Studying the Pierre Auger Fluorescence Detector Using a Flying Light Source

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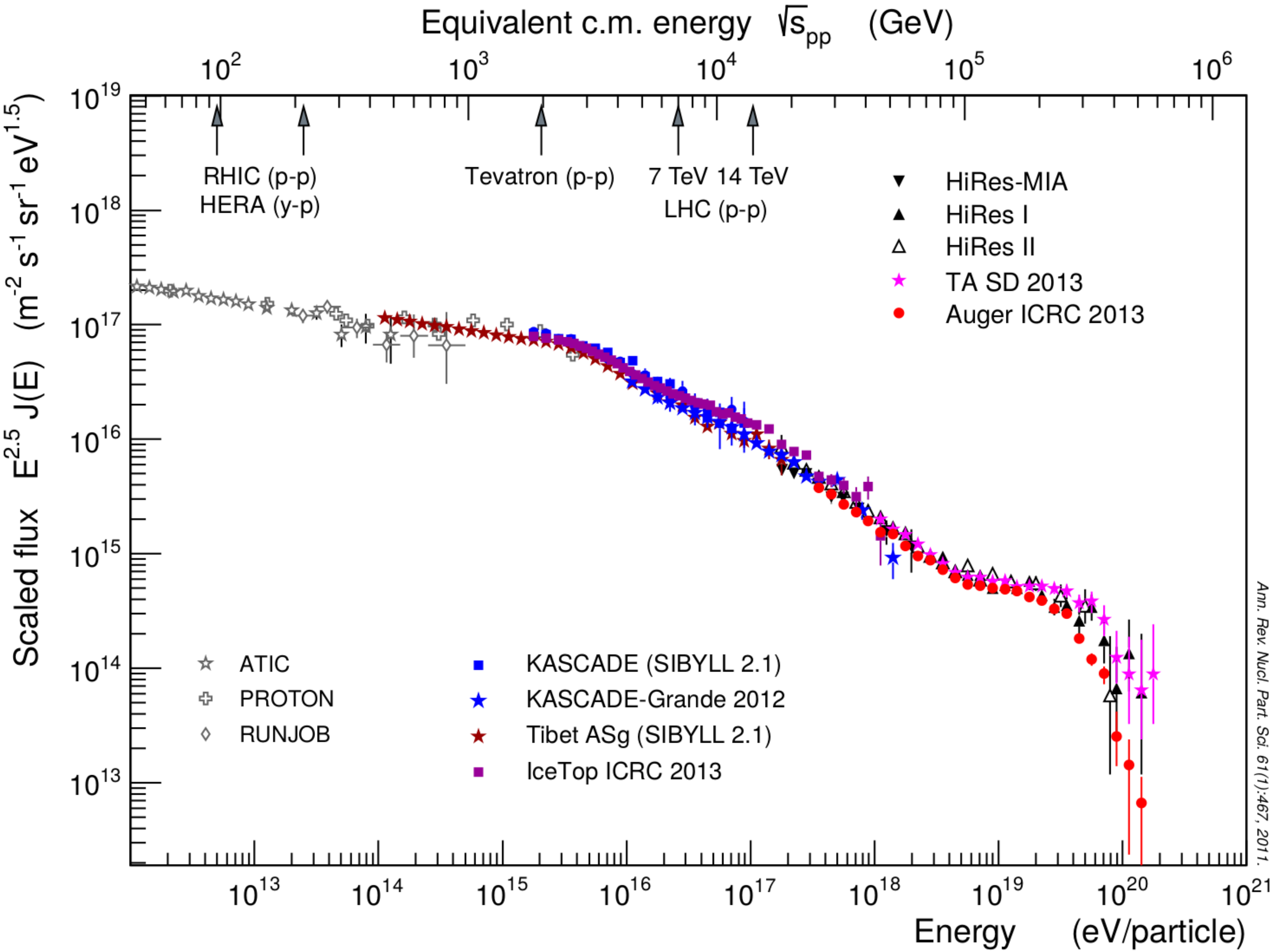
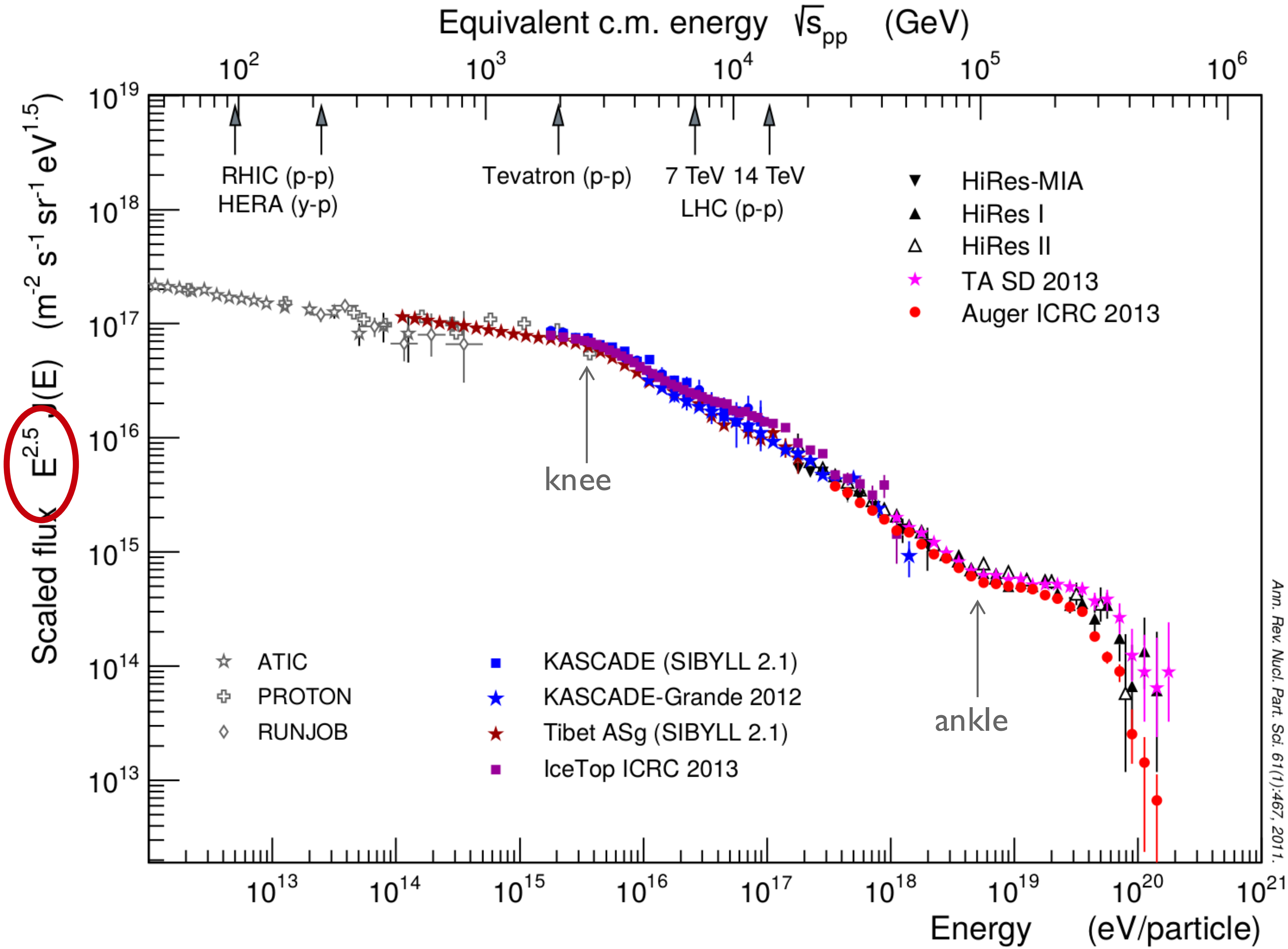
3rd KSETA Plenary Workshop, Durbach, Feb 2016

Contents

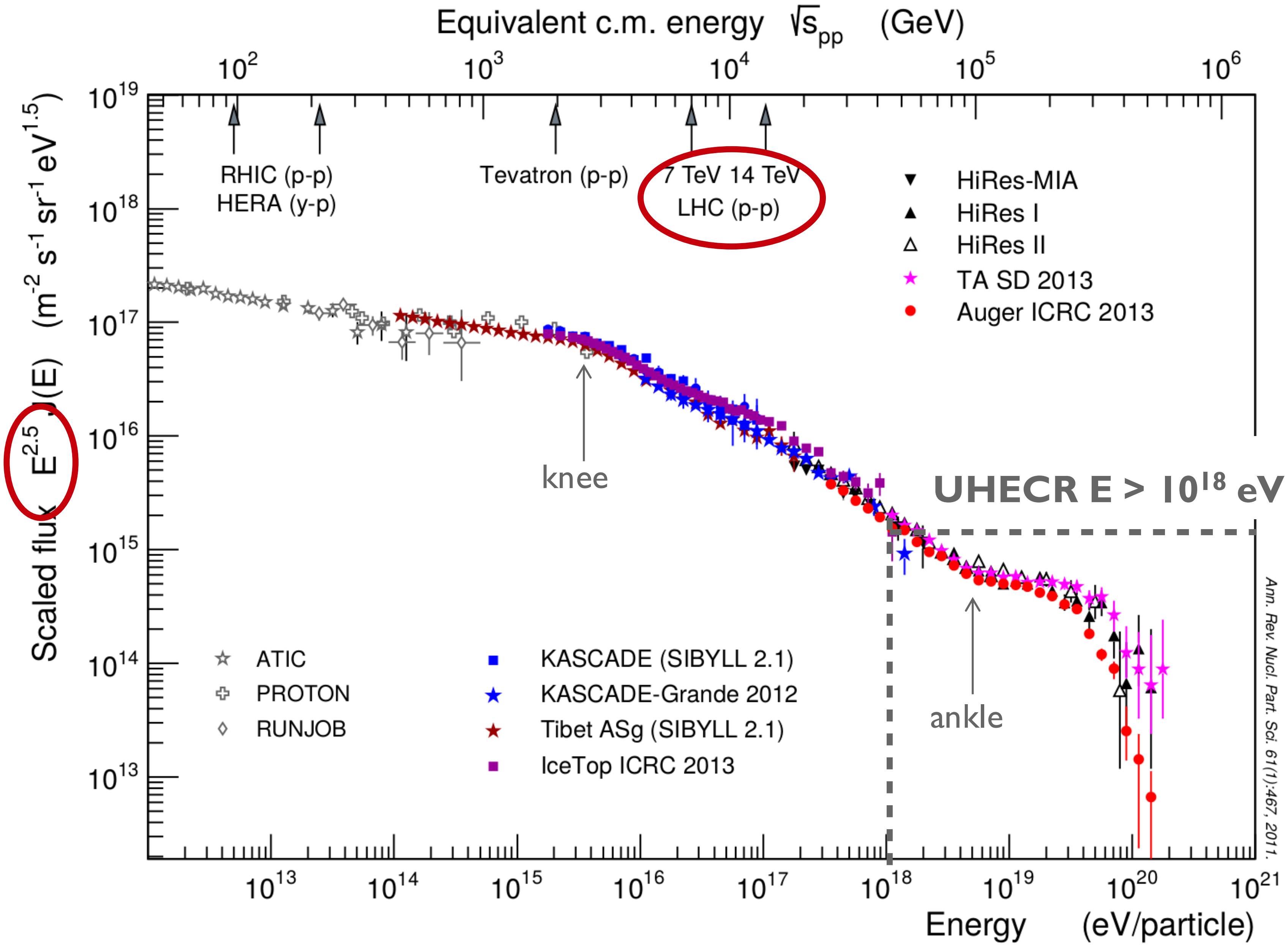
All-particle spectrum



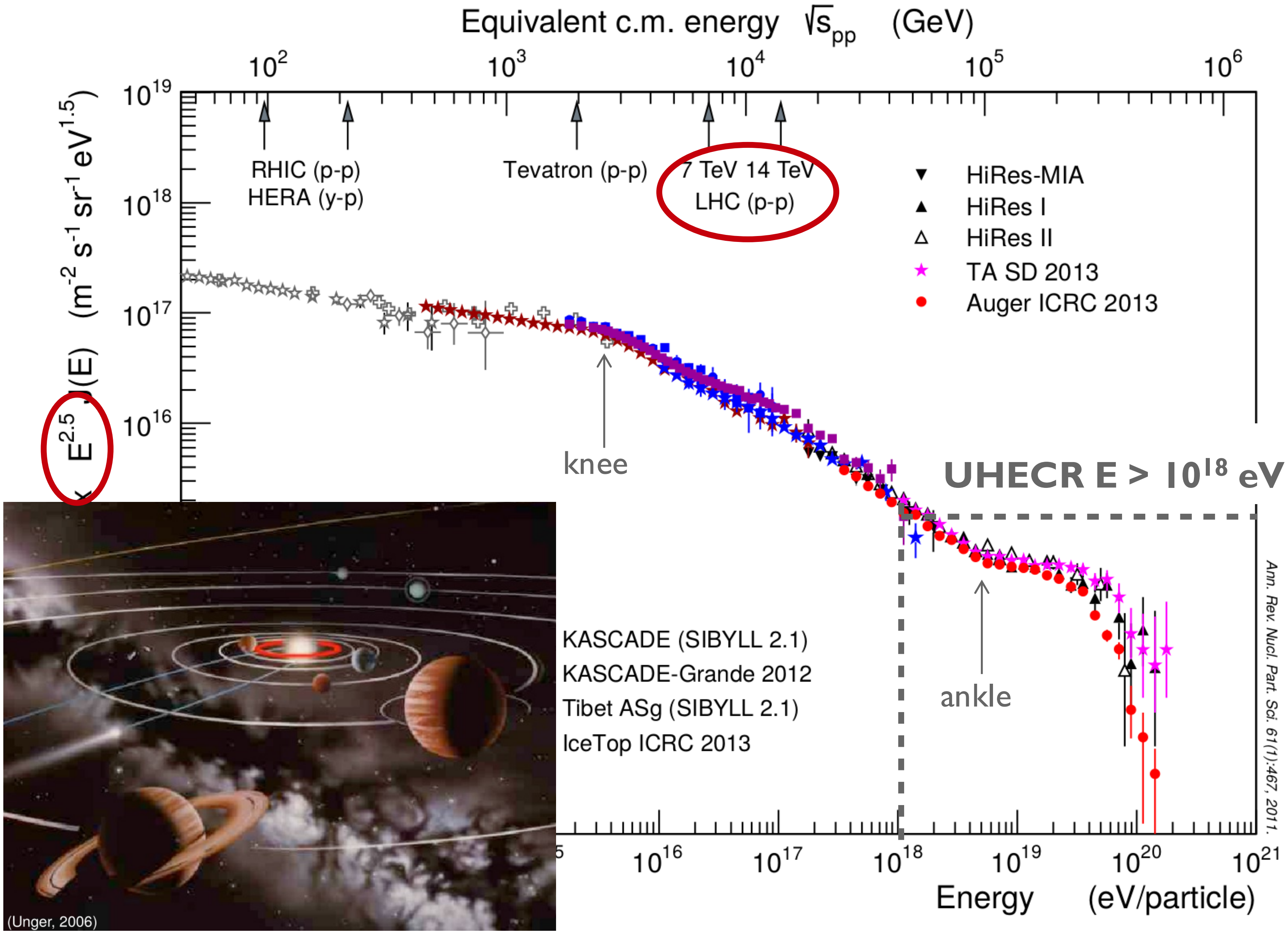
All-particle spectrum

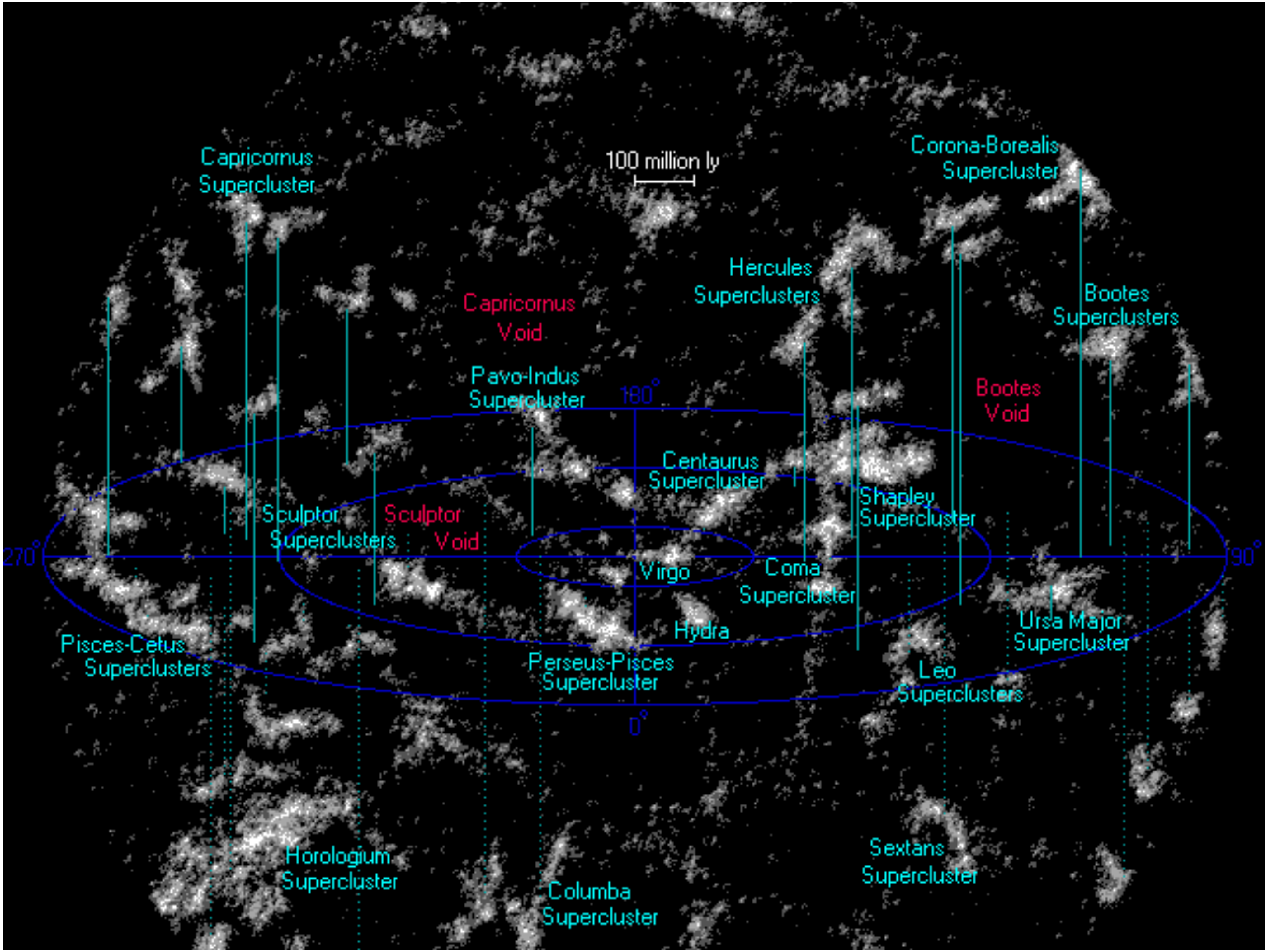


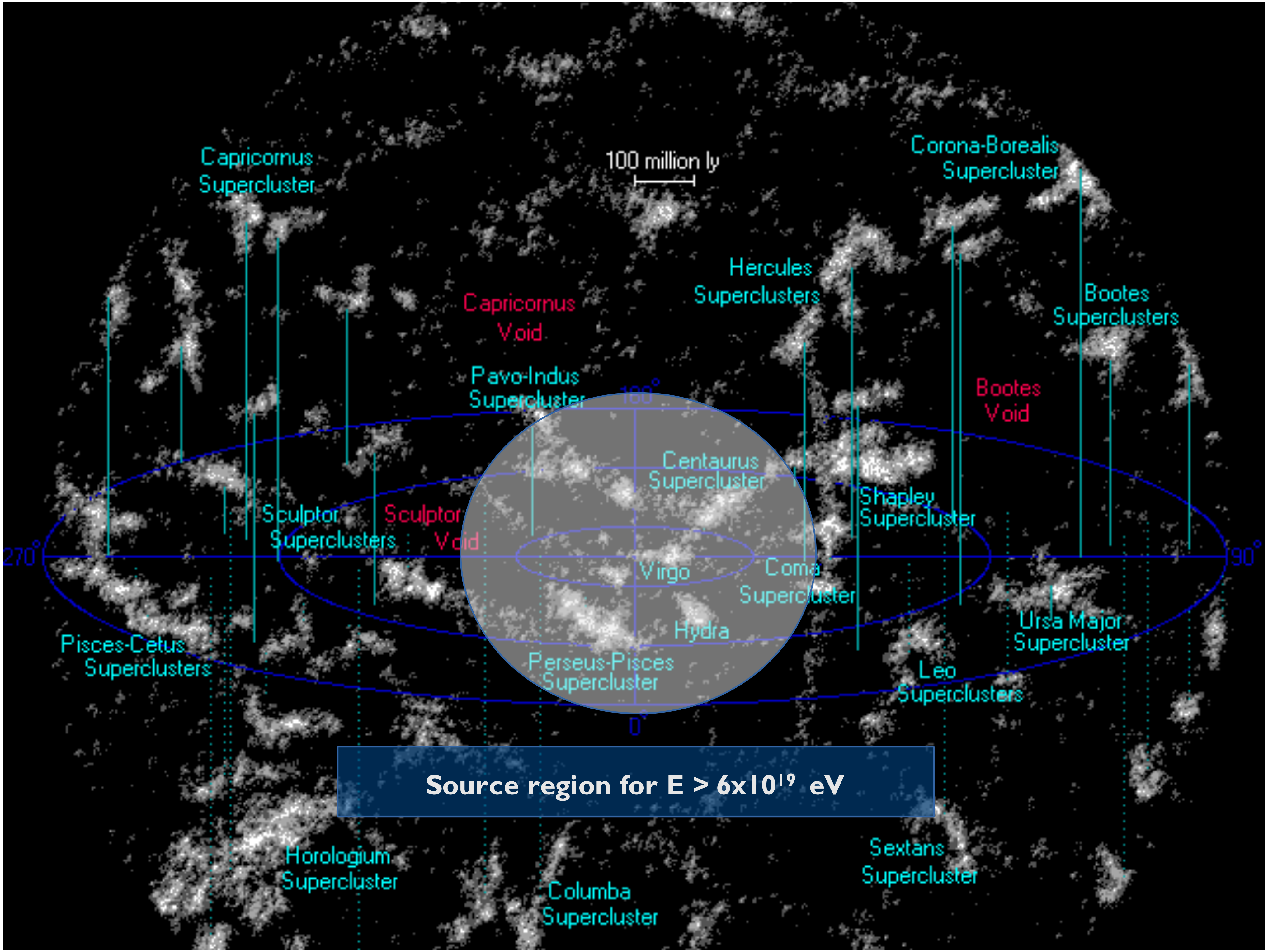
All-particle spectrum



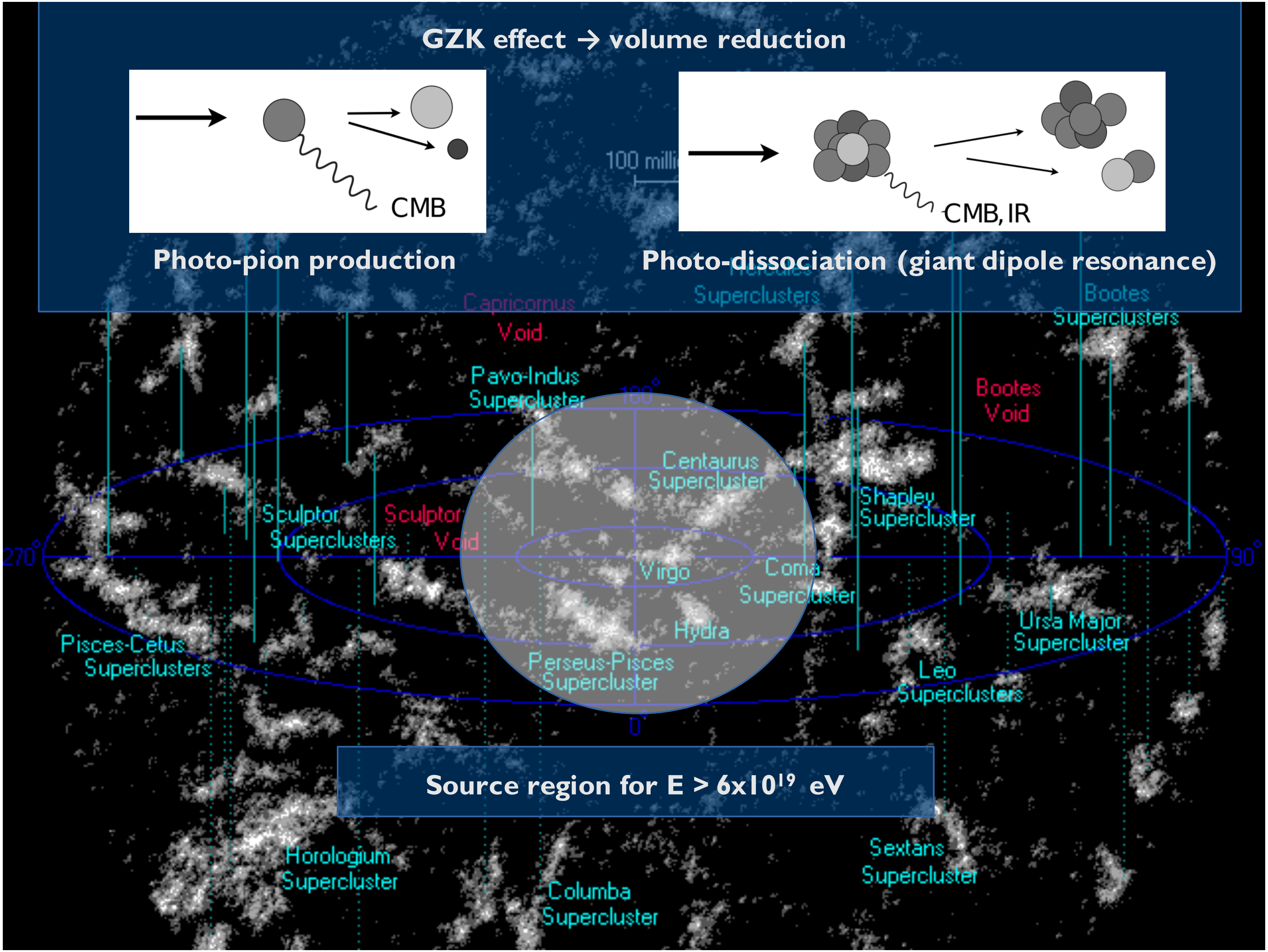
All-particle spectrum




100 million ly
Capricornus Supercluster
Capricornus Void
Corona-Borealis Supercluster
Hercules Superclusters
Bootes Superclusters
Bootes Void
Pavo-Indus Supercluster
180°
Centaurus Supercluster
Shapley Supercluster
Sculptor Superclusters
Sculptor Void
270°
90°
Virgo
Coma Supercluster
Hydra
Ursa Major Supercluster
Pisces-Cetus Superclusters
Perseus-Pisces Supercluster
Leo Superclusters
0°
Horologium Supercluster
Columba Supercluster
Sextans Supercluster

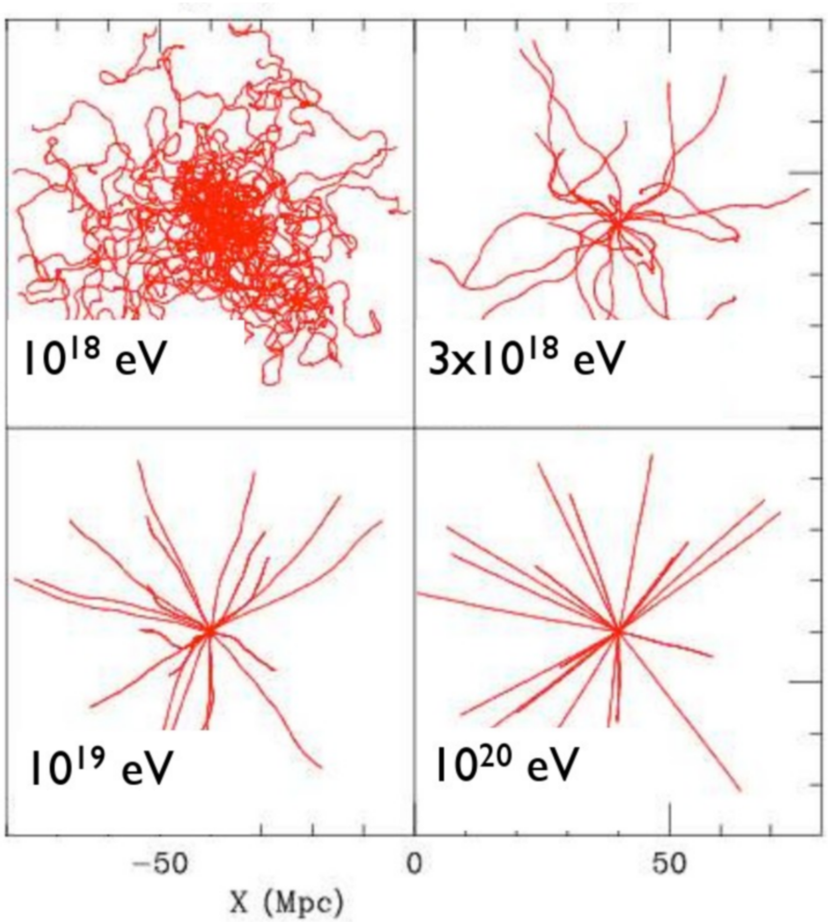


Source region for E > 6×10^{19} eV

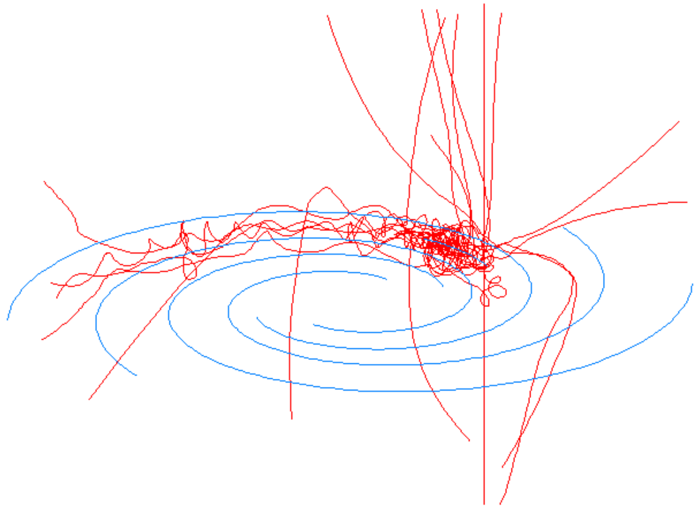

GZK effect → volume reduction
CMB
Photo-pion production
CMB, IR
Photo-dissociation (giant dipole resonance)
Capricornus Void
Superclusters
Bootes Superclusters
Pavo-Indus Supercluster
Bootes Void
180°
Centaurus Supercluster
Shapley Supercluster
Sculptor Superclusters
Sculptor Void
270°
90°
Virgo
Coma Supercluster
Hydra
Ursa Major Supercluster
Pisces-Cetus Superclusters
Perseus-Pisces Supercluster
Leo Superclusters
0°
Source region for E > 6x10^19 eV
Horologium Supercluster
Columba Supercluster
Sextans Supercluster

Magnetic deflection

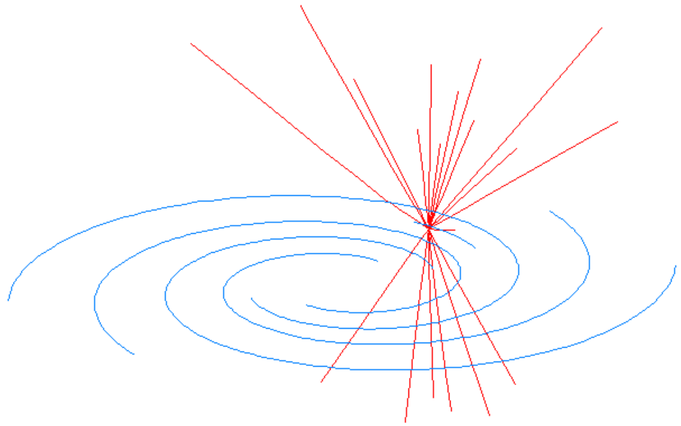
Galactic and extragalactic contributions



$$\delta \simeq 3^o \frac{B}{3\,\mu G} \frac{L}{kpc} \frac{6\times 10^{19} eV}{E/Z}$$



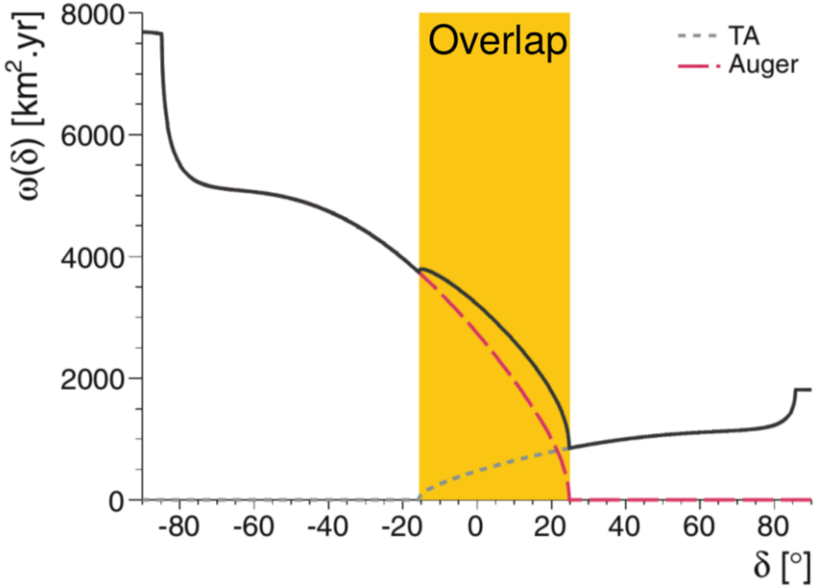
Proton E = 1 EeV



Proton E = 100 EeV

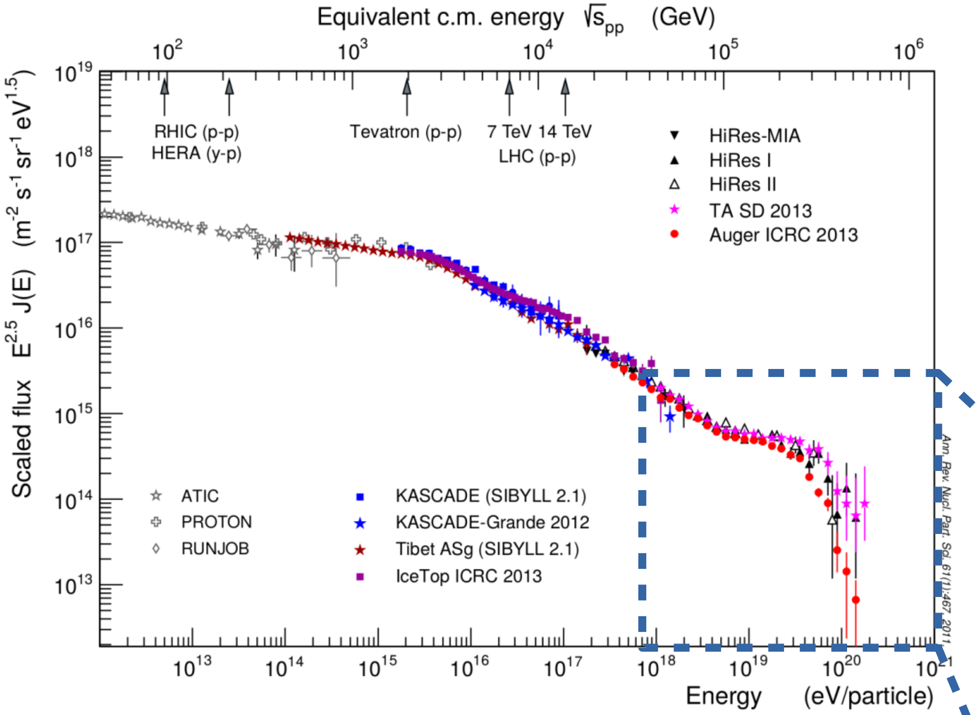
Current UHECR observatories

Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km²
36 fluorescence telescopes

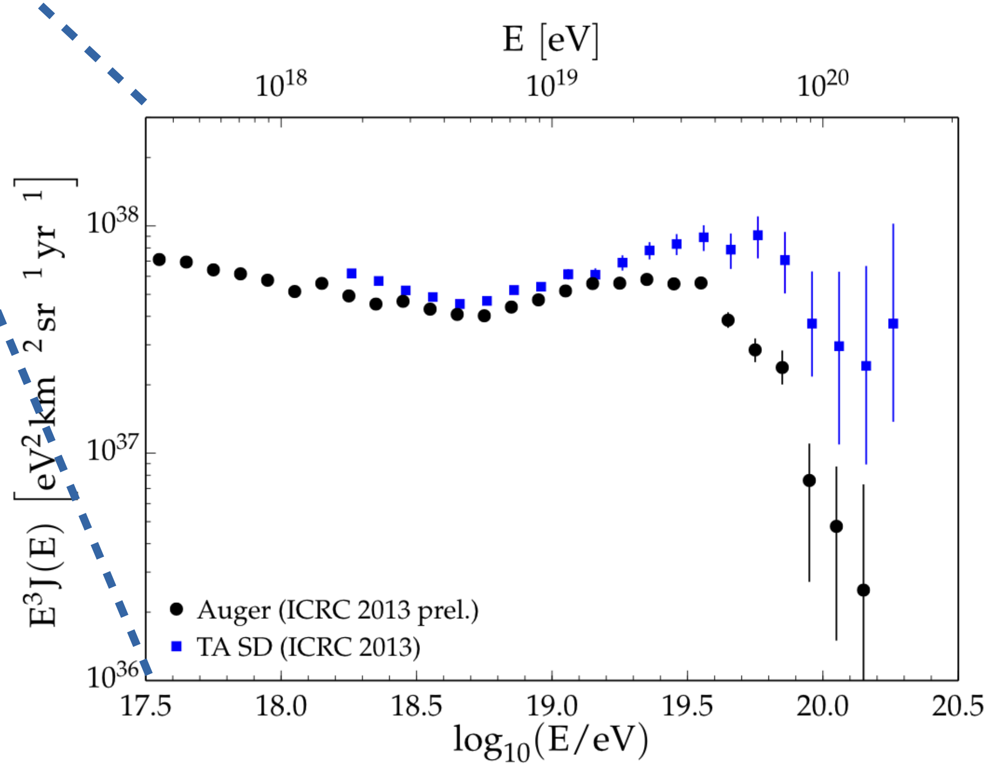


Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km²
27 fluorescence telescopes

Difference in Auger and TA spectra

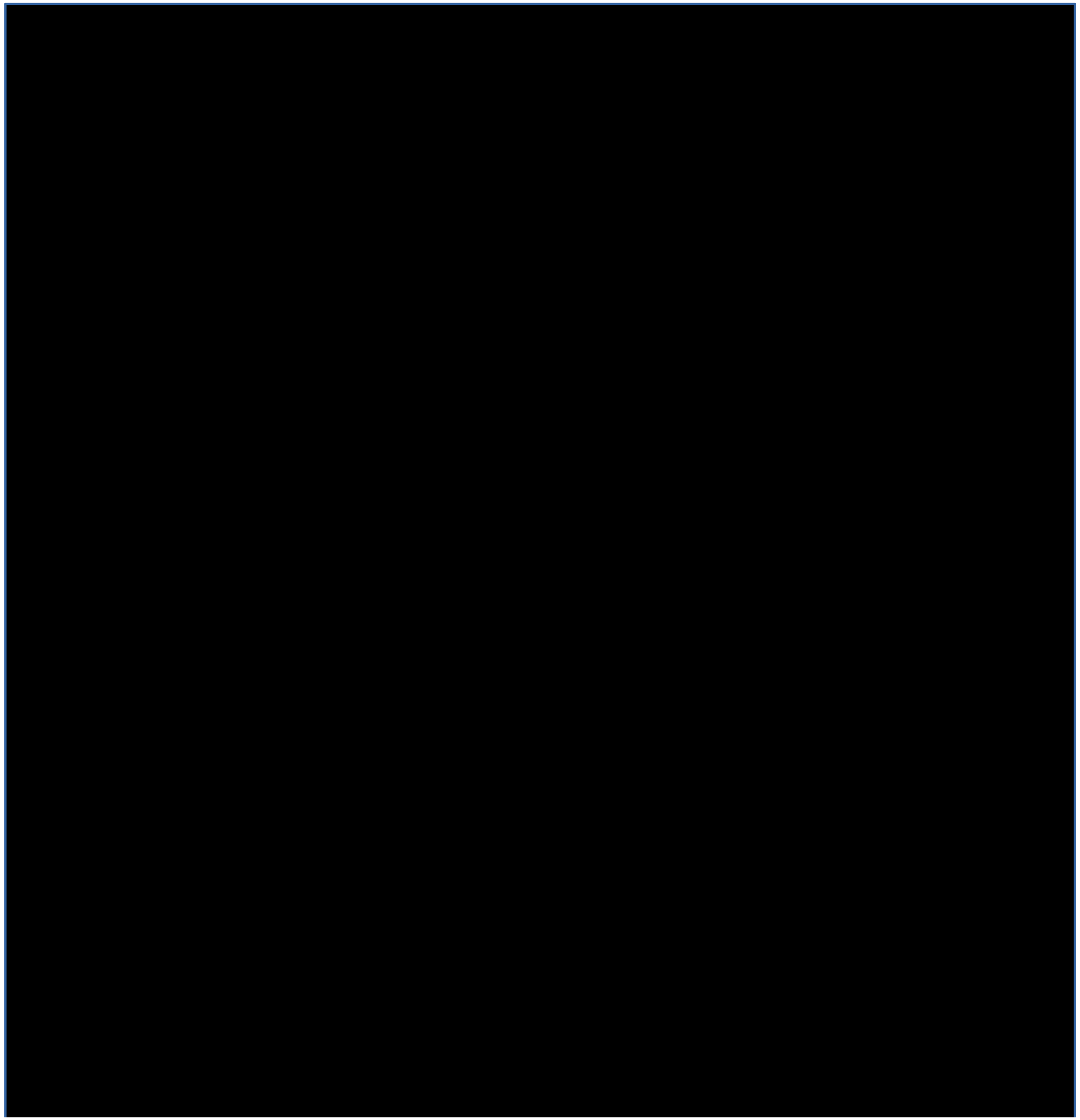


Real difference due to
large-scale anisotropy
or an **artifact of calibration?**

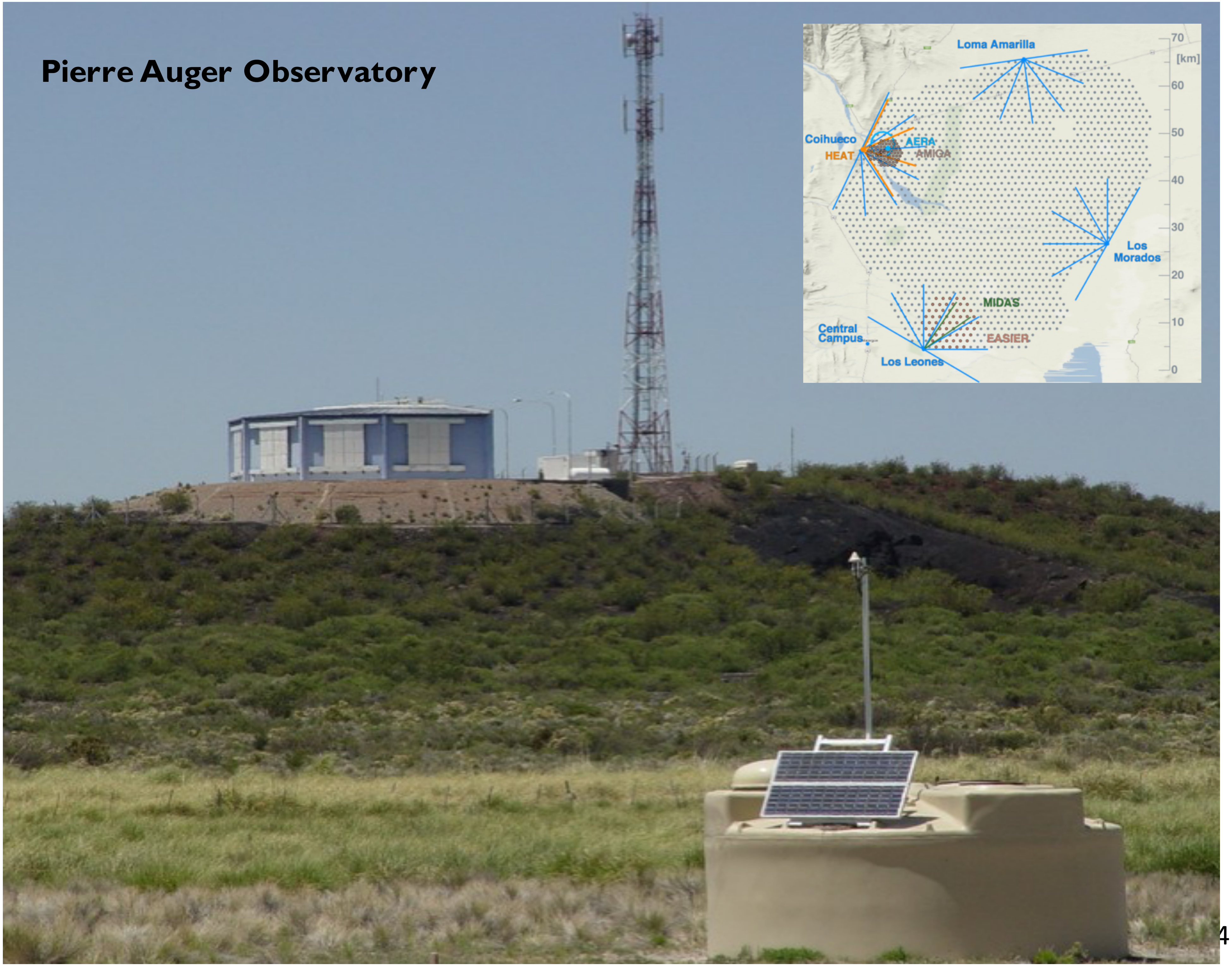


	Energy scale	FD calibration
Auger	14%	9.9%
TA	21%	10%

Extensive air shower



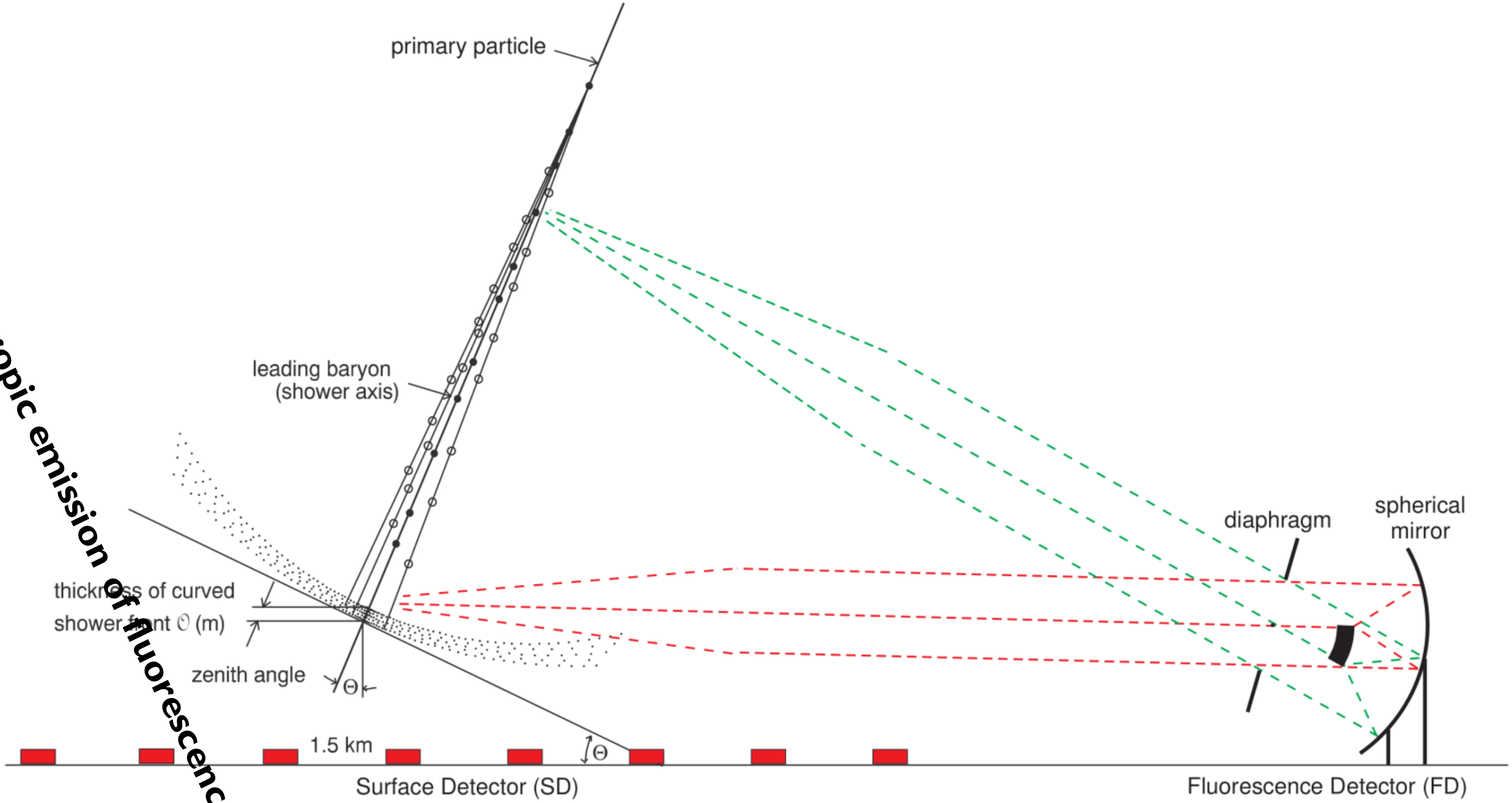
Pierre Auger Observatory



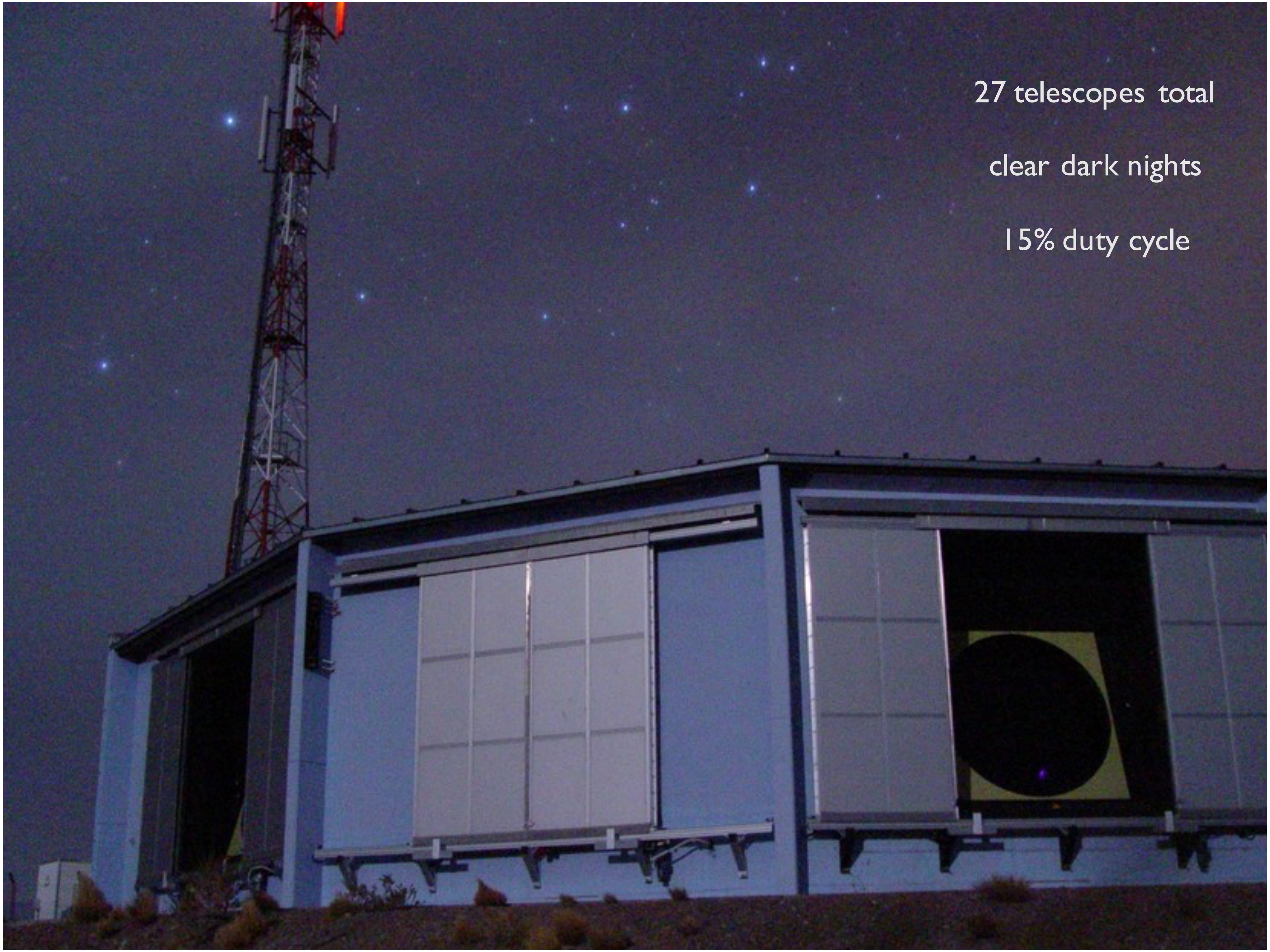
Shower detection by fluorescence telescopes

1. **Calorimetric energy** model-indep

2. **Longitudinal shower profile** indicative of p



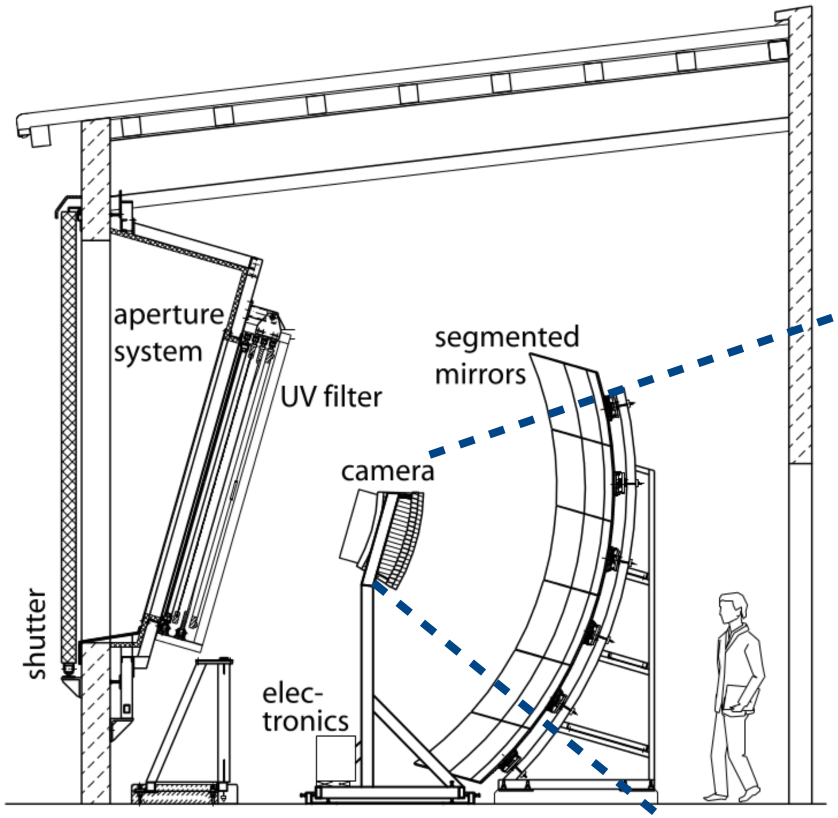
Isotropic emission of fluorescence ligh


27 telescopes total
clear dark nights
15% duty cycle

2.2m diameter aperture with UV filter

13m^2 segmented mirror

440 PMTs per camera



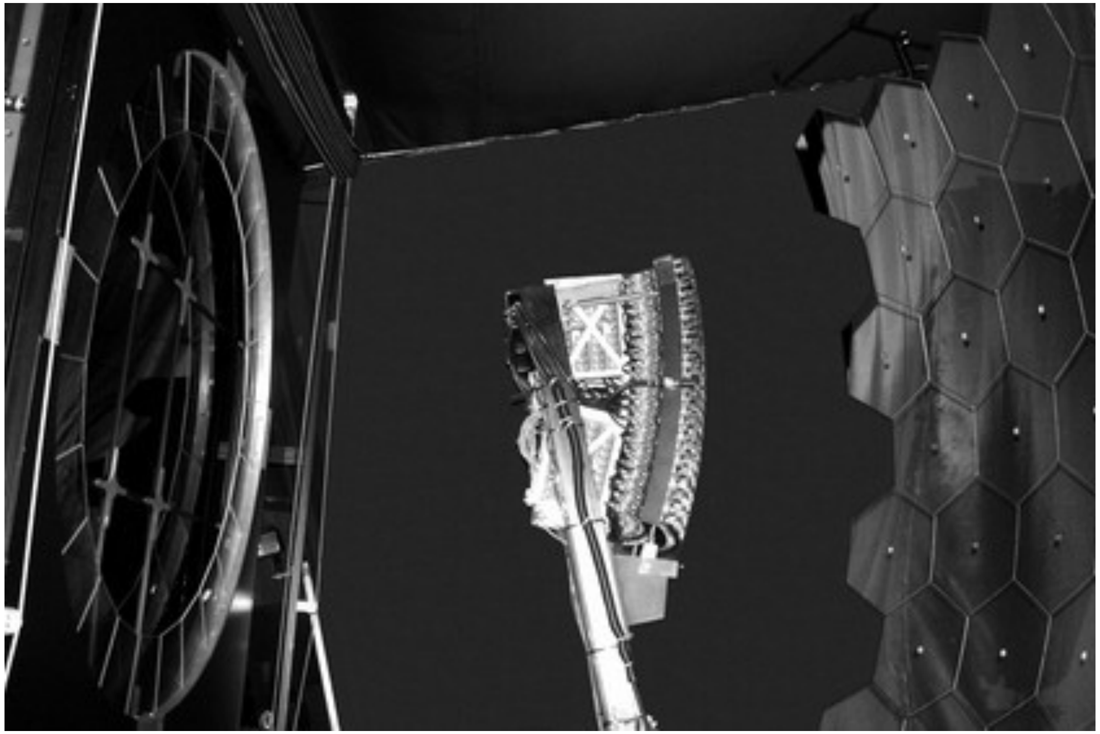


Image of shower on camera

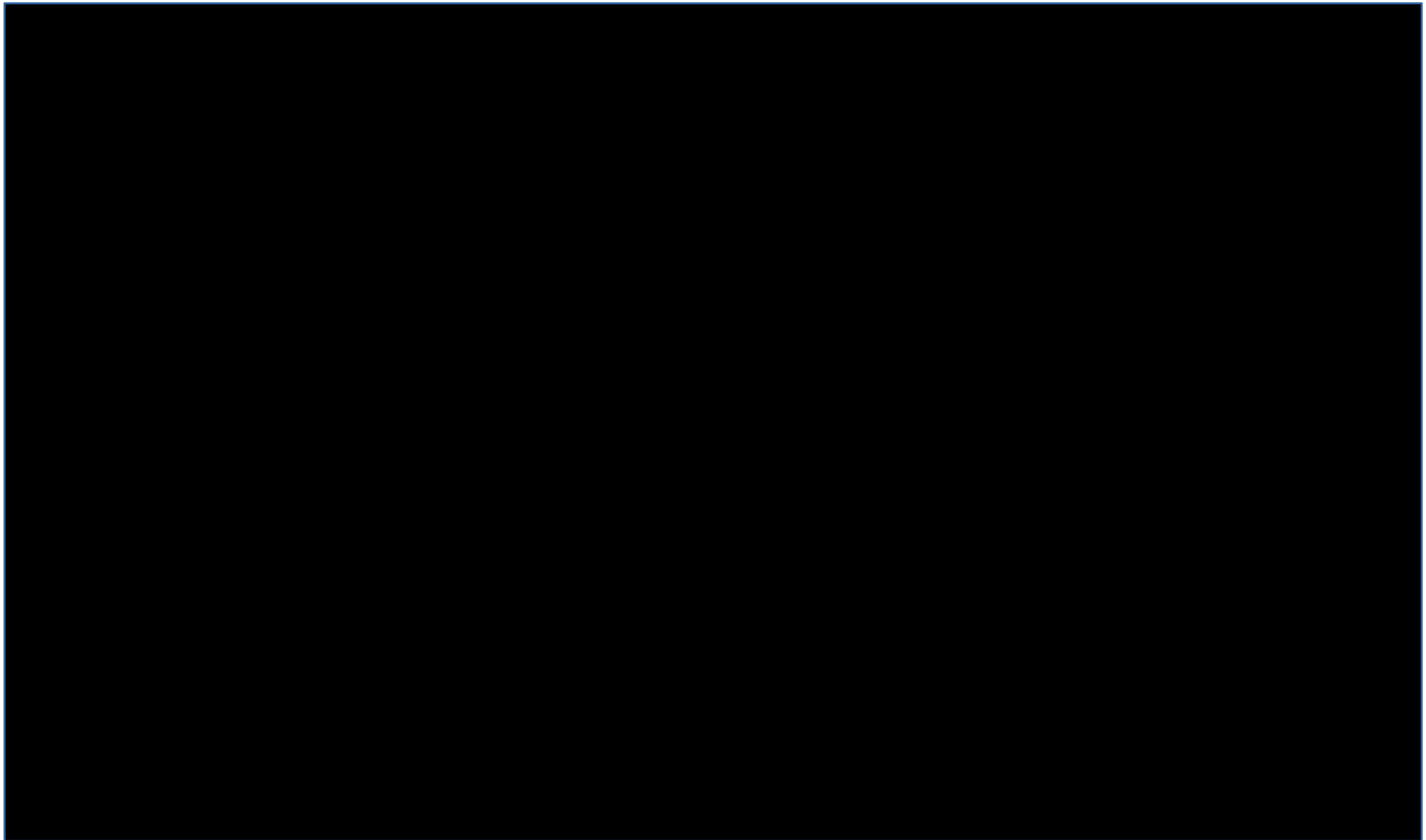
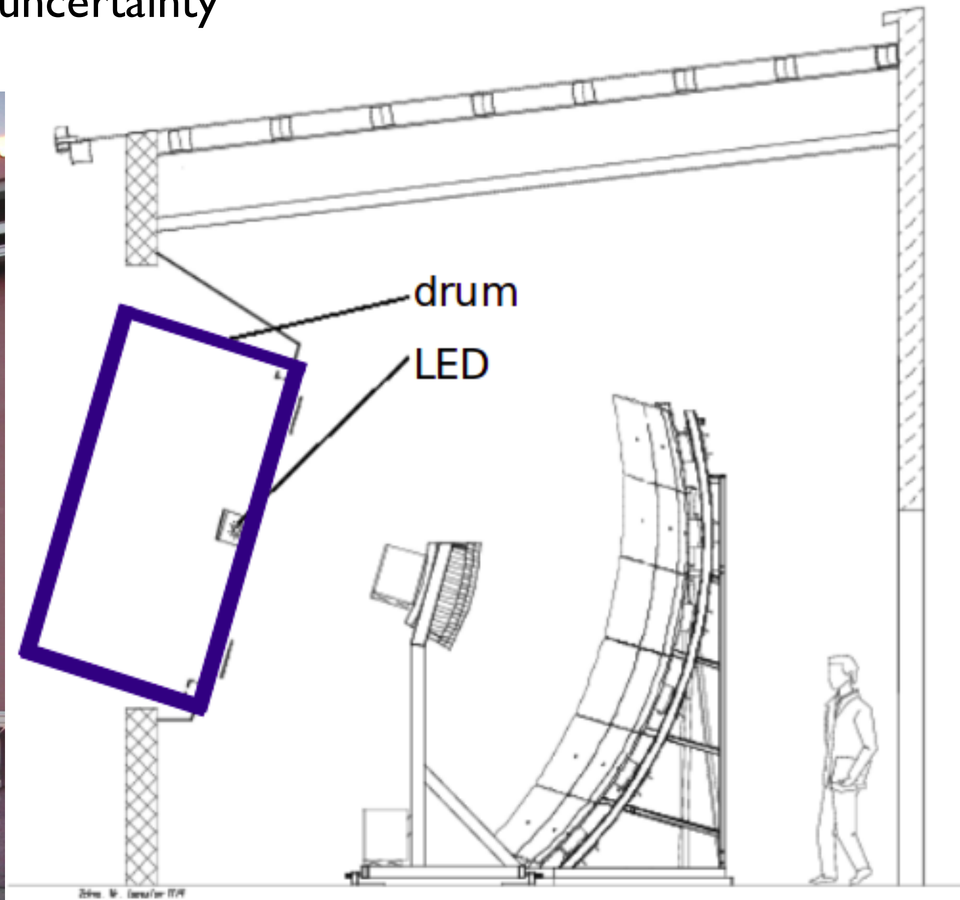


Image of shower on camera

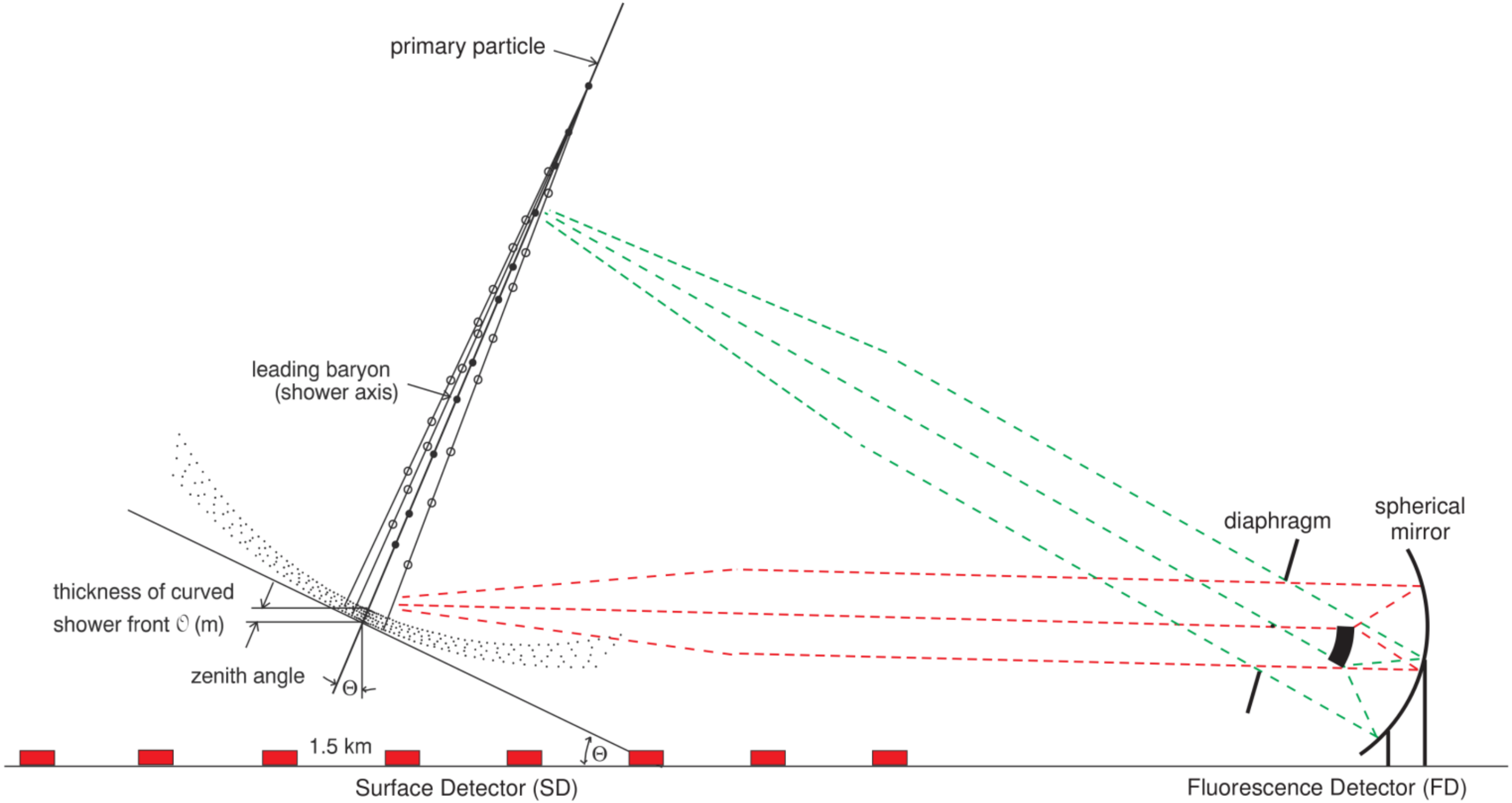
Absolute (drum) calibration

- Large-diameter Lambertian source
- Entire camera read out simultaneously
- Very “un-shower-like”
- 9.9% systematic uncertainty



Flying light source

The idea: replace air shower by a light source of known properties



Flying light source

The idea: replace air shower by a light source of known properties

The Octocopter

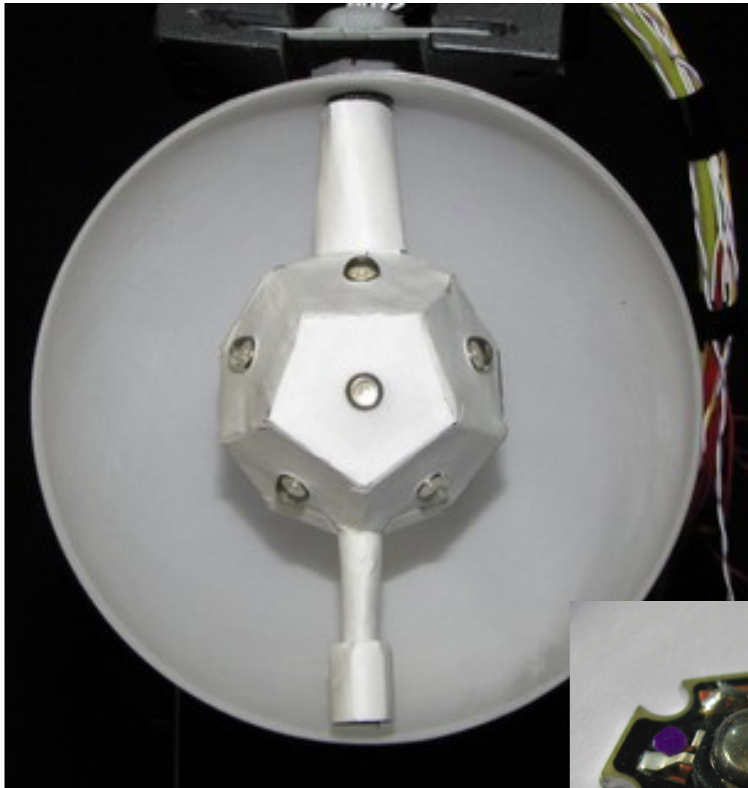
- Remotely flown commercial platform (mikrokopter)
- Redundancy of 1–2 rotors
- Payloads up to ~1 kg
- 3D GPS-assisted waypoint flight → fly in the FOV
- Electronically stabilized
- Flight time up to 20 min

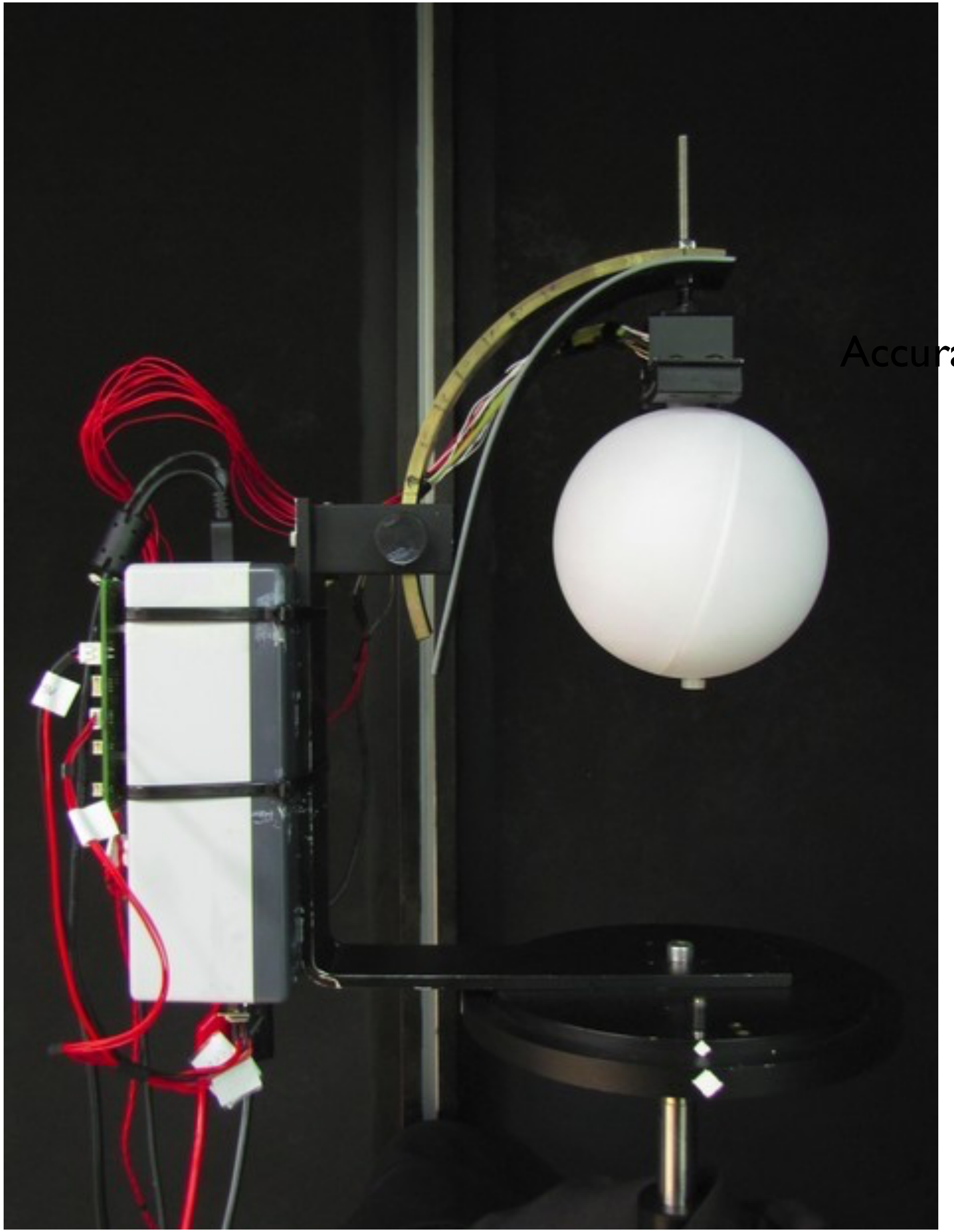
Light source

- Emission spectrum in **UV**
- **Isotropic & homogeneous**
- **Point-like**

regular dodecahedron structure
12 individually driven LEDs
inside coated with Tyvek
diffuser sphere

isotropic to 0.5%
⌀ 10 cm, 150 g total



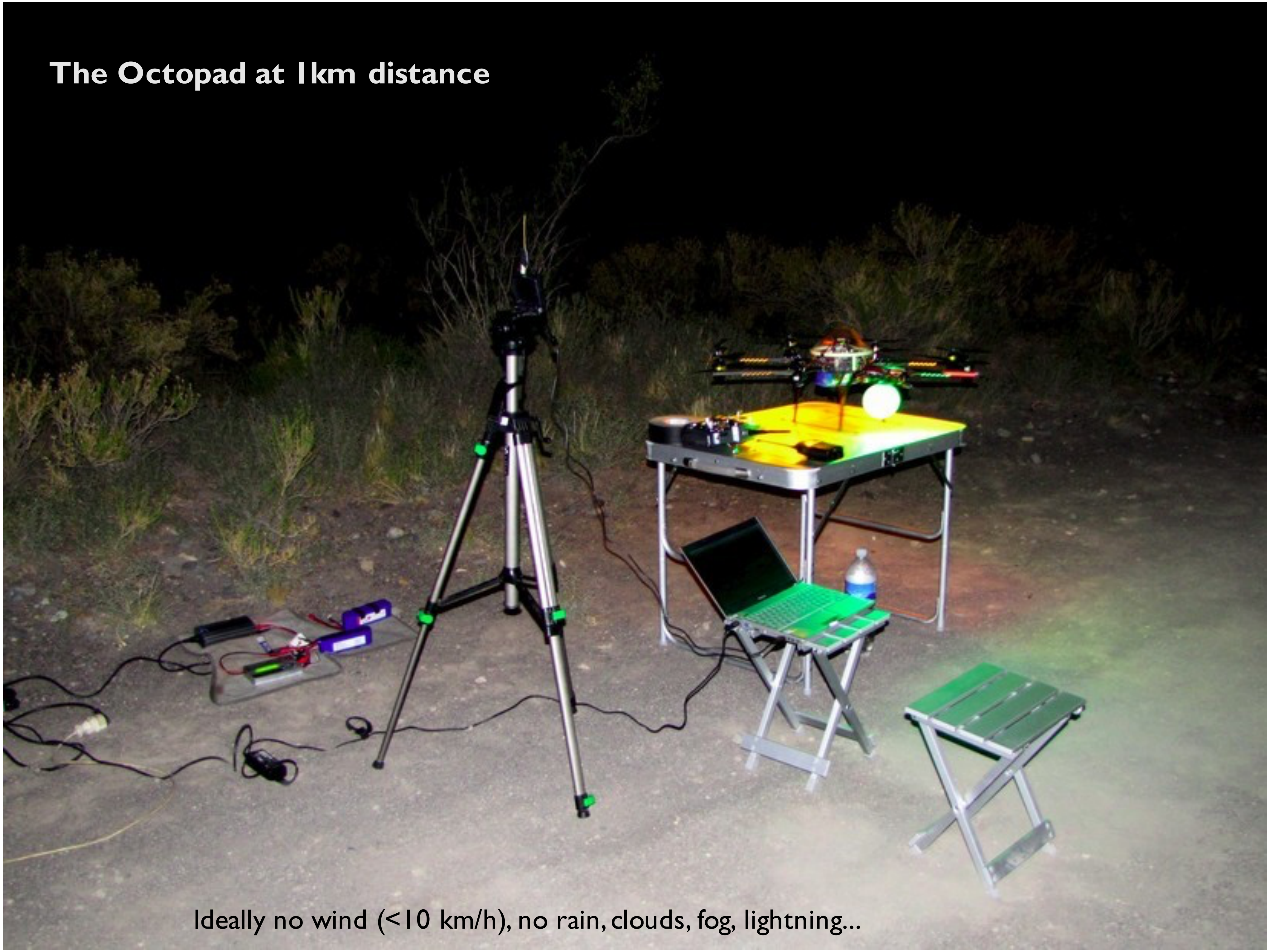


Absolute light source calibration

Accuracy of number of photons at the aper

Error source	%
Energy msmt.	1.4
Intensity stability	1.2
Atmospheric effects	1.4
Flight distance	0.6
Isotropy	0.5
Other	0.2
TOTAL	**3.7**

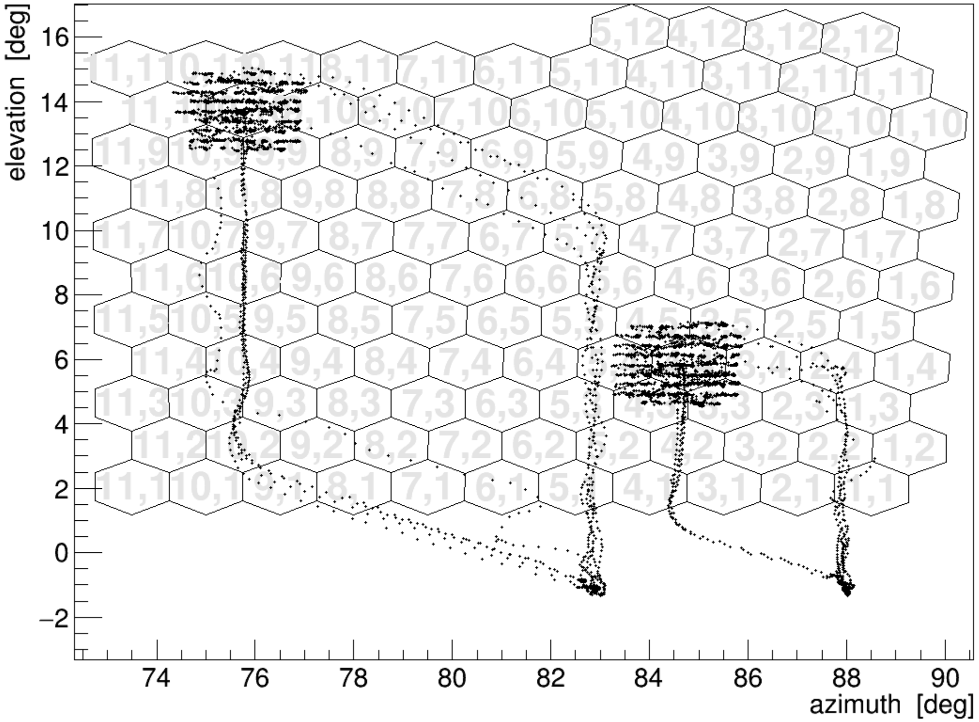
The Octopad at 1km distance



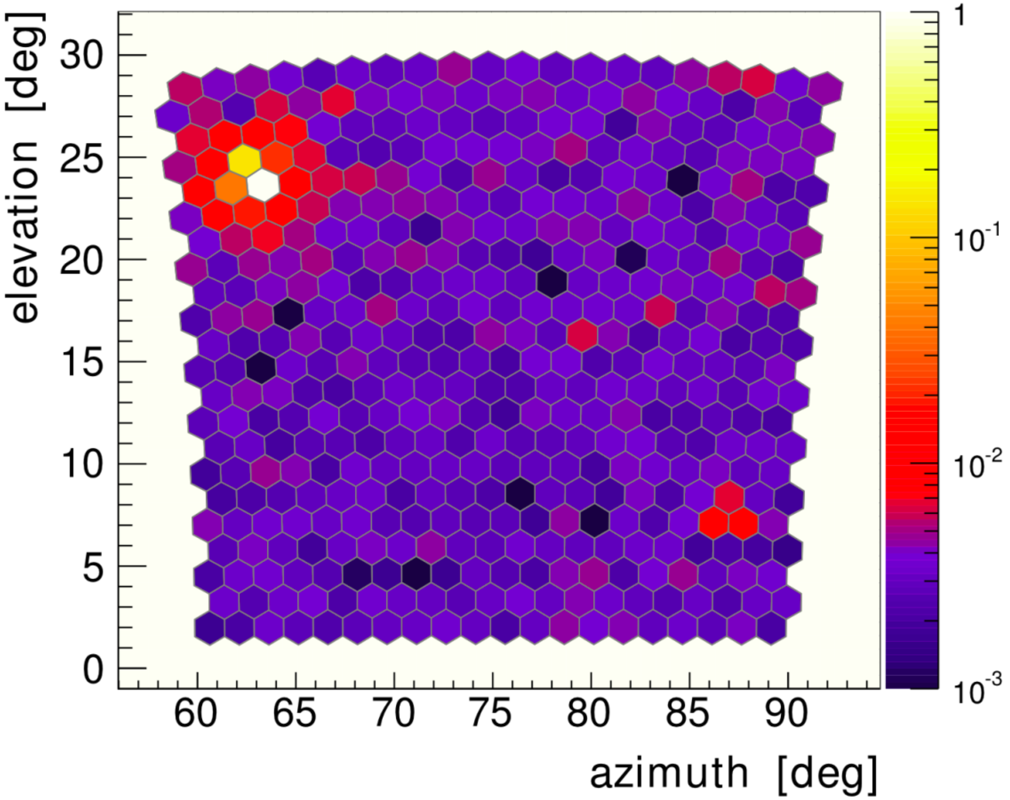
Ideally no wind (<10 km/h), no rain, clouds, fog, lightning...

Stiff-neck-prevention program...

Octocopter image on the camera



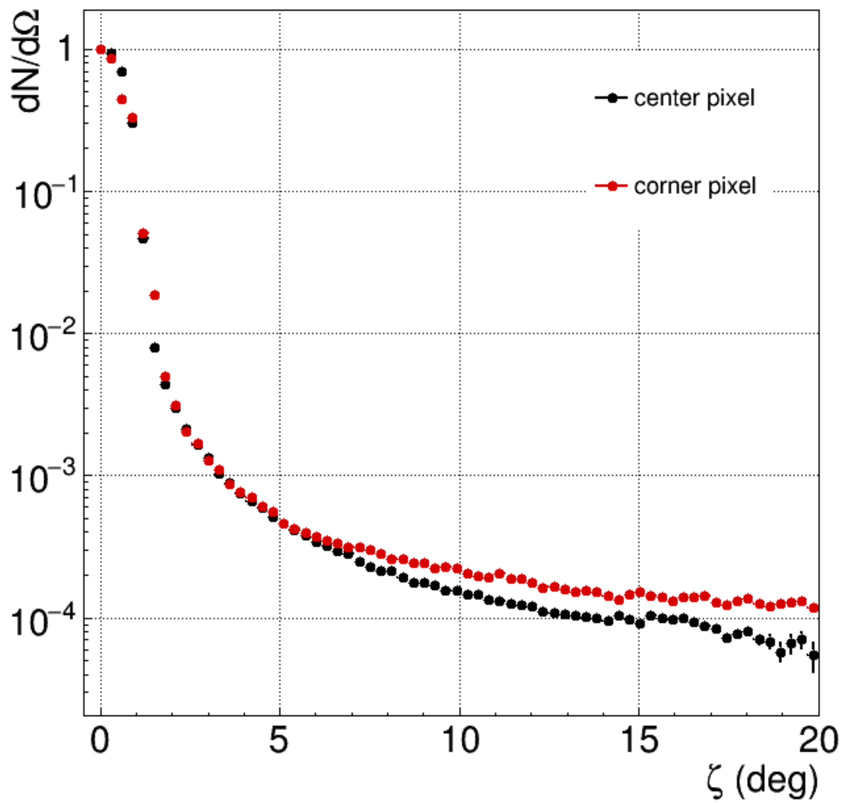
Octocopter image



∅ of pixel FOV 1.5°

∅ of light source at 1 km <0.01°

Effective spot size ~0.6°



Optical halo: widening of the image

Ghost image (multiple reflections)

Absolute calibration cross-check

e the **reconstructed number of photons at the aperture** with the **expectation from Oct**

$$\text{Reconstructed light fraction} = \frac{N_\gamma^{\text{reconstructed}}}{N_\gamma^{\text{Octocopter}}}$$

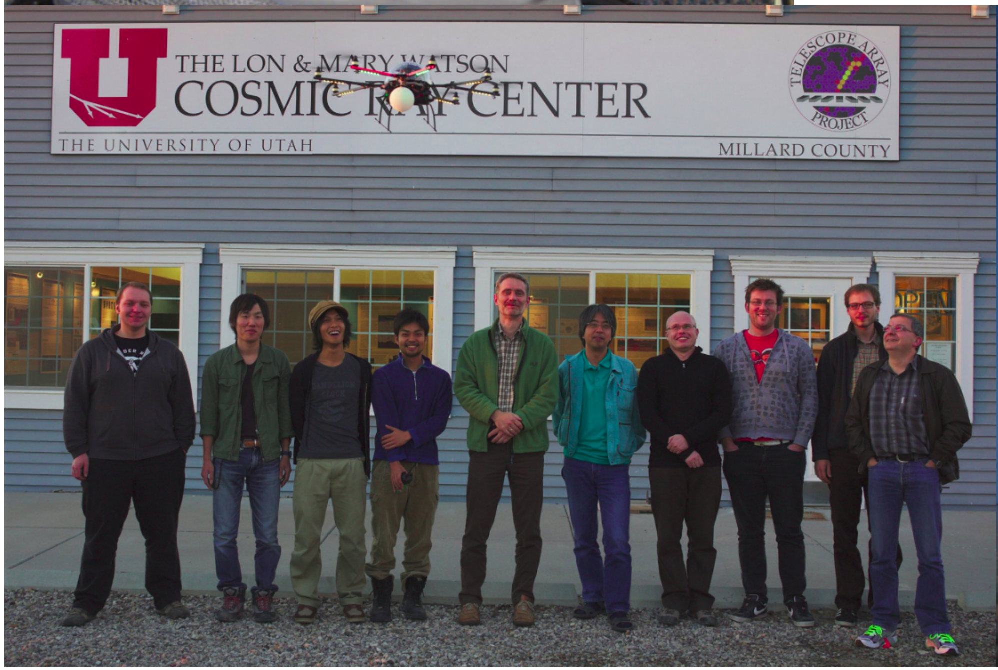
Using standard FD calibration co

From Octocopter light source c

Integration region	Pixel	
	r10/c10 p208	r04/c17 p356
Hottest pixel	0.675 ± 0.028	0.653 ± 0.027
$\zeta = 1.14°$	0.812 ± 0.034	0.772 ± 0.032
$\zeta = 4.0°$	0.863 ± 0.036	0.817 ± 0.034
Entire camera	0.919 ± 0.039	0.880 ± 0.037

Cross-calibration with TA

- Octocopter fits into a carry-on, fully portable
- First cross-calibration measurements at TA dor
- Analysis in progress



Conclusions

- Energy calibration of observatories is of key importance
- Octocopter is well suited for end-to-end in-situ studies
- Alternative calibration at Auger with 5% accuracy (prev. 9.9%)
- Improved understanding of the point spread function

References & acknowledgements

[1] J. N. Matthews for the Pierre Auger and Telescope Array Collaborations, Progress Towards a Cross-Calibratio

[2] K. Machida for the Pierre Auger and Telescope Array Collaborations, Light Source Test At the Telescope Array

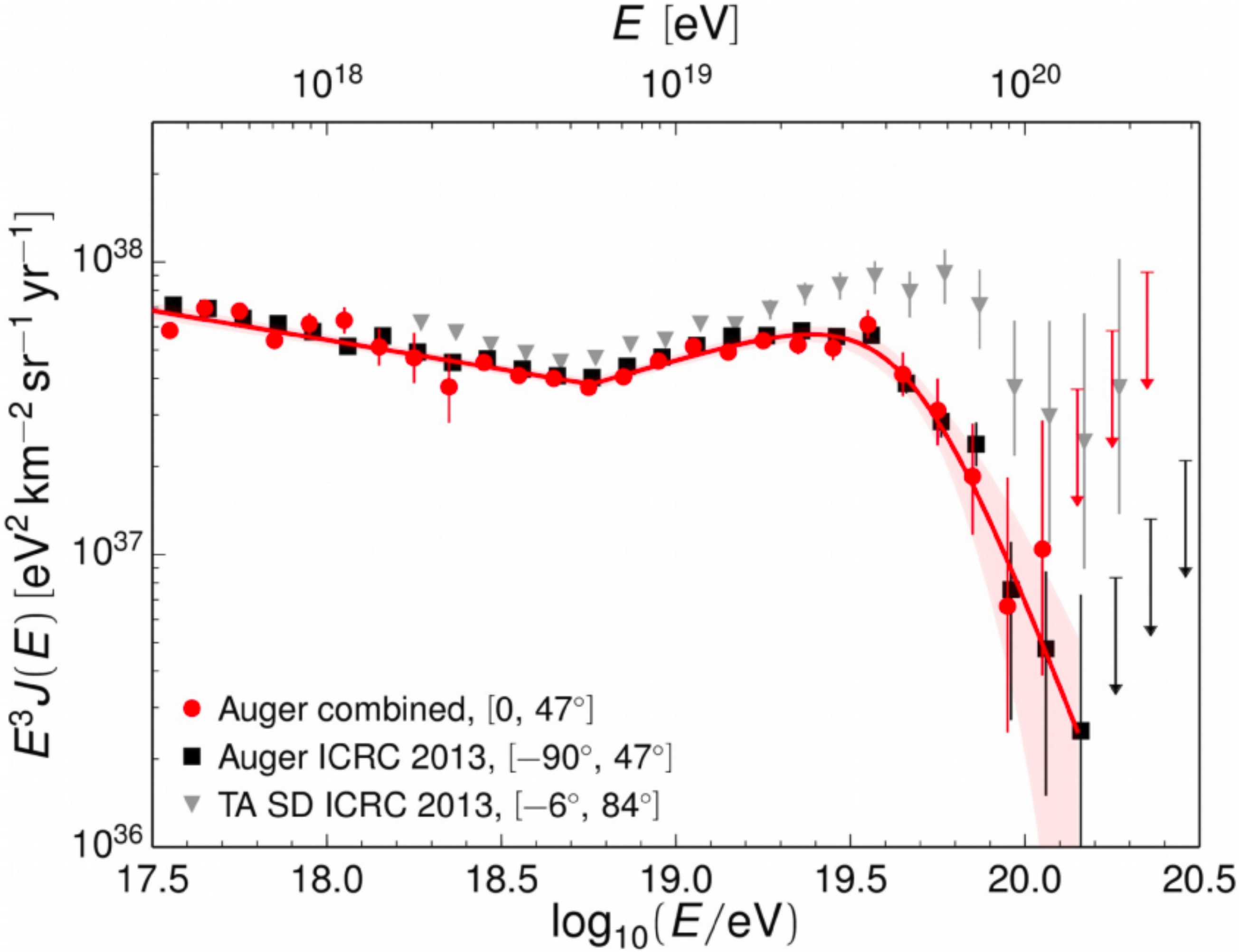
Many thanks to all of my colleagues who generously contributed with their plots and photos to this presentation.

Backup

Energy scale systematics

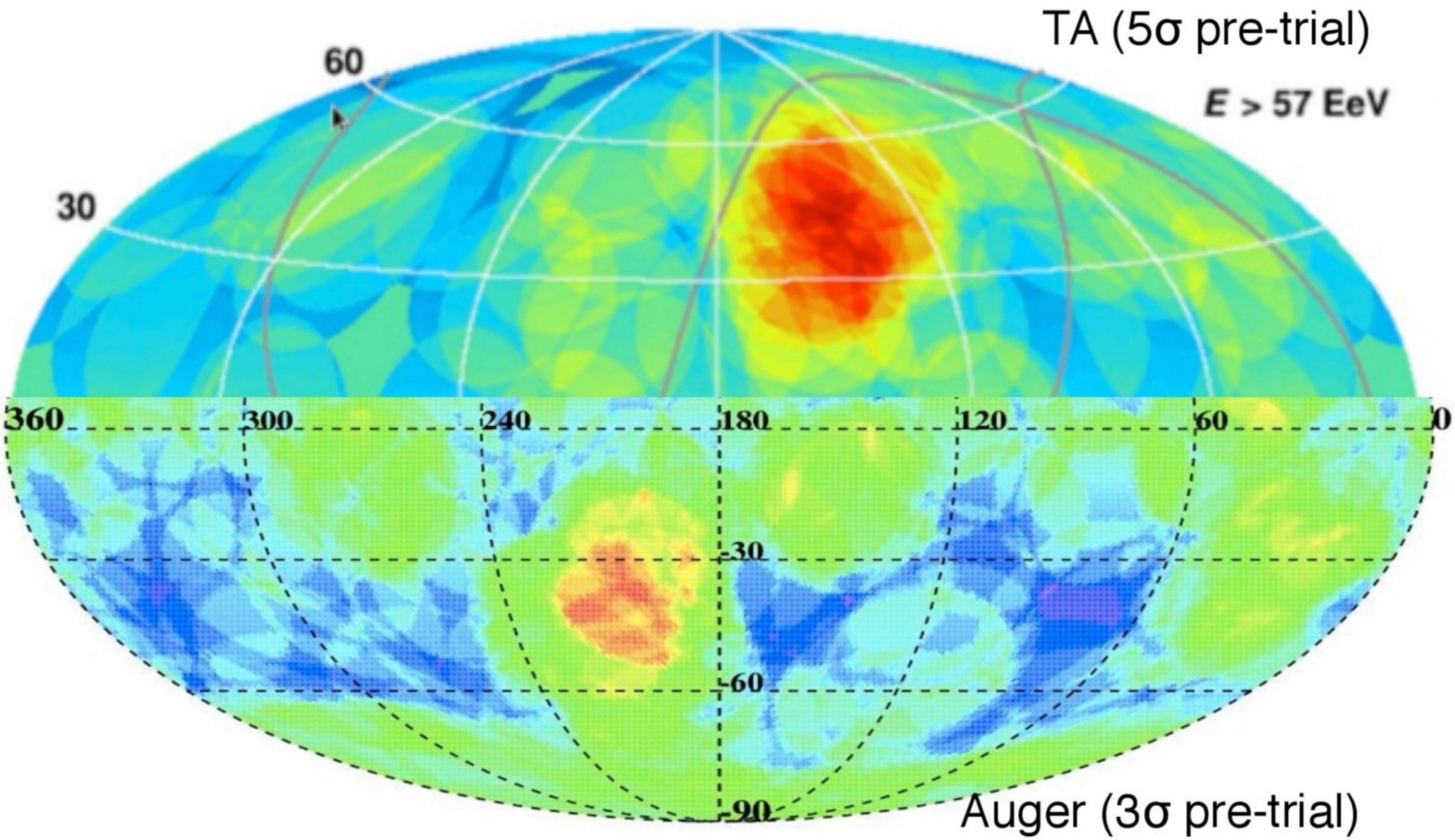
Systematic uncertainties on the energy scale	
Absolute fluorescence yield	3.4%
Fluor. spectrum and quenching param.	1.1%
Sub total (Fluorescence yield - sec. 2)	**3.6%**
Aerosol optical depth	3%÷6%
Aerosol phase function	1%
Wavelength depend. of aerosol scatt.	0.5%
Atmospheric density profile	1%
Sub total (Atmosphere - sec. 3)	**3.4%÷6.2%**
Absolute FD calibration	9%
Nightly relative calibration	2%
Optical efficiency	3.5%
Sub total (FD calibration - sec. 4)	**9.9%**
Folding with point spread function	5%
Multiple scattering model	1%
Simulation bias	2%
Constraints in the Gaisser-Hillas fit	3.5% ÷ 1%
Sub total (FD profile rec. - sec. 5)	**6.5% ÷5.6%**
Invisible energy (sec. 6)	**3%÷1.5%**
Stat. error of the SD calib. fit (sec. 7)	**0.7%÷1.8%**
Stability of the energy scale (sec. 7)	**5%**
Total	**14%**

Declination-dependent spectra

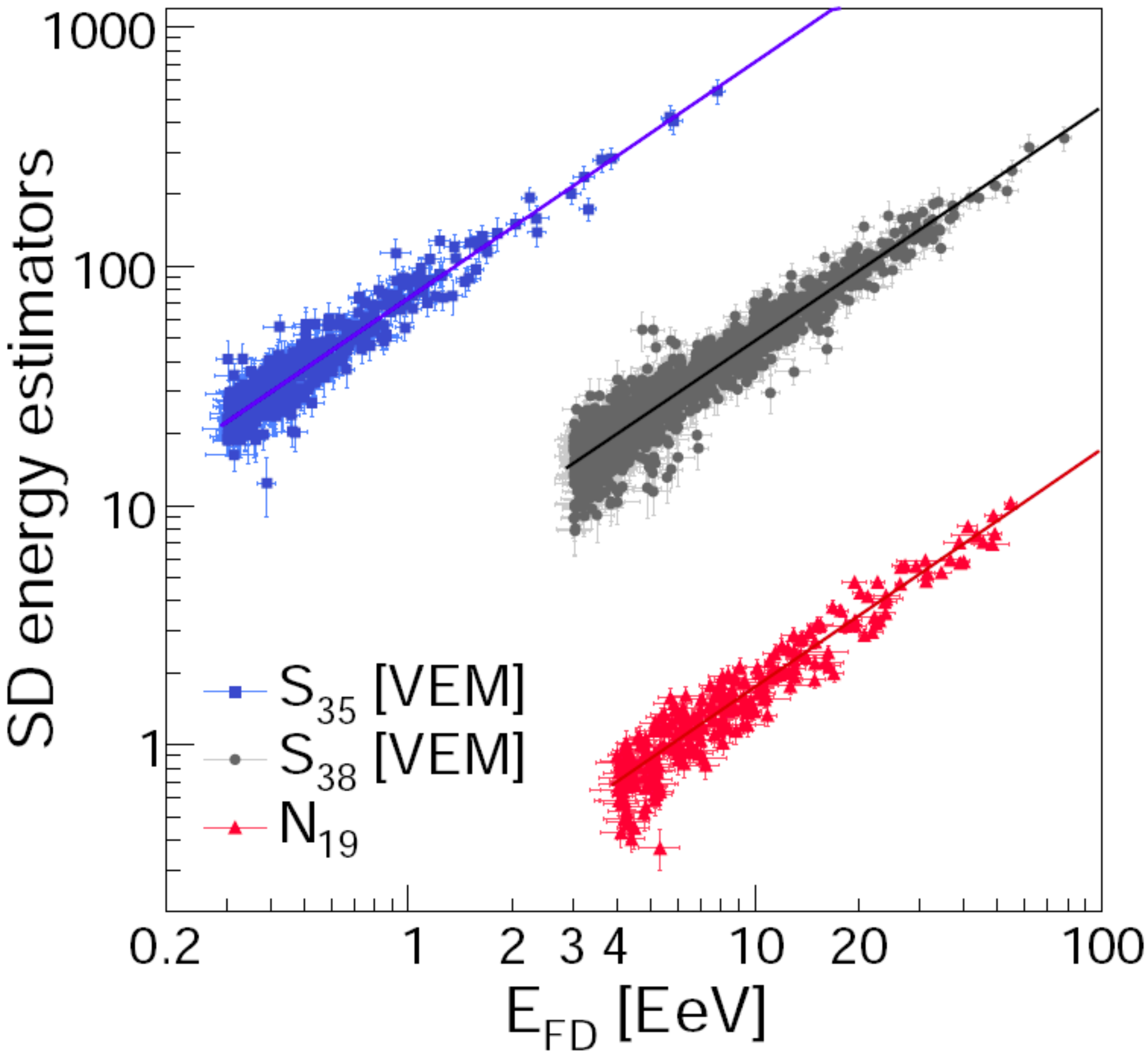


Northern Auger flux is not more similar to flux measured by TA

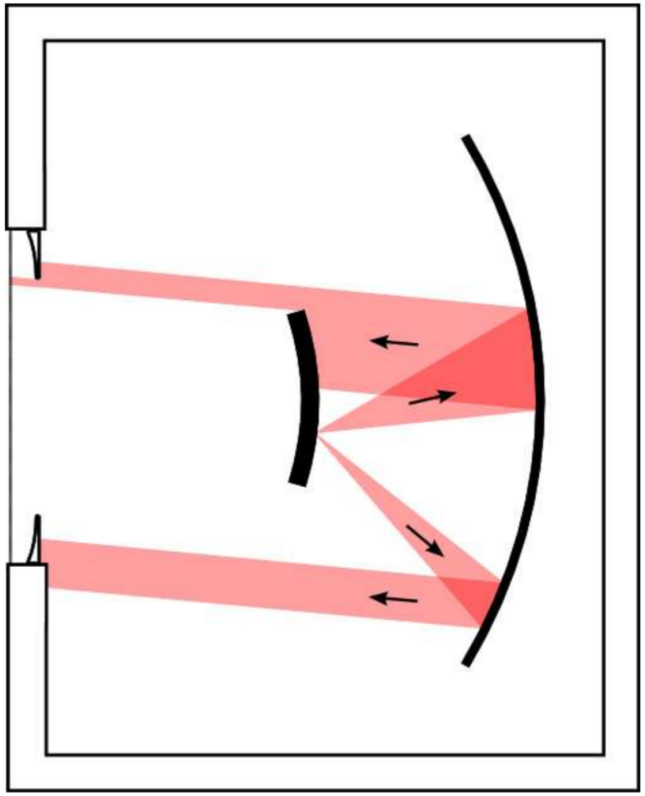
TA hotspot & Auger warmspot: E>57 Eev



Energy calibration

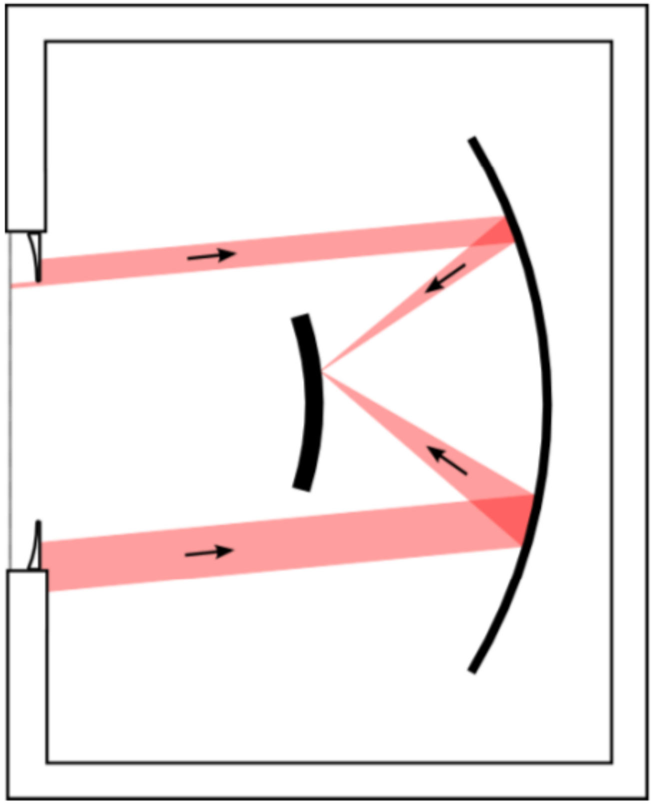


Point spread function



PMT reflections

1. photons reflect off PMTs
2. reflect on mirror again
3. hit camera in broad beam



Ghost formation

1. photons reflect off PMTs
2. miss mirror & reflect on aperture
3. produce center-symmetric image