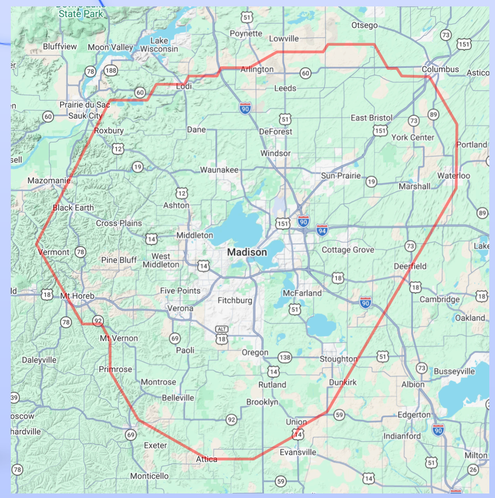
Composition measurements at the Pierre Auger Observatory and their relation to neutrino studies

Nicolas San Martin[1]
for the Pierre Auger Collaboration[2]

[1]Dept. of Physics, Colorado School of Mines
Golden, CO, USA,
nicolas_sanmartin@mines.edu

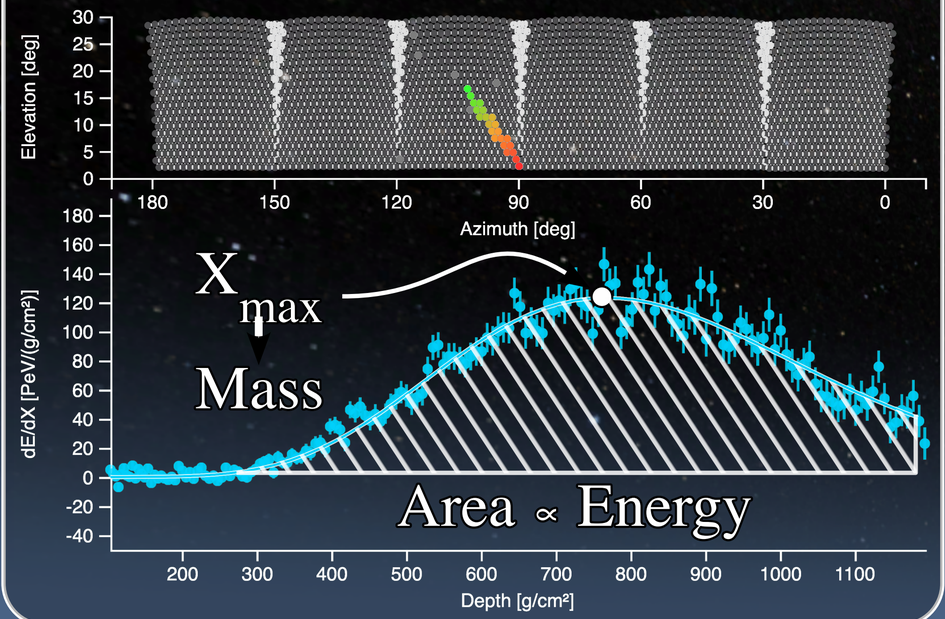
[2]Malargüe, Mendoza, Argentina,
spokesperson@auger.org



IPA 2026
October 14th 2026
Madison, WI

PIERRE AUGER OBSERVATORY

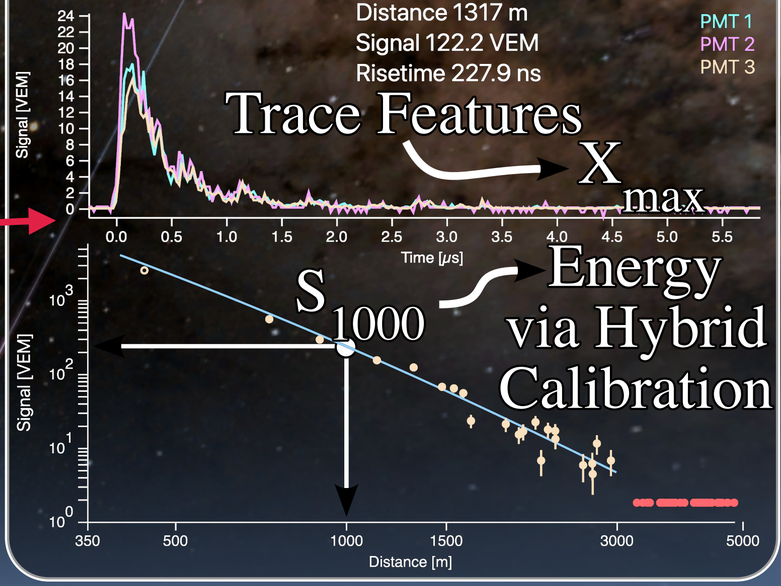
FD Site Los Leones - Measurment



- Energy
- Composition(X_{max})
- Arrival Direction
- ~14% duty cycle

- Energy
- Arrival Direction
- ~99% duty cycle

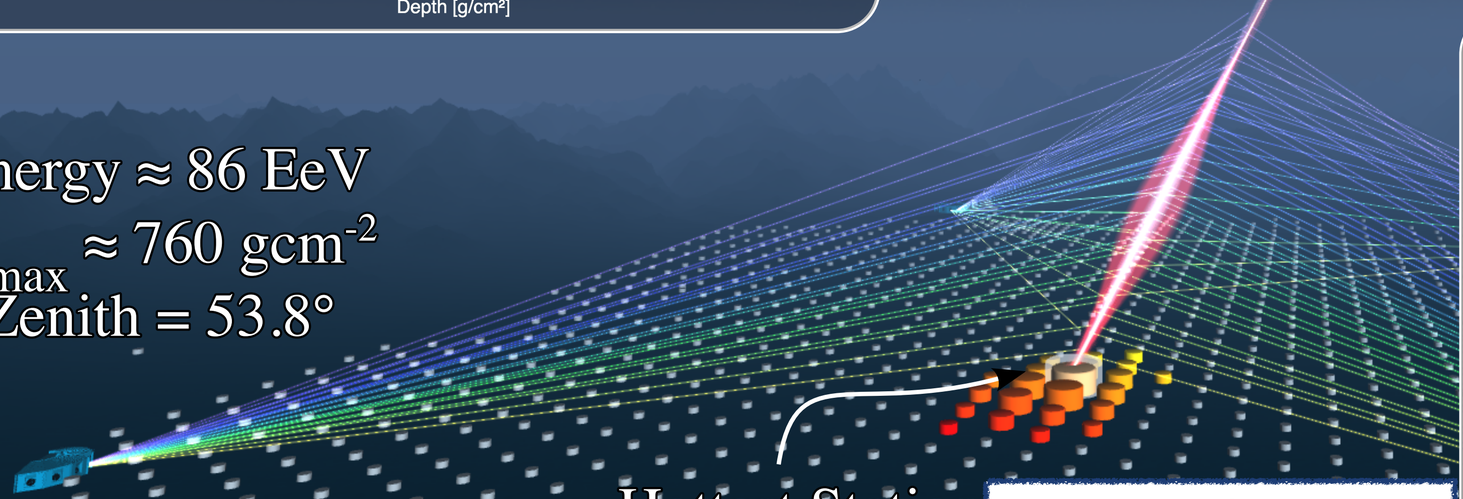
SD WCD - Measurment



Energy ≈ 86 EeV

X_{max} ≈ 760 gcm^{-2}

Zenith = 53.8°

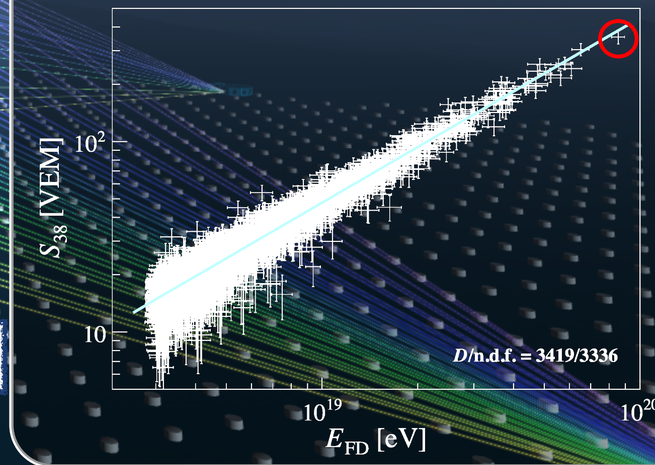


FD: Los Leones

Hottest Station

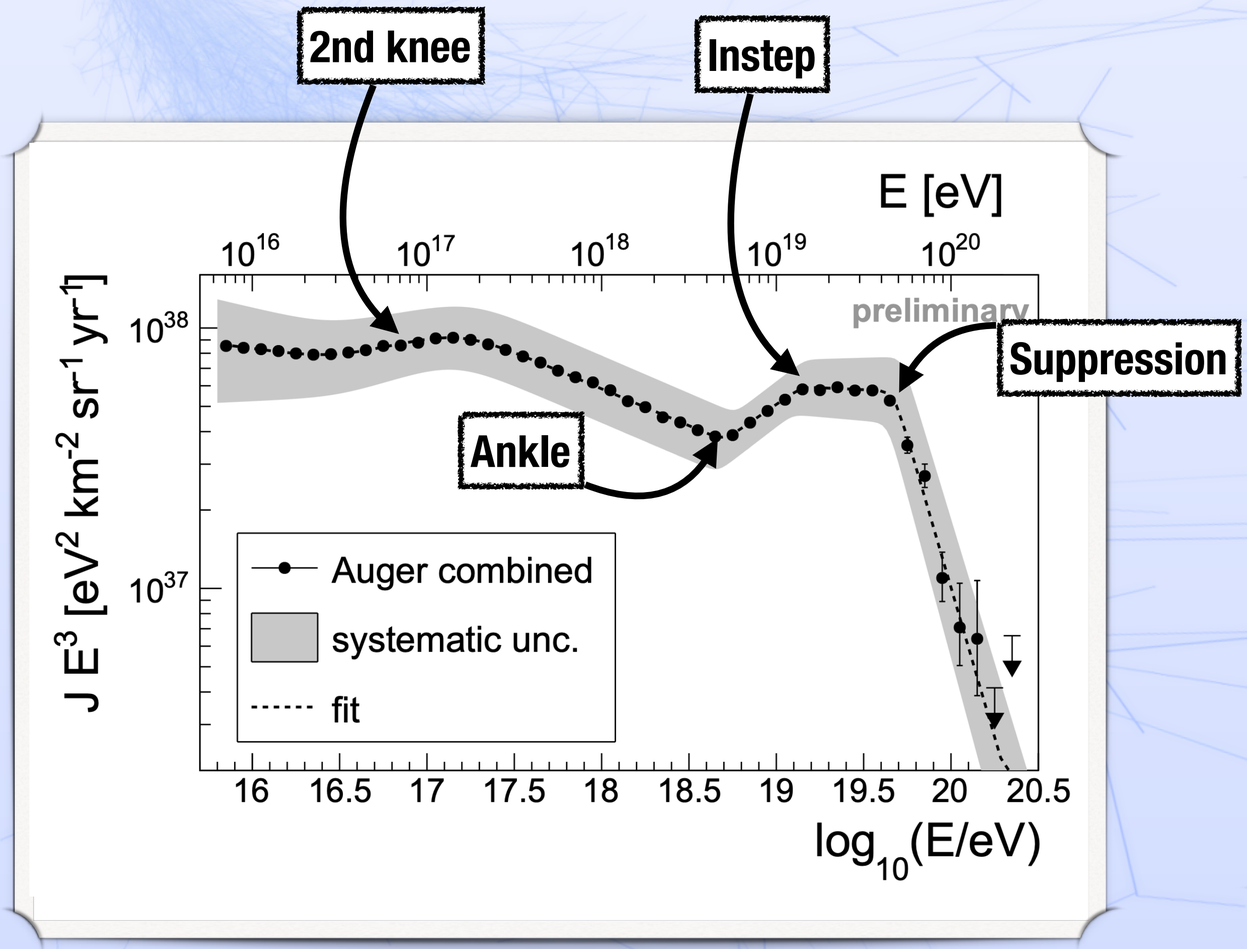
- 27 Fluorescence telescopes (4+1 sites)
- 1660 WCD stations

Hybrid Calibration of SD Energy Scale



Energy spectrum

Energy Spectrum: CRIS-MAC 2024 [2501.01736]



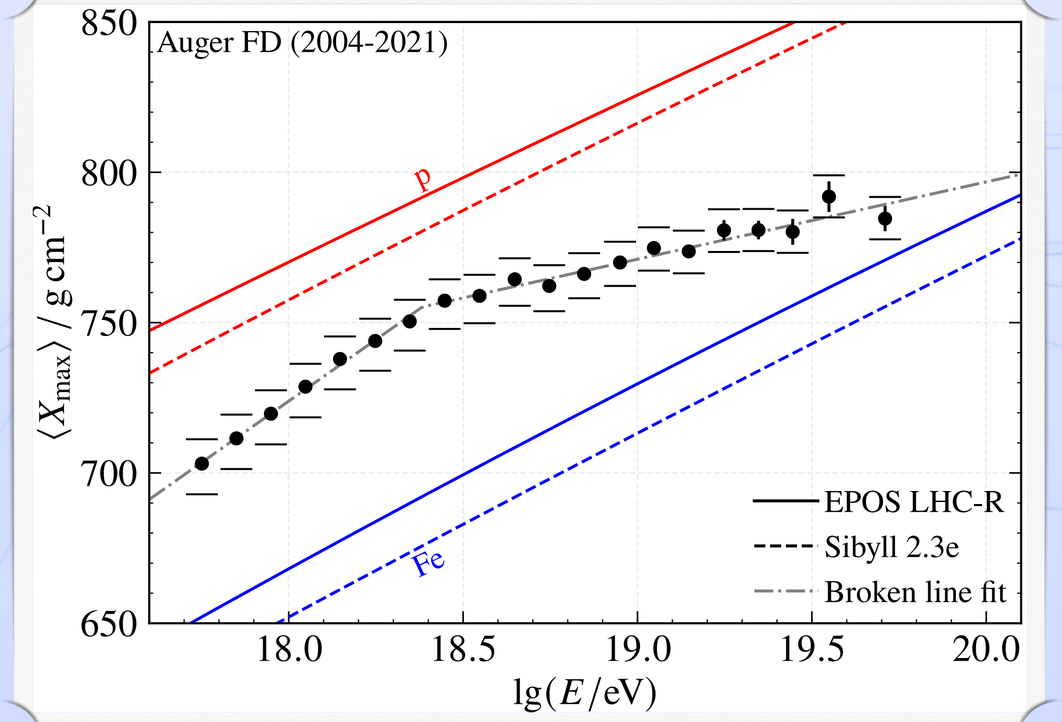
- **2nd knee (~0.1 EeV)**
  - Normally understood as an “Iron knee”
- **Ankle (~5 EeV)**
  - Transition between source populations
  - Propagation effects
- **Suppression (>40 EeV)**
  - Source maximum rigidity
  - Energy loses during propagation
- **Interpretation**
  - Source physics and propagation shape the observed spectrum.
  - Spectrum alone cannot identify the dominant mechanism
  - Composition is needed to brake degeneracy.

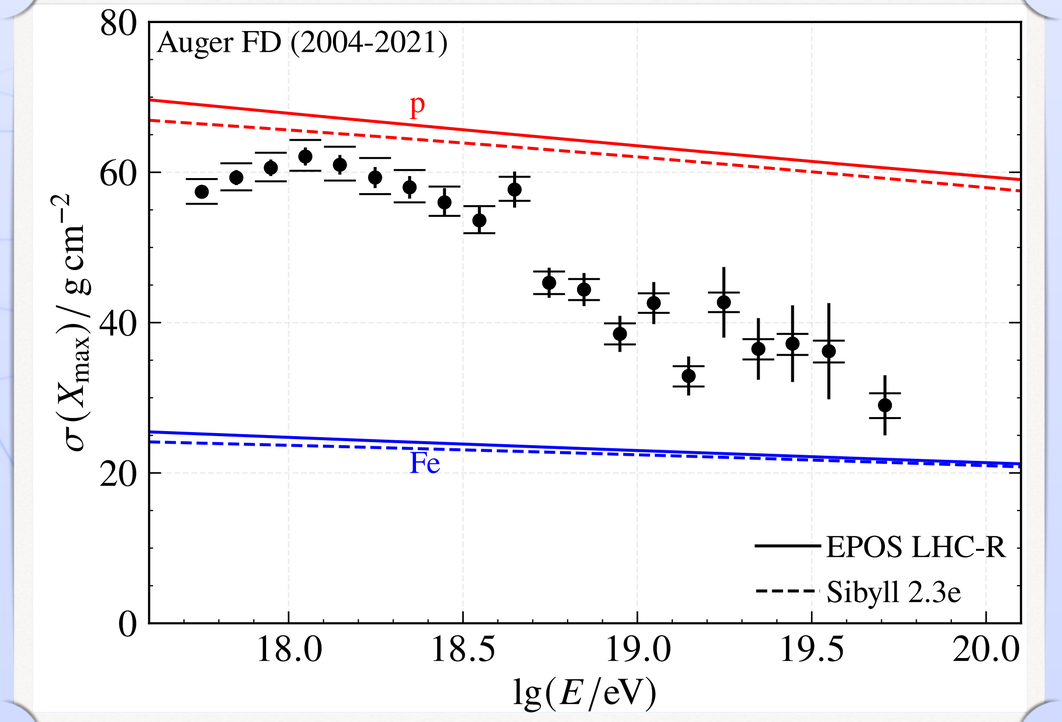
X_{max} moments: newly updated results

FD Hybrid 2026: Phys. Rev. D, [2605.12598]

- 2.4 times larger exposure
- Improved profile fit
- Improved aerosols estimations

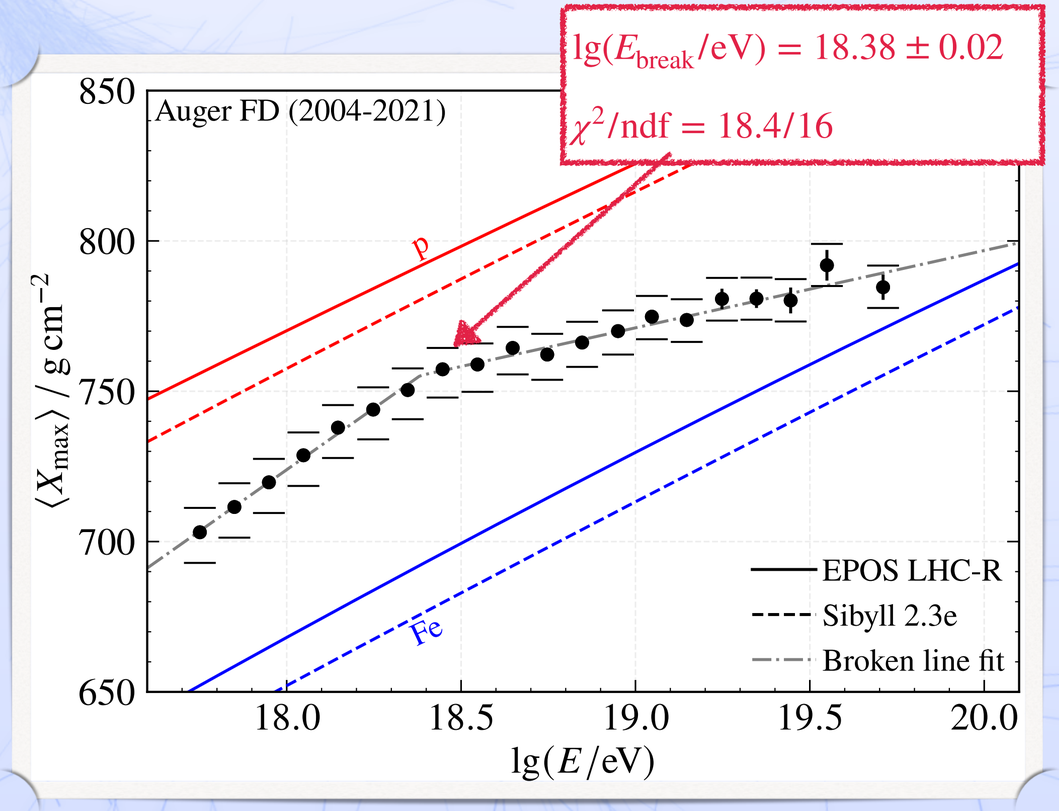
- Acceptance, bias and resolution effects considered
- Cross checks on simulations and data splits ensure fidelity of the results

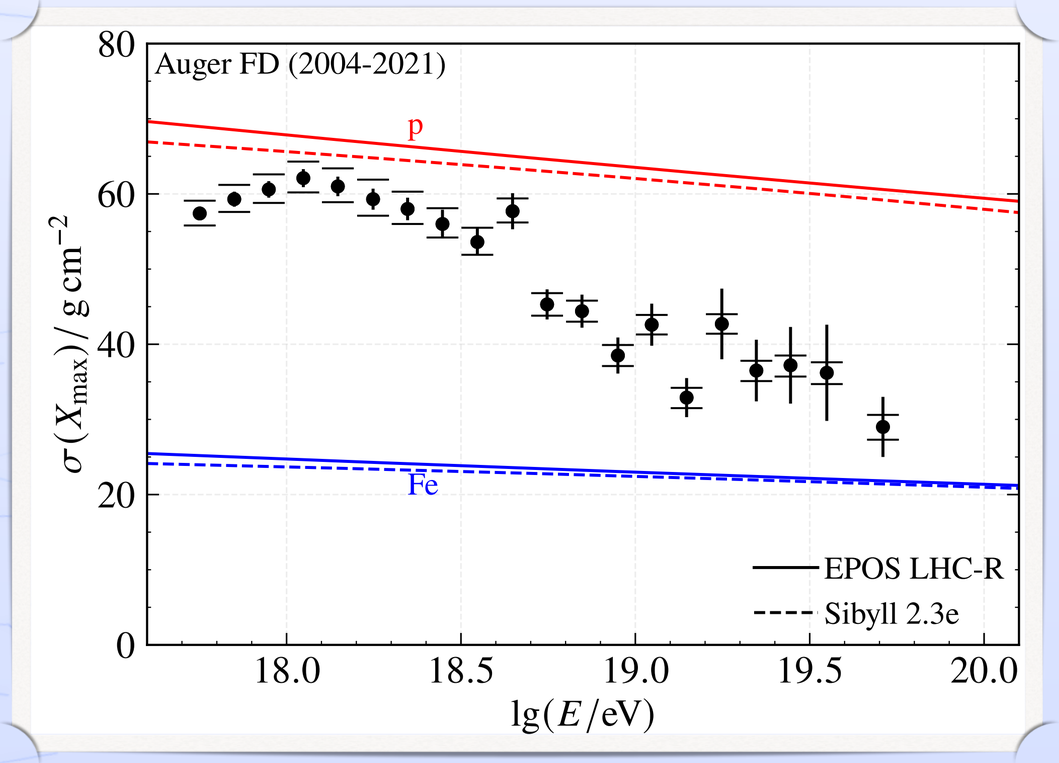




X_{max} moments: newly updated results

FD Hybrid 2026: Phys. Rev. D, [2605.12598]



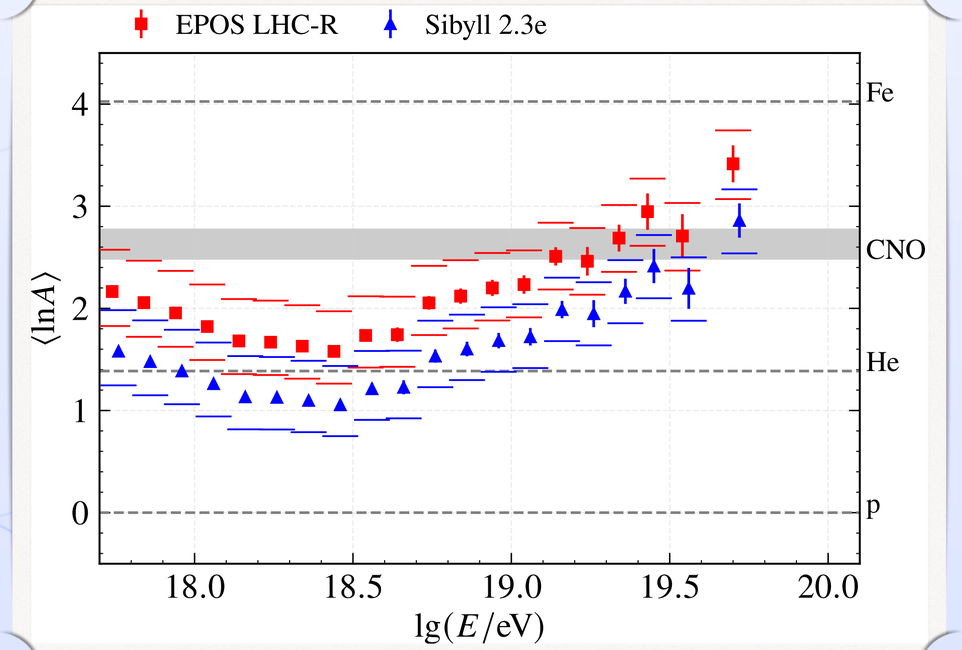


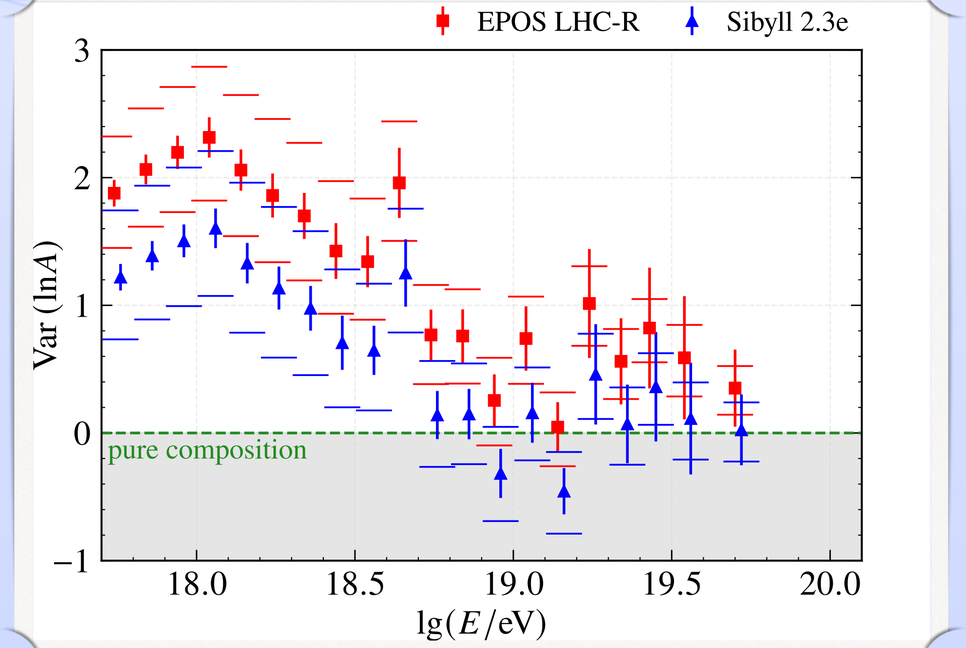
Both $\langle X_{max} \rangle$ and $\sigma(X_{max})$ are consistent with a decrease in the mass of cosmic rays until E~$10^{18.4}$ eV followed by an increase in mass and purity

Mass evolution with energy

- **$10^{17.7}$ eV ≤ E < $10^{18.5}$ eV**
  - Average mass decreasing
  - Minimum mass compatible with He reached ~$10^{18.5}$ eV
  - High degree of mixing
- **$10^{18.5}$ eV ≤ E < 10^{19} eV**
  - Monotonic growth of mass with energy
  - Mixed but decreasingly so
- **E > 10^{19} eV**
  - Continued monotonic growth of mass with energy
  - No plateau has yet been observed
  - Heaviest mean between CNO and Fe
  - Compatible with almost pure composition
- **EPOS LHC-R trends heavier than Sibyll 2.3e**

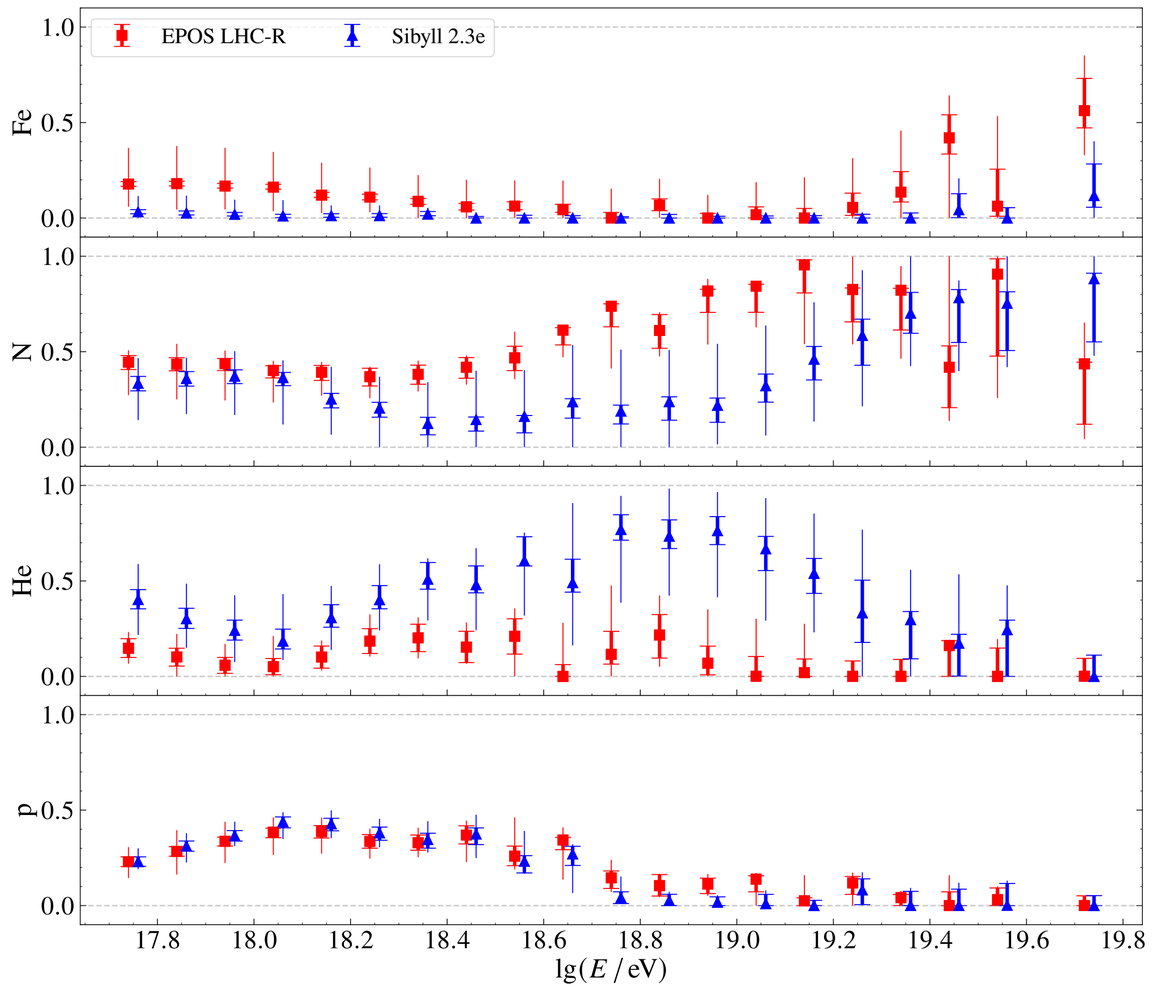
FD Hybrid 2026: Phys. Rev. D, [2605.12598]





Fractional fits to X_{max} distributions

FD Hybrid 2026: Phys. Rev. D, [2605.12598]



- **Both models show composition getting heavier with energy.**
- **Combination of p+N around 1 EeV**
- **For Sibyll 2.3e**
  - The N component decreases.
  - Proton component gets replaced by He.
  - At 10 EeV the He component fades away giving place to a new Nitrogen component.
  - Agrees with Peter Cycle acceleration, proportional to the rigidity (E/Z).
- **For EPOS LHC-R**
  - The proton component gets replaced by Nitrogen directly.
  - Almost no He.
  - Non-zero Fe fraction at the highest energy.

Combined fit: model description

Combined Fit 2023: JCAP [2211.02857]

➢ **Fit to spectrum and composition at Earth**

➢ **Two EG source population**
- One low energy (LE) and one high energy (HE)
- LE component can represent a different type of source or secondary protons generated at the HE sources

➢ **Emission for both modeled as:**

$$\widetilde{Q}_A(E) = \widetilde{Q}_{0A} \left(\frac{E}{E_0}\right)^{-\gamma} \begin{cases} 1, & E \leq Z_A R_{\rm cut}; \\ \exp\left(1 - \frac{E}{Z_A R_{\rm cut}}\right), & E > Z_A R_{\rm cut}, \end{cases}$$

➢ **Each can have its own source evolution:**

$$S(z) \propto (1+z)^m$$

➢ **Adiabatic energy losses from the expansion of the universe:**

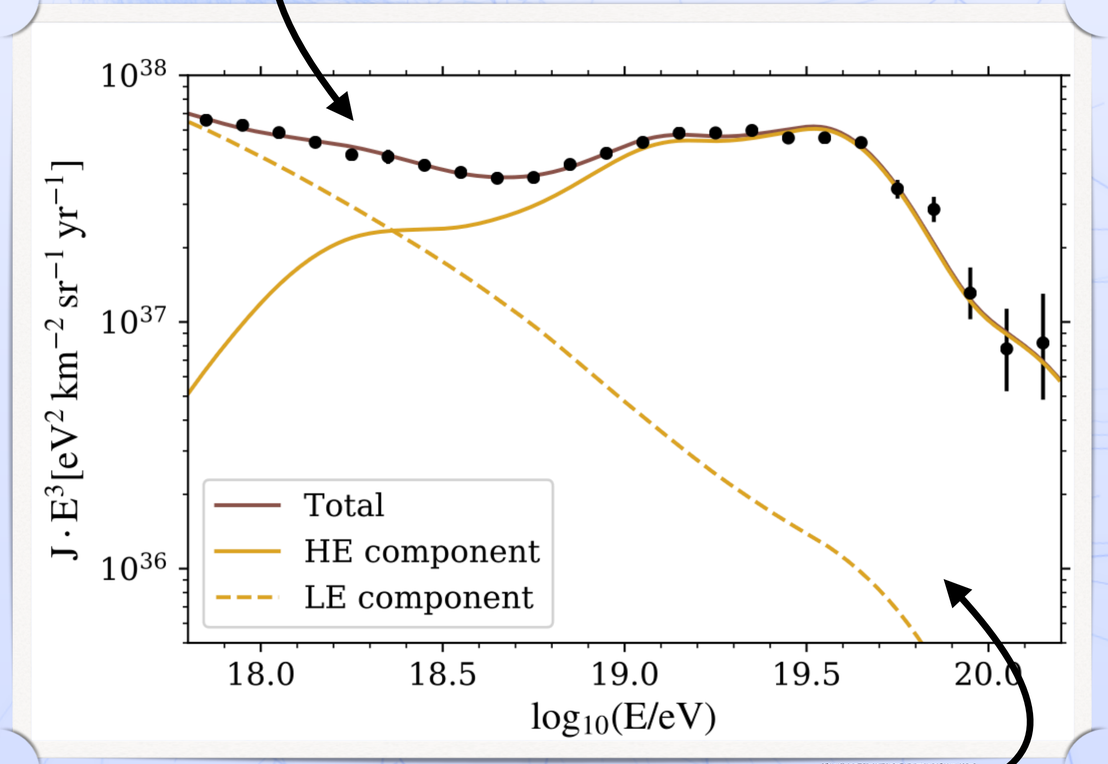
$$(\mathrm{d}t/\mathrm{d}z)^{-1} = -H_0(1+z)\sqrt{\Omega_{\rm m}(1+z)^3 + \Omega_\Lambda},$$

➢ **Interaction with background photons (CMB and EBL):**
- Electron-positron pair photo-production
- Pion photo-production
- Photo-disintegration of nuclei

➢ **No extragalactic magnetic field effects**

Combined fit: m=0

Ankle explained by transition between EG source populations

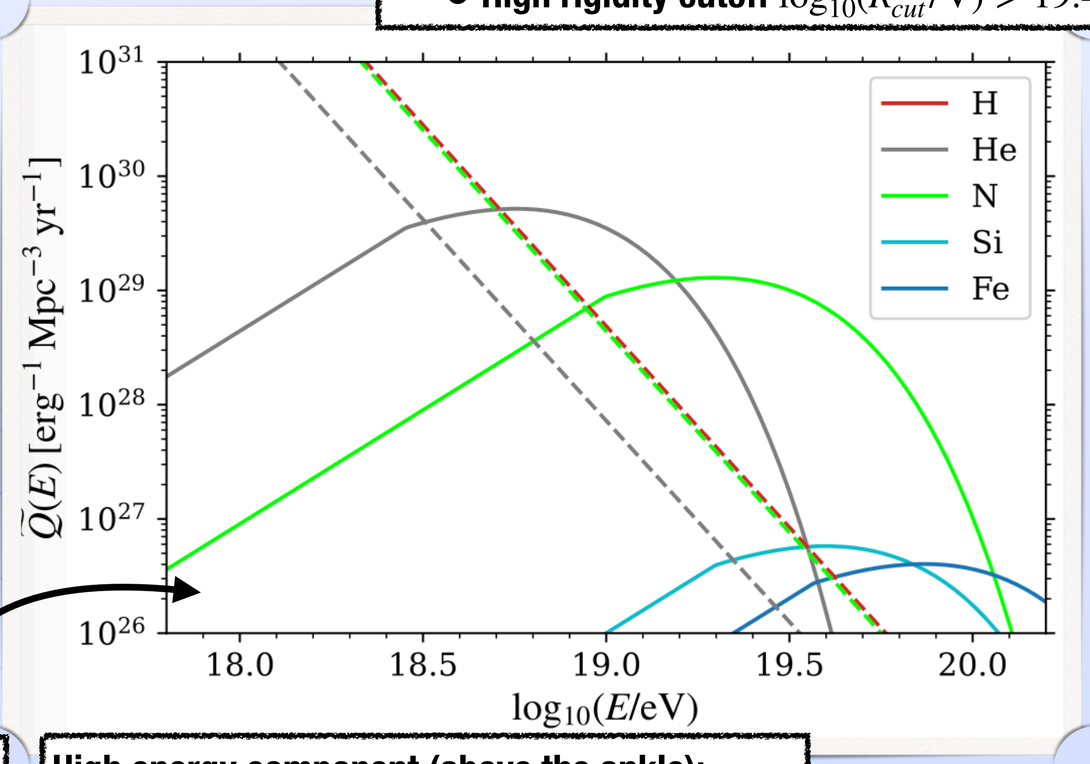


At Earth

Alternatively the Nitrogen component can be replaced by a galactic contribution

Low energy component (below the ankle):

- **Mainly protons and Nitrogen**
- **Very steep** ($\gamma_{LE} \sim 3.5$)
- **High rigidity cutoff** $\log_{10}(R_{cut}/\mathrm{V}) > 19.4$



At the source

High energy component (above the ankle):

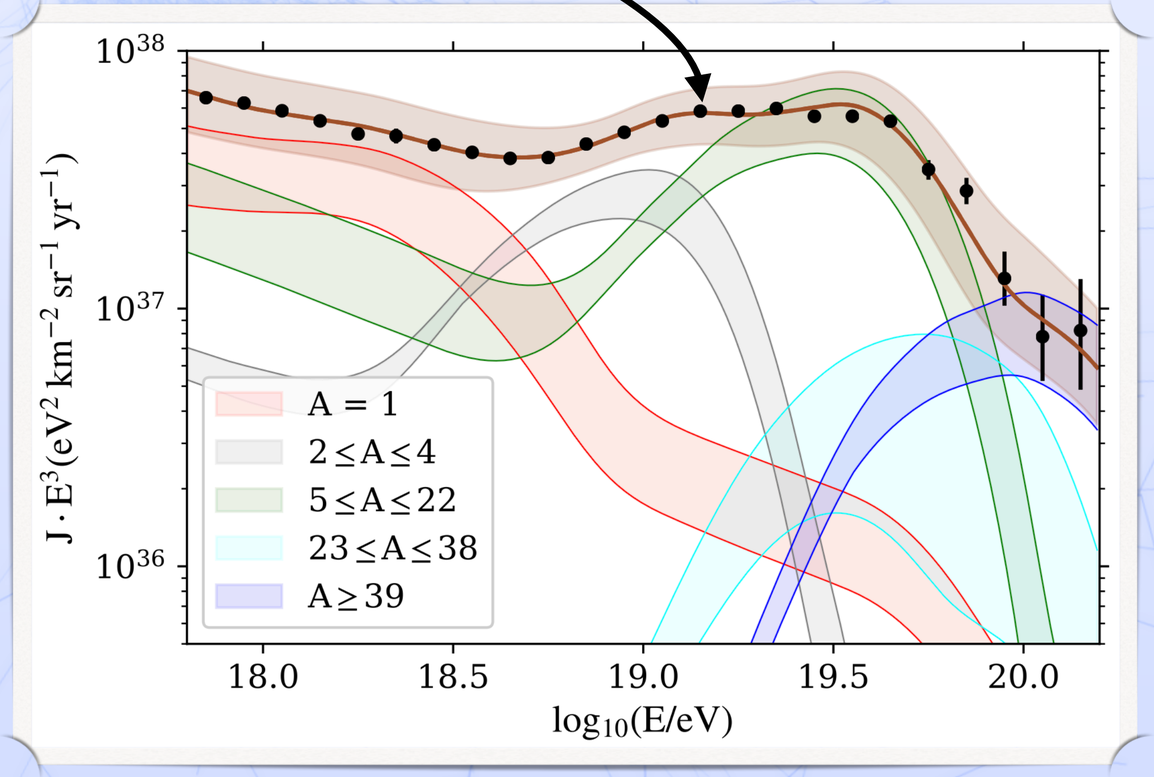
- **Mixed composition**
- **Nitrogen dominates near the suppression**
- **Very hard spectrum** ($\gamma_{HE} \sim -2$)

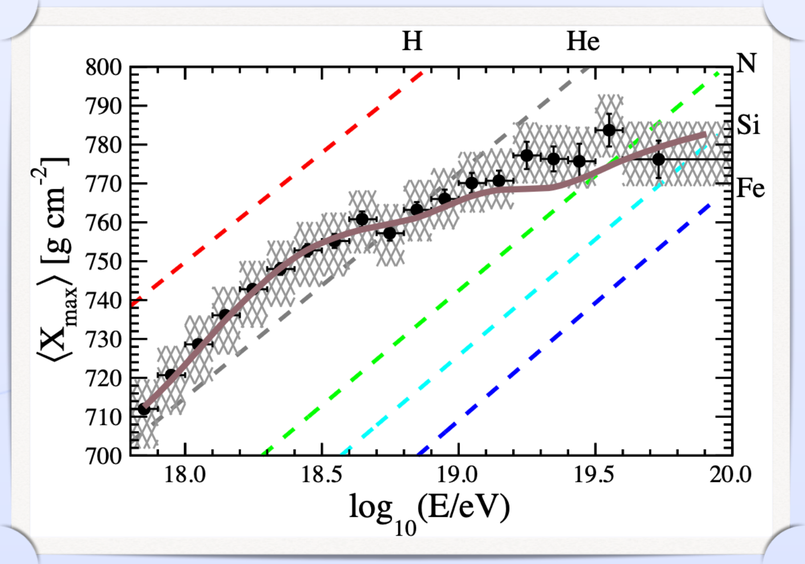
Combined Fit 2023: JCAP [2211.02857]

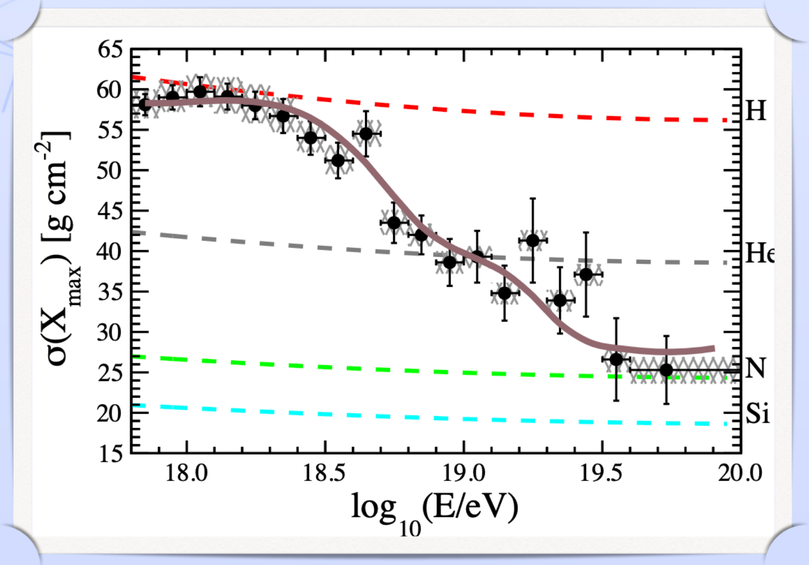
Combined fit: m=0

Combined Fit 2023: JCAP [2211.02857]

HE hard spectrum needed to explain pronounced spectrum features and rapidly increasing composition with low mixing







Error bands for systematic uncertainties -> stable results

Combined fit: source evolution and neutrino fluxes

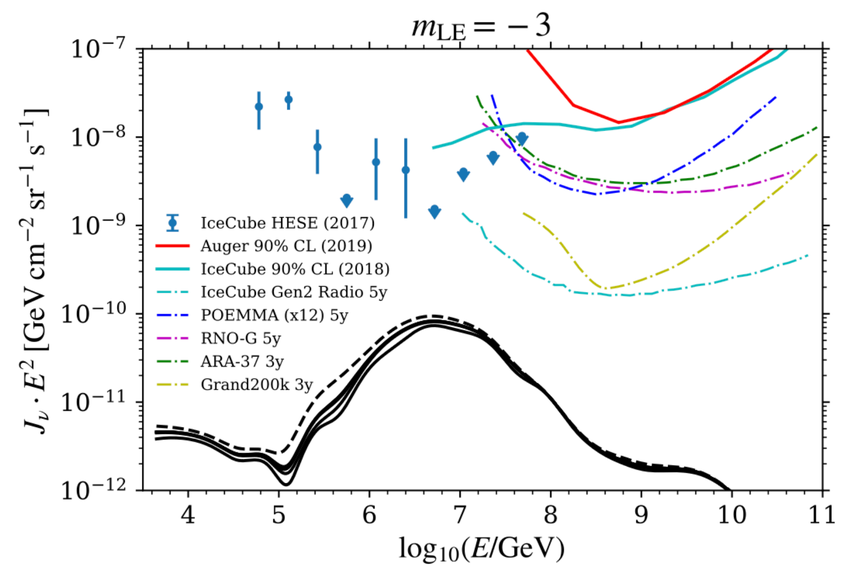
$$S(z) \propto (1+z)^m$$

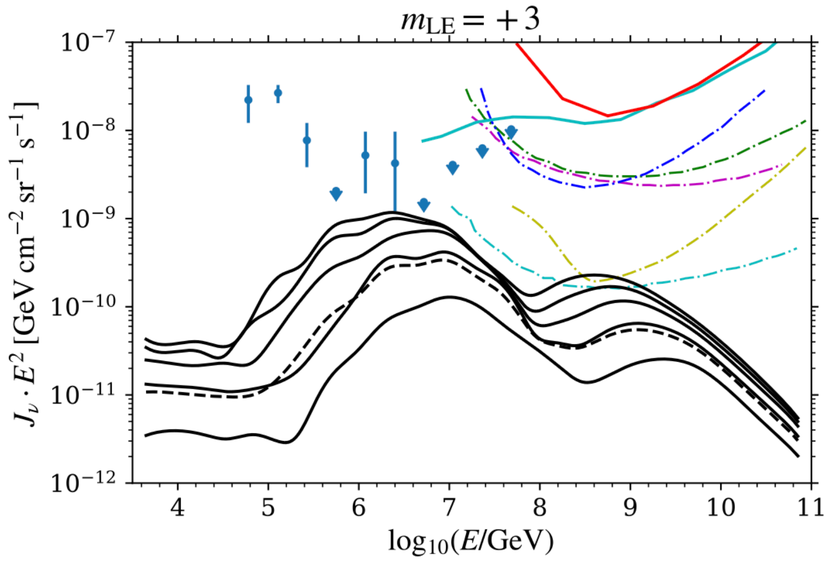
HE component:

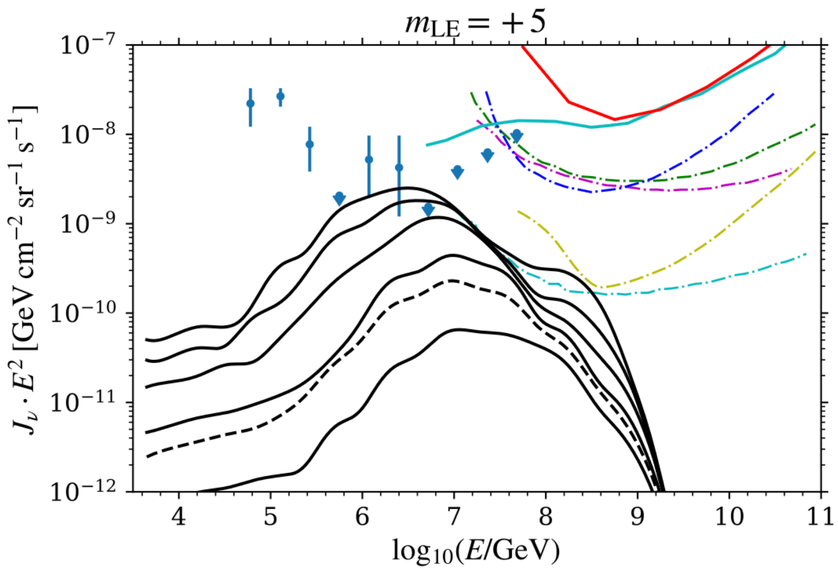
- Strong positive source evolution (m=+5) rejected by the fit
- Hard to constrain softer source evolutions
- Low UHE neutrino emissions due to low rigidity cutoff

LE component:

- Equally good fit for the tested source evolutions
- Source evolution affects composition, spectral parameters and propagation times
- Can be constrained using neutrino fluxes due to low rigidity cutoff.



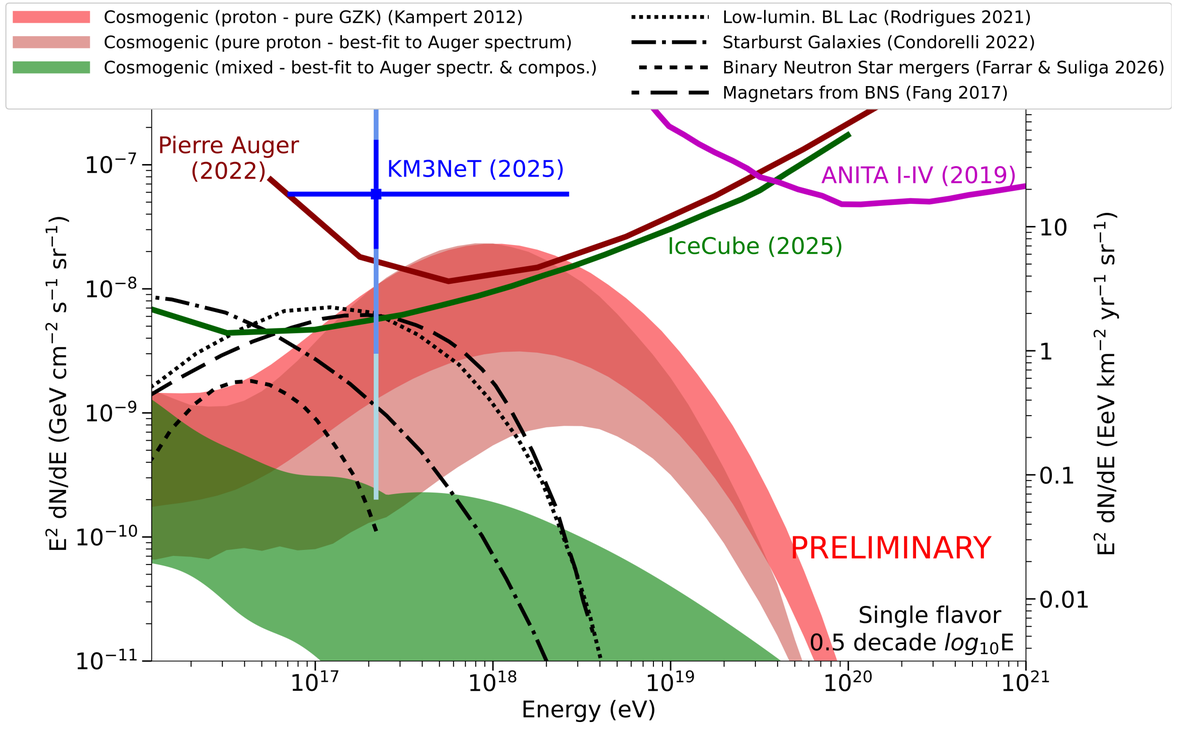




- Dashed: flat S(z) from $z_{\rm max}$ 1 to 3
- Continuous: $z_{\rm max}$ =1,2,3,4,5 from the bottom to the top

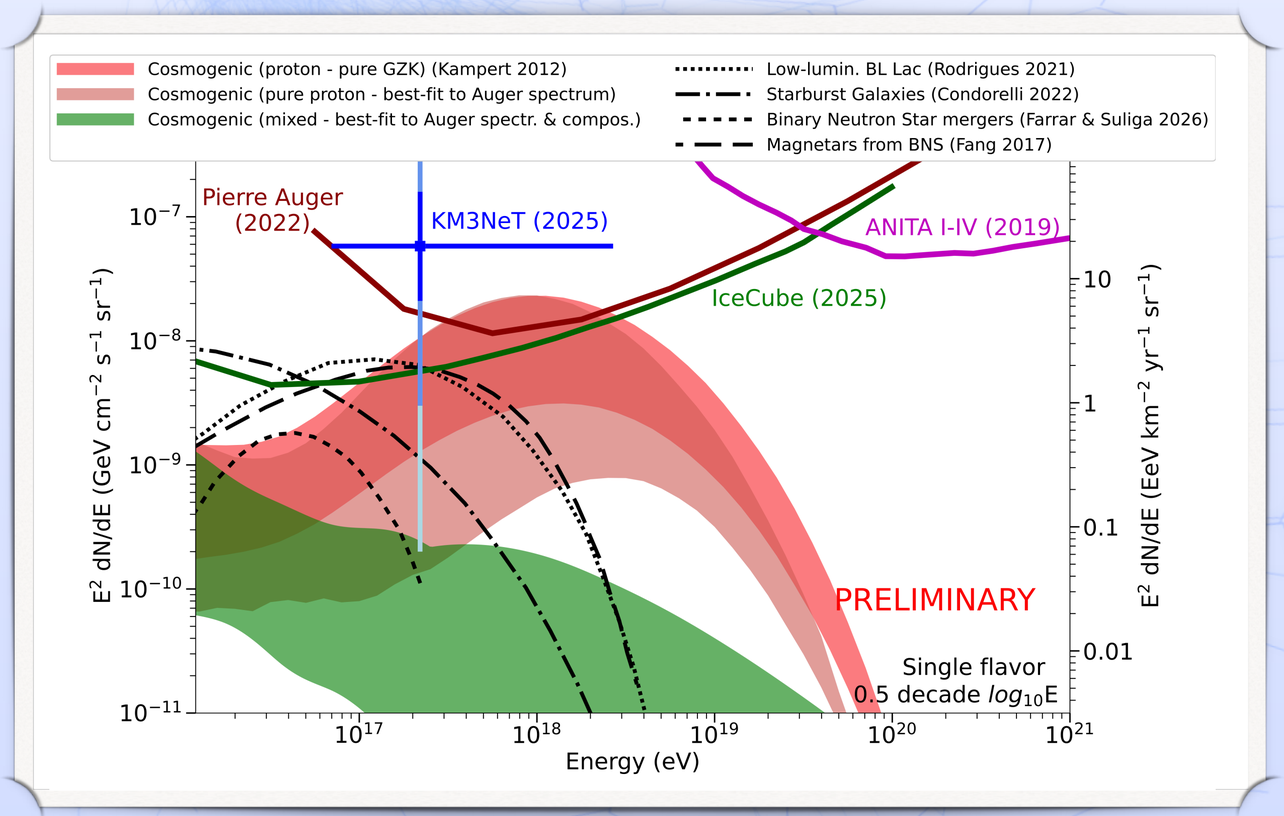
Combined Fit 2023: JCAP [2211.02857]

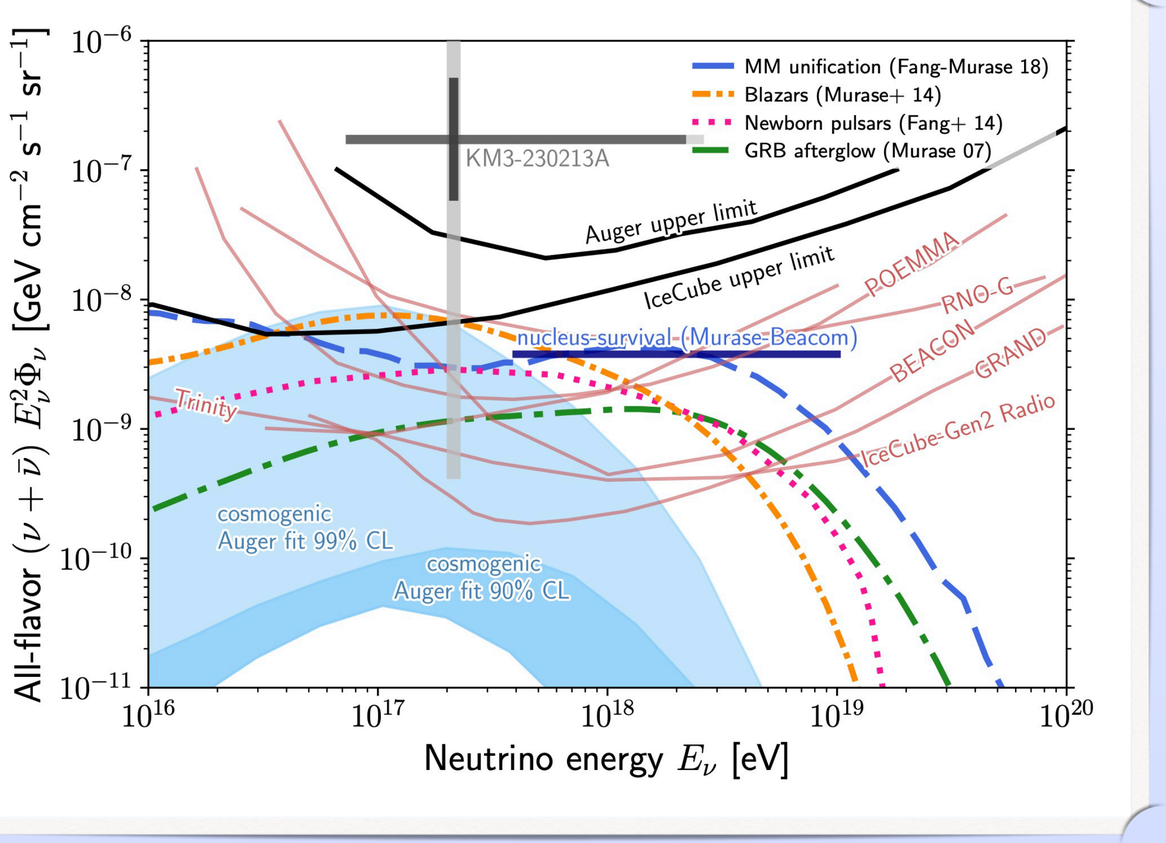
Carrying Auger Findings to Neutrino flux predictions and constraints



- **Current composition+spectrum measurements predict a predominant astrophysical neutrino component around and below 1EeV**
- **Current Auger and IceCube neutrino upper limits:**
  - Already constraining pure GZK-proton predictions.
  - Approaching astrophysical models: SBGs, AGNs, BNS mergers, etc.
- **However, there is a long way to go until we are able to measure UHE-neutrino fluxes predicted by Auger measurements**

Carrying Auger Findings to Neutrino flux predictions and constraints

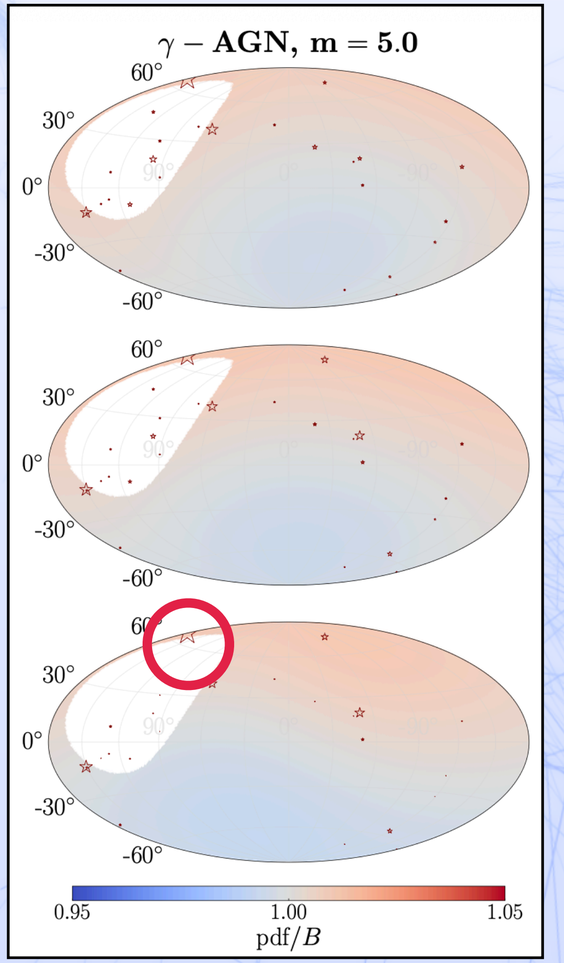


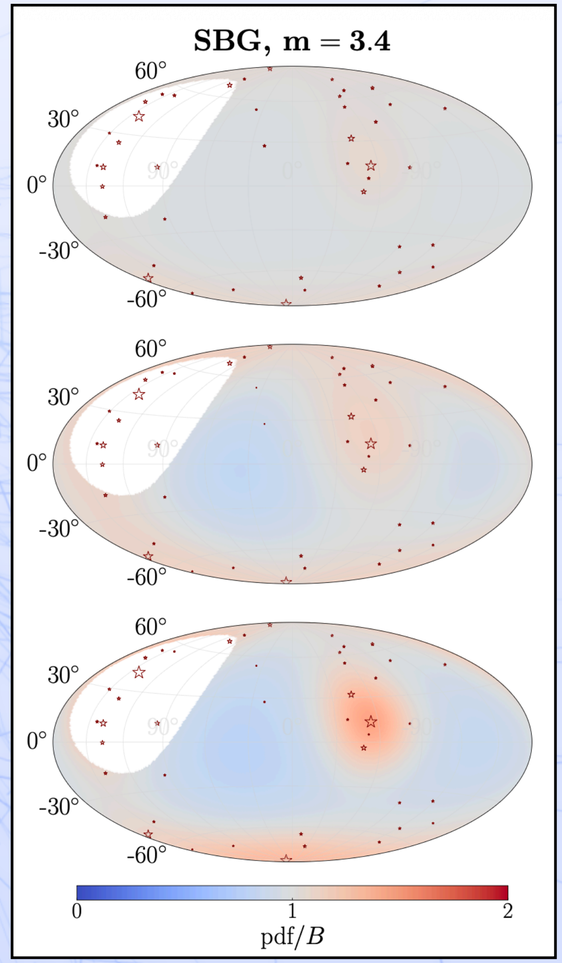


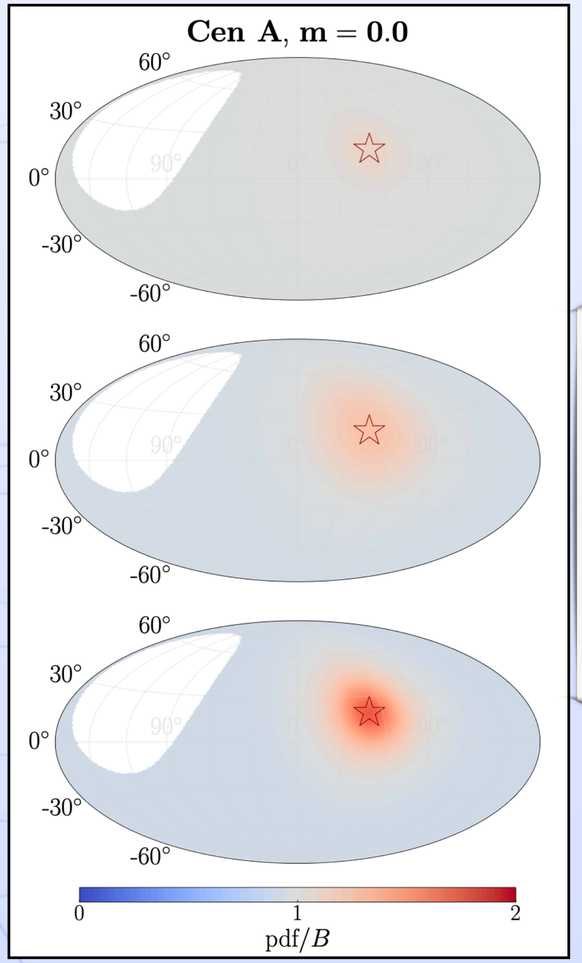
From Kohta Murase talk earlier today

Combined fit with arrival-directions

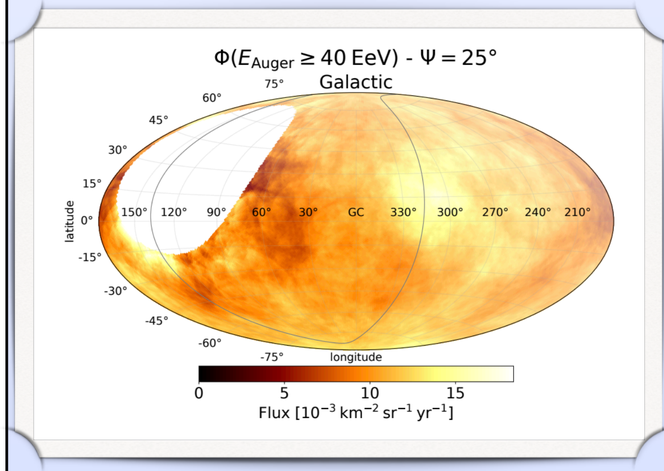
Combined Fit + AD 2024: JCAP [2305.16693]







Data



- γ – AGN **doesn't describe the data well**
- **Markanian-421 overweighted**

- **SBGs: best-fit model**
- 4.5σ **preference over homogeneous model**

- **Cen A alone can't be statistically preferred or rejected over SBGs.**

UHECR Mass Composition:

- ☞ Below 1EeV is very mixed
- ☞ Lighter and mixed from 1EeV to 5EeV
- ☞ Increasingly heavy and purer after 5EeV
- ☞ Models significantly change details of interpretations

Astrophysical interpretation from UHECR Spectrum and Composition:

- ☞ Below ankle at least partly extragalactic: soft emission spectrum
- ☞ Above the ankle extragalactic with hard emission spectrum and heavy composition

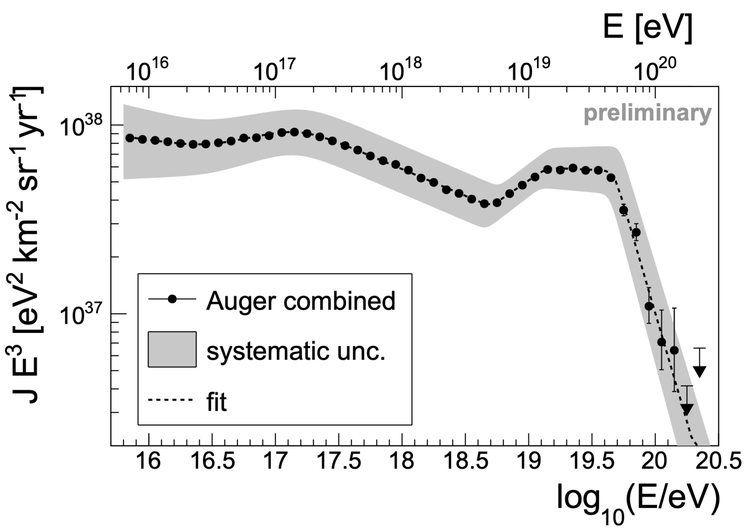
Connection to Neutrinos

- ☞ Flux upper limits already constraining pure proton scenarios
- ☞ Low cosmogenic fluxes predicted by best-fit scenario
- ☞ Astrophysical neutrinos would dominate UHE flux
- ☞ Further constraints will be possible in the not-so-distant future

Observables

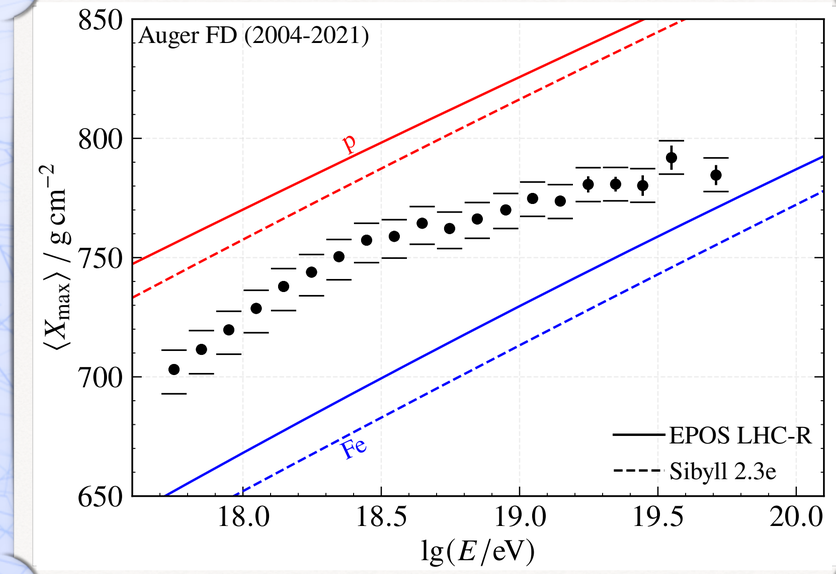
Energy Spectrum: CRIS-MAC 2024 [2501.01736]
FD Hybrid 2026: Phys. Rev. D, accepted [2605.12598]
Dipole 2024: APJ [2408.05292v3]
Medium Scales 2022: APJ [2206.13492]

Energy Spectrum



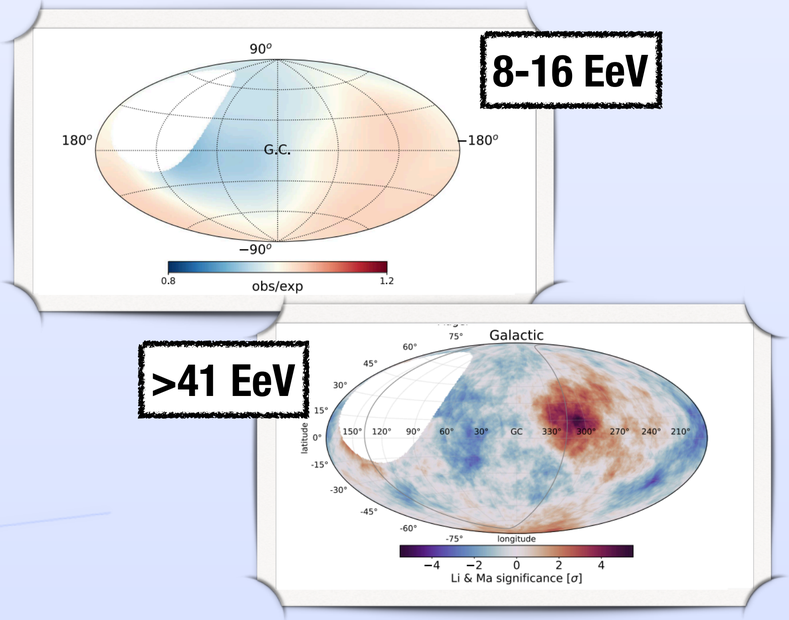
- SD events with FD energy calibration
- Very large statistics
- 14% systematic energy calibration uncertainty

Mass Composition: X_{max}



- Uses hybrid events (FD+SD)
- Limited energy range, last bin at ~19.7
- Deeper and wider X_{max} distributions: lighter composition
- Can infer average composition through post-LHC hadronic interaction models

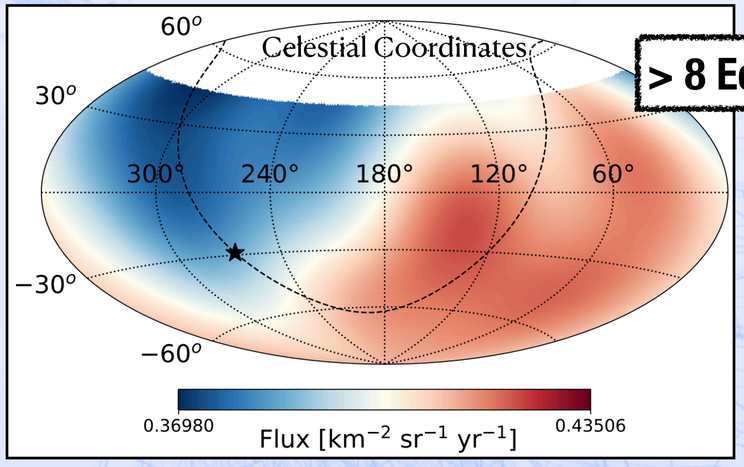
Arrival Direction



- SD events with tighter selection cuts
- $\sim 1^{\circ}$ directional resolution

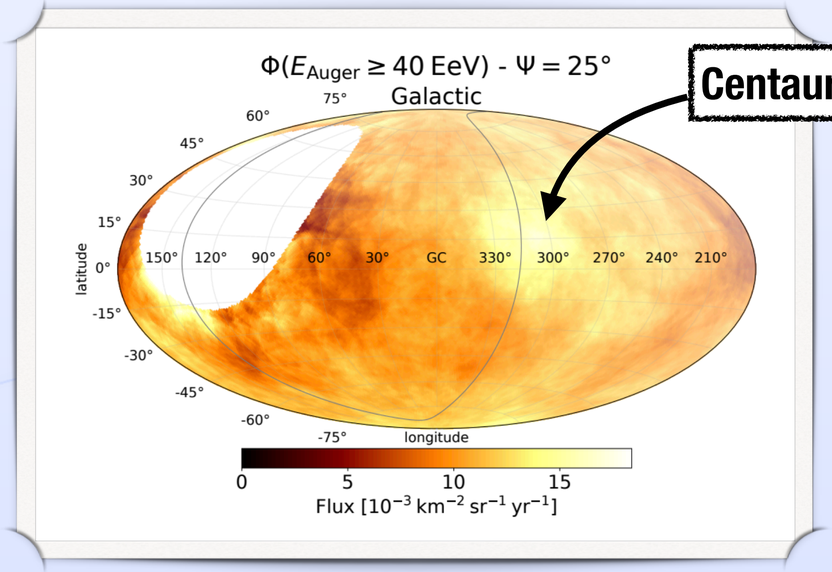
Arrival Directions and Source Distribution

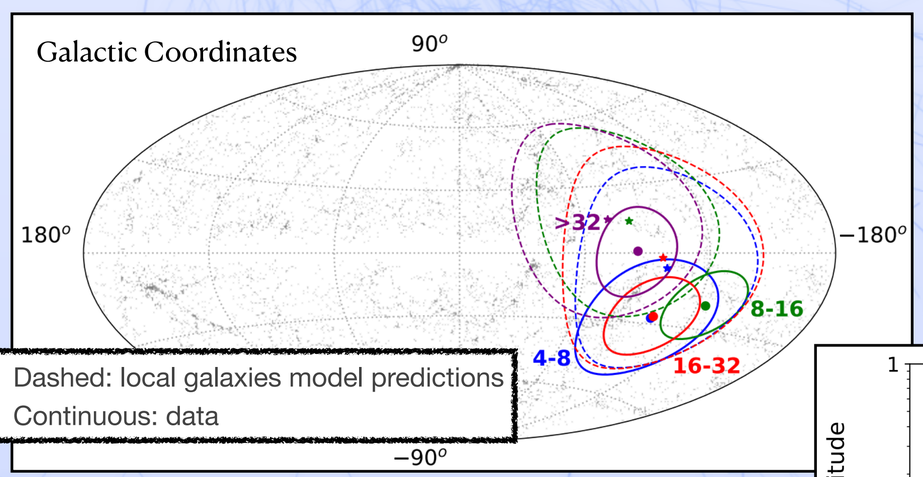
Dipole 2024: APJ [2408.05292v3]
Medium Scales 2022: APJ [2206.13492]



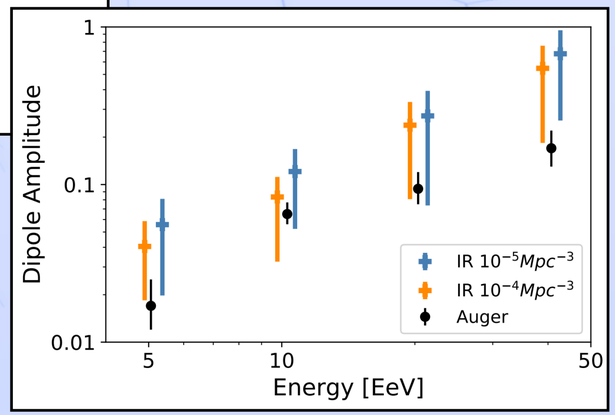
> 8 EeV

- 6.8σ RA sinusoidal modulation
- 7.4% dipole amplitude
- Uncompatible with GC
- Compatible with local IR galaxy distribution $(d < 120\,\mathrm{Mpc})$





- Dashed: local galaxies model predictions
- Continuous: data



- Dipole amplitudes and directions compatible with local infrared-detected galaxy distribution.

- **Medium scale anisotropies at the highest energies.**
- **Centaurus A region hotspot.**
- **Good correlation with SBGs catalog and Cen A only.**
- **No small scale features nor magnetic alignment evidence.**
- **Consistent with heavy composition.**

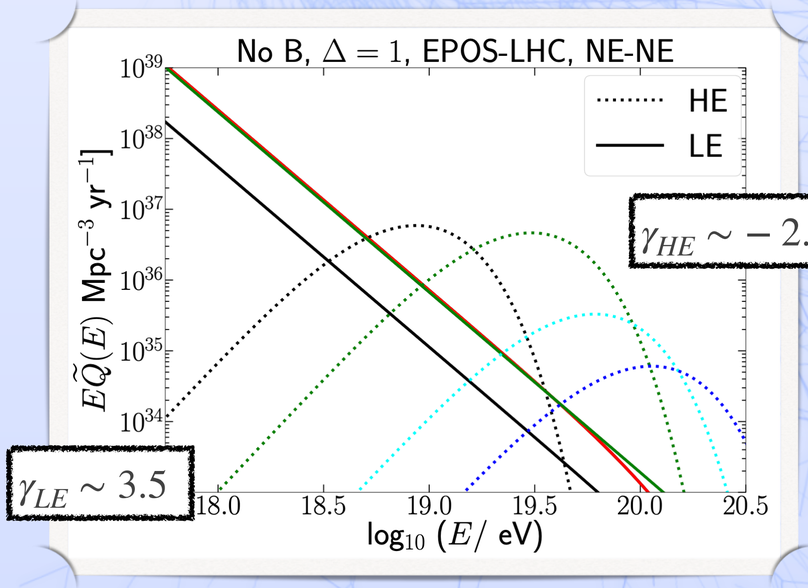
Combined fit with EG magnetic fields

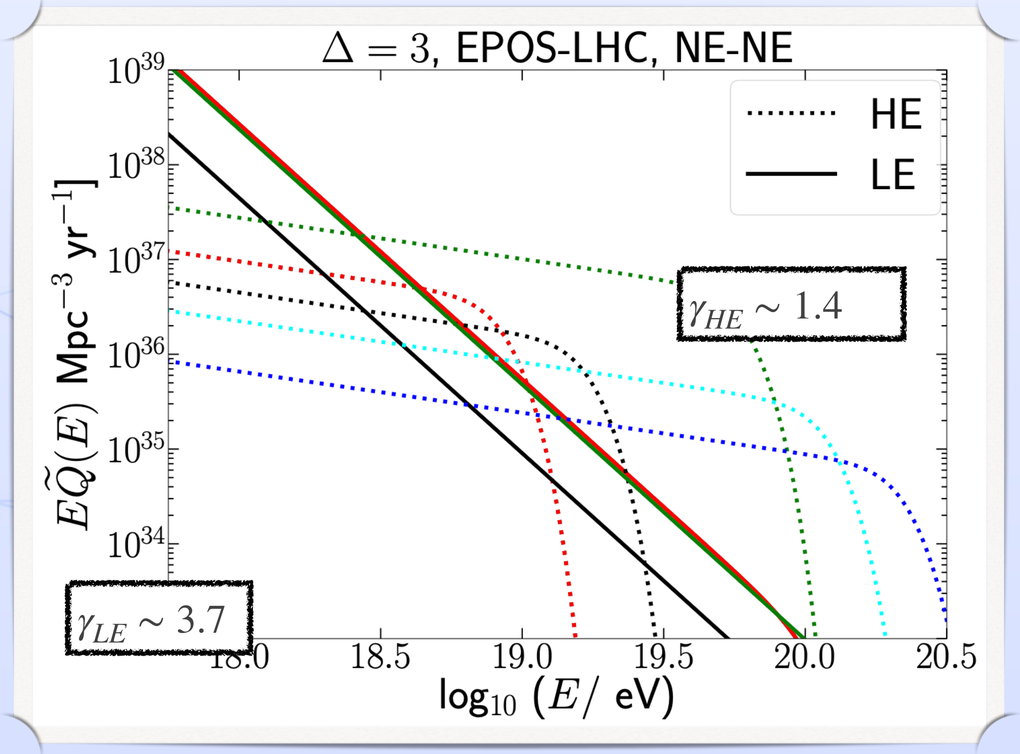
Combined Fit + EGMF 2024: JCAP [2404.03533]

$$\tilde{Q}_A(E) = \tilde{Q}_{0A} \left(\frac{E}{E_0}\right)^{-\gamma} \begin{cases} 1, & E \le Z_A R_{\rm cut}; \\ \exp\left(1 - \frac{E}{Z_A R_{\rm cut}}\right), & E > Z_A R_{\rm cut}, \end{cases}$$

$$\mathrm{sech}\left[\left(E/(ZR_{cut})\right)^{\Delta}\right]$$

$\Delta = 1$ **shape similar to exp**



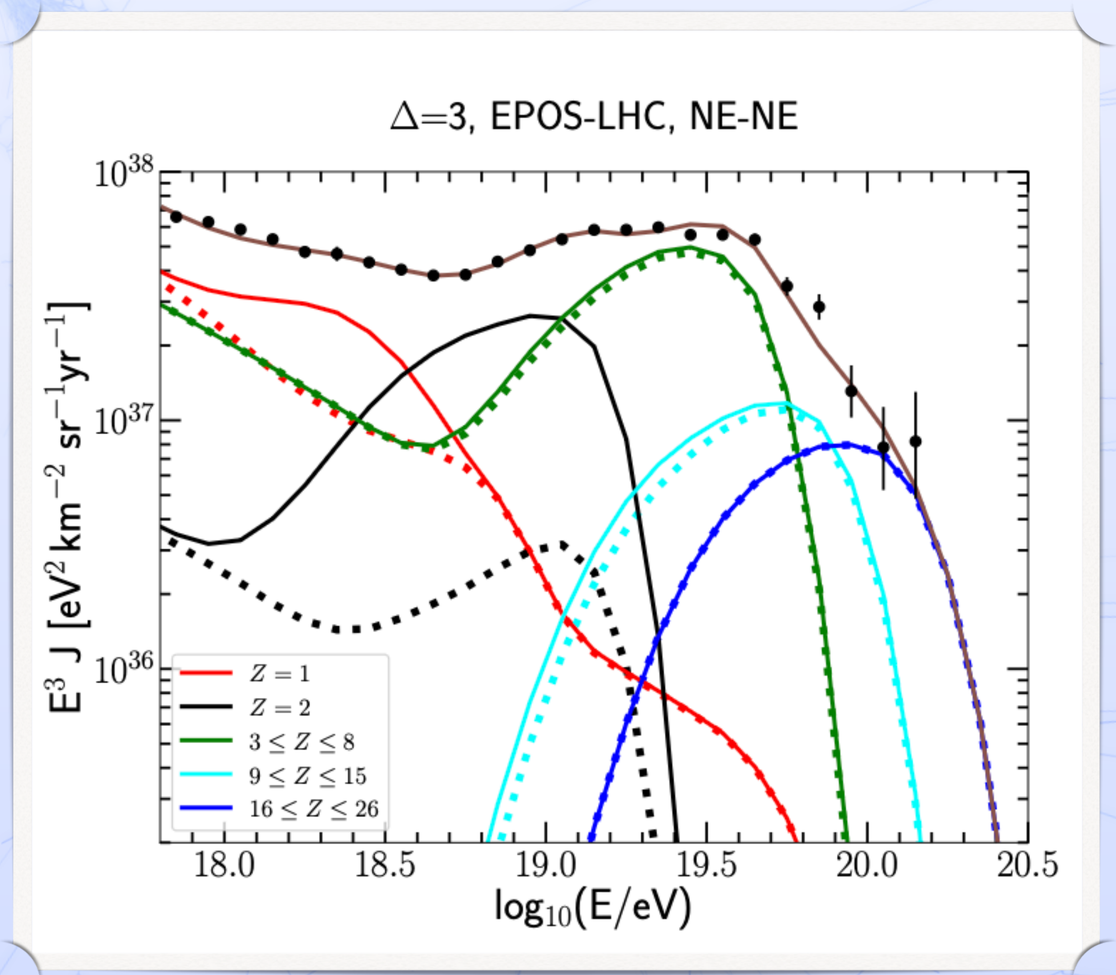


- Including EG magnetic fields as free parameters with $\Delta = 1$ the model prefers no magnetic field.
- Similar results to previous case with exponential cutoff

- Including EG magnetic fields as free parameters with $\Delta = 3$ the model prefers a strong magnetic field/low source density
- HE emission spectrum closer to Fermi Acceleration
- Slightly worse likelihood than $\Delta = 1$ case

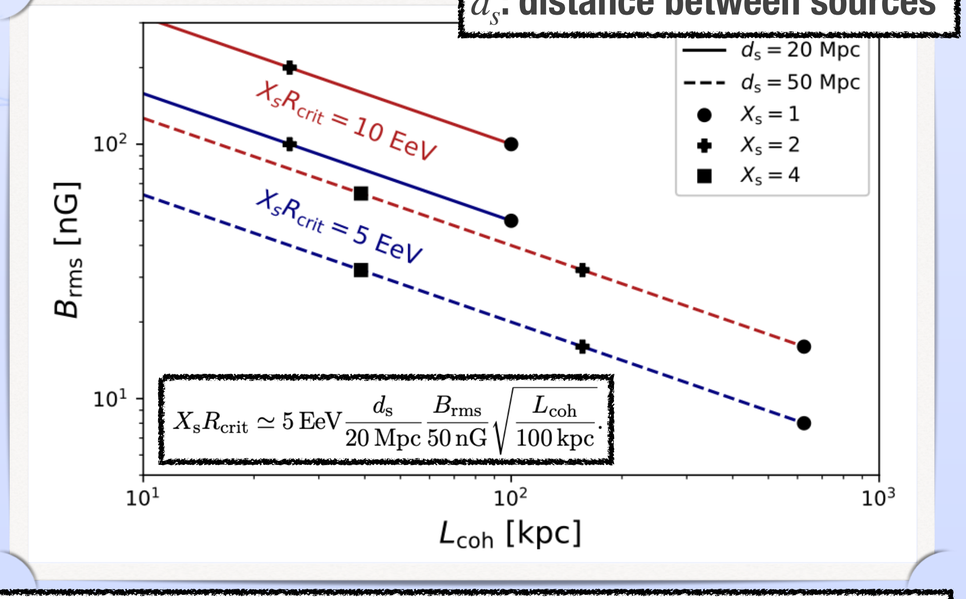
Combined fit with EG magnetic fields

Combined Fit + EGMF 2024: JCAP [2404.03533]



- Behavior at Earth very similar to $\Delta = 1$ or exponential case.
- Hard spectrum now explained by magnetic horizon effect.
- Low rigidity particles haven't reached the Earth yet due to diffusion in EGMF
- Pronounced spectrum and low mixing from steep cutoff $\Delta = 3$

d_s: distance between sources



- Model predicts strong magnetic fields ($\sim 10 - 200\,\mathrm{nG}$)
- And low source density

Combined fit with arrival-directions

Combined Fit + AD 2024: JCAP [2305.16693]

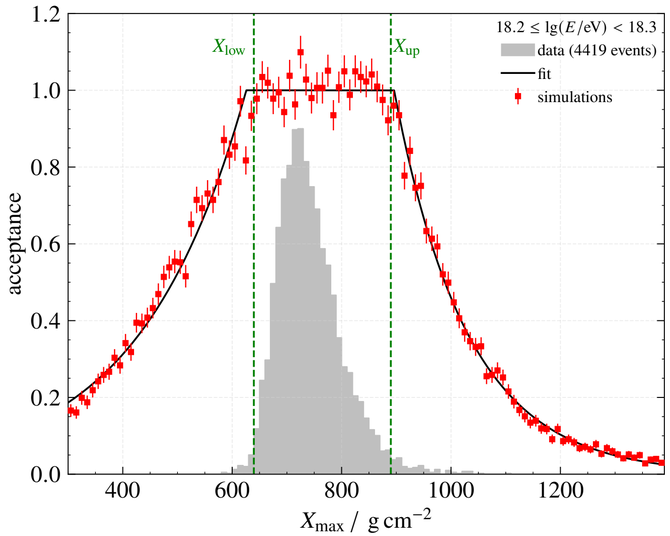
$$\widetilde{Q}_A(E) = \widetilde{Q}_{0A} \left(\frac{E}{E_0}\right)^{-\gamma} \begin{cases} 1, & E \leq Z_A\, R_{\rm cut}; \\ \exp\left(1 - \frac{E}{Z_A\, R_{\rm cut}}\right), & E > Z_A\, R_{\rm cut}, \end{cases}$$

Back to exponential cutoff

- **Fit to:**
  - Spectrum and composition above 10 EeV
  - Arrival directions above 16 EeV.
- **Only High Energy component: sources identical to background**
- **Three catalogs considered:**
  - $\gamma - \mathrm{AGN}$: source weights from Fermi-LAT γ-ray flux
  - Starburst Galaxies: source weights from radio flux at 1.4 GHz
  - Centaurus A: standalone
- **EGMF considered through a rigidity dependent blurring (1 free parameter)**
- **No magnetic horizon effects considered (high rigidities)**
- **Homogeneous background at $d > 3\,\mathrm{Mpc}$ with source evolution**

Acceptance

$$\varepsilon(X_{\max}) = \begin{cases} e^{+(X_{\max}-X_1)/\lambda_1}, & X_{\max} < X_1; \\ 1, & X_1 \le X_{\max} \le X_2; \\ e^{-(X_{\max}-X_2)/\lambda_2}, & X_2 < X_{\max}\,. \end{cases}$$



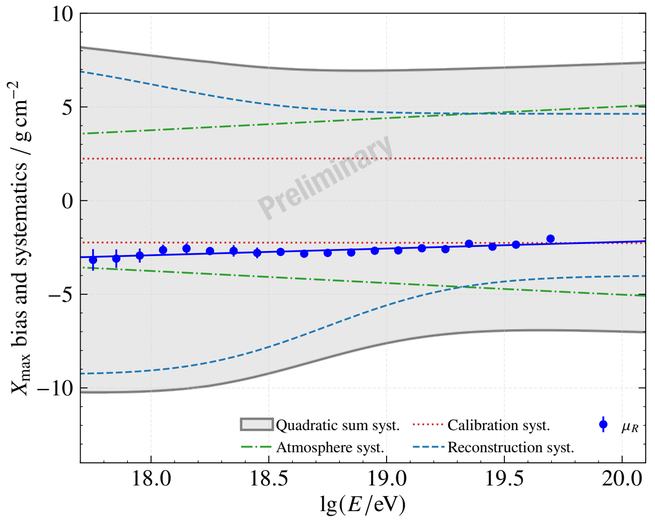
➢ **Acceptance:**

- From flat $X_{\max}$ simulations
- Exponential tails
- Parameters fit against energy to upweight distribution tails

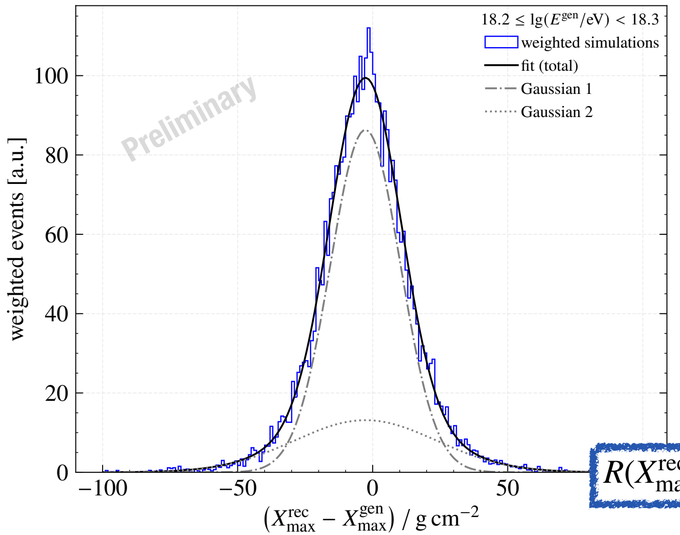
Bias and Resolution

FD Hybrid: Phys. Rev. D (2026) in preparation.

- **Estimations from Real MC:**
  - Full shower+detector simulations
  - Air showers from Conex+Sybill2.3d
  - Detector up-time included
  - Atmospheric aerosols and weather conditions considered



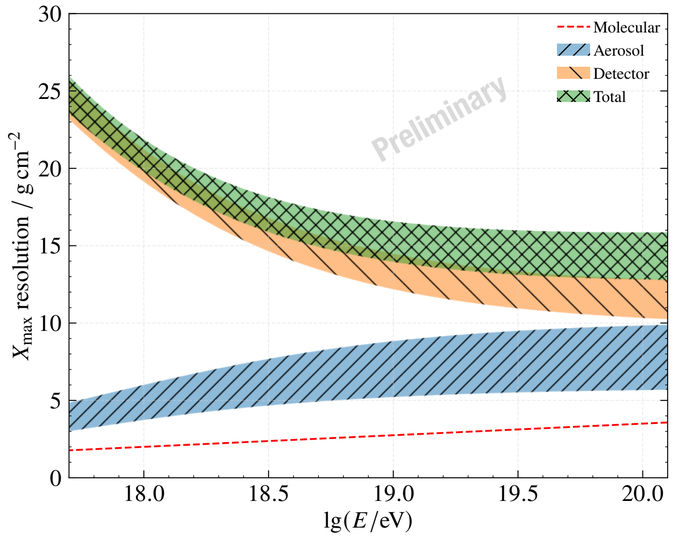
- **Bias from -4 to -3 g/cm2**
- **Well contained within systematic uncertainties**
- **Systematics from modeling uncertainty**
  - Atmosphere effects
  - Calibration
  - Shower profile parametrization



- **Bias and resolution:**
  - Simulations weighted to follow data $X_{\max}$ distribution.
  - Double-gaussian fit in each energy bin.
  - Parameters fit against energy to correct $X_{\max}$ and second moment

$$R(X^{\mathrm{rec}}_{\max} - X_{\max}) = f\,G(\mu, \sigma_1) + (1-f)\,G(\mu, \sigma_2)$$

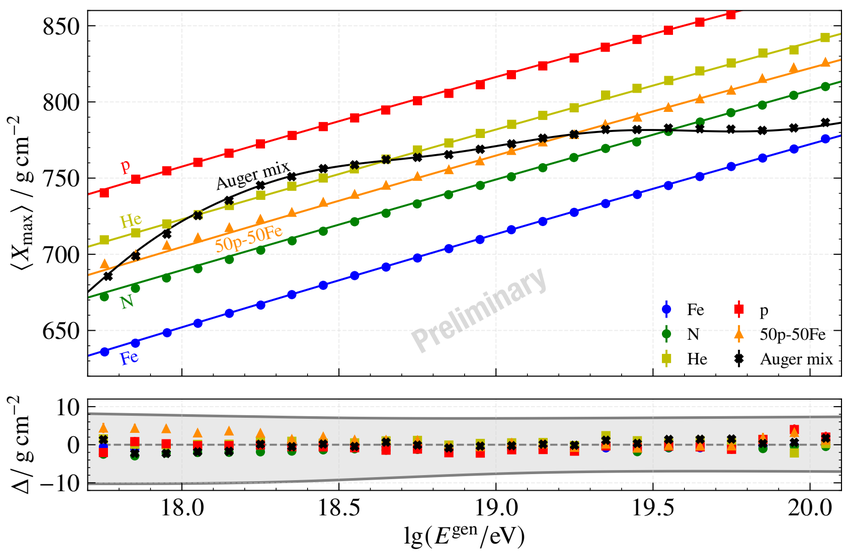
- **Resolution from 25 to 15 g cm^{-2} at high energies**
- **Systematics in resolution estimation propagated to second moments**
- **Sources other than reconstruction:**
  - Telescope alignment
  - Aerosol and molecular density profile uncertainty

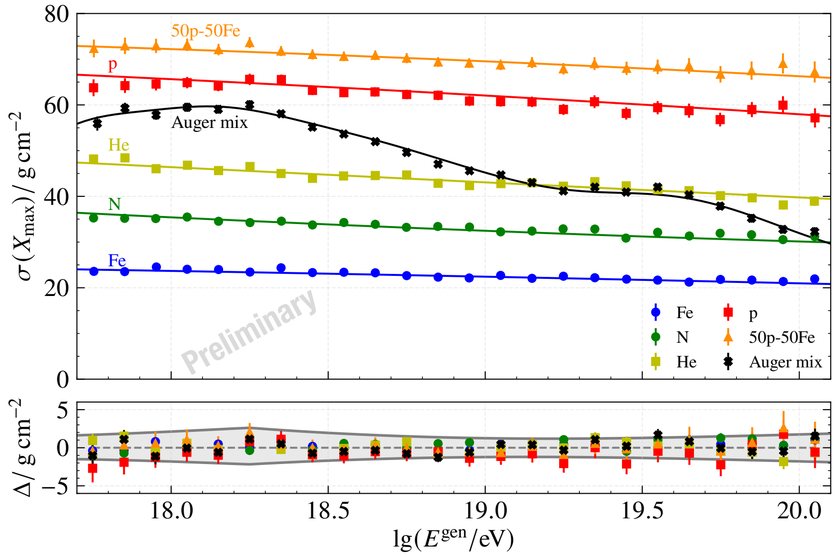


Analysis Cross-Checks

FD Hybrid: Phys. Rev. D (2026) in preparation.

- **End-to-end analysis on different simulated compositions show:**
  - $\langle X_{\max} \rangle$ reconstruction error lower than 4 g/cm2
  - $\sigma\left(X_{\max}\right)$ error lower than 3 g/cm2
  - All errors are compatible with systematics uncertainties





- **Stereo events comparison between data and RealMC:**
  - First two moments compatible
  - $\chi^2/\mathrm{ndf} = 26.12/23$
  - Validates resolution estimation

