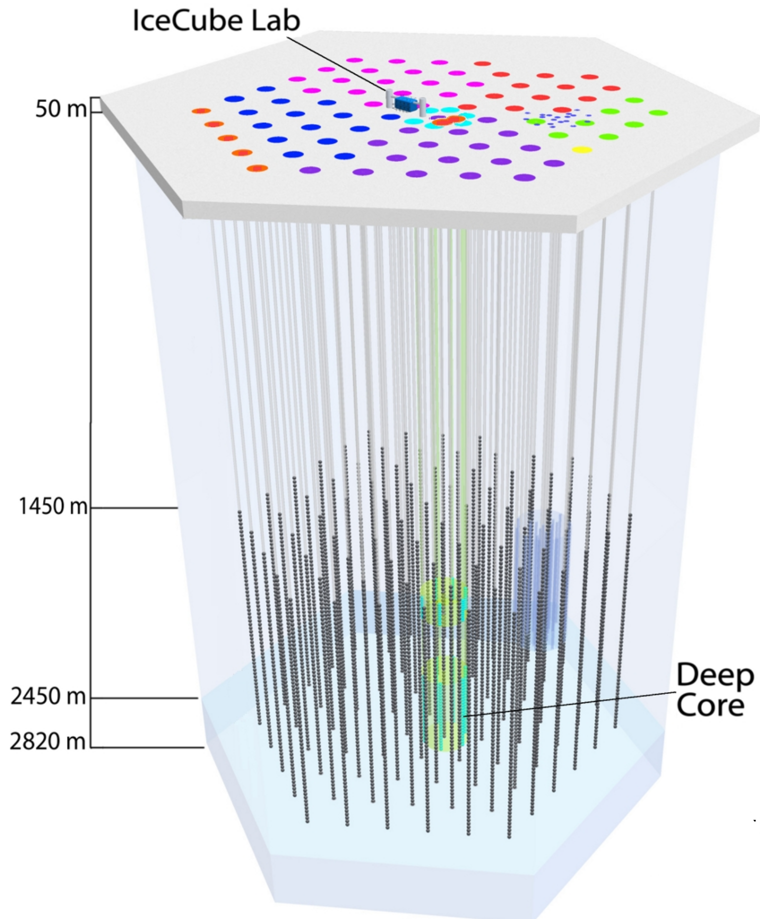
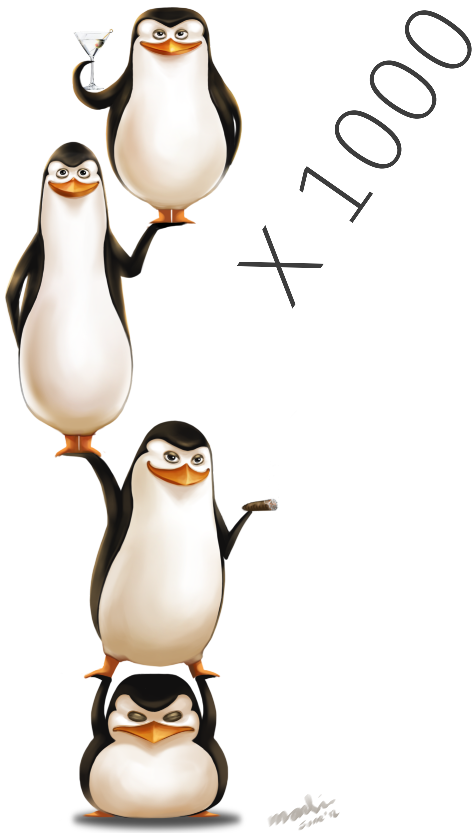




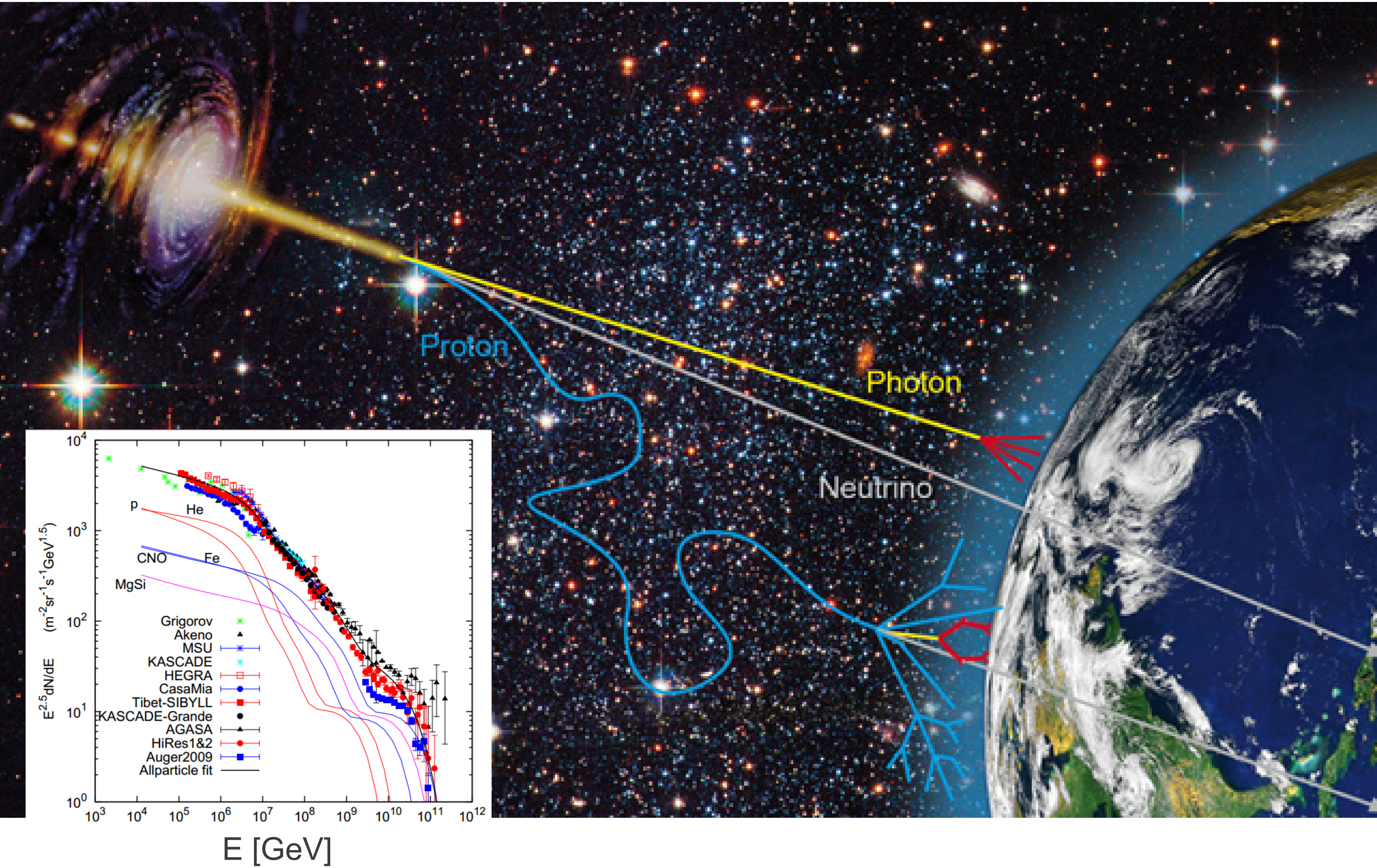
Diffuse astrophysical and prompt atmospheric neutrinos in IceCube

Anne Schukraft for the IceCube Collaboration
RWTH Aachen University

CERN Workshop on Results and prospects of forward physics at the LHC
Feb 12, 2013

IceCube
RWTH AACHEN UNIVERSITY
Deutsche Telekom Stiftung
Bundesministerium für Bildung und Forschung

Cosmic rays and neutrinos

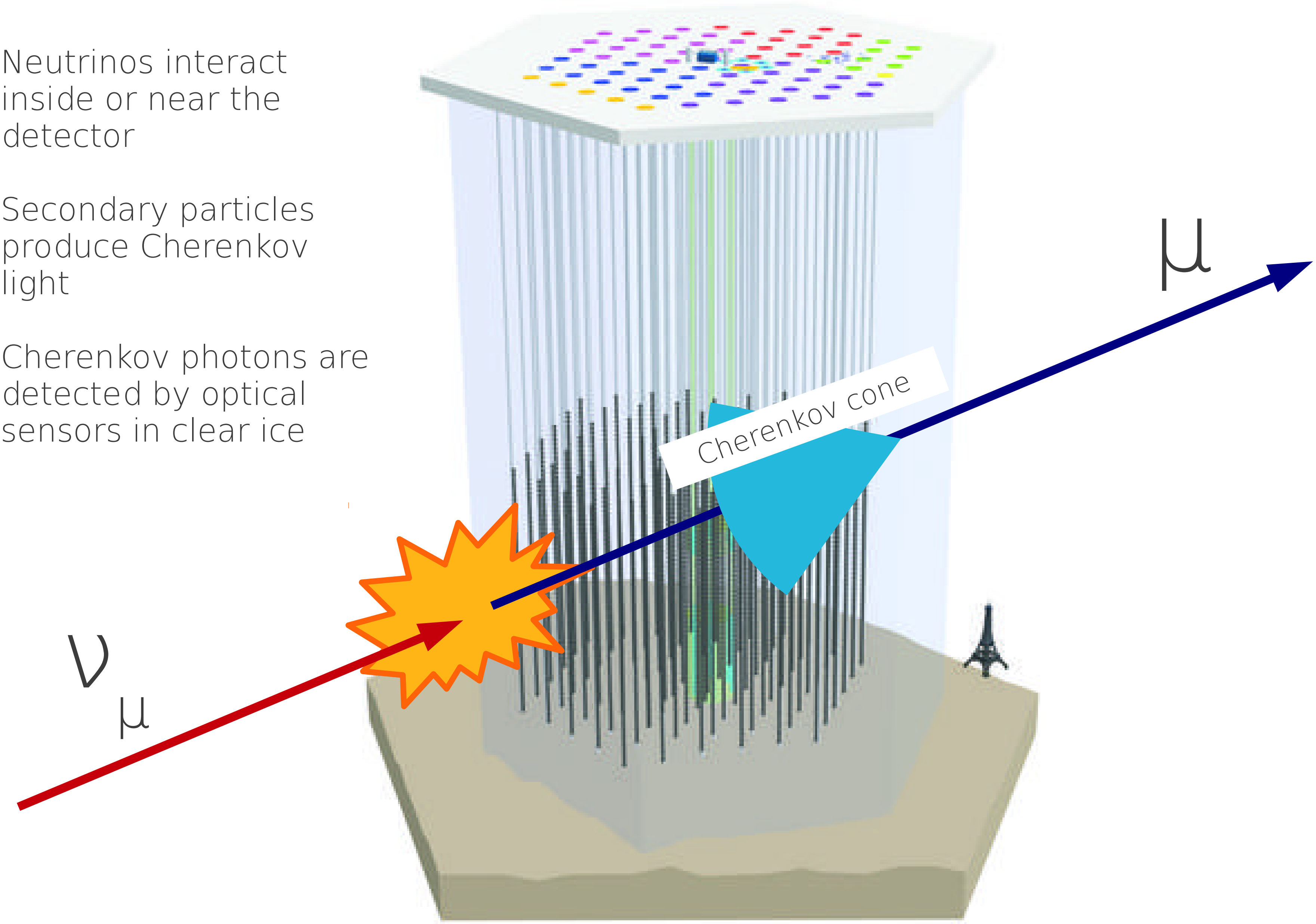


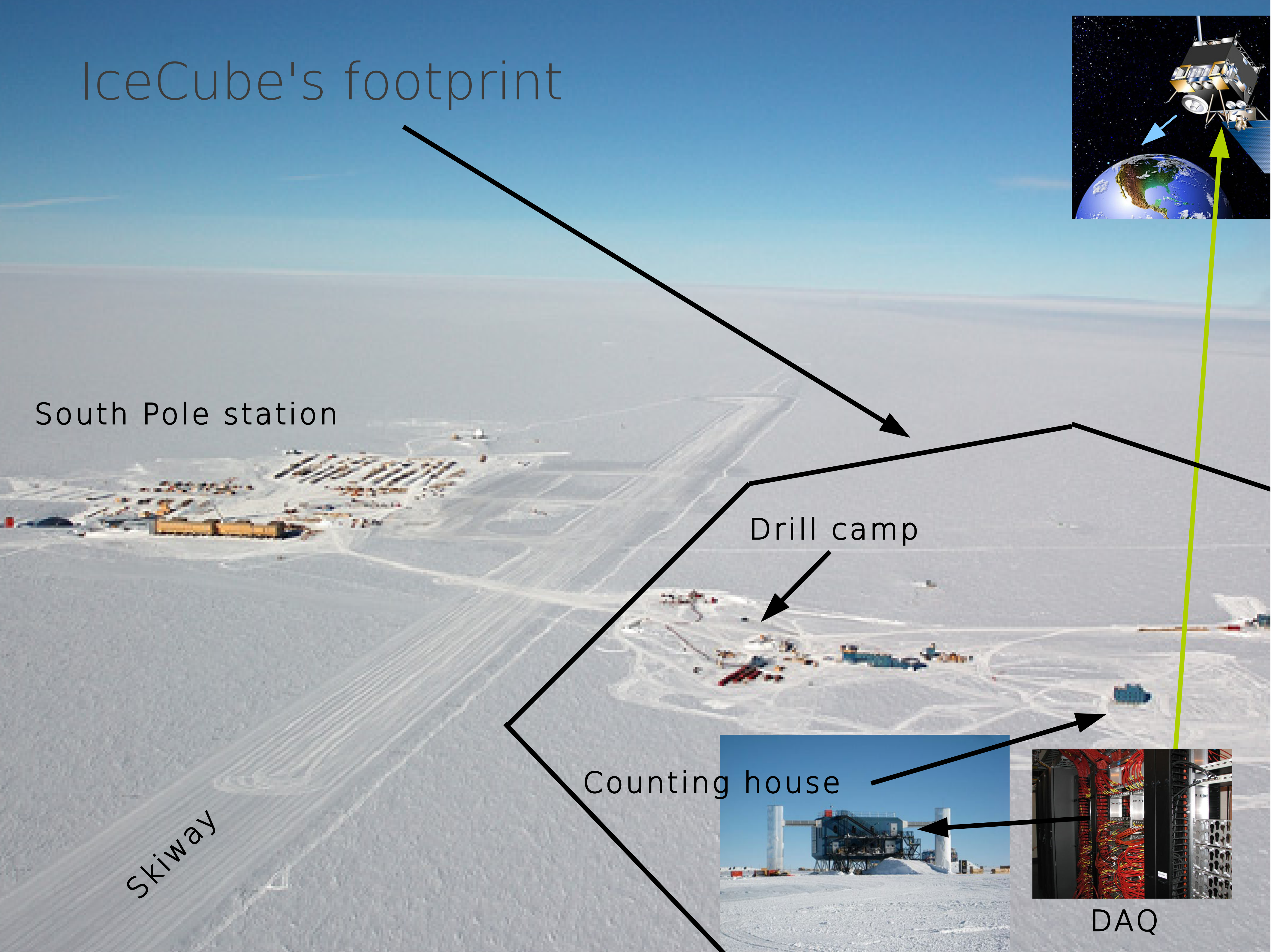
The IceCube Neutrino Observatory

Neutrinos interact inside or near the detector

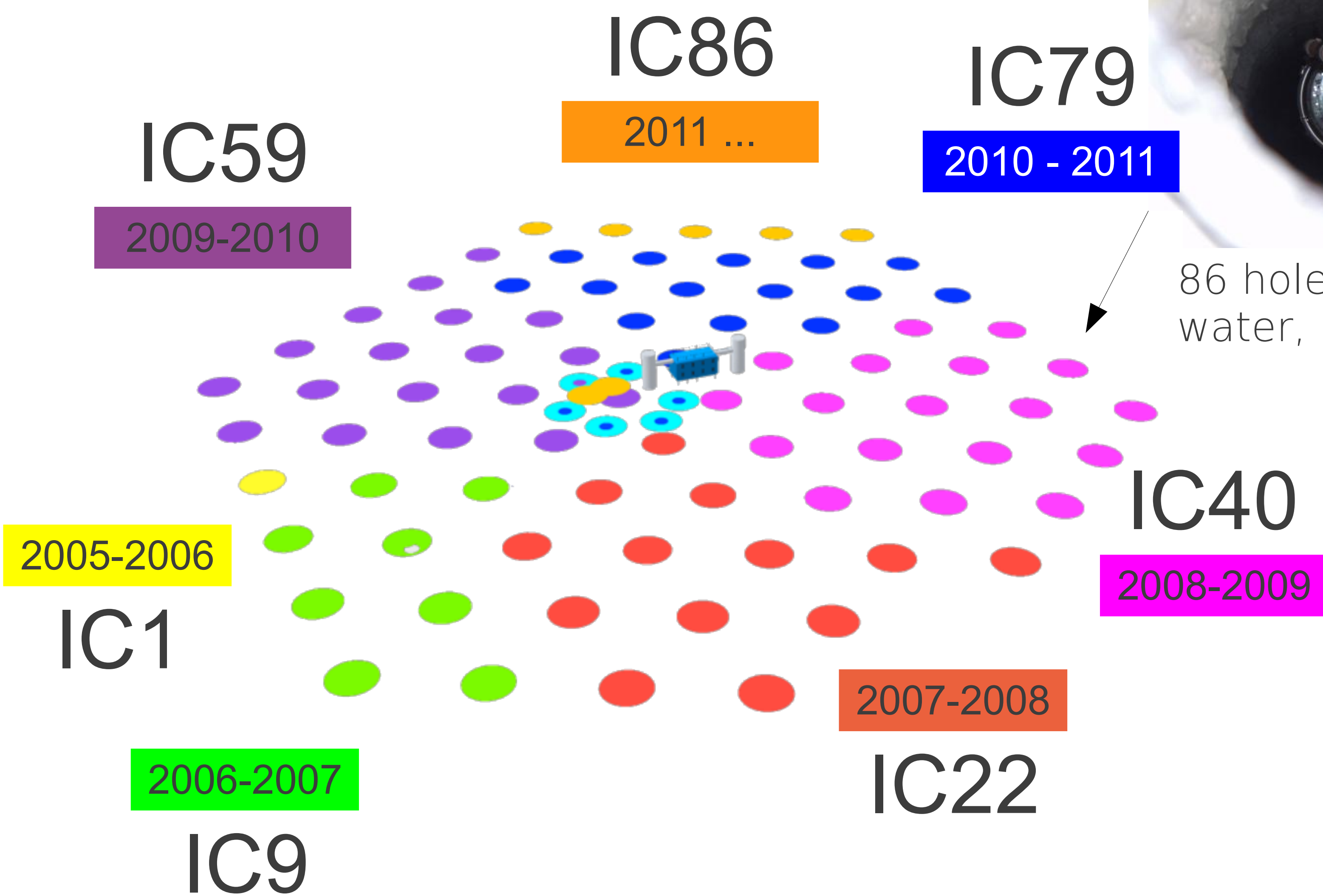
Secondary particles produce Cherenkov light

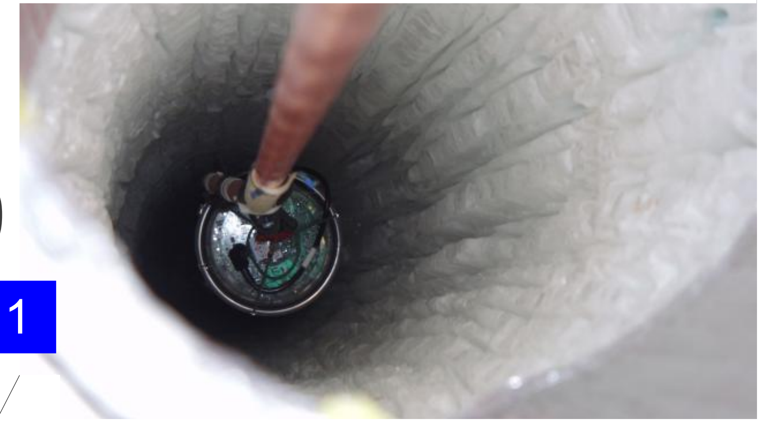
Cherenkov photons are detected by optical sensors in clear ice




IceCube's footprint
South Pole station
Drill camp
Counting house
DAQ
Skiway

7 years of construction



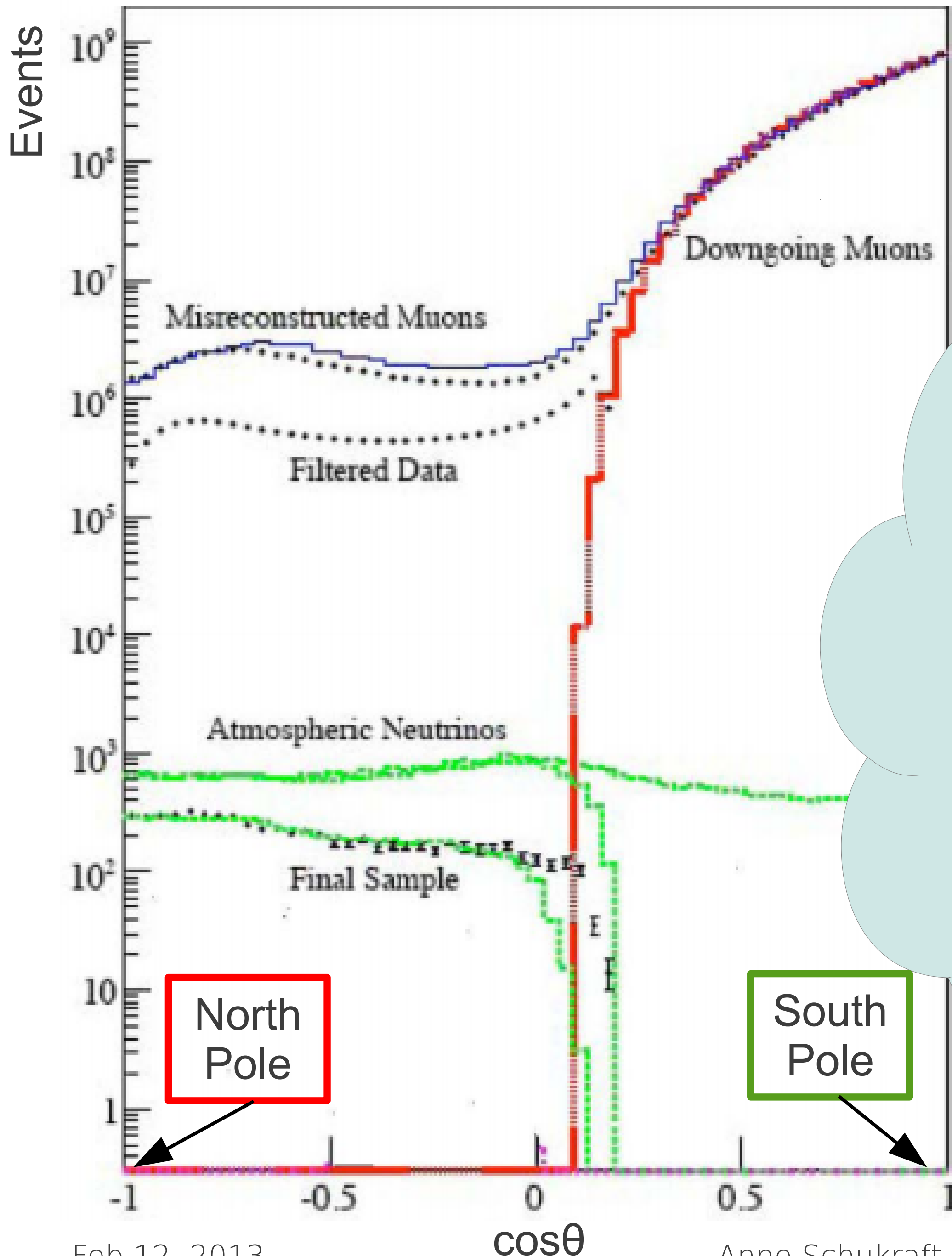


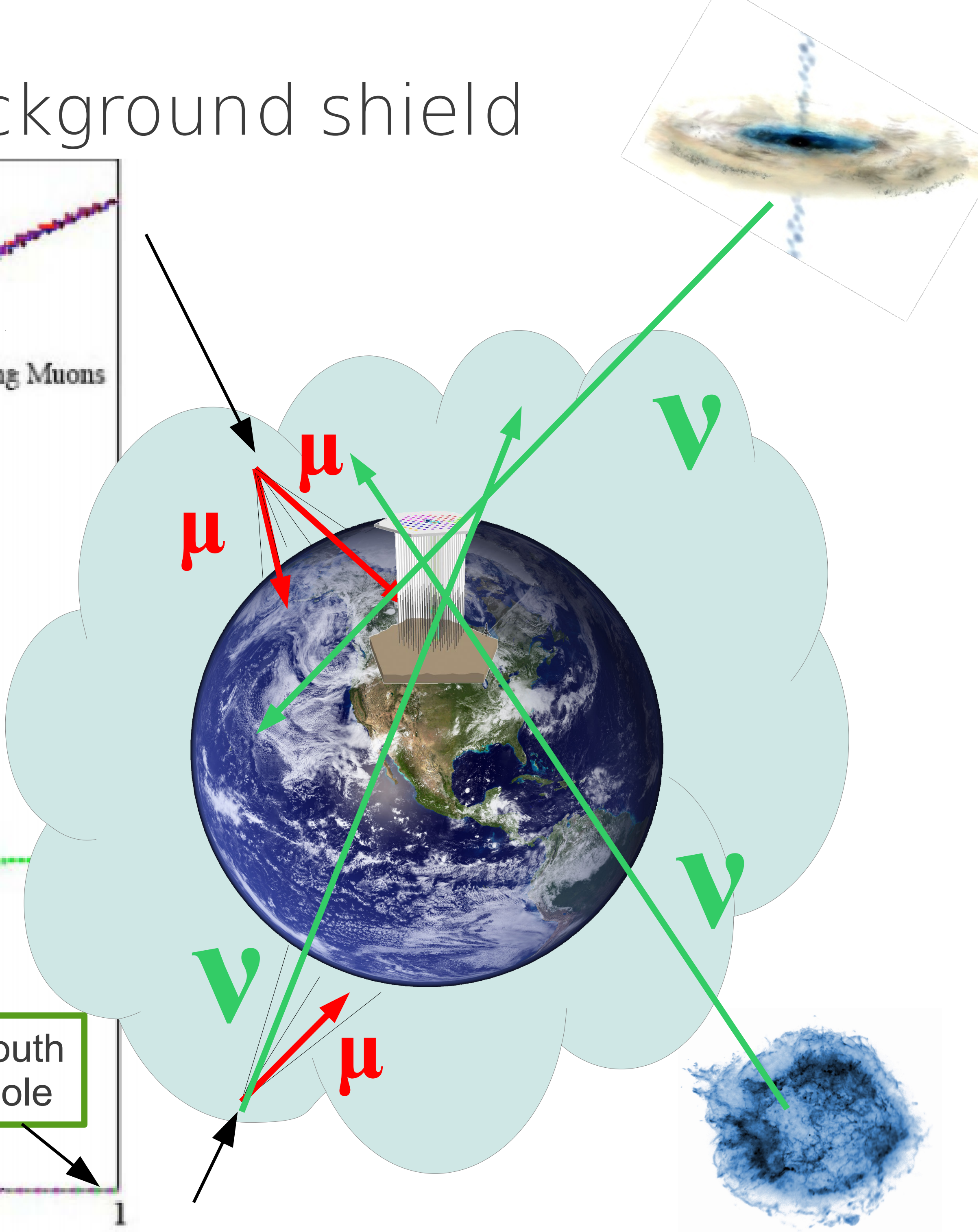
86 holes drilled with hot water, up to 2500m deep

5160 optical sensors deployed

Data taking since 2005 – completed in 2010!

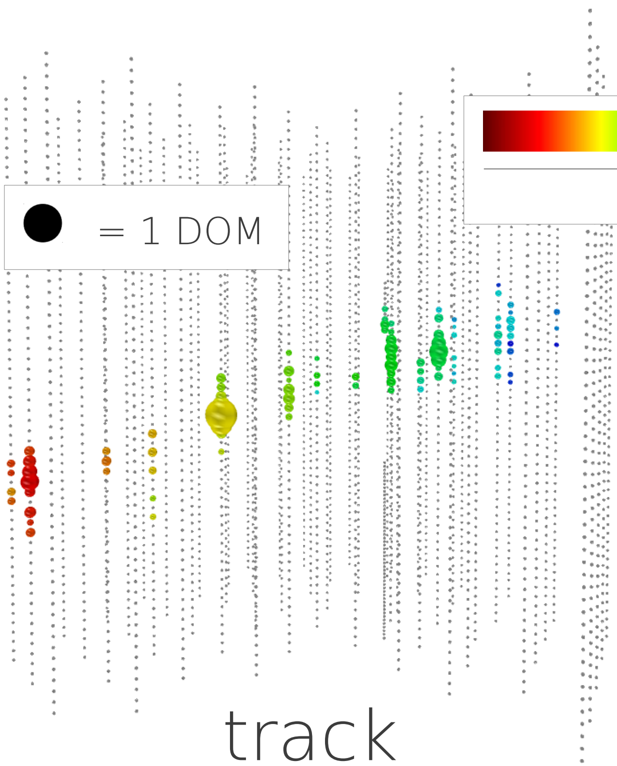
The Earth as a background shield





Neutrino event signatures

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



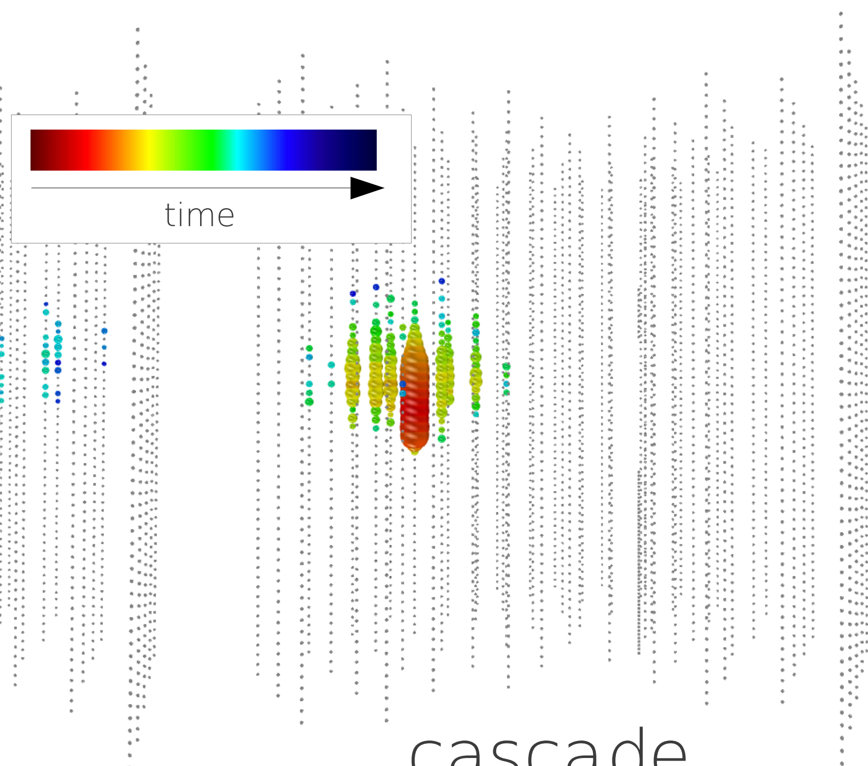
track

450 TeV muon

(simulation)

$\nu_e + N \rightarrow e + X$

$\nu_x + N \rightarrow \nu_x + X$

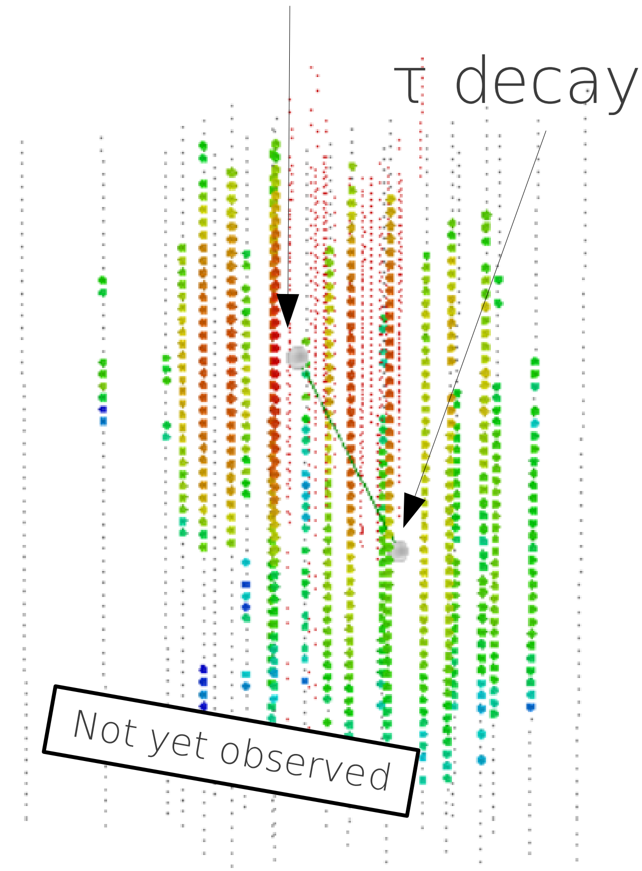


cascade

1 PeV electron

(simulation)

$\nu_\tau + N \rightarrow \tau + X$



"double bang"

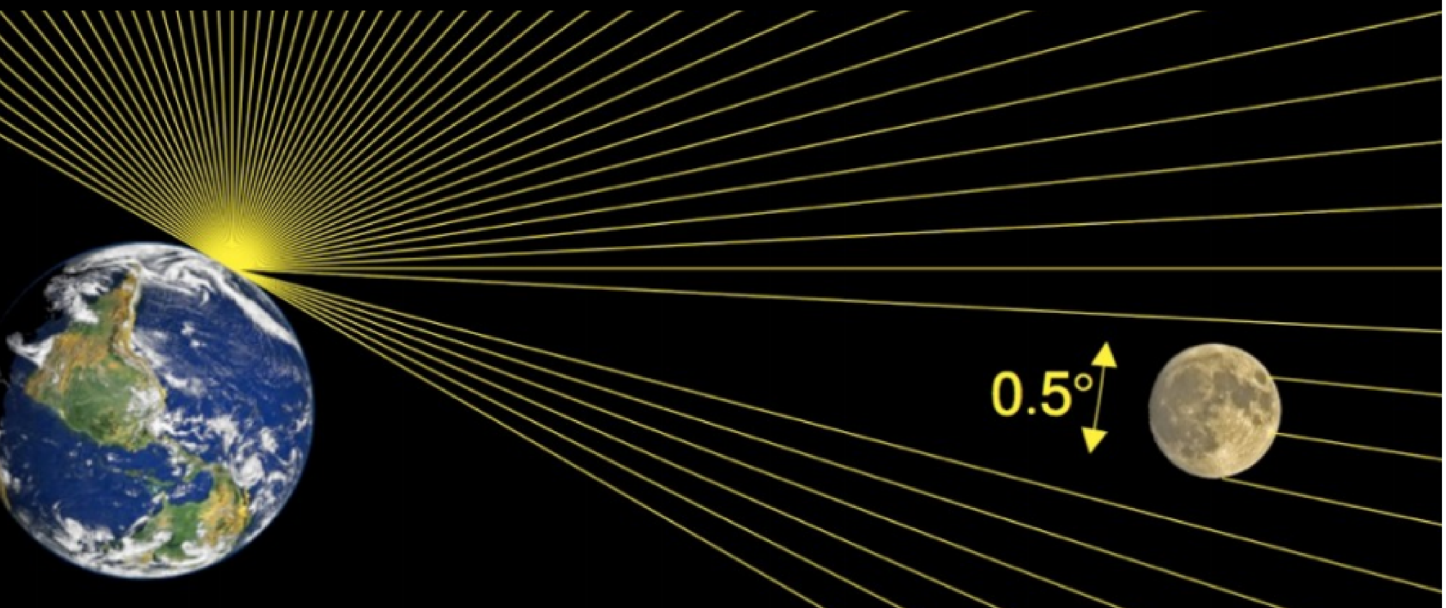
(or lollipop)

50 PeV tau

(simulation)

Our "standard candle": the moon

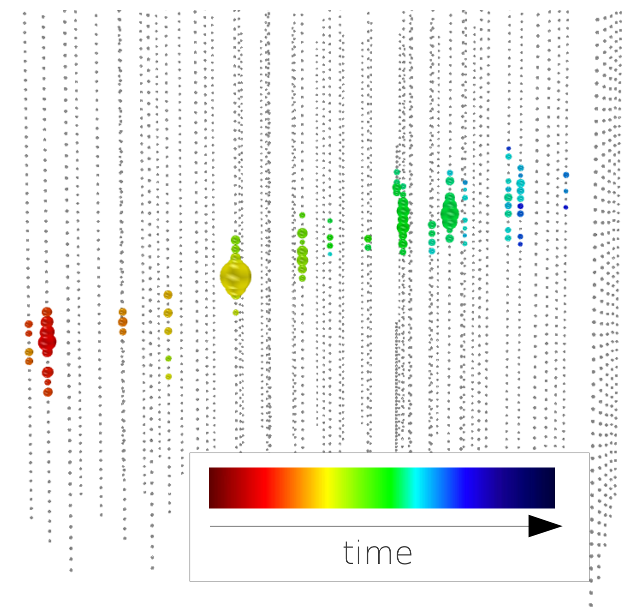
Cosmic rays are blocked by the moon



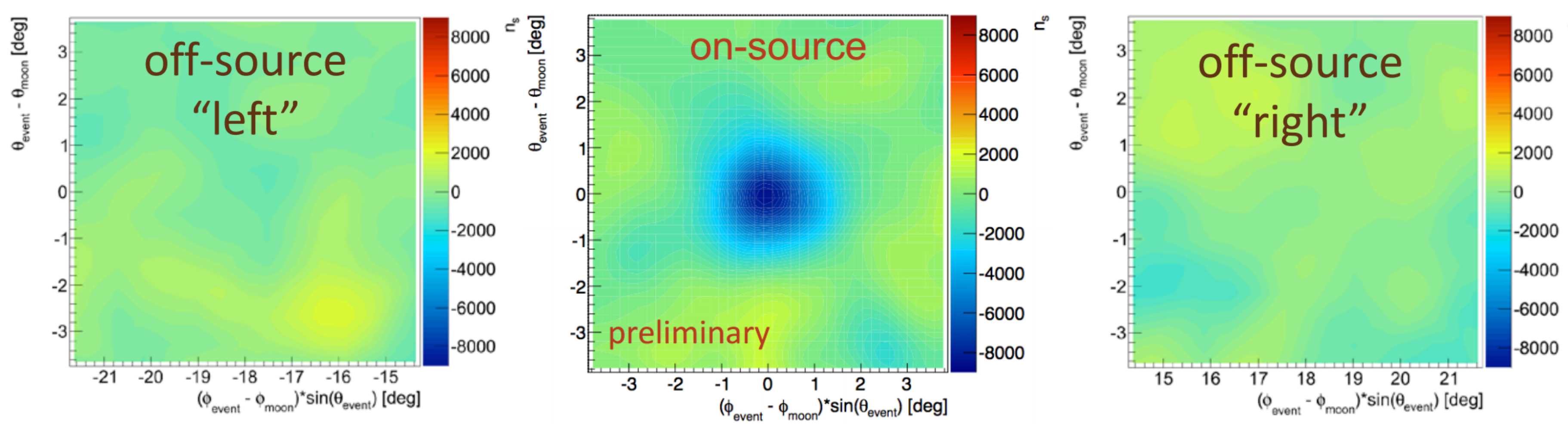
IceCube observes a deficit of atmospheric background muons from the direction of the moon

Track reconstruction:

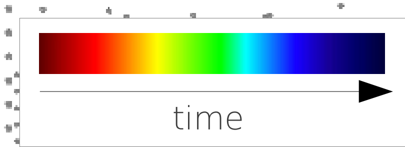
Collect information from photon arrival times



IC59 analysis



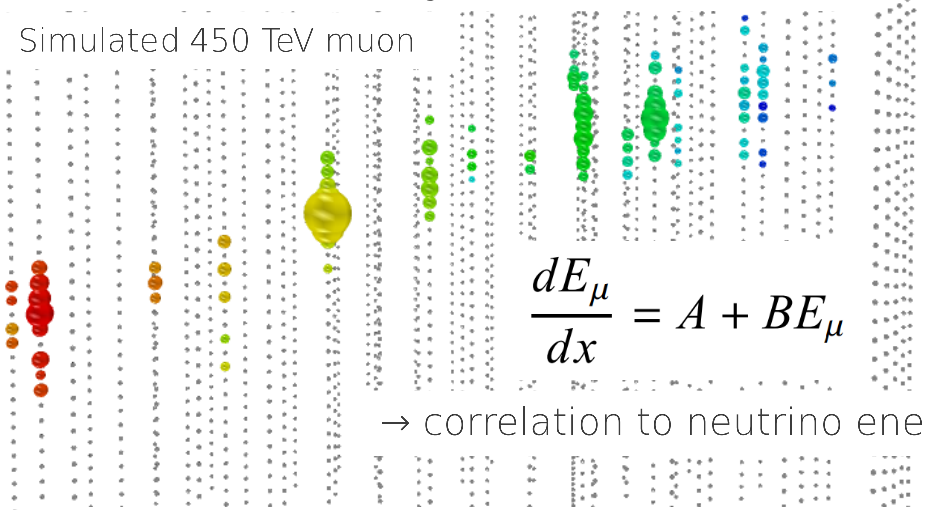
Energy reconstruction



For tracks:

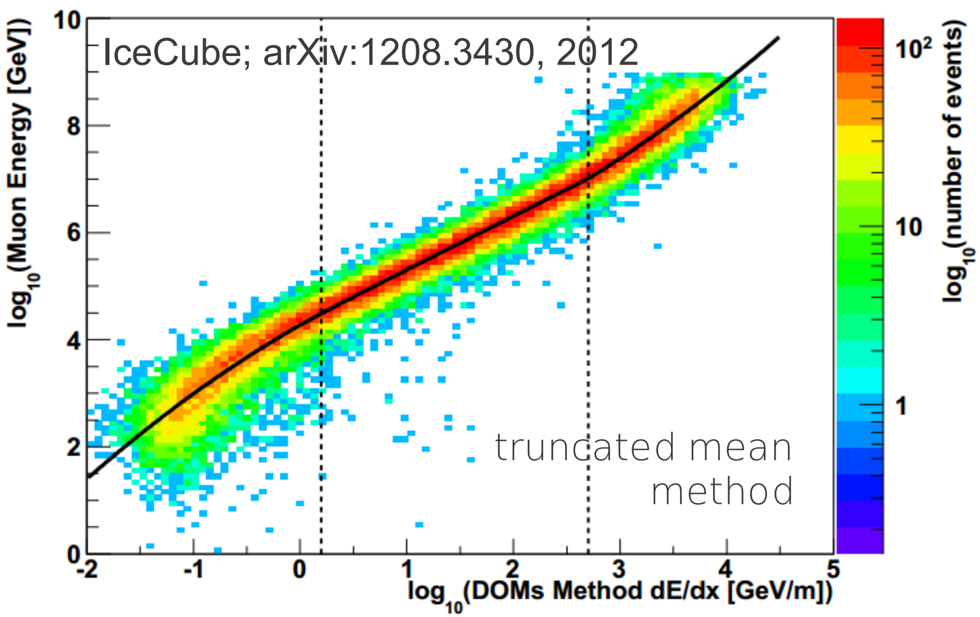
Measure the energy loss of the muon

Simulated 450 TeV muon



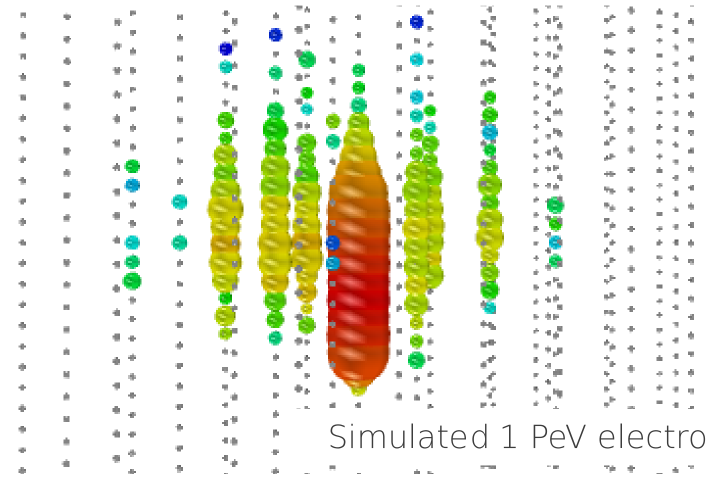
$$\frac{dE_\mu}{dx} = A + BE_\mu$$

→ correlation to neutrino energy

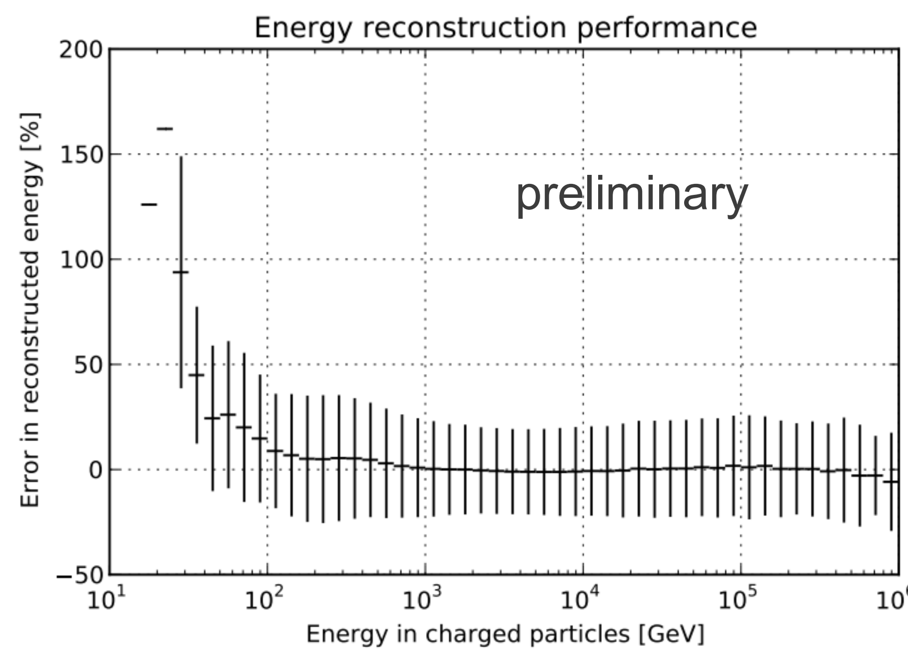


For cascades:

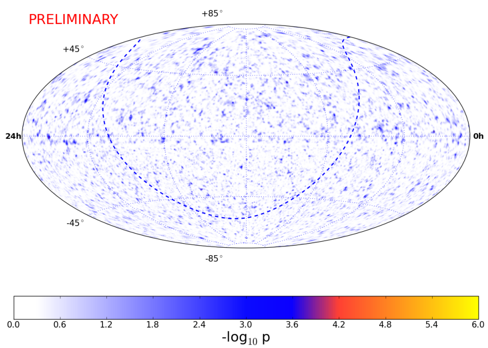
Collect all deposited light



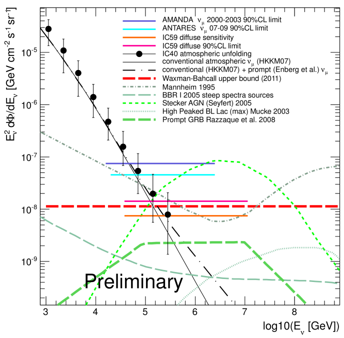
Simulated 1 PeV electron

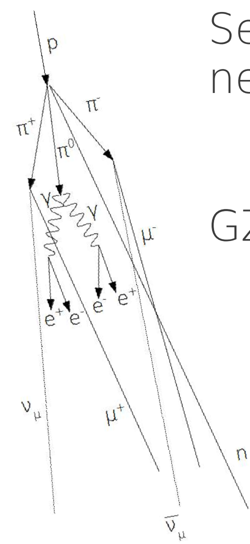


The IceCube physics program



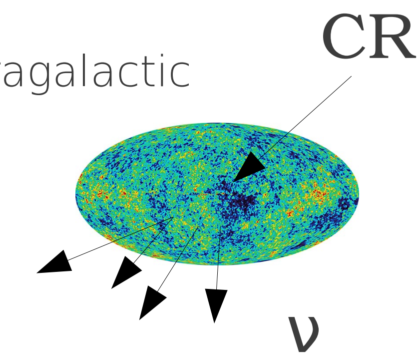
Diffuse/ atmospheric



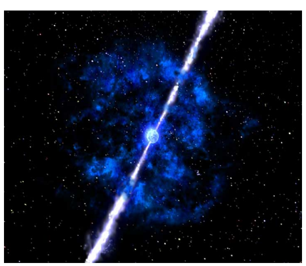


Search for an extragalactic neutrino signal

GZK neutrinos



Point source

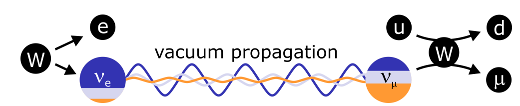


Search for point-like sources
→ galactic (e.g. SNR)
→ extragalactic (e.g. AGN)

Transient sources
→ GRB, flaring objects

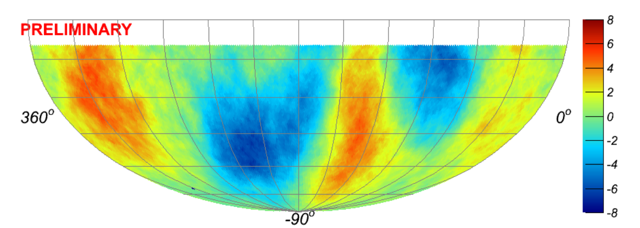
Optical follow-up programs

Prompt atms. neutrinos



Neutrino oscillations

Cosmic ray physics

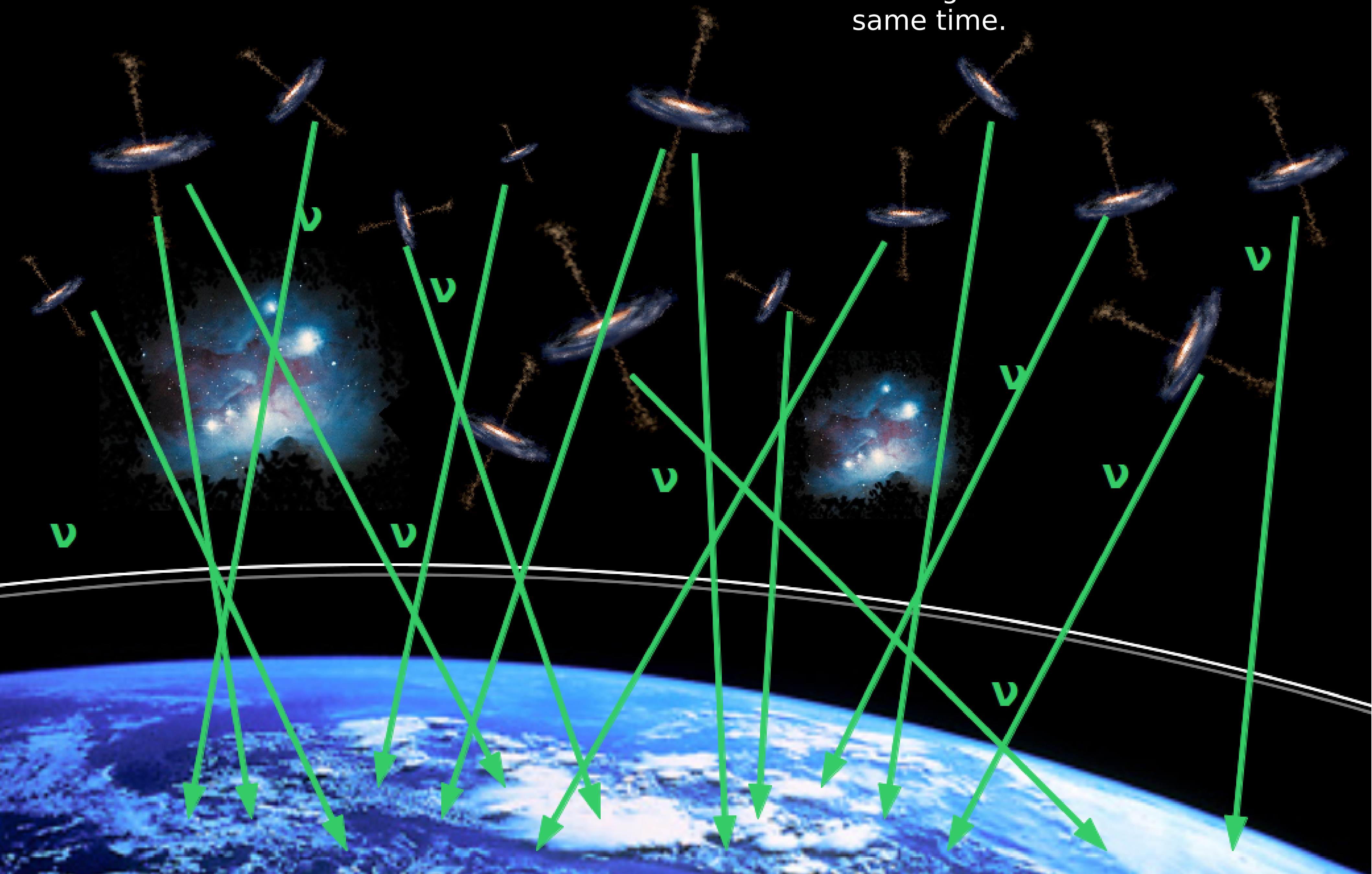


Dark Matter

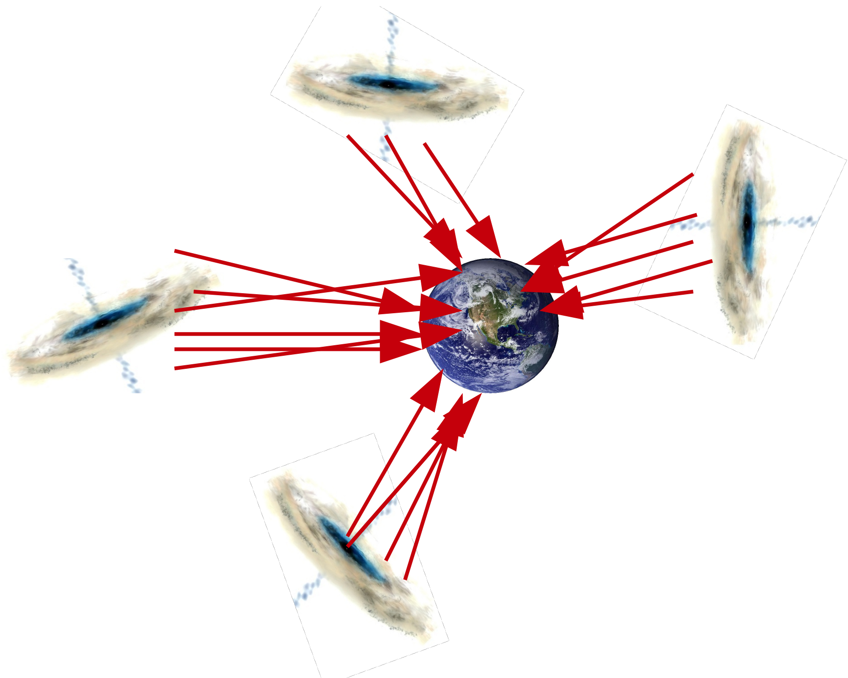
Exotic particles

What is a diffuse search?

Looking into all directions at the same time.



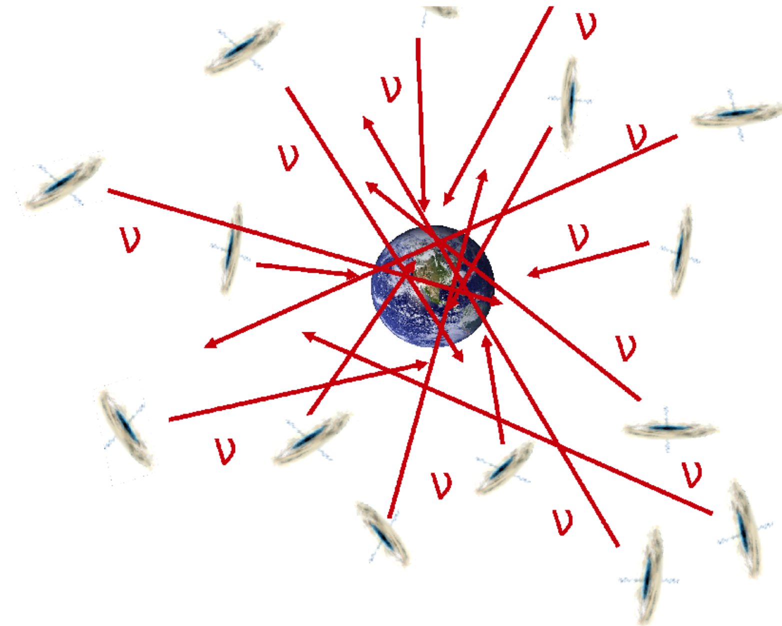
Why diffuse?



Point source search

$$\phi_{\mathrm{single}}\left(E|L,z\right) = \frac{\epsilon_\nu \cdot L \cdot E^{-\gamma}}{4\pi d_L(z)^2 \cdot (z+1)^{\gamma-1}}$$

More promising for
- rare bright sources (e.g. GRB)
- transient sources
- galactic sources



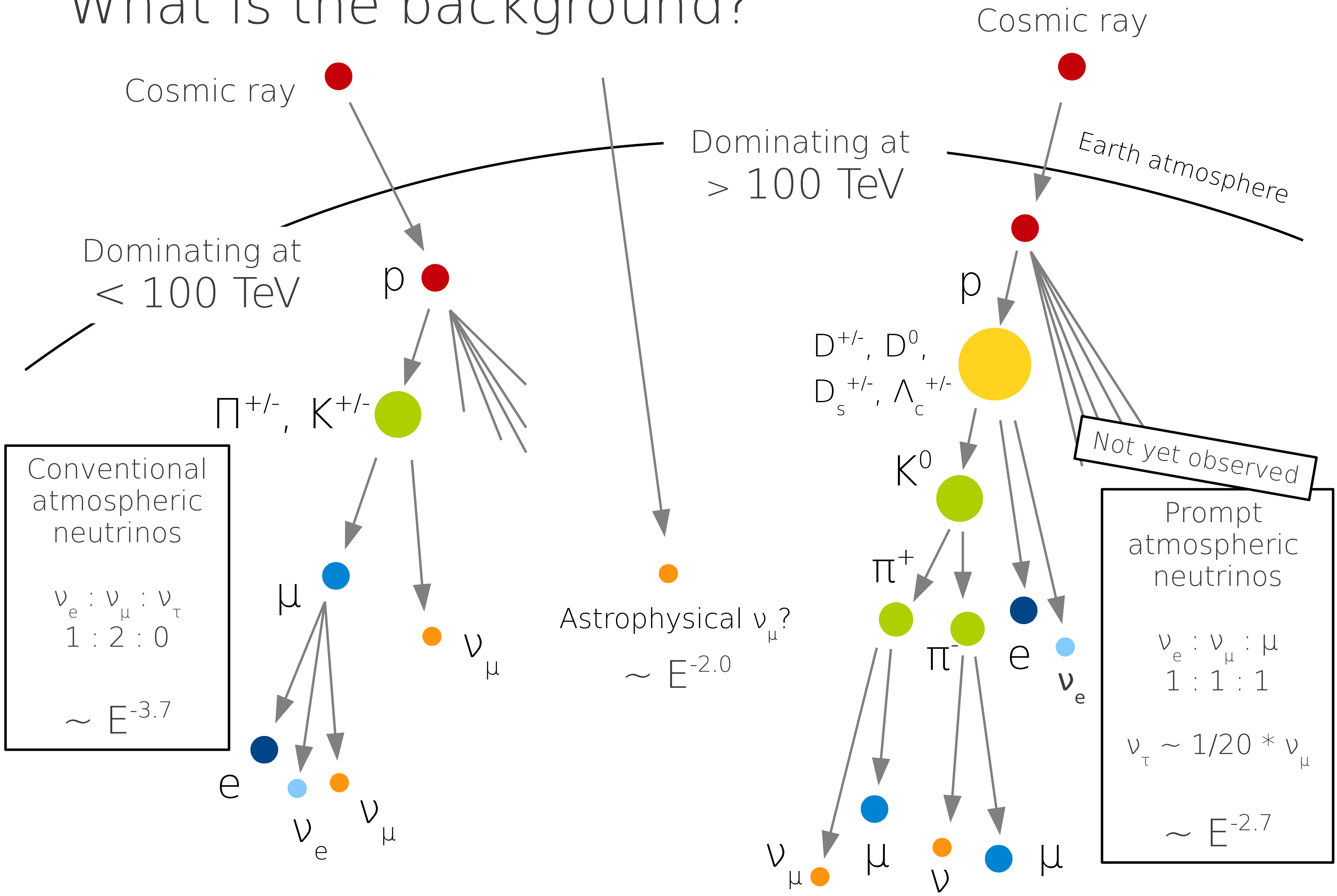
Diffuse search

$$\phi_{\mathrm{diffuse}}\left(E|L,z\right) = \int\int\int \phi_{\mathrm{single}}\left(E|L,z\right) \frac{d^2 n(L,z)}{dz\,dL} dz\,dL\,d\Omega$$

More promising for
- abundant extragalactic sources (e.g. AGN)

An extragalactic neutrino flux could be detected even if the individual source flux is below the detection threshold!

What is the background?

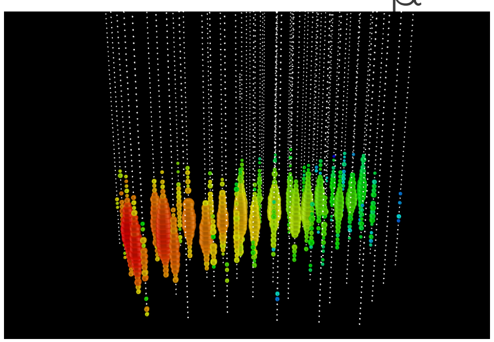


Outline

Results from four completely independent diffuse searches

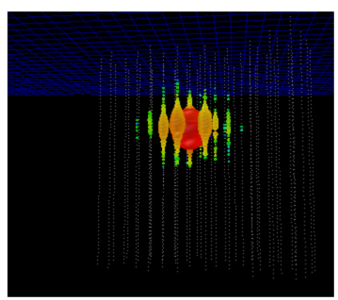
- Different event signature
- Different data taking period
- Different detector geometry

IC59 ν_μ



May 2009 – May 2010

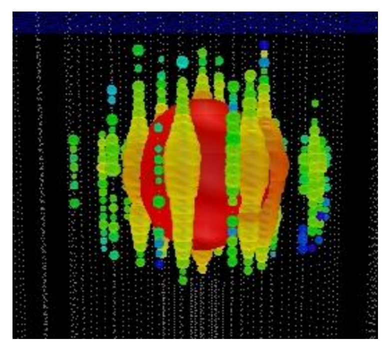
IC40 casacades



April 2008 – May 2009

IC79+IC86

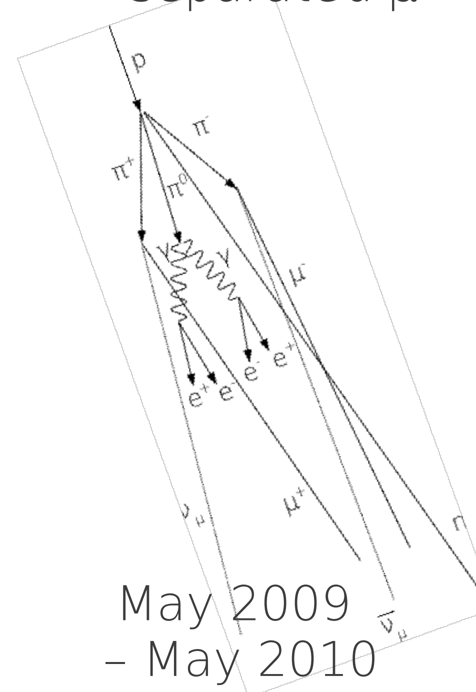
extremely high-energy casacades



June 2010 – May 2012

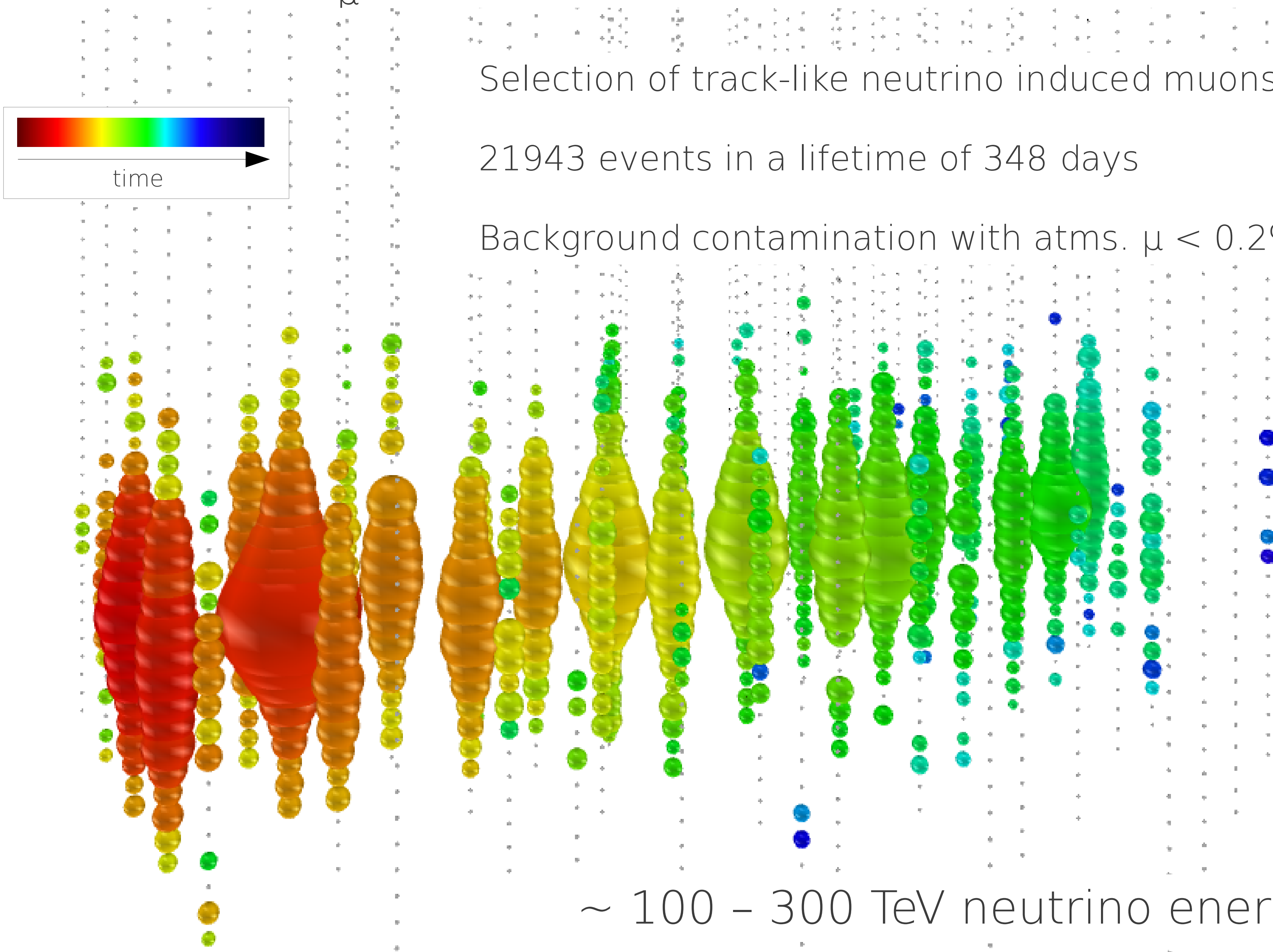
IC59

Laterally separated μ



May 2009 – May 2010

The IC59 ν_μ analysis



Selection of track-like neutrino induced muons

21943 events in a lifetime of 348 days

Background contamination with atms. μ < 0.2%

~ 100 – 300 TeV neutrino energy

The signature of a diffuse astrophysical flux

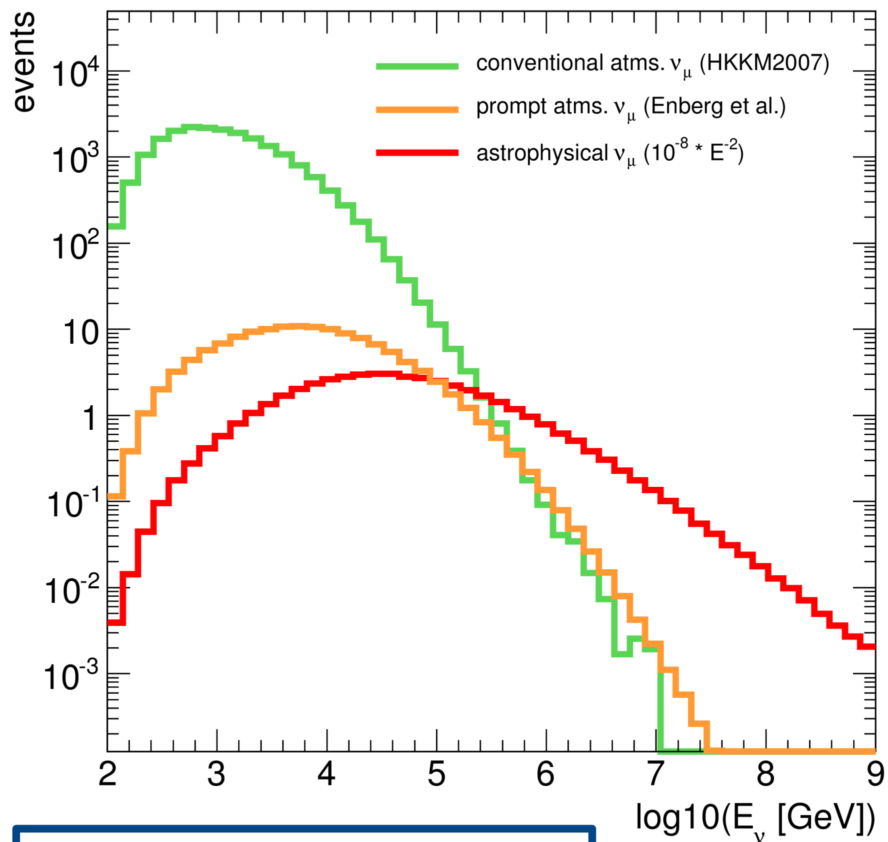
What we expect in the IC59 data sample:

~ 20 000 conv. atms. ν_μ (Honda et al.)

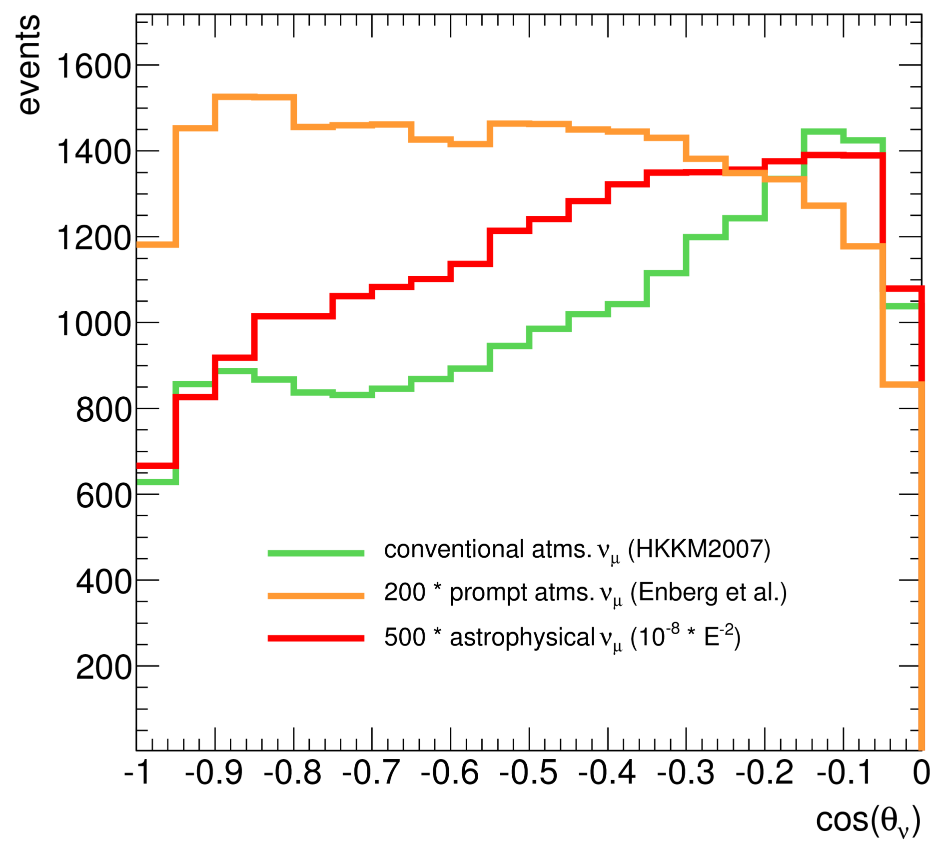
~ 70 prompt neutrinos (Enberg et al.)

< 40 astrophysical ν_μ (Waxman-Bahcall)

Energy distribution



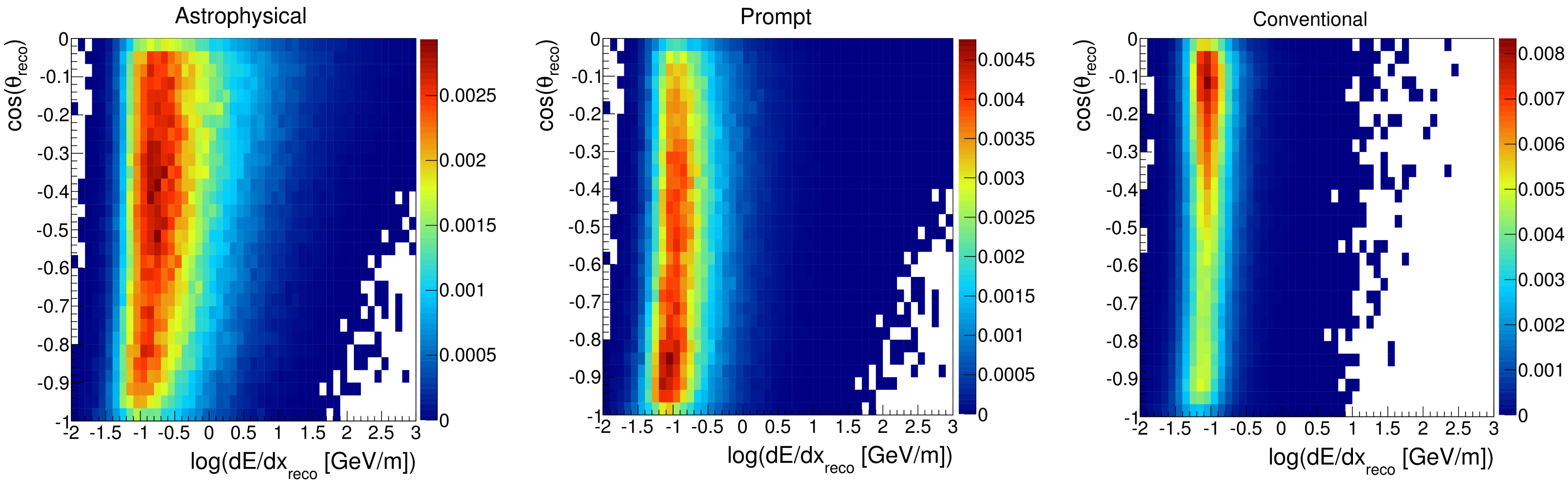
Zenith angle distribution



~ 30 μ background (<0.2% contamination!)

(including absorption in the Earth and detector acceptance)

The analysis method



→ 2-dim global fit

→ Taking full advantage of energy and zenith angle information (sensitive to the shapes of distributions!)

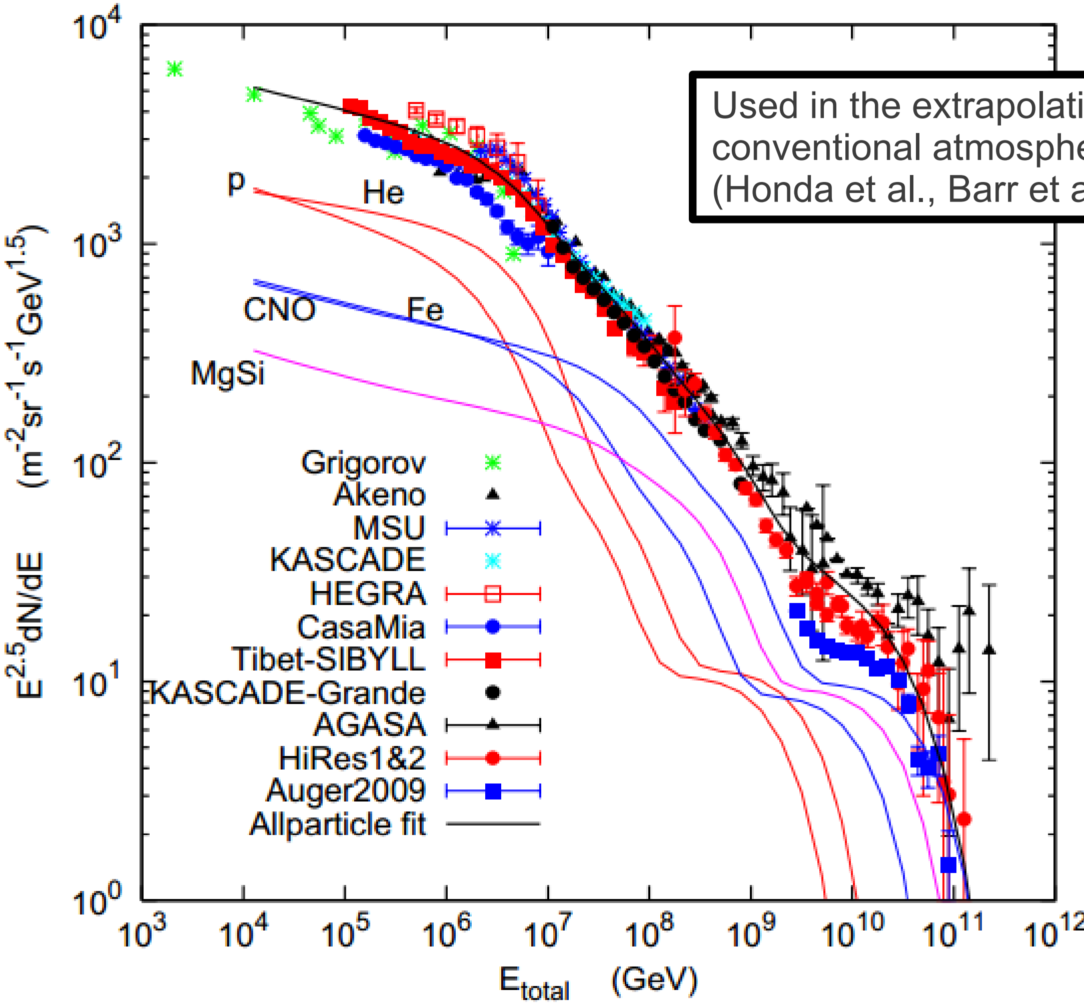
→ Systematic uncertainties are parameterized and taken into account as free fit nuisance parameters

→ Fit for nuisance parameters and signal parameters at the same time

→ The high statistical power of conventional atmospheric neutrinos determines the systematic uncertainties

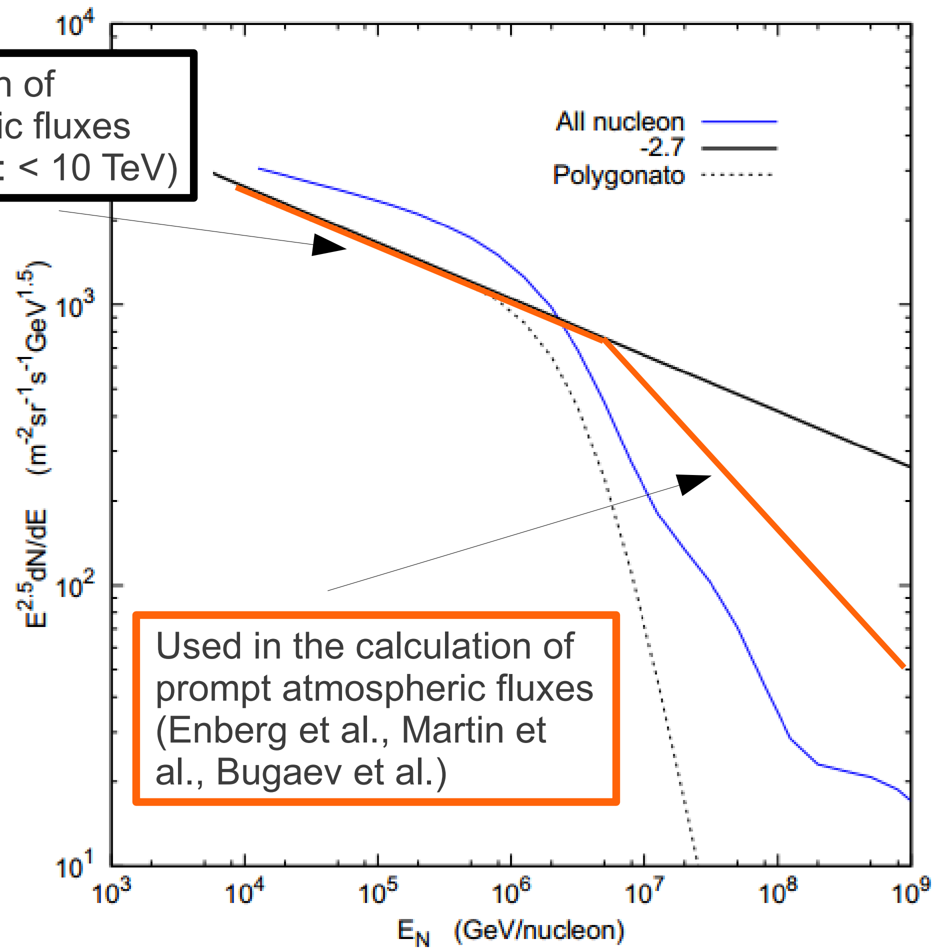
Example: uncertainties in the atmospheric background predictions

All particle spectrum



Used in the extrapolation of conventional atmospheric fluxes (Honda et al., Barr et al.: < 10 TeV)

Nucleon spectrum



Used in the calculation of prompt atmospheric fluxes (Enberg et al., Martin et al., Bugaev et al.)

Gaisser; Astropart. Phys. 35 (2012) 801

Atmospheric neutrino background predictions are not based on the most accurate cosmic ray flux parameterizations.

The "neutrino-knee"

Recalculation of neutrino fluxes:

$$\phi_\nu (E_\nu, \theta) = \int dE_0 \quad \phi_N (E_0) \cdot Y_\nu (E_\nu, E_0, \theta)$$

Neutrino energy

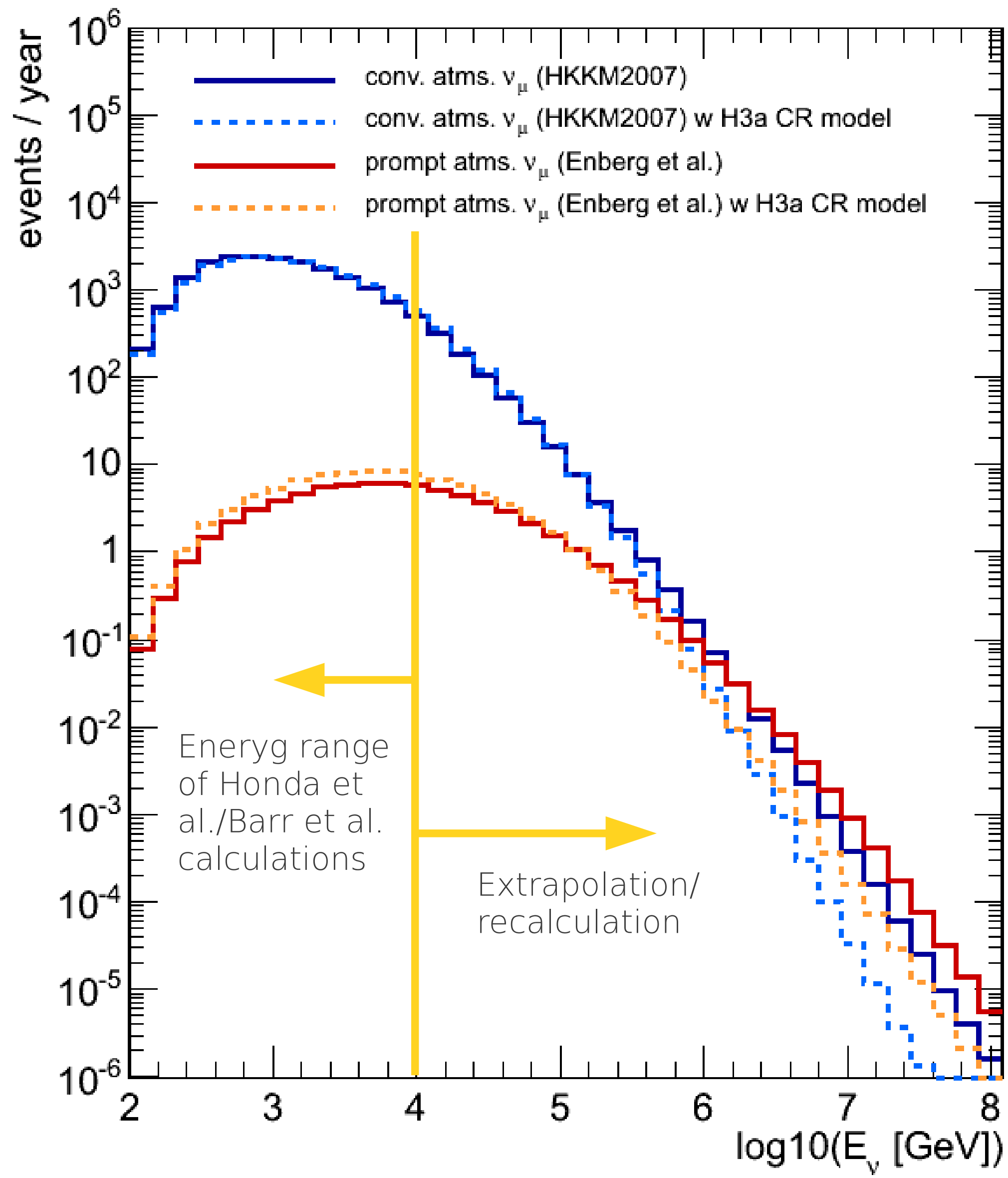
Nucleon energy

Nucleon primary flux (from model fits to CR data)

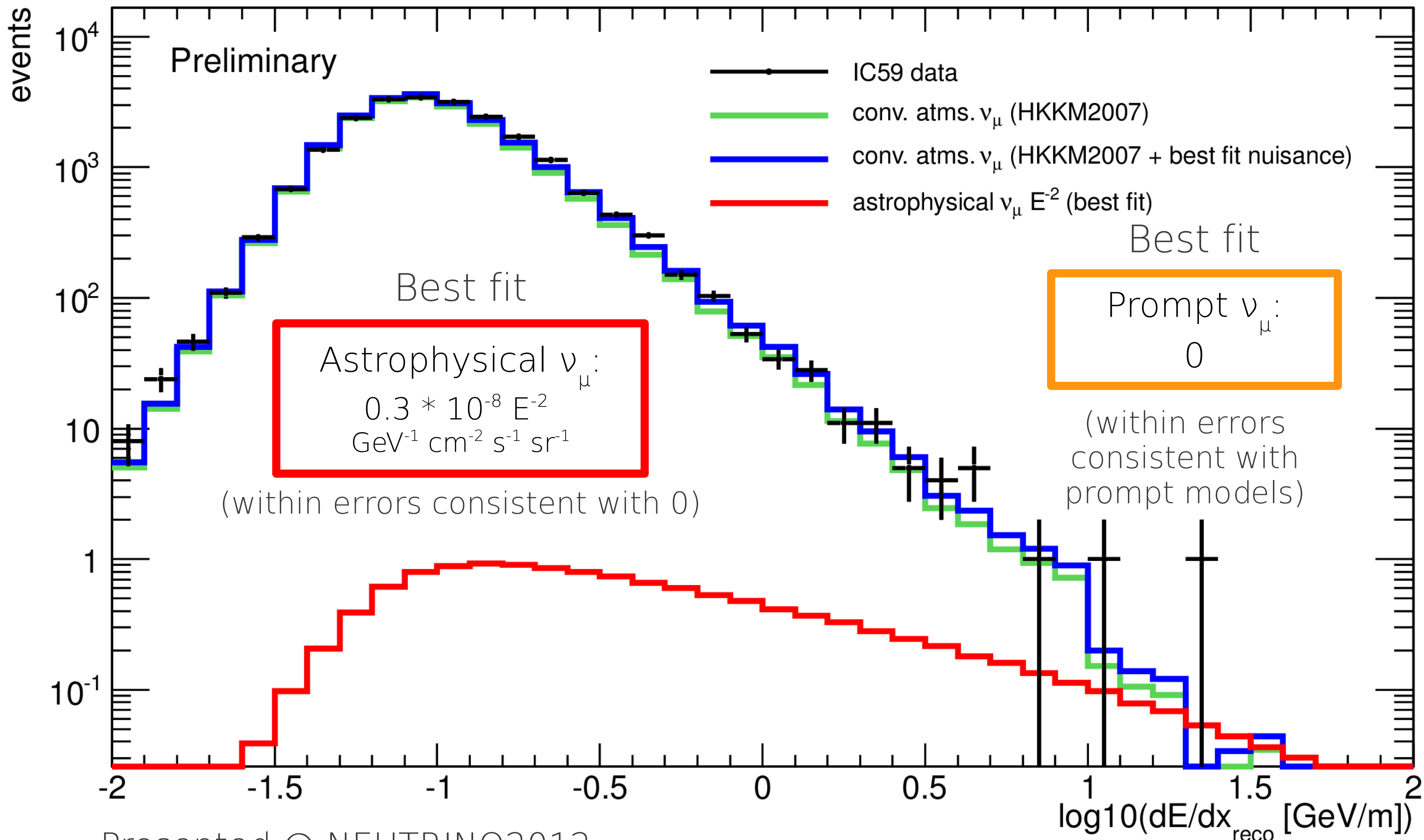
Neutrino yield per nucleon (from simulation)

With a realistic CR primary flux the atmospheric background prediction at high energies decreases

→ increases the chances for a discovery of astrophysical neutrinos

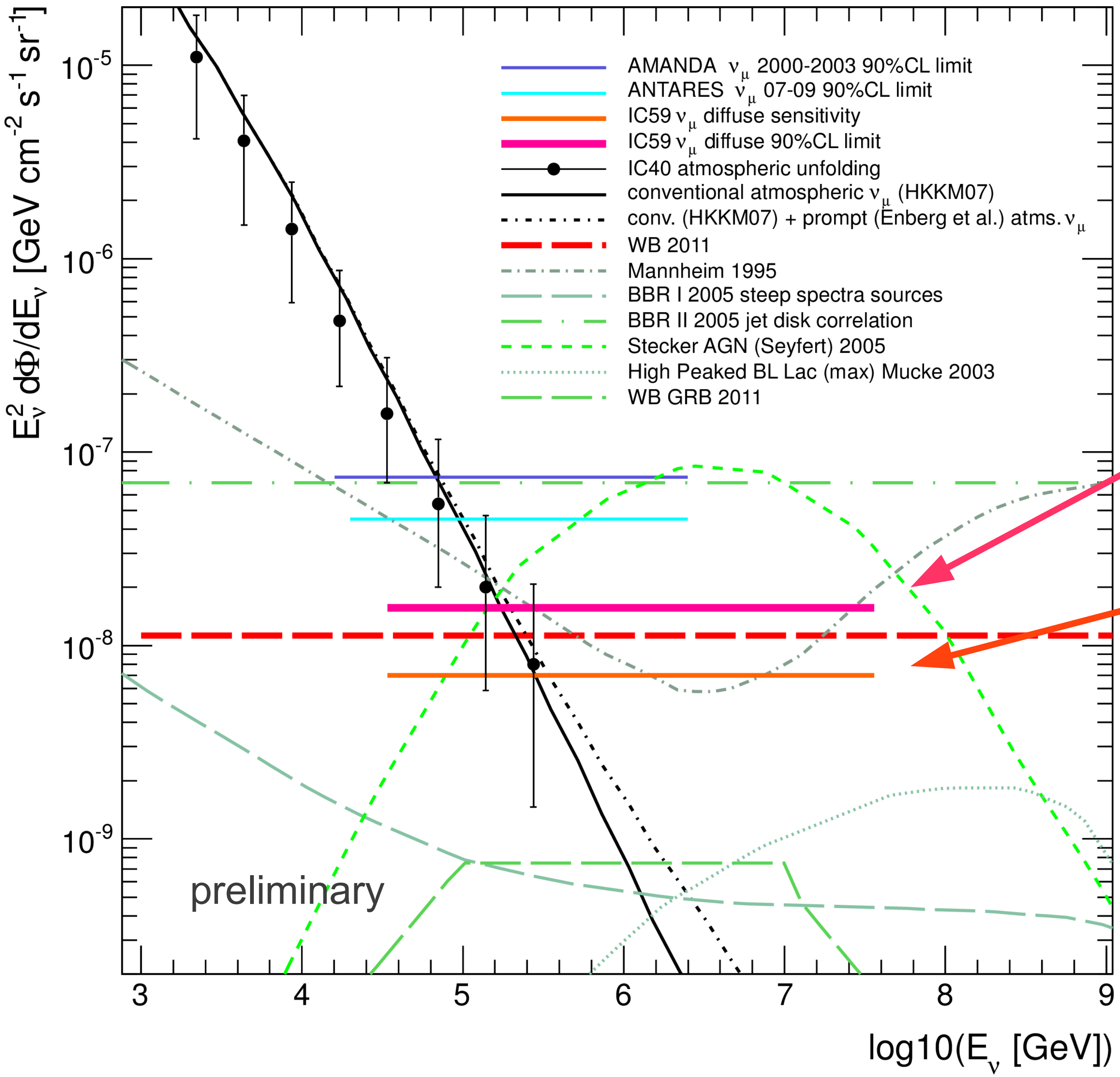


Results



Presented @ NEUTRINO2012

Experimental constraints on astrophysical models



90%CL upper limit

sensitivity

Factor 1.5 above the Waxman-Bahcall upper bound

Experimental constraints on prompt models

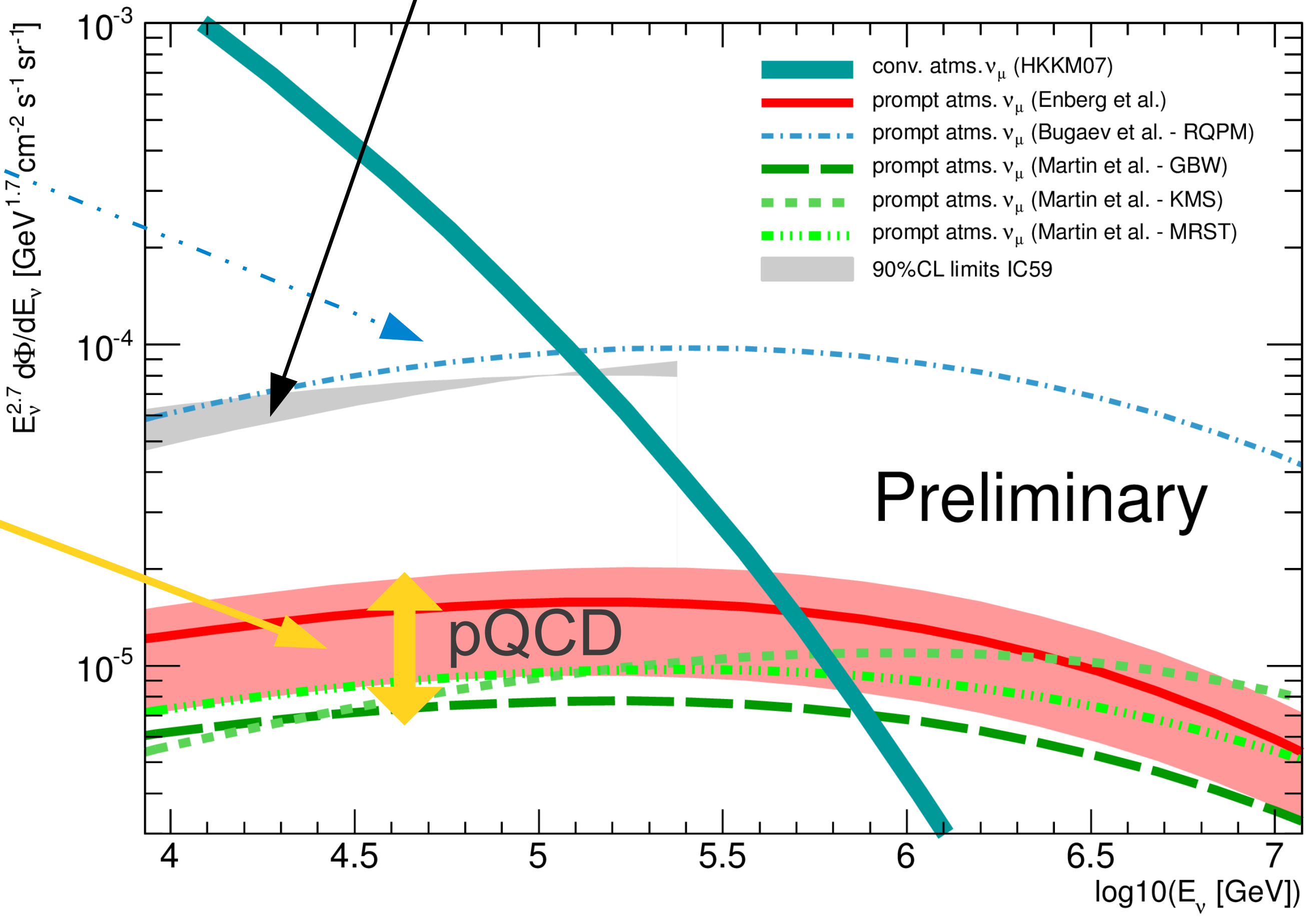
Range of 90%CL upper limits

(Shape of the limit is slightly model dependent)

Intrinsic charm model
(Bugaev et al.)
ruled out at 90%CL.

pQCD prompt atms. neutrino flux predictions are not yet in reach.

Limits are ~ factor 5 above model predictions

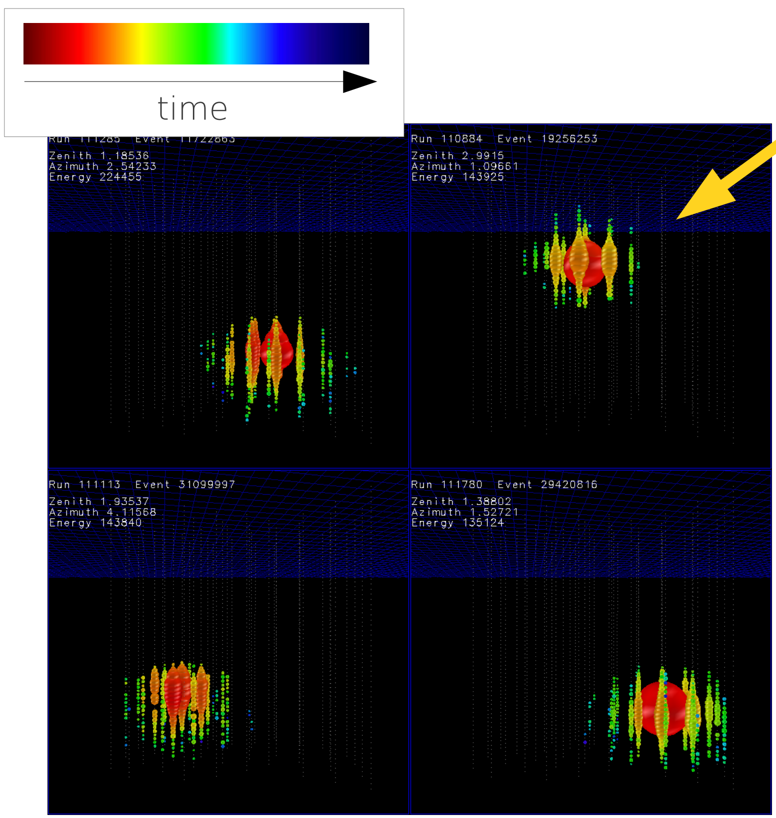


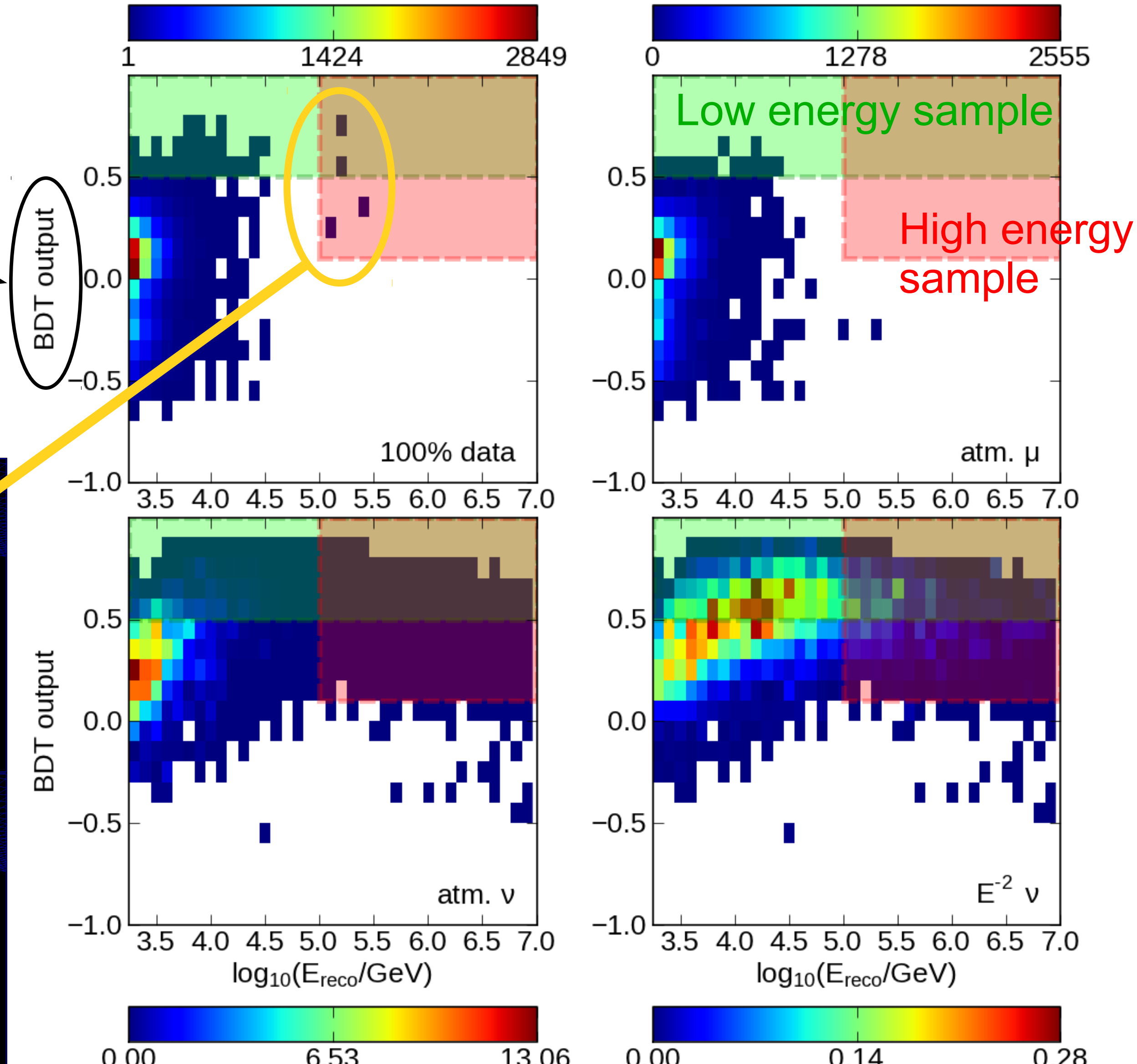
(models shown here as published without knee correction)

Search for cascade events in IC40

Search for
- contained
- spherical

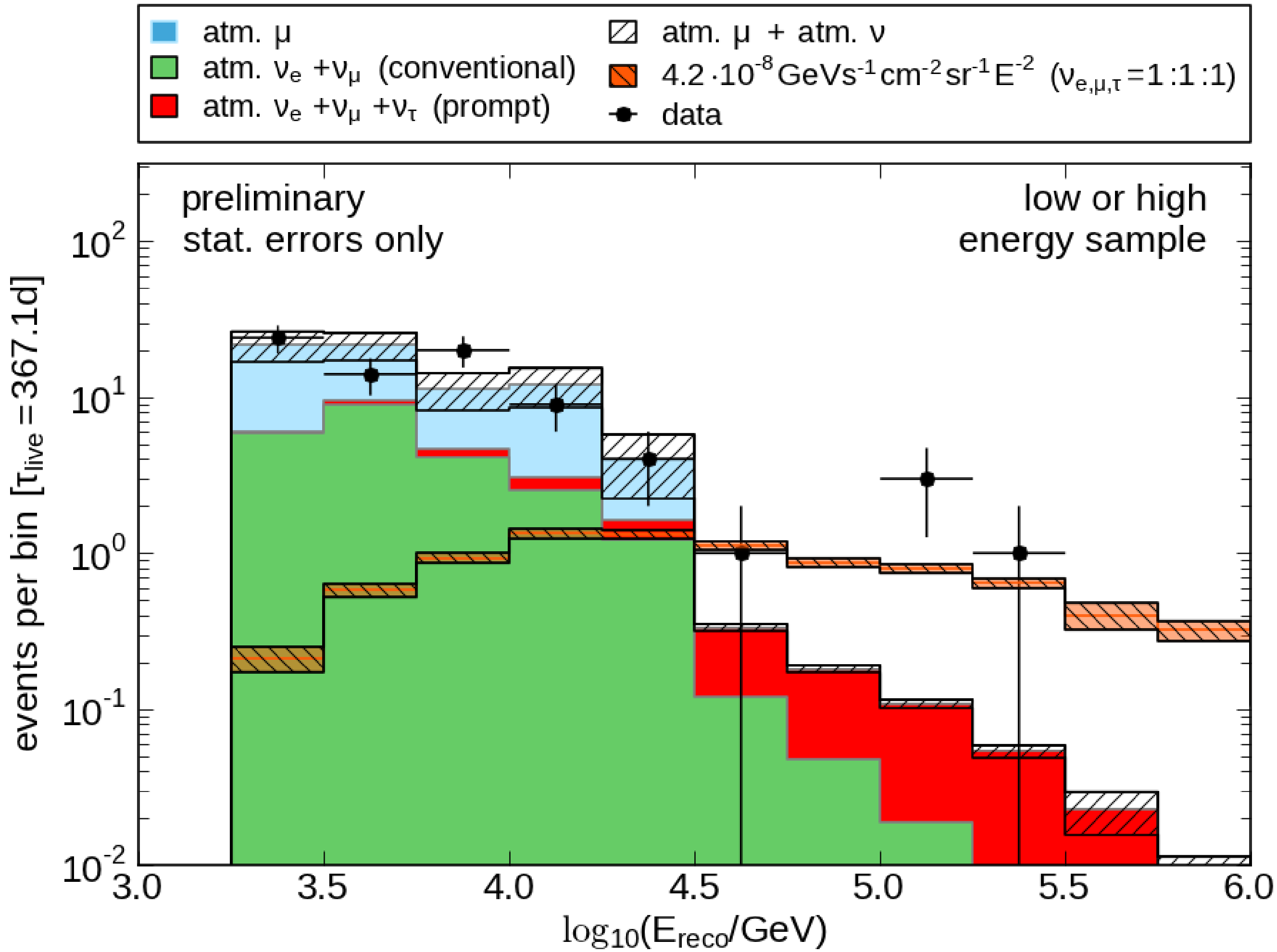
cascade-like neutrino events





The cascade energy spectrum

2.4σ excess over atmospheric
ν + μ background (conv. + prompt (Enberg et al.))



What are the HE events?

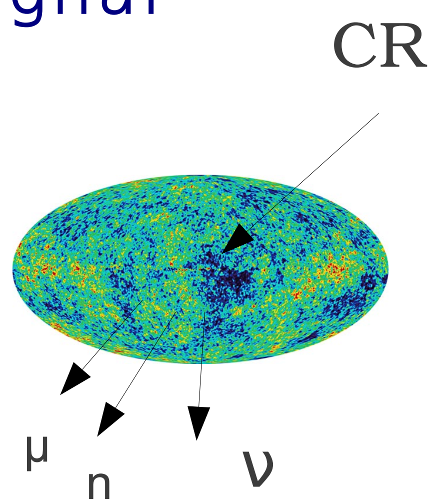
Conventional atms?
Unlikely

Prompt?
Not very likely
Enberg et al. Prediction would have to be increased by > factor 10

Astrophysical?
Maybe
(consistent with the muon channel and present limits)

Searching for extremely high-energy events

The signal



Cosmic rays interacting with CMB:

$$p + \gamma_{CMB} \to \Delta^+ \to n + \pi^+$$

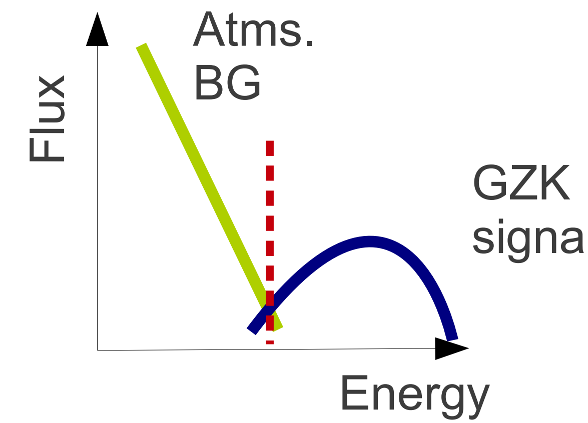
$$\to n + \mu^+ + \nu \to \dots$$

Energy threshold: $6 * 10^{19}$ eV

The analysis strategy:

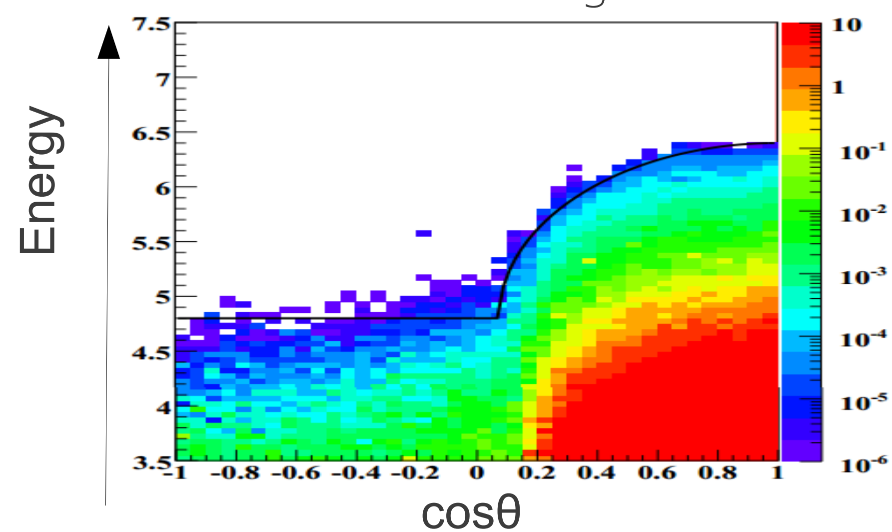
EHE neutrinos are blocked by the Earth

→ look up!



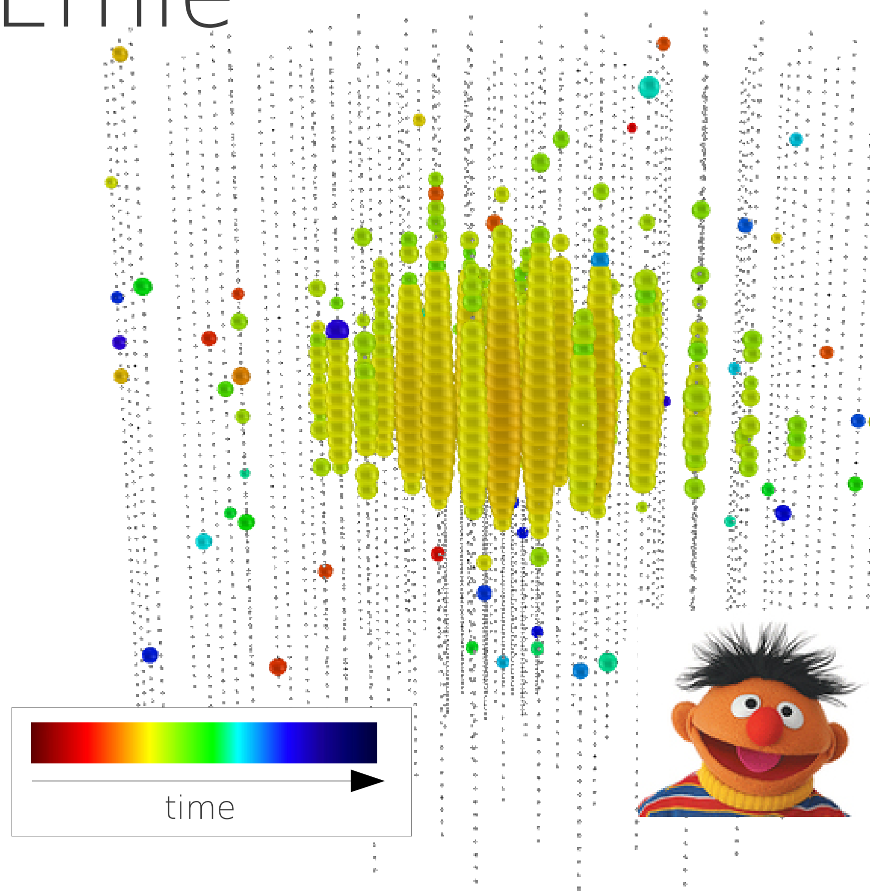
Remove background with an energy cut

Total atms. background



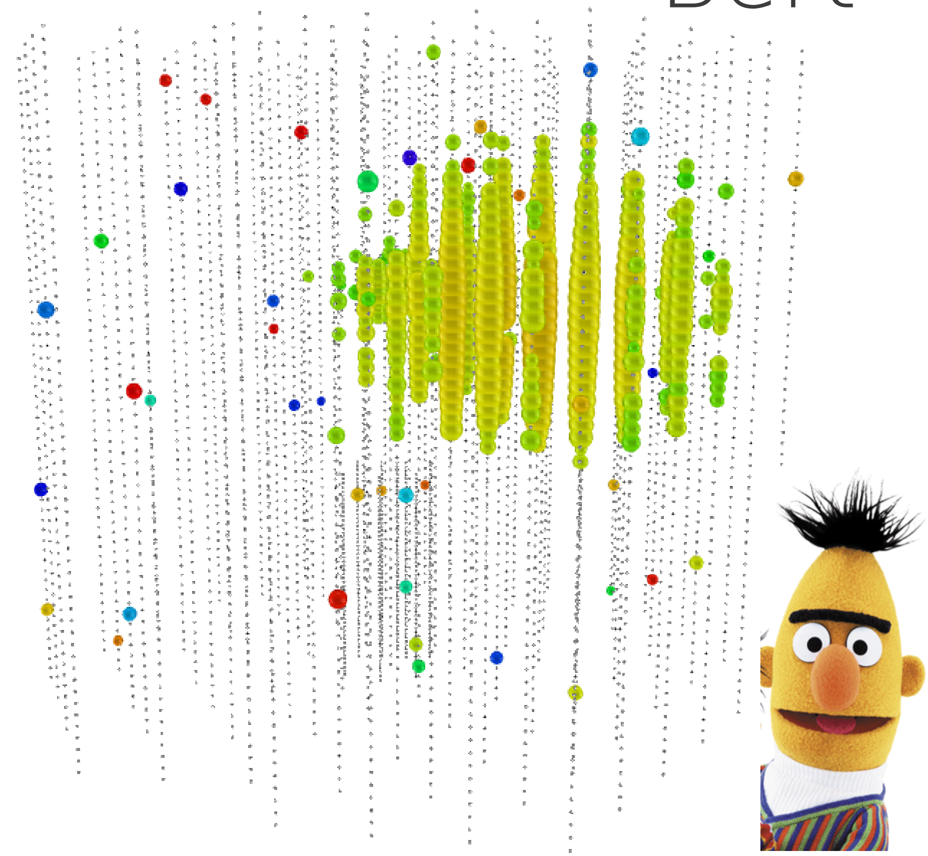
IceCube's first PeV events

Ernie



1.3 PeV

Bert



1.1 PeV

+/- 35% systematic uncertainty on energy reco

Presented @ NEUTRINO2012

What are they?

Expected event numbers:

Conv. Atmospheric ν + μ:
~ 0.05

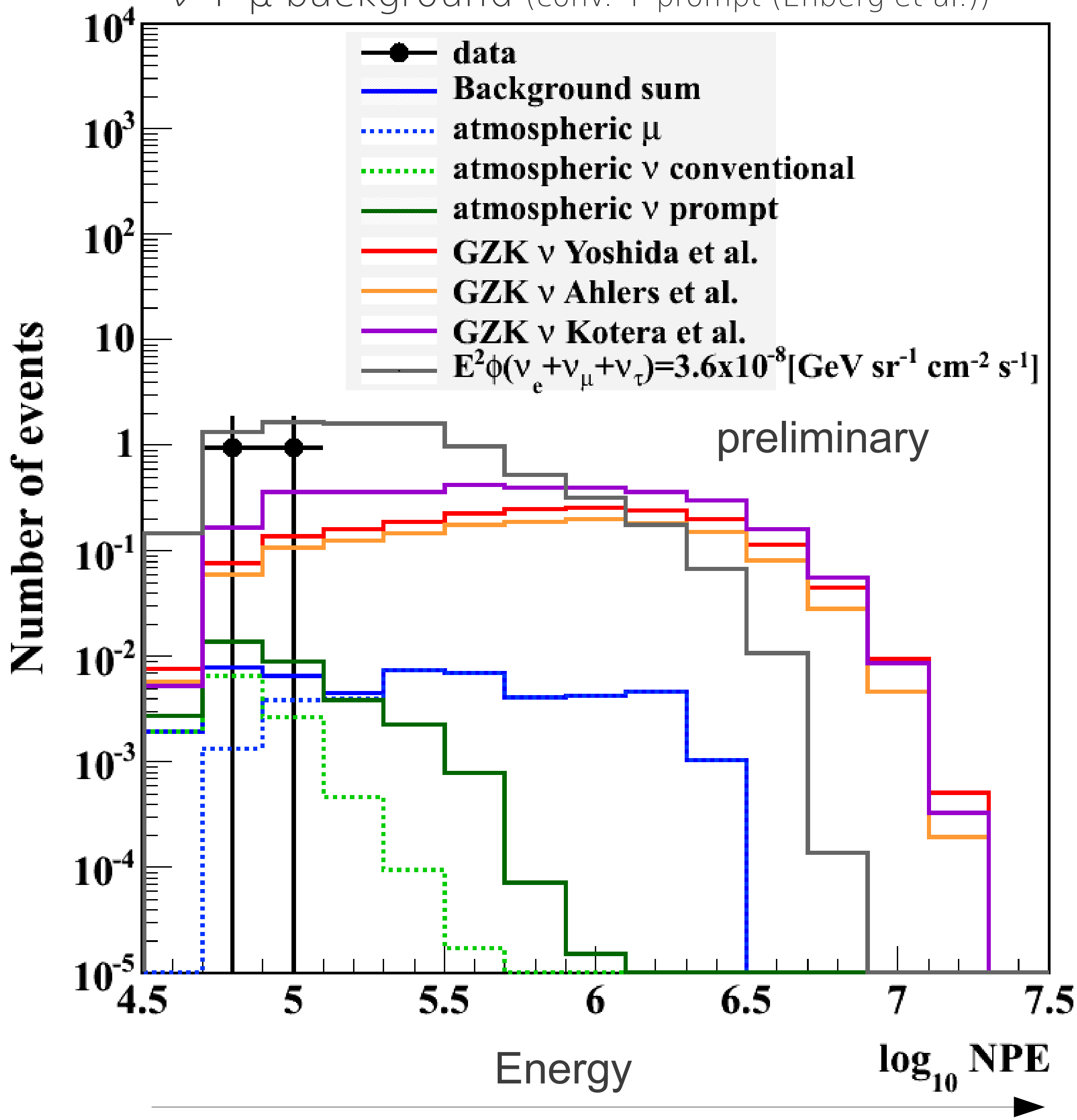
Steep energy spectrum
→ unlikely

Prompt atmospheric ν
~ 0.1 (Enberg et al.)

GZK?
Unlikely
too low energy

Astrophysical?
Maybe
Expectation depends on normalization, slope and cutoff energy

2.7σ excess over atmospheric ν + μ background (conv. + prompt (Enberg et al.))



Laterally separated muons in IC59

IceCube as a cosmic ray detector:

Select events with

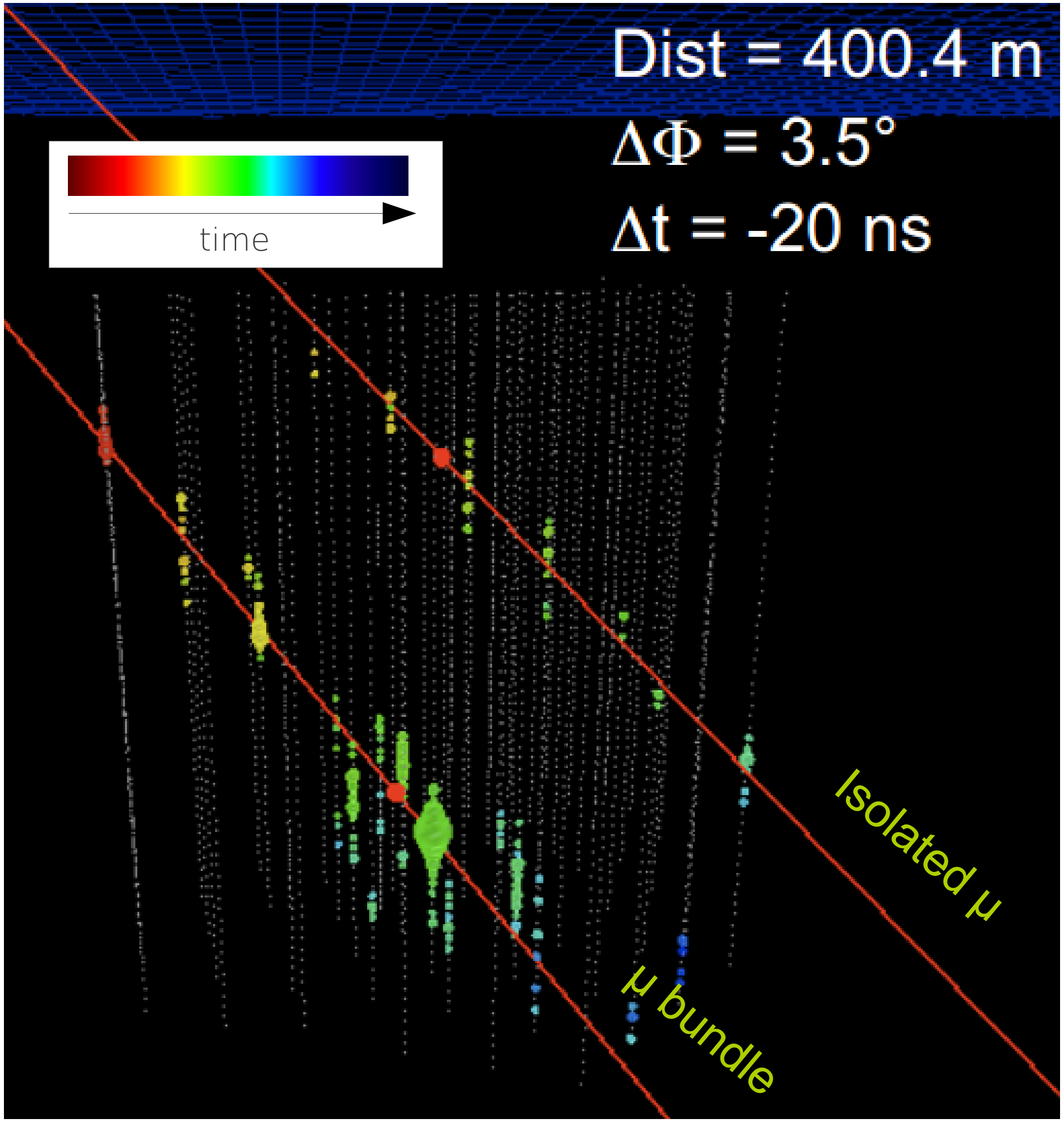
$\mu + \mu$ bundle

and measure the distance
(= distance from shower core)

height

$$d_T \simeq \frac{p_T H c}{E_\mu \cos(\theta)}$$

Transverse momentum



Sensitive to

- CR composition
- Interaction models

Probing the transition from soft to hard interactions

34,754 laterally separated muons found in one year of IC59 data taking

$$d_T \approx \frac{p_T H c}{E_\mu \cos(\theta)}$$

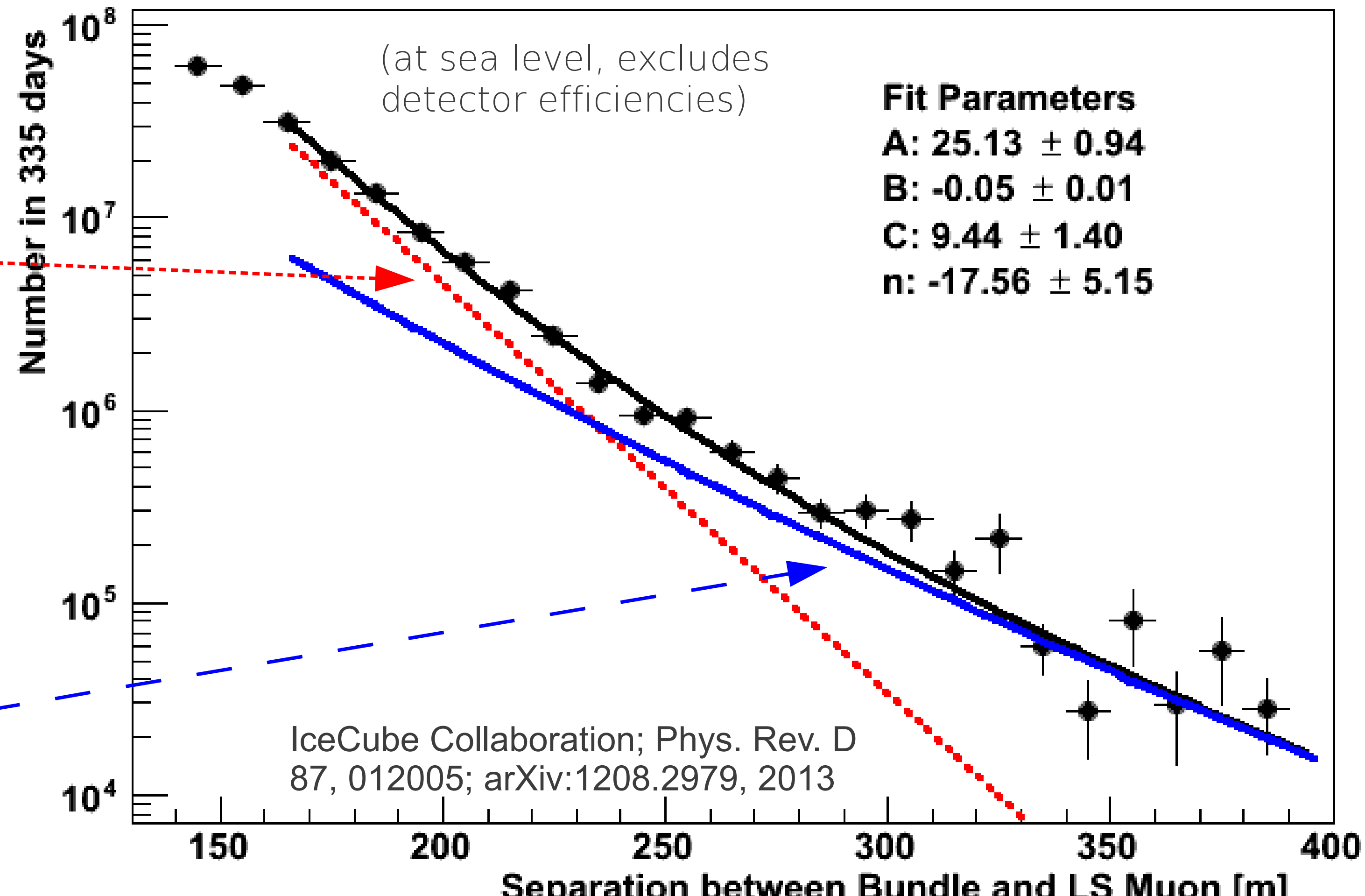
Different energies and zenith angles relate to different pT.

$< \sim 2$ GeV
(for pions)

Soft interactions described by an exponential

$> \sim 2$ GeV
(for pions)

Hard interactions (pQCD) described by a power law

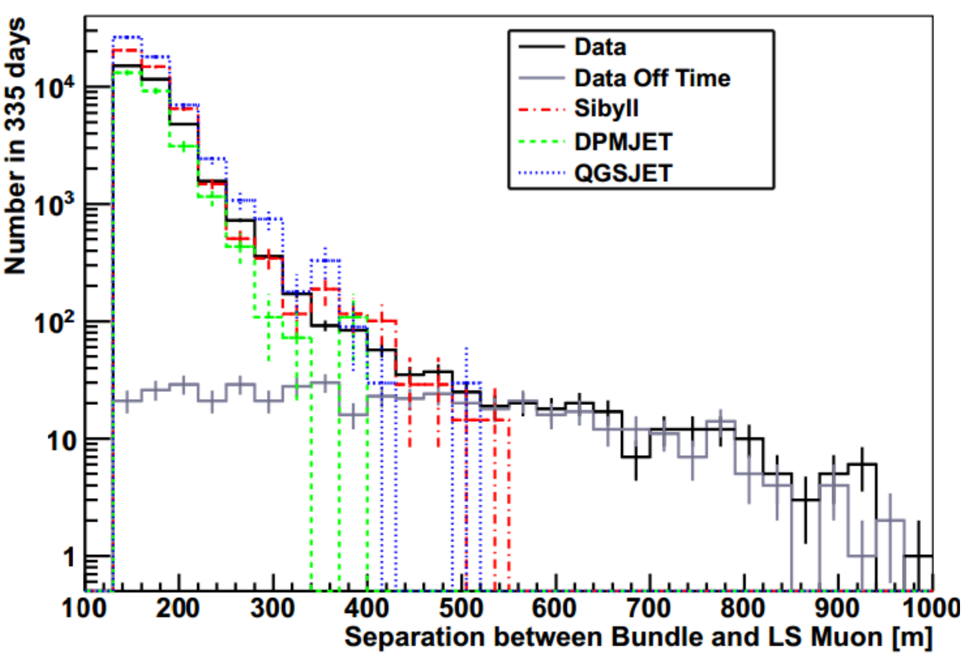


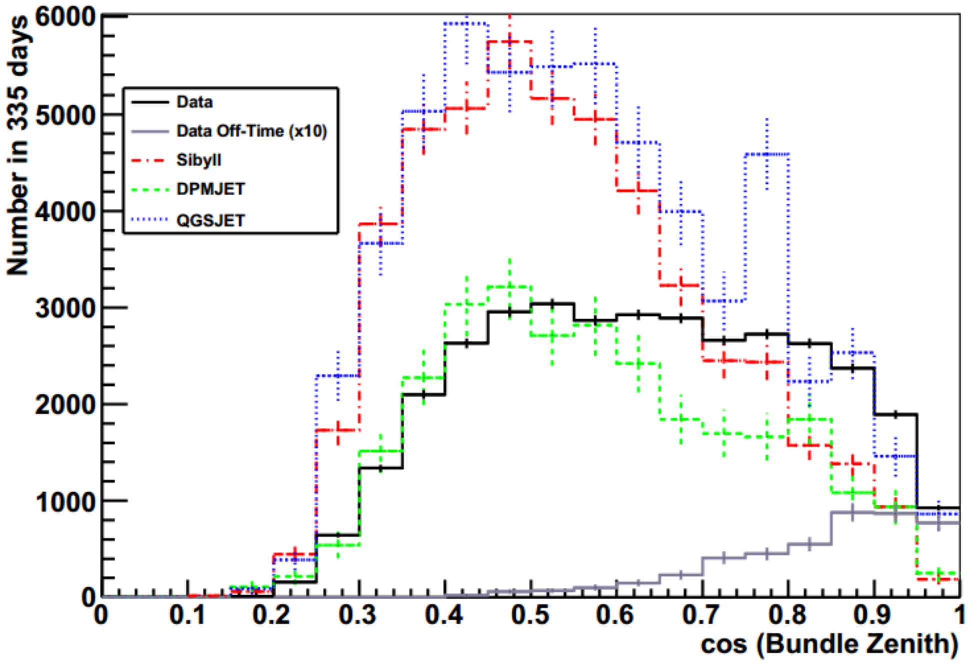
Comparison to different interaction model MC

Simulations here:

- Sibyll: no charm
- QGSJET: only lightest charm particles, negligible flux
- DPMJET: all charm particles, predominately from hard mini-jets

CR composition: Hoerandel polygonato





Studies showed that the data/MC agreement improves for

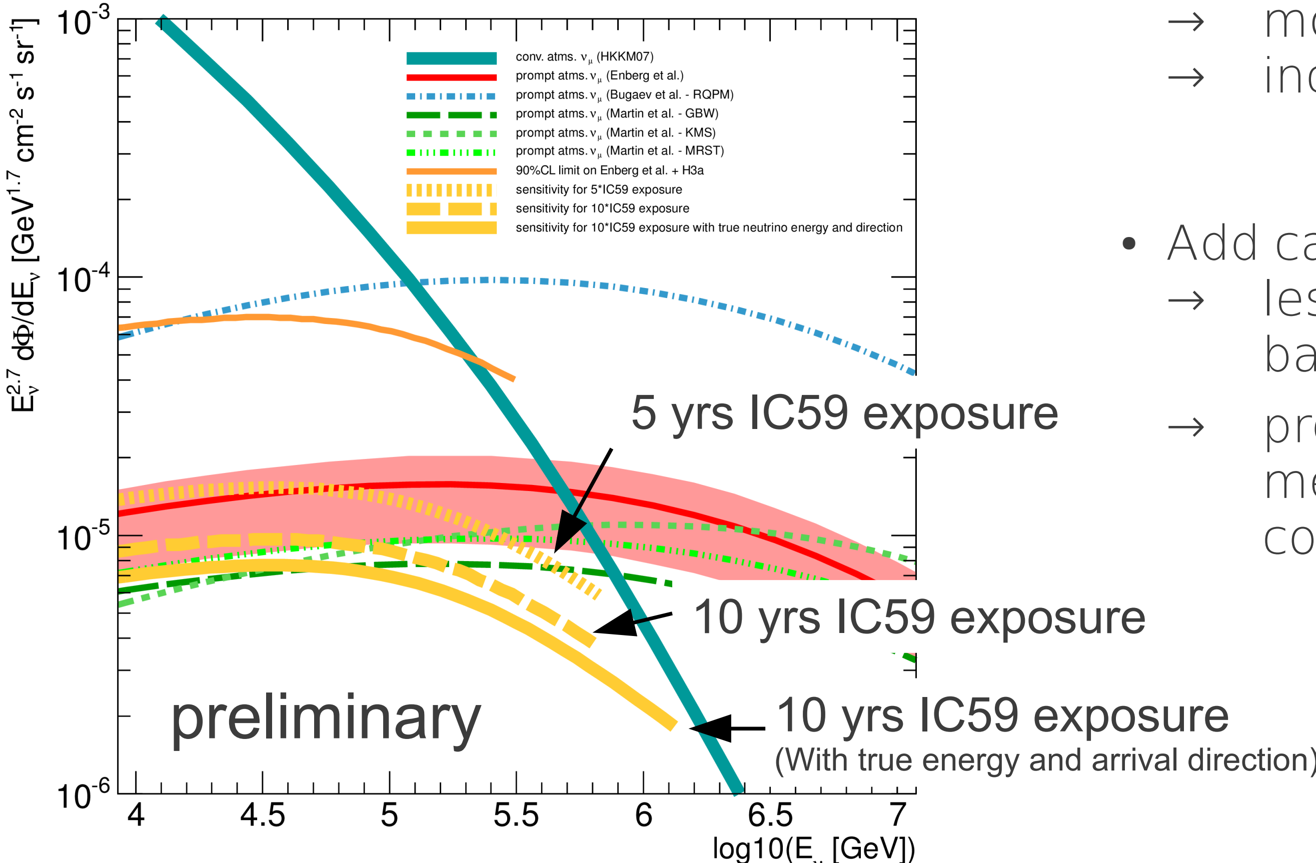
- an increase in kaon contribution
- an increase in charm contribution
- a change in CR composition towards lighter primaries

Summary

- We have a completed and well performing detector with a broad physics program
- We have recent results and many on-going searches for diffuse neutrino fluxes in complementary channels
- We found some interesting high-energy events in diffuse searches this summer - are we getting closer to the discovery of astrophysical neutrinos?
- We are now reaching sensitivity to prompt neutrinos in the order of prompt neutrino flux predictions

Outlook

What can we expect from the muon channel?



Includes systematic uncertainties

Prompt models might be in reach for future analyses!

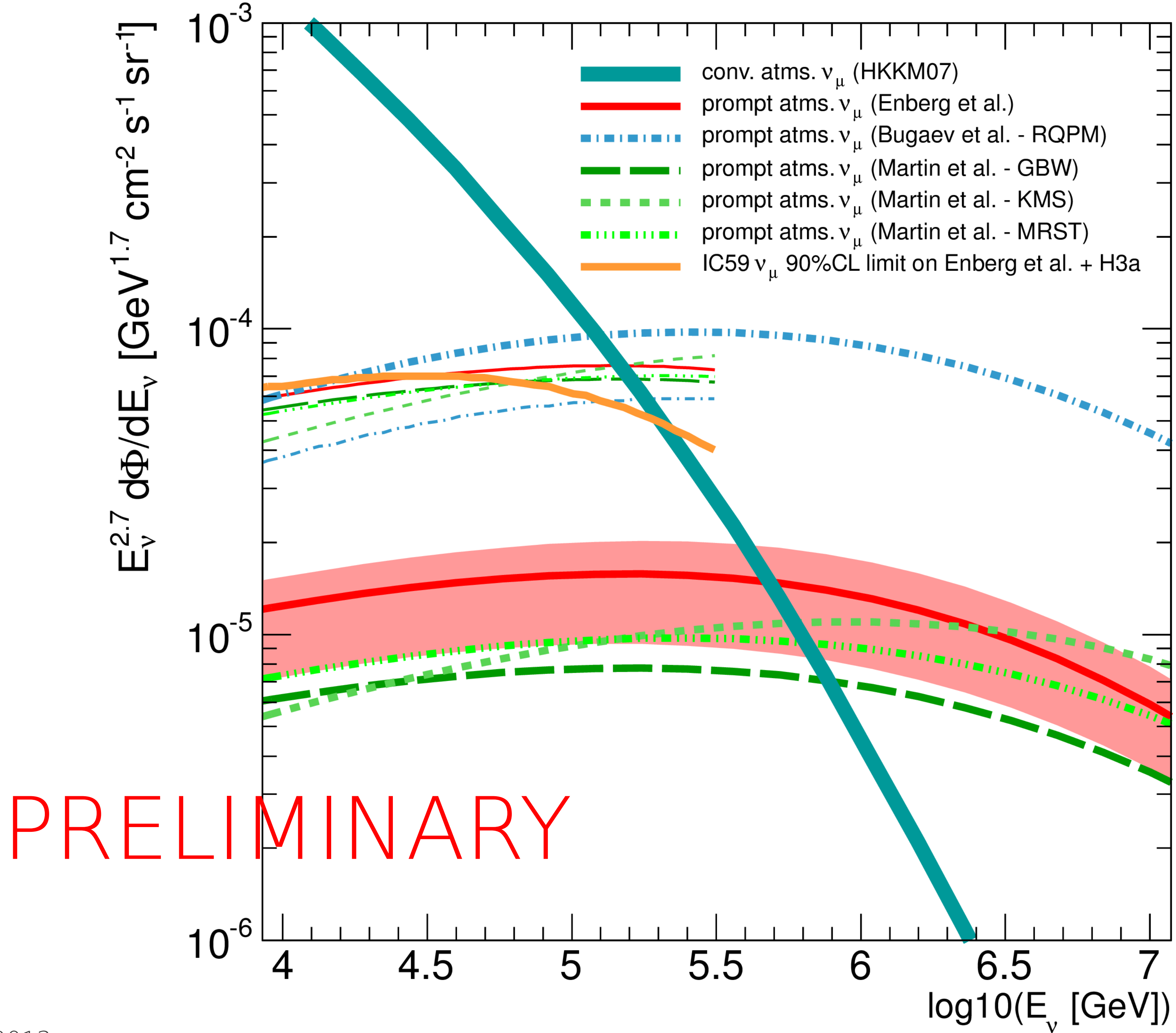
What else can we do?

- Full (= larger) detector
  → more statistics
  → increases energy range
- Add cascade channel
  → less conv. atmospheric background for ν_e
  → precise energy measurement for contained events

Caveat:

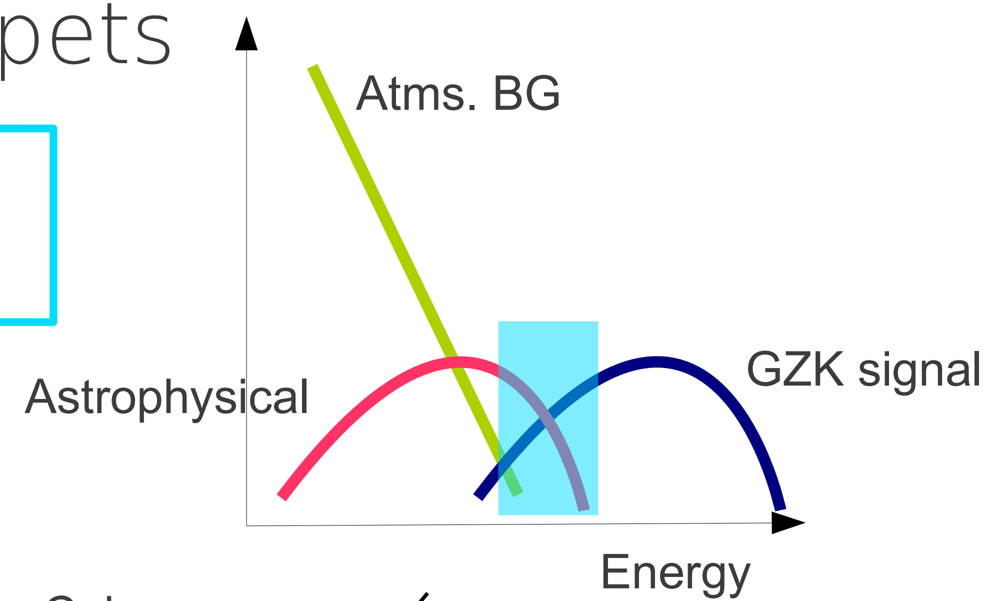
In the presence of an astrophysical diffuse neutrino flux, prompt becomes much more challenging…

- Backup -


conv. atms. ν_μ (HKKM07)
prompt atms. ν_μ (Enberg et al.)
prompt atms. ν_μ (Bugaev et al. - RQPM)
prompt atms. ν_μ (Martin et al. - GBW)
prompt atms. ν_μ (Martin et al. - KMS)
prompt atms. ν_μ (Martin et al. - MRST)
IC59 ν_μ 90%CL limit on Enberg et al. + H3a
$E_\nu^{2.7}\, d\Phi/dE_\nu$ [$GeV^{1.7}\, cm^{-2}\, s^{-1}\, sr^{-1}$]
log10(E_ν [GeV])
PRELIMINARY

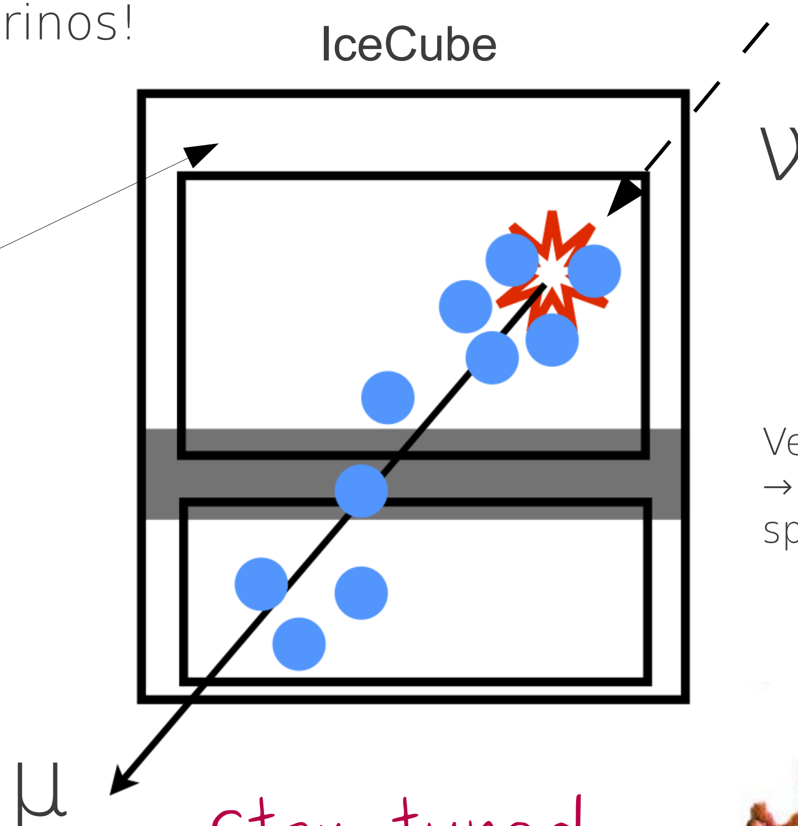
How to find more Muppets

Exploring the Northern & Southern sky in the energy range between IC40 cascade / IC59 numu and EHE



Look for starting tracks in the detector

→ these must be neutrinos!



Efficient veto
for atmospheric muons

Sensitive to cascade- and track-like events

Very dirty ice layer
→ needs some special treatment

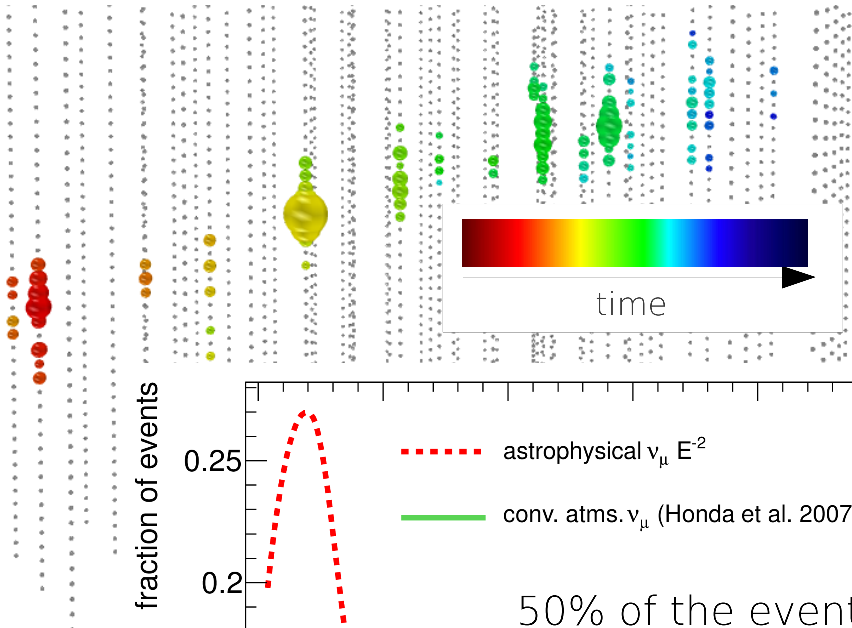
If the observed overfluctuations are a signal, this type of analysis will be able to proof it!

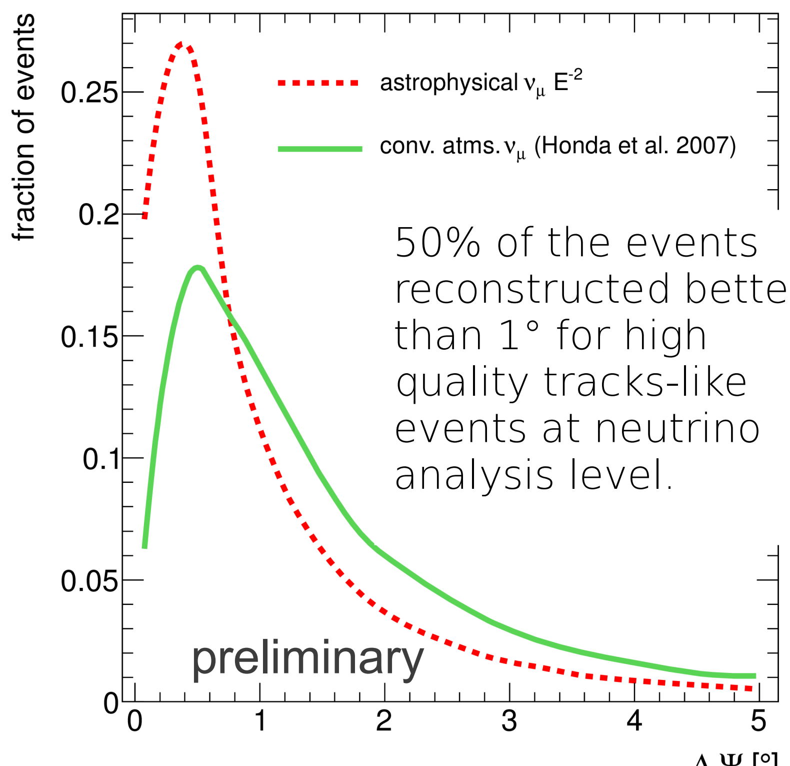
Stay tuned...

Angular reconstruction

For tracks:

Collect information from photon arrival times

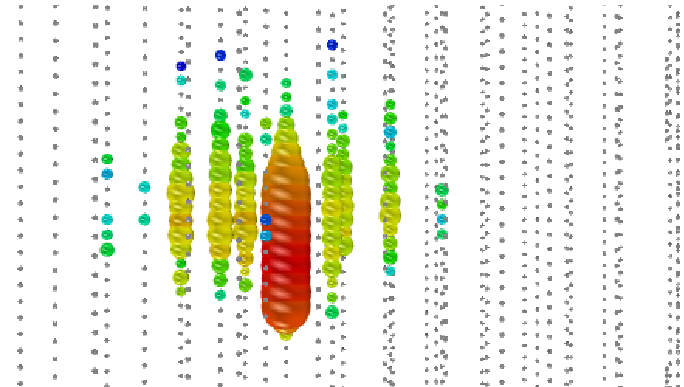




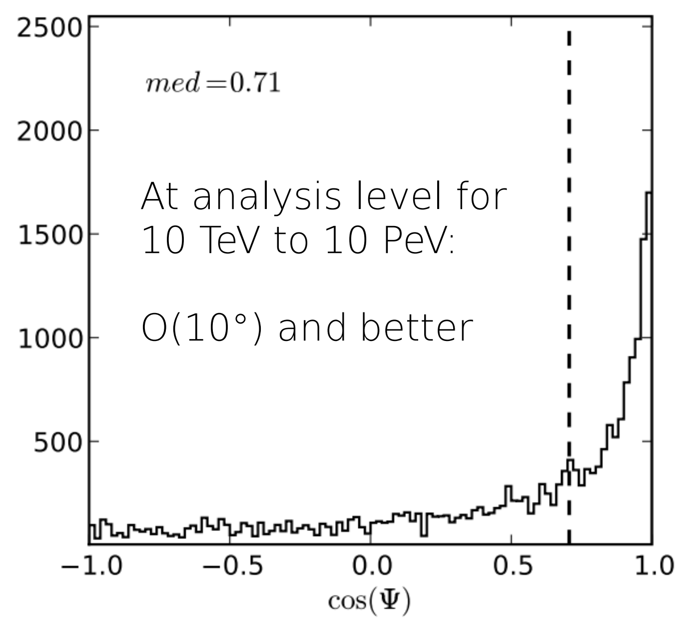
50% of the events reconstructed better than 1° for high quality tracks-like events at neutrino analysis level.

For cascades:

Challenging, because of spherical shape!



Boost in the observed cascade allows an angular reconstruction.

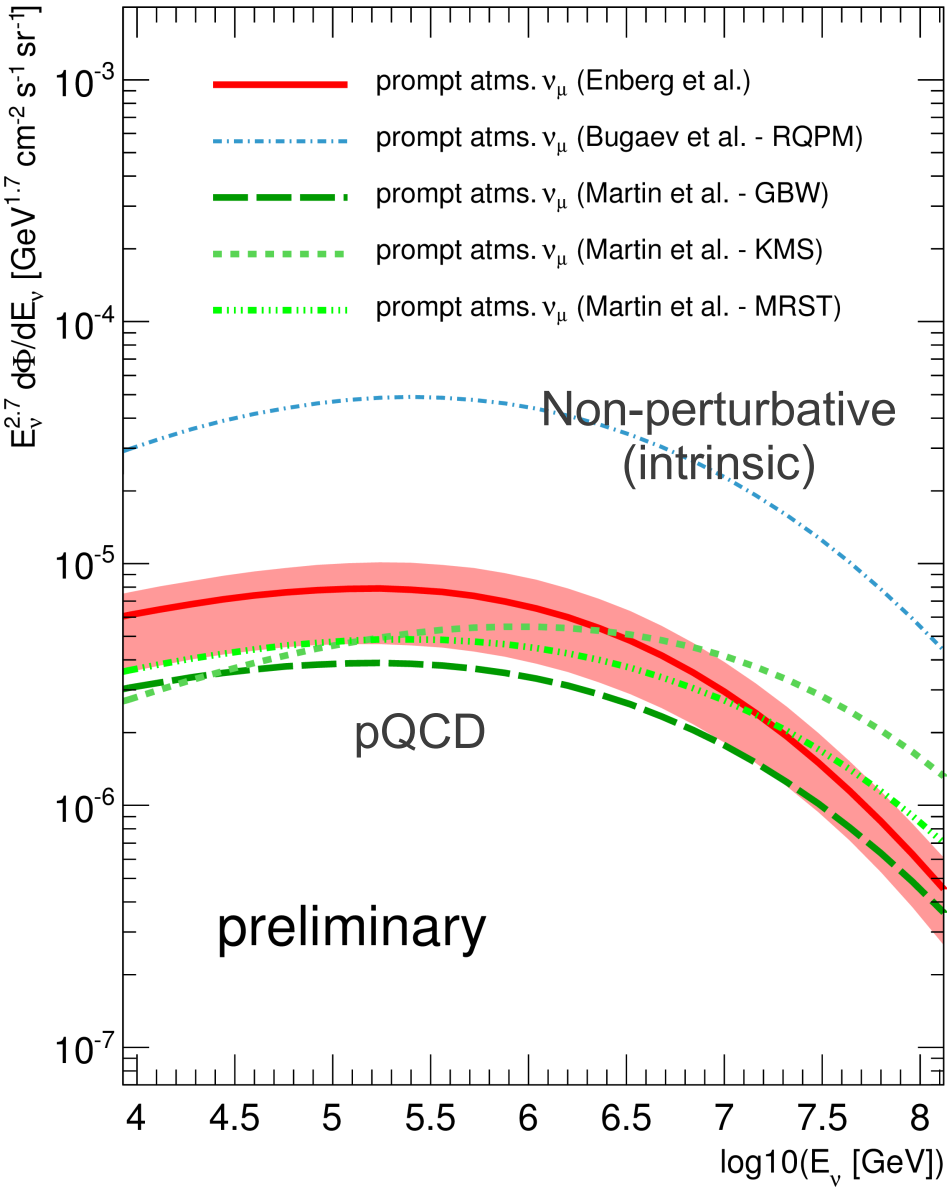


At analysis level for 10 TeV to 10 PeV:

O(10°) and better

Midell et al.; ICRC2009

Prompt atmospheric neutrinos



Enberg et al.: Phys.Rev.D78:043005,2008
Martin et al.: Acta Phys.Polon.B34:3273-3304,2003
Bugaev et al.: Phys. Rev. D58:054001, 1998

Ingredients:

- Primary cosmic ray nucleon flux
- Differential cross section for gg → ccbar, qqbar → ccbar
- Nucleonic and charm attenuation and interaction lengths in the atmosphere
- Charm semi-leptonic decay spectra

Gluon distribution function at small x

Predict 50 – 300 prompt events in the data sample of 22 000 events

Shape very similar!

The diffuse neutrino energy spectrum