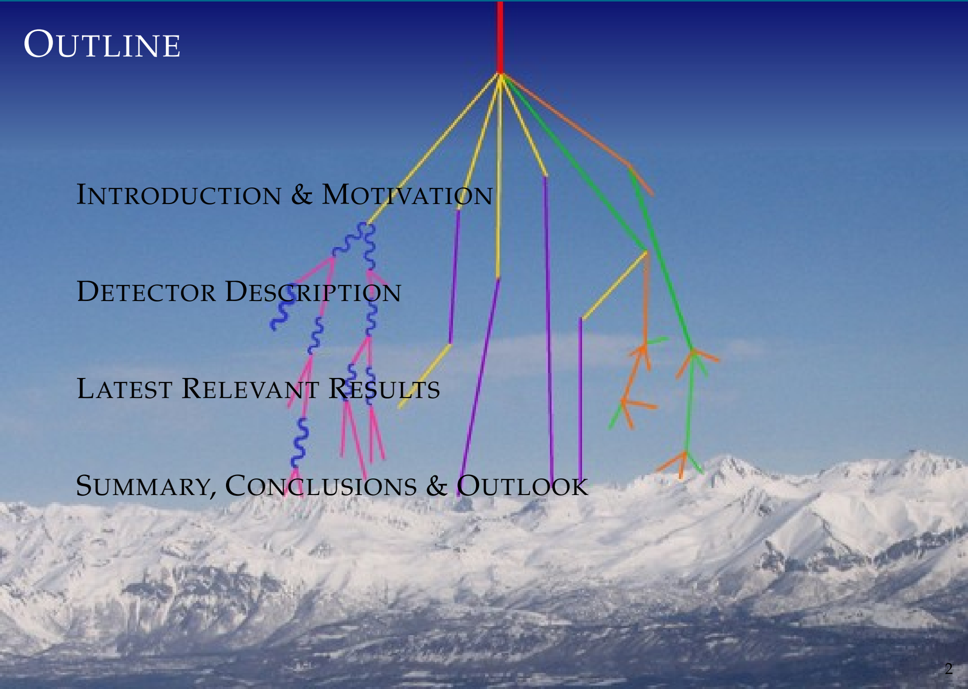
ON THE DETECTION OF THE HIGHEST ENERGY PARTICLES IN THE UNIVERSE WITH THE PIERRE AUGER OBSERVATORY

Miguel A. Mostafá

PennState

6th International Workshop on
High Energy Physics in the LHC Era
Valparaiso, Chile — January 6 – 12, 2016

OUTLINE



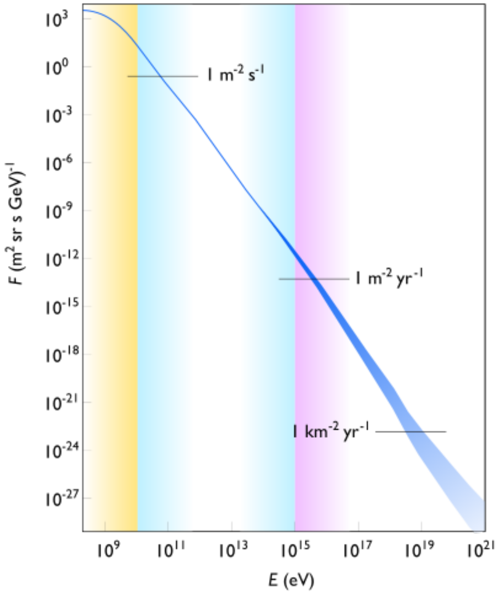
INTRODUCTION & MOTIVATION

DETECTOR DESCRIPTION

LATEST RELEVANT RESULTS

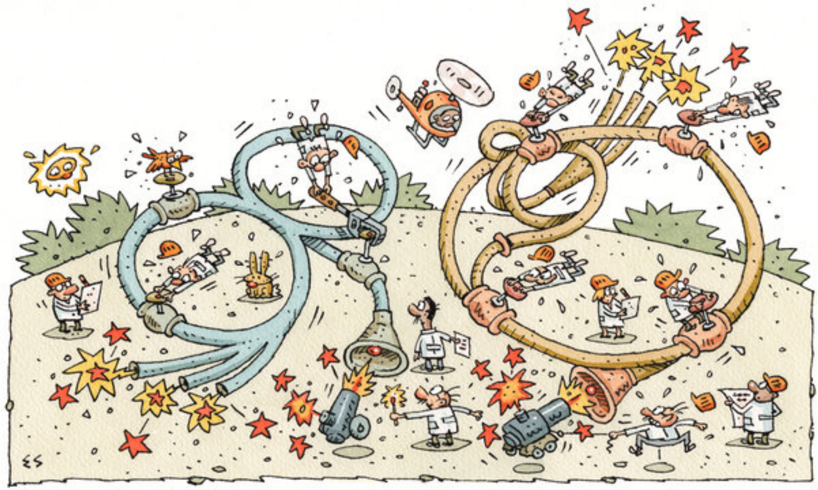
SUMMARY, CONCLUSIONS & OUTLOOK

THE COSMIC RAY ENERGY SPECTRUM



- 10^9 eV: galactic, strong solar modulation
- 10^9 eV to 10^{15} eV: galactic, probably from SNR
- 10^{15} eV to 10^{19} eV some hints of:
  - galactic anisotropy at 10^{18} eV
  - composition from heavy to light
- Above 10^{19} eV: UHECR
  terra incognita!

Particle Accelerators Full of Spin and Fury, Signifying Something



Elwood H. Smith

Published in the NYT on August 1, 2011

Black Holes Belch Universe's Most Energetic Particles

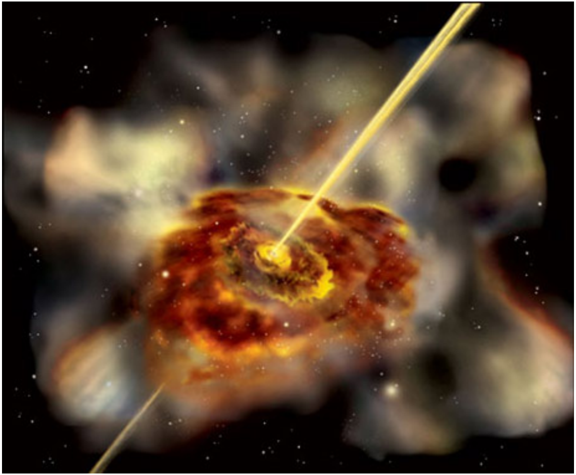


Image courtesy NASA E/PO, Sonoma State University, Aurore Simonnet

Published in National Geographic News on November 8, 2007

Black Holes Belch Universe's Most Energetic Particles

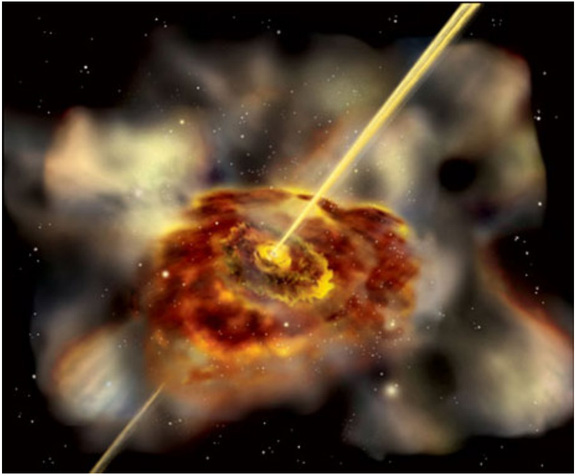
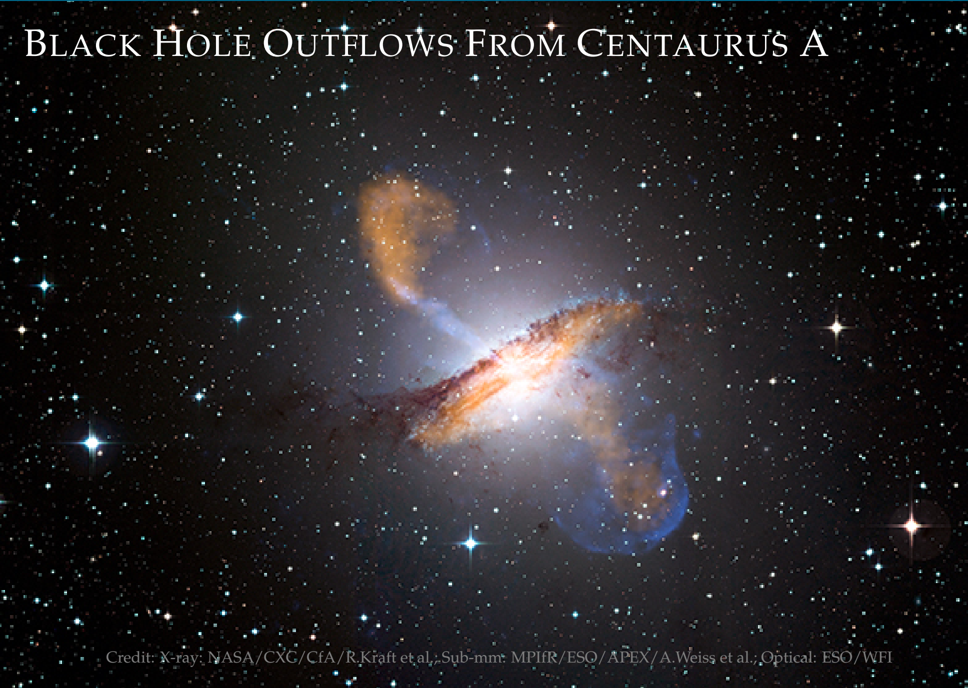


Image courtesy NASA E/PO, Sonoma State University, Aurore Simonnet

Published in National Geographic News on November 8, 2007
"We discovered the sources of the highest-energy particles in the universe,"
said team member Miguel Mostafa...

BLACK HOLE OUTFLOWS FROM CENTAURUS A



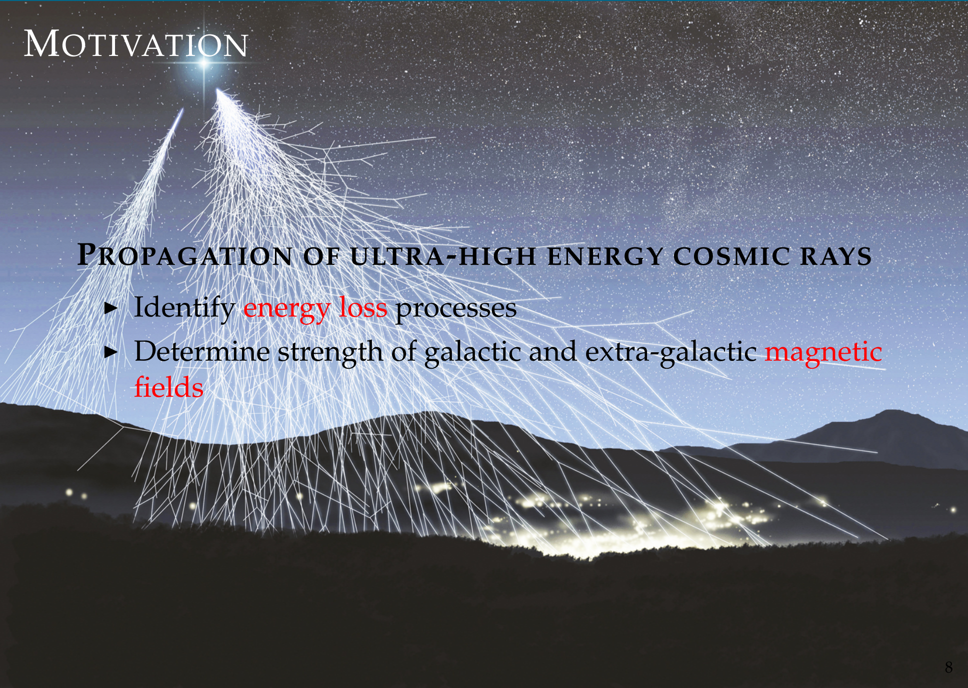
Credit: X-ray: NASA/CXC/CfA/R.Kraft et al.; Sub-mm: MPIfR/ESO/APEX/A.Weiss et al.; Optical: ESO/WFI

MOTIVATION

SOURCES OF UHECRS

- Determine acceleration or other production mechanism
- Find maximum energy of sources
- Discover sources or source regions

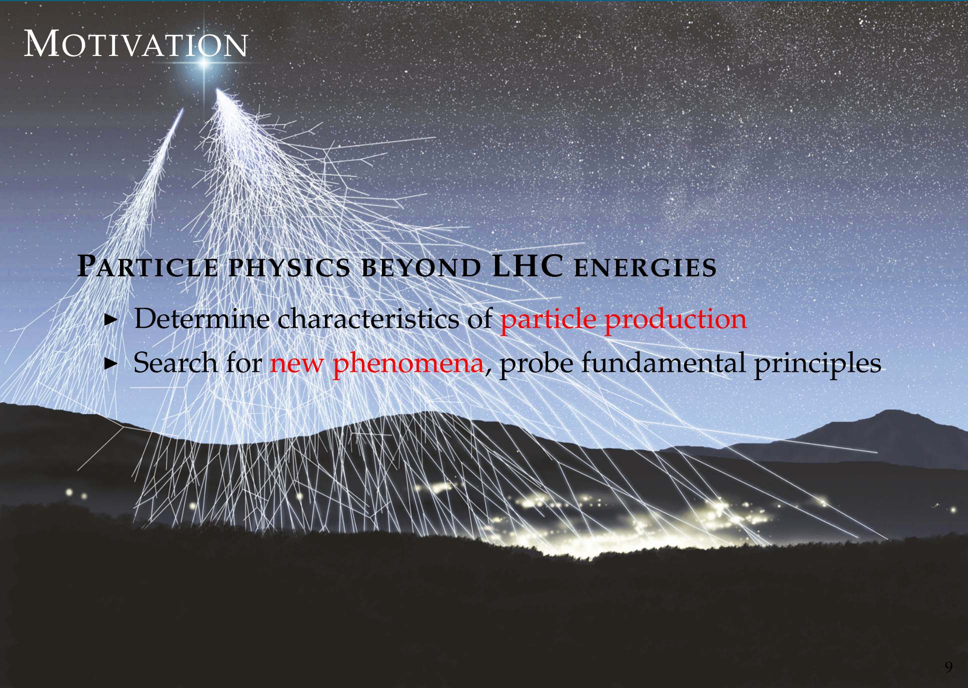
MOTIVATION



PROPAGATION OF ULTRA-HIGH ENERGY COSMIC RAYS

- Identify energy loss processes
- Determine strength of galactic and extra-galactic magnetic fields

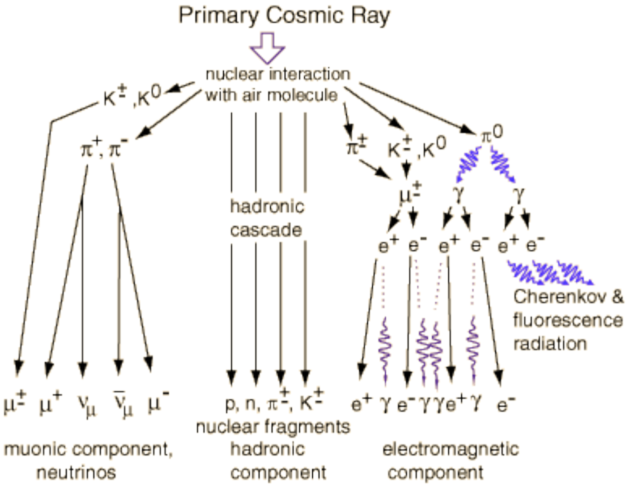
MOTIVATION



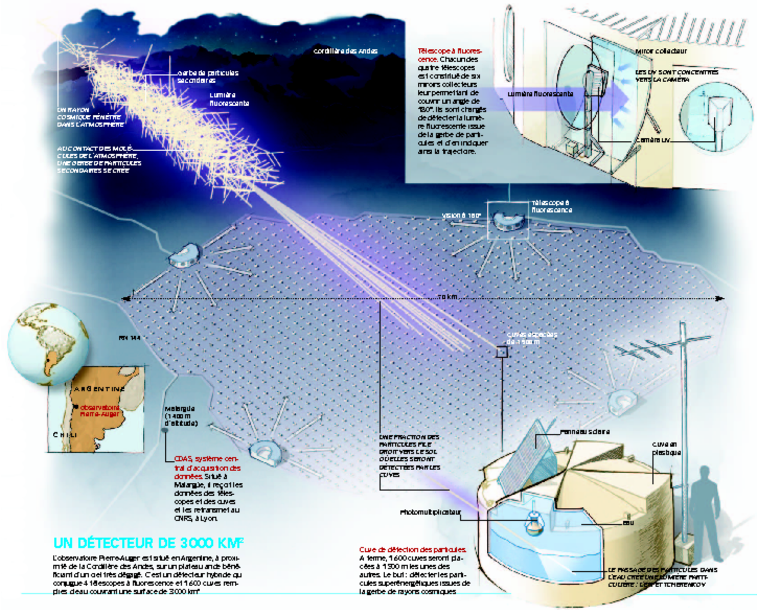
PARTICLE PHYSICS BEYOND LHC ENERGIES

- Determine characteristics of particle production
- Search for new phenomena, probe fundamental principles

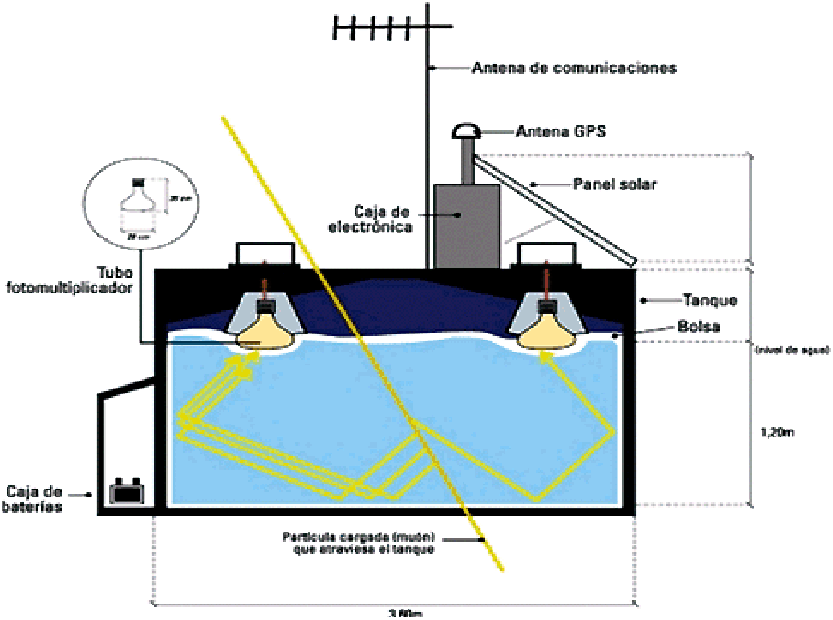
EXTENSIVE AIR SHOWERS



THE PIERRE AUGER OBSERVATORY



THE AUGER SURFACE DETECTOR



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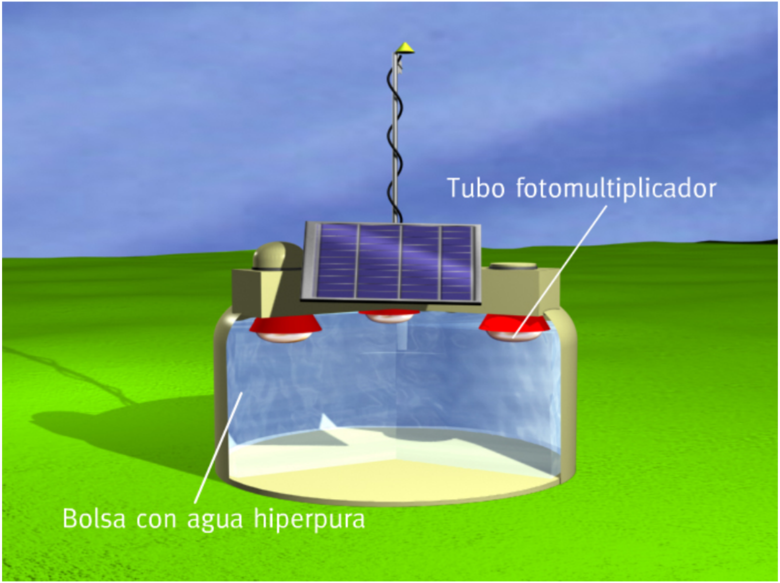

THE AUGER SURFACE DETECTOR

THE AUGER FLUORESCENCE DETECTOR

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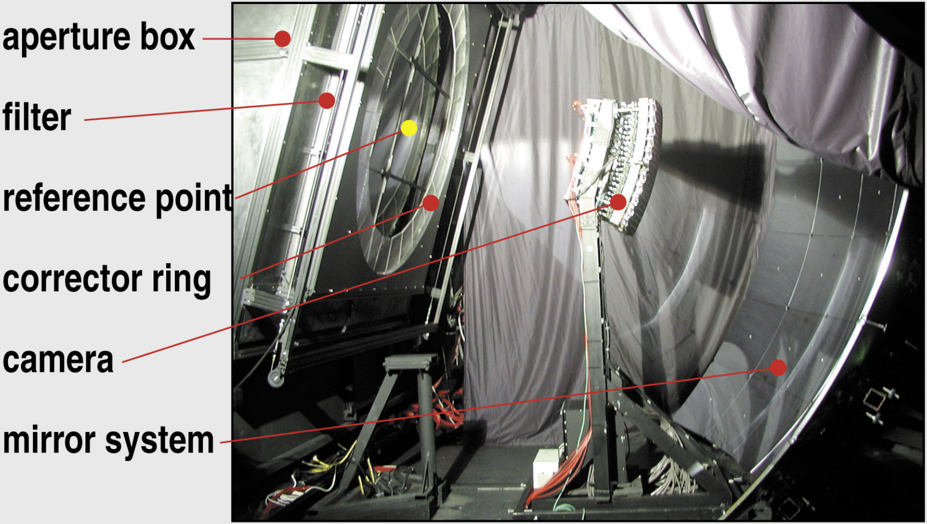

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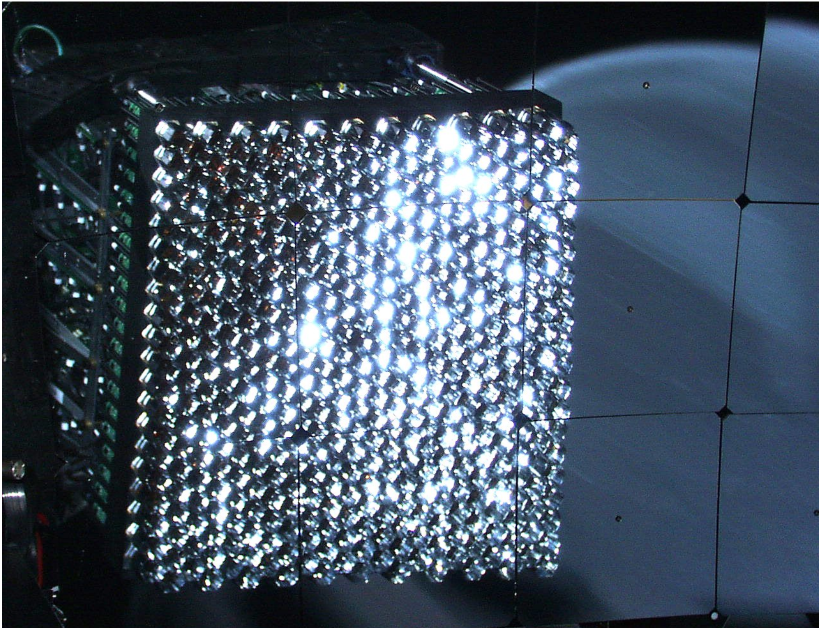
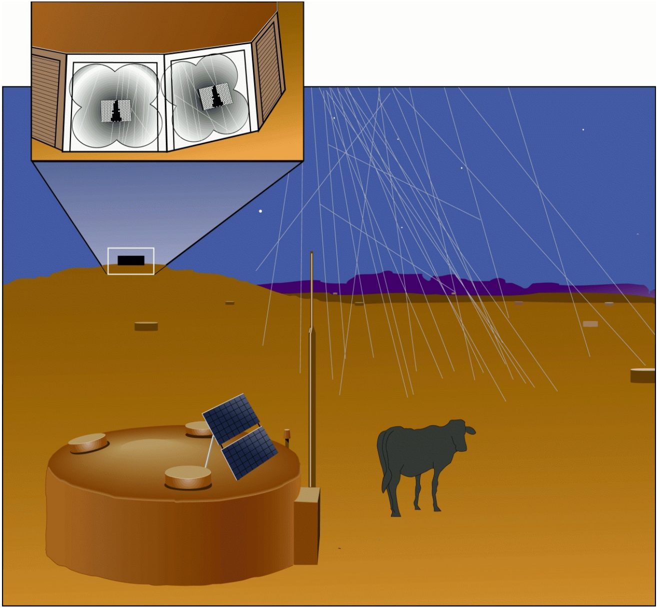


I HAD A HYBRID DREAM...



I HAD A HYBRID DREAM...

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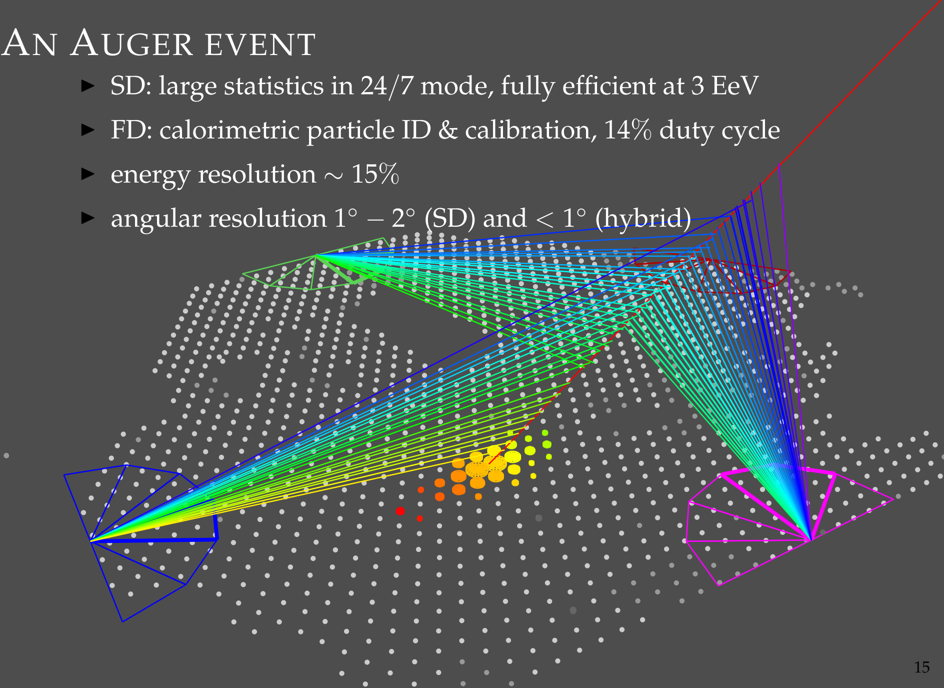
An Auger event

- SD: large statistics in 24/7 mode, fully efficient at 3 EeV
- FD: calorimetric particle ID & calibration, 14% duty cycle
- energy resolution $\sim 15\%$
- angular resolution $1^\circ - 2^\circ$ (SD) and $< 1^\circ$ (hybrid)



SIZE OF THE AUGER OBSERVATORY

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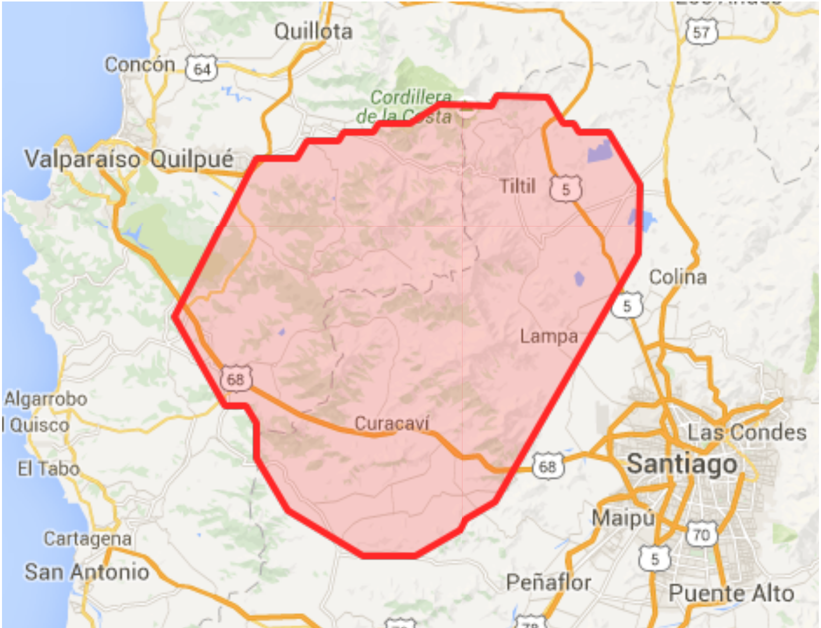

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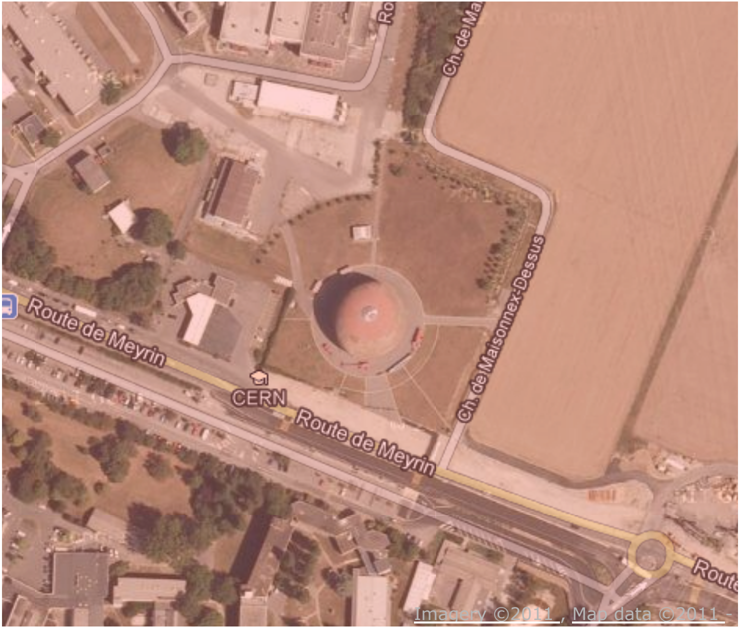

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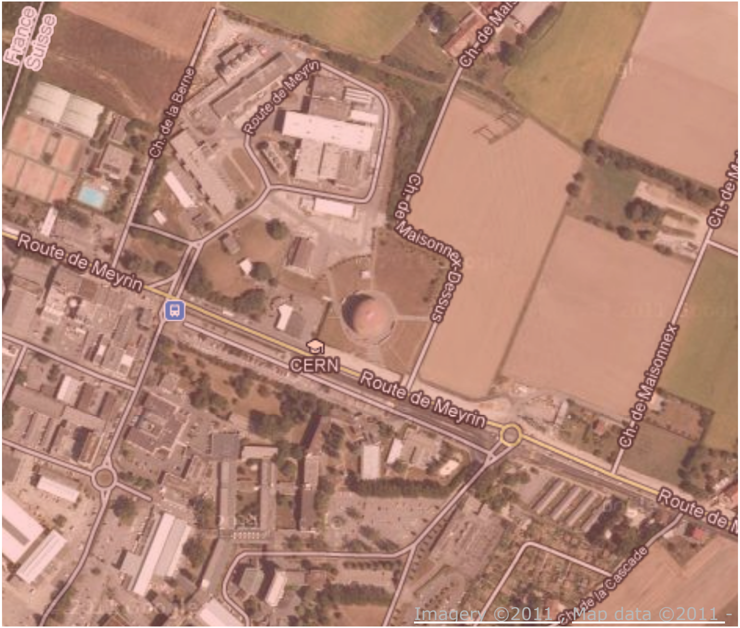

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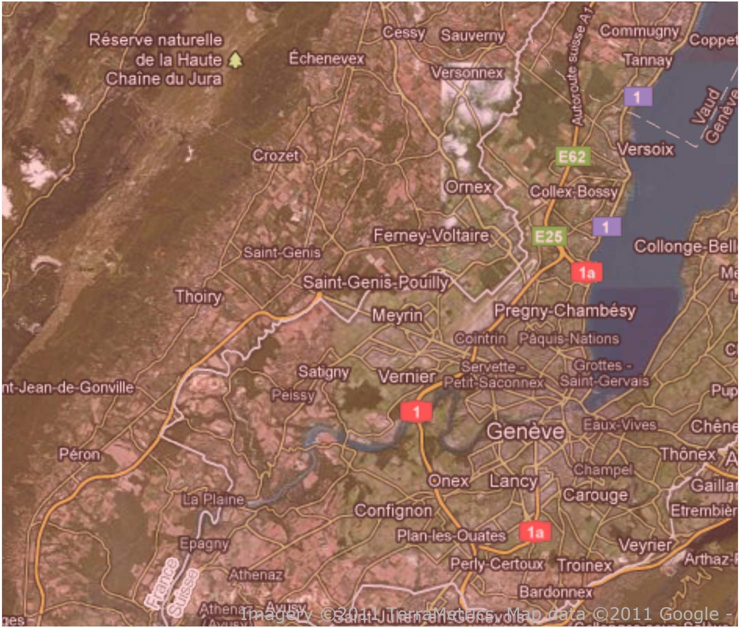

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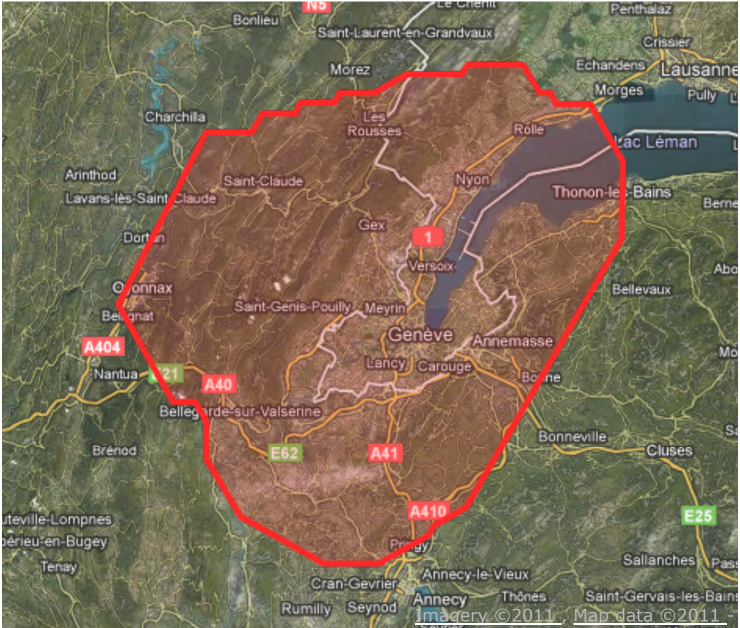
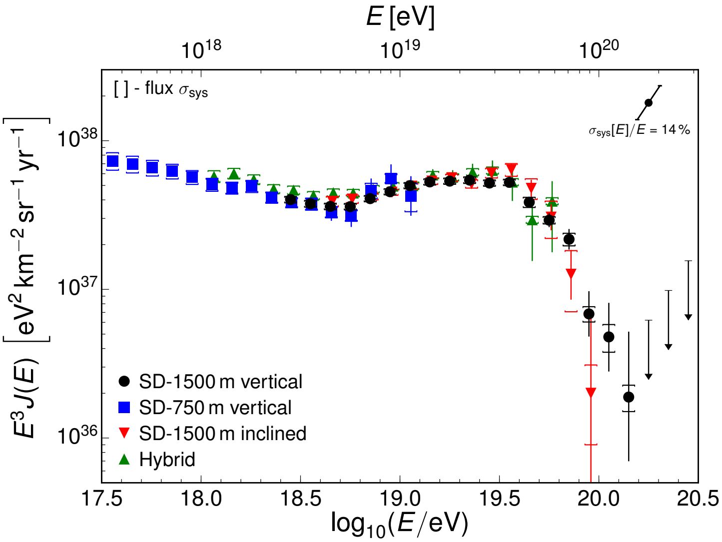


ENERGY SPECTRUM



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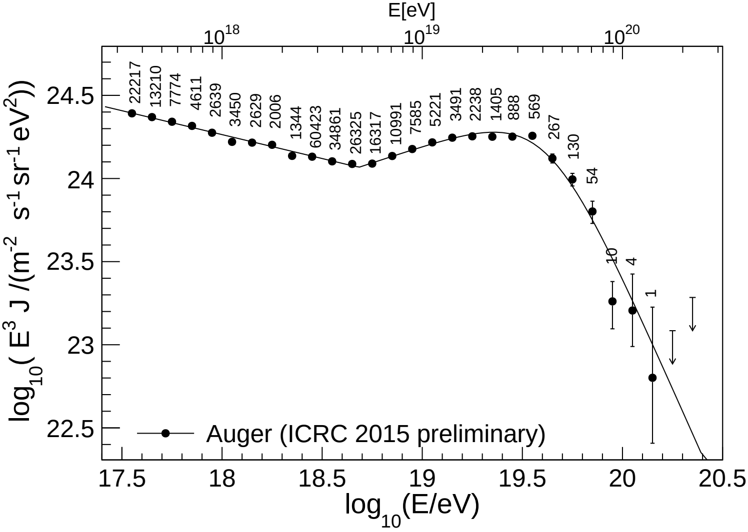
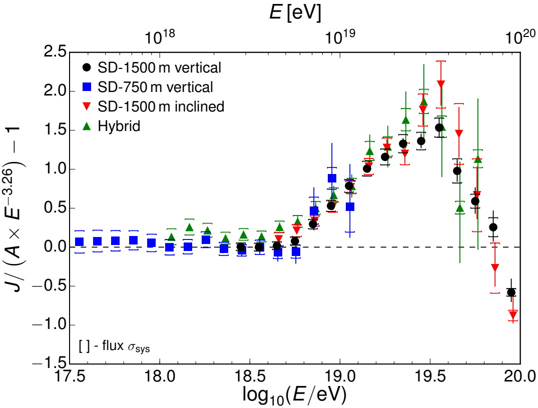


Inés Valiño, ICRC2015

TAKE HOME MESSAGE I

- total systematic uncertainty: 14% (energy scale)
- flux uncertainty: 6% (SD)



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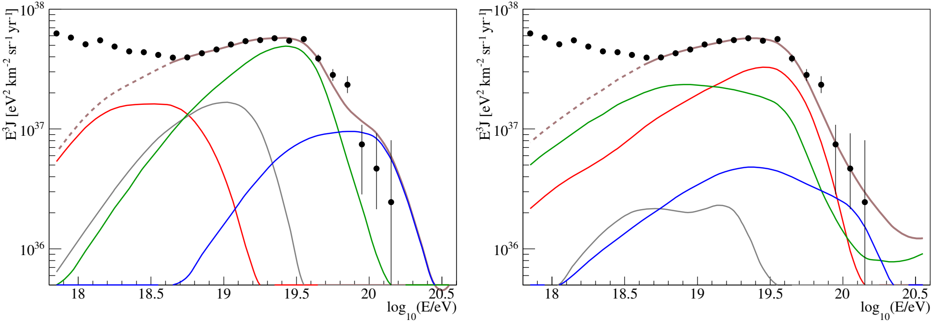
TAKE HOME MESSAGE II

- Many ways to fit the spectrum!



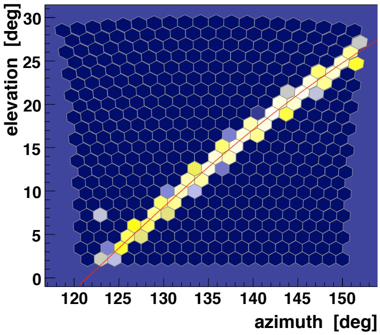
Partial spectra are grouped according to the mass number: $A = 1$ (red), $2 \leq A \leq 4$ (gray), $5 \leq A \leq 26$ (green), $27 \leq A$ (blue), and total (brown).

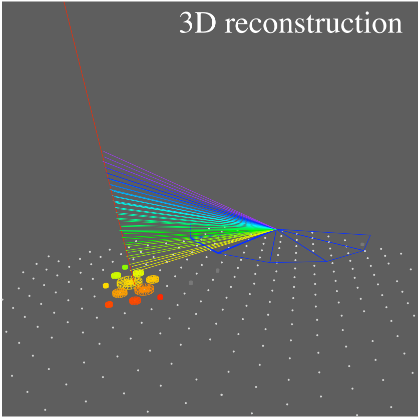
Armando di Matteo, ICRC2015

PRIMARY COMPOSITION

- Longitudinal profile information from FD

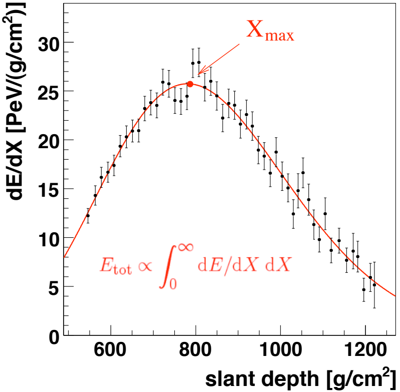
camera view

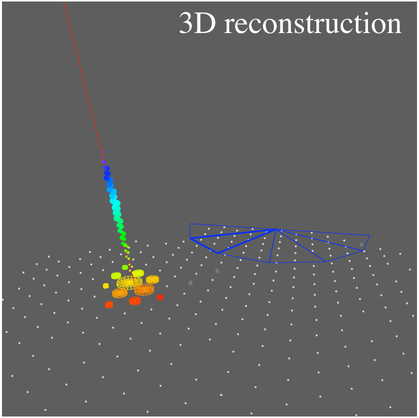




PRIMARY COMPOSITION

- Longitudinal profile information from FD

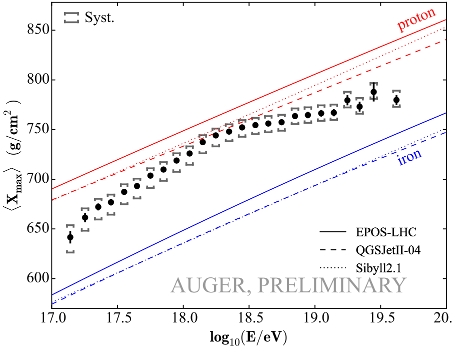




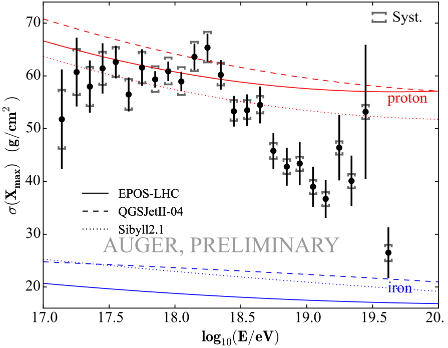
LONGITUDINAL SHOWER DEVELOPMENT

SHOWER MAXIMUM (X_{max}) CORRELATES WITH PRIMARY MASS

average



standard deviation



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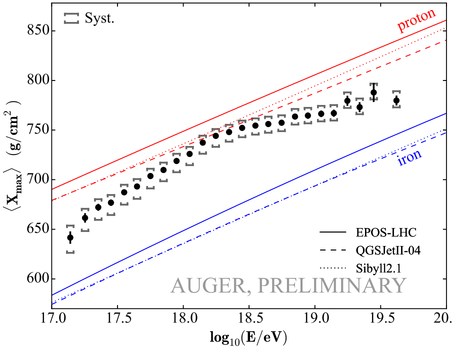
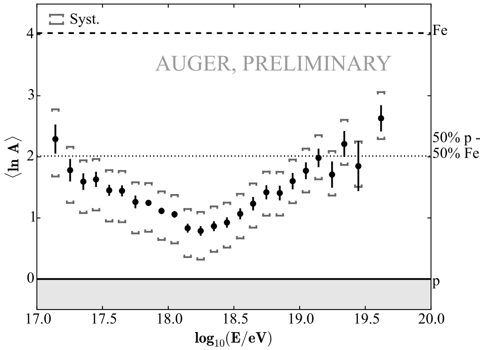


interpretation (EPOS-LHC)



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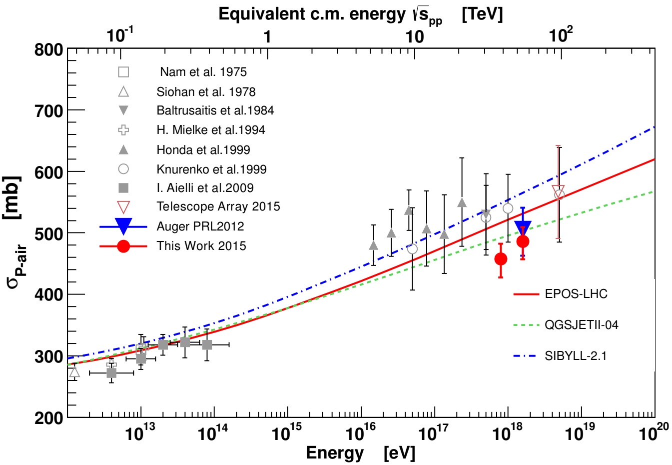
PROTON-AIR CROSS-SECTION

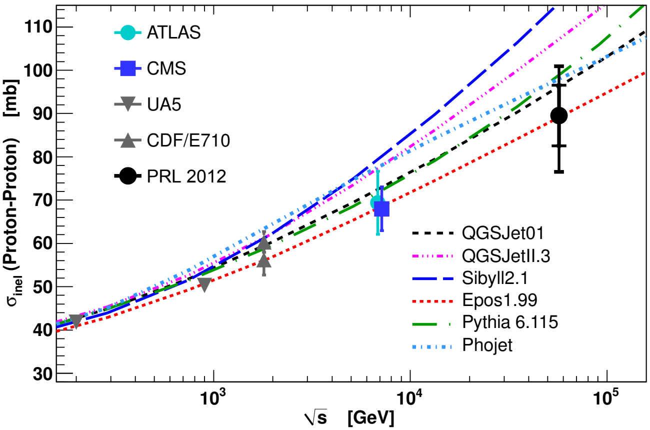


$$\sigma_{\mathbf{p}\text{-air}} = \left[\mathbf{458}\ \pm \mathbf{18}_{\text{stat}}\ \left({}^{+\mathbf{19}}_{-\mathbf{25}}\right)_{\text{sys}}\right]\ \text{mb} \qquad 10^{17.8}\ \text{eV} \leq \text{E} < 10^{18}\ \text{eV}$$

$$\sigma_{\mathbf{p}\text{-air}} = \left[\mathbf{486}\ \pm \mathbf{16}_{\text{stat}}\ \left({}^{+\mathbf{19}}_{-\mathbf{25}}\right)_{\text{sys}}\right]\ \text{mb} \qquad 10^{18}\ \text{eV} \leq \text{E} < 10^{18.5}\ \text{eV}$$

INELASTIC PROTON-PROTON CROSS-SECTION

STANDARD GLAUBER CONVERSION + PROPAGATION OF MODELING UNC.

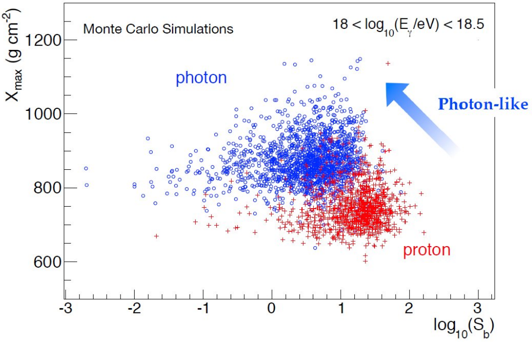


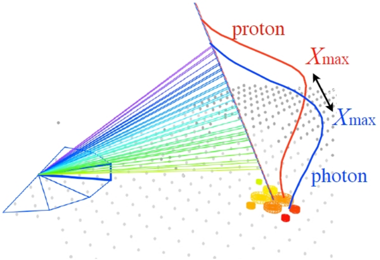
$$\sigma_{pp}^{inel}\left(\sqrt{s} = [57 \pm 6]\ \text{TeV}\right) = \left[92 \pm 7_{stat}\ \left({}^{+9}_{-11}\right)_{sys} \pm 7_{Glauber}\right]\ \text{mb}$$

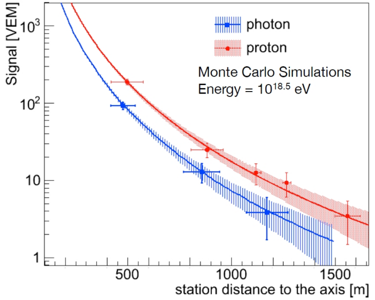
Phys. Rev. Lett. 109, 062002 (2012)

UHE PHOTON LIMITS

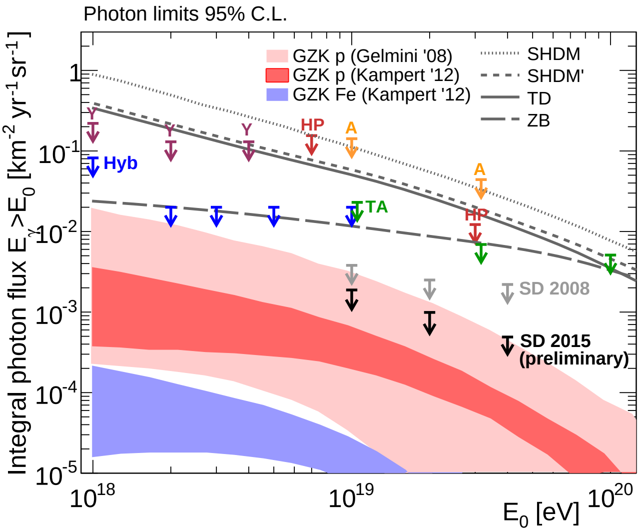
PRINCIPAL COMPONENT ANALYSIS





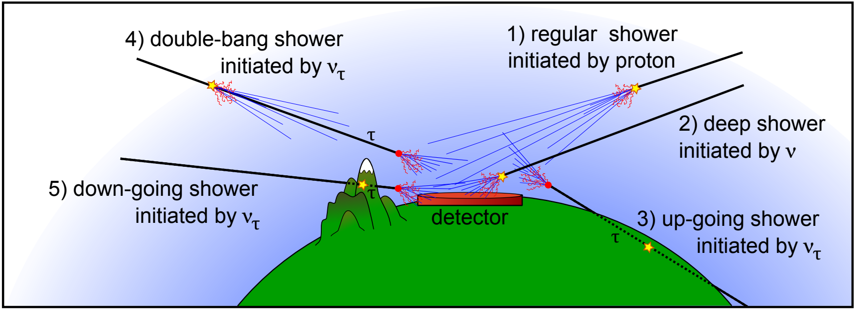


PHOTON FLUX LIMITS



UHE NEUTRINO SEARCHES

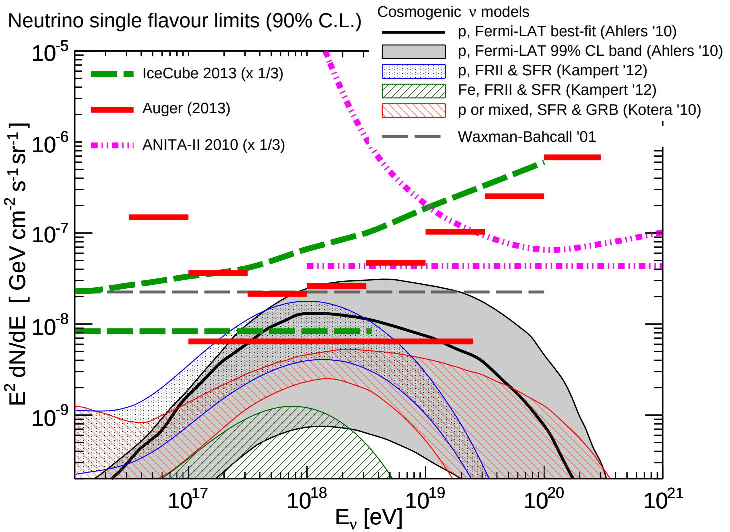
VERY INCLINED SHOWERS



Search for:

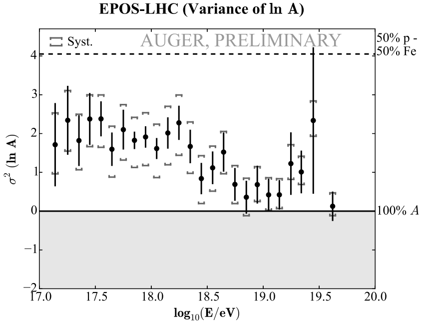
- up-going (Earth skimming) showers
- down-going deep showers

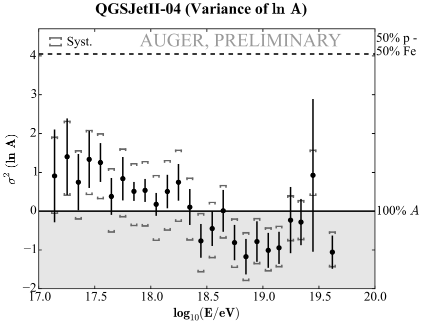
DIFFUSE NEUTRINO LIMITS



TAKE HOME MESSAGE III

- new method to extend composition measurement
- mass *interpretation* is model dependent
- cross section measurement beyond LHC energies





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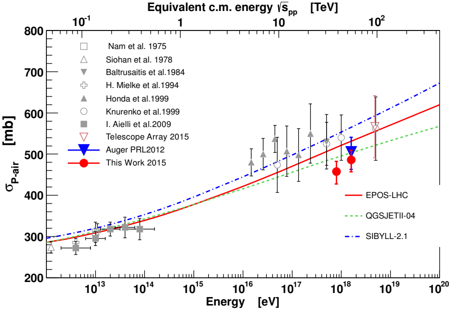
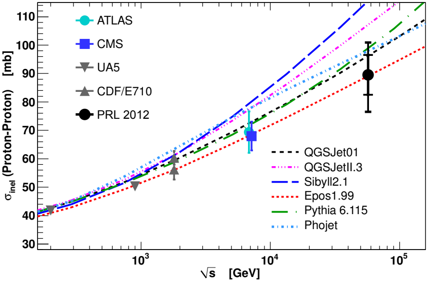
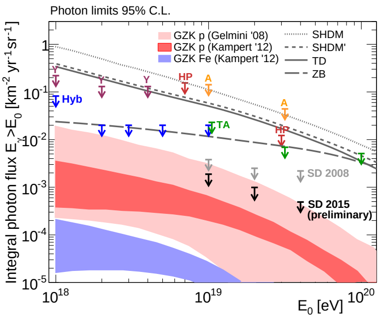
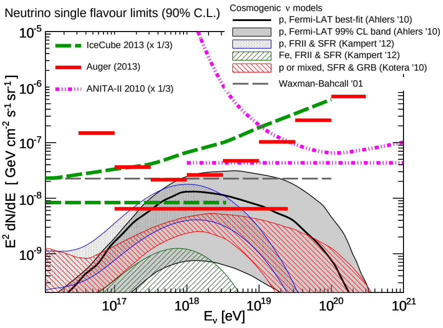




TAKE HOME MESSAGE IV

- updated limits closing on GZK predictions
- competitive limit to UHE neutrino diffuse flux
- sensitivity to point sources

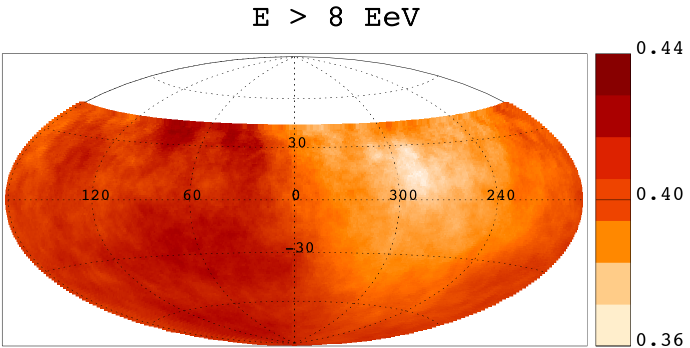




LARGE SCALE ANISOTROPY

DIPOLE SEARCHES

- largest departure from isotropy above 8 EeV with a $(4 \pm 1)\%$ amplitude in the first harmonic in RA
- phase transition from 270° to 90° at $\sim$1 EeV



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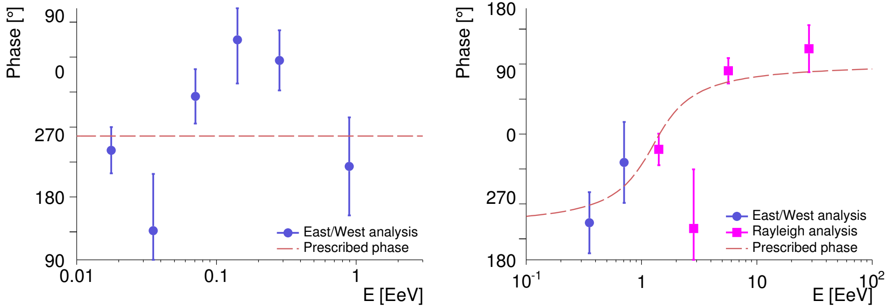


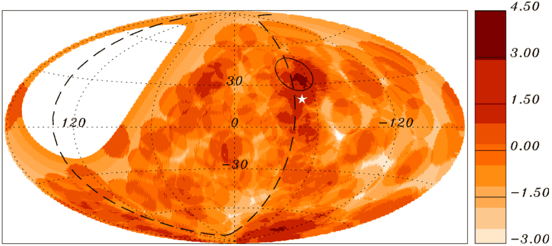
Imen Al Samarai, ICRC2015

SMALL SCALE ANISOTROPY

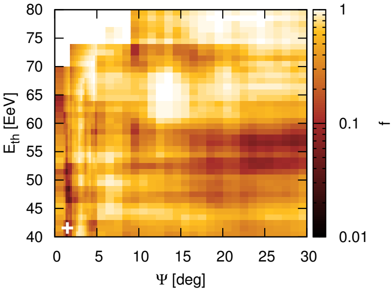
INTRINSIC SEARCHES

- Search for a localized excess flux
- Autocorrelation of events

Blind search



Auto-correlation



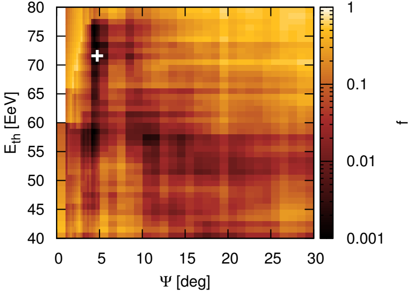
Julien Aublin, ICRC2015

SMALL SCALE ANISOTROPY

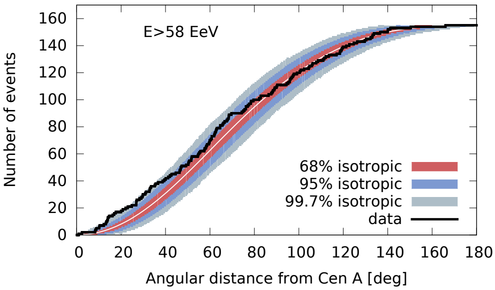
CROSS-CORRELATIONS WITH ASTROPHYSICAL SOURCES

- Cross-correlation with flux-limited catalogs
- Cross-correlation with bright AGNs
- The Cen A region

Radio galaxies with jets



Cen A region

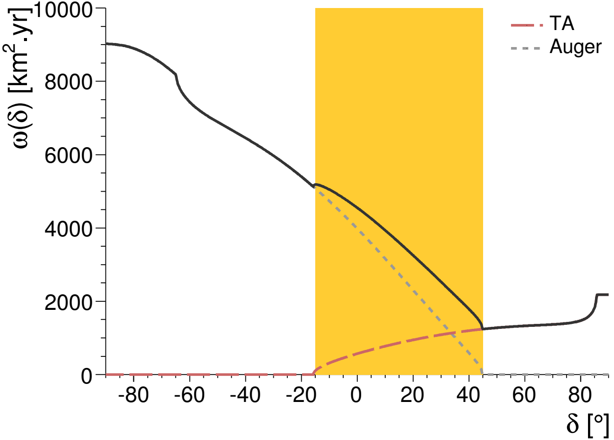


Julien Aublin, ICRC2015

JOINT STUDIES

LARGE SCALE ANISOTROPY

- Combine Auger and Telescope Array data
- Dipole above 10^{19} eV with amplitude $(6 \pm 2)\%$



Olivier Deligny, ICRC2015

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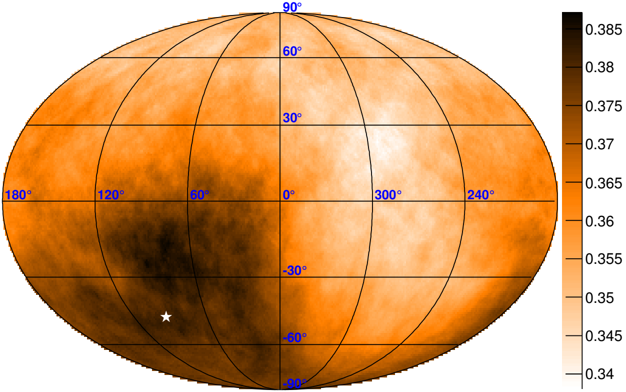
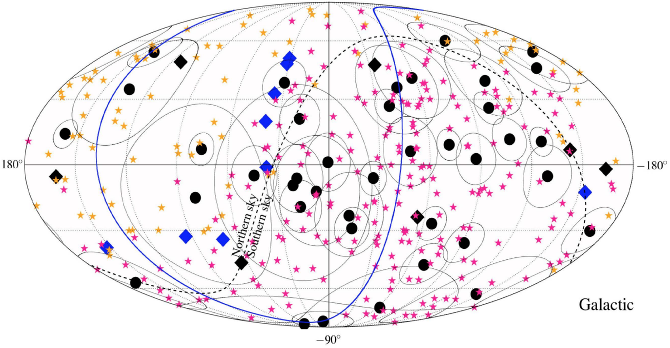


Olivier Deligny, ICRC2015

MULTI-MESSENGER STUDIES

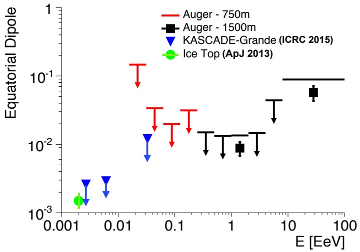
CROSS-CORRELATION BETWEEN ν'S AND UHECRS

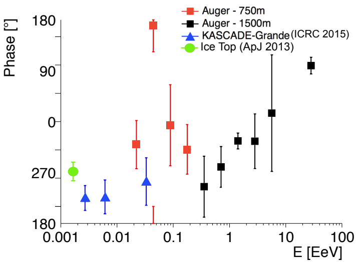
- First joint IceCube/Auger/Telescope Array analysis.
- Three a posteriori cross-correlation tests.
- Potentially interesting result with high-energy cascades.



arXiv:1511.09408, Accepted for publication in JCAP

TAKE HOME MESSAGE V





- percent-level amplitudes in dipole searches
- possible phase transition around the "ankle" energy
  - exploit lower energy data
- hints of small-scale anisotropy only above $\sim$ 50 EeV
- joint and multi-messenger analysis

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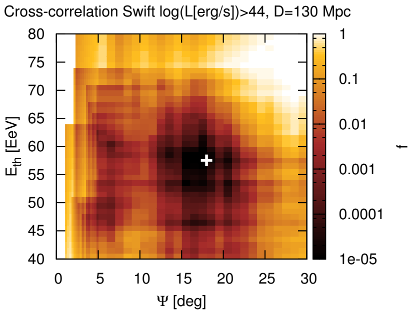

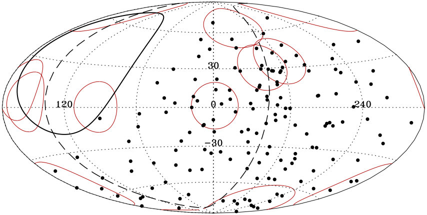

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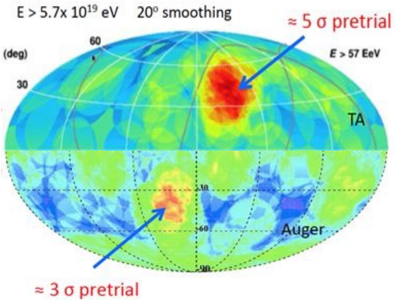

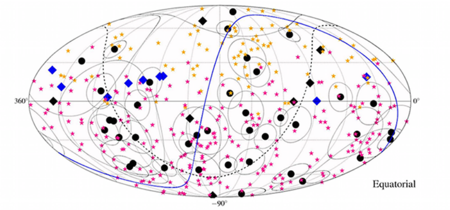

- percent-level amplitudes in dipole searches
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  - exploit lower energy data
- hints of small-scale anisotropy only above ~ 50 EeV
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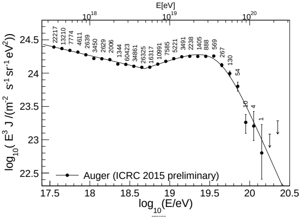
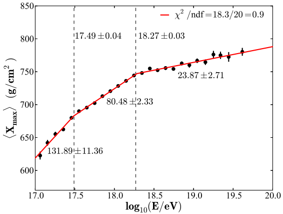
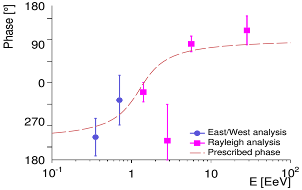
CONCLUSIONS

- ENERGY SPECTRUM
  - improved statistics over 3 orders of magnitude
  - good agreement on spectral features
- PRIMARY MASS
  - no clear picture above ~ 40 EeV
  - $p-$air and $p-p$ cross section at $\sqrt{s} = 57$ TeV
  - photon and neutrino limits start probing GZK limits
- ARRIVAL DIRECTIONS
  - hints of small-scale anisotropy at the highest energies
  - no candidate source identified
  - interesting modulation in RA

CONCLUSIONS SUMMARY







THANK YOU VERY MUCH!