IceCube: A ν-window into the Universe

Tianlu Yuan

University of Wisconsin-Madison & WIPAC

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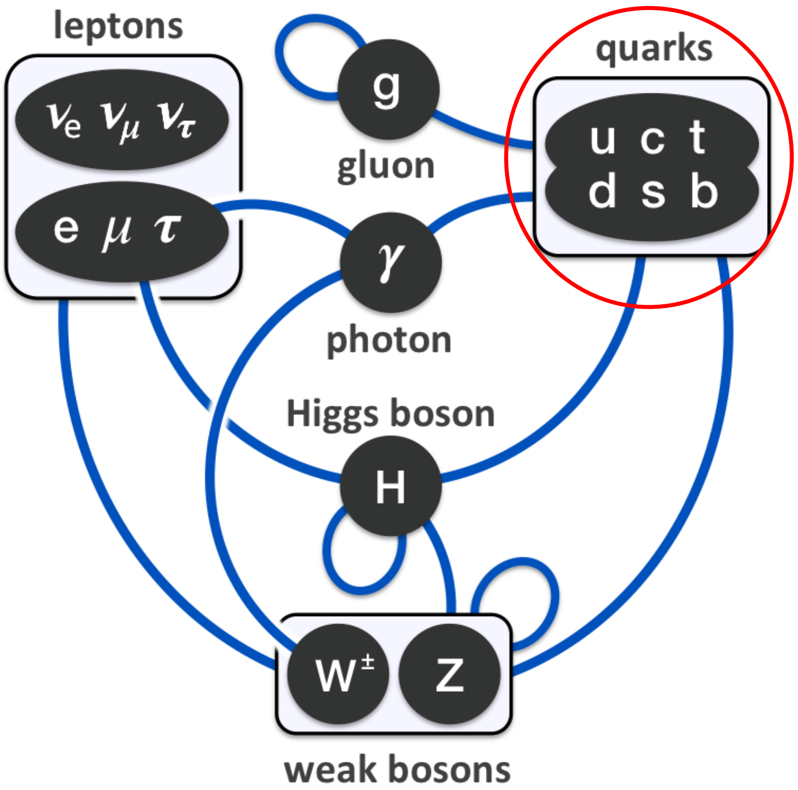
Credit: F. Pedreros, IceCube/NSF

In the Standard Model

There are…

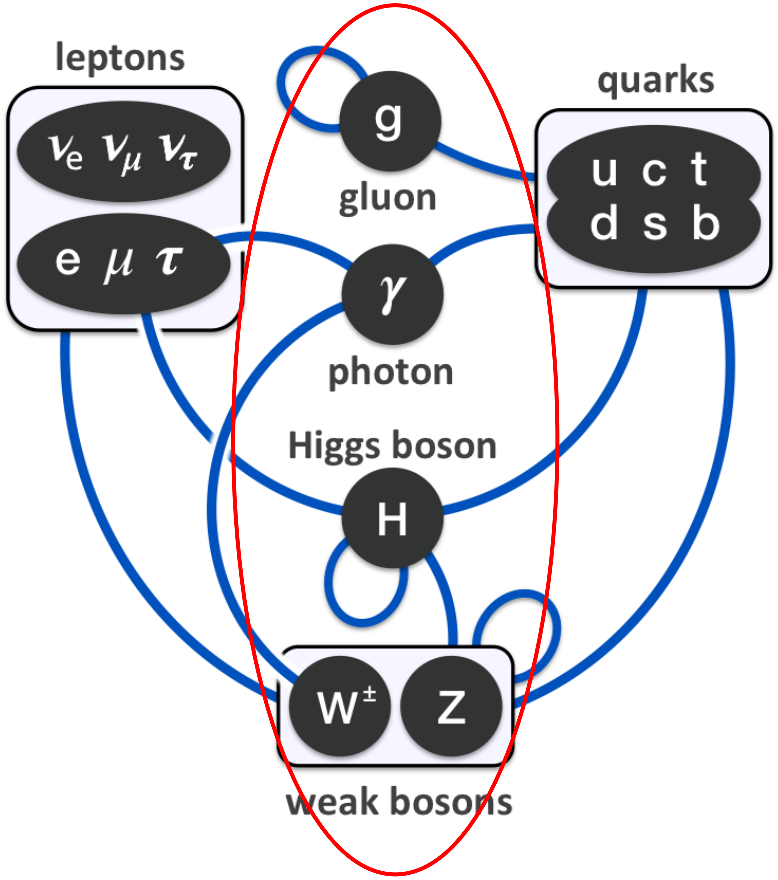
1. quarks, which make up composite particles like protons and neutrons



In the Standard Model

There are…

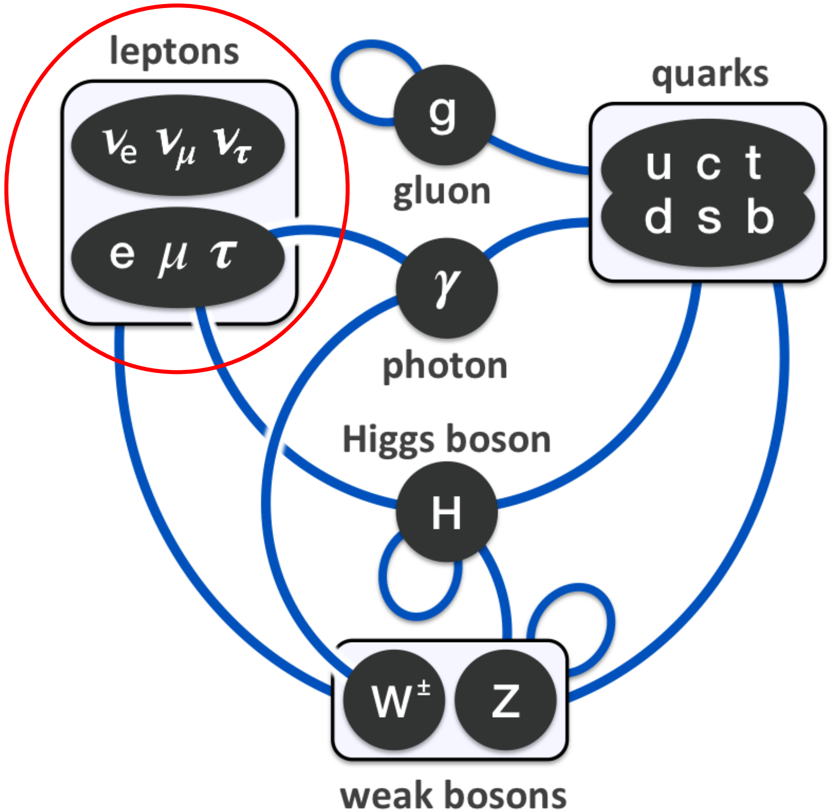
1. quarks, which make up composite particles like protons and neutrons
2. force carriers, bosons which mediate the fundamental interactions



In the Standard Model

There are…

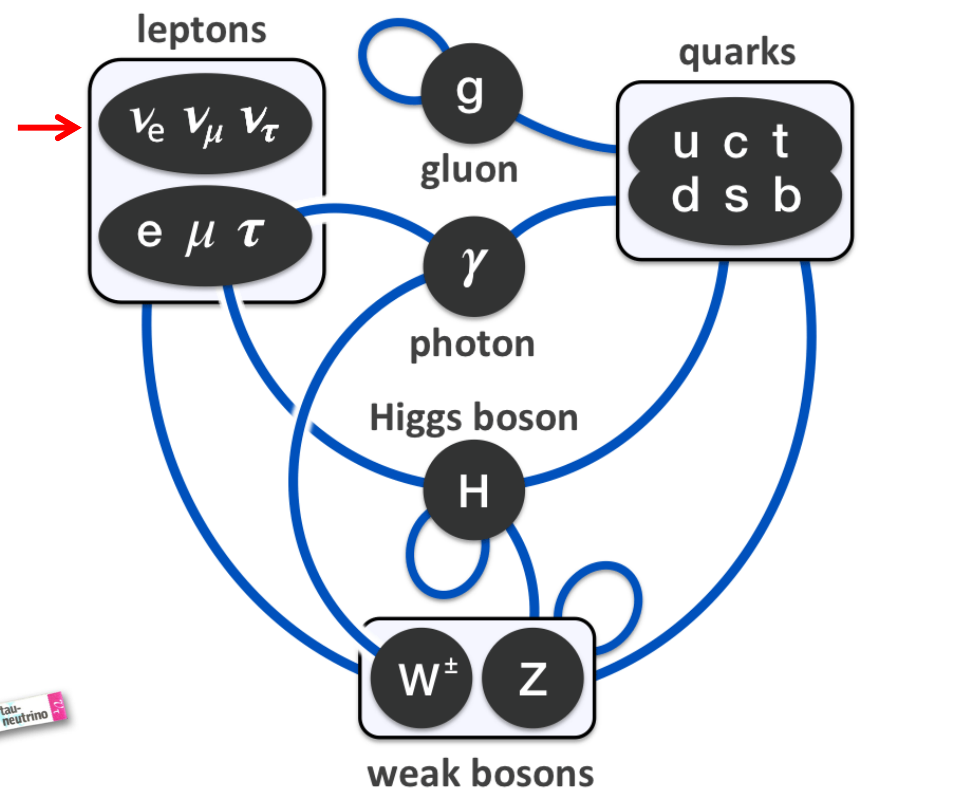
1. quarks, which make up composite particles like protons and neutrons
2. force carriers, bosons which mediate the fundamental interactions
3. leptons, electroweak elementary particles



Neutrino properties

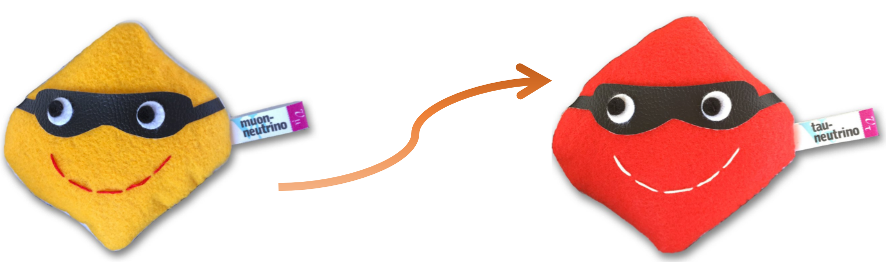
Neutrinos…

- are neutral leptons
- only interact through the weak force
- come in three flavors corresponding to their charged lepton counterparts



Neutrinos have nonzero mass

- Discovered via **oscillations**



Oscillation

Mass eigenstate in a superposition of flavor (measured) eigenstates

$$|\nu_i\rangle = \sum_\alpha U_{\alpha i}|\nu_\alpha\rangle$$

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix

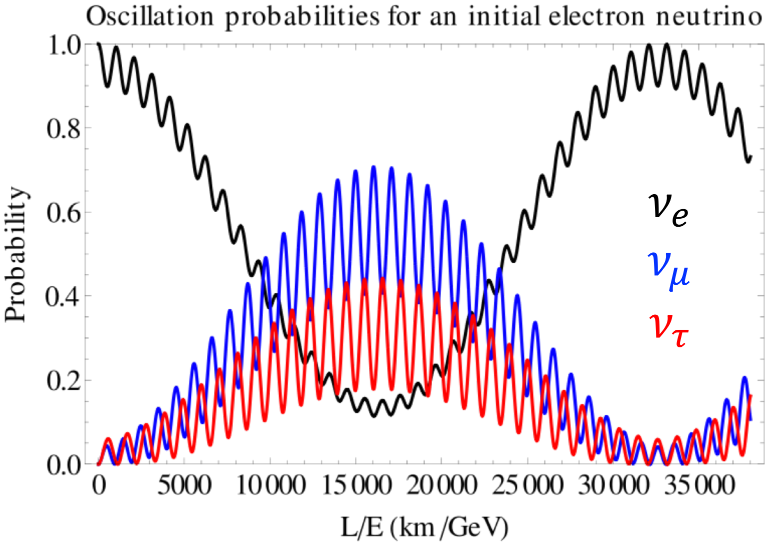
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij} \text{ and } c_{ij} = \cos\theta_{ij}$$

Leads to non-zero oscillation probability

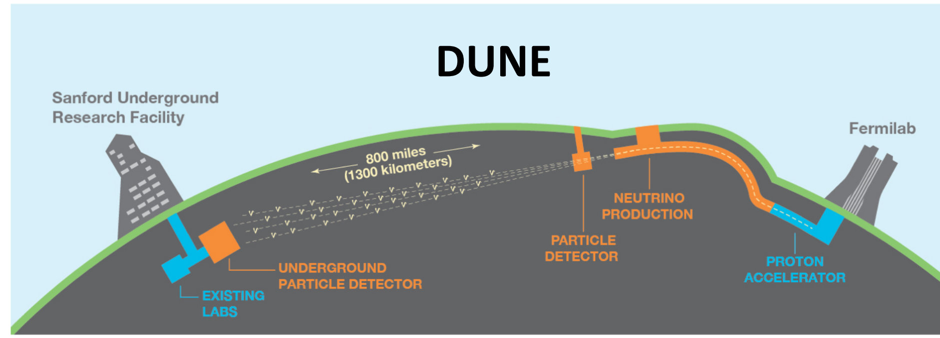
$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} \exp\left(-i\frac{\Delta m^2_{kj} L}{2E}\right)$$

Experiments know L/E

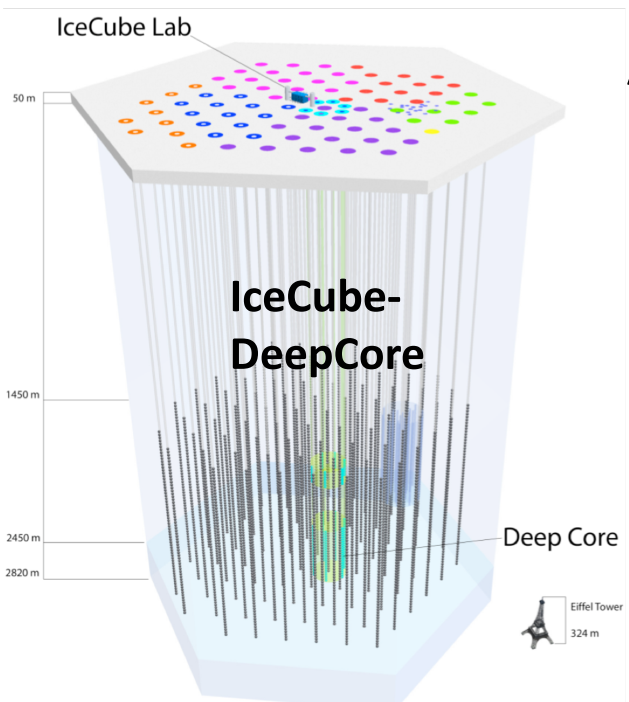


Measuring neutrino properties

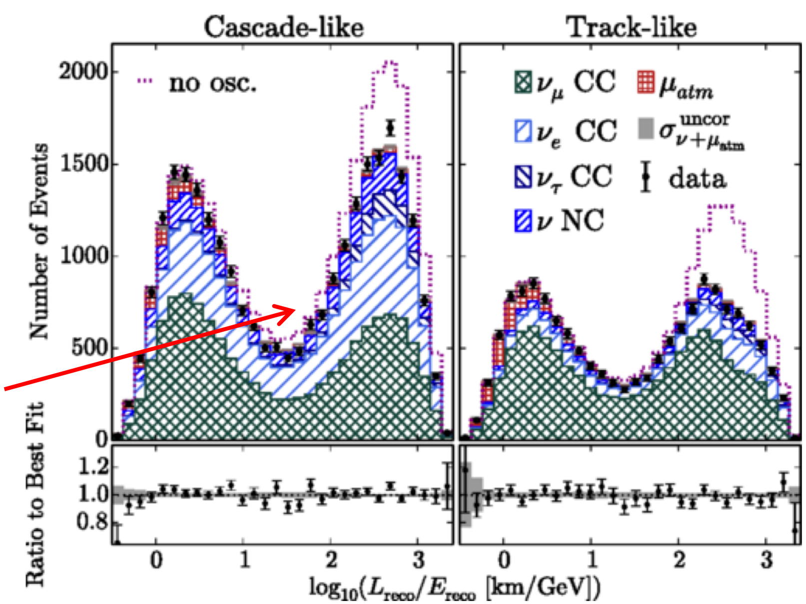
Long-baseline accelerator



Atmospheric



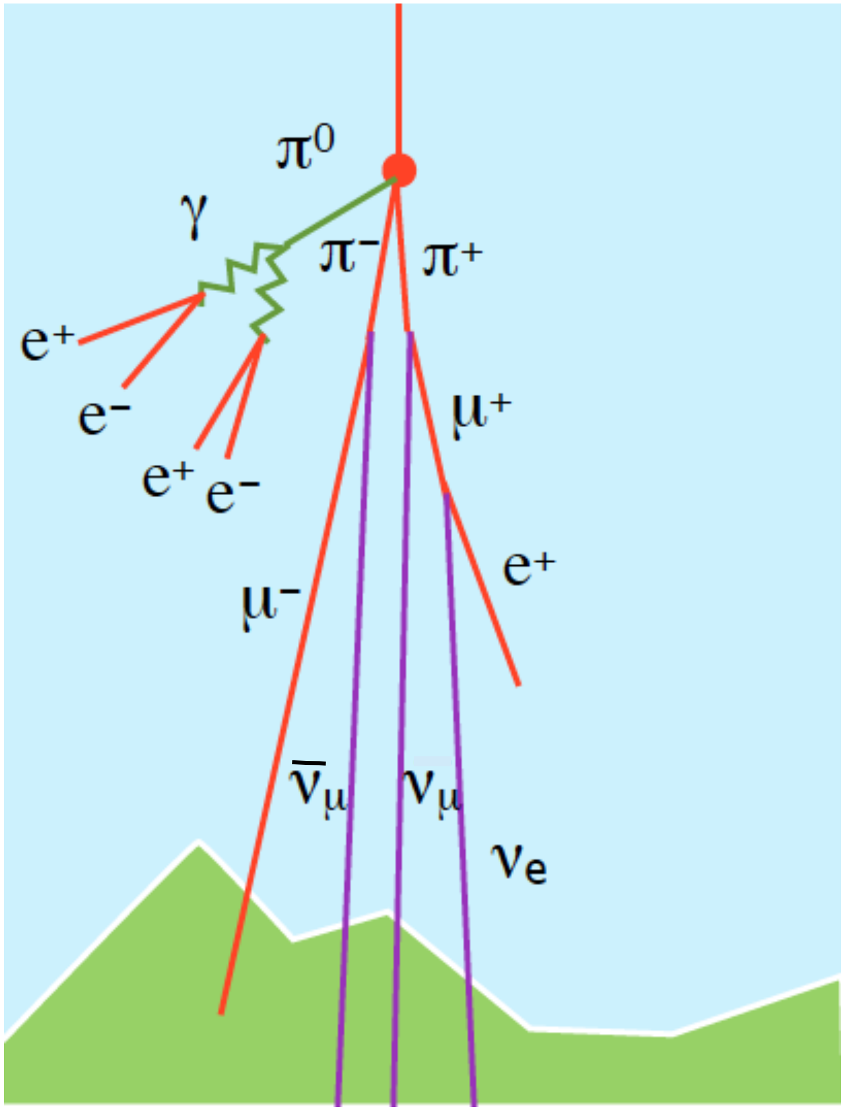
PRL **120**, 071801



Oscillation visible
in up-going peak

Neutrinos produced in the atmosphere

Atmospheric shower



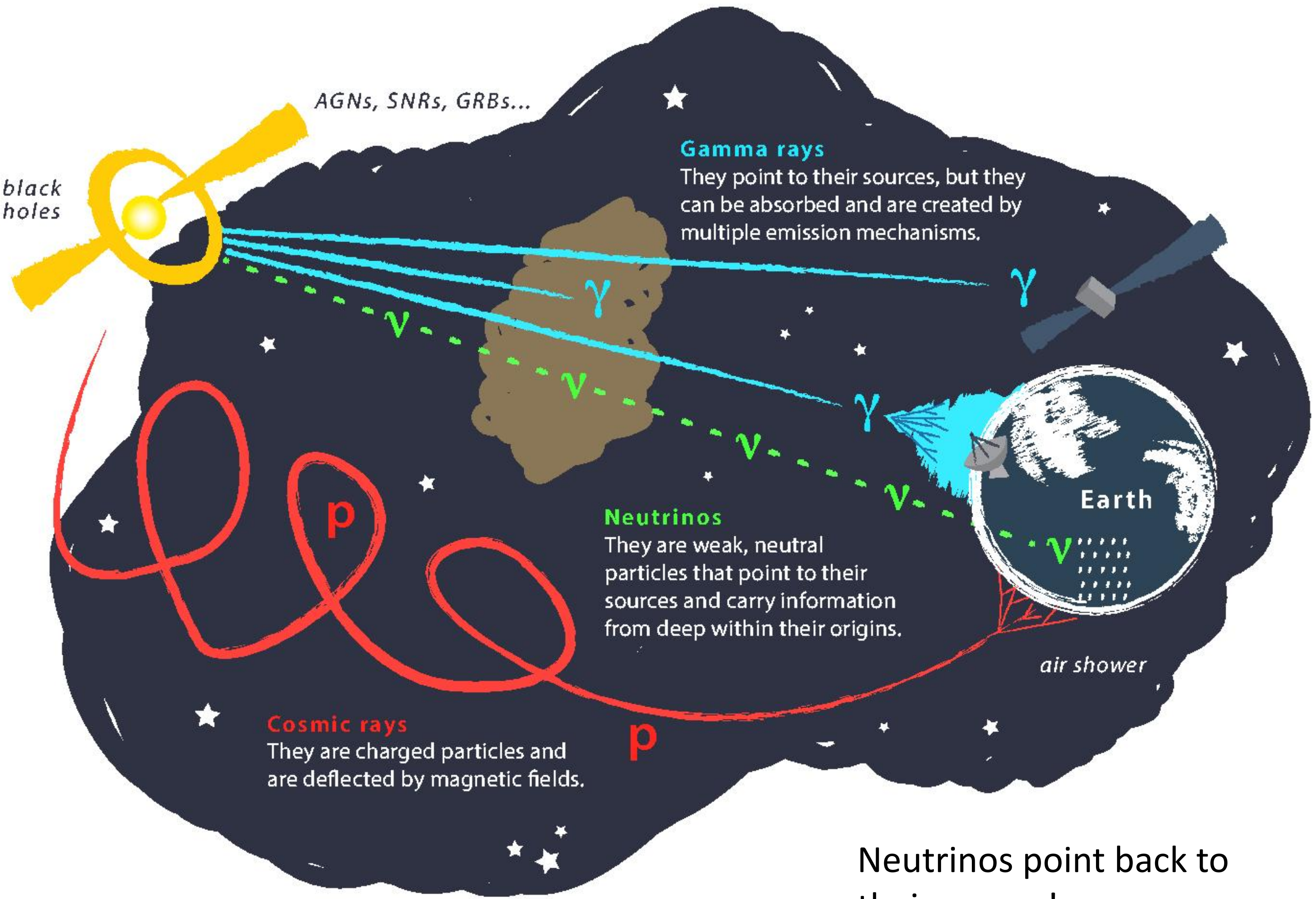
Conventional atmospheric: Parent particle is pion or kaon; longer lifetime

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

Signal for IceCube oscillation measurements

Background for astrophysical neutrino searches

Astrophysical neutrinos as a window to our Universe



Neutrinos point back to their source!

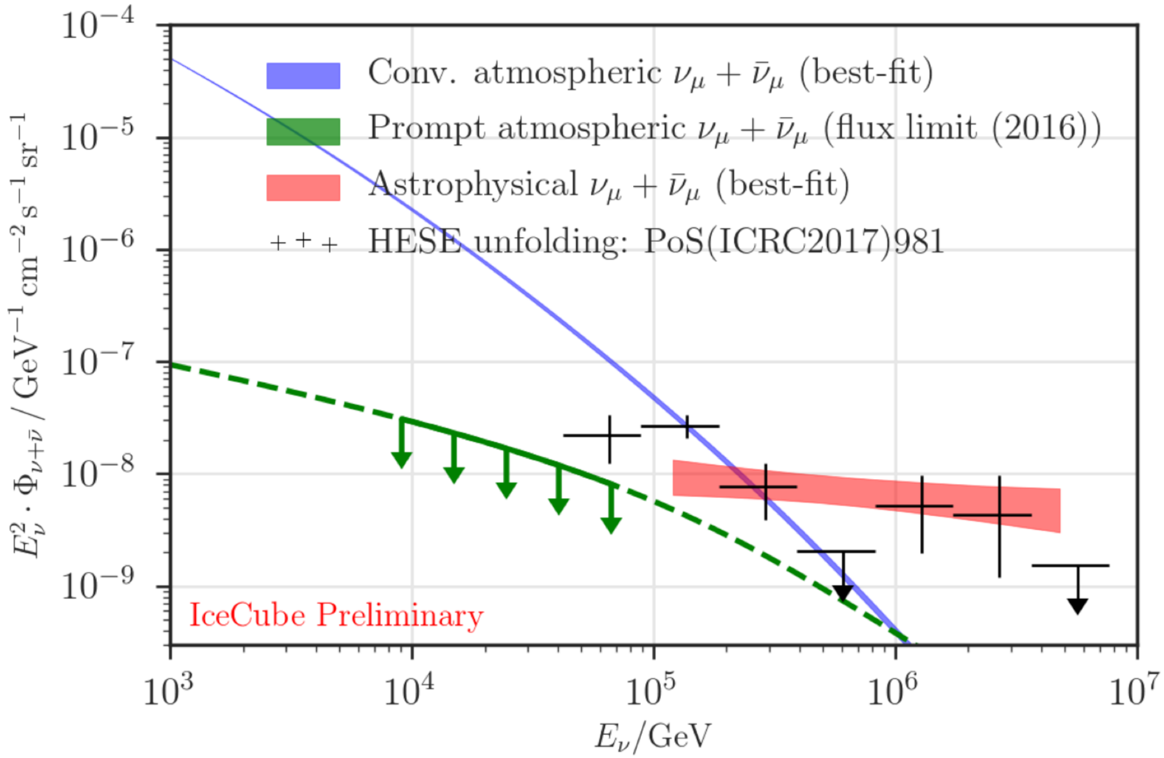
A neutrino telescope

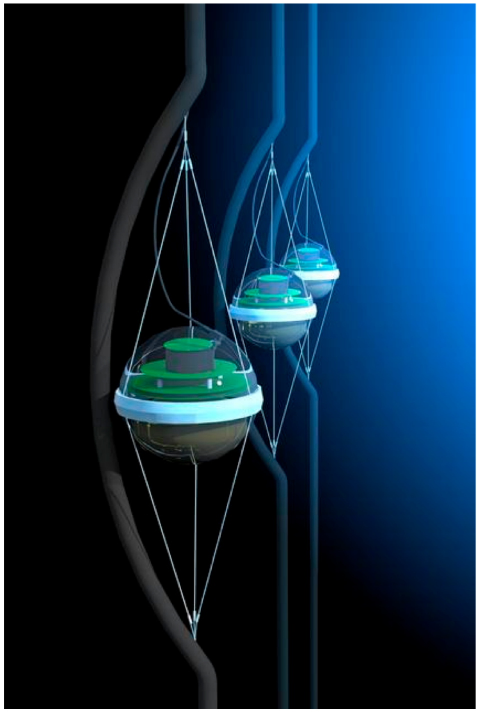
Steeply falling neutrino flux is partially compensated by increasing cross-section as function of energy

Still, need **large-volume** detector for **PeV-scale** neutrinos

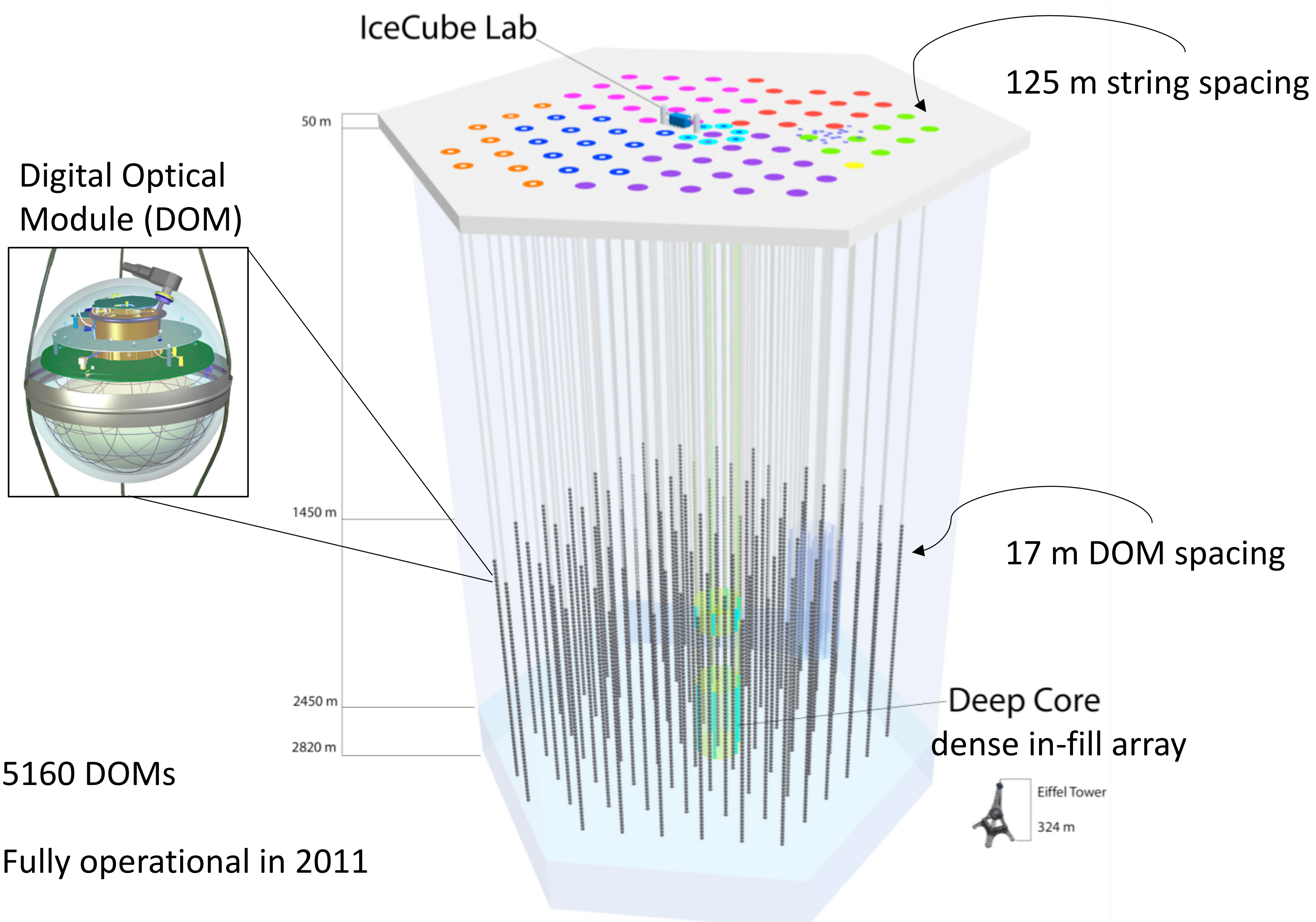
South-Pole ice is extremely clear, why not use as detector medium and place some PMTs in it?

C. Haack, ICRC2017





IceCube



5160 DOMs

Fully operational in 2011

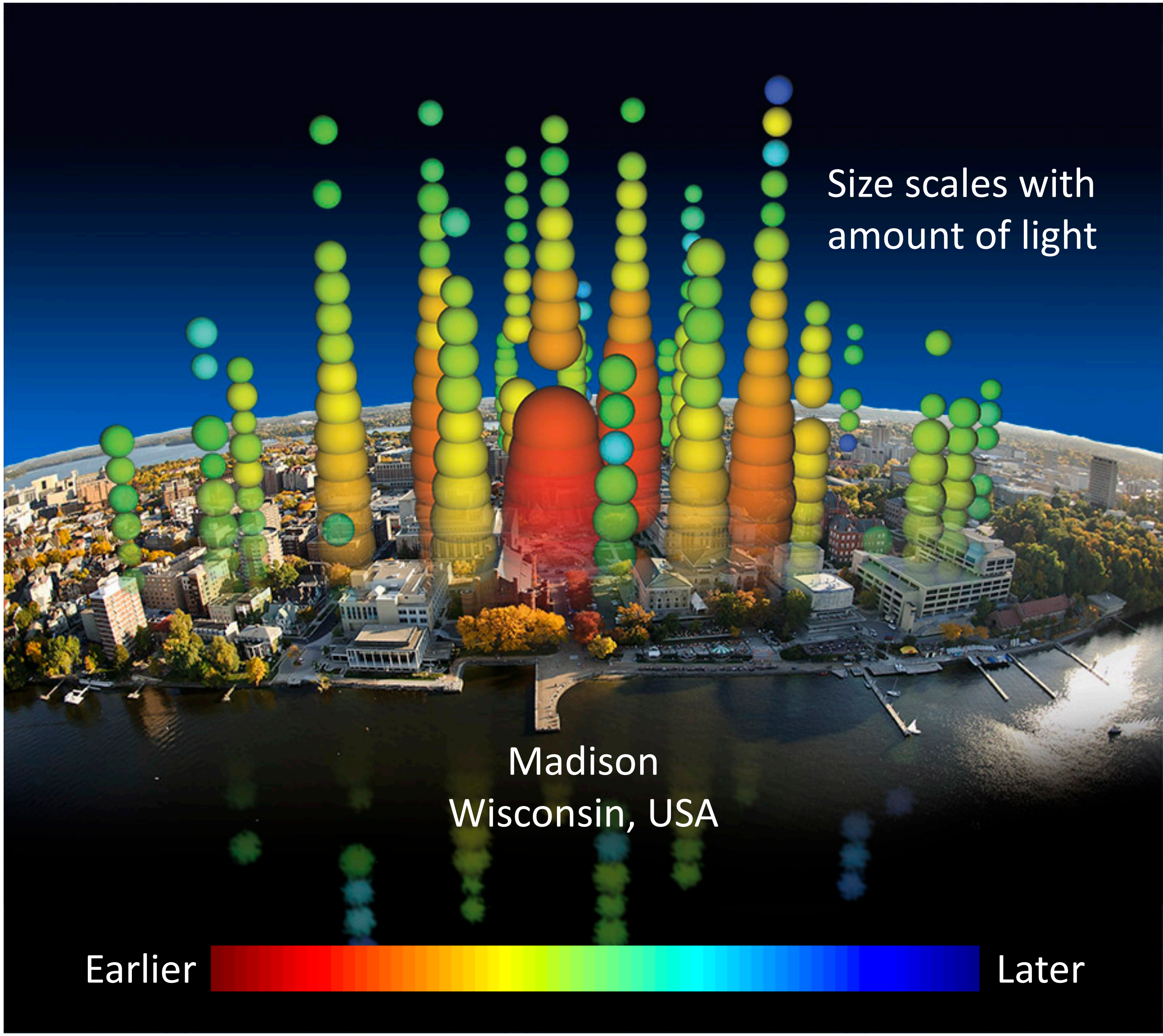
The world's largest neutrino detector

1 km^3

1 Gton of ice

Each bubble centers on a PMT

10 GeV – 10 PeV



Detection principals

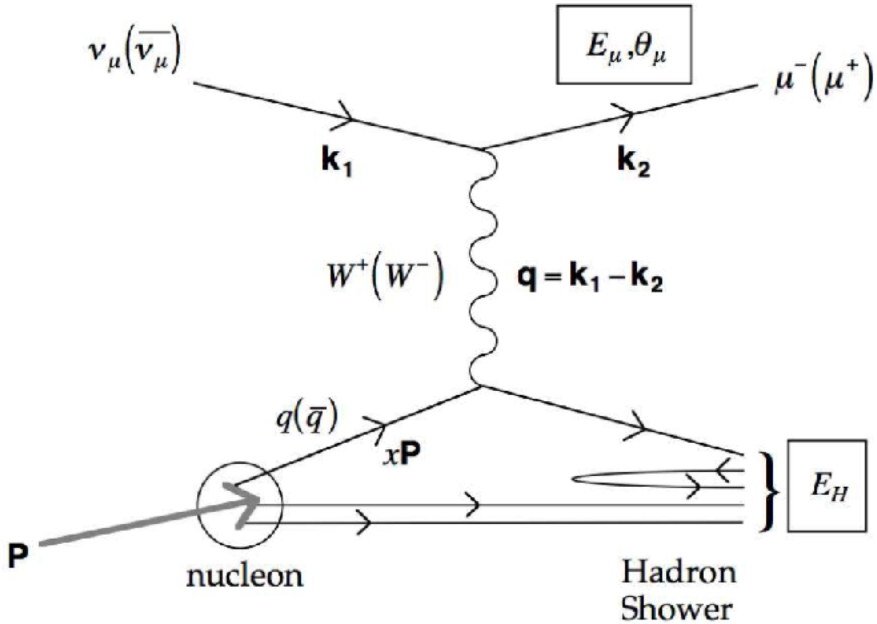
Neutrino interacts via weak force with targets in ice

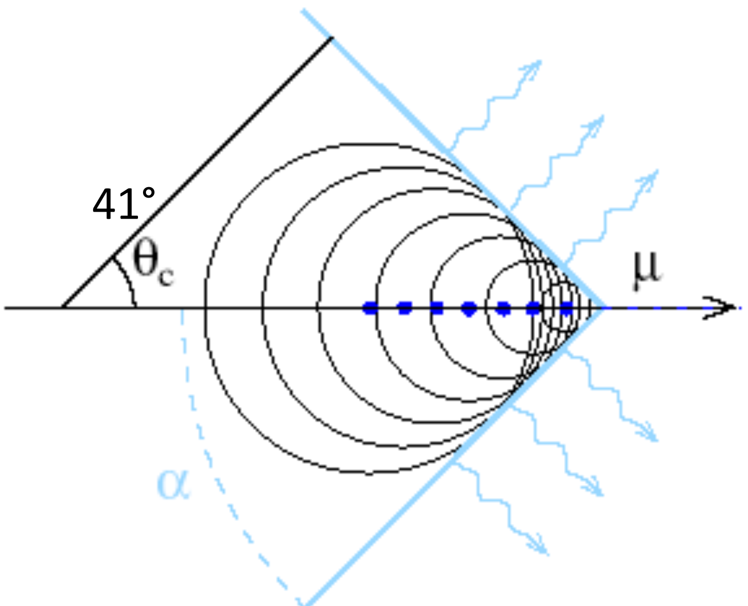
- At IceCube energies, primarily deep-inelastic scattering (DIS) off nucleons

Nucleon breaks apart; outgoing particles may be charged

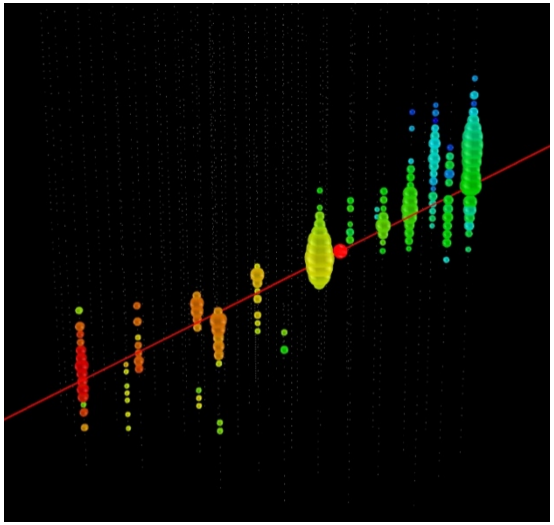
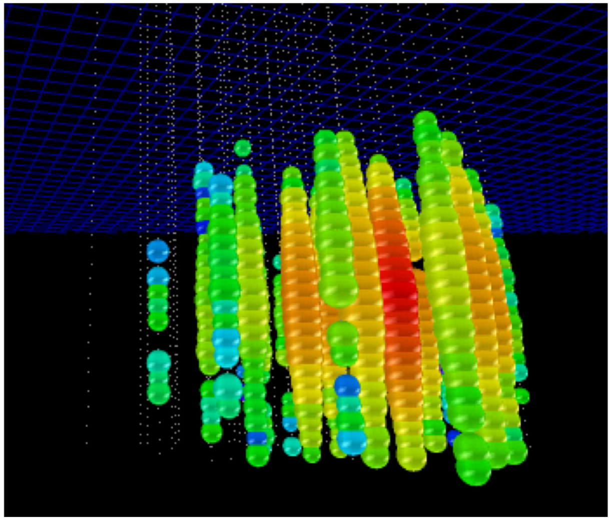
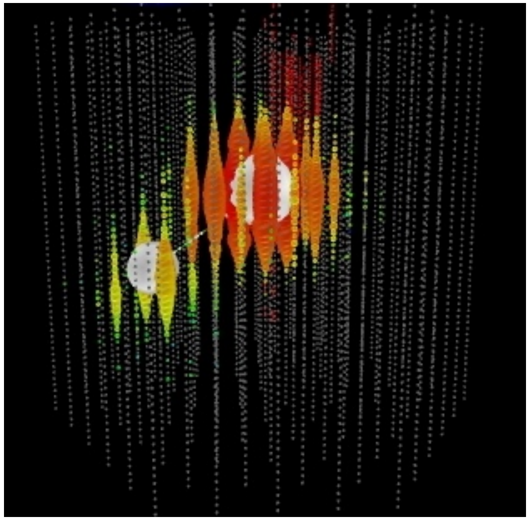
Charged particles emit Cherenkov radiation detectable by PMTs

Rev. Mod. Phys. 84, 1307





Event topologies in IceCube

CC muon neutrino	NC or CC electron neutrino	CC tau neutrino
		
$\nu_\mu + N \rightarrow \mu + X$	$\nu_e + N \rightarrow e + X$ $\nu_x + N \rightarrow \nu_x + X$	$\nu_\tau + N \rightarrow \tau + X$
track (data)	shower (data)	"double-bang" (simulation)
angular resolution ~ 0.5° energy resolution ~ x2	angular resolution ~ 10° energy resolution ~ 15%	not yet observed ~2 expected in 6 years

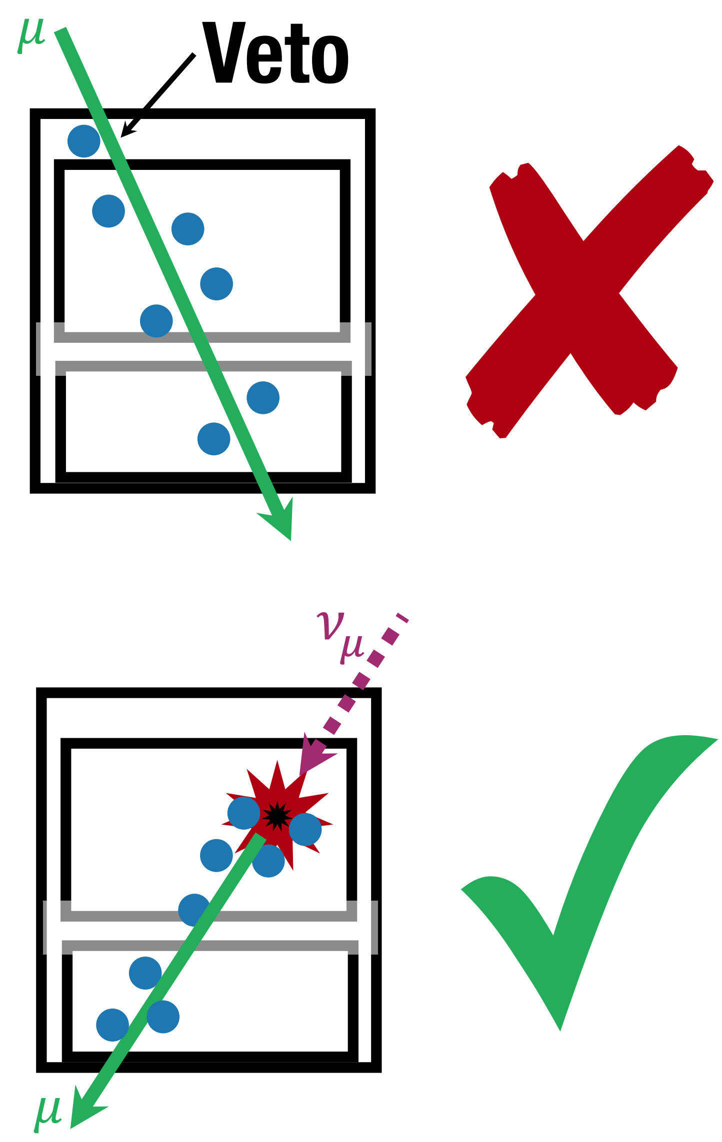
High energy starting event (HESE) selection

Contained search at high energies

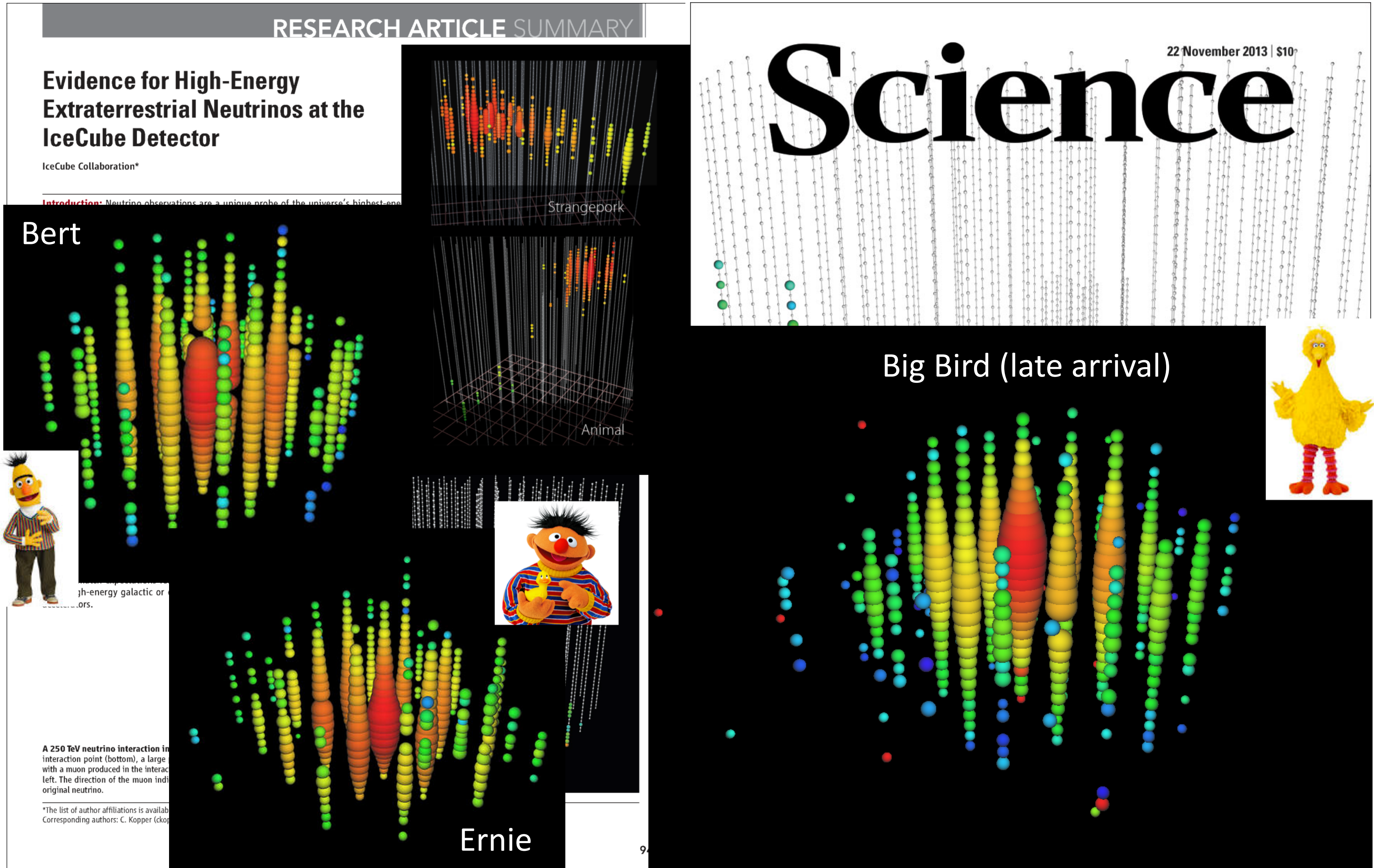
Cut on $Q_{tot} > 6000$ p.e.

Sensitive above 60 TeV

Outer layer acts as active veto of atmospheric muon *and* indirect veto of atmospheric neutrino background



First evidence for high-energy astrophysical neutrinos in 2013

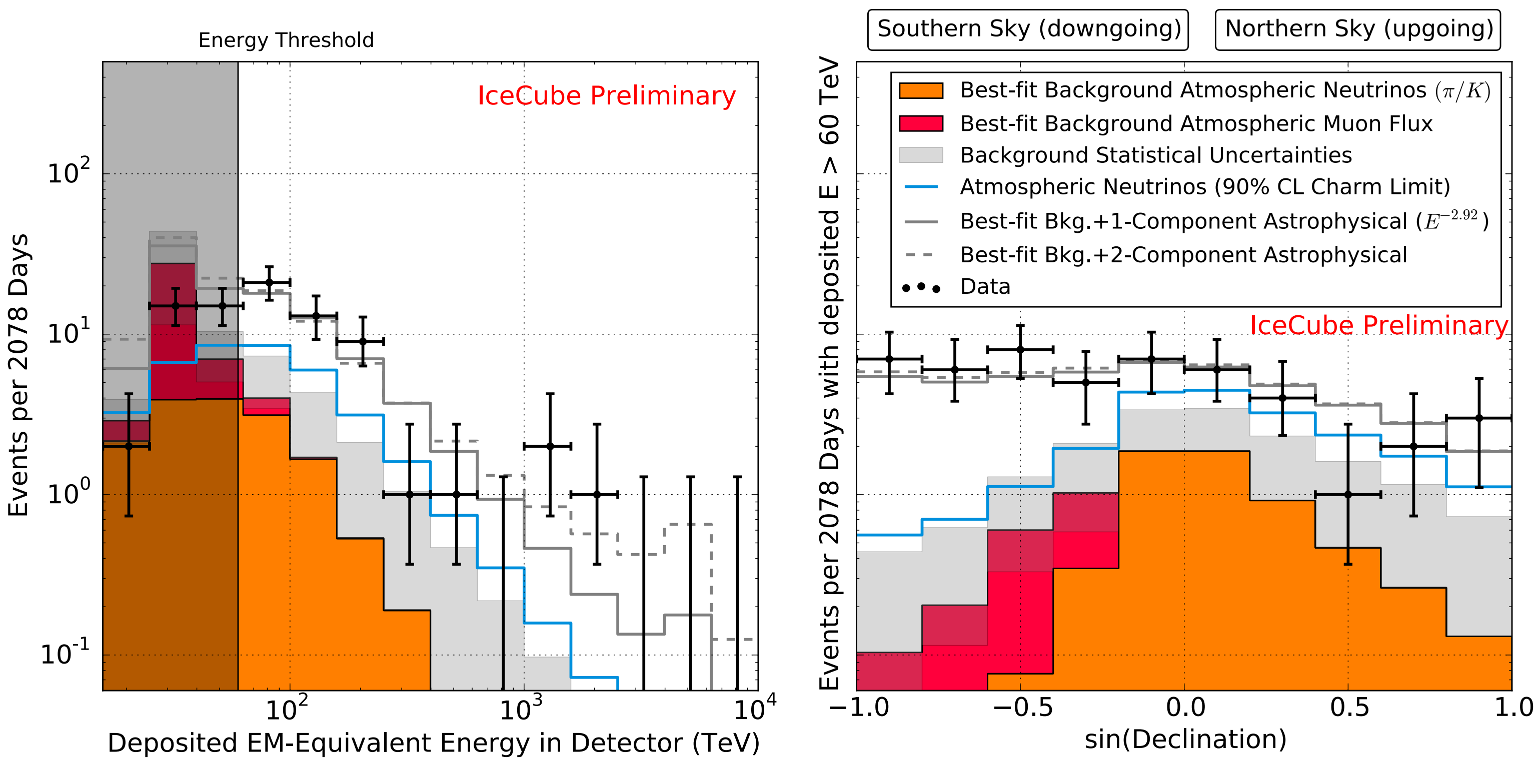


HESE with 6 years of data

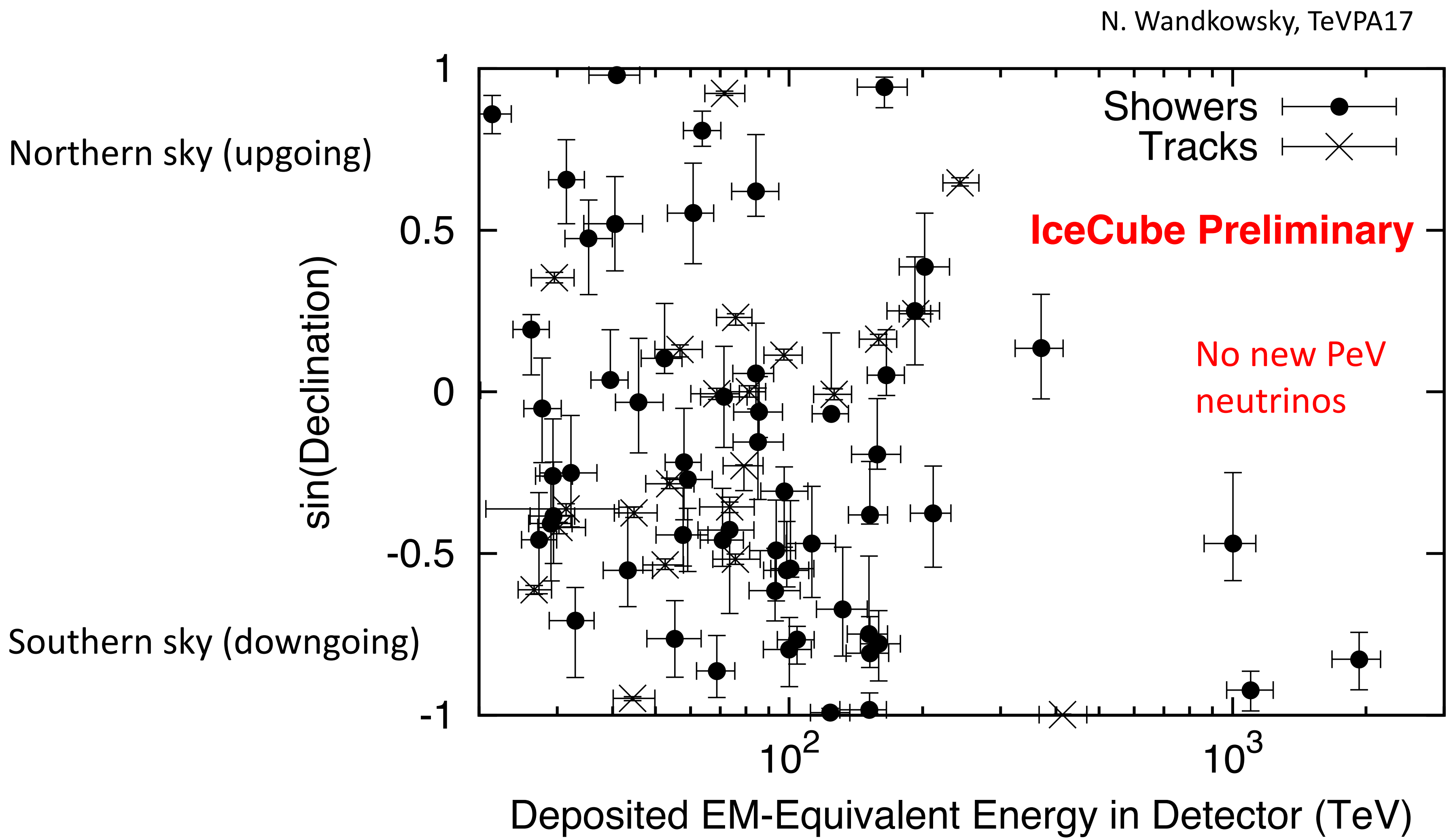
6-yr astrophysical

N. Wandkowsky, TeVPA17

- Best-fit: ϕ = 2.46±0.8 x 10^{-18} $GeV^{-1}cm^{-2}s^{-1}sr^{-1}$, γ=-2.92±0.3
- Background-only hypothesis rejected by ~8σ



HESE distributions with 6 years of data



Recent improvements for HESE with 7 years of data

Updated likelihood treatment to account for finite simulation statistics

Additional ice systematics

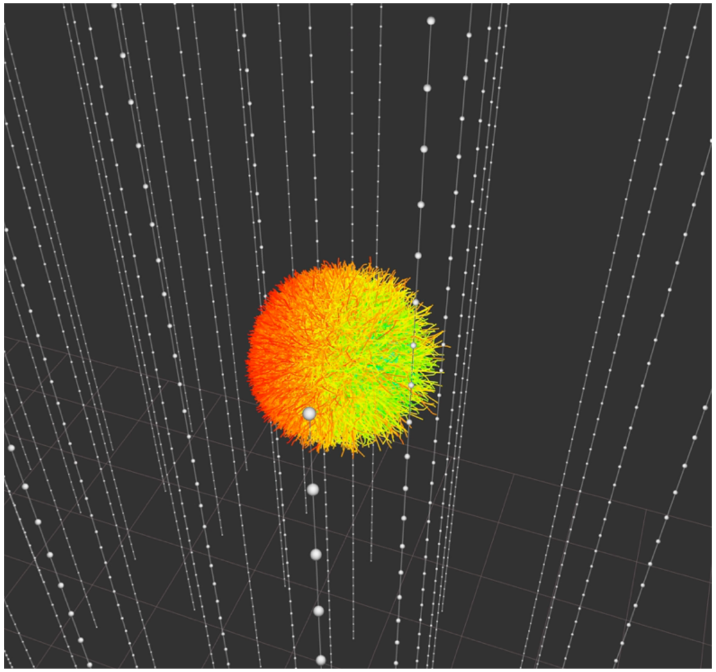
→ **Improved ice-model for event reconstruction**

A new high-energy cross-section measurement

A novel calculation of the atmospheric neutrino background

Event reconstruction

Emitted

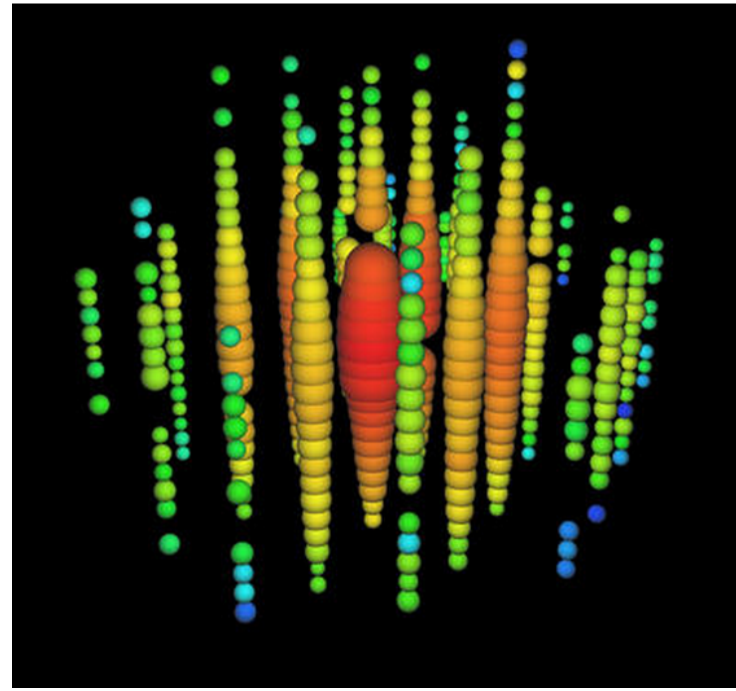


Asymmetry in photon emission helps with directional reconstruction

Information loss

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

Detected



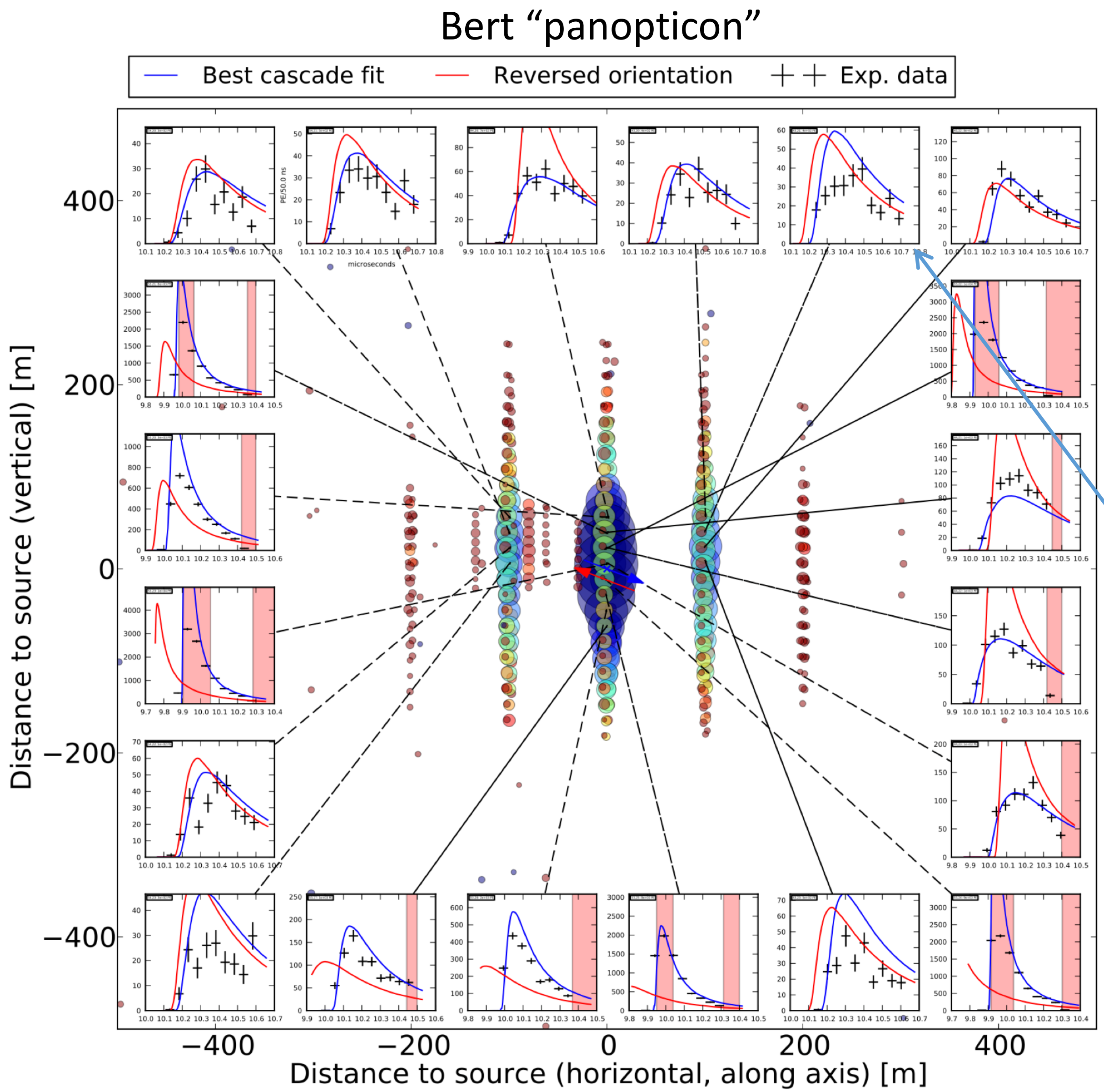
Physics model (emission, absorption, scattering)

$$\mathbf{\Theta} = (x, y, z, \theta, \phi, E, t)$$

$$X = q_{DOM}\ (t)$$

Maximize $\mathcal{L}(\mathbf{\Theta}|\mathrm{X}_{\mathrm{Data}})$

Waveforms and cascade orientation



Differences between best-fit and reversed-orientation

Some disagreement between best-fit and data remain

Time-windows where PMT saturates or failed calibration are shaded

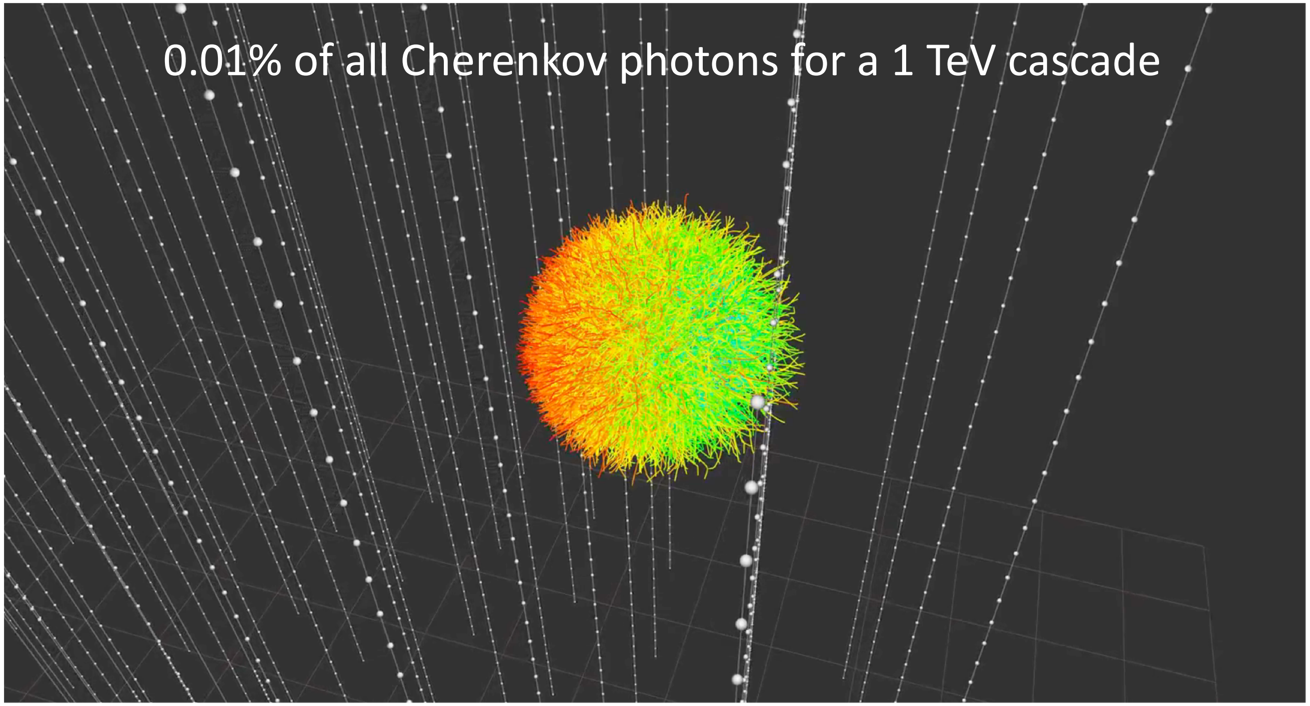
Challenges in cascade reconstruction

Large distances between DOMs means not many detected photons

Small asymmetry means high dependence on ice modeling

Sheer number of photons difficult to simulate

1. Tabulate photon yields for a single ice model
   - Fast, less flexible, table generation time-consuming
2. Directly propagate all photons for any ice model
   - Slow, more flexible



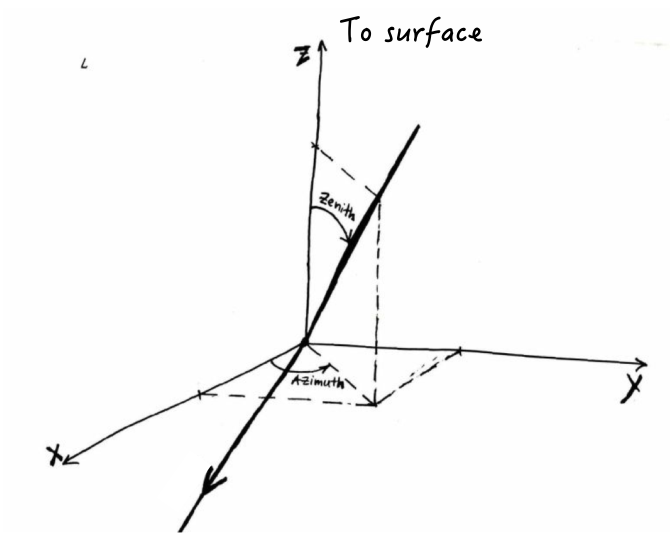
The ideal case

Assume we know ice properties exactly

1. Simulate an cascade at fixed location/direction and various energies with a single ice-model

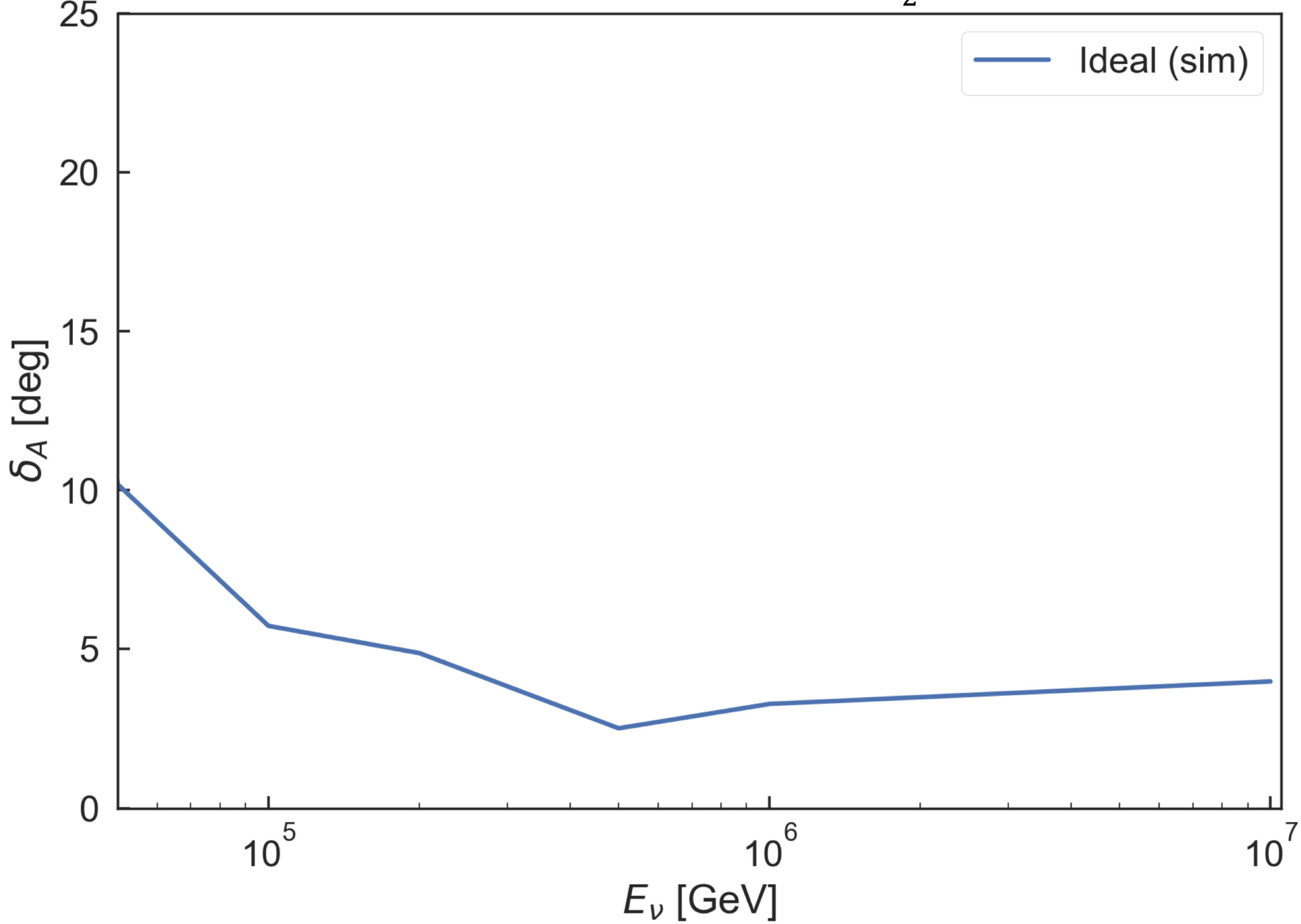
$$(x, y, z, \theta_{zen}, \phi_{azi}) = (0,0,300,\frac{\pi}{2},0)$$

2. For each simulated cascade, reconstruct with direct photon propagation
3. Evaluate directional uncertainties using Approximate Bayesian Calculation (ABC) MCMC

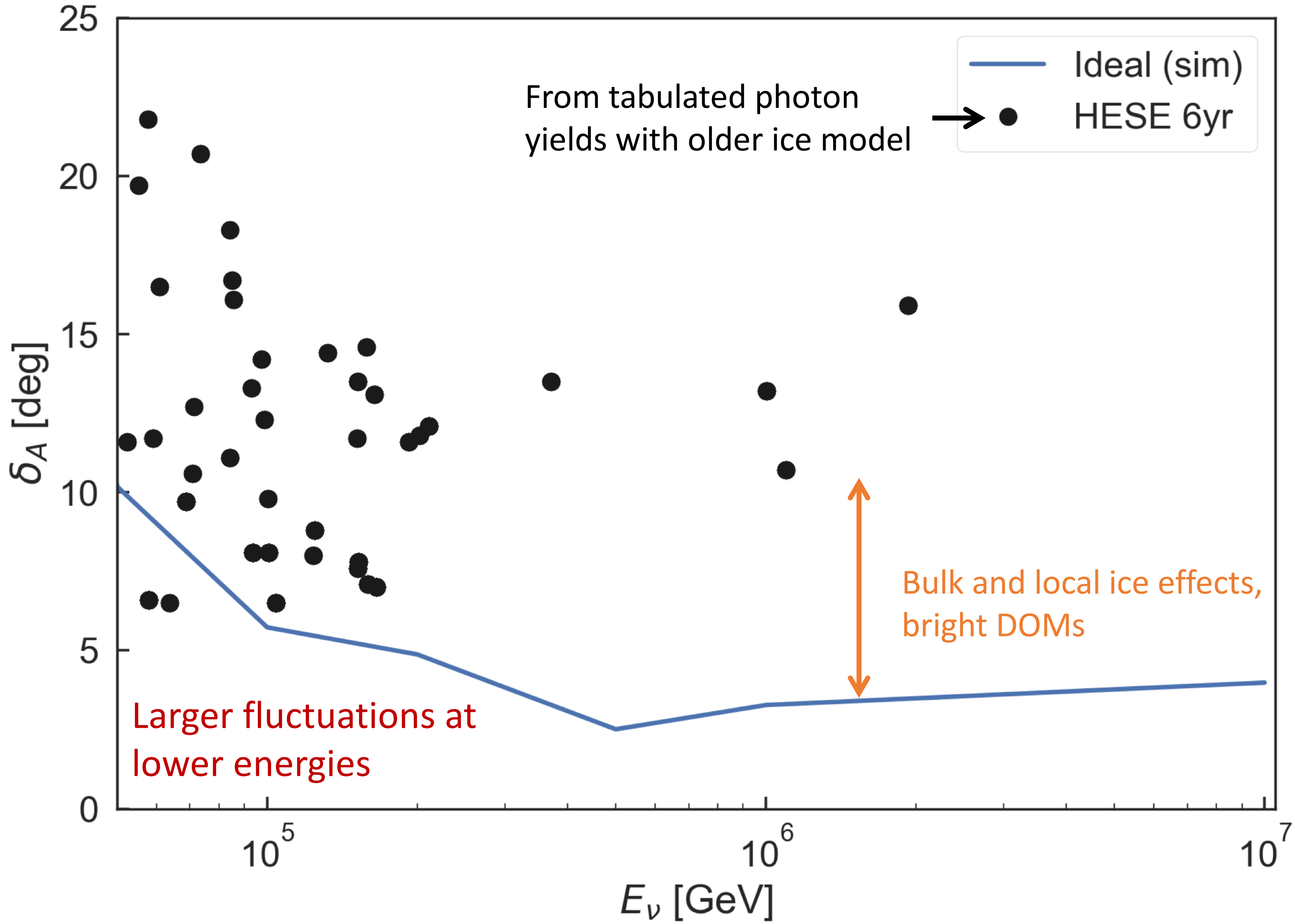


Idealized angular resolution

Median angular resolution for ideal reconstruction of cascade at
$(x, y, z, \theta_{zen}, \phi_{azi}) = (0{,}0{,}300, \frac{\pi}{2}, 0)$

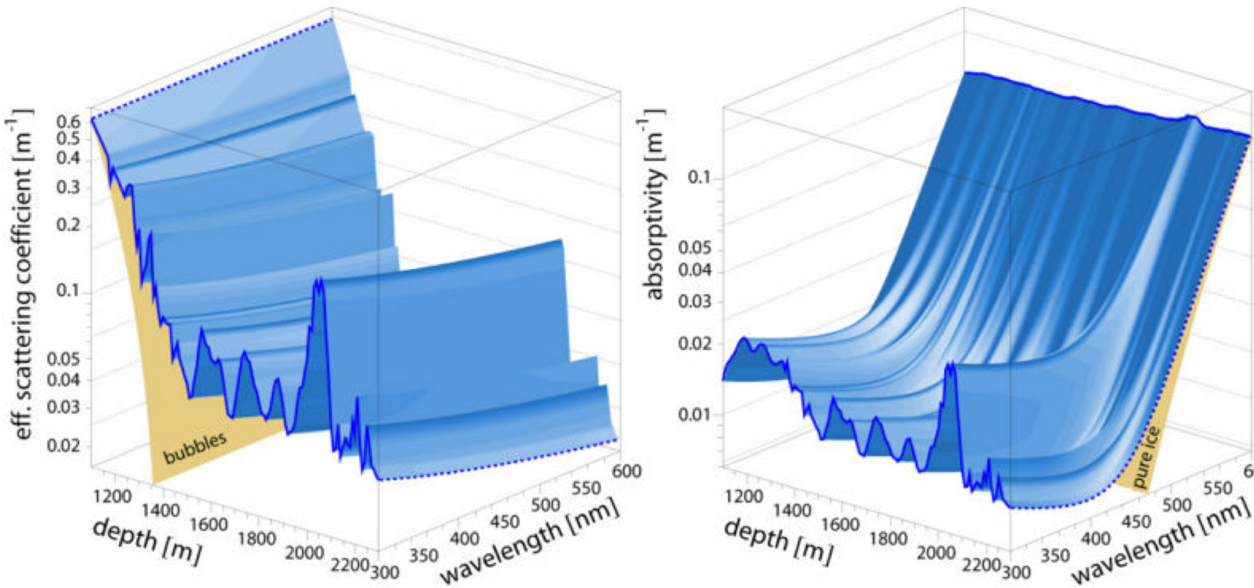


HESE angular resolution



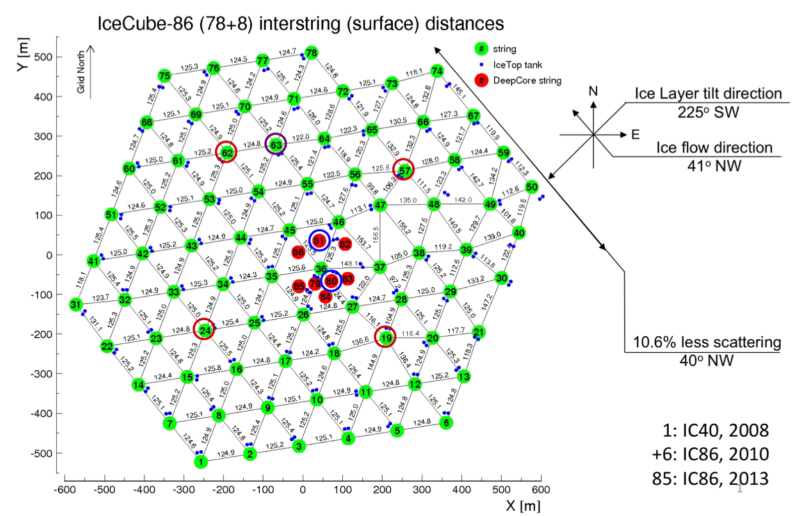
Bulk ice properties in brief

Bulk ice described by scattering and absorption coefficients as a function of depth → these have been refined over time



Ice layers were found to be tilted [arXiv:1301.5361]

Ice was also discovered to be anisotropic [ICRC 2013, 0580]



Local effects

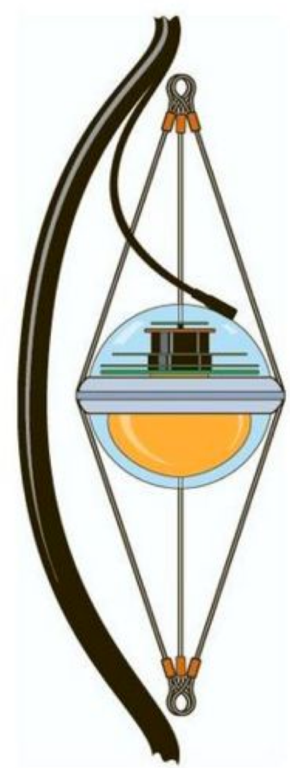
Hole-ice

- Refrozen central column with high scattering

DOM orientation

- Thick, support cable may impede direct photons if vertex is nearby
- A few DOMs may not be perfectly horizontal

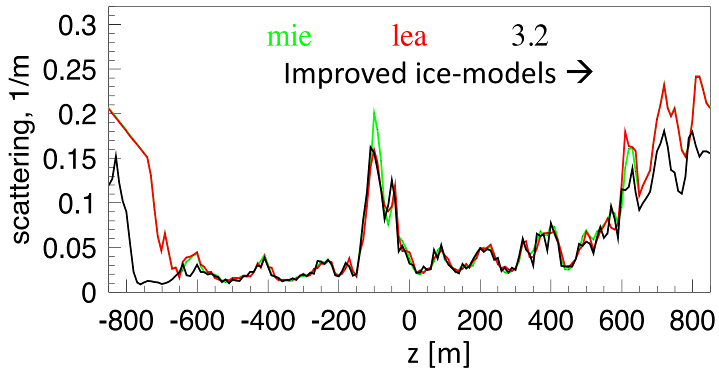
Looking up the string

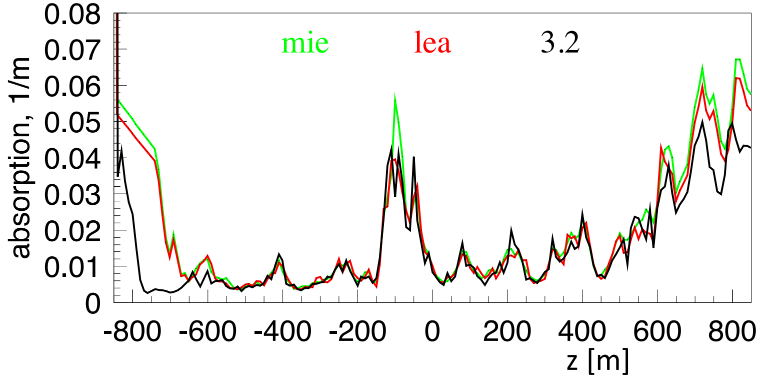


Two approaches to improved reconstruction

1. Improve ice model for more **accurate** directional reconstruction

D. Chirkin

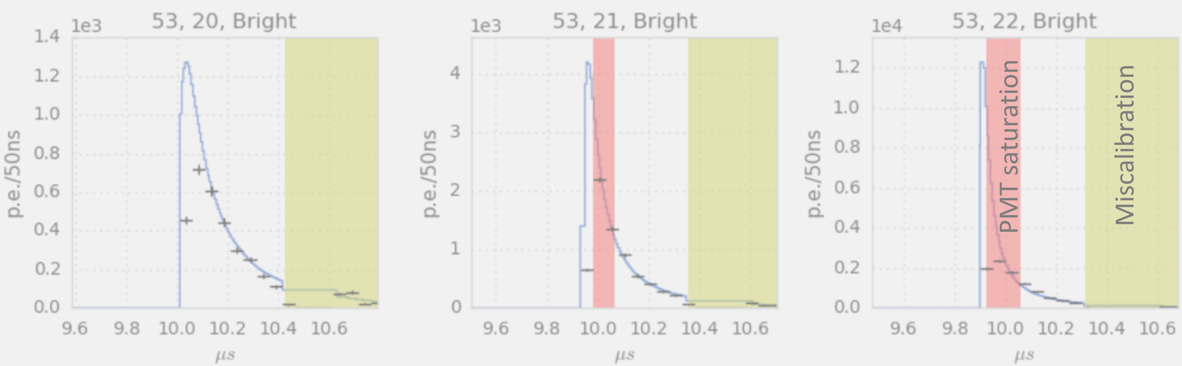




2. Include unused data for more **precise** directional reconstruction

A few examples of unused waveforms

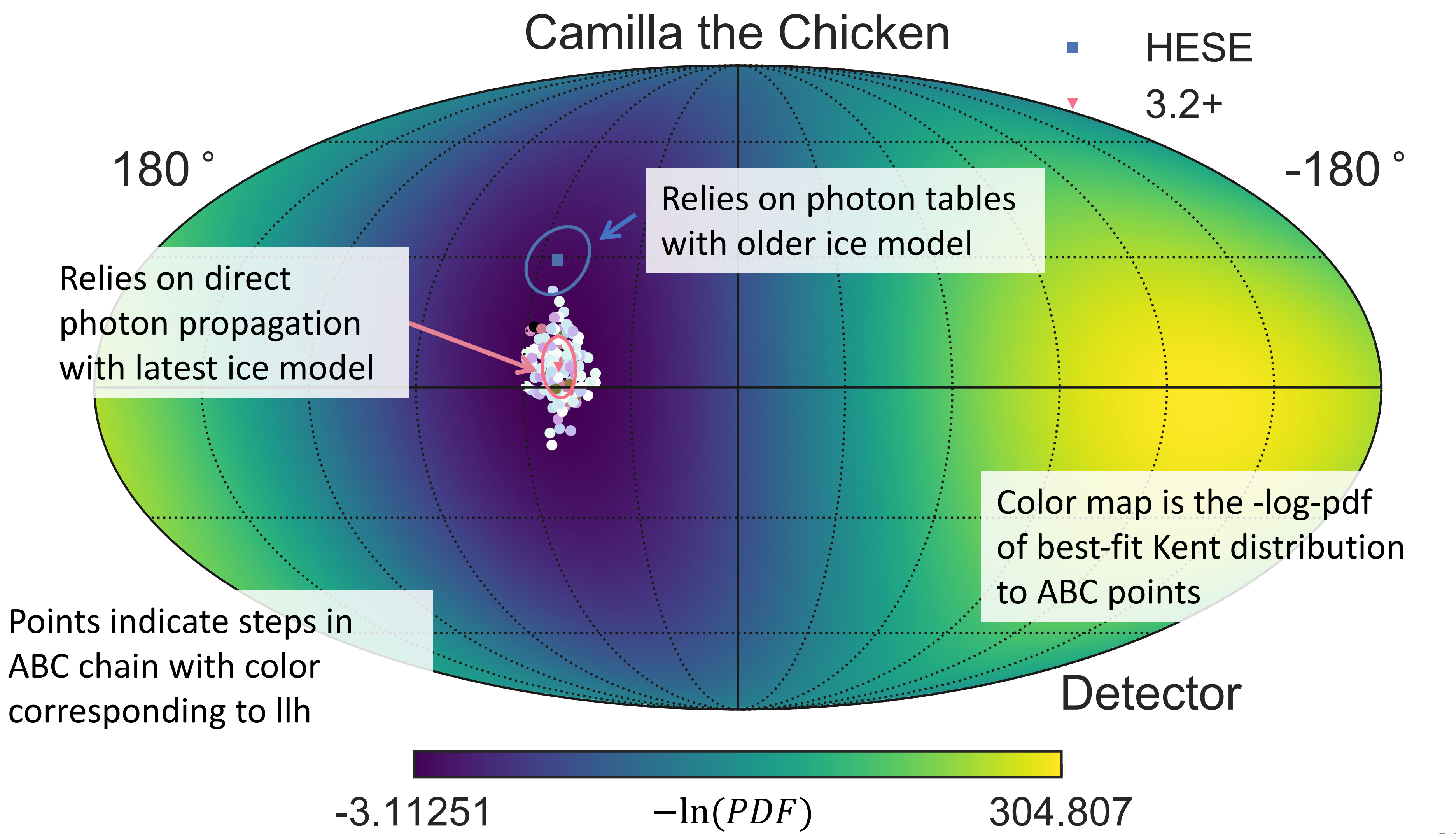
Bert waveforms on closest string



Bright DOMs are ignored in reconstruction

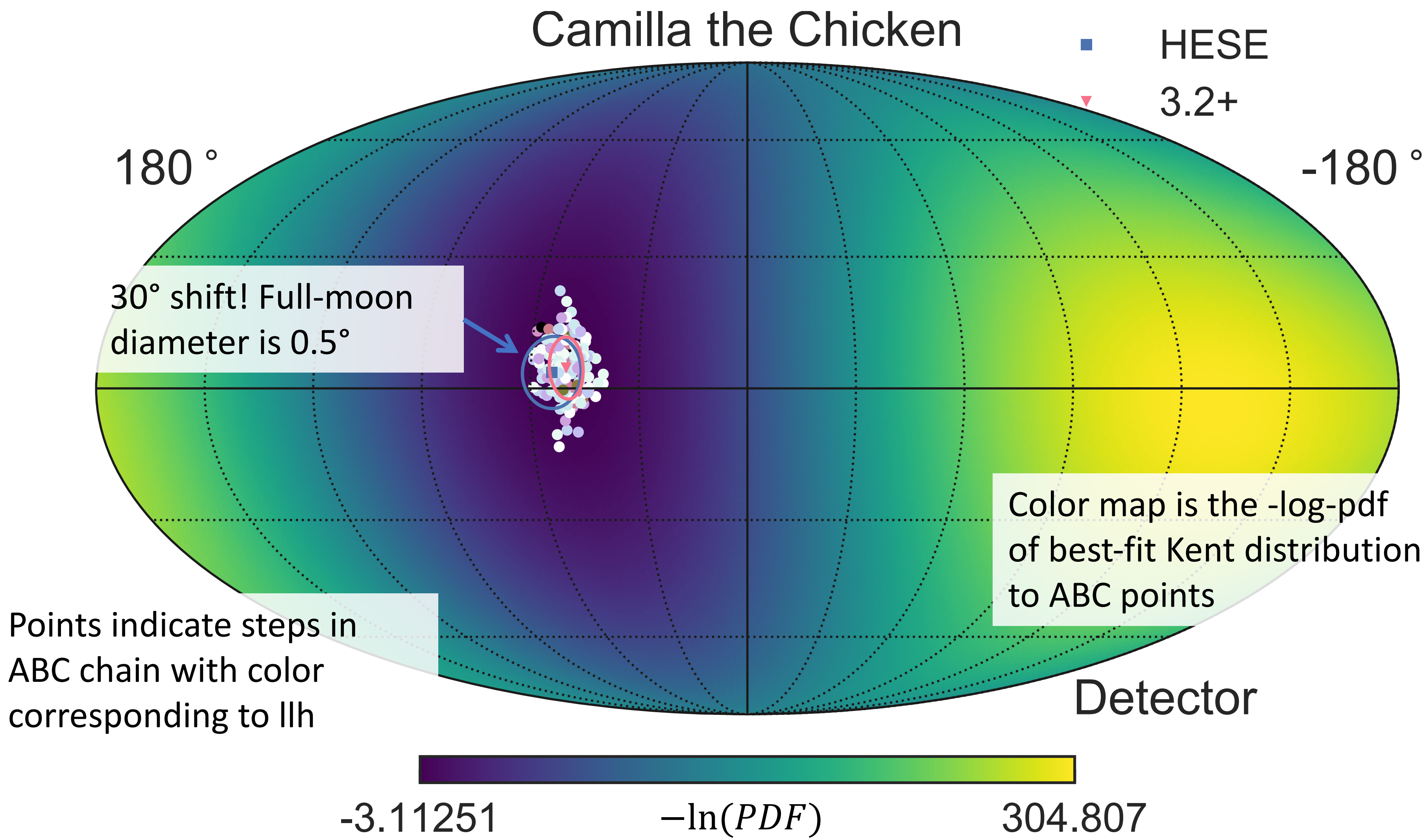
Directional bias due to different ice models

Previous HESE reconstruction uses photon tables for older ice model



Reduction in bias with updated ice model

Better agreement with updated tables that includes anisotropy [PoS(ICRC2017), 974]

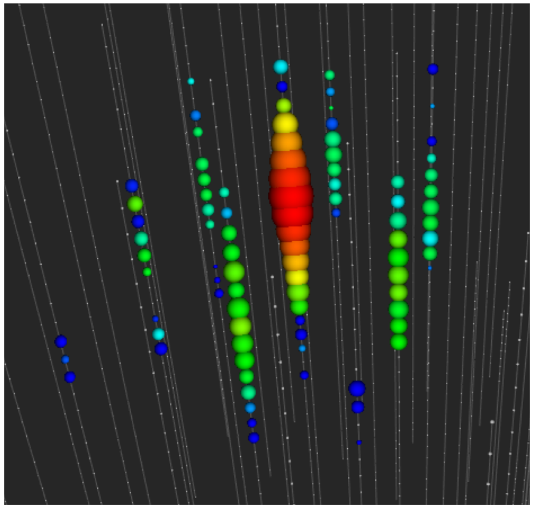


No more median angular resolution

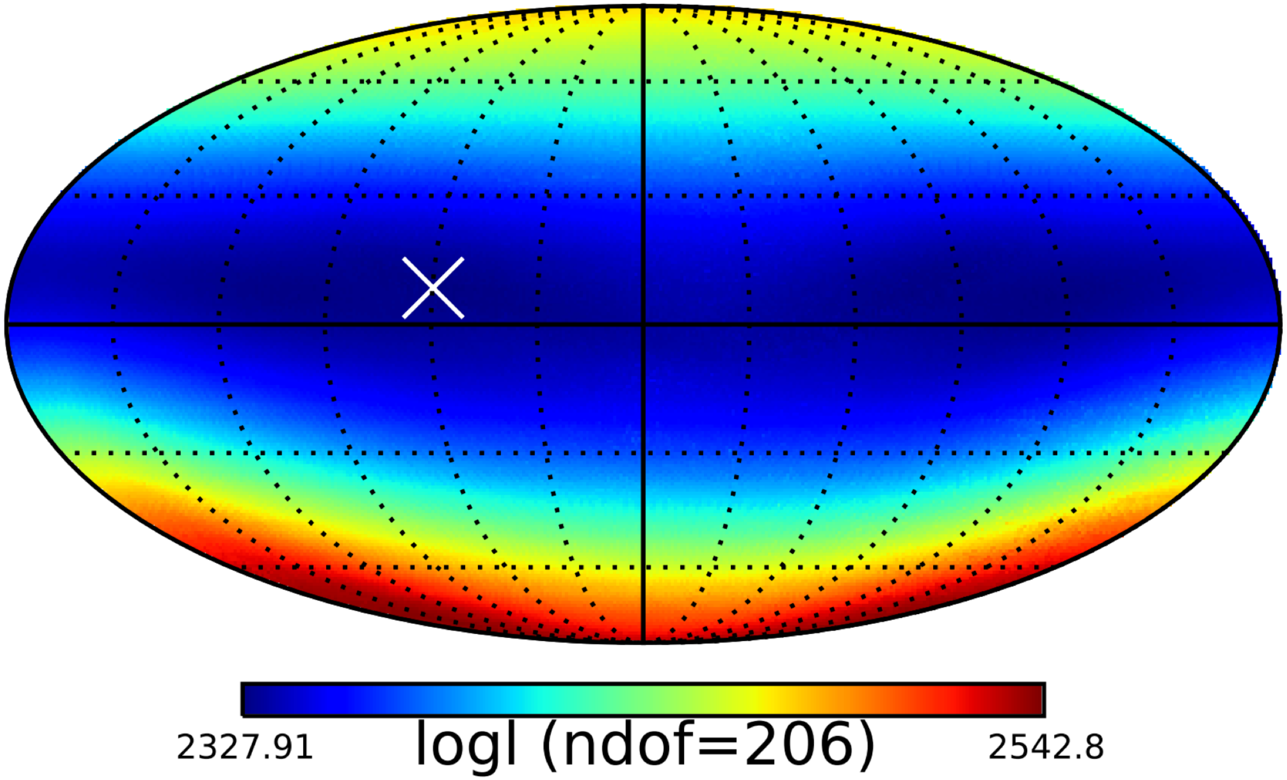
Additionally, will report full likelihood maps instead of median angular resolution

Full-sky pdfs cannot, in general, be described by a single number!

HESE cascade



Full-sky pdf



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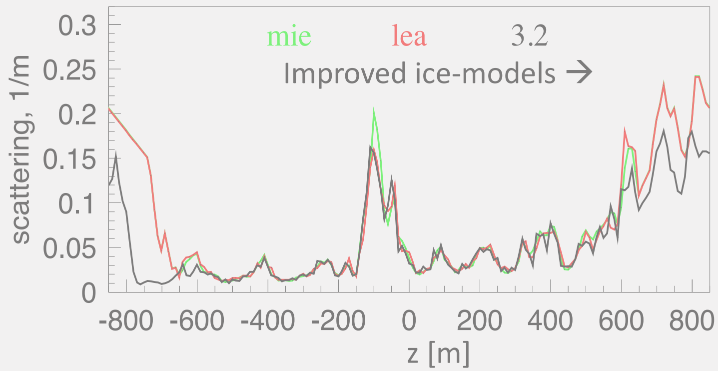

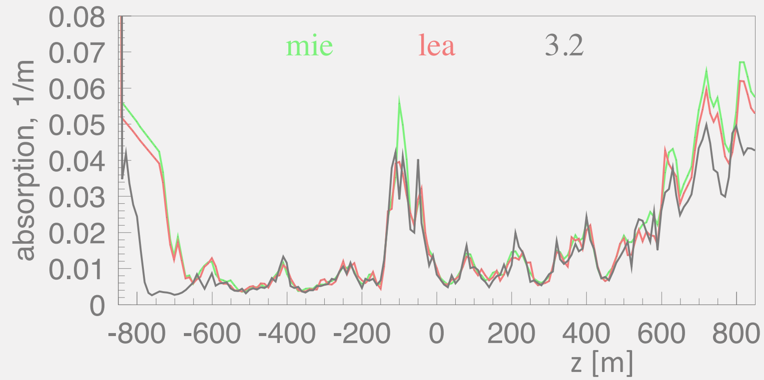

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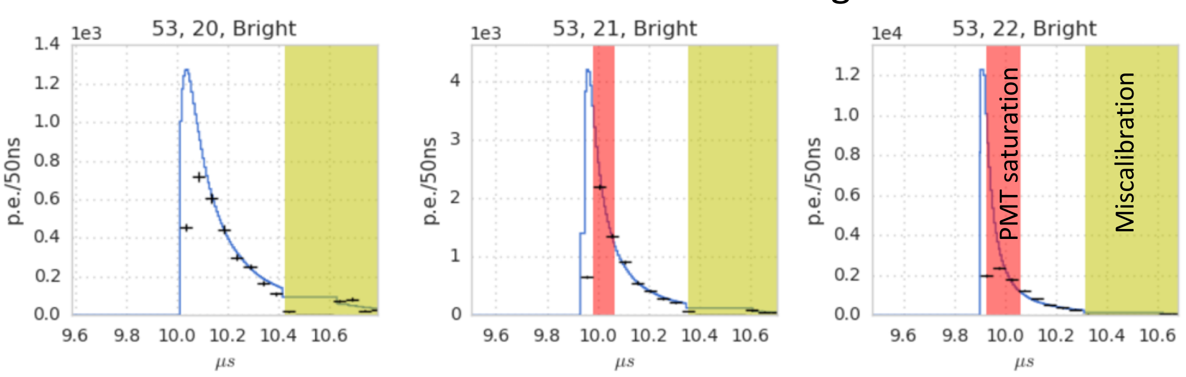
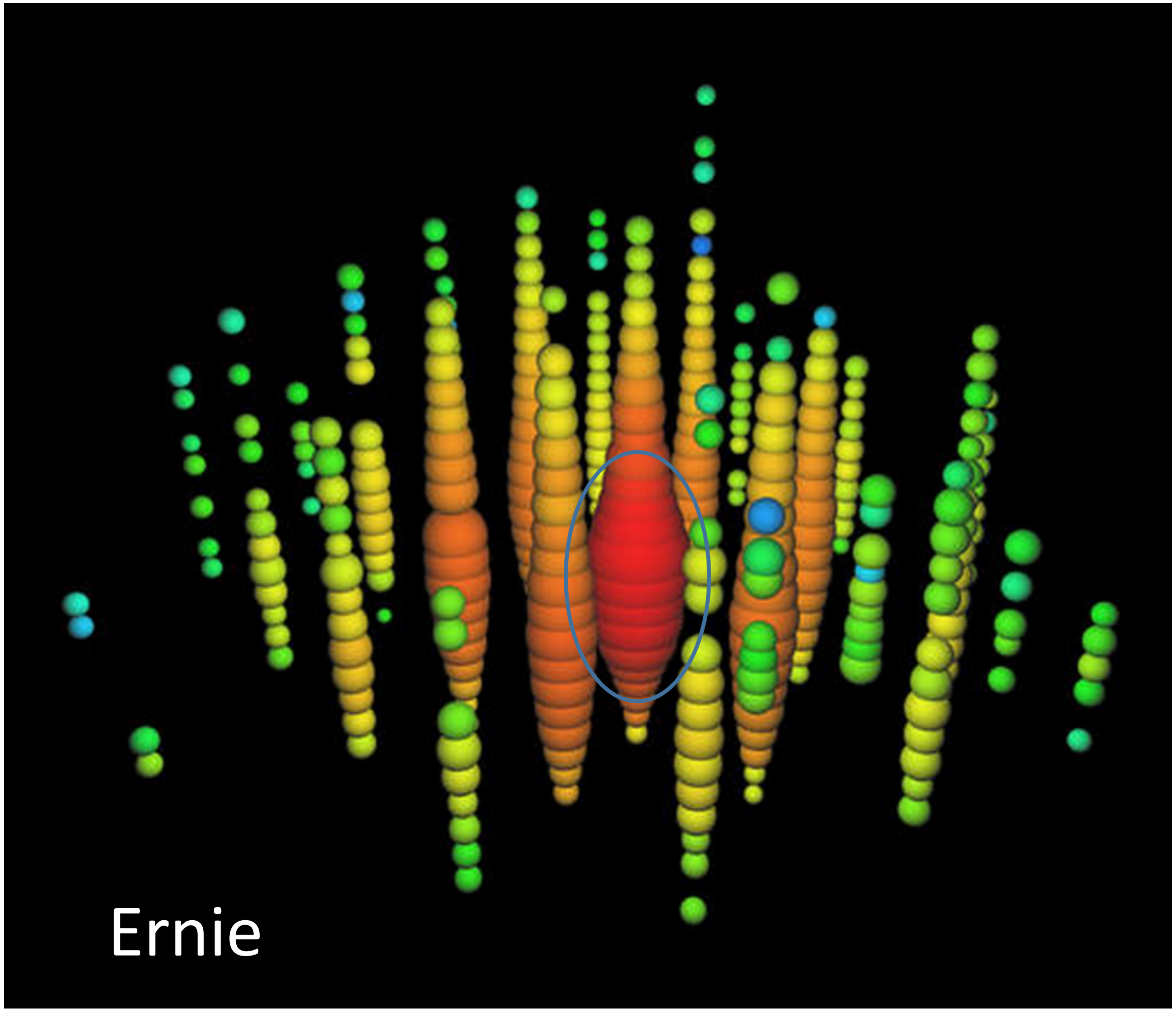


Bright DOMs are ignored in reconstruction

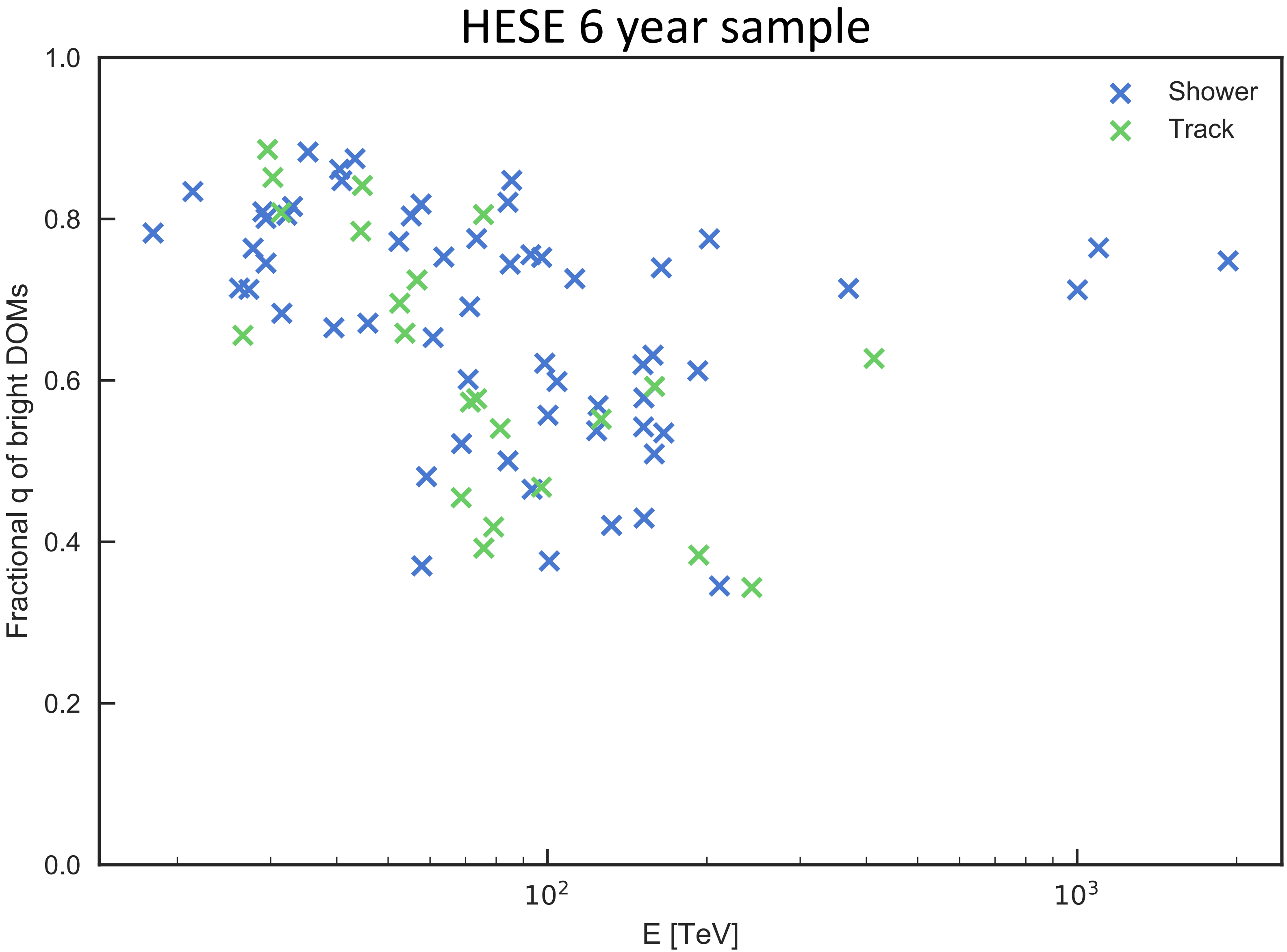
Bright DOMs

DOMs with $Q_{bright} > 10*Q_{avg}$ are classified as "Bright"

PMT not necessarily saturated, but excluded because unmodeled systematic uncertainties start to dominate at high photon statistics

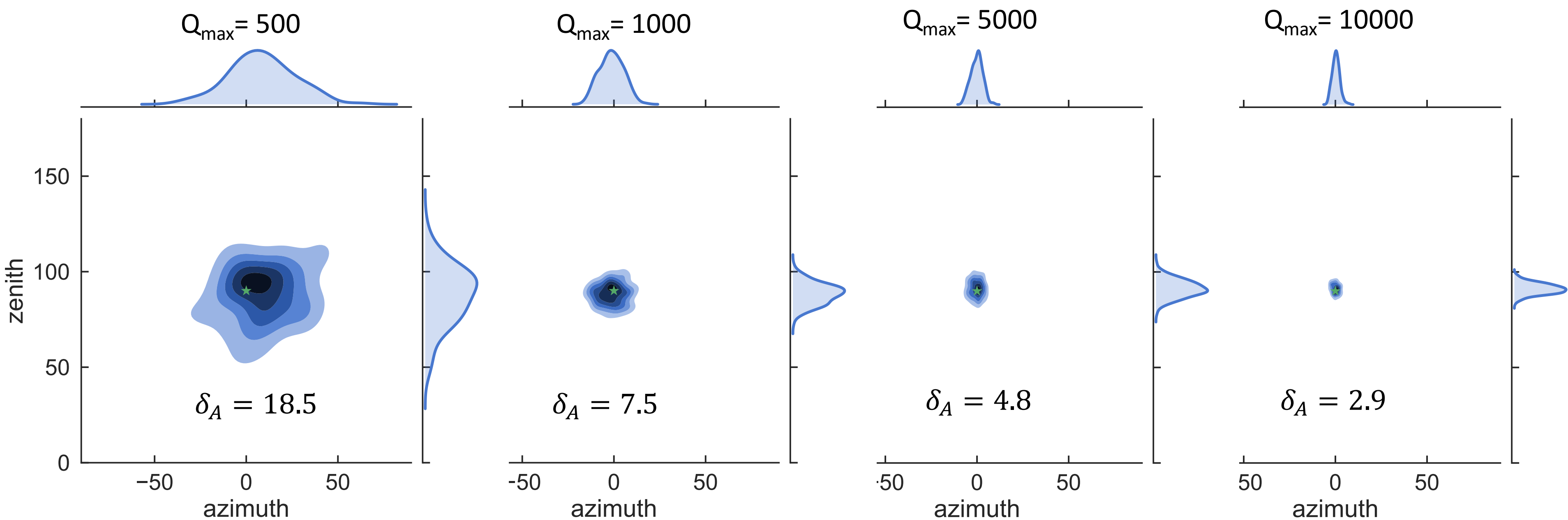


Excludes a lot of charge



Potential impact on angular resolution

Simulate **1 PeV** cascade with true $(\theta, \phi) = (90{,}0)$ and reconstruct with different cut-offs: Q_{max}



Less charge used → More charge used

Identical ice model for simulation and reconstruction

Current status of bright DOMs

Not included for official HESE reconstruction yet

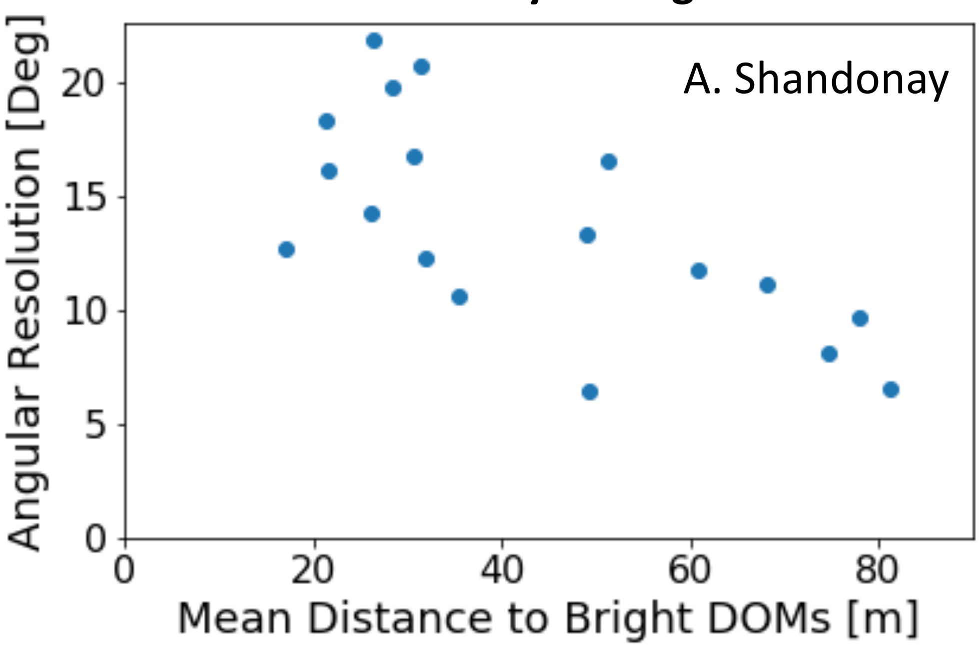
Local ice effects still not 100% understood

Need to understand the systematic uncertainties on DOMs close to interaction vertex

Anti-correlation between vertex distance and angular resolution

Somewhat counter-intuitive at first glance

Official 6 year ang. res.



Recent improvements for HESE with 7 years of data

Updated likelihood treatment to account for finite simulation statistics

Additional ice systematics

Improved ice-model for event reconstruction

→ **A new high-energy cross-section measurement**

A novel calculation of the atmospheric neutrino background

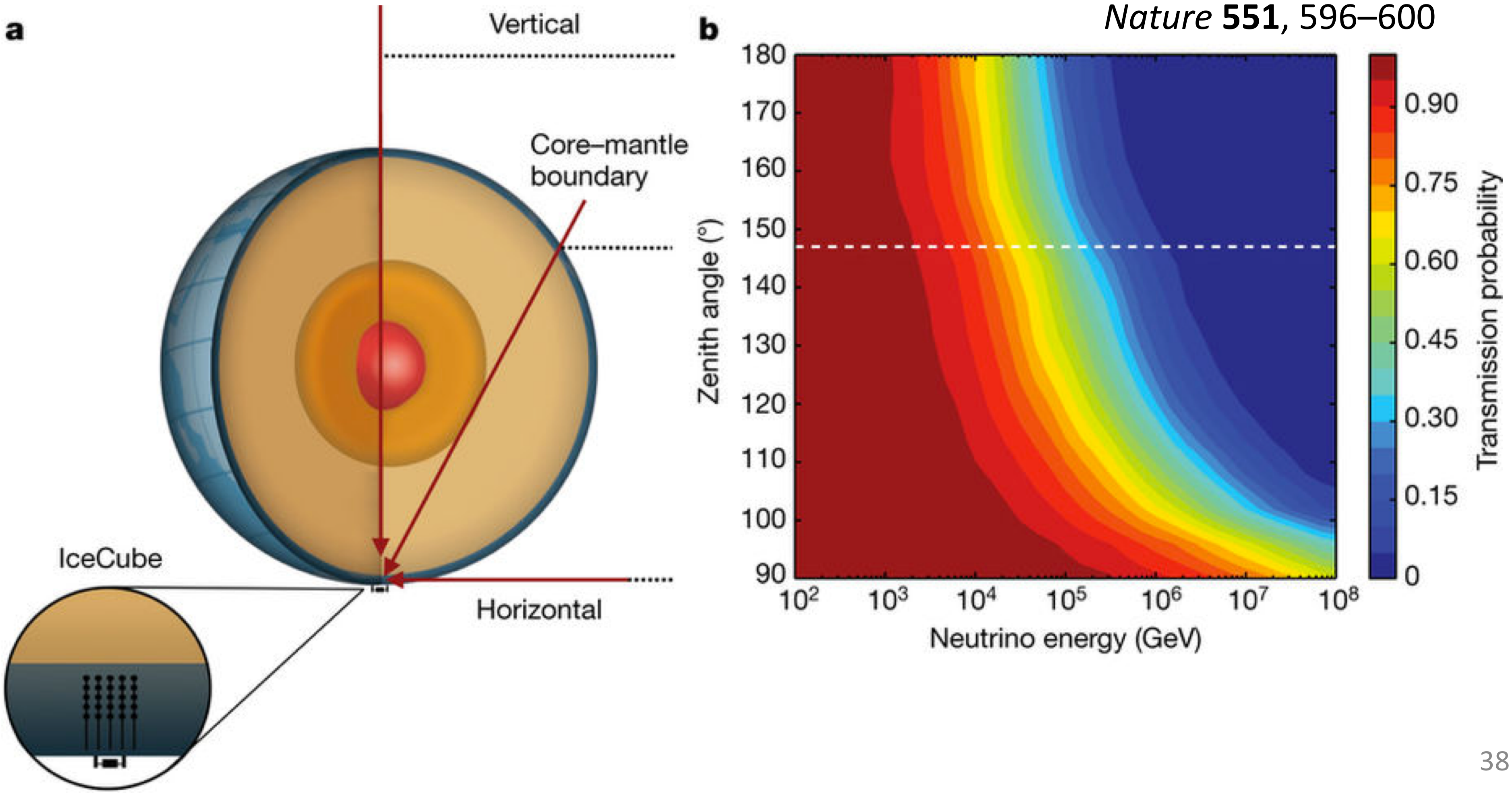
In-Earth flux attenuation

High-energy neutrinos interact in the Earth → flux attenuation

Depends on energy E_ν and direction θ_ν

Accurate **directional reconstruction** is important!

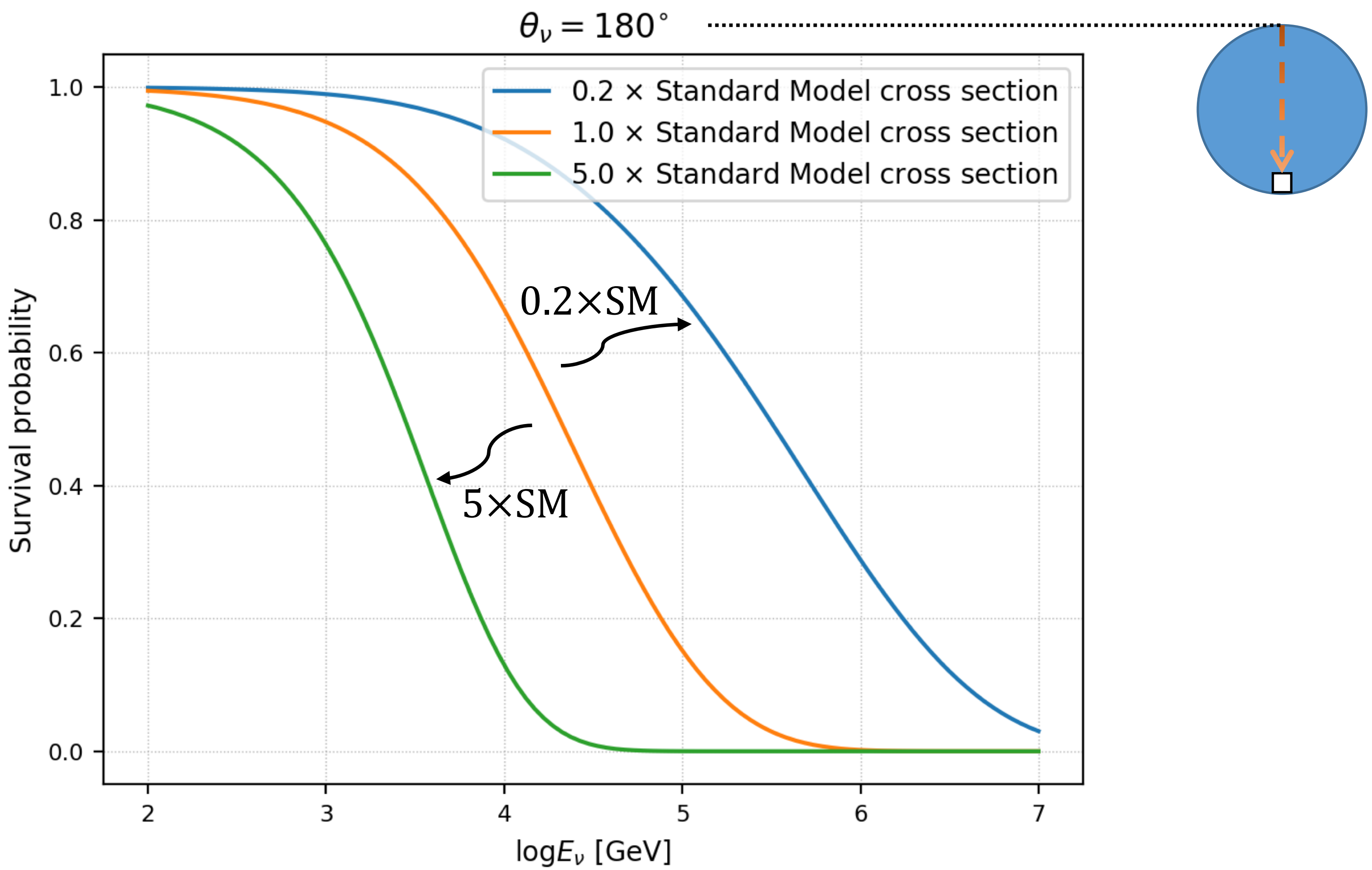
Nature **551**, 596–600



Dependence on cross section

Changing cross-section will change predicted flux at detector

Exponential approximation: $F_d(E_\nu, \theta_\nu) = F_0 e^{-\sigma(E_\nu)t(\theta_\nu)}$, t is Earth column density



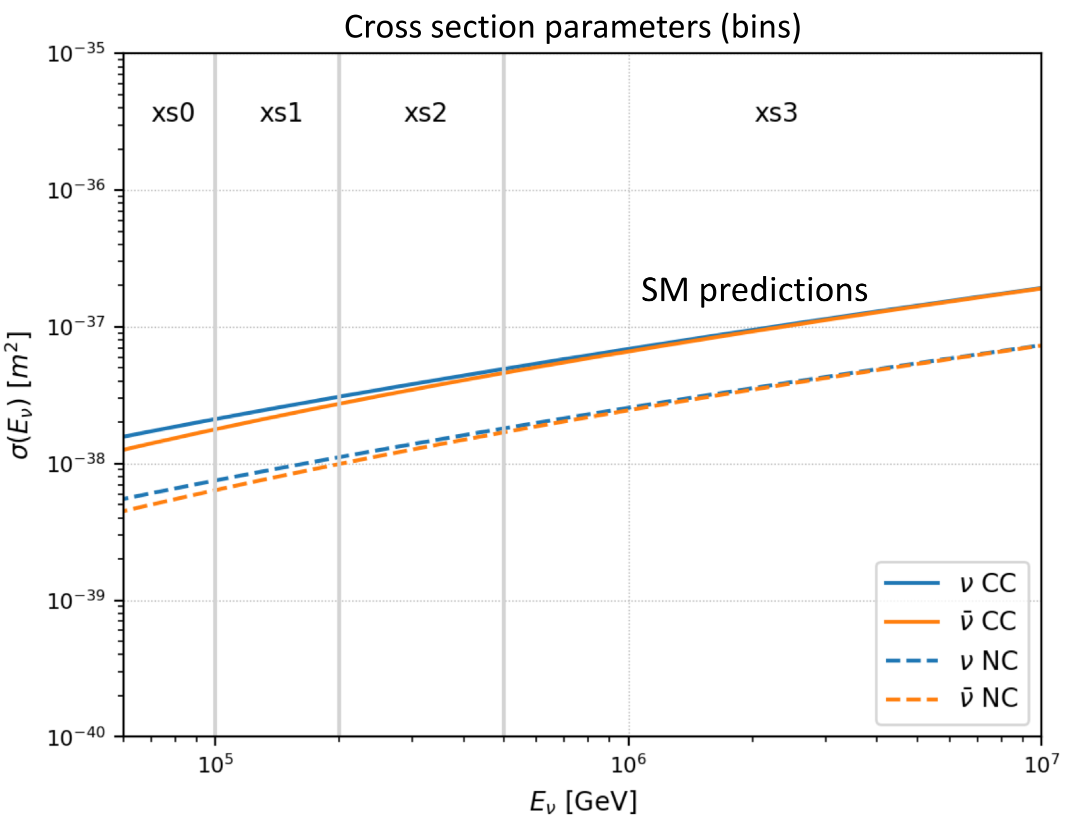
High-energy cross section

Measure cross section via **Earth-absorption**, fitting reconstructed zenith and energy distributions

Assume ratio of $\frac{\sigma_\nu}{\sigma_{\bar{\nu}}}$ and $\frac{\sigma_{CC}}{\sigma_{NC}}$ is fixed

Four **scaling parameters** that modify cross section as a **function of energy**

- Inspired by Bustamante & Connolly [arXiv:1711.11043]
- SM predictions by Cooper-Sarkar, Mertsch & Sarkar [JHEP (2011) 2011: 42]

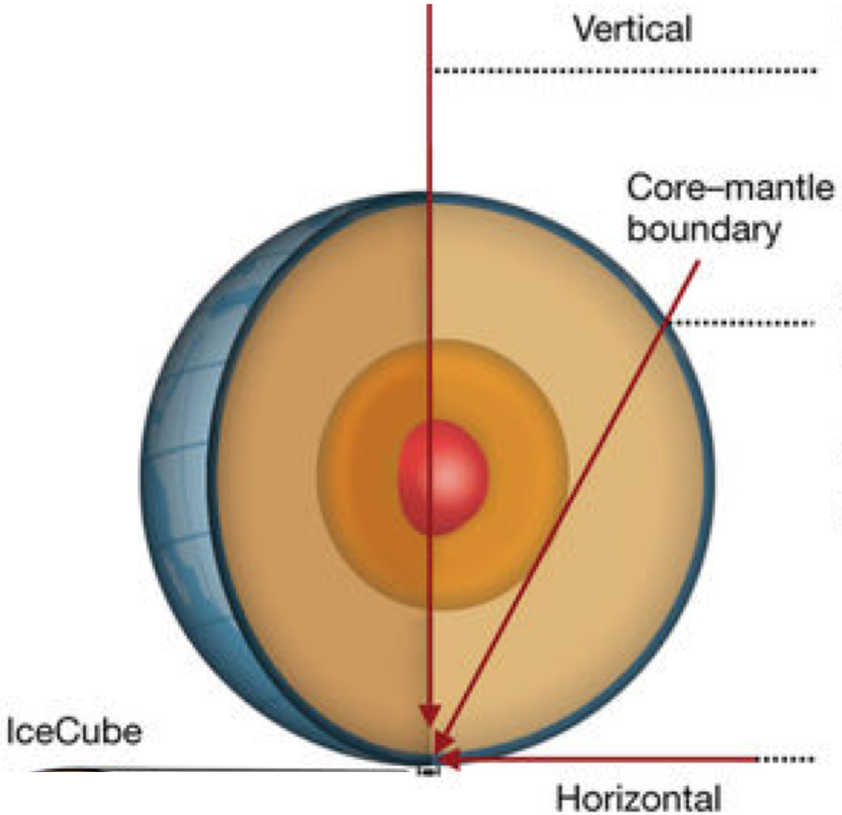


Including NC interactions

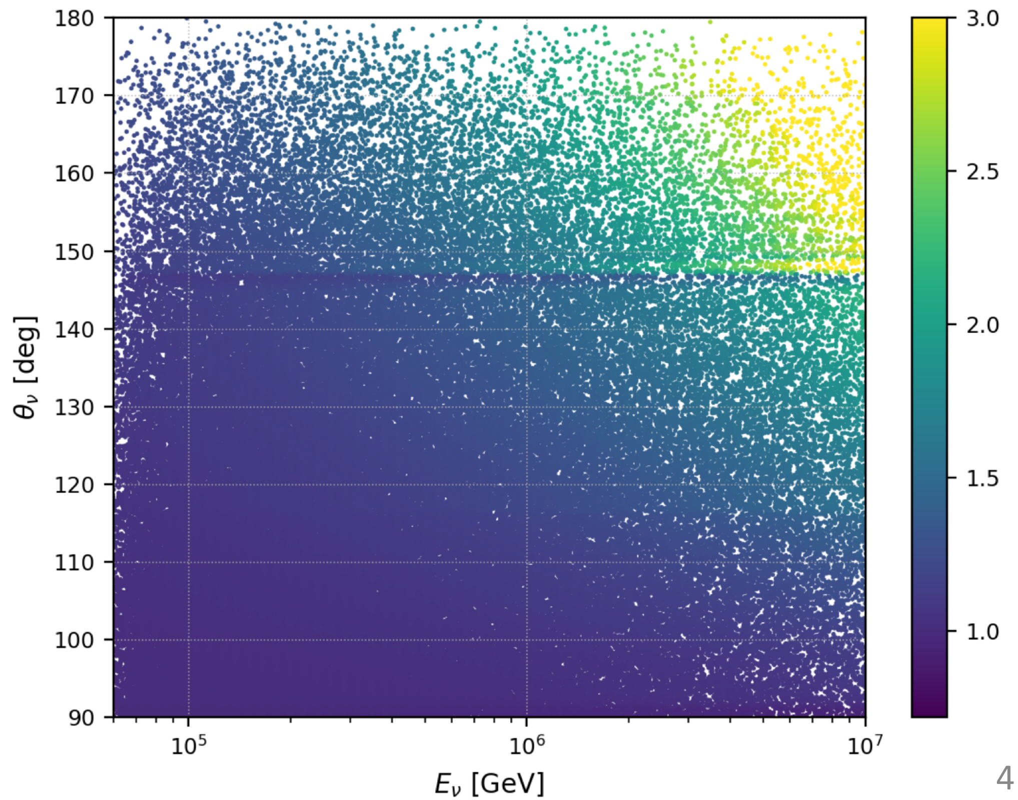
In NC interactions neutrinos are not destroyed but cascade down in energy

Accounted for by NuSQuIDS, a fast neutrino propagation solver

- https://github.com/arguelles/nuSQuIDS

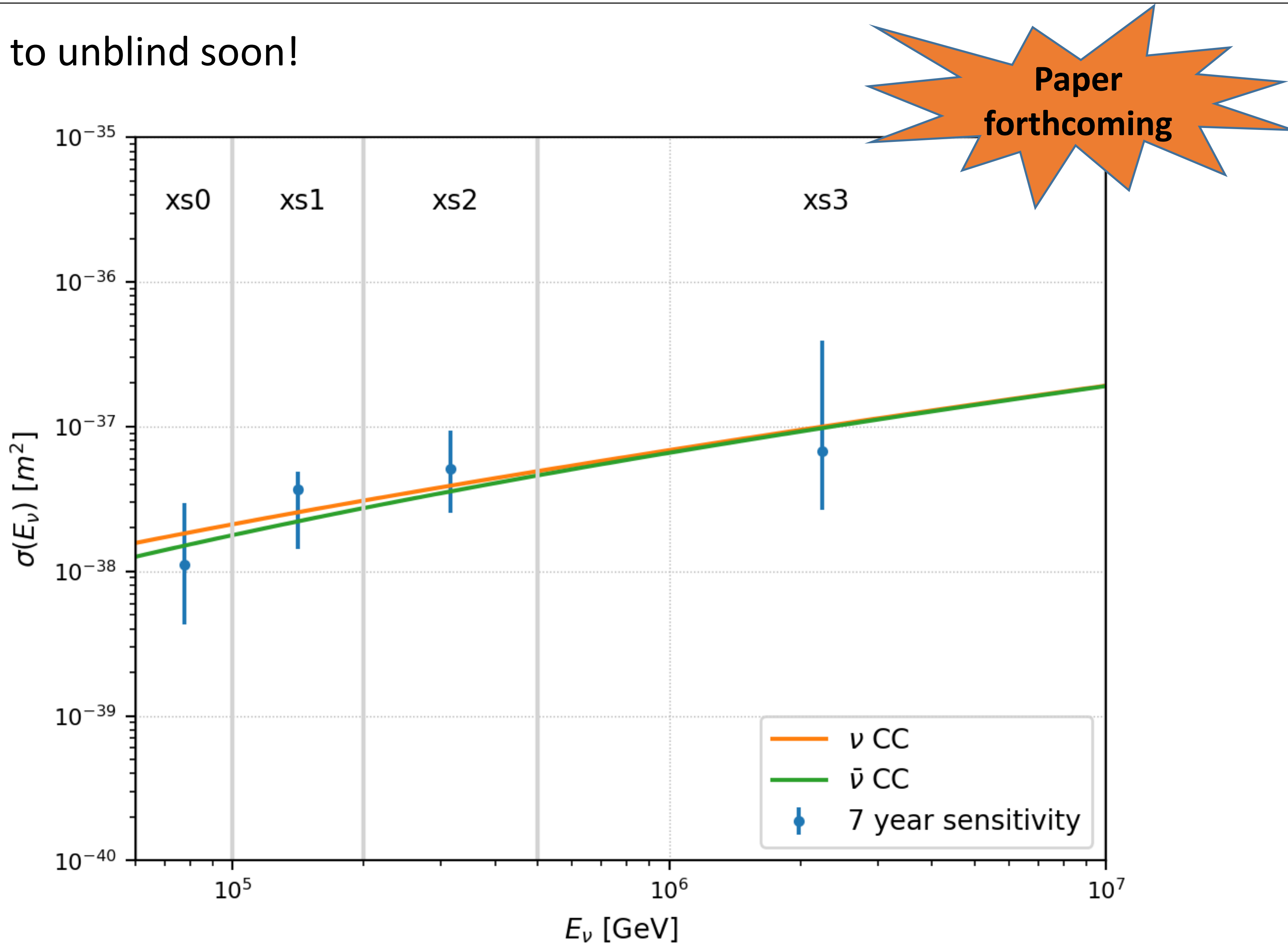


Full-cascade solution/Exponential approx.



Asimov sensitivity

Hope to unblind soon!



Recent improvements for HESE with 7 years of data

Updated likelihood treatment to account for finite simulation statistics

Additional ice systematics

Improved ice-model for event reconstruction

A new high-energy cross-section measurement

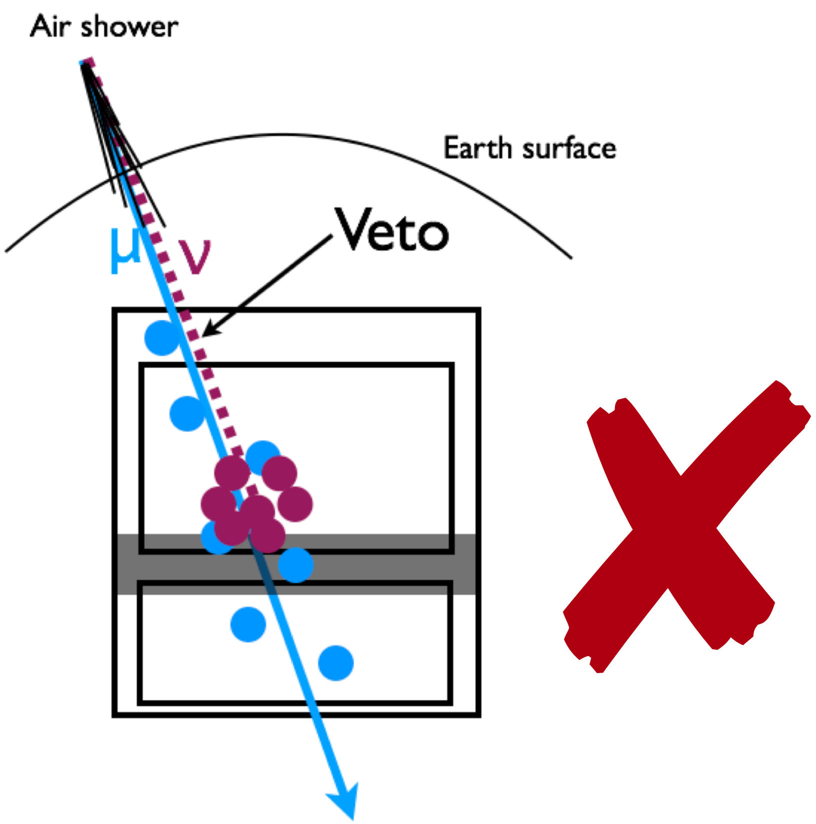
→ **A novel calculation of the atmospheric neutrino background**

Atmospheric neutrino (self) veto

Atmospheric neutrinos from the **southern sky** may be vetoed if accompanied by high-energy muon

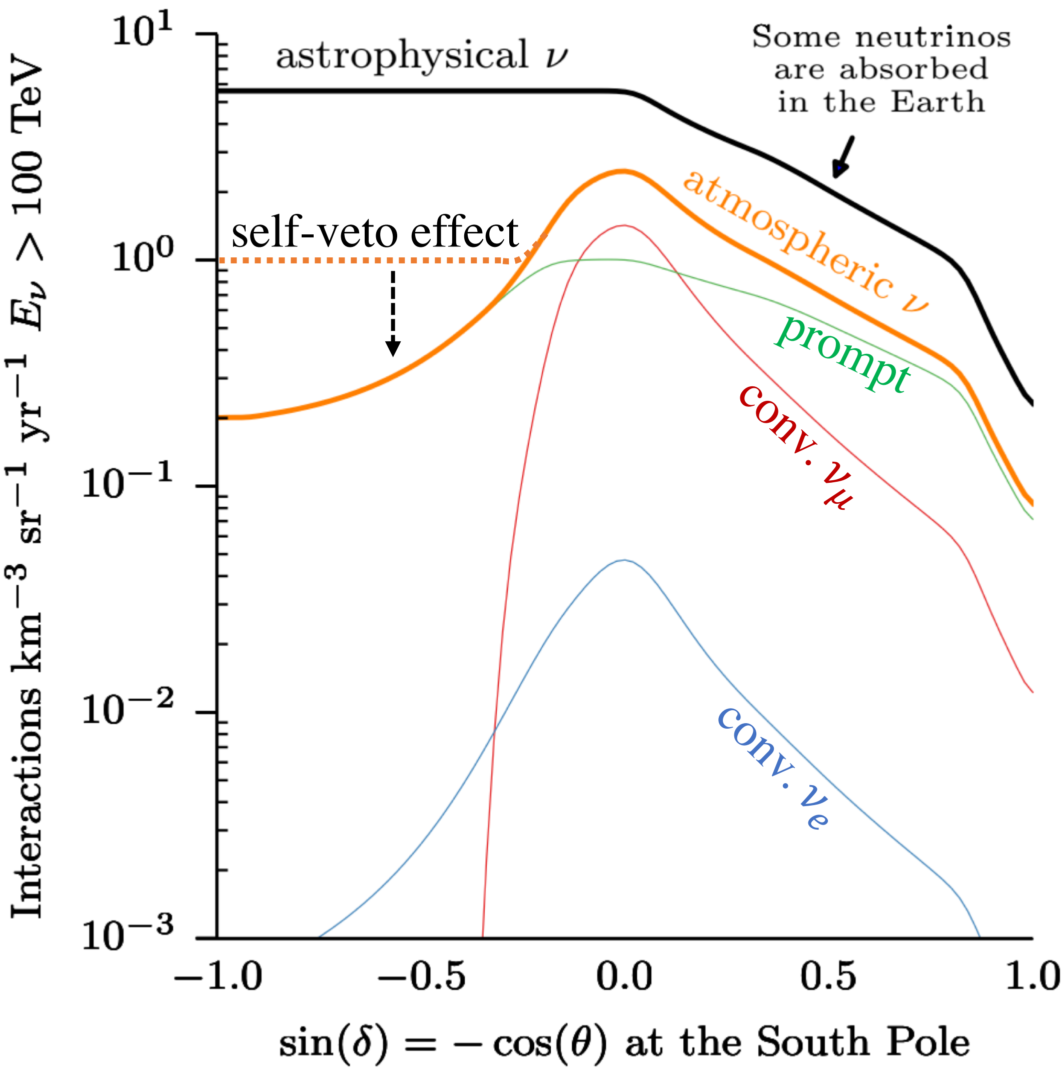
Veto probability correlated with energy and direction of neutrino

Need to understand how atmospheric neutrinos make it into our sample



Zenith dependence

J. van Santen, ICRC2017



Southern sky

Northern sky

Passing fraction: probability of an atmospheric neutrino to not be vetoed

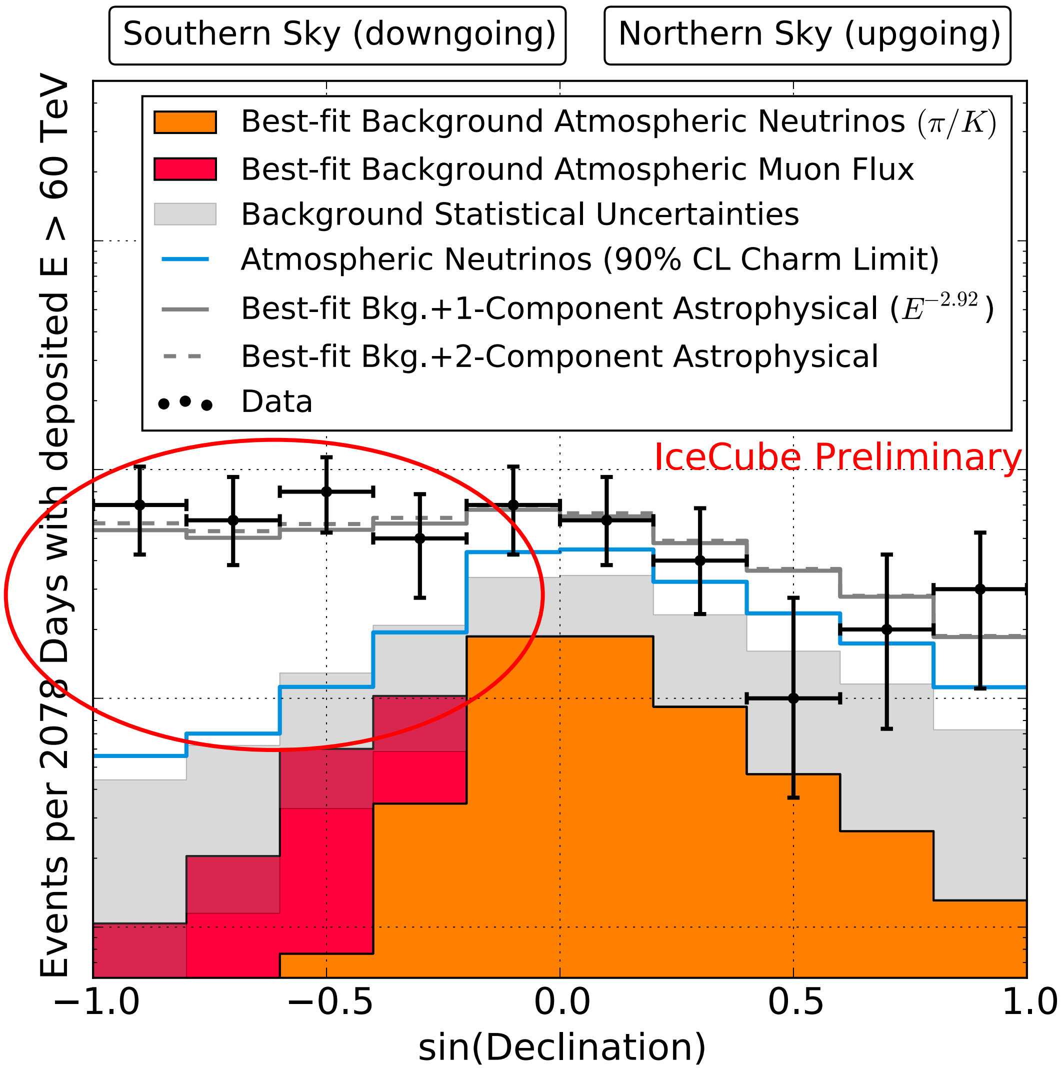
- $N_{det} = N_{total} \times \text{Passing fraction}$

Alters the zenith distribution of atmospheric neutrinos in the **southern sky**

HESE 6 year zenith distribution

Zenith distribution in southern-sky incompatible with background

But this background suppression is entirely due to the self-veto

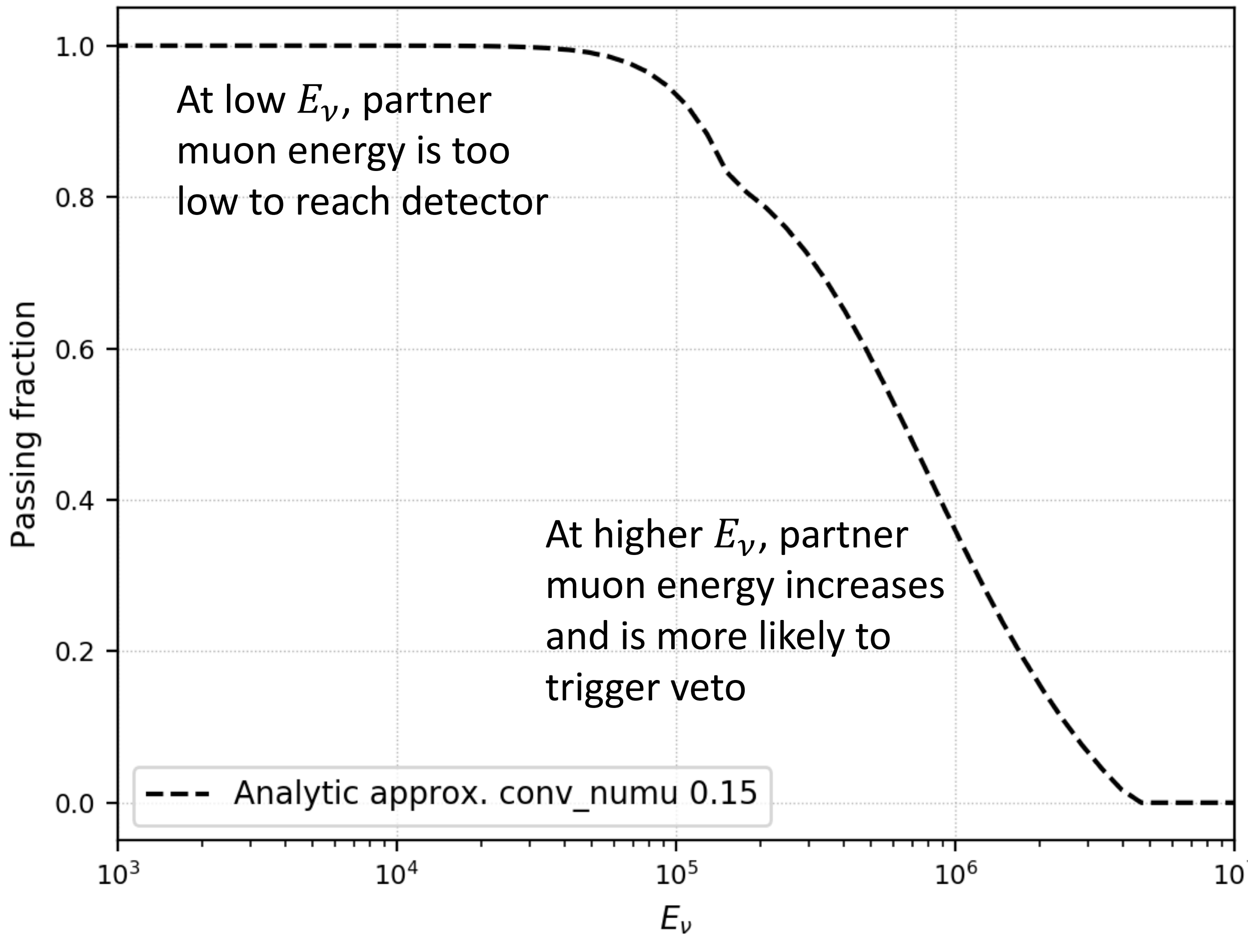


Previous treatments

Analytic calculation has single set of assumptions for primary flux, hadronic interaction and muon range

- PRD 79, 043009 (2009) and PRD 90, 023009 (2014)

No systematic uncertainty applied



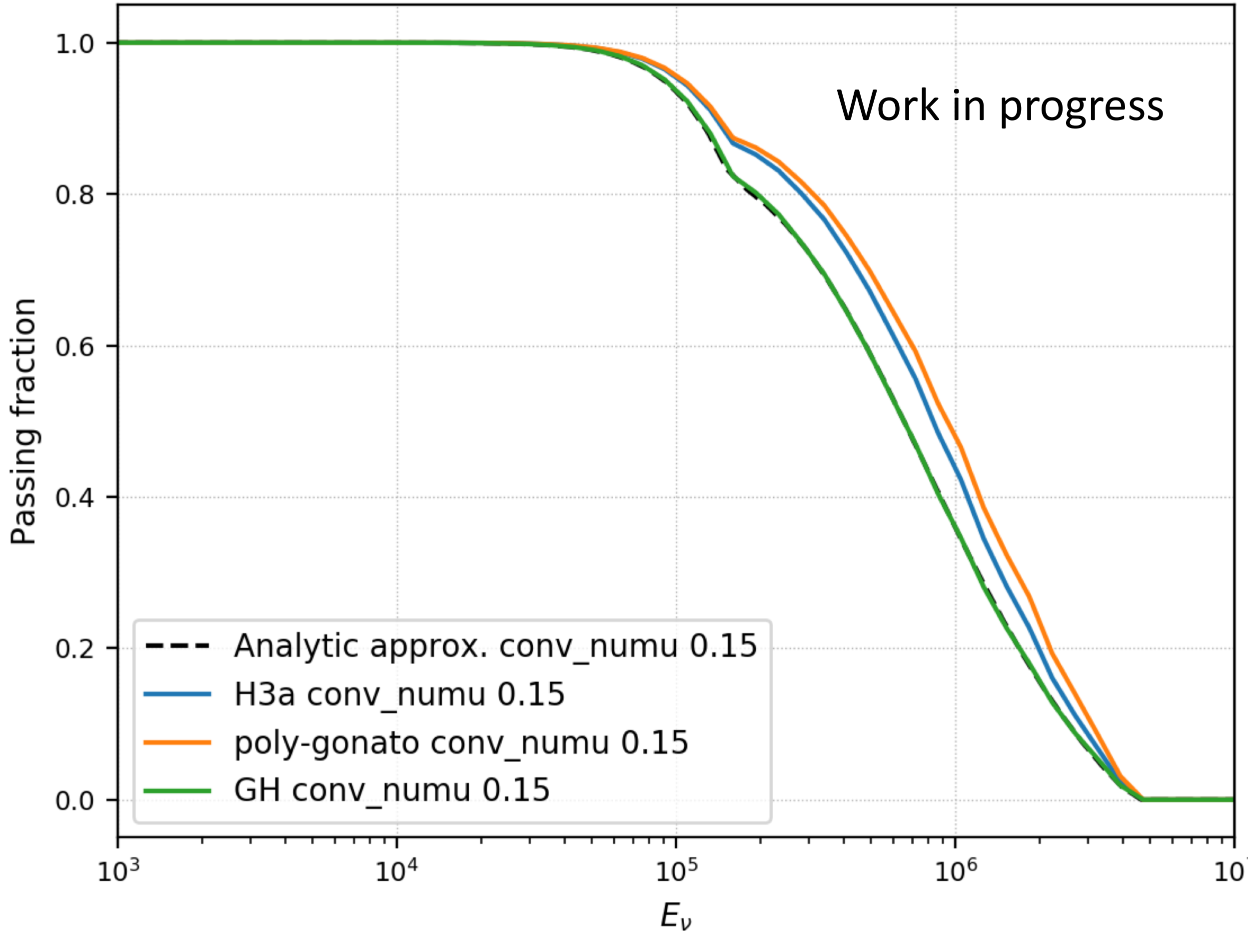
New approach

C. Arguelles, S. Palomares-Ruiz,
A. Schneider, L. Wille, and **T. Yuan**

Calculate passing fraction with MCEq [EPJ 99, 08001]

$$\frac{1}{\phi_\nu(E_\nu,\theta)}\sum_p \int \frac{1}{\lambda}\frac{dN_p}{dE_\nu}(E_p,E_\nu)\phi_p(E_p,h,\theta)[1-Prob(E_\mu^i > E_{thres})]dE_p dh$$

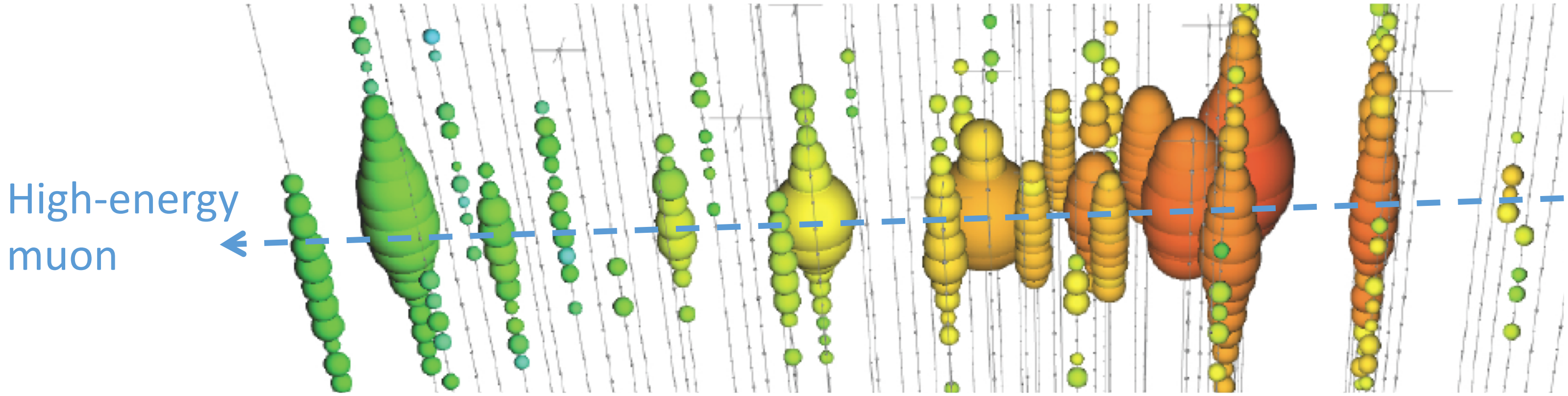
Can input different primary cosmic-ray spectra, hadronic interaction models etc.

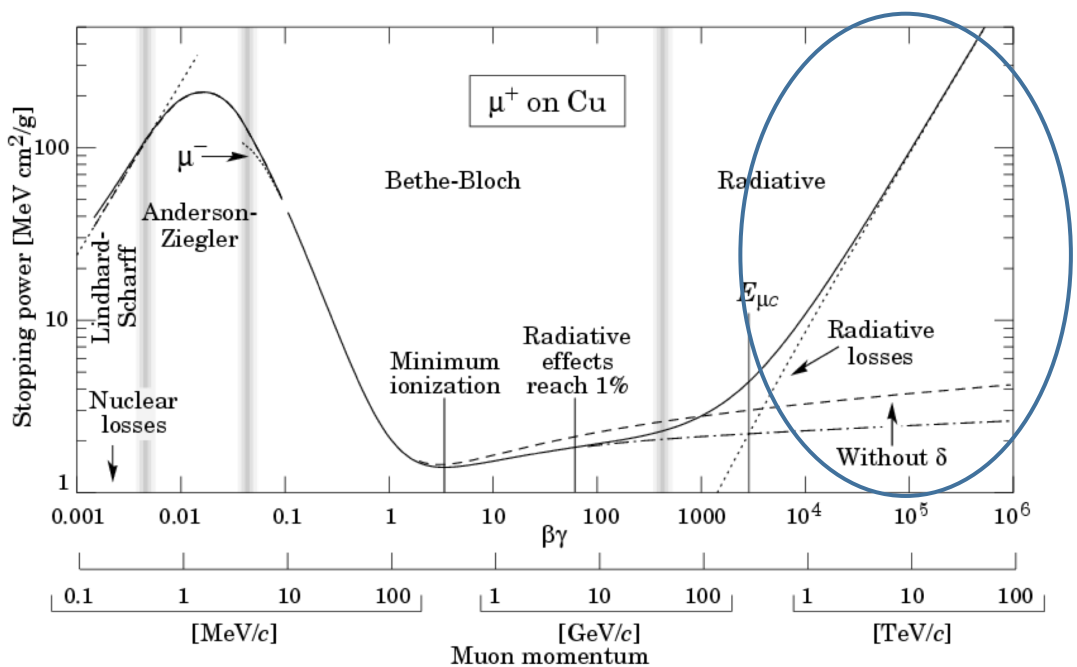


Muon range

At high energies, muon is no longer minimum ionizing

Stochastic energy losses become important



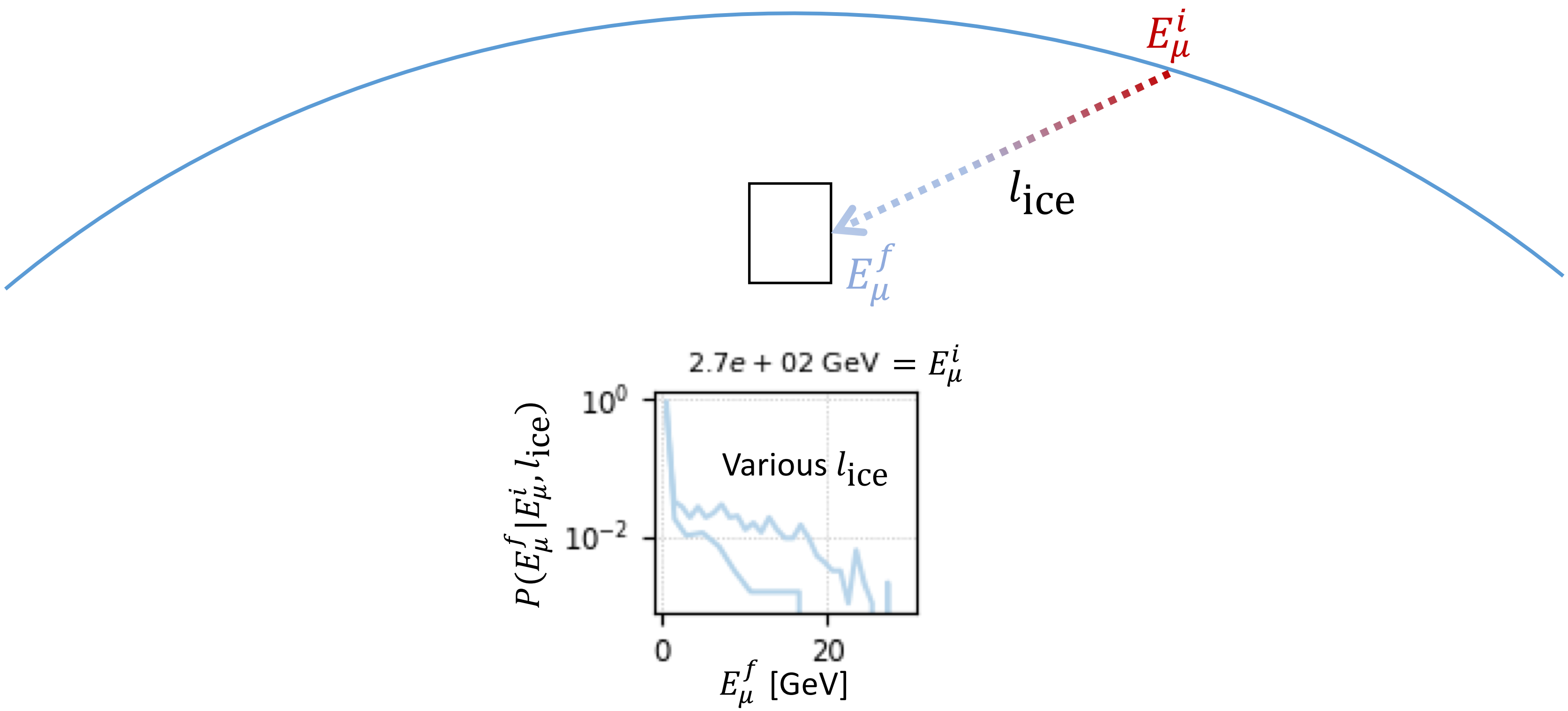


Muon range pdfs

Previous analytic treatment neglects stochastic losses

- Assumes average muon range

Need to evaluate $P(E_\mu^f | E_\mu^i, l_{\mathrm{ice}})$, the pdf of the muon energy at depth, E_μ^f, as a function of E_μ^i at surface and l_{ice} the overburden

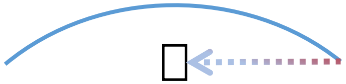


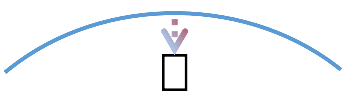
Detection probability

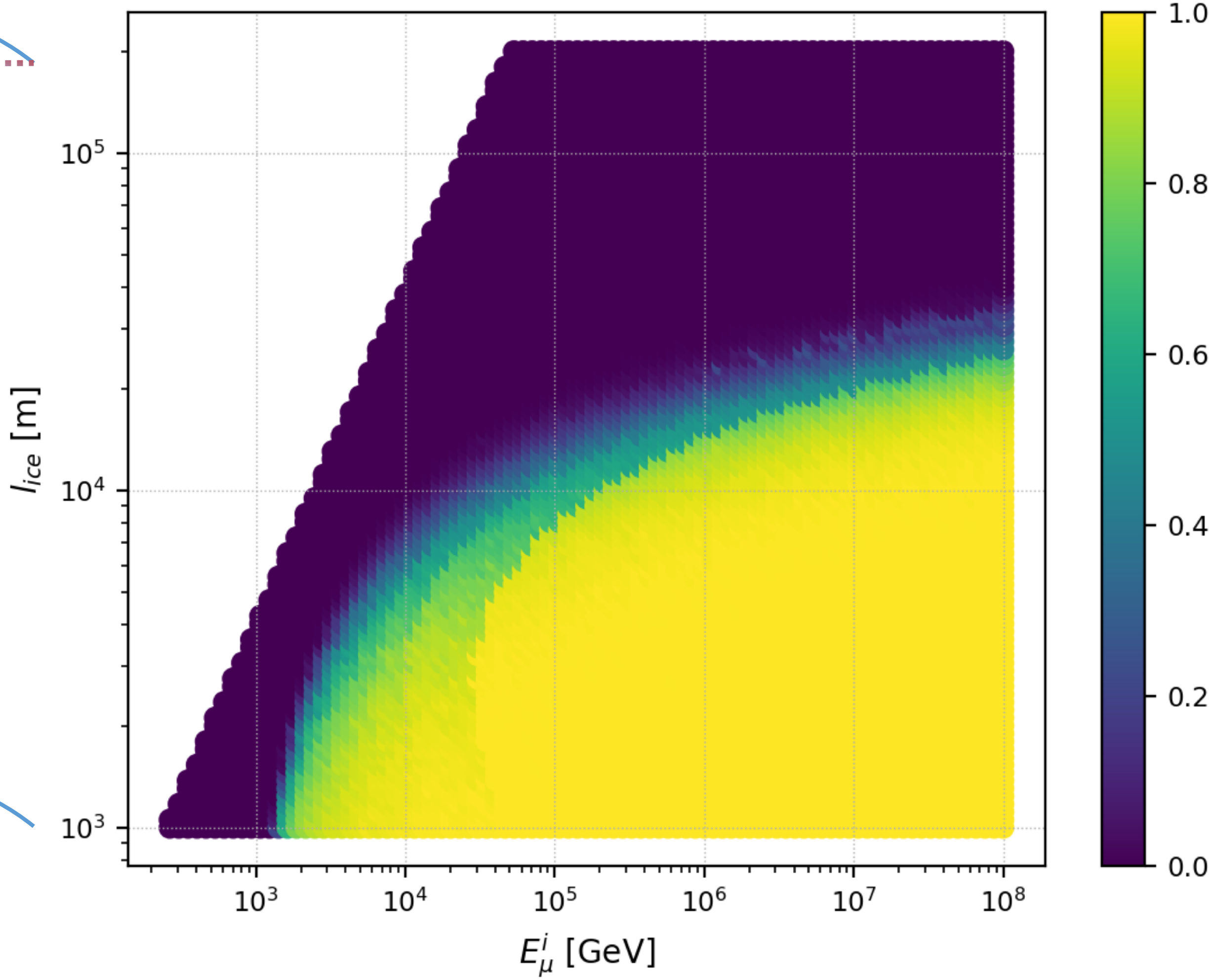
Simulate muons using MMC [arXiv:hep-ph/0407075] and build pdfs

Integrate over detector response to get detection probability

$$P\left(E_\mu^f > 1\ \mathrm{TeV} \middle| E_\mu^i, l_{\mathrm{ice}}\right)$$



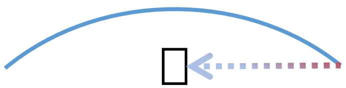




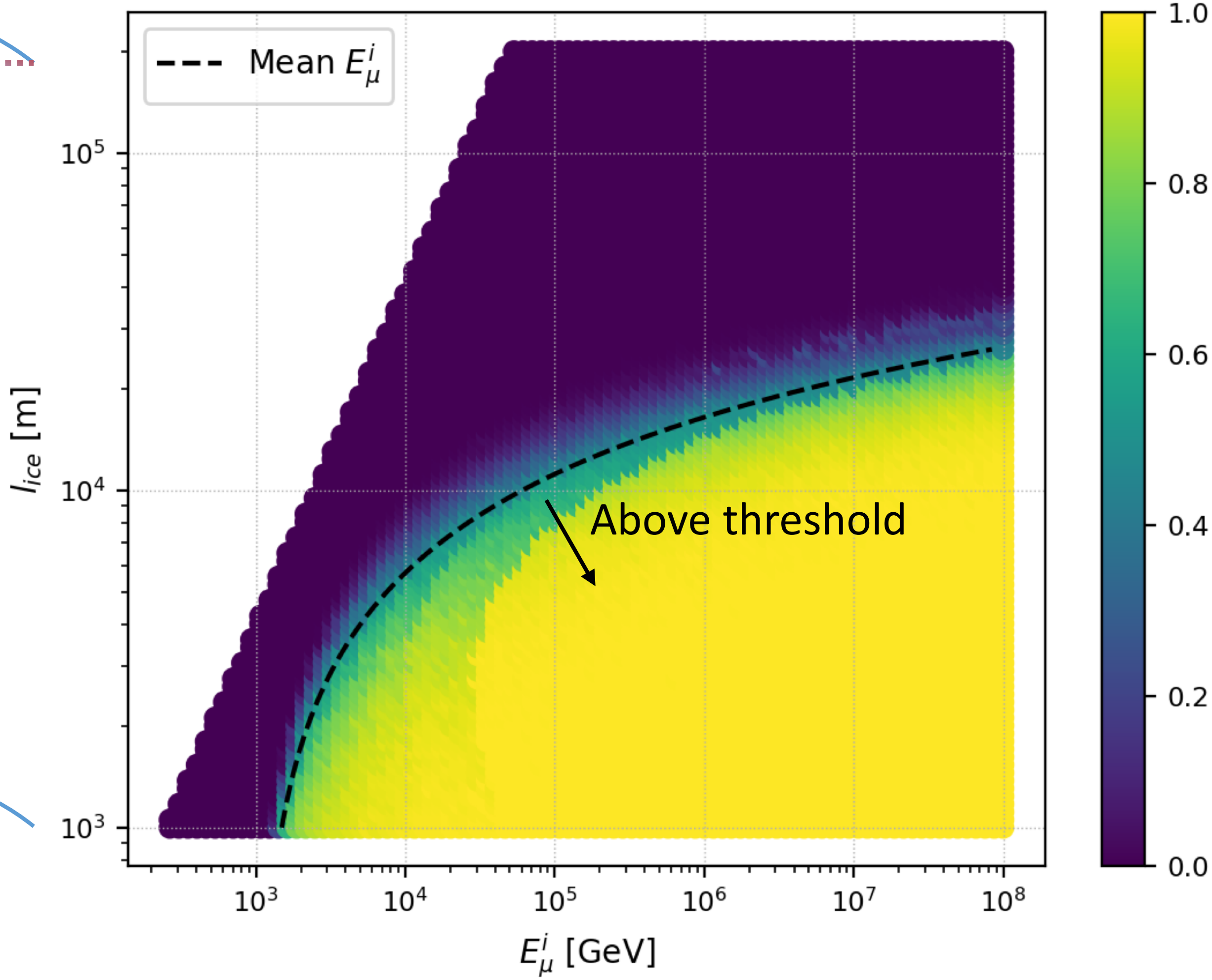
Detection probability

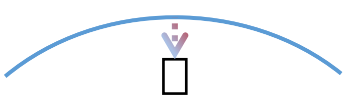
Previously, an average muon range assumed

- Step function probability



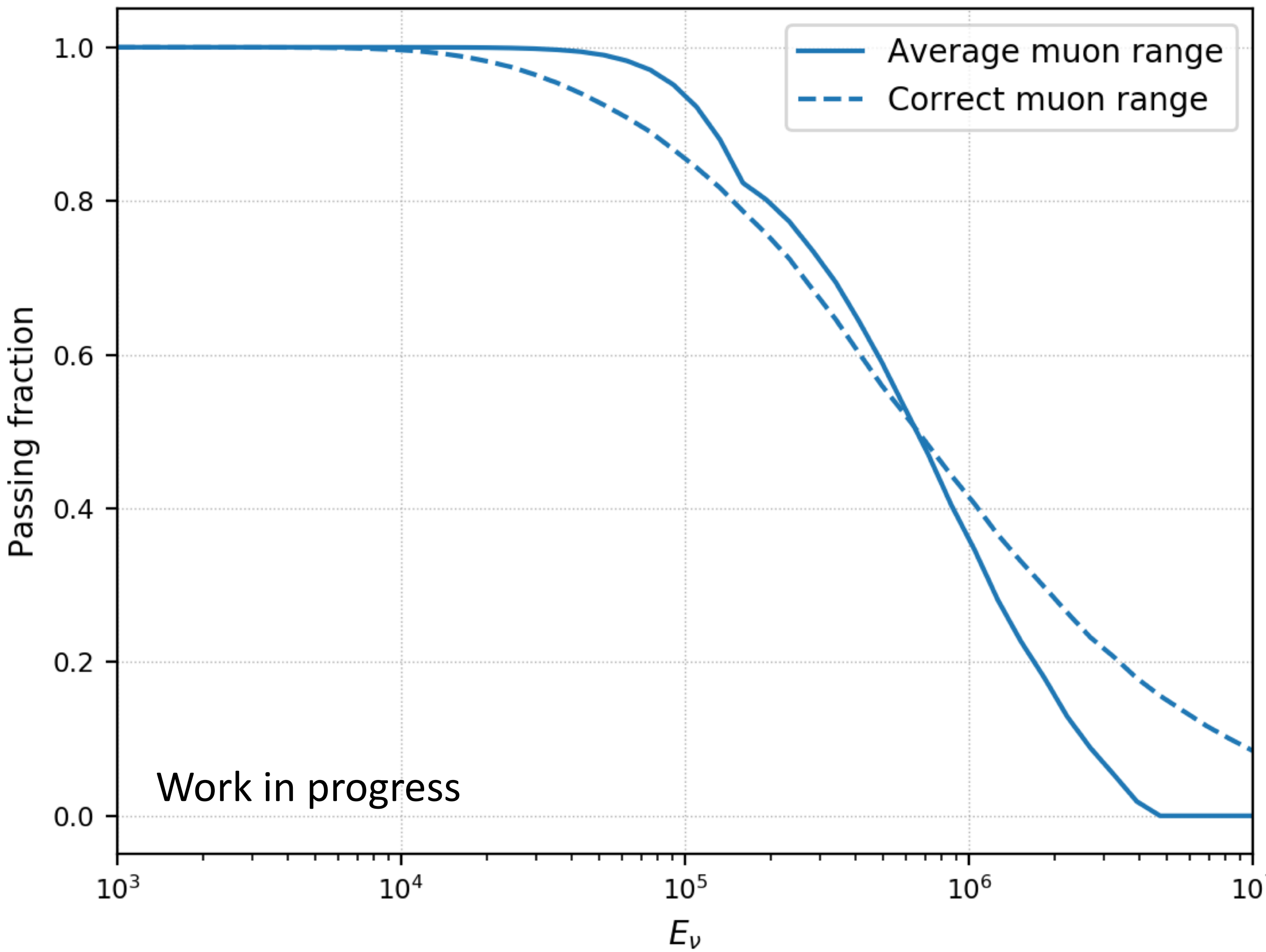
$$P\left(E_\mu^f > 1\ \mathrm{TeV} \middle| E_\mu^i, l_{\mathrm{ice}}\right)$$



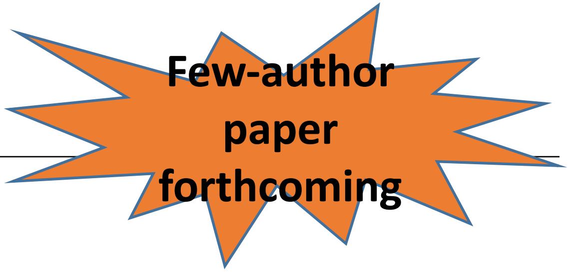


Passing fraction with muon stochastics

Significant effect on passing fraction

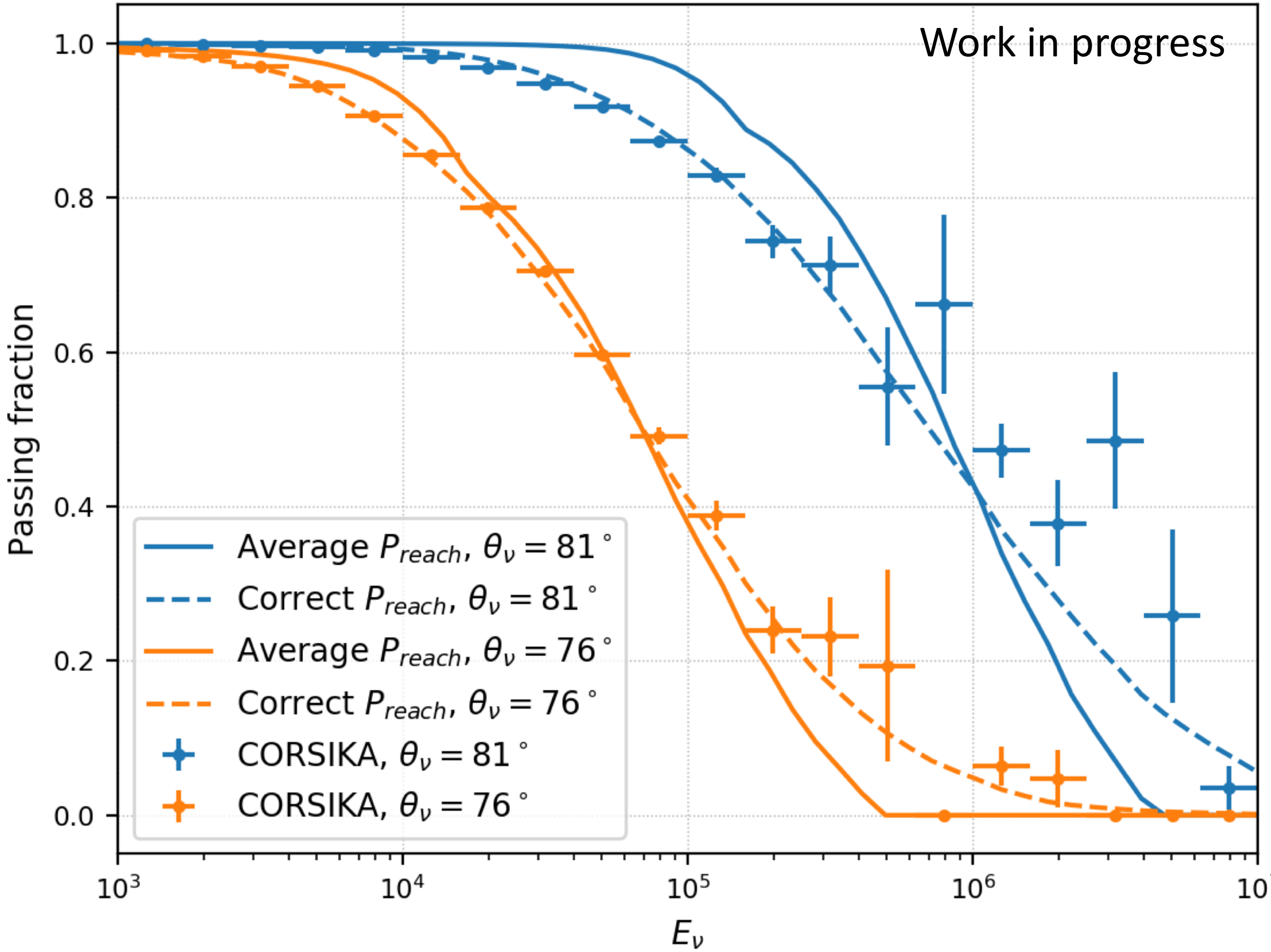


Conventional ν_μ



No fit performed!

Calculations match state-of-the-art CORSIKA simulation!

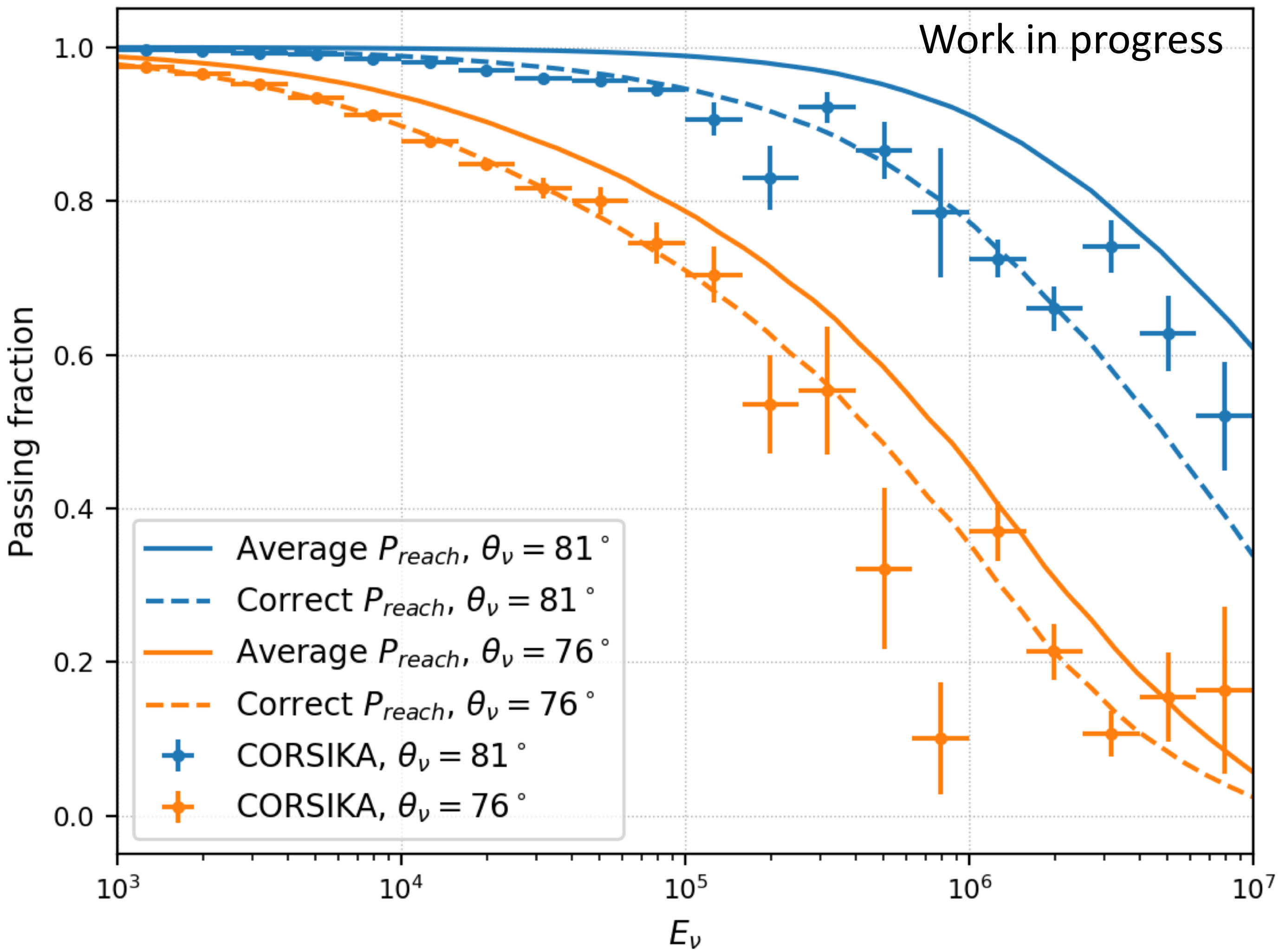


Prompt ν_e

Few-author paper forthcoming

No fit performed!

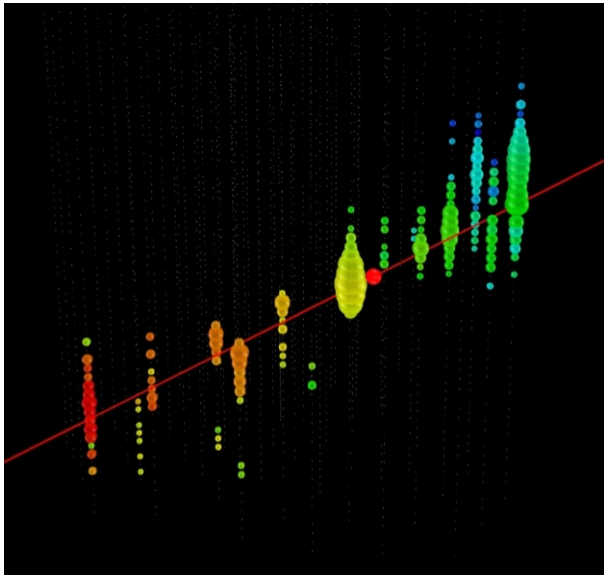
Calculations match state-of-the-art CORSIKA simulation!



Implications for the future

Main topologies in IceCube

CC muon neutrino

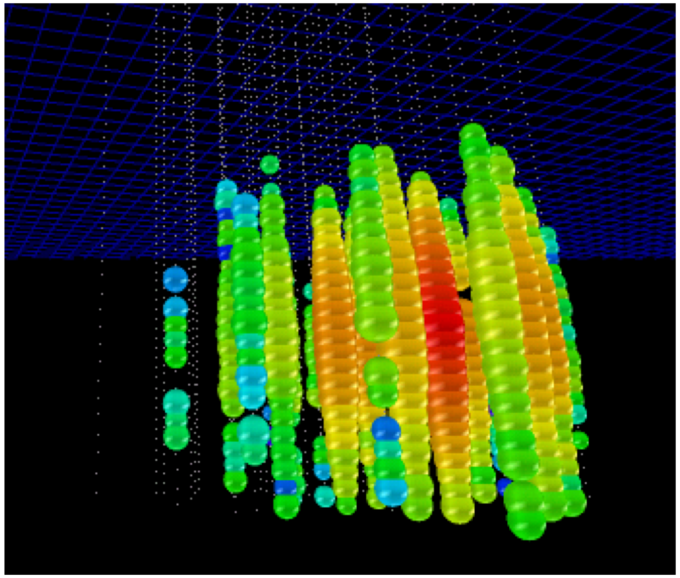


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

angular resolution ~ 0.5°
energy resolution ~ x2
trigger for real-time

NC or CC electron neutrino

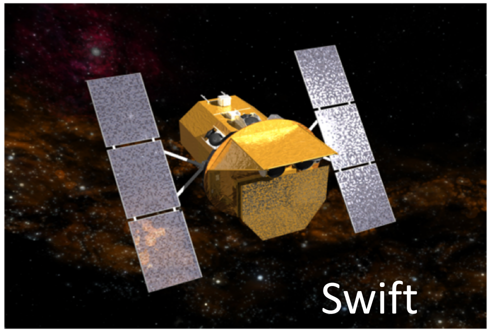


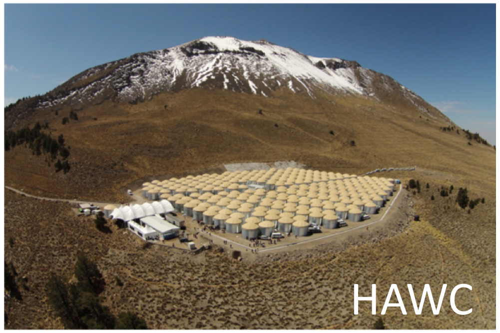
$$\nu_e + N \rightarrow e + X$$
$$\nu_x + N \rightarrow \nu_x + X$$

shower (data)

angular resolution ~ 10°
energy resolution ~ 15%
not used for real-time

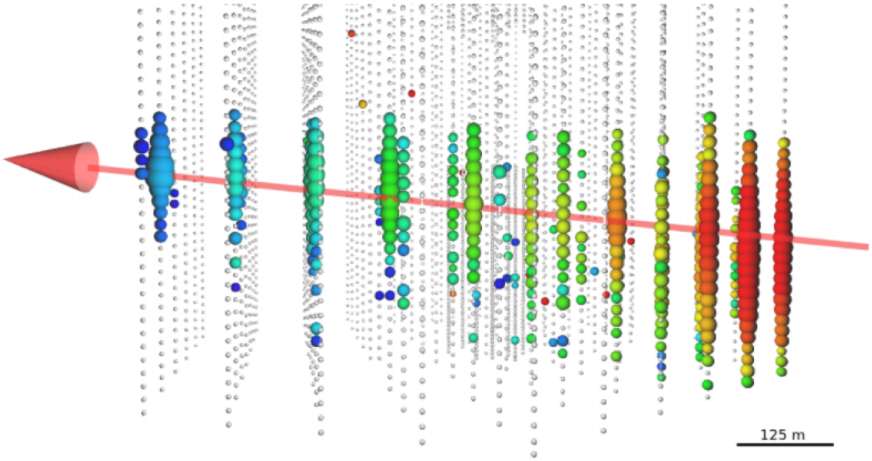
Real-time follow up



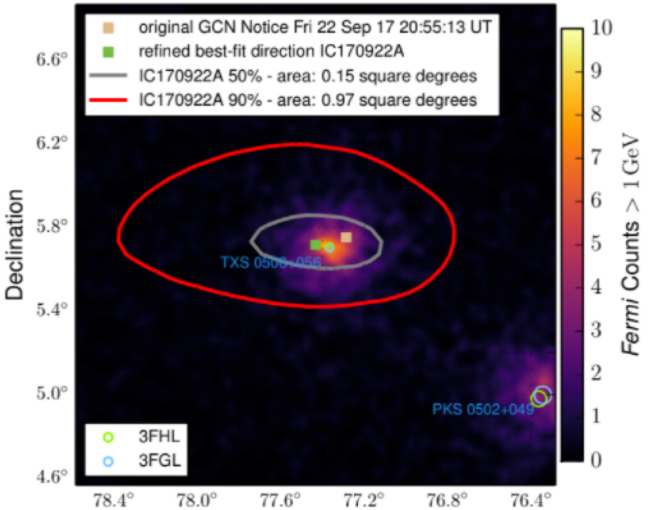


Part of Astrophysical Multimessenger Observatory Network (AMON)

IC170922



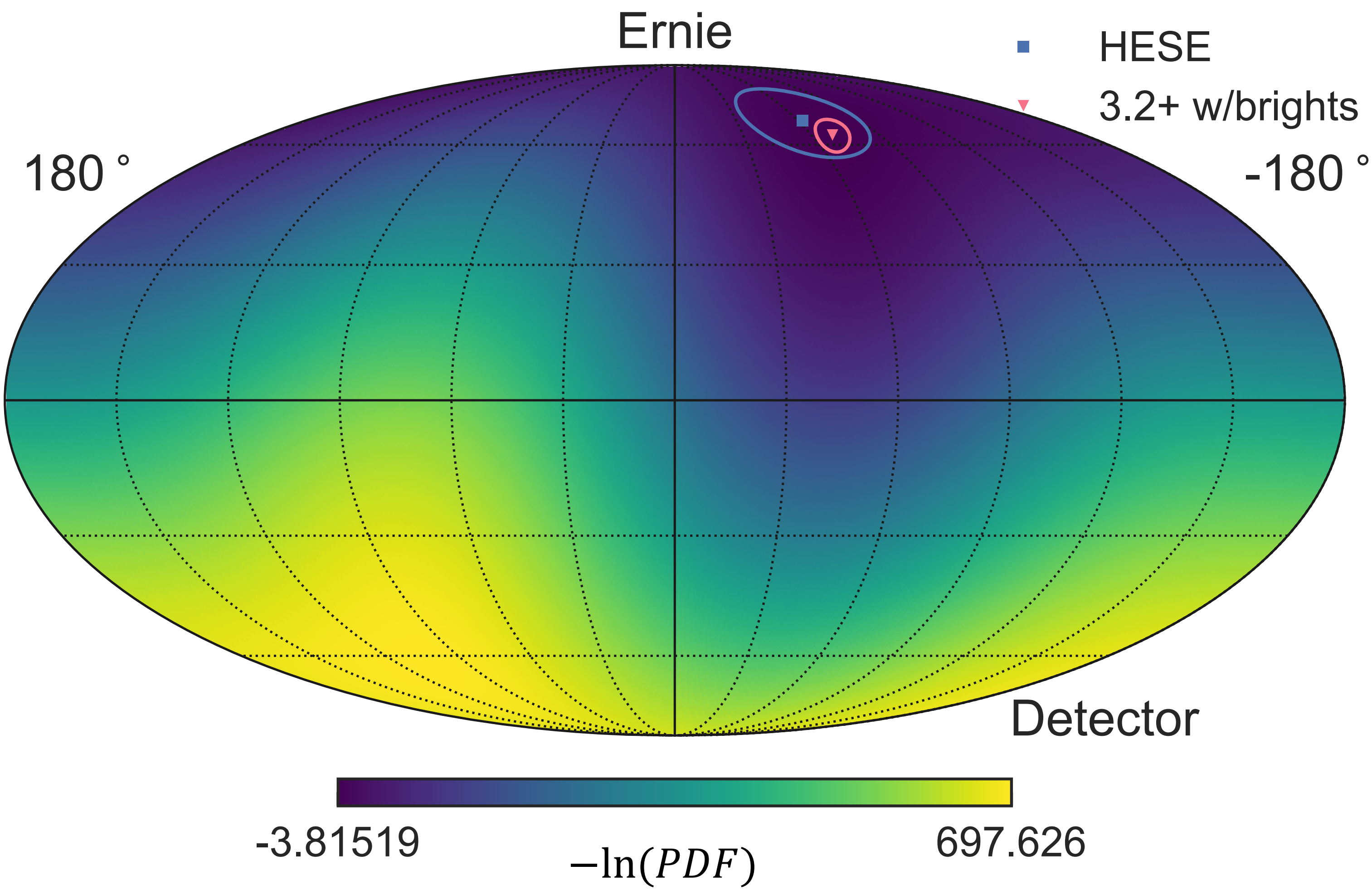
Coincident with TXS 0506+056



Cascades in real-time

Currently alerts only triggered by high-energy **tracks**

If we can get ~3 degree resolution for cascades at 1 PeV, why not trigger on **cascades** as well!



Cascades in real-time

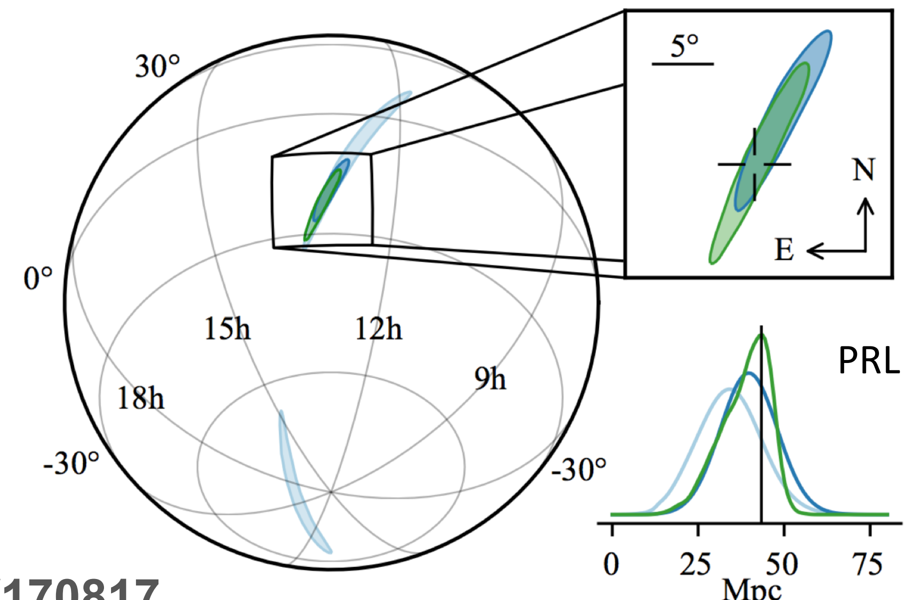
Need to reconstruct direction **accurately** → latest ice model

Need to reconstruct direction **precisely** → bright DOMs

Needs to be computationally **fast**

Current reconstruction routines are not quite there for all three

LIGO releases large contours and they found a multi-wavelength correlation last year



PRL 119, 161101 (2017)

GW170817

Atmospheric neutrinos from charm hadrons

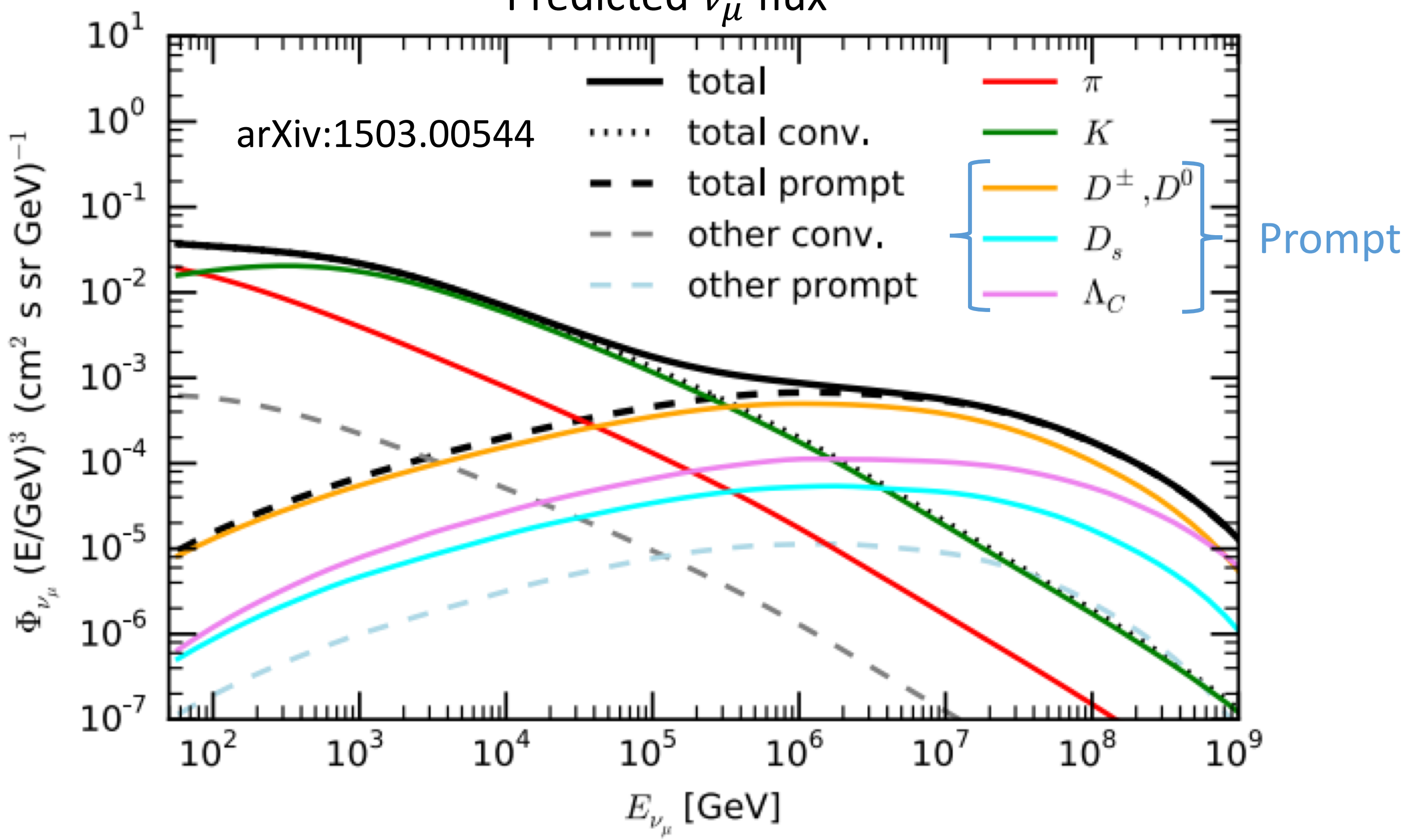
Charm hadrons have short lifetime and decay immediately to produce neutrinos

These are called "prompt" atmospheric neutrinos

Dominant above 100 TeV, isotropic

Only upper limits exist

Predicted ν_μ flux



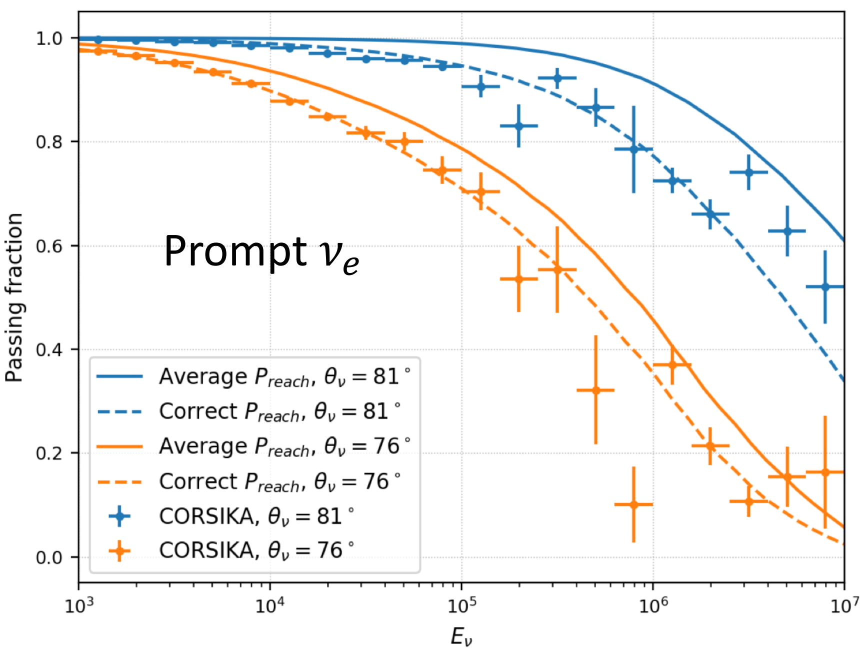
A measurement of prompt neutrinos

Low-threshold starting events sample extends HESE to lower energies

With better treatment of atmospheric **self-veto**, can be used to measure **prompt atmospherics**

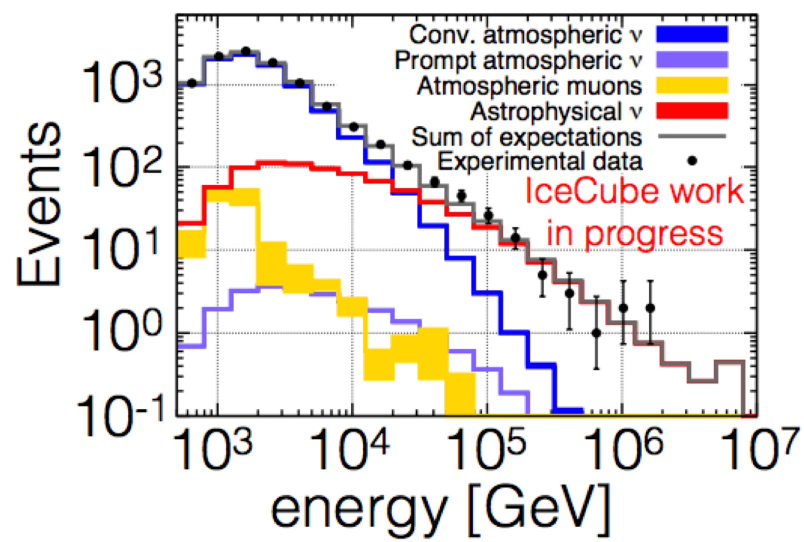
- Self-veto breaks degeneracy between prompt and astrophysical neutrinos

Improved self-veto treatment

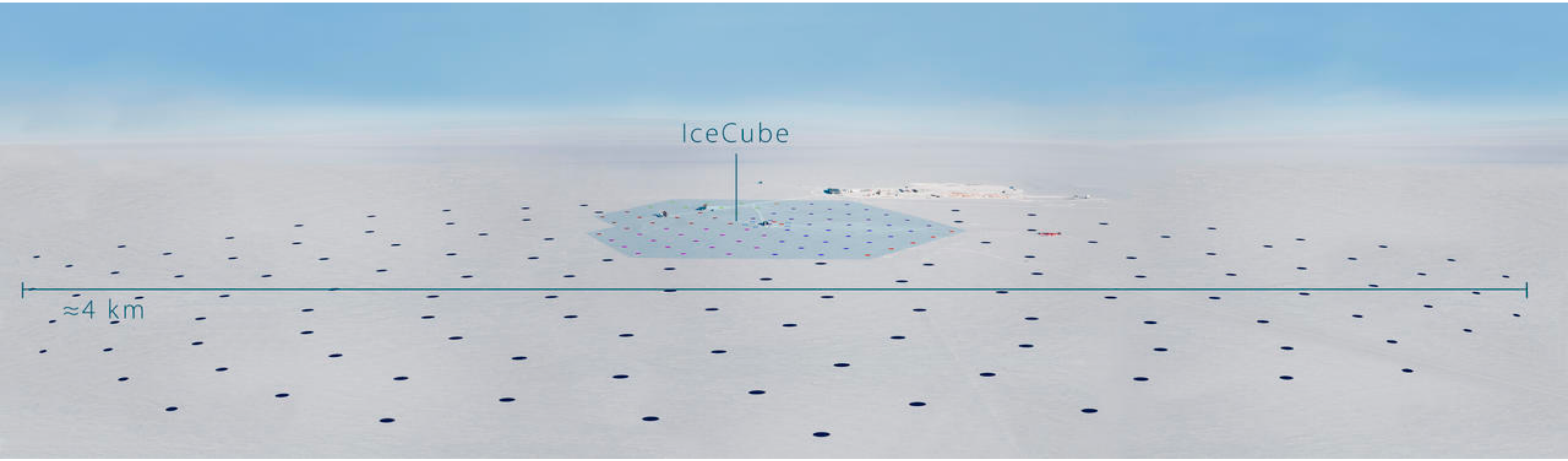


N. Wandkowsky, TeVPA17

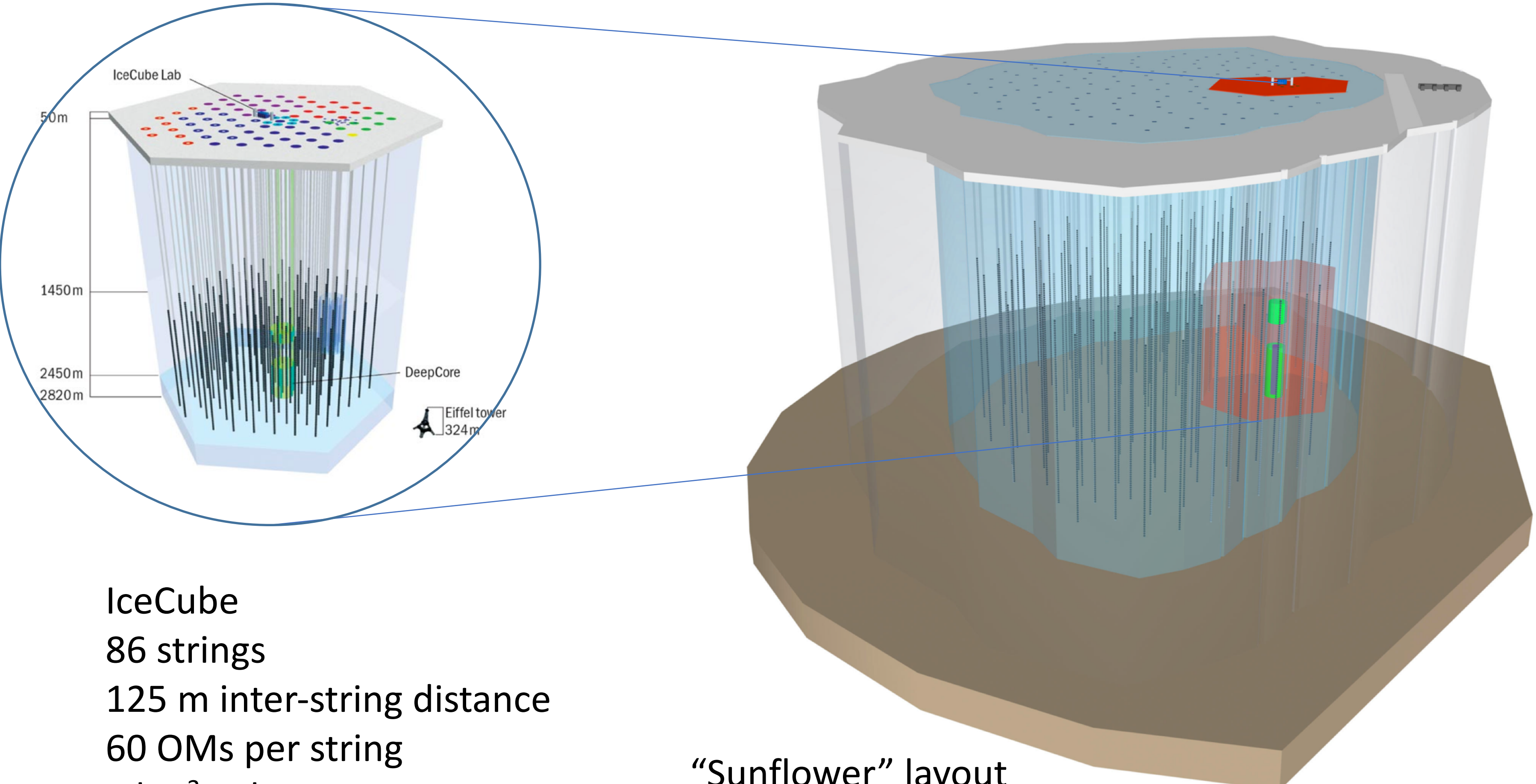
Low-threshold sample (6 years)



Prospects for IceCube-Gen2



Extending IceCube



IceCube
86 strings
125 m inter-string distance
60 OMs per string
1 km^3 volume

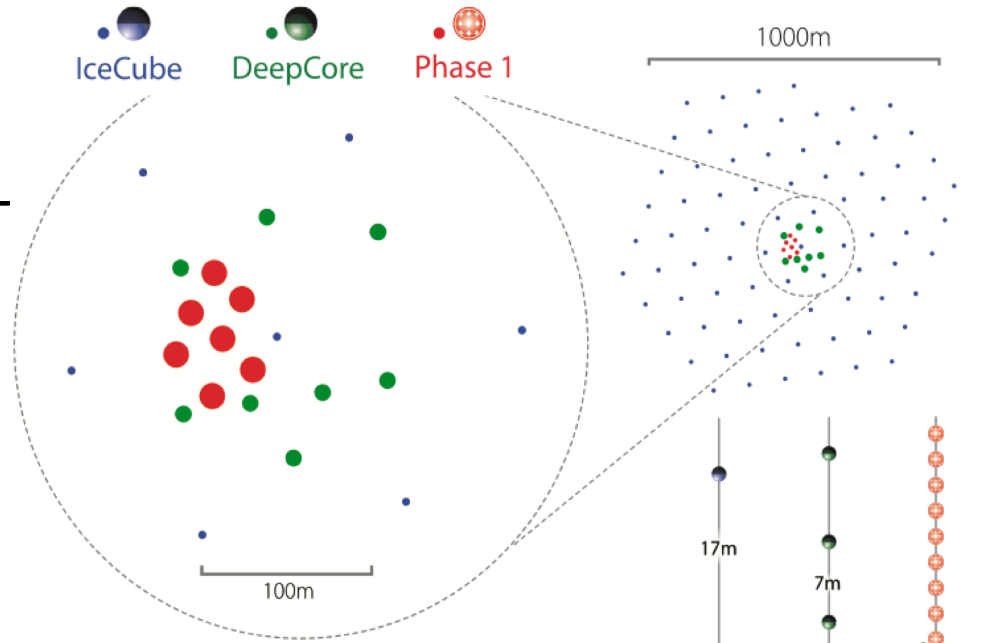
“Sunflower” layout
120 new strings
240 m inter-string distance
80 OMs per string
8 km^3 volume

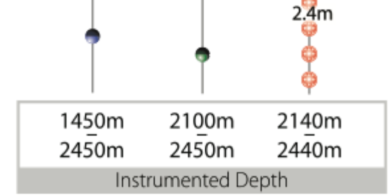
First steps: The IceCube Upgrade

Seven additional strings with inter-string spacing of 22 m

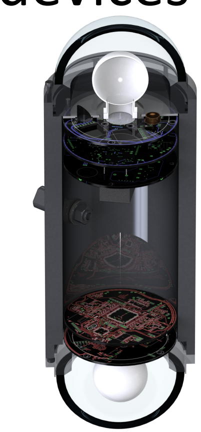
Instrumented with multi-PMT digital optical modules (mDOMs)

- Better directionality
- Doubles photocathode area





New calibration devices



Outlook and summary

Improving IceCube reconstruction will allow for a complete reanalysis of all data!

Already, have incorporated updates into HESE

- New high-energy cross-section measurement

Improved treatment of atmospheric neutrino background will affect all veto-based analyses!

Long-term: IceCube-Gen2; first steps with IceCube Upgrade

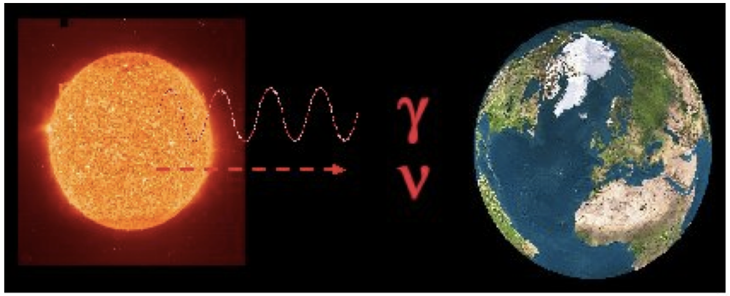
Thank you!

Backups

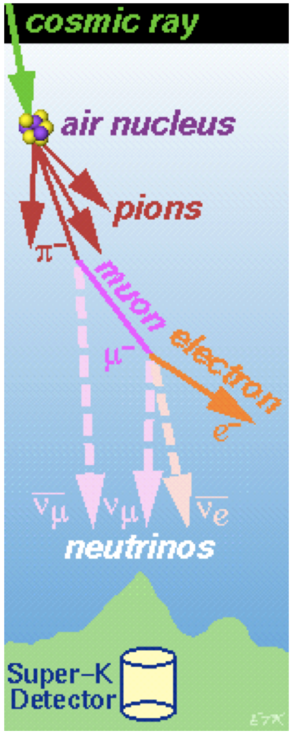
Discovery of neutrino oscillation

- In the SM, neutrinos are massless
  - Assumption leads to incorrect predictions

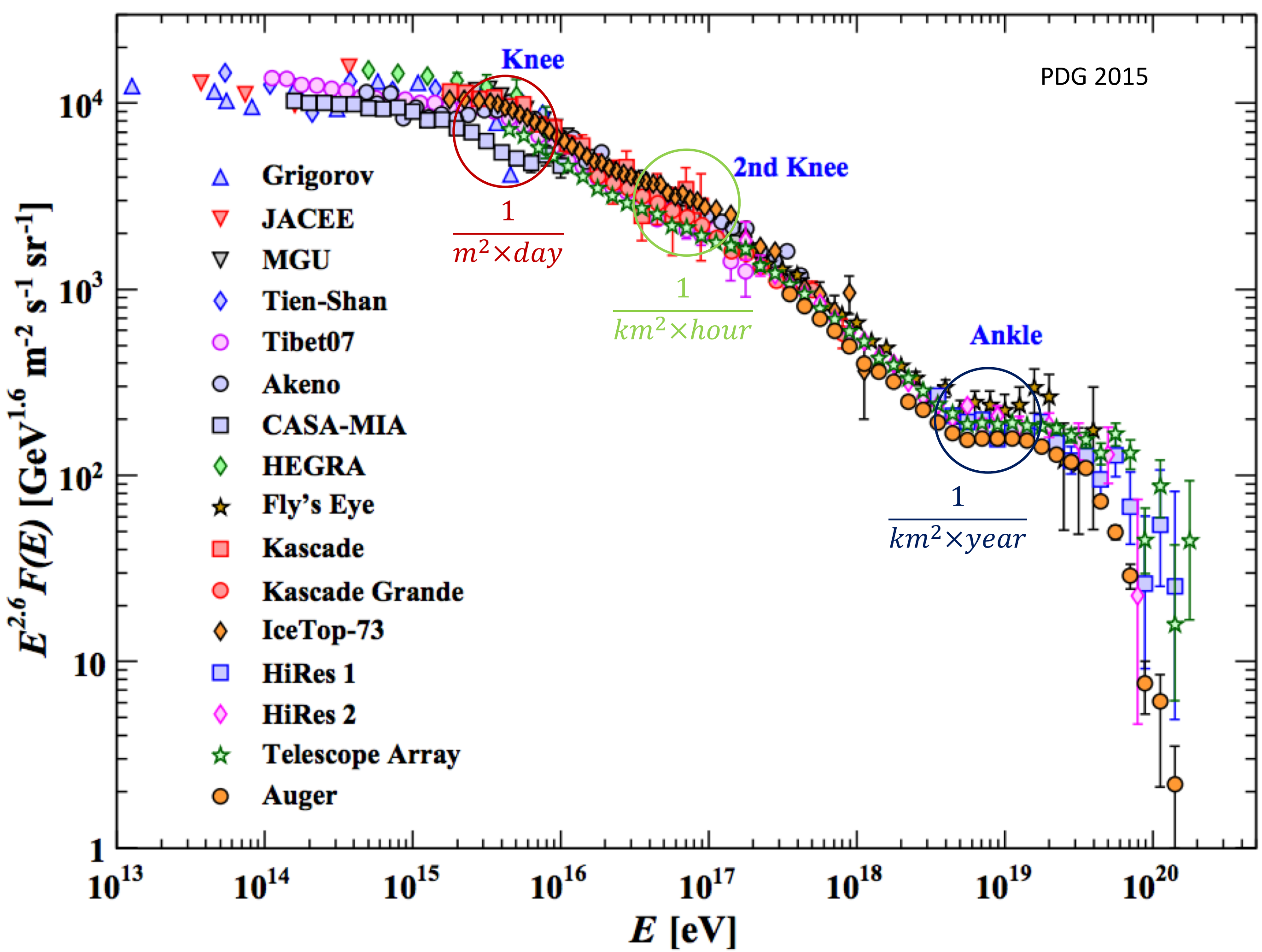
1. Solar neutrino problem
   - Neutrinos produced inside the sun
   - Measured smaller rate than expected from standard solar model



2. Atmospheric neutrino anomaly
   - Cosmic rays interacting with the atmosphere produce a shower of hadrons that in turn produce neutrinos
   - Expected: $\frac{N_{\nu_\mu}}{N_{\nu_e}} \cong 2$
   - Some experiments saw smaller ratio than expected

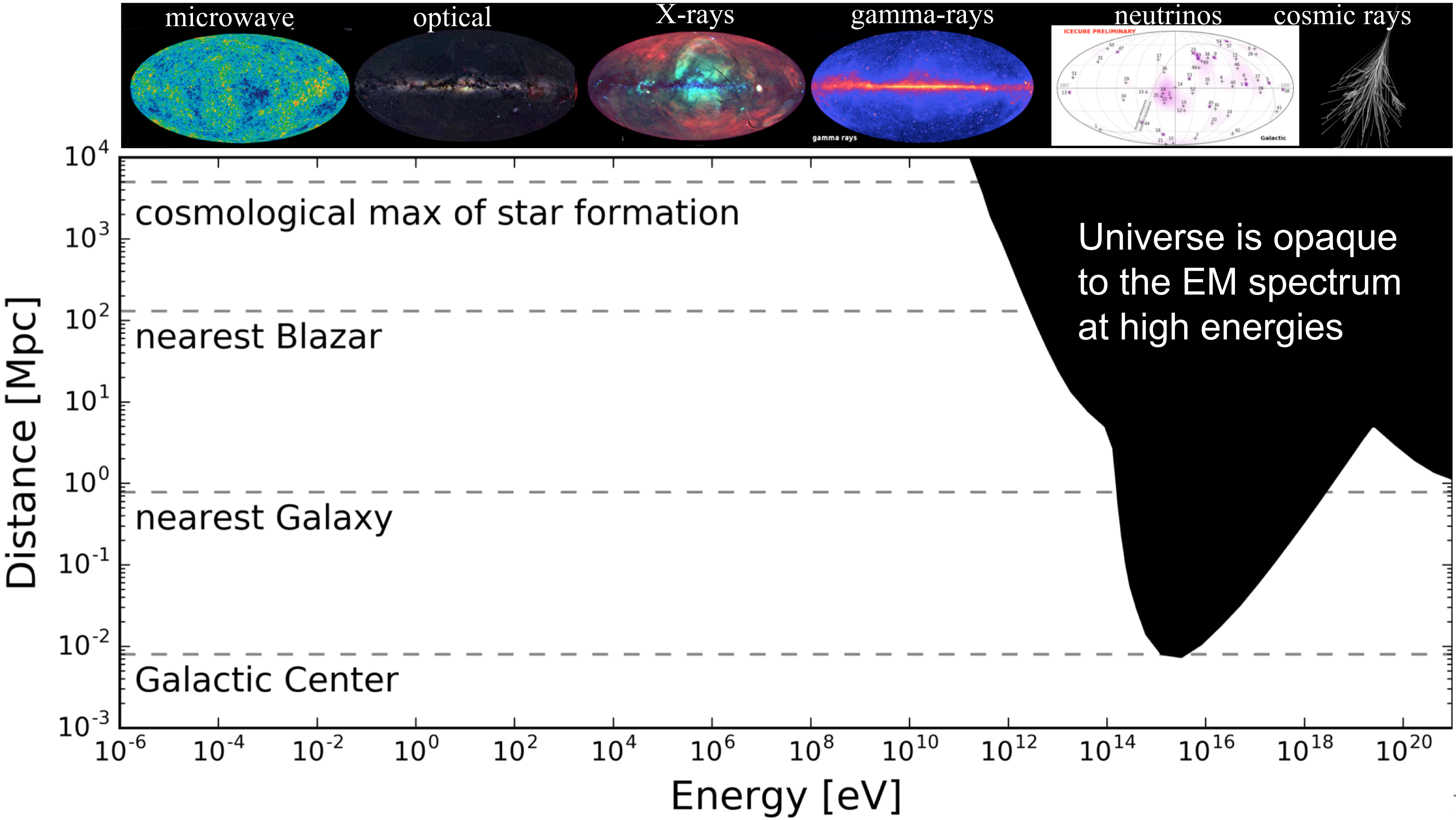


All-particle cosmic rays



Multimessenger astrophysics

Observing high-energy astrophysical neutrinos allows constraints on production mechanisms



Two approaches to reconstruction

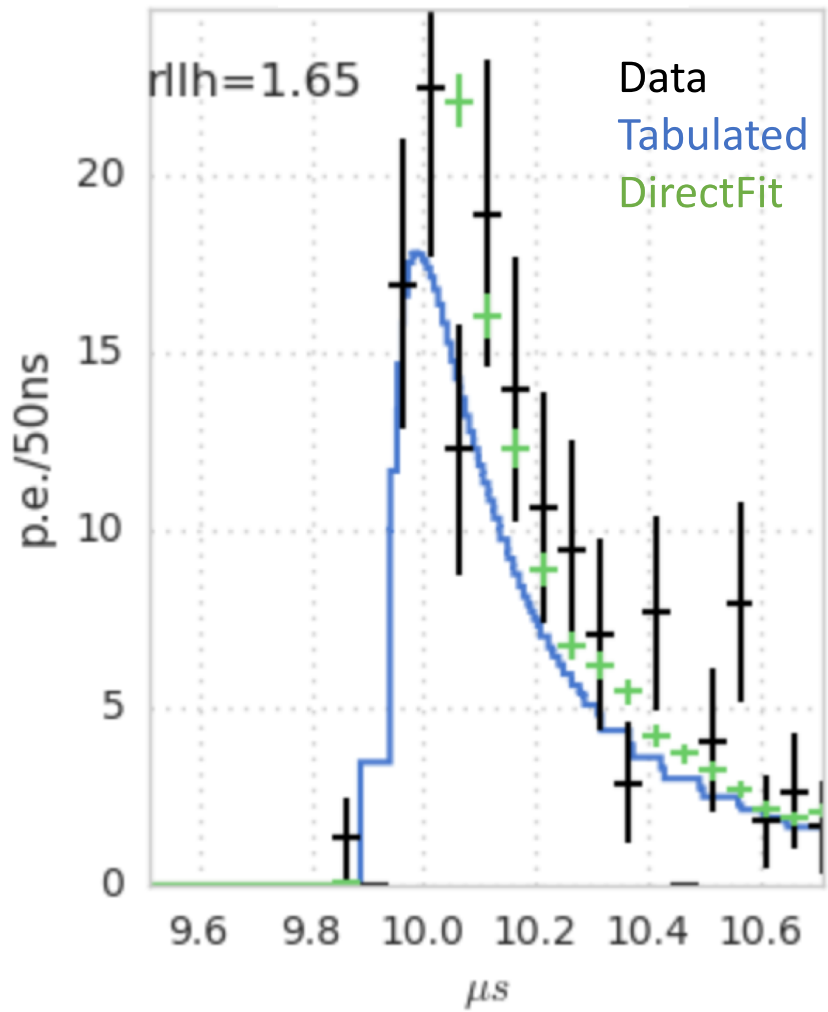
Tabulated photon yields

- Pros: Fast runtime; simple llh
- Cons: Limited ice-models

Direct photon propagation

- Pros: Any ice-model can be used
- Cons: Statistical uncertainties from both data and MC; slow

Example waveform

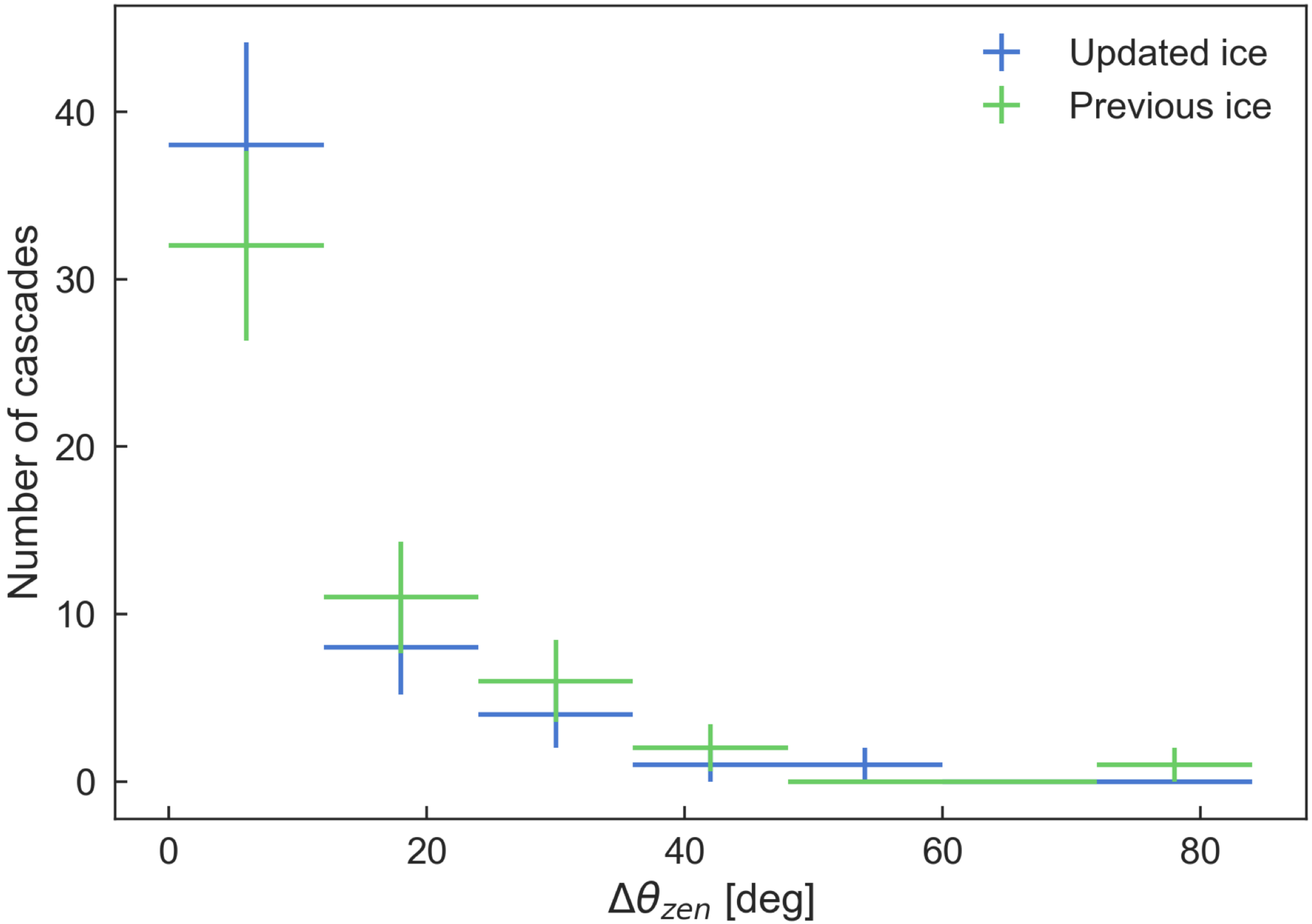


IC collaboration, 1311.4767
D. Chirkin, arXiv:1304.0735

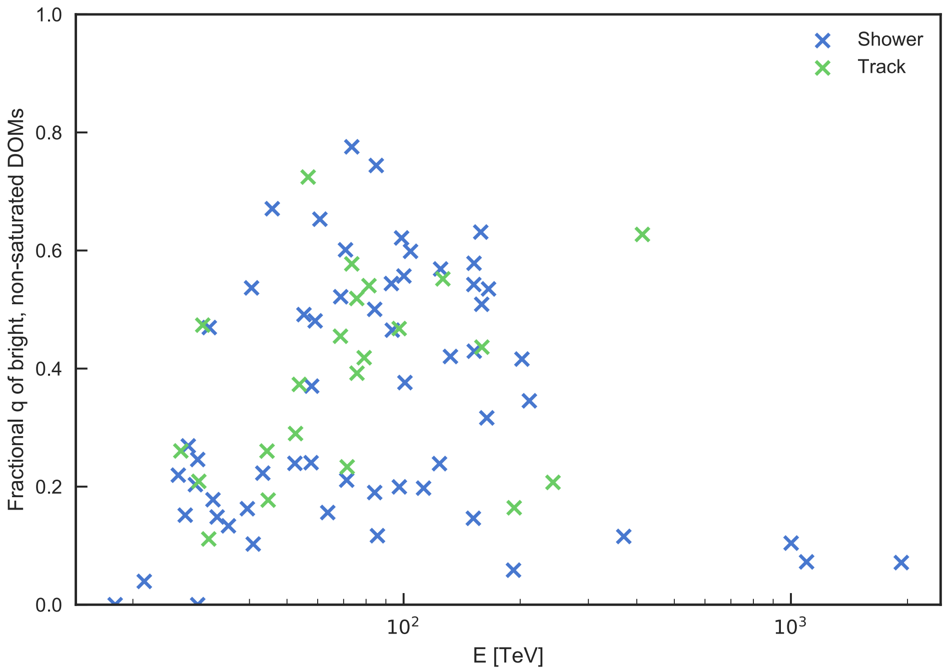
Overall improvement

Assume DirectFit best-fit as benchmark

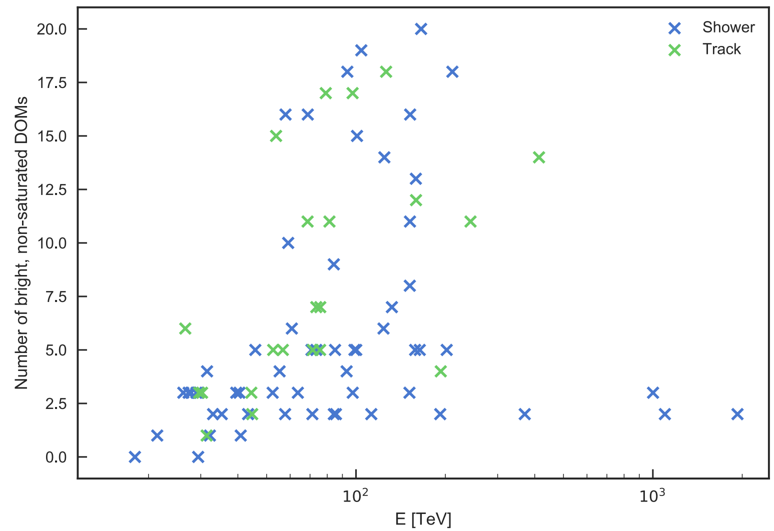
$\Delta\theta_{zen}$= difference in zenith angle between photon-table reconstruction and DirectFit

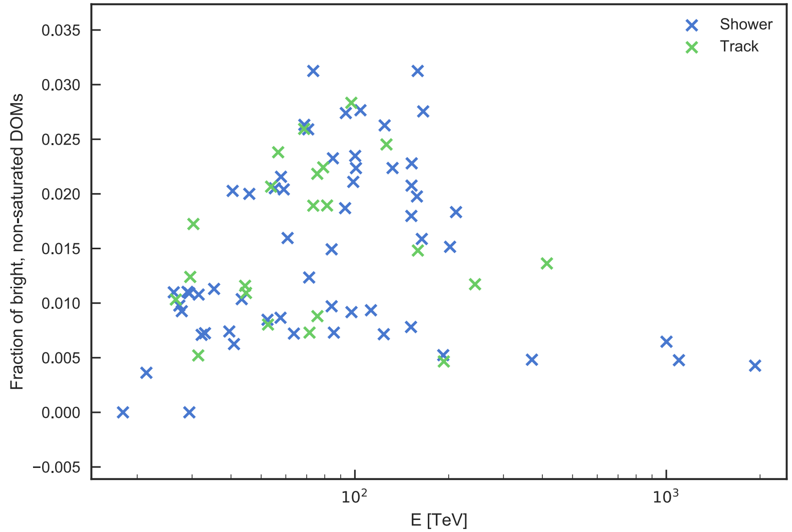


Bright but not saturated

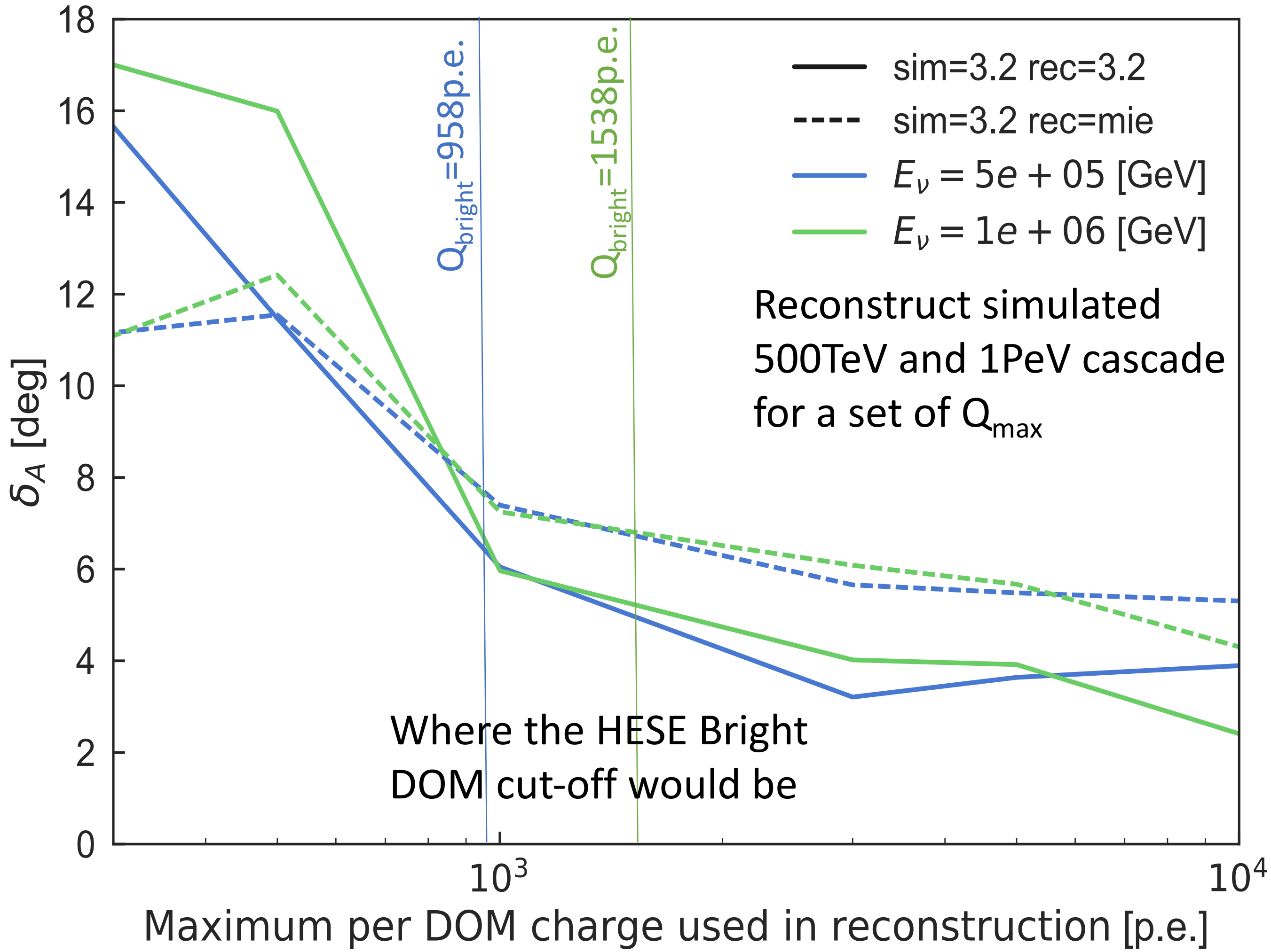


Saturated DOMs are typically a subset of bright DOMs.





Effect of Q_{max} on angular resolution

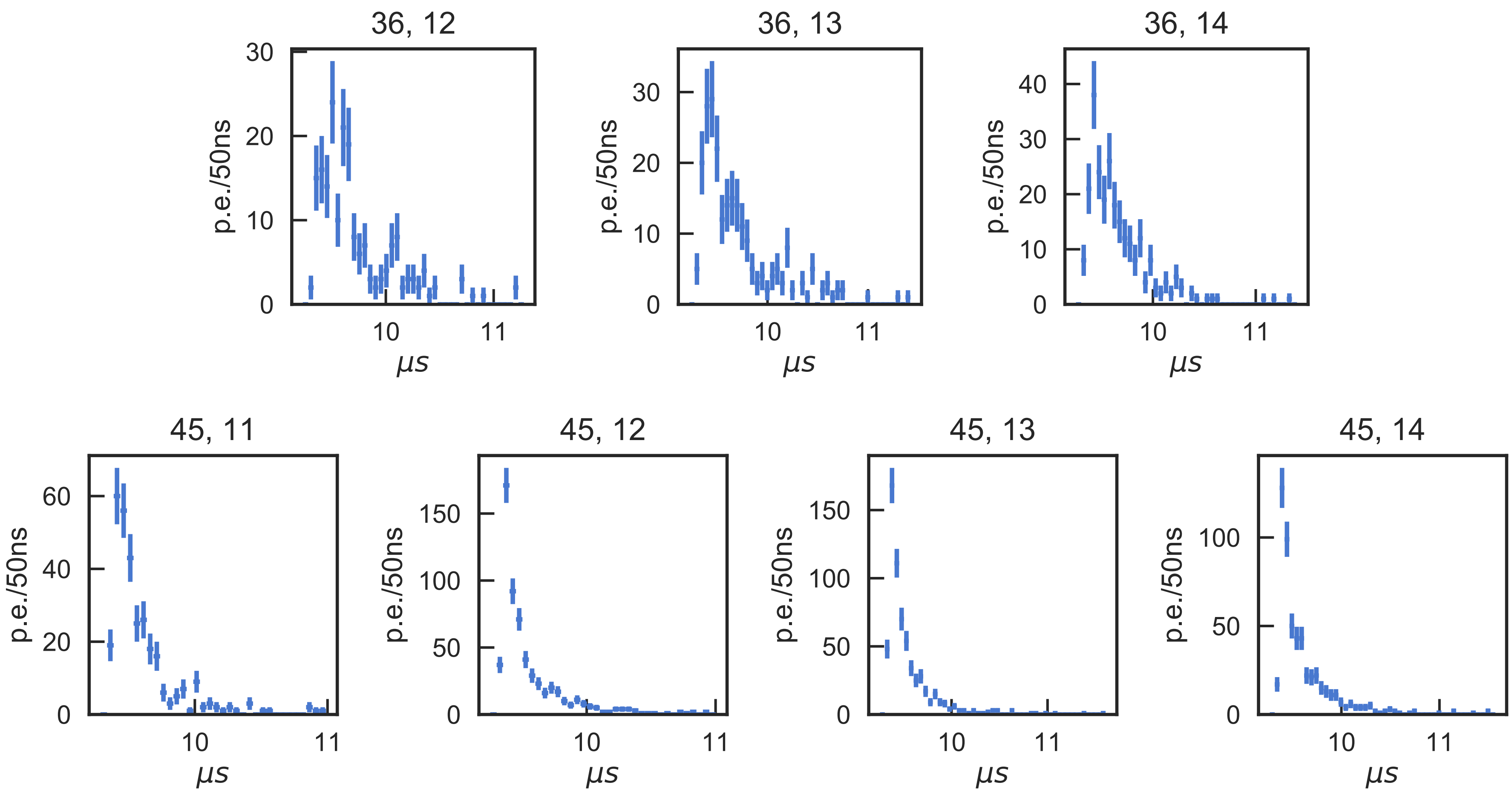


Tested with an identical sim-reco ice-model (3.2) and a different reco ice-model (mie)

Both show a trend towards better angular resolution as more DOMs are included (increasing Q_{max})

Simulated waveforms

Direct photon simulation with GPUs [D. Chirkin, arXiv:1304.0735]

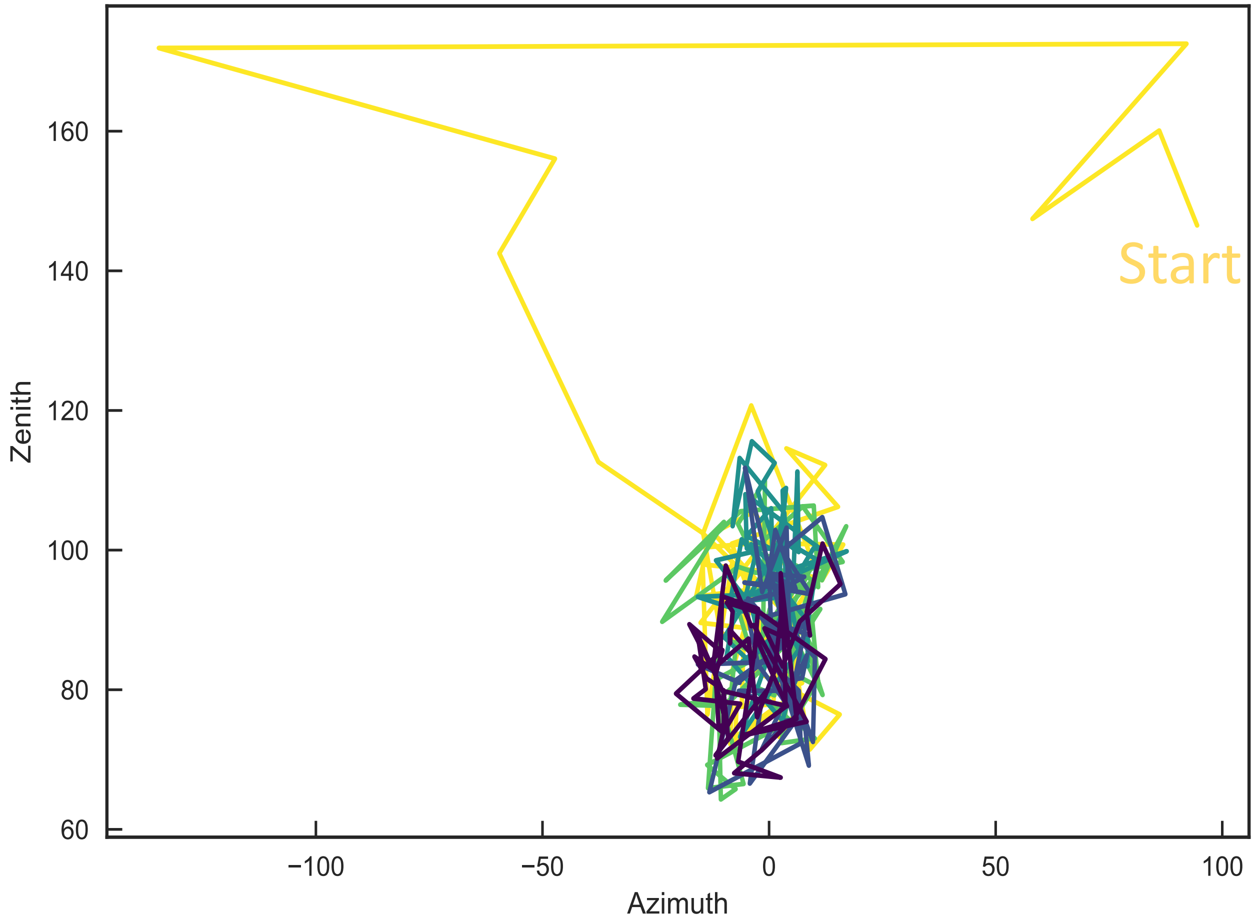


Construct $\mathcal{L}(\boldsymbol{\Theta}|\mathrm{X}_{\mathrm{Data}})$ taking into account finite simulation statistics

Cascade reconstruction with DirectFit

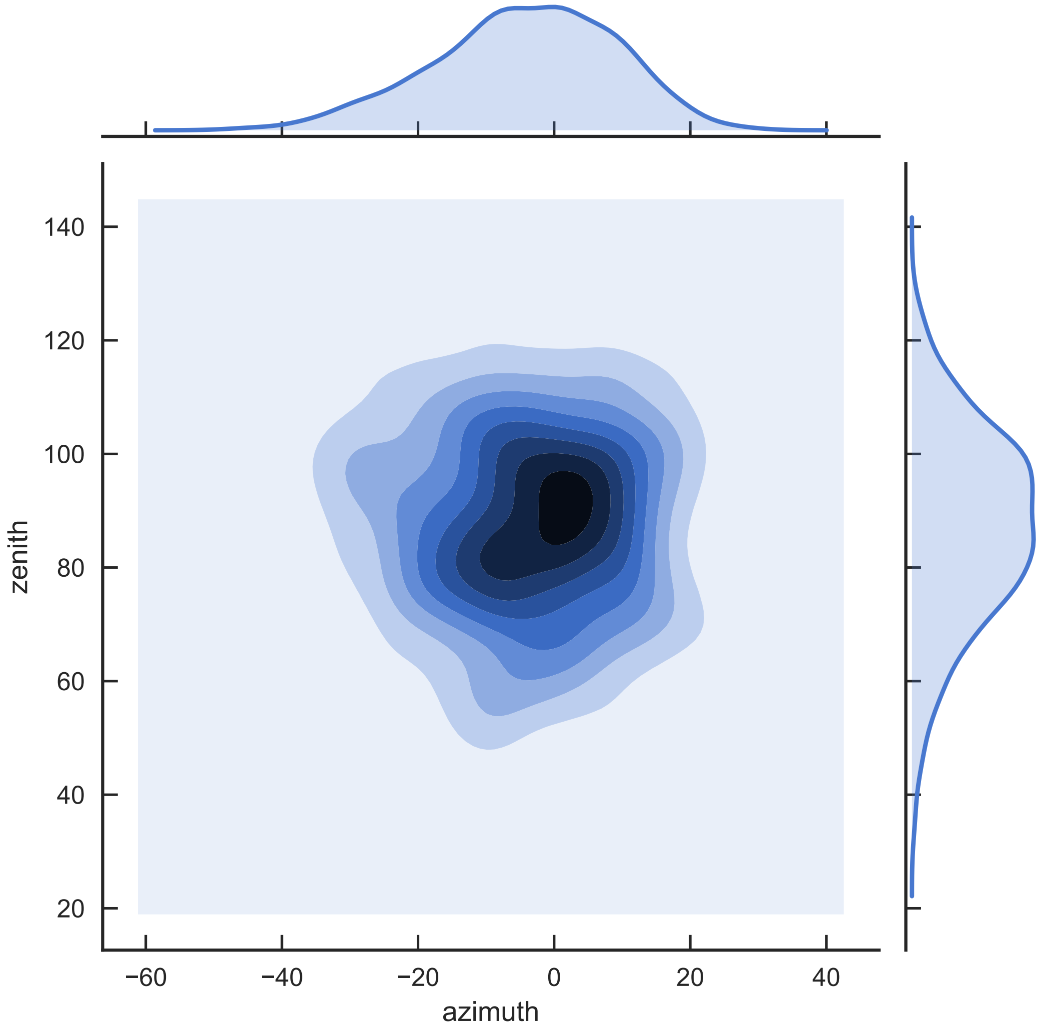
Step in position and direction maximizing the likelihood at each step

Run several iterations to find best-fit parameters

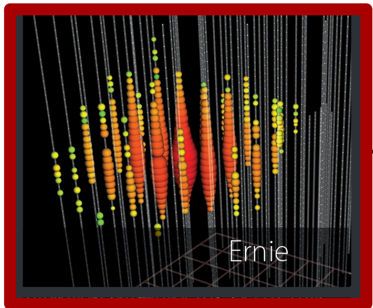


Cascade reconstruction with DirectFit

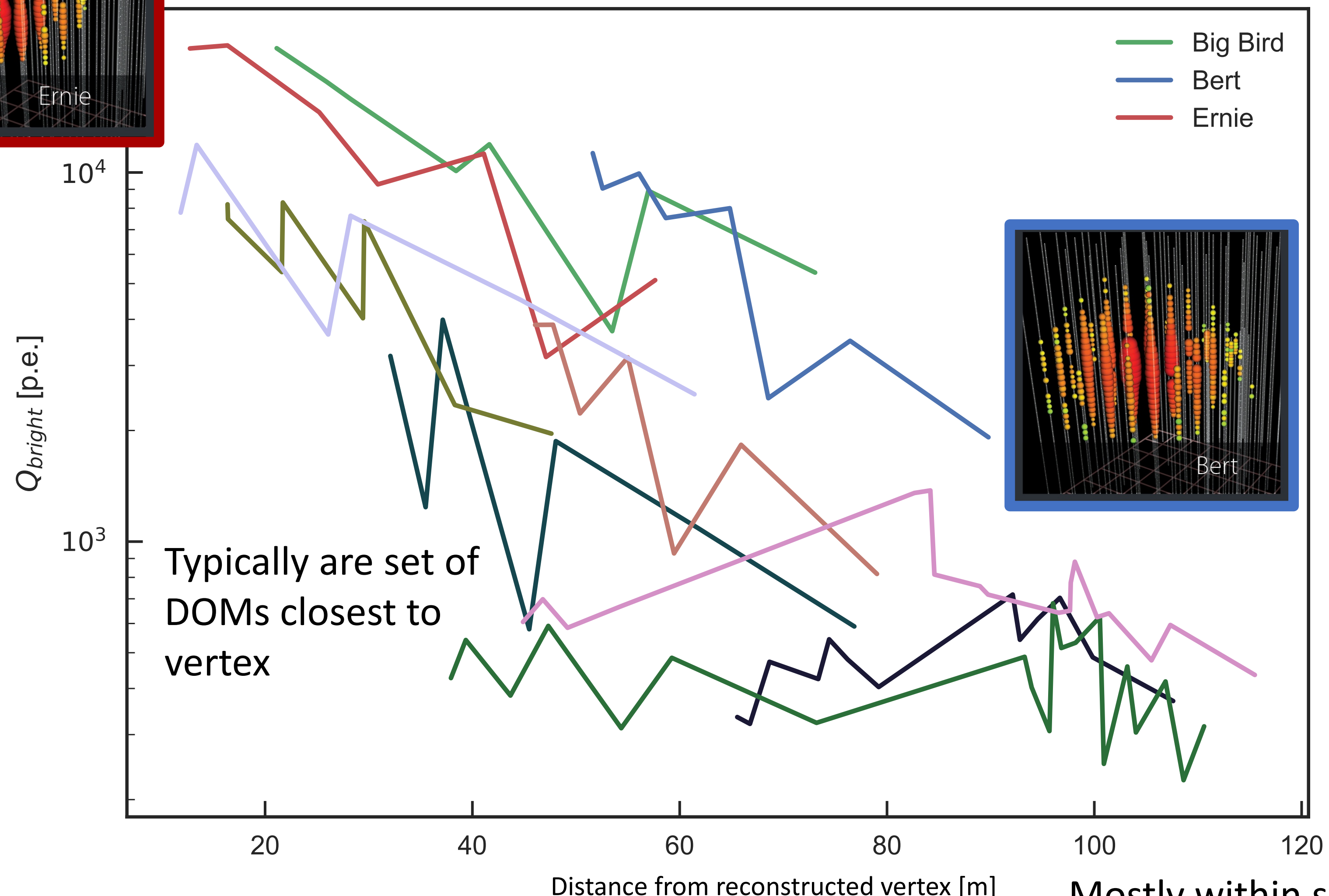
Approximate Bayesian calculation (ABC) with uniform prior to estimate posterior parameter probabilities



Distance of bright DOMs to vertex



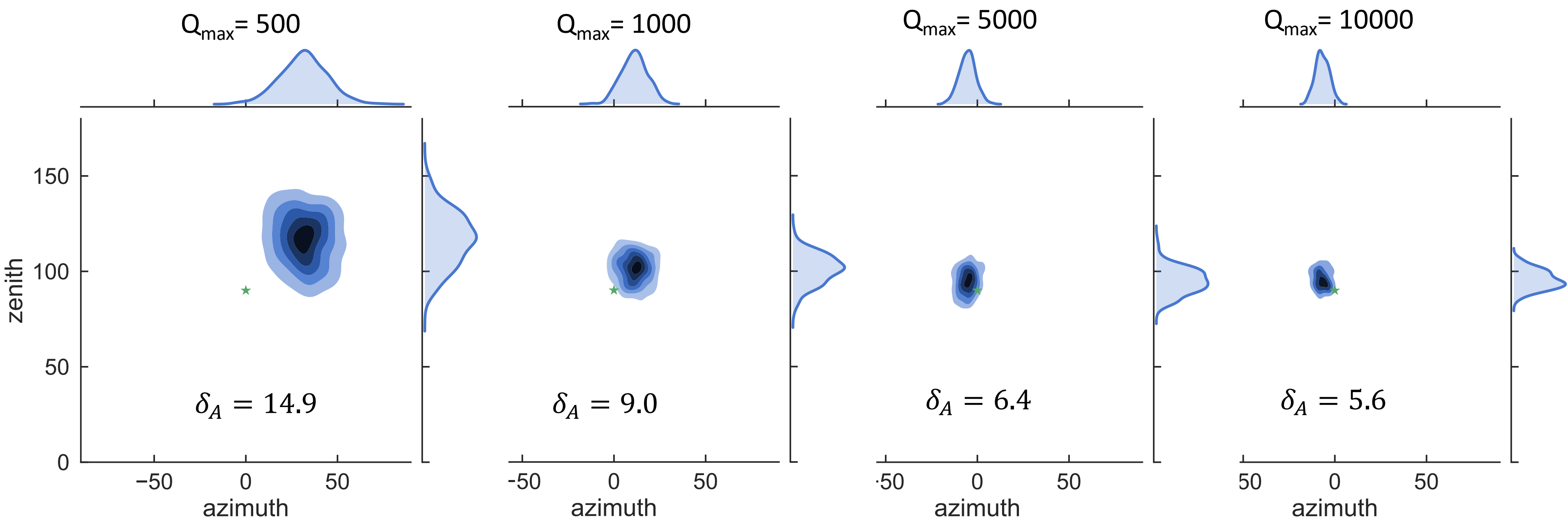
Top 10 energetic cascades in HESE 6 year



Mostly within single string spacing (125m)

Impact on angular resolution

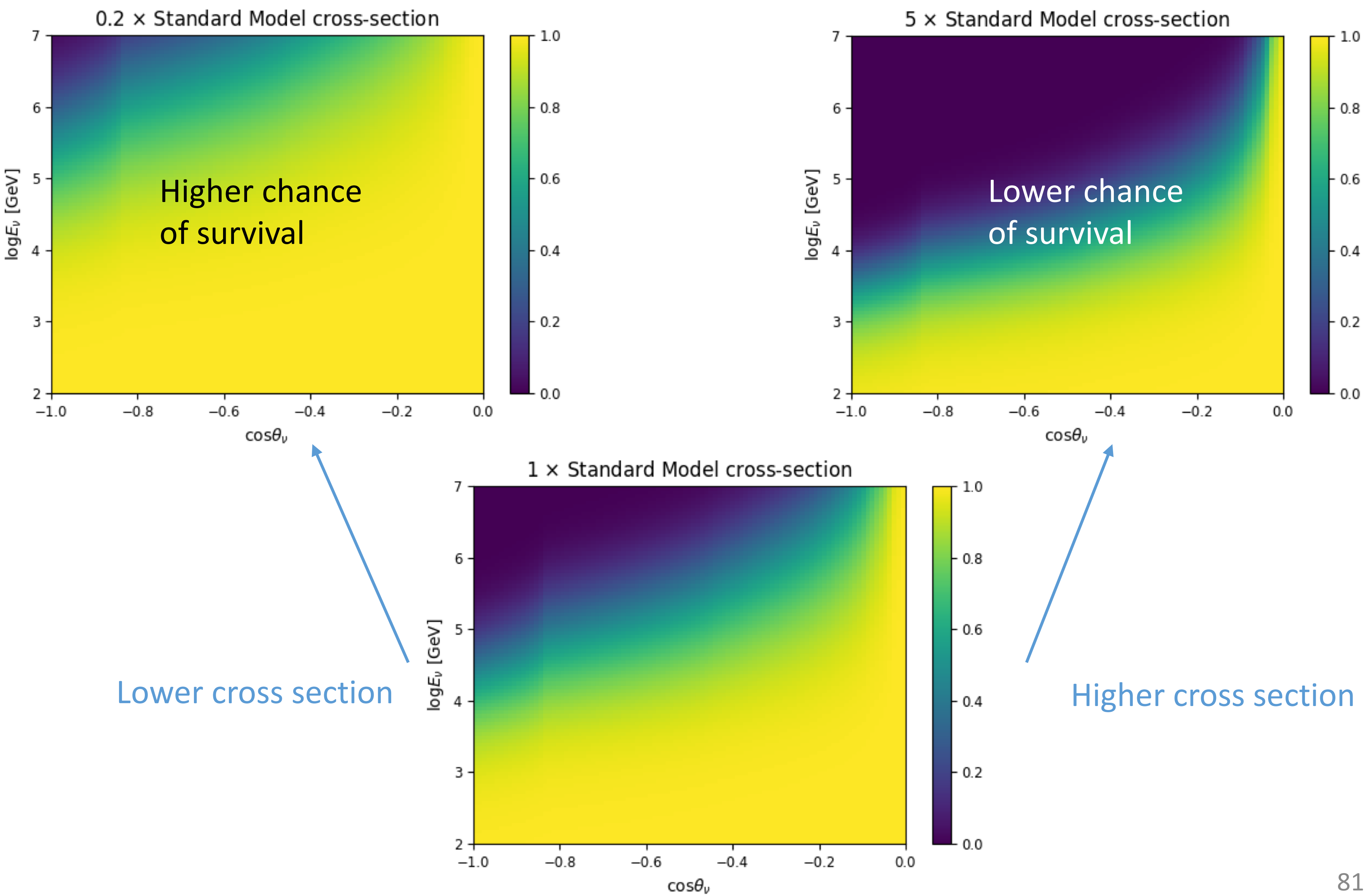
Simulate **1 PeV** cascade with true $(\theta, \phi) = (90{,}0)$ and reconstruct with different cut-offs: Q_{max}



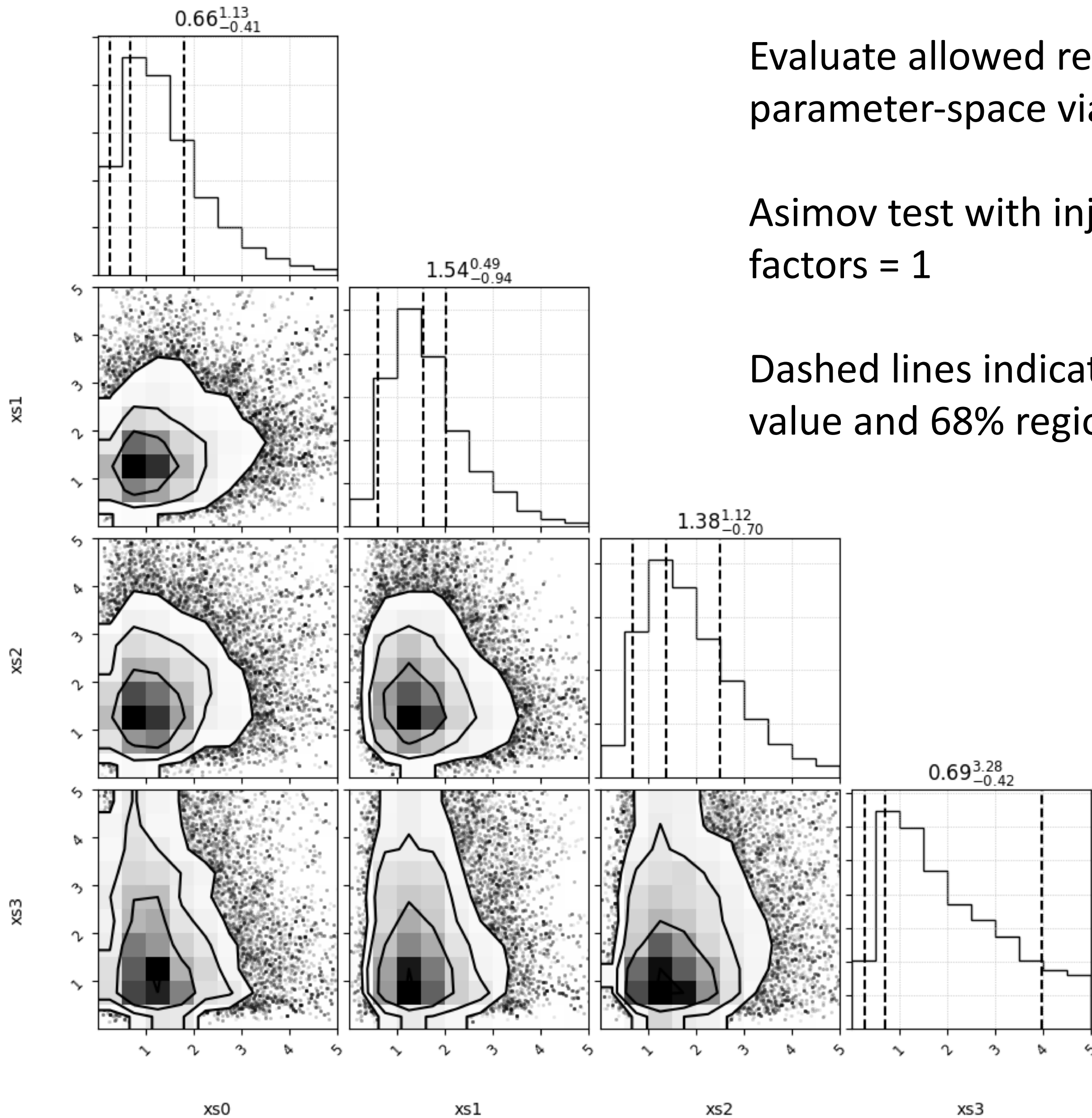
Less charge used → More charge used

Different ice model for simulation and reconstruction

Attenuation modified by cross section



Asimov posterior distributions



Evaluate allowed regions in parameter-space via MCMC

Asimov test with injected scale-factors = 1

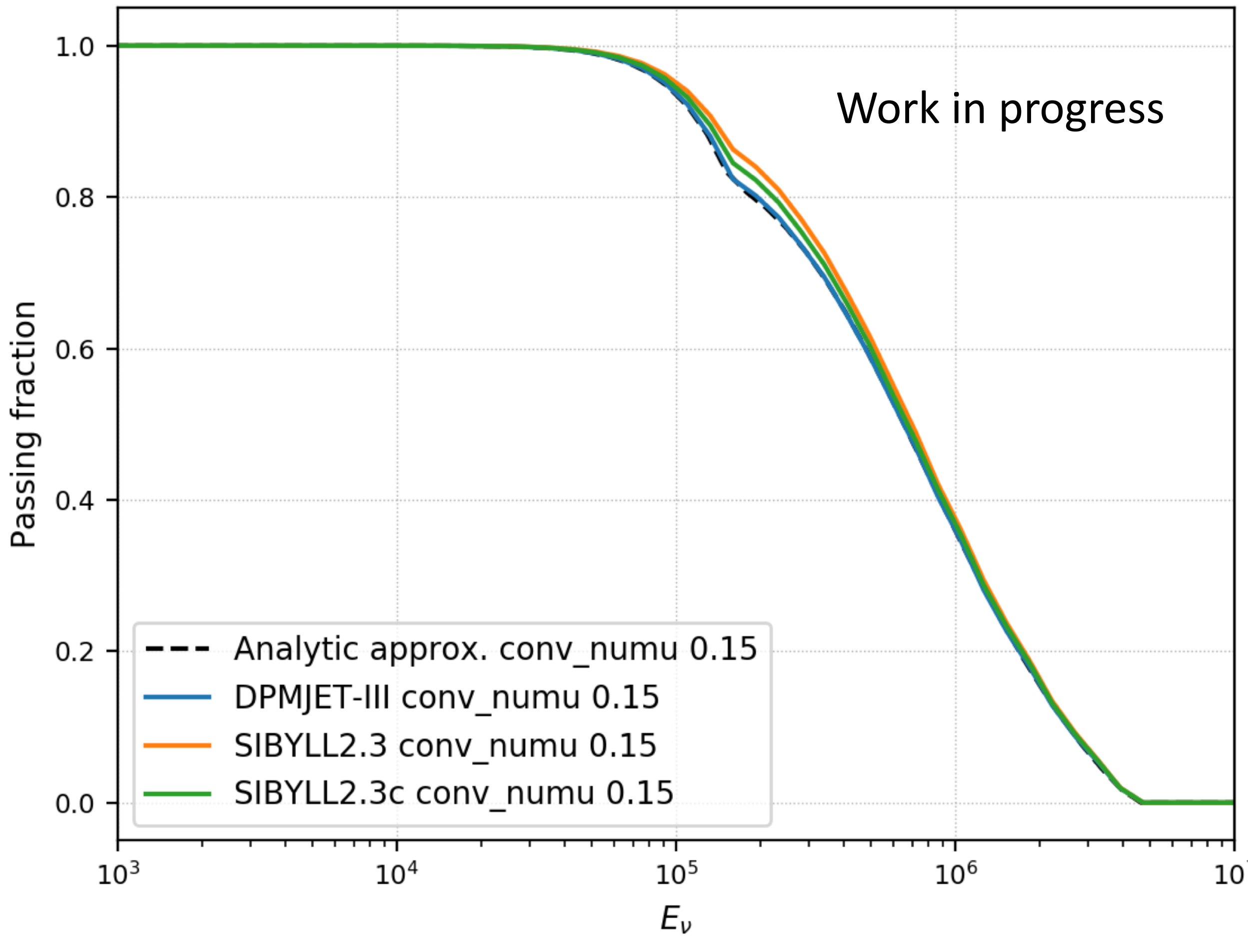
Dashed lines indicate most probable value and 68% region

New approach

Can input different hadronic interaction models

Solves a problem previously described as “computationally impossible”!

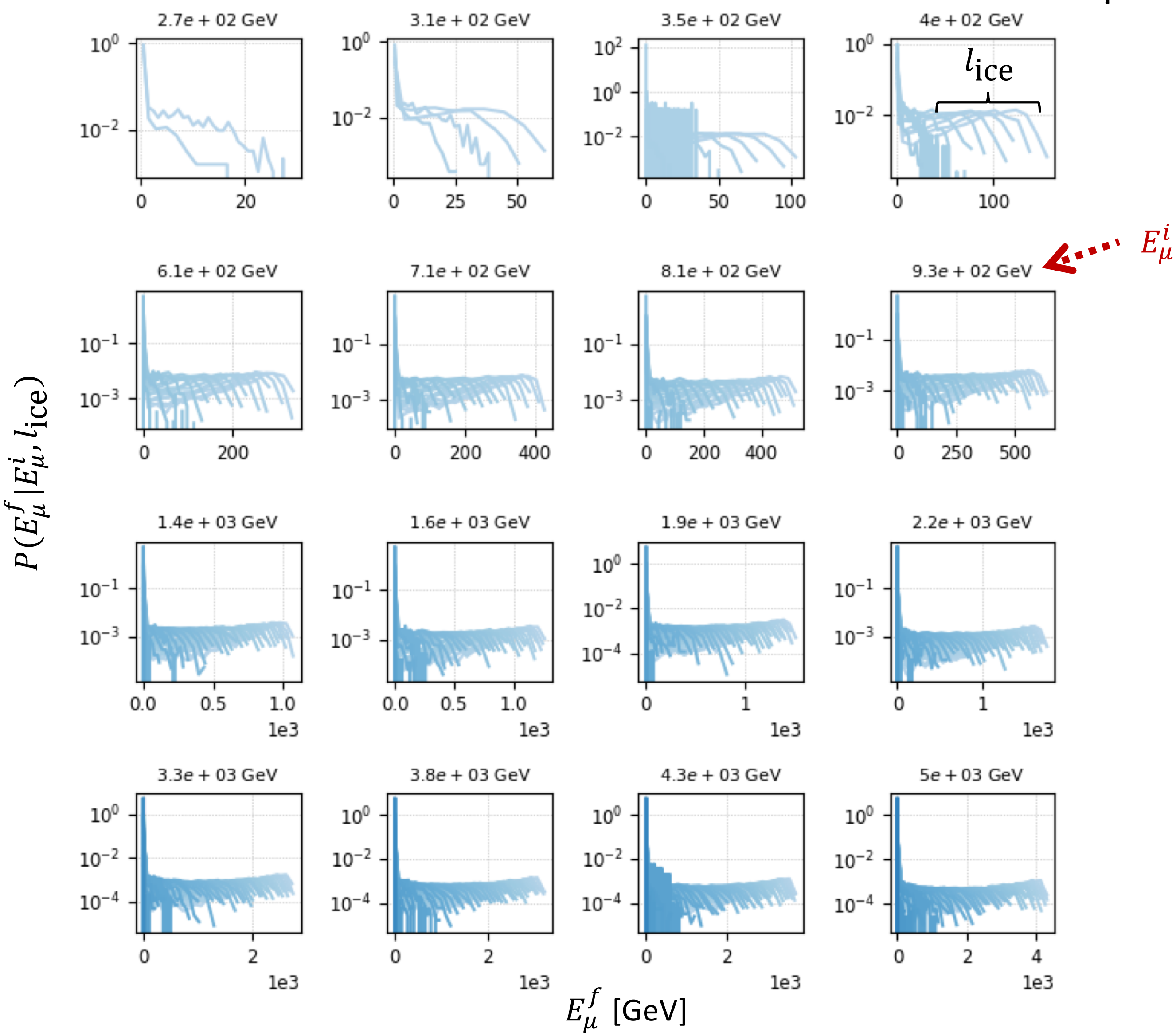
Really fast!



Muon range pdfs

arXiv:hep-ph/0407075

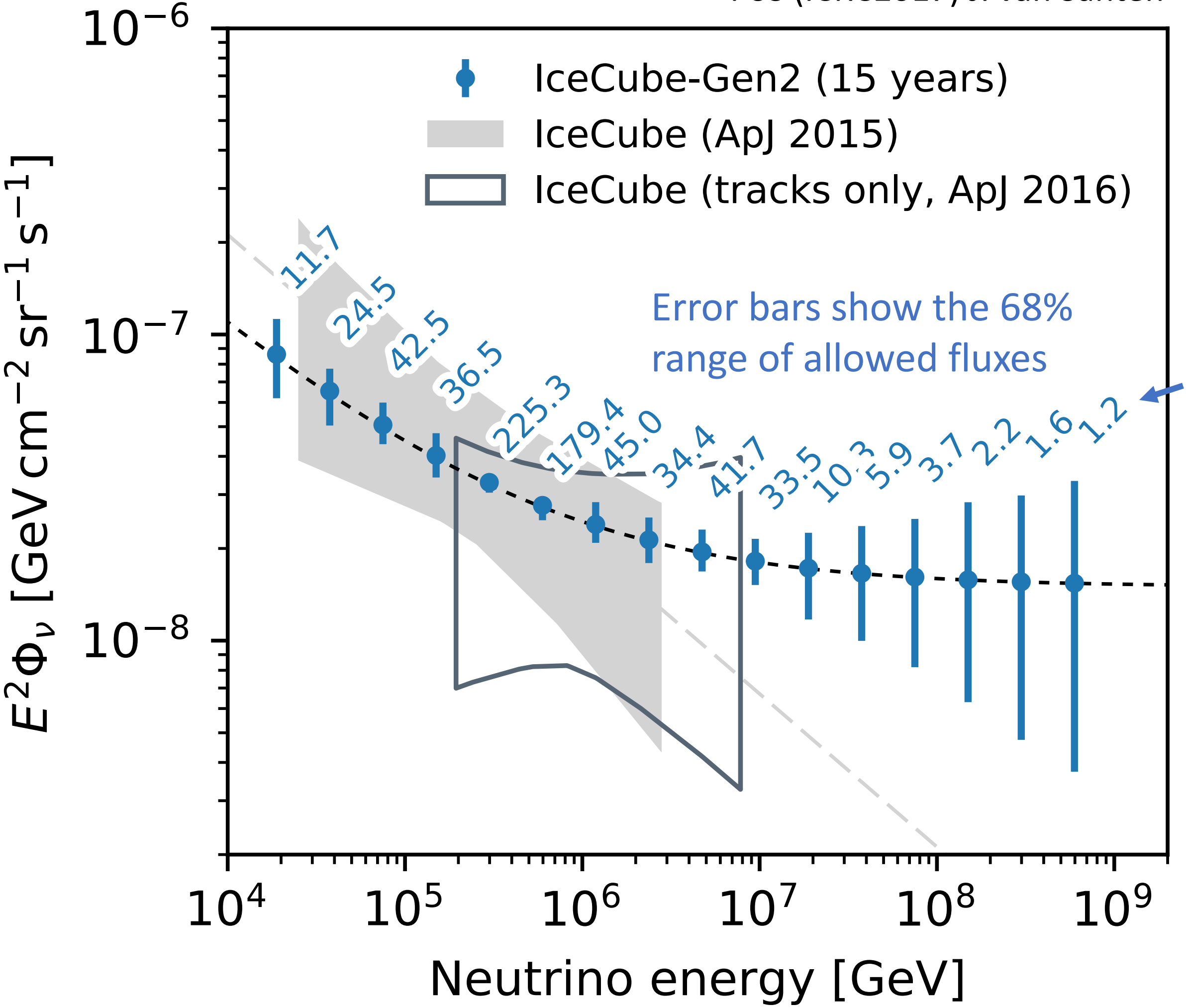
Simulate muons using MMC (Muon Monte-Carlo) and build $P(E_\mu^f|E_\mu^i, l_\text{ice})$



Diffuse sensitivity

Clear distinction of different spectra possible

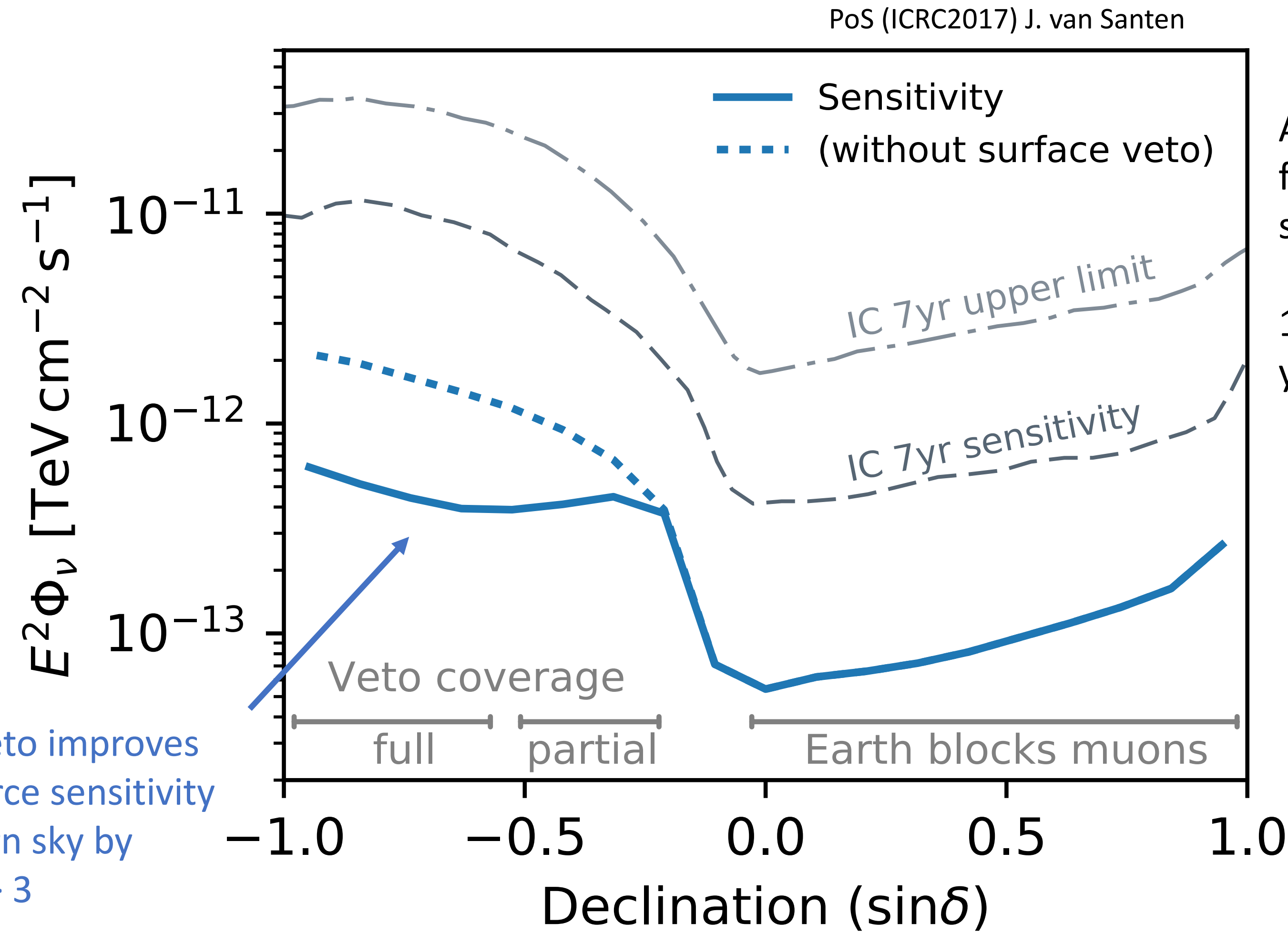
PoS (ICRC2017) J. van Santen



Number of events in each energy range

Double power law $E^{-2} + E^{-2.5}$ injected flux

Point source sensitivity



Assuming E^{-2} flux from single source

15 years IC + 15 years IC-Gen2

Surface veto improves point-source sensitivity in southern sky by factor of > 3