Results from IceTop: The Surface Array of the IceCube Observatory

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Vrije Universiteit Brussel / IIHE
(Previously @ University of Delaware / Bartol)

Outline

- Background
- IceCube and IceTop
- Cosmic-ray measurements
  - Spectrum and Composition
  - Low Energy Spectrum
  - GeV Muon Density
- PeV Gamma-ray Searches
  - Motivation
  - Diffuse Emission from Galactic Plane
  - Point Sources
- Muon Neutrino Search using IceTop as Veto
  - Motivation
  - Veto Efficiency of IceTop
  - Neutrino Candidates
- Future of IceTop
  - Scintillator and Radio Array
  - Non Imaging Air Cerenkov Telescopes

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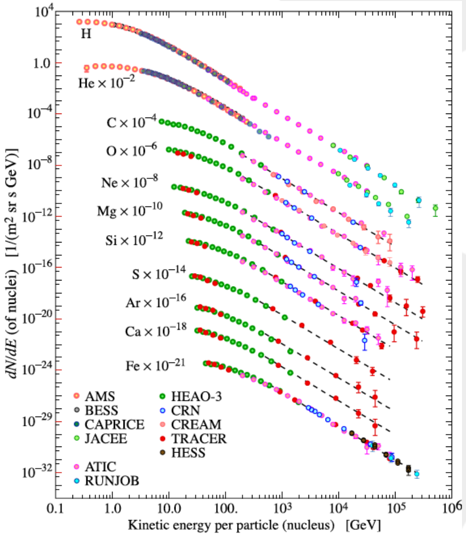
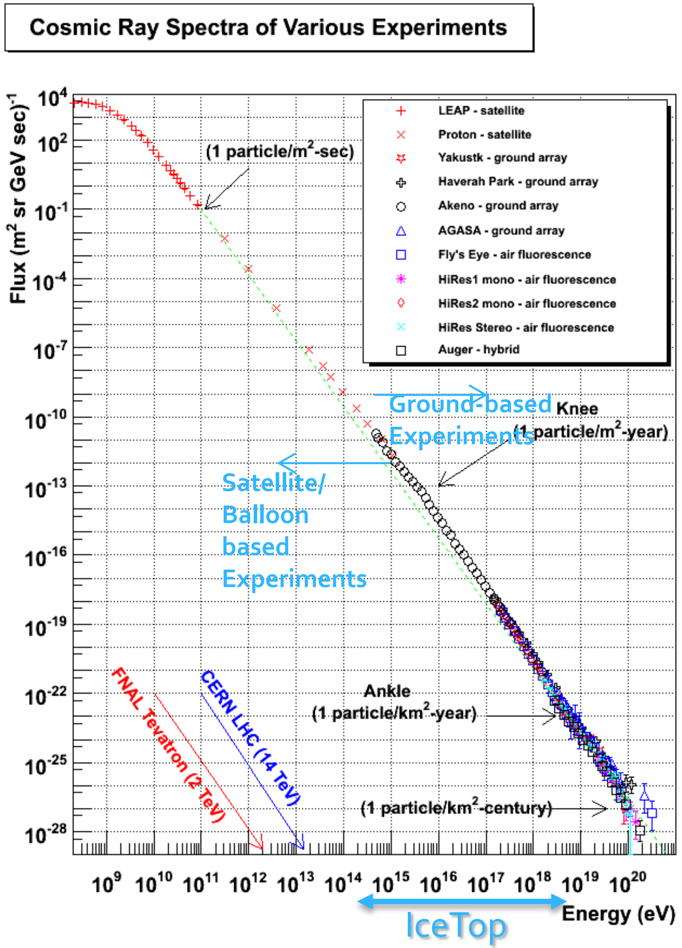
Cosmic Rays

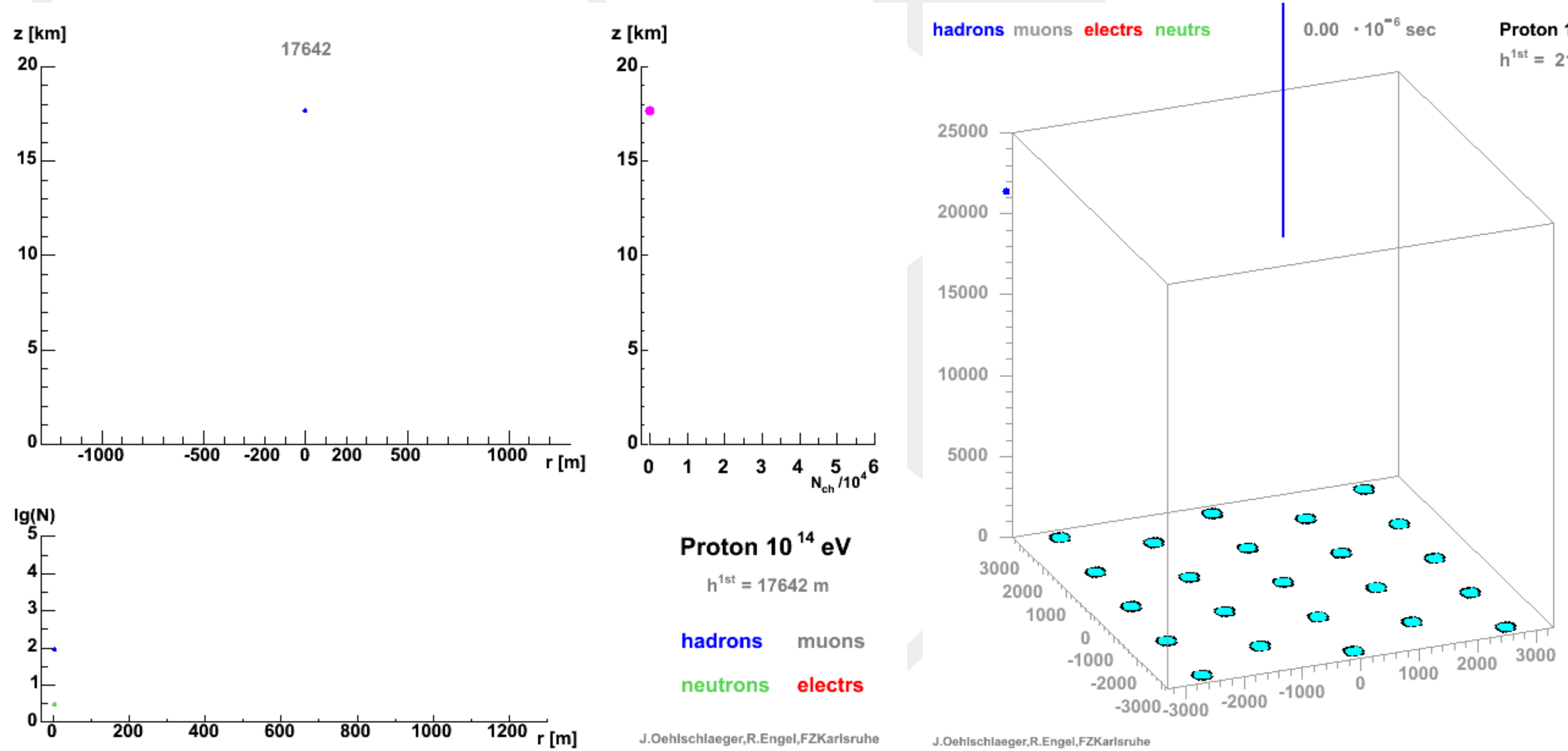
- Ionized nuclei and e^+, e^-, $\bar{p}$
- Relativistic energies : 10^6 - 10^{20} eV
- $E^{-2.7}$ / $E^{-3.0}$ spectrum
- CR composition





Extensive Air Showers

100 TeV Proton Shower



Movies have been created by J. Oehlschläger and R. Engel, KIT.

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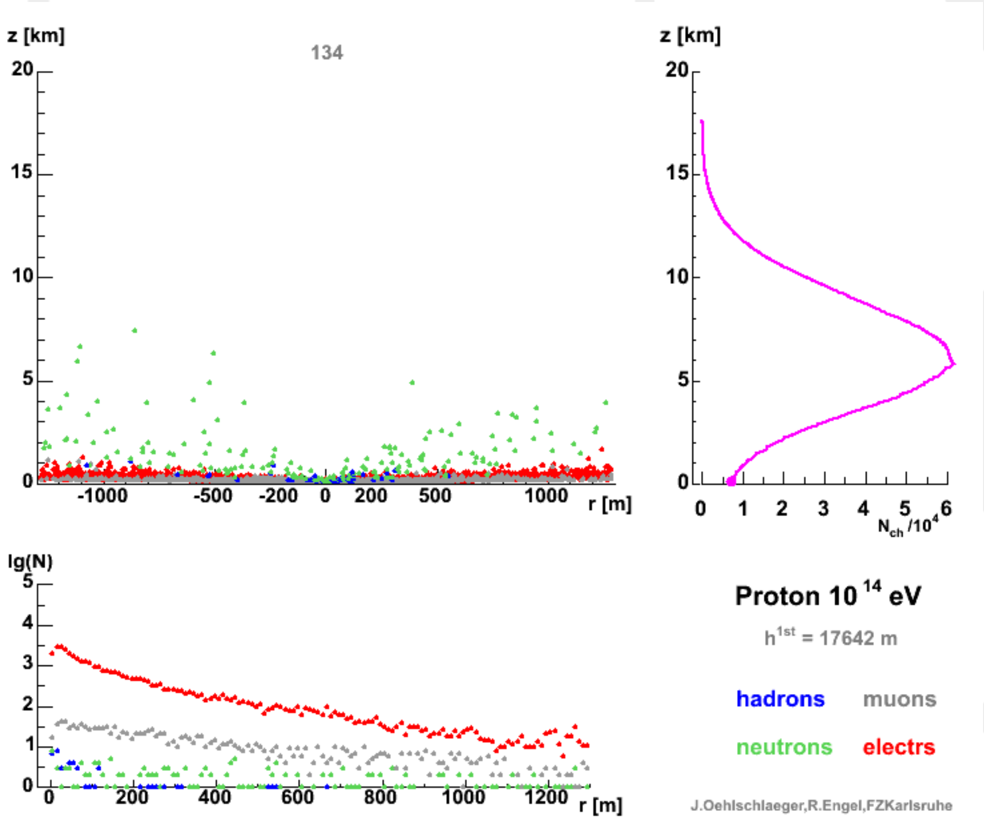

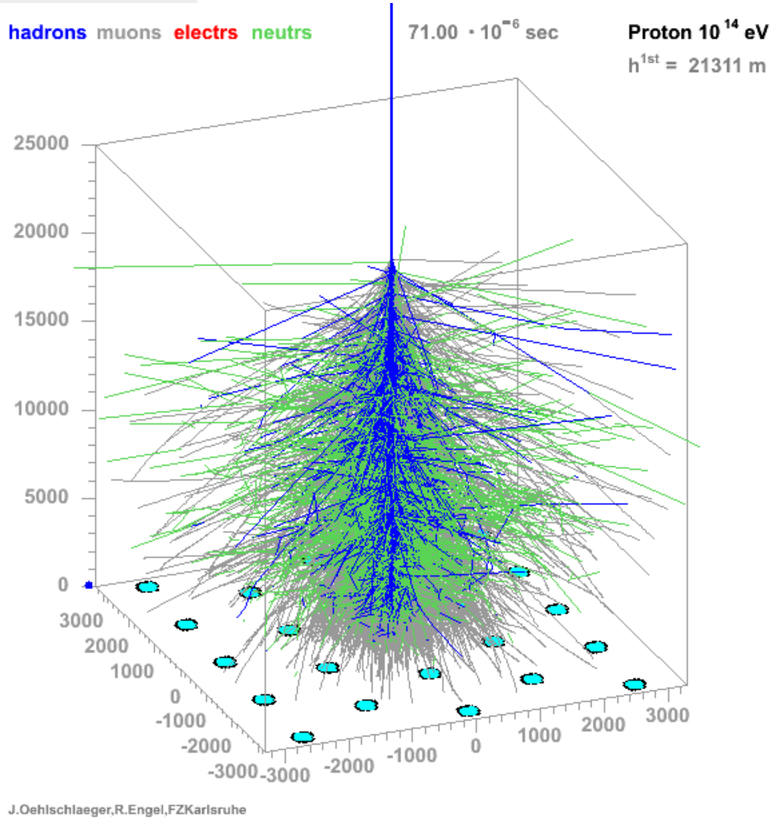

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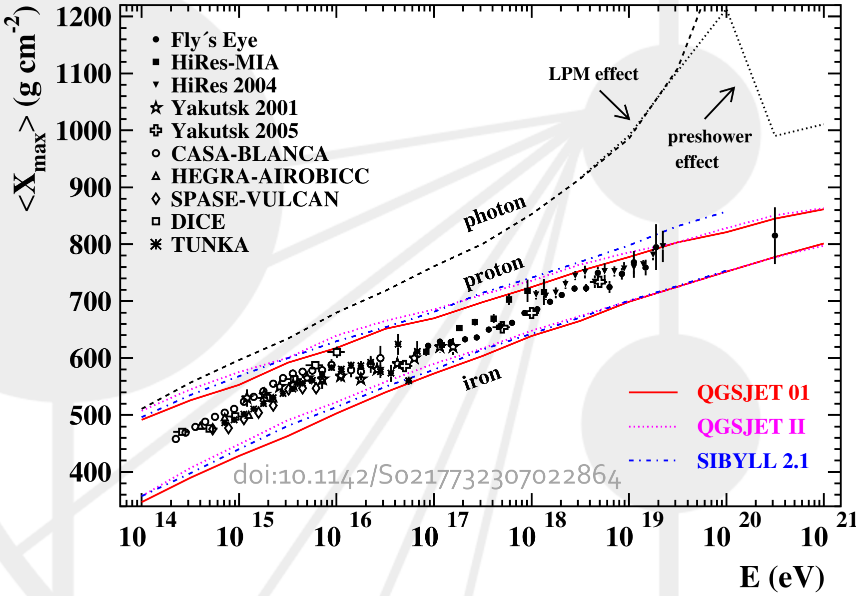
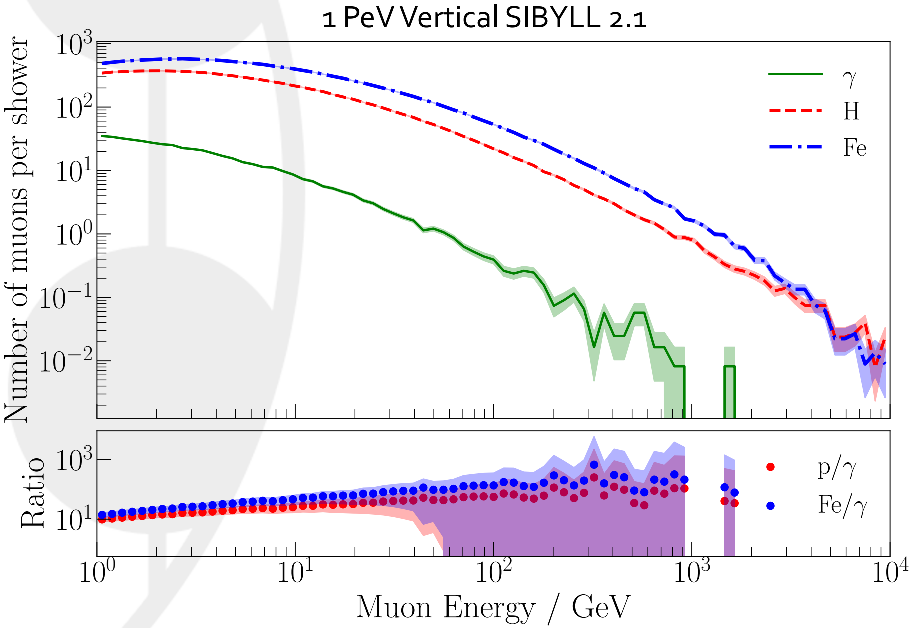
Air Shower Characteristics

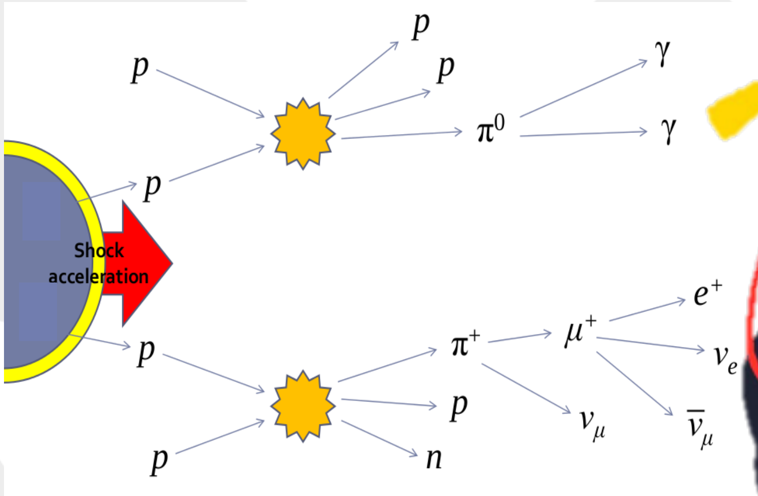


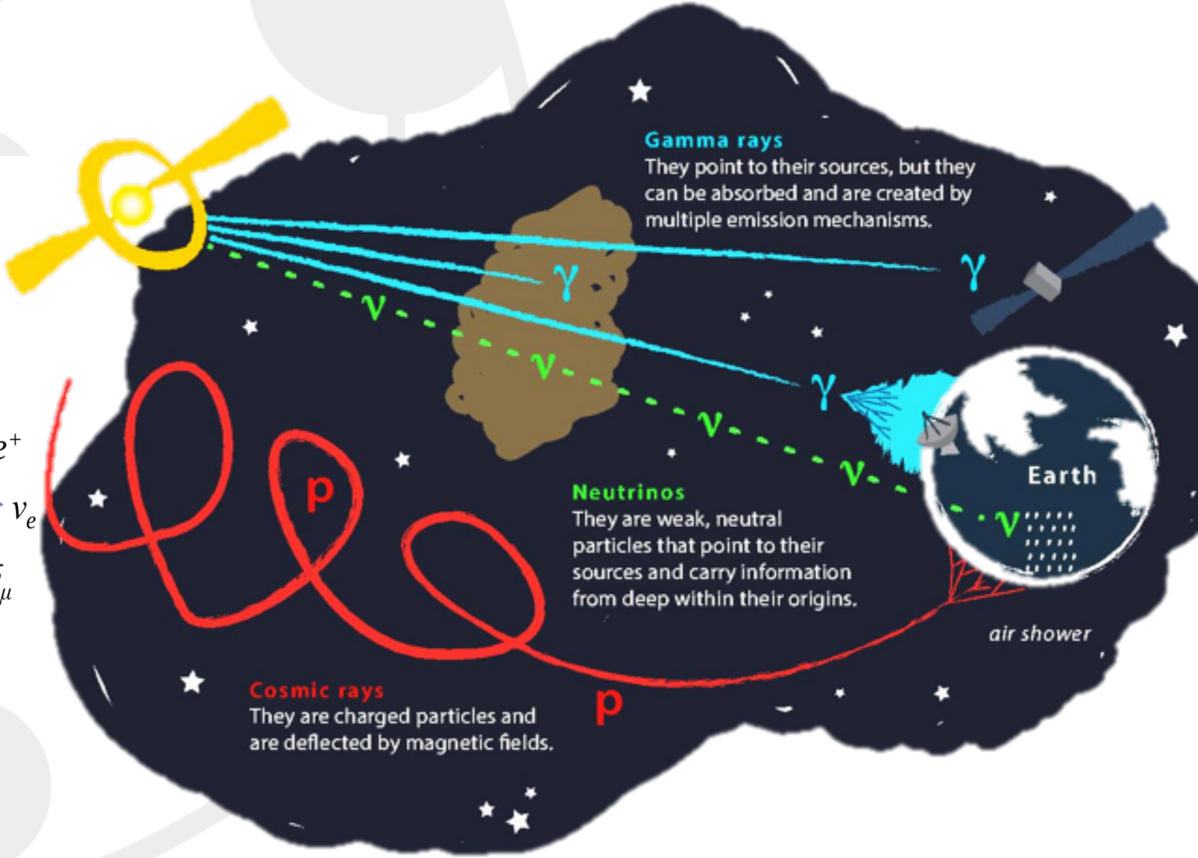


Photon, proton showers reach their maximum size deeper into atmosphere as compared to heavier nuclei

Photon showers have fewer GeV muons and even fewer TeV muons

Neutral Messengers: γ-rays and $\nu's$





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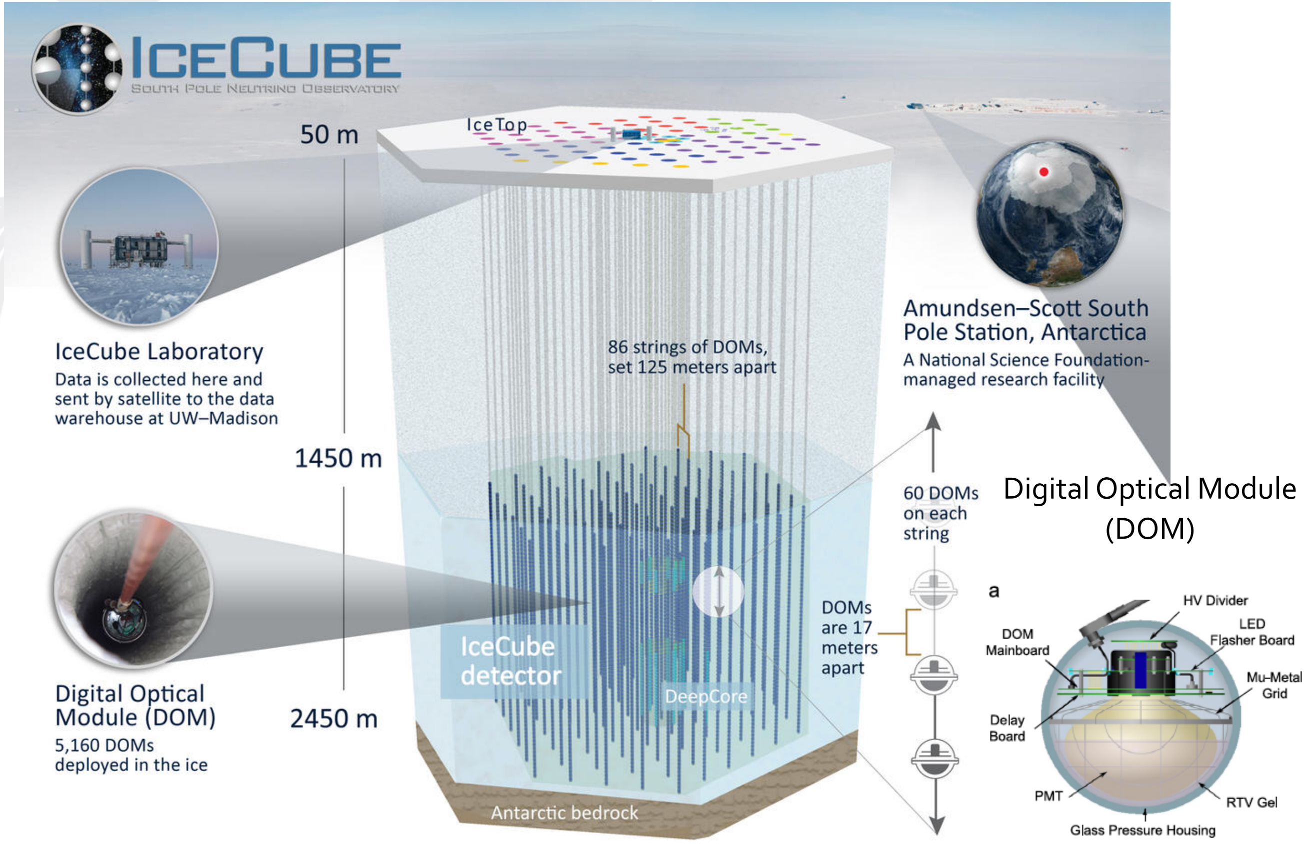
IceCube Observatory

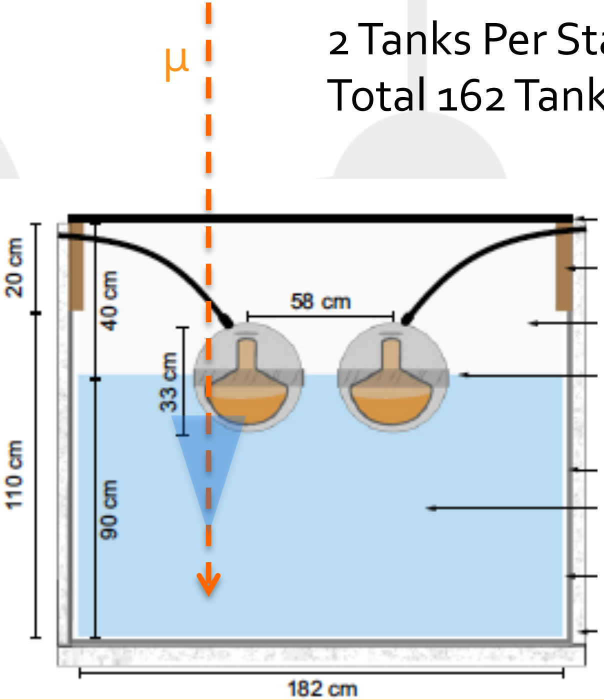
Detection Principle

Measure Cerenkov radiation emitted by particles moving at speeds greater than the speed of light in the medium (Ice)

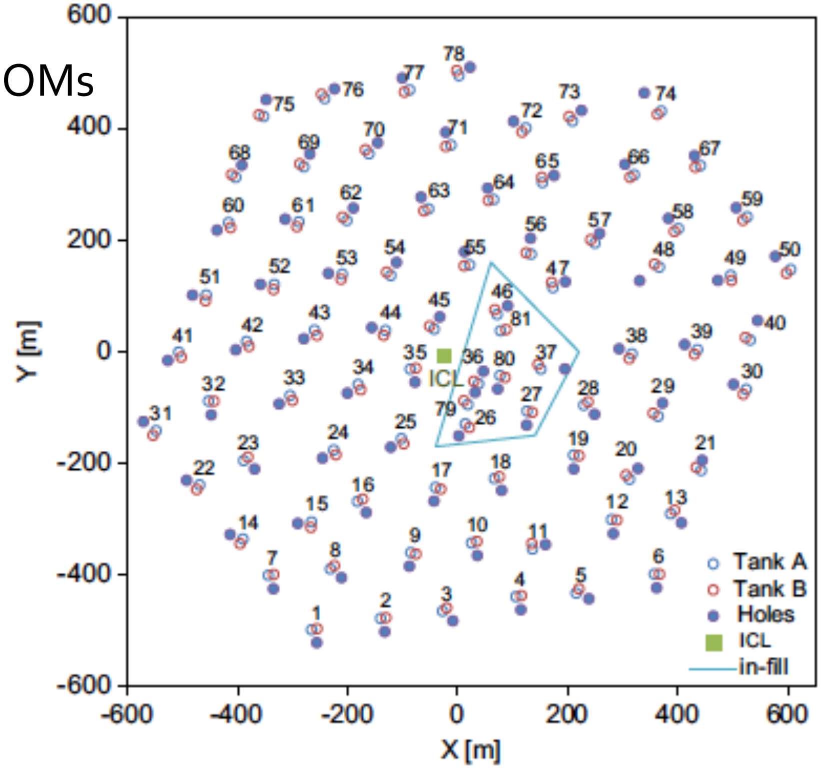


IceTop Surface Air Shower Array

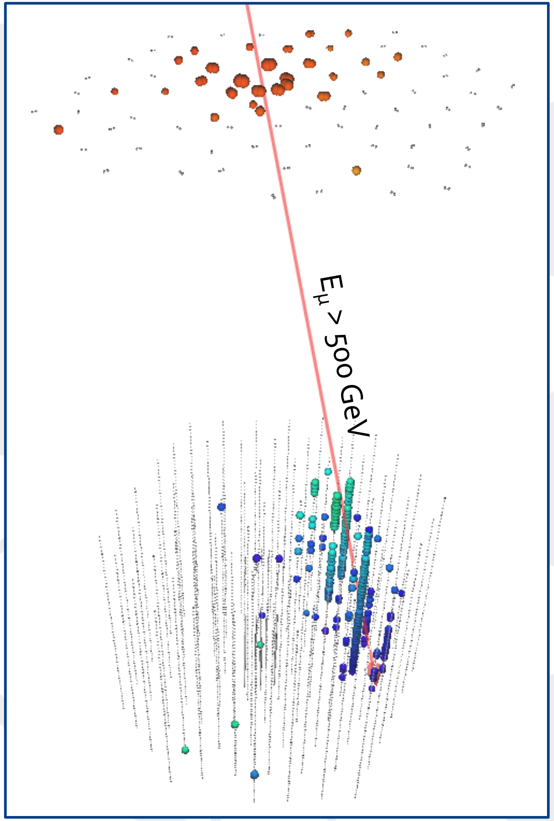
2 Tanks Per Station
Total 162 Tanks, 324 DOMs



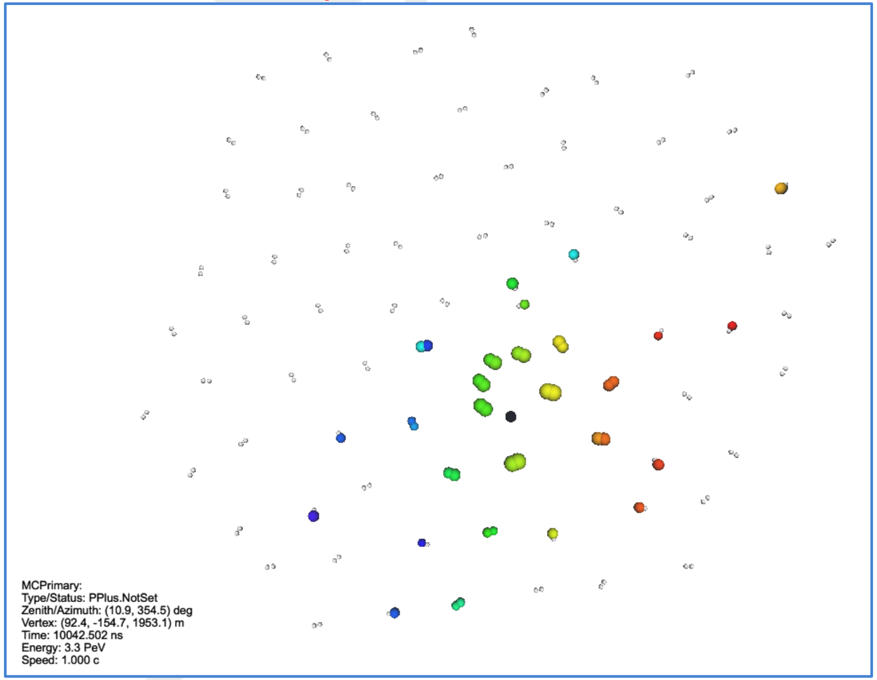
1 VEM= Vertical Equivalent of Muon



Air Shower Event in IceCube & IceTop

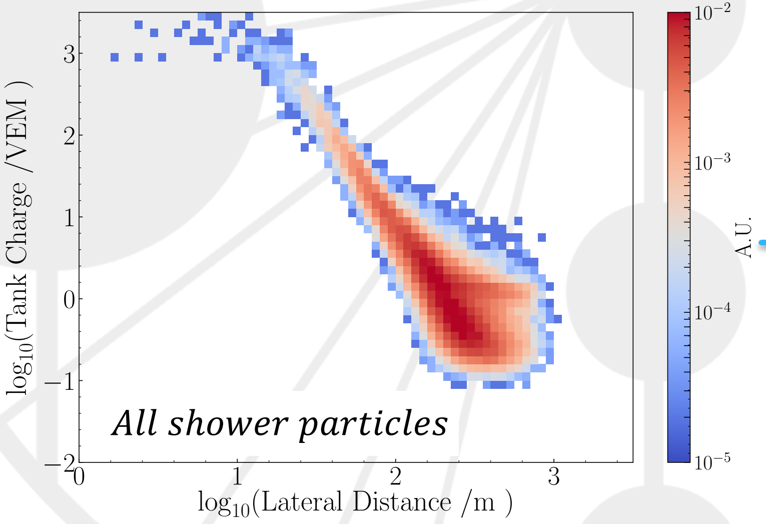


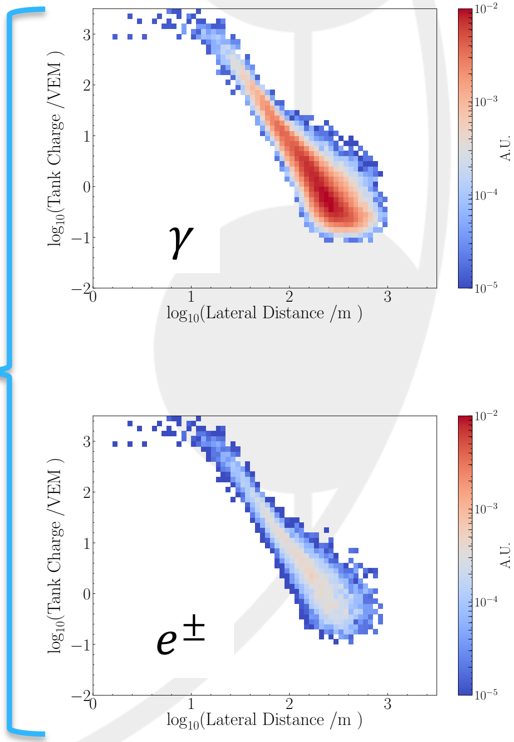
Red→ Early, Blue→ Late



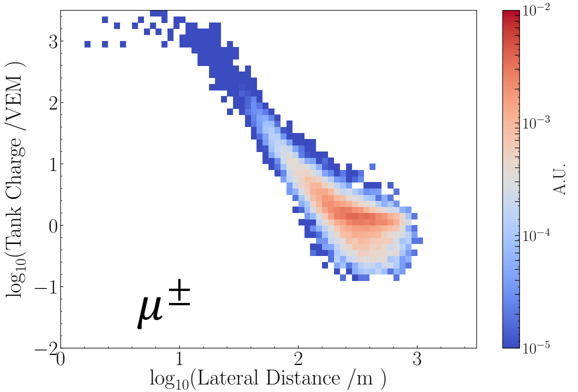
IceTop Response To Shower Components

Energy Deposited
Vs.
Dist to Shower Axis





The Muon Thumb

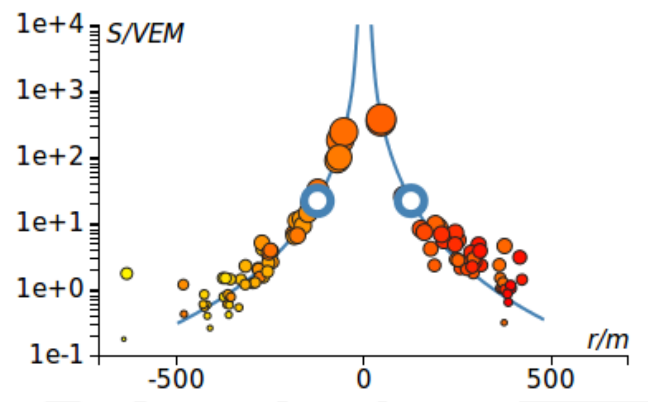


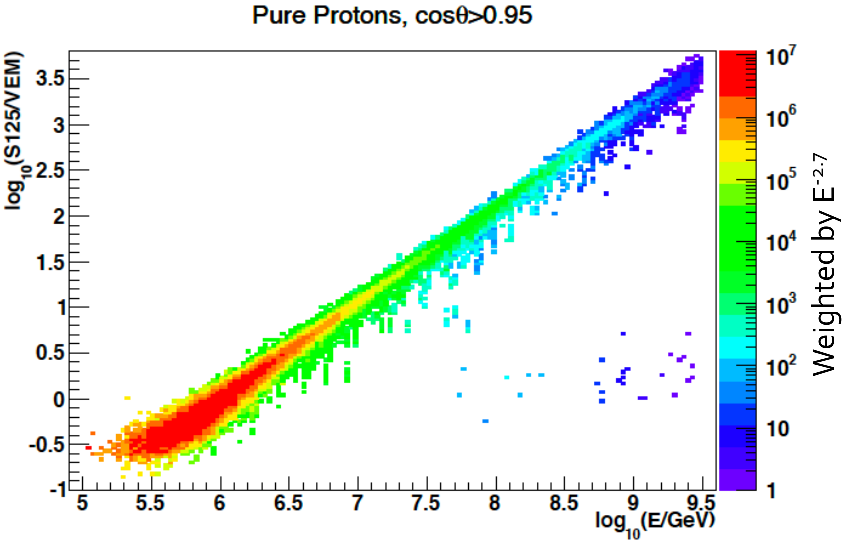
IceTop Energy Reconstruction

Lateral Distribution Function

$$S(R) = S_{125} \left(\frac{R}{125\ m}\right)^{-\beta - 0.303 \log_{10}\left(\frac{R}{125\ m}\right)}$$

Signal at 125m (S_{125}) = Energy Proxy





https://doi.org/10.1103/PhysRevD.100.082002

FIG. 7. Relationship between S_{125} and primary energy: updated version of Figure 4 from [5], for primary protons at high ($\cos(\theta) \geq 0.95$) zenith angles.

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Measuring Spectrum and Composition

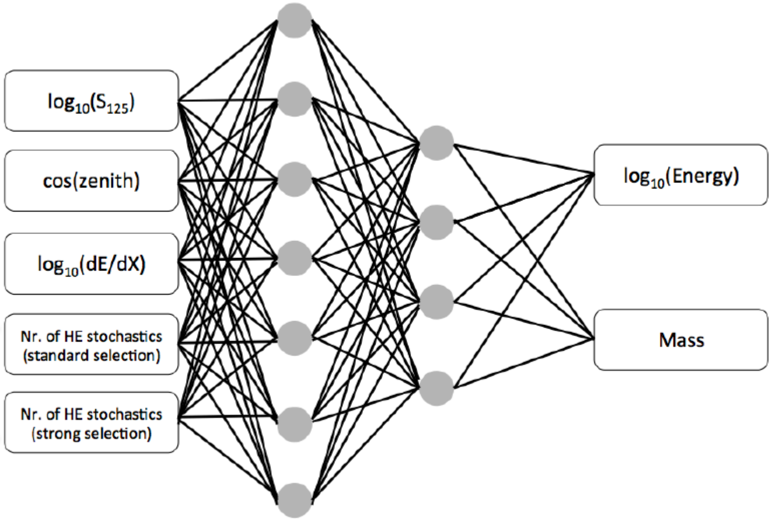
Neural Network For Energy / Mass Reconstruction

Energy Proxy

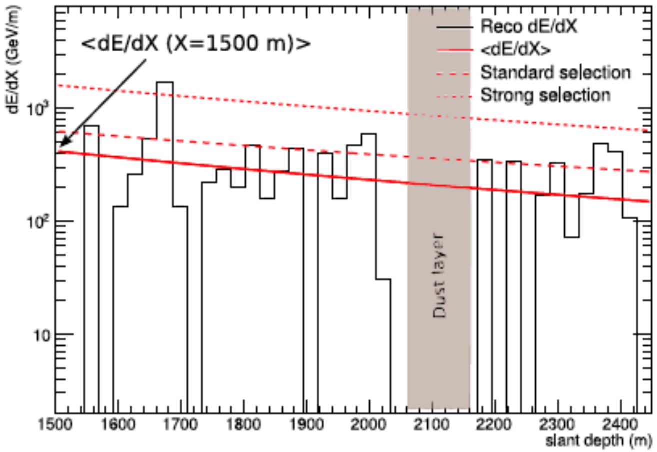
Direction

Muon Bundle Energy Loss InIce

Muon Bundle Stochastic Losses



Muon Energy Deposition in Ice



Air shower muons with energy > 500 GeV will deposit energy in IceCube

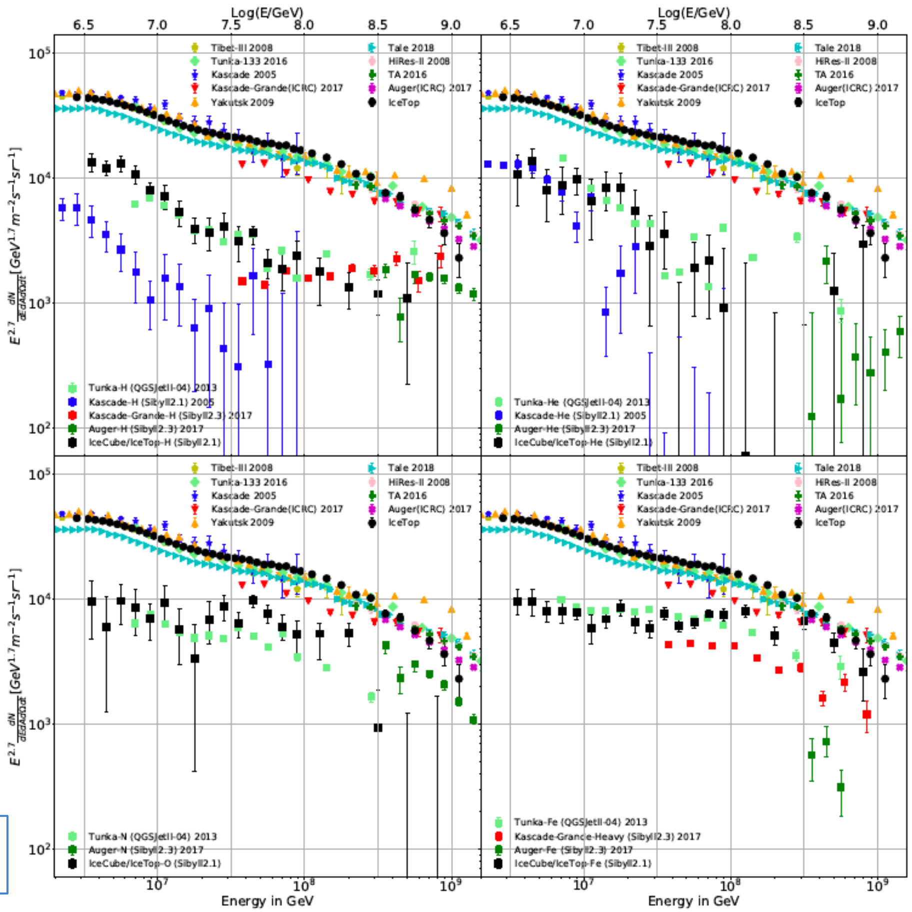
Measuring Spectrum and Composition

H

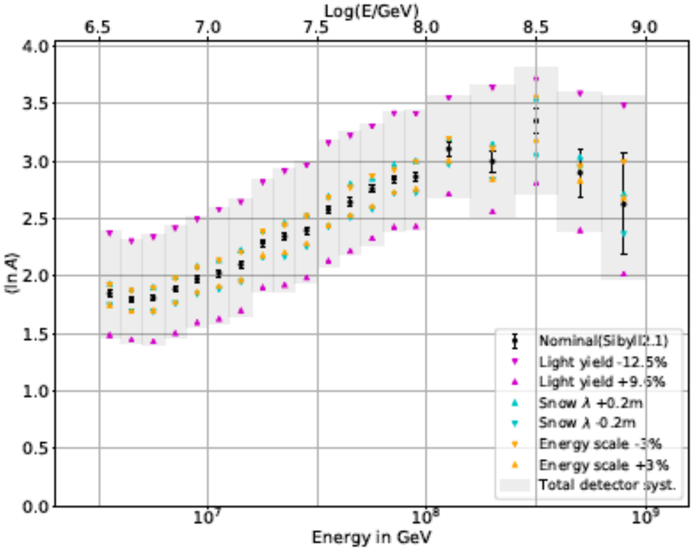
He

N/O

Fe



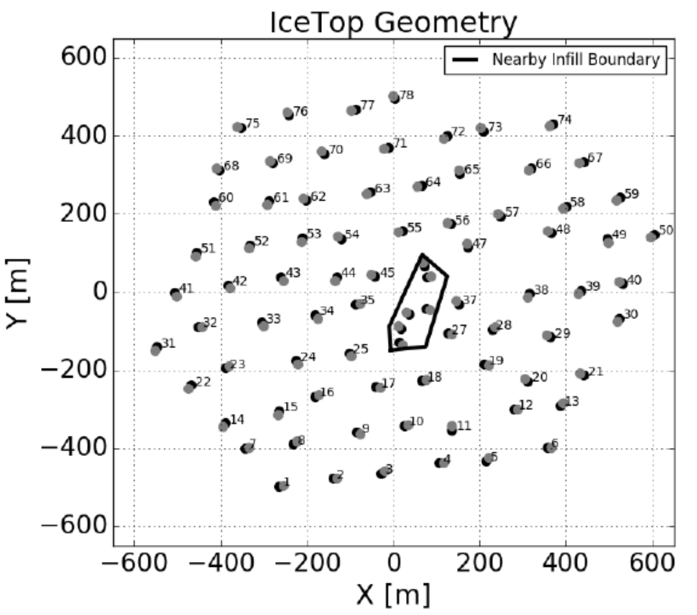
Mean ln(A) Vs. Energy

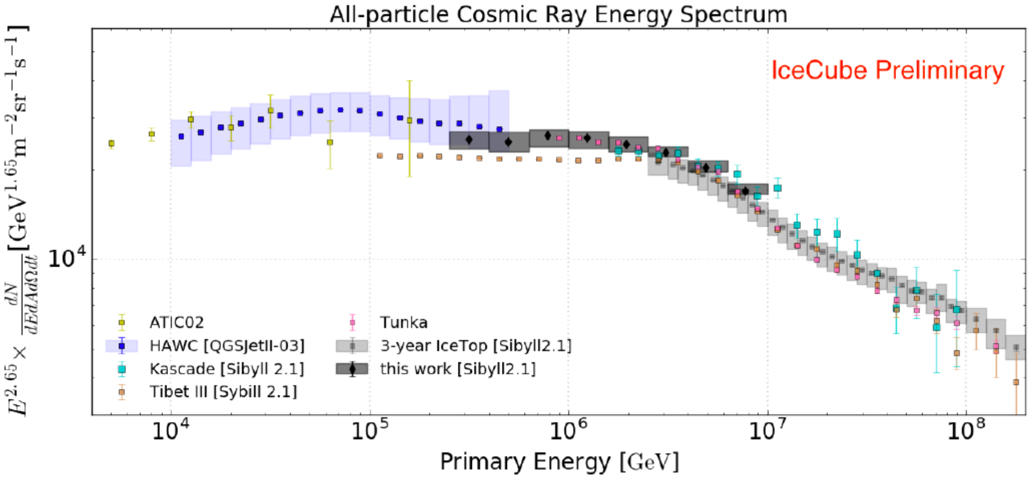


https://doi.org/10.1103/PhysRevD.100.082002

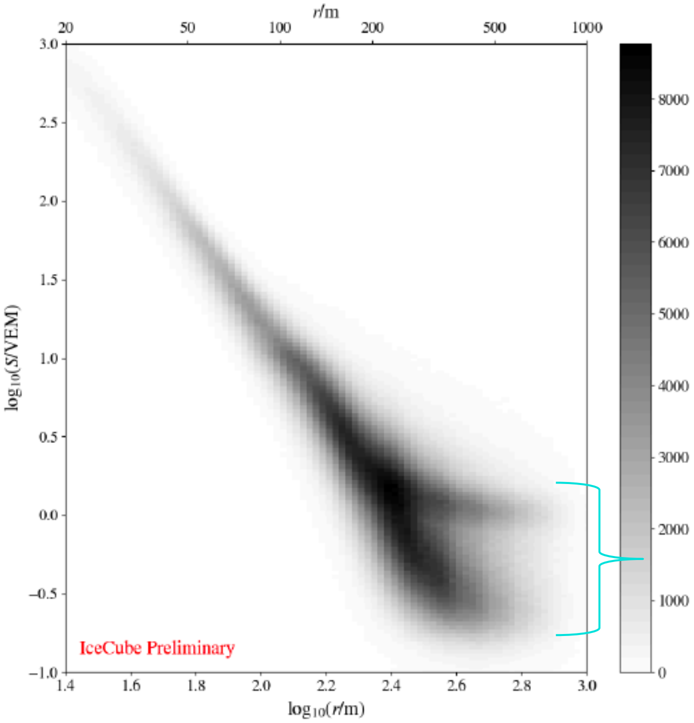
Measuring CR Spectrum below PeV

Triggering on InFill stations with separation < 50 m

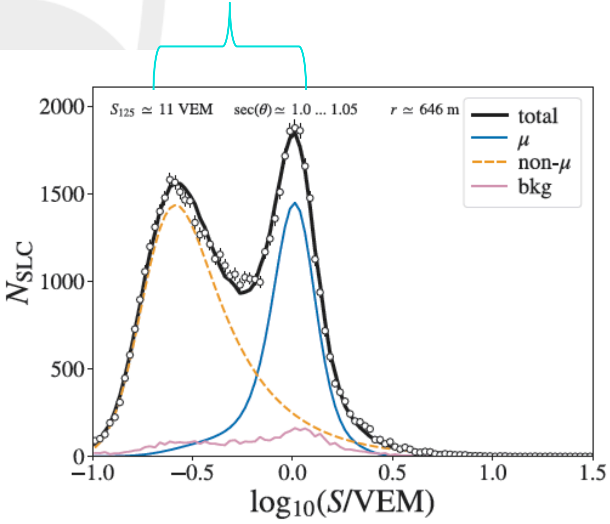




GeV Muon Density Measurement



- ✧ Lateral charge distribution based on only the stations where one of the two Tanks are hit.
- ✧ i.e. Biasing the selection towards muons



GeV Muon Density Measurement

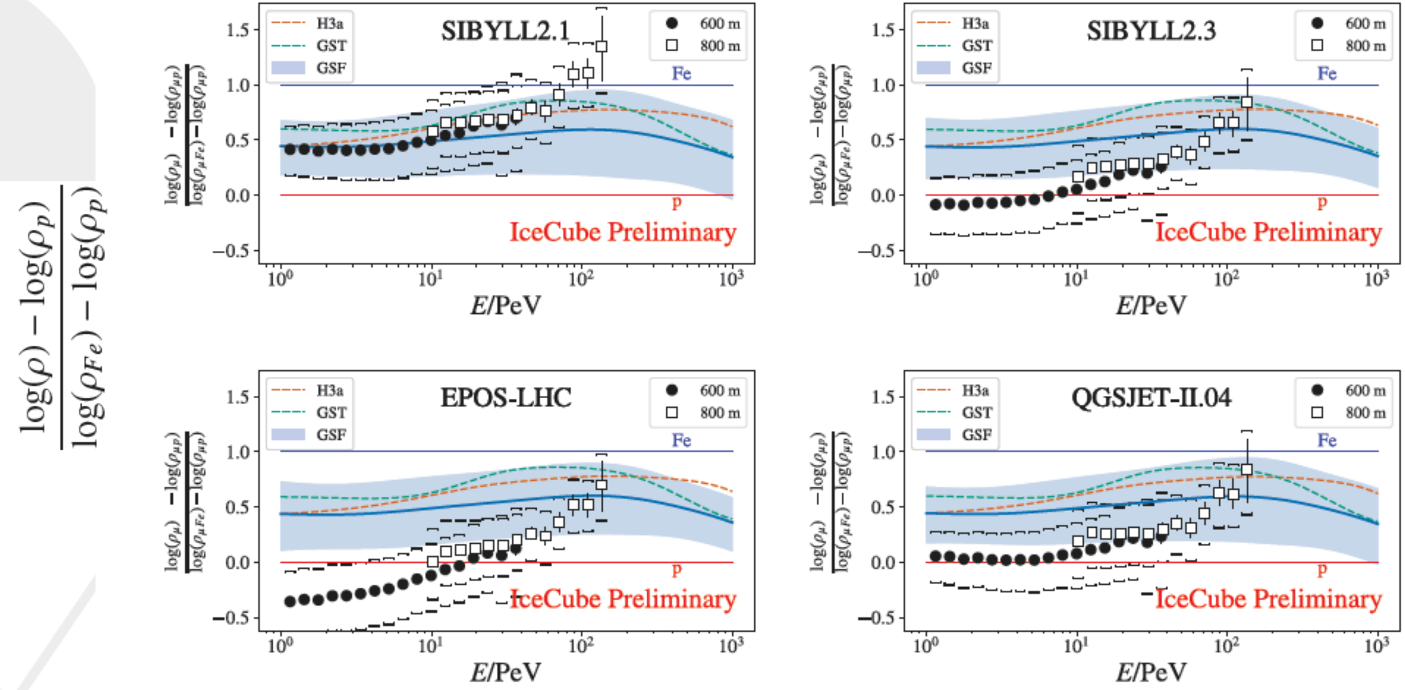


Figure 8. Measured muon density divided by the muon density in air showers for a pure-proton flux and scaled by the difference between iron and proton (see equation 4).

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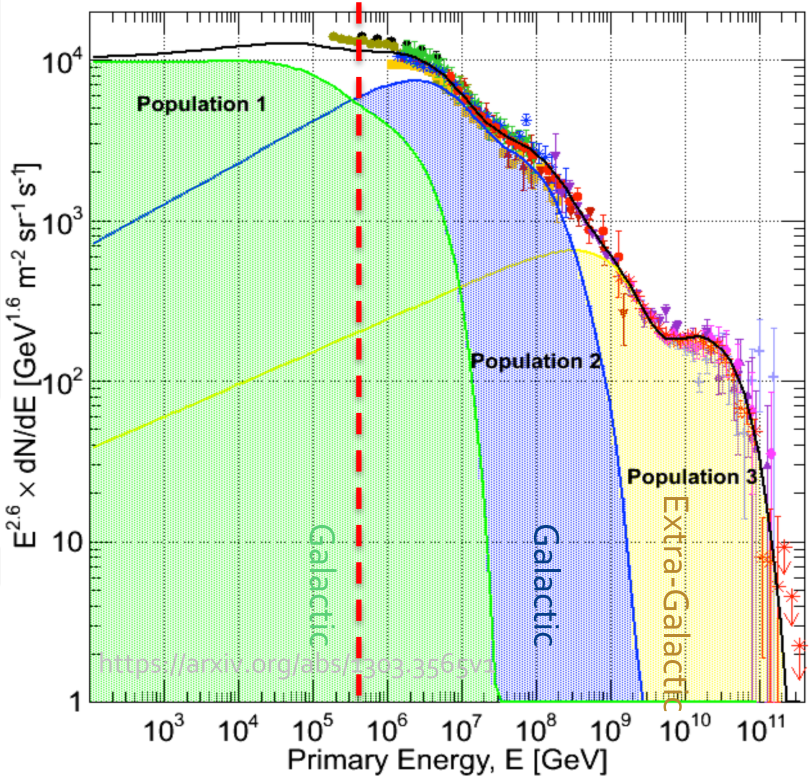
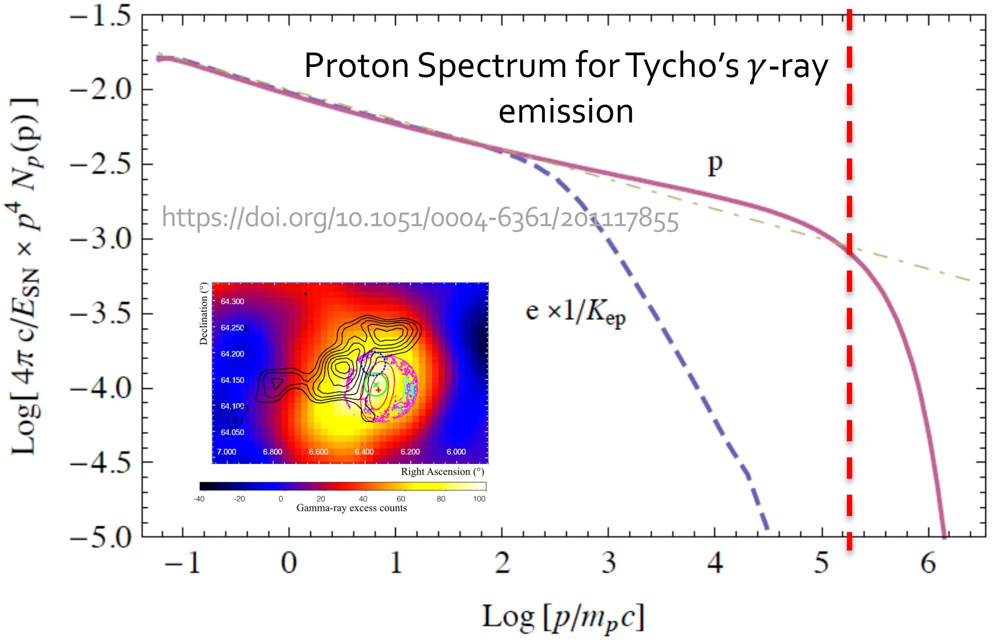
PeV γ-rays Produced At CR Acceleration Sites

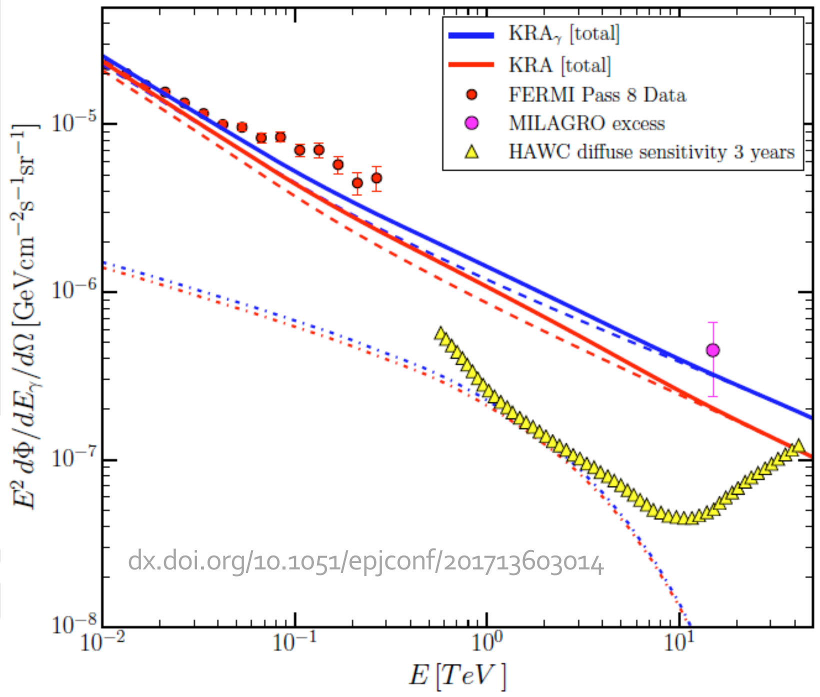
Hypothesis For Origin of Cosmic Rays



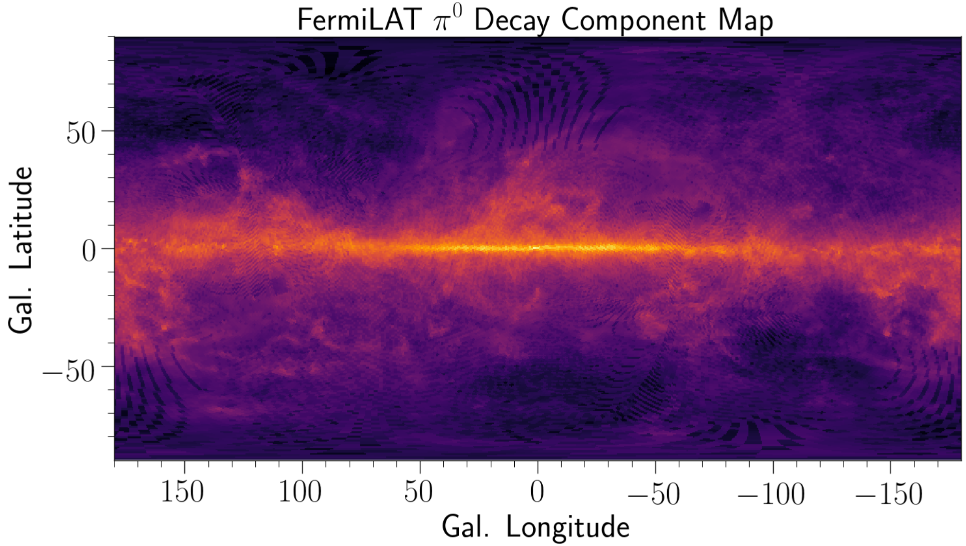
- SNRs can explain CRs at most up to 10^5 GeV
- What about higher energy CRs?



PeV γ-rays Produced in CR collisions with ISM



- Diffuse emission measured in TeV range
- Probes cosmic ray diffusion through the Galaxy
- Is cosmic ray spectrum constant throughout Galaxy or gets harder near the center?

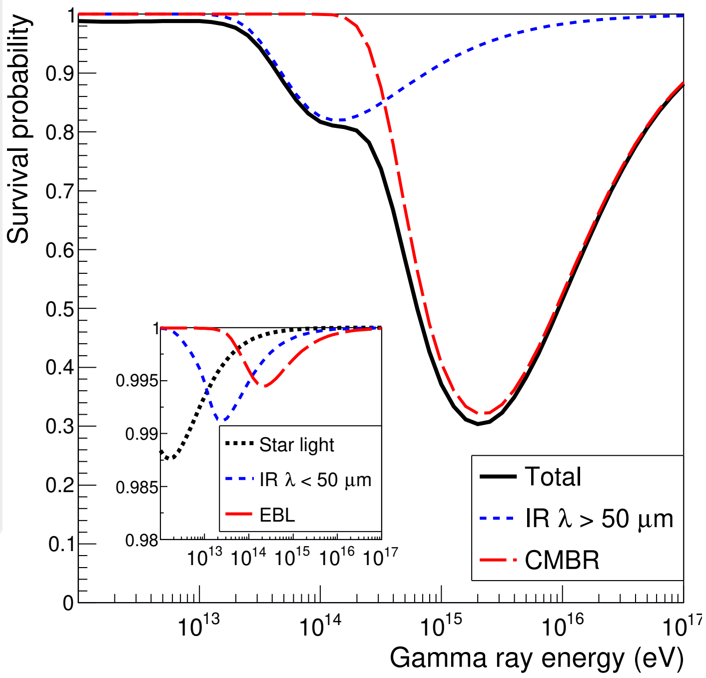


https://doi.org/10.3847/1538-4357/ab6d67

PeV γ-ray Attenuation

- Gamma rays pair produce via interaction with background radiation fields
  - Infra-red (IR)
  - Cosmic microwave background (CMB)
- $\gamma + \gamma_{CMB} \rightarrow e^+ \ e^-$ dominates in PeV regime
- Attenuation is most significant at ~2 PeV where IceCube is most sensitive to γ-rays
- Only Galactic PeV γ-rays can be observed

PeV γ-rays from Galactic center



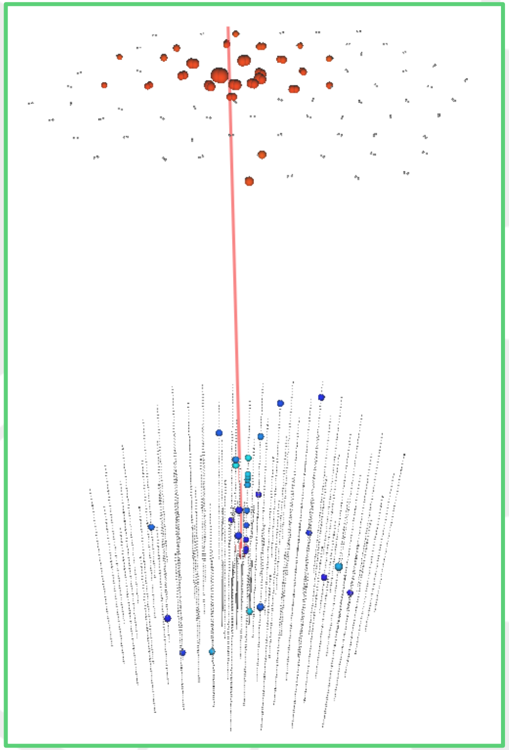
Classify γ-ray and CR showers

- Expected fraction of γ-rays in the IceCube air shower data is less than 1 for every 10^4 CR showers ! (∵ CASA-MIA result)

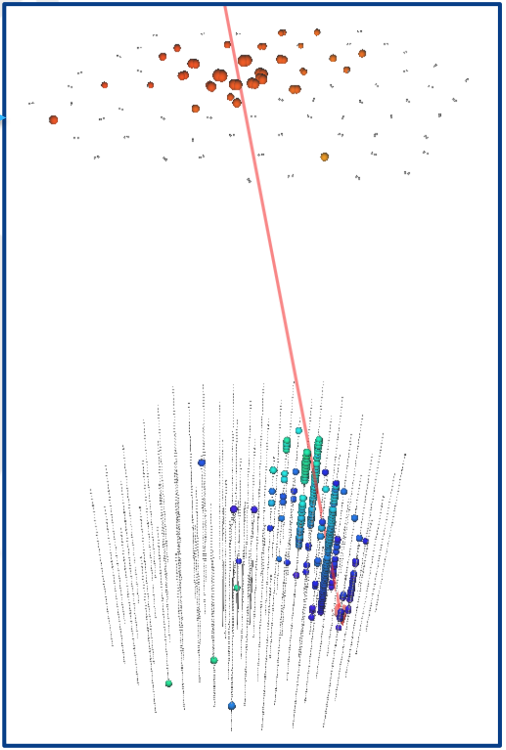
- What shower properties separate γ-rays from CRs?

γ-ray Candidate in IceCube

γ-ray Simulation



Proton Simulation



Shower Footprint Differences

Due to Depth of Shower Maximum ,
Local Charge Fluctuations,
GeV Muon count

TeV Muon Count

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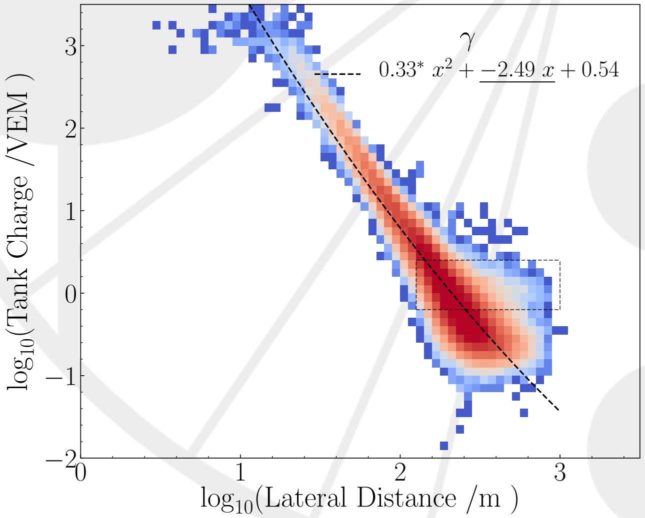
IceTop Radial Distribution of Charges

- Distribution of tank charges as a function of distance to the shower core
- ↑ Primary Mass ⇒ ↑ Muons , ↓ Slope, ↑ Local Charge Fluctuations

- $0.8 \leq \log_{10}(S_{125}) < 0.9$ i.e. ≈6.3 PeV
- $0.85 \leq \cos(\theta) < 0.9$

γ-ray Simulation



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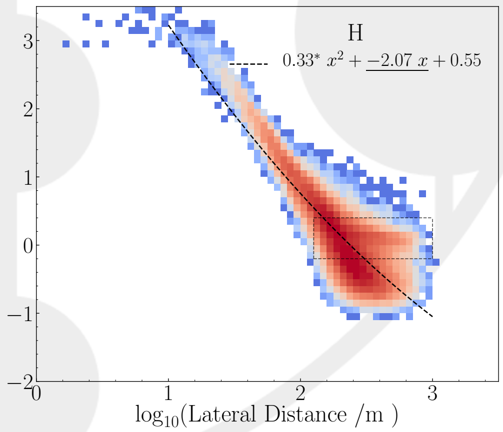
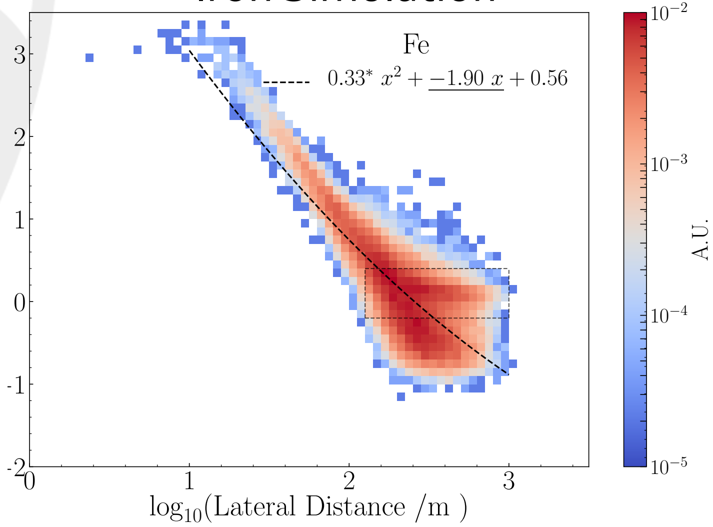


Iron Simulation



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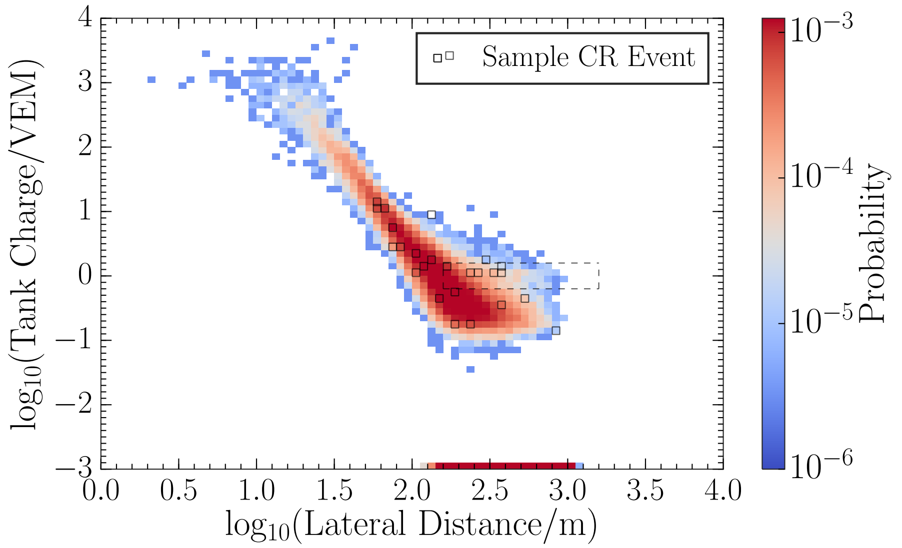
IceTop Log-likelihood Ratio (IT-LLHR)

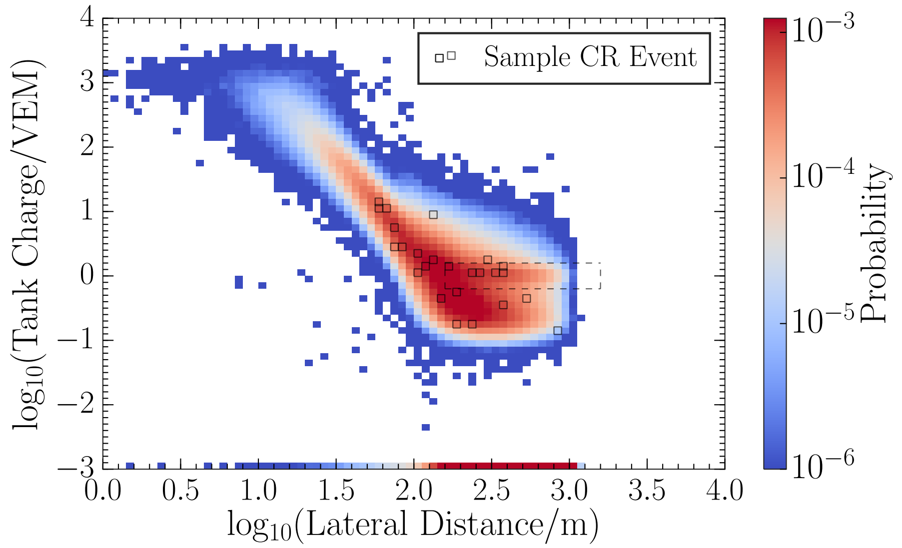
- Log-likelihood ratio for event classification between class A and B is defined as,
  - $\Lambda_{A,B} = \log_{10}\left(\frac{L_A}{L_B}\right)$
  - $L_A = \prod_{i=1}^{162} P\,(q_i, t_i, r_i \mid H_A)$
  - P = probability for observing an IceTop tank with q_i, t_i, r_i under hypothesis H_A
- IT-LLHR gives the degree to which an event favors one class over the other
- For IceTop, the hypotheses are normalized histograms (PDFs) in charge/ time/ distance dimensions.

IceTop Log-likelihood Ratio (IT-LLHR)

$H_{\gamma,QR}$ Constructed From Simulations



$H_{CR,QR}$ Constructed From Data



$$L_{\gamma,QR} = \prod_{i=1}^{162} P\left(q_i, r_i \mid H_{\gamma,QR}\right)$$

$$\Lambda_{CR,\gamma}(QR) = \log_{10}\left(\frac{L_{\gamma,QR}}{L_{CR,QR}}\right)$$

$$L_{CR,QR} = \prod_{i=1}^{162} P\left(q_i, r_i \mid H_{CR,QR}\right)$$

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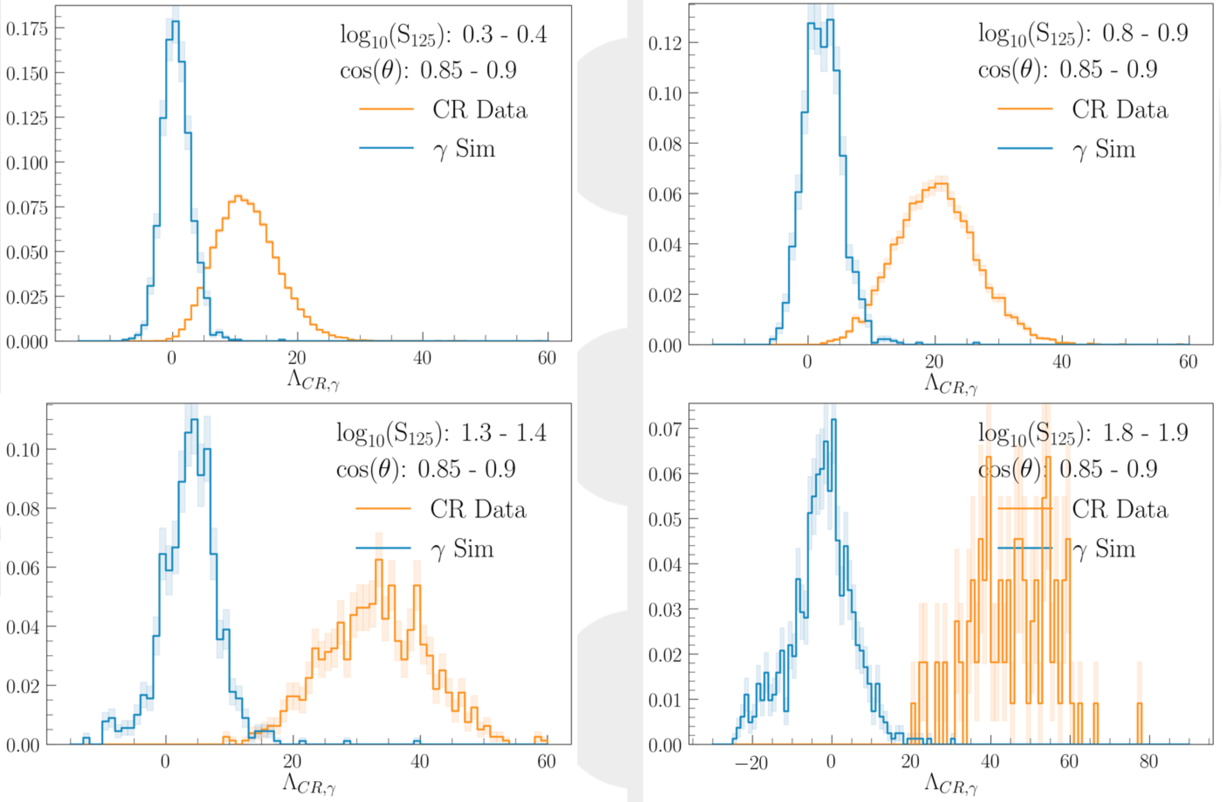
Combined IT-LLHR

$$\Lambda_{CR,\gamma} = \Lambda_{CR,\gamma}(Q\ R) + \Lambda_{CR,\gamma}(Q\ \Delta T) + \Lambda_{CR,\gamma}(\Delta T\ R)$$



- Can also use these PDFs :
  - Charge Vs Time ($Q\ \Delta T$)
  - Time Vs Radius ($\Delta T\ R$)

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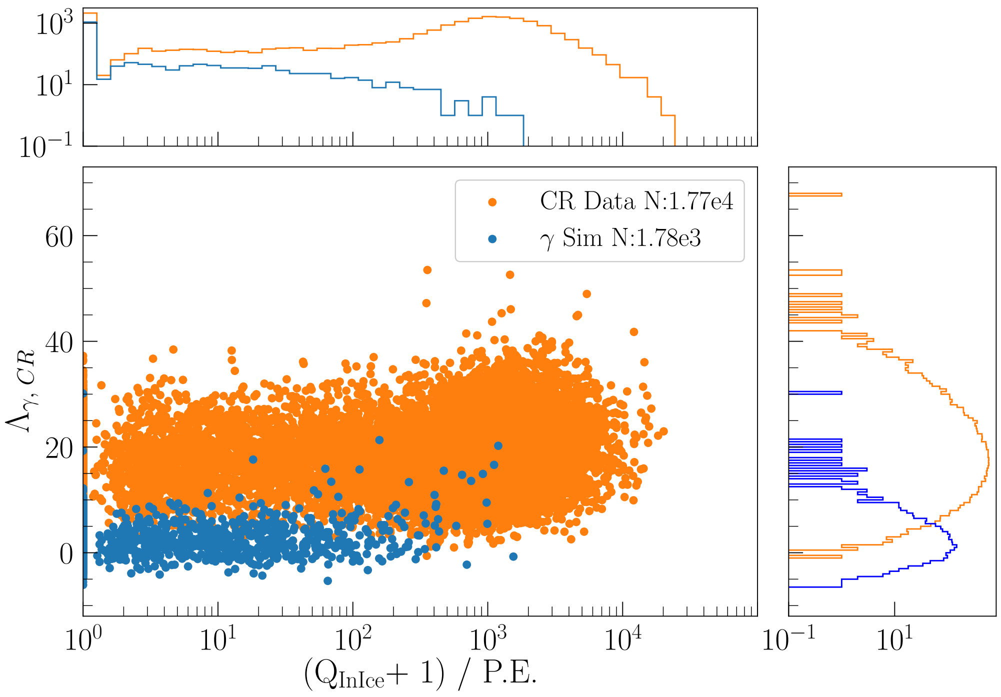
IceTop + IceCube Gamma-Hadron Separation

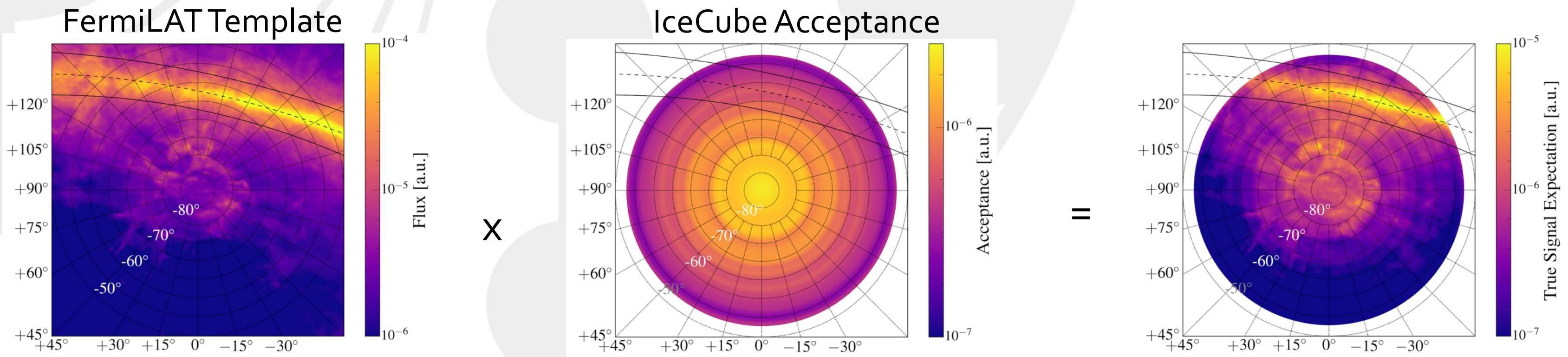
- The total charge from the In Ice Muon: Q_{InIce}
- The following features are used in a Random Forest classifier:
  - $\log_{10}(S_{125})$, $\cos(\theta)$, $\Lambda_{CR,\gamma}$, Q_{InIce} , C
  - C = parameter for shower axis' containment within in-ice array
- A sample of γ-ray like events is obtained based on the random forest score
  - Optimised to increase sensitivity in sky searches



Sky Searches for PeV Gamma Rays

- Unbinned maximum likelihood search for :
  - Point Sources in IceTop Field of View i.e. declination -90° to -55°
  - Diffuse emission from the Galactic plane

- Template used for diffuse emission expectation:
  - Neutral pion decay component from the fit to Fermi-LAT's data



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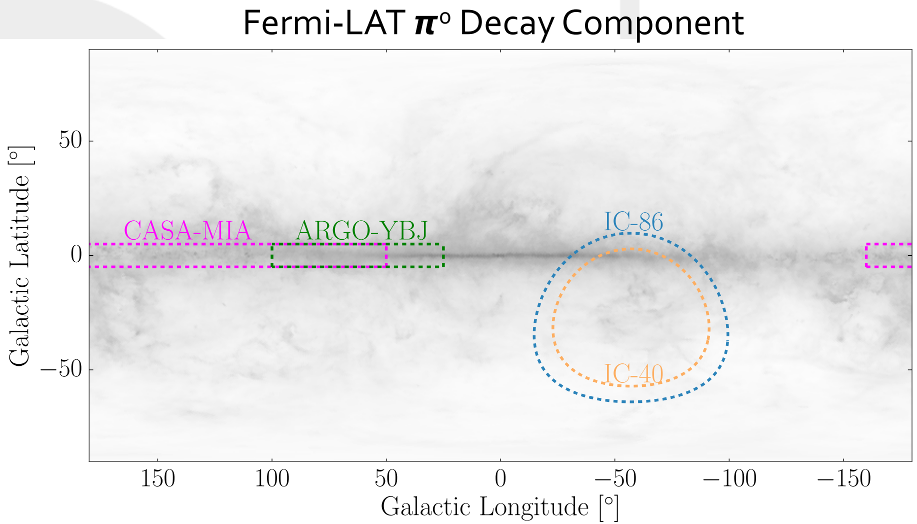
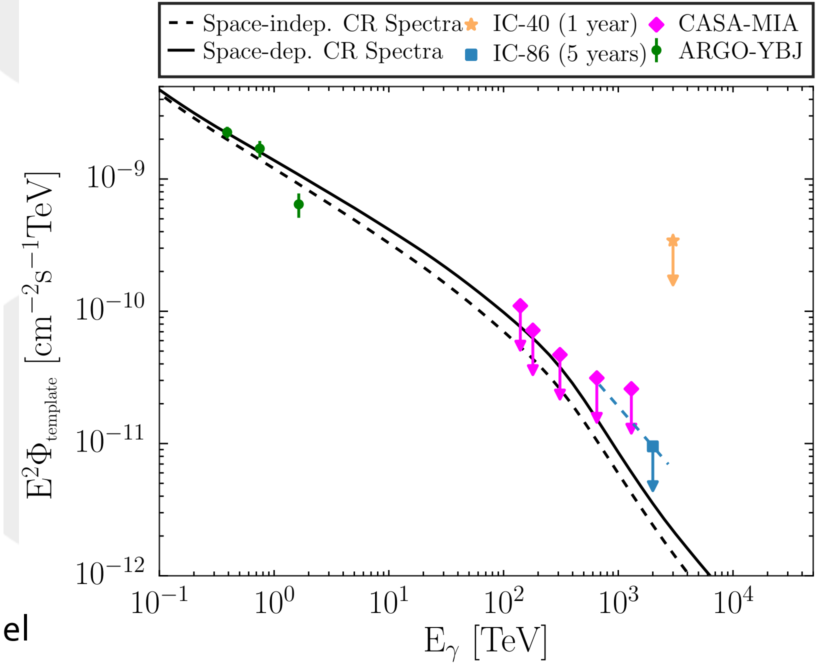
Diffuse Emission From Galactic Plane





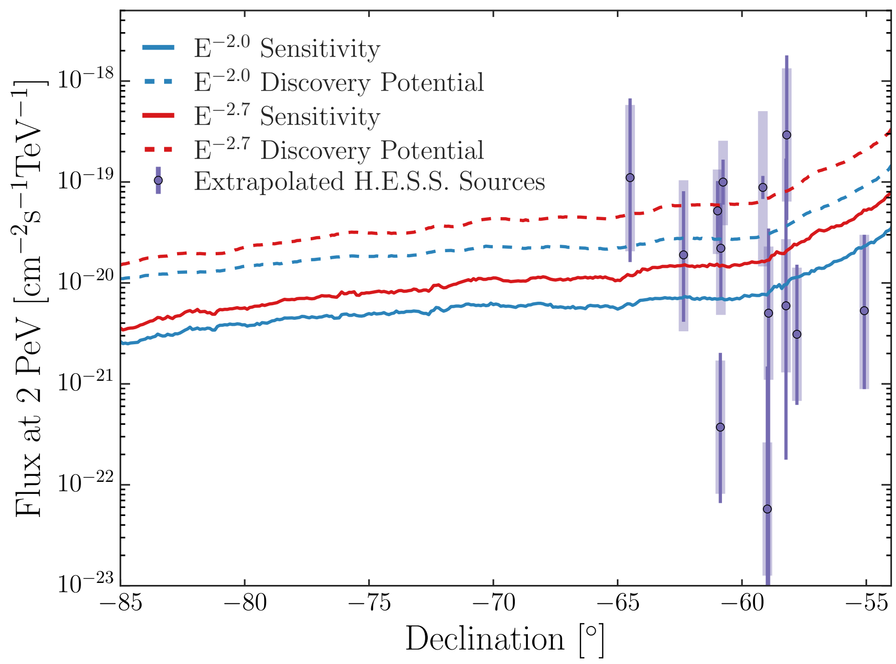
- Improvement over IC-40, more than 1 order of magnitude
- Slightly above the model predictions
- Strongest upper limit for E > 1 PeV

$$\Phi_{template} = \Phi\Delta\Omega \frac{\int_{all\ sky} S_{Fermi} d\Omega}{\int_{\Delta\Omega} S_{Fermi} d\Omega}$$

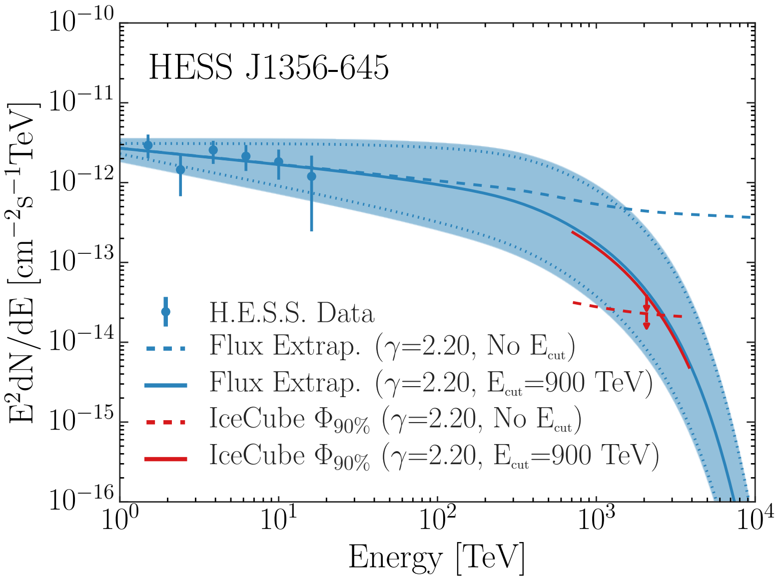
Result from Point Source Search

- No evidence of a point source in all sky search

Analysis Sensitivity to Point Sources



Maximum E_{cutoff} for some of the sources



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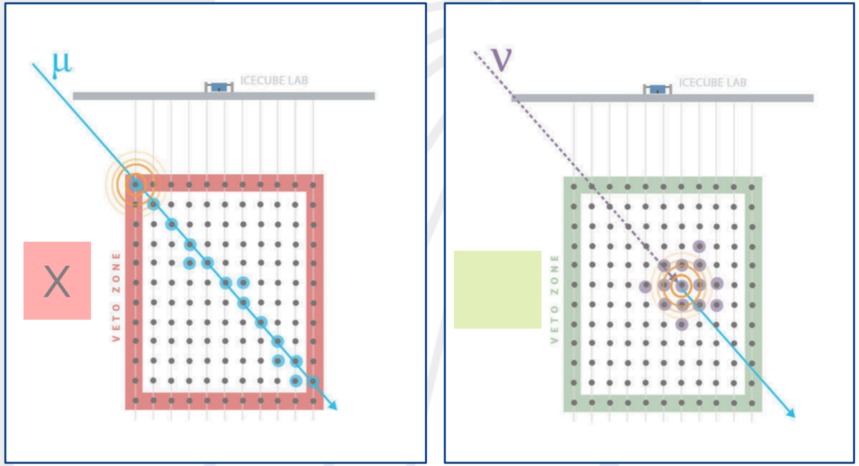
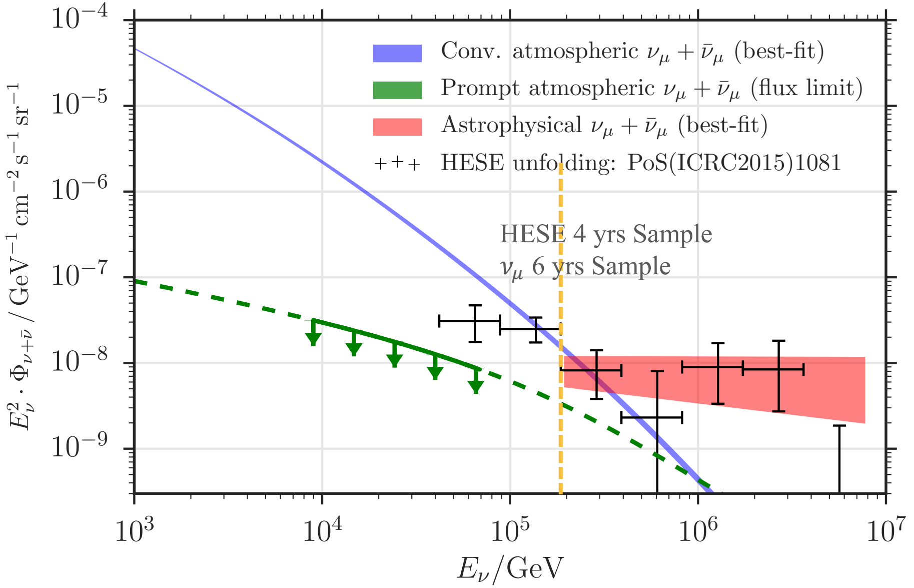
IceCube's High Energy ν Sample

Veto atmospheric (air shower) muons by requiring interaction inside the fiducial volume

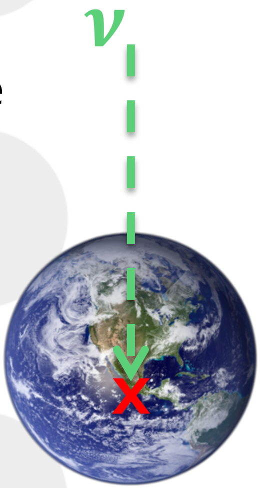


Atmospheric ν flux drops below Astrophysical flux above $E_\nu \approx 10^5$ GeV

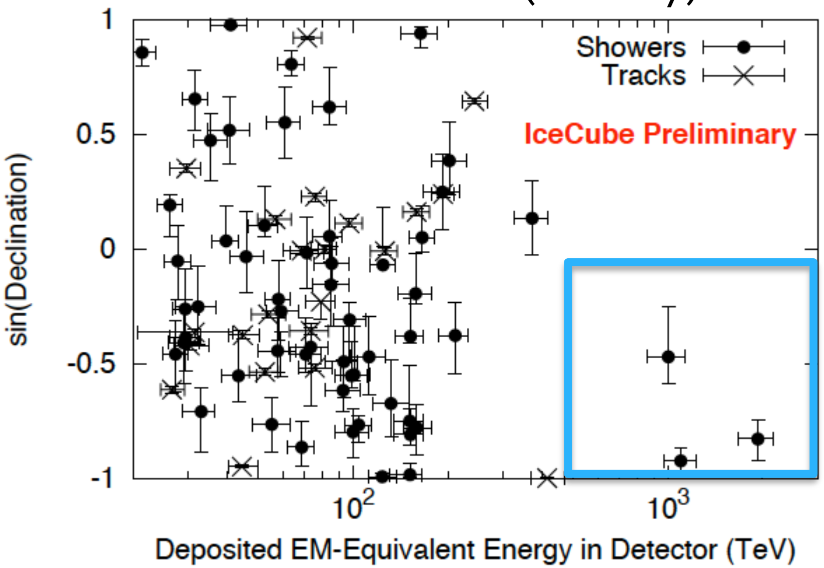


IceTop For ν Search

- High energy ν's cannot pass through Earth
  - $E_\nu > 100$ TeV, 30% neutrinos from sin(declination) = 1 will survive
  - $E_\nu > 1000$ TeV, 0% survive

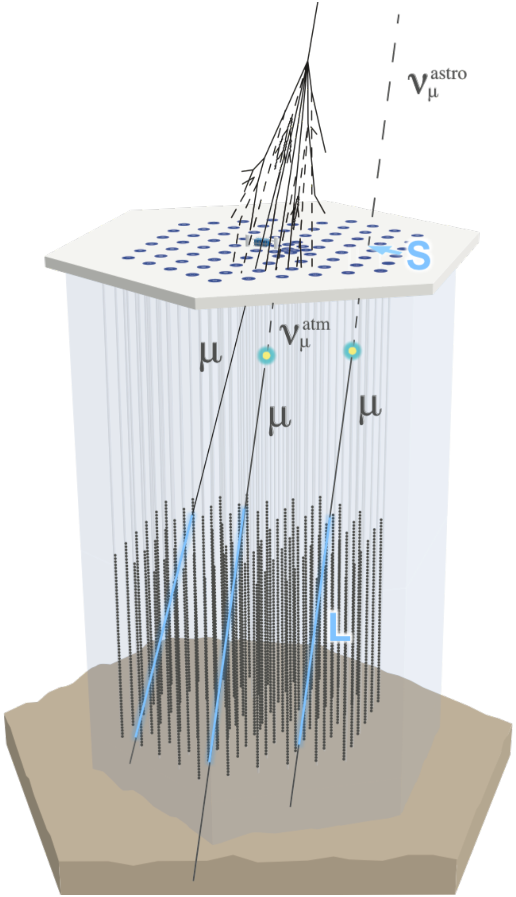


6 Yrs H.E.S.E. (ICRC'17)



IceTop For ν Search

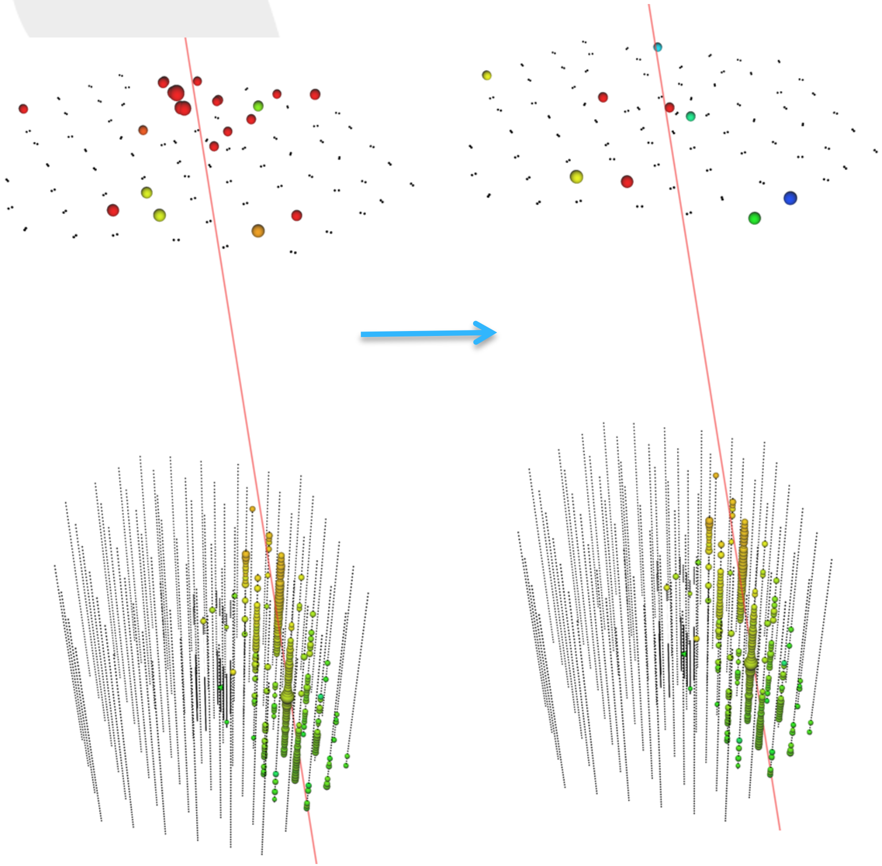
- Using IceTop can allow detection of $\nu's$ that interact above IceCube's fiducial volume
- Basic Principle :
  - Look for IceTop hits correlated to the reconstructed in-ice muon track
- IT-LLHR developed for Gamma-Hadron further improved and applied here
- Events required to have:
  - Axis passing through both IceTop and InIce
  - Bright muon track in ice for good angular reconstruction (effectively E_{CR}>100 TeV)



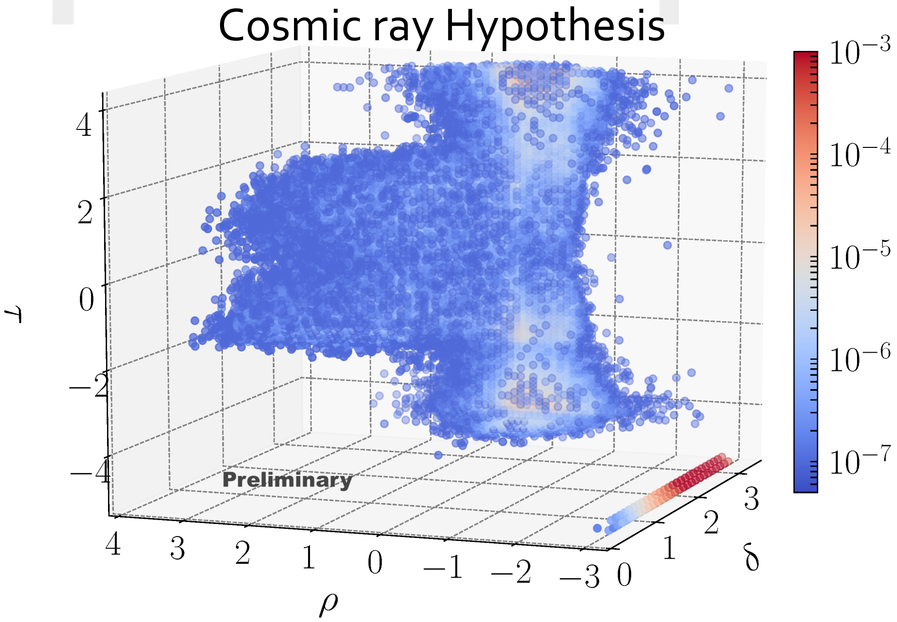
Construction of IceTop ν Hypothesis

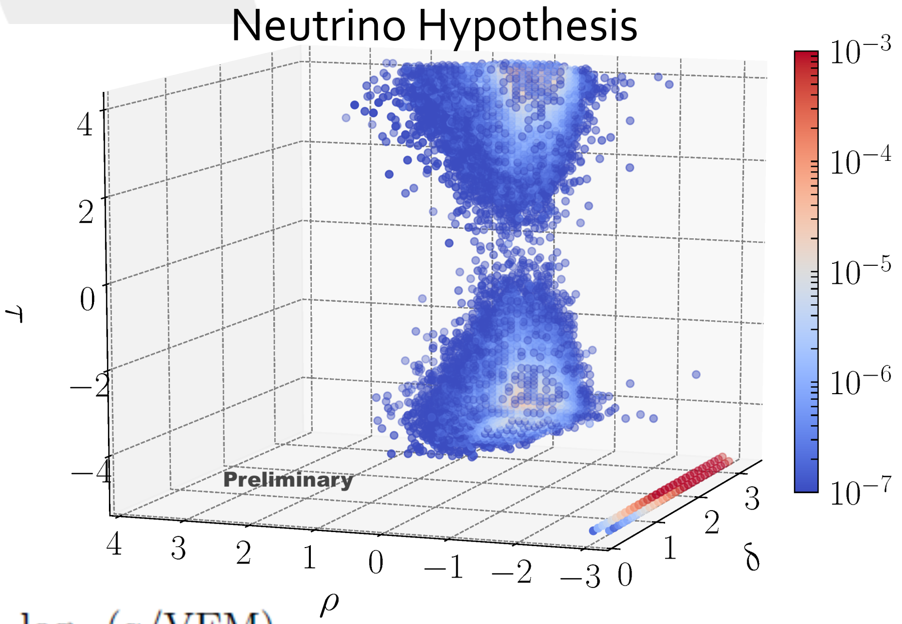
- What does a neutrino event look like in IceTop?
  - Has non-correlated background hits.

- Constructing Neutrino-like IceTop event:
  - Take a regular cosmic ray muon event
  - Erase its IceTop hits
  - Periodic (every 30 s) unbiased recording of IceTop (for 10 ms) contains background hits
    - ...from stray muons or particles from very low energy air showers
    - Copy-Paste a snapshot of these background hits onto IceTop



IT-LLHR 3D PDFs





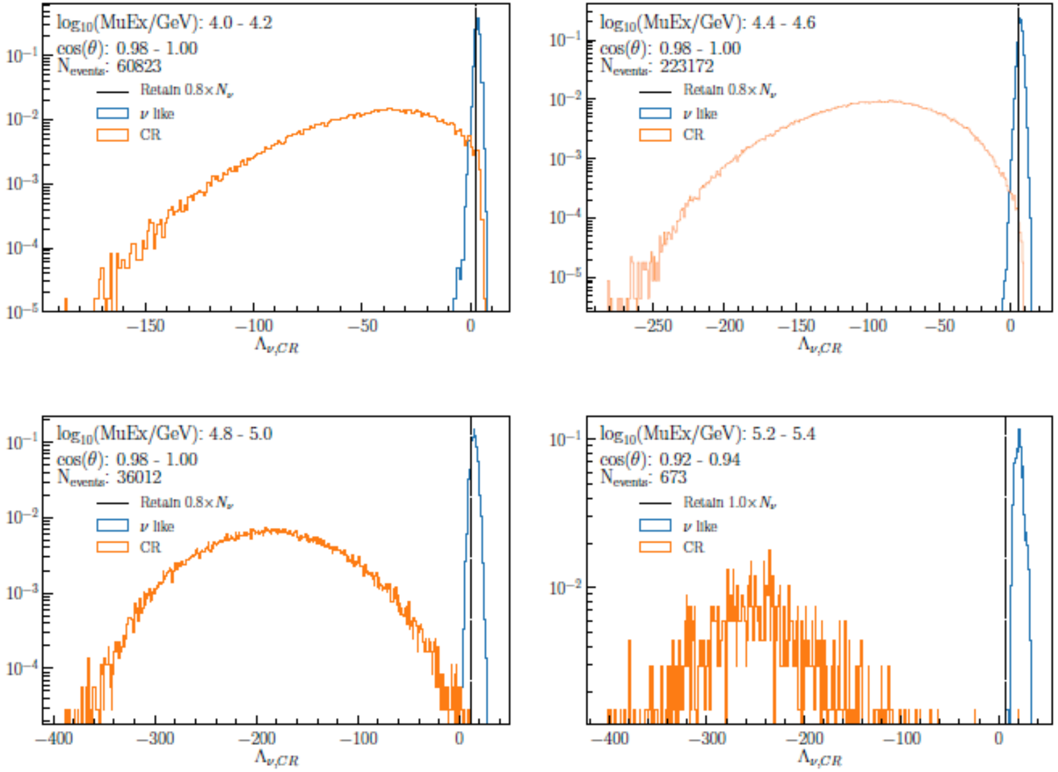
$$\rho = \log_{10}(\mathrm{q/VEM})$$

$$\tau = \mathrm{sign}(\Delta t_{\mathrm{offset}}/ns)\ \log_{10}(|\Delta t_{\mathrm{offset}}/ns| + 1)$$

$$\delta = \log_{10}(r/m + 1).$$

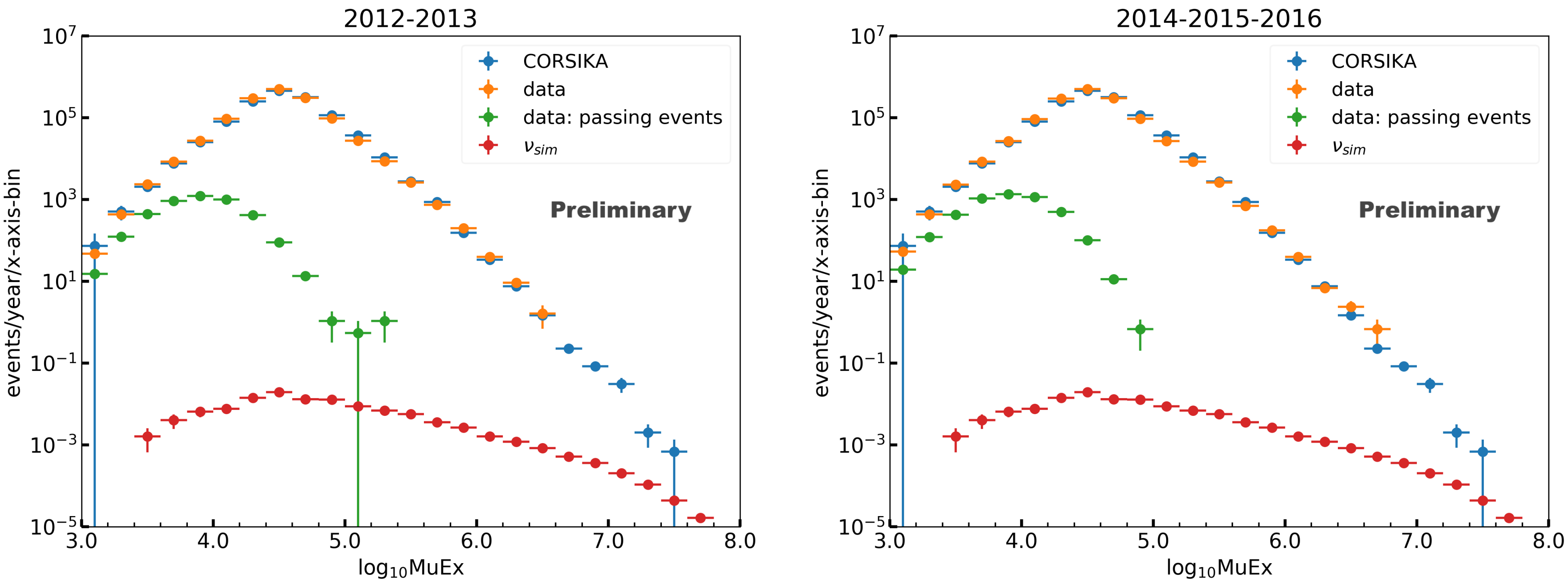
IT-LLHR Performance

- Classification cut fixed using LLHR distribution for Neutrino-like events (Blue histogram)
  - 80% Nu-like retention for log(MuEx)< 5.2
  - 100% Nu-like retention for log(MuEx)>=5.2

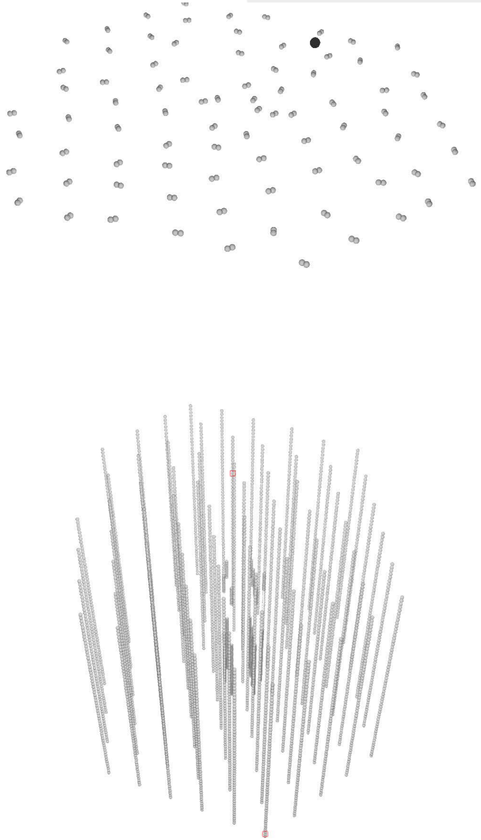


Veto Efficiency of IceTop

2×10^{-5} to 5×10^{-6} reduction in atmospheric background
at Energy Proxy (MuEx) = 80 TeV i.e. minimum Neutrino Energy of 100 TeV



Neutrino Candidate



230 TeV Energy Proxy (MuEx)
i.e.
1 PeV (median) neutrino primary
Or
10-30 PeV cosmic ray primary

Outline

- Background
- IceCube and IceTop
- Cosmic-ray measurements
  - Spectrum and Composition
  - Low Energy Spectrum
  - GeV Muon Density
- PeV Gamma-ray Searches
  - Motivation
  - Diffuse Emission from Galactic Plane
  - Point Sources
- Muon Neutrino Search using IceTop as Veto
  - Motivation
  - Veto Efficiency of IceTop
  - Neutrino Candidates
- Future of IceTop
  - Scintillator and Radio Array
  - Non Imaging Air Cerenkov Telescopes

Future of IceTop

- Snow accumulation over the years raises the trigger threshold of IceTop
- Scintillator panels will lower the trigger threshold as well as help characterize effect of snow on IceTop tanks
- Inherent drawback of surface particle detectors:
  - Capture a snapshot of the shower
  - Interpretation dependent on hadronic interaction models used during simulations
- Solution: Measuring calorimetric energy deposition by electromagnetic part of the shower
  - Radio Antennae
  - Non Imaging Air Cerenkov Telescopes

Planned Scintillator + Radio Extension

- Scintillators required for triggering
- Radio would provide calorimetric energy estimate, Xmax reconstruction
- Prototypes of scintillator panels, antennae, DAQ, being tested currently.
- More Details: https://pos.sissa.it/358/418/

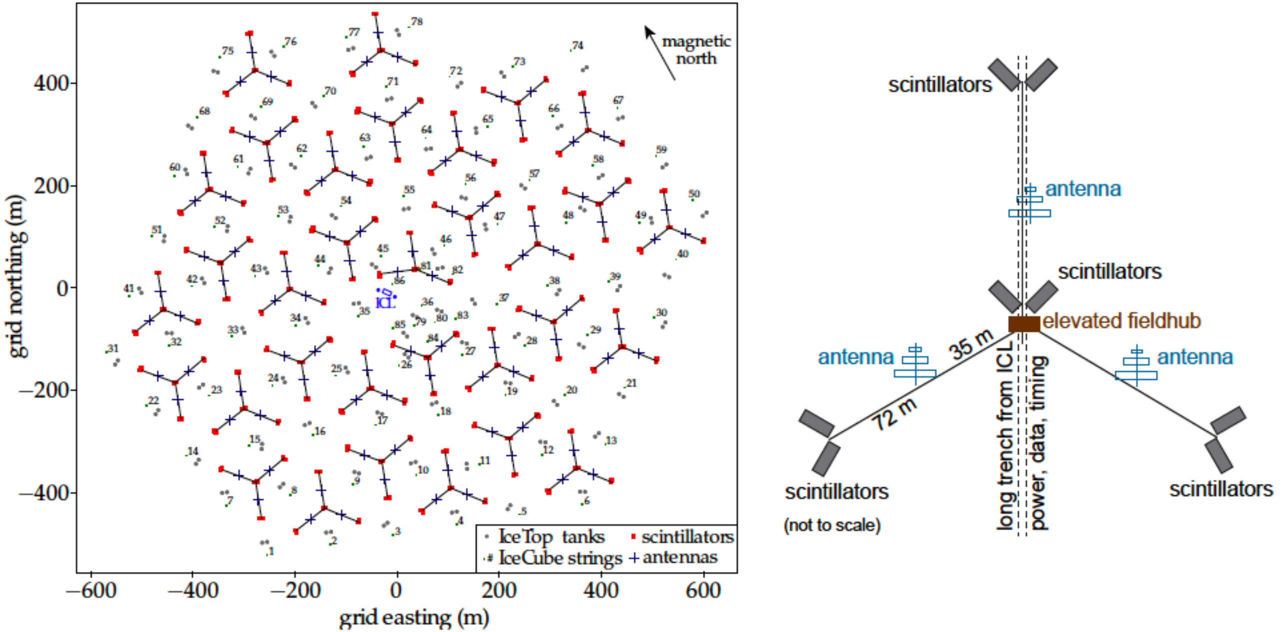
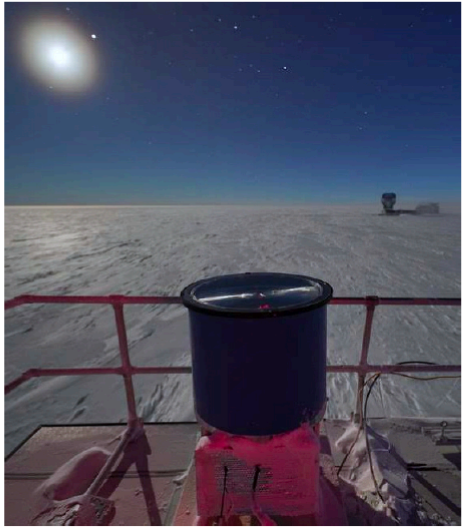


Figure 1: Conceptual layout of the scintillator-radio hybrid array (left) comprised of 32 stations (right). Each station consists of 8 scintillation panels arranged in pairs, one pair at the center of the station where the local data-acquisition is located in an elevated field hub, and three pairs at 72 m distance from the station center. Along the same spoke-trenches to these scintillators, three radio antennas with two polarization channels each will be deployed in 35 m distance to the center.

Non Imaging Air Cerenkov Telescopes

- Can trigger without scintillators but IceTop/IceCube hits required for proper shower reconstruction
- Prototype being developed for South Pole environment, array configuration not yet fixed.
- Will provide independent air shower composition measurements
- Can lower energy threshold for veto of air showers
  - Shower might decay before reaching IceTop surface
  - Cerenkov emission higher up in the atmosphere is still measurable
- More details: arXiv:1910.06945v2



(a) IceAct roof-telescope on the roof of the Ice-Cube Laboratory (ICL) in the antartic winter 2019.

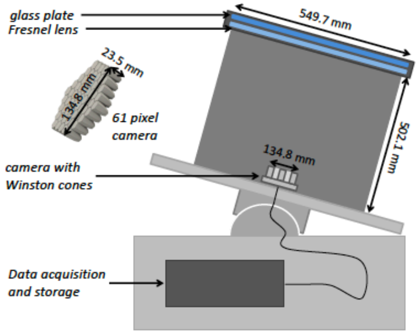


Figure 1: Drawing of the IceAct telescope design. The IceAct demonstrator of 2016 was equipped with a 7-pixel camera with 4° field-of-view and was deployed at the South Pole on the roof of the ICL. In the figure a 61 pixel version of the camera is shown which is the current default design of IceAct.

Thank you.