New results with high-energy neutrinos in IceCube

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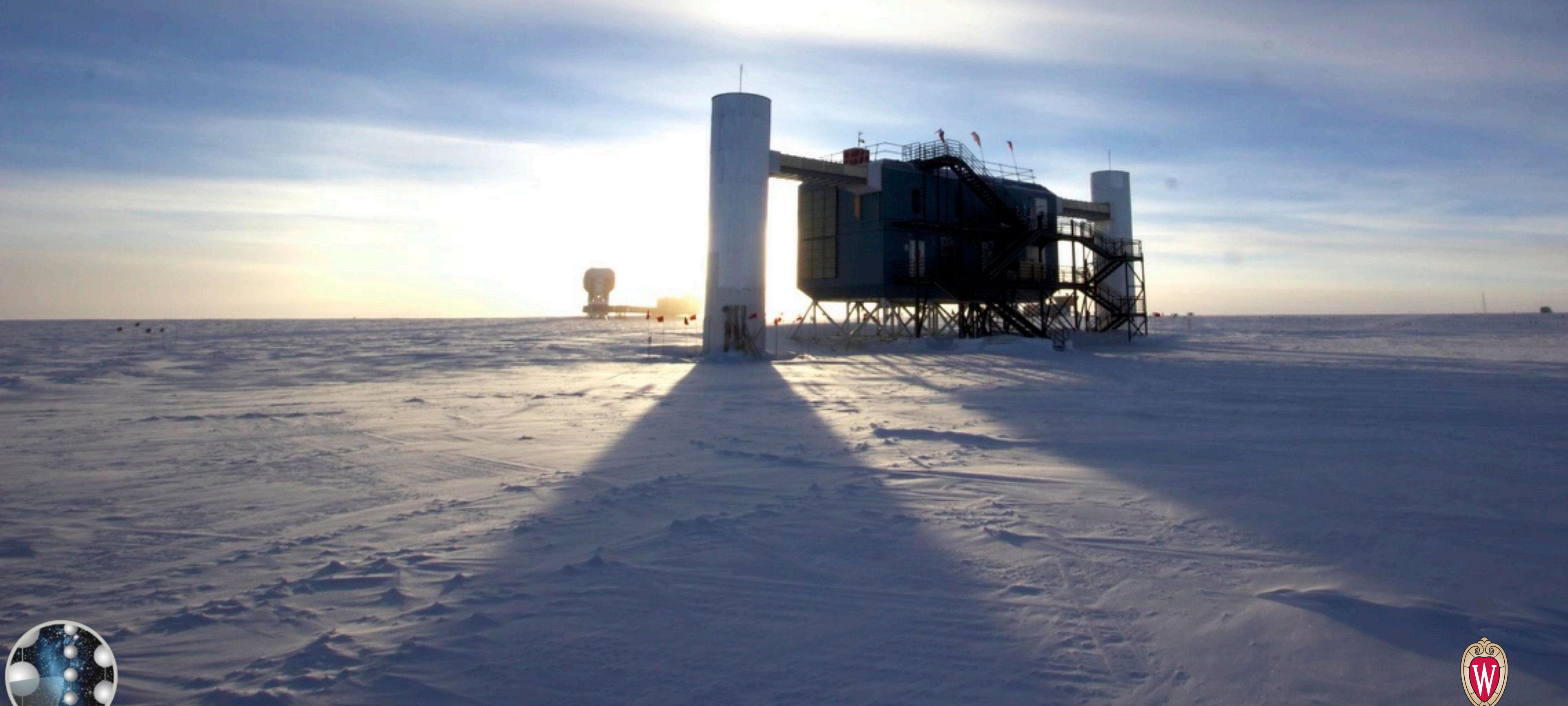
UW Madison & WIPAC

Fermilab Neutrino Seminar

August 30, 2018

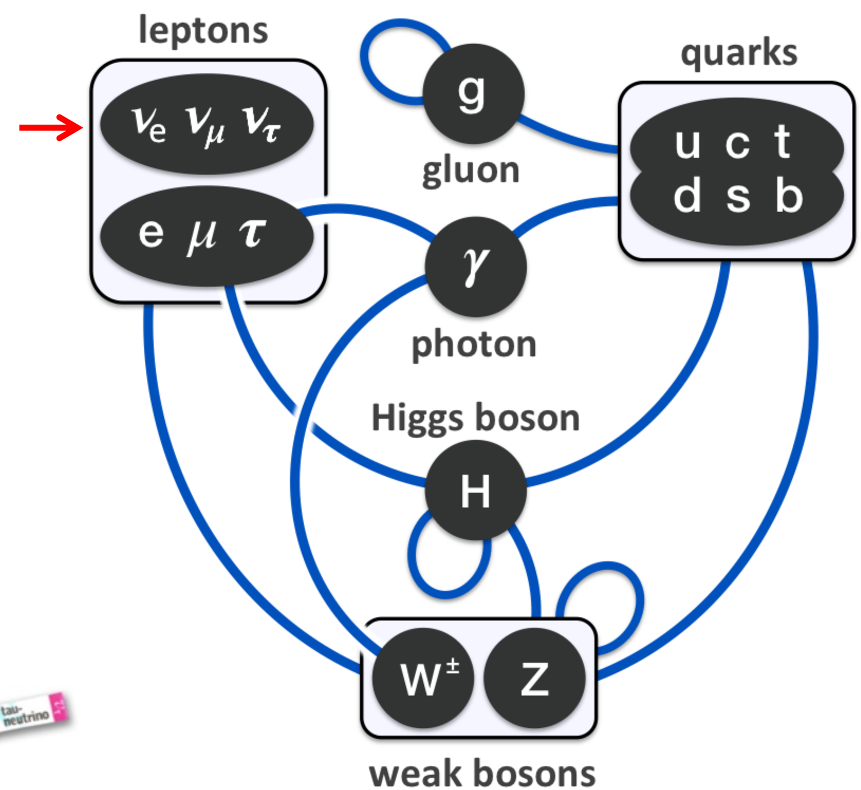


Credit: F. Pedreros, IceCube/NSF

Neutrino properties

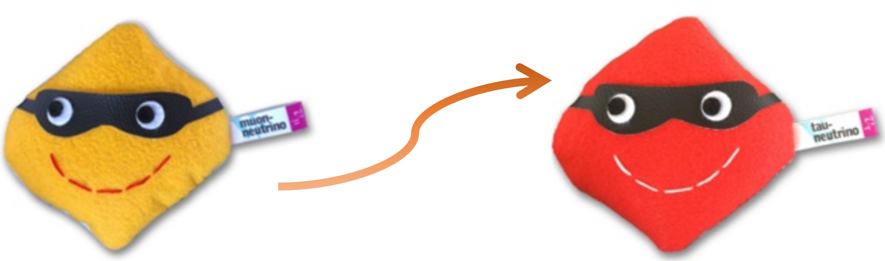
Neutrinos…

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



Neutrinos have nonzero mass

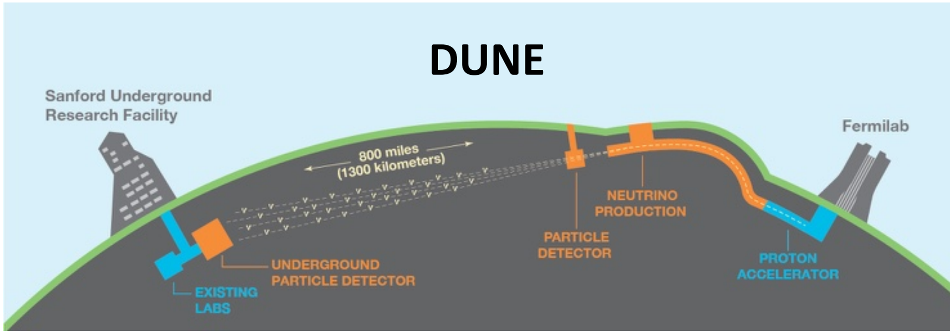
- Discovered via **oscillations**



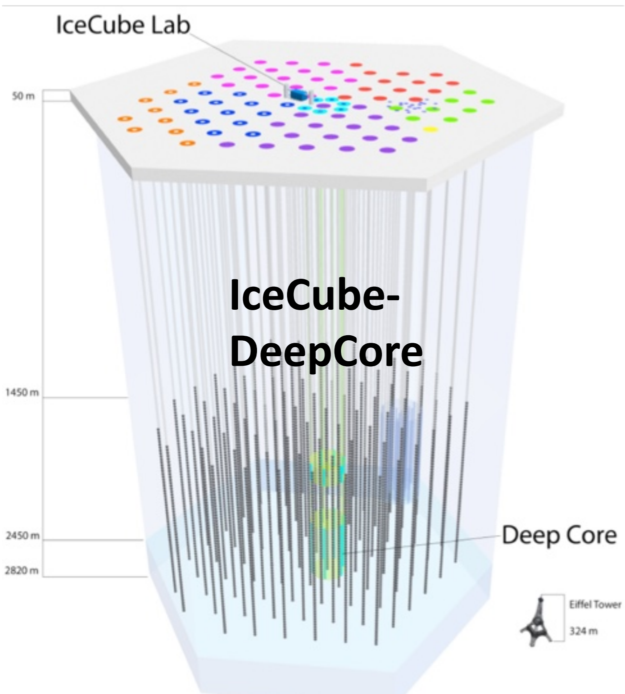
Measuring neutrino properties

Long-baseline accelerator

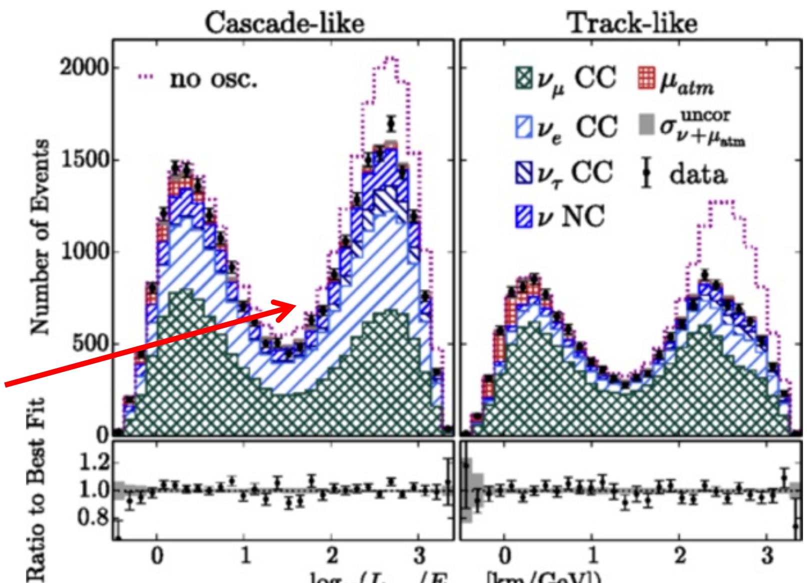
T2K



Atmospheric



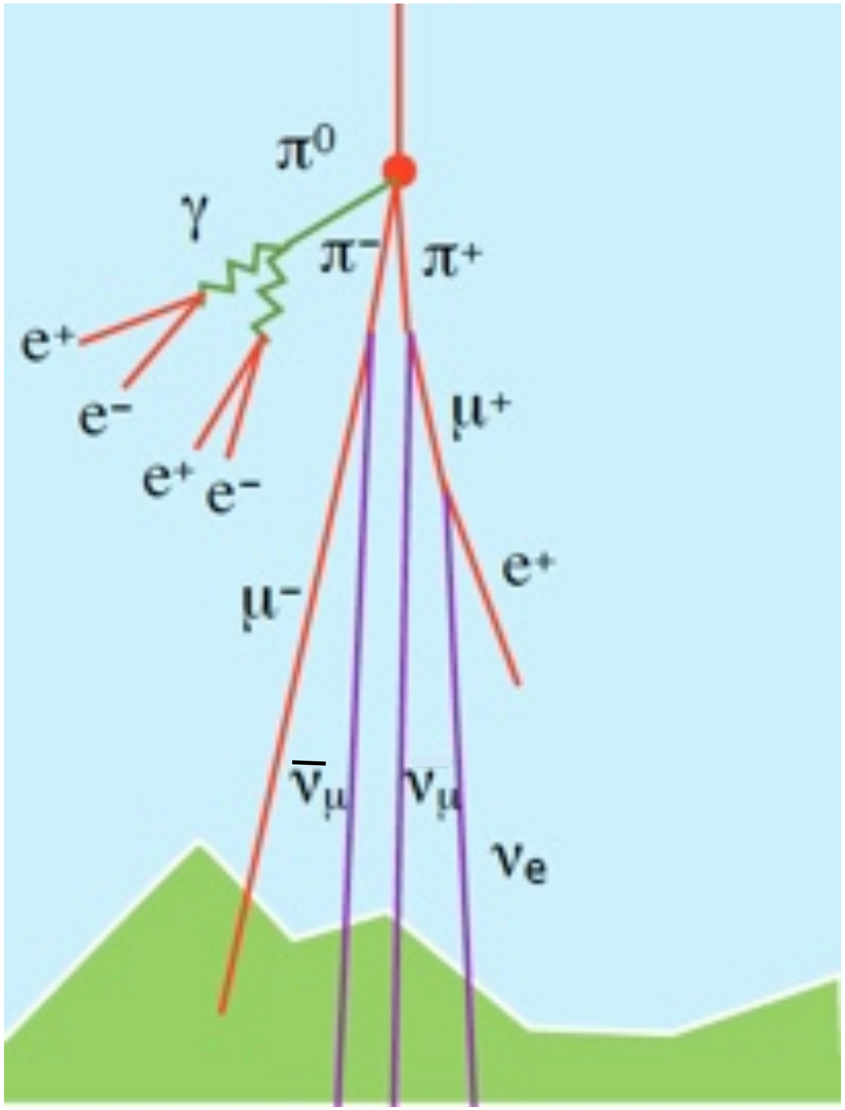
PRL **120**, 071801



Oscillation visible
in up-going peak

Atmospheric neutrinos terminology

Atmospheric shower



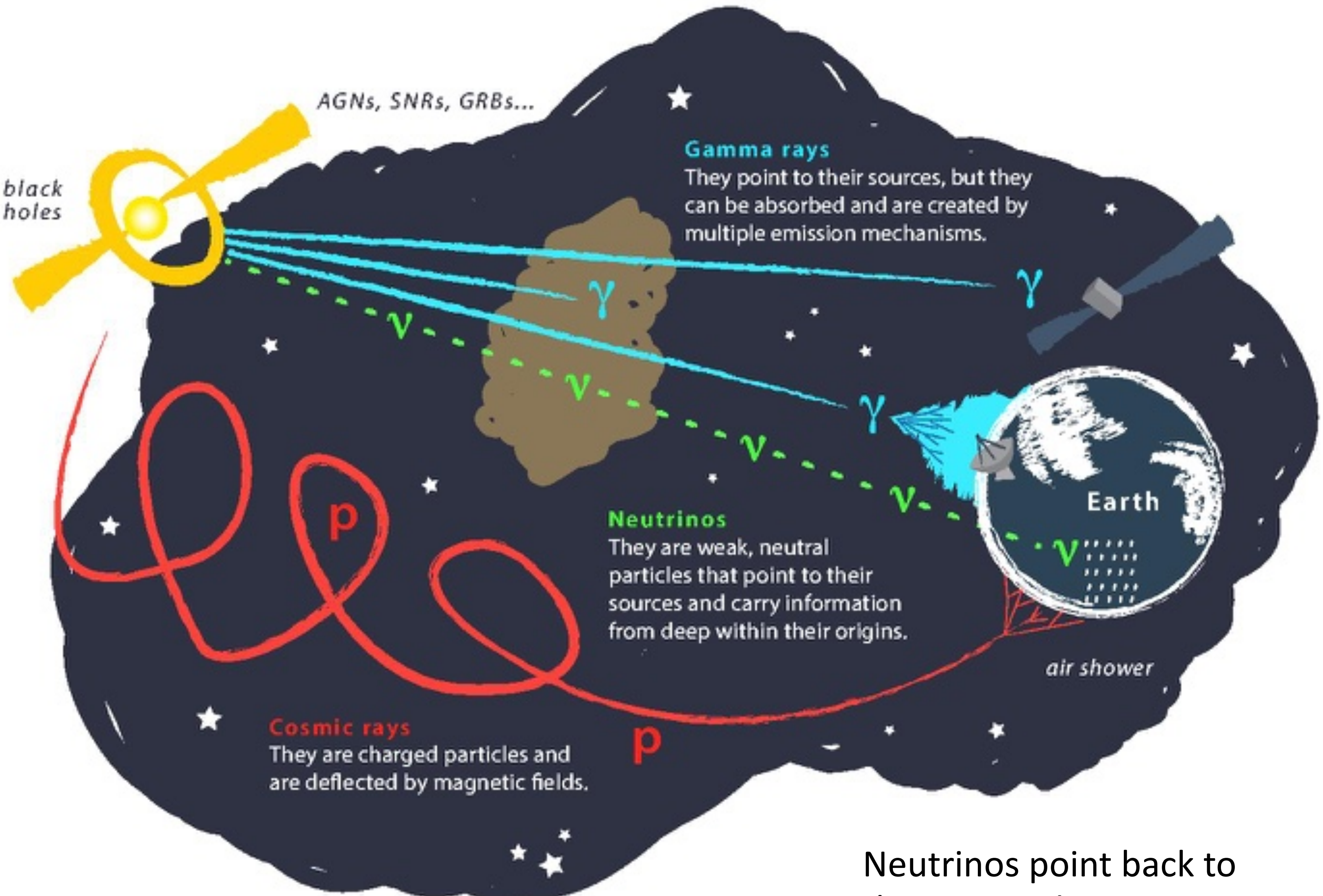
Conventional atmospheric: Parent particle is pion or kaon; longer lifetime

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!

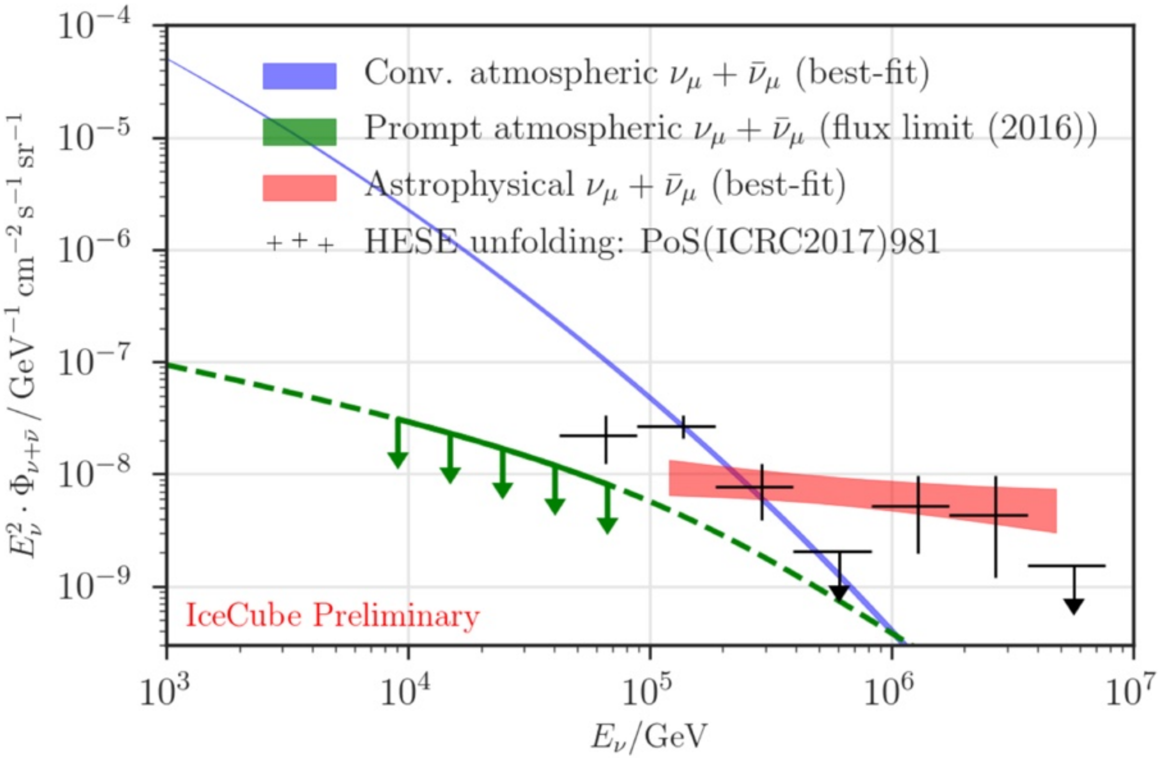
A neutrino telescope

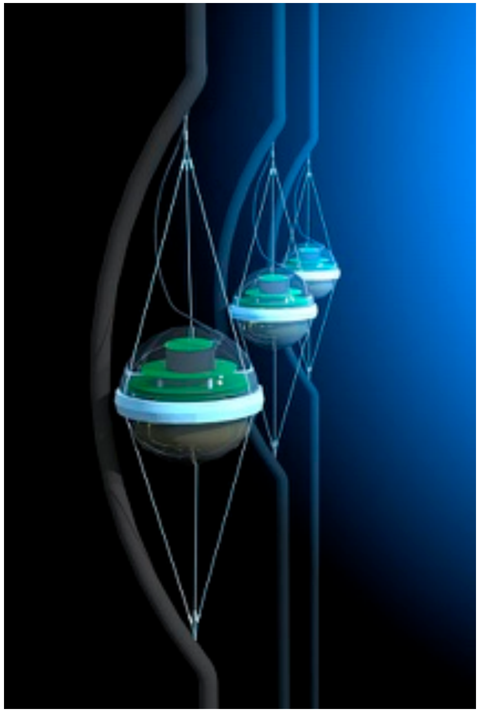
Steeply falling neutrino flux as a function of energy

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?

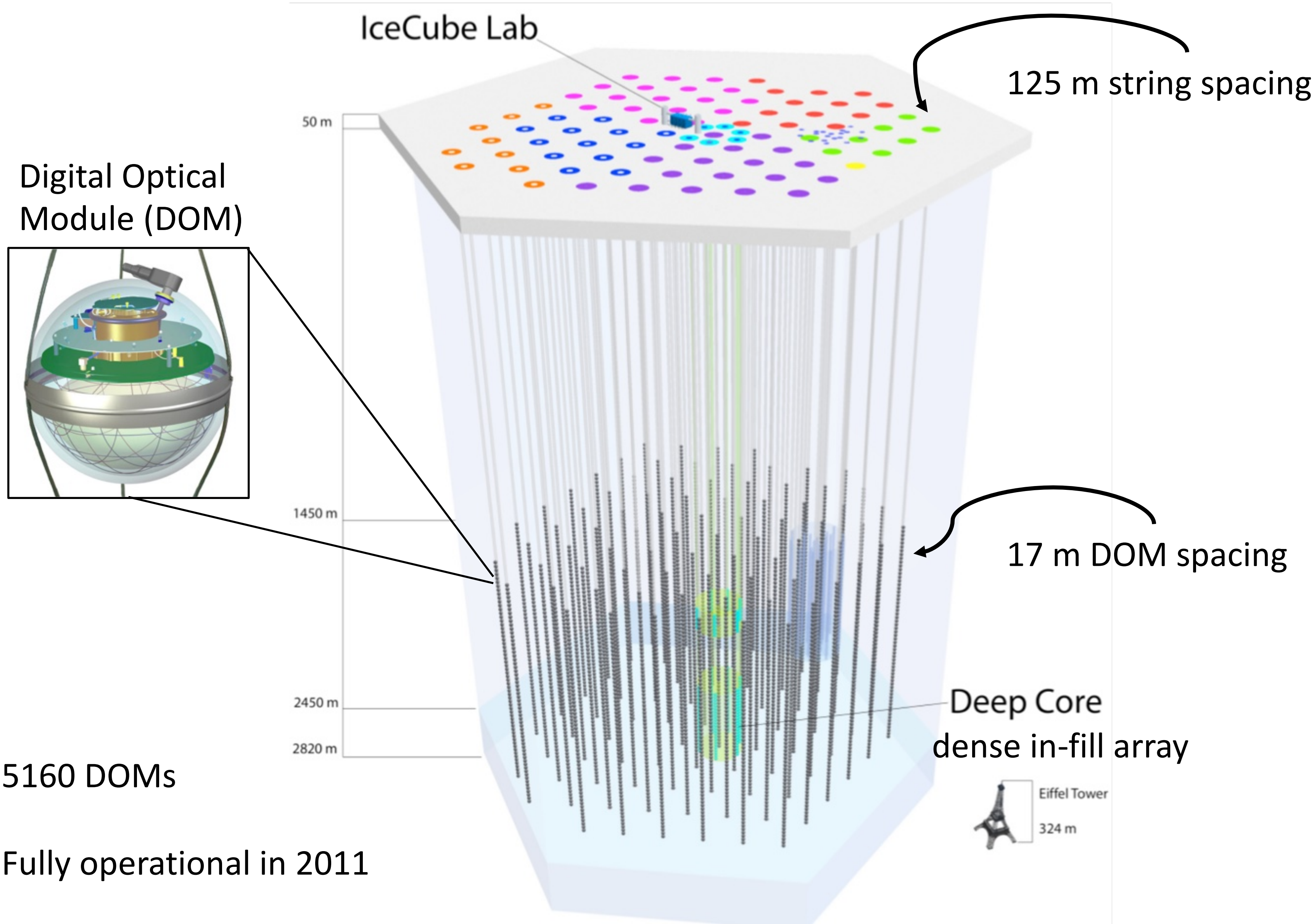
C. Haack, ICRC2017





IceCube

Digital Optical Module (DOM)



5160 DOMs

Fully operational in 2011

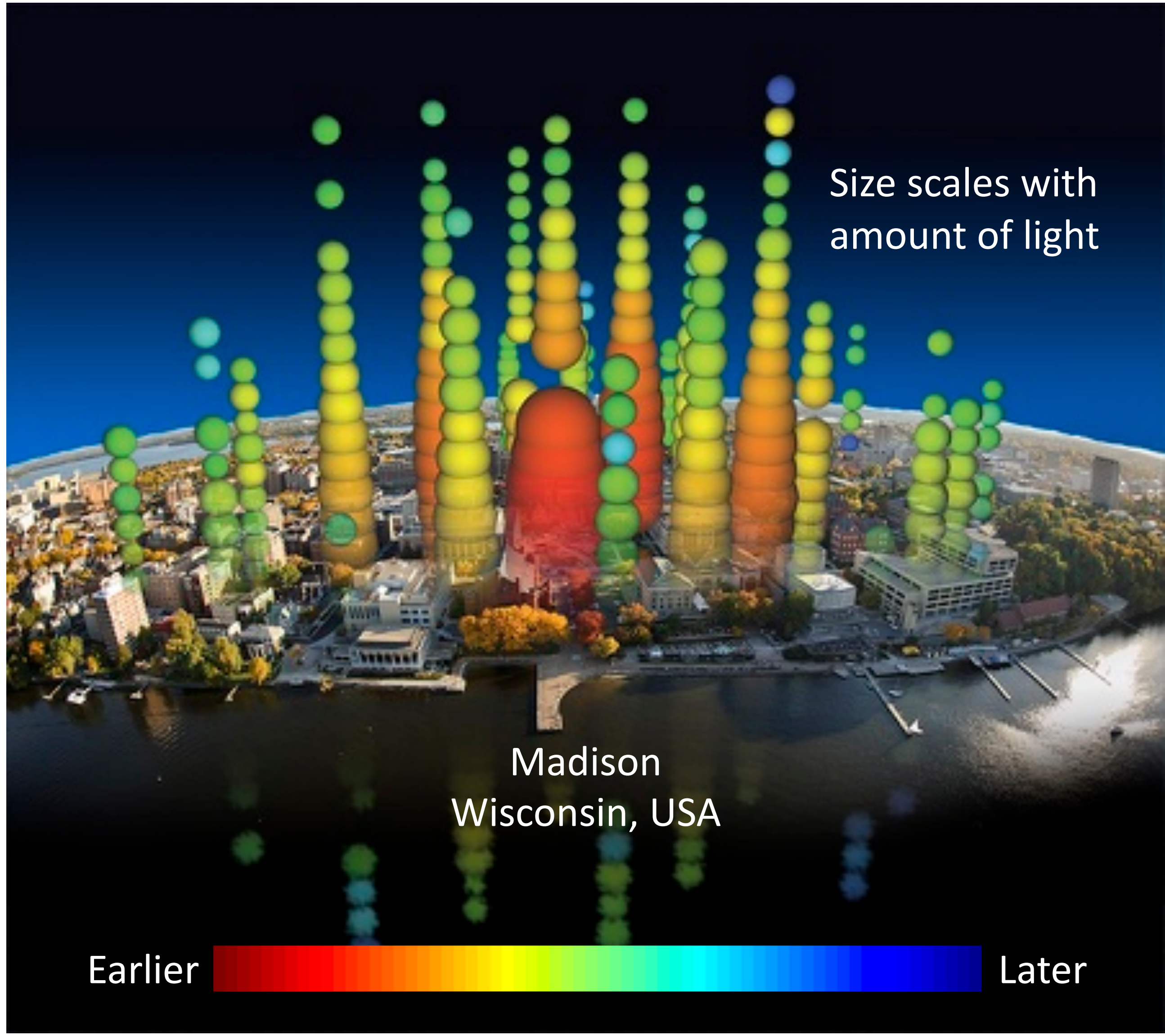
The world's largest neutrino detector

1 km^3

1 Gton of ice

Each bubble centers on a PMT

10 GeV – 10 PeV



Detection principals

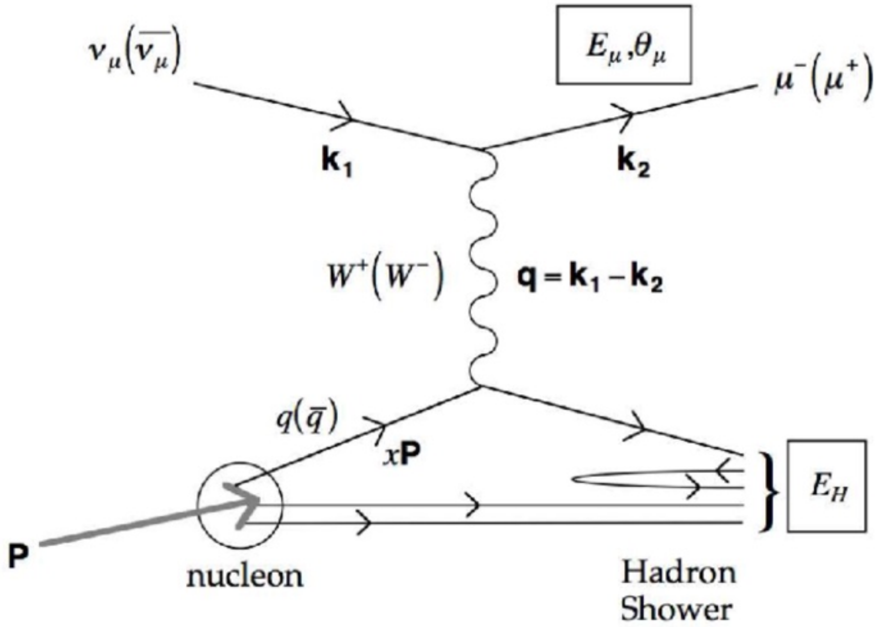
Neutrino interacts via weak force with targets in ice

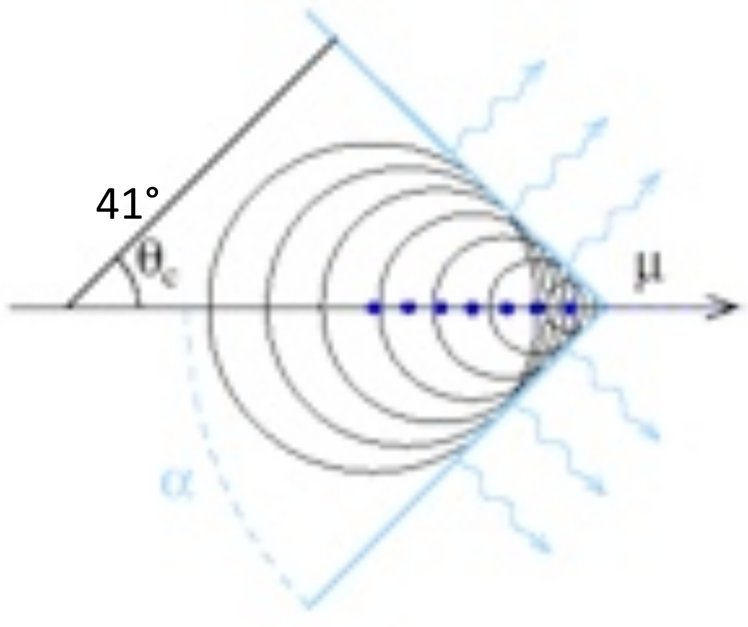
- At IceCube energies, primarily deep-inelastic scattering (DIS) off nucleons

Nucleon breaks apart; outgoing particles may be charged

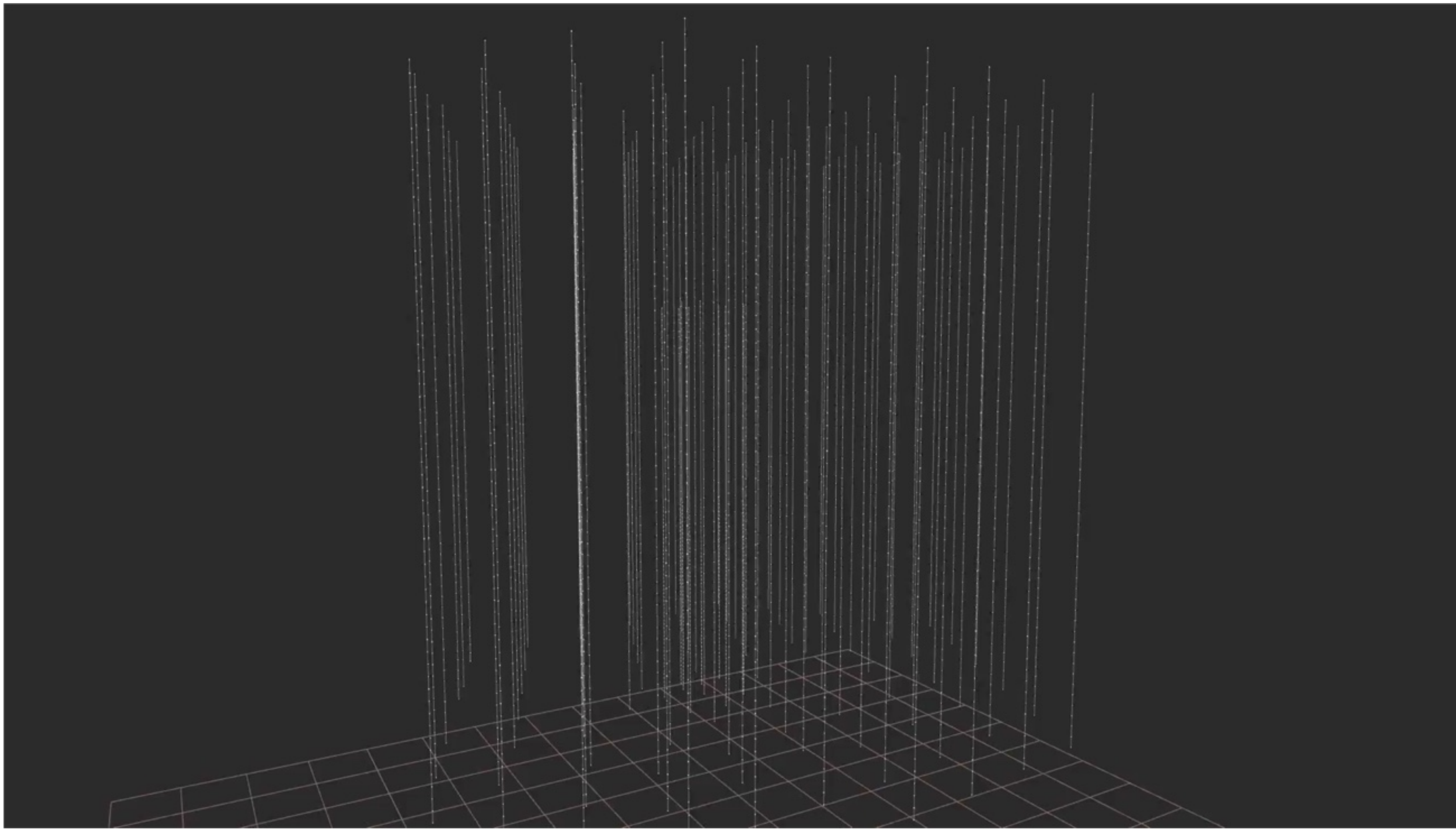
Charged particles emit Cherenkov radiation detectable by PMTs

Rev. Mod. Phys. 84, 1307



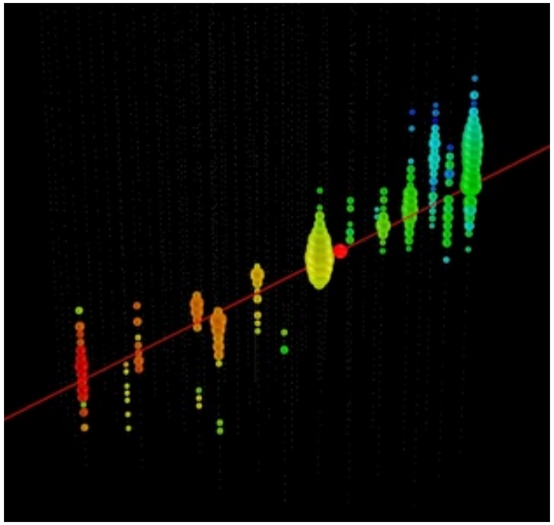


A high-energy muon in IceCube



Event topologies

CC muon neutrino

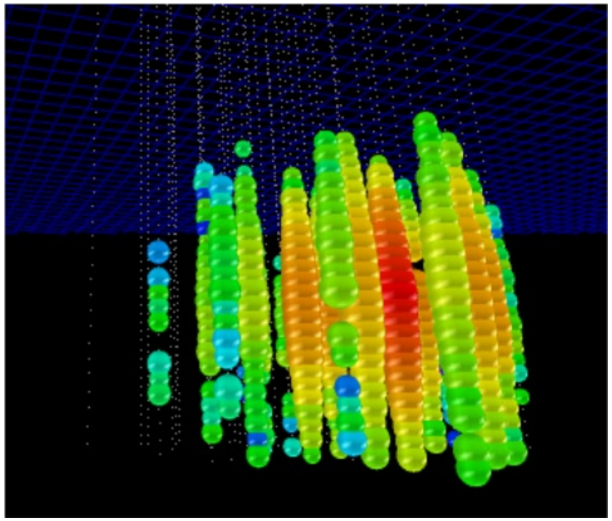


$\nu_\mu + N \rightarrow \mu + X$

track (data)

angular resolution ~ 0.5°
energy resolution ~ x2

NC or CC electron neutrino

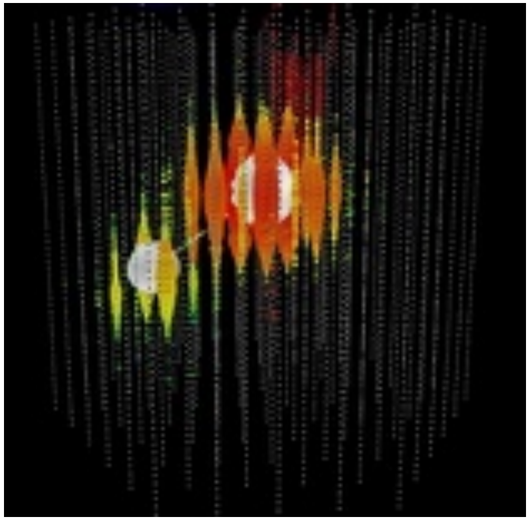


$\nu_e + N \rightarrow e + X$
$\nu_x + N \rightarrow \nu_x + X$

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

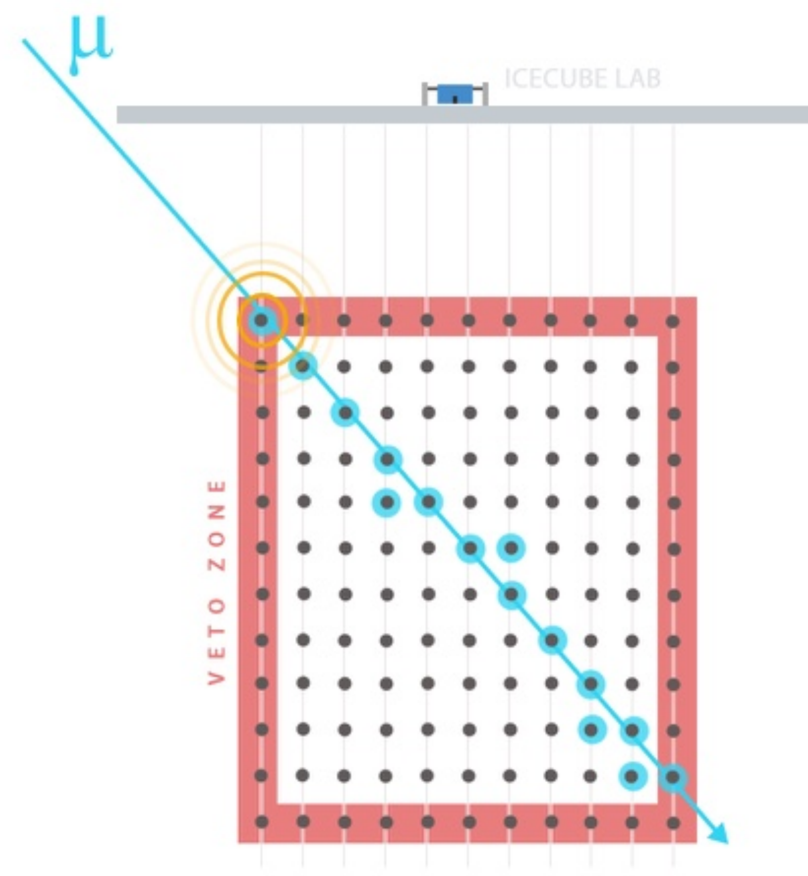
High energy starting event (HESE) selection

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



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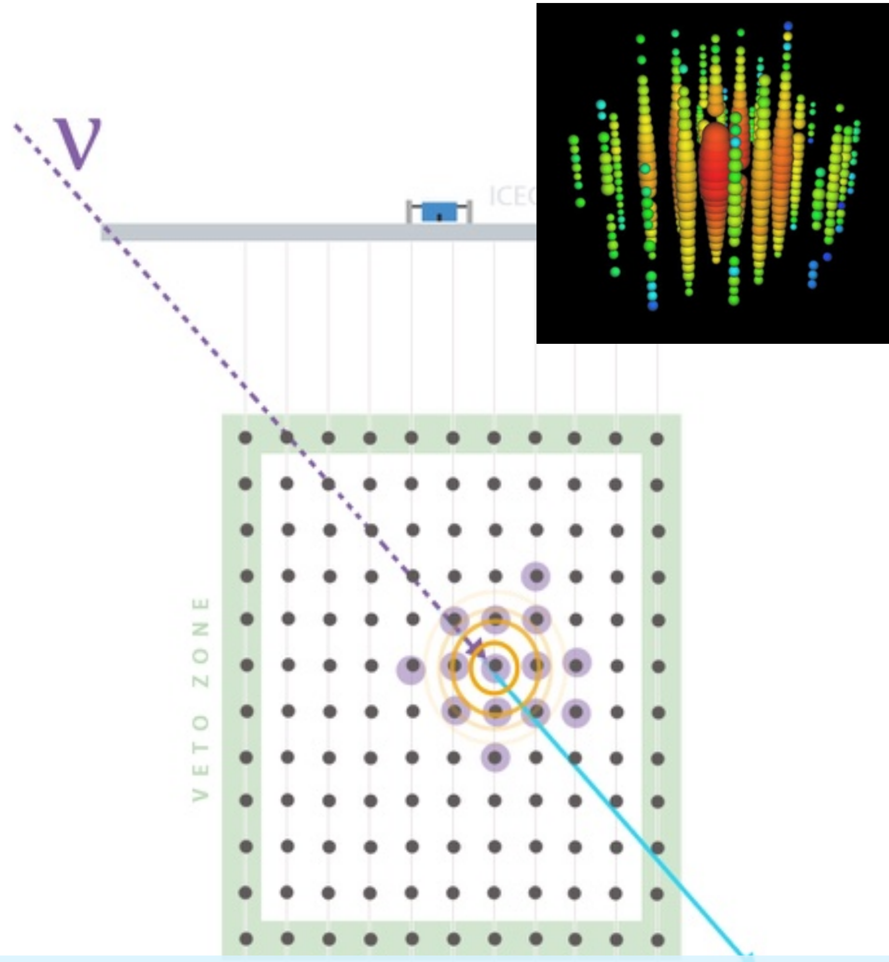


First evidence for high-energy astrophysical neutrinos (Science 2013)

Improvements for HESE with 7.5 years of data

Atmospheric neutrino flux calculation

Atmospheric neutrino passing fractions

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

- Pile-up

High stats CORSIKA is a challenge

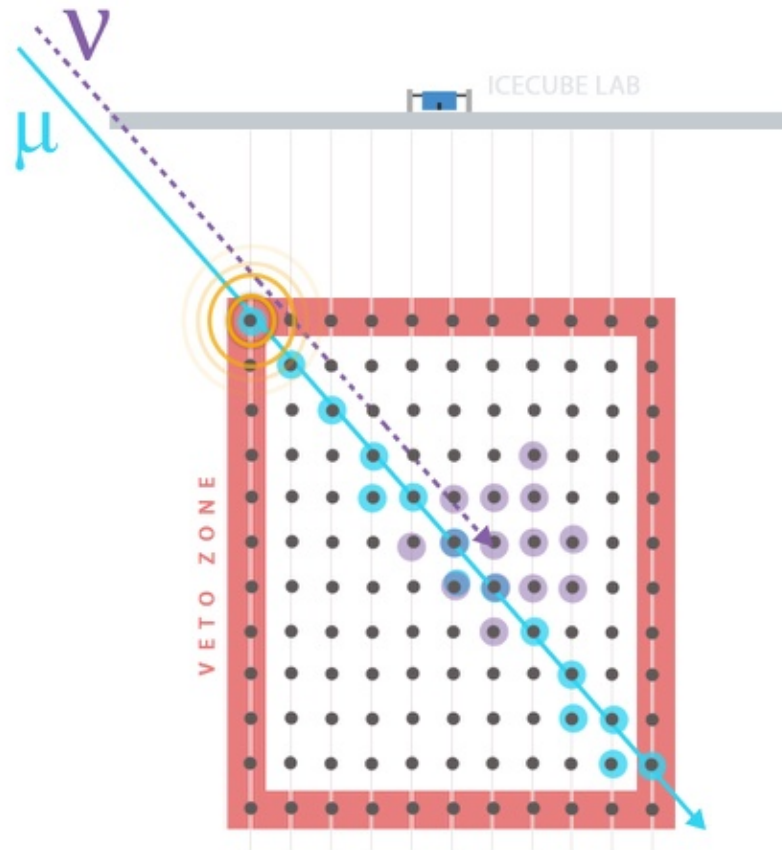
Calculate **Veto probability** correlated with energy and arrival-direction of neutrino

PRD 79 043009 (2009)

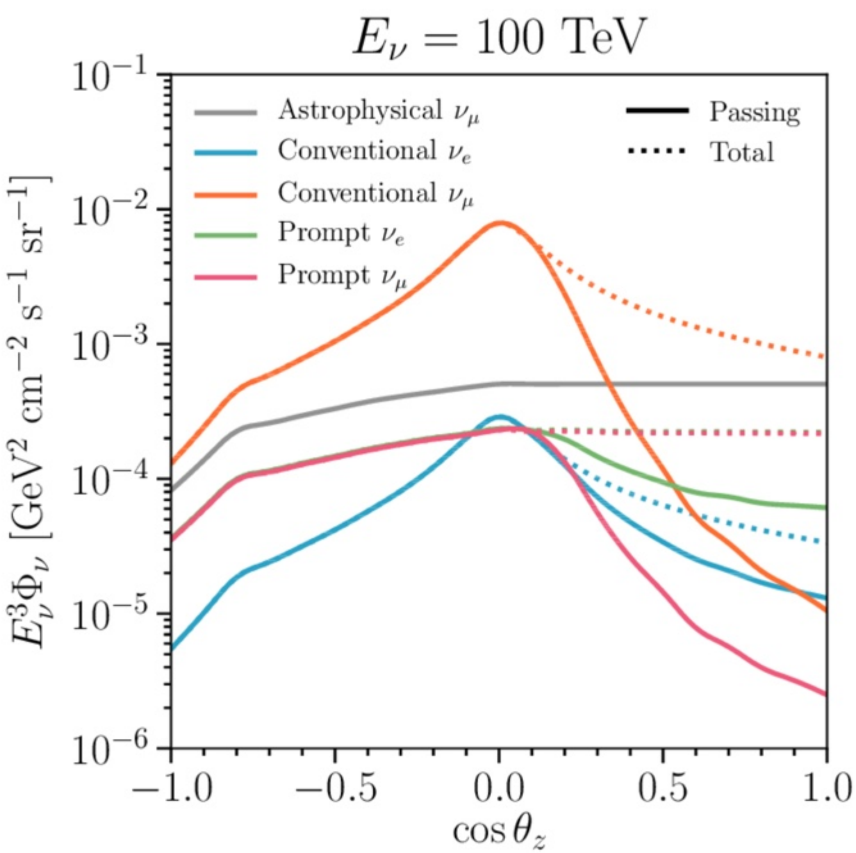
PRD 90 023009 (2014)

JCAP 1807 (2018) no.07, 047

→ Argüelles, Palomares-Ruiz, Schneider, Wille, & TY



Flux expectations vs zenith angle



Northern sky Southern sky

Passing fraction: ratio of solid to dotted lines

- $\mathcal{P}_{pass}(E_\nu, \theta_z) = \frac{\phi_\nu^{pass}(E_\nu,\theta_z)}{\phi_\nu\,(E_\nu,\theta_z)}$

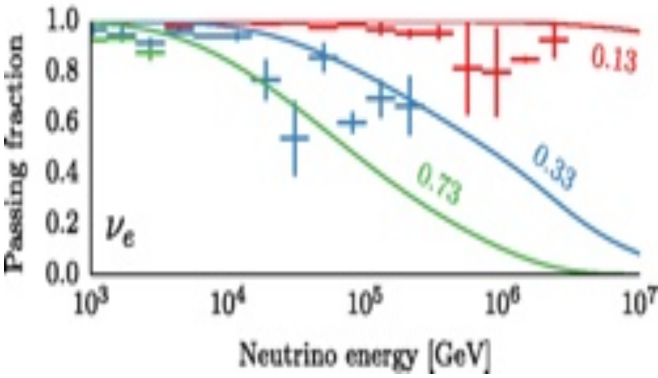
Breaks degeneracy between astrophysical and prompt fluxes

Drives current bound on prompt

Previous treatment

Fit to CORSIKA [GJKvS, PRD 90 023009 (2014)]

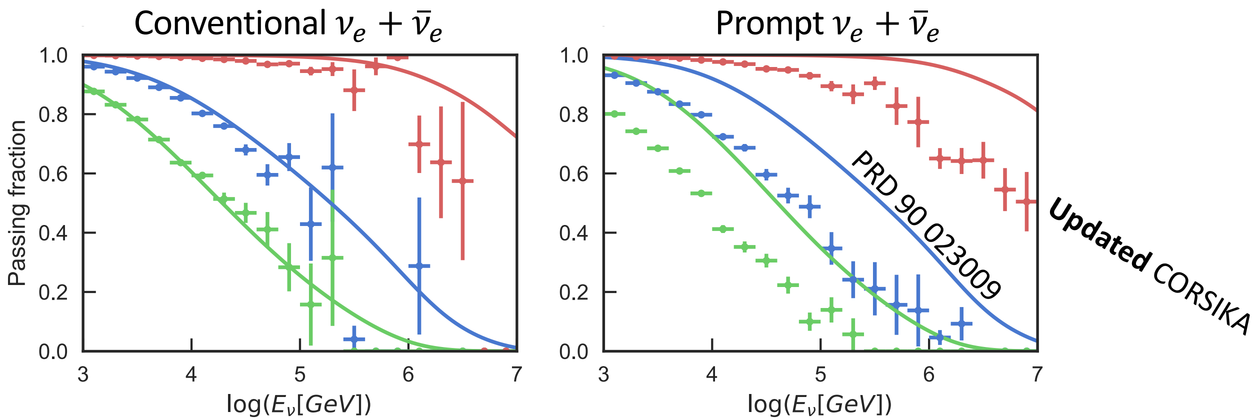
Lines: PRD 90 023009
Crosses: Outdated CORSIKA



Outdated hadronic interaction model

Several simplifying assumptions

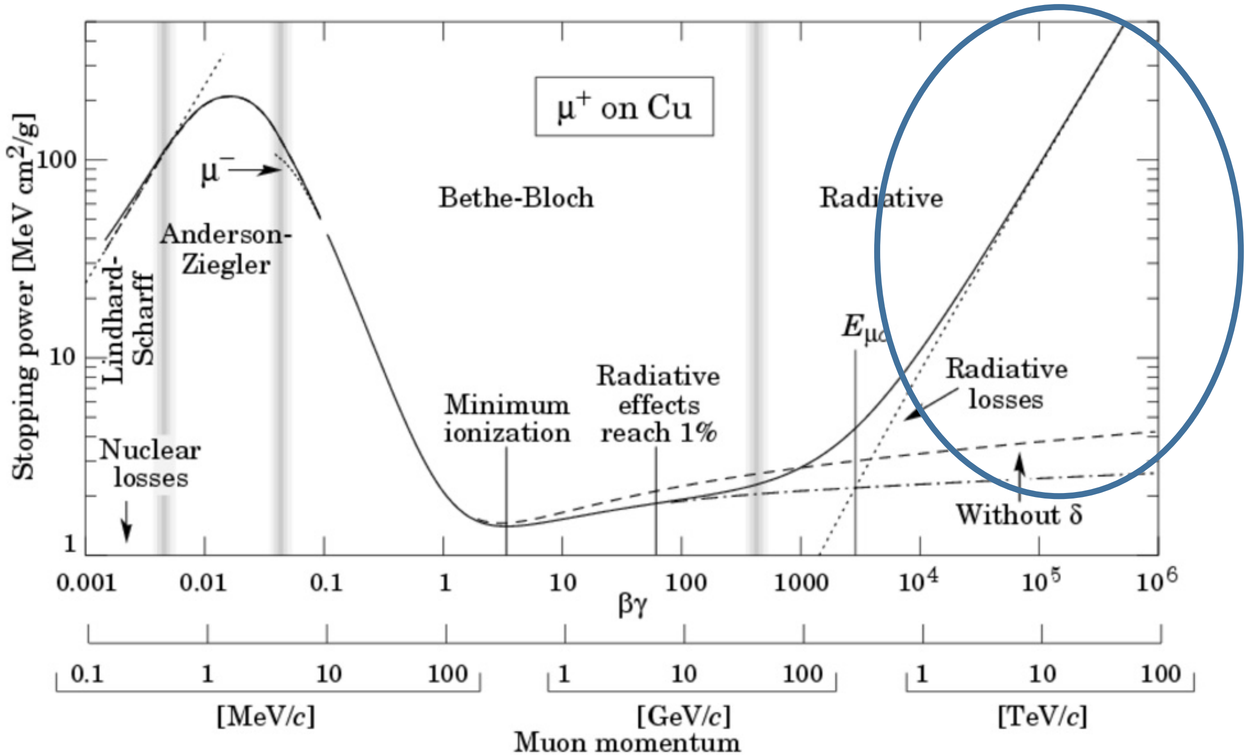
Discrepancy vs latest version of CORSIKA



Idea: Tabulate physics quantities and calculate. No more fit.

Example: Muon range

Veto is triggered by muons → Ask how likely an atmospheric muon is to reach the detector

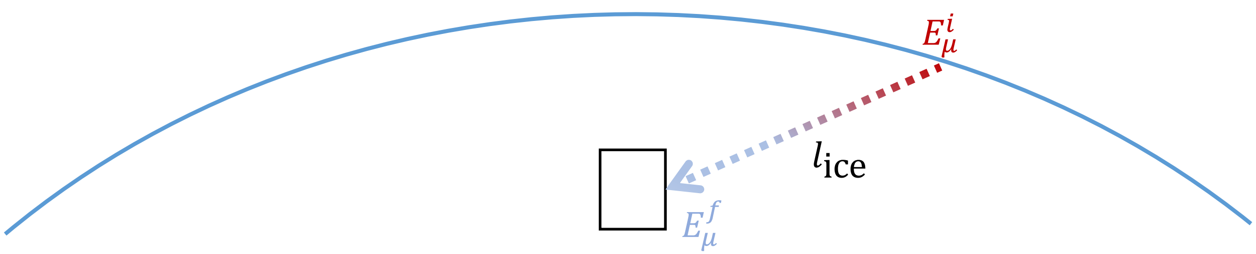


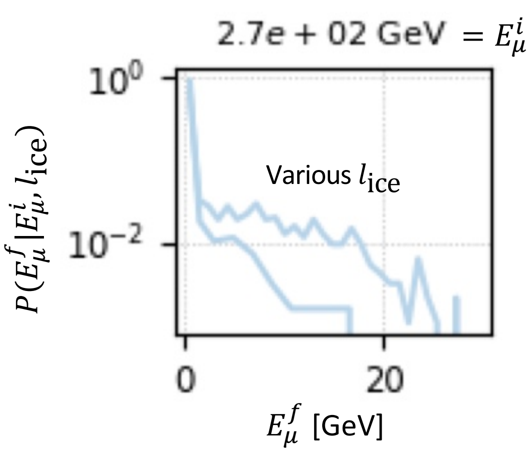
At high energies, muon is no longer minimum ionizing

Stochastic energy losses become important

Muon range pdfs

Need to evaluate $\mathcal{P}_{reach}(E_\mu^f | E_\mu^i, l_{\text{ice}})$, 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



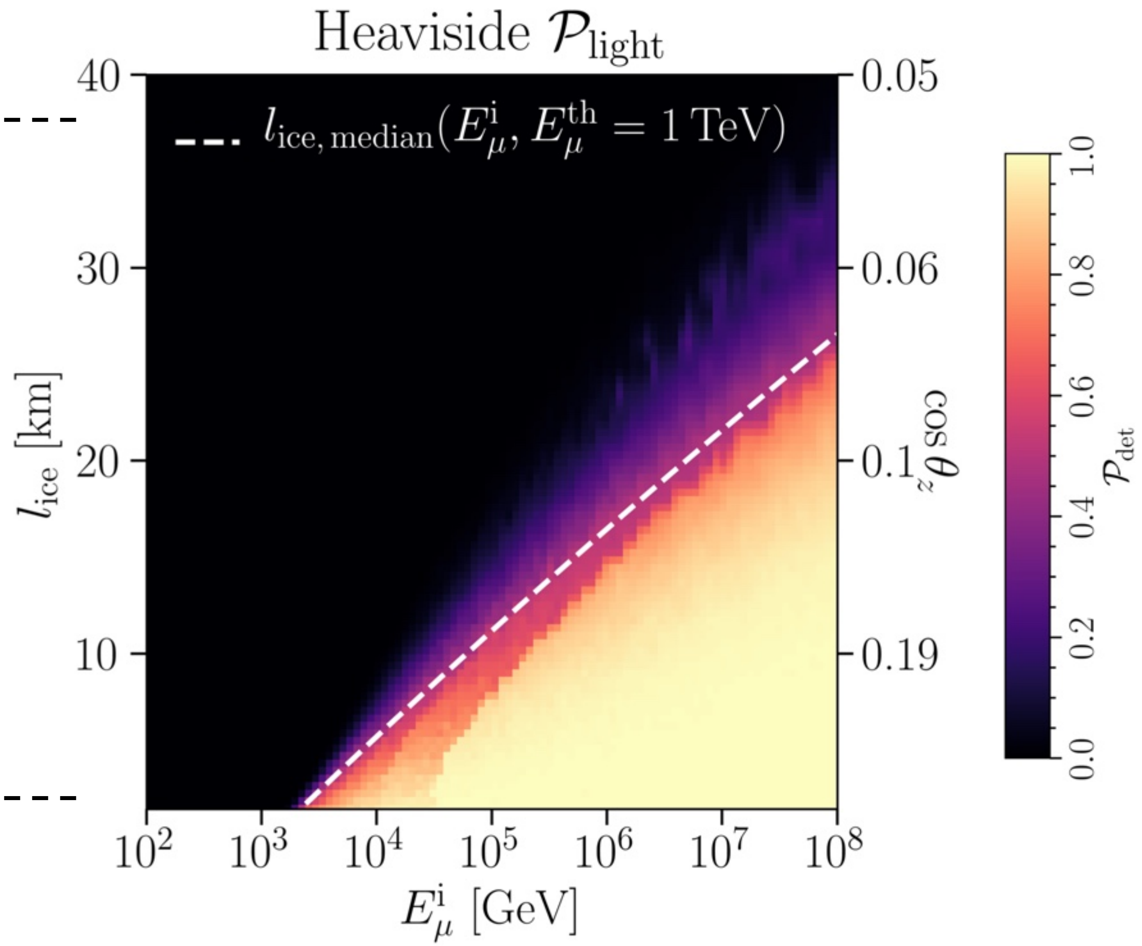


Detection probability

$$\mathcal{P}_{\rm det}\left(E_\mu^{\rm i},\, X_\mu(\theta_z)\right) \equiv \int dE_\mu^{\rm f}\, \mathcal{P}_{\rm reach}\left(E_\mu^{\rm f} \,|\, E_\mu^{\rm i},\, X_\mu(\theta_z)\right)\, \mathcal{P}_{\rm light}(E_\mu^{\rm f})$$

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

Convolute with detector response, $\mathcal{P}_{light}(E_\mu^f)$, to get detection probability

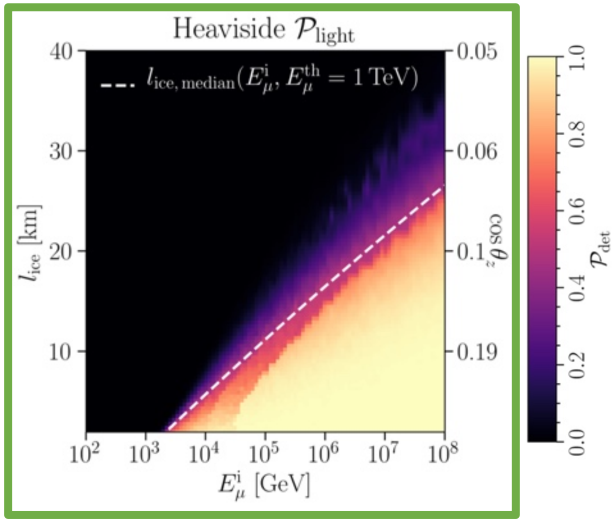


Unified treatment

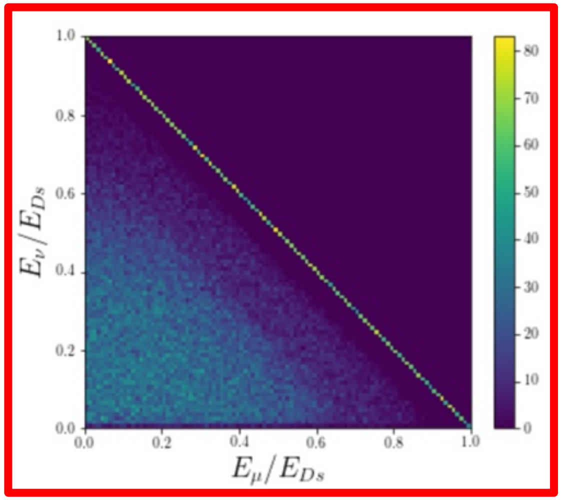
JCAP 1807 (2018) no.07, 047

Removes many approximations from previous treatments

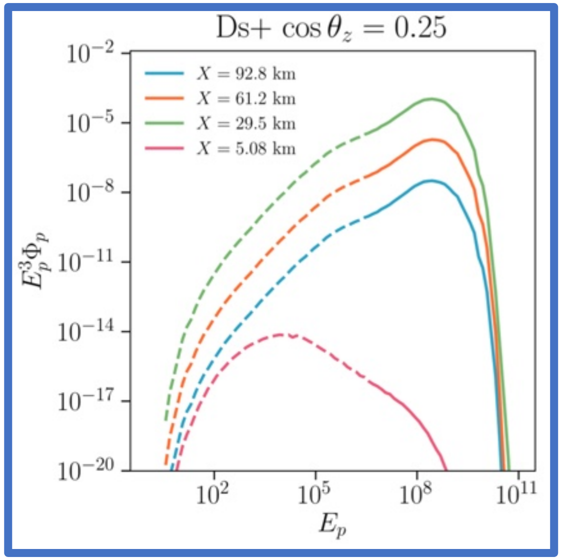
Use tabulated distributions; faster than full MC



Muon-range from **MMC**
[arXiv:hep-ph/0407075]



n-body decays from **Pythia 8.1**
[CPC 178, 852-867]



Fluxes and yields from **MCEq**
[PoS ICRC2015 (2016) 1129]

$$\mathcal{P}_{\rm pass}(E_\nu,\theta_z) = \frac{1}{\phi_\nu(E_\nu,\theta_z)} \sum_A \sum_p \int dE_p \int \frac{dX}{\lambda_p(E_p,X)} \int dE_{\rm CR} \frac{dN_{p,\nu}}{dE_\nu}(E_p,E_\nu)\,\frac{dN_{A,p}}{dE_p}(E_{\rm CR},E_p,X)\,\phi_A(E_{\rm CR})$$
$$\times\, \mathcal{P}^{\rm sib}_{0\text{-}\mu}(\theta_z|E_p,E_\nu)\, \mathcal{P}^{\rm shower}_{0\text{-}\mu}\left(N_\mu = 0; \bar{N}_{\mu,A}(E_{\rm CR}-E_p,\theta_z)\right),$$

Correlated, sibling muon

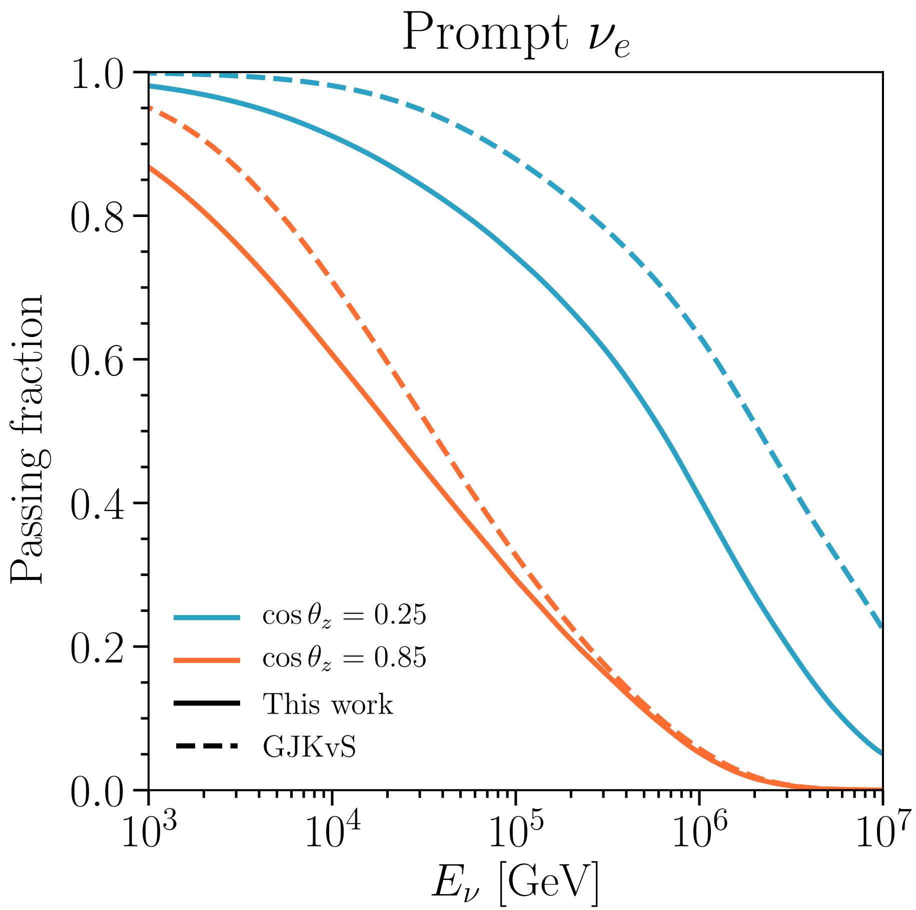
Uncorrelated, proto. shower muons; Poisson

Comparison against previous calculation

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

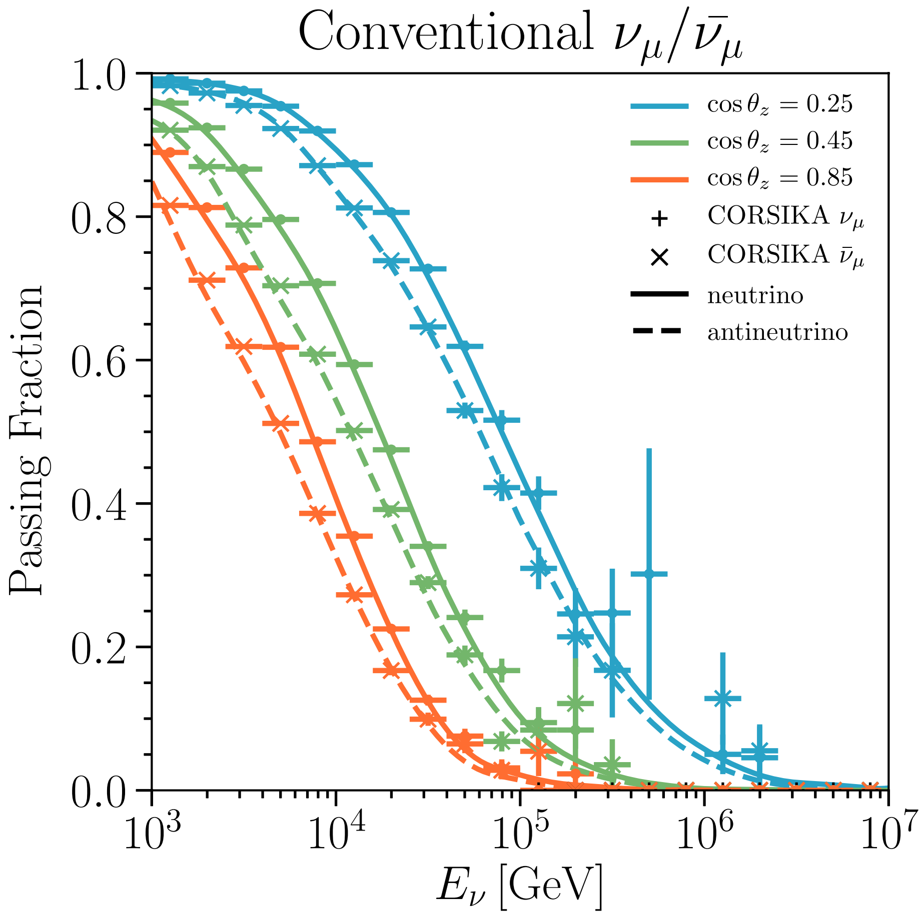
Verification against CORSIKA w. SIBYLL 2.3

Under the same settings as CORSIKA, recover the same atmospheric passing fractions

Excellent agreement for both neutrino and antineutrino

No fitting performed!

νeto obviates need for high-statistics CORSIKA!

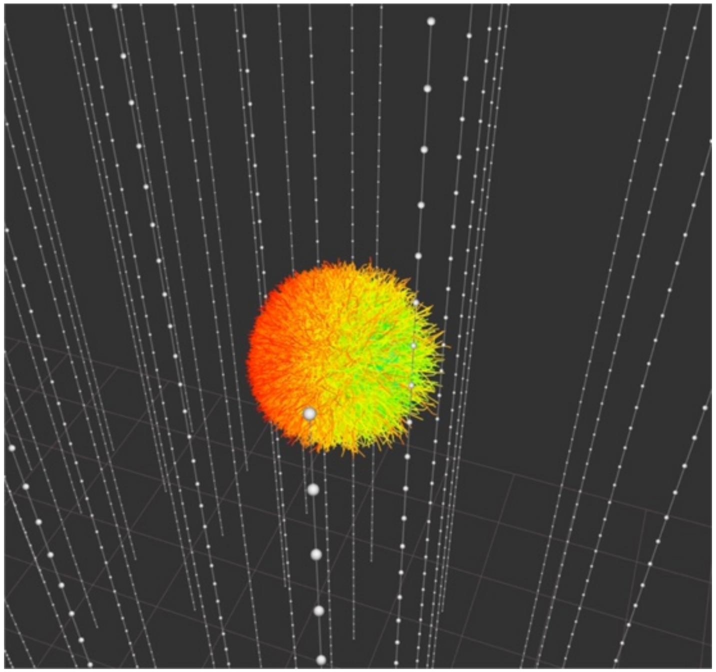


Improvements for HESE with 7.5 years of data

Improved ice model for reconstruction

Event reconstruction

Emitted

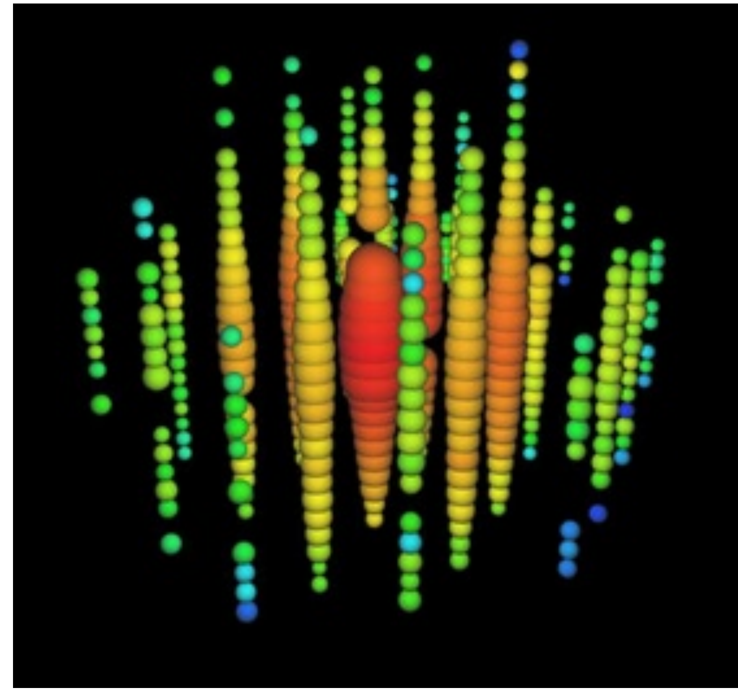


Asymmetry in photon emission helps with directional reconstruction

Information loss

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

Detected



Physics model (emission, absorption, scattering)

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

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

Maximize $\mathcal{L}(\boldsymbol{\Theta}|\mathrm{X_{Data}})$

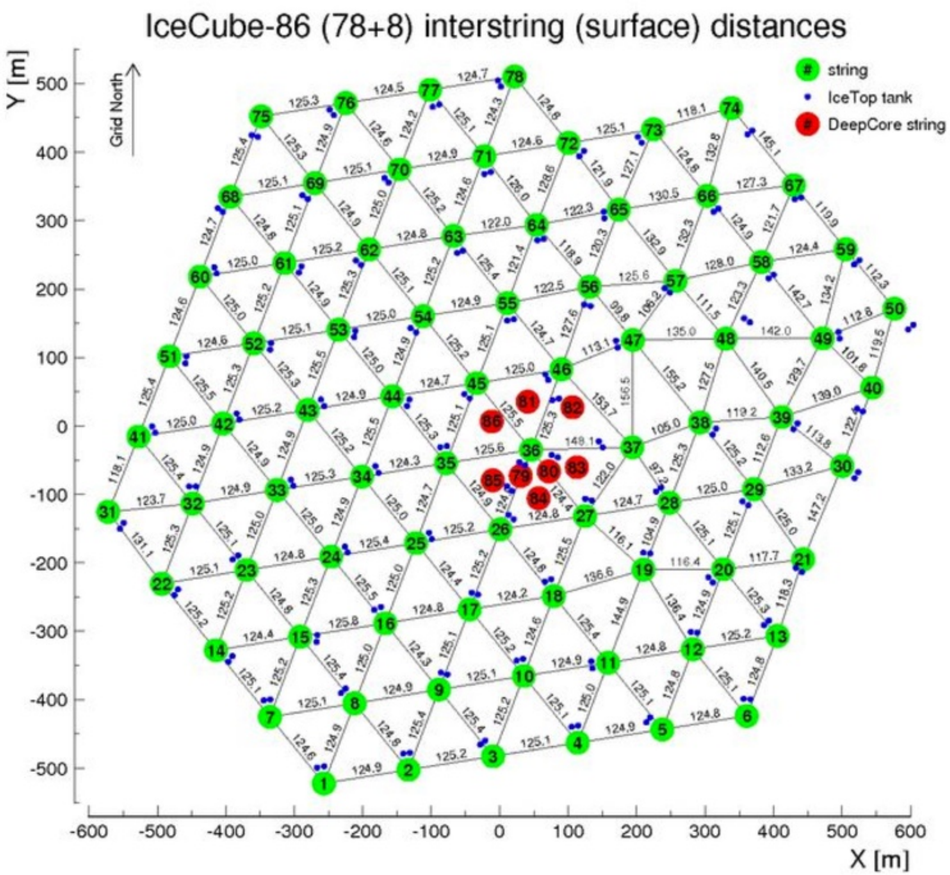
Physics parameters and IceCube coordinates

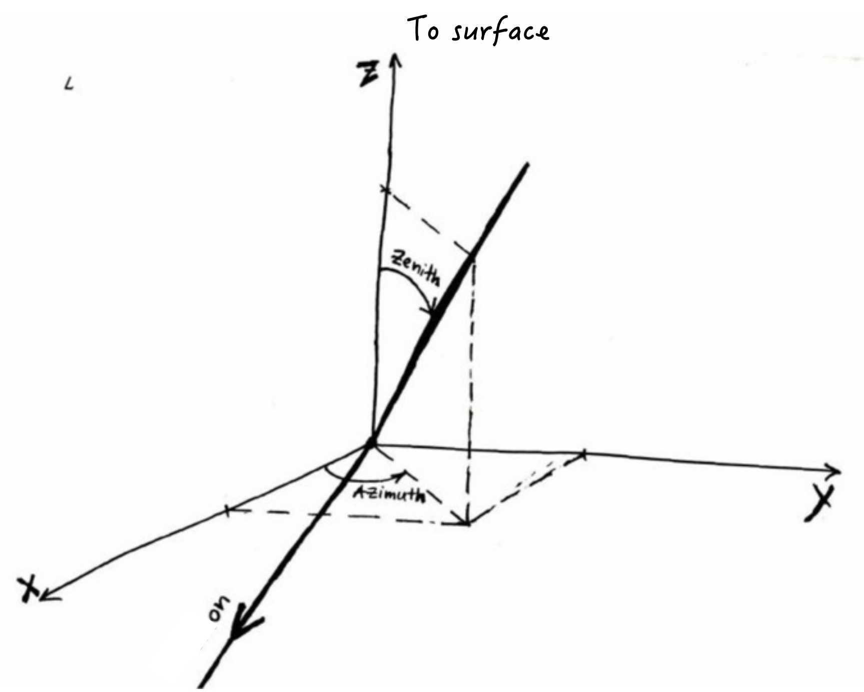
$$\mathbf{\Theta} = (x, y, z, \theta, \phi, E, t)$$

Detector coordinate system centered in middle of detector

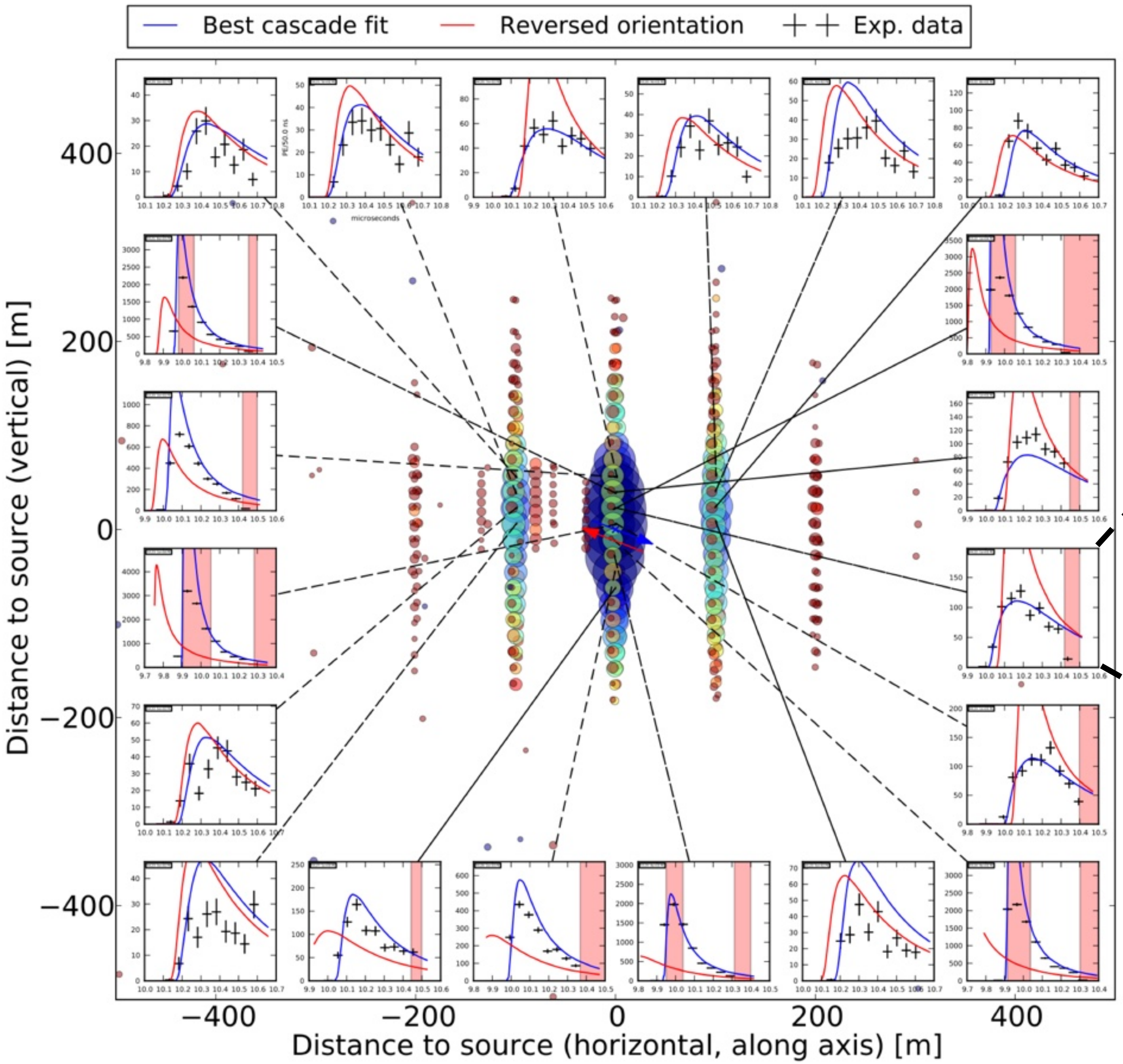
(θ, ϕ) = (zenith, azimuth) corresponds to *arrival* direction

Usually, (θ, ϕ, E) are the physics parameters we're most interested in

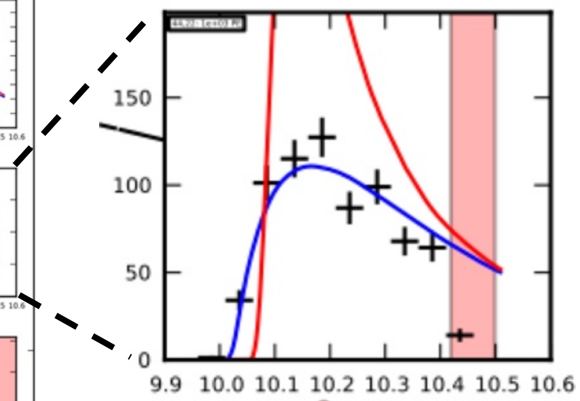




Cascade orientation from PMT waveforms



Differences between best-fit and reversed-orientation from Monopod



Time-windows where PMT saturates or calibration failed are shaded

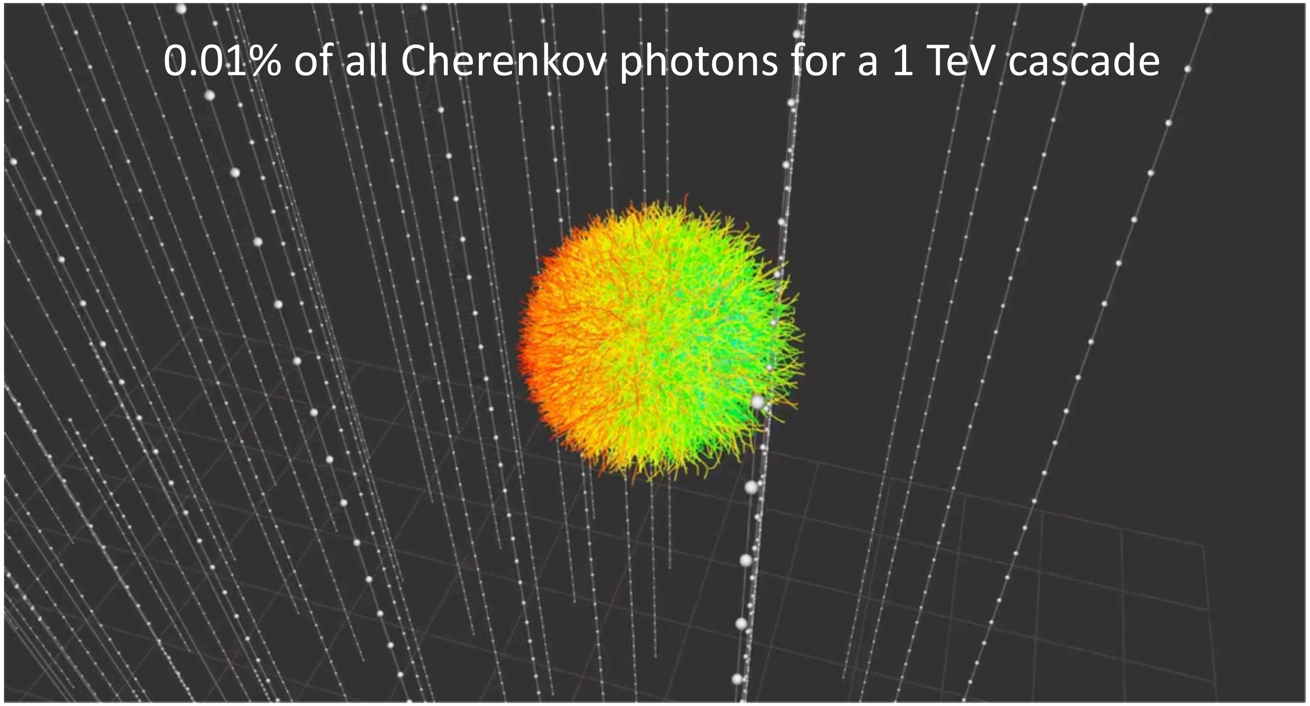
Challenges in cascade reconstruction

Large distances between DOMs means not many detected photons

Small asymmetry means high dependence on ice modeling

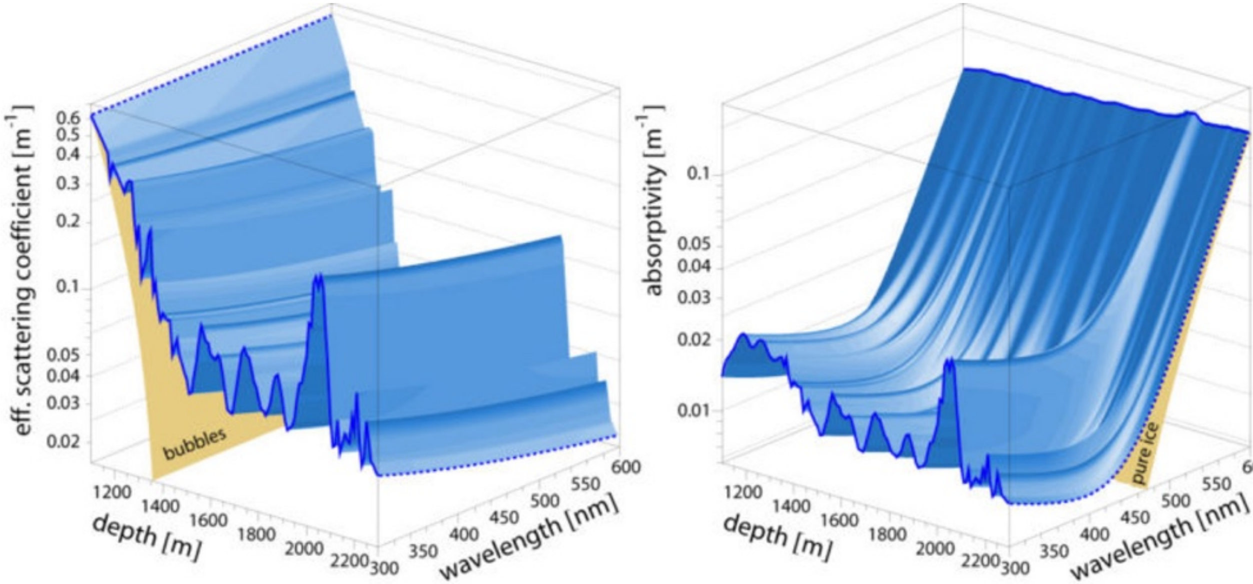
Sheer number of photons difficult to simulate

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



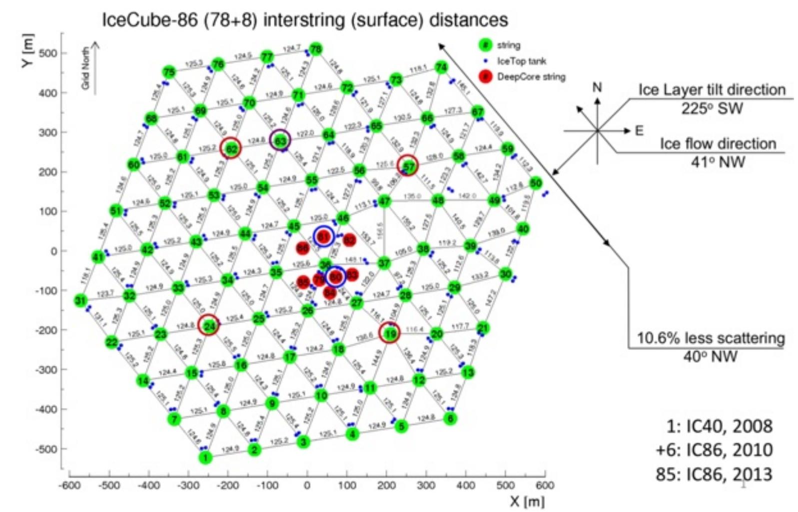
Bulk ice properties in brief

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



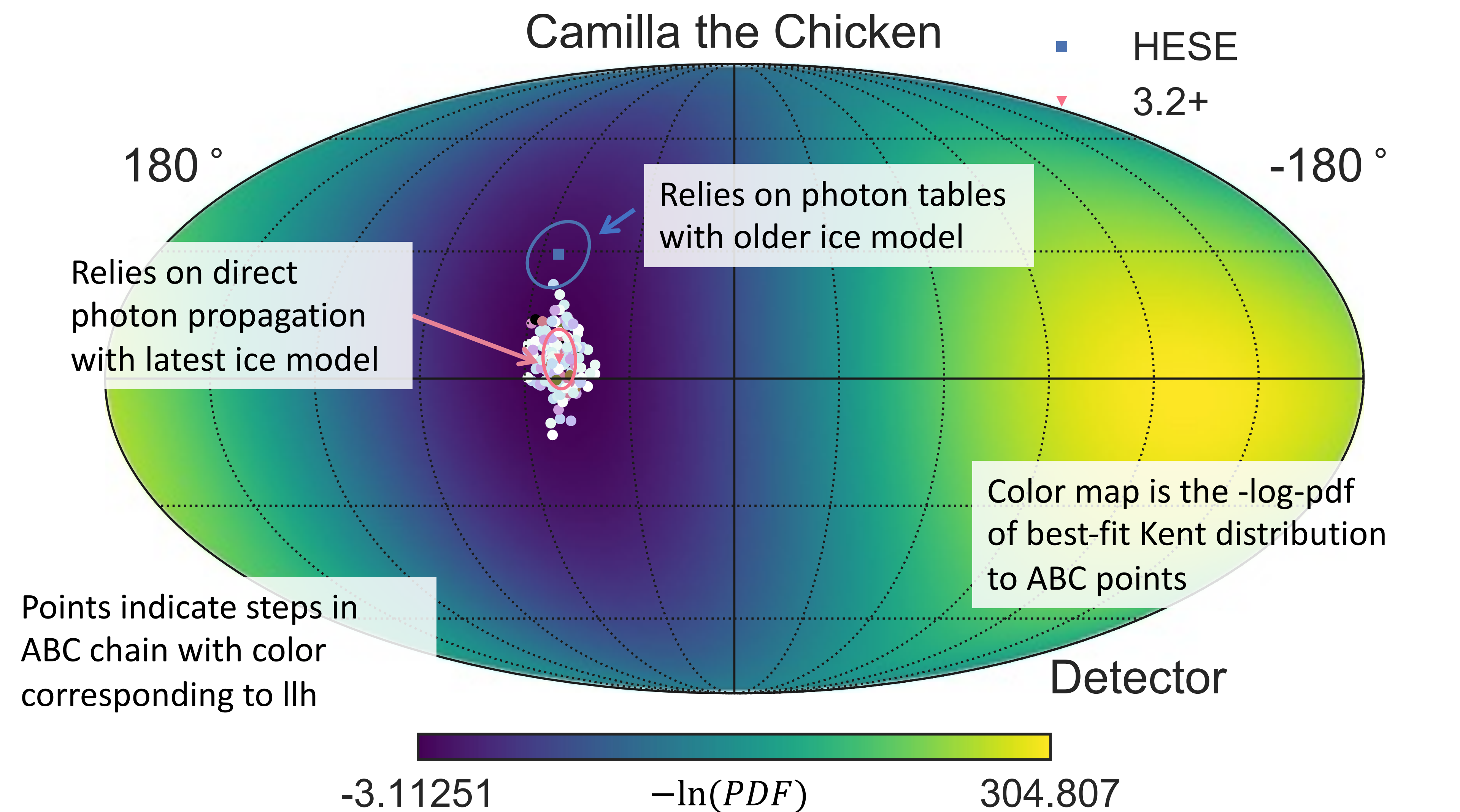
Ice layers were found to be tilted [arXiv:1301.5361]

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



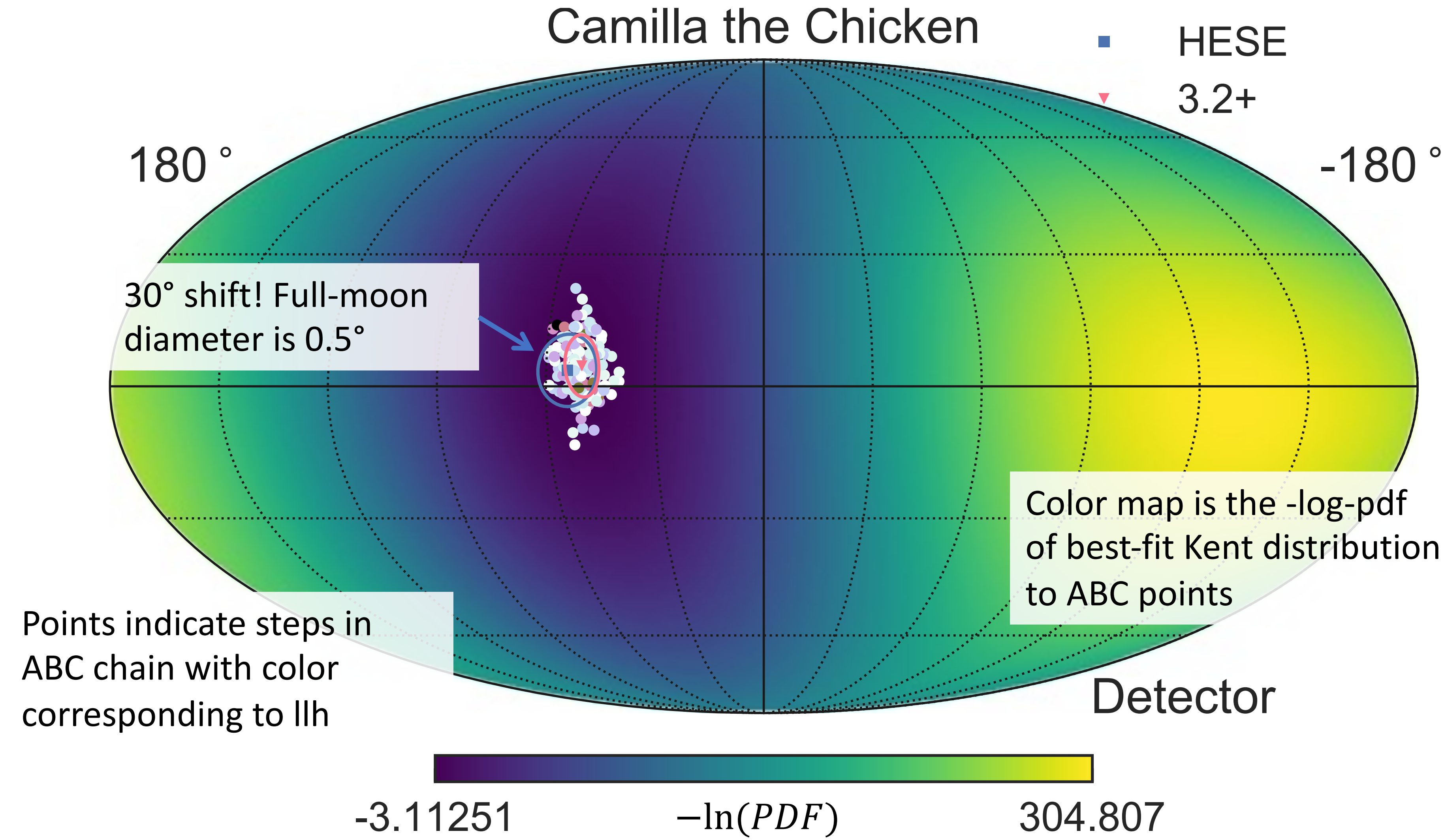
Directional bias due to different ice models

Previous HESE reconstruction uses photon tables for older ice model



Improved directional reconstruction

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



Results from HESE-7.5

Diffuse・Point source・Cross section・ Flavor composition・ BSM・Dark matter

Event distribution in HESE-7.5

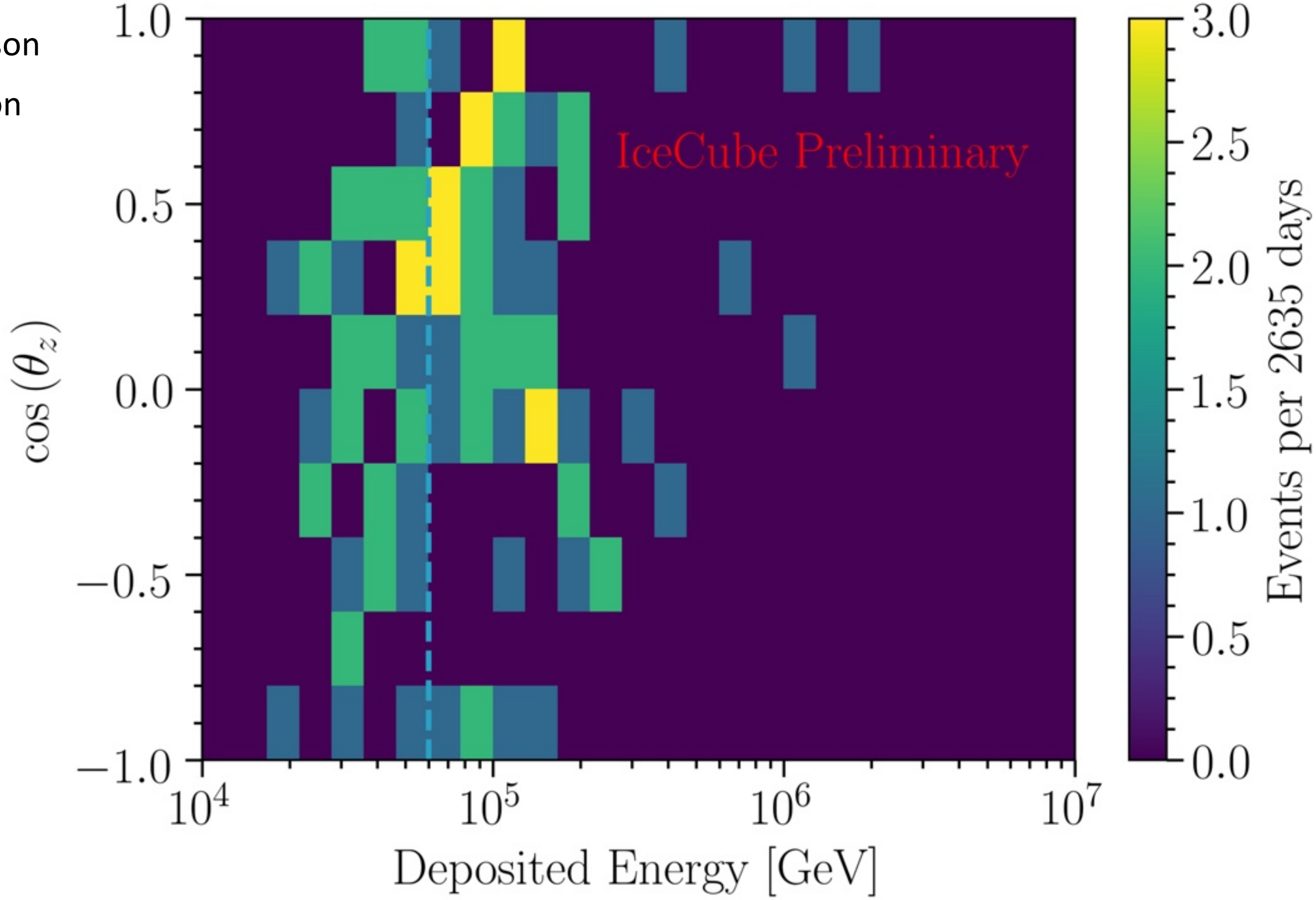
103 events, with **60 events >60 TeV**

Fitting performed for events above 60 TeV

Above 60 TeV

12 new events in 2016 season

4 new events in 2017 season



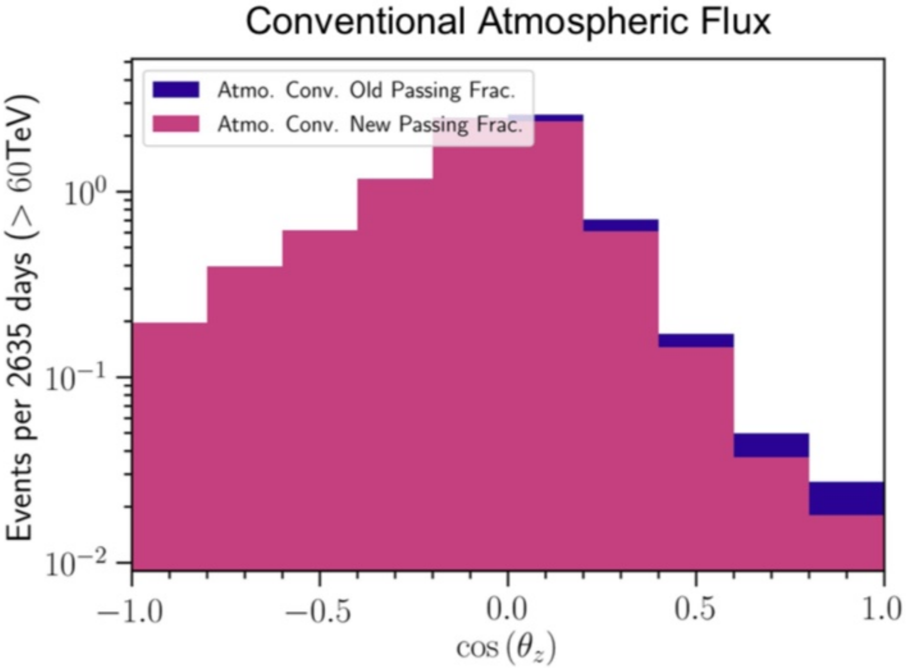
Effect of new passing fractions

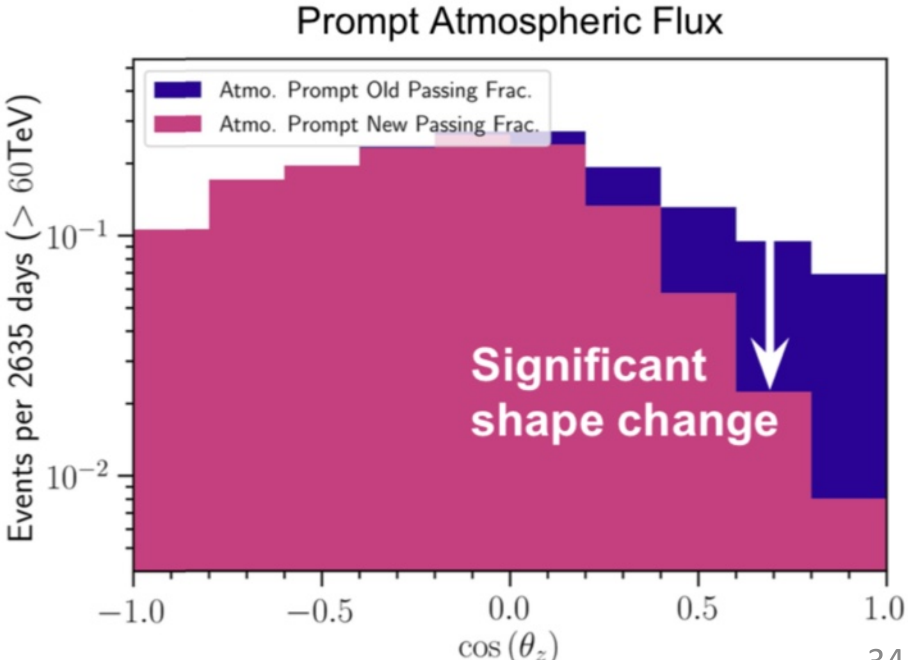
MC templates for

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

New passing fractions affect template shapes

Nominal, pre-fit expectations





Diffuse flux

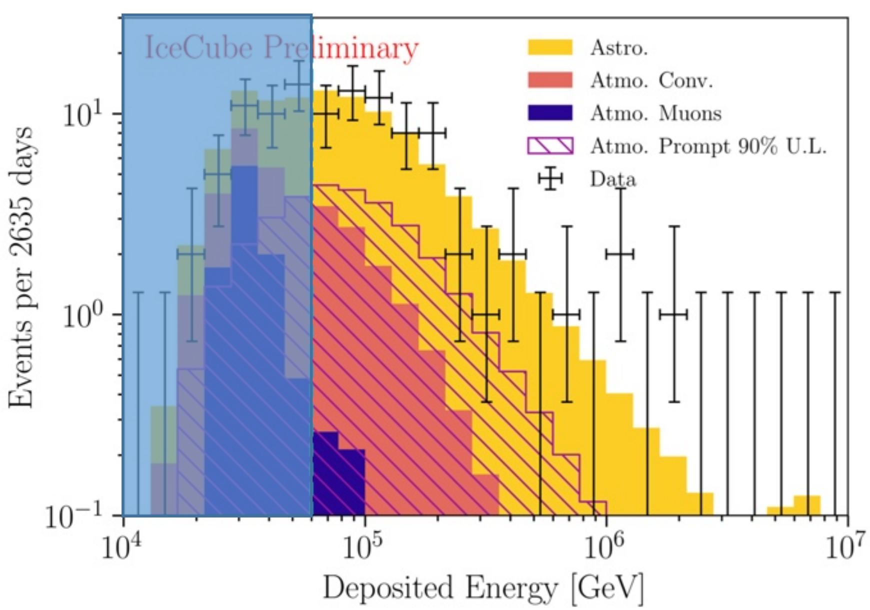
Forward-folded fit in zenith and energy

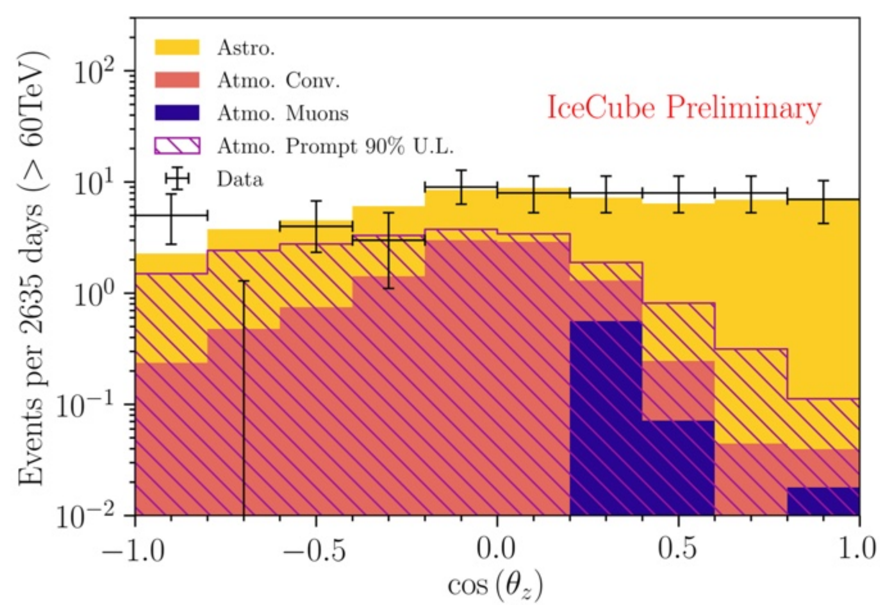
Best-fit single-power-law: $E^2\Phi = 2.19\times10^{-18}\left(\frac{E}{100\text{ TeV}}\right)^{-0.91}$ [GeV cm^{-2}s^{-1}sr^{-1}]

Prompt atmospheric best-fit → 0

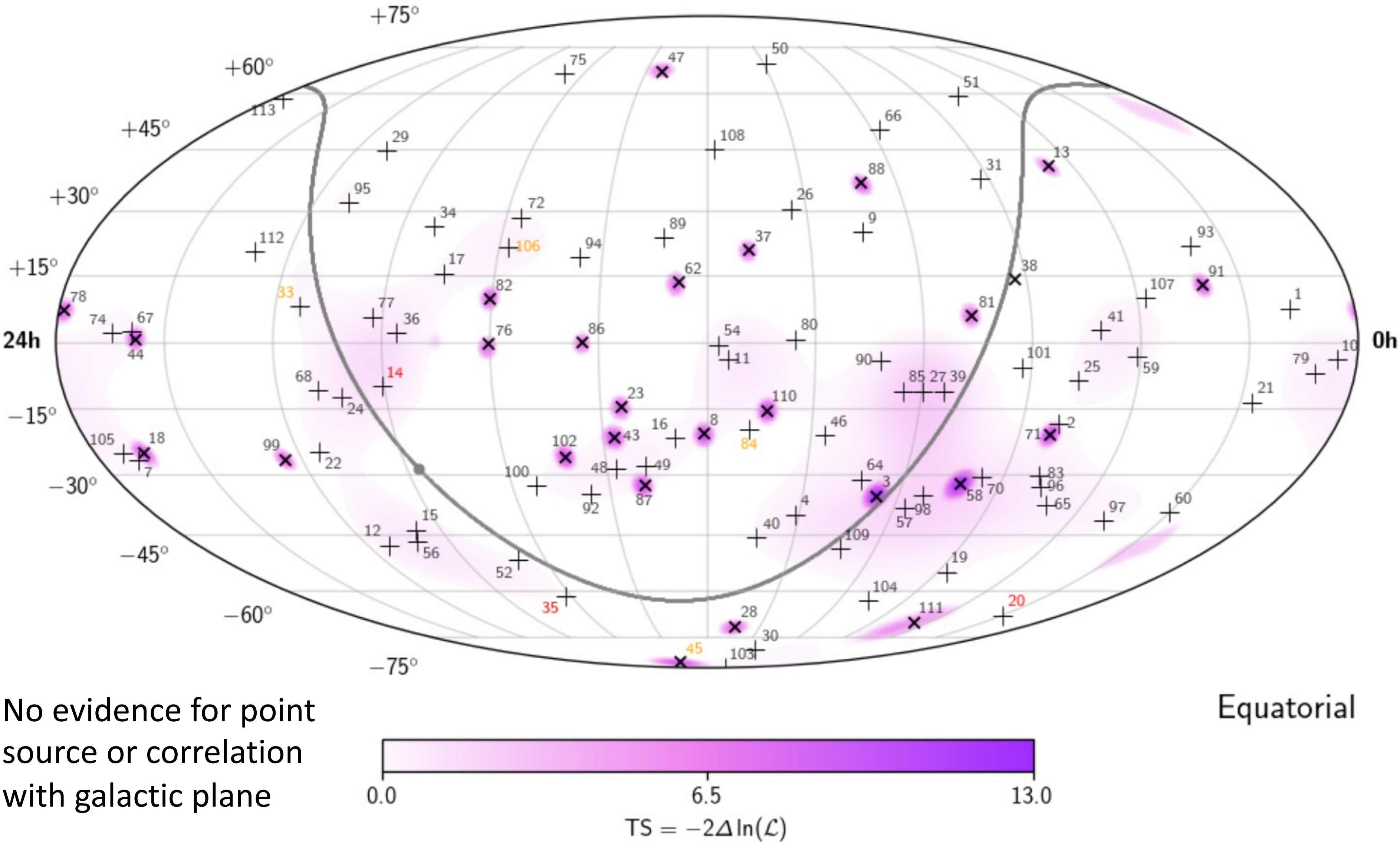
Prompt 90% UL → 12.3 * BERSS model

Consistent with 6-yr result





Point-source search



No evidence for point source or correlation with galactic plane

$E < 300$ TeV   300 TeV $< E <$ 1 PeV   1 PeV $< E$

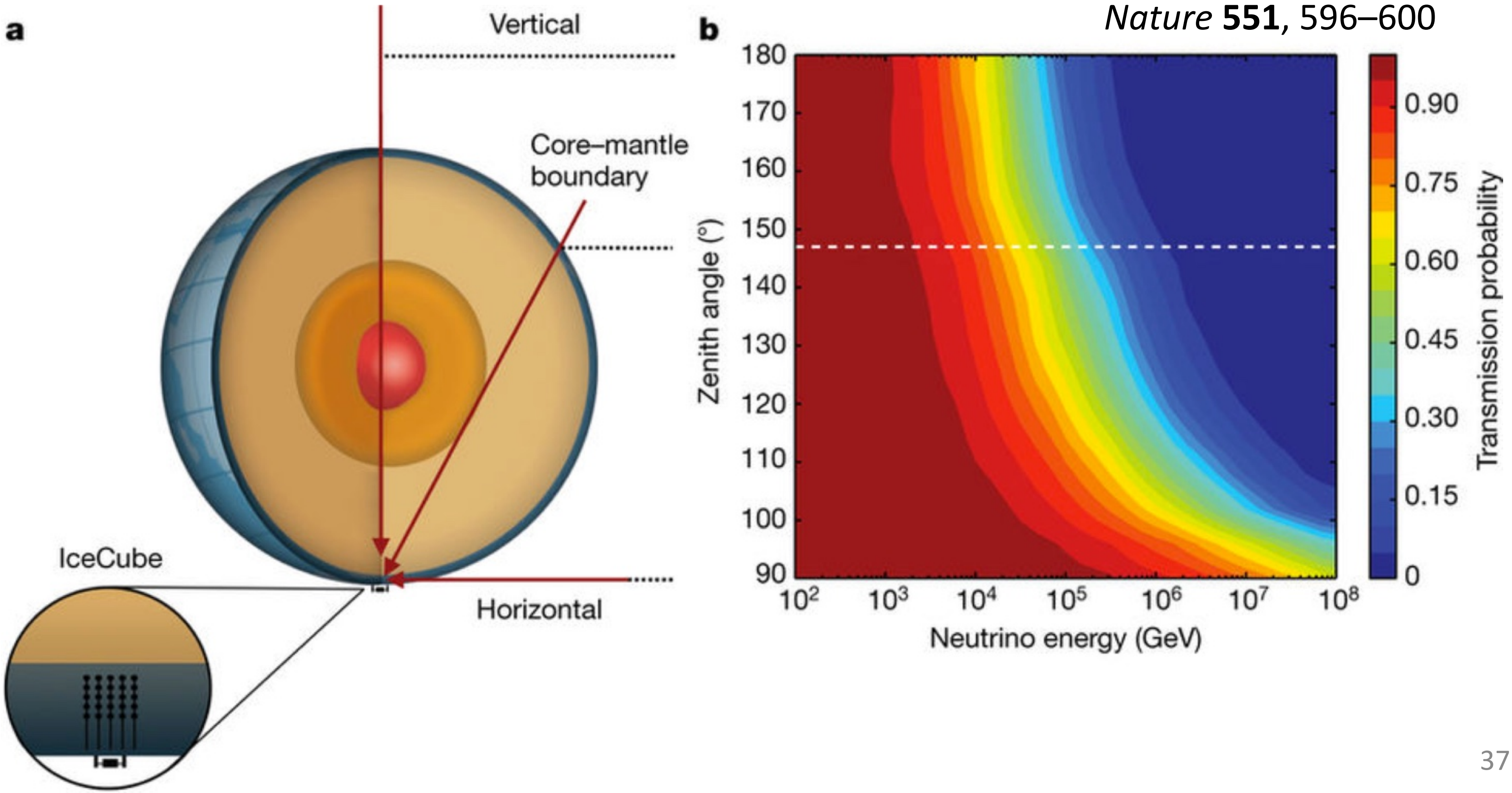
In-Earth flux attenuation

High-energy neutrinos interact in the Earth → flux attenuation

Depends on energy E_ν and direction θ_ν

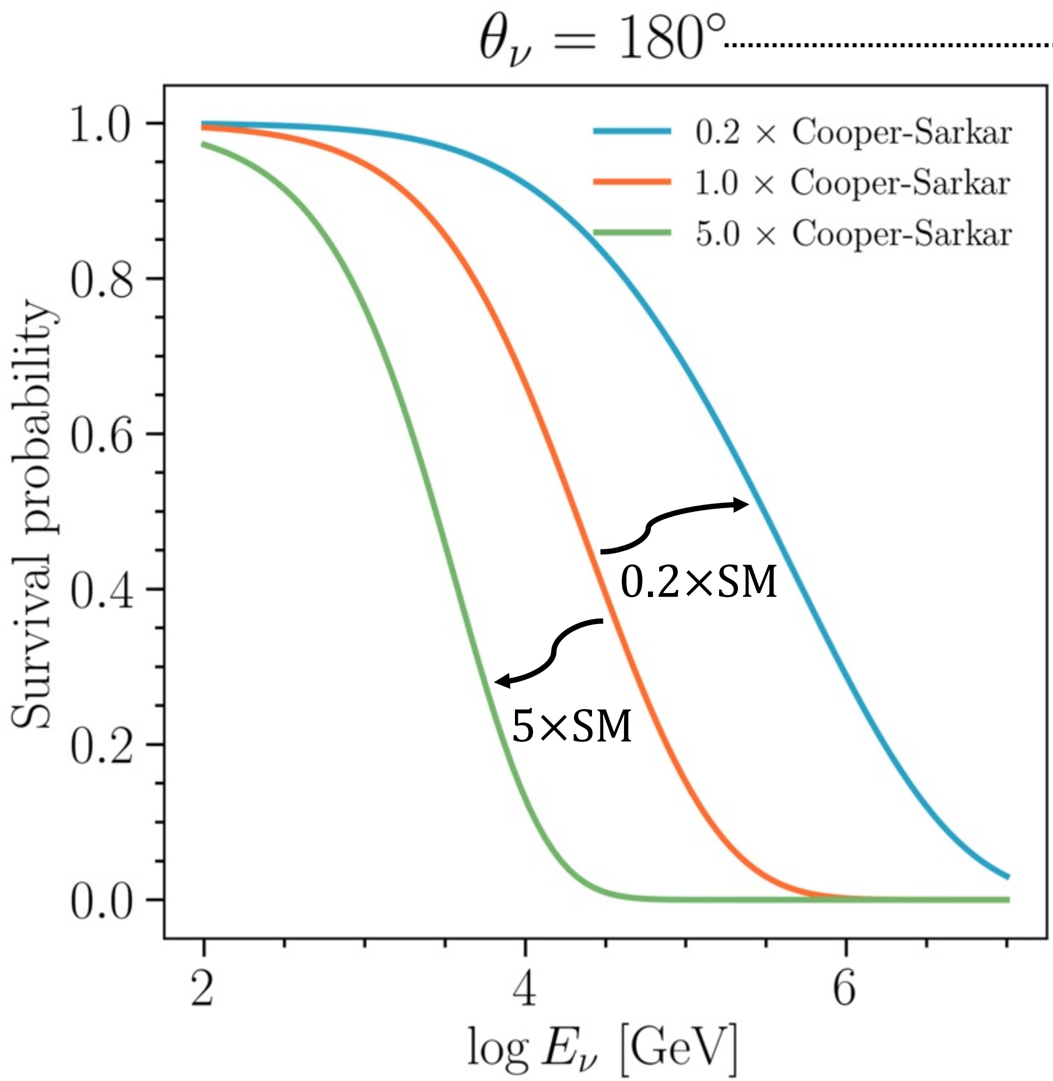
Accurate **directional reconstruction** is important!

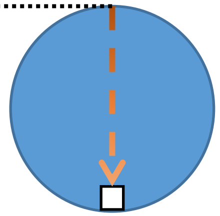
Nature **551**, 596–600



Dependence on cross section

Changing cross-section will change predicted flux at detector



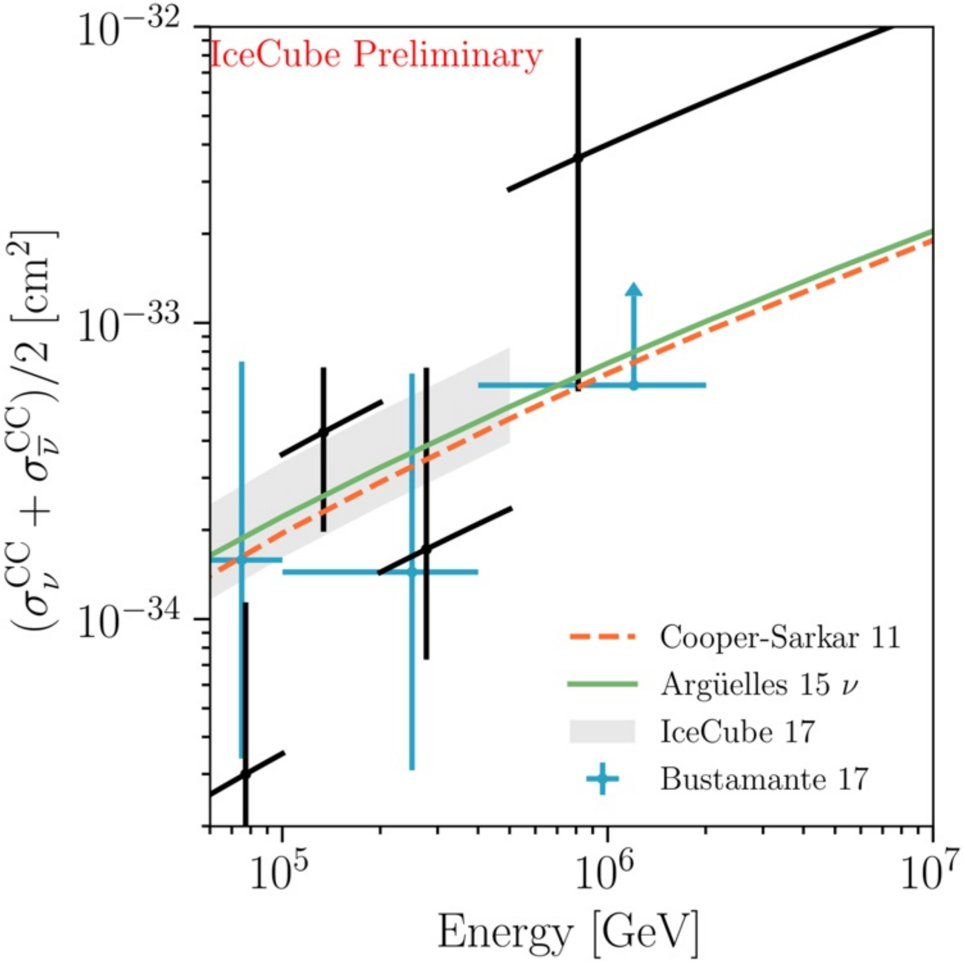


High-energy cross section

Measure cross section via **Earth-absorption**

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

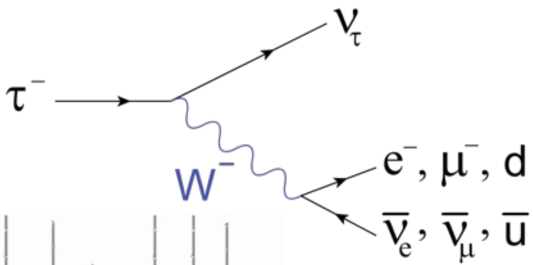
Four **scaling parameters** that modify cross section as a **function of energy**

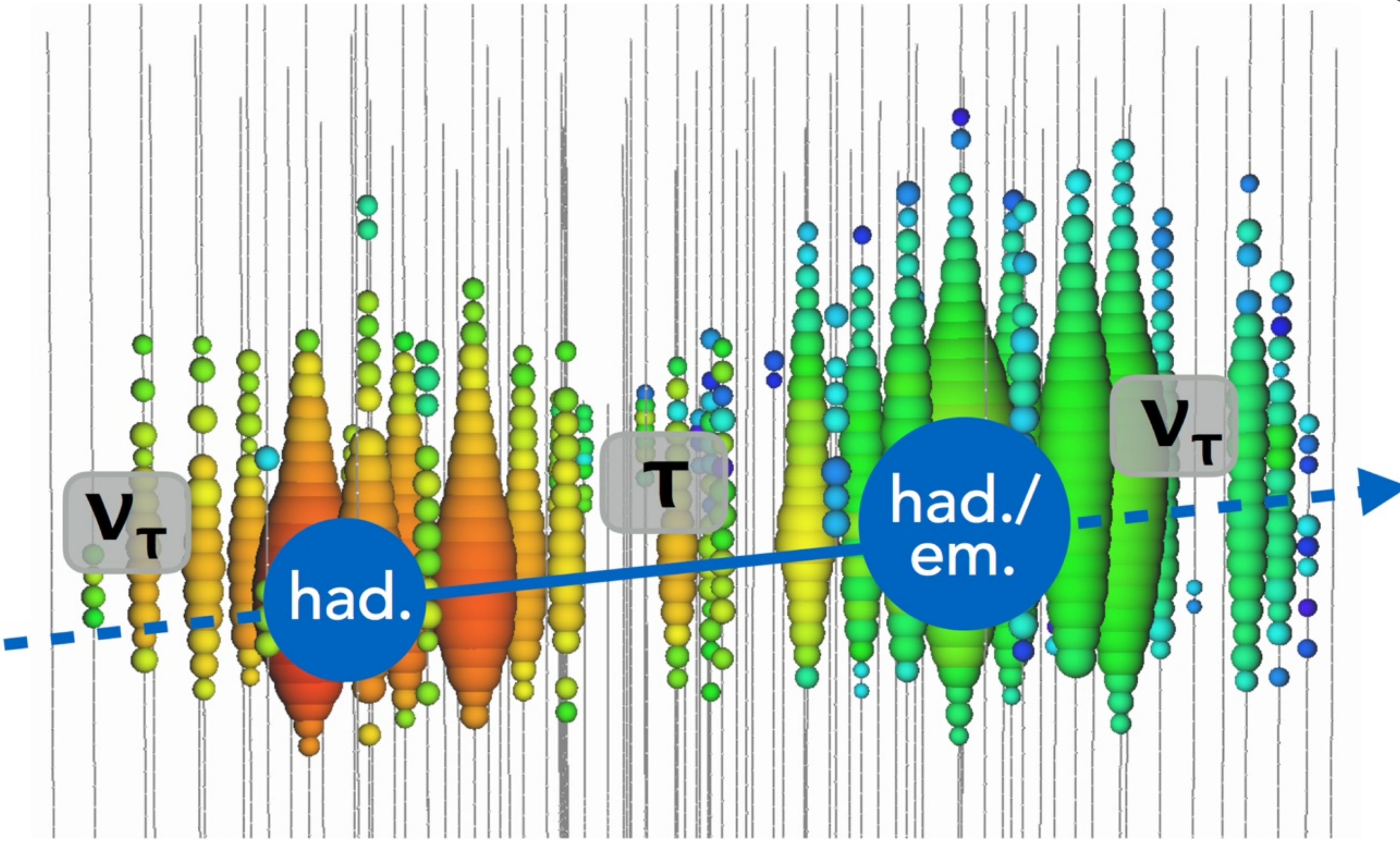


The double cascade channel

Require both cascades with E > 1 TeV

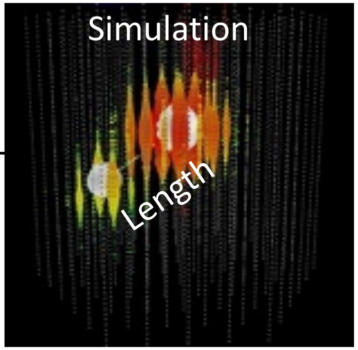
Require separation distance > 10 m





PoS(ICRC2017)973

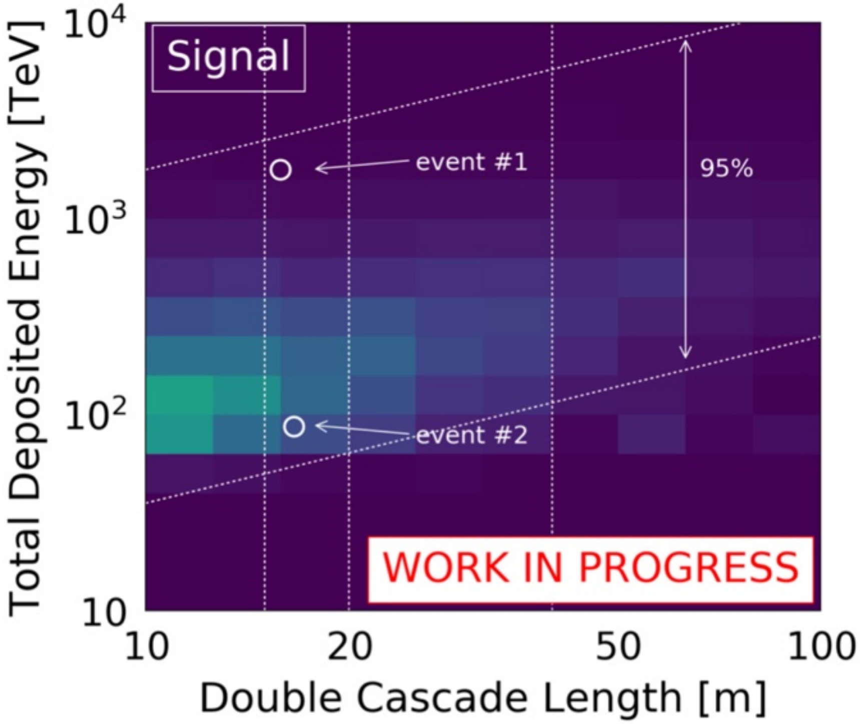
Flavor identification

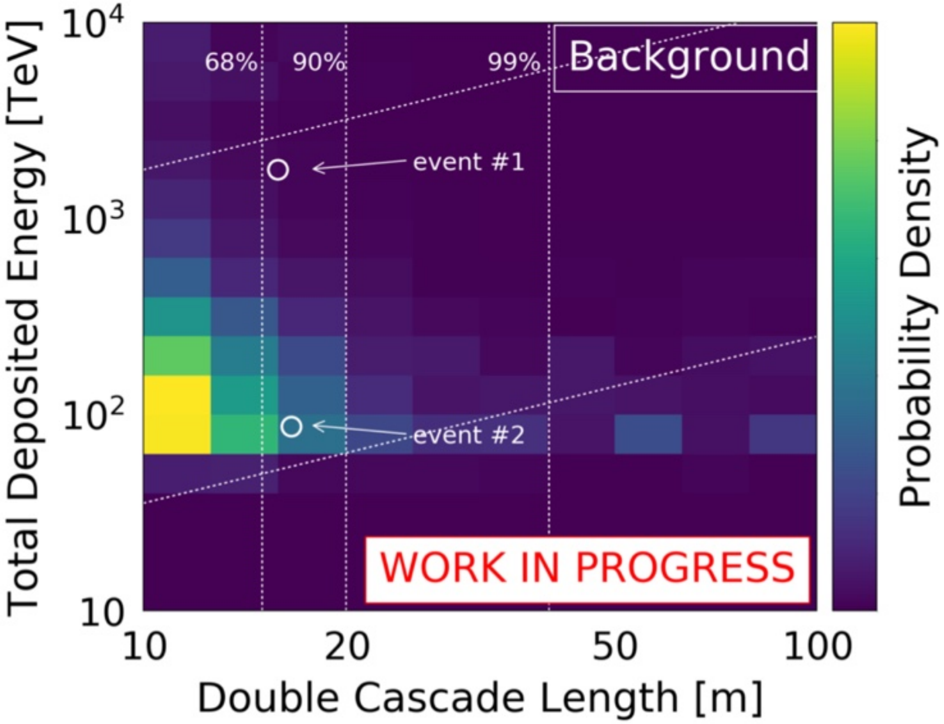


Ternary-PID of cascades, tracks and double-cascades

Two double-cascade events

Could be due to ν_τ or mis-id background; affects flavor interpretation



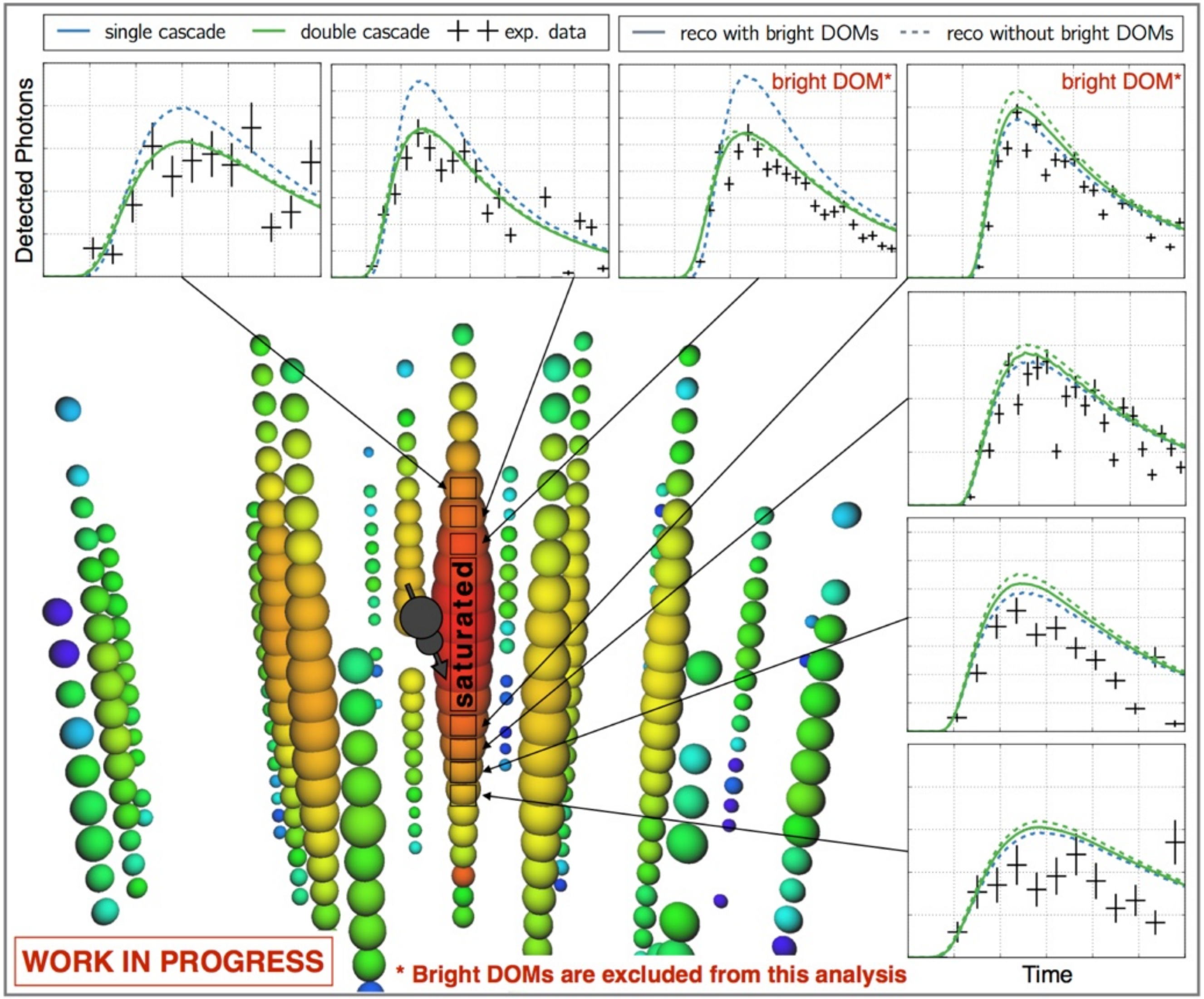


Double-cascade event 1

Length separation on threshold of cut

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

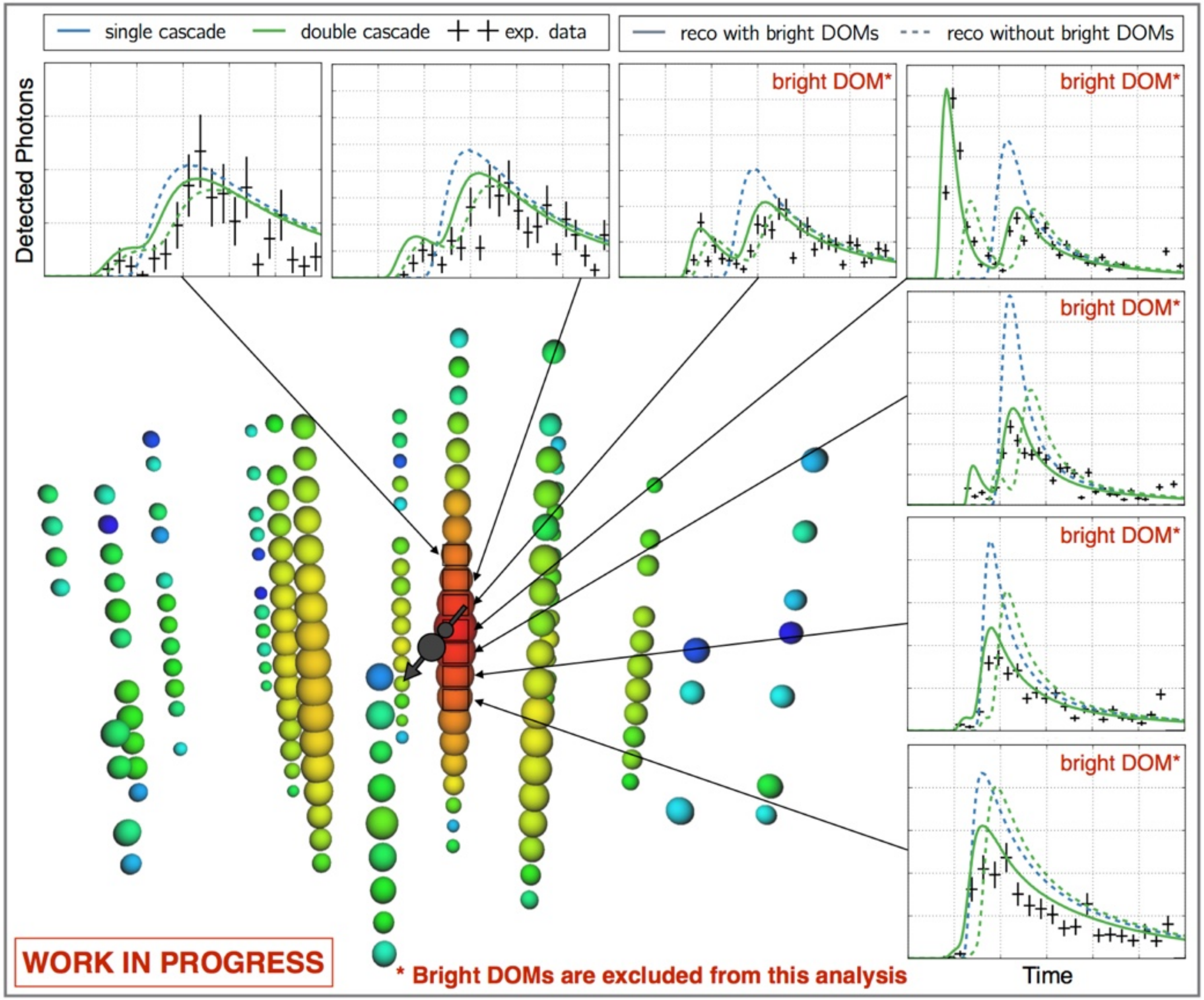
Dedicated studies ongoing



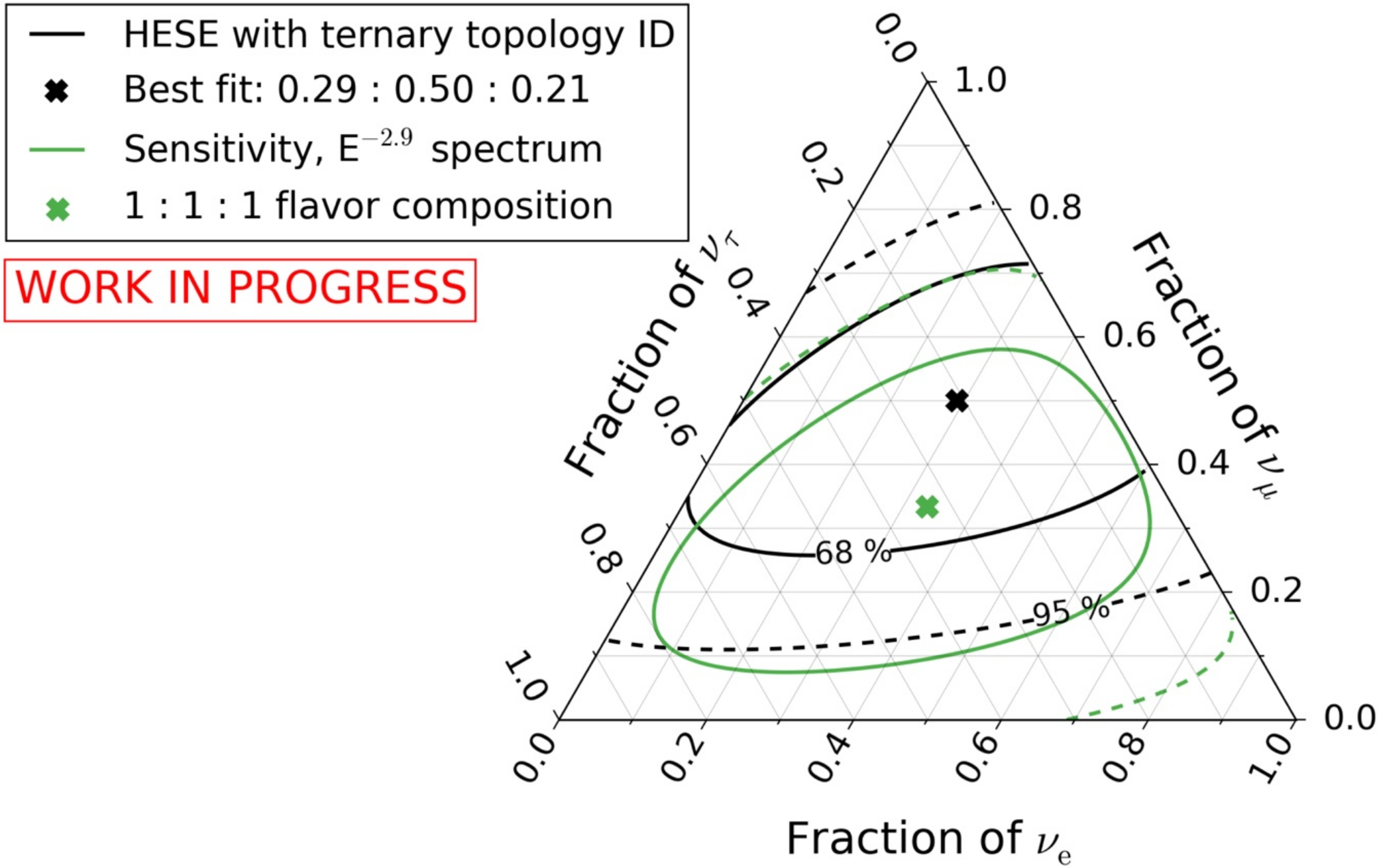
Double-cascade event 2

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

Dedicated studies ongoing



Astrophysical flavor composition



Non-zero best-fit for tau-component

Physics beyond the Standard Model

New physics can affect neutrino oscillations at high energies

Astrophysical flavor a powerful probe

Effective Hamiltonian with energy-dependent scale parameter Λ_d

$$H_d = \frac{1}{2E} U M^2 U^\dagger + \frac{E^{d-3}}{\Lambda_d} \tilde{U}_d O_d \tilde{U}_d^\dagger = V_d(E) \Delta V_d^\dagger(E)$$

Dimension

Standard Mixing

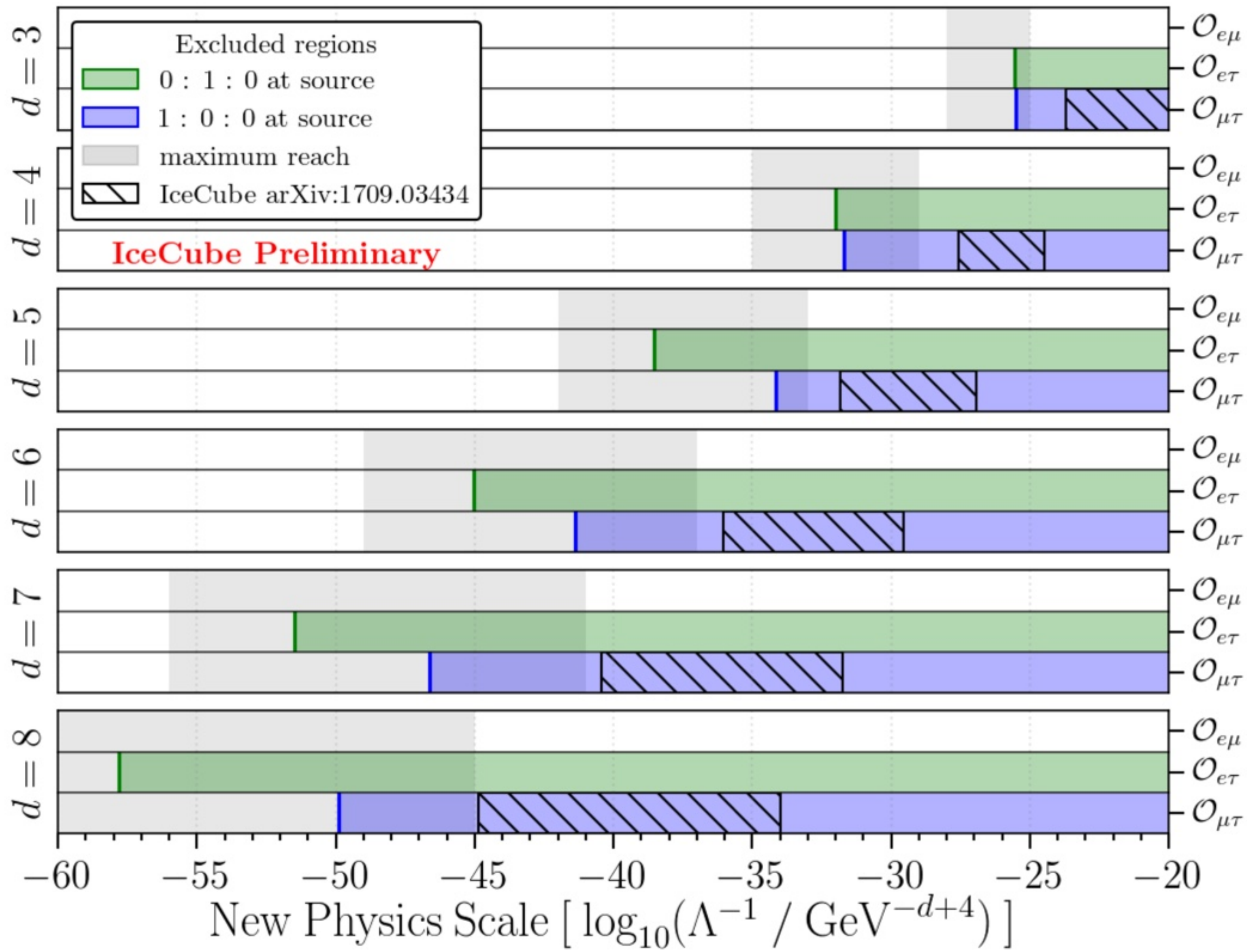
New Physics Terms

Mixing Matrix with New Physics

Physics beyond the Standard Model

Exclusion limits obtained for Λ_d (horizontal axis) for dimension-three to dimension-eight SME coefficients at IceCube

For fixed flavor ratio at production and maximal mixing

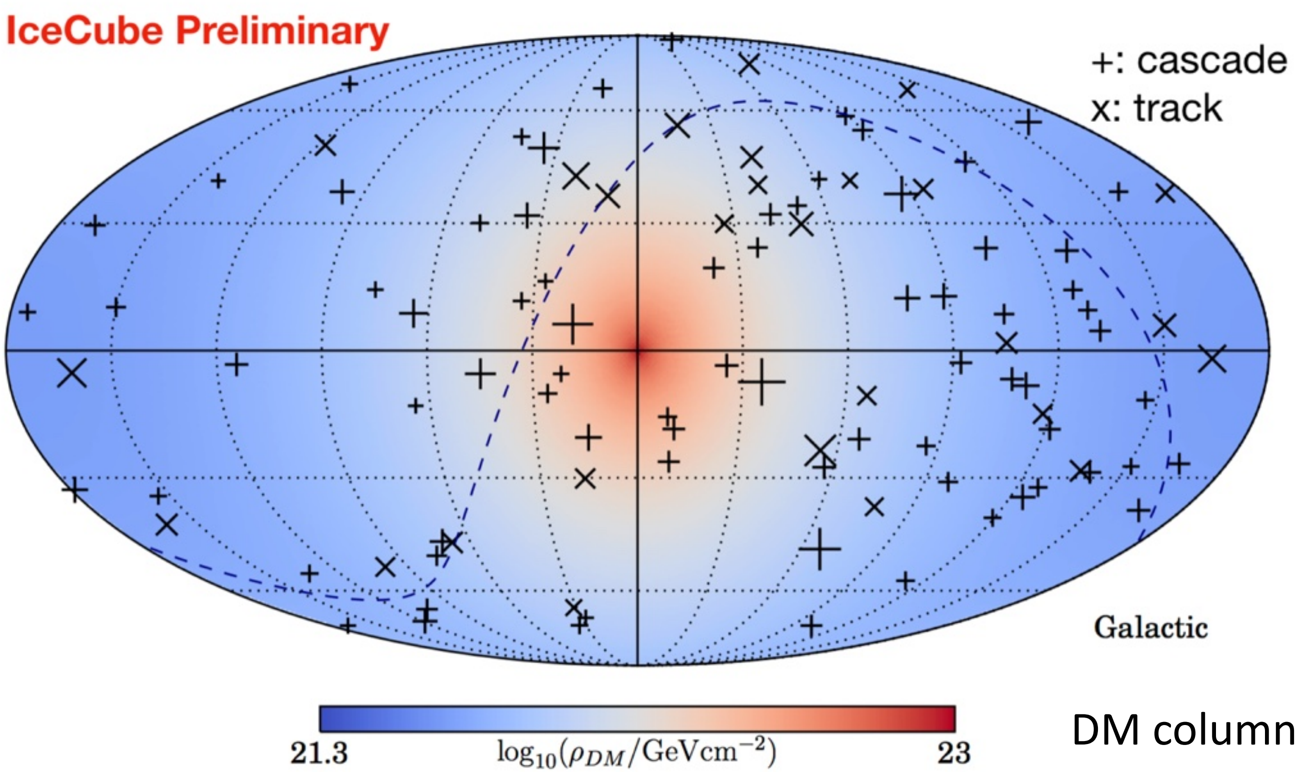


Dark matter searches

Probe various dark matter scenarios under assumed Einasto profile

Test:

1. Heavy DM self-annihilating into SM particles
2. Heavy DM decaying into SM particles
3. Astrophysical ν scattering off light DM

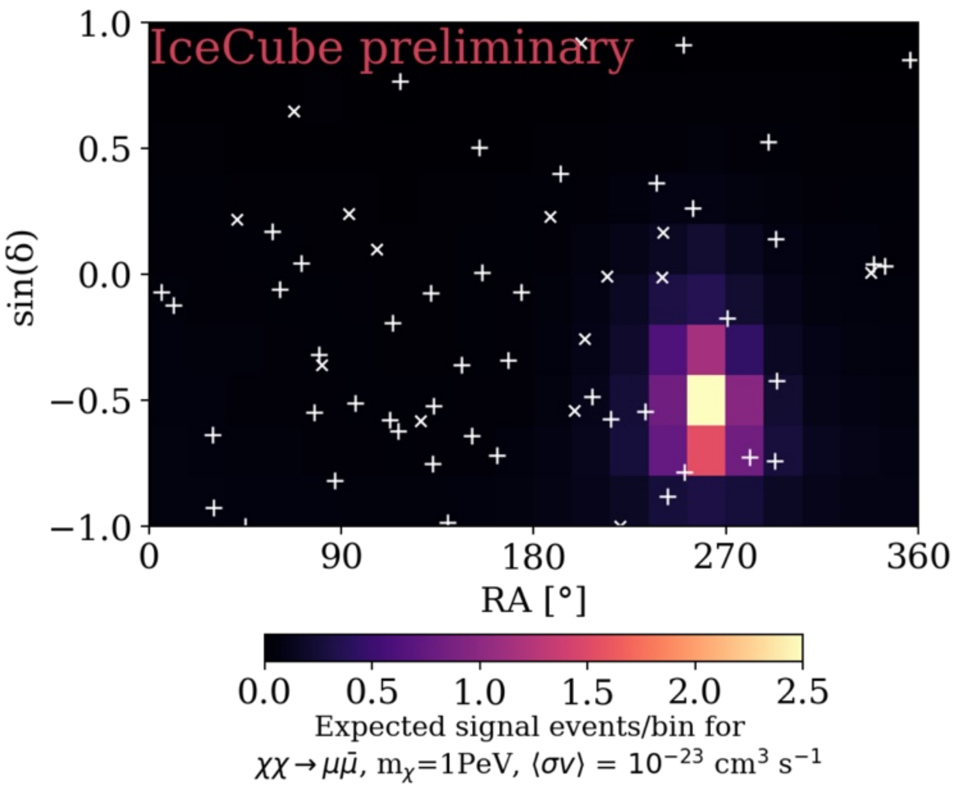


DM column density

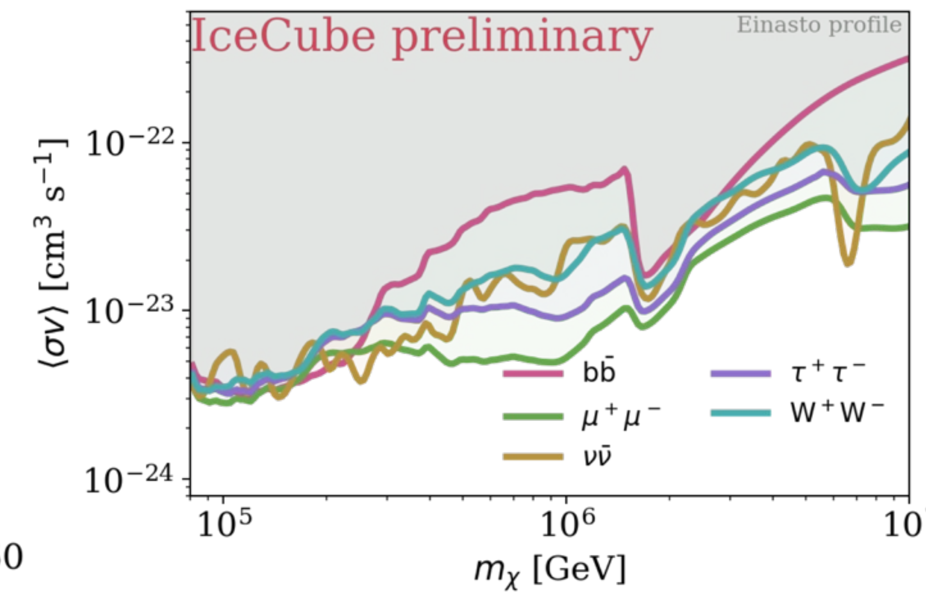
Dark matter annihilation limits

Expected excess from galactic halo and cosmological DM

No significant clustering



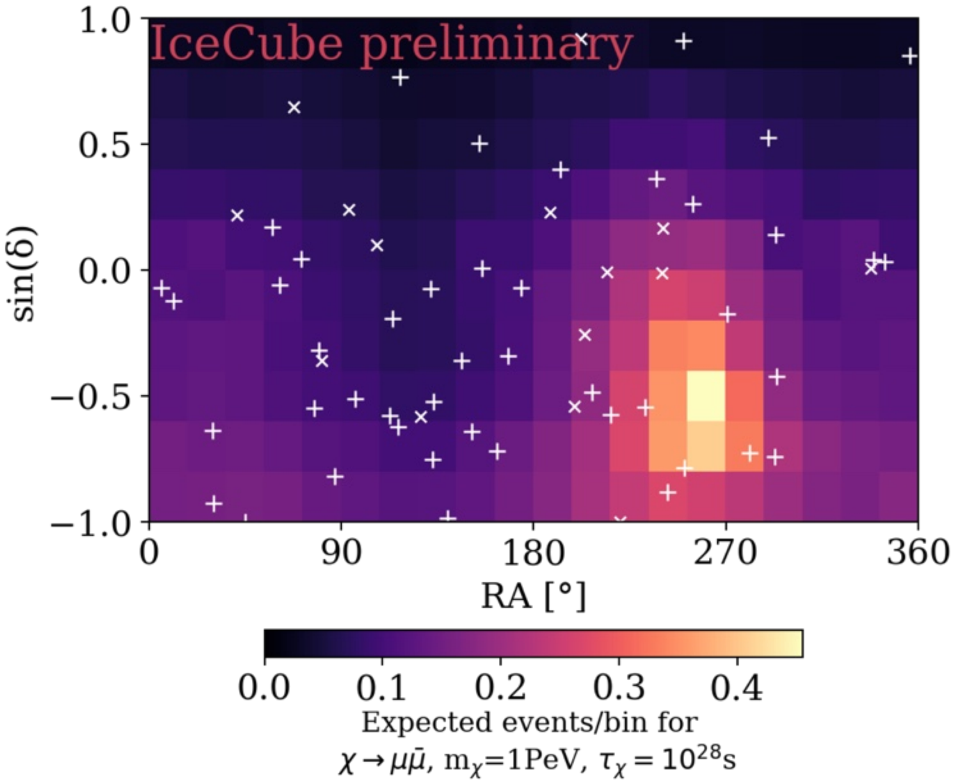
Limits on annihilation cross section



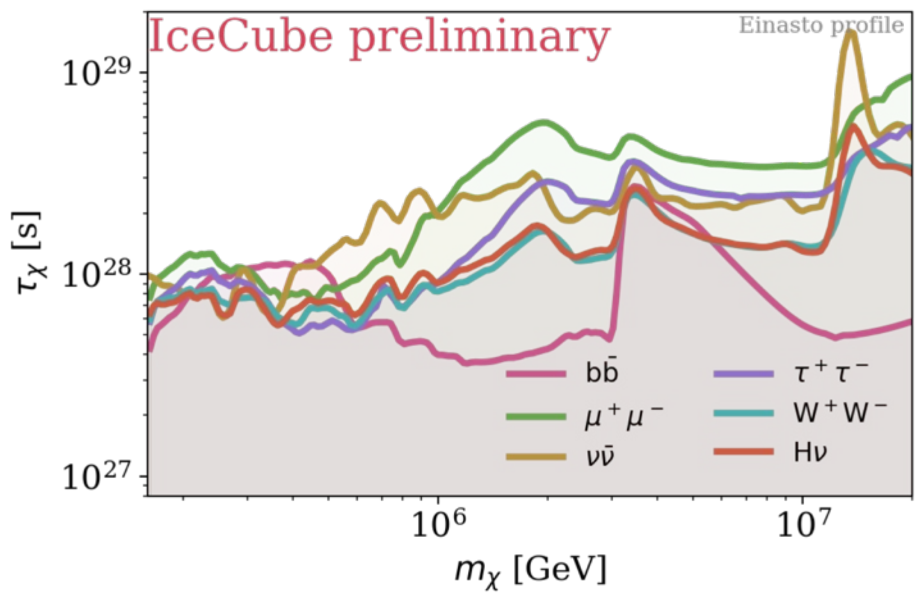
Dark matter decay limits

Expected excess from galactic halo and cosmological DM

No significant clustering

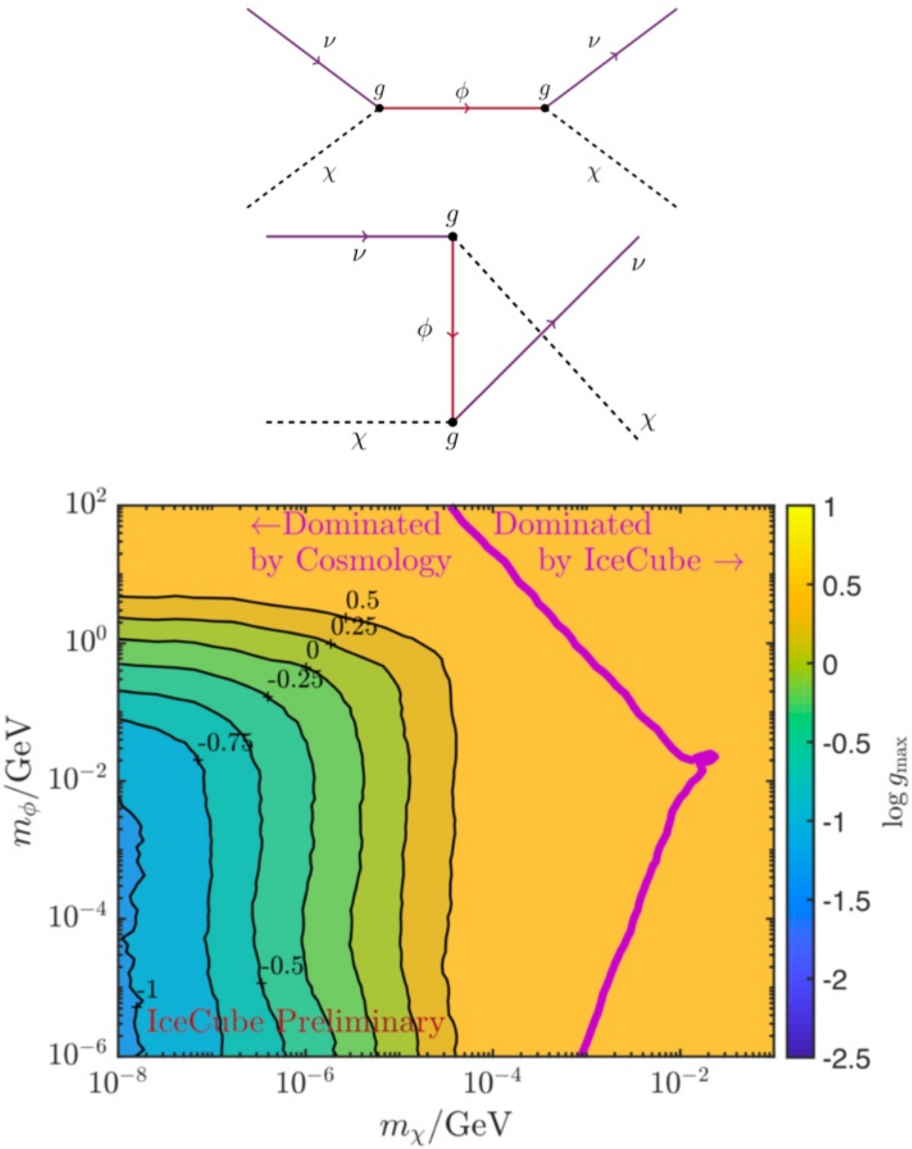


Limits on decay lifetime

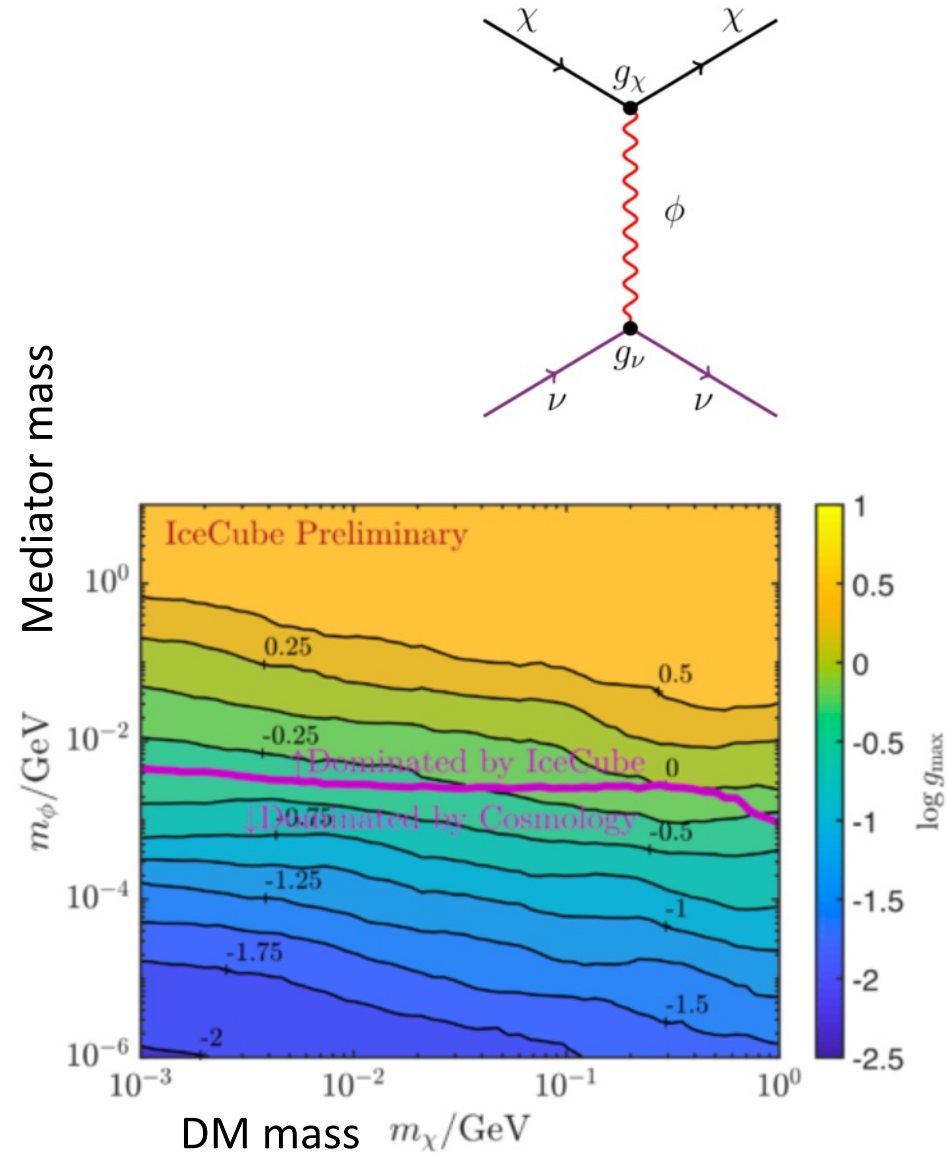


Dark matter scattering limits

Scalar DM – Fermion mediator



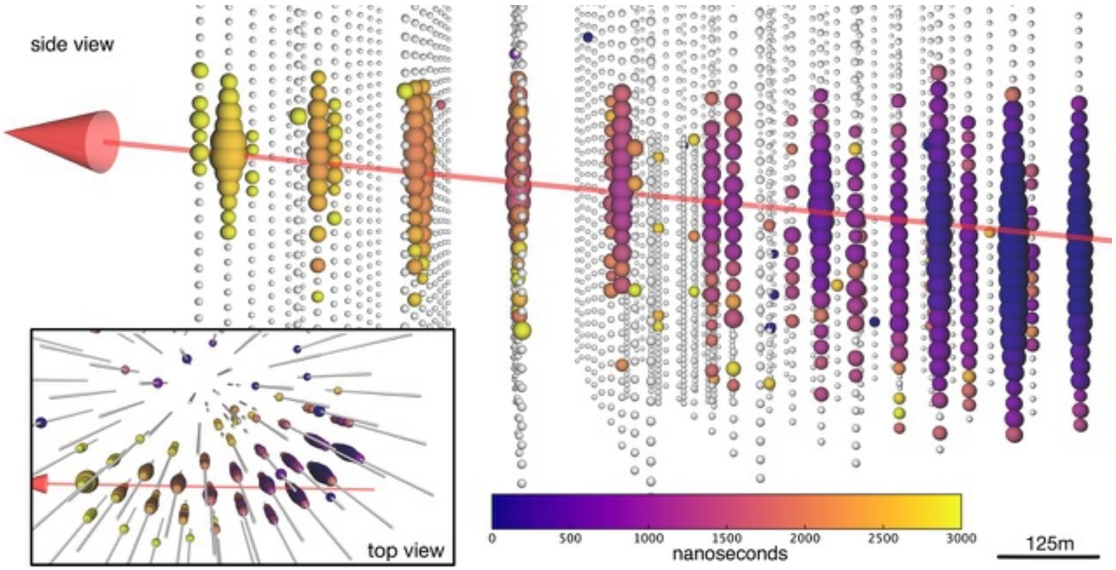
Fermion DM – Vector mediator



Highlight

TXS 0506+056

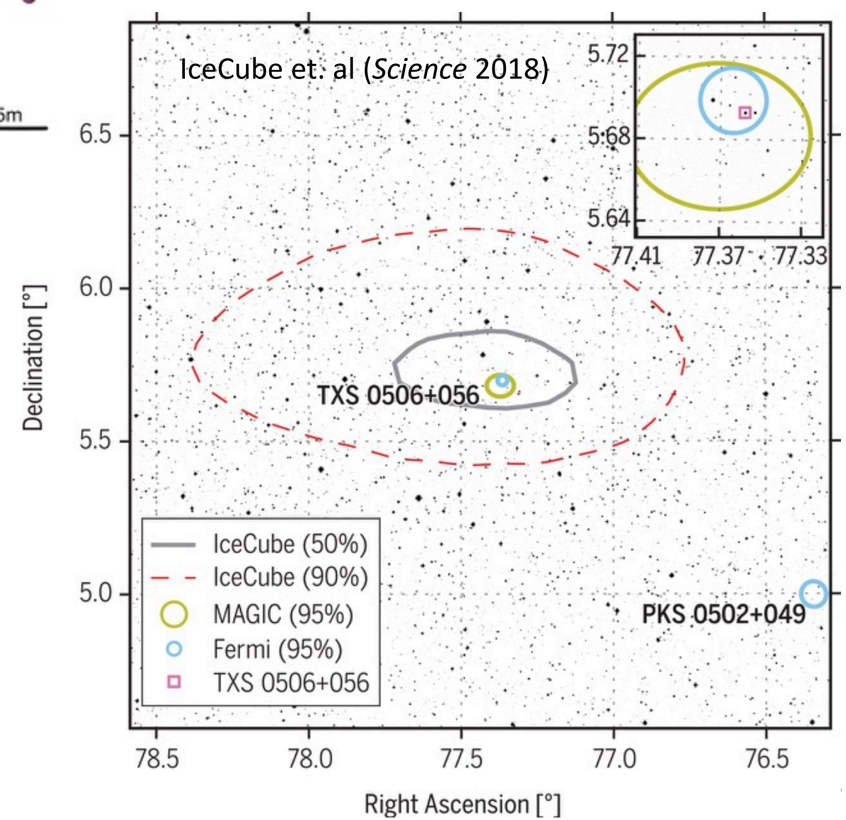
IceCube-170922A



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

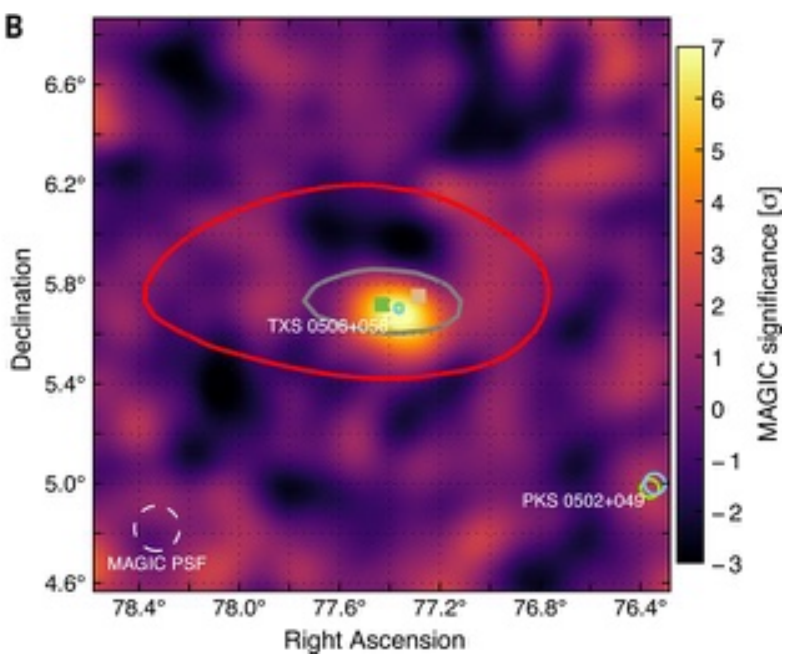
Evidence for a point source

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

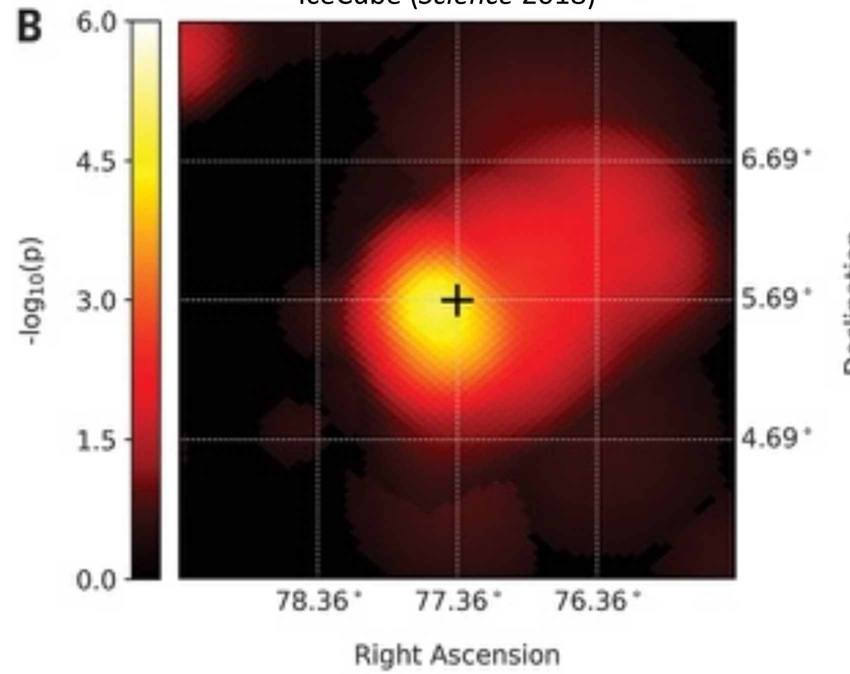
Significant excess seen by Fermi-LAT and MAGIC shortly after IC alert (3σ)

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

IceCube et. al (*Science* 2018)



IceCube (*Science* 2018)

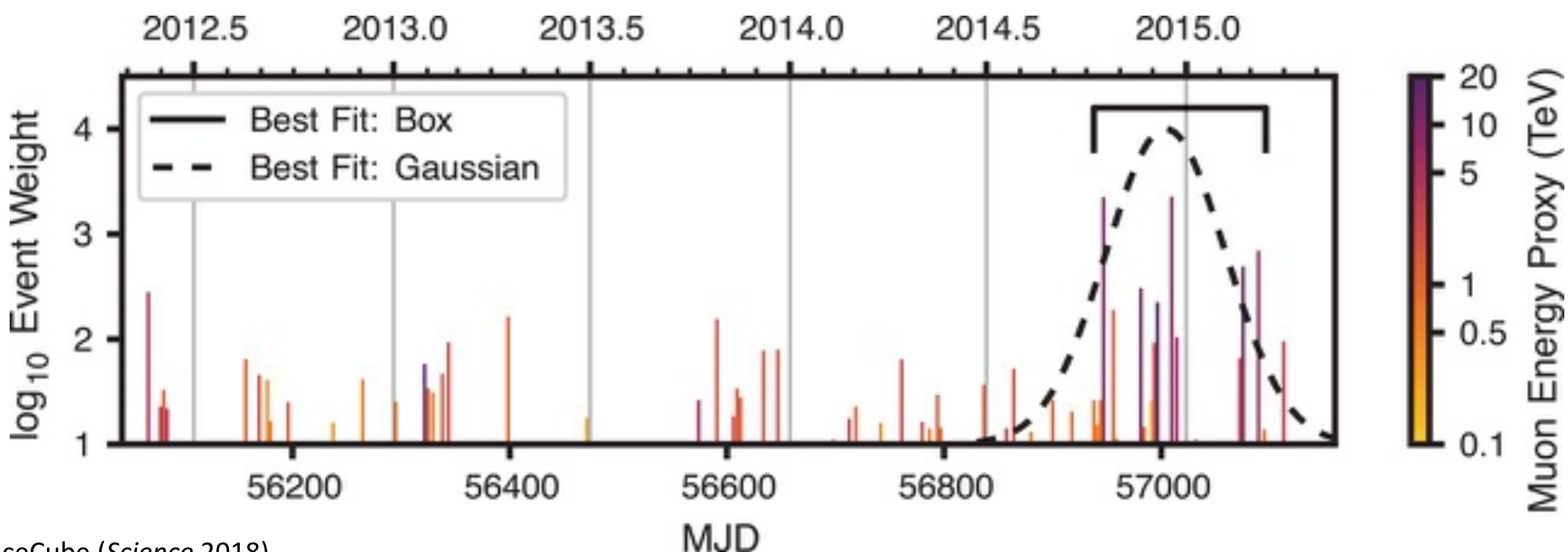


Time dependence in historical IceCube data

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!



IceCube (*Science* 2018)

Highlight

Glashow resonance candidate

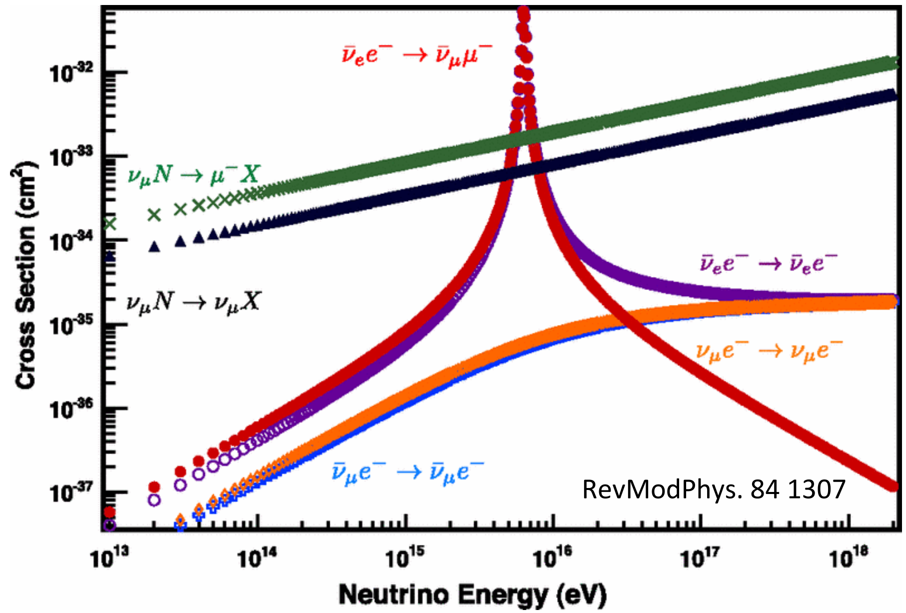
Uncontained event at ~6 PeV

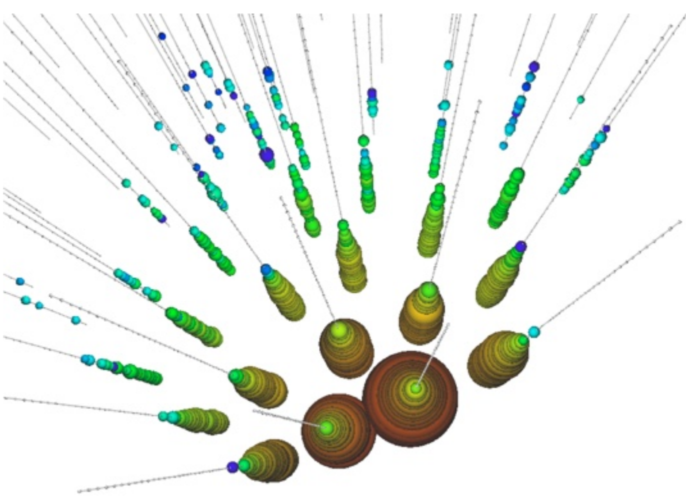
Glashow resonance: $\bar{\nu}_e + e^- \rightarrow W^-$

For at rest electron, require

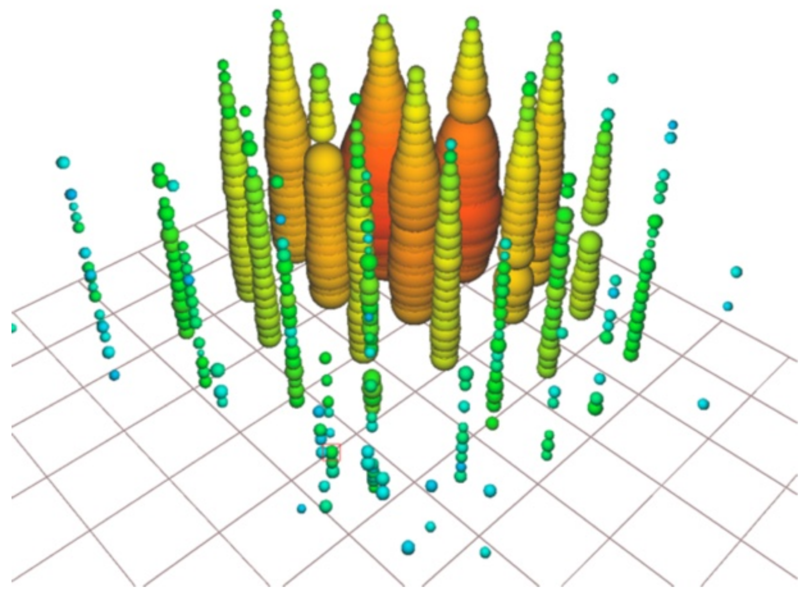
$$E_\nu = 6.3\ PeV$$

Highest energy event in **partially-contained** event selection is a candidate





Top view

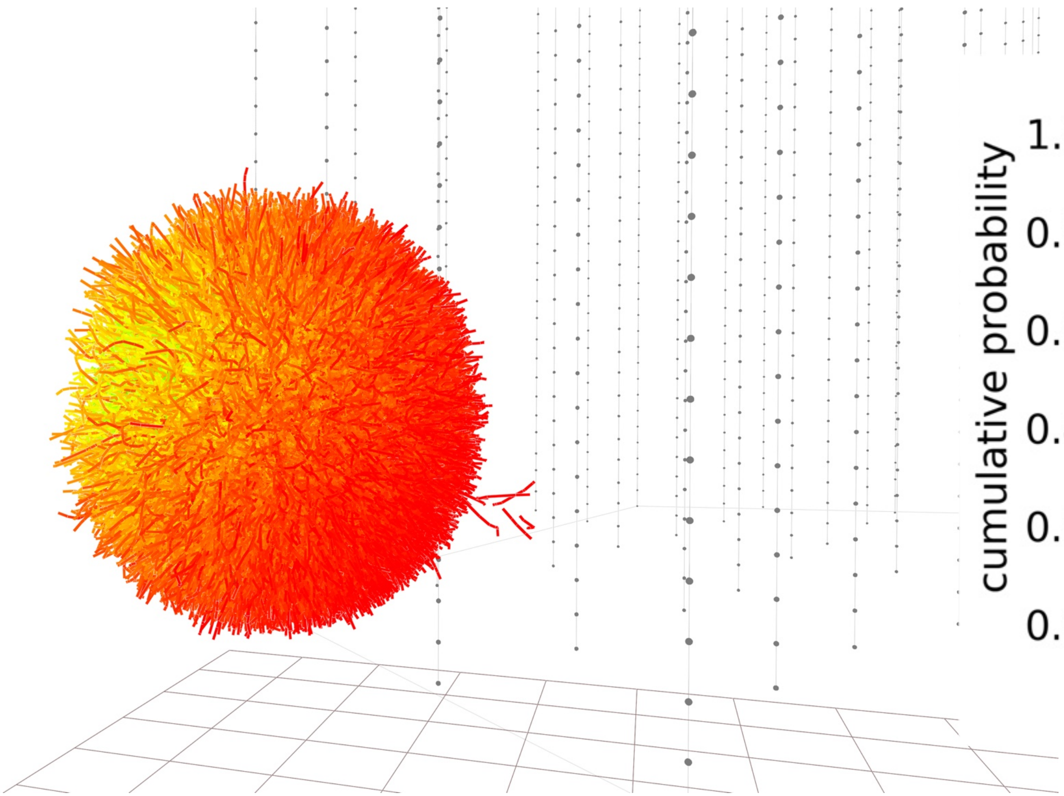


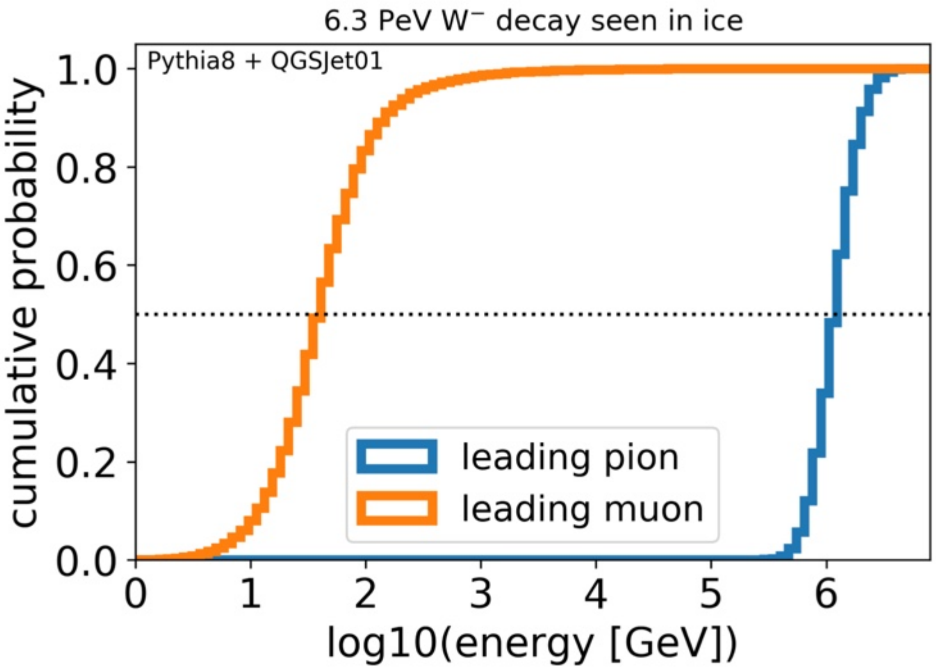
W-boson decays

W decays primarily hadronically

Hadrons then decay to lower energy muons

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

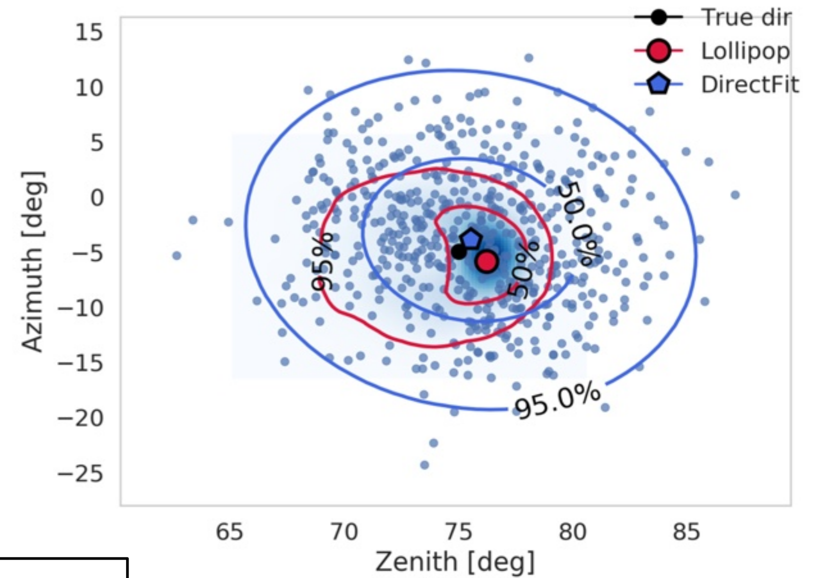




Early-hits for reconstruction

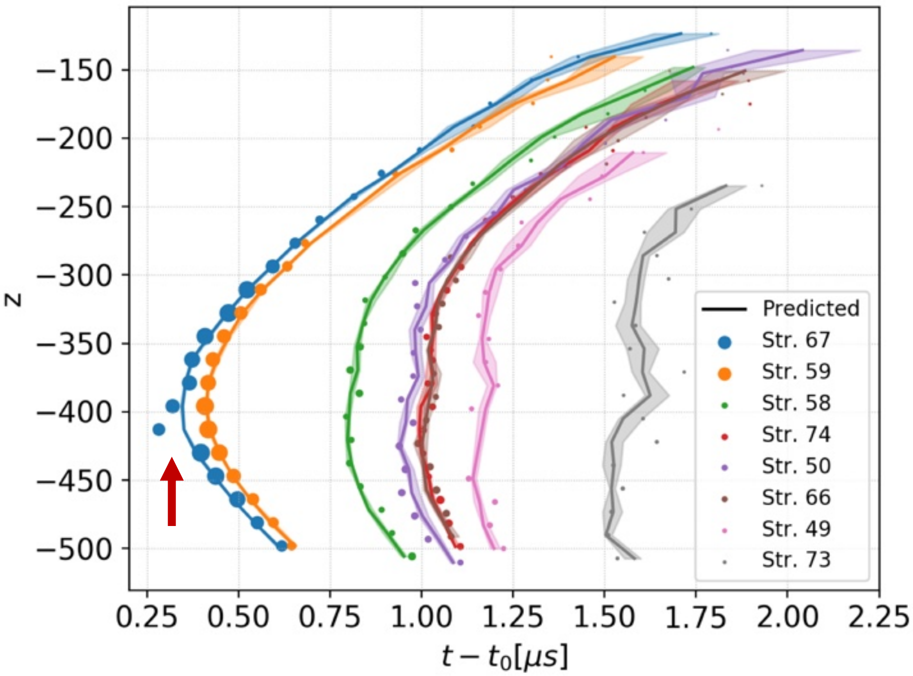
Cascades are difficult to reconstruct in terms of direction

Additional information from early muons helpful for directional constraints

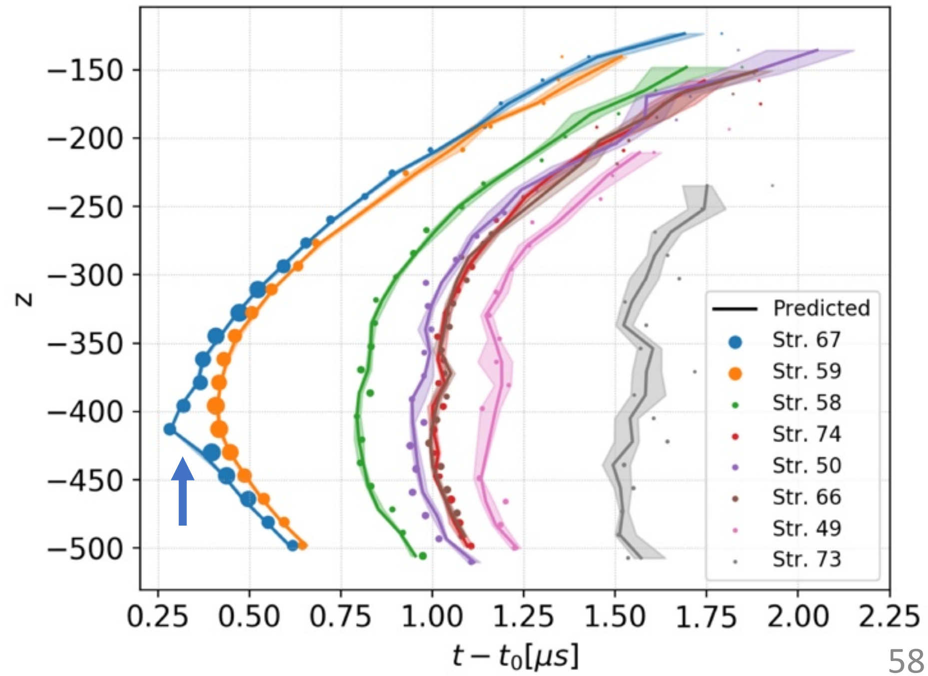


Simulated event

w/o early muons



w. early muons



Conclusion

Much improved HESE analysis with 7.5 years of data

- Improved passing flux calculations
- Updated ice model
- Better systematics, likelihood update (no time to cover)

Will likely affect analyses beyond HESE

→ Two double-cascade events, possibly from ν_τ

→ First evidence for astrophysical neutrino source

→ Highest energy event, partially contained, possibly from W-resonance

Thank you!

Credit: B.K. Tiong, IceCube/NSF

Backups

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

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

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

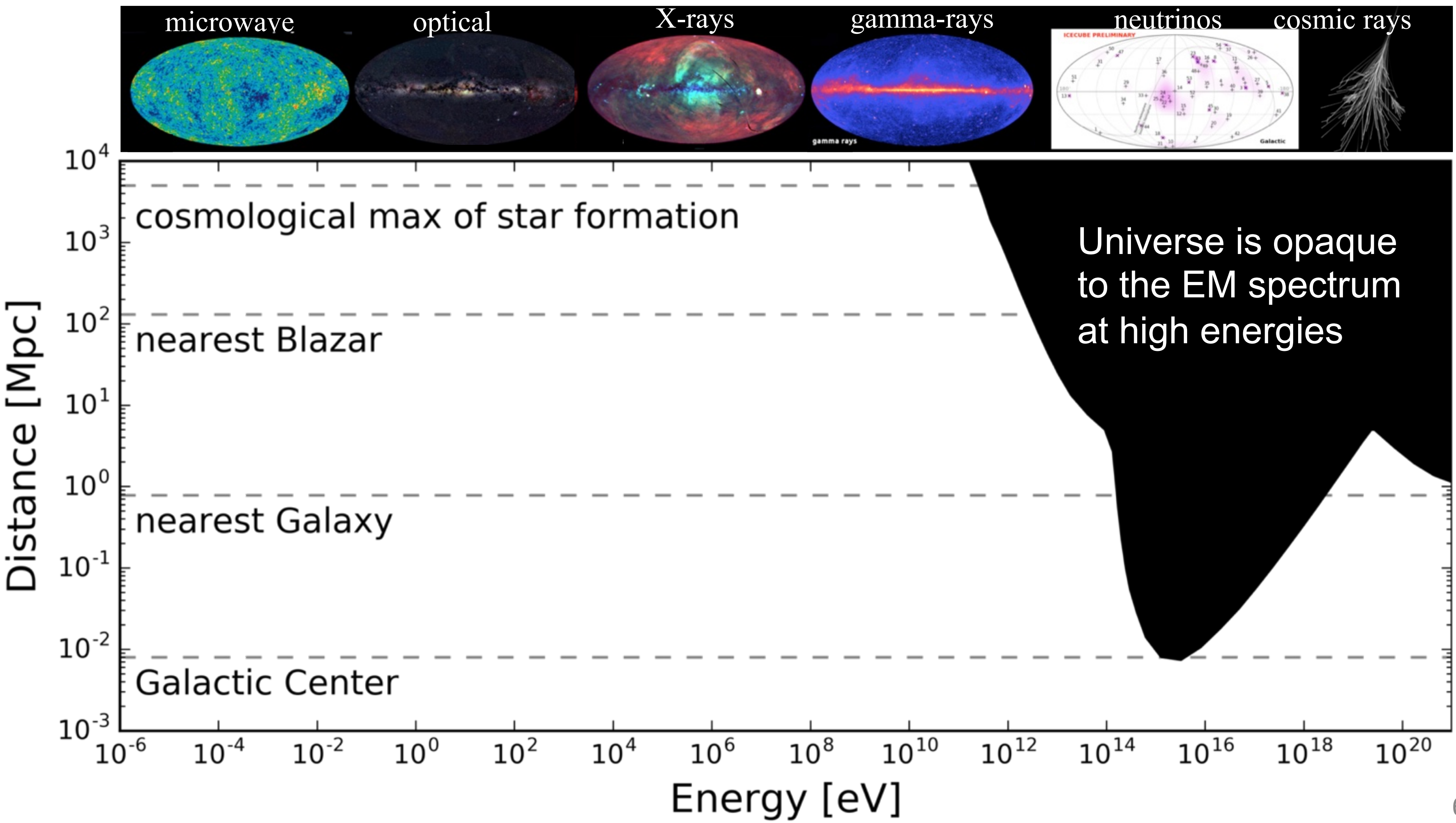
Leads to non-zero oscillation probability after propagation

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

Experiments know L/E

Multimessenger astrophysics

Observing high-energy astrophysical neutrinos allows constraints on production mechanisms

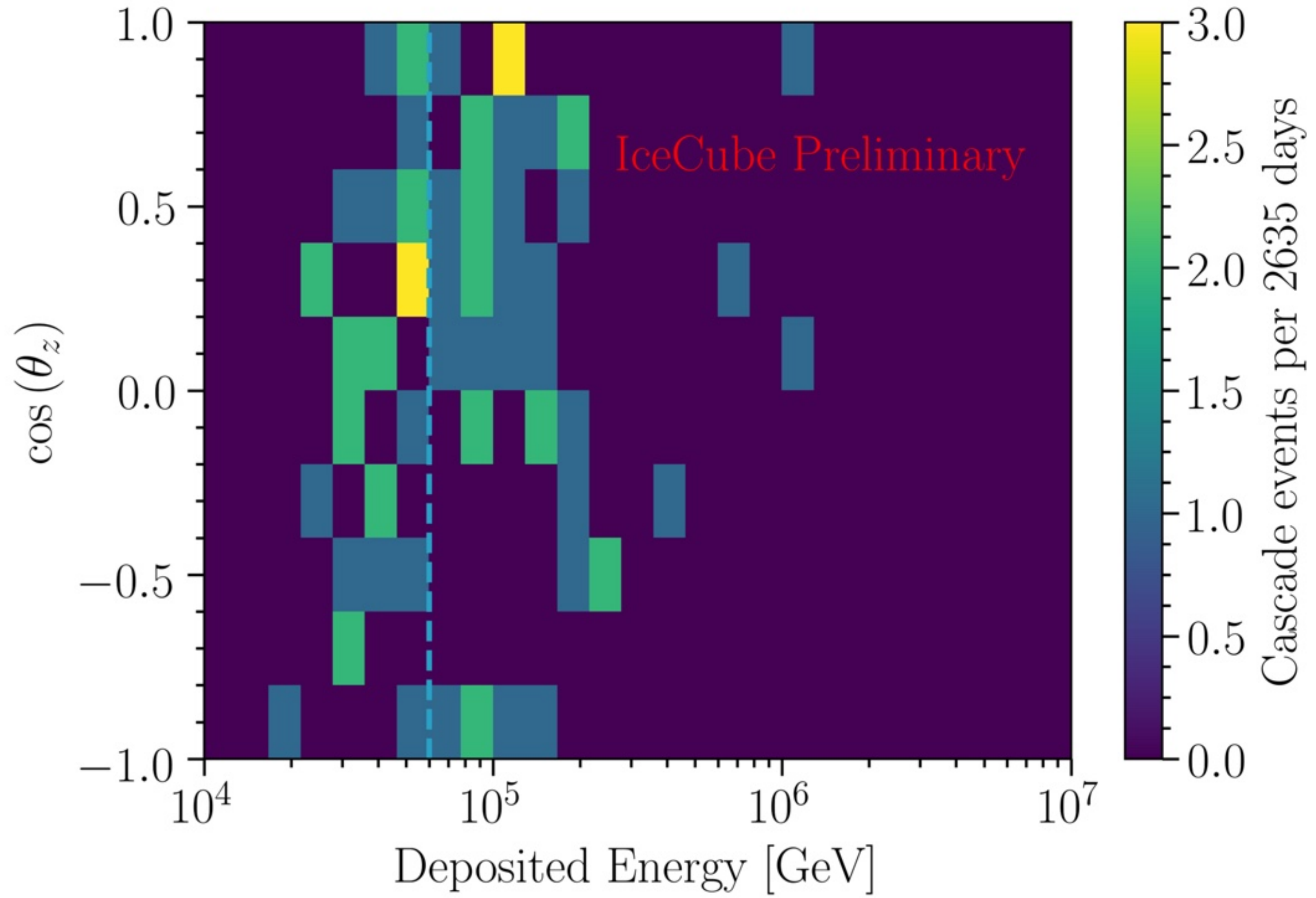


Cascades

Above 60TeV:42 events

8 new events in 2016 season

4 new events in 2017 season

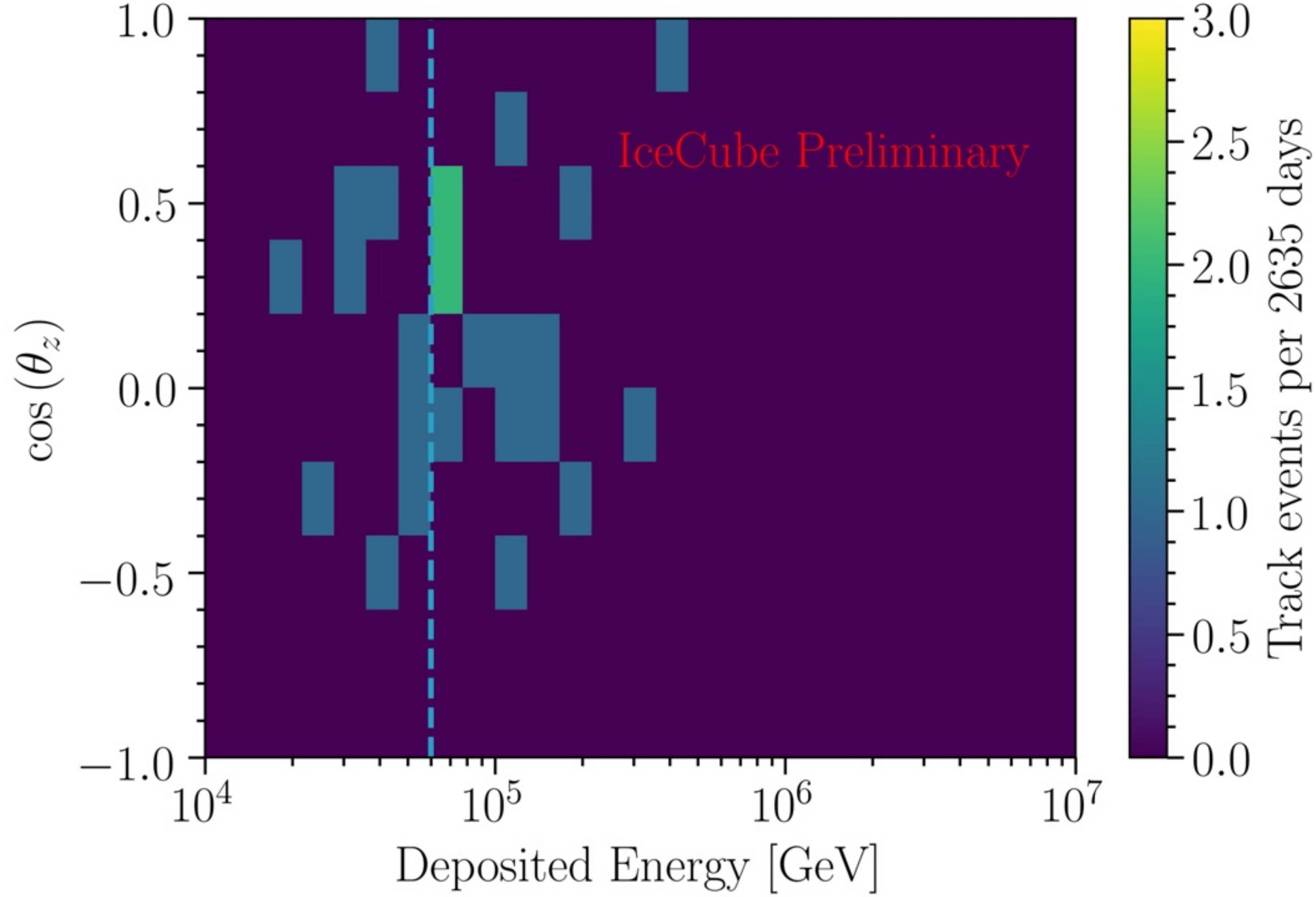


Tracks

Above 60TeV: 16 events

4 new events in 2016 season

1 new event in 2017 season

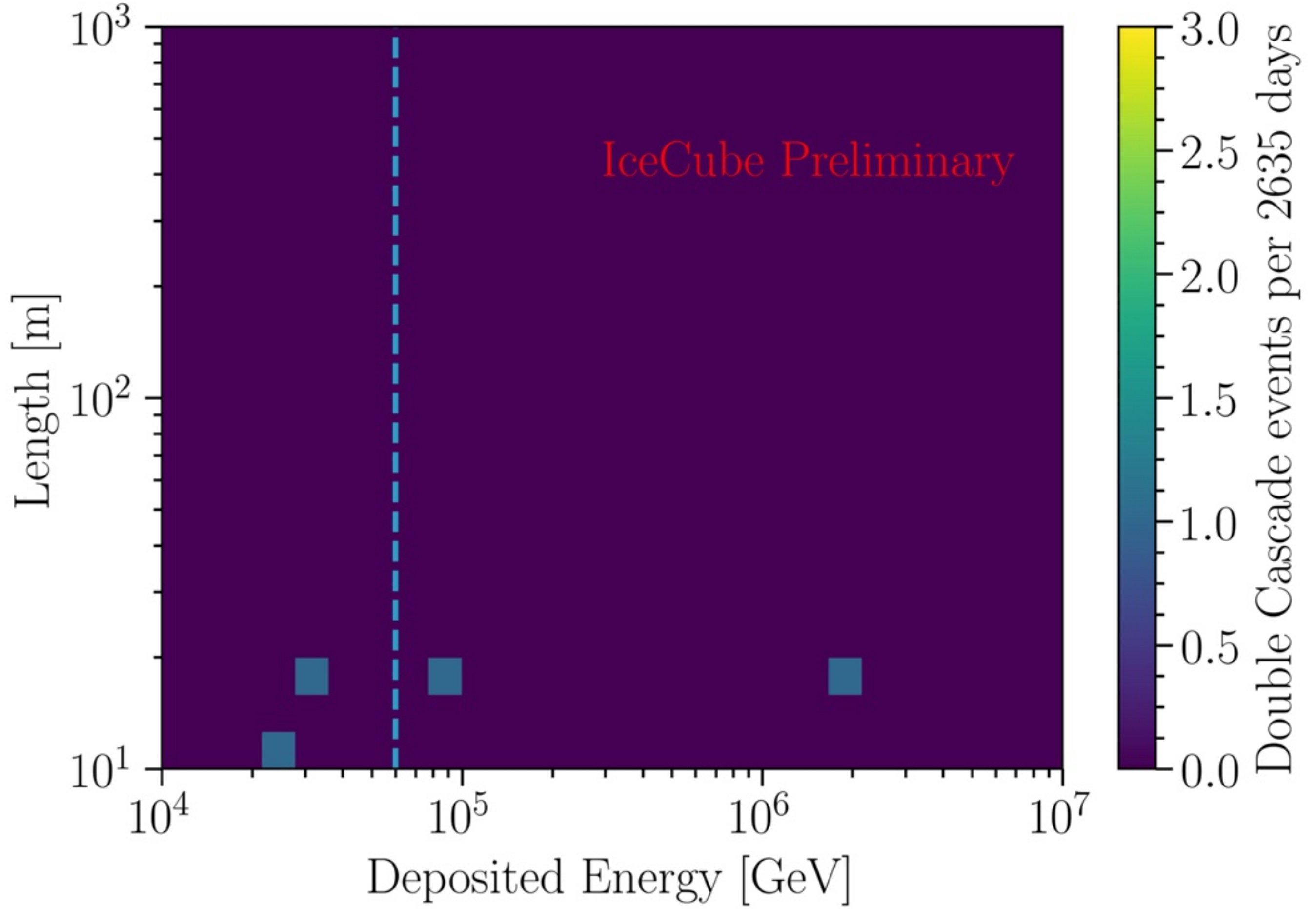


Double cascades

Above 60TeV: 2 events

0 new events in 2016 season

0 new events in 2017 season



Two approaches to reconstruction

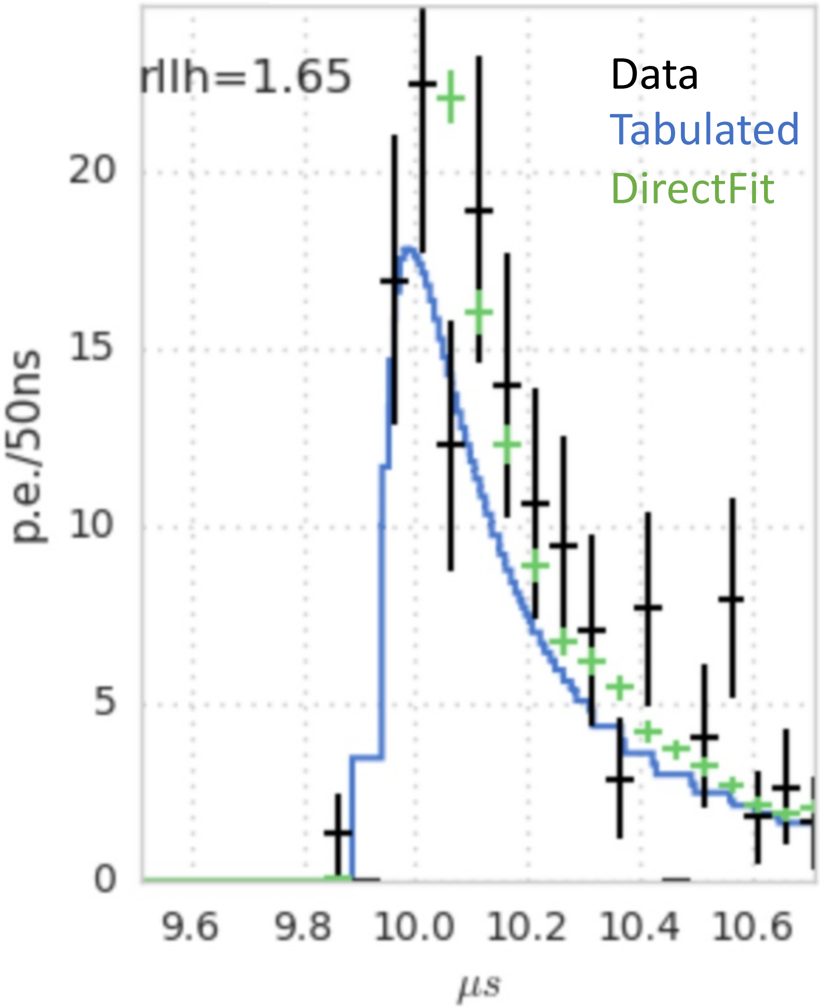
Tabulated photon yields

- 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

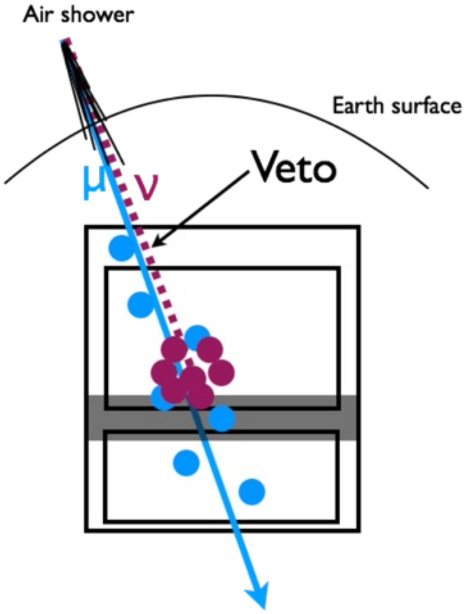


IC collaboration, 1311.4767
D. Chirkin, arXiv:1304.0735

Uncorrelated muons

GJKvS, 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

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

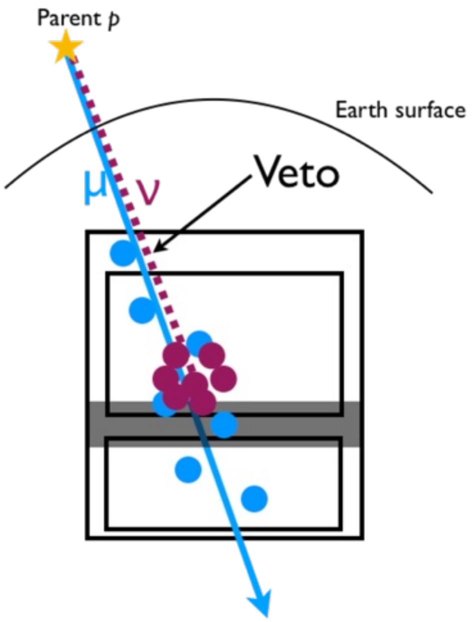
Assuming median muon-range

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

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

Correlated muons

SGRS, 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

Muon range pdfs

arXiv:hep-ph/0407075

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