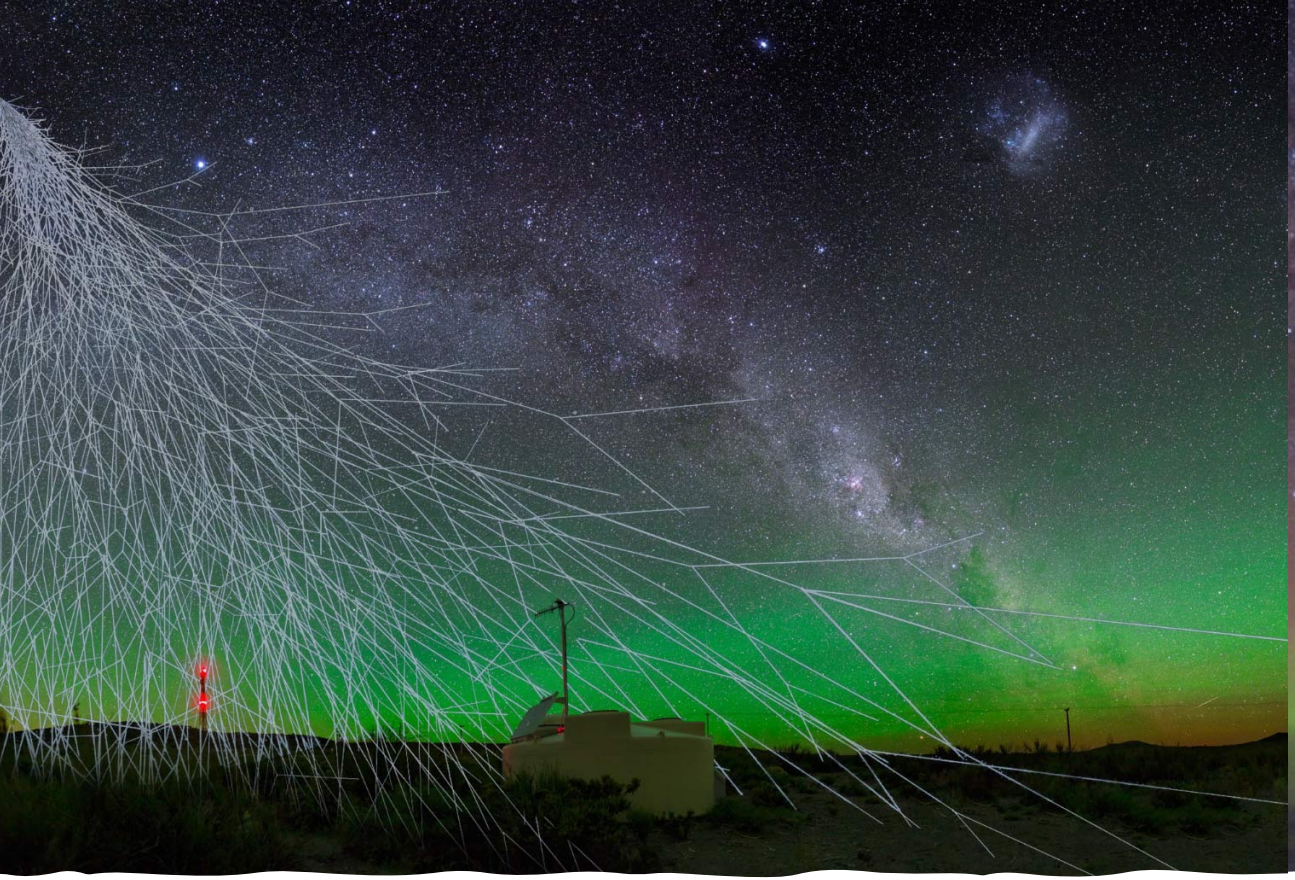
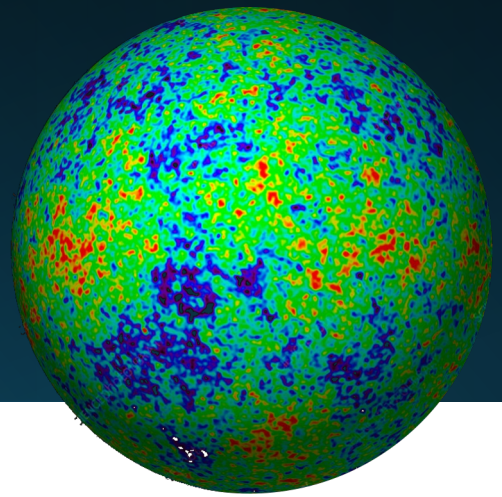


A Combined Fit of Ultra-High-Energy Cosmic Rays and Neutrinos from Pierre Auger and IceCube Observatories

Marco Muzio[1], Tianlu Yuan[2], Lu Lu[2]

1. Penn State University 2. University of Wisconsin-Madison



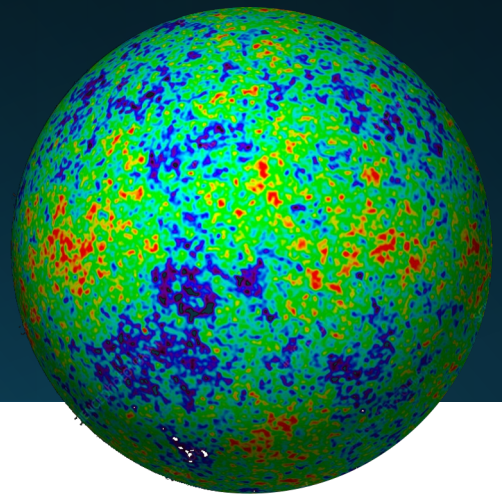
Source

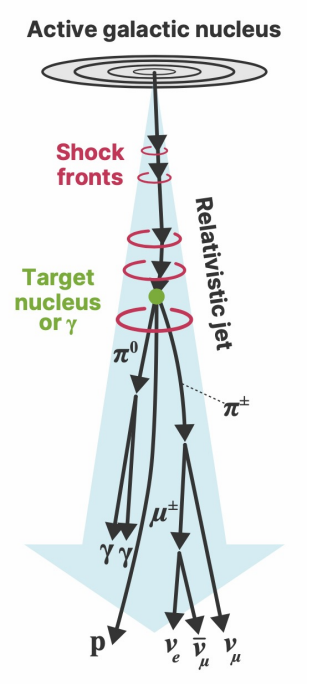
Intergalactic medium
10^-6 protons / cm3
400 photons / cm3

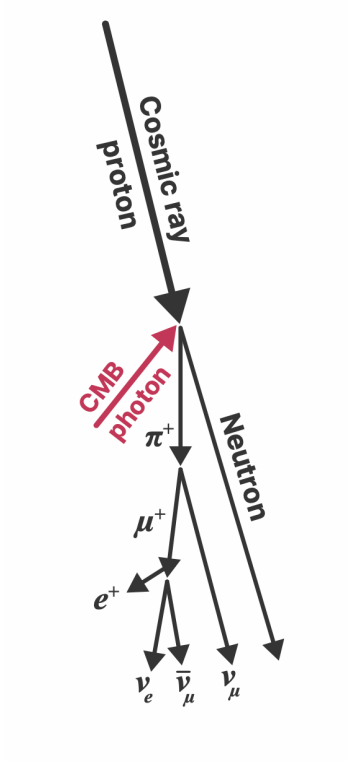
Interstellar medium
1 proton / cm3

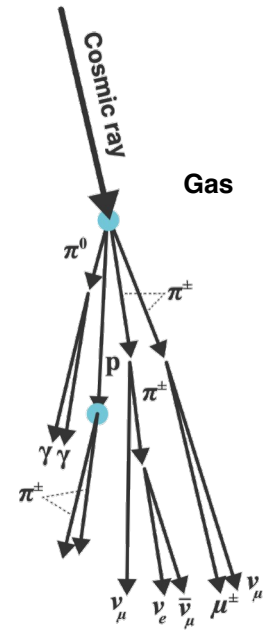
Earth atmosphere
7x10^20 proton / cm3

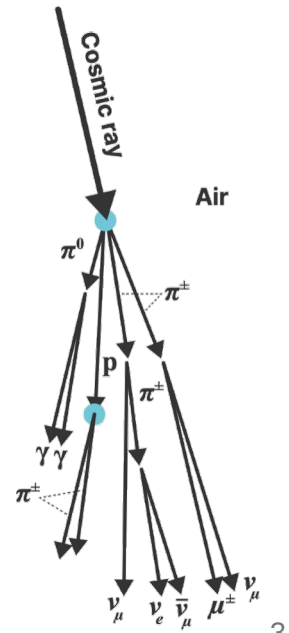
Neutrino production: proton and matter targets




Active galactic nucleus
Shock fronts
Relativistic jet
Target nucleus or γ
π^0
$\pi^\pm$
$\mu^\pm$
$\gamma\gamma$
p
ν_e $\bar{\nu}_\mu$ ν_μ

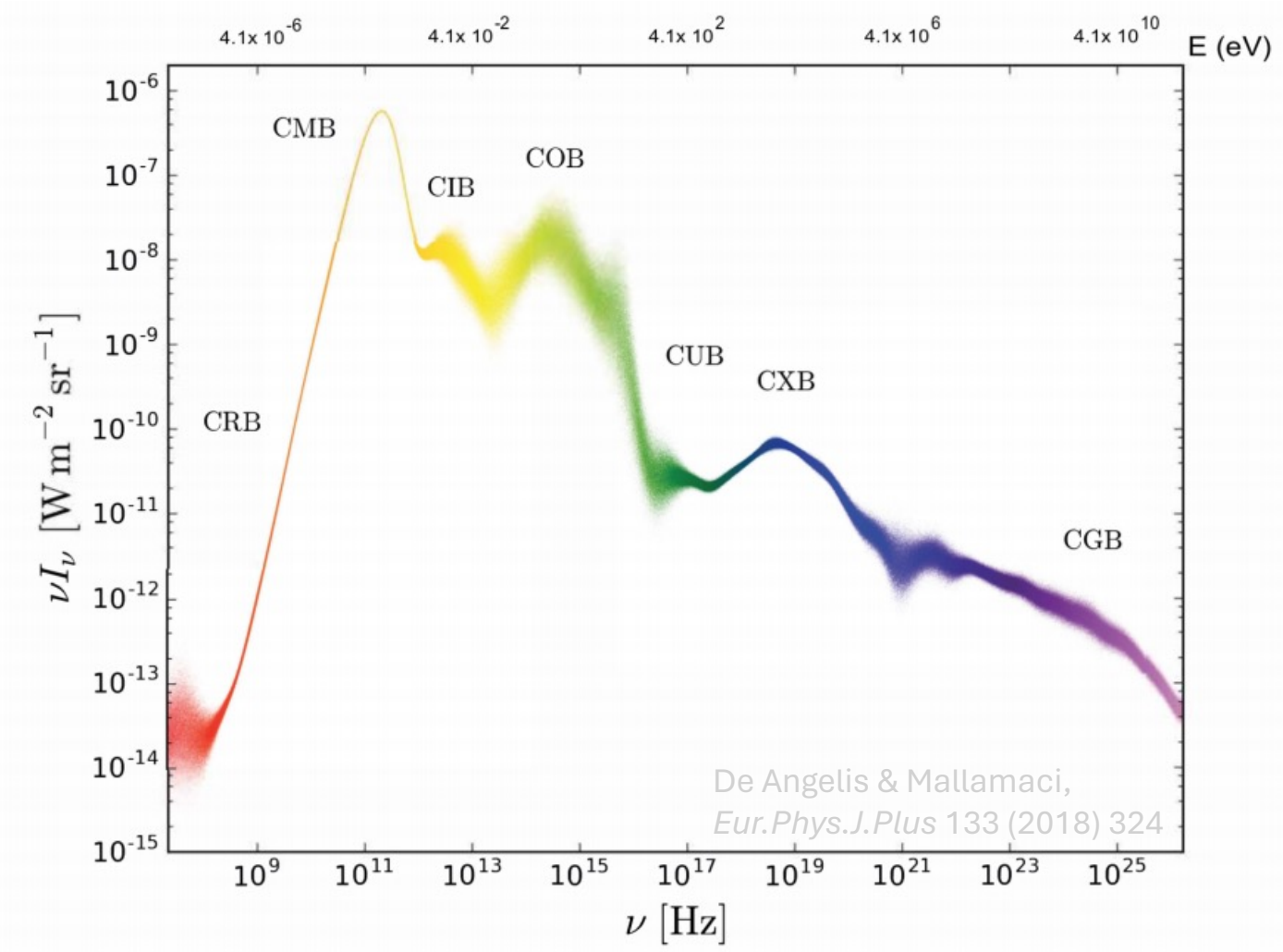

Cosmic ray proton
CMB photon
Neutron
π^+
μ^+
e^+
ν_e $\bar{\nu}_\mu$ ν_μ


Cosmic ray
Gas
π^0
$\pi^\pm$
p
$\gamma\gamma$
ν_μ ν_e $\bar{\nu}_\mu$ $\mu^\pm$ ν_μ


Cosmic ray
Air
π^0
$\pi^\pm$
p
$\gamma\gamma$
ν_μ ν_e $\bar{\nu}_\mu$ $\mu^\pm$ ν_μ

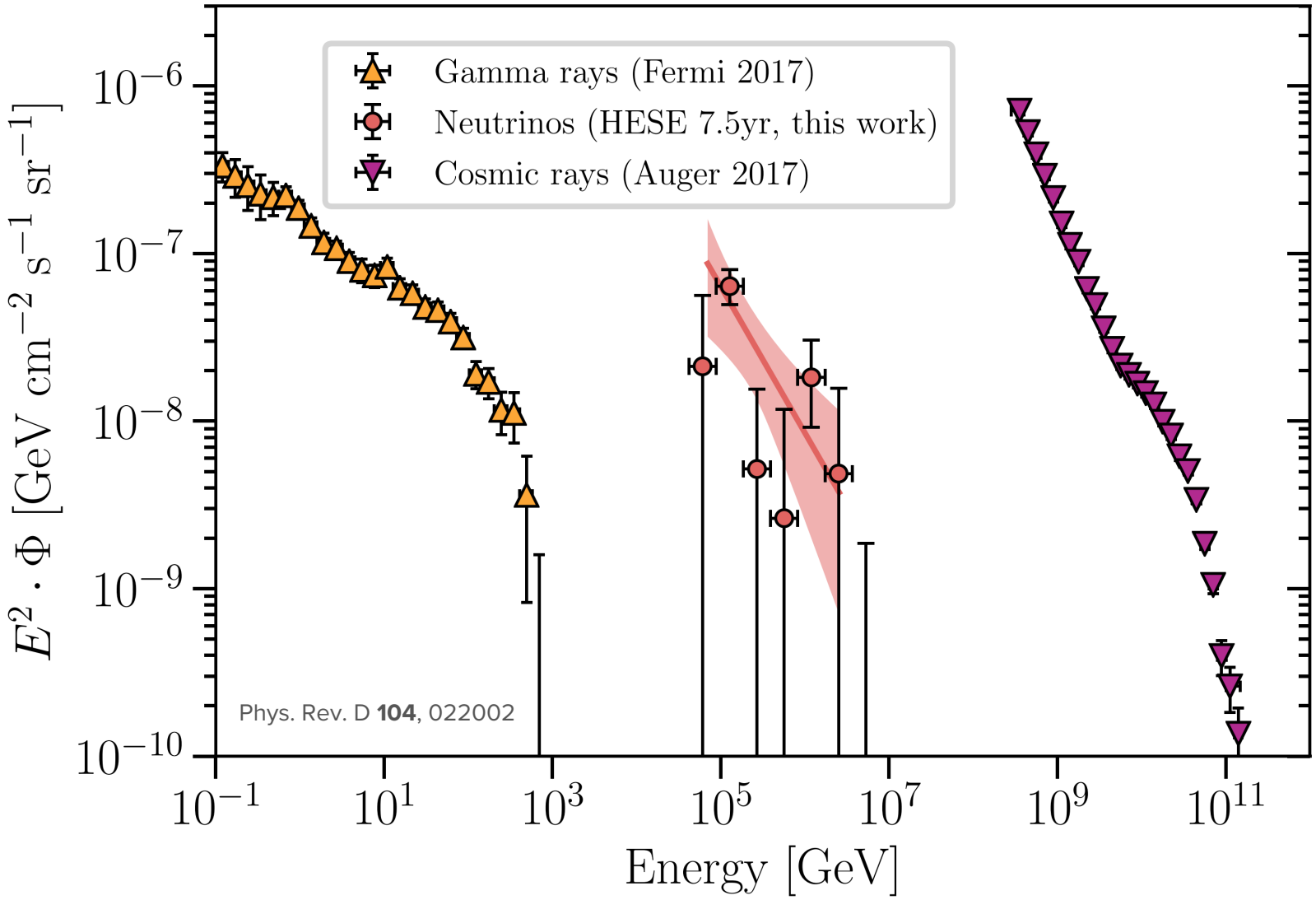
UHE neutrinos: a smoking gun signature

- Photopion produced neutrinos have 1/20 the primary energy-per-nucleon
- CMB target: $10^{19.7}$ eV energy threshold => EeV energy neutrinos
- CIB target: 10^{18} eV energy threshold => **O(10 PeV)** neutrinos
  - **Ambient photons** in source can also serve as target



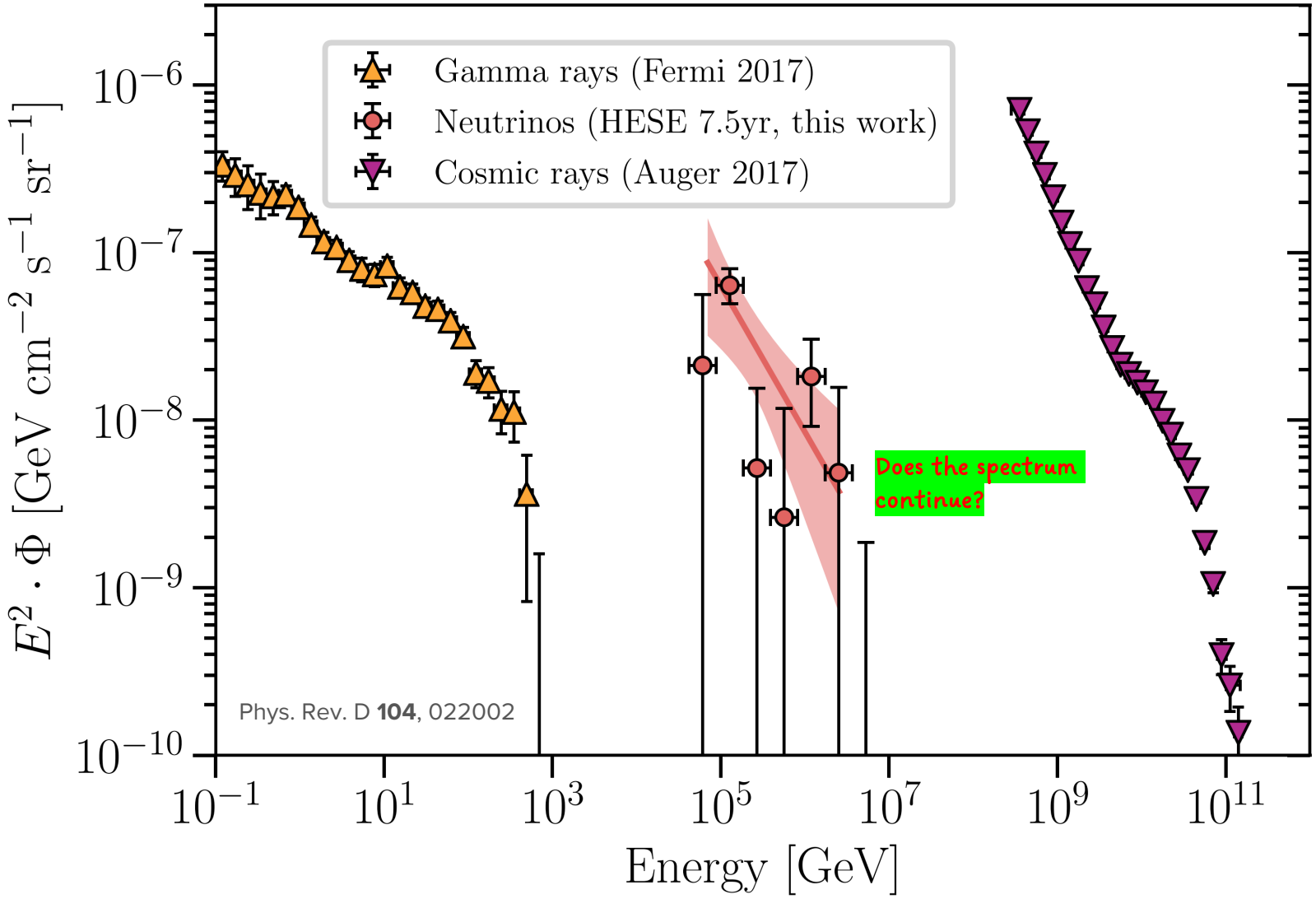
Neutrinos gateway to UHECR puzzle?

Energy generation rates are comparable among three messengers: common origin?

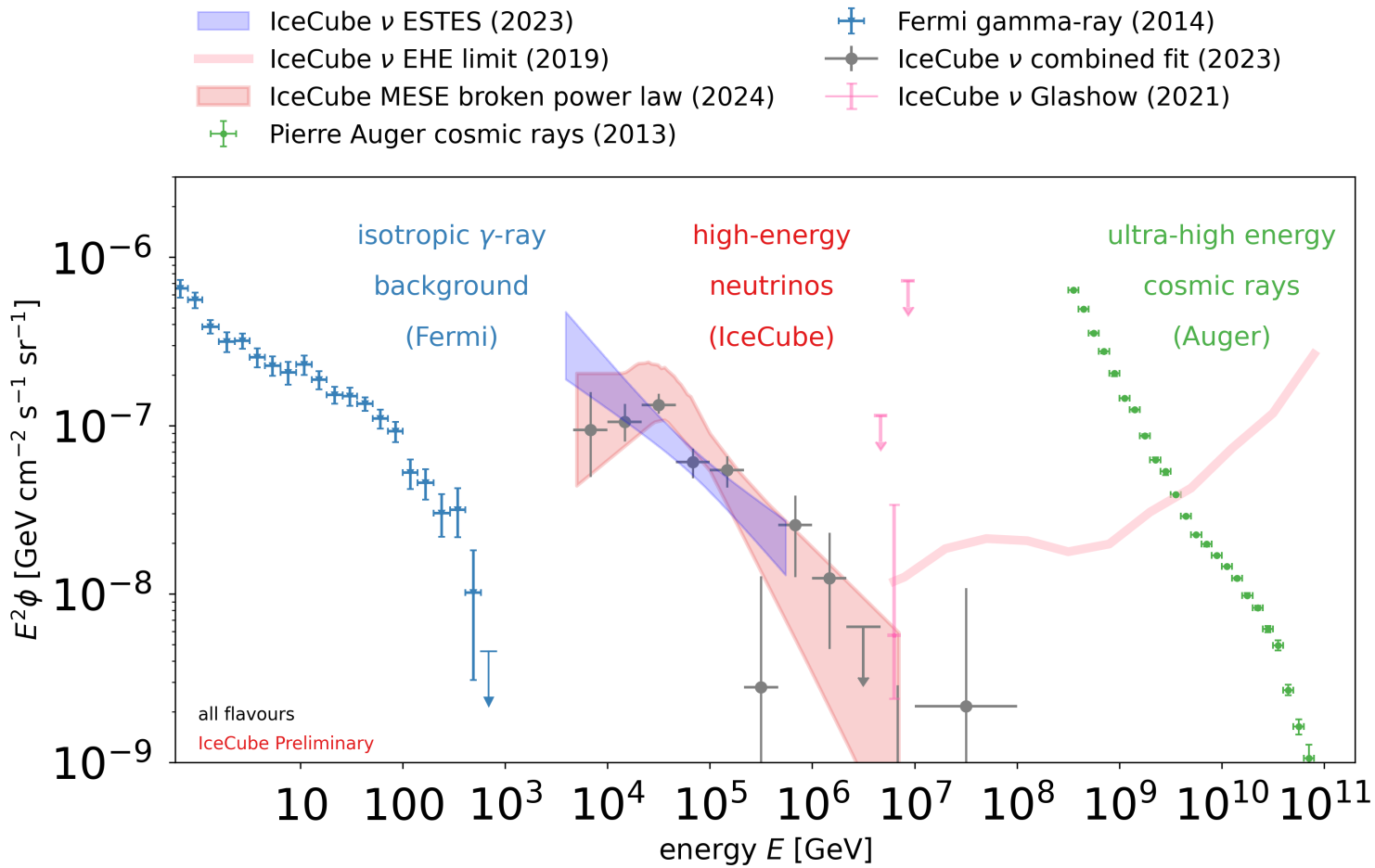


Neutrinos gateway to UHECR puzzle?

Data: Energy generation rates are comparable among three messengers



IceCube data at the highest energies



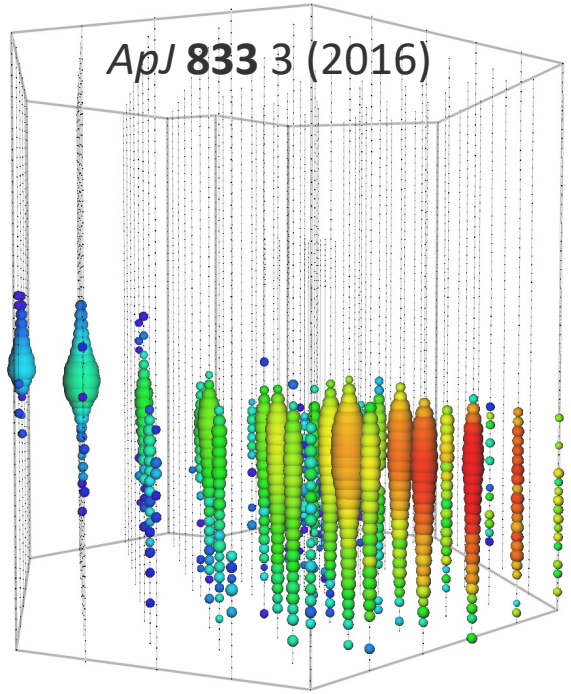
- **Combined fit**
  - Through-going tracks and contained cascades
  - More see Zoe Rechav's talk (Wednesday 4pm)
- **MESE**
  - Starting tracks and contained cascades
  - More see Vedant Basu's (Monday 5:15pm)
- **PEPE**
  - Partially contained cascades

New round of combined fits suggest a broken power law feature with a soft high-energy component

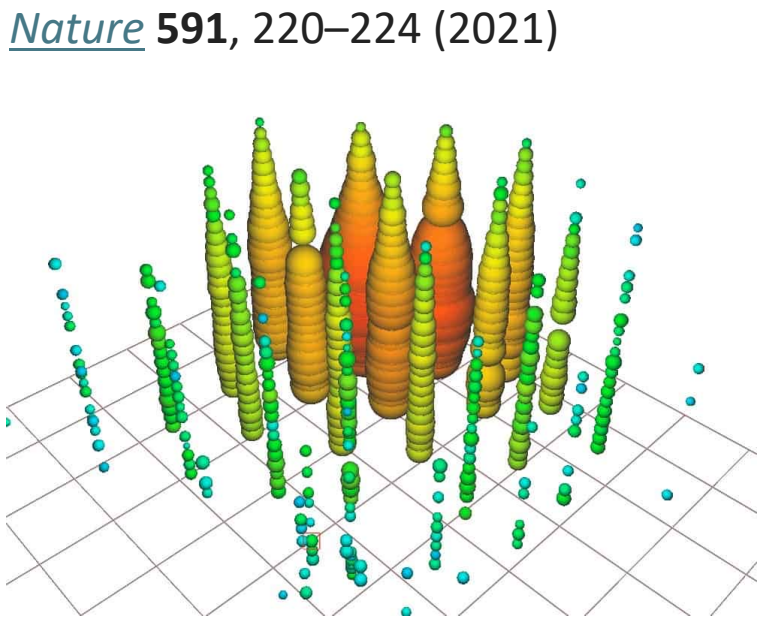
Uncertainties are at large beyond 10 PeV

The highest energy neutrinos

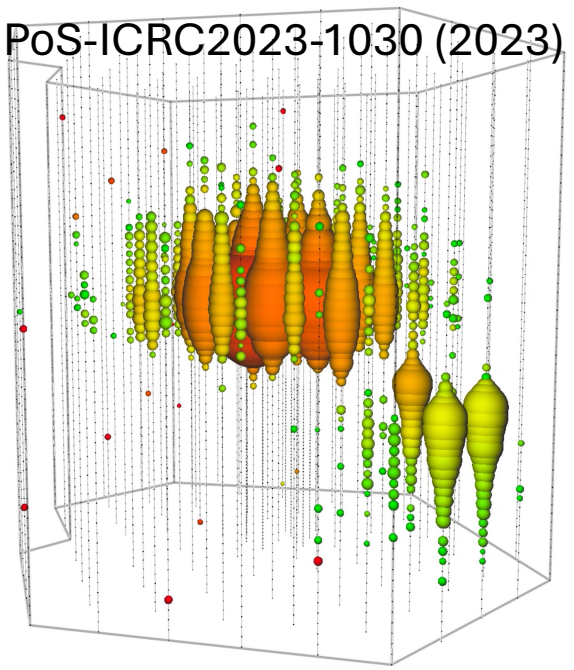
- 3 events with neutrino energy > 5 PeV over a decade of data taking



Muon energy: 4.5±1.2 PeV
Nu energy ~ 9 PeV



Deposited energy: 6.05 ±0.72 PeV
Nu energy ~6.3 PeV

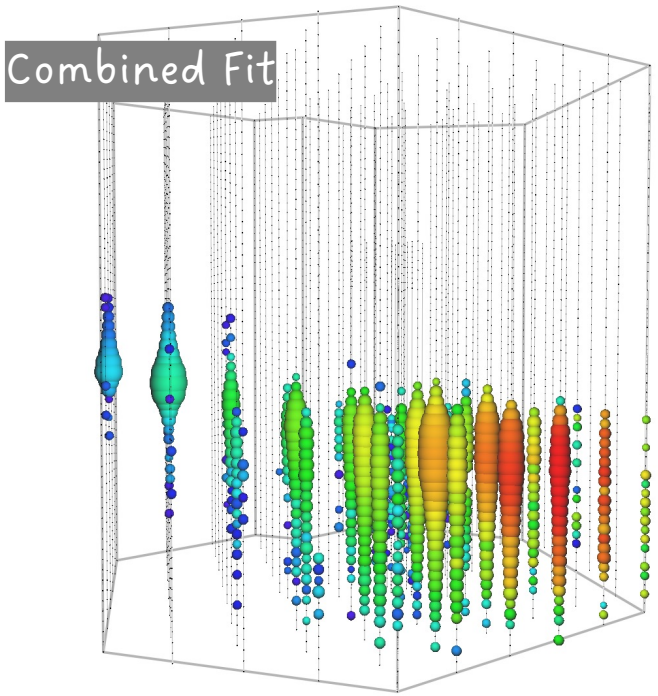


Nu energy ~11.4±2.5 PeV

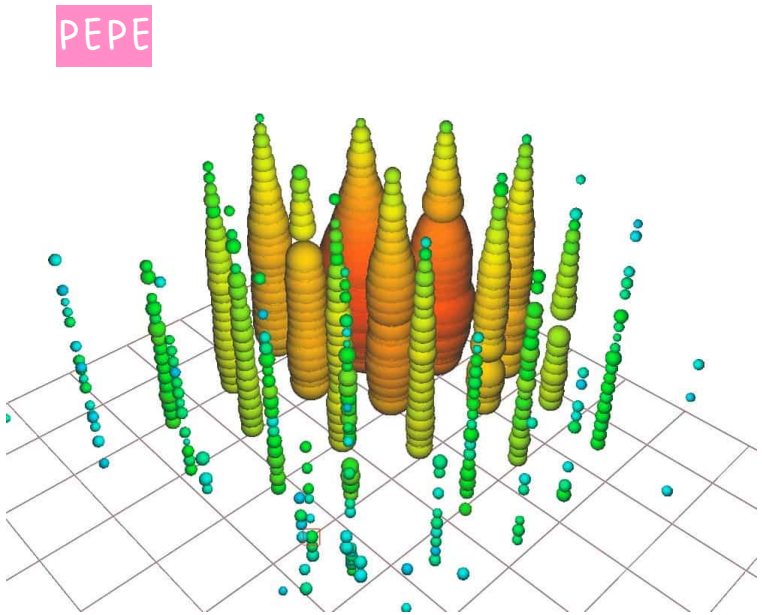
The highest energy neutrinos

Can we make a more conclusive statement on 10 PeV+ neutrino flux with all available datasets?

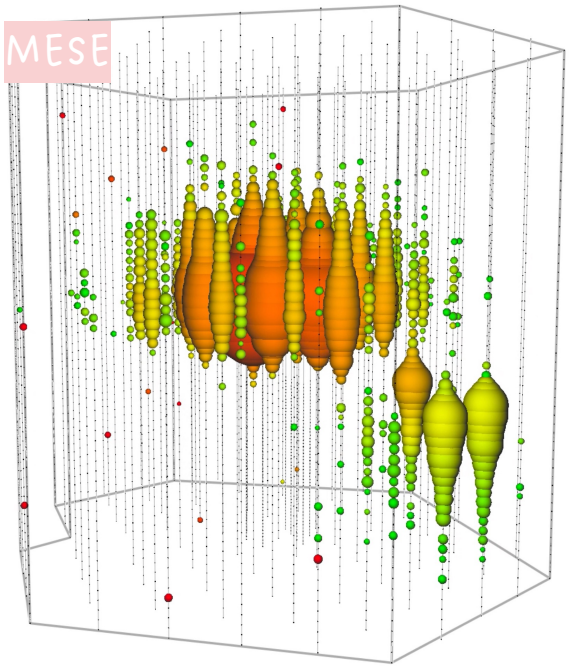
- 3 events with neutrino energy > 5 PeV over a decade of data taking



Muon energy: 4.5±1.2 PeV
Nu energy ~ 9 PeV



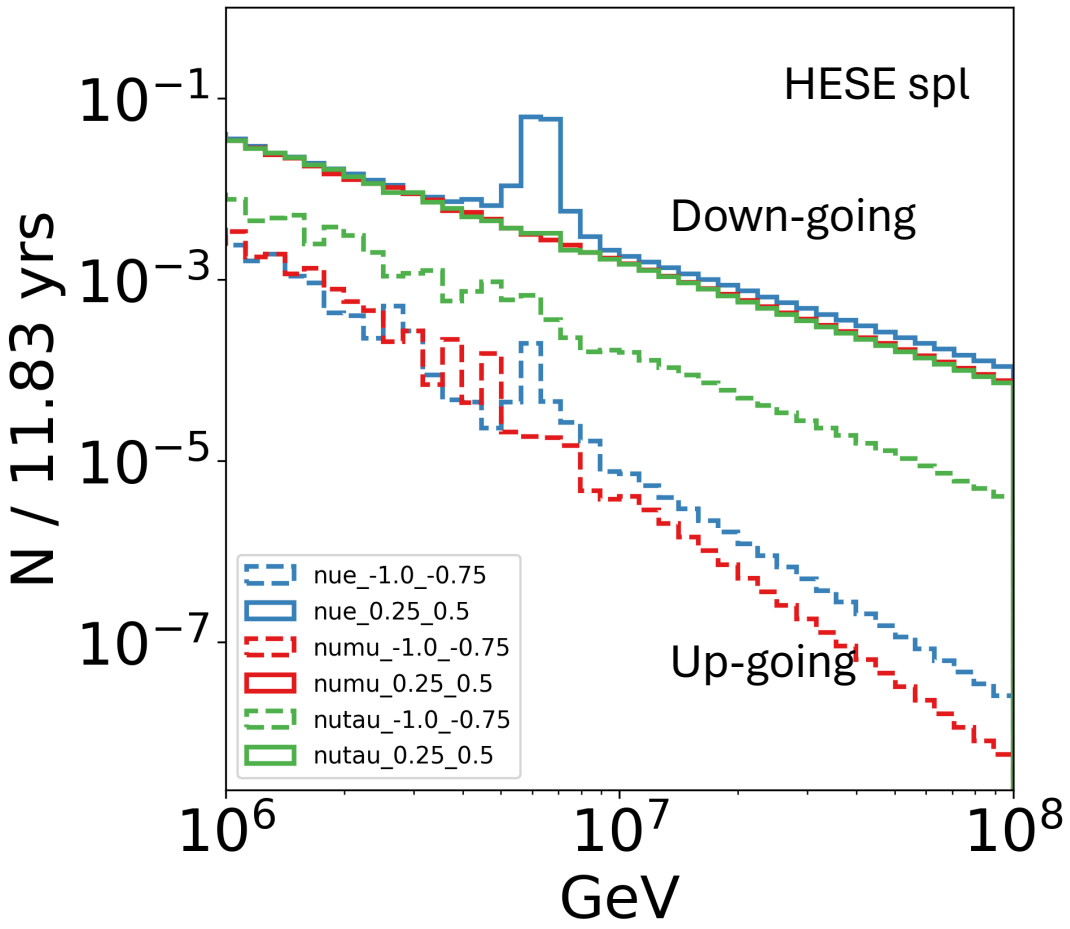
Deposited energy: 6.05 ±0.72 PeV
Nu energy ~6.3 PeV



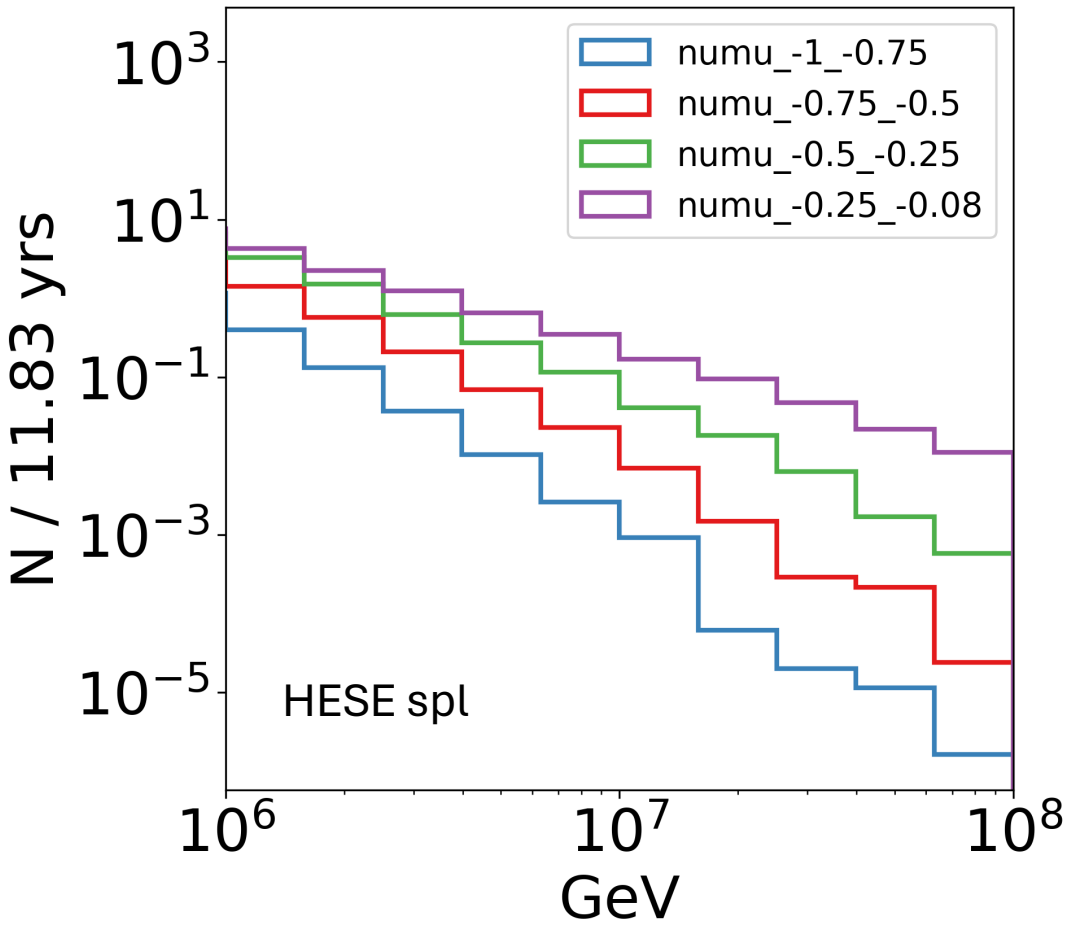
Nu energy ~11.4±2.5 PeV

Combining high-energy neutrino samples

HESE (PEPE independently x2 effective area)



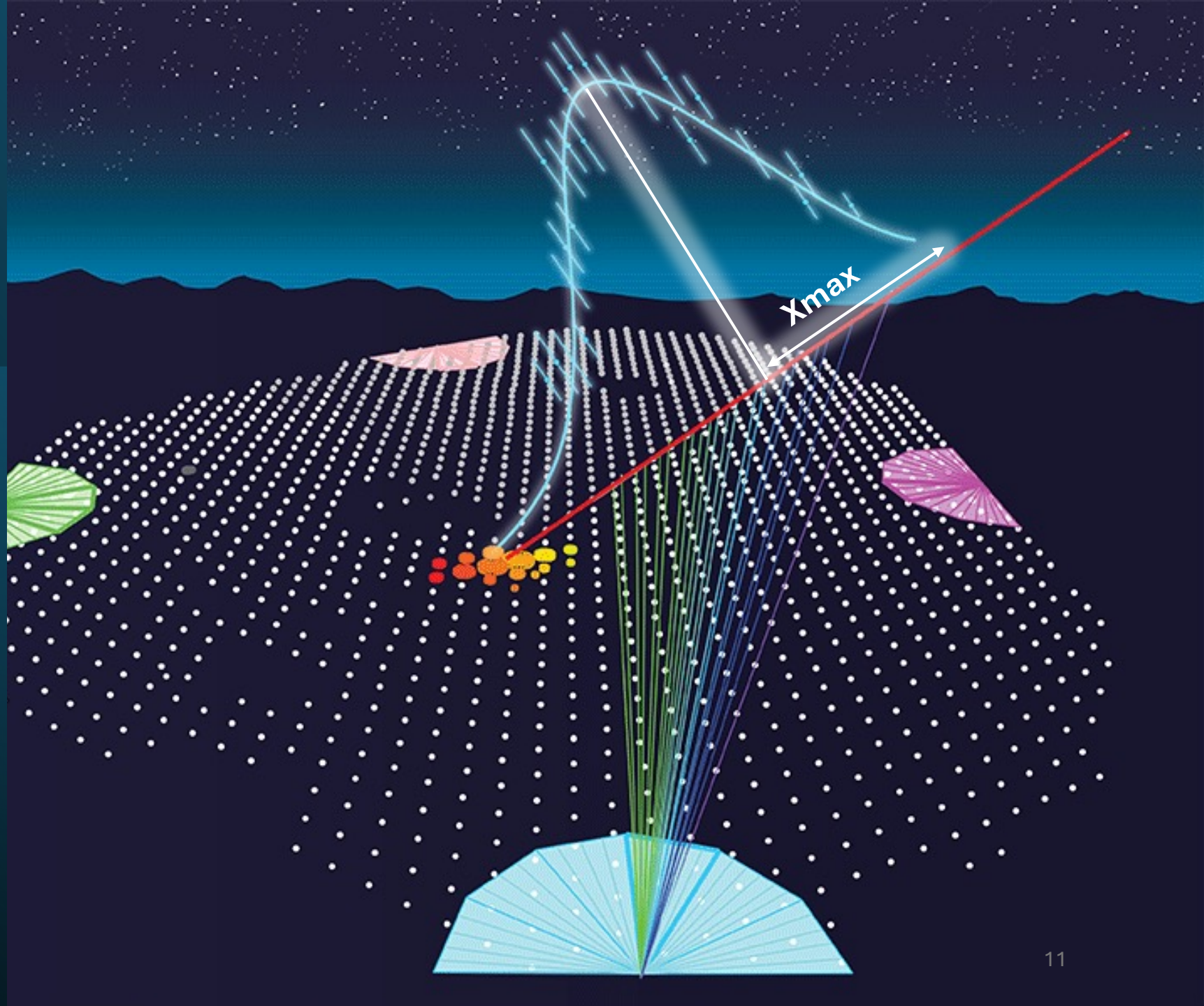
Northern track (through-going)



Hybrid air shower detections from the Pierre Auger Observatory (2004 to now)

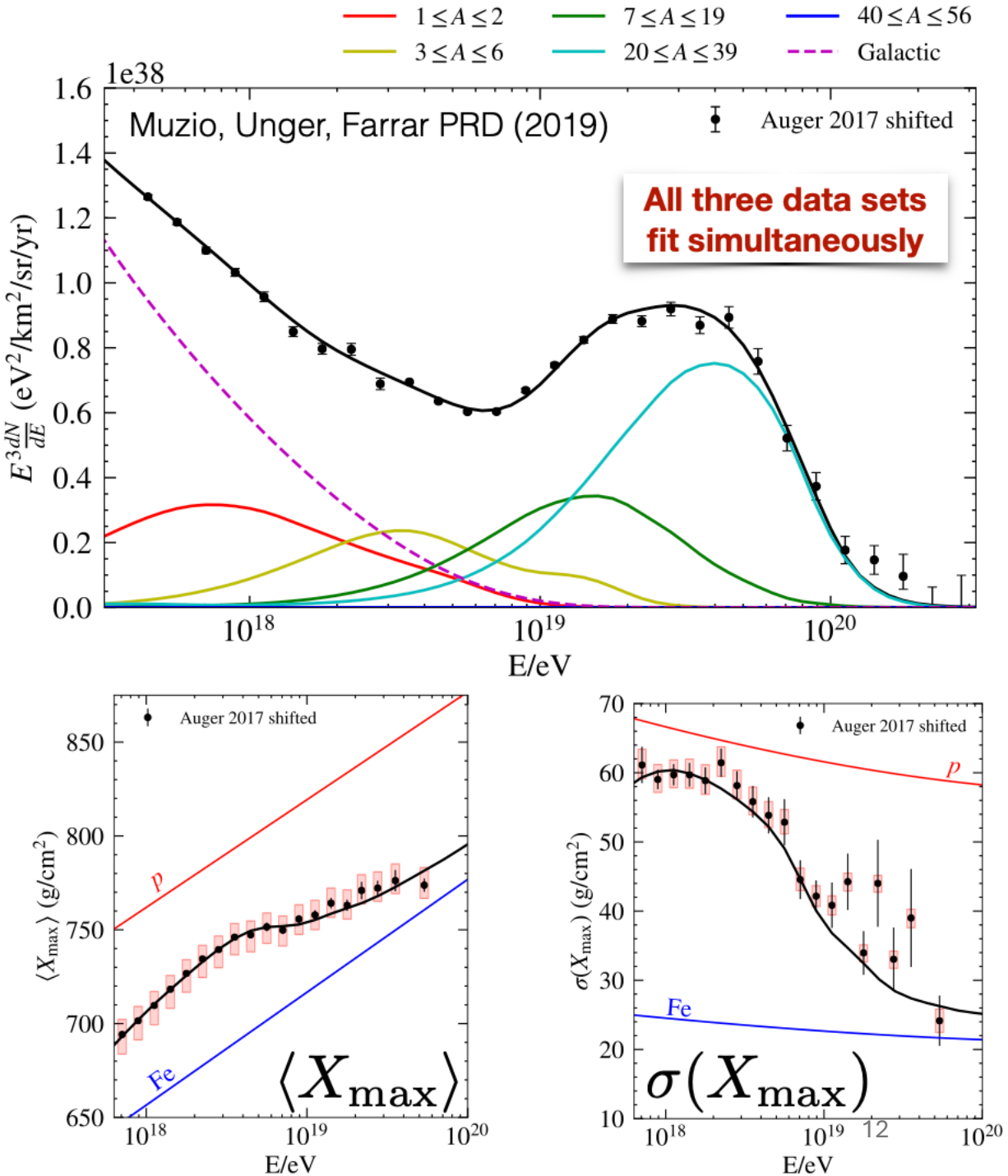
The highest energy cosmic rays

Observables: cosmic ray flux; mass composition via Xmax



CR Source Model

- Unger-Farrar-Anchordoqui model (UFA, 2015 PRD):
  1. Inject CRs into source environment
  2. **CRs processed by *photon* interactions**
  3. CRs escape source environment
  4. CRs propagate to Earth
- Accounts for observed spectrum (>$10^{17.5}$ eV) & composition (>$10^{17.8}$ eV)



Joint UHECR-neutrino likelihood maximization

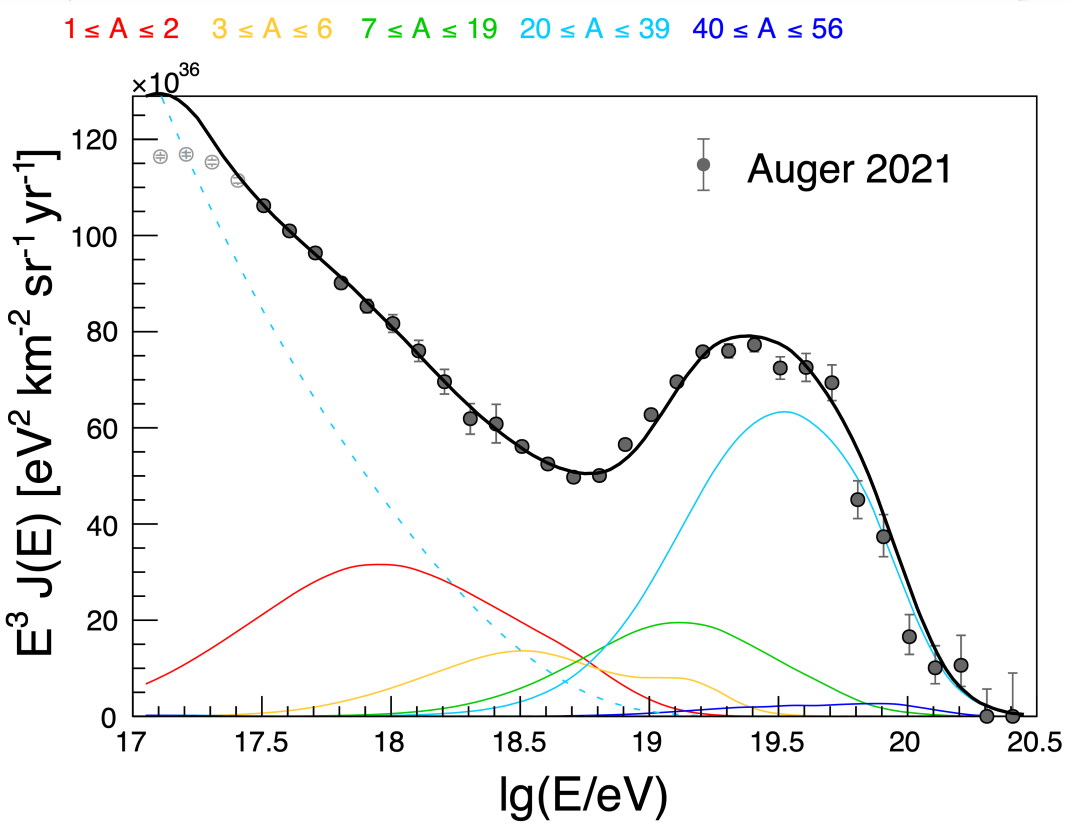
- High energy neutrinos**
  - Poisson distribution in energy-zenith-flavor bins >5 PeV**
  - Non-observation of neutrinos >15 PeV**
- Ultra high energy cosmic rays
  - Flux >$10^{17.5}$ eV
  - Full Xmax distributions >$10^{18.6}$ eV**
    - Rather than fitting only first two moments

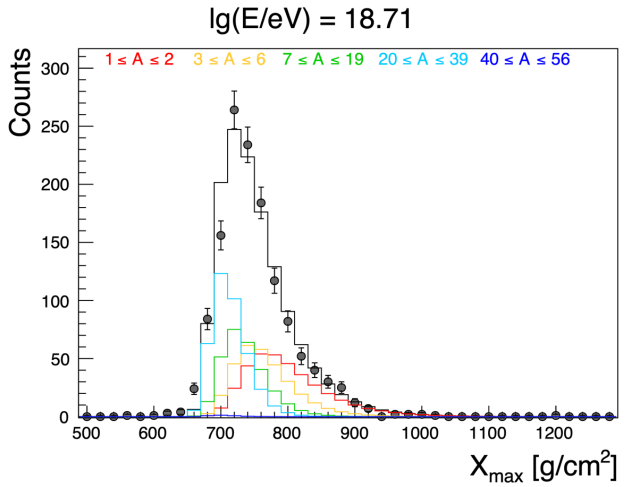
**NEW THIS ANALYSIS

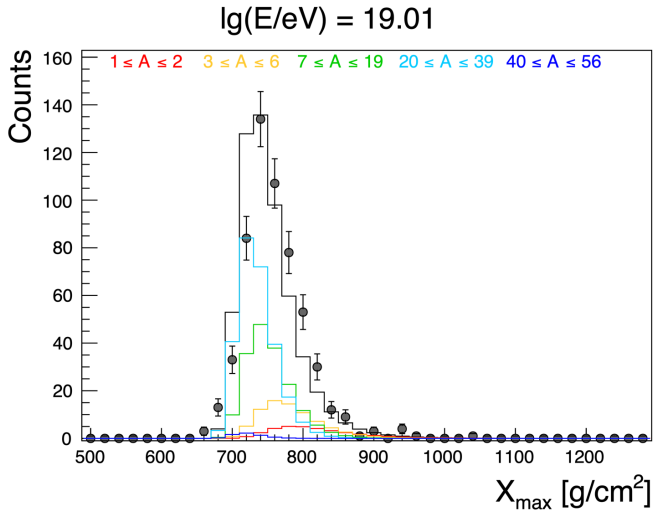
$$\ln \mathcal{L} = \ln \mathcal{L}_{\mathrm{UHECR}} + \ln \mathcal{L}_{\nu}$$

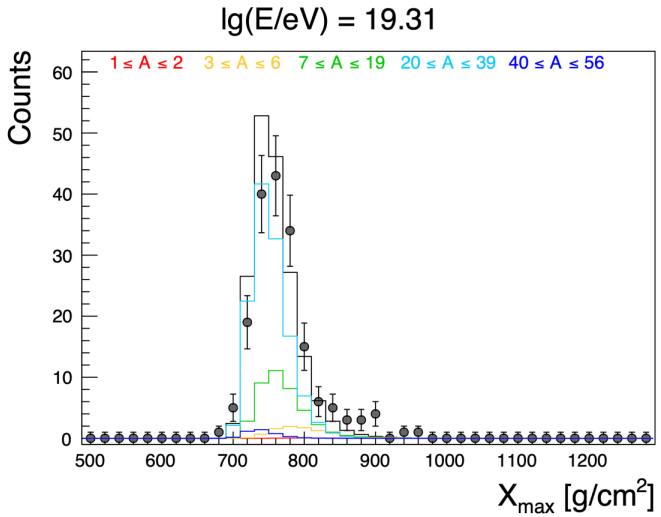
Assumptions: standard sources, SFR source evolution, mixed composition injection, Sibyll2.3d hadronic interaction model,
Auger energy scale shifted by +1σ, Xmax scale by -1σ

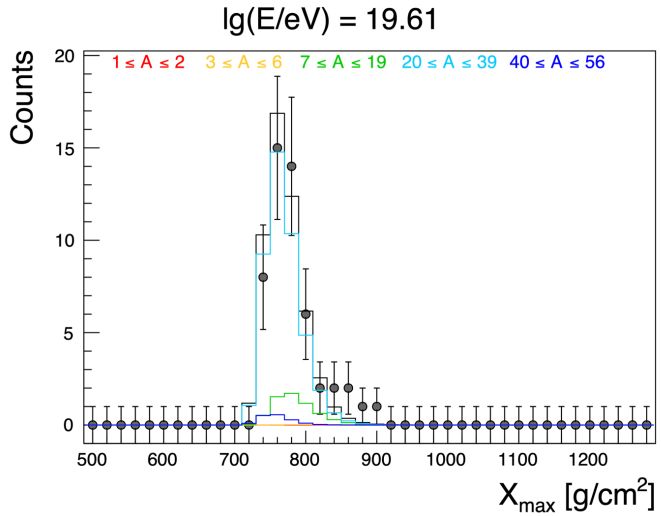
Result: UHECR parameters



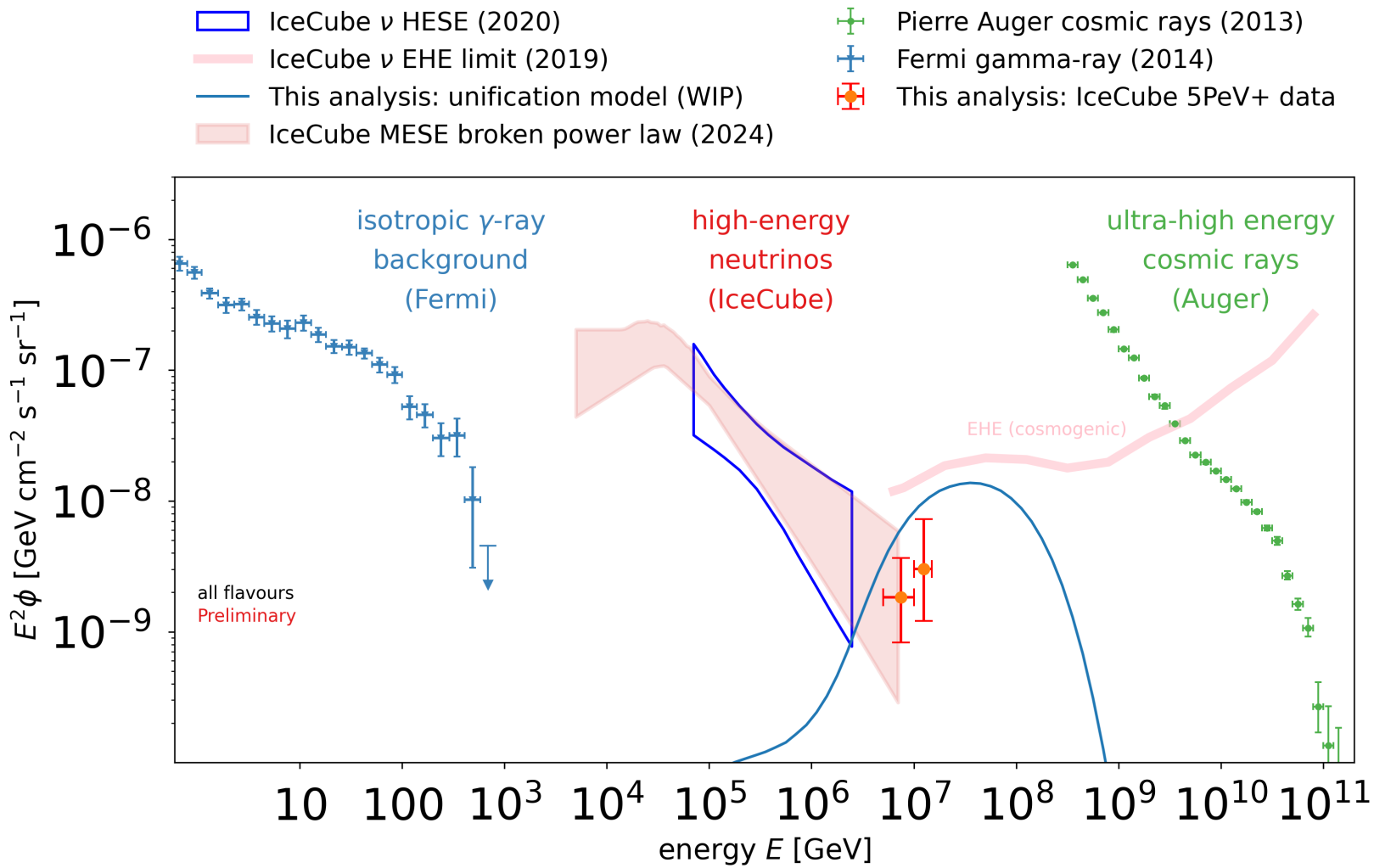




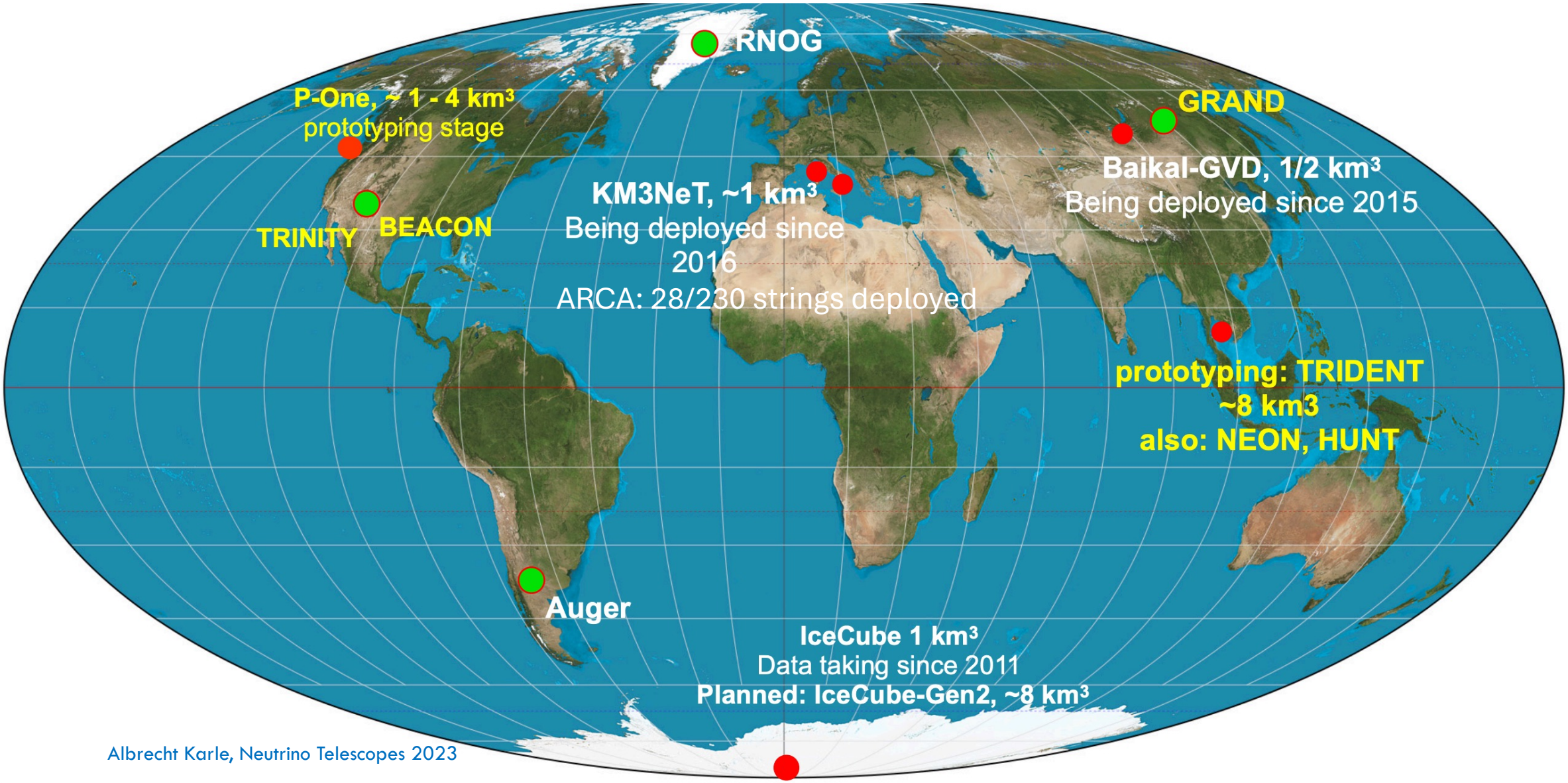




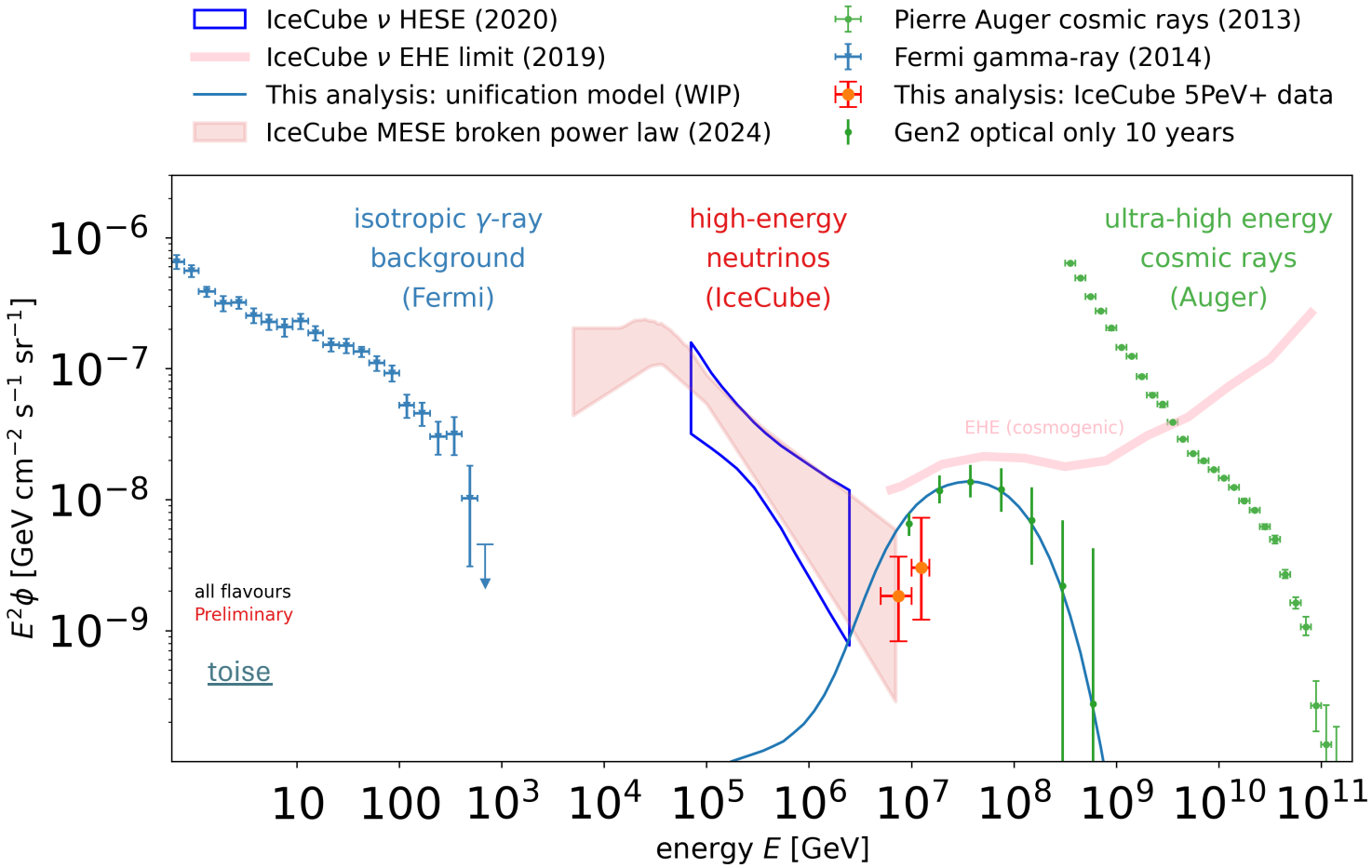
Implication: 10-100 PeV p-gamma bump in diffuse nu from UHECR sources



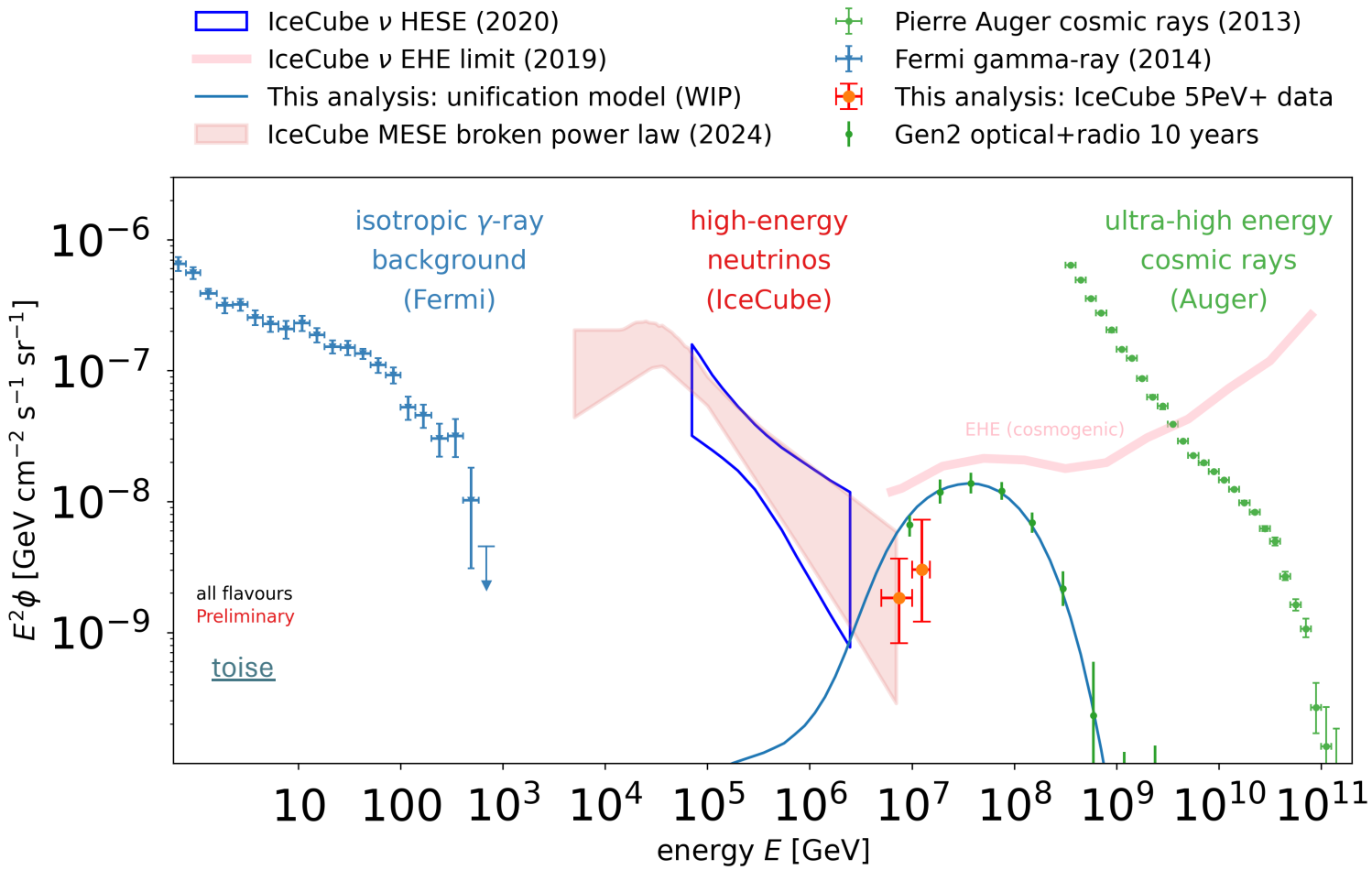
Current/future neutrino experiment landscape

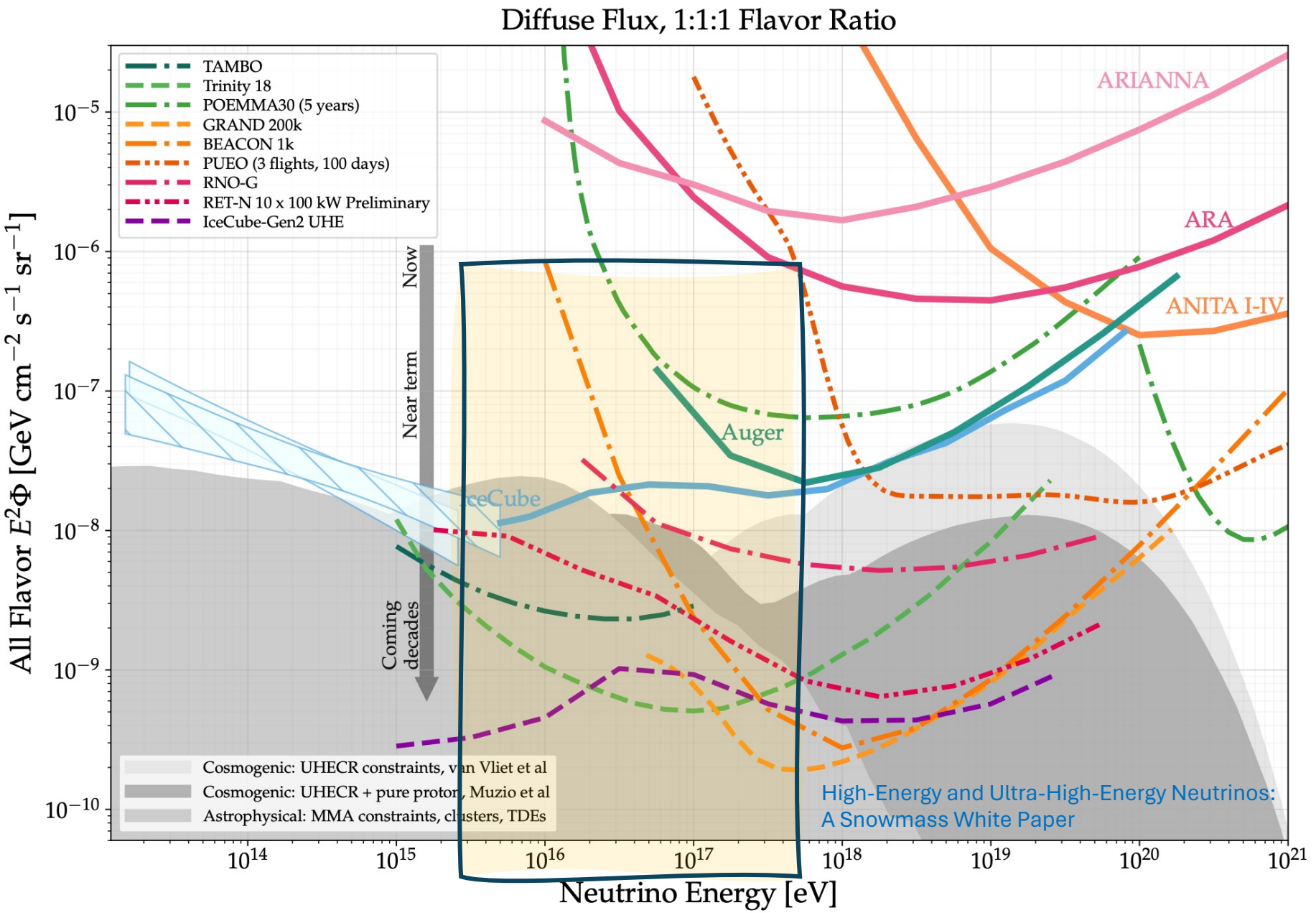


IceCube-Gen2 optical projection (10 yrs)



IceCube-Gen2 optical+radio projection (10 yrs)

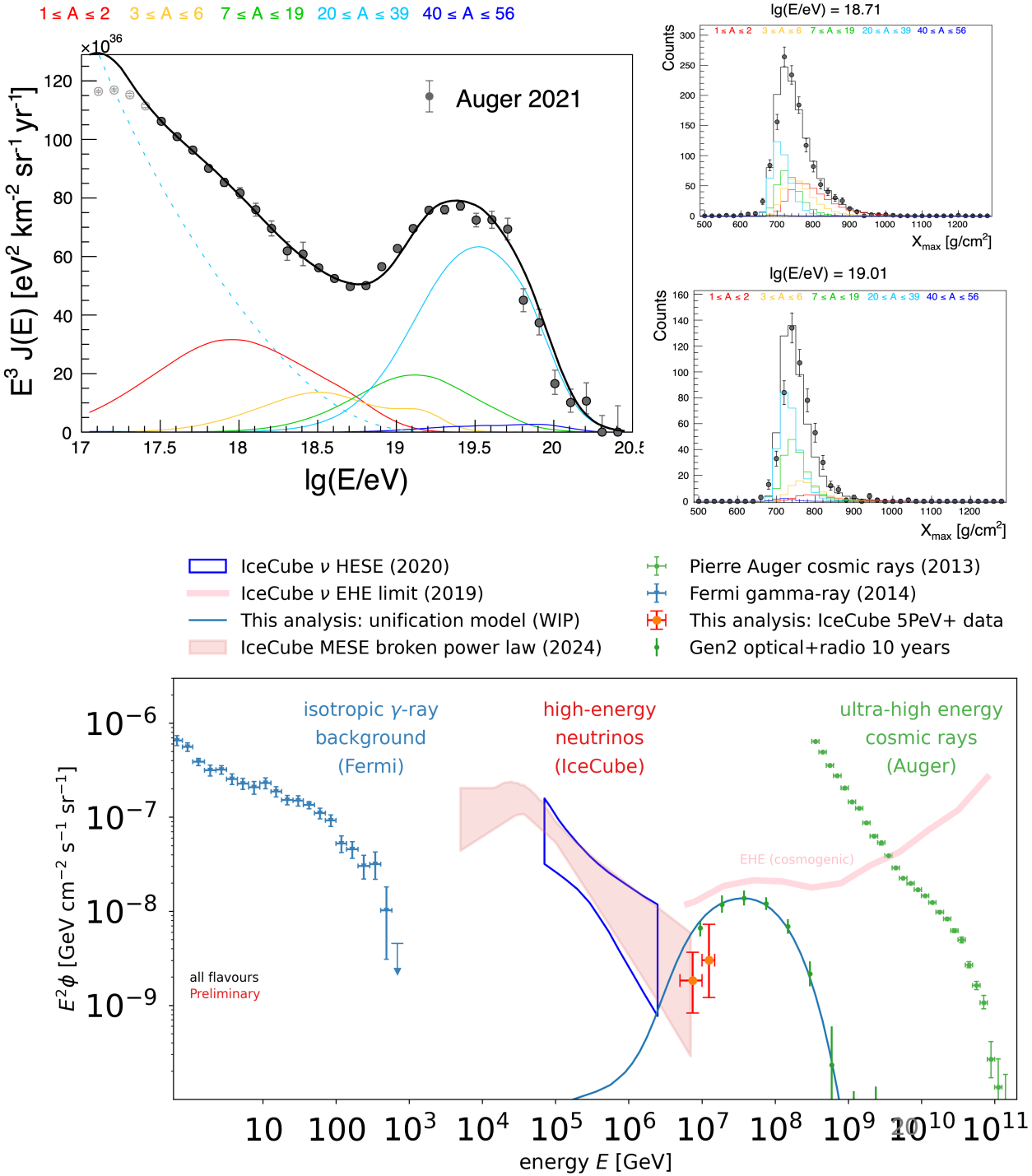


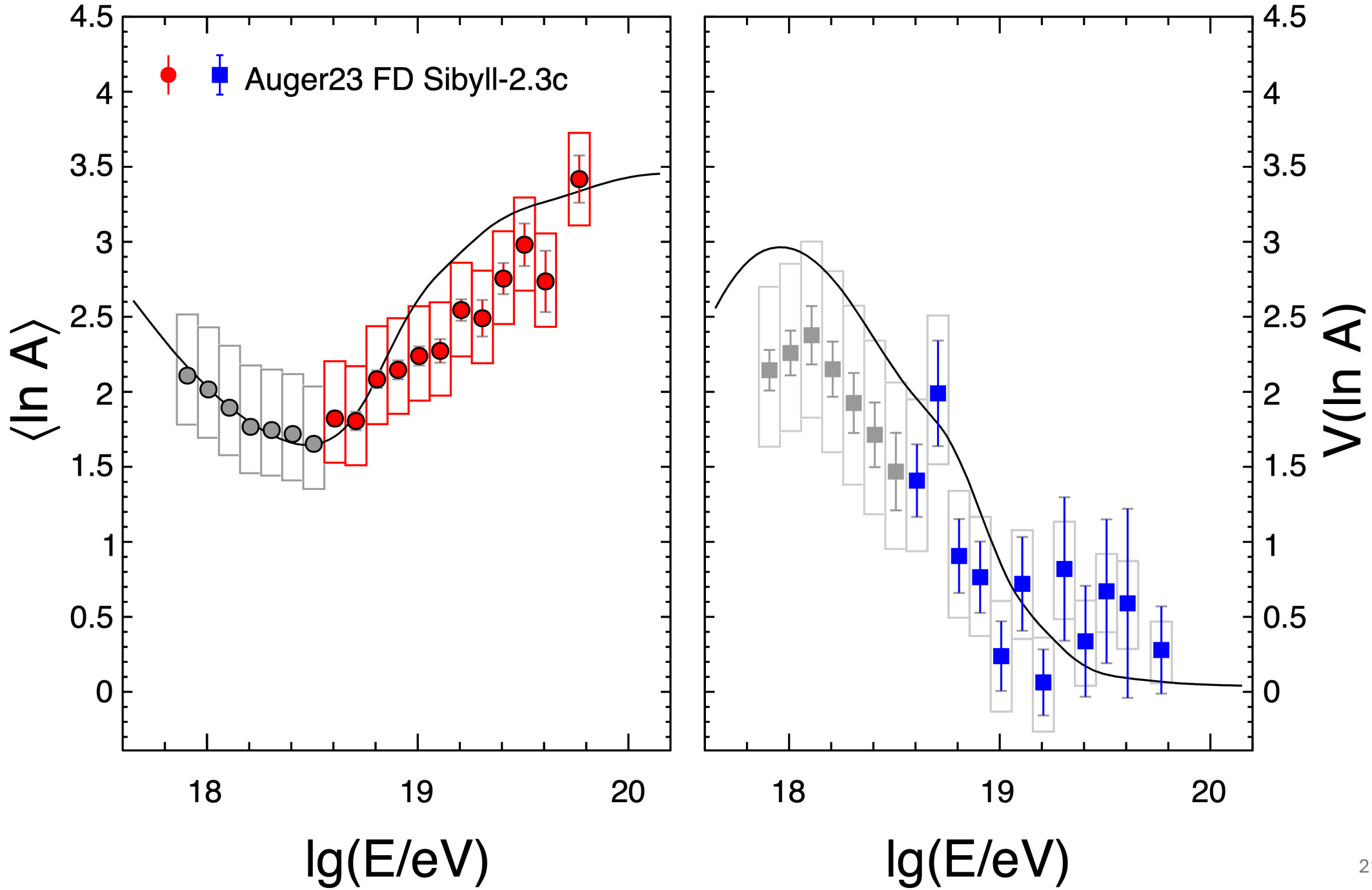


Trinity
TAMBO
IceCube-Gen2
…

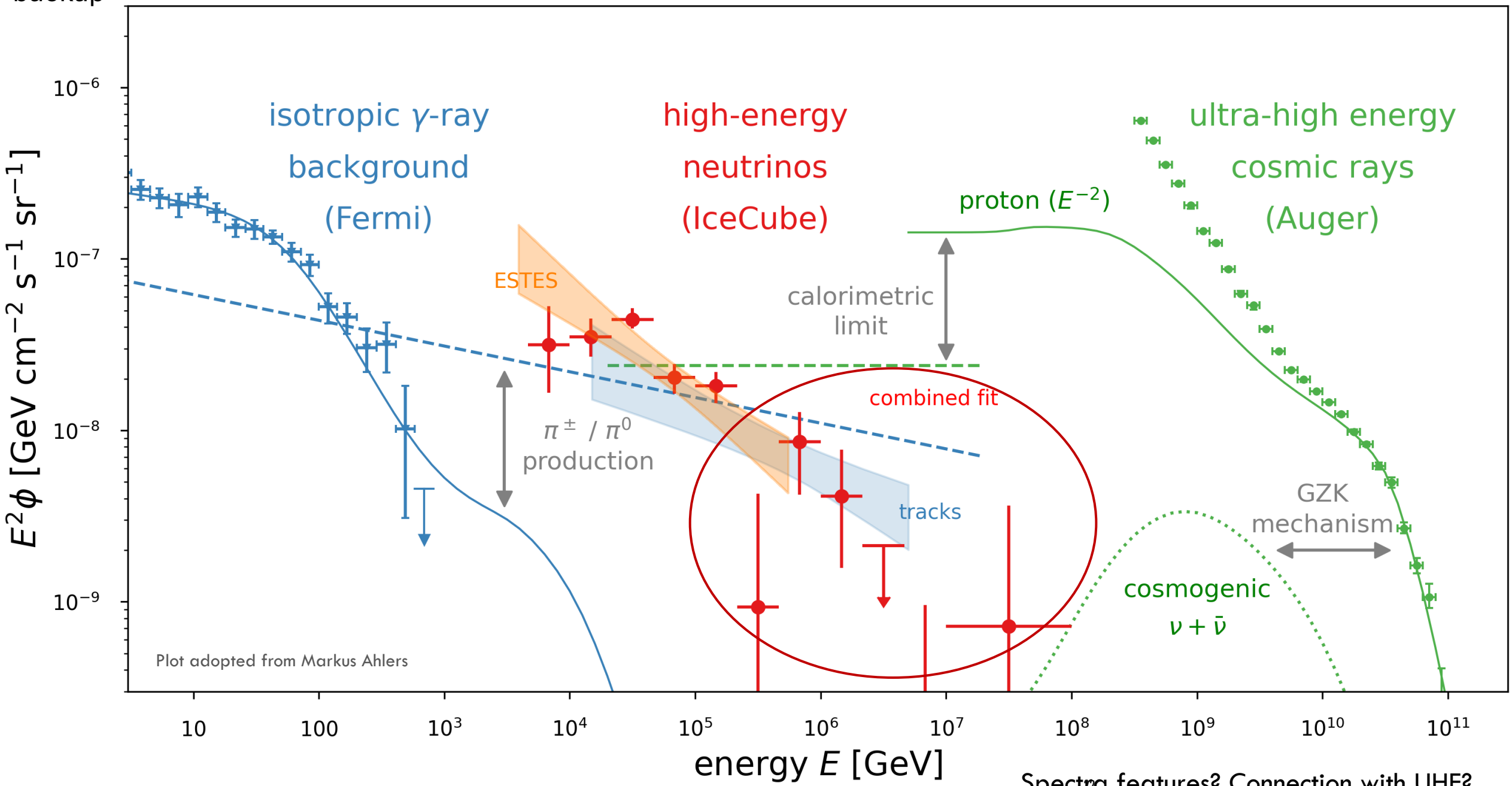
Conclusion

- Performed joint fit to UHECR spectrum & Xmax data along with >5 PeV neutrinos
- > 10 PeV neutrino spectrum predicted by realistic UHECR source models
  - Production mainly in-source photon fields
  - Secondary through UHECR x CIB
- Hints of the 10 PeV neutrino recovery from IceCube & KM3Net?
- Next-generation detectors required to robustly detect recovery
  - Smoking gun source identification




Auger23 FD Sibyll-2.3c
⟨ln A⟩
V(ln A)
lg(E/eV)
lg(E/eV)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
18
19
20

backup



Spectra features? Connection with UHE?

Km3net – an intriguing event

See ICHEP talk from Paschal Coyle

Potentially with muon energy >> 10 PeV. Background probability, angular and energy uncertainties under study