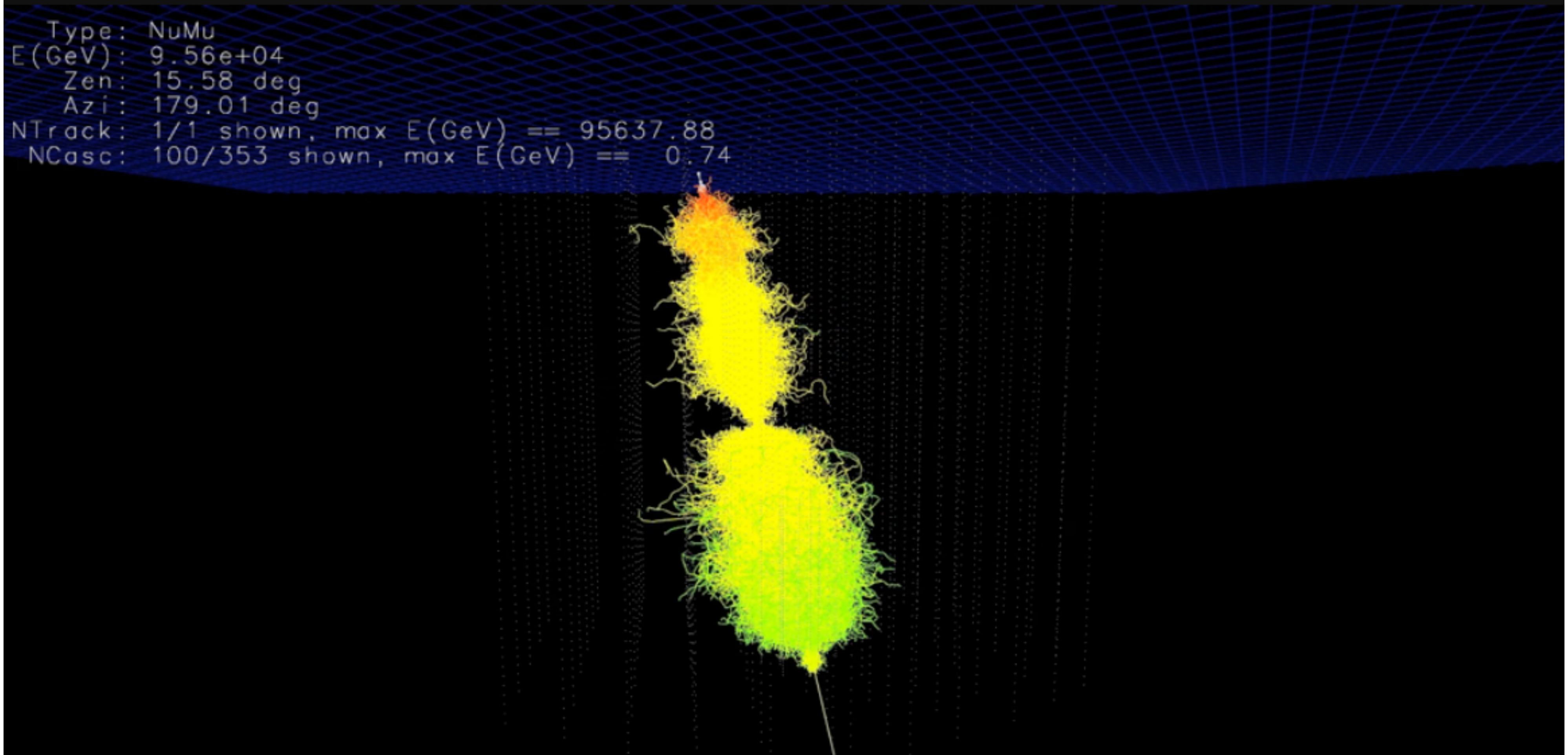
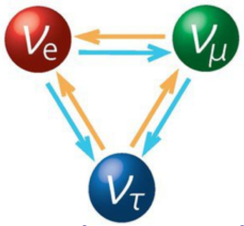
The IceCube experiment and the MC simulation

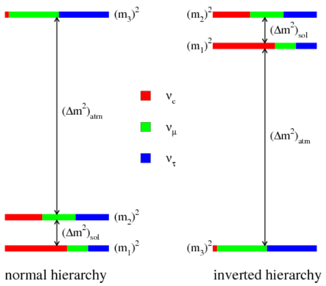


K. Mase, Chiba Univ.

Neutrino astrophysics

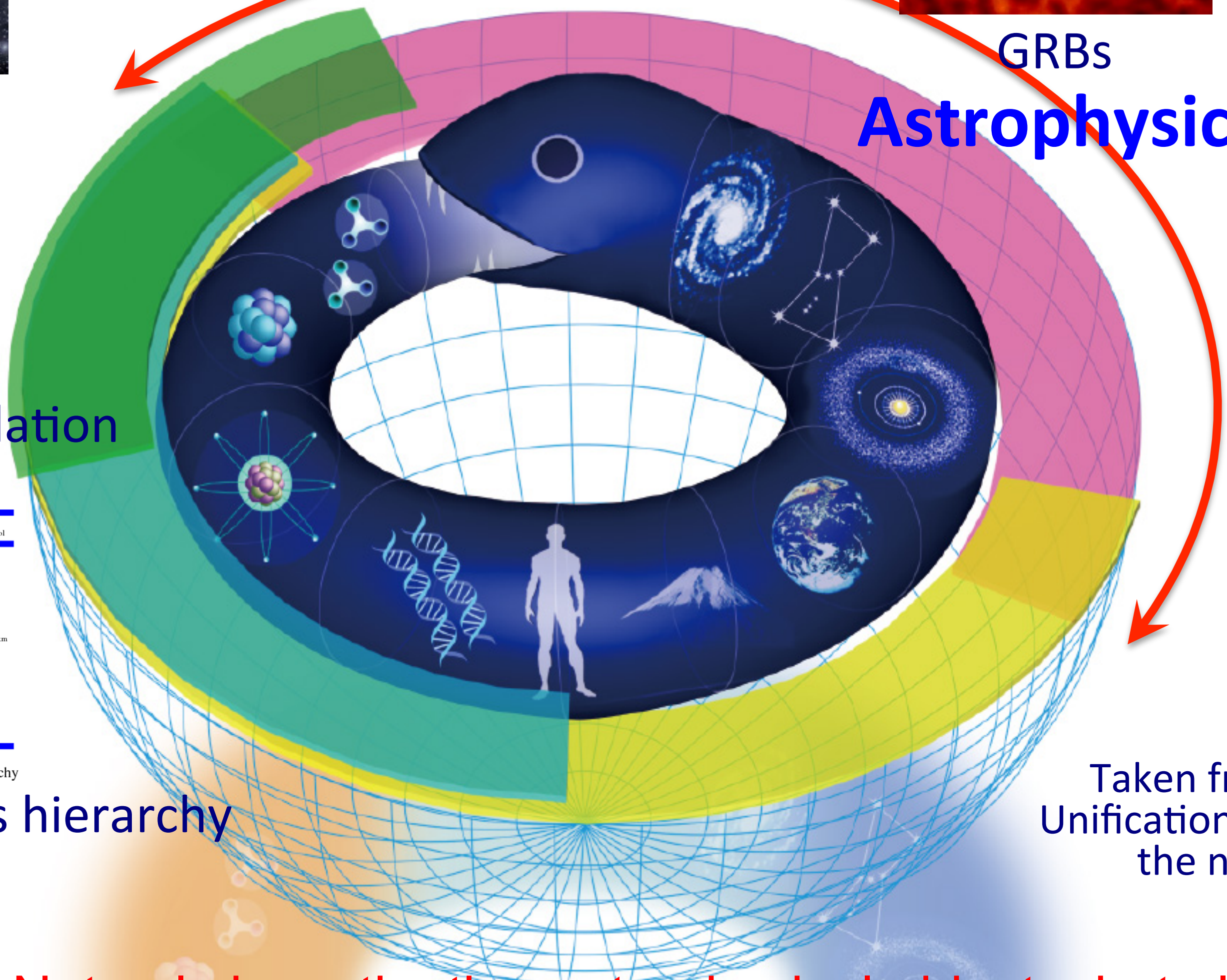

Dark matters


Neutrino oscillation

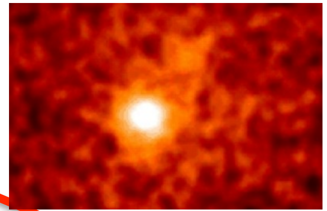


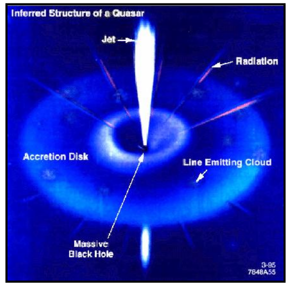
Neutrino mass hierarchy

Elementary particle physics

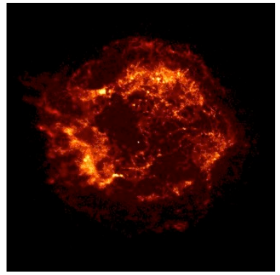


Astrophysics


GRBs



AGNs

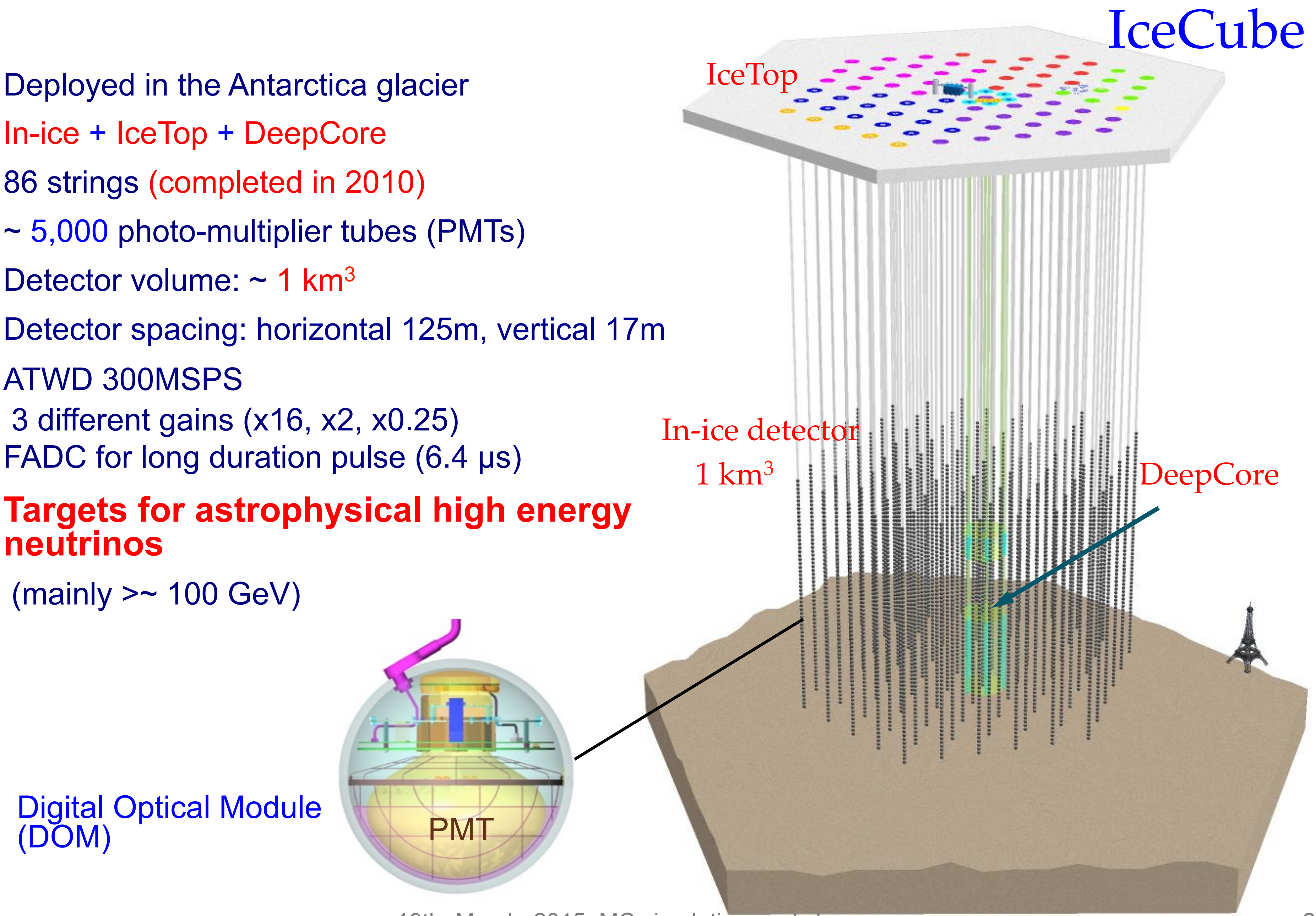

Supernovae

Taken from a web page of Unification and development of the neutrino frontier

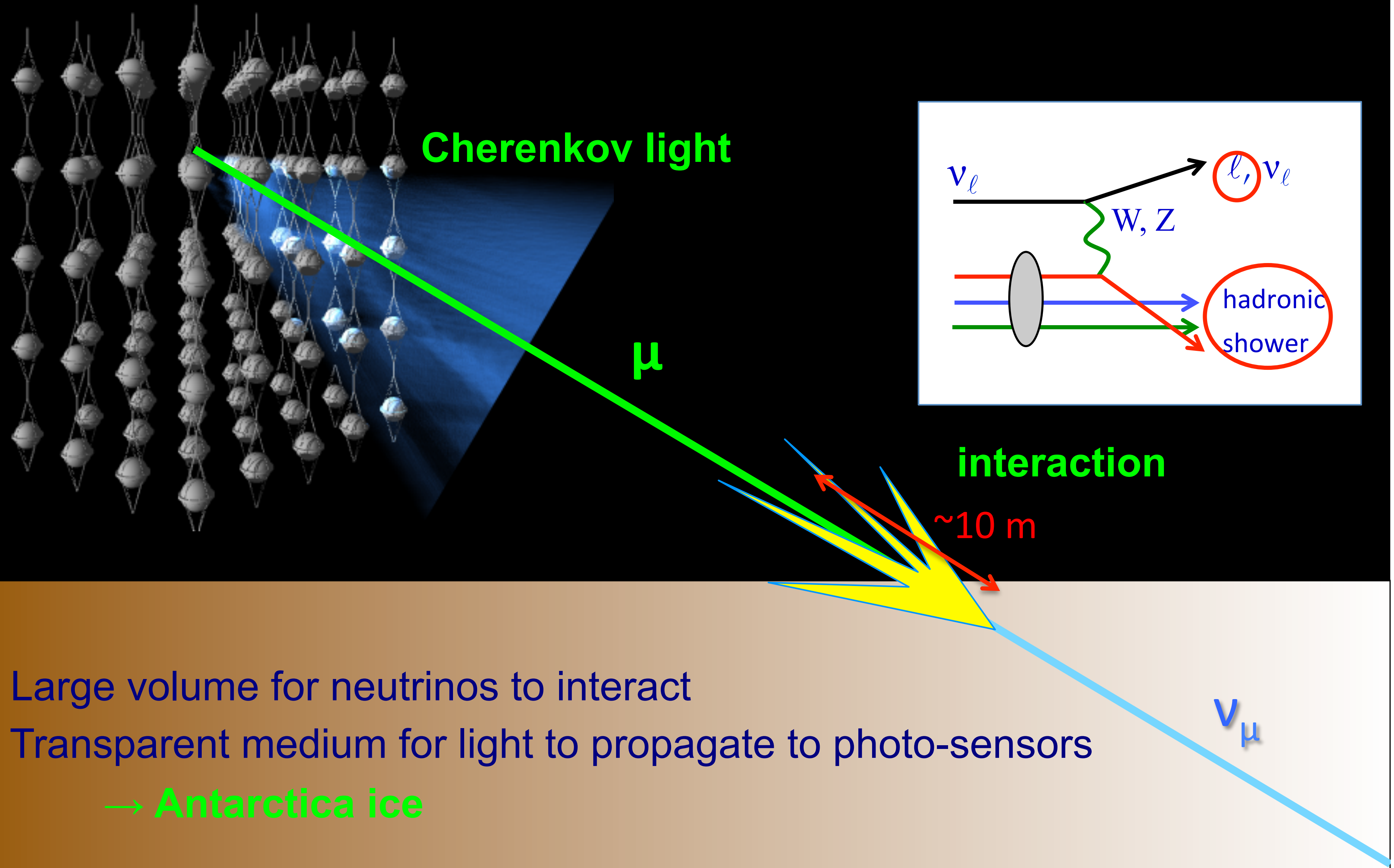
Not only investigating astrophysical objects, but also researching on elementary particles by observing universe

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 astrophysical high energy neutrinos**
  (mainly >~ 100 GeV)



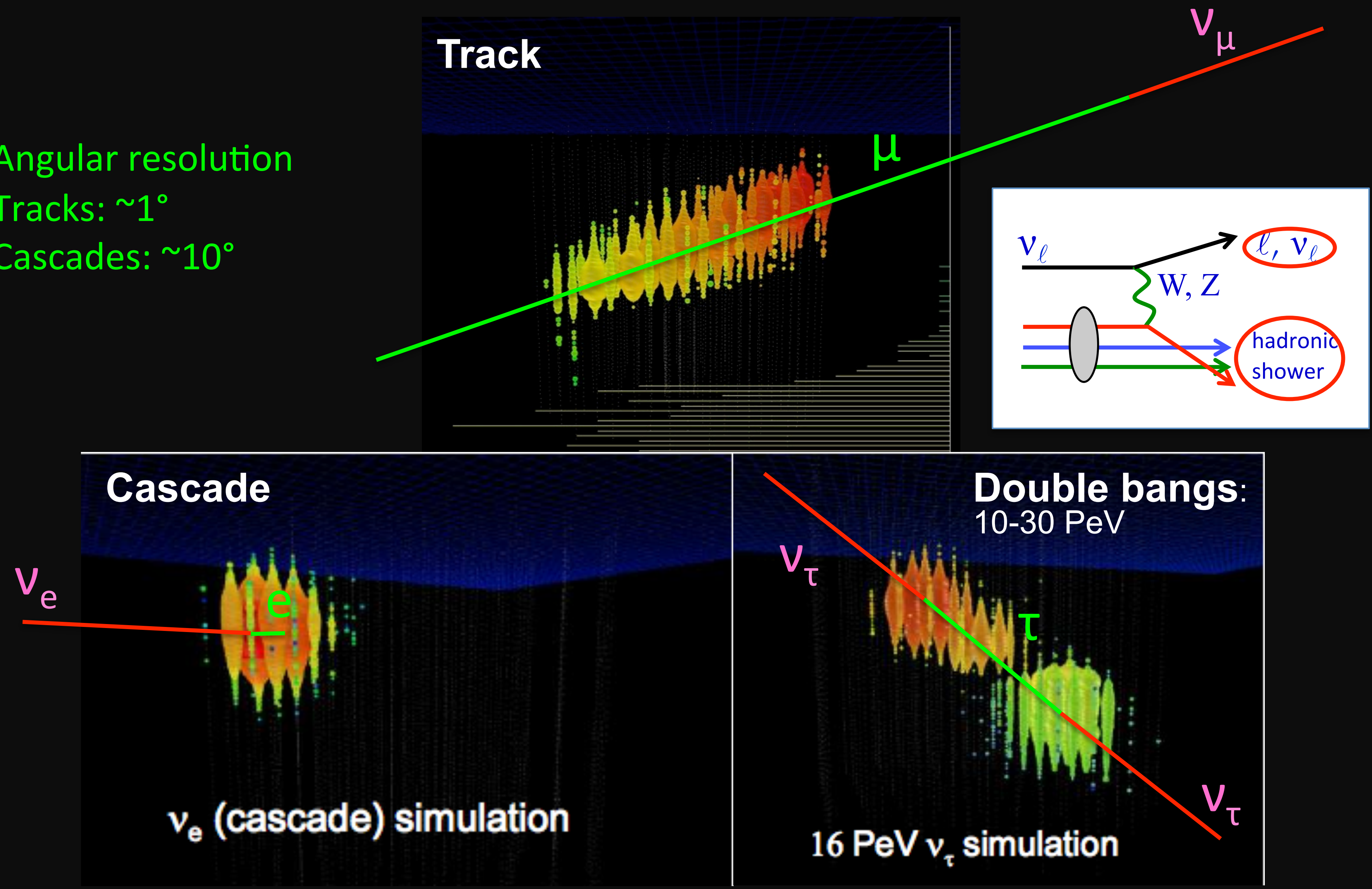
How do we detect neutrinos?



- Large volume for neutrinos to interact
- Transparent medium for light to propagate to photo-sensors
  - → **Antarctica ice**

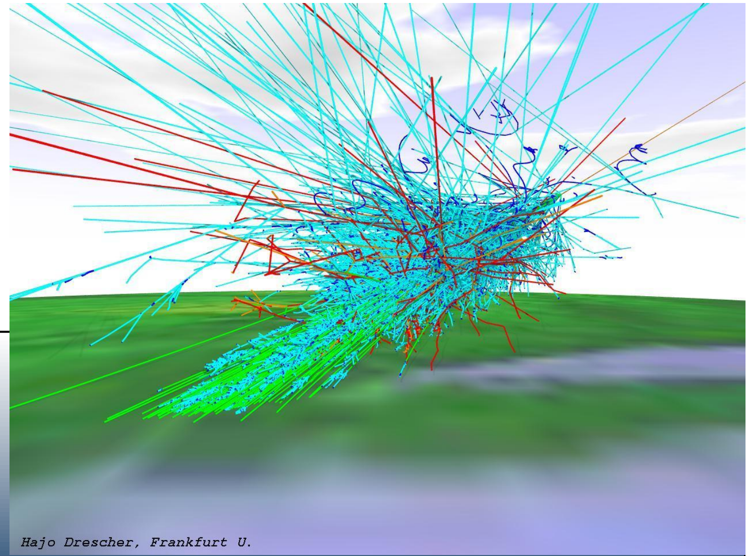
Flavor identification

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



Note: neutral current events also generate cascades

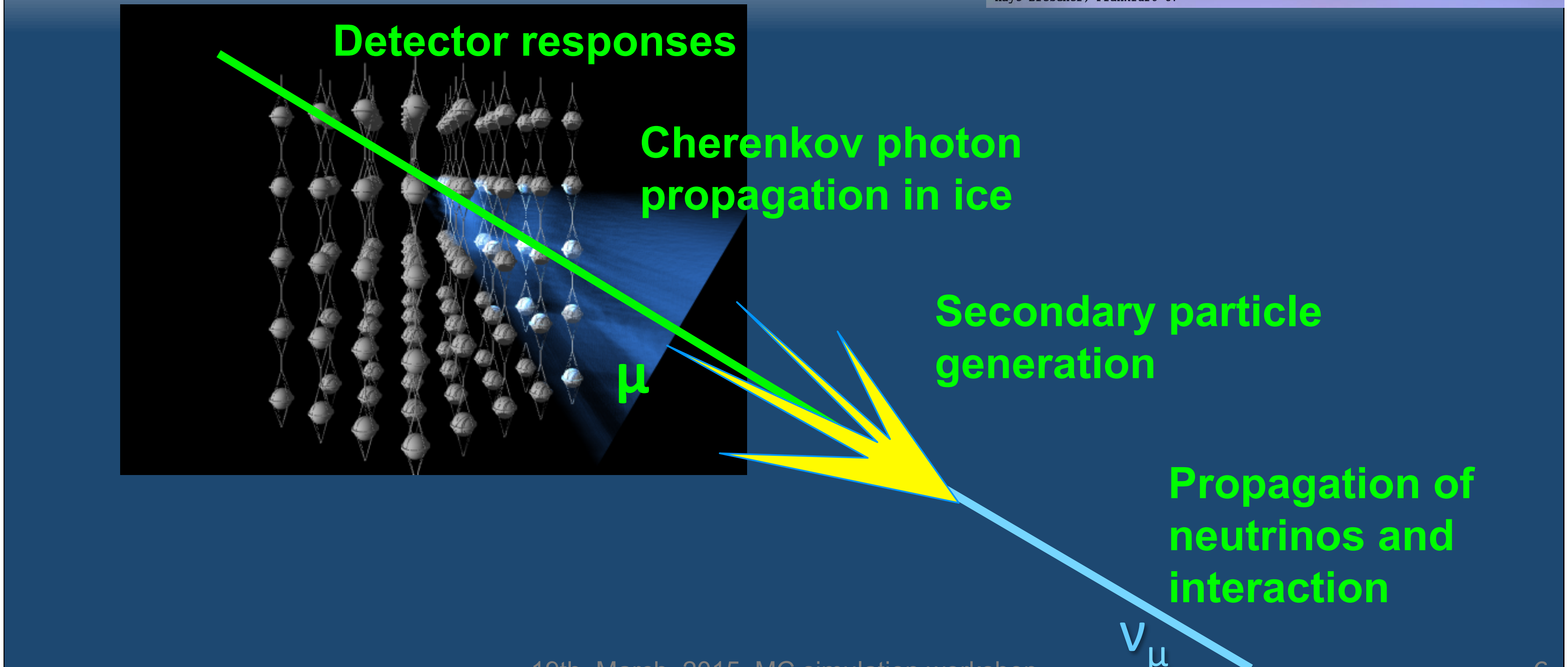
Simulation scheme



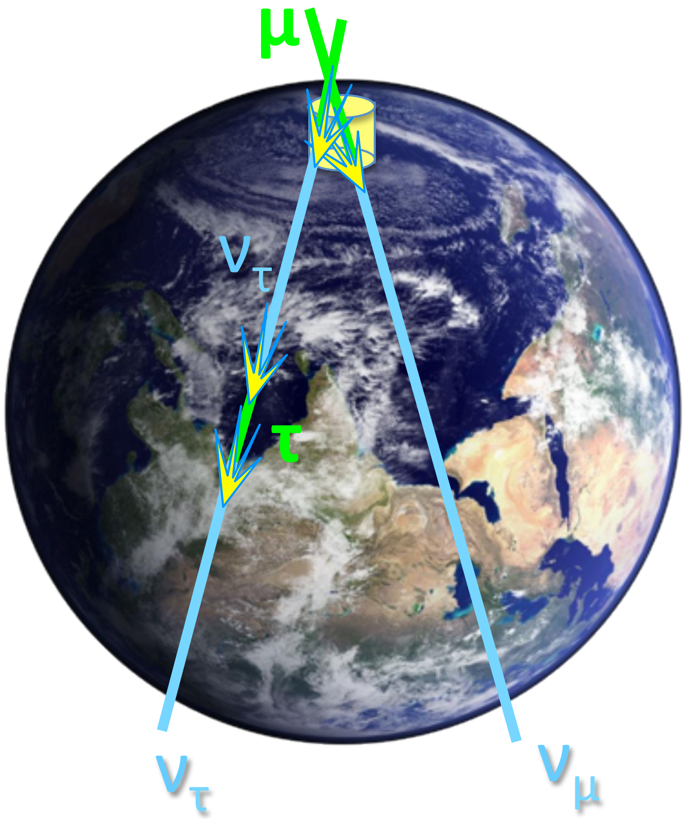
Atmospheric backgrounds:

Neutrinos (flux weighted)

Muons (CORSIKA)



Propagation of neutrinos and interaction



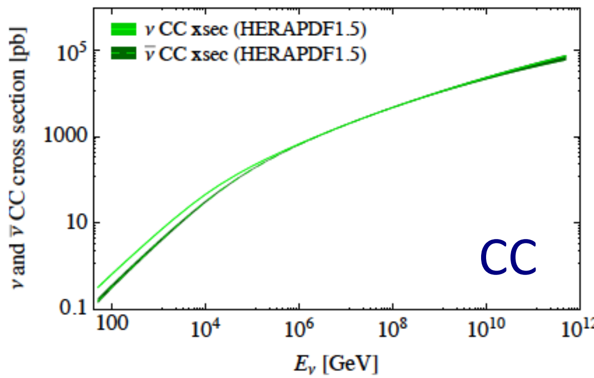
- Propagate neutrino in the earth and make interactions

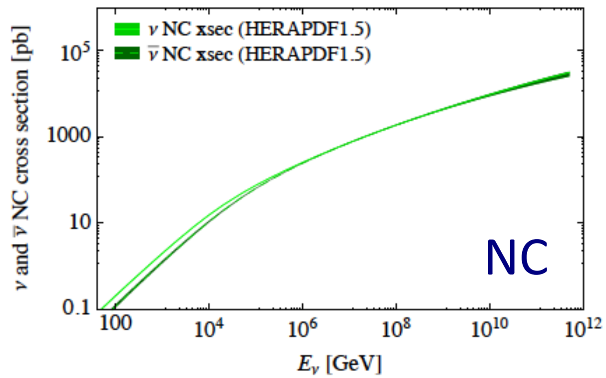
$$p_{surv} = e^{-x/L_{\mathrm{int}}}$$

- Force to interact inside a volume

$$p_{\mathrm{int}} = 1 - e^{-x/L_{\mathrm{int}}} \approx x / L_{\mathrm{int}}$$

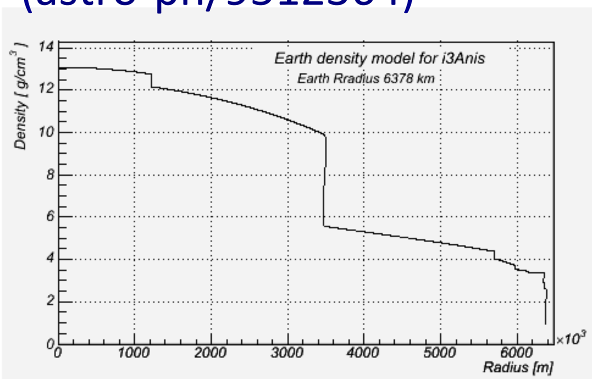
Cross section from HERAPDF1.5 (arXiv:1106.3723)



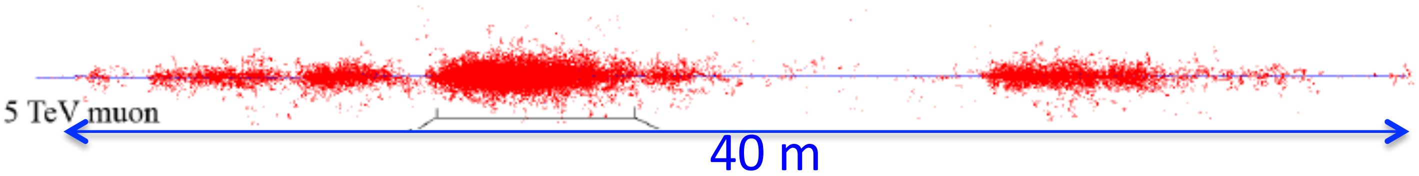


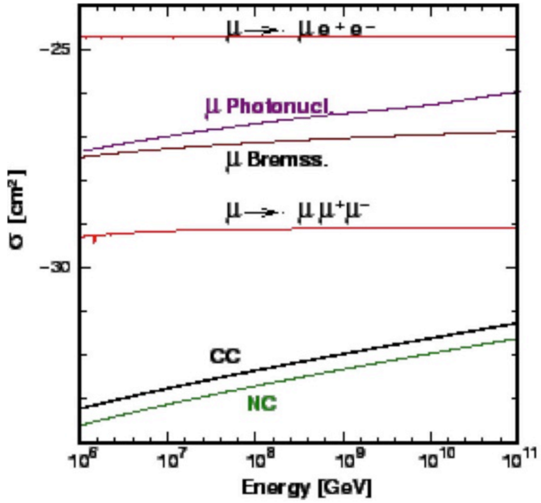
Uncertainty ~5%

Preliminary Earth Model (astro-ph/9512364)

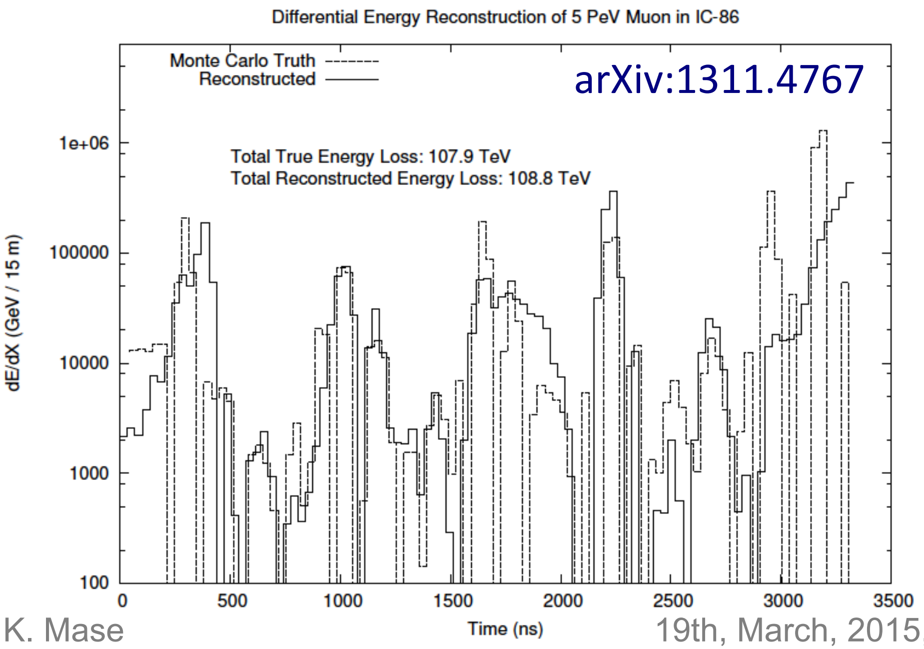


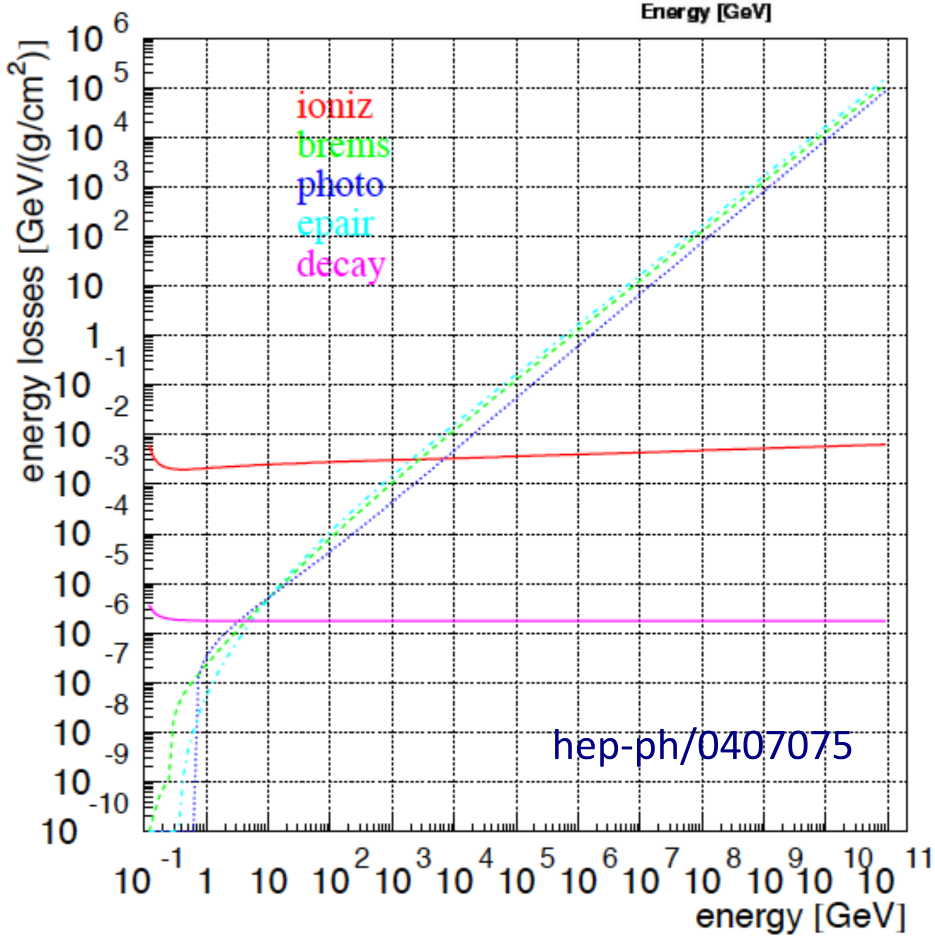
Secondary particle generation





- High energy muons / taus generate secondary particles by stochastic interactions
- Energy loss scales with muon / tau energy → The energy estimation possible
- Uncertainty of photo-nuclear process: ~10% effect on an analysis

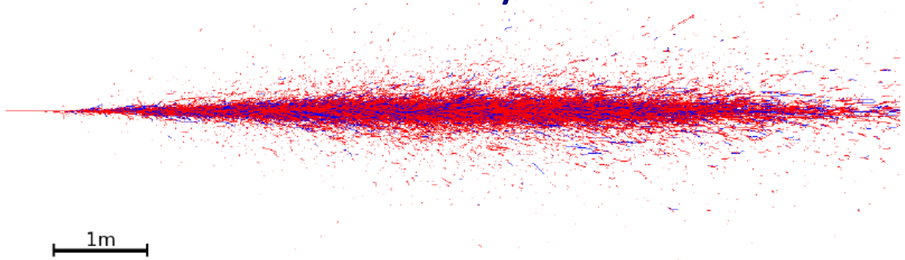




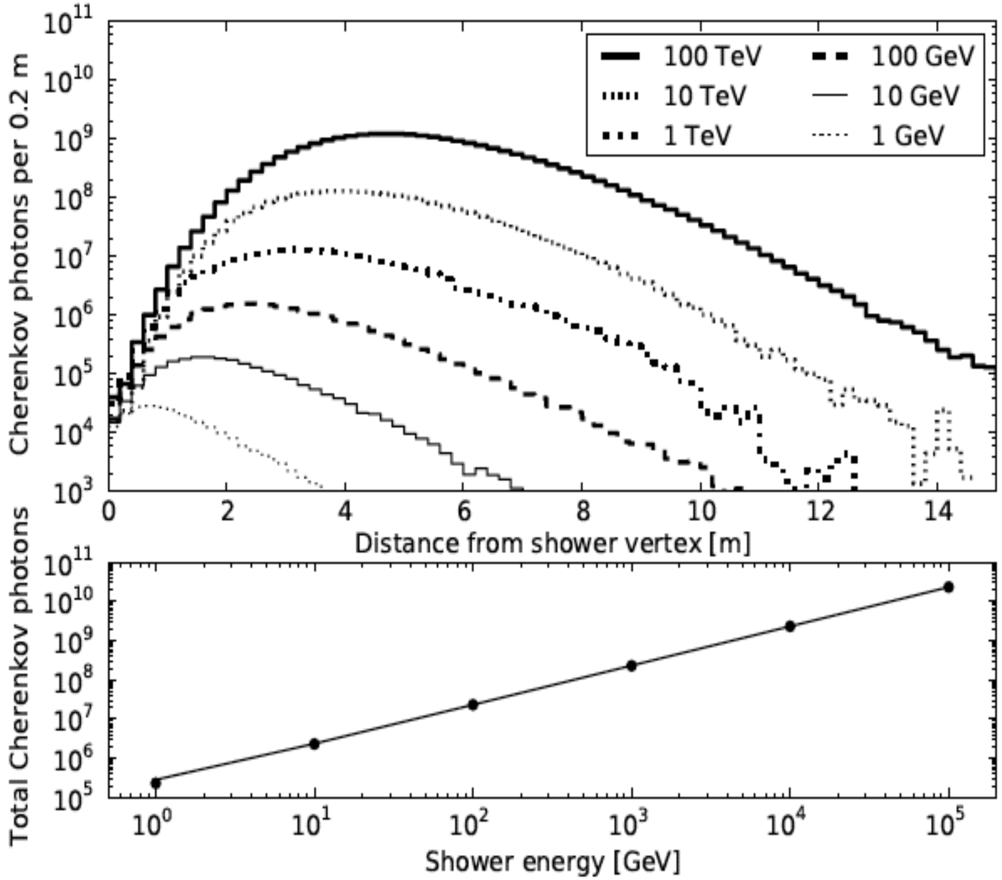
Cherenkov photon generation

- Number of Cherenkov photon from showers was estimated by GEANT4
- Photon number scale with energy
- Photons are ~20% lower from hadronic showers compared to EM showers

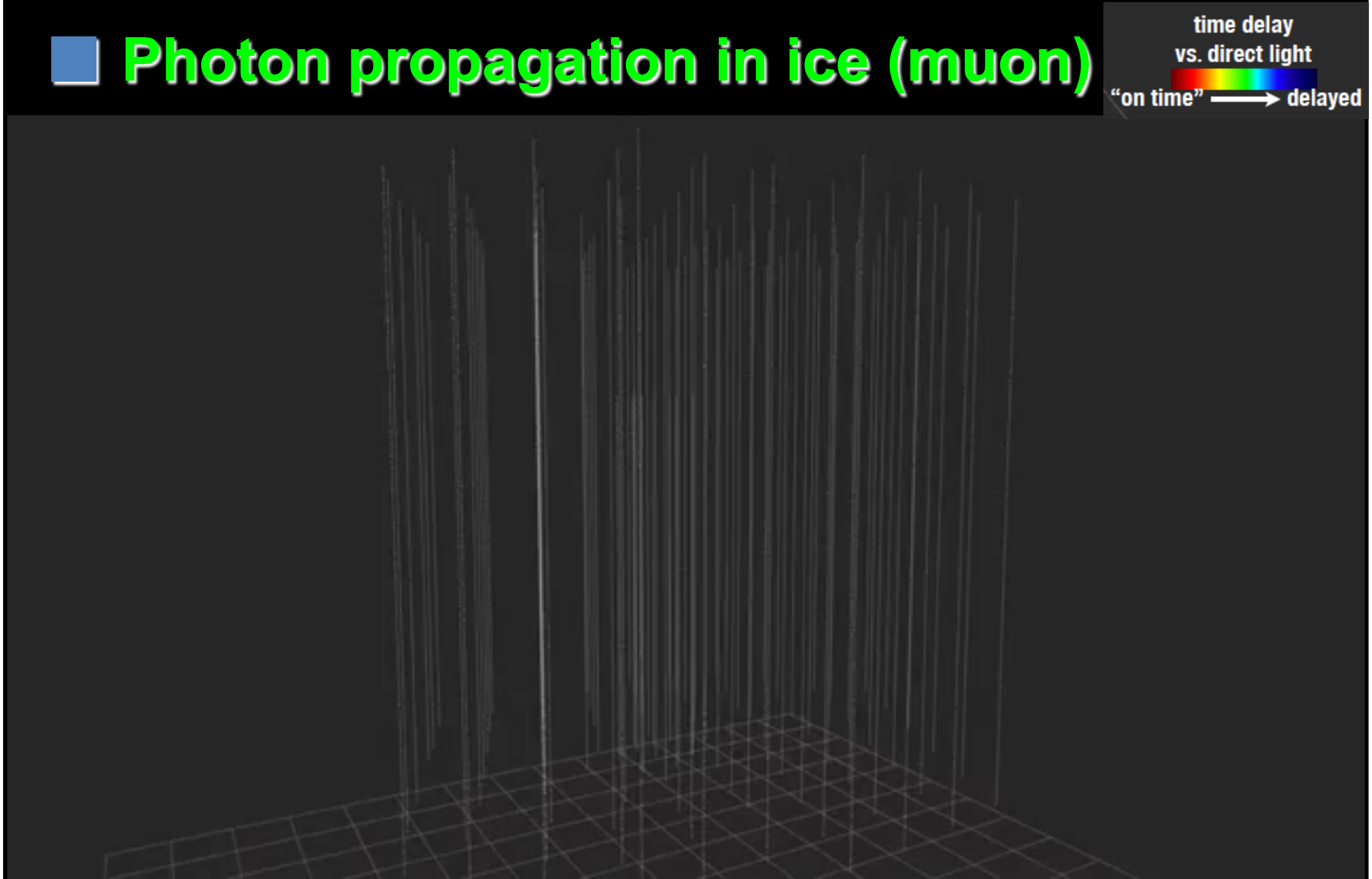
1 TeV EM shower by GEANT4



arXiv:1311.4767



Photon propagation in ice (muon)



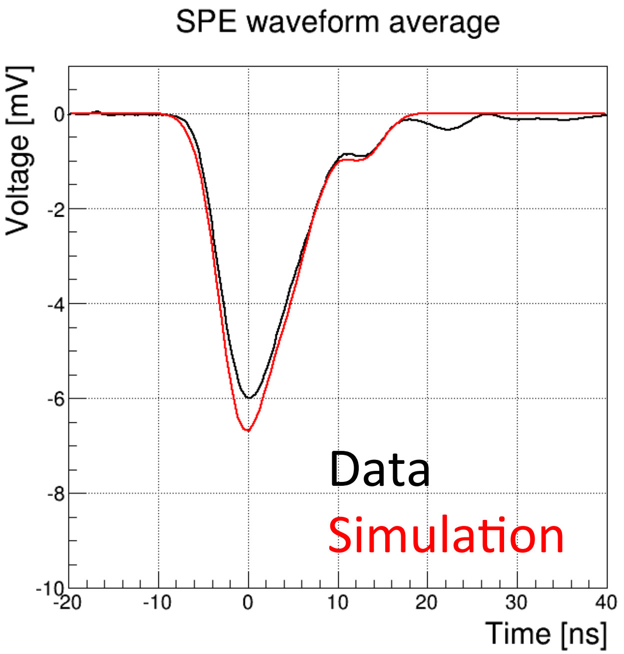
http://youtube.com/gzk9000

Photon propagation in ice (EM)

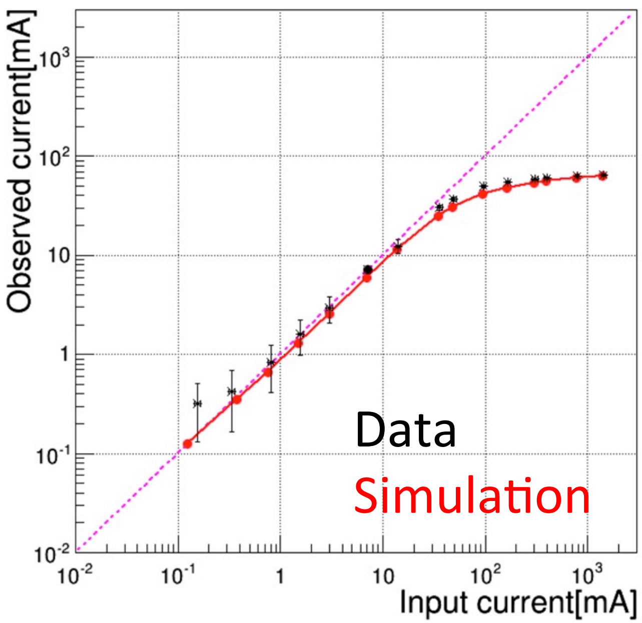
http://youtube.com/gzk9000

Detector responses

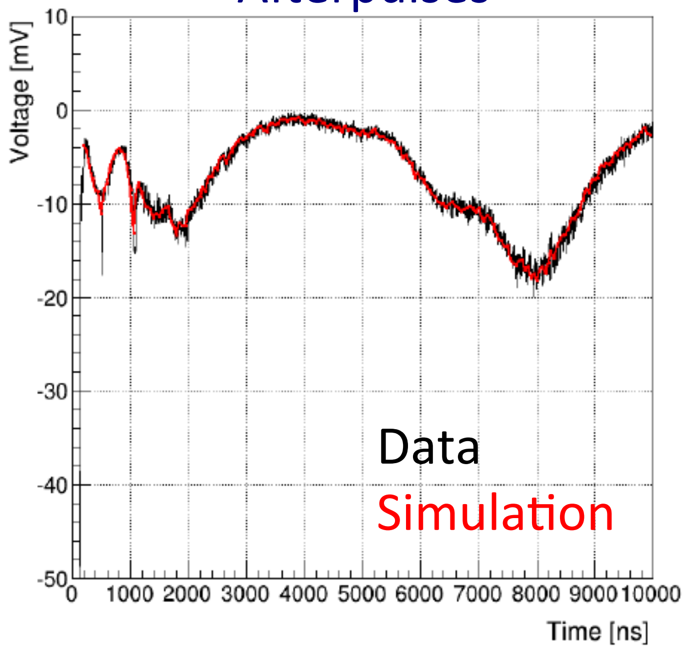
- Detector responses are simulated to describe our data



PMT Saturation

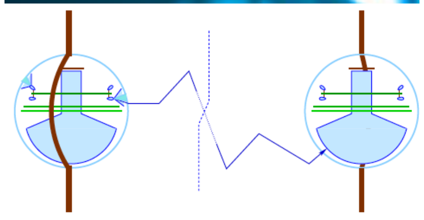


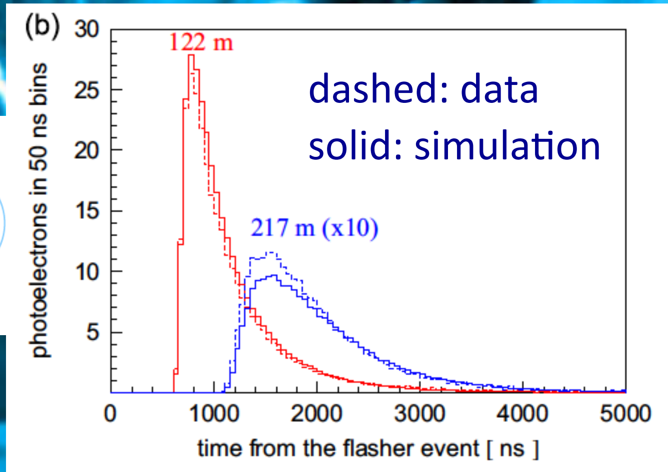
Afterpulses

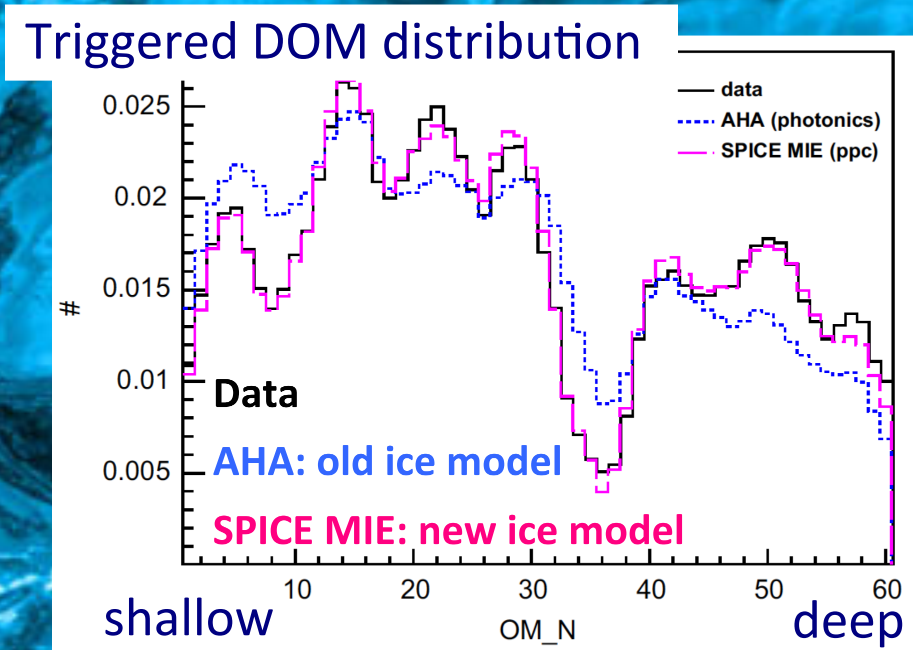


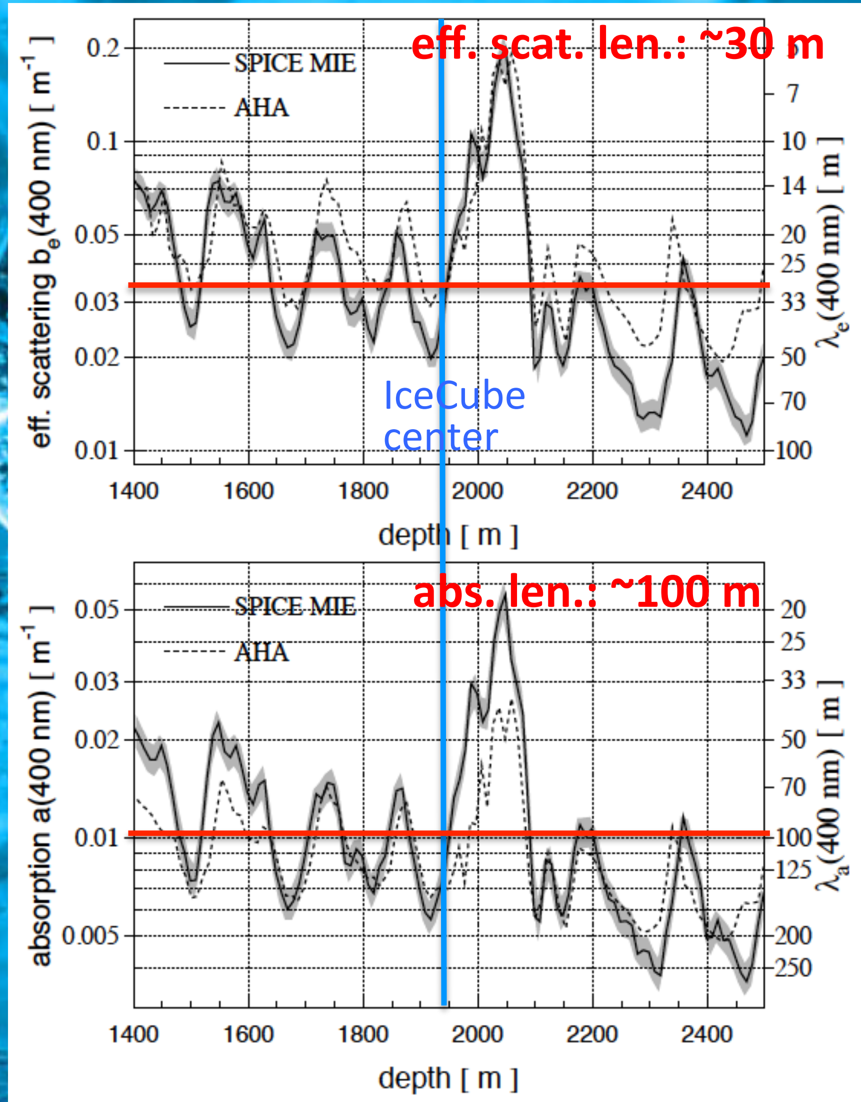
Calibration of our detector: ice

Ice properties calibrated by LEDs installed in DOMs NIM A, 711, 73 (2013)





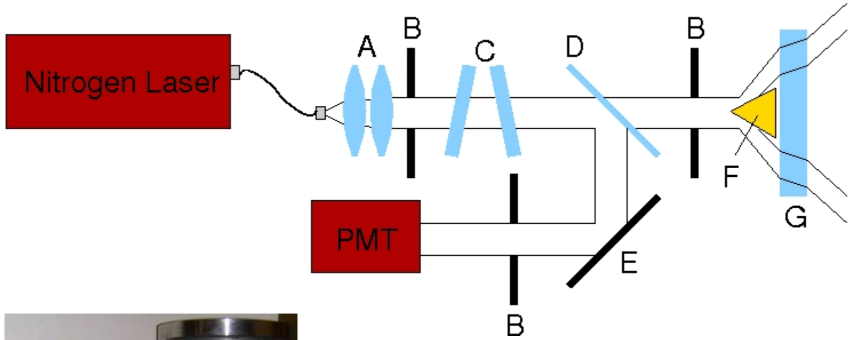


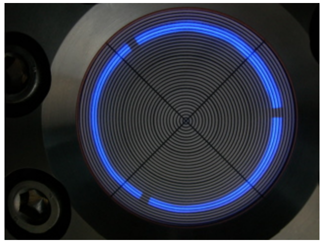


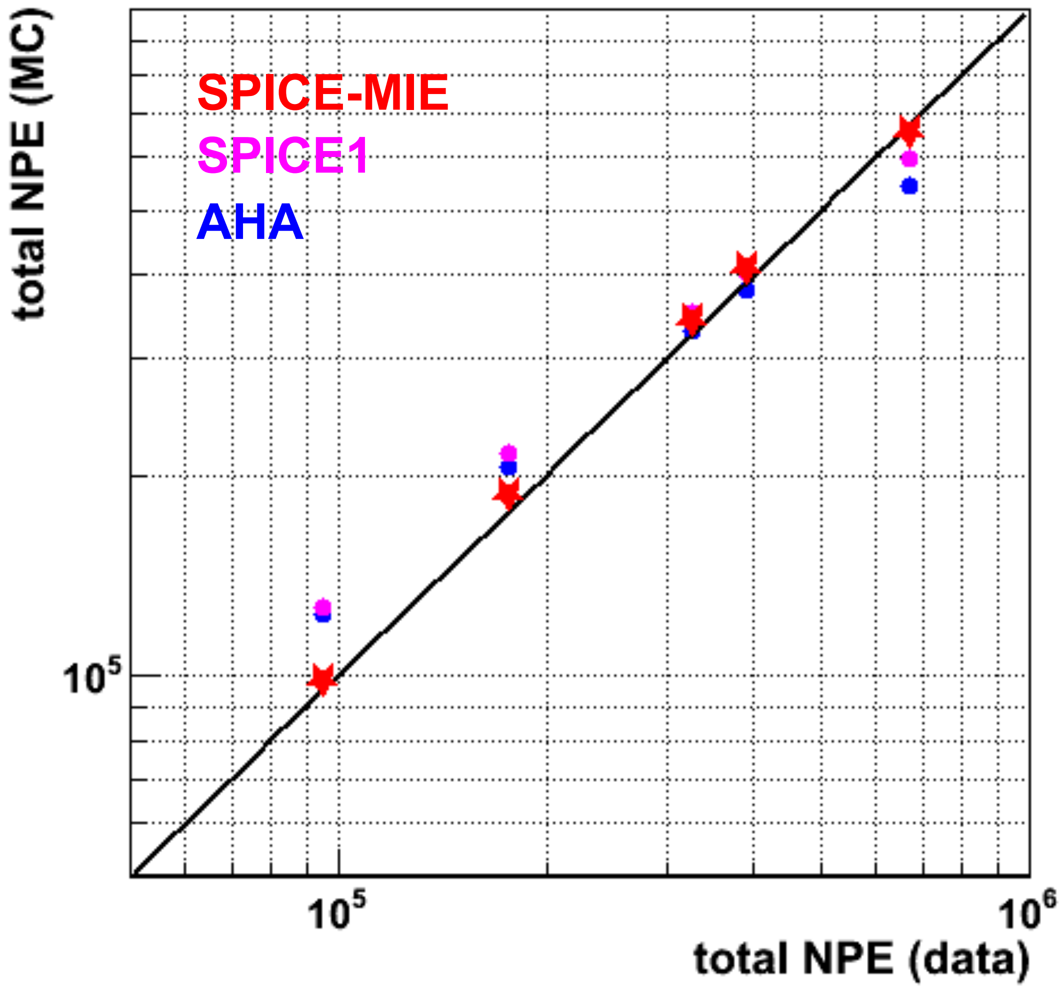
We understand the ice properties better!

Calibration in ice using standard candle

- Absolutely calibrated source
- 337 nm (nitrogen laser)
- Intensity can be changed



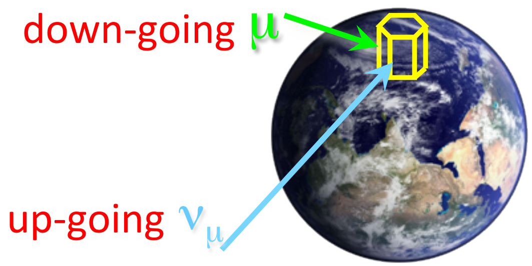




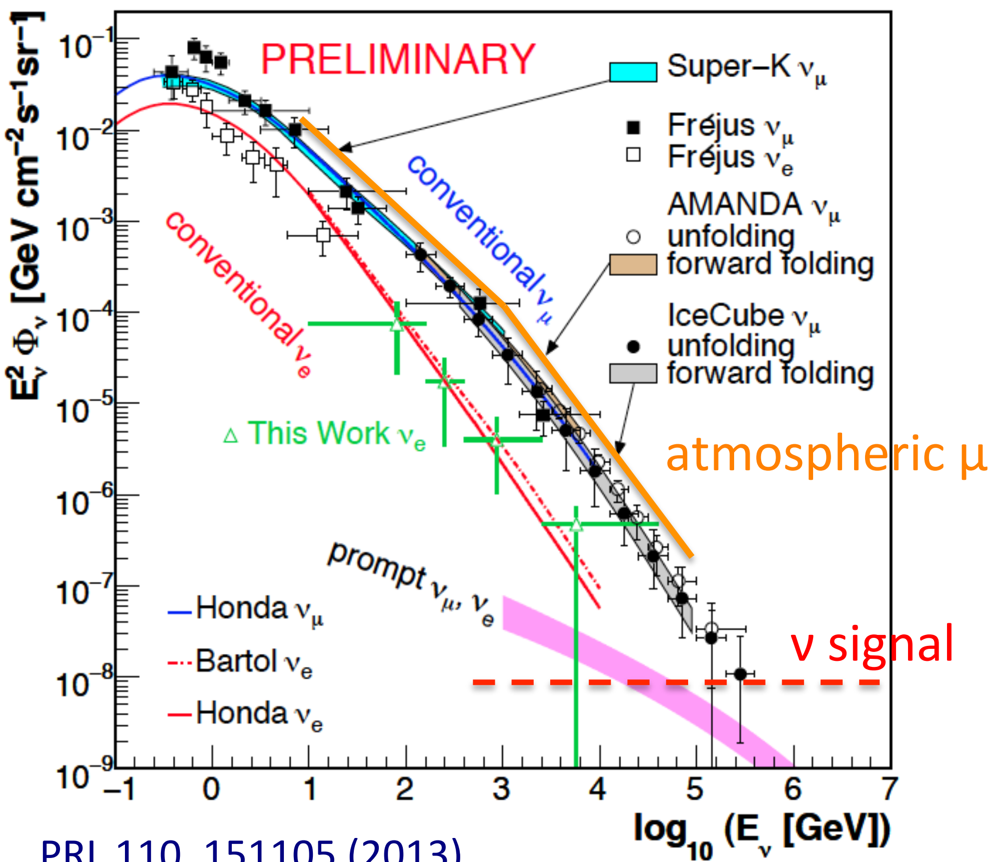
New ice model (SPICE-MIE) describes our data

Difference on an energy estimator is about 5%

Backgrounds

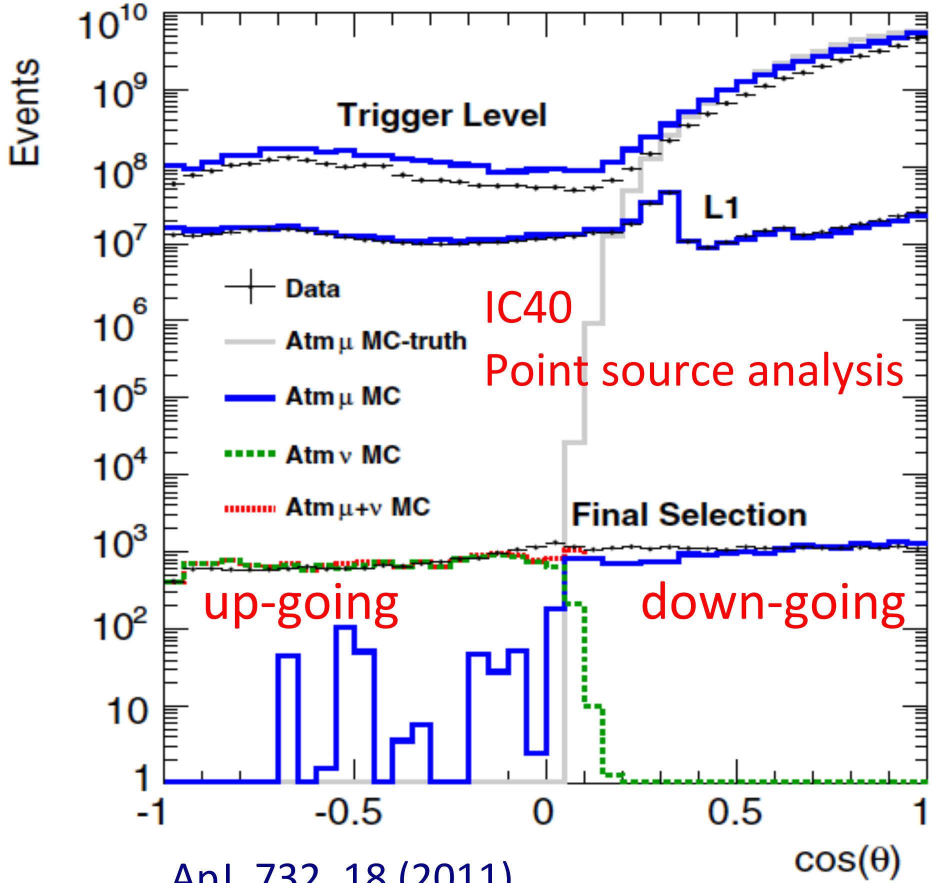


Energy spectra @ surface



PRL 110, 151105 (2013)

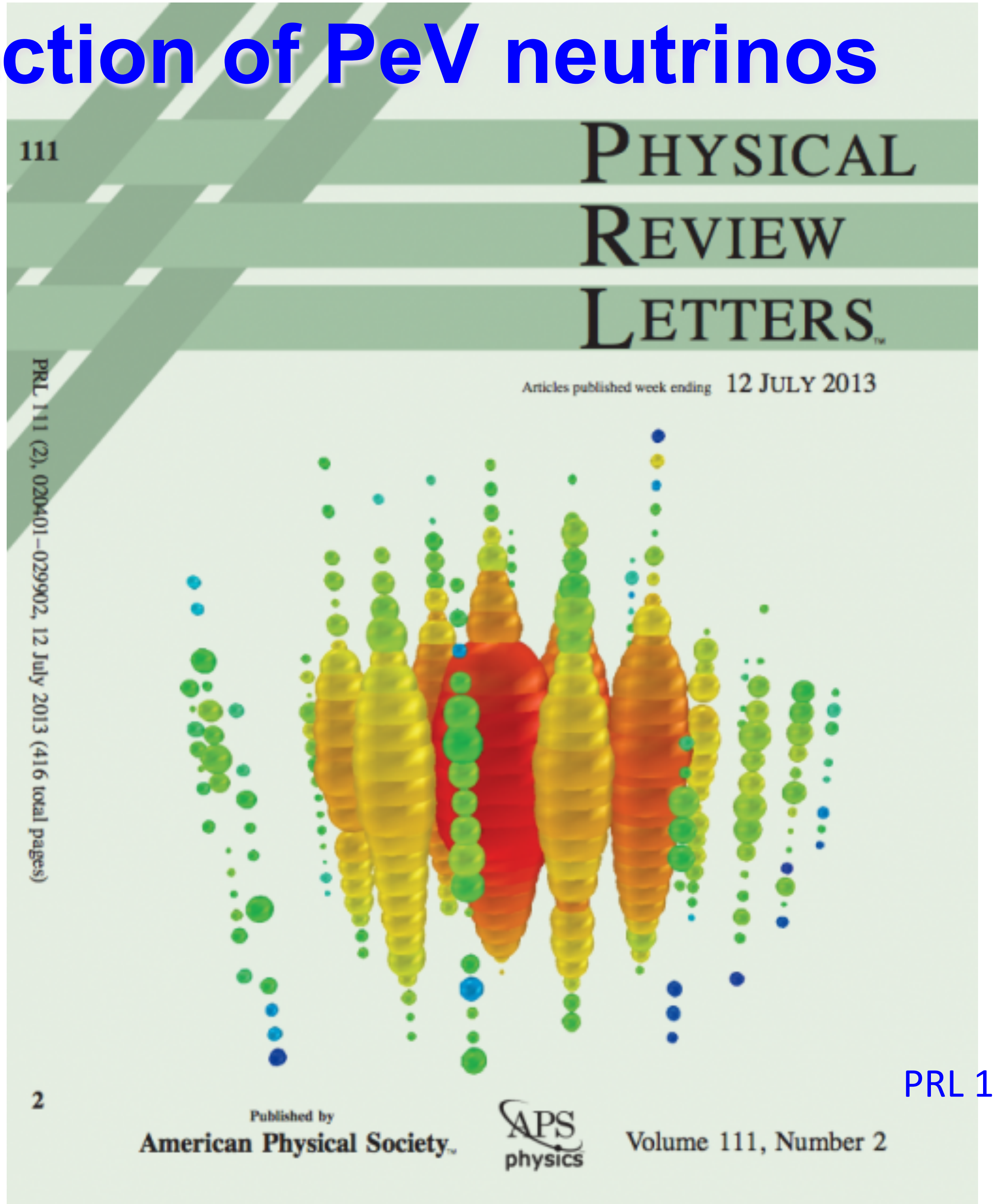
Zenith angle distribution @ detector



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

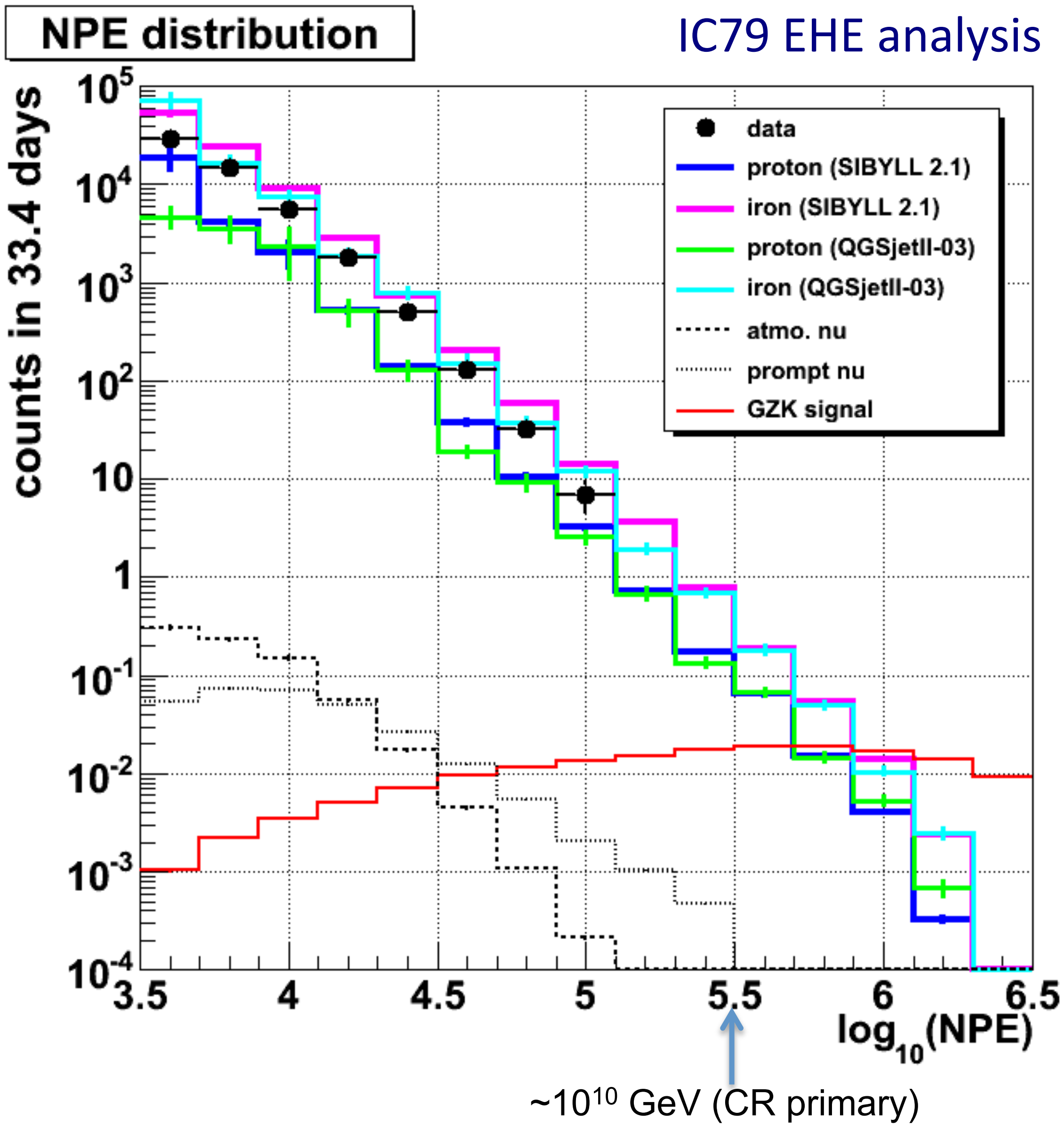
Detection of PeV neutrinos



PRL 111, 021103 (2013)

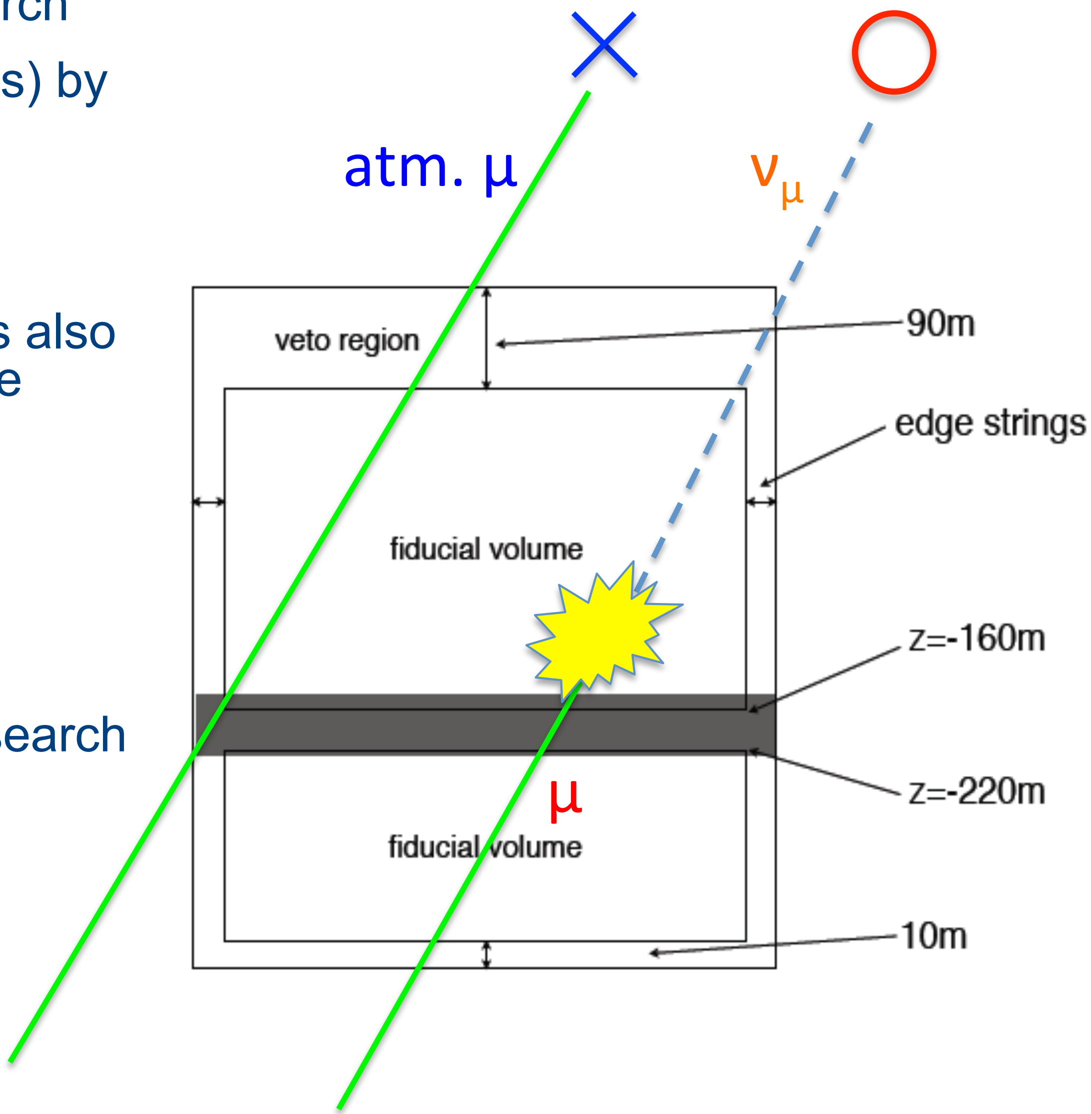
High energy interaction models in air showers

- The SIBYLL 2.1 is the standard in IceCube
- The energy estimator is robust against the high energy interaction model
- Difference is ~20% in flux
- Reasonable agreement with data
- Note only high energy muon (>~ 300 GeV at surface) can visit the IceCube detector
- QGSjet II-04 (LHC parameters included) data are being produced to estimate the systematic errors further



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

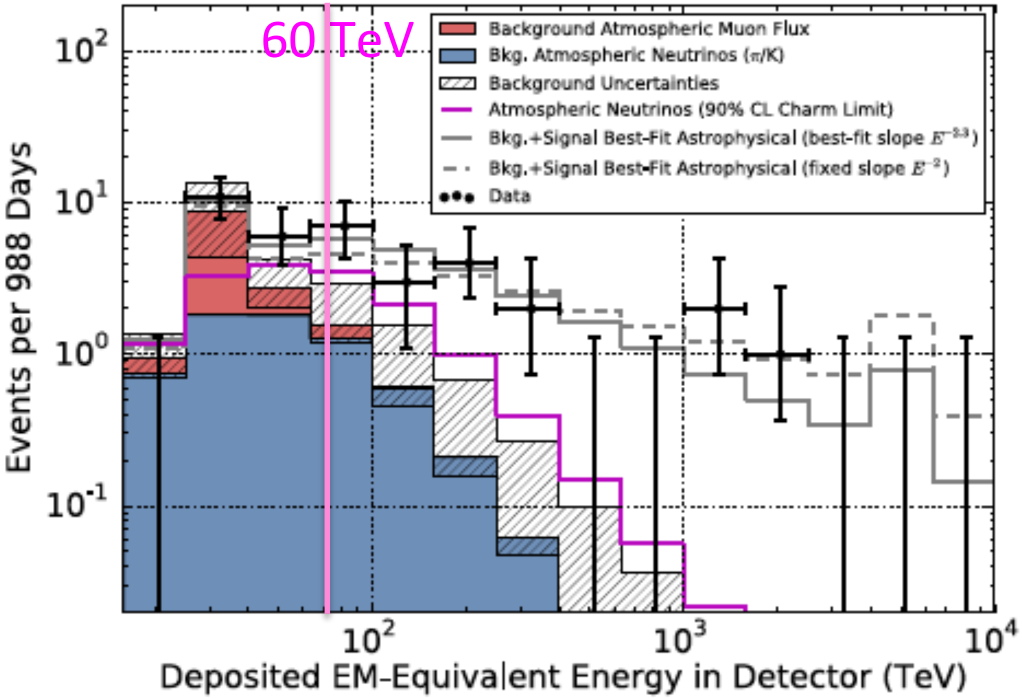
3 year data (988 days)

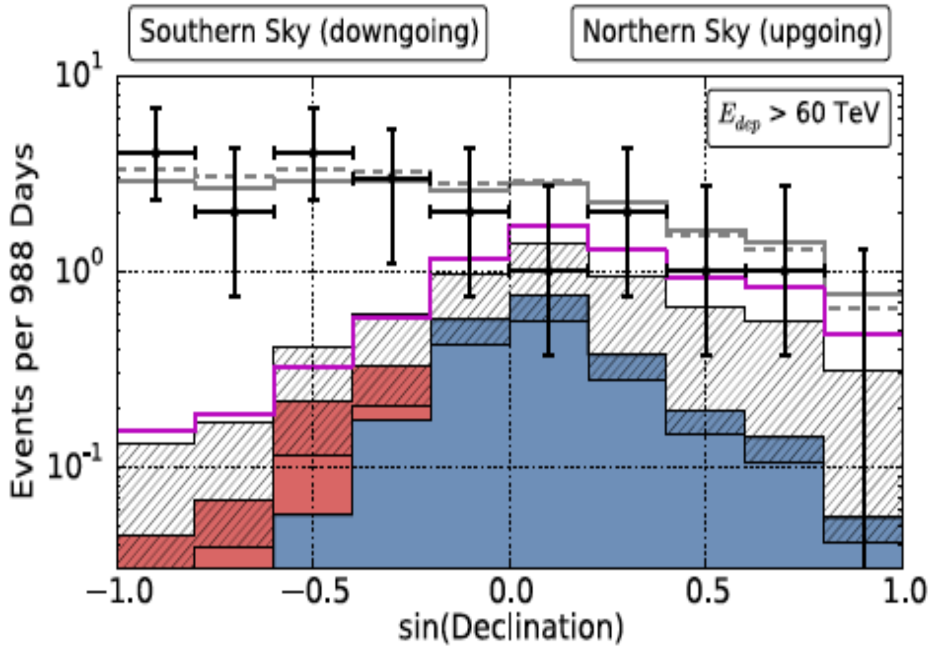
37 neutrino candidates found! (28 cascades, 7 tracks, 2 obvious muons)

Significance: 5.7σ (Expected BG: 15)

PRL, 113, 101101 (2014)

E > 60 TeV





- Energy spectrum harder than that of backgrounds
- Best fit: $E^{-2.3\pm0.3}$
- $E^2\varphi = 0.95 \pm 0.3 \times 10^{-8}$ GeV/cm^2/s/sr (per flavor)
- Consistent with a flavor ratio of 1:1:1

Sky map and the significance

Test null hypothesis against the most likely

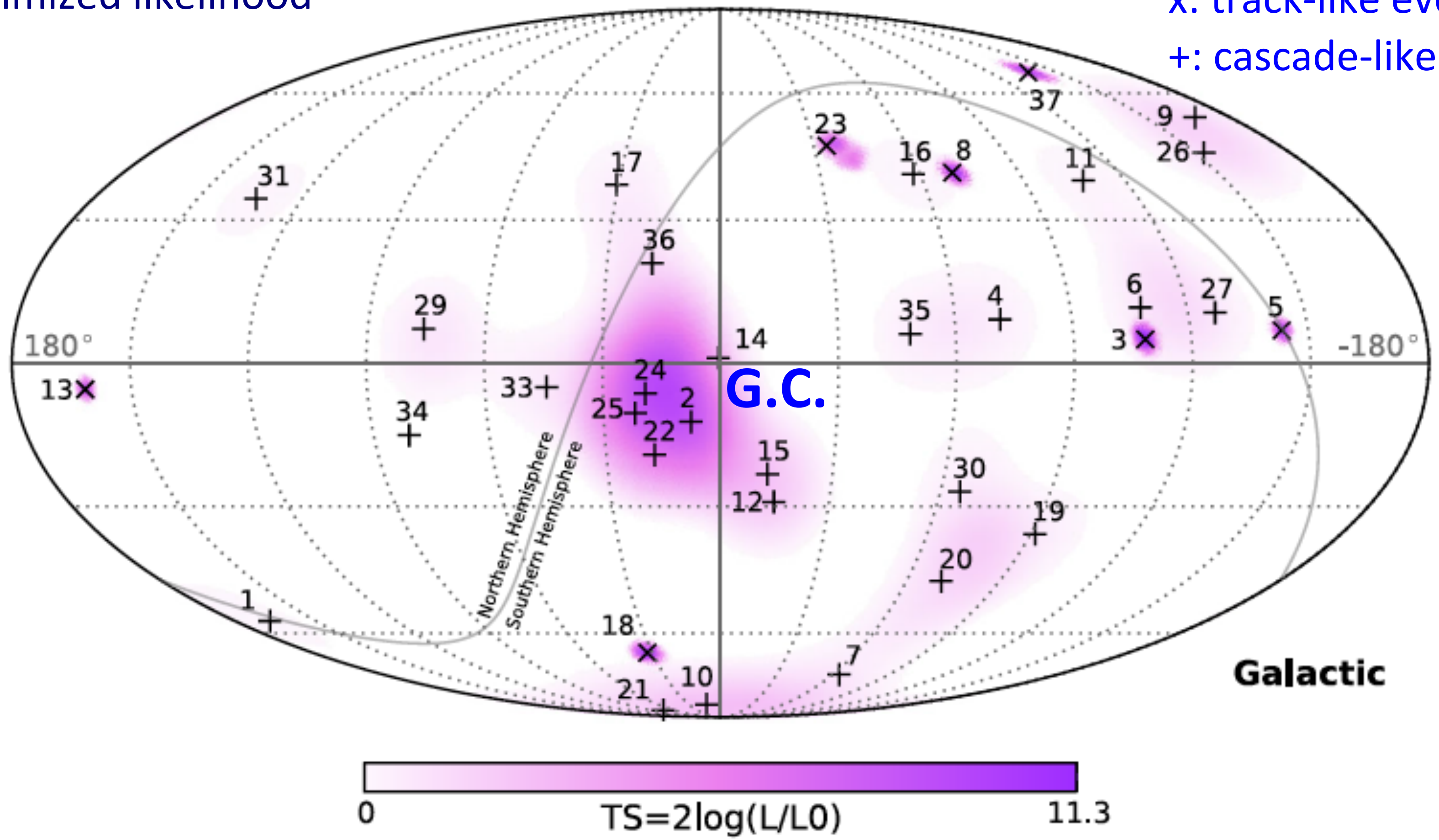
L0: null hypothesis

L: maximized likelihood

PRL, 113, 101101 (2014)

x: track-like events

+: cascade-like events



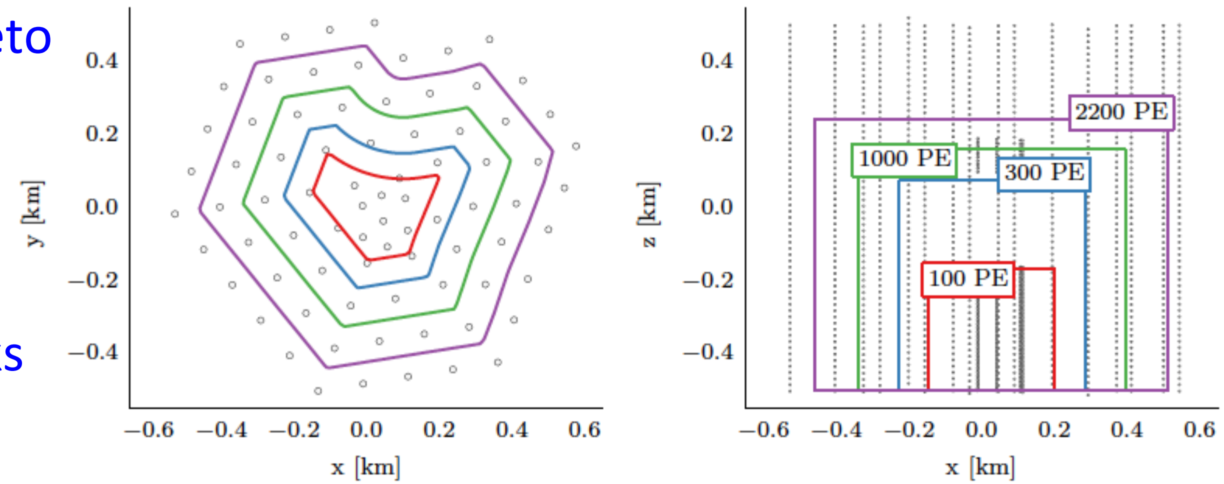
No statistically significant correlation

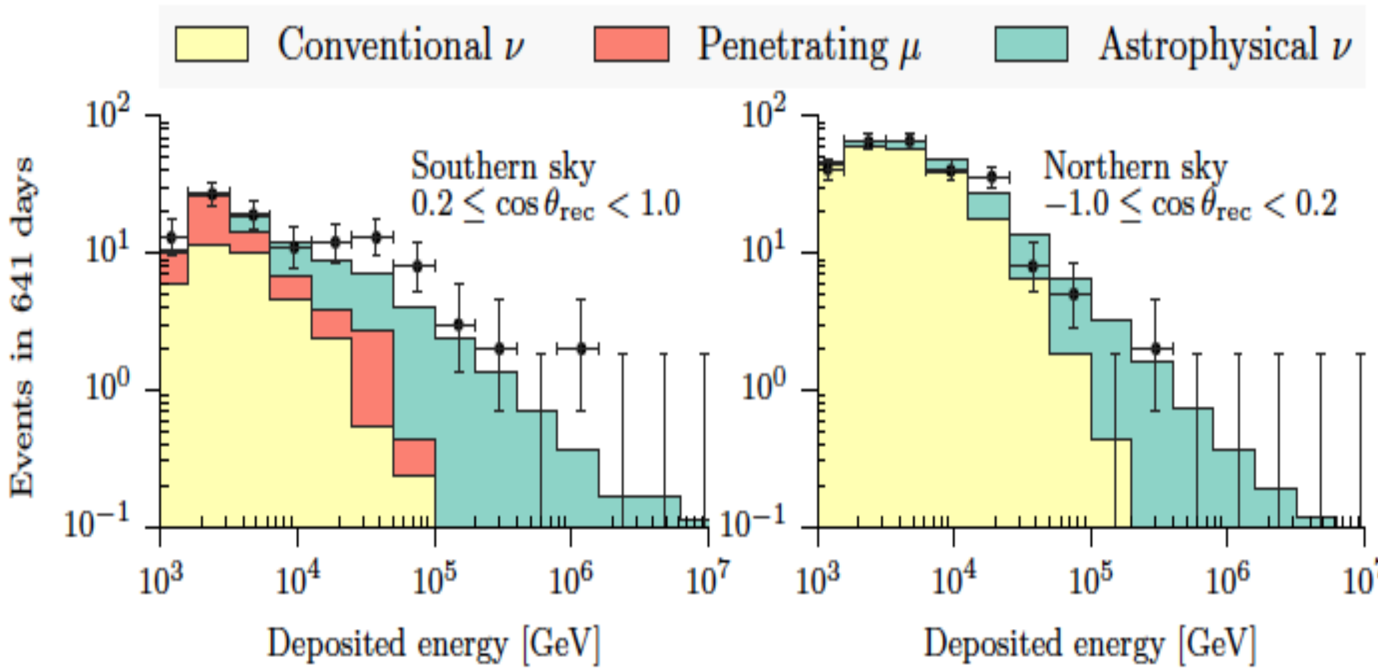
High latitude events → extra-galactic component

Cascade analysis

PRD 91, 022001 (2015)

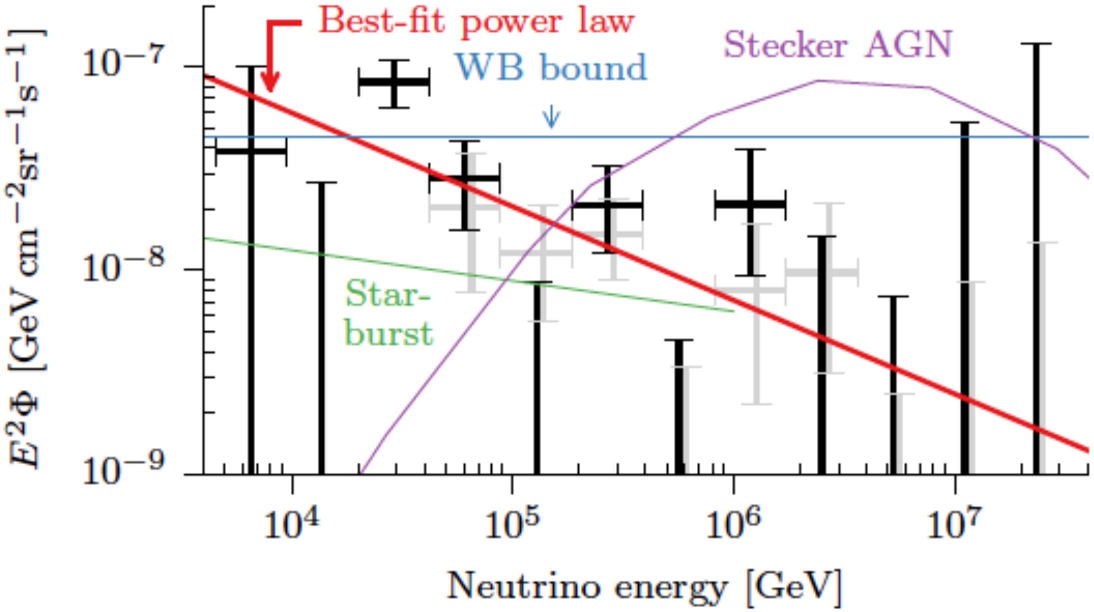
- ✓ Even more sophisticated veto
  → lower threshold
- ✓ 1 TeV – 1 PeV
- ✓ 2010-2012 (641 days)
- ✓ 283 cascades and 105 tracks

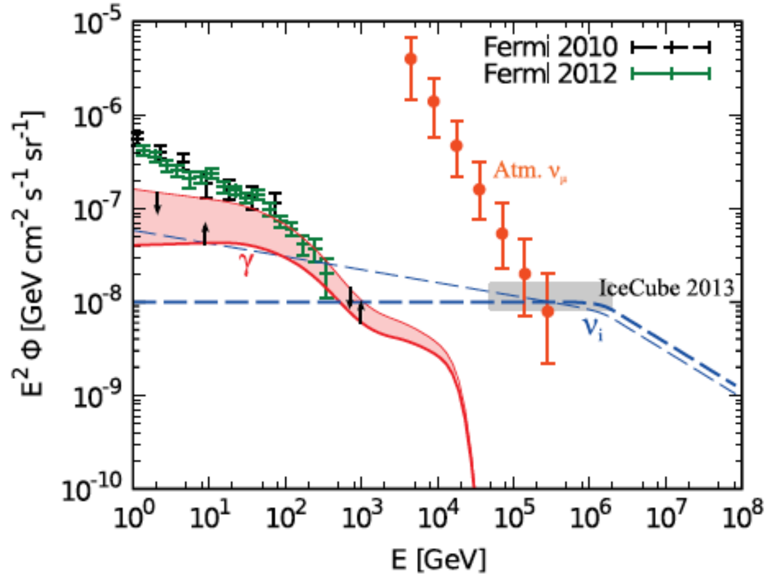




Cascade analysis (cont'd)

PRD 91, 022001 (2015)



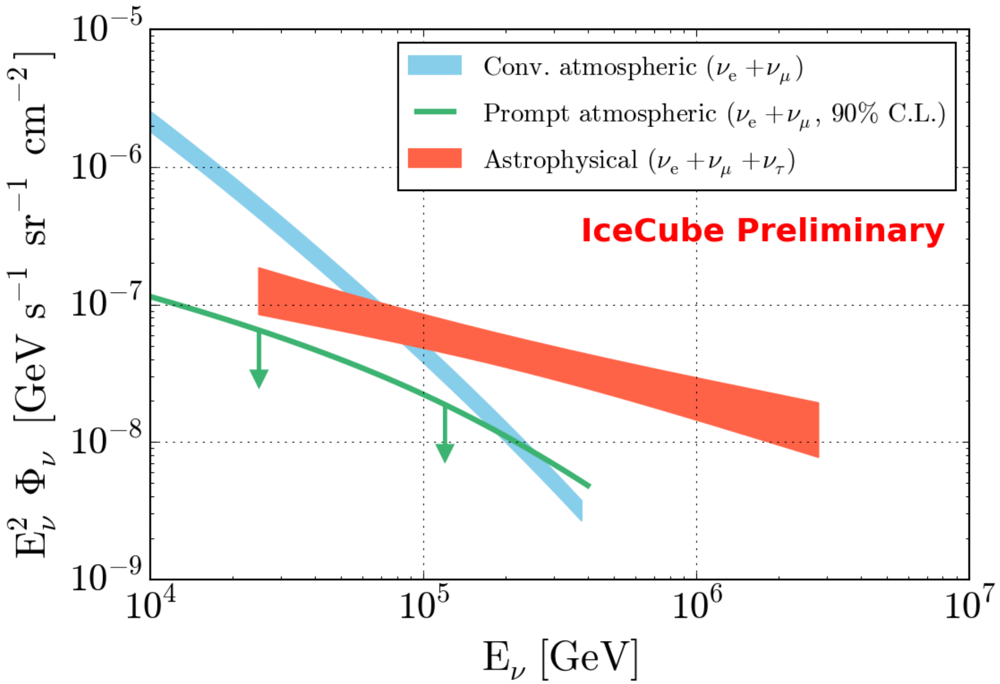


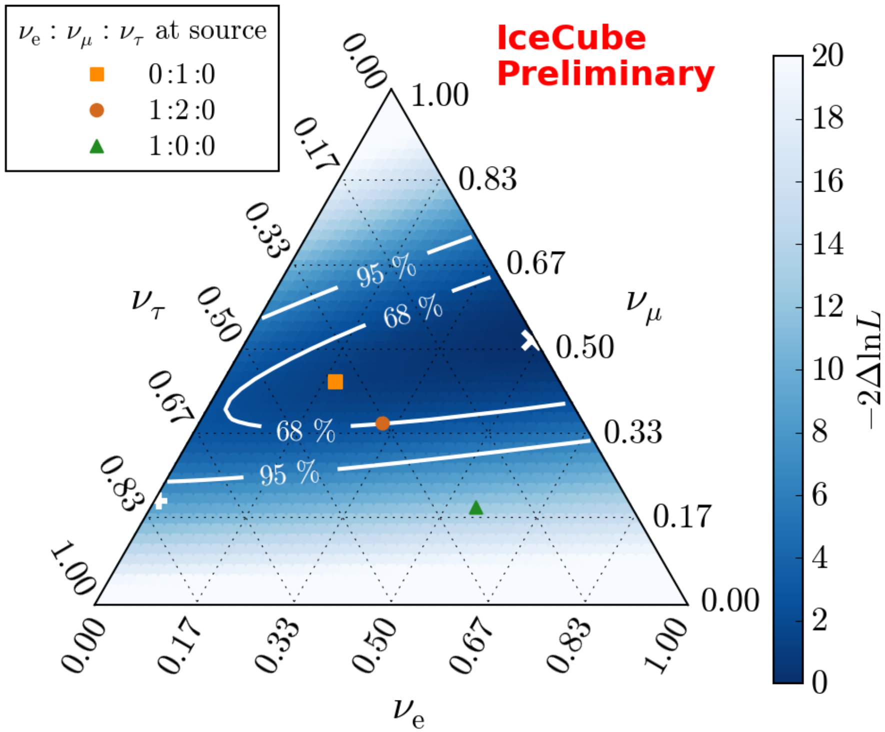
K. Murase, M. Ahlers and B. C. Lacki, PRD 88, 121301 (2013)

- ✓ Spectral index: 2.46 ± 0.12 (softer)
- ✓ Consistent with the previous results
- ✓ In case of a simple pp scenario, the spectral index has to be less than 2.2 to satisfy diffuse gamma rays observed by Fermi
- ✓ The simple pp scenario is rejected with 90% C.L.
- ✓ Charm flux < 1.5 x ERS (90% C.L.)

Combined analysis

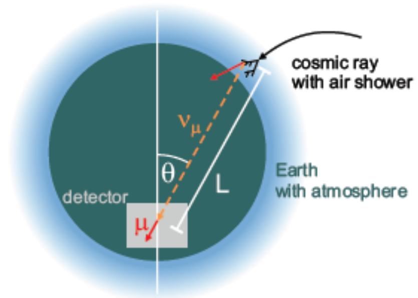
- Combines diffuse IceCube analyses (HESE, cascade, diffuse)
- Spectral index: 2.50 ± 0.09
- The observed flavor ratio is consistent with 1:1:1
- Electron dominant flavor ratio at source (1:0:0) is rejected more than 95%



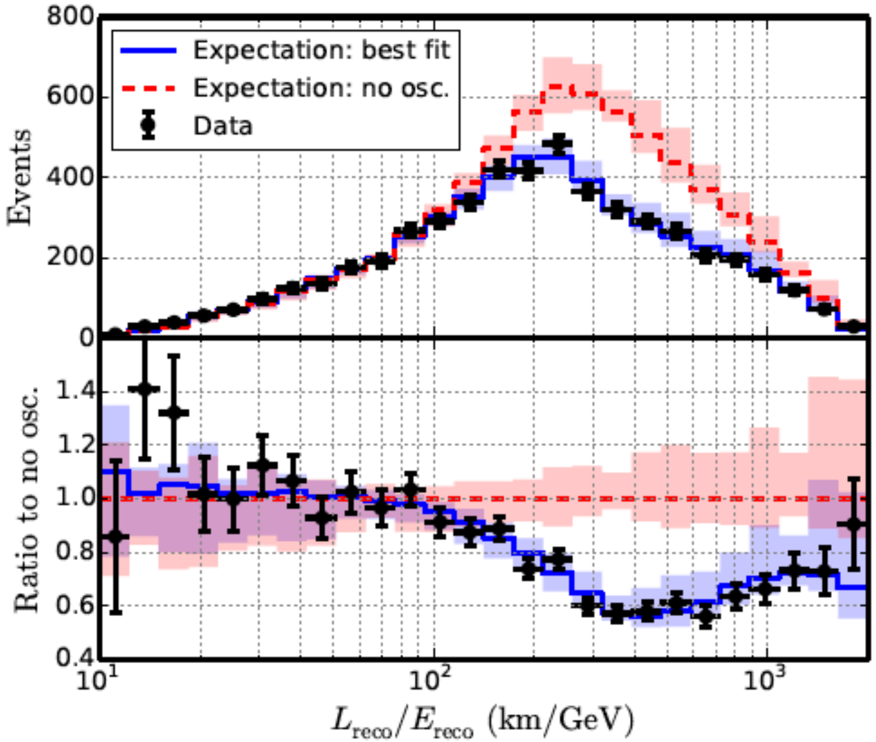


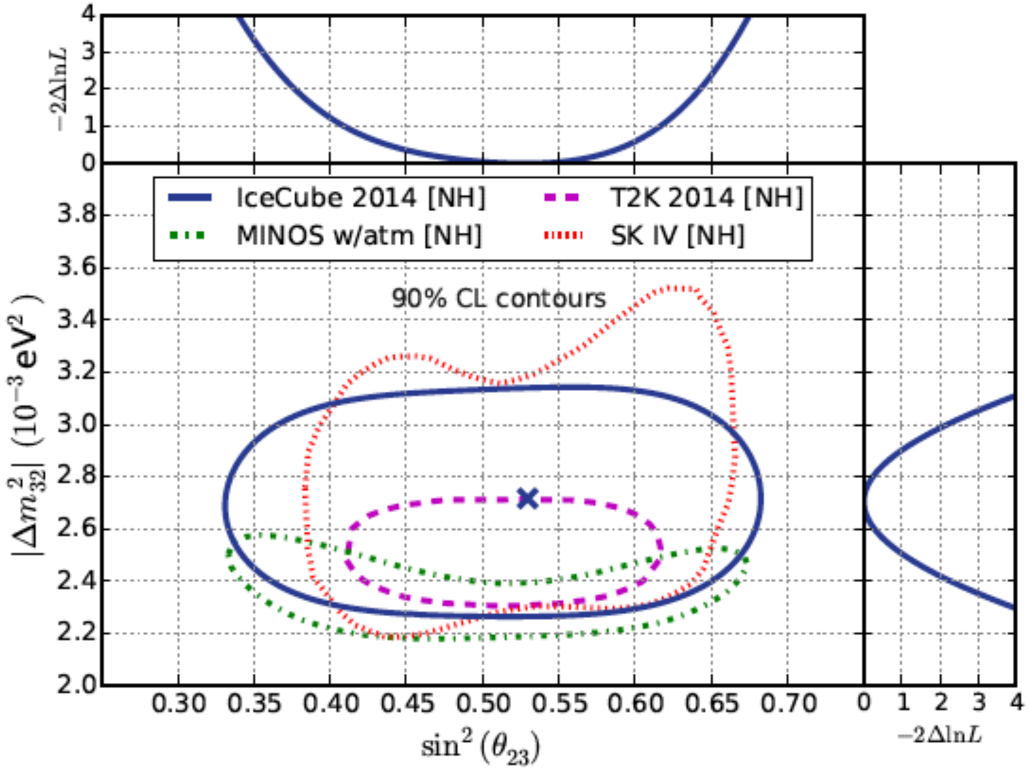
Atmospheric neutrino oscillation

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



- ✓ 3yr data (953 days)
- ✓ Competitive with other experiments





$$\left|\Delta m^2_{32}\right| = (2.72^{+0.19}_{-0.20}) \times 10^{-3}\ eV^2$$

$$\sin^2\theta_{23} = 0.53^{+0.09}_{-0.12}\ \ (NH)$$

❑ Summary

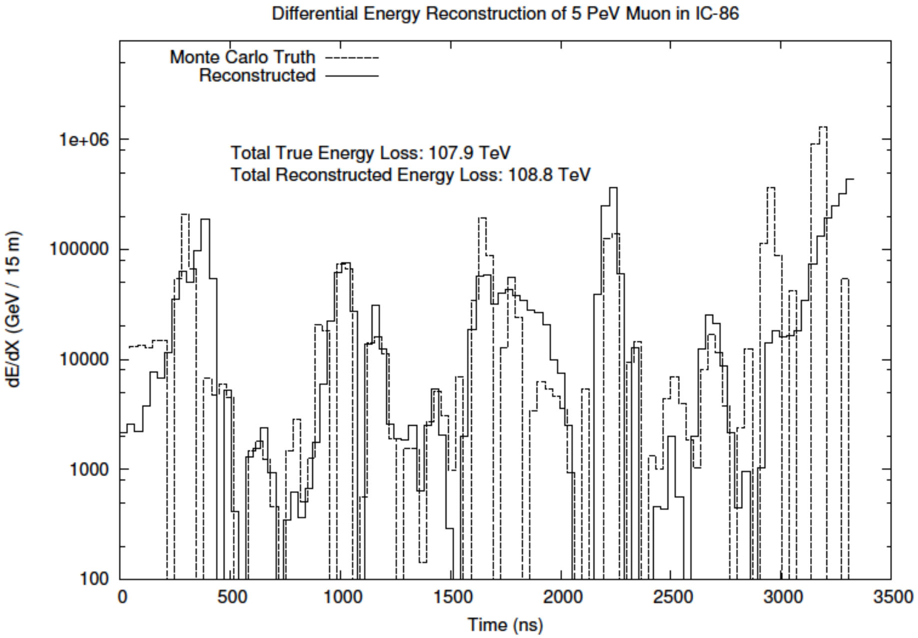
- **IceCube MC scheme and the detail were presented**
- **Astrophysical neutrinos observed**
- **Gradual understanding of the observed events**
- Contribution to particle physics
- **More data and results are coming**

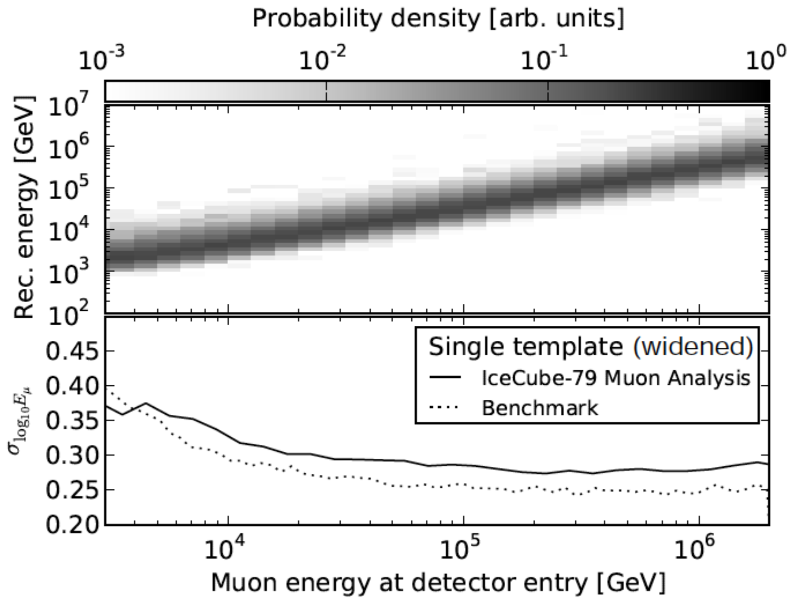
A NEW DAWN
THE BEGINNING OF LIFE
BY BURNING LIQUID

backups

Cherenkov photon generation

arXiv:1311.4767



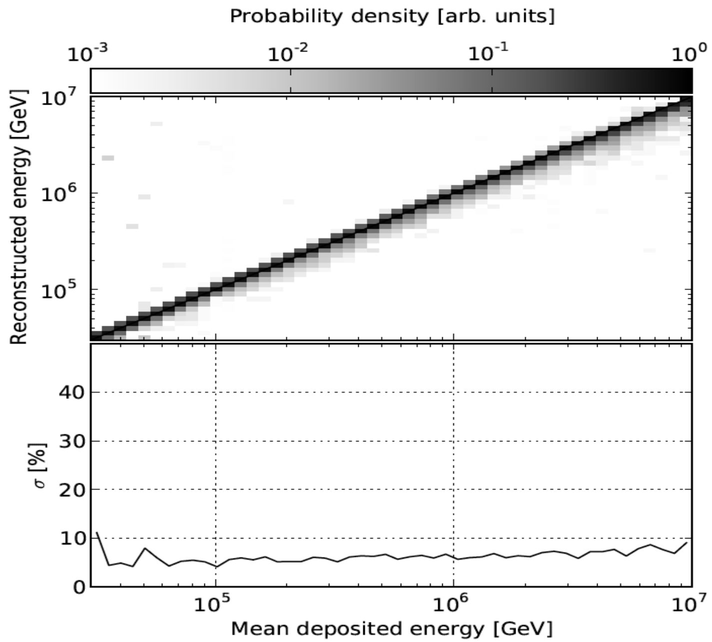


Energy deposit 10~15%

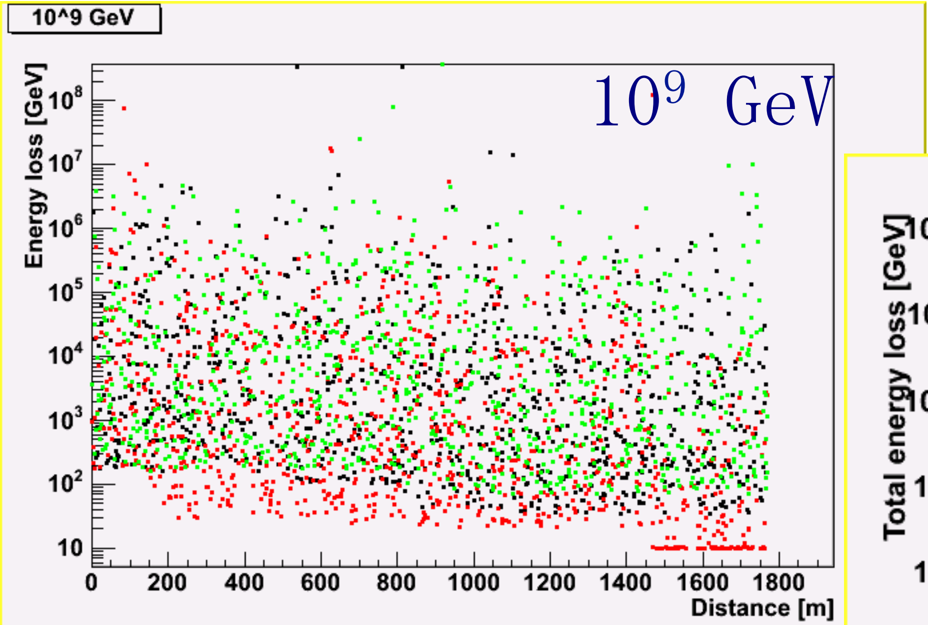
Muon energy resolution: 30%

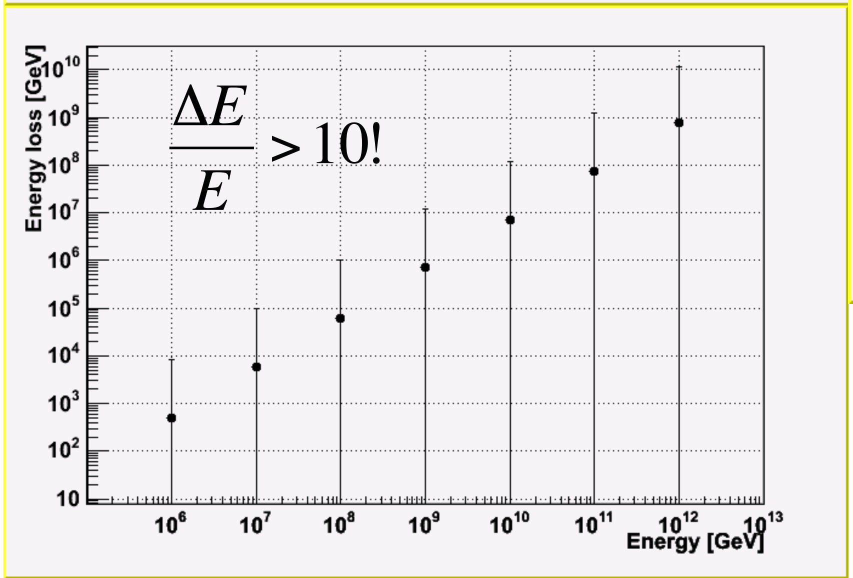
Numu energy resolution: 100%

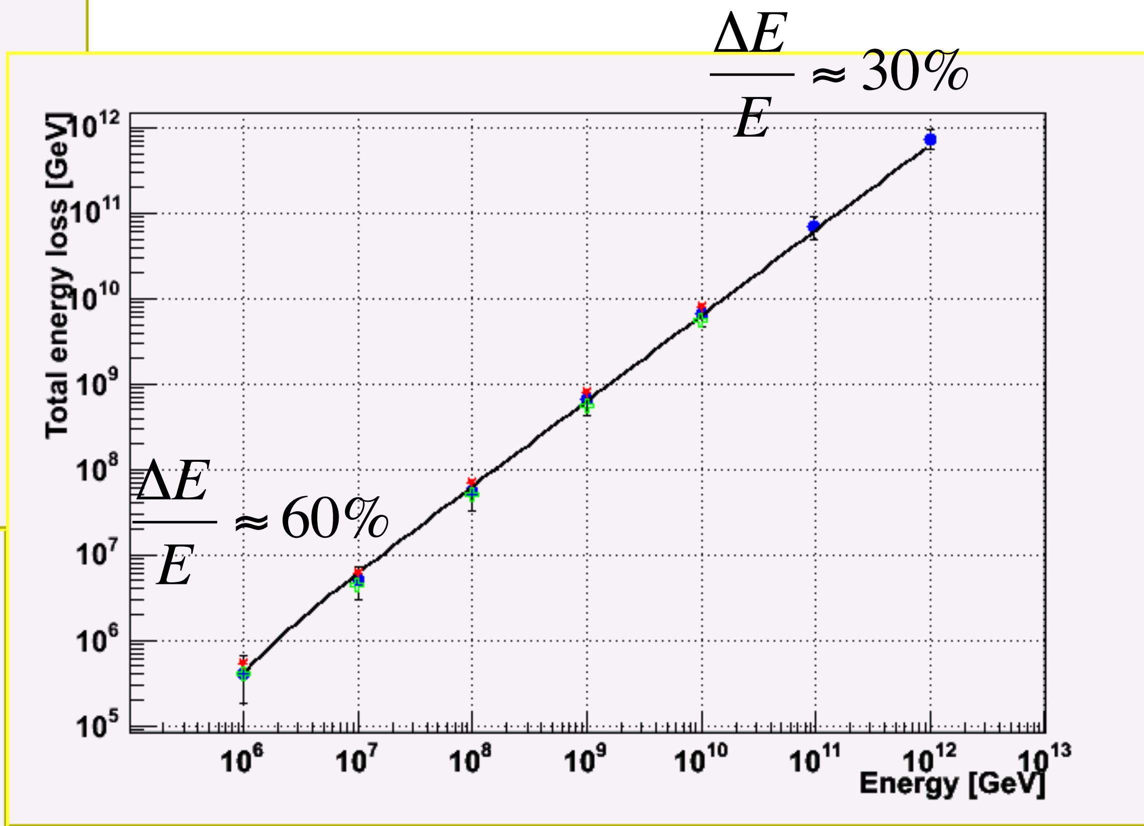
nue energy resolution : 10%



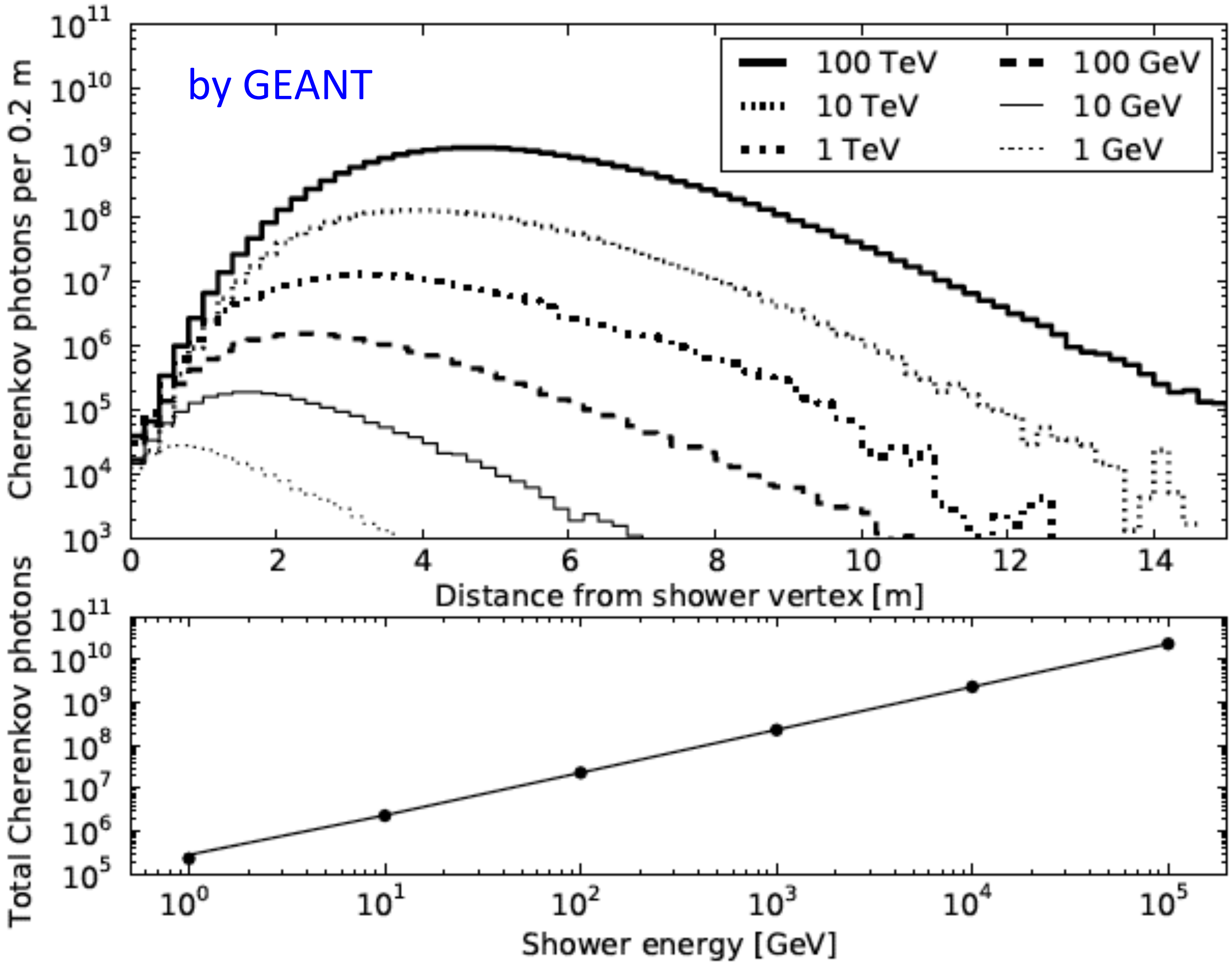
The properties of cascades from UHE muons



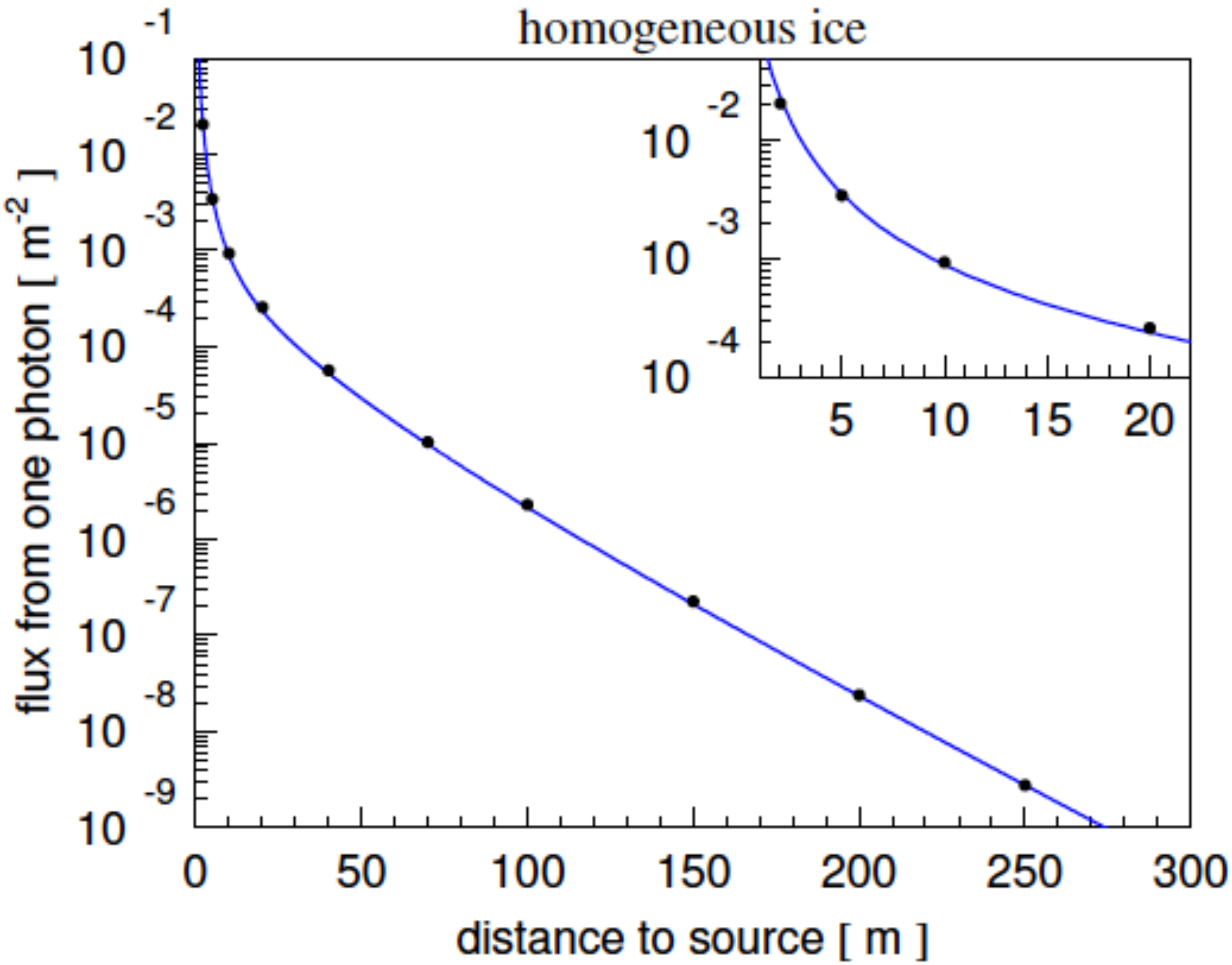


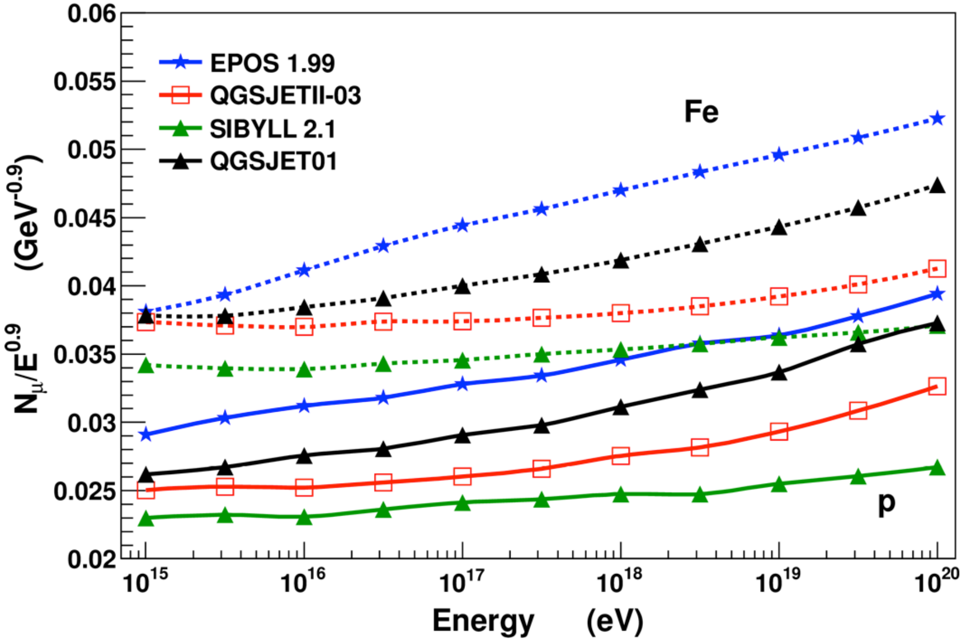


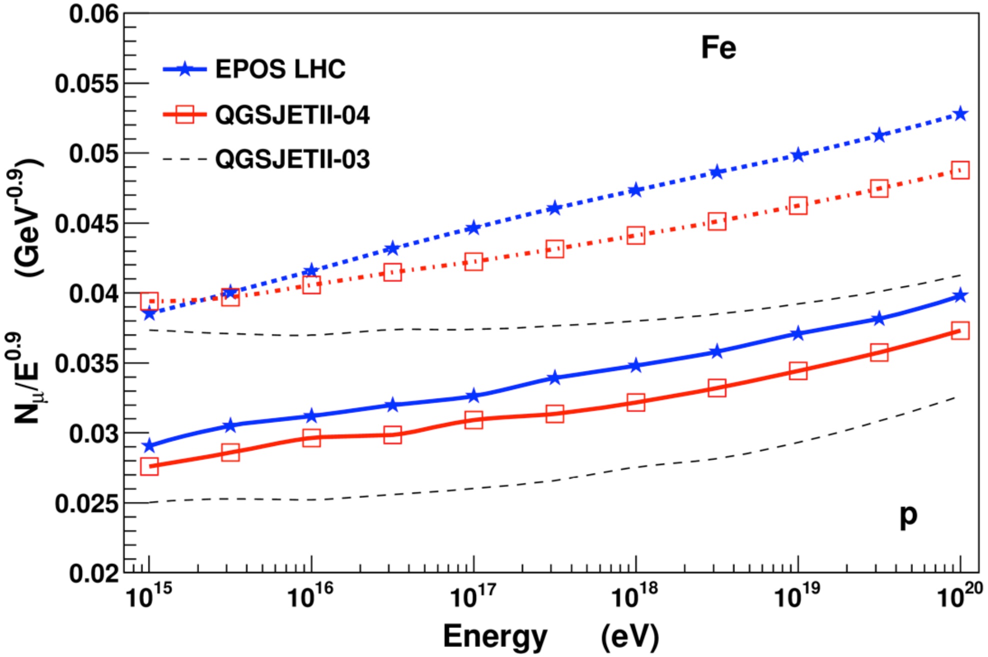
Longitudinal shower development in ice

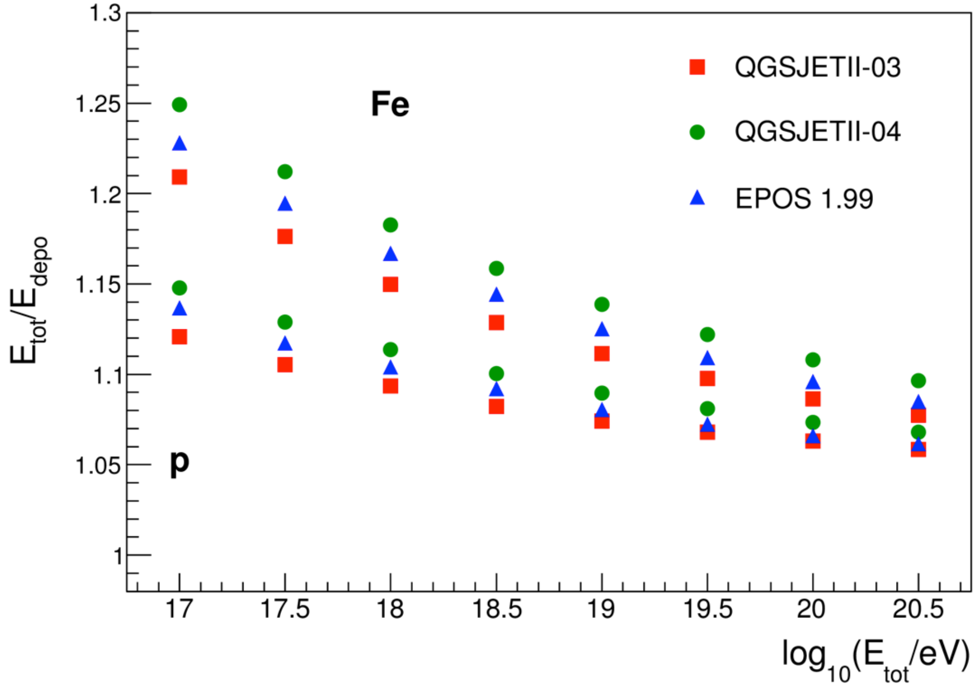


Light yield vs. distance for a point-like source









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