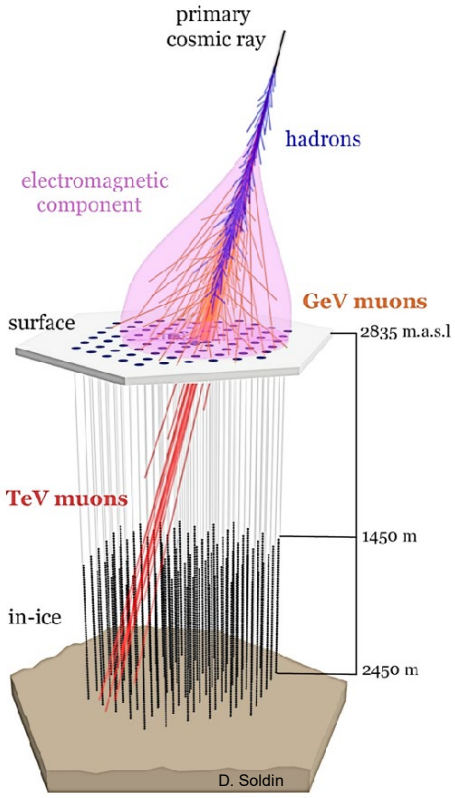
Cosmic-Ray Studies with the Surface Instrumentation of IceCube / IceCube-Gen2

ICRC, July 2021
PoS (ICRC2021) 336
Andreas Haungs for the IceCube Collaboration

IceTop: the surface instrumentation of IceCube

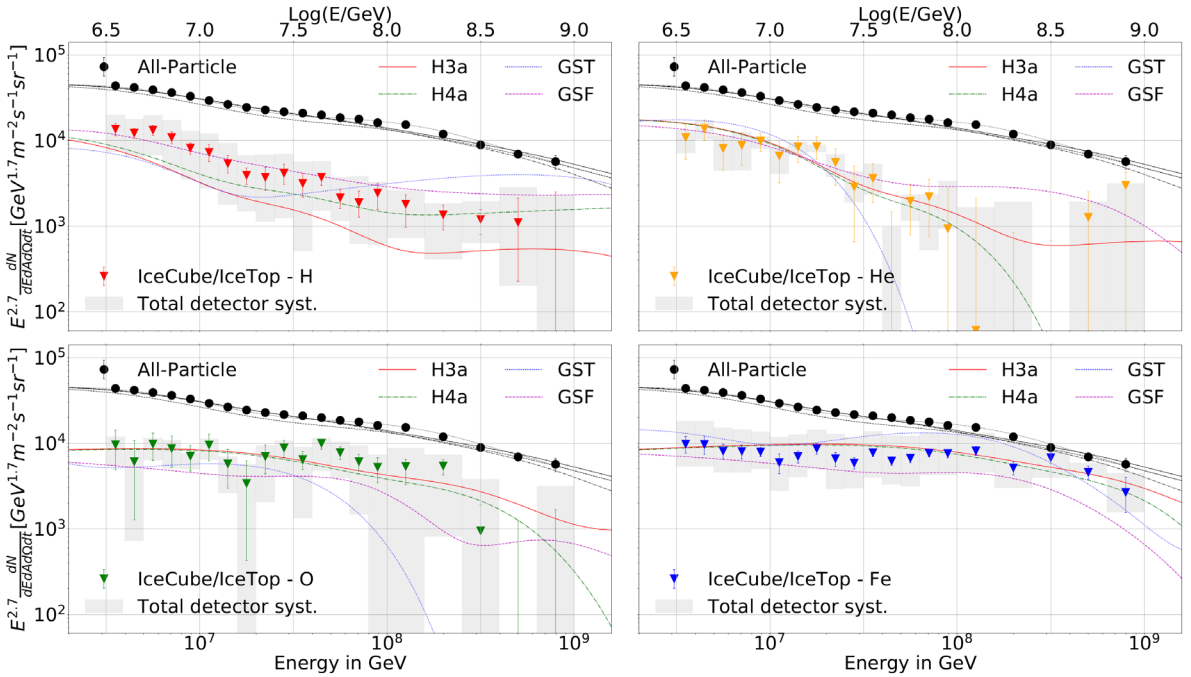
- **Why does IceCube need a surface instrumentation**
  - Important to understand atmospheric neutrinos and muons
  - IceCube is a unique instrument also for cosmic ray air showers
  - Galactic Multi-Messenger Astronomy
- **Surface array of IceCube**
  - 81x2 ice-Cherenkov detectors above strings (c. 1 km^2)
  - 9 years of air-shower data
  - 10^{15} eV – $10^{17.5}$ eV EAS primary energy range
- **Science**
  - Air-shower veto for IceCube neutrinos
  - Cosmic ray physics
  - Calibration of IceCube
- **Challenges**
  - Non-uniform snow coverage increasing with time
  - small exposure for IceTop + in-ice coincidences



IceTop: cosmic ray composition result

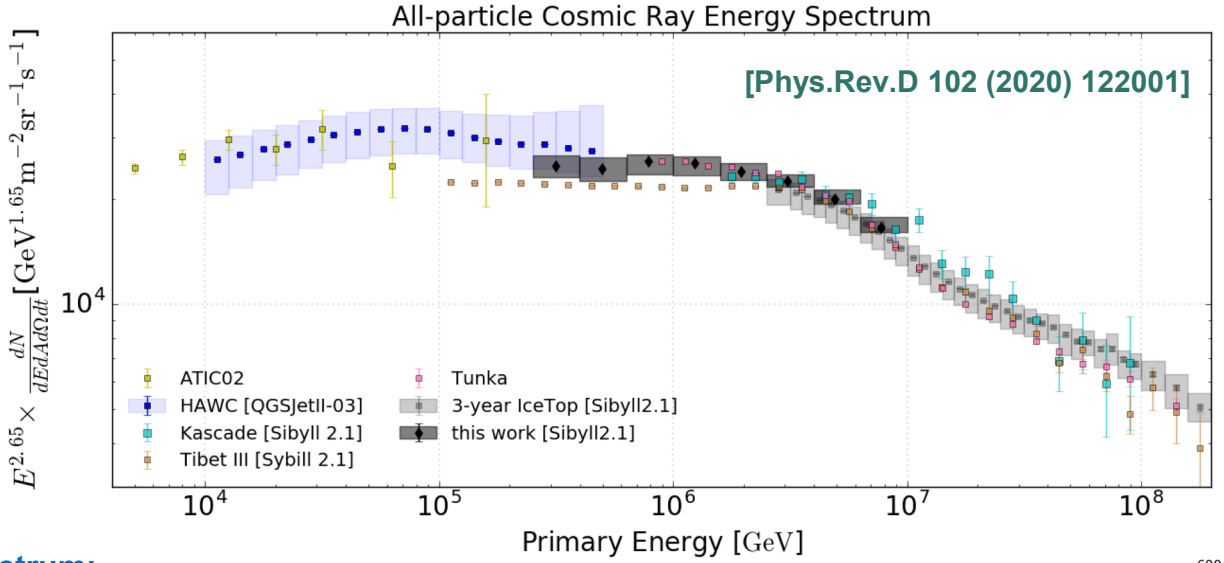
- **3-year data composition analysis**
  - Energy spectra of individual mass groups
  - Knee(s) in each group
  - Slight dependence on hadronic interaction models
- **However:**
  - Snow coverage, 3y-data only, limited exposure
    ➔ large systematic uncertainties
  - energy threshold above PeV

➔ Improvements envisaged



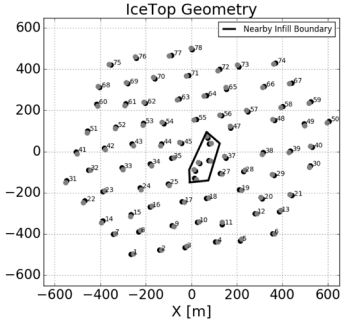
[Phys.Rev.D 100 (2019) 8, 082002]

IceTop: low energy (all-particle) spectrum

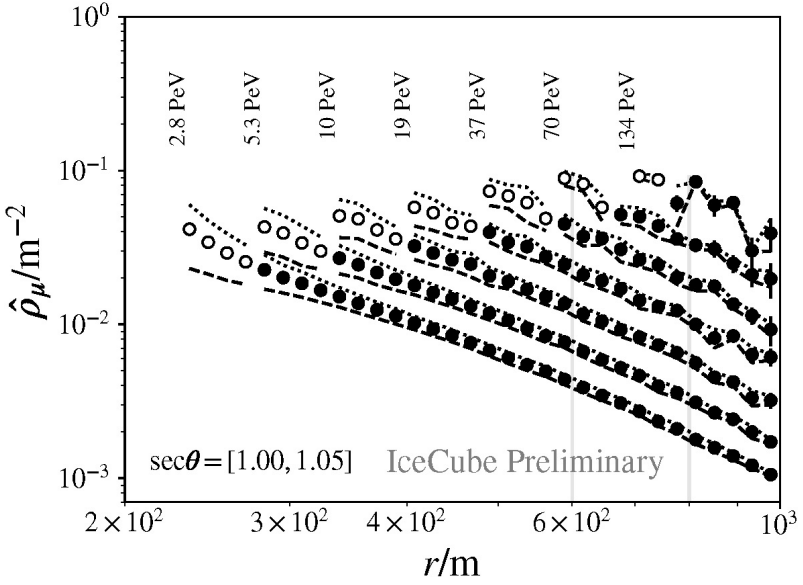


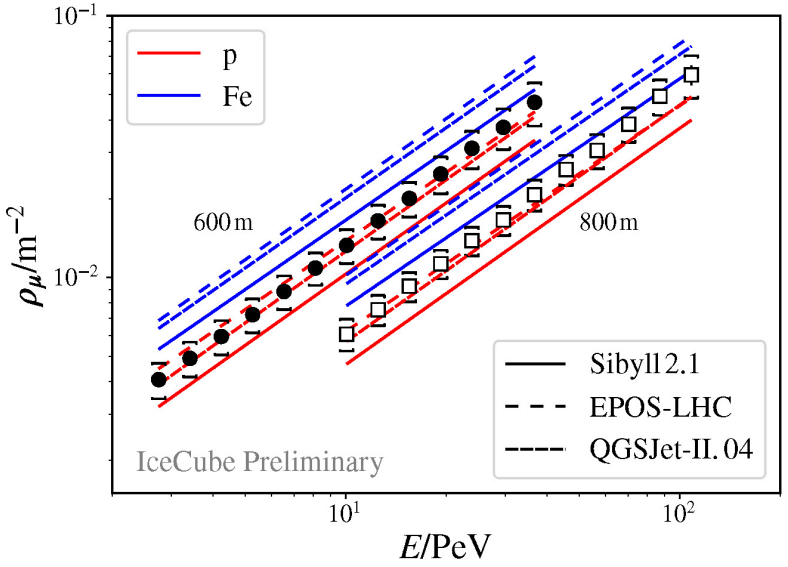
- **Low energy spectrum:**
  - Lower threshold by going to IceTop infill area (250 TeV – 10 PeV)
  - Overlap with HAWC -- Overlapping region with 3y-composition paper -- Knee structure visible
- **However:**
  - Snow coverage, 3y-data, limited exposure ➔ large systematic uncertainties
  - Not yet in-ice information used; Not yet composition information

  ➔ improvements envisaged



IceTop: muon density measurements



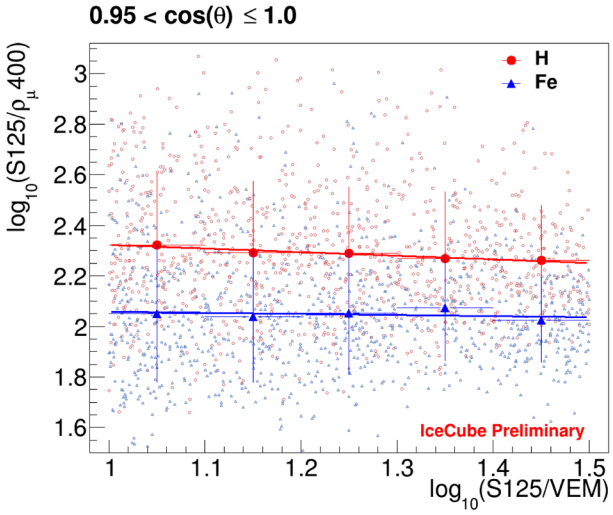


- **Muon Densities**
  - Muon number extraction from the Ice-Cherenkov-tank signal possible at large distances
  - Muon lateral distributions for bins in zenith angle and primary energy
  - Comparisons with model predictions
  - Input for WHISP working group (muon puzzle)

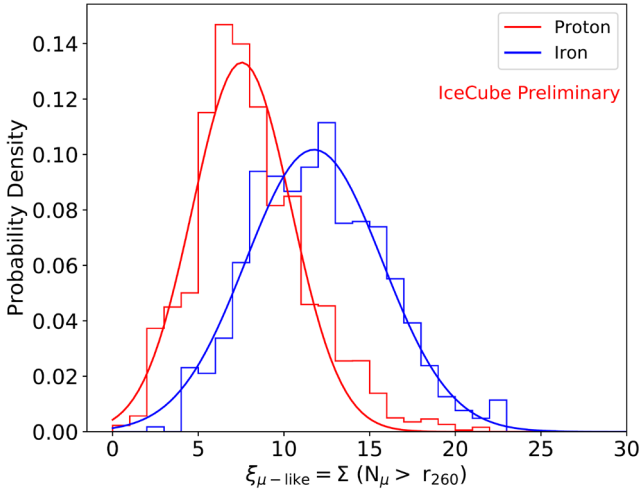
[IceCube, D.Soldin: PoS (ICRC2021) 342]
[WHISP, D.Soldin: PoS (ICRC2021) 349]

IceTop: muon density parameter per event

[IceCube, D.Kang: PoS (ICRC2021) 312]



[IceCube, A.Balagopal: PoS (ICRC2021) 212]

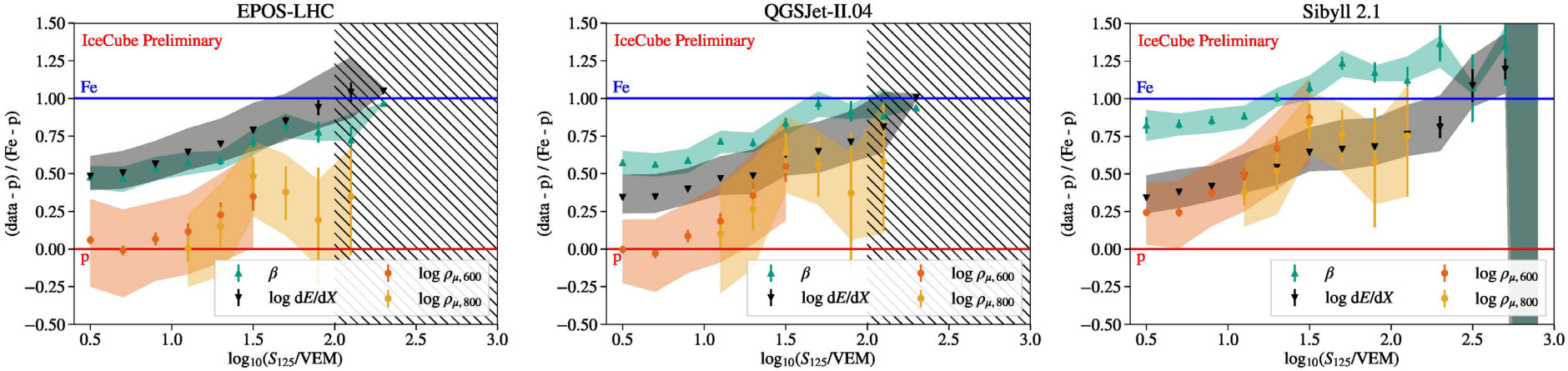


- **New parameter in composition determination**
  - Determine average muon density at a certain distance per event
  - GeV muon density as new mass sensitive parameter
  - Method promising for composition measurement
  - Soon to be applied to data

- **Measurement of inclined showers**
  - Investigating air showers of 45°-60° zenith angle
  - Extracted muon densities per event shows mass dependency
  - Independent composition study
  - Test of hadronic interaction models

IceTop: tests of hadronic interaction models

[IceCube, S.Verpoest: PoS (ICRC2021) 357]



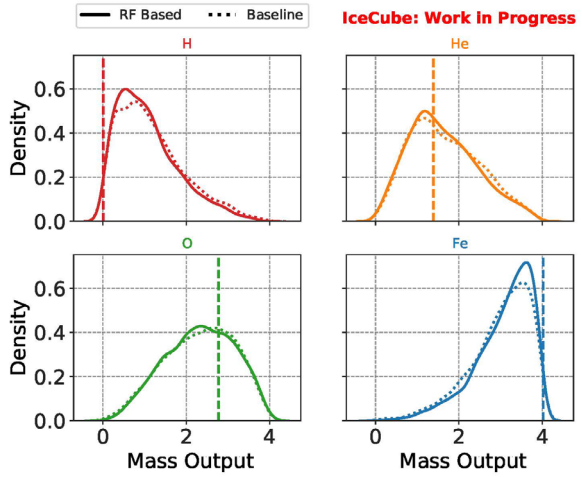
- **Study of 4 air shower observables at IceCube**
  - Slope of charge particle lateral distribution; energy deposit in-ice of TeV muons; GeV muon density at 2 different shower core distances
  - All parameters show mass sensitivity, comparison to predictions of 3 different hadronic interaction models
- **Findings**
  - No consistency of parameters for all 3 models
  - In particular LDF-slope vs GeV muons in all models and TeV muons vs GeV muons in post-LHC models

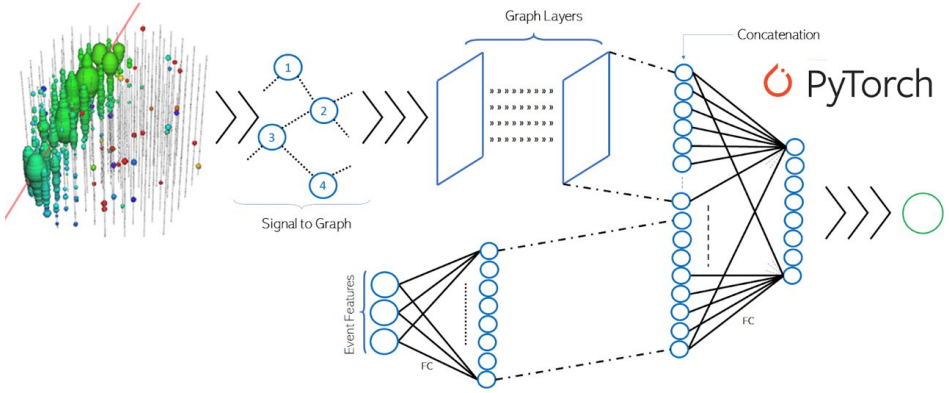
IceTop: Deep Learning applications

[IceCube, P.Koundal: PoS (ICRC2021) 323]

To improve composition results there are several attempts in addition to use more data:

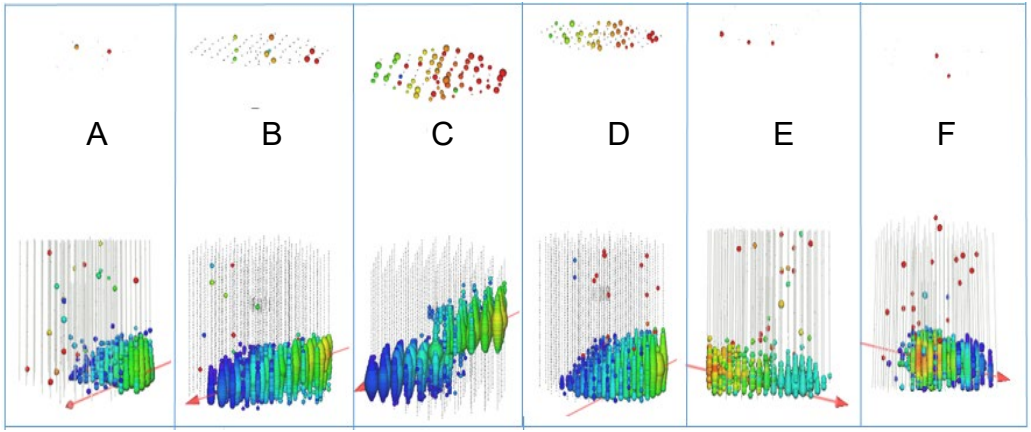
- **Random Forest**
  - Methodologically based on the 3y-composition paper
  - New mass sensitive parameters for reduction of systematic uncertainties
- **Graph Neural Network**
  - Use of full signal footprint of in-ice sensors
  - Pattern recognition
  - Combination with surface parameters
- **Boosted Decision Tree**
  - Including in-ice parameters for low-energy composition analysis

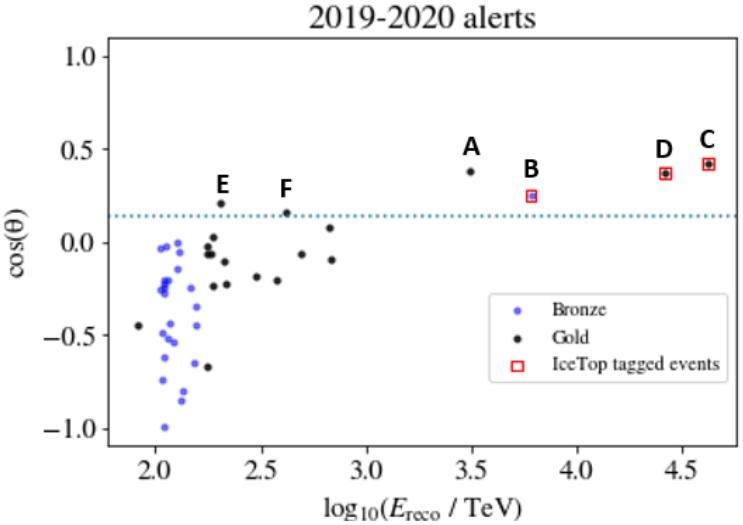




IceTop: air shower veto to neutrino alerts

[IceCube, N.M. Binte Amin]





- **IceTop data in the IceCube Realtime Alert System**
  - 6 down-going (<82°) public alerts: Jun 19, 2019 – Dec 31, 2020
  - 3 energetic down-going events (B, C, D) have significant and correlated IceTop signature
  - Considered are time residuals of pulses with respect to in-ice muon track
  - Correlated in-ice and IceTop pulses cluster together within 0 to 1 μs

- **IceTop activity in 2019-2020 down-going alert events:**

  C: event triggered IceTop → cosmic ray event

  B: did not trigger IceTop, but has 9 correlated pulses → cosmic ray event

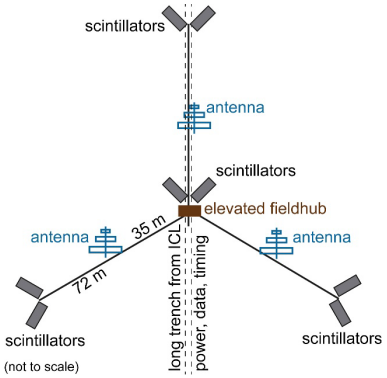
  E: low energy event, is expected to have reduced IceTop activity

  A: passes a very short distance through the detector, uncertainty is high

IceTop: hybrid detector enhancement

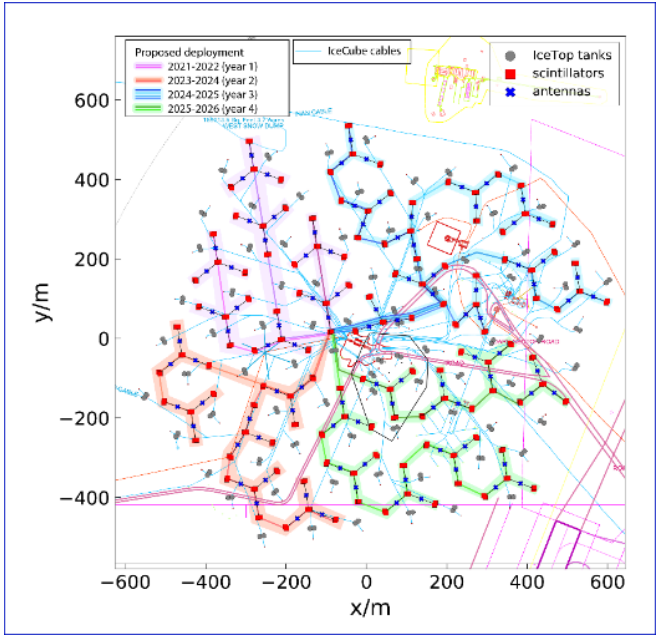
[IceCube, M.Oehler: PoS (ICRC2021) 225]

- **A Multi-Detector IceTop-Enhancement**
  - Operating IceTop (and IceCube) + Scintillators within IceTop area + Radio antennas + Cherenkov light telescopes (IceACT)
  - To be deployed until 2024/25
- **Science Goals**
  - Improved veto for present IceCube
  - Lower the primary energy threshold
  - Improved CR composition measurements
  - Particle physics in extreme forward direction
  - Composition dependent anisotropy studies
  - Improved Gamma-ray search

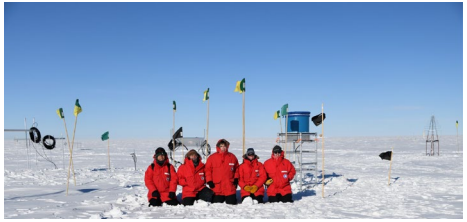


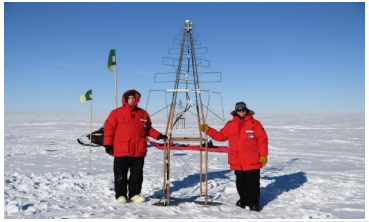
A scintillator-radio hybrid station

Deployment Plan for 32 stations



Prototyping at South Pole in 2020*

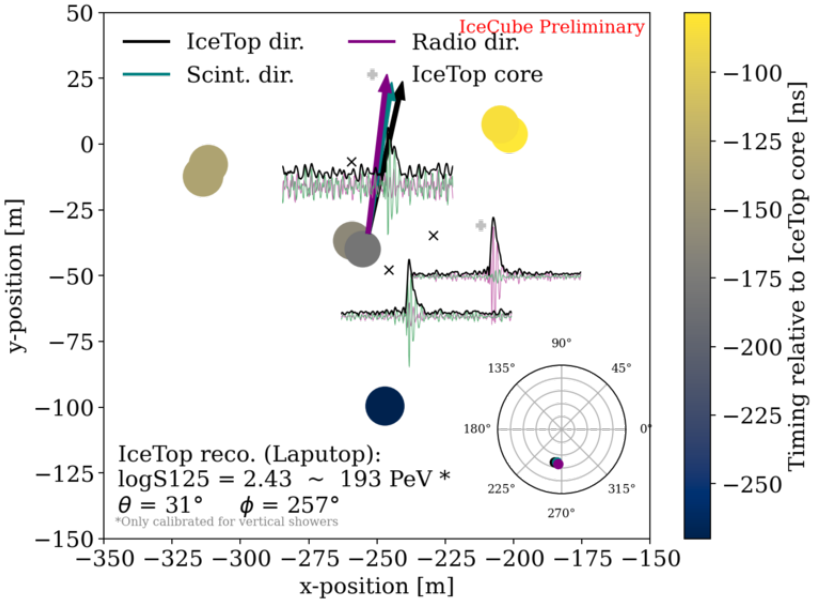




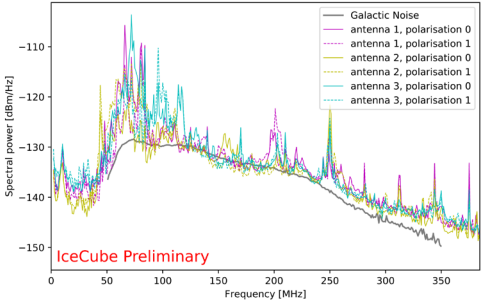
*Antennas and Scintillators are elevated to avoid snow coverage

IceTop: hybrid detector enhancement prototype results

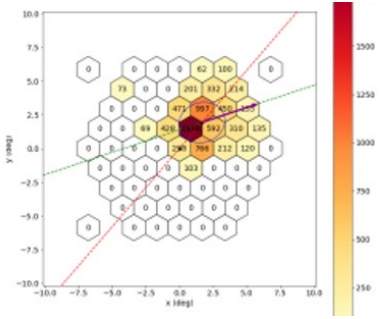
- **Prototype Station**
  - Installed 2019/20
  - 8 panels + 3 antennas
  - 2 IceAct telescopes
  - Scintillators trigger radio antennas
  - Offline correlated with IceTop and in-ice
  - All functioning
  - Hybrid EAS measurements



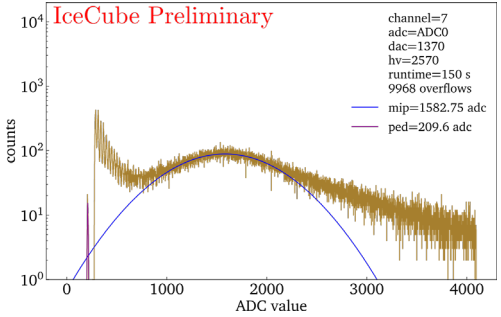
Measured hybrid air-shower event



Radio noise measurements



IceAct EAS image



SiPM-readout scintillator signals

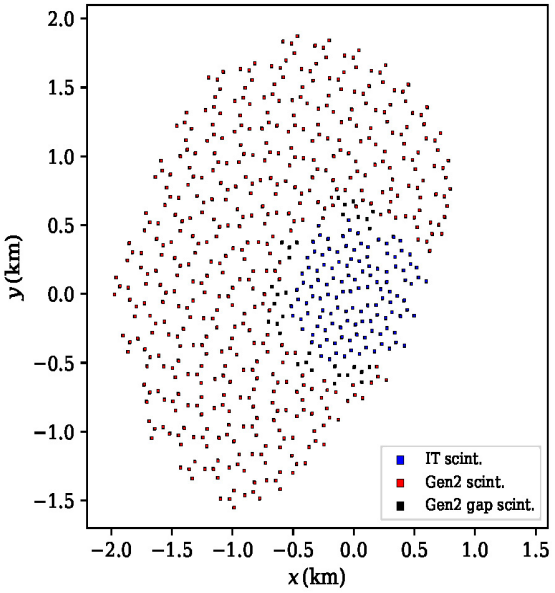
[IceCube, H.Dujmovic: PoS (ICRC2021) 314]

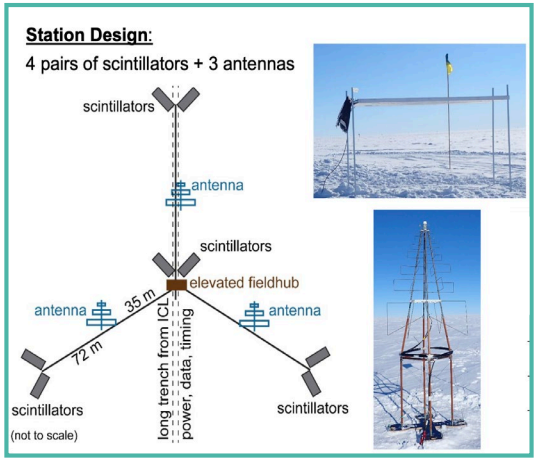
[IceCube, L.Paul: PoS (ICRC2021) 276]

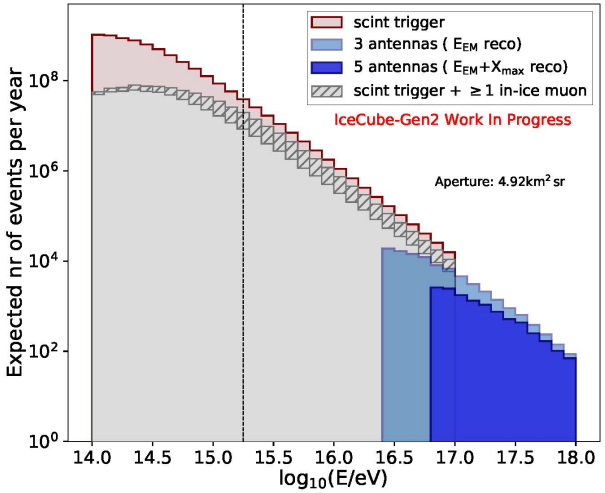
[IceCube, A.Coleman: PoS (ICRC2021) 317]

IceCube-Gen2 Surface Array

[IceCube, A.Leszczynska: PoS (ICRC2021) 411]





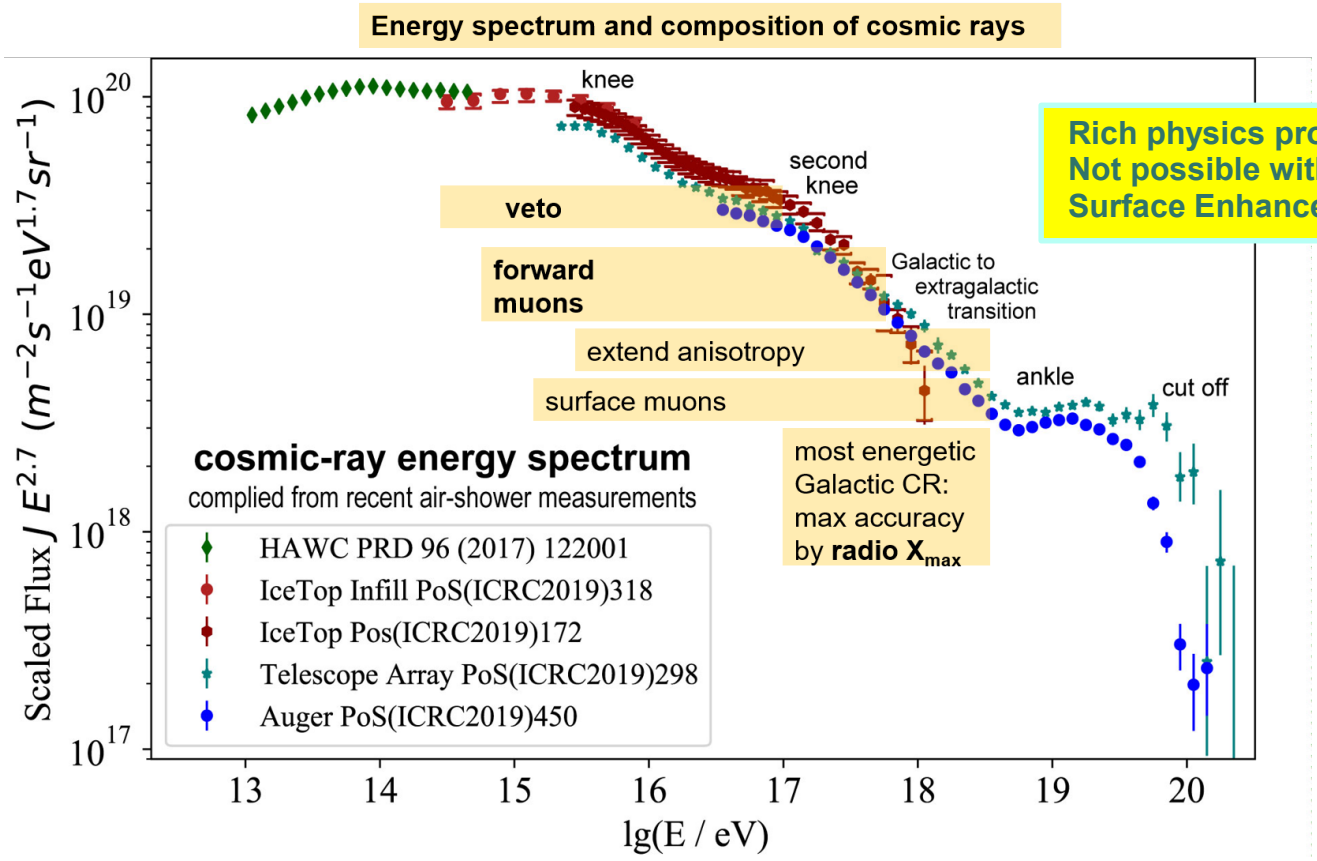


Simulation of number of events per year

- **Gen2 Surface Array**
  - Scientific Heritage: IceTop and Surface Enhancement Array in IceCube
  - Baseline design: 1 hybrid station on top of each new Gen2 string
  - The IceCube-Gen2 surface array will be a unique and needed cosmic ray detector in the PeV-EeV primary energy range!

IceCube-Gen2 Surface Array

[IceCube, F.Schröder: PoS (ICRC2021) 407]



Rich physics program!
Not possible with IceTop or IceCube Surface Enhancement alone

Summary / Outlook

- IceCube is a unique hybrid CR detector
- Many CR activities are not covered in this talk (e.g. lepton physics)
- Many interesting analyses upcoming...
- Bright future with surface enhancements and IceCube-Gen2 surface array
- …Stay tuned!