Probing the universe with high-energy neutrinos

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UW Madison/WIPAC

IPA18 Cincinnati, USA

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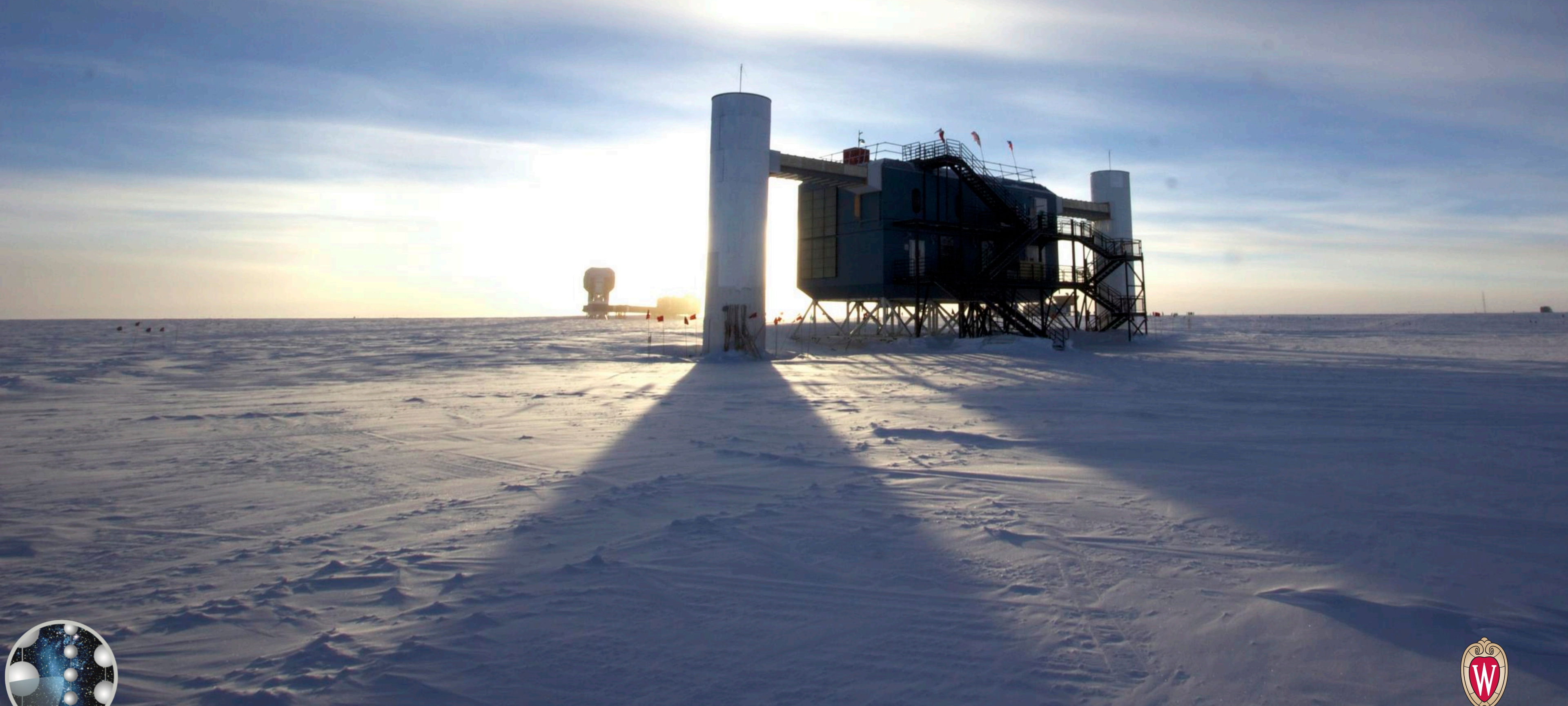


Credit: F. Pedreros, IceCube/NSF

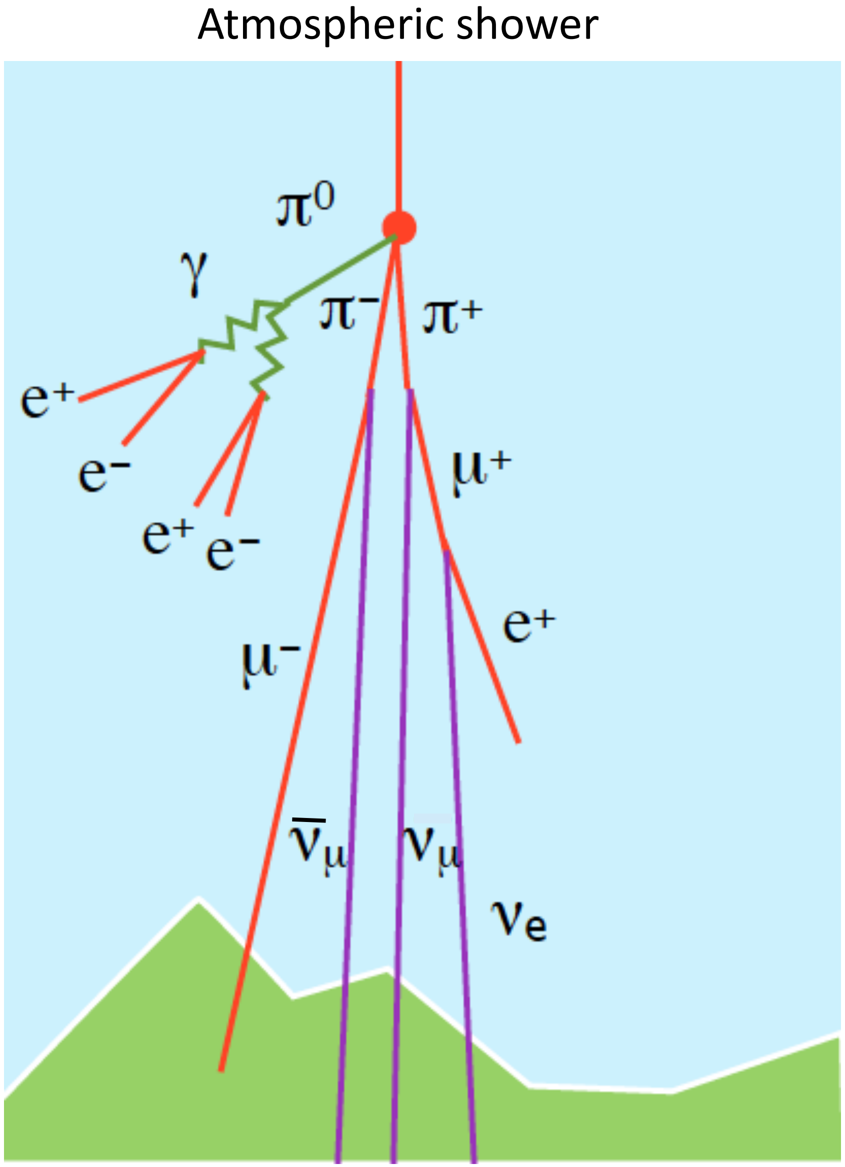
Highlights in this talk

Update to contained, high-energy sample finds two double-cascade events, possibly due to $\boldsymbol{\nu_\tau}$

First evidence of a **source** of high-energy astrophysical neutrinos from a flaring blazar TXS 0506+056

High-energy, partially contained neutrino detected by IceCube with energy around **Glashow resonance**

Some terminology



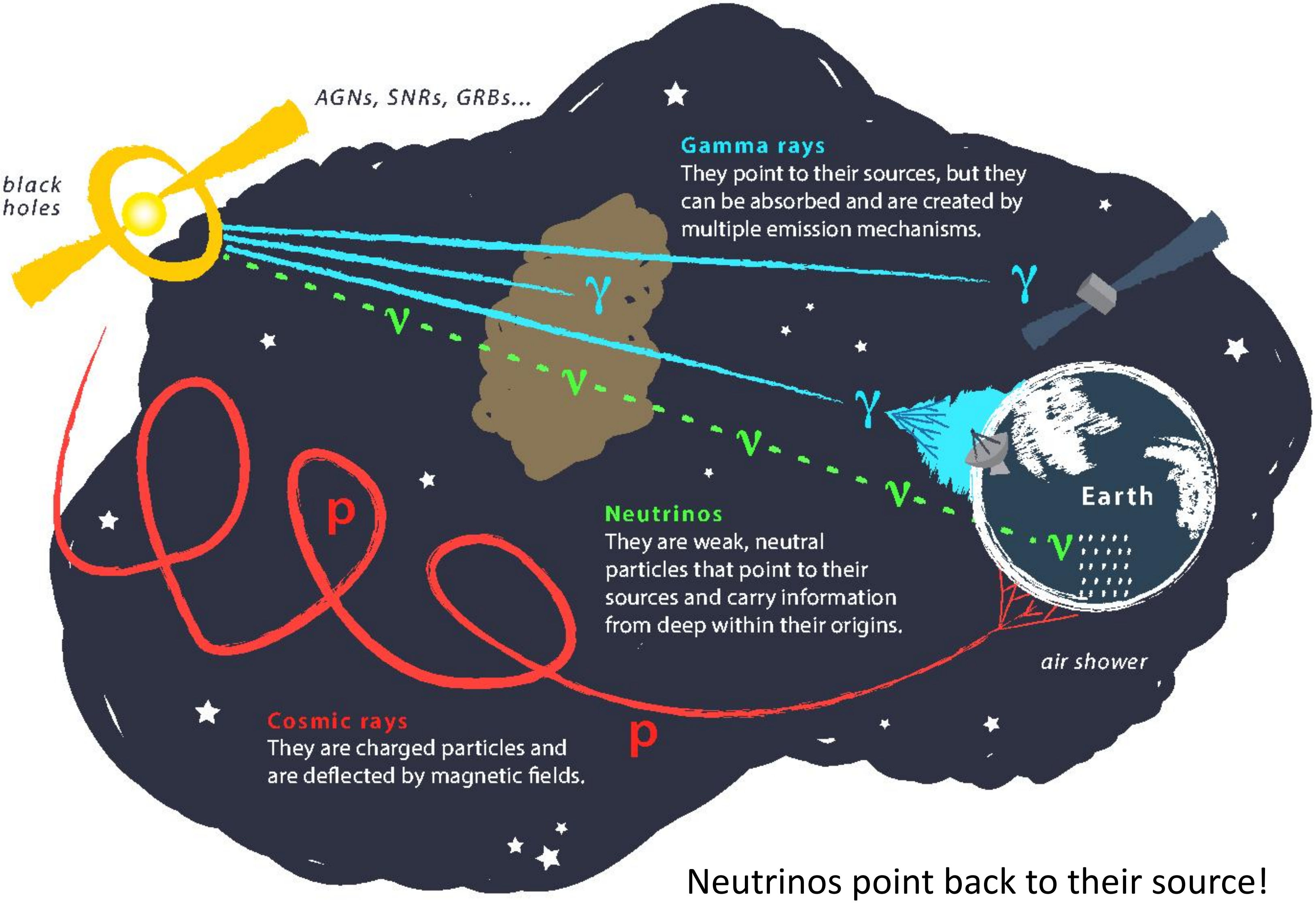
Conventional atmospheric: Parent particle is pion or kaon; longer lifetime

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!

A neutrino telescope

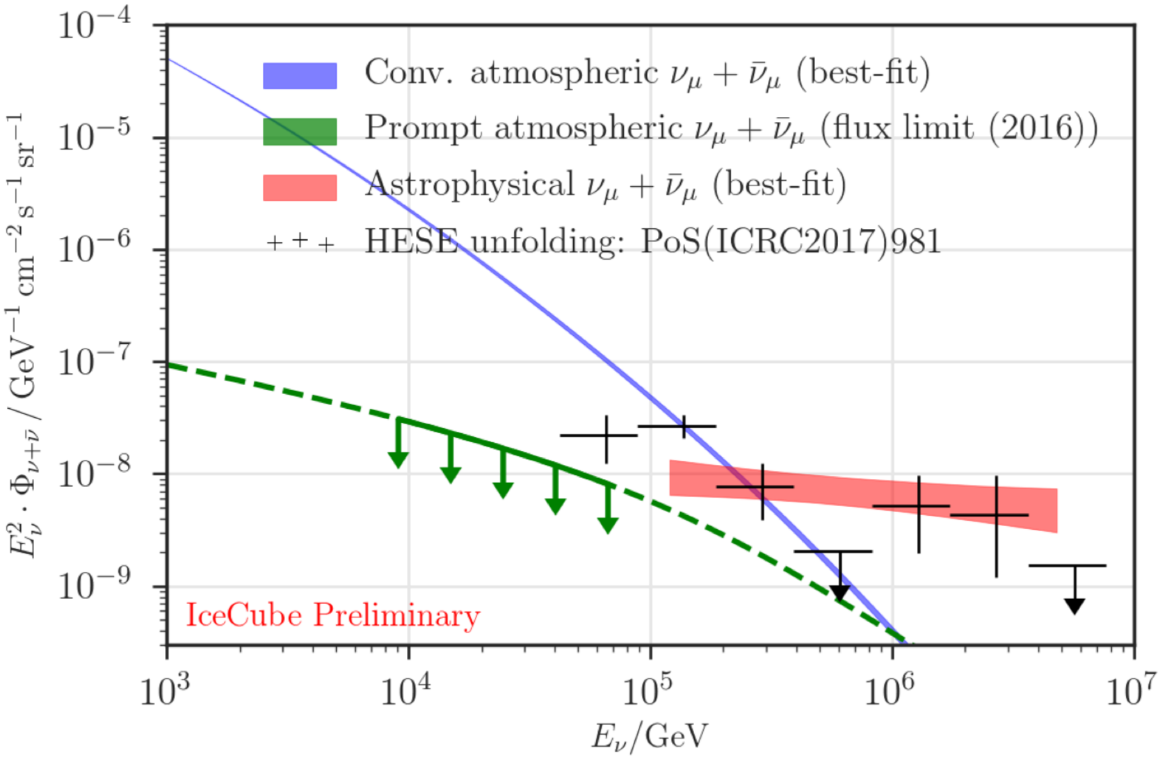
Astrophysical neutrino flux harder than background

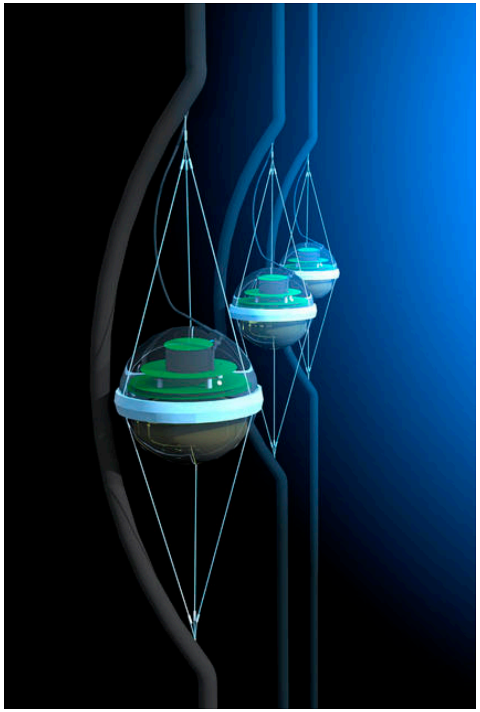
Energy useful as a discriminator

Need **large-volume** detector for **PeV-scale** neutrinos

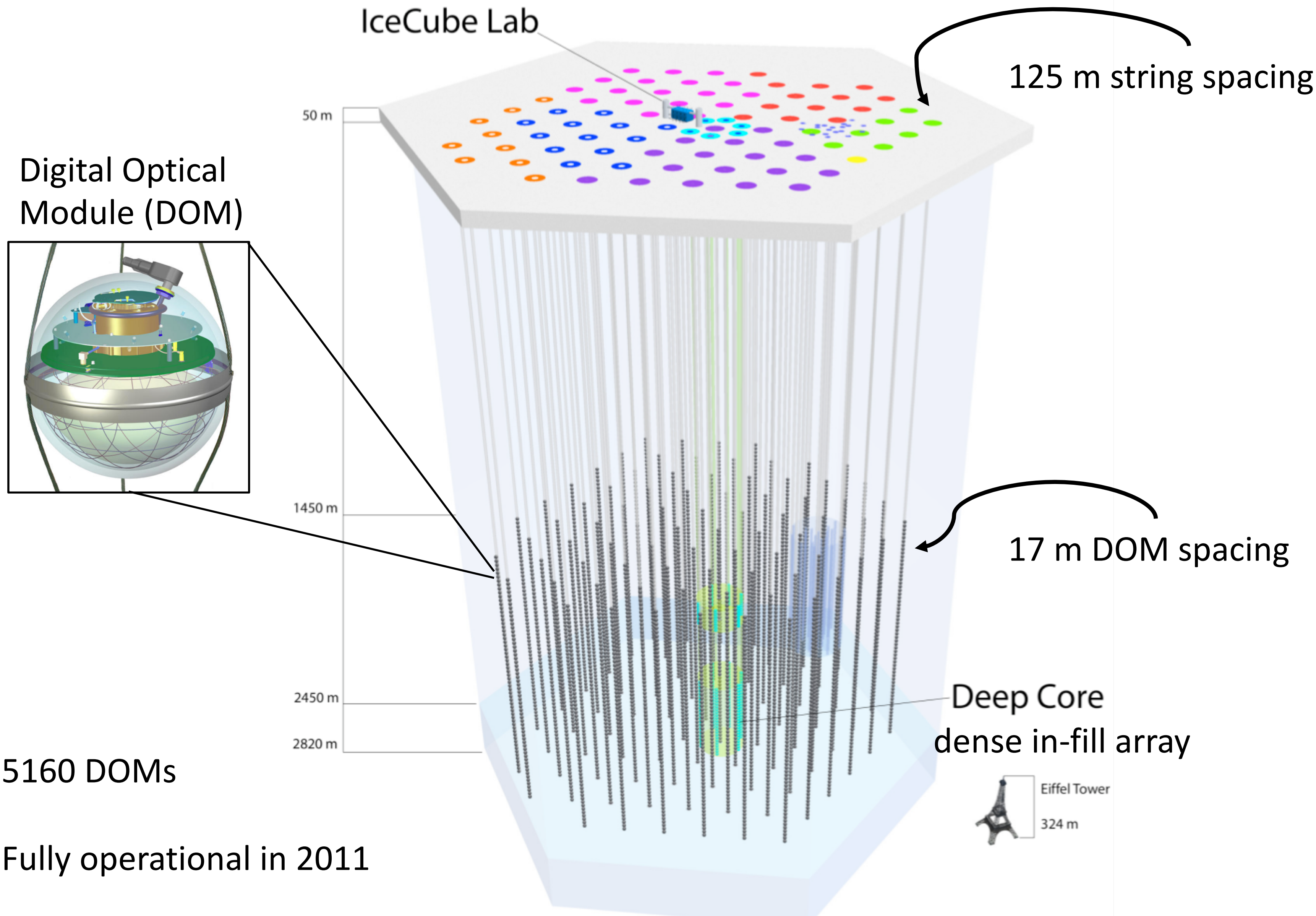
South-Pole ice is extremely clear, why not use as detector medium

C. Haack, ICRC2017





IceCube



5160 DOMs

Fully operational in 2011

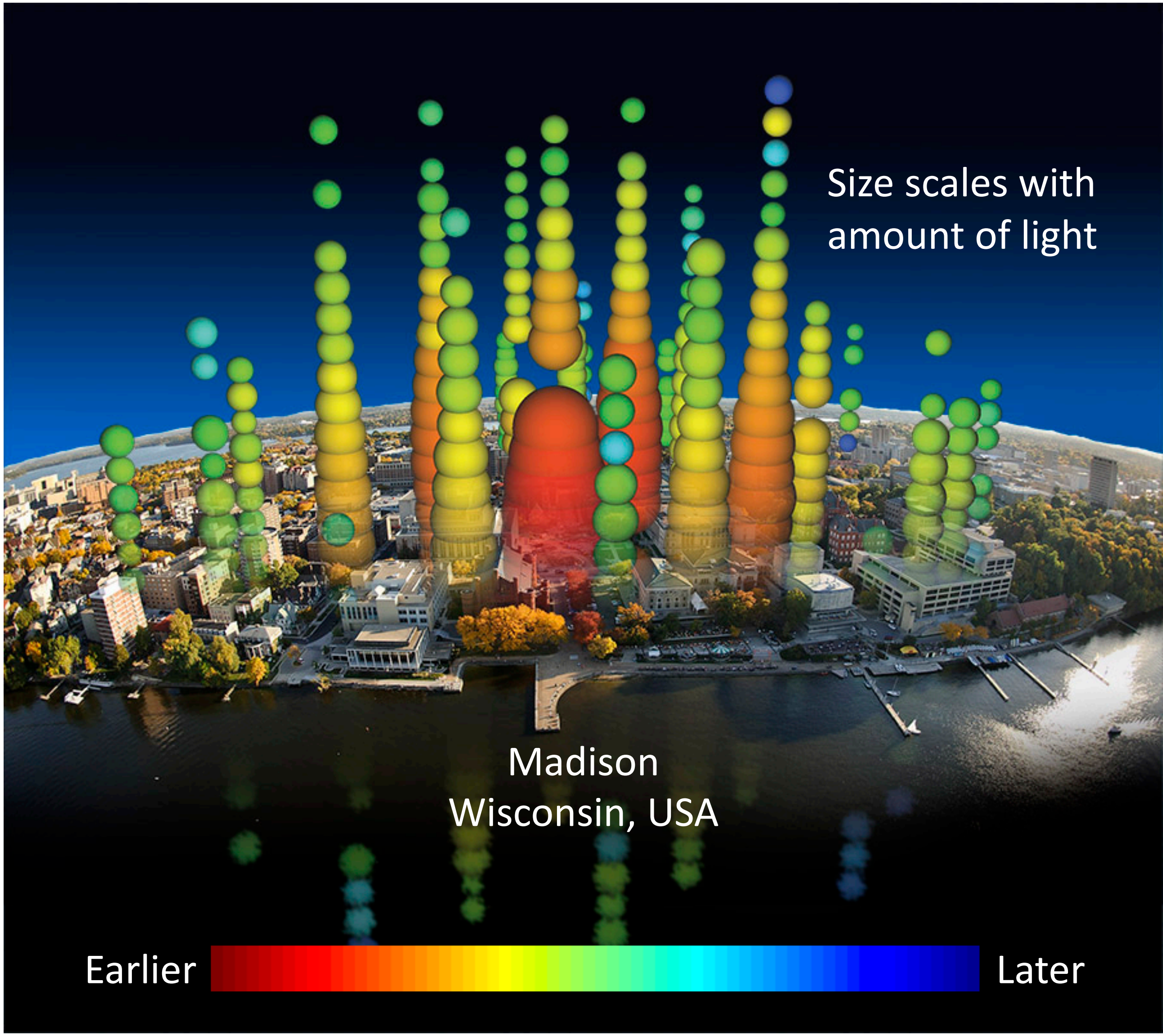
A sense of scale

1 km^3

1 Gton of ice

Each bubble centers on a PMT

10 GeV – 10 PeV



Detection principals

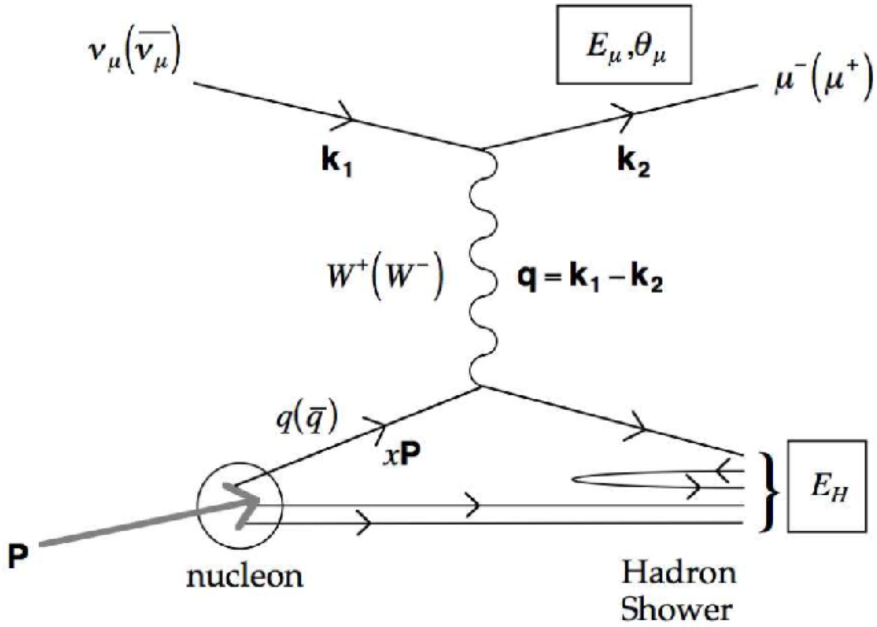
Neutrino interacts via weak force with targets in ice

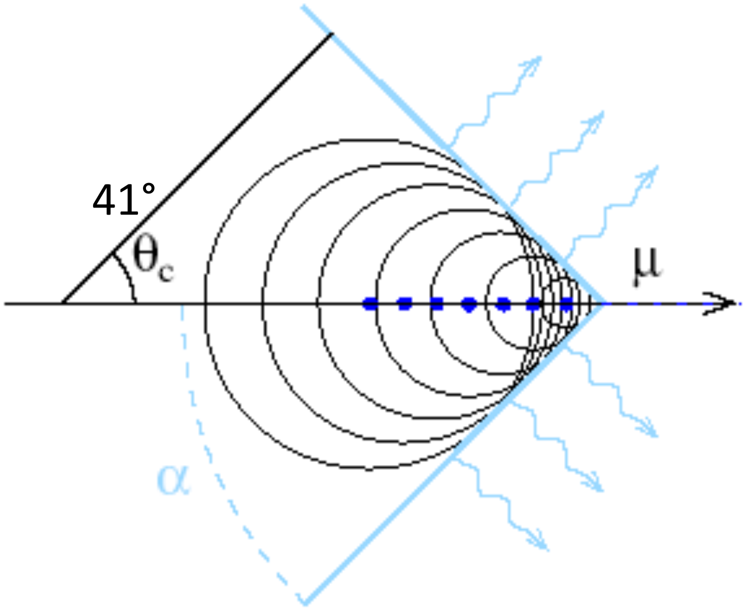
- At IceCube energies, primarily deep-inelastic scattering (DIS) off nucleons

Nucleon breaks apart; outgoing particles may be charged

Charged particles emit Cherenkov radiation detectable by PMTs

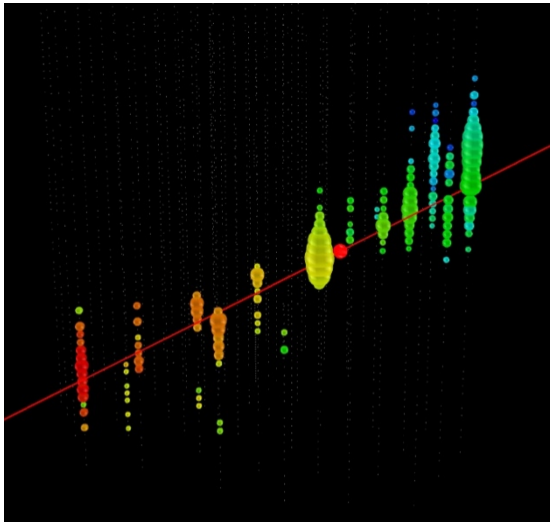
Rev. Mod. Phys. 84, 1307





Event topologies

CC muon neutrino

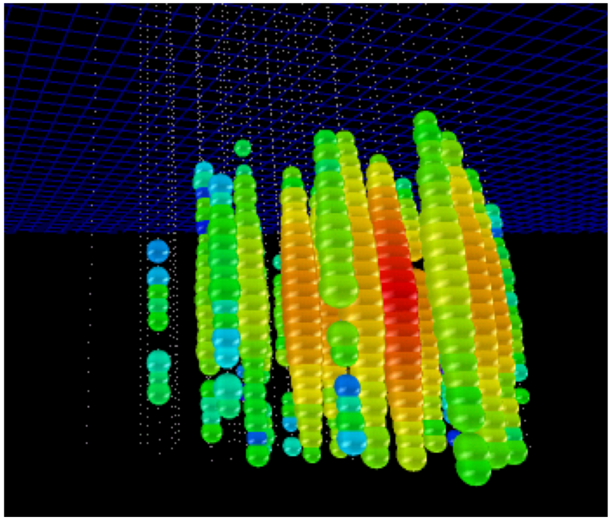


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

angular resolution ~ 0.5°
energy resolution ~ x2

NC or CC electron neutrino

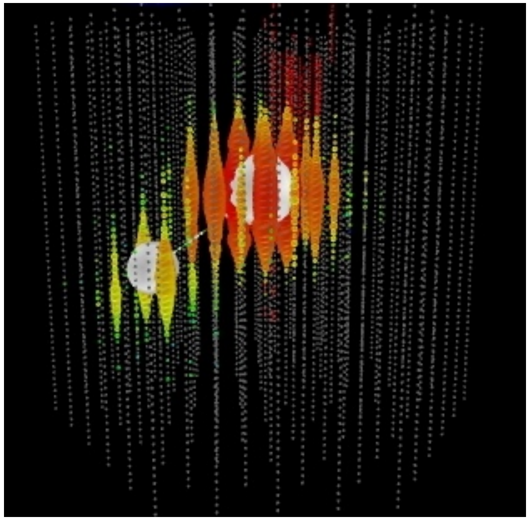


$$\nu_e + N \rightarrow e + X$$
$$\nu_x + N \rightarrow \nu_x + X$$

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

Selected results from HESE with 7.5 years of data

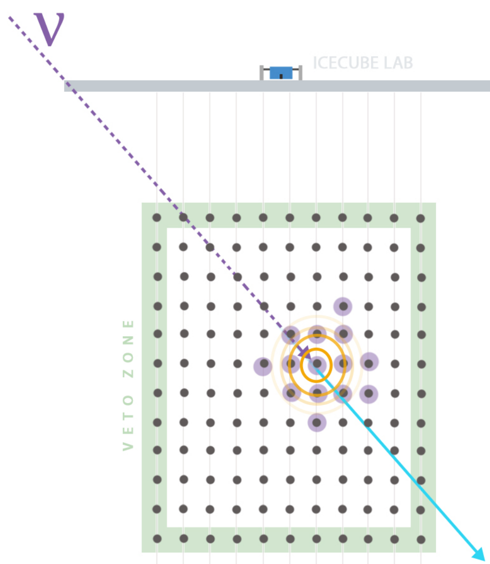
High energy starting event (HESE) selection

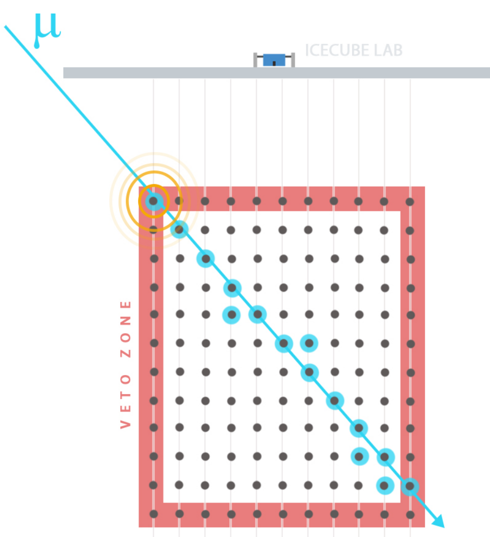
Contained search at high energies

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

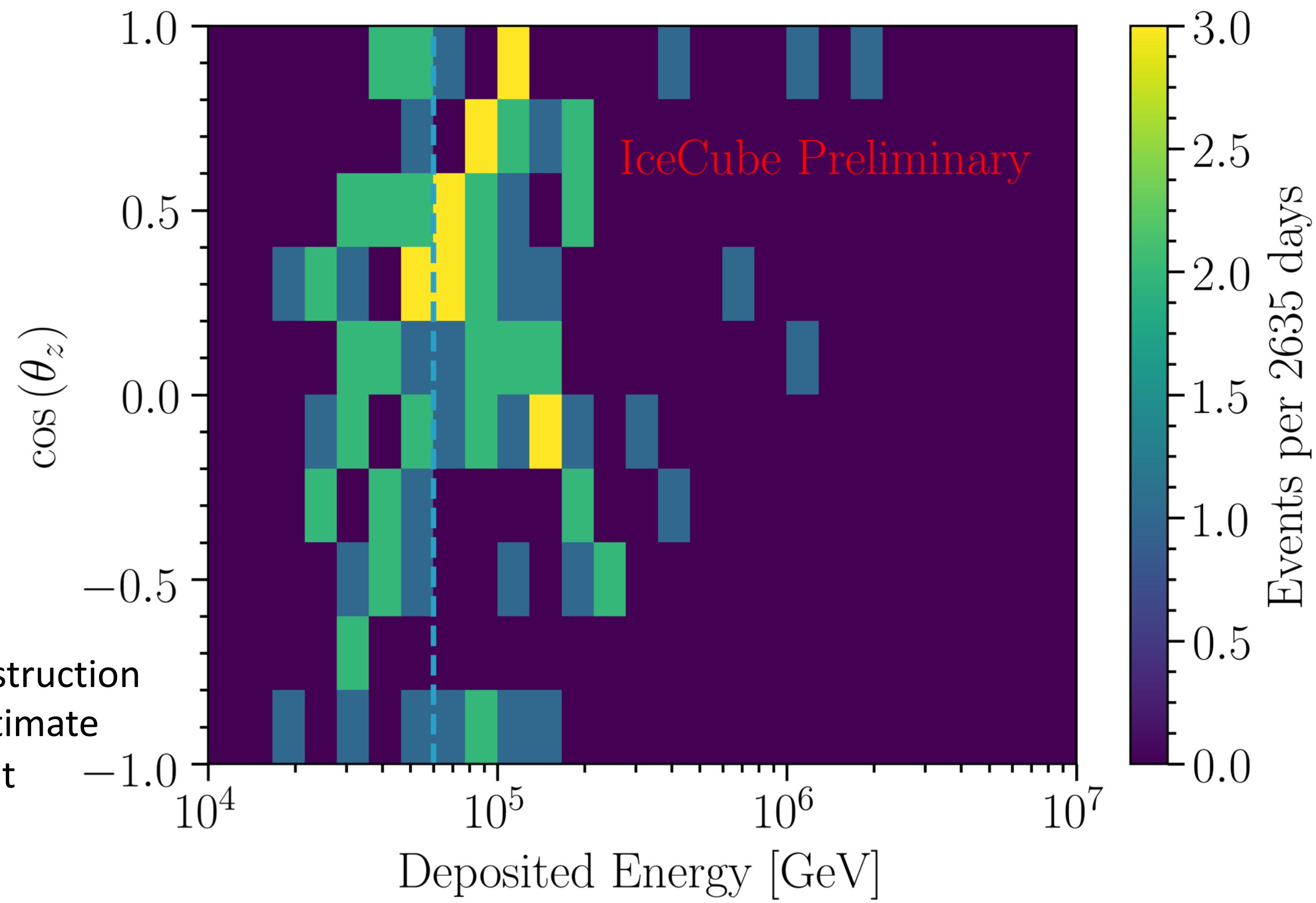




Event distribution in HESE-7.5

103 events, with **60 events >60 TeV**

Fitting performed for events above 60 TeV



Updates:
Newer ice model and reconstruction
Improved atmospheric-ν estimate
Better systematics treatment

Above 60 TeV:
16 new events since 2016 season

Diffuse flux

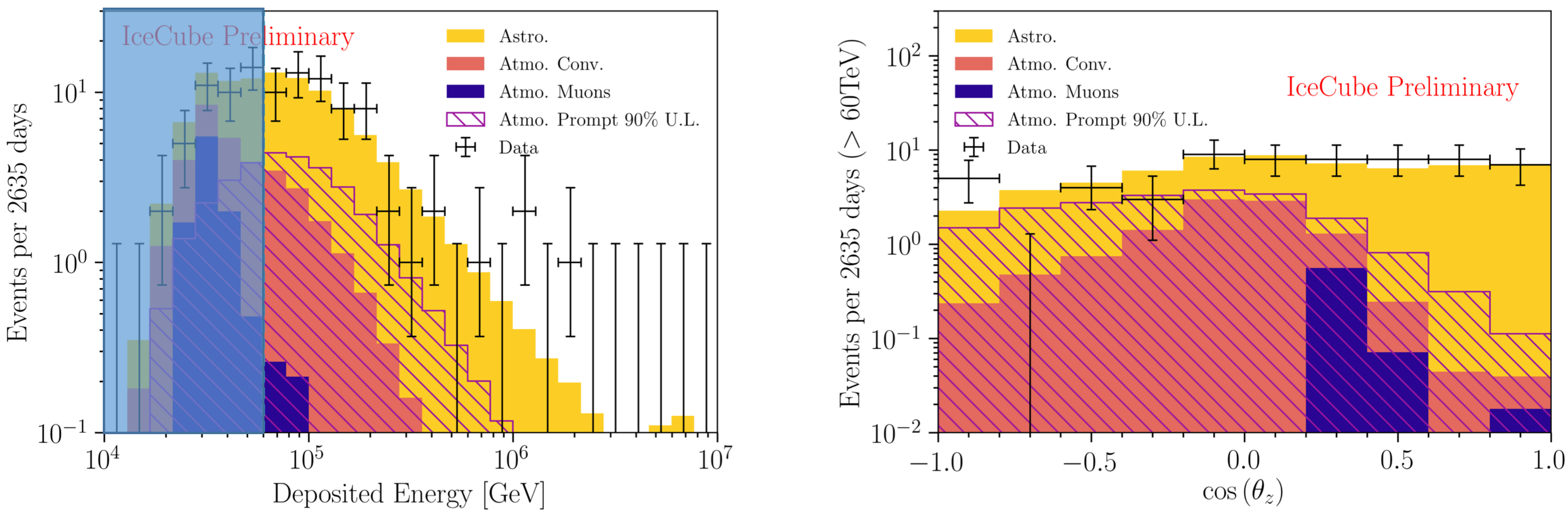
Forward-folded fit in zenith and energy

Best-fit SPL: $E^2\Phi = 2.19\times10^{-18}\left(\frac{E}{100\ \mathrm{TeV}}\right)^{-0.91}$ $[\mathrm{GeV\ cm^{-2}s^{-1}sr^{-1}}]$

Prompt atmospheric best-fit → 0

Prompt 90% UL → 12.3 * BERSS model

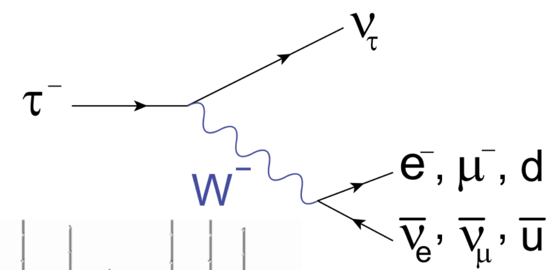
Consistent with 6-yr result

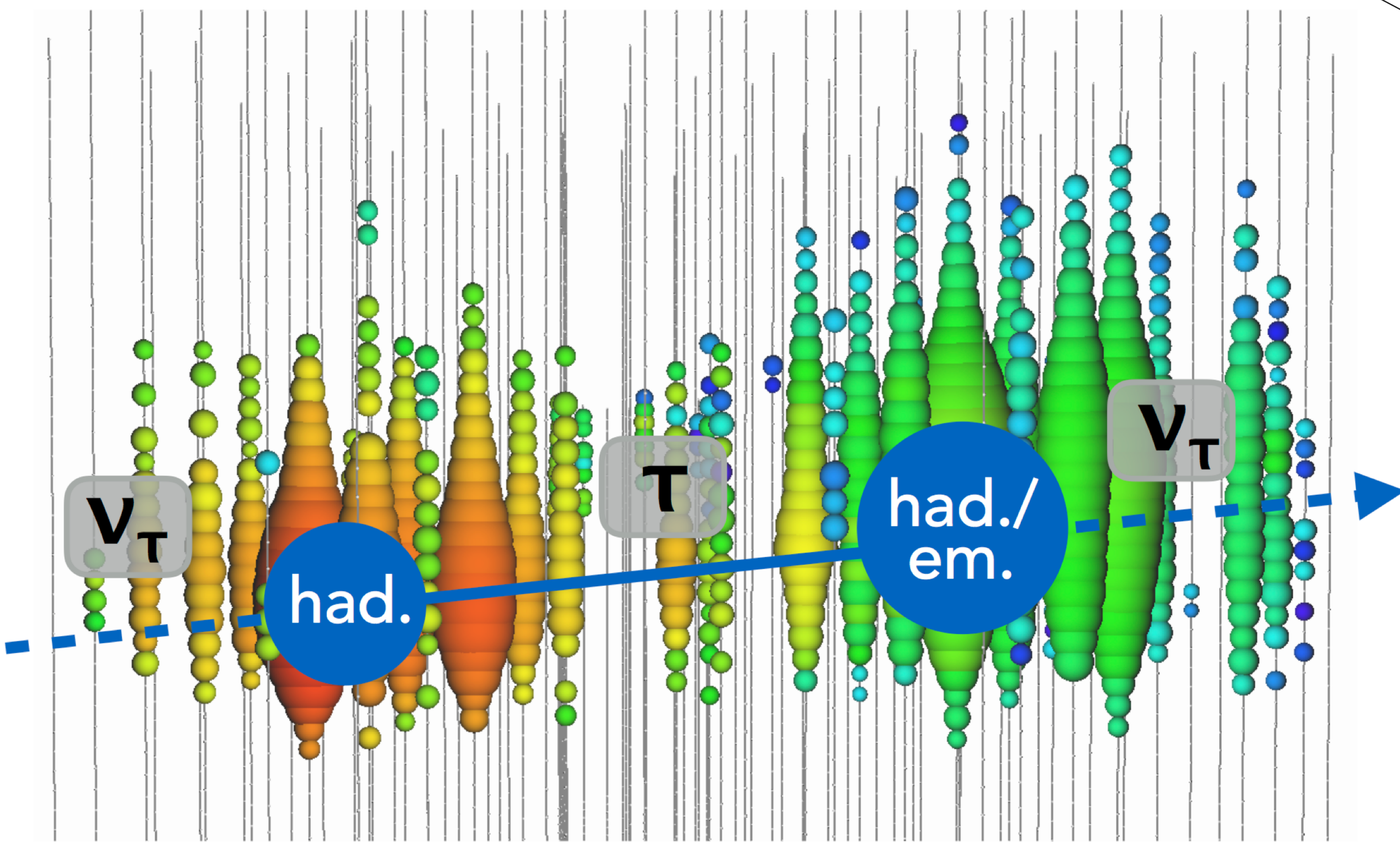


The double cascade channel

Require both cascades with E > 1 TeV

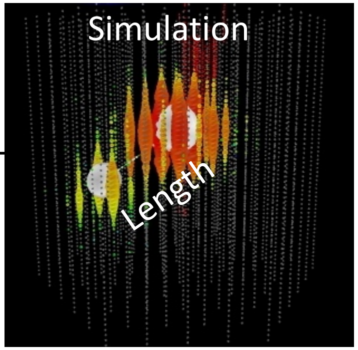
Require separation distance > 10 m



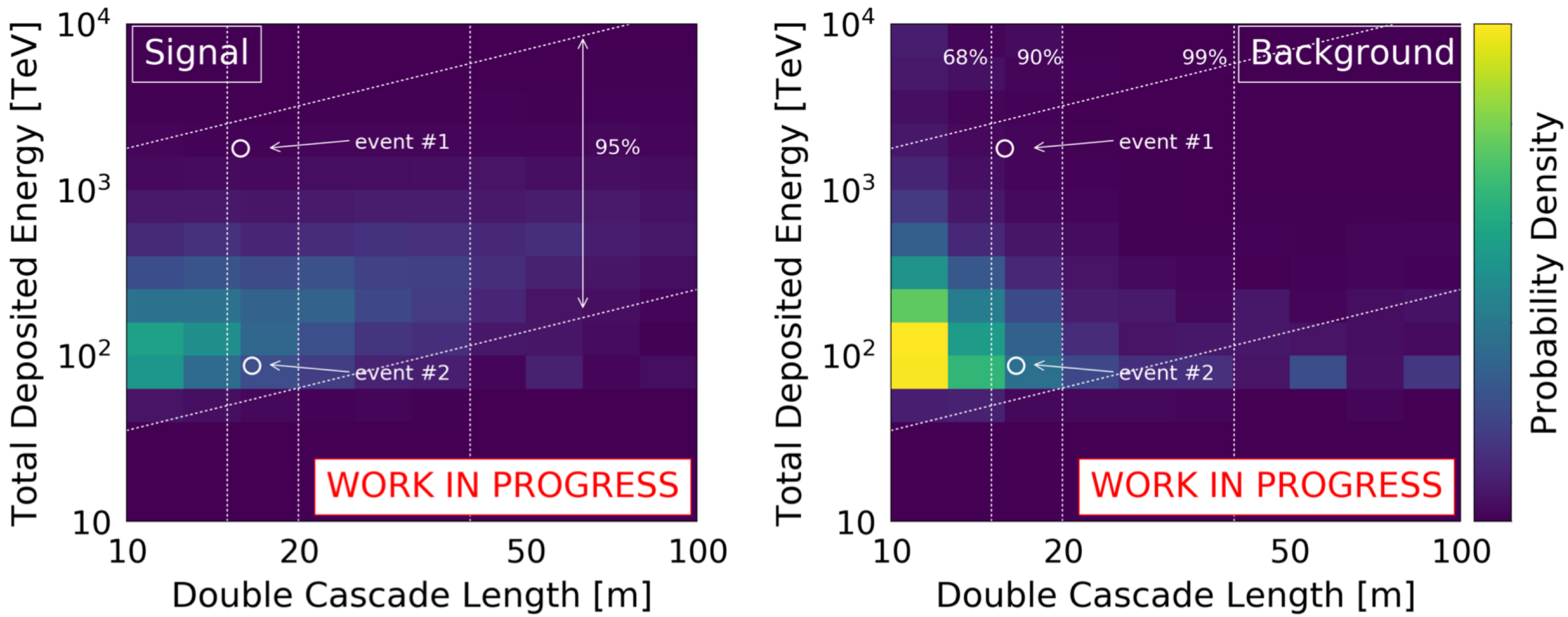


PoS(ICRC2017)973

Flavor identification



- Ternary-PID of cascades, tracks and double-cascades
- **Two double-cascade events**
- Could be due to ν_τ or mis-id background; affects flavor interpretation

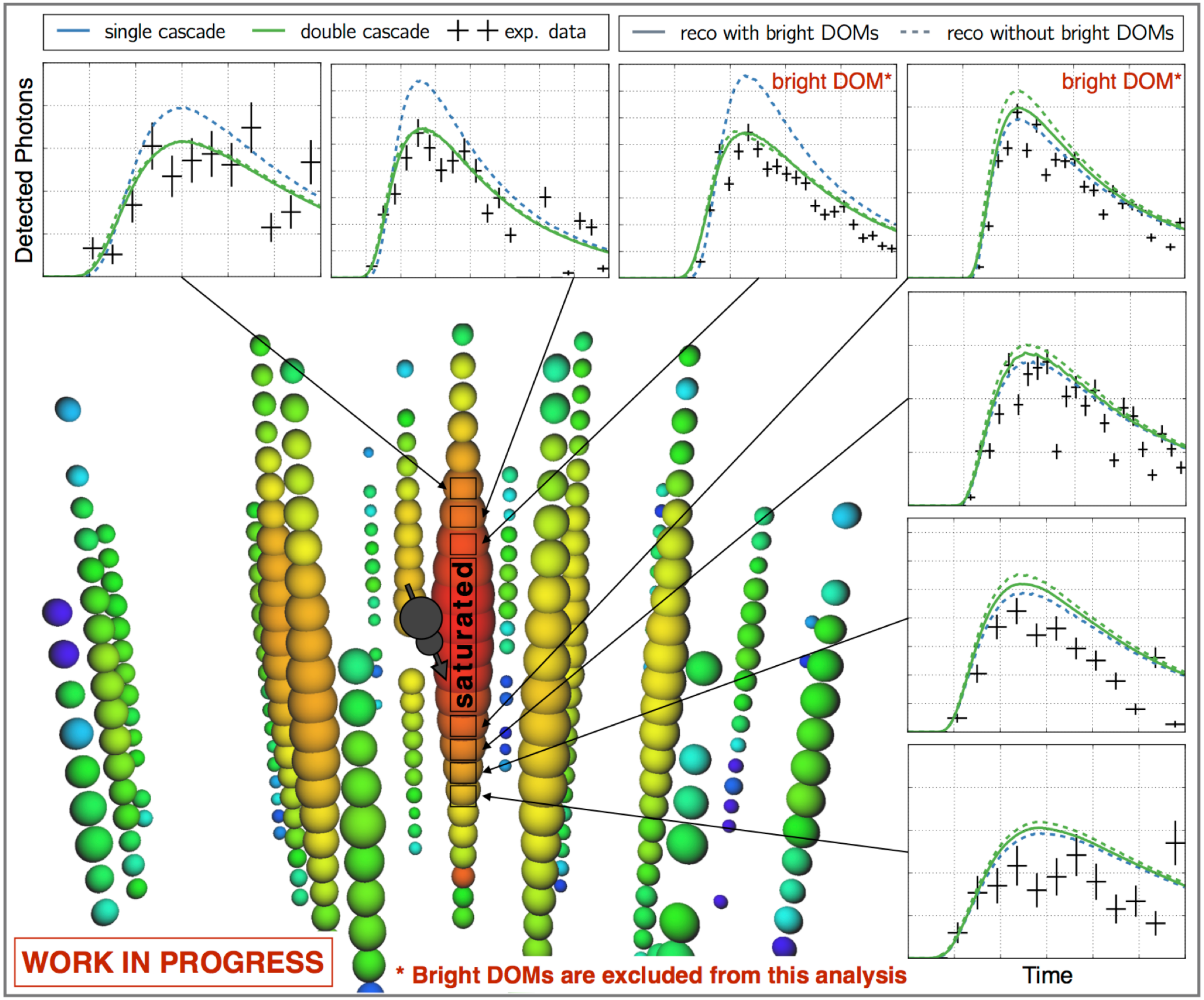


Double-cascade event 1

Slight preference for double cascade over single cascade based on DOM-to-DOM charge distributions

No longer a double cascade when including bright DOMs

Dedicated studies ongoing

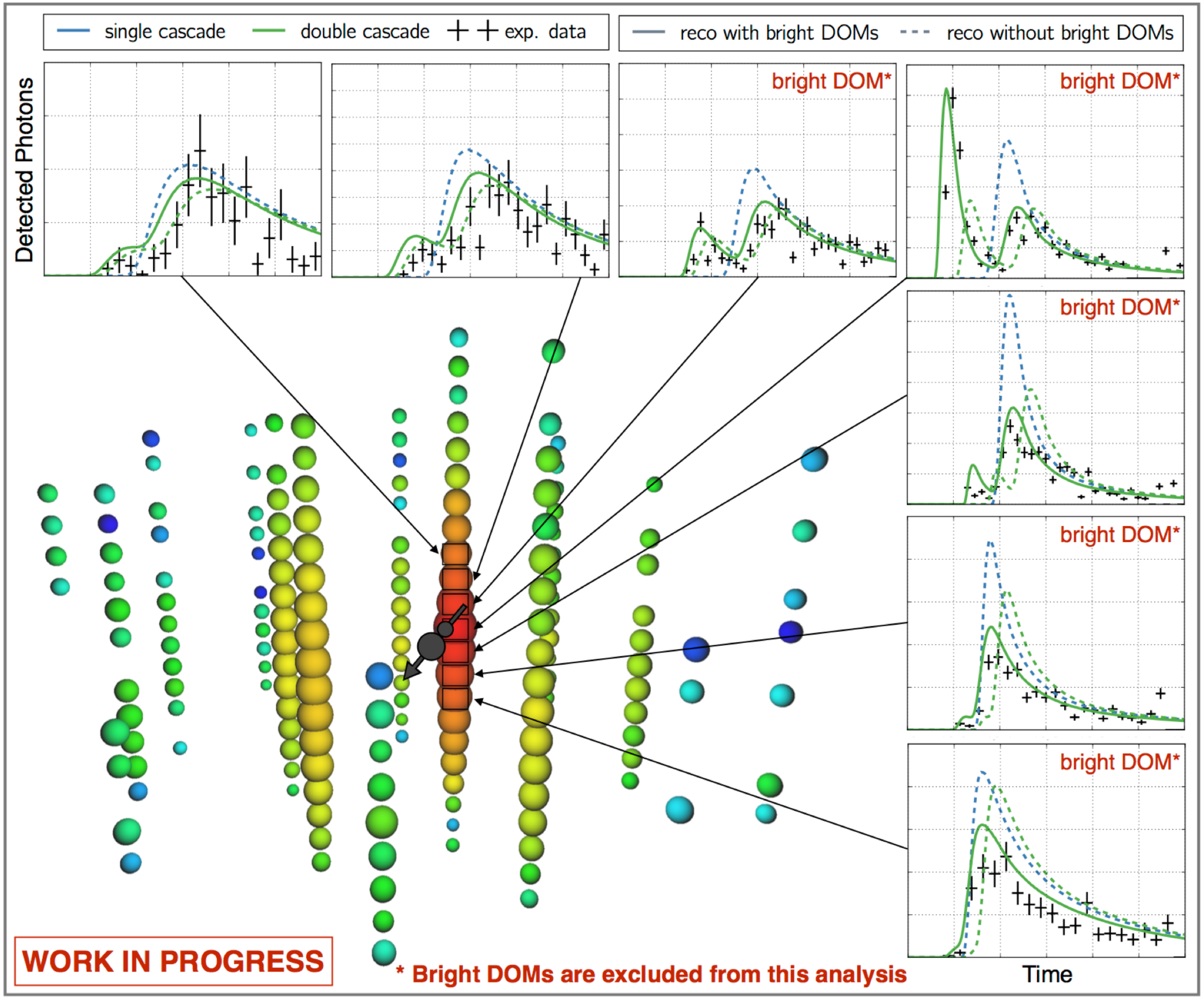


Double-cascade event 2

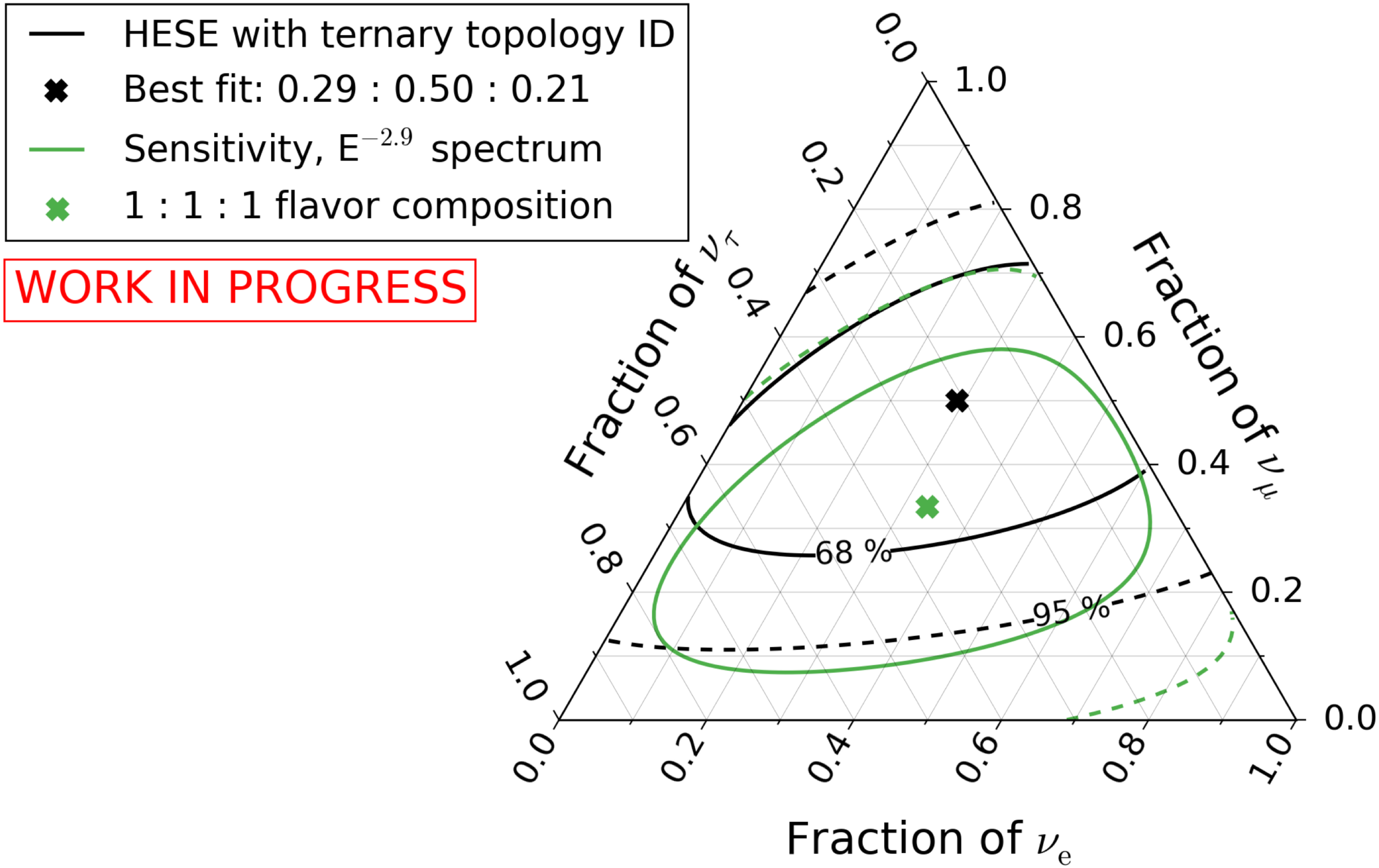
Strong preference for double cascade over single cascade based on DOM-to-DOM charge distributions

Remains a double cascade when including bright DOMs

Dedicated studies ongoing



Astrophysical flavor composition

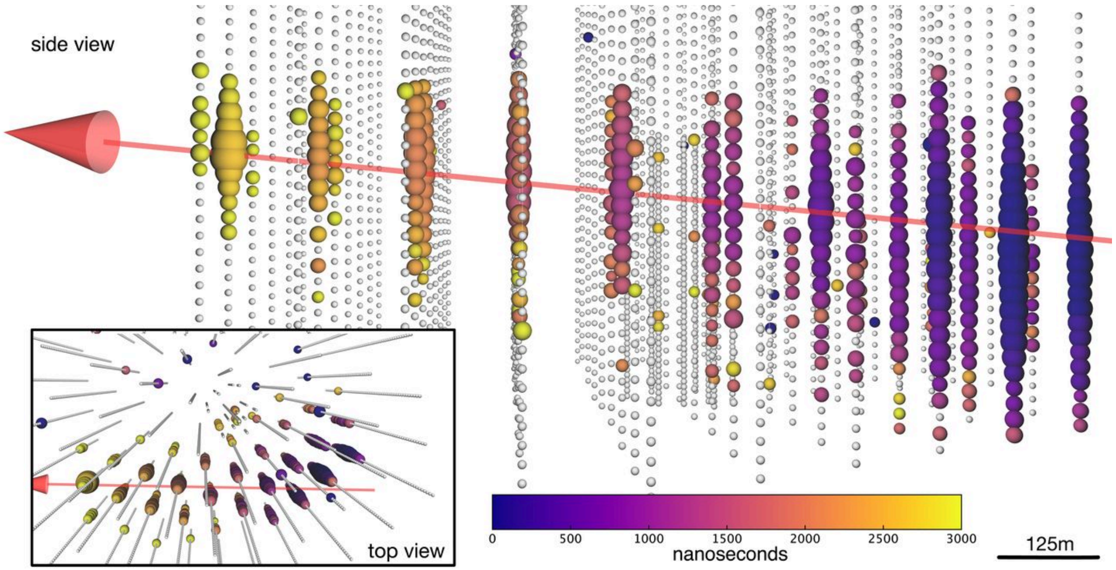


New: non-zero best-fit for ν_τ component

Evidence for a source of high-energy astrophysical neutrinos

TXS 0506+056

IceCube-170922A



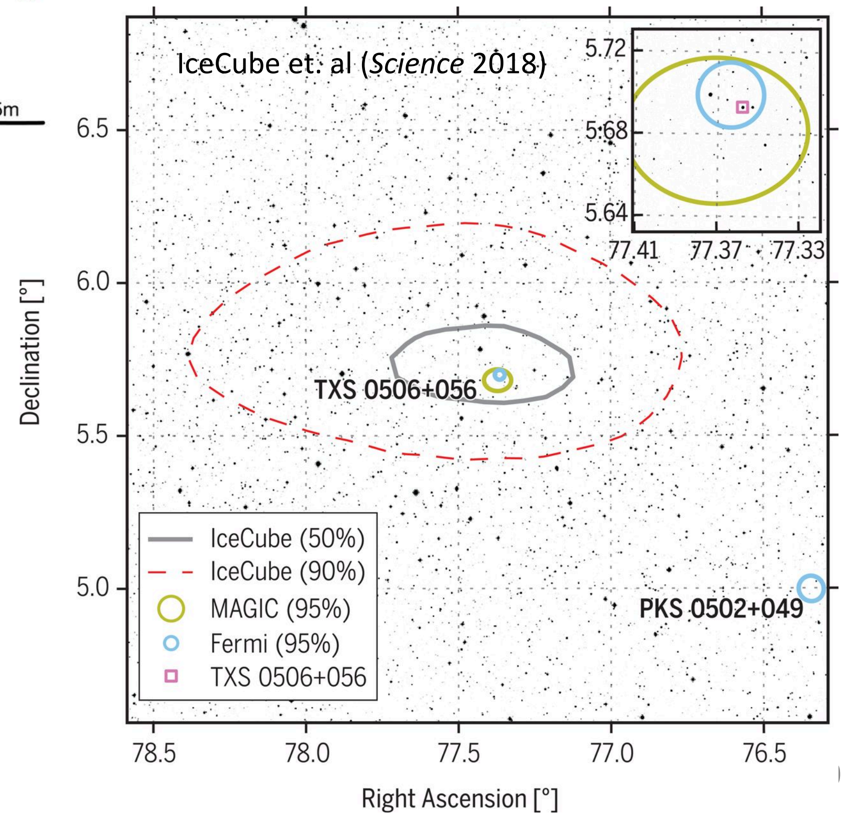
Alert on Sept. 22, 2017

~5800 p.e. track, E~290 TeV

Follow up by MAGIC, Fermi and others

TXS 0506+056 is a blazar located at z=0.34 or roughly 4 billion ly away

Blazars are active galactic nuclei with jets that can flare, producing gamma-rays



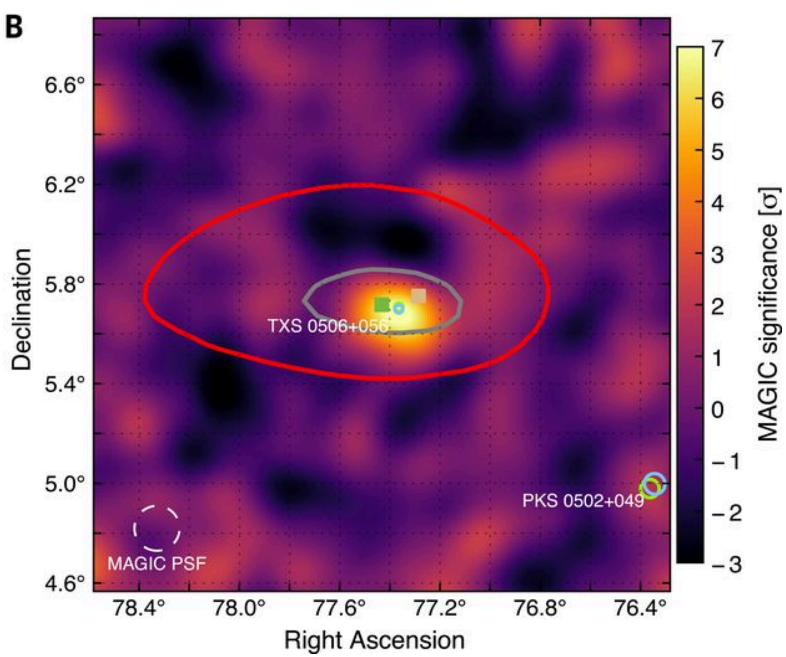
Evidence for a point source

Direction of IceCube-170922A consistent with TXS 0506+056 a known γ-ray source

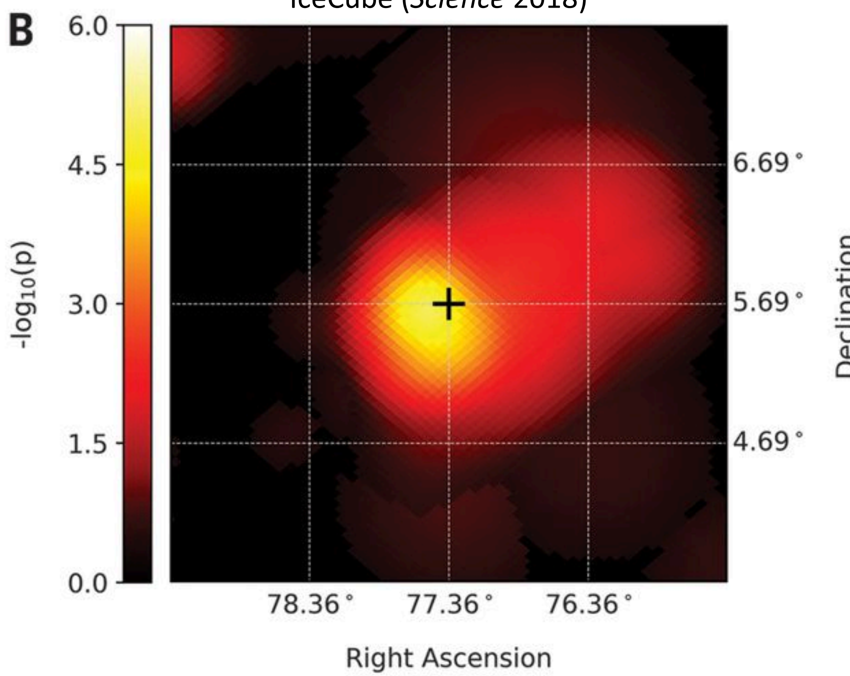
Significant excess seen by Fermi-LAT and MAGIC shortly after IC alert (3σ)

Historical IceCube data indicates independent **neutrino flare** in 2014-15 (3.5σ)

IceCube et. al (*Science* 2018)



IceCube (*Science* 2018)

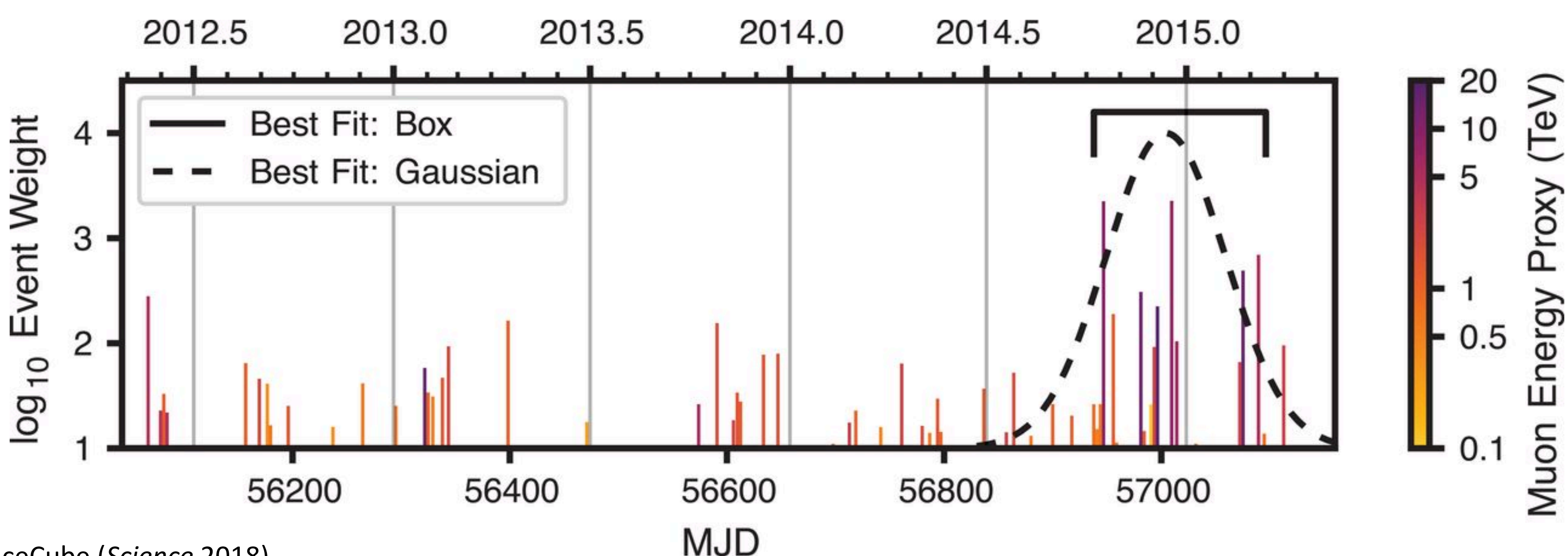


Time dependence in historical IceCube data

Time dependence is crucial!

13 ± 5 muon-neutrino tracks on clustered in space and time, $E^{-2.1}$ spectrum

Summary: first evidence for very high-energy, astrophysical neutrino source. Implications for blazars as an origin of high-energy cosmic rays.



IceCube (*Science* 2018)

Possible Glashow resonance event

~6.3 PeV reconstructed energy

W-boson resonance

The channel:

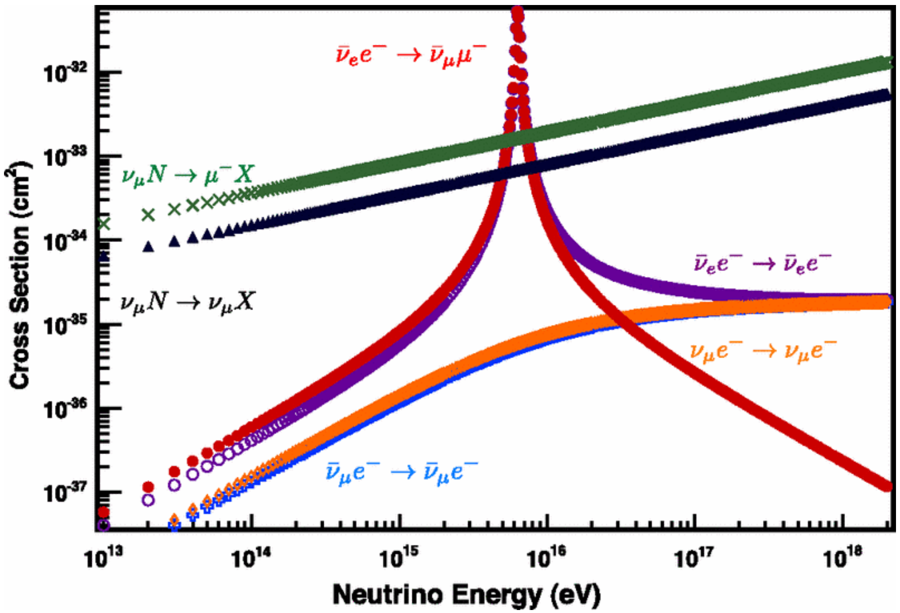
$$\bar{\nu}_e + e^- \rightarrow W^-$$

For at rest electron, require

$$E_\nu = 6.3\ PeV$$

Boosts neutrino cross section

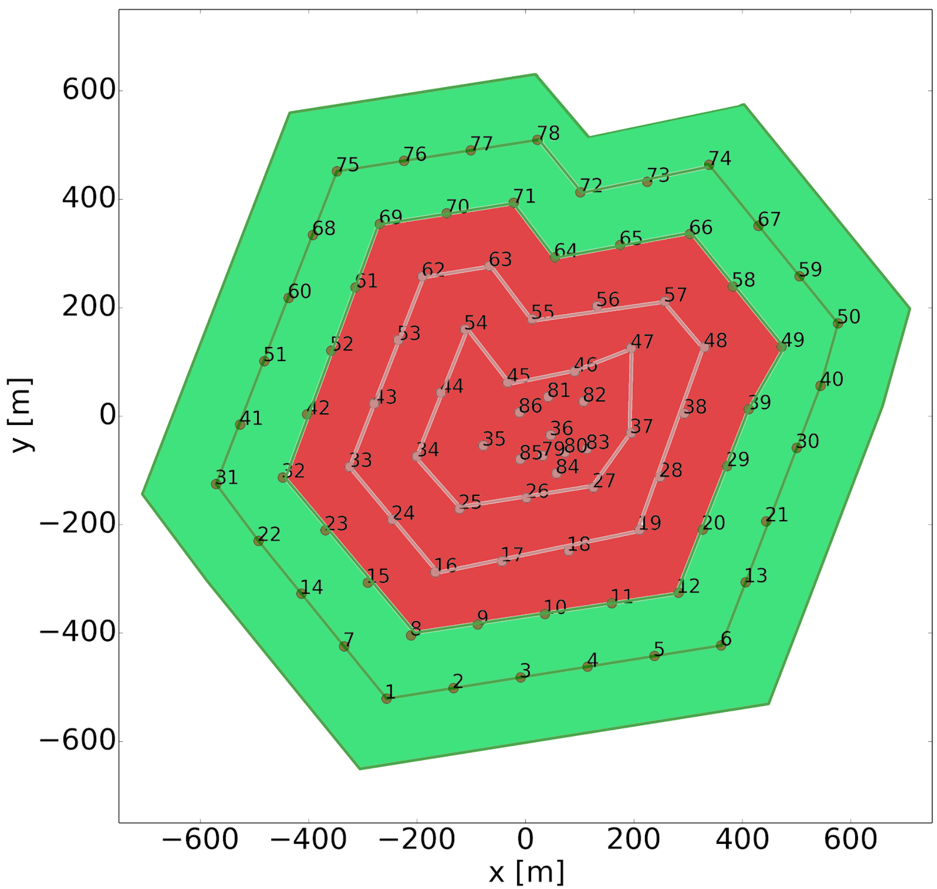
RevModPhys. 84 1307

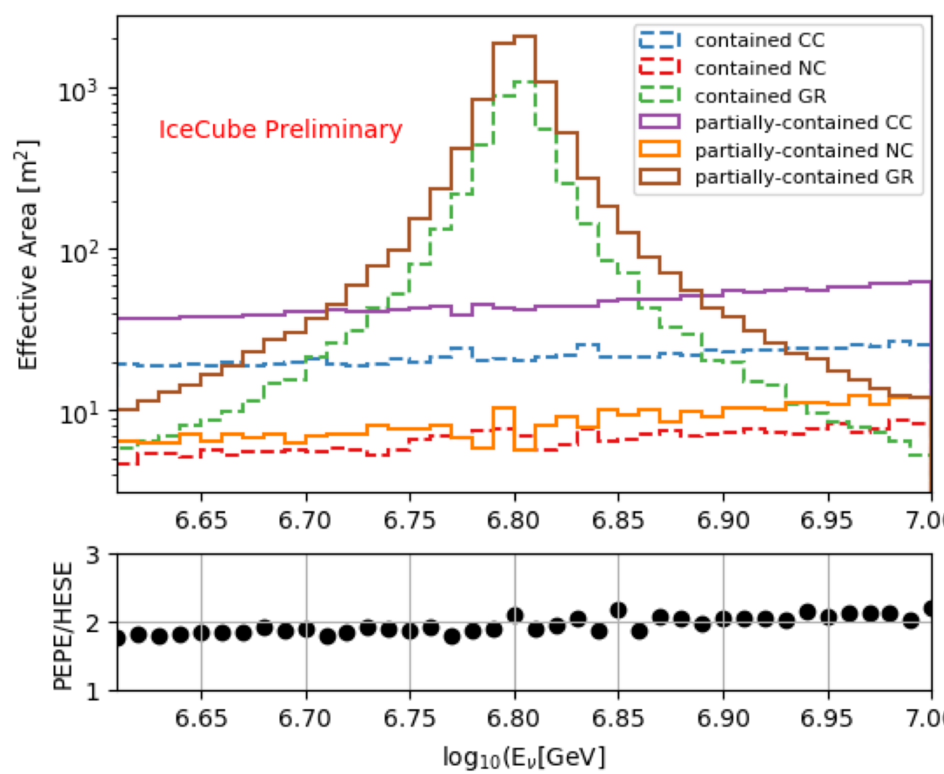


Partially contained (PEPE) selection

BDT trained on 11 features to select high-energy cascades in outer layer of detector

Twice the effective area for probing Glashow resonance: $\bar{\nu_e} + e^- \rightarrow W^-$



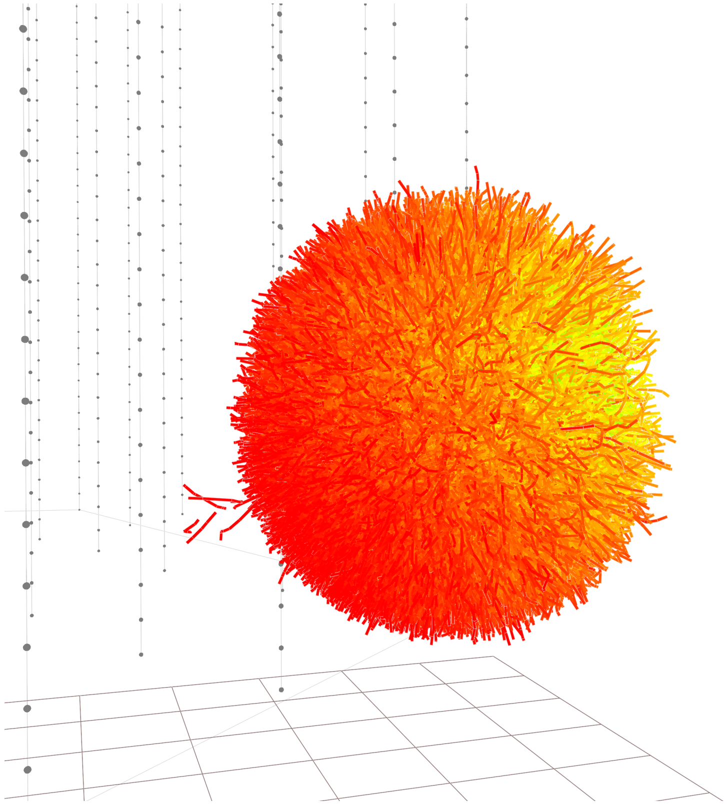


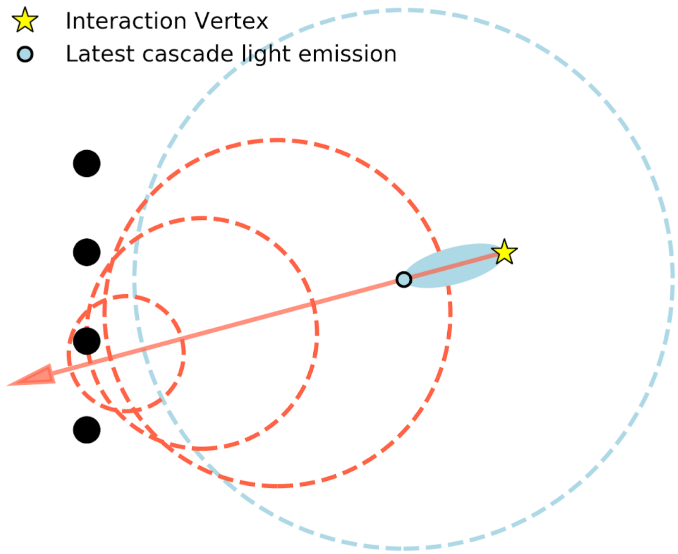
W-boson decays

W decays primarily hadronically

Hadrons then decay to lower energy muons

These muons travel ahead of Cherenkov wavefront, depositing **early hits**

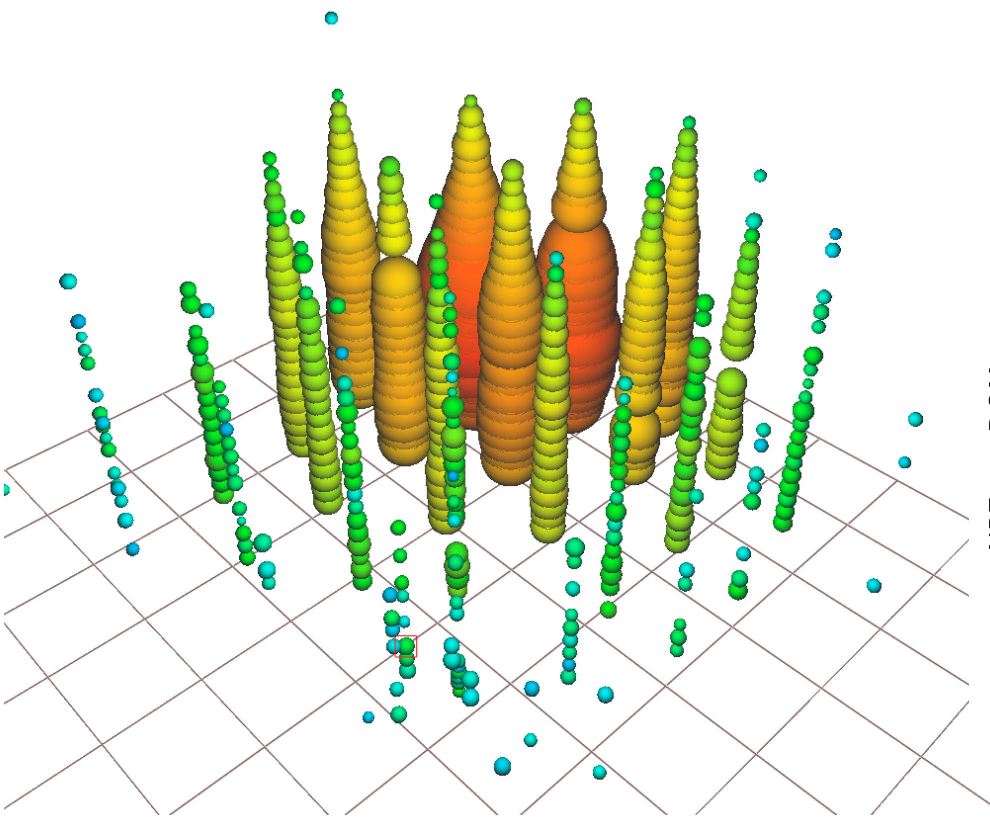


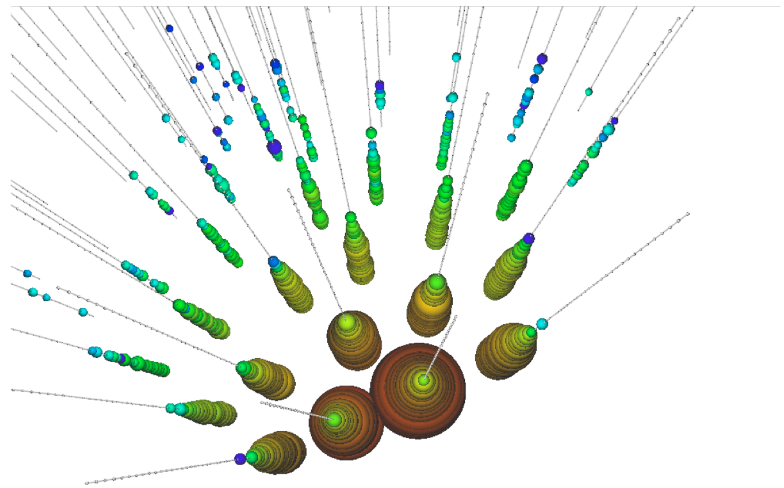


The highest energy event in PEPE

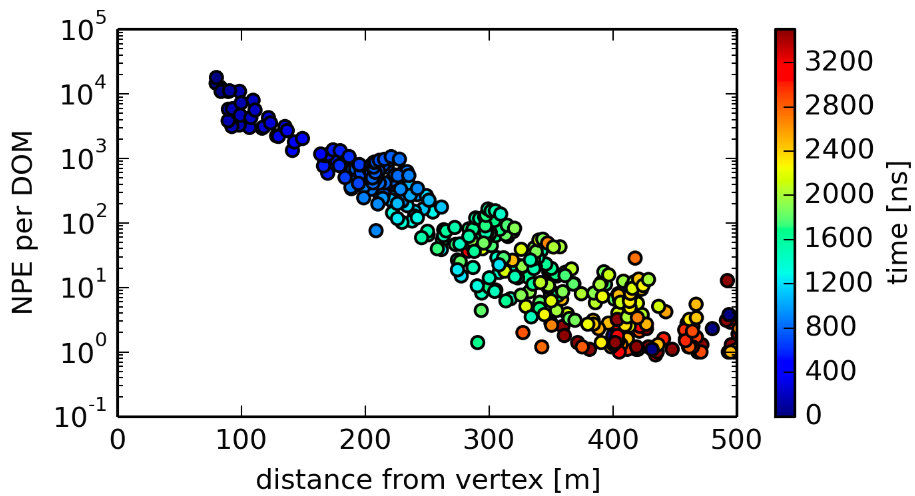
Occurred in 2017

Best-fit vertex outside detector





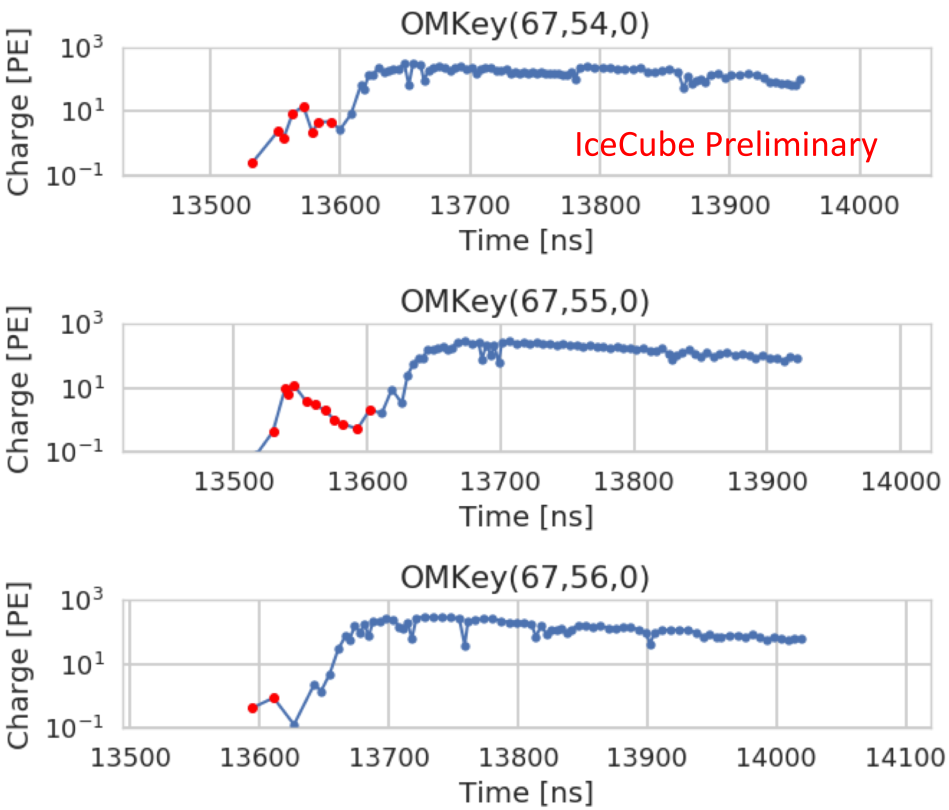
Top view



The highest energy event in PEPE

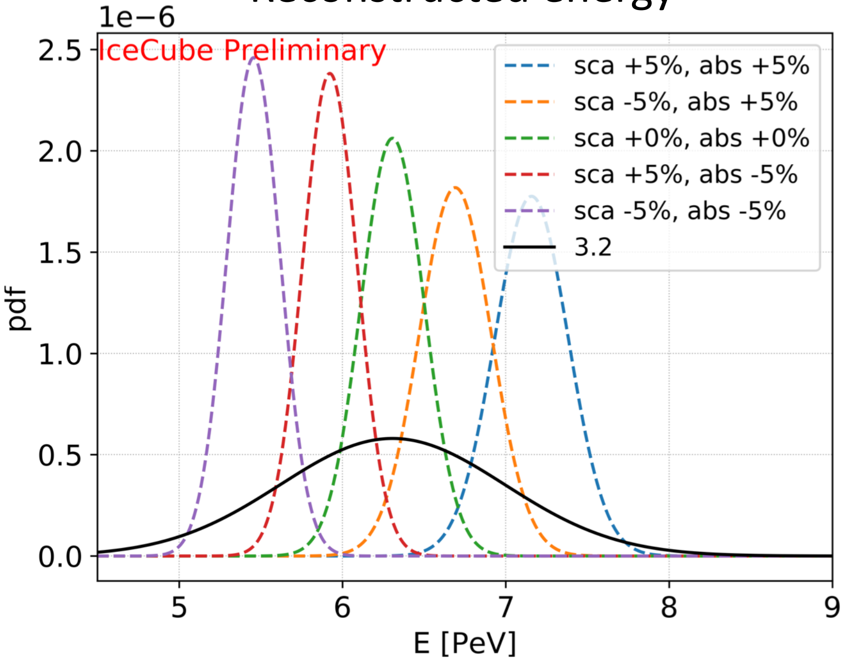
Features: Early hits, reconstructed energy of 6.3 ± 0.7 PeV including statistical uncertainty and systematics due to bulk-ice only

Early hits observed on 3 DOMs

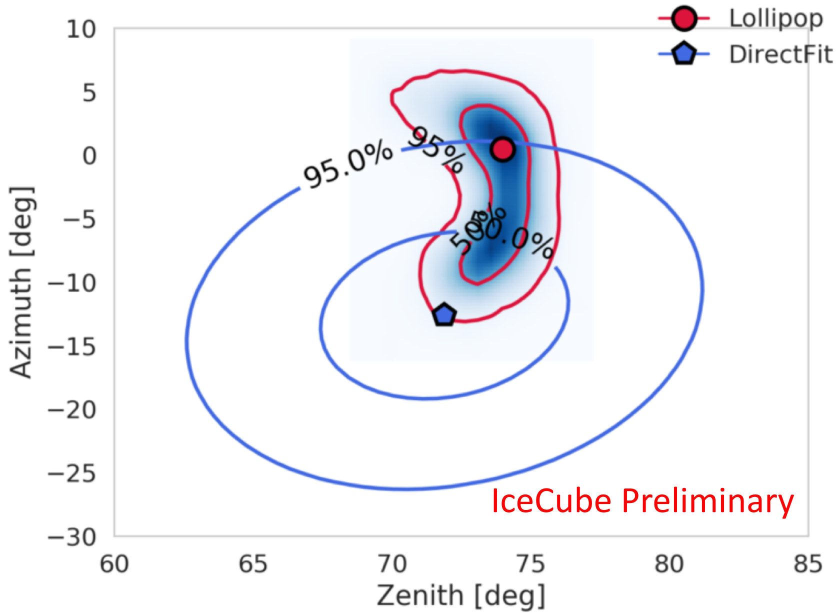


charge per bin

Reconstructed energy



Early muons

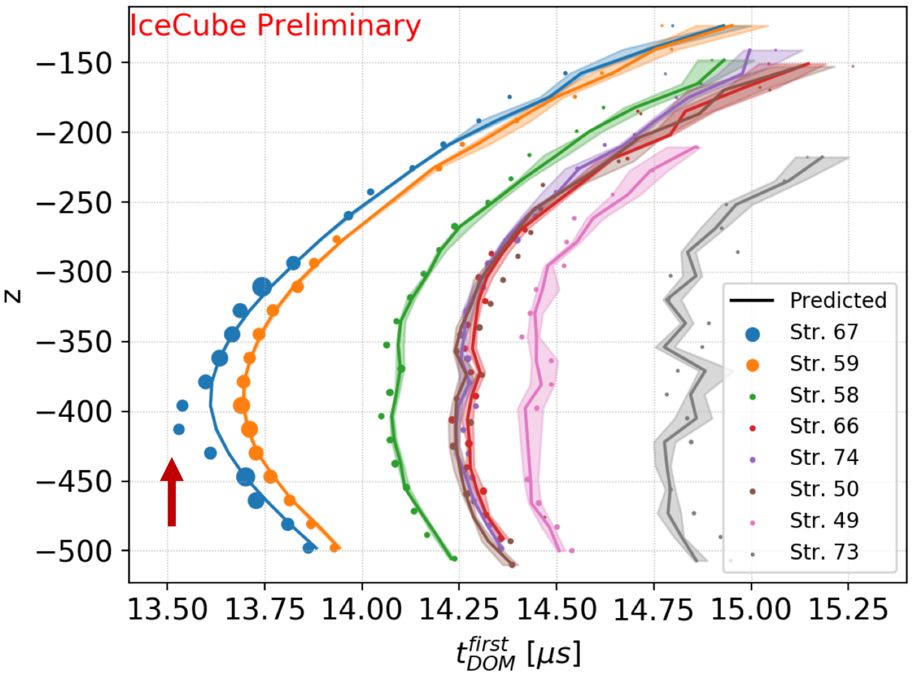


Hadronic cascade alone does not predict first-arrival times

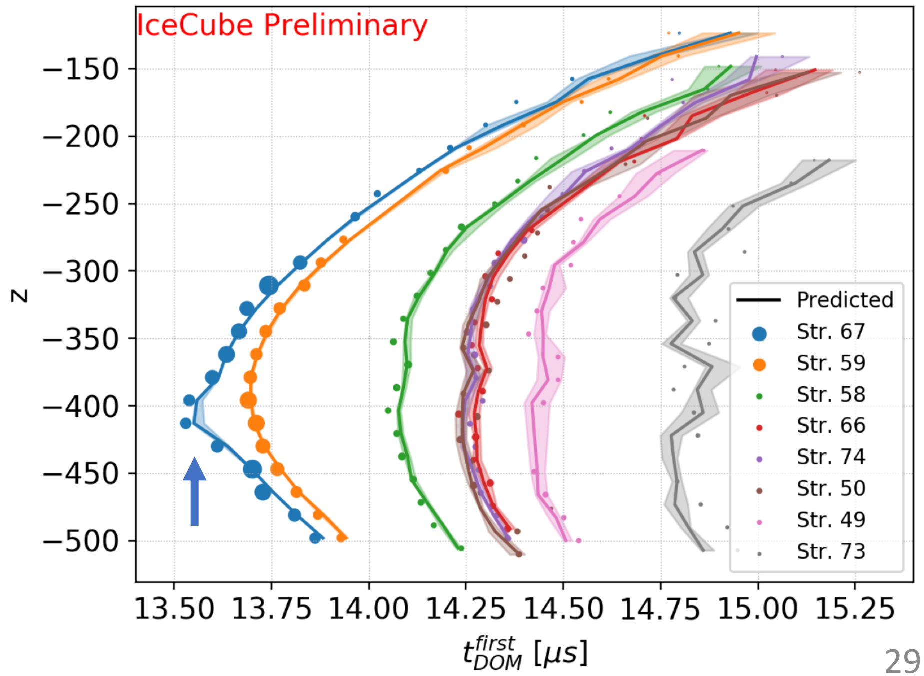
Requires early muon

Helpful for directional constraints

w/o early muons



w. early muons

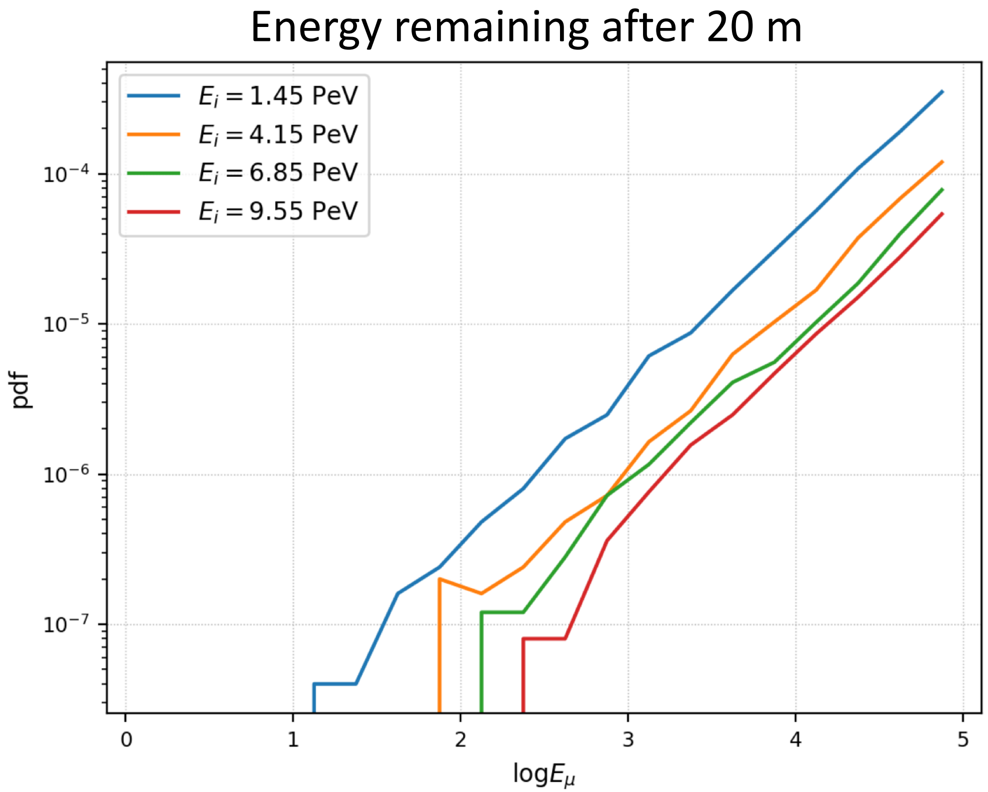


Atmospheric muon background rejection

Can an atmospheric muon fake the event signature of PeV-scale cascade and GeV-scale muon?

Would require a PeV-scale energy loss over short distance

Extremely unlikely for ~6 PeV muon to travel ~20 m and be left with < 100 GeV

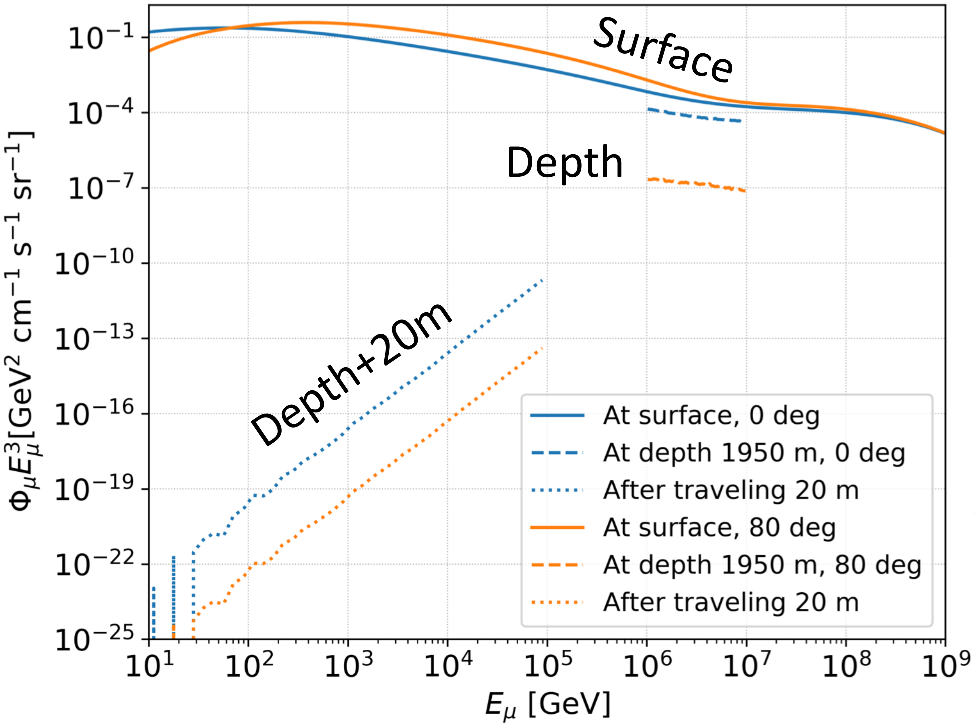


Atmospheric muon background rejection

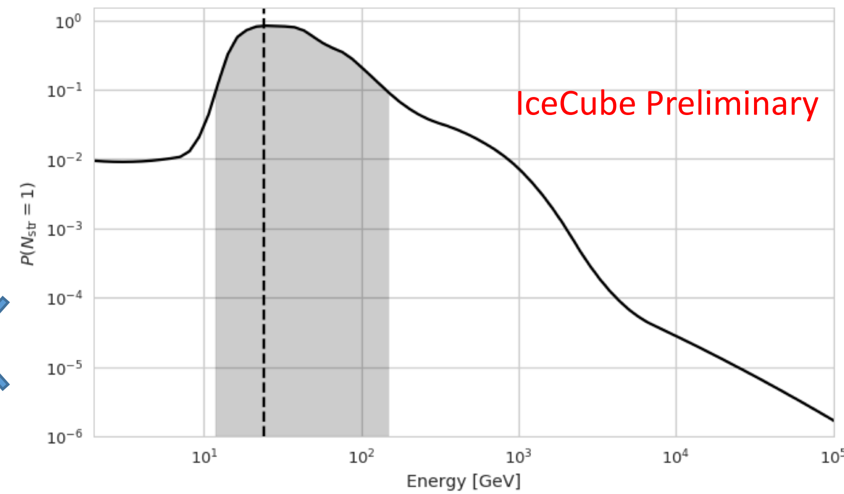
Conservative estimate is to take the flux of all such muons intersecting the detector → Numerically evaluated with MCEq and MMC

Preliminary estimate of such events ~1e-7 in 4.6 yrs, which corresponds to exclusion of CR hypothesis ~ **5σ**

Extremely unlikely to be muon background



O(10-100 GeV)

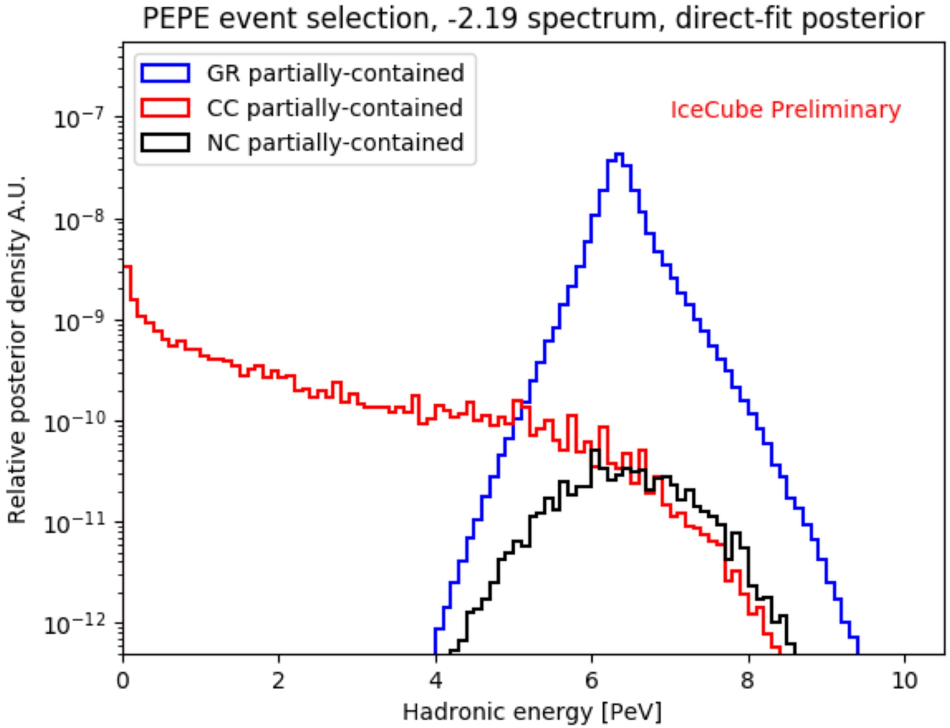


Likelihood of early-muon energy based on data

Glashow resonance vs Charged Current ν_e

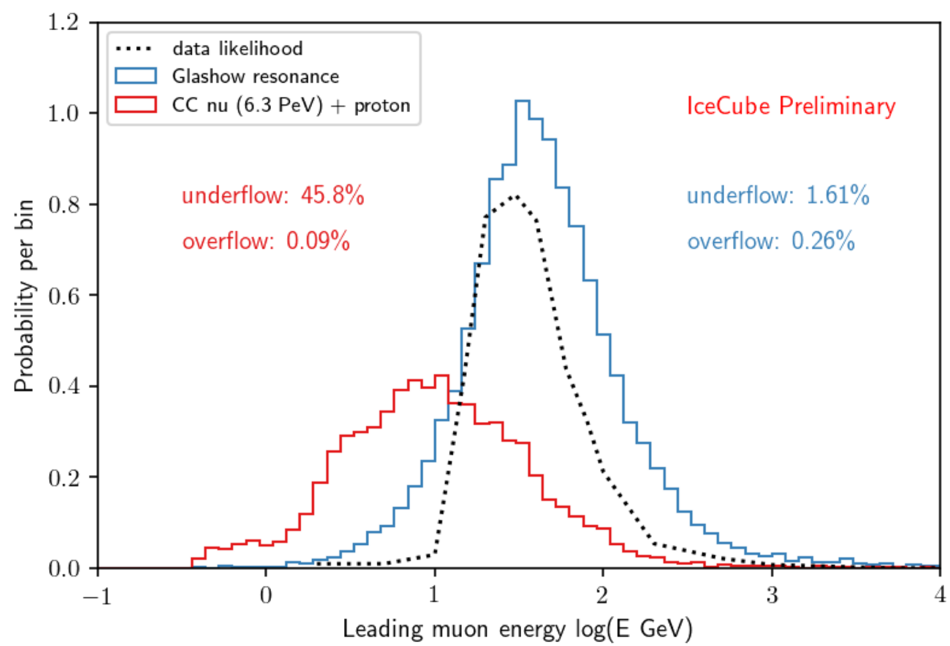
Early muons come from hadronic decay

CC ν_e interactions are not purely hadronic → different muon distributions



CC interactions deposit **less** hadronic energy

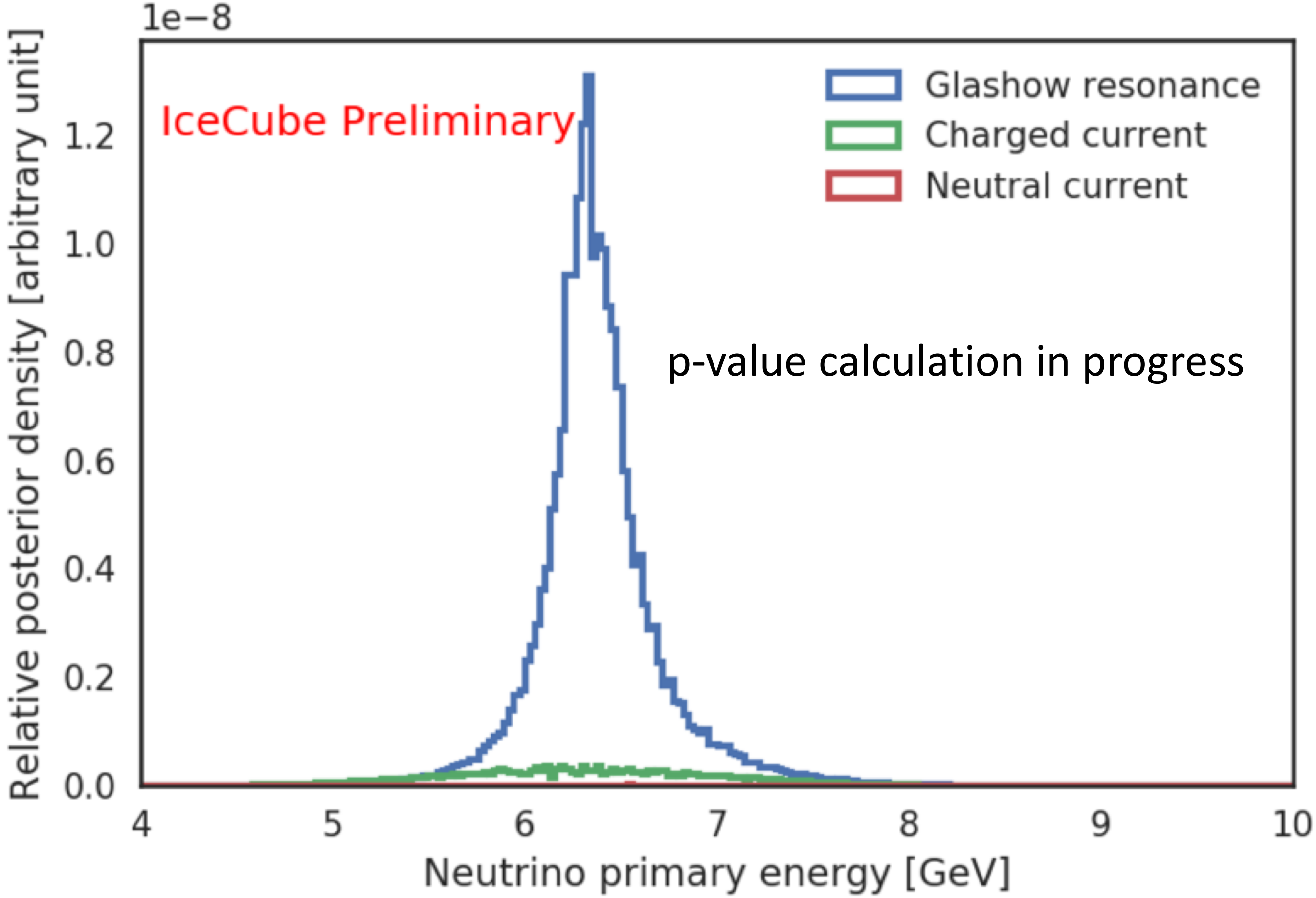
For 6.3 PeV CC, muon energy distribution doesn't agree as well with data likelihood



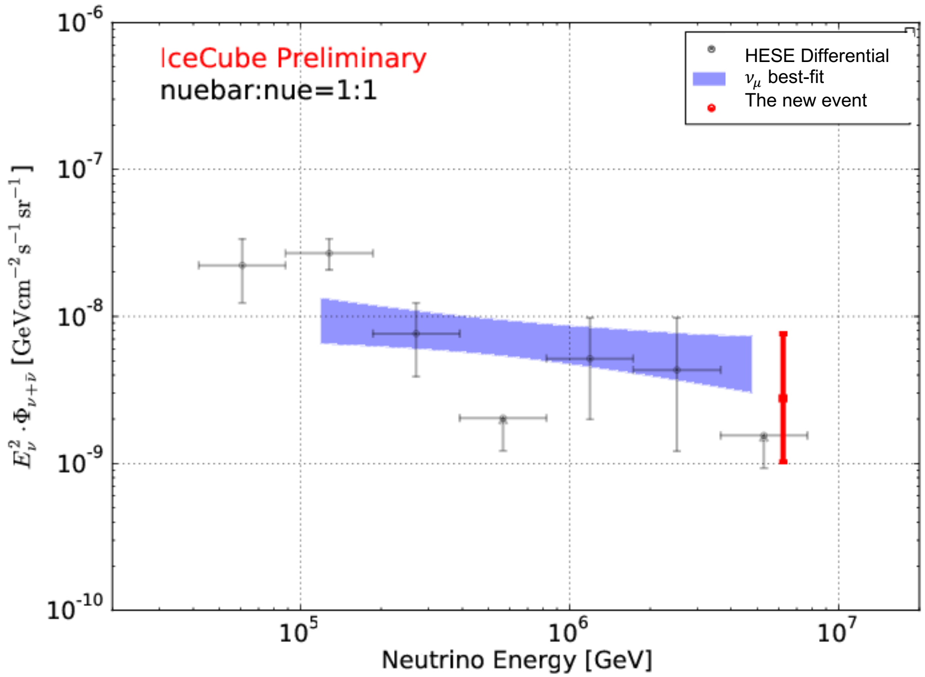
Most probable neutrino energy

Rely on MC to unfold from E_{dep} back to E_ν

Relative comparison of probabilities for GR/CC/NC



Astrophysical flux and implications

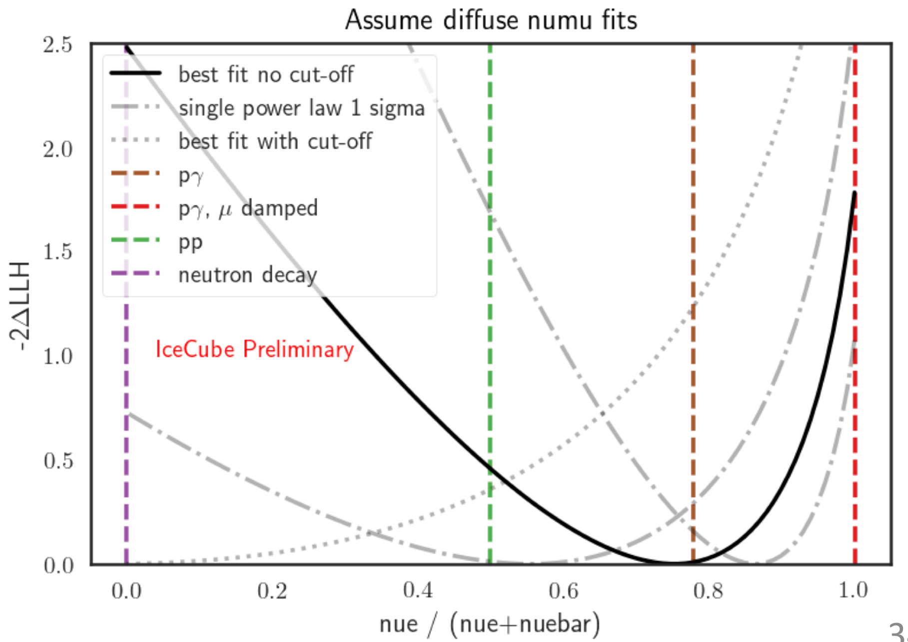


Assuming equal fraction of ν_e and $\overline{\nu_e}$

Single-bin, differential flux measurement

By fixing diffuse spectrum, can probe $\nu_e : \overline{\nu_e}$ ratio

One event is not constraining



Take home message

IceCube continues to consistently collect exciting new results!

Two double-cascade events, possibly due to ν_τ, discovered

First evidence of a source of high-energy astrophysical neutrinos from a flaring blazar TXS 0506+056

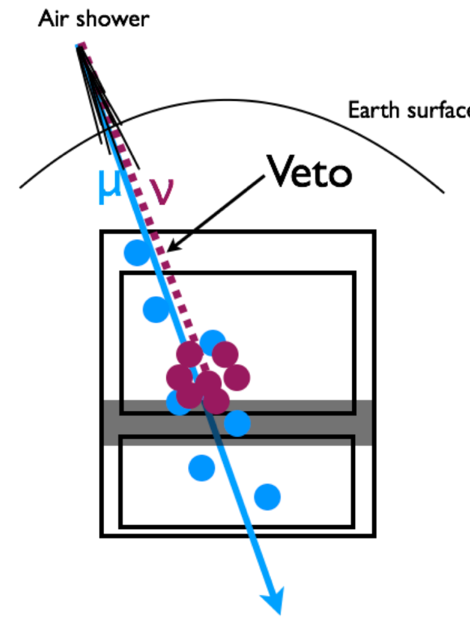
A partially contained, high-energy neutrino has an energy ~6-7 PeV, around the Glashow resonance

Backups

Atmospheric neutrino rejection (uncorrelated)

PRD 90, 023009 (2014)

Atmospheric **electron neutrinos** may coincide with muons from other branches in shower



Expected number of muons from proto. shower to trigger veto

Detection probability

$$\bar{N}_{A,\mu}(E_{\mathrm{CR}},\theta_z) = \int dE_\mu^{\mathrm{i}} \underbrace{\frac{dN_{A,\mu}}{dE_\mu^{\mathrm{i}}}(E_{\mathrm{CR}},E_\mu^{\mathrm{i}},\theta_z)}_{\text{Muon yield from prototypical shower}} \overbrace{\mathcal{P}_{\mathrm{det}}\left(E_\mu^{\mathrm{i}},\theta_z\right)}^{\text{Detection probability}}$$

Muon yield from prototypical shower

Assuming median muon-range

$$P_{det}^{SGRS} = \Theta(X_\mu^{median} - X_\mu)$$

$$\mathcal{P}_{\mathrm{pass}}^{\mathrm{uncor,GJKvS}}(E_\nu,\theta_z) = \frac{1}{\phi_\nu(E_\nu,\theta_z)} \sum_A \int dE_{\mathrm{CR}} \underbrace{\frac{dN_{A,\nu}}{dE_\nu}(E_{\mathrm{CR}},E_\nu,\theta_z)}_{\text{Neutrino yield from prototypical shower}} \phi_A(E_{\mathrm{CR}}) \underbrace{\mathcal{P}_{0\text{-}\mu}^{\mathrm{shower}}\left(N_\mu = 0; \bar{N}_{A,\mu}^{\mathrm{GJKvS}}(E_{\mathrm{CR}},\theta_z)\right)}_{\text{Poisson probability of detecting 0 muons from proto. shower}}$$

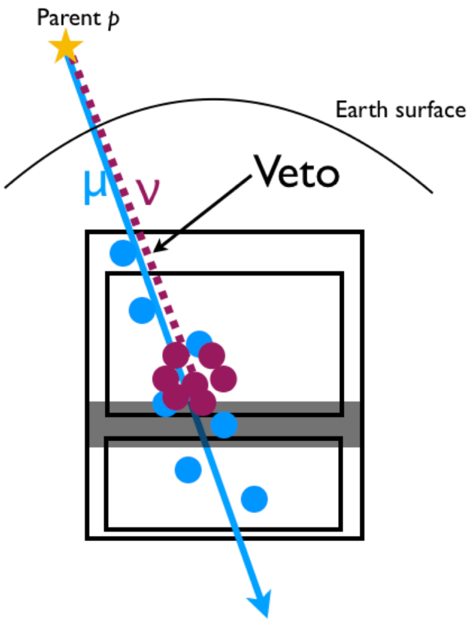
Neutrino yield from prototypical shower

Poisson probability of detecting 0 muons from proto. shower

Atmospheric neutrino rejection (correlated)

PRD 79, 043009 (2009)

Atmospheric **muon neutrinos** always have a sibling muon in addition to other branches



Muon decay spectrum; conditional on E_p, E_ν

$$\mathcal{P}^{\rm sib}_{0\text{-}\mu}\left(\theta_z|E_p,E_\nu\right)=1-\int dE^{\rm i}_\mu\,\mathcal{P}_{\rm det}\left(E^{\rm i}_\mu,\theta_z\right)\frac{dN_{p,\mu}}{dE^{\rm i}_\mu}(E_p,E_\nu,E^{\rm i}_\mu)$$

Assuming 2-body

$$\frac{dN_{p,\mu}}{dE^i_\mu}=\delta(E_p-E_\nu+E^i_\mu)$$

$$\mathcal{P}^{\rm cor,SGRS}_{\rm pass}(E_\nu,\theta_z)=\frac{1}{\phi_\nu(E_\nu,\theta_z)}\sum_A\sum_p\int dE_p\int\frac{dX}{\lambda_p(E_p,X)}\frac{dN_{p,\nu}}{dE_\nu}(E_p,E_\nu)\,\phi_{A,p}(E_p,X)\,\left[1-\mathcal{P}^{\rm SGRS}_{\rm det}\left(E_p-E_\nu,\theta_z\right)\right]$$

Neutrino yield from parent p

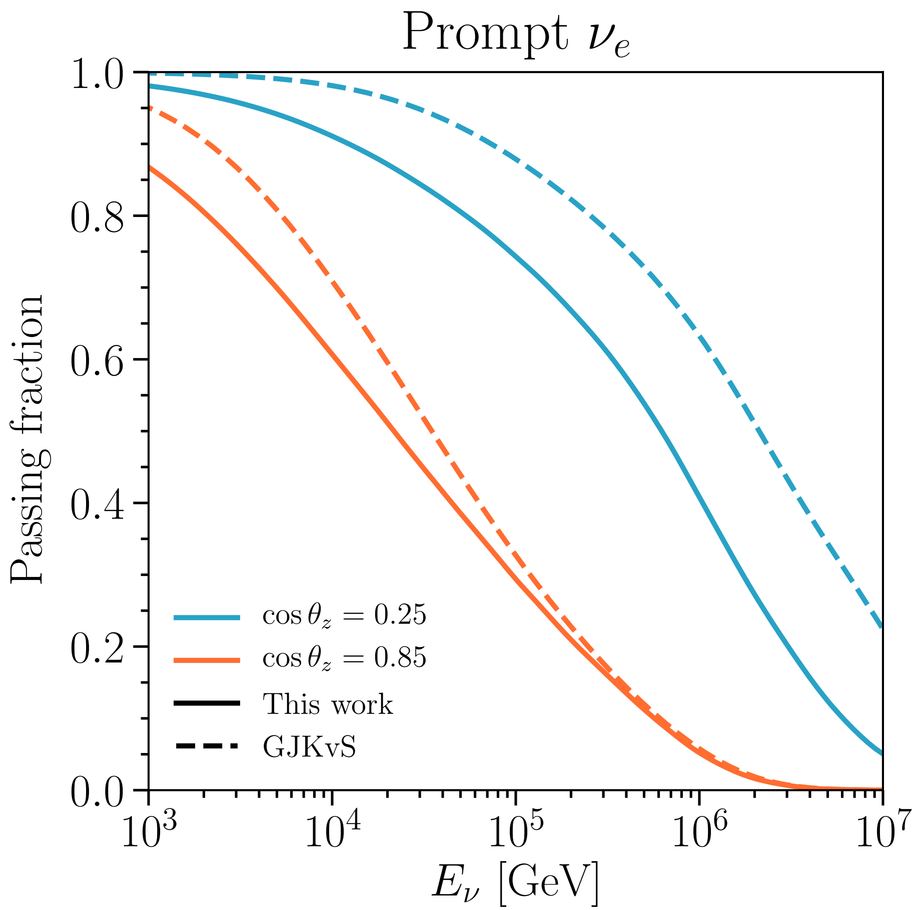
Parent flux at X from proto. shower

Updated atmospheric neutrino passing fractions

Previous calculation (dashed) for a fixed set of approximations

- In-part **analytically** calculated
- In-part from **fit** to CORSIKA

New calculation (solid) allows for plug-and-play of different models



Muon energy tends to increase with E_ν

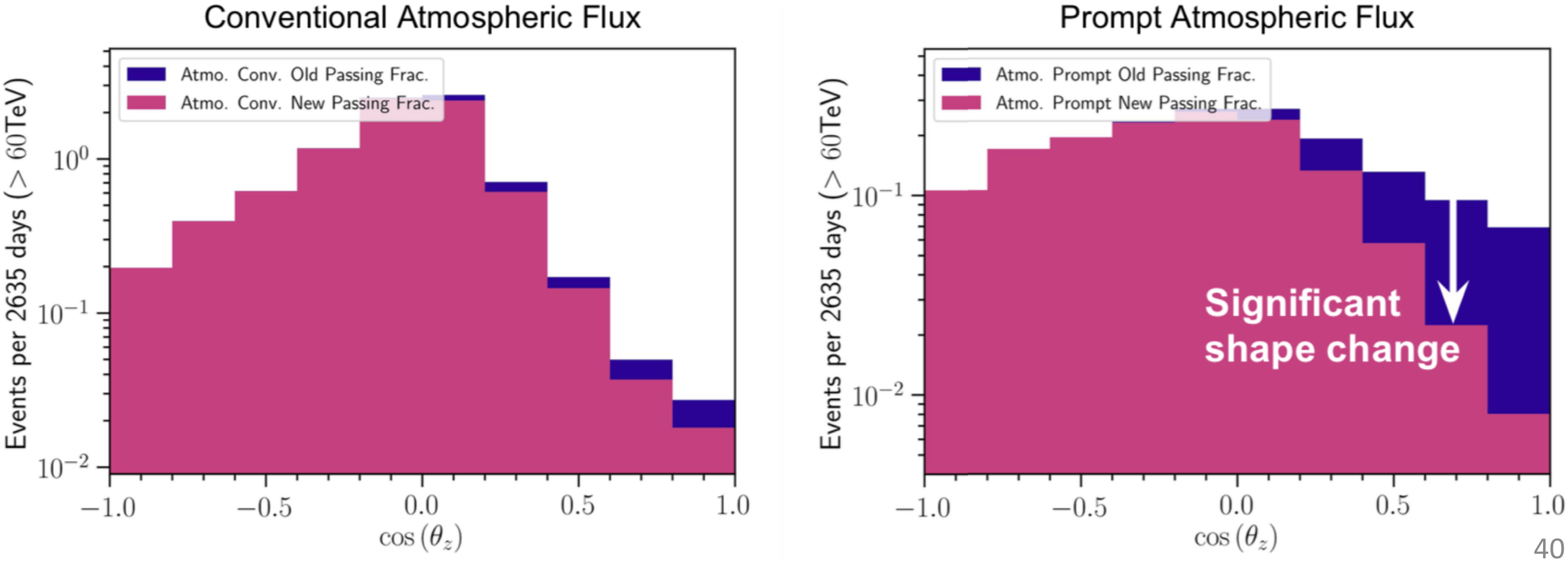
Effect of new passing fractions

MC templates for

- Conventional and prompt atmospheric neutrinos
- Atmospheric muons
- Isotropic, single-power law, diffuse astrophysical flux

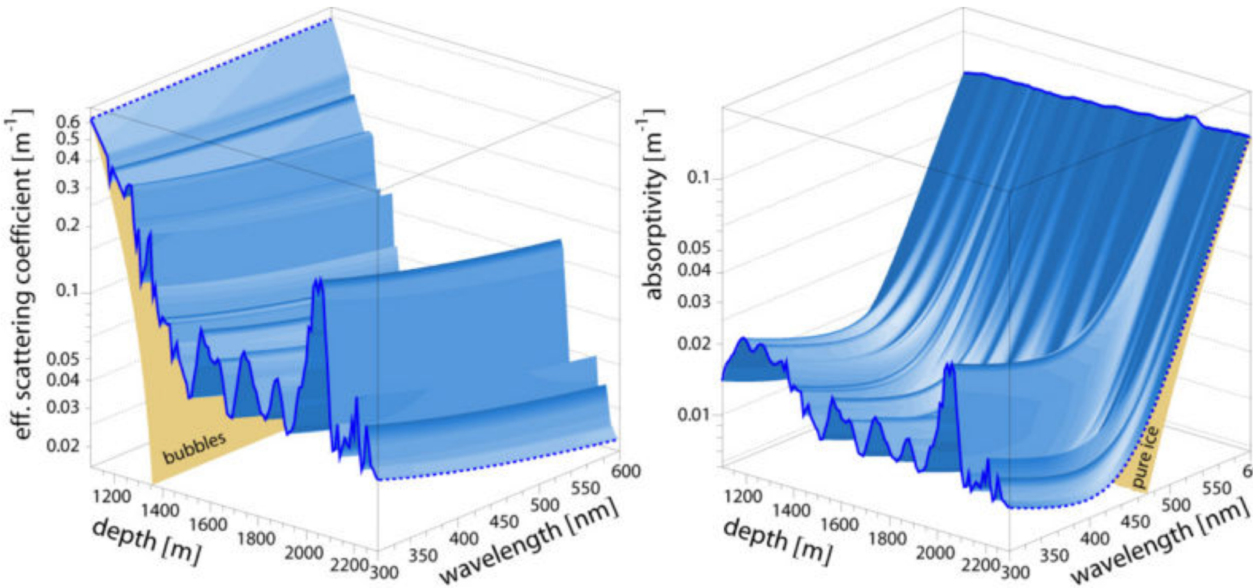
New passing fractions affect template shapes

Nominal, pre-fit expectations



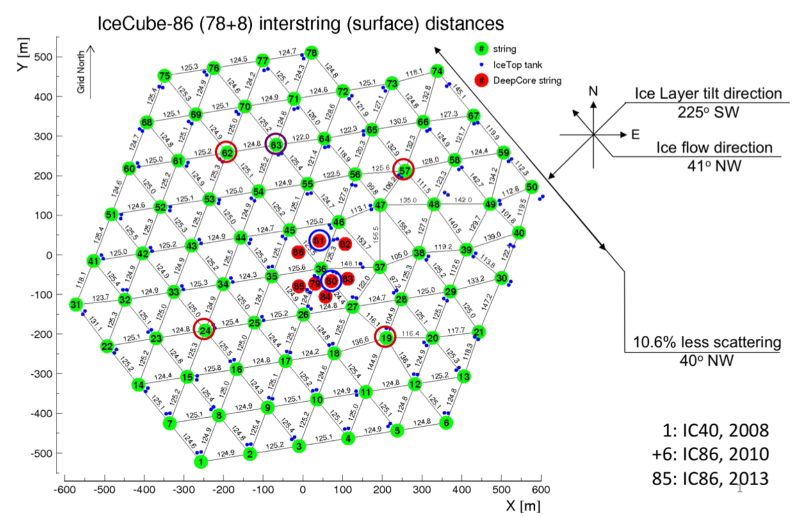
Bulk ice properties in brief

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]

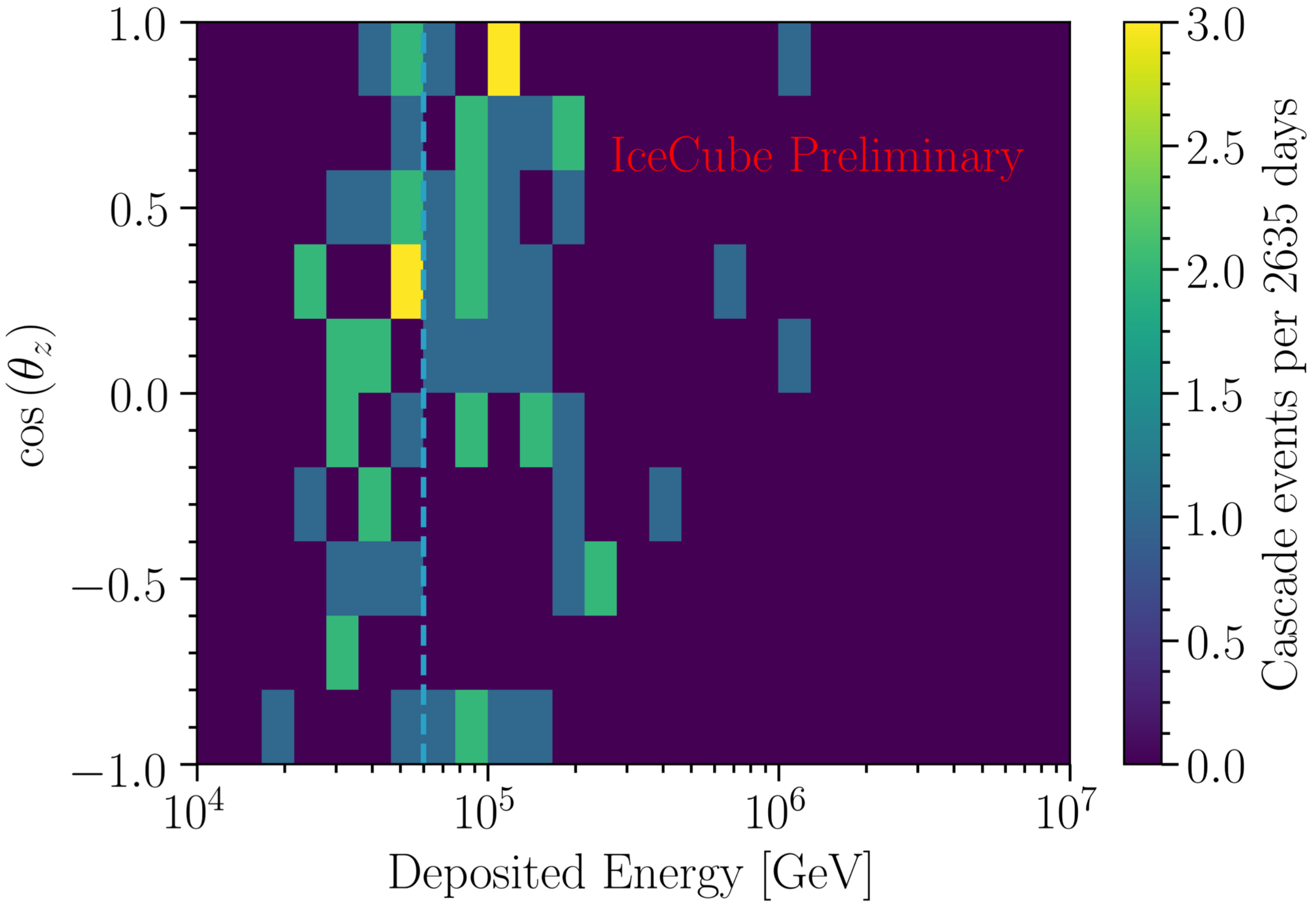


Cascades

Above 60TeV:42 events

8 new events in 2016 season

4 new events in 2017 season

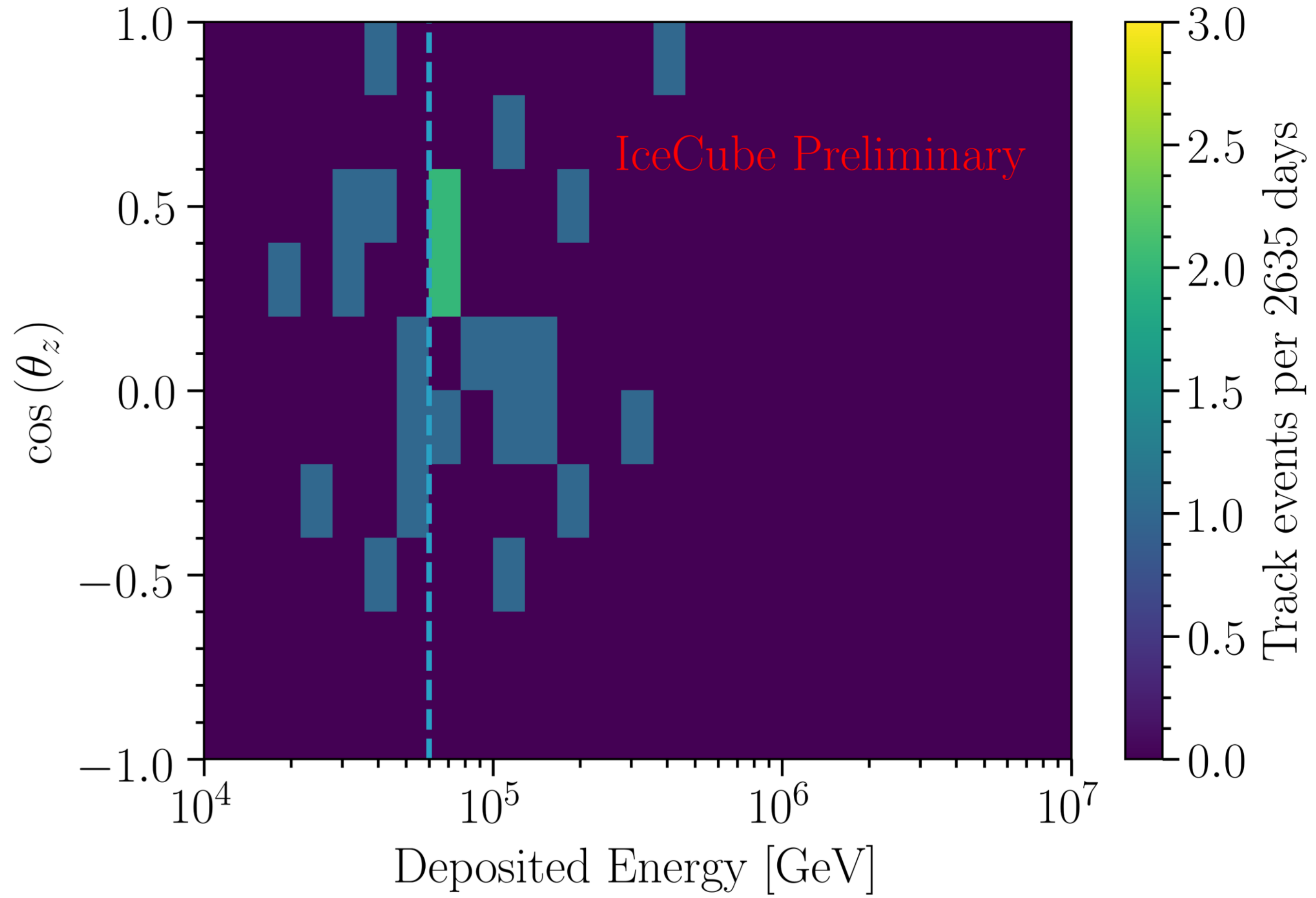


Tracks

Above 60TeV: 16 events

4 new events in 2016 season

1 new event in 2017 season



Double cascades

Above 60TeV: 2 events

0 new events in 2016 season

0 new events in 2017 season