Study of ultra high energy cosmic rays with AERA

Richard Dallier - Subatech

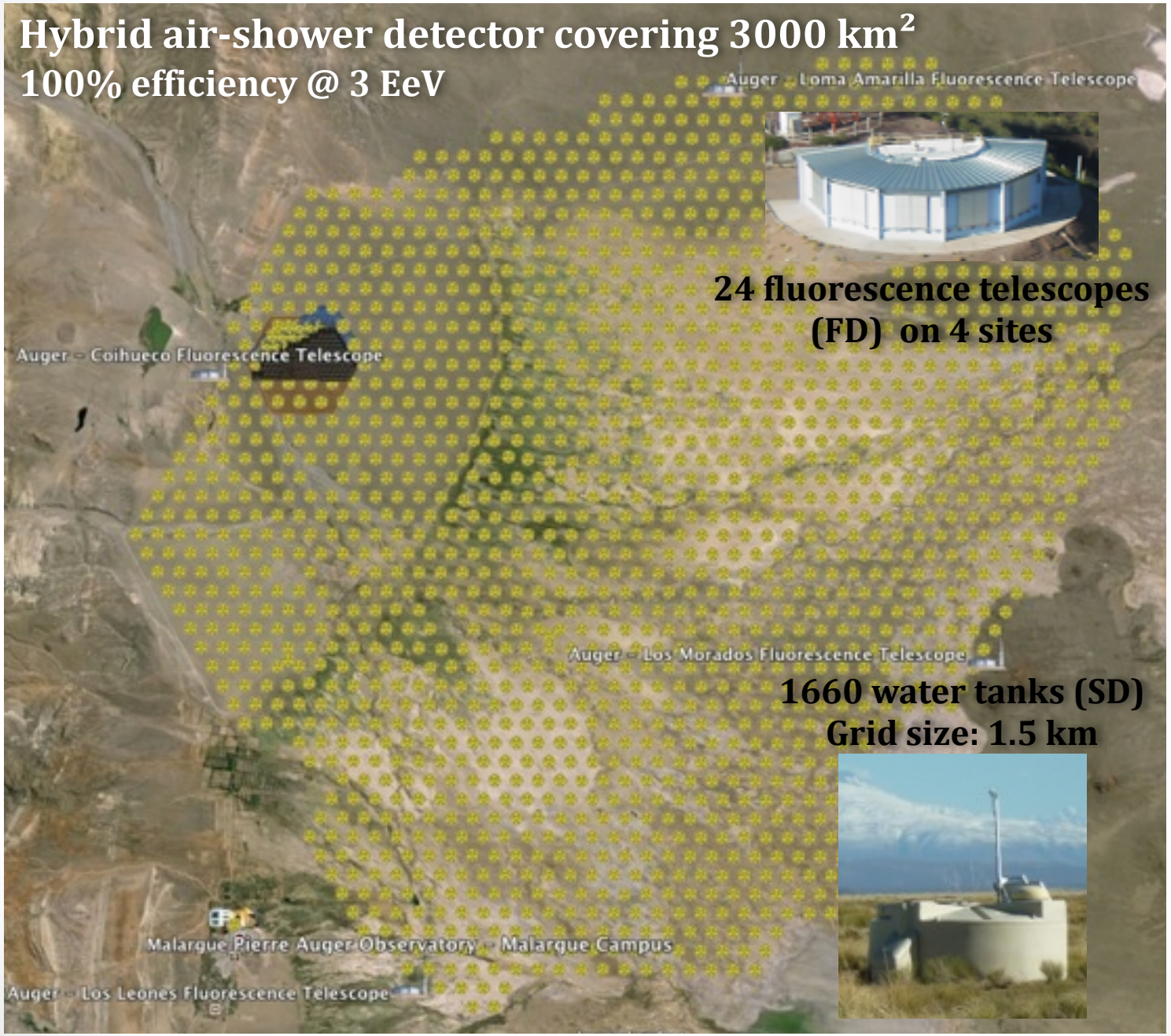
Thanks to Jennifer Maller for most of the slides...

PIERRE AUGER OBSERVATORY

Colloque PNHE Grands Instruments
02 & 03 avril 2014 - Paris

Subatech

The Pierre Auger Observatory



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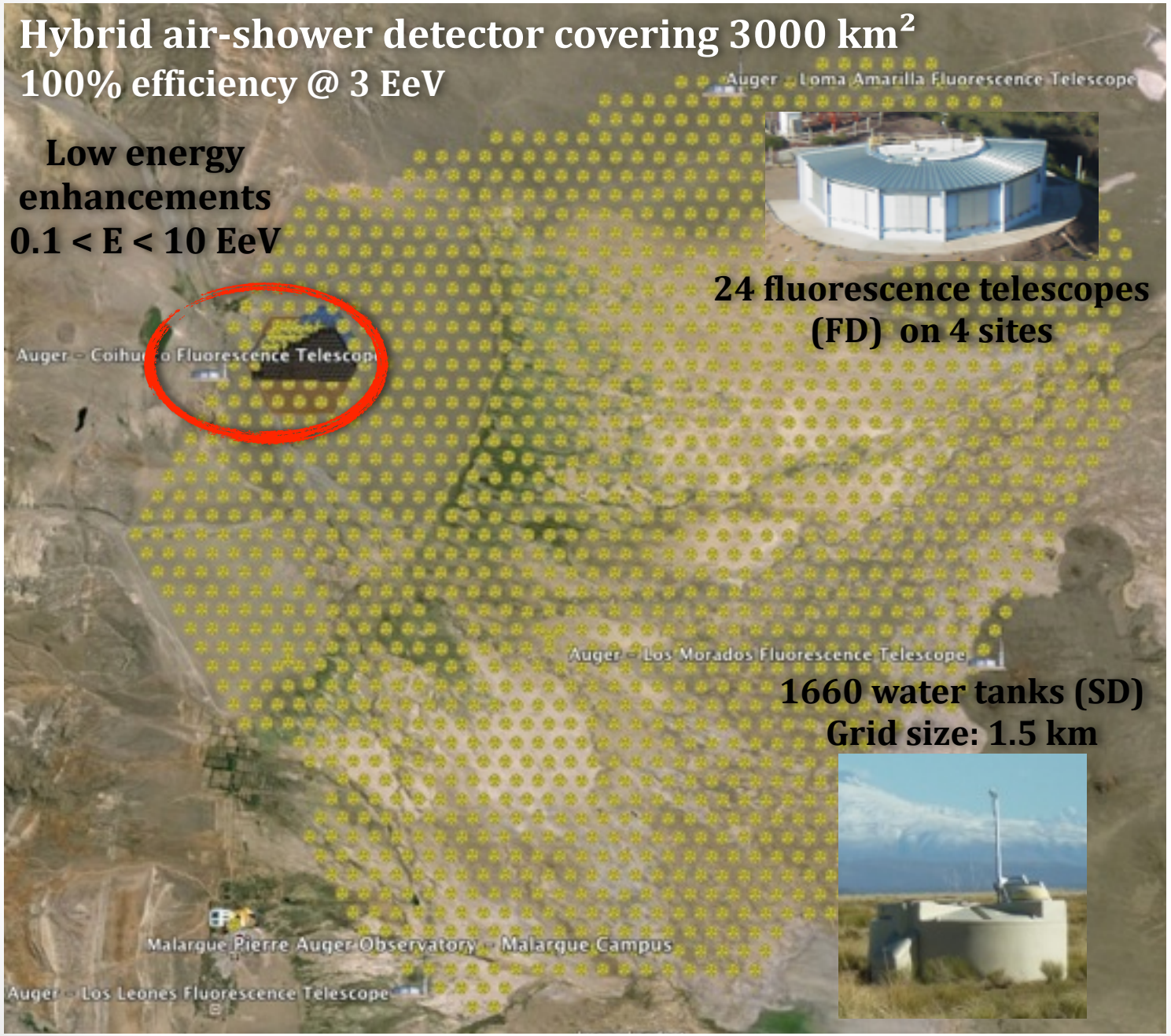

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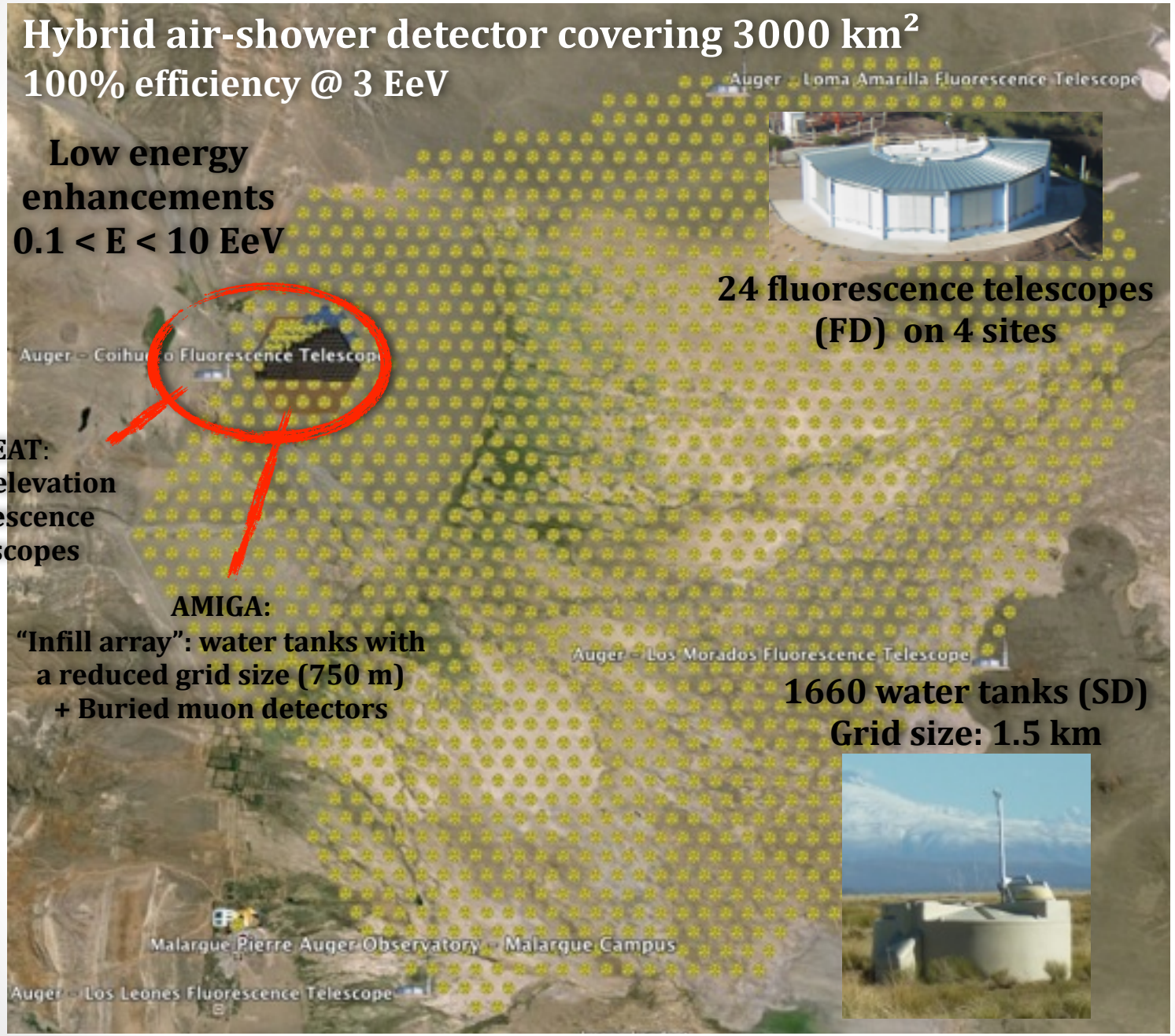

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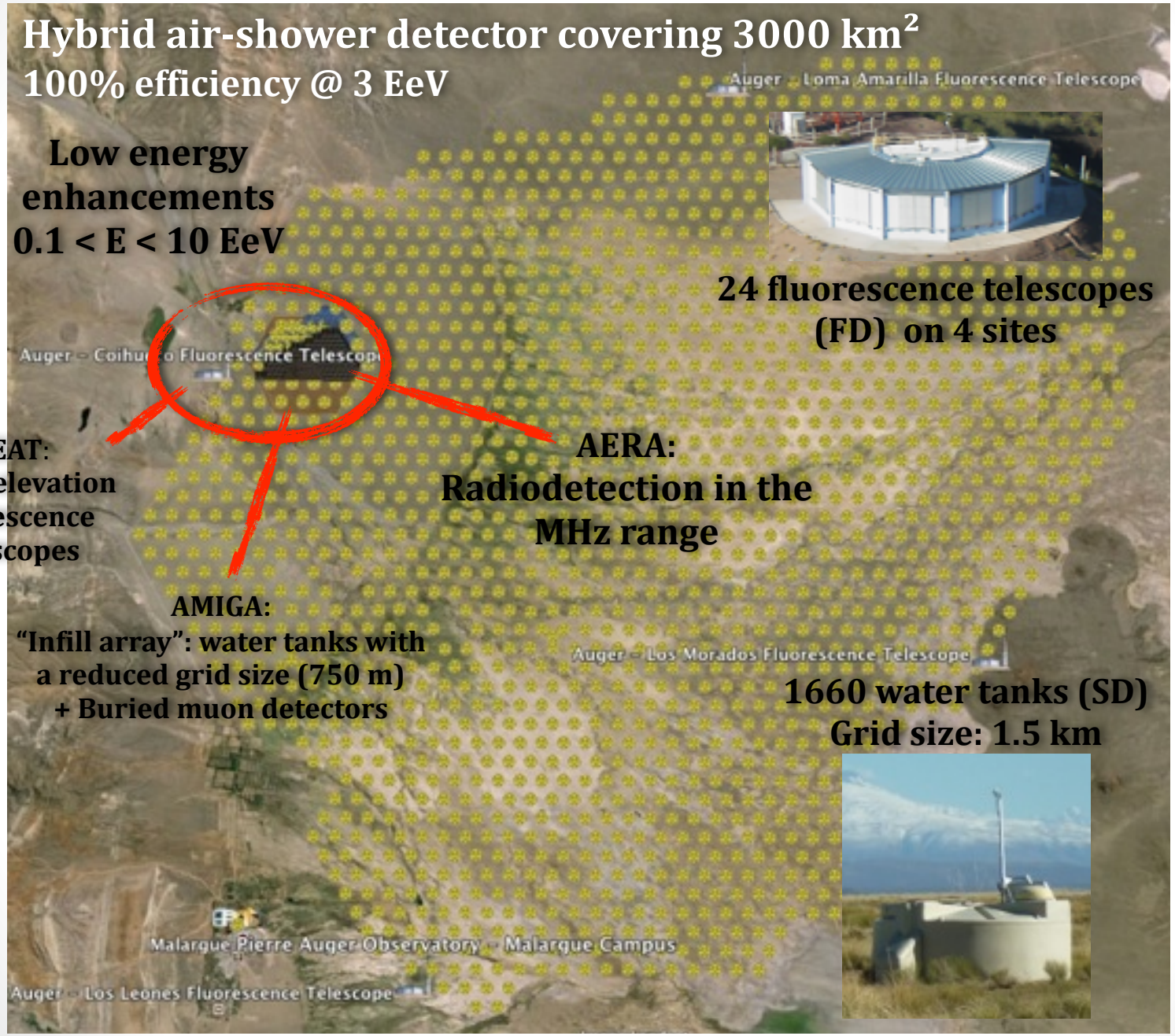
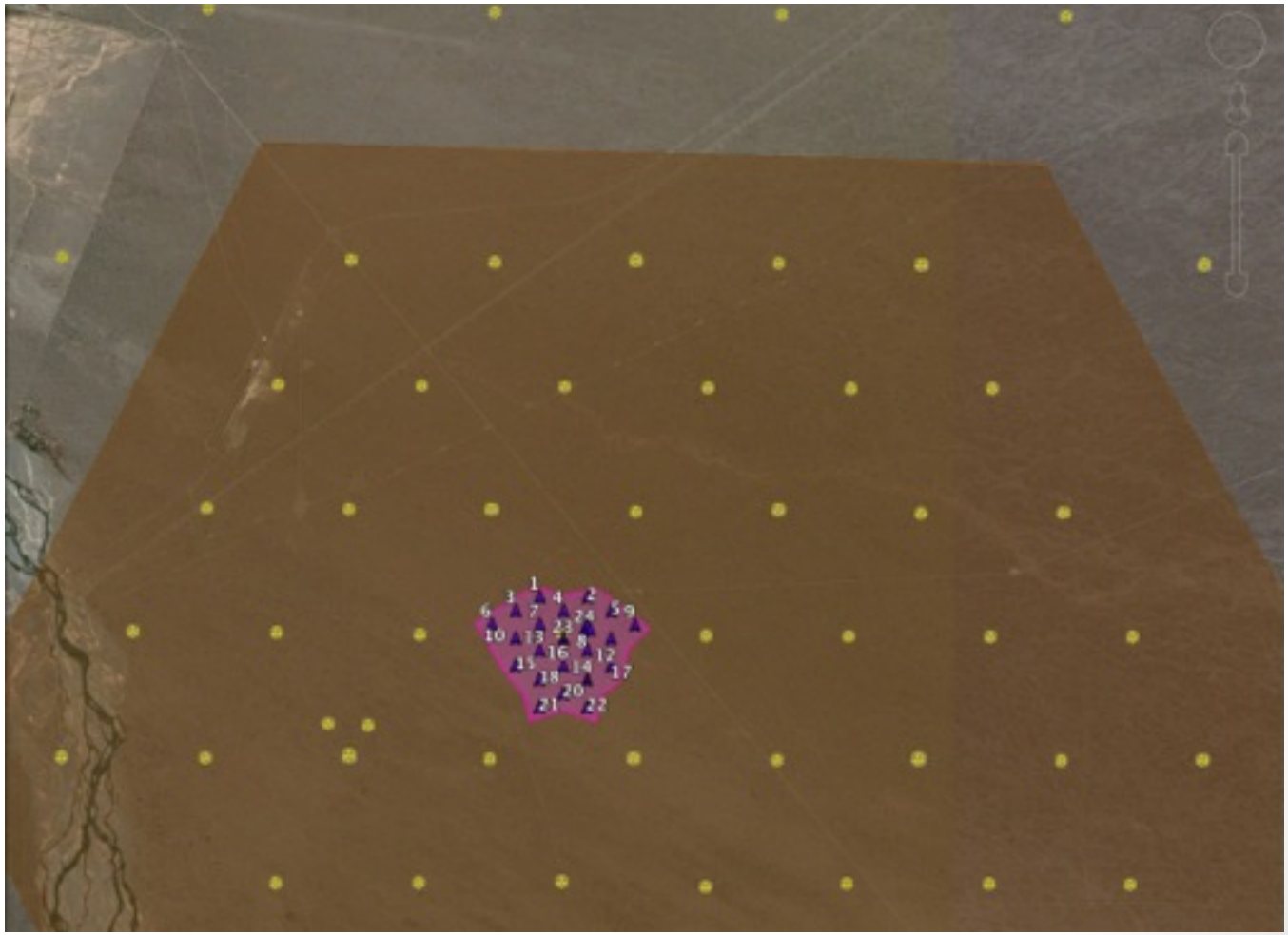


AERA: Auger Engineering Radio Array

- Radiodetection of cosmic rays with 17.2 < logE/eV < 19
- Disentangle emission mechanisms
- Primary cosmic ray characteristics (arrival direction, energy, nature) in energy region of transition from galactic to extragalactic cosmic rays
- Test the performances of a large radio array

- 24 autonomous stations late 2010 (0.5 km^2)



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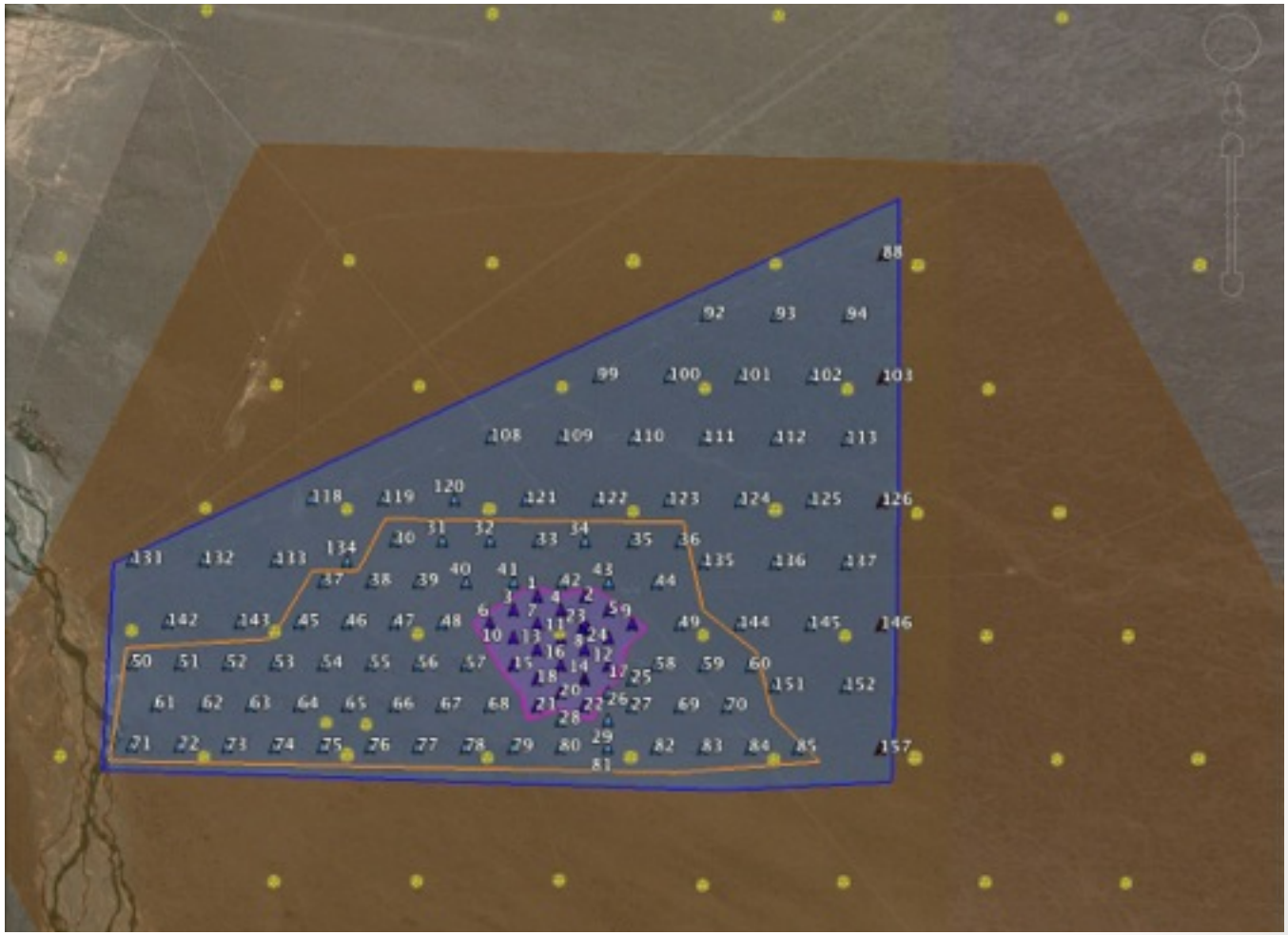
- 124 autonomous stations in May 2013 (7 km^2)



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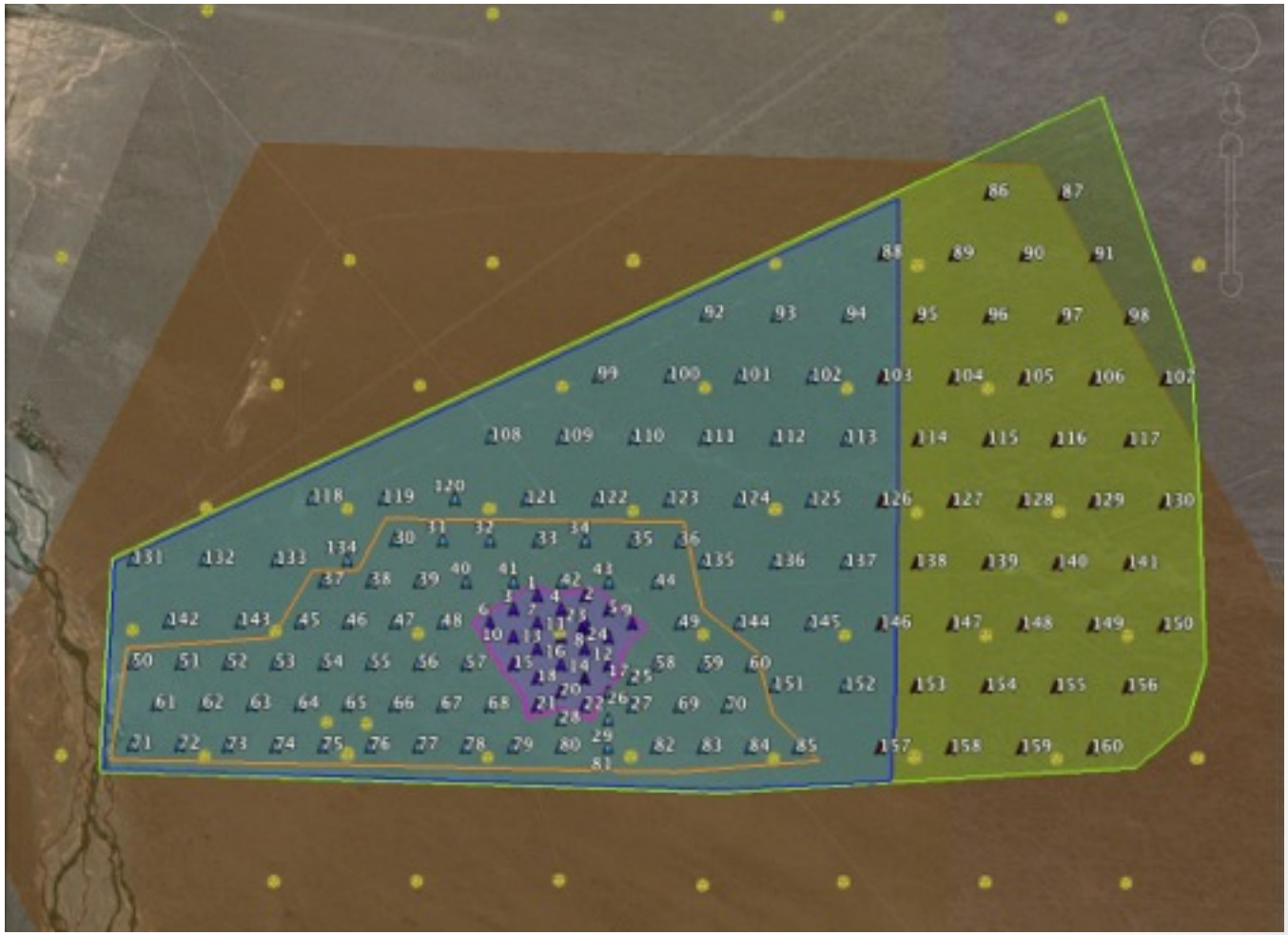
- 124 autonomous stations in May 2013 (7 km^2)
- 160 foreseen (~13 km^2)



AERA: origins and facts

- French proposal for a test of radio detection @ Auger in March 2006
- Joint effort of radio R&D from german and dutch groups in November 2006
- "Radio task force" in Auger created late 2006 (co-task leaders: D, NL and F)
- 2 separate prototypes (Subatech/LPSC: RAuger @ CLF - KIT/KVI/NIKHEF: MAXIMA @ BLS)
- RAuger 1 was the first self-triggered attempt (prototype of further CODALEMA station): 3 autonomous stations, triangular grid, 140 m side
- RAuger 1 installed in Nov. 2006, 1st event in coincidence with Auger detected in July 2007. Average rate: ~ 1 event / 12 days > 10^{17} eV
- Despite several tries, MAXIMA has never been self-triggered (additional scintillators)
- March 2009: proposal for AERA made to Auger boards, accepted. French responsibilities: project co-task leader, DAQ WP leader, antenna and EMC housing WP leaders
- RAuger 2 (with current CODALEMA stations) upgraded in May 2010, first events in coincidence 3 days later ! Average rate: ~ 1 event / 4 days > 10^{17} eV
- First AERA stations deployed in November 2010 ; first coincidence with Auger April 2011
- AERA second stage: decided late 2011. Antenna selected in March 2012 (the CODALEMA "Butterfly" antenna and its LNA)
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Setup AERA 1st stage – 0.5 km²

Dense core installed in 2010, taking data since spring 2011

24 stations spaced by **144 m** composed of :

- a **LPDA antenna** measuring both **EW & NS polarizations** in the **30 – 80 MHz** band
- an **EMC box** containing the **electronics** to prevent triggering of the station by RFI from the embedded electronics
- **solar panels and batteries** for power supply
- **GPS** for precise time measurement

Setup AERA 2nd stage – 6 km²

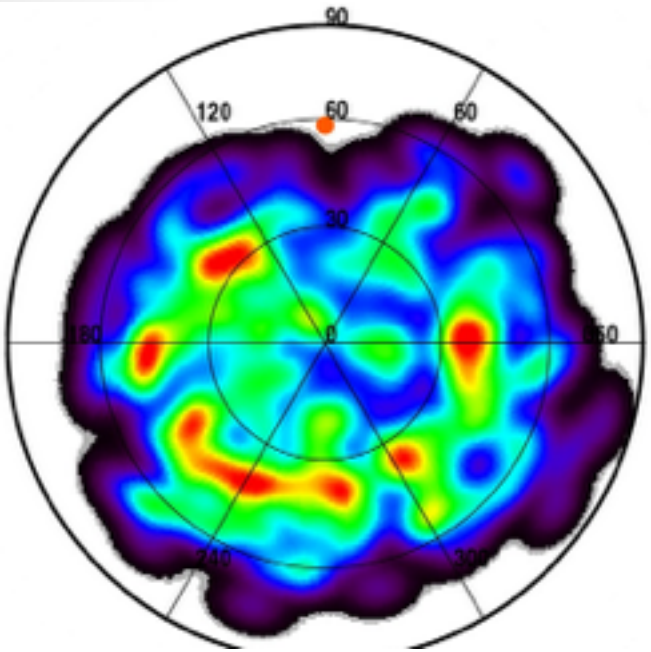
Deployed since May 2013

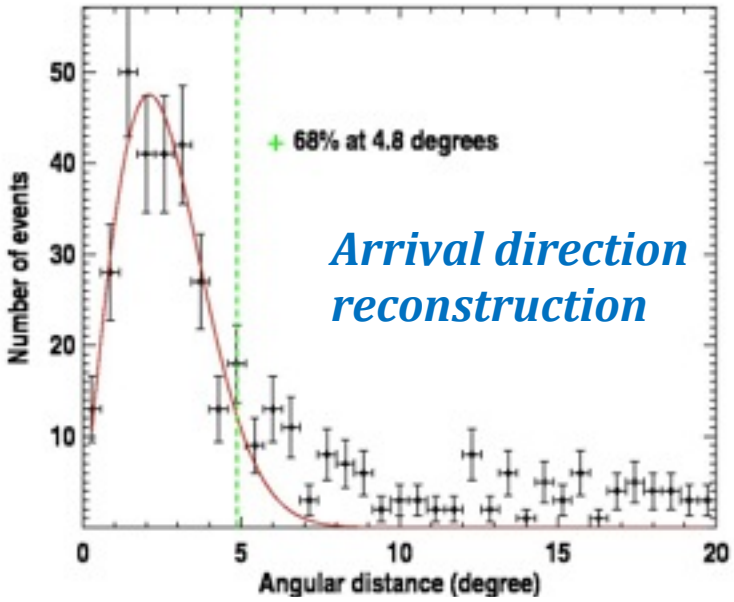
100 new stations installed around AERA24, **250 m** and **375 m** pitch, equipped with:

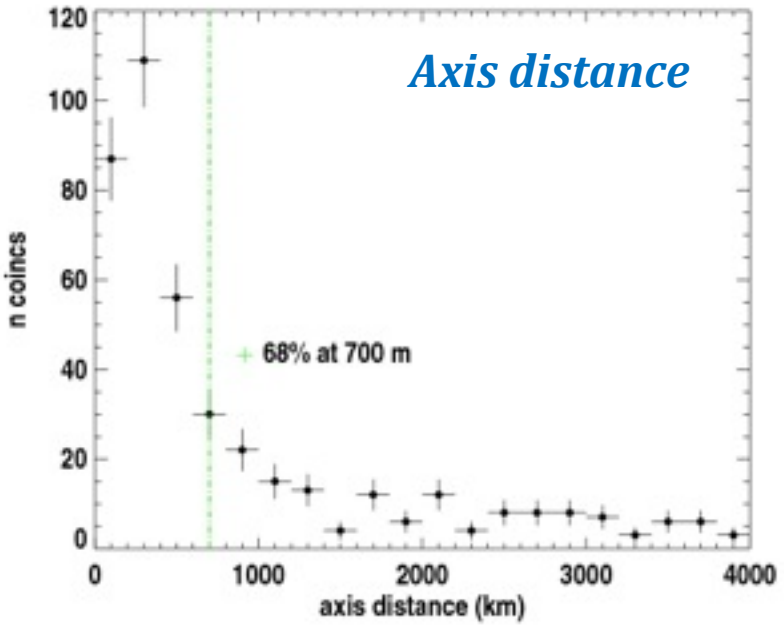
- the **CODALEMA** "**Butterfly**" antenna
- a pair of **scintillators** in 40 of them
- 2 different **electronics** (180 and 200 MS/s)
- 3 different **trigger modes** (self-trigger, external trigger on SD/FD, external trigger on scintillators)
- WiFi link to central DAQ

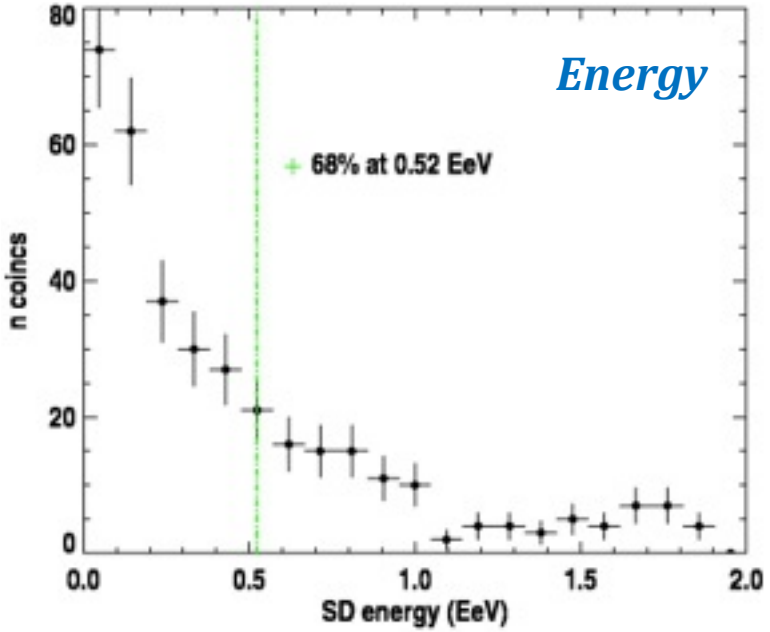
Results for a 5 month period (AERA24)

3 to 6 coincidences each day





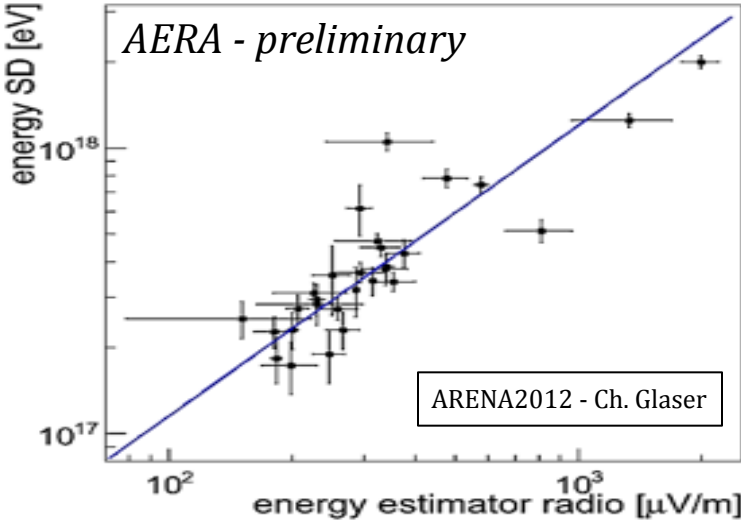


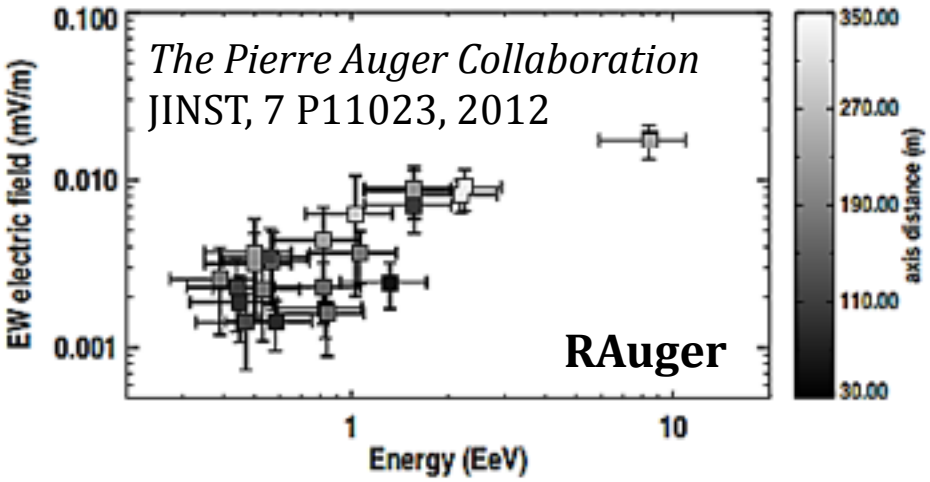


A first step toward an energy estimate

Requirement:

- Deconvolving of the antenna response
- Efficient energy estimate from SD and FD
- Study of systematics errors





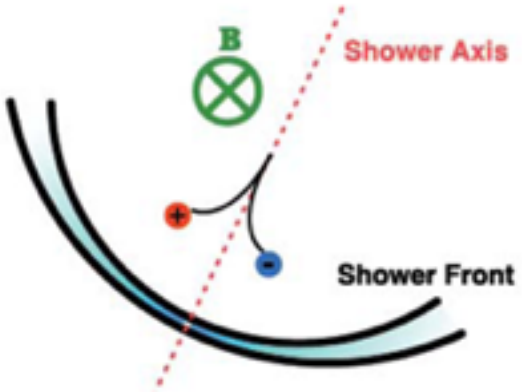
AERA24 preliminary results: good agreement with other experiments

- Linear dependence between infill SD energy and the preliminary radio energy estimator
- Needs more statistics ⇒ **AERA124**

E-field polarization: a tool to disentangle the emission mechanisms

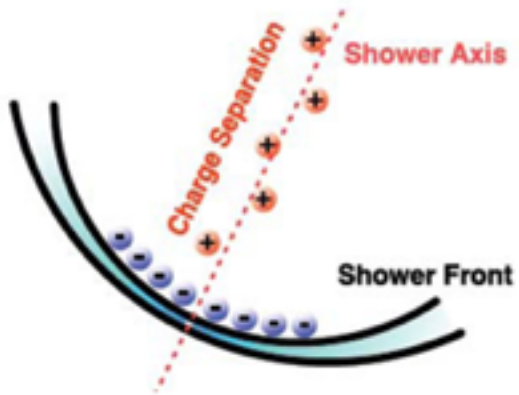
Geomagnetic effect

Kahn et Lerche - 1966

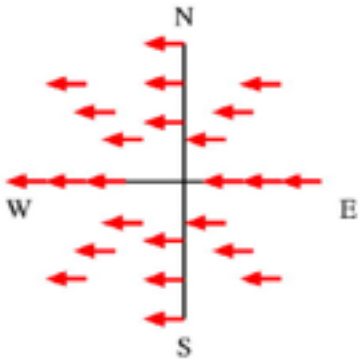


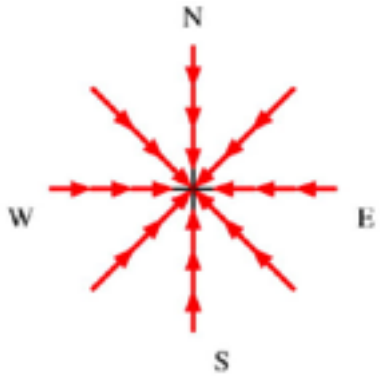
Charge excess effect

Askaryan - 1962



Unidirectional polarization → Aligned with the direction of $-\boldsymbol{v} \times \boldsymbol{B}$





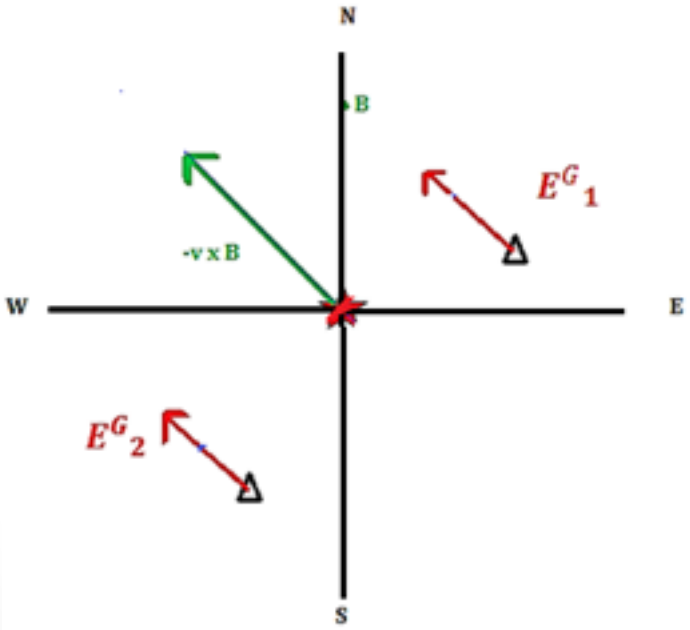
Radial polarization with respect to the shower axis

For the relevant period: $\boldsymbol{B} \equiv (54.4°, 87.3°)$
$|B| = 24\ \mu T$

$$\boldsymbol{E}(t) = \boldsymbol{E}^{G} + \boldsymbol{E}^{A}$$

E-field polarization: a tool to disentangle the emission mechanisms

→ Electric field due to the geomagnetic effect does **not** depend on the radio station position



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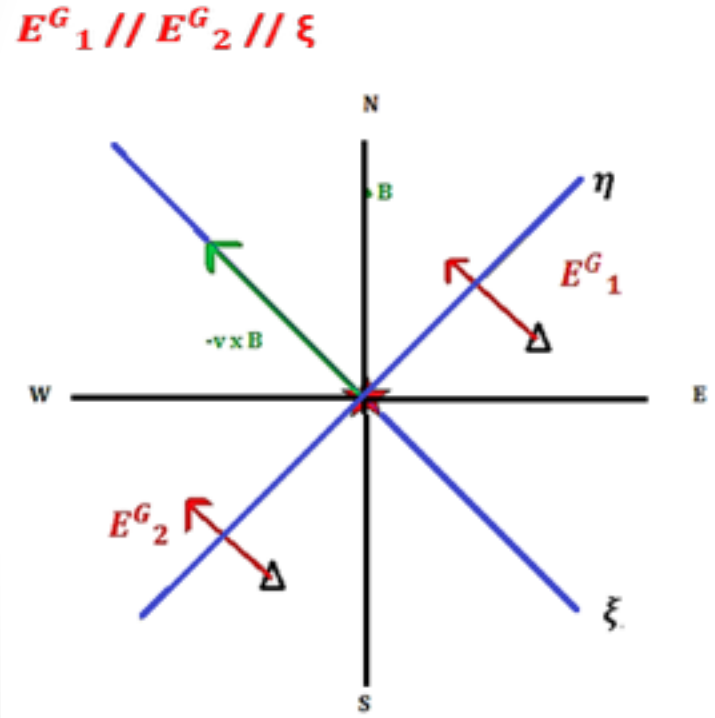
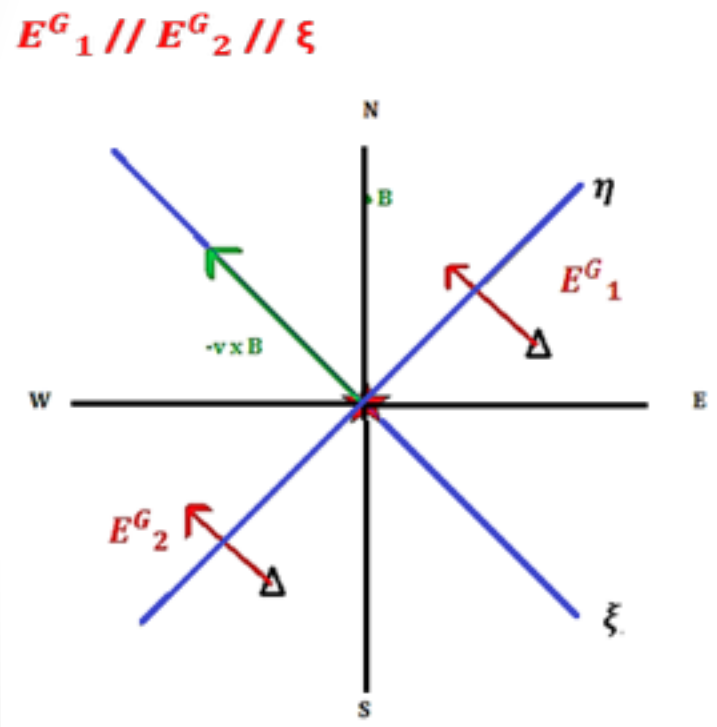


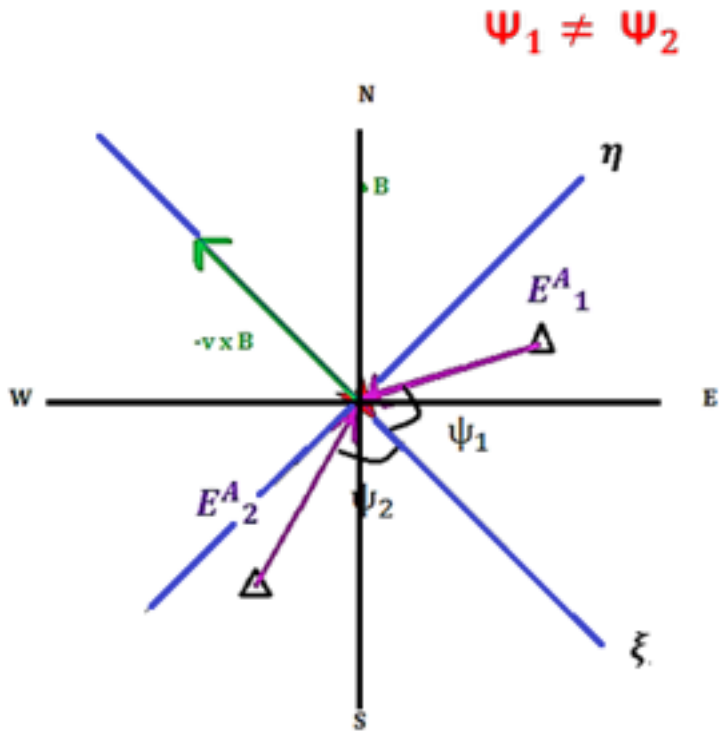
→ Use of a rotated coordinate system in the ground plane (ξ,η), with ξ the projection of ($-\vec{v} \times \vec{B}$) onto the shower plane and η orthonormal to ξ

E-field polarization: a tool to disentangle the emission mechanisms

→ Electric field due to the geomagnetic effect does **not** depend on the radio station position

→ Electric field due to the charge excess **depends** on the radio station position





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Ψ is the observation angle ≡ angle between ξ and the direction of the stations measured at the core position

E-field polarization: the "R" parameter

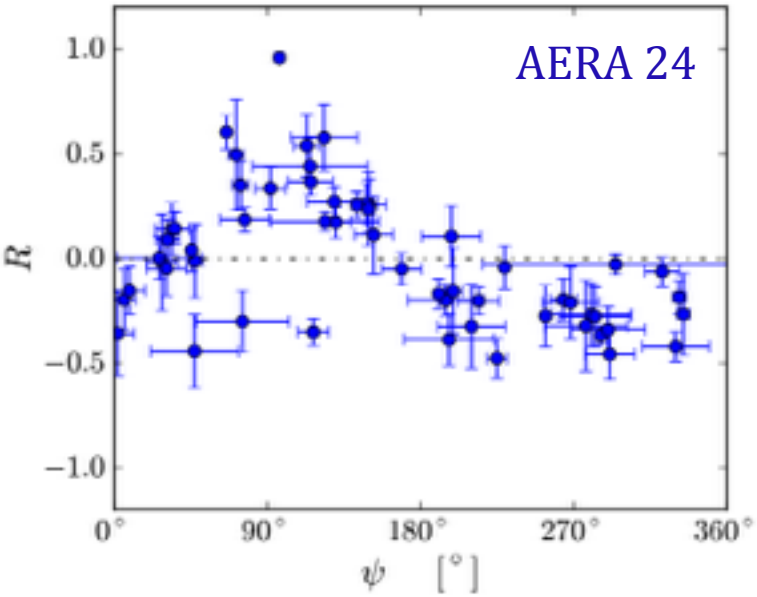
In the rotated coordinate system in the ground plane (ξ, η)

$$R(\psi) = \frac{2\sum_{i=1}^{N} Re(\varepsilon_\xi(t_i).\varepsilon_\eta(t_i))}{\sum_{i=1}^{N}(|\varepsilon_\xi(t_i)|^2+|\varepsilon_\eta(t_i)|^2)} \propto \sin\psi$$

By construction $\boldsymbol{\varepsilon_\eta}$ has no component in the case of a pure geomagnetic emission as $E^G \;//\; \xi$

→ **This implies in this case R=0**

→ **R ≠ 0 indicates a component different from the geomagnetic effect**



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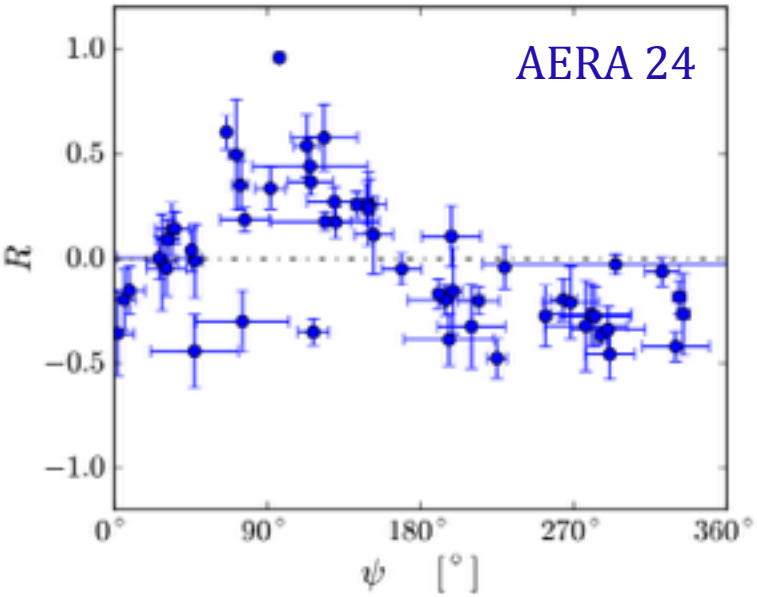

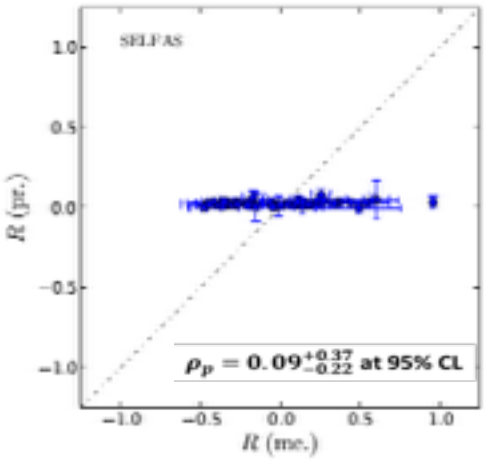

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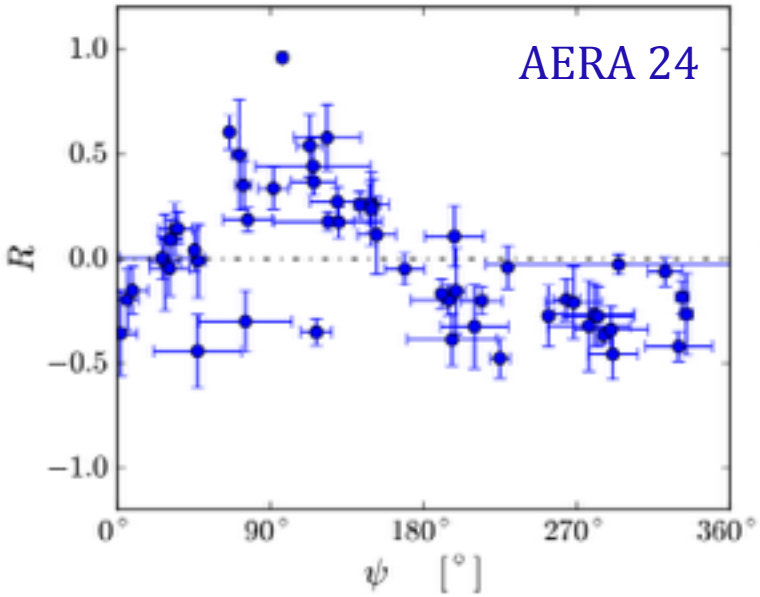

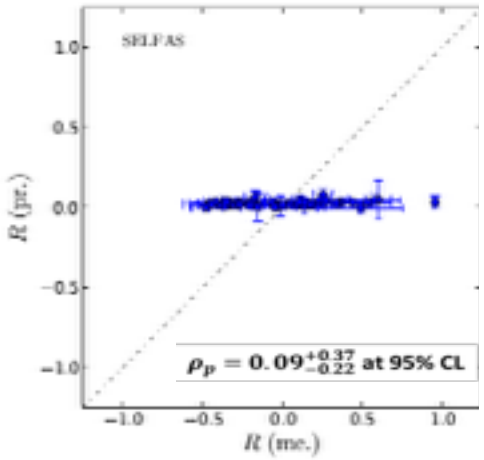

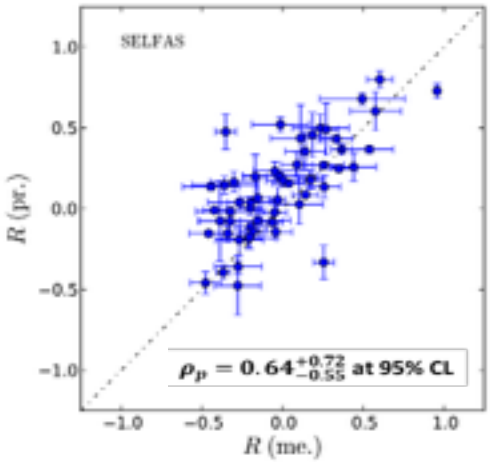

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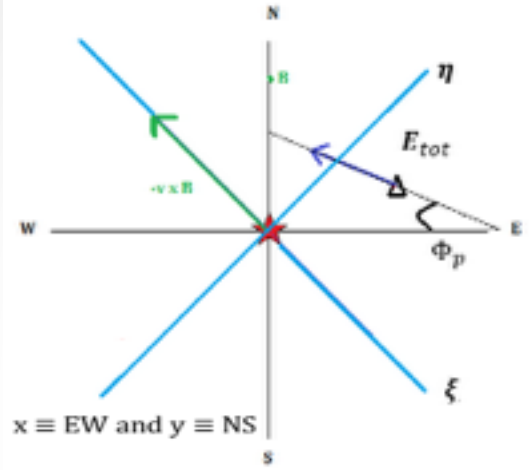
Quantification of the deviation from geomagnetic effect

Comparison of the measured azimuthal polarization angle and the predicted one, assuming a simple model including a secondary emission process with a radial polarization

The **predicted** azimuthal polarization angle is given by:

$$\Phi_p = \tan^{-1} \frac{E^{tot}{}_y}{E^{tot}{}_x}$$



Where:

$$E^{tot}{}_x = |\boldsymbol{E}_G| \left(\cos\Phi_G \sin\alpha + \frac{|\boldsymbol{E}_A|}{|\boldsymbol{E}_G|} \sin\alpha \cos\Phi_A\right)$$

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Φ^G the azimuthal angle of the geomagnetic contribution

Φ^A the one of the charge excess contribution

a = relative strength of the radial contribution vs the geomagnetic one

$$a = \frac{|\boldsymbol{E}_A|}{|\boldsymbol{E}_G|} \sin\alpha$$

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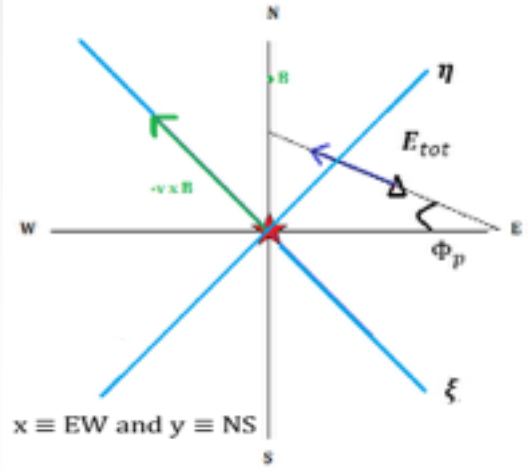

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The **measured** azimuthal polarization angle is calculated thanks to the Stokes parameters Q and U:

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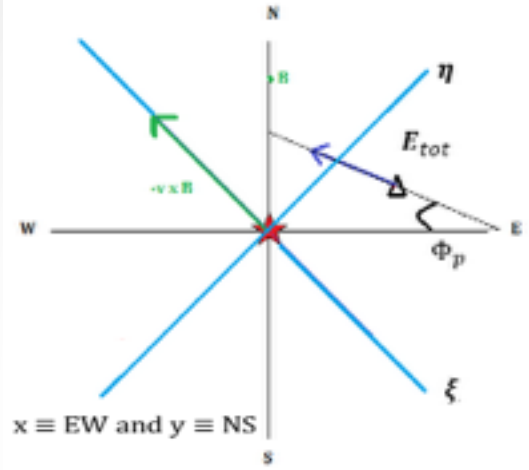

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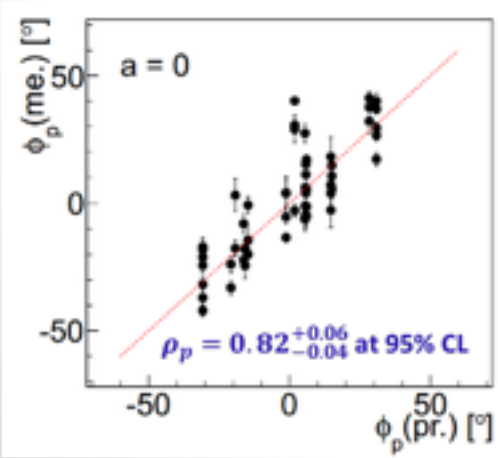

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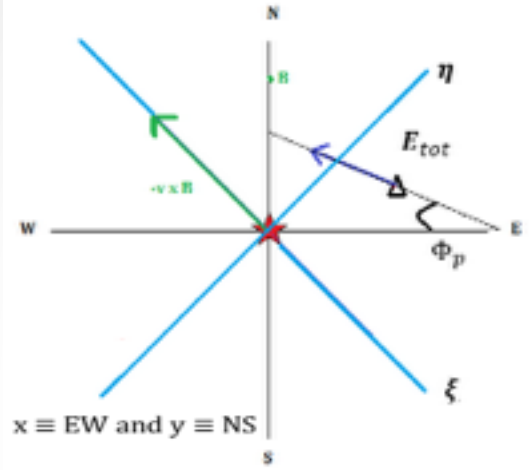


Where:

$$E^{tot}{}_x = |E_G| \left(\cos\Phi_G \sin\alpha + \frac{|E_A|}{|E_G|} \sin\alpha \cos\Phi_A\right)$$

$$E^{tot}{}_y = |E_G| \left(\sin\Phi_G \sin\alpha + \frac{|E_A|}{|E_G|} \sin\alpha \sin\Phi_A\right)$$

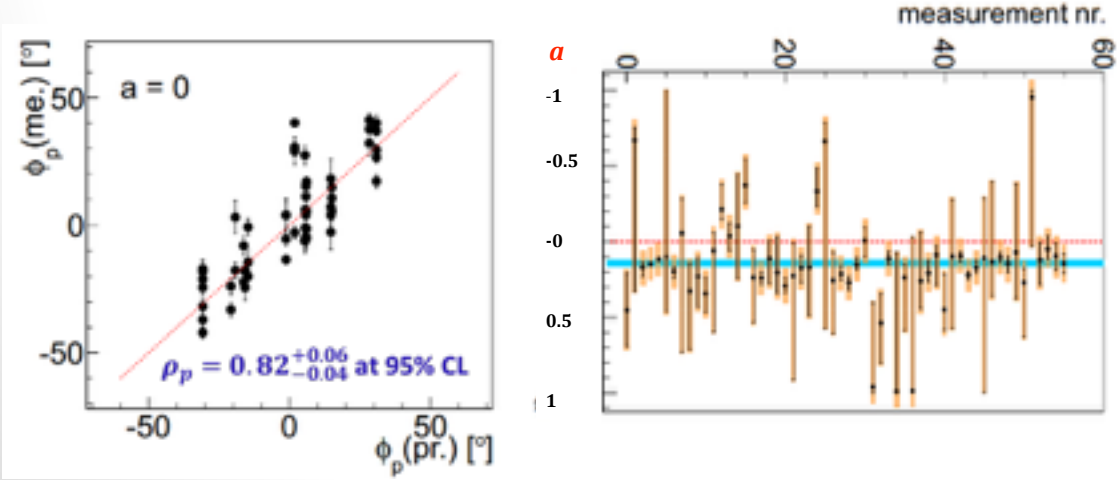
with
Φ^G the azimuthal angle of the geomagnetic contribution
Φ^A the one of the charge excess contribution

a = relative strength of the radial contribution vs the geomagnetic one

$$a = \frac{|E_A|}{|E_G|} \sin\alpha$$

The **measured** azimuthal polarization angle is calculated thanks to the Stokes parameters Q and U:

$$\Phi_p(me) = \frac{1}{2} \tan^{-1} \frac{U}{Q}$$



Quantification of the deviation from geomagnetic effect

Comparison of the measured azimuthal polarization angle and the predicted one, assuming a simple model including a secondary emission process with a radial polarization

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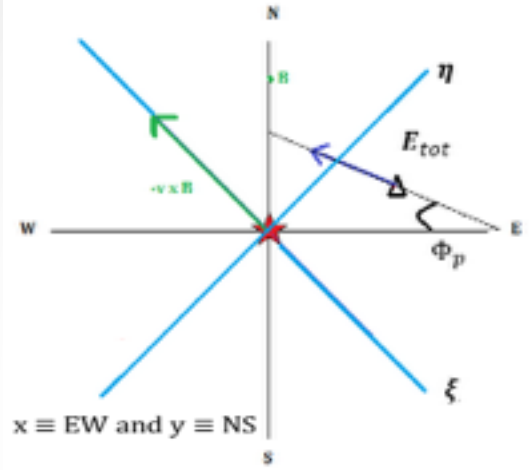

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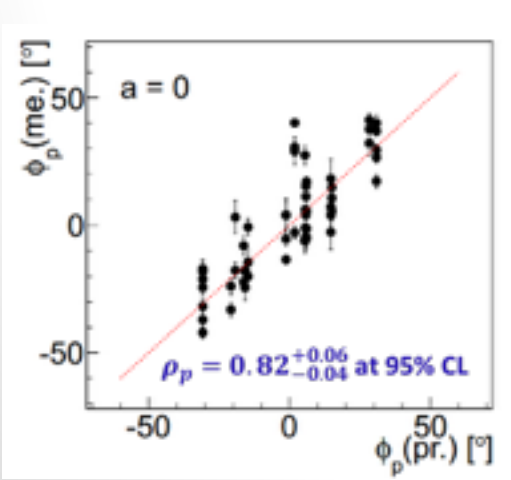
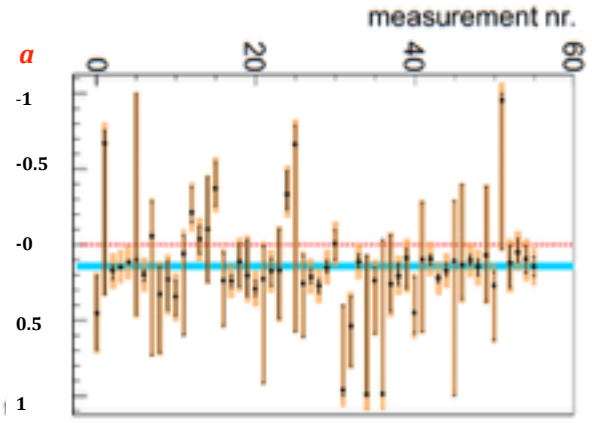
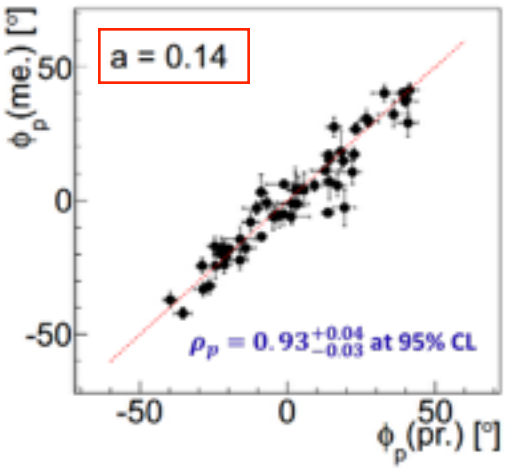
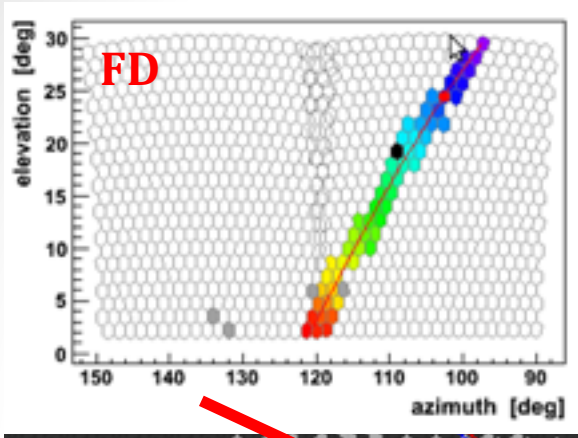


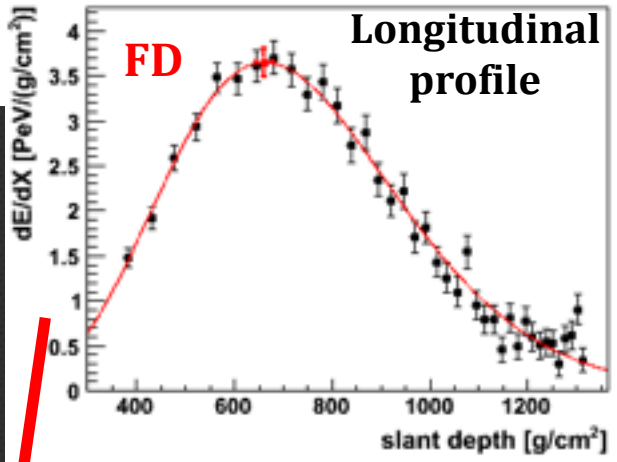




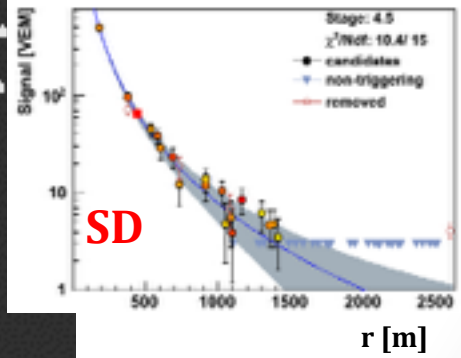
Hybrid coincidences:

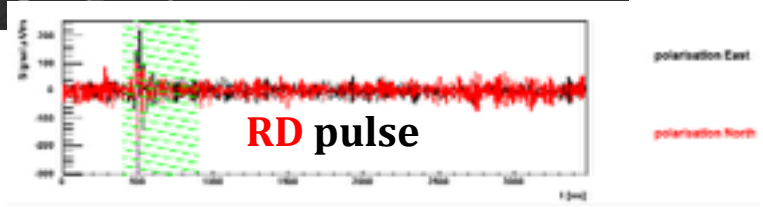
- Comparison of radio observables with SD and FD data
- Study of the whole shower development





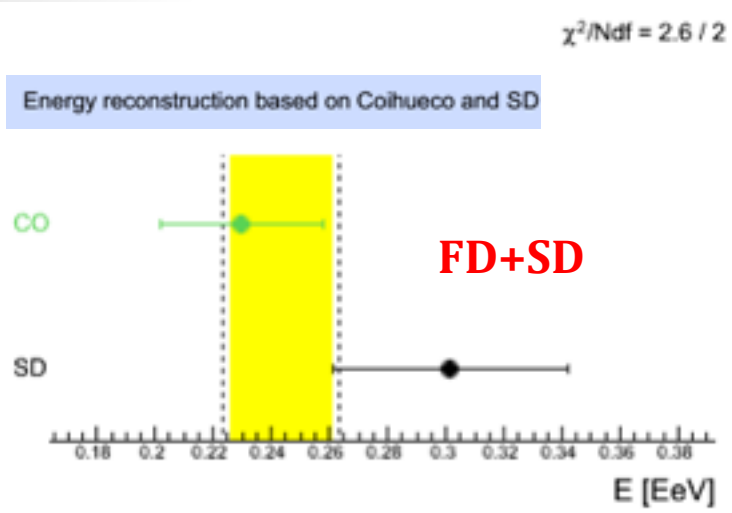
Lateral distribution function (LDF)

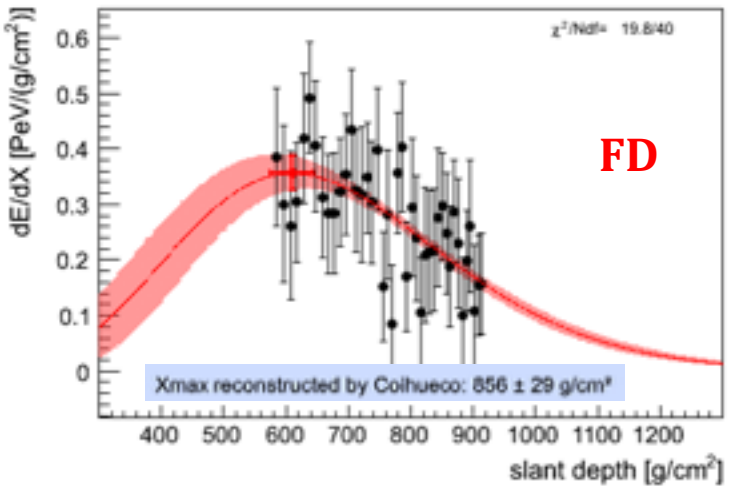


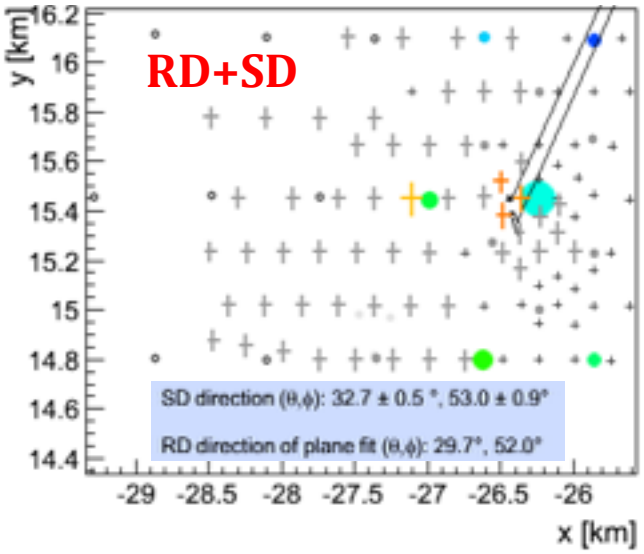


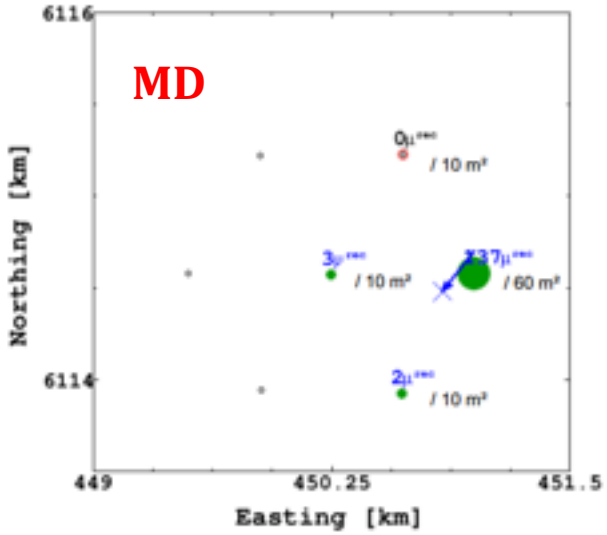
RD + SD reconstruction

A first quadruple hybrid event in RD, SD, FD and MD









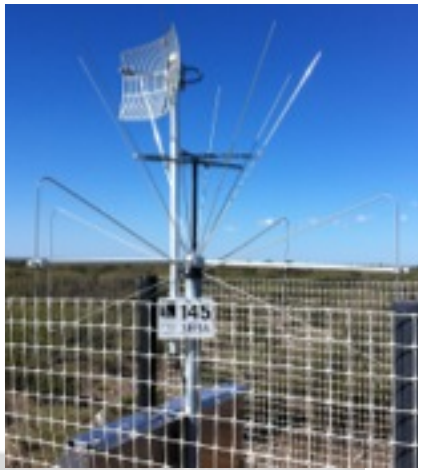
⇒ Toward an analysis through "Universality" of showers ?

AERA: Auger Engineering Radio Array

And thus, some new instruments on test:

- Vertical polarization ("3D" E-field and inclined shower detection)
- Low frequency antenna



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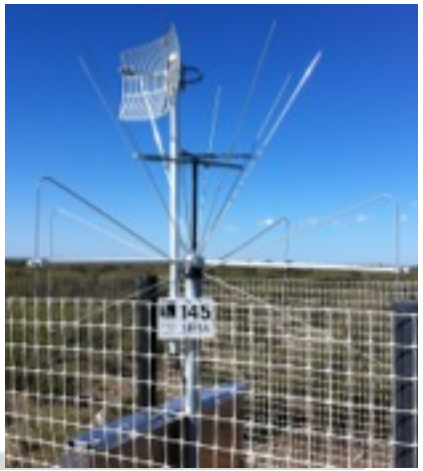

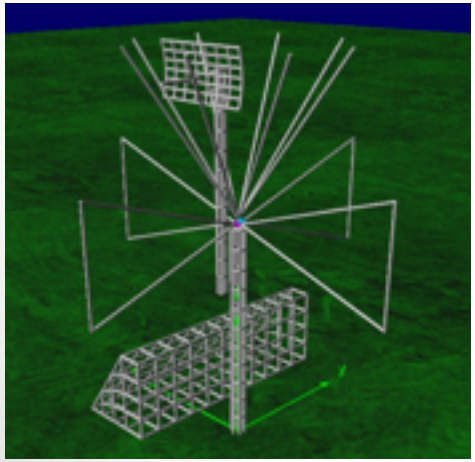

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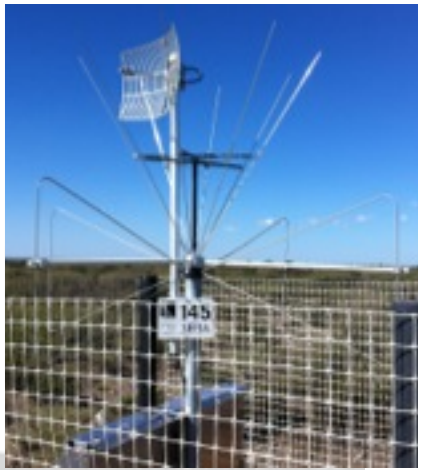

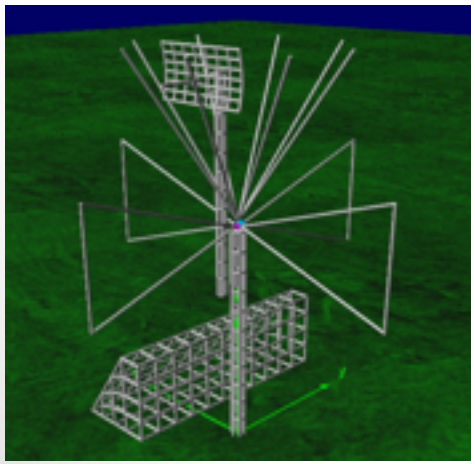

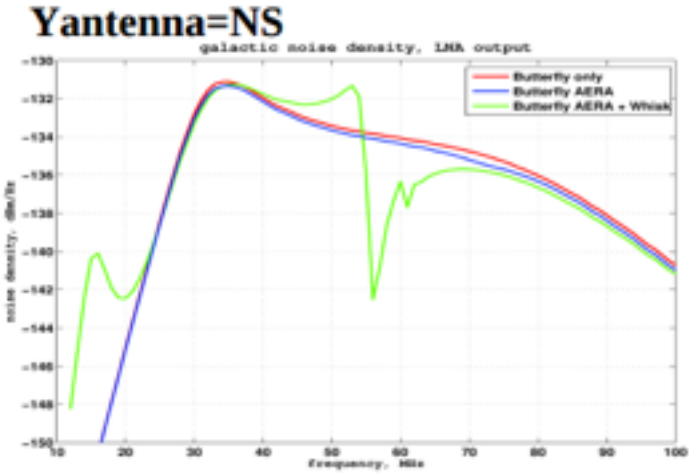

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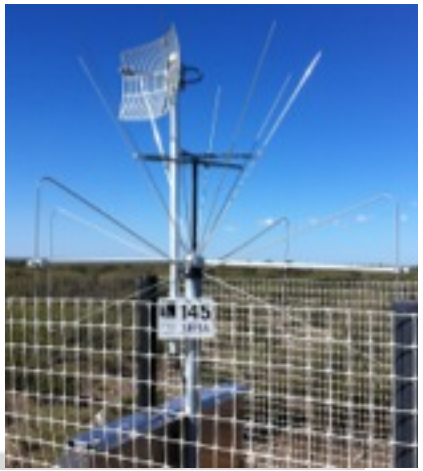

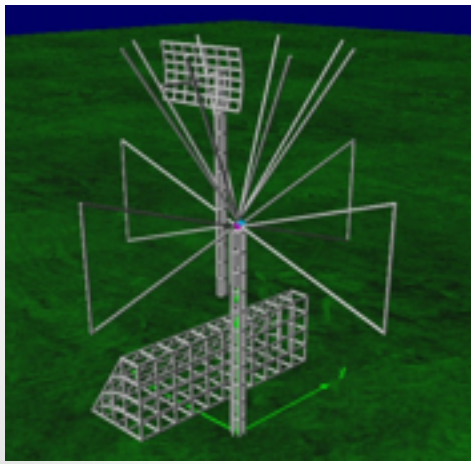

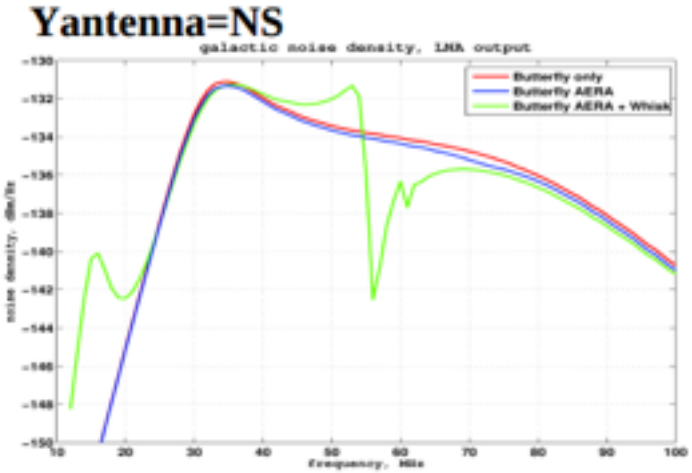

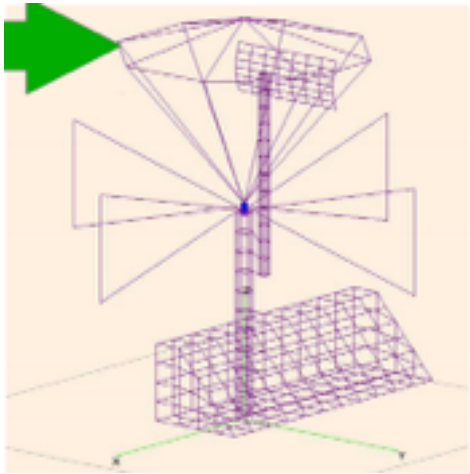

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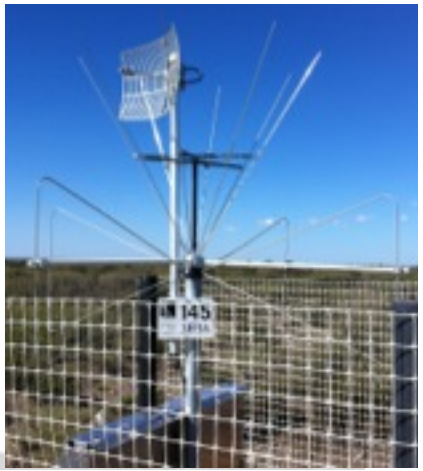

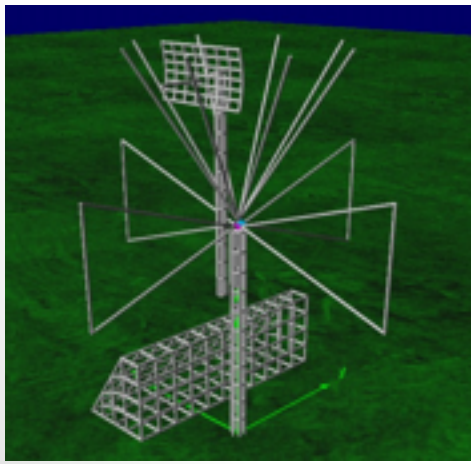

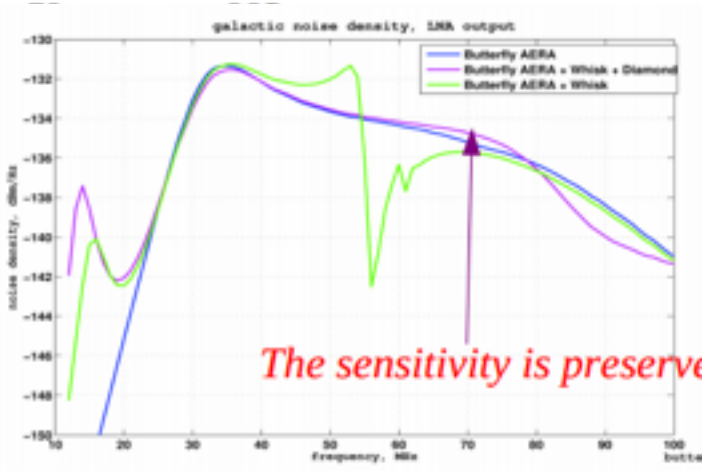

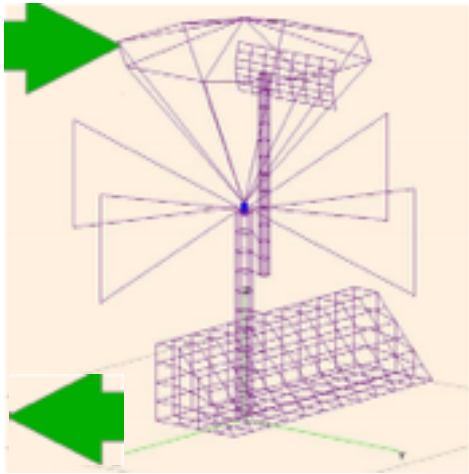

Conclusion/Outlook

- AERA is working, AERA124 will bring larger statistics and higher quality data (better antenna sensitivity, hybrid events, X_{max} determination…).
- 4 “full author list” Auger papers in 3 years: prototype RAuger (from Subatech), OffLine analysis software, antenna selection paper and polarisation paper.
- AERA greatly helped understanding of emission processes and their quantification (“polarisation paper”), in agreement with CODALEMA results. The “MHz” radio emission processes are understood (simulations).
- Though a running instrument, still an engineering array: developments made elsewhere (mainly on CODALEMA) can be tested and installed on AERA.
- Ongoing developments: vertical polarisation (for complete E-field description and inclined showers), tentative use of Universality for hybrid analysis.
- The “French” contribution: 95 % from Subatech (LPSC on GUI of DAQ). We are in charge of the antenna (the CODALEMA-Butterfly one) and the EMC housing, and responsible for central DAQ (“T3 Maker”); we are also involved in trigger algorithms and data selection.
- AERA is now part of Auger routinely operated instruments (but not yet considered as “enhancement”).