



Astroparticles

Cosmic rays, Neutrinos and Gamma rays

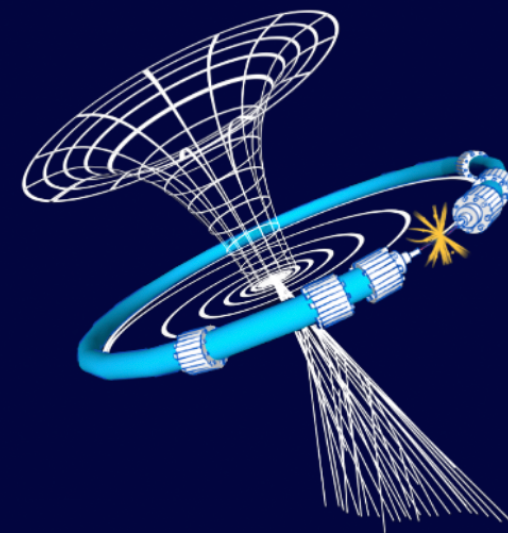
Arman Esmaili

Pontifícia
Universidade Católica
do Rio de Janeiro
(PUC-Rio), Brazil

15th IDPASC Summer School

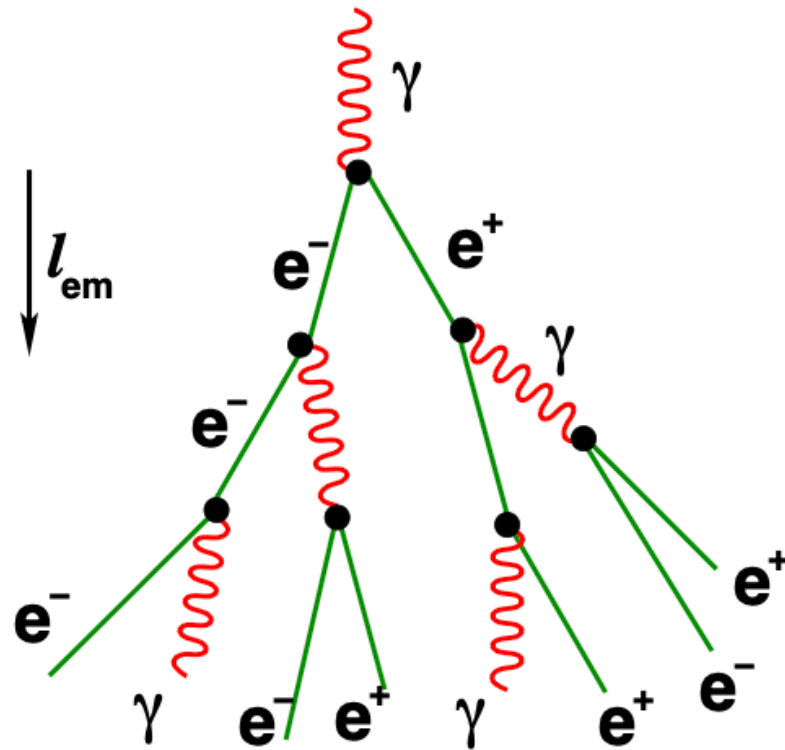
20 - 29 July 2026

Natal, Brazil

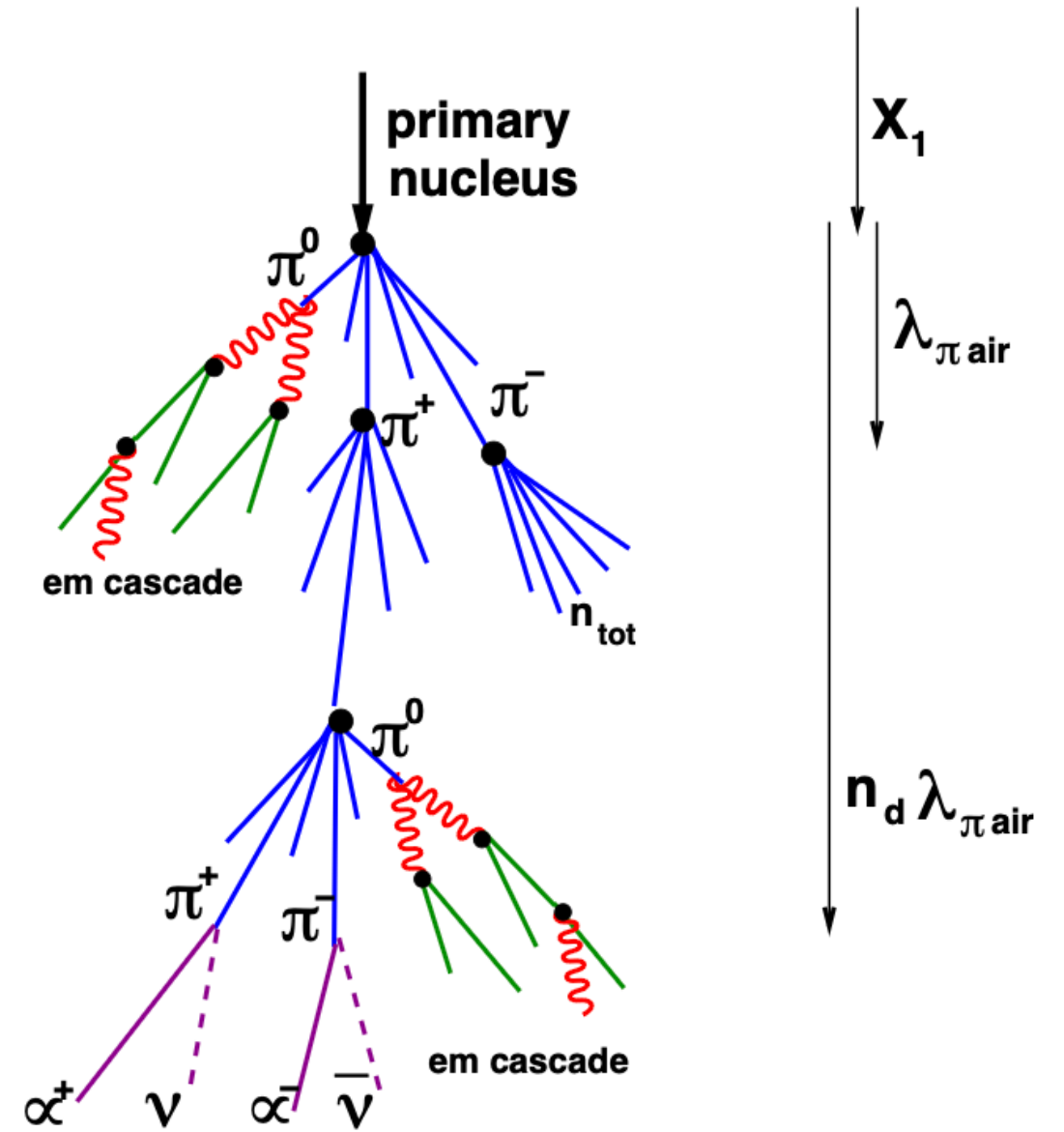


Air Showers

em cascade



hadronic cascade

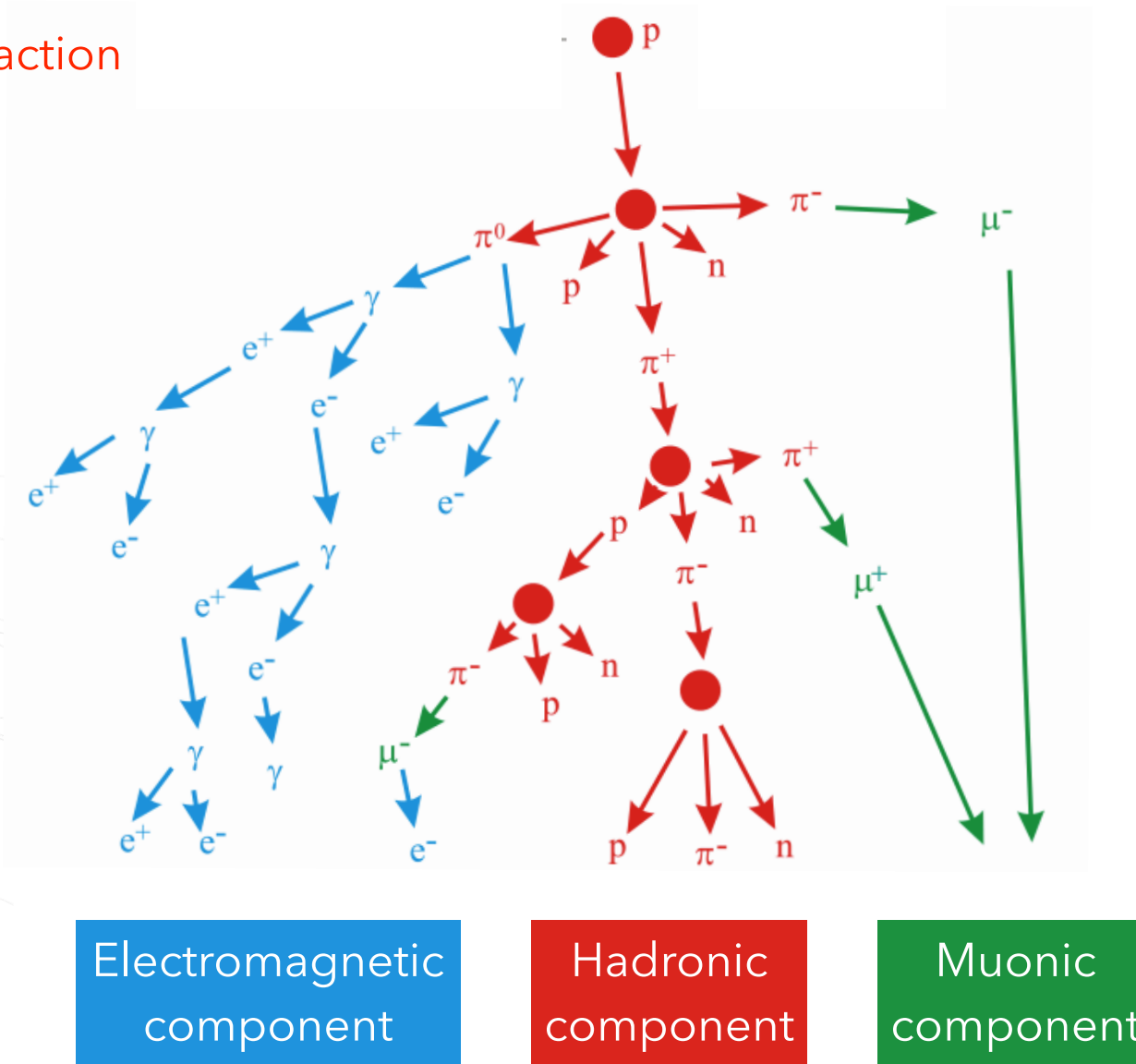


Air Shower Physics

Monte Carlo EAS simulation [CORSIKA]

Primary Particle

First interaction

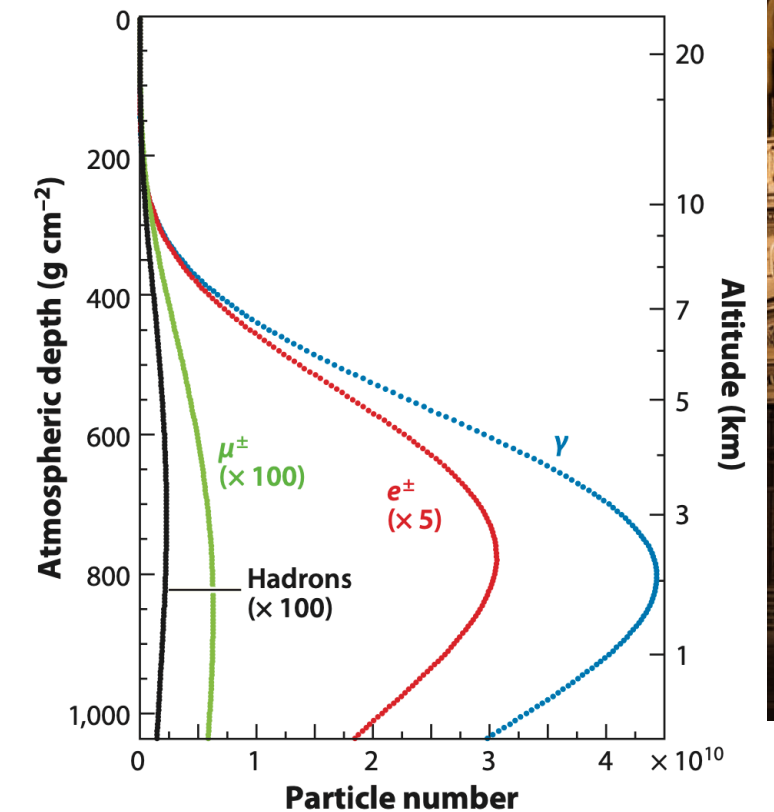
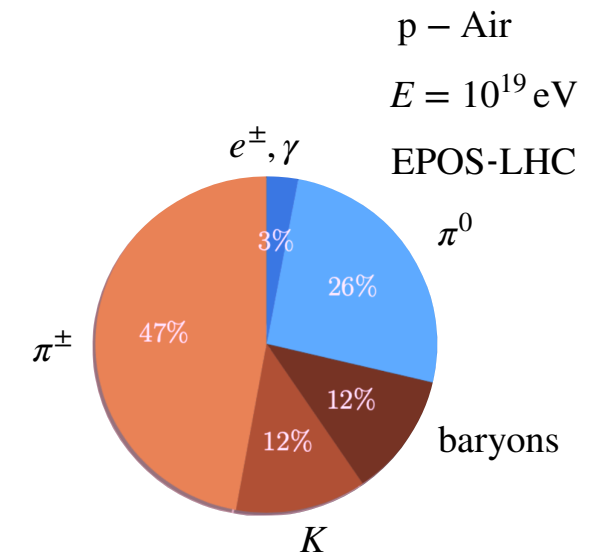


Electromagnetic component

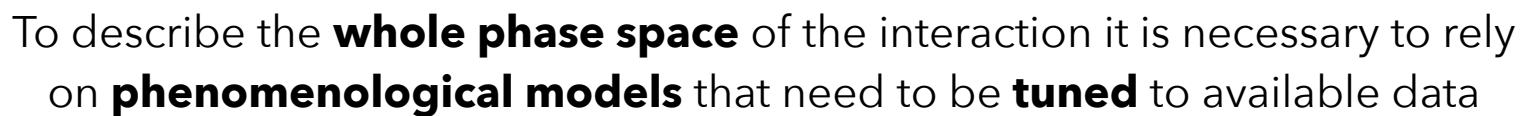
Hadronic component

Muonic component

Ruben Conceição



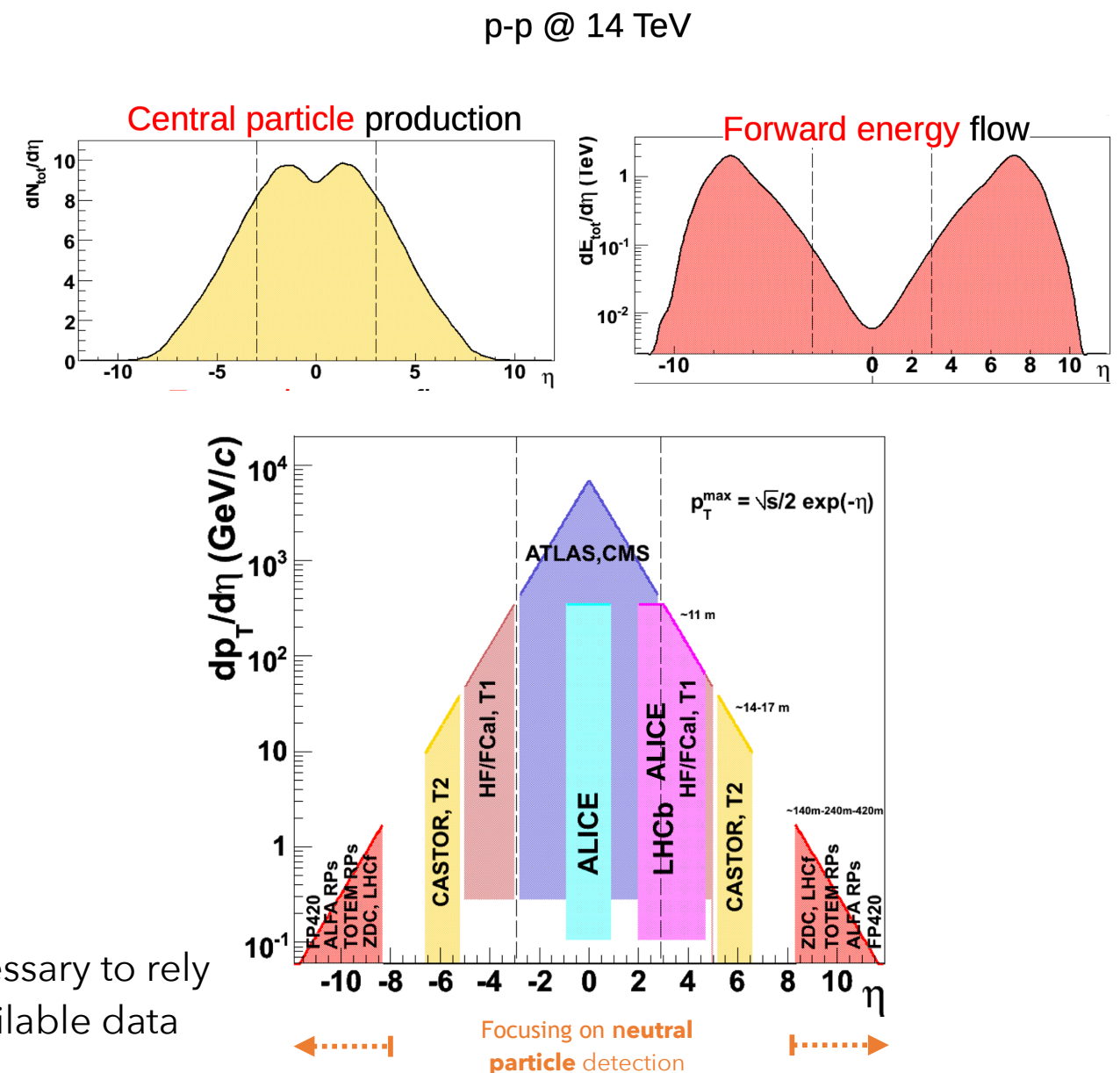
Slide from R. Conceição



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Arman Esmaili

22/July/2026



The Pierre Auger Observatory

- East of Andes
- Province of Mendoza, Argentina *PoS(ICRC2025)1236; I. Alekotte*
- 2000: Engineering Array
- 2004: start...
- 2008: ... end of construction of Auger
- 2023: Start of Phase II data taking
- 2024: completion of AugerPrime
- Data taking till > 2035
- ≥ 2035

Phase I

Phase II



Local staff



Pierre Auger Collaboration

Argentina
Australia
Belgium
Brasil
Colombia*
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Romania
Slovenia
Spain
USA

*associated

Slide from Markus Roth

The Pierre Auger Observatory — Phase I

Fluorescence detector (FD)

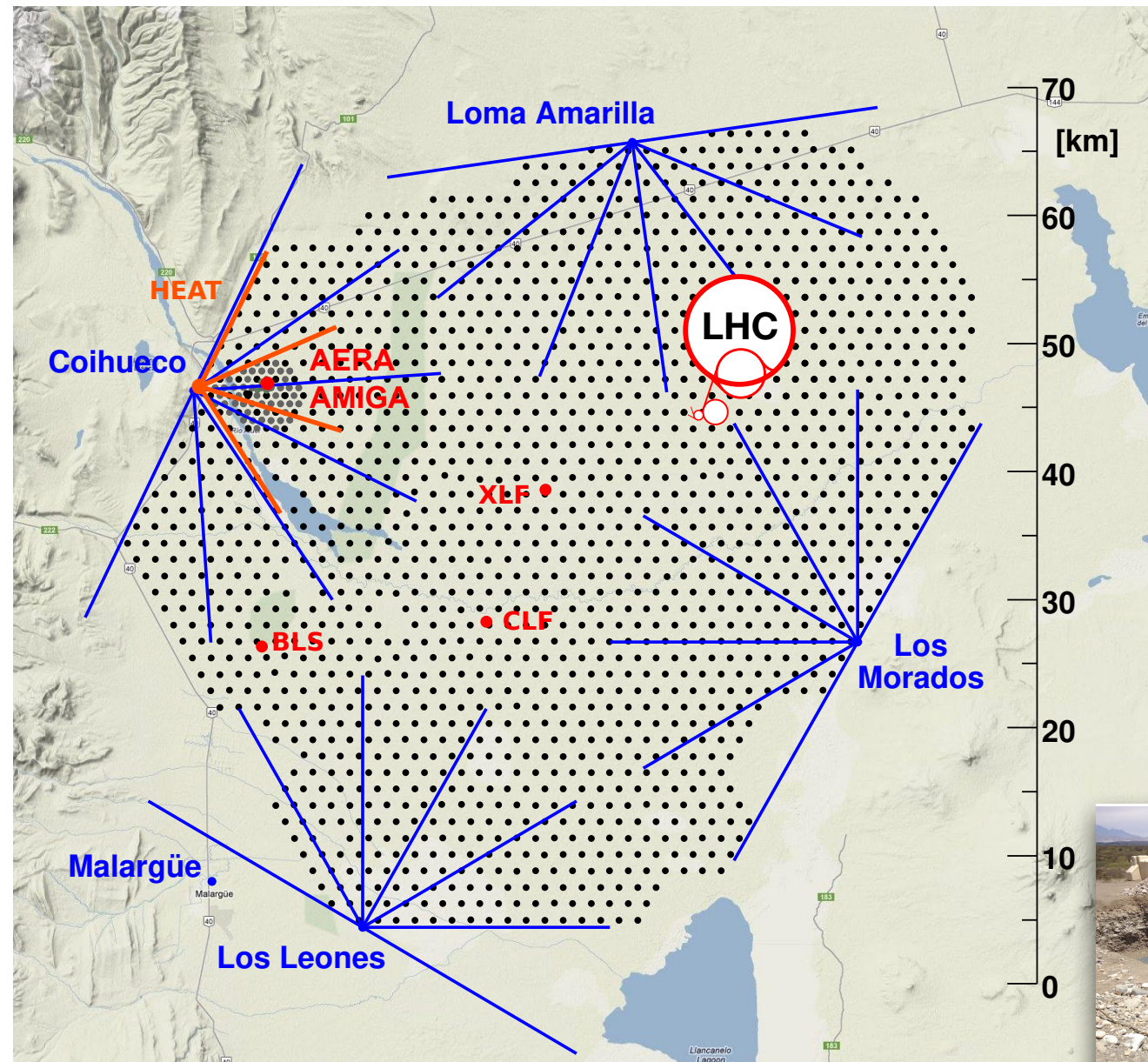
- 4 sites
- $E > 10^{18}$ eV
- HEAT
- $E > 10^{17}$ eV

Surface detector array (SD)

- Water Cherenkov Tanks (WCD)
- Grid of 1500 m / 750 m / 433 m
 - 3000 km² / 24 km² / 2 km²
 - 1660 stations / 61 / 19
 - Thresholds: 10^{18.5} eV, 10^{17.5} eV, 6x10¹⁶ eV
- Grid of 750 m and 433 m
 - Incl. underground muon counters
 - $E > 10^{17.5}$ eV

Radio array (AERA)

- 153 stations
- 17 km²



Slide from Markus Roth

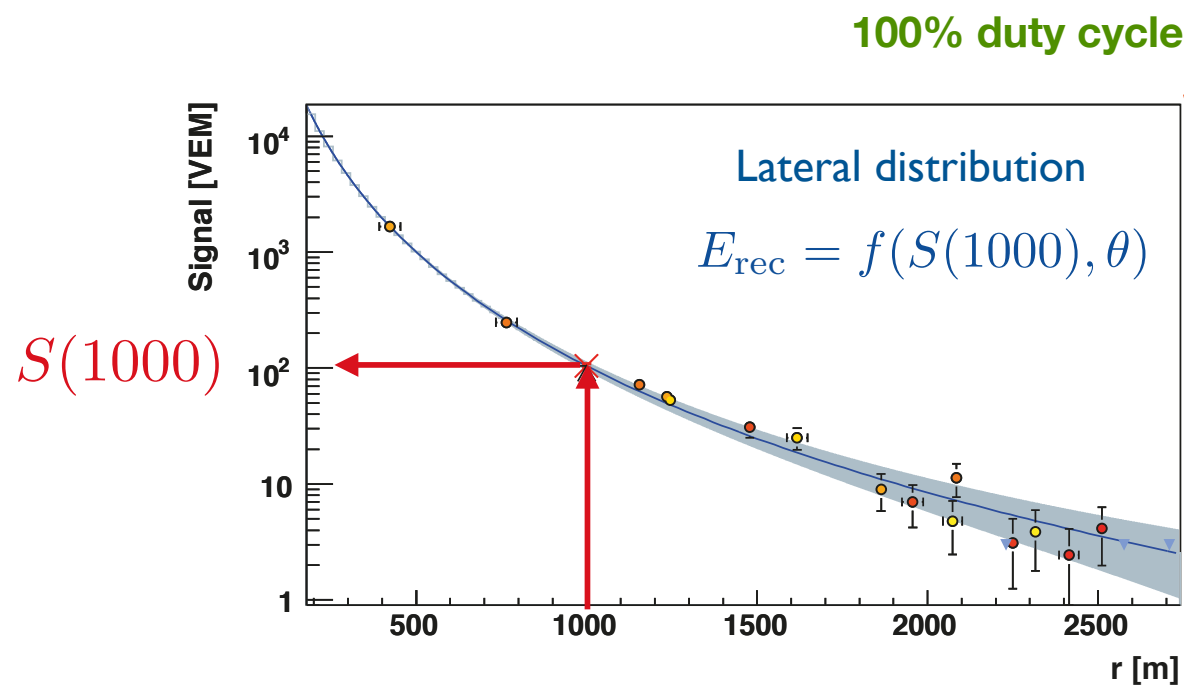
Hybrid detection

Fluorescence Detector (FD):

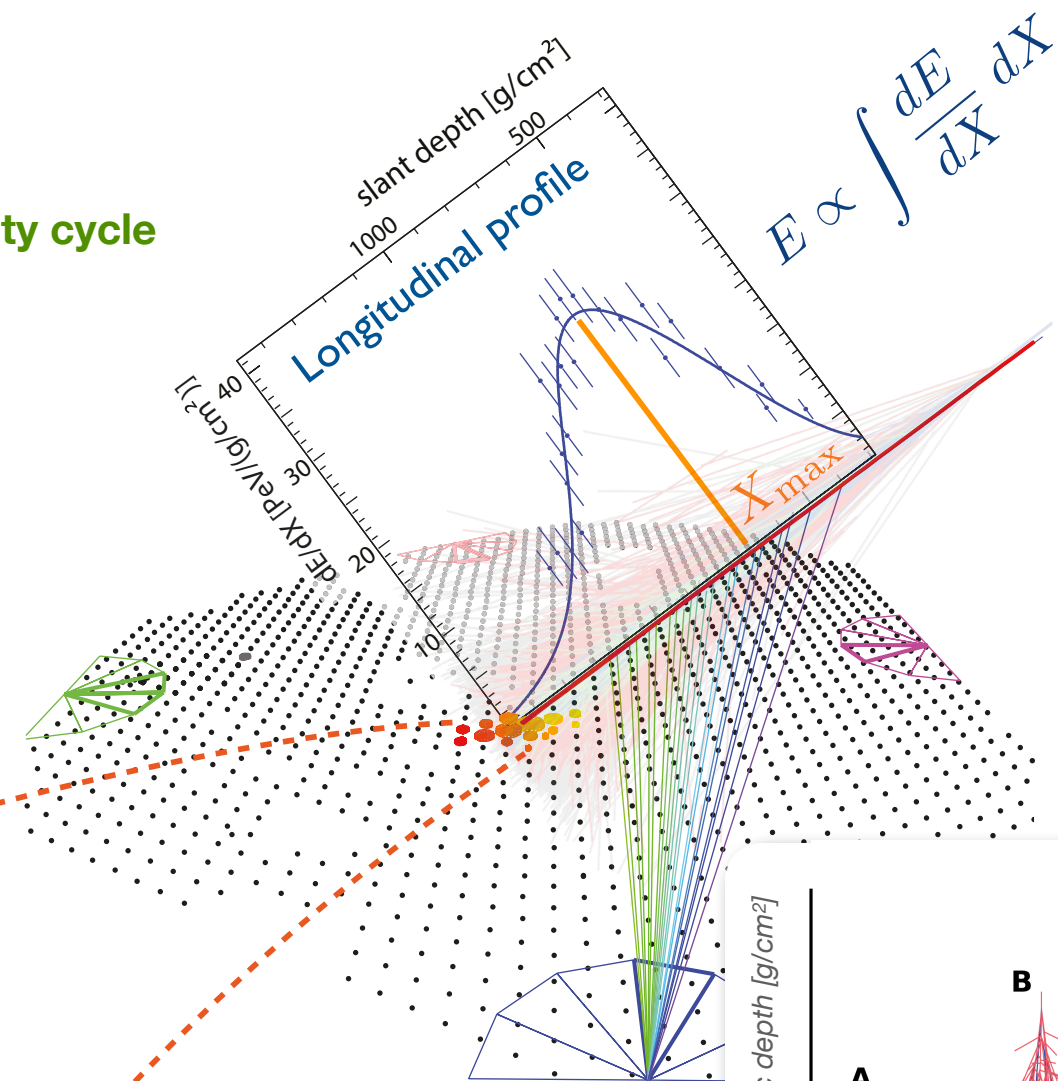
- calorimetric measurement of energy
- ca. 15% duty cycle

Surface Detector (SD):

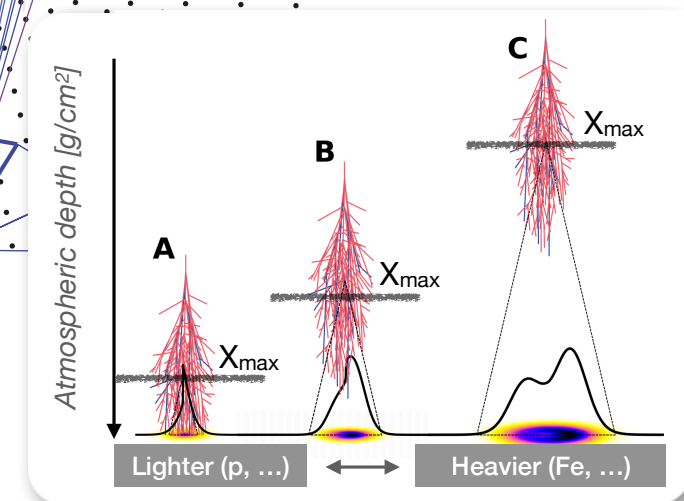
- data driven shape of Lateral Distribution function (LDF)
- optimal distance at 1000 m
- ca. 100% duty cycle



15% duty cycle



Event observed at the Observatory

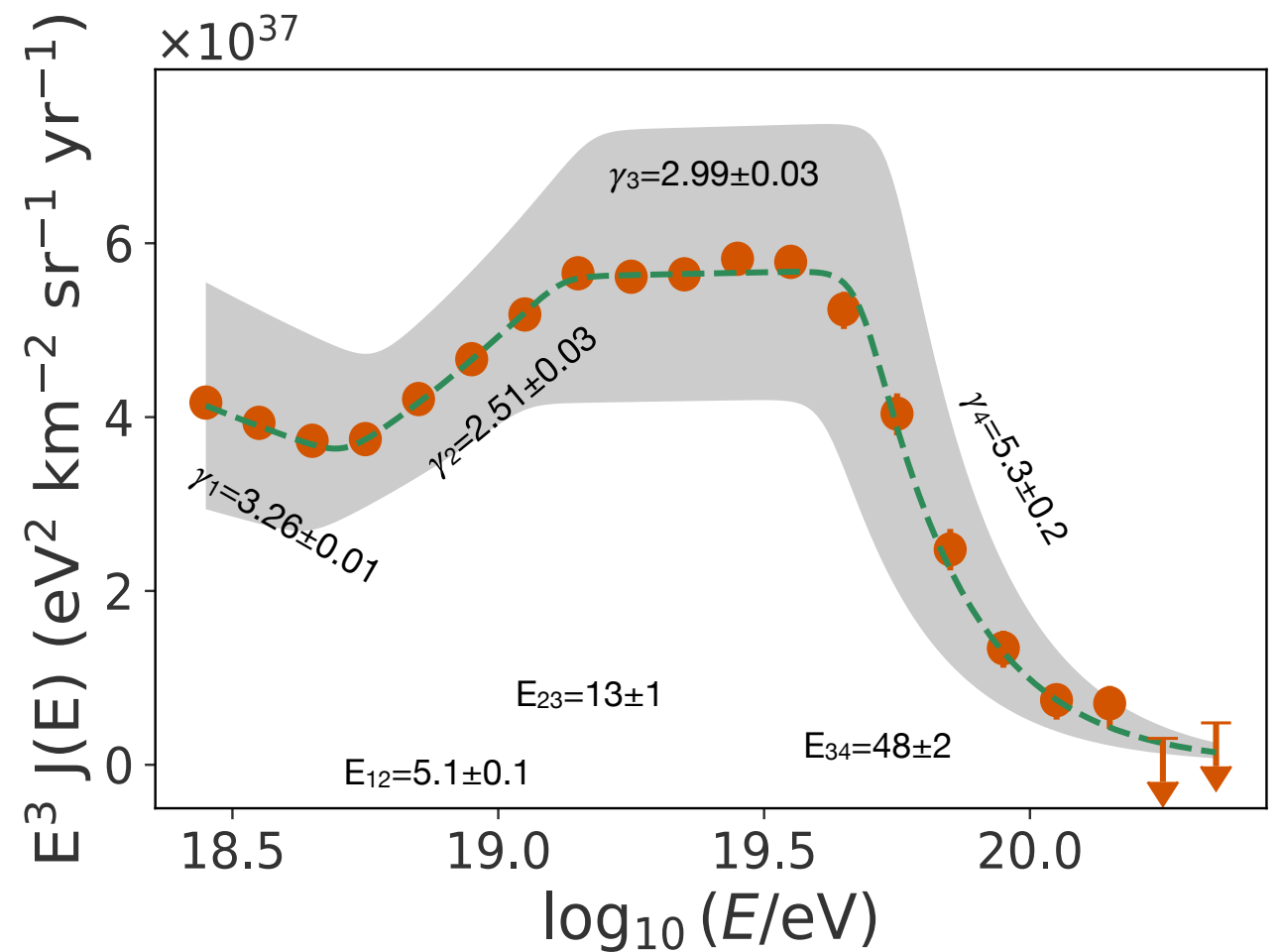
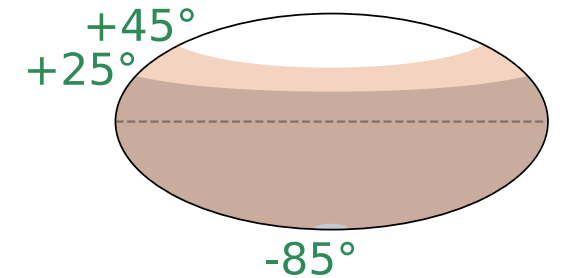


Slide from Markus Roth

Combination of SD spectra

- Combination of data of 1500 m spacing
 $0^\circ < \theta < 60^\circ$ $E > 2.5 \times 10^{18}$ eV
 $60^\circ < \theta < 80^\circ$ $E > 4.0 \times 10^{18}$ eV
 performed in common declination band
 studying systematic effects
- 19 years of data
- Exposure $104\,900 \pm 3000$ km sr yr
- Instep feature significance about 5.5σ
- Is there a declination dependence?
- Potential imprint of dipole anisotropy?

Combined spectrum
for δ in $[-85^\circ, 45^\circ]$
Equatorial coordinates



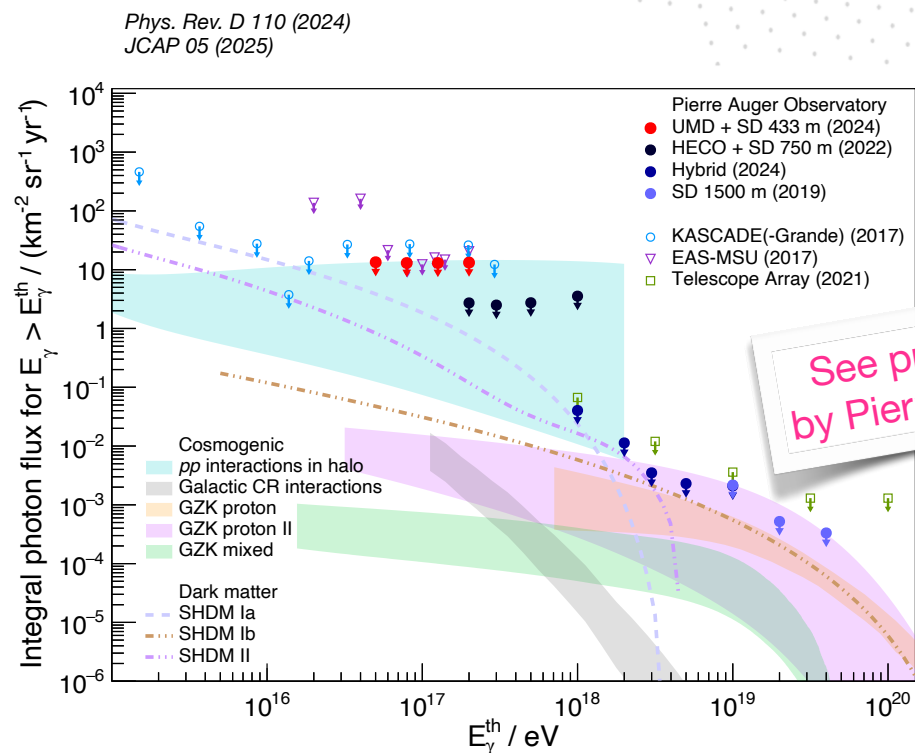
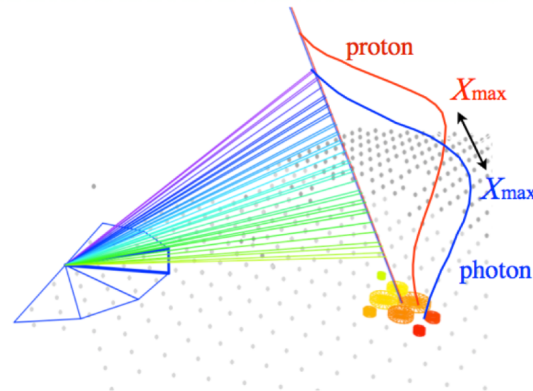
PRL 135 (2025) 241002
Editors' Suggestion

Slide from Markus Roth

Multimessenger searches: Neutrinos and photons

γ search

- **No candidates found**; best available limits across 4 decades of energy
- Closing gap to lower energies thanks to analysis using UMD data

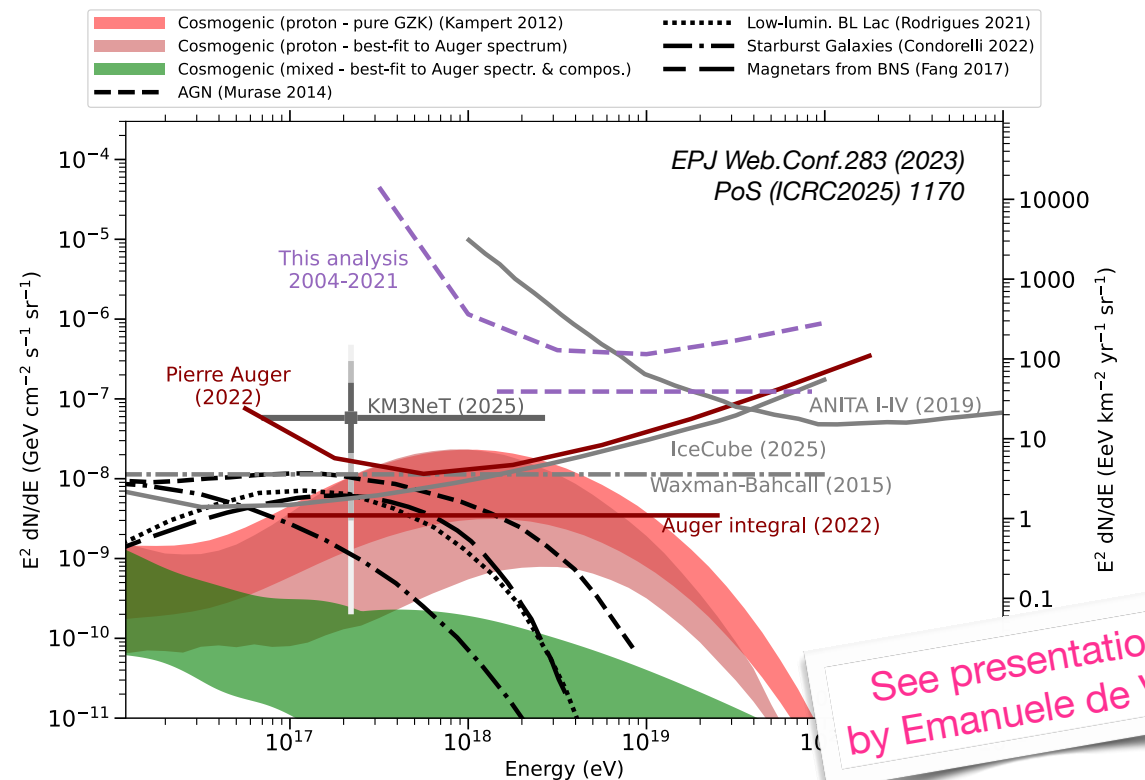


See presentation
by Pierpaolo Savina

γ : Sensitivity reaches GZK predictions
Also used to constrain DM models

ν search

- **No candidates found**; best sensitivity slightly below 10^{18} eV
- Background very low, sensitivity limited by exposure
- Aperture comparable to that of IceCube if source direction is favourable



See presentation
by Emanuele de Vito

ν : Limits constrain GZK & astrophysical neutrino models

Slide from Markus Roth

SIGNATURES OF A PHOTON-INITIATED SHOWER

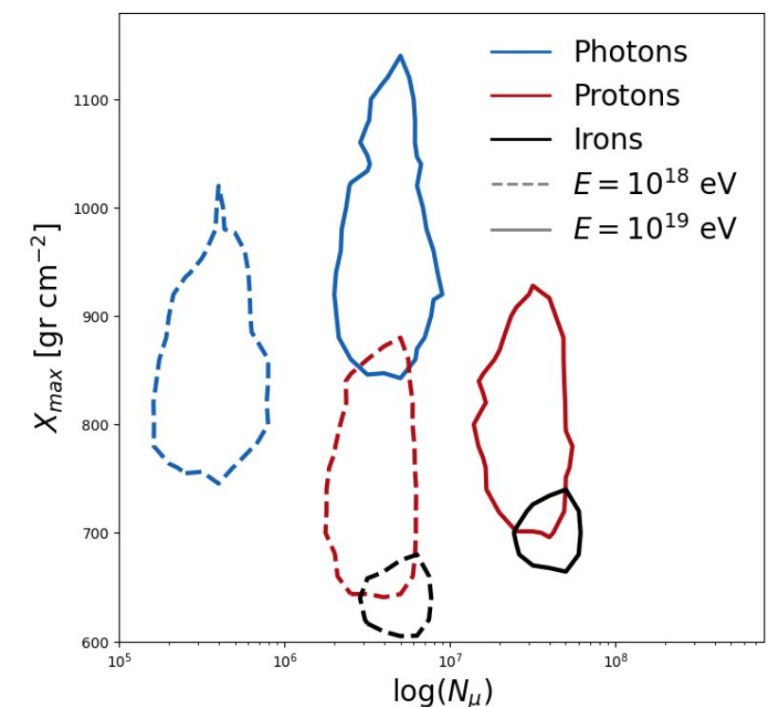
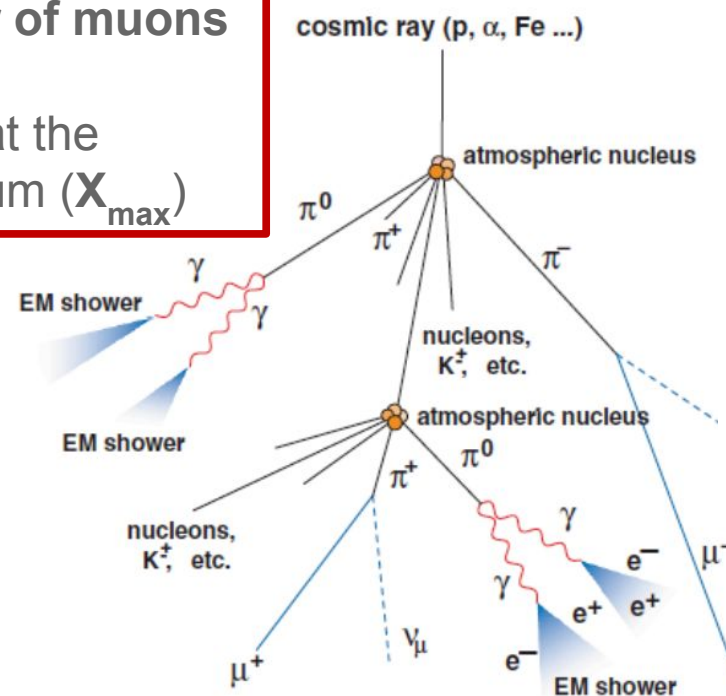
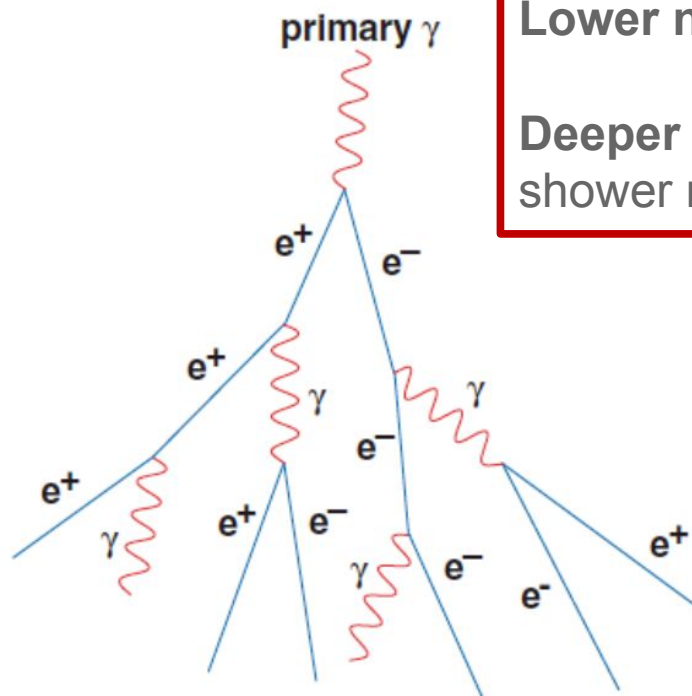
Steeply falling spectrum requires **large detector areas**.

Ground based experiments measure secondary products generated by primary cosmic rays in atmosphere

Separation exploiting the
**different nature of the
interactions**

Lower number of muons

Deeper depth at the
shower maximum ($X_{\max}$)



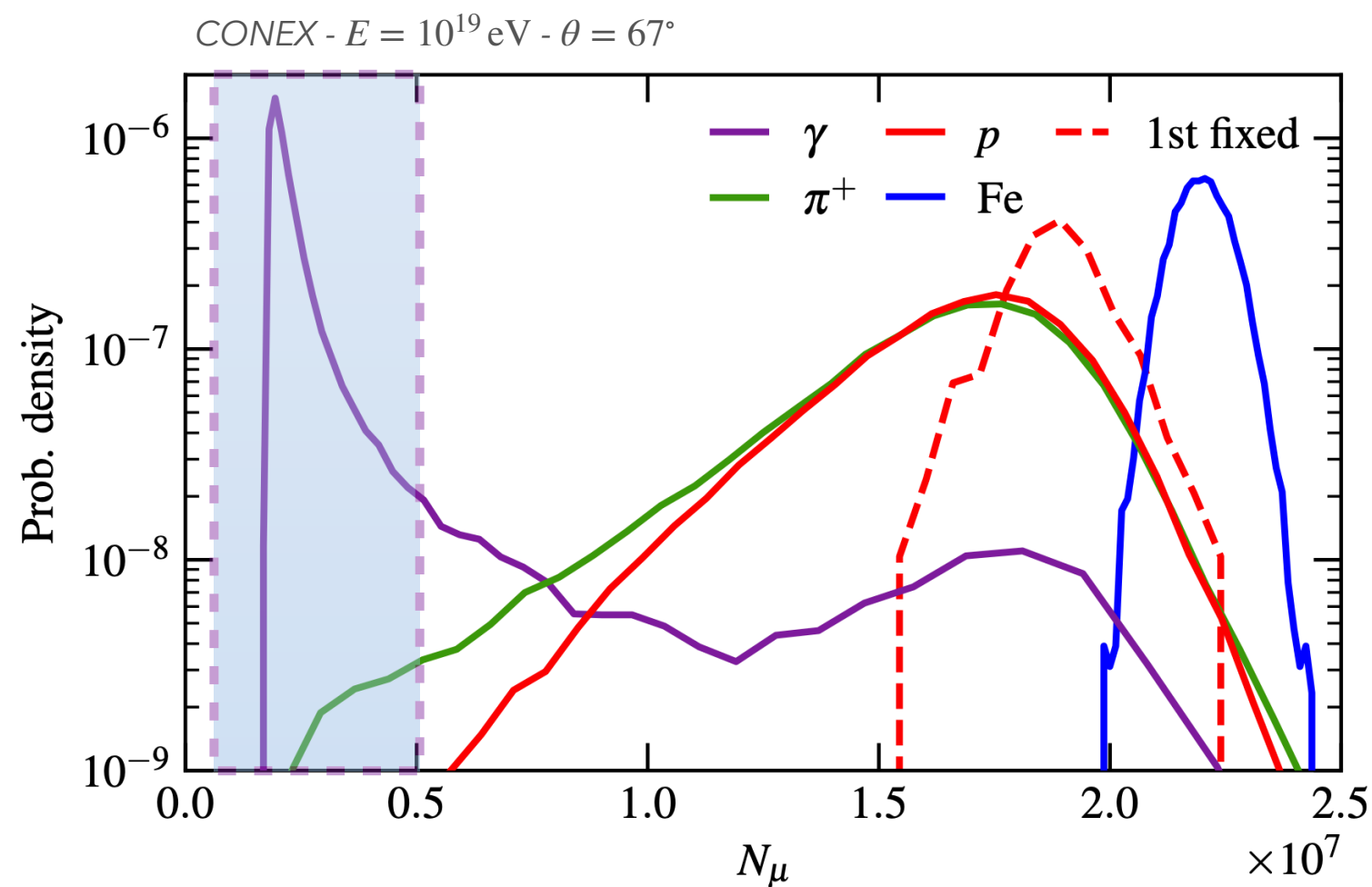
P. Savina (Pierre Auger Collaboration) | ISVHECRI 2026

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Slide from P. Savina

Muons as a proxy for the shower “hadronicity” level

Using the number of muons as an effective discriminator between gamma- and hadron-induced showers



Ruben Conceição

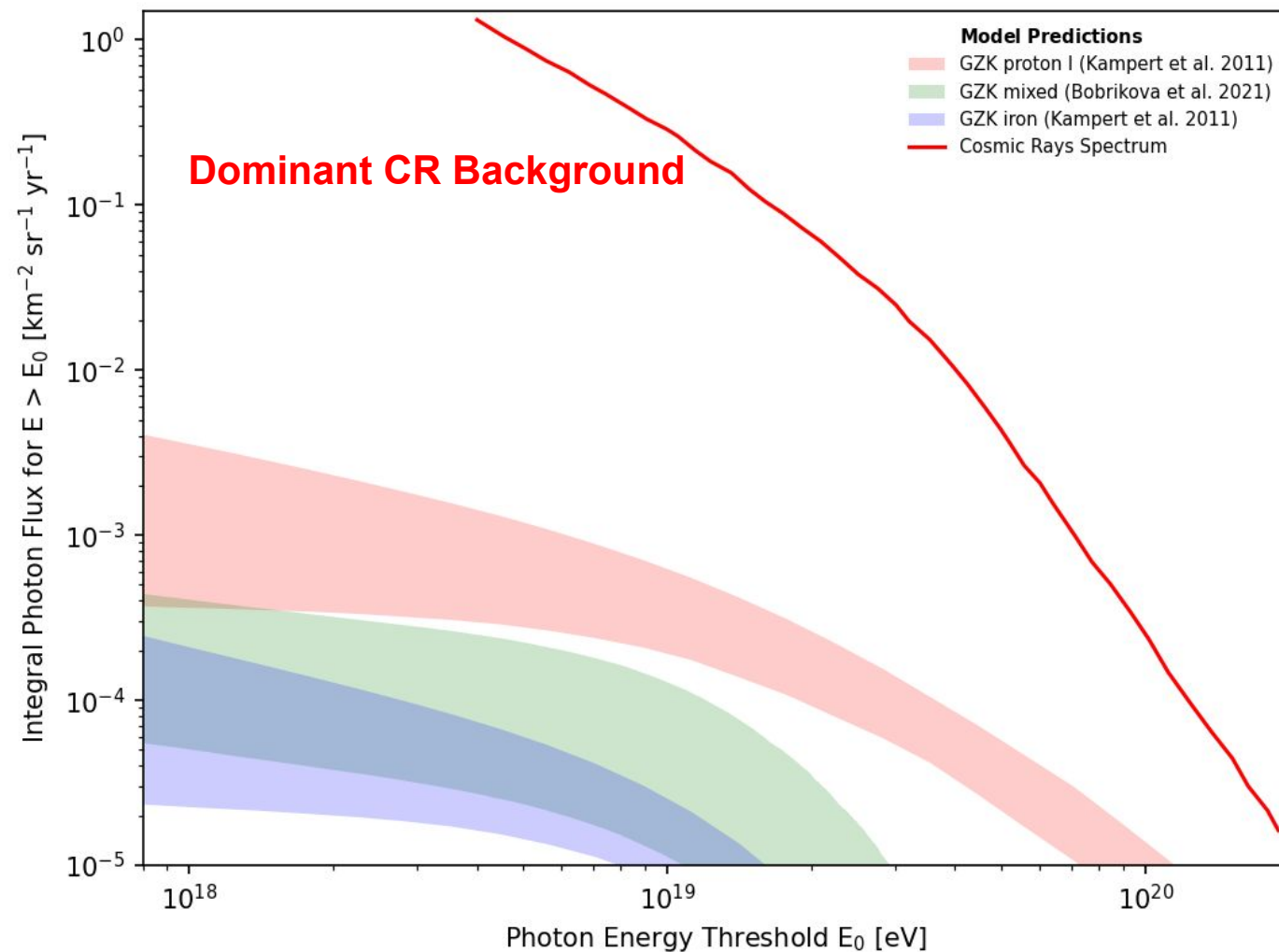
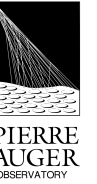


Slide from R. Conceição

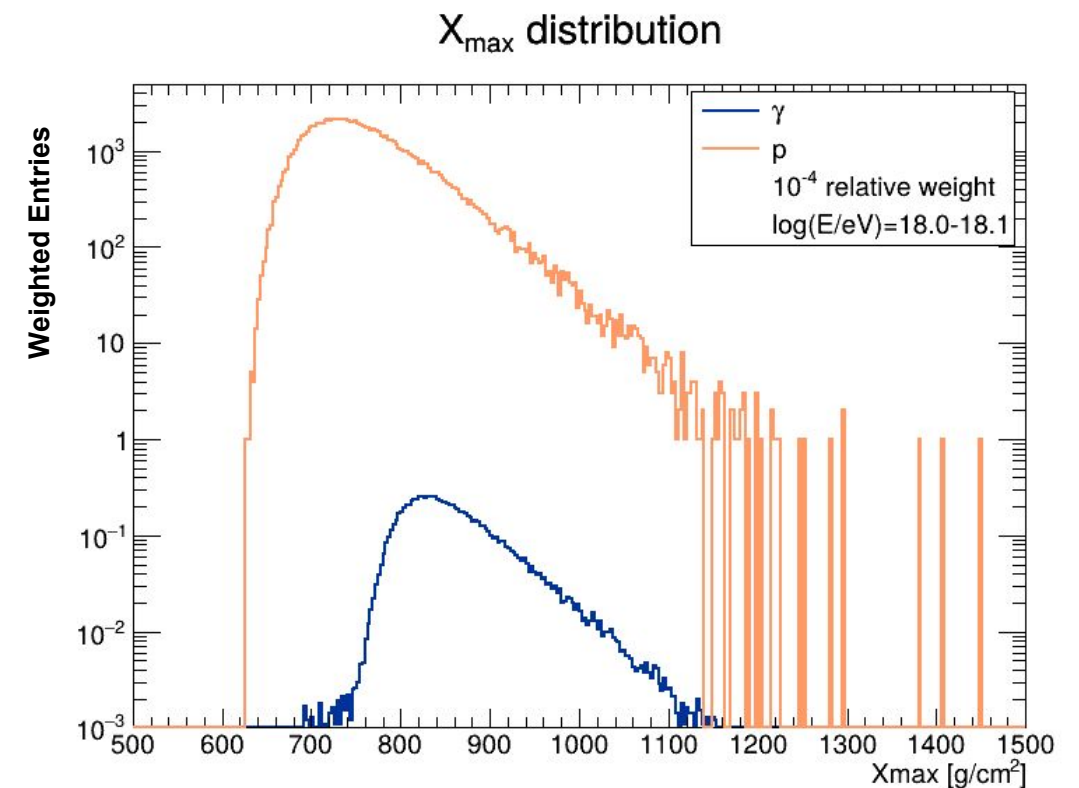
Cosmic Rays



A NEEDLE IN AN HAYSTACK



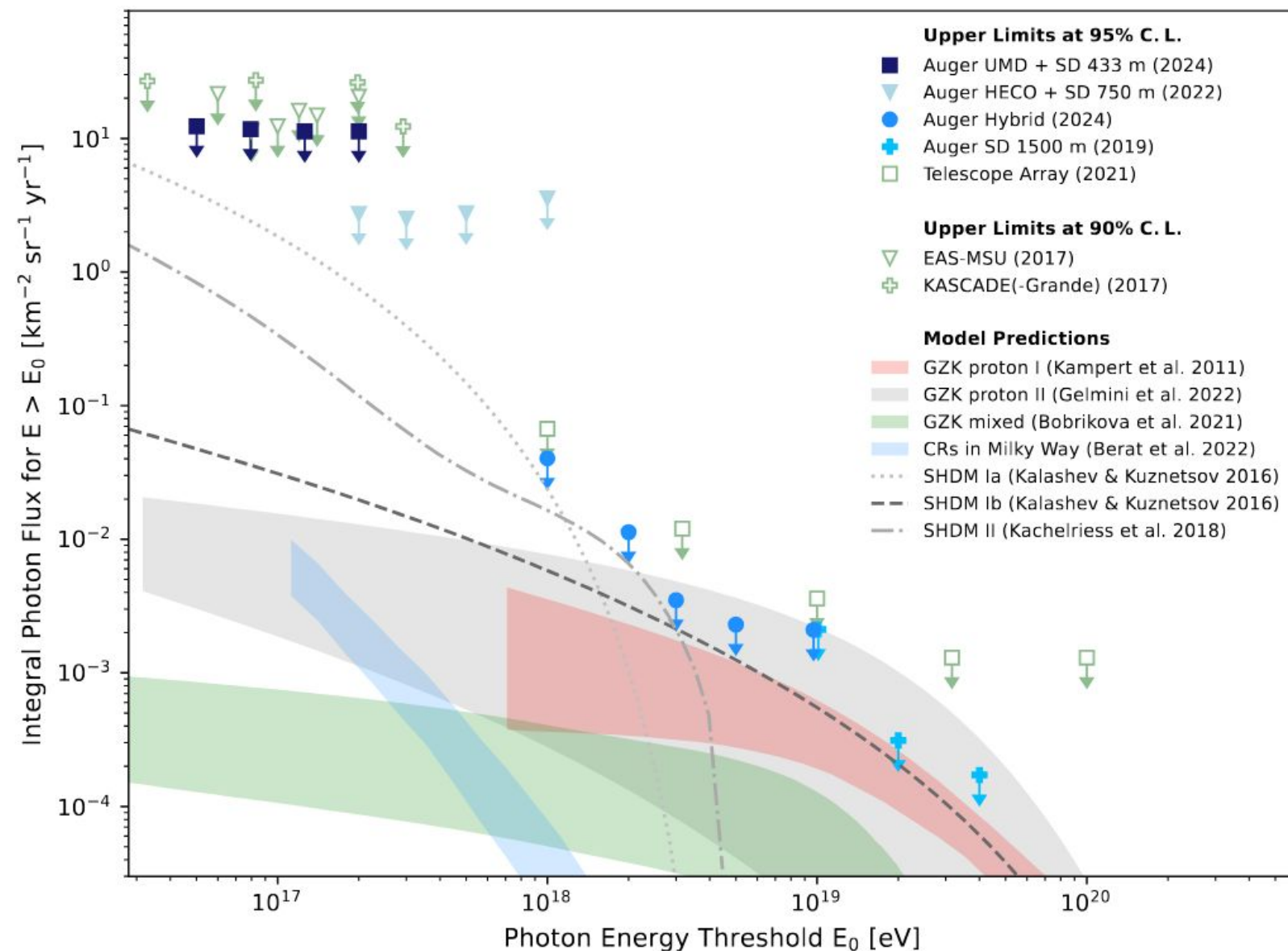
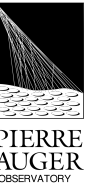
The discrimination is powerful but the expected number of photon events is very low



Slide from P. Savina

Cosmic Rays

UPPER LIMITS ON THE DIFFUSE UHE-PHOTON FLUX



No primary UHE-photon unambiguously identified so far

Most stringent limits on the diffuse flux of photons over a wide energy range come from Auger

Predictions of some theoretical models are within reach

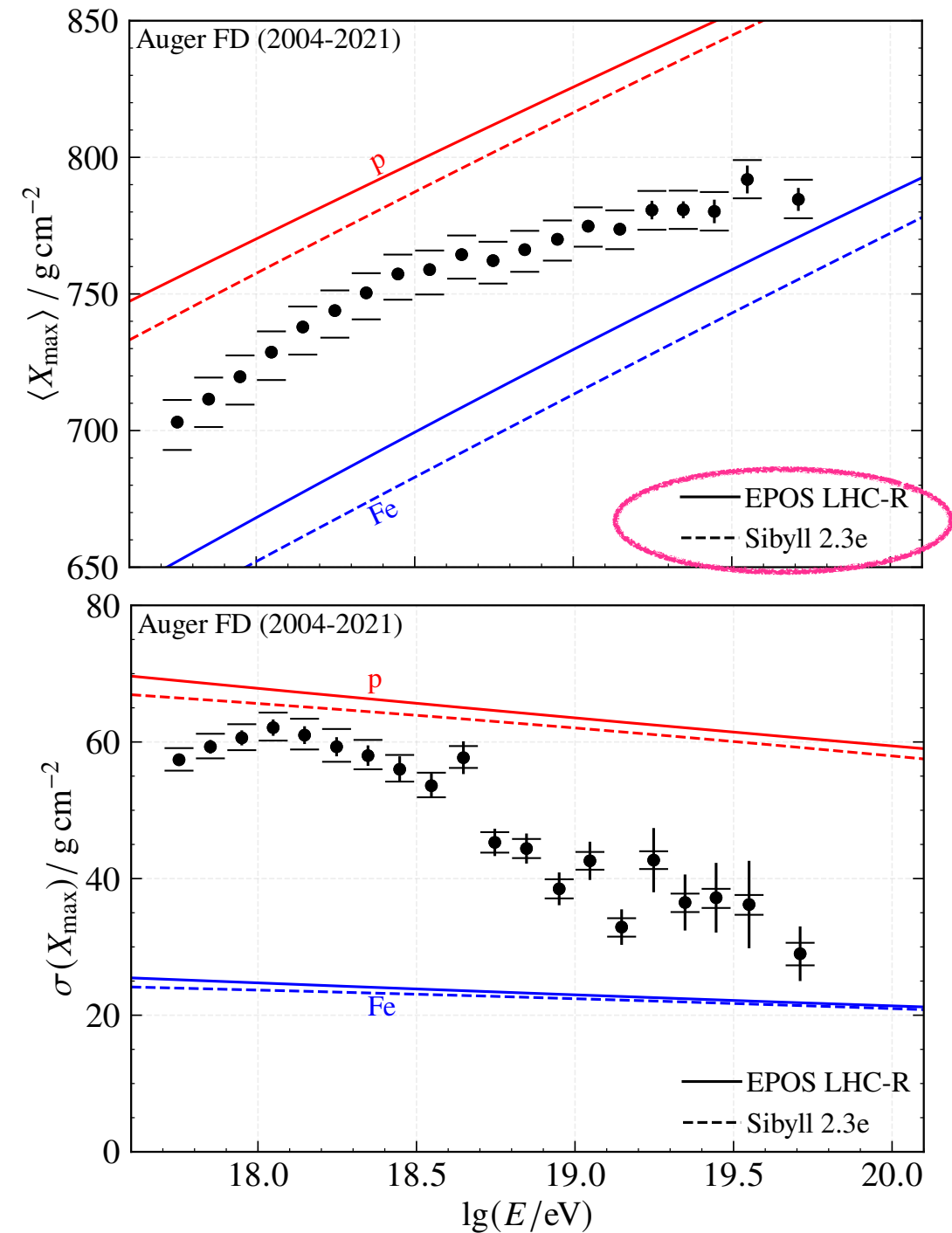
Limits can constrain SHDM models [Phys. Rev. D (2024) 109, L081101] and Lorentz Invariance Violation [JCAP 01 (2022) 023]

Mass composition using $X_{\max}$ from FD

Measurement from the
Longitudinal profile of the Fluorescence Detector
with about 15% Duty Cycle
compared to EPOS.LHC-R and Sibyll 2.3e

- $\langle X_{\max} \rangle$ gets lighter up to $\sim 2 \times 10^{18}$ eV and heavier above
- $\sigma(X_{\max})$ shows a trend towards heavier (and less mixed) composition above $\sim 2 \times 10^{18}$ eV
- $\sigma(X_{\max})$ at highest energies
 - excludes large fraction of protons (DNN and FD) in agreement with IceCube *IceCube PRL 135 (2025)*
 - excludes the GZK as the dominant cause of spectral cutoff

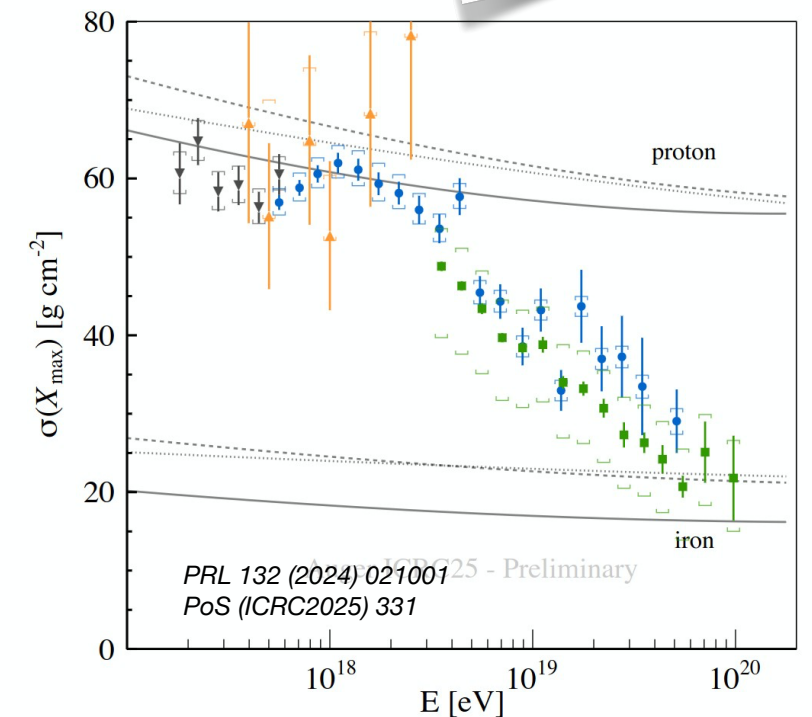
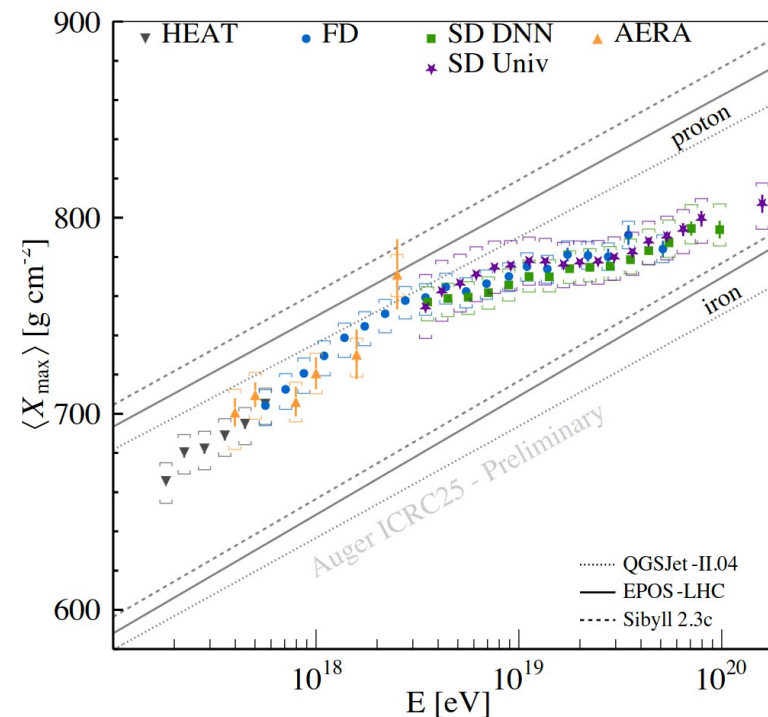
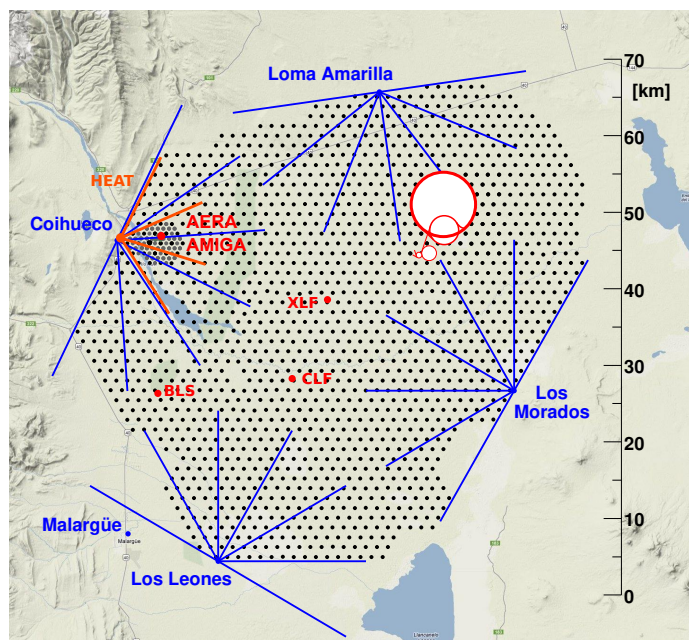
arXiv:2605.12598
paper submitted to PRD



Slide from Markus Roth

Radio measurement of $X_{\max}$ with AERA

See presentation
by Julian Rautenberg



$\langle X_{\max} \rangle$ and $\sigma(X_{\max})$ measured in four different ways

- Longitudinal profile (FD, ~15% Duty Cycle)
- Temporal and lateral distributions (SD, ~100% DC)
 - DNN
 - Universality
- Radio footprint (RD, ~100% DC)

PoS(ICRC2025)331 E. Mayotte
PoS(ICRC2025)284 S. Hahn

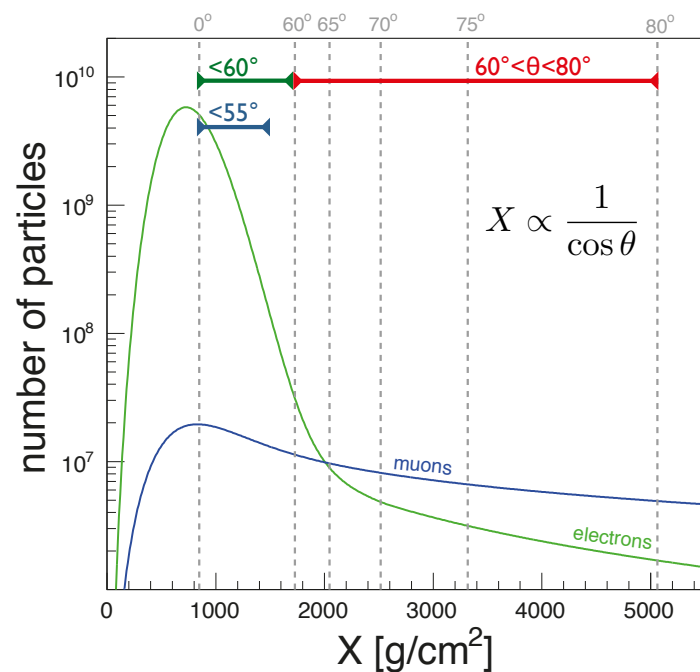
- 594 events after selection cuts $10^{17.5} \text{ eV} < E < 10^{18.8} \text{ eV}$
- Resolution of about 15 g/cm² can be reached (energy dependent)
- LHC-tuned interaction models used for interpretation (EPOS-LHC, Sybill 2.3d, QGSJet II.04)

Slide from Markus Roth

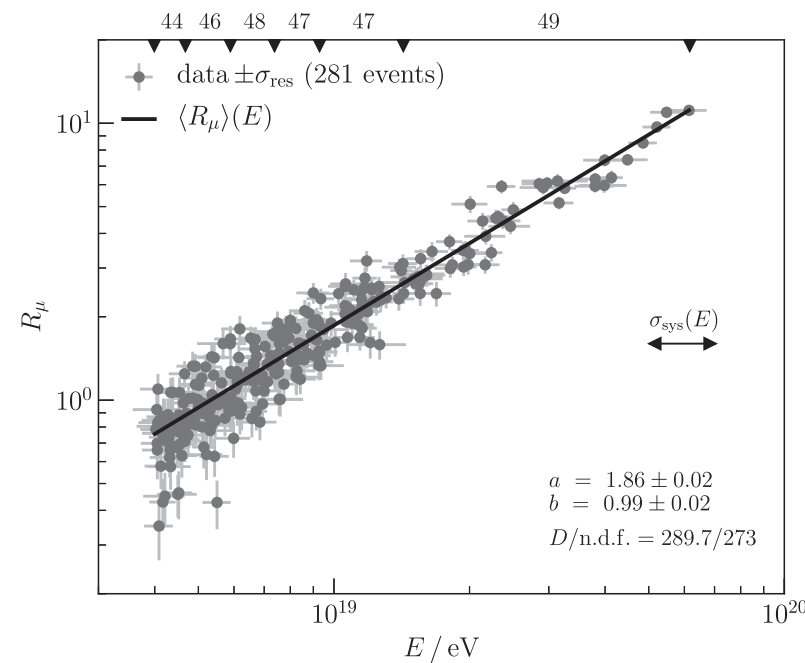
Mean muon number in inclined air showers

hybrid data: WCD + FD

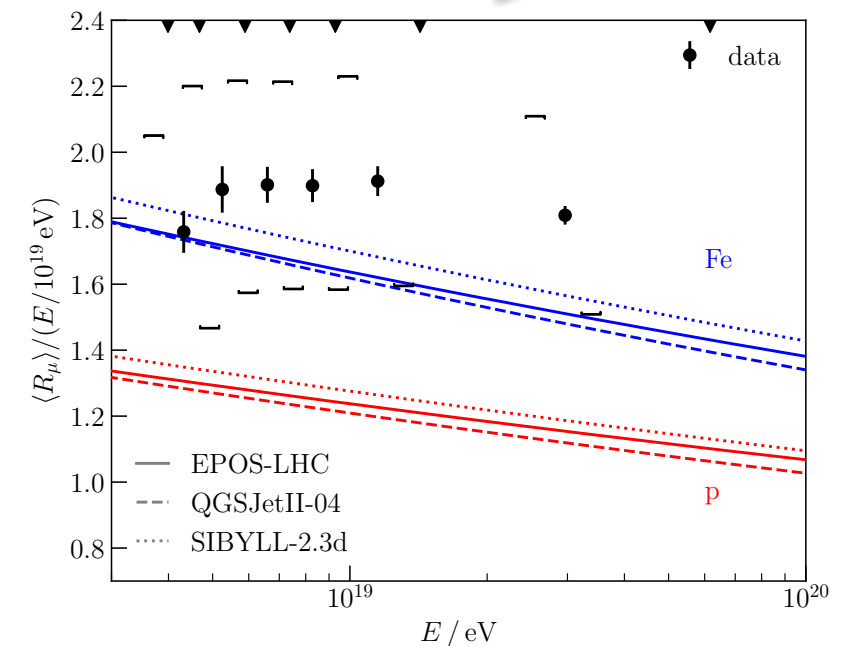
See presentation
by Kevin Cheminant



For inclined showers ($\approx 60^\circ$),
the **electromagnetic component is absorbed** by
the atmosphere



R_μ : **Integrated number** of
muons at the ground,
normalized by reference value
for proton $R_\mu^{\text{MC}}(E=10^{19} \text{ eV})$
given by simulations



Mean relative **muon number**
not consistent with the
predictions of high-energy
hadronic interaction models

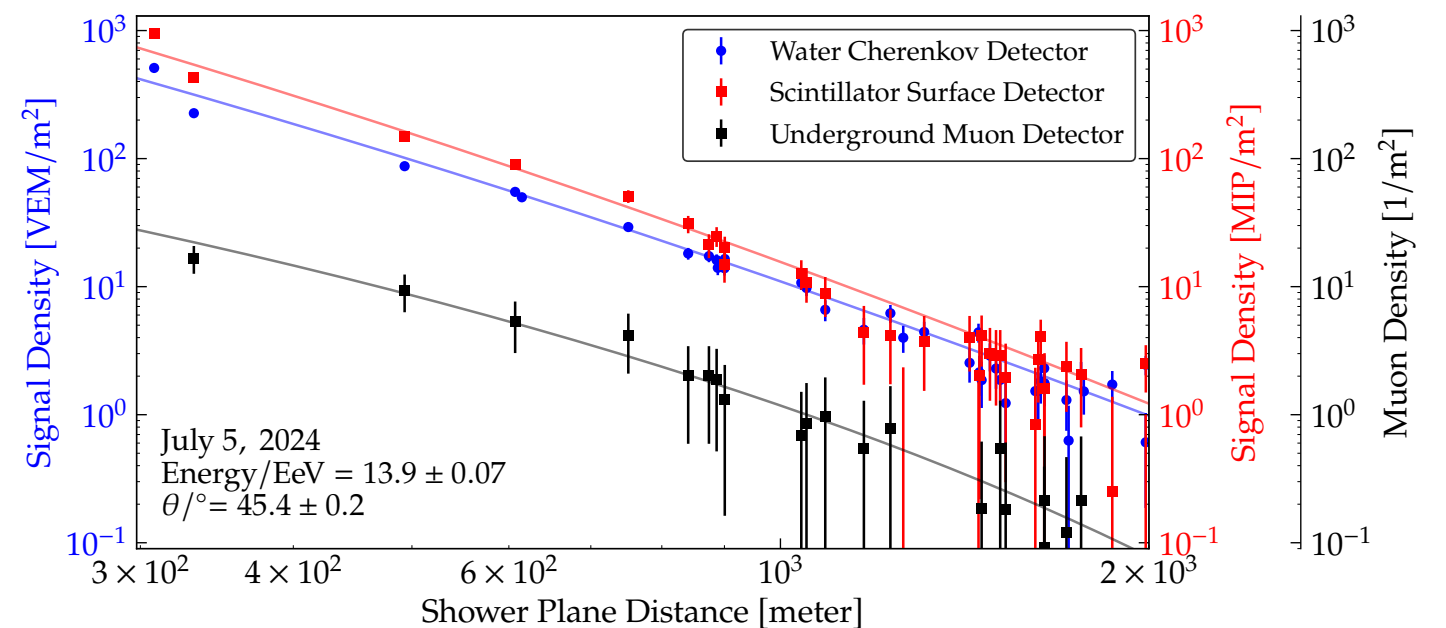
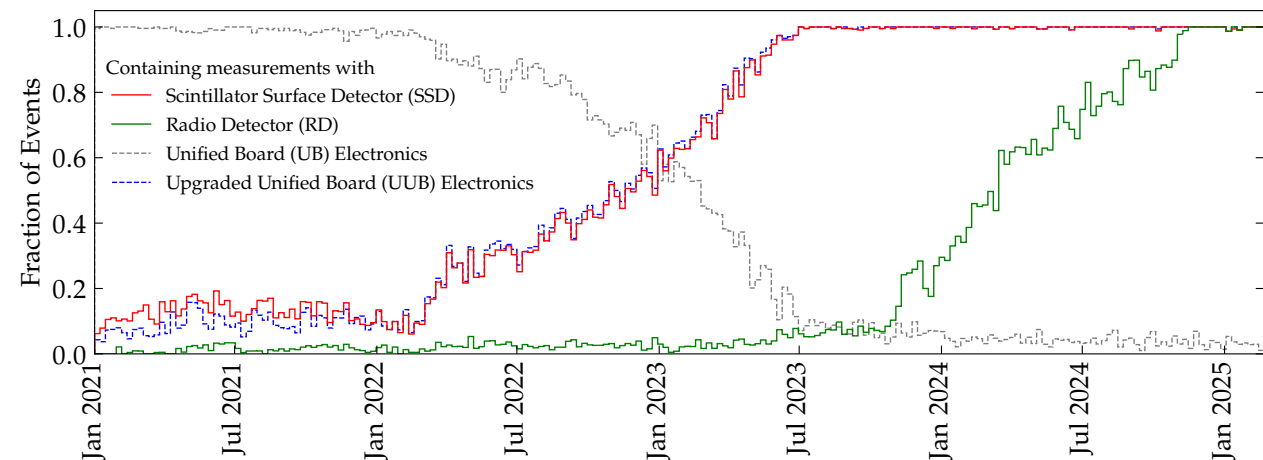
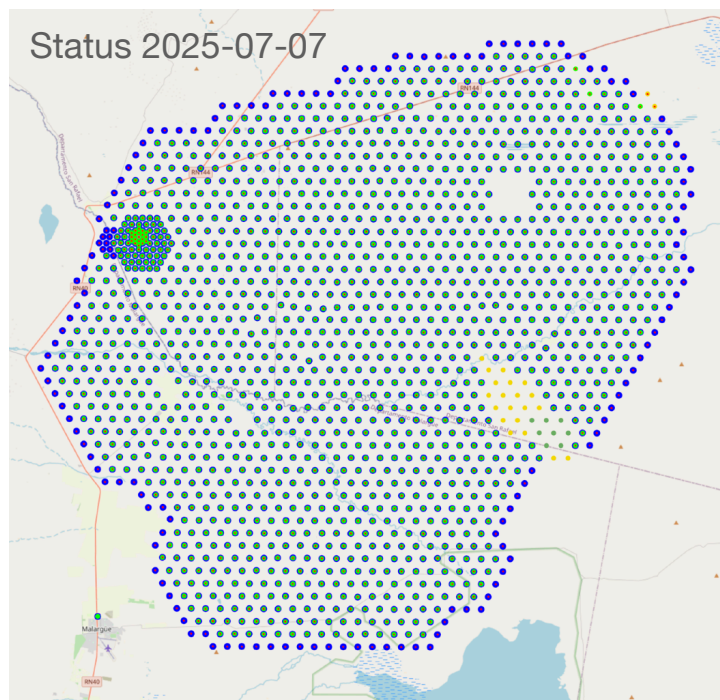
Muon puzzle

PRD 2015
PRL 2021

Successful multihybrid data acquisition by AugerPrime

AugerPrime (7/2025)

- 1479 scintillators installed
- 1529 with new electronics (incl. rim)
- 1584 radio antennas

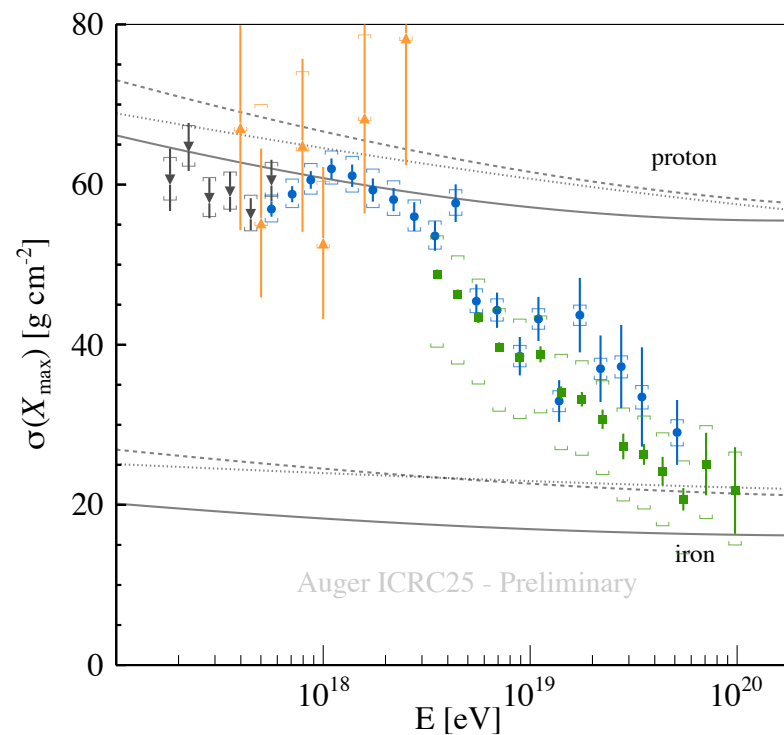
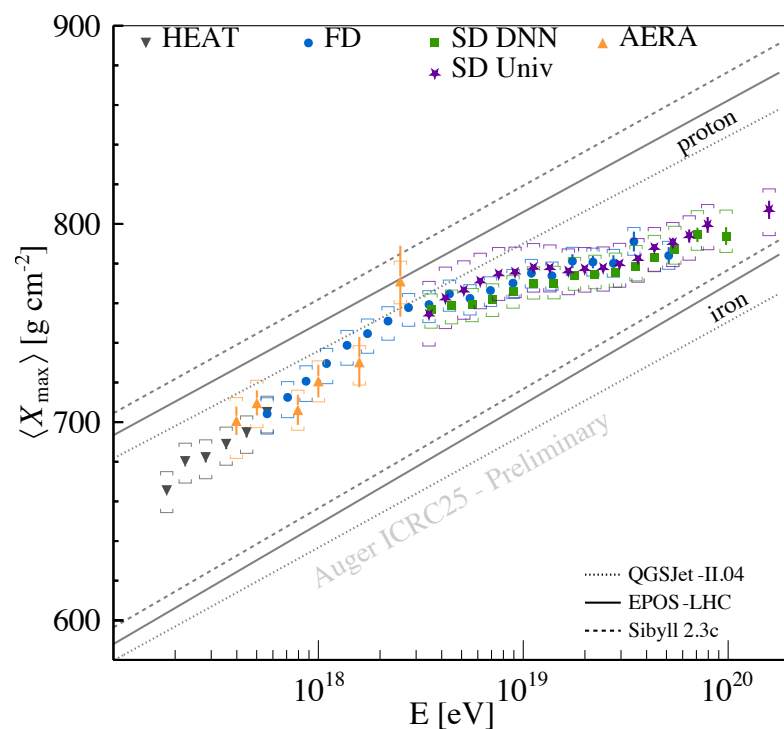


PoS(ICRC2025)385 D. Schmidt

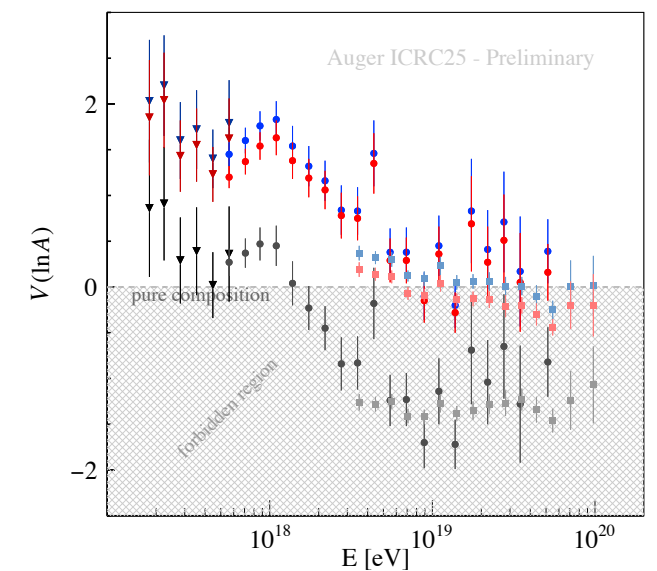
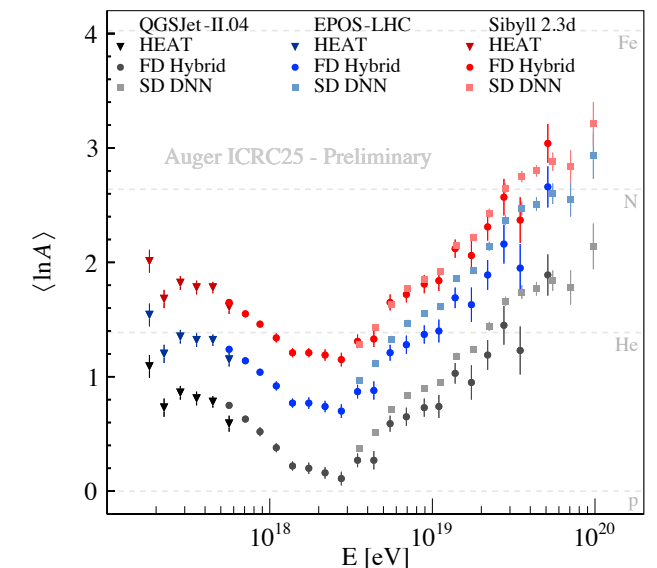
Slide from Markus Roth

Cosmic Rays

A consistent composition picture across observables



- $\langle X_{\max} \rangle$ and $\sigma(X_{\max})$ measured with independent techniques are consistent across the entire energy range.
- The inferred composition becomes **progressively heavier above the ankle**.
- The **absolute mass scale** ($\langle \ln A \rangle$ and $V(\ln A)$) depends on the hadronic interaction model, while the **overall evolution remains robust**.



Independent observables support the same qualitative evolution; hadronic models shift the absolute mass scale.

Telescope Array (TA) Detector

Surface Detectors (SD)

507 SDs
3m² plastic scintillator
1.2 km spacing
~700 km²



Fluorescence Detectors (FD)

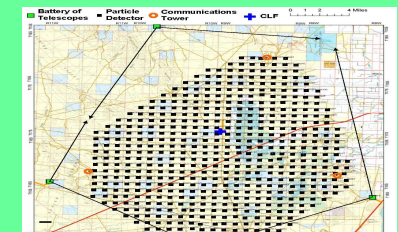
3 FD stations
Totally 38 telescopes

Long Ridge (LR)



12 telescopes

Middle Drum (MD)



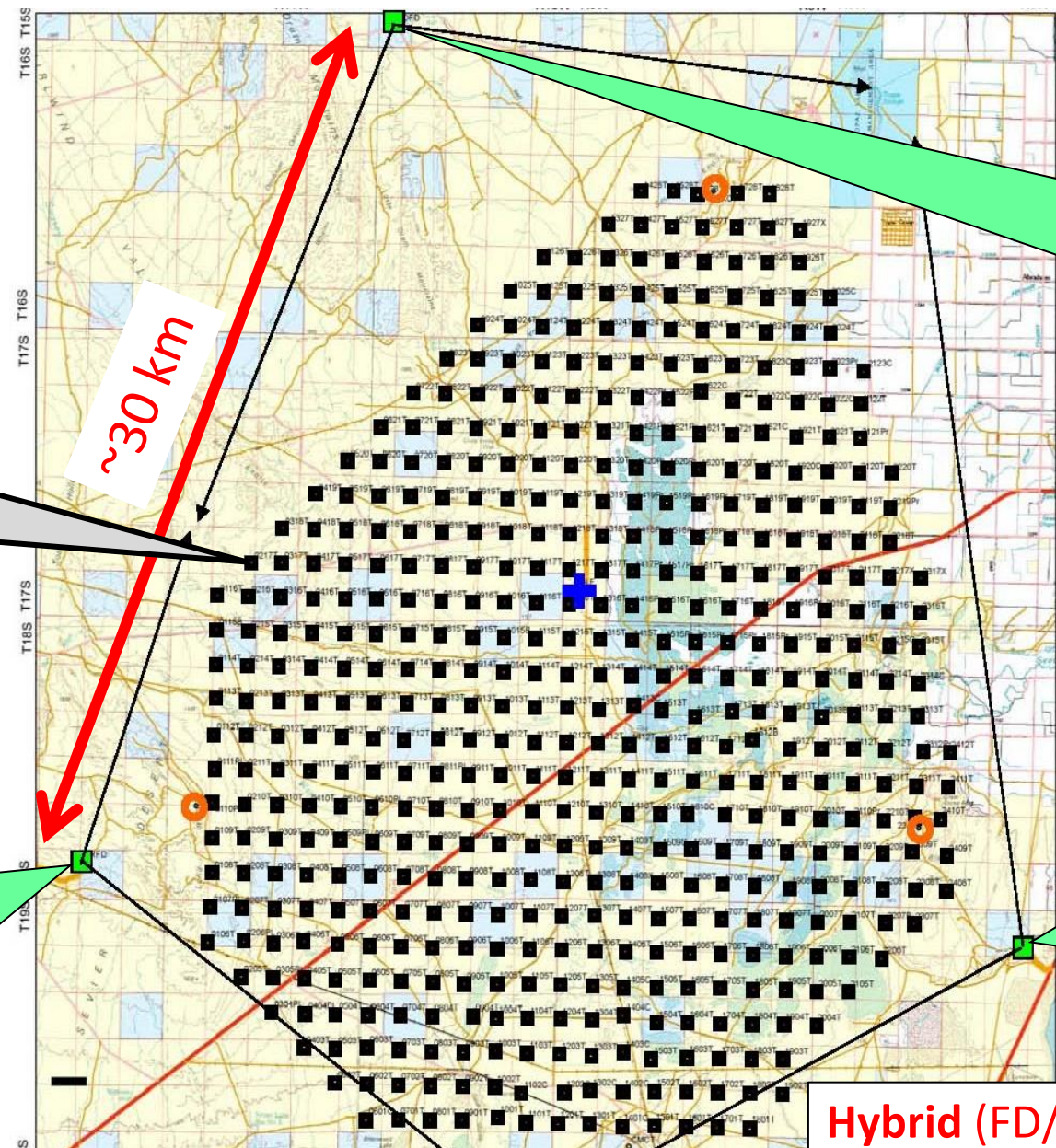
14 telescopes

Black Rock Mesa (BR)



12 telescopes

Hybrid (FD/SD) observation started in 2008

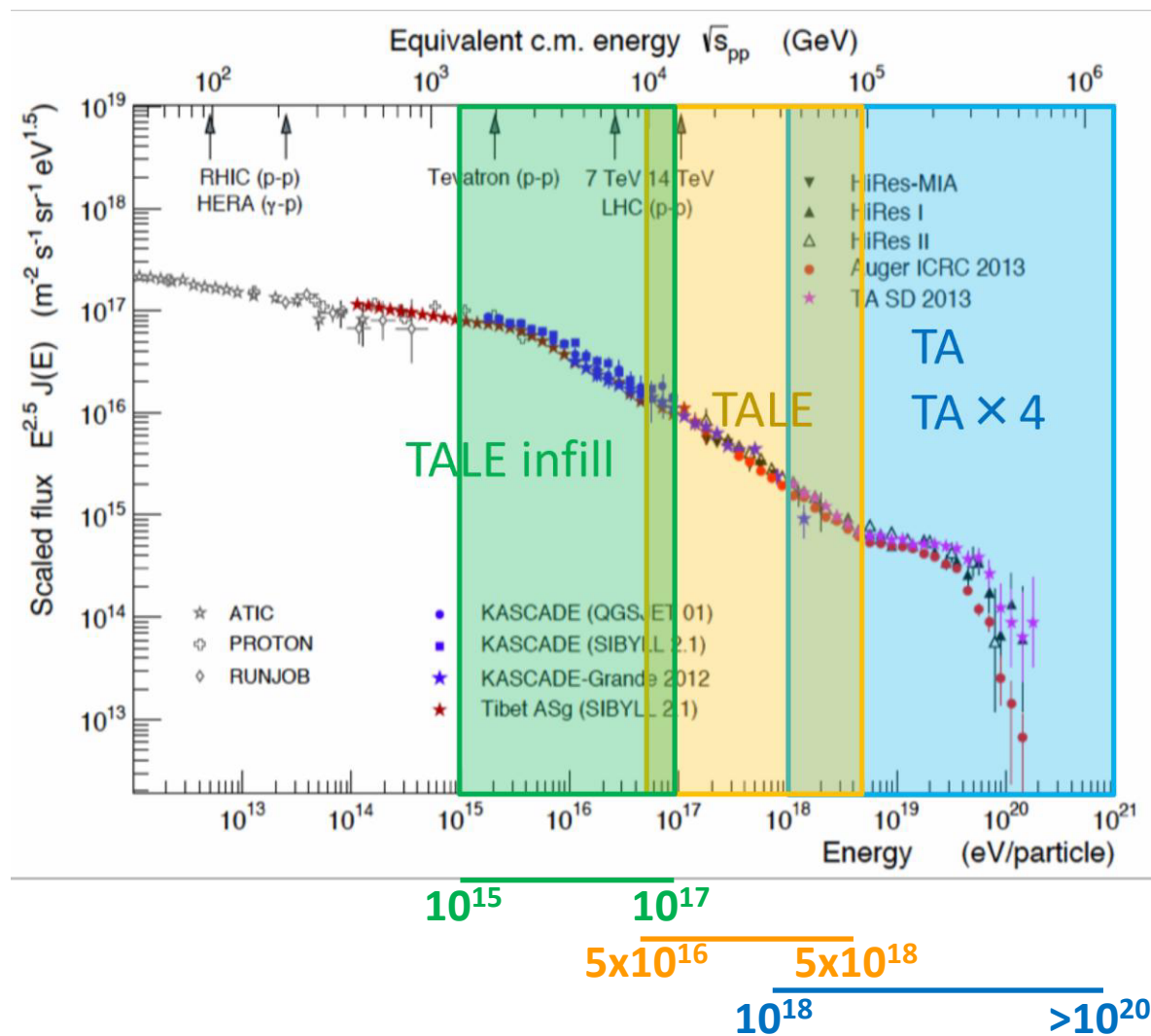


Utah, USA
39.3°N, 112.9°W
~1400 m a.s.l.

Slide from H. Sagawa

Cosmic Rays

Energy Range Measured by the TA detector systems



<1 events/(100km²yr) (E > 10²⁰eV)

From ~10¹⁵ eV to beyond 10²⁰ eV
More than five orders of magnitude

2026/7/06

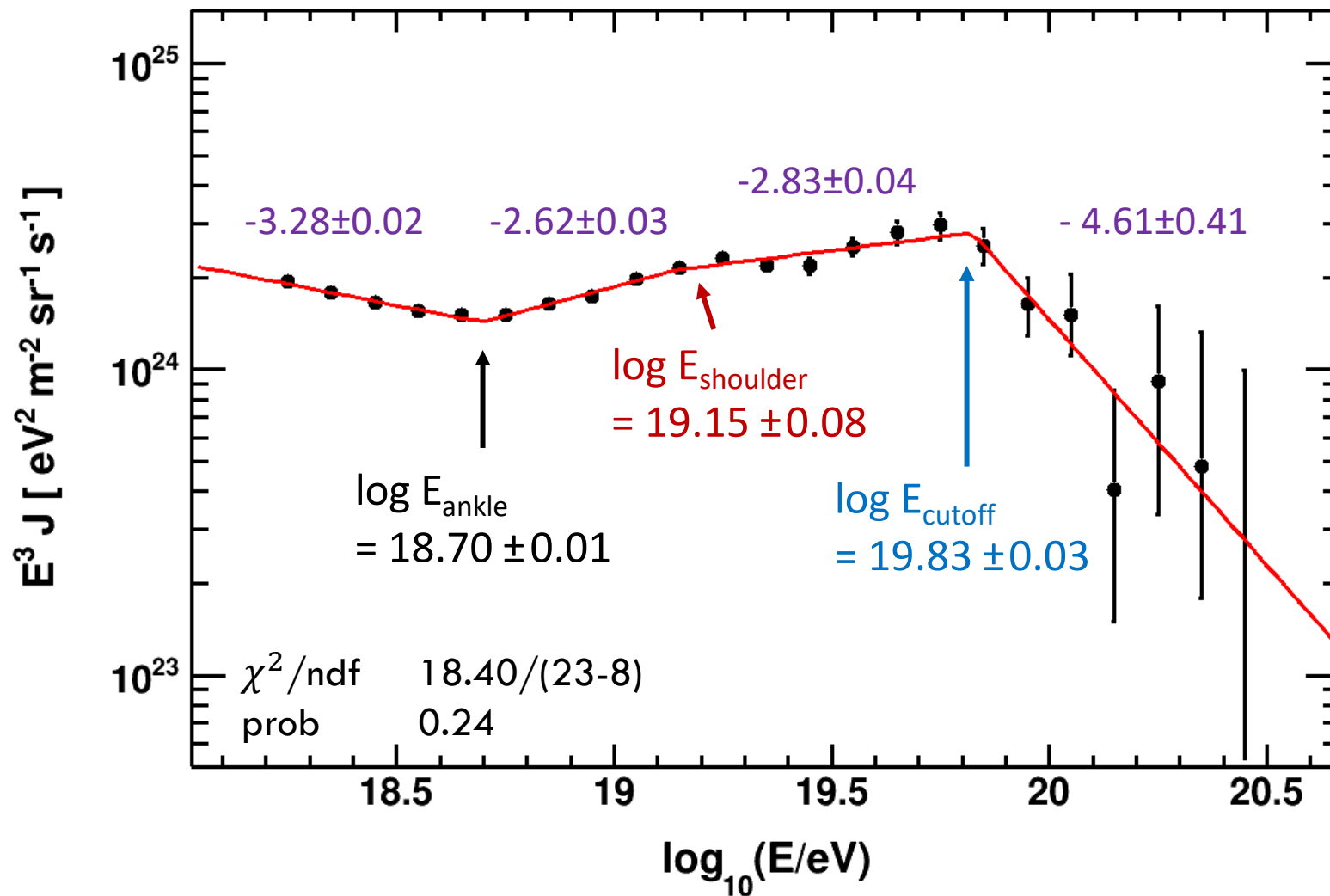
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Slide from H. Sagawa

Spectral Features from 16 years of TA SD Data

Data collection: 2008-05-11 through 2024-05-10



- **Cutoff feature at $10^{19.83}$ eV**
 $N_{\text{exp}}: 173.7$
 $N_{\text{obs}}: 97$
 Chance probability: 1.6×10^{-10} ($\sim 6.3\sigma$)
- **Shoulder feature at $10^{19.15}$ eV**
 $N_{\text{exp}}: 2156.4$
 $N_{\text{obs}}: 1921$
 Chance probability: 1.3×10^{-7} ($\sim 5.2\sigma$)
 - Softening observed at $10^{19.15 \pm 0.08}$ eV
 - Significance: a 5.2σ
 - Auger observed it at $10^{19.15 \pm 0.03}$ eV (with +9% energy rescaling)
 - TA agrees with Auger

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Slide from H. Sagawa

Cosmic Rays

Comparison with TA and Auger Spectra



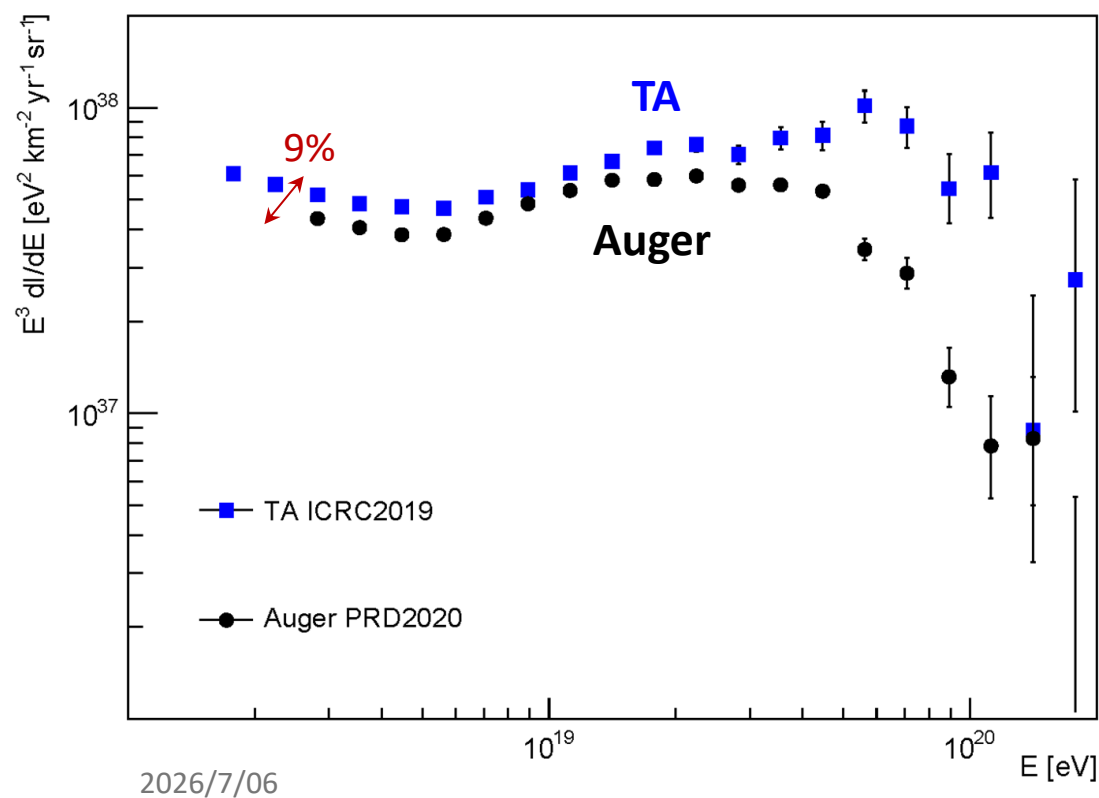
Energy systematic uncertainty:

TA: 21%

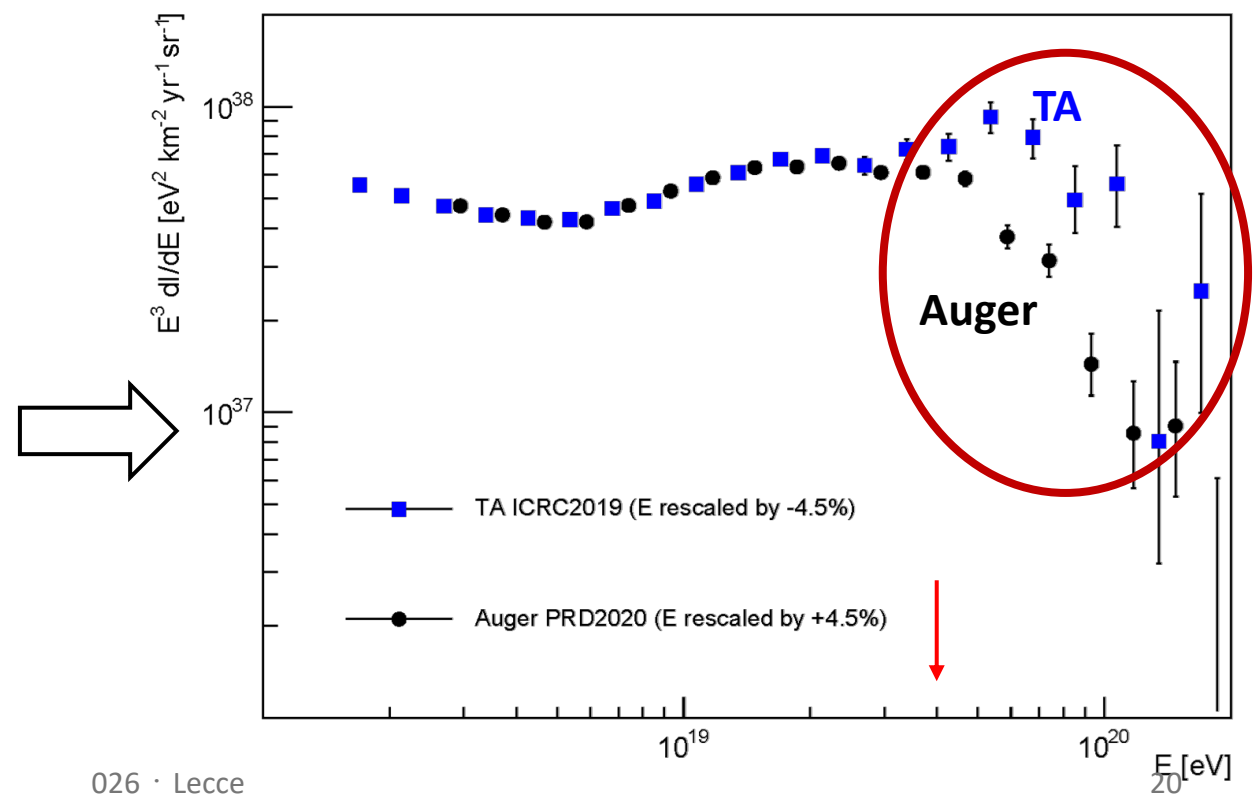
Auger: 14%

Y. Tsunesada+(Auger+TA Spectrum WG)
PoS(ICRC2021)337

TA vs. Auger (original scales)



TA vs. Auger ($\pm 4.5\%$ rescaled)

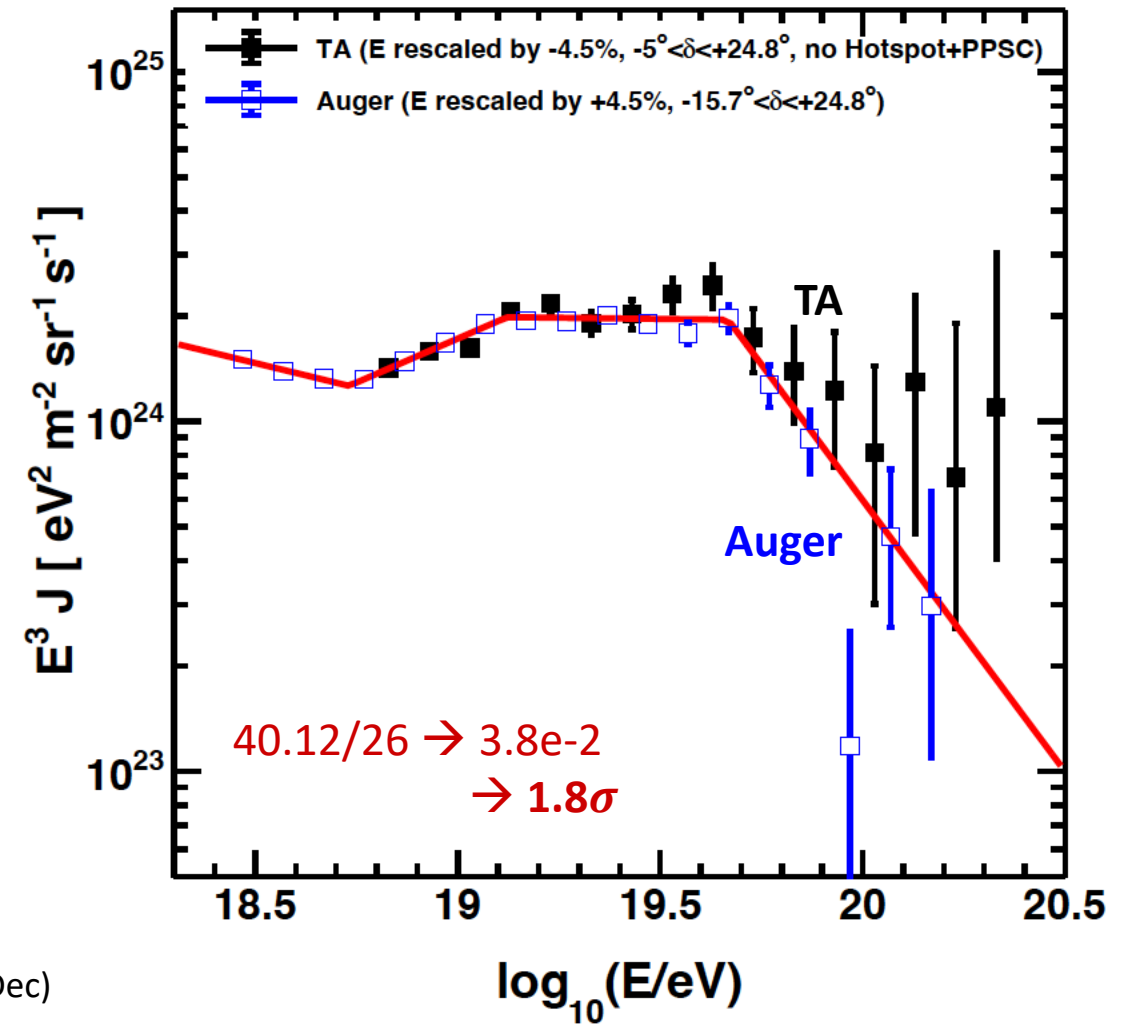
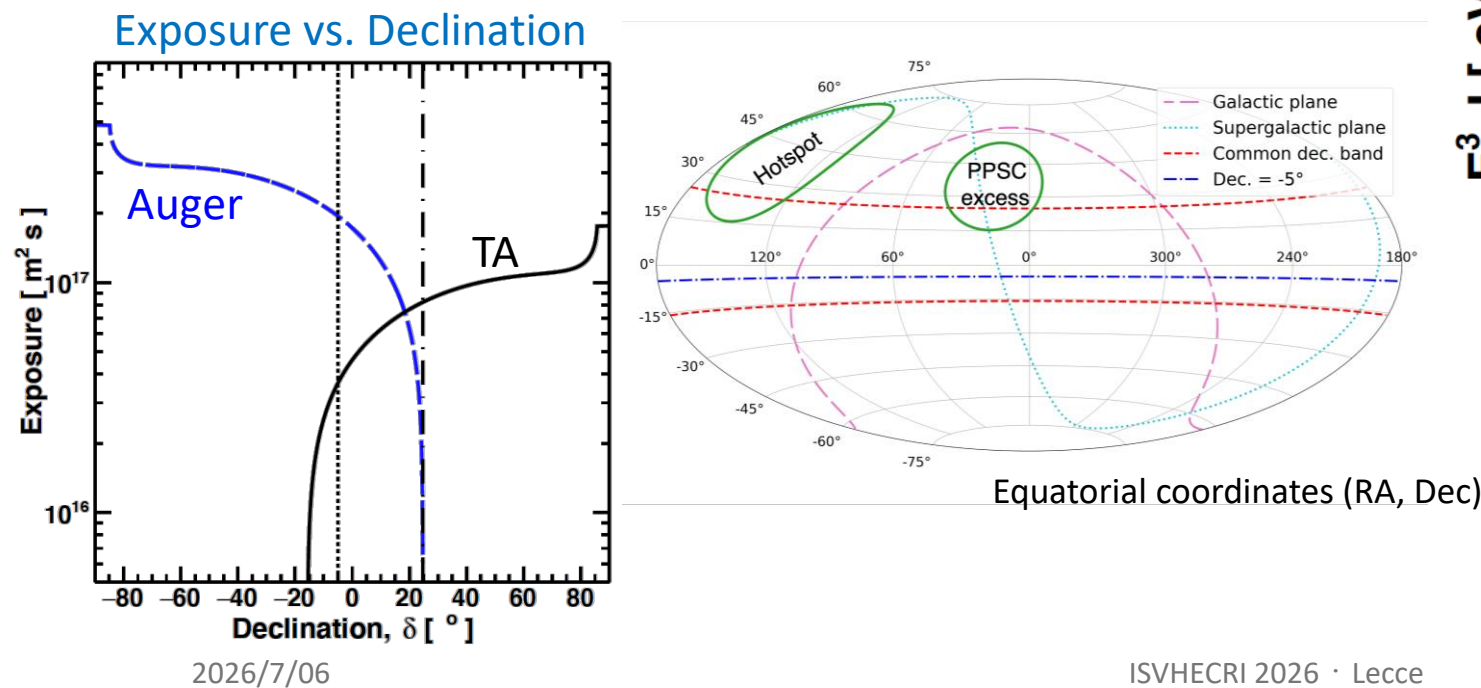


Slide from H. Sagawa

Cosmic Rays

Validate the Methodology Using the Common Sky

- **Common sky selection**
 - Auger: $-15.7^\circ < \delta < 24.8^\circ$
 - TA: $-5^\circ < \delta < 24.8^\circ$
 - TA exposure is very small and rapidly drops off
- **Mask TA excess regions from TA**
 - Exclude all events within *a priori* established TA excess regions, where Auger exposure rapidly drops off

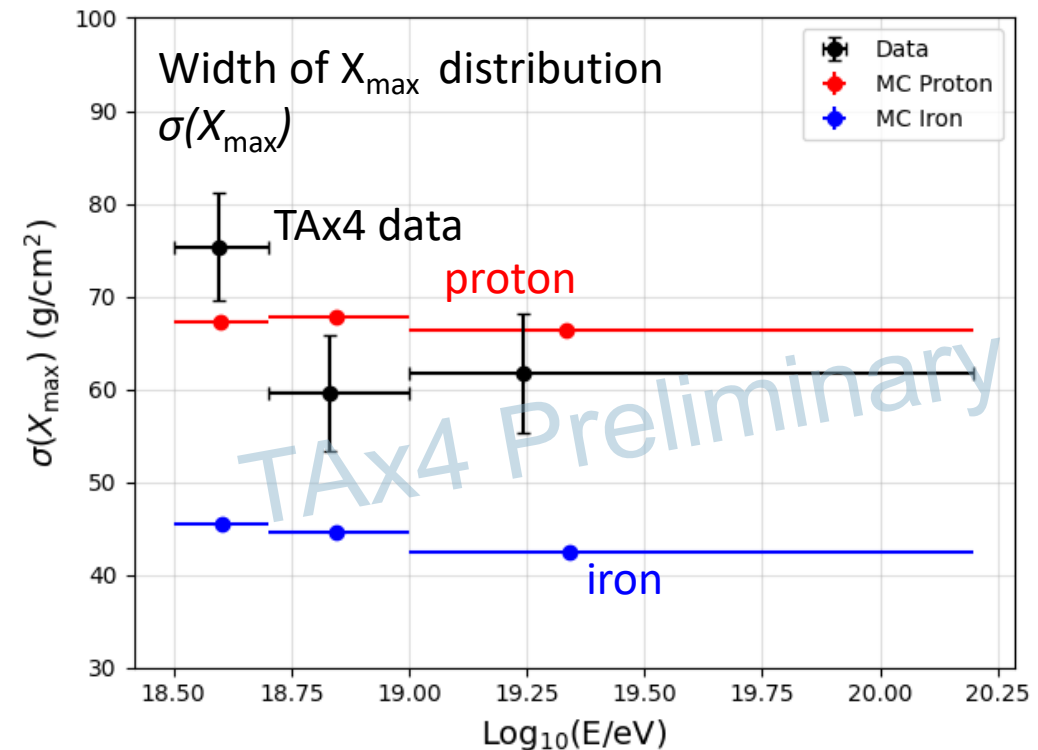
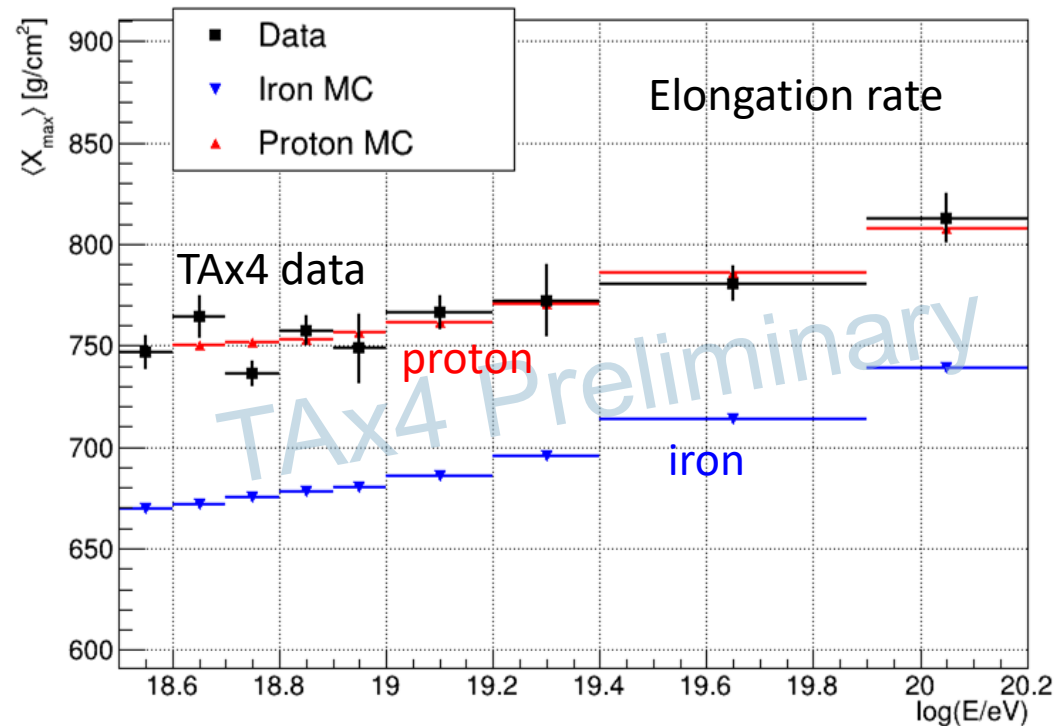


→ TA and Auger spectra agree (1.8σ)

Slide from H. Sagawa

TAx4 Hybrid $X_{\max}$

Z. Gerber, PoS(ICRC2025)269



- TAx4 hybrid data (4 years)
→ compared with MC primaries ([QGSJET-II-03](#))
- Elongation rate
→ Data $\approx$ MC **protons**
- $\sigma(X_{\max})$: the width of the $X_{\max}$ distribution
→ **less model-dependent**, but needs **large statistics**

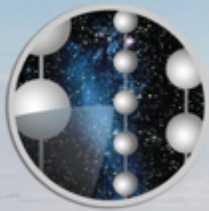
Here, TAx4 means the additional array for the current TAx4

2026/7/06

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Slide from H. Sagawa



ICECUBE

SOUTH POLE NEUTRINO OBSERVATORY

50 m

IceTop



IceCube Laboratory

Data is collected here and sent by satellite to the data warehouse at UW-Madison

1450 m



Digital Optical Module (DOM)

5,160 DOMs deployed in the ice

2450 m

IceCube detector

86 strings of DOMs, set 125 meters apart

DeepCore

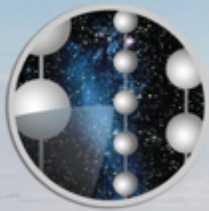
Antarctic bedrock

Amundsen-Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility

60 DOMs on each string

DOMs are 17 meters apart





ICECUBE

SOUTH POLE NEUTRINO OBSERVATORY

50 m

IceTop



IceCube Laboratory

Data is collected here and sent by satellite to the data warehouse at UW-Madison

1450 m



Digital Optical Module (DOM)

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Antarctic bedrock

Amundsen-Scott South Pole Station, Antarctica
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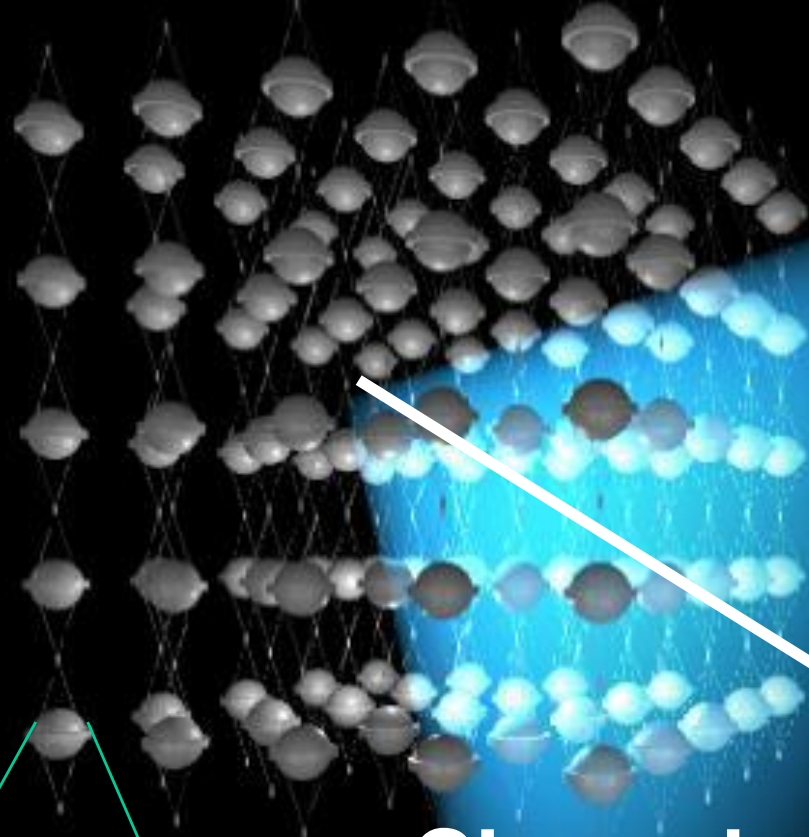
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY



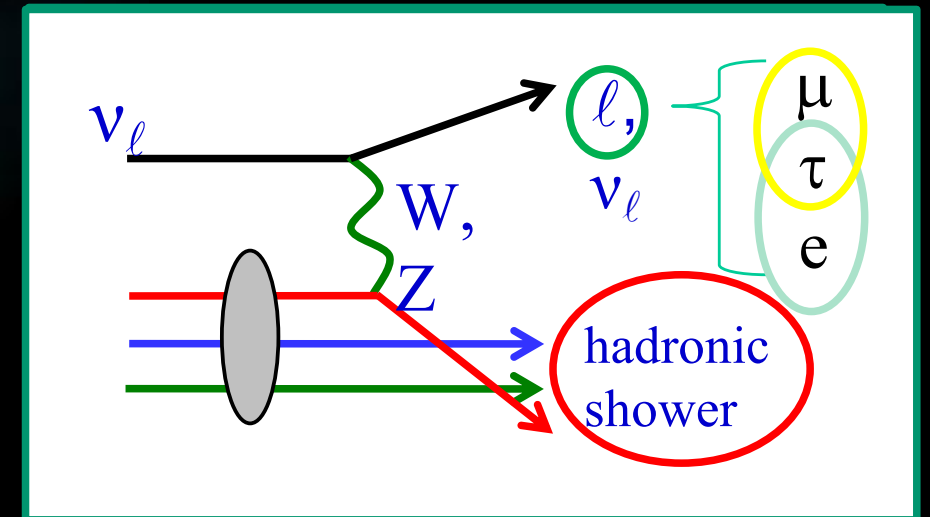
Detection Principle

Slide from
A. Ishihara

An array of photomultiplier tubes + Dark and transparent material

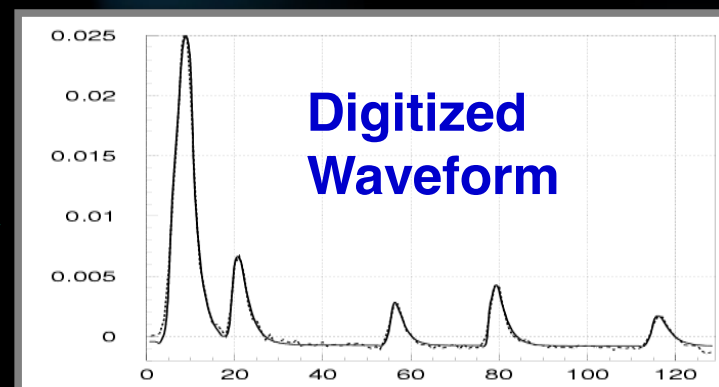
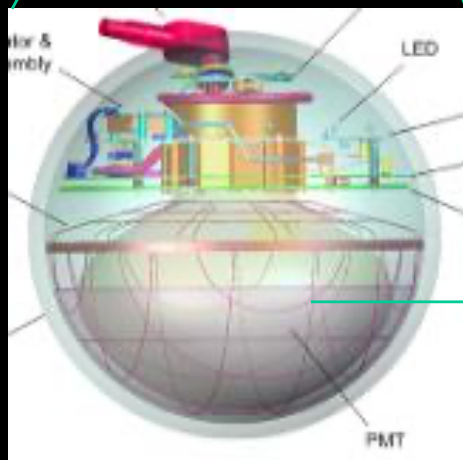


Cherenkov light



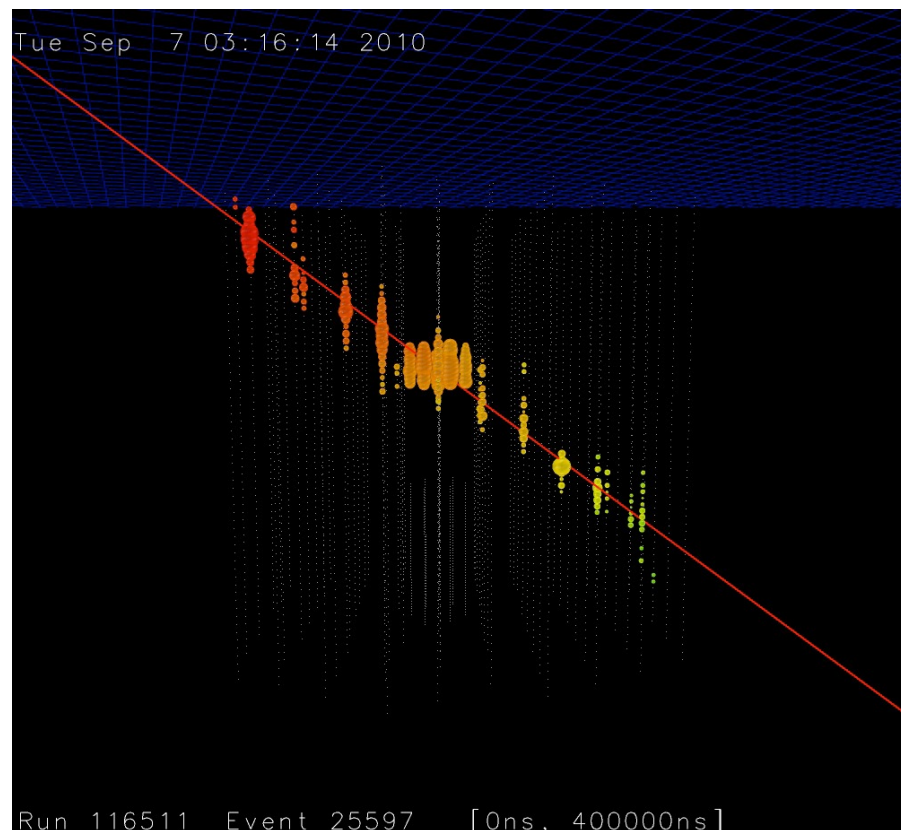
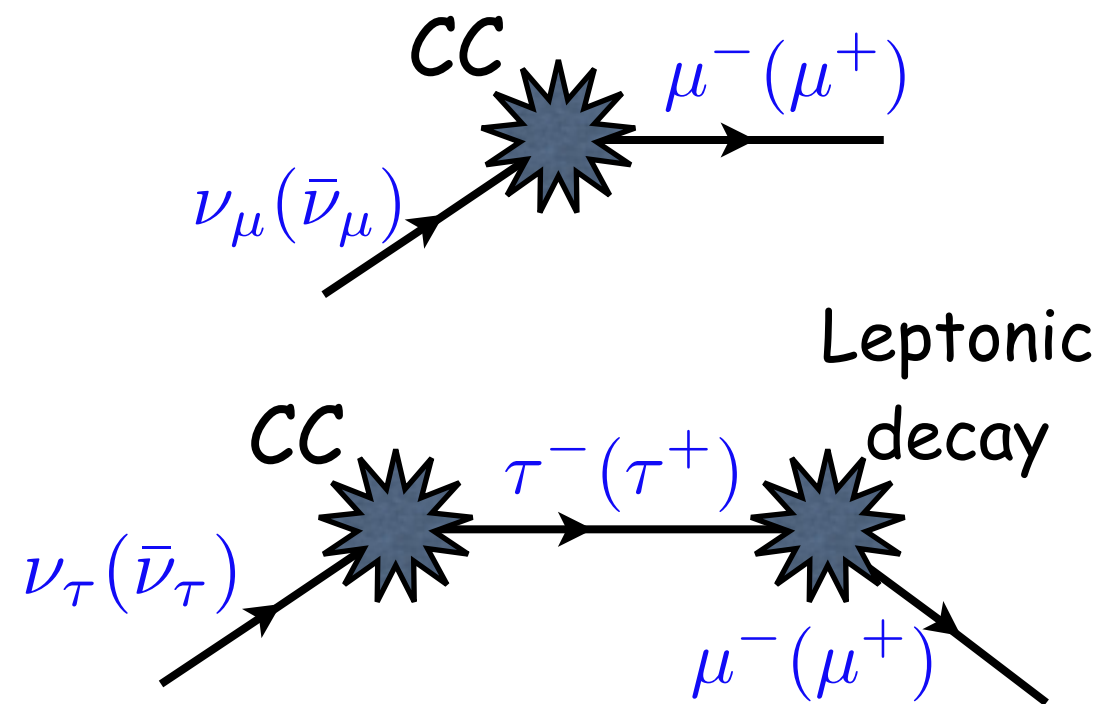
Charged
Particles

ν

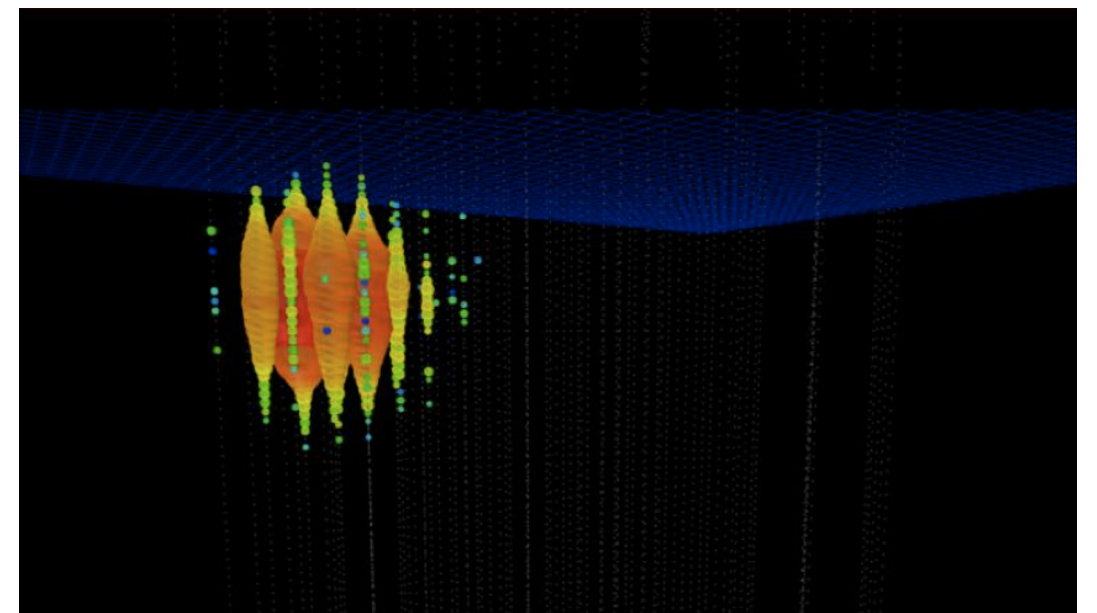
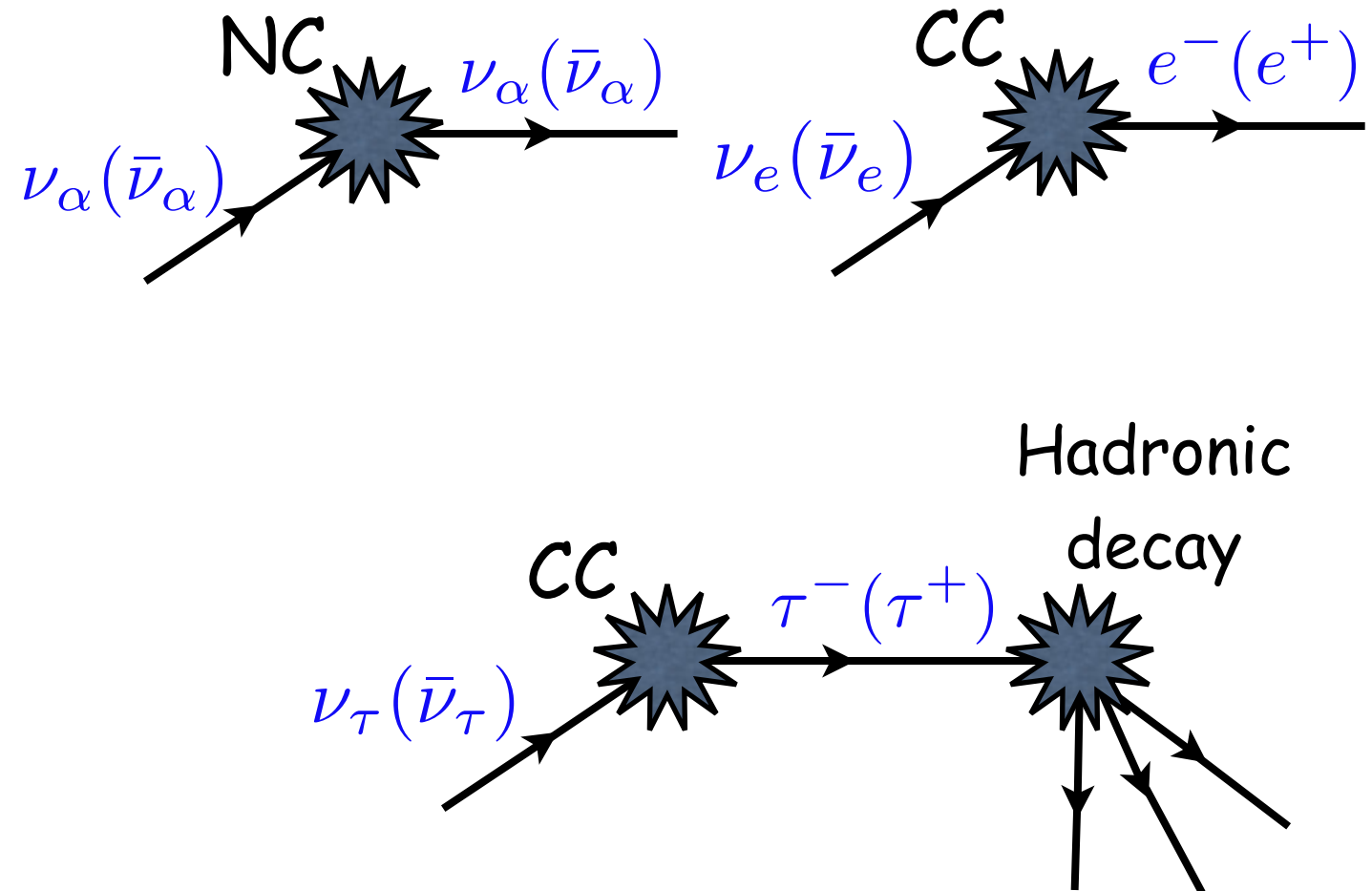


Flavoring at IceCube

muon-track events



cascade events



figures from
IceCube
website

Flavoring at IceCube

muon-track events

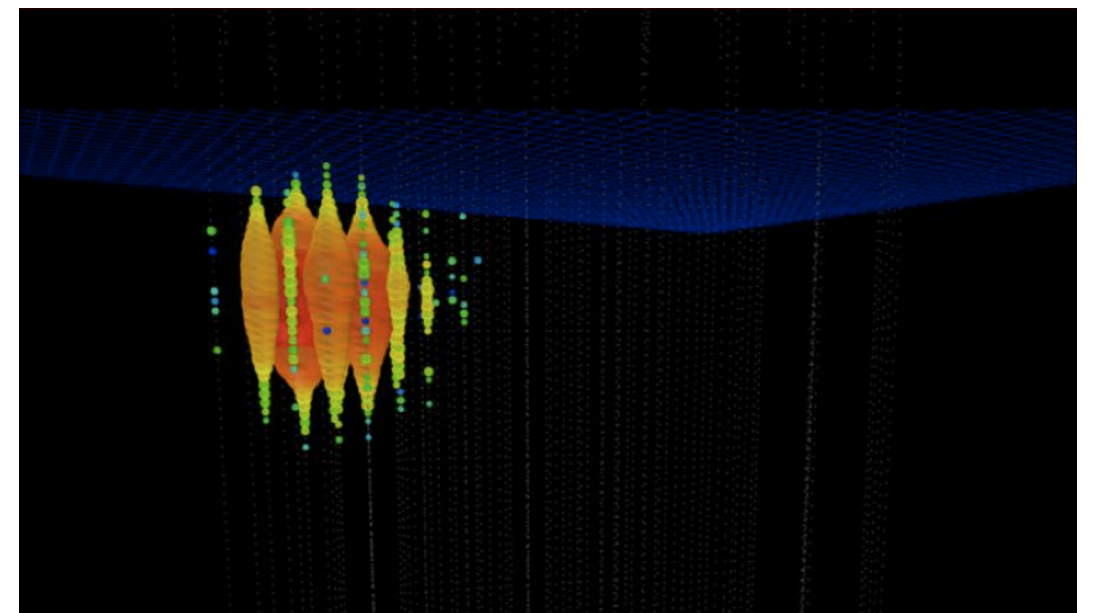
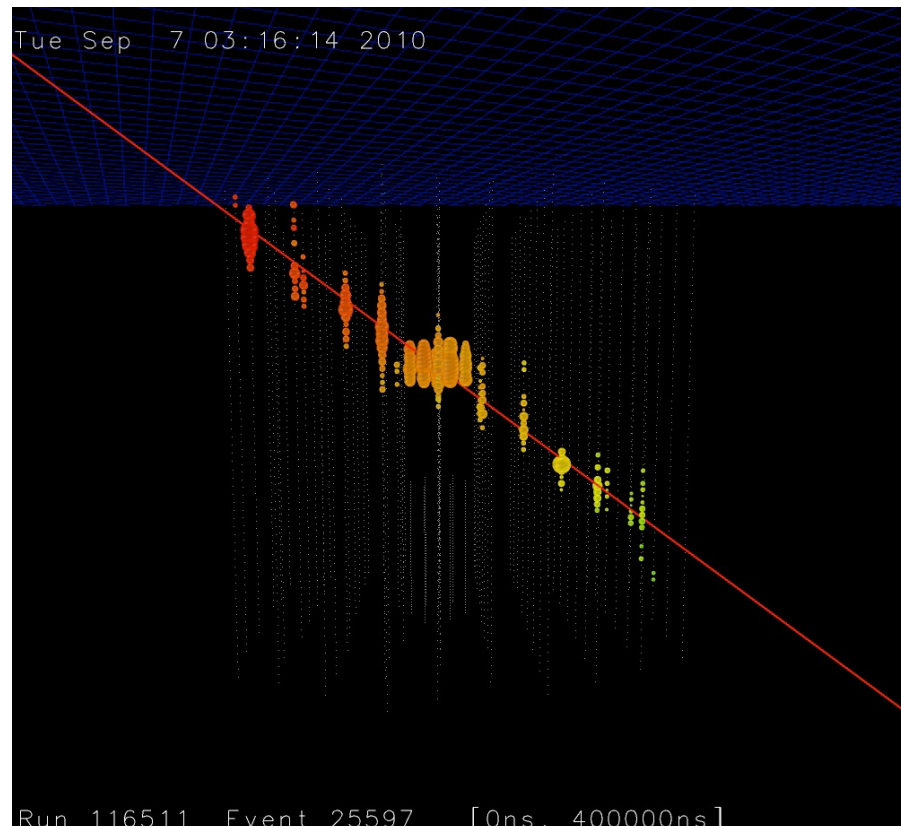
good angular
resolution ($< 1^\circ$)

moderate energy
resolution ($\sigma_E \sim E$)

cascade events

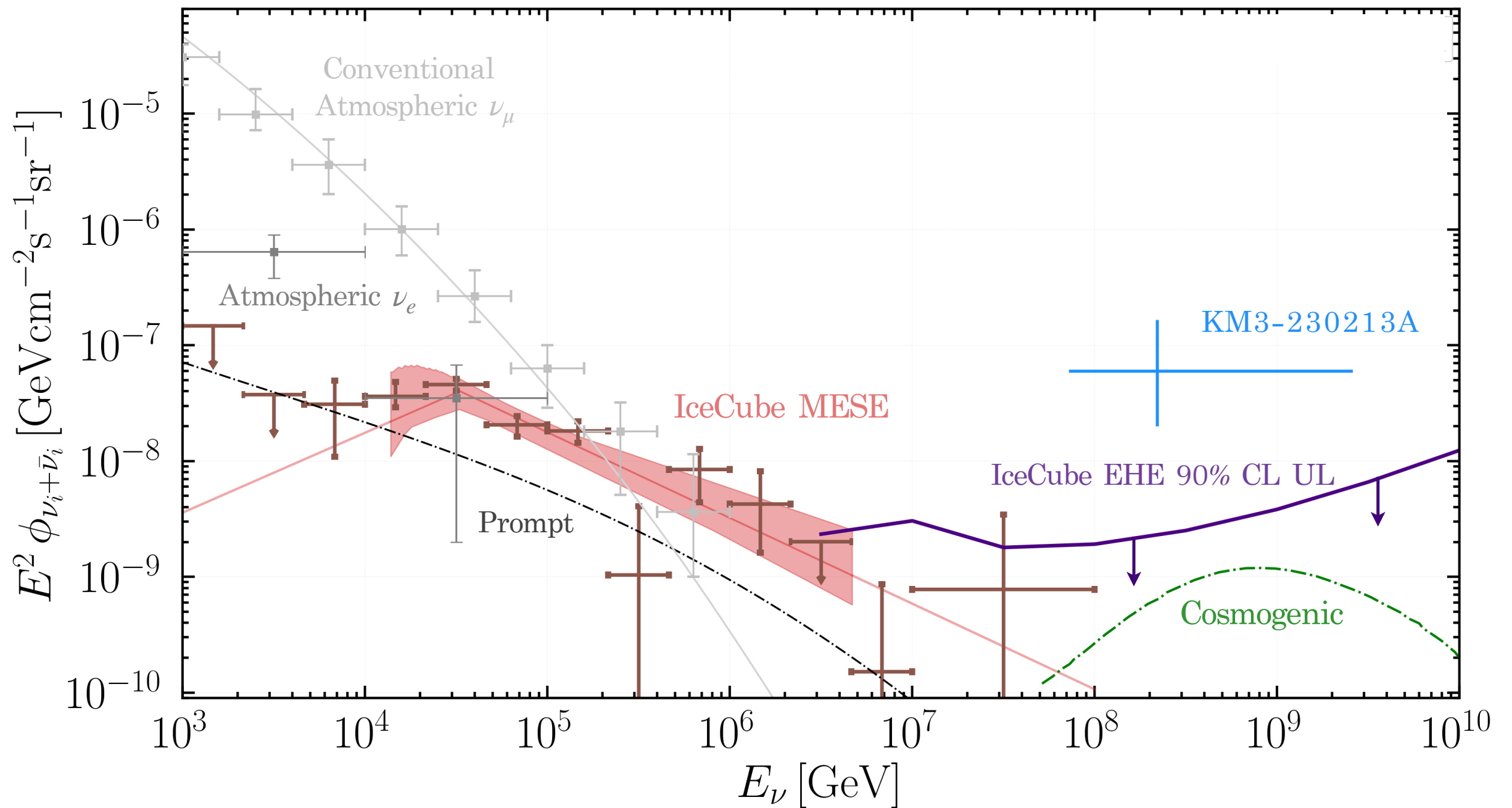
poor angular resolution
($< 10^\circ - 20^\circ$)

good energy resolution
($\sigma_E \sim 0.15 \times E$)

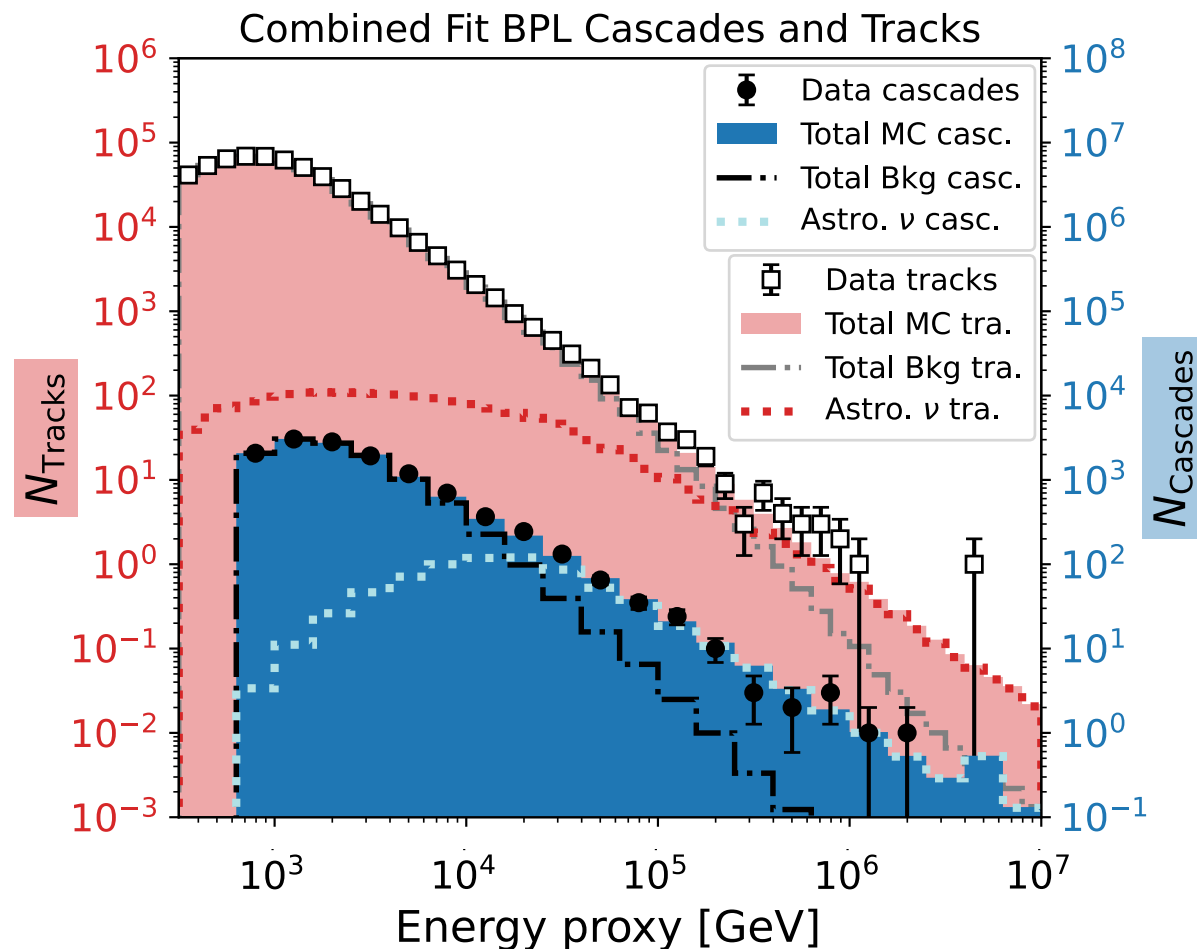


figures from
IceCube
website

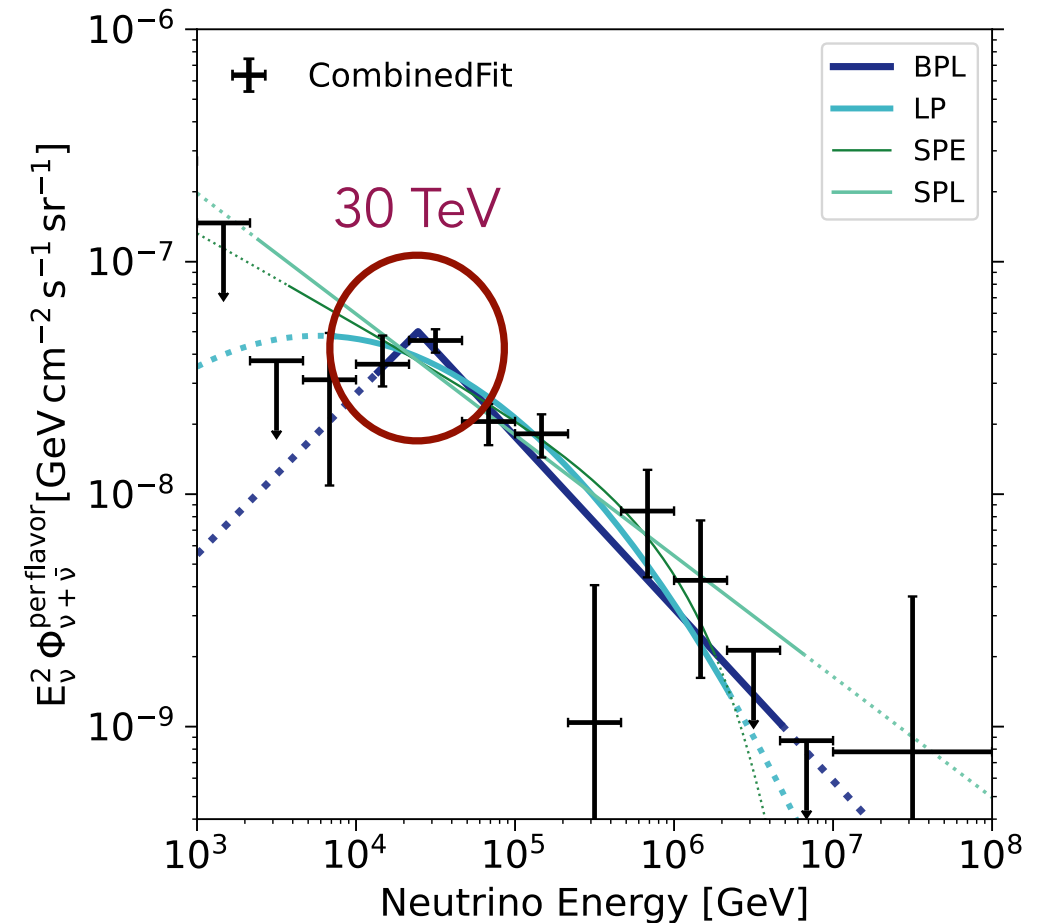
High-Energy Neutrino Flux



Evidence for Spectral Break



IceCube PRL 2026

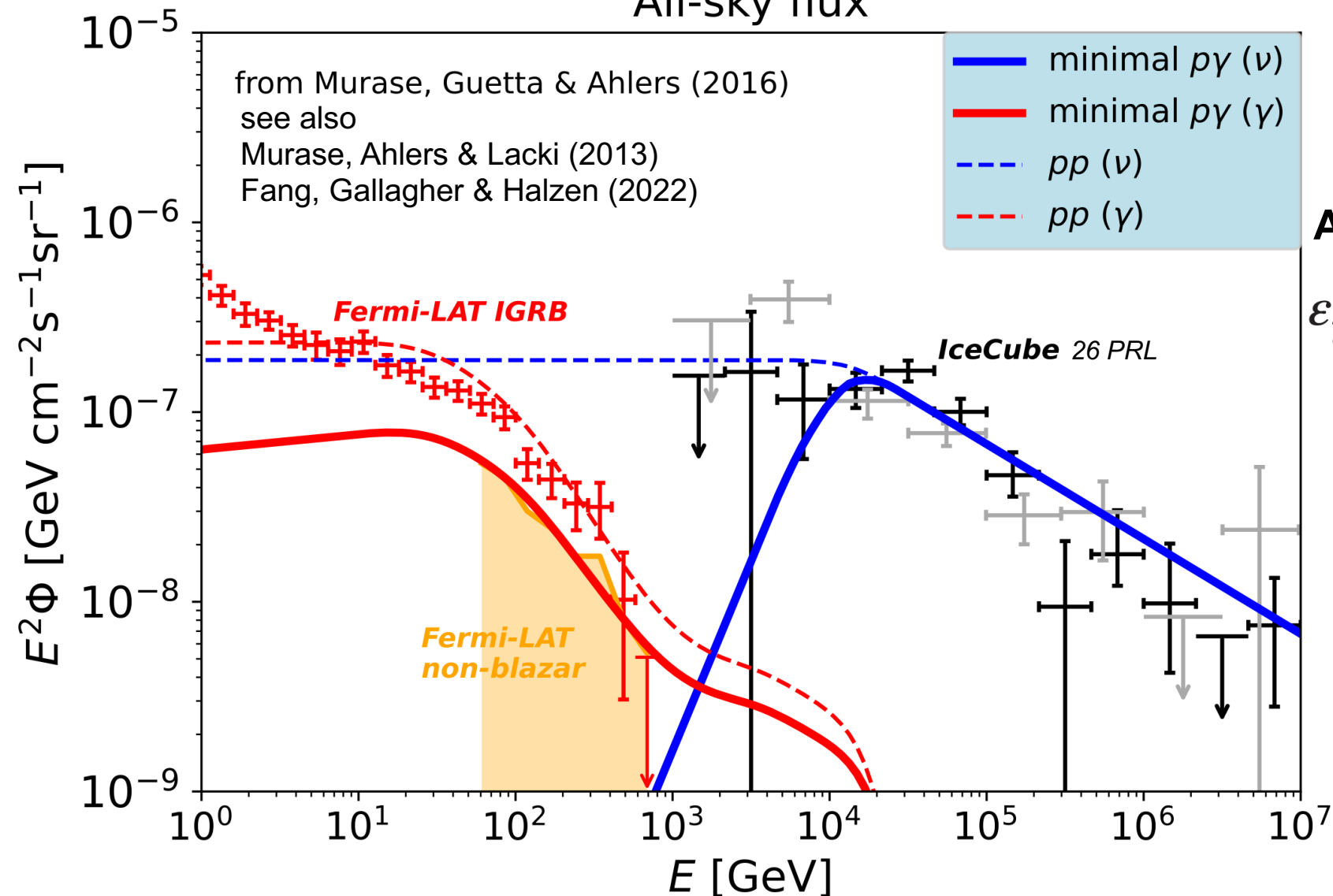


IceCube PRD 2026

- Combined analysis of Medium Energy Starting Events (MESE) and Combined Track and Cascade data show departure from single power law (SPL) at 4σ
- Spectral break at $\sim 30 \text{ TeV}$

Extragalactic Multimessenger Connection

10-100 TeV ν IceCube data: large fluxes of $\sim 10^{-7}$ GeV cm $^{-2}$ s $^{-1}$ sr $^{-1}$
All-sky flux



At sources

$$\epsilon_\gamma Q_{\epsilon_\gamma} \approx \frac{4}{3K} (\epsilon_\nu Q_{\epsilon_\nu})|_{\epsilon_\nu = \epsilon_\gamma/2}$$

$$K = \pi^\pm / \pi^0$$

$$pp: K \sim 2$$

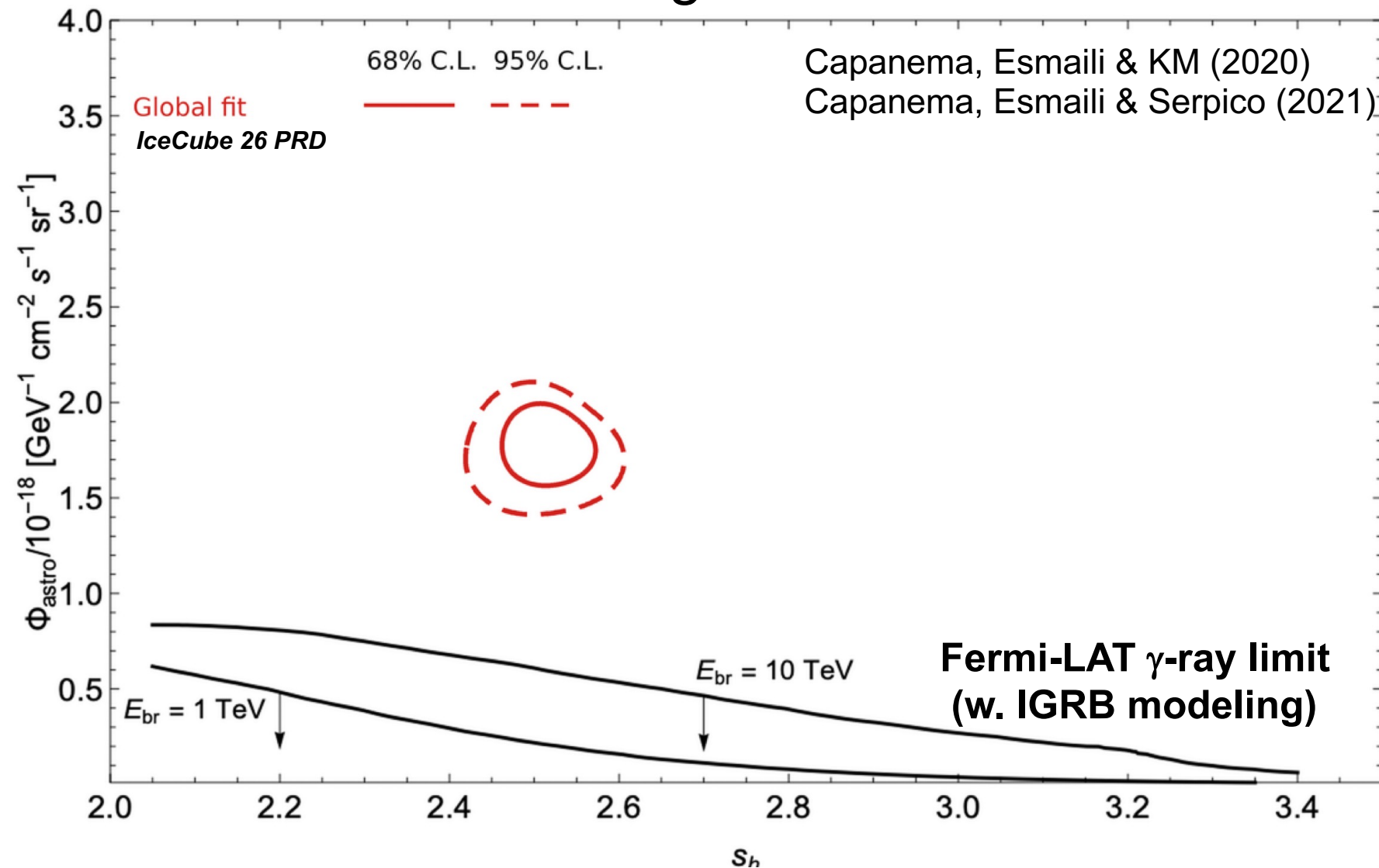
$$p\gamma: K \sim 1$$

pp scenarios (e.g., star-forming galaxies) are excluded **if γ -ray transparent**
tension w. γ -ray data ($> \sim 3\sigma$) even for the minimal $p\gamma$ scenario **if γ -ray transparent**
→ majority of ~ 30 TeV ν s: **hidden (i.e., γ -ray opaque)** cosmic-ray accelerators

Slide from K. Murase

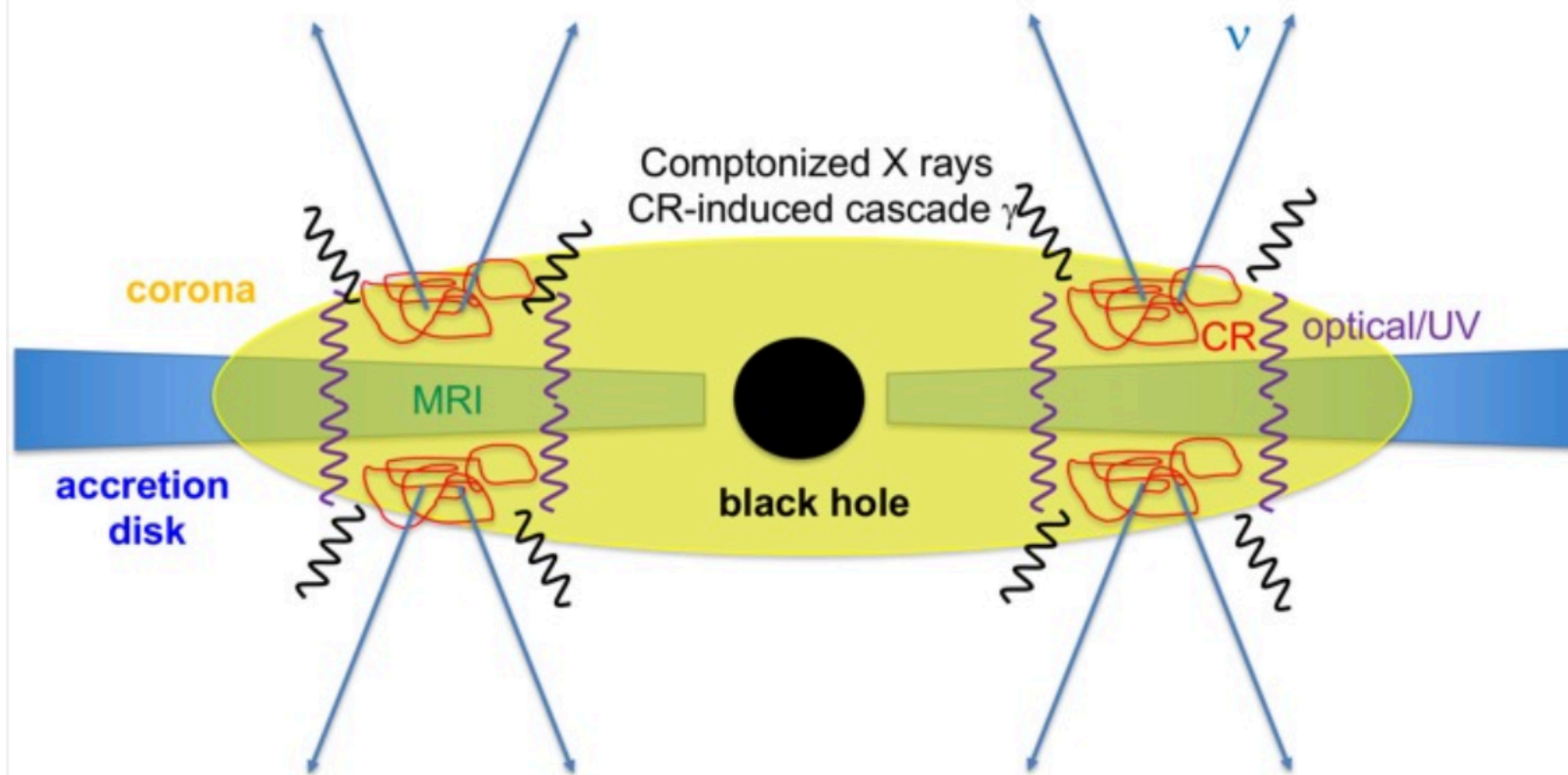
Extragalactic Multimessenger Connection

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 $\rightarrow$ majority of ~ 30 TeV ν s: **hidden (i.e., γ -ray opaque)** cosmic-ray accelerators

Slide from K. Murase



disk-corona

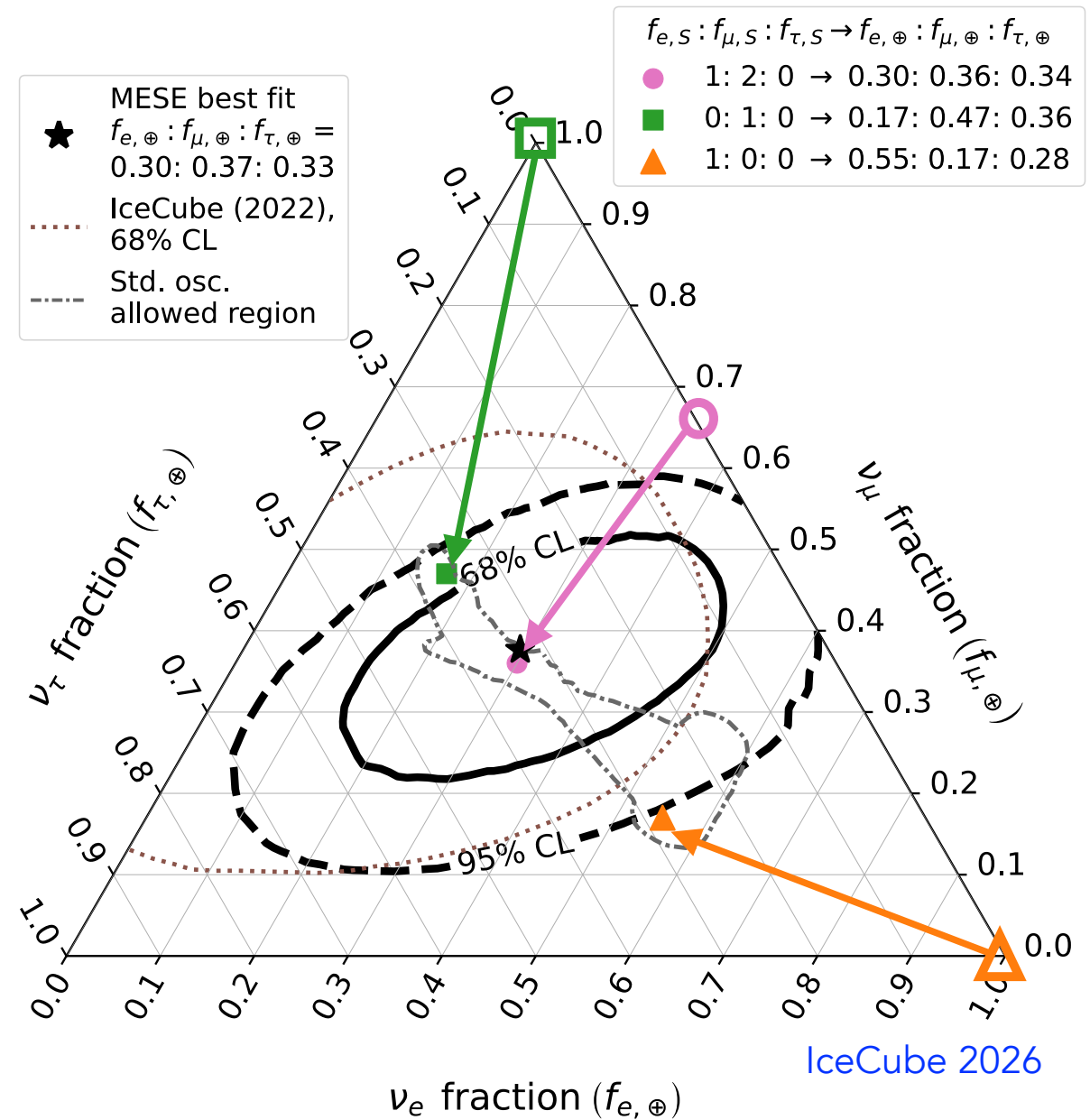
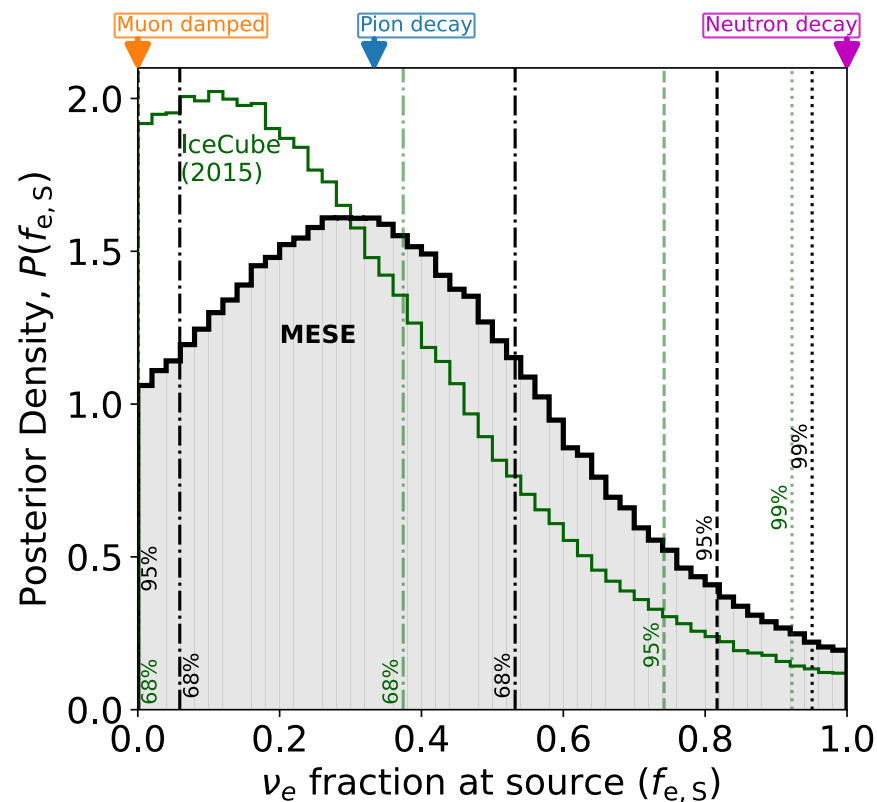
**opt/UV=multi-temperature blackbody
from disks**

**X-ray=Comptonization by hot electrons
in coronae ($kT_e \sim 10\text{-}100\text{ keV}$)**

Slide from K. Murase

Cosmic Neutrinos Flavor Composition

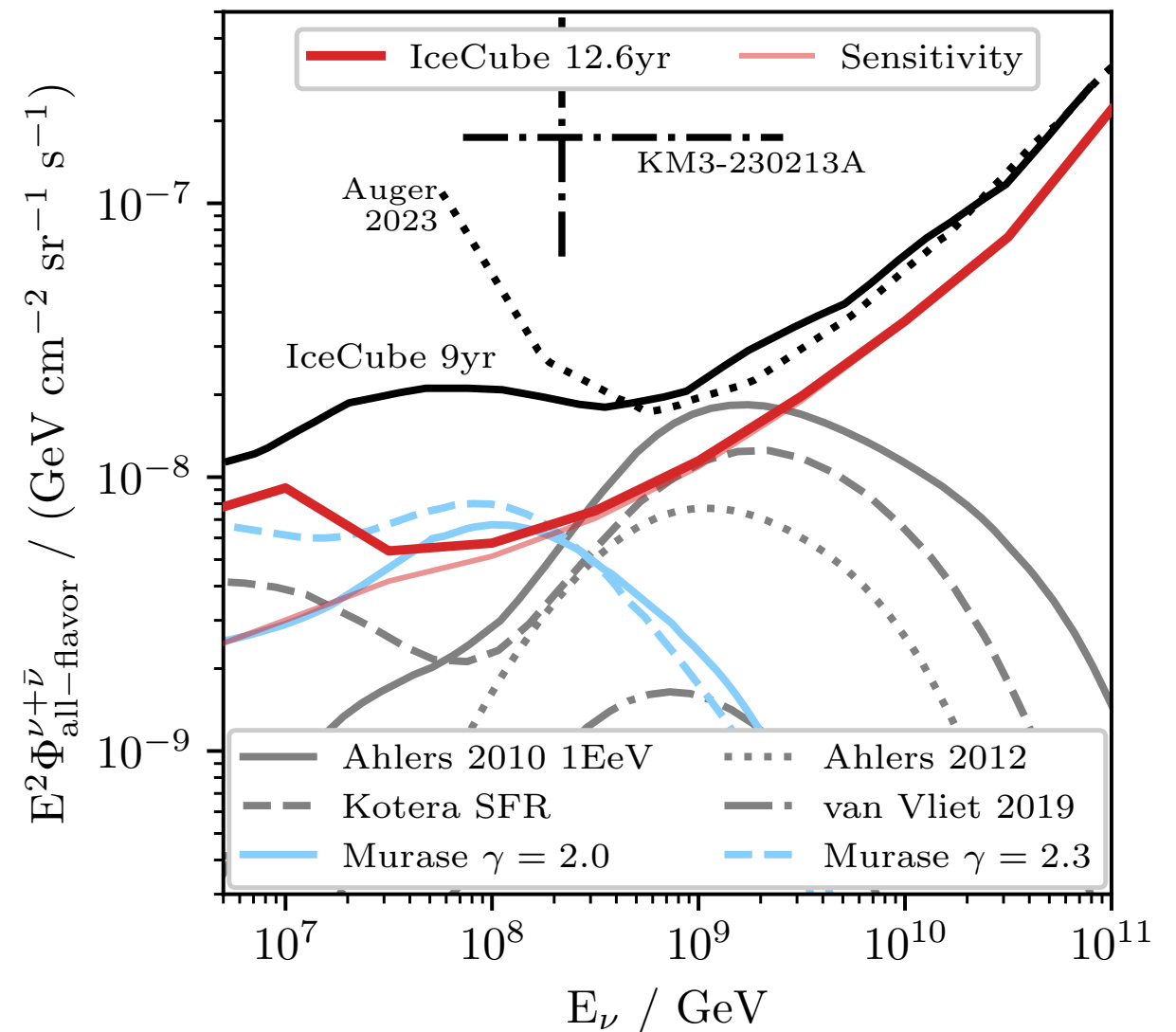
- ▶ Neutrino oscillation modifies the flavor composition of neutrinos after their production.
- ▶ 11.4 yr MESE: 5 TeV - 10 PeV
- ▶ All flavor analysis with improved double cascades identification above 30 TeV.
- ▶ Best fit very close to the nominal expectation of $\sim(1:1:1)$ from π decay.
- ▶ 1st time all flavors are nonzero at 68% C.L



➔ Neutron decay rejected at ~ 4 sigma (posteriori)

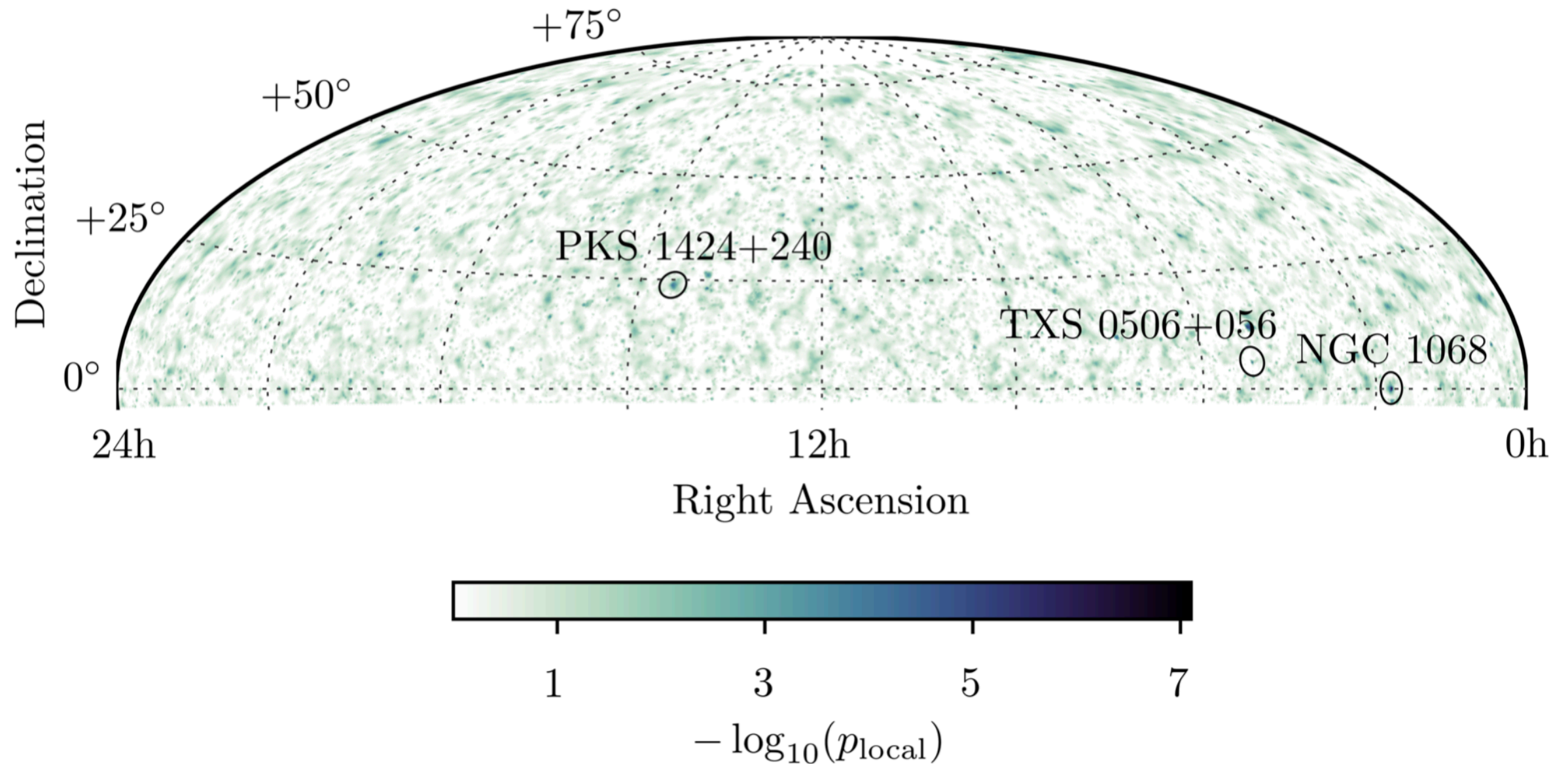
Cosmogenic Neutrinos

- ▶ Cosmogenic neutrinos are produced via interaction of UHE CRs with the background radiation
- ▶ The Spectrum is expected to peak at EeV energies
- ▶ The expectations depend on the composition of the UHE CRs:
 - Optimistic: high proton fraction
- ▶ Improved IceCube UL constrains the proton fraction beyond 30 EeV
- ▶ KM3-230213A UHE event and IceCube's non-observation yield a 3σ tension



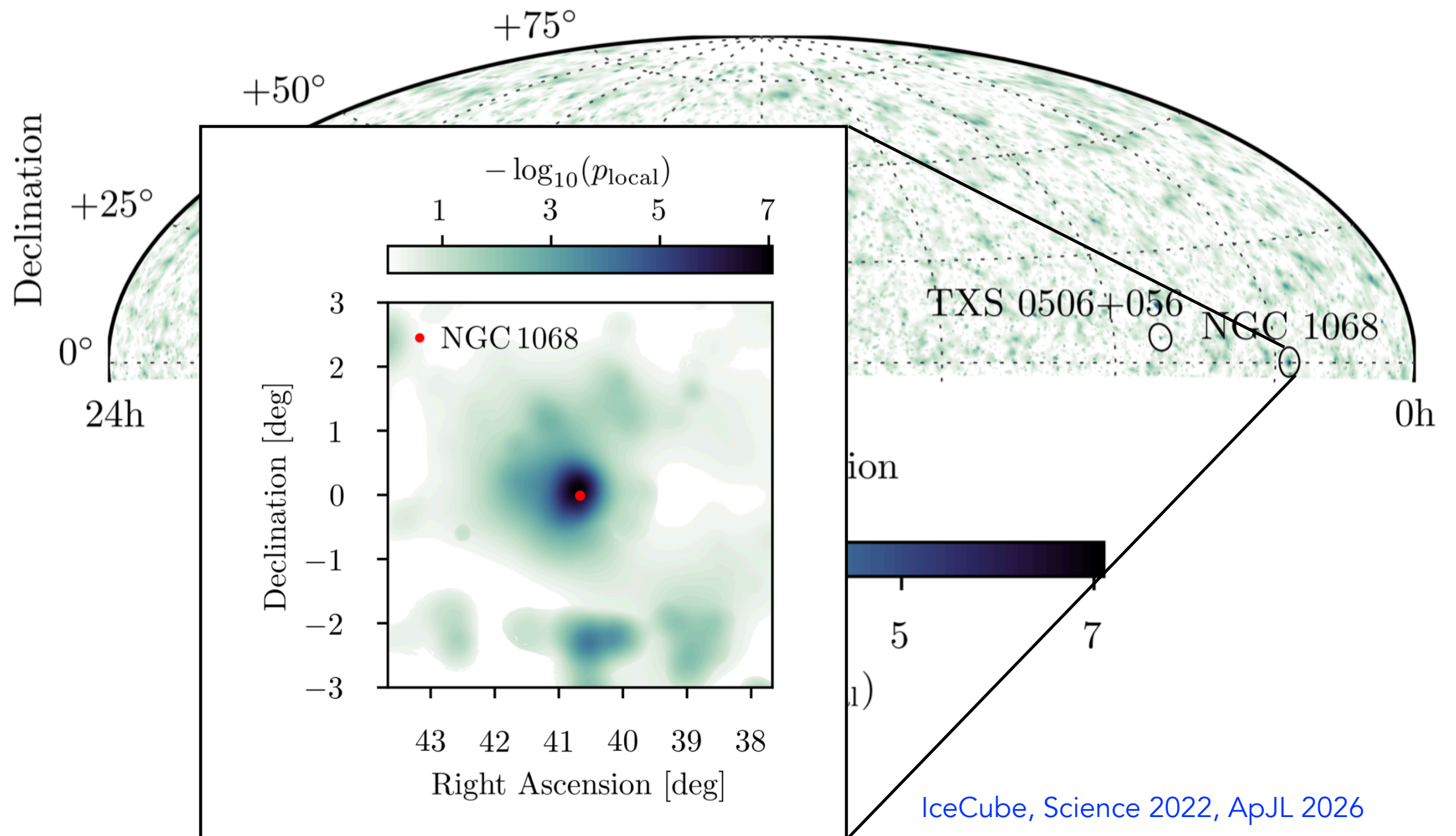
IceCube, PRL 2025

NGC 1068; Brightest Source in Nu Sky



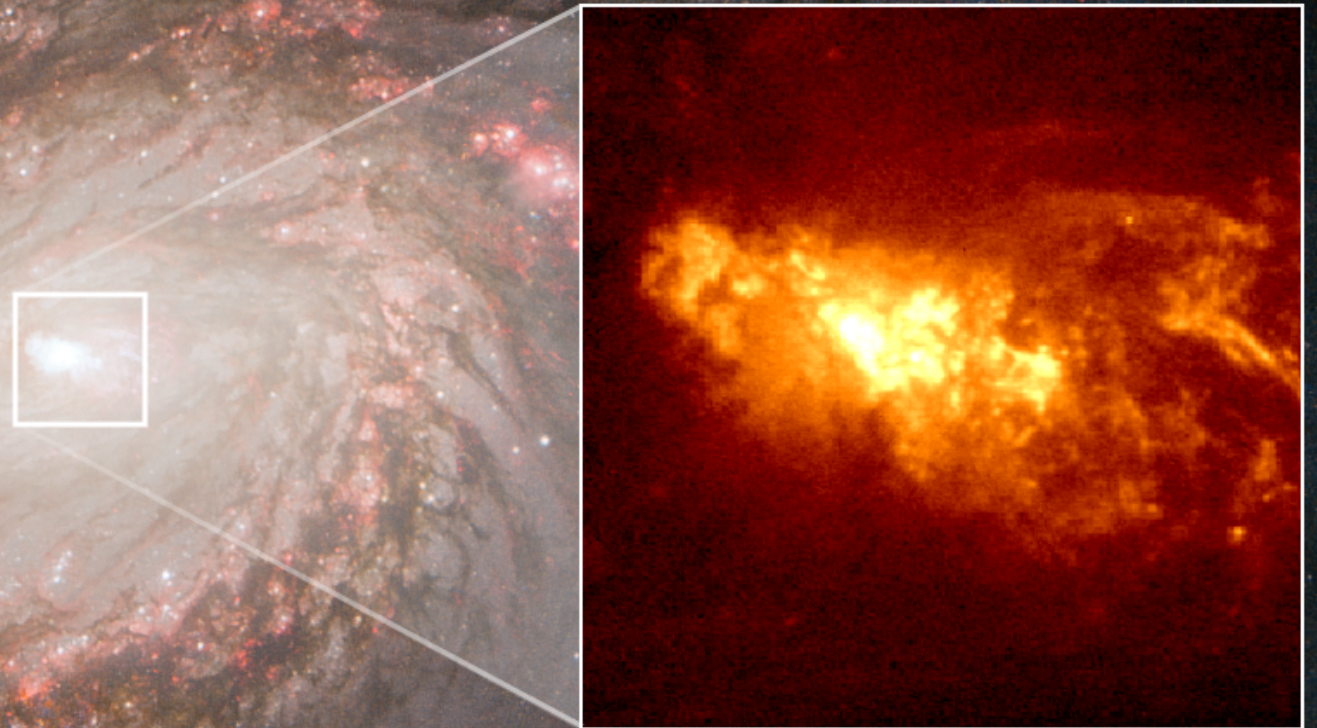
IceCube, Science 2022, ApJL 2026

NGC 1068; Brightest Source in Nu Sky



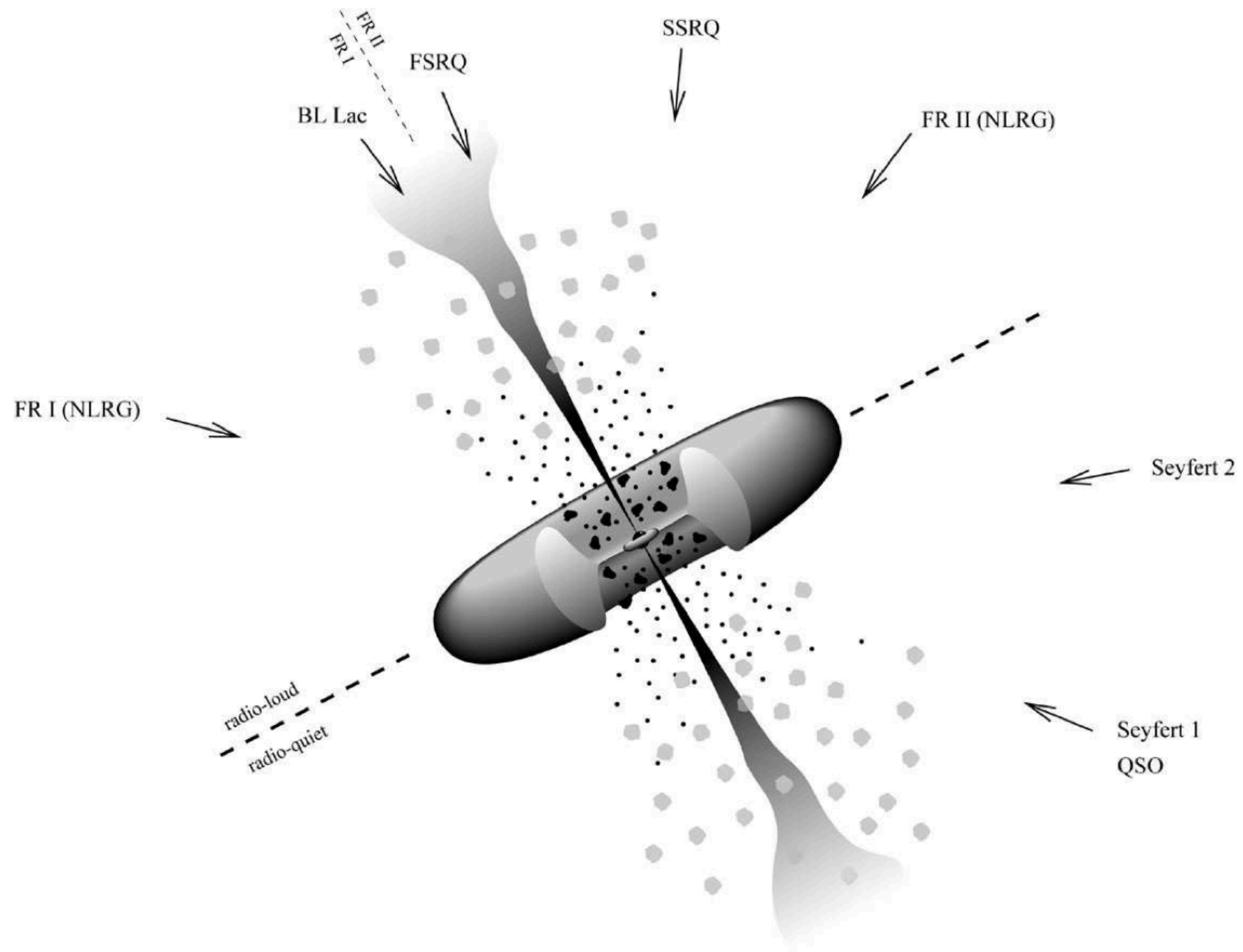
NGC 1068

- NGC 1068 is a Seyfert 2 galaxy with a heavily obscured nucleus
- One of the best studied Active Galactic Nuclei (AGN), which played a major role in AGN unification scheme

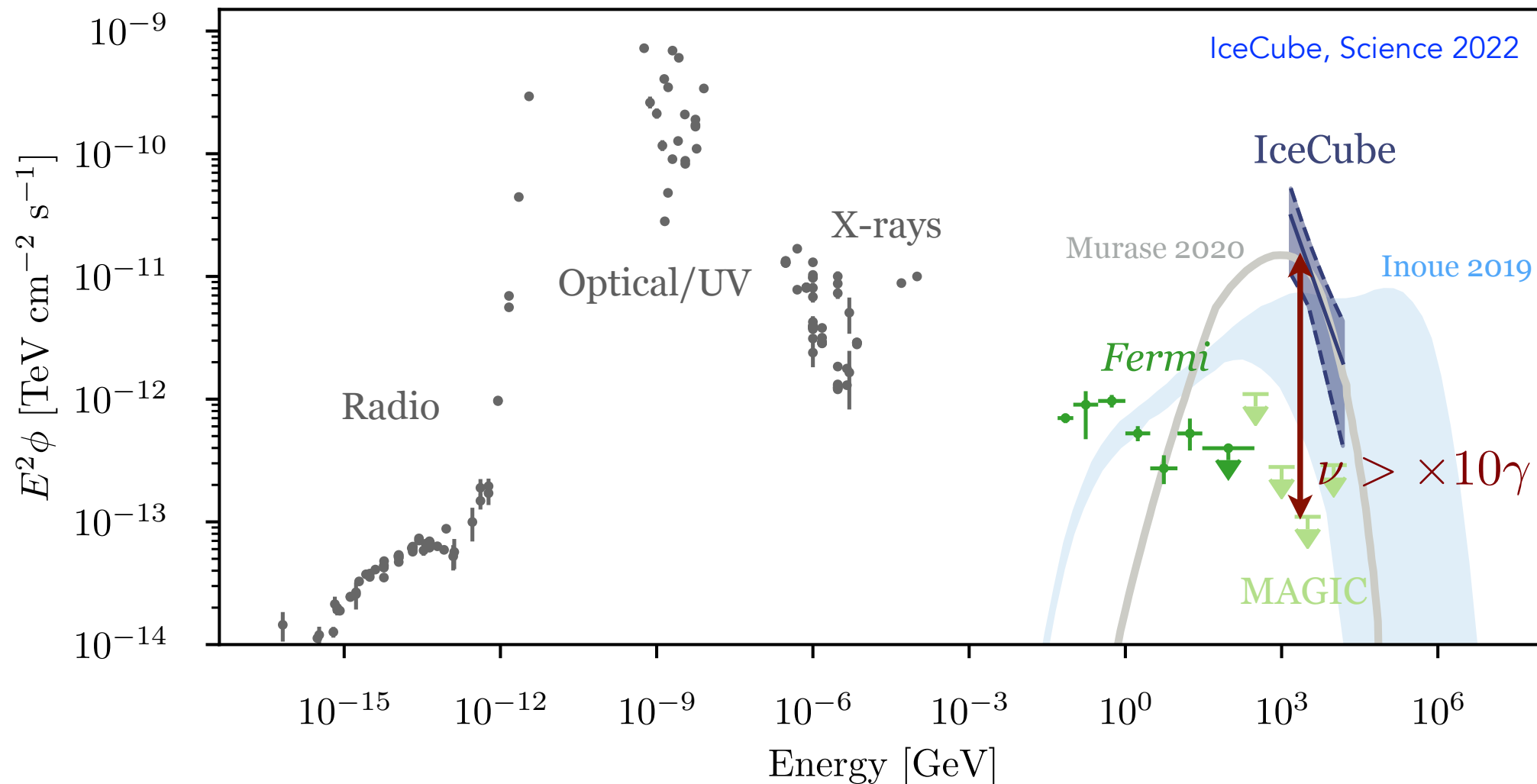


- Compton thick environment with Column density $\sim 10^{25} \text{ cm}^{-2}$
- Bright in X-ray, and high infrared luminosity indicating high level of star formation
 - ▶ *Historically considered as a promising cosmic-ray accelerator.*

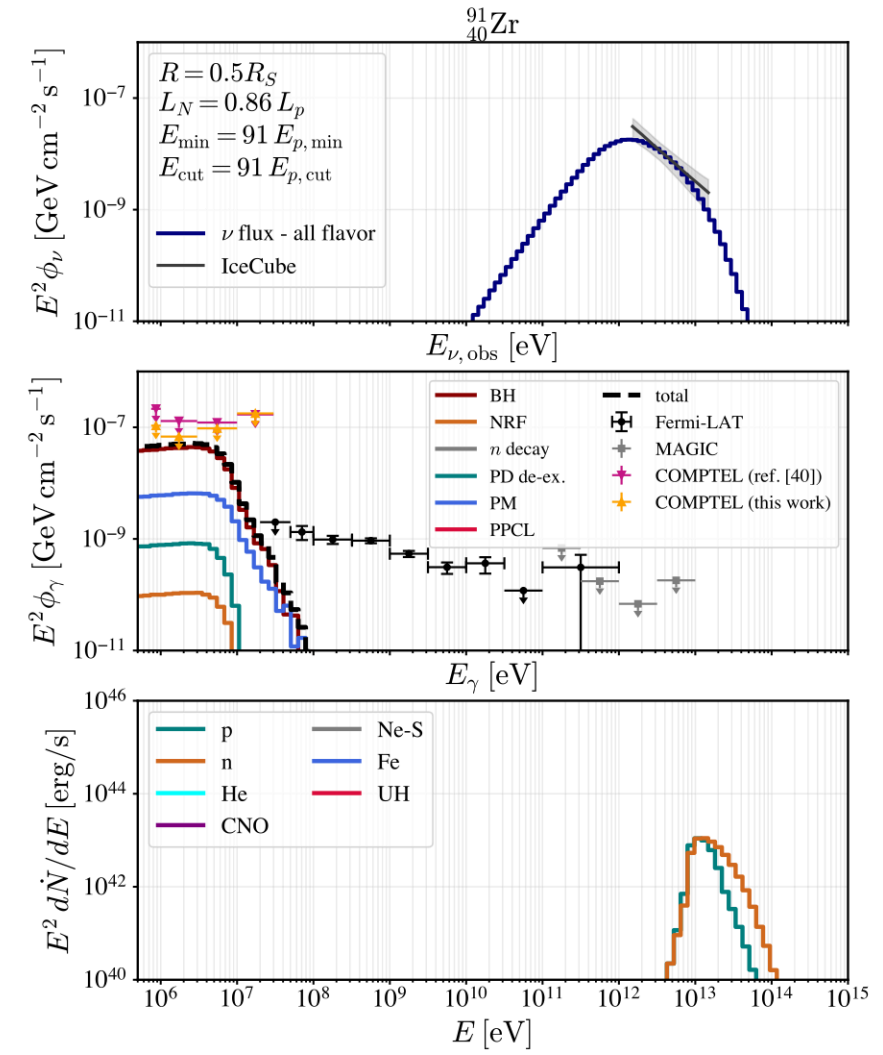
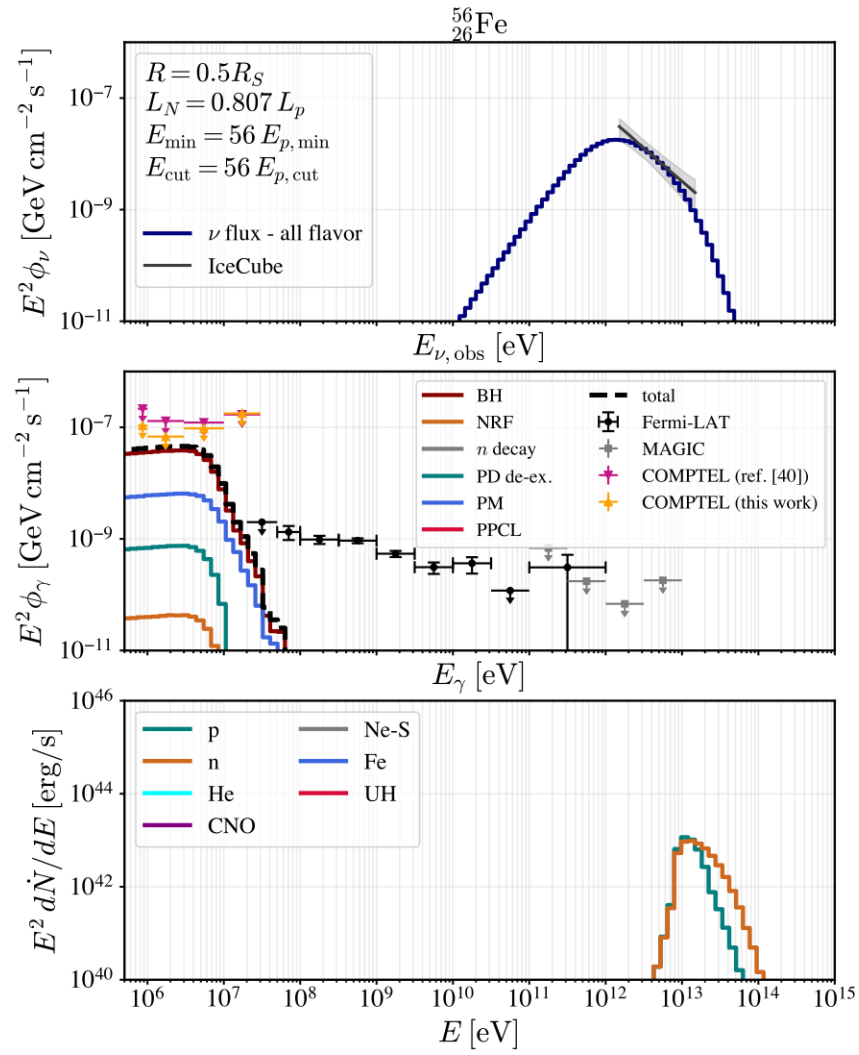
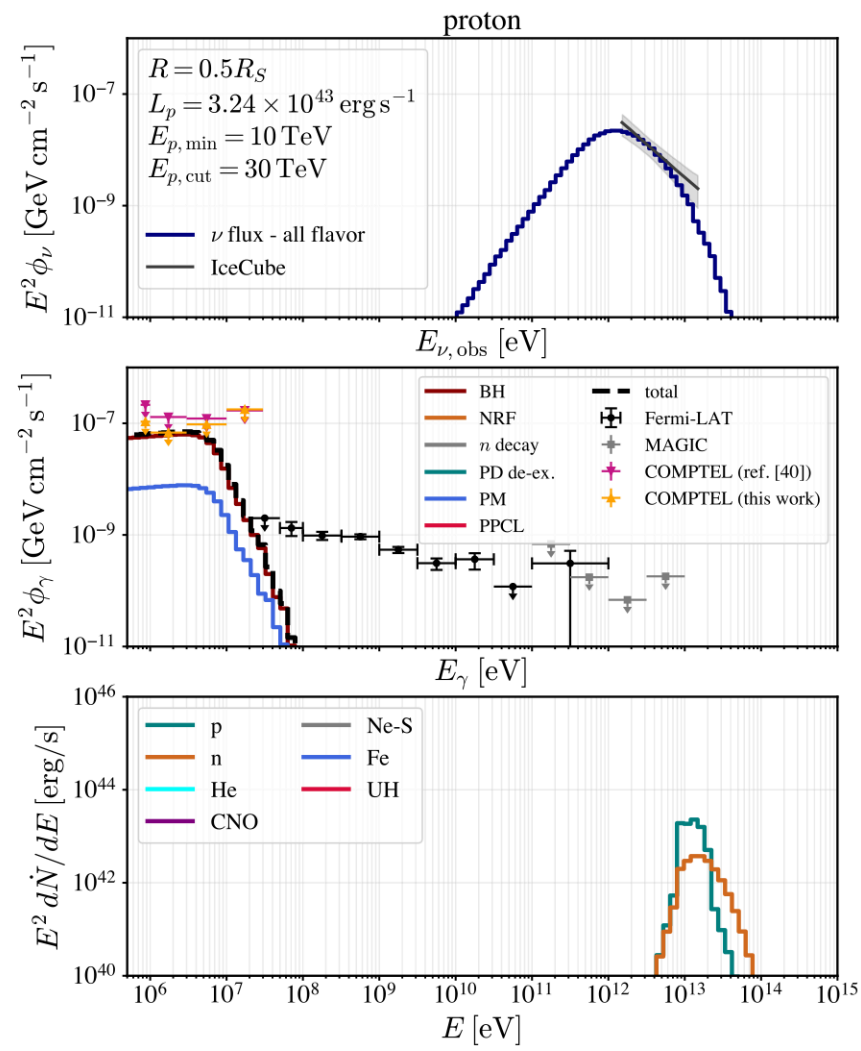
Unified picture of AGN

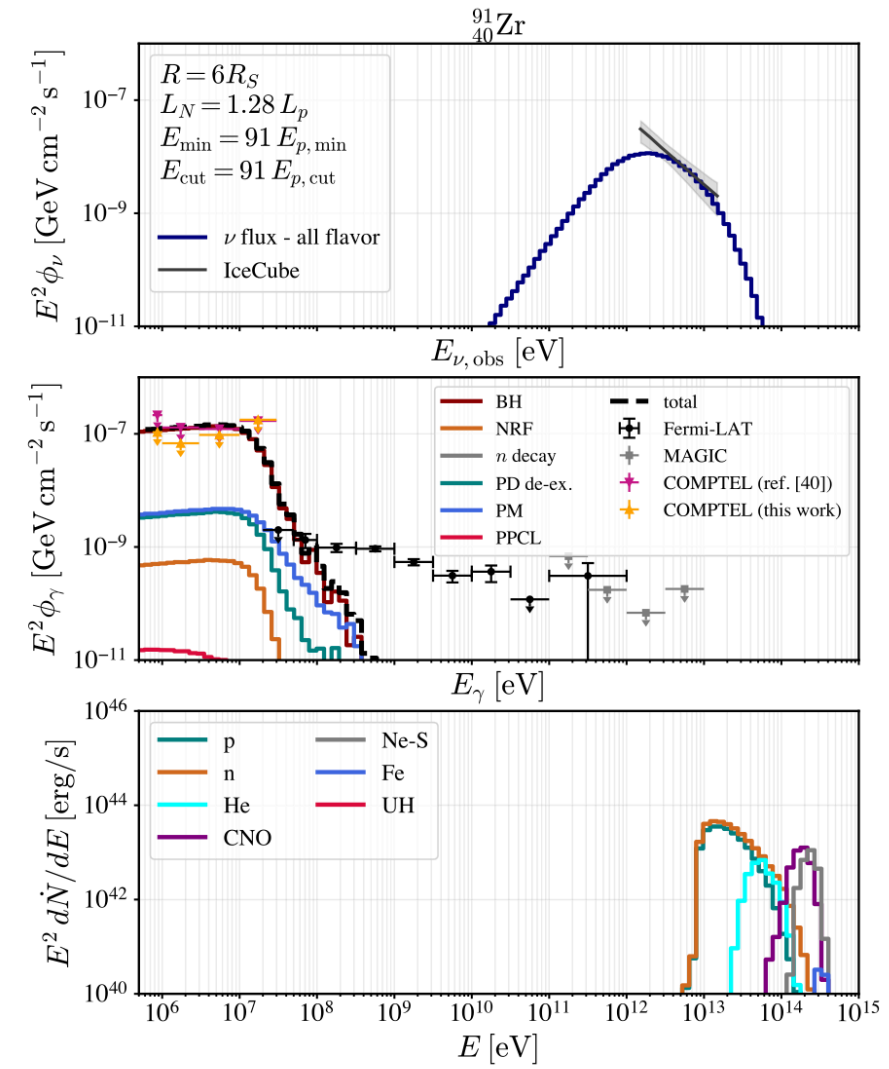
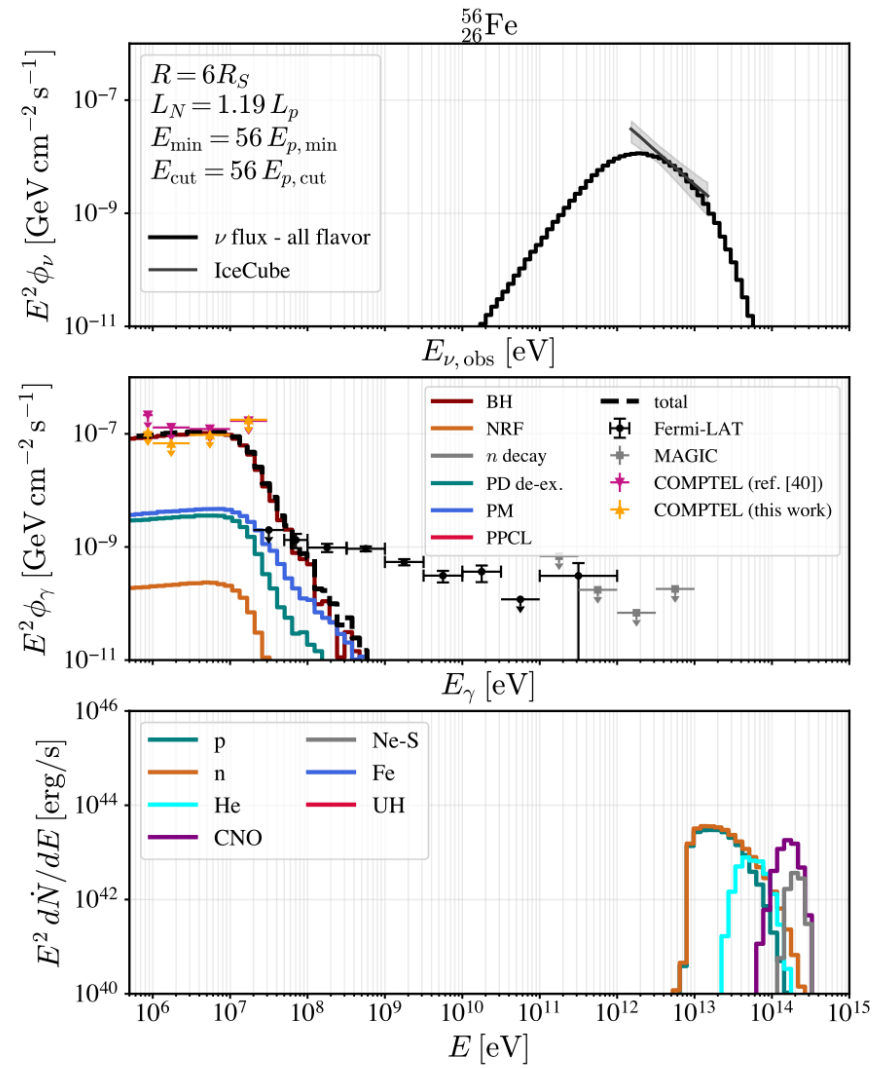
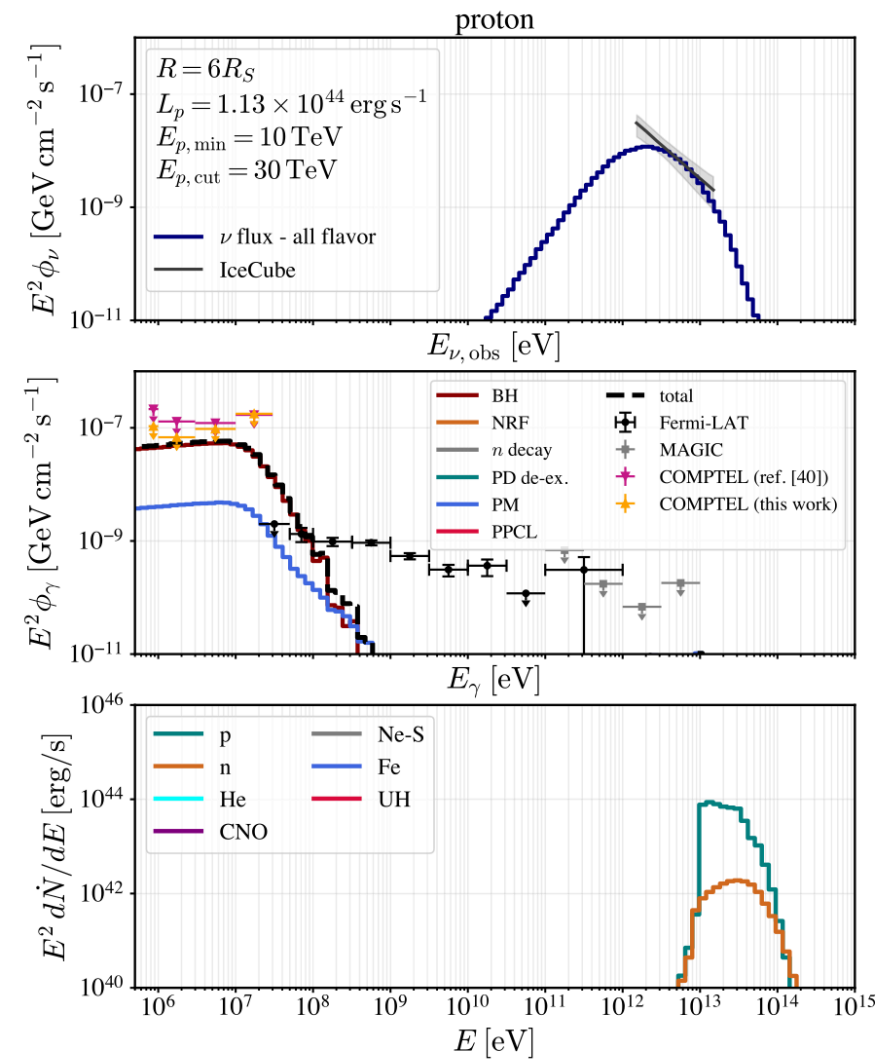


NGC 1068 Spectrum



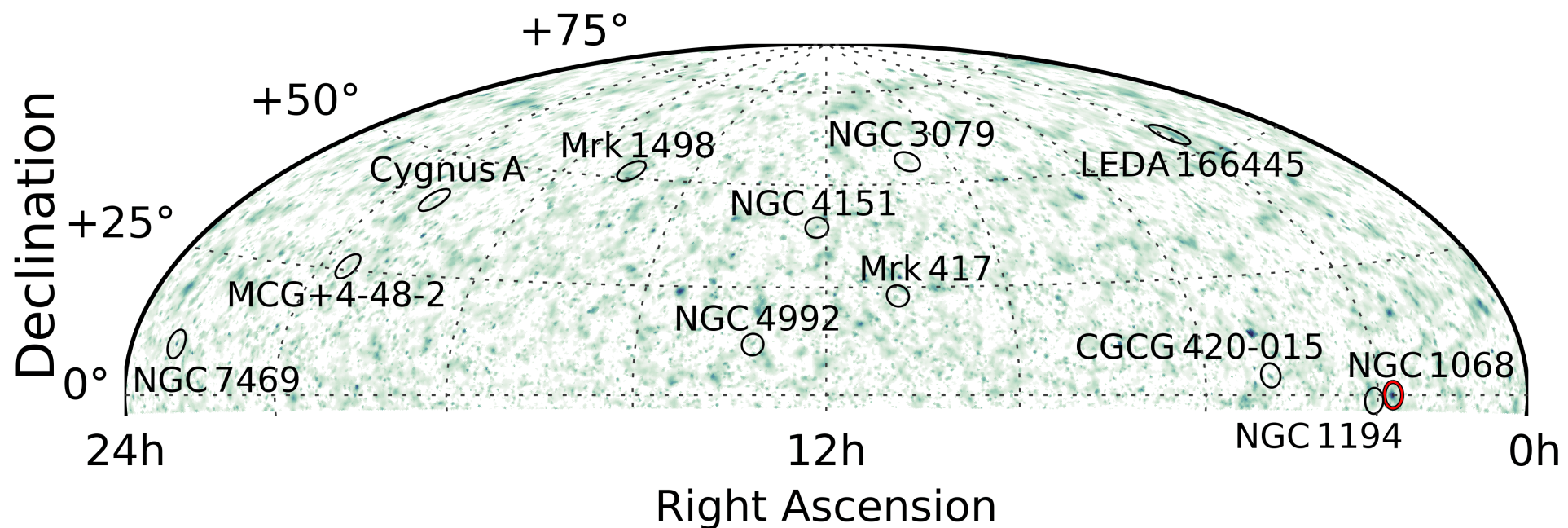
- ▶ The neutrino flux much higher than the measured γ -ray flux.
- ▶ Models built on Fermi γ -ray flux by cannot accommodate the neutrino flux.
- ▶ **Obscuring** necessary to absorb the pionic γ -ray accompanying neutrinos.
- ▶ The high opacity indicates that the neutrinos are produced in dense environment in the vicinity of AGN core ($< 100 R_s$) $\rightarrow$ Consistent with the multimessenger picture for the HE cosmic neutrino flux





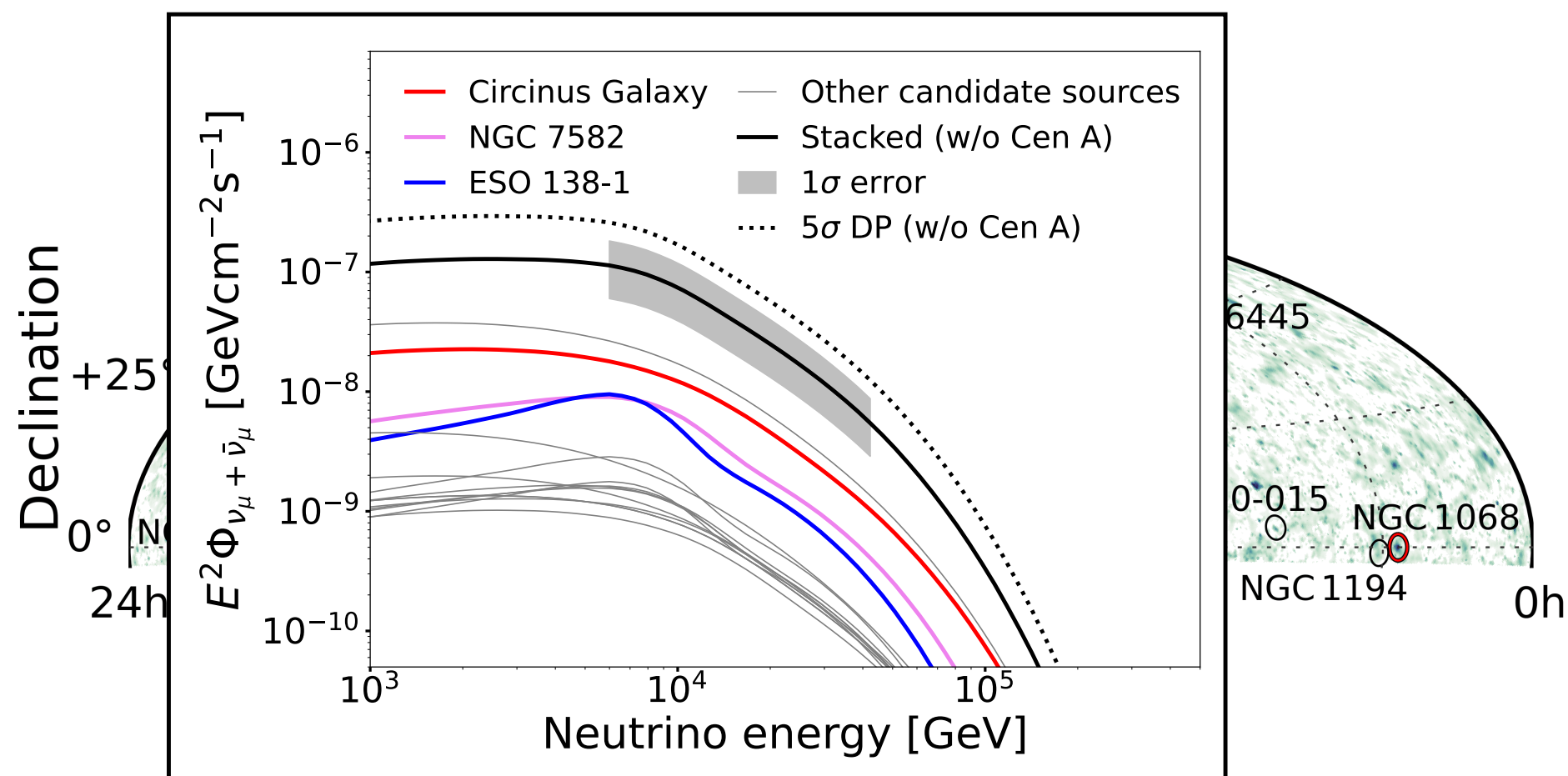
Neutrino-Bright AGN

- ▶ Accumulating evidence for correlation of IceCube neutrinos in the direction of γ -ray obscured AGN.
 - ▶ 3.3σ excess from ensemble of 11 sources in the Northern Sky (excluding NGC 1068)
 - ▶ 2.9σ excess from the direction of NGC 4151
 - ▶ 3.0σ excess in the stacking search in the Southern sky

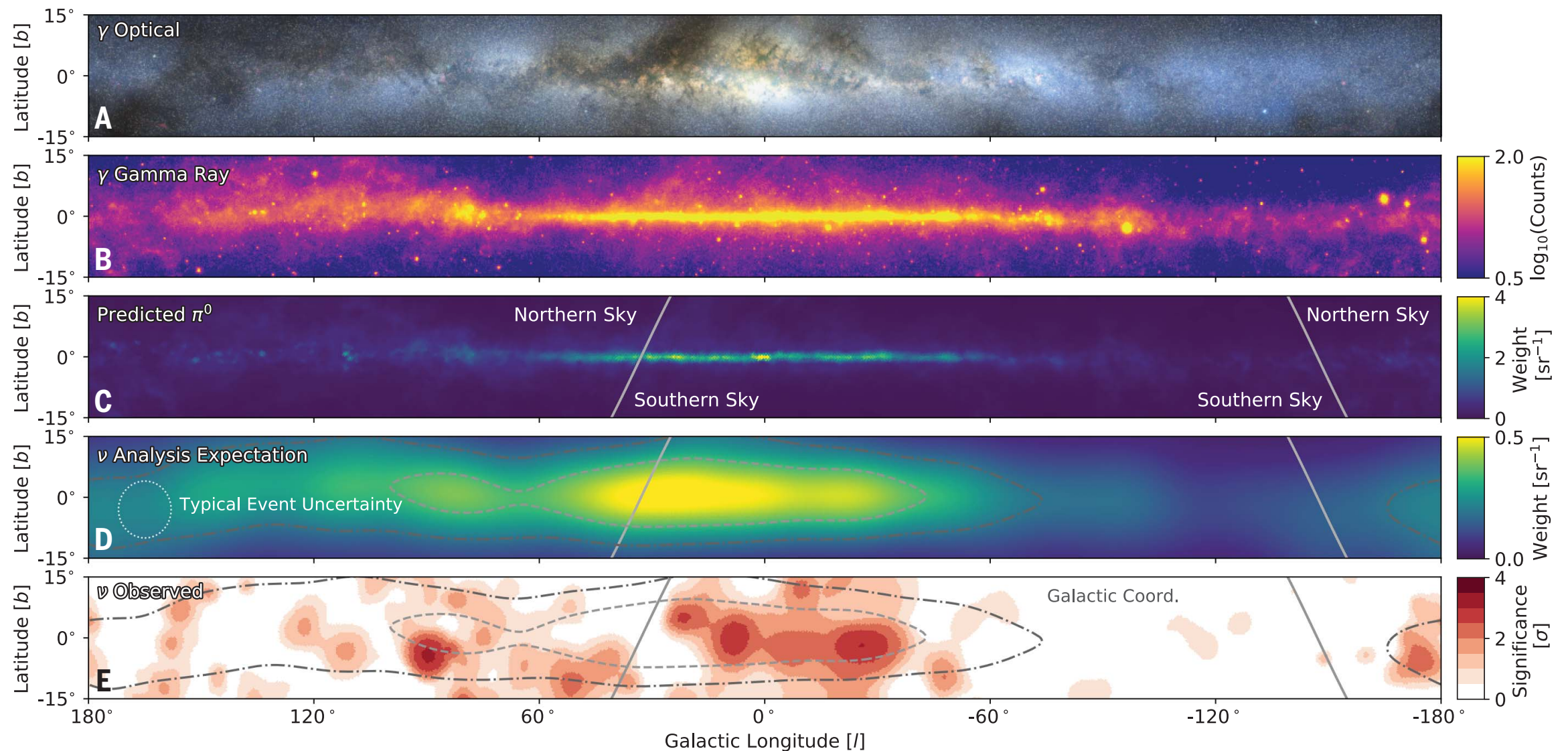


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Galactic Neutrino Emission

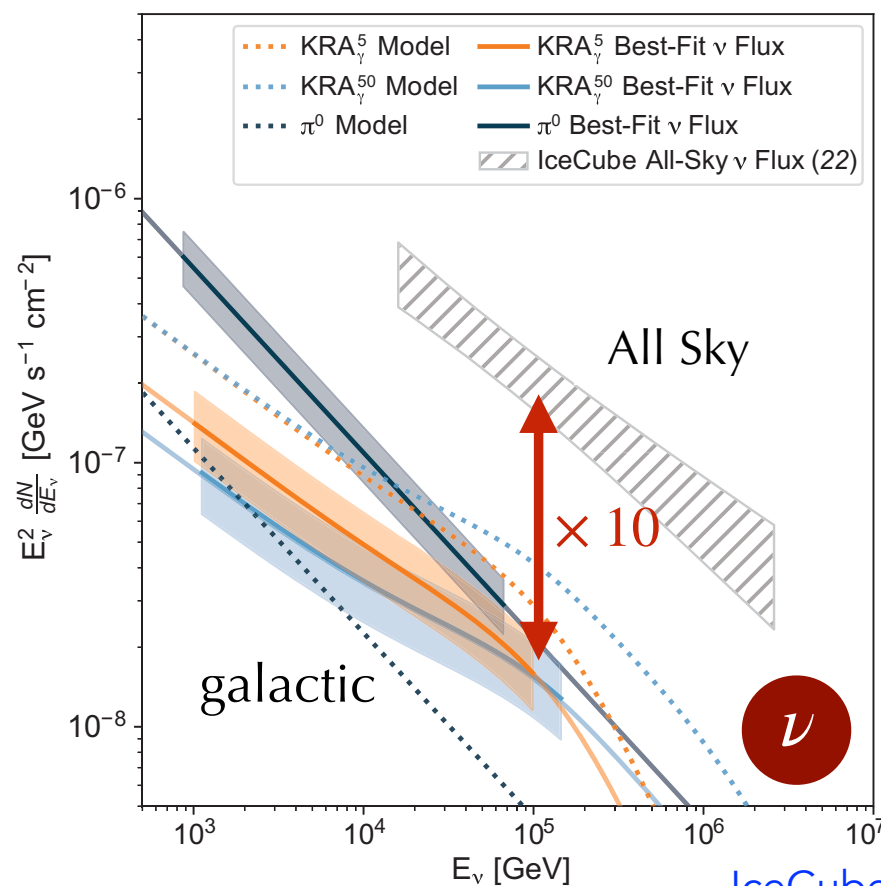


10 years of cascade data identified neutrino emission from
the Milky Way at 4.5σ

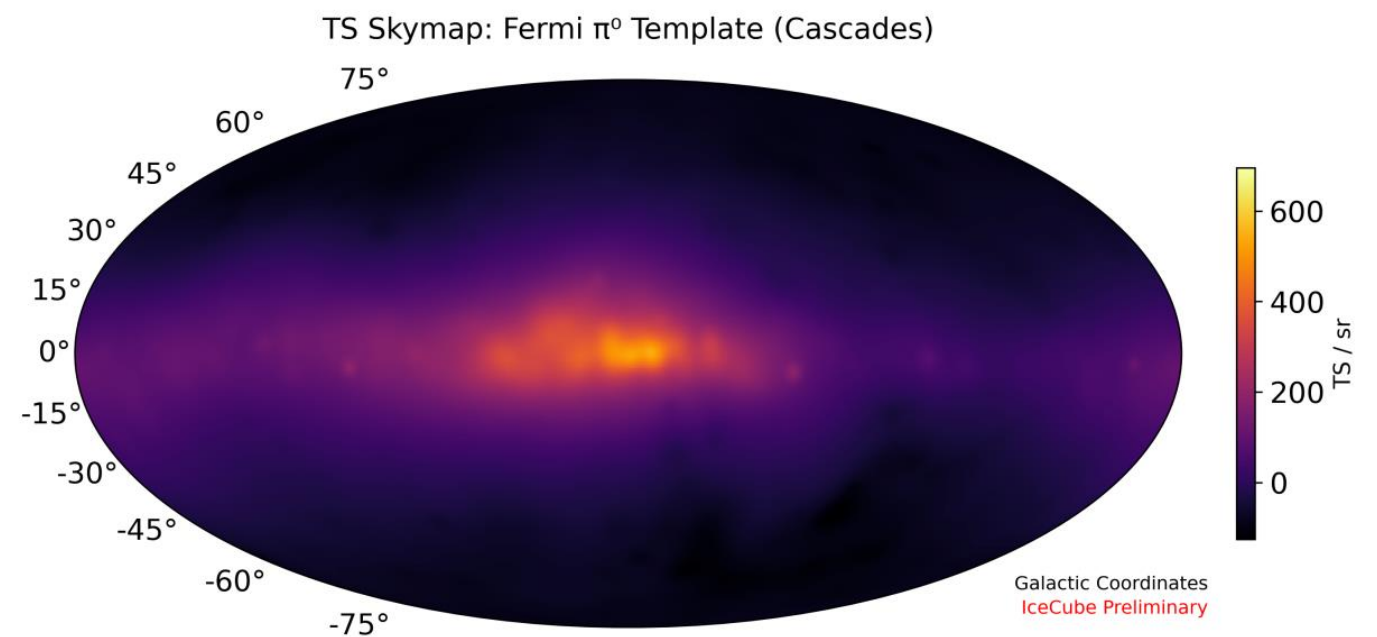
Galactic Neutrino Emission

Cascades boost IceCube sensitivity to extended emission in the Southern sky.

- ▶ New analysis with additional years, combined dataset, and improved systematics rejects the no Galactic hypothesis at $> 5\sigma$ significance
- ▶ Current analyses reject no Galactic component hypothesis but cannot distinguish between models
- ▶ The nature of Galactic neutrinos (source vs diffuse) remains an open question



IceCube, Science 2023



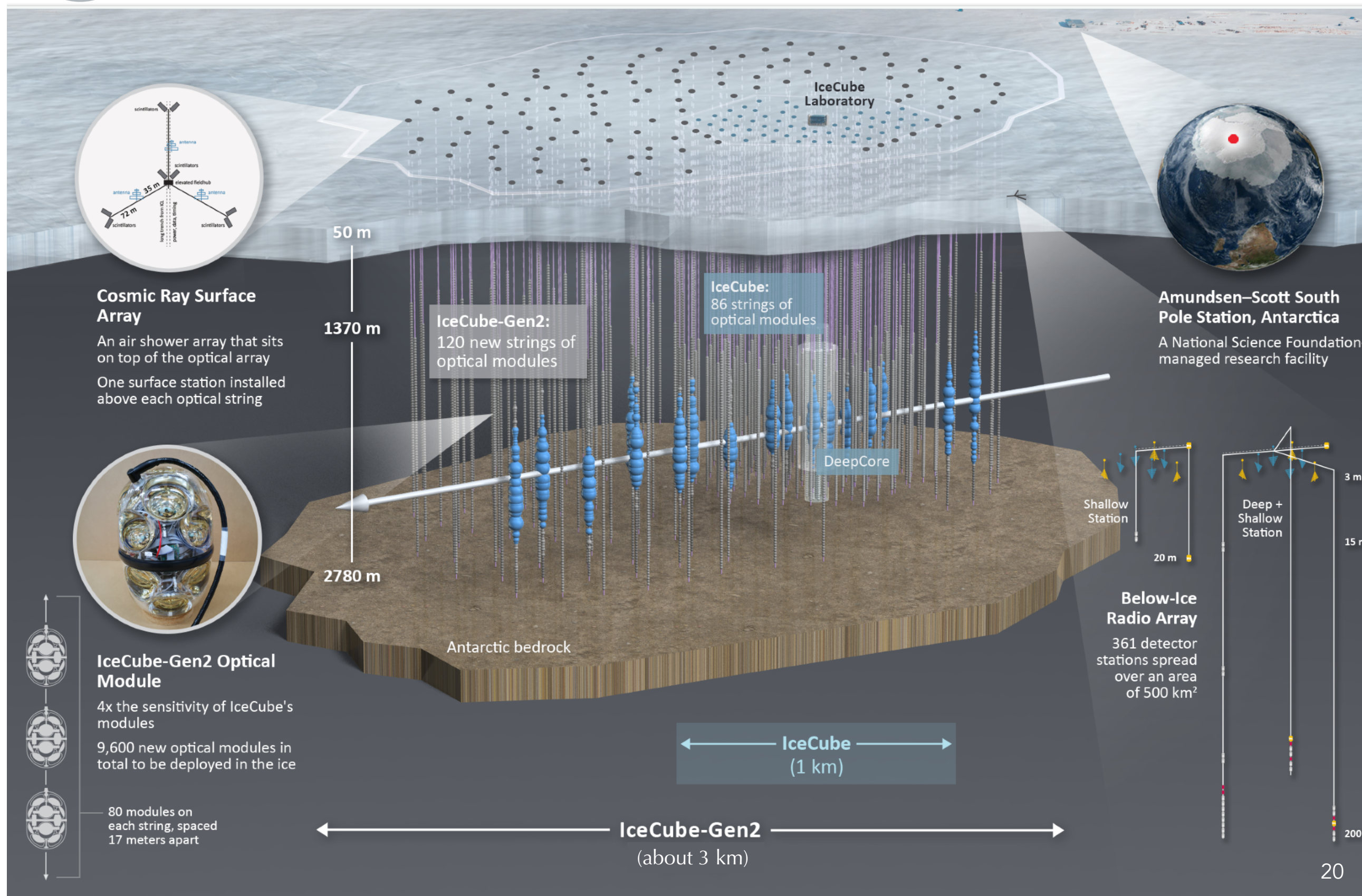
M. Thiesmeyer, ICRC 2025

Ali Kheirandish (UNLV)

17

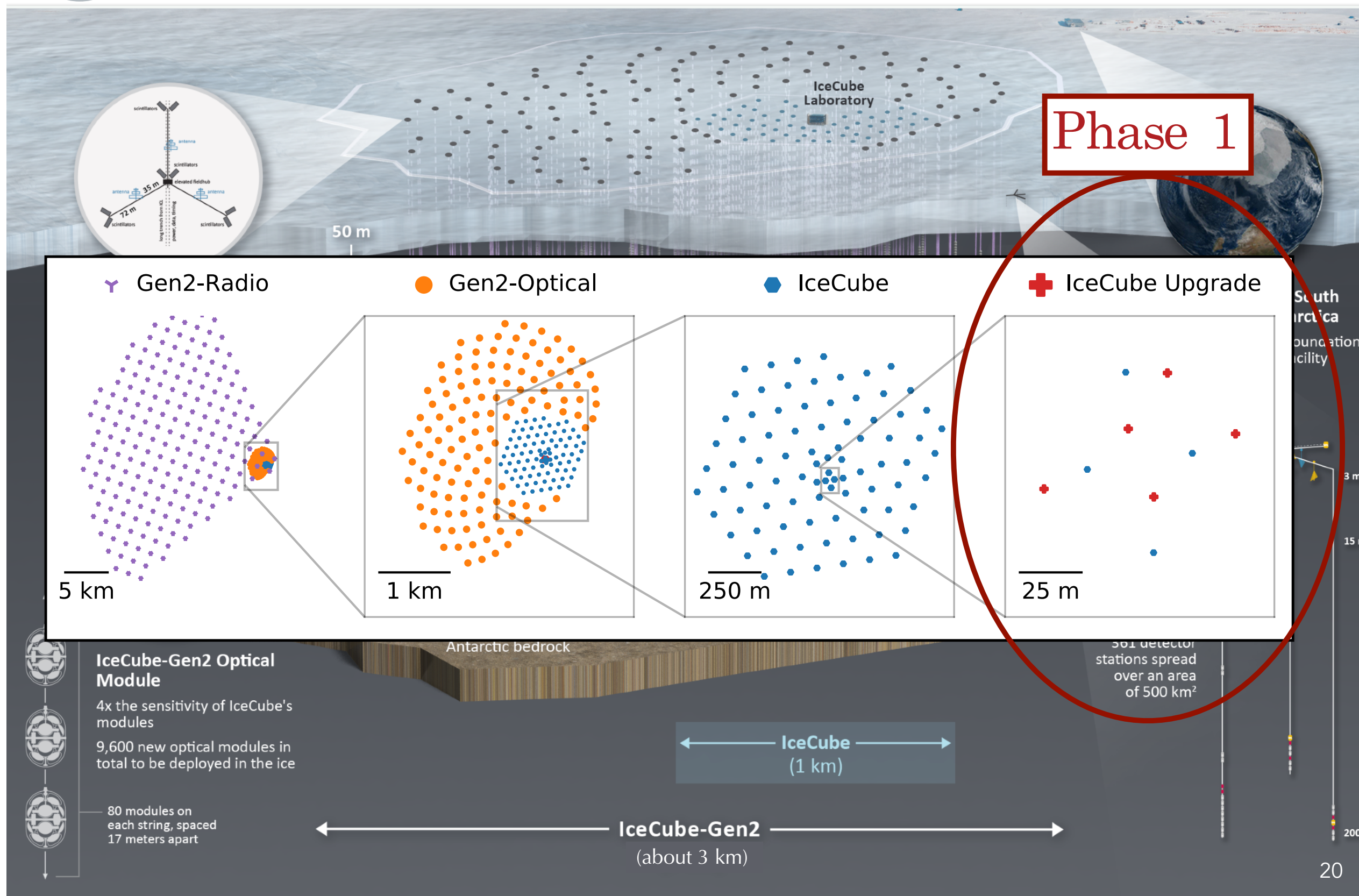


ICECUBE GEN2

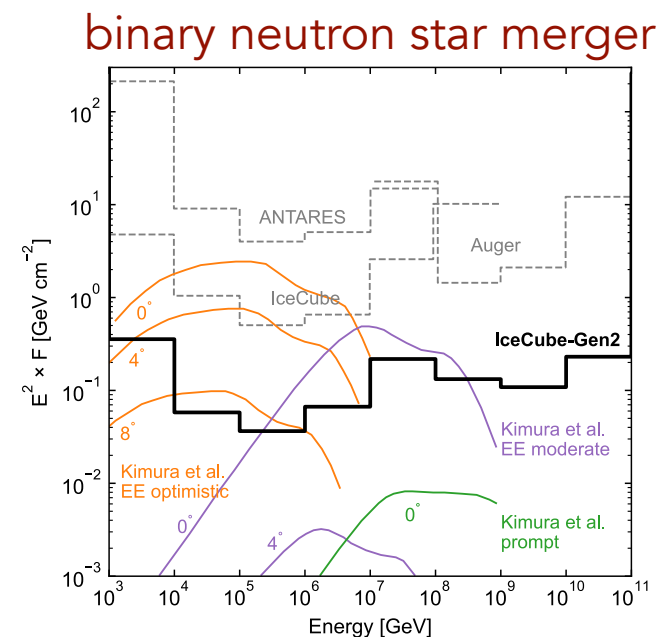
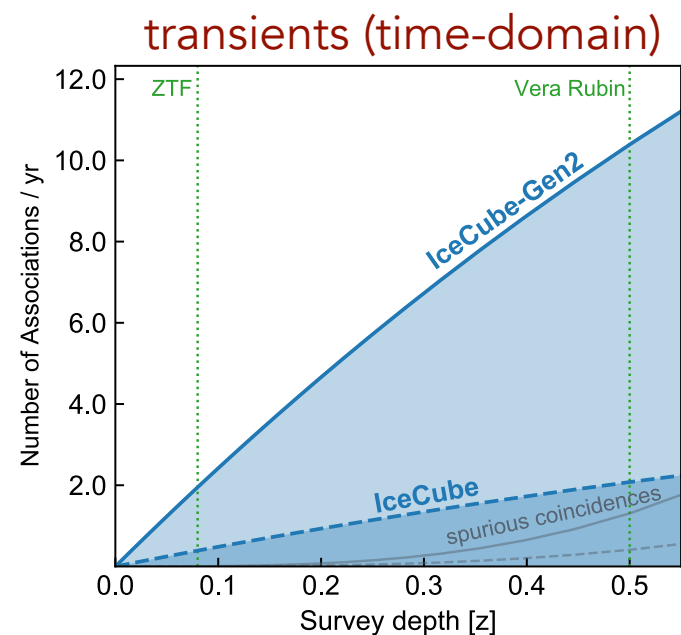
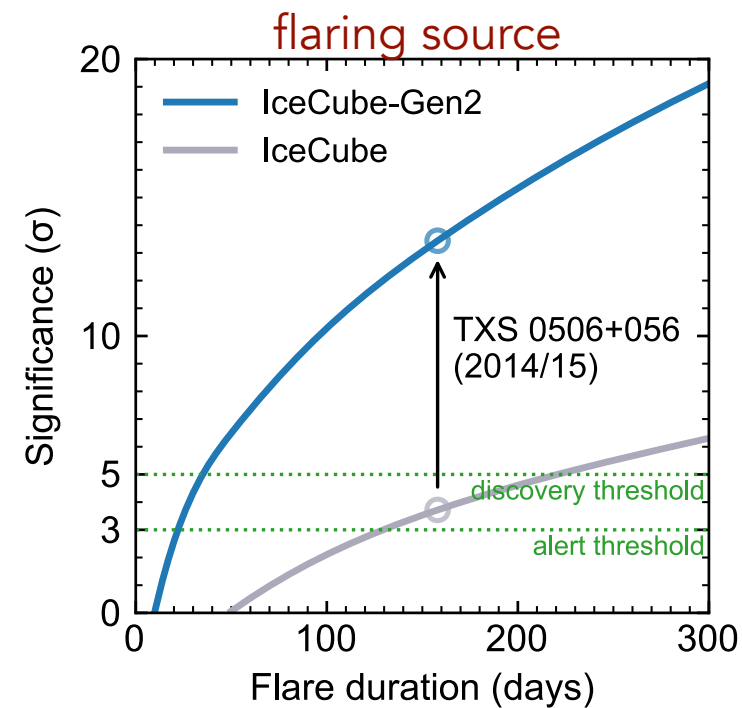
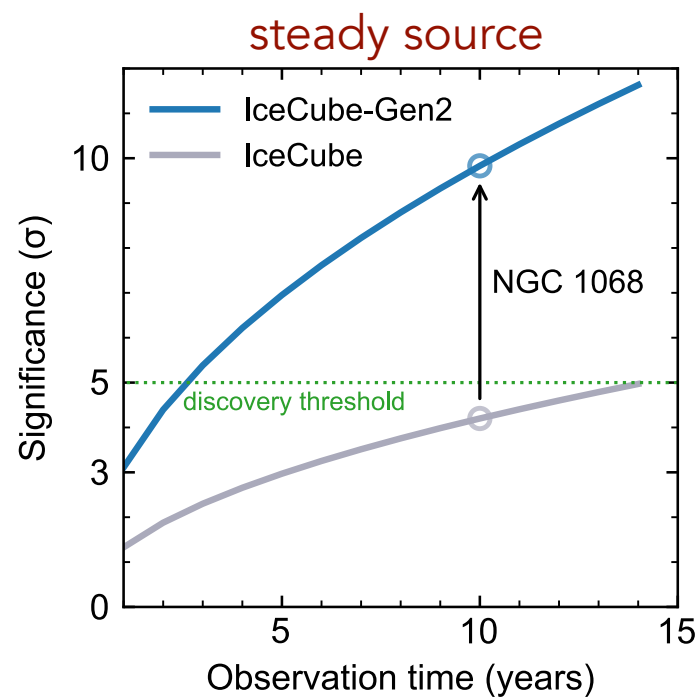




ICECUBE GEN2

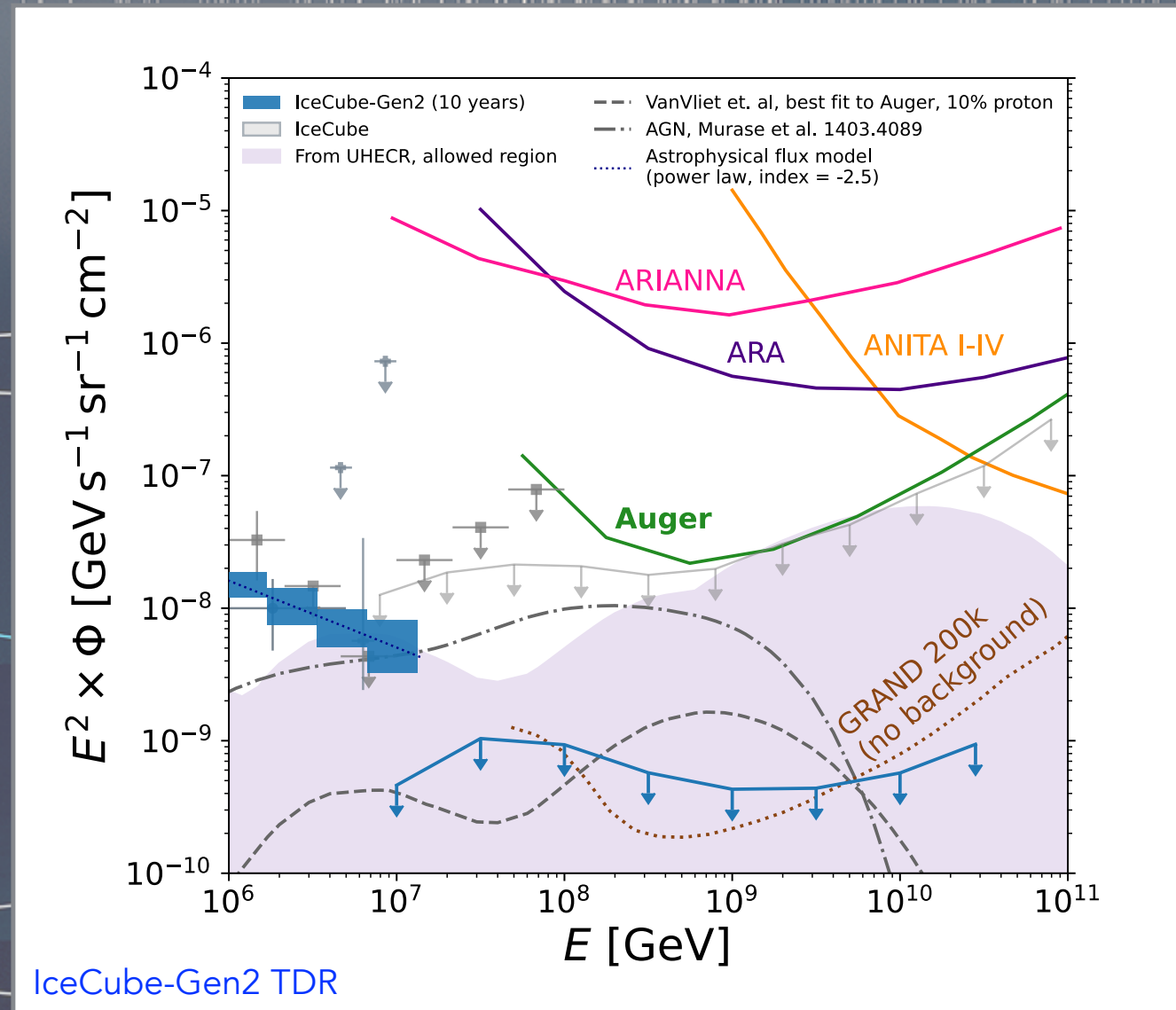


IceCube-Gen2: Source Identification



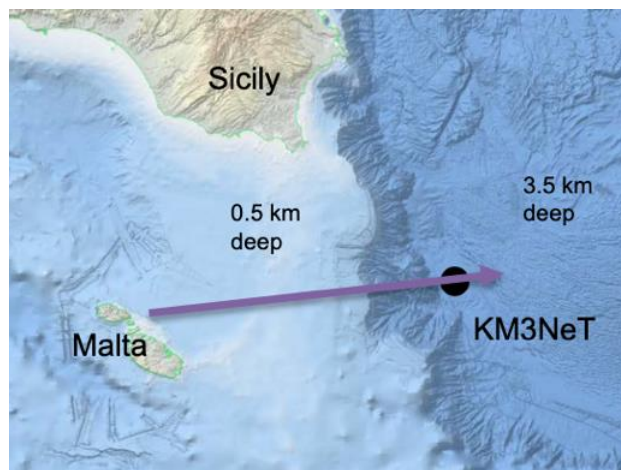
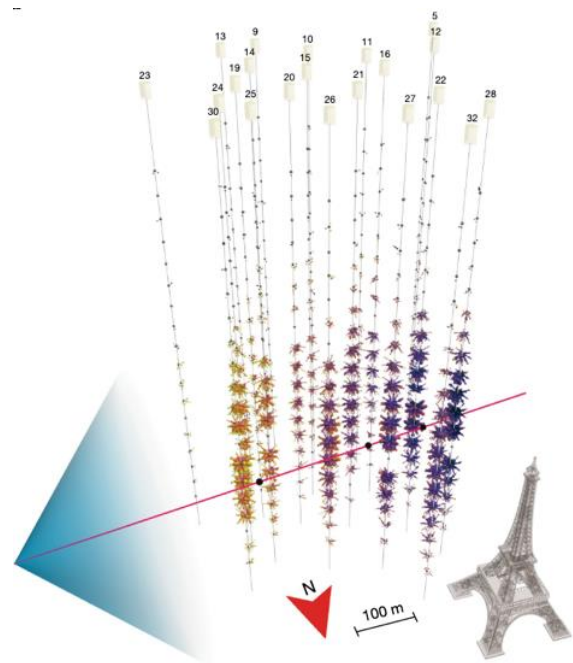
IceCube-Gen2 TDR

IceCube-Gen2: Cosmogenic Neutrinos

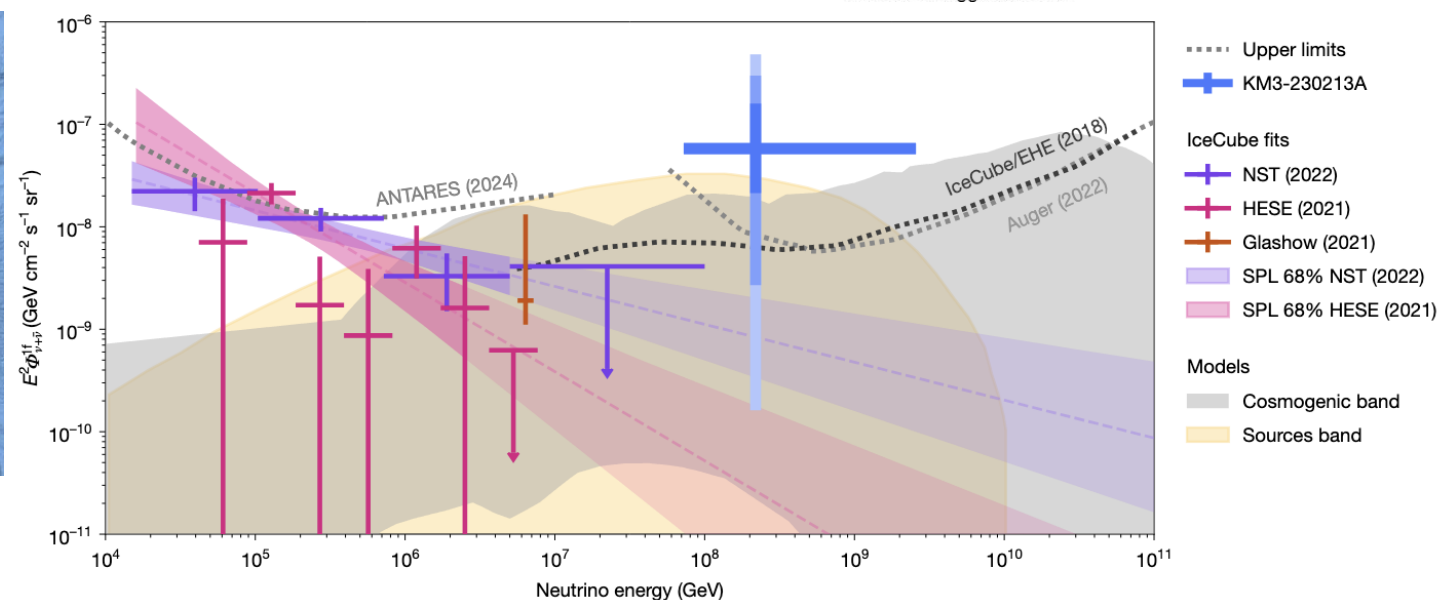
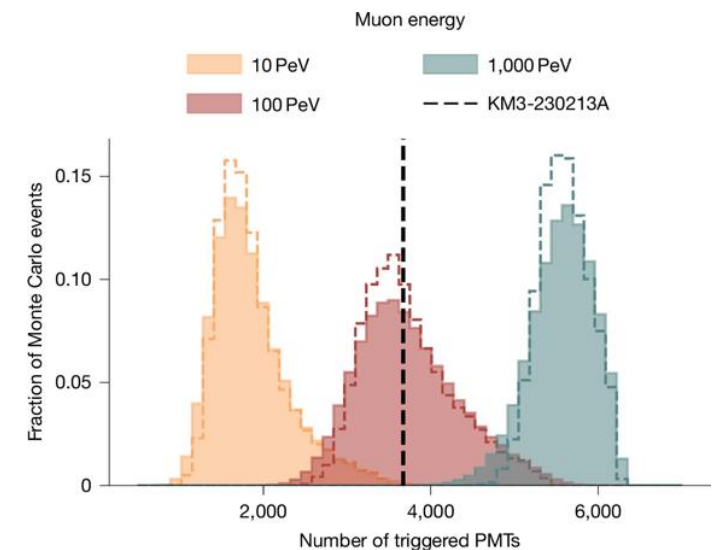


The Highest Energy Neutrino Ever Detected

- 10^{17} eV Neutrino Event seen with KM3Net
- A single UHE event was detected in Summer 2024
- Is this the first hint of cosmogenic neutrinos?
(see S. Celli talk tomorrow)



KM3Net Coll., Nature 2025

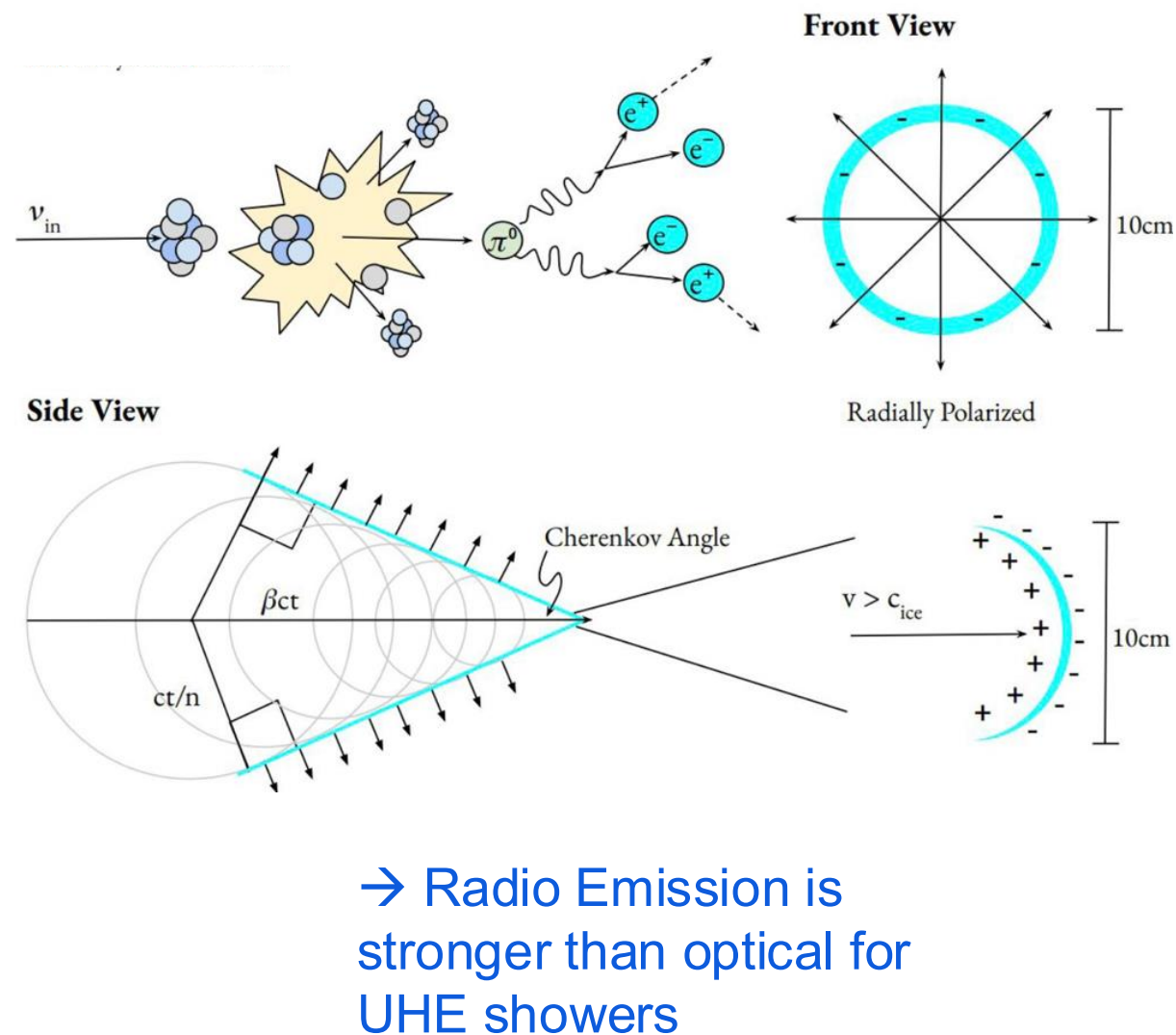


Neutrino 2026

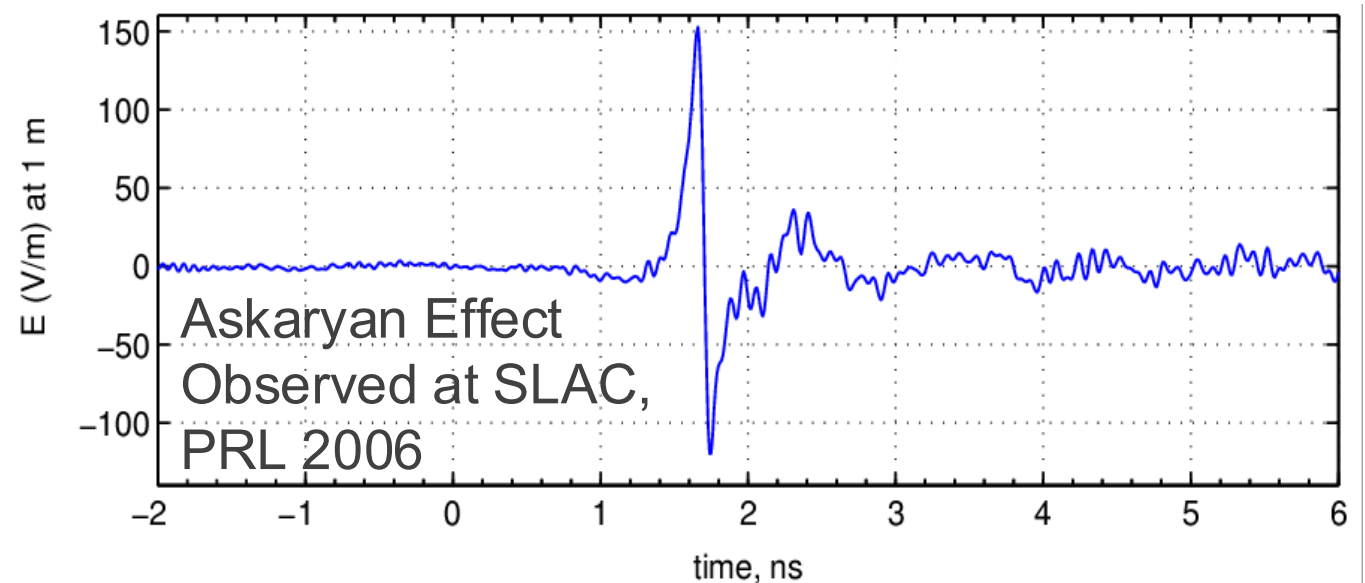
4

Slide from A. Viereggs

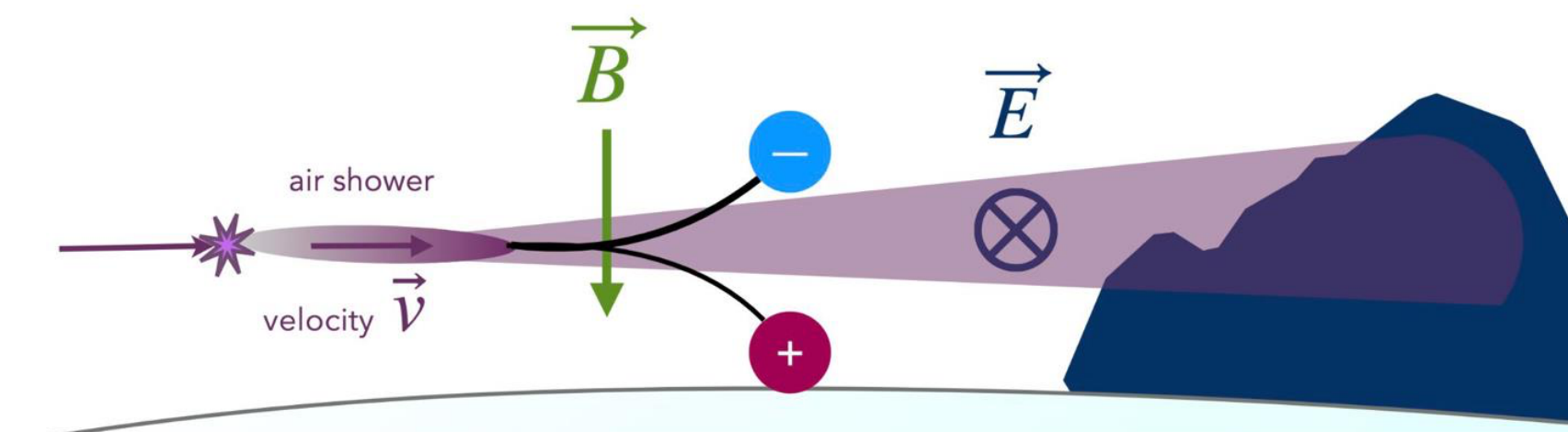
Method 1: Radio emission from neutrino interactions in a dielectric



- EM shower in dielectric (ice, sand) → moving negative charge excess
- Coherent radio Cherenkov radiation ($P \sim E^2$) if $\lambda >$ Moliere radius, called the **Askaryan Effect**



Method 2: Emission (Radio or Optical) from Tau Neutrino Induced Air Showers

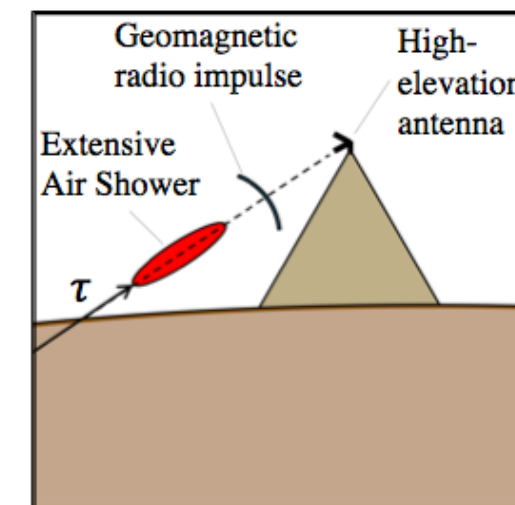
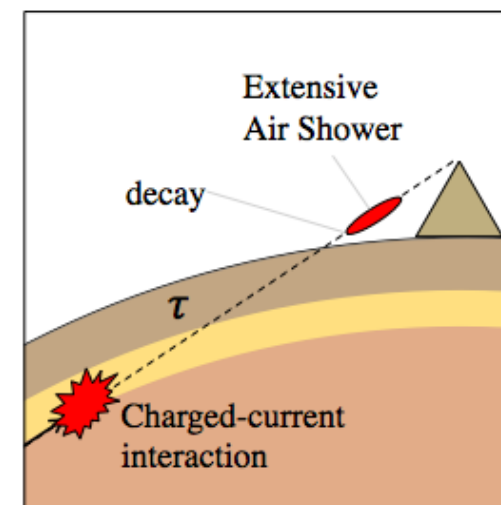
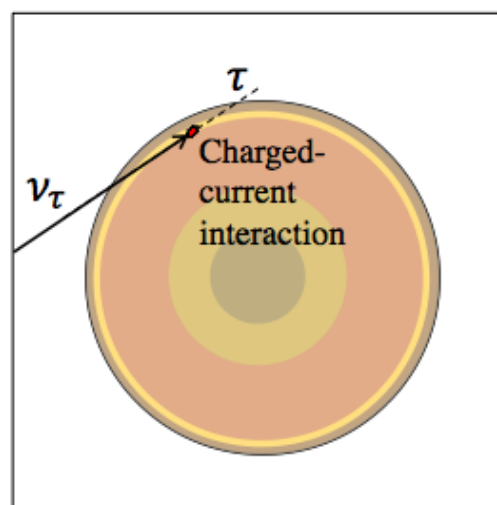


Extensive air showers initiated by high energy particles hitting the atmosphere make geomagnetic radio emission

S. Wissel

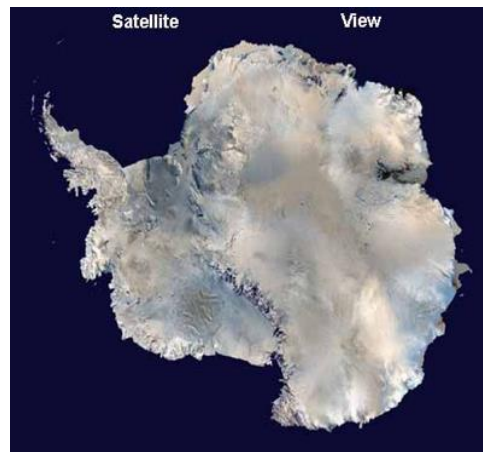
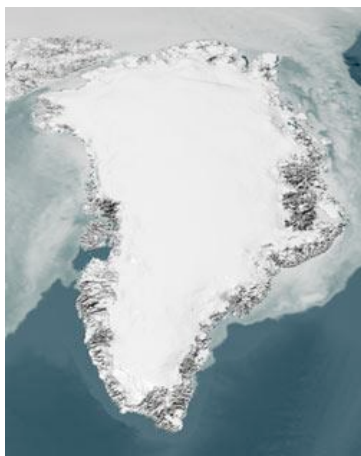
Neutrino-induced signals:

- Looks like an upward going cosmic ray air shower
 - Observe from surface, a mountain, balloon, or space
- (See posters from C. Trimarelli, R. Thong, K. Tran, C. Arguelles Delgado, A. Roy)



Radio Neutrino Astronomy Across Energy Scales

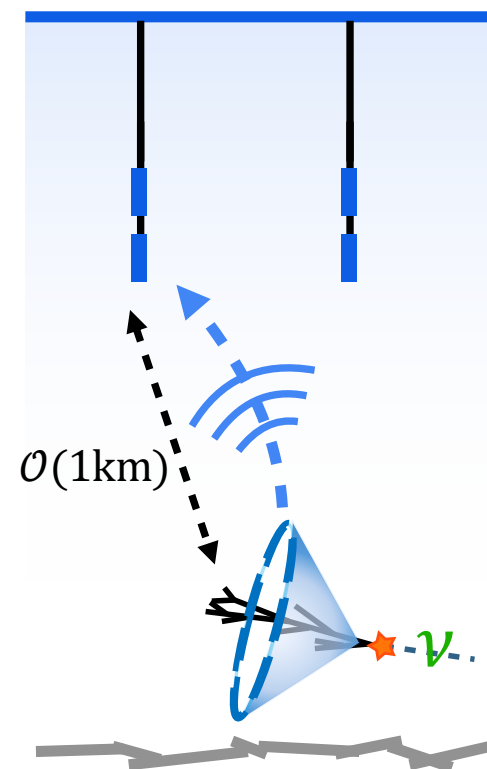
Need a huge ($\sim 100 \text{ km}^3$), radio-transparent detector: glacial ice



We need different instruments to cover the full energy range of expected cosmogenic neutrinos, above the energy range of IceCube and KM3NeT

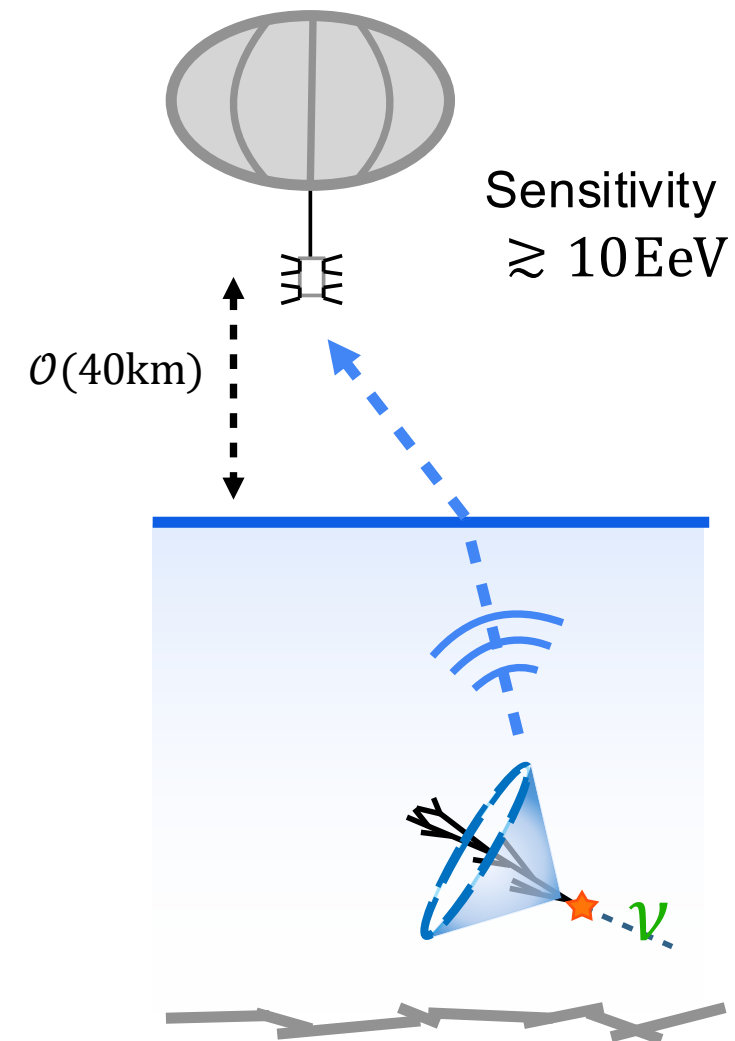
Ground-based

Sensitivity
 $\gtrsim 100 \text{ PeV}$



Balloon-based

Sensitivity
 $\gtrsim 10 \text{ EeV}$

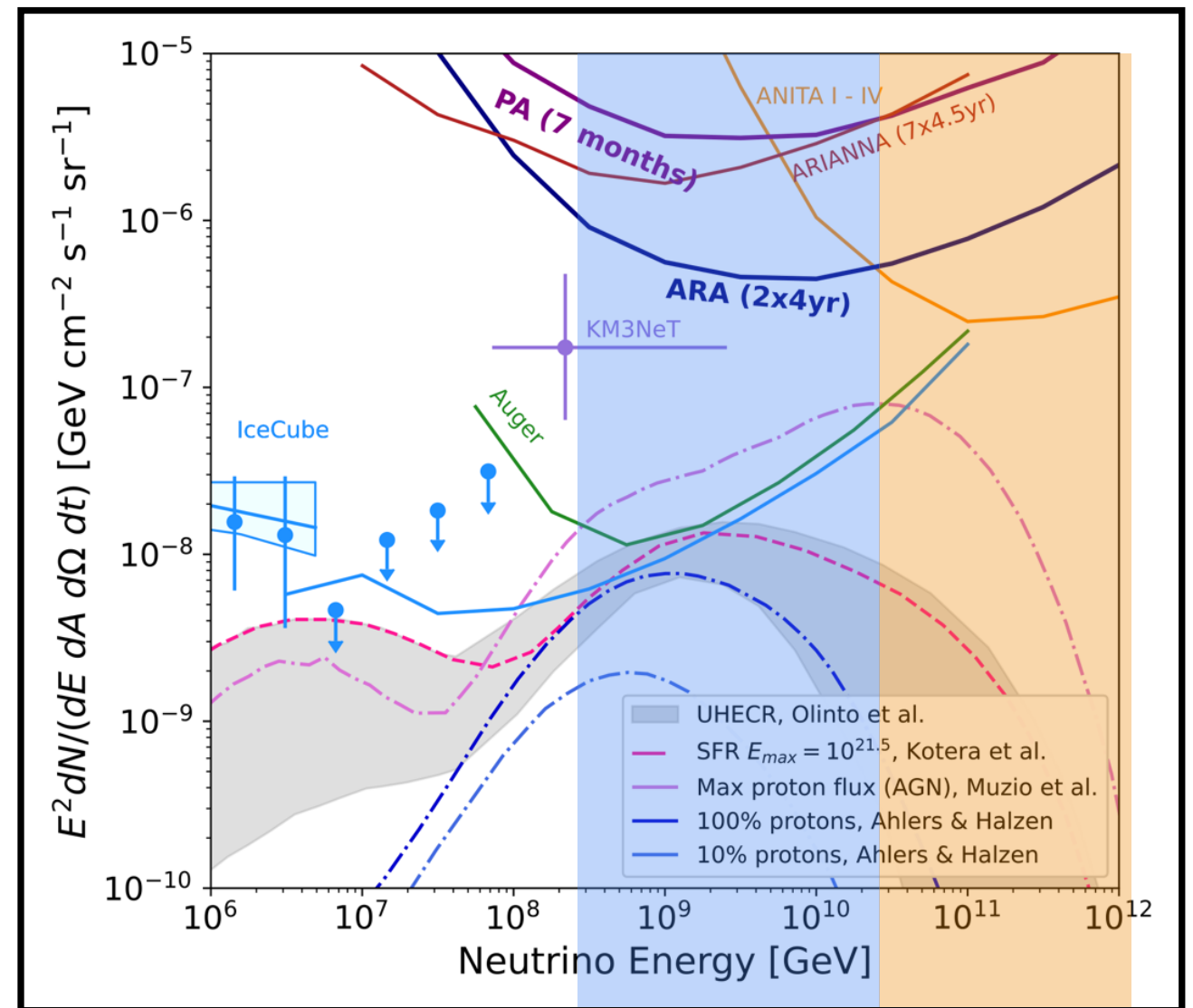


Best Constraints at the Highest Energies

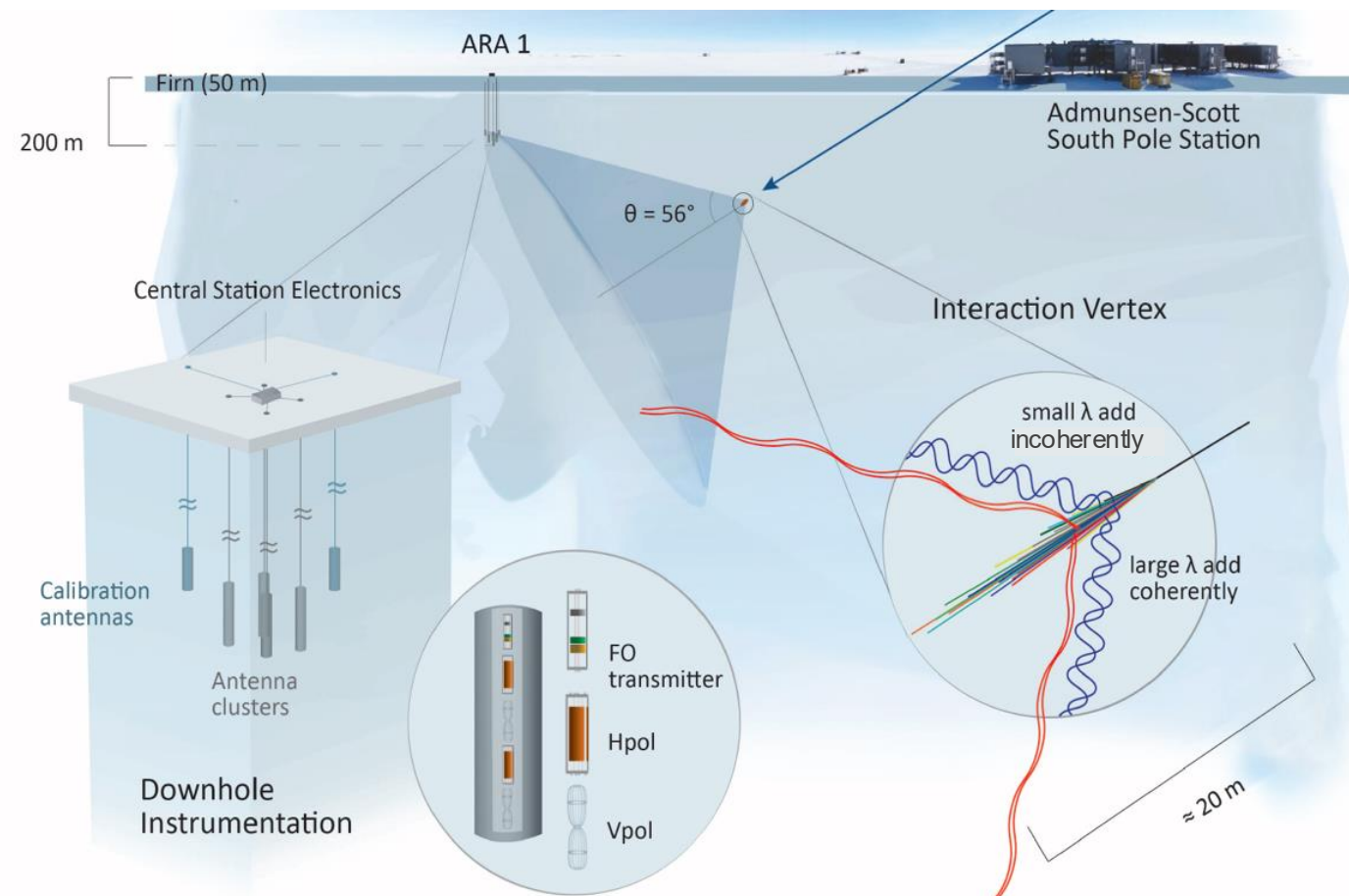
The best sensitivity up to $10^{19.8}$ eV is currently from IceCube.

Small ground-based in-ice radio experiments have provided constraints (e.g. ARA, ARIANNA), and a larger array is currently under construction (RNO-G).

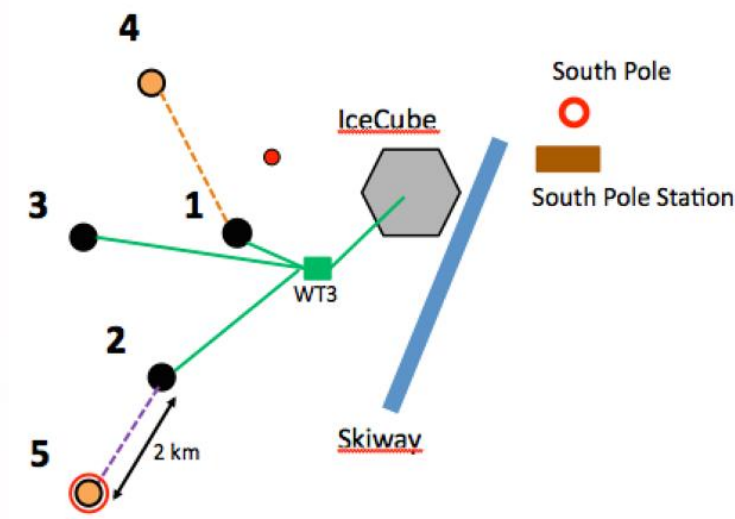
At the highest energies, the best constraints come from a balloon-borne experiment (ANITA), and the next-generation experiment just flew (PUEO)



The Askaryan Radio Array (ARA)



- 5 Stations of Ground-Based Radio Detectors at the South Pole
- Most recent instrumentation install was 2017/18



New Results This Year: Observation of Askaryan Emission

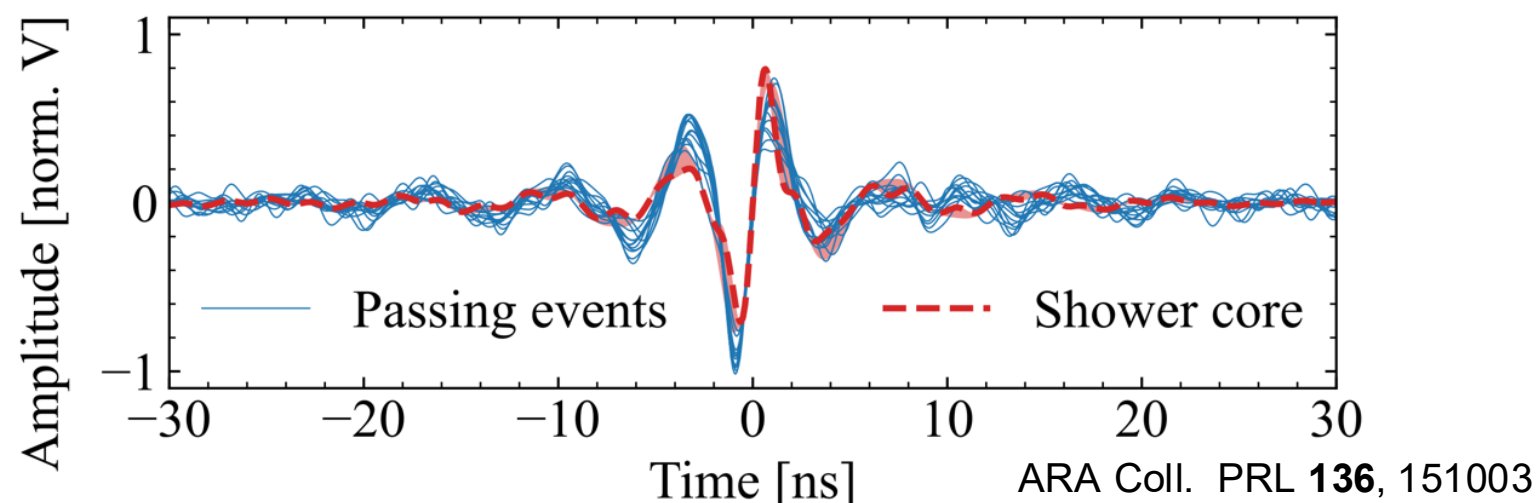
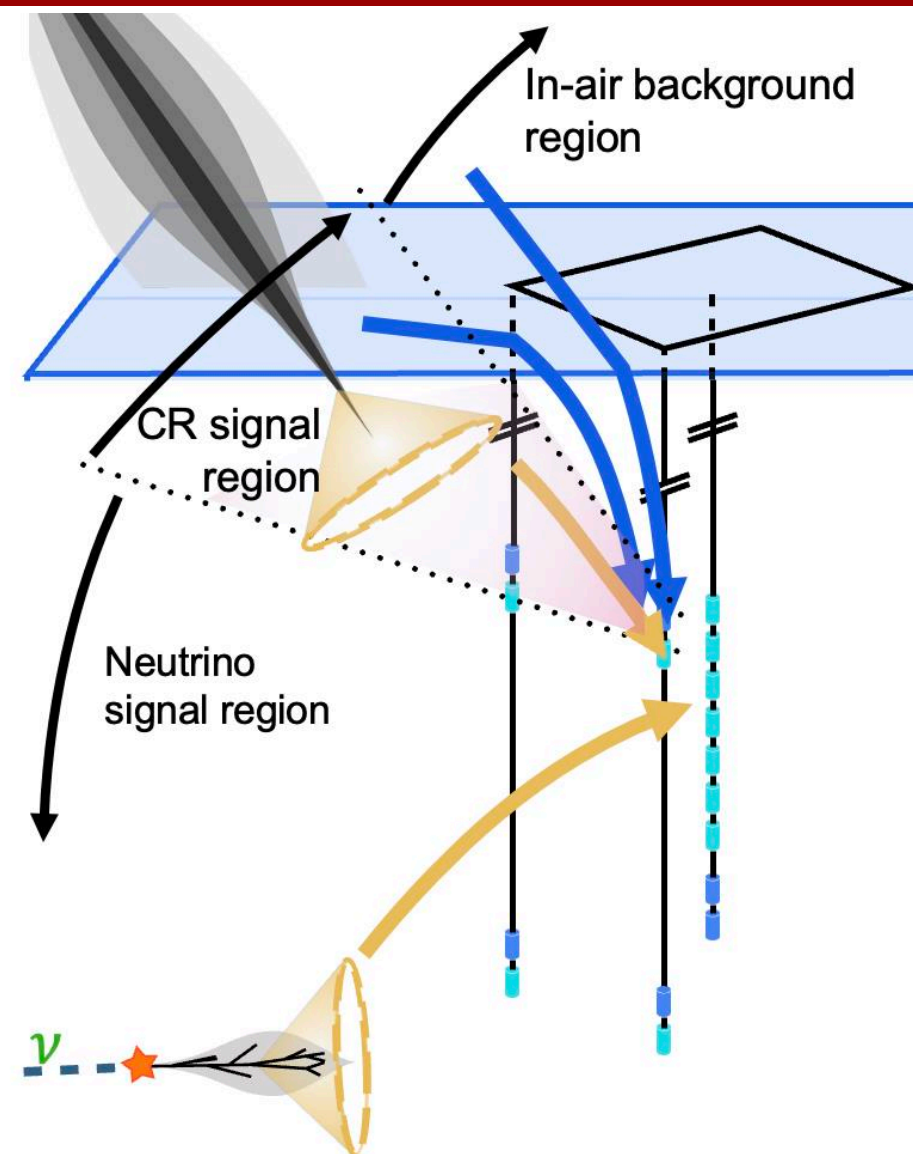


Observation of Askaryan Emission from Ultrahigh Energy Cosmic Rays in Ice

- 13 events observed (5.1σ above background)
- Similar event shape, frequency content, the same electric field polarity, and match simulations (signal shape as well as expected event rates) well.

Why is this important?

- First validation of Askaryan emission models and dense shower physics at these energies
- Calibration and validation of neutrino sensitivity for Askaryan detectors



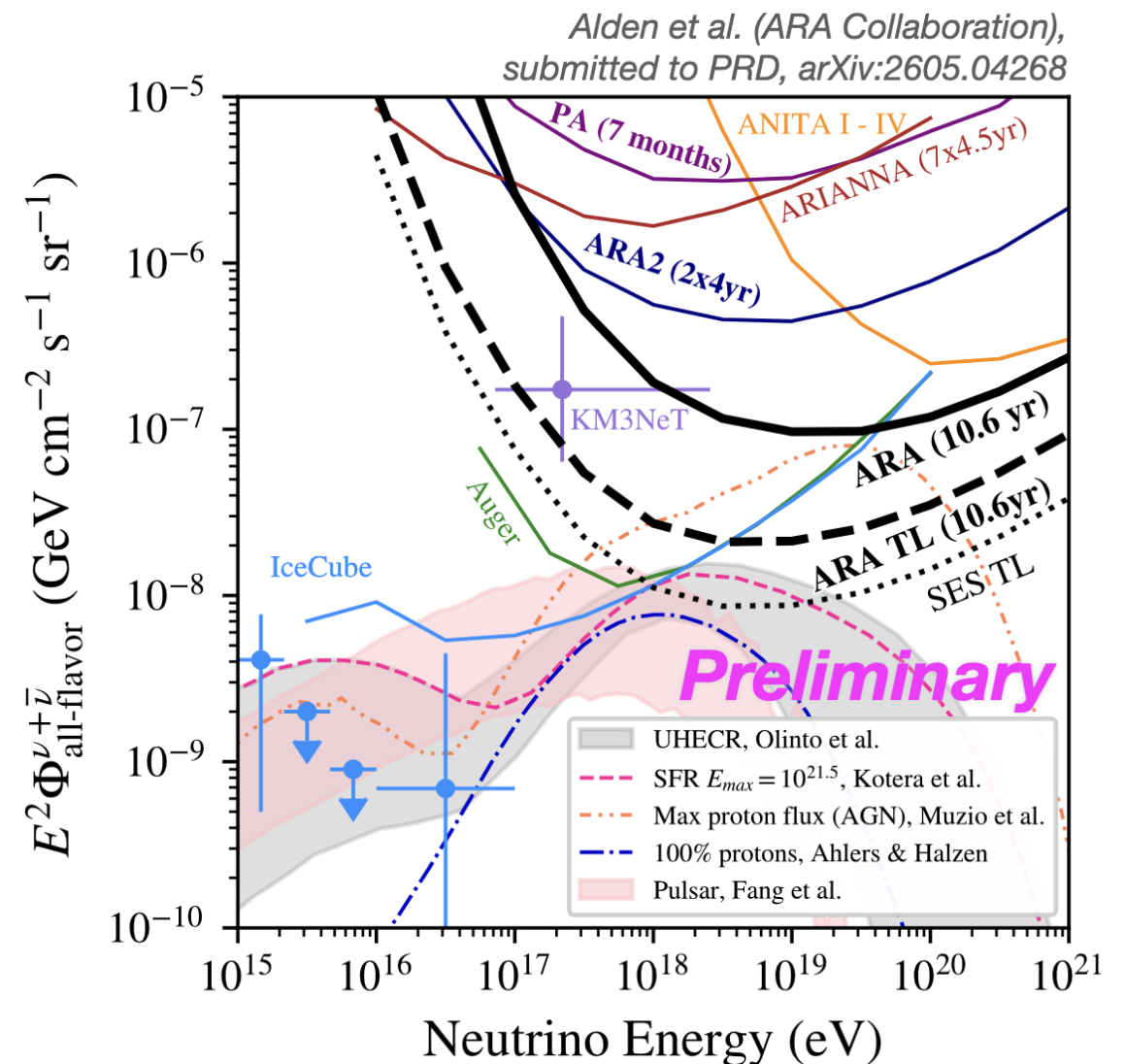
New Results This Year: New Constraints on Diffuse Flux



New Constraints on the UHE Diffuse Neutrino Flux (Unblinded Last Month!)

- Analyzed 10 Years of ARA Data from all 5 ARA stations: 2013-2023
- Best sensitivity to date above $10^{19.5}$ eV
- Background estimate across 10 years and 5 stations is: 0.13 ± 0.01
- Unblinding: 1 event observed (further inspection of the event indicates it is likely to be background from the detector itself)

See poster from M. Seikh!



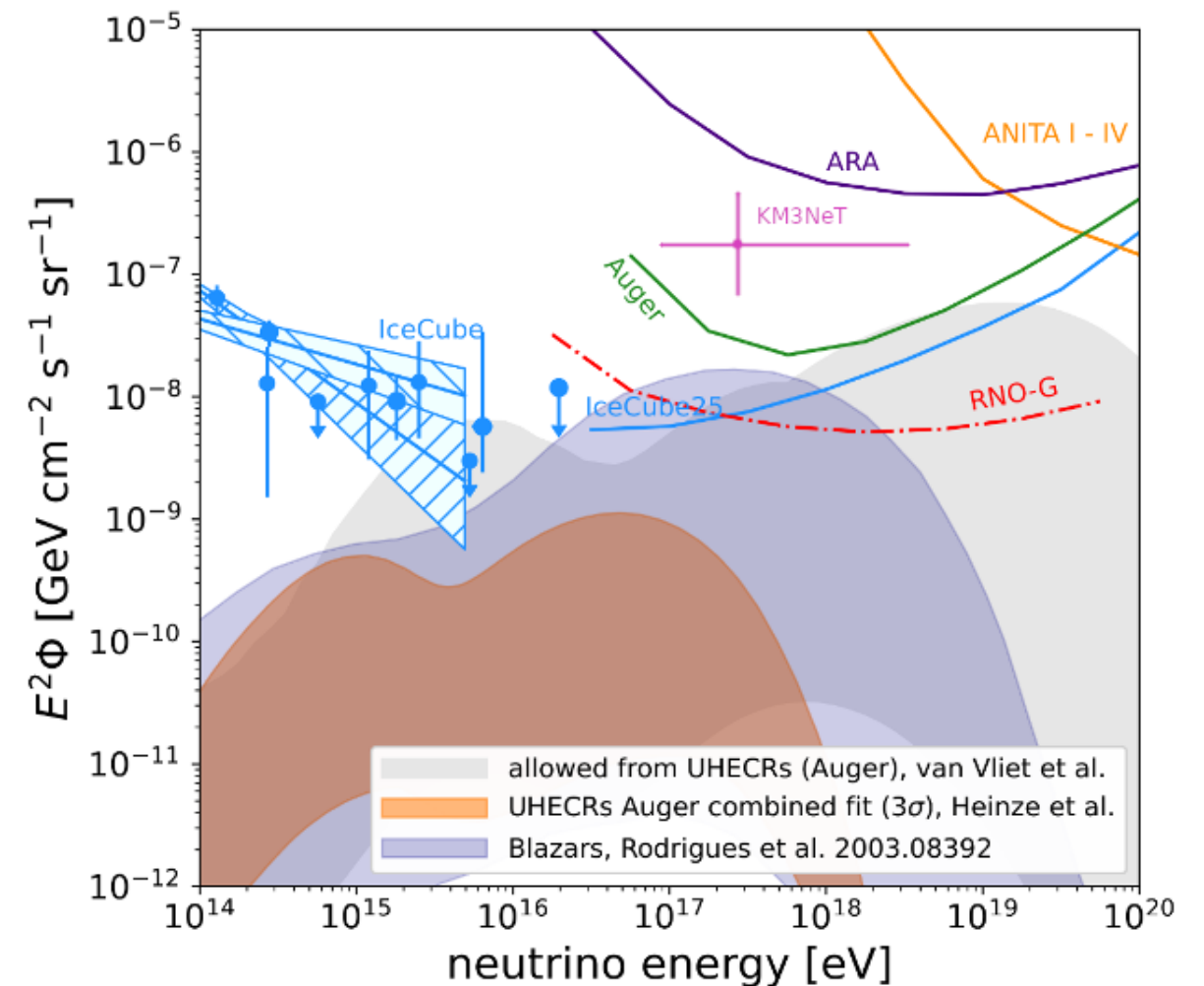
Radio Neutrino Observatory in Greenland (RNO-G)



- RNO-G is currently being installed at Summit Station in Greenland (first hardware deployed in 2021).
- RNO-G is designed to be scalable to even larger arrays (IceCube-Gen2 Radio Array)



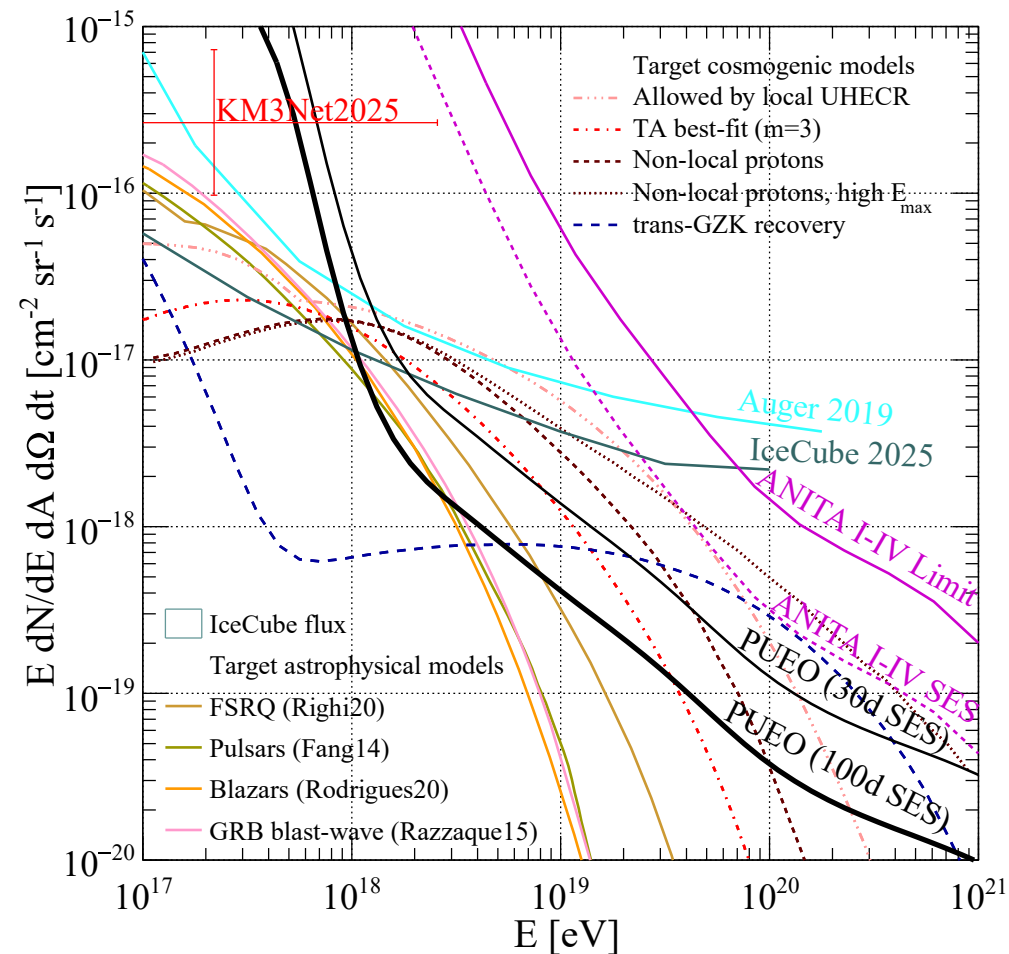
See Poster from A. Nozdrina



PUEO: The Payload for Ultrahigh Energy Observations



PUEO Neutrino Sensitivity Projections



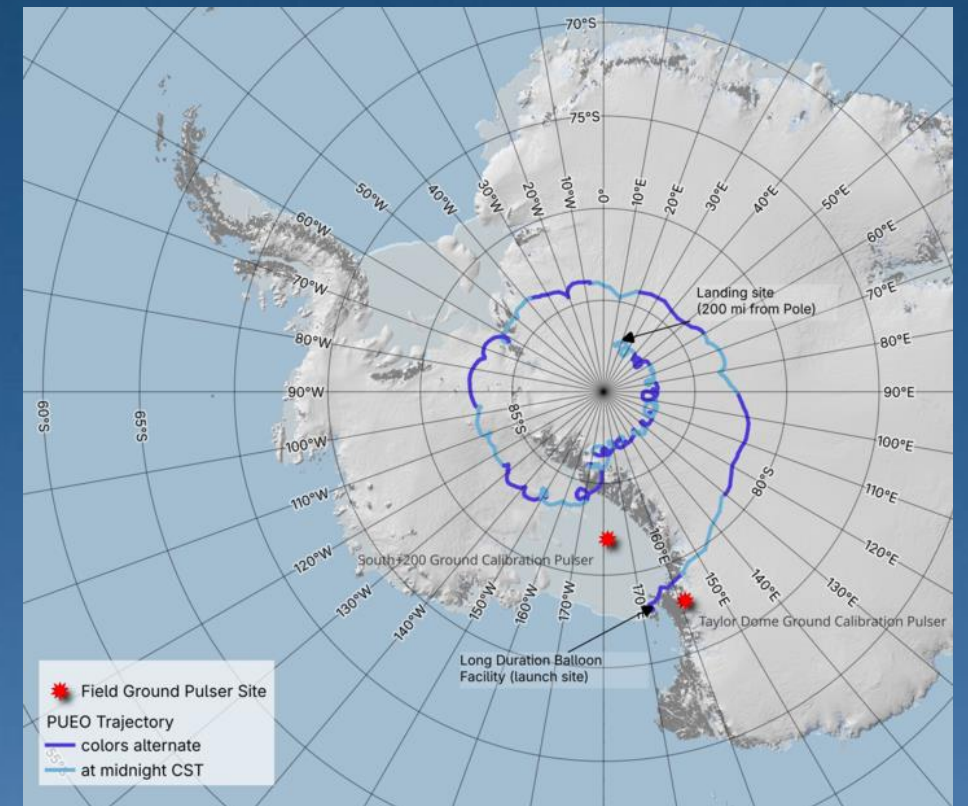
See Posters from R. Scrandis and T. Coakley

Neutrino 2026

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Slide from A. Viereggs

Launch: December 20, 2025
23 Day Flight

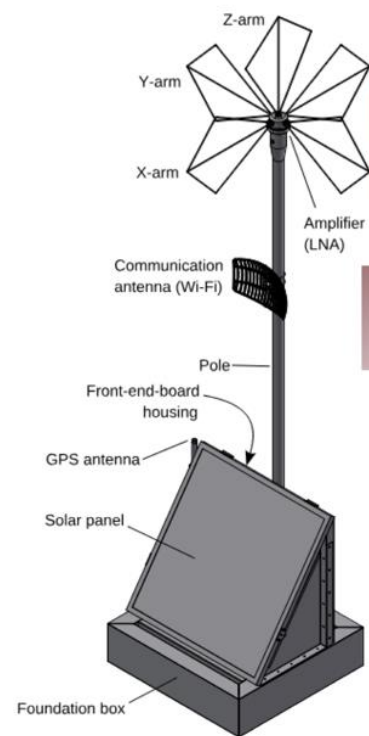


Slide from A. Vieregg

GRAND: Giant Radio Array for Neutrino Detection



✱ GRANDProto300 & other prototypes: **experimental setup**



Deployment of 13 antennas in Gansu (China)
65 in 2025 and 200 more later

Deployed Feb 2023

Deployment of 10 antennas on the Auger site
in Malargüe, Argentina (cross-calibration)

Deployed Aug 2023

Deployment of 4 antennas in Nançay radio
observatory (France) for trigger test (LPNHE)

Deployed Oct 2022



Full GRAND: 200,000 antennas, on a plateau, looking for skimming air showers induced by tau neutrino interactions in the Earth



GRAND Coll. ICRC 2025

GRAND Coll. Moriond 2025 (Ferrière, Guelfand, Lavoisier)

Neutrino 2026

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Slide from A. Viereggs

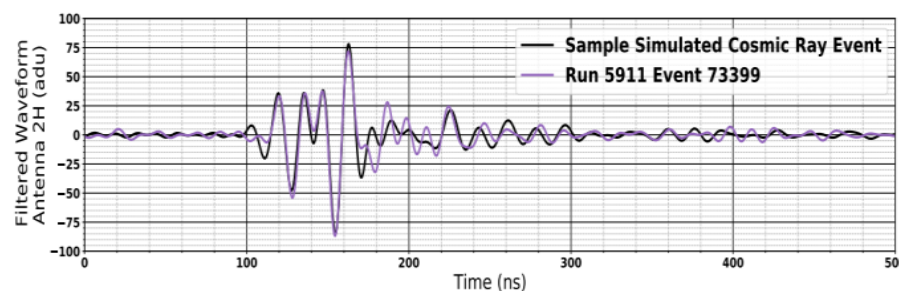
BEACON: The Beamforming Elevated Array for Cosmic Neutrinos



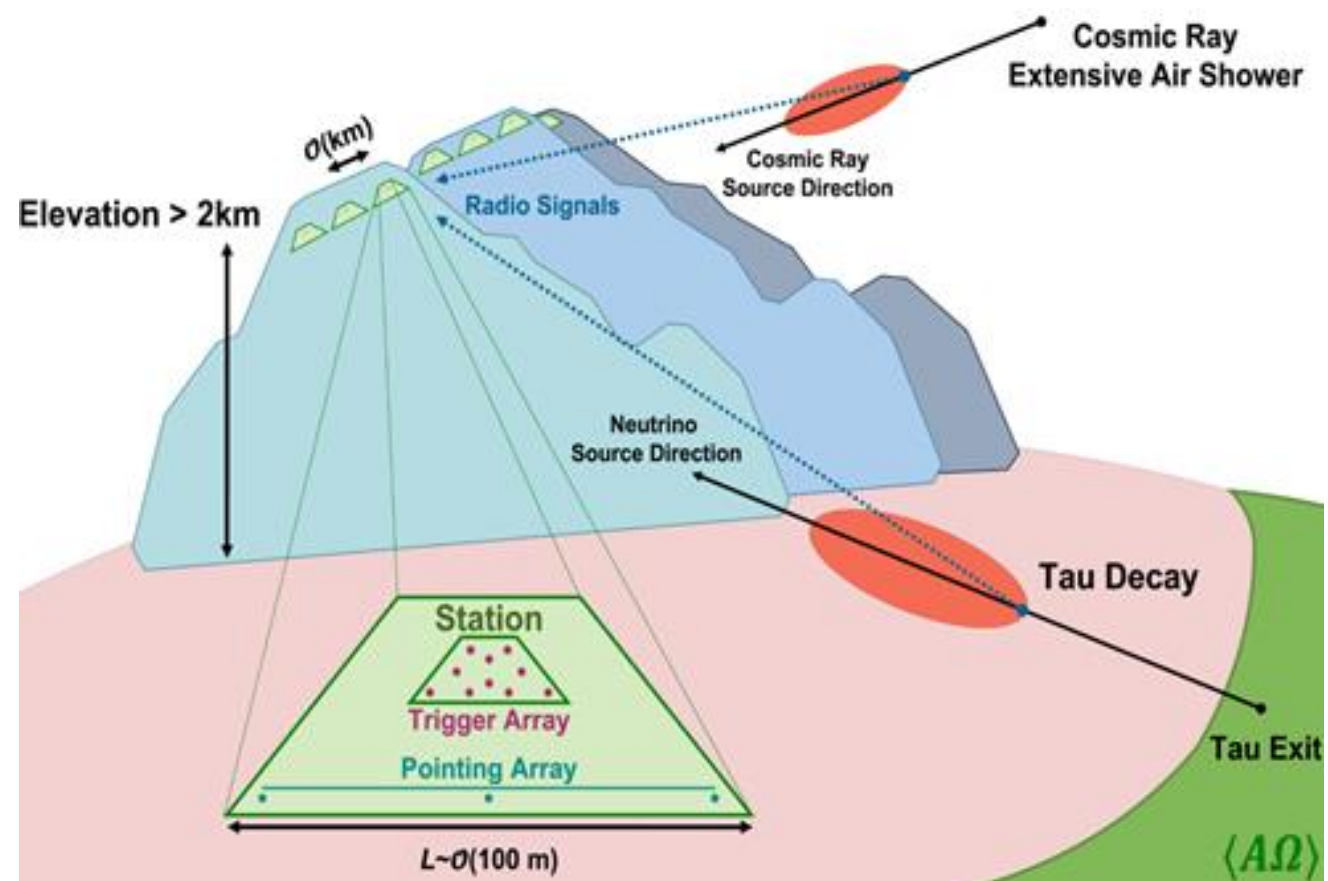
Concept: $\mathcal{O}(1000)$ antennas, in beamforming stations on high mountaintops, designed to detect the radio emission of upgoing air showers created by earth-skimming ν_τ . Being on a mountain helps.



Cosmic-ray candidates event identified with prototype



S. Wissel et al. JCAP11(2020)065, D. Southall et al NIM-A 2022



Neutrino 2026

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Slide from A. Viereg

HERON: Hybrid Elevated Radio Observatory for Neutrinos



HERON=BEACON+GRAND

- 24 compact beamforming stations, of 24 antennas each, are embedded within a large sparse array of 360 standalone antennas
- Elevated 1-2 km above a valley floor
- Each beamforming station triggers the 15 nearest standalone antennas
- Sparse array provides offline event reconstruction and background rejection, and a separate veto trigger.

Site: San Juan Province, Argentina.

Full construction (936 antennas) was funded recently by an ERC grant; plan is to construct and calibrate the full array in the coming 5 years.

