Ultra-high energy cosmic rays and their secondary signals

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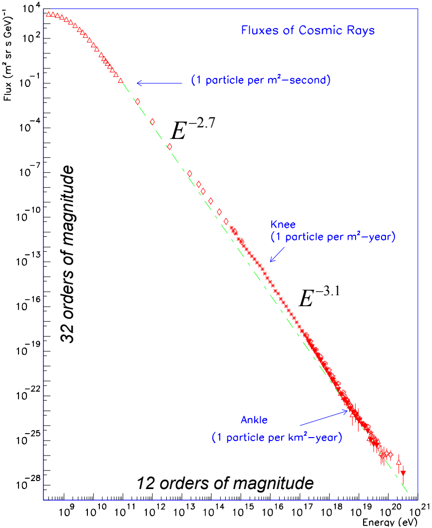
Overview

1. Introduction
    - Observation Techniques
    - Observables
2. Experimental Results
    - Energy Spectrum
    - Arrival Directions
    - Composition study
3. Modeling UHECR
    - Attenuation
    - Phenomenological source models
4. Secondary signals from UHECR
    - Neutrons
    - UHE ν and γ
    - Isotropic γ-ray background
5. Summary

Cosmic Ray Spectrum

Each energy range addresses different physics:

- Solar modulation:
  $10^8 eV \leq E \leq 10^{11} eV$
- Galactic sources:
  $10^{11} eV \leq E \lesssim 10^{18}? eV$
- Extragalactic sources:
  $E \gtrsim 10^{18}? eV$



Brief History

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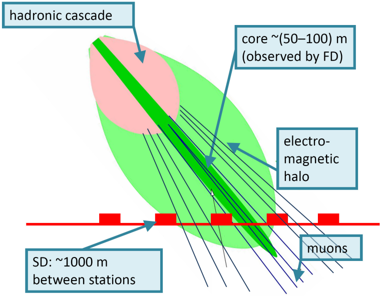
- 1984-2003: AGASA, 111 scintillators in 100 km2- NO GZK..!
- 1997-2006: High Res. Flys Eye, 2 fluorescence telescopes - GZK observed.
- 2004-now: Pierre Auger Observatory: Hybrid observatory in southern hemisphere, cutoff confirmed. Data favors heavy nuclei primaries
- 2008-now: Telescope Array Experiment: Hybrid observatory in northern hemisphere - cutoff confirmed. Consistent with proton or light nuclei primaries

UHECR Observation Techniques



Arrays of surface detectors (SD)
Detects particles of a EAS at the ground level by an array of Cherenkov detectors with the spacing about 1 km

Fluorescence detectors (FD)
Detects UV emission caused by fluorescence of atmospheric N molecules which are excited by charged particles of the shower.

UHECR Observation Techniques

Arrays of surface detectors (SD)

- Observe mostly the periferic part of 2D slice of the shower
- Determine lateral distribution function (LDF) of the particle density in the shower.
- Observe electromagnetic and muon component
- Works independently of the weather conditions and time of the day

Fluorescence detectors (FD)

- See the central core
- Observe longuitudinal development of a shower
- Sensitive to the electron component only
- Operates on clear moonless nights only (roughly, 10% of time)

UHECR Observation Techniques

SD

- Volcano Ranch
- Haverah Park
- Yakutsk
- AGASA

FD

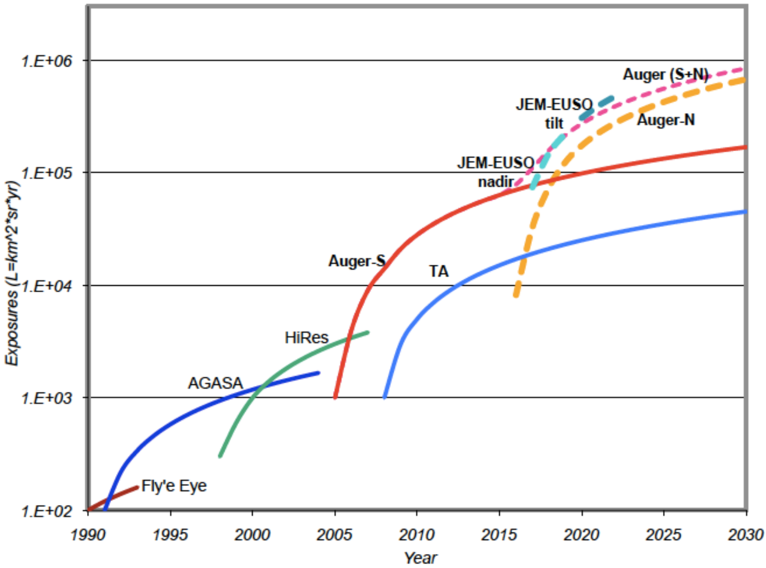
- Fly's Eye
- HiRes Fly's Eye

Hybrid

- Pierre Auger Observatory
- Telescope Array

Experimental progress

Exposure for $E > 10^{18} eV$



Principal observables

1. Energy

2. Arrival direction

3. The type of the primary particle

Principal observables

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   - Reconstructed indirectly, model dependent
   - $\sqrt{S} \sim 10 - 100\,TeV \rightarrow$ extrapolation needed
   - statistical error of $\sim 15 - 20\%$
   - systematic uncertainty of $\sim 25\%$
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    - Least model dependent, pure geometrical reconstruction
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    - Precision decreases with the growth of the effective area (currently $\sim 1.5^\circ$, for HiRes $\sim 0.6^\circ$)
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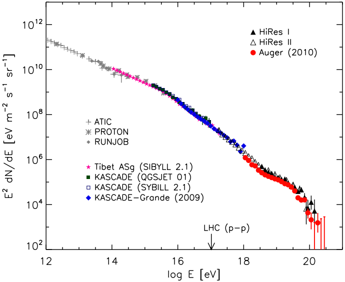
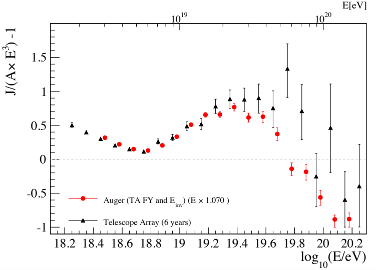
3. The type of the primary particle
    - Fluctuations and Similarities → Practically impossible for individual event
    - Strongly model dependent study of EAS properties
    - SD: Signal rise time, muon and electromagnetic component, front shape
    - FD: Depth of the maximal shower development

Energy Spectrum



- Knee at $E \sim PeV$
- Ankle at $E \sim 3EeV$
- Suppression at $E \gtrsim 30EeV$



Arrival Directions

Puzzles to be solved

- No bright spots of few degree angular size (expected for protons with $E \gtrsim E_{GZK}$)
  - If protons, high density of sources $\rho > 10^{-4} Mpc^{-3}$. Hard to explain but not impossible *(see e.g. O.K. et al. Phys.Rev. D86)*
- Auger CenA excess and TA $\sim 20^\circ$ hot spot for $E > 57 EeV$ *(JCAP 1106 (2011);Astrophys.J. 790 (2014))*
  - No clustering at lower energies E_{max}/Z: If primaries are heavy nuclei, narrow composition?
  - If primaries are protons from Cen A EGMF must be high: $B \gtrsim 2 \times 10^{-8} G$

Composition study

Observables

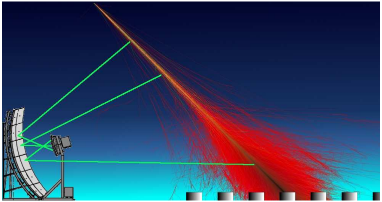
Experiment	detector	Observable
HiRes	fluorescence stereo	X_{MAX}
Pierre Auger	fluorescence + SD (hybrid)	X_{MAX}
Telescope Array	stereo	X_{MAX}
Telescope Array	hybrid	X_{MAX}
Yakutsk	muon	$\rho_\mu(1000)$
Pierre Auger	SD	X^μ_{MAX}
Pierre Auger	SD	risetime asymmetry

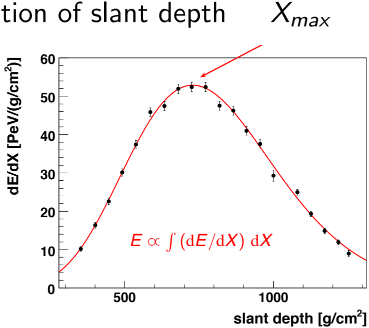
SD – surface detector
X_{MAX} *– depth of the shower maximum*
X^μ_{MAX} *– muon production depth*
risetime – time from 10% to 50% for the total integrated signal

Composition study

Flourescence Detector: Longitudinal Shower Profiles

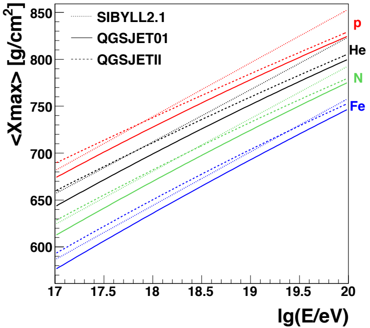
Detection of fluorescence light as a function of slant depth

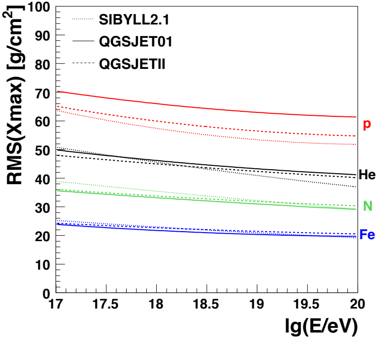




Composition study

Light and heavy nuclei



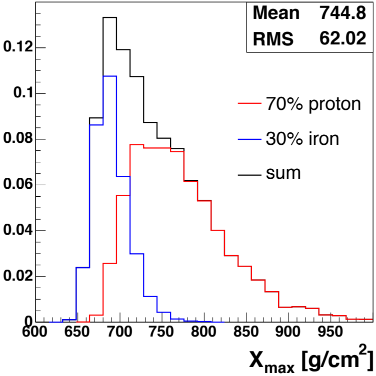


$$\overline{X_{max}} \simeq D\, log(E/A) + const$$

$$\sigma_{X_{max}}(A_1) < \sigma_{X_{max}}(A_2)$$
for $A_1 > A_2$

Composition study

Light and heavy nuclei



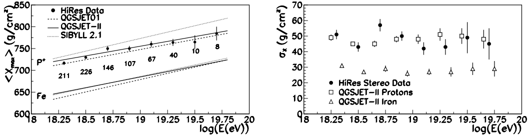
Mixed composition

- $\overline{X_{max}} \propto \overline{log(A)} + const$
- Difference in X_{max} contributes to RMS

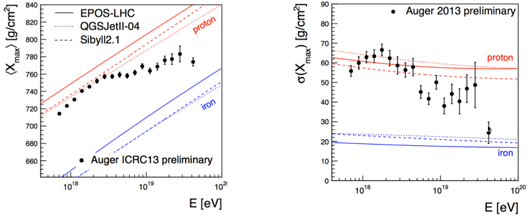
Composition study

Light and heavy nuclei. Observations

HiRes



Auger



Light

- HiRes
- Telescope Array

Heavy

- Pierre Auger
- Yakutsk

Composition study

Light or heavy nuclei

light	**HEAVY**

Experiment:

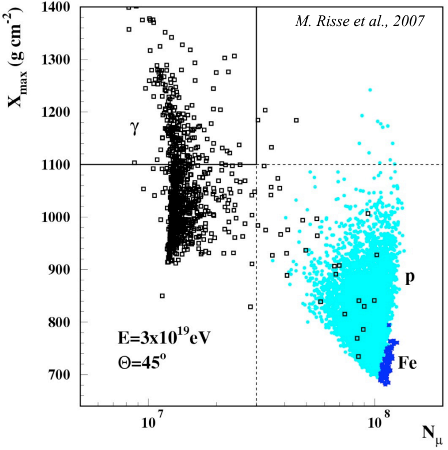
HiRes	Auger
TA	Yakutsk

Theory:

nuclei abundance and survival in cosmic accelerators are questionable	nuclei are accelerated to higher energies than protons
$\sigma(X_{MAX})$ data indicate sharp composition change	density of sources; non-observation of clustering

Composition study

Photon identification with EAS



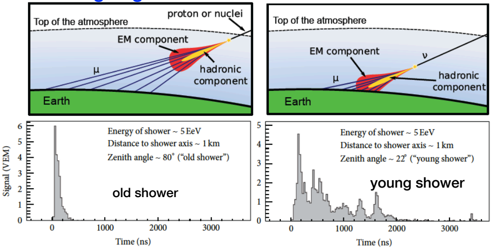
- Deep shower development
- Poor muon content

- No UHE γ identified so far. Strong limits (see below)

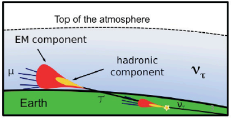
UHE Neutrino

Search with Pierre Auger Observatory

- **down-going**



- **up-going (Earth-Skimming)**



ν_τ **flavor**

Earth-Skimming (90º, 95º)

contrib. to total evt rate **73%**

ν selected as inclined showers with large EM component (time spread of SD signals)

NO CANDIDATES FOUND

UHECR source models

- Top-Down (decay or annihilation of exotic particles)

- Bottom-Up (acceleration of charged particles)

UHECR source models

- Top-Down (decay or annihilation of exotic particles)
  - Topological Defects (Hill 1983; Berezinky, Vilenkin 1997)
  - SHDM (Berezinsky et.al. 1997; Kuzmin, Rubakov 1997; Birkel, Sarkar 1998)
  - Z-bursts (Fargion, Mele, Salis-1999; Weiler -1999)
  - UHECR are mostly γ and ν (see e.g. O.K. et al 2009)
- Bottom-Up (acceleration of charged particles)

UHECR source models

- Top-Down (decay or annihilation of exotic particles) disfavoured
  - Topological Defects (Hill 1983; Berezinky, Vilenkin 1997)
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  - UHECR are mostly γ and ν (see e.g. O.K. et al 2009)
- Bottom-Up (acceleration of charged particles)
  - Proton primaries
  - Mixed composition primaries

Acceleration of cosmic rays

Conditions to be fulfilled by source candidates

1. **Geometry:** accelerated particle should be kept inside the source enough time (Hillas criterion) $E \lesssim qBR$
2. **Radiation and interaction losses:** energy lost by a particle should not exceed the energy gain
3. **Emissivity:** total number (density) and power of sources should be able to provide the observed UHECR flux
4. **Accompanying radiation:** of photons, neutrinos and low-energy cosmic rays should not exceed the observed fluxes, both for a given source and for the diffuse background

Sources of UHECR

Maximal energy, Hillas criterion and radiation losses

$E_{max} = min\{E_H, E_{loss}\}$, where

$$\frac{dE^+}{dt}|_{E=E_{loss}} = -\frac{dE^-}{dt}|_{E=E_{loss}}$$

$$E_H = qBR,$$

$$\frac{dE^+}{dt} \propto qB$$

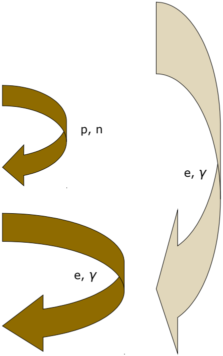
see e.g. Ptitsyna, Troitsky 2010

1. diffusive acceleration (shock waves) $E_{loss} \propto \left(\frac{A}{Z}\right)^4$
2. inductive acceleration with synchrotron-dominated losses (AGN jets) $E_{loss} \propto \frac{A^2}{Z^{3/2}}$
3. inductive acceleration with curvature-dominated losses (immediate vicinity of neutron stars and black holes) $E_{loss} \propto \frac{A}{Z^{1/4}}$

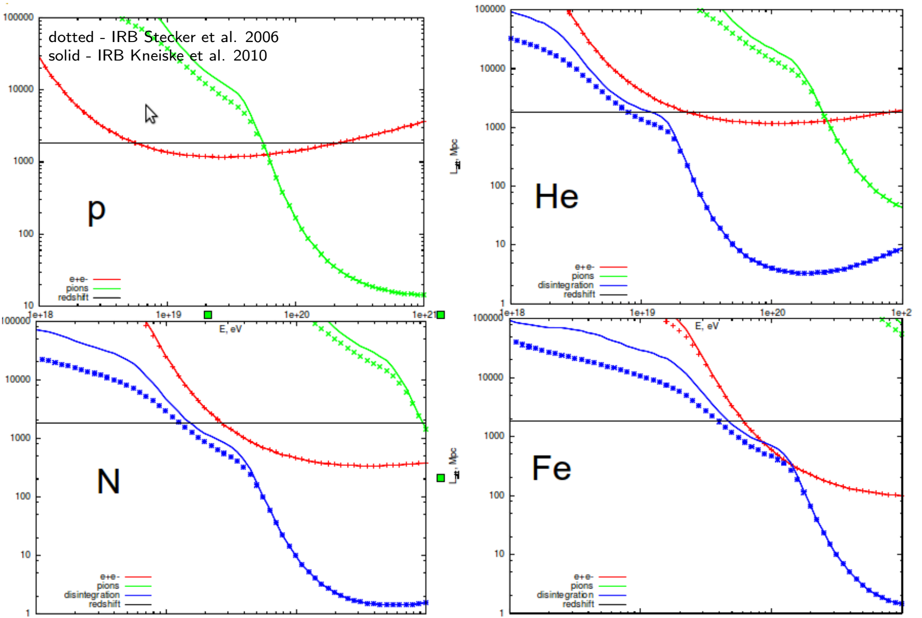
Attenuation of UHECR

Main attenuation channels

- Nuclei
    - $A\gamma_b \to A'N$
    - $A\gamma_b \to A\pi..$
    - $A\gamma_b \to Ae^+e^-$
- Protons and neutrons
    - $N\gamma_b \to N'\pi..$
    - $p\gamma_b \to pe^+e^-$
    - $n \to pe^-\overline{\nu}_e$
- Electron-photon cascade
    - $e\gamma_b \to e\gamma$
    - $\gamma\gamma_b \to e^+e^-$
    - e synchrotron losses



Attenuation Lengths



dotted - IRB Stecker et al. 2006
solid - IRB Kneiske et al. 2010

Attenuation of UHECR

Deflection

- Deflections in galactic magnetic field for particles crossing disk:

$$\frac{\Delta\Theta}{Z} \simeq 2.5^{\circ}\frac{100EeV}{E}\frac{B}{3\mu G}$$

- Deflections in extragalactic magnetic field (EGMF):

$$\frac{\Delta\Theta}{Z} \lesssim 0.4^{\circ}\frac{100EeV}{E}\frac{B}{0.1nG}\frac{\sqrt{L\lambda_{cor}}}{10Mpc}$$

  Current observational limits on EGMF strength B and correlation length λ_{cor}[1]:

$$10^{-16}G \lesssim B \lesssim 10^{-9}G$$

  Detailed simulations [2] show that EGMF has effect on UHECR spectrum if $B \gtrsim 10^{-10}G$ (assuming $\lambda_{cor} = 1Mpc$)

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[1] for review see R. Durrer and A. Neronov, Astron. Astrophys. Rev. **21**, 62 (2013)

[2] V. Berezinsky and A. Z. Gazizov, Astrophys. J. **669**, 684 (2007)

Attenuation of UHECR

Numerical simulations

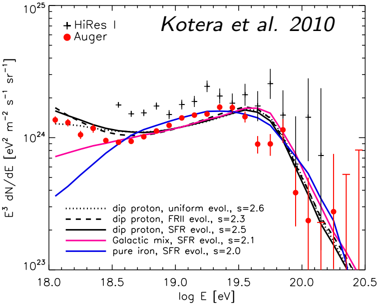
- Continuous energy loss approximation *(e.g. Waxman 1995, Beresinsky et al. 2002)*
    - Fastest, not very accurate around cut-off, fluctuations disregarded
- Solution of transport equations *(e.g. Yoshida et al. 1993; O.K. et al. 2003)*
    - Relatively fast and precise for homogeneous source distribution, no deflections.
- Monte-Carlo *(e.g. Allard et al. 2005; Aloisio et al. 2012; Kampert et al. 2013)*
    - Relatively slow, good for simulations of propagation in strong magnetic fields

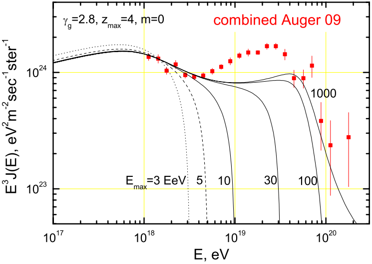
Phenomenological source models

Injection spectrum of nucleus with charge Z and atomic mass A:
$Q_A(E,z) \propto c_A E^{-s} N(z)$ with $E_{max,A} = E_{max,p} \times f(A,Z)$
Evolution either specific (AGN, SFR, etc.) or generic $N(z) \propto (1+z)^{3+m}$

Parameter	Range	Description
s	$1 < s < 2.7$	Power of the Injection Spectrum
c_A	$0 < c_A < 1$	Element abundances
$E_{max,p}$	$5 - 1000 EeV$	Maximal energy of protons
m	$0 < m < 6$	Evolution factor
z_{min}	$0 < z_{min} < 0.01$	nearest source redshift
z_{max}	$1 < z_{max} < 5$	maximal source redshift

Fitting spectrum of UHECR





- 'dip' model *(Berezinsky et al. 2006)*
  - ankle is caused by $p\gamma \to e^+e^-$
  - minimum of model parameters $s = 2.3 - 2.7$
  - proton dominated composition
- 'Galactic composition' *(Allard et al. 2005)*
  - $E_{max} \propto Z$, $E_{max,p} \gtrsim 100 EeV$
  - Fit spectrum well assuming $p = 2.2 - 2.3$
  - proton dominated composition
- 'Disappointing' model *(Aloisio et al. 2009)*
  - $E_{max} \propto Z$, $E_{max,p} \simeq 4 - 10 EeV$
  - Composition fine tuning is needed (too many *CNO*), *see e.g. Hooper et al. 2009; O.K. & Rubtsov 2012* ▸ details

Secondary signals from UHECR

- Nuclei
  - $A\gamma_b \to A'N$
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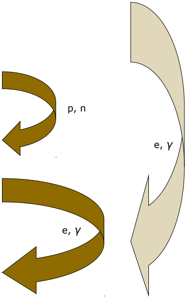


GZK γ,ν,n
n from photo-disintegration
ν from
$\beta-$decay

Diffuse
γ-background

UHE Neutrons

- Neutron decay (Mean travel distance $9.2E/[EeV]kpc$) → only galactic region accessible.
- Proton-like EAS
- No magnetic deflection: point-like excess expected
- Search in Auger and TA (coincidence with Fermi bright Galactic sources). No significant access found. Upper limits on neutron flux: $\sim 0.07/(km^2 yr)$ at $1EeV$

UHE ν and γ

Production

- Typically produced as decay products in *pp* & *p*γ collisions, e.g.

$$\begin{tikzcd}
 & & & \gamma+\gamma & \\
p+\gamma_b \arrow[r] & \Delta(1232) \arrow[r] \arrow[dr] & p+\pi^0 \arrow[ur] & & \\
 & & n+\pi^+ \arrow[r] & \mu^+ + \nu_\mu \arrow[dr] & \\
 & & & & e^+ + \overline{\nu}_\mu + \nu_e
\end{tikzcd}$$

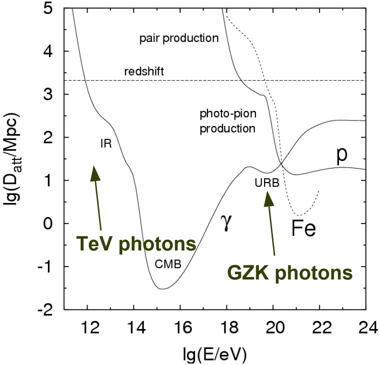
$$E_\gamma/E_p \simeq 0.1$$

$$E_\nu/E_p \simeq 0.05$$

- Also may be produced in Top-Down models (decay or annihilation of exotic particles)

UHE ν and γ

Propagation: photons local; neutrinos all universe

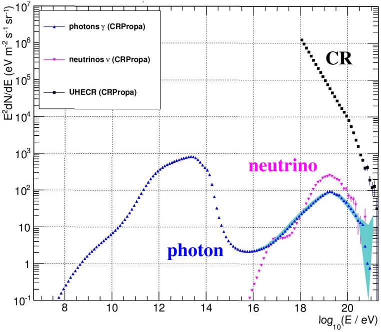


URB purely known

- Rectlinear propagation!
- ν: no interaction except mixing
- γ: initiate EM cascade

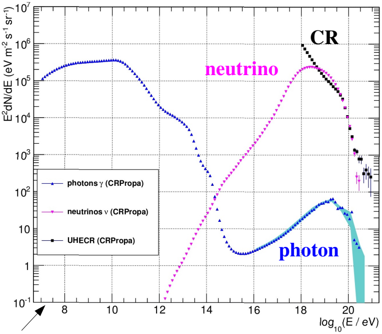
UHE ν and γ

Examples (N. Nierstenhofer, A. van Vliet)



Nearby Source (10 Mpc)

$F_\nu \sim F_\gamma \sim 1\% F_{CR}$



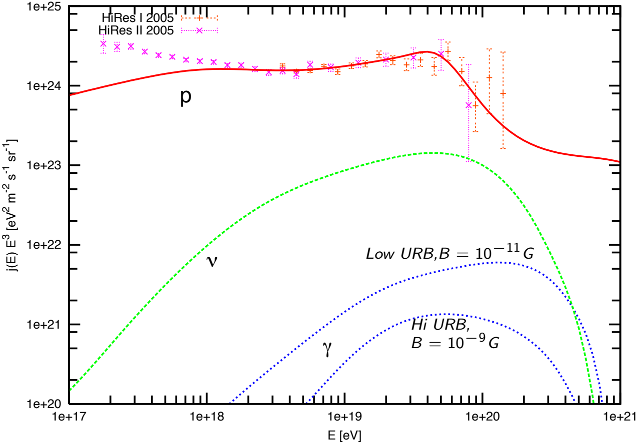
Distant Sources

$F_\nu \sim F_{CR} \qquad F_\gamma \sim 0.1\% F_{CR}$

UHE ν and γ

Examples (Gelmini, O.K. et al.)

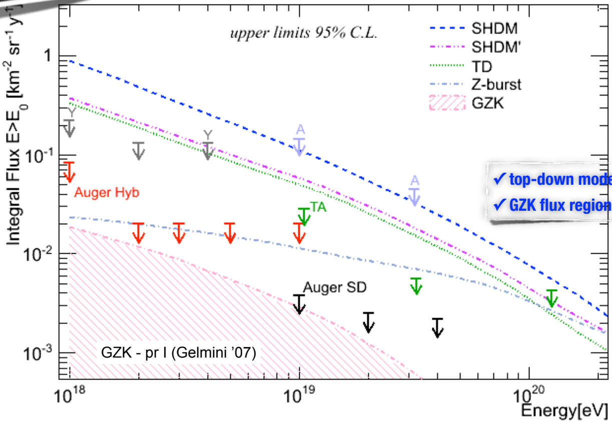
- UHE γ flux strongly depends on radio background and EGMF



Photon flux limits

Current status reported on UHECR 2014 (M. Settimo et al.)

No UHE photons identified so far!!

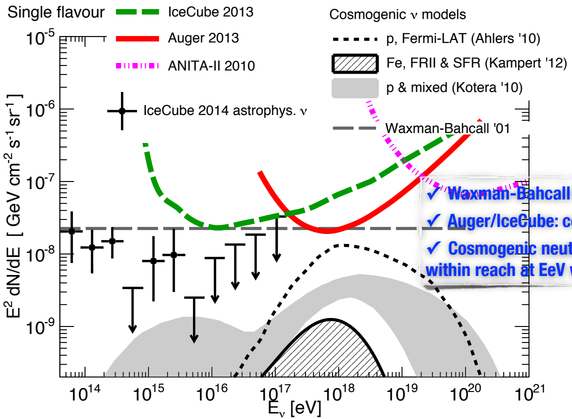


✓ top-down models disfavored

✓ GZK flux region within reach

Diffuse UHE Neutrino Limits

Current status reported on UHECR 2014 (M. Settimo et al.)



- ✓ **Waxman-Bahcall landmark reached**
- ✓ **Auger/IceCube: complementary energy range**
- ✓ **Cosmogenic neutrino in proton scenarios within reach at EeV with Auger**

ANITA/Auger/RICE: 90% C.L. differential upper limits in bins of 0.5 in $\log_{10}$(E)
IceCube arrows: 68% C.L. differential upper limits

IceCube Coll., Phys.Rev. D 88 (2013), 112008
IceCube Coll., PRL 113 (2014) 101101

ANITA Coll., Phys. Rev. D 85 (2012) 049901(E)
Pierre Auger Coll. ICRC 2013

Isotropic γ-ray background (IGRB)

- UHE γ and e create EM cascade which develops down to e^+e^- production threshold

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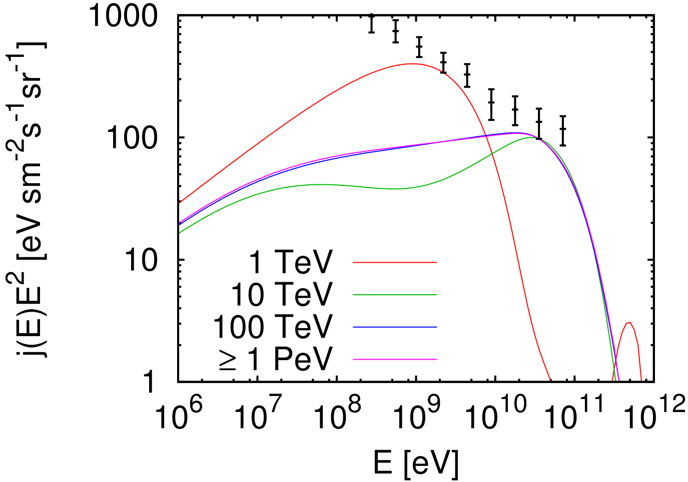
Isotropic γ-ray background (IGRB)

- UHE γ and e create EM cascade which develops down to e^+e^- production threshold
- Distant UHECR sources contribute the flux as in case of ν
- Not sensitive to initial spectrum. Only sensitive to evolution and power of sources

Development of EM cascade

Propagated spectra from monochromatic γ injection at z=1 (Berezinsky & O.K. 2015)



information on initial UHE γ spectrum is lost if $E_{ini} \gtrsim 10^{14} eV$ ▸ details

Isotropic γ-ray background (IGRB)

- UHE γ and e create EM cascade which develops down to e^+e^- production threshold
- Distant UHECR sources contribute the flux as in case of ν
- Not sensitive to initial spectrum. Only sensitive to evolution and power of sources

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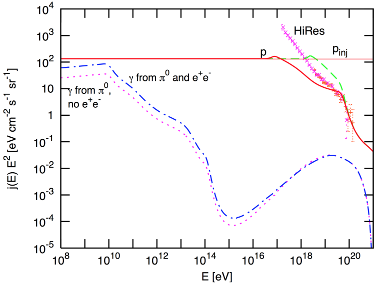
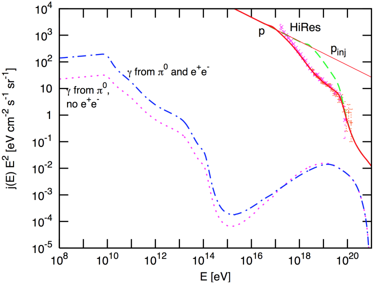
Example

Contribution of π and e^+e^- production to IGRB (O.K. et. al Phys.Rev.D79)

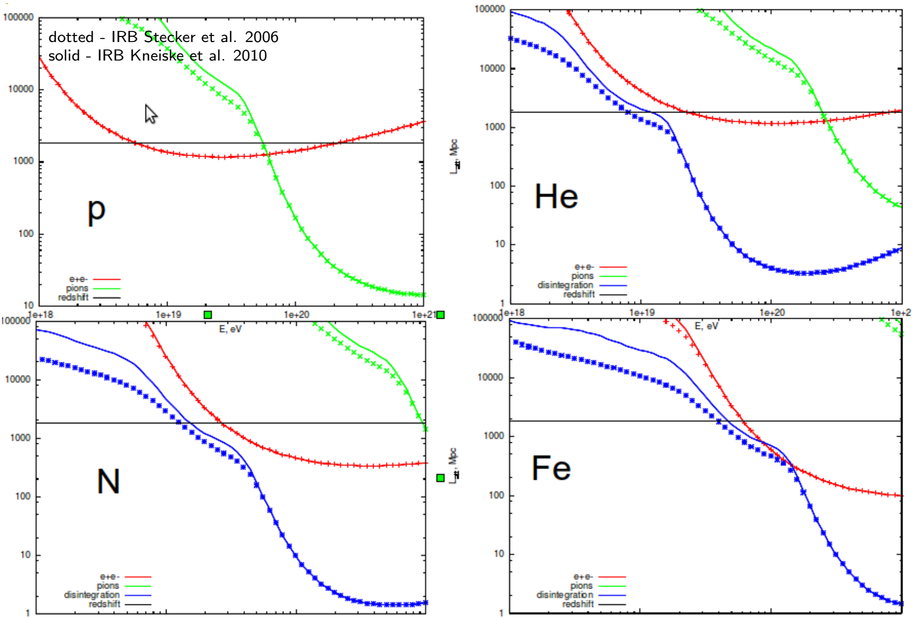


E^{-2} protons



$E^{-2.45}$ protons

Attenuation Lengths



dotted - IRB Stecker et al. 2006
solid - IRB Kneiske et al. 2010

Isotropic γ-ray background (IGRB)

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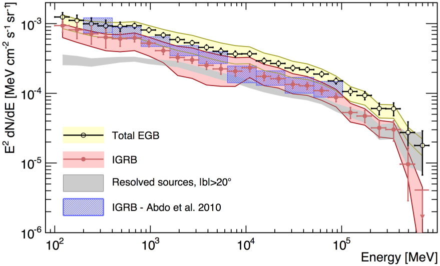
- Equal or higher contribution from UHECR via $N+\gamma \rightarrow N+e^+e^-$.
- Smaller fluxes expected from nuclei.
- Observed by FERMI LAT in the range $100MeV \gtrsim E_\gamma \gtrsim 800GeV$

Fermi γ-ray Space Telescope

Launched from Cape Canaveral Air Station 11 June 2008

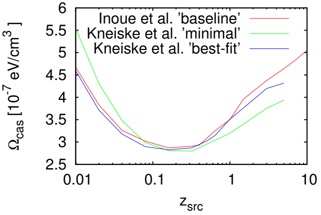
IGRB estimated between 100 MeV and 820 GeV
(M. Ackermann *et al.* arXiv:1410.3696 [astro-ph.HE])



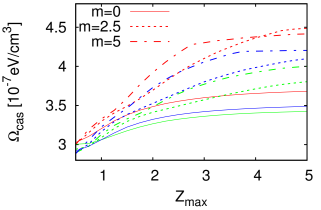
IGRB power density. Ultimate limit on UHECR models

Berezinsky & O.K. 2015

The shape of $GeV - TeV$ spectrum doesn't depend on initial E_γ if $E_\gamma \gtrsim 10^{14} eV$

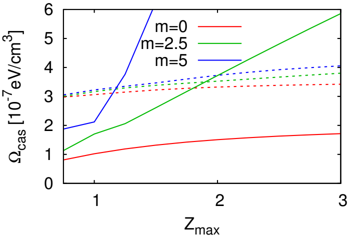


- Single parameter Ω_{cas} - power density injected to EM cascade
- Only moderate redshift dependence.



$N(z) = (1+z)^{3+m}$

Ω_{cas} in dip model



Restricting UHECRs and cosmogenic neutrinos by diffuse γ flux

V. S. Berezinsky and A. Y. Smirnov, Astrophys. Space Sci. **32**, 461 (1975).
O. E. Kalashev, V. A. Kuzmin, D. V. Semikoz and G. Sigl, Phys. Rev. D **66**, 063004 (2002)
M. Ahlers, L. A. Anchordoqui, M. C. Gonzalez-Garcia, F. Halzen and S. Sarkar, Astropart. Phys. **34**, 106 (2010)
V. Berezinsky, A. Gazizov, M. Kachelriess and S. Ostapchenko, Phys. Lett. B **695**, 13 (2011)
G. B. Gelmini, O. Kalashev and D. V. Semikoz, JCAP **1201**, 044 (2012)

- 'top-down' models disfavored
- 'dip' models with strong evolution are constrained
- So far IGRB estimate imposed more strict limits on UHECR models then UHE ν & γ, but situation changes

Summary

- UHECR spectrum cut-off exists
- UHECR are not galactic (isotropy, no UHE neutrons)
- UHECR composition at highest energies unclear
- Ω_{cas} constrains models with primary p or high E_{max}
- Proton source models allowed by Ω_{cas} may be constrained by UHE γ and ν limits in near future
- UHE γ and ν if observed will point to source

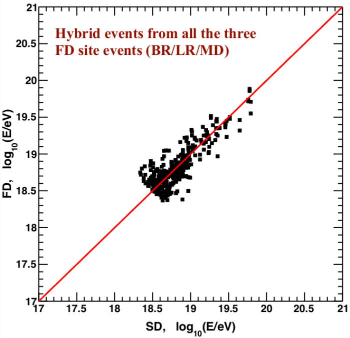
Thank You

Appedix

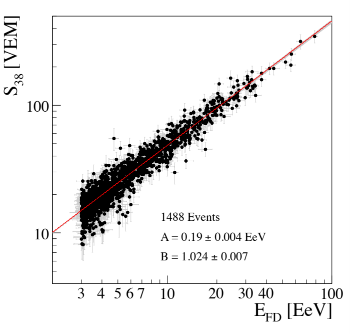
Energy spectrum systematic uncertainties

Auger-TA working group report on UHECR 2014

Telescope Array



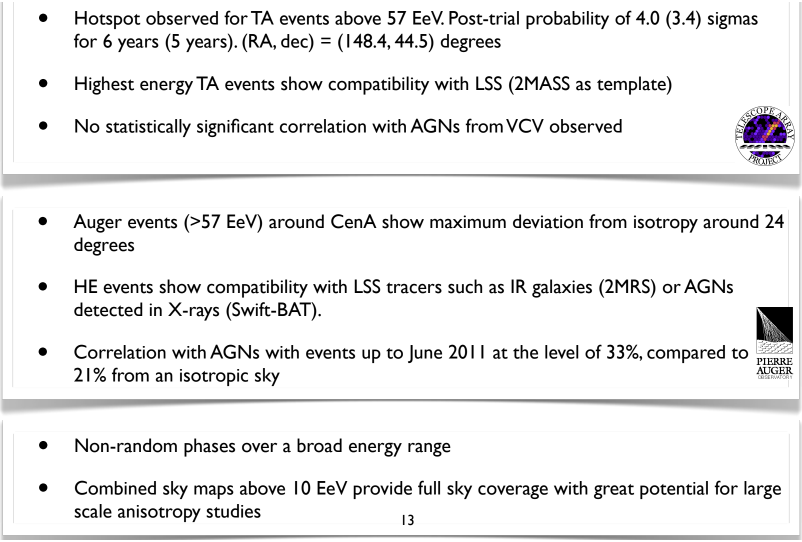
Auger



	Auger[%]	Telescope Array [%]
Atmosphere	3.4 - 6.2	11
Detector	9.9	10
Reconstruction	6.5 - 5.6	9
Stability of the energy scale	5	-
Sub-total	13	17

Anisotropy Study Summary

Auger-TA working group report on UHECR 2014



- Hotspot observed for TA events above 57 EeV. Post-trial probability of 4.0 (3.4) sigmas for 6 years (5 years). (RA, dec) = (148.4, 44.5) degrees
- Highest energy TA events show compatibility with LSS (2MASS as template)
- No statistically significant correlation with AGNs from VCV observed

- Auger events (>57 EeV) around CenA show maximum deviation from isotropy around 24 degrees
- HE events show compatibility with LSS tracers such as IR galaxies (2MRS) or AGNs detected in X-rays (Swift-BAT).
- Correlation with AGNs with events up to June 2011 at the level of 33%, compared to 21% from an isotropic sky

- Non-random phases over a broad energy range
- Combined sky maps above 10 EeV provide full sky coverage with great potential for large scale anisotropy studies

Radiation Losses

$$E_{max} = \min\{E_H, E_{loss}\}$$

$$E_H = 9.25\times10^{23}\, eV\, Z \frac{R}{kpc}\frac{B}{G}$$

Radiation losses criterion

$$\frac{dE^{(+)}}{dt} = -\frac{dE^{(-)}}{dt}$$

$$\frac{dE^{(+)}}{dt} = q\eta B \qquad \eta \le 1$$

diffusive acceleration

(shock wave etc.)

$$E_{loss} = 2.91\times10^{16}\, eV \frac{A^4}{Z^4}\left(\frac{R}{kpc}\right)^{-1}\left(\frac{B}{G}\right)^{-2}$$

inductive acceleration with synchrotron-dominated losses

(jets of powerful active galaxies)

$$-\frac{dE^{(-)}}{dt} = \frac{2}{3}\frac{q^4}{m^4}E^2B^2$$

$$E_{loss} = 1.64\times10^{20}\, eV \frac{A^2}{Z^{3/2}}\left(\frac{B}{G}\right)^{-1/2}\eta^{1/2}$$

inductive acceleration with curvature-dominated losses

(immediate vicinity of neutron stars and black holes)

$$-\frac{dE^{(-)}}{dt} = \frac{2}{3}\frac{q^2}{r^2}\left(\frac{E}{m}\right)^4$$

$$E_{loss} = 1.23\times10^{22}\, eV \frac{A}{Z^{1/4}}\left(\frac{R}{kpc}\right)^{1/2}\left(\frac{B}{G}\right)^{1/4}\eta^{1/4}$$

Transport equations

$$\partial_t N_p(E_p) = -N_p(E_p) \int d\epsilon\, n(\epsilon) \int d\mu \frac{1-\beta_p\mu}{2}(\sigma_{\mathrm{p},\pi} + \sigma_{\mathrm{p,e}}) +$$

$$\int dE'_p N_p(E'_p) \int d\epsilon\, n(\epsilon) \int d\mu \frac{1-\beta'_p\mu}{2} \left(\frac{d\sigma_{\mathrm{p},\pi}}{dE_p} + \frac{d\sigma_{\mathrm{p,e}}}{dE_p}\right) +$$

$$\int dE'_n N_n(E'_n) \int d\epsilon\, n(\epsilon) \int d\mu \frac{1-\beta'_n\mu}{2} \frac{d\sigma_{\mathrm{n},\pi}}{dE_p} + N_n(E_p)\frac{m_n}{E_p}\tau_n^{-1} + Q_{\mathrm{p}}(E_p)$$

$$\partial_t N_n(E_n) = -N_n(E_n) \int d\epsilon\, n(\epsilon) \int d\mu \frac{1-\beta_n\mu}{2}\sigma_{\mathrm{n},\pi} +$$

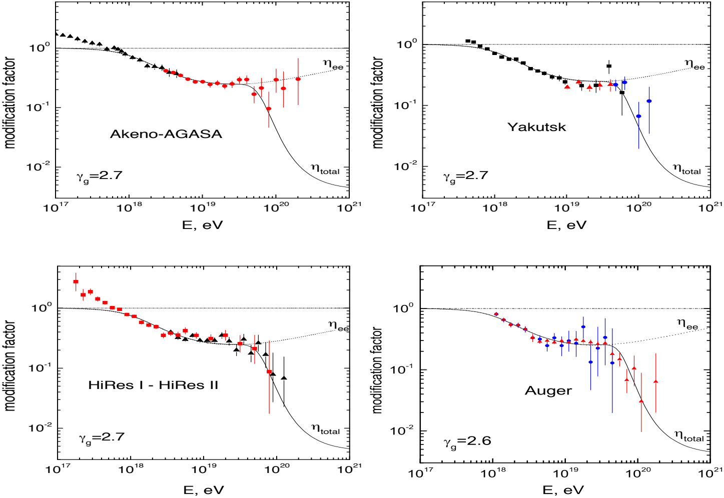
$$\int dE'_p N_p(E'_p) \int d\epsilon\, n(\epsilon) \int d\mu \frac{1-\beta'_p\mu}{2} \frac{d\sigma_{\mathrm{p},\pi}}{dE_n} +$$

$$\int dE'_n N_n(E'_n) \int d\epsilon\, n(\epsilon) \int d\mu \frac{1-\beta'_n\mu}{2} \frac{d\sigma_{\mathrm{n},\pi}}{dE_n} - N_n(E_n)\frac{m_n}{E_n}\tau_n^{-1} + Q_{\mathrm{n}}(E_n)$$

Dip in UHECR spectrum

Modification factor $\eta(E) = \frac{J_p(E)}{J_p^{ad}(E)}$

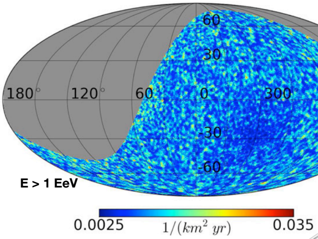
$J_p(E)$ - all energy losses; $J_p^{ad}(E)$ adiabatic losses only



UHE Neutrons

Search with Auger and Telescope Array

Search for excess of CR events (proton-like) from discrete sources within the angular resolution.
Only galactic region accessible (Mean travel distance ~ 9.2 E/[EeV] kpc)



Southern Sky (dec. [-90º, +15º])
The Pierre Auger Coll., ApJ, 760 (2012) 148

Auger-SD data, Jan 2004 - Sept 2011
energy ranges: 1-2 EeV, 2-3 EeV, ≥ 1 EeV, ≥ 3 EeV
upper limits on flux and constrains on astrophysical source models

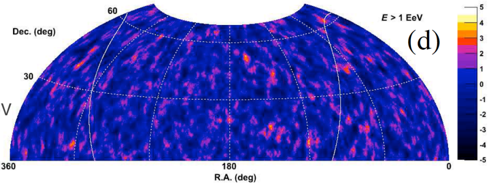
Target search performed
The Pierre Auger Coll., ApJ, 789 (2014) L34

No significant excess found

Northern Sky (dec. [0, 70º])

TA-SD, May 2008 - May 2013
energy ranges: 0.5-1 EeV, 1-2 EeV, ≥ 1 EeV, ≥ 2 EeV
mean upper limits on neutron flux: ~ 0.07/(km² yr) @ 1EeV
coincidence with 29 Fermi bright Galactic sources

The Telescope Array Coll., 1407.6145



Fitting Auger Spectrum and Composition

O.K.&G.Rubtsov - Quarks 2012

- Binned maximum likelihood function is used for both spectrum and Xmax distribution in each bin (X range is splitted onto N bins with roughly equal event counts)
- Poisson probability of the observed event set is maximized
- Goodness of fit is calculated by randomly generating sets of hypothetical experiments according to Poisson probabilities given by model.

$$L(\mathbf{n};\boldsymbol{\nu}) = \prod_i^N \frac{\nu_i^{n_i}}{n_i} e^{\nu_i}$$

Phenomenological source model:

$$F(E) = \sum_A c_A E^{-\alpha} \qquad E_{max,A} = E_{max,p} f(A,Z) \qquad 1 \le \alpha \le 2.7$$

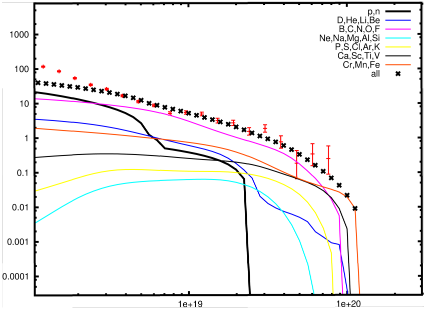
Free parameters: $c_A, \alpha, E_{max,p}, \Delta E/E, \Delta X$

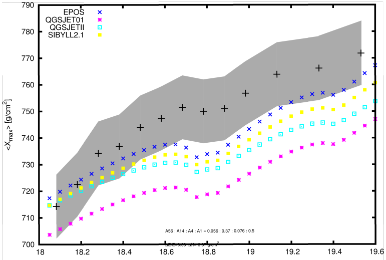
Using mixture of p,He,N,Fe as primary source $A = 1, 4, 14, 56$

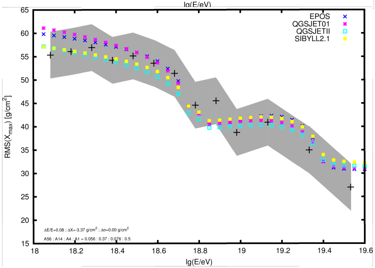
Fitting Auger Spectrum and Composition

O.K.&G.Rubtsov - Quarks 2012

Sample fit







$$E_{fit} > 2EeV \qquad \alpha = 2.2, E_{max} \propto \left(\frac{A}{Z}\right)^4$$

$$E_{max,p} = 10^{0.75}EeV$$

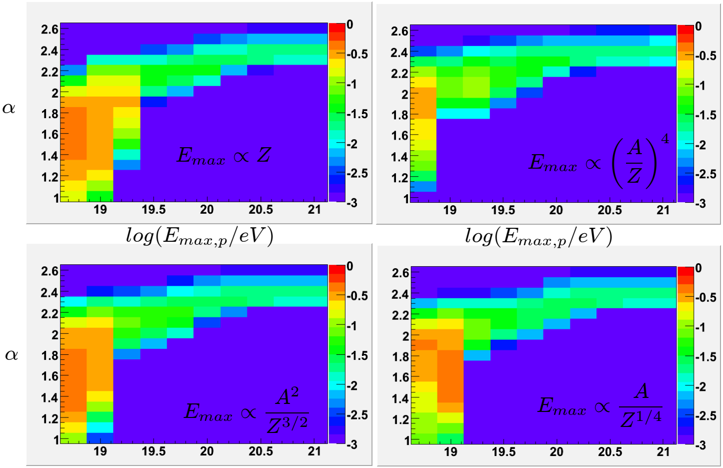
$$c_{Fe} : c_N : c_{He} : c_p = 0.06 : 0.36 : 0.08 : 0.5$$

$$\Delta E/E = 0.08 \qquad \Delta X = -3.4g/cm^2$$

Fitting Auger Spectrum and Composition

O.K.&G.Rubtsov - Quarks 2012

$E_{fit} > 5EeV$ P-value plots



Fitting Auger Spectrum and Composition

O.K.&G.Rubtsov - Quarks 2012

We require GOF>0.05 for E>5EeV and maximize P fraction

		$min(N_A/N_{tot})$
	$E_{max} \propto Z$	0.05
Diffusive acc. with synchrotron losses	$E_{max} \propto \left(\frac{A}{Z}\right)^4$	0.025
One-shot acc. with synchrotron losses	$E_{max} \propto \frac{A^2}{Z^{3/2}}$	0.03
One-shot acc. with curvature losses	$E_{max} \propto \frac{A}{Z^{1/4}}$	0.06

$$F(E) = \sum_A c_A E^{-\alpha}$$

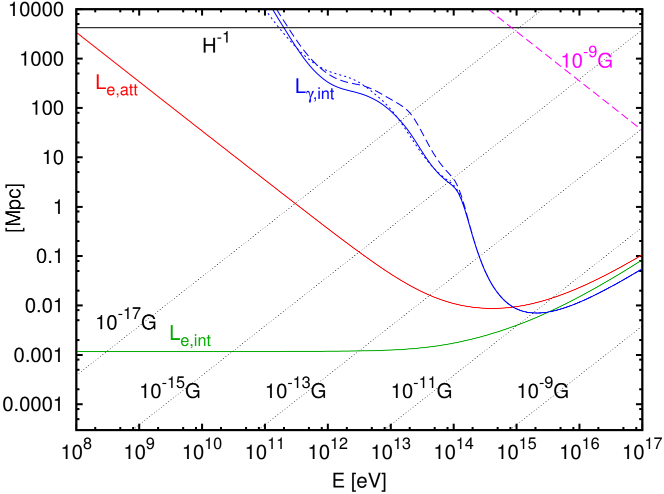
$$E_{max,A} = E_{max,p} f(A,Z)$$

$$\frac{c_A}{c_p} = \frac{N_A}{N_p} f(A/Z)^{\alpha-1}$$

▸ back to fits

Development of EM cascade

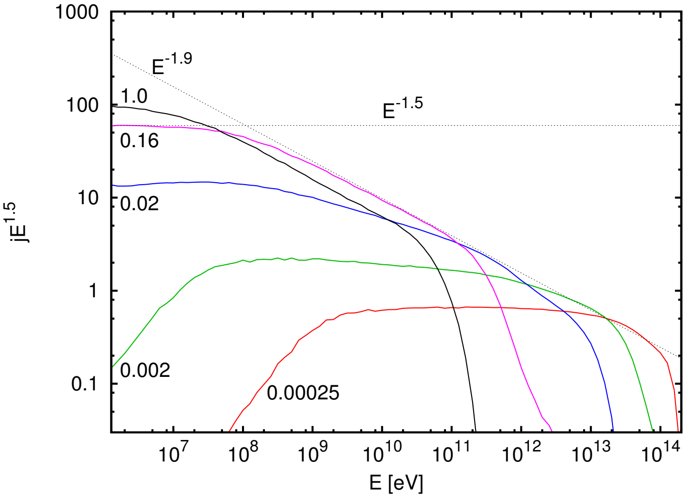
Interaction lengths of e and γ



information on initial UHE spectrum is lost

Development of EM cascade

Berezinsky & O.K. 2015



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