AMIGA:
an infill array and underground muon detectors for the Pierre Auger Observatory

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Outline

1. Introduction

- Ultra High Energy Cosmic Rays (UHECR) open questions
- The Pierre Auger Observatory (PAO) + Auger Muon and Infill for the Ground Array (AMIGA)

2. PAO & AMIGA-SD results

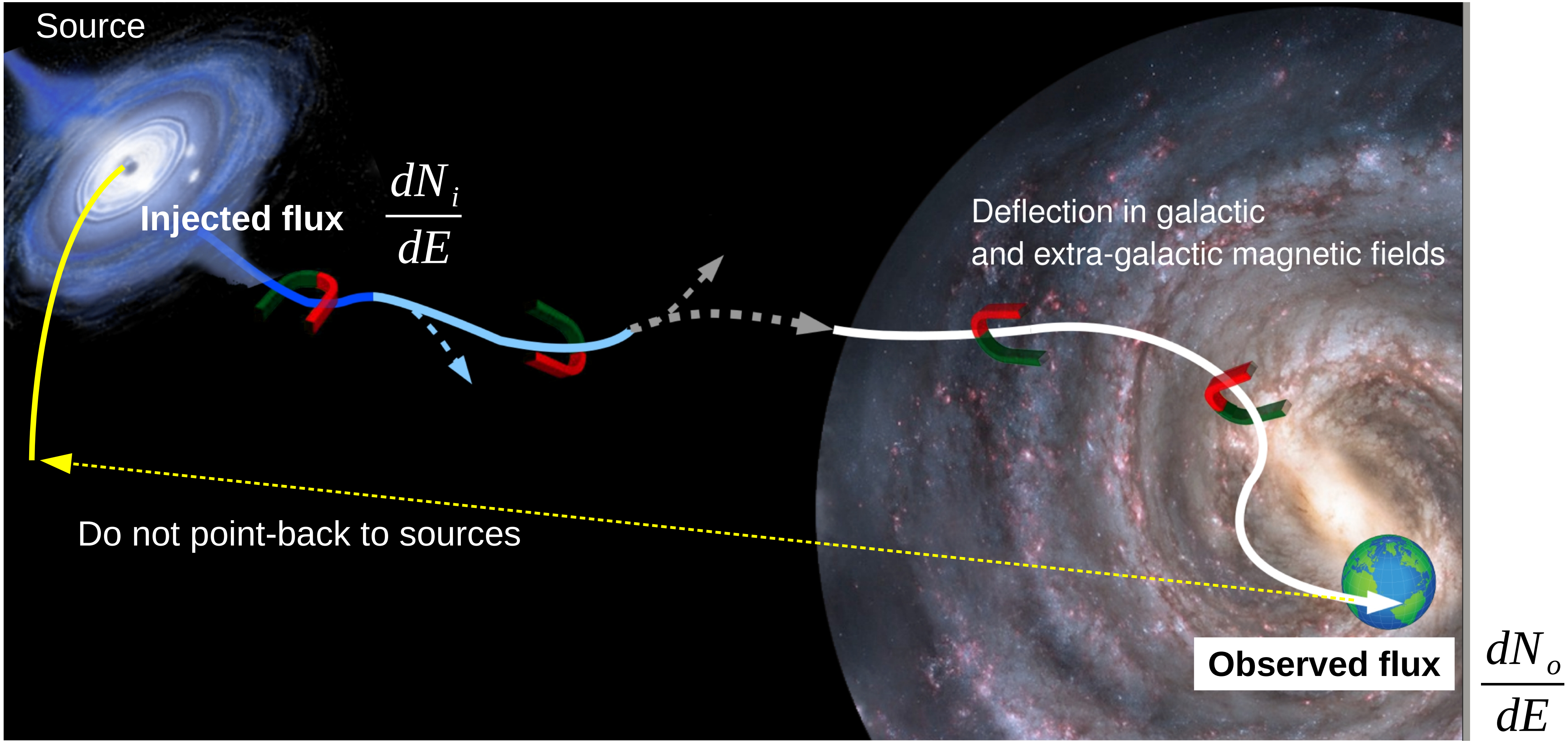
- **Energy spectrum**
- **Composition**
- Anisotropy (not covered in this talk)

$\}$ New and unexpected (before Auger) scenario for UHECR

3. AMIGA-UMD R&D and first Engineering Array (UMD-EA) physics results

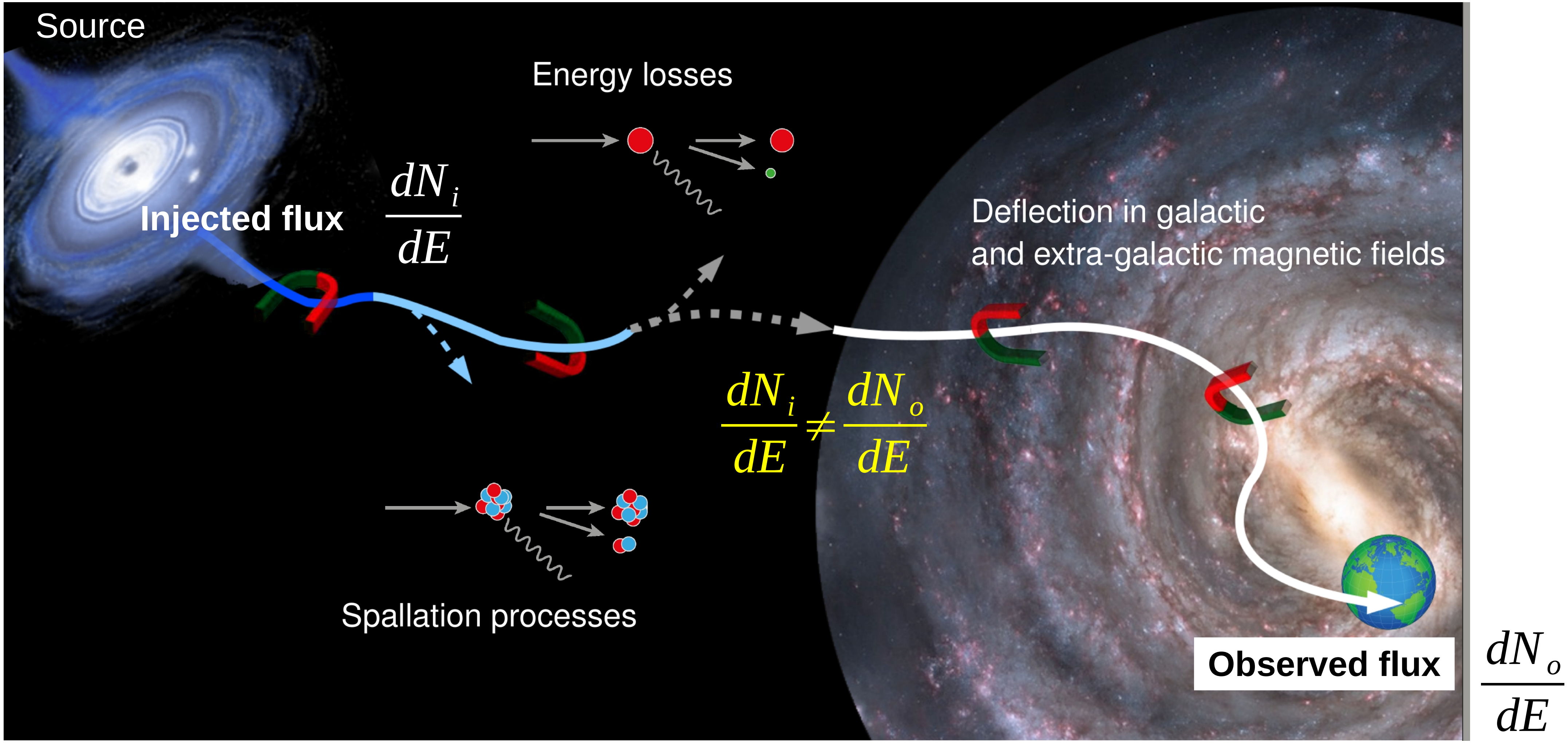
4. AMIGA final design & production

Introduction: Ultrahigh Energy Cosmic Rays



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

Introduction: Ultrahigh Energy Cosmic Rays



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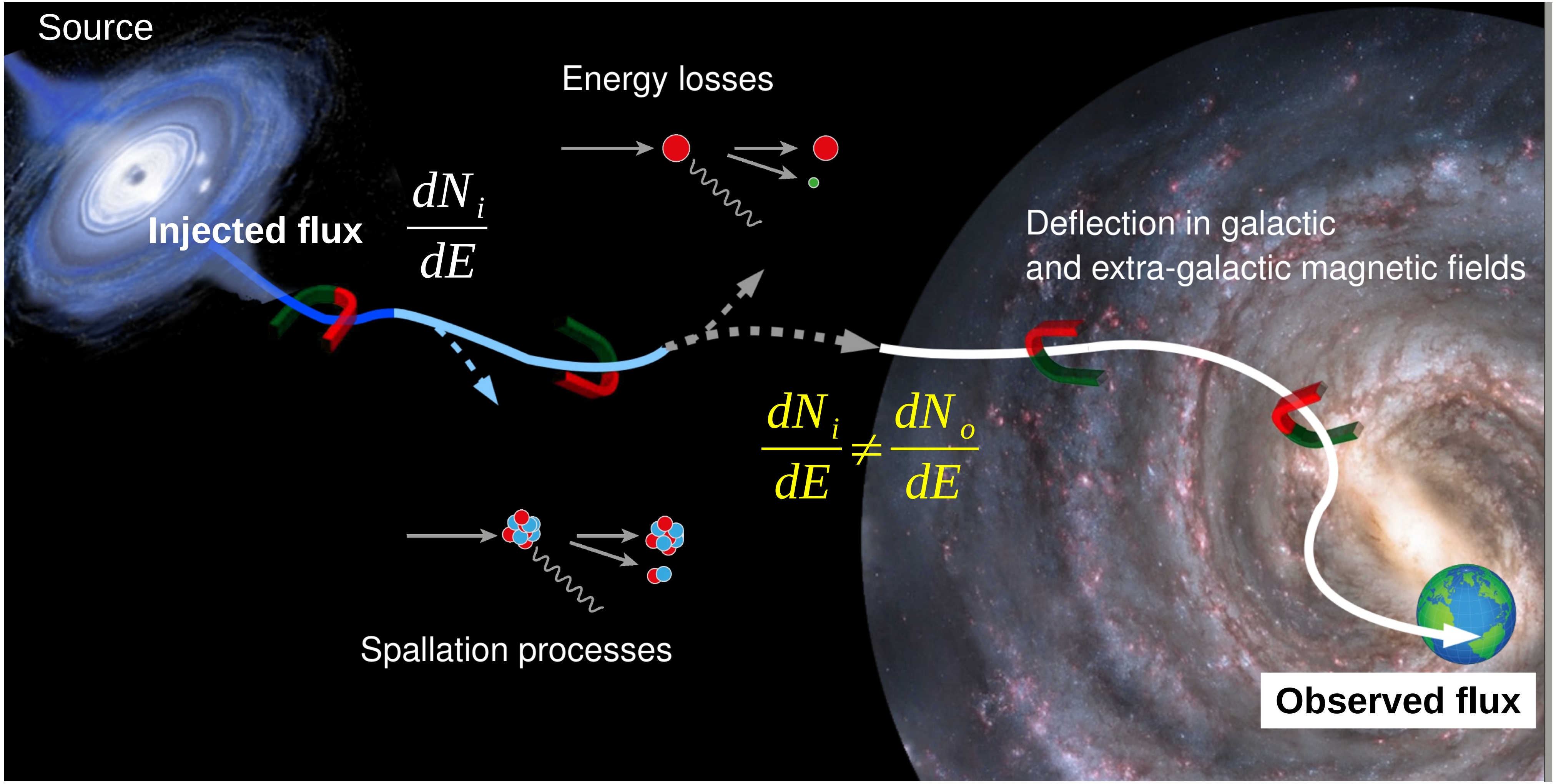
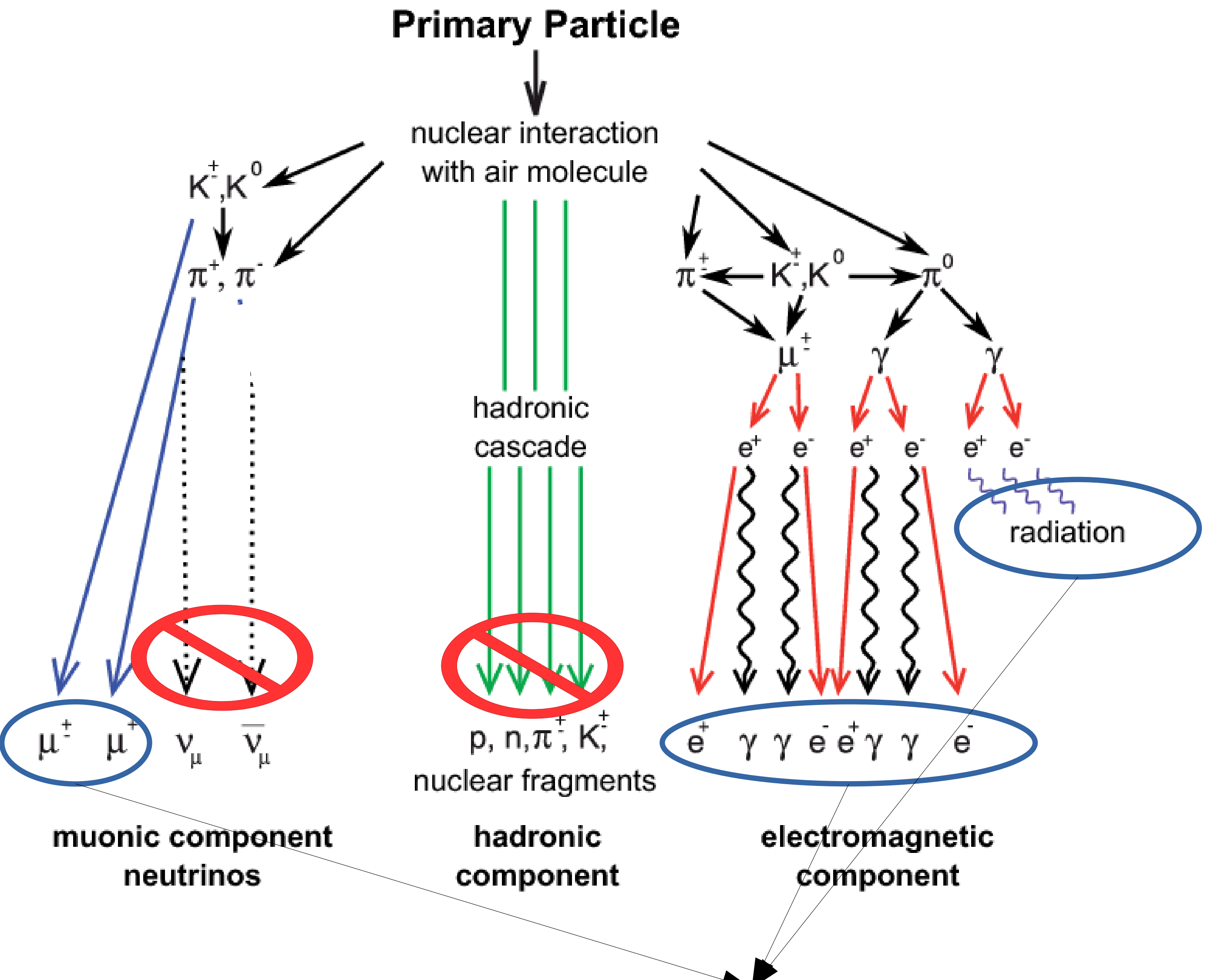


$$\frac{dN_o}{dE}$$

Where do they come from?	How are they accelerated?	What is their composition?
¿? Large scale anisotropy (dipole)	**Top-down (exotic) scenarios (at least) highly disfavored**	**Mixed above 10^{19} eV, heavier at highest energies**

Introduction: Ultrahigh Energy Cosmic Rays



Primary Particle

nuclear interaction with air molecule

$K^{\pm}, K^0$

π^+, π^-

hadronic cascade

$\pi^{\pm}$ $K^{\pm}, K^0$ π^0

$\mu^{\pm}$ γ γ

e^+ e^- e^+ e^- e^+ e^-

radiation

$\mu^{\pm}$ $\mu^{\pm}$ ν_{μ} $\bar{\nu}_{\mu}$

p, n, $\pi^{\pm}$, $K^{\pm}$, nuclear fragments

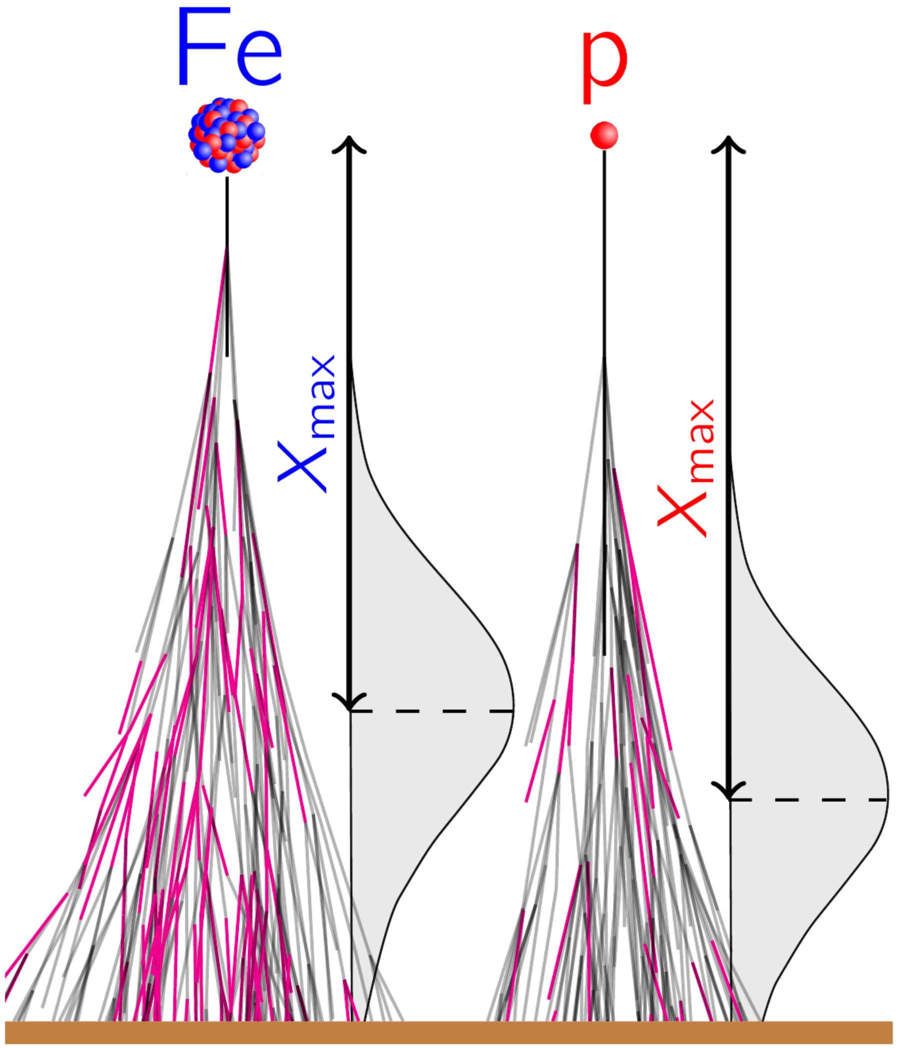
e^+ γ γ e^- e^+ γ γ e^-

muonic component neutrinos

hadronic component

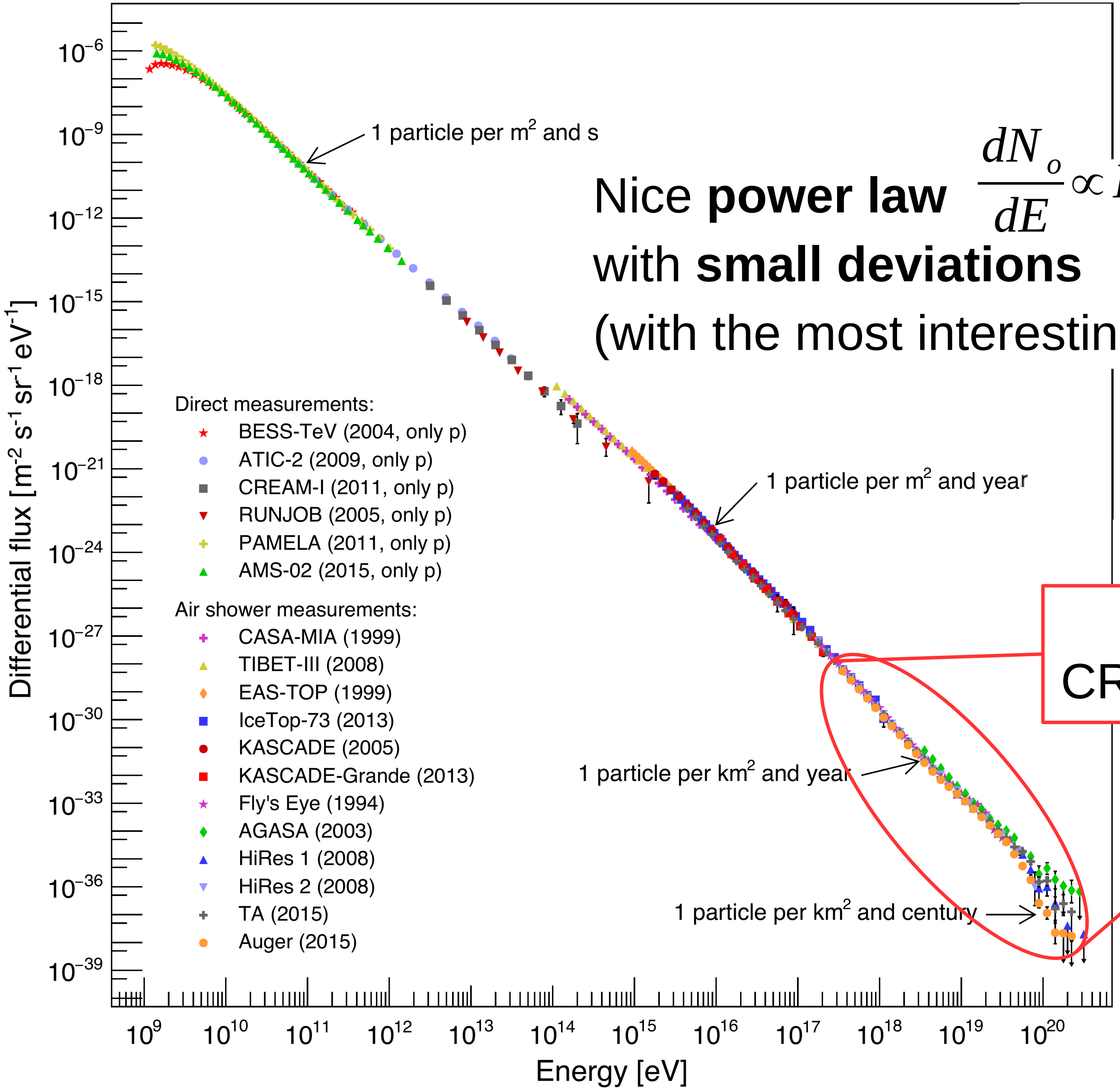
electromagnetic component

Accessible to ground based experiments



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

Introduction: Ultrahigh Energy Cosmic Rays



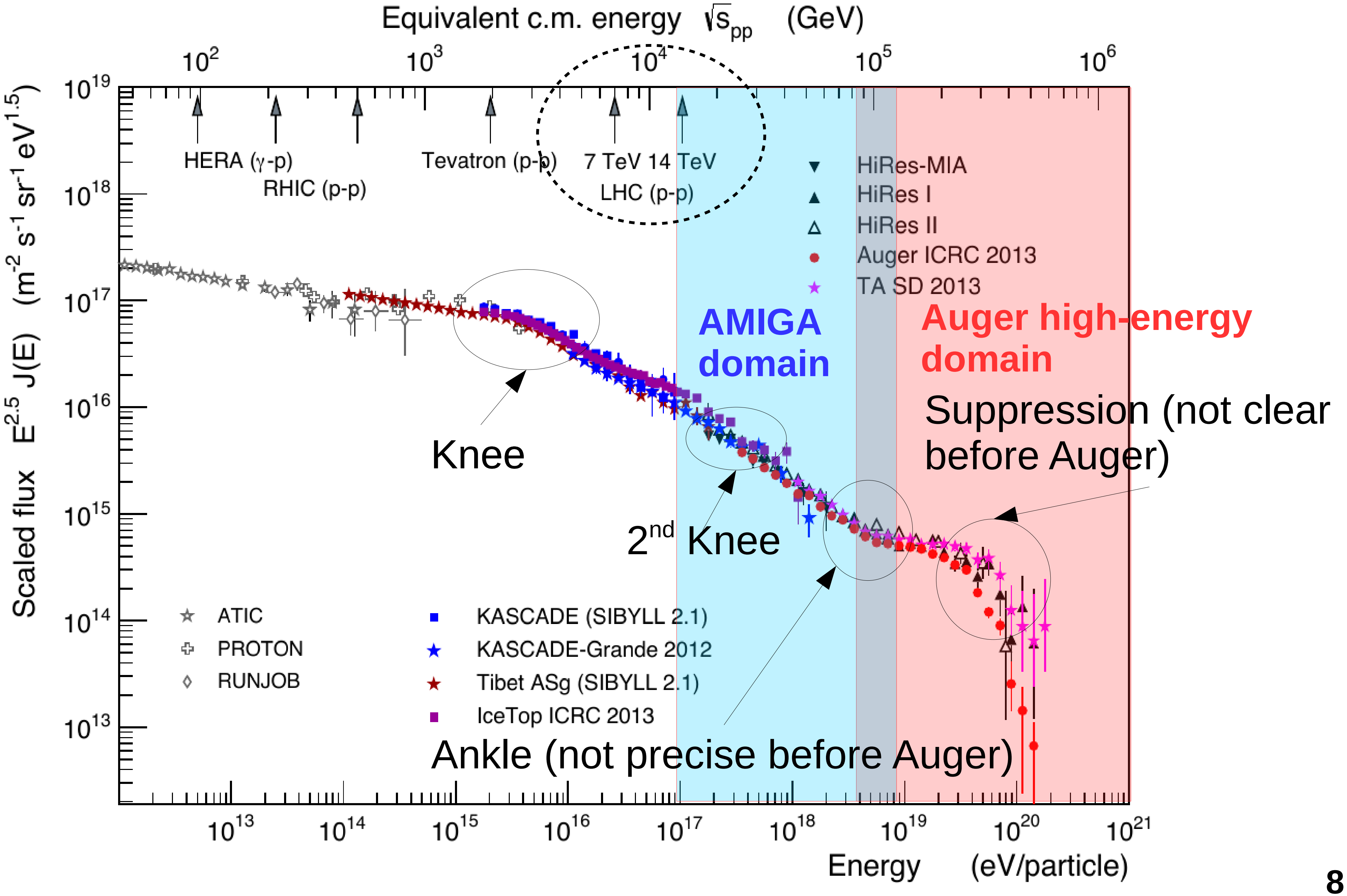
Nice **power law** $\frac{dN_o}{dE} \propto E^{-3}$

with **small deviations**

(with the most interesting information!)

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

Introduction: Ultrahigh Energy Cosmic Rays



Knee

2nd Knee

AMIGA domain

Auger high-energy domain

Suppression (not clear before Auger)

Ankle (not precise before Auger)

Introduction: the Pierre Auger Observatory, a brief story-line

- 1992 J. Cronin & A. Watson suggest building a giant array
- 1995 Design report + collaboration + **site selection**
- 1999 1st Signature of International Agreement
- 2001 PAO **Engineering Array (EA)** operated for 6 months

PAO Concept & Validation **9 years**

- **2006** **AMIGA** + HEAT approved by the collaboration
- **2008** **End of PAO construction** & hints for **flux suppression** $>4\times10^{19}\,eV$
- 2009 **Photon flux limits** above $10^{18}\,eV$
- 2010 X_{max} observations for **mass composition**
- 2012 **proton-proton cross section** at $\sqrt{s}$ of 57 TeV
- 2013 **Neutrino flux limits**
- 2015 **Muon deficit** in predictions of hadronic interaction models at $10^{19}\,eV$
- 2015 2nd Signature of International Agreement & **AugerPrime**
- 2017 Observation of **large scale anisotropies** & **AMIGA-UMD** EA for 1 year
- 2019 **Limits to neutrino point-like sources** at ultra-high energies
- 2020 **Ankle & suppression** confirmed + **new feature**
  muon deficit with **AMIGA-UMD** at $10^{17.5}\,eV$ & $10^{18}\,eV$

Analysis & Results **>12 years**

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- 1992 J. Cronin & A. Watson suggest building a giant array
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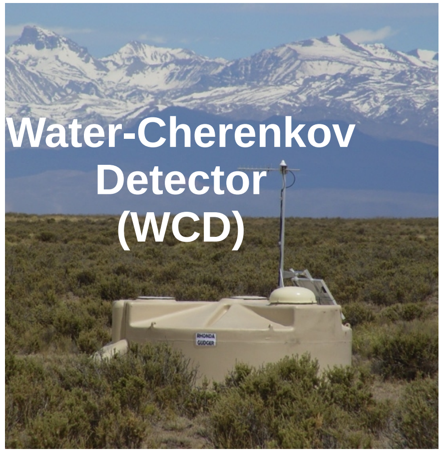
AMIGA
Concept
&
Validation
11 years

Analysis & Results
>12 years

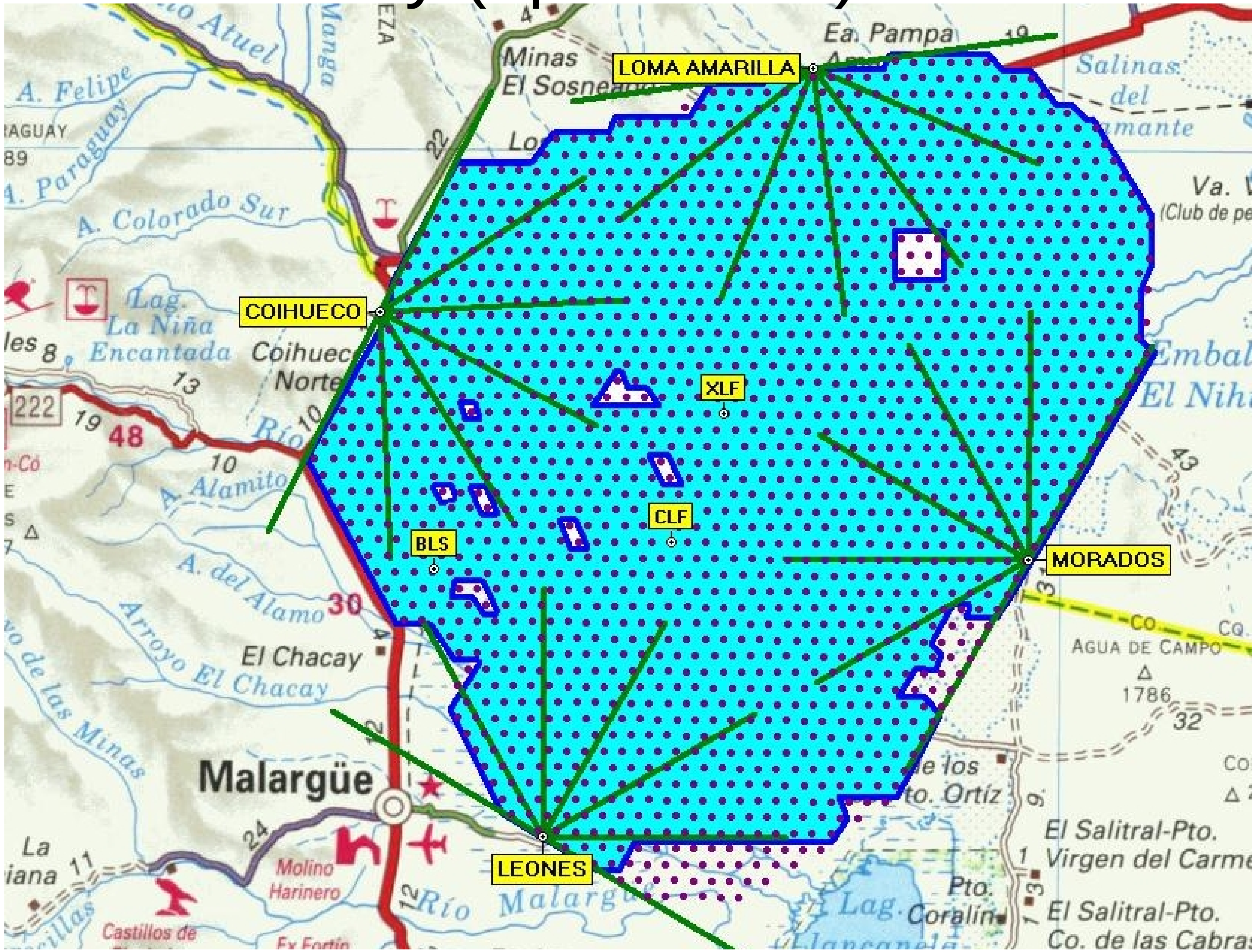
Introduction: the Pierre Auger Observatory (up to 2008)



Surface detector (SD)

100% duty cycle

SD-1500
3000 km^2
1600 WCDs

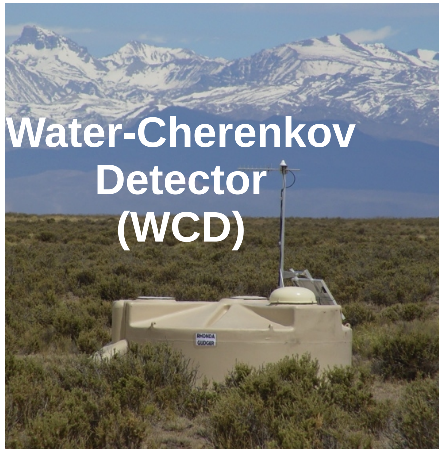


Fluorescence detector (FD)

15% duty cycle

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

Introduction: the PAO & Enhancements (after 2008)



Surface detector (SD)

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AMIGA

SD-750 23.5 km² 61 WCDs	**SD-433** 1.9 km² 19 WCDs
UMD-750 23.5 km² 61Plastic Scintillators	**UMD-433** 1.9 km² 19 Plastic Scintillators

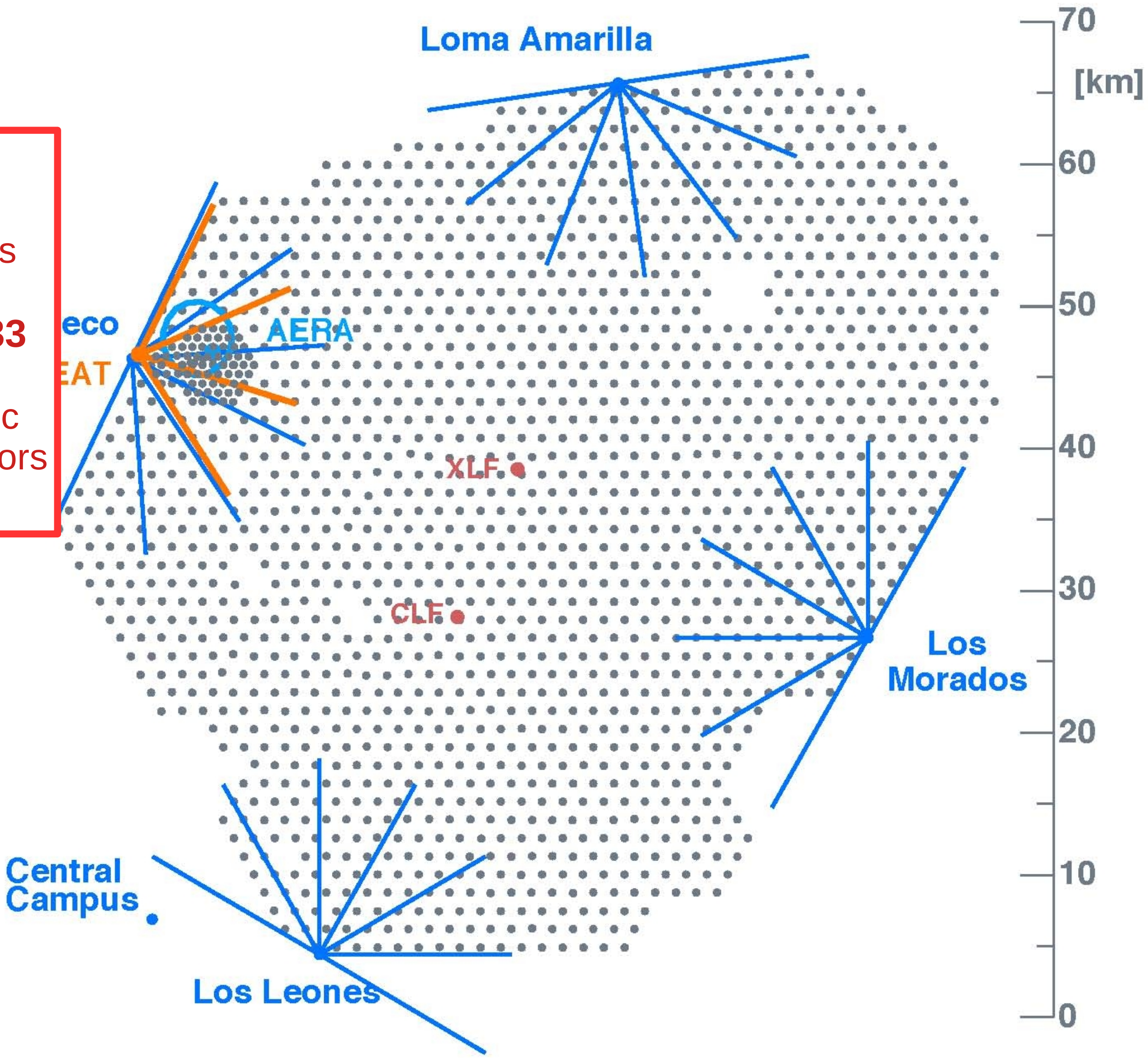
Fluorescence detector (FD)

15% duty cycle

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

HEAT

1 units x 3 telescopes
overlooking SD-750m
FoV 30º x 30º
Minimum elevation 30º



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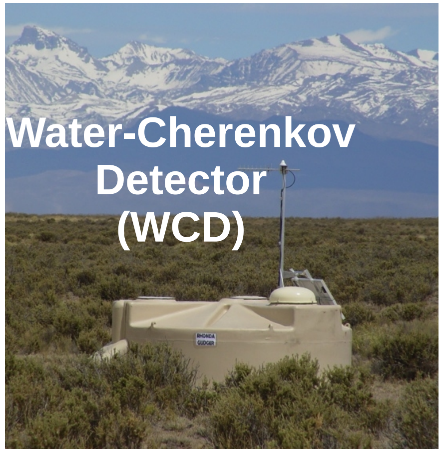

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AMIGA

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1.9 km^2
19 WCDs

UMD-750
23.5 km^2
61Plastic Scintillators

UMD-433
1.9 km^2
19 Plastic Scintillators

Have to be developed from scratch (R&D)

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}

HEAT

1 units x 3 telescopes
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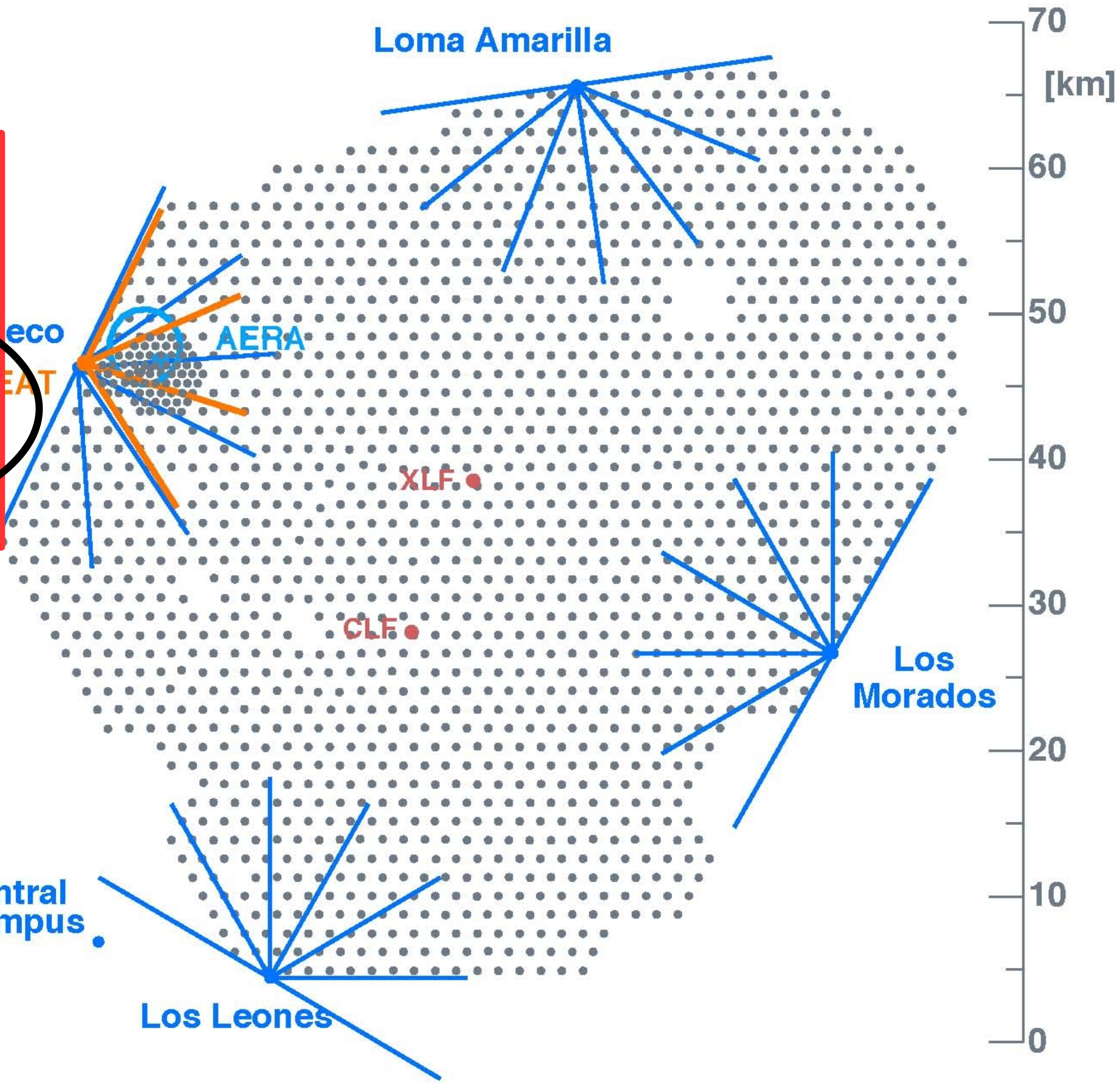
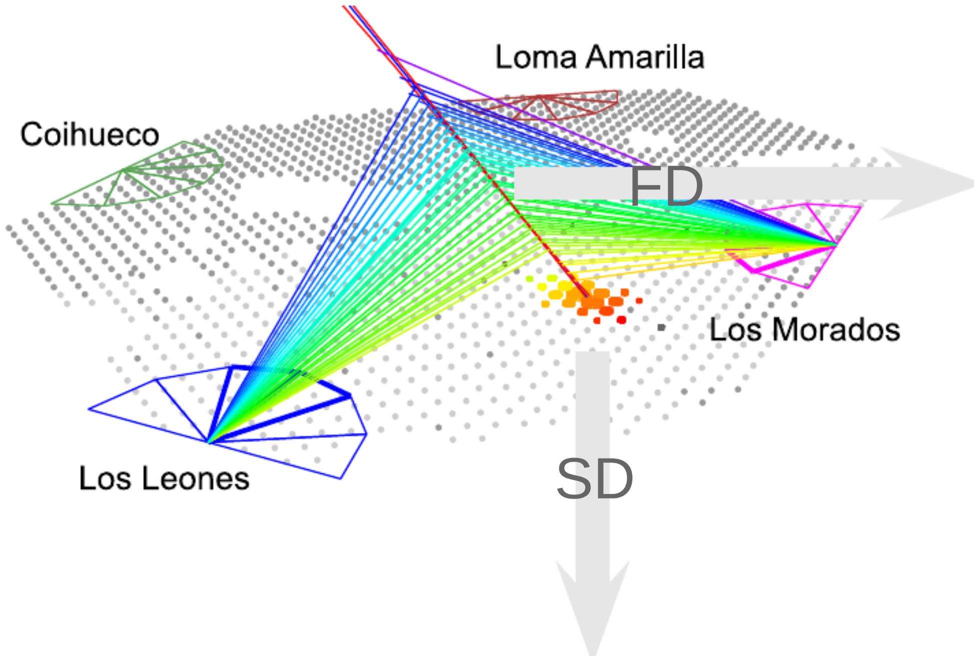
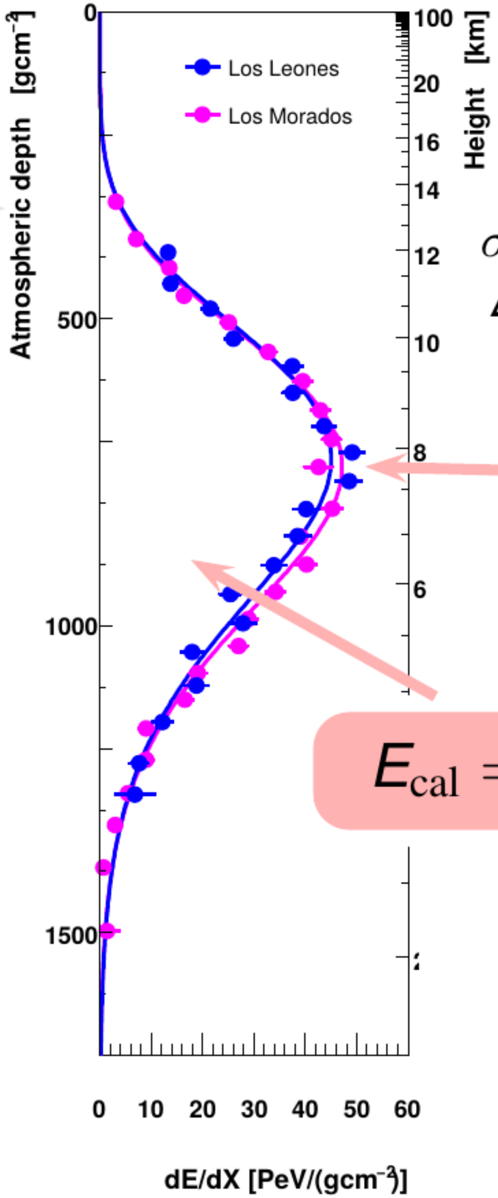
Minimum elevation 30^{o}



Introduction: the hybrid technique





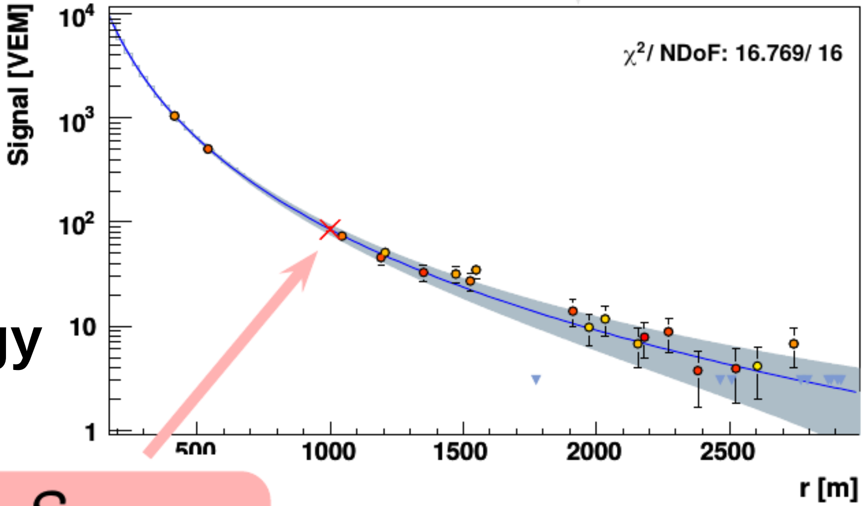
$$\sigma X_{\max} \leq 20\,\mathrm{g/cm^2}$$
$$\Delta_{\mathrm{sys}} \leq 10\,\mathrm{g/cm^2}$$

$X_{\max}$

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

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

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

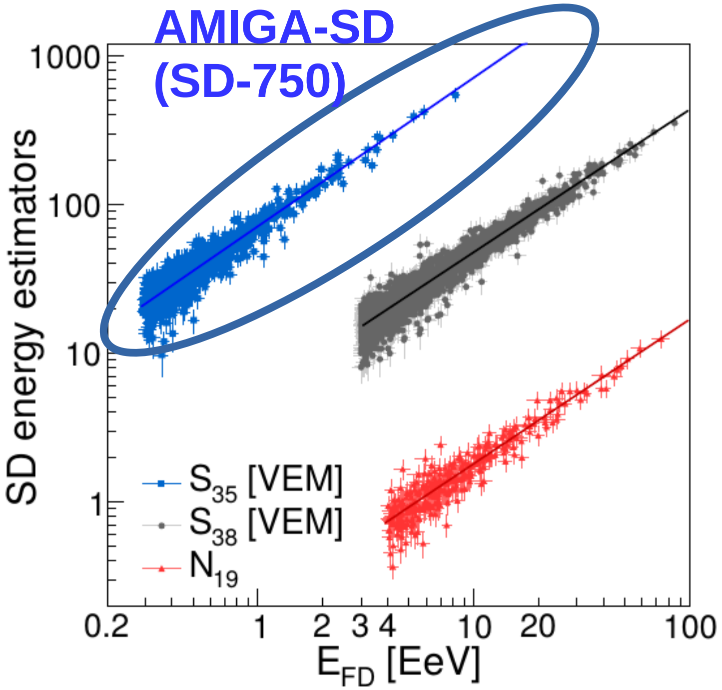


S_{1000}

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

Introduction: the hybrid technique

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



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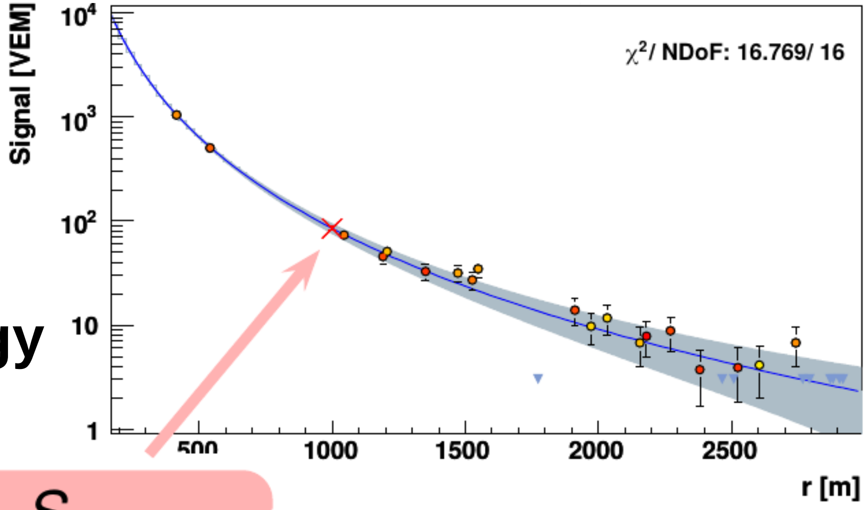

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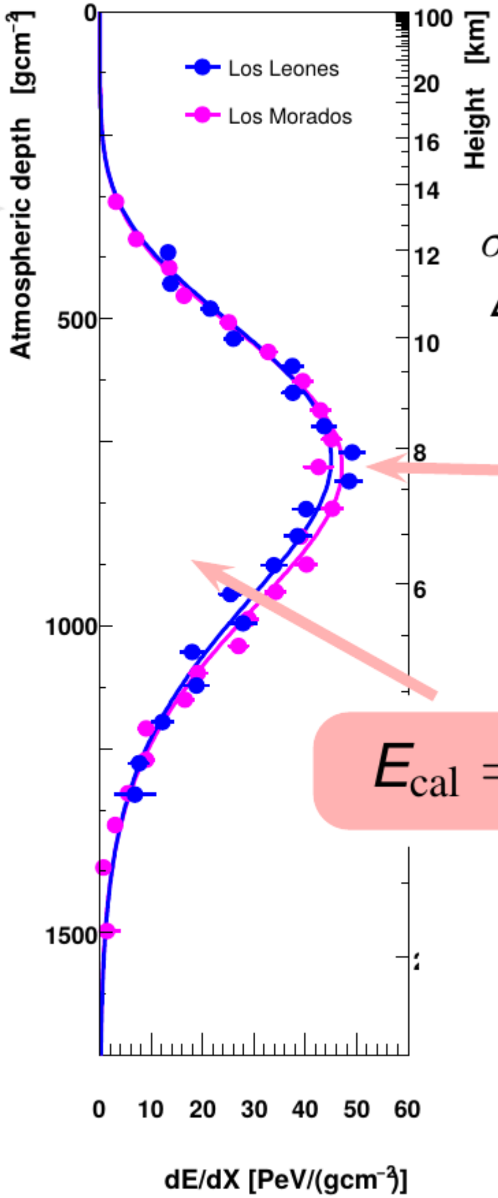

$$\sigma_{X_{\mathrm{max}}} \lesssim 20\,\mathrm{g/cm^2}$$
$$\Delta_{\mathrm{sys}} \lesssim 10\,\mathrm{g/cm^2}$$

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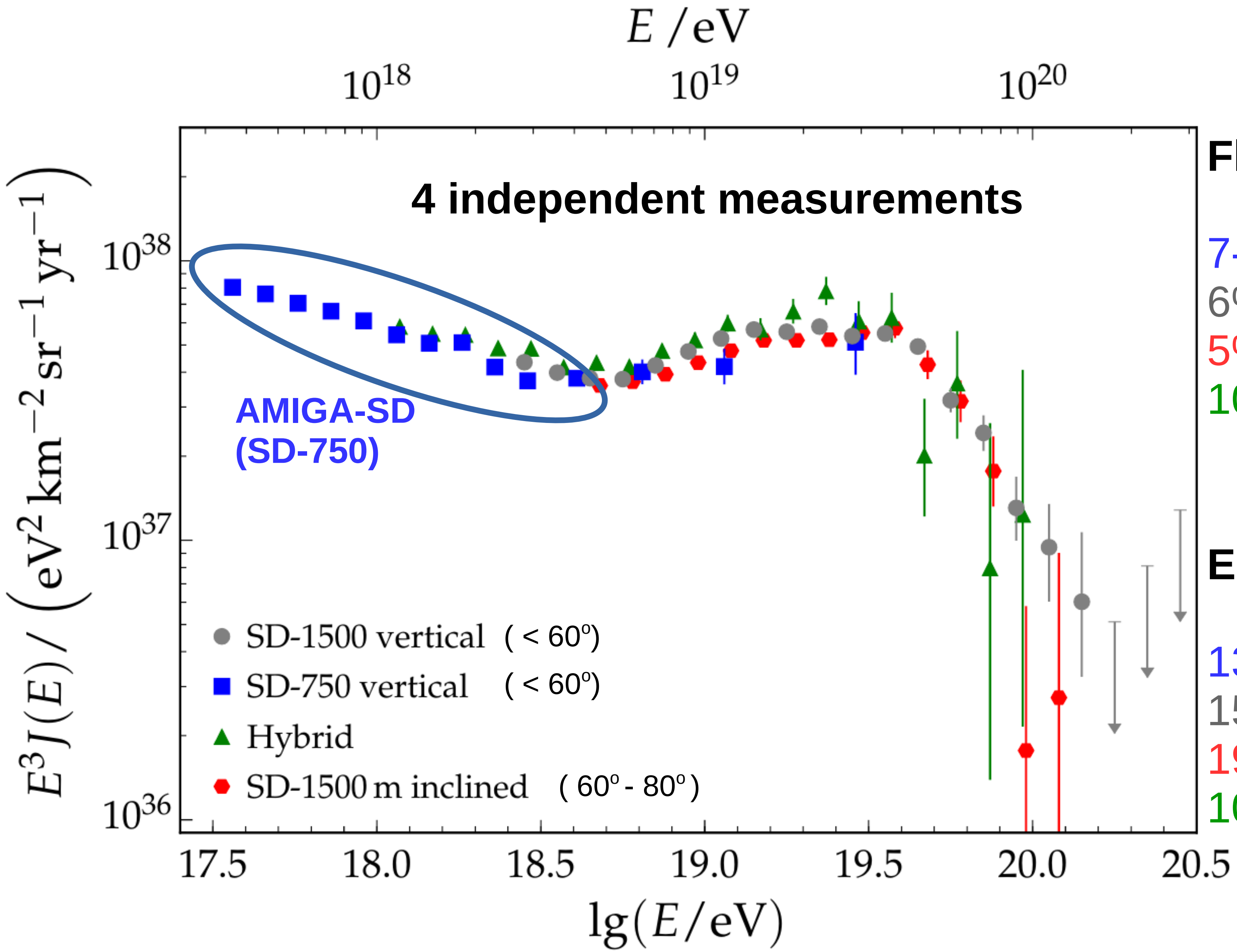
2. PAO & AMIGA-SD results

Energy spectrum: all-particle flux



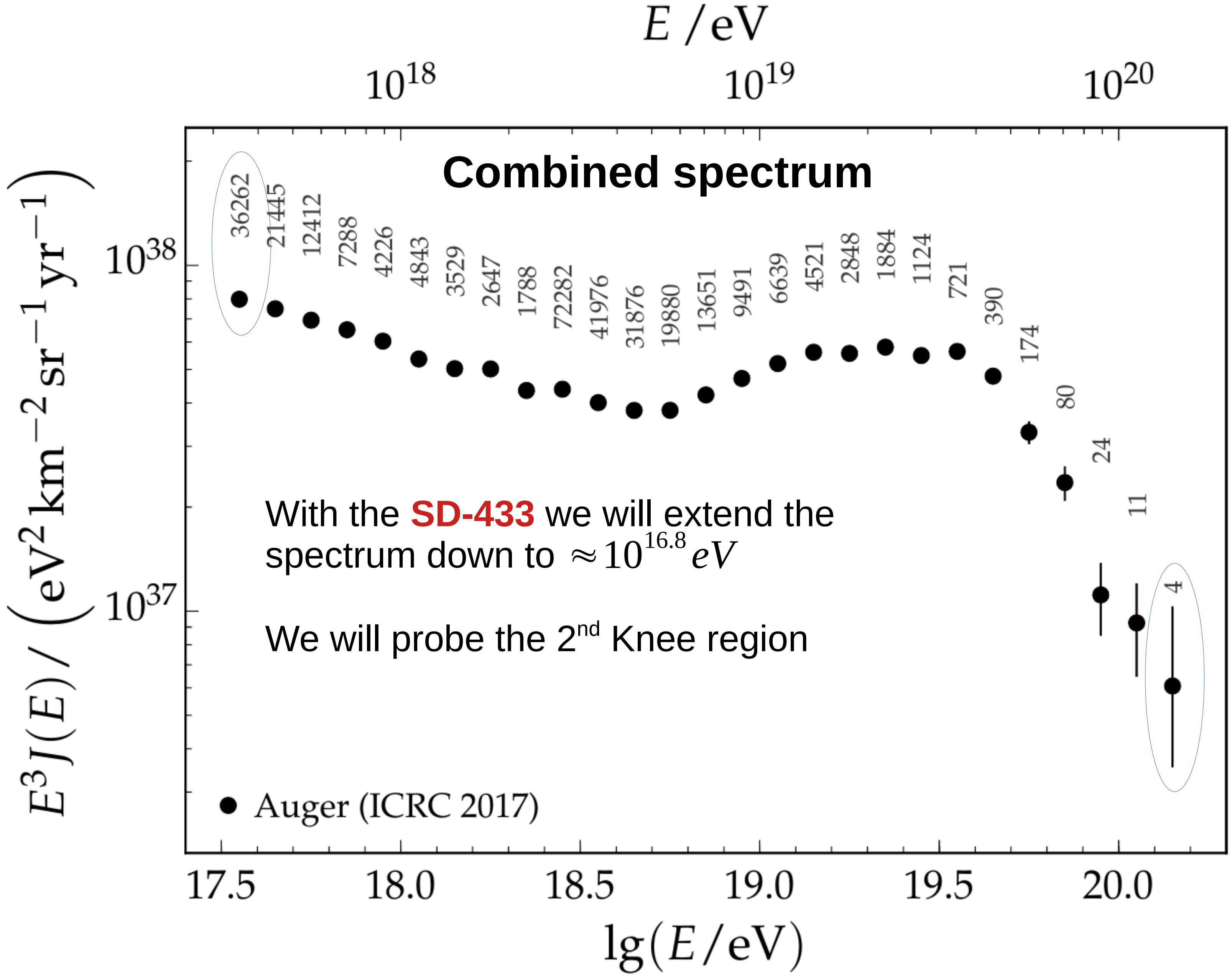
Flux uncertainties:

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

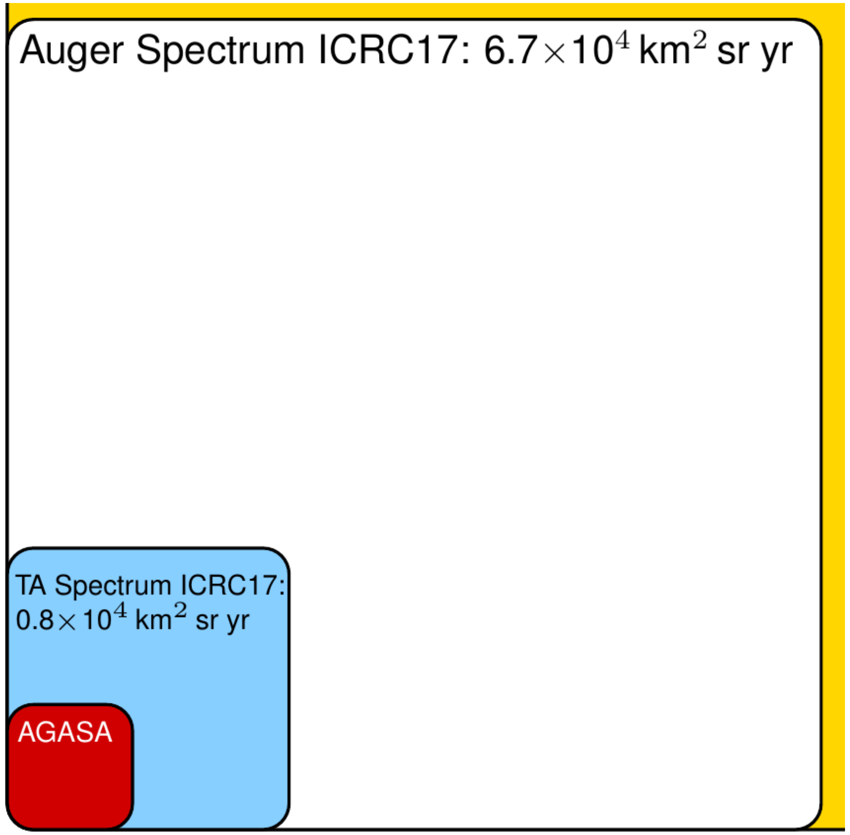


Combined spectrum

With the **SD-433** we will extend the spectrum down to $\approx 10^{16.8}\,eV$

We will probe the 2nd Knee region

Unprecedented statistics!!



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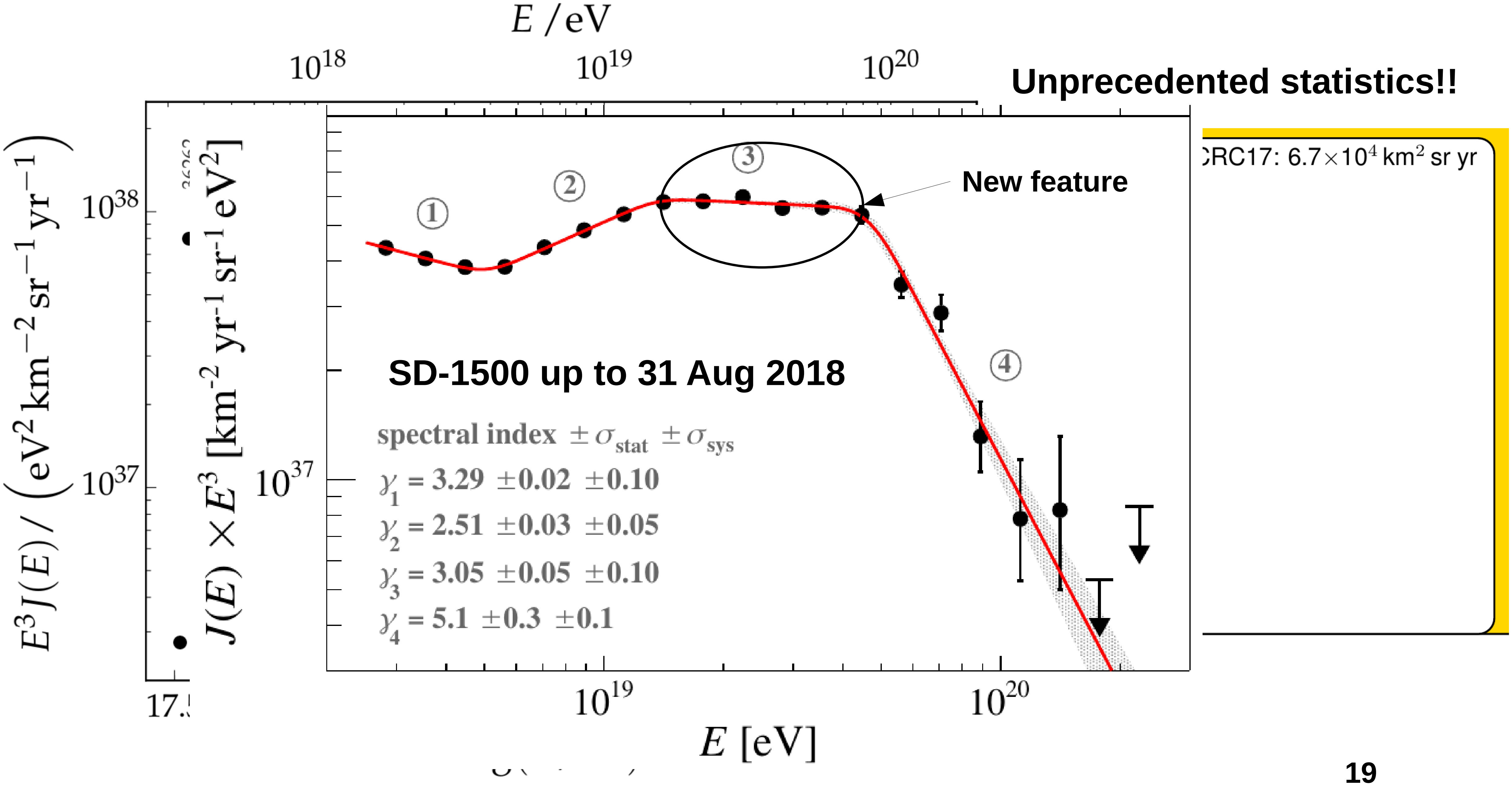


New feature

SD-1500 up to 31 Aug 2018

spectral index $\pm \sigma_{stat}$ $\pm \sigma_{sys}$

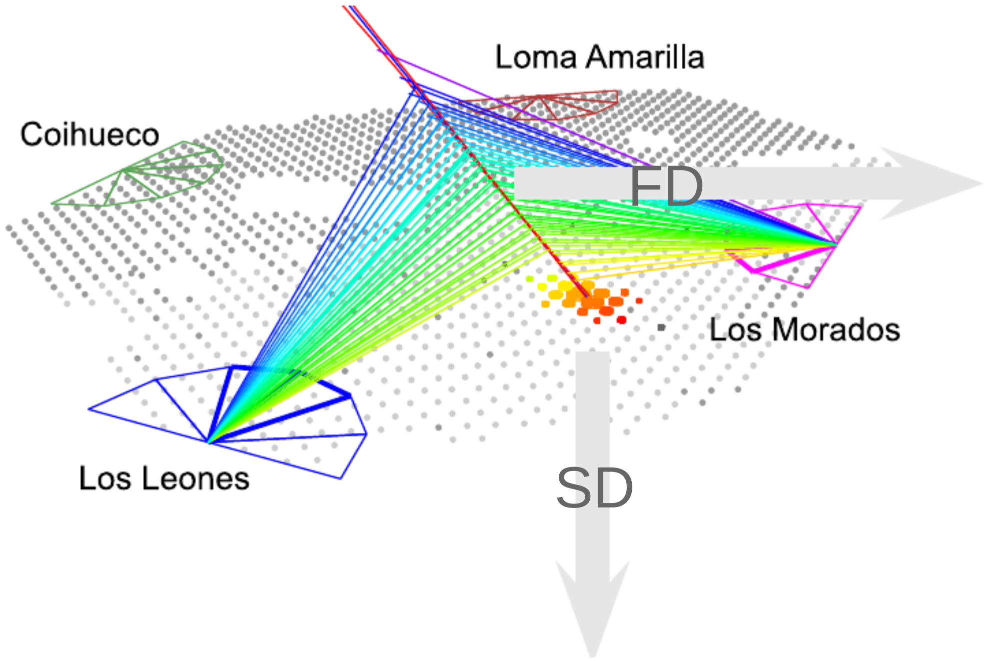
$\gamma_1 = 3.29 \pm 0.02 \pm 0.10$

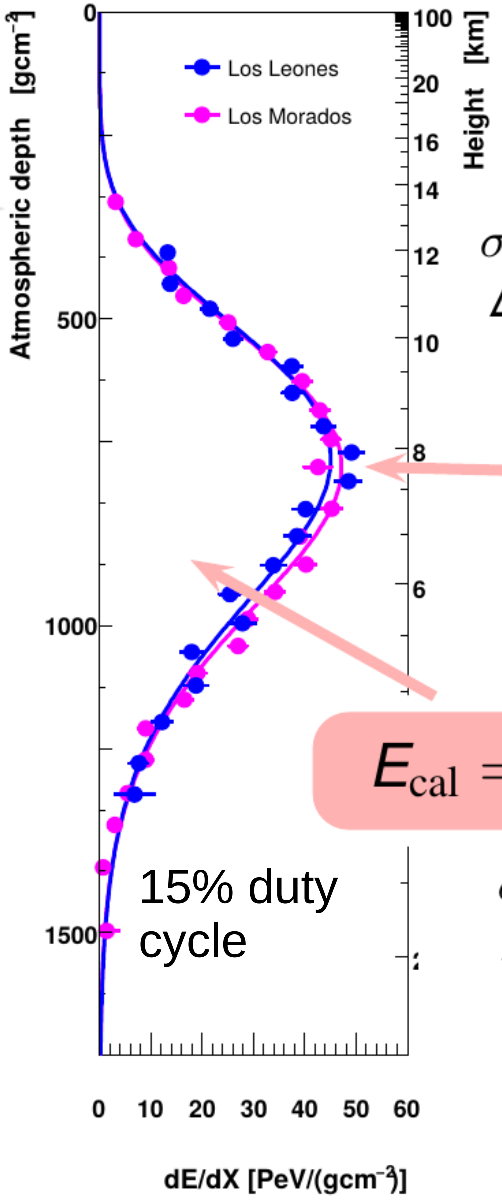
$\gamma_2 = 2.51 \pm 0.03 \pm 0.05$

$\gamma_3 = 3.05 \pm 0.05 \pm 0.10$

$\gamma_4 = 5.1 \pm 0.3 \pm 0.1$

Composition





15% duty cycle

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

X_max contains information on primary mass

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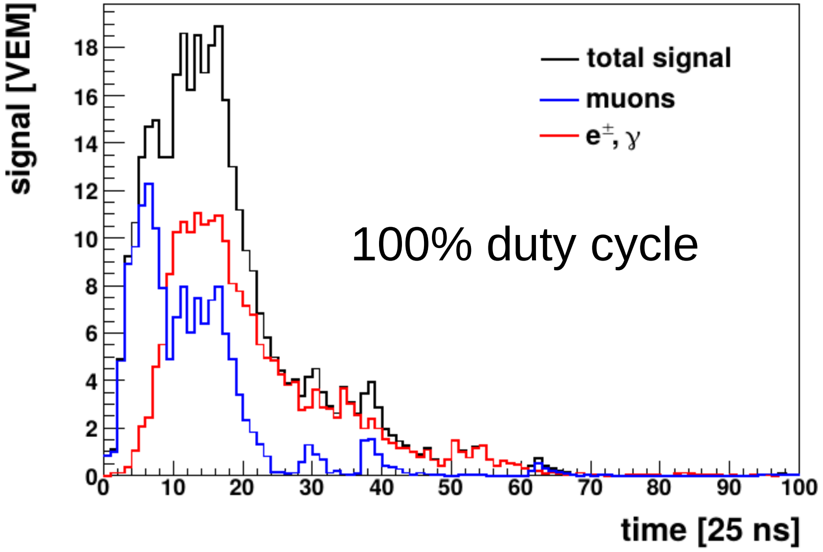
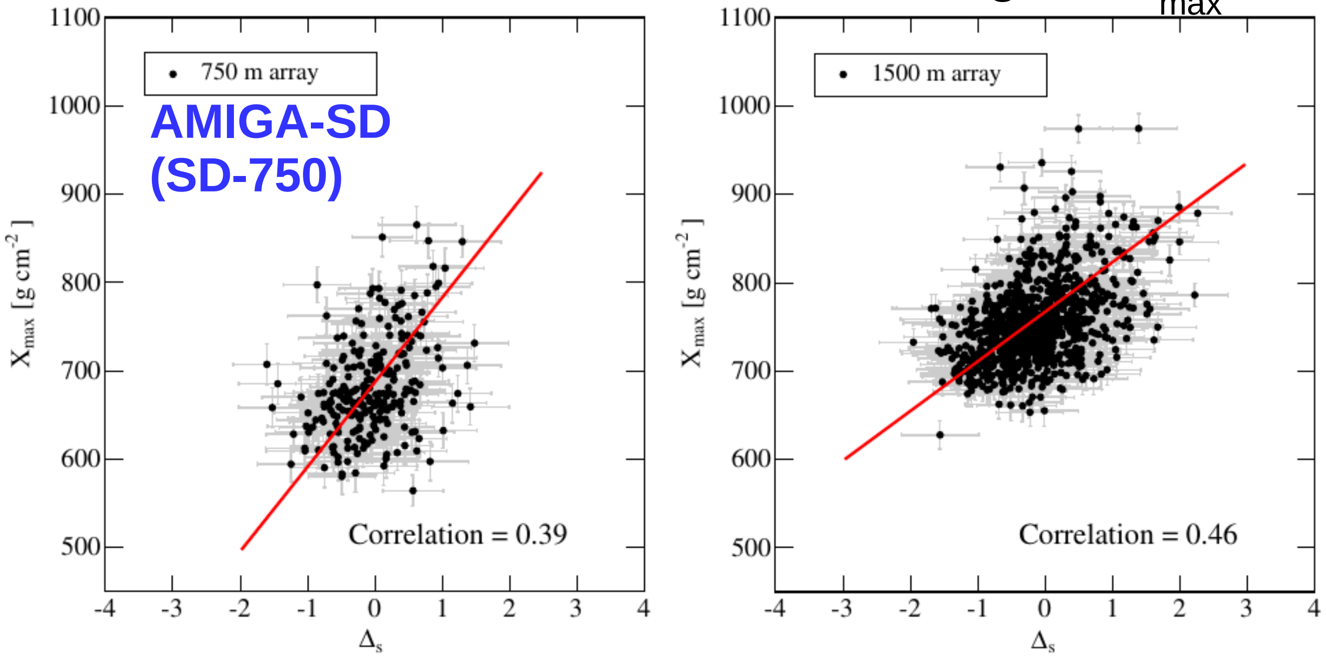
Timing of secondaries contains information on **primary mass**

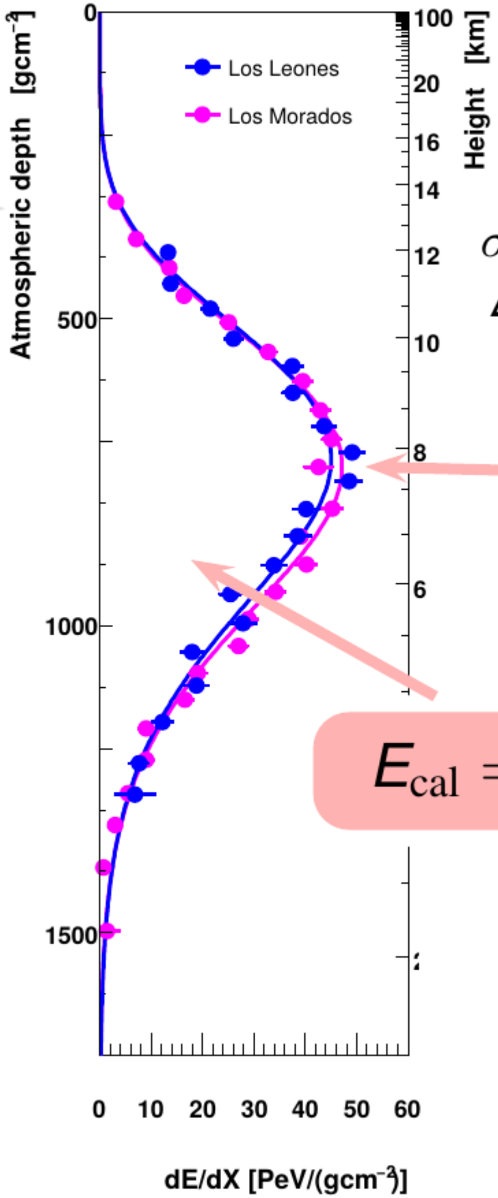


100% duty cycle

Composition

Calibration of timing Vs X_{max}





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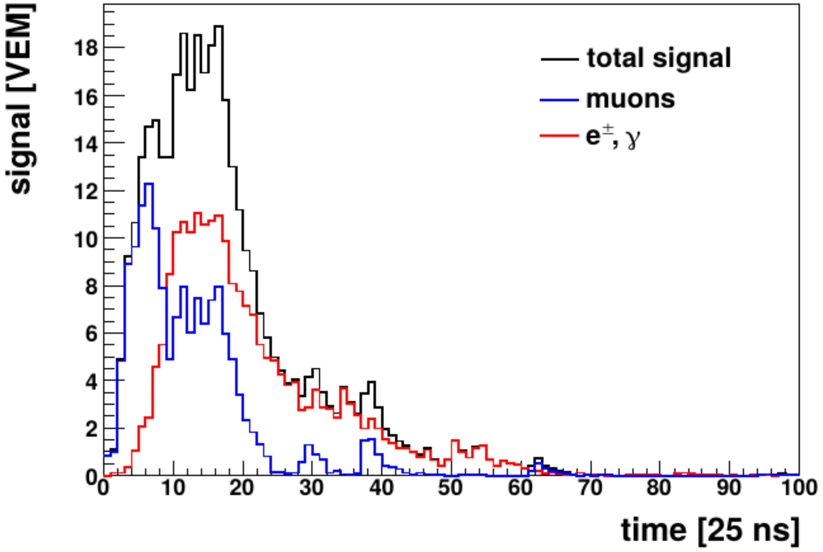

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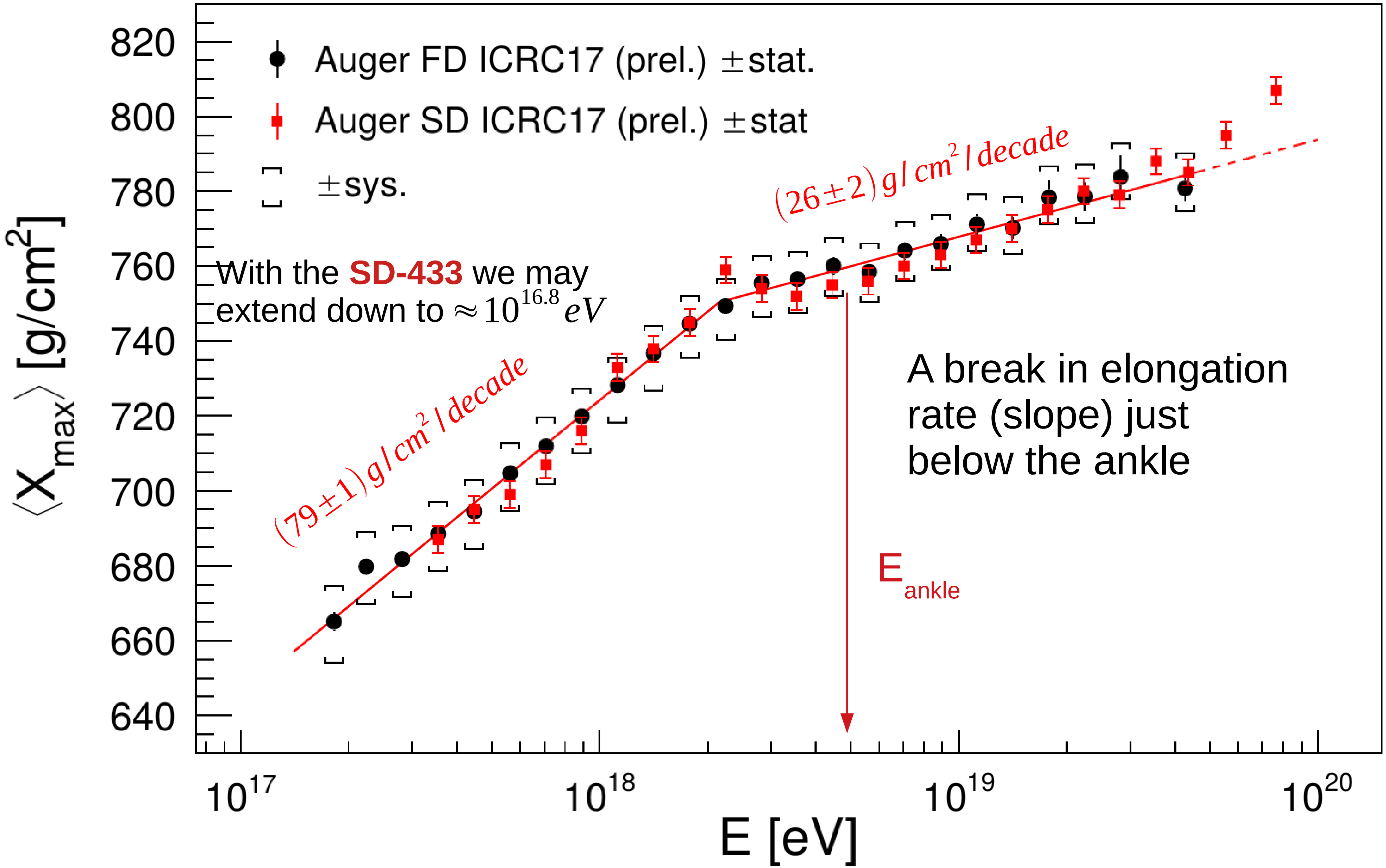
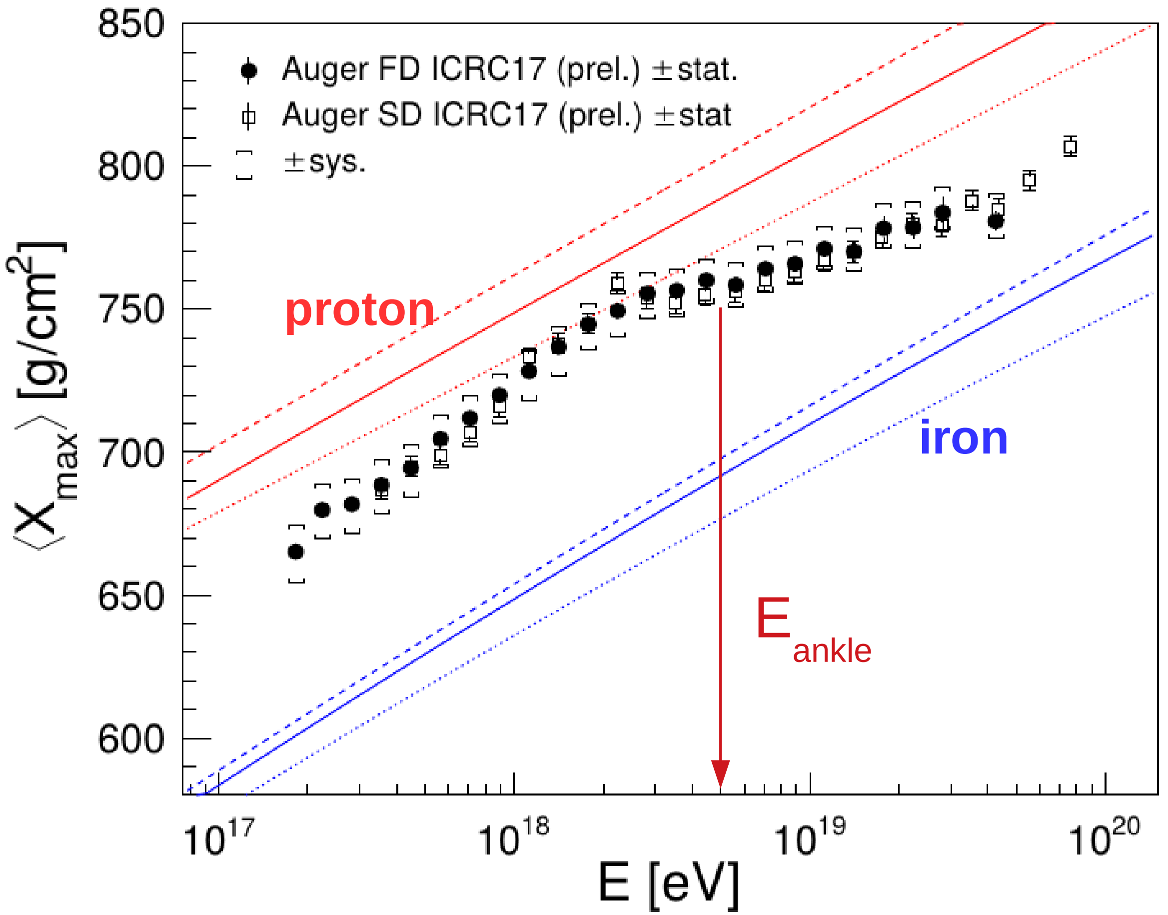
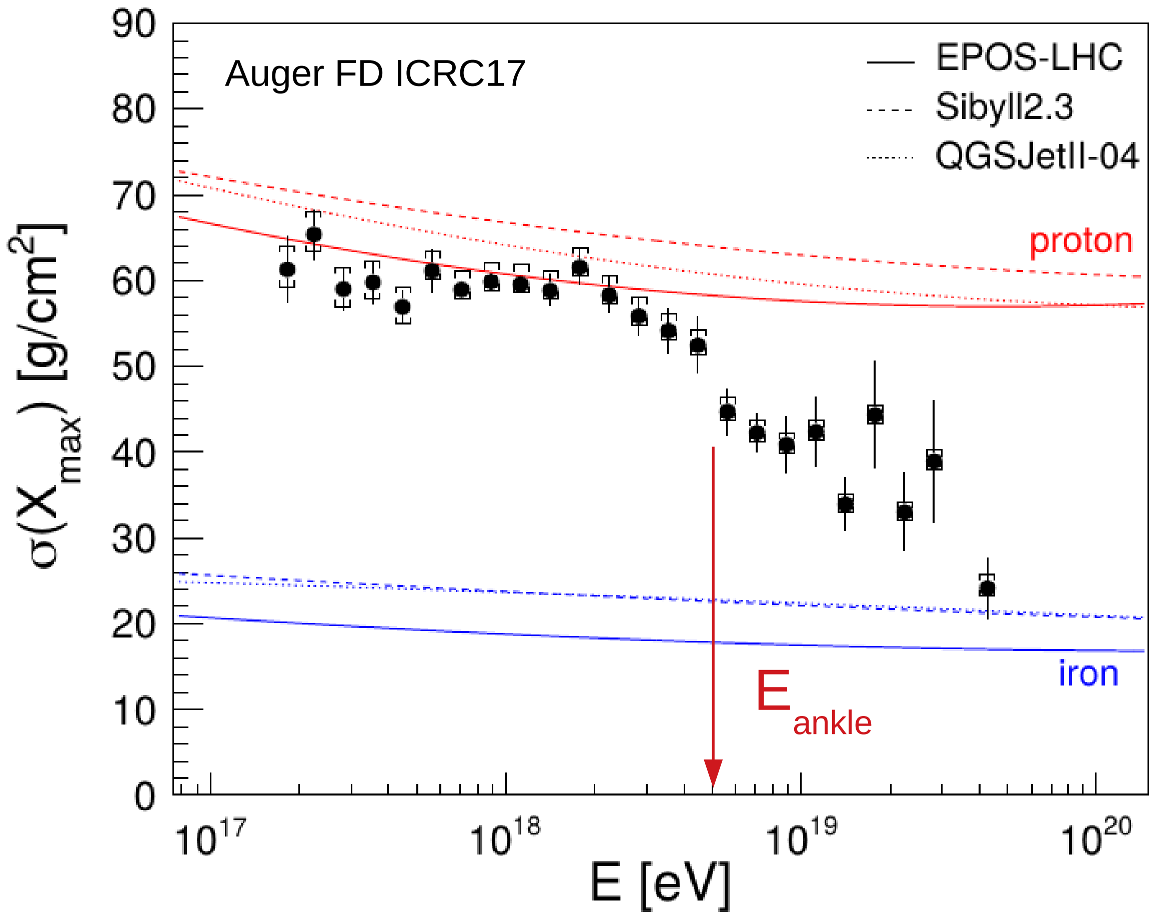


With the **SD-433** we may extend down to $\approx 10^{16.8}\,eV$

A break in elongation rate (slope) just below the ankle

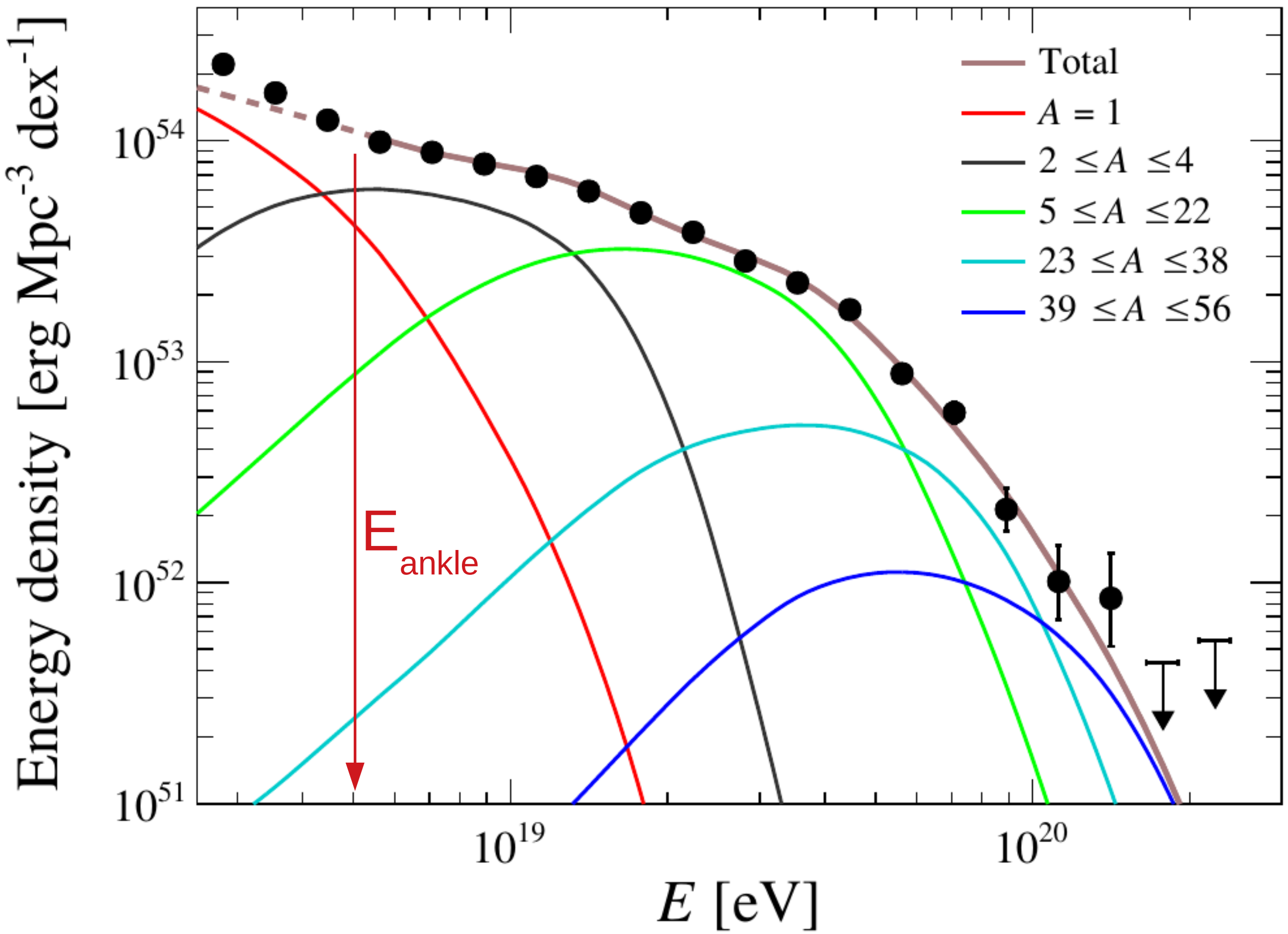
Composition





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

Combining spectrum + composition + propagation from sources + injection flux



To improve our understanding of the complete picture **we need to increase the mass sensitivity**:

I) at higher energies with **SSD (Surface Scintillator Detector)**

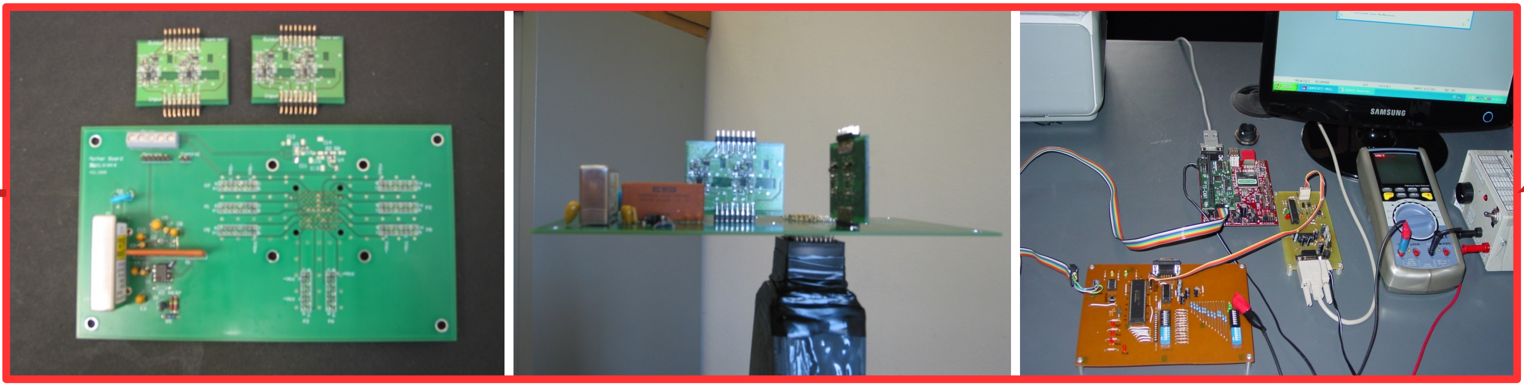
II) at lower energies **AMIGA-UMD**

3. AMIGA-UMD R&D and first Engineering Array (UMD-EA) physics results

AMIGA: prototyping mechanics & electronics

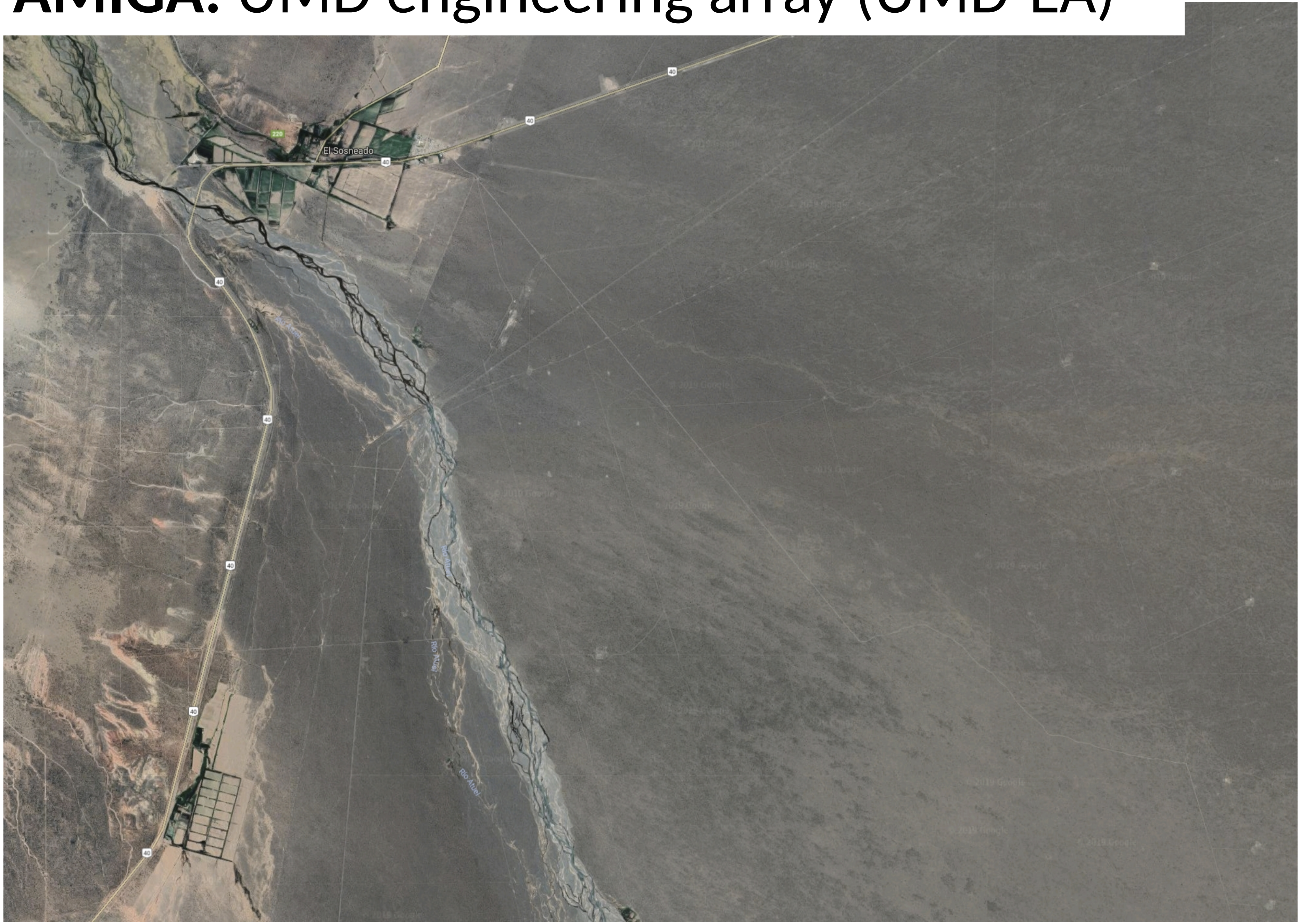
2007: first prototype @ CAC

2008: first electronics boards



2009: first 5m^2 umd in the field

AMIGA: UMD engineering array (UMD-EA)



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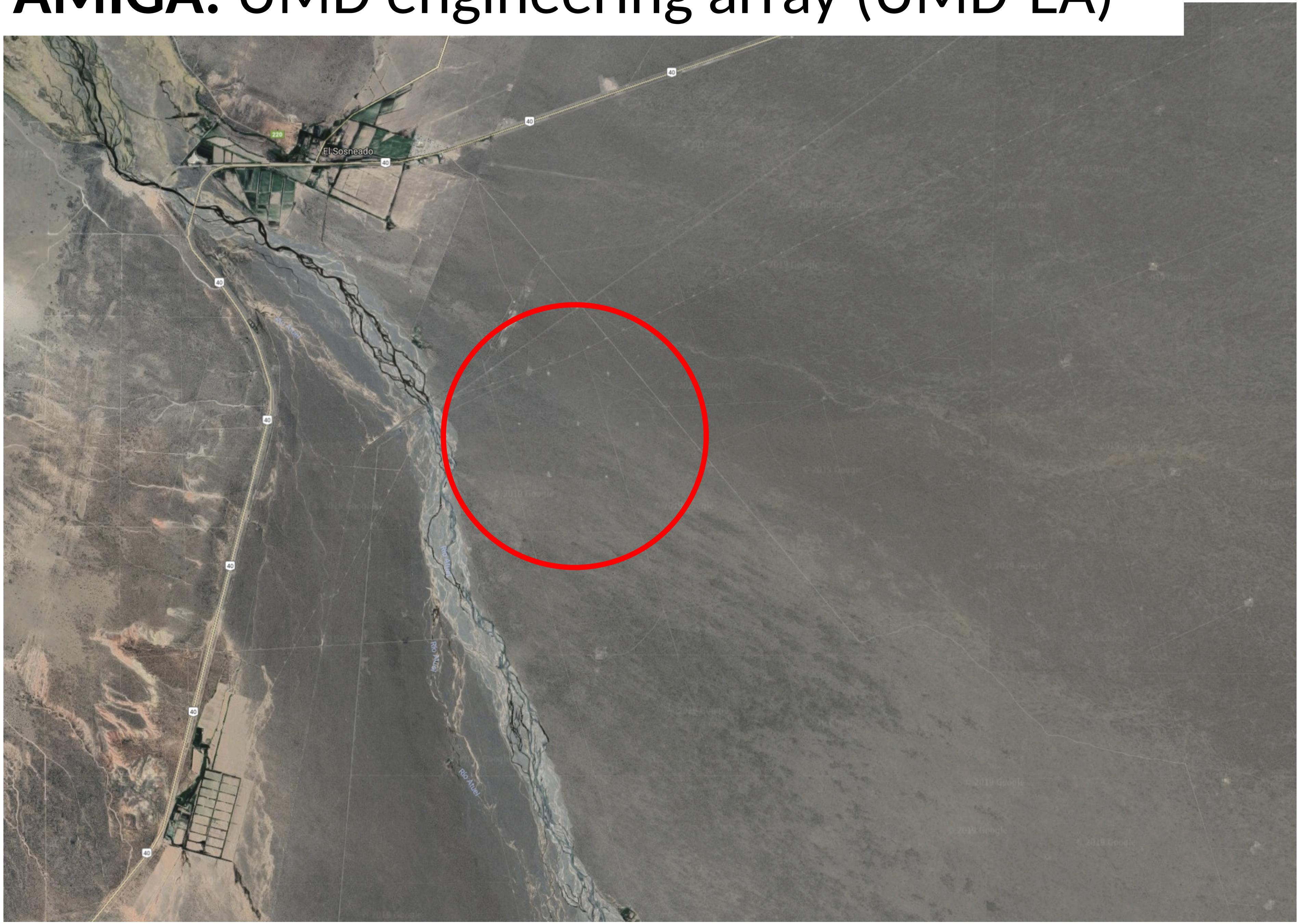

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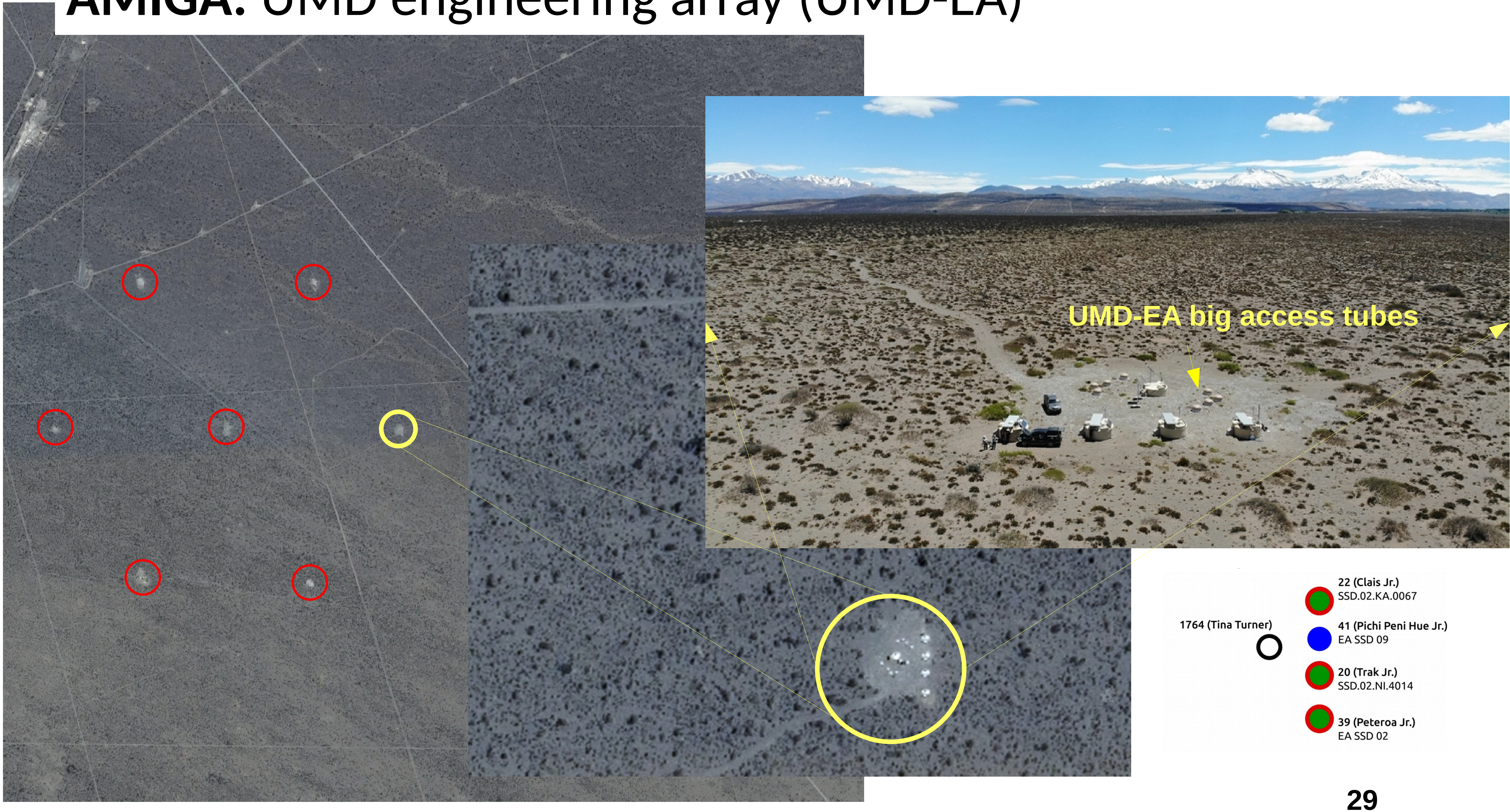
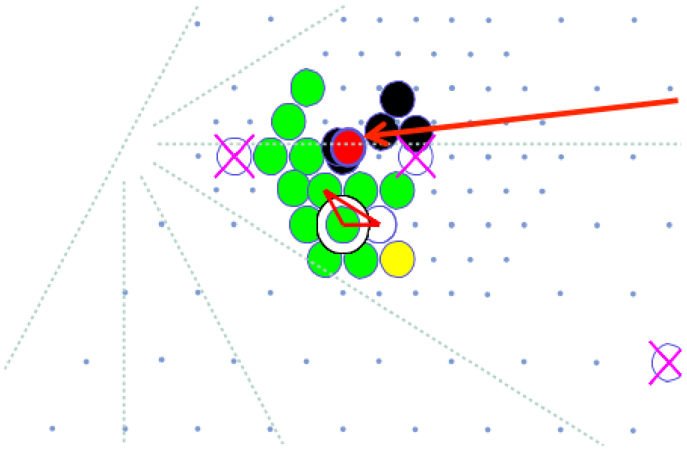


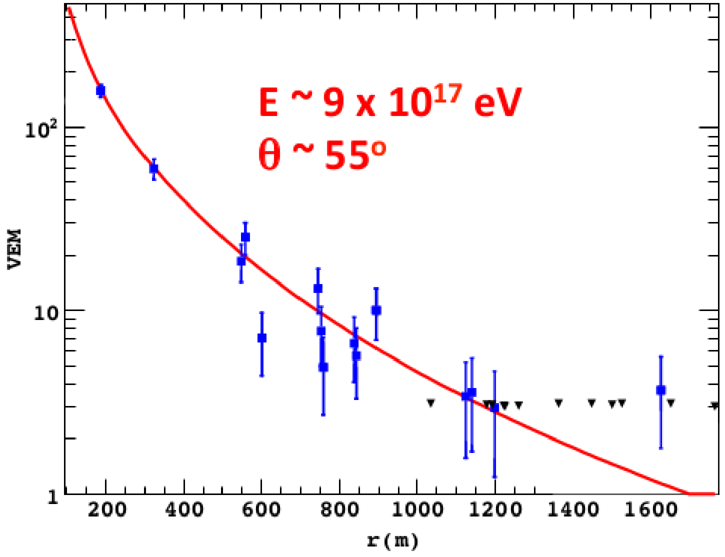
AMIGA: UMD engineering array (UMD-EA)

THE VERY FIRST T3: FRIDAY 2012/02/10 @ 21:49:55 hs

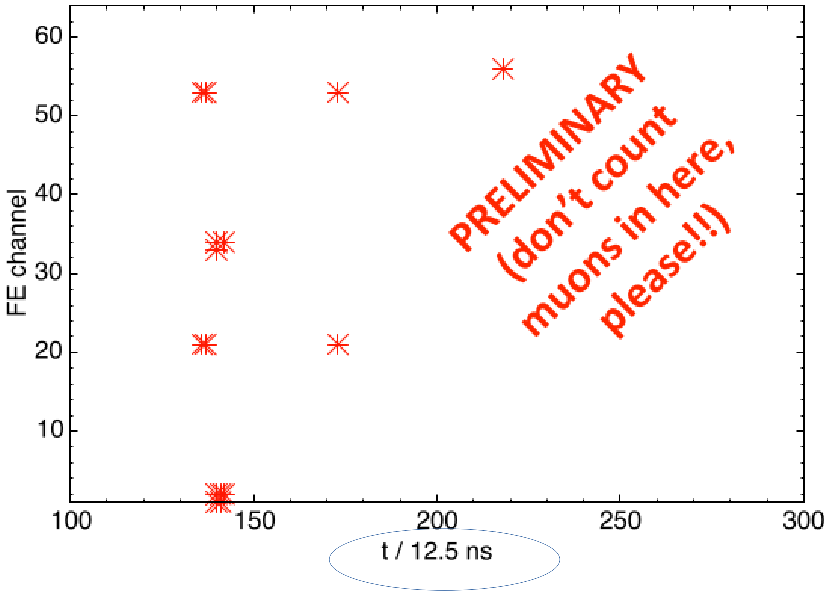


Corrientes: SD+MD

The first synchronized shower event



E ~ 9 x 10^{17} eV
θ ~ 55°

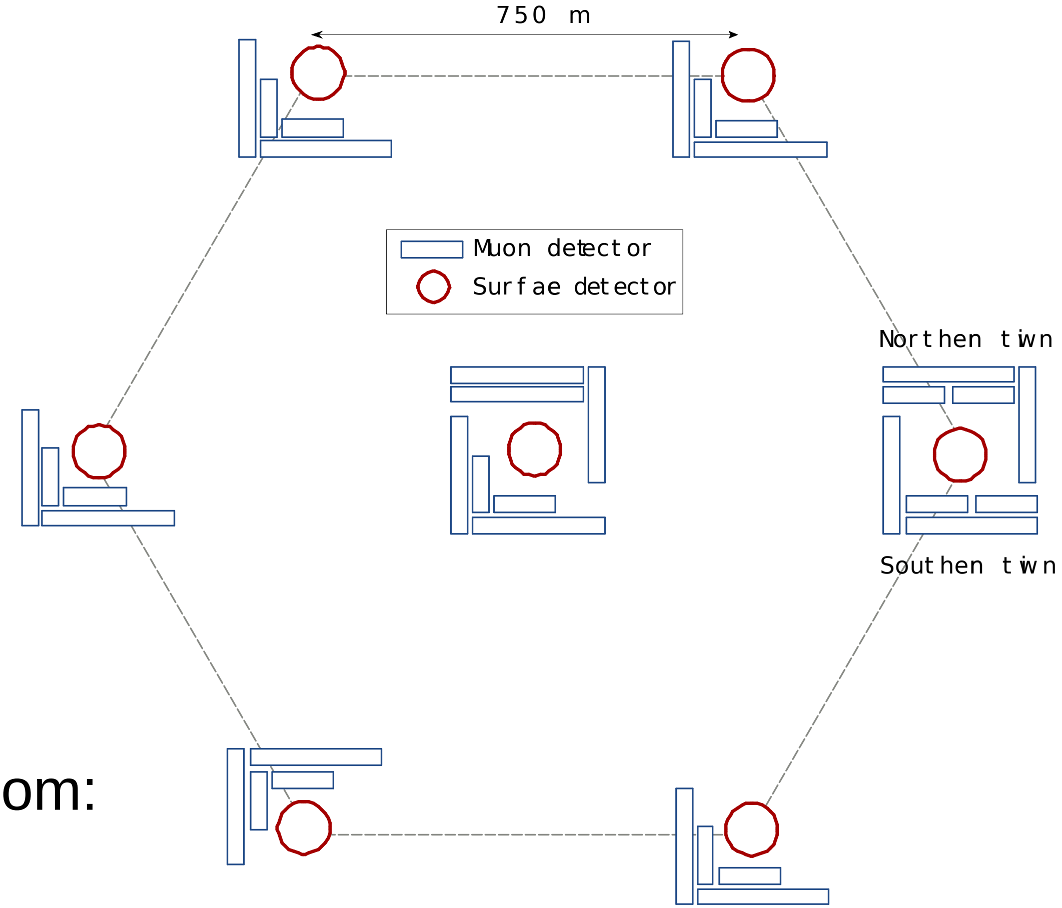


PRELIMINARY
(don't count
muons in here,
please!!)

First MD+SD hybrid event!

AMIGA: UMD engineering array (UMD-EA)

Engineering Array (UMD-EA):
Operated until Nov. 2017



UMD-EA served for:

1) Validation of detection system (End-to-End)
2) Optimization of optical devices (PMT → SiPM)
3) Optimization of electronics (ASICs)
4) Optimization of dynamic range (2 extra analog channels)

Physics observables are basically extracted from:

- **signal size → number of muon**
- **signal timing → timing of muon**

UMD-EA: from raw binary traces to muons

Highly **segmented** scintillators: 64 per unit

Binary traces in raw (real) events

Sampling @ 3.125 ns

time	Signal in 32 strips
0	00000000000000000000000000000000
⋮	
494	00000000000000000000010000000000
495	00010000000010000000010000000000
496	00010000000010000000010000000100
497	00010000000010000000010000000000
498	00000000000010000000010000000000
499	00000000000010000000010000000000
500	00000000000000000000010000000000
501	00000000000000000000010000000000
⋮	
1024	00000000000000000000000000000000

25 ns

3 muons ("111" or "101" minimal pattern required) + 1 noise

UMD-EA: efficiency and resolution

Efficiency
Resolution } based on { → units of different areas ($5 m^2$ & $10 m^2$)
→ units of identical areas ($30 m^2$ Vs $30 m^2$)

Relative efficiency

Ratio of counts per unit $$r = \frac{\epsilon_1}{\epsilon_2} \cdot \frac{a_1}{a_2}$$

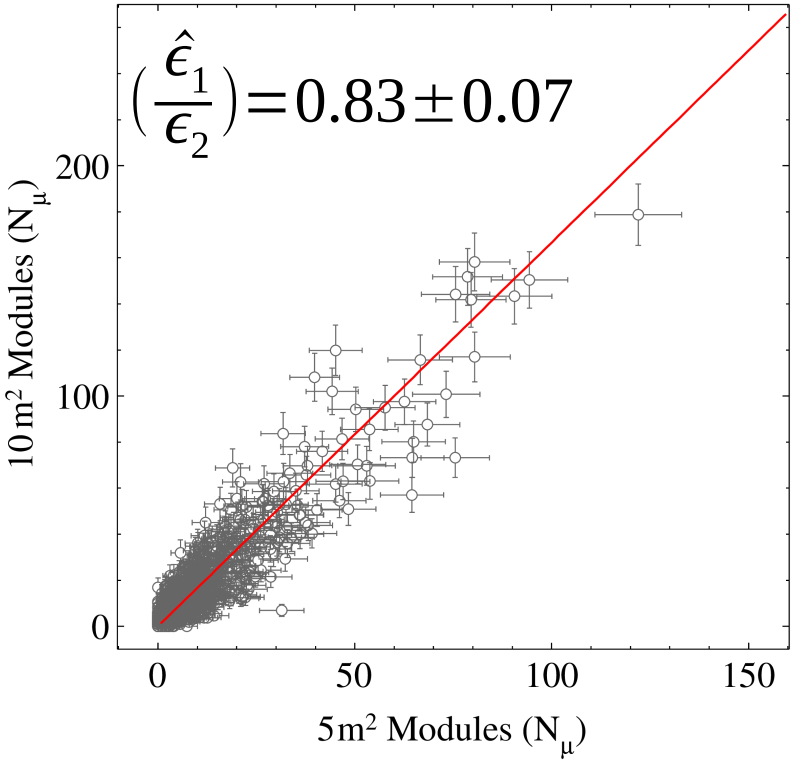
where ϵ_i , a_i efficiency and area

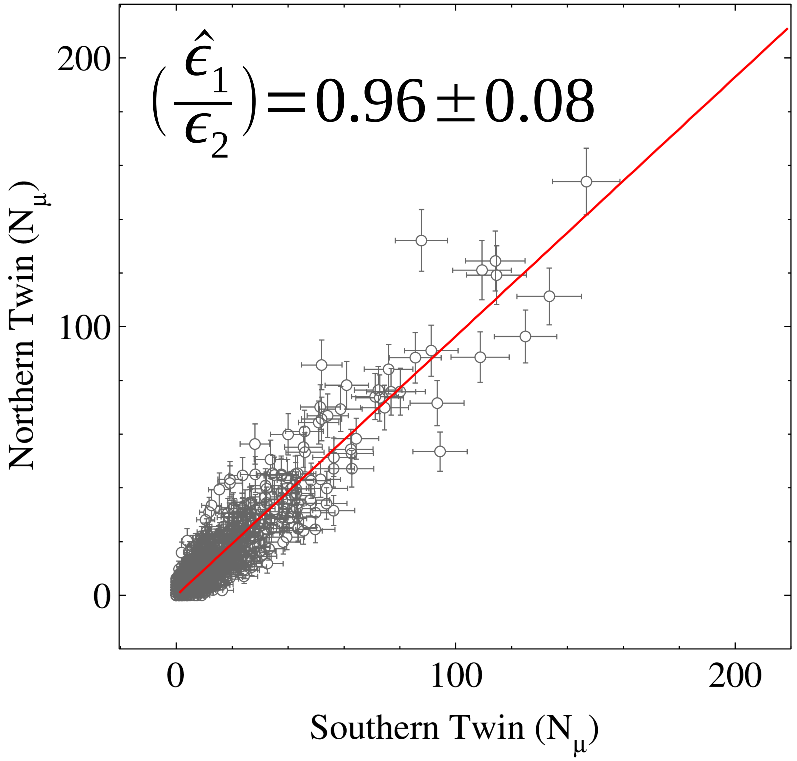
$$\Rightarrow \left(\frac{\hat{\epsilon}_1}{\epsilon_2} \right) = \frac{a_1}{a_2} \cdot \frac{\langle N_2 \rangle}{\langle N_1 \rangle}$$

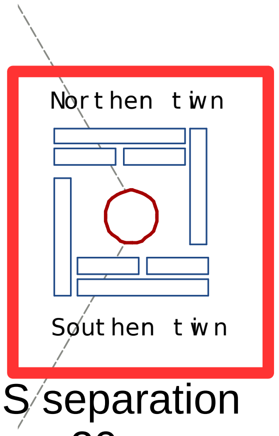
Rel. eff. estimator

Twin **detectors:**

$30 m^2$ North + $30 m^2$ South of same WCD highly segmented (4+4 units)







N-S separation
~ 20 m

UMD-EA: efficiency and resolution

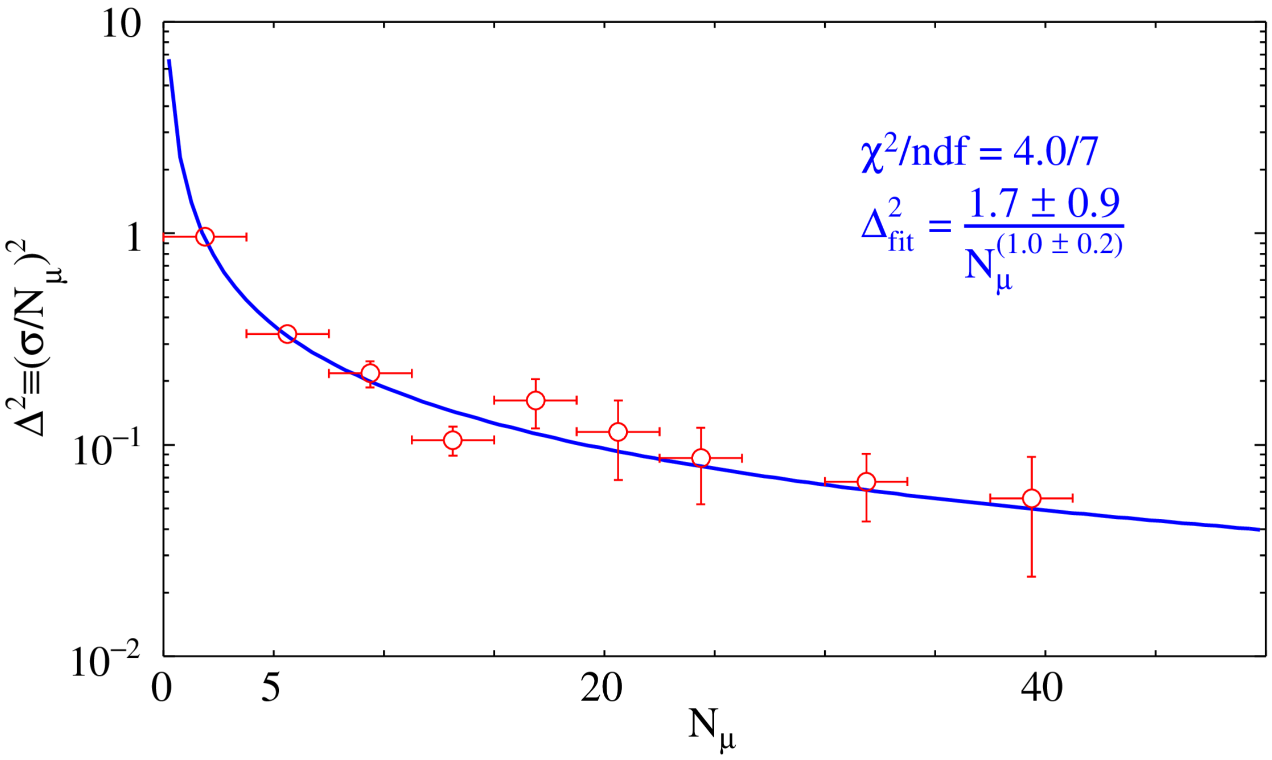
Efficiency
Resolution } based on {
→ units of different areas ($5m^2$ & $10m^2$)
→ units of identical areas ($30m^2$ Vs $30m^2$)

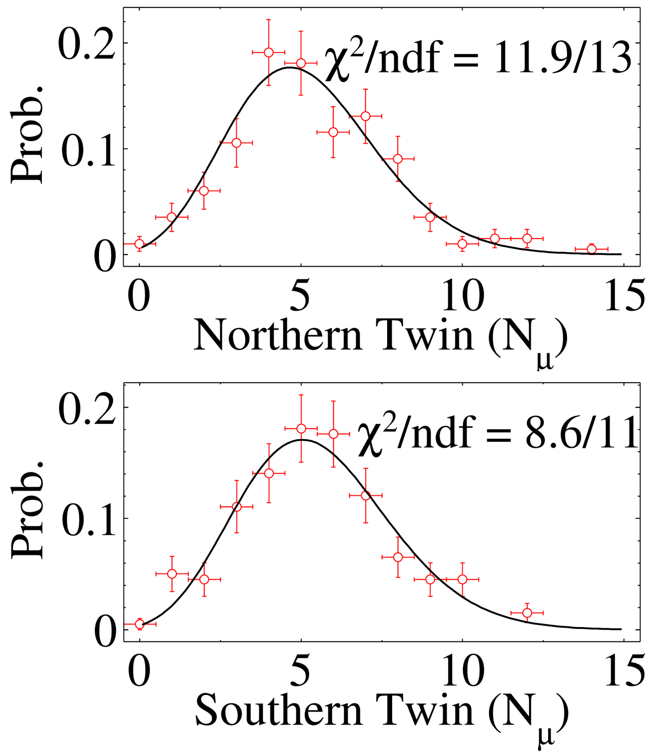
Resolution ⇨ **Estimator**

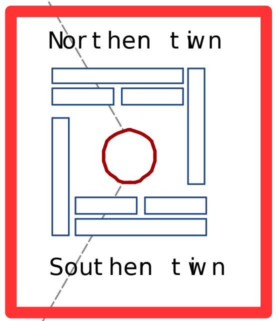
Square ratio of mean and variance

$$\left(\frac{\sigma}{\langle N\rangle}\right)^2 \Rightarrow \left(\frac{\hat{\sigma}}{\langle N\rangle}\right)^2 = 2\left(\frac{N_1 - N_2}{N_1 + N_2}\right)^2$$

Twin **detectors:**
$30m^2$ North + $30m^2$ South of same WCD highly segmented (4+4 units)





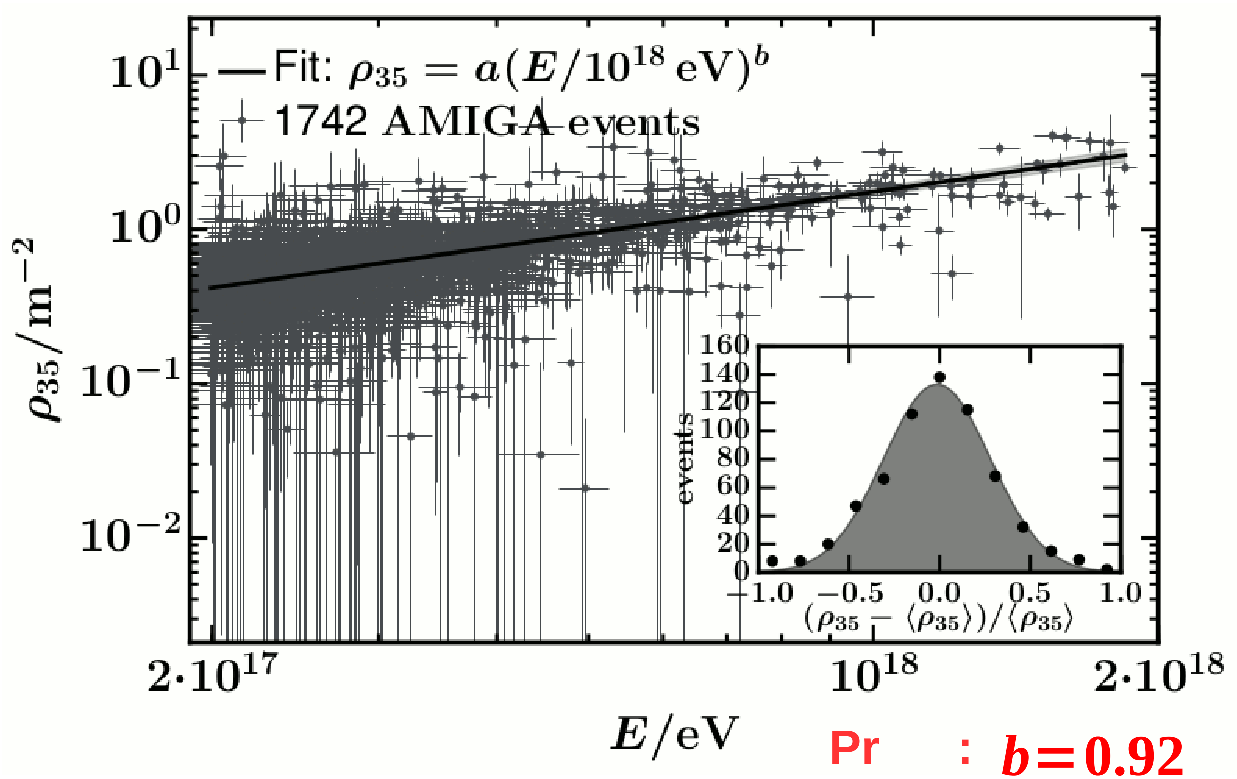


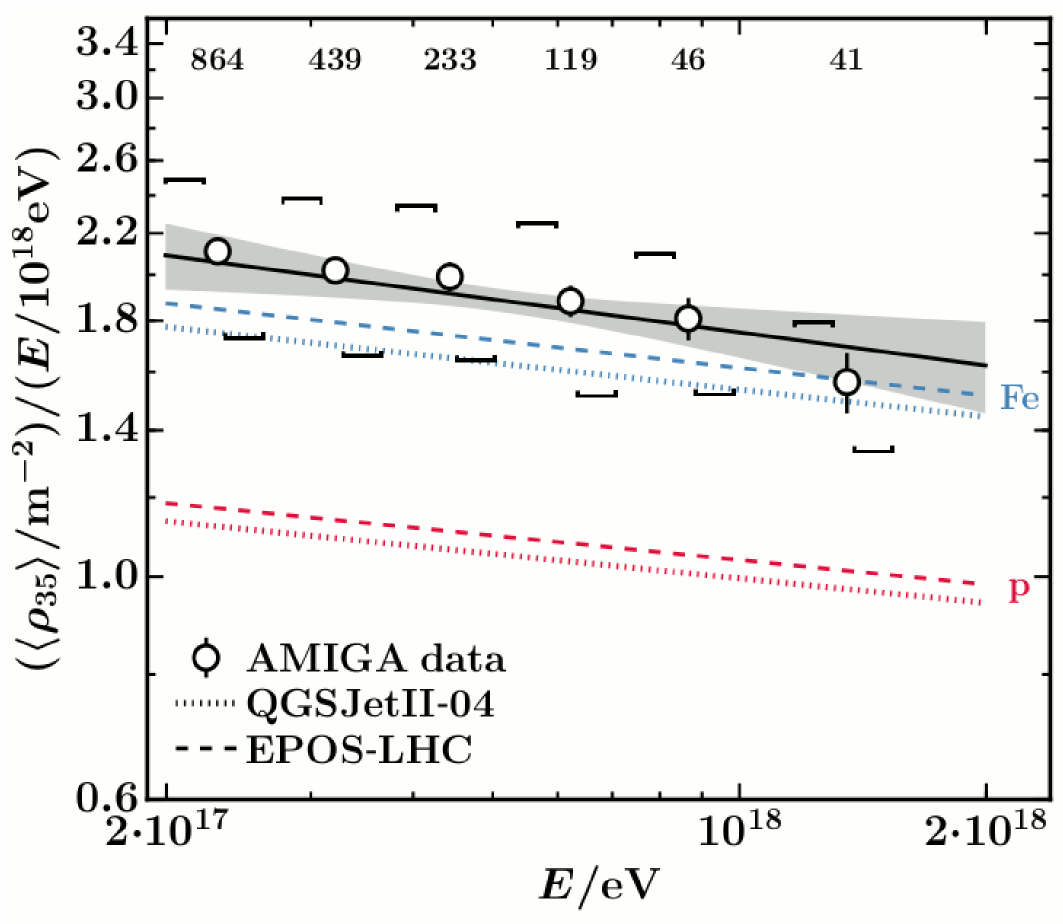
N-S separation
~ 20 m

UMD-EA: muon densities $\Rightarrow \rho_{35}(E)$

First direct measurement of the muon densities at energies $10^{17.3}$ eV < E < $10^{18.3}$ eV

- ✔ Geometry & Energy from SD alone
- ✔ Event core contained in UMD hexagon
- ✔ Zenith < 45°





$$\rho_{35}(E) = a \cdot \left(E/10^{18}\,eV\right)^b$$

Pr : $b = 0.92$

Fe : $b = 0.91$ → **8% (EPOS) – 14% (QGSJet) below measurements**

Data : $b = 0.89 \pm 0.04(stat) \pm 0.04(sys)$

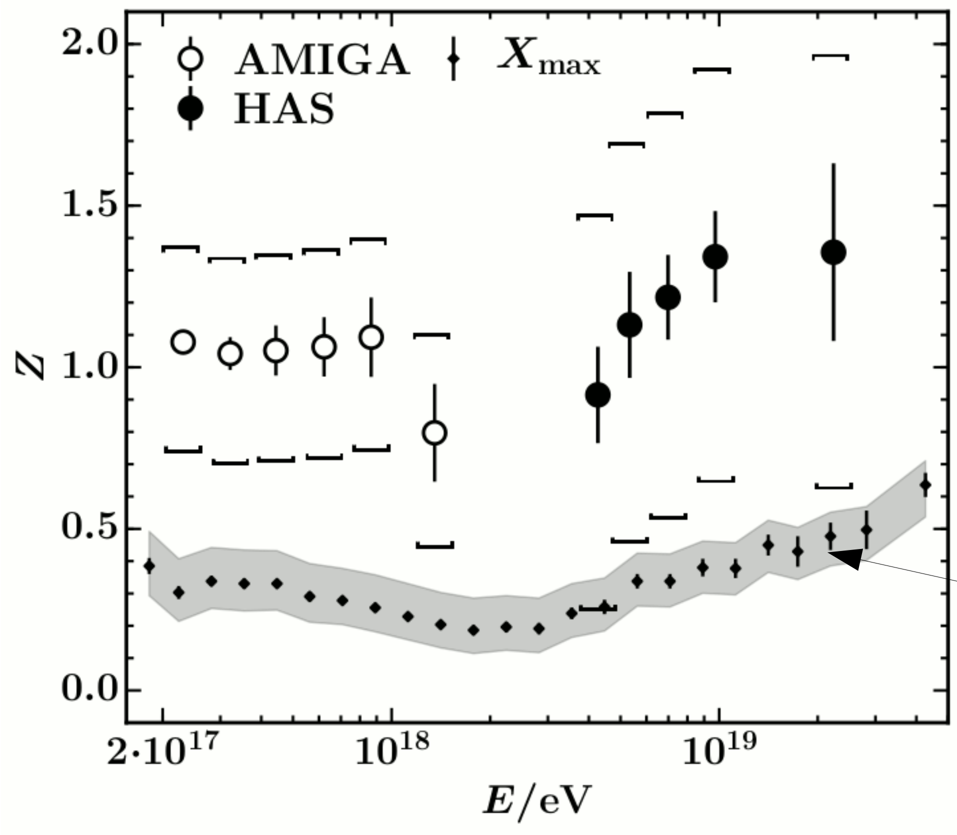
UMD-EA: comparison with other Auger measurements I

$$z_{\alpha}=\frac{\langle \ln(\alpha)\rangle-\langle \ln(\alpha)\rangle_{p}}{\langle \ln(\alpha)\rangle_{Fe}-\langle \ln(\alpha)\rangle_{p}}$$

$\Rightarrow$ same composition sensitive observable for

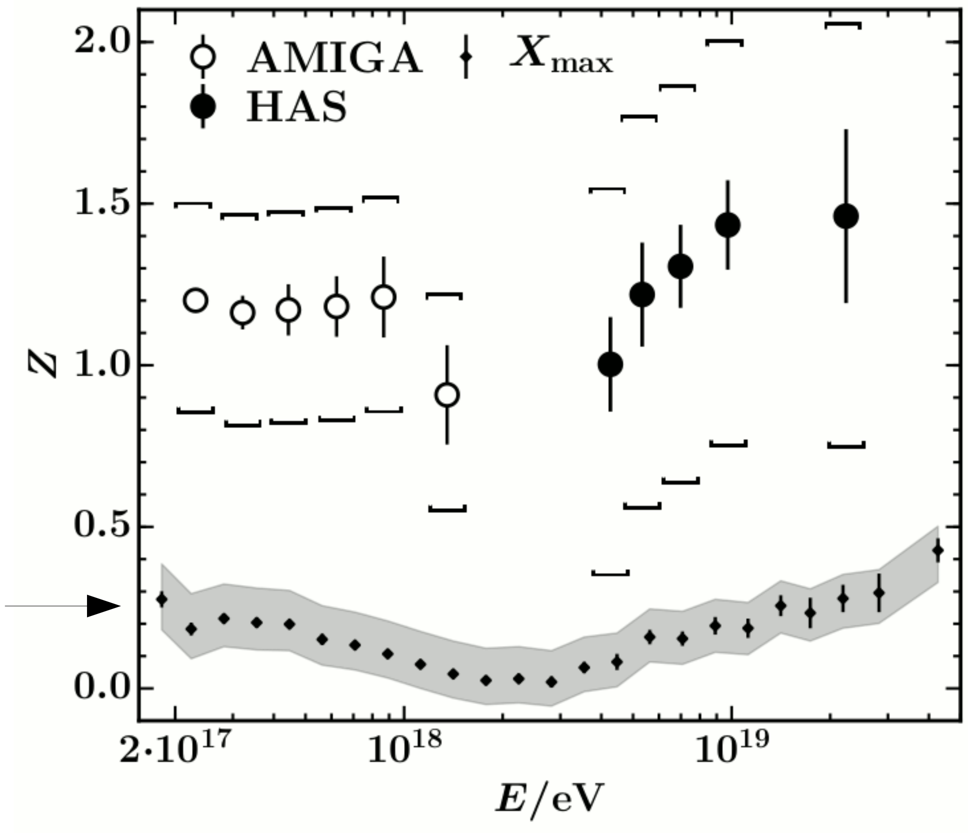
- SD → R_{μ}
- FD → X_{max}
- UMD → ρ_{35}

EPOS



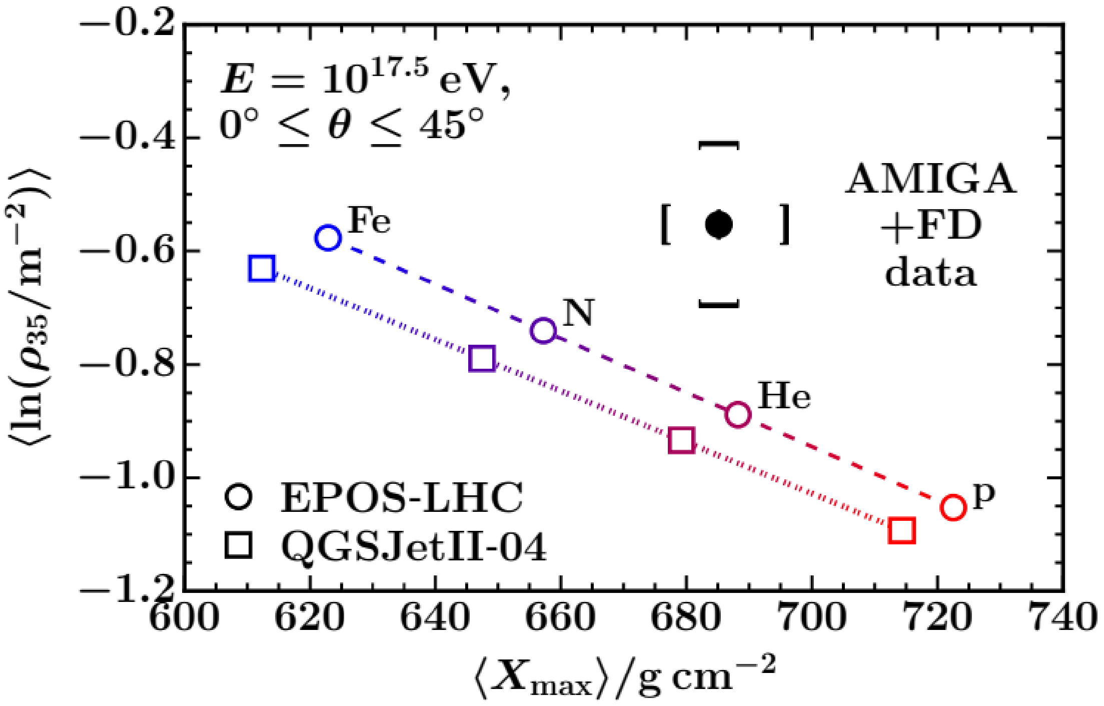
$$z_{X_{max}}=\frac{\langle \ln(A)\rangle}{\ln(56)}$$

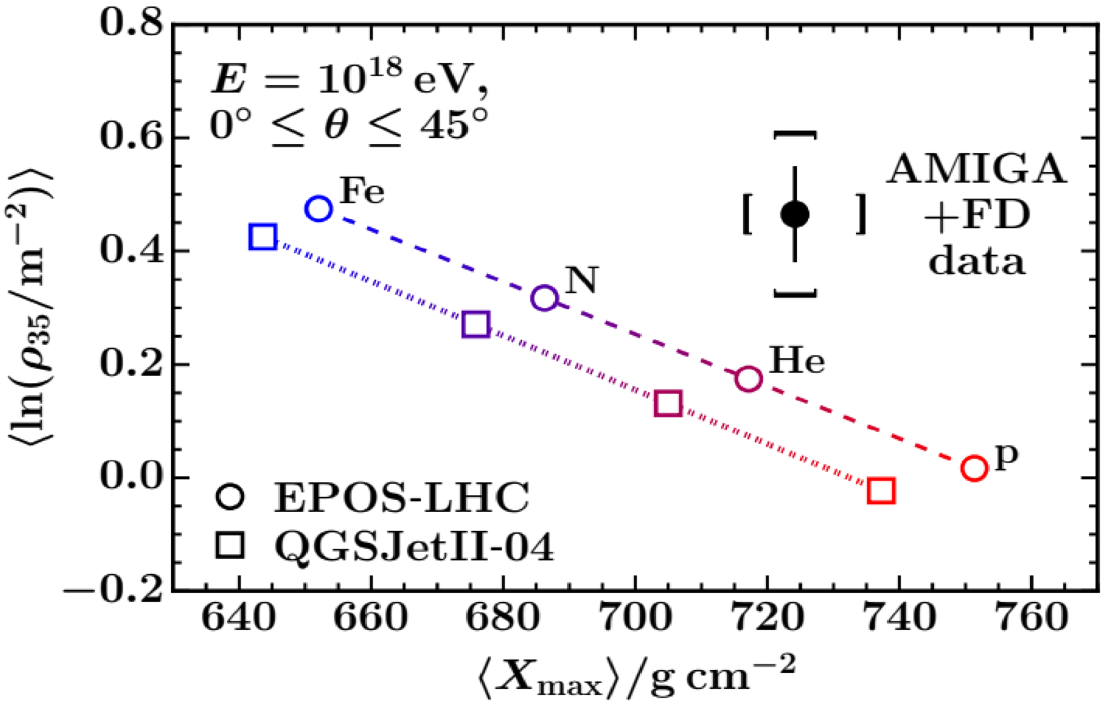
QGSJet



UMD-EA: comparison with other Auger measurements II

Bi-parametric analysis: X_{max}, ρ_{35}





muon deficits in LHC-tuned hadronic models

@$10^{17.5}$ eV

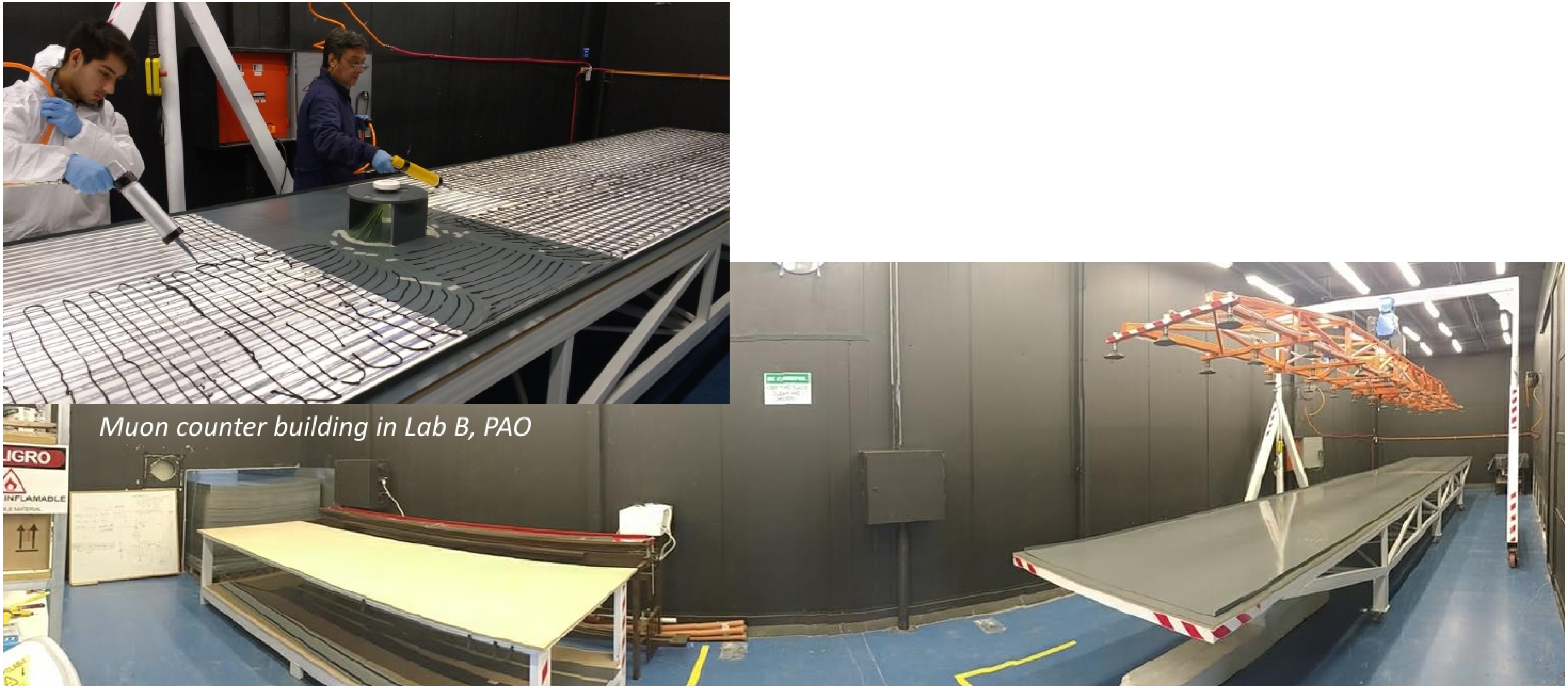
EPOS	**38%**
QGSJet	**50%**

@$10^{18.0}$ eV

EPOS	**38%**
QGSJet	**53%**

4. AMIGA final design & production

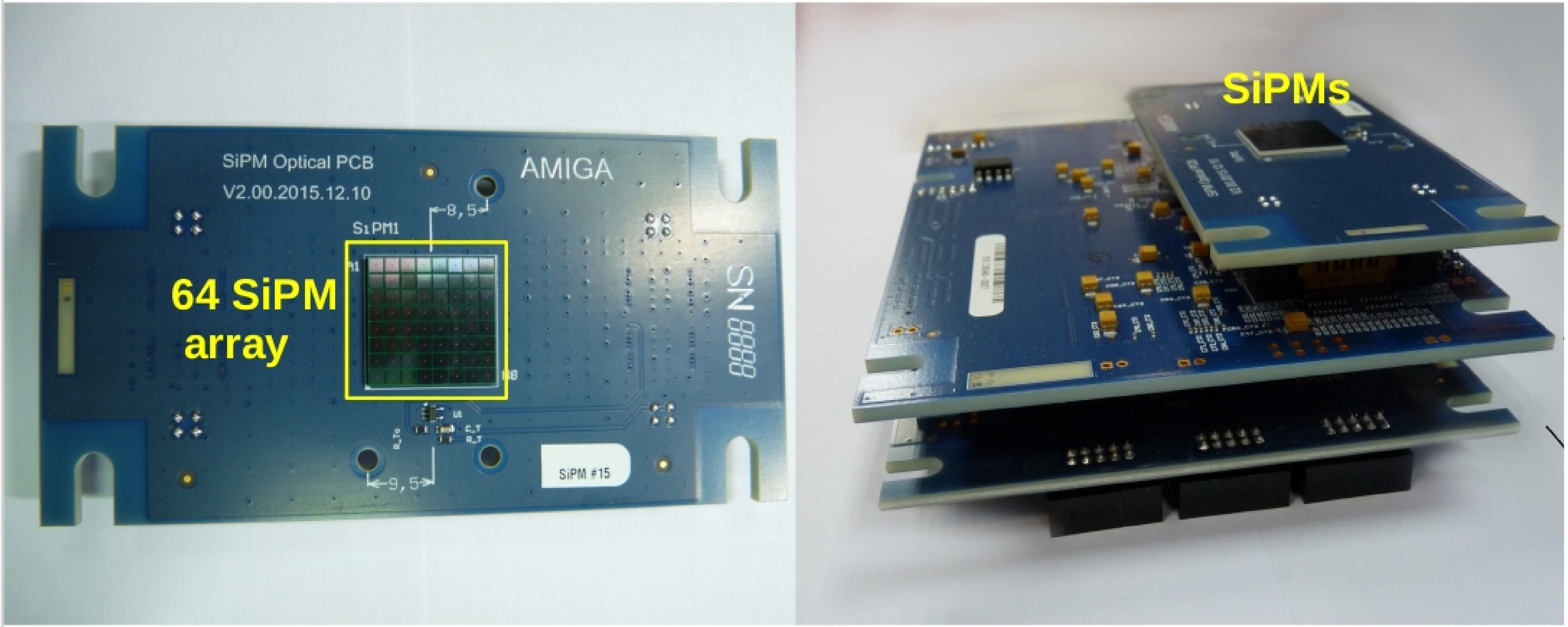
AMIGA: module assembling @ PAO



Muon counter building in Lab B, PAO

AMIGA: electronics with Silicon Photo-Multipliers (SiPMs)

eKit (buried) = SiPM board + front-end board + acquisition board



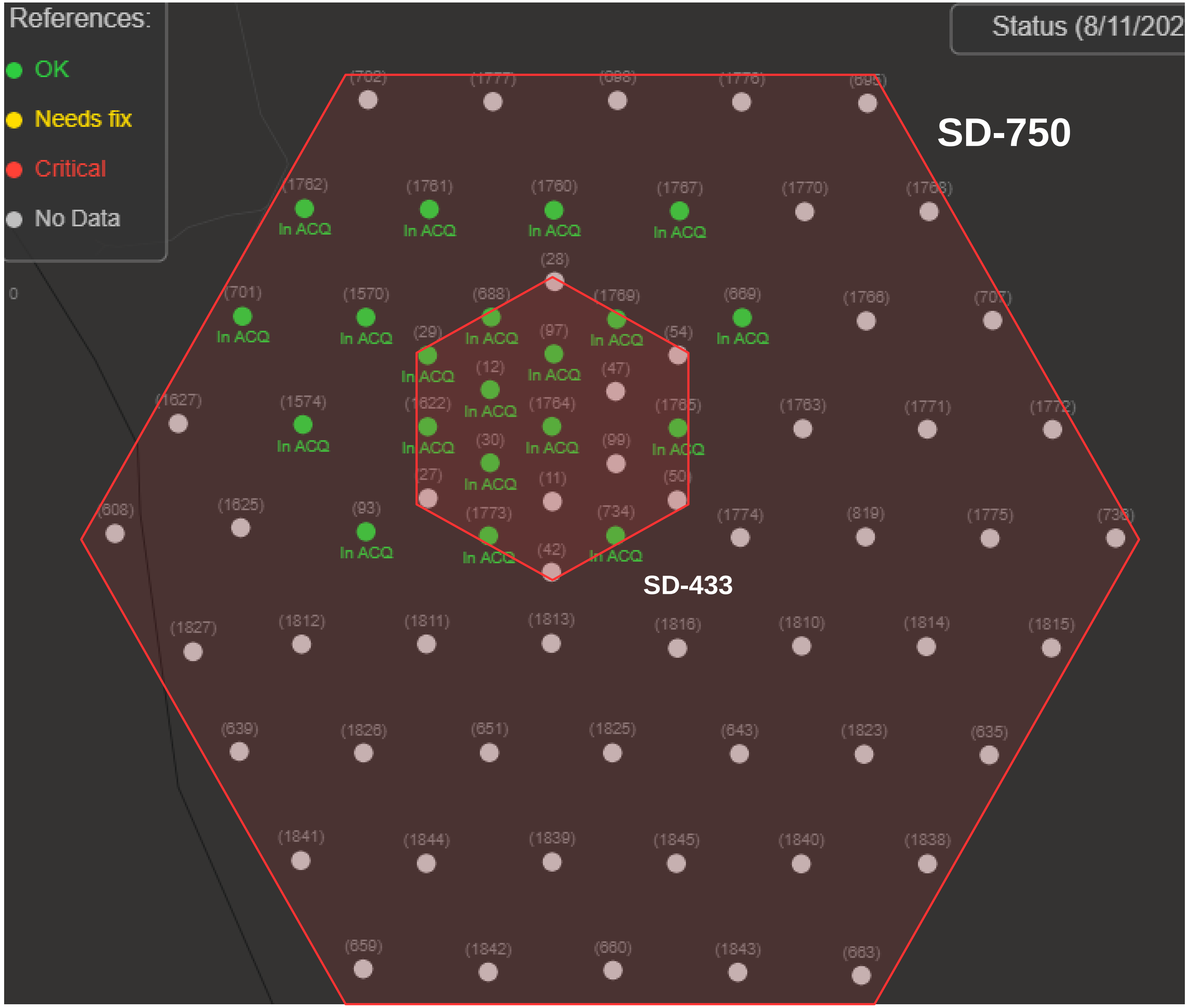
Two acquisition modes:

Binary (as in the EA) + <u>Integrator</u> (new!) channels to increase dynamic range of the UMD modules

AMIGA: module deployment

Production rate: 2 positions (30m^2 detectors) / month

AMIGA: present status (Nov. 2020)



SD-750: 61 positions

SD-433: 12 extra positions

(both SD arrays are complete)

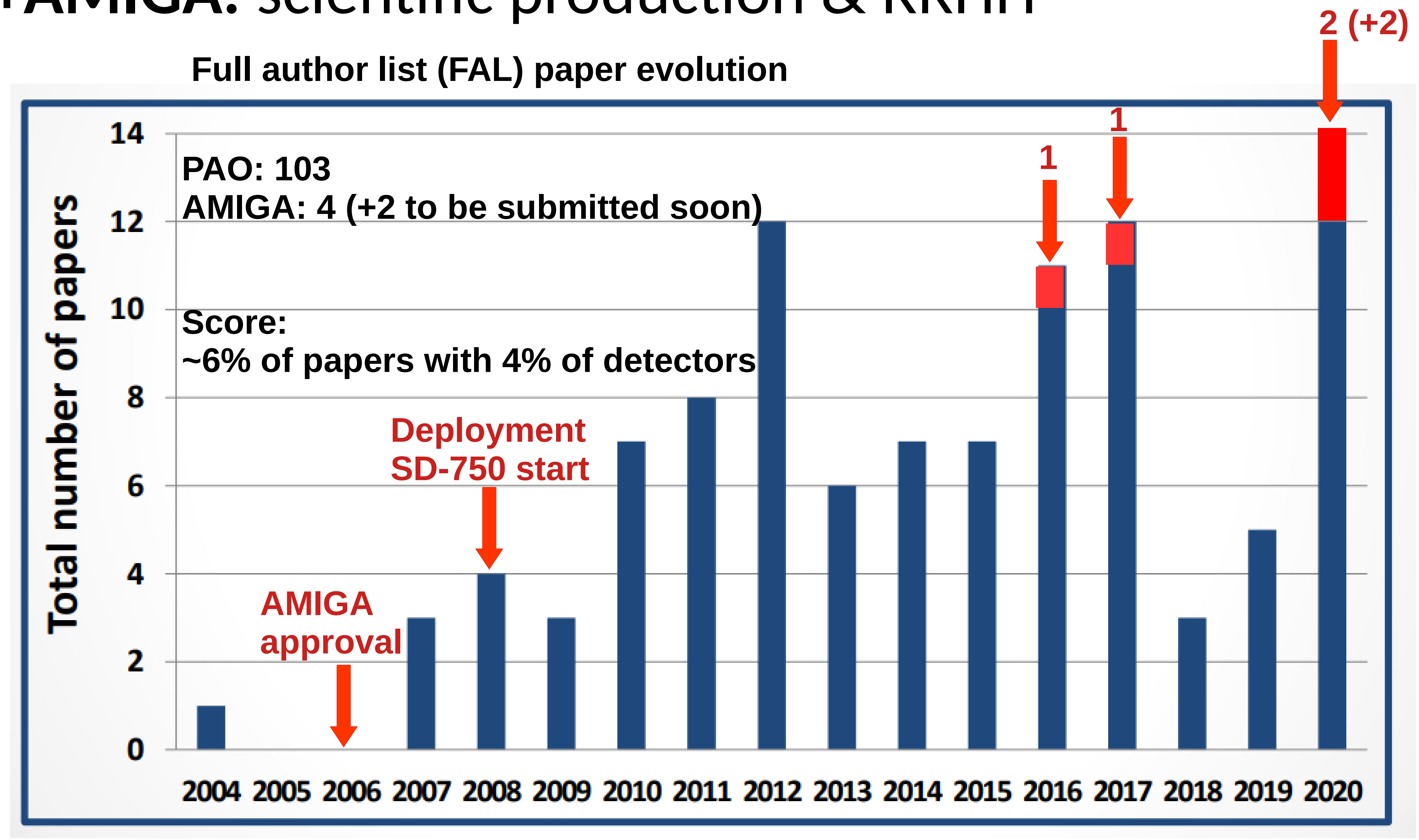
UMD-750: 16 positions in ACQ

UMD-433: 4 positions in ACQ

(but one 433 hexagon complete!)

PAO+AMIGA: scientific production & RRHH

Full author list (FAL) paper evolution



PAO: 103
AMIGA: 4 (+2 to be submitted soon)

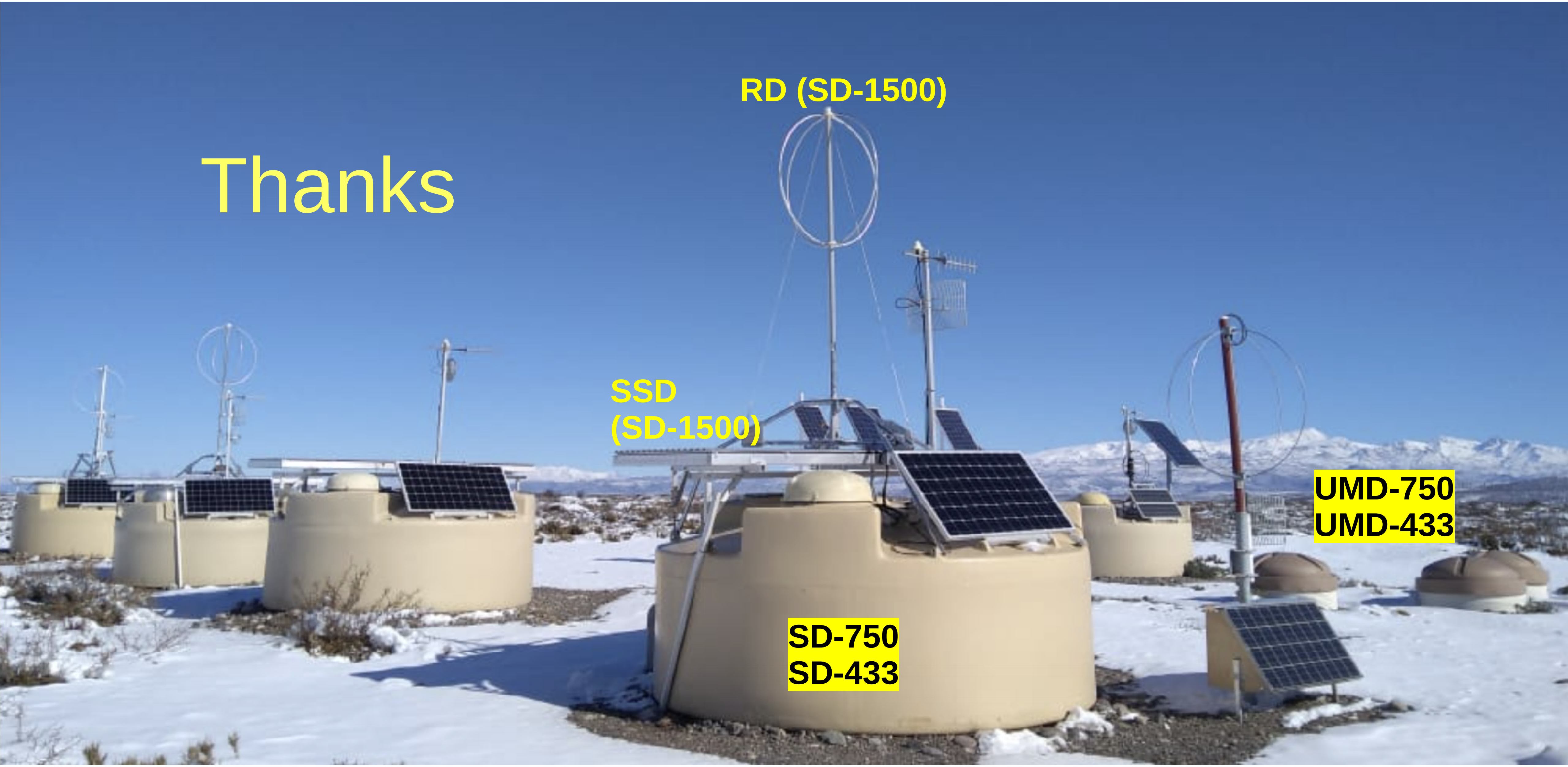
Score:
~6% of papers with 4% of detectors

Deployment
SD-750 start

AMIGA
approval

Up to 2019: 33 researchers, 39 finished PhD (first one in 2001) and 22 on-going PhD

AMIGA in AugerPrime



Thanks

Backup

UMD-EA: systematic uncertainties I

Sources of systematic uncertainty analyzed:

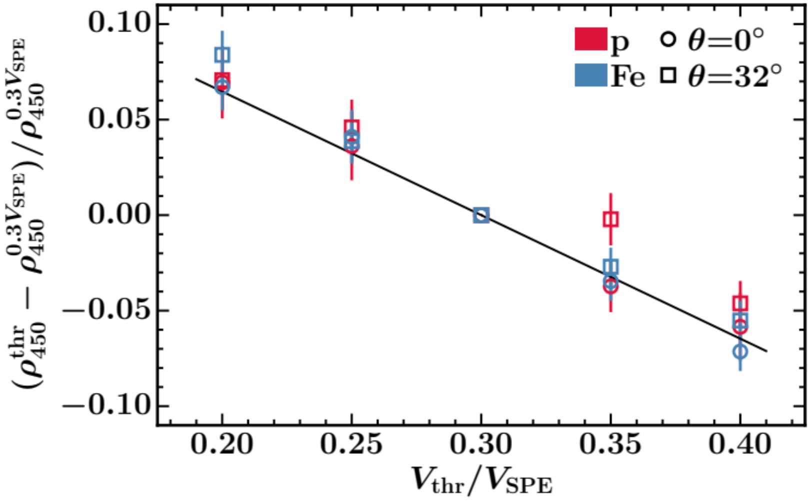
i. Calibration procedure → uncertainty in the “operation” point of each of 2240 electronic channels

ii. Soil density variations → uncertainty in shielding by overburden

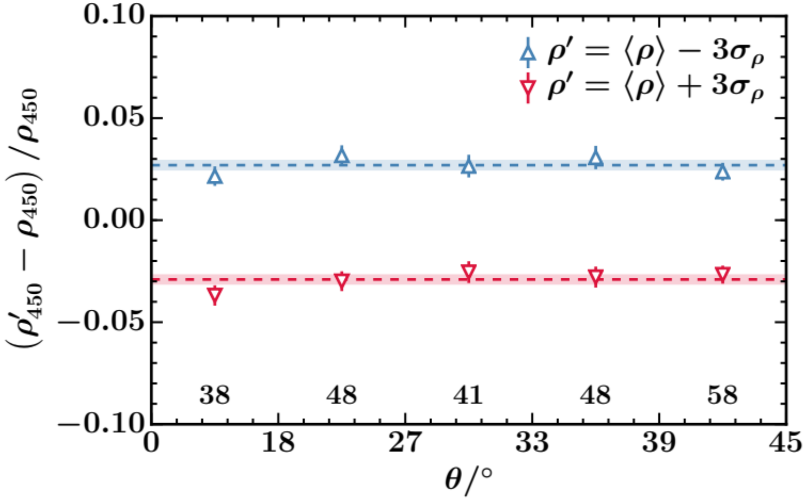
iii. Shape of muon lateral distribution function → slope $\beta(\theta)$ parametrization based on simulations

Simulation based

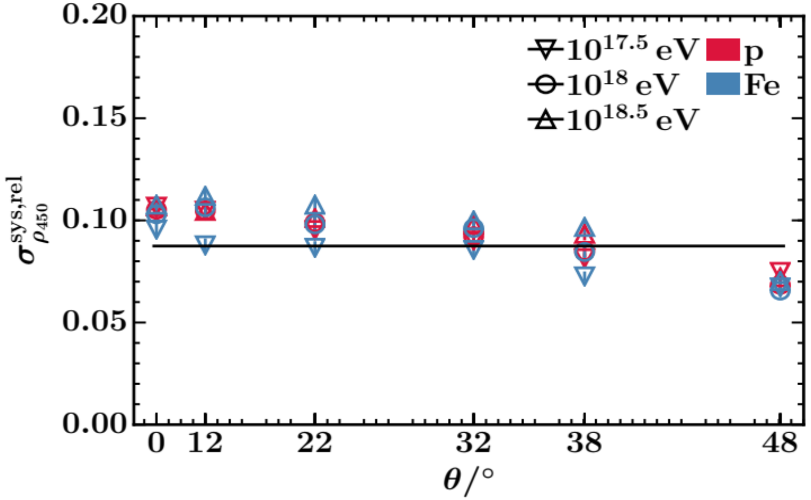
i.



ii.



iii.



σ/ρ_{450}	3.9%	2.8%	8.8%

UMD-EA: systematic uncertainties II

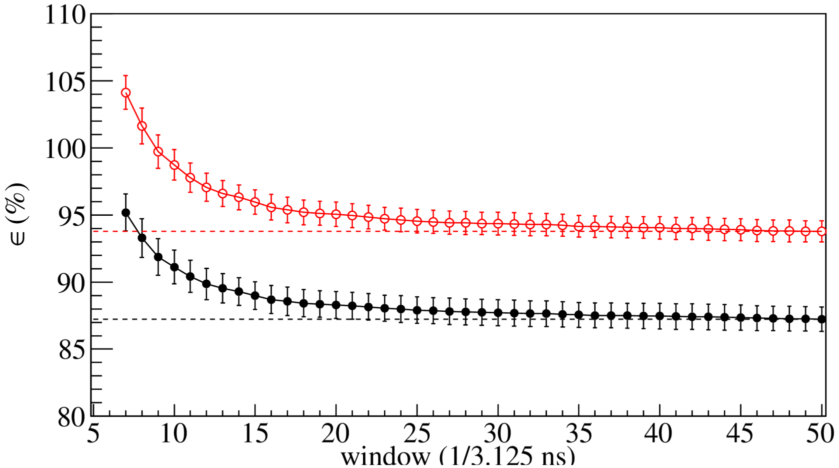
Sources of systematic uncertainty analyzed:

i. Efficiency correction → dependent time width selected to identify signals

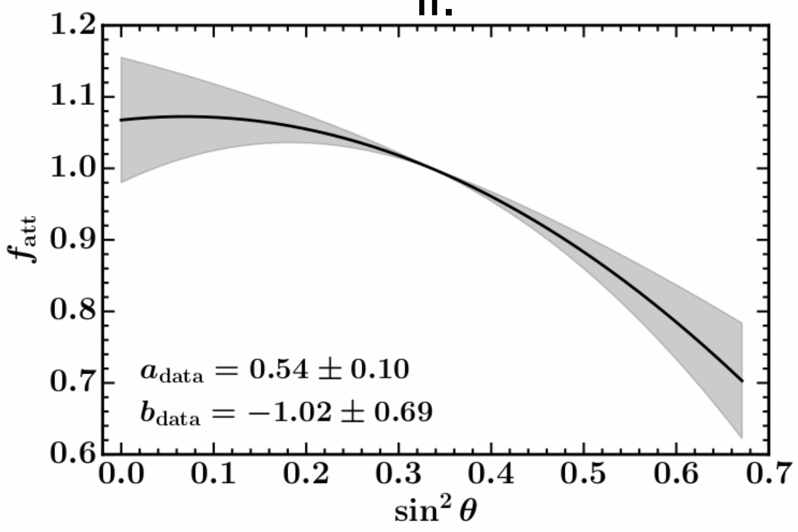
ii. Constant Intensity Cut (CIC) correction → uncertainty in parametrization

Data based

i.



ii.



σ/ρ_{450}	9.9%	2.3%

Total uncertainty:

σ/ρ_{35} 14.3%

Combining spectrum and composition

from simple to complex

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

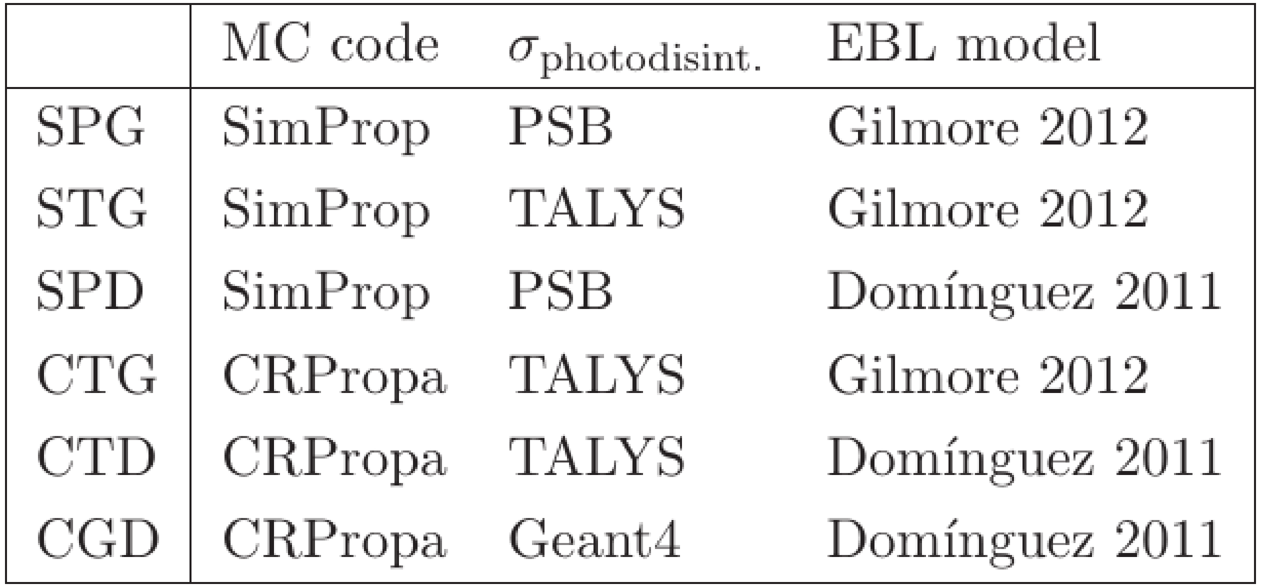
Injection flux:

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

Free parameters:

J_0 R_{cut} γ f_α

Models for propagation



	MC code	$\sigma_{\text{photodisint.}}$	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

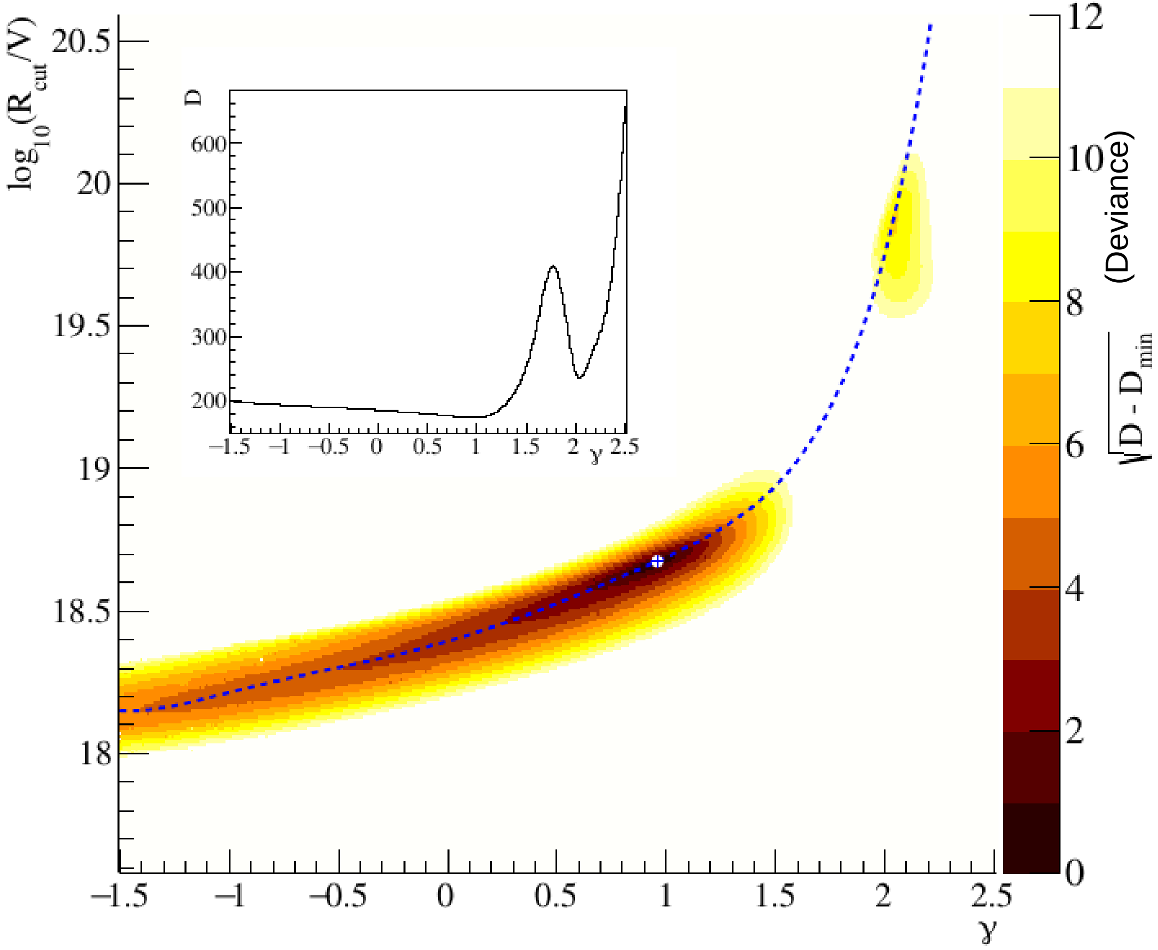
EPOS-LHC

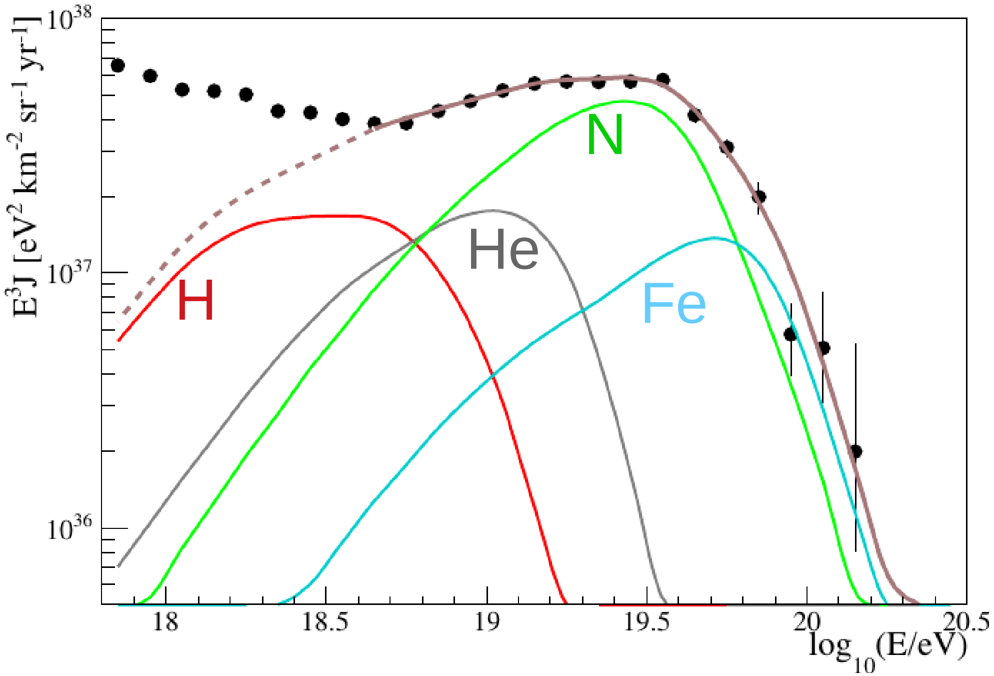
Sybill 2.1

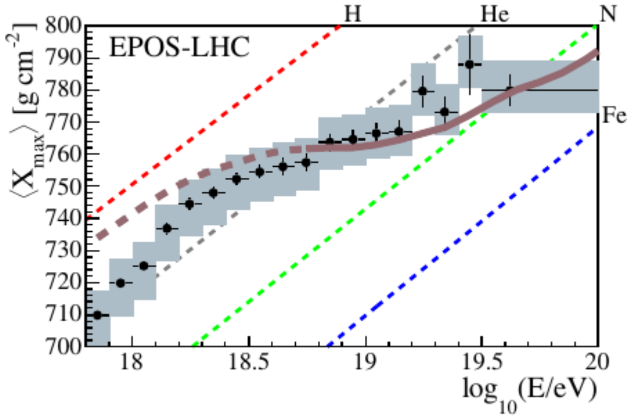
QGSJet II-04

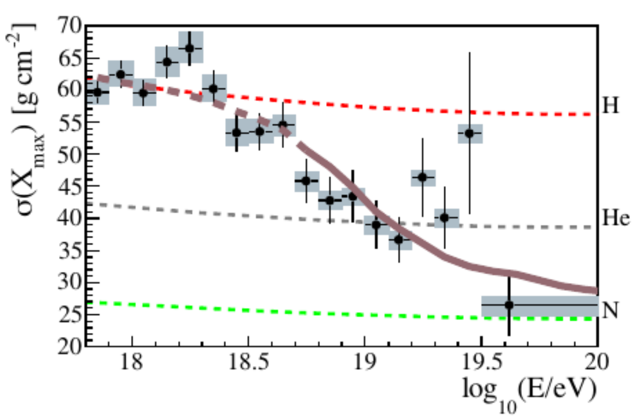
Combining spectrum and composition

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



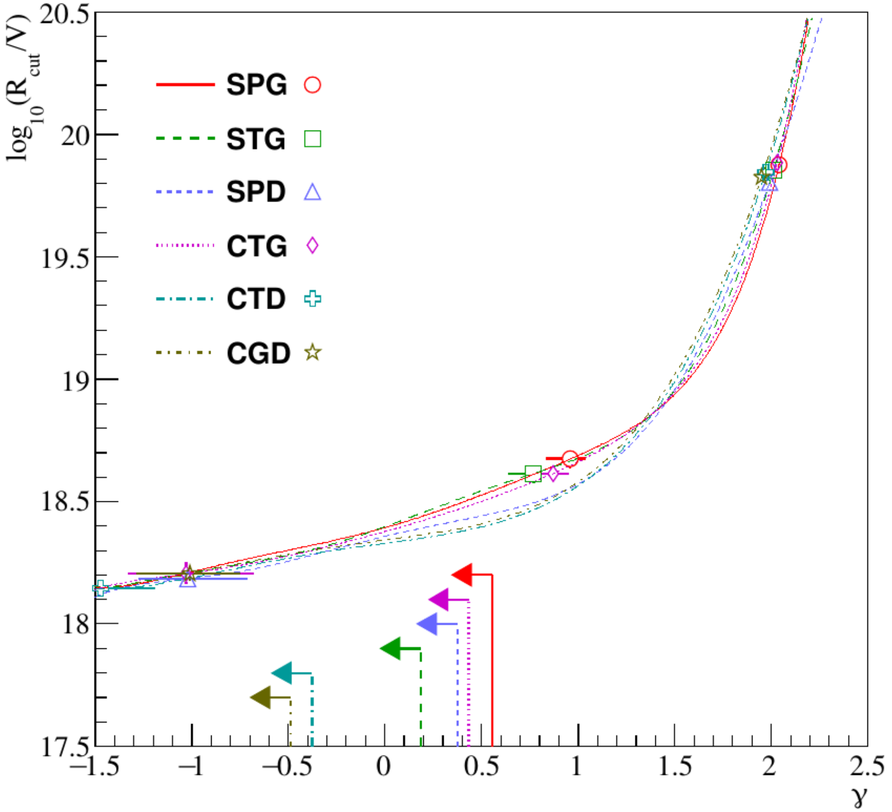






Combining spectrum and composition

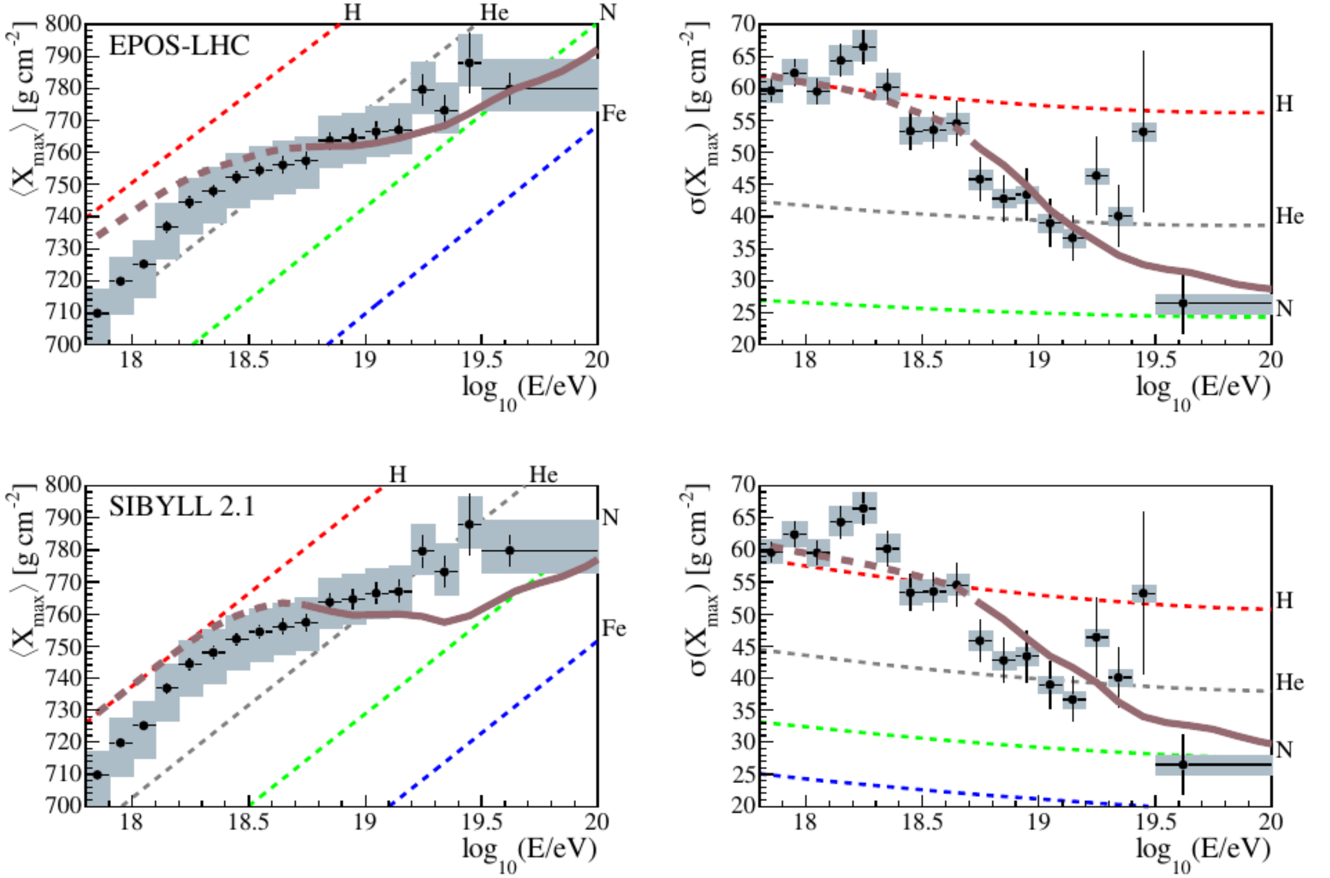
Changing models for propagation



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

Local minimum (spectral index ~ 2) is model independent

Changing hadronic models for EAS



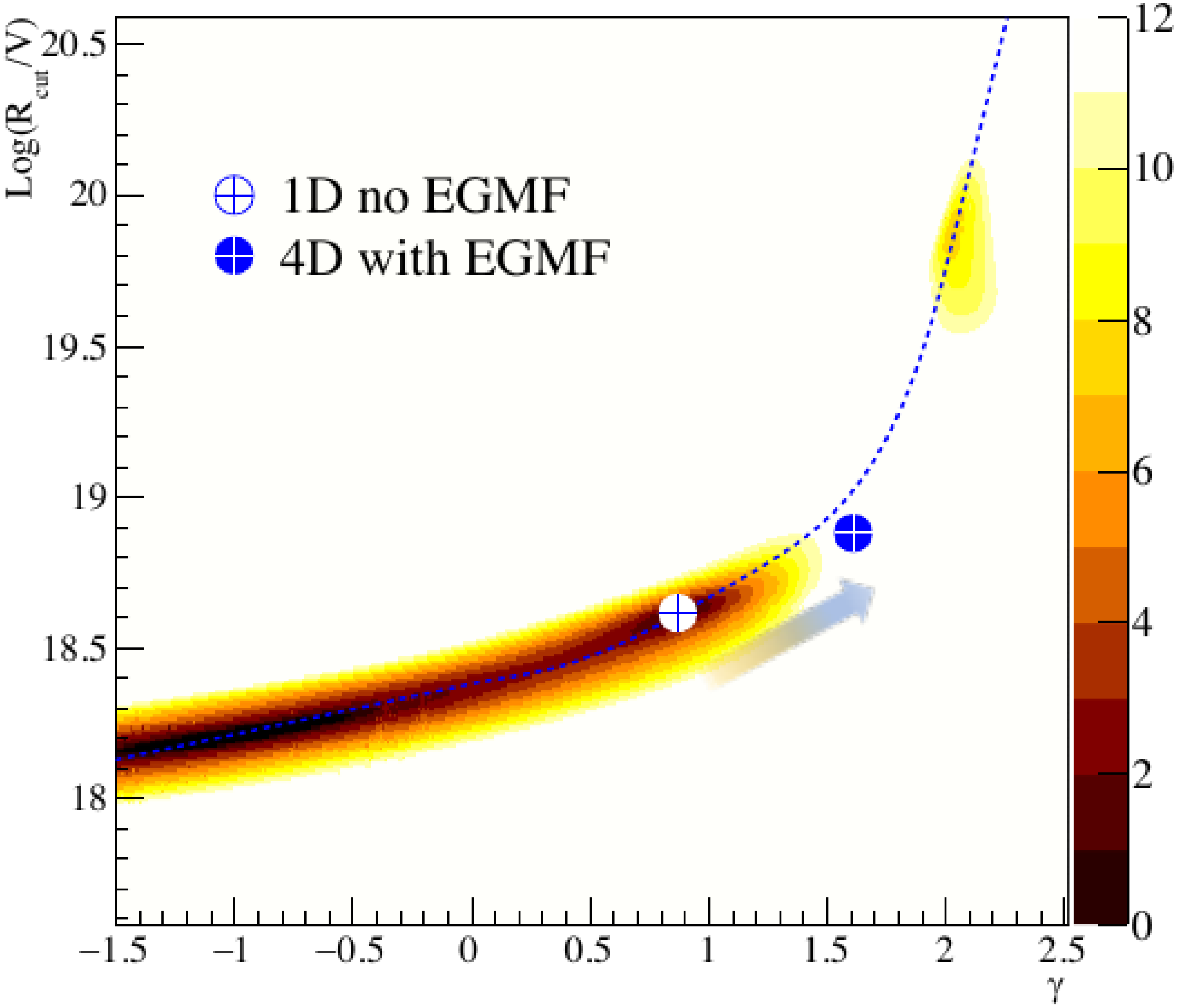
EPOS-LHC **best**

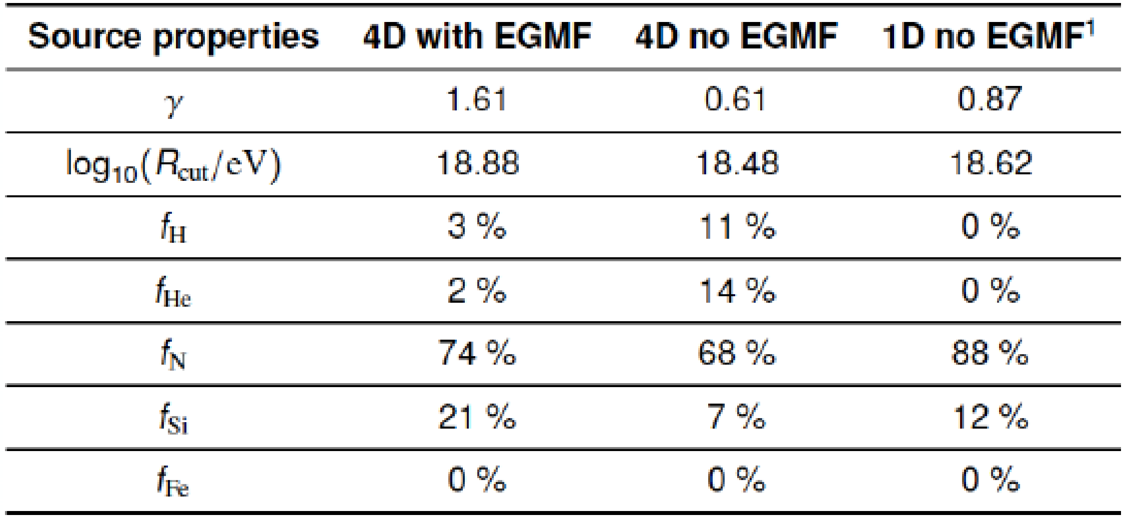
Sibyll2.1

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

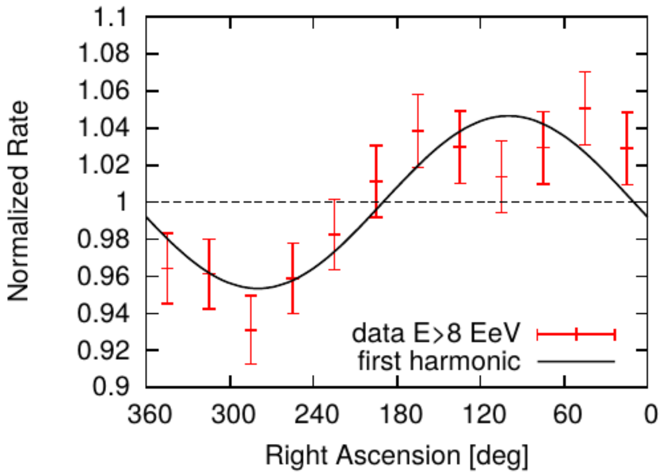
The **magnetic fields** in the intergalactic space needs be taken into account when interpreting data

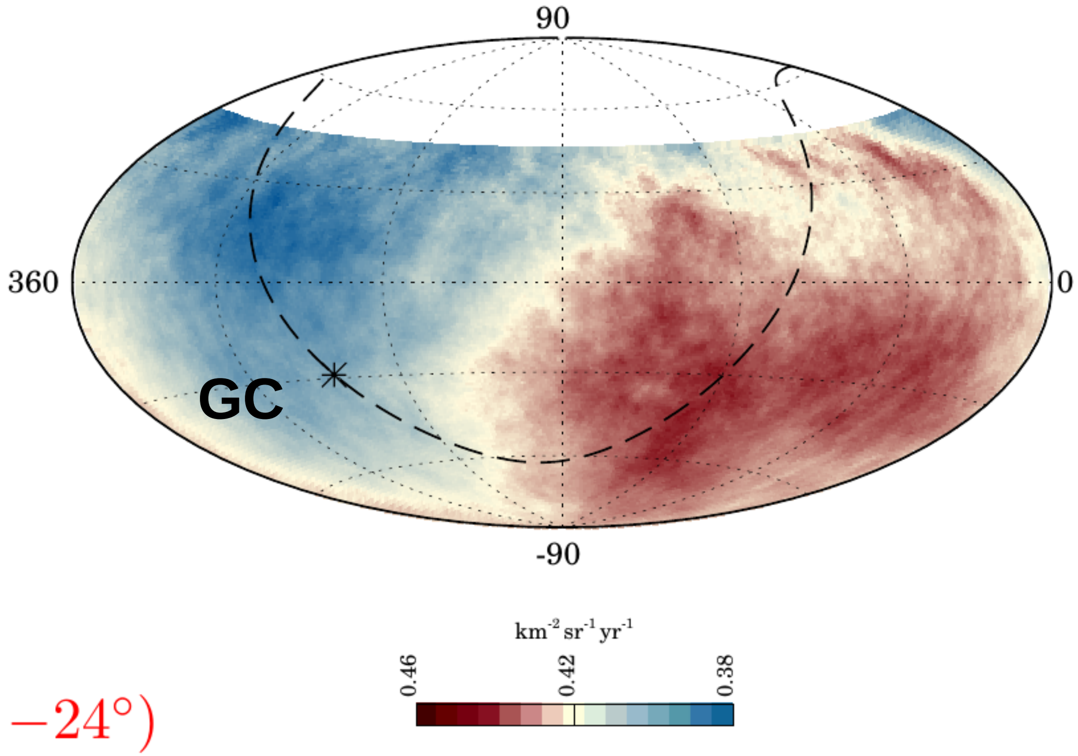
Arrival directions: large scale and moderate energy

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 $(\alpha, \delta) = (100^\circ, -24^\circ)$

Arrival directions: large scale and moderate energy

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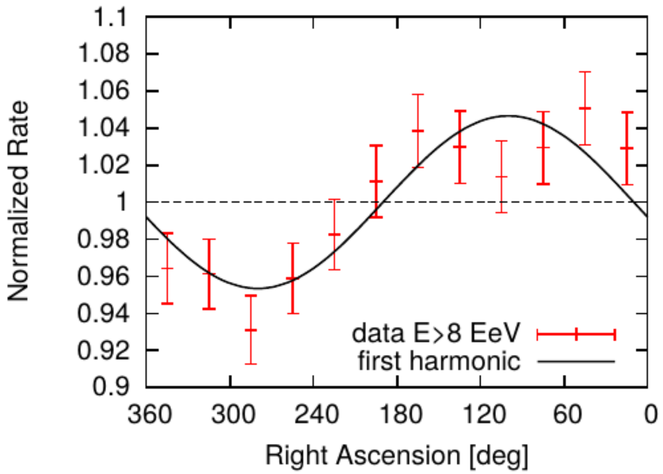

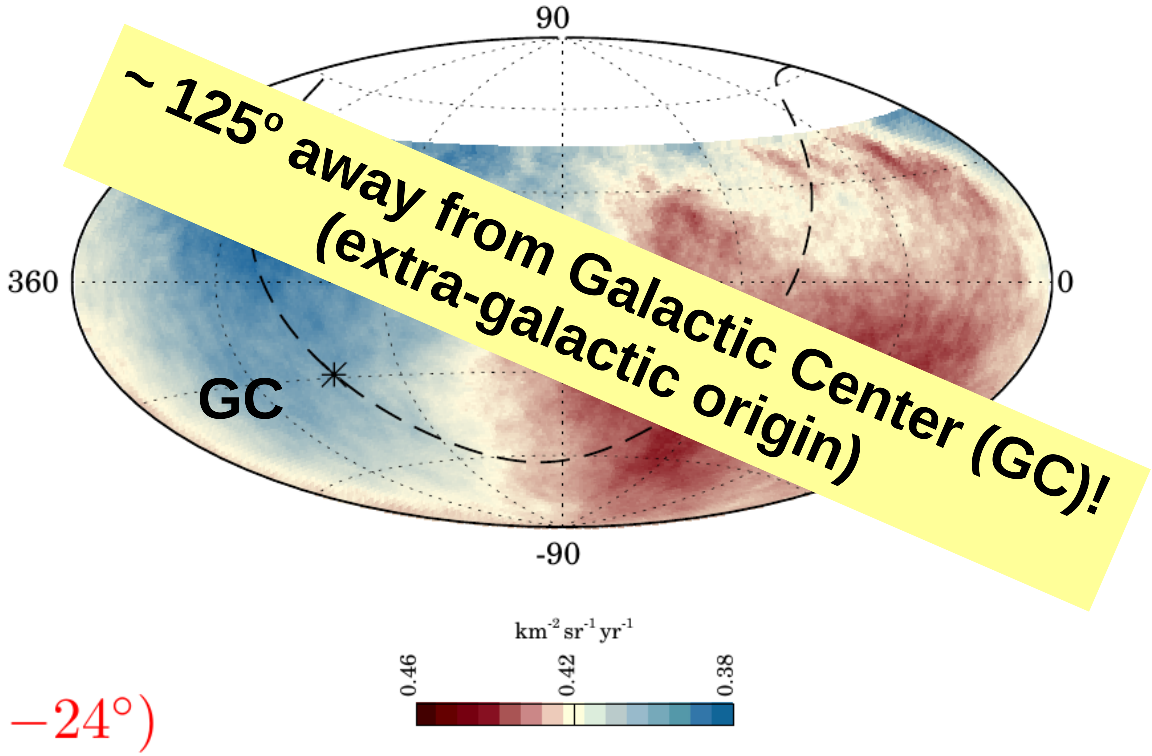

~ 125° away from Galactic Center (GC)!
(extra-galactic origin)

3-d dipole above 8 EeV:

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