Common misconceptions about the physics of ultra-high-energy cosmic rays

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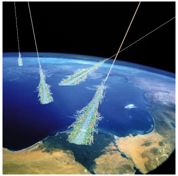


26 June 2020

~~Dis~~claimer

Unless otherwise stated, the claims in this talk are **not** just my personal opinions.

They mostly are well-established findings, which have been presented at plenty of conferences (and in a few journal papers) by mainstream theorists and major experimental collaborations, in some cases for *years* (though lots of people seem to stay unaware of them for some reason).

Almost all slides will have links to sources — generally the most recent available ones (including conference proceedings — you can find older journal papers in their references).

Slides available for download at
`http://personalpages.to.infn.it/~adimatte/slides-20200626.pdf`
(there will be a QR code on the last slide)

Misconception

"The observation of trans-GZK events is evidence for new physics."

Fact

- The GZK energy loss lengths are much longer than some people believe ($\approx$ 100 Mpc for p, Fe at 100 EeV), and there are plenty of potential sources within 100 Mpc. We do expect a suppression in the spectrum, but not an infinitely sharp one.
- In the 1990s, AGASA observed a power-law spectrum with no suppression up to 200 EeV (which *would* have been problematic if confirmed), but it had no fluorescence detectors $\rightarrow$ huge systematic uncertainties.
- All recent experiments (HiRes, Auger, TA) do see a suppression roughly where expected $\rightarrow$ AGASA most likely systematically overestimated energies.

Misconception

"The observation of a spectrum suppression is evidence against new physics."

Fact

- For all we know, the observed suppression might as well be entirely due to the sources.
- If anything, preliminary Auger fits seem *better* with propagation interactions switched off (but they still don't fully account for the systematic uncertainties).

R.G. Lang [for the Auger collab.], PoS (ICRC2019) 327 ↓

	Scenario	γ	$\lg(R_{cut}/V)$	f_H	f_{He}	f_N	f_{Si}	$D(J)$	$D(X_{max})$	D_{total}
std. phys.	LI, $\delta_{had} = 0$	−1.13	18.25	70.1	29.5	0.4	0.02	19.9	236.6	256.5
weakened interactions	LIV, $\delta_{had}^{(0)} = 5\times10^{-24}$	−1.26	18.24	68.9	30.8	0.3	0.02	19.5	235.6	255.1
	LIV, $\delta_{had}^{(0)} = 1\times10^{-23}$	−1.20	18.25	67.4	32.2	0.4	0.02	19.9	236.1	256.0
	LIV, $\delta_{had}^{(0)} = 1\times10^{-22}$	−1.42	18.22	68.4	31.4	0.2	0.01	17.7	231.8	249.5
no interact.	max LIV, $\delta_{had} \to \infty$	0.91	18.47	52.3	42.3	5.4	0.	34.4	189.7	224.1

Table 1: Best fit parameters for the LI reference model and LIV cases (using *SimProp* simulations).

Misconception

"The Auger combined fit (*JCAP* **04** (2017) 038) *was intended to be astrophysically realistic."*

Fact

- A number of simplifying assumptions were deliberately made:
  - Fit only above the ankle energy (5 EeV)
  - Homogeneous distrib. of identical sources
    → Intergalactic magnetic fields irrelevant
    (R. Aloisio & V. Berezinsky, *ApJ* **612** (2004) 900)
  - Power-law injection spectrum with broken or simple exponential cutoff
  - Any combination of p, He, N, Si, Fe possible
- Main goal: to demonstrate the constraining power of Auger data and to quantify the effects of various sources of uncertainty

Effects of uncertainties (largest to smallest)

Hadronic interactions:	overwhelming
Systematics on $X_{\max}$:	large
Evolution of sources:	large
Extragal. background light:	sizeable
Photodisintegration:	small
Shape of injection cutoff:	minor
Statistics:	minor
Systematics on energy:	minor

(But more recent hadronic interaction models are less bad.)

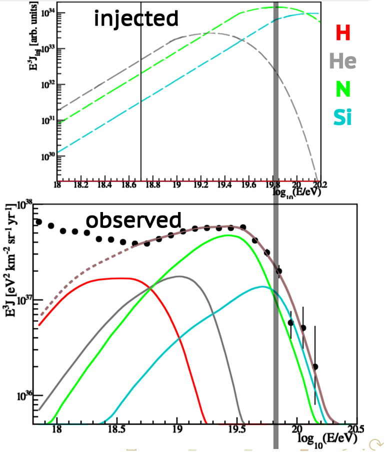
Misconception

*"In the Auger best fit (JCAP **04** (2017) 038), the observed spectrum suppression is mainly due to the sources, not to the propagation (GZK effect)."*

Fact

- The injection does have a cutoff starting at $R \approx 5$ EV ($E \approx 67$ EeV for silicon), but photodisintegration further drastically reduces fluxes at $E/A \gtrsim 1.5$ EeV ($E \gtrsim 40$ EeV).
- The main observable effect of the source cutoff is a suppression in the *secondary* proton spectrum starting at $ZR/A = R/2 \approx 2.5$ EeV.

Note: Both Greisen (1966) and Zatsepin & Kuz'min (1966) did mention disintegration of nuclei as well as pion production, so it's not historically accurate to call the former "not GZK".



Misconception

"Once a nucleus is photodisintegrated, I can disregard the resulting free nucleons."

Fact

- If a nucleus with energy E and mass A fully disintegrates, we get A nucleons each with E/A.
- If the injection spectrum is $\propto E^{-\gamma}$, assuming all nuclei with $E > E_*$ fully disintegrate, at each energy $E_*/A < E < E_*$ we get $A^{2-\gamma}$ secondary nucleons for each surviving primary nucleus (AdM & P. Tinyakov, *MNRAS* **476** (2018) 715).
  - That's negligible if $A \gg 1$ **and** $\gamma \gtrsim 2.5$, but not otherwise.
- The only way to not get secondary nucleons at E is if there's an injection cutoff below AE.

Misconception

"Secondary photons carry important information about UHECR sources."

Fact (assuming standard physics)

- EeV photons undergo $\gamma_{\text{HE}} + \gamma_{\text{bg}} \to e^+ + e^-$, with interaction lengths ~ 1 Mpc.
- Then $e^\pm + \gamma_{\text{bg}} \to e^\pm + \gamma_{\text{HE}}$, and so on $\to$ cascades of $\lesssim 100$ GeV photons, whose spectrum shape is independent on the initial energy and only weakly dependent on the initial redshift, which contribute to the extragalactic gamma-ray background
  - Or do they? A.E. Broderick et al., *ApJ* **868** (2018) 87 suggest they get dispersed.
- In principle, we could use this to constrain UHECR source evolution or composition.

But we don't know the foregrounds well, or even the expected angular spread of cascades (point-like to isotropic, depending on the IGMF strength) → various authors got very different results.

- Cf. e.g. N. Globus et al., *ApJL* **839** (2017) L22 and R.-Y. Liu et al., *PRD* **94** (2016) 043008

- The non-observation of EeV photons can set limits on non-standard physics only if there is no low source cutoff; otherwise, not many EeV photons are produced in the first place.

Misconception

“Secondary neutrinos from beta decay are non-negligible. Pion production on the EBL is negligible.”

Fact

- A beta-decay neutrino with energy E_ν must come from a neutron with energy $\sim 10^3 E_\nu$, whereas a neutrino from pion decay from a nucleon with energy $\sim 20E_\nu$.
- Of course, there are many ($\sim 50^\gamma \approx 40\text{k}\times$) more of the latter than of the former $\rightarrow$ at any given E_ν, beta-decay neutrinos are way subdominant w.r.t. pion decay ones.
- Pion production on the EBL: produces only $\sim 10\%$ effects on the nucleon spectrum, but most of the cosmogenic neutrinos $\lesssim 100$ PeV (R. Alves Batista et al., *JCAP* **10** (2015) 063)
- Note: most IceCube neutrinos can**not** be secondaries from intergalactic propagation (if they were, there would be many more ~ 10 PeV ones and fewer ~ 100 TeV ones) (R. Aloisio et al., *JCAP* **10** (2015) 006).

Misconception

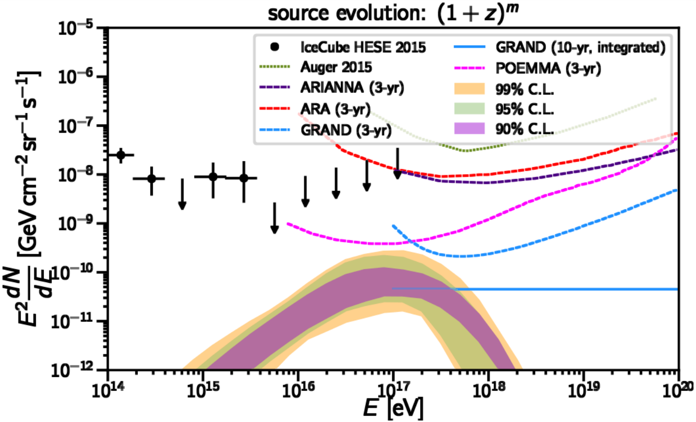
"Next-generation neutrino detectors will be able to detect cosmogenic neutrinos even in pessimistic scenarios."

Fact

Models with a low rigidity injection cutoff (e.g. the Auger best fit) and no or "negative" (time-decreasing) source evolution can predict neutrino fluxes below even the 10-year GRAND-200k sensitivity.

R. Alves Batista et al., *JCAP* **01** (2019) 002

→



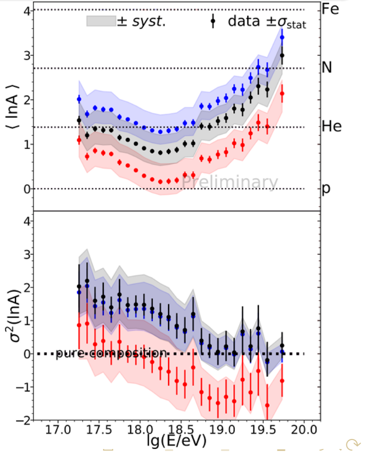
Misconception

"The UHECR mass composition is different in the two hemispheres: proton-dominated in the north (as seen by TA) and heavy in the south (as seen by Auger)."

Fact

1 UHECR masses can be estimated from atmospheric depths of shower maxima $X_{\max}$, but with **large statistical and systematic uncertainties** and **dependence on hadronic interaction models**.

$X_{\max}$ measured by FDs, only during clear moonless nights (≈ 15% of time)



Mass composition from Auger $X_{\max}$ measurements, interpreted according to the **Sibyll 2.3c**, **EPOS-LHC** and **QGSJet II-04** hadronic interaction models (preliminary)

A. Yushkov [for the Auger collab.], PoS (ICRC2019) 482 →

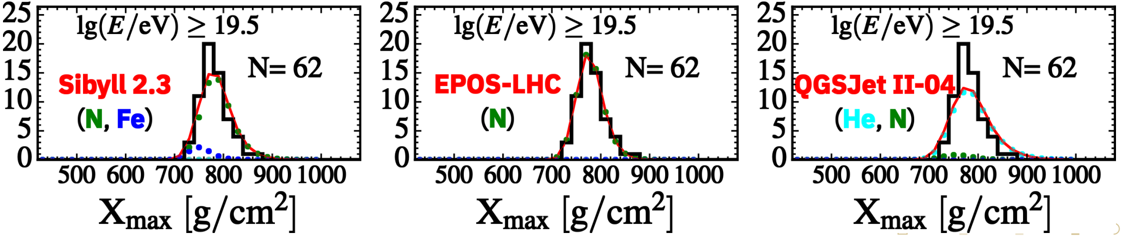
Misconception

"The UHECR mass composition is different in the two hemispheres: proton-dominated in the north (as seen by TA) and heavy in the south (as seen by Auger)."

Fact

2 Auger data do indicate a composition getting heavier with energy ($A \propto E^{0.7}$) above 2 EeV, but even in the highest energy bin [$10^{19.5}$ eV, 10^{20} eV) there seems to be **little or no iron** (mostly nitrogen with Sibyll 2.3 or EPOS-LHC, helium with QGSJet II-04).

J. Bellido [for the Auger collab.], PoS (ICRC2017) 506 ↓



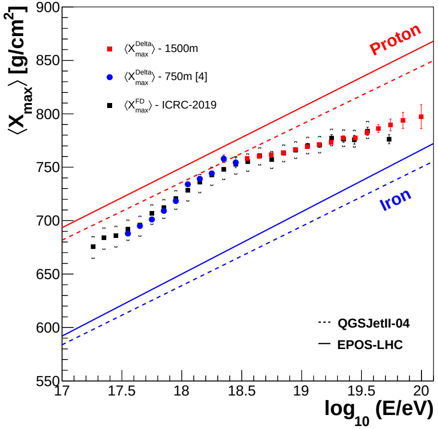
Misconception

"The UHECR mass composition is different in the two hemispheres: proton-dominated in the north (as seen by TA) and heavy in the south (as seen by Auger)."

Fact

3 If you **extrapolate** the Auger trend to energies where fluorescence detectors run out of statistics, you might guess it's going to be iron-dominated — but preliminary estimates via surface detectors (active ≈ 24 hours a day) **don't quite seem to agree**.

C. J. Todero Peixoto [for the Auger collab.], PoS (ICRC2019) 440 →



Misconception

"The UHECR mass composition is different in the two hemispheres: proton-dominated in the north (as seen by TA) and heavy in the south (as seen by Auger)."

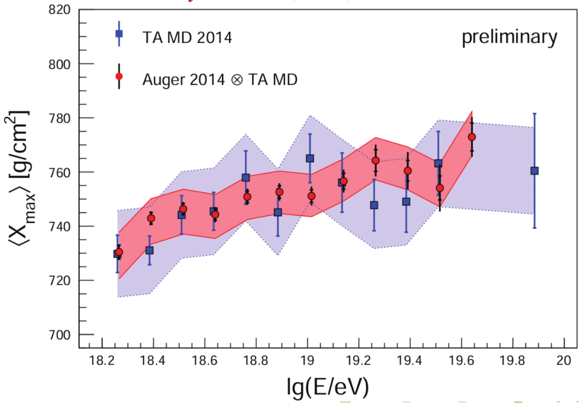
Fact

4 The TA Middle Drum and Auger $\langle X_{max} \rangle$ are **on top of each other** when accounting for detector effects.

- Nontrivial comparison: detector effects usually folded into simulations by TA, out of measurements by Auger
  → had to fold TA detector effects into Auger measurements

All differences in interpretations due to hadronic interaction models!
(QGSJet → lighter, EPOS or Sibyll → heavier)

R. Abbasi et al. [for the Auger and TA collabs.], *JPS Conf. Proc.* **9** (2016) 010016 ↓



Misconception

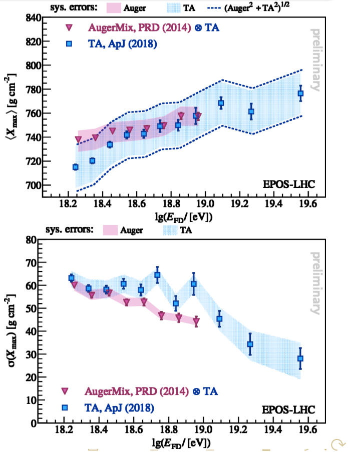
"The UHECR mass composition is different in the two hemispheres: proton-dominated in the north (as seen by TA) and heavy in the south (as seen by Auger)."

Fact

5 If anything, the TA Black Rock and Long Ridge $\langle X_{\max} \rangle$ seem a bit shallower → heavier than the Auger ones at low energies (though **within the systematic uncertainties** of the former). The TA BR and LR $\sigma_{X_{\max}}$ seem a bit wider than the Auger ones, but get narrower at higher energies **just like the Auger ones**.

- Detector effects treated as with Middle Drum (see previous slide)

A. Yushkov [for the Auger and TA collabs.], *EPJ Web Conf.* **210** (2019) 01009 →



Misconception

"The UHECR mass composition is different in the two hemispheres: proton-dominated in the north (as seen by TA) and heavy in the south (as seen by Auger)."

Fact

Below $10^{18.8}$ eV TA compatible with pure H; can exclude any other **pure** element at $p < 10^{-3}$

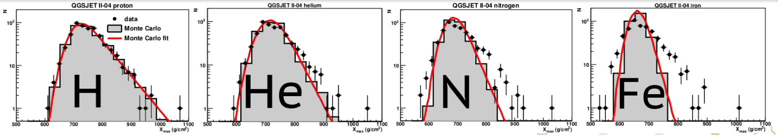
- Note: "Compatible with" just means "cannot exclude" — it does **not** mean "can exclude anything else"! In particular, TA data are **also compatible with an Auger-like mix**.

Below $10^{19.1}$ eV TA can exclude any **pure** element other than H or He at $p < 10^{-3}$.

- Best-fit four-element mix: 57% H + 18% He + 17% N + 8% Fe

Above $10^{19.4}$ eV TA cannot exclude anything up to Fe at $p < 5\%$ (not enough statistics).

BR+LR data vs **QGSJet II-04 sims**
W. Hanlon [for the TA collab.], PoS (ICRC2019) 440 →



Misconception

"To estimate the effect of uncertainties on hadronic interactions, we can just try two or three different models and be done with it."

Fact

- Interactions in air showers in regimes not easily accessible by accelerator experiments:
  - Early interactions with $\sqrt{s} = \mathcal{O}(10^2\ \text{TeV})$
  - Later interactions mainly initiated by pions
  - Medium-mass targets (N, O)
  - Very high pseudorapidity
- The extrapolation itself introduces uncertainties on predictions whose size is comparable to differences among models.

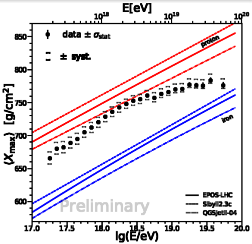
My recommandation: Always use nuisance parameters for systematics and model uncertainties

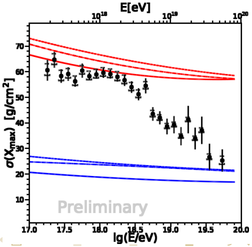
Misconception

"All the features of the $X_{\max}$ distributions are severely model-dependent."

Fact

- While $\langle X_{\max}\rangle$ predictions for showers with a given A, E are strongly model-dependent, their derivatives w.r.t. $\log_{10} E$ (elongation rate) and $\ln A$ are in much better agreement among models: they can be estimated with reasonable precision via a Heitler-like model from the radiation length of air and well-constrained properties of hadronic interactions (J. Matthews, *Astropart. Phys.* **22** (2005) 387).
- Hence, estimates of $\partial\langle\ln A\rangle/\partial E$ are nearly model-independent.
- The dependence of $\sigma(X_{\max})$ on A is also relatively model-independent.





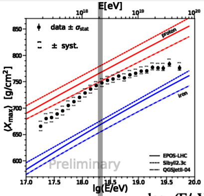
A. Yushkov [for the Auger collab.], PoS (ICRC2019) 482 →

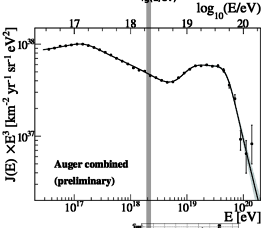
Misconception

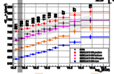
"Auger sees a break in the elongation rate at the ankle; it's weird that TA doesn't."

Fact

- The best-fit position of the Auger elongation rate break is $10^{18.32}$ eV, a factor ≈ 3 lower than the ankle ($\approx 10^{18.7}$ eV).
- The TA $\langle X_{max} \rangle$ measurements only have one bin below that ($[10^{18.2}$ eV, $10^{18.3}$ eV$)$), so no wonder no break is seen there.







A. Yushkov [for the Auger collab.], PoS (ICRC2019) 482 ↗
V. Verzi [for the Auger collab.], PoS (ICRC2019) 450 →
R.U. Abbasi et al. [TA collab.], *ApJ* **858** (2018) 76 ↘

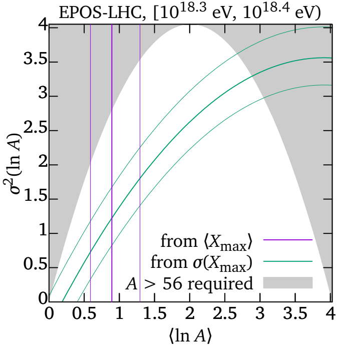
Misconception

"$\sigma(X_{max})$ can be used to estimate UHECR masses independently of $\langle X_{max} \rangle$."

Fact

- Among all showers with primary mass A and energy E, $\langle X_{max} \rangle$ linearly depends on $\log(E/A)$ → in any ensemble of showers with the same E, $\langle X_{max} \rangle$ linearly depends on $\langle \ln A \rangle$.
- On the other hand, $\sigma(X_{max})$ includes **both** the fluctuations among showers with the same A (whose size itself depends on A) **and** the differences between showers with different A → depends **both** on $\langle \ln A \rangle$ **and** $\sigma(\ln A)$.
- Different mass distributions can result in the same $\sigma(X_{max})$ even if they have neither $\langle \ln A \rangle$ nor $\sigma(\ln A)$ in common (Auger collab., *JCAP* **02** (2013) 026).

My plot, data from A. Yushkov [for the Auger collab.], PoS (ICRC2019) 482



Misconception

“$\sigma(X_{max})$ can be used to estimate UHECR masses independently of $\langle X_{max}\rangle$.”

Fact

- Among all showers with primary mass A and energy E, $\langle X_{max}\rangle$ linearly depends on $\log(E/A)$ → in any ensemble of showers with the same E, $\langle X_{max}\rangle$ linearly depends on $\langle \ln A\rangle$.
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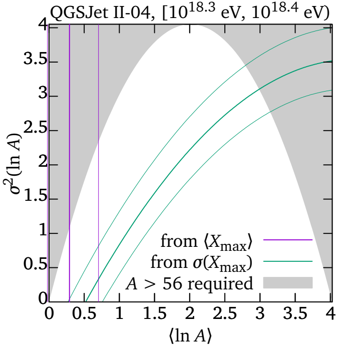


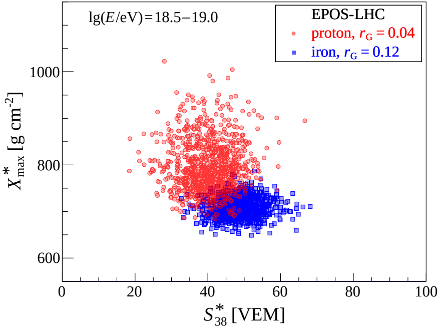
Misconception

"The composition might still be ≈ 100% protons at all energies, if the low elongation rate is due to an unknown drastic change in hadronic interactions above a certain energy."

Fact

- Among showers with the same primary mass, the observables S^*_{38} and X^*_{max} are predicted to be uncorrelated or slightly positively correlated.
- For different masses, they should be anticorrelated.
- There are correlation measures which are robust to outliers, e.g. r_G (R. Gideon & R. Hollister 1987).
- Any systematic errors in S^*_{38} or X^*_{max} predictions or measurements **cannot have any impact** on r_G unless shower-by-shower correlated to each other ($r_G(f(x), g(y)) = r_G(x, y)$ for **any** monotonic f, g).

A. Yushkov [for the Auger collab.], PoS (ICRC2019) 482 ↓



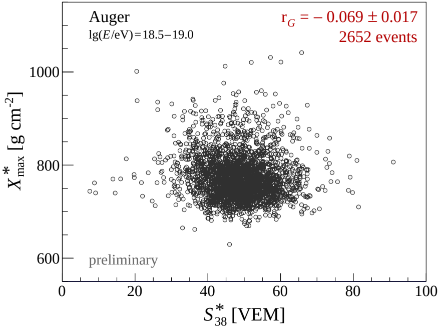
Misconception

"The composition might still be ≈ 100% protons at all energies, if the low elongation rate is due to an unknown drastic change in hadronic interactions above a certain energy."

Fact

- S^*_{38} and $X^*_{\max}$ in Auger data anticorrelated, $r_G = -0.069 \pm 0.017$ (stat.) $^{+0.01}_{-0.02}$ (syst.)
- All pure compositions excluded at $\gtrsim 6\sigma$
  - Pure proton $r_G = +0.04$ (Sibyll), $+0.04$ (EPOS), $+0.12$ (QGSJet)
  - Pure iron $r_G = +0.12$ (EPOS)
- All p + He mixes excluded at $\gtrsim 5\sigma$
- Result **robust to even artificial modifications** to hadronic interaction models (all effects $\lesssim 0.03$), and to 'slicing' data by zenith angle, telescope, etc. (Auger collab., *Phys. Lett.* **B762** (2016) 288)

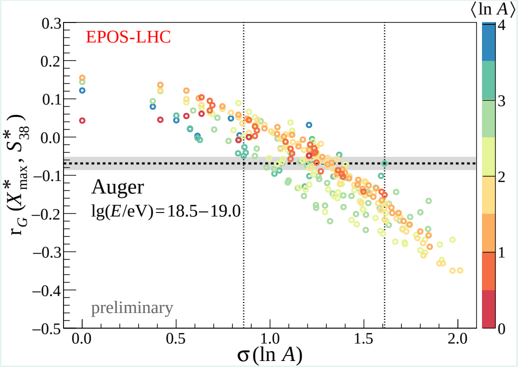
A. Yushkov [for the Auger collab.], PoS (ICRC2019) 482 ↓

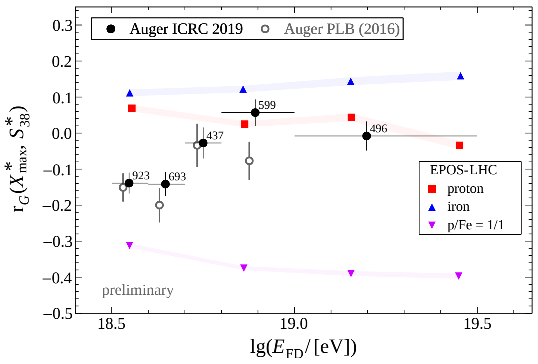


Misconception

"The composition might still be ≈ 100% protons at all energies, if the low elongation rate is due to an unknown drastic change in hadronic interactions above a certain energy."

Fact: both H/He and heavier stuff at $E \lesssim 6$ EeV A. Yushkov [for the Auger collab.], PoS (ICRC2019) 482 ↓





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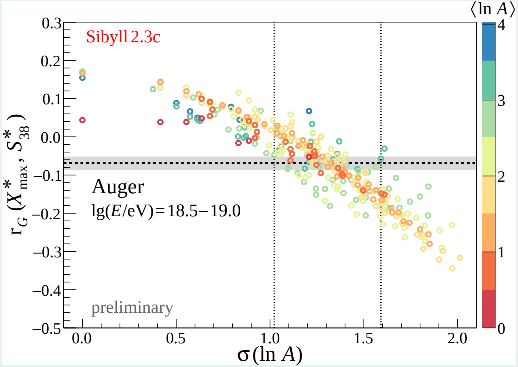
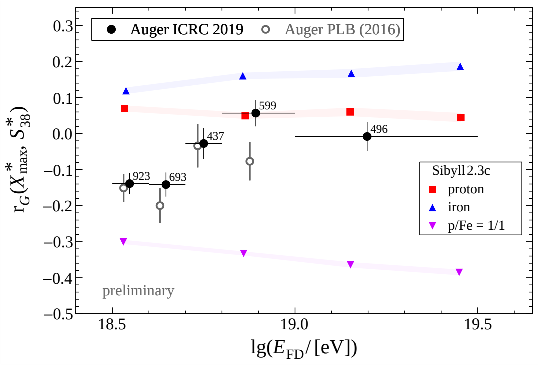




Misconception

"The μ discrepancy might just be due to something anomalous at extremely high energies."

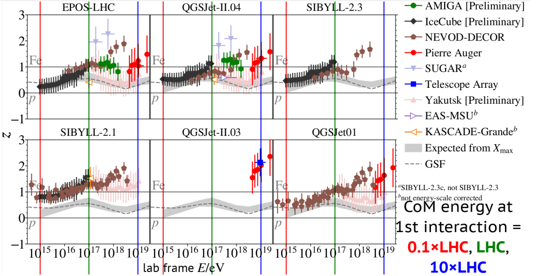
Fact

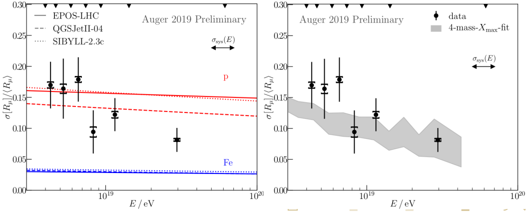
- The effect is already present (but smaller) at $E \leq 10^{17}$ eV $\rightarrow \sqrt{s_{1\text{st}}} \leq$ LHC.

  L. Cazon [for eight collabs.], PoS (ICRC2019) 214 →

- Sizes of shower-to-shower fluctuations in N_μ agree with model predictions.
  - → Average mismatch due to small errors accumulating throughout the shower, not to one huge error at the top

  F. Riehn [for the Auger collab.], PoS (ICRC2019) 404 →





Misconception

"We know the so-called "Oh-My-God Particle" was a proton."

D.J. Bird et al., *ApJ* **441** (1995) 144 ↓

DETECTION OF A COSMIC RAY WITH MEASURED ENERGY WELL BEYOND THE EXPECTED SPECTRAL CUTOFF DUE TO COSMIC MICROWAVE RADIATION

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Received 1994 May 31; accepted 1994 September 13

Fact

We don't.

ABSTRACT

We report the detection of a 51 Joule ($3.2 \pm 0.9 \times 10^{20}$ eV) cosmic ray by the Fly's Eye air shower detector in Utah. This is substantially greater than the energy of any previously reported cosmic ray. A Greisen-Zatsepin-Kuz'min cutoff of the energy spectrum (due to pion photoproduction energy losses) should occur below this energy unless the highest energy cosmic rays have traveled less than ~30 Mpc. The error box for the arrival direction in galactic coordinates is centered on $b = 9\overset{\circ}{.}6$, $l = 163\overset{\circ}{.}4$. The particle cascade reached a maximum size near a depth of 815 g cm^{-2} in the atmosphere, a depth which does not uniquely identify the type of primary particle.

Subject headings: cosmic microwave background — cosmic rays — elementary particles — radiation mechanisms: nonthermal

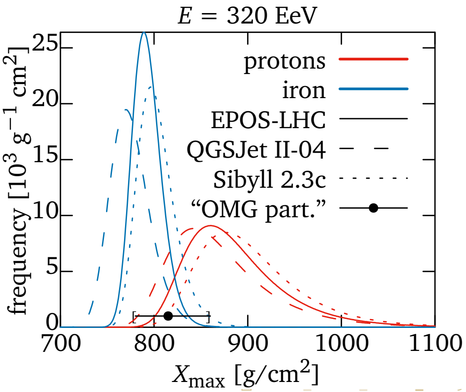
Misconception

"We know the so-called "Oh-My-God Particle" was a proton."

D.J. Bird et al., *ApJ* **441** (1995) 144 ↓

(plot **not** from the paper)

The longitudinal profile of the Fly's Eye shower does not identify the primary particle type. The best-fit X_{max} value is consistent with the expectation for a midsize nucleus (Gaisser et al. 1993). However, in view of the uncertainty in X_{max} and fluctuations in shower development, it could have been a nucleon or a heavy nucleus. It might even have been a gamma ray. Its arrival direction is nearly perpendicular to the local geomagnetic field. A gamma ray of such high energy would likely initiate an electromagnetic cascade in Earth's magnetosphere (McBreen & Lambert 1981) and enter the atmosphere as a superposition of lower energy electromagnetic particles. This would cause the air shower to reach maximum size earlier than the 1050 g cm^{-2} given by the Greisen formula (Greisen 1965) for an electromagnetic cascade at 320 EeV. (This early development contrasts with the expectation for gamma rays which do not encounter a transverse field. Because of the LPM effect (Landau & Pomeranchuk 1953; Migdal 1957; Mizumoto 1993), they should develop even deeper than a Greisen formula shower.)



Fact

We don't.

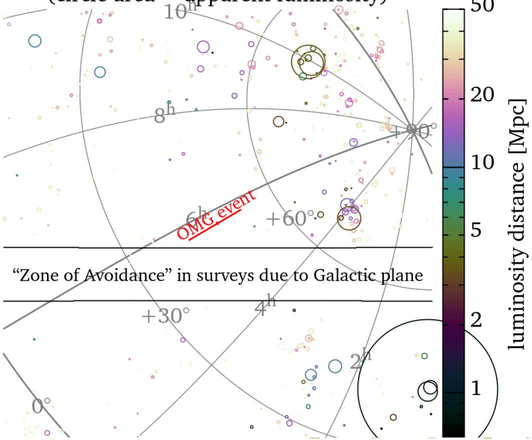
Misconception

"We know the so-called "Oh-My-God Particle" was a proton."

My opinion

- Due to interactions with CMB photons, 320 EeV nuclei cannot have originated from more than a few tens of Mpc away (if protons or heavy; even less if in between).
- The closest plausible sources are in the IC 342/Maffei Group, 25° from the event (but there may be closer ones hidden by Gal. plane).
- Magnetic deflections $\approx 25^\circ$ are plausible only if $Z \gtrsim 20$ (esp. near the Galactic anticenter).

galaxies in 2MRS and Cosmicflows-3 surveys
(circle area ∝ apparent luminosity)



See also: T. Fitoussi et al., PoS (ICRC2019) 256 (**not mine**)

Misconception

"We know that there are several orders of magnitude fewer UHE neutrinos than nuclei."

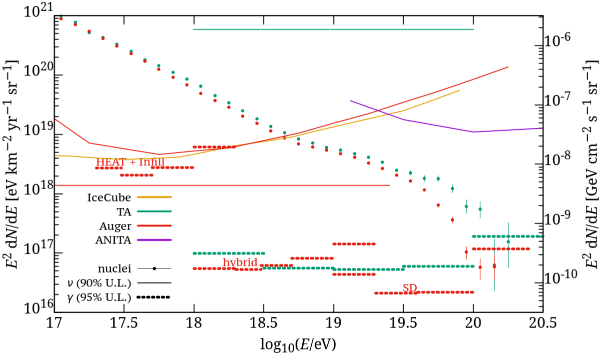
Fact

Differential upper limits to ν fluxes:

- just about an order of magnitude below UHECR fluxes around 1 EeV
- comparable to UHECR fluxes at a few EeV
- one order of magnitude **higher** than UHECR fluxes above 30 EeV (much less exposure to ν than to nuclei)

Above 100 EeV, top-down mechanisms might still be dominating! (e.g. R. Aloisio, S. Matarrese, A.V. Olinto, *JCAP* **08** (2015) 024)

My plot, data from: PoS (ICRC2019) 979 (Auger ν); PoS (ICRC2019) 398 (Auger γ); *JEPT* (in press) [1905.03738] (TA ν); *Astropart. Phys.* **110** (2019) 8 (TA γ)



Summary of mass composition results

⋮	Dominated by H and He	
$10^{18.5}$ eV		
	Mixed, with both H/He and heavier stuff	(but details are model-dependent)
$10^{19.0}$ eV		
	Increasingly less mixed and heavier (but still not iron-like)	(ditto)
$10^{19.5}$ eV		
	Same as above?	(not enough statistics to be sure)
$10^{20.0}$ eV		
⋮	Not enough data	(Probably heavy? Medium-light nuclei can't survive for long, and if protons we might see EeV neutrinos and small-scale anisotropies soon, which we still haven't seen.)

- No evidence for north–south differences
- Few or no ν, γ except possibly at highest E

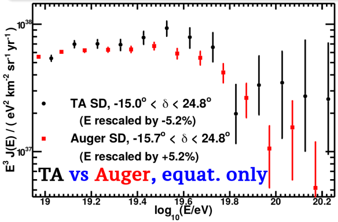
Misconception

“The differences between TA and Auger spectrum measurements can be due to either just a systematic energy over- or underestimate by TA or Auger, or just a north-south difference.”

Fact

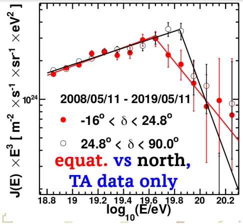
Both explanations are required, and go in the same direction by coincidence:

- The fields of view of the two experiments overlap in a declination band around the equator.
- Noticeable differences **both** when looking only at the common band with both experiments, **and** when looking at both the common band and the north polar cap with TA only



← O. Deligny [for the Auger and TA collabs.], PoS (ICRC2019) 234

D. Ivanov [for the TA collab.], PoS (ICRC2019) 298 →



Misconception

"The differences between TA and Auger spectrum measurements can be due to either just a systematic energy over- or underestimate by TA or Auger, or just a north-south difference."

Fact

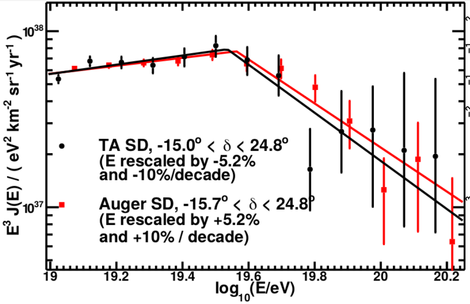
- We can recalibrate Auger and TA energies to each other in the equatorial band, but differences between the polar caps persist at high energies.

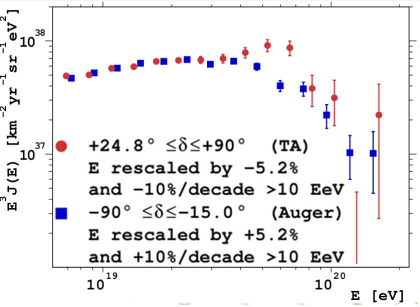
O. Deligny [for the Auger and TA collabs.], PoS (ICRC2019) 234 →

Precision with which the linearity can be validated:

Auger ±3%/decade

TA ±9%/decade





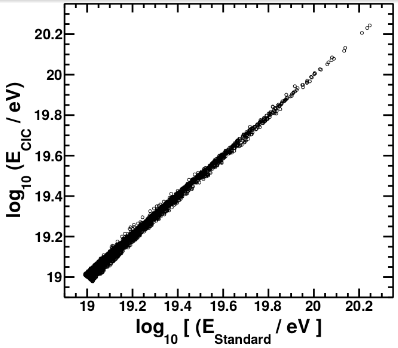
Misconception

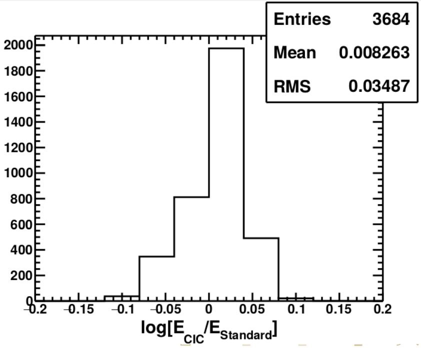
"The Auger–TA energy scale mismatch might be because Auger uses the constant intensity cut method whereas TA uses scaled Monte Carlo simulations."

Fact

- Switching to CIC would change TA event energies by just a few per cent.

D. Ivanov [for the TA collab.], *EPJ Web Conf.* **210** (2019) 01001 →



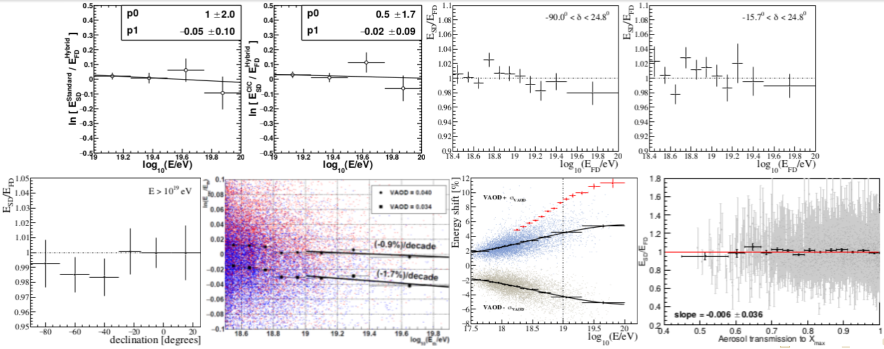


Misconception

"The Auger–TA energy scale mismatch might be due to nonlinearities in the FD→SD calibration or to aerosols."

Fact

- Those have been checked (T. AbuZayyad et al. [for Auger and TA], *EPJ Web Conf.* **210** (2019) 01002).

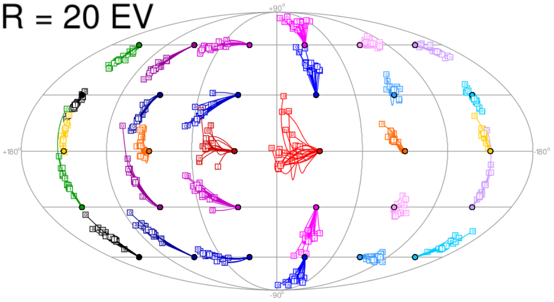


Misconception

"Magnetic deflections are likely to make searches for anisotropies hopeless."

Fact

1. Whereas we don't know for sure the 3D structure of the Galactic magnetic field, we do have a reasonable idea of its order of magnitude (a few μG $\times$ a few tens of kpc). Regular deflections are expected to range from ~ 15 to $\sim 40 \times (R/10\ \mathrm{EV})^{-1}$ degrees (where $R = E/Z$) (R. Šmída & R. Engel, PoS (ICRC2015) 470).
2. Regular deflections can only rotate/deform anisotropies, not erase them → only impair targeted searches, not full-sky ones.



↑ Deflections from a variety of GMF models
M. Unger & G. Farrar, *EPJ Web Conf.* **210** (2019) 04005

Misconception

"Magnetic deflections are likely to make searches for anisotropies hopeless."

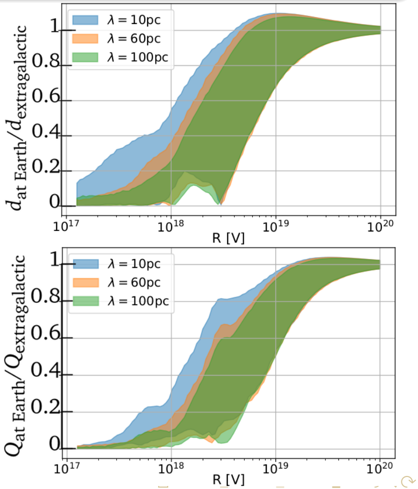
Fact

3 Turbulent Galactic deflections smaller than regular ones ($\Delta\theta_{\text{rms}}(10\text{ EV}) \lesssim 27°$ (Gal. plane), $\lesssim 3.5°$ (Gal. poles))
M.S. Pshirkov, P.G. Tinyakov, F.R. Urban, *MNRAS* **436** (2013) 2326

→ Only minor impact on large-scale anisotropy strengths, with most of the dipole and a sizeable fraction of the quadrupole amplitude surviving except $\lesssim$ a few EV

B. Eichmann and T. Winchen, *JCAP* **04** (2020) 047 →

4 Intergalactic magnetic fields are basically unknown, but almost all estimates of the deflections range from $\mathcal{O}(10^{-6})$ to $\mathcal{O}(1)\times$ Galactic ones.



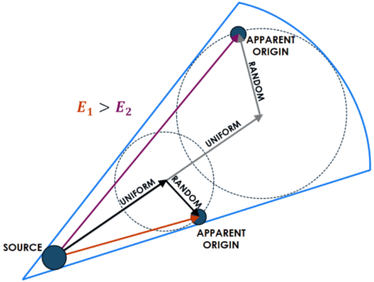
Misconception

"Magnetic deflections are likely to make searches for anisotropies hopeless."

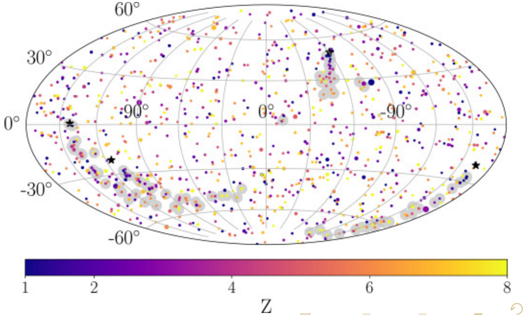
Fact

5 In any event, we might be able to reconstruct source positions by taking into account that deflections are proportional to $1/R$ and extrapolating to $R \to \infty$.

TA collab., *ApJ* (submitted) [2005.07312] ↓



M. Erdmann et al., *Astropart. Phys.* **108** (2019) 74 ↓



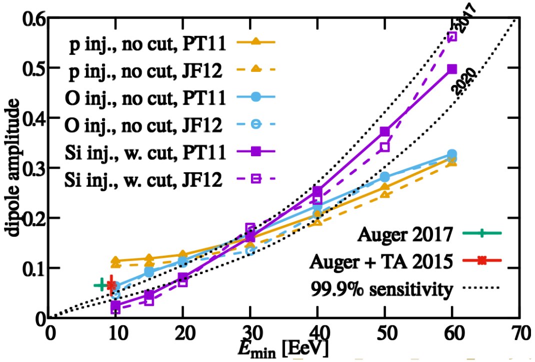
Misconception

"The higher we go in energy, the more likely we are to find anisotropies, because both the propagation horizon and the magnetic deflections are smaller."

Fact

- We do expect anisotropies to get stronger with energy for those reasons; but conversely, the statistics decreases, making it harder to detect anisotropies of a given strength.
- Which of the two effects dominates depends, among other things, on the UHECR masses.
- Indeed, the only anisotropy ever detected with $\geq 5\sigma$ so far is in the $[8\ \mathrm{EeV}, +\infty)$ bin (Auger collab., *ApJ* **891** (2020) 142).

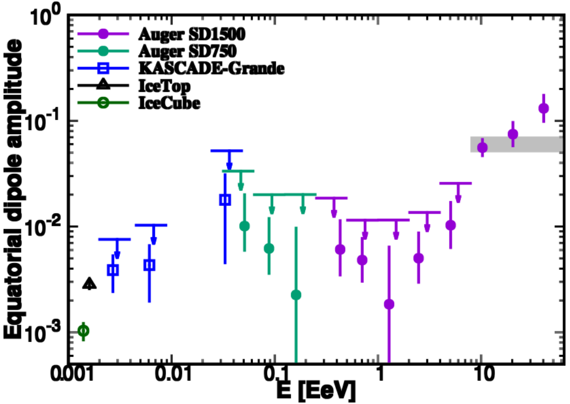
↓ AdM & P. Tinyakov, *MNRAS* **476** (2018) 715



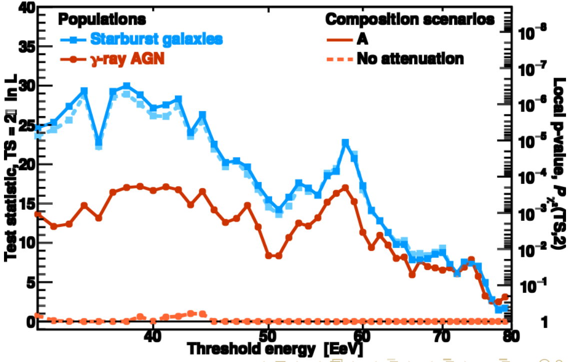
Misconception

"The higher we go in energy, the more likely we are to find anisotropies, because both the propagation horizon and the magnetic deflections are smaller."

Auger collab., *ApJ* **891** (2020) 142 ↓



L. Caccianiga [for the Auger collab.], PoS (ICRC2019) 206 ↓



Misconception

"We should expect the IceCube PeV neutrinos to come from UHECR sources."

Fact

- Neutrinos are produced in photohadronic interactions of nucleons with $E_N \sim 20E_\nu$ ($\lesssim$ a few tens of PeV for IceCube events).
- These do not necessarily come from the same kind of sources as multi-EeV nuclei.
- Even assuming that they do, nuclei can only reach us from the nearest such sources (within a few hundred Mpc), whereas neutrinos also from those farther away.
- Hence we aren't likely to find correlations between them (A. Palladino et al., *MNRAS* **494** (2020) 4255) (unless the source number density is very low, in which case we would expect to have seen several neutrinos from the same source, which we haven't).
- And indeed, no correlation is found between IceCube/ANTARES and Auger/TA (A.M. Barbano [for the IceCube, Auger, TA and ANTARES collabs.], PoS (ICRC2019) 842).

Thanks for your attention!

(adapted from https://xkcd.com/386/)

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