Ultrahigh Energy Cosmic Rays

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CDY Initiative for Understanding the Physics of the Extreme Accelerators in our Universe
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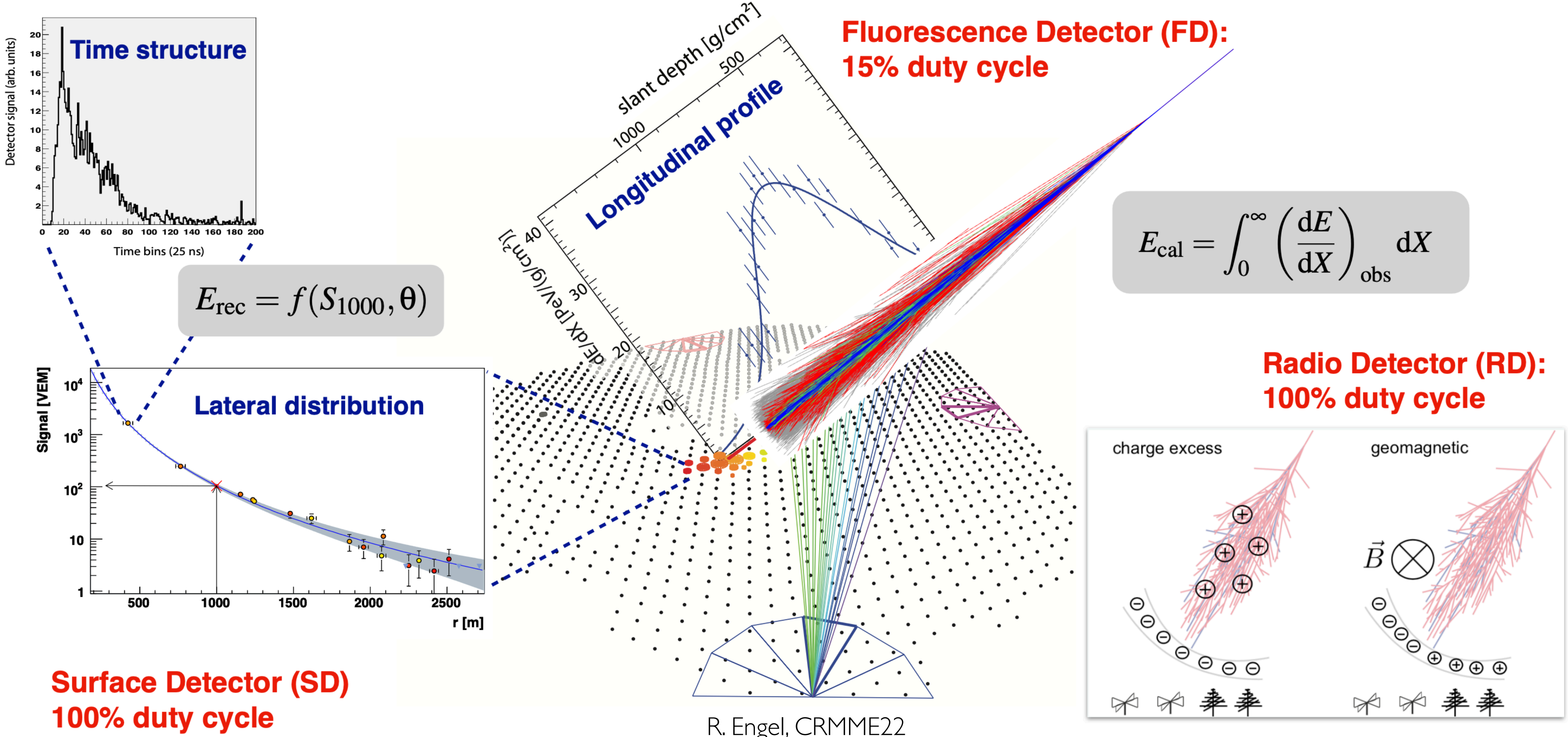
UHECRs: Essential Facts

- Mixed composition, evolves with energy
- Upper limit on energy mainly from accelerator(s)
- Sources apparently abundant rather than few & powerful

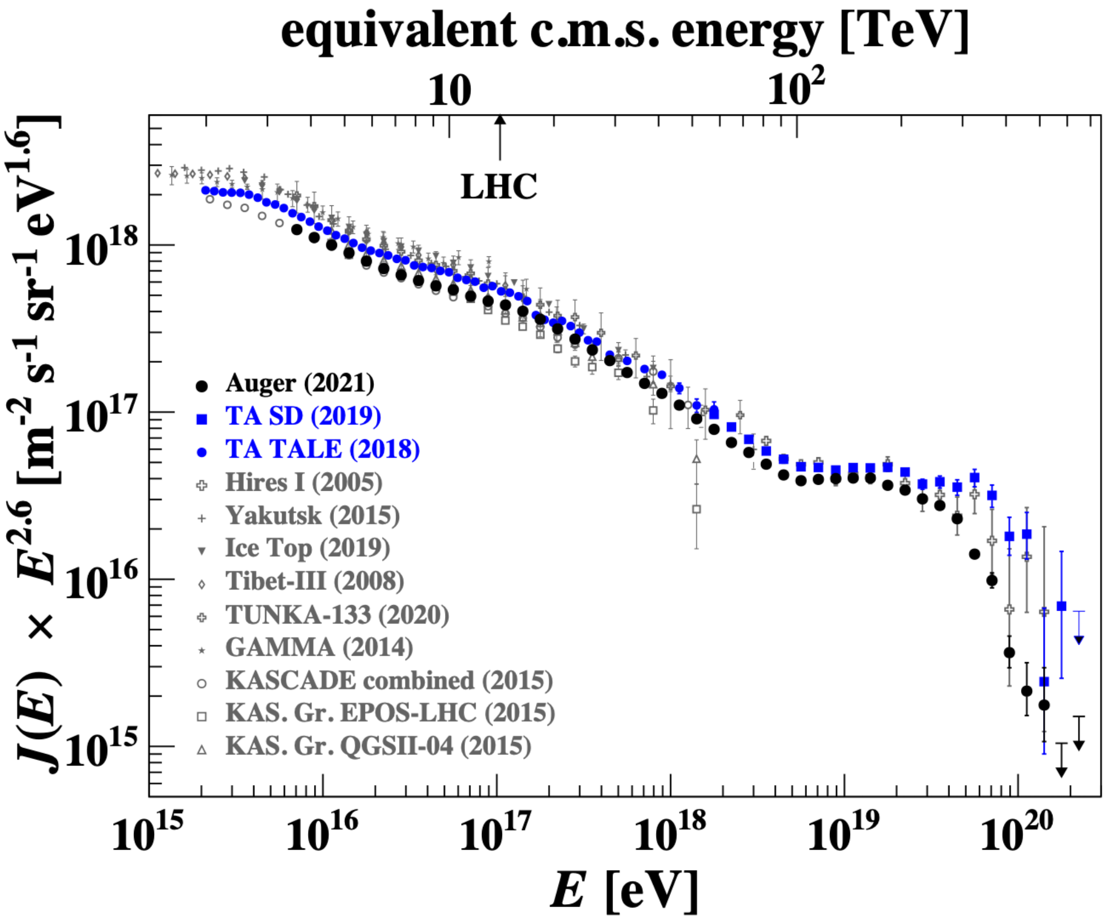
Air shower observables (hybrid observation)



Energy Spectrum

- Upper limit on energy comes mainly from accelerator(s)
  - Rigidity cutoff R = (E/Z) ≈ 5 EV (70 EeV Si, 35 EeV N)
- Distinct features emerging in spectrum
- Auger and TA agree within uncertainties (Auger has ~5x statistics and direct energy calibration; less reliance on modeling)
- Highest energy Galactic CRs overlap the lowest energy extragalactic UHECRs

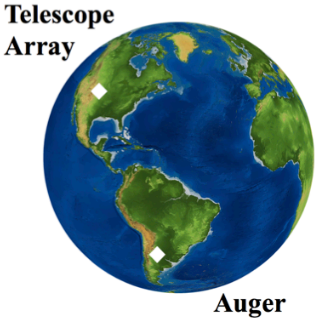
The joint Auger TA working group on energy spectrum



Understand the difference among the measurements at the UHEs:

- information on astrophysical phenomena
- correct combination of the data to achieve the full sky coverage

see F. Urban at this conference



UHECR 2010	Nagoya, Japan
UHECR 2012	Cern, Geneva
UHECR 2014	Springdale (Utah), USA
UHECR 2016	Kyoto, Japan
ICRC 2017	Busan, Korea
UHECR 2018	Paris, France
ICRC 2019	Madison, USA
ICRC 2021	Berlin, Germany

V. Versi, UHECR22

UHECR Hybrid Observatories

V.Versi, UHECR22

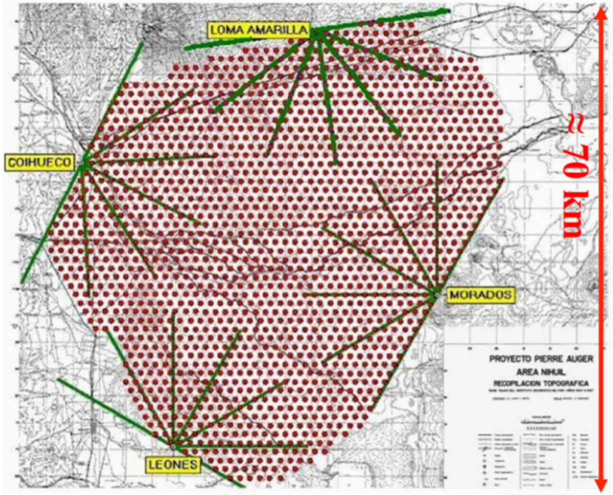
PIERRE AUGER OBSERVATORY

Malargüe Mendoza (Argentina)
35^0 S latitude

3000 km^2

1660 WCDs
1500 m spacing
triangular grid

4 FD sites



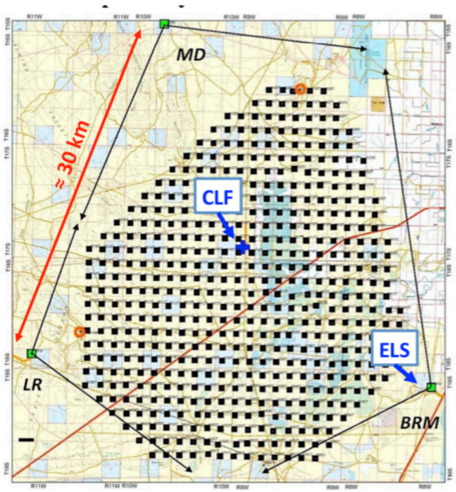
TELESCOPE ARRAY

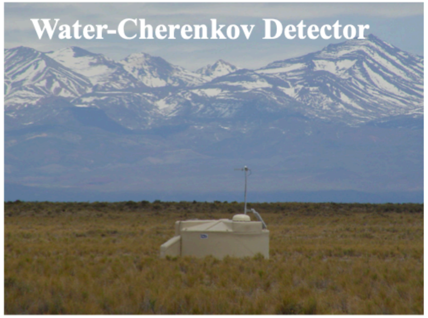
Millard County Utah (USA)
39^0 N latitude

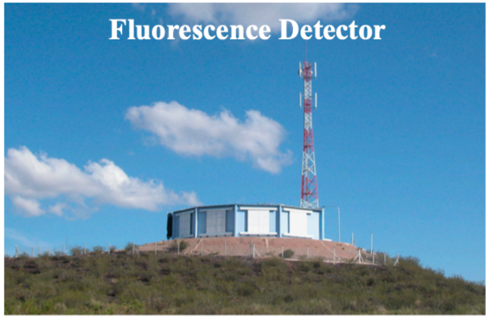
700 km^2

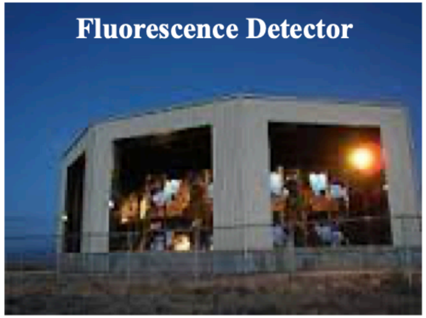
507 scintillators
1200 m spacing
square grid

3 FD sites

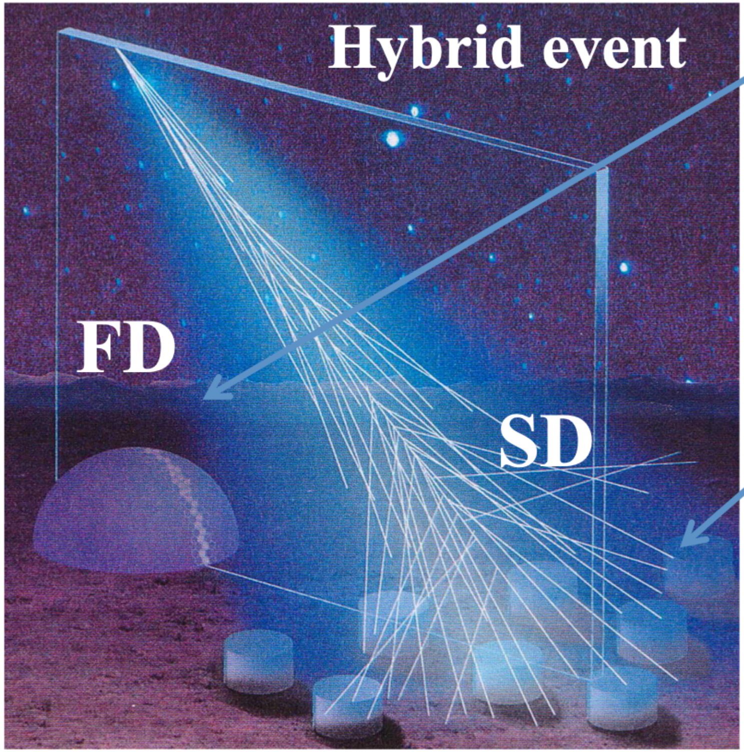






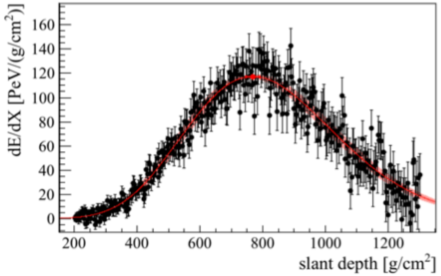


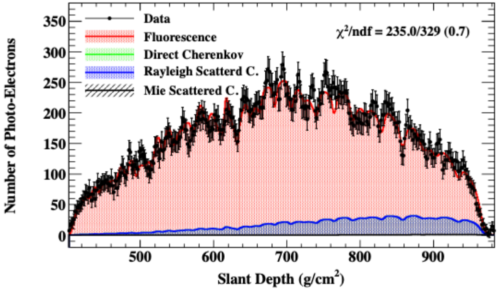
The hybrid detection technique

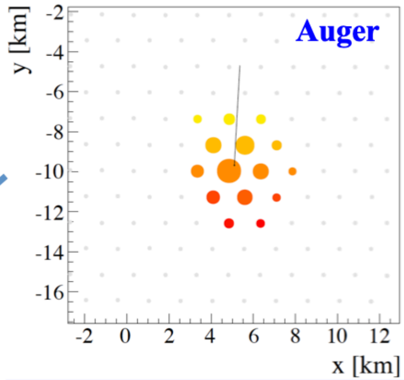


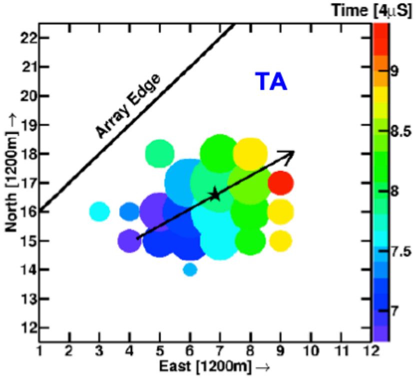
15% duty cycle

100% duty cycle









UHECR spectrum

- **high efficiency of SD**
- **calorimetric energy scale from FD**

The energy scale

AUGER

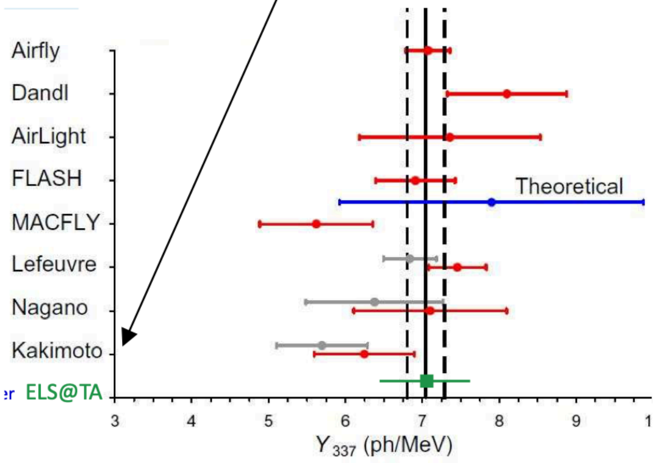
Proc. 34 ICRC 2013 (Rio de Janeiro, Brazil) [arXiv:1307.5059]

Absolute fluorescence yield	3.4%
Fluores. spectrum and quenching param.	1.1%
Sub total (Fluorescence Yield)	**3.6%**
Aerosol optical depth	3% ÷ 6%
Aerosol phase function	1%
Wavelength dependence of aerosol scattering	0.5%
Atmospheric density profile	1%
Sub total (Atmosphere)	**3.4% ÷ 6.2%**
Absolute FD calibration	9%
Nightly relative calibration	2%
Optical efficiency	3.5%
Sub total (FD calibration)	**9.9%**
Folding with point spread function	5%
Multiple scattering model	1%
Simulation bias	2%
Constraints in the Gaisser-Hillas fit	3.5% ÷ 1%
Sub total (FD profile rec.)	**6.5% ÷ 5.6%**
Invisible energy	**3% ÷ 1.5%**
Statistical error of the SD calib. fit	**0.7% ÷ 1.8%**
Stability of the energy scale	**5%**
TOTAL	**14%**

TA

Proc. 32nd ICRC 2011 (Beijing, China), 12, 67 (2011)
Astropart.Phys. 61 (2015) 93-101

Item	Error (%)	Contributions
Detector sensitivity	10	PMT (8%), mirror (4%), aging (3%), filter (1%)
Atmospheric collection	11	aerosol (10%), Rayleigh (5%)
Fluorescence yield	11	model (10%), humidity (4%), atmosphere (3%)
Reconstruction	10	model (9%) missing energy (5%)
Sum in quadrature	21	



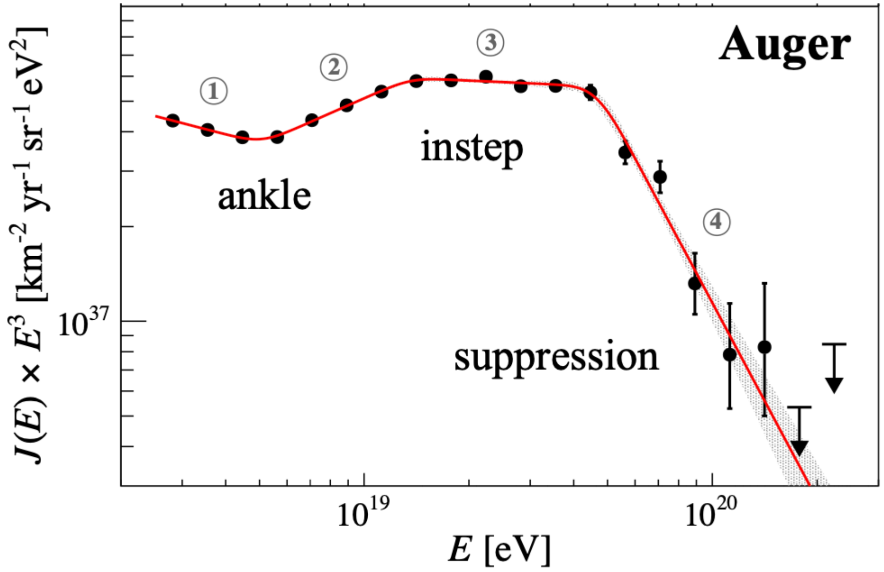
Auger uses Airfly
Astrop. Phys. 42. 90 (2013)
Astrop. Phys. 28, 41 (2007)

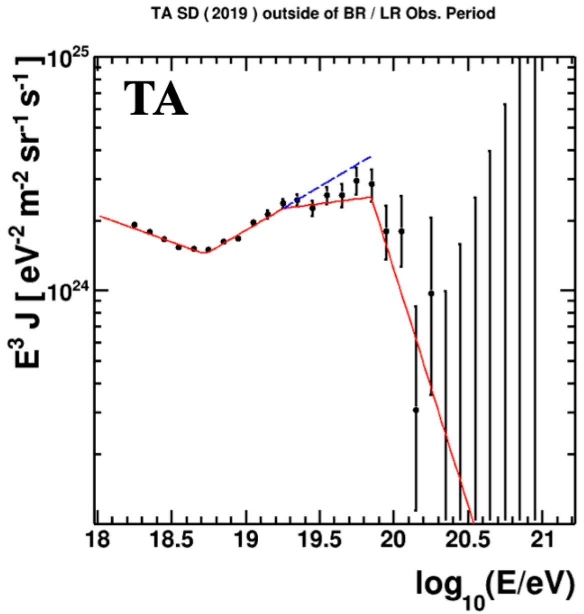
figure from M. Fukushima, GCOS workshop 2022

TA uses Kakimoto et al.
NIM-A 372, 527 (1996)
+FLASH spectrum

TA 21% Auger 14% both almost energy independent

Measurements at the two observatories



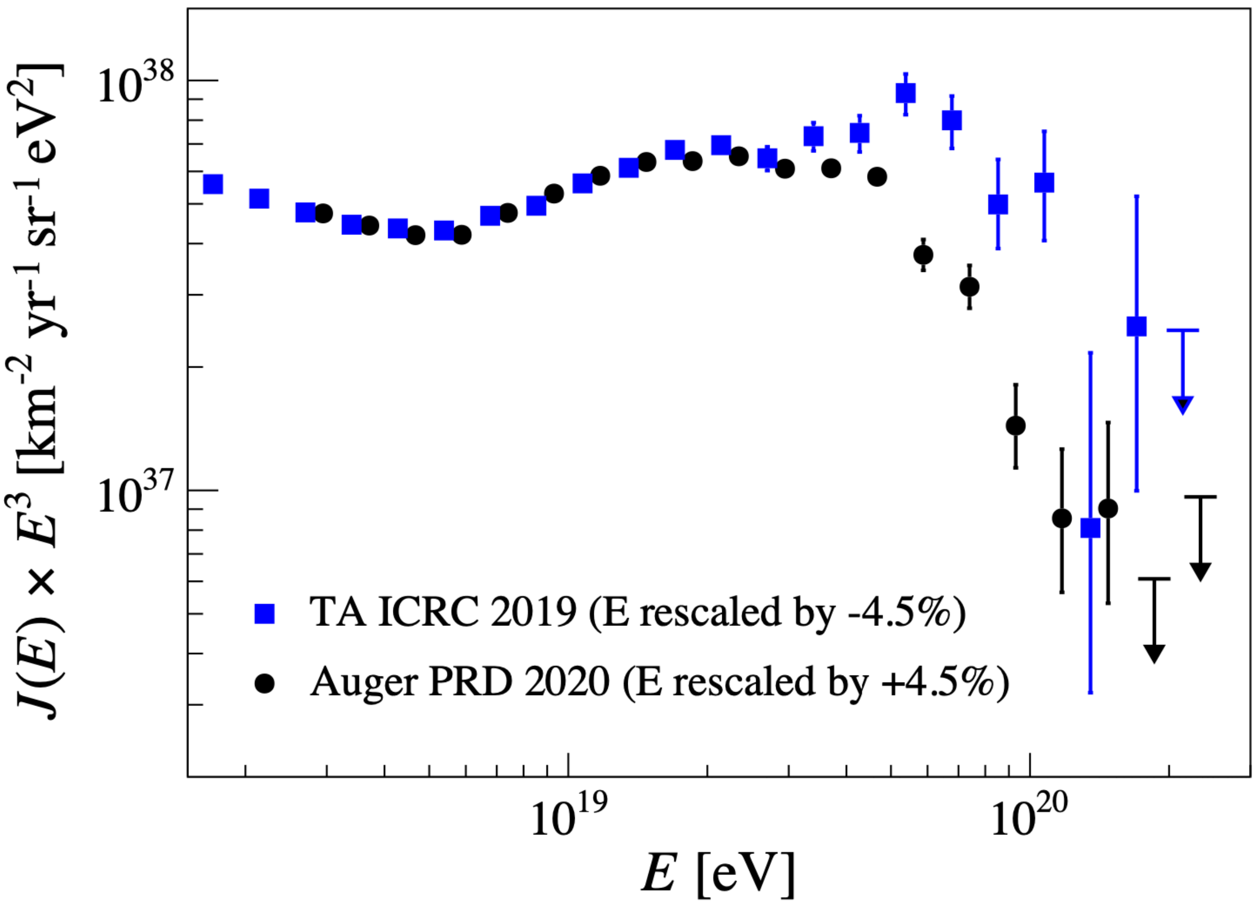


Auger, Phys. Rev. D 102 (2020) 062005
TA, PoS (ICRC2019) 298
see also WG report PoS (ICRC2021) 337

Parameter	Auger	TA
γ_1	3.29 ± 0.02	3.23 ± 0.01
γ_2	2.51 ± 0.03	2.63 ± 0.02
γ_3	3.05 ± 0.05	2.92 ± 0.06
γ_4	5.1 ± 0.3	5.0 ± 0.4
$E_{\mathrm{ankle}}/\mathrm{EeV}$	5.0 ± 0.1	5.4 ± 0.1
$E_{\mathrm{instep}}/\mathrm{EeV}$	13 ± 1	18 ± 1
$E_{\mathrm{cut}}/\mathrm{EeV}$	46 ± 3	71 ± 3

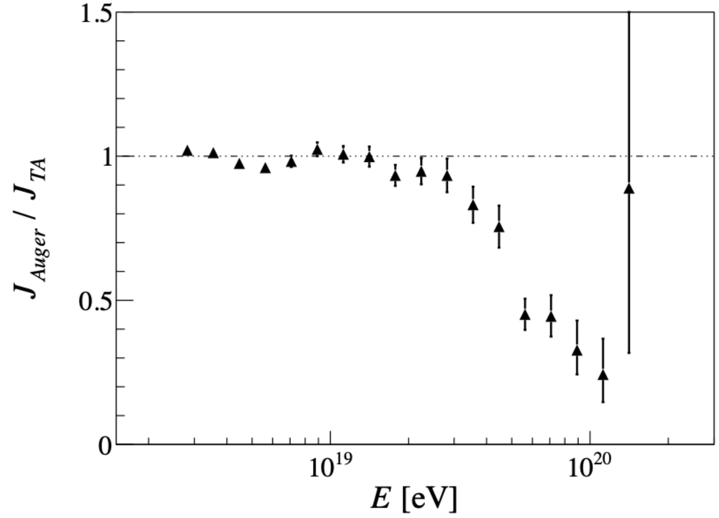
- **same characterization of the spectral features**
- **agreement at the ankle and some tension at highest energies**
- **common declination band to disentangle astrophysical from experimental effects:** $-15^{\circ} < \delta < 24.8^{\circ}$

Measurements in the full sky



good agreement up to ≈ 10^{19} eV after an overall 9% rescaling of the energies

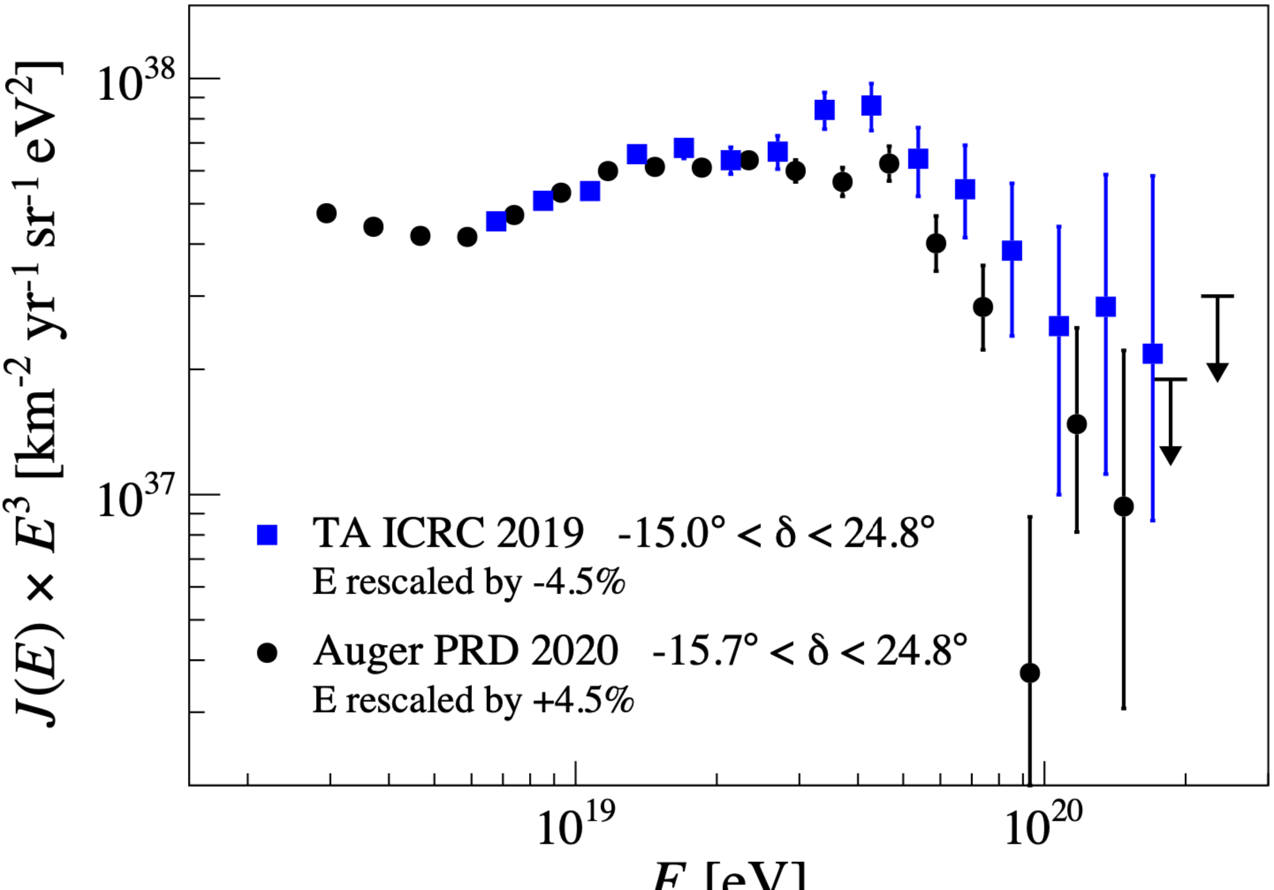
significant discrepancy at the highest energies



V.Versi, UHECR22

Measurements in the common declination band

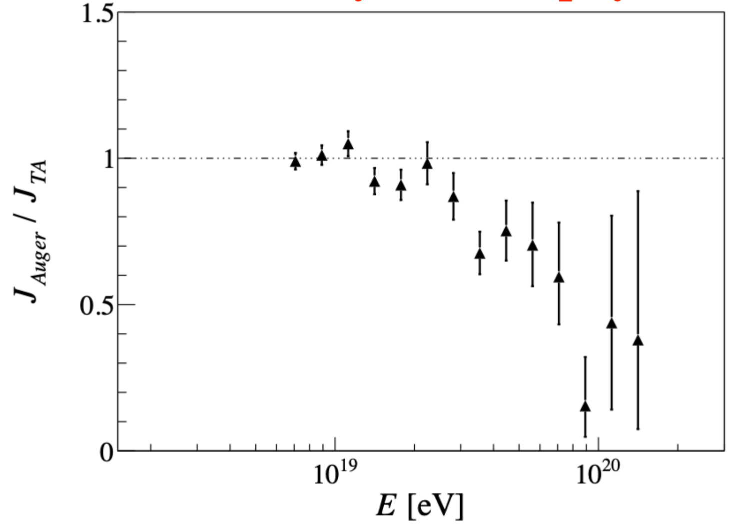
note: TA full trigger efficiency E>$10^{18.8}$ eV



Low energy discrepancy resolved by common fluorescence yield & invisible energy

discrepancy at the highest energies persists in the common declination band

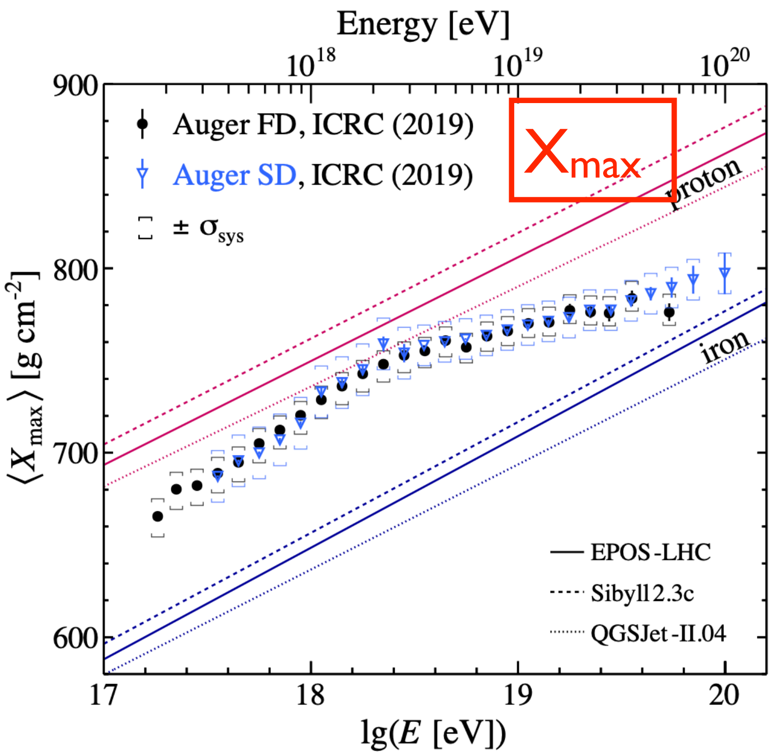
➔ spectrum discrepancy ≳30EeV; cannot mostly be astrophysical

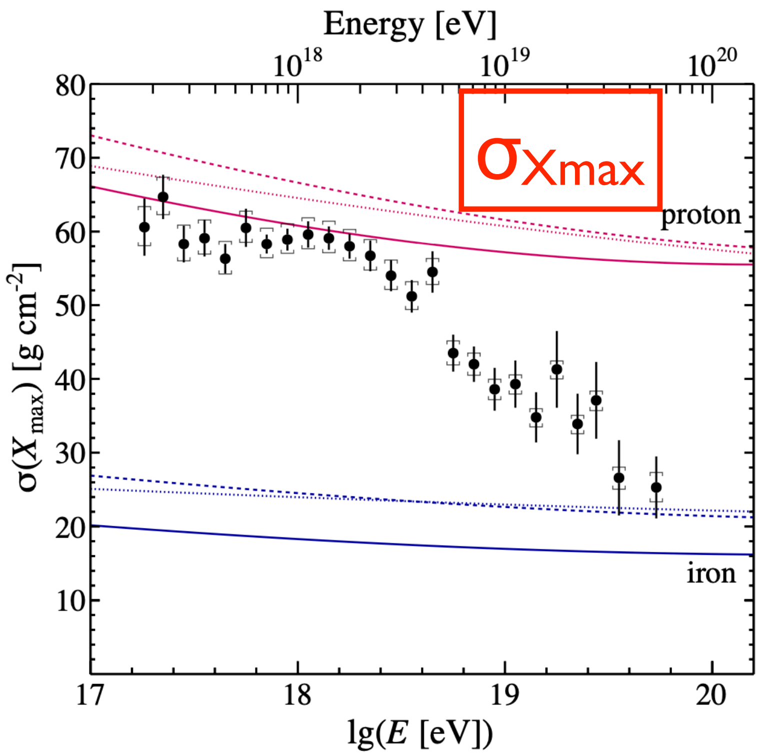


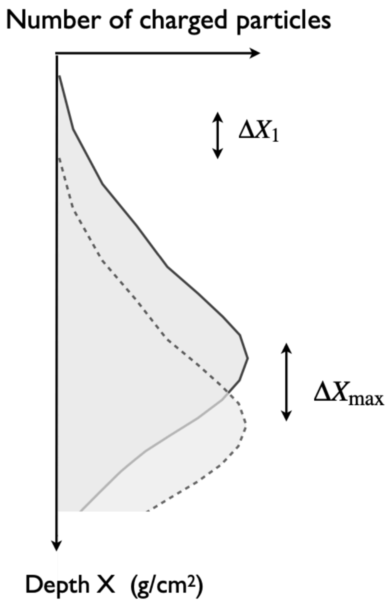
Composition

- Composition becomes heavier with energy
- TA & Auger observations agree
- Interpreting data to infer actual composition requires UHE air shower modeling

Mass composition results (i)







$$\frac{dP}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

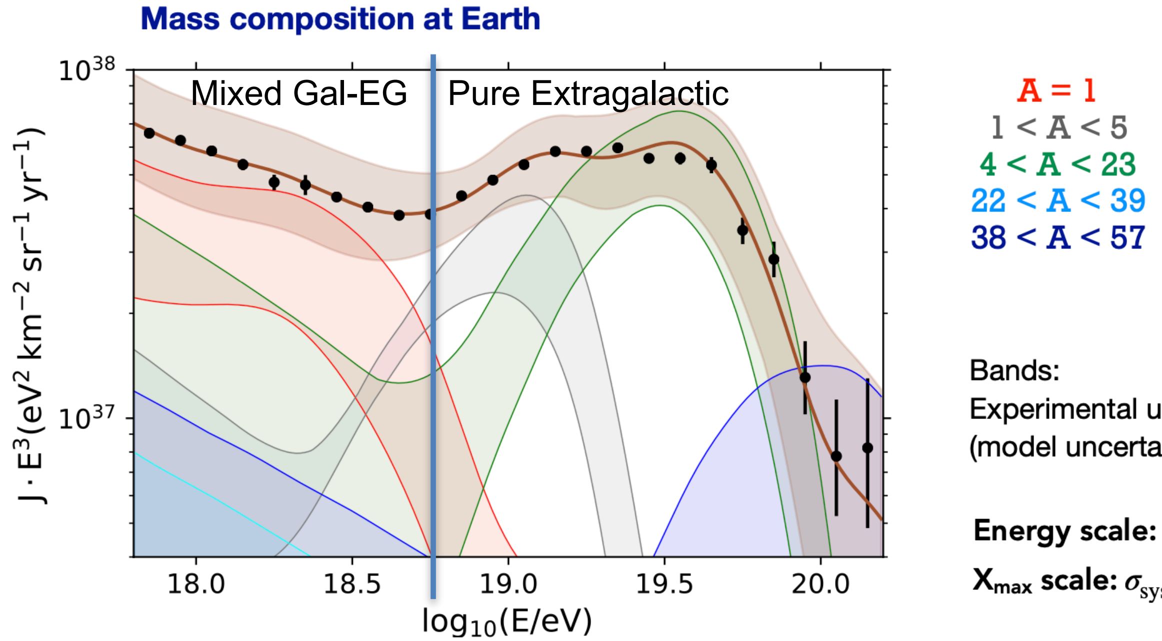
Important: LHC-tuned interaction models used for interpretation

$$\sigma_{X_1,p} \sim 45 - 55\,\mathrm{g/cm^2}$$
$$\sigma_{X_1,Fe} \sim 10\,\mathrm{g/cm^2}$$

($E \sim 10^{18}$ eV)

(Phys. Rev. D90 (2014), 122005 & 122005, updated ICRC 2019)

(Phys. Rev. D96 (2017), 122003)

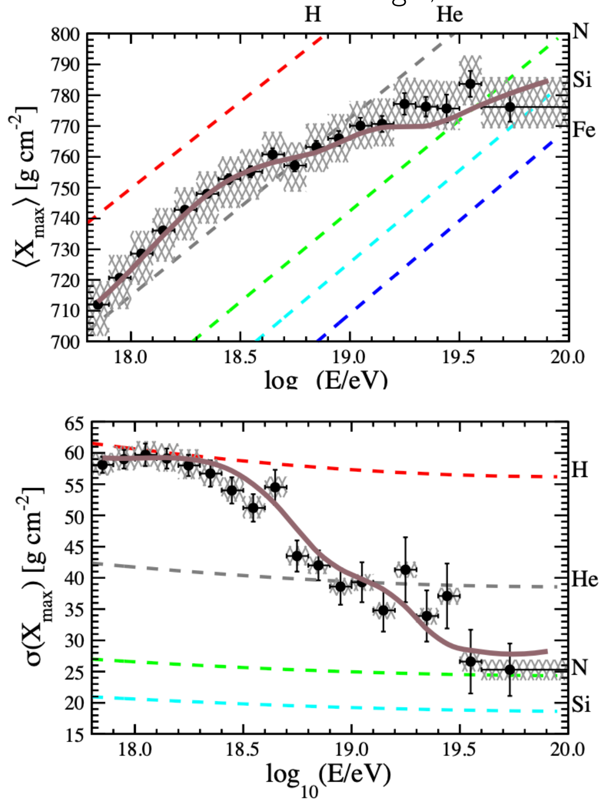


Bands:
Experimental uncertainties
(model uncertainties smaller)

Energy scale: $\sigma_{sys}(E)/E = 14\,\%$

X_{max} scale: $\sigma_{sys}(X_{max}) = 6 \div 9\ g\ cm^{-2}$

R. Engel, CRMME22



Different model scenarios considered for low-energy part
(transition to galactic component), similar results for total composition obtained

- Roughly consistent with “Peters cycle”: rigidity dependent acceleration
- Note relatively narrow range for each mass: rises and falls quickly

TA measurement of composition is consistent with Auger’s

Testing the Compatibility of the Depth of the Shower Maximum Measurements performed at Telescope Array and the Pierre Auger Observatory

Auger-TA Mass Composition Working Group Report

D.R. Bergman, J. Bellido, V. de Souza, R. Engel, Z. Gerber, J.H. Kim, E. Mayotte, O. Tkachenko, M. Unger, A. Yushkov for the TA and Auger collaborations

Conclusion

We have constructed a representation of Auger X_{max} measurements as would have been seen in the TA detector using the Sibyll 2.3d high-energy interaction model.

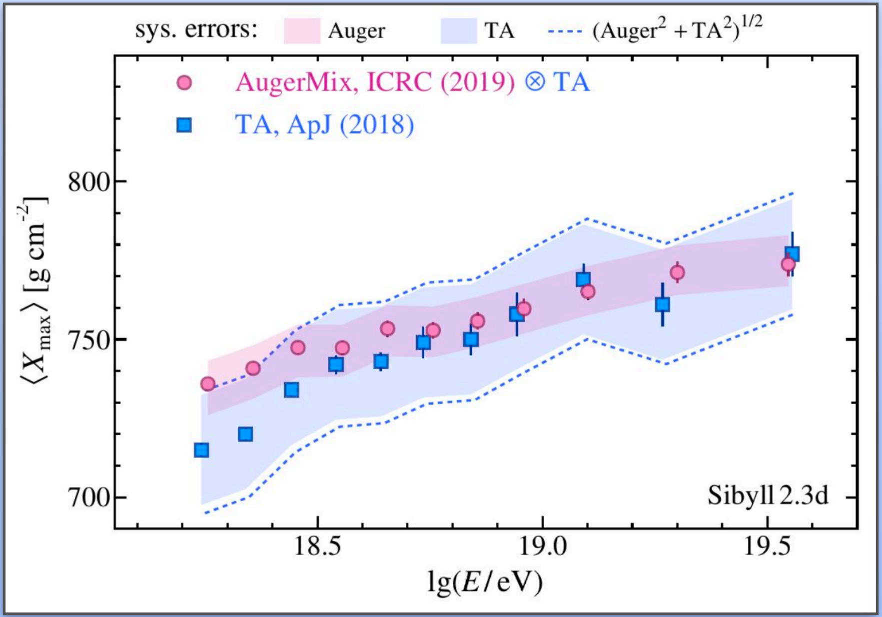
This representation agrees with TA $<X_{max}>$ measurements well, but there is disagreement at some energies in $\sigma(X_{max})$. This disagreement is plausibly due to the handling of X_{max} resolution due to varying aerosols at TA

A robust difference between the Auger and TA X_{max} measurements **has not been found**

A journal publication from the Mass Composition Working Group is forthcoming

Earlier differences due to:

- TA reliance on simulations
- low statistics
- sensitivity to shower modeling



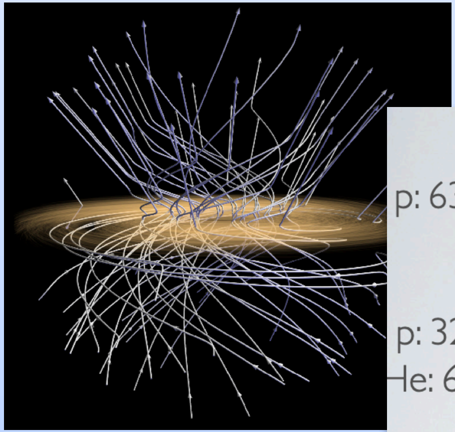
UHECR air shower modeling

- Leading models: Sibyll23.d and EPOS-LHC [also QGSJET]
- Tuned to LHC-data
- Discrepancies describing UHE air showers (10x greater CM energy; not p-p: UHECR + air nucleus, then pi's,etc + air)
    - ~30% more muons observed than models predict
    - predicted <X_{max}> ~ 1σ too deep
    - muon production depth,…

➜ Composition may be somewhat heavier than current models

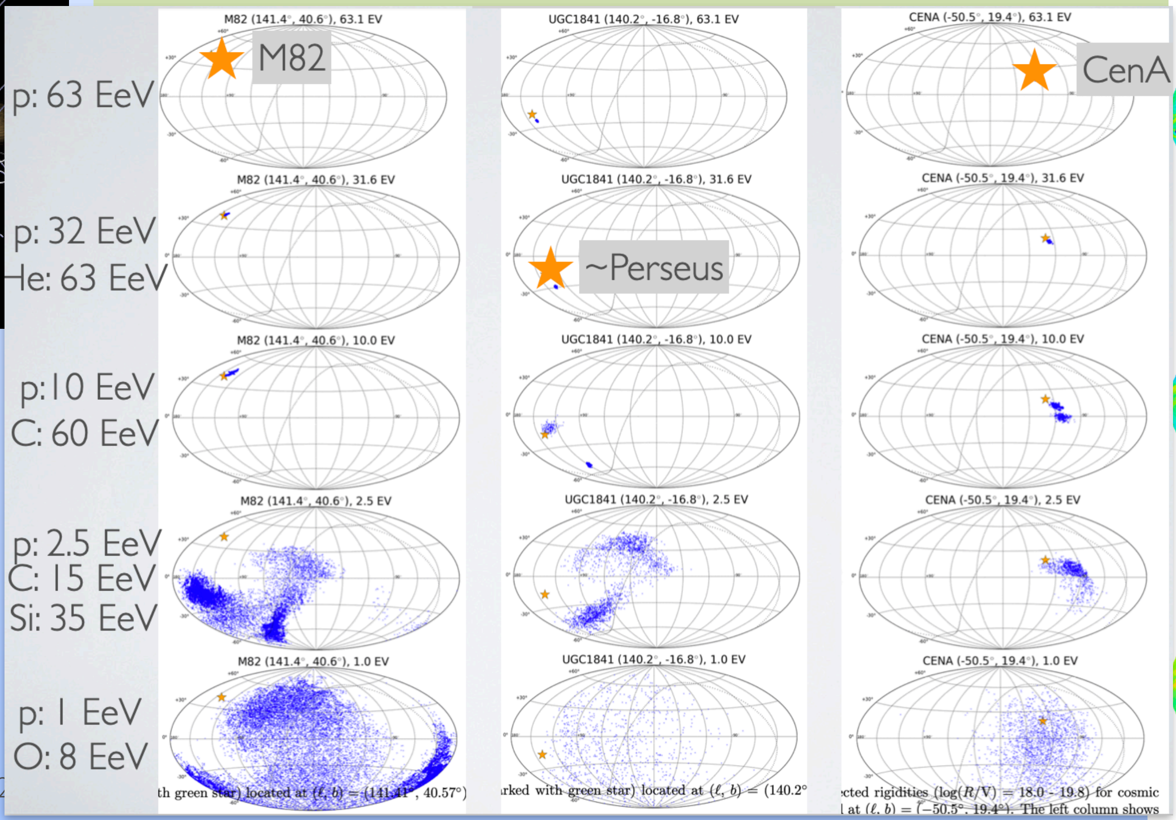
What do we know about UHECR sources?

Magnetic deflections make source ID difficult

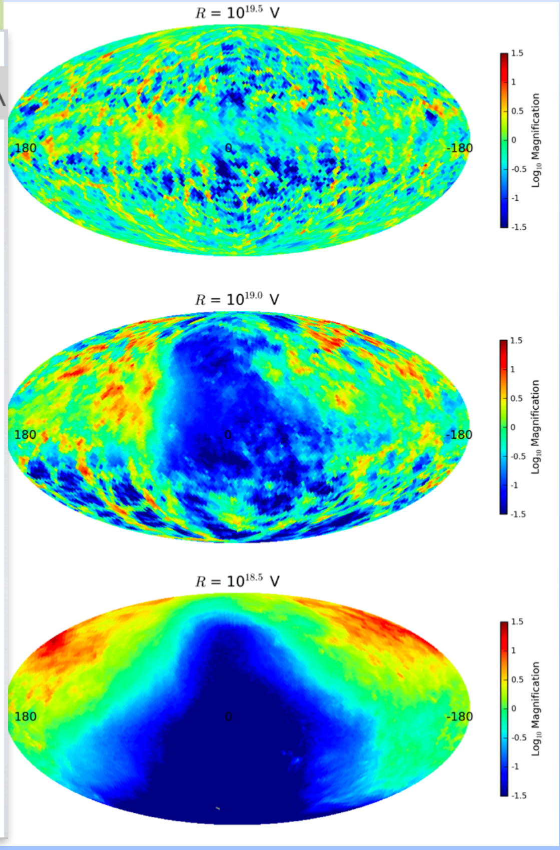


Larmor radius = 1.1 kpc $(R_{EV} / B_{\mu G})$

Deflections in JF12 field model; GF+M.Sutherland, JCAP19

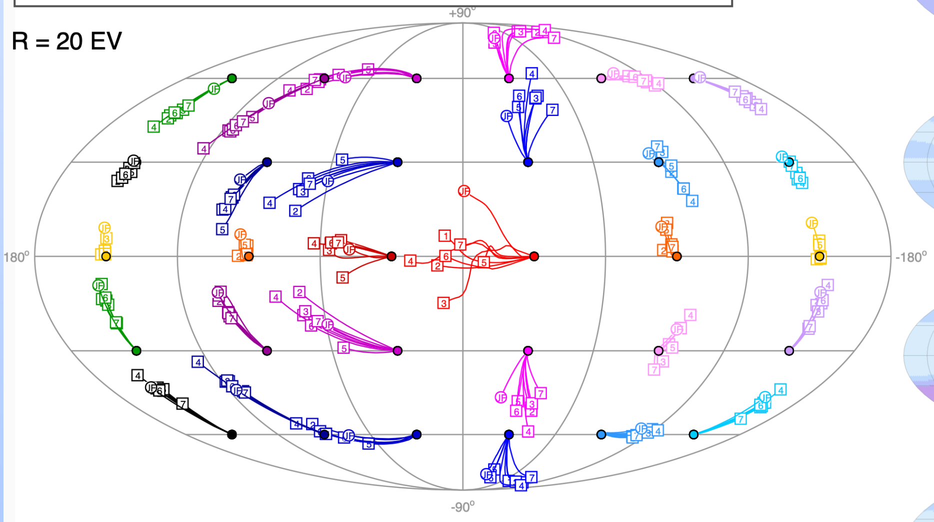


(de)Magnification too!

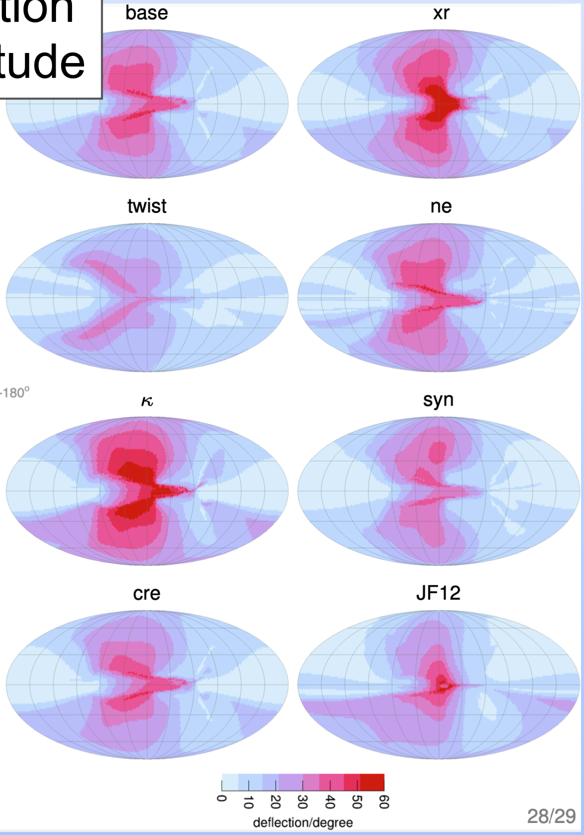


Magnetic deflections are large and uncertain at low rigidity

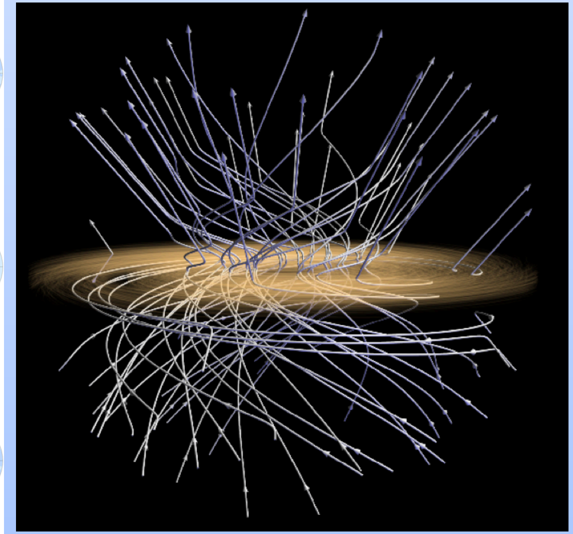
Source direction at E/Z = 20 EV



Deflection magnitude



Larmor radius :
1.1 kpc (R_{EV} / $B_{\mu G}$)



Unger-Farrar 2023 Model Suite

M. Unger, CRA23 & MU+GF to appear soon

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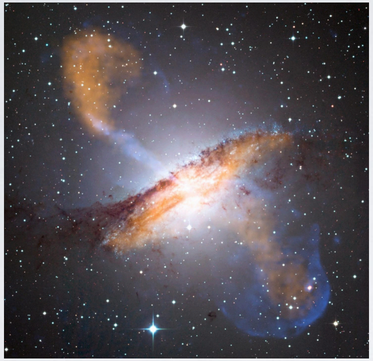
Indirect constraints on sources

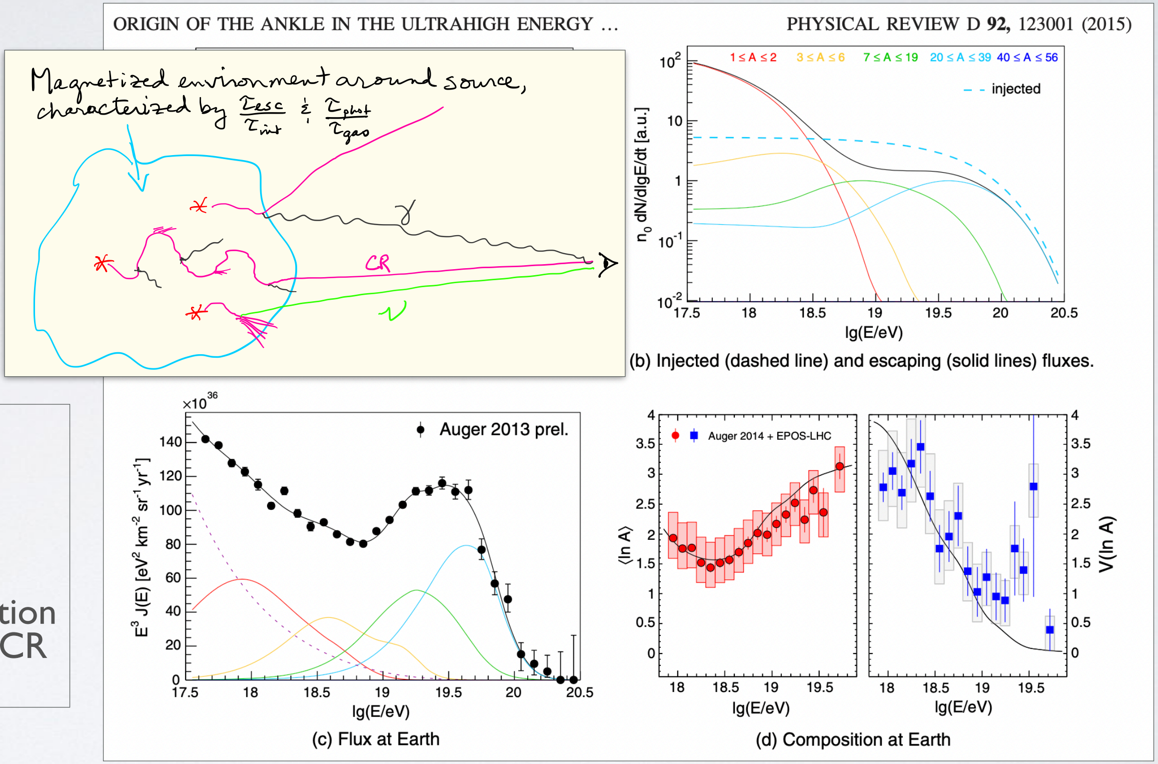
- Detailed fit to spectrum & composition ➜ processing in source environment [M. Muzio+GF, ApJL23]
- Large scale anisotropy [T. Bister+GF, in prep]
- [Hotspots]

UFA 2015 model proposed to explain light population below ankle

Cosmic Rays are Accelerated, then fragmented

Unger, GF & Anchordoqui 2015





(b) Injected (dashed line) and escaping (solid lines) fluxes.

(c) Flux at Earth

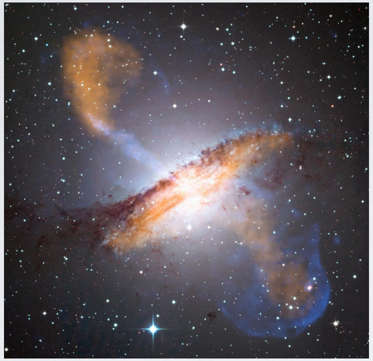
(d) Composition at Earth

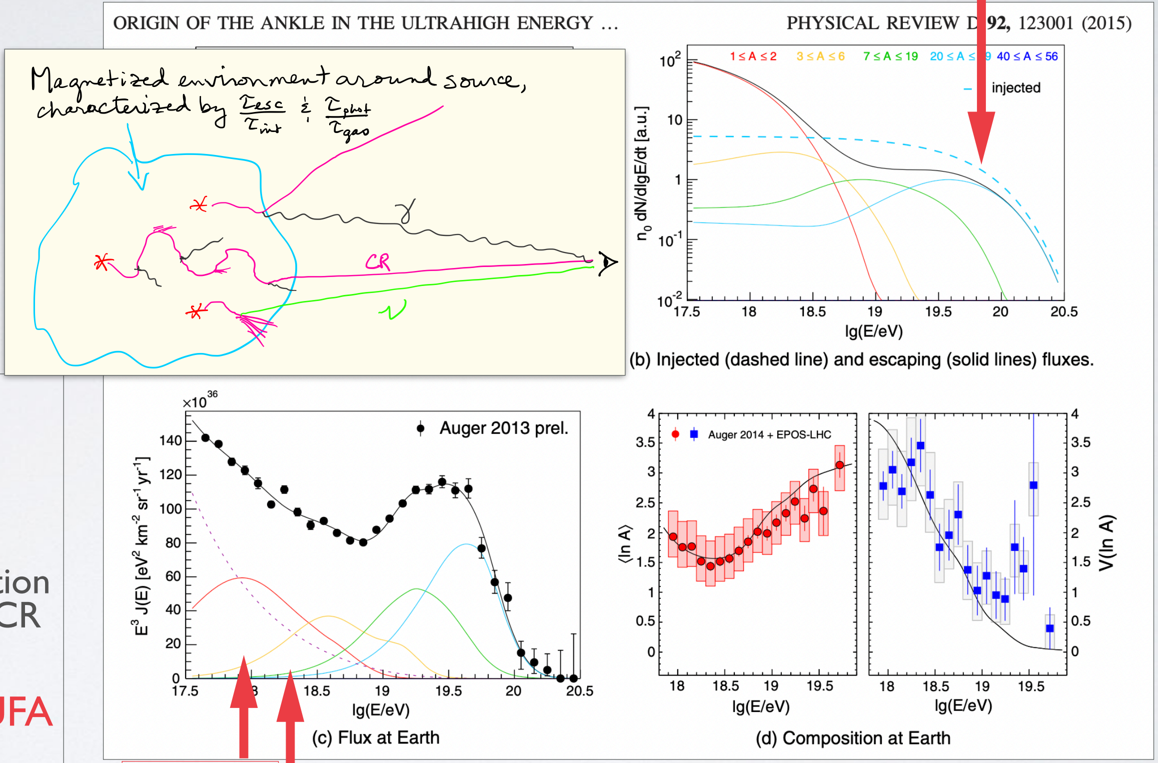
- Excellent fit to spectrum & composition
- Explains light population between between GCR & UHECR

Cosmic Rays are Accelerated, then fragmented

Unger, GF & Anchordoqui 2015

Note large fraction of fragmented primaries





(b) Injected (dashed line) and escaping (solid lines) fluxes.

(c) Flux at Earth

(d) Composition at Earth

E_{max} / A_{max}

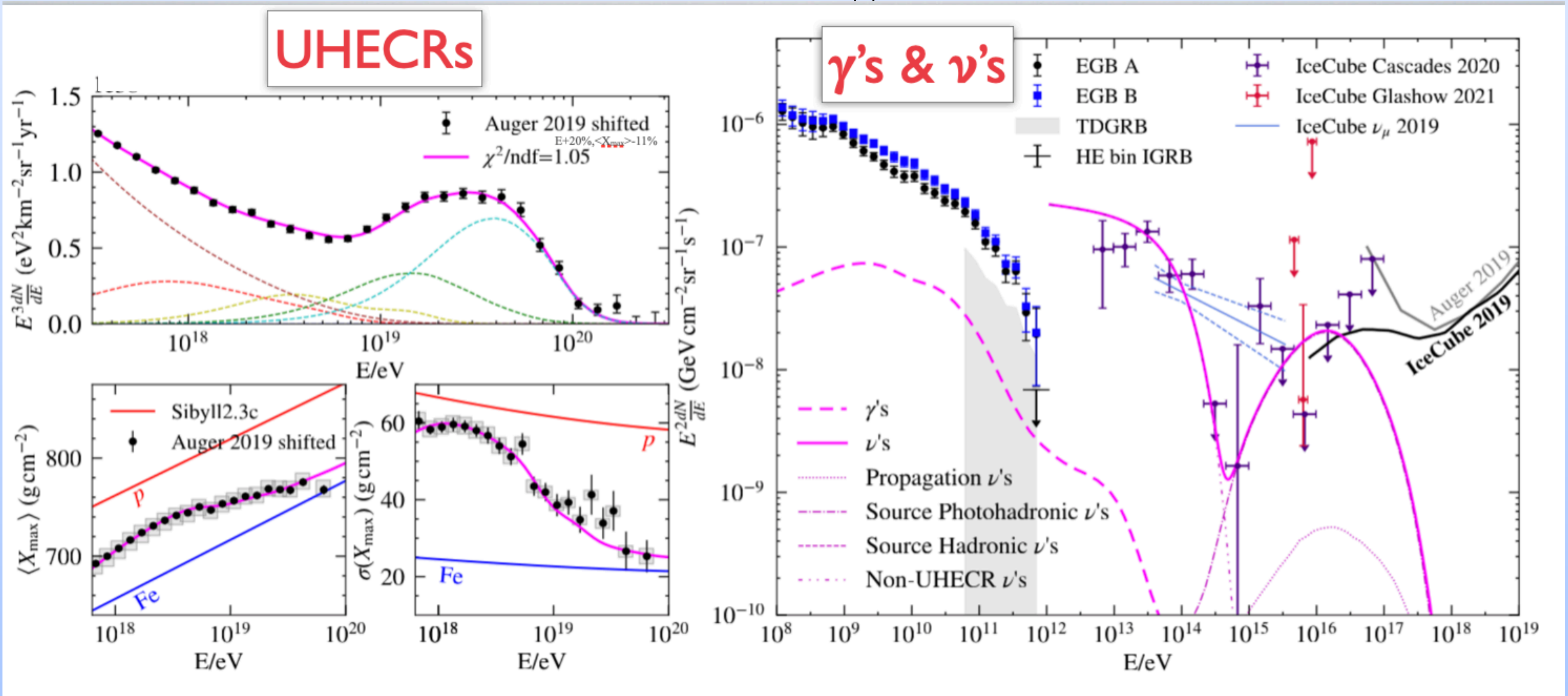
Peter's cycle protons would peak here

- Excellent fit to spectrum & composition
- Explains light population between between GCR & UHECR
- Smoking gun for UFA mechanism:

$E_p \sim E_{max} / A_{max}$ not E_{max} / Z_{max}

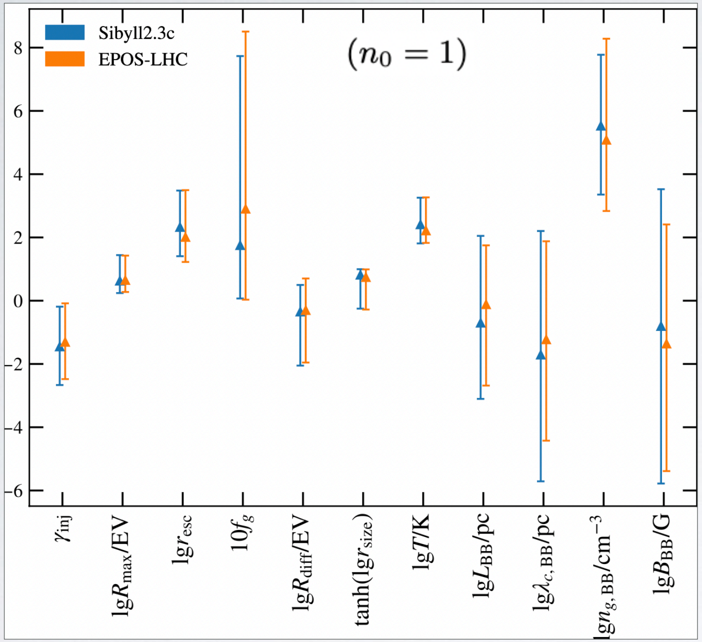
Constrains the source environment (T, B,…)!

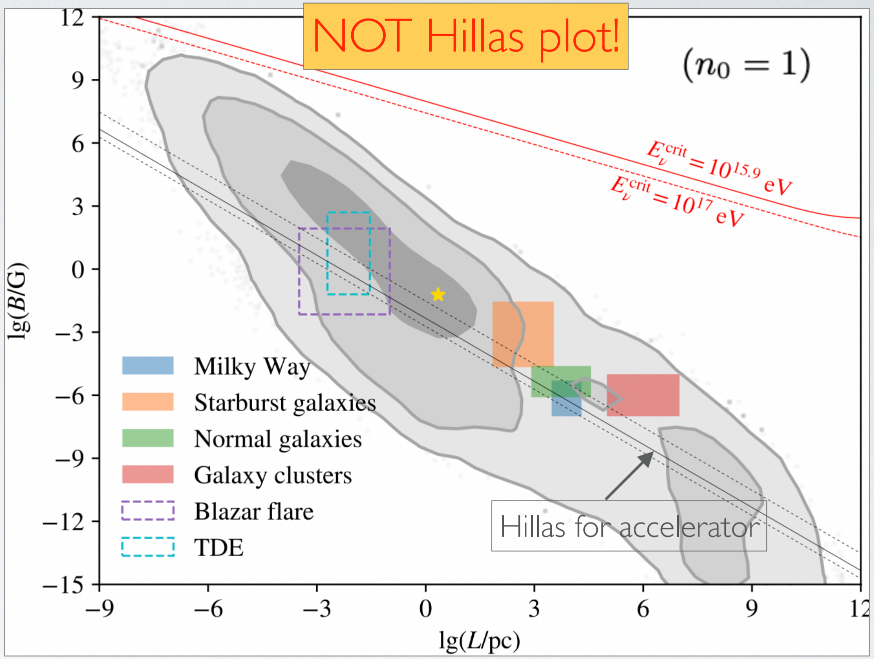
Muzio+GF ApJL23



γ_{inj} = $-1.45^{+1.25}_{-1.15}$ ➜ Diffusive Shock Accel. OK *(accelerator ≠ source)*

Constrain the **Surroundings** of UHECR Accelerators (M. Muzio+GF, ApJL2032)





btw: $\gamma_{\rm inj} = -1.45^{+1.25}_{-1.15}$ ➜ Diffusive Shock Accel. OK *(accelerator ≠ source)*

$T_{\rm surround}$ = 60 - 2000 K

{$B_{\rm rms}$, L} ***of source*** *(not accelerator as in Hillas)* ***is constrained***

black-body case $n_0 = 1$; the conversion for other n_0 values is $L = L_{\rm BB}/n_0$, $B = n_0 B_{\rm BB}$, $\lambda_c = \lambda_{c,{\rm BB}}/n_0$, and $n_g = n_0\, n_{g,{\rm BB}}$.

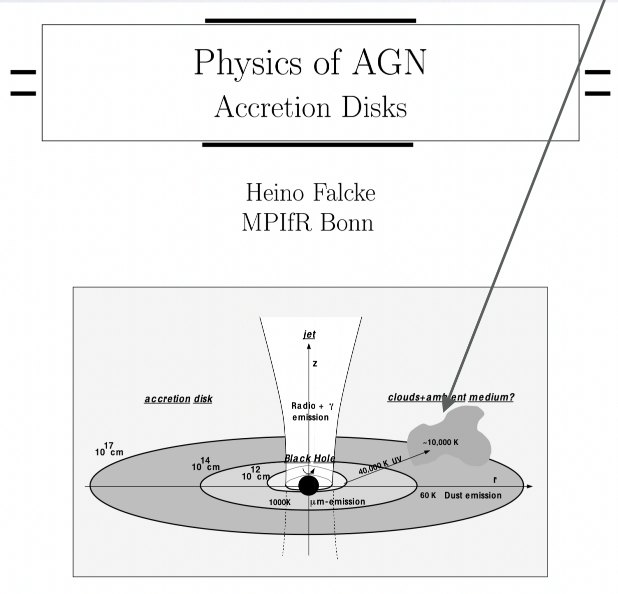
Muzio&GF arXiv:2209.08068

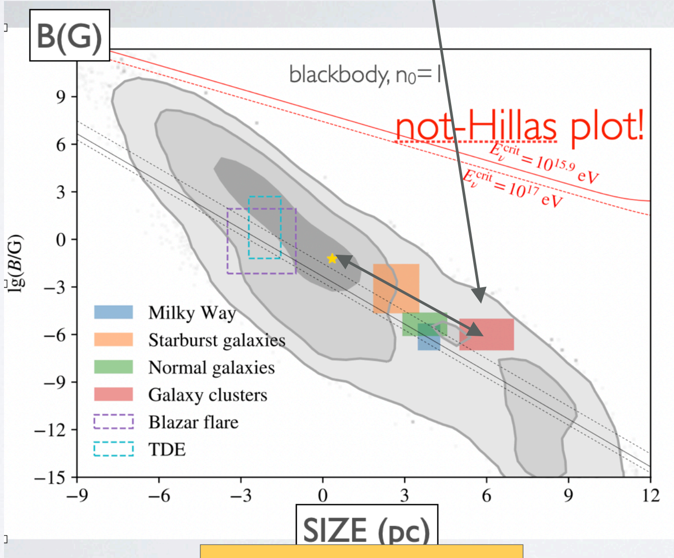
$T_{surround}$ = 60 - 2000 K excludes many candidate acceleration regions

~~Massive Galaxy Clusters~~ (2 x disfavored: T = $10^{7\text{-}8}$ K; n_0 = 1)

AGN:

- ~~radio lobes~~ (T ≈ few keV)
- ?internal shocks in jet? may be problematic; must also account for boost
- inner AGN disk: maybe ok (T=60-1000 K)
  - but nearby dangerous regions & must account boost



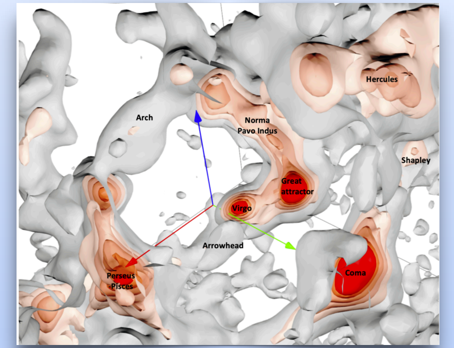


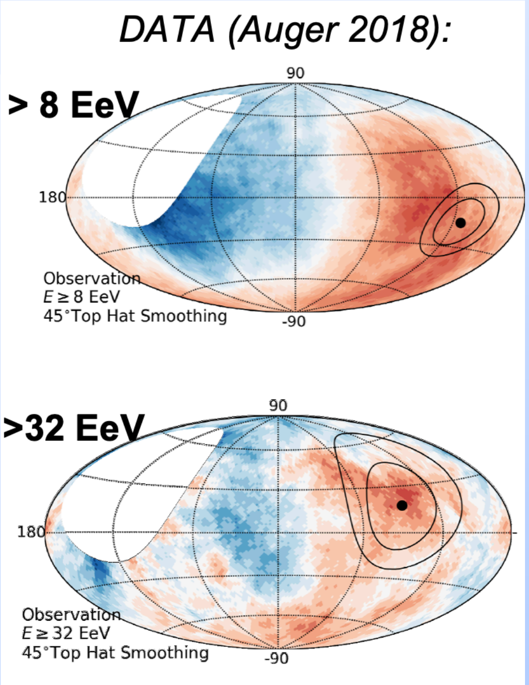
Massive Galaxy Clusters: poor fit to UHECRs

Source Density Constraint from Anisotropy

Teresa Bister + GF, to appear soon

- Ansatz: UHECR sources ~ large scale structure
  ➜ approximate illumination map
  + GMF deflections:
  Good accounting of dipole magnitude, direction & energy dependence.
  [Ding, Globus, GF ApJL 2021]

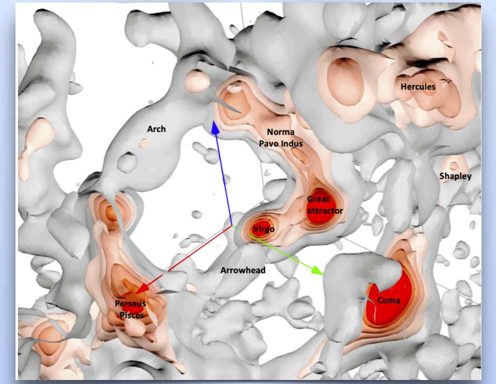




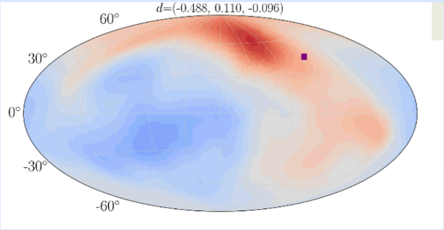
- New: [T. Bister+GF, in prep]
  - Self-consistent spectrum & composition
  - "Bias" of sources relative to LSS? (none seen)
  - Place constraints on source density

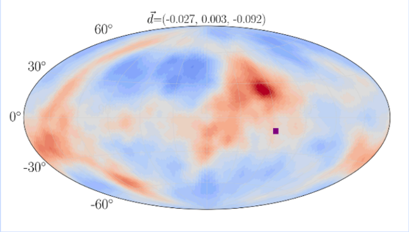
Modeling Anisotropy above 8 EeV

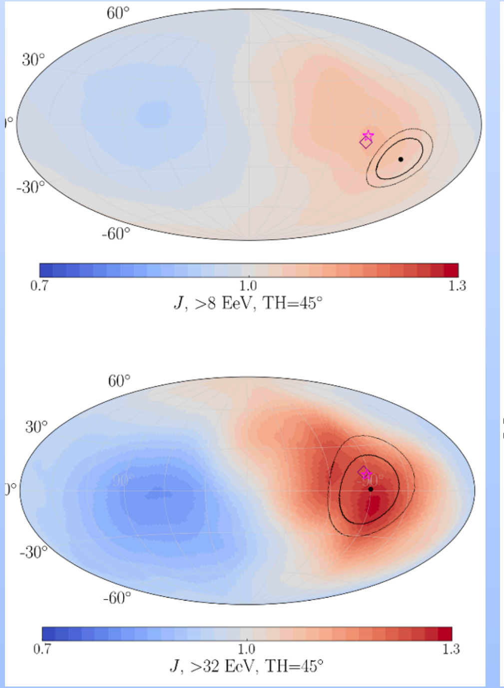
Teresa Bister + GF, in prep,

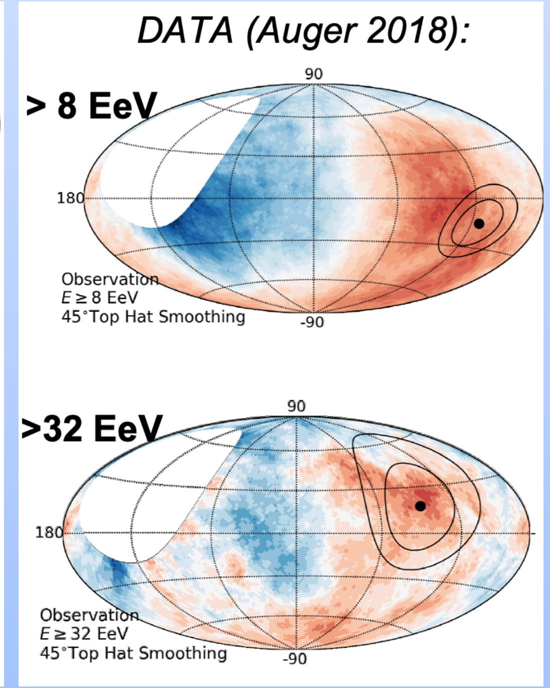


- LSS ➜ Illumination map
- propagate thru GMF
- good fit to dipole







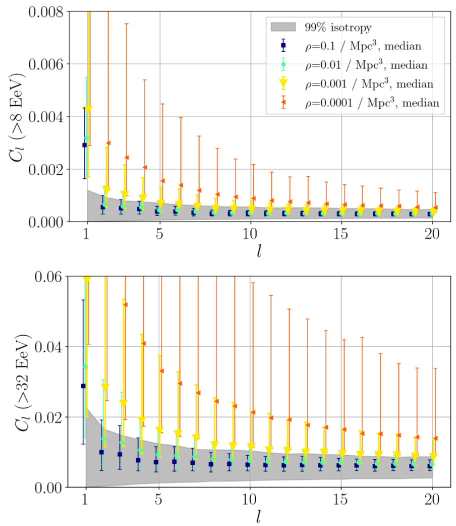


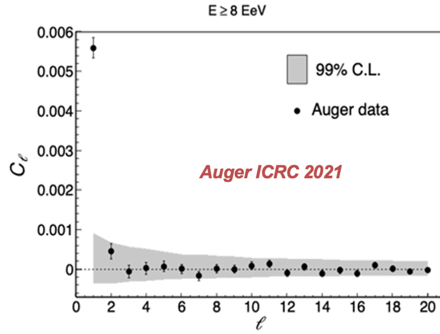
Source density < 10^{-3} Mpc^{-3} strongly disfavored

Teresa Bister + GF, to appear soon

Continuum model gives good fit to dipole. Create 1000 "source catalogs", source densities 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6} Mpc^{-3}

Sampling source density: Angular Power Spectrum





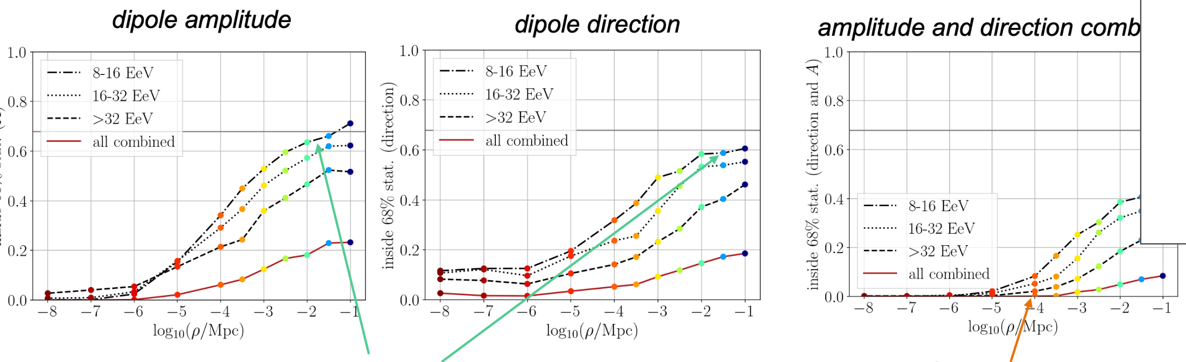
✓ densities >= $10^{-2.5}$ / Mpc^3

✗ densities < 10^{-3} / Mpc^3

c_l's are even more constraining on source density than dipole

Sampling source density: Dipole Amplitude and Direction

fraction within statistical uncertainty:



densities >10^{-2} / Mpc^3:

- behave as continuous model: 68% within 68% statistical
- combining direction & amplitude: almost independent ($0.68^2 = 0.46$)

densities <=10^{-4} / Mpc^3:

number of examples where dipole direction & amplitude fit at the same time: 0 / 1000

Expect intermediate multipoles if source density < 10^{-3} Mpc^{-3}.

Unlikely to see observed dipole direction and magnitude for density < 10^{-3} Mpc^{-3}.

Data take-aways

- Auger & TA in agreement on both spectrum and composition
- Spectrum now very well measured; multiple breaks.   Rigidity cuts off at ~ 5 EV.
- Lowest energy extragalactic CRs are protons and He.
- Composition becomes heavier with E, possibly reaching Fe

Interpretations

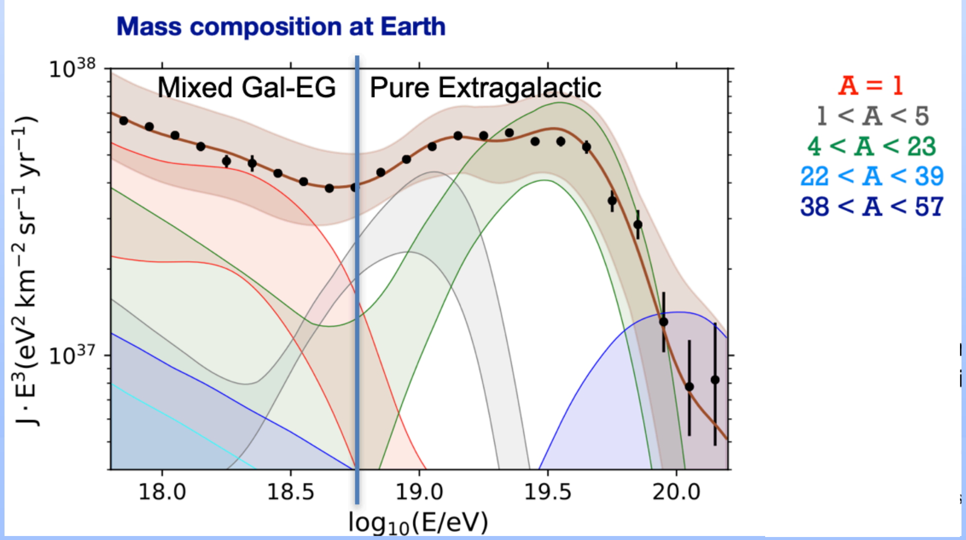
- Processing in region surrounding sources (UFA, MUF, …)
  - naturally explains sub-ankle extragalactic population
  - ➜ Spectral index can be consistent with DSA: escape from source environment hardens intrinsic spectrum of accelerator

✦ Sources appear to be abundant and relatively weak

✦ Tidal disruption? (GF+Gruzinov, ApJ2009)

Puzzle

- Why is there so little ($\lesssim$ factor-3) variation in composition and R_{max} of sources? Ehlert, Oikonomou, Unger 2023



Thanks