Collaborations between collaborations in astroparticle physics

The example of the Pierre Auger Observatory and Telescope Array

Armando di Matteo

armando.dimatteo@to.infn.it

Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Torino, Turin, Italy

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Outline

1. Introduction
   - Ultra-high-energy cosmic rays and extensive air showers
   - The current generation of UHECR observatories: Auger and TA
2. The Auger–TA joint working groups
   - Energy spectrum
   - Mass composition
   - Arrival directions
3. Future prospects

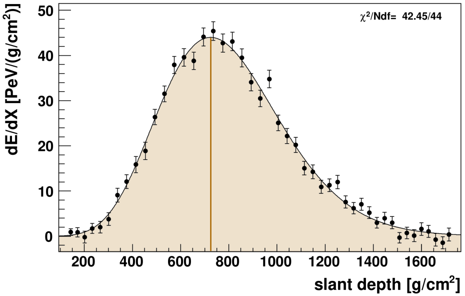
- Ultra-high-energy cosmic rays (UHECRs): atomic nuclei (mainly protons) from outer space with energies $E \geq 1\ \mathrm{EeV} = 10^{18}\ \mathrm{eV} \approx 0.16\ \mathrm{J}$
  - Observed since the 1960s, with E up to a few hundred EeV per nucleus
  - ~ 300 nuclei/(km^2 yr sr), steeply decreasing with energy

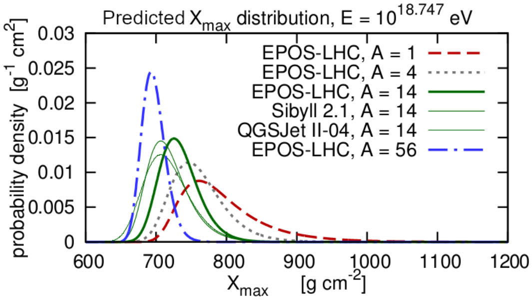
- Extensive air shower (EAS): a hadronic cascade initiated by a UHECR nucleus in the atmosphere, spread over an area $\gg 1\ \mathrm{km}^2$
  - UV **fluorescence light** emitted by N_2 molecules excited by charged EAS particles: detected by fluorescence detector (FD) telescopes during clear moonless nights
  - EAS particles **reaching ground level** (electrons, photons, muons): detected by surface detector (SD) arrays (e.g. water Cherenkov, plastic scintillators)

- Modern UHECR observatories: combining **both FD telescopes and SD arrays**
- EAS events simultaneously detected by both (hybrid events): used for calibrating SD reconstructions (with much larger statistics) to FD ones (better systematics)

EAS reconstruction from FD measurements

- By dividing fluorescence light measurements by the fluorescence yield of air, we get the shower profile $\mathrm{d}E/\mathrm{d}X$ (energy deposit per unit atmospheric depth).
- Calorimetric energy: $E_{\mathrm{cal}} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$, from which we can find the total energy E by adding an estimate of the invisible energy E_{inv} taken underground by ν, μ
- Shower maximum depth: $X_{\max} = \arg\max_X \frac{\mathrm{d}E}{\mathrm{d}X}$, whose distribution is sensitive to the UHECR mass composition (but also to properties of hadronic interactions)





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The Pierre Auger Observatory (Auger) (2004–)

The largest CR detector array in the world 373 collaborators from 91 institutions in 18 countries

Location Mendoza Province, Argentina
35.2° S, 69.2° W, 1 400 m a.s.l. ($\approx 880\ \mathrm{g/cm^2}$)

Main array for UHE operating since 01 Jan 2004:

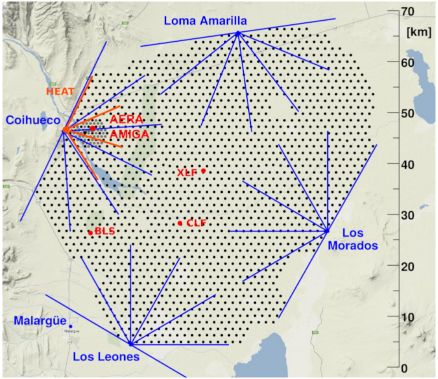
- **SD** 1 600 water Cherenkov detectors spread over a 3 000 km^2 triangular grid (1.5 km spacing)
- **FD** 24 telescopes on 4 sites on edge of SD array

Aperture $\theta_{\mathrm{zenith}} < 80^\circ$ (declination $\delta < +44.8^\circ$)

Systematic uncertainty on energy scale $\pm 14\%$

Low-energy extension (HEAT and AMIGA):

- 3 extra FD telescopes at higher elevation
- 73 extra SDs with 750 m and 433 m spacing



The Telescope Array (TA) (2008–)

Largest CR detector array in the Northern Hemisphere 140 collaborators, 32 institutions, 7 countries

Location Millard County, Utah, USA
39.3° N, 112.9° W, 1 400 m a.s.l. (≈ 880 g/cm^2)

Main array for UHE operating since 11 May 2008:

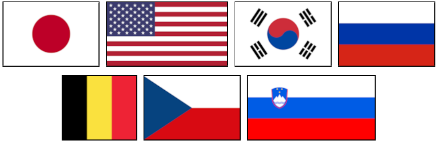
- **SD** 507 plastic scintillator detectors spread over a 700 km^2 square grid (1.2 km spacing)
- **FD** 38 telescopes on 3 sites on edge of SD array

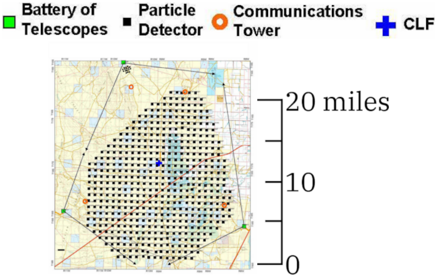
Aperture $\theta_{\text{zenith}} < 55°$ (declination $\delta > -15.7°$)

Systematic uncertainty on energy scale $\pm 21\%$

Low-energy extension (TALE):

- 10 extra FD telescopes at higher elevation
- 80 extra SDs with 400 m and 600 m spacing



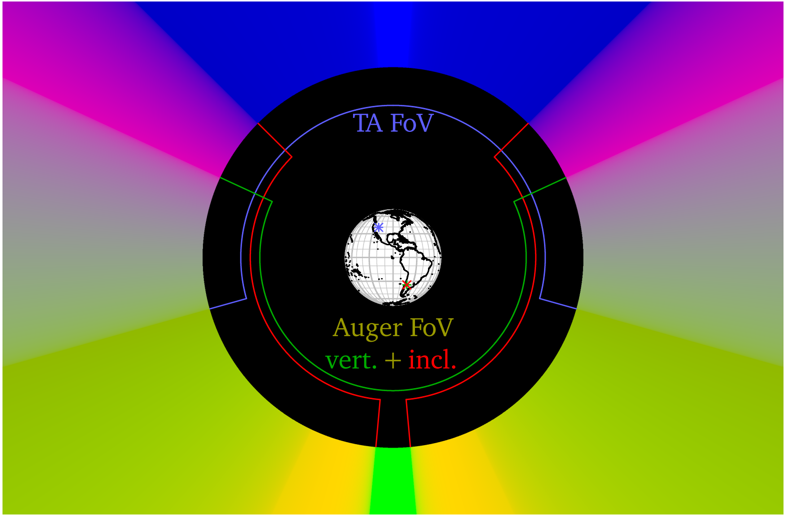


Fields of view of Auger and TA

- Neither TA alone nor Auger alone covers the full sky.
- Together they do:

  TA full northern hemisphere plus part of southern one

  Auger vice versa
- Overlap in a band surrounding the celestial equator



Auger–TA joint working groups (WGs)

- Several Auger–TA joint WGs have been established since the early 2010s to perform **full-sky UHECR studies**:
  - Energy spectrum
  - Mass composition
  - Arrival directions
  - Auger@TA
- **Data in the common band** allow us to know whether any disagreements can be due to different fields of view or must be due to systematic errors.
- A few WGs also include other collaborations:
  - Hadronic interactions and shower physics (with EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DECOR, SUGAR and Yakutsk)
  - Neutrinos (with ANTARES and IceCube)
- The WGs usually present their results (list at http://tiny.cc/Auger-TA) at the International Symposium on Ultra-High-Energy Cosmic Rays (UHECR) and sometimes at the International Cosmic Ray Conference (ICRC).
- I am an Auger Collaboration member, a former TA Collaboration member, and a member of the joint WG on arrival directions (but not here on behalf of either).

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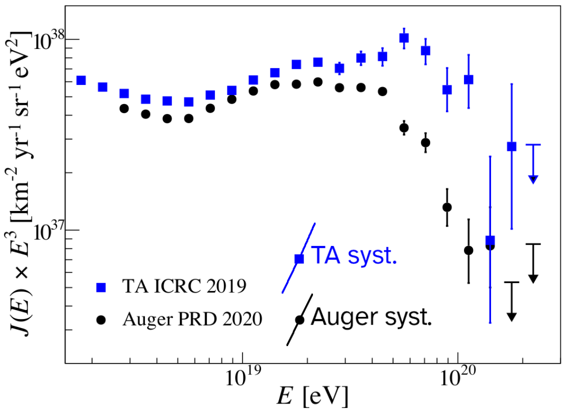
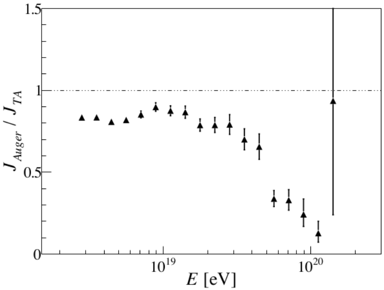
Full-sky energy spectrum

Auger: declinations $-90° \le \delta < +24.8°$; TA: declinations $-15.7° < \delta \le +90°$



(Auger & TA collabs. UHECR 2022)

- At low energies: Auger and TA data **in agreement** within systematics ☺
- At the highest energies: **considerable discrepancy** — Auger measurements lower than TA ones

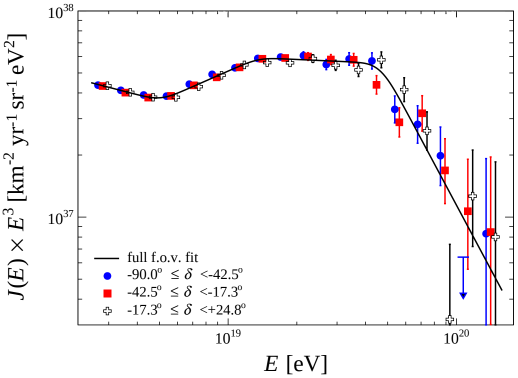


Might *part* of this be astrophysical? (Yes.)

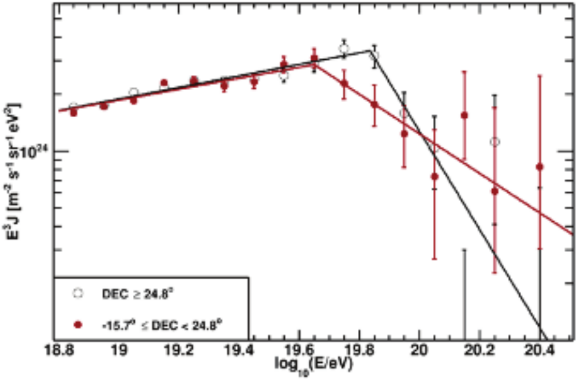
“southern” = [−90°, −15.7°], “equatorial” = (−15.7°, +24.8°), “northern” = [+24.8°, +90°]

TA data: spectrum cutoff higher at “northern” than at “equatorial” declinations

Auger data: spectrum at “southern” and “equatorial” declinations in good agreement



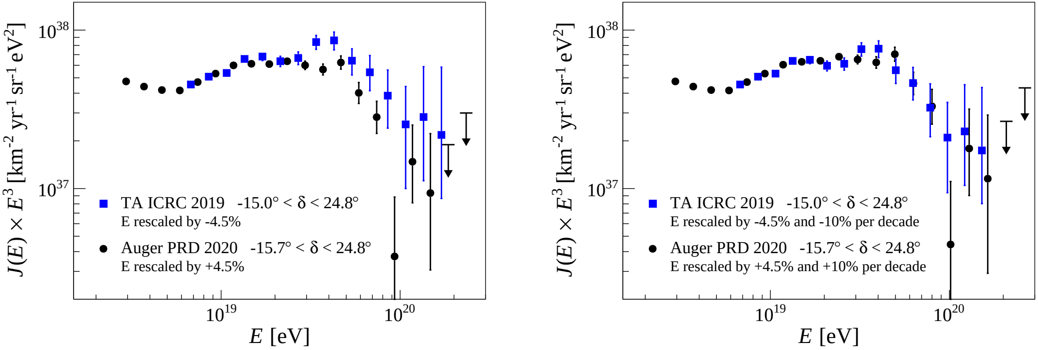
(Auger collab. 2020)



(TA collab. UHECR 2022)

But what about the common declination band?

- Some of the difference even looking at declinations $-15.7° < \delta < +24.8°$ only (Auger & TA collabs. UHECR 2022), hence **not all of it astrophysical**
- Energies must be underestimated by Auger &/or overestimated by TA $(9\% + \frac{20\%}{\text{dex}})$
  - Note: spectrum approximately $\propto E^{-3}$, so overestimating event energies by $X\%$ results in an overestimate $\sim 2X\%$ of the spectrum at a given energy



What might be causing this?

- 9% mismatch in energies at 10 EeV **well within known systematics**

Systematic uncertainties in the energy scale

	TA	Auger
Fluorescence Yield	11%	3.6%
Atmosphere	11%	3.4%–6.2%
FD Calibration	10%	9.9%
FD Reconstruction	9%	6.5%–5.6%
Invisible Energy	5%	3%–1.5%
Other contributions		5%
Total	21%	14%

(Auger & TA collabs. UHECR 2022)

- Possible causes of the 20%/decade increase with energy **under investigation** (known systematics so far: ±3%/dex in Auger, ±9%/dex in TA)

The fluorescence yield

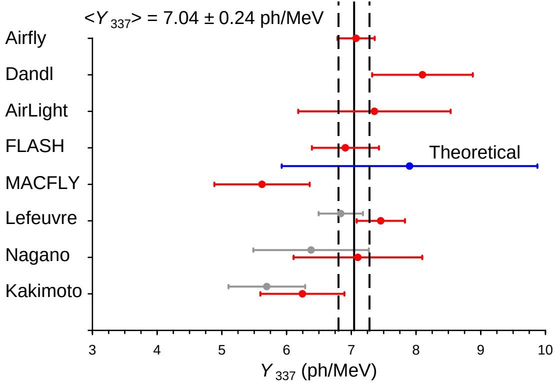
- Auger uses AIRFLY measurements (AIRFLY collab. 2007, AIRFLY collab. 2013) $\approx 7.1\,\frac{\text{ph}}{\text{MeV}}$.
- TA uses the FLASH wavelength spectrum (Abbasi et al. 2008) normalized to the Kakimoto absolute yield (Kakimoto et al. 1996) $\approx 6.2\,\frac{\text{ph}}{\text{MeV}}$.
- Using the TA model in Auger would increase **Auger energies** by 12%.
- Using the Auger model in TA would decrease **TA energies** by 14% (Auger & TA collabs. UHECR 2014).
- Which one is closer to the truth?
- A WG had been tasked to devise a common model, with a series of workshops from 2002 to 2011 (see Keilhauer et al. UHECR 2012, Tsunesada et al. ICRC 2013, and references therein), but it apparently has not been active for over a decade, and each collaboration has persisted in sticking to its own model.
- “The convergence toward the use of the same models in both experiments would have obvious benefits for both the Collaborations and the community.” (Auger & TA collabs. UHECR 2022)

The invisible energy

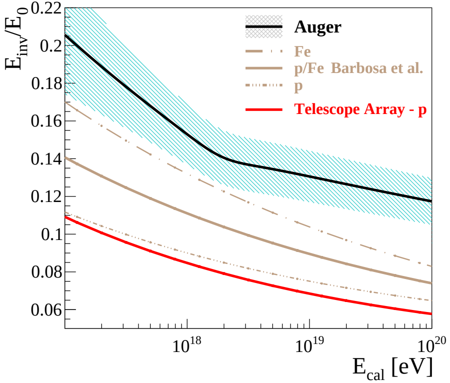
- Auger estimates the invisible energy based on SD **measurements** of muons in EASs (Auger collab. 2019) $\sim 0.13E$.
  - Neutrinos and muons: both produced by the decay of charged pions hence **presumably proportional to each other**
- TA estimates the invisible energy based on QGSJET II-03 **simulations** of proton-initiated EASs (TA collab. ICRC 2017) $\sim 0.07E$.
  - Hadronic interaction models, including QGSJET II-03: now known to severely **underestimate the muons** in EASs (eight collabs. UHECR 2022 and references therein).
  - UHECRs: now known to include a sizeable fraction of nuclei heavier than protons, whose EASs **contain more muons**

- Using the TA invisible energy in Auger would **decrease Auger energies** by 6%.
- Using the Auger invisible energy in TA would **increase TA energies** by 7%.

Fluorescence yield and invisible energy



(Rosado et al. 2014)



(Auger collab. 2019)

- Using both the same FY and the same E_{inv} would bring the Auger and TA spectra **almost on top of each other** (within a few per cent) up to several tens of EeV!
- This has been known since 2014 (Auger & TA collabs. UHECR 2014)!

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Mass composition

- Folk lore has it that TA measurements in the north indicate UHECRs are protons, and Auger measurements in the south indicate a heavier composition.
  - Why?

- Mass composition of UHECRs **estimated** from $X_{\max}$ distributions
- **Considerable differences** among hadronic interaction models (especially pre-LHC ones)

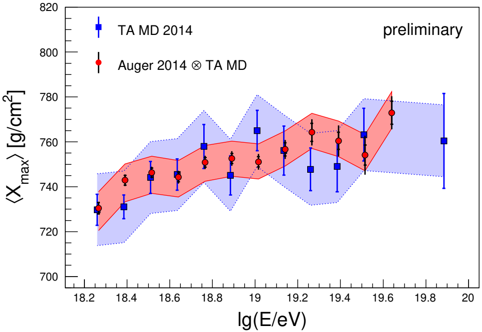
- To be sure that Auger–TA differences are not due to hadronic interaction models, $X_{\max}$ **distributions themselves** should be compared, not mass estimates.
- Complicated by **different treatments of detector biases** (usually folded *into* simulations by TA, *out of* measurements by Auger): TA biases to be folded into Auger measurements

Results

- Auger and TA results **on top of each other** when comparing apples to apples:

$$\langle X_{\max}\rangle_{\text{Auger}} - \langle X_{\max}\rangle_{\text{TA}} = (2.9 \pm 2.7_{\text{stat}} \pm 18^{*}_{\text{syst}})\ \text{g/cm}^2$$

- **This has been known since 2014!**
- How come claims to the contrary have persisted much longer than that?



(Auger & TA collabs. UHECR 2014)

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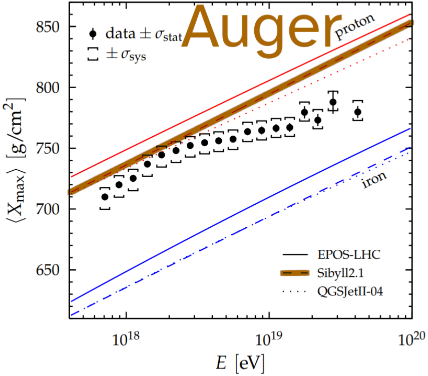
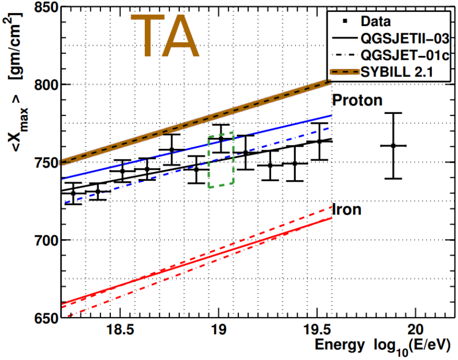
*Eighteen**, *not* a typo for 1.8 (17 g/cm^2 roughly corresponds to a factor of 2 in the mass number A)

Reasons for Auger–TA differences

1. Different hadronic interaction models:

	Auger-only	TA-only
ICRC 2015	EPOS-LHC, QGSJET II-04, SIBYLL 2.1	QGSJET II-03, QGSJET 01c, SIBYLL 2.1
ICRC 2017	EPOS-LHC, QGSJET II-04, SIBYLL 2.3	QGSJET II-03, QGSJET II-04
ICRC 2019	EPOS-LHC, QGSJET II-04, SIBYLL 2.3c	QGSJET II-04





2. Different analyses:
   - Auger fits X_{max} distributions as a mixture of hydrogen, helium, nitrogen and iron, with f_H, f_{He}, f_N as free parameters and $f_{Fe} = 1 - f_H - f_{He} - f_N$
     Assuming QGSJet: gradual transition from H to He dominance around $10^{18.9}$ eV;
     N and Fe compatible with zero at all E; **poor fit to width of distribution**
     Assuming EPOS or Sibyll: gradual transition from H to He around $10^{18.5}$ eV, then
     from He to N around $10^{19.2}$ eV; Fe compatible with zero (Auger collab. ICRC 2017)
   - Until 2018, TA **only considered pure compositions**, shifting model predictions by a fitted parameter to account for model uncertainty (and measurement systematics)
     $E < 10^{18.8}$ eV: Any pure element other than H excluded at $p < 10^{-3}$
     $E < 10^{19.2}$ eV: Pure elements other than H or He excluded at $p < 10^{-3}$
     $E \geq 10^{19.4}$ eV: Not enough data to exclude anything from H to Fe at $p < 5\%$
     (TA collab. UHECR 2018)
   - In 2019, TA started considering mixed compositions, and did find sizeable fractions of heavier elements at the best fit (TA collab. ICRC 2019)
3. Larger statistical error bars in TA, making it harder to rule out QGSJet protons

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The issue of the energy scale cross-calibration

- The mismatch between Auger and TA energy scales would yield **spurious north–south anisotropies** unless corrected for.
- For example, assume events with $E_{\text{true}} = 10$ EeV are reconstructed as $E_{\text{rec}} = 9$ EeV by Auger and as $E_{\text{rec}} = 11$ EeV by TA:
  - If we select all events with $E_{\text{rec}} \geq 10$ EeV, then events with $E_{\text{true}} = 10$ EeV are included if detected by TA but not if detected by Auger.
  - This would look like the UHECR flux from the north was larger than from the south.
- Hence, we should correct for the energy scale mismatch **the best we can.**
- **Measurements in the common declination band** can be used for this.

Techniques for the energy scale cross-calibration — I

δ = declination, α = right ascension, $\hat{\mathbf{n}} = (\cos\alpha\cos\delta, \sin\alpha\cos\delta, \sin\delta)$, $\mathrm{d}\Omega = \mathrm{d}\alpha\,\mathrm{d}(\sin\delta)$

2014–2015 (Auger & TA collabs. 2014, Auger & TA collabs. ICRC 2015)

1. Auger events $E \geq 8.5$ EeV and TA events with $E \geq 10$ EeV selected
2. Residual energy mismatch treated as an **exposure correction**, i.e. directional exposure assumed to be $\omega(\hat{\mathbf{n}}) = \omega_{\mathrm{TA}}(\hat{\mathbf{n}}) + b\,\omega_{\mathrm{Auger}}(\hat{\mathbf{n}})$, using an iterative procedure to estimate b

2016–2019 (Auger & TA collabs. UHECR 2016, Auger & TA collabs. UHECR 2018)

1. TA data used to estimate the cumulative flux $\int_{10\ \mathrm{EeV}}^{+\infty} \int_{\delta_{\min}}^{\delta_{\max}} J(E, \hat{\mathbf{n}})\,\mathrm{d}E\,\mathrm{d}\Omega$
2. Auger data used to estimate $\int_{E_{\min}}^{+\infty} \int_{\delta_{\min}}^{\delta_{\max}} J(E, \hat{\mathbf{n}})\,\mathrm{d}E\,\mathrm{d}\Omega$ as a function of $E_{\min}$, searching for the value resulting in a flux as close as possible to the TA one

Techniques for the energy scale cross-calibration — II

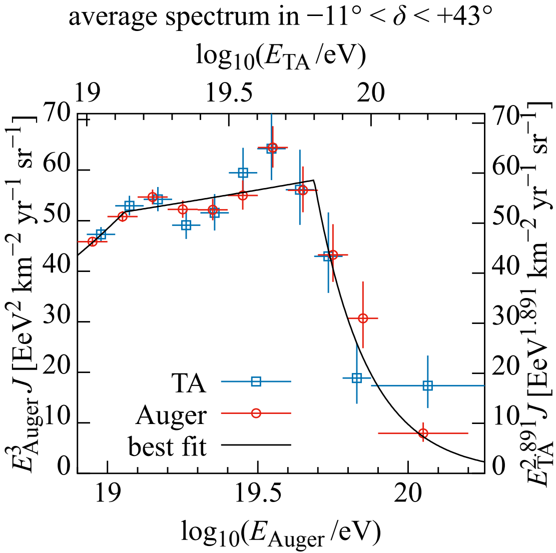
δ = declination, α = right ascension, $\hat{\mathbf{n}} = (\cos\alpha\cos\delta, \sin\alpha\cos\delta, \sin\delta)$, $\mathrm{d}\Omega = \mathrm{d}\alpha\,\mathrm{d}(\sin\delta)$

2021–present (Auger & TA collabs. ICRC 2021, Auger & TA collabs. UHECR 2022)

1. Auger and TA data to estimate $\int_{E_j}^{E_{j+1}} \int_{\delta_\mathrm{min}}^{\delta_\mathrm{max}} J(E, \hat{\mathbf{n}})\,\mathrm{d}\Omega\,\mathrm{d}E$ in various energy bins j
2. Establish parameterizations $E_\mathrm{TA} = \mathrm{PL}(E_\mathrm{Auger}|\boldsymbol{\theta}_E)$, $\int_{\delta_\mathrm{min}}^{\delta_\mathrm{max}} J(E, \hat{\mathbf{n}})\,\mathrm{d}\Omega = \mathrm{BPL}(E|\boldsymbol{\theta}_J)$, where PL = power law and BLP = broken power law
3. Simultaneously fit the parameters $\boldsymbol{\theta}_E$ and $\boldsymbol{\theta}_J$ to the binned data
4. Use the best-fit $\boldsymbol{\theta}_E$ to convert Auger energies to the TA scale and vice versa

(Note: with these parameterizations, it's irrelevant whether Auger energies are assumed correct and TA energies are converted to the Auger scale or vice versa — identical results are obtained either way.)

Energy cross-calibration results (Auger & TA collabs. UHECR 2022)



- $$\frac{E_{Auger}}{10\ \mathrm{EeV}} = a\left(\frac{E_{TA}}{10\ \mathrm{EeV}}\right)^b,$$ where:
  - $\ln a = -0.159 \pm 0.012$
  - $b = 0.945 \pm 0.016$
  - $\mathrm{corr}(\ln a, b) = -0.17$

  $\chi^2/n = 20.7/14\ (p = 0.11)$

  $E_{Auger} = 8.53\ \mathrm{EeV} \longleftrightarrow E_{TA} = 10\ \mathrm{EeV}$

  $E_{Auger} = 10\ \mathrm{EeV} \longleftrightarrow E_{TA} = 19.5\ \mathrm{EeV}$

  $E_{Auger} = 16\ \mathrm{EeV} \longleftrightarrow E_{TA} = 40.5\ \mathrm{EeV}$

- Note: different datasets than used by the spectrum WG; results ***not*** to be extrapolated to lower energies

Large-scale anisotropy results (Auger & TA collabs. UHECR 2022)

Less significant than Auger-only ones (Auger collab. ICRC 2021) due to higher energy threshold

Table 1. Our measurements of the dipole and quadrupole moments. The first uncertainty is statistical, the second is due to the uncertainty in the cross-calibration of energy scales. Values in *italics* (**bold**) are locally significant at $\geq 2\sigma$ ($\geq 4\sigma$).

E_{Auger} [EeV]	$[8.53, 16)$	$[16, 32)$	$[32, +\infty)$
E_{TA} [EeV]	$[10, 19.49)$	$[19.49, 40.5)$	$[40.5, +\infty)$
d_x [%]	$-0.2 \pm 1.1 \pm 0.0$	$+0.9 \pm 1.9 \pm 0.0$	$-4.4 \pm 3.7 \pm 0.1$
d_y [%]	$\boldsymbol{+5.0 \pm 1.1 \pm 0.0}$	$\mathit{+4.4 \pm 1.9 \pm 0.0}$	$\mathit{+10.0 \pm 3.5 \pm 0.0}$
d_z [%]	$-3.0 \pm 1.3 \pm 1.2$	$-8.4 \pm 2.2 \pm 1.3$	$+3.3 \pm 4.4 \pm 3.5$
$Q_{xx} - Q_{yy}$ [%]	$-4.3 \pm 4.6 \pm 0.0$	$+12.9 \pm 8.1 \pm 0.0$	$\mathit{+39.7 \pm 15.0 \pm 0.0}$
Q_{xz} [%]	$-2.7 \pm 2.7 \pm 0.0$	$+4.1 \pm 4.7 \pm 0.0$	$+4.9 \pm 9.7 \pm 0.1$
Q_{yz} [%]	$-4.3 \pm 2.7 \pm 0.0$	$-8.3 \pm 4.6 \pm 0.1$	$+12.8 \pm 9.1 \pm 0.3$
Q_{zz} [%]	$+0.5 \pm 3.1 \pm 1.5$	$+4.5 \pm 5.4 \pm 1.5$	$+22.0 \pm 10.3 \pm 4.1$
Q_{xy} [%]	$+1.3 \pm 2.3 \pm 0.0$	$-0.6 \pm 4.0 \pm 0.1$	$+4.0 \pm 7.8 \pm 0.1$

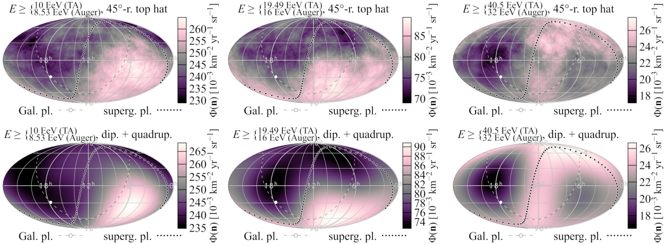
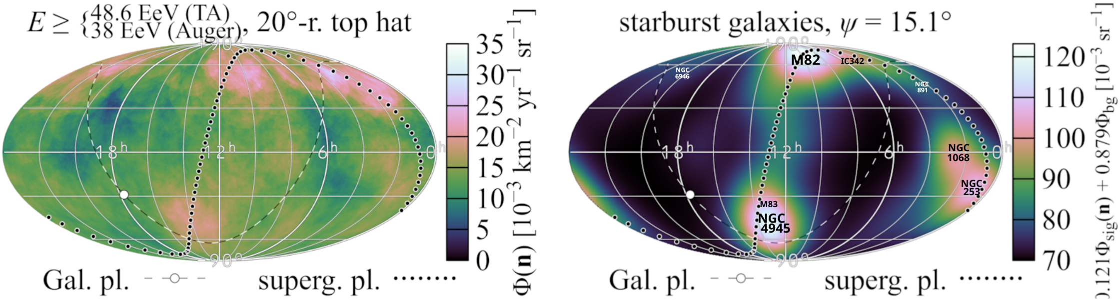


Figure 2. The observed flux in the three energy bins used for the large-scale anisotropies (top panels), and the reconstructed directional flux truncated to $\ell \leq 2$ (bottom panels).

Medium-scale anisotropy results (Auger & TA collabs. UHECR 2022)

- UHECR propagation effects neglected for the time being
- Correlation with galaxies at distances 1 Mpc $\leq D <$ 250 Mpc (Skrutskie et al. 2006) significant at 2.8σ post-trial
- Correlation with starburst galaxies at 1 Mpc $\leq D <$ 130 Mpc (Lunardini et al. 2019) significant at 4.7σ post-trial



Future prospects ("Soon" = ICRC 2023; "eventually" = my personal wishes)

Energy spectrum

Soon: Continued investigation into energy-dependent discrepancy

Eventually: Convergence to common FY and E_{inv}

- Bijective $E_{TA} \longleftrightarrow E_{Auger}$ mapping with goodness of fit and uncertainties (à la anisotropy WG)

Arrival directions

Soon: simulations to estimate the effect of neglected UHECR propagation effects

Eventually: more studies (harmonic-space cross-correlation power spectrum, two- and three-point autocorrelation function, ...)

Mass composition

Soon: Continued study of compatibility between Auger and TA X_{max} distribution, and investigation into any differences

Eventually: Only using modern hadronic interaction models (EPOS-LHC, Sibyll 2.3d) in Auger-only, TA-only, and Auger+TA

- Comparisons of northern vs equatorial vs southern sky (à la spectrum WG)
- Systematics as nuisance parameters
- Use of SD-based mass estimators (using machine learning, upgraded detectors, ...) in Auger+TA


That's all Folks!