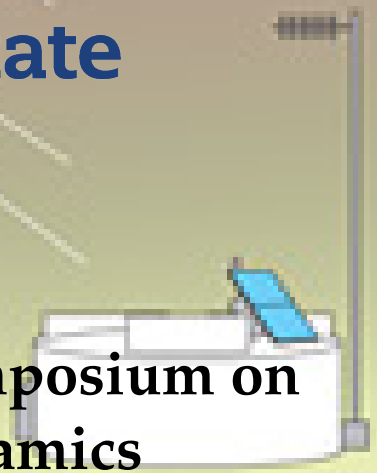
ON THE DETECTION OF THE HIGHEST ENERGY PARTICLES IN THE UNIVERSE WITH THE PIERRE AUGER OBSERVATORY

Miguel A. Mostafá

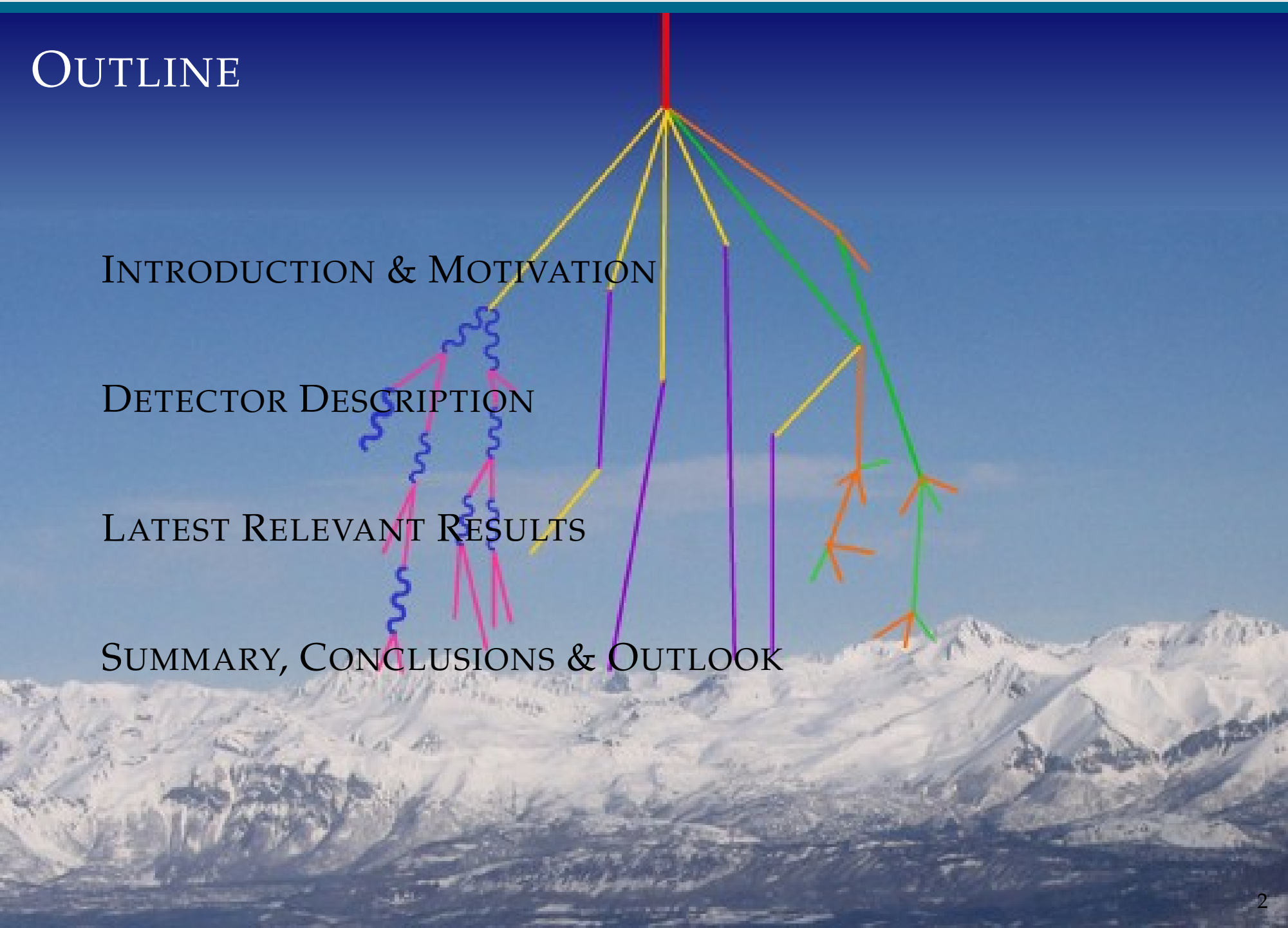
PennState



XLVII International Symposium on Multiparticle Dynamics

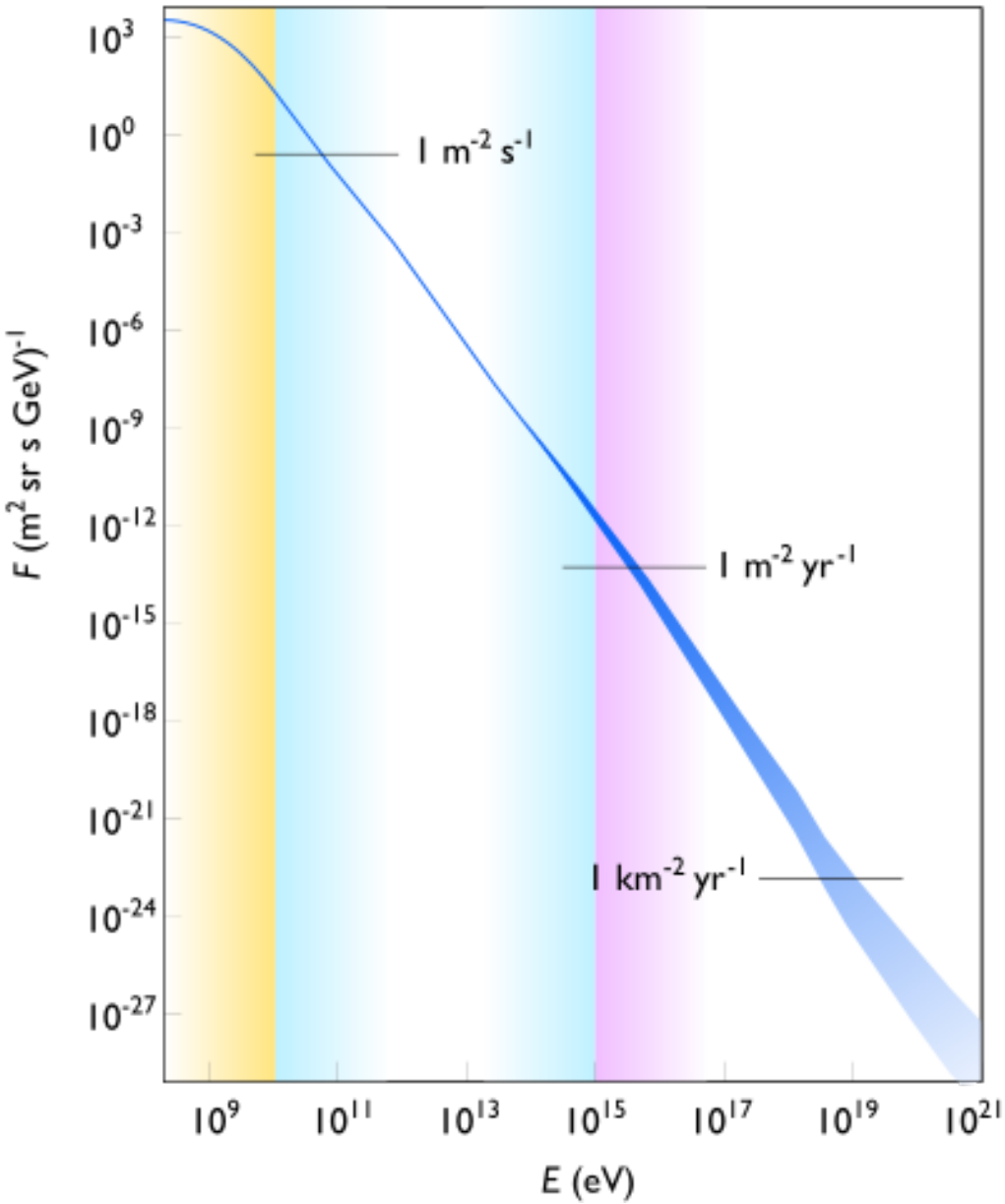
Tlaxcala, Mexico — September 11 – 15, 2017

Outline



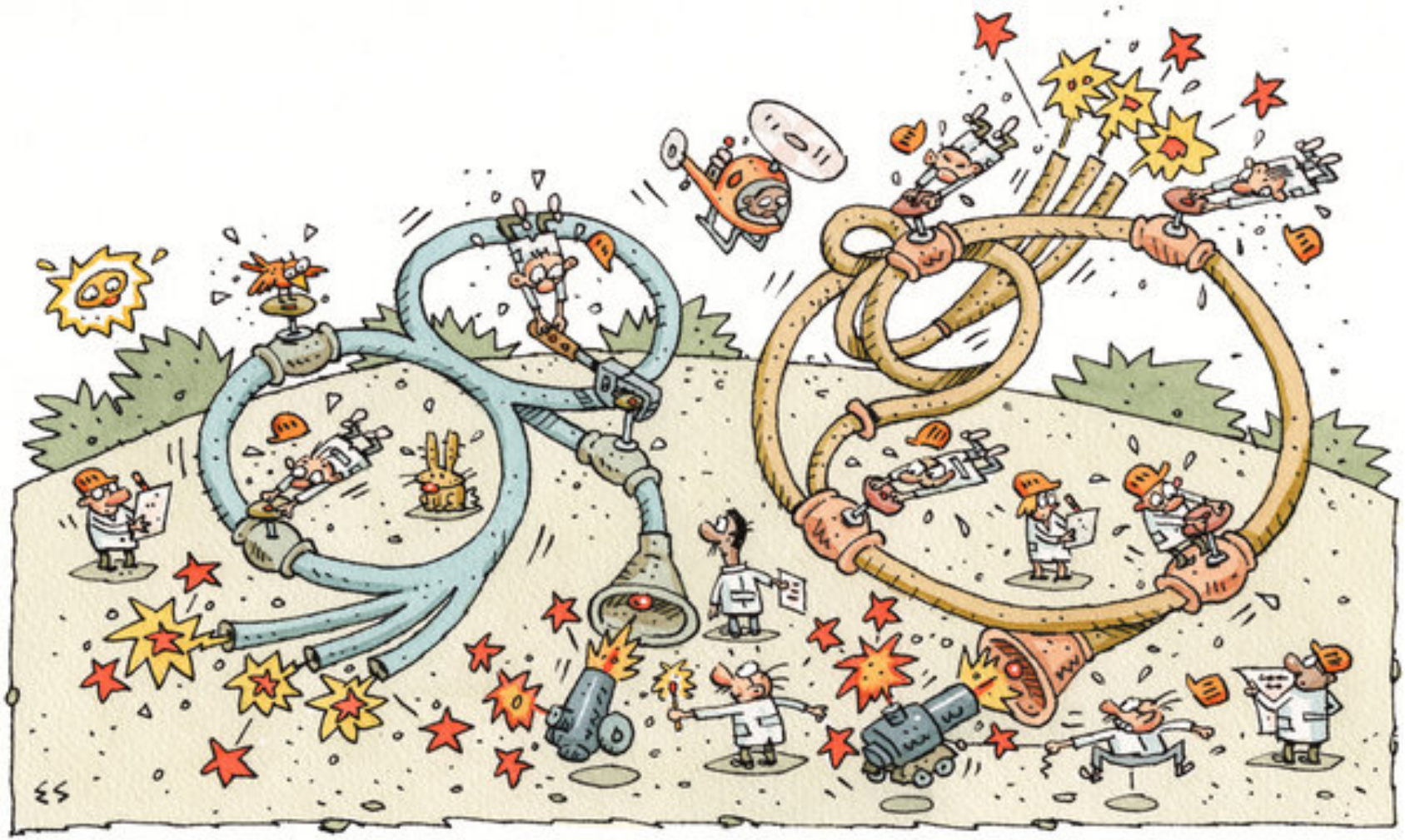
- Introduction & Motivation
- Detector Description
- Latest Relevant Results
- Summary, Conclusions & Outlook

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

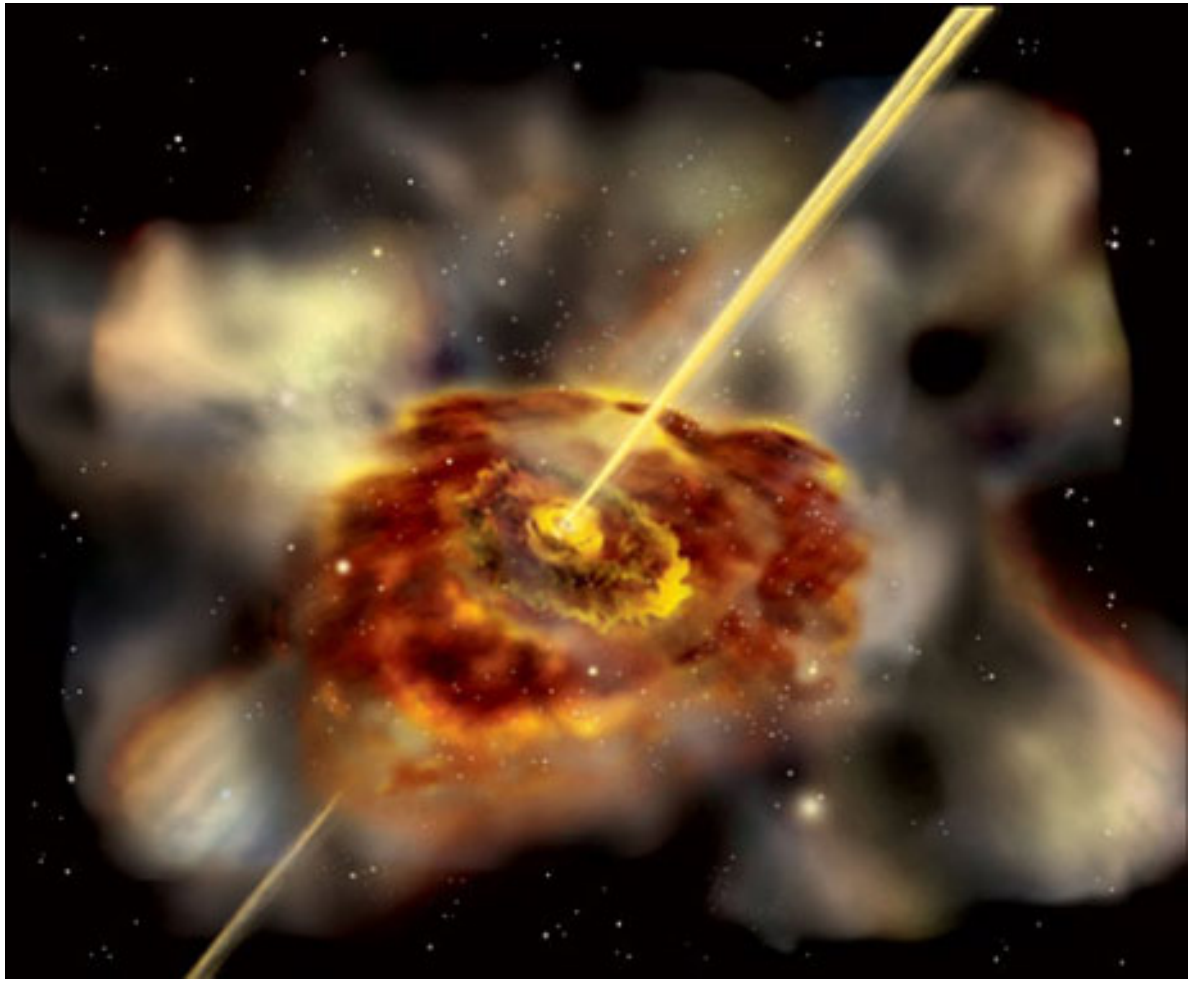


Image courtesy NASA E/PO, Sonoma State University, Aurore Simonnet

Published in National Geographic News on November 8, 2007

Black Holes Belch Universe's Most Energetic Particles

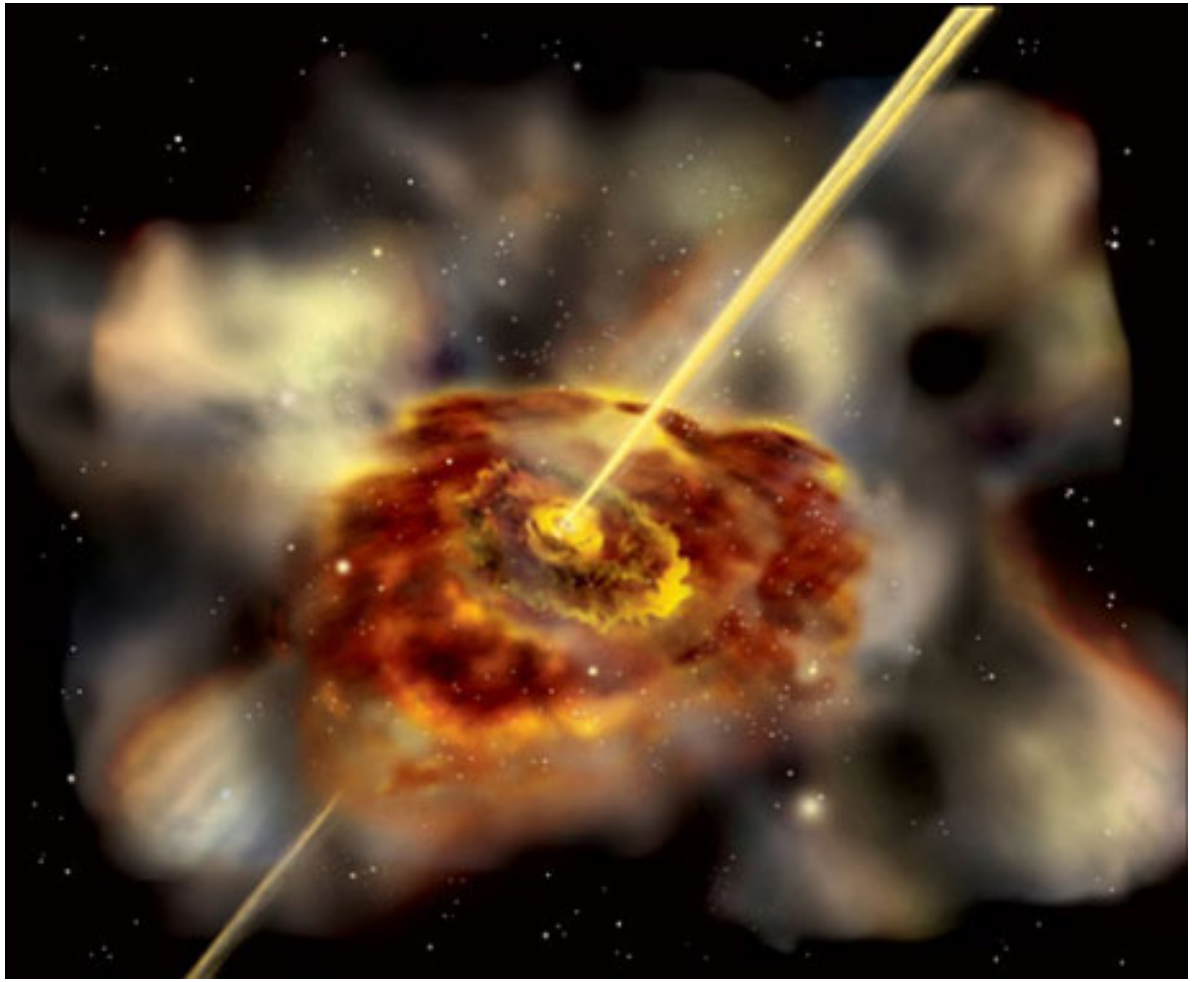
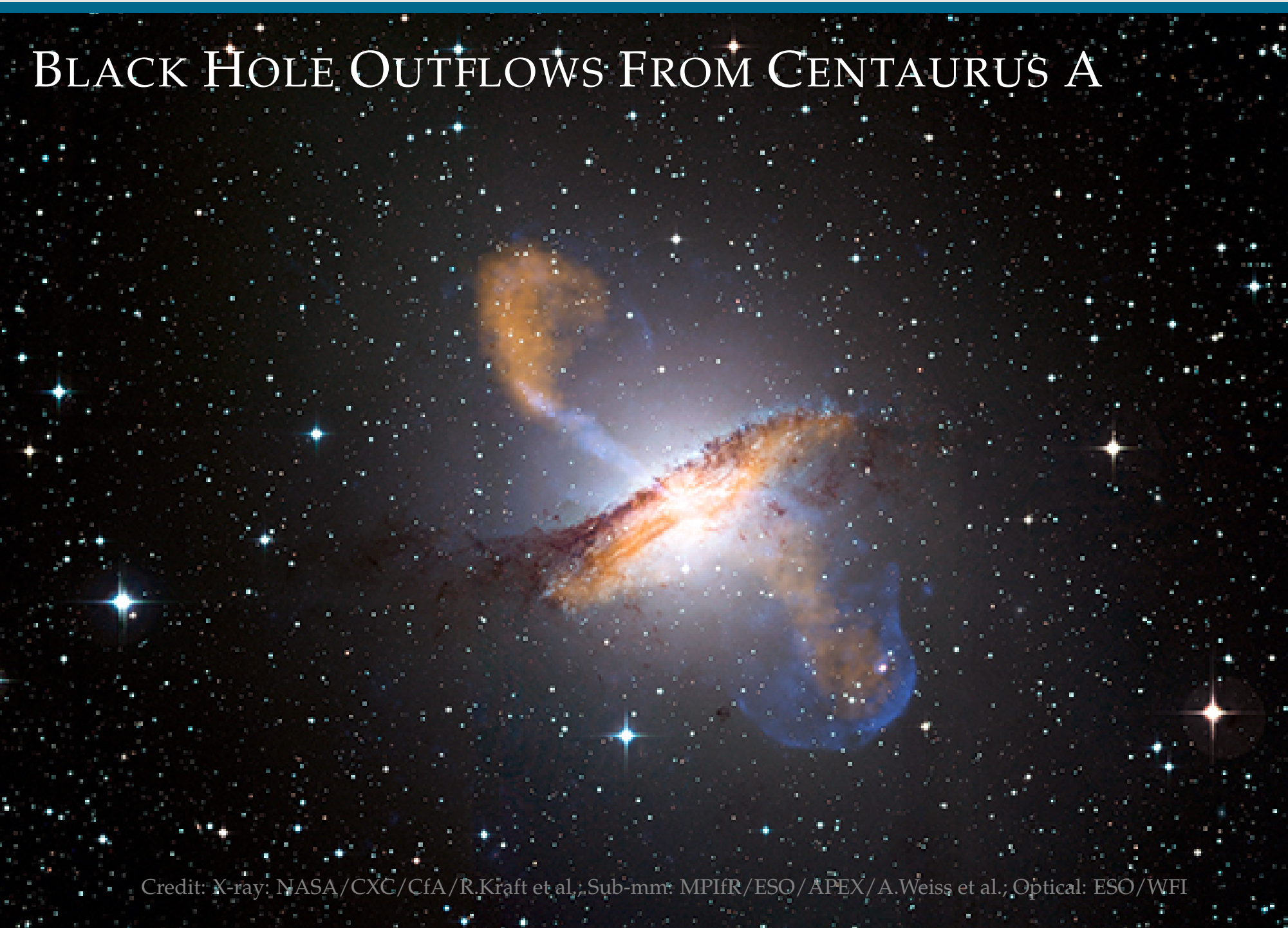


Image courtesy NASA E/PO, Sonoma State University, Aurore Simonnet

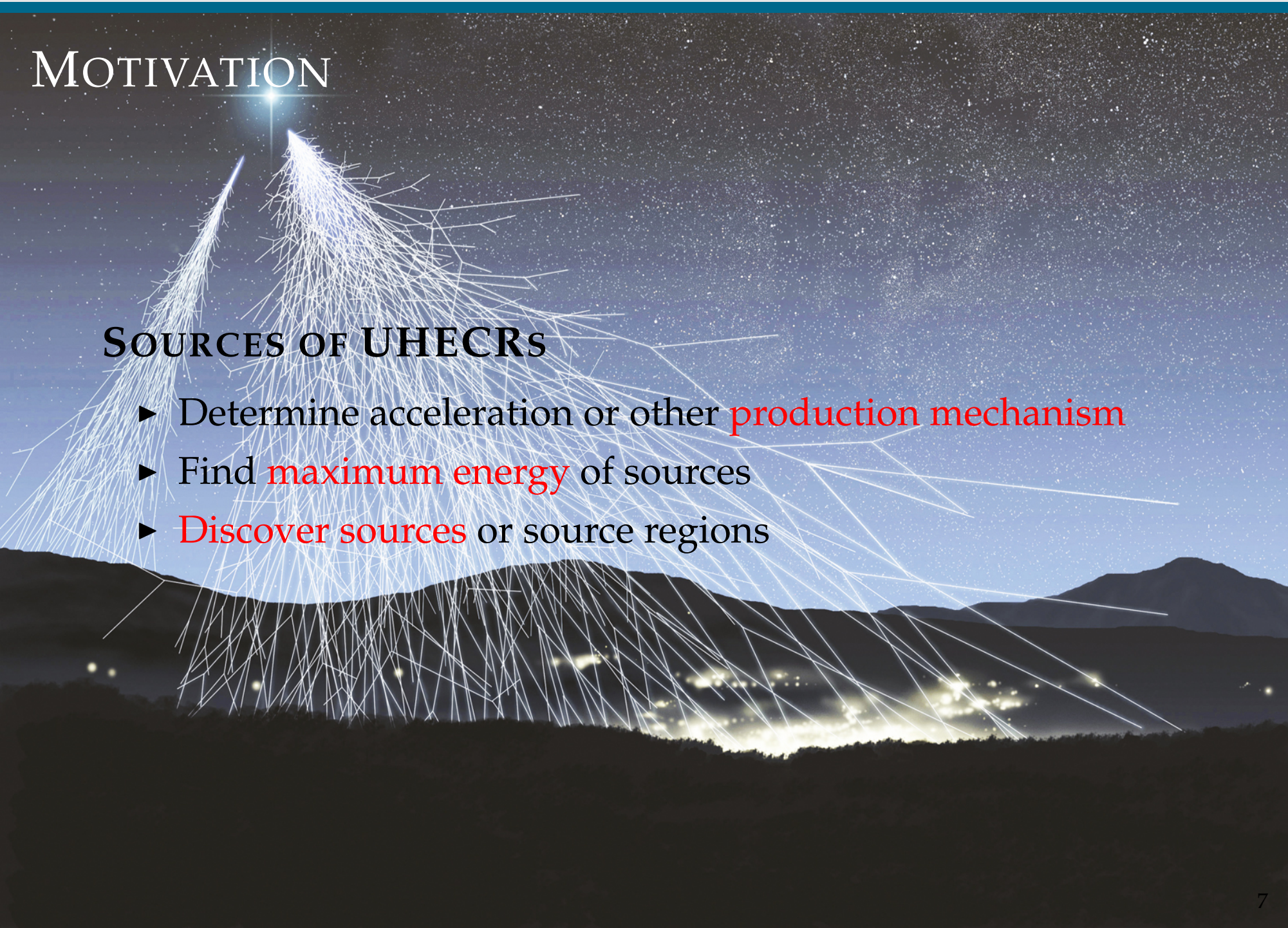
Published in National Geographic News on November 8, 2007
"We discovered the sources of the highest-energy particles in the universe," said team member Miguel Mostafa...

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

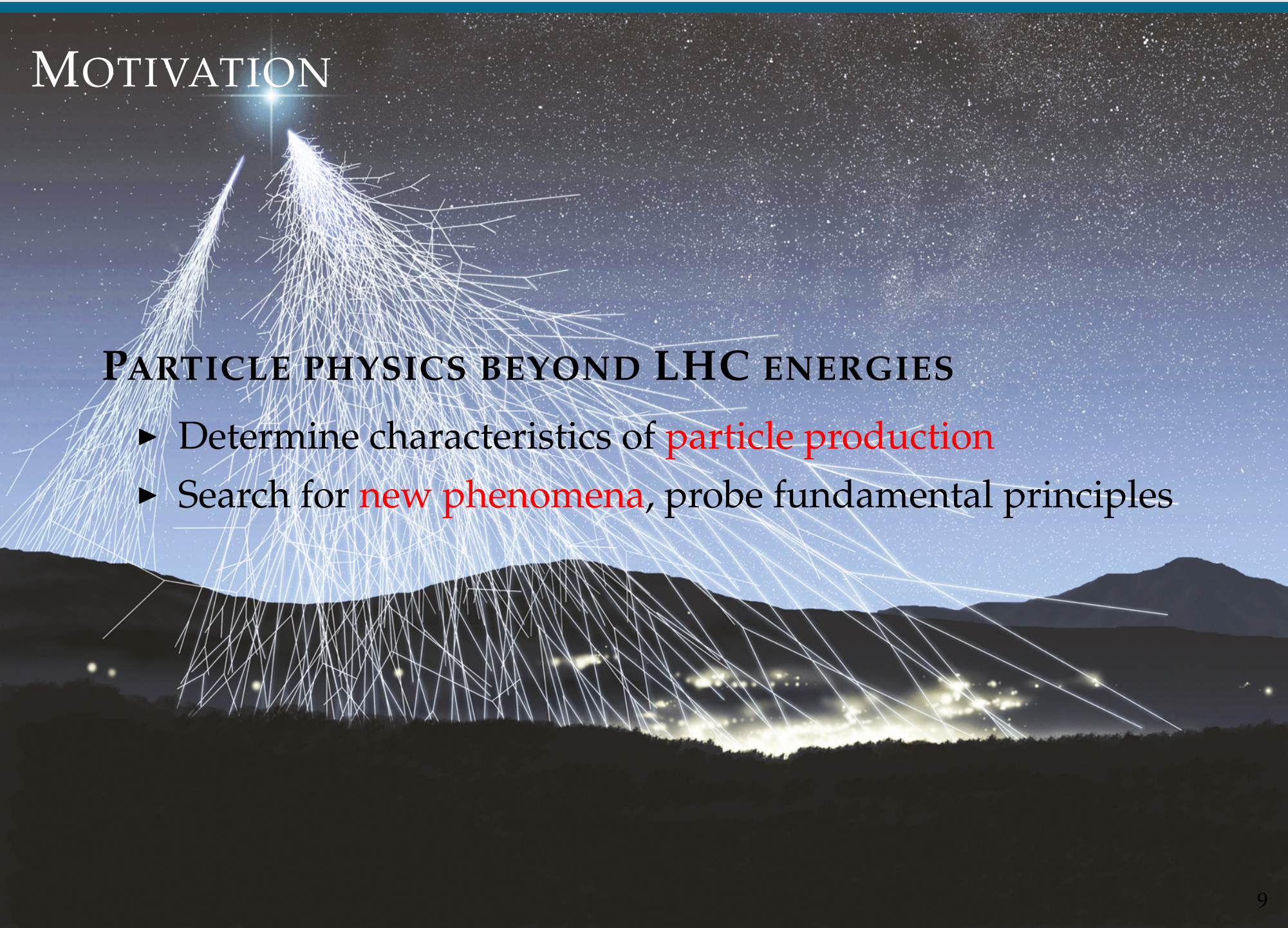
- Determine acceleration or other production mechanism
- Find maximum energy of sources
- Discover sources or source regions

MOTIVATION

PROPAGATION OF ULTRA-HIGH ENERGY COSMIC RAYS

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

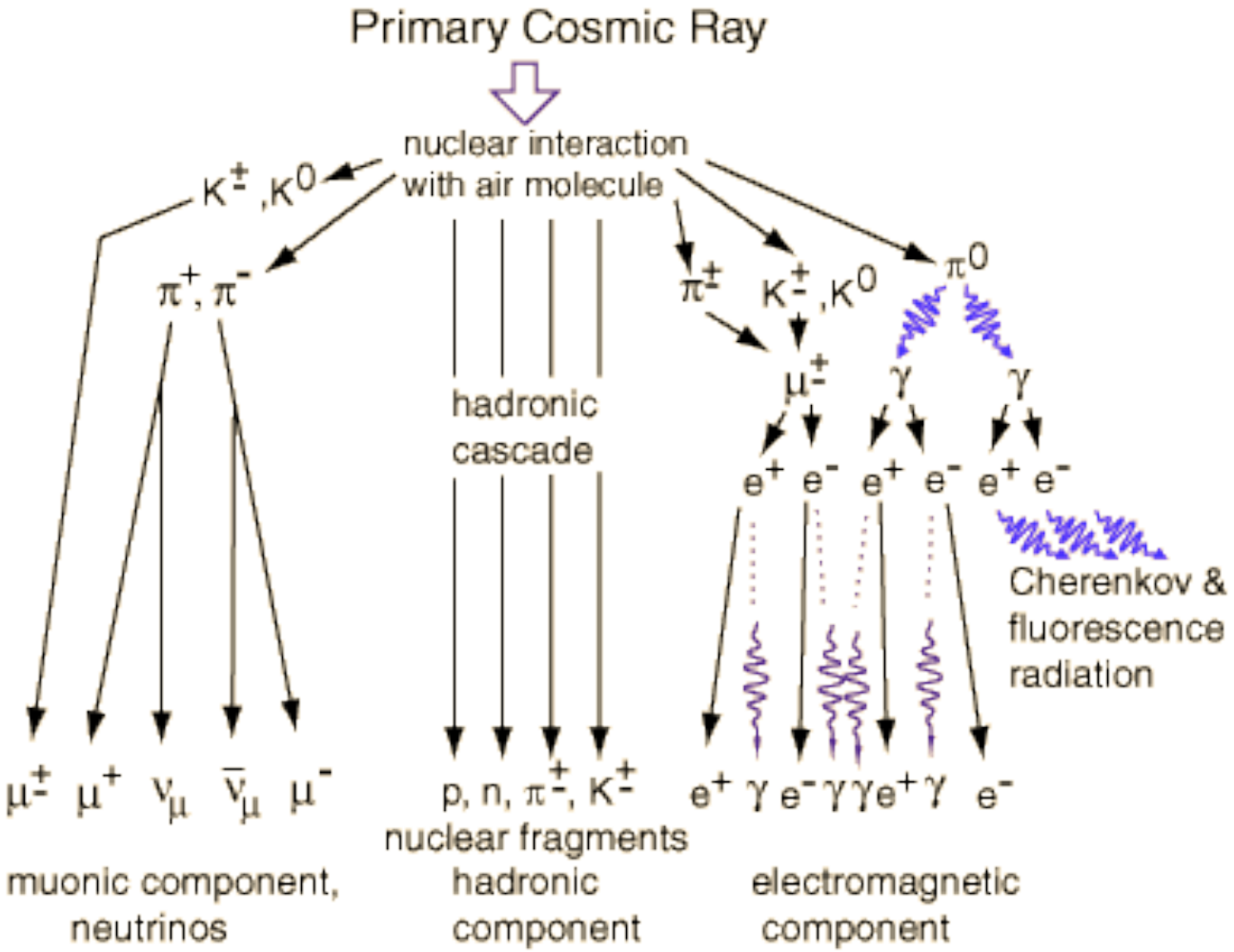
MOTIVATION



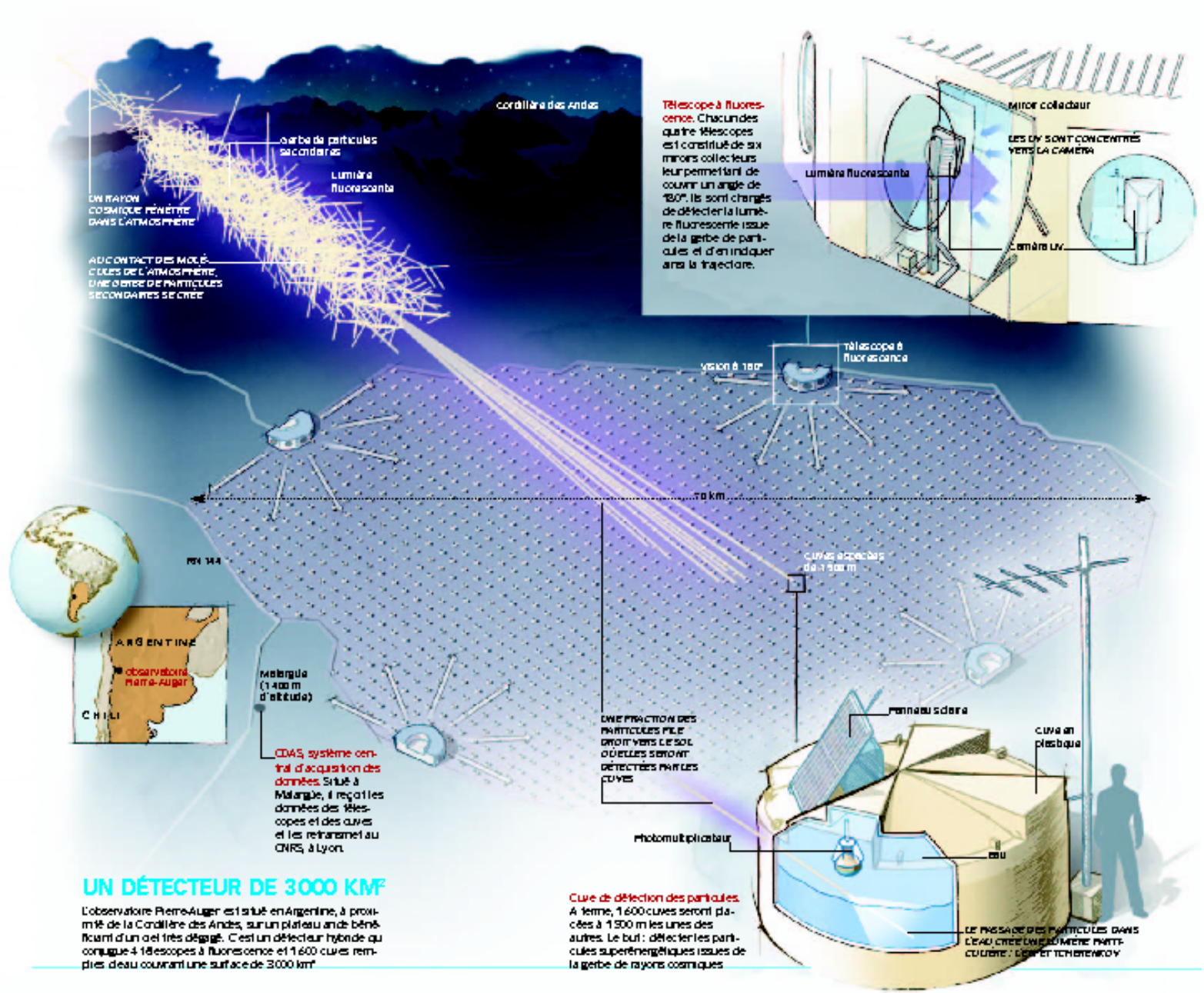
PARTICLE PHYSICS BEYOND LHC ENERGIES

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

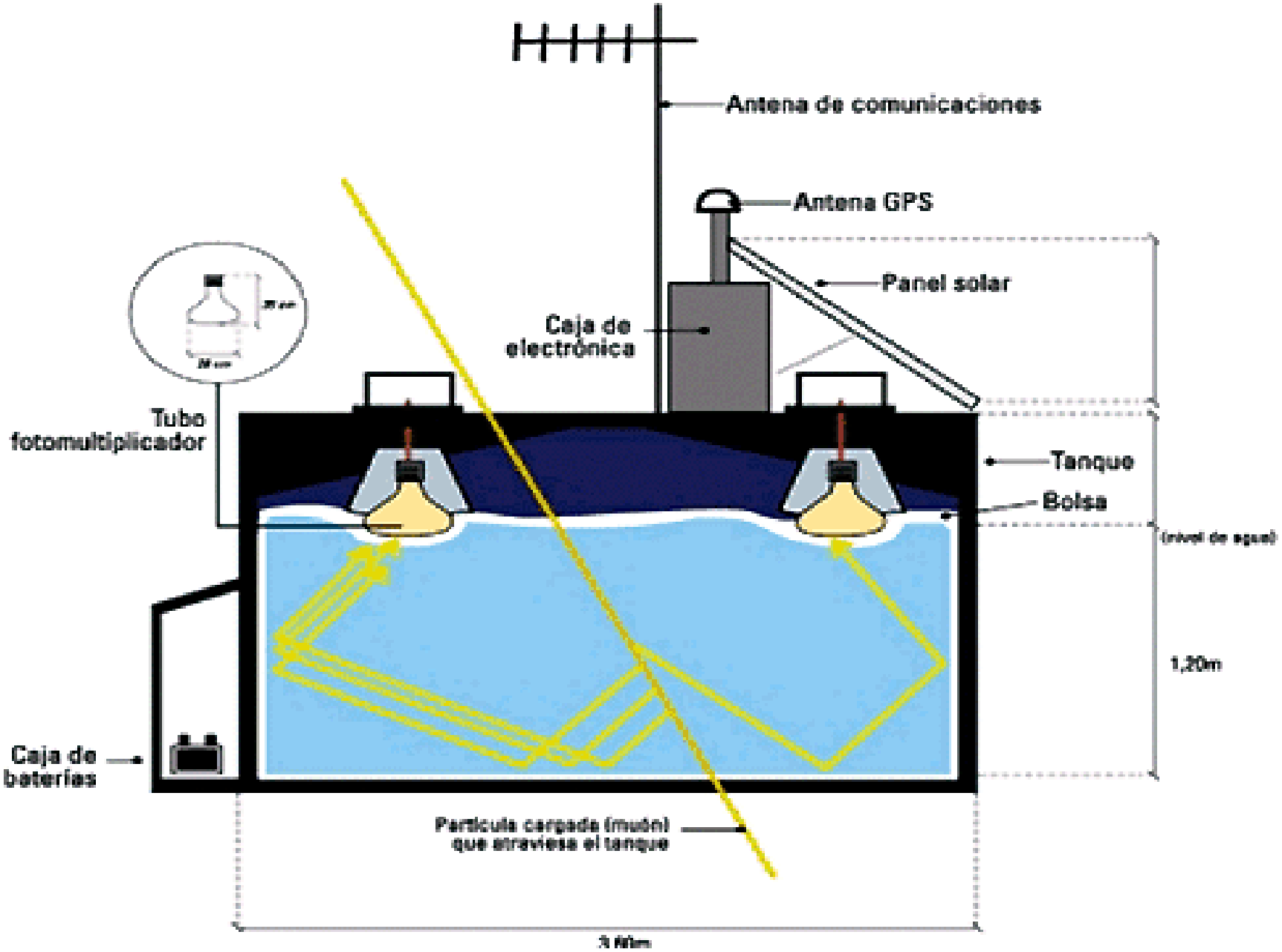
EXTENSIVE AIR SHOWERS



THE PIERRE AUGER OBSERVATORY



THE AUGER SURFACE DETECTOR



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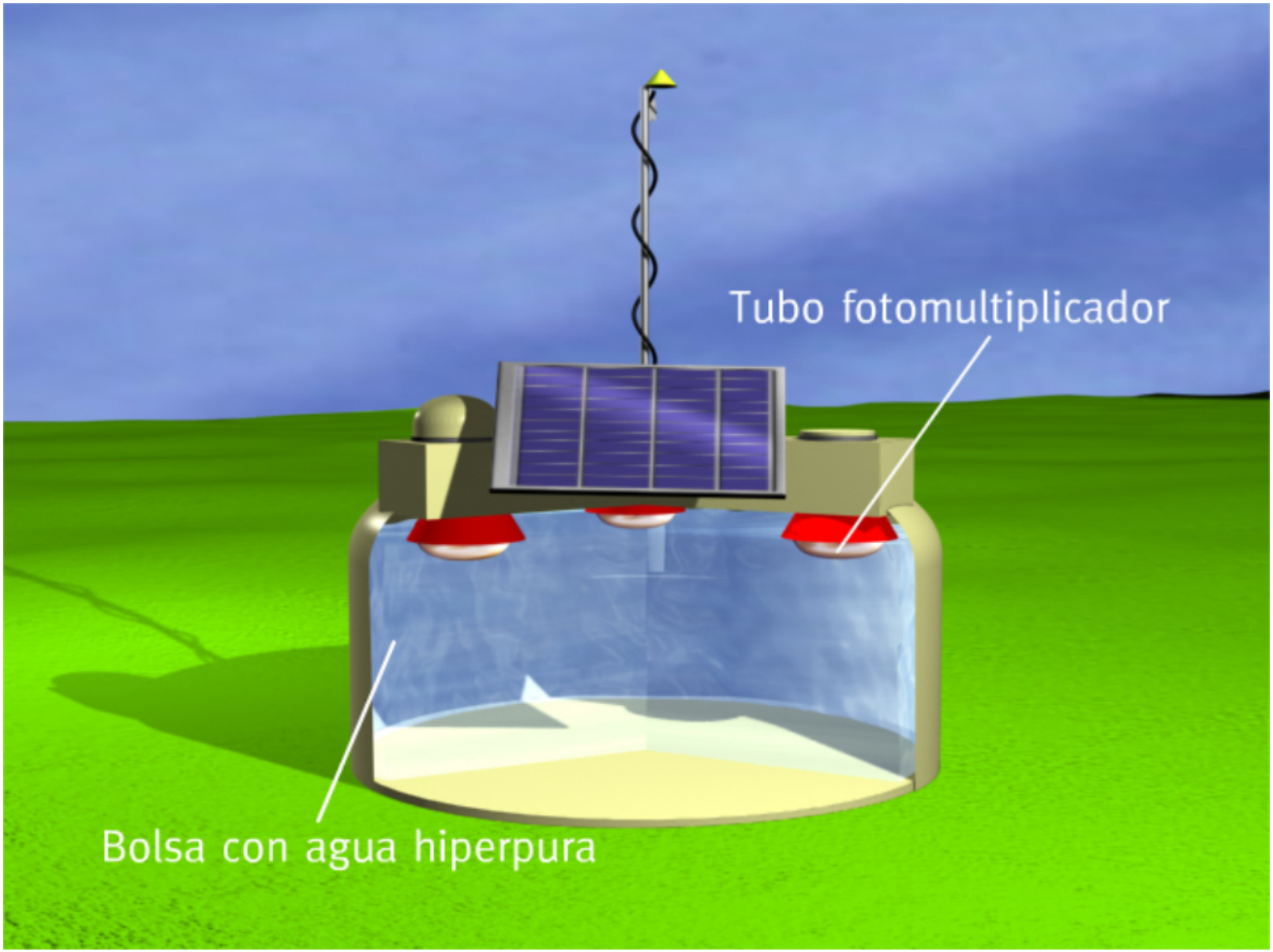

THE AUGER SURFACE DETECTOR

THE AUGER FLUORESCENCE DETECTOR

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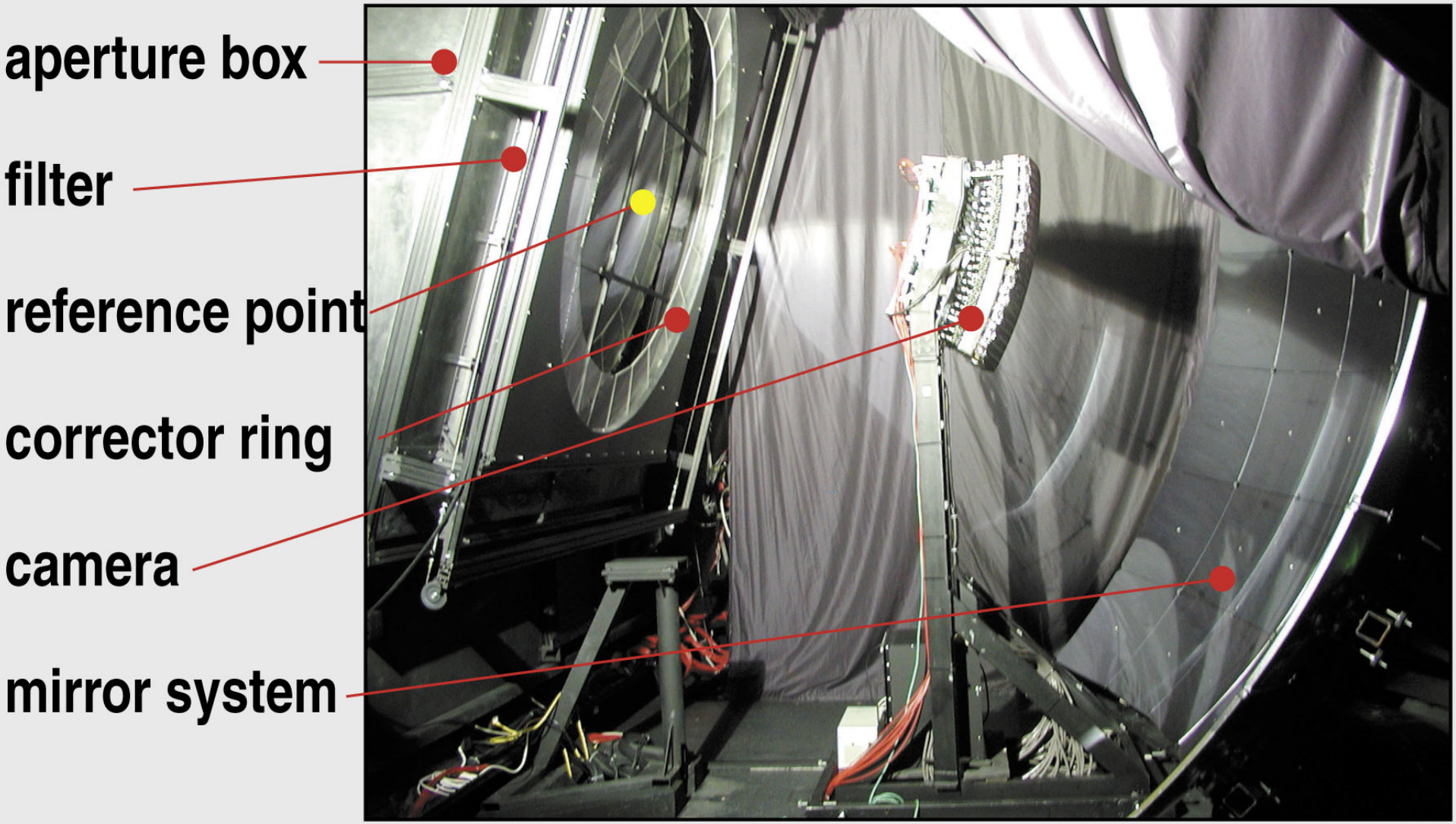

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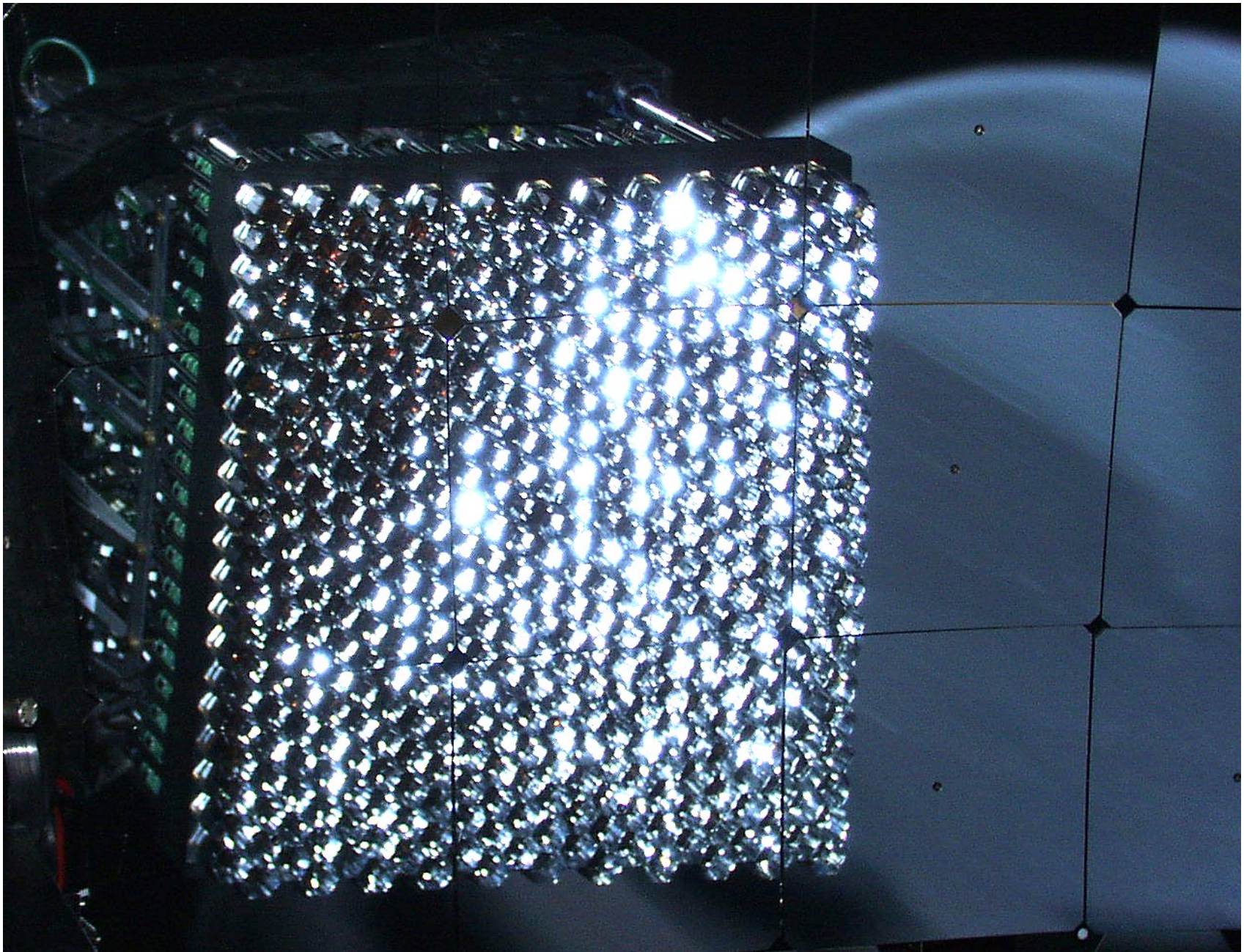
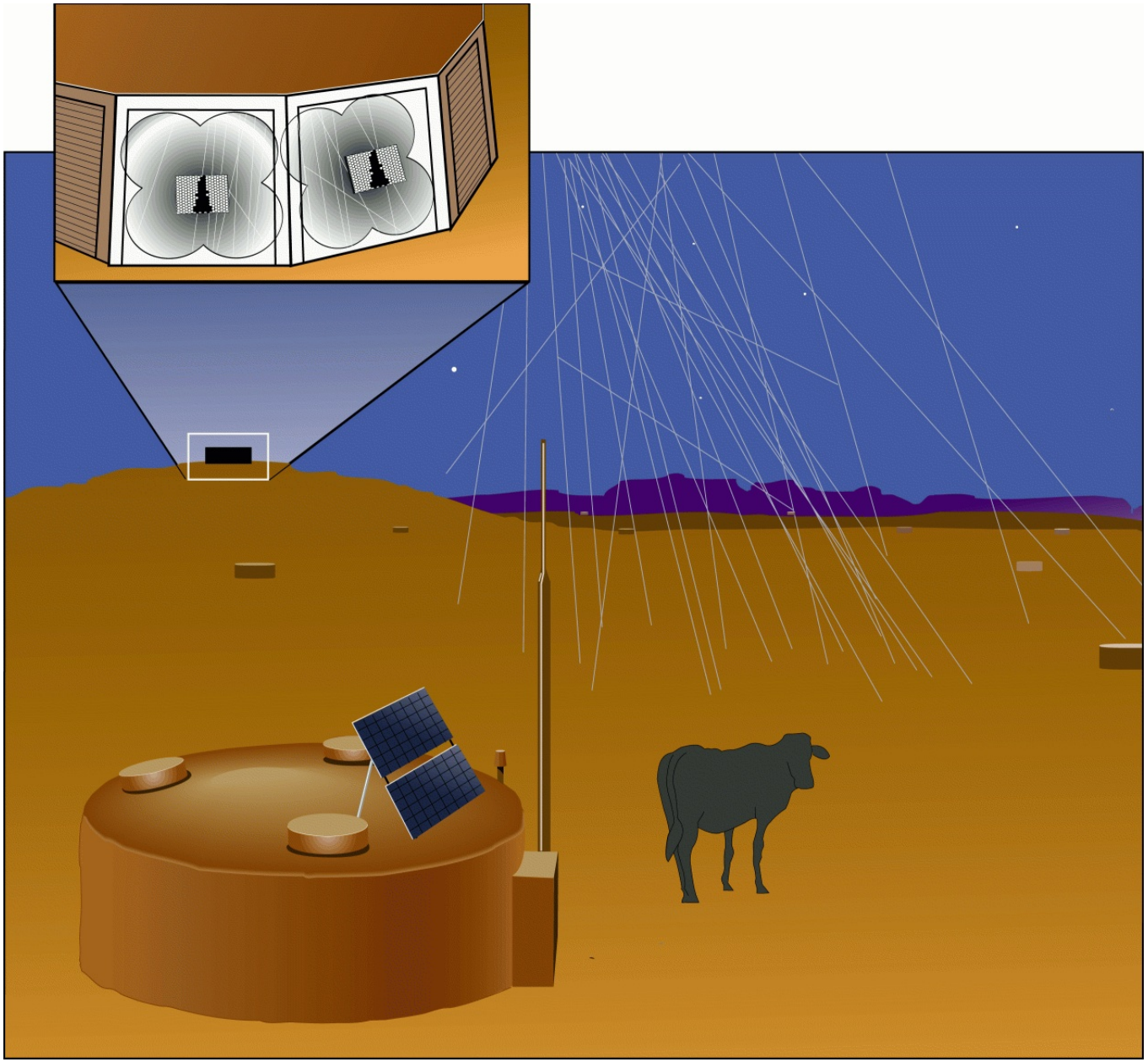


I HAD A HYBRID DREAM...

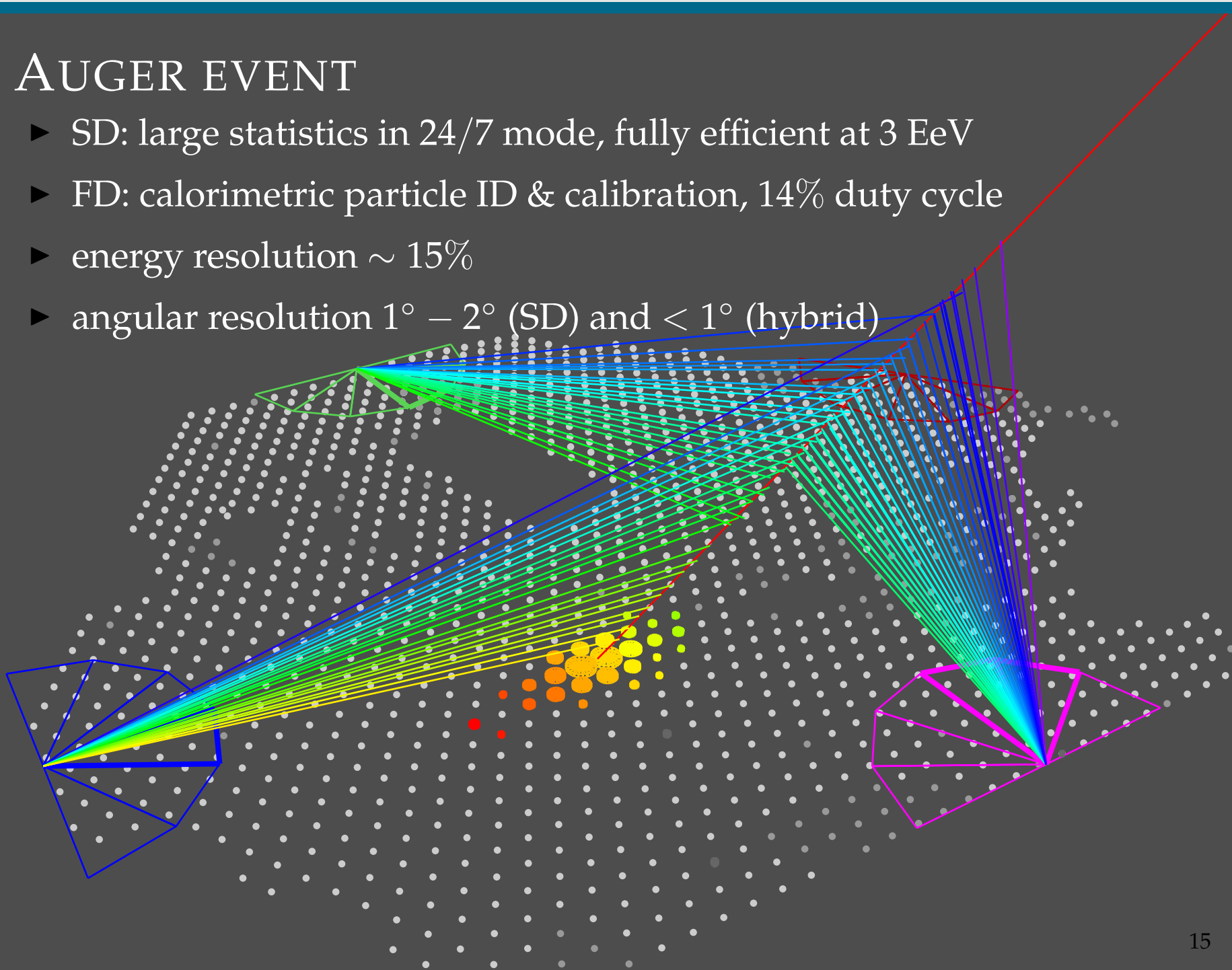


I HAD A HYBRID DREAM...

I HAD A HYBRID DREAM...

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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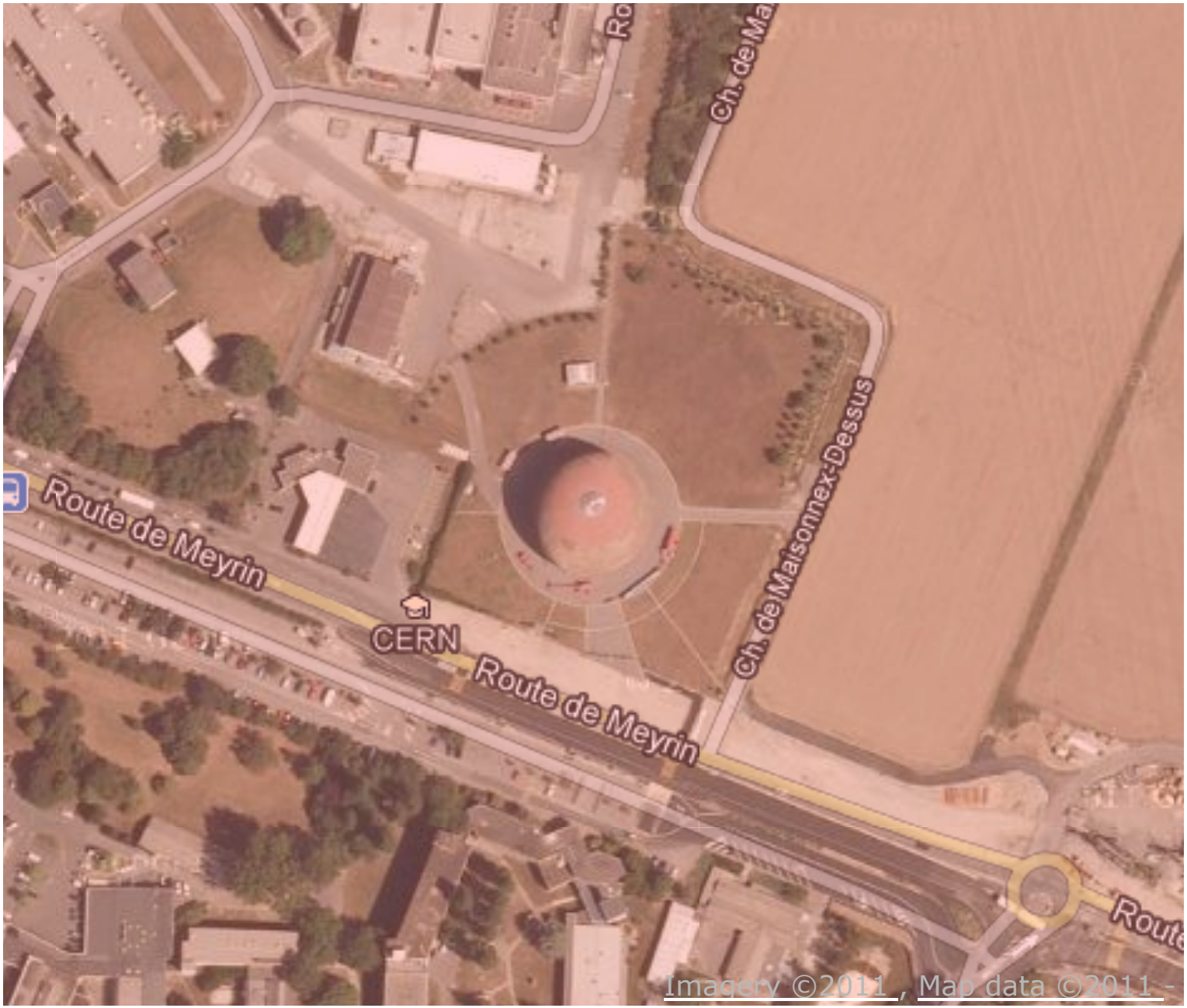

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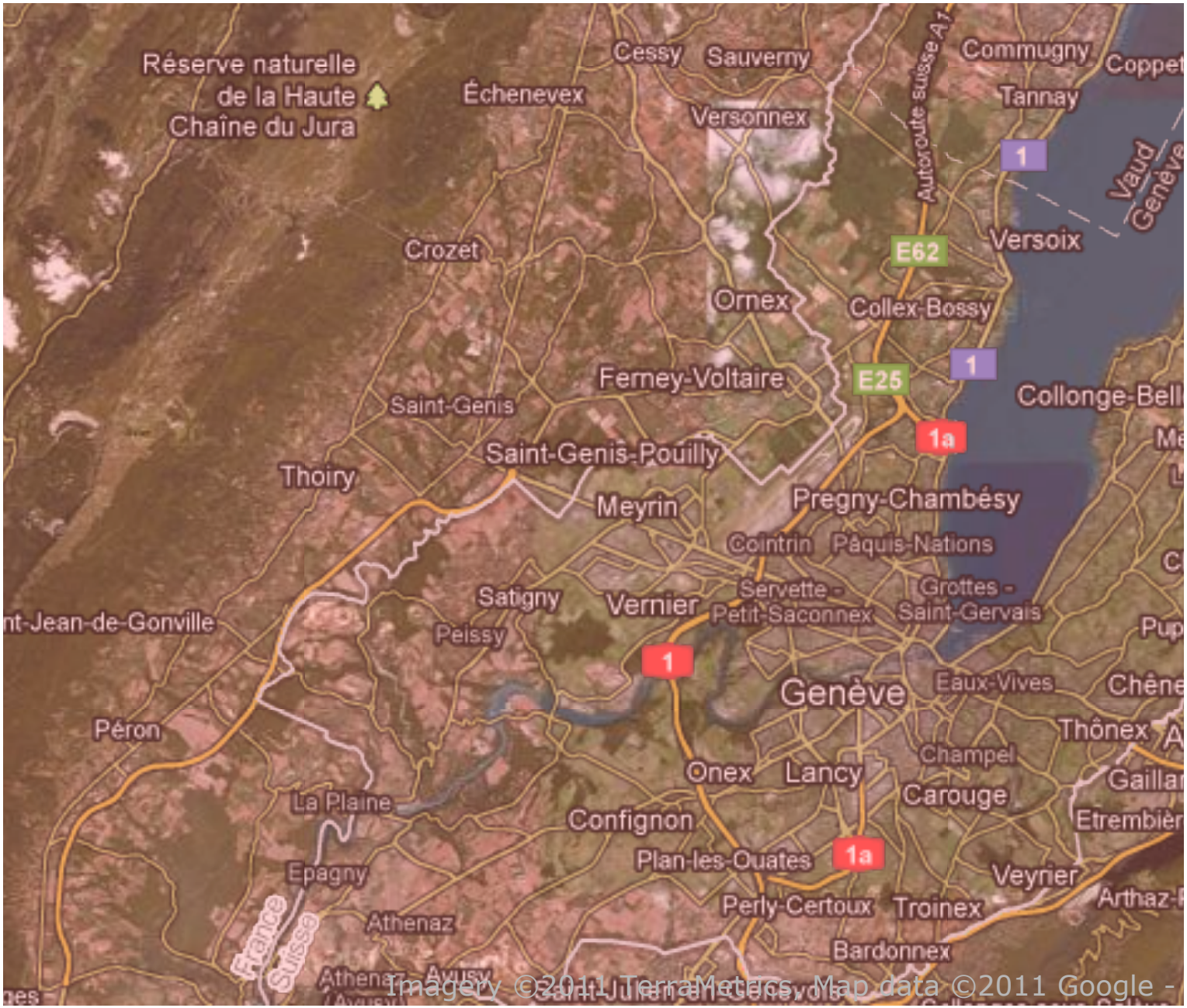

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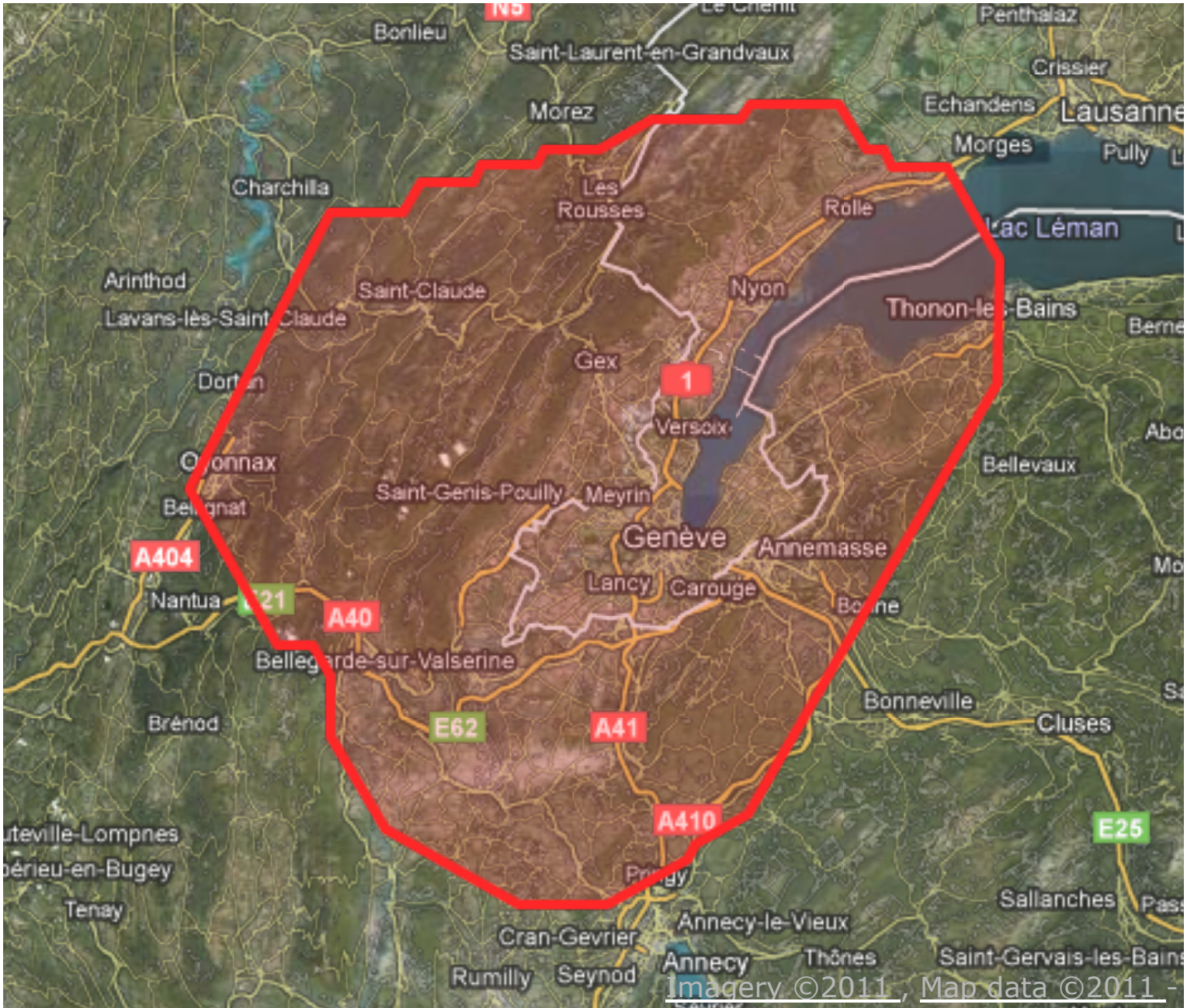
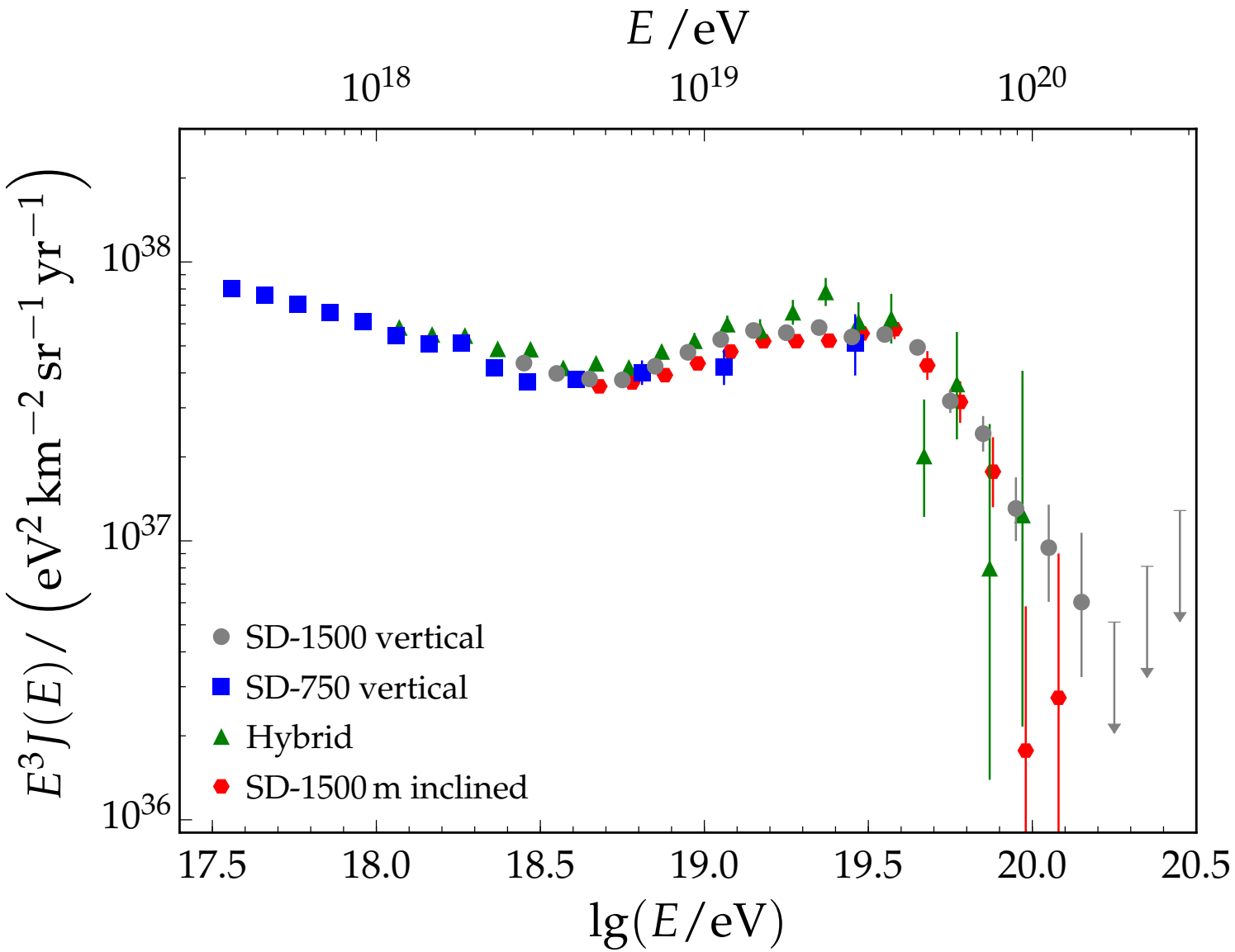
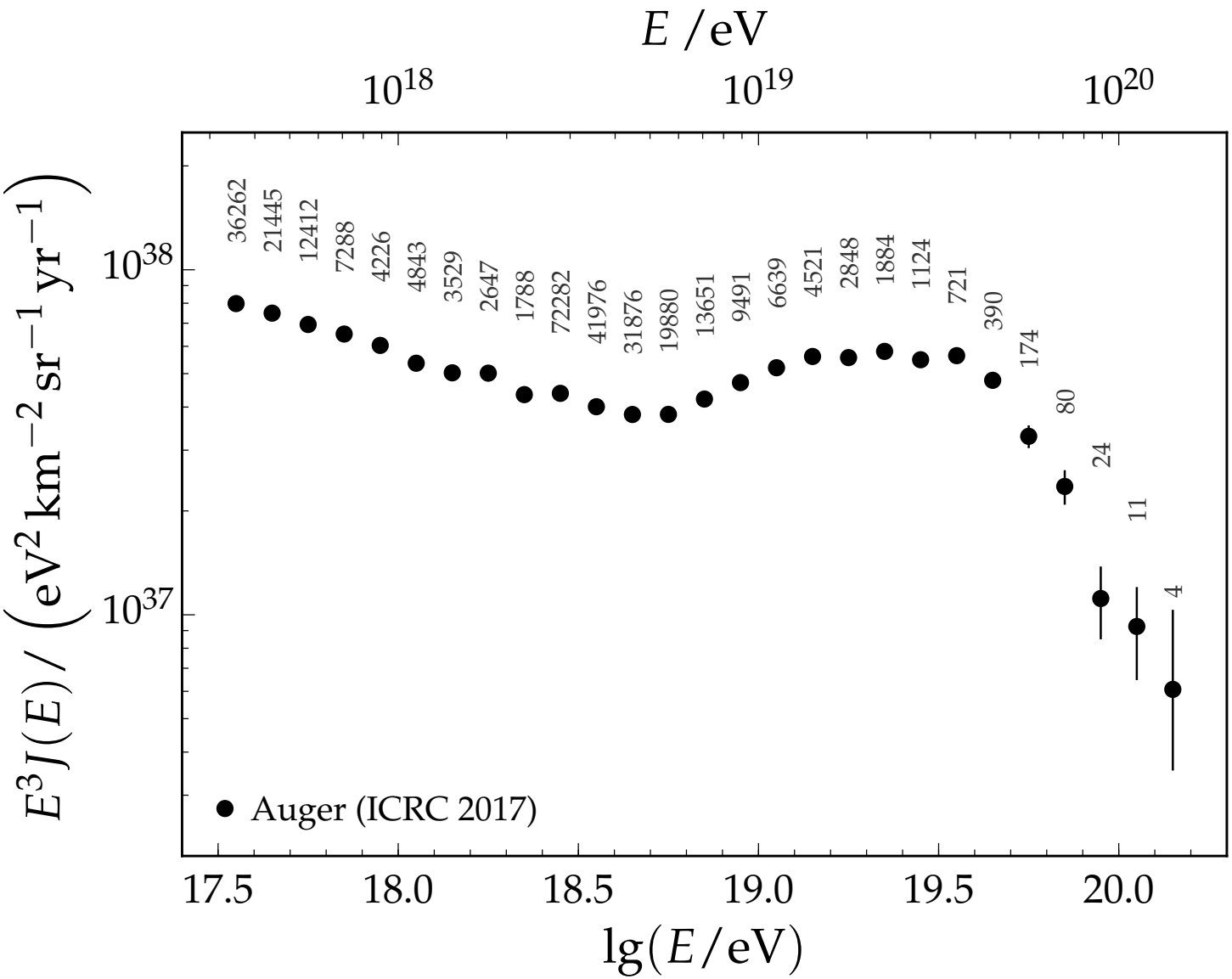


ENERGY SPECTRUM



Auger Collab., ICRC2017

ENERGY SPECTRUM



Auger Collab., ICRC2017

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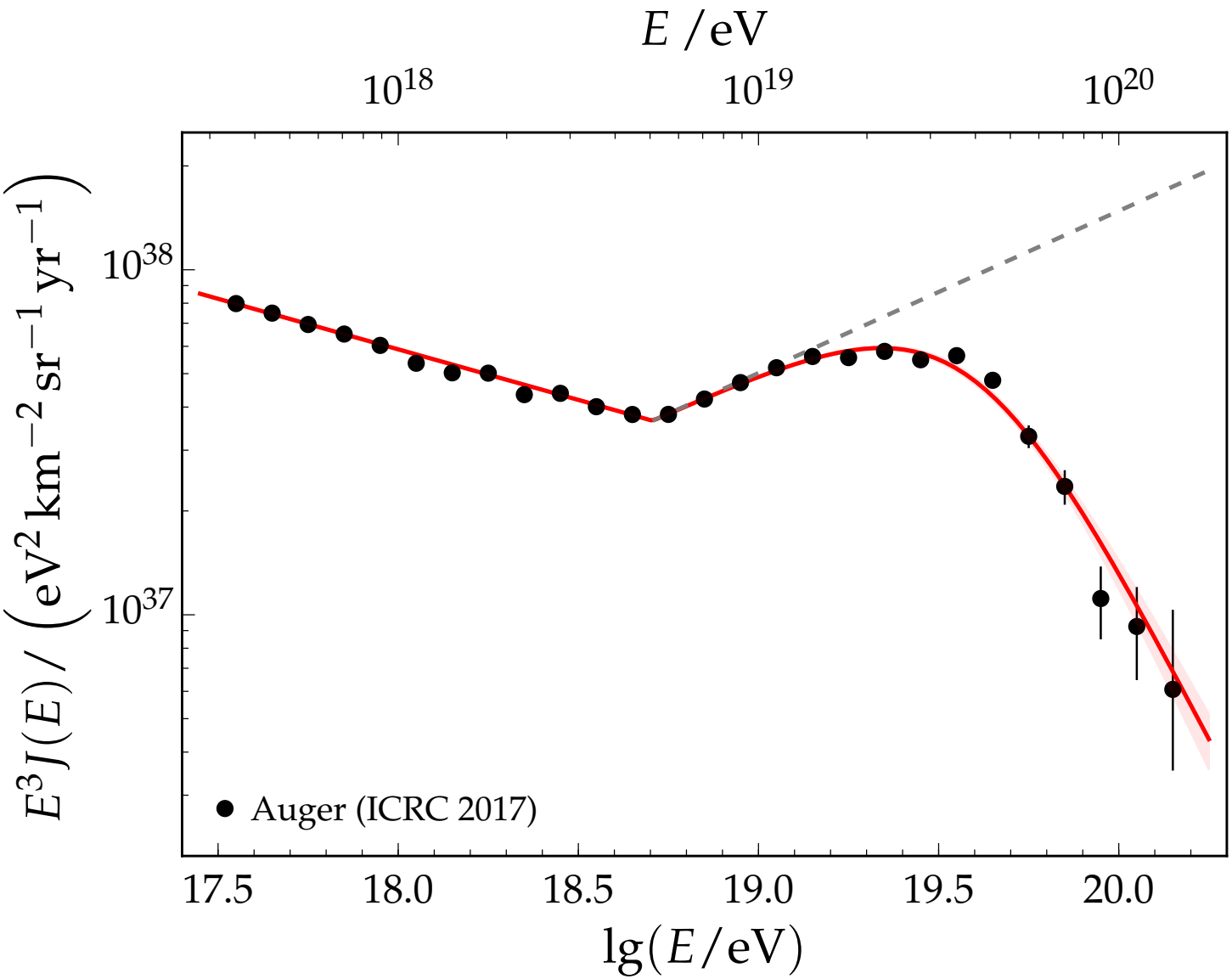

Auger Collab., ICRC2017

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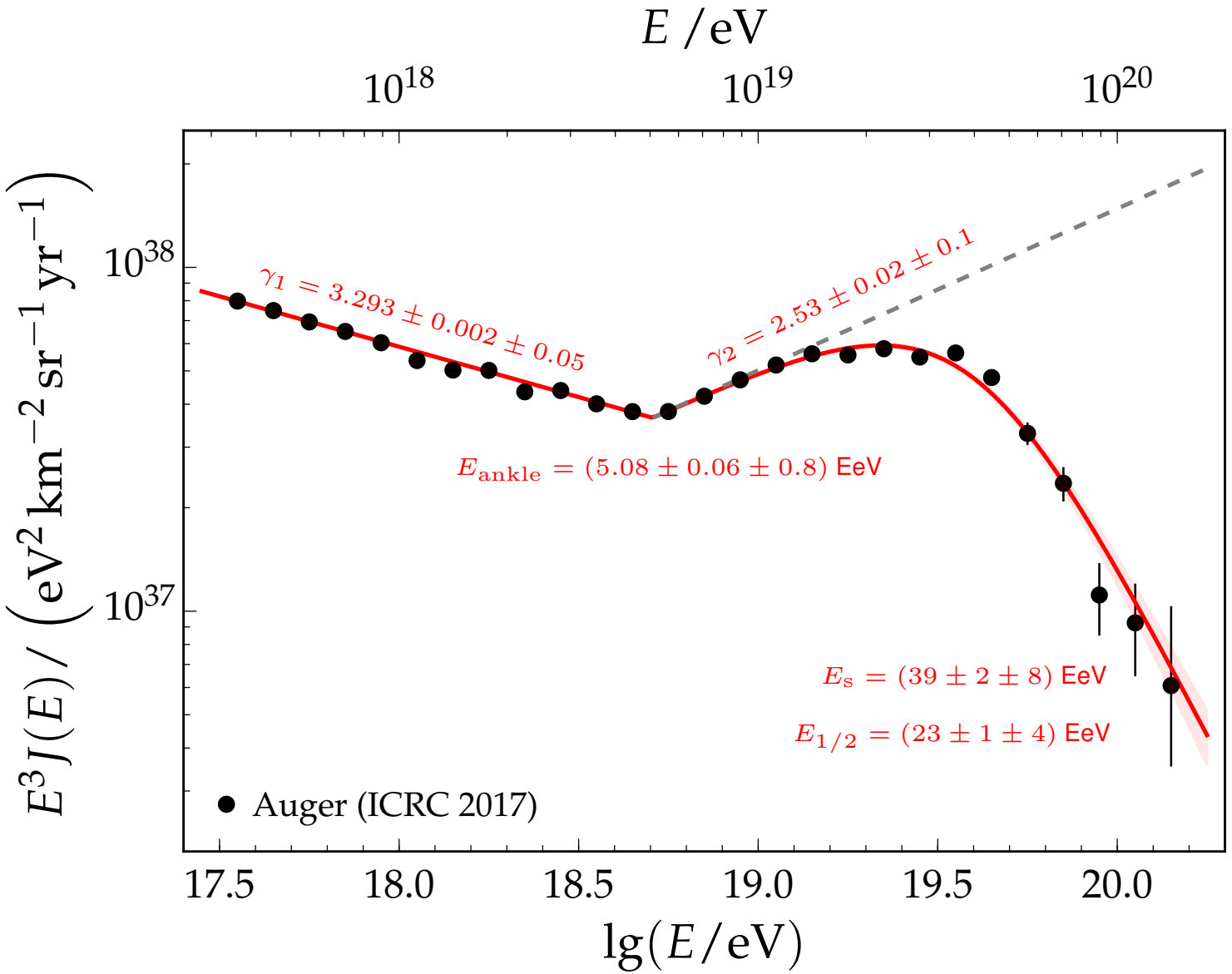
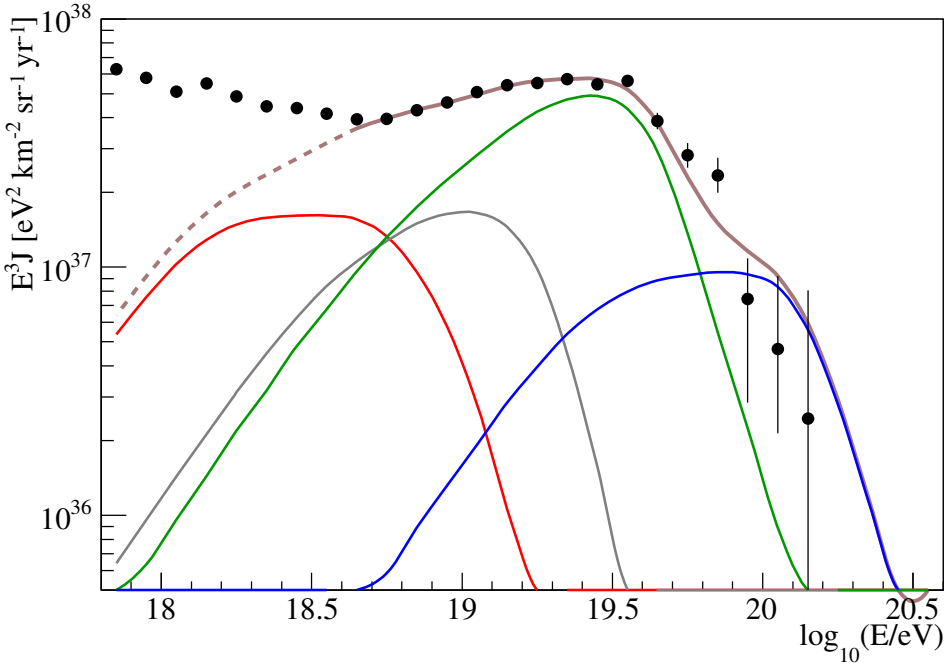
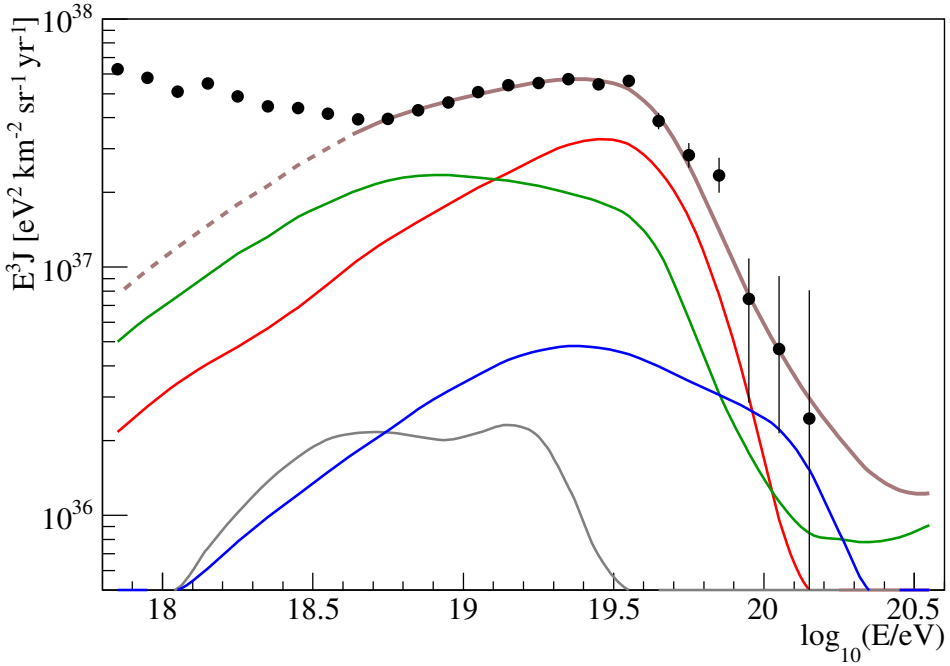


TAKE HOME MESSAGE I

- Many ways to fit the spectrum!



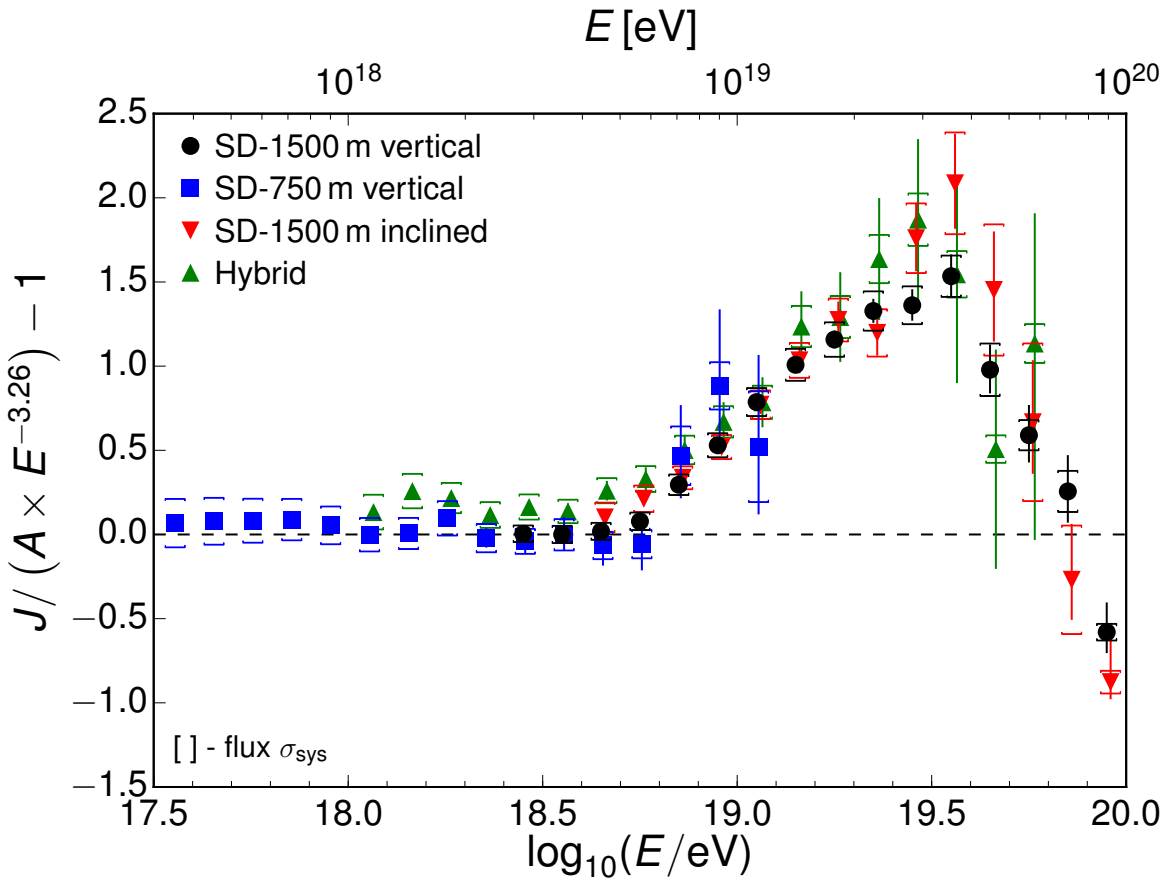


Partial spectra are grouped according to the mass number:
$A = 1$ (red), $2 \leq A \leq 4$ (gray), $5 \leq A \leq 26$ (green),
$27 \leq A$ (blue), and total (brown).

Armando di Matteo, ICRC2015

TAKE HOME MESSAGE II

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

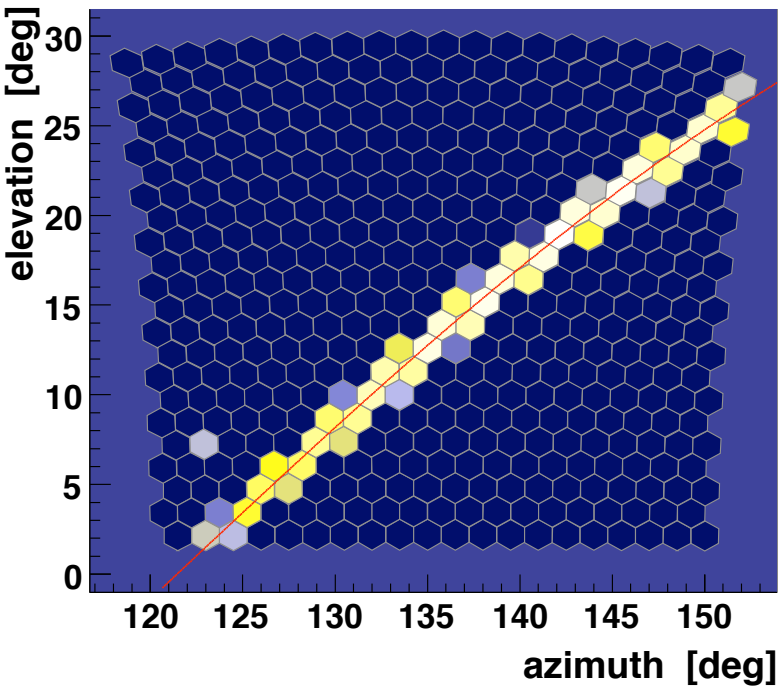


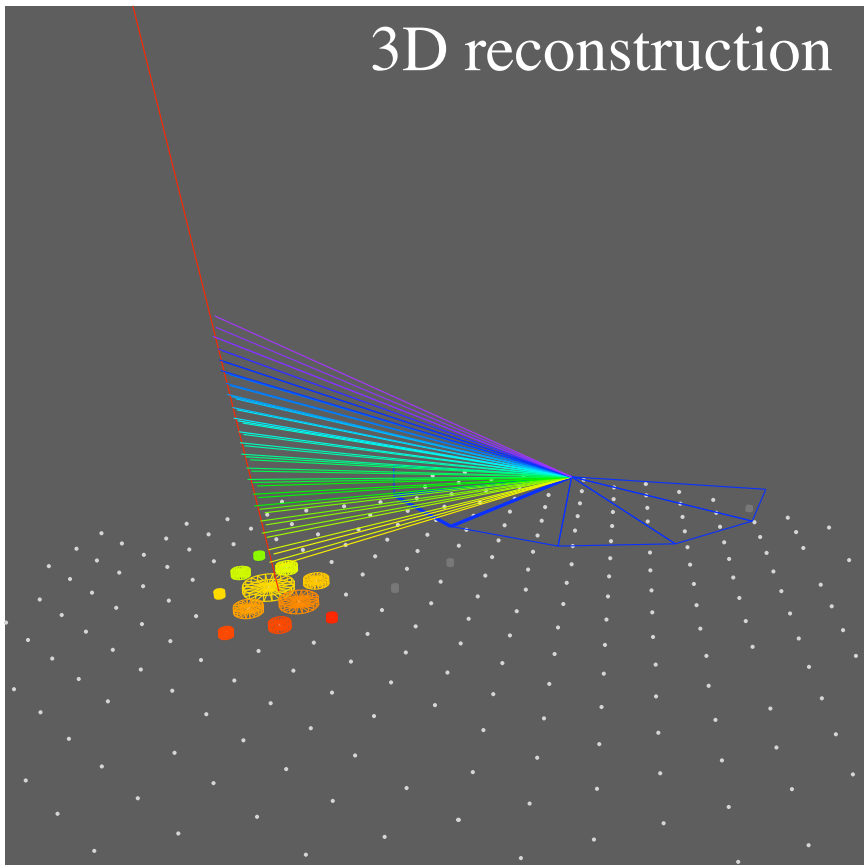
Inés Valiño, ICRC2015

PRIMARY COMPOSITION

- Longitudinal profile information from FD

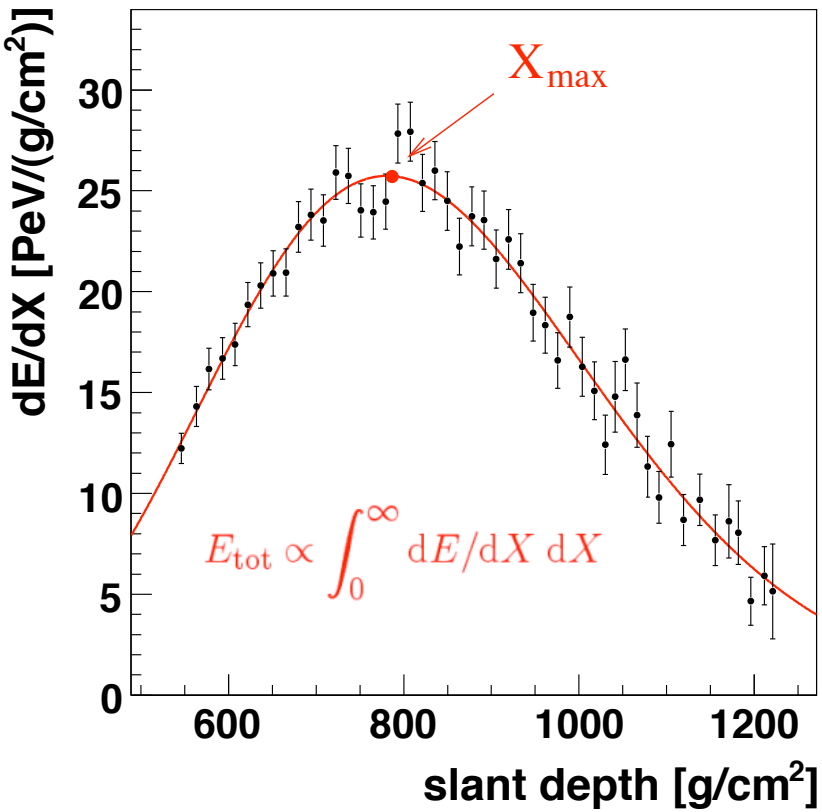
camera view

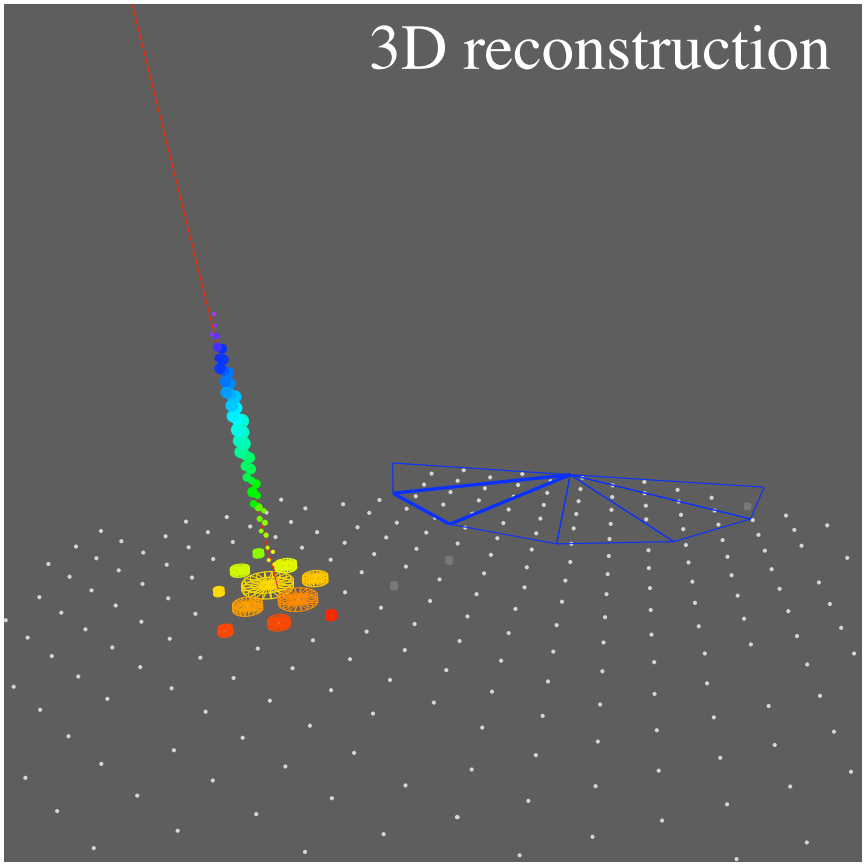




PRIMARY COMPOSITION

- Longitudinal profile information from FD

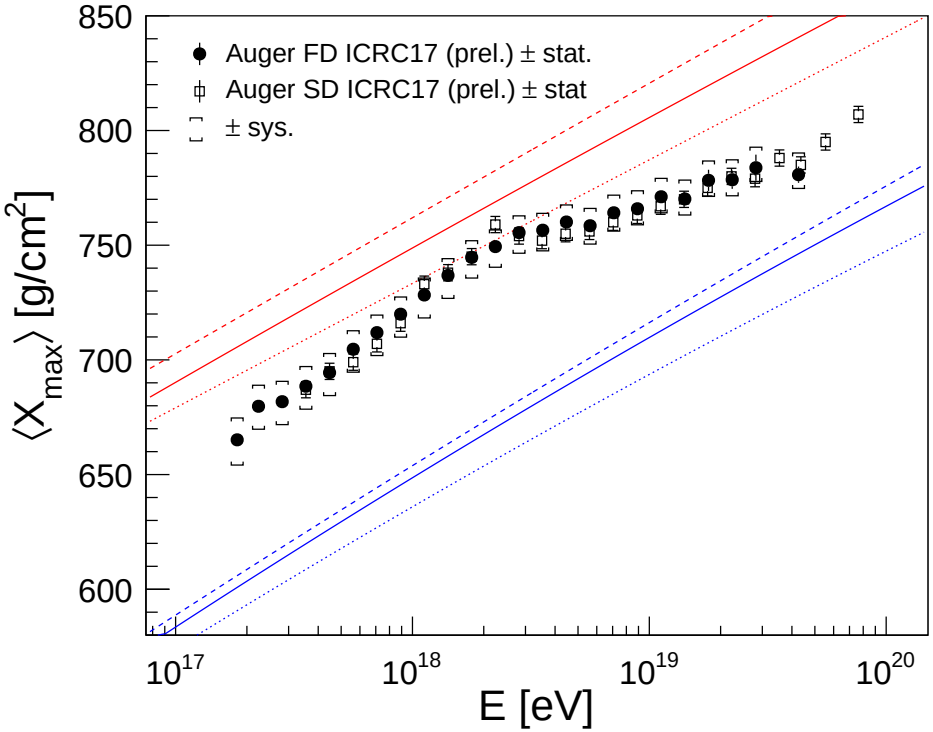




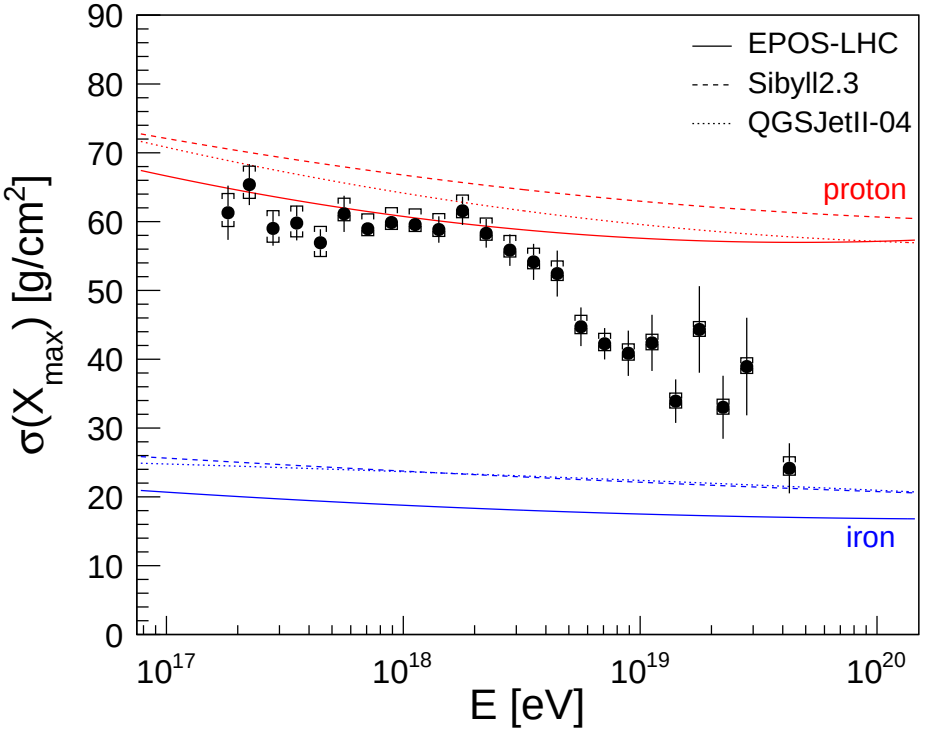
LONGITUDINAL SHOWER DEVELOPMENT

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

average



standard deviation



Auger Collab., ICRC2017

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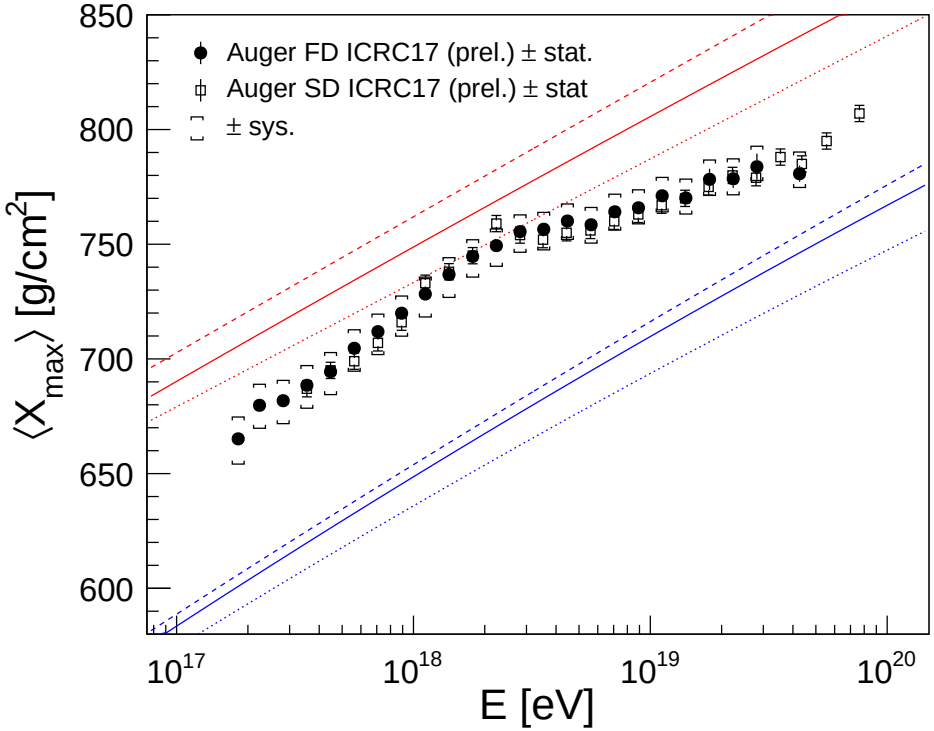
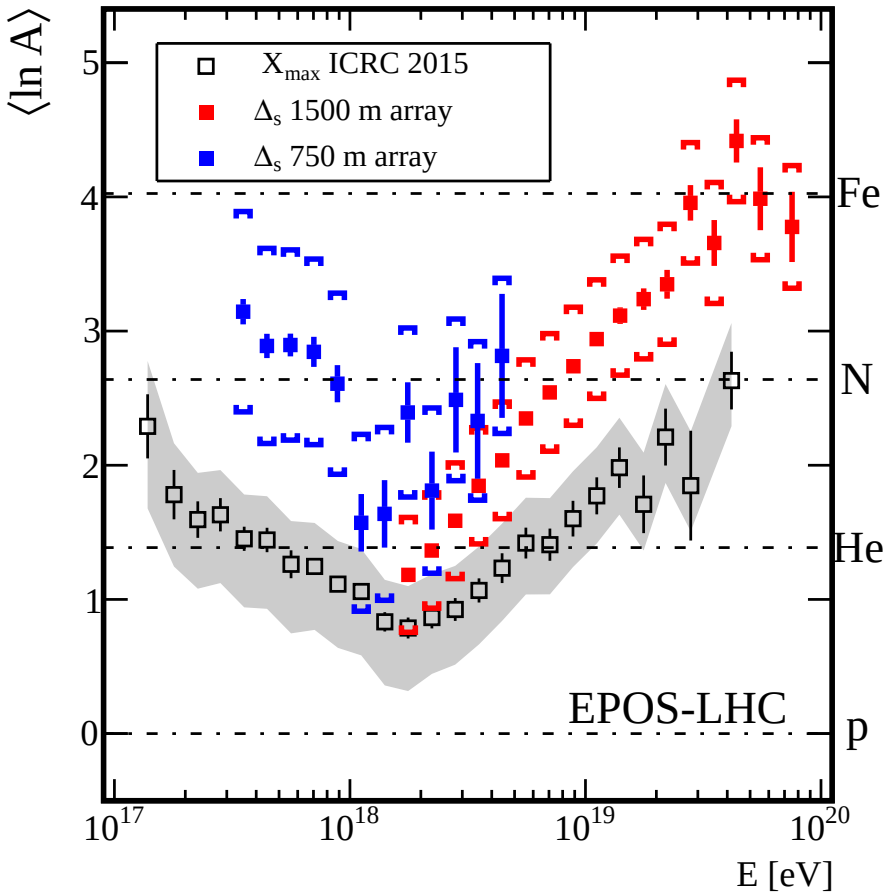
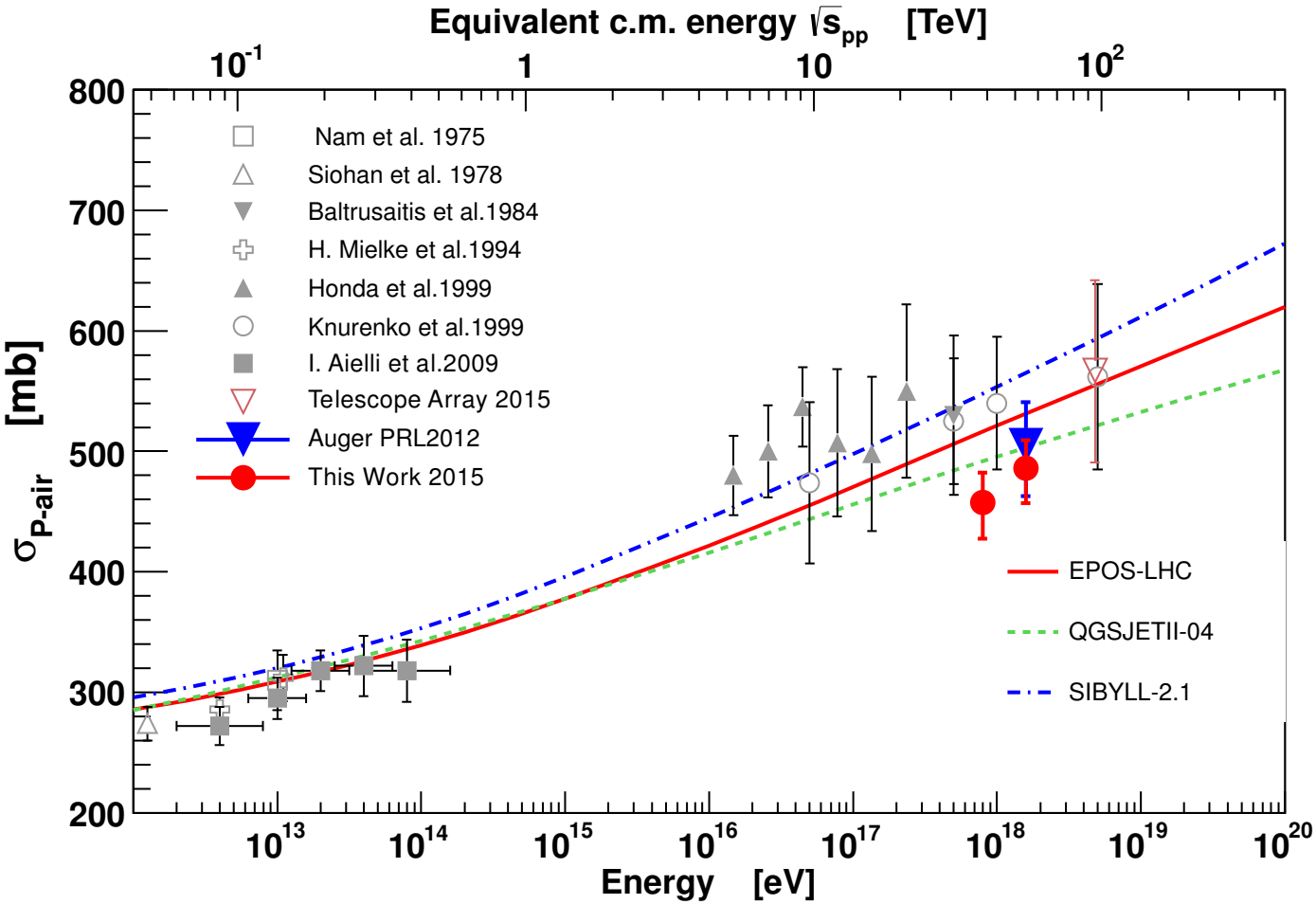


interpretation (EPOS-LHC)



PROTON-AIR CROSS-SECTION

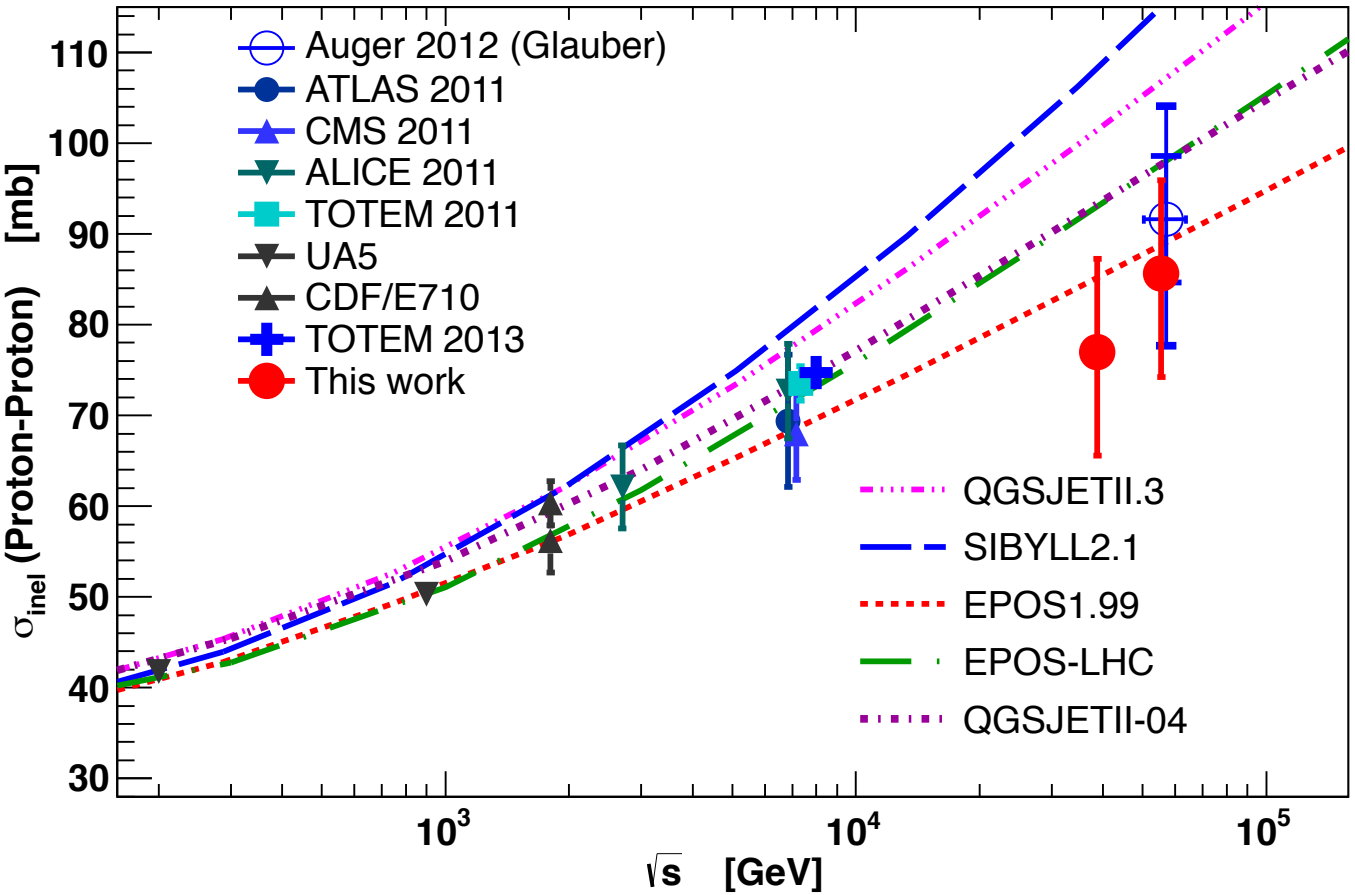


$$\sigma_{\mathbf{p}\text{-air}} = \left[\mathbf{458} \pm \mathbf{18}_{\text{stat}} \left(^{+\mathbf{19}}_{-\mathbf{25}}\right)_{\text{sys}}\right] \text{ mb} \qquad 10^{17.8}\ \text{eV} \leq \text{E} < 10^{18}\ \text{eV}$$

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

INELASTIC PROTON-PROTON CROSS-SECTION

STANDARD GLAUBER CONVERSION + PROPAGATION OF MODELING UNC.

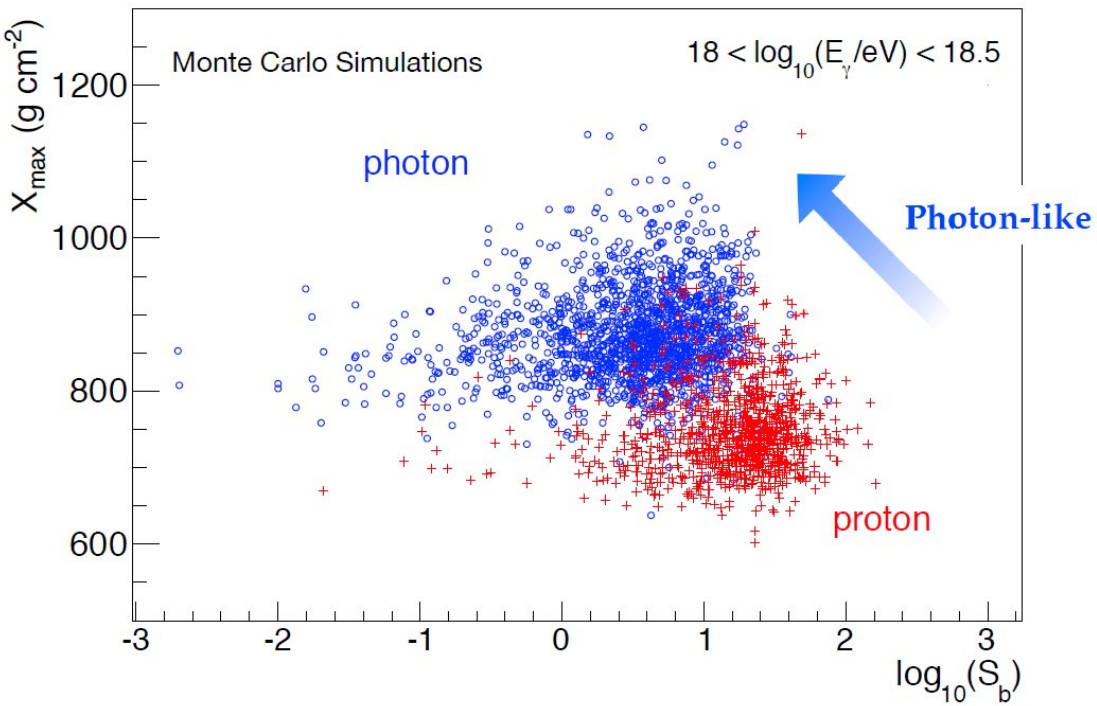


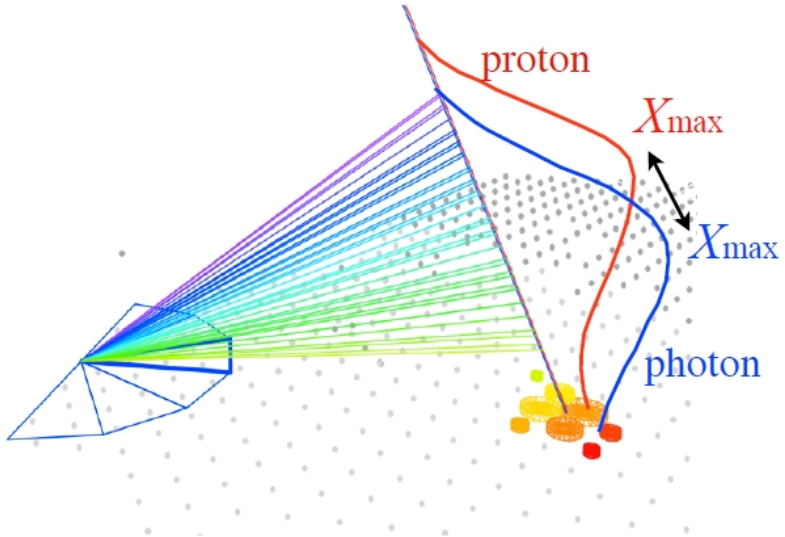
$$\sigma_{pp}^{inel}\left(\sqrt{s} = [39 \pm 3]\ \text{TeV}\right) = \left[77 \pm 5_{stat}\ (^{+5}_{-7})_{sys} \pm 7_{Glauber}\right]\ \text{mb}$$

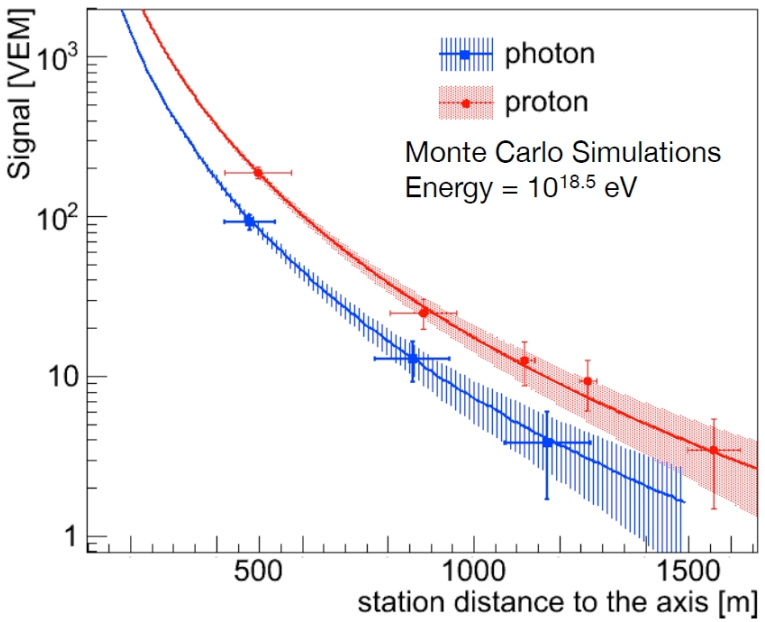
$$\sigma_{pp}^{inel}\left(\sqrt{s} = [56 \pm 4]\ \text{TeV}\right) = \left[86 \pm 5_{stat}\ (^{+6}_{-7})_{sys} \pm 7_{Glauber}\right]\ \text{mb}$$

UHE PHOTON LIMITS

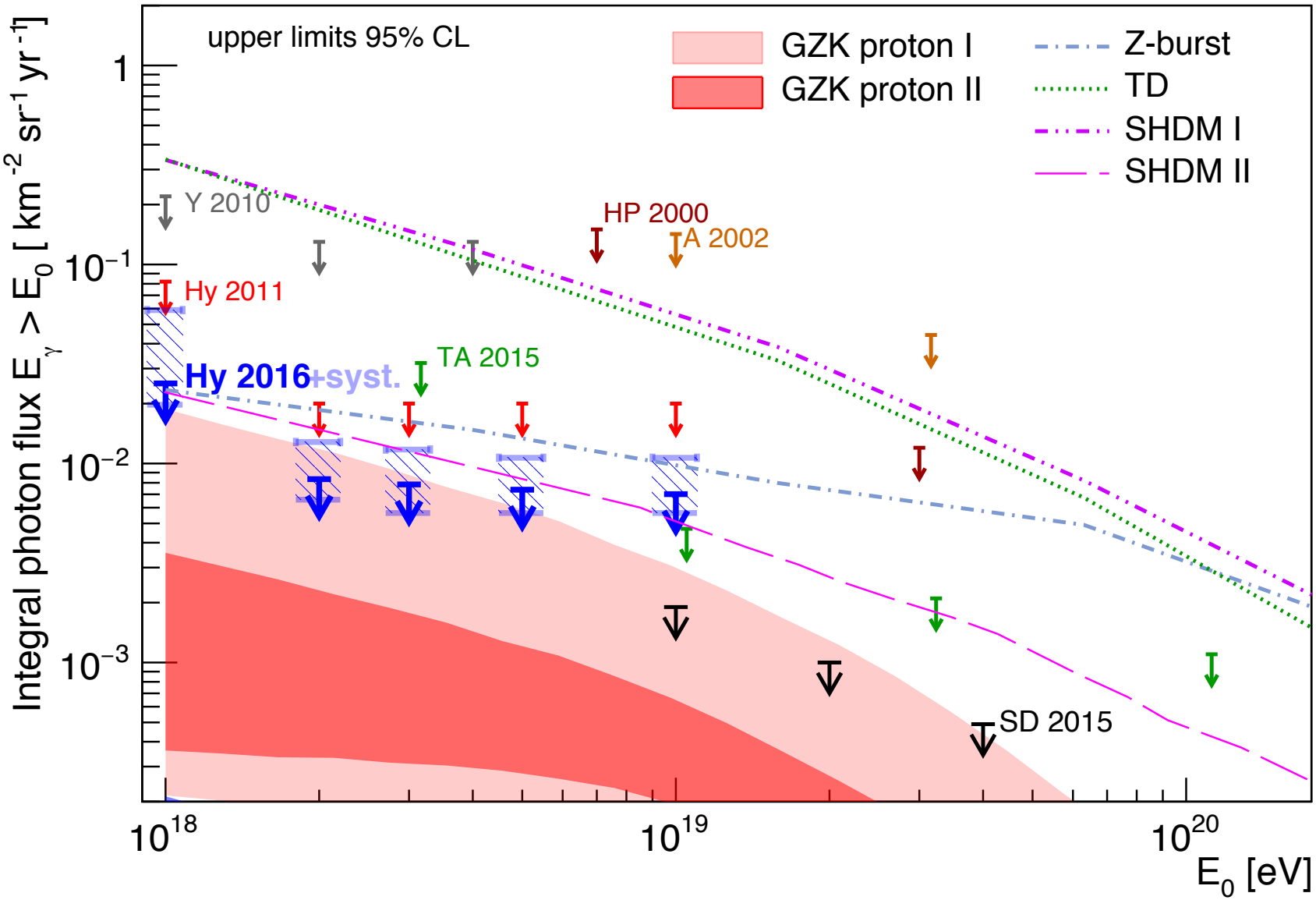
PRINCIPAL COMPONENT ANALYSIS







PHOTON FLUX LIMITS

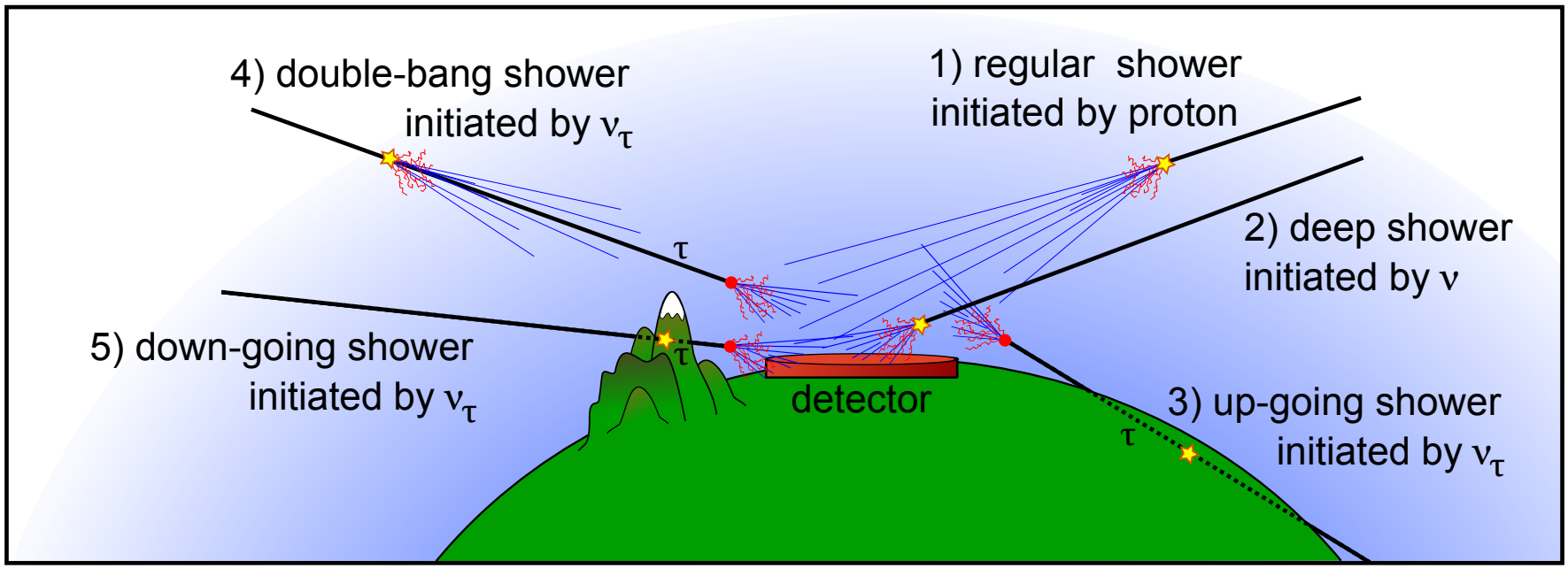


$p + \gamma_{\mathrm{CMB}} \Longrightarrow p + \pi^0$

Auger Collab., ICRC2017

UHE NEUTRINO SEARCHES

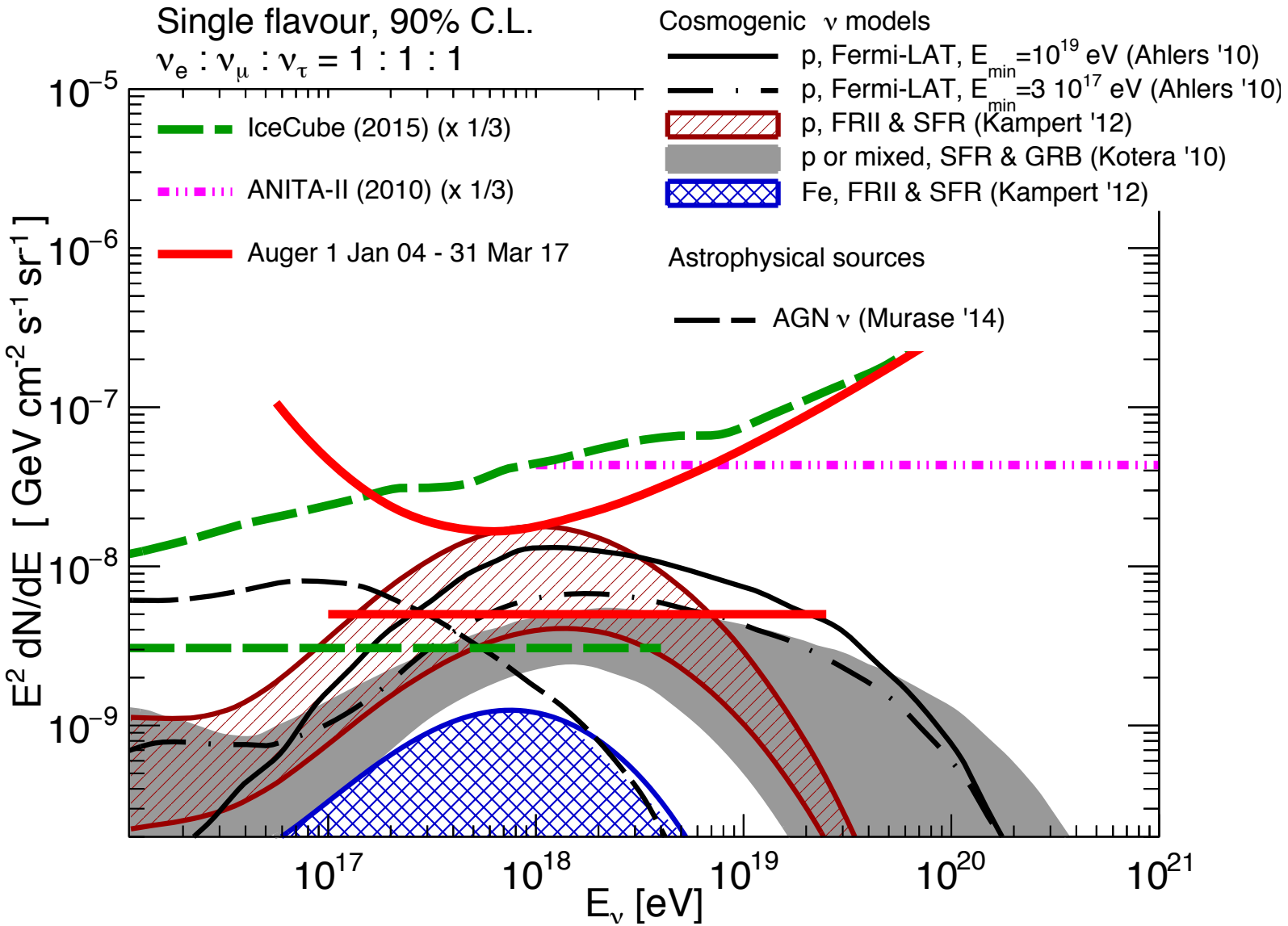
VERY INCLINED SHOWERS



Search for:

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

DIFFUSE NEUTRINO LIMITS



$p + \gamma_{\mathrm{CMB}} \Longrightarrow n + \pi^+$

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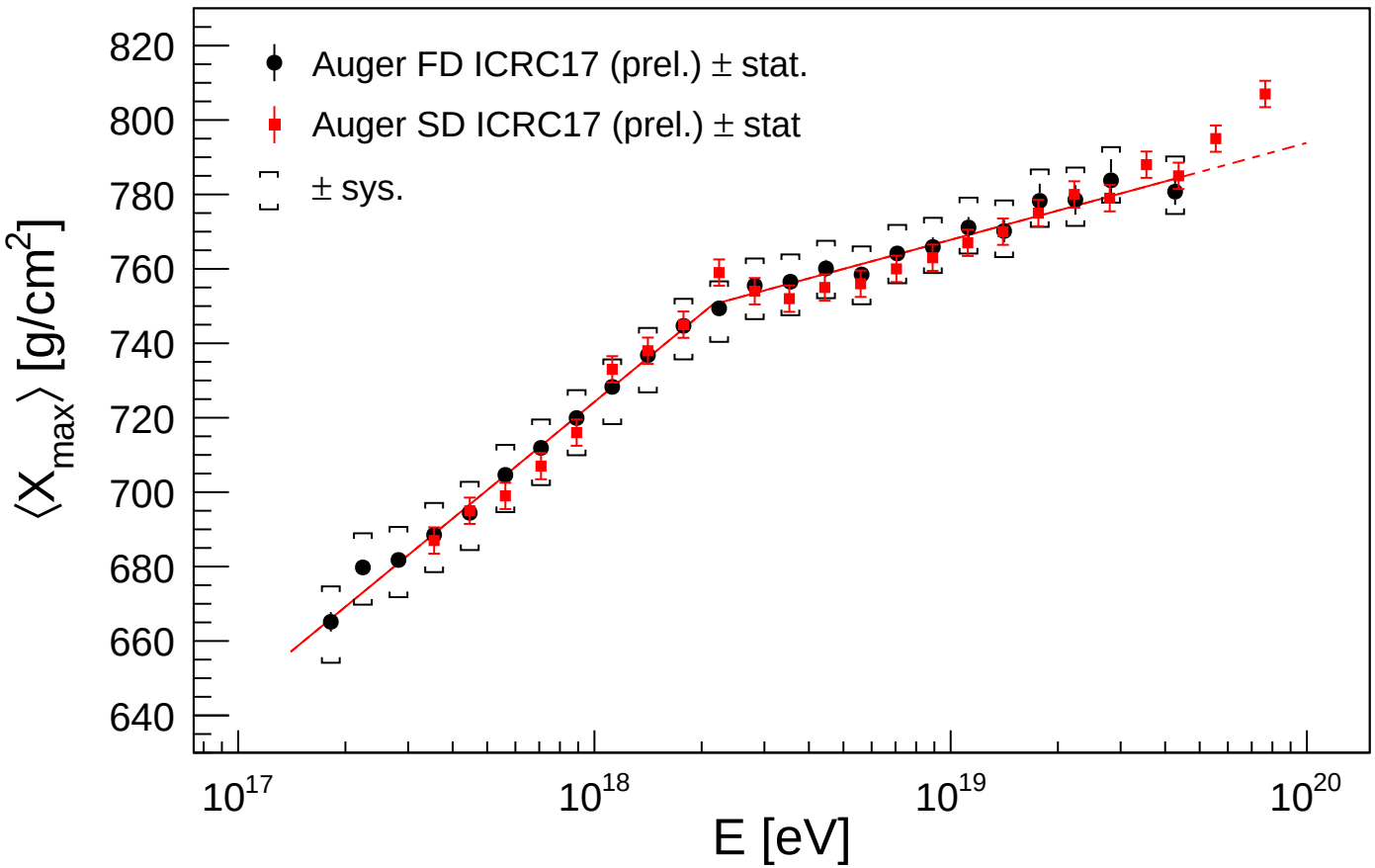
TAKE HOME MESSAGE III

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



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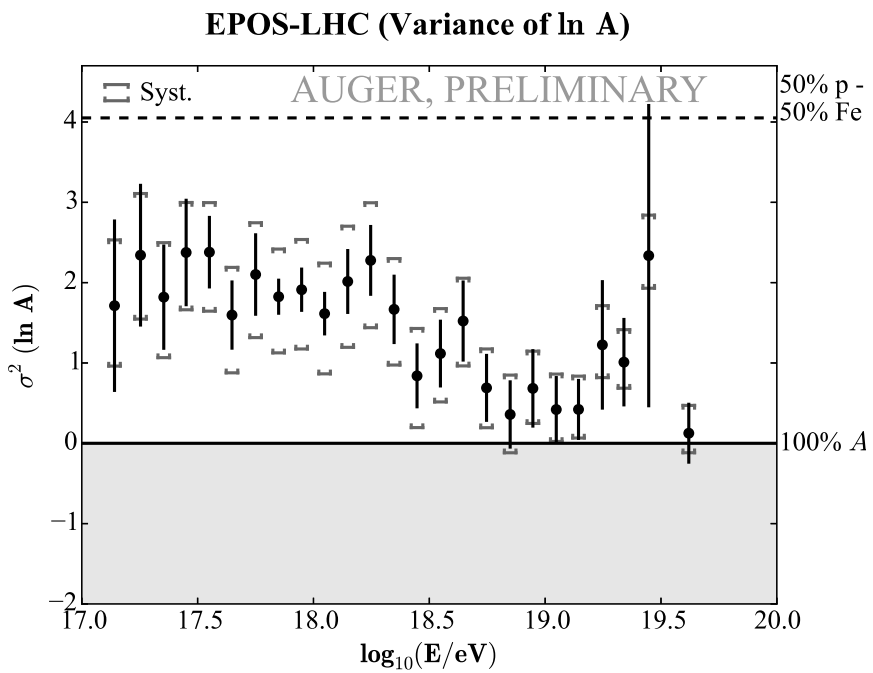

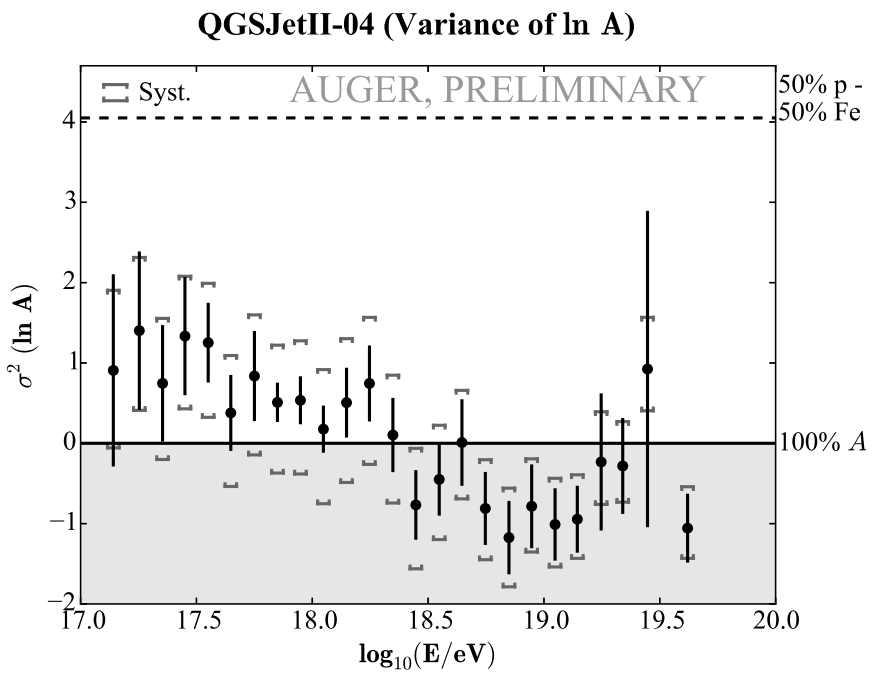

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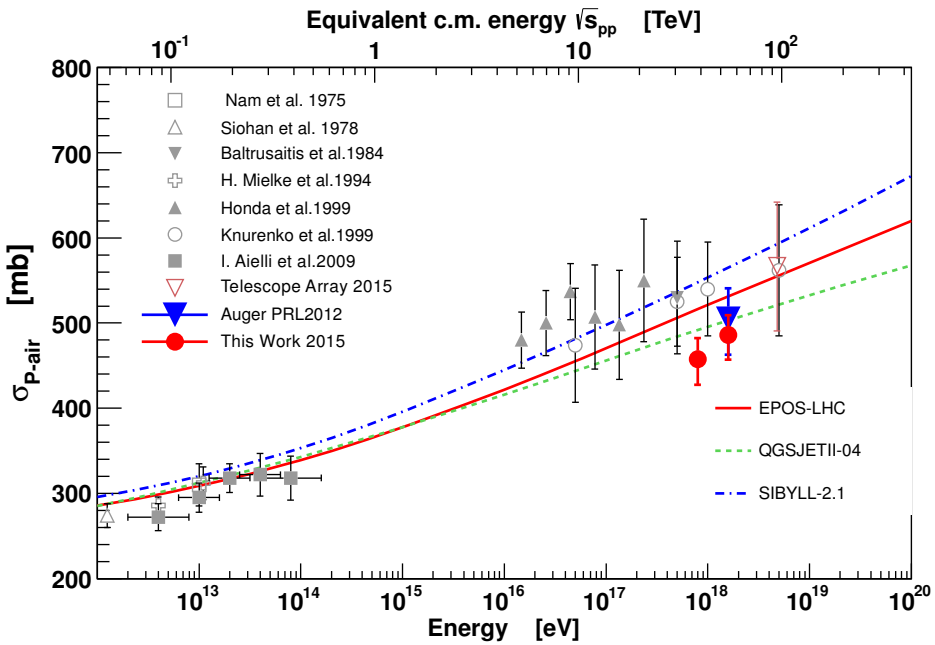
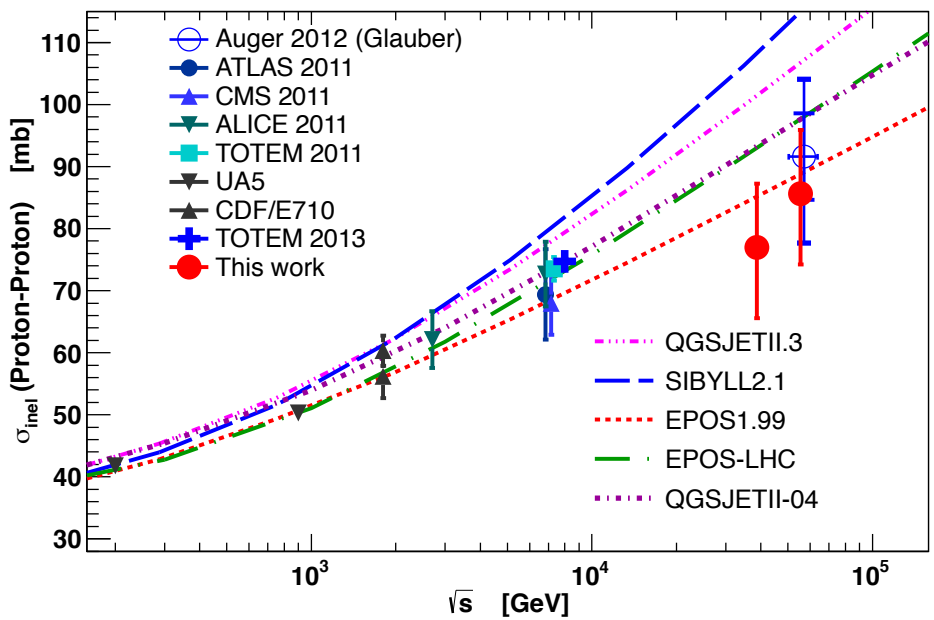
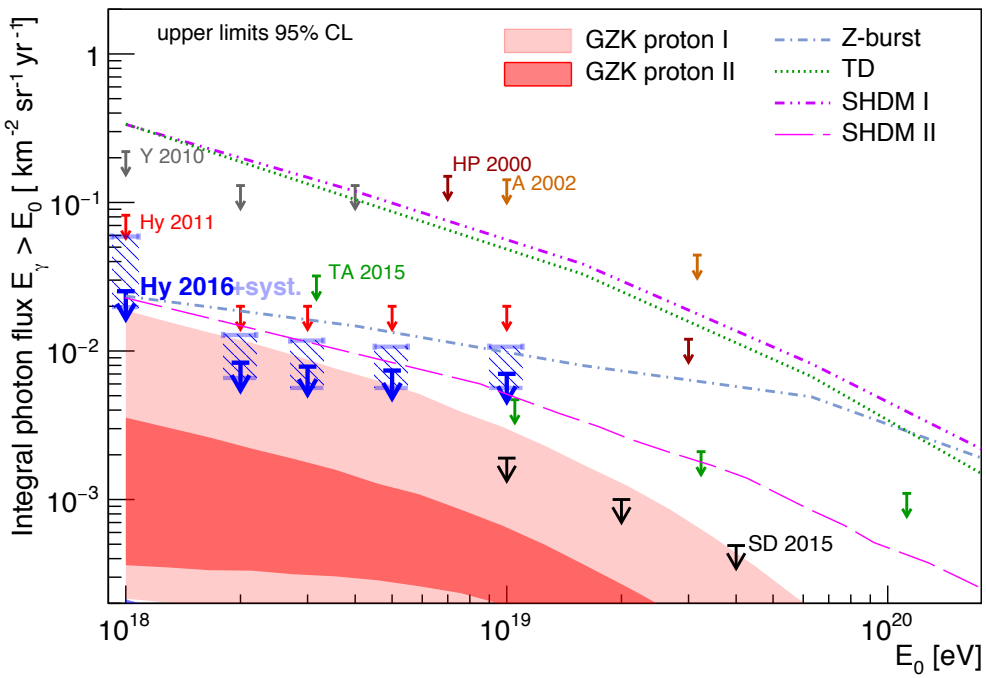
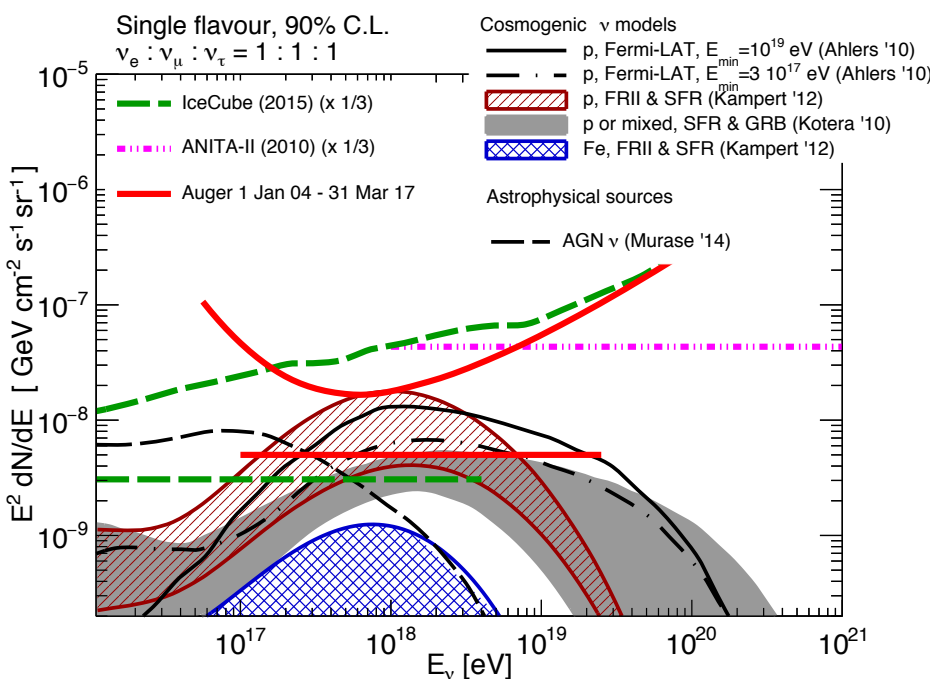




TAKE HOME MESSAGE IV

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

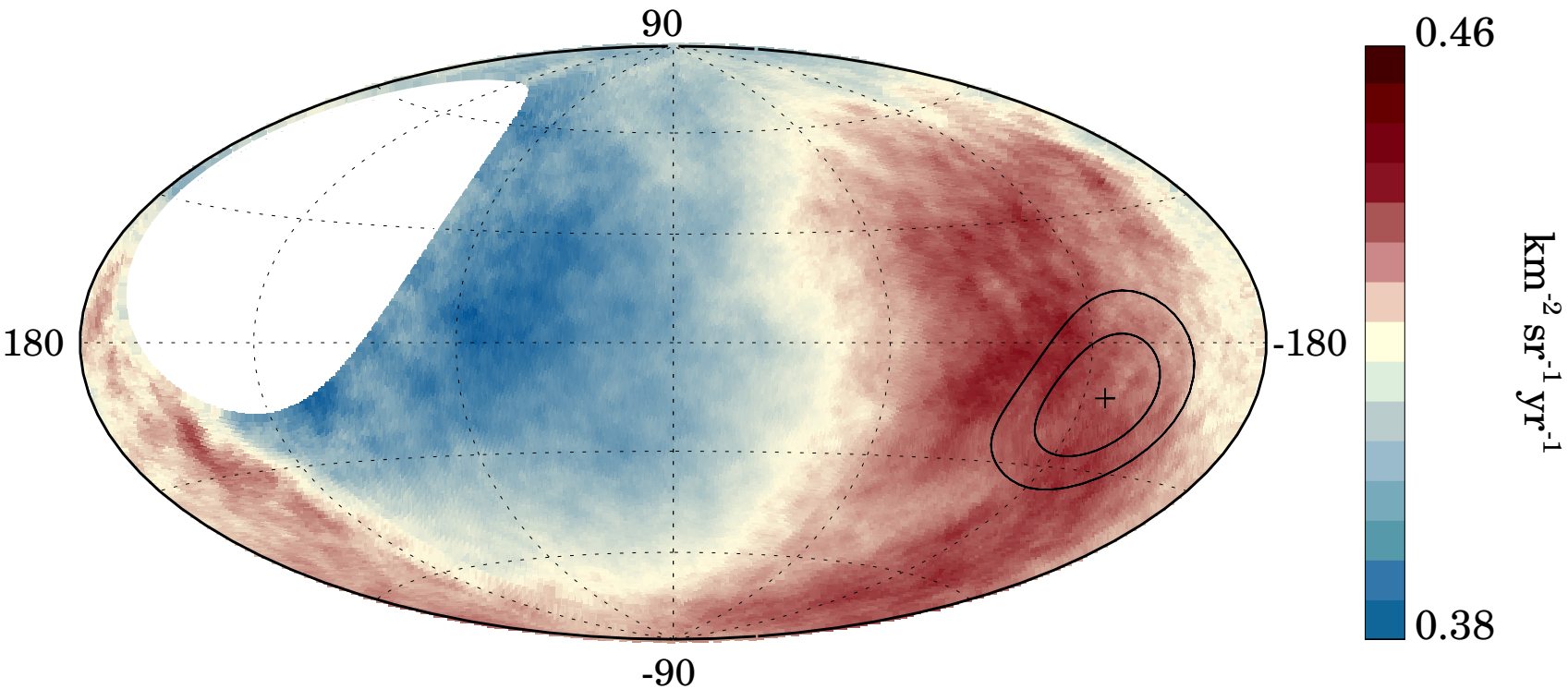




LARGE SCALE ANISOTROPY

DIPOLE SEARCHES

- significant ($> 5\sigma$) departure from isotropy **above 8 EeV** with a $\sim (5 \pm 1)\%$ amplitude in the first harmonic in RA
- phase transition from 270° to 90° at ∼1 EeV



Auger Collab., accepted for publication

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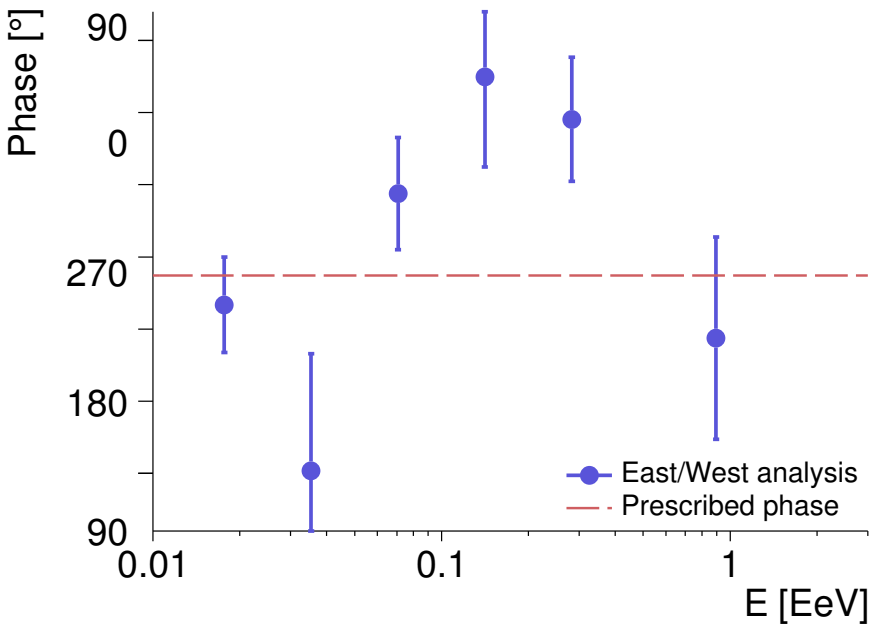
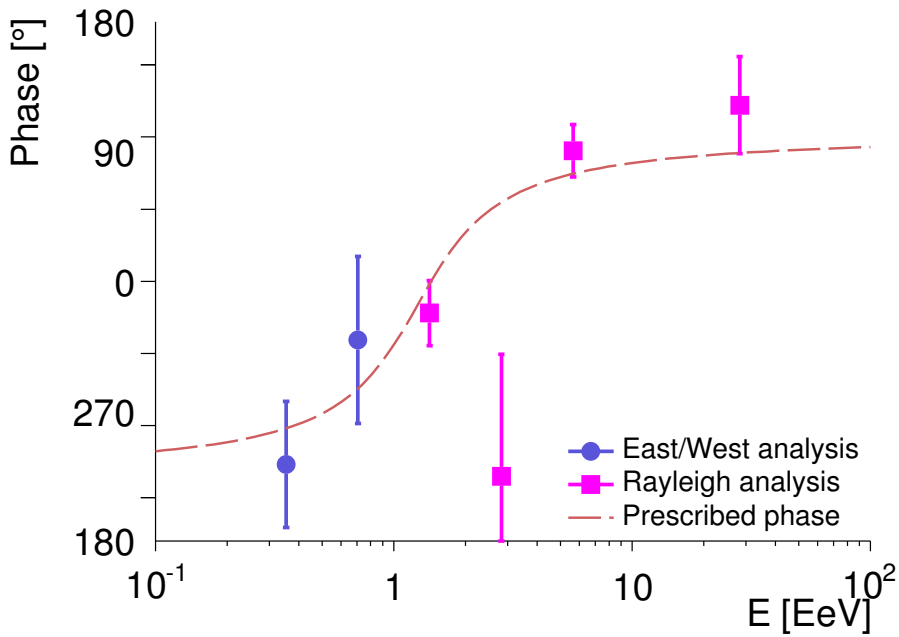


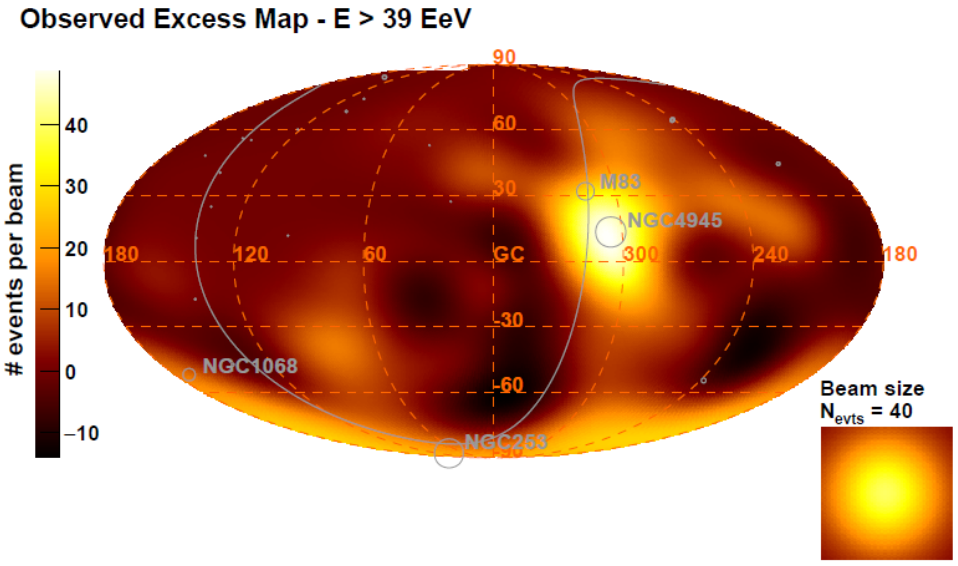


INTERMEDIATE SCALE ANISOTROPY

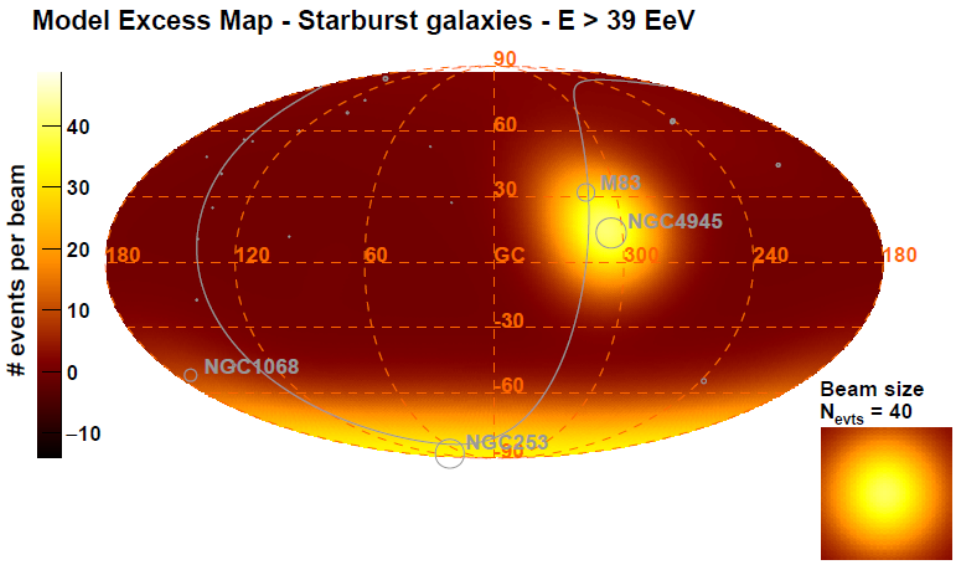
CROSS-CORRELATIONS WITH ASTROPHYSICAL SOURCES

- Cross-correlation with flux-limited catalogs
- Cross-correlation with bright AGNs & star-forming regions of starburst galaxies

Data

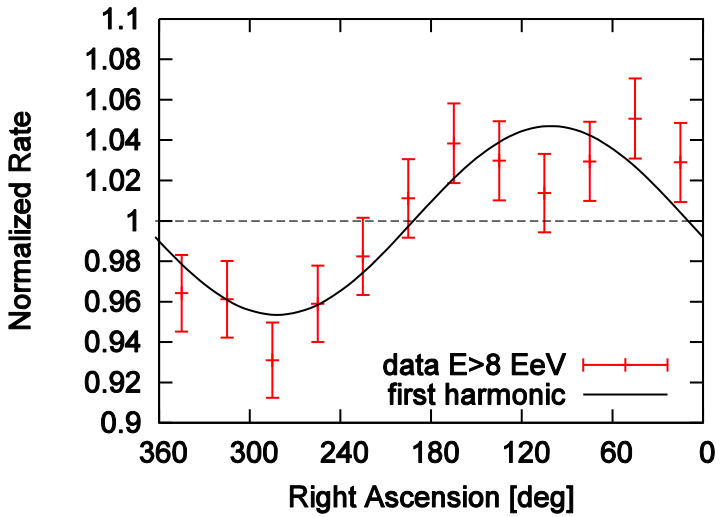


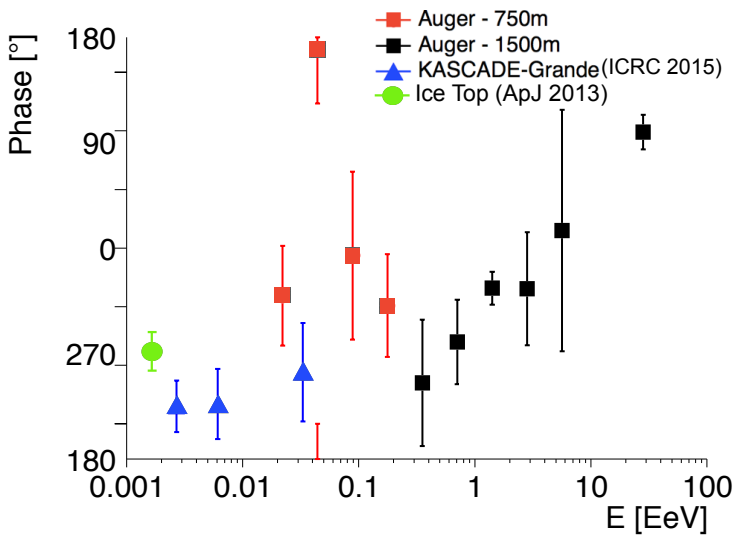
Model



VERY PRELIMINARY

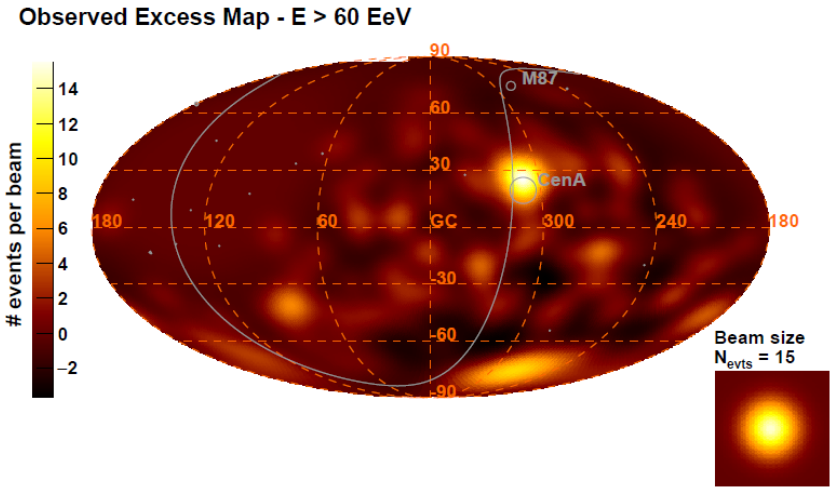
TAKE HOME MESSAGE V

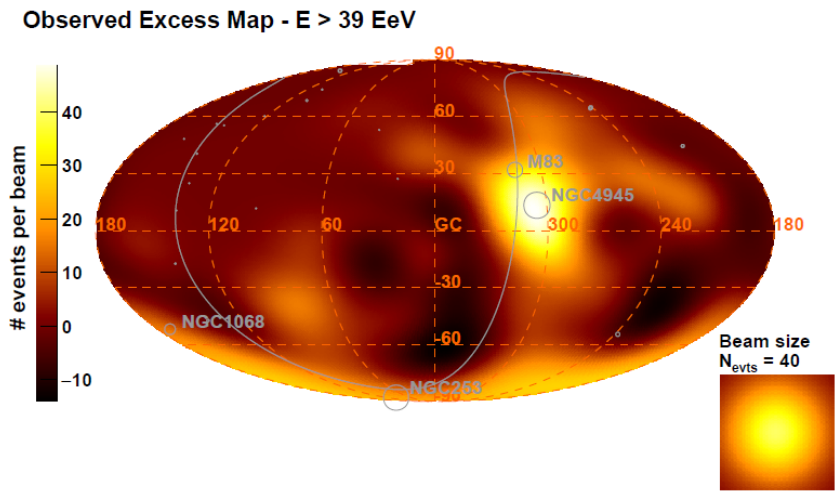




- significant observation of dipolar anisotropy
- possible phase transition around the "ankle" energy
  - exploit lower energy data
- hints of intermediate scale anisotropy only above "suppression" energy
- joint and multi-messenger analysis

TAKE HOME MESSAGE V





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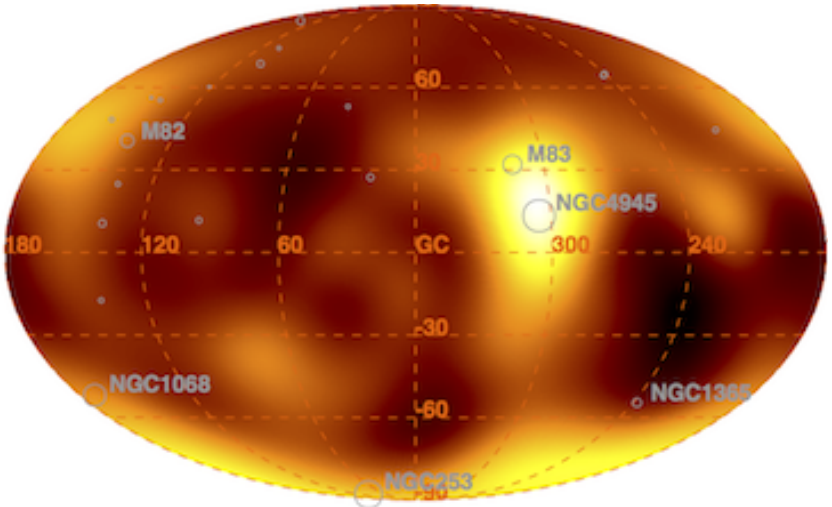

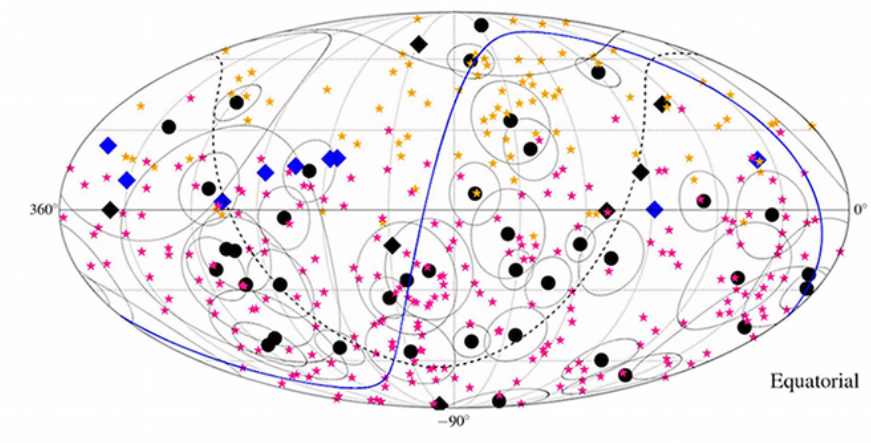

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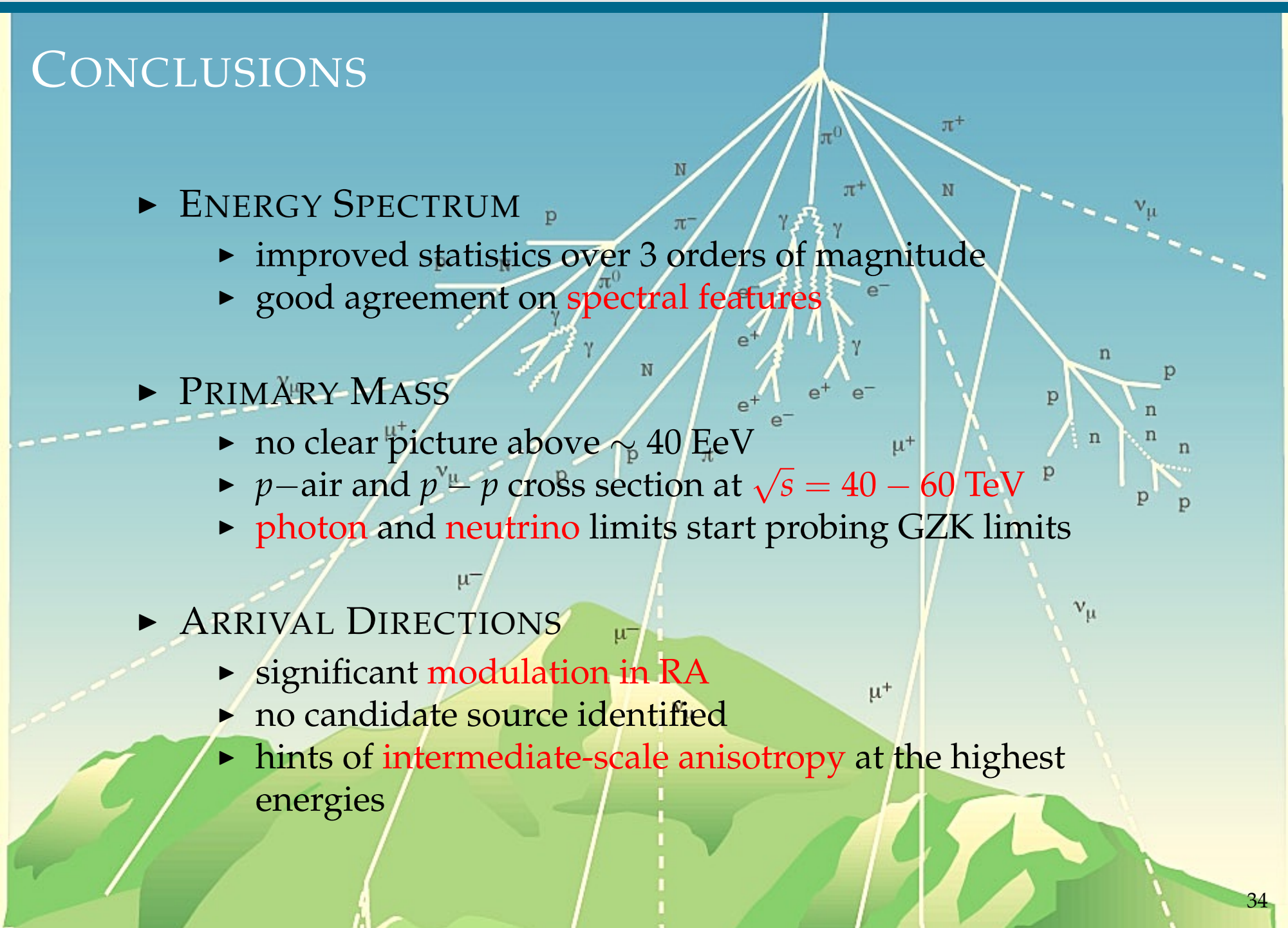
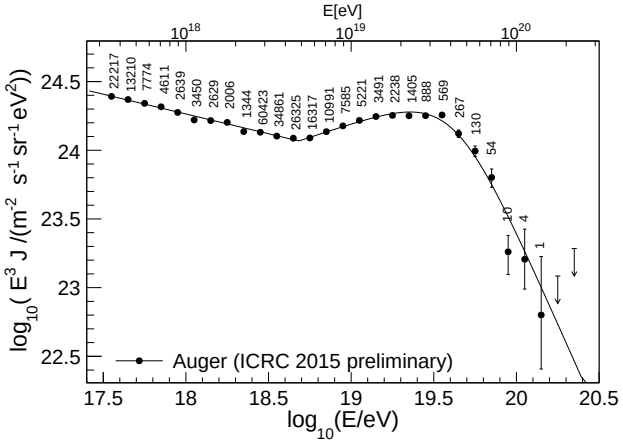
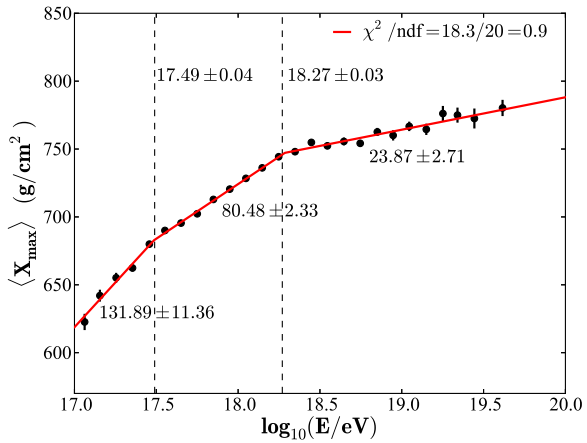
CONCLUSIONS

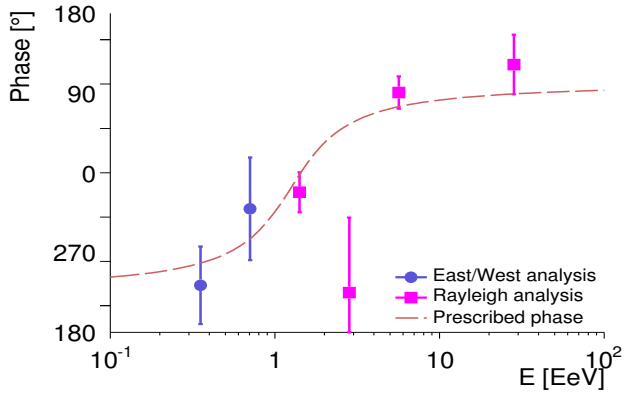


- ENERGY SPECTRUM
  - improved statistics over 3 orders of magnitude
  - good agreement on spectral features
- PRIMARY MASS
  - no clear picture above ~ 40 EeV
  - $p-$air and $p-p$ cross section at $\sqrt{s} = 40 - 60$ TeV
  - photon and neutrino limits start probing GZK limits
- ARRIVAL DIRECTIONS
  - significant modulation in RA
  - no candidate source identified
  - hints of intermediate-scale anisotropy at the highest energies

CONCLUSIONS SUMMARY



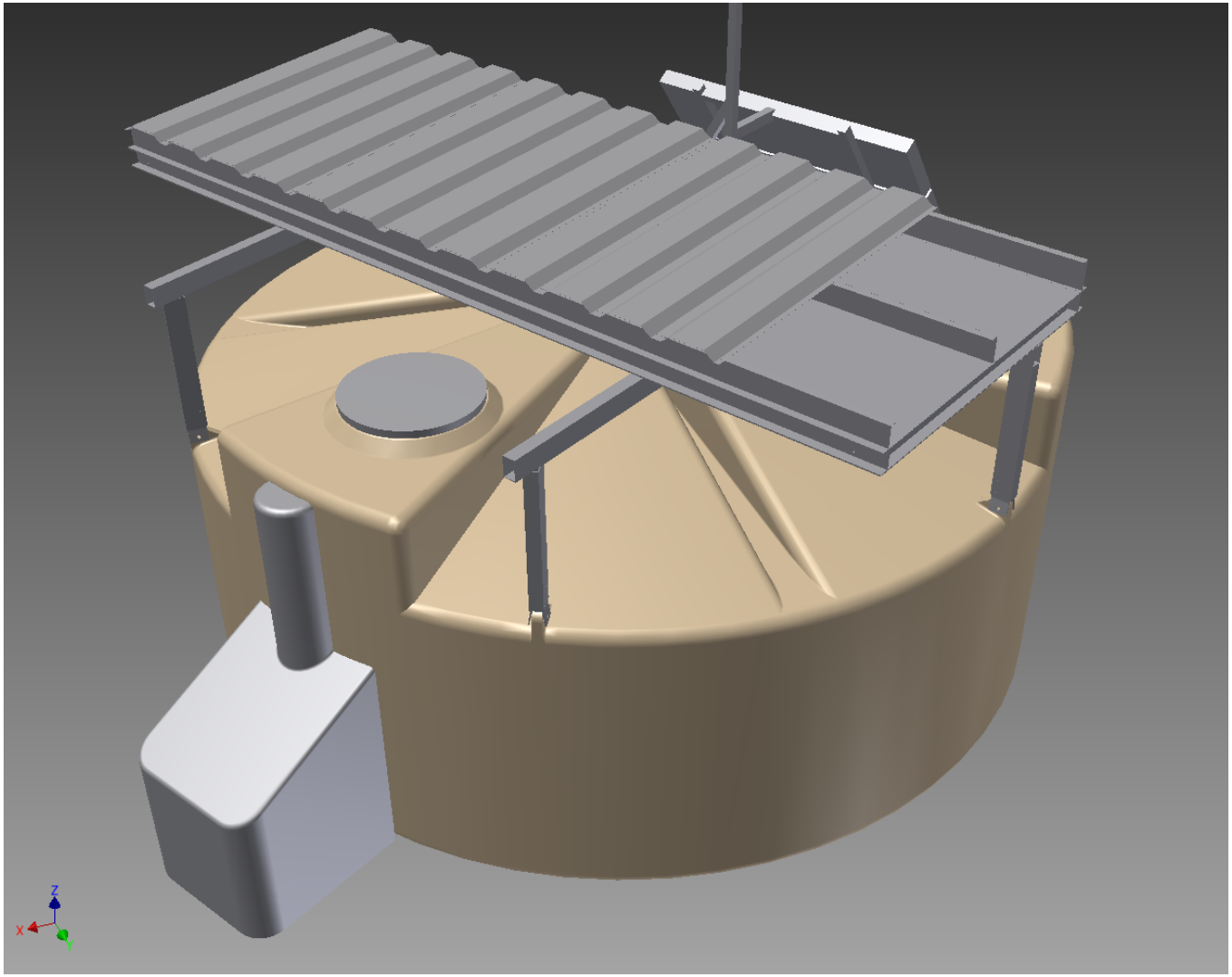




THANK YOU VERY MUCH!

BACK-UP SLIDES

DETECTOR UPGRADE



COMPARISON OF ELONGATION RATES