Cosmic ray measurements with IceCube

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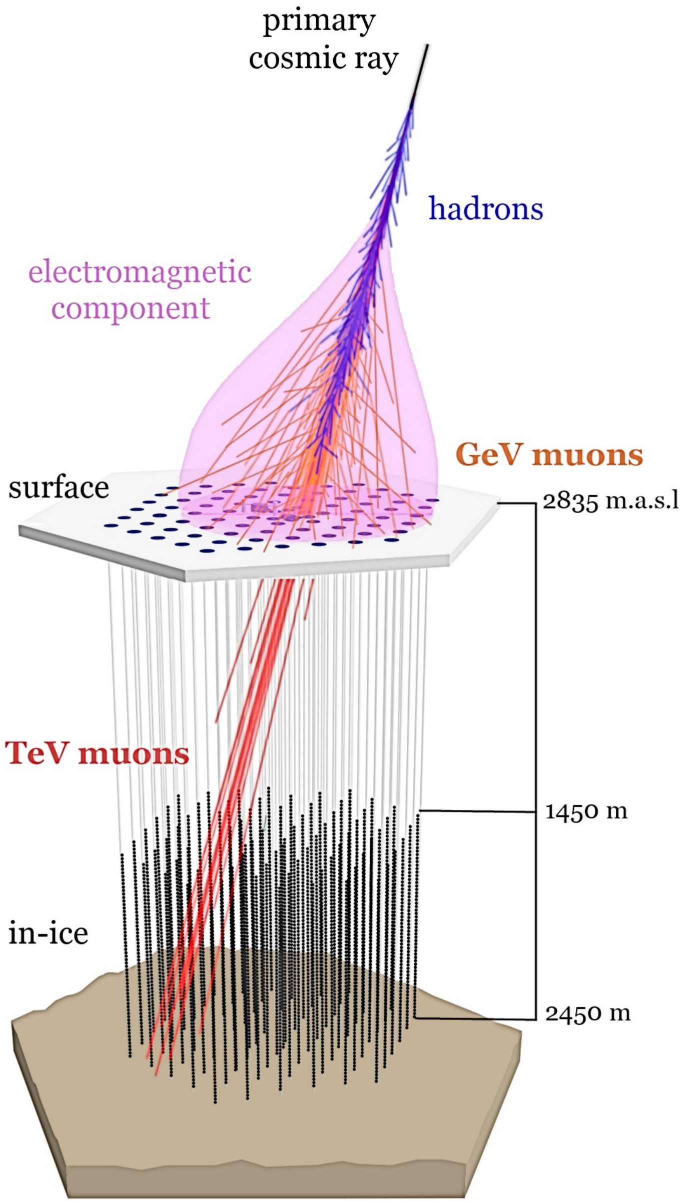
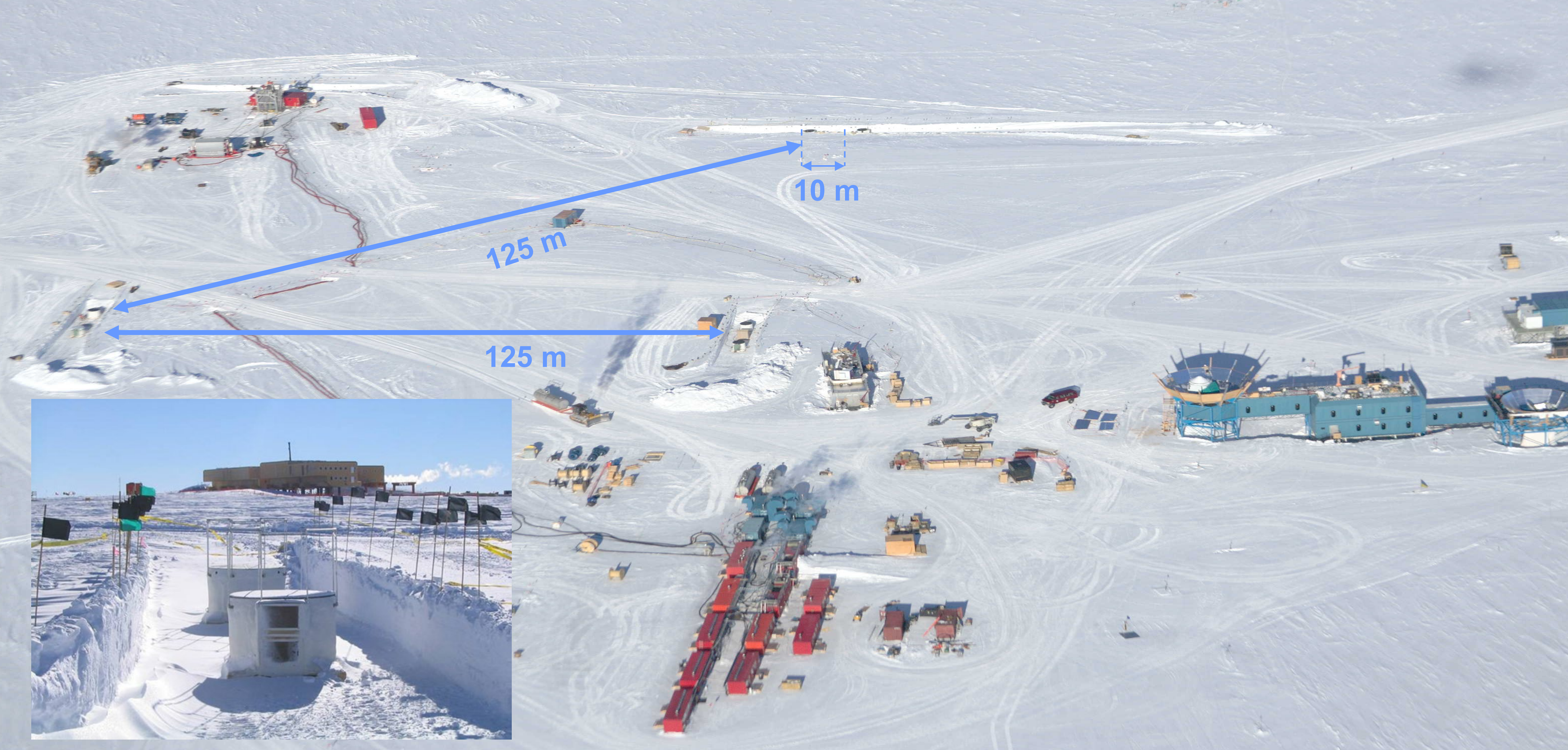
Cosmic Ray Physics with IceCube and IceTop

A three-dimensional Cosmic Ray Detector:

- IceTop 1-km^2 surface array
  - Cosmic ray energy and direction
  - Electromagnetic and muonic signal
    ($E_\mu \approx 1$ GeV, “GeV muons”)
- IceCube 1-km^3 in-ice detector
  - Muon tracks/bundles in the ice
    ($E_\mu > 400$ GeV, “TeV muons”)
  - Bundle reconstruction
  - *dE/dx* along the track

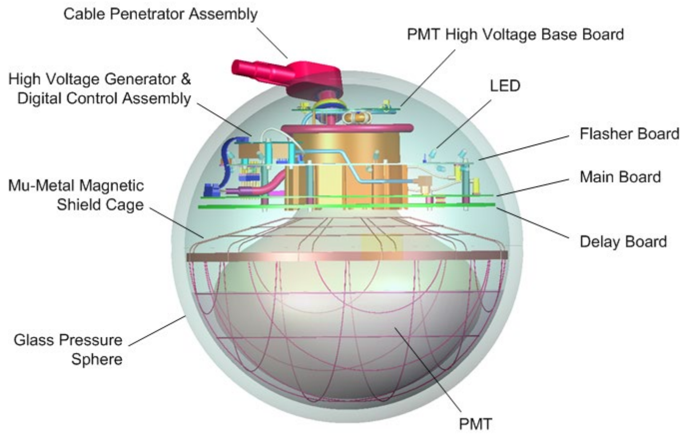


Aerial view of IceCube/IceTop

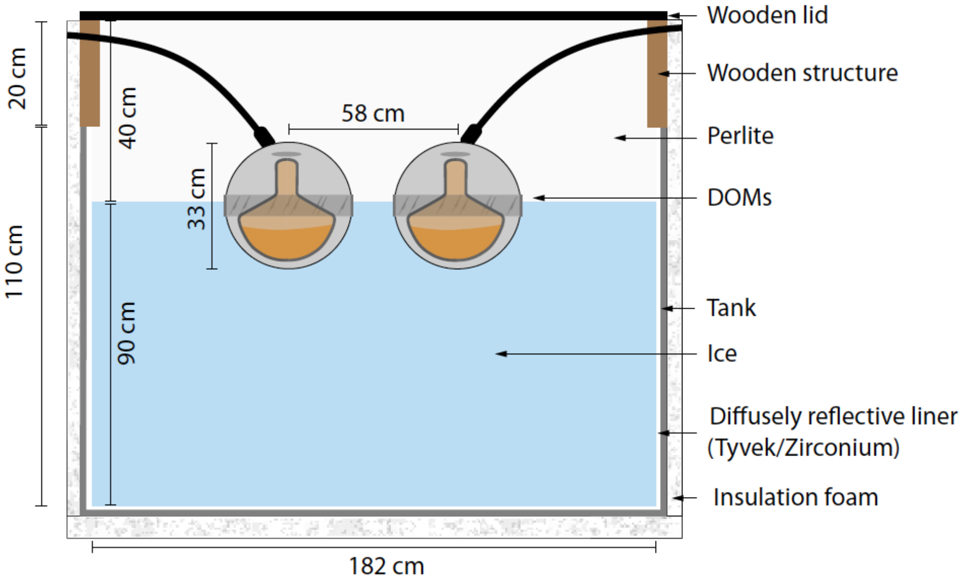


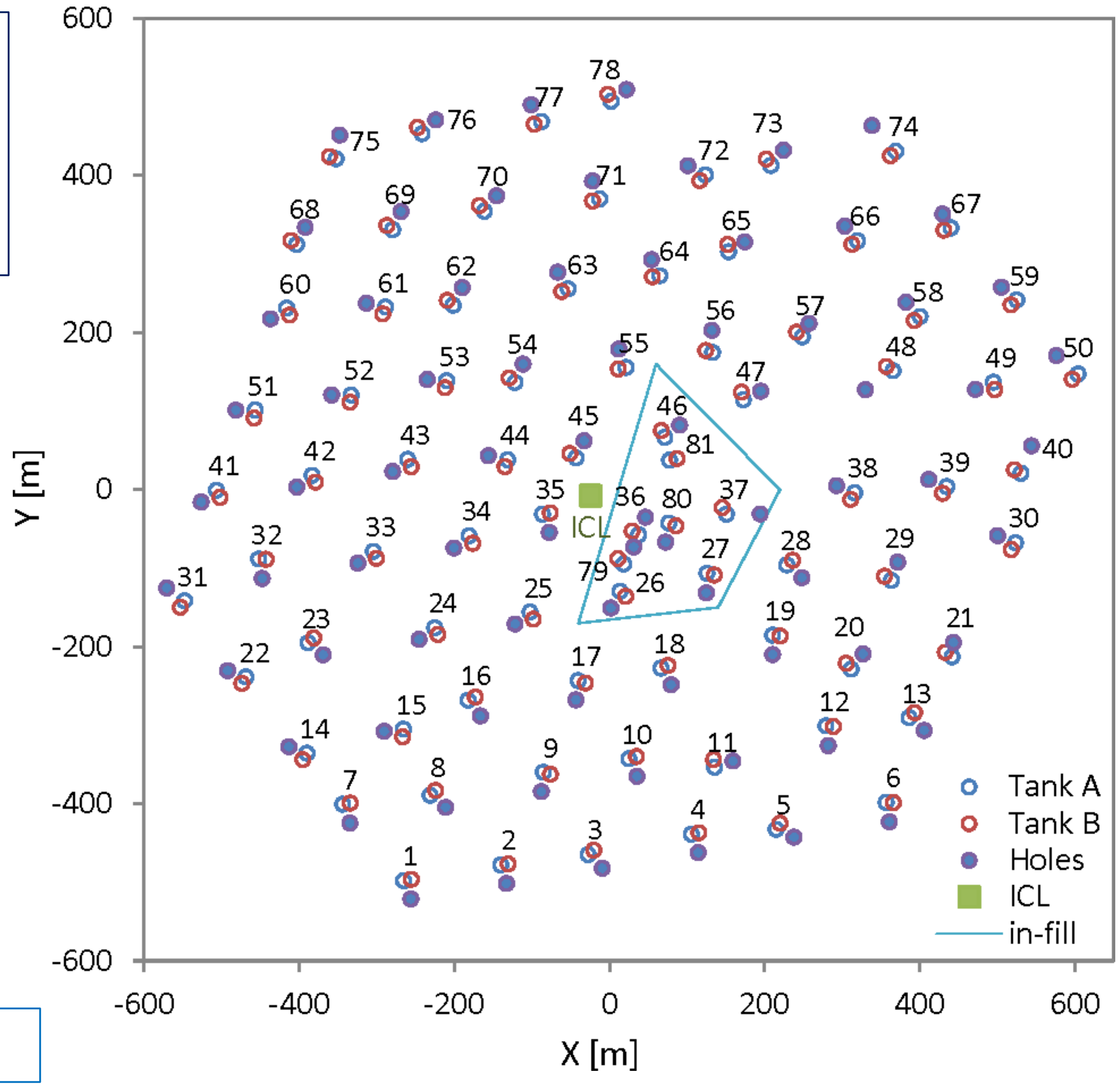
The surface air shower array IceTop

IceCube NIM A 700 (2013) 188



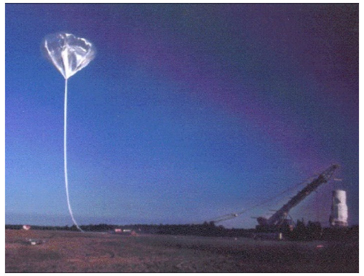
IceCube and IceTop are both Cherenkov detectors using the same technology



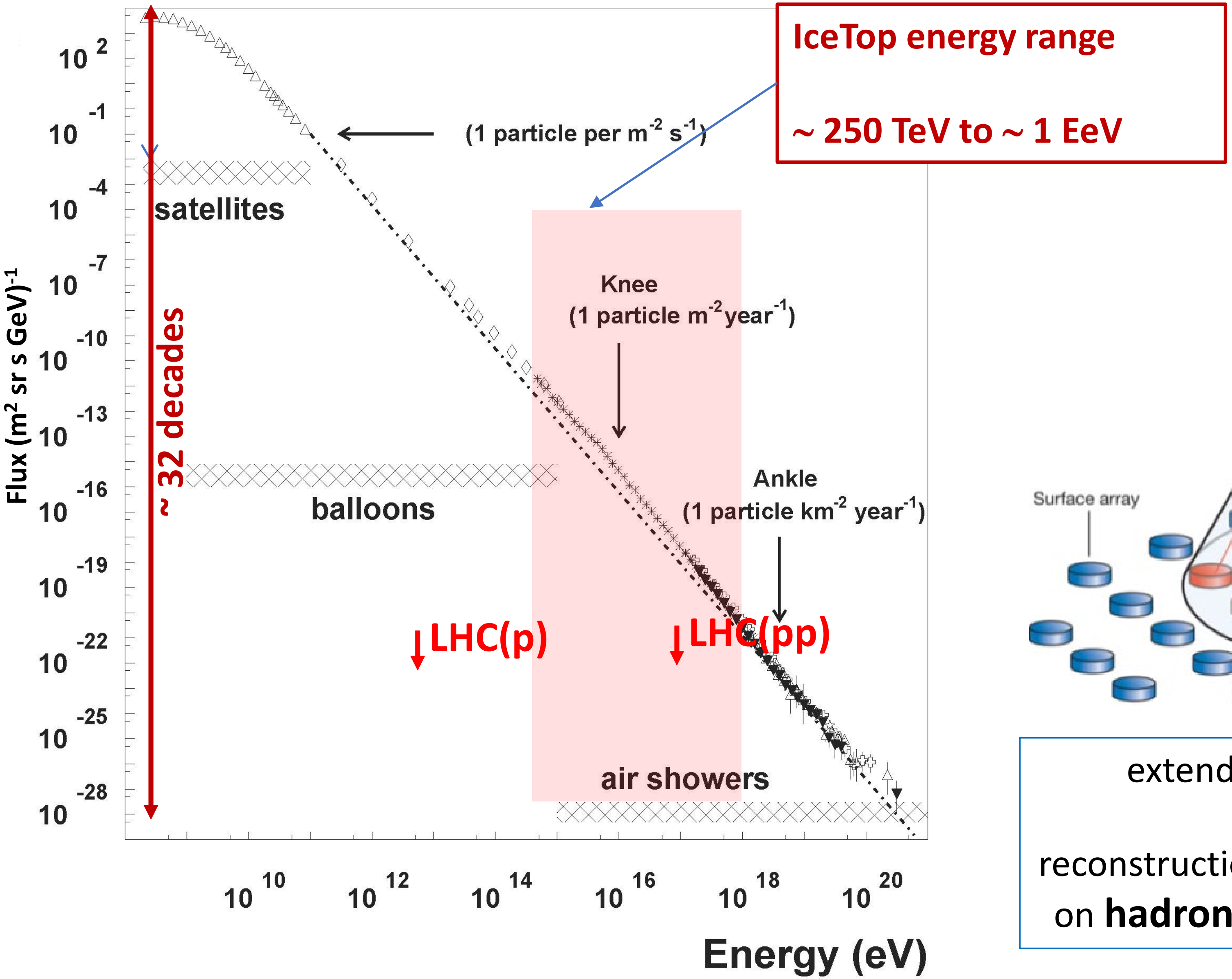


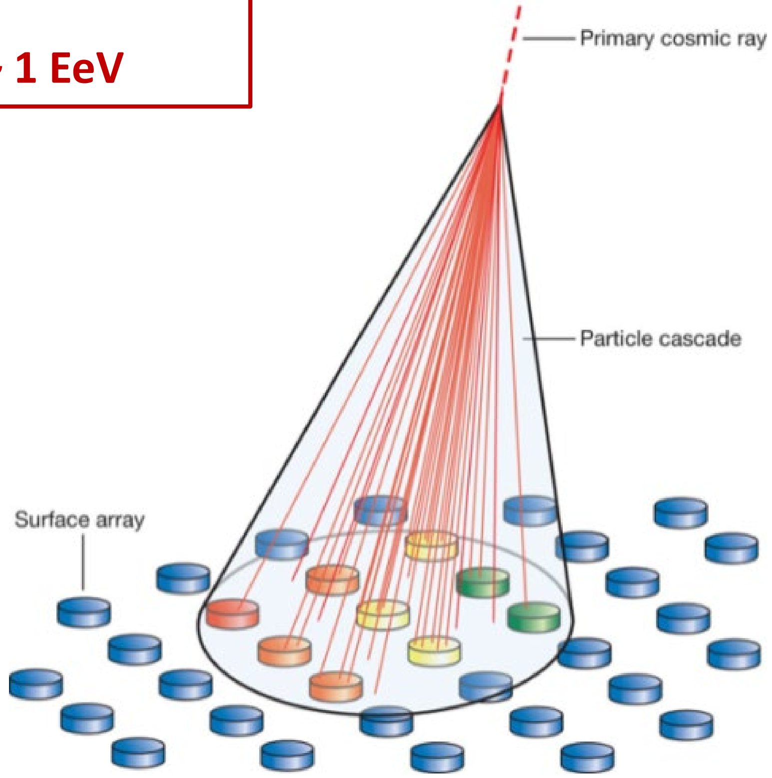
Tank signals expressed in VEM = vertical equivalent muon

Charged Cosmic Ray Spectrum



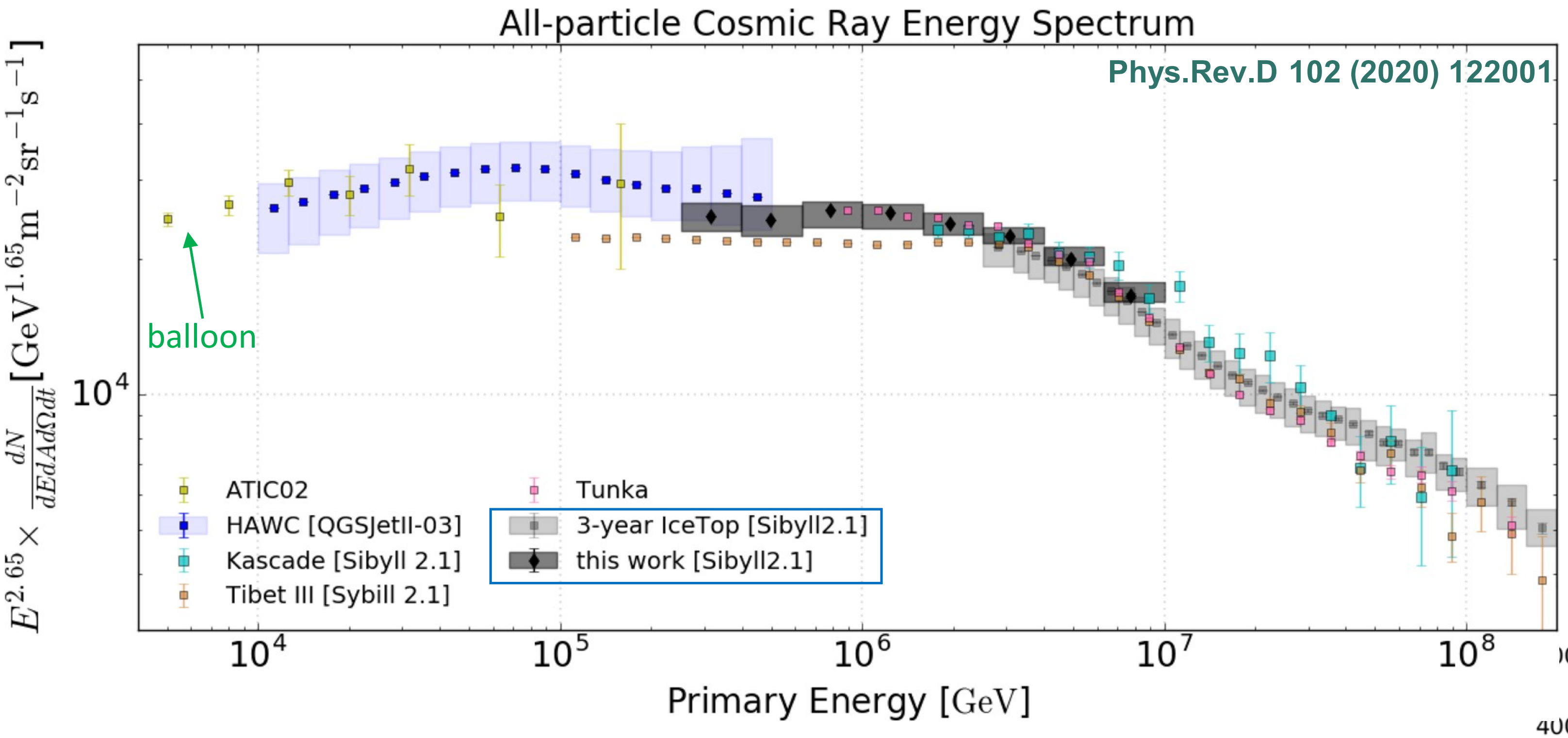
limited by CR flux

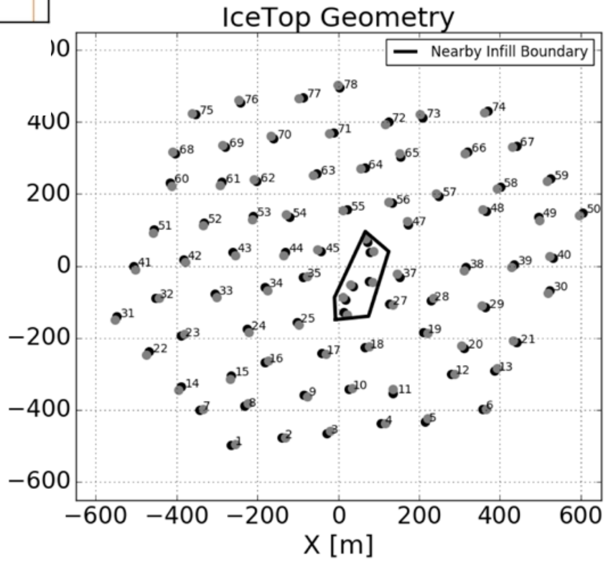




extends to very low fluxes
but:
reconstruction of primaries depends on **hadronic interaction models**

All-Particle Spectrum (IceTop only)





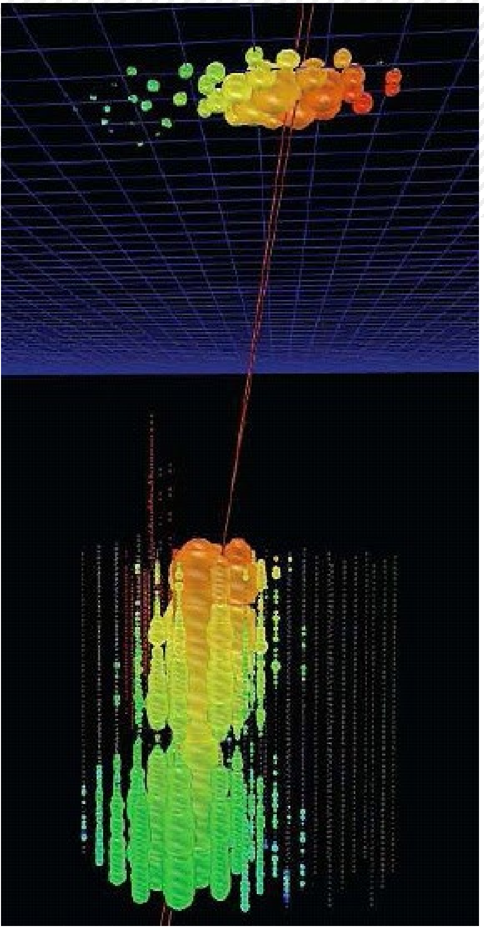
Latest results: extension to low energies:

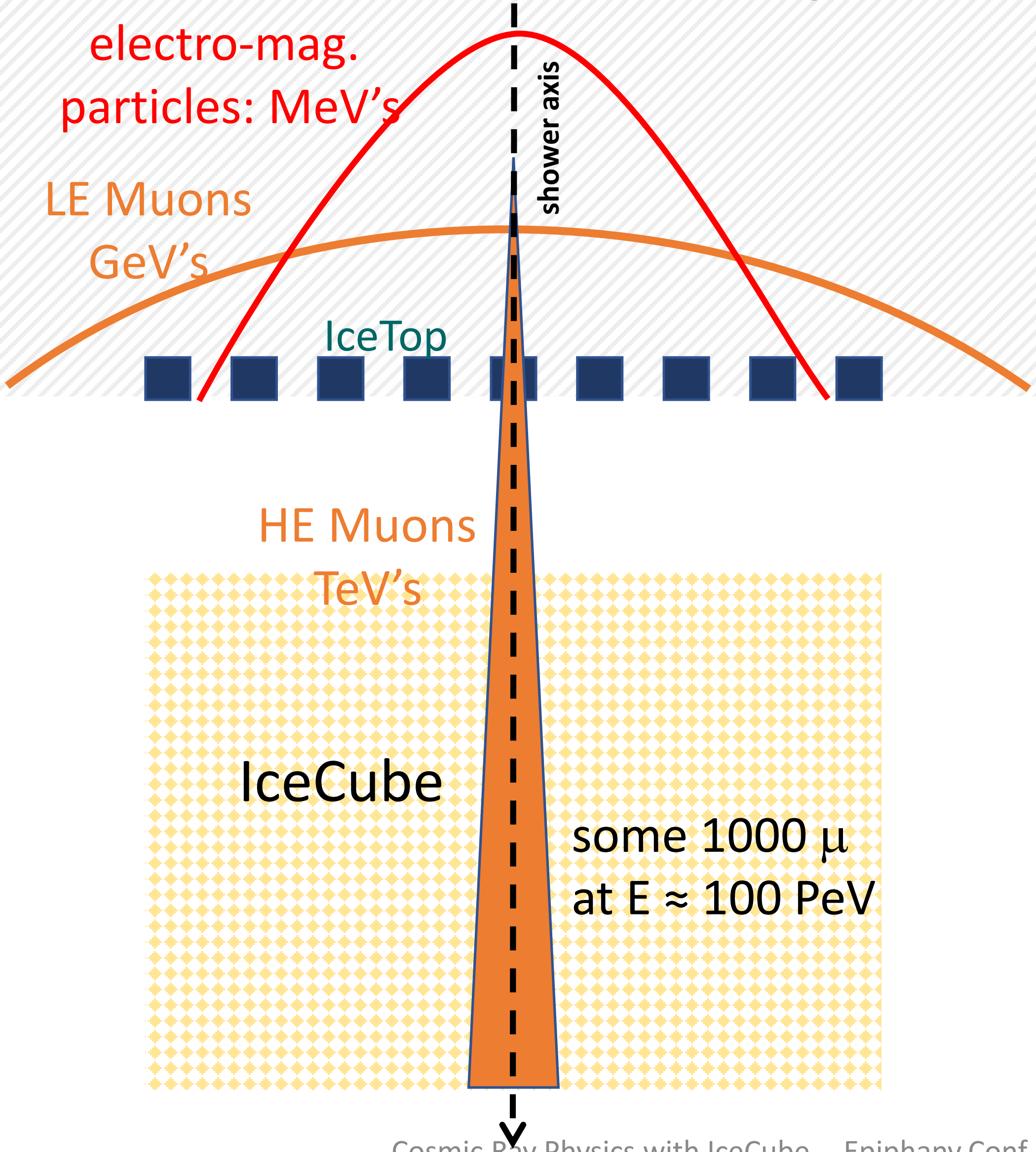
- Lower threshold by using IceTop infill (250 TeV – 10 PeV)
- Connecting to balloon data; overlap with HAWC (high altitude surface detector)
- Overlapping region with 3-year analysis – exhibits the knee structure

Uncertainties mostly dominated by systematics

Spectrum and Composition: the Role of Muons

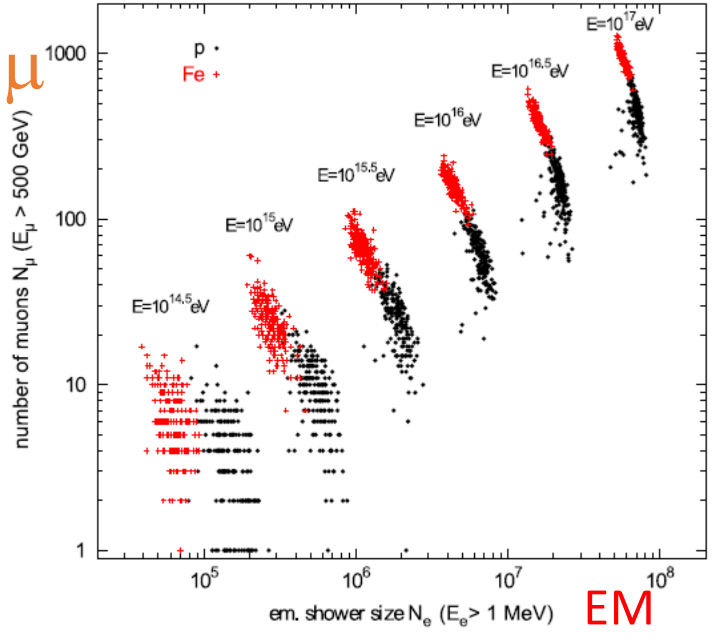
IceCube/IceTop's Strength





Nucleus with A nucleons i
energy per nucleon $E_i = E/A$

$$N_\mu(E,A) \propto A(E/A)^\beta$$
$$\Downarrow$$
$$N_\mu(E,A) \propto A^{1-\beta} E^\beta \qquad (\beta \approx 0.9)$$



Cosmic Ray Mass Composition

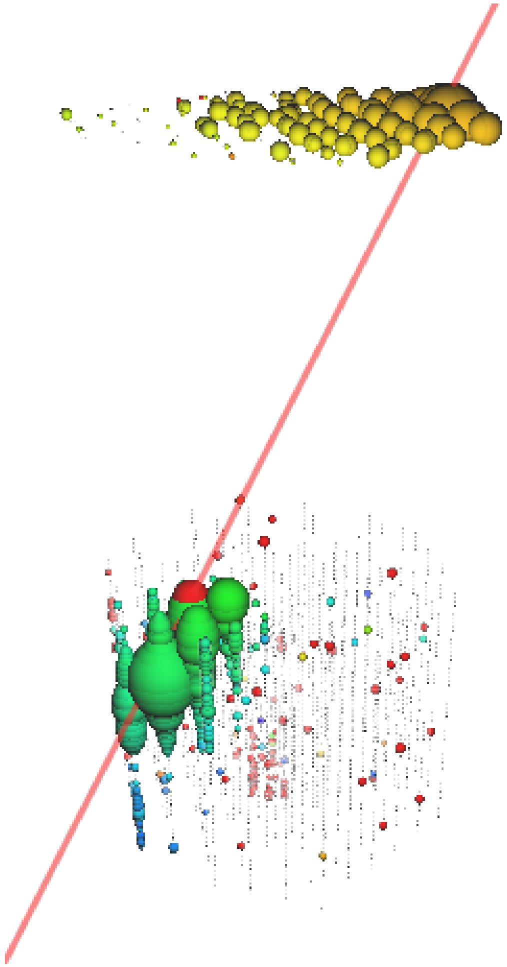
PRD 100, 082002 (2019)

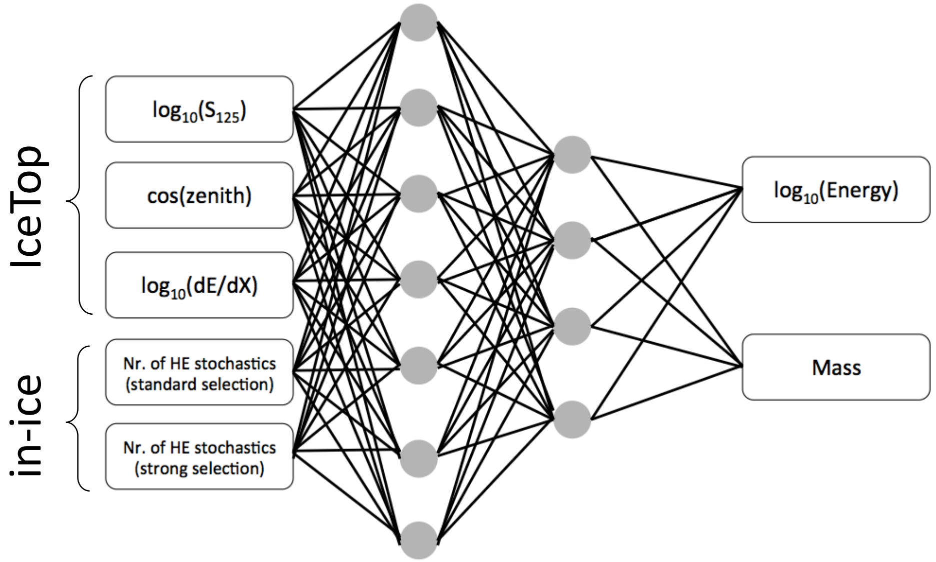
Combine IceTop with in-ice IceCube

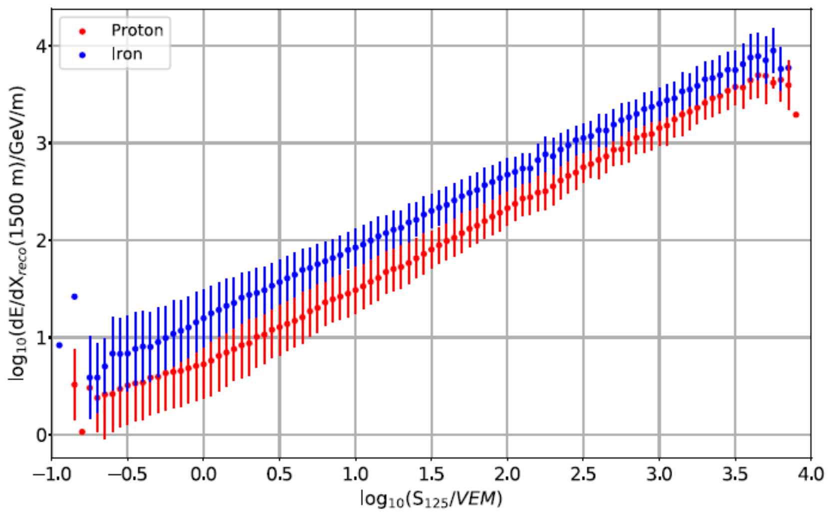
- Events with IceTop and in-ice hits
- Mean muon number

  $N_\mu(E,A) \propto A(E/A)^\beta,\ \beta \approx 0.9$
- Energy E from IceTop
- Muon number proxy from IceCube

  → **Mass number *A***





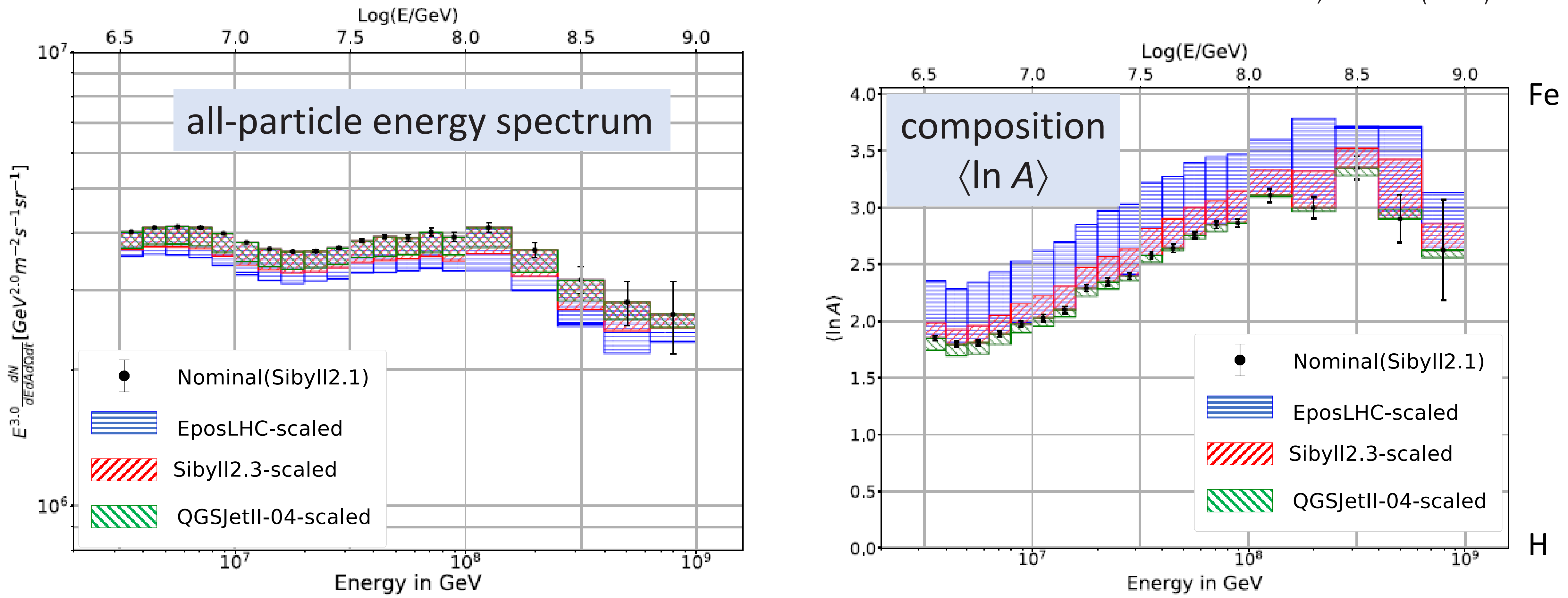


Similar concepts for **PeV gamma ray searches,** employing **muon-poor** sample

[IceCube, Astrophys. J. 891 (2020)]

Cosmic Ray Mass Composition (TeV muons)

PRD 100, 082002 (2019)



Hadronic interaction model uncertainty for
EposLHC, Sibyll2.3 and QGSJetII-04

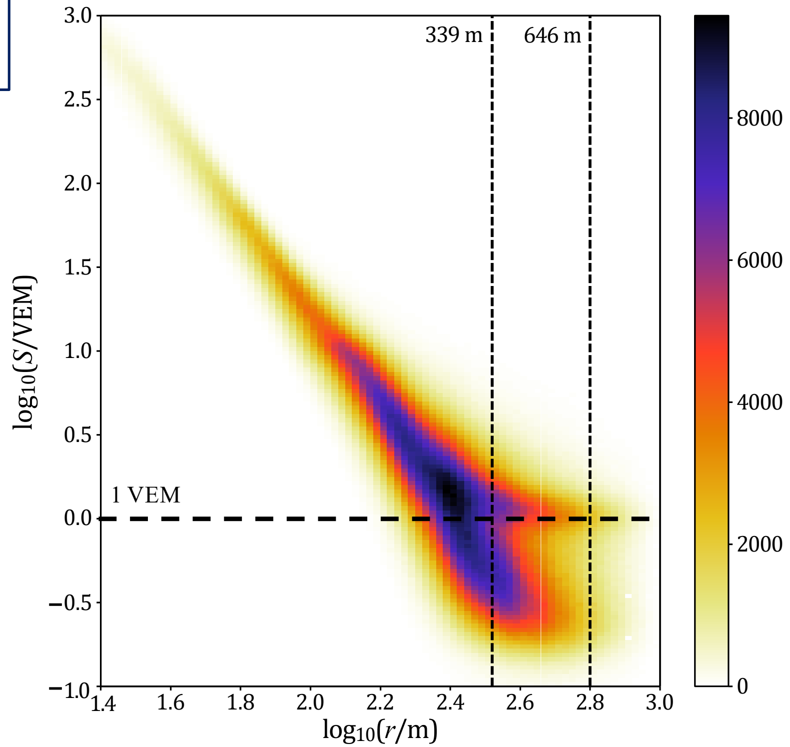
GeV Muons in IceTop

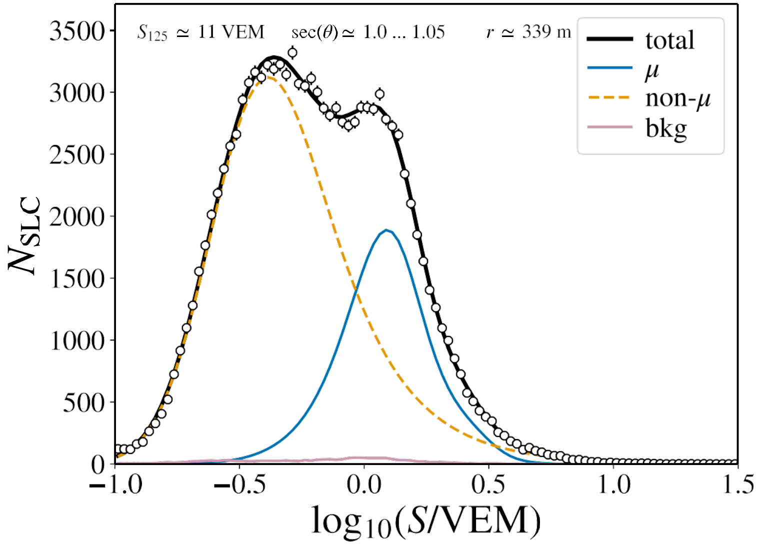
PoS ICRC2021-342

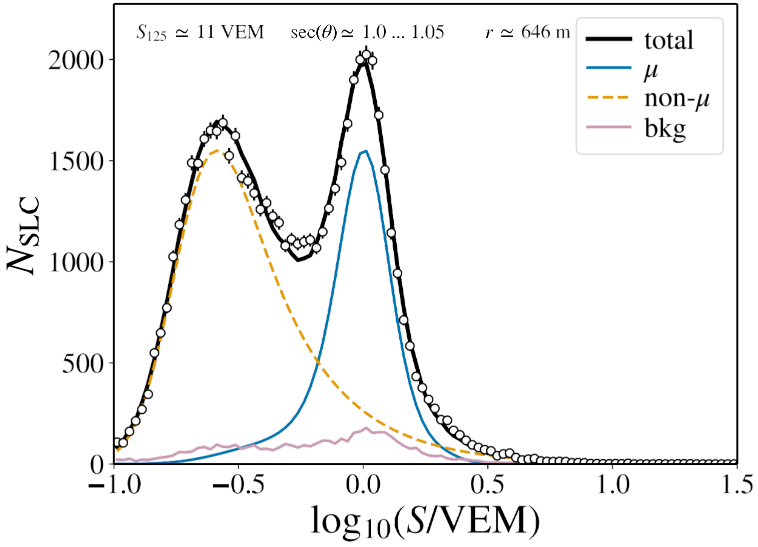
- Tank signals in terms of VEM = `vertical equivalent muon’ have a **muon peak** at 1 VEM
- Muon peak more pronounced at large distances *r* from shower core
- Derive muon density $\rho_\mu(r)$ by “counting” muons per tank
- Reference distance

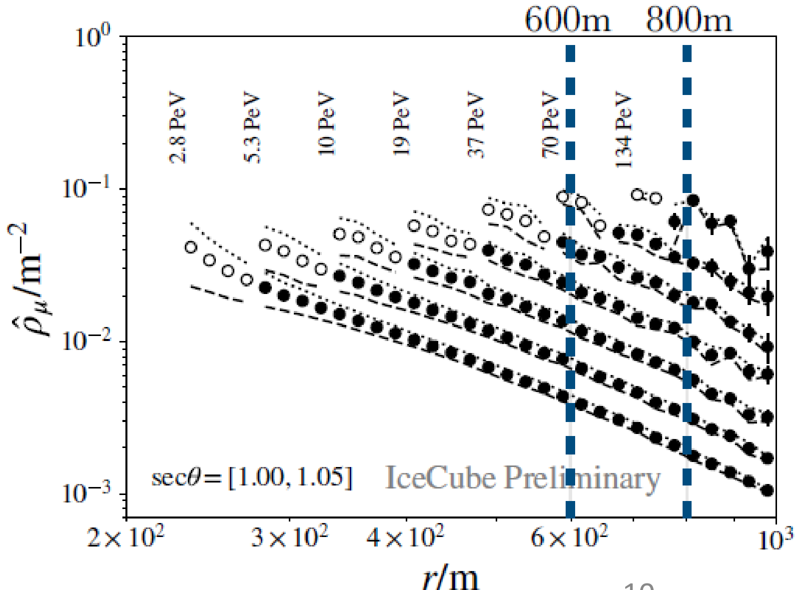
  r = 600 m for E = 2.5 – 40 PeV

  r = 800 m for E = 9.0 – 120 PeV







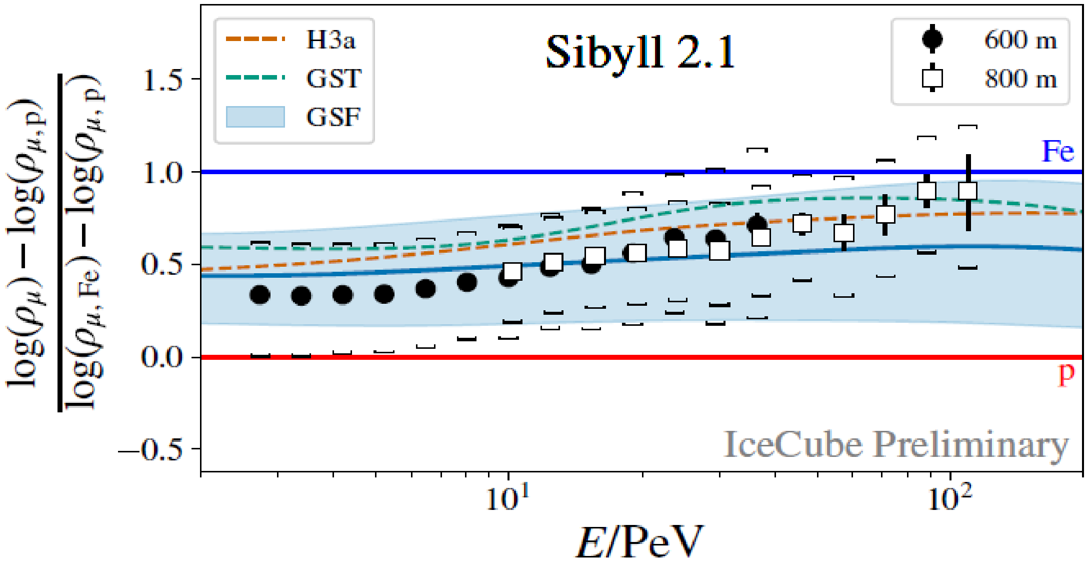


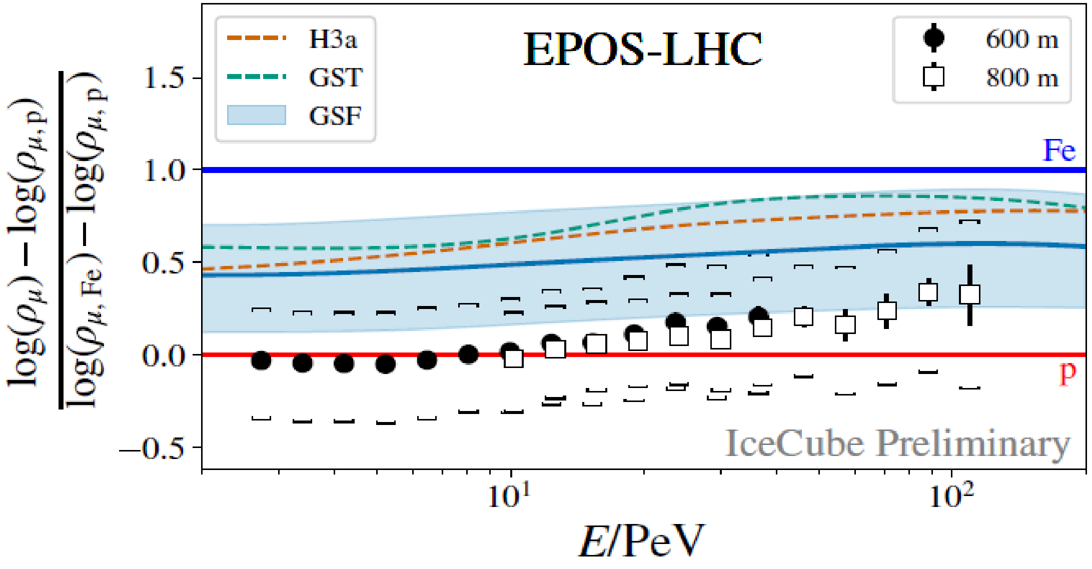
GeV muon density compared to models

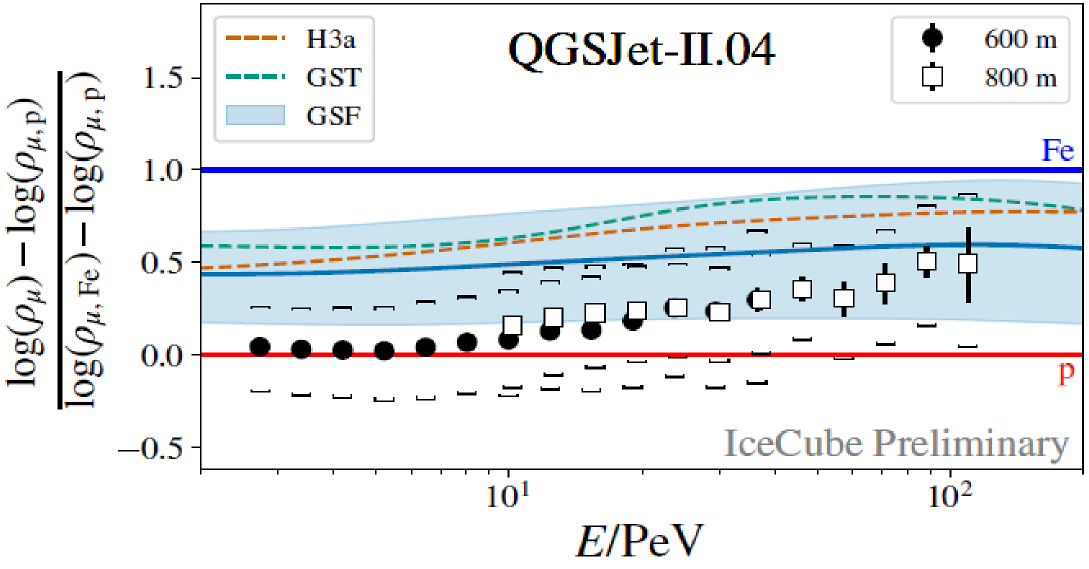
- Results in terms of "z-values":

$$z = \frac{\log \rho_\mu - \log \rho_{\mu,p}}{\log \rho_{\mu,Fe} - \log \rho_{\mu,p}}$$

- hadronic interaction models
  - pre-LHC: Sibyll 2.1
  - post-LHC: EPOS-LHC, QGSJet-II.04
- flux composition models H3a, GST, GSF



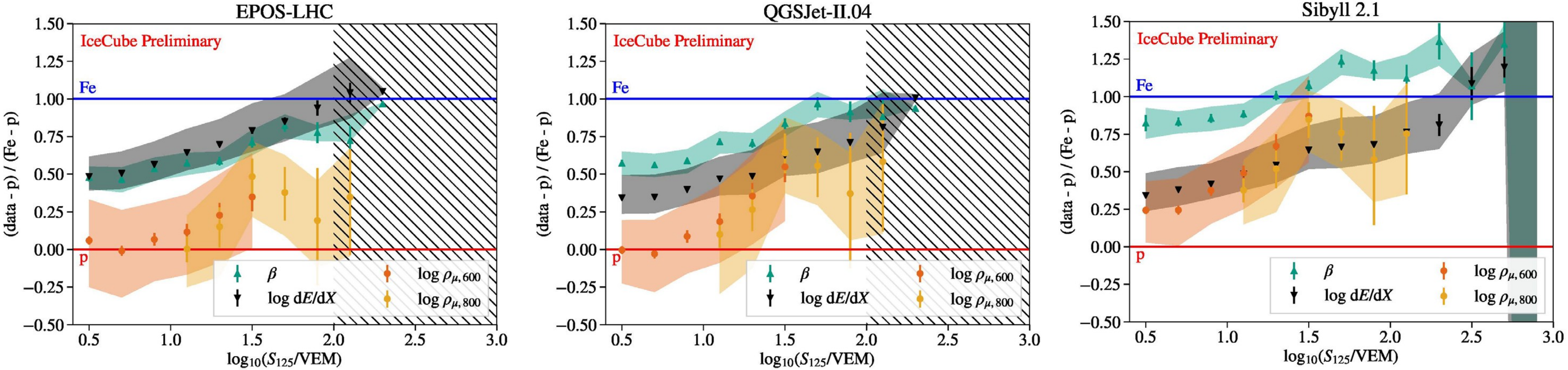




IceTop: tests of hadronic interaction models

PoS (ICRC2021) 357

air shower observables with mass sensitivity —— 3 different hadronic interaction models



β		slope of charge particle lateral distribution;
$\log \rho_{\mu,600}$		GeV muon density r=600 m;
$\log \rho_{\mu,800}$		GeV muon density r=800 m;
$\log dE/dX$		energy deposit in-ice of TeV muons;

- all models not consistent for all parameters
- TeV muons vs GeV muons not consistent in post-LHC models

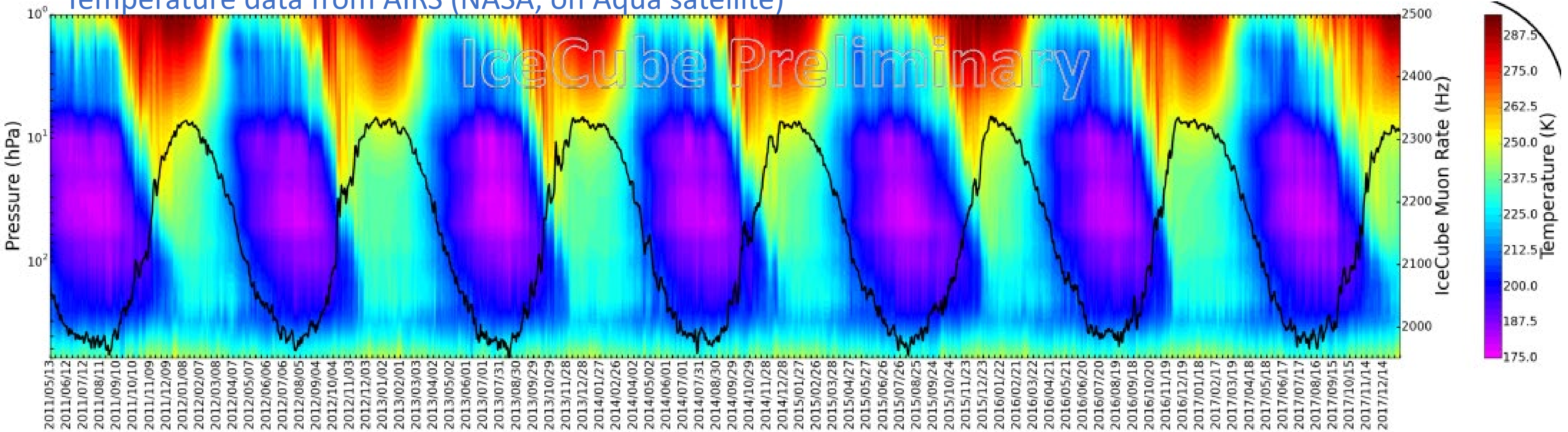
Conclusion: - we see inconsistencies between models

- no obvious “muon puzzle” at low energies

Seasonal Variations of Atmospheric Muon Rates

PoS(ICRC2019)894

Temperature data from AIRS (NASA, on Aqua satellite)



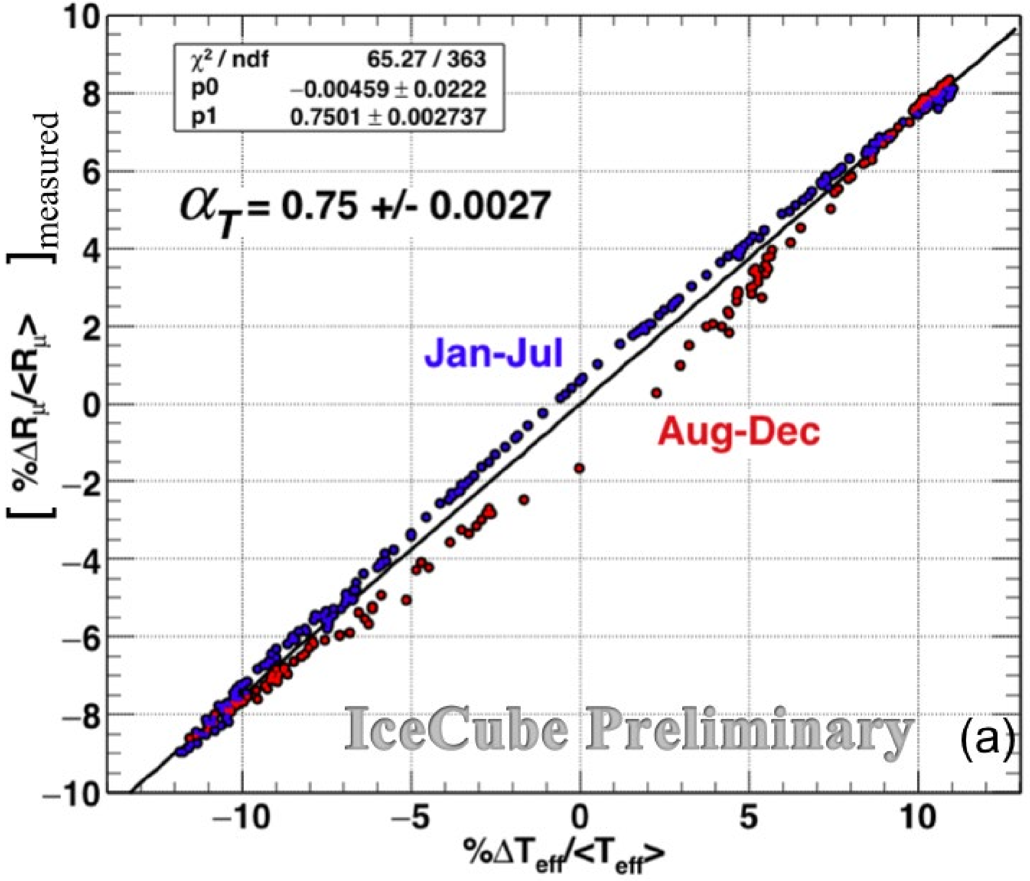
$$\frac{\Delta R_\mu}{\langle R_\mu \rangle} = \alpha_T^{exp} \frac{\Delta T_{eff}}{\langle T_{eff} \rangle}$$

Coeff. α depends on relative **decay and interaction** rates of **kaons and pions**: warmer/thinner atmosphere ⇒ less interactions, more decays (more μ and ν)

$$T_{eff}(\theta) = \frac{\int E_\mu \int dX\, \mathcal{P}_\mu(E_\mu, \theta, X)\, A_{eff}(E_\mu, \theta)\, T(X)}{\int E_\mu \int dX\, \mathcal{P}_\mu(E_\mu, \theta, X)\, A_{eff}(E_\mu, \theta)}$$

X atmospheric slant depth
P_μ muon production yield
T atmospheric temperature profile
A_{eff} effective area for muon detection

Seasonal Variations of Atmospheric Muon Rates



Features, even small ones, are well reproduced by analytical calculations.

Overall somewhat higher ΔR amplitude:

$$\alpha_T^{meas} = 0.75 < \alpha_T^{calc} = 0.85$$

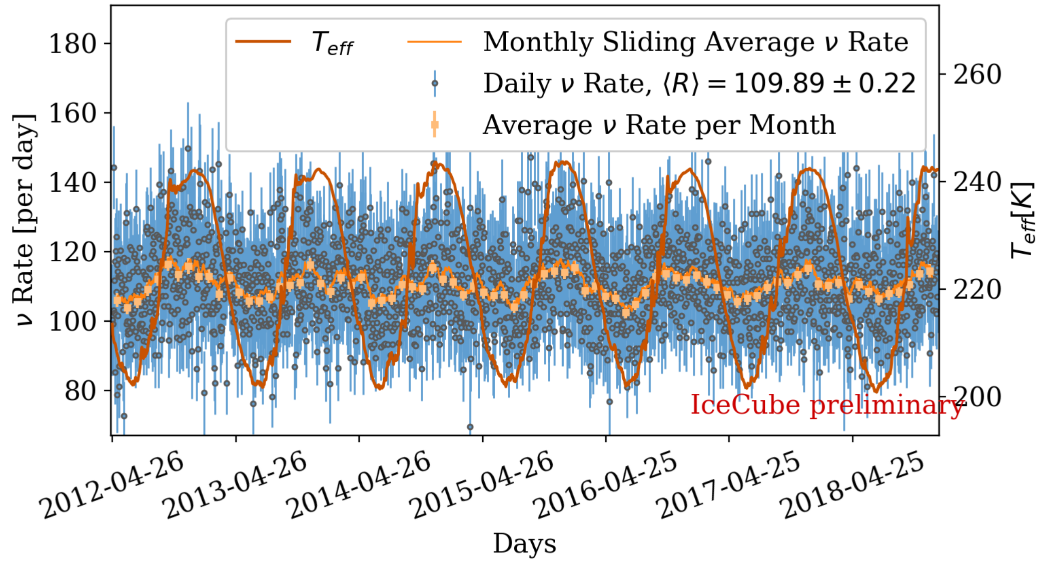
Deviations from linearity:
hysteresis due to different temperature profiles in spring and autumn

Calculations have to be refined [see also APP 133 (2021) 102630]:

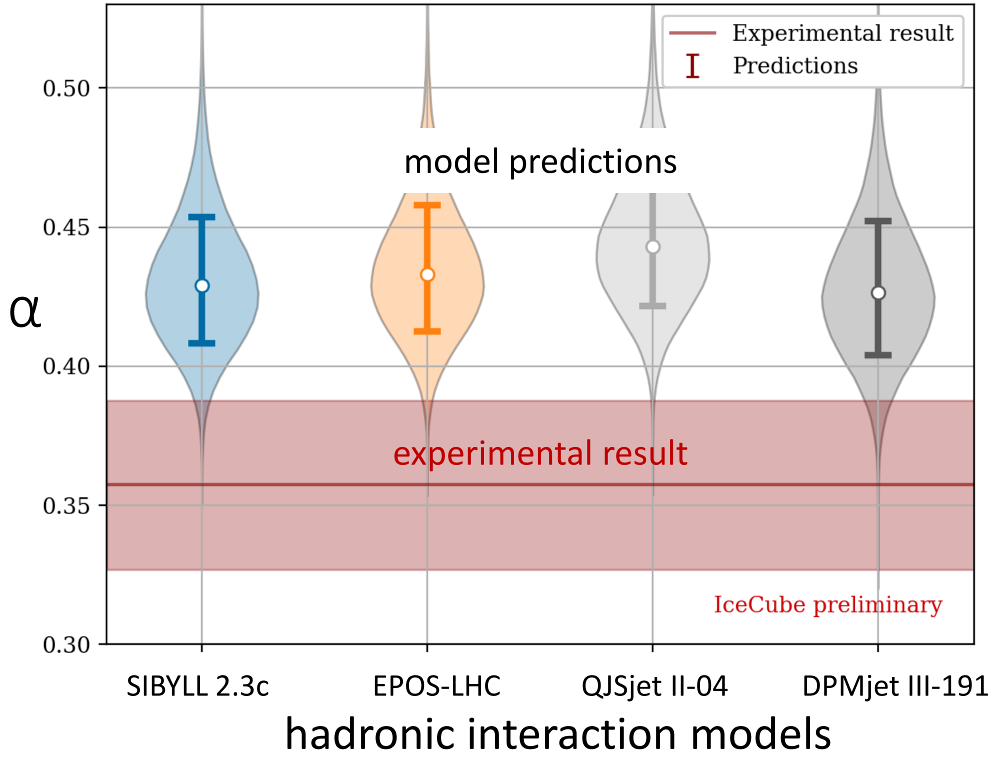
- explicit T profile (instead of average)
- muon multiplicity in the bundles
- mass composition
- ….

seasonal variations of atmospheric neutrino rates

Up-going neutrinos test Northern hemisphere



daily bins monthly bins effective temperature

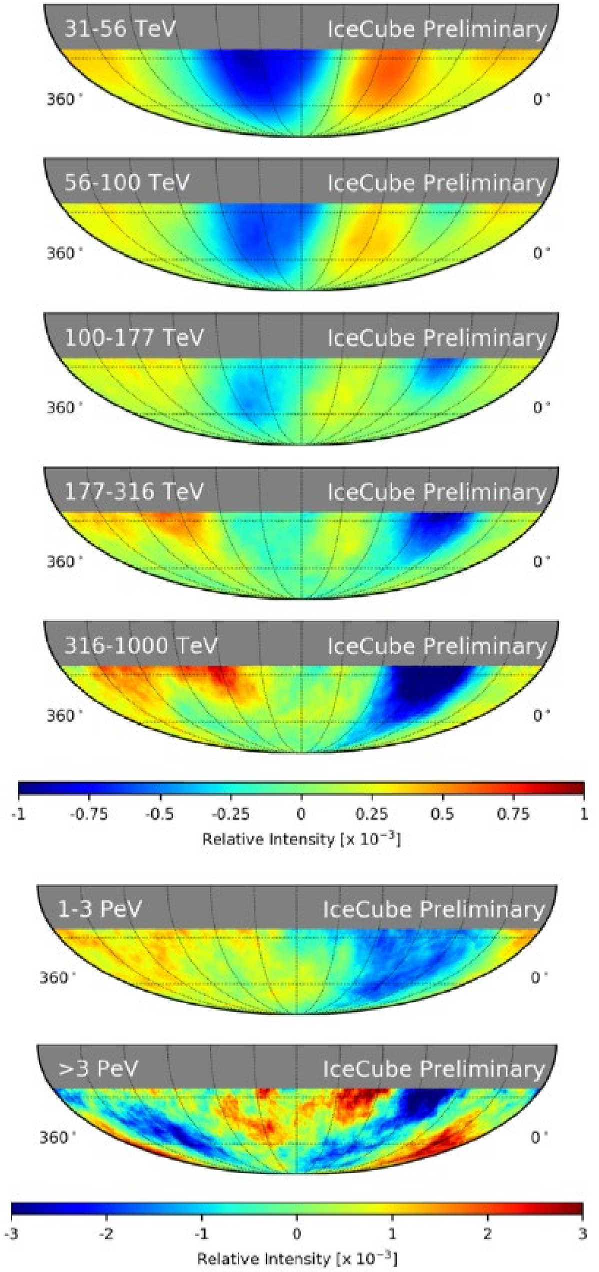


Because of decay kinematics at high energies kaon decays contribute relatively more to the neutrino rate than to muon rate ⇒ ν-μ comparison sensitive to kaon/pion ratio

⇒ all models predict similar coefficient α but higher than observed from ν rate variations

see also PoS(ICRC2019)465

IceCube Cosmic Ray Anisotropy (10 TeV – 5 PeV)

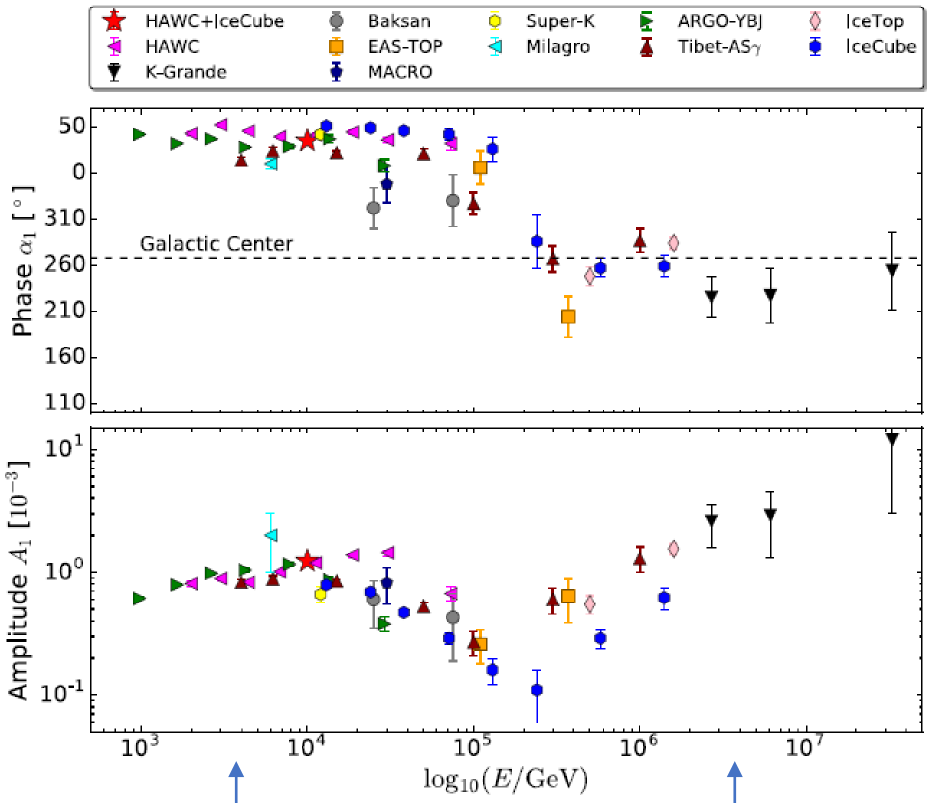


from PoS(ICRC2021)320

IceCube, APJ 826 (2016)

IceCube, APJ 765 (2013)

Dipole phase and amplitude

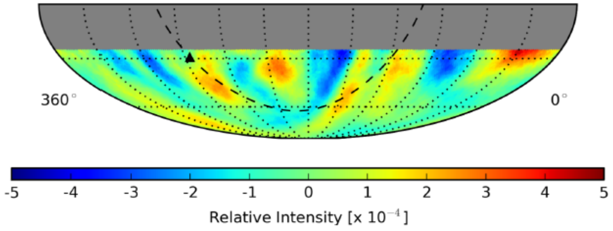


dominance of (?)

heliosphere

interstellar B field

- Dominant dipole at large scale (10^{-3})
- Significant small scale structure (10^{-4})

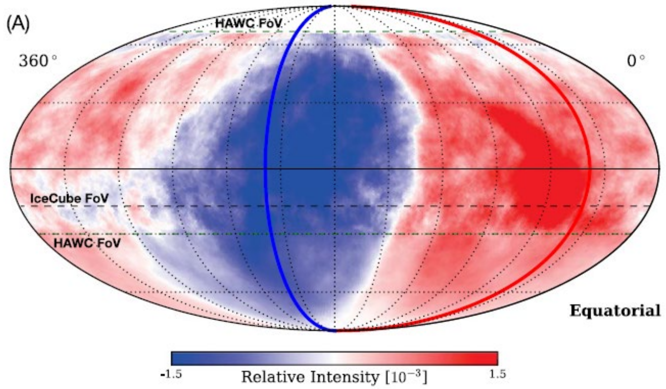


- Phase shift of dipole around 150 TeV
- Turning point of amplitude at ~10 TeV (transition heliosphere – interstellar magnetic field?)
- Details of effects of magnetic fields need all-sky analyses

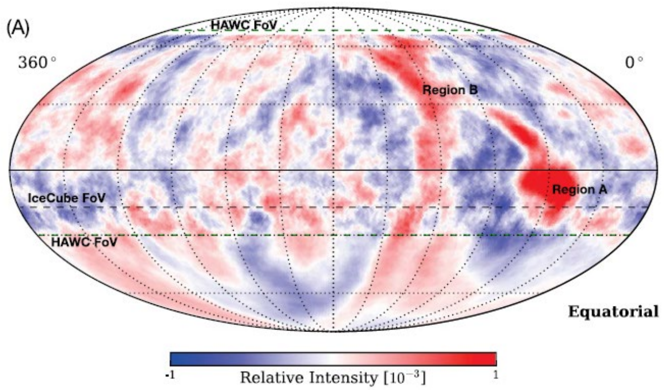
IceCube/HAWC All-Sky Anisotropy at 10 TeV

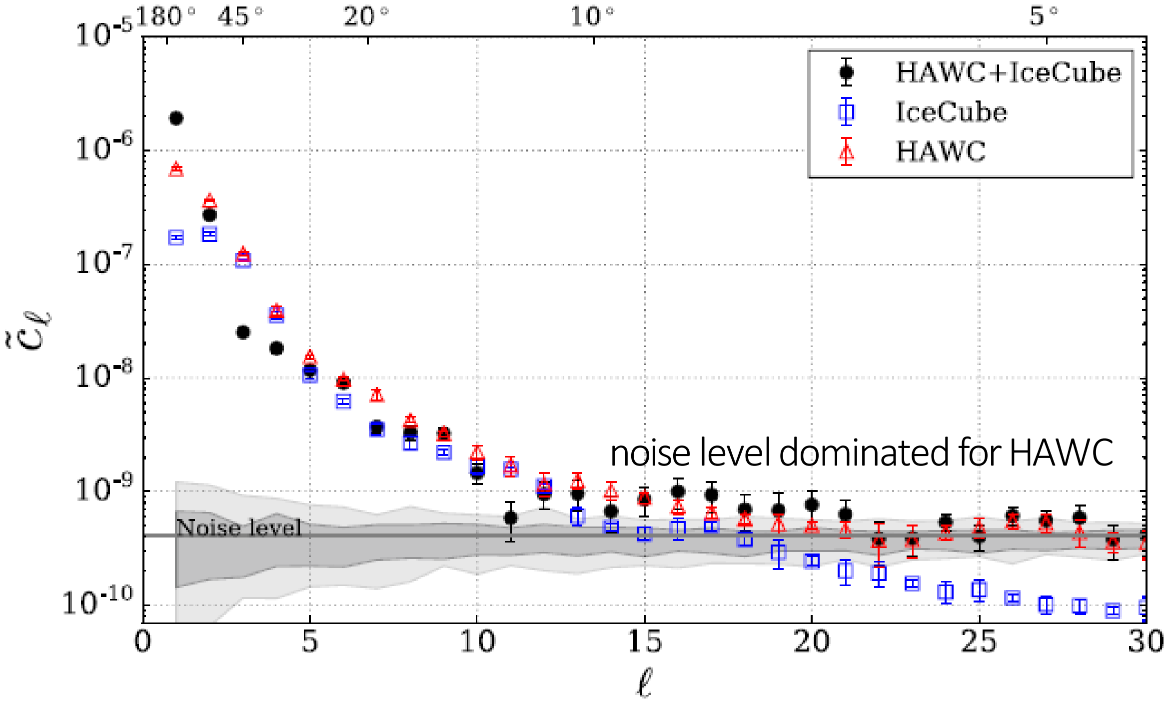
IceCube & HAWC, Astrophys. J. 871 (2019), 96

large scale



small scale ($l \geq 3$)





Decomposition of relative intensity into spherical harmonics

$$\delta I(\boldsymbol{u}_i) = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\boldsymbol{u}_i).$$

→ Angular power spectrum

$$\tilde{\mathcal{C}}_\ell = \frac{1}{2\ell} \sum_{m=-\ell, m\neq 0}^{\ell} |a_{\ell m}|^2$$

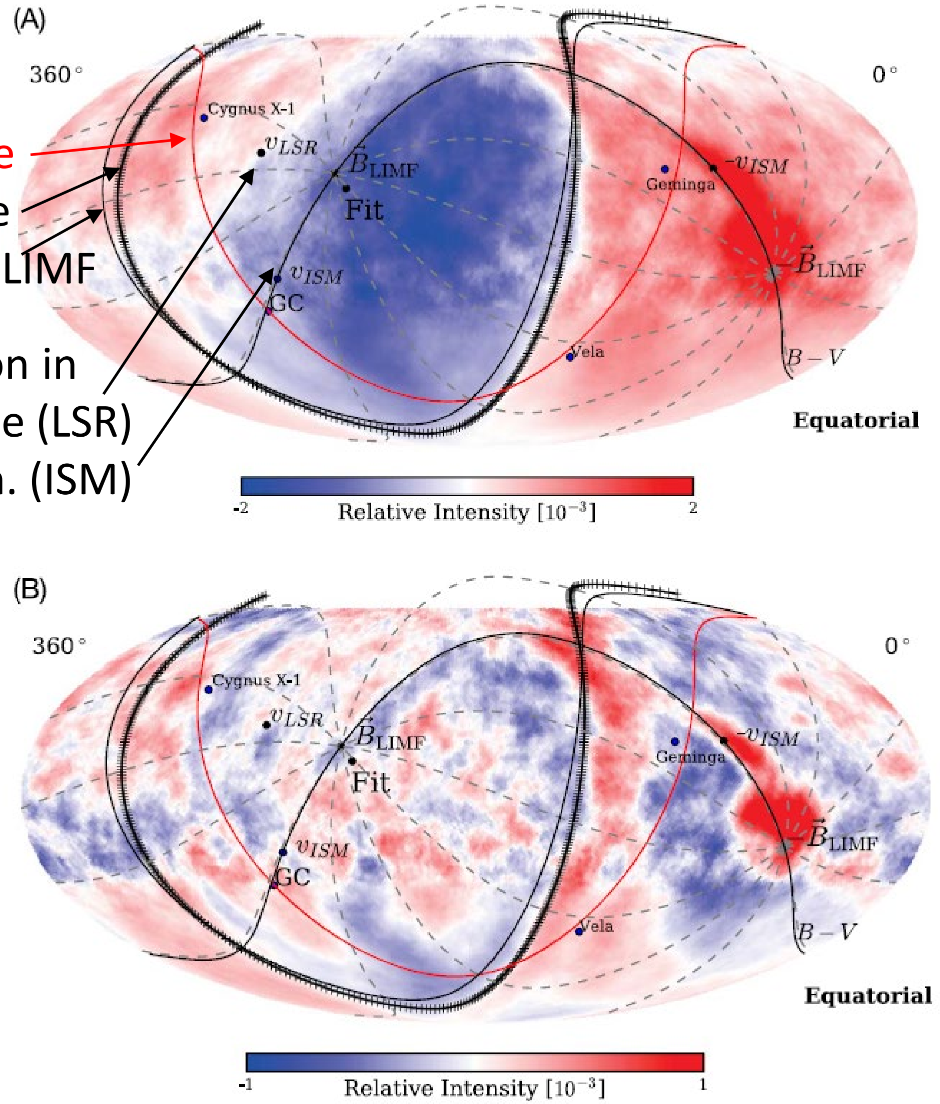
method insensitive to North-South asymmetries (background determined in declination bands)

All-Sky Anisotropy at 10 TeV;
the Local Interstellar Magnetic Field (LIMF) and the Heliospere

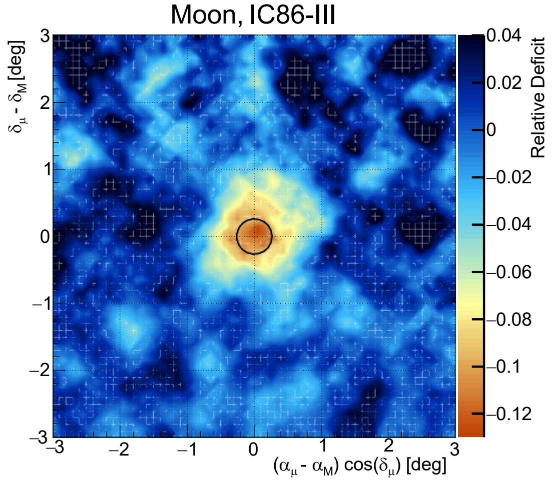
Diffusion by scattering on magn. turbulences
⇒ on large scales **isotropy; anisotropies** from local effects (sources, fields, ..) or movements (Compton-Getting effect)

- Fit plane along the boundary between large scale excess and deficit (fits ~dipole axis)
- Dipole points roughly into the **direction** of the local interstellar magnetic field (B_{LIMF}) determined by independent observations
- **Small-scale structures** ($l \leq 3$ subtracted) correspond to large gradients, aligned with features in LIMF and heliosphere
- Assuming dipole aligned with LIMF yields estimate of **North-South** dipole component

IceCube & HAWC, APJ 871 (2019)

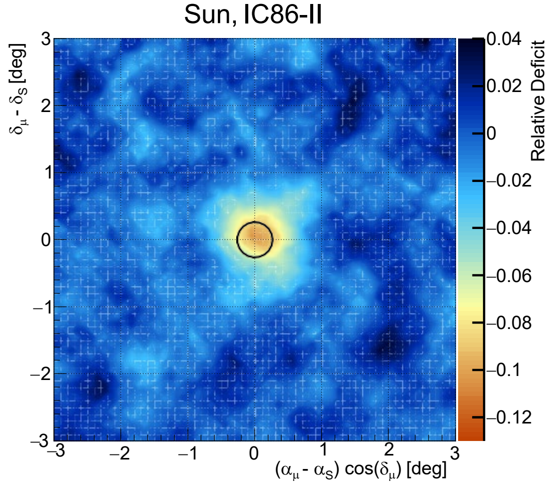


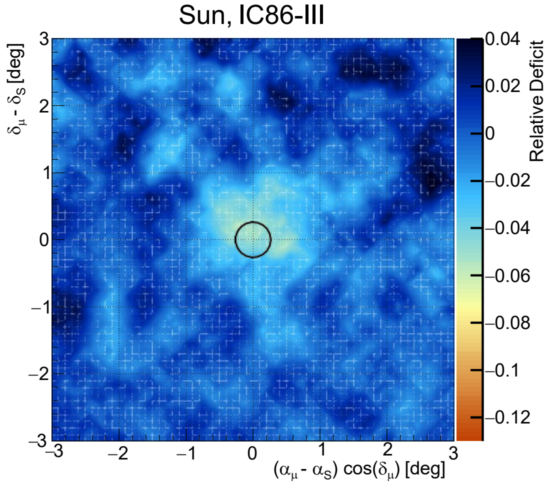
Measurements of the Moon and Sun Shadows

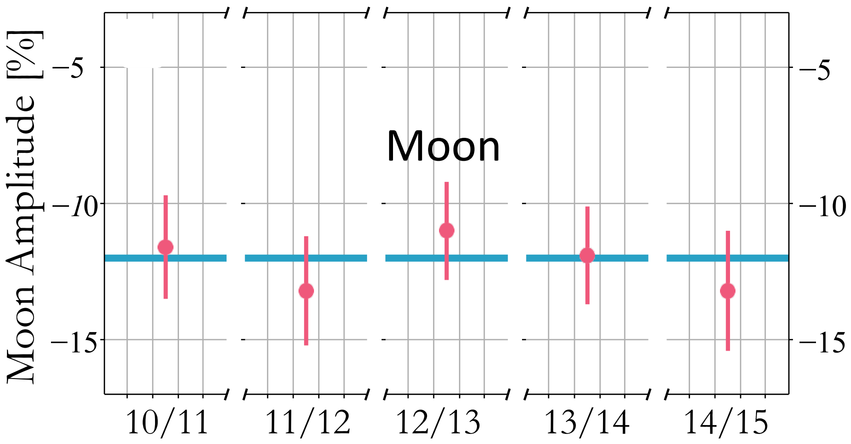


Selected events:

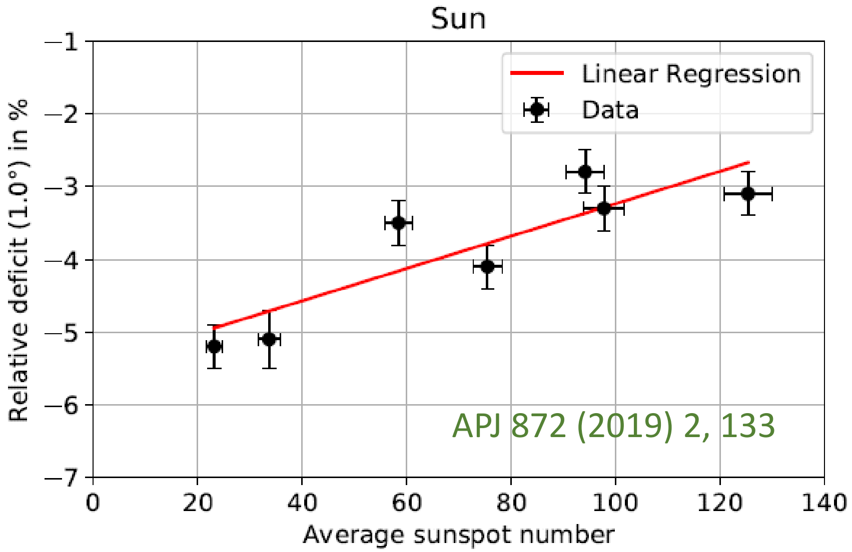
- median prim. $E_0 \approx 40$ TeV
- 68% of events: $11 \text{ TeV} < E_0 < 200 \text{ TeV}$







constant moon shadow amplitude
=> stable detector



Sun shadow correlates with sunspot number (11-year cycle)

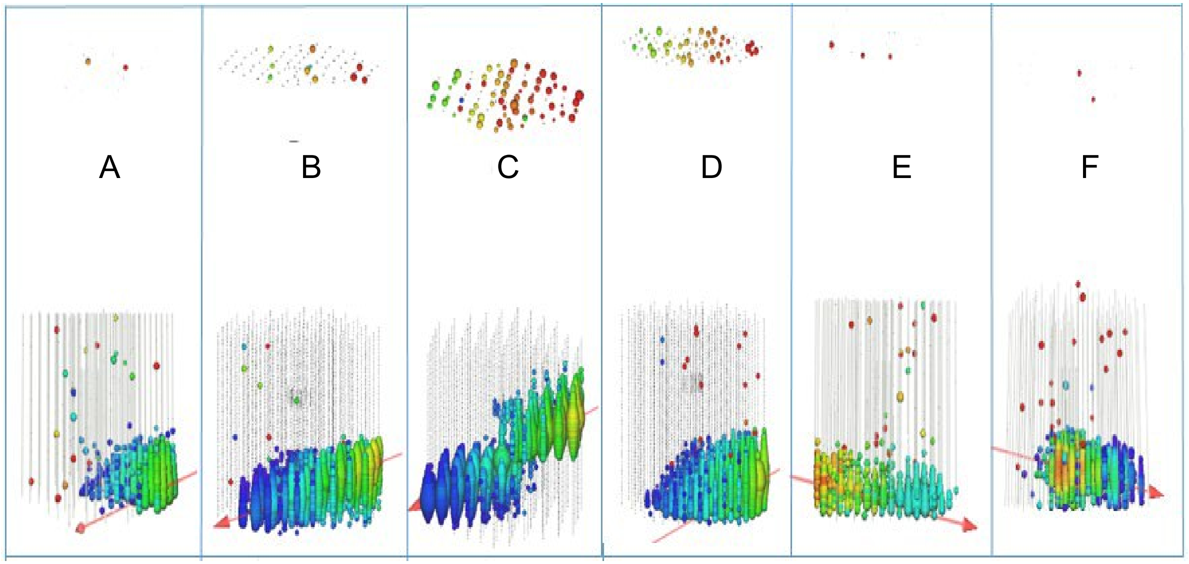
Further studies: influence of sun magnetic field, models to reproduce the shadow.
PoS(ICRC2021)1334; A&A 633, A83 (2020)

Also: Solar Atmospheric Neutrino Searches (PoS(ICRC2021)1174)

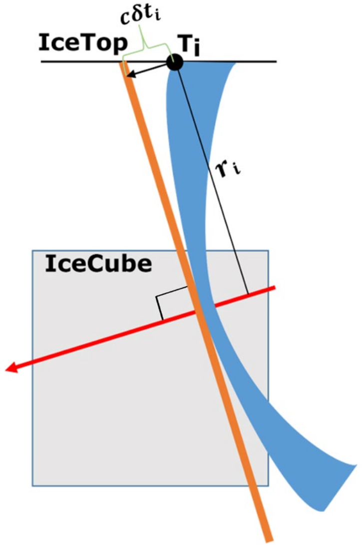
Cosmic Ray Veto for the Detection of Astrophysical Neutrinos

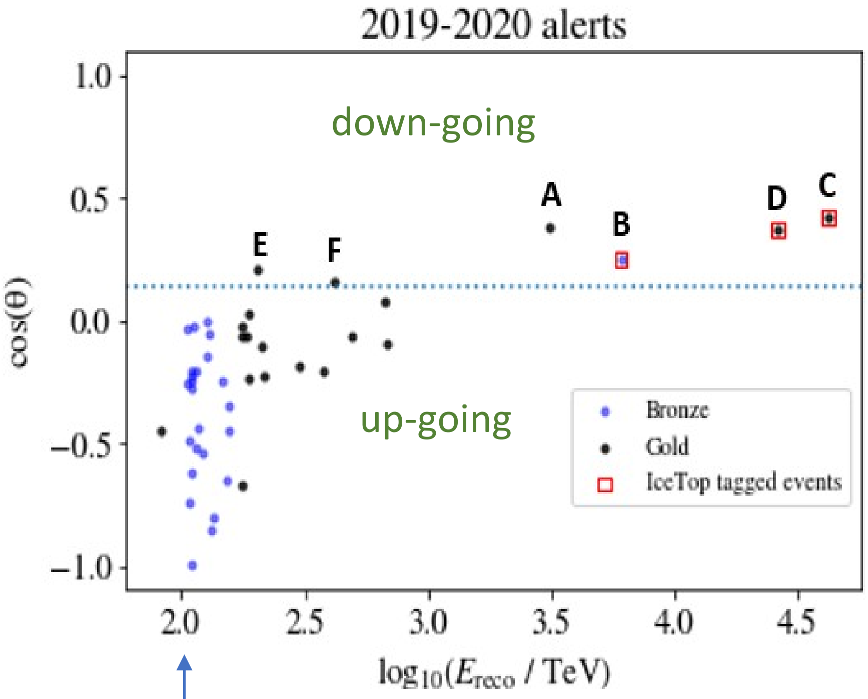
PoS ICRC 2021 342

IceTop: air shower veto to real-time neutrino alerts



IceTop hits within a 1 μs time window





- Earth diameter = average neutrino range in Earth @ 100 TeV
- Earth becomes opaque for high energy neutrinos
- but: down-going neutrinos suffer from CR background

IceTop: hybrid detector enhancement

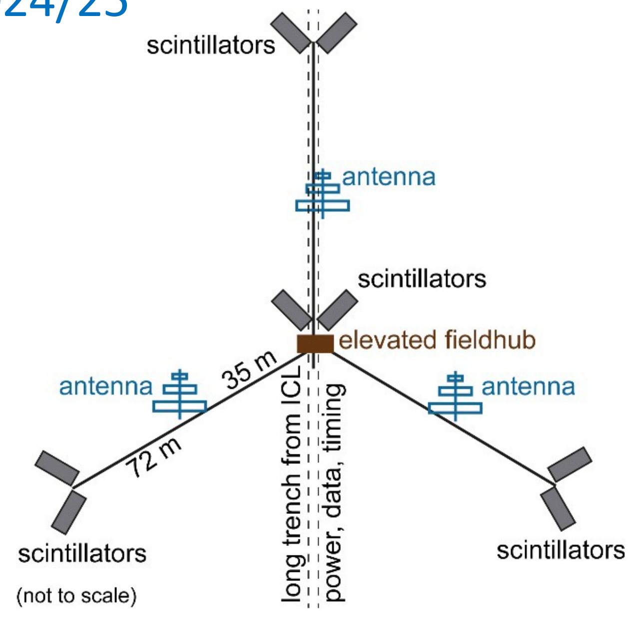
[PoS (ICRC2021) 225]

A Multi-Detector IceTop-Enhancement until 2024/25

Adding to IceTop Cherenkov tanks
- Scintillator panels
- Radio antennas
- Cherenkov light telescopes (IceACT)

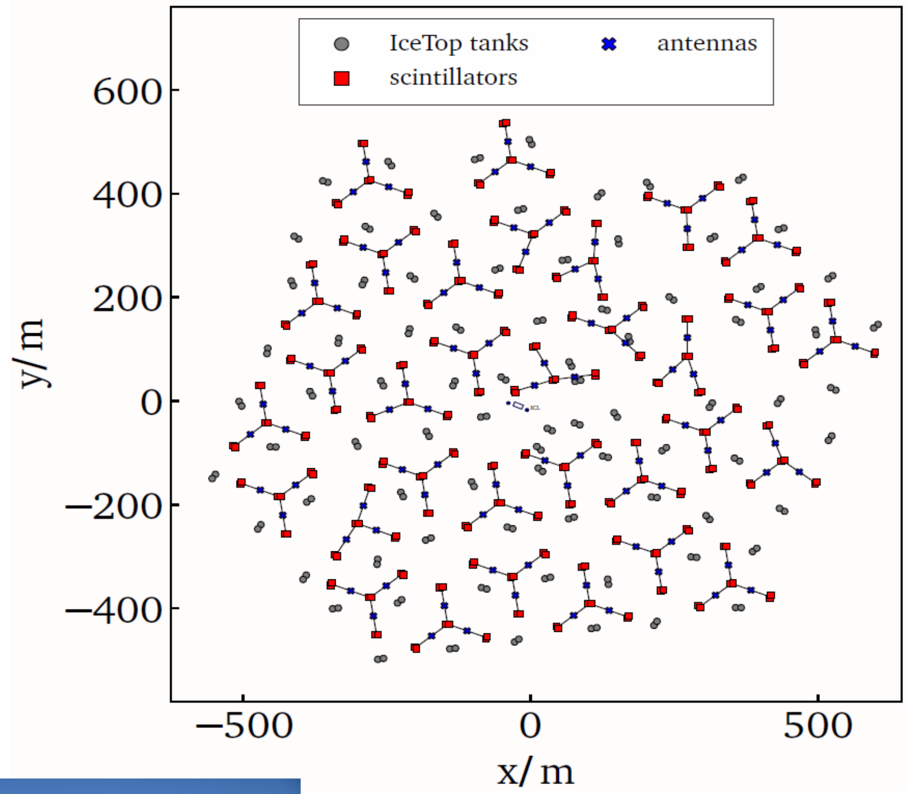
Goals

- improve systematics due to snow coverage
- improve CR veto for neutrino searches
- improve composition measurements
- towards composition dependent anisotropy
- improve PeV gamma ray search
- develop hadronic interaction models

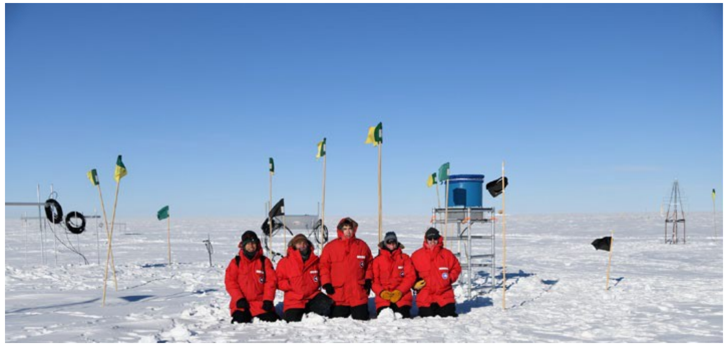


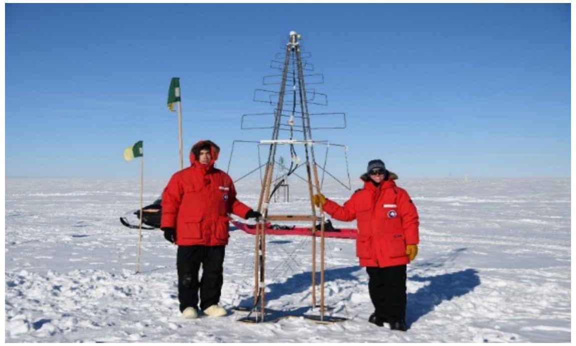
A scintillator-radio hybrid station

Deployment Plan for 32 stations



Prototyping at South Pole in 2020





Antennas and scintillators are elevated to avoid snow coverage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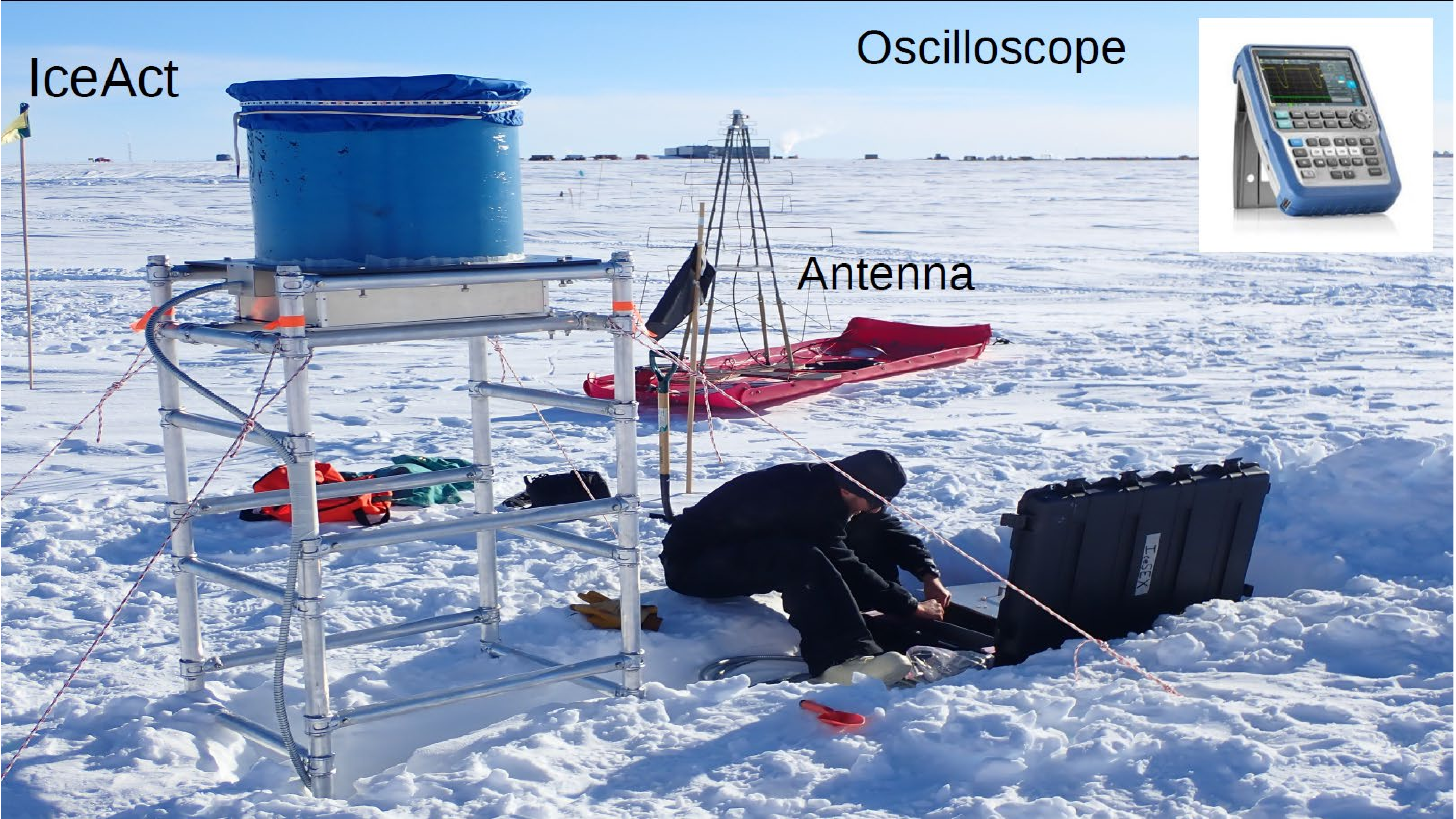
Happy Year 2022

Full prototype station deployed in January 2020


IceAct
Oscilloscope
Antenna