Latest results from the Pierre Auger Observatory

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for the Pierre Auger Collaboration

15th Dark Side of the Universe 2019

Buenos Aires, Argentina

ITeDA

CNEA - CONICET - UNSAM

PIERRE AUGER OBSERVATORY

Outline

1. Introduction

- Ultra High Energy Cosmic Rays (UHECR)
- The Pierre Auger Observatory

2. Current results

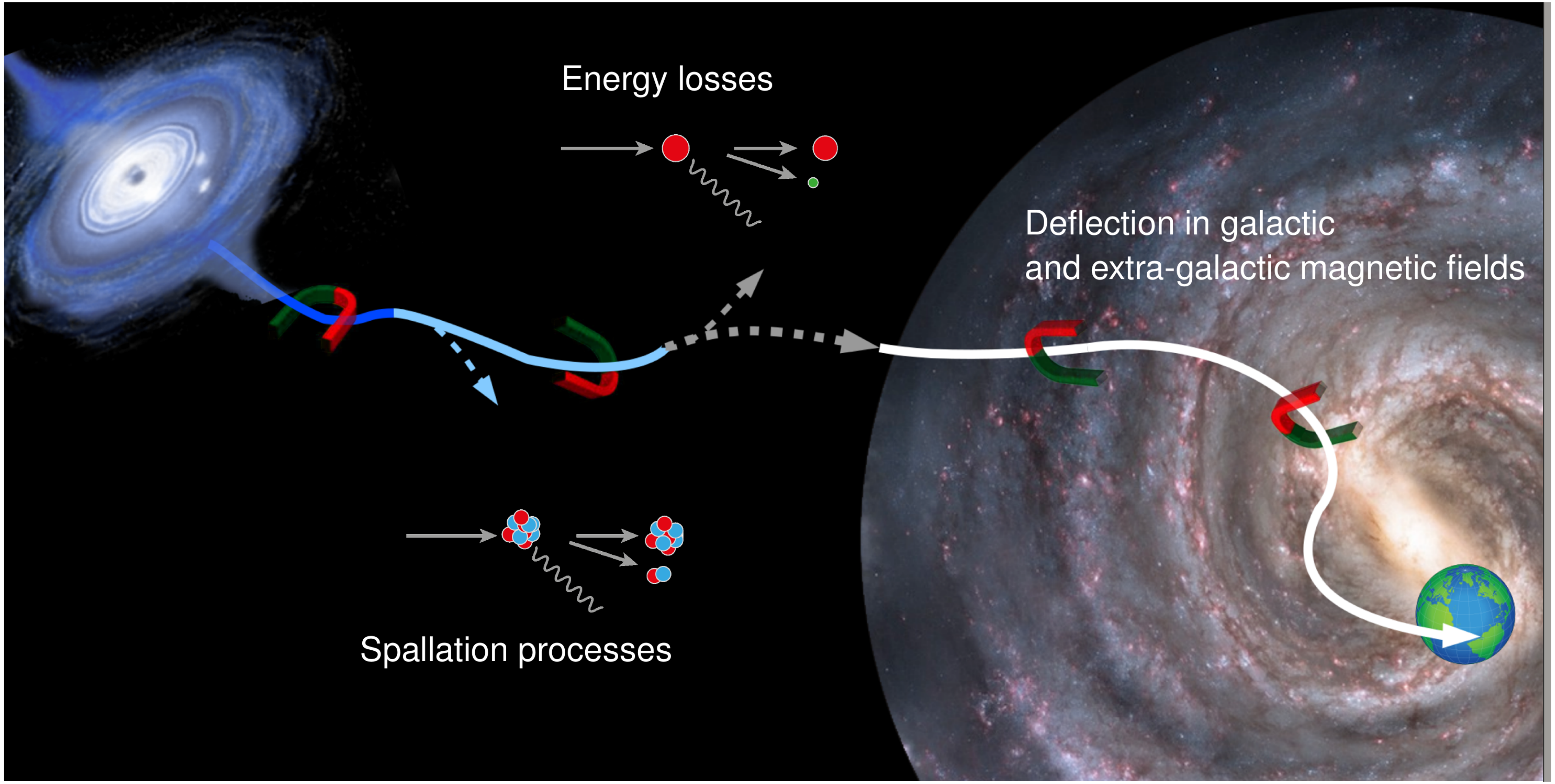
- Energy spectrum
- Composition
- Anisotropy
- DM constraints

New and unexpected (before Auger) scenario for UHECR

3. Perspectives (to solve open issues)

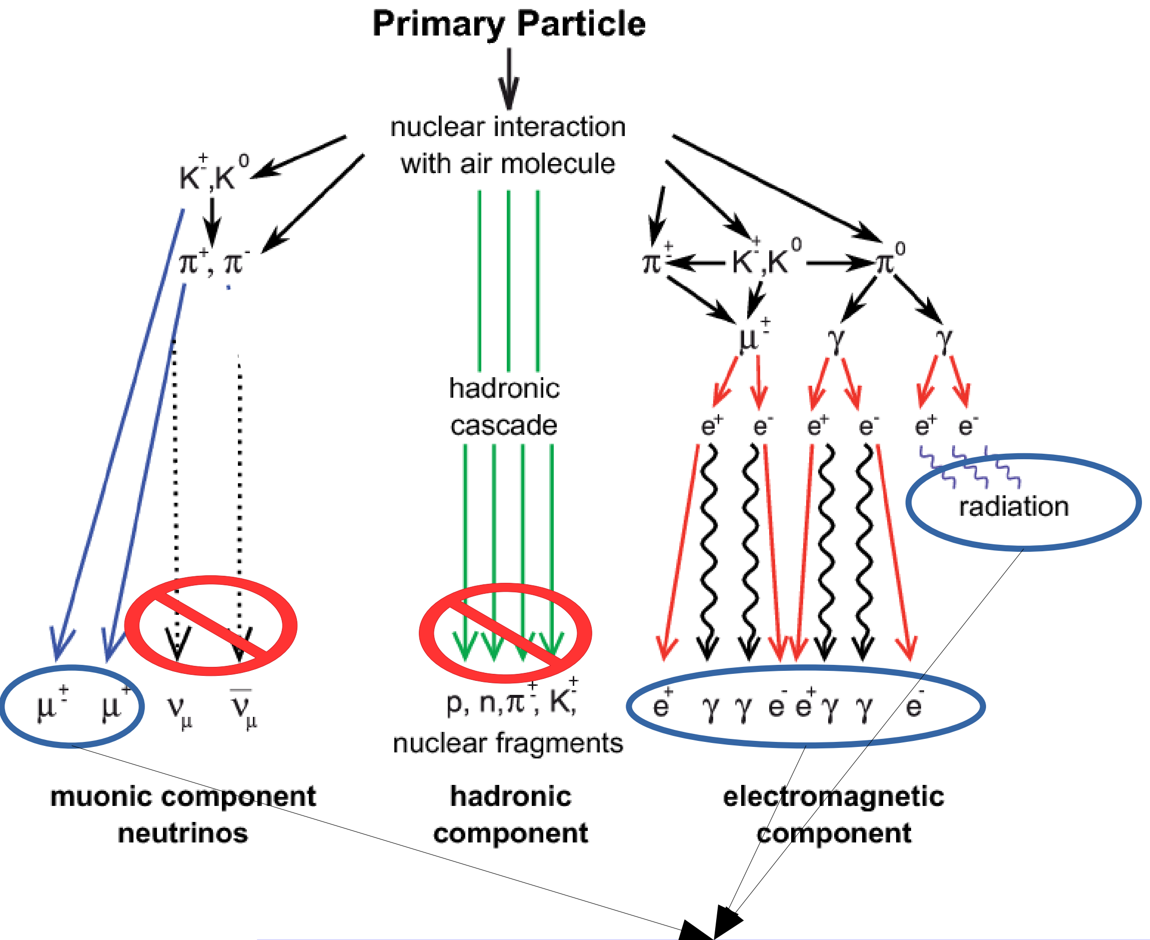
- AugerPrime (only if somebody in the audience ask for it :))

Ultrahigh Energy Cosmic Rays

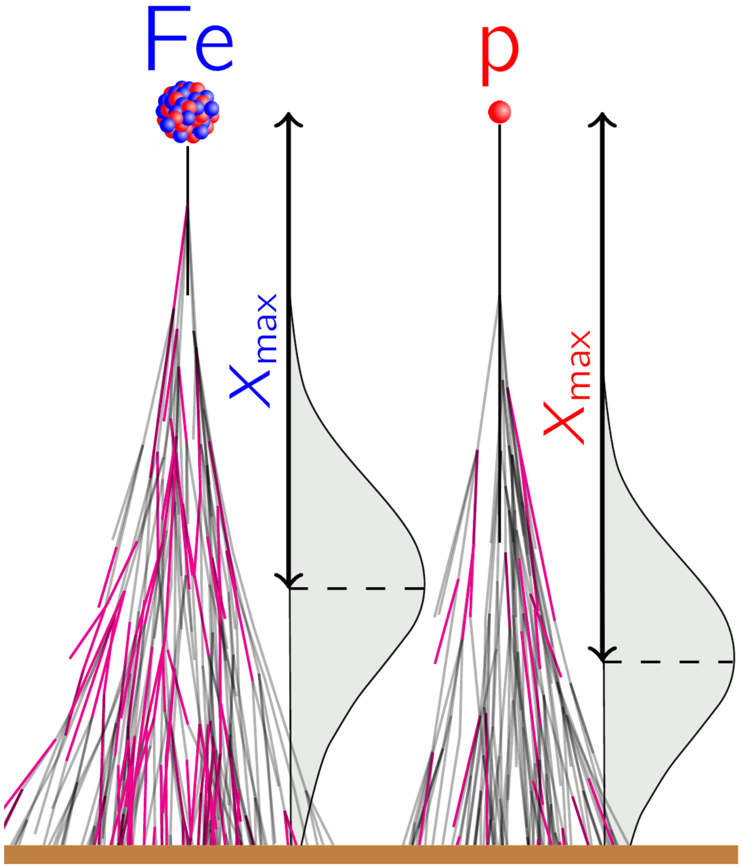


Where do they come from? How are they accelerated? What is their composition?

Ultrahigh Energy Cosmic Rays

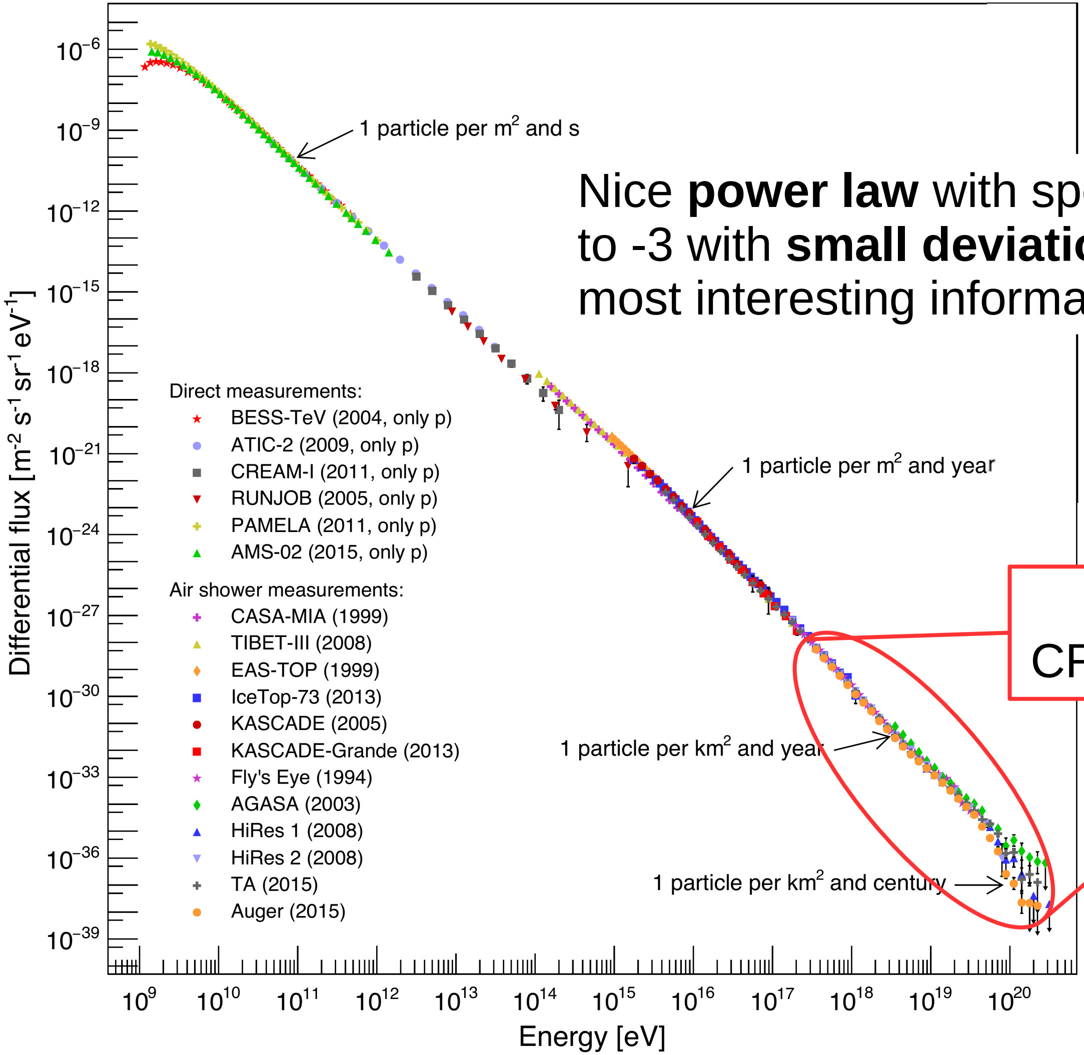


Accessible to ground based experiments



The **heavier** the particle the **shallower** the EAS and **lesser** the fluctuations shower-to-shower

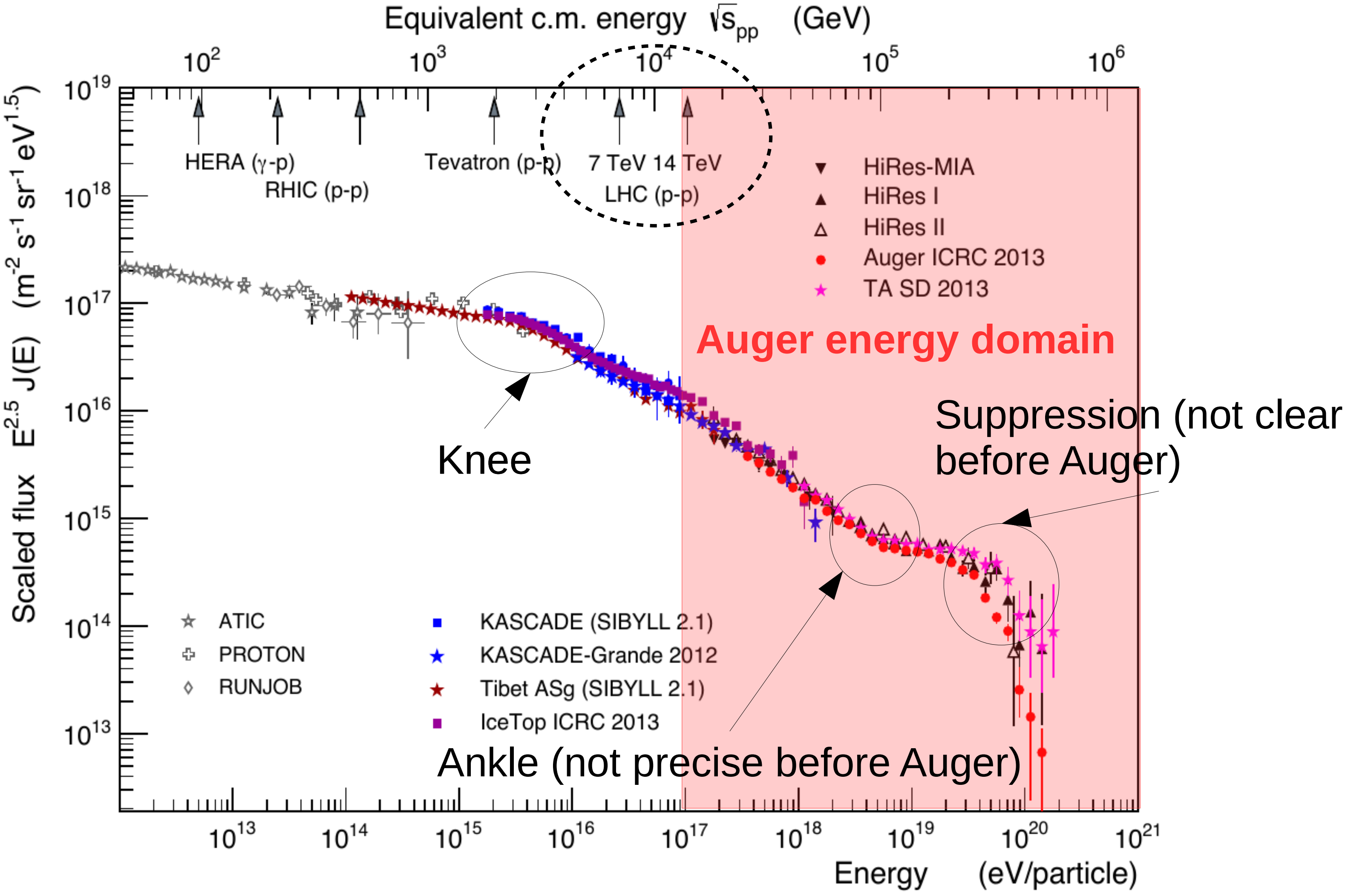
Ultrahigh Energy Cosmic Rays



Nice **power law** with spectral index close to -3 with **small deviations** (with the most interesting information!)

This talk:
CR with energy > 10^{17} eV

Ultrahigh Energy Cosmic Rays



The Pierre Auger Observatory

Surface detector (SD)

100% duty cycle

SD-1500m
3000 km^2
1600 WCDs

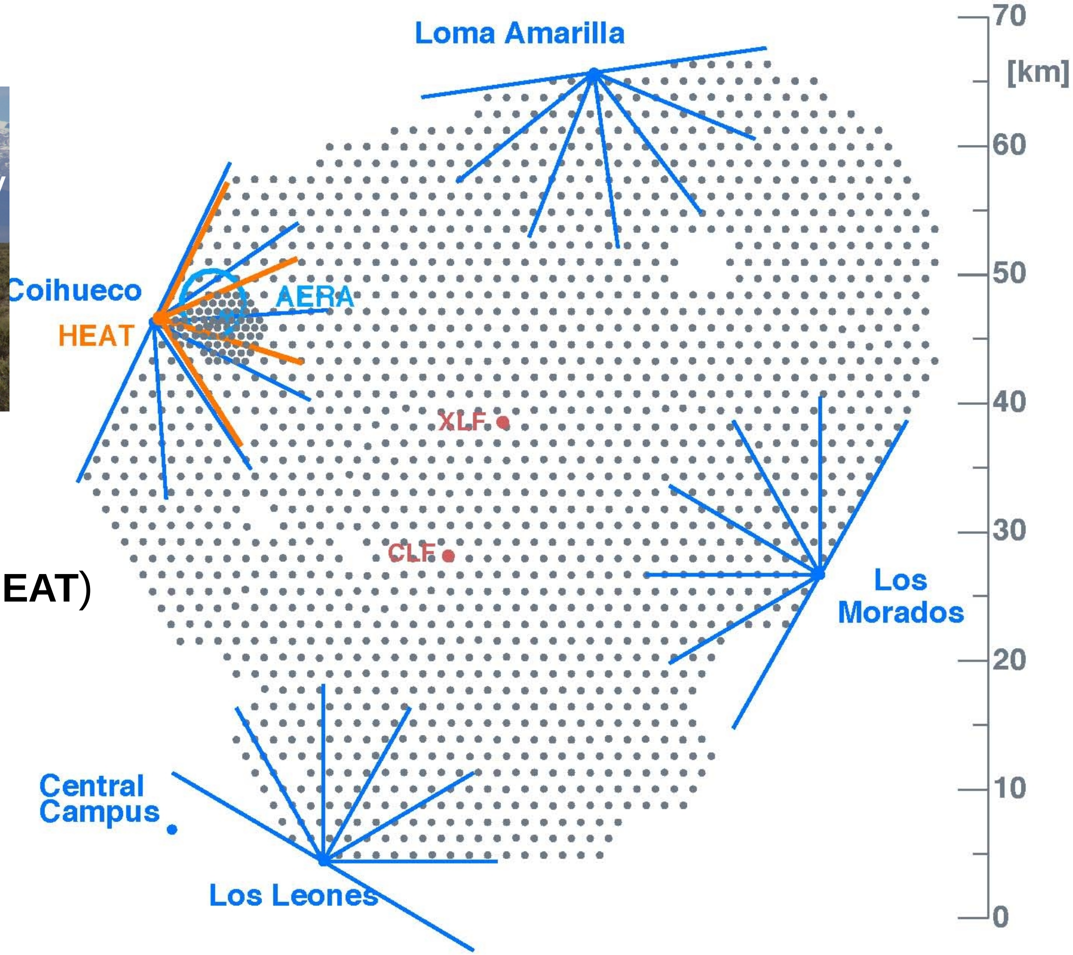
SD-750m
23.5 km^2
61 WCDs

Fluorescence detector (FD)

15% duty cycle

4 units x 6 telescopes
overlooking SD-1500m
FoV 30^o x 30^o
Minimum elevation 1.5^o

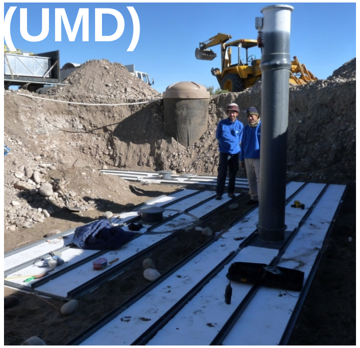
1 units x 3 telescopes (**HEAT**)
overlooking SD-750m
FoV 30^o x 30^o
Minimum elevation 30^o



The Pierre Auger Observatory

Underground muon detector (UMD)

100% duty cycle

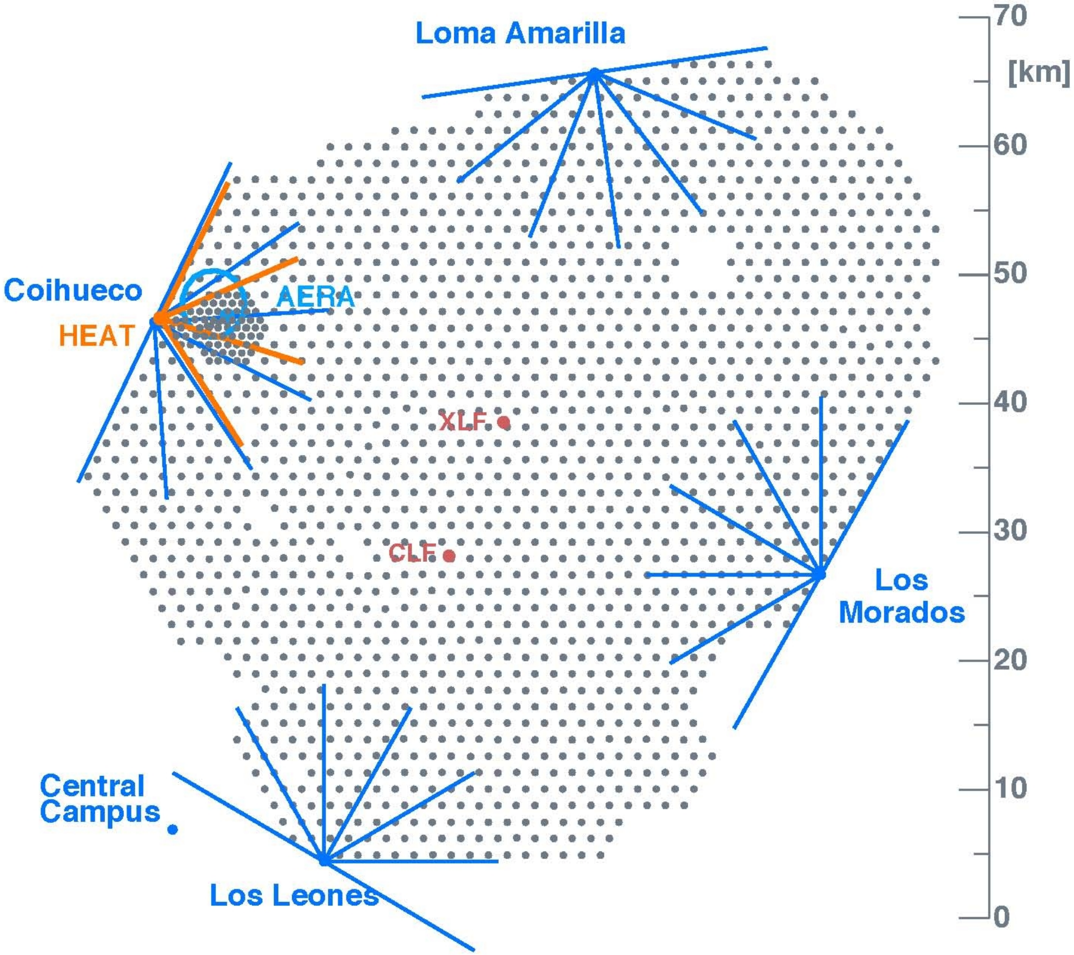


UMD-750m (AMIGA)
23.5 km^2
61x30m^2 Plastic Scintillators
buried 2.3m triggering from WCDs

Radio detector (RD)

100% duty cycle

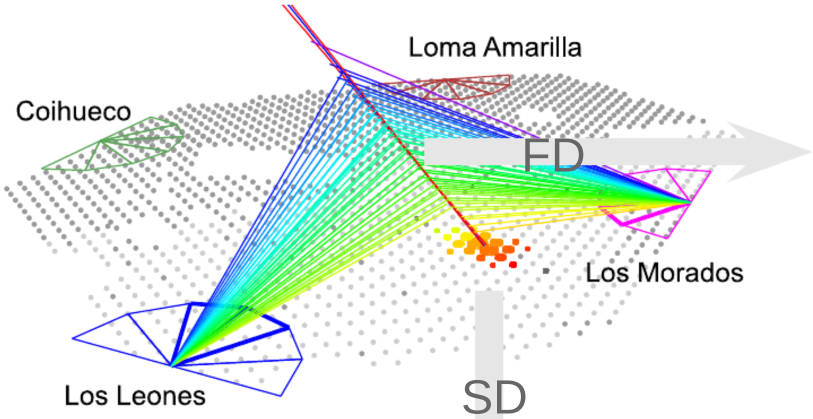
30-80 MHz (AERA)
153 radio stations over 17 km^2
Spacing from 150m to 750m

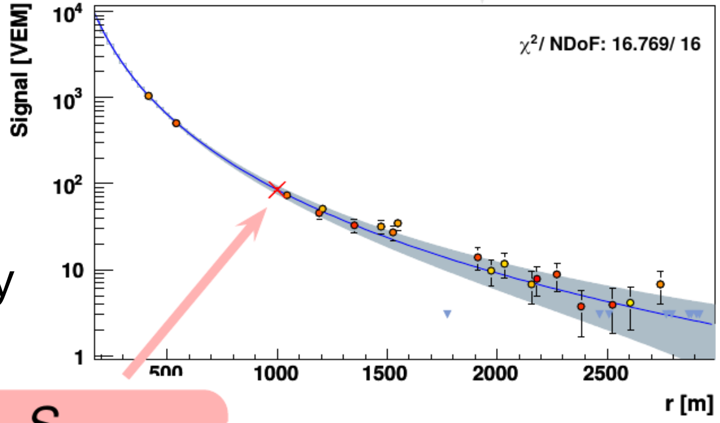


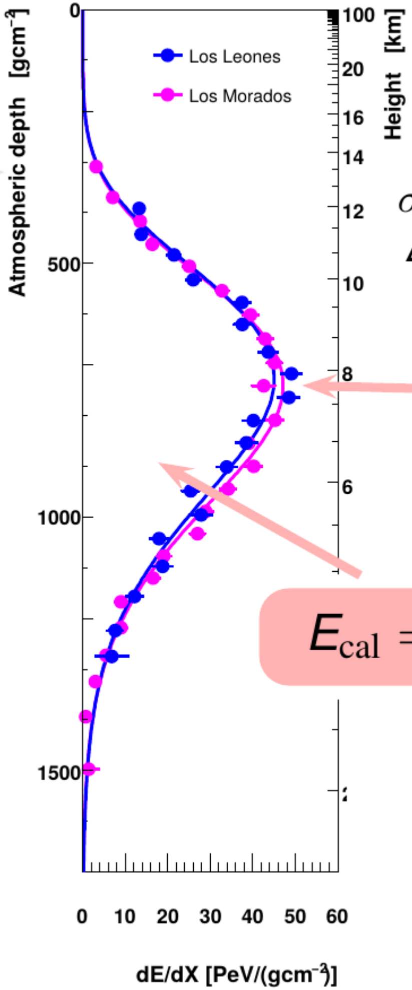
Physics observables must basically be extracted from:

- **signal size**
- **signal timing**

The hybrid technique







Number of secondaries contains information on primary energy

S_{1000}

$E_{\mathrm{surface}} = f(S_{1000},\ \theta)$

$\sigma X_{\mathrm{max}} \leq 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \leq 10\,\mathrm{g/cm^2}$

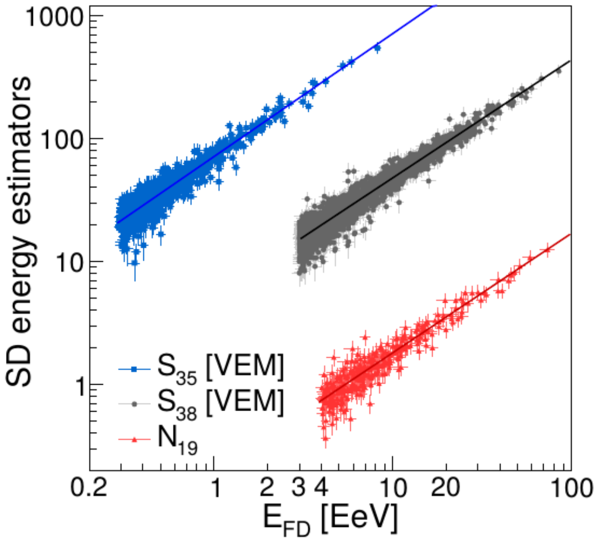
X_{max}

$E_{\mathrm{cal}} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$

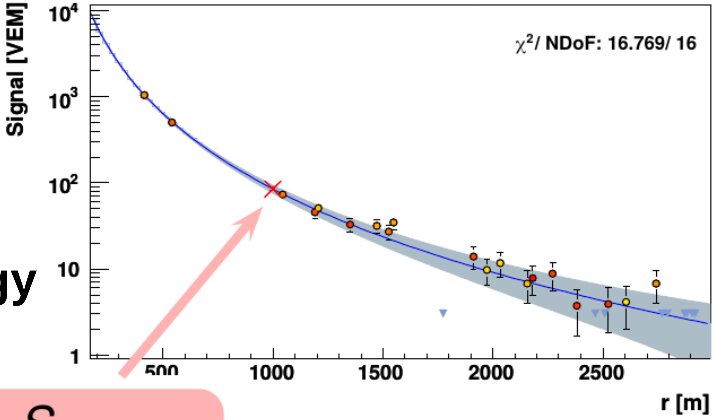
$\sigma_E/E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 15\,\%$

The hybrid technique

Calibration of SD signals (with ~10% of the events)



Number of secondaries contains information on **primary energy**



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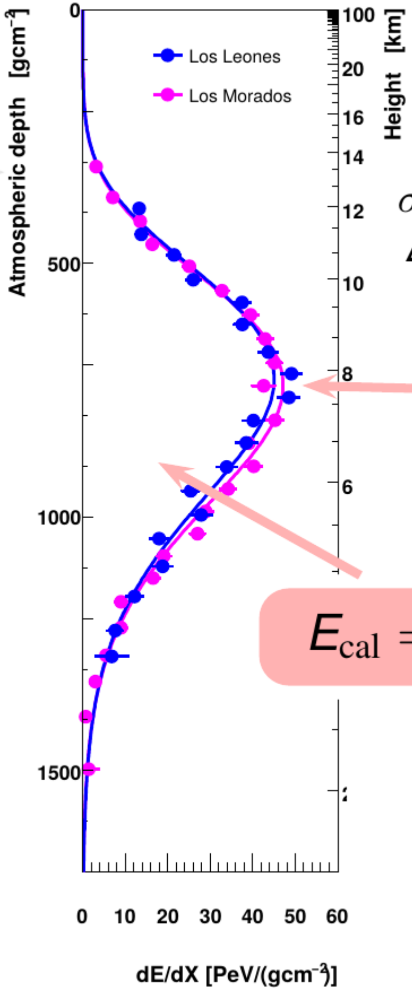

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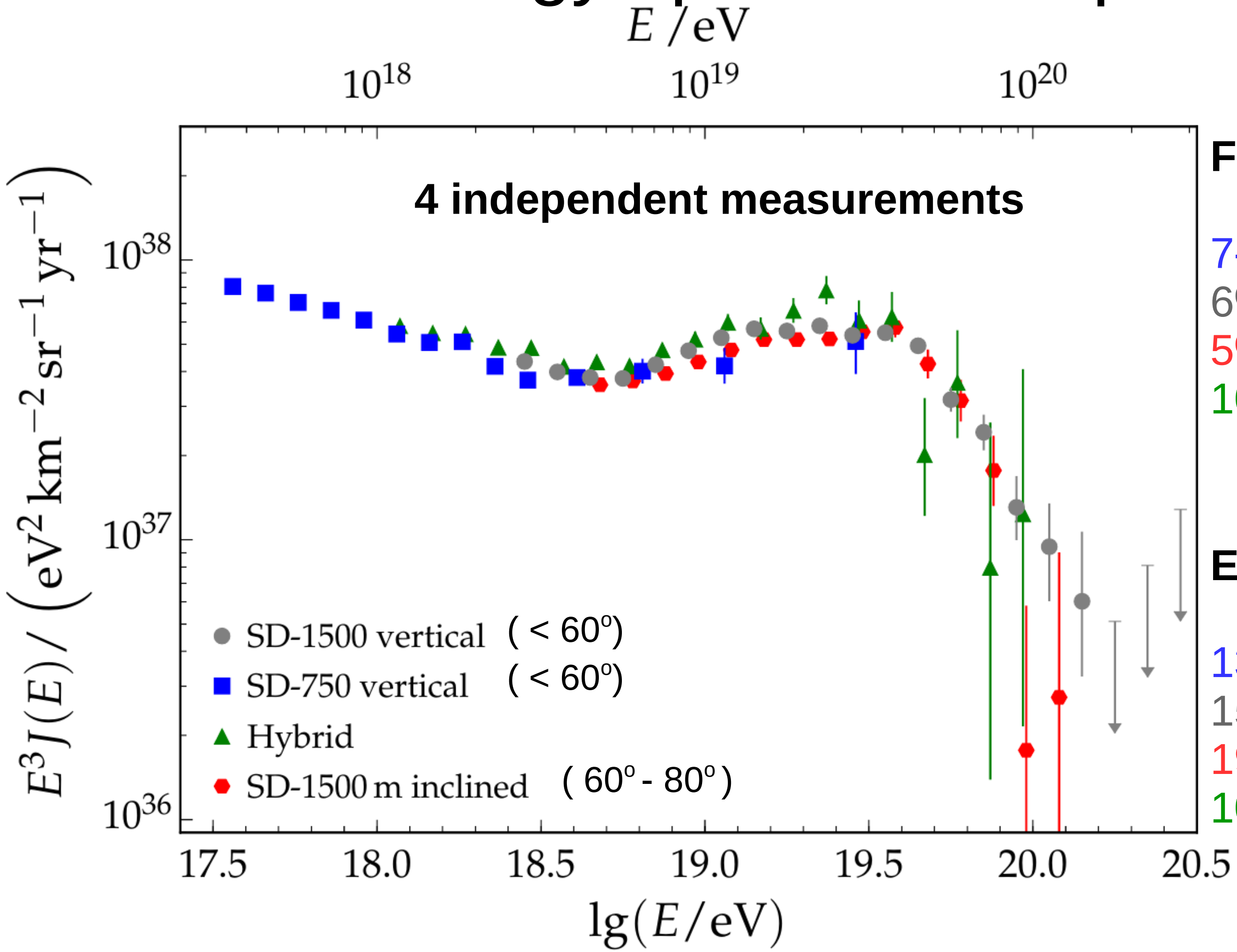
Energy spectrum: all-particle flux



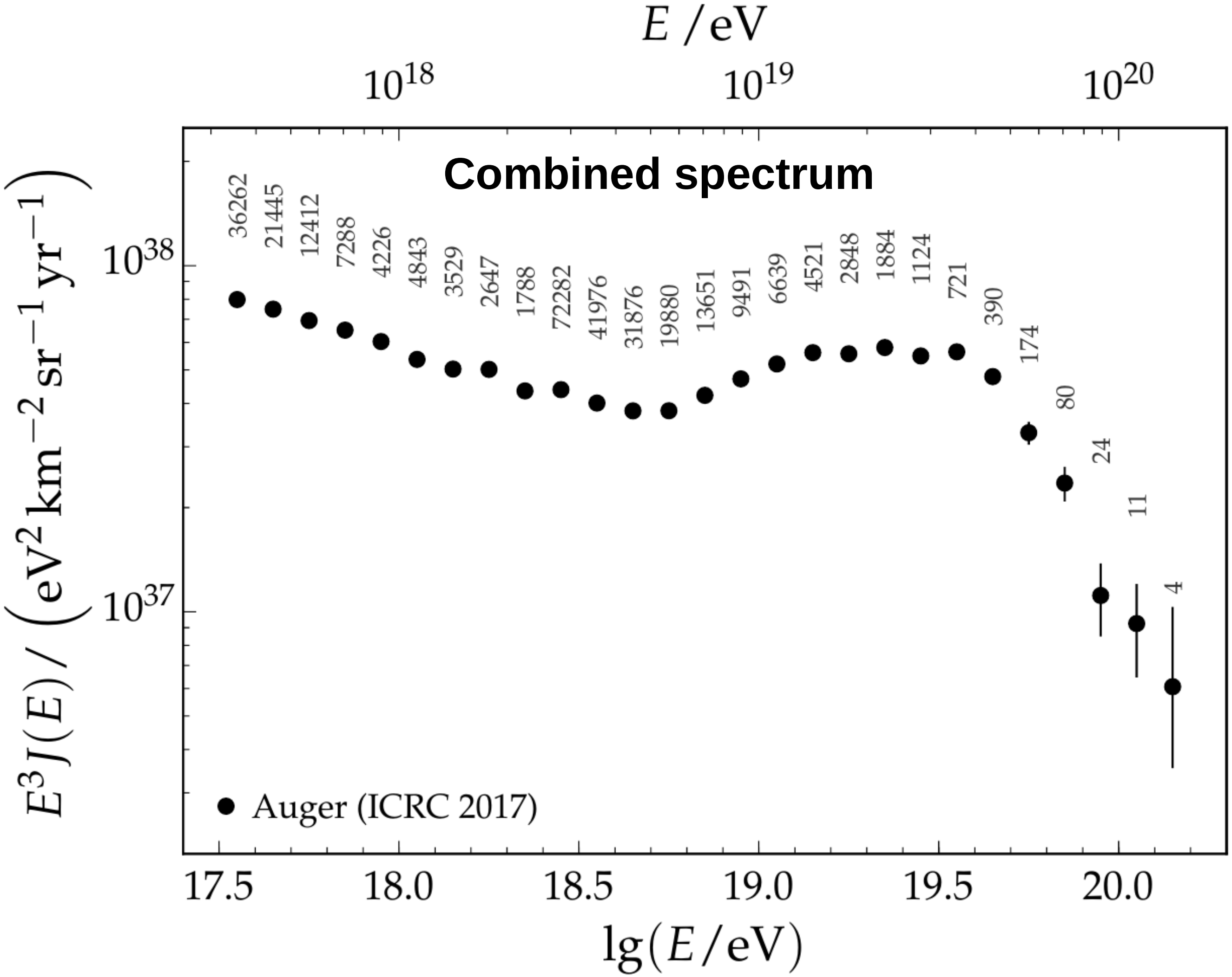
Flux uncertainties:

7-14% SD-750 vertical
6% SD-1500 vertical
5% SD-1500 inclined
10% Hybrid vertical

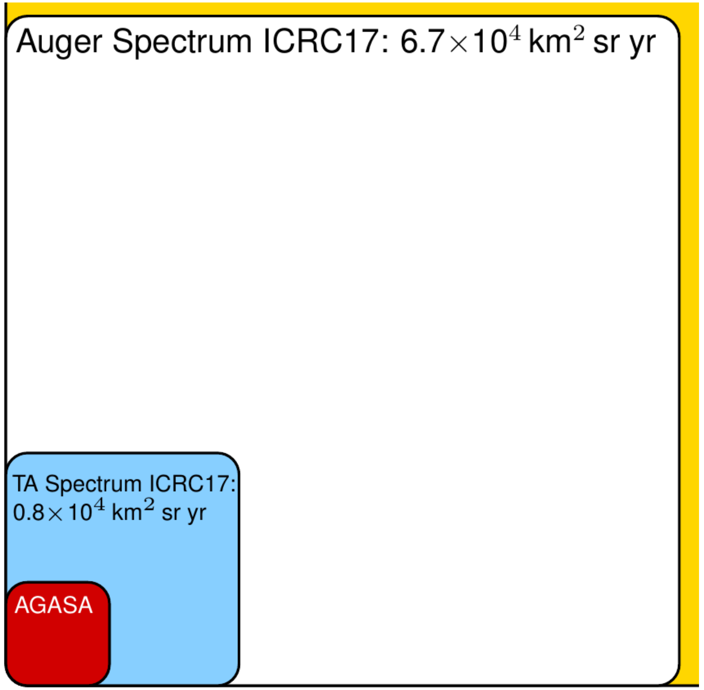
Energy resolution:

13% SD-750 vertical
15% SD-1500 vertical
19% SD-1500 inclined
10% Hybrid vertical

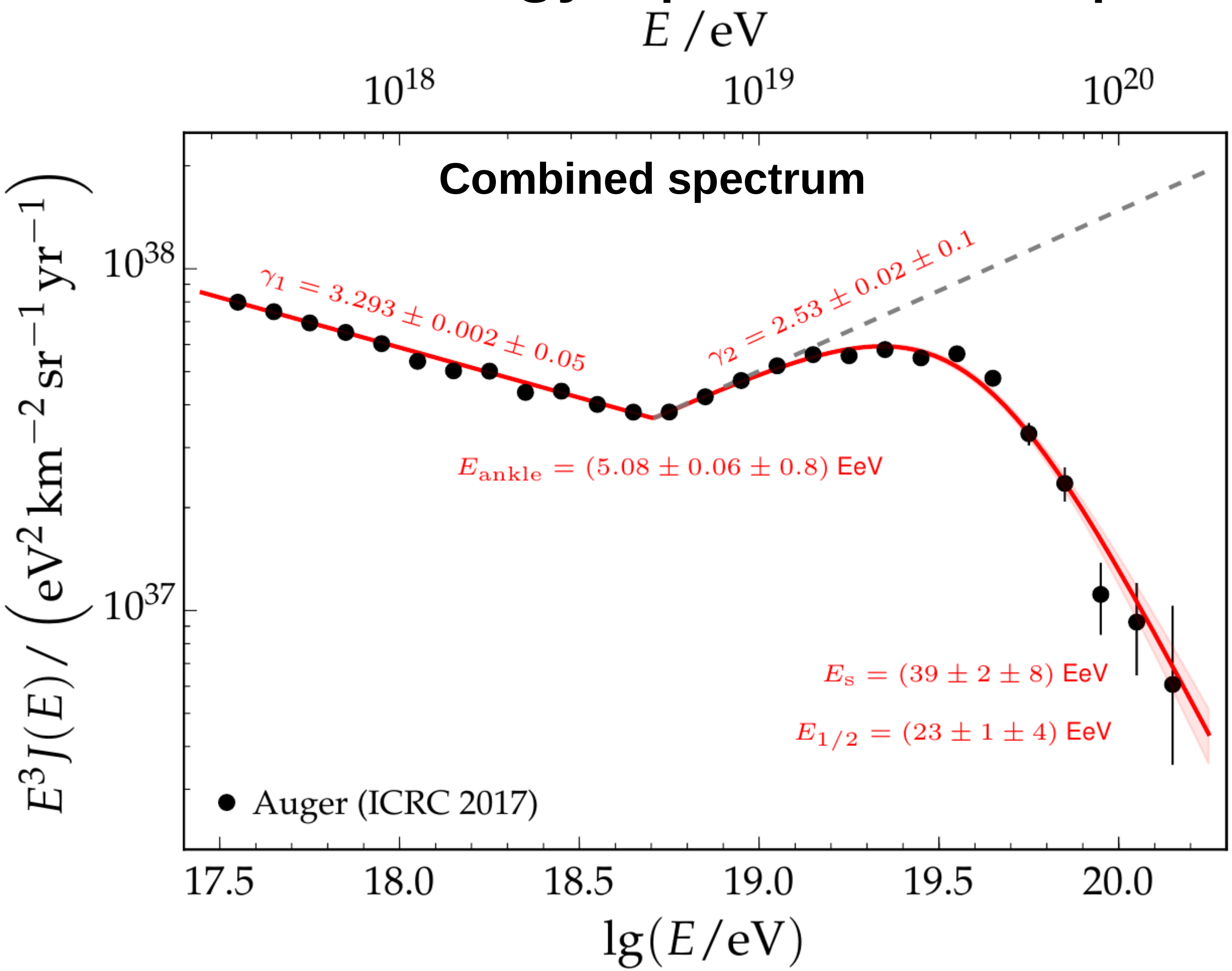
Energy spectrum: all-particle flux



Unprecedented statistics!!



Energy spectrum: all-particle flux



What is the origin of the flux suppression?

- *Propagation effect?*
  "Greisen-Zatsepin-Kuzmin"

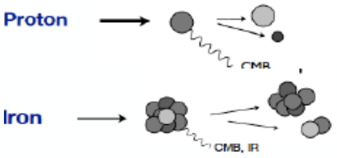


Photo-pion production

Photo-disintegration

- *Maximum injection energy?*

What is the origin of the ankle?

- *Propagation effect?*

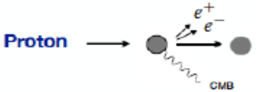
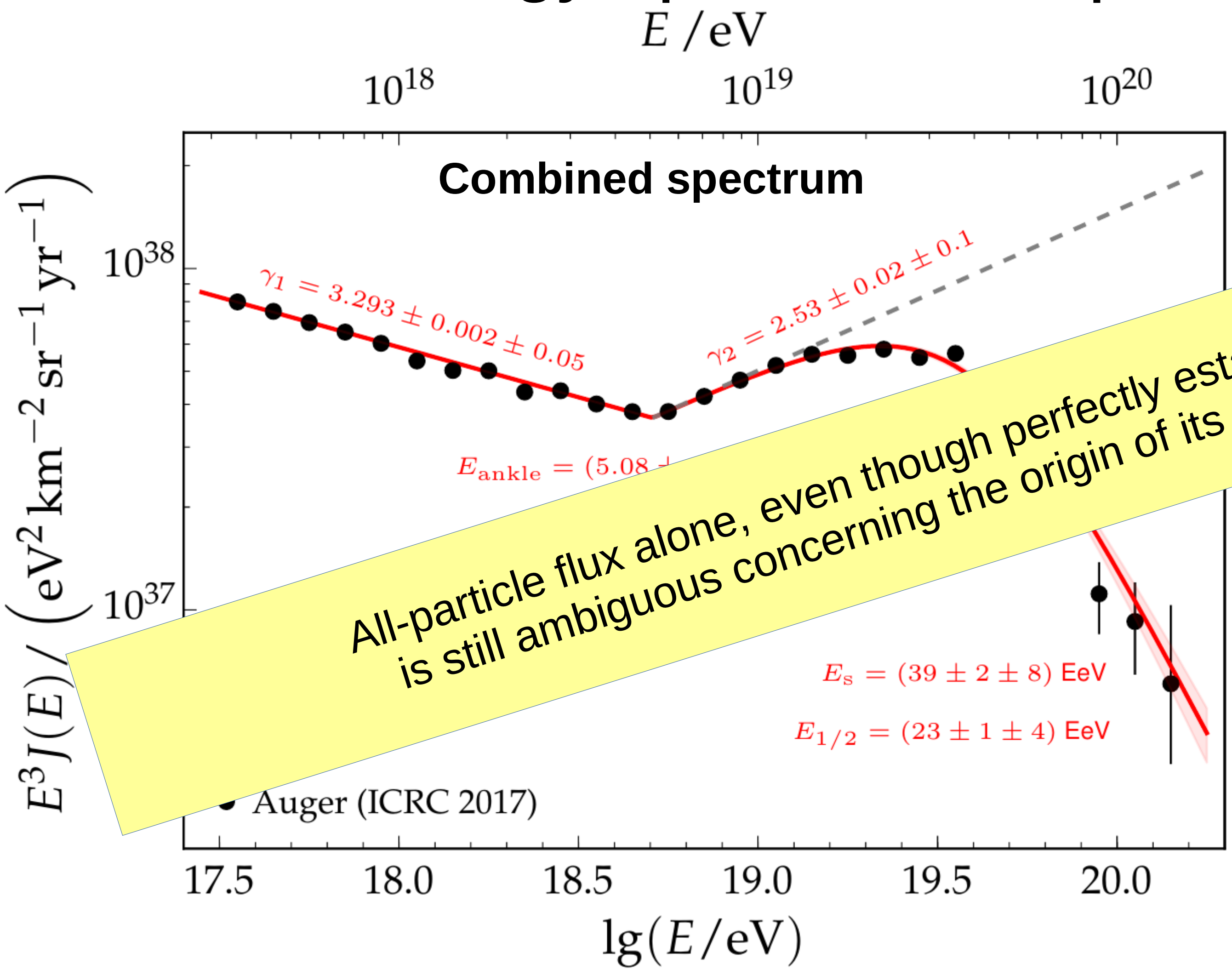


Photo-pair production

- *Transition effect?*
- *Interactions in the source environment?*

Energy spectrum: all-particle flux



All-particle flux alone, even though perfectly established,
is still ambiguous concerning the origin of its features

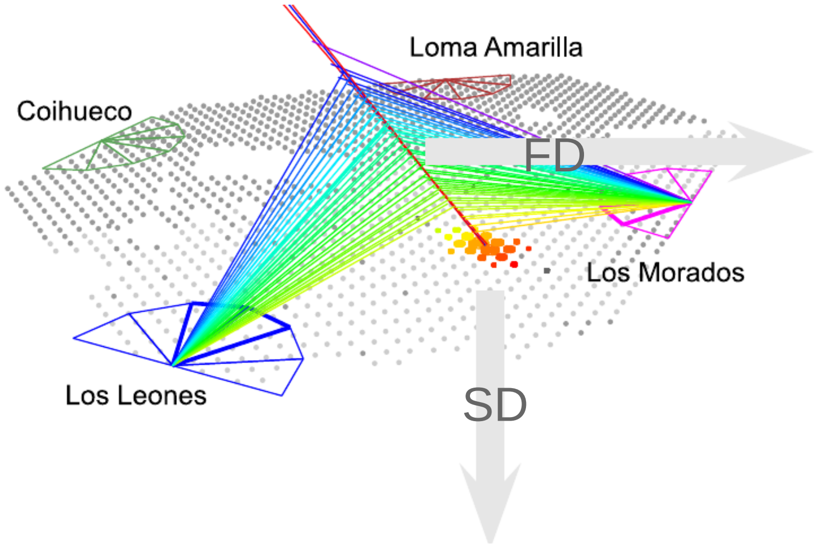
What is the origin of the flux suppression?

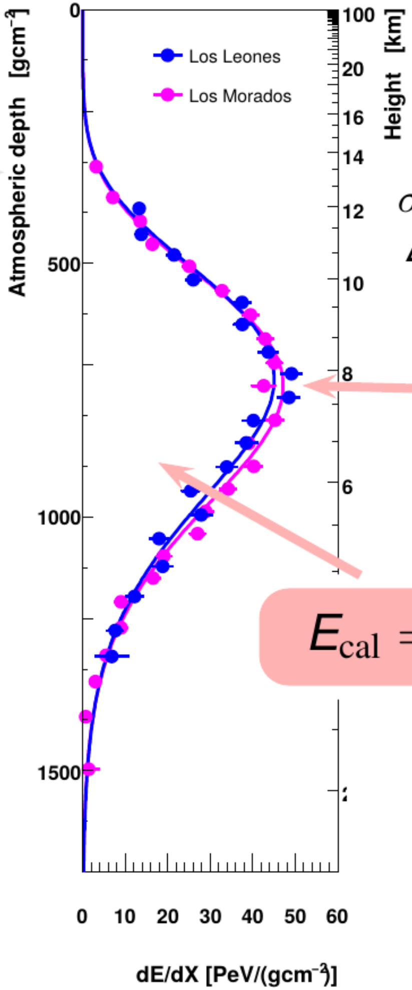
- *Propagation eff*
  “Greise *min”*
  on production
  hoto-disintegration
- *Maximum injection energy?*

What is the origin of the ankle?

- *Propagation effect?*
  Proton → e^+ e^- CMB Photo-pair production
- *Transition effect?*
- *Interactions in the source environment?*

Composition





$\sigma X_{\max} \lesssim 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \lesssim 10\,\mathrm{g/cm^2}$

$X_{\max}$
contains information on primary mass

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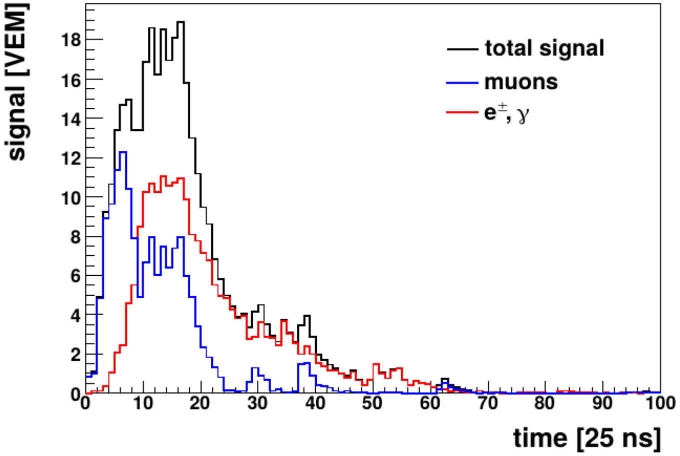
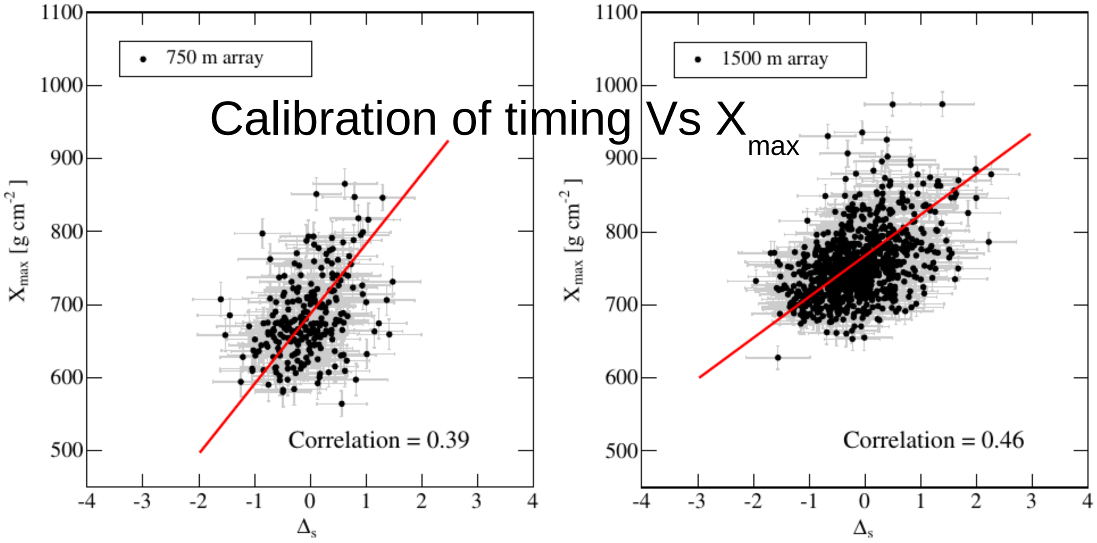
Timing of secondaries contains information on primary mass



Composition

Calibration of timing Vs X_{max}



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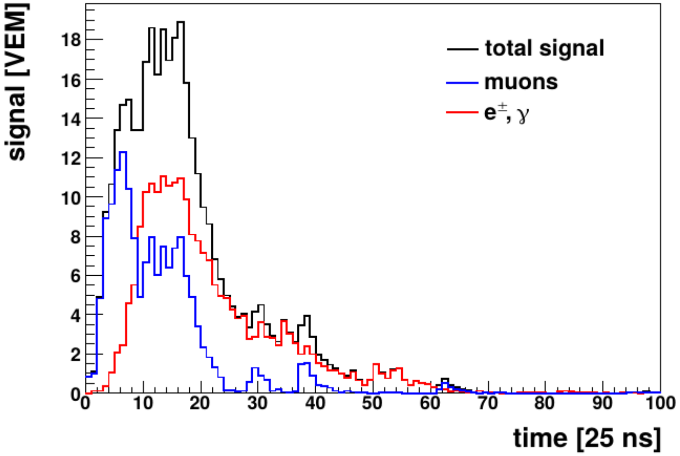

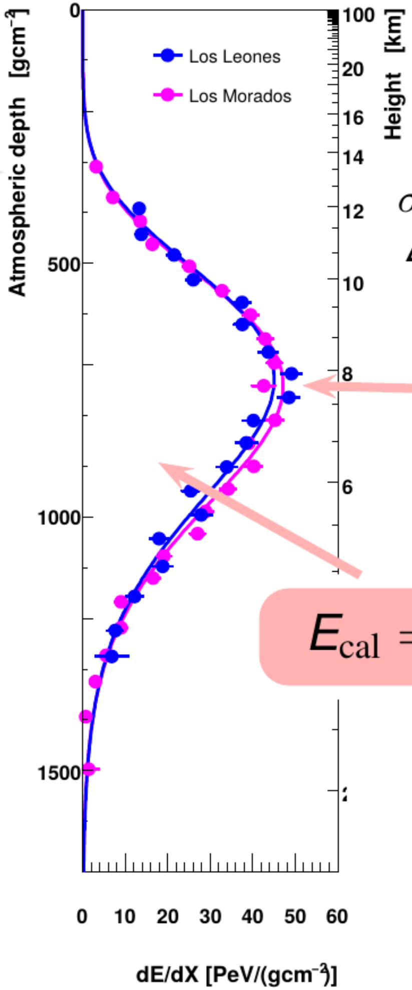

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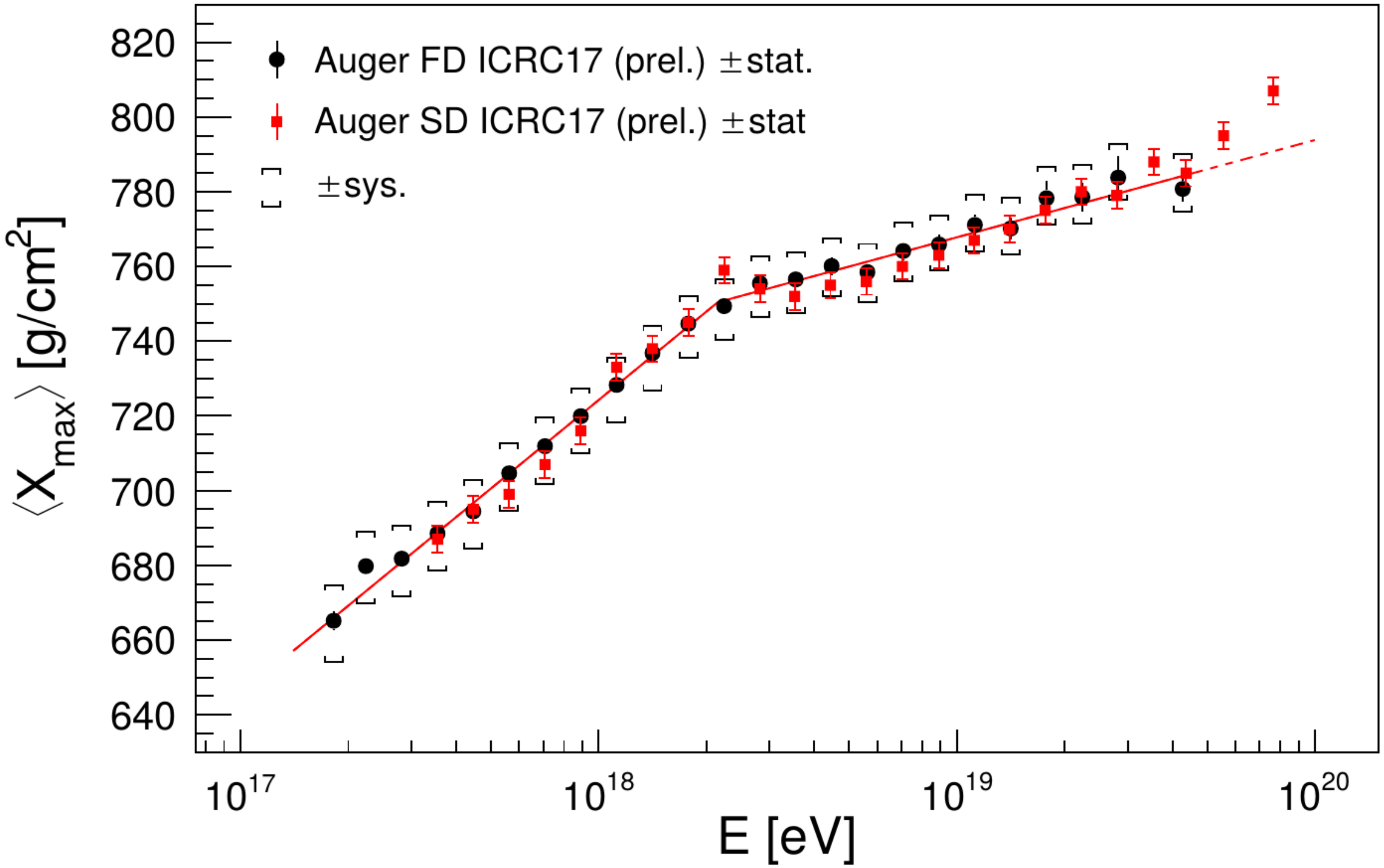

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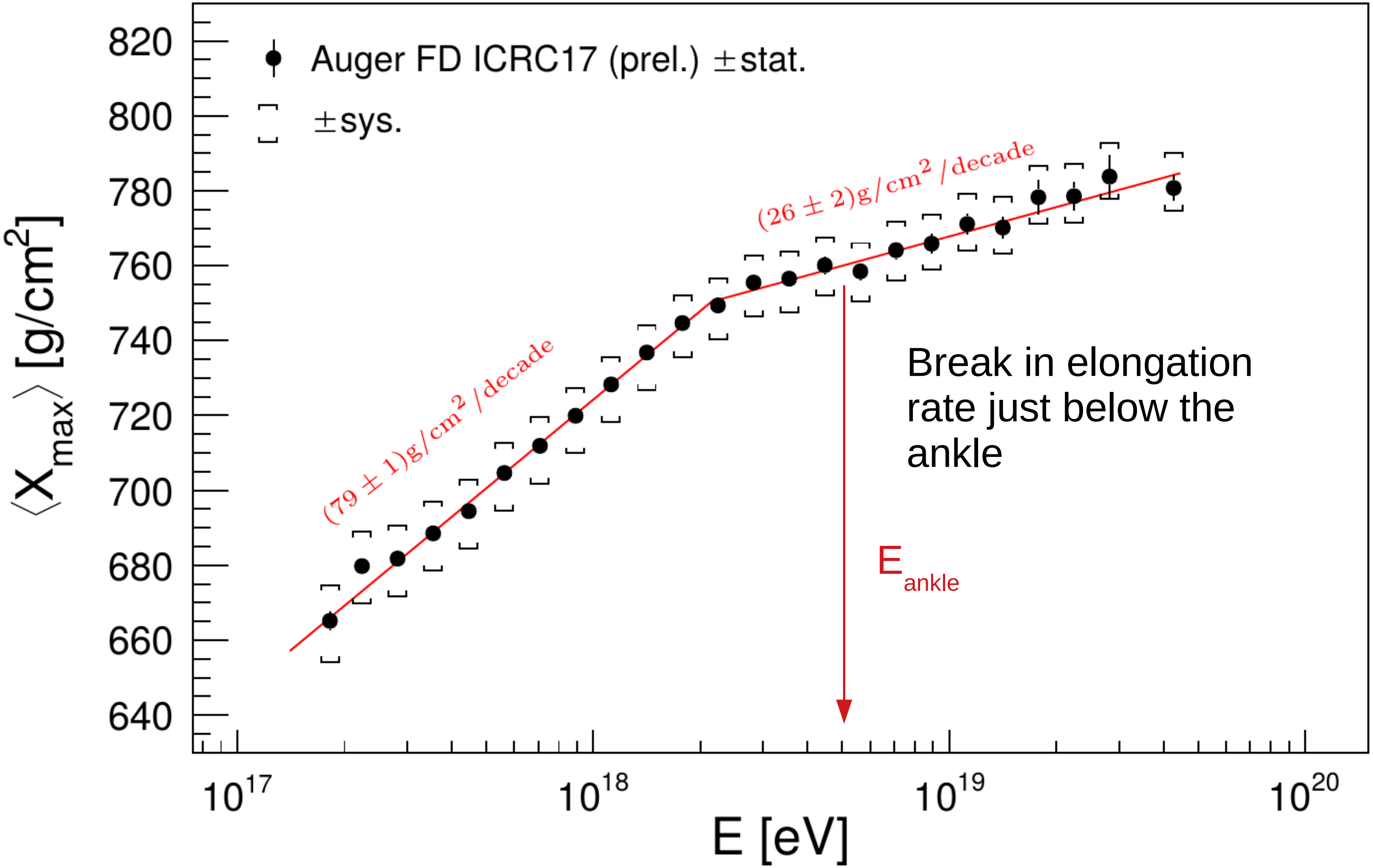
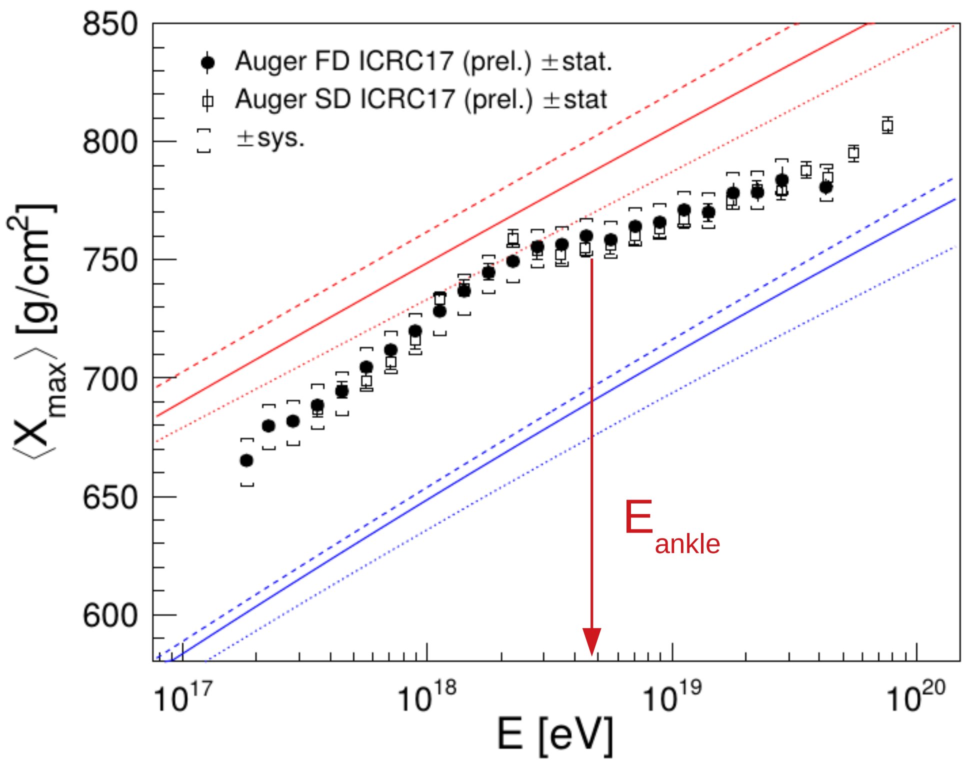
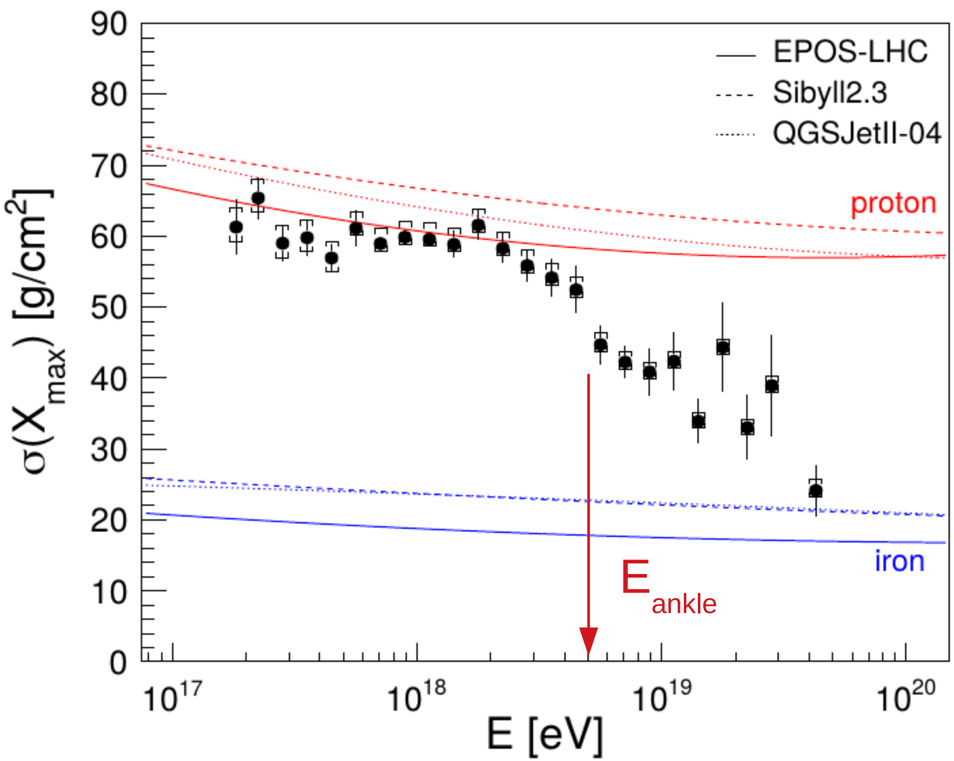


Break in elongation rate just below the ankle

Composition



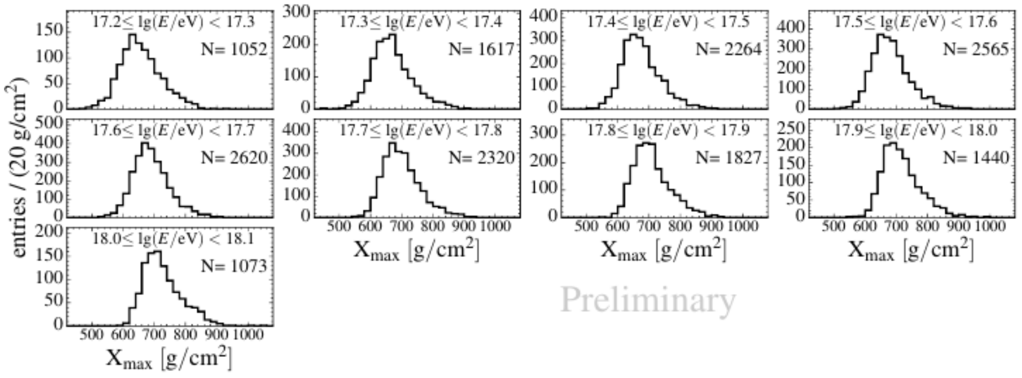


Transition towards heavier elements just **below the ankle**

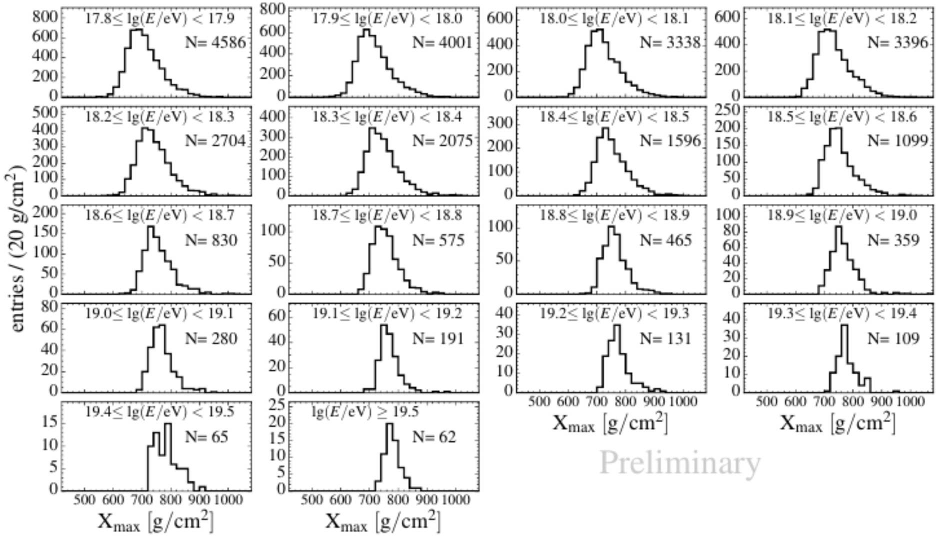
Can we says something on **relative abundances?**

Composition

$\lg(E/\mathrm{eV}) = 17.2\ldots18.1$

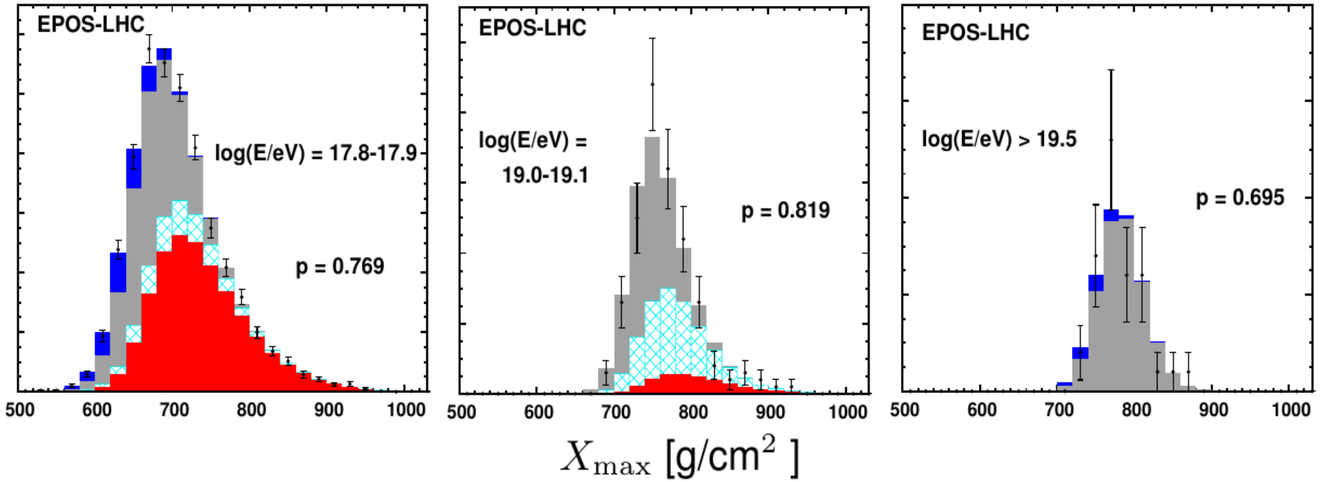


$\lg(E/\mathrm{eV}) = 17.8\ldots > 19.5$

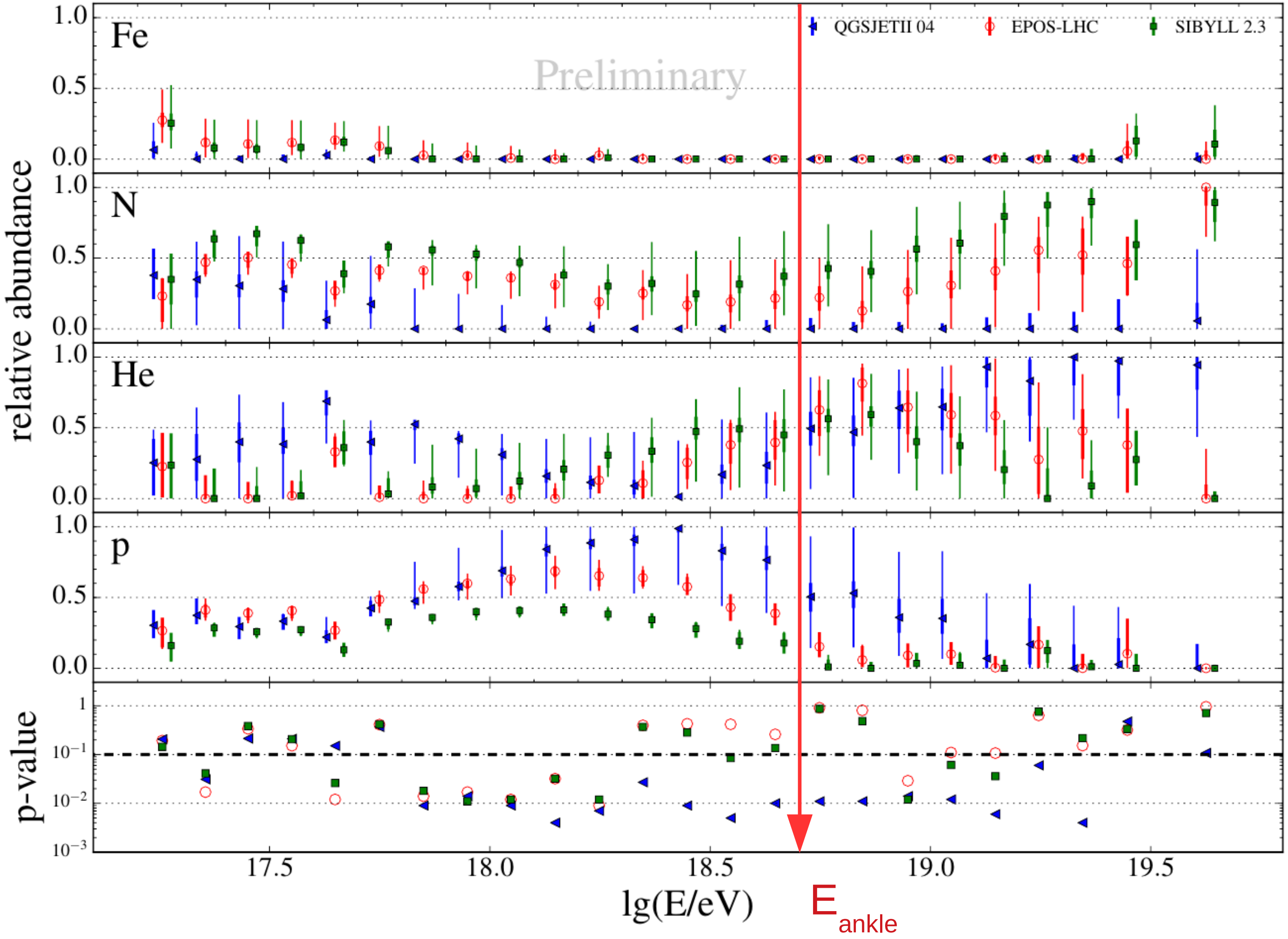


Example of 4-component fit

p
He
N
Fe



Composition



Ankle origin as a propagation effect highly disfavored (needs only protons above E_{ankle})

- What is the **composition at the sources?**
- What is the **injected flux?**

Combining spectrum and composition
from simple to complex

- **Identical uniformly distributed sources** with a rigidity-dependent injection of nuclei (E/Z)

Injection flux:

$$\frac{dN}{dE} = J_0 \sum_\alpha f_\alpha E_0^{-\gamma} \begin{cases} 1 & \text{for} \quad E_0/Z_\alpha < R_{\mathrm{cut}} \\ \exp\left(1 - \frac{E_0}{Z_\alpha R_{\mathrm{cut}}}\right) & \text{for} \quad E_0/Z_\alpha \geq R_{\mathrm{cut}} \end{cases}$$

Free parameters:

J_0 R_{cut} γ f_α

Models for propagation

	MC code	$\sigma_{\mathrm{photodisint.}}$	EBL model
SPG	SimProp	PSB	Gilmore 2012
STG	SimProp	TALYS	Gilmore 2012
SPD	SimProp	PSB	Domínguez 2011
CTG	CRPropa	TALYS	Gilmore 2012
CTD	CRPropa	TALYS	Domínguez 2011
CGD	CRPropa	Geant4	Domínguez 2011

Models for EAS

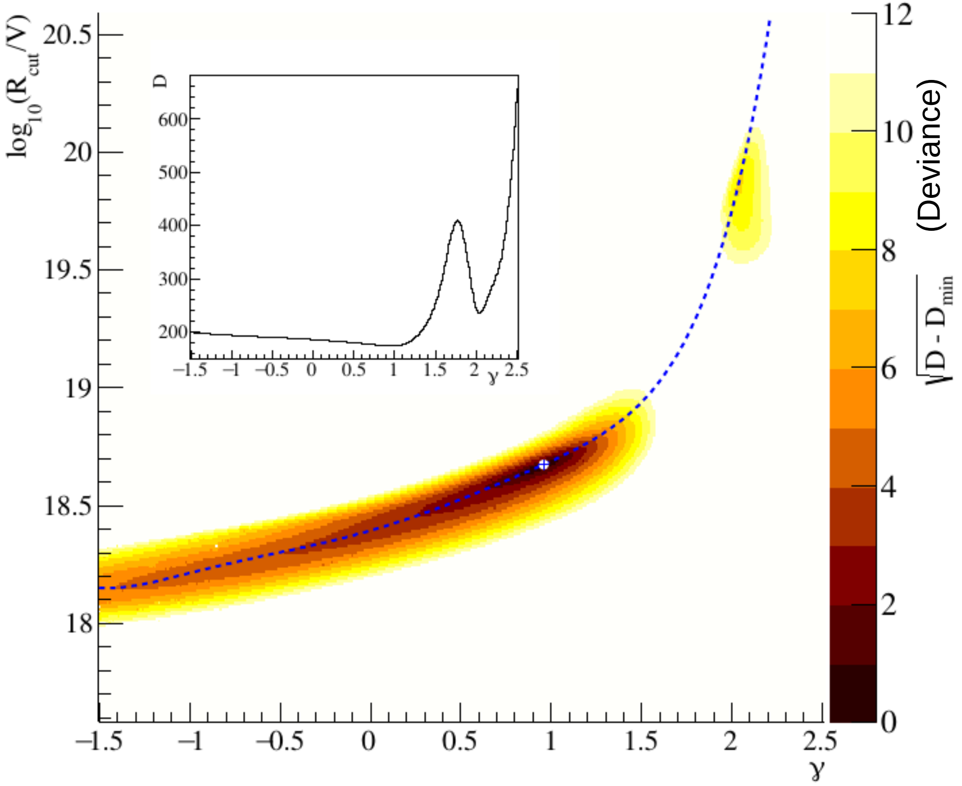
EPOS-LHC

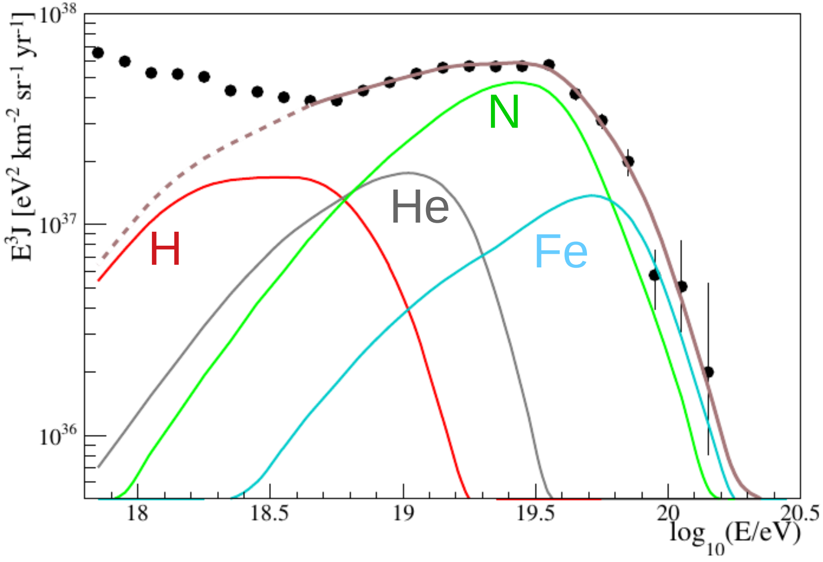
Sybill 2.1

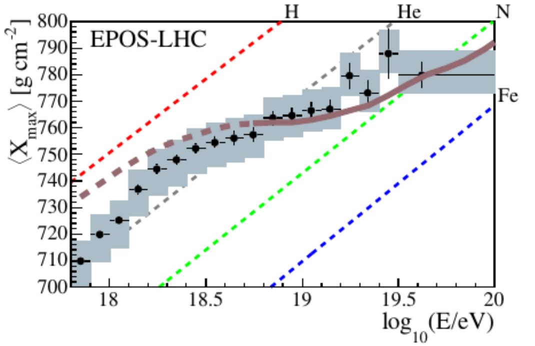
QGSJet II-04

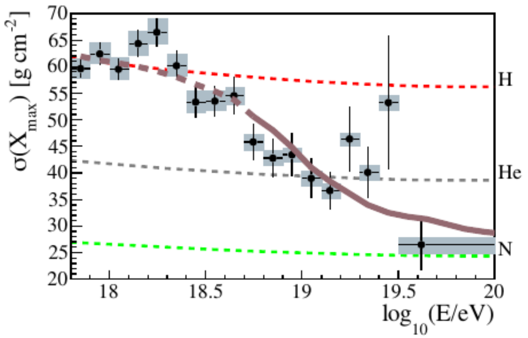
Combining spectrum and composition

Reference model (SPG+EPOS):
SimProm + PSB cross section + Gilmore ‘12 EBL + EPOS-LHC



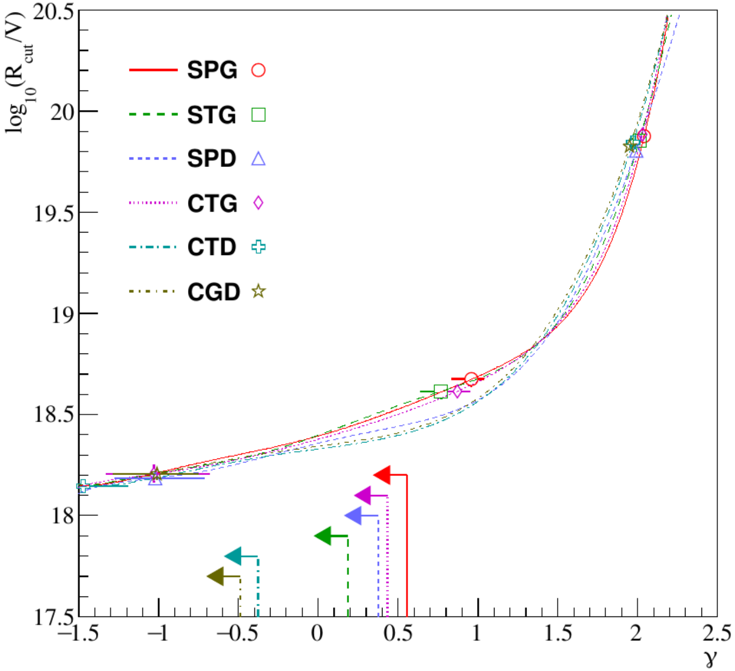






Combining spectrum and composition

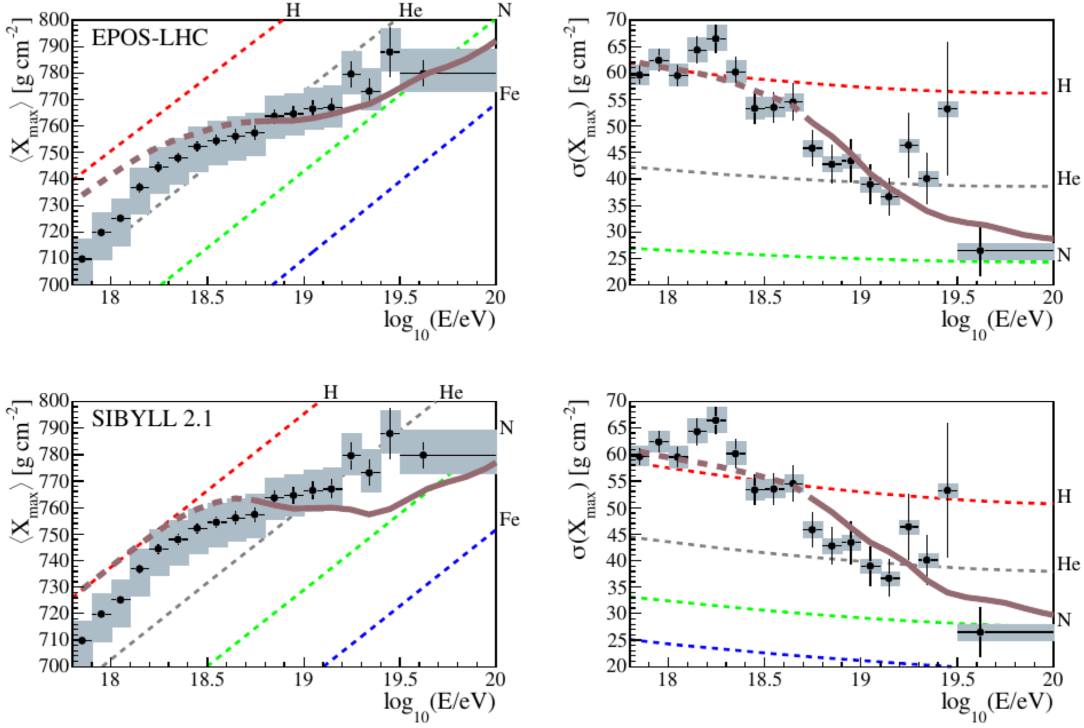
Changing models for propagation



Best minimum (spectral index < 1) very dependent on the model parameters

Local minimum (spectral index ~ 2) is model independent

Changing hadronic models for EAS



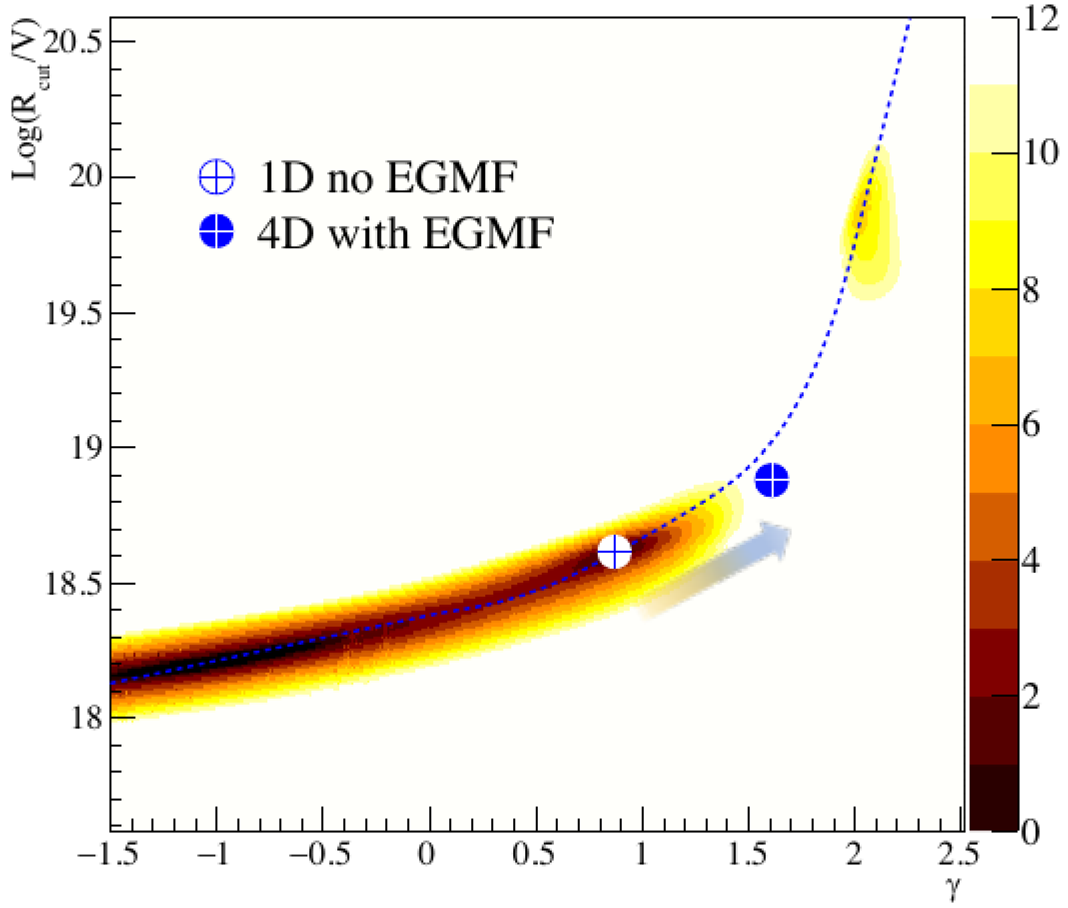
EPOS-LHC best

Sibyll2.1

QGSJet II-04 worst

Combining spectrum and composition

- **Discrete sources** (according to the model of the local large-scale structure) and **CGT** model with/without **EGMF**



Source properties	4D with EGMF	4D no EGMF	1D no EGMF[1]
γ	1.61	0.61	0.87
$\log_{10}(R_{cut}/eV)$	18.88	18.48	18.62
f_H	3 %	11 %	0 %
f_{He}	2 %	14 %	0 %
f_N	74 %	68 %	88 %
f_{Si}	21 %	7 %	12 %
f_{Fe}	0 %	0 %	0 %

Several **poorly know parameters** to model properly the observed data

The **scenario** is certainly more **complex** than previously expected

The **magnetic fields** in the intergalactic space needs be taken into account when interpreting data

Arrival directions: intermediate scale and high energy

Search for correlations at intermediate angular scale with:

1. **Active Galactic Nuclei** from 2FHL catalog:

- Distance < 250 Mpc
- Flux > 50 GeV

17 objects (~ 90% contribution to UHECR flux within 150 Mpc)

⇩

taking into account distance of the objects

⇧

2. **Starburst galaxies** from Fermi-LAT catalog

- Distance < 250 Mpc
- Flux > 0.3 Jy

23 objects (~ 90% contribution to UHECR flux within 10 Mpc)

Likelihood ratio analysis

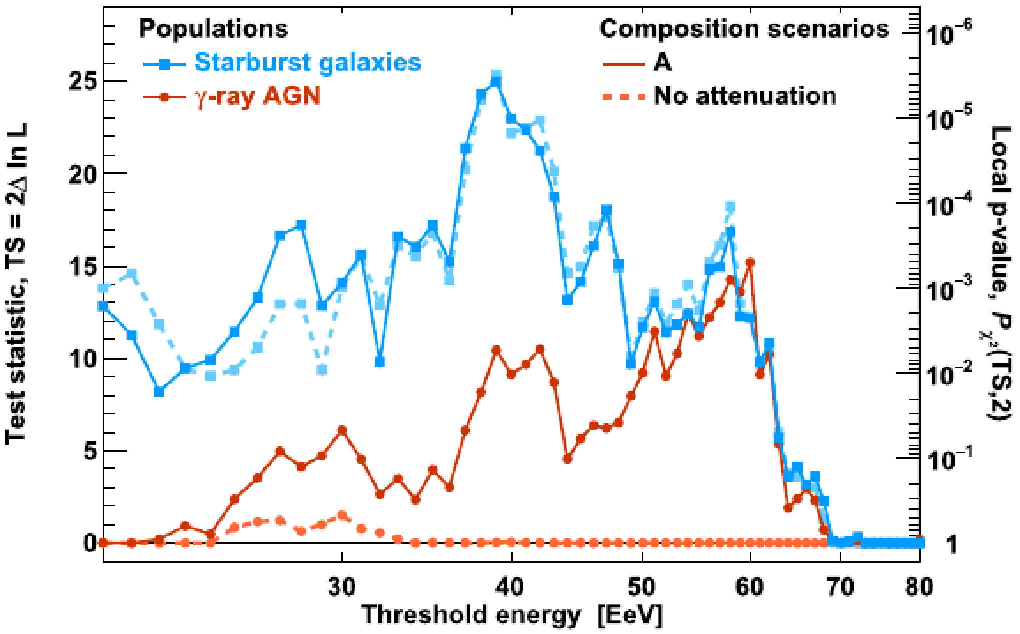
- smearing angle ψ
- H_0: isotropy
- H_1: $(1-f)\times$ isotropy + $f\times$ fluxMap(ψ)

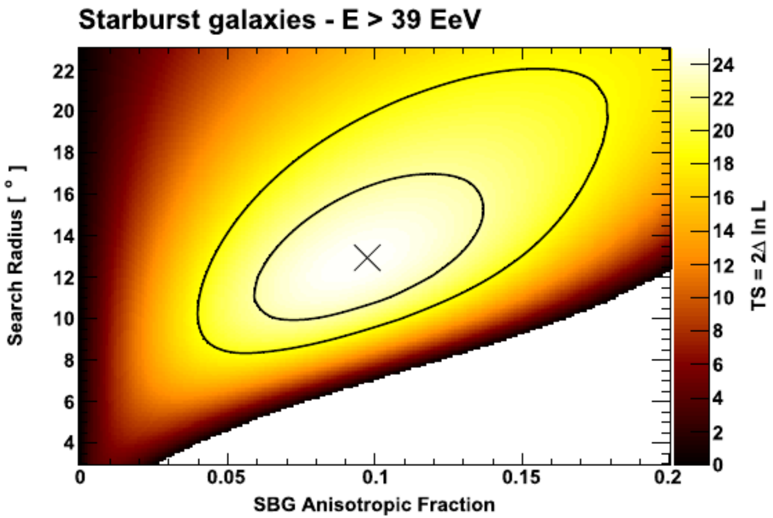
Free parameters are:

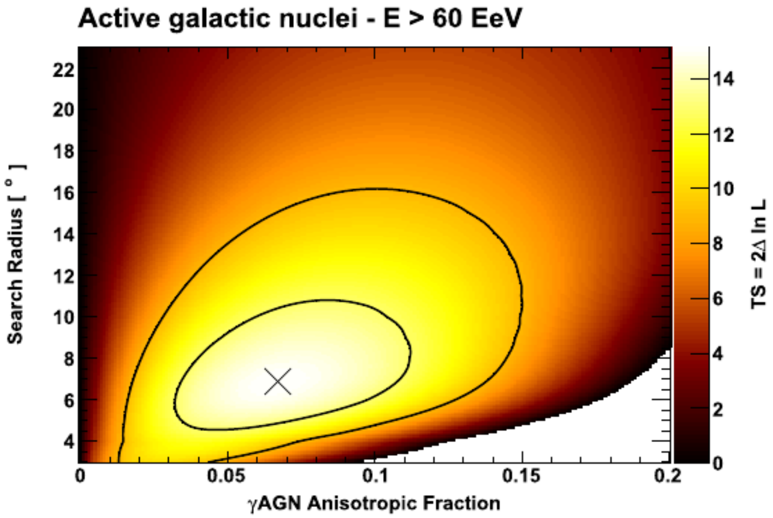
- ✓ **the threshold energy**
- ✓ **the smearing angle**
- ✓ **the fraction of anisotropy**

- $\mathrm{TS} = 2\log(H_1/H_0)$

Arrival directions: intermediate scale and high energy







SBGs:

E>60 EeV
f = 7%
Radius 7^o
2.7σ

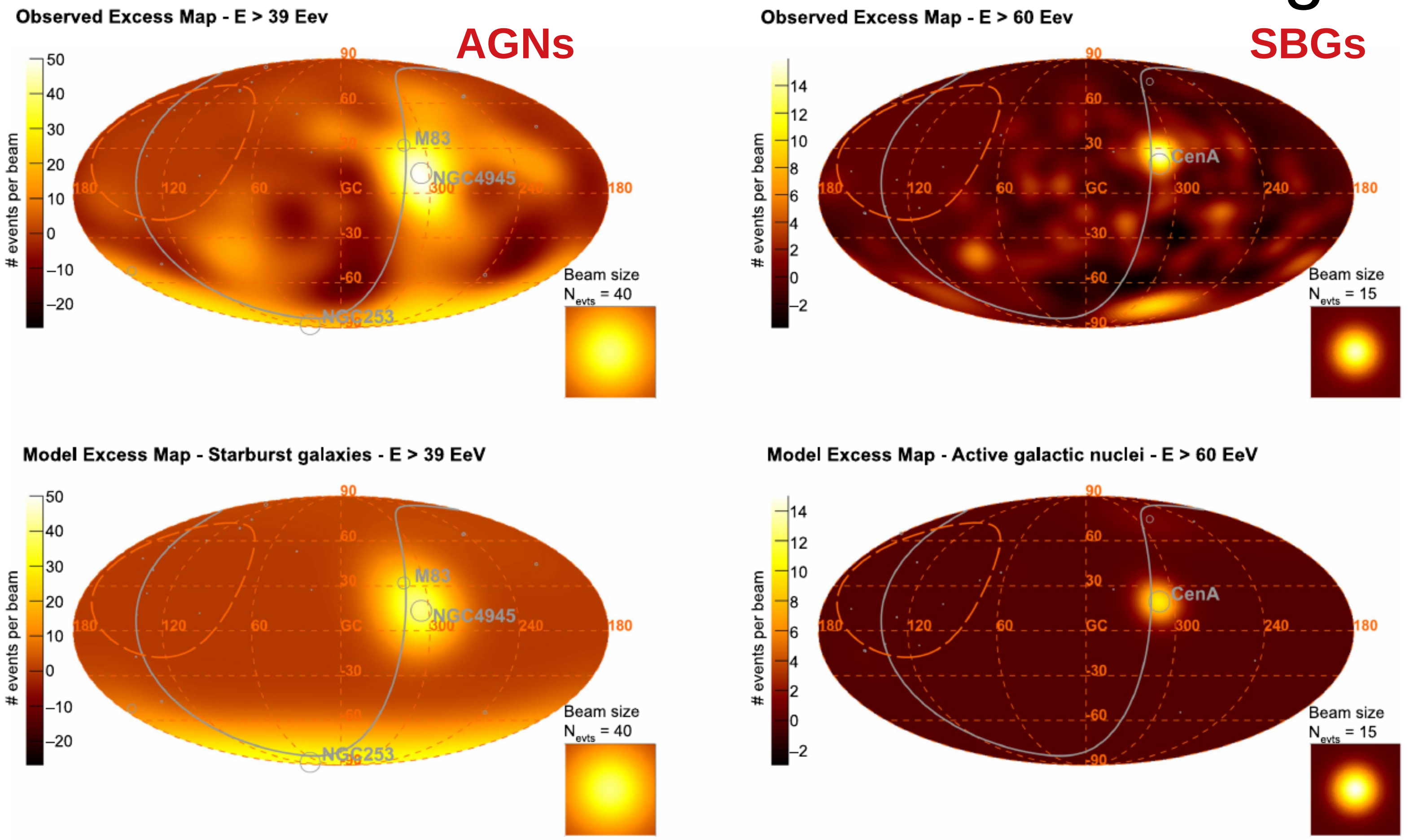
AGNs:

E>39 EeV
f = 10%
Radius 13^o
4.0σ

Arrival directions: intermediate scale and high energy

Observed event excess

Model event excess



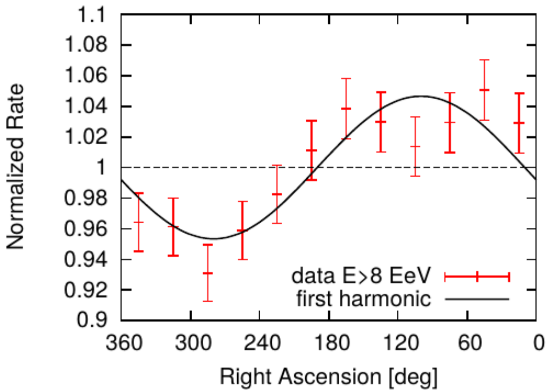
Isotropy is **disfavored** at intermediate scales at **4σ** level for SBGs
Results indicative of an excess if events from **strong nearby sources**

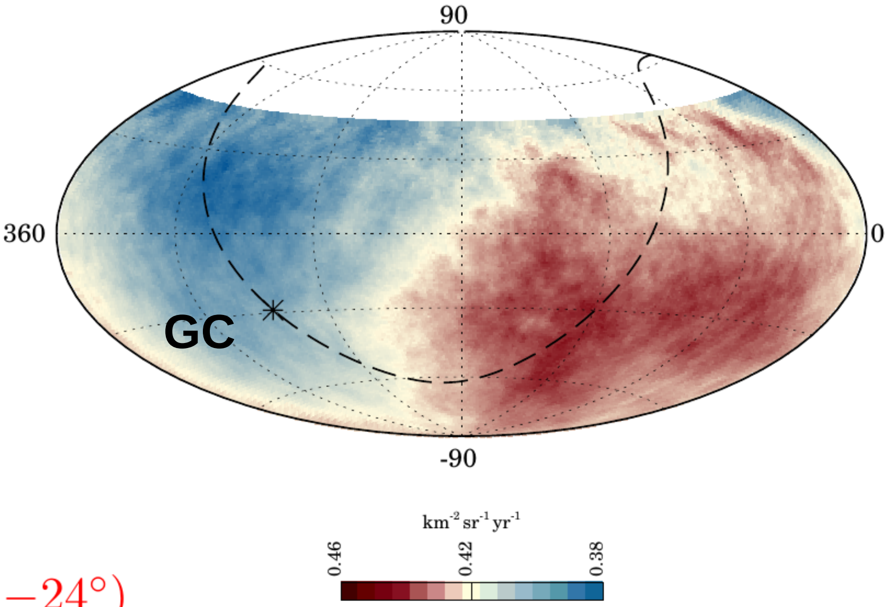
Arrival directions: large scale and moderate energy

Harmonic analysis in right ascension α

E [EeV]	events	amplitude r	phase [deg.]	$P(\geq r)$
4-8	81701	$0.005^{+0.006}_{-0.002}$	80 ± 60	0.60
> 8	32187	$0.047^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

significant modulation at 5.2σ (5.6σ before penalization for energy bins explored)





3-d dipole above 8 EeV:

$(6.5^{+1.3}_{-0.9})\%$ at $(\alpha, \delta) = (100°, -24°)$

Arrival directions: large scale and moderate energy

Harmonic analysis in right ascension α

E [EeV]	events	amplitude r	phase [deg.]	$P(\geq r)$
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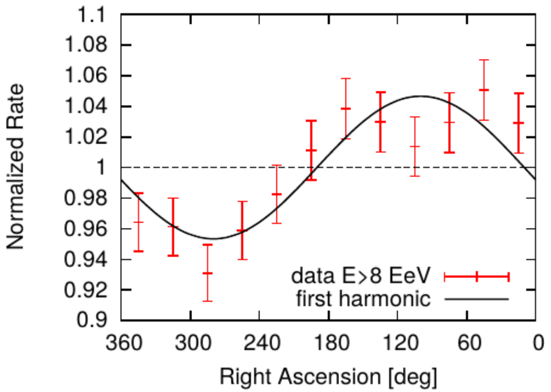
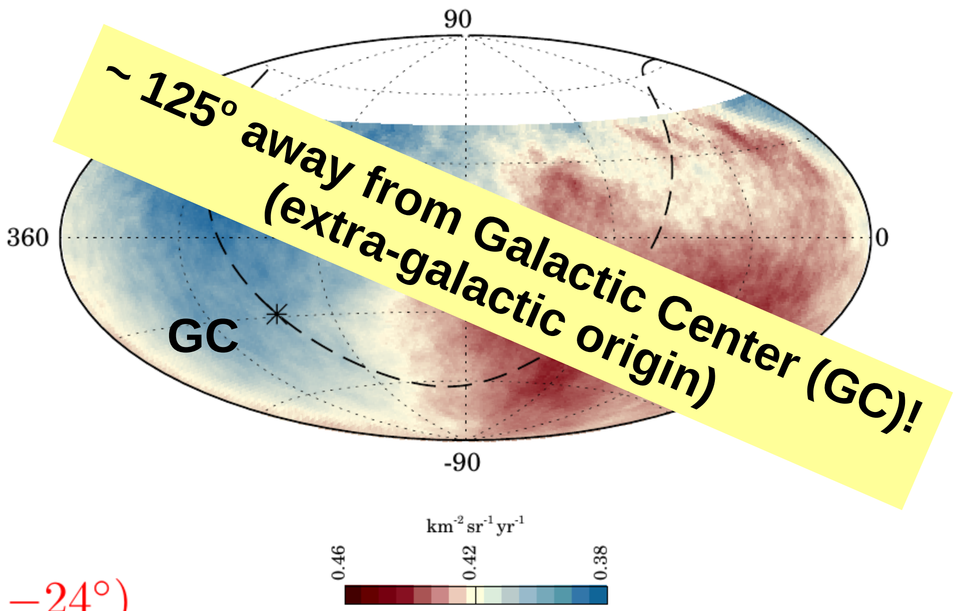
significant modulation at 5.2σ (5.6σ before penalization for energy bins explored)

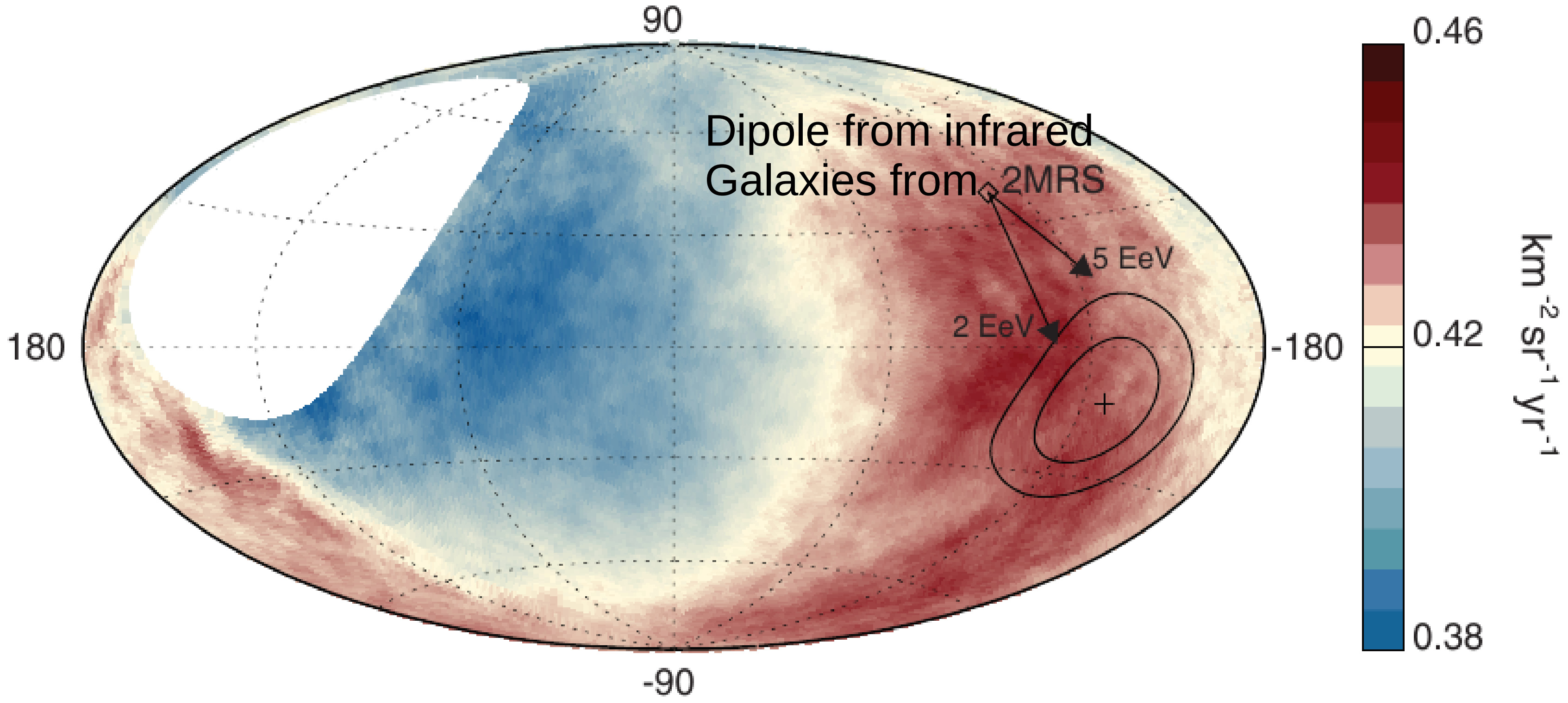




3-d dipole above 8 EeV:

$(6.5^{+1.3}_{-0.9})\%$ at $(\alpha, \delta) = (100°, -24°)$

Arrival directions: large scale and moderate energy



In galactic coordinates (l, b) = (233°, -13°)

- Dipole structure is expected if cosmic rays diffuse to the Galaxy from sources distributed similar to **nearby galaxies** (e.g. **2MRS catalog**)
- Strong indication for **extragalactic origin** if UHECR **above 8 EeV (recall E_{ankle} ~ 5 EeV)**

State of the art UHECR scenario

Observational facts

Spectrum → has a well defined change in spectral index at ~ 5 EeV (ankle)
→ has a strong suppression above ~ 40 EeV

Composition → light (but mixed) dominated below the ankle
→ heavier nuclei towards the highest energies

Source models & propagation → difficult to interpret data due to poorly known model parameters

Anisotropy → firmly (~5σ and 4σ level) arising from data at large (>8 EeV) and intermediate (>39 EeV) angular scales
→ extragalactic origin above 8 EeV highly favoured

Nice understanding of data, but to still many open questions. Moreover, to make our life not so easy… **hadronic models do not reproduce muon data (the most sensitive observable to primary masses)**!

What about DM?

Analyzing the diffuse photon flux “top-down” and “bottom-up” models may be distinguished

Photon showers:

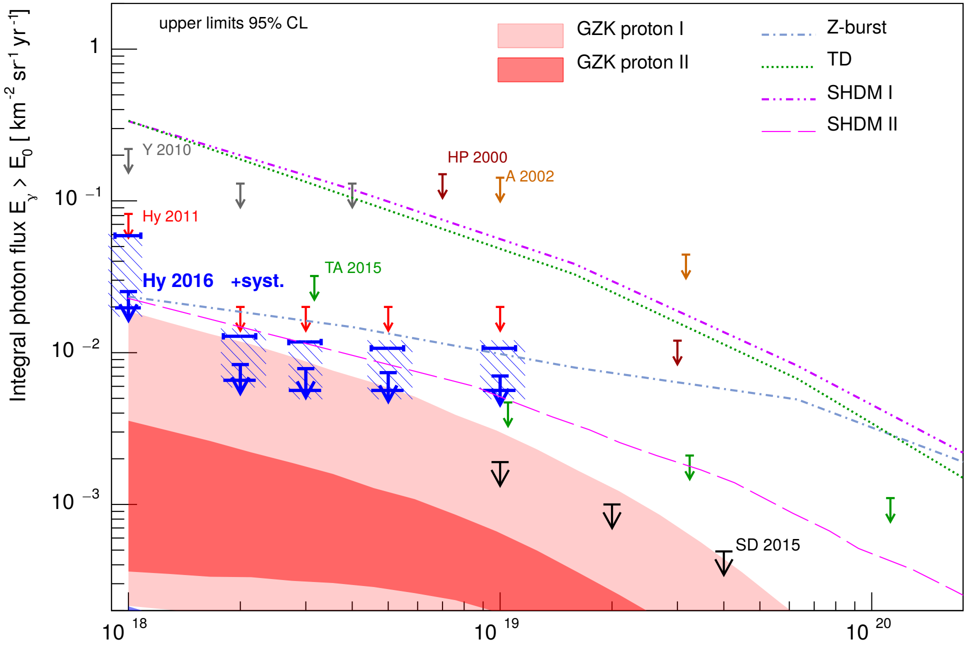
✔ penetrate deeper in the atmosphere

✔ produce less muons than showers initiated by hadrons

hybrid observations allows both the longitudinal development and the particle densities at ground to be measured

What about DM?

Upper limits on the integral photon flux derived for a photon flux E^{-2}



Results severely constrain "top-down" models in which it is assumed that UHECRs are the decay products of super-heavy dark matter (SHDM), topological defects (TD) or Z_0 bosons (Z-burst)

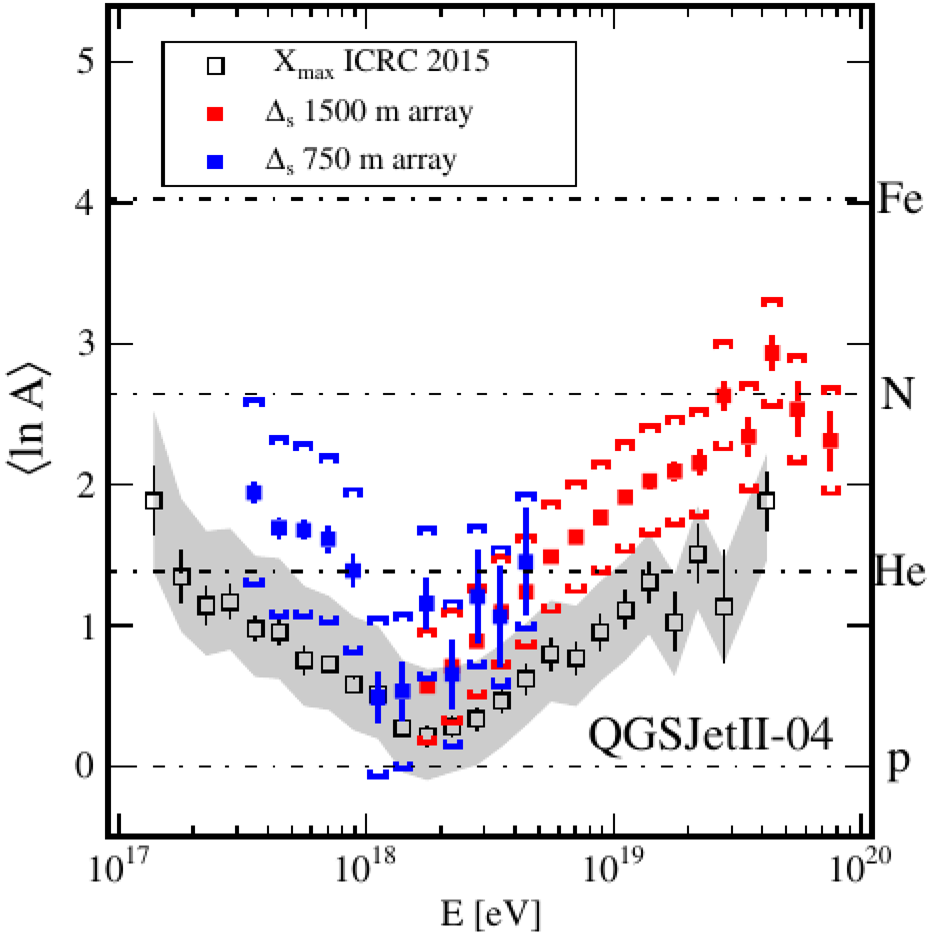
Conclusions

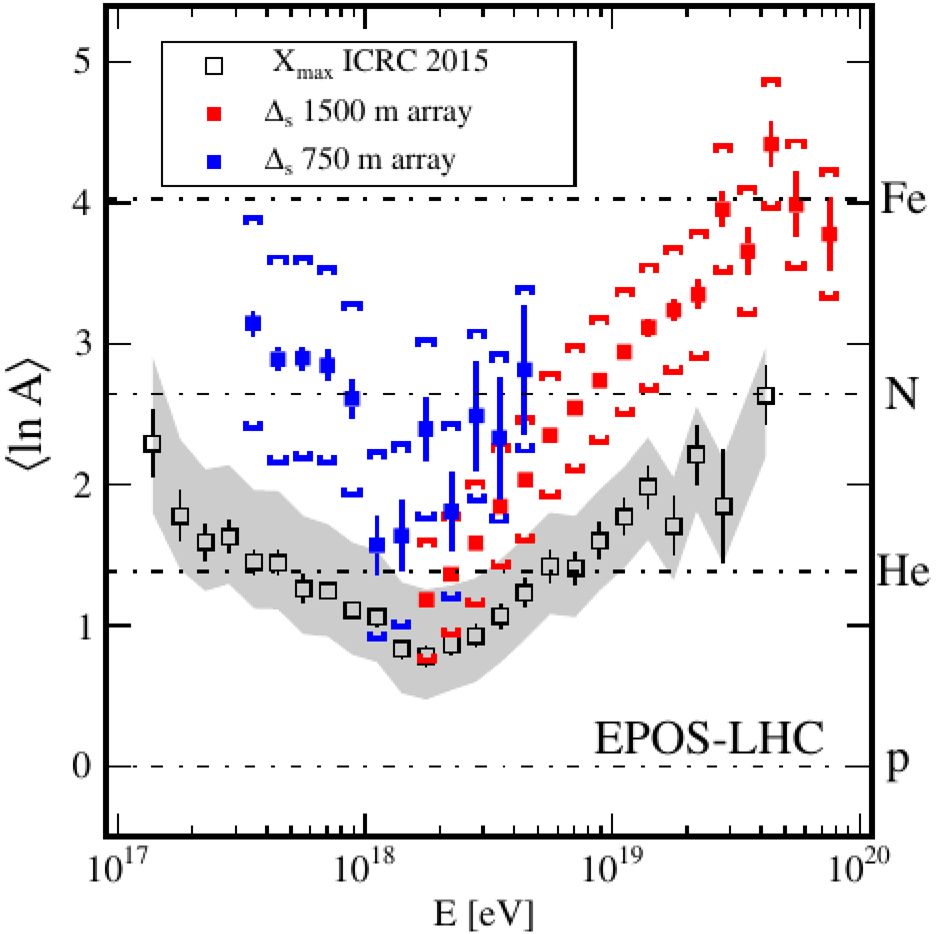
goto slide 32 :)

Thanks

Back up

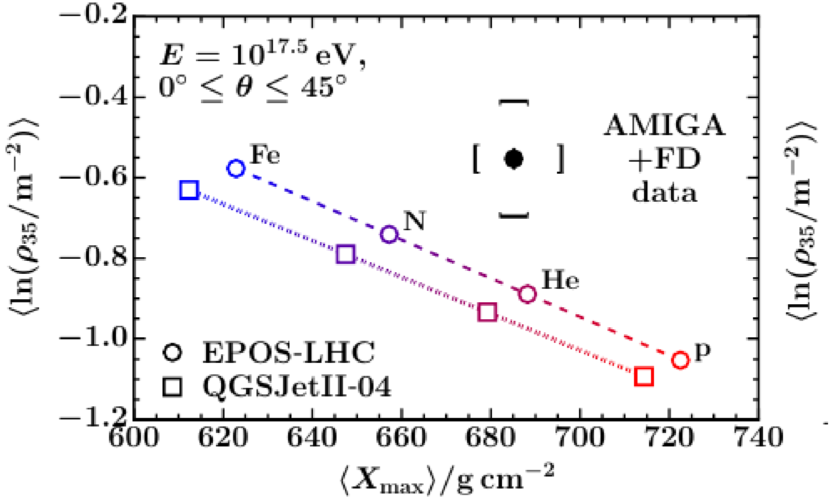
Hadronic models: muon deficit

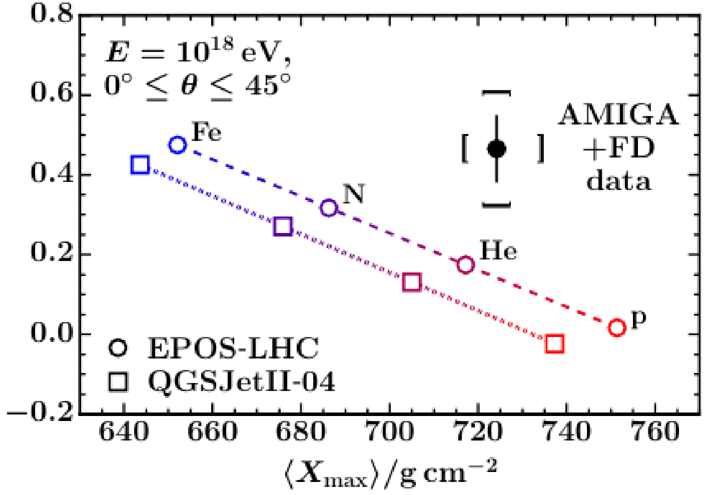




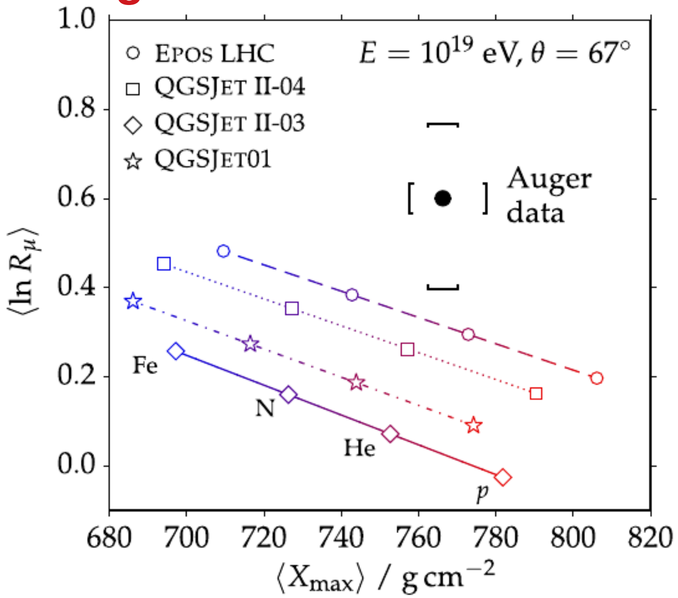
Hadronic models: muon deficit

Underground detectors





Onground detectors + inclined showers

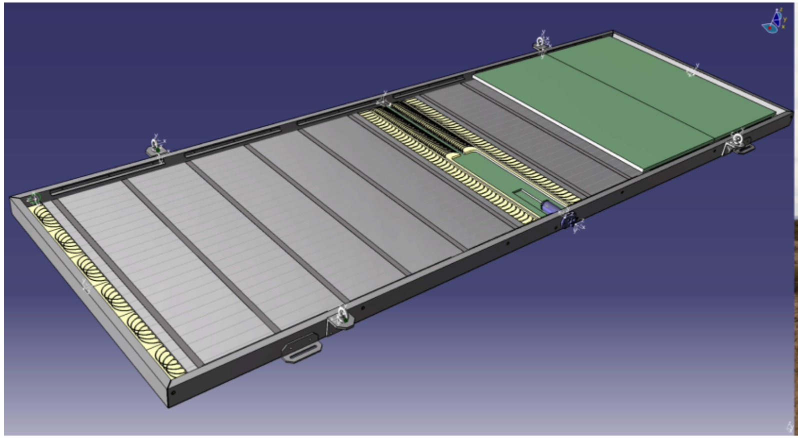


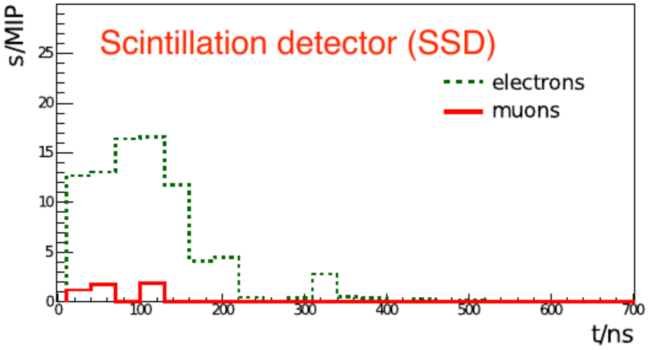
All hadronic models (post-LHC) fail to reproduce muon data from $10^{17.5}$ to $10^{19.0}$ eV!

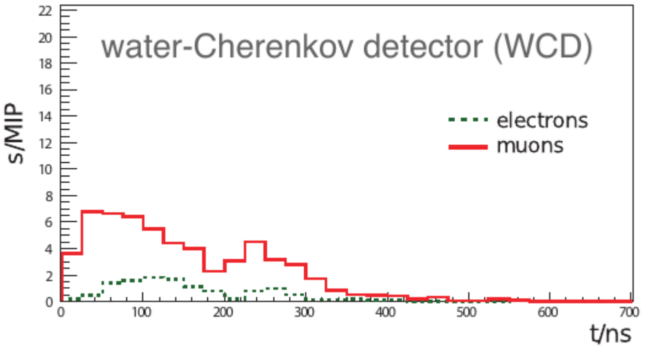
Future perspective: AugerPrime

Aim: to build a **composition sensitive detector** up to the highest energies (above suppression ~ 40 EeV) with **100% duty cycle**

- $3.8\ \mathrm{m}^2$ scintillators (SSD) on each 1500-m array station
- upgrade of station electronics
- additional small PMT to increase dynamic range
- buried muon counters in 750-m array (AMIGA)
- increased FD uptime

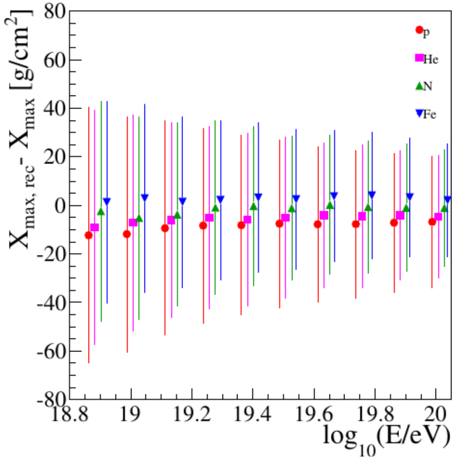




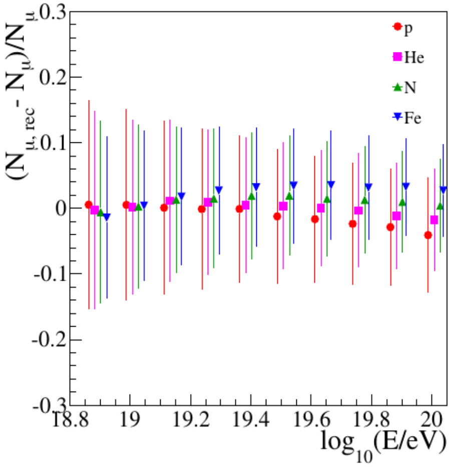


Future perspective: AugerPrime

$X_{\max}$ determination:

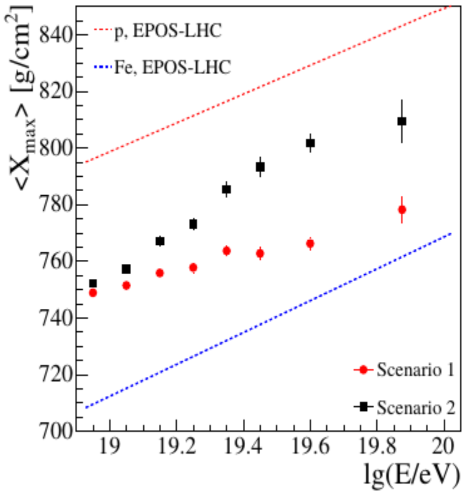


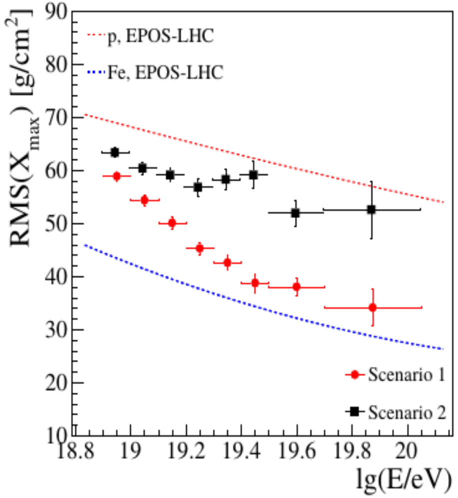
muon determination:



With composition data at highest energies

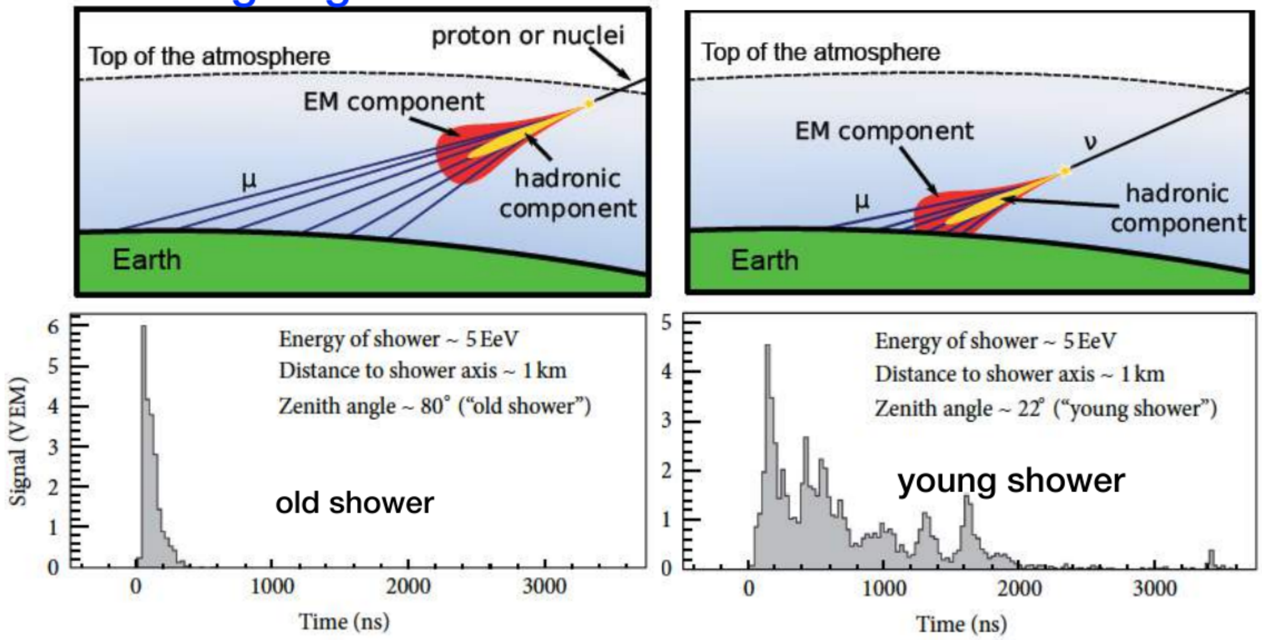
Discrimination power to disentangle low and high R_{cut} scenarios



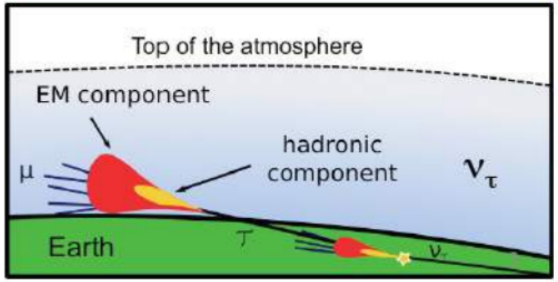


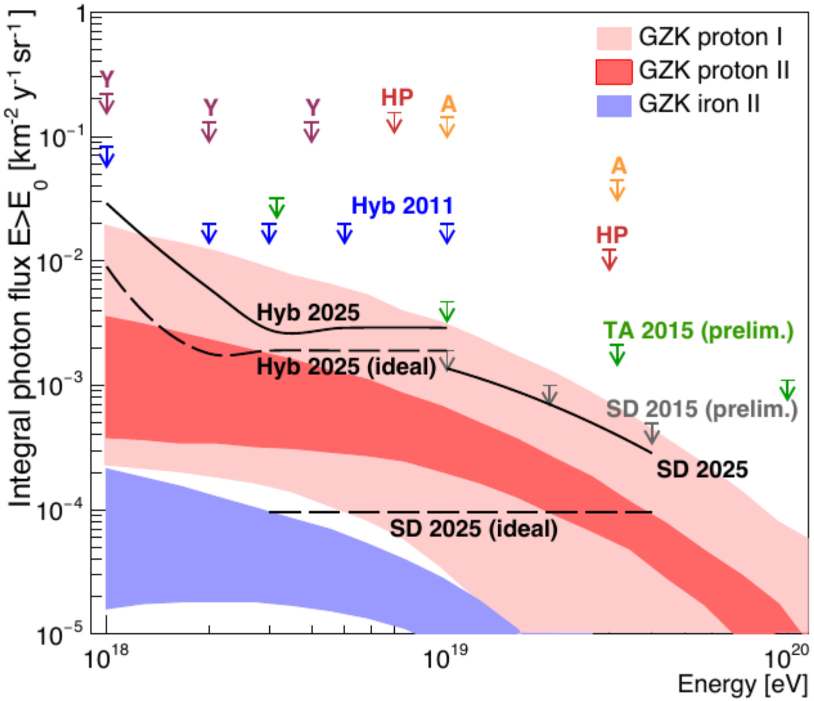
2016: engineering array of 12 stations
2018-2019: mass production and deployment
2019-2025: data taking (40,000km^2 sr yr)

- down-going

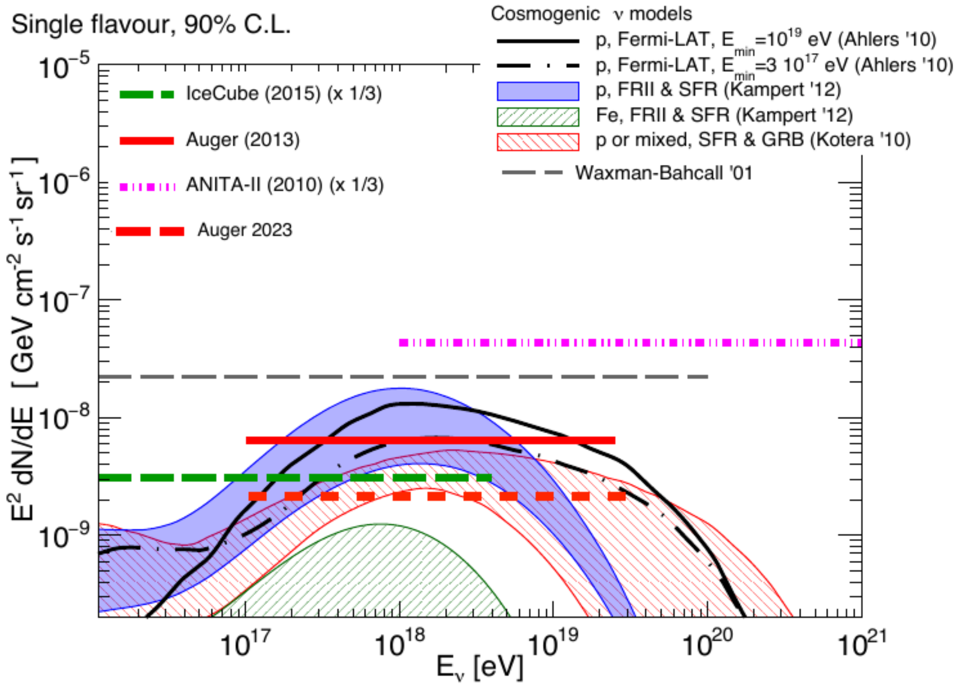


- up-going (Earth-Skimming)





GZK proton I
GZK proton II
GZK iron II
Y
Y
Y
HP
A
A
HP
Hyb 2011
Hyb 2025
Hyb 2025 (ideal)
TA 2015 (prelim.)
SD 2015 (prelim.)
SD 2025
SD 2025 (ideal)
Integral photon flux E>E0 [km^-2 y^-1 sr^-1]
Energy [eV]



Single flavour, 90% C.L.
Cosmogenic ν models
p, Fermi-LAT, Emin=10^19 eV (Ahlers '10)
p, Fermi-LAT, Emin=3 10^17 eV (Ahlers '10)
p, FRII & SFR (Kampert '12)
Fe, FRII & SFR (Kampert '12)
p or mixed, SFR & GRB (Kotera '10)
Waxman-Bahcall '01
IceCube (2015) (x 1/3)
Auger (2013)
ANITA-II (2010) (x 1/3)
Auger 2023
E^2 dN/dE [GeV cm^-2 s^-1 sr^-1]
Eν [eV]

- **Searches for neutrinos** in association with **gravitational wave events** detected by LIGO and Virgo
  - Discussed here: **GW170817** (binary neutron star merger)
  - 2 s later detection of a **gamma-ray burst** (GRB170817A) by Fermi GBM and INTEGRAL
  - **Follow-up observations** by many observatories and instruments; searches for associated neutrinos by **IceCube, Antares and Auger**