U.S. National Foundation-EPSCoR (RII Track-2 FEC, award #2019597)

EXPLORING THE COSMIC FRONTIERS: ICECUBE'S UPDATE ON NEUTRINOS AND COSMIC RAYS

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July 8, 2024

ISVHECRI 2024
Puerto Vallarta, Mexico

IceCube South Pole Neutrino Observatory

SOUTH DAKOTA MINES

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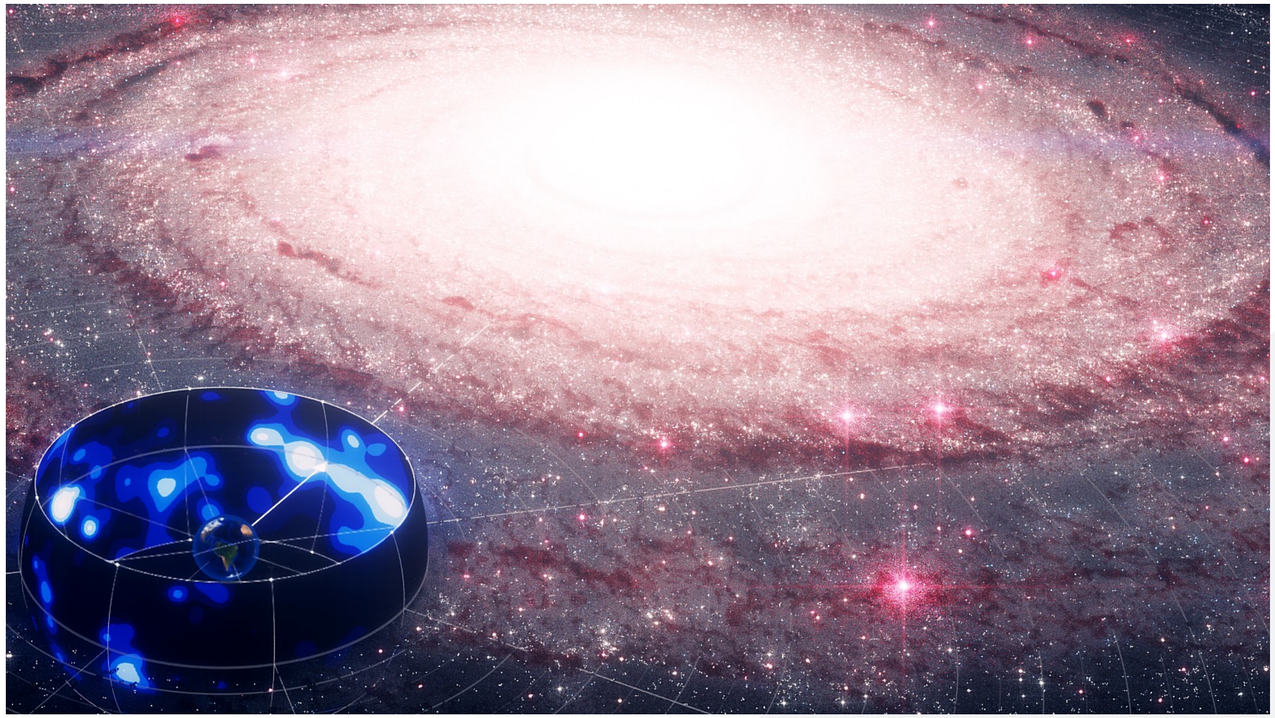
OUTLINE

- IceCube Neutrino Observatory
- Recent results on cosmic rays
- Recent results on neutrinos
- Outlook to IceCube-Gen2



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ICECUBE NEUTRINO OBSERVATORY

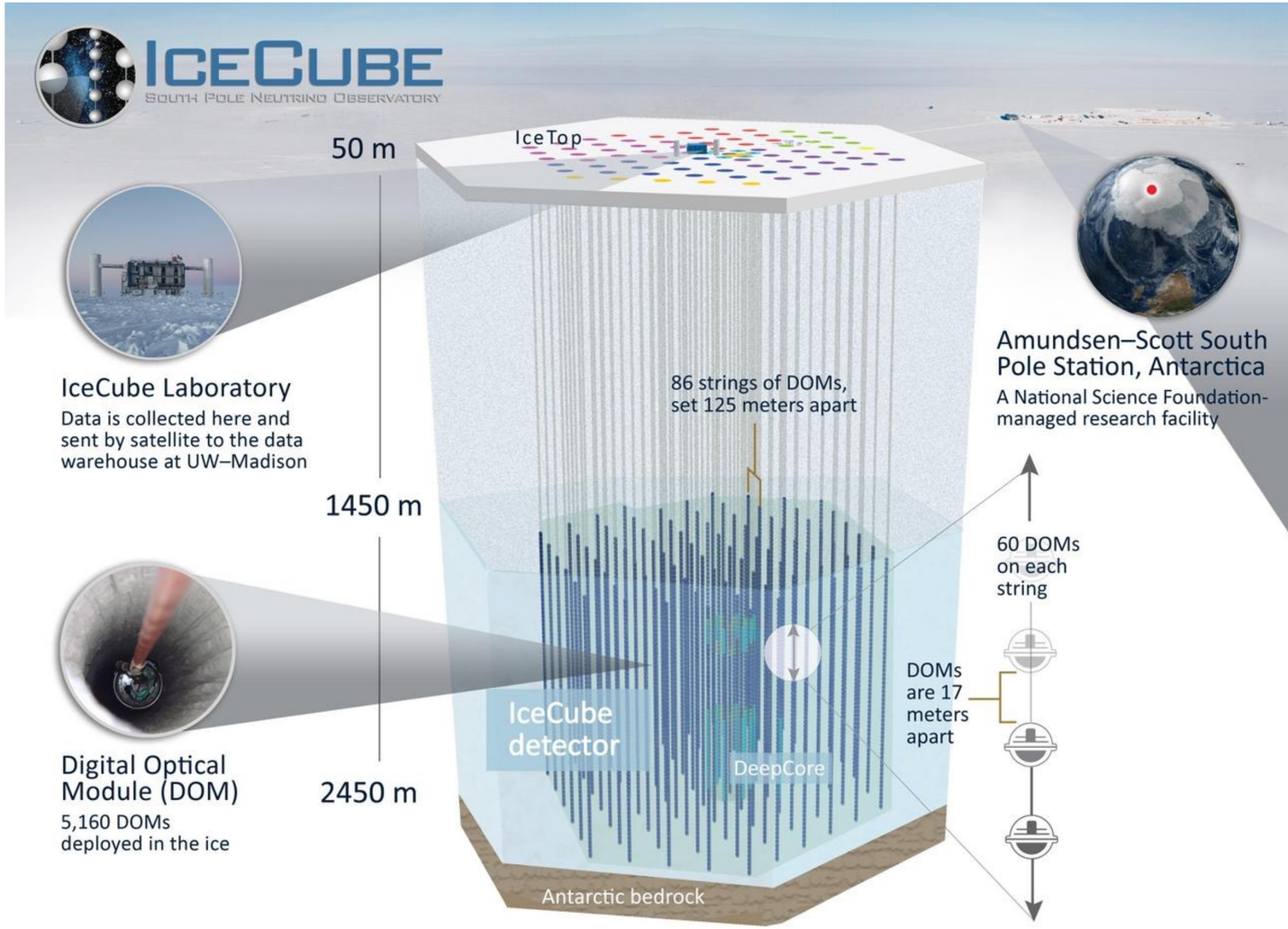
Unique astroparticle detector at the South Pole for high-energy particles

IceTop

- Mostly electromagnetic particles and low-energy muons

IceCube

- High-energy air shower muons
- Neutrinos (indirect)



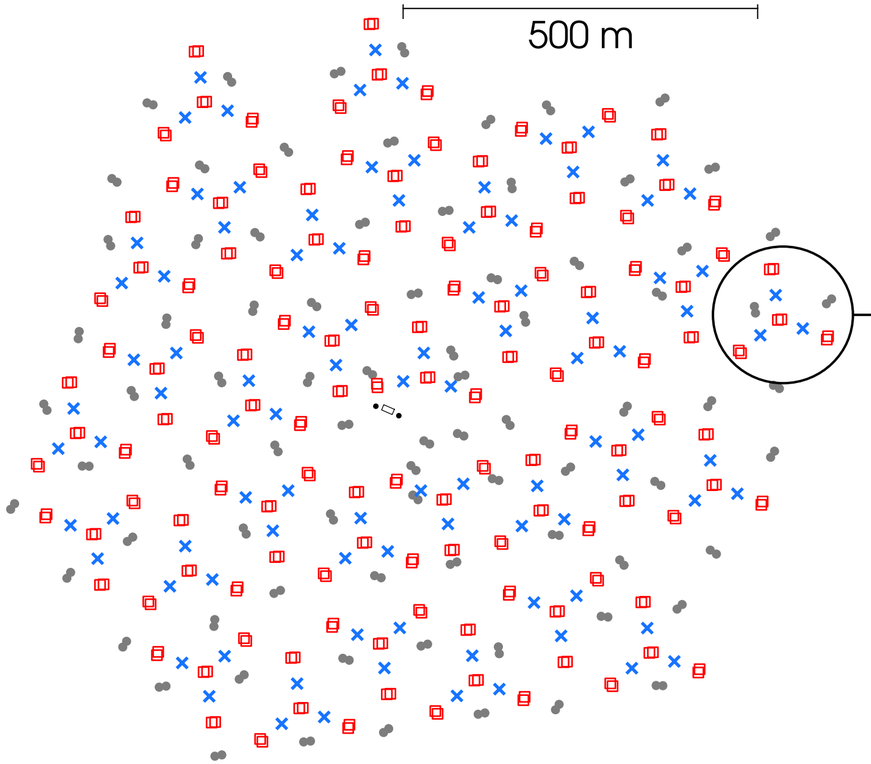
ICETOP + SURFACE ENHANCEMENT ARRAY

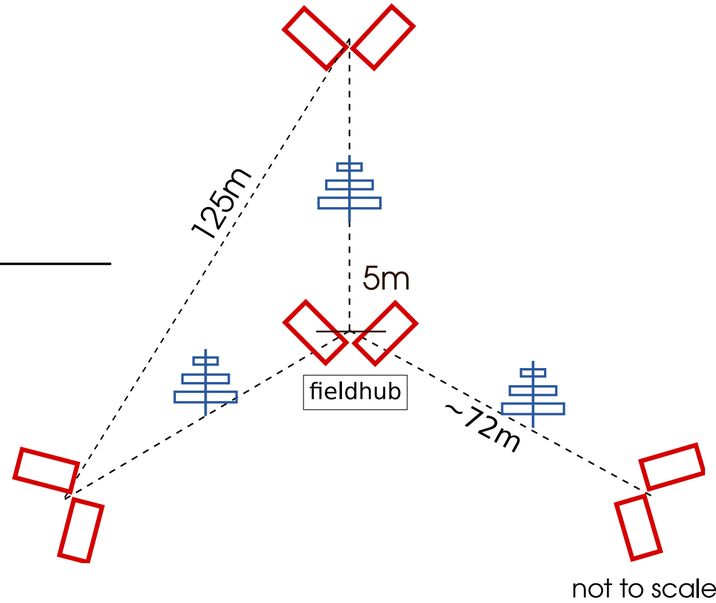
- IceTop is a 1 km^2 ice-Cherenkov tank air shower array under the snow surface
- Scintillator panels and radio antennas are planned to mitigate increasing snow coverage and add composition sensitivity
- Scintillator triggers similarly to IceTop. Radio is passively read out in case of a surface trigger

Radio antenna

Prototype station is running since 2020

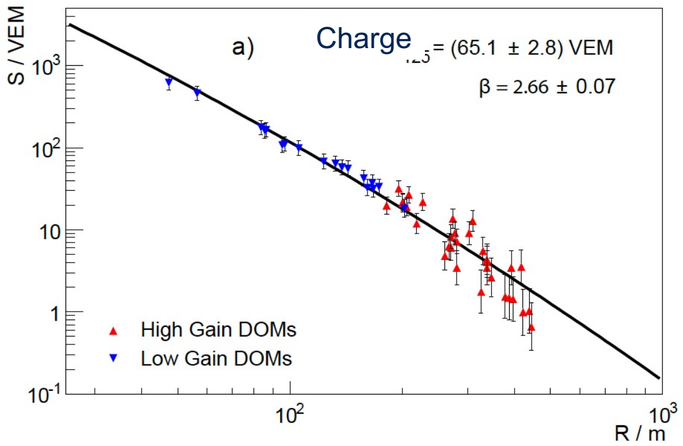
Scintillator panel

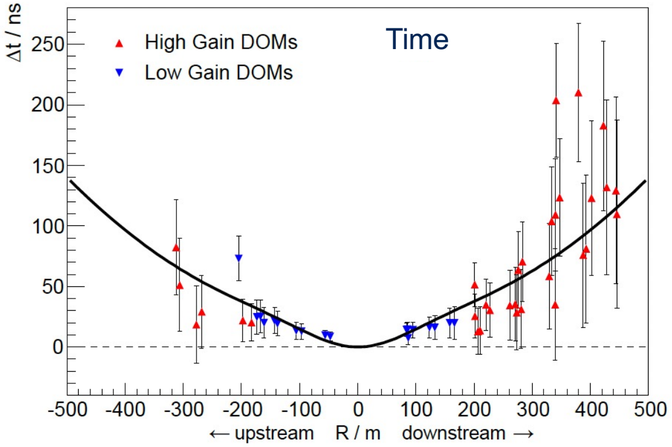




1 station =
8 scintillator modules + 3 antennas

COSMIC RAY AIR SHOWER RECONSTRUCTION



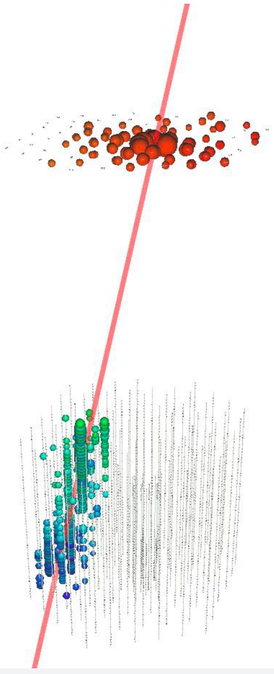


https://arxiv.org/abs/1207.6326

- IceTop
  - Fit to IceTop signals
    - Lateral distribution function (charge)
    - Shower front (time)

  → Direction & core position

  → Shower size S_{125} : proxy for primary energy
- In-Ice
  - Energy loss reconstruction
  - Along the reconstructed IceTop track

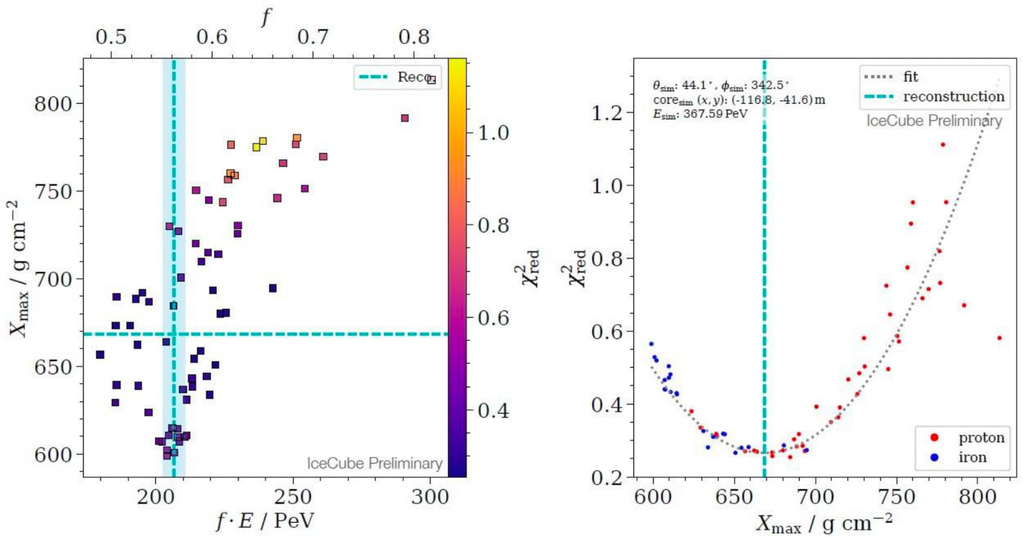


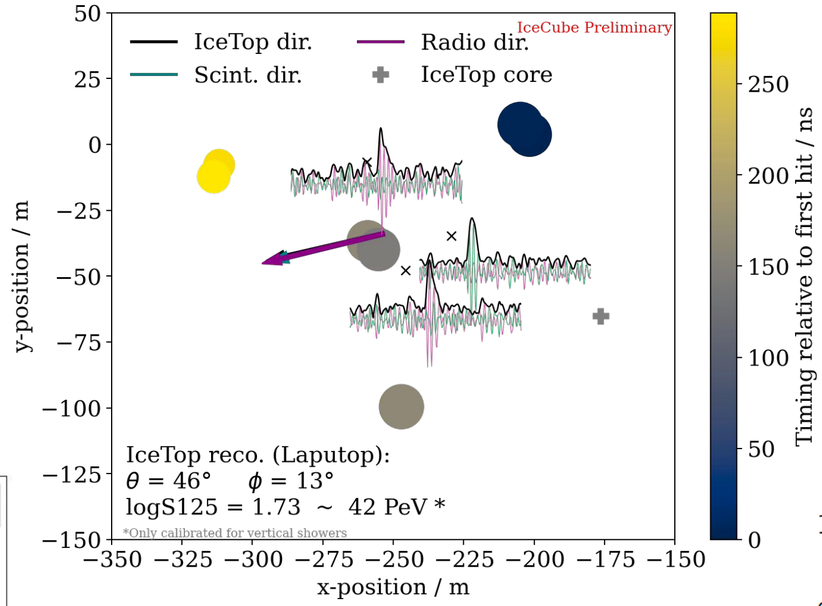
- Combined Reconstruction Surface Detector+Radio and deep In-Ice
  - Direction & core position
  - Shower size and energy loss reconstruction
  - With Radio X_{max}

SURFACE SCINTILLATOR+RADIO ENHANCEMENT

Radio :

- Direct X_{max} measurement for inclined high-energy shower

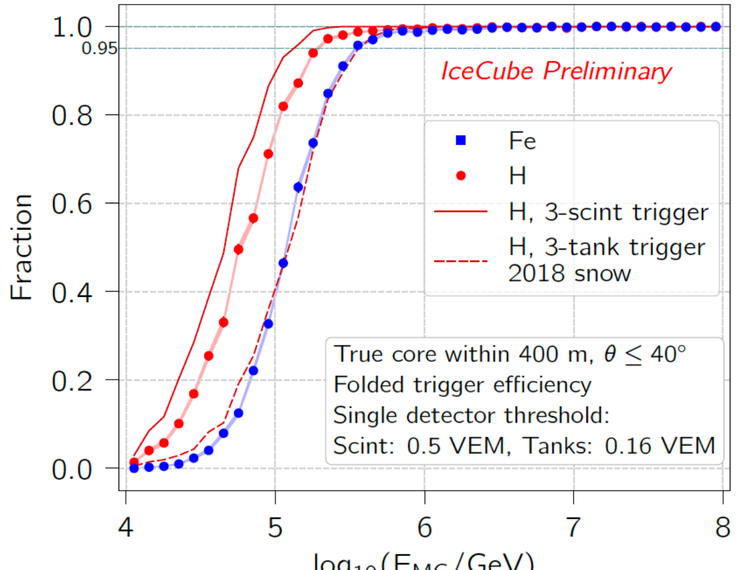




Event seen by IceTop, the R&D scintillators and radio antennas

Scintillator:

- Lower trigger probability
- Improved muon density measurements at the surface level



https://arxiv.org/abs/2205.05845

DOI: 10.22323/1.358.0332

IMAGING AIR CHERENKOV TELESCOPES ICEACT

Low energy (10 TeV - 200 TeV) air shower particles barely reach the ground making ‘classic’ surface reconstruction challenging

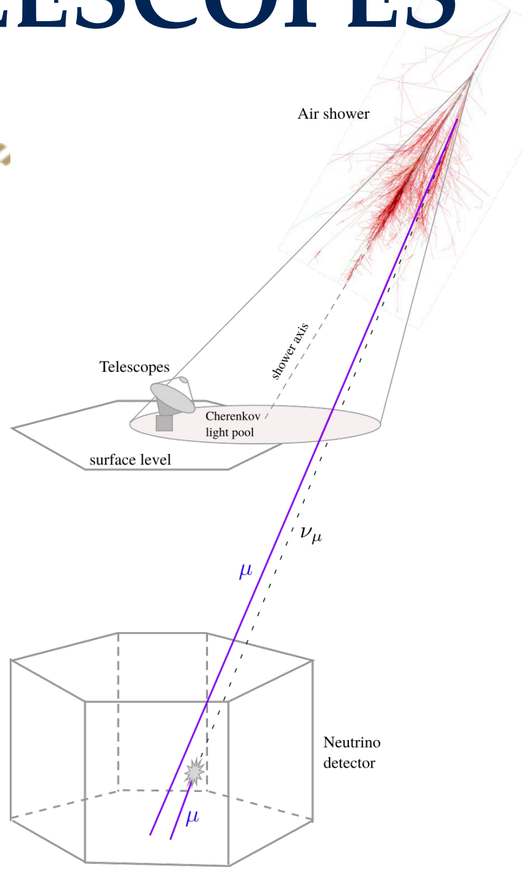
IceAct

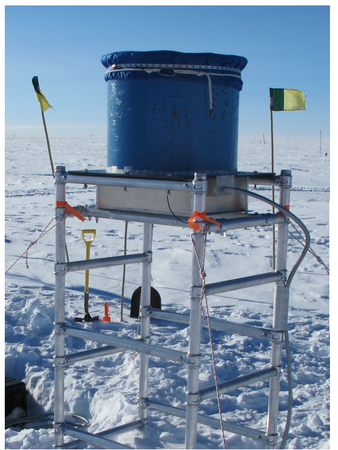
- measure the el.-mag. shower component inside the atmosphere from TeV to PeV
- combine with particle footprint on ground level and in-ice muon reconstruction:
  - calibration of geometry and energy
  - hybrid composition studies
  - possible veto capability

- Since 2019 two R&D telescopes have been deployed at the South Pole and are taking data, a third telescope is currently being deployed

The telescopes can only operate during the Antarctic night (roughly 4.5 months stop) and good atmospheric conditions

- Duty cycle ~ 20%





- 50 cm Fresnel lens
- 50 cm focal length
- 61 hexagonal pixel

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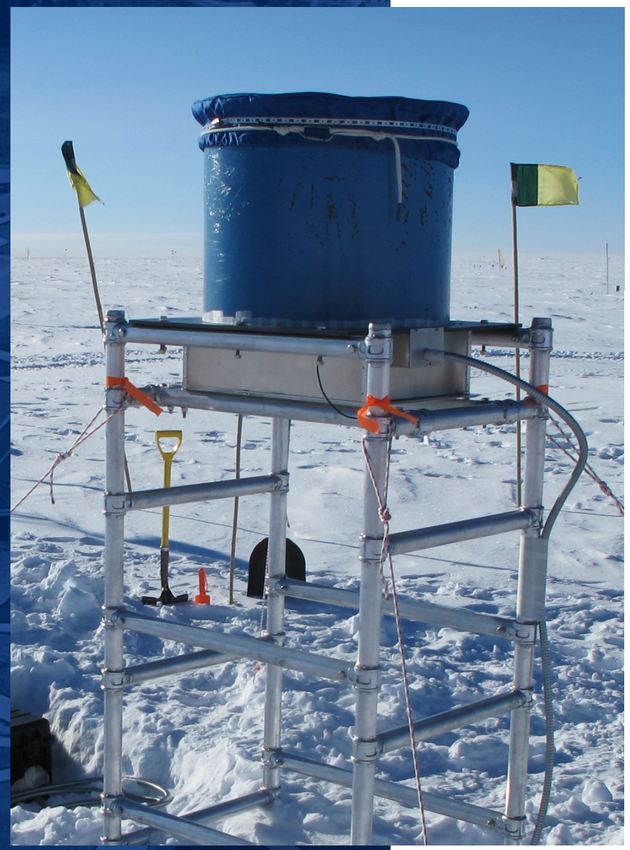
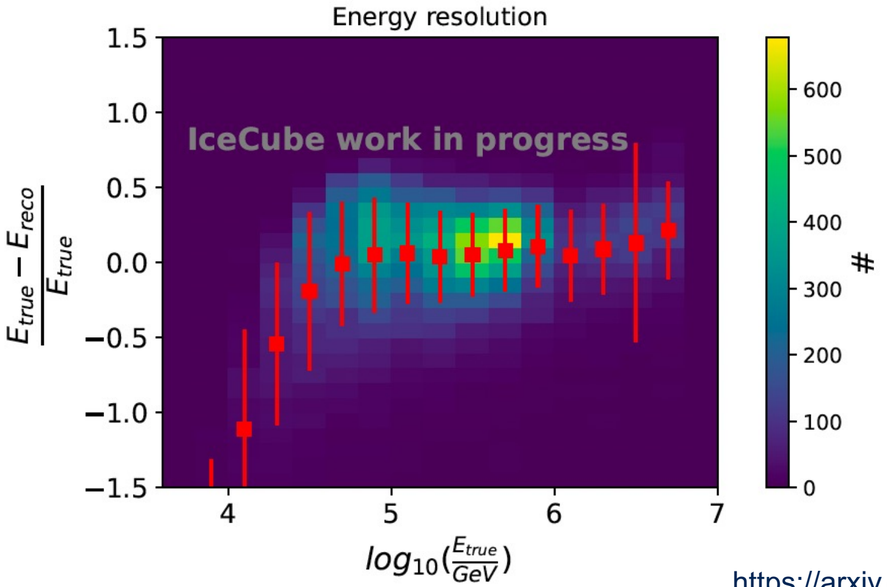
IMAGING AIR CHERENKOV TELESCOPES ICEACT

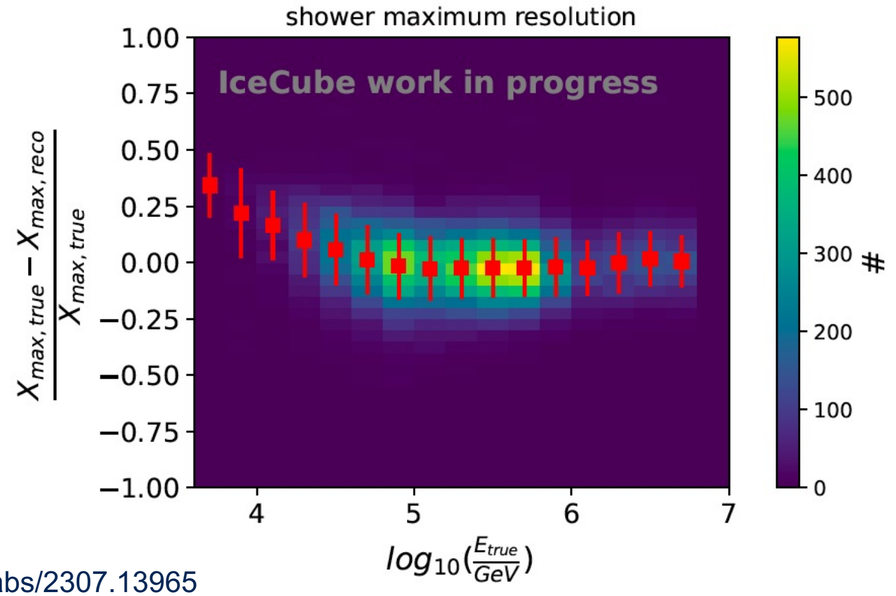
- A first approach of single telescope Graph Neural Network reconstruction

- Simultaneously determines:
  - Air shower geometry
  - Energy
  - X_{max}

for vertical low-energy air shower







https://arxiv.org/abs/2307.13965

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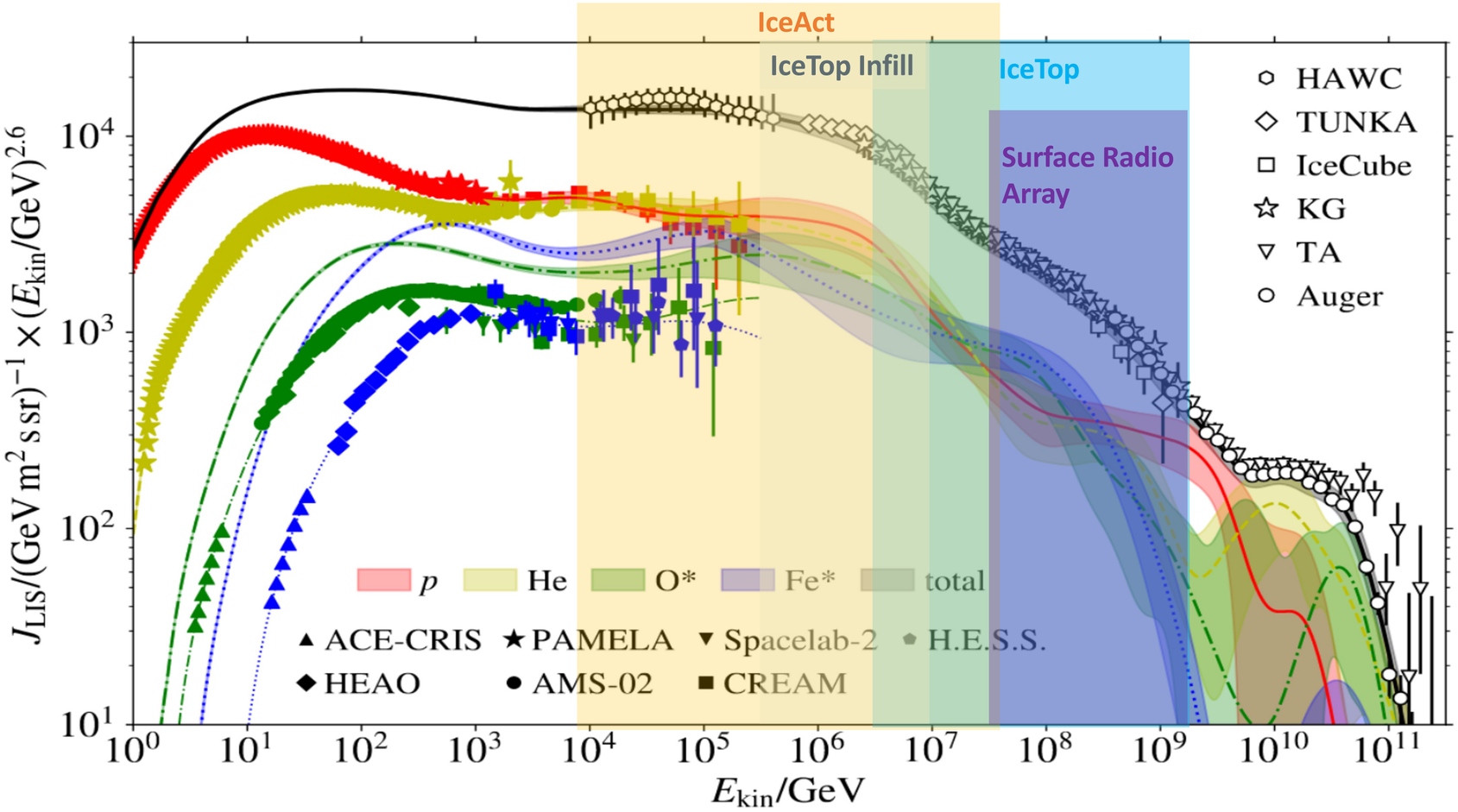
CR ENERGY RANGE OF ICECUBE/ICETOP



https://arxiv.org/abs/1902.08124

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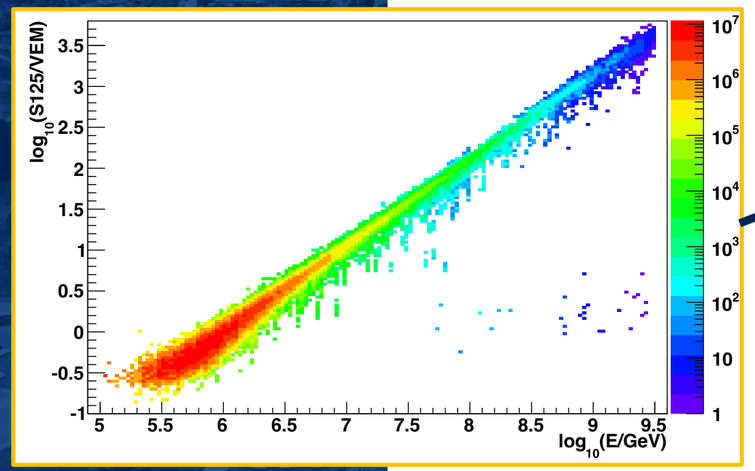
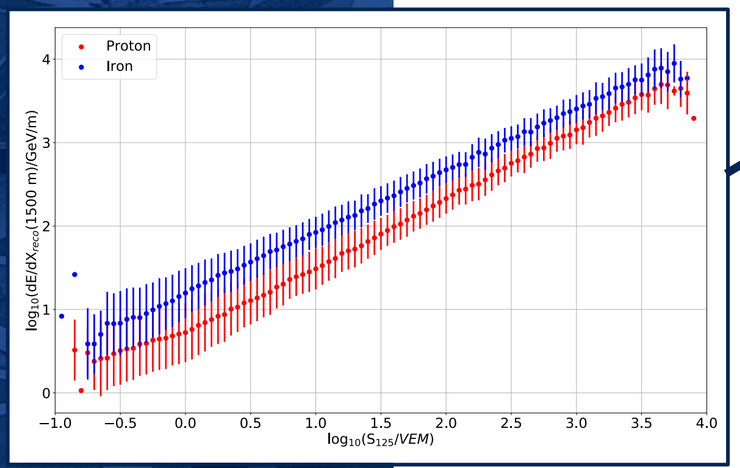
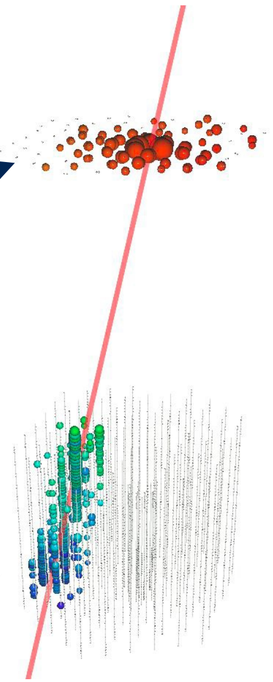
ICETOP-ICECUBE MASS COMPOSITION



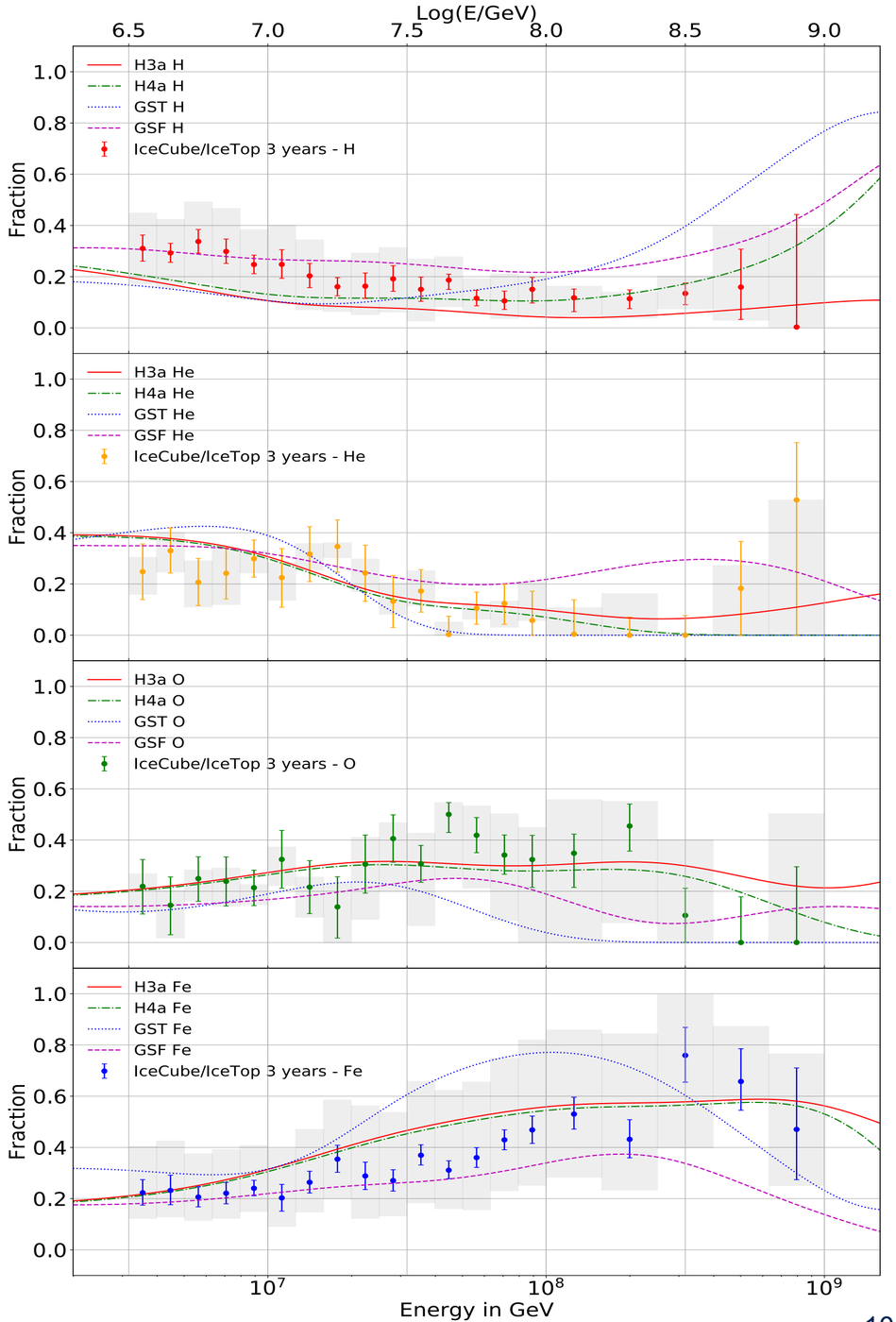




Elementary groups

- H
- He
- CNO
- Fe

- Coincident event analysis
  - Data 2011-2013
  - Energy Proxy from IceTop
  - Energy deposit profile from IceCube



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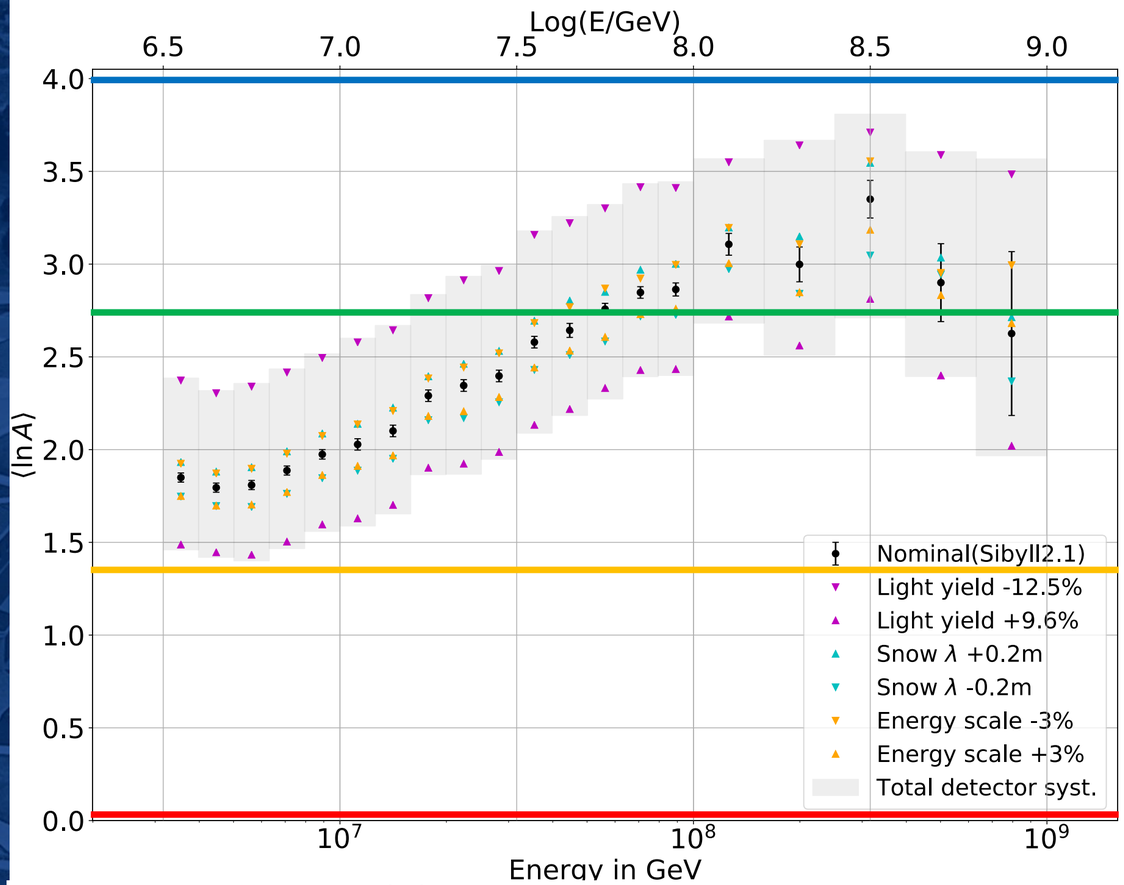
https://doi.org/10.1103/PhysRevD.100.082002

SYSTEMATIC UNCERTAINTY

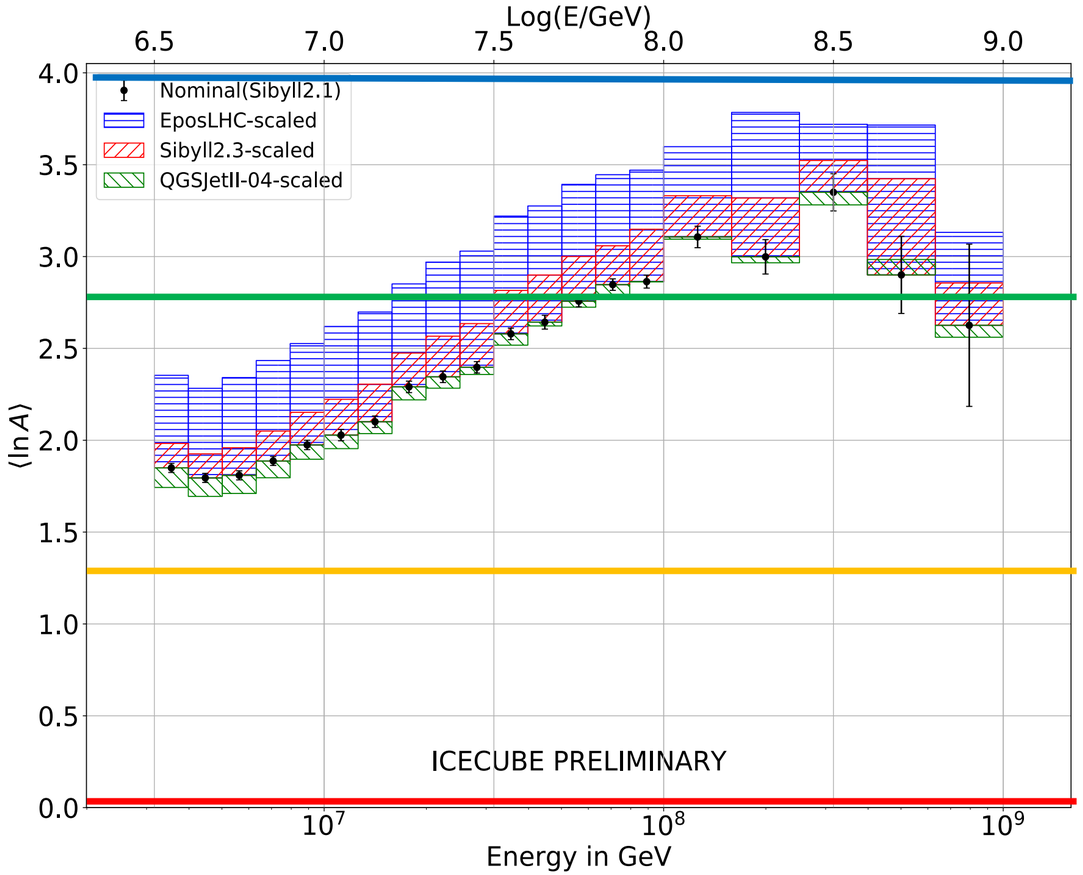


100% Fe

100% O

100% He

100% H



Systematic offsets <ln(A)> due to:

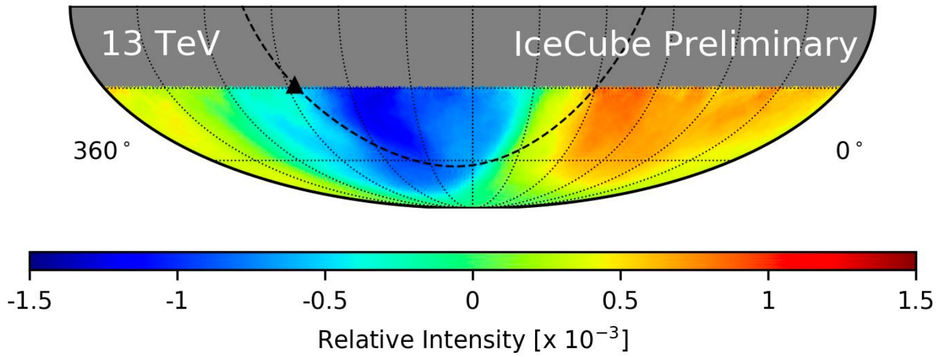
- Snow (±0.2 m)
- Light yield (-12.5% , +9.6%)
- Energy scale (±3%)

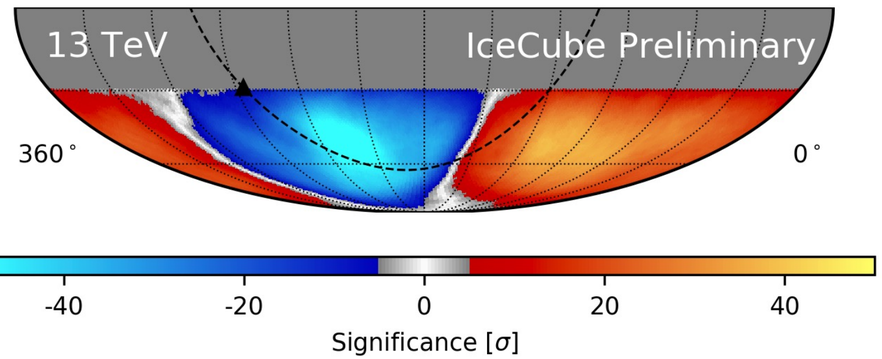
- Large systematic uncertainties hadronic interaction model
- Epos LHC
- Sibyll2.3
- QGSJetII-04

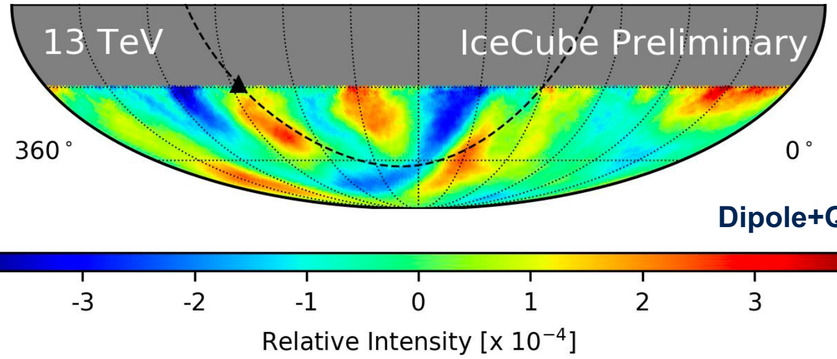
https://doi.org/10.1103/PhysRevD.100.082002

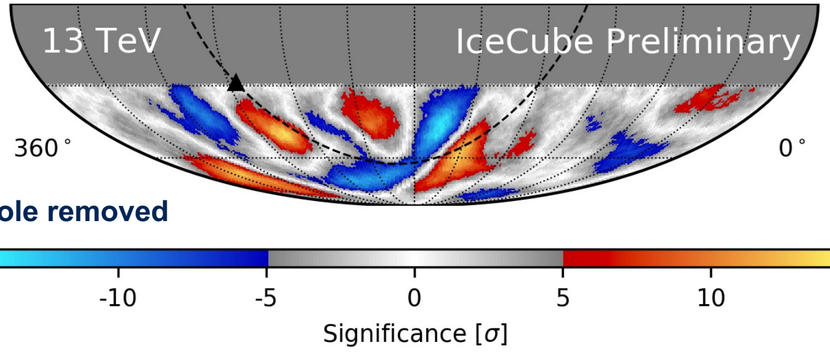
CR ANISOTROPY IN 11 YEARS OF DATA

- Update of analysis published in 2016 (Paper under collaboration review)
- Improved statistics:
  - Eleven years of data (~700 billion events)
- Improved simulation:
  - Newer, dataset-specific, increased statistics
- Improved systematics:
  - Shift from detector to calendar years, stable detector configuration

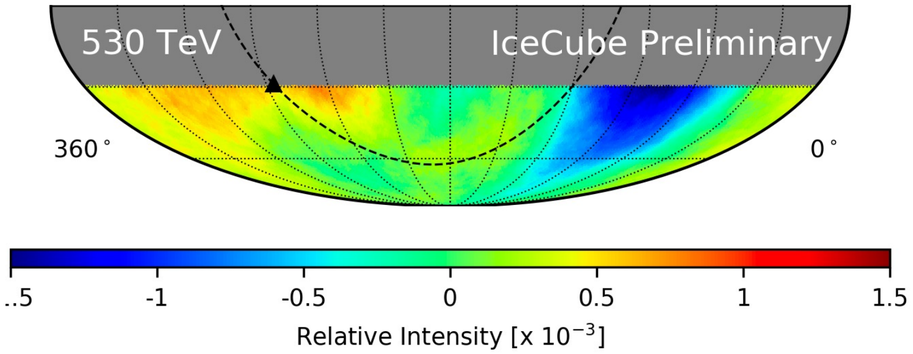


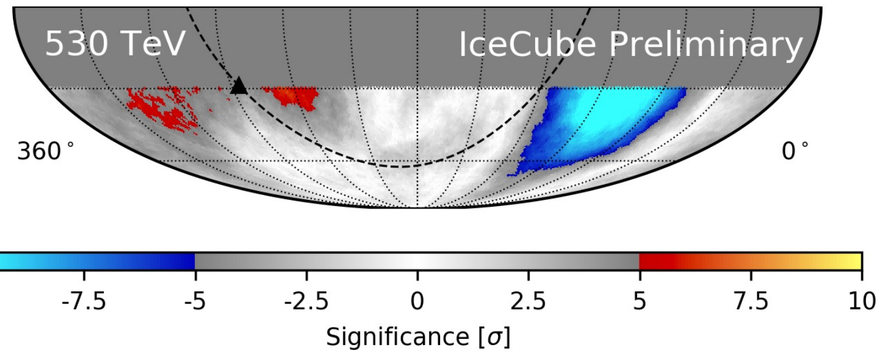






Dipole+Quadrupole removed



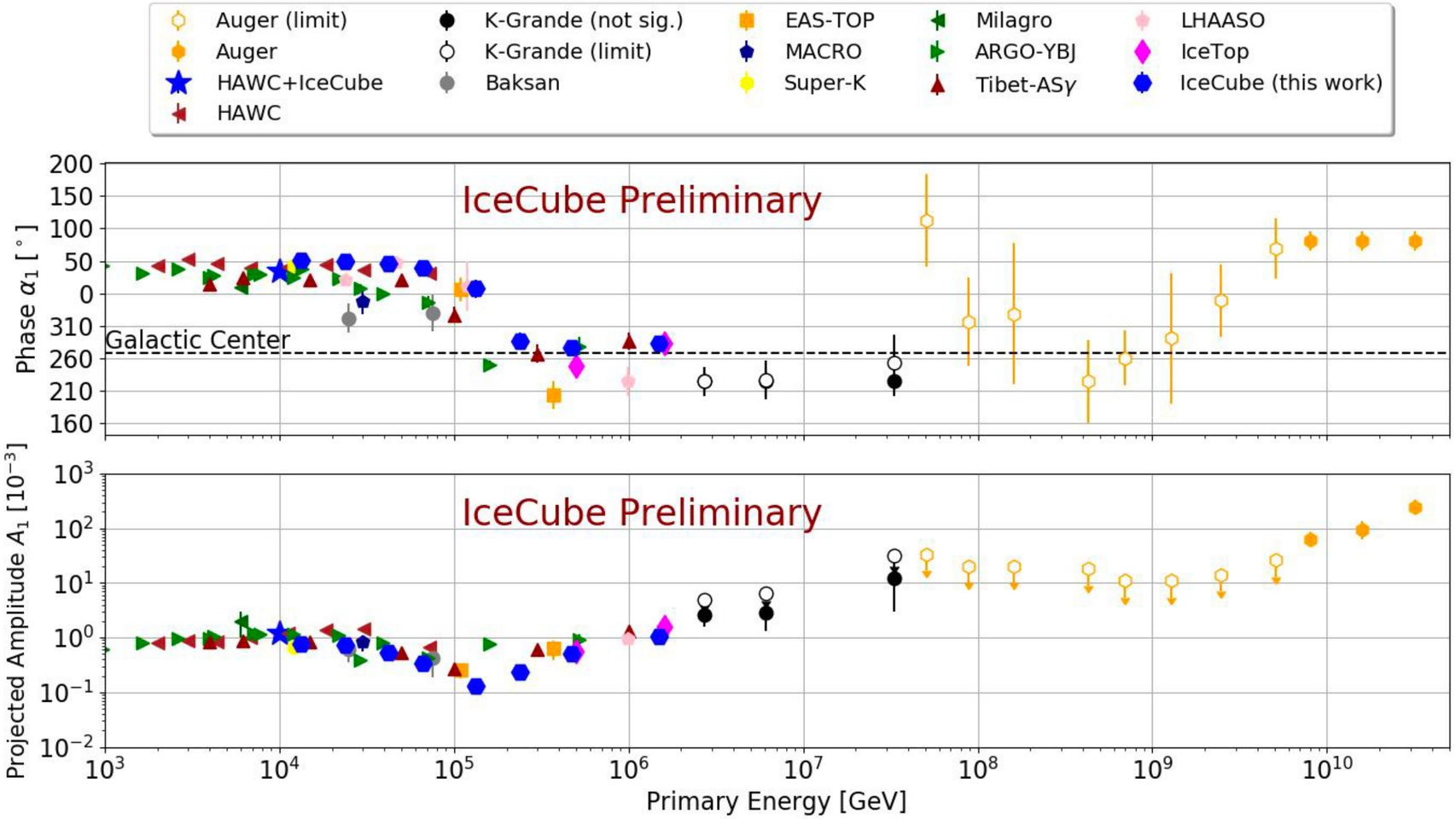


https://arxiv.org/abs/2308.02331

DIPOLE PHASE & AMPLITUDE

https://arxiv.org/abs/2308.02331

- New simulation and statistics only slightly change energy maps
- Transition still occurs around 100 TeV
- Structure at highest energy now consistent with other PeV measurements
- Phase and amplitude of best-fit dipole consistent with other experiments

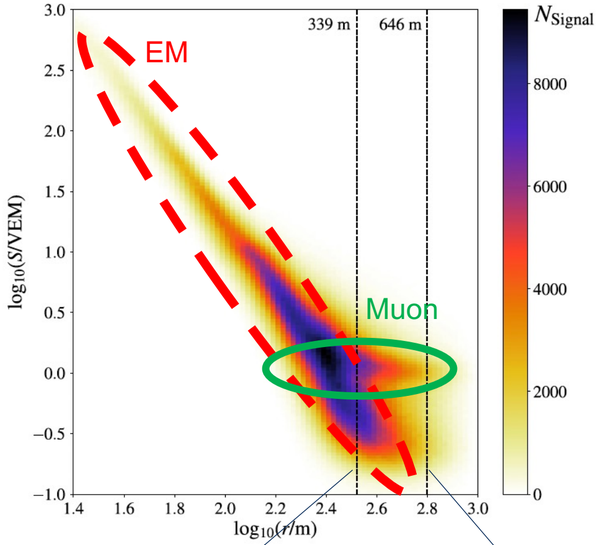


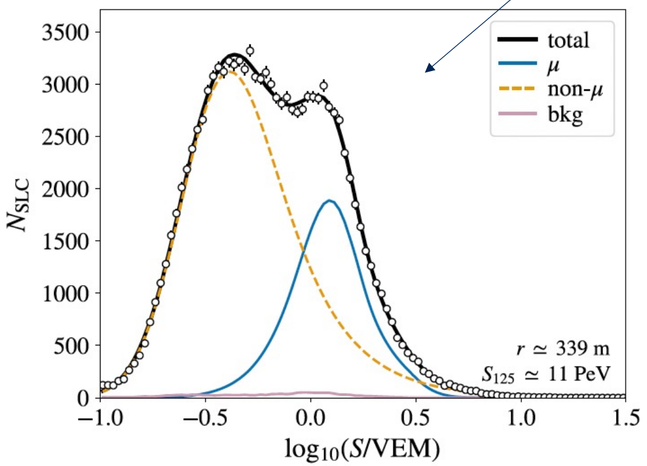
SURFACE MUON DENSITY

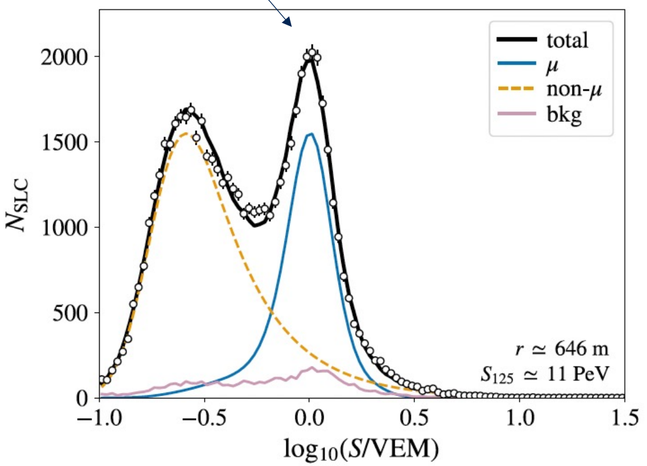
- Tank signal includes:
  - muons
  - electromagnetic component
  - background

- Due to EM contamination, the density of muons is evaluated at 600 and 800 m from the shower axis

- Mostly low-energy (~GeV) muons





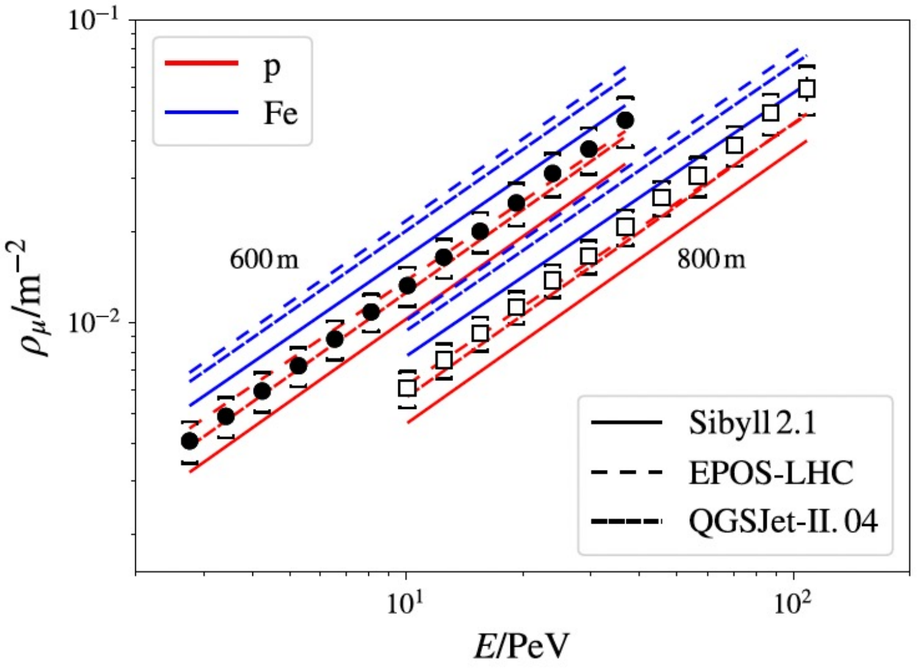


For TeV-muon multiplicity studies with the deep in-ice IceCube, see Stef Verpoest's talk tomorrow

https://doi.org/10.1103/PhysRevD.106.032010

SURFACE MUON DENSITY

Muon densities compared to hadronic model predictions

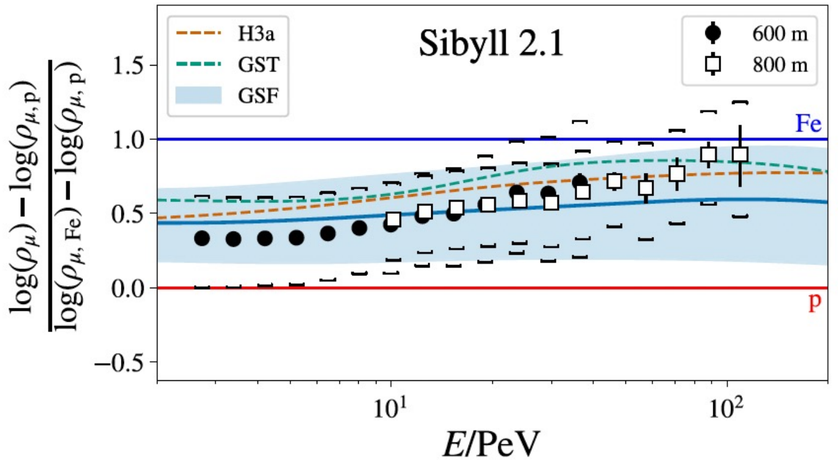


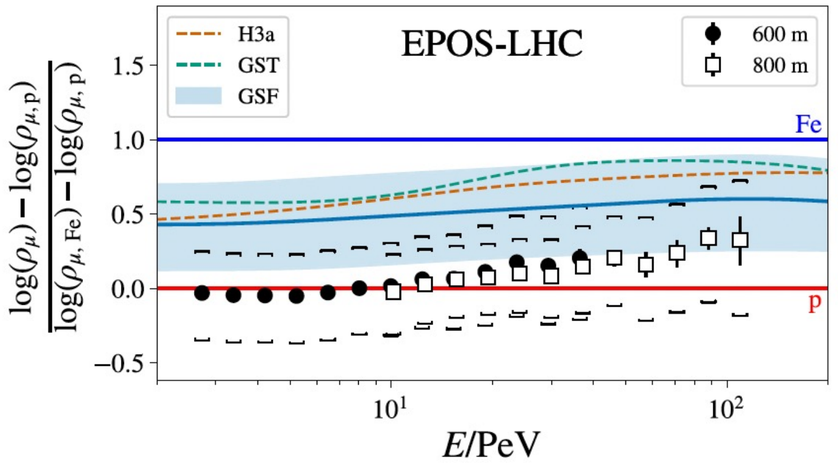
The z-scale:

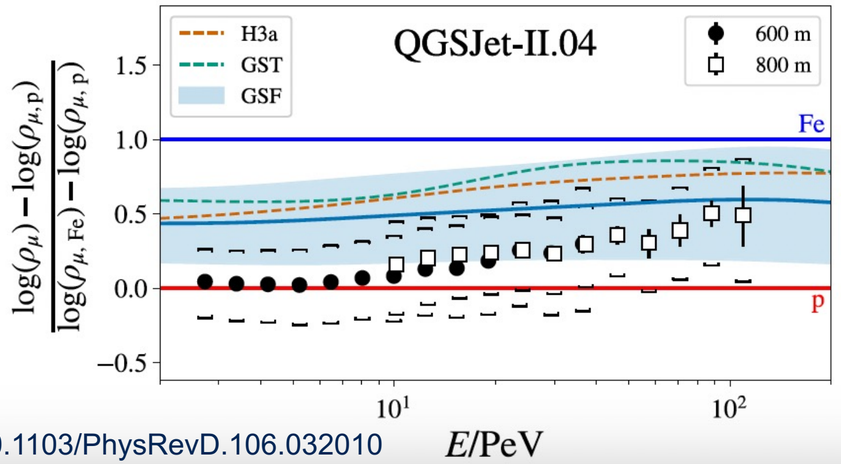
$$z = \frac{\log(\rho_\mu) - \log(\rho_{\mu,p})}{\log(\rho_{\mu,Fe}) - \log(\rho_{\mu,p})}$$

Proton: 0
Iron: 1

- Comparison of measured data to different flux model predictions
  - Best data/MC agreement for Sibyll 2.1
  - EPOS-LHC and QGSJet-II.04 yield very light masses







https://doi.org/10.1103/PhysRevD.106.032010

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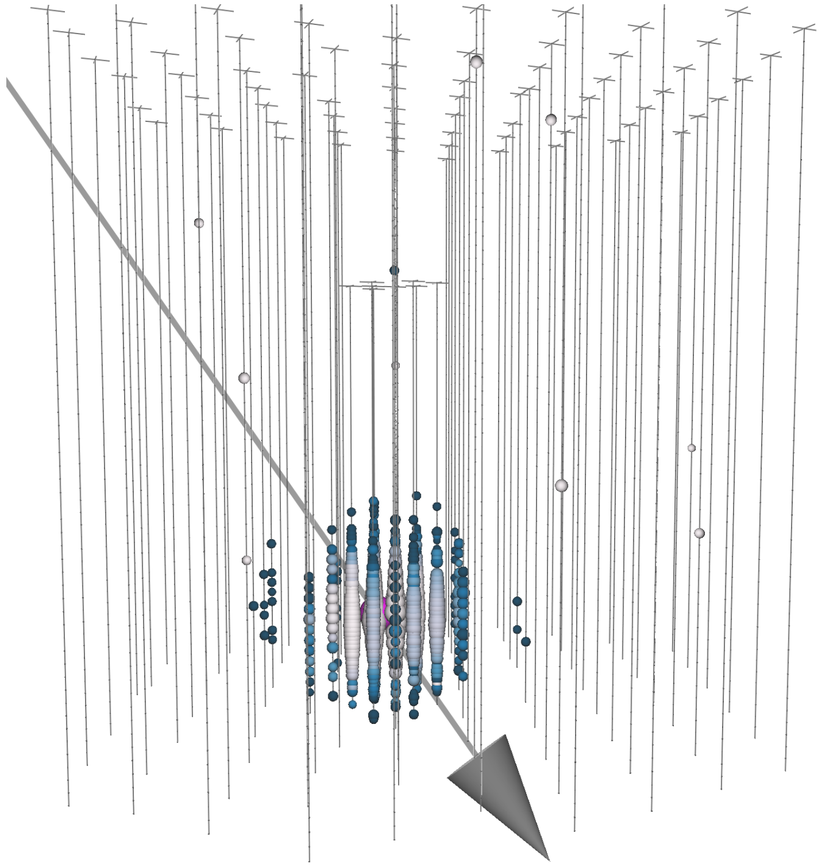
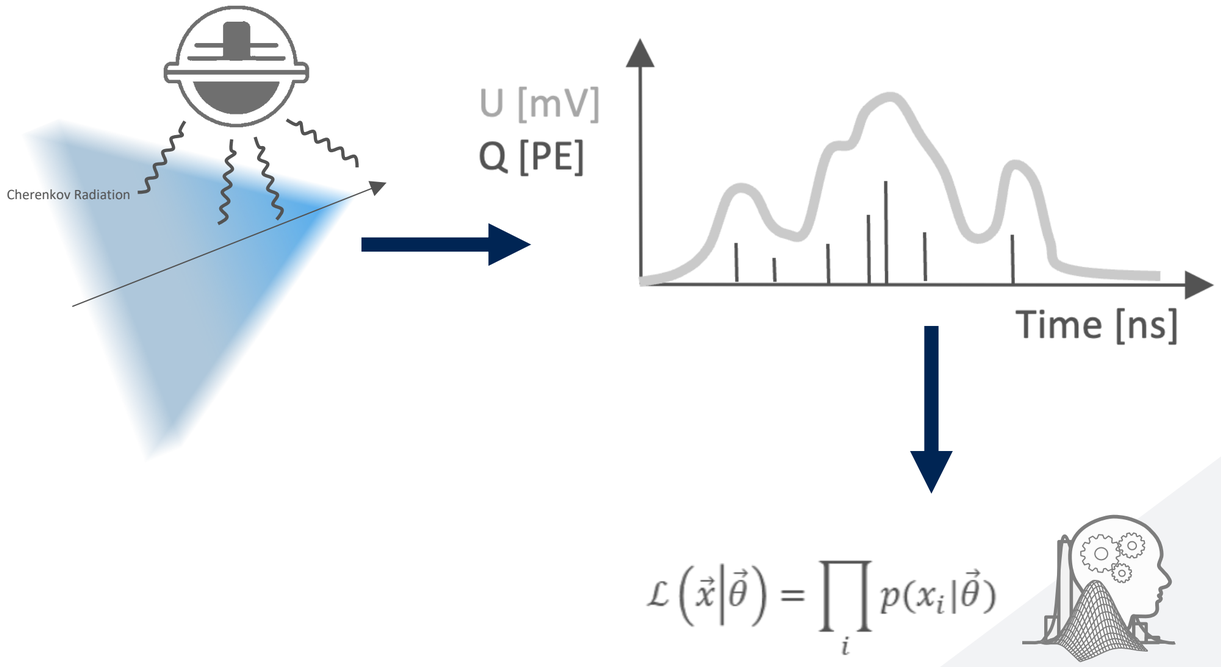
NEUTRINO EVENT RECONSTRUCTION



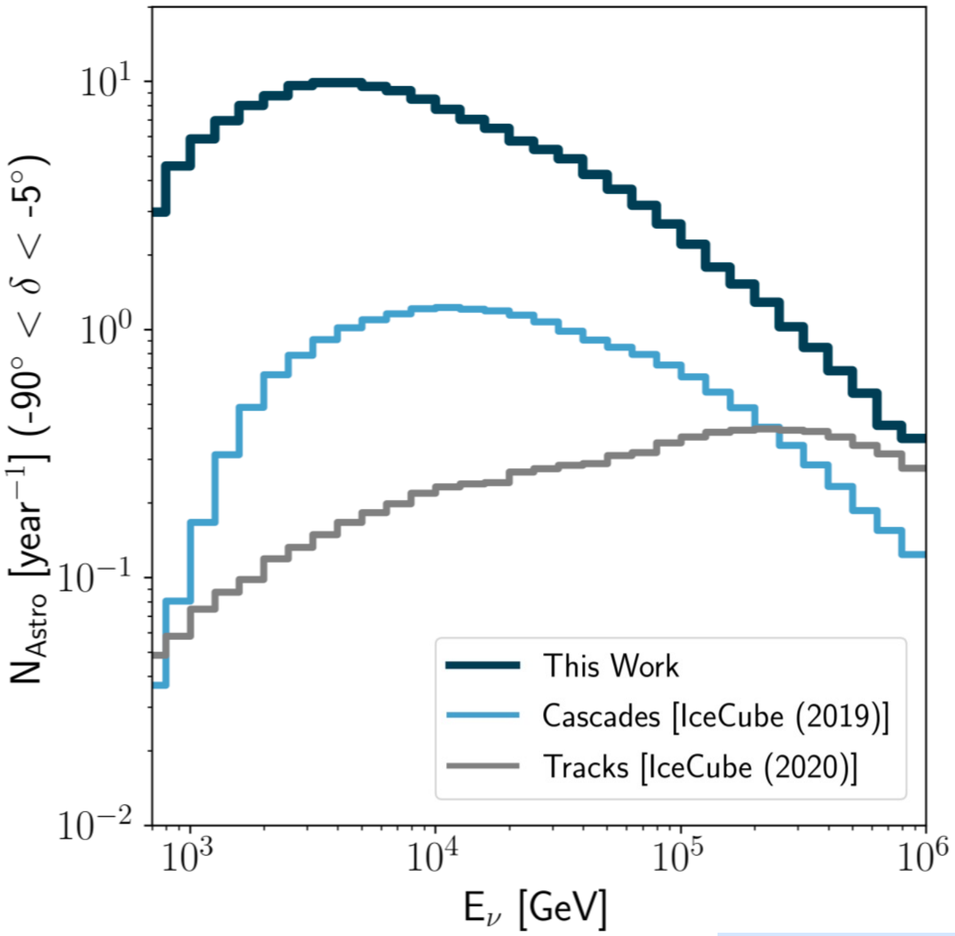


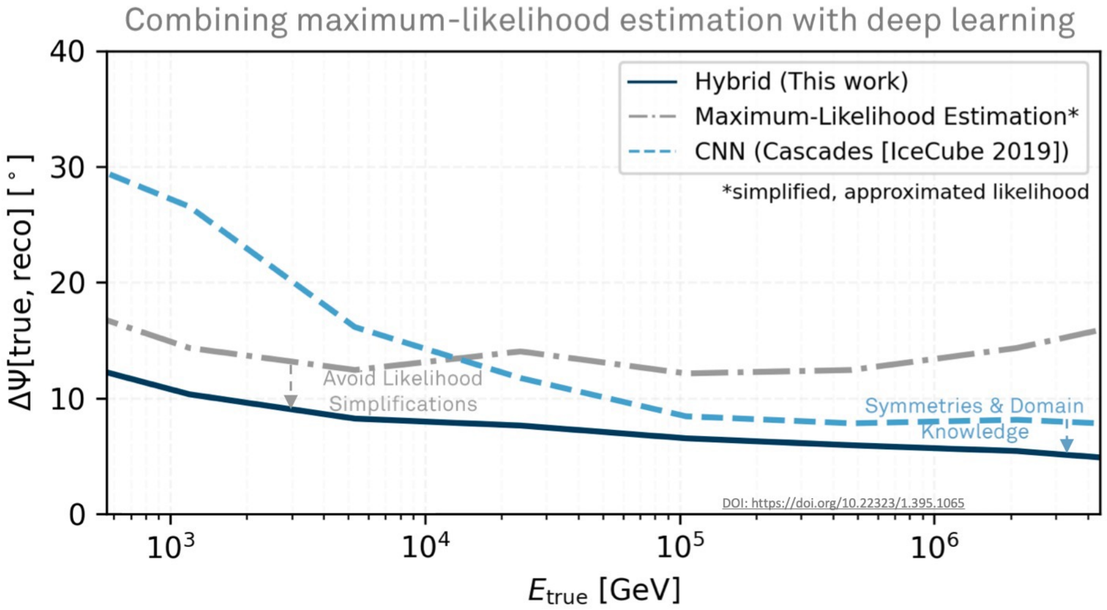
$$\mathcal{L}\left(\vec{x}\middle|\vec{\theta}\right) = \prod_i p(x_i|\vec{\theta})$$

Event reconstruction:

- Neutrino events are characterized by their energy and direction
- Properties are inferred from observed light pattern in detector

RECENT NEUTRINO RECONSTRUCTION IMPROVEMENTS





Improvements due to novel machine learning:

- Improved reconstruction resolution over the entire energy range
- 30 times as many events
- Analysis sensitivity improved by a factor of 3

https://doi.org/10.22323/1.395.1065

The equivalent of 75 years of detector lifetime and > $500 million

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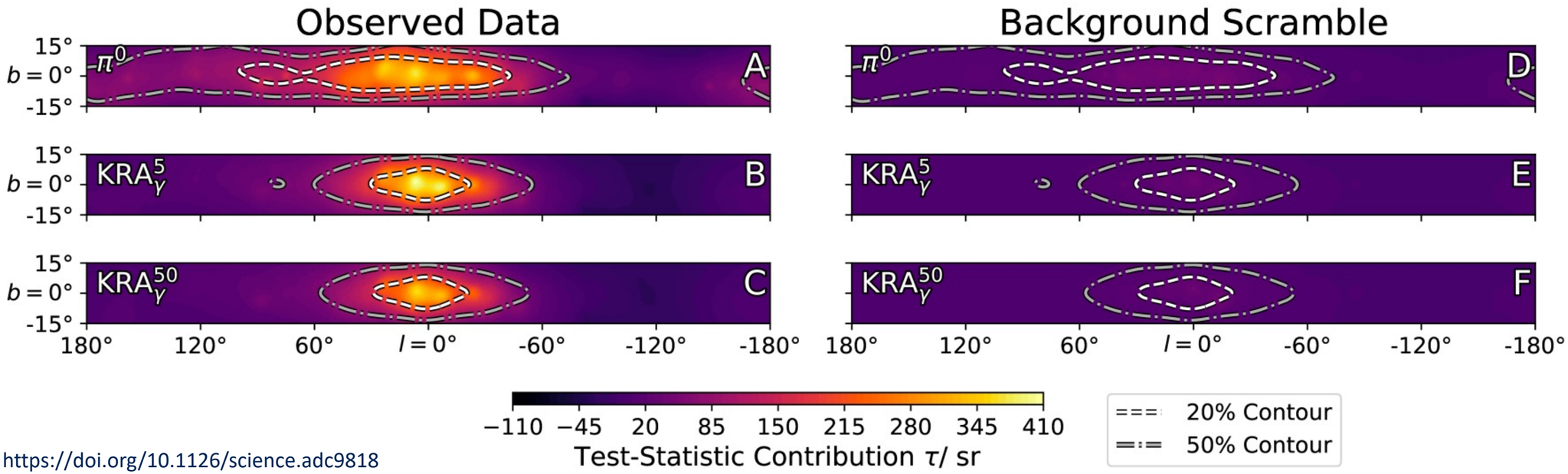
GALACTIC NEUTRINO SEARCHES

- Evidence for neutrino emission from the galactic plane
  - Global significance: 4.5σ
  - 3σ significance from stacking catalogs
- Data-driven background estimation



https://doi.org/10.1126/science.adc9818

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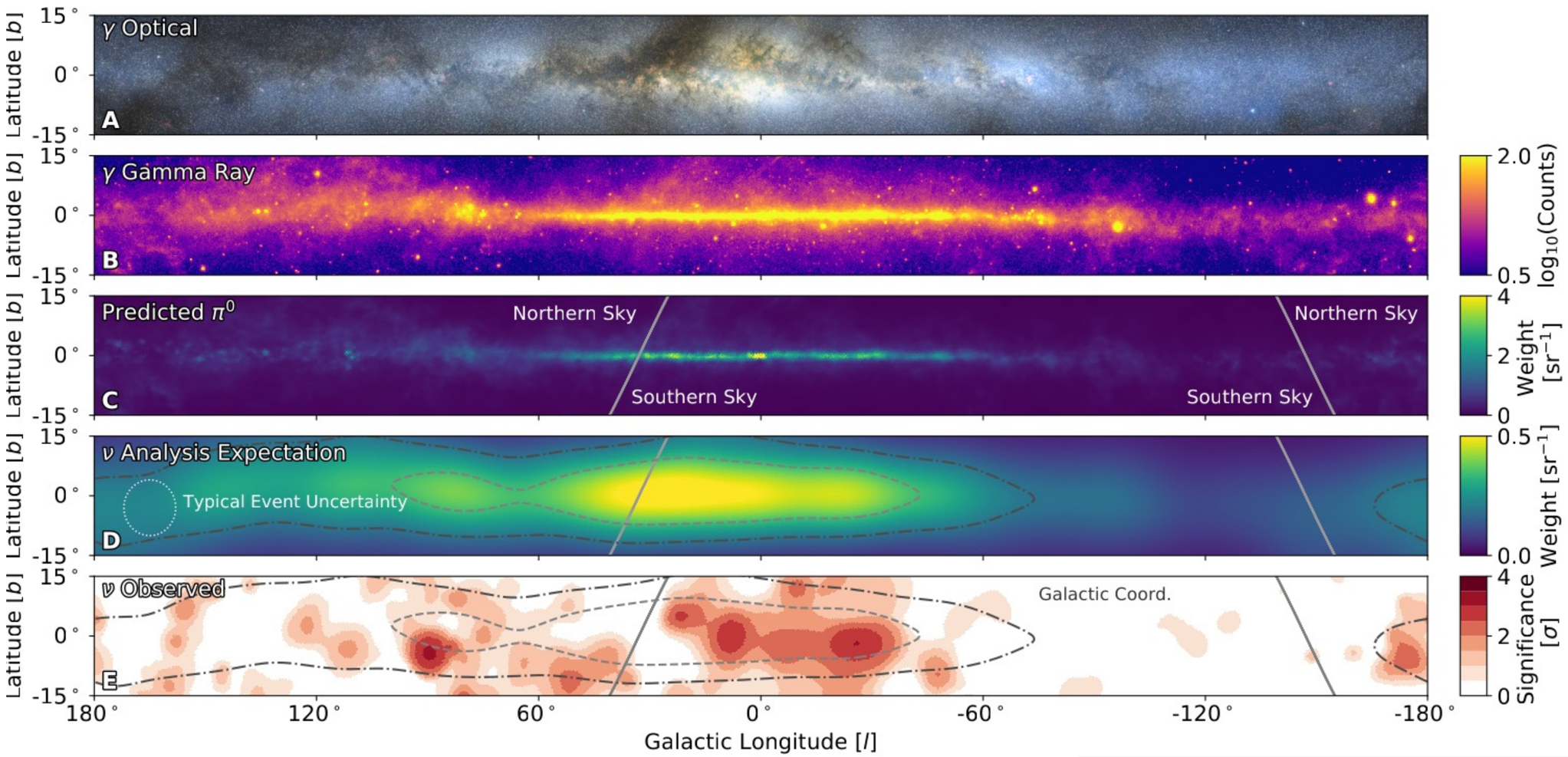
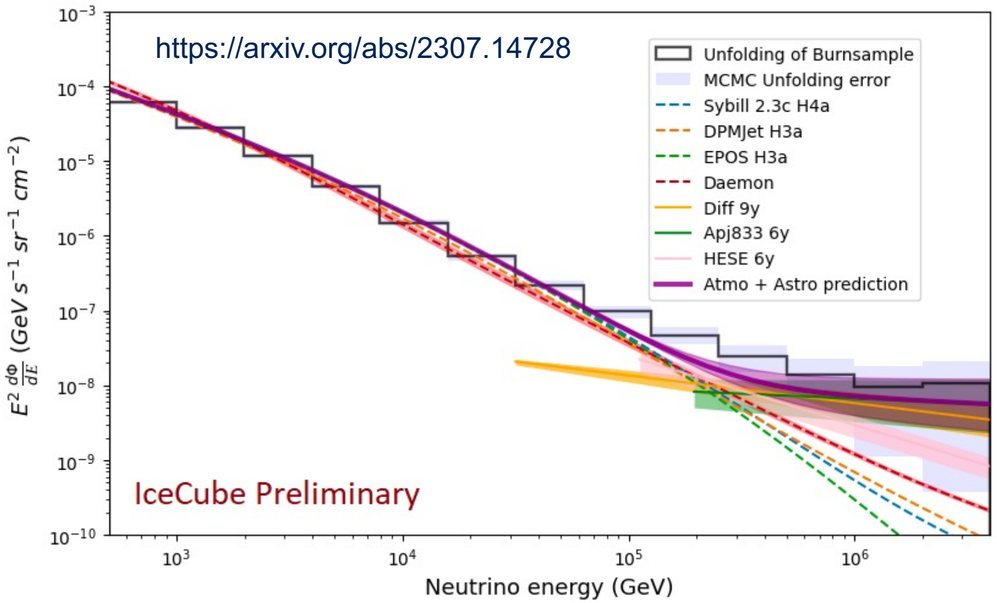
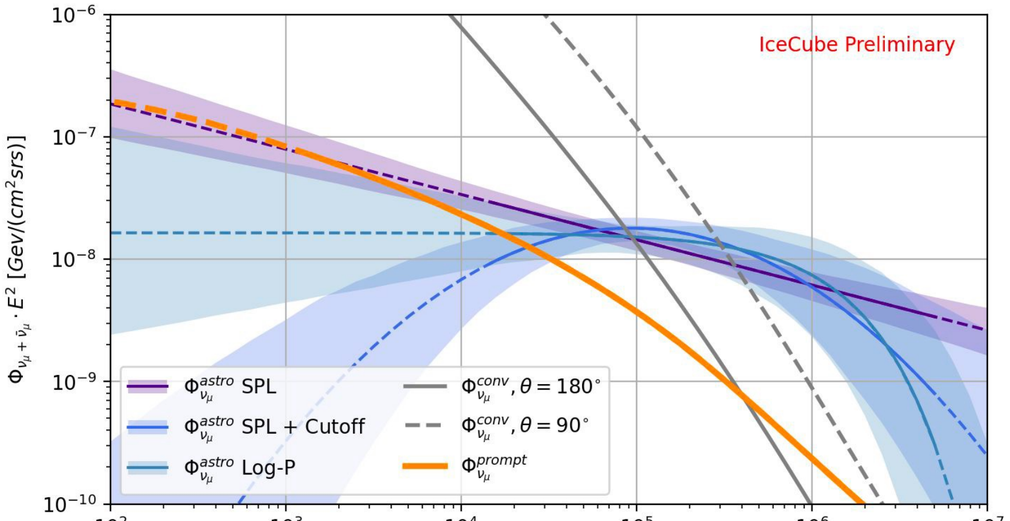
GALACTIC PLANE NEUTRINO EMISSION



https://doi.org/10.1126/science.adc9818

NEUTRINO FLUX MEASUREMENTS

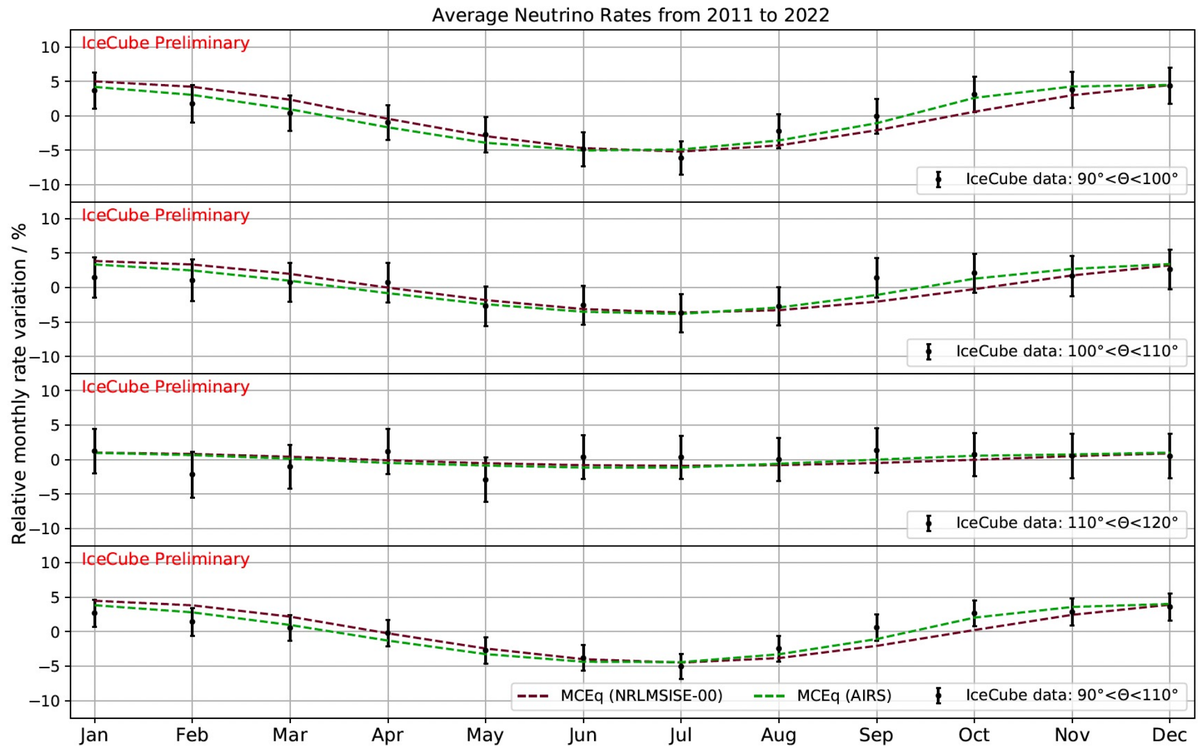




https://arxiv.org/abs/2309.07560

Comparison of measured atmospheric neutrino flux to model prediction

- Measurement of the neutrino flux
- Measurement of the prompt muon production
- Measurement of seasonal variation in the neutrino flux



https://arxiv.org/abs/2307.14724

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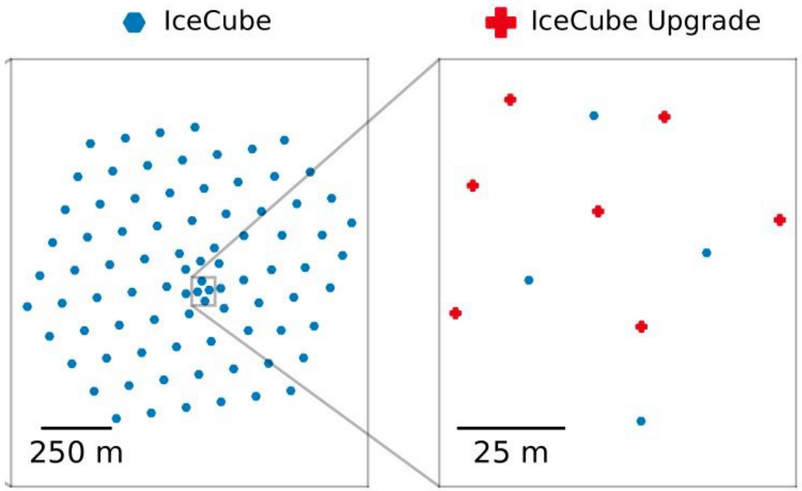
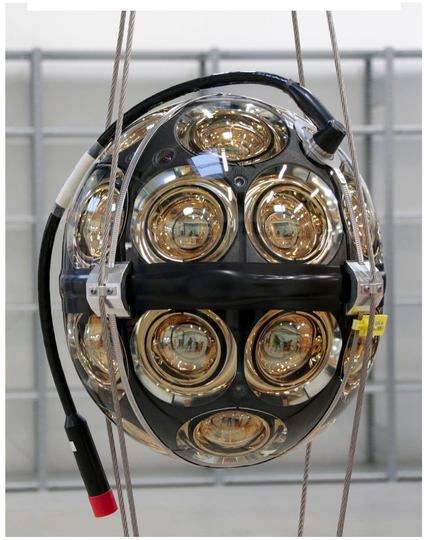
NEXT STEP IN DETECTOR EVOLUTION



Multi-PMT DOMs



IceCube Upgrade (scheduled deployment 2025/26)

- Denser optical array by 7 additional strings
- 1 GeV min. energy for neutrinos

➢ R&D for IceCube-Gen2
➢ Improve calibration to decrease detector systematics
➢ Oscillation physics

D-Eggs

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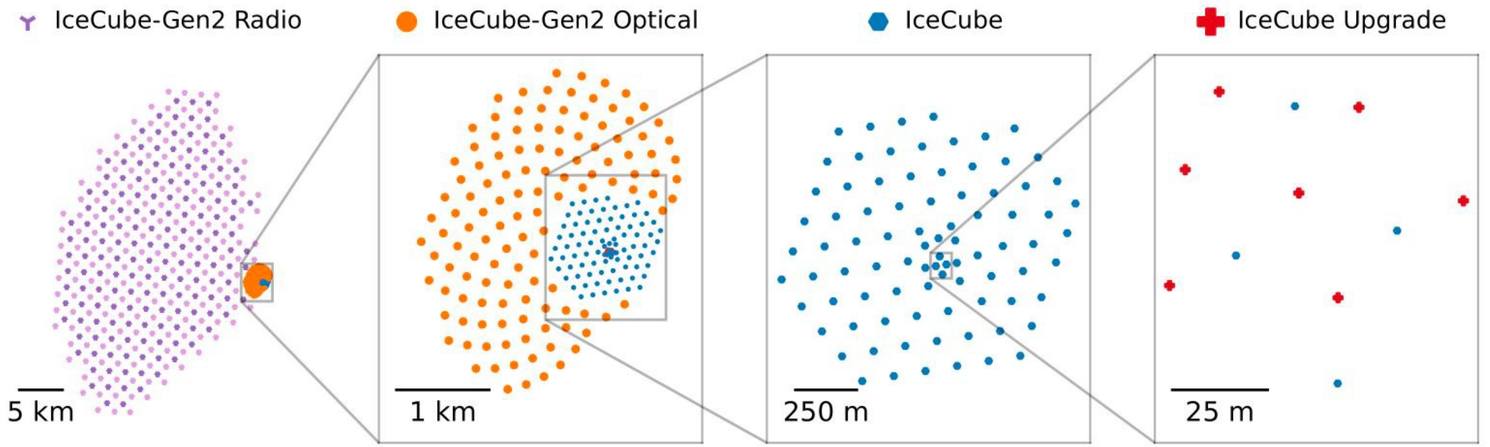
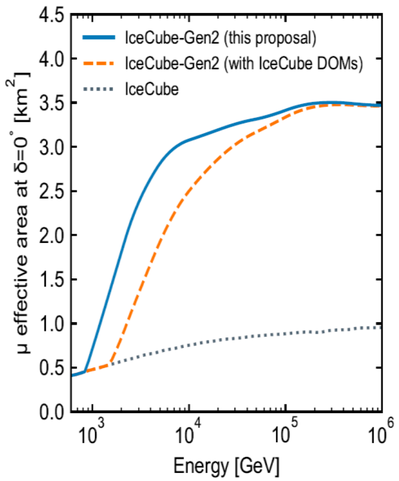
ICECUBE-GEN2

IceCube-Gen2 TDR

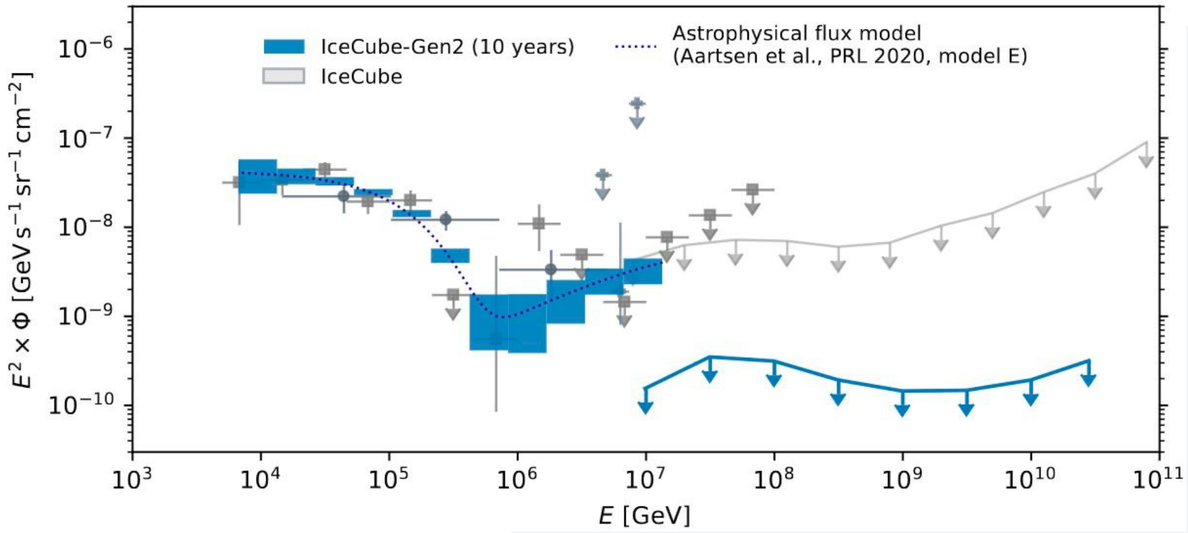




- Increase effective volume
- Increase upper energy threshold

- Measure flux of high-energetic neutrinos above PeV energies
- Improve sensitivity to astrophysical neutrino sources by factor of ~5

IceCube-Gen2 TDR



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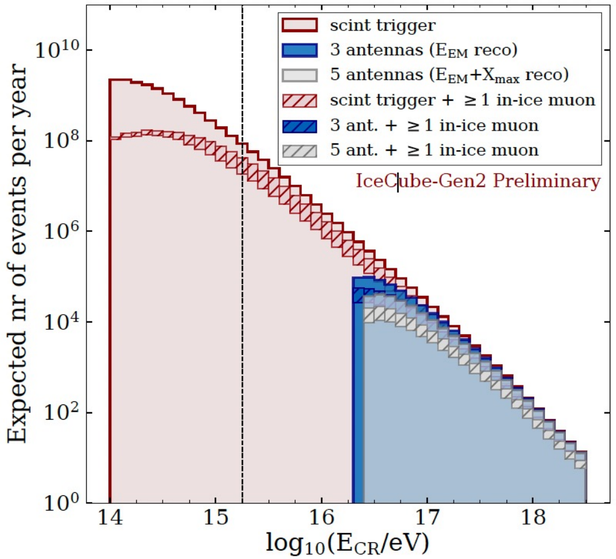
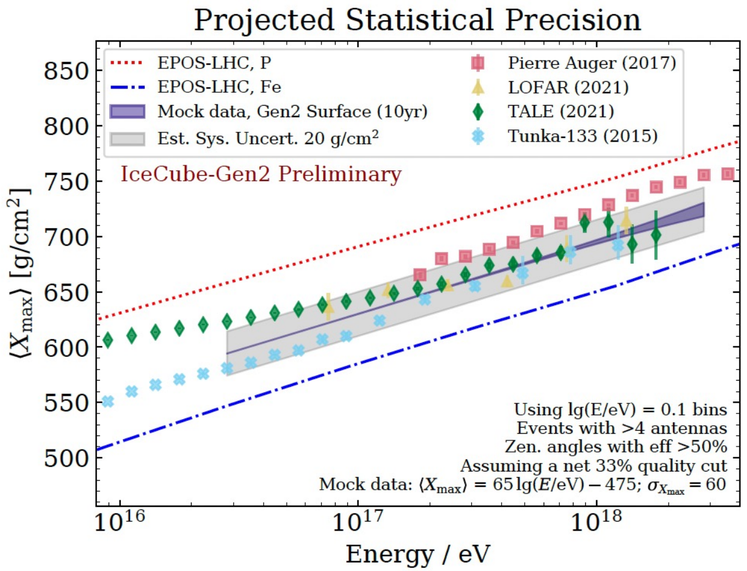
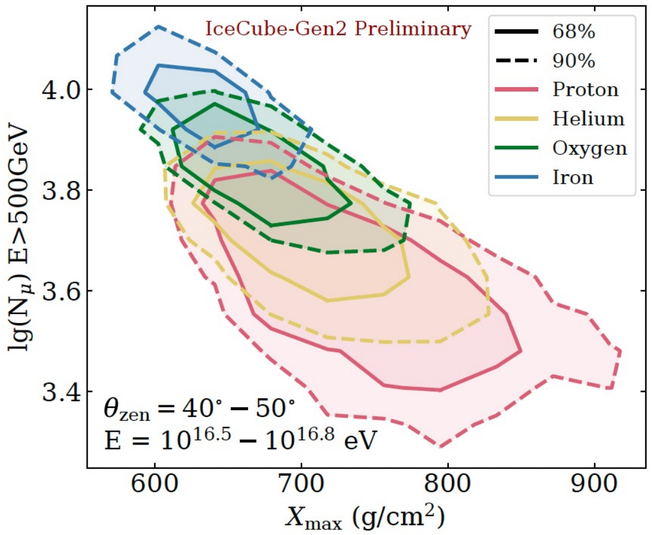
ICECUBE-GEN2 SURFACE-ARRAY

IceCube-Gen2 TDR







- Radio antennas will be sensitive starting at 30 PeV, and will set energy scale and provide X_{max} measurements
- About 25% of detected air showers will have associated in-ice signals to study the high-energy air shower content
- High statistics for more anisotropy measurements

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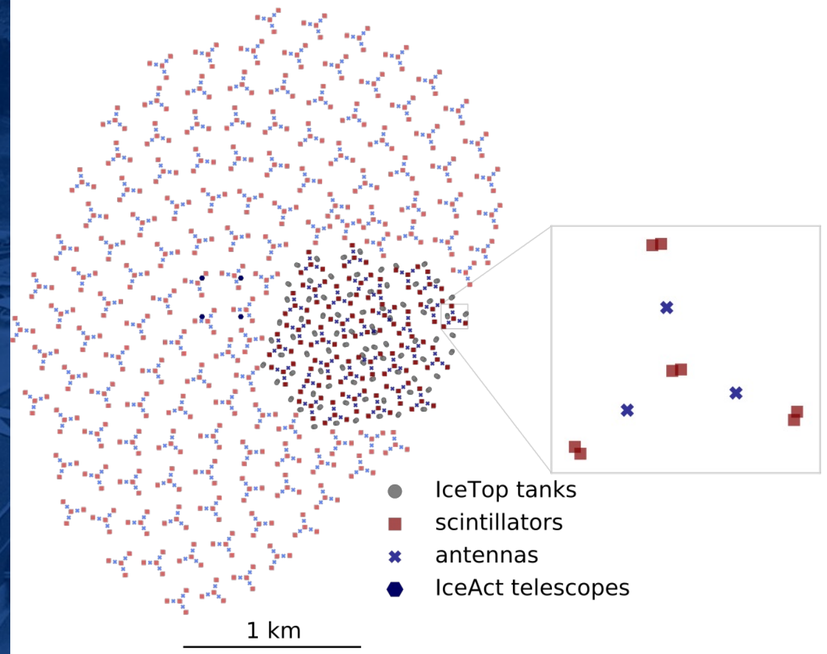
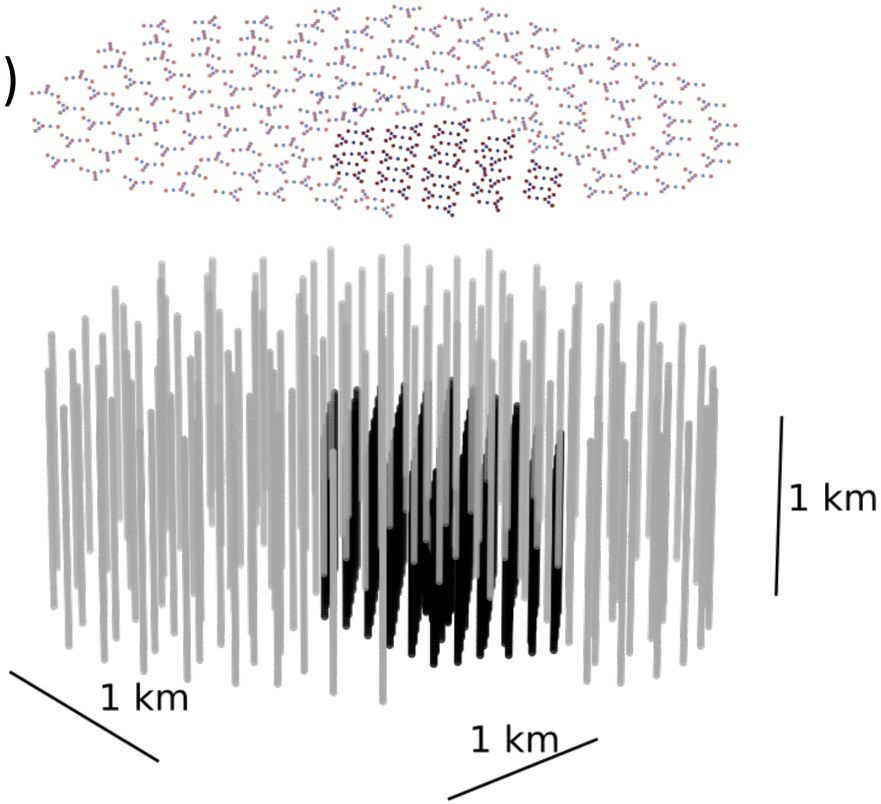
ICECUBE-GEN2 NUMBERS

IceCube-Gen2 TDR



IceCube-Gen2 (IceCube) numbers

- Area: ~6.5km^2 (0.9)
- Instrumented depth: 1.26 km (1.0)
- Instrumented volume: 8 km^3 (1.0)
- 9600 optical sensors (5160)
- 120 strings (86)



Surface array number:

- 274 scintillator panels
- 102 radio antennas
- 4 IceAct station in Fly's eye configuration

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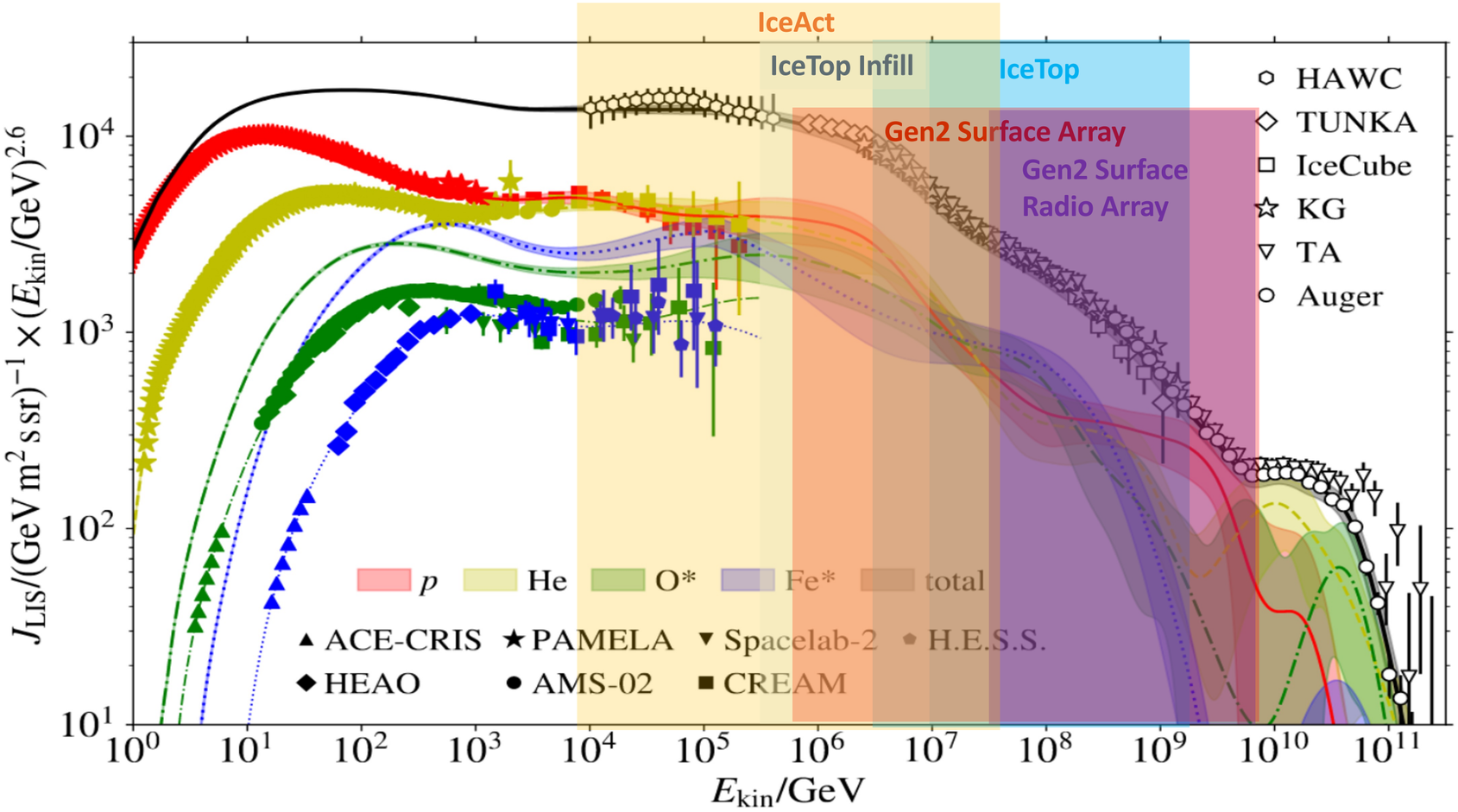
CR ENERGY RANGE OF ICECUBE/ICETOP



https://arxiv.org/abs/1902.08124

SUMMARY

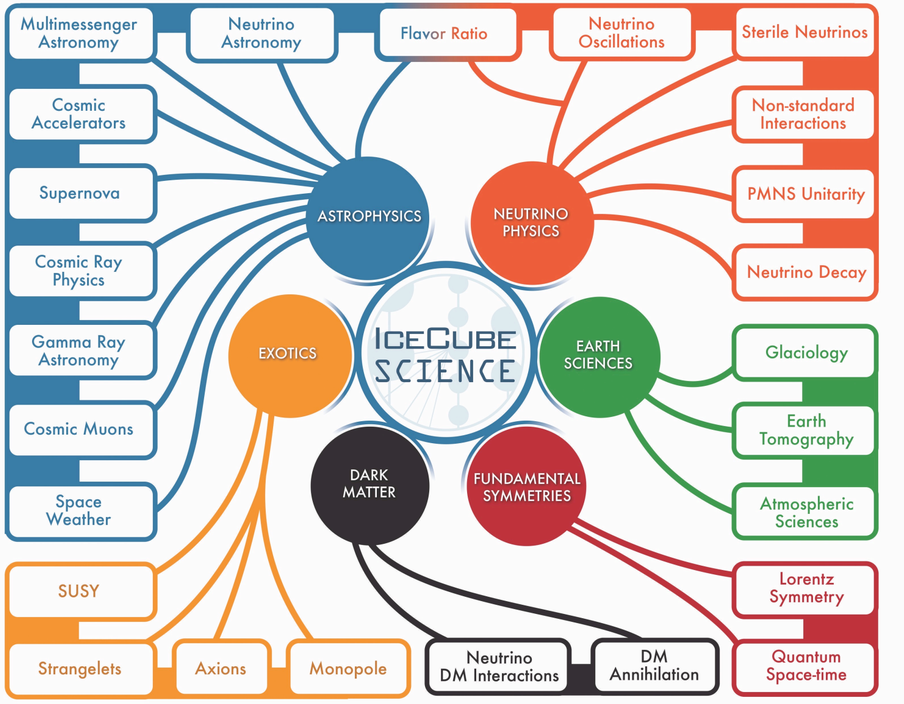
- IceCube Observatory is a versatile neutrino/cosmic ray observatory

- The combination of surface and deep in-ice detector allows unique studies of air shower physics from TeV to EeV

- In cosmic rays and air shower physics, we are measuring
  - Energy spectrum and mass composition
  - Anisotropy
  - Testing hadronic interaction models

- The first evidence of neutrino emission from the galactic plane was measured with 4.5σ

- IceCube Upgrade and IceCube-Gen2 will enhance the physics capabilities even further



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BACKUP

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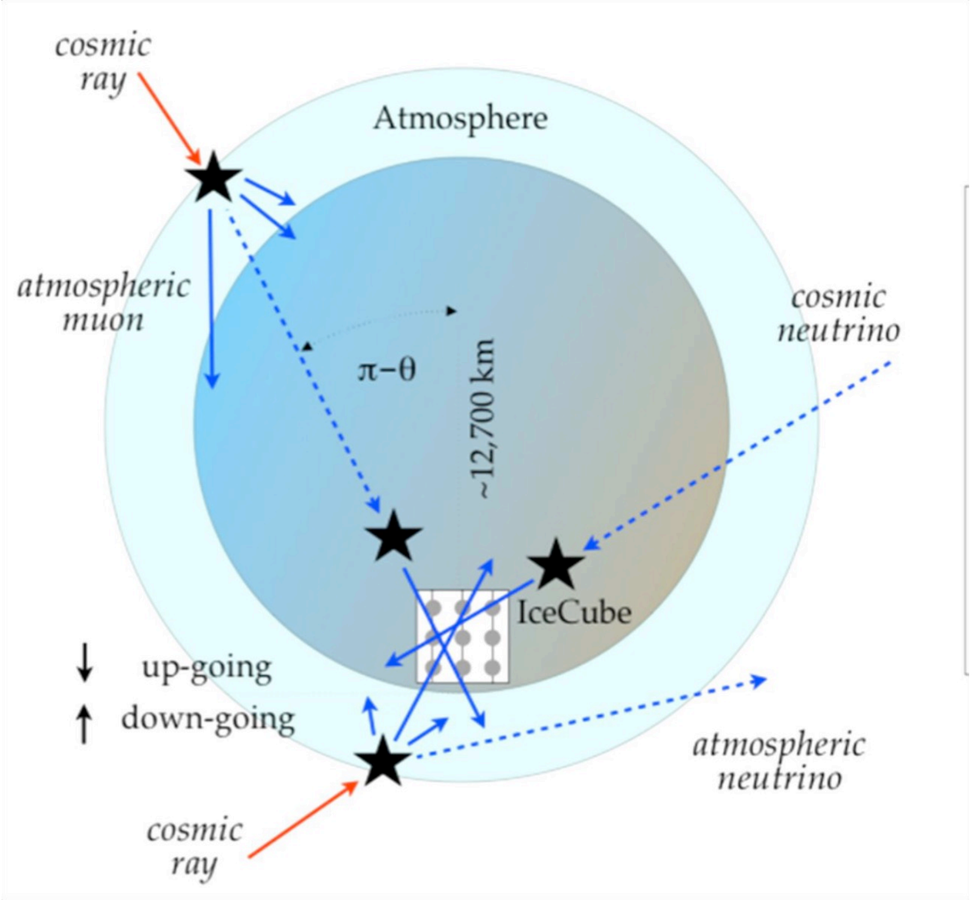
NEUTRINO SIGNALS AND BACKGROUNDS

- Dominant signal:
  - Downgoing muons from cosmic rays interacting in the atmosphere
  - ~2600/sec (~10^{11}/year)
- Neutrino discriminators:
  - Upgoing (through Earth) or starting inside the array
  - ~12/hour (~10^{5}/year)
- Astrophysical discriminators:
  - Energy: Crossover ~ 100TeV
  - Muon veto (starting events)
  - Spatial: Clusters/Catalogs
  - Time: Bunches/Multimessenger
  - 10s per month (~100s/year)



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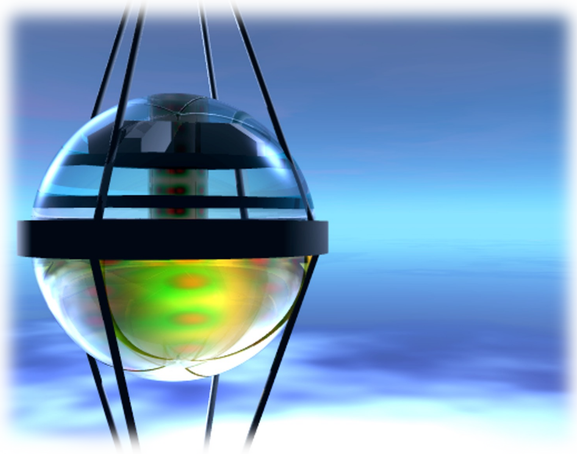
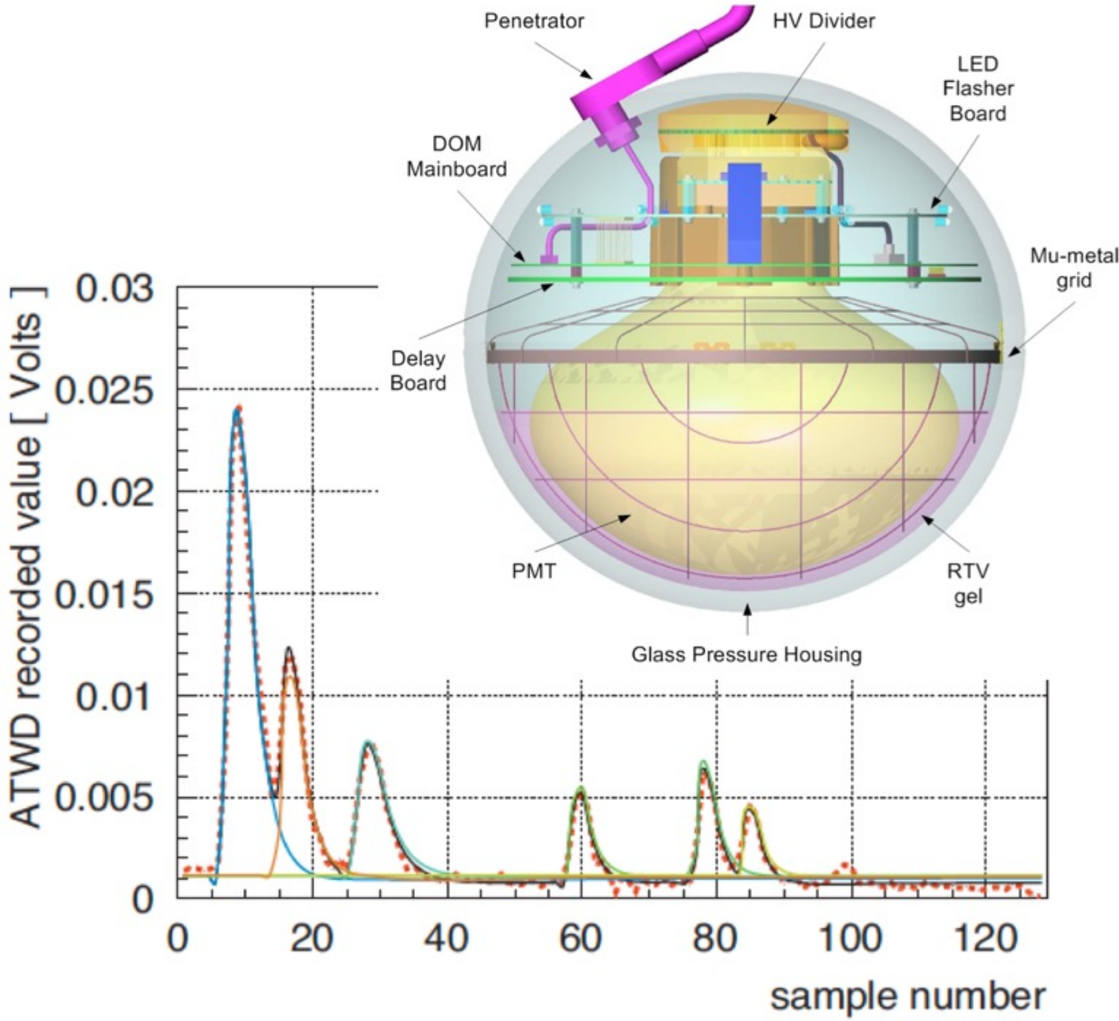
DIGITAL OPTICAL MODULE

Each Digital Optical Module (DOM) operates independently

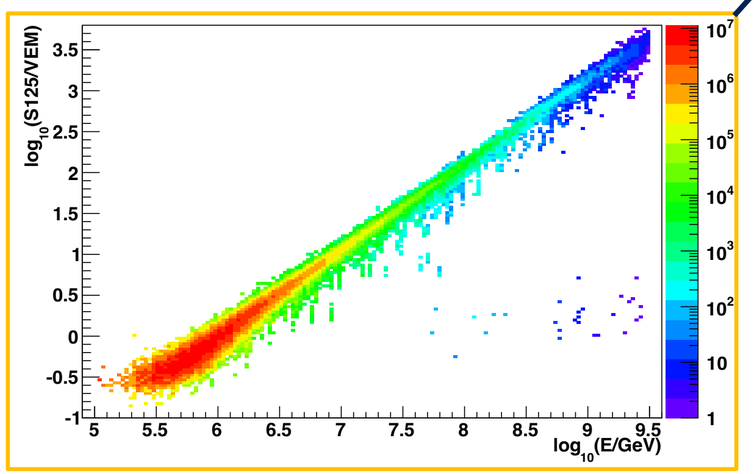
- collects light signal
- digitizes
- time stamp with 2 nanoseconds precision
- Send results to a computer on the surface for further reconstruction

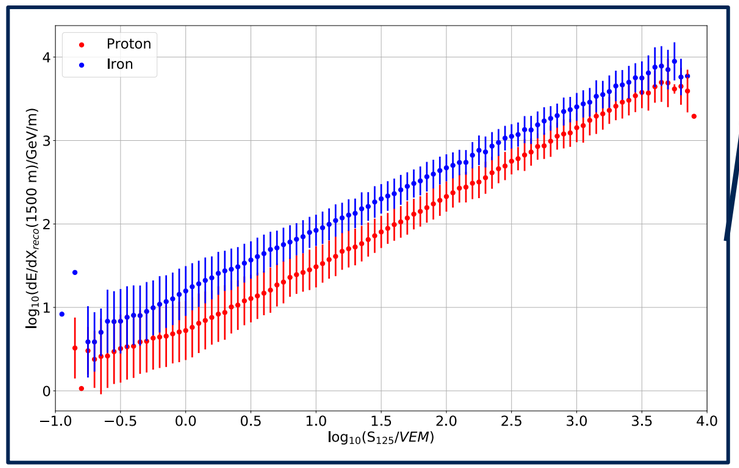


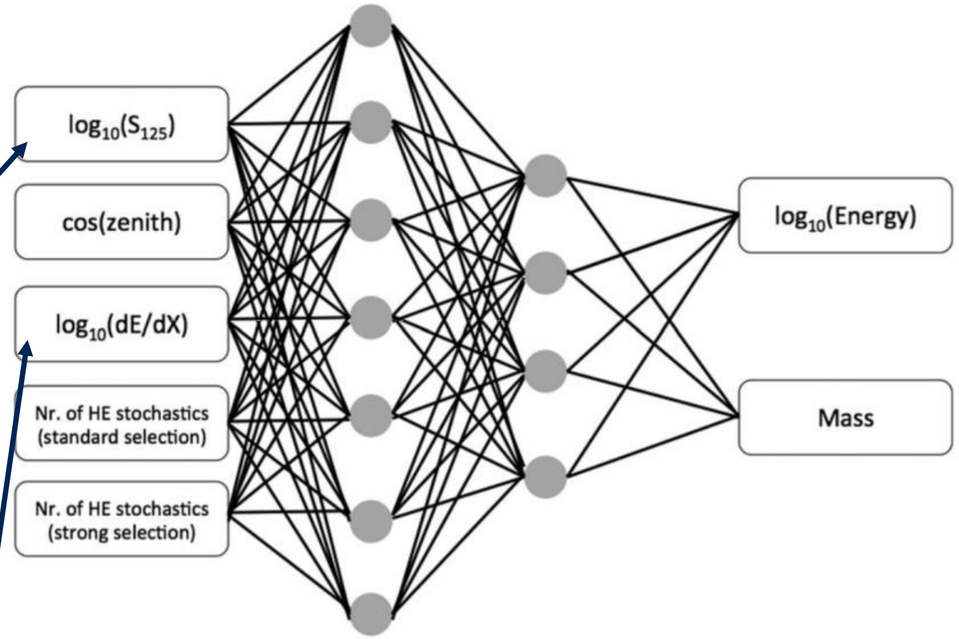


ICETOP-ICECUBE MASSCOMPOSITION

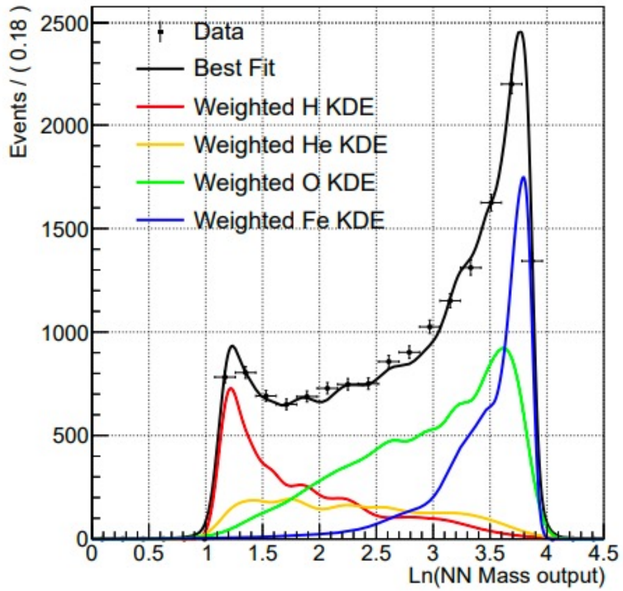
- Data 2011-2013
- Log(E/GeV) = 6.5 … 9.0
- Primary elementary groups
  - H, He, CNO, Fe
- Input variables
  - IceTop
    - S125 (Energy estimator)
    - Zenith
  - IceCube
    - dEdx at 1500m slant depth
    - Number of HE stochastic losses







Log(E/GeV): 7.4 - 7.5



https://arxiv.org/abs/1906.04317

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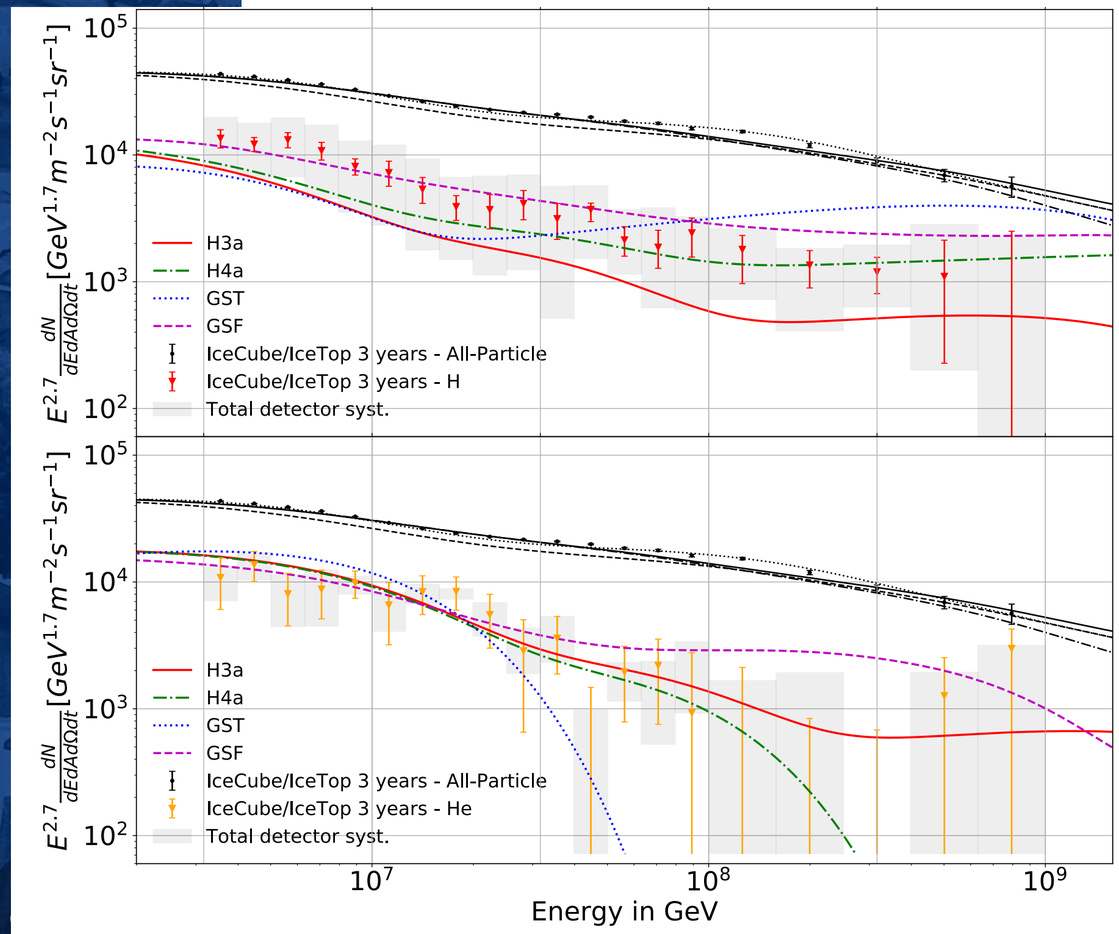
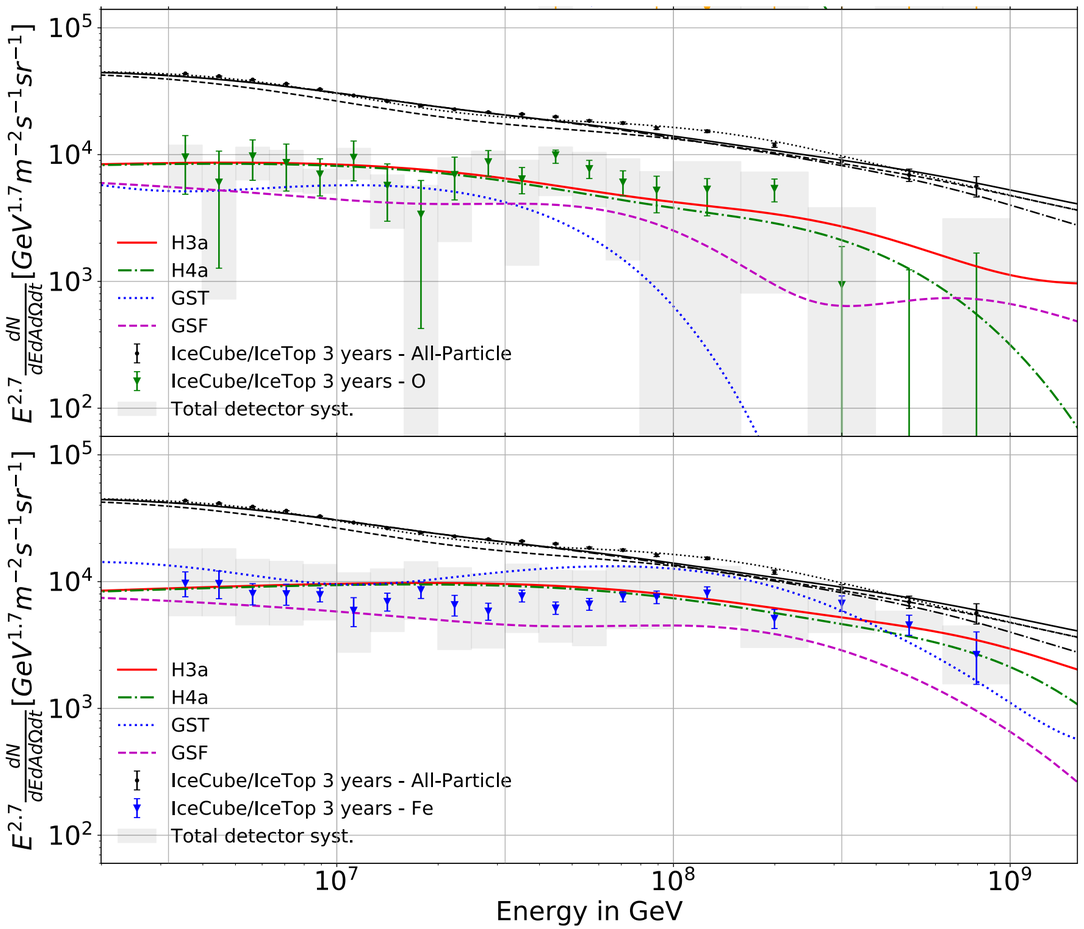
CR MASS-COMPOSITION FLUX





https://arxiv.org/abs/1906.04317

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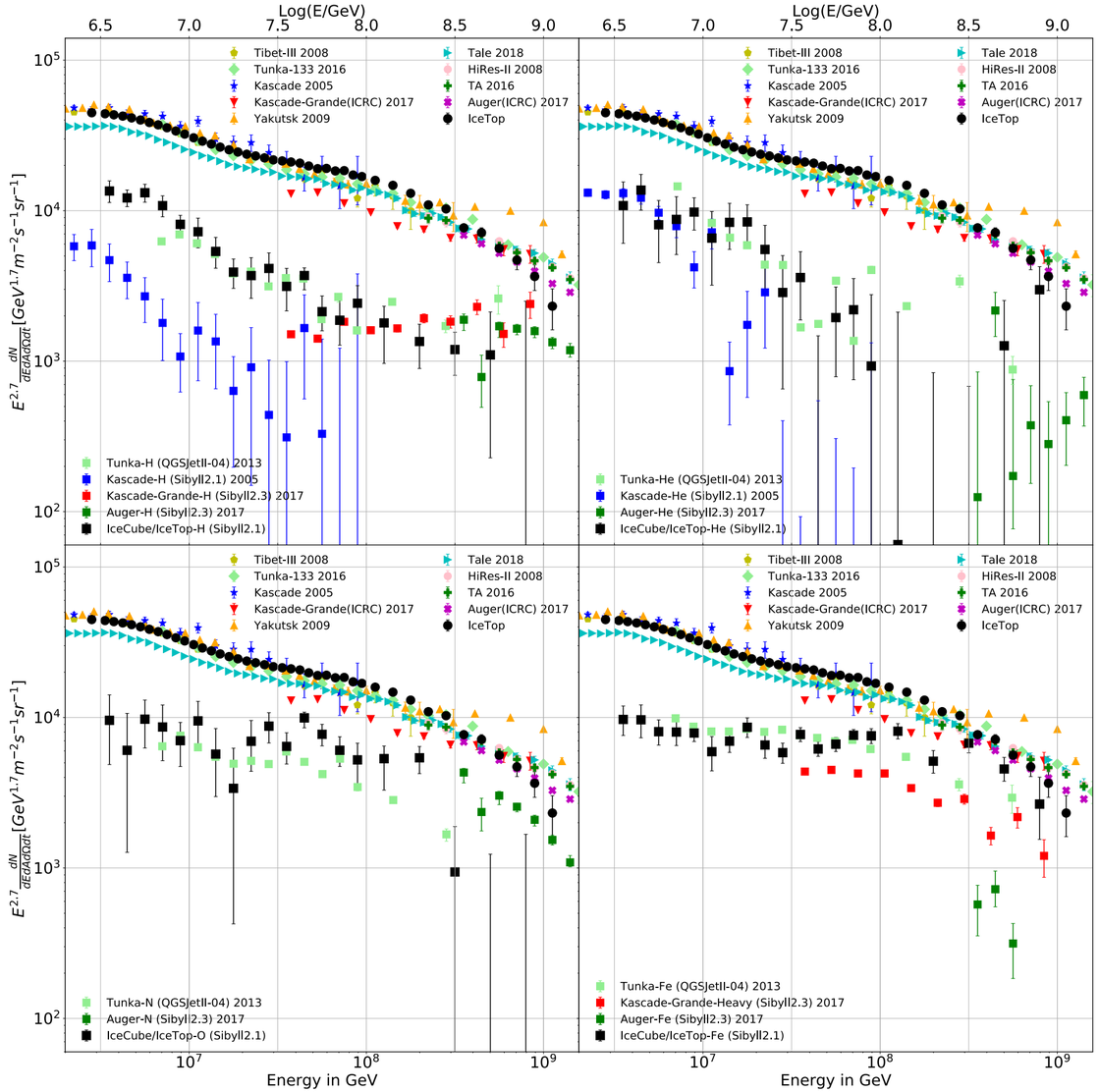
CR ENERGY SPECTRUM



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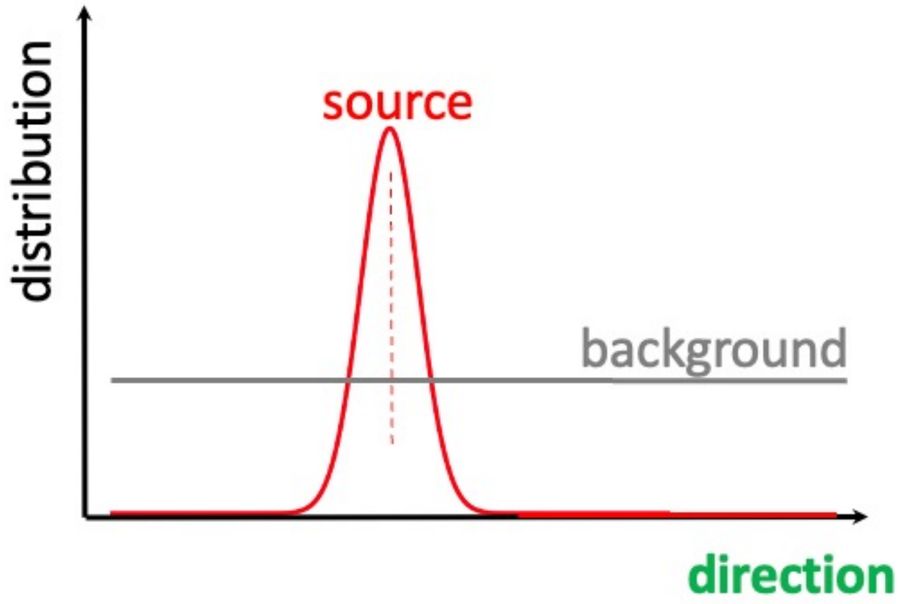
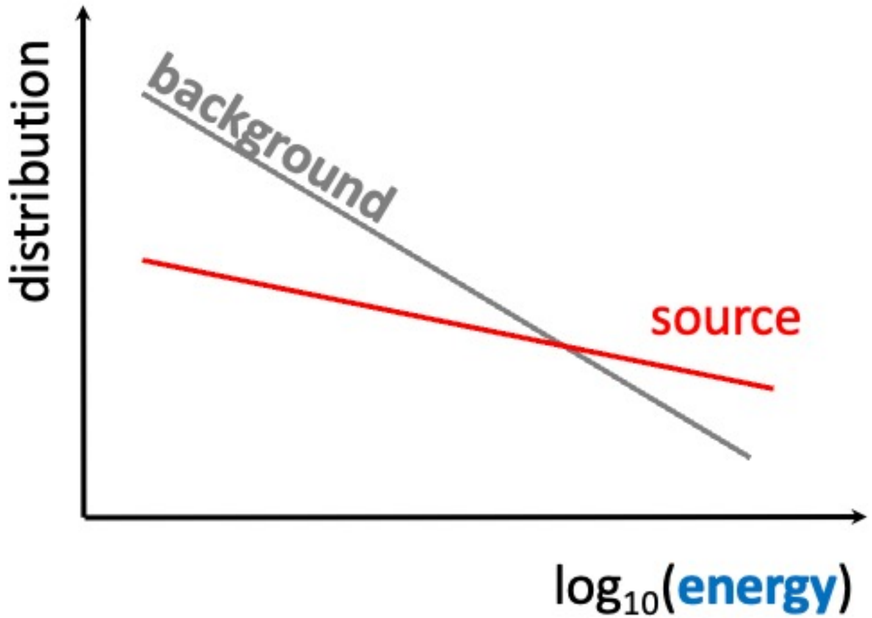
SEARCHING FOR NEUTRINO SOURCES

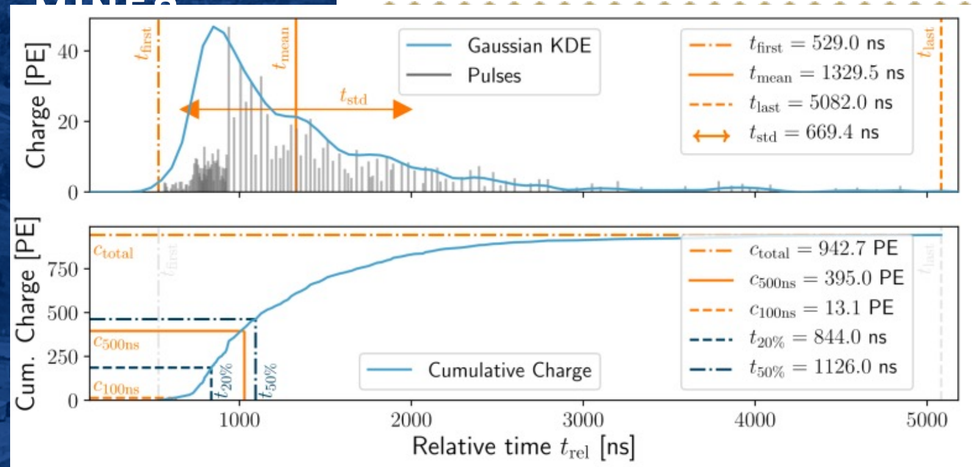
Need good reconstruction of directions and energies
and model of how they differ between signal and background

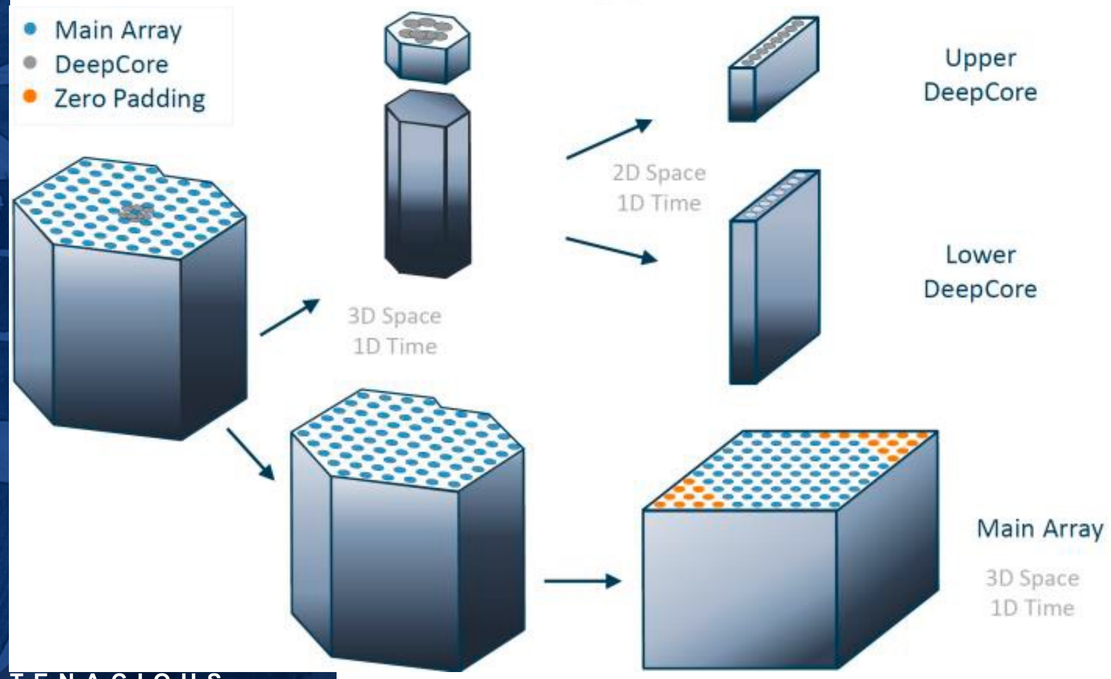
We improved in both areas!





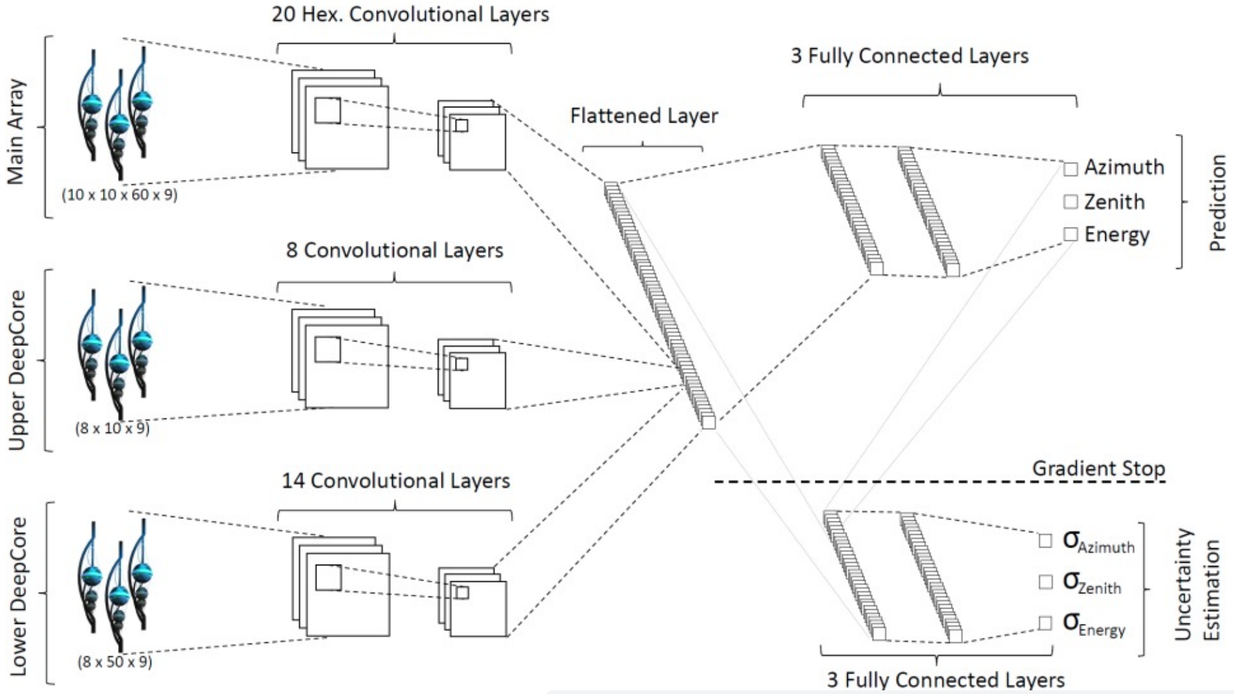
CONVOLUTIONAL NEURAL NETWORK IN ICECUBE





Modification for IceCube

- Unify time dimension into a fixed set of input features
- Transform IceCube geometry such that it can be utilized by standard CNNs
- Hexagonal convolutional kernels
- Additional uncertainty estimation layer via Gaussian likelihood



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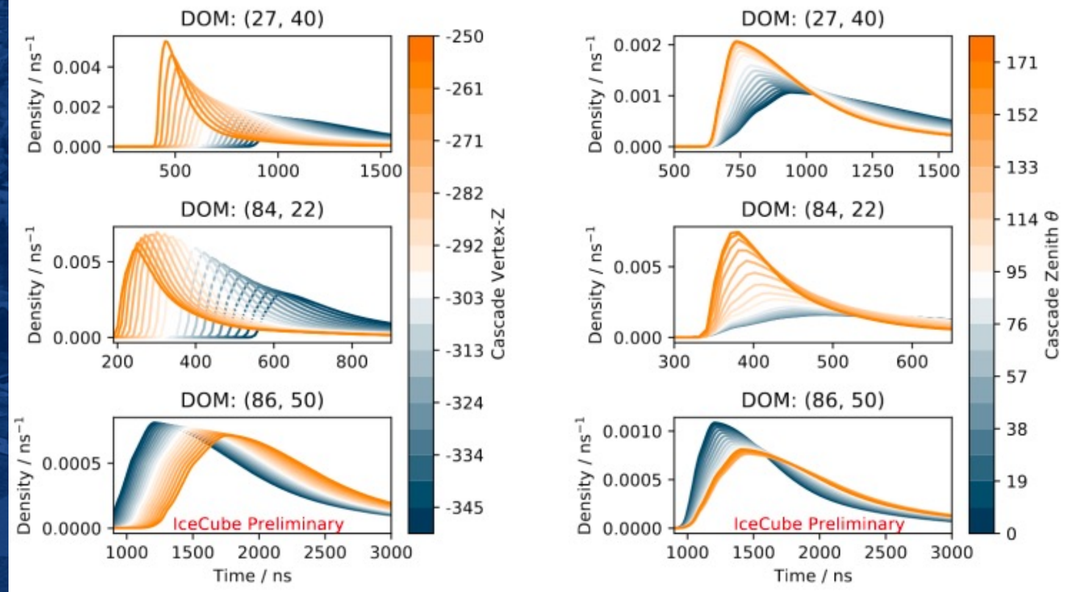
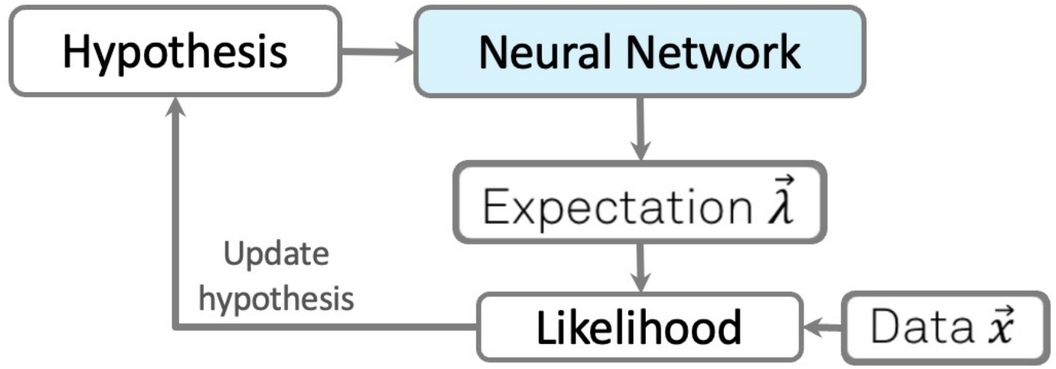
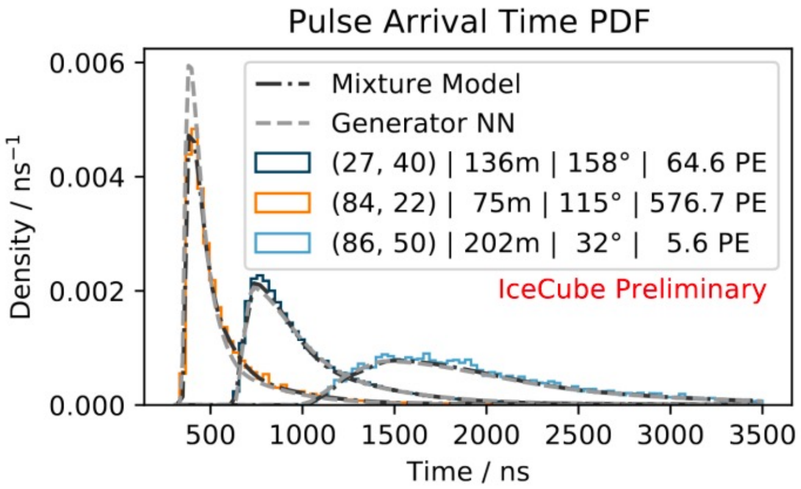
RECONSTRUCTING EVENT PROPERTIES







Hybrid reconstruction method:

- Combines maximum-likelihood estimation with deep learning
- Modeling of high-dimensional PDFs via neural networks
- Exploits available information and symmetries

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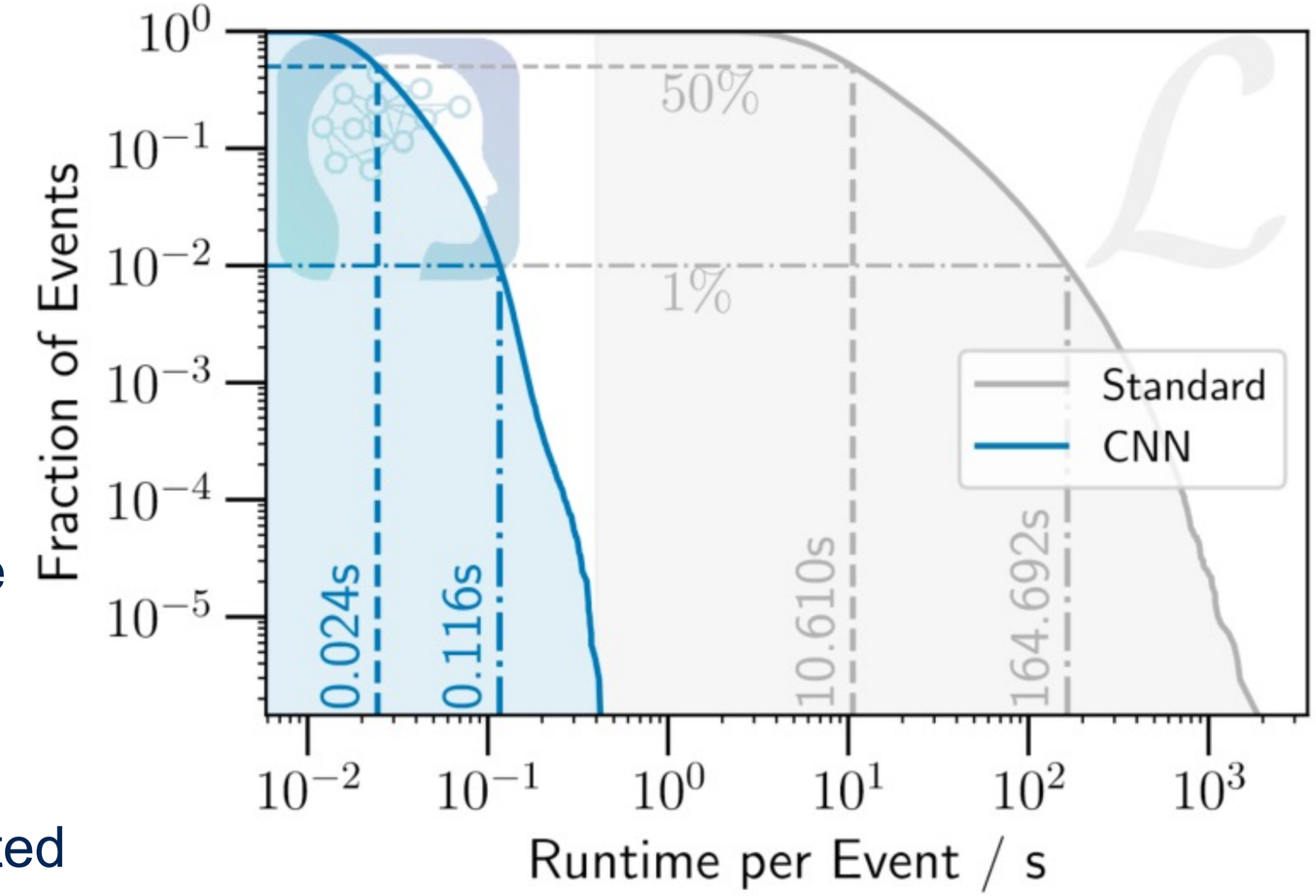
CONVOLUTIONAL NEURAL NETWORK IN ICECUBE

Achievements of CNNs in IceCube

- Versatile tool for event reconstruction
- Improved reconstruction accuracy at high energies
- Reduced per-event runtime by 3 orders of magnitude

- Allows ‘Online’ event reconstruction with the limited hardware at the South Pole



https://doi.org/10.22323/1.395.1065

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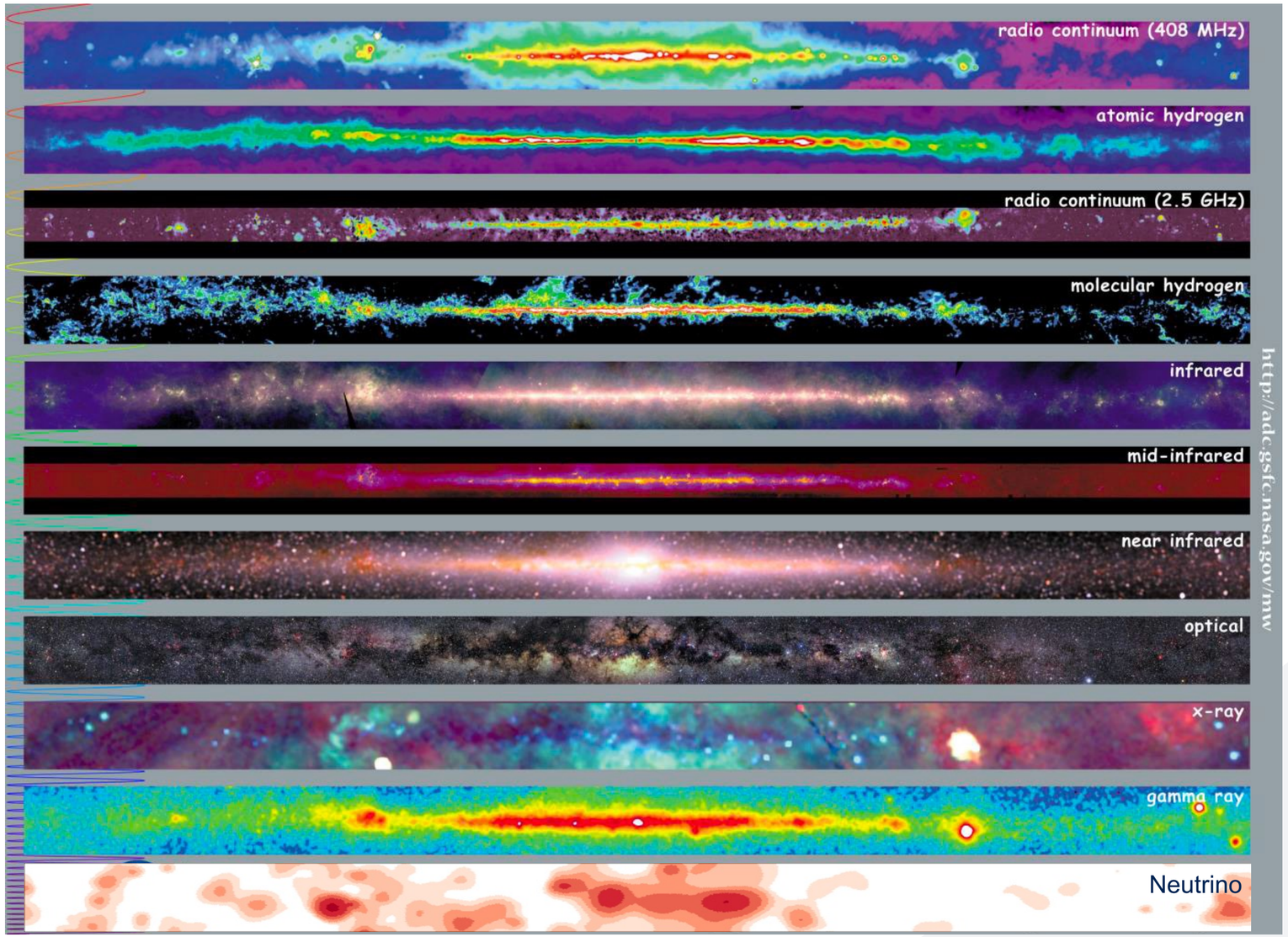
THE MULTIWAVELENGTH MILKY WAY



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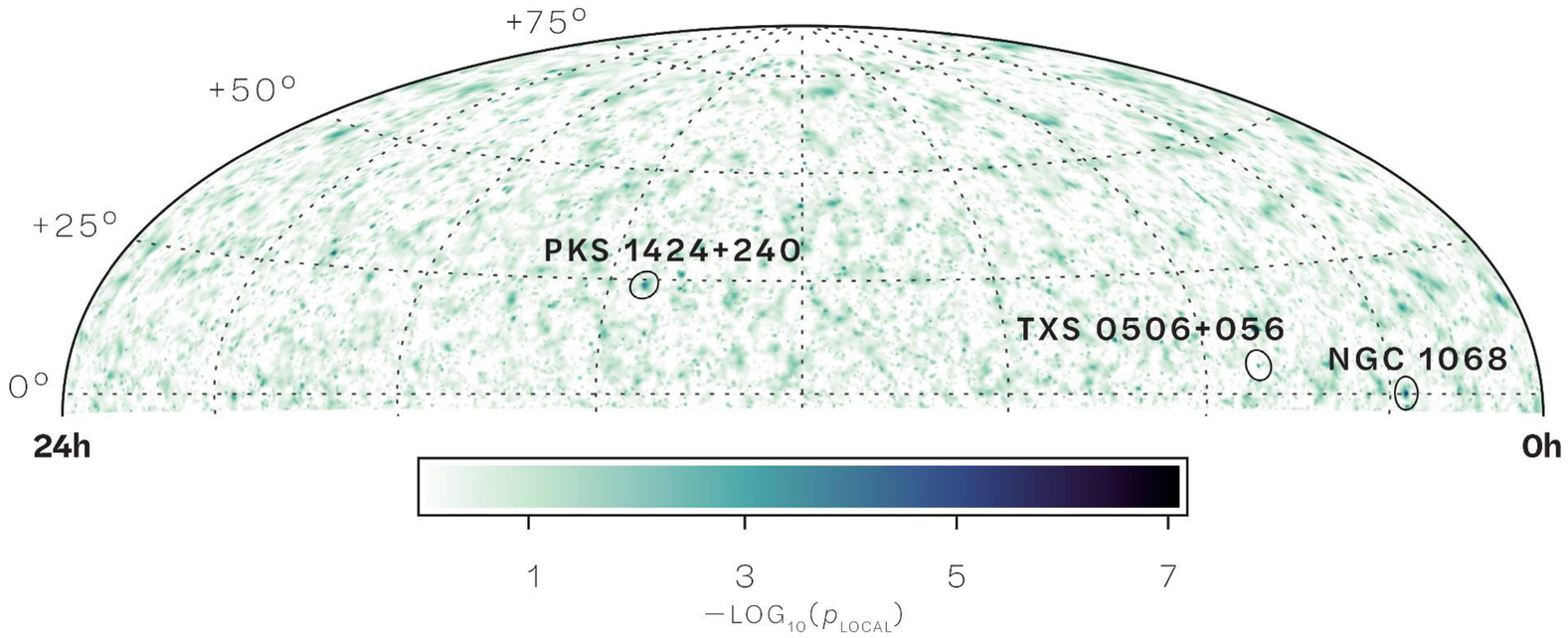
ICECUBE IDENTIFIES NGC 1068 AS LIKELY NEUTRINO SOURCE

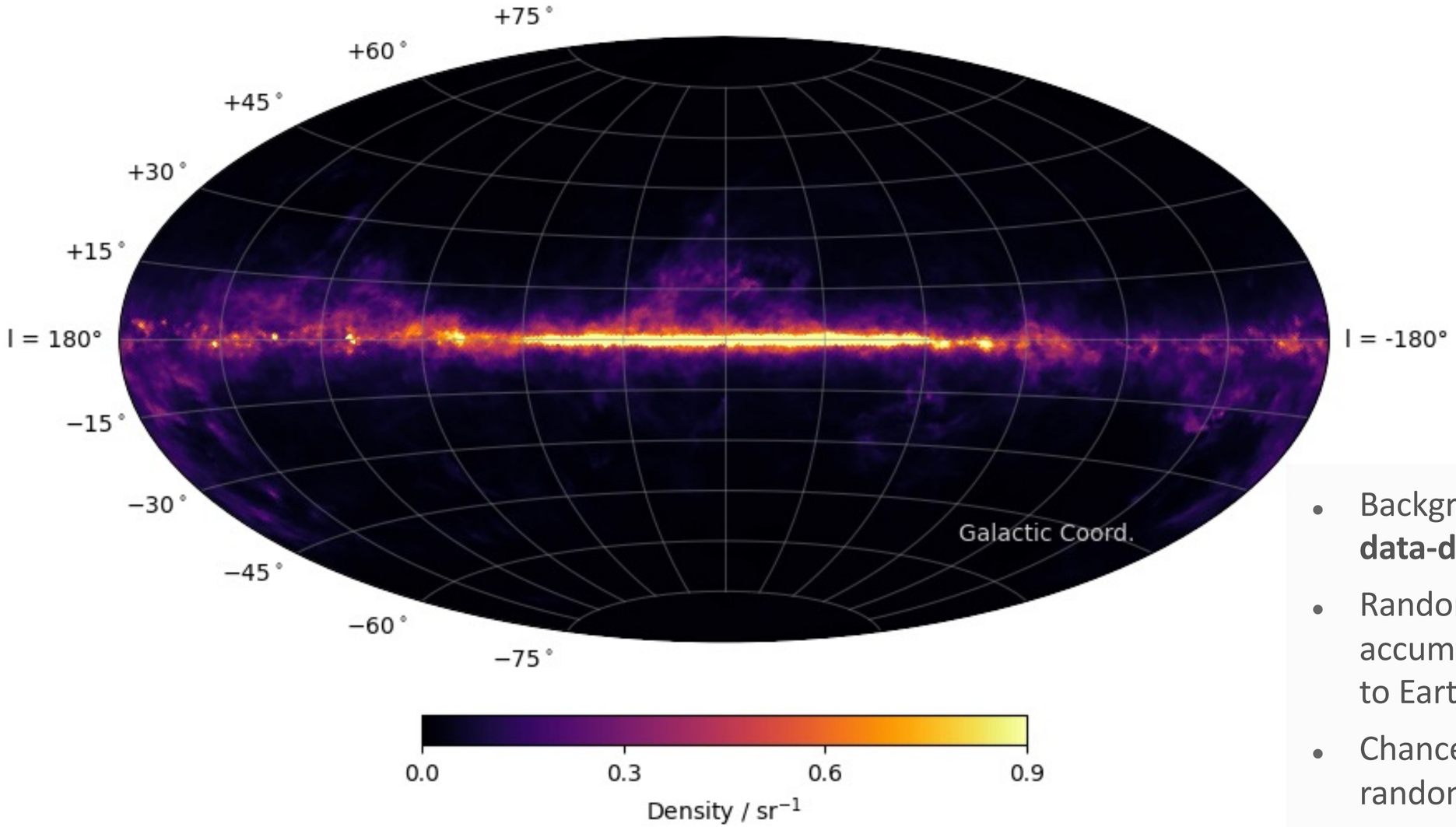


- Search for significant clustering of events versus isotropic null hypothesis
- Brightest point in sky correlates with Seyfert galaxy NGC 1068
- NGC 1068 rejects isotropic hypothesis at 4.2sigma after trials correction

https://doi.org/10.1126/science.abg3395

Data-Driven Search Method

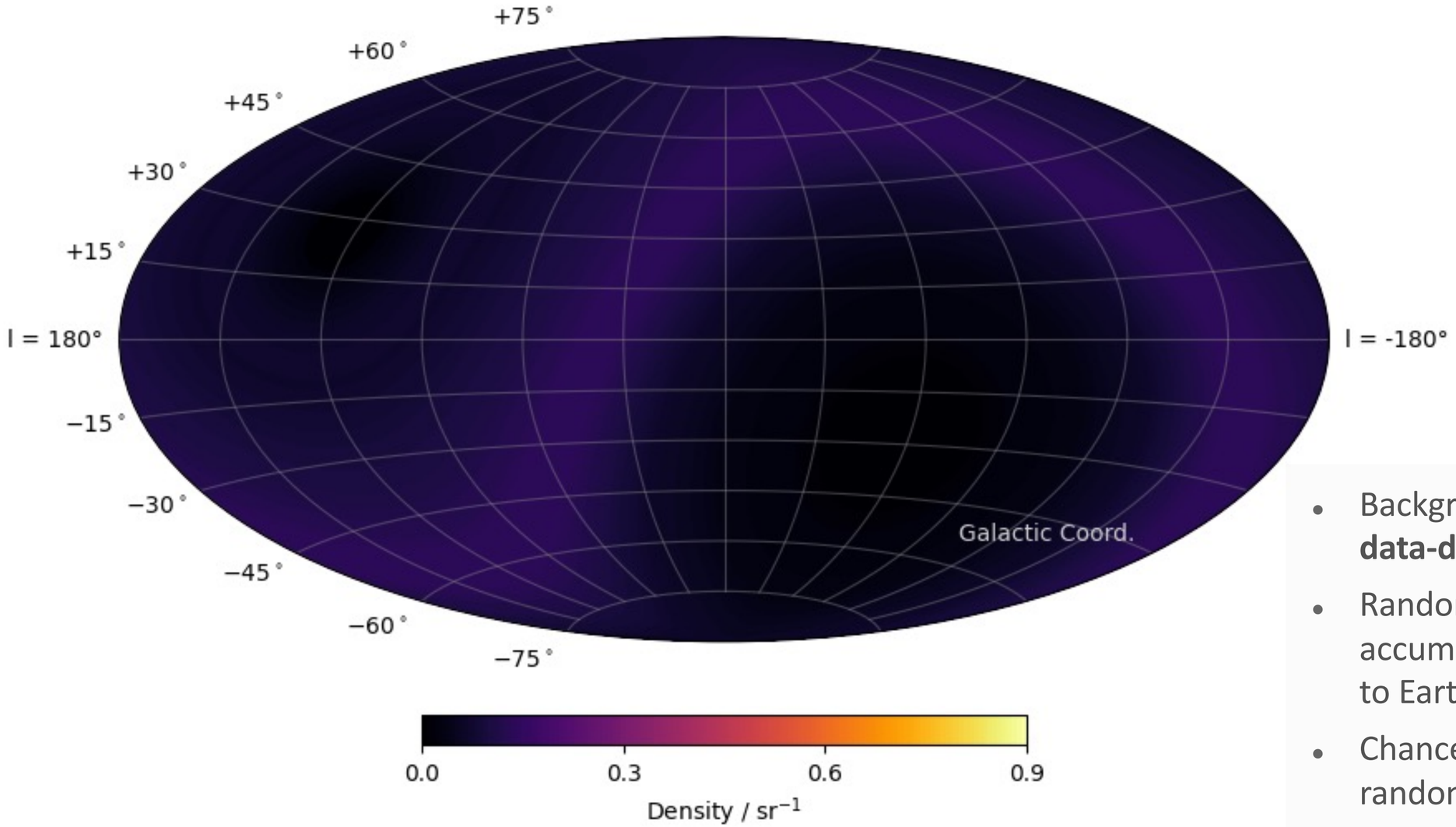
Model expectations based on Fermi-LAT measurements



- Backgrounds are modeled in **data-driven** approach
- Randomization in time removes accumulation along Galactic plane due to Earth's rotation
- Chance probability calculated via randomized pseudo-experiments

Data-Driven Search Method

Scrambled background distribution (no signal present)



- Backgrounds are modeled in **data-driven** approach
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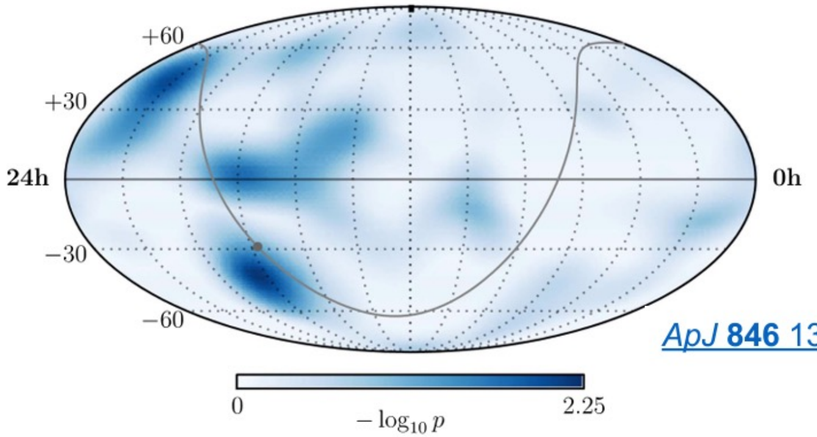
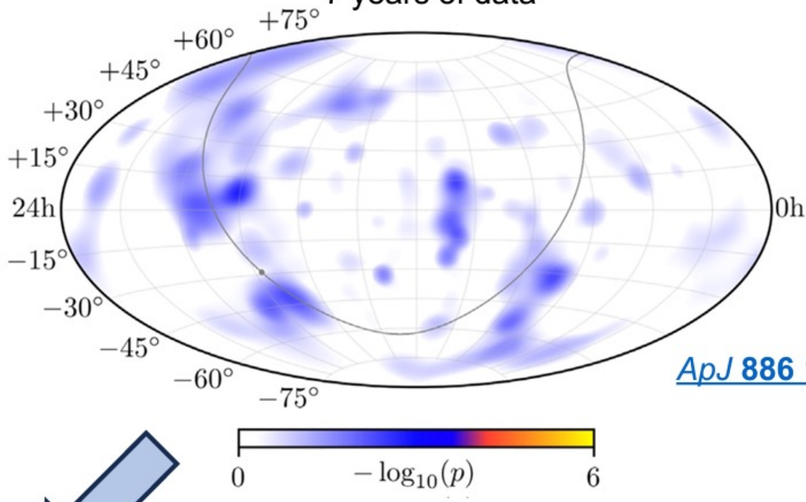
2 years of data



ApJ **846** 136

Galactic plane p-value: 65%

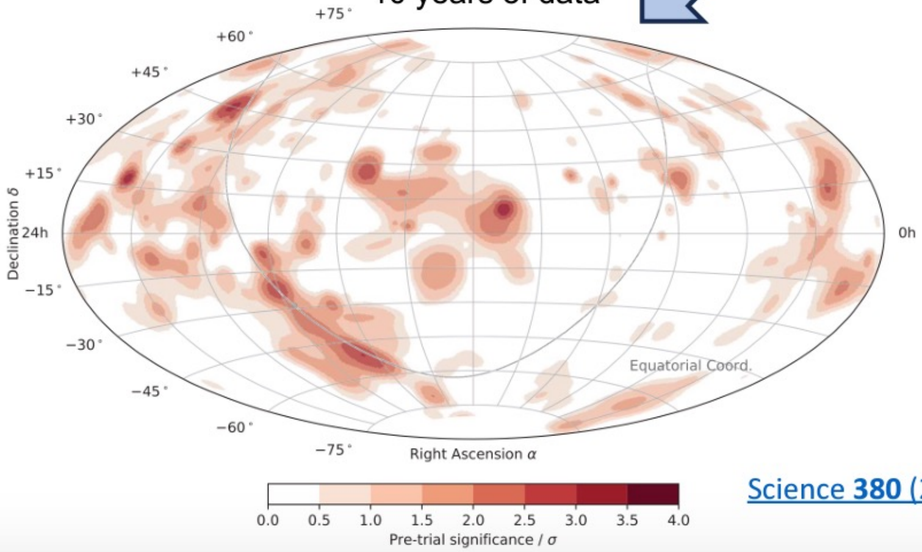
7 years of data



ApJ **886** 12

Galactic plane p-value: 2.1% (2σ)

10 years of data



Galactic plane p-value: 0.0004% (4.5σ)

Science **380** (2023) 1338

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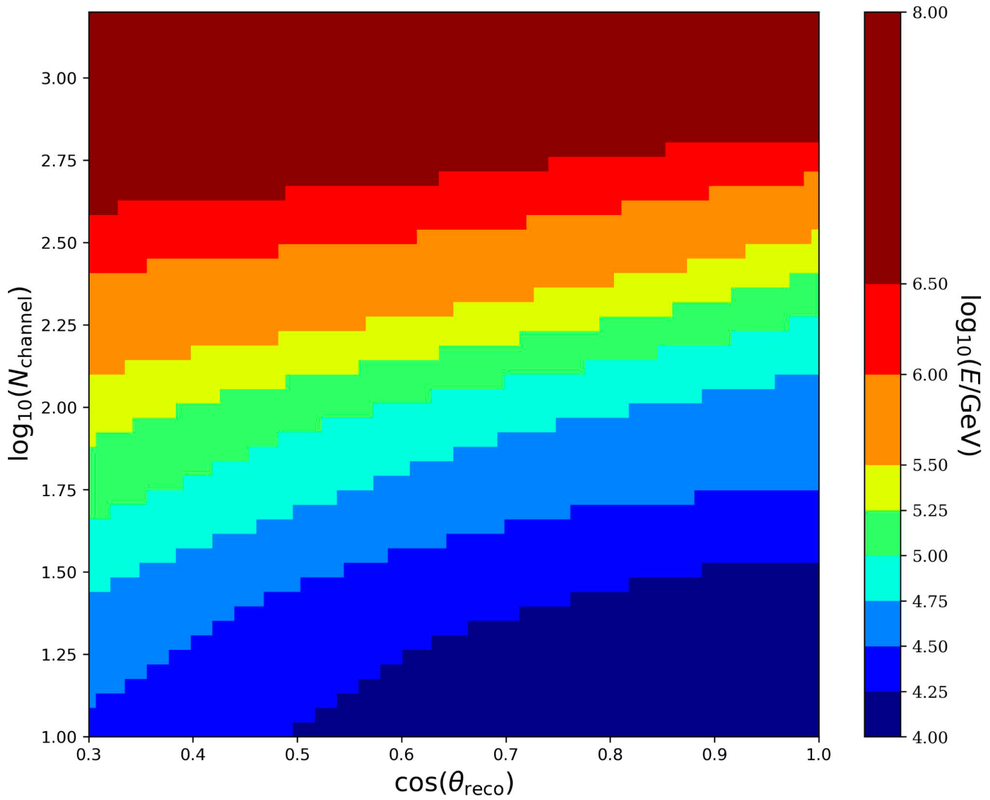
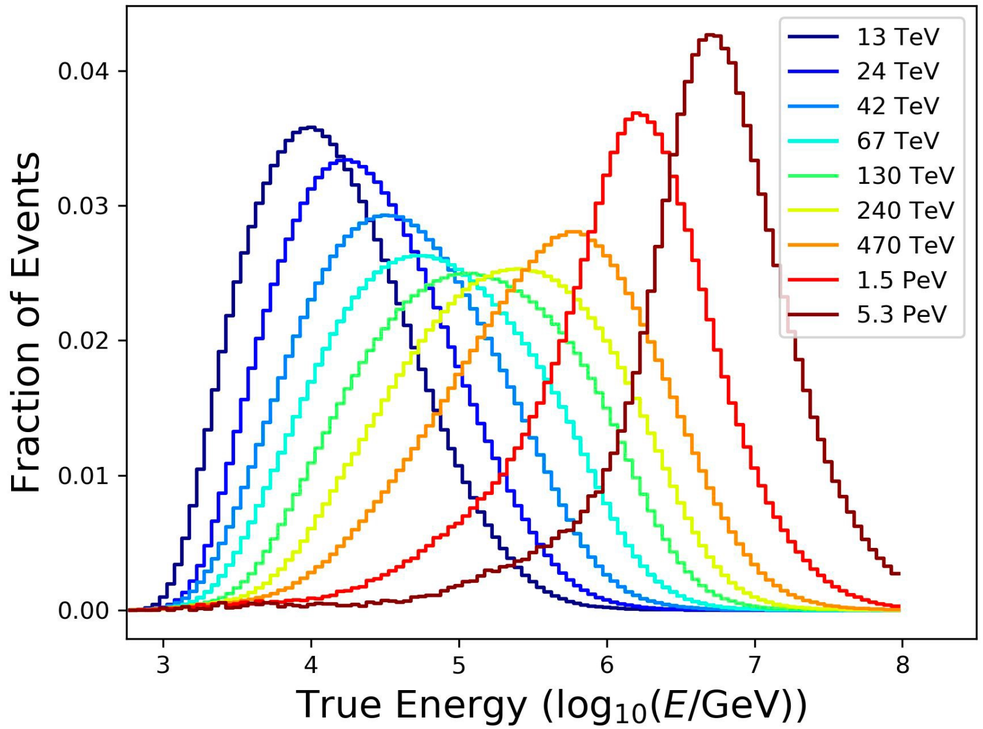
ENERGY ESTIMATION ANISOTROPY





https://arxiv.org/abs/2308.02331

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