UHE photons, neutrinos, and hadrons at the Pierre Auger Observatory: Current status and prospects for the future

D. Nitz[1] *for the Auger Collaboration*[2]

[1]Michigan Technological University, Houghton, MI 49931
[2]Observatorio Pierre Auger, Av. San Martin Norte 304, Malargüe, Argentina

IceCube Particle Astrophysics Symposium
Madison, May 2013

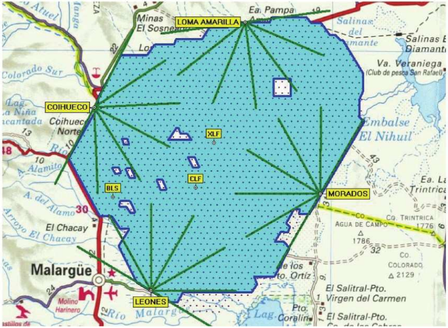
Outline

- Cosmic ray composition (with comparison to other experiments)
- Implications for photons & neutrinos
- Photons
- Neutrinos - See talk by Luis Anchordoqui "Neutrino Physics @ Auger" this afternoon
- The future

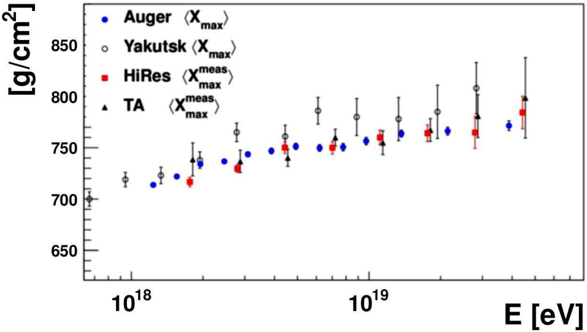
PIERRE AUGER OBSERVATORY

The Observatory

Michigan Tech
Create the Future



X_{max}



Mass Composition Working Group Report

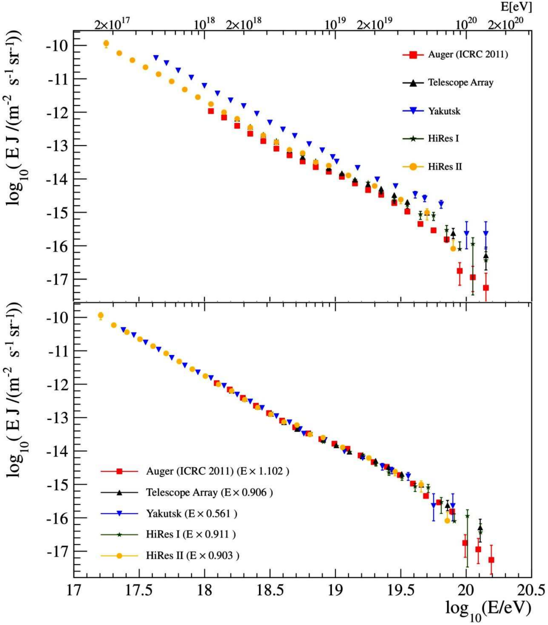
E. Barcikowski, J. Bellido, J. Belz, Y. Egorov, S. Knurenko, V. de Souza, Y. Tsunesada, and M. Unger

for the HiRes, Pierre Auger, Telescope Array and Yakutsk Collaborations

Proceedings of the UHECR 2012 Symposium (submitted)

- Data points are shifted to a common energy scale (see next slide).
- To estimate an average mass composition:
  - Auger: $\langle X_{max} \rangle$ can be compared directly with the predictions from air shower simulations (within systematic uncertainties).
  - HiRes & TA: $\langle X_{max} \rangle$ should be compared with that obtained from a convolution of simulated showers with a model of the detector, atmosphere and reconstruction.

Energy Scale



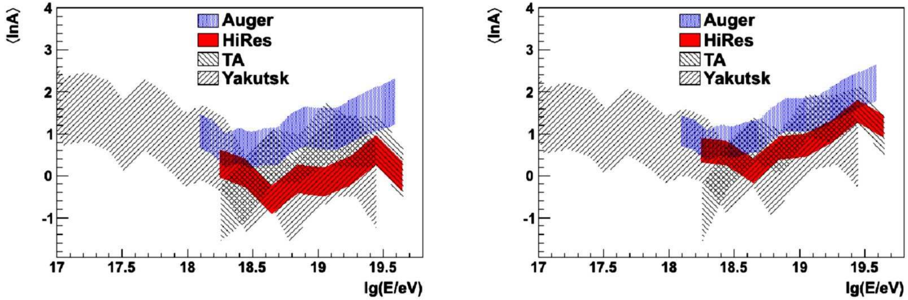
The Energy Spectrum of Cosmic Rays at the Highest Energies (Working group report)

Bruce R. Dawson, Ioana C. Maris, Markus Roth, Francesco Salamida, Tareq Abu-Zayyad, Daisuke Ikeda, Dmitri Ivanov, Yoshiki Tsunesada, Mikhail I. Pravdin, and Artem V. Sabourov, for the Pierre Auger, Telescope Array and Yakutsk Collaborations

Proceedings of the UHECR 2012 Symposium (submitted)

LnA - Model Dependence

Mass Composition Working Group Report

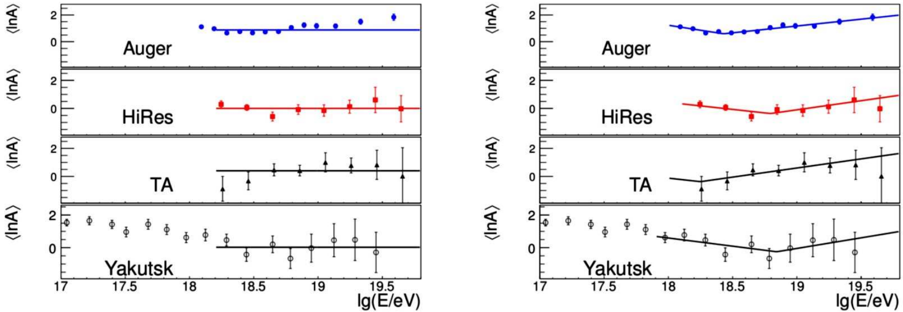


(a) using QGSJet-II model. (b) using SIBYLL model.

- Conversion from $\langle X_{max} \rangle$ to $\langle \ln A \rangle$:
  - Removes differences between experiments in $\langle X_{max} \rangle$ presentation
  - Is model dependent

LnA - Data

Mass Composition Working Group Report (using SIBYLL model)



- All 4 experiments are consistent with average mass getting heavier above 10^{19}eV.
  - Break points are not the same, but also not well determined.
- HiRes, TA, and Yakutsk are also consistent with constant light composition above $10^{18.5}$eV.

LnA - Fits (more details)

	Auger	HiRes	TA	Yakutsk
Constant ⟨lnA⟩	1.11 ± 0.03	0.6 ± 0.1	0.8 ± 0.2	0.3 ± 0.2
χ^2/ndf	133.6/10	4.4/7	9.8/7	7.7/7

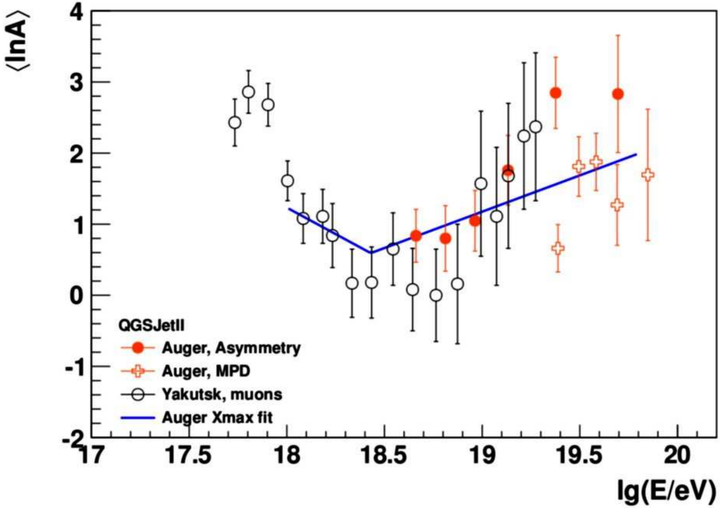
Table 2. Fitting a horizontal line to the ⟨lnA⟩ as a function of energy.

	Auger	HiRes	TA	Yakutsk
First Slope	-1.0 ± 0.3	-1.0	-1.0	-1.0
Second Slope	1.3 ± 0.1	1.3	1.3	1.3
$\lg(E_{break}/eV)$	18.43 ± 0.04	18.65 ± 0.07	$18.26\ {+0.14}/{-\infty}$	18.62 ± 0.14
$\langle \ln(A) \rangle_{break}$	0.75 ± 0.05	0.26 ± 0.10	$0.05\ {+0.22}/{-\infty}$	0.08 ± 0.15
χ^2/ndf	7.4/9	1.23/6	3.37/6	4.22/8

Table 3. Fitting a broken line to the ⟨lnA⟩ as a function of energy. For HiRes, TA and Yakutsk the slopes were fixed to the Auger ones, only the position of the breaking points were fitted

Beyond $\langle X_{max} \rangle$

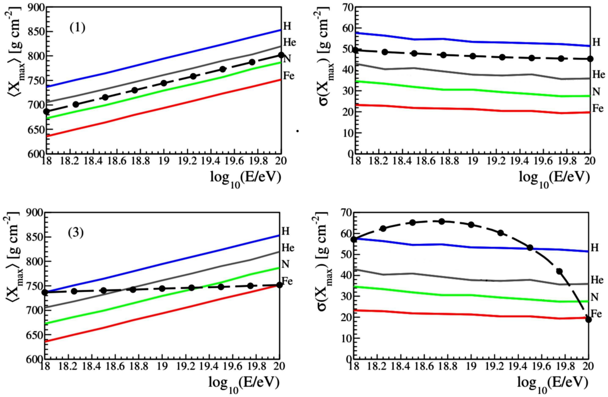
Mass Composition Working Group Report (using QGSJet-II model)



- Other mass (interaction) dependent variables give similar results

More than just $\langle X_{max} \rangle$

Interpretation of the depths of maximum of extensive air showers measured by the Pierre Auger Observatory, The Pierre Auger Collaboration, JCAP02 (2013) 026.



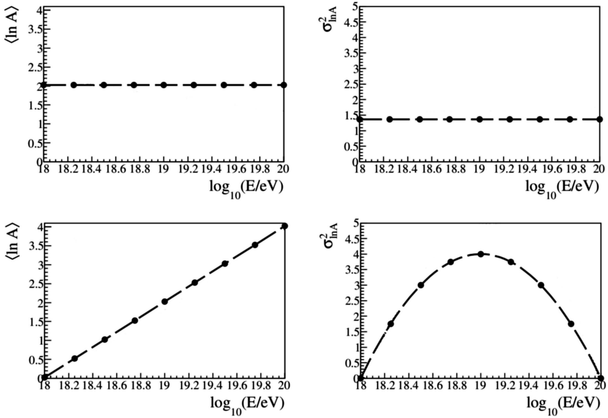
Composition uniform in $\ln A$ independent of energy

p+Fe composition, proton fraction decreasing from 100% to 0% linearly with $\log E$ from 10^{18} to 10^{20}eV

- $< X_{max} >$ measures mean of composition distribution, independent of spread
- $\sigma(X_{max})$ measures spread of distribution independent of mean

In Terms of $\ln A$ ...

JCAP02 (2013) 026



Composition uniform in $\ln A$ independent of energy

p+Fe composition, proton fraction decreasing from 100% to 0% linearly with $\log E$ from 10^{18} to 10^{20}eV

Conversion to $\ln A$

$$\langle \ln A \rangle = \frac{\langle X_{max} \rangle - \langle X_{max} \rangle_p}{f_E} \qquad \sigma^2_{\ln A} = \frac{\sigma^2(X_{max}) - \sigma^2_{sh}(\langle \ln A \rangle)}{b\sigma_p^2 + f_E^2}$$

Measurement

$\langle X_{max} \rangle$ is the average X_{max} at energy E

$\sigma^2(X_{max})$ is the X_{max} variance at energy E

Simulation

$\langle X_{max} \rangle_p$ is the average X_{max} at energy E

$\sigma^2_{sh}(\langle \ln A \rangle)$ is the X_{max} variance from shower fluctuations for mass A

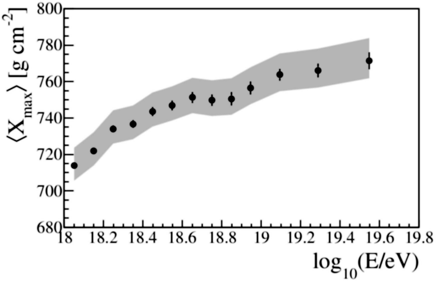
f_E is determined from $f_E = \left[\langle X_{max} \rangle_A - \langle X_{max} \rangle_p\right] / \ln A$

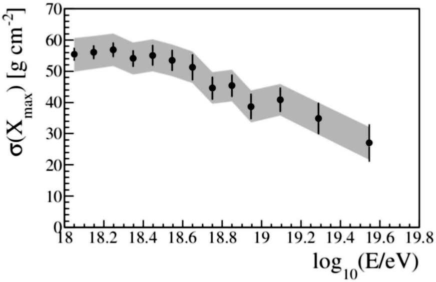
σ_p^2 is the X_{max} variance from shower fluctuations for proton showers

b is determined from $\sigma^2_{sh}(\ln A) = \sigma_p^2 \left[1 + a \ln A + b (\ln A)^2\right]$

Auger Data

JCAP02 (2013) 026





Model Dependent Conversion of $\langle X_{max} \rangle$ to $\langle \ln A \rangle$

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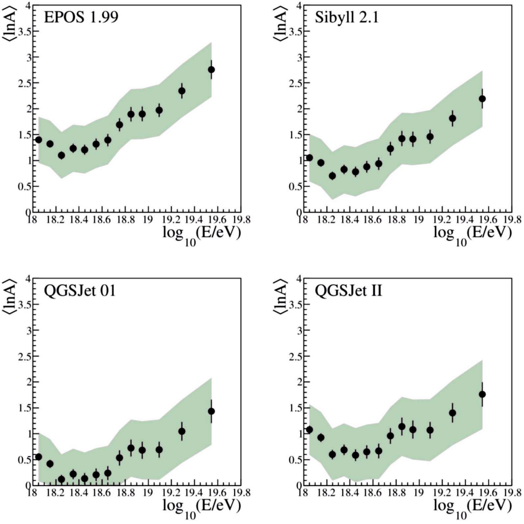
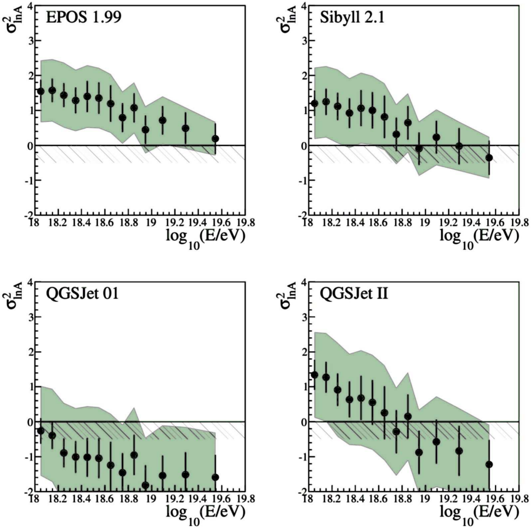


JCAP02 (2013) 026

Shaded regions indicate combined systematic uncertainties from both X_{max} measurement and published 22% FD energy scale uncertainty

Model Dependent Conversion of $\langle X_{max} \rangle$ and $\sigma(X_{max})$ to $\sigma^2_{\ln A}$

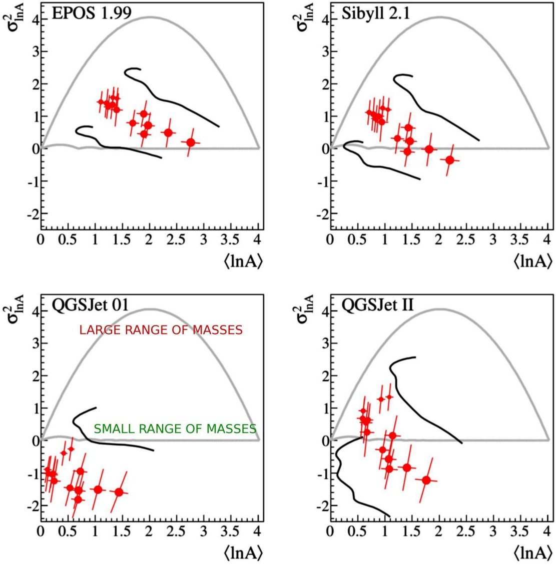


JCAP02 (2013) 026

Shaded regions indicate combined systematic uncertainties from both measurement and 22% FD energy scale uncertainty.

Lower limit of $\sigma^2_{\ln A}$ is indicated by exclusion line at 0. This occurs when $\sigma(X_{max})$ is smaller than model prediction for a single species corresponding to $\langle X_{max} \rangle$.

Combined $\ln A$ & $\sigma^2_{\ln A}$



JCAP02 (2013) 026

- Marker sizes proportional to $\log_{10} E$
- Statistical errors indicated on markers
- Heavy black lines indicate systematic uncertainties
- Grey lines enclose allowed physical region

Implications

Auger, HiRes, TA, and Yakutsk measurements are consistent with increasing heavy composition above $10^{18.5}$ eV

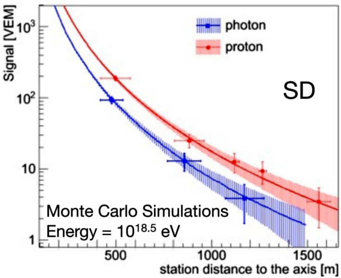
- Or changes in hadronic interactions not accounted for in the current models
  - Phase space for such changes becoming smaller with Auger cross section measurement at $\sqrt{s} = 57$ TeV and new LHC data
- Increasing $\ln A$ is problematic for UHE neutrino and photon searches

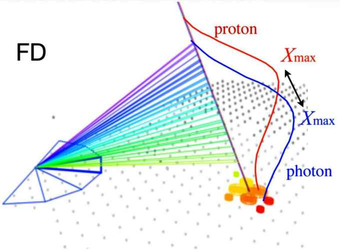
Auger indicates that as $\ln A$ increases, the spread of masses remains small

- Disfavors simple p+Fe composition
- A challenge for astrophysical models
- Problematic for JEM-EUSO: Energy & X_{max} resolution become even more important for source searches

- However:
  - Statistical error bars are still large
  - Most measurements extend only to $10^{19.5}$ eV, well below the GZK cutoff
- Need composition measurements with smaller error bars at the highest energies!

Photon Search Hybrid Method





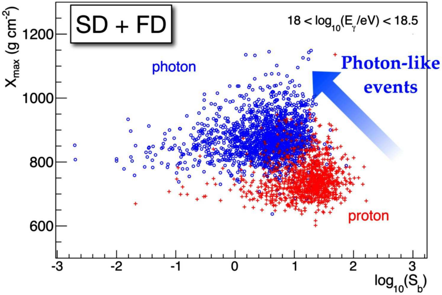
- **Deeper development of the air showers**

- **Smaller detected signal at a given distance**
- **Fewer triggered stations**

$$S_b = \sum_i S_i \left(\frac{R_i}{1000} \right)^4$$

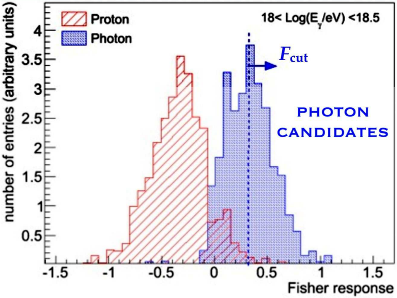
S_i : station signal [VEM]
R_i : station distance to the shower axis [m]

details on S_b: G. Ros et al., arXiv 1104.3399



M.S. for the Pierre Auger Collaboration, ICRC 2011, arXiv: 1107.4805

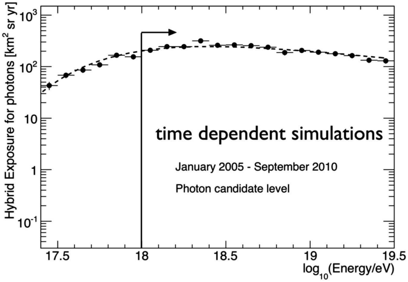
Photon Search Hybrid Method



Fisher Analysis combining $\mathbf{X_{max}}$ and $\mathbf{S_b}$

"a priori" cut @ photon selection efficiency = 50%
Events are marked as photon candidates for $F > F_{cut}$

- Proton Background on average ≲ 1%



Hybrid data Jan 2005 - Sep 2010

6, 0, 0, 0 and 0 candidates above
1, 2, 3, 5 and 10 EeV

Number of candidate compatible with the expected nuclear background and additionally checked with dedicated simulations for each candidate

Upper Limits to the Integral Photon Flux:

$$\phi_\gamma^{95CL}(E_\gamma > E_0) = \frac{N_\gamma^{95CL}(E_\gamma > E_0)}{\mathcal{E}_{\gamma,min}}$$

Photon Search SD Method

- Events observed by SD-alone

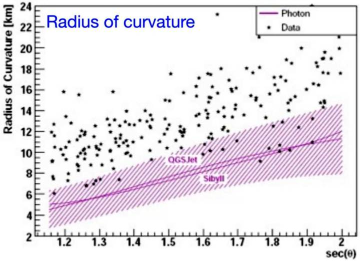
- **radius of curvature** and **risetime** $t_{1/2}$ at 1000 m used for photons identification

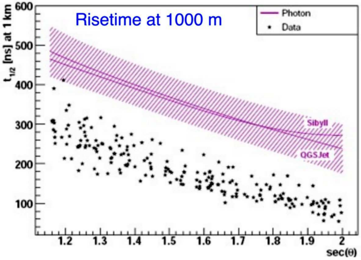
SELECTION CRITERIA

- at least 5 triggered detectors with 10 VEM signal
- impact point within the array
- 30° < zenith < 60°
- $E_\gamma > 10^{19}$ eV

DATA SAMPLE:
JAN 2004 - DEC 2006

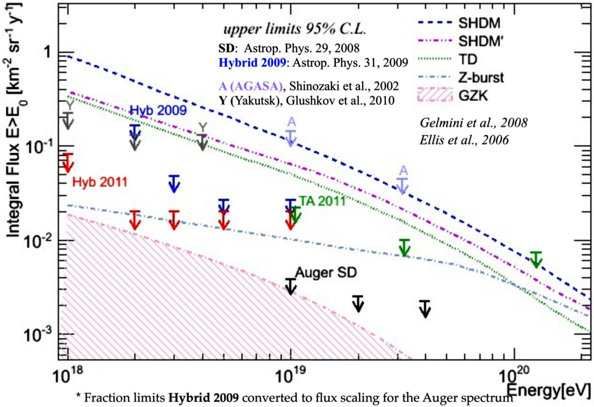
Deviations of data from the mean value of R and $t_{1/2}$ expected for photon showers combined with a **Principal Component Analysis**





DATA AND PHOTON SIMULATIONS WELL SEPARATED:
NO PHOTON CANDIDATES FOUND

Current Photon Limits



* Fraction limits **Hybrid 2009** converted to flux scaling for the Auger spectrum

E_0 [EeV]	N_γ	$\phi_\gamma^{95CL}(E_\gamma > E_0)$ [km^{-2} sr^{-1} y^{-1}]
1	6	8.2×10^{-2}
2	0	2.0×10^{-2}
3	0	2.0×10^{-2}
5	0	2.0×10^{-2}
10	0	2.0×10^{-2}

Impact of systematic uncertainties

(Exposure, ΔX_{max}, ΔS_b, Energy scale, hadronic interaction model and mass composition assumptions)

$^{+20\%}_{-64\%}$ $(E_0 = 1$ EeV$)$

$^{+15\%}_{-36\%}$ $(E_0 > 1$ EeV$)$

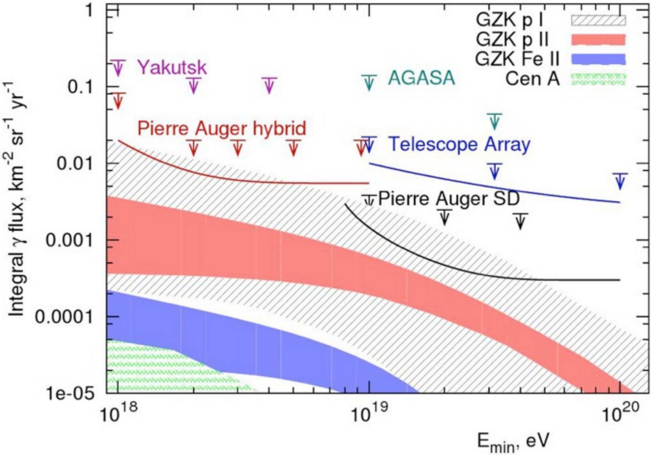
Upper limits to the integral photon fraction assuming the **Auger Spectrum**

0.4%, 0.5%, 1.0%, 2.6% and 8.9% @ E>1, 2, 3, 5 and 10 EeV

M.S. for the Pierre Auger Collaboration, ICRC 2011, arXiv: 1107.4805

Near Future Photon Limits

Expected sensitivity in 2015 with Telescope Array and Pierre Auger Observatory



Gelmini et al. 2008

B. Sarkar et al. 2011

Kachelriess et al. 2010

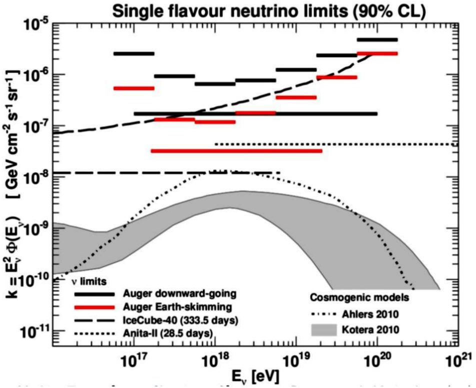
Photon observation possible (in optimistic models)

M. Risse et al., Symposium UHECR 2012, CERN

Neutrino Limits

Limits to diffuse fluxes

After unblinding : 0 candidates survive the cuts
Assuming a flux $\phi(E) = k \times E^{-2}$
$k < 3.2 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} in 1.6×10^{17} eV$< E < 2 \times 10^{19}$ eV
$k < 1.7 \times 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1} in 1×10^{17} eV$< E < 1 \times 10^{20}$ eV



$$k = \frac{N_{\rm up}}{\int_{E_{\rm min}}^{E_{\rm max}} \phi(E)\mathcal{E}dE}$$

Search sample :

- Earth skimming : Jan. 04 - May 10
- Down going : Nov. 07 - May 10

The Pierre Auger Collaboration, Advances in High Energy Physics, 2013 (2013) 708680
See also talk by Luis Anchordoqui "Neutrino Physics @ Auger" this afternoon

What Next?

The Auger Collaboration is planning an upgrade of the observatory to address:

- The origin of the flux suppression at the highest energies
  - GZK cutoff?
  - Top end of cosmic accelerators?
- The flux contribution of protons up to the highest energies
  - Peters cycle?
  - Composition enhanced anisotropy searches
  - Search for GZK secondaries as tracers of proton primaries
  - Search for ultra-high energy secondary photons produced in or near cosmic ray sources
- The study of extensive air showers and hadronic multi-particle production
  - Changes in hadronic interaction properties at the highest energies?

Upgrade Plans

The FD only operates $\approx 10\%$ of the time $\Longrightarrow$ focus on upgrading the SD

Detector upgrades being discussed include:

- Upgraded SD electronics
  - Faster FADCs
  - More powerful FPGA and processor
  - Better timing
  - Increased dynamic range
- Dedicated muon counting additions to the SD

Increased measurement capabilities include:

- Composition (& interaction) measurements to the highest energies
  - Faster FADCs, increased dynamic range, & dedicated muon detection
- Improved photon limits
  - Better photon/hadron separation through improved muon counting
- Improved neutrino limits
  - Increased aperture via more sensitive triggers implemented in powerful FPGA