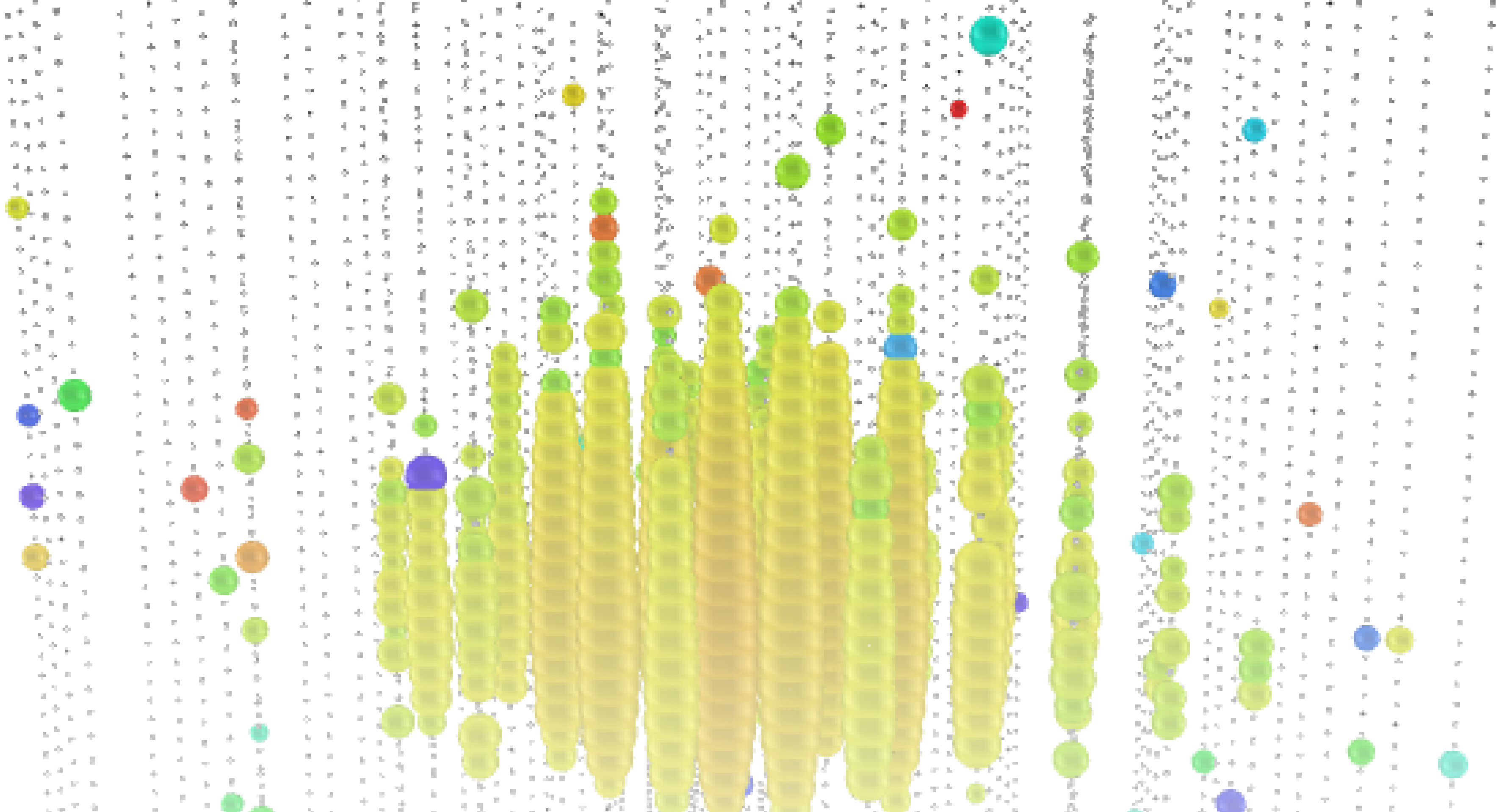


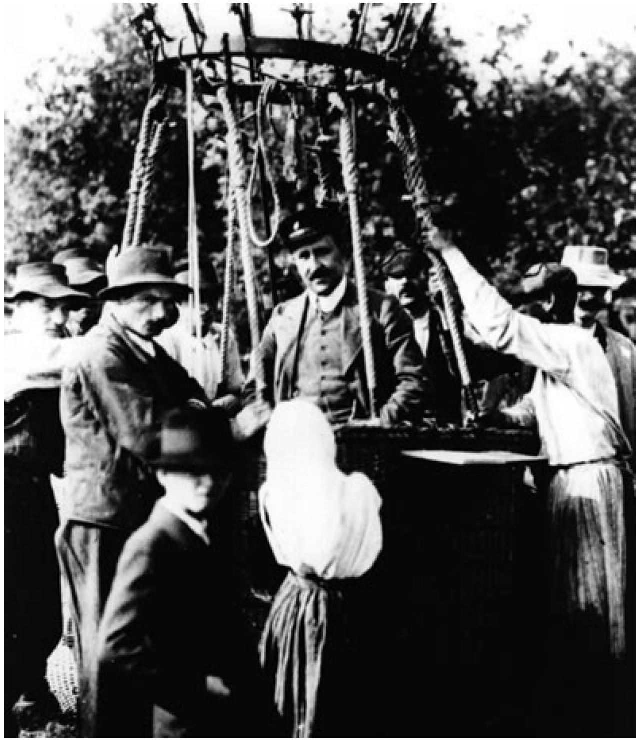
Latest results from (astrophysical neutrino searches with) the IceCube Neutrino Observatory

Anne Schukraft
RWTH Aachen University

April 15, 2013, DESY Hamburg

Deutsche Telekom Stiftung
HELMHOLTZ | GEMEINSCHAFT
Allianz für Astroteilchenphysik
Bundesministerium für Bildung und Forschung

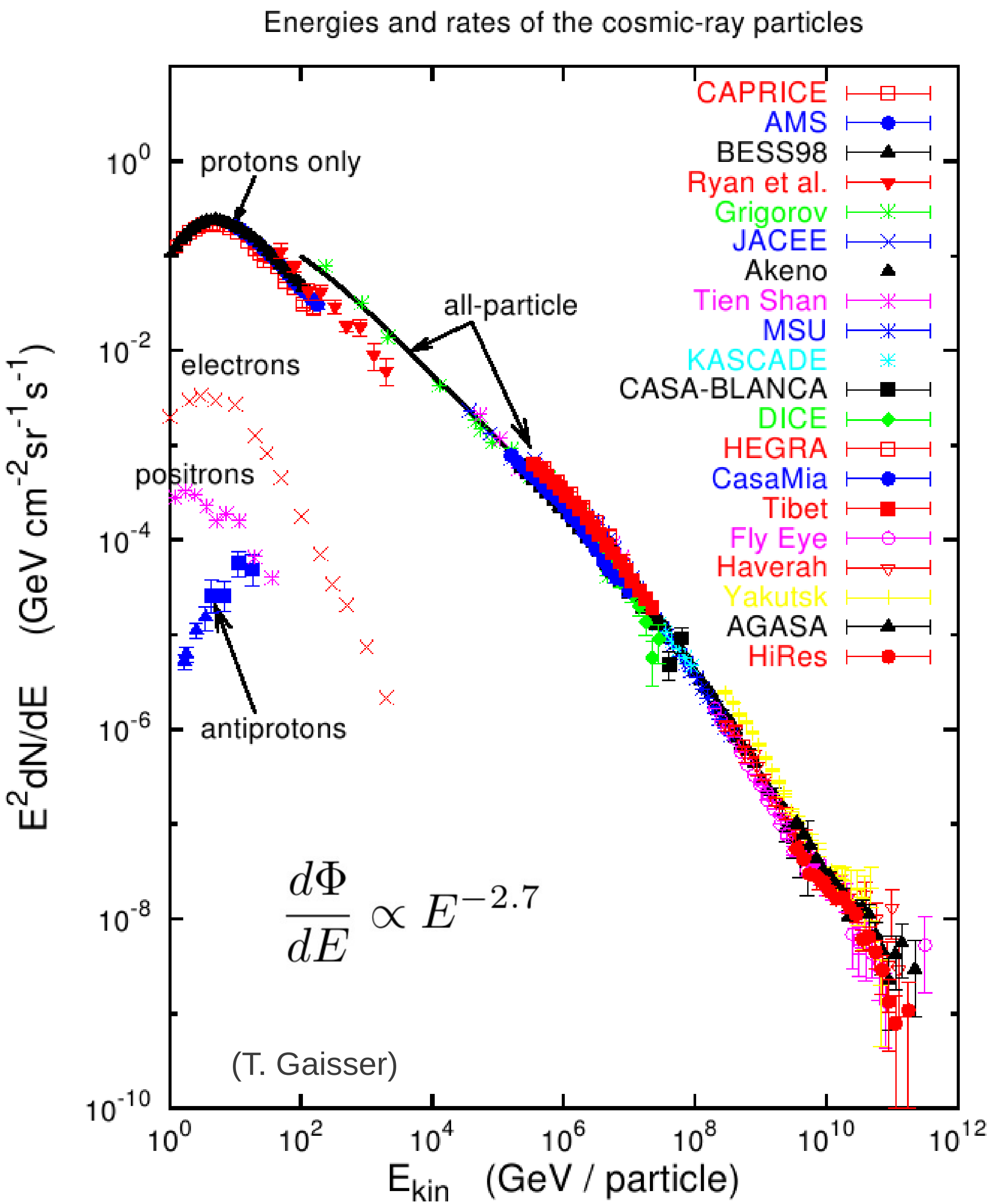
Cosmic rays



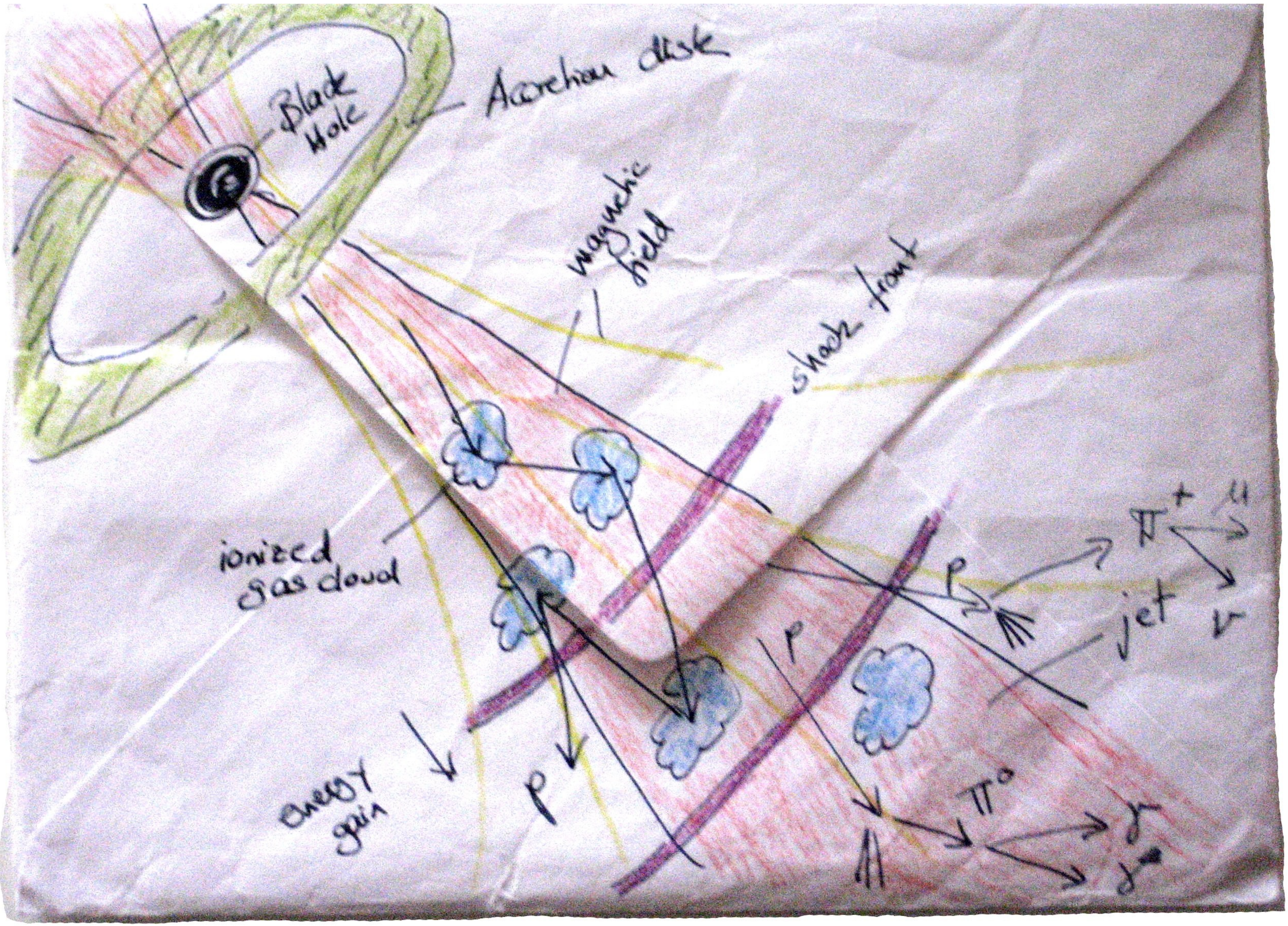
Discovered by V. Hess in 1912

What is the acceleration mechanism?

What are the sources?



A model for CR acceleration on the back of an envelope



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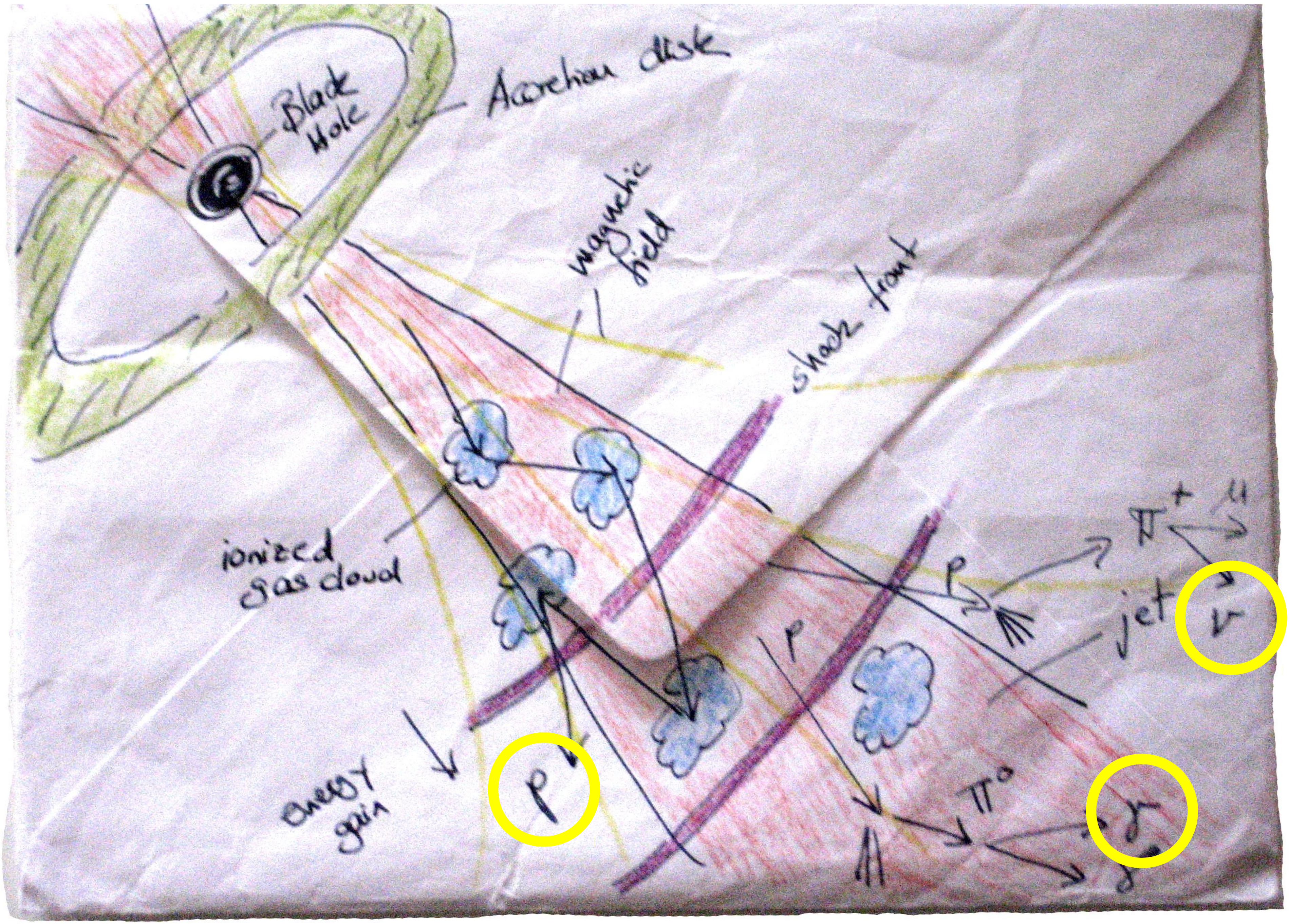

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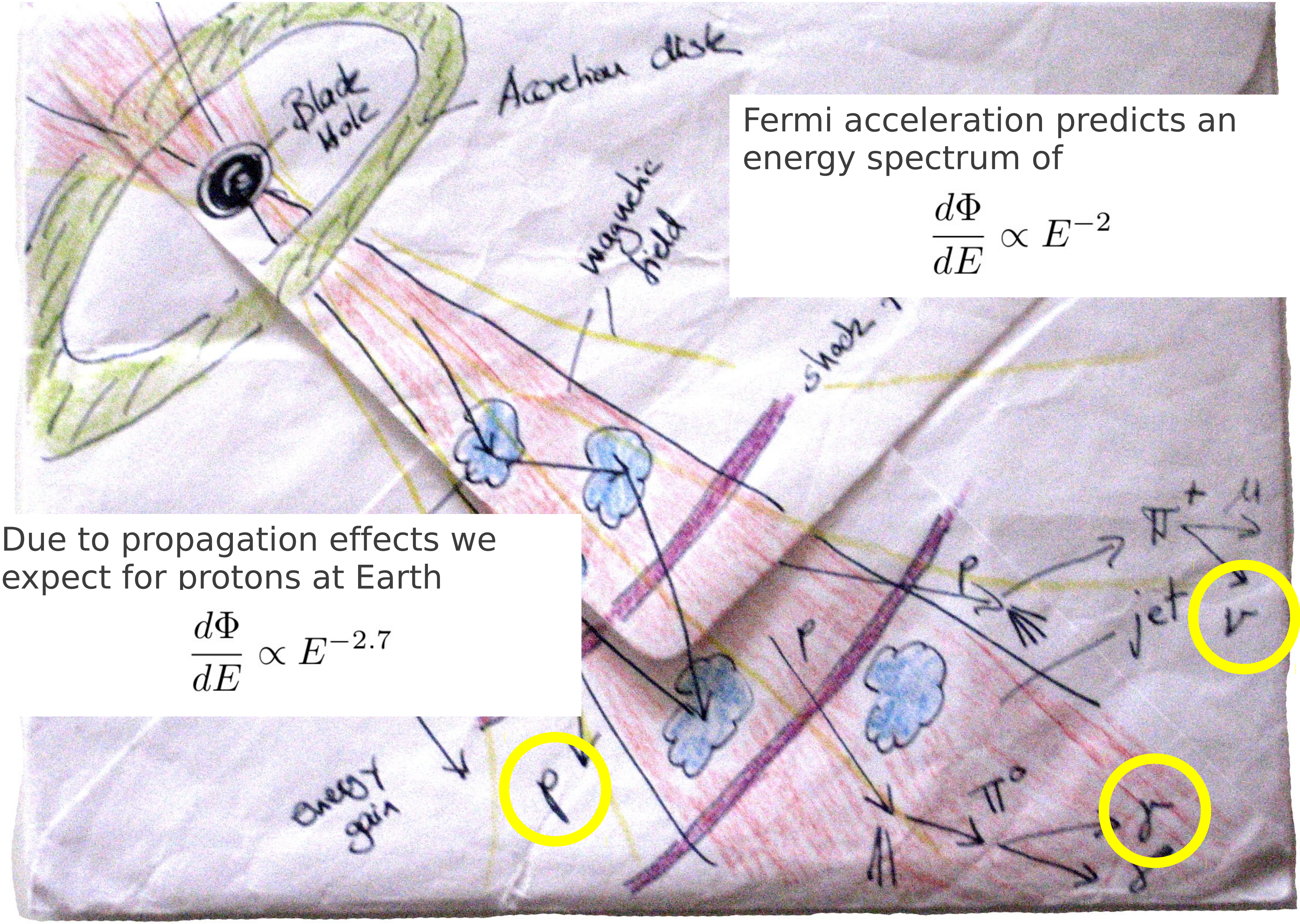


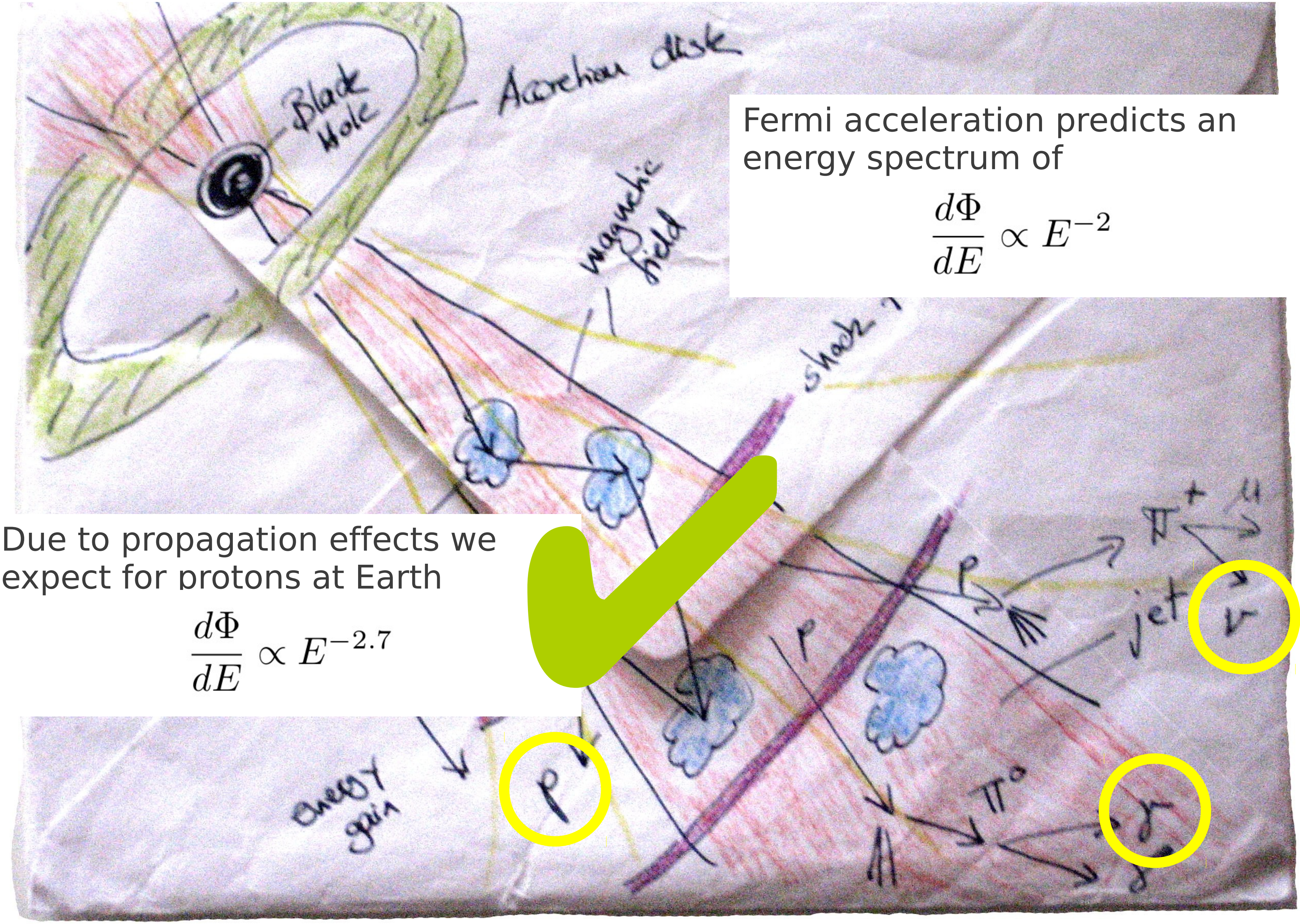
Fermi acceleration predicts an energy spectrum of

$$\frac{d\Phi}{dE} \propto E^{-2}$$

Due to propagation effects we expect for protons at Earth

$$\frac{d\Phi}{dE} \propto E^{-2.7}$$

A model for CR acceleration on the back of an envelope



Fermi acceleration predicts an energy spectrum of

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Due to propagation effects we expect for protons at Earth

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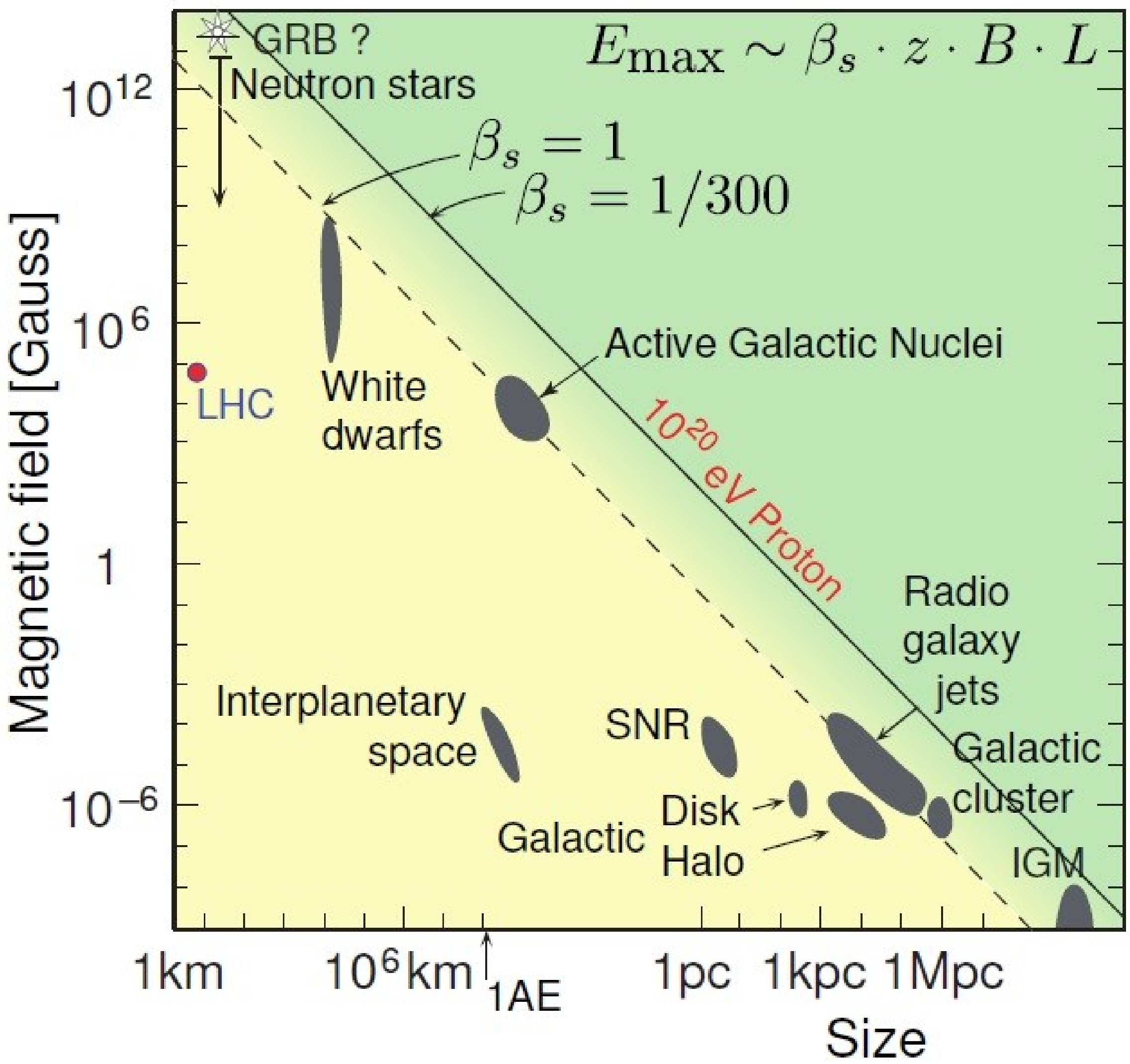
Source candidates



Maximum energy is constrained by magnetic field strength and Size of the object

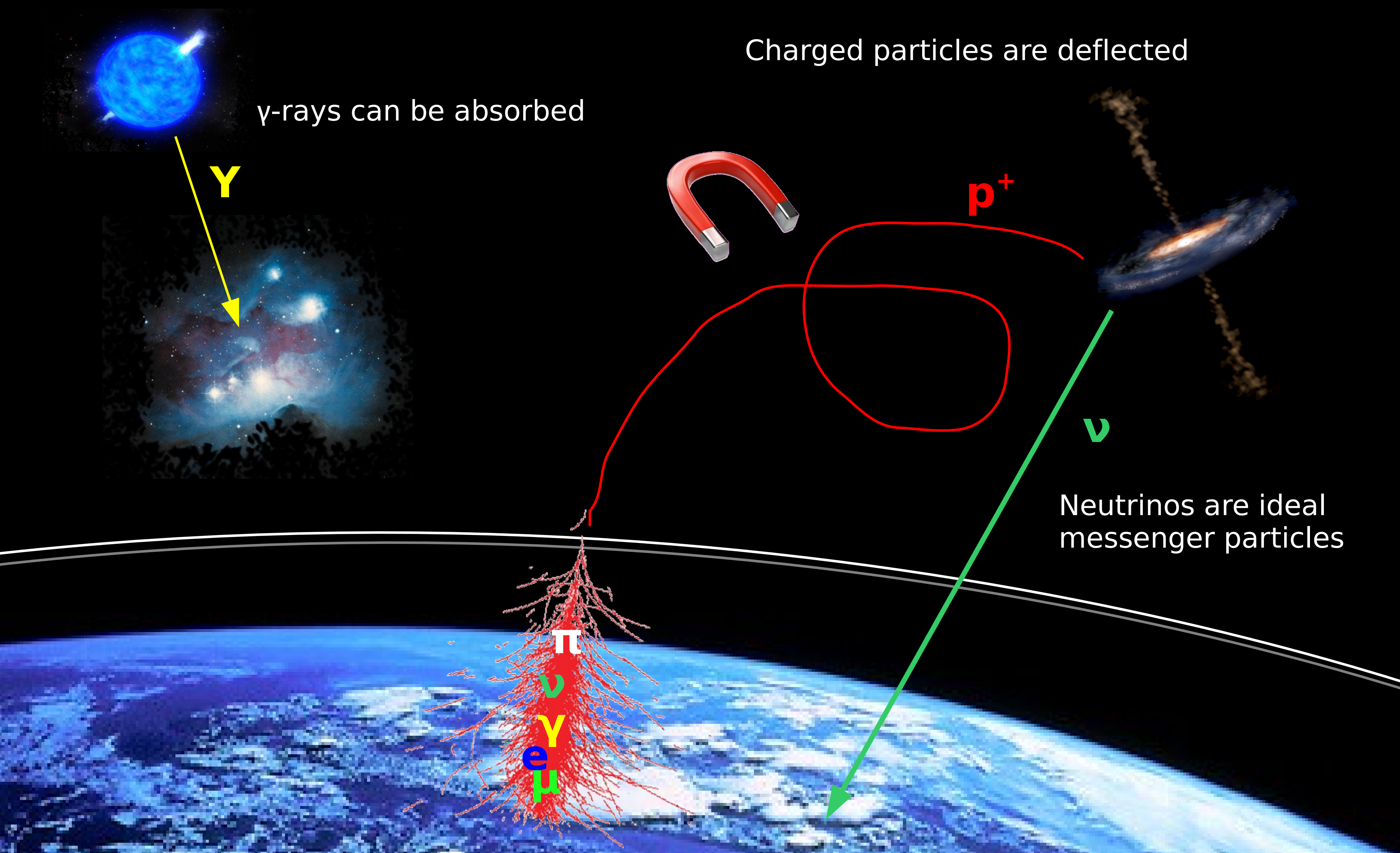
Research status:

Proton sources?	NO
γ-ray sources?	YES

But: only < 100 TeV and no confirmation of hadronic acceleration, yet

Neutrino sources?	NO

The multi-messenger approach

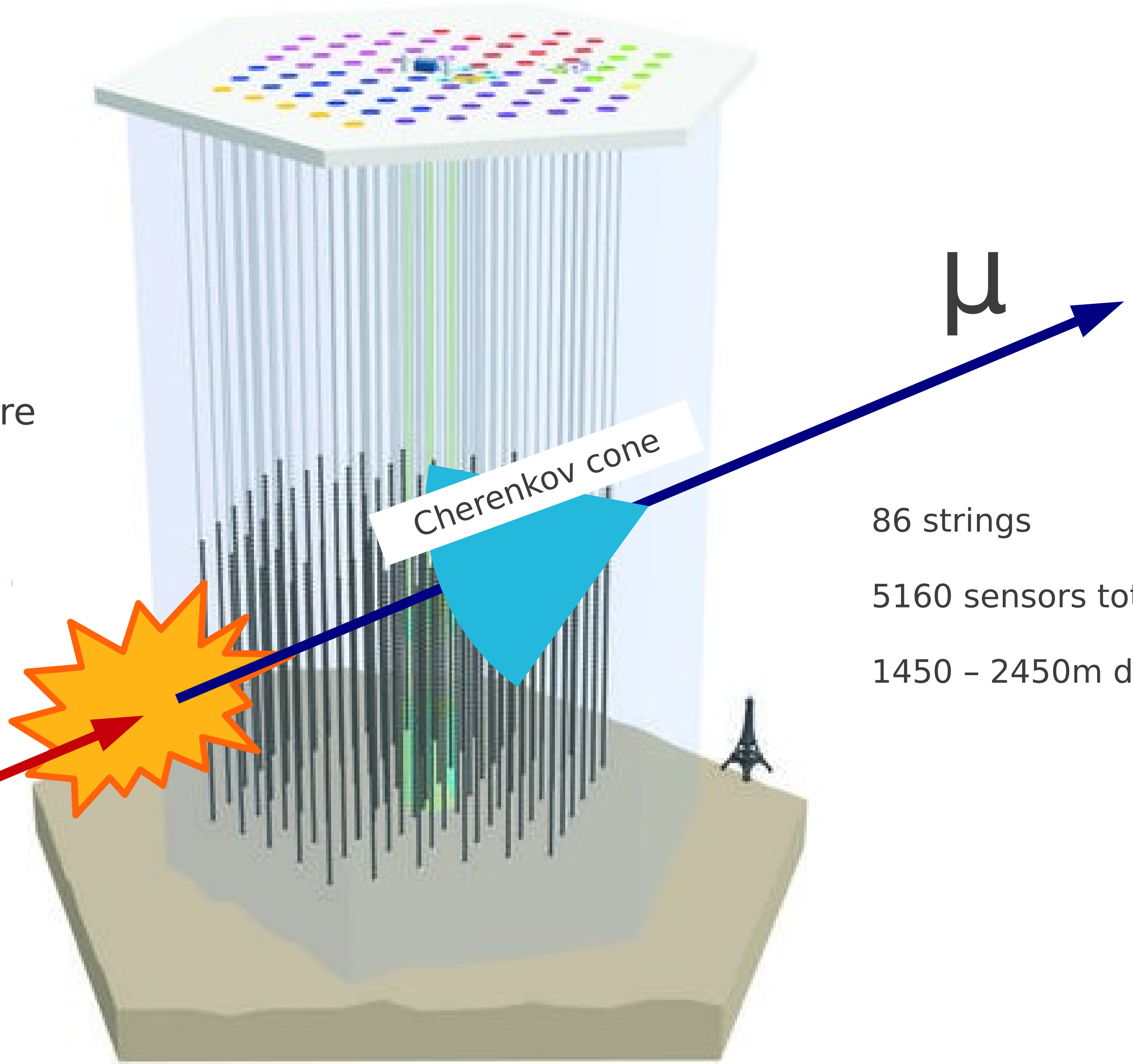


The IceCube Neutrino Observatory

Neutrinos interact inside or near the detector

Secondary particles produce Cherenkov light

Cherenkov photons are detected by optical sensors in clear ice



ν_μ

86 strings

5160 sensors total

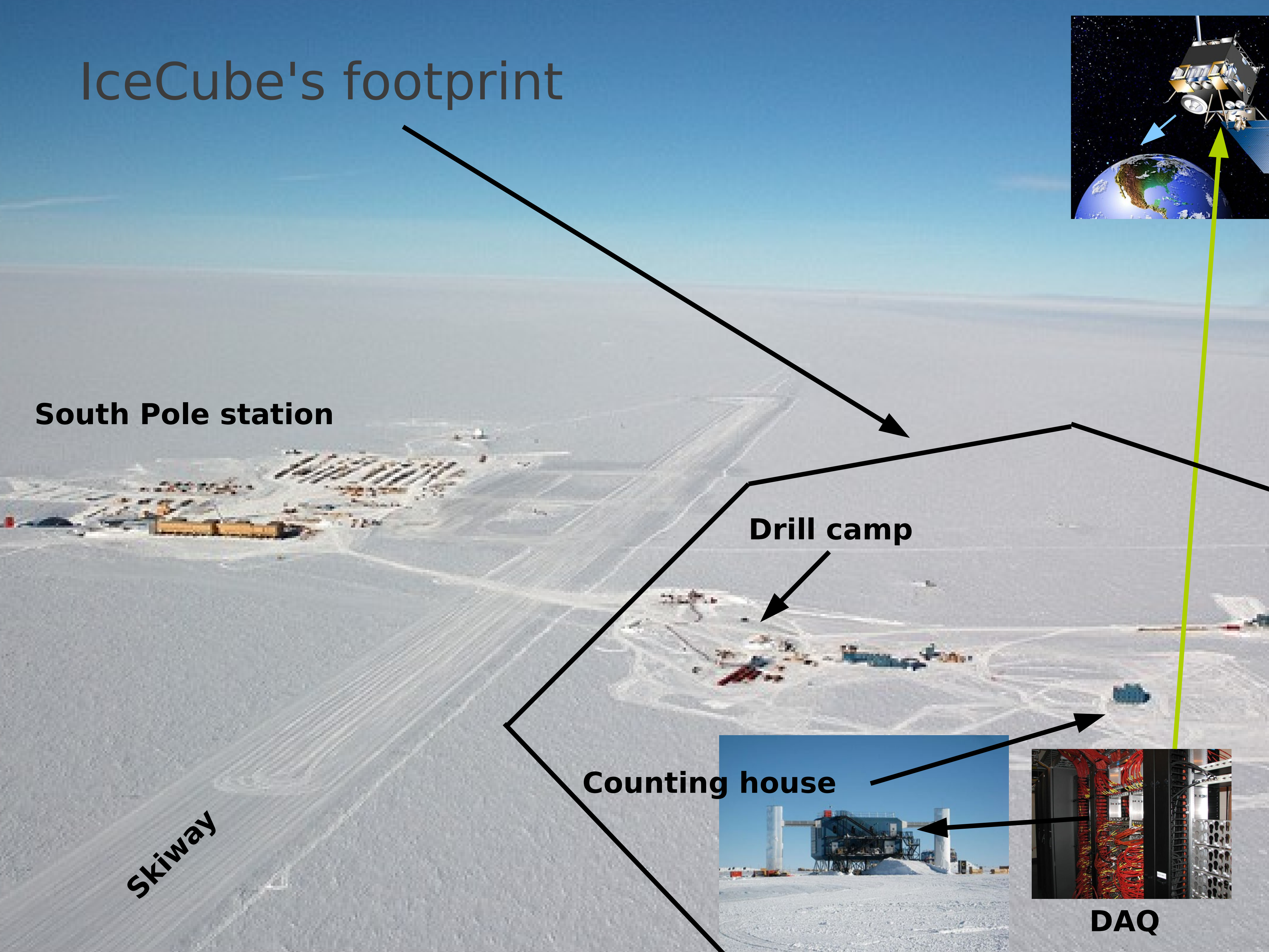
1450 – 2450m depth

The IceCube Collaboration

International Funding Agencies

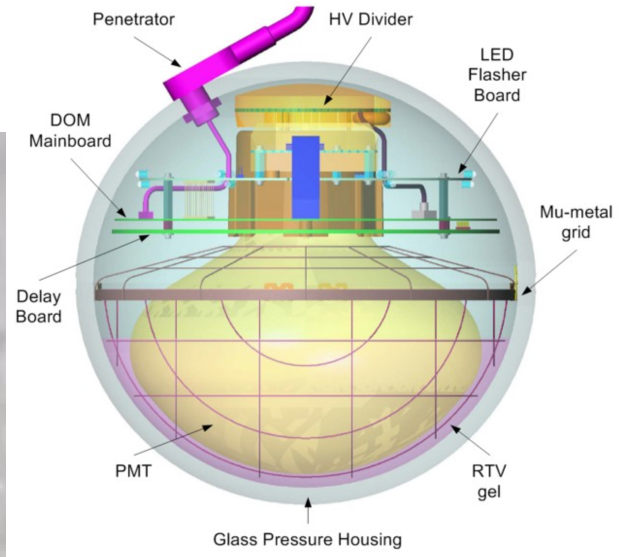
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

IceCube's footprint

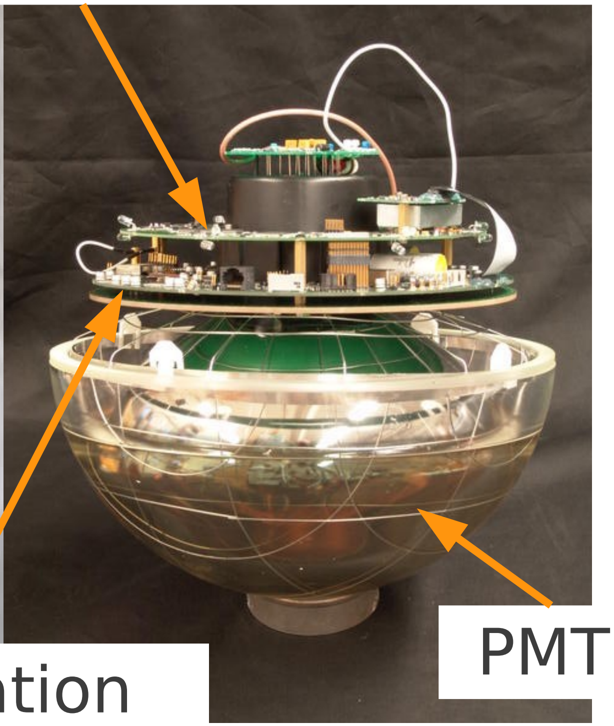


IceCube's optical modules

Holes drilled with hot water, up to 2500m deep



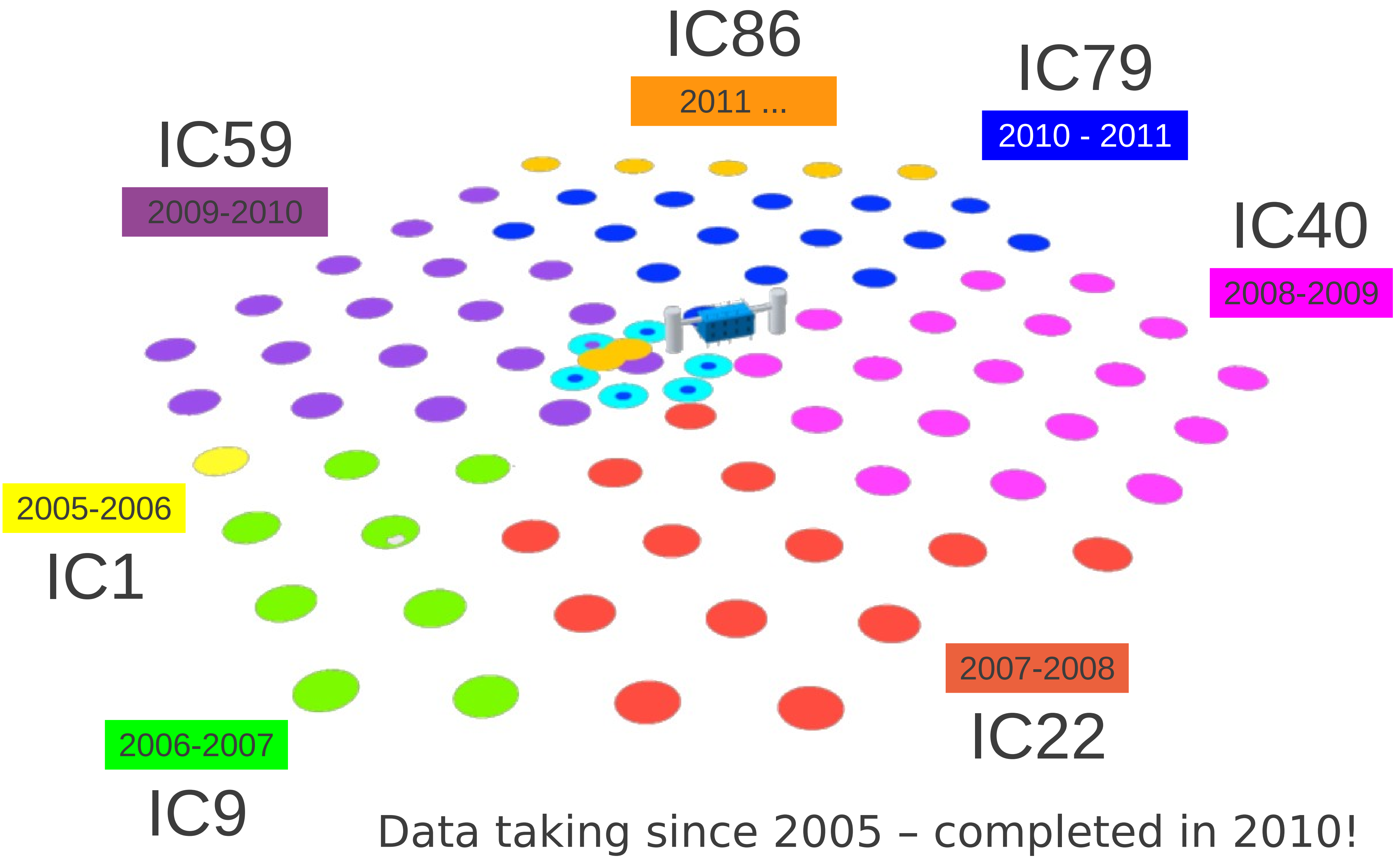
Calibration devices



Signal digitization

PMT

7 years of construction



Data taking since 2005 – completed in 2010!

How IceCube looks like now:

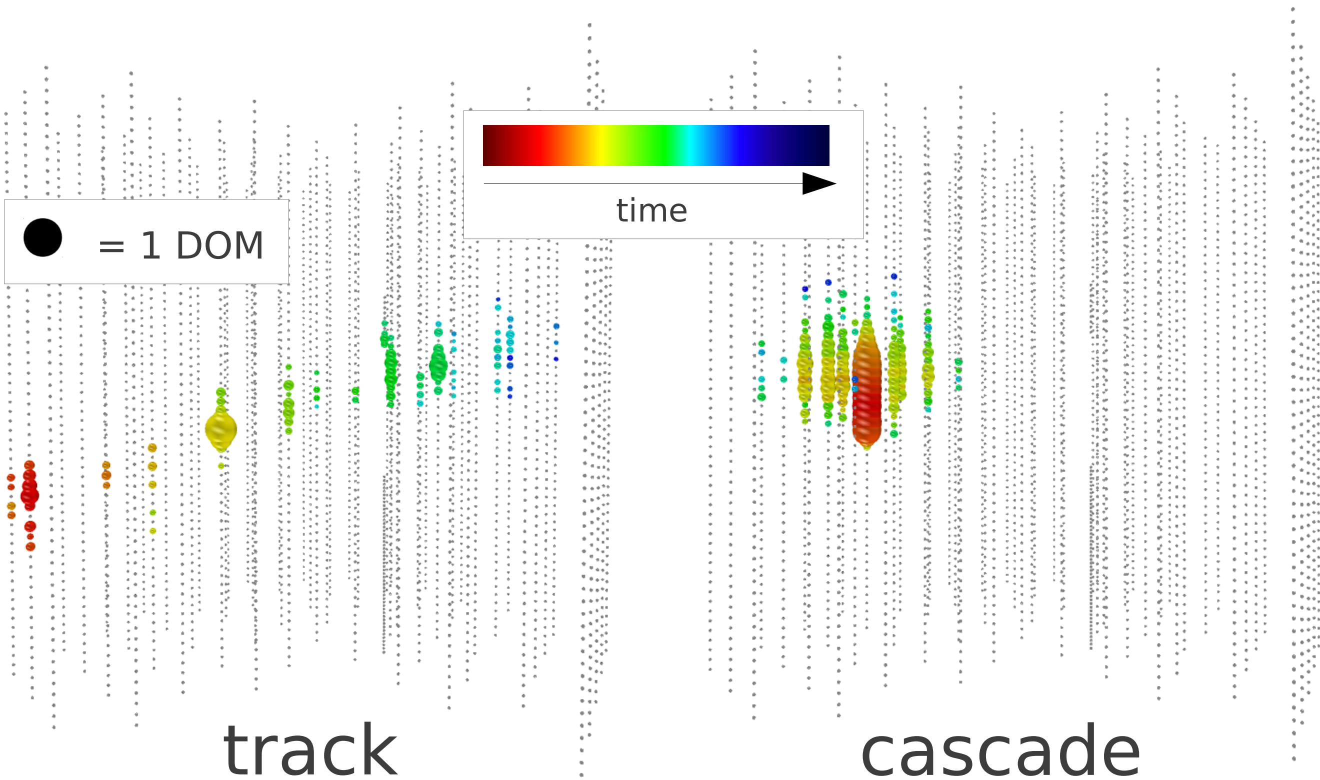
Neutrino event signatures

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

$\nu_e + N \rightarrow e + X$

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

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



track

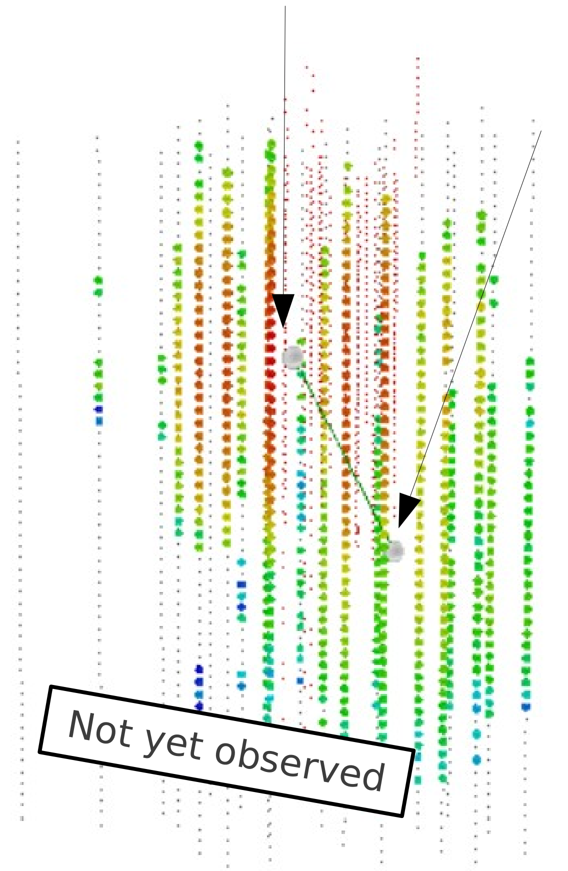
450 TeV muon

(simulation)

cascade

1 PeV electron

(simulation)



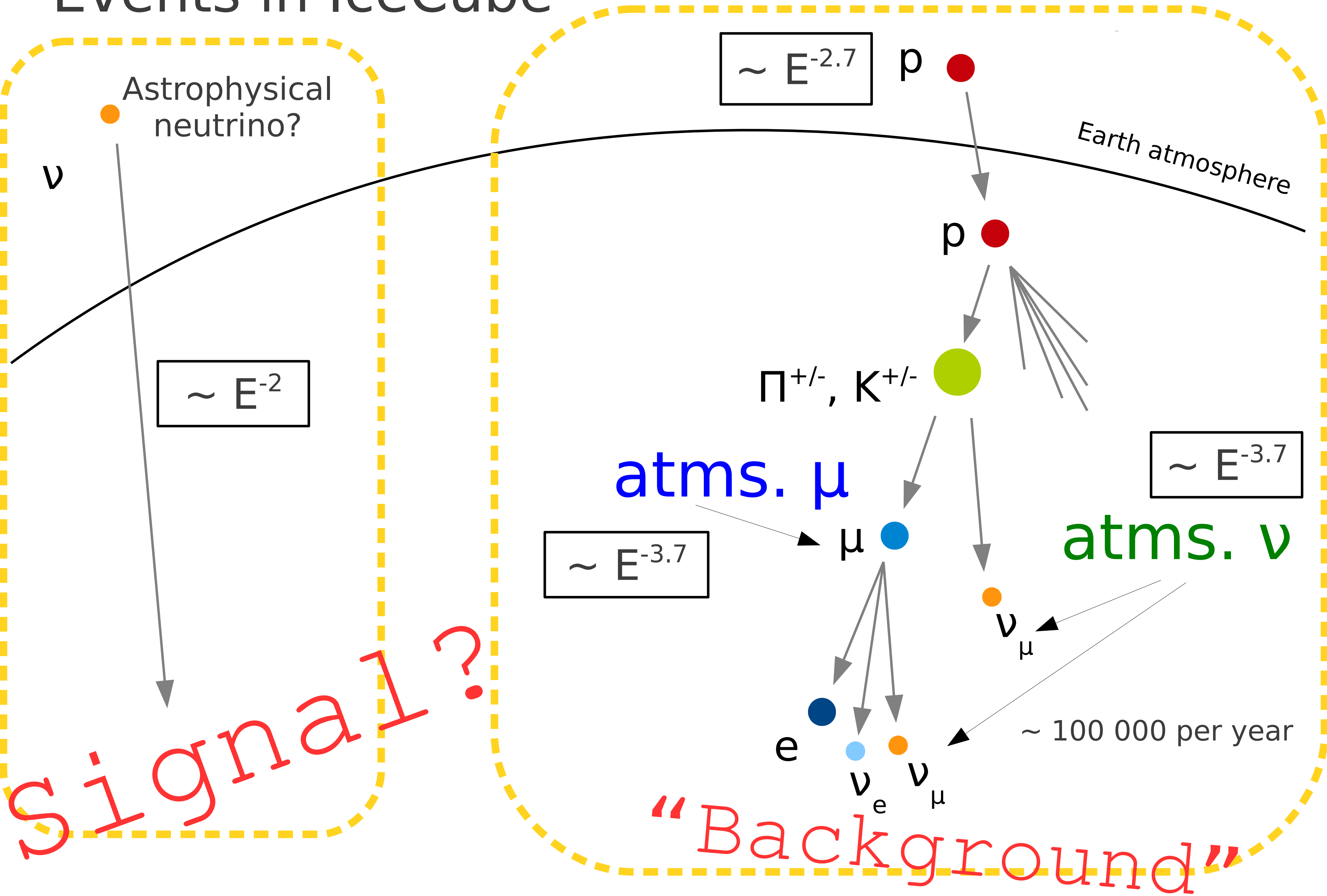
"double bang"

(or lollipop)

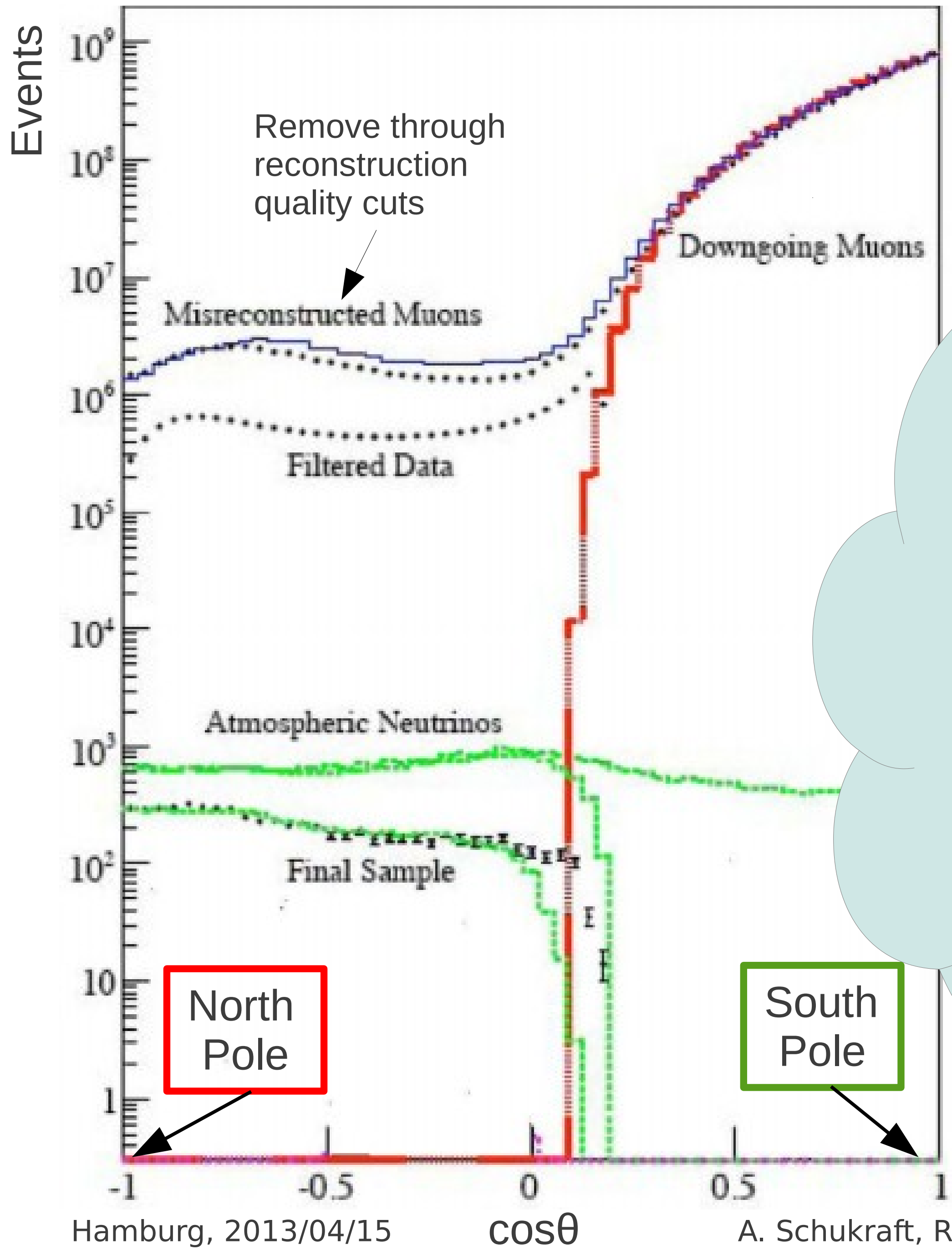
50 PeV tau

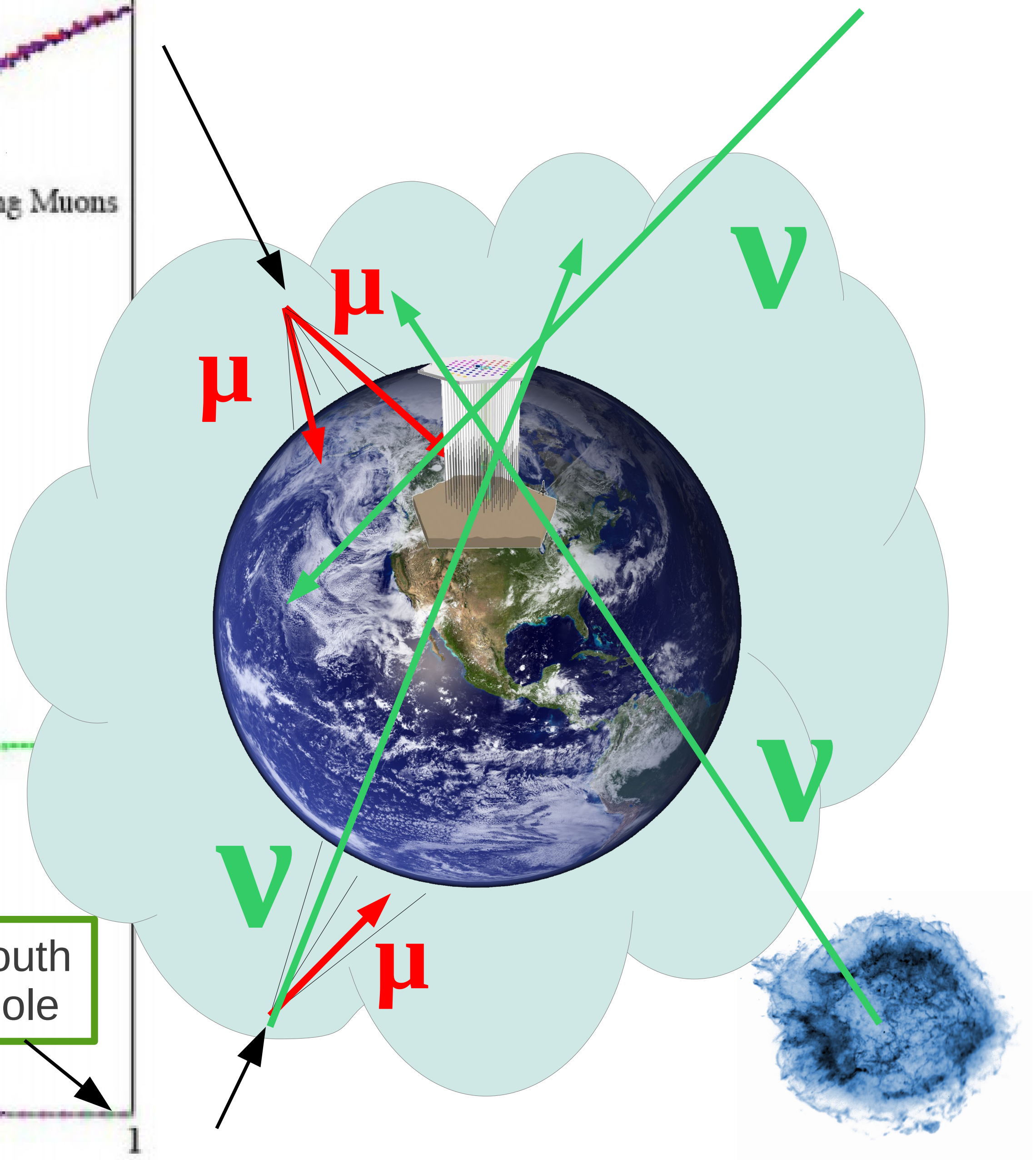
(simulation)

Events in IceCube

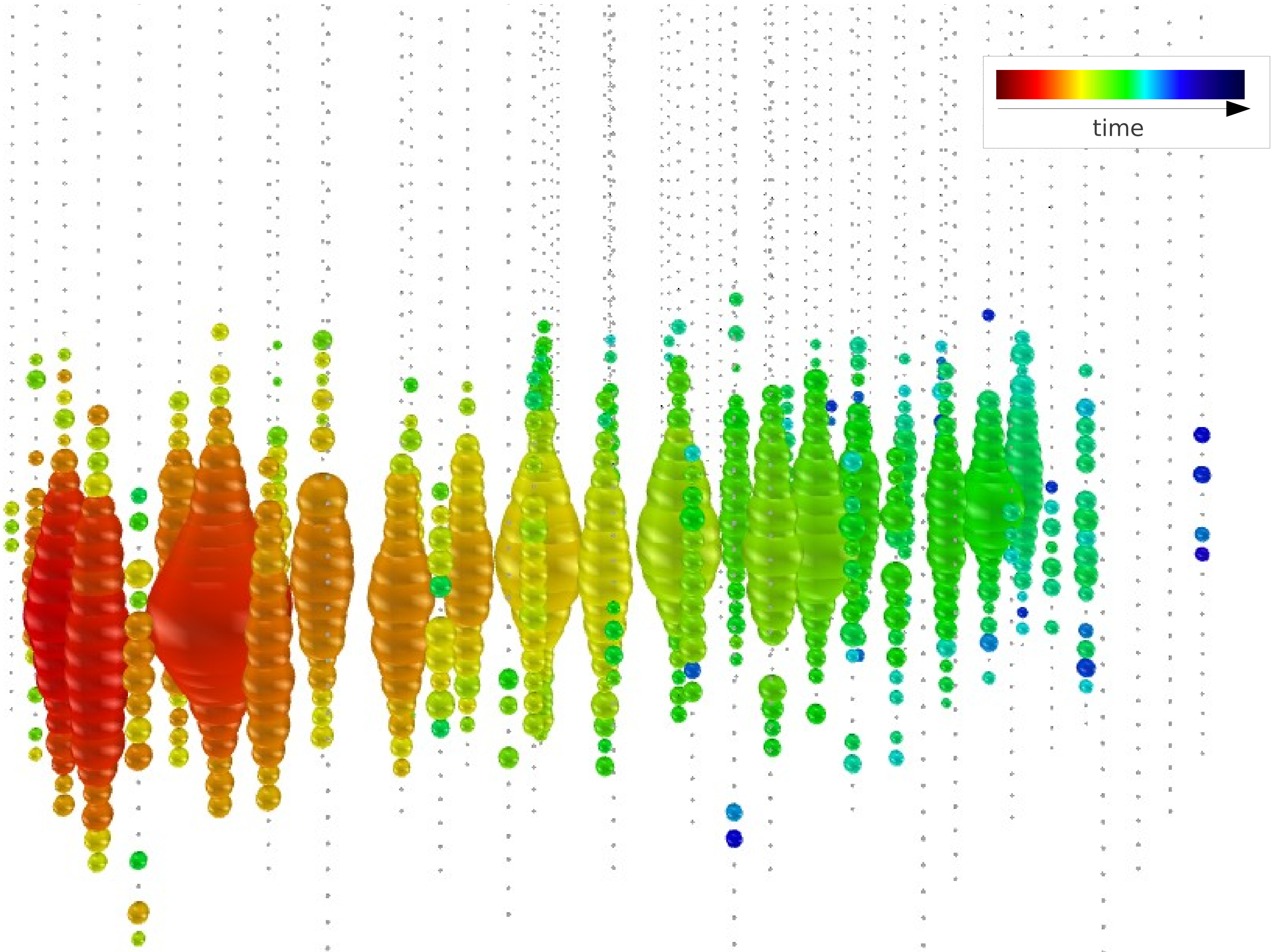


The Earth as a background shield





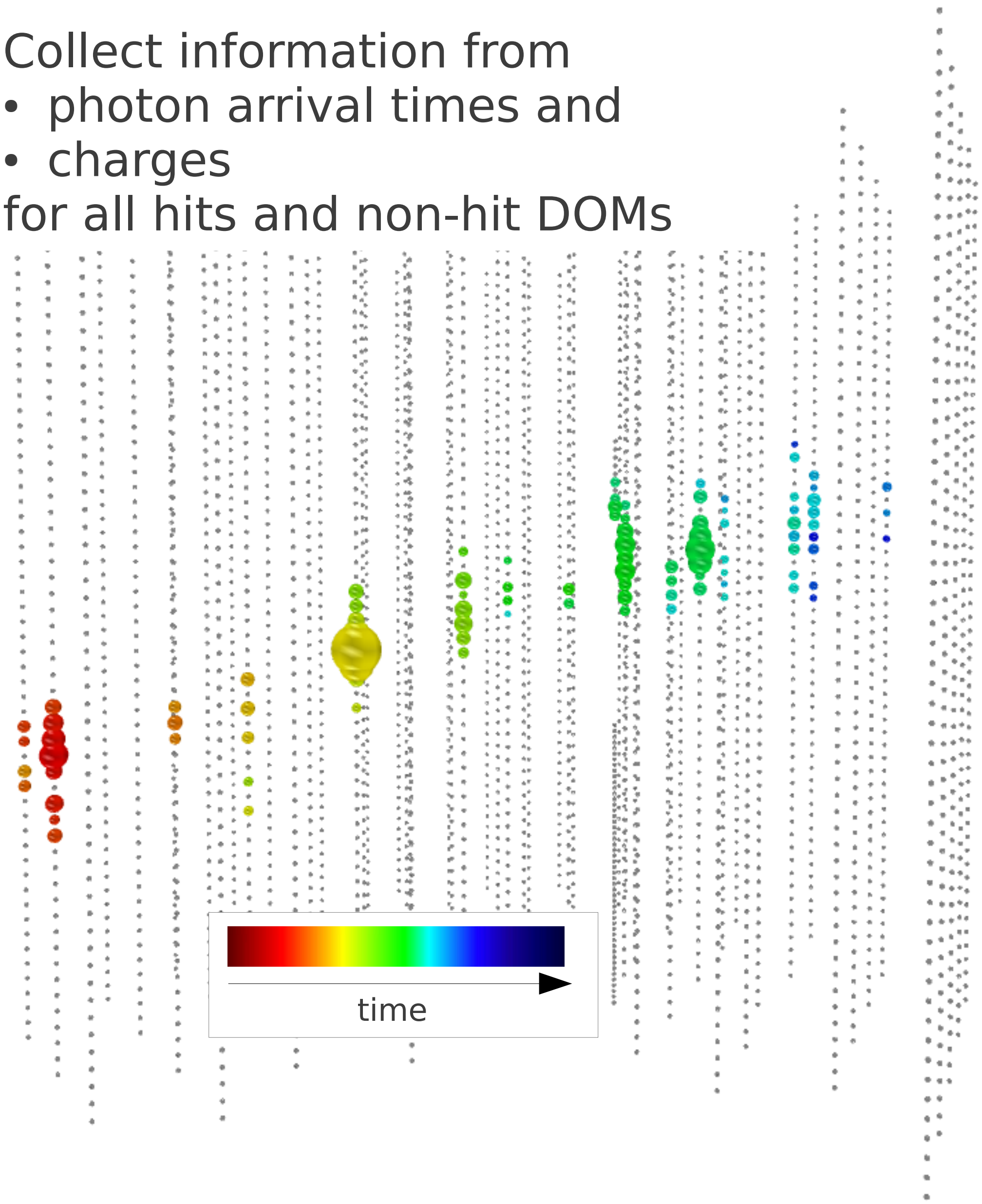
Apollon – the highest-energy ν_μ event in IC59



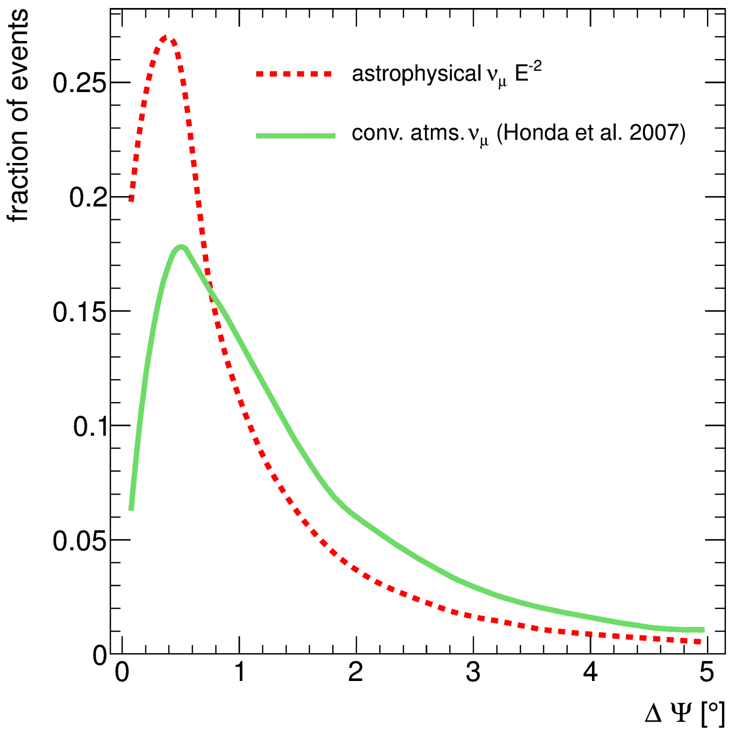
Angular reconstruction

Collect information from
- photon arrival times and
- charges

for all hits and non-hit DOMs



Angular resolution for a typical ν_μ sample

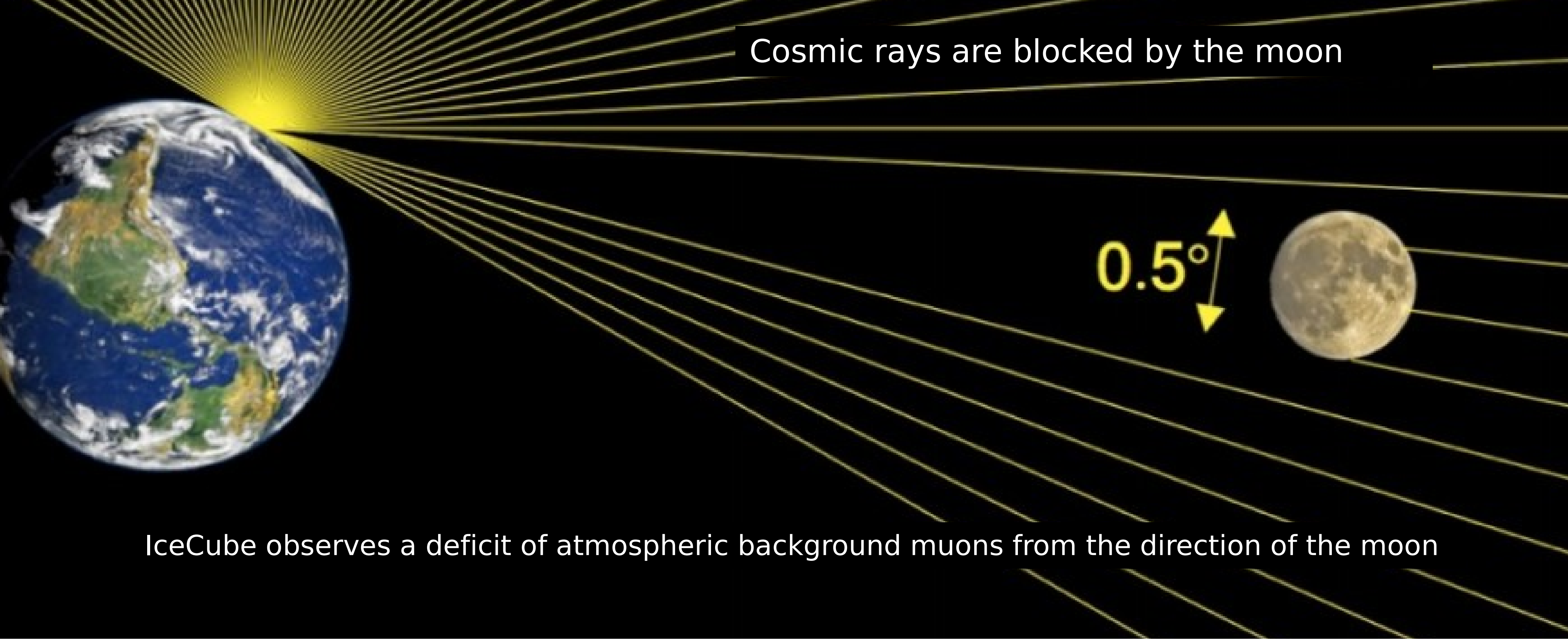


50% of the events reconstructed better than 1° for high quality tracks-like events.

For cascades:

Angular reconstruction more challenging!
Resolution of O(10°) through boost in the spherical event shape.

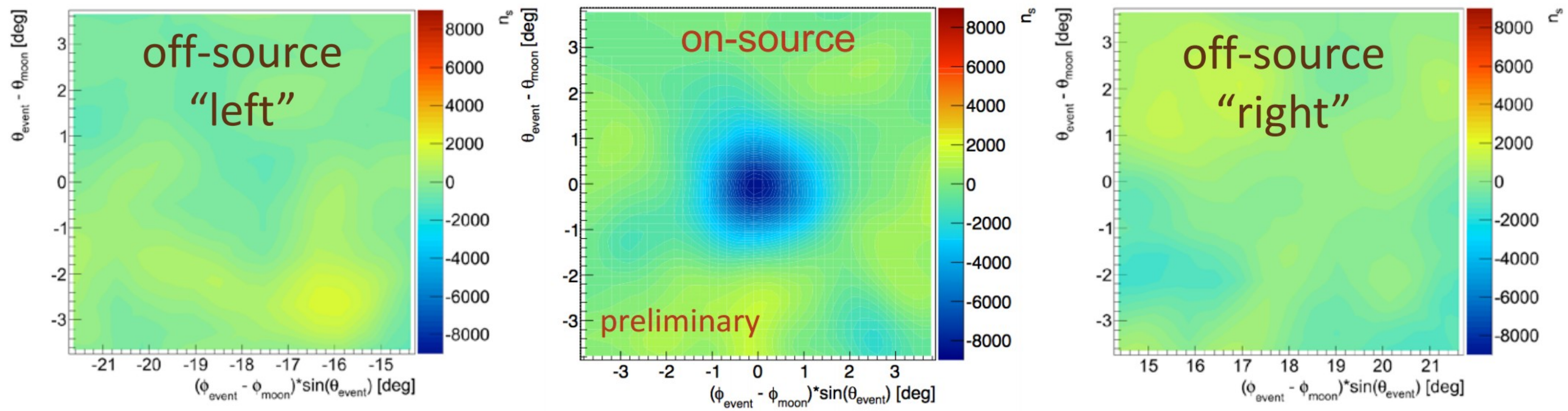
Our “standard candle”: the moon



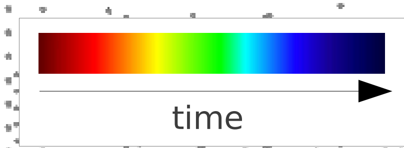
Cosmic rays are blocked by the moon

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

IC59 analysis



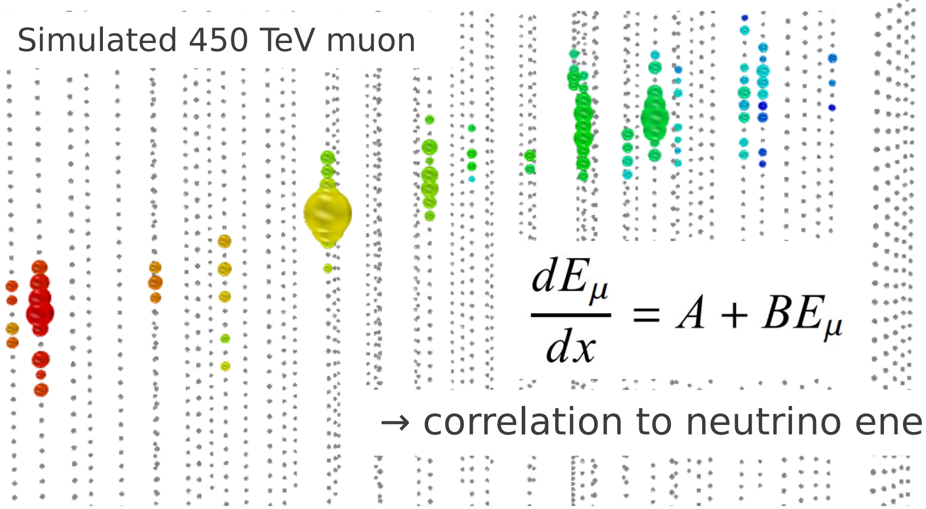
Energy reconstruction



For tracks:

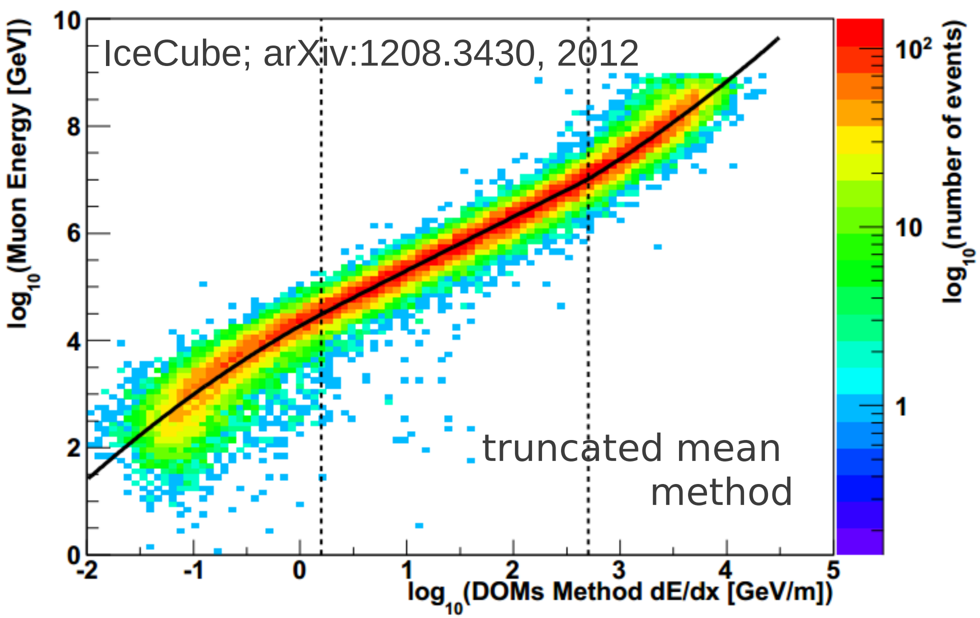
Measure the energy loss of the muon

Simulated 450 TeV muon



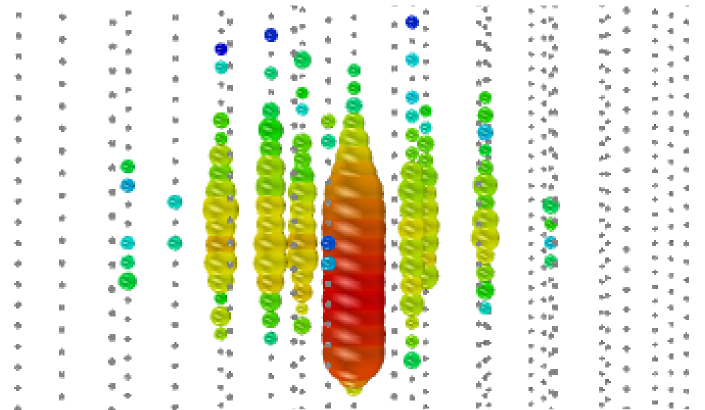
$$\frac{dE_\mu}{dx} = A + BE_\mu$$

→ correlation to neutrino energy

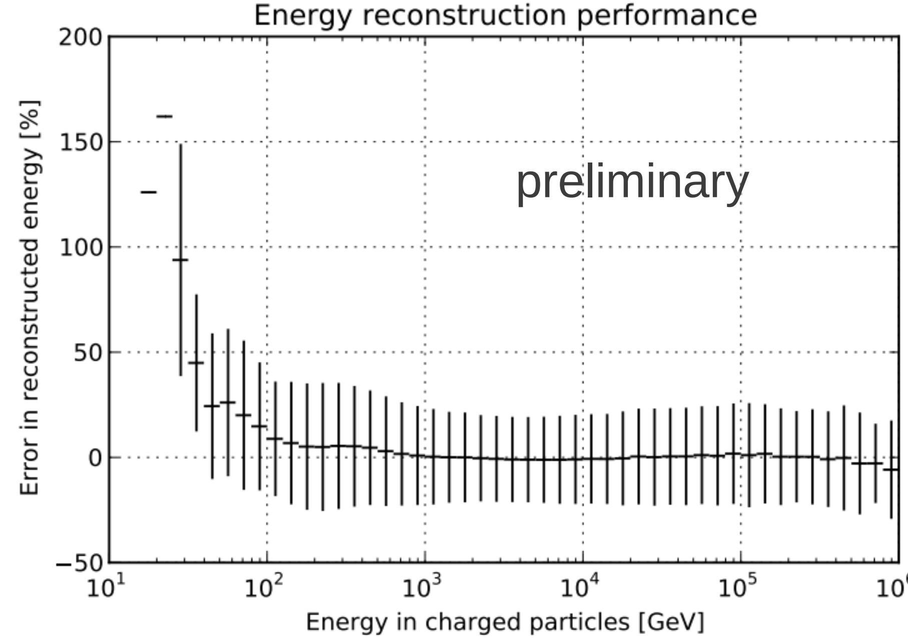


For cascades:

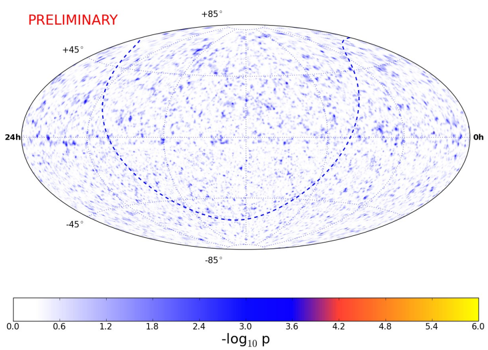
Collect all deposited light



Simulated 1 PeV electron

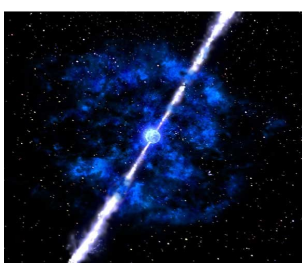


The IceCube physics program



Point source

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

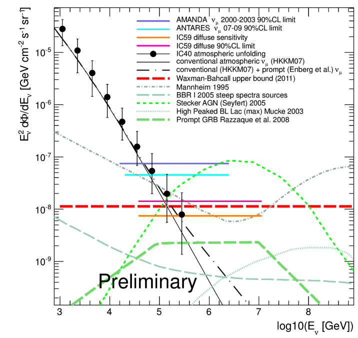


Transient sources
→ GRB, flaring objects

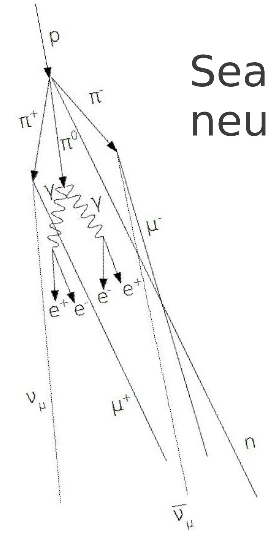
Optical follow-up programs

Dark Matter

Exotic particles

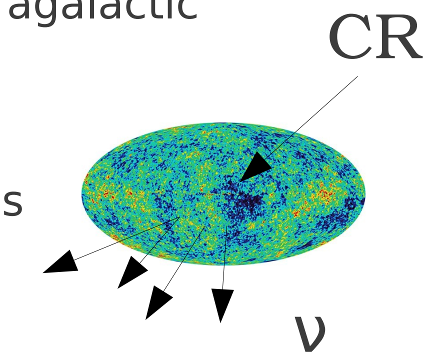


Diffuse/atmospheric



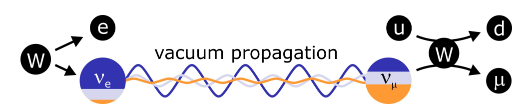
Search for an extragalactic neutrino signal

GZK neutrinos

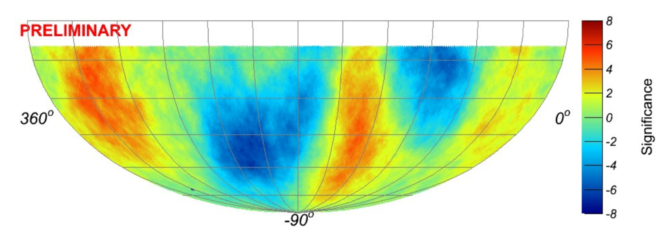


Prompt atms. neutrinos

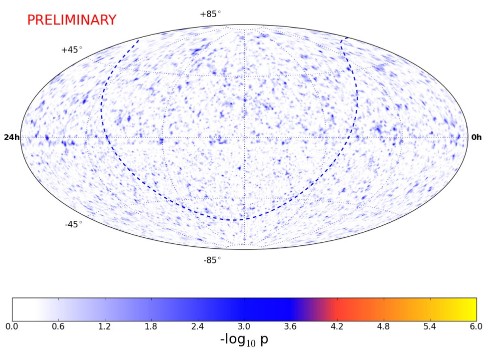
Neutrino oscillations

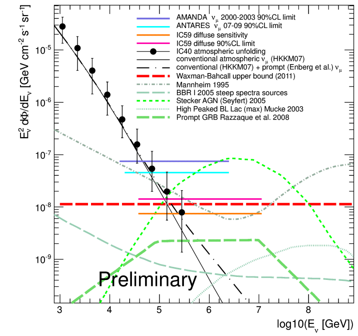


Cosmic ray physics

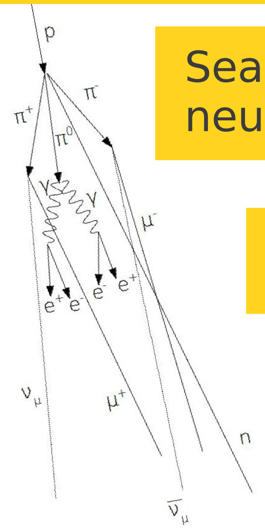


The IceCube physics program





2. Diffuse/atmospheric



Search for an extragalactic neutrino signal

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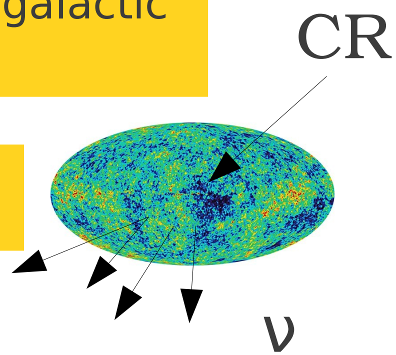

Prompt atms. neutrinos

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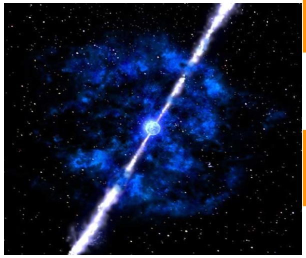
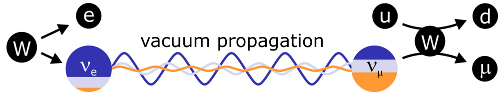


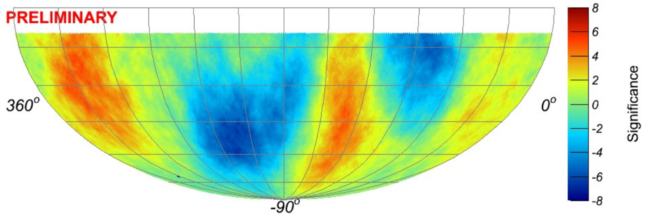
Transient sources
→ GRB, flaring objects

Optical follow-up programs

3. Neutrino oscillations



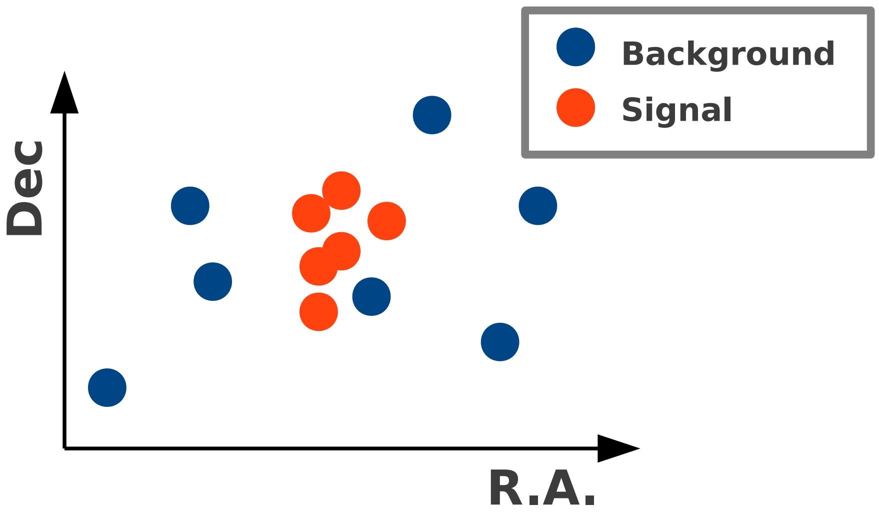
Cosmic ray physics

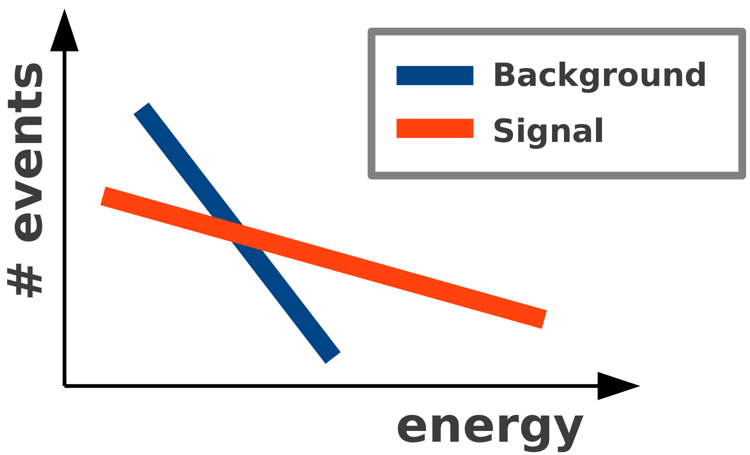


Dark Matter

Exotic particles

Point-source all-sky scan



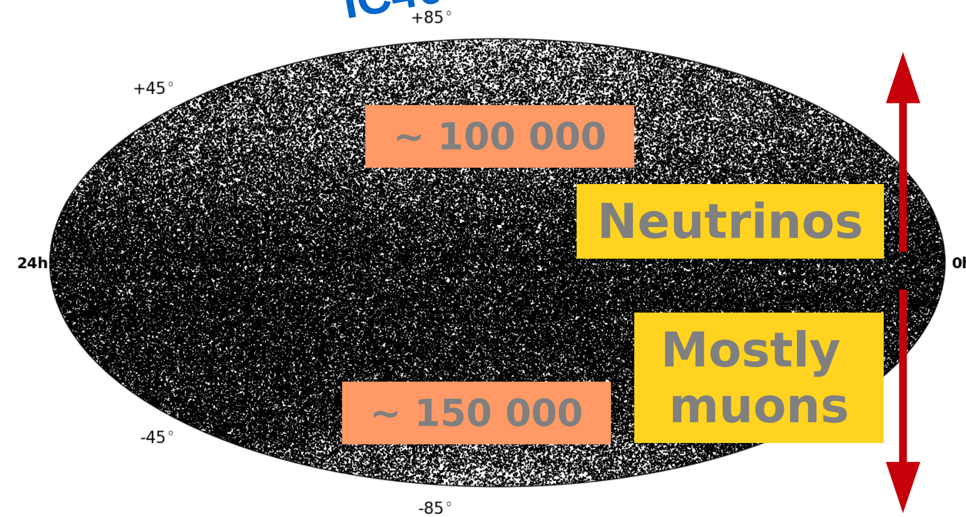


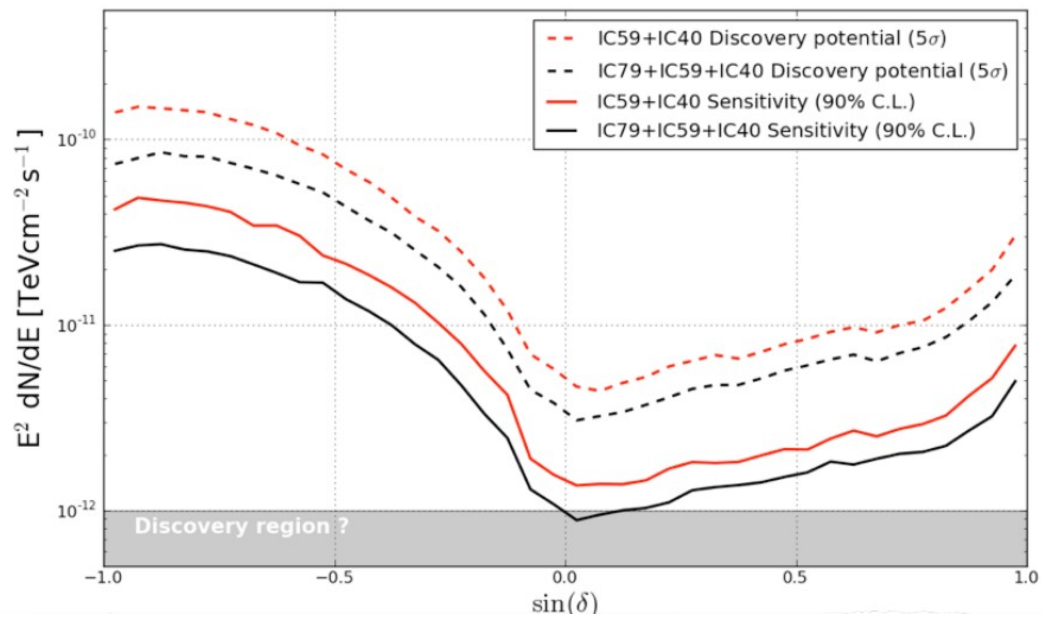
Unbinned likelihood analysis using energy and angular information

Combined search with 3years of data
April 2008 – May 2011

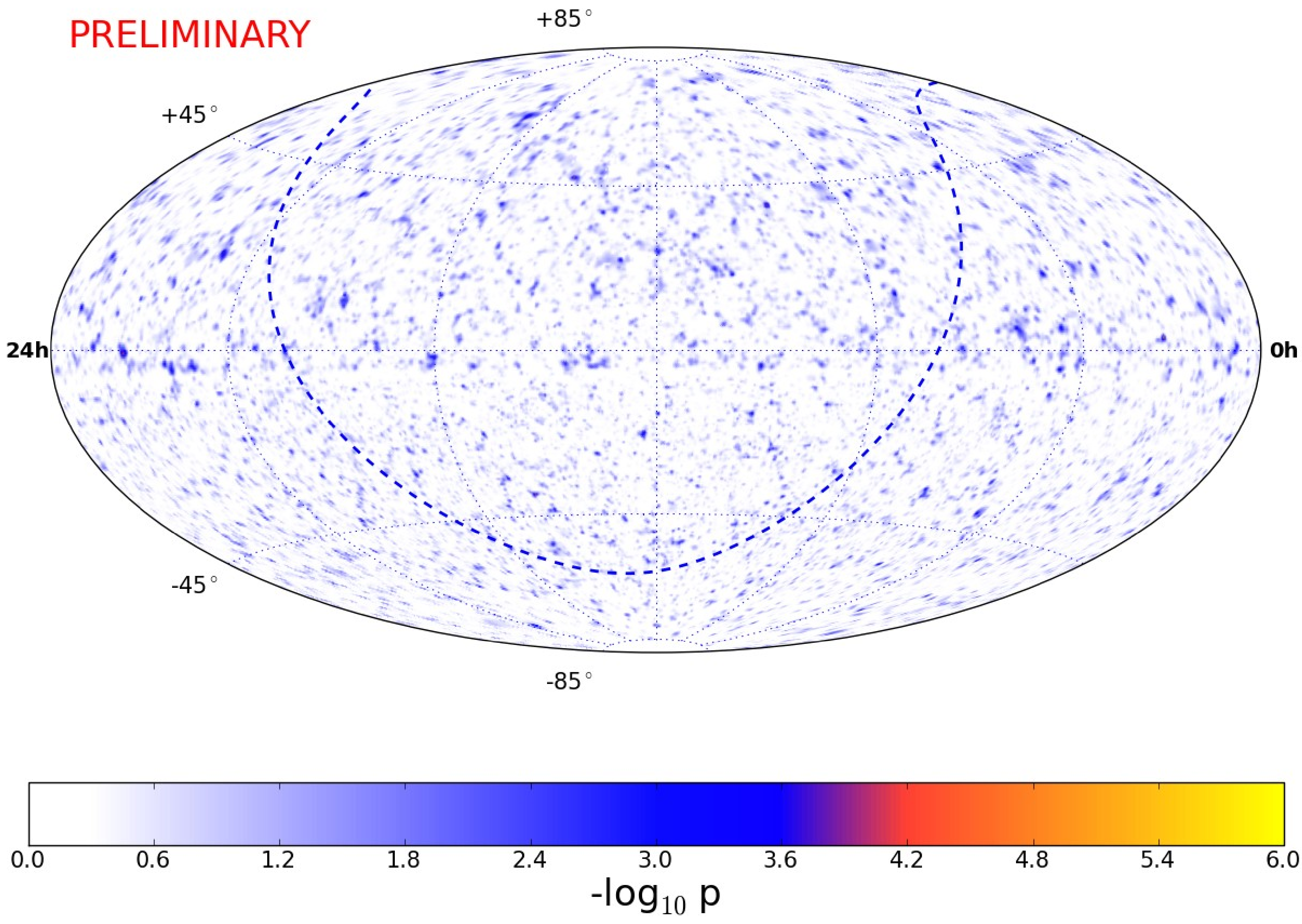
PRELIMINARY

Detector configurations:
IC40 + IC59 + IC79

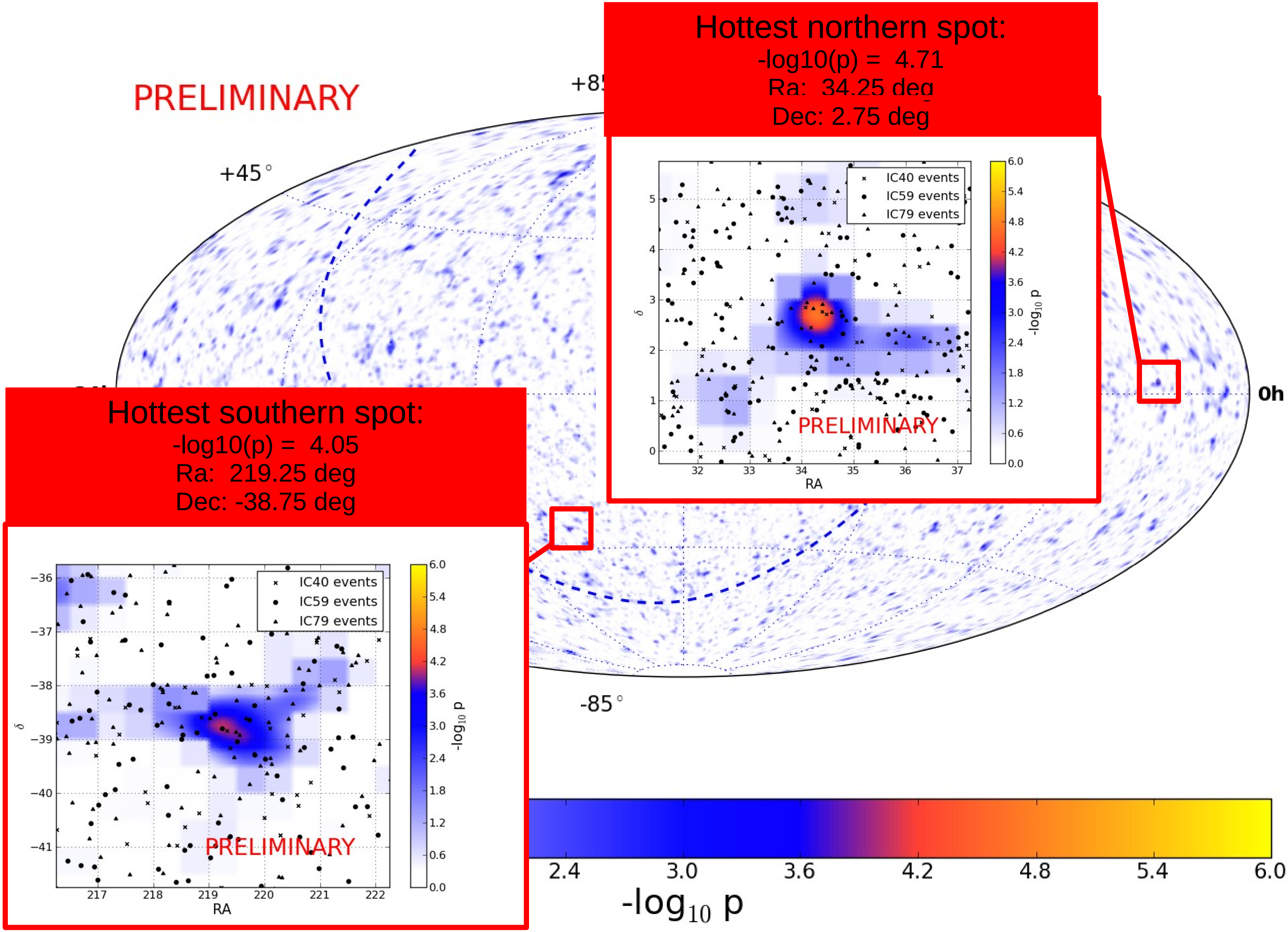




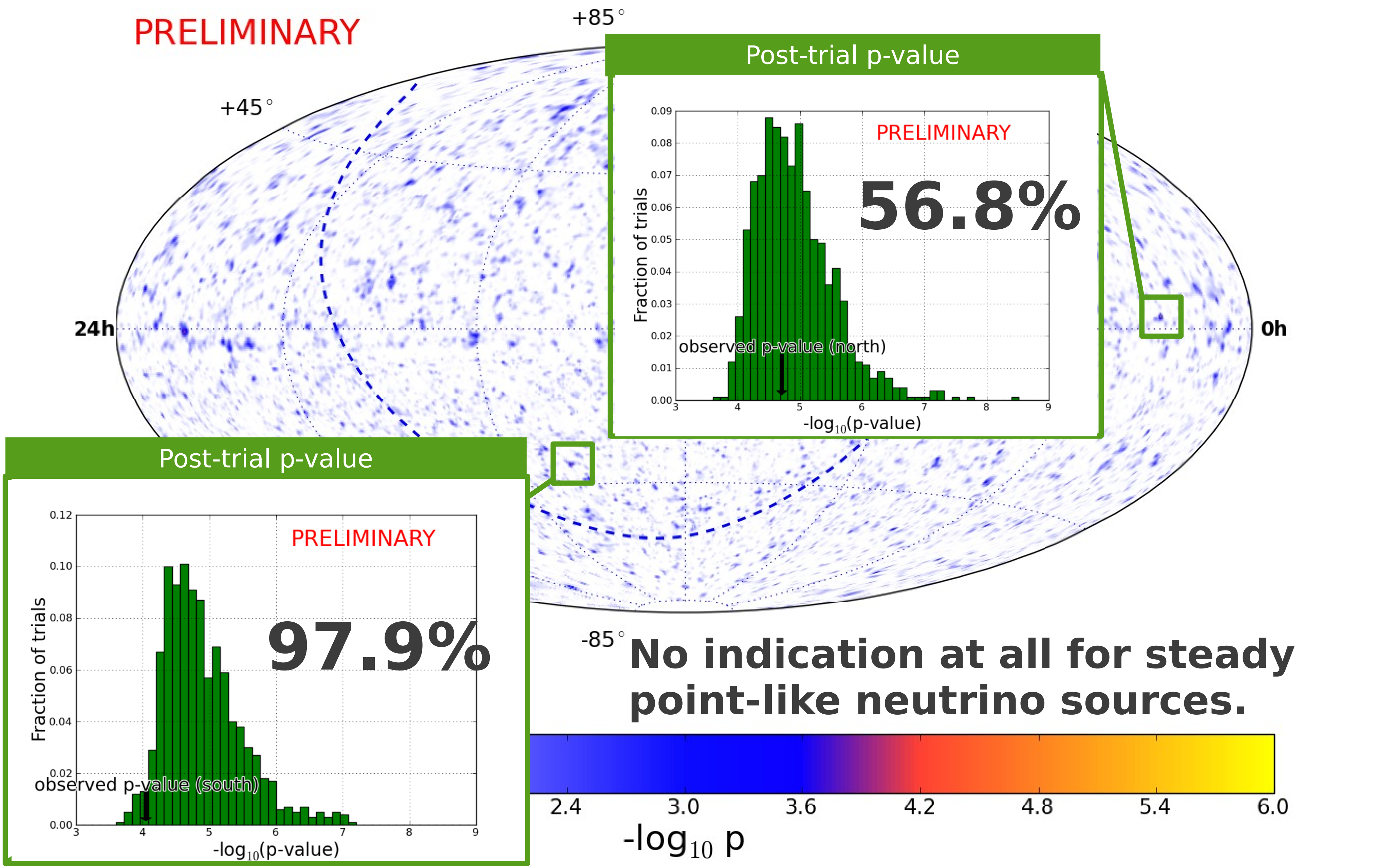
IC40+IC59+IC79 point source results



IC40+IC59+IC79 point source results



IC40+IC59+IC79 point source results



No indication at all for steady point-like neutrino sources.

Gamma ray bursts as sources of cosmic rays?

GRBs could be responsible for the entire extragalactic CR flux

~ 500 – 1000 bursts per year

Neutrino production in p-γ interactions

Signal events

Transient sources (e.g. GRB)

Steady point sources (e.g. AGN, SNR, ...)

Background events

TeV γ-rays

$$p + \gamma \rightarrow \pi^0 + p$$

$$\rightarrow \gamma + \gamma + p$$

Cosmic rays?

$$\rightarrow \pi^+ + n$$

TeV neutrinos?

$$\rightarrow \mu^+ + \nu_\mu + p$$

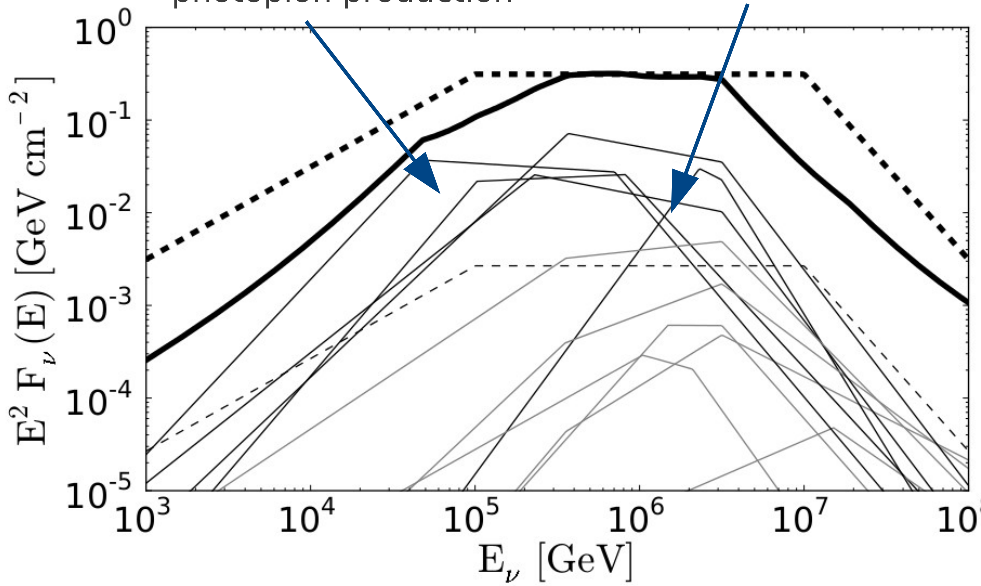
$$\rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu + p$$

2. Break

Onset of synchrotron radiation for muons and pions

1. Break

Threshold for photopion production



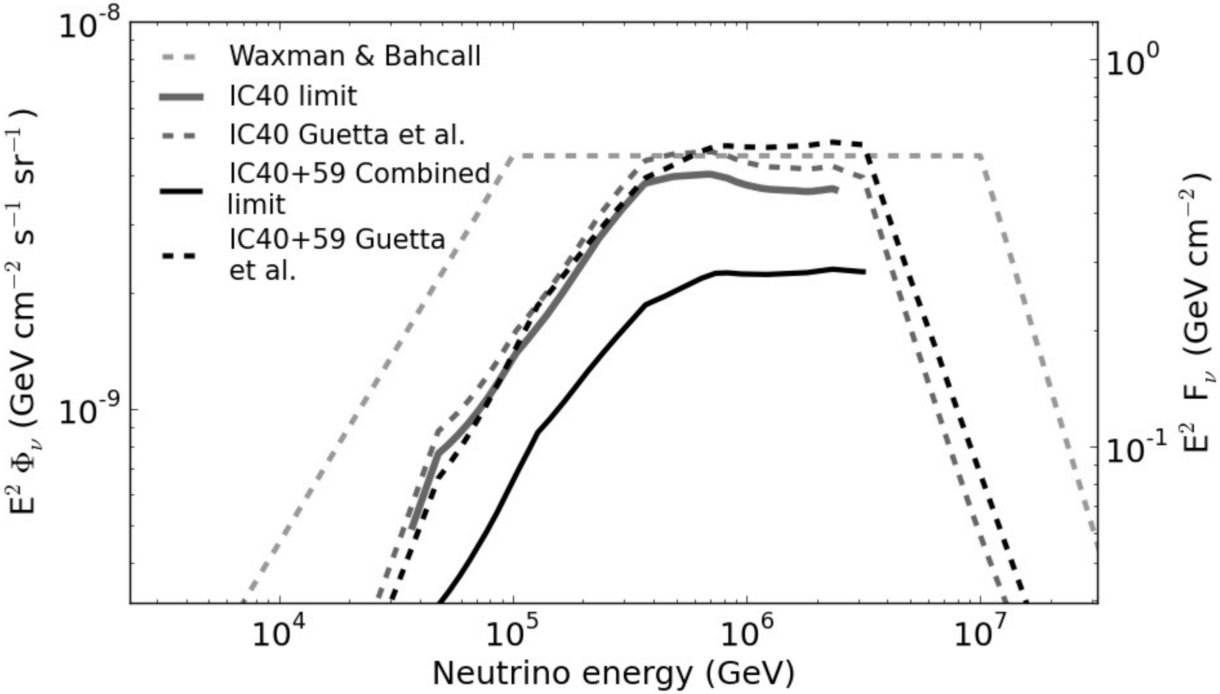
Searches for νs from GRB – model dependent

Model-Dependent Analysis:

Look for a correlation of neutrinos with gamma ray burtsts assuming per-burst spectra from γ observations

Live during window of maximum gamma emission (T90 ≈ 30 s)

→ no correlation found.



Model assumptions:

Waxman-Bahcall: GRBs are the sources of extragalactic cosmic rays. Proton shock acceleration, production of gamma rays and neutrinos. Normalization to cosmic-ray flux.

Magnetic Confinement Models: GRBs are the sources of extragalactic cosmic rays. Protons trapped by magnetic fields – escape as neutrons (Rachen et al. 1998, Ahlers et al. 2011).

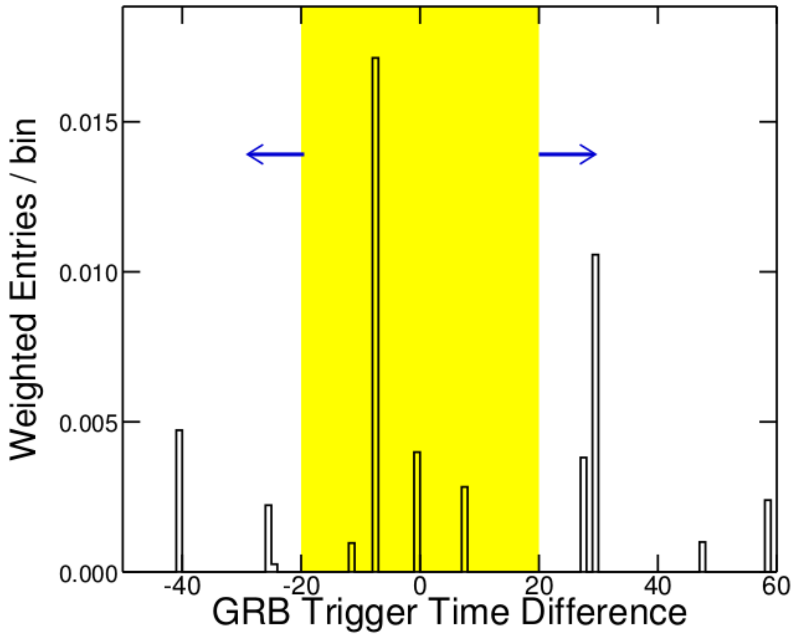
Non-Cosmic Ray Models: Fixed fraction of total GRB energy transferred to protons, which do not necessarily escape (Guetta et al. 2004, Huemmer et al. 2012).

Searches for νs from GRB – model independent

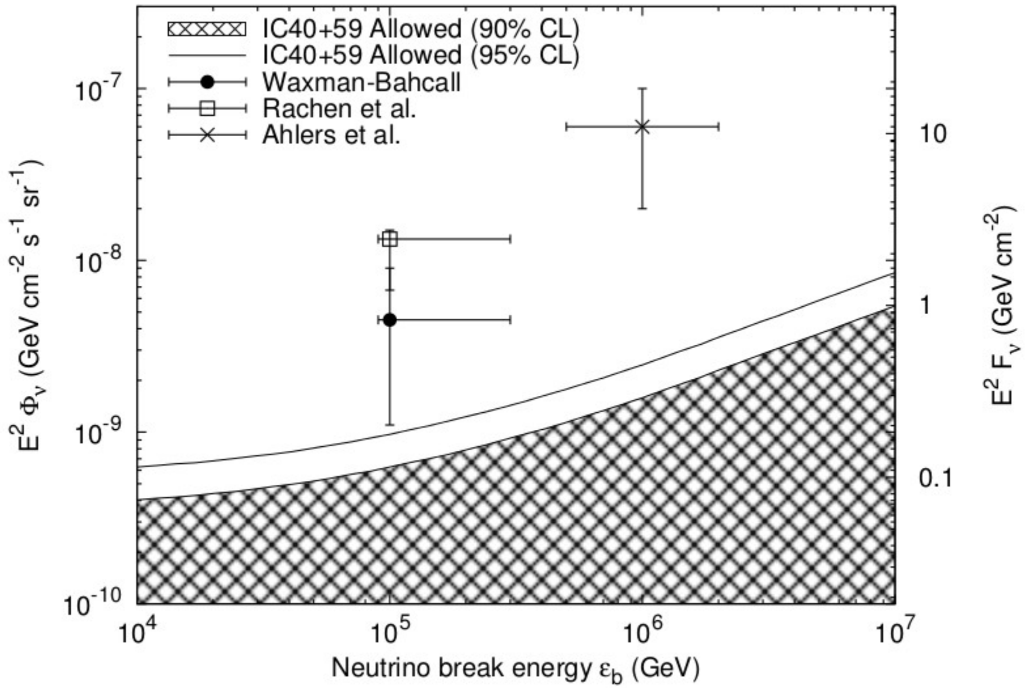
Model-Independent Analysis:

Search for neutrinos in all energy bands in timely correlation with GRB

Wide time window from +/- 10s to +/- 1 day



→ no correlation found.



Nature 484 (2012), arXiv:1204.4219

Limits are cutting hard into the favored parameter space of theoretical models.

Summary point source searches

We have searches for all kinds of point-like neutrino sources:

All-sky search, stacking searches, transient searches, …

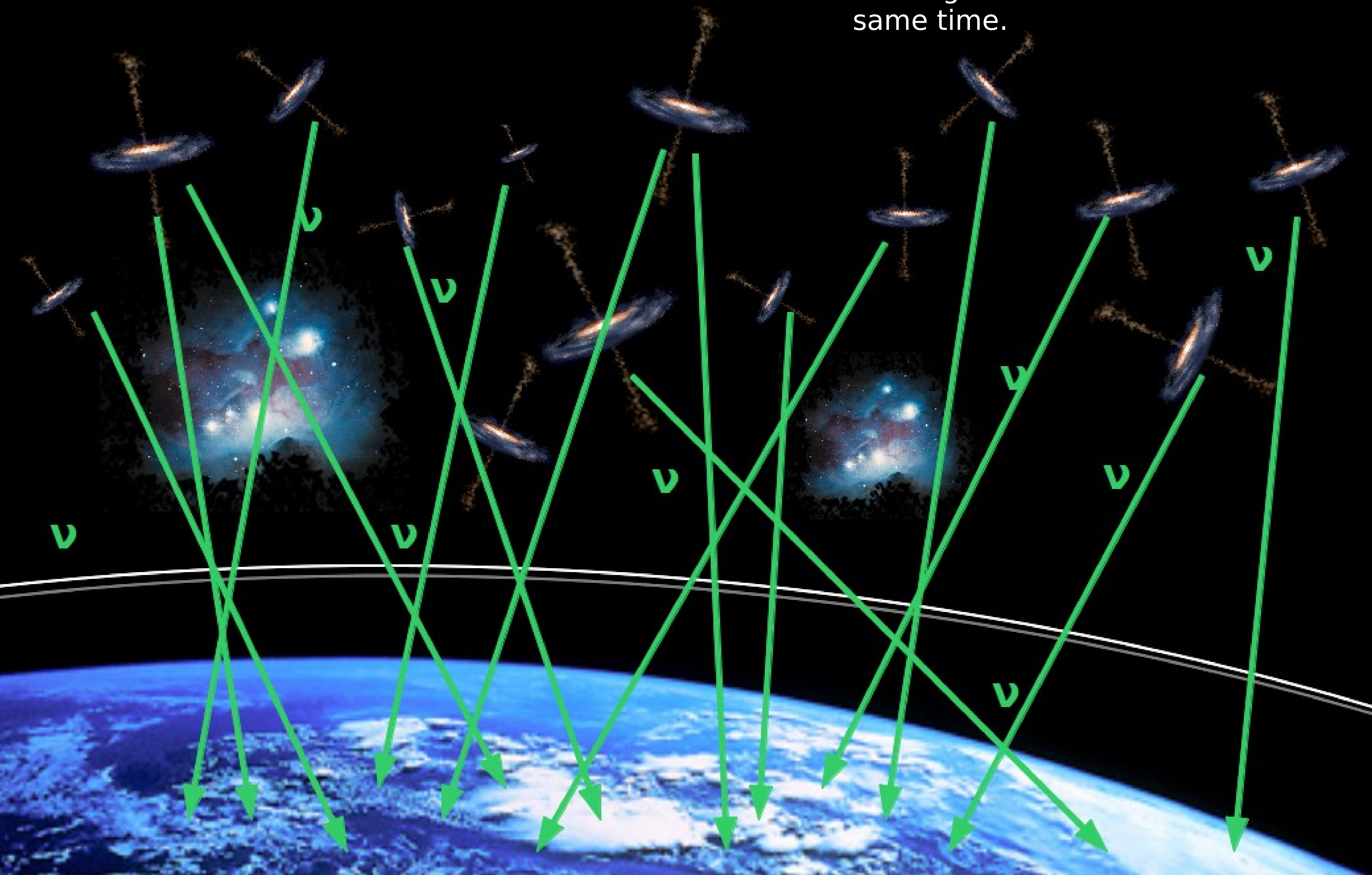
→ No event clustering found in IC22 – IC79 searches

→ No hint on extraterrestrial point-like neutrino sources, yet.

… let's look for diffuse fluxes!

What is a diffuse search?

Looking into all directions at the same time.



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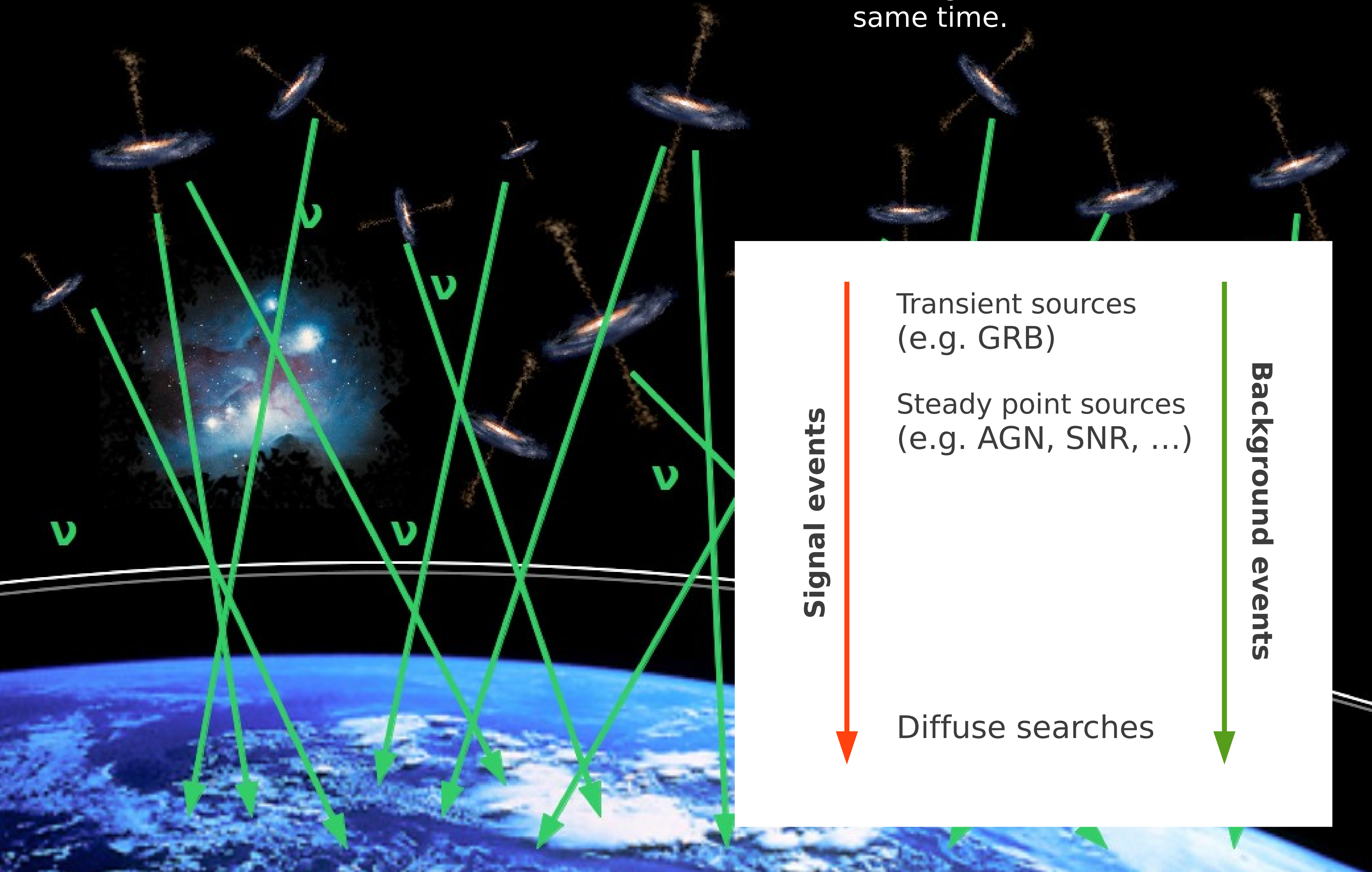
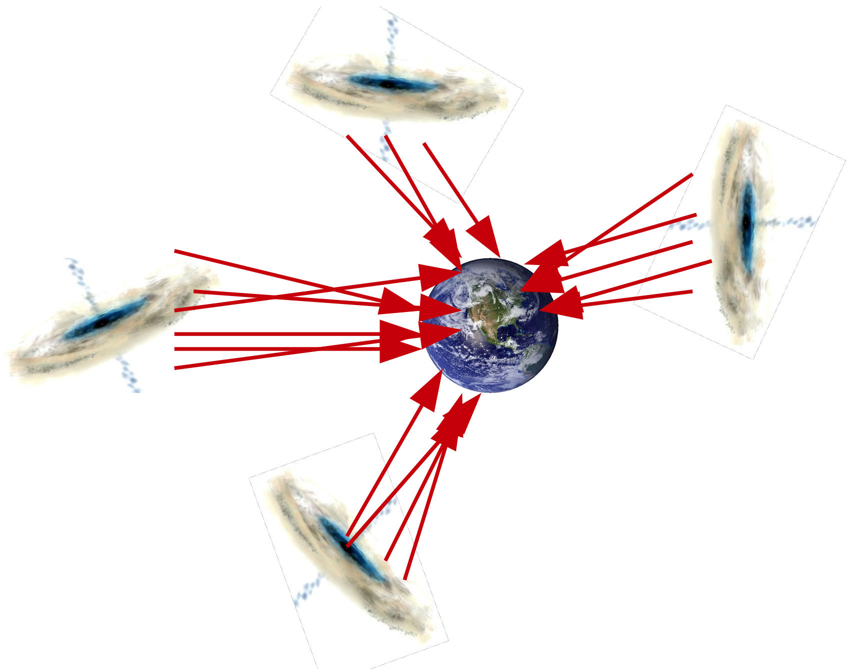
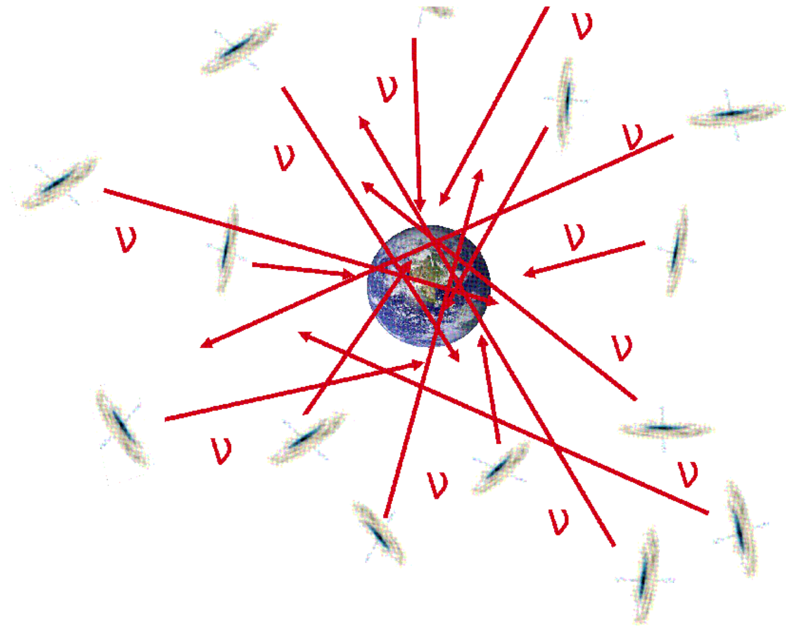


Why diffuse?





Point source search

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

More promising for

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

Diffuse search

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

More promising for

- abundant extragalactic sources (e.g. AGN)

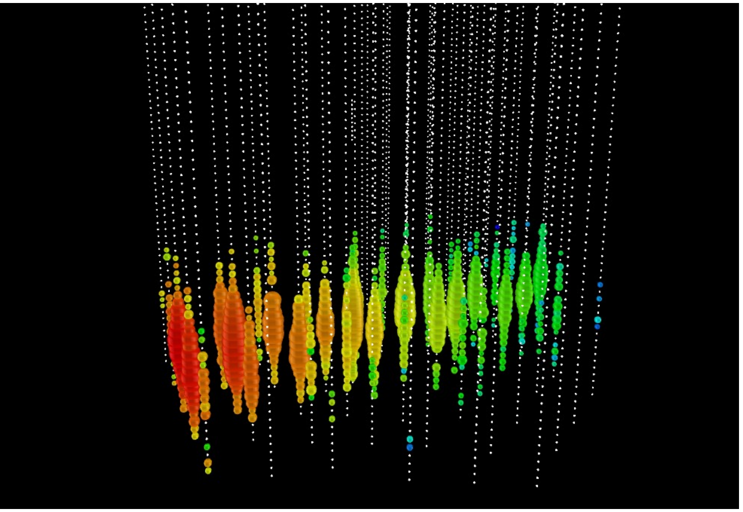
An extragalactic neutrino flux could be detected even if the individual source flux is below the detection threshold!

Three recent diffuse searches

Complementary!

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

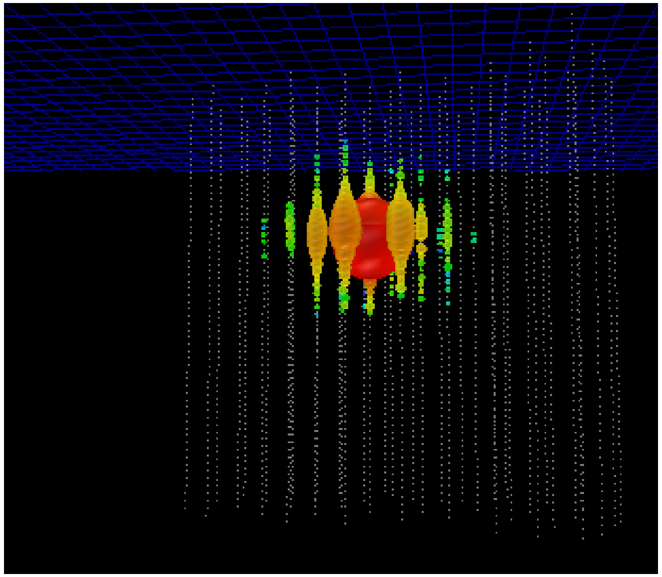
IC59 ν_μ



May 2009 – May 2010

IC40

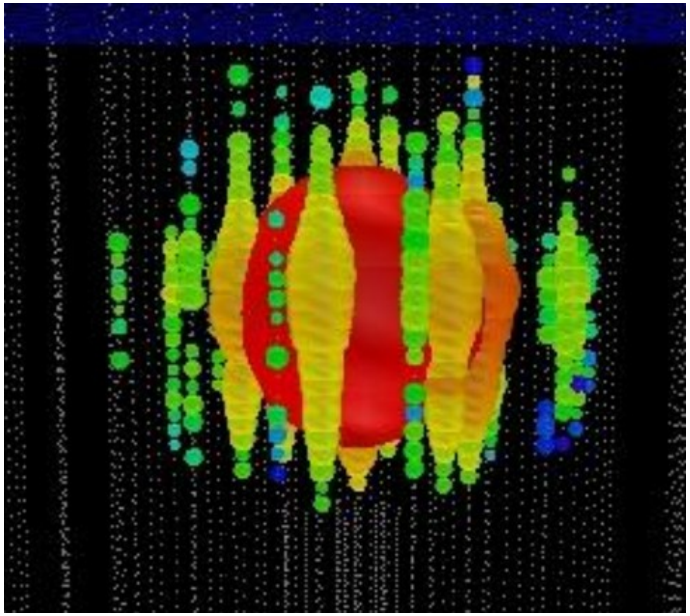
casacades



April 2008 – May 2009

IC79+IC86

Extremely high-energy cascades



June 2010 – May 2012

The signature of a diffuse astrophysical flux

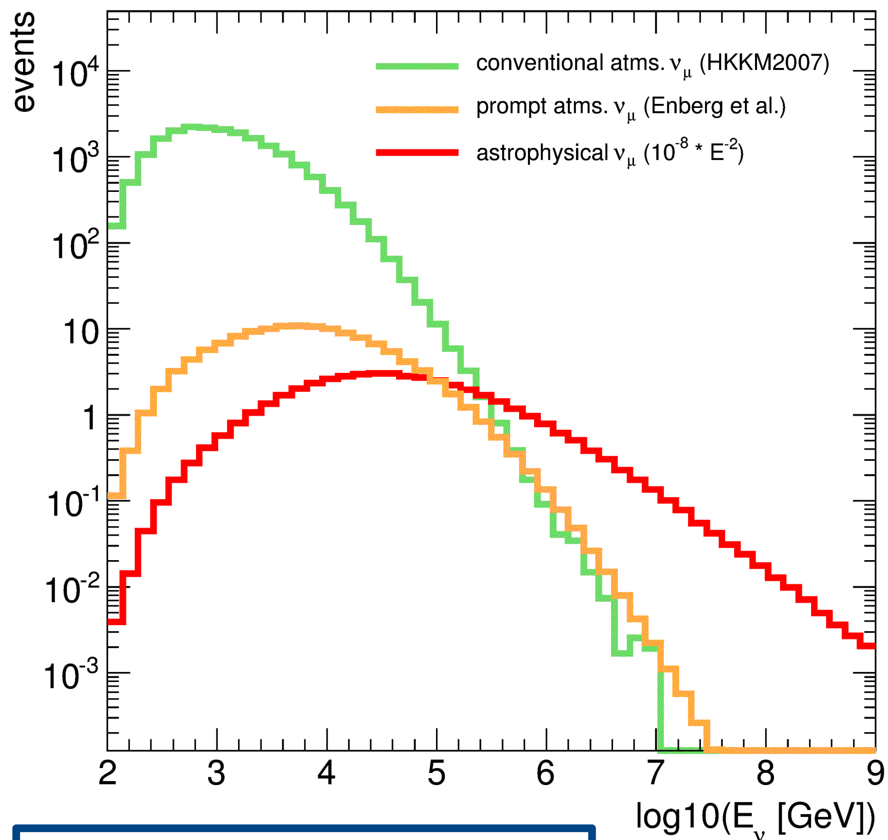
What we expect in the IC59 data sample:

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

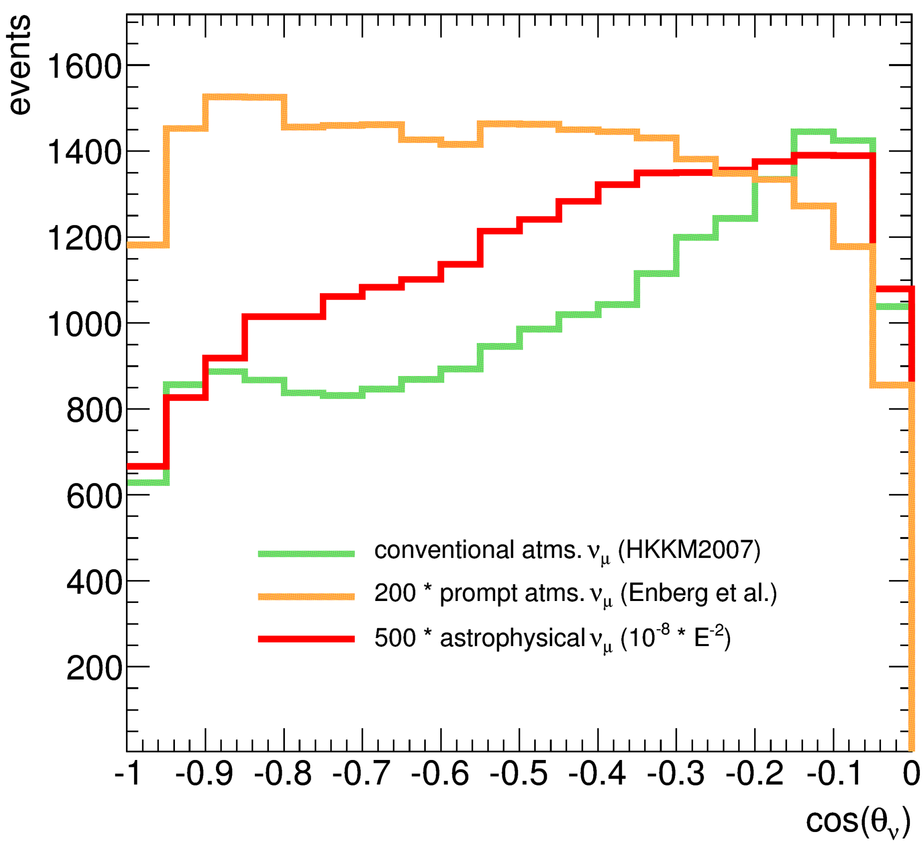
~ 70 prompt neutrinos (Enberg et al.)

< 40 astrophysical ν_μ (Waxman-Bahcall)

Energy distribution



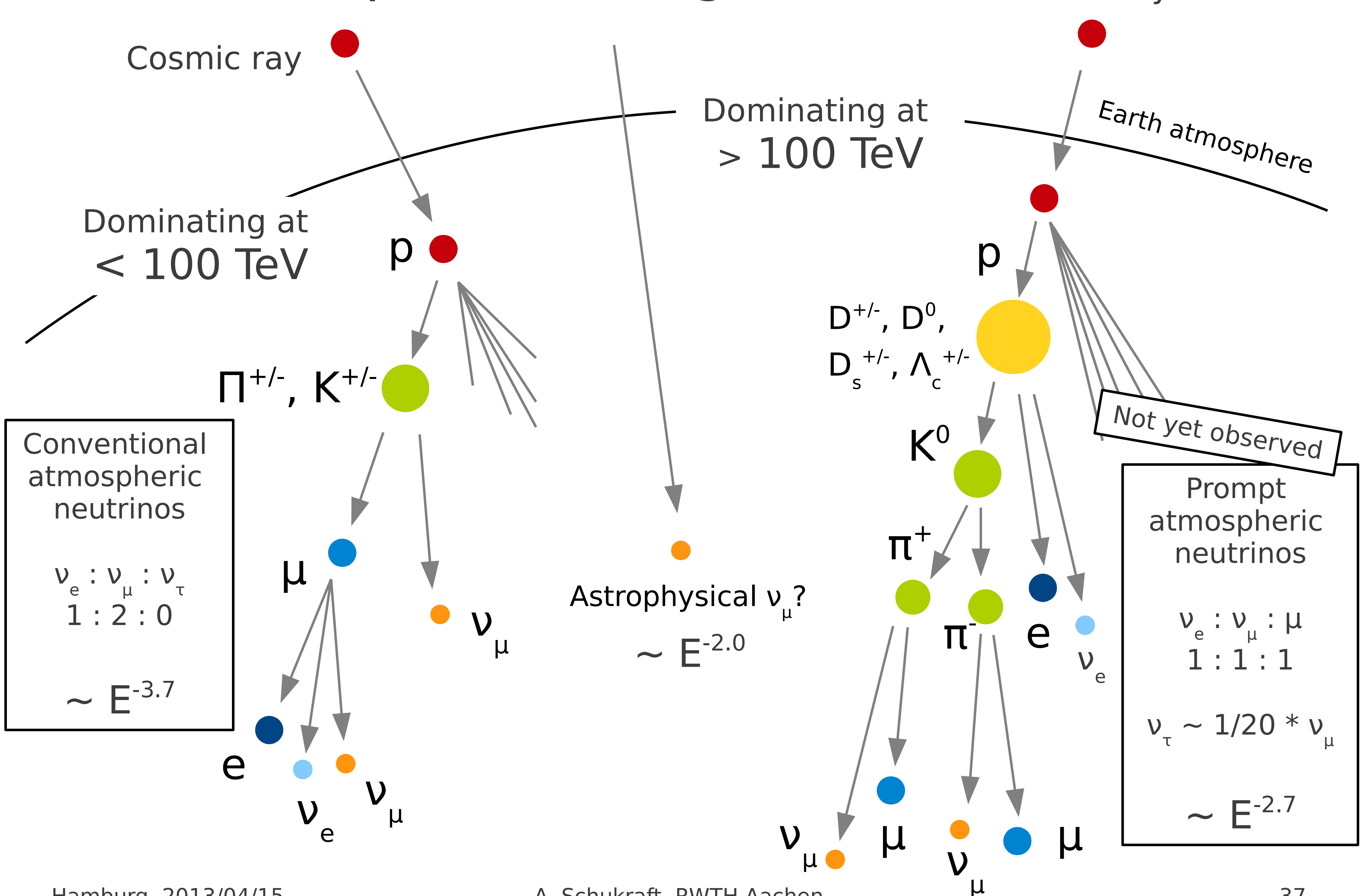
Zenith angle distribution



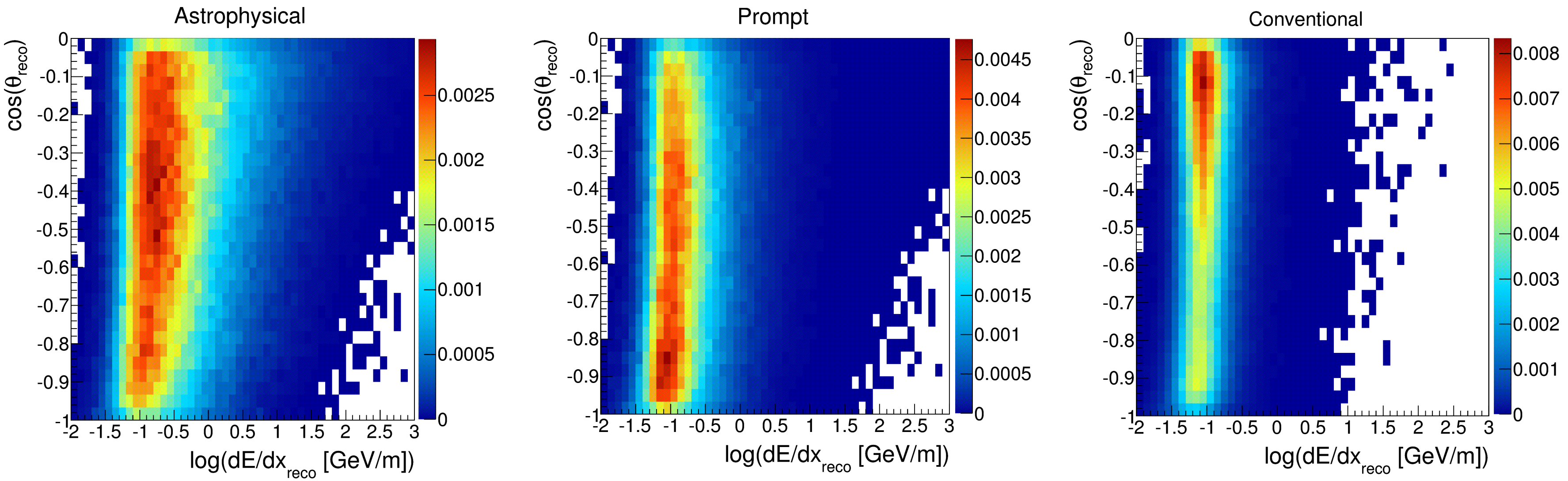
(including absorption in the Earth and detector acceptance)

~ 30 μ background (<0.2% contamination!)

The atmospheric background



The analysis method



→ 2-dim global fit

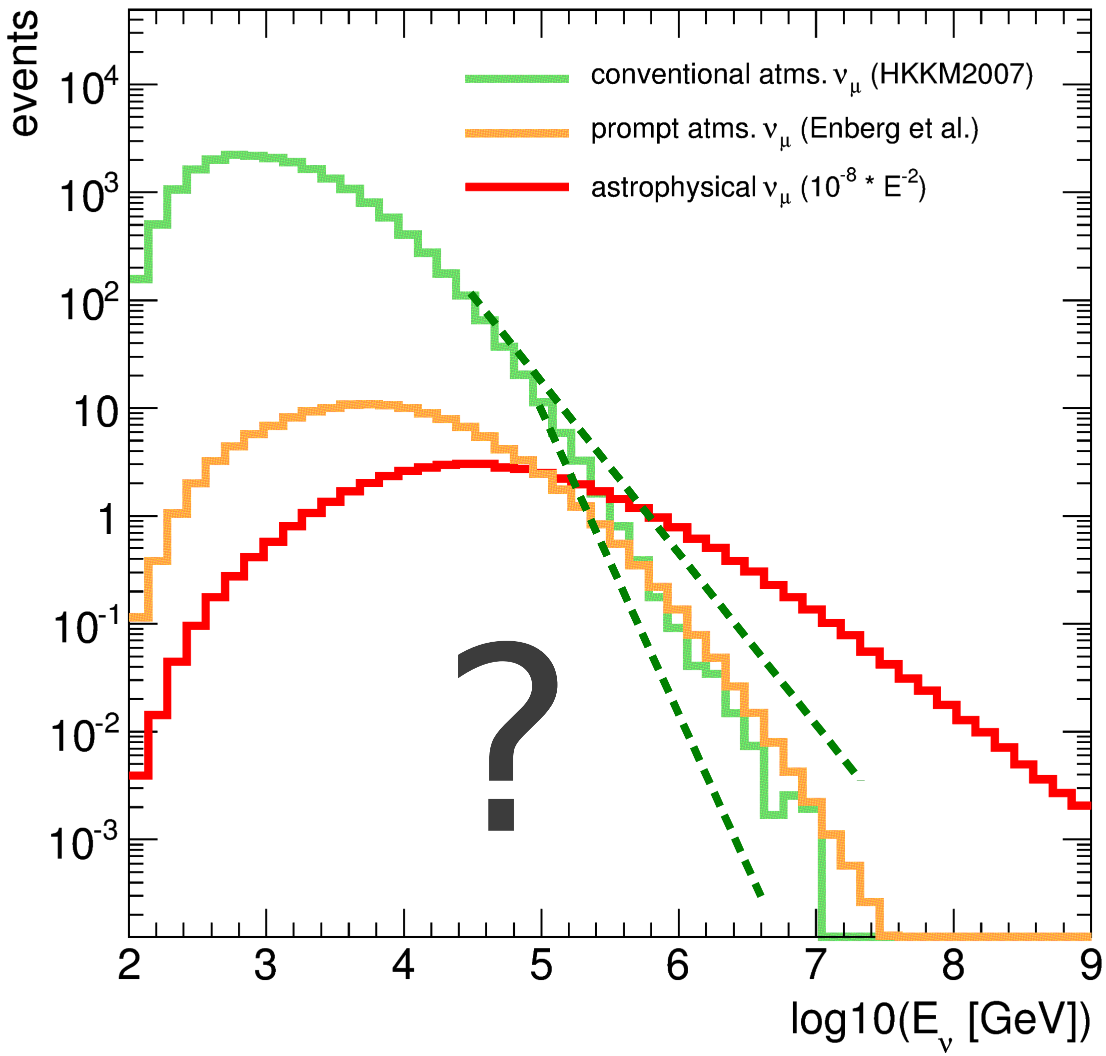
→ Taking full advantage of energy and zenith angle information (sensitive to the shapes of distributions!)

→ 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

The challenge: systematic uncertainties



Systematic uncertainties affect the shape of signal and background distributions

Detection uncertainties:

- Optical ice properties at South Pole
- Optical efficiency of sensors
- Neutrino interaction cross sections
- Muon energy loss cross sections

Atmospheric neutrino prediction uncertainties:

- Rate, shape and composition of the primary cosmic ray spectrum
- Pion-Kaon ratio in air showers

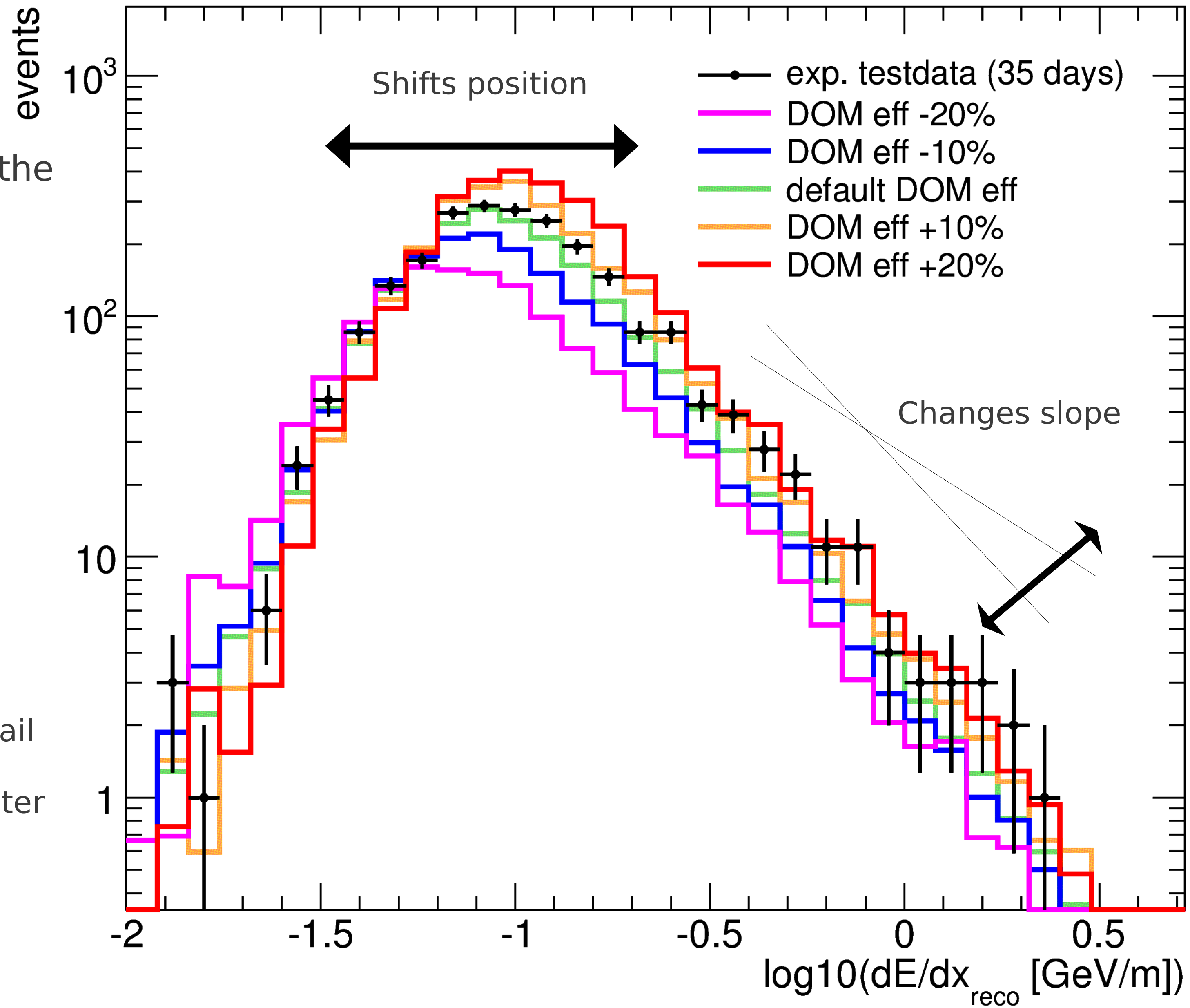
Example: Optical efficiency

Relative uncertainty of the optical efficiency composes of:

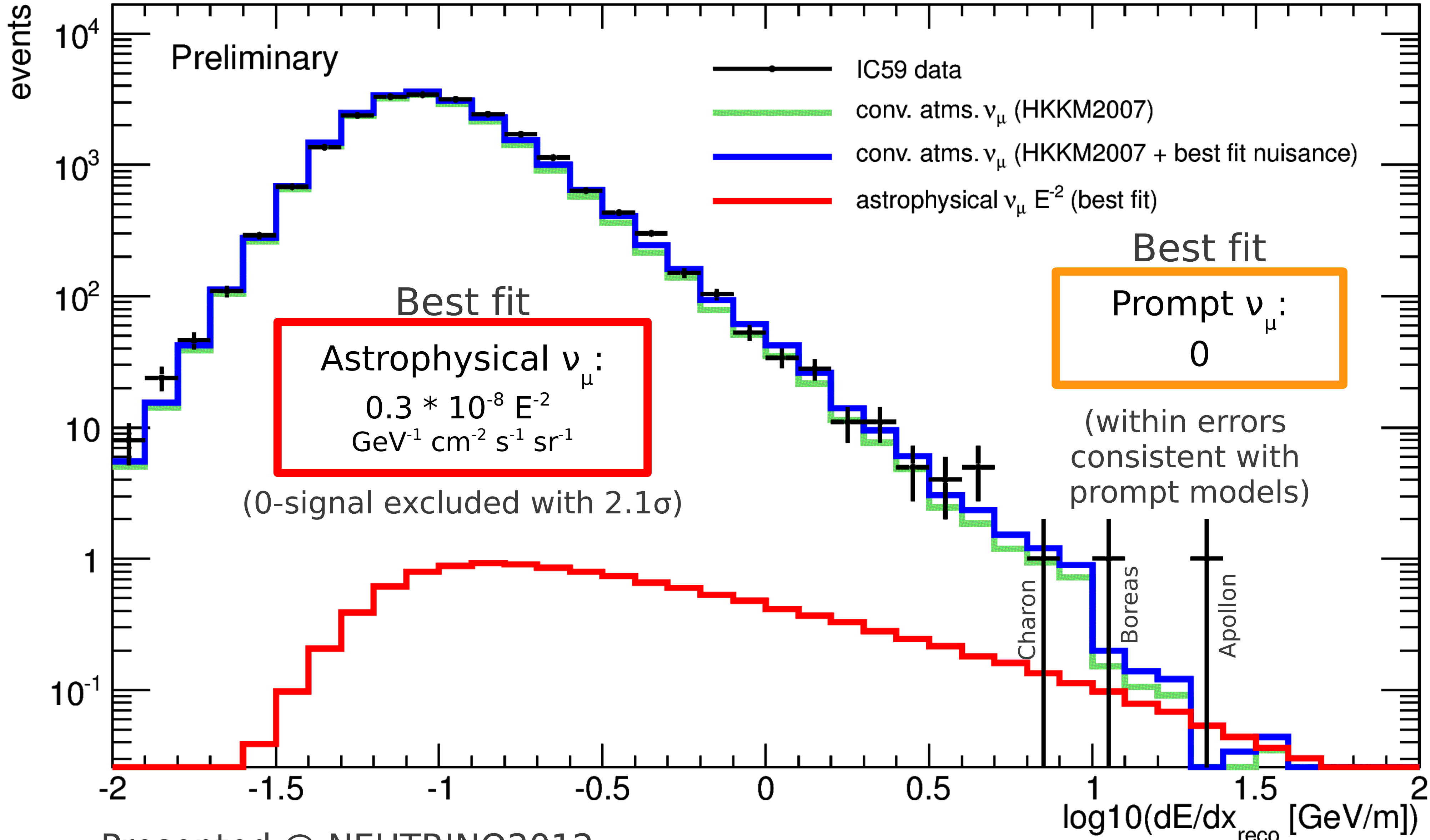
- Photon light yield
- Absolute PMT efficiency
- Cable and metal grid shadowing
- Global ice transparency

Total uncertainty: O(15%)

Affects event rates in the tail of the energy distribution
→ free fit nuisance parameter

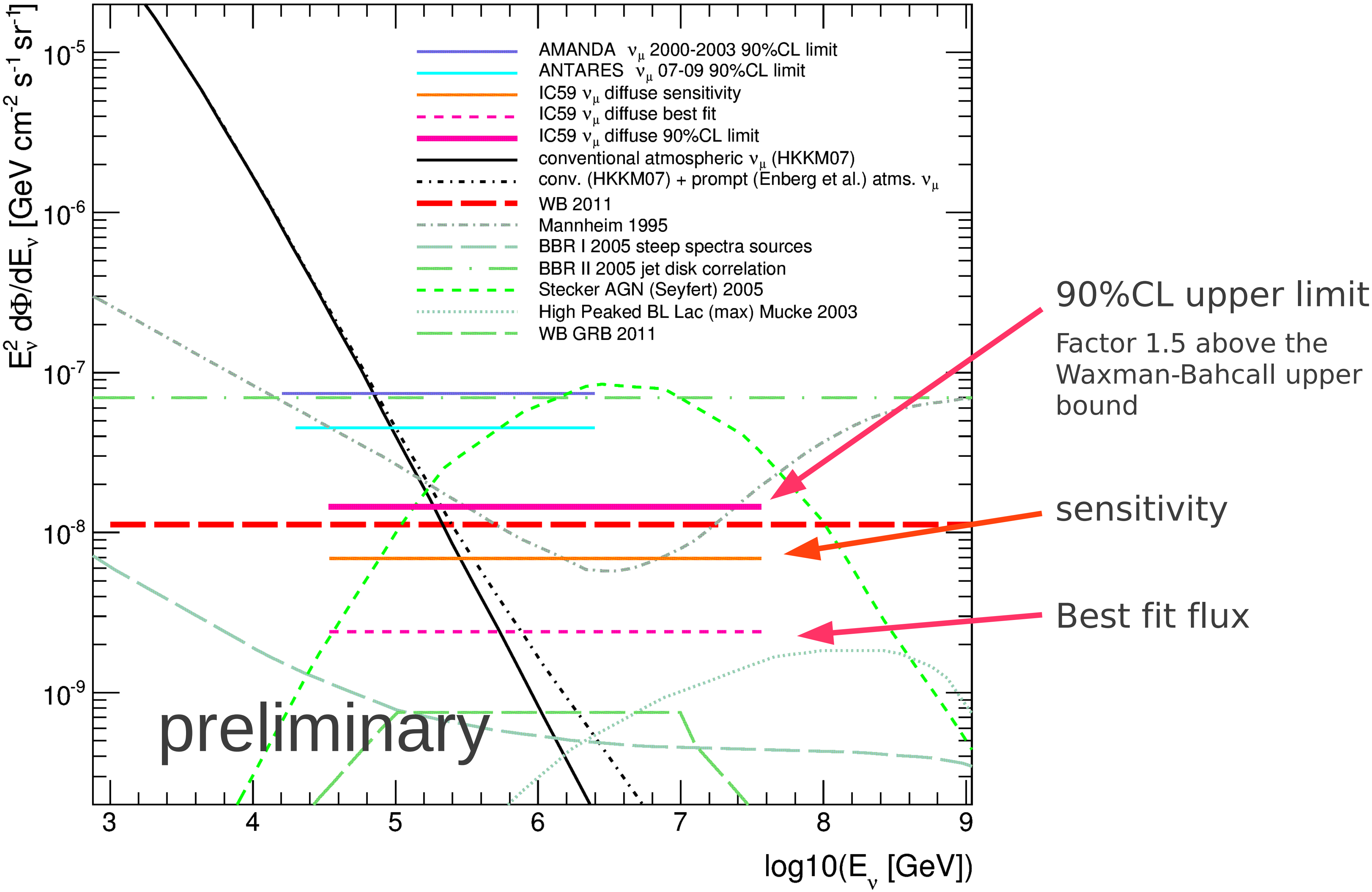


Results

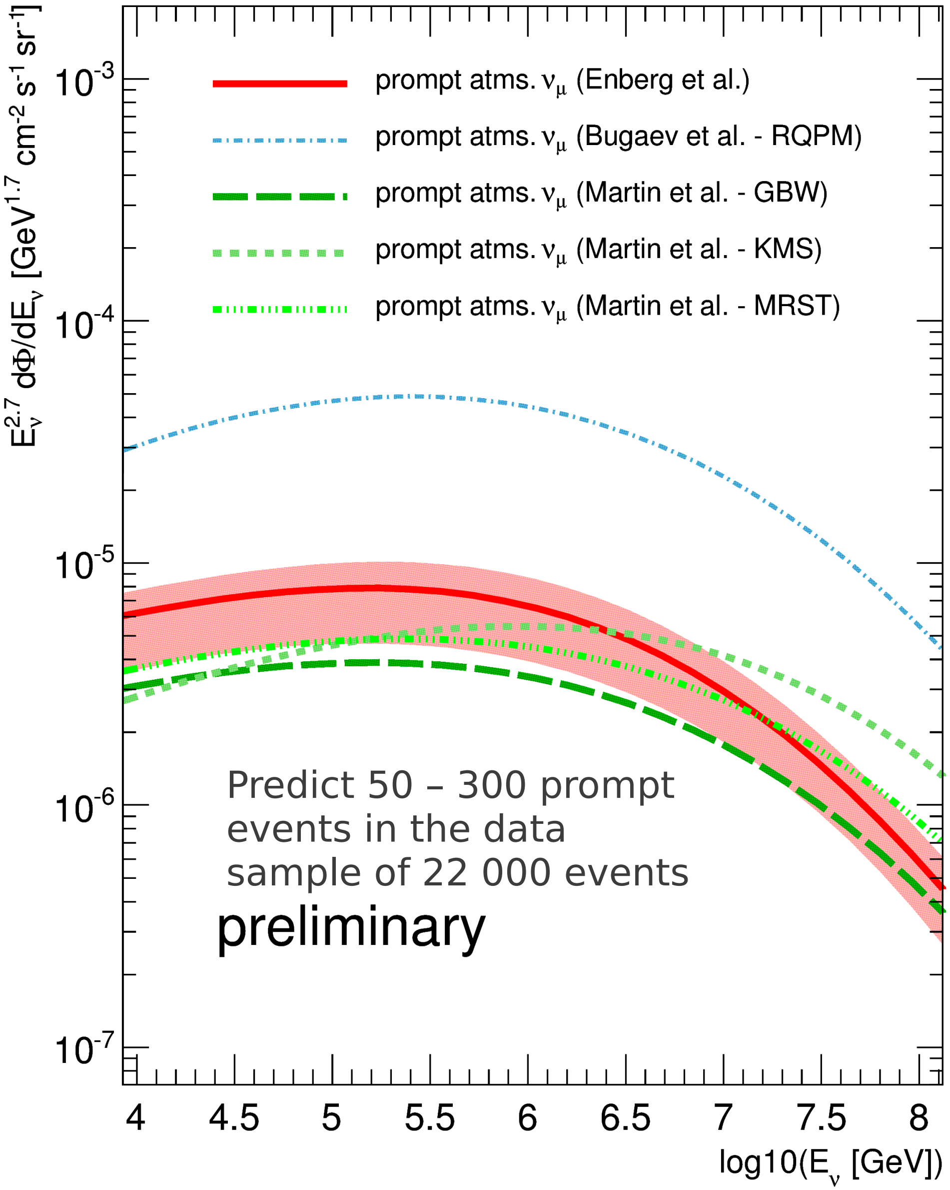


Presented @ NEUTRINO2012

Experimental constraints on astrophysical models



Models for prompt neutrino fluxes



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, qq → ccbar
- Nucleonic and charm attenuation and interaction lengths in the atmosphere
- Charm semi-leptonic decay spectra

Interesting because:

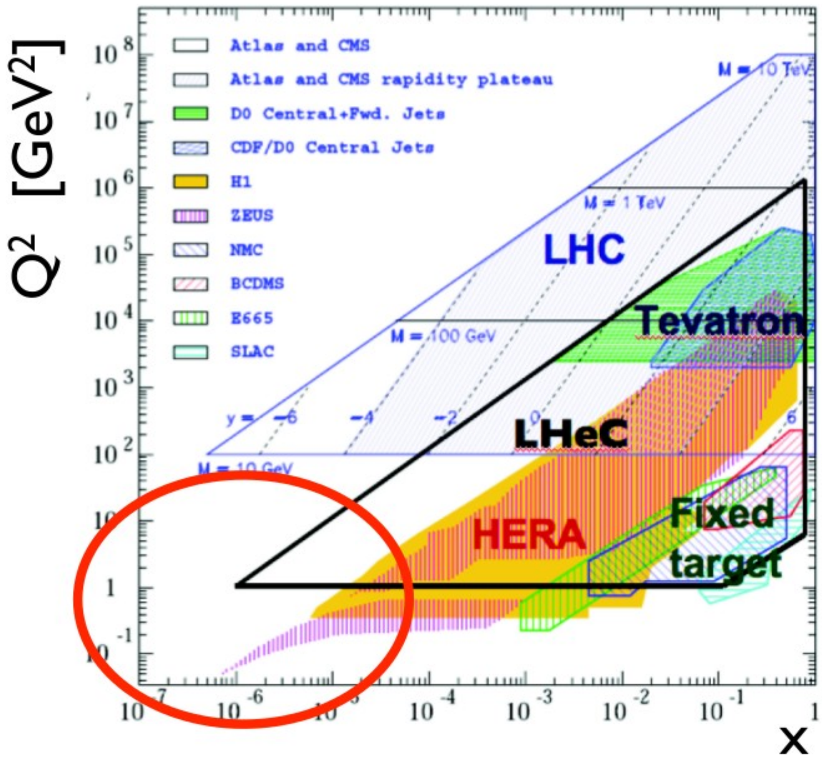
Provides experimental input to QCD physics at small x

Parton distribution functions at small x
– the challenge in the prediction of prompt fluxes

R. Enberg et al.

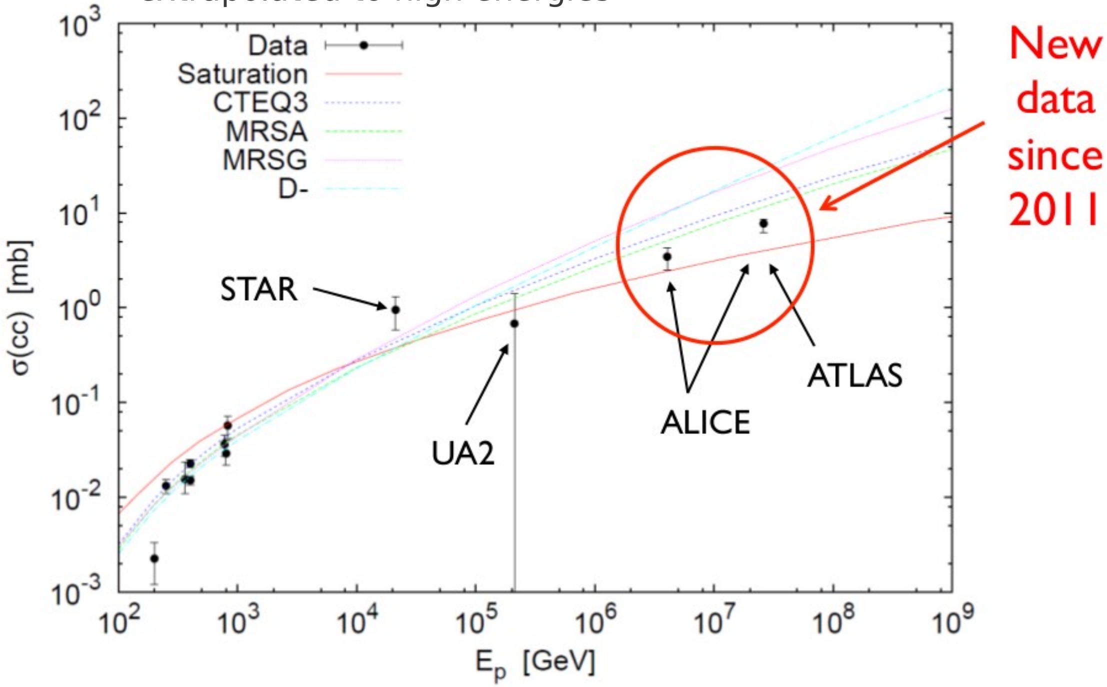
High energies (PeV, EeV) + forward direction
→ x = O (10^{-7})

This region is hard to access for collider experiments!



Total pp → cc cross section:

Different calculations give very different results if extrapolated to high energies



Experimental constraints on prompt models

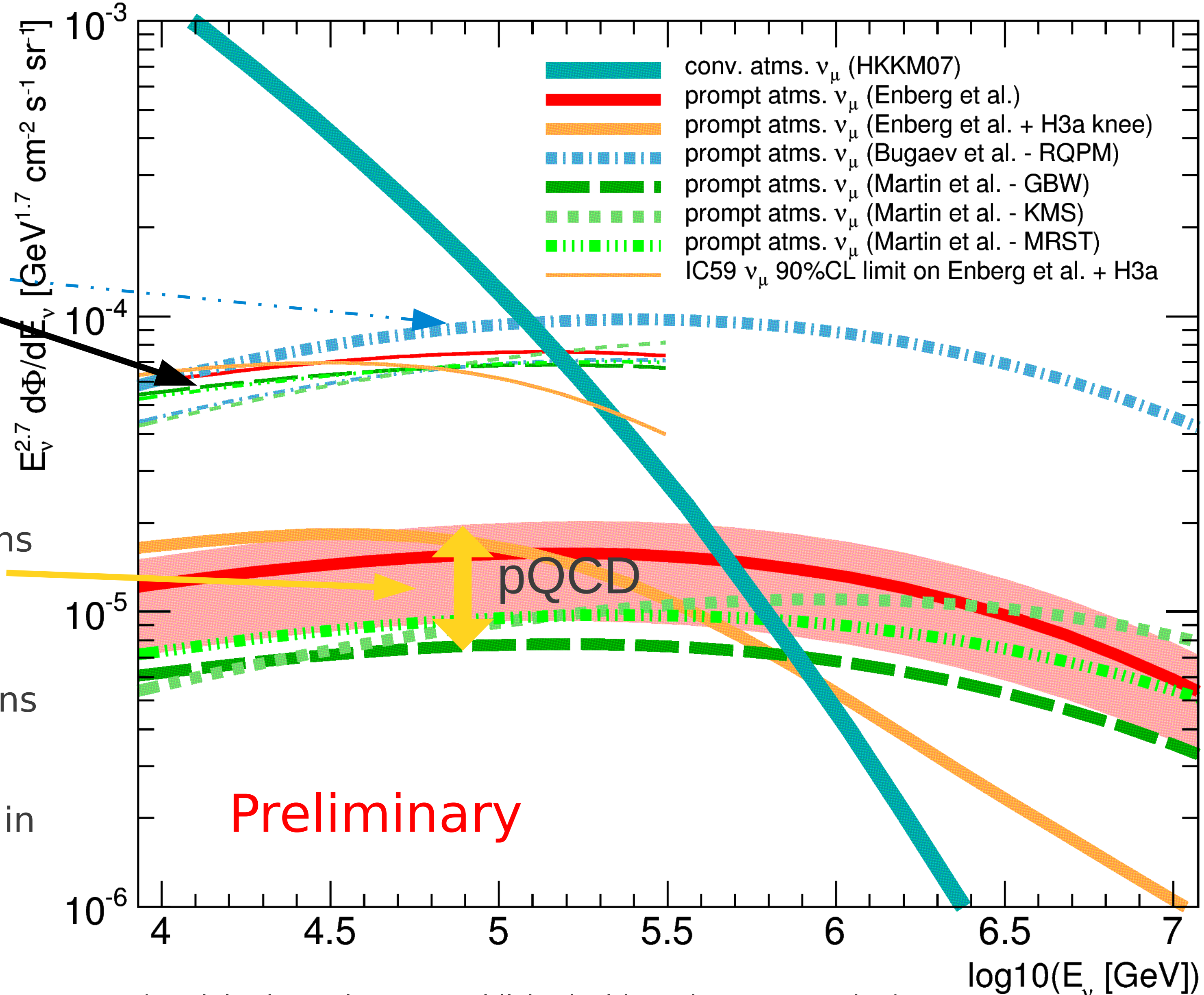
90%CL upper limits

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

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

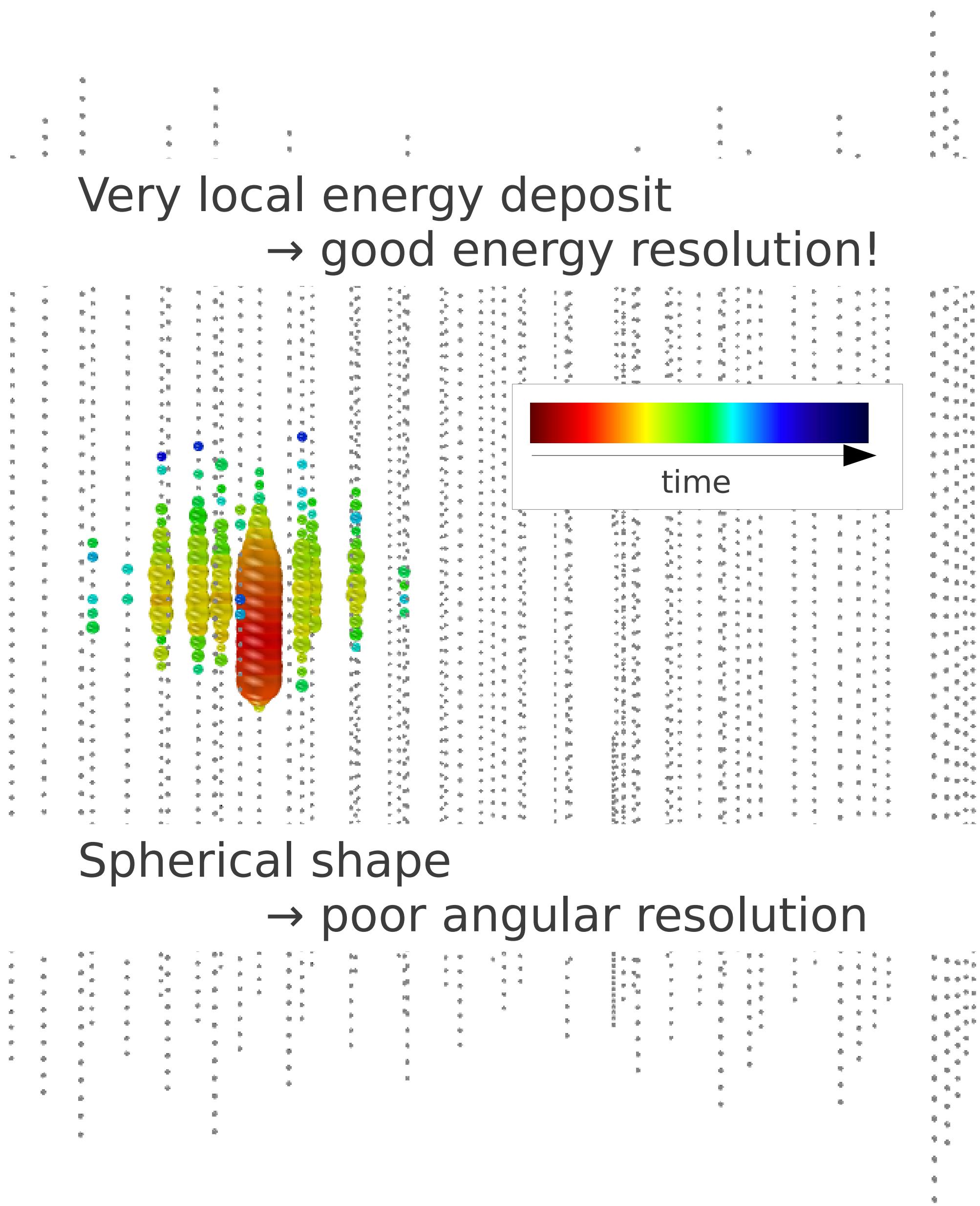
Limits are ~ factor 5 above model predictions

Only experimental constraints on prompt in this energy region!



(models shown here as published without knee correction)

IC40 cascade analysis



Very local energy deposit
→ good energy resolution!

Spherical shape
→ poor angular resolution

Requires different techniques for background rejection:

- Require spherical shape
- Require containment inside the detector (BG rejection)
- Require timely constraint of arrival times

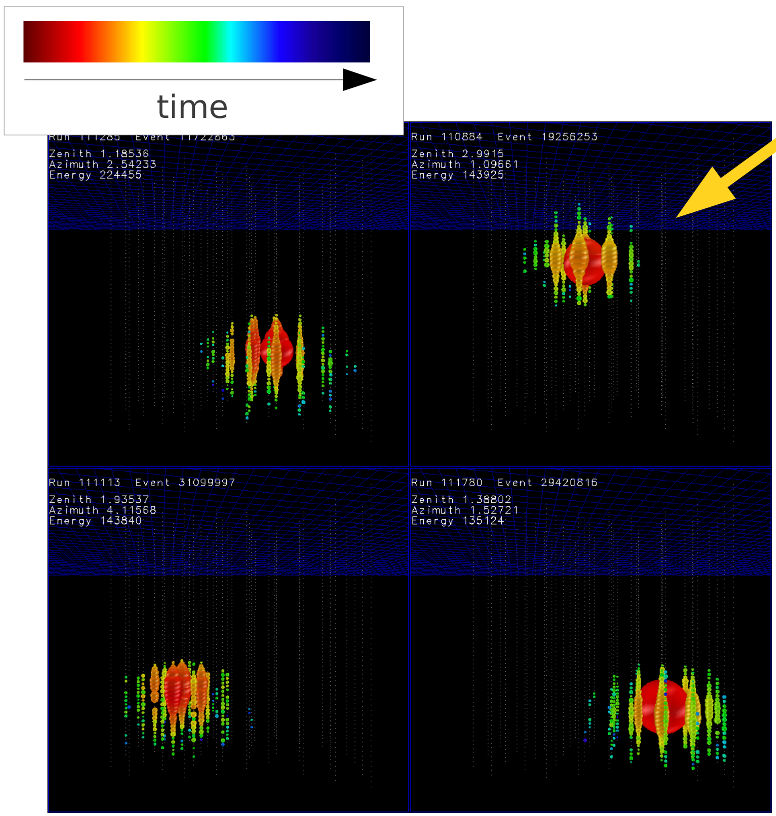
Provides a very good consistency check to the IC59 ν_μ analysis:

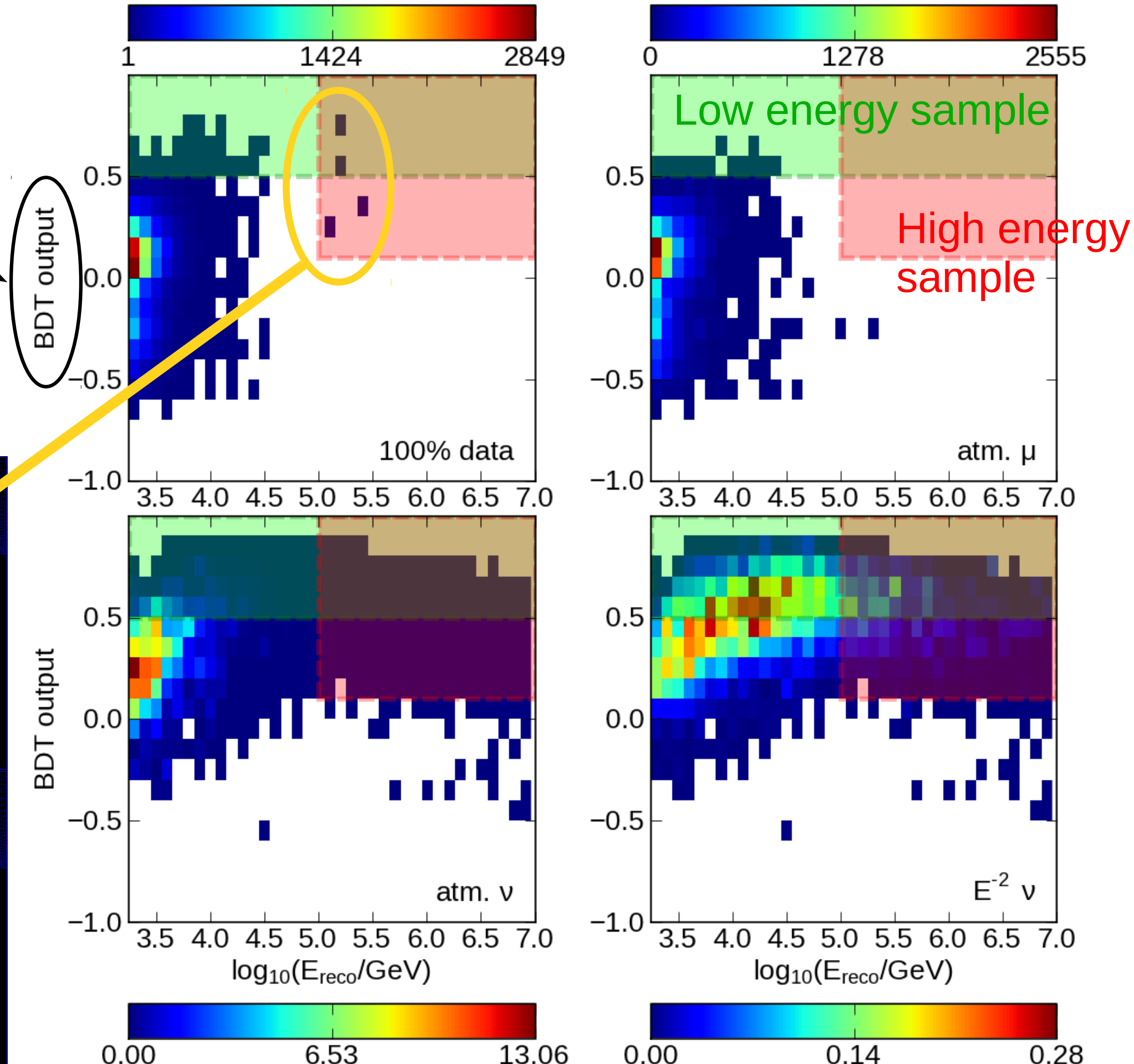
- Different signature
- Different detector geometry
- Different year
- Same energy range

Selection of high-energy cascades

Search for
- contained
- spherical

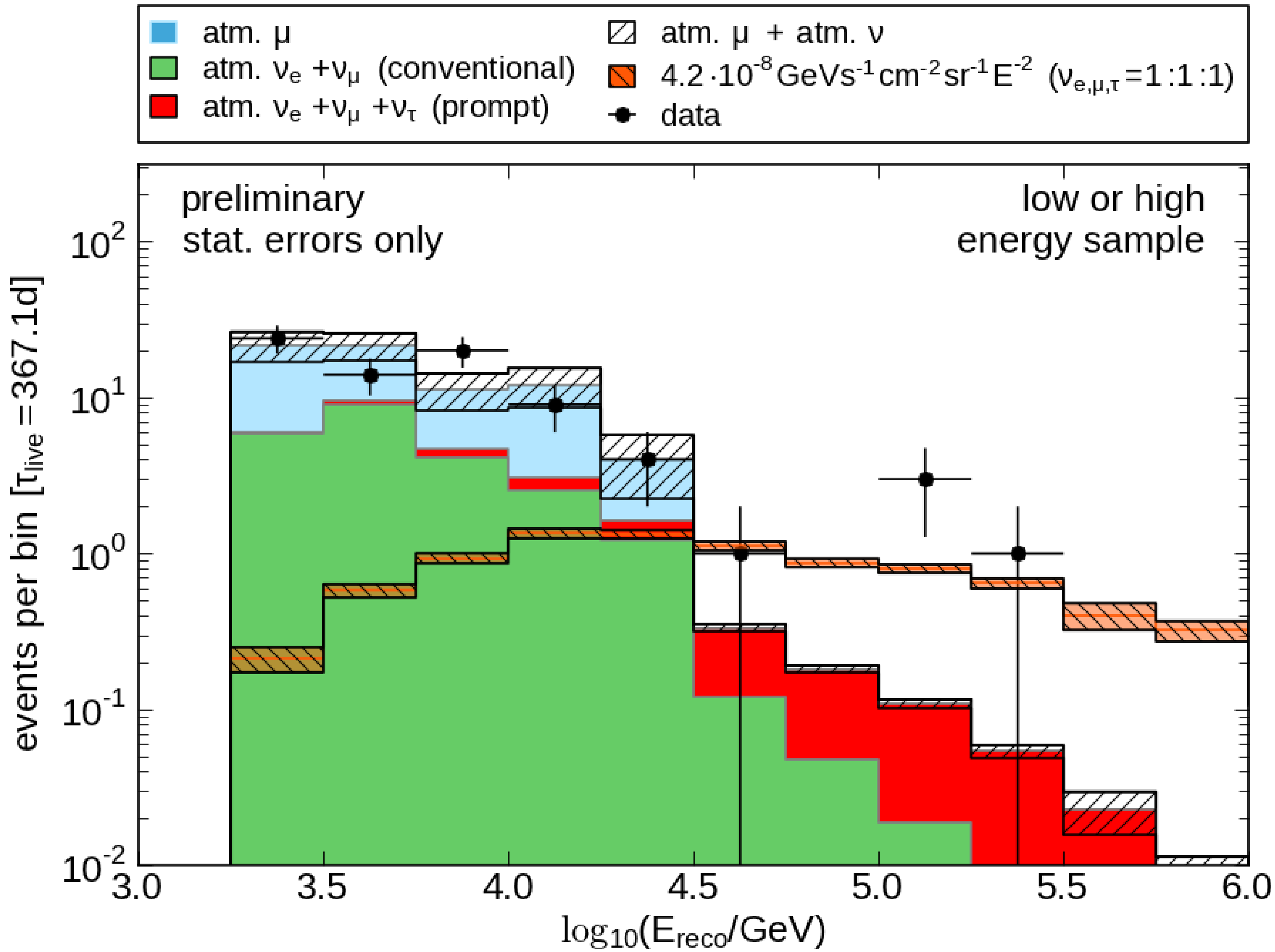
cascade-like neutrino events





The IC40 cascade energy spectrum

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



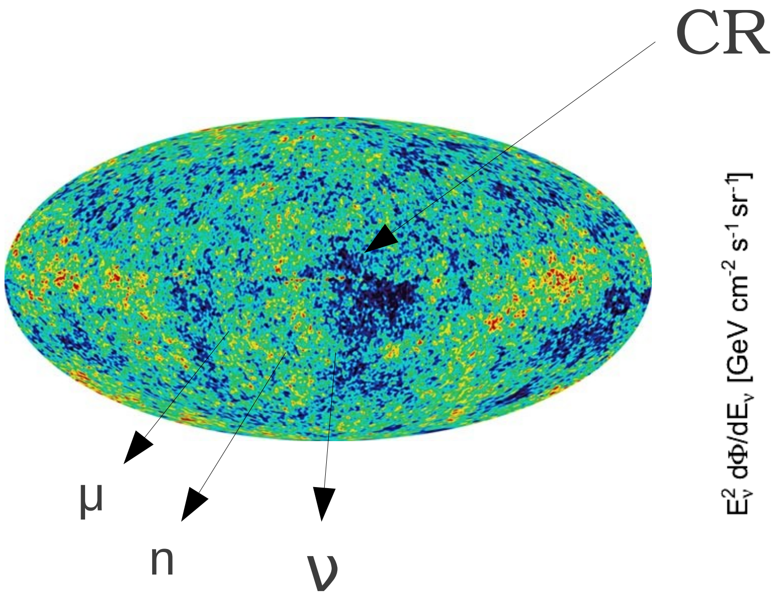
What are the HE events?

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)

EHE neutrinos from the GZK effect

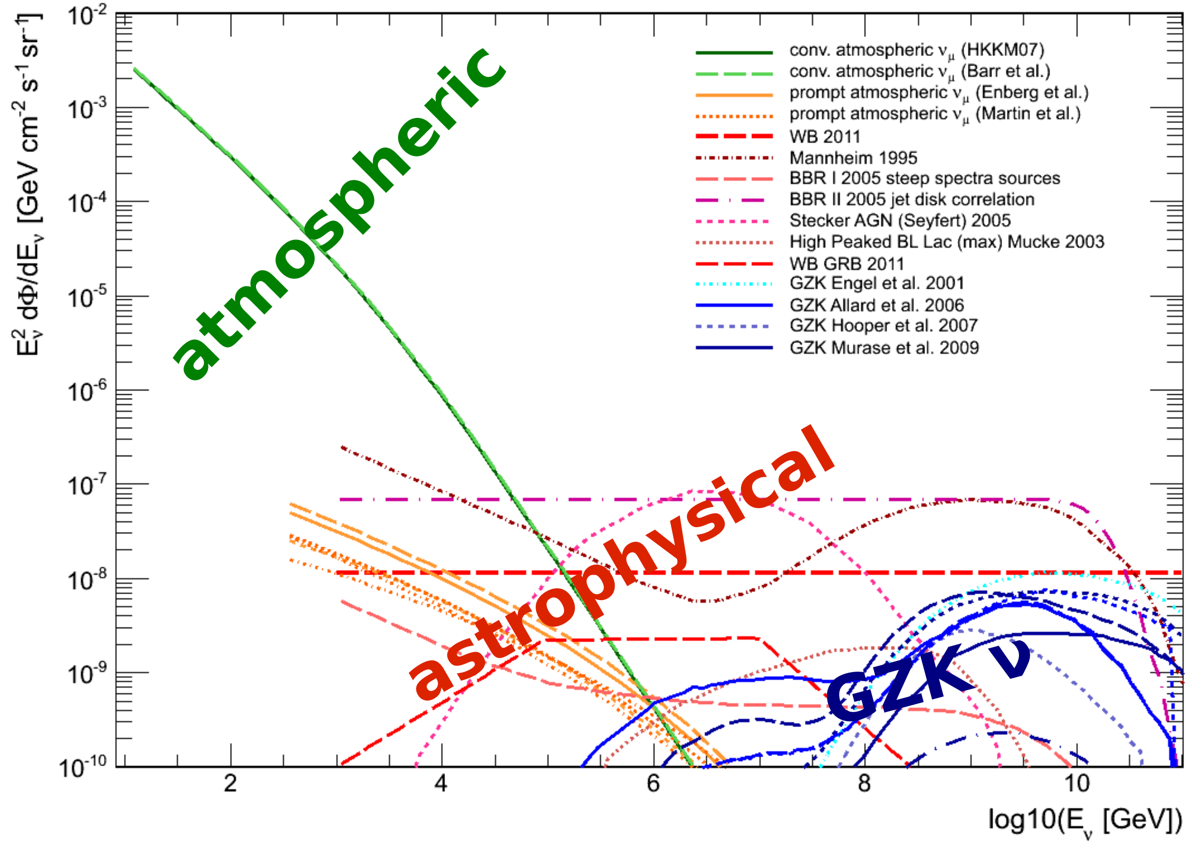


Cosmic rays interacting with CMB:

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

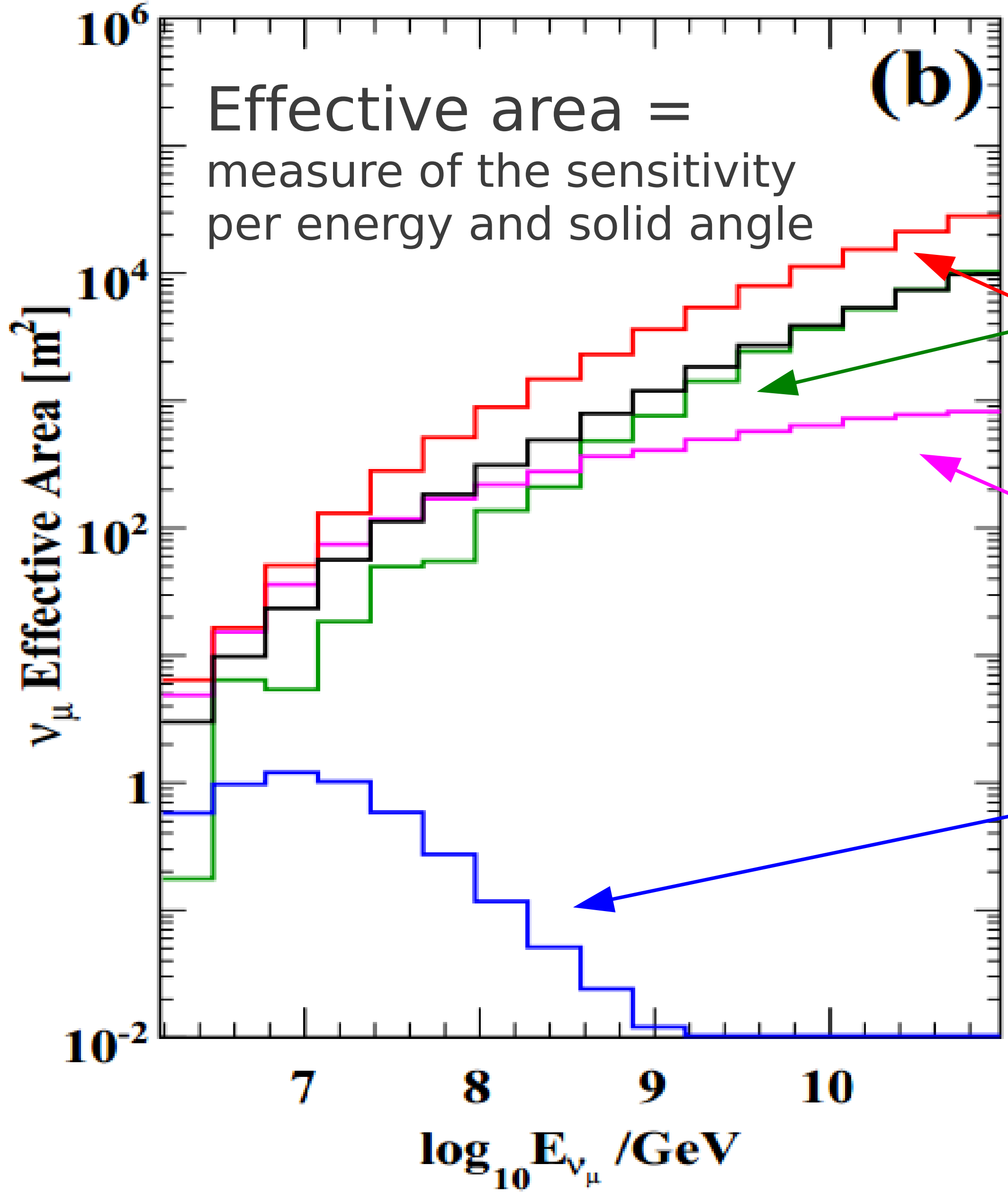
$$\rightarrow n + \mu^+ + \nu \rightarrow ..$$

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

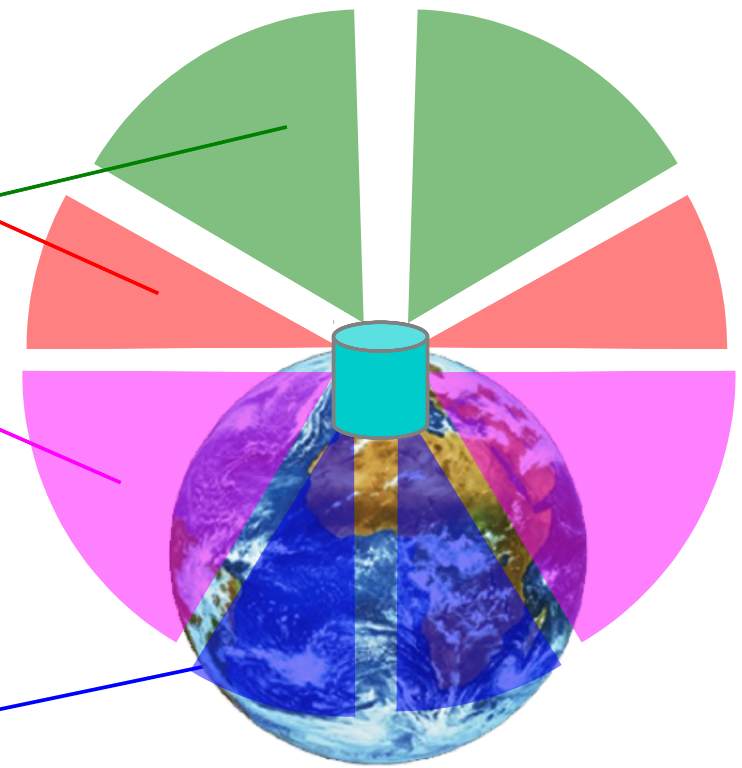


~ EeV energies

Angular acceptance for EHE events



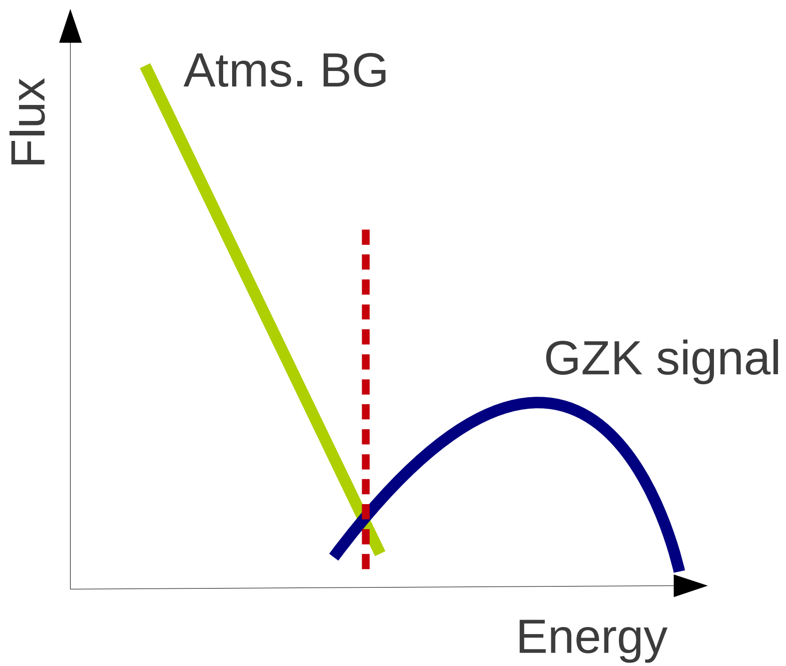
> PeV neutrinos are absorbed by the Earth



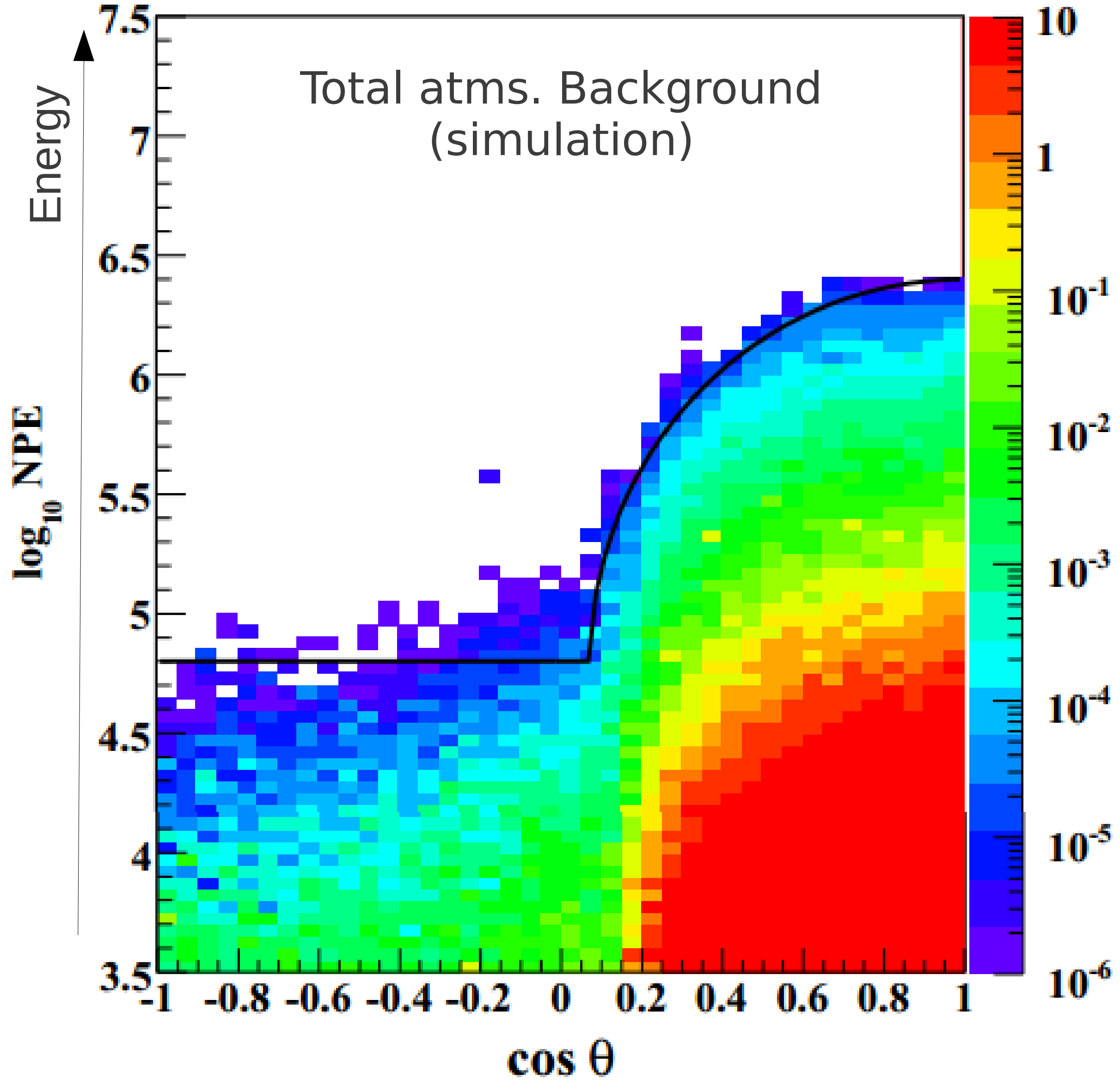
Need to look upwards!

Need different background rejection techniques!

Background rejection in the EHE analysis

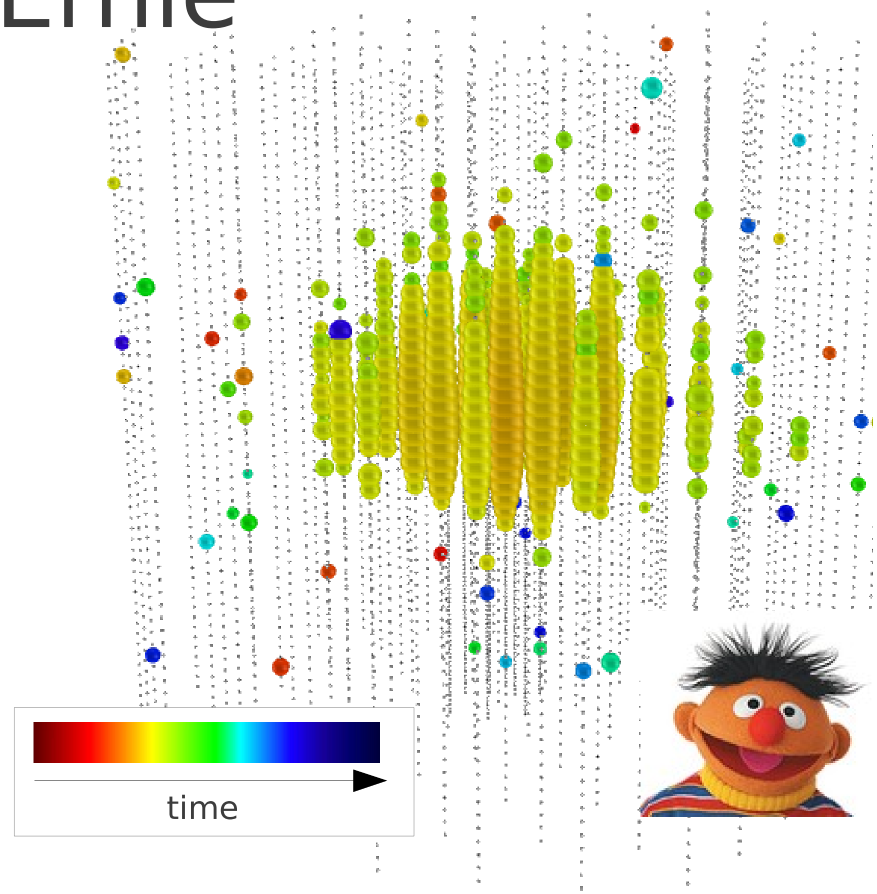


Remove background with an energy cut



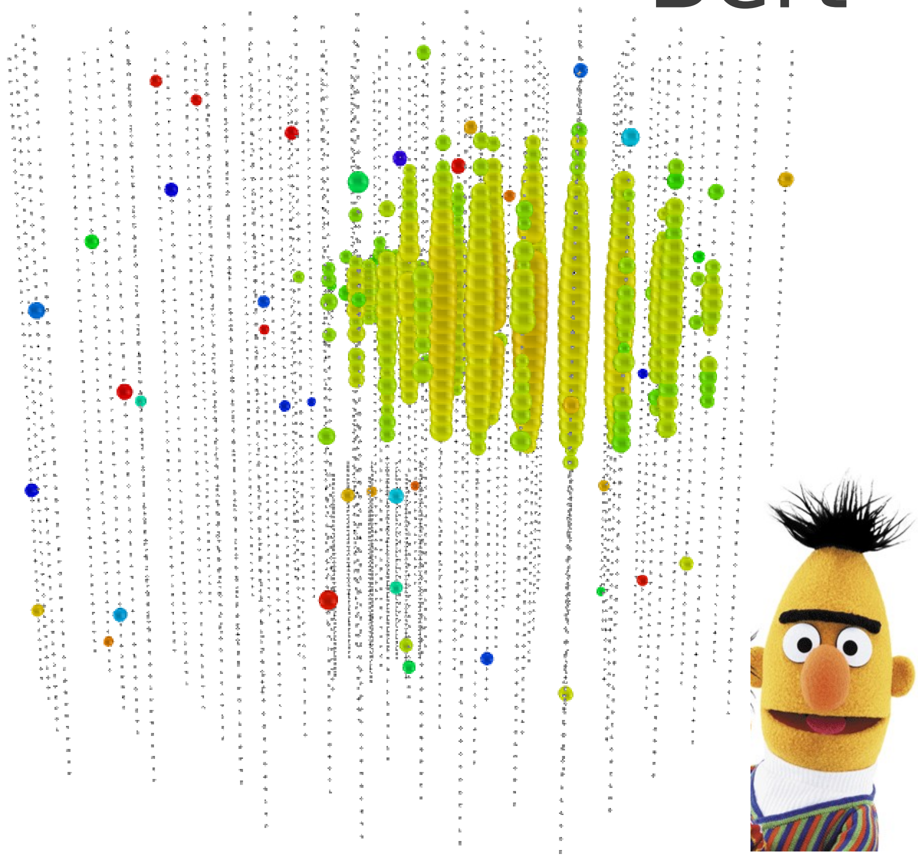
IceCube's first PeV events

Ernie



1.1 +/- 0.2 PeV

Bert



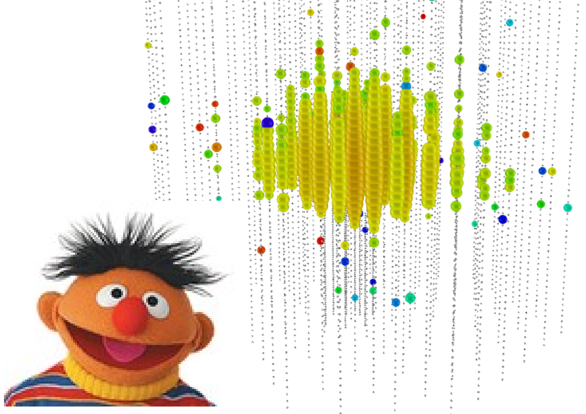
1.0 +/- 0.2 PeV

Preliminary

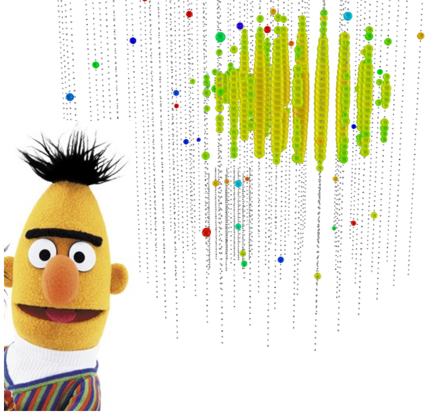
Presented @ NEUTRINO2012

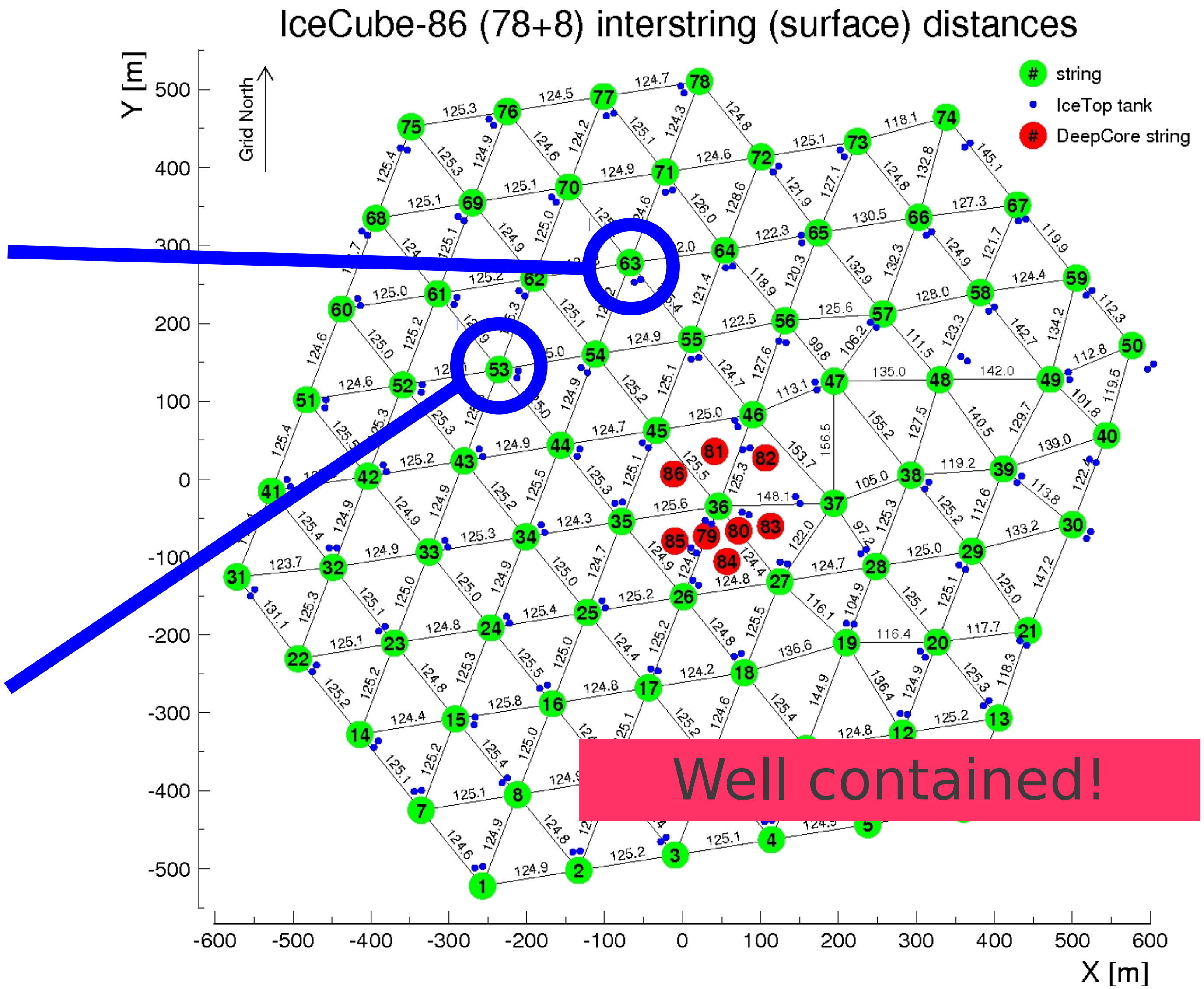
Brightest string positions in IceCube

Ernie

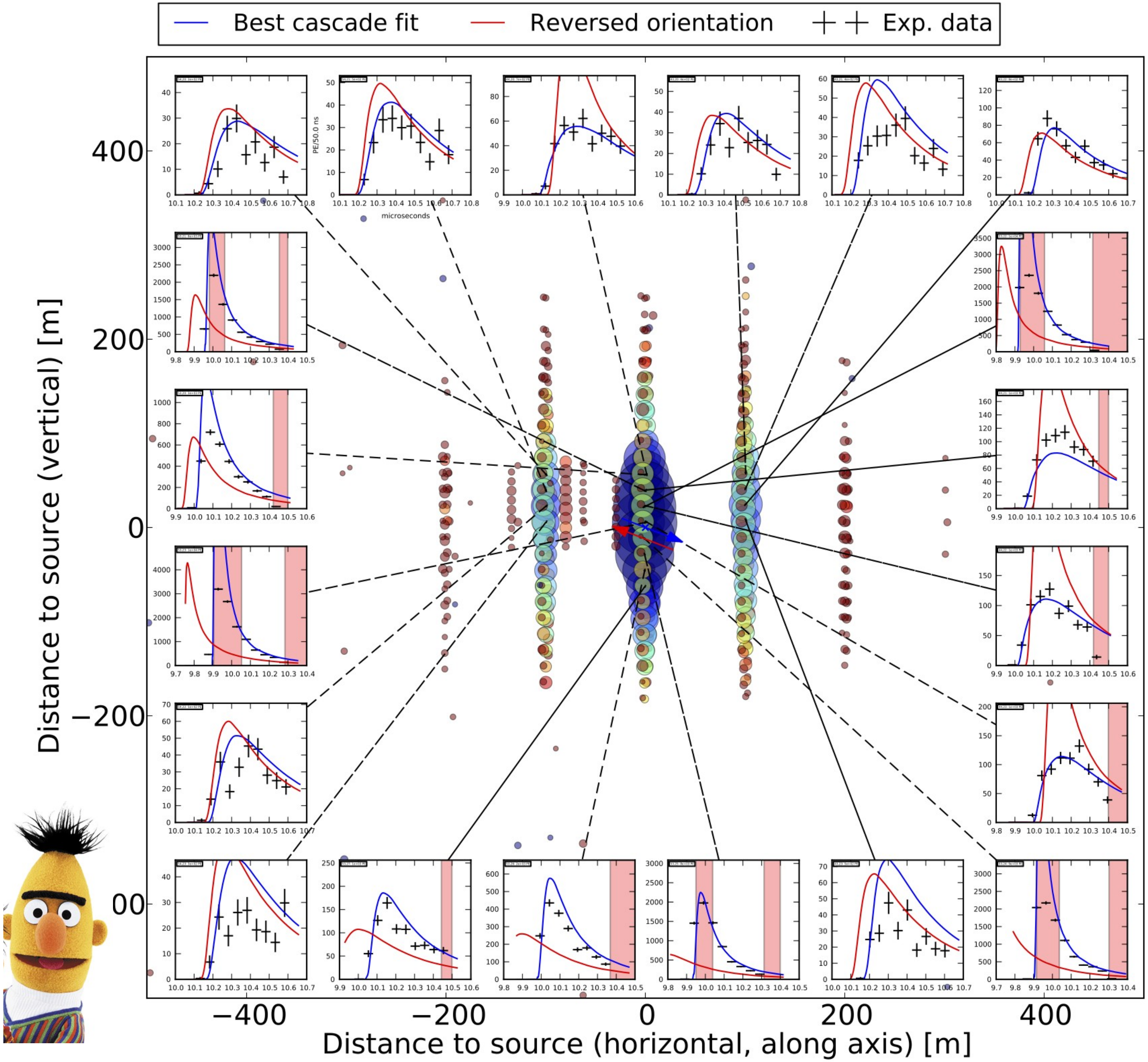


Bert





Reconstruction of EHE cascade events



Width of waveform related to direction of Cherenkov cone

Height proportional to energy

What are they?

Expected event numbers:

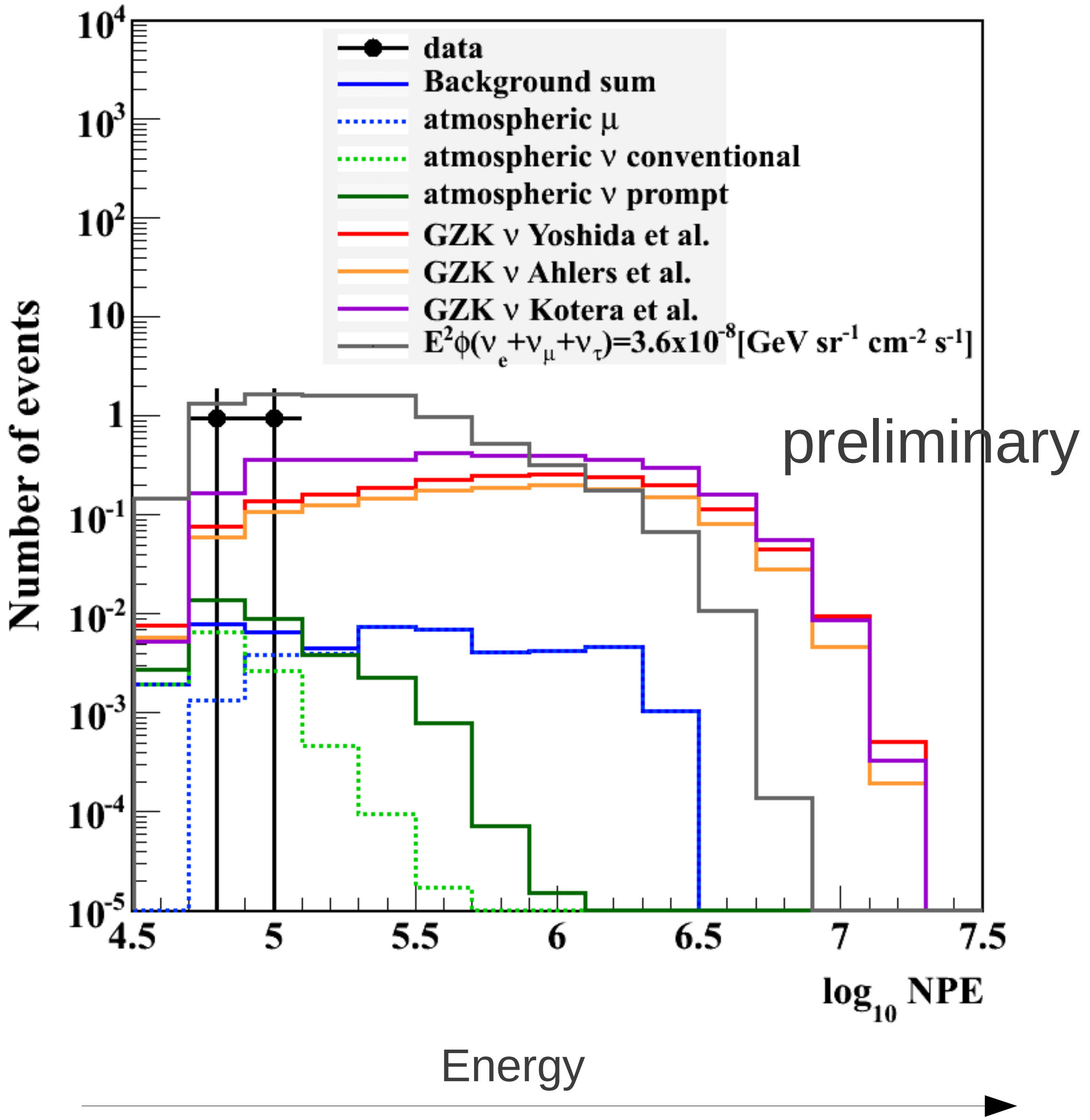
Conv. Atmospheric ν + μ:
~ 0.05

Prompt atmospheric ν
~ 0.1 (Enberg et al.)

GZK?
Unlikely
too low energy

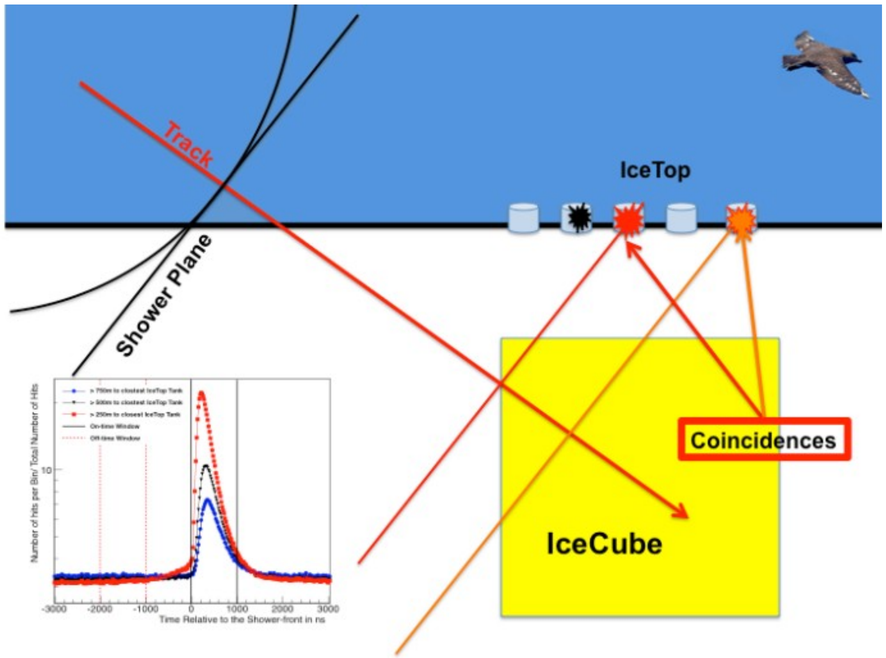
Astrophysical?
Maybe
Expectation depends on normalization, slope and cutoff energy

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

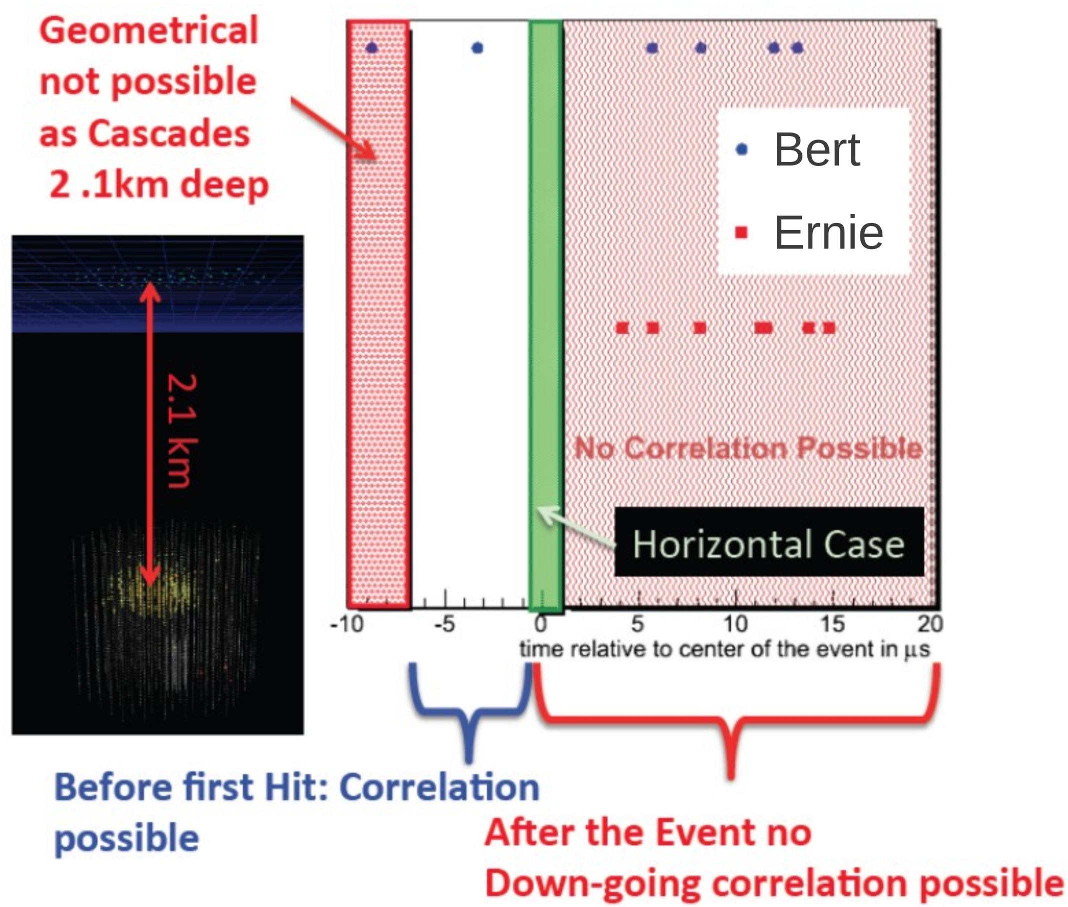


Check coincidence with IceTop

Atmospheric background neutrinos would be accompanied by an air shower, which can be seen with IceTop



IceTop hits in the trigger time window of Ernie and Bert



- Ernie: no IceTop hit
- Bert: 1 IceTop hit

- Expected random coincidence: 2.1 events

→ no hint on CR shower for Ernie & Bert

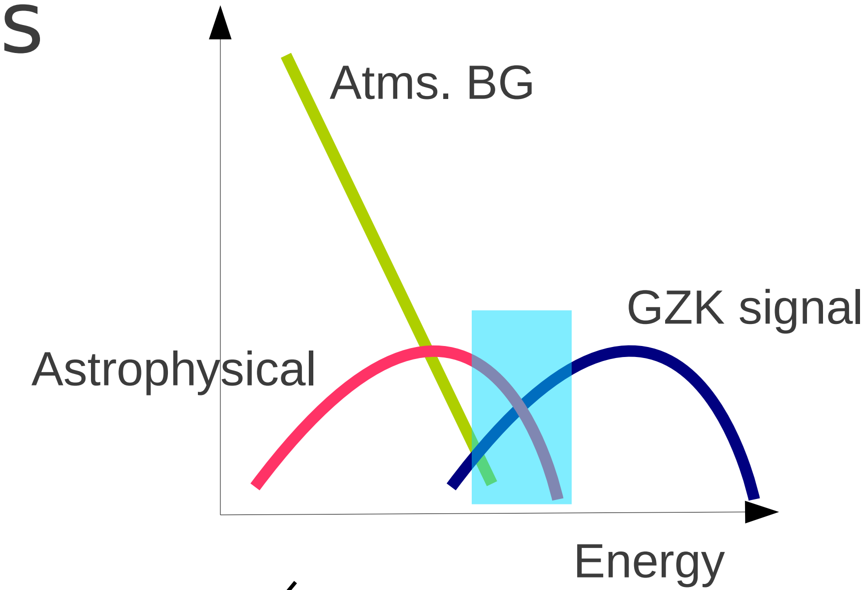
How to find more Muppets

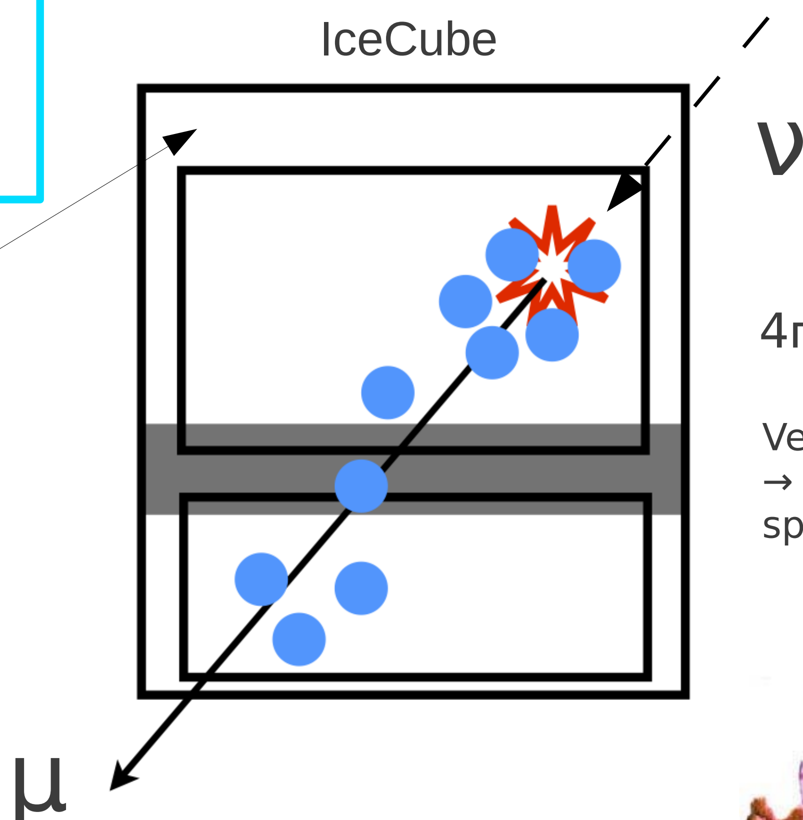
Idea:
Lower the energy threshold of the EHE analysis

Challenge:
atmospheric background coming in!

Strategy:
Look for starting events in the detector

→ these must be neutrinos!!!





Efficient veto
for atmospheric muons

Sensitive to cascade- and track-like events

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

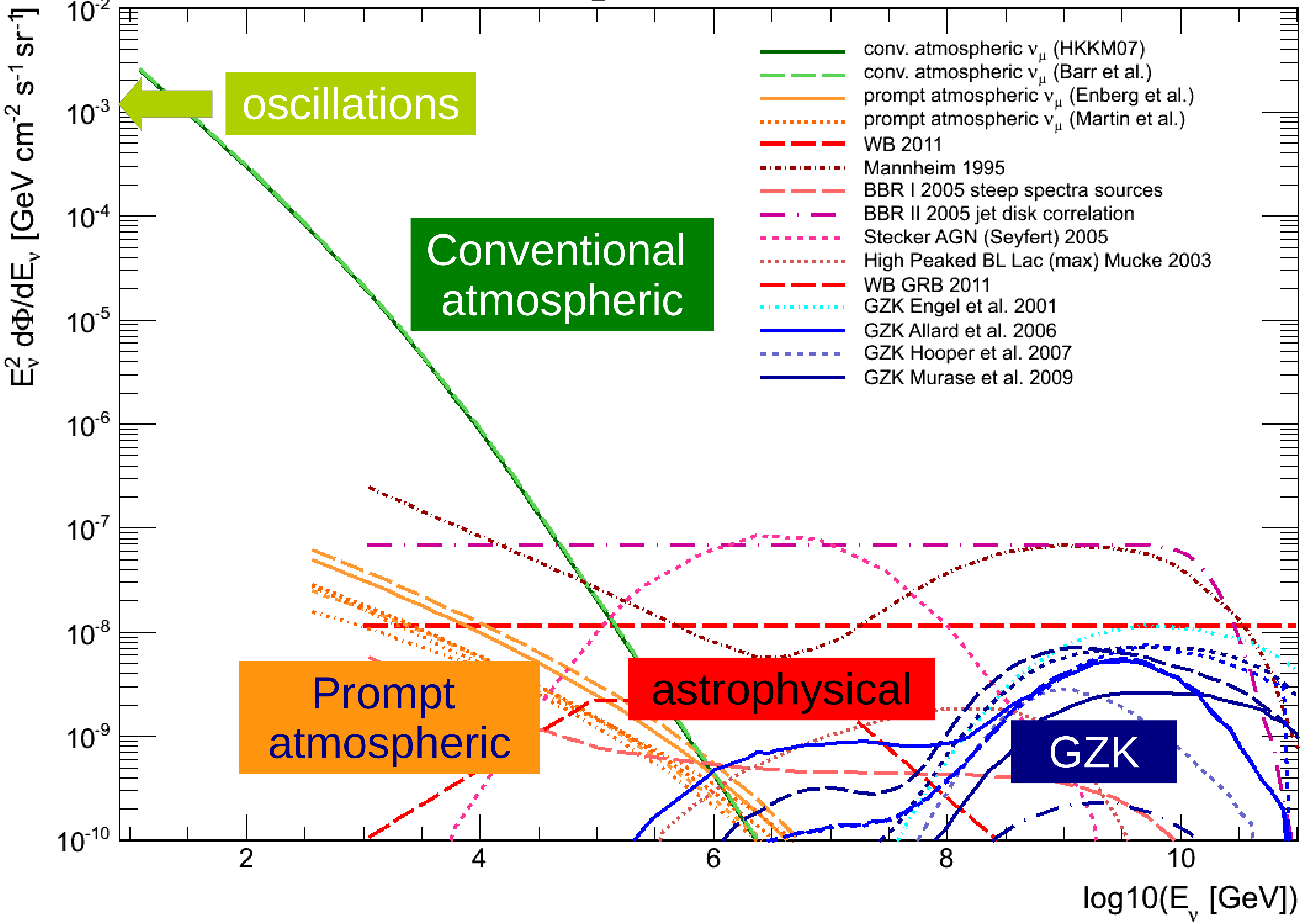
4π angular coverage!

Very dirty ice layer
→ needs some special treatment

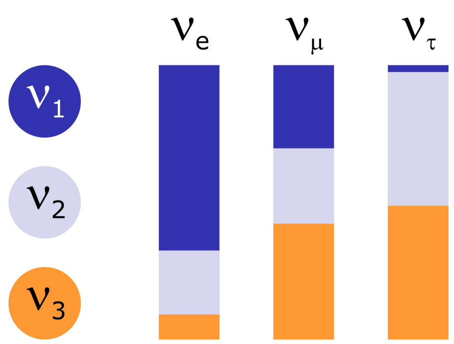
Summary on IceCube's searches for astrophysical neutrinos

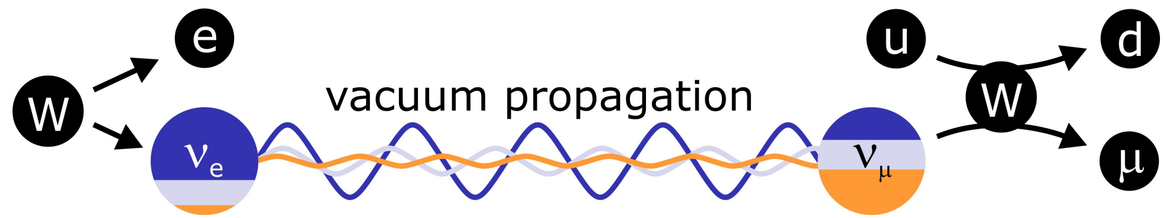
- IceCube is completed, running stable and has reached the sensitivity to challenge theoretical predictions for astrophysical neutrinos
- No hint on galactic or extragalactic neutrinos in steady and transient point source searches
- In the diffuse channel, we observed high-energy excesses at the level of 2-3σ in complementary analyses
- We do not know yet, what these high-energy neutrinos are
- An astrophysical interpretation is consistent with all analyses
- We are working on exciting follow-up analyses!
  Results are expected very soon!

Back to “low” energies

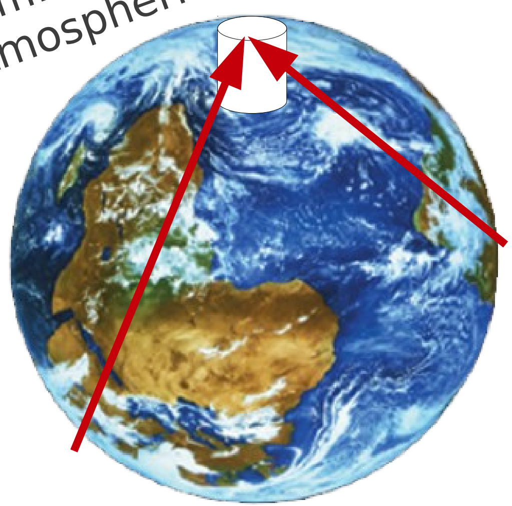


IceCube as a long-baseline experiment

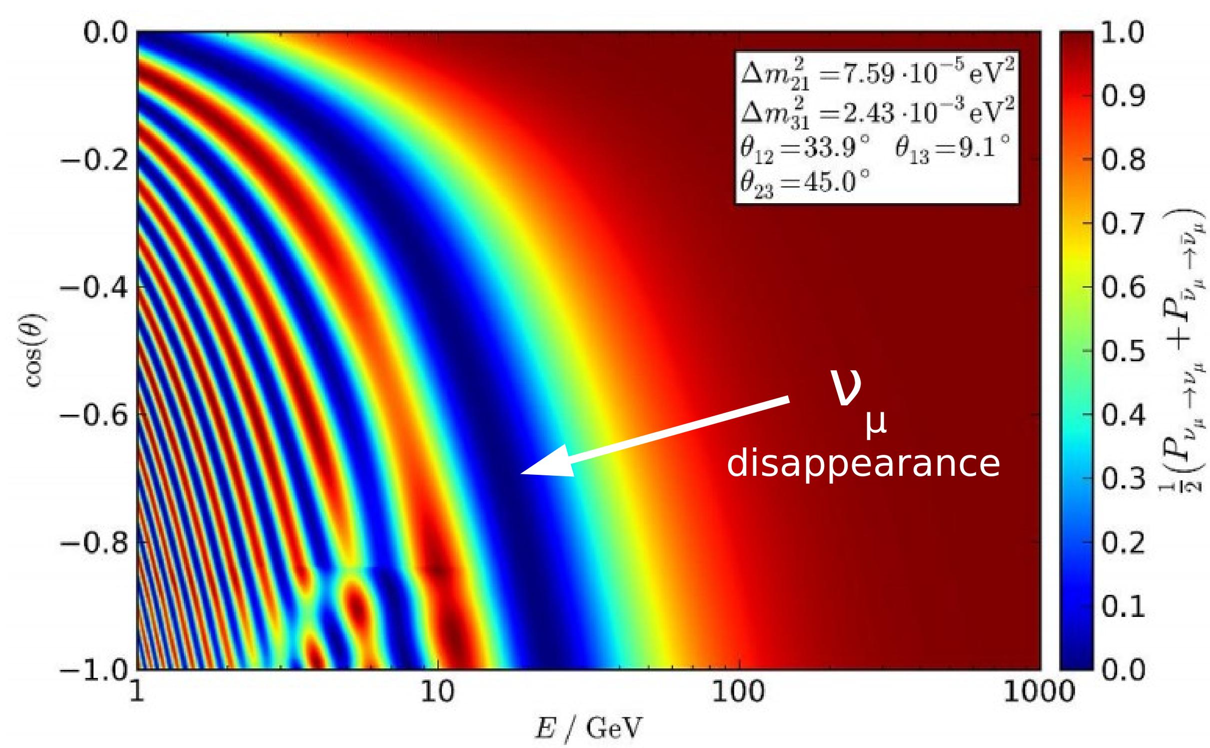




No beam.
Use atmospheric neutrinos!

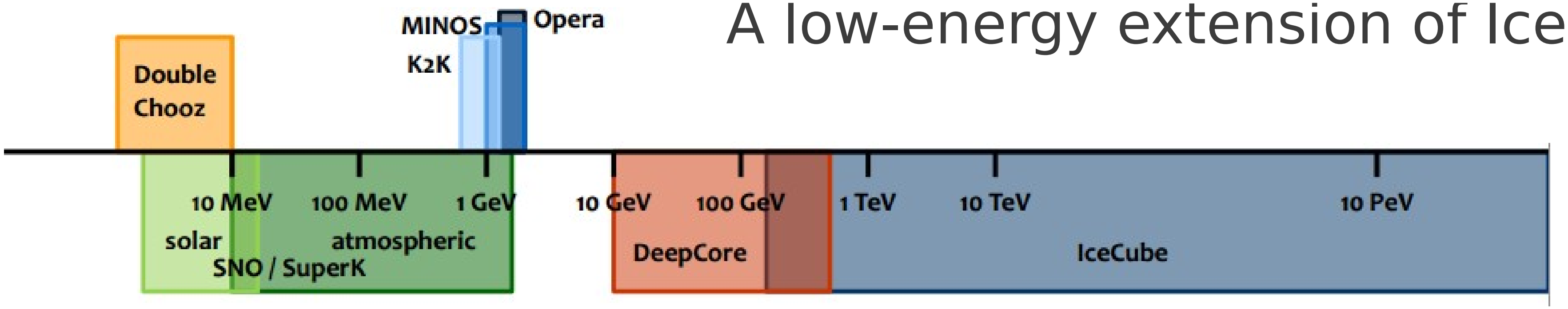


Baselines from several 100 to ~ 13 000 km!



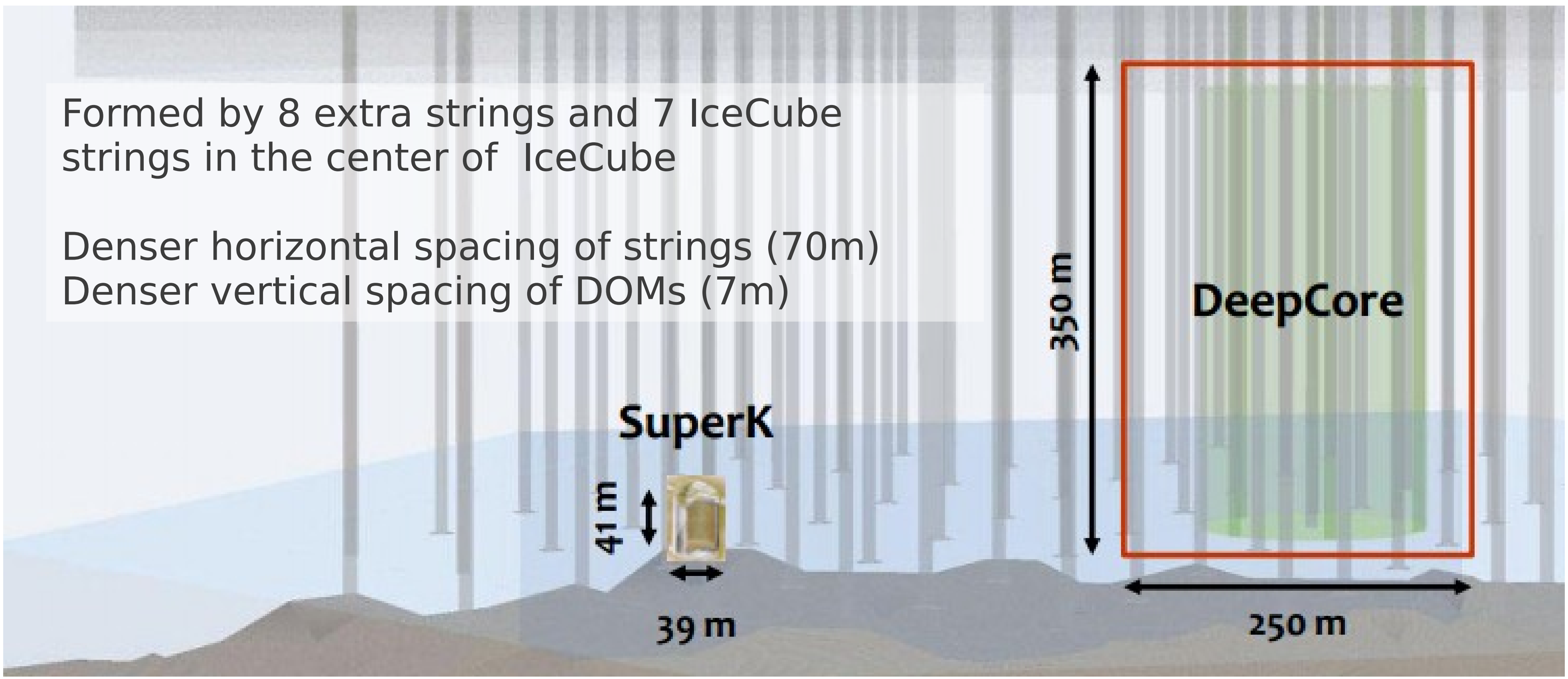
IceCube/DeepCore

A low-energy extension of IceCube



Formed by 8 extra strings and 7 IceCube strings in the center of IceCube

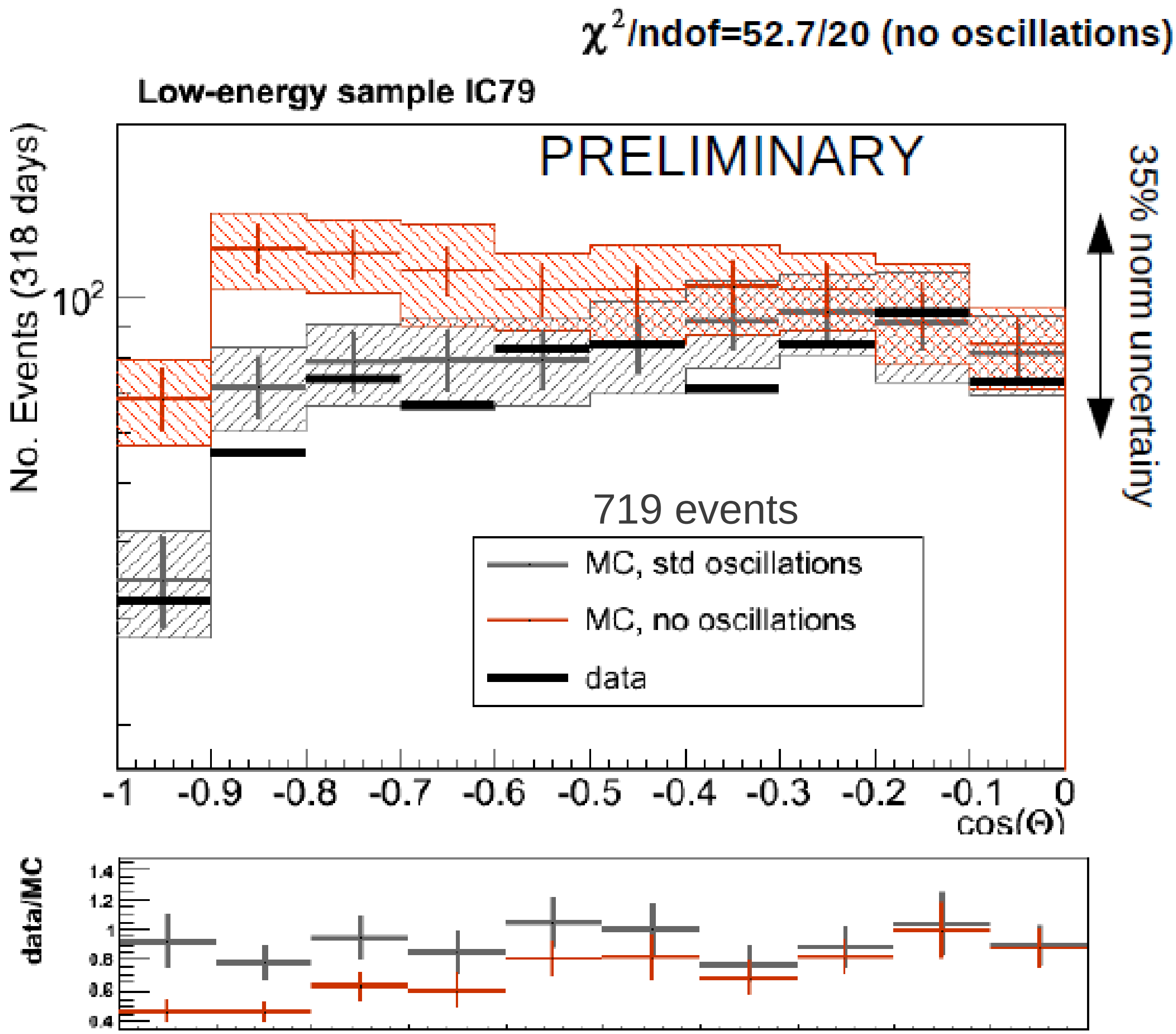
Denser horizontal spacing of strings (70m)
Denser vertical spacing of DOMs (7m)



First oscillation results with IC79

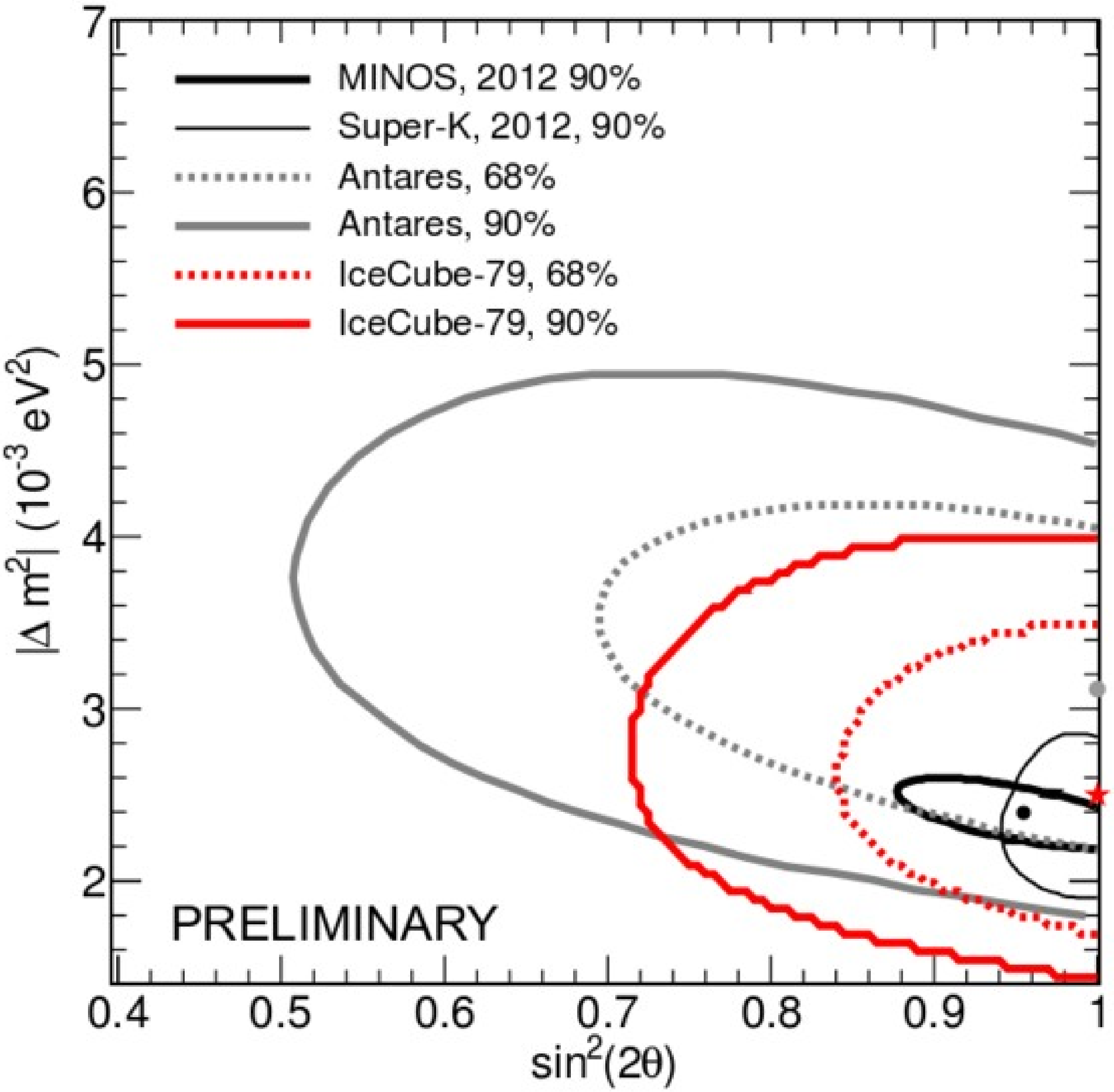
The no-oscillation scenario is rejected at the level of 5.8σ

Neutrino energies:
20GeV – 100GeV



Presented @ NEUTRINO2012

Mixing parameters

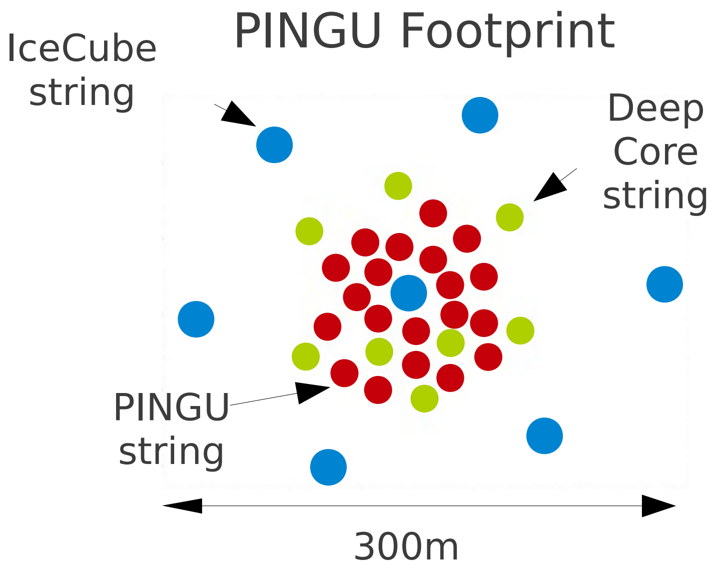


Extracted mixing parameters are consistent with other measurements.

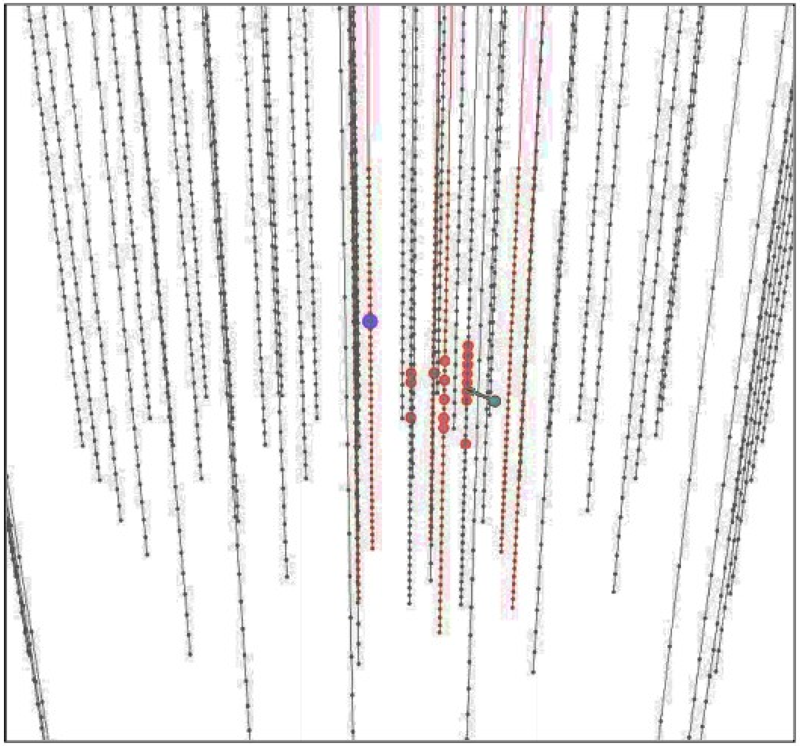
Follow-up analyses with larger statistical samples (factor ~10) and the use of energy information are ongoing

Future plans: PINGU

Precision IceCube Next Generation Upgrade



A proposal to increase the IceCube/ DeepCore performance at low energies

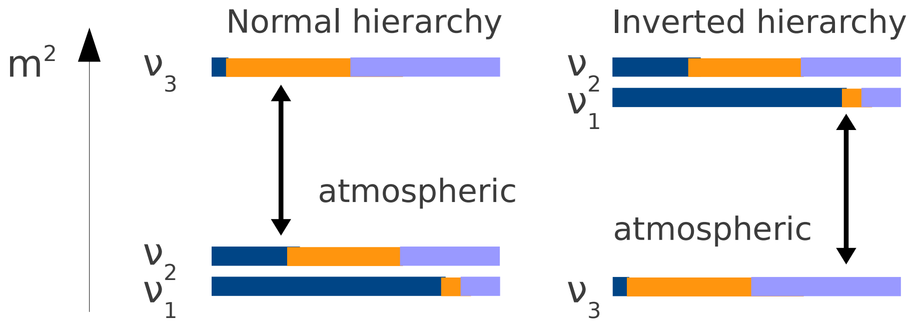


DeepCore Only

DeepCore + PINGU

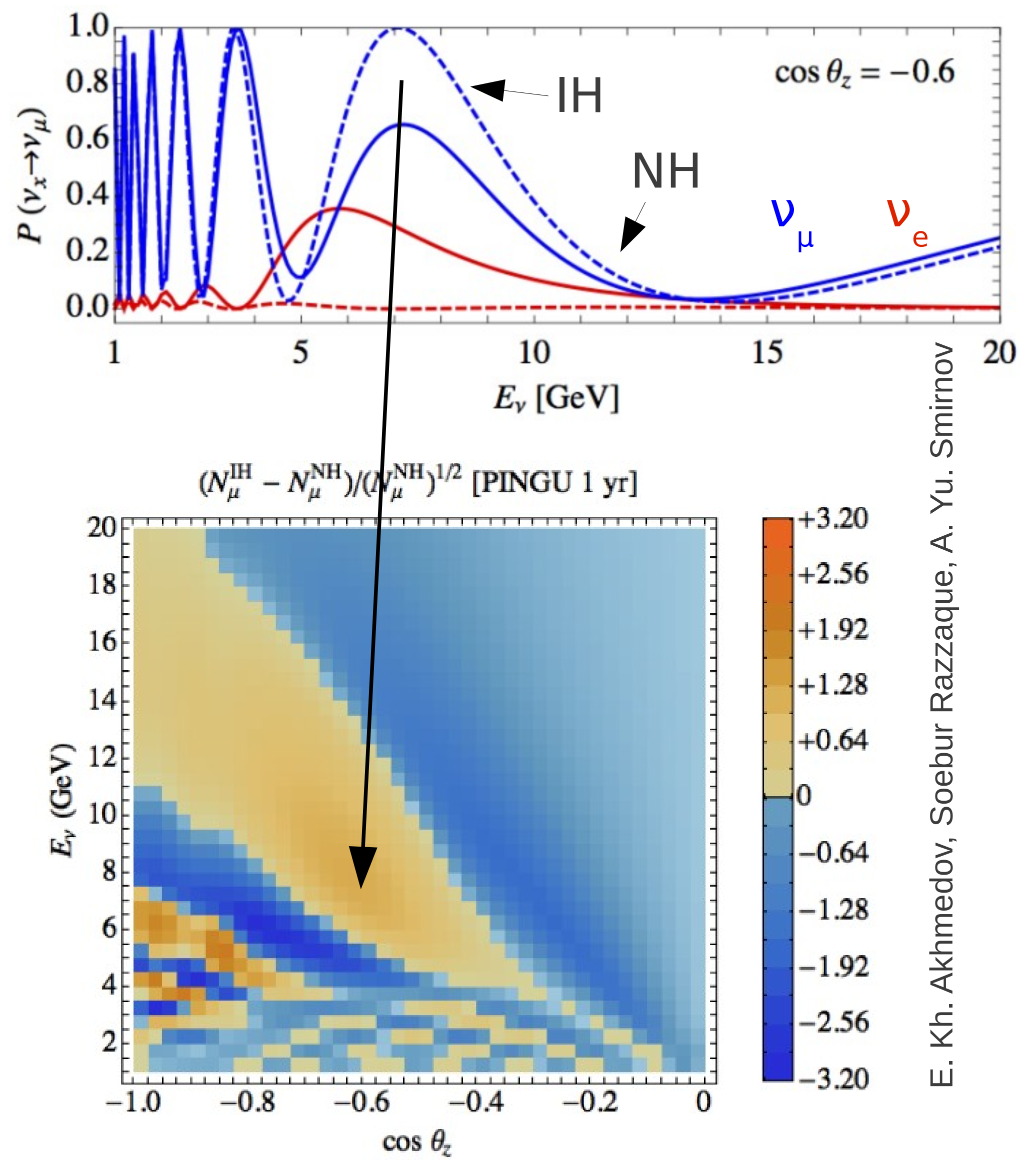
PINGU physics goals

- ν_μ disappearance
- ν_τ appearance
- Neutrino mass hierarchy



- Dark matter
- Proton decay

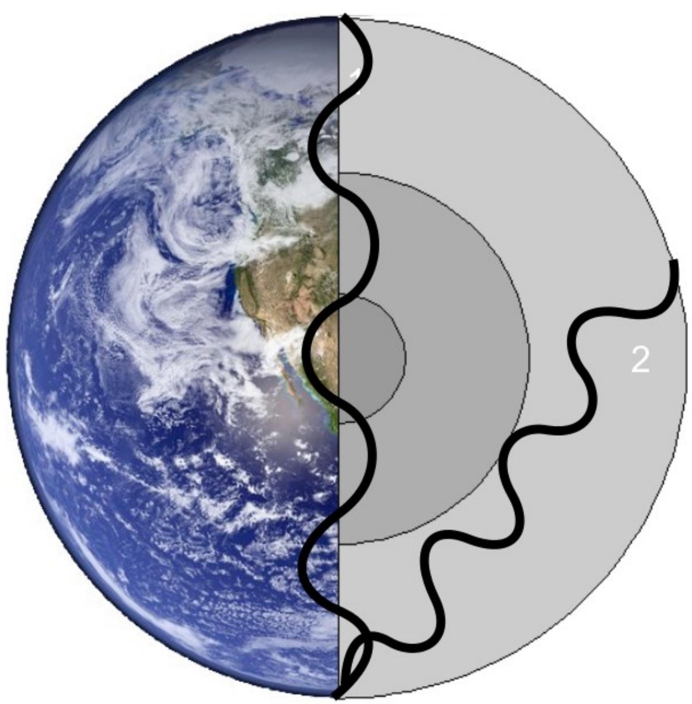
Due to the MSW-effect electron neutrinos behave different in matter.



E. Kh. Akhmedov, Soebur Razzaque, A. Yu. Smirnov

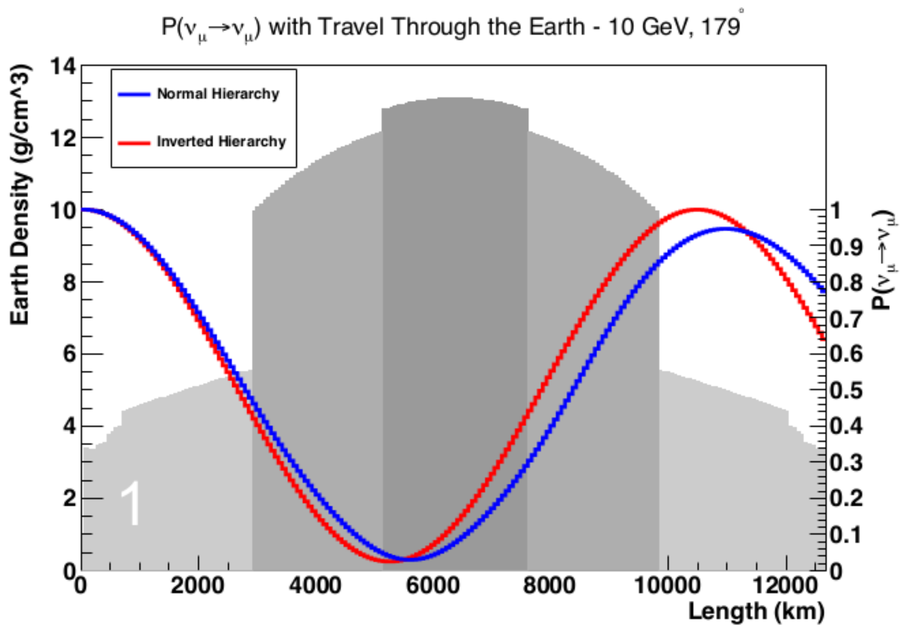
PINGU matter oscillations

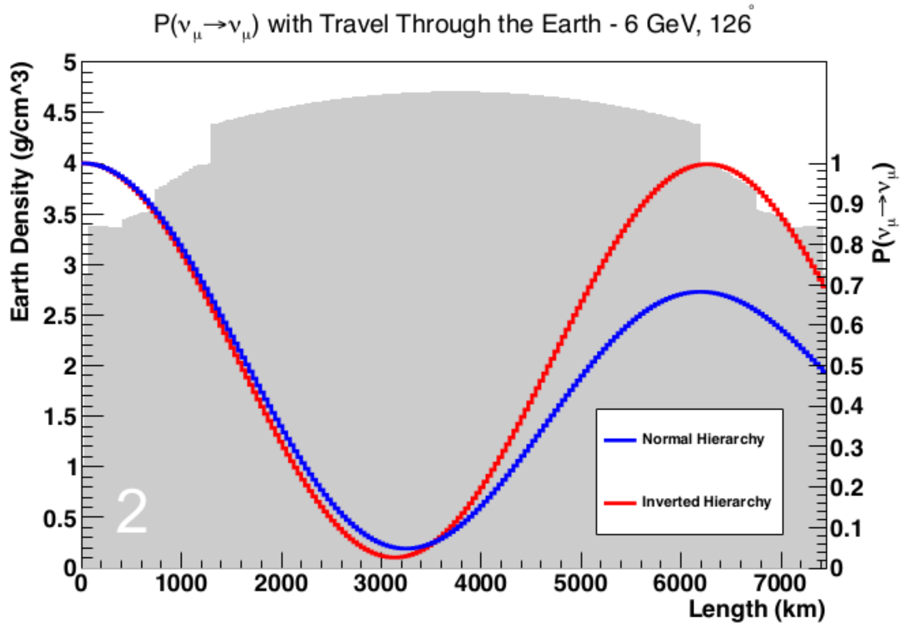
Electron neutrinos propagate differently in matter



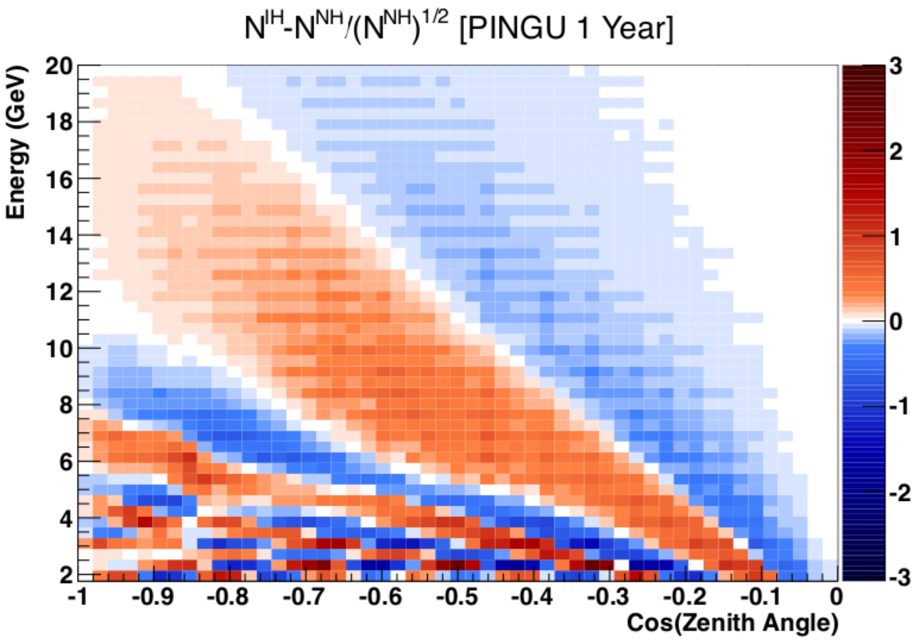
Oscillation pattern depends on the traversed density/Earth profile

→ strong zenith angle dependence!



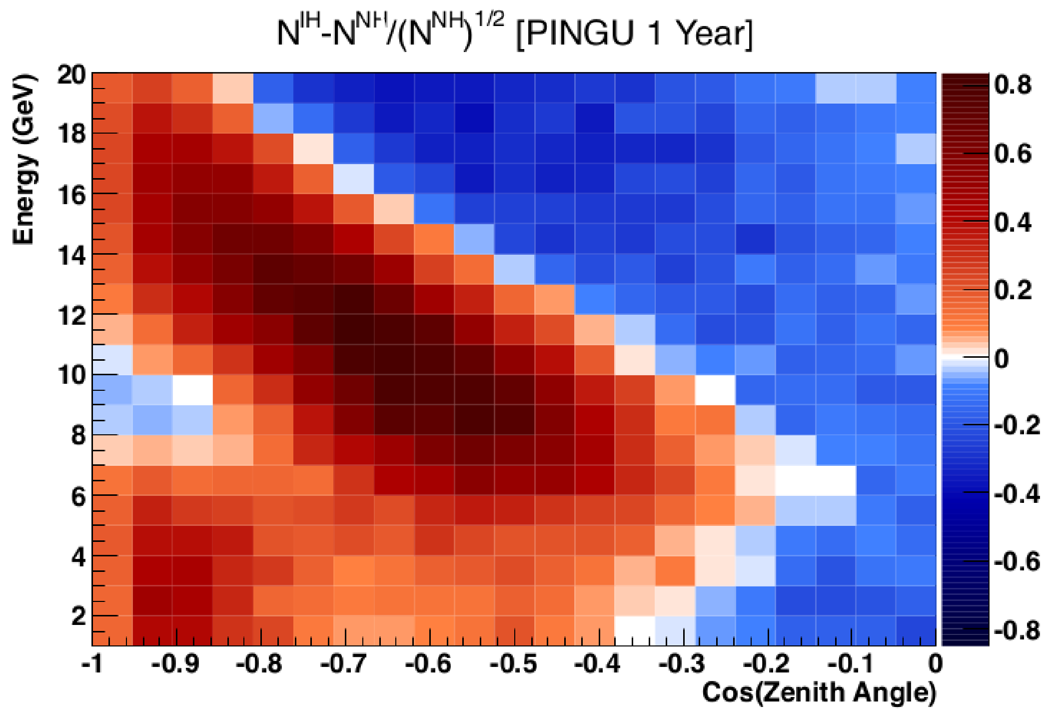


Hierarchy signature



Truth

Reco?



smeared: 3 GeV in ν_μ energy and 11.25° in μ zenith resolution

The performance of PINGU will strongly depend on the accuracy in

- Energy reco
- Zenith angle reco
- Flavor identification

→ work in progress!

Thanks!