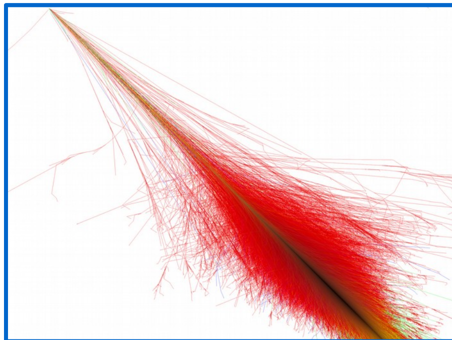
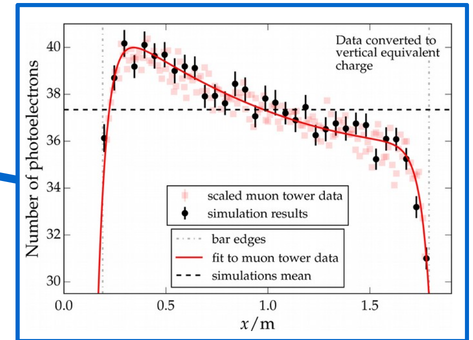
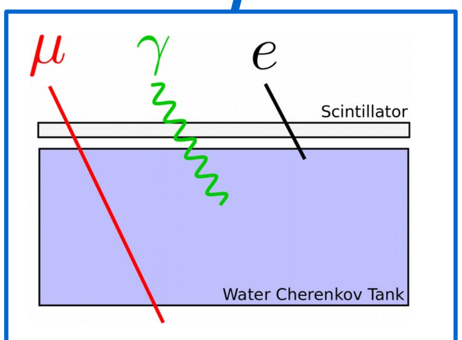




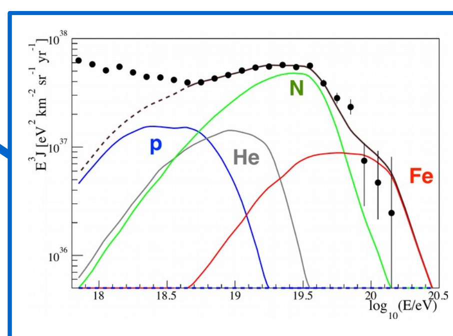
The Scintillator upgrade detectors of the Auger Observatory

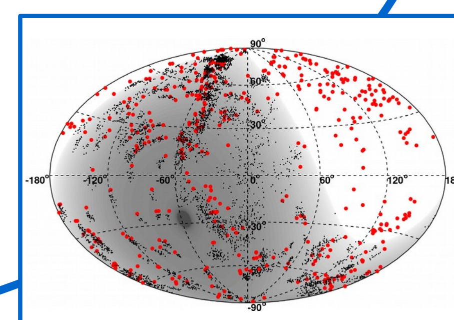


David Schmidt

Institute for Experimental Particle Physics

Karlsruhe Institute of Technology



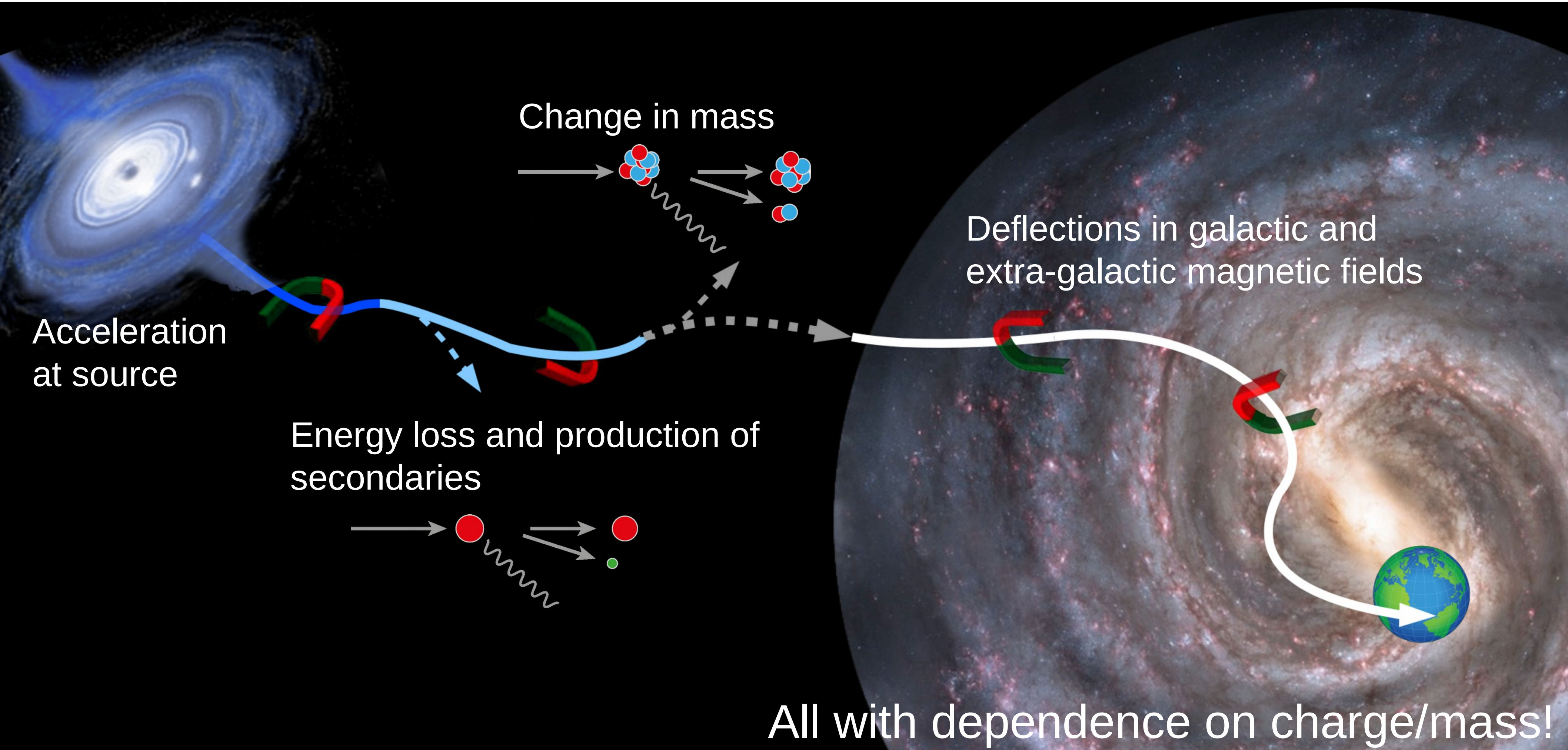


Ultra-high-energy cosmic rays above 10^{18} eV

What are their sources?

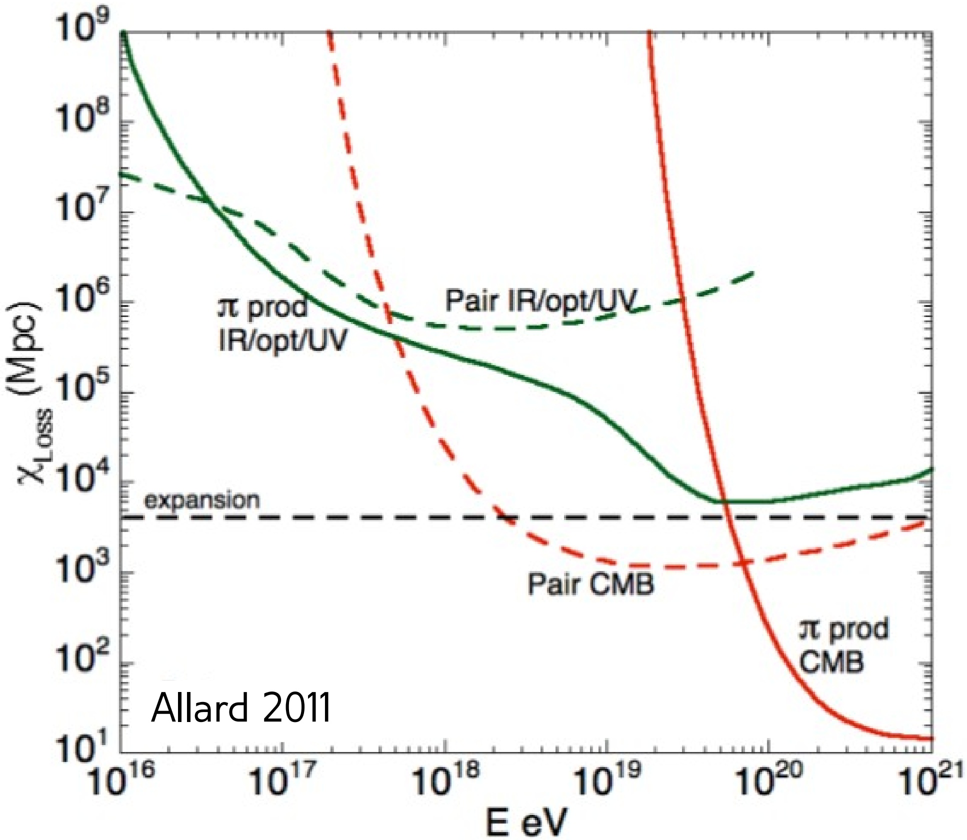
How are they accelerated?

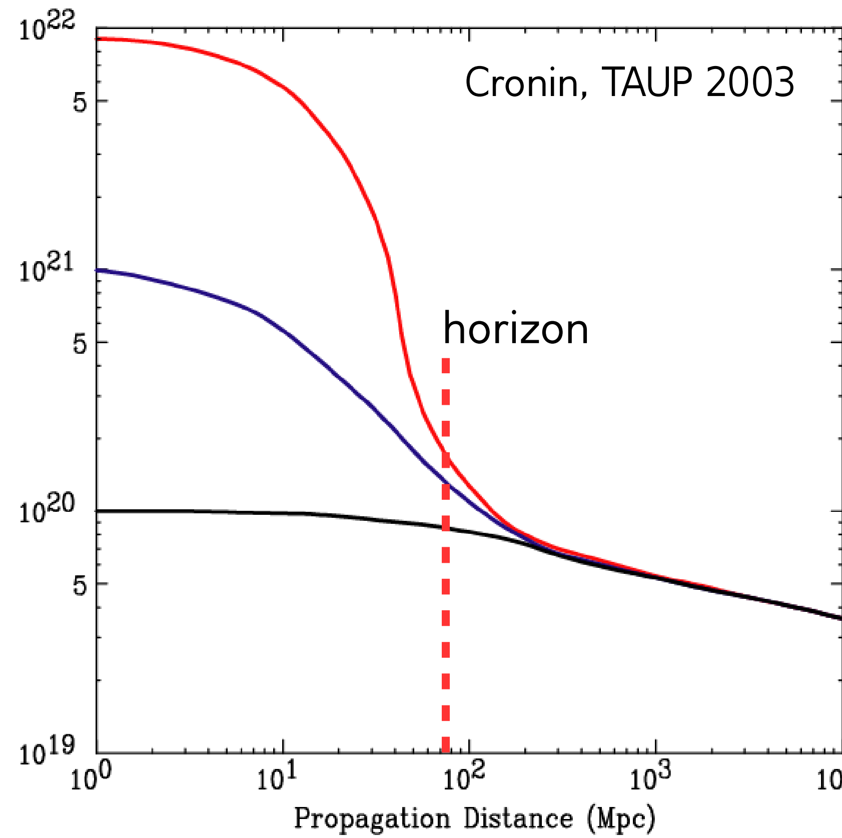
How do they change as they propagate to Earth?

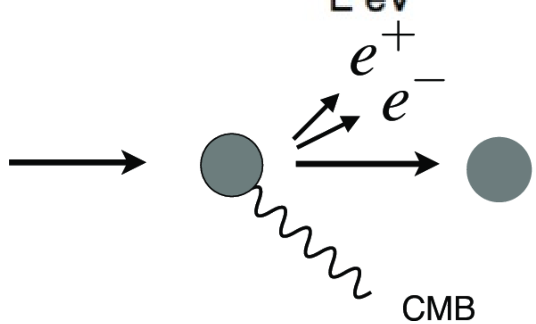


Propagation

Energy loss







Pair production (appx. 2-70 EeV)

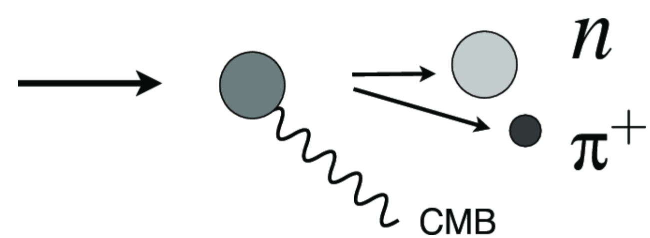
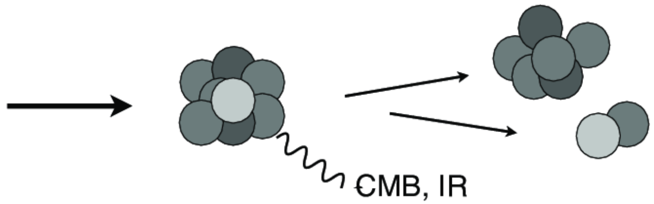


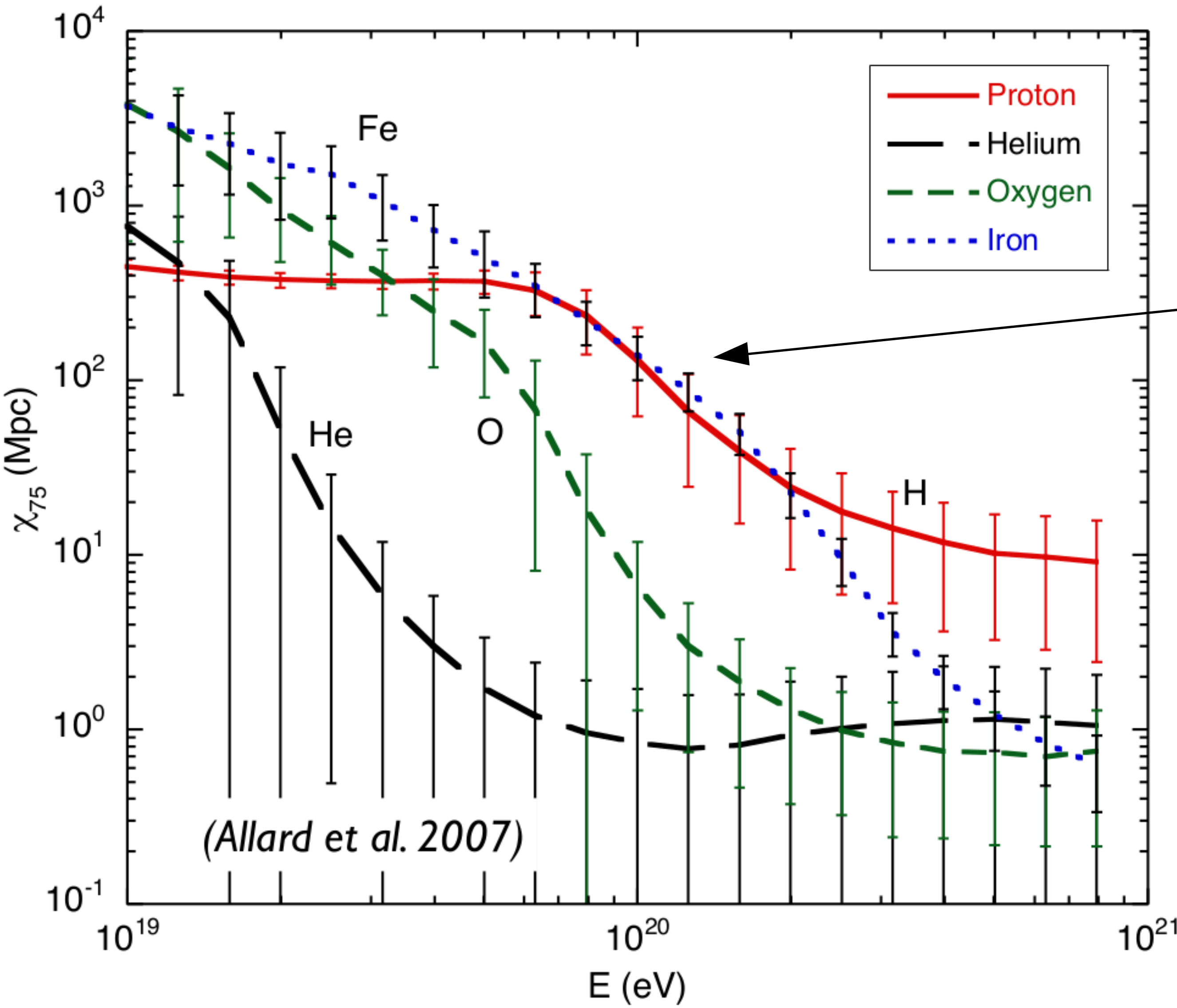
Photo-pion production (above appx. 70 EeV)
(mainly Δ resonance)

Propagation

Nuclei

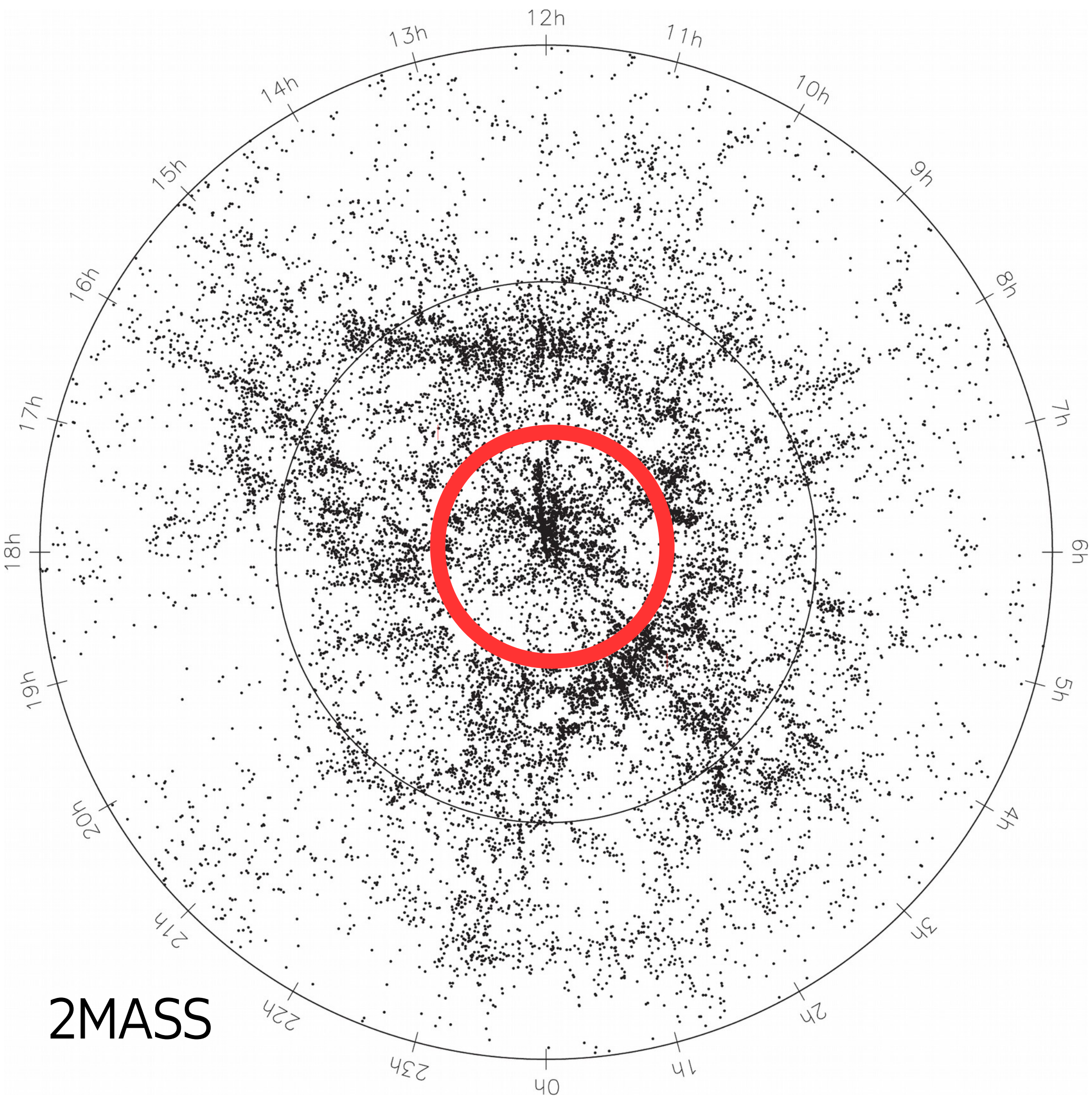
Photo-disintegration:
(giant dipole resonance)





Coincidentally, proton and iron have very similar suppression

Near-sightedness

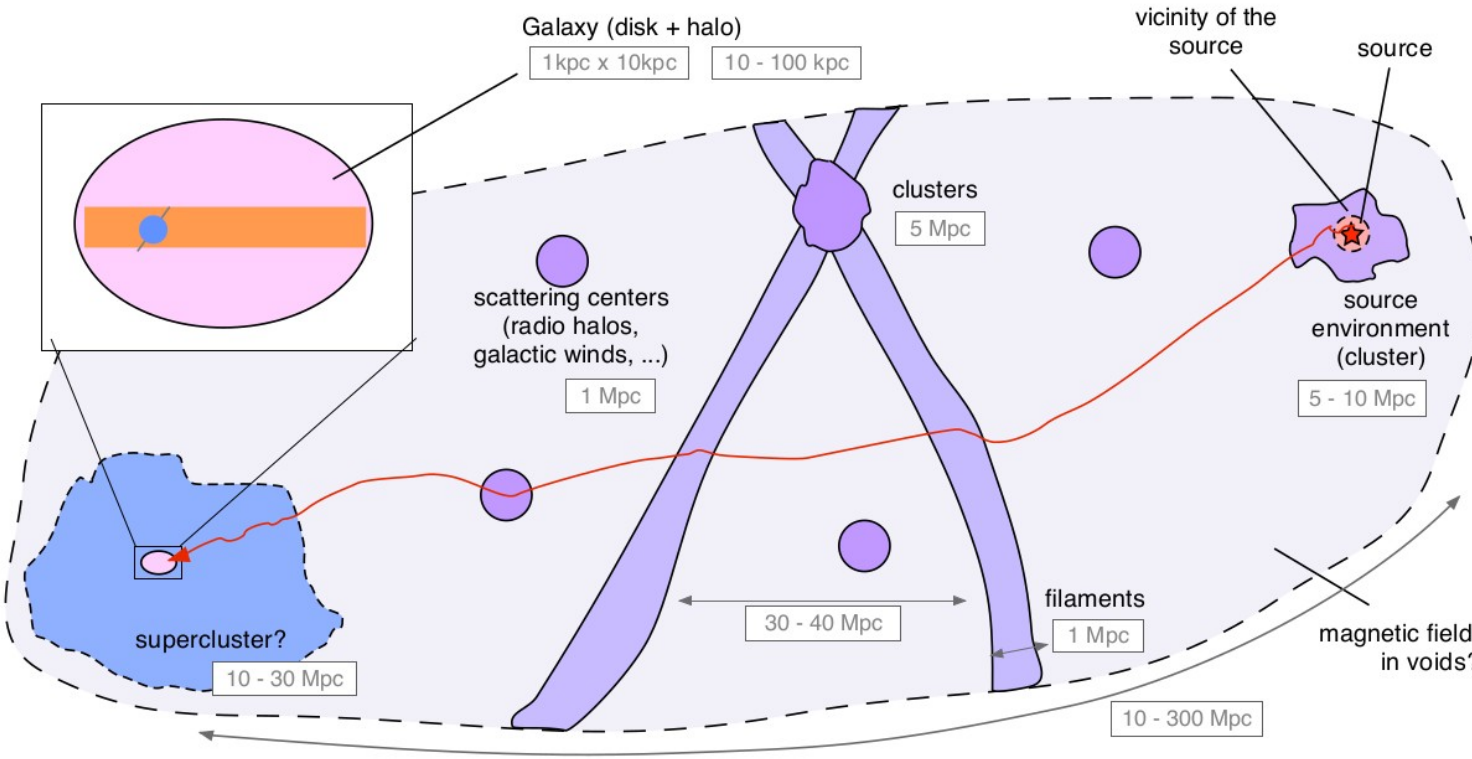


GZK horizon of ~75 Mpc

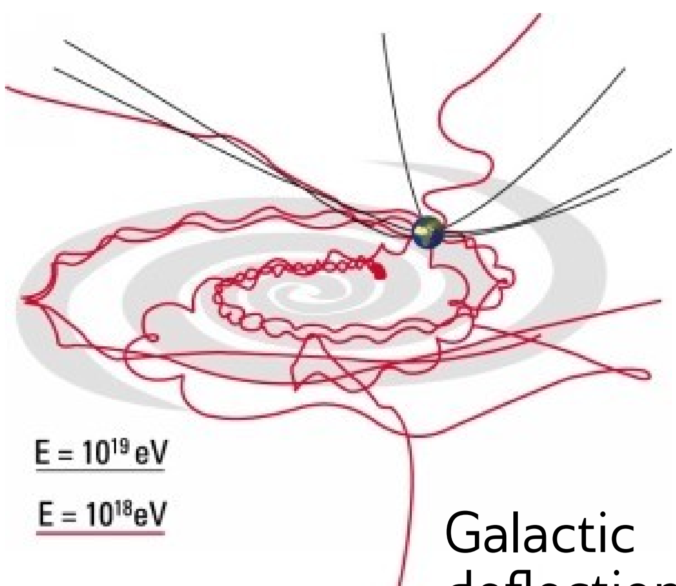
Beyond this, universe is generally opaque to UHECRs

Magnetic deflection

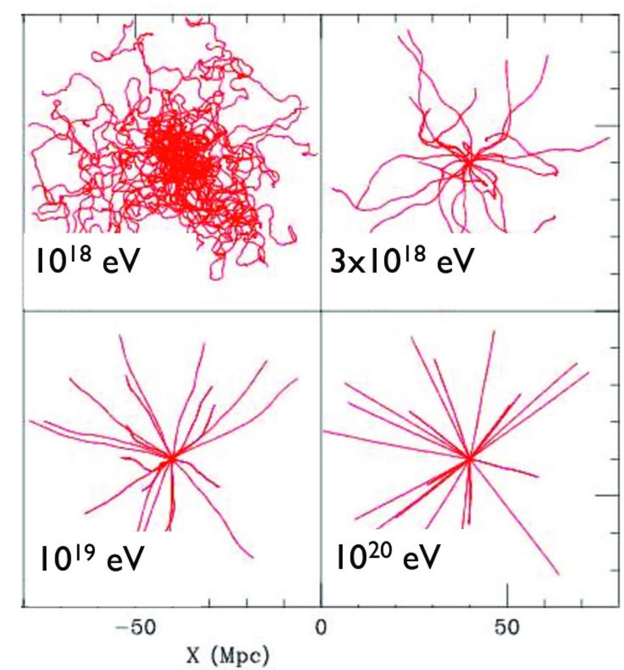
Kotera, Olinto



Deflection power scales with charge



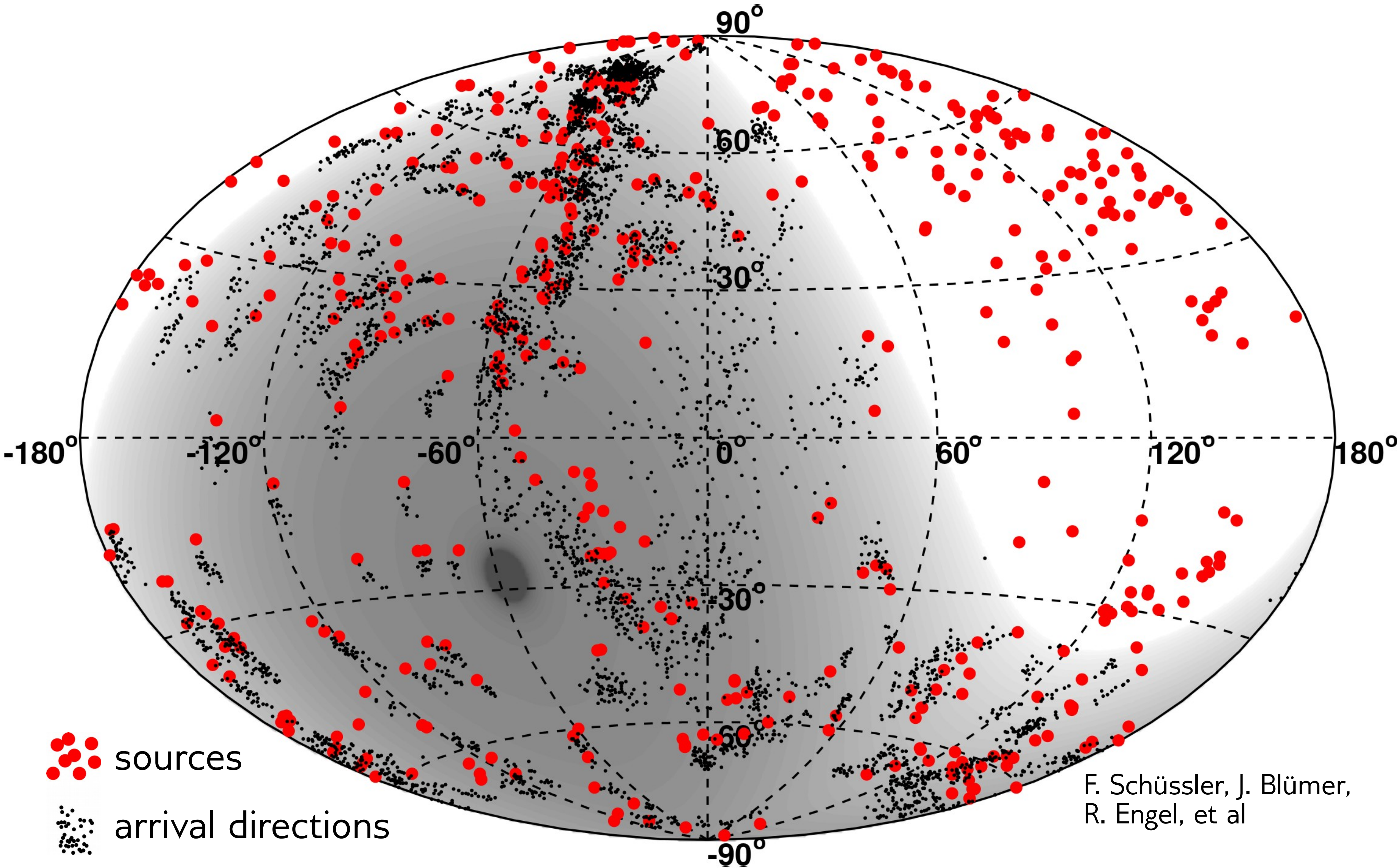
Galactic deflections



Extra-galactic deflections

Magnetic deflection

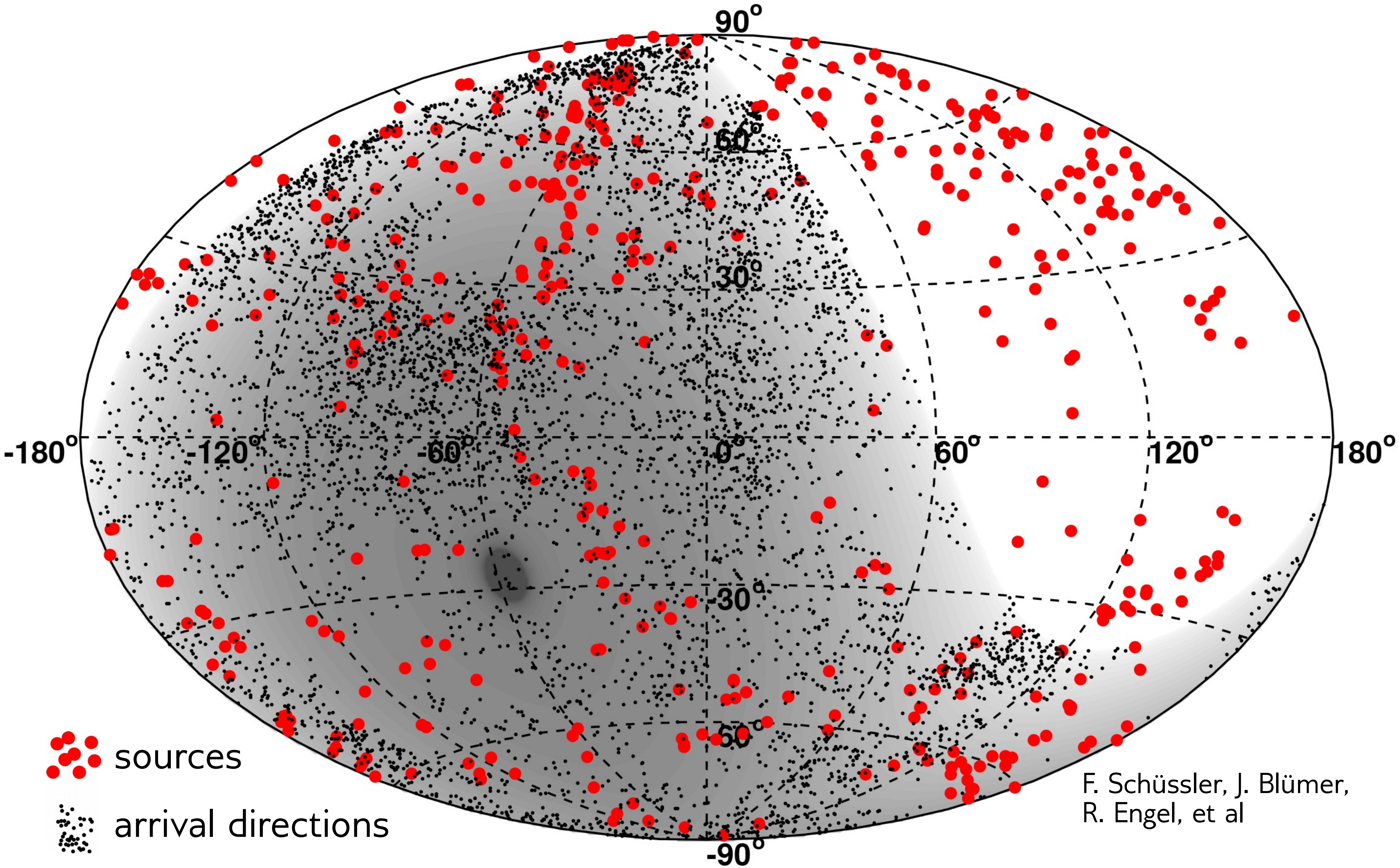
Proton



F. Schüssler, J. Blümer,
R. Engel, et al

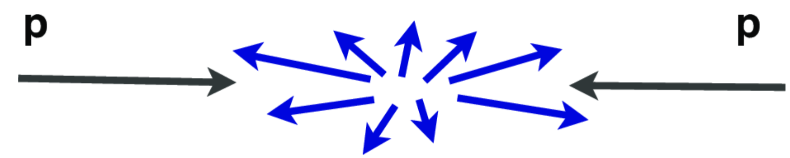
Magnetic deflection

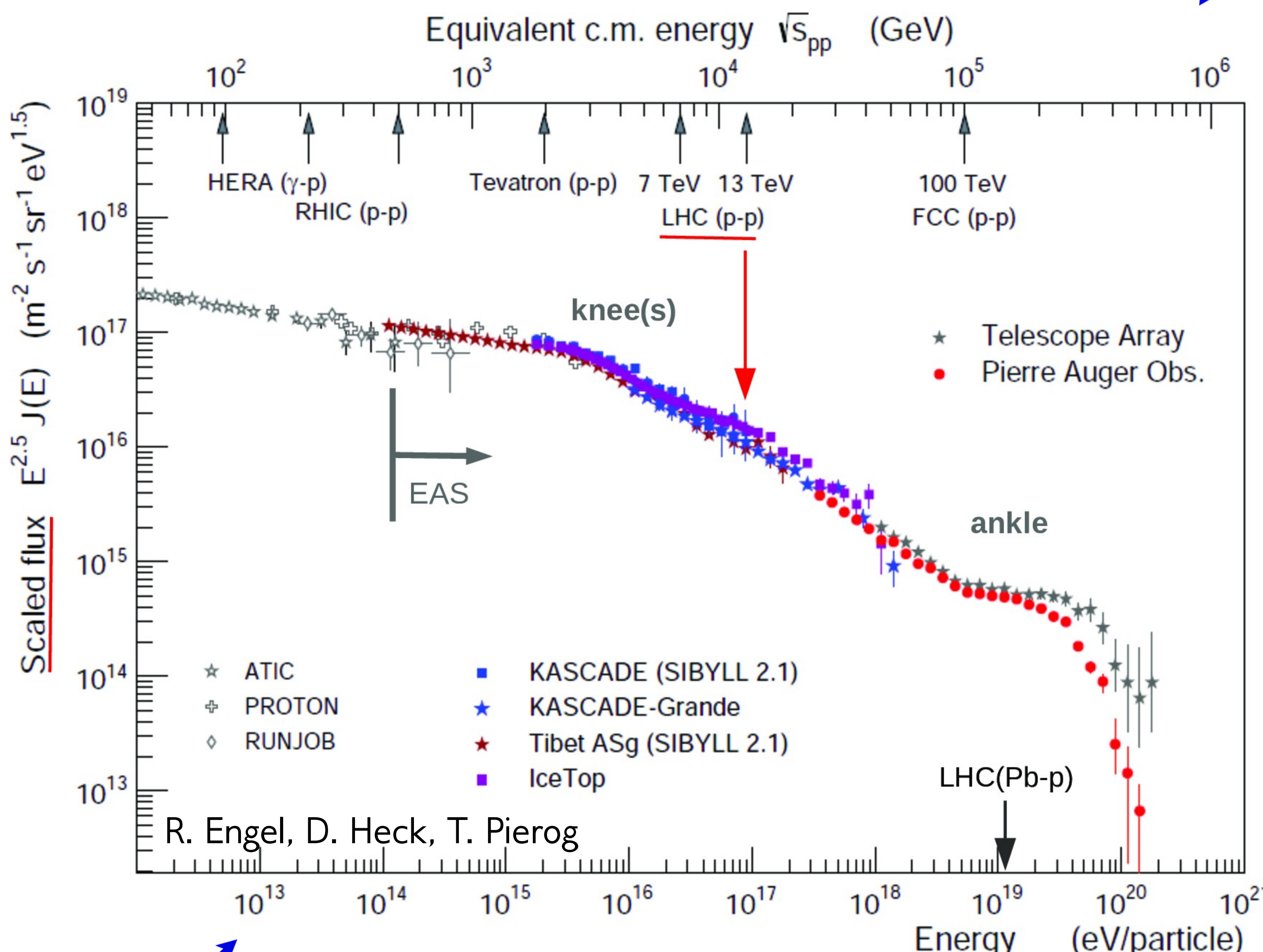
Carbon



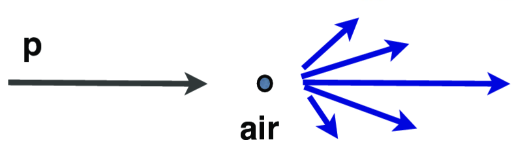
F. Schüssler, J. Blümer, R. Engel, et al

Energy spectrum



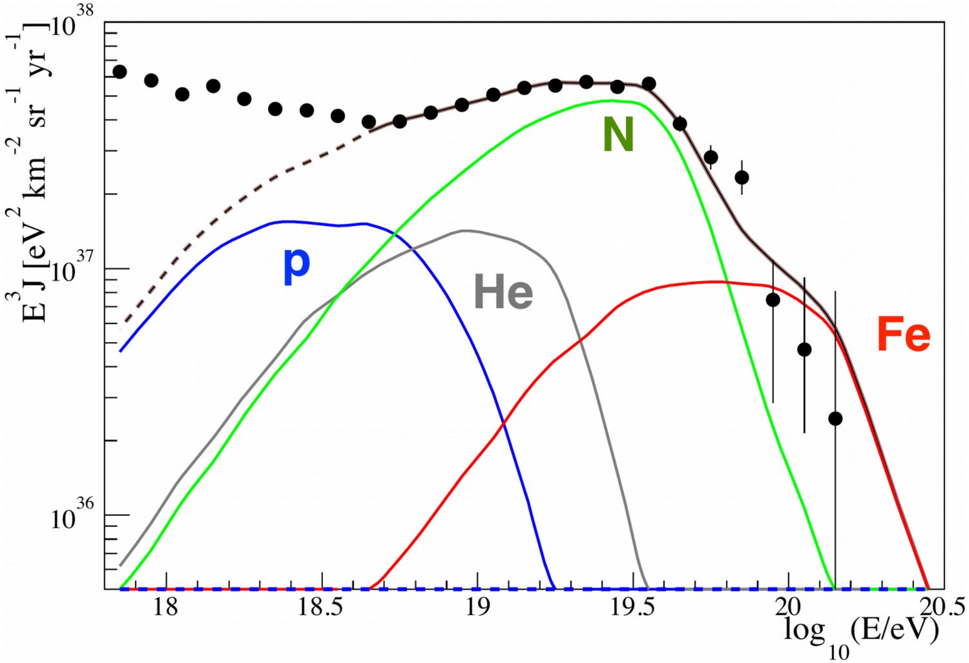


$$\frac{1 \text{ particle}}{\text{km}^2 \text{ century}}$$

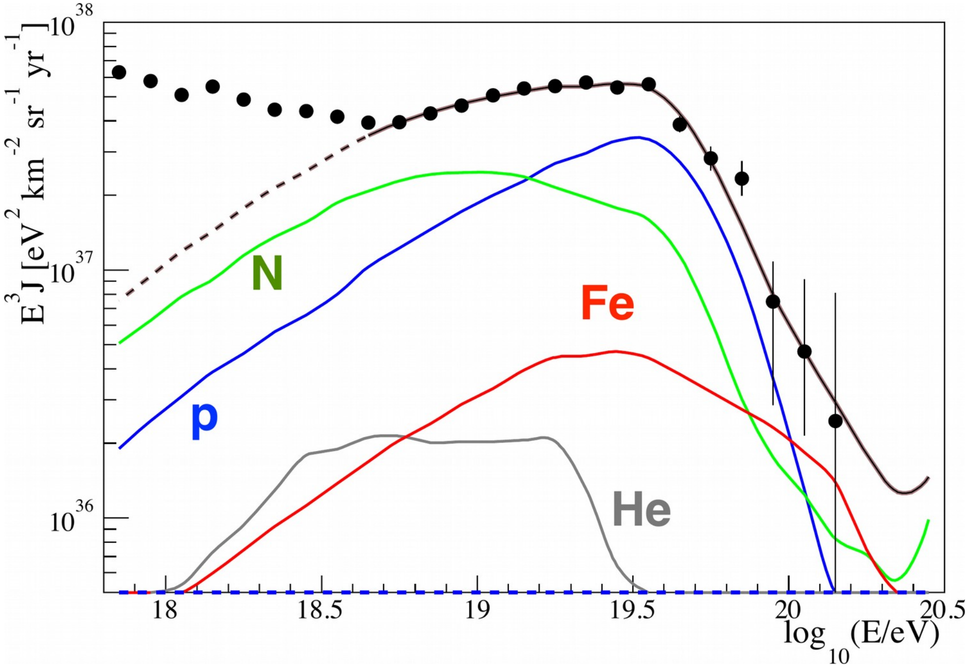


Energy spectrum

Composition scenarios

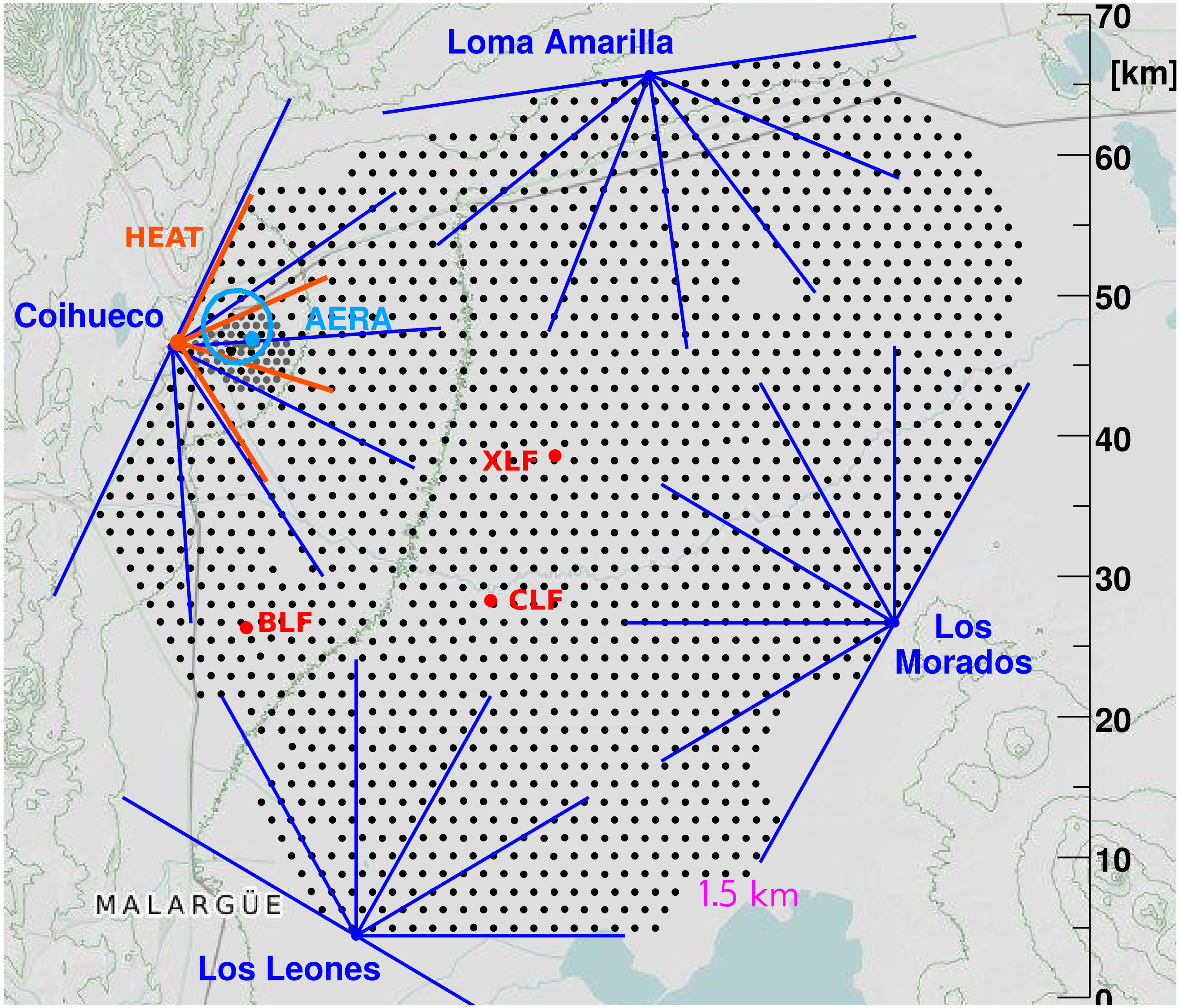


Rigidity dependent
(maximum acceleration potential
of nearby source)



Propagation dominated scenario

Pierre Auger Observatory

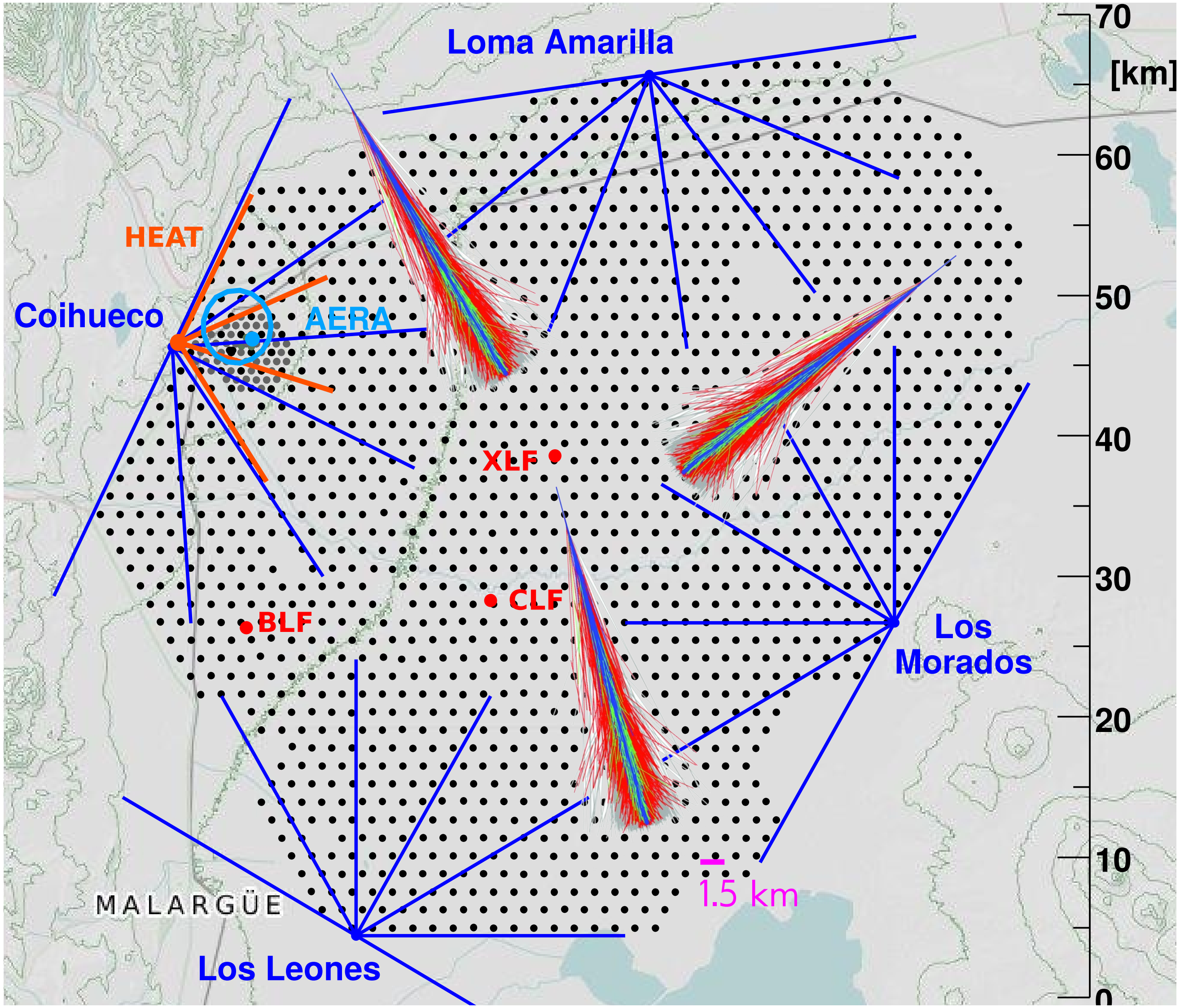


Fluorescence Detector (FD)
27 telescopes, 15% duty cycle

Surface Detector (SD)
1660 water-cherenkov detectors
100% duty cycle

Location:	Malargüe, Mendoza, Argentina
Height:	1450 meters
Atm. Depth:	860 g/cm^2
Energy Threshold:	$10^{17.5}$ eV

Pierre Auger Observatory



Fluorescence Detector (FD)

27 telescopes, 15% duty cycle

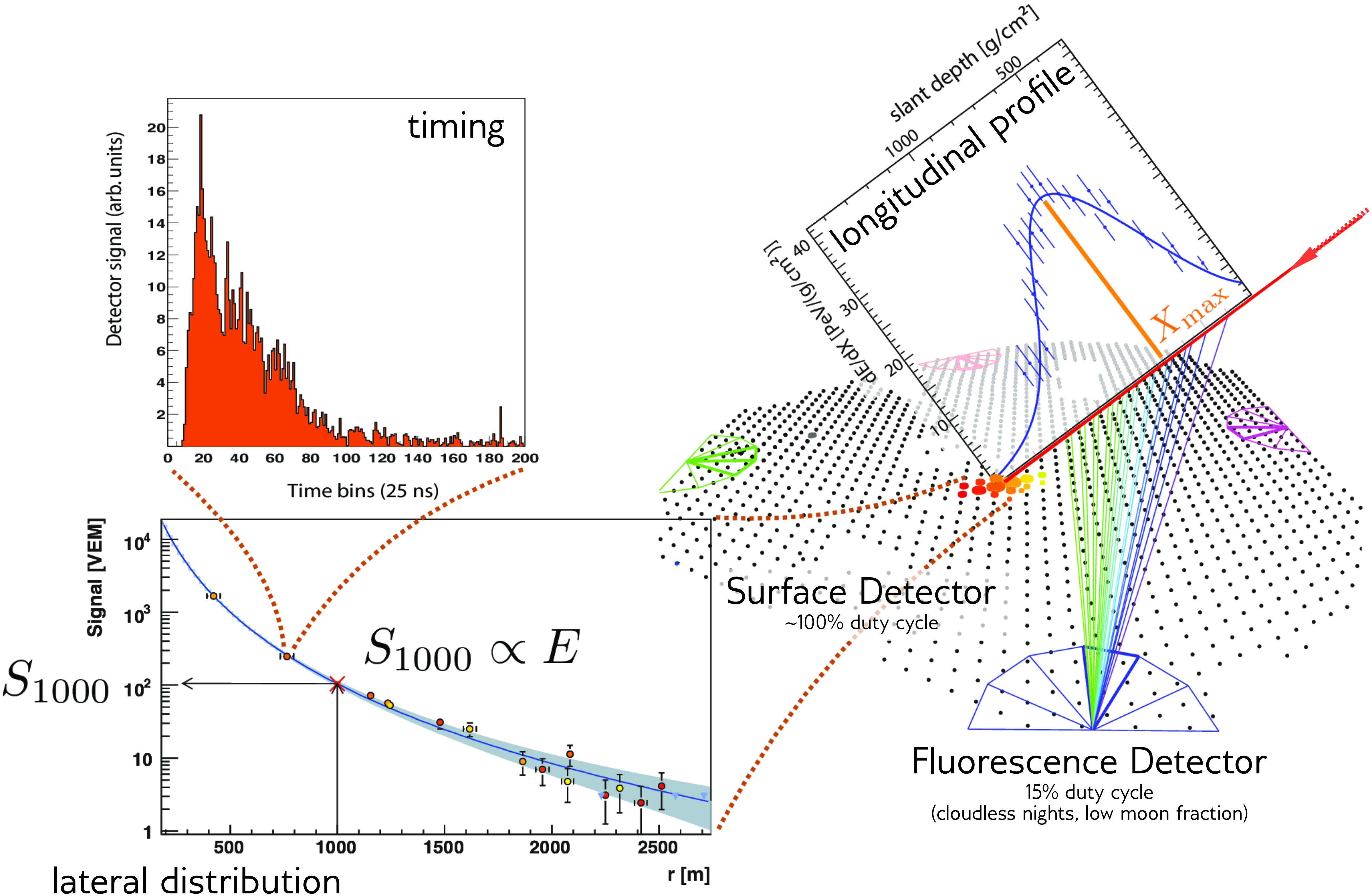
Surface Detector (SD)

1660 water-cherenkov detectors

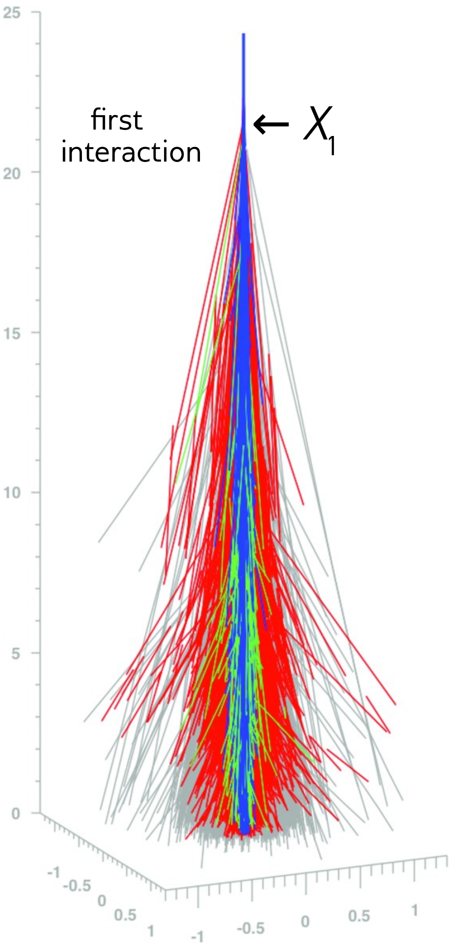
100% duty cycle

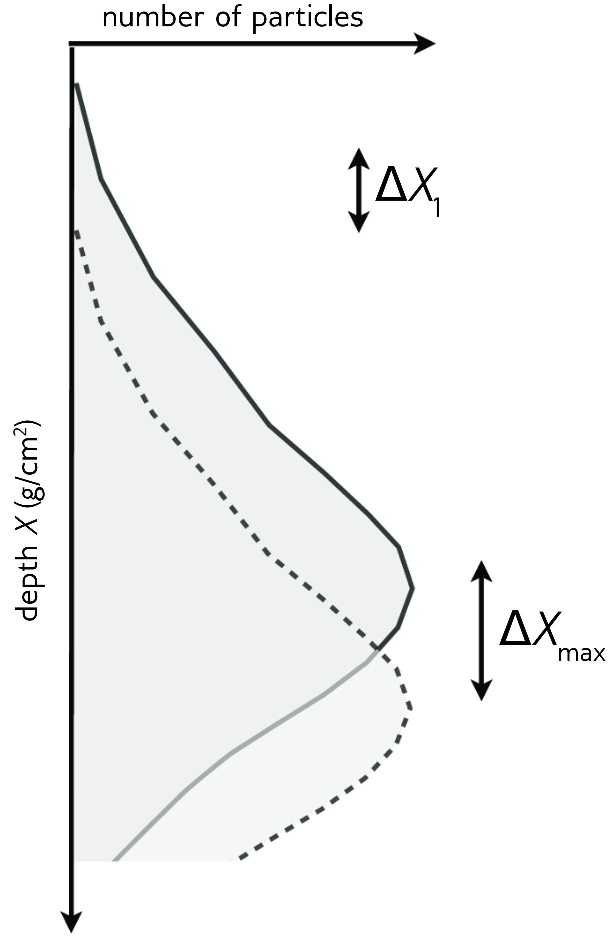
Location: Malargüe, Mendoza, Argentina
Height: 1450 meters
Atm. Depth: 860 g/cm^2
Energy Threshold: $10^{17.5}$ eV

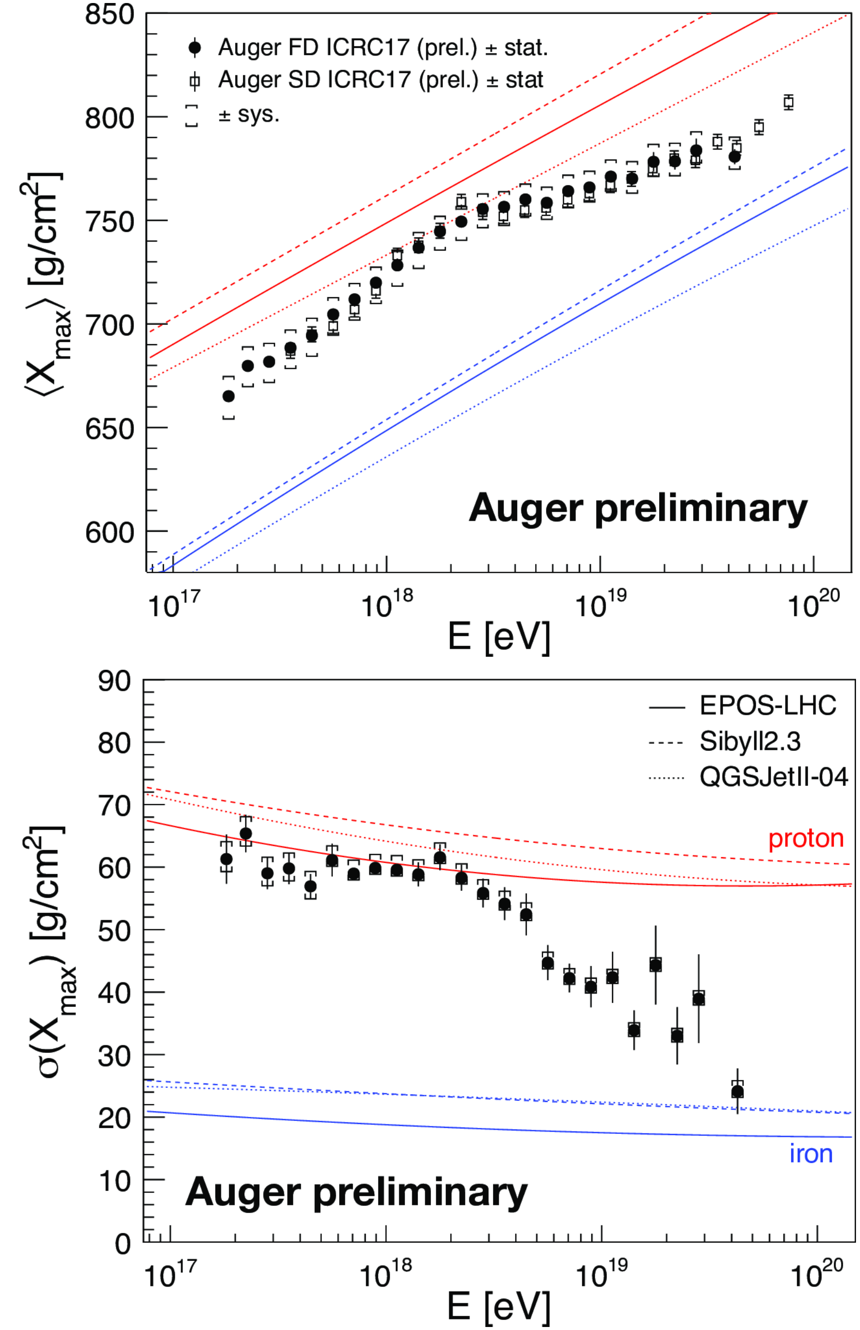
Extensive air shower observables



Shower profile

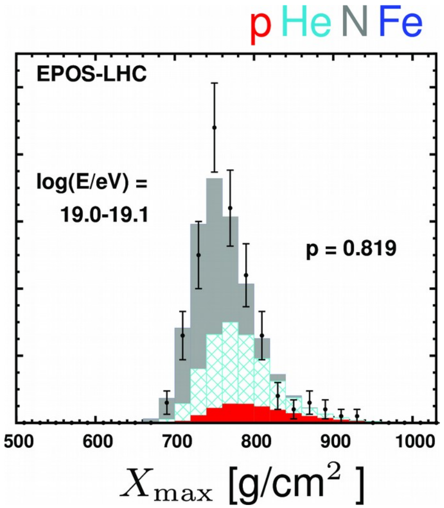




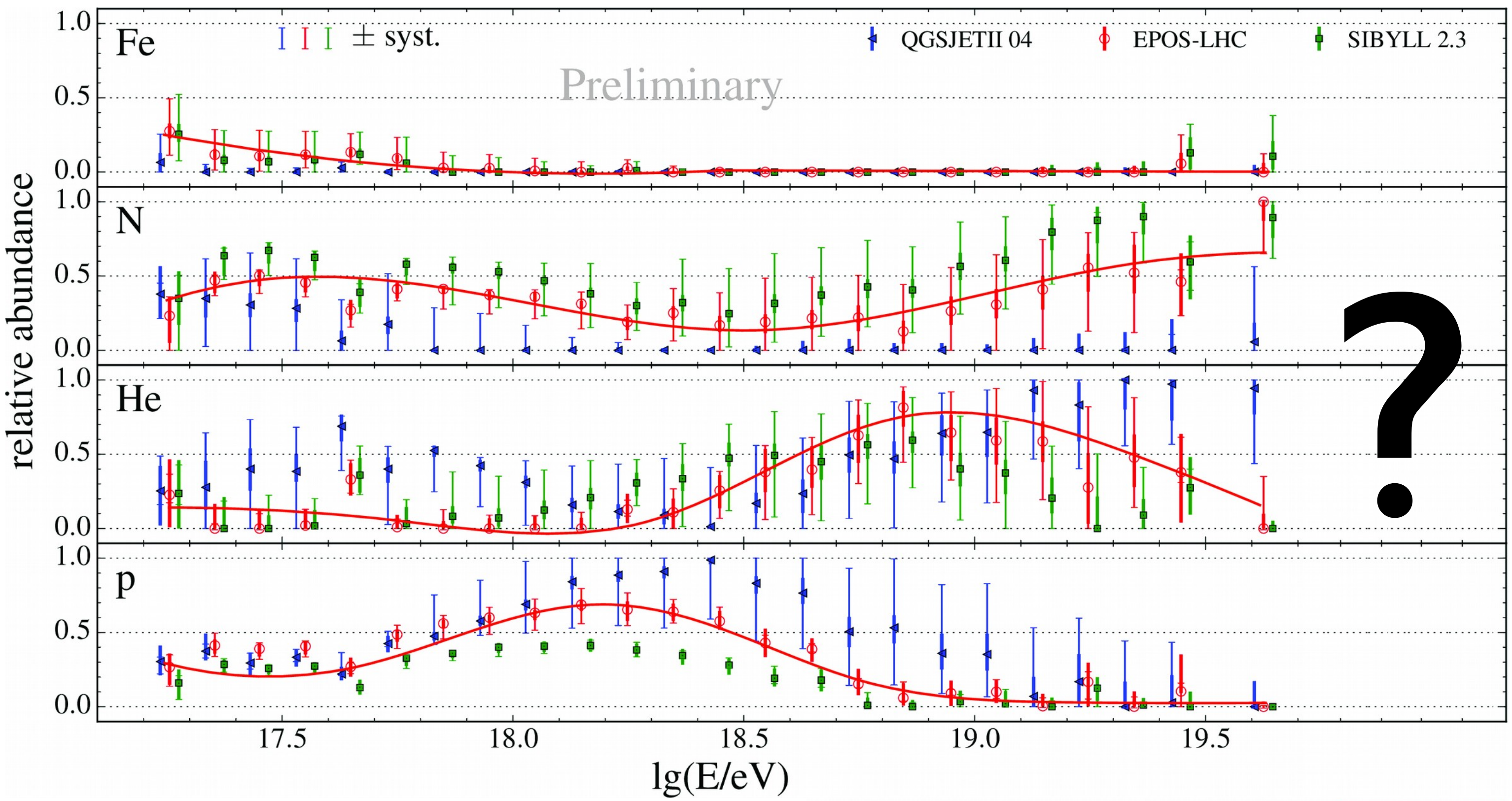


Depth of shower maximum
and fluctuations therein
correlated with mass

Composition fits with X_{max}



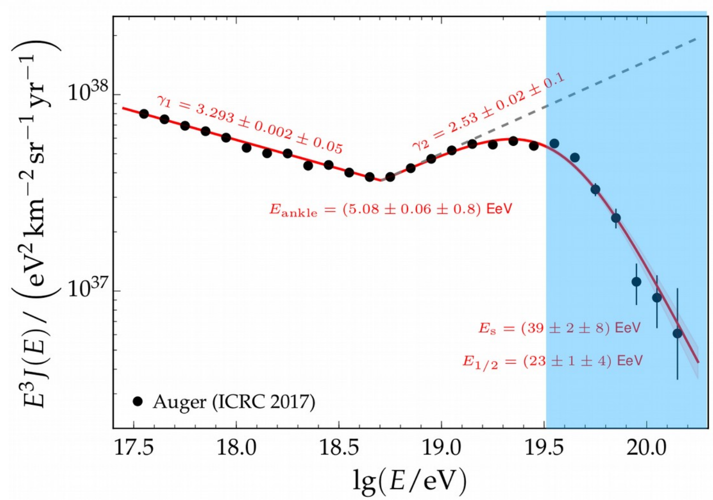
Monte-carlo Xmax distributions fit to data



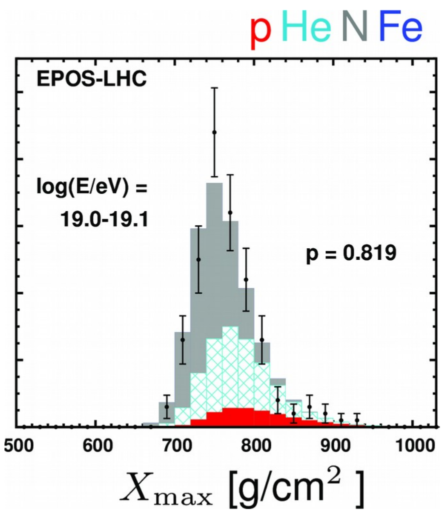
?

Need mass sensitive measurement with nearly 100% duty cycle

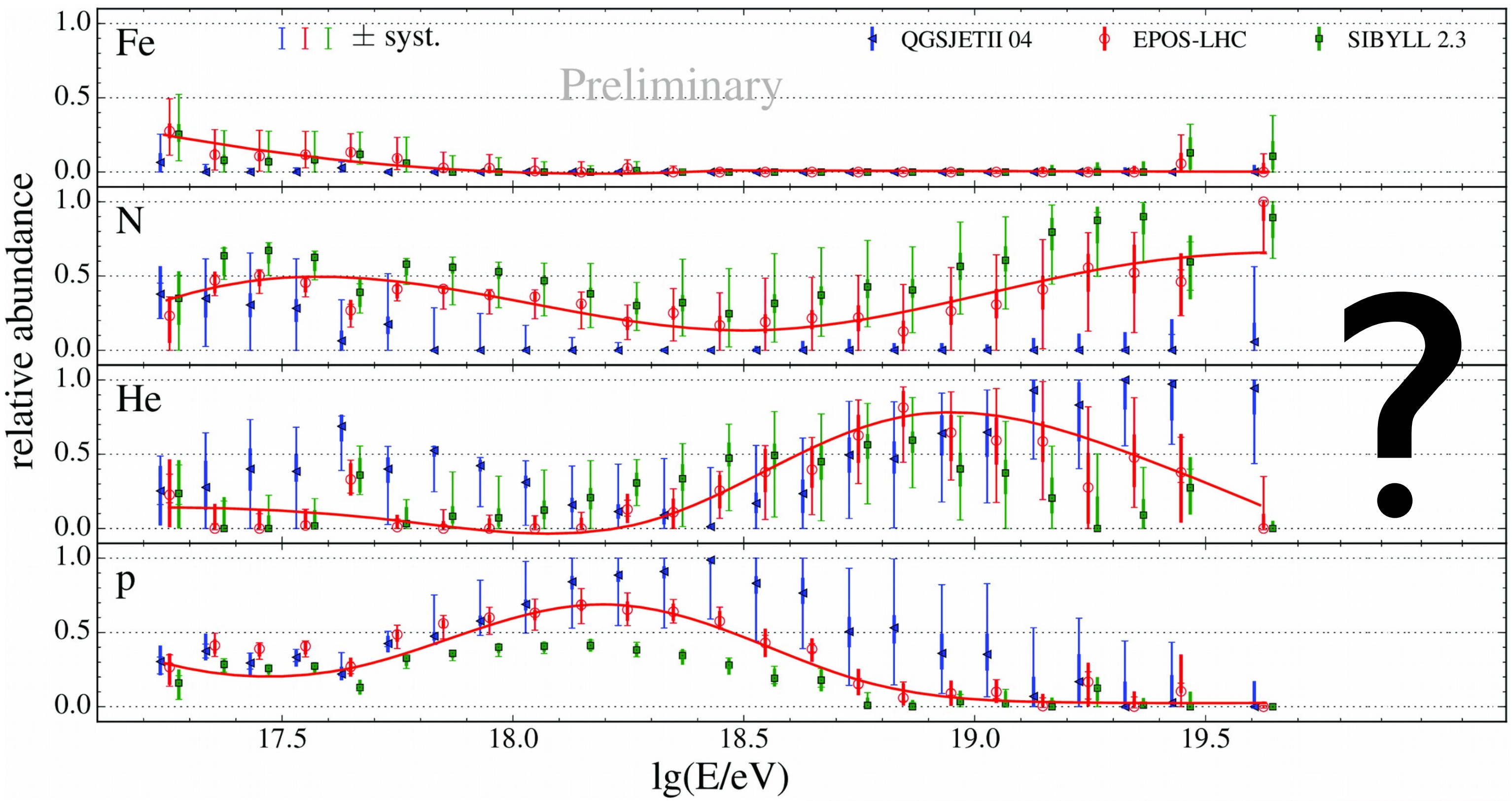
... with decent single event resolution on mass for light element selection



Composition fits with X_{max}

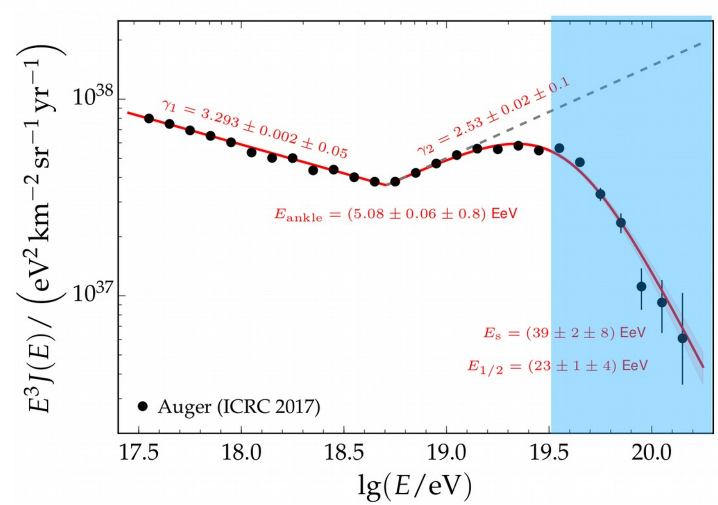


Monte-carlo Xmax distributions fit to data

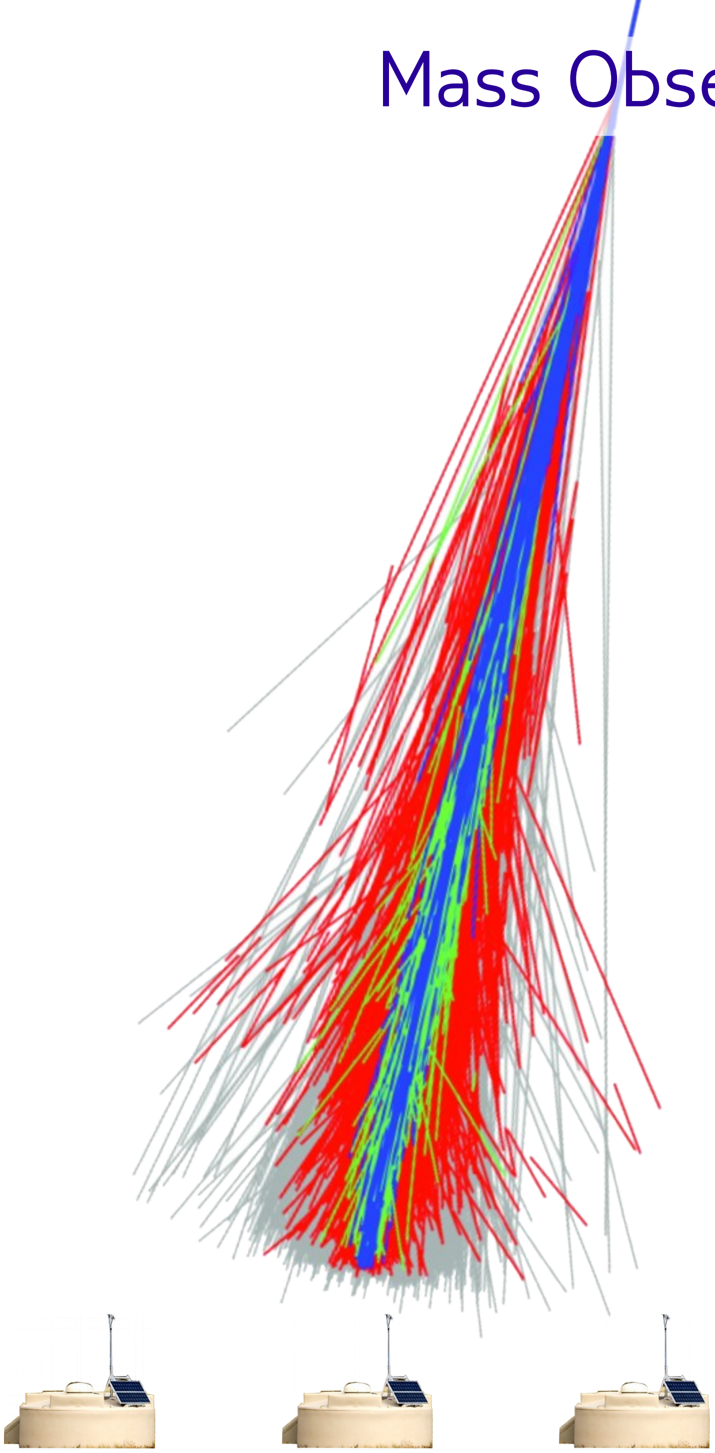


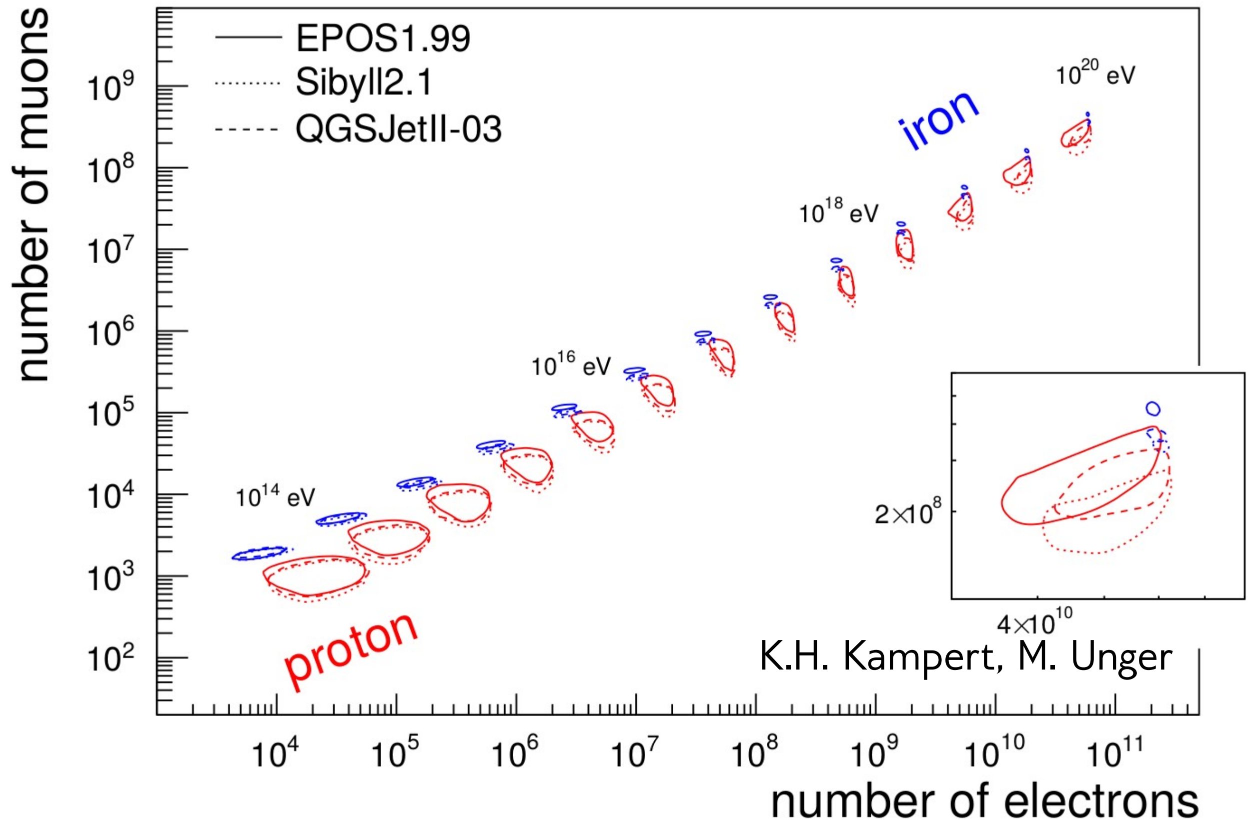
Need to equip surface detector to be mass sensitive

... with decent single event resolution on mass for light element selection



Mass Observables for Surface Detector

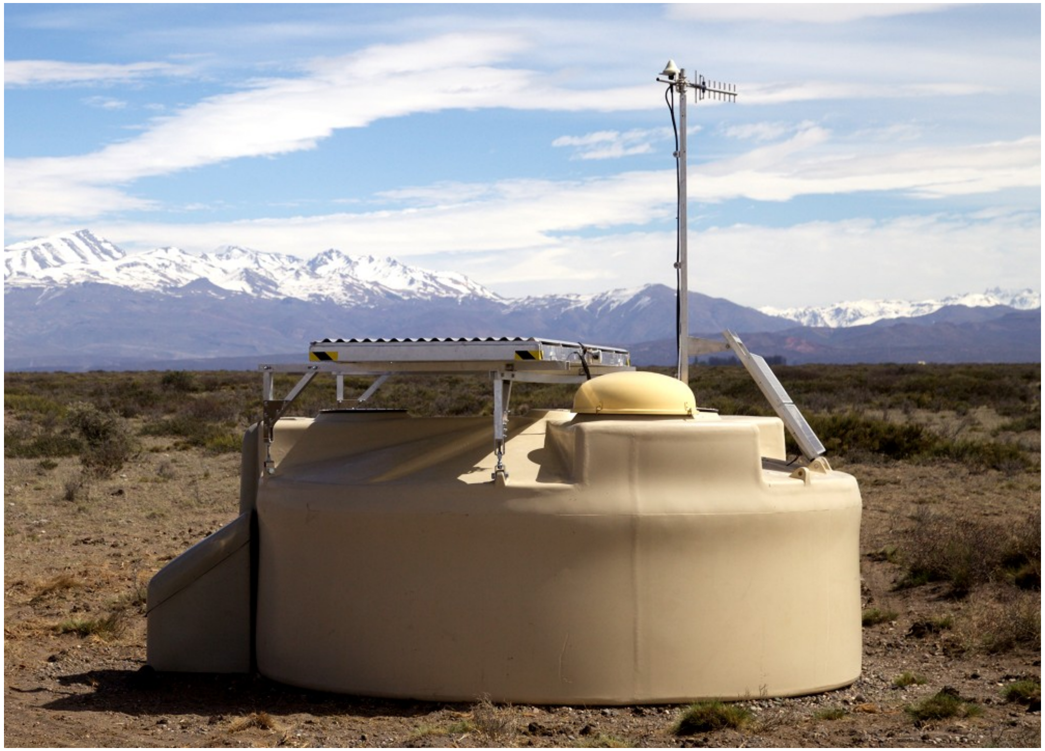




Heavier primaries induce showers with larger hadronic component and therefore **more muons**

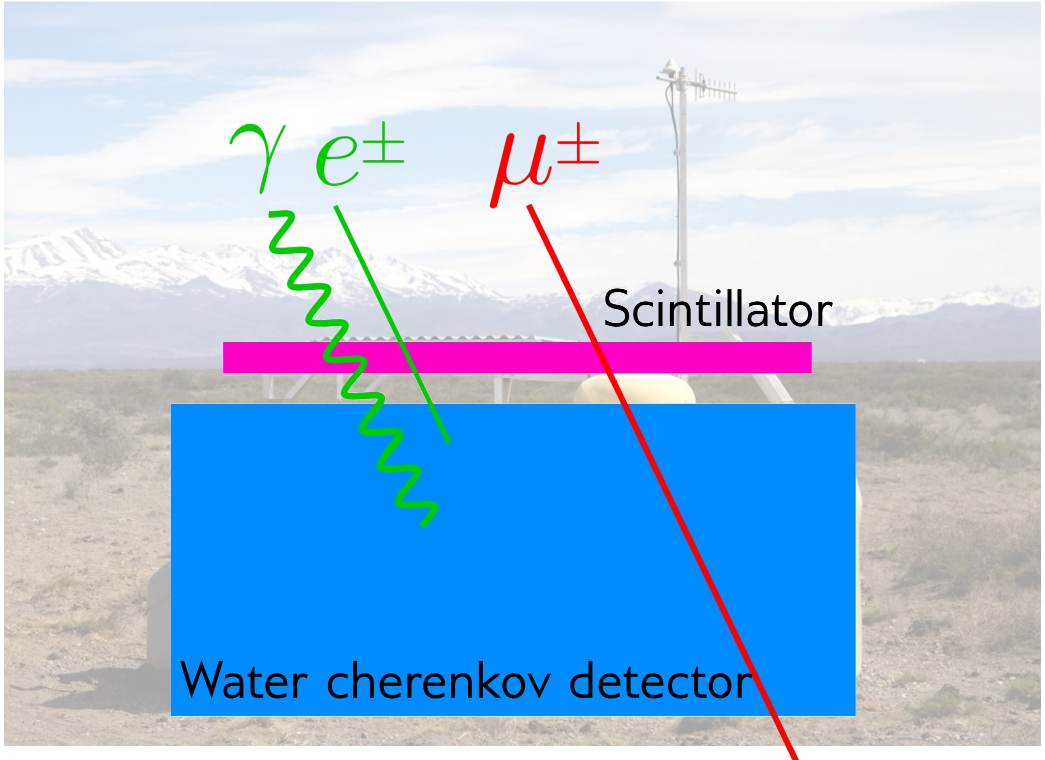
Showers from **light primaries** develop deeper in the atmosphere which are less attenuated at Auger's observation height and therefore have **more electrons**

AugerPrime



- 4 m^2 **S**cintillator **S**urface **D**etector atop each of the existing **W**ater-**C**herenkov **D**etectors

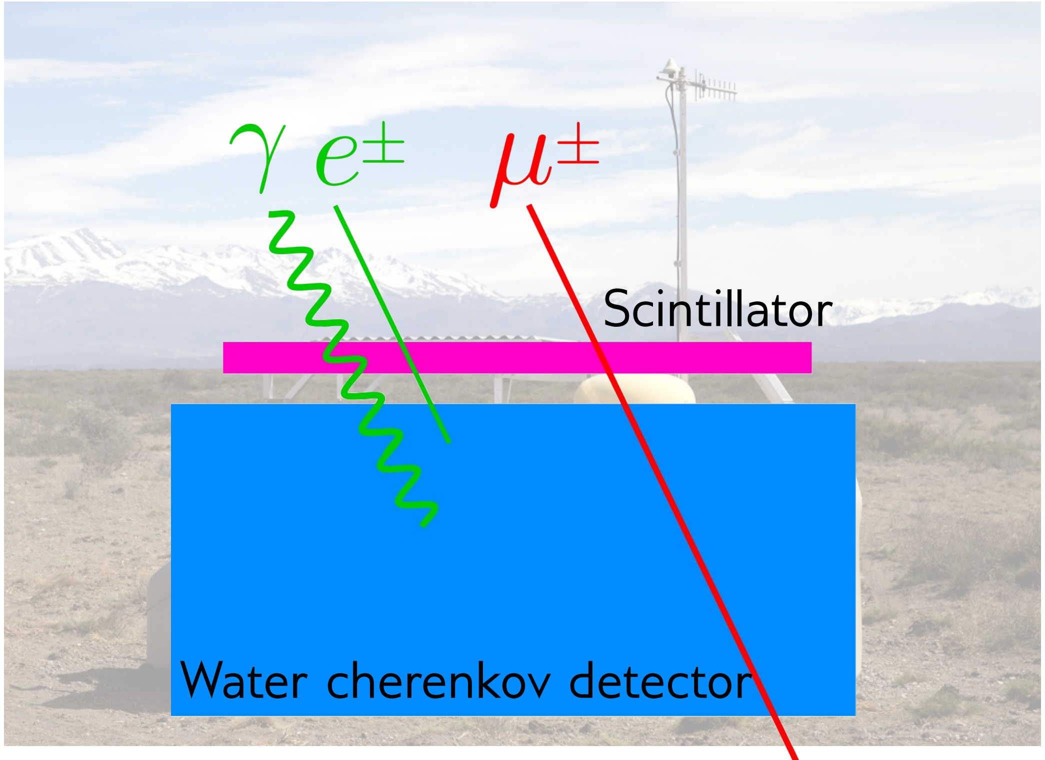
AugerPrime



Disentangle **muonic** and **electromagnetic** shower components using differing responses

- 4 m^2 **S**cintillator **S**urface **D**etector atop each of the existing **W**ater-**C**herenkov **D**etectors

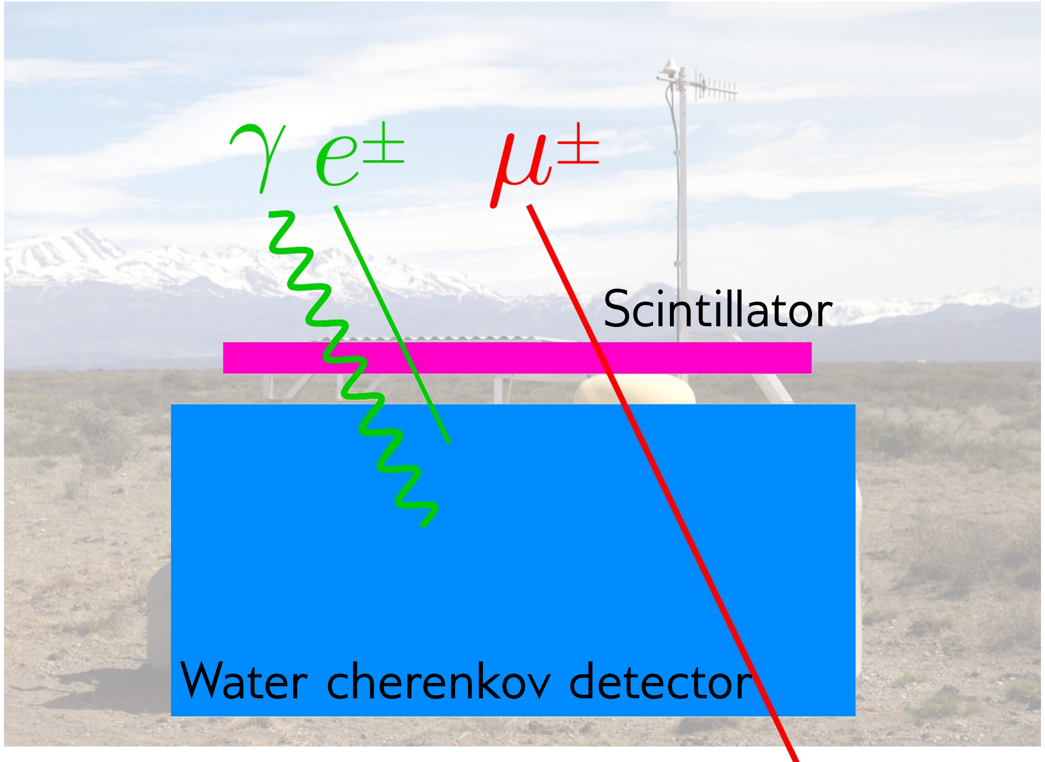
AugerPrime



Disentangle **muonic** and **electromagnetic** shower components using differing responses

- 4 m^2 **S**cintillator **S**urface **D**etector atop each of the existing **W**ater-**C**herenkov **D**etectors
- A small PMT for extended dynamic range and improved 12-bit 120 MHz electronics for more precisely measured waveforms
- An **U**nderground **M**uon **D**etector covering 23.5 km^2 for direct muon measurements
- A radio antenna atop each SSD+WCD to extend mass sensitive sky coverage and exposure

AugerPrime



Disentangle **muonic** and **electromagnetic** shower components using differing responses

- 4 m^2 **S**cintillator **S**urface **D**etector atop each of the existing **W**ater-**C**herenkov **D**etectors
- A small PMT for extended dynamic range and improved 12-bit 120 MHz electronics for more precisely measured waveforms
- An **U**nderground **M**uon **D**etector covering 23.5 km^2 for direct muon measurements
- A radio antenna atop each SSD+WCD to extend mass sensitive sky coverage and exposure

Objetives:

→ Elucidate the mass composition and the origin of the flux suppression at the highest energies

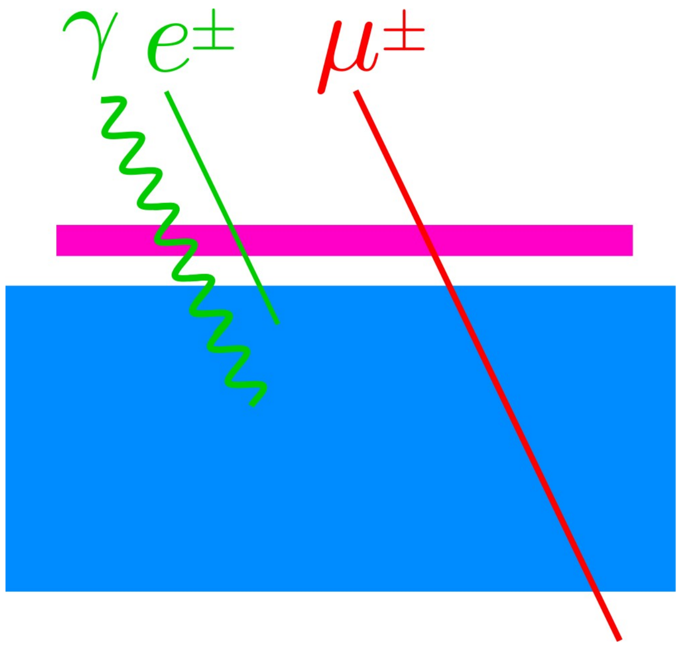
→ Search for a flux contribution of protons up to the highest energies

→ Study extensive air showers and hadronic multi-particle production

Deconvolving Detector Responses

$$\begin{pmatrix} E_{\rm scin} \\ E_{\rm wcd} \end{pmatrix} = \begin{pmatrix} f^{\gamma,e^\pm} & f^{\mu^\pm} \\ 1 - f^{\gamma,e^\pm} & 1 - f^{\mu^\pm} \end{pmatrix} \begin{pmatrix} E^{\gamma,e^\pm} \\ E^{\mu^\pm} \end{pmatrix}$$

$$f^{\gamma,e^\pm} = \frac{E^{\gamma,e^\pm}_{\rm scin}}{E^{\gamma,e^\pm}}$$



$$f^{\mu^\pm} = \frac{E^{\mu^\pm}_{\rm scin}}{E^{\mu^\pm}}$$

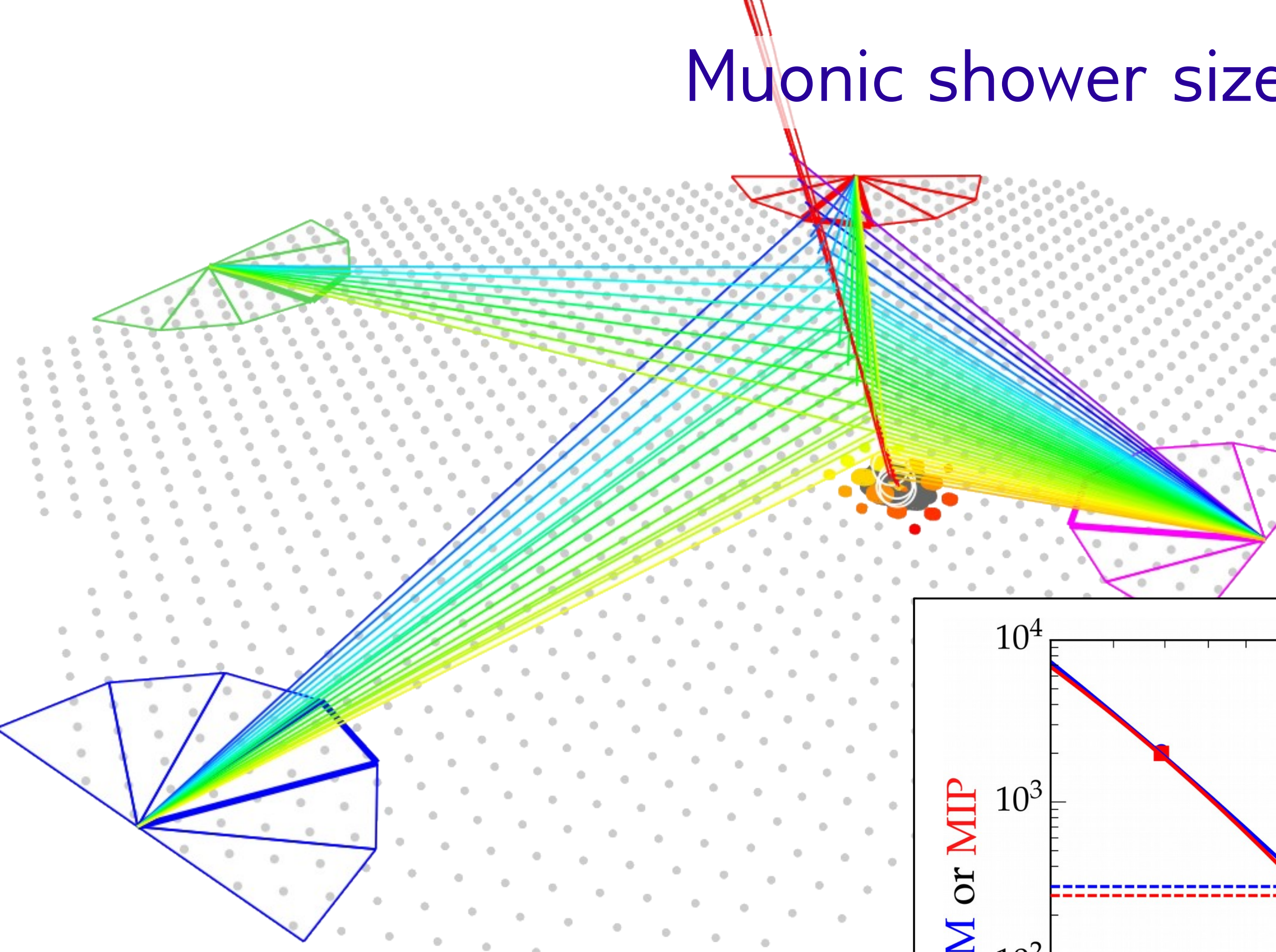
By means of inversion:

$$S^{\mu^\pm}_{\rm wcd} = -u S_{\rm scin} + (1-v) S_{\rm wcd}$$

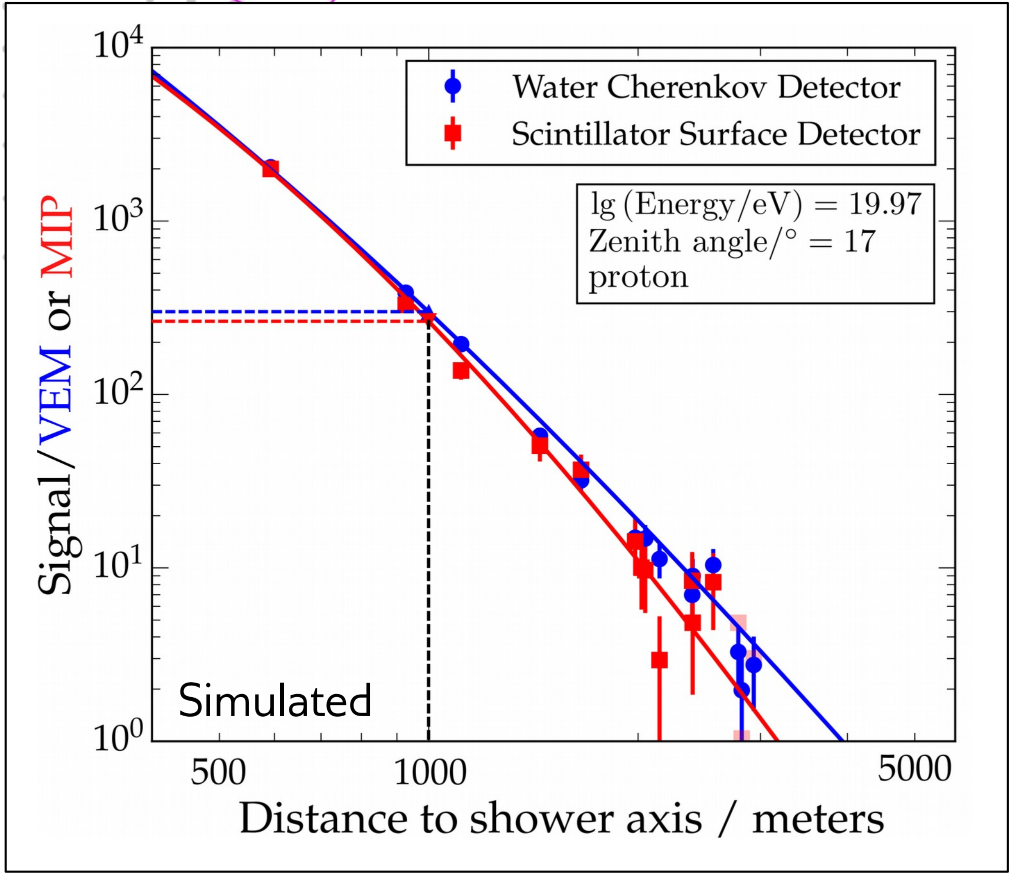
$$S^{\gamma,e^\pm}_{\rm wcd} = u S_{\rm scin} + v S_{\rm wcd}$$

$$\boxed{\begin{aligned} S_{\rm scin} &= C_{\rm scin} E_{\rm scin} \\ S_{\rm wcd} &= C_{\rm wcd} E_{\rm wcd} \end{aligned}}$$

Muonic shower size

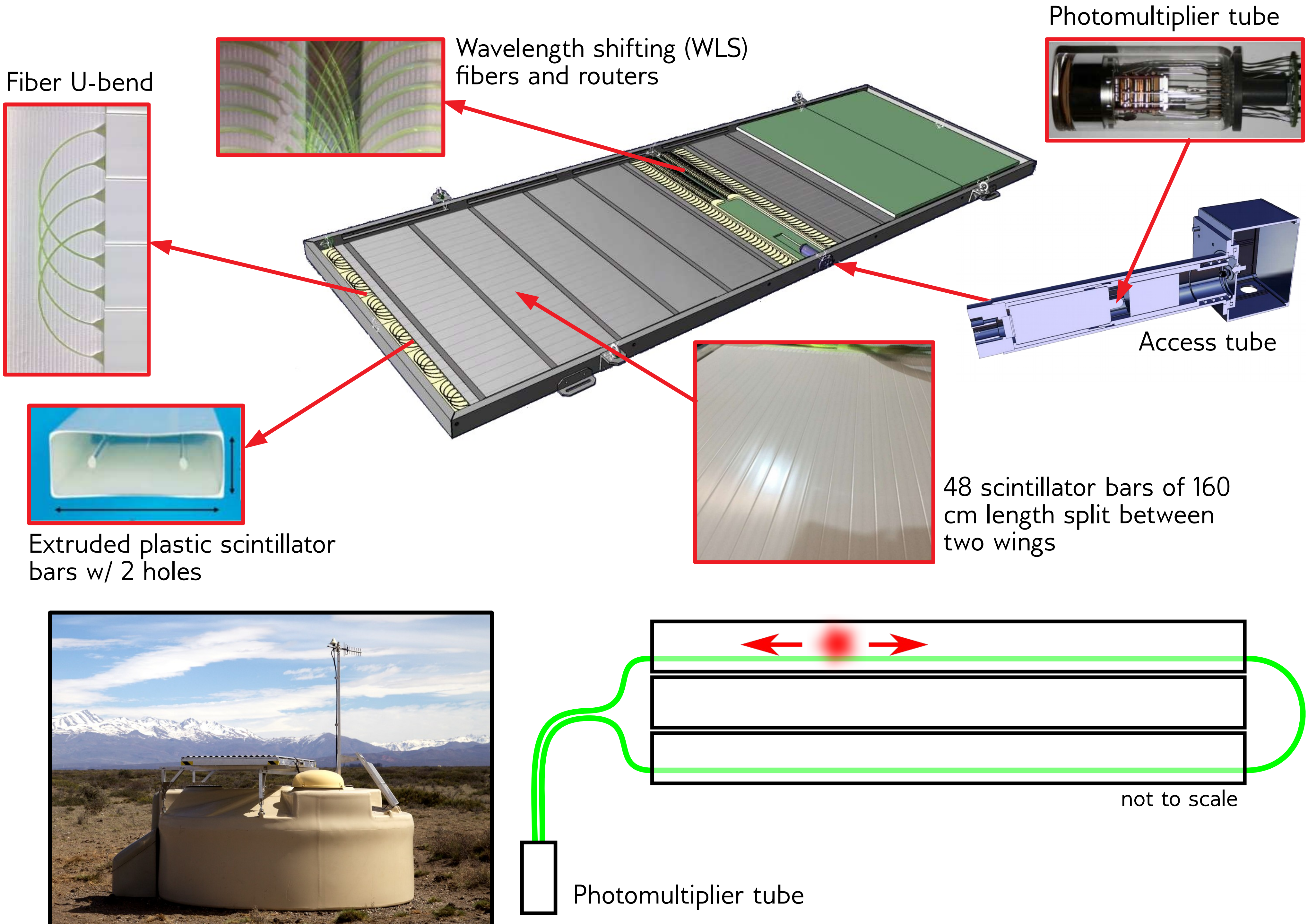


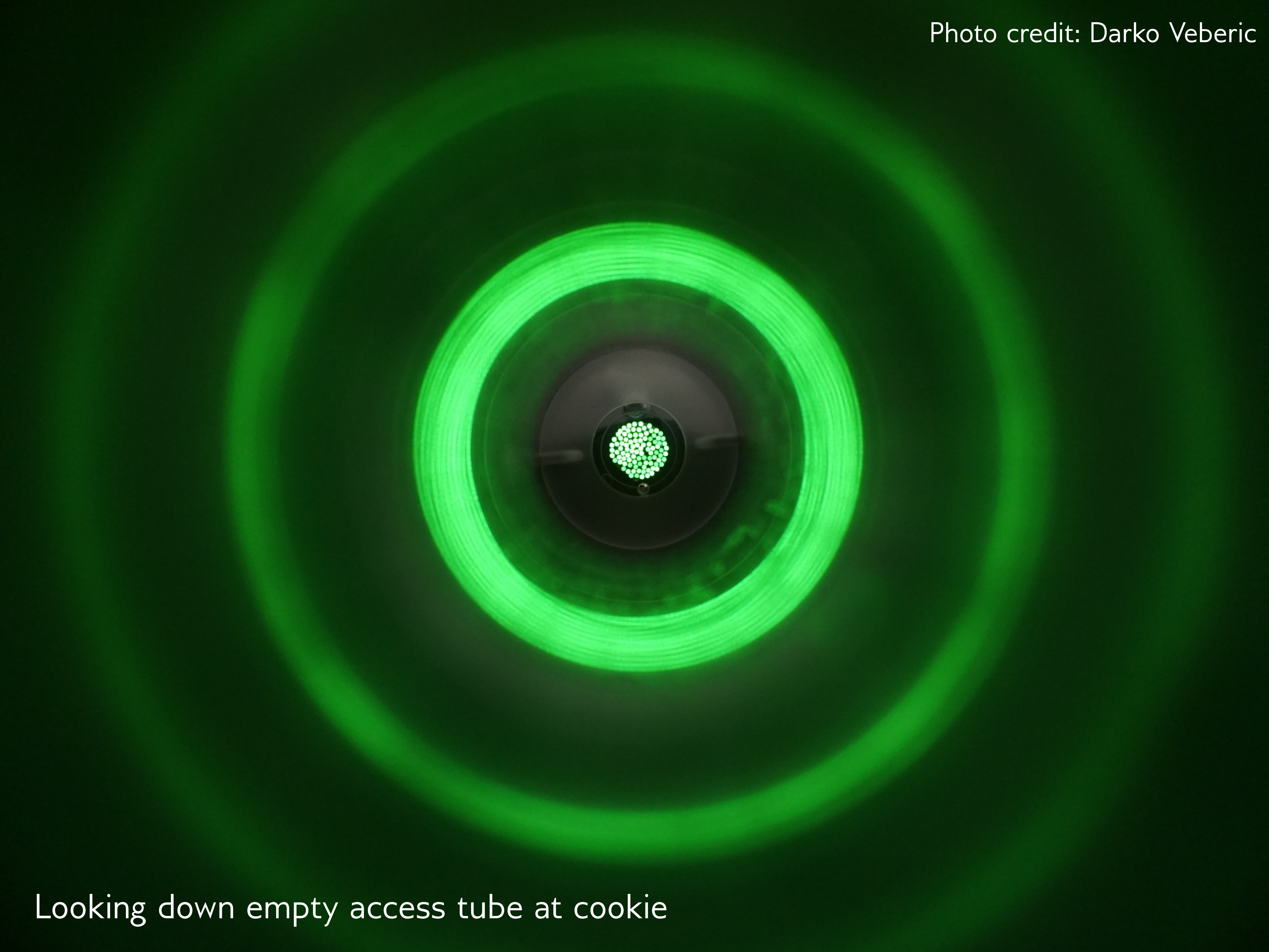
Lateral distributions
of detector signals



Deconvolution to obtain
electromagnetic and muonic
shower sizes

Surface Scintillator Detector





Looking down empty access tube at cookie

Flashlight shined onto one scintillator bar end reveals fiber routing

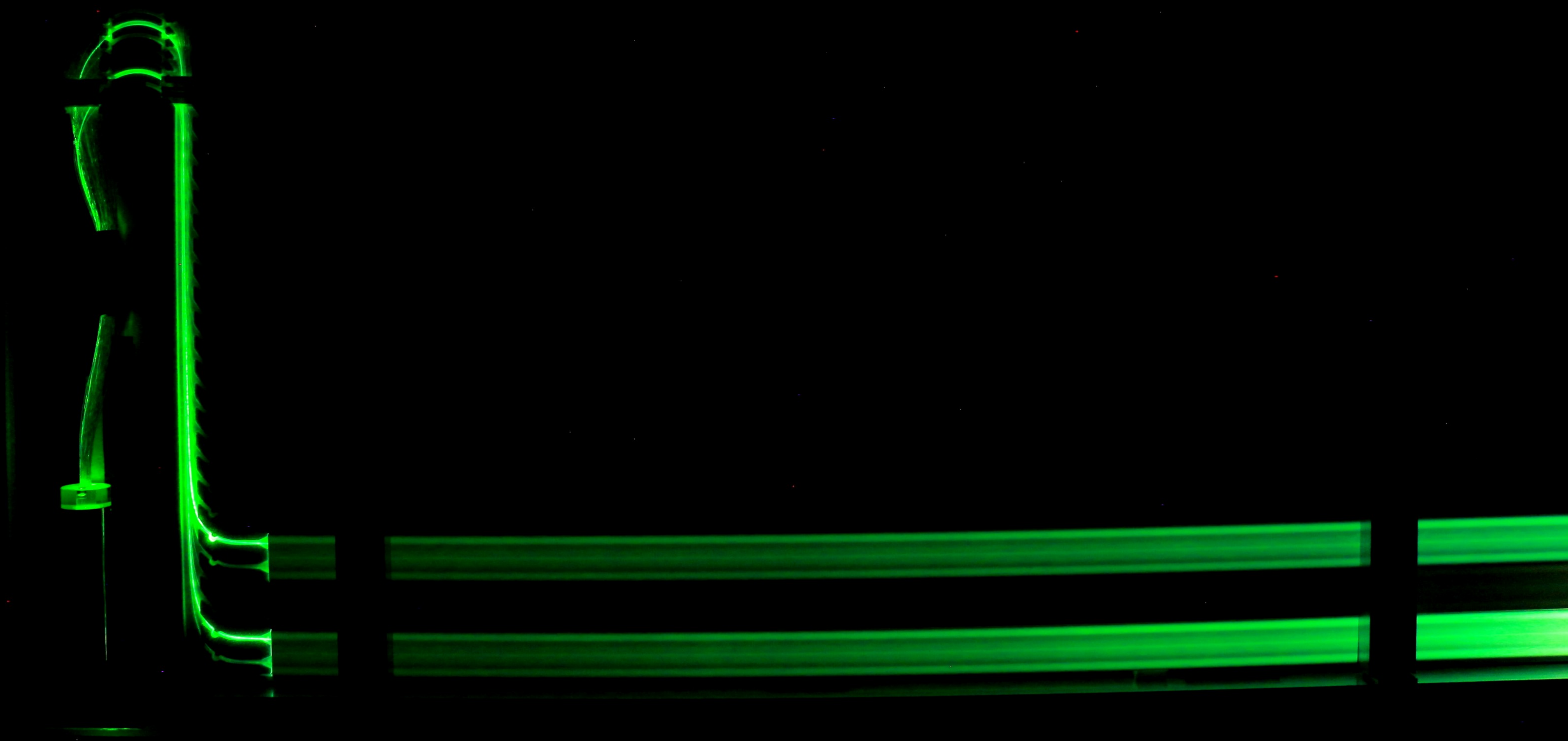
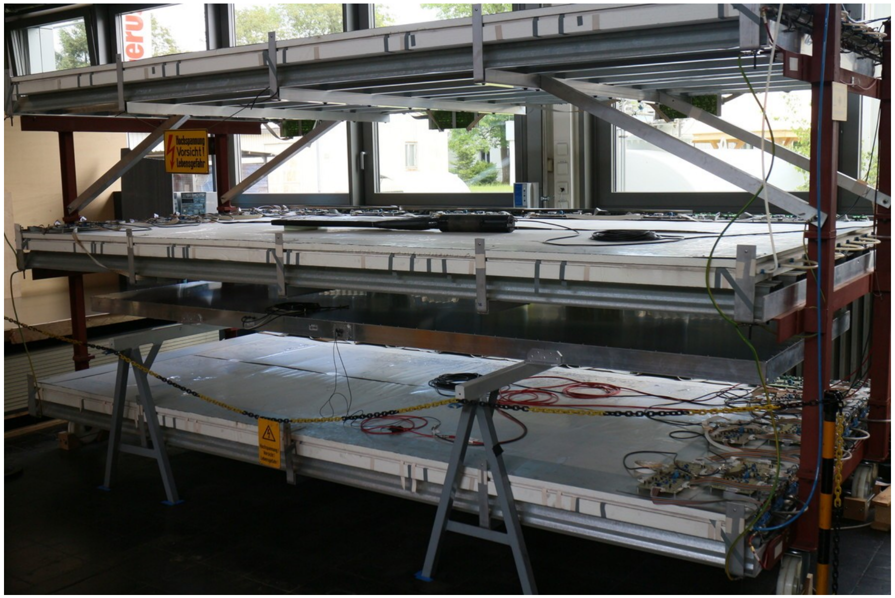
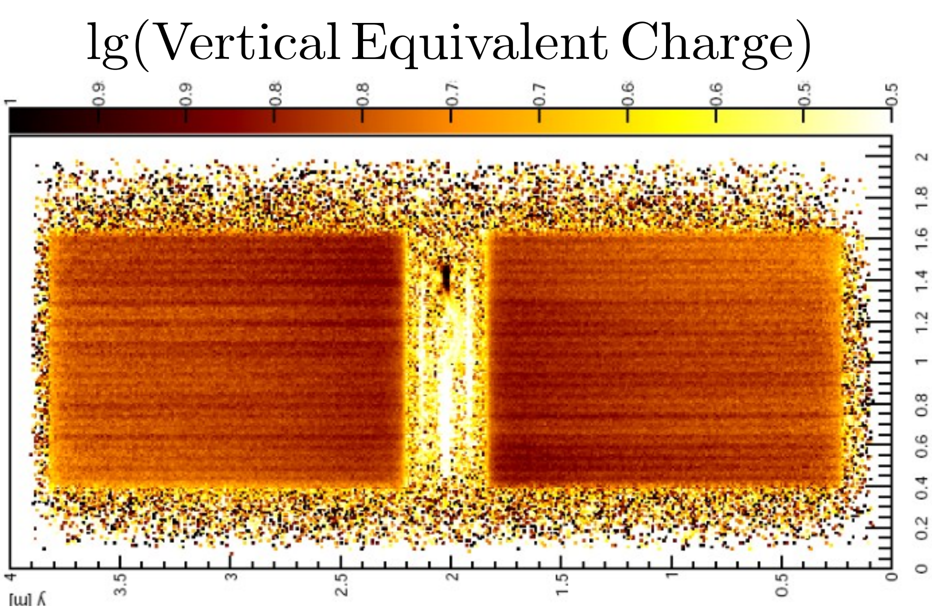


Photo credit: Darko Veberic

Characterization and validation

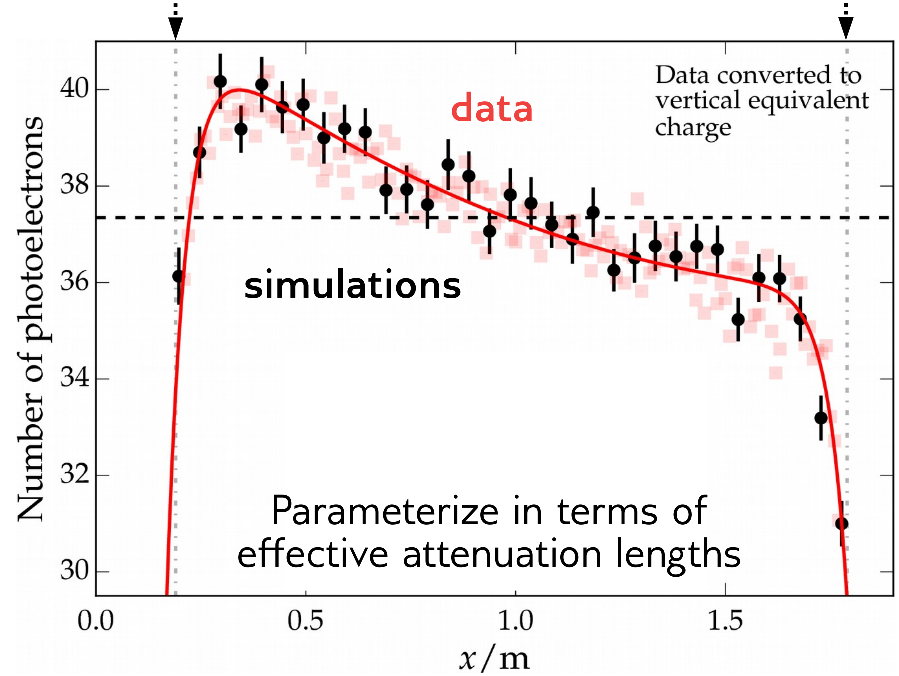
Centimeter precision muon telescope





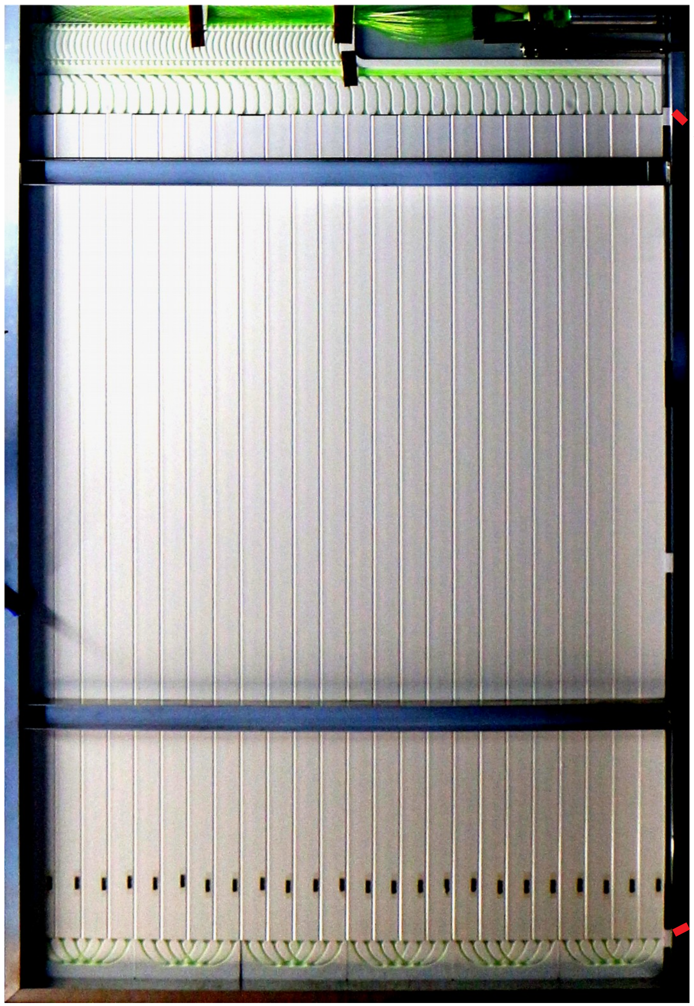
Resolve individual bars and fibers

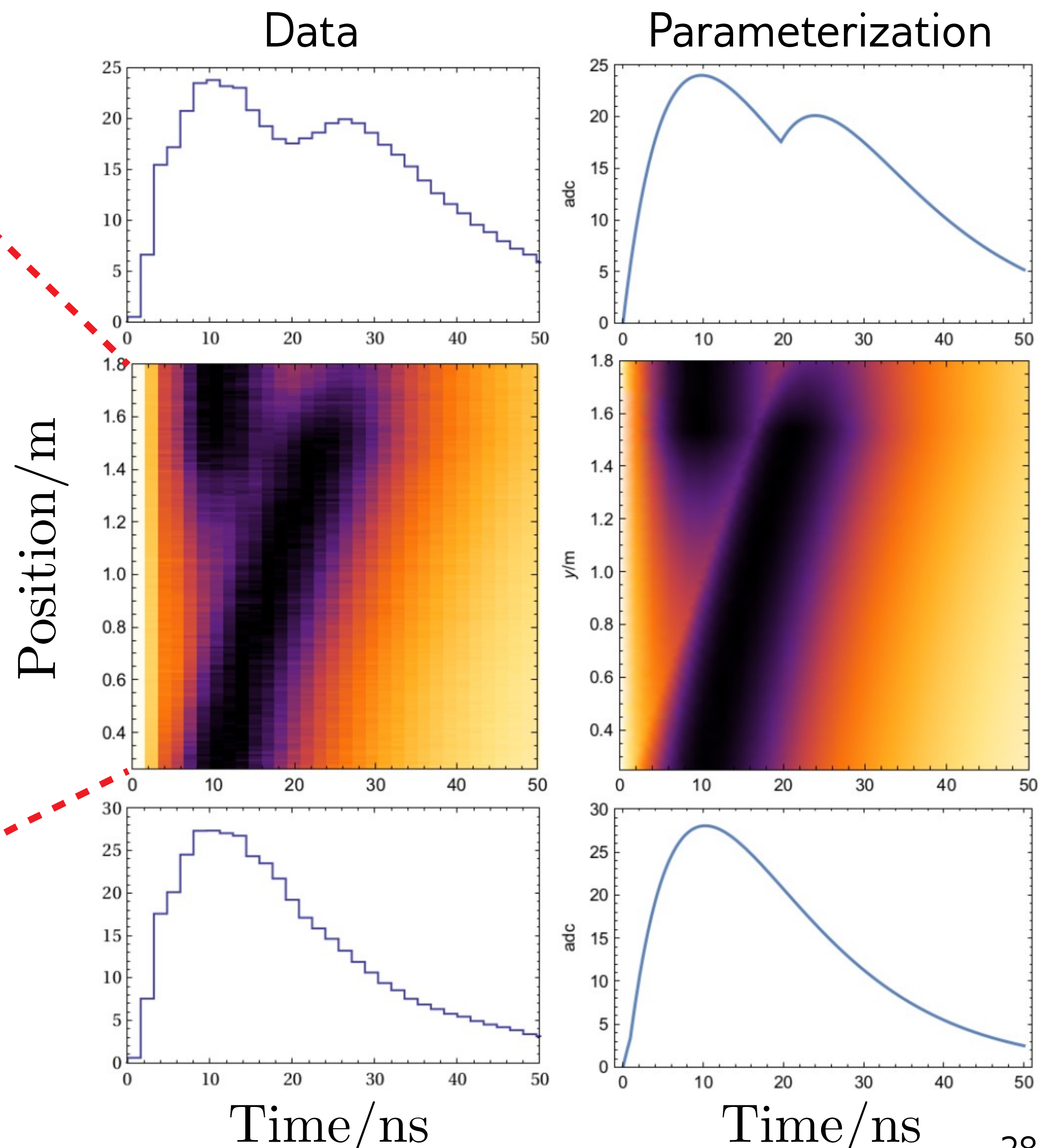
Signal response



Characterization and validation

Timing response

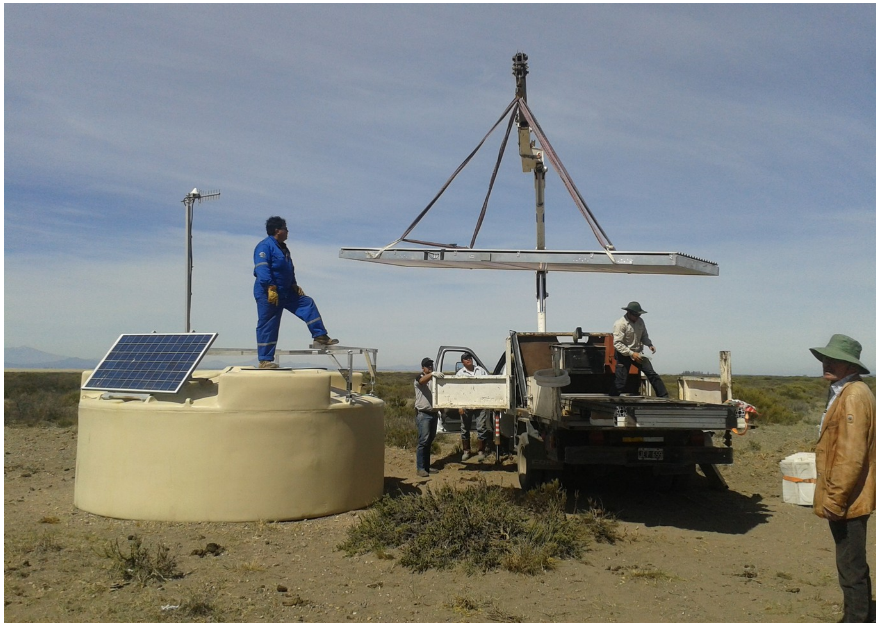


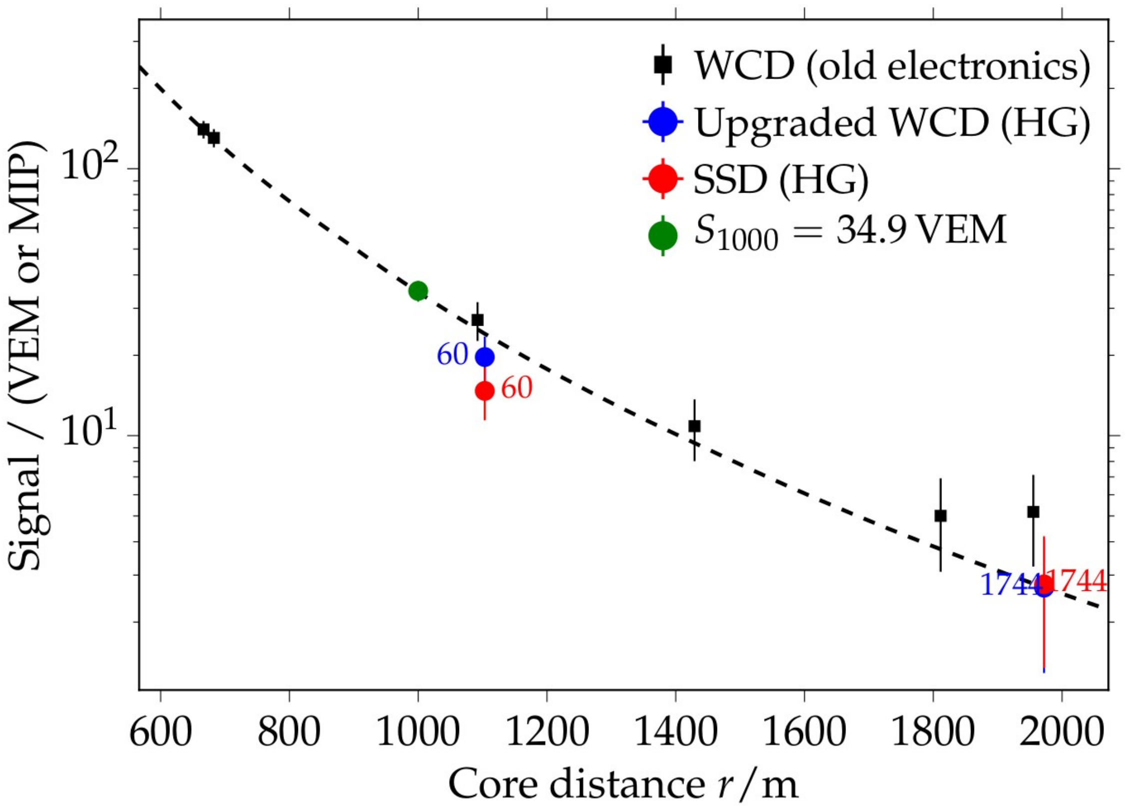


Parameterize data in terms of decay constants and effective index of refraction

Engineering Array

- Deployed September 2016
- 12 prototype detectors
- Test bed for
  - Scintillator module design
  - Upgrade electronics
  - WCD small PMT
  - Etc.





SSD Production/Deployment

Production performed at 5 European institutes (starting Oct. 2017)

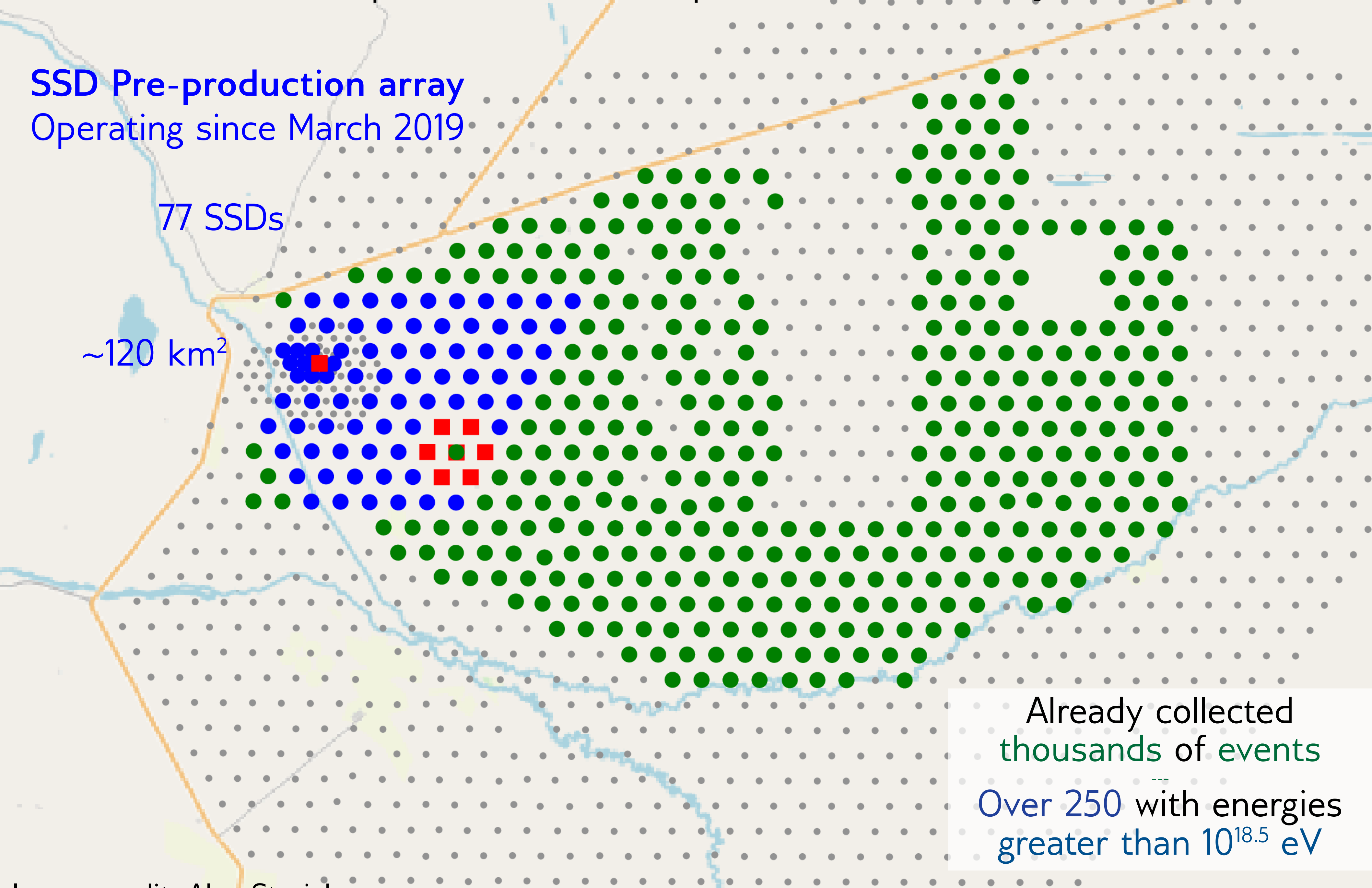
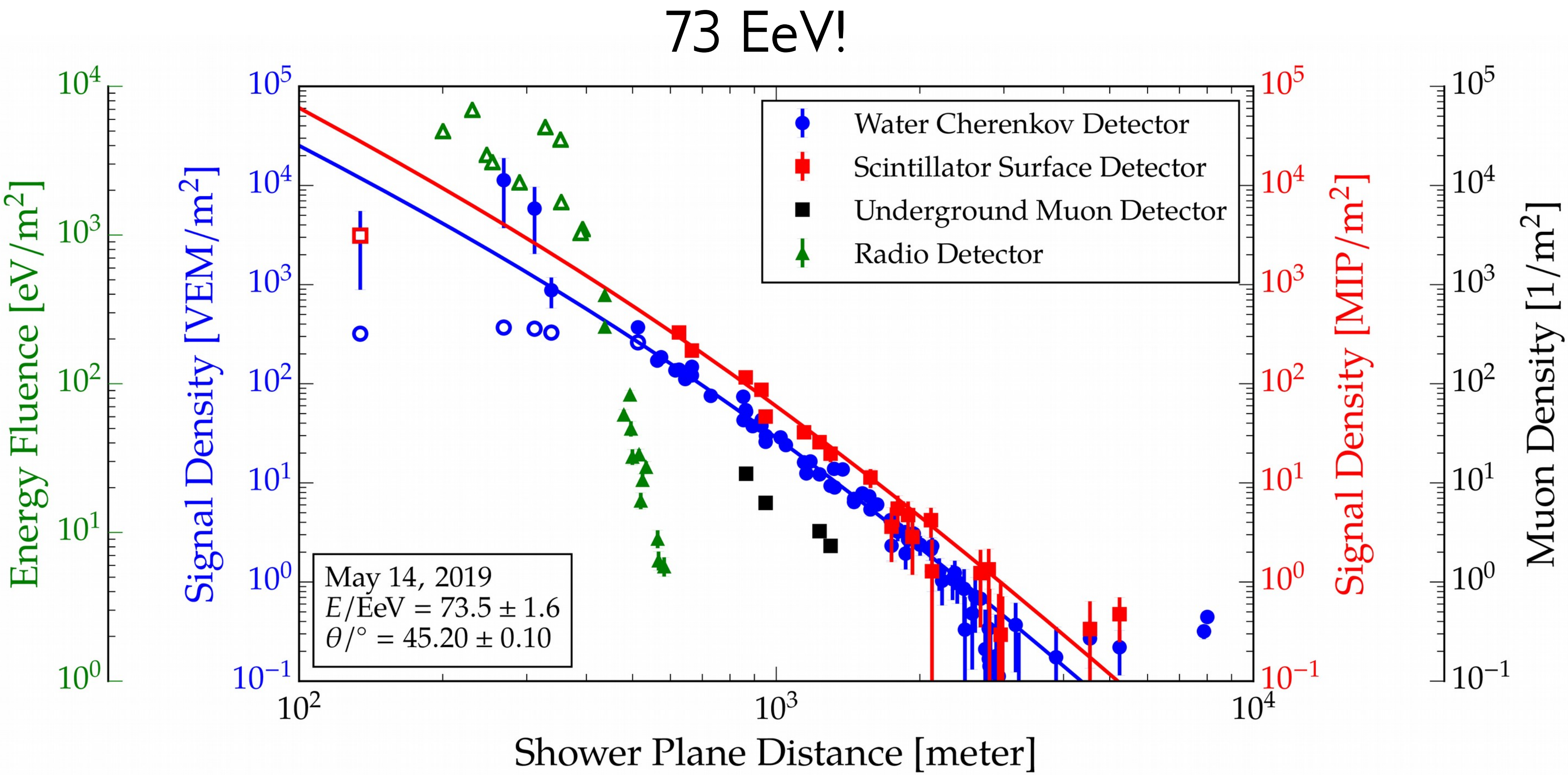


Image credit: Alex Streich

Quad-hybrid AugerPrime Event

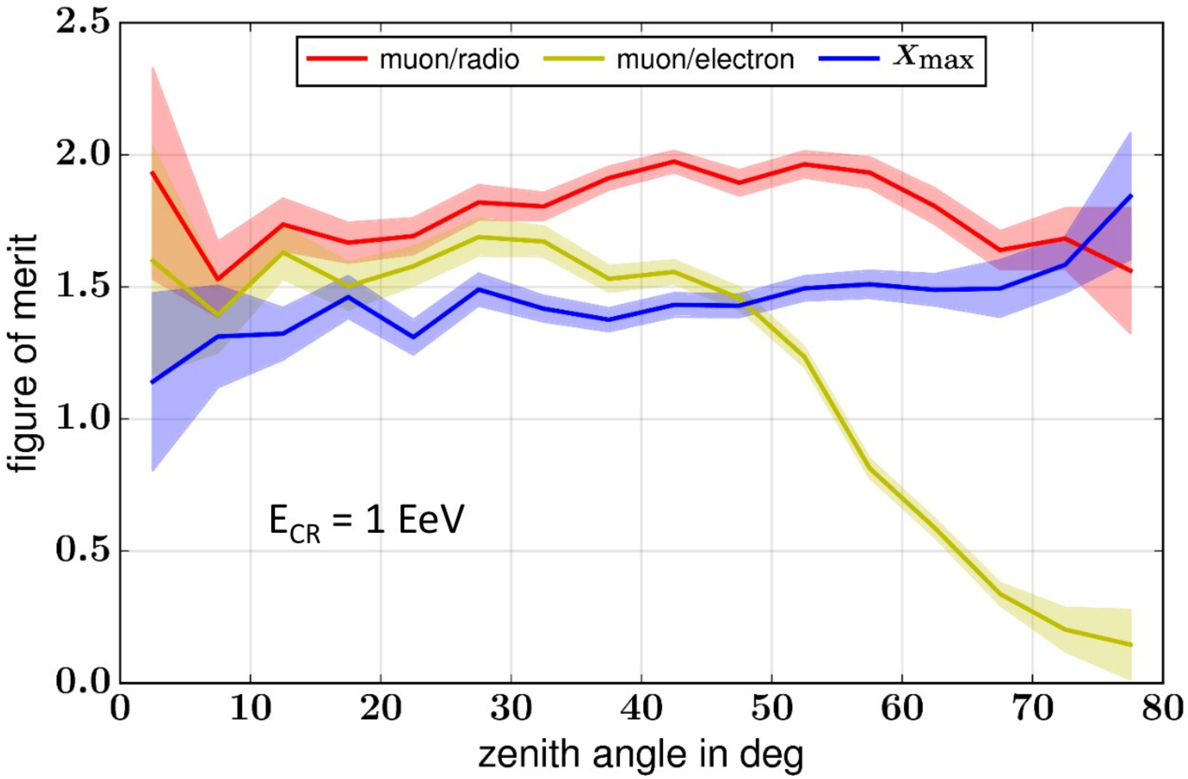


Thanks to Felix Schlüter, Ana Botti, and Alvaro Taboada for providing the Radio, UMD, and SSD data!

Radio Upgrade

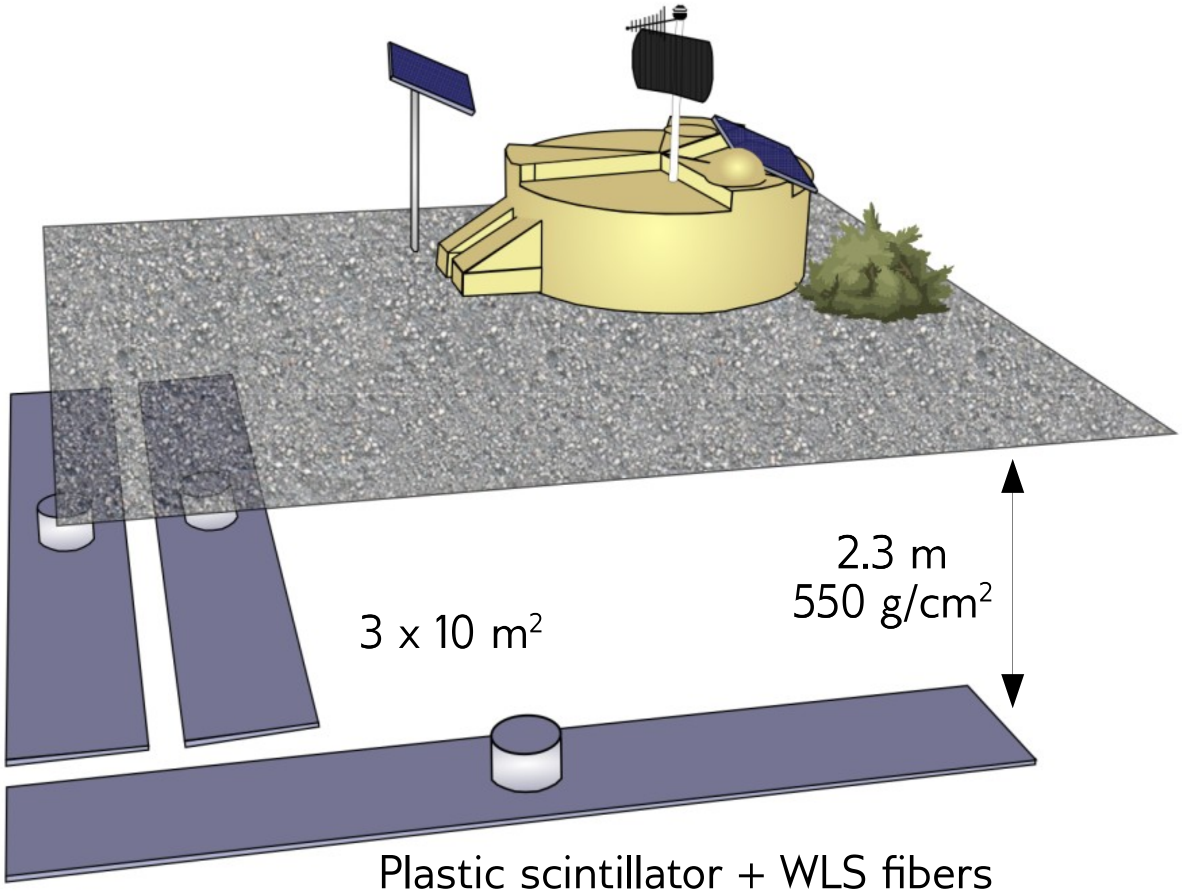
Antenna to be placed on top of each WCD/SSD

Extends composition sensitivity to more inclined showers increasing exposure and sky coverage



Prototype antenna installed in the AugerPrime engineering array

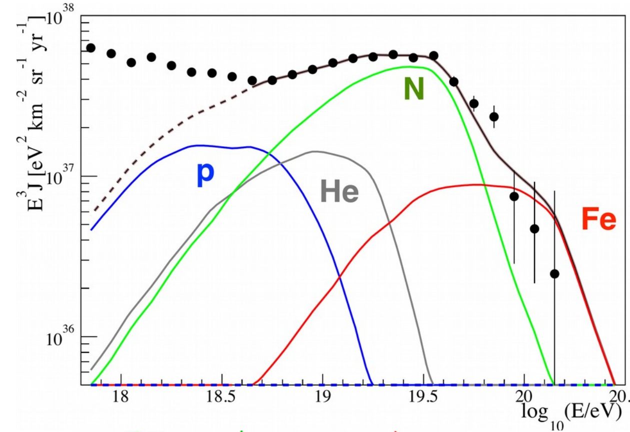
Underground Muon Detector

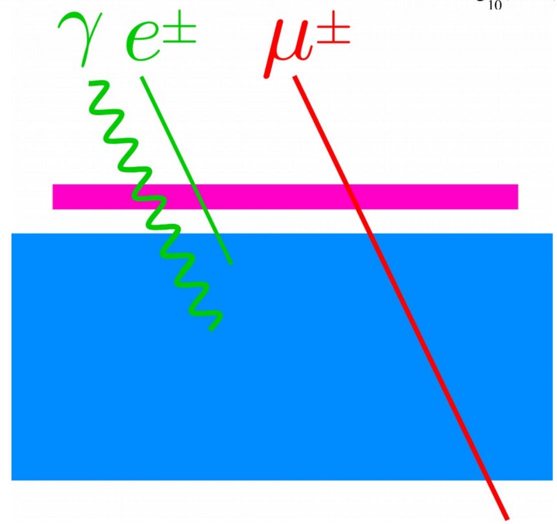


- Buried scintillator detectors for direct muon counting
- Counter and integrator modes
- Cover an area of 23.5 km^2
- Provides valuable cross check on WCD+SSD muon reconstruction

Summary

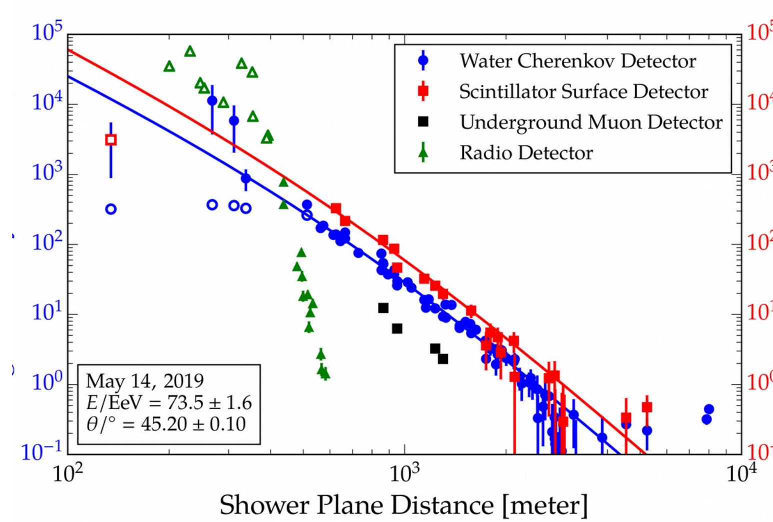
- UHECR sources (type, distribution, and internal mechanisms) largely remain a mystery
- Shape and features of energy spectra give clues but impact of photo-disintegration and photo-pion production yet to be properly understood
- primary mass measurement needed



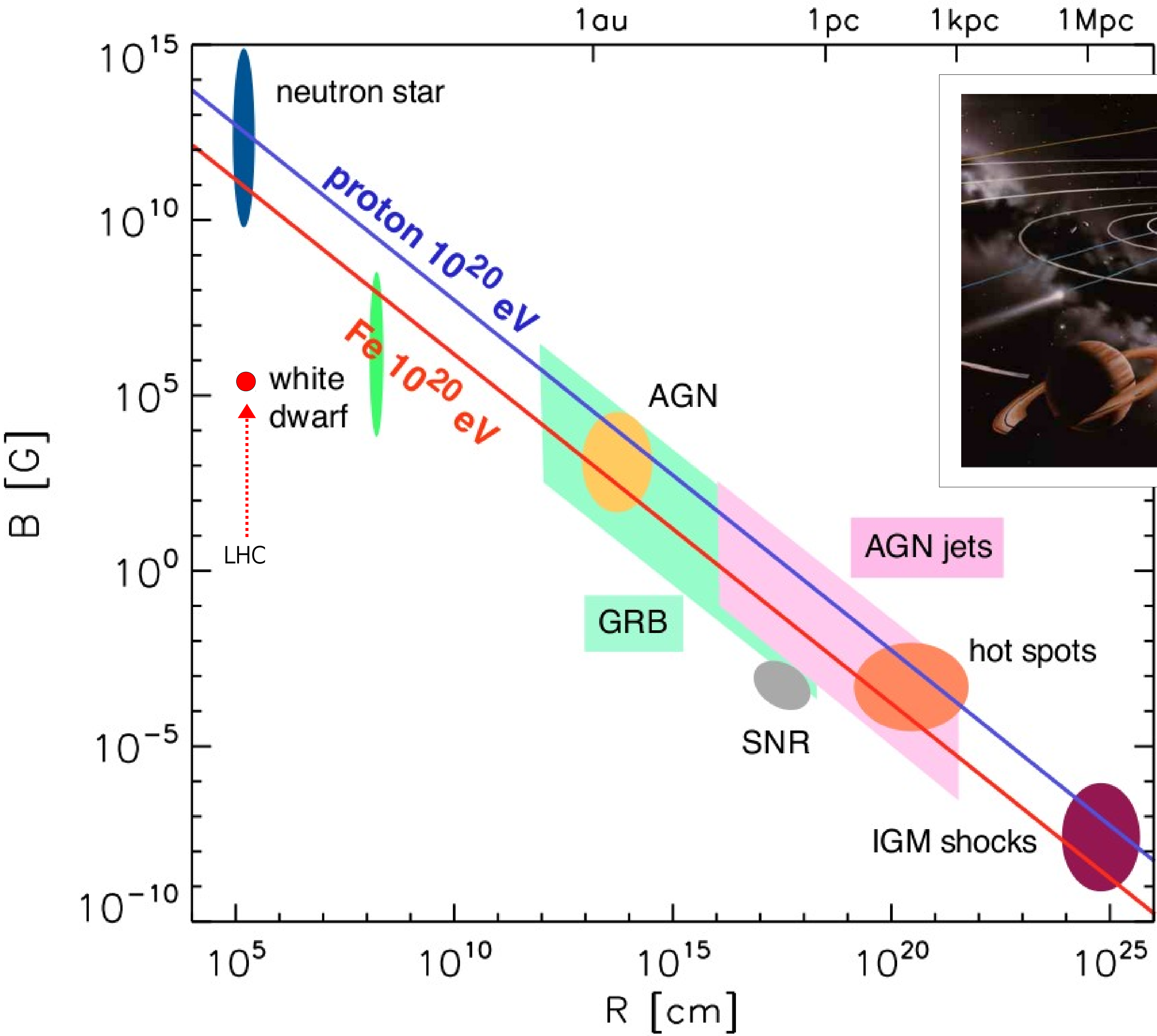


AugerPrime

- Will provide means to reconstruct mass with 100% duty cycle
- Scintillator detector response studied and well understood
- Design validated in the field through engineering array and pre-production array measurements. Absolute calibration underway.
- First high-energy measurements as deployment underway



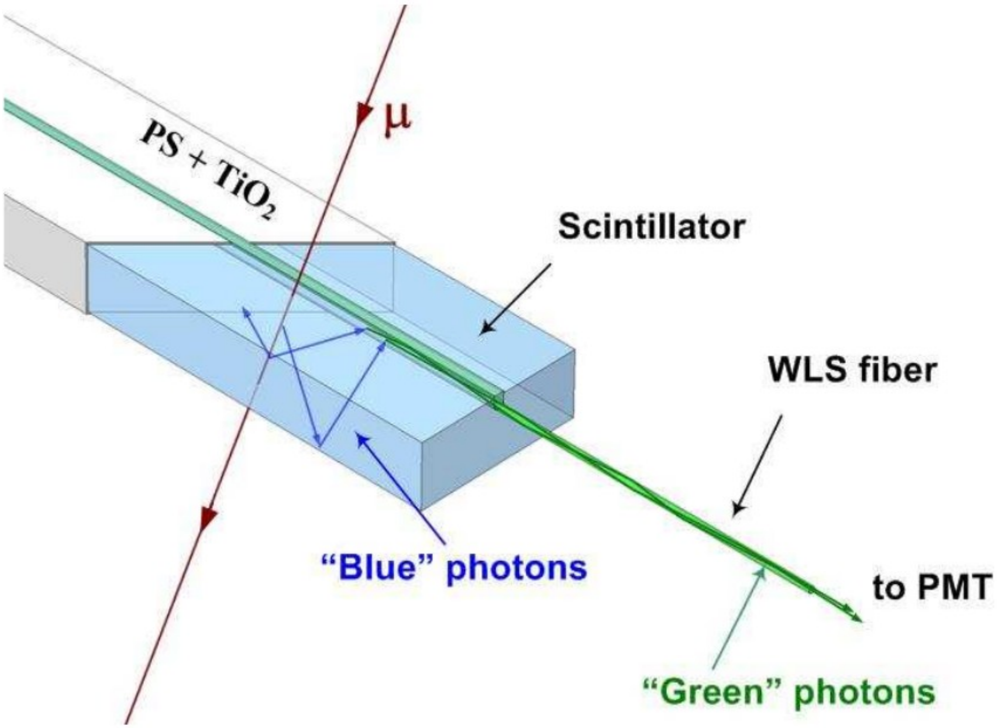
UHECR Acceleration

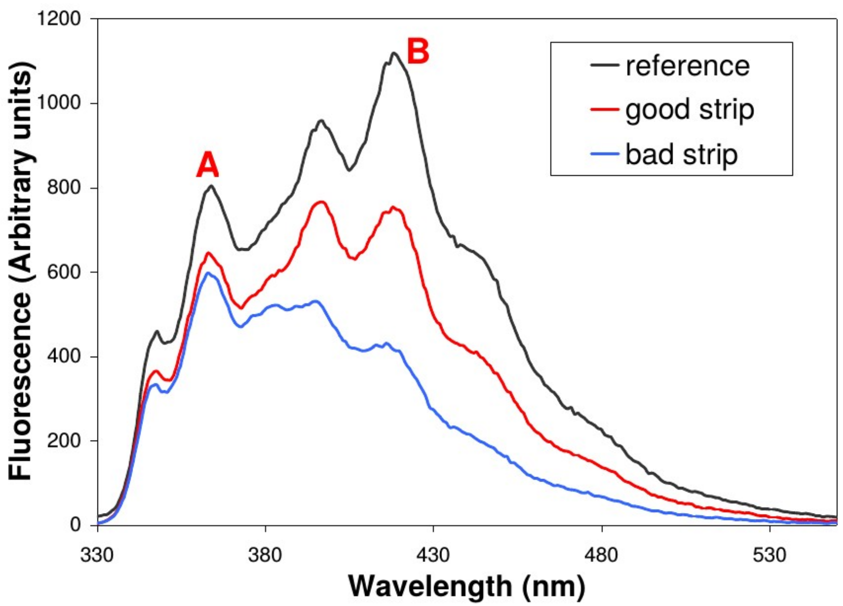


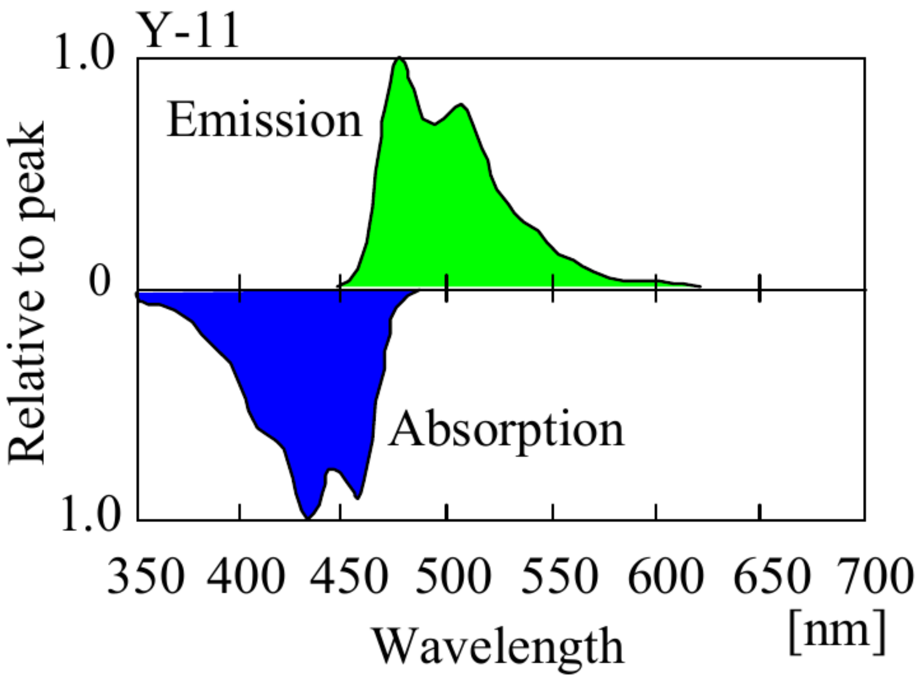
Michæl Unger

LHC technology with orbit of Mercury needed for 10^{20} eV protons

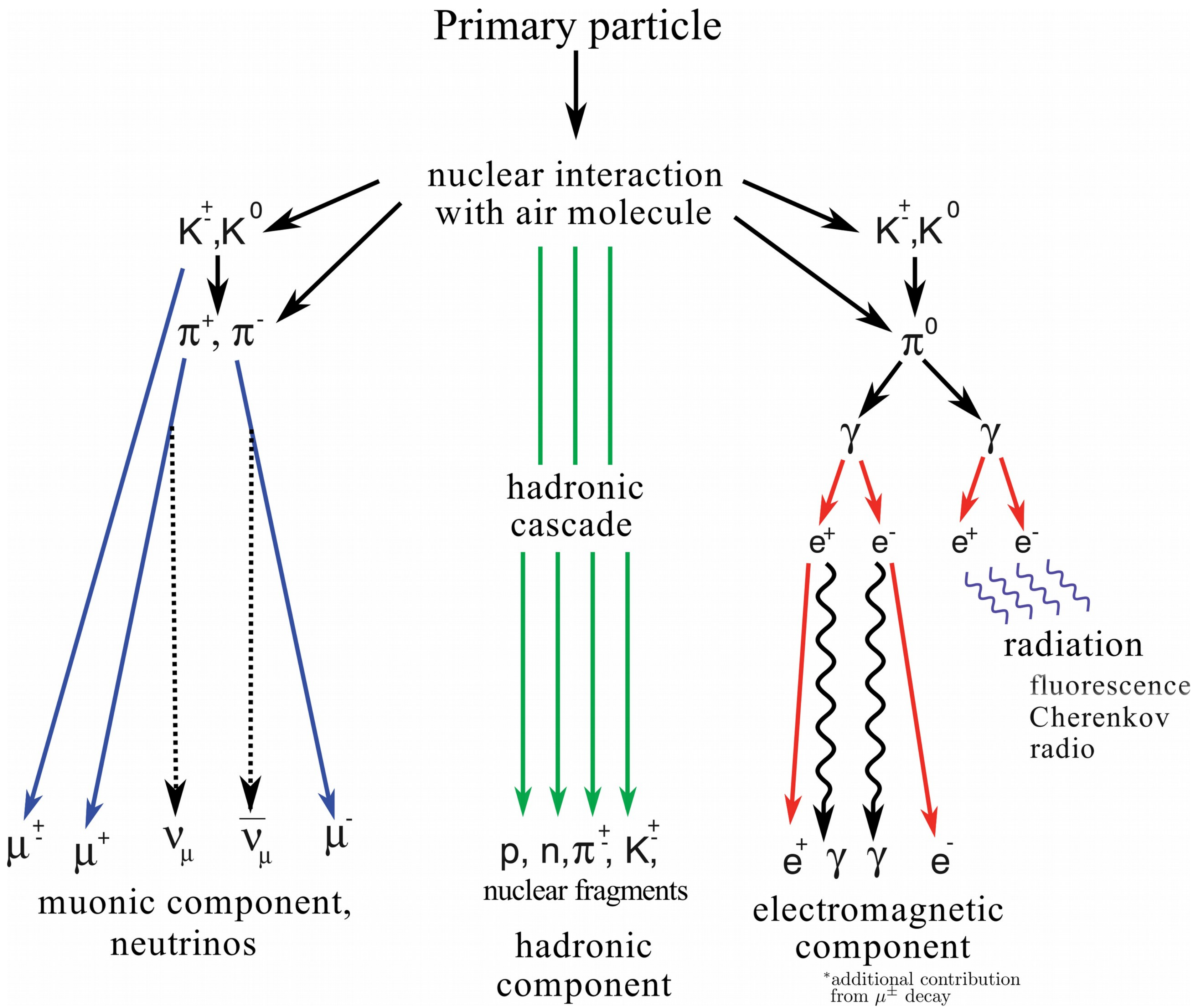
Scintillator & WLS Fibers







EAS


Primary particle
nuclear interaction
with air molecule
K±, K0
π+, π-
K±, K0
π0
γ
γ
e+
e-
e+
e-
hadronic
cascade
radiation
fluorescence
Cherenkov
radio
μ±
μ+
νμ
ν̄μ
μ-
muonic component,
neutrinos
p, n, π±, K±,
nuclear fragments
hadronic
component
e+
γ
γ
e-
electromagnetic
component
*additional contribution
from μ± decay