Measurement of the high-energy all-flavor neutrino-nucleon cross section with IceCube

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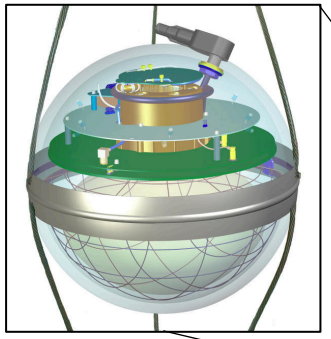
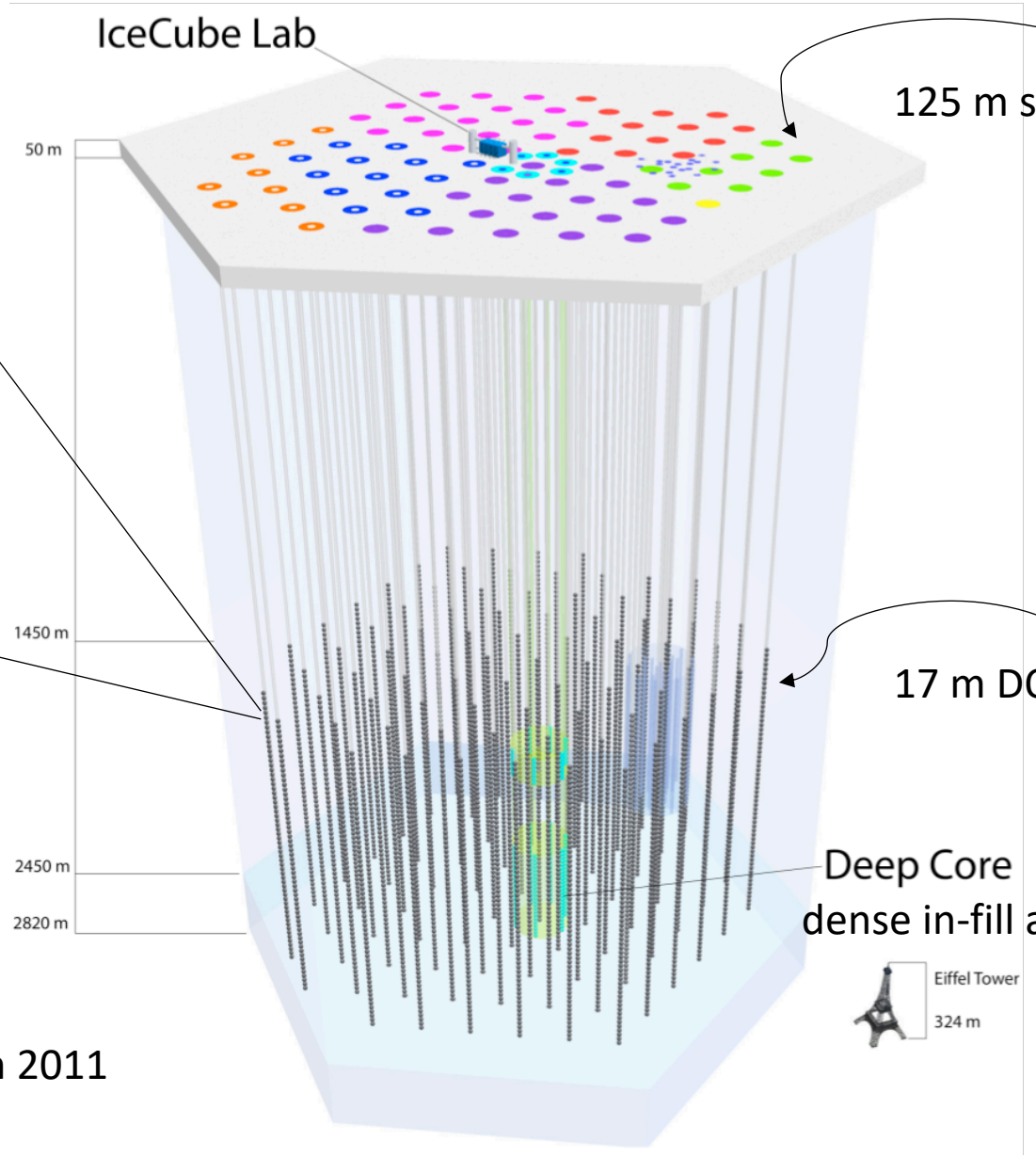
ICECUBE

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

IceCube

Digital Optical Module (DOM)

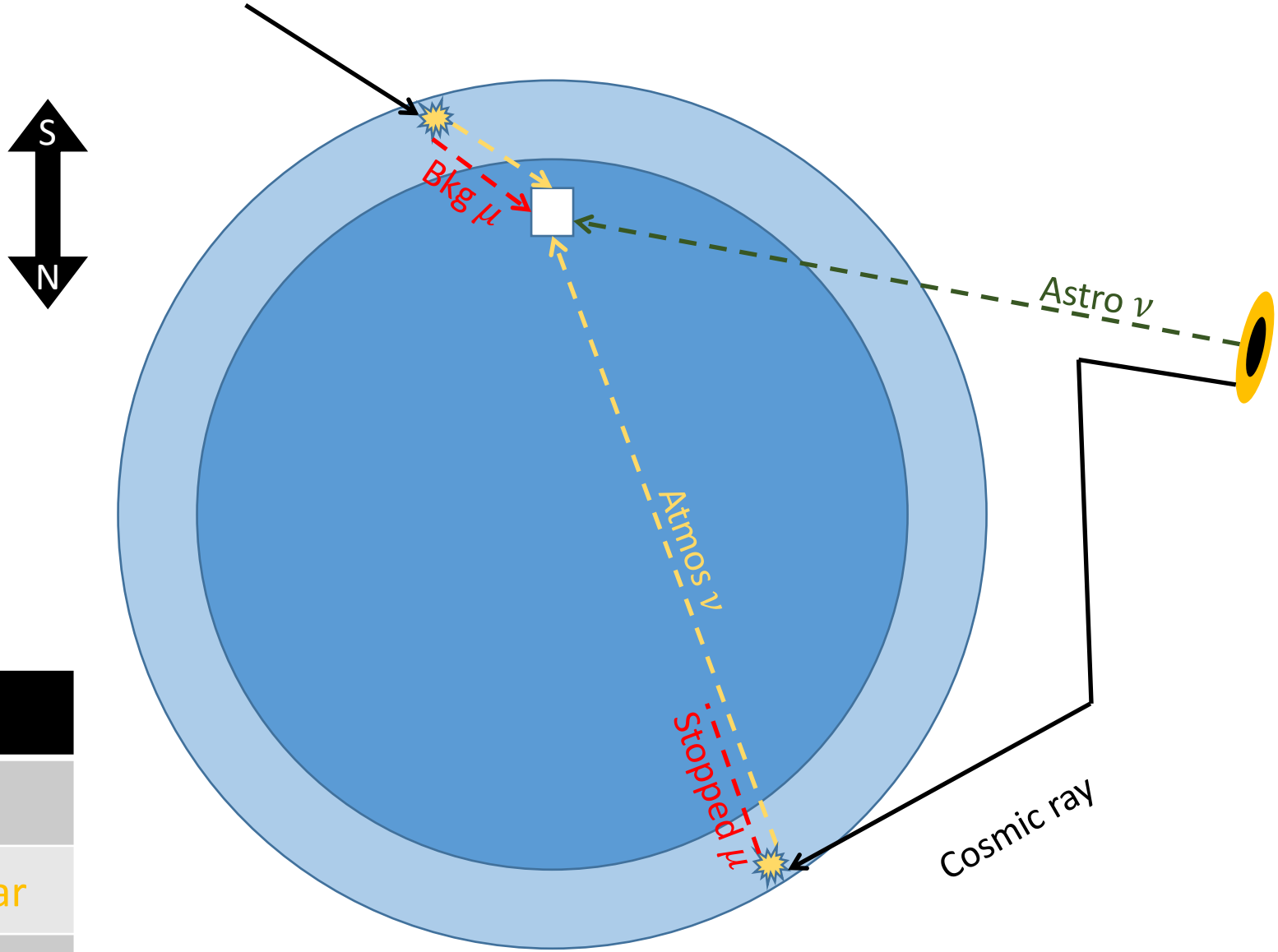




5160 DOMs

Fully operational in 2011

Muons and neutrinos



Event type	Rate
Atmospheric μ	~3 kHz
Atmospheric ν	~100k per year
Astrophysical ν	~100 per year

Detection principles

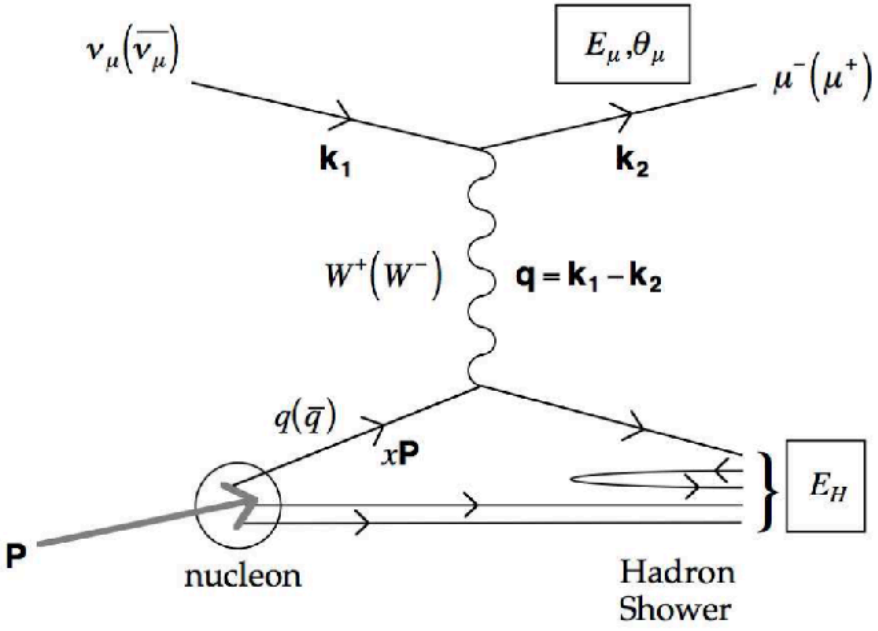
Neutrino interacts via weak force with targets in ice

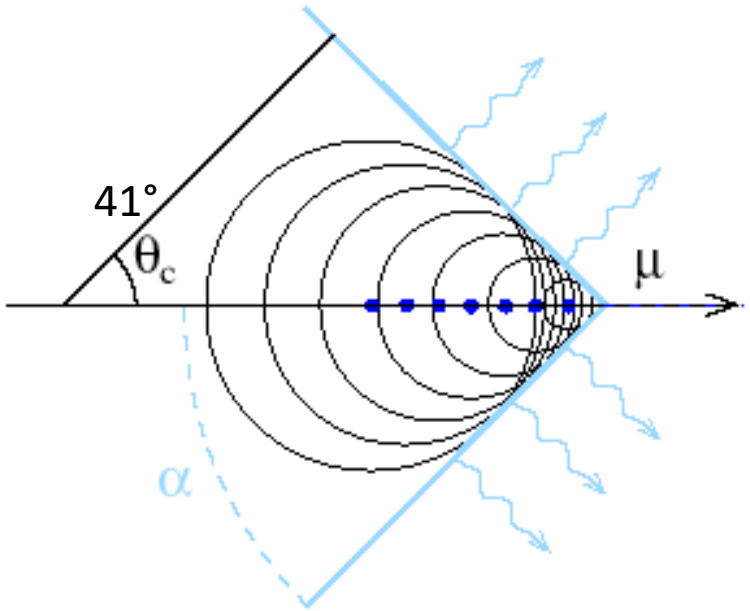
- At IceCube energies, primarily deep-inelastic scattering (DIS) off nucleons

Nucleon breaks apart; outgoing particles may be charged

Charged particles emit Cherenkov radiation detectable by PMTs

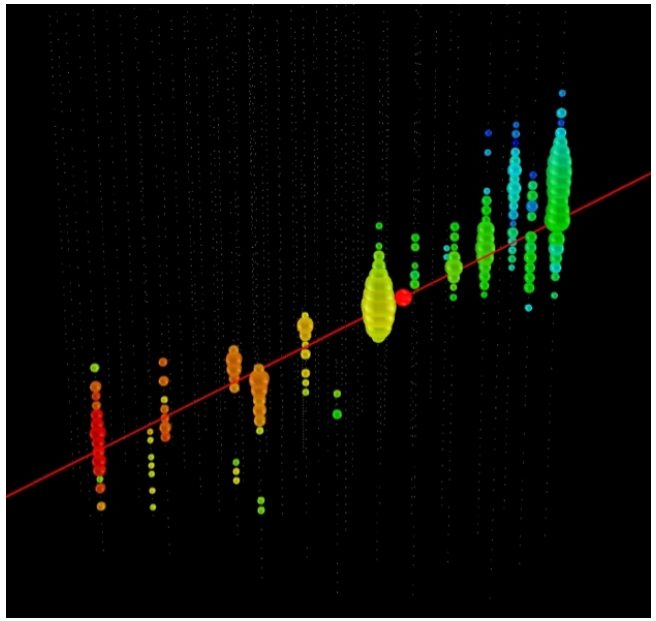
Rev. Mod. Phys. 84, 1307





Event topologies

CC muon neutrino

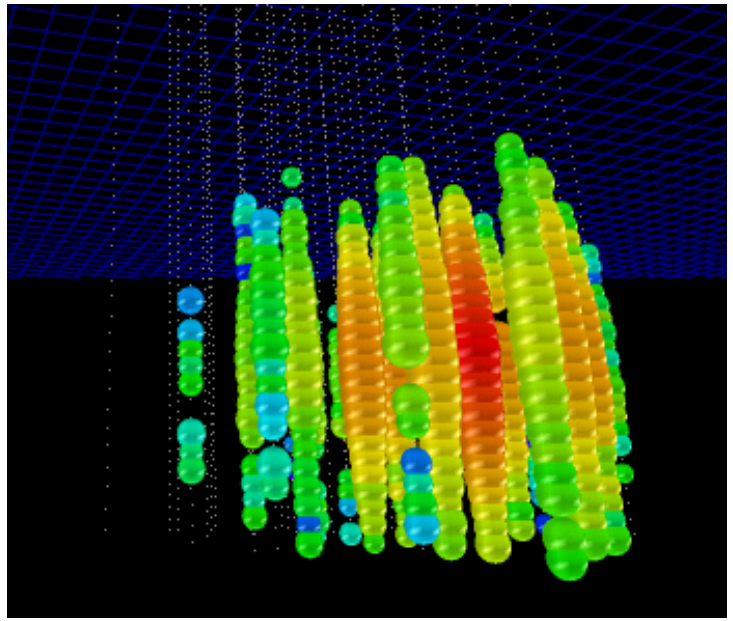


$\nu_\mu + N \rightarrow \mu + X$

track (data)

angular resolution ~ 0.5°
energy resolution ~ x2

NC or CC electron neutrino

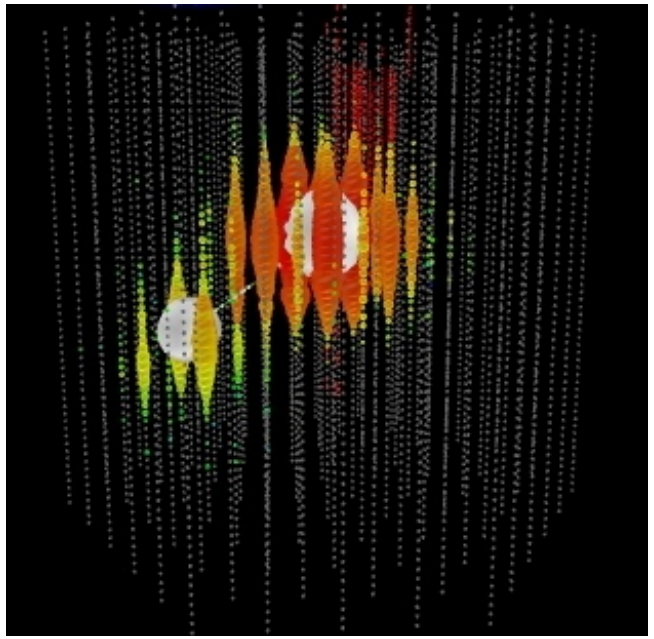


$\nu_e + N \rightarrow e + X$
$\nu_x + N \rightarrow \nu_x + X$

cascade (data)

angular resolution ~ 10°
energy resolution ~ 15%

CC tau neutrino



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

"double-cascade"
(simulation)

~2 expected in 6 years

TeV+ neutrino-nucleon cross section

Up to now two published results

1. Using 79-string IceCube **upgoing** muons *Nature* **551**(2017) 596-600
2. Using public data from 6yr IceCube **cascades** *PRL* **122**(2019) 041101

This talk: cross section using IceCube HESE sample with 7.5 years of data

- **Ternary** PIDs for three neutrino flavors, **full-sky** information, **improved** detector modeling and background calculations

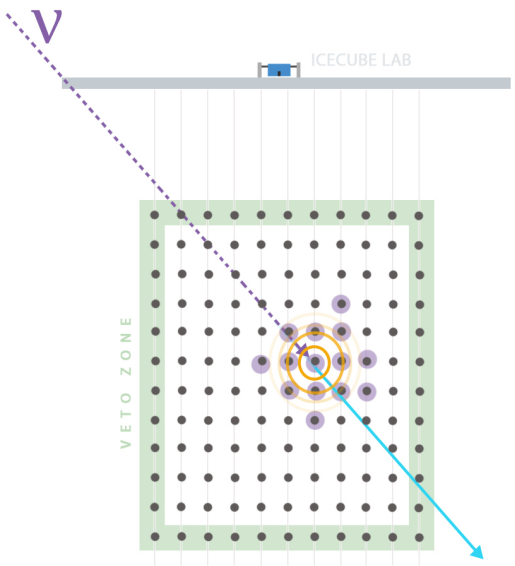
High energy starting event (HESE) selection

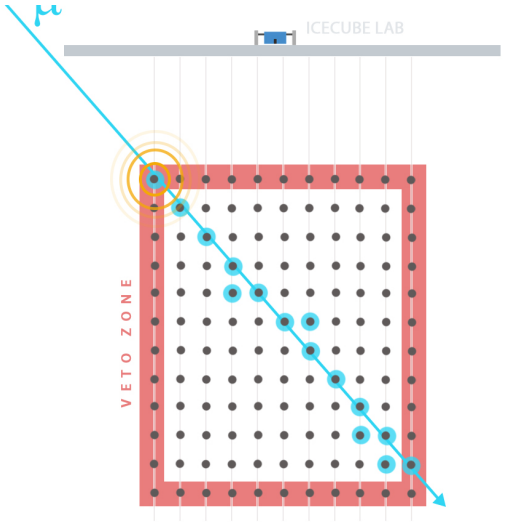
Contained search at high energies

Cut on $Q_{tot} > 6000$ p.e.

Sensitive above **60 TeV**

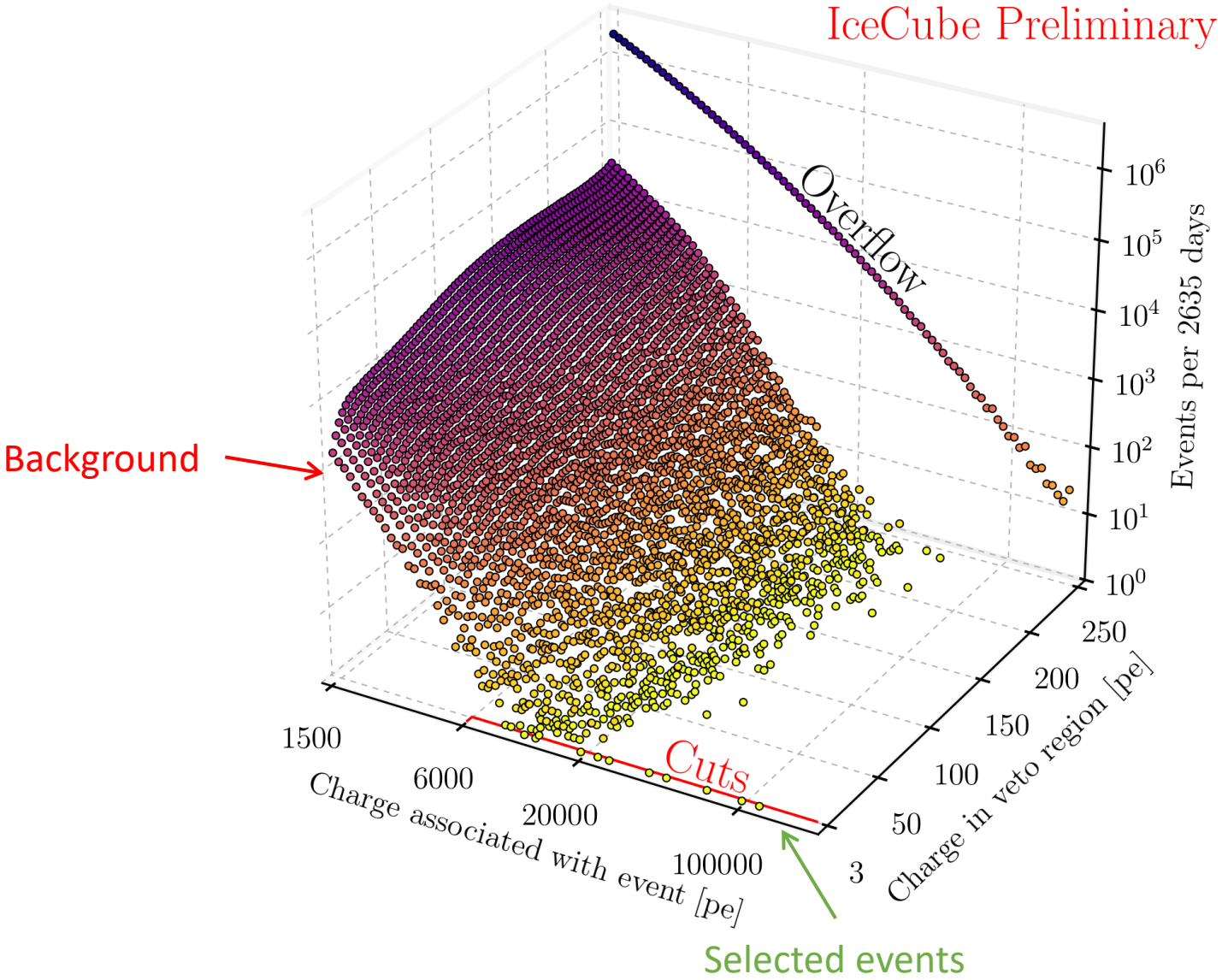
Outer layer acts as **active veto** of atmospheric muon *and* **indirect veto** of atmospheric neutrinos accompanied by sibling muons





Neutrinos in a haystack

Large muon background **rejected** by veto



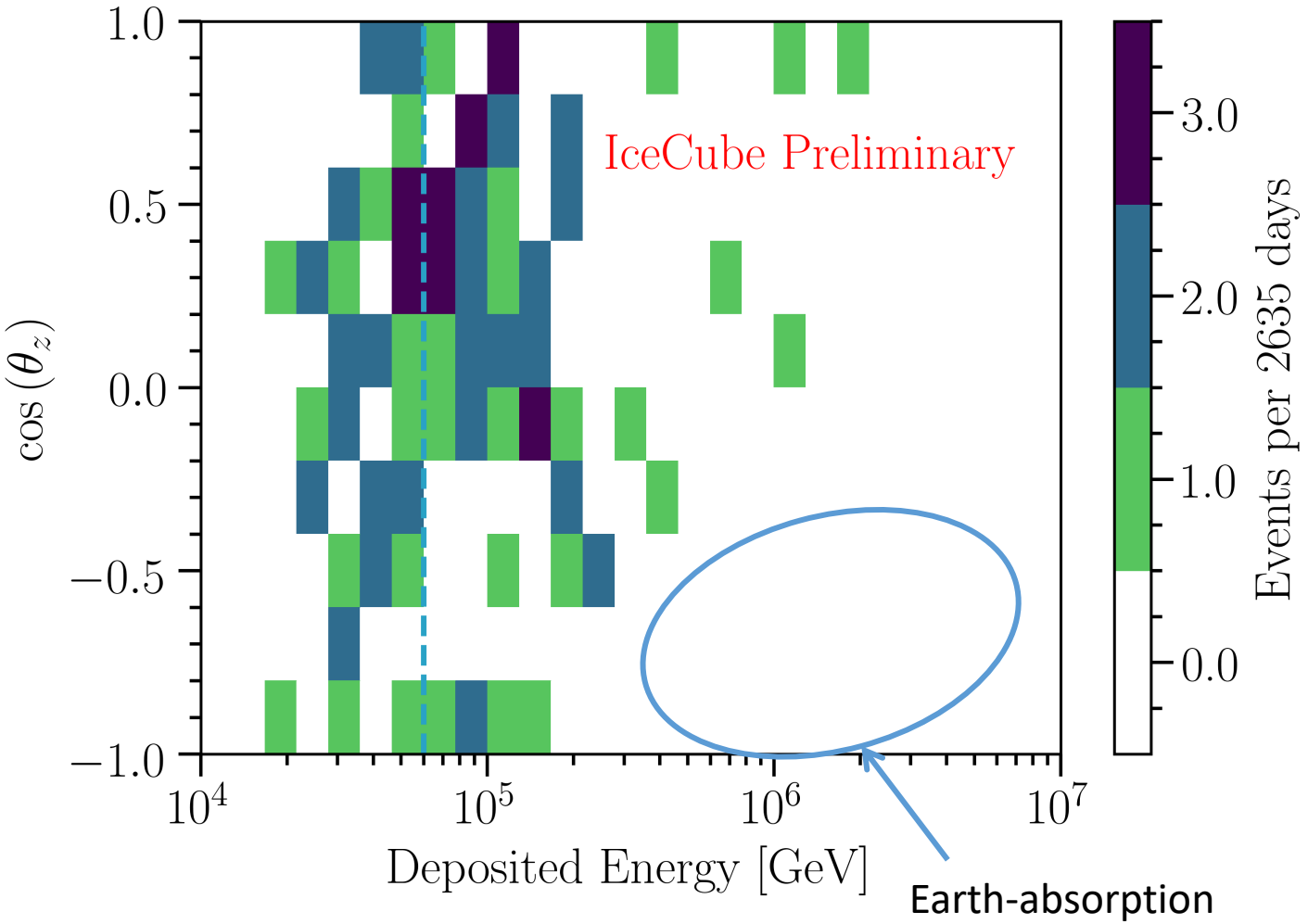
Event distribution in HESE-7.5

102 events, with **60 events >60 TeV**

Fit performed for events above 60 TeV

Updates:

- MC-likelihood **JHEP06(2019) 030**
- Newer ice model and reconstruction
- Updated atmospheric-ν estimate **JCAP 1807 (2018) no.07, 047**
- Additional systematics treatment



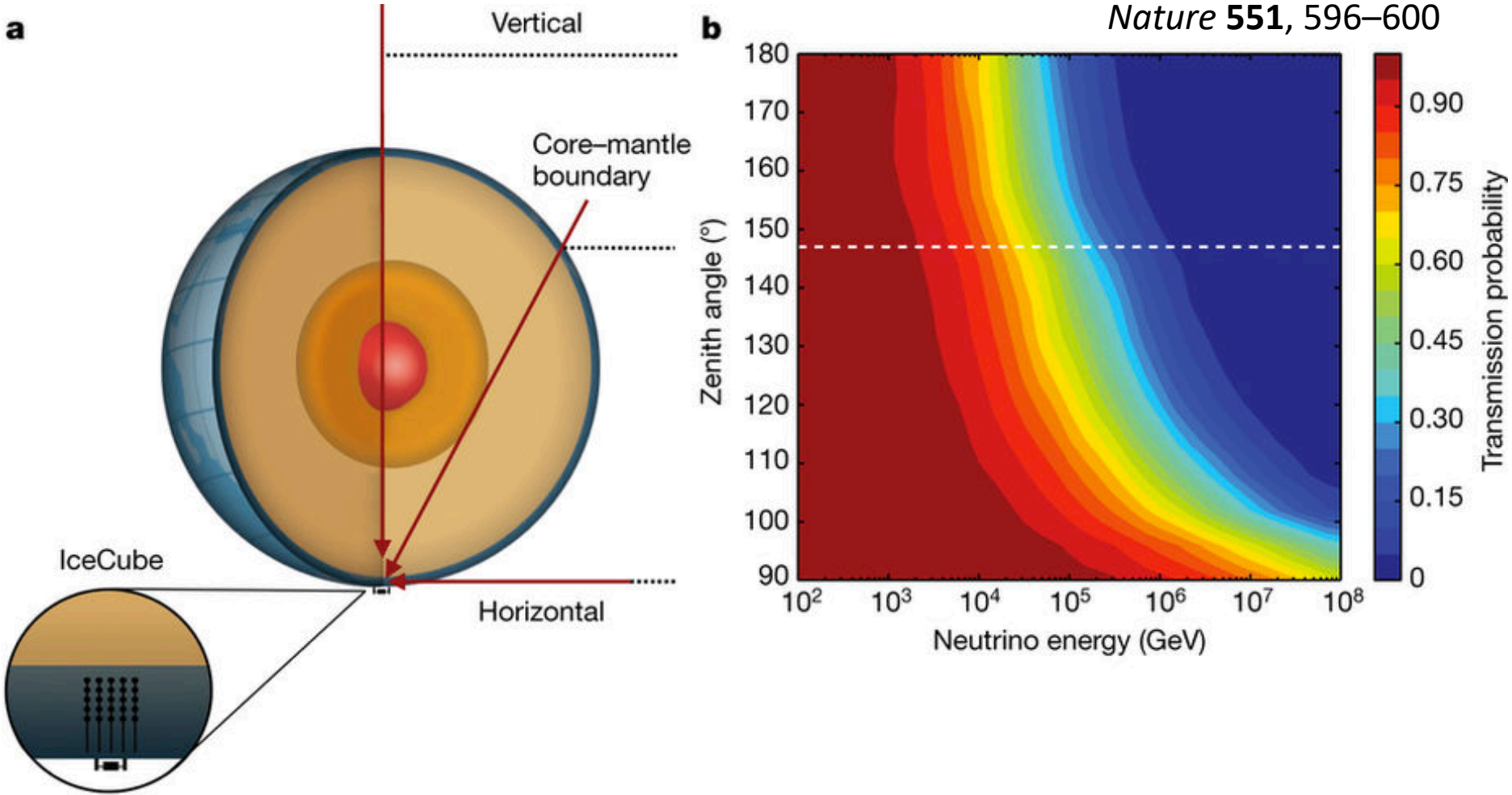
Above 60 TeV:

16 new events in last 1.5 years

In-Earth flux attenuation

High-energy neutrinos interact in the Earth → flux attenuation

Depends on energy E_ν and direction θ_ν

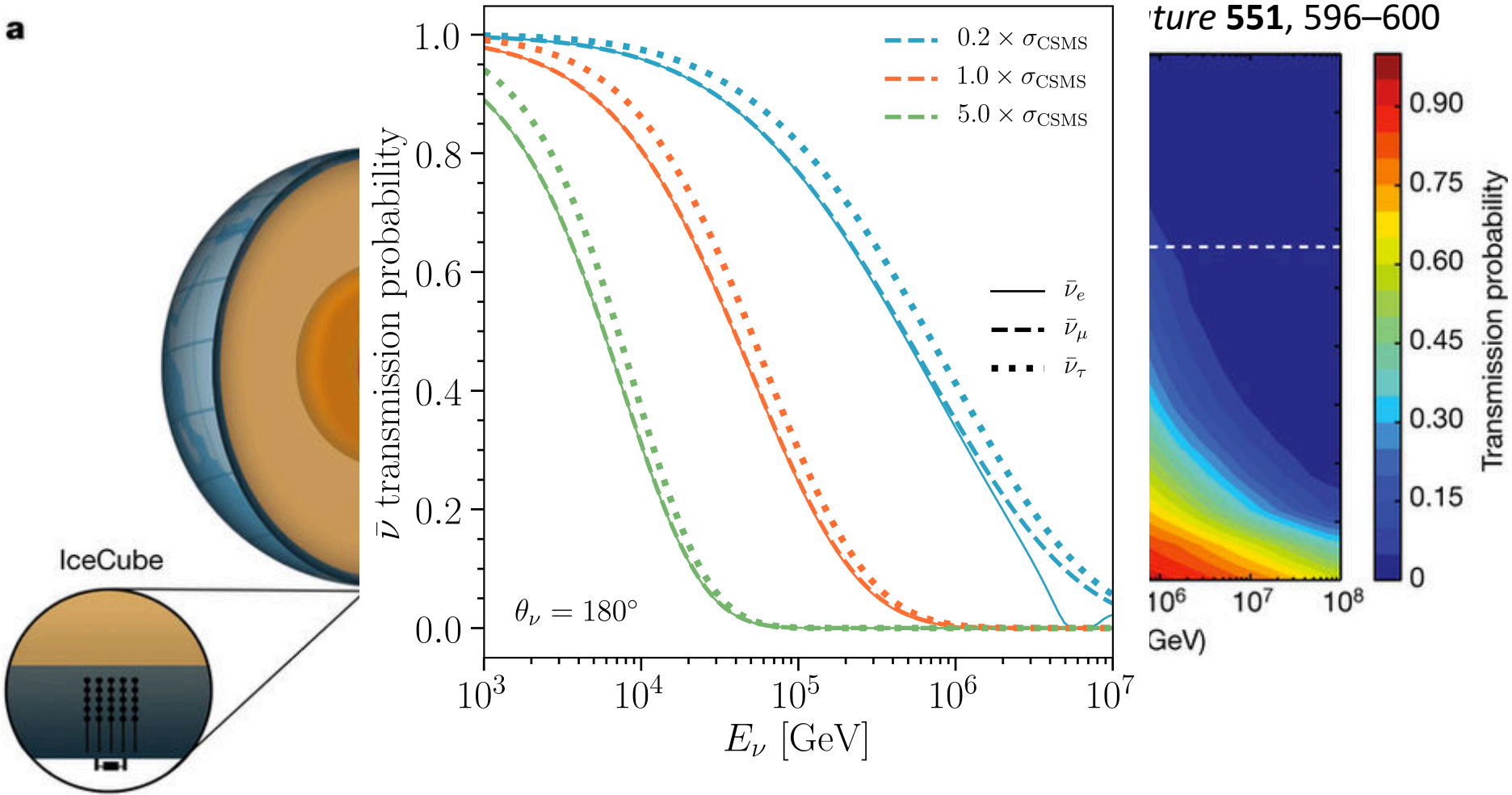


Nature **551**, 596–600

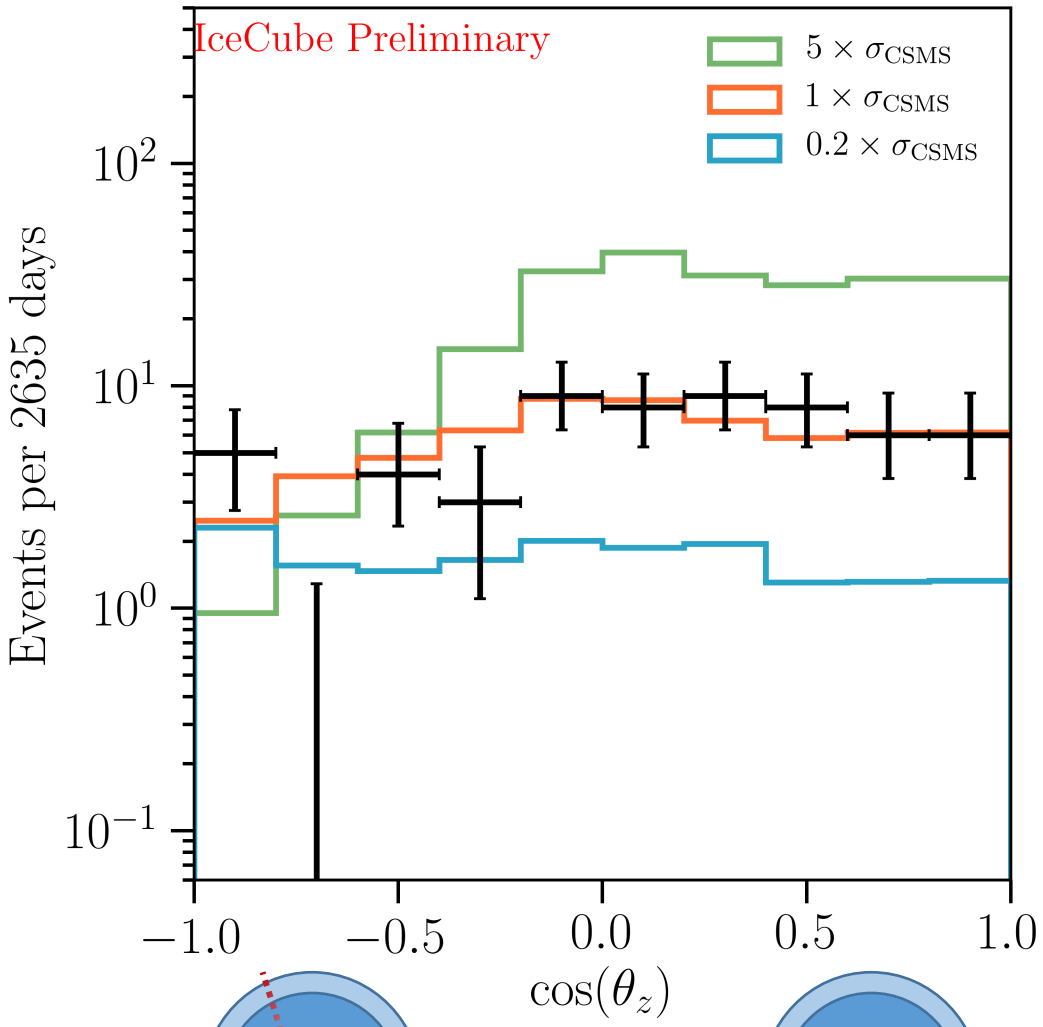
In-Earth flux attenuation

High-energy neutrinos interact in the Earth → flux attenuation

Depends on energy E_ν and direction θ_ν **and cross section**

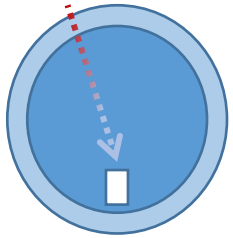


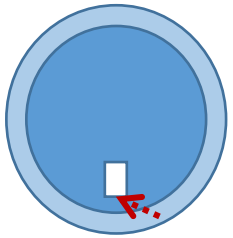
Expected distributions and data



Assuming SPL flux with floating normalization can **measure** cross section

N. sky: Flux attenuation depends on cross section, energy, zenith





S. sky: Event rate **linearly** scales with cross section

Analysis method

Four bins as a function of E_ν, with edges at 60 TeV, 100 TeV, 200 TeV, 500 TeV, and 10 PeV

- Denoted as: x_0, x_1, x_2, x_3

Scale nominal neutrino-nucleon cross section (CSMS) in each bin separately

- Assume: fixed σ_{CC}/σ_{NC} ratio, fixed $\sigma_\nu/\sigma_{\bar{\nu}}$ ratio, single-power-law flux

Varied cross section leads to different **MC expectations**

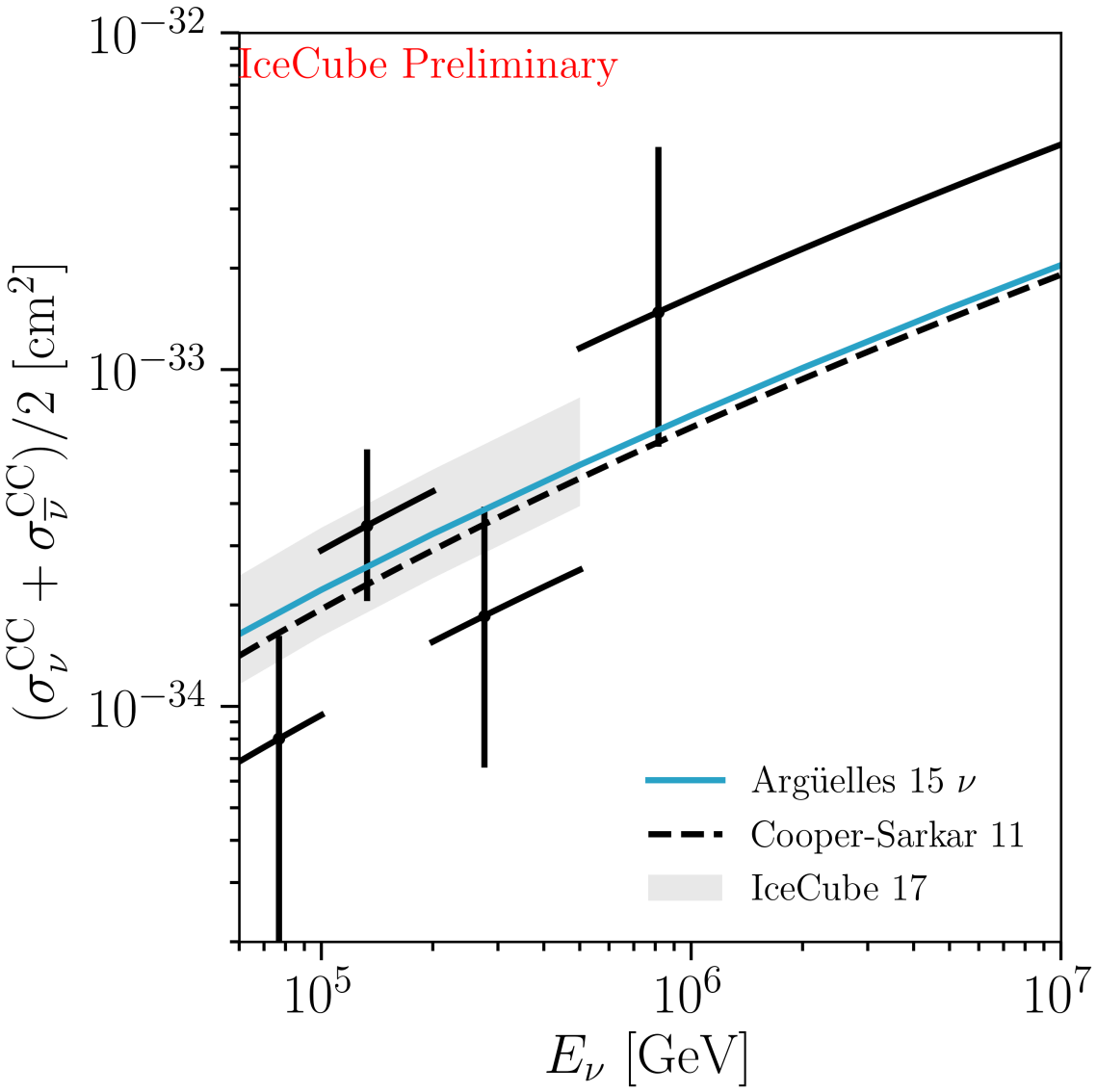
Profile-llh scan for frequentist result or **MCMC** for Bayesian posterior

Systematics and priors/constraints

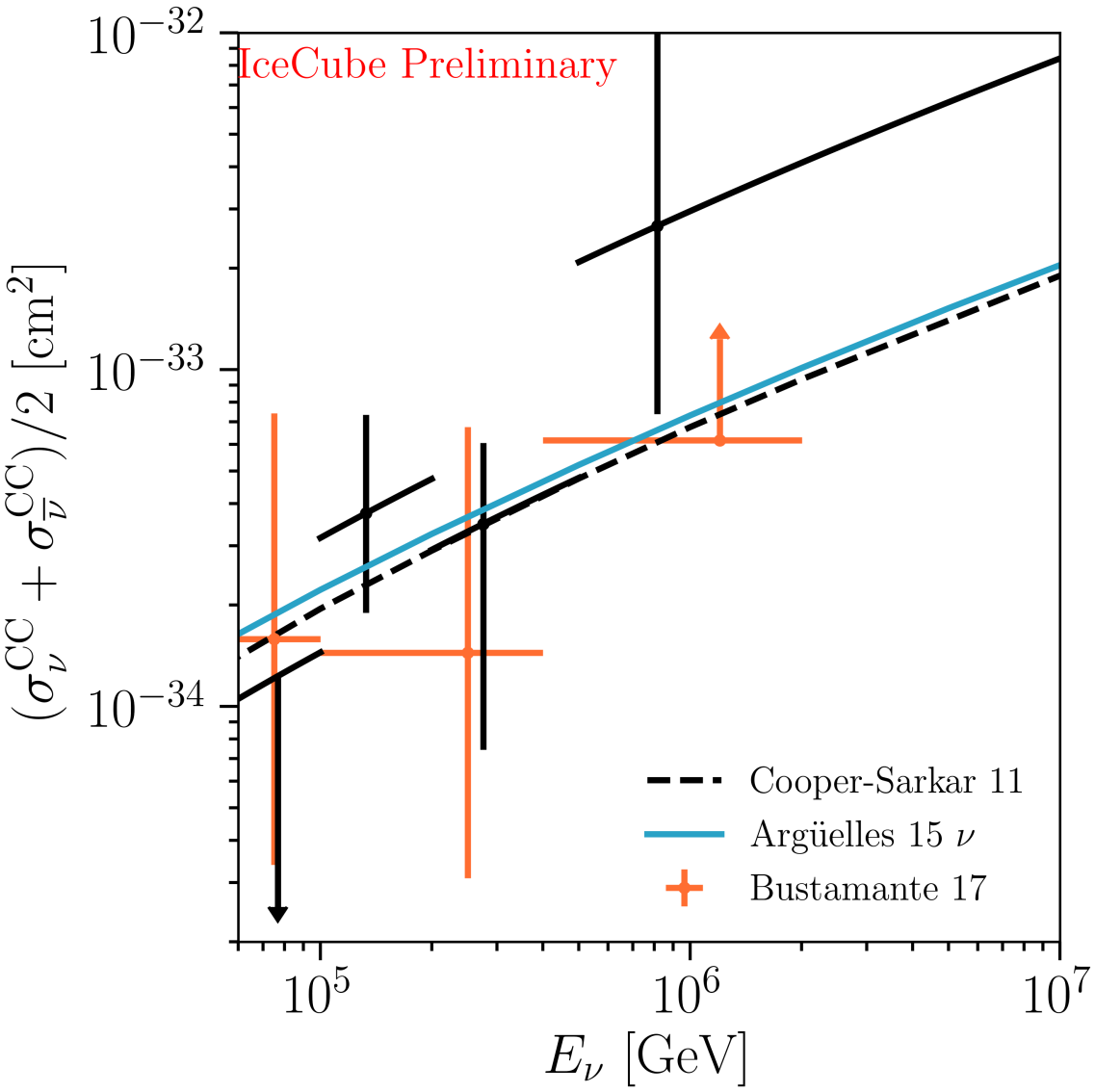
Parameter	Constraint/Prior	Range
Astrophysical neutrino flux:		
$\Phi_{\texttt{astro}}$	-	$[0, \infty)$
$\gamma_{\texttt{astro}}$	2.0 ± 1.0	$(-\infty, \infty)$
Atmospheric neutrino flux:		
$\Phi_{\texttt{conv}}$	1.0 ± 0.4	$[0, \infty)$
$\Phi_{\texttt{prompt}}$	1.0 ± 3.0	$[0, \infty)$
π/K	1.0 ± 0.1	$(-\infty, \infty)$
$2\nu/(\nu + \bar{\nu})_{\texttt{atmo}}$	1.0 ± 0.1	$[0, 2]$
Cosmic ray flux:		
$\Delta\gamma_{\texttt{CR}}$	-0.05 ± 0.05	$(-\infty, \infty)$
Φ_{μ}	1.0 ± 0.5	$[0, \infty)$

High-energy neutrino cross section

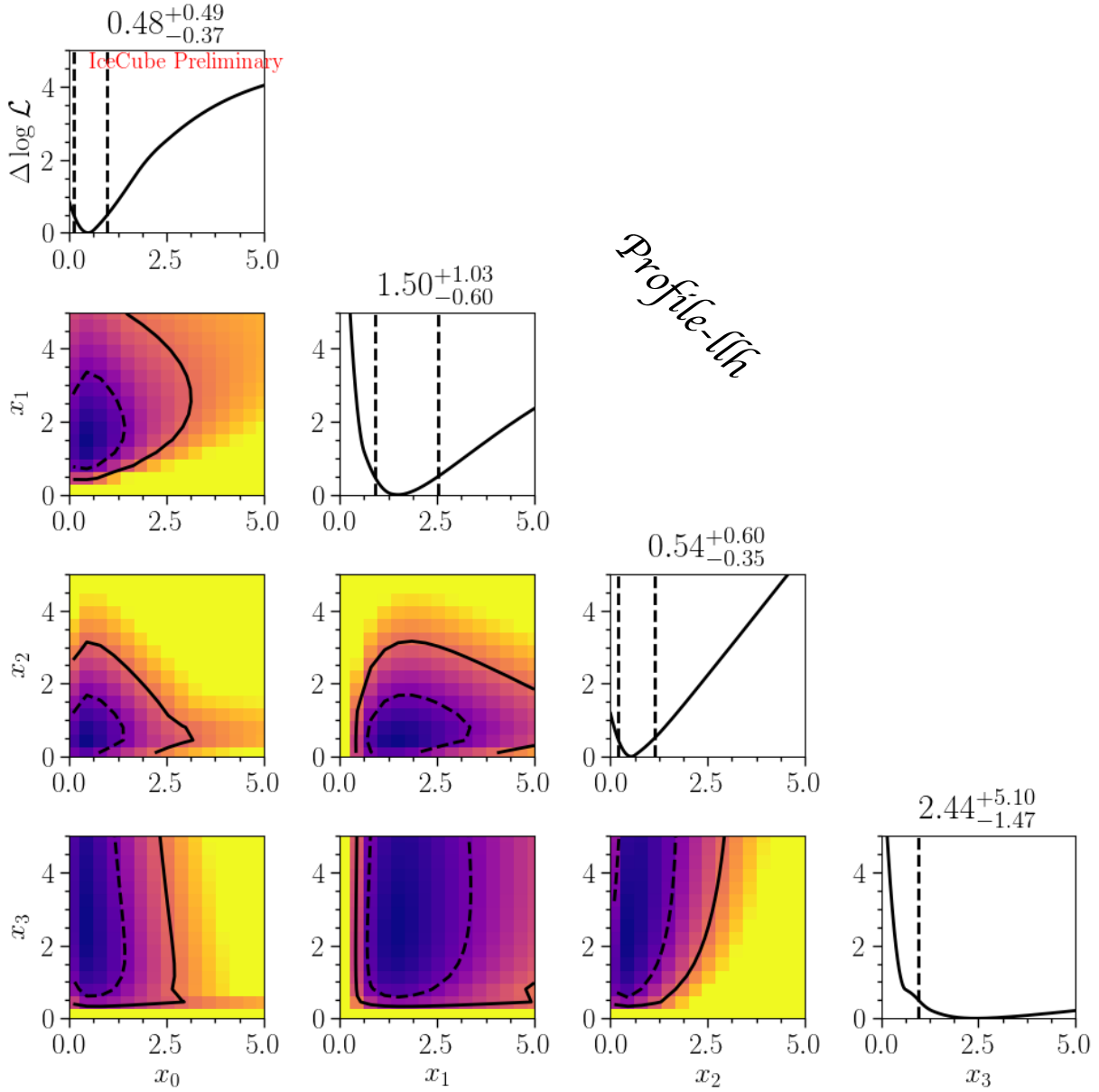
Frequentist result

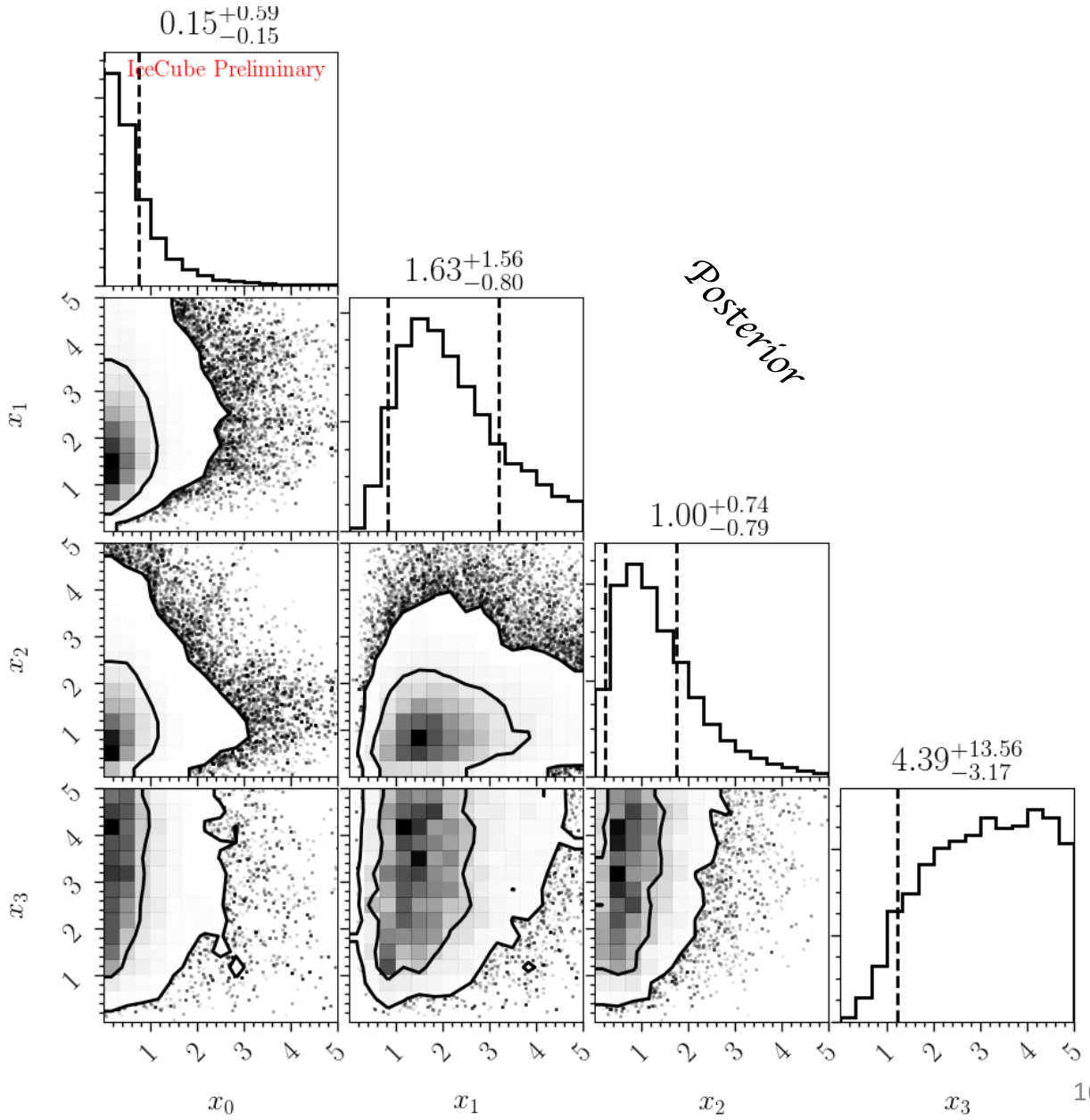


Bayesian result



Likelihood and posterior





Conclusions

High-energy starting event sample with 7.5 years of data with several updates and improvements

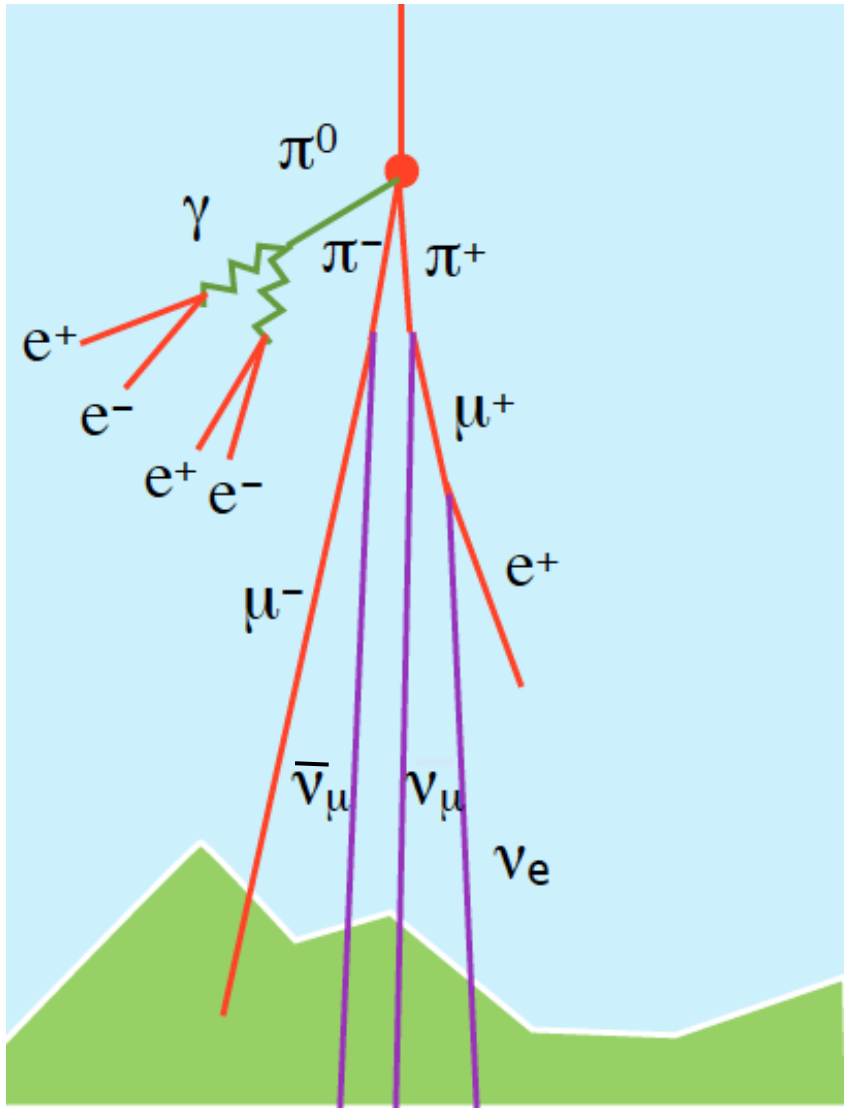
Neutrino-nucleon cross section measured via forward-folding likelihood

Frequentist and Bayesian results obtained

Paper in preparation

Backups

Atmospheric neutrinos



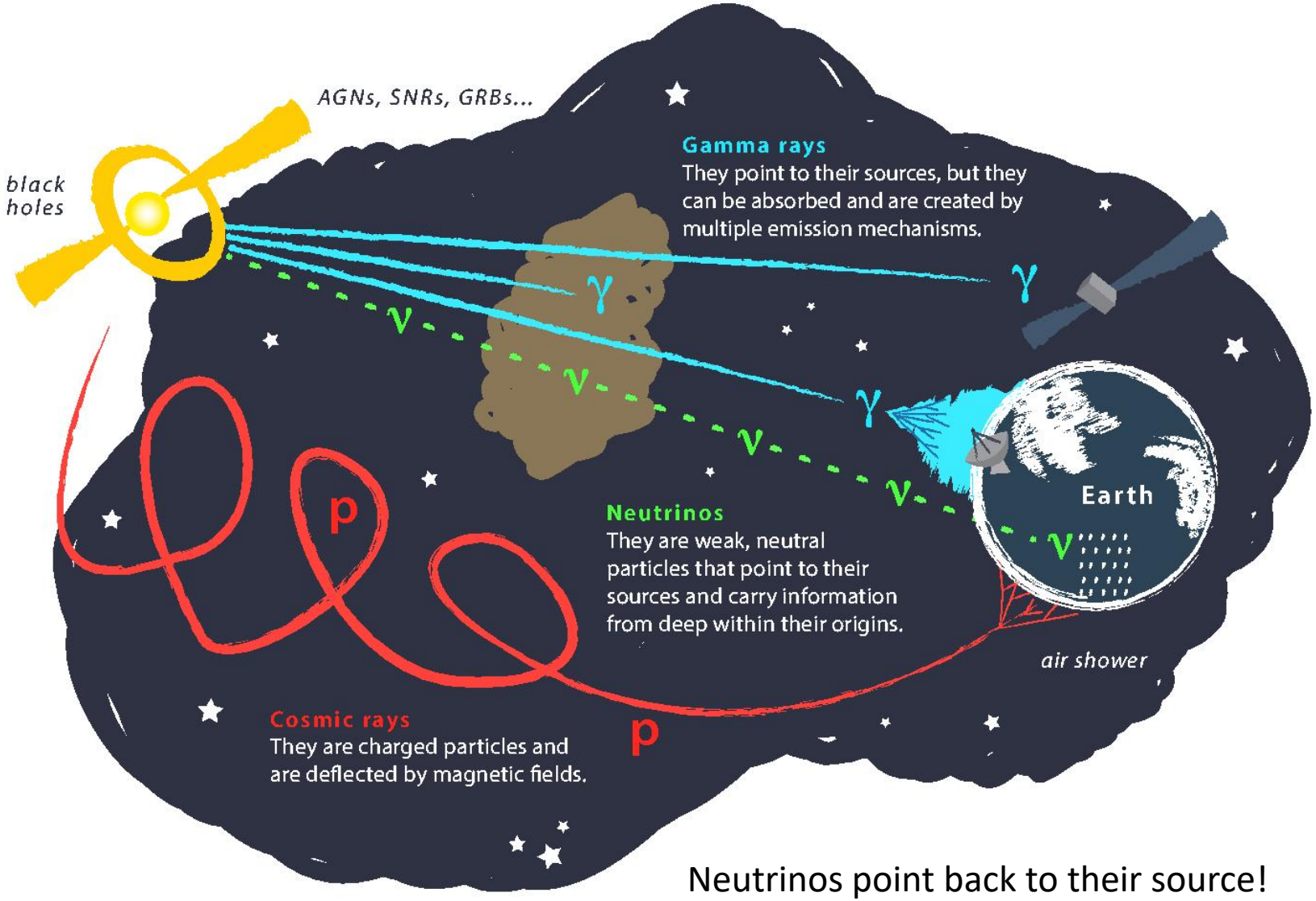
Conventional atmospheric: Parent particle is pion or kaon; longer lifetime

Prompt atmospheric: Parent particle contains a charm quark; short lifetime

Signal for neutrino oscillation measurements

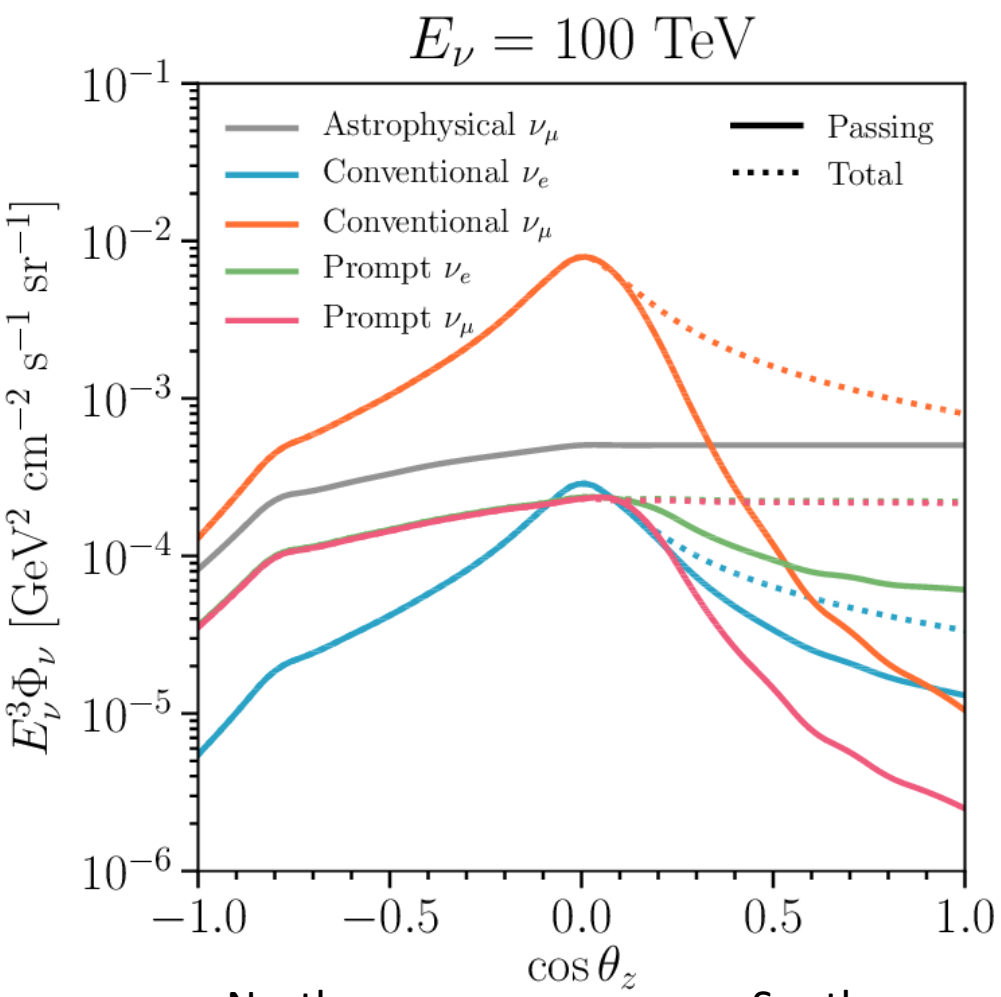
Background for astrophysical neutrino searches

Astrophysical neutrinos as a window to our Universe



Neutrinos point back to their source!

Atmospheric neutrino passing fractions



Northern sky

Southern sky

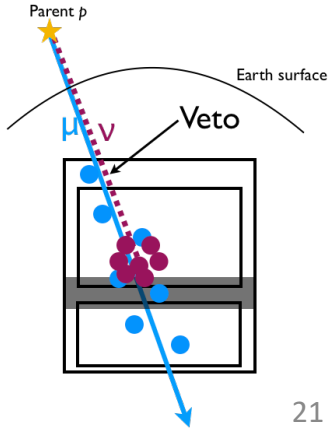
Pile-up MC challenging

Passing fraction: ratio of solid to dotted lines

- $\mathcal{P}_{pass}(E_\nu, \theta_z) = \frac{\phi_\nu^{pass}(E_\nu,\theta_z)}{\phi_\nu\,(E_\nu,\theta_z)}$
- Apply via **reweighting** MC atmospheric neutrinos

Breaks degeneracy between astrophysical and prompt fluxes

Drives current bound on prompt



Flux correlations