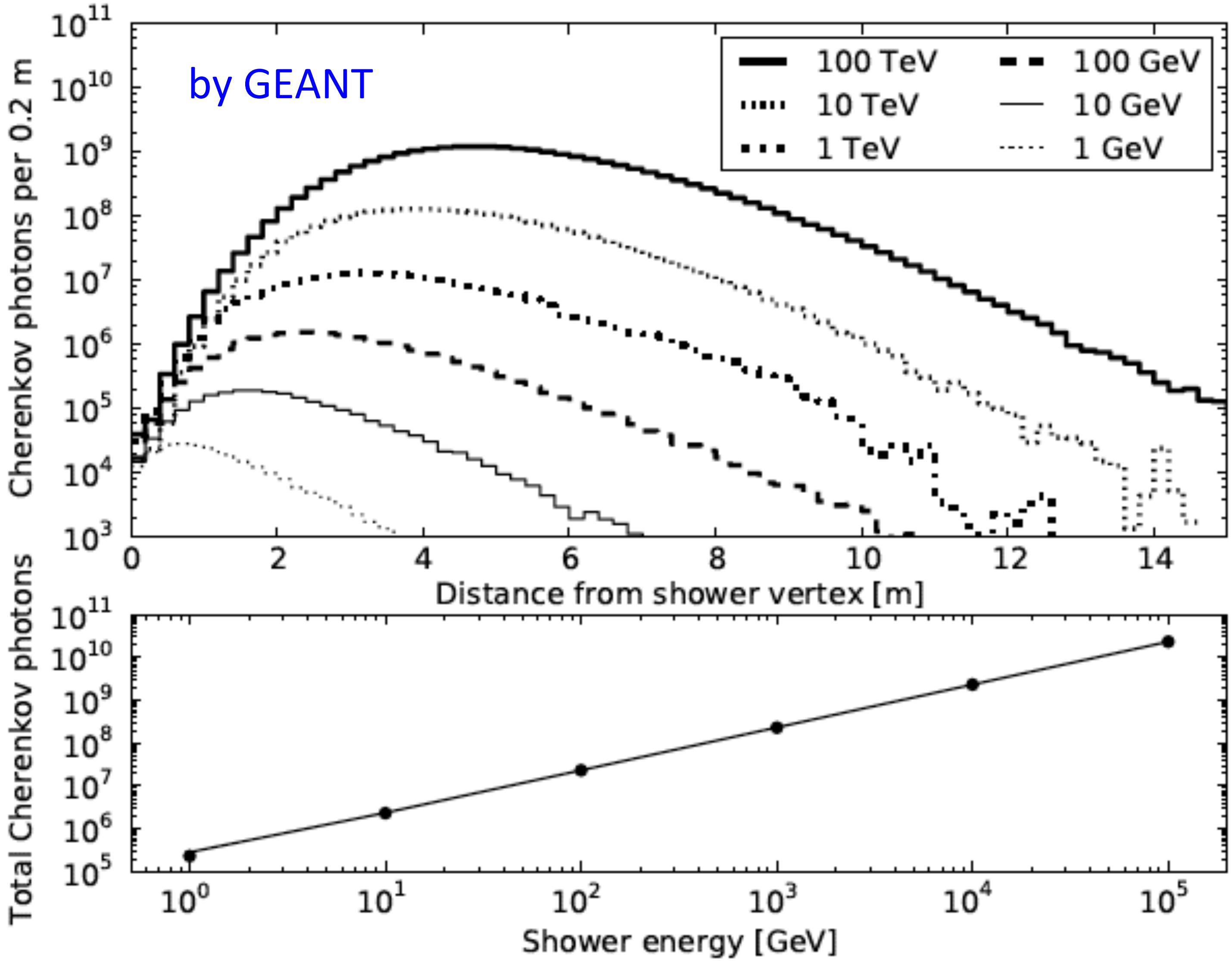


Declination vs deposited energy

- 21 showers vs 7 tracks
  Suggesting signals.
- In case of conventional atmospheric:
  track : cascade = 2:1
- Most of events come from southern sky because events from north are absorbed by the Earth
- Excess in south is not due to atm. ν since they are reduced in south by our muon veto
- low energy 4 tracks look atmospheric origin (consistent with the prediction of 6±3.4)
- Neutrino energy for track events can be very high compared to the deposited energy



Longitudinal shower development in ice



Light yield vs. distance for a point-like source