

Coherent radio emission from cosmic ray air showers computed by Monte-Carlo simulation

Subatech

cnrs
IN2P3
LES DEUX INFIRMS



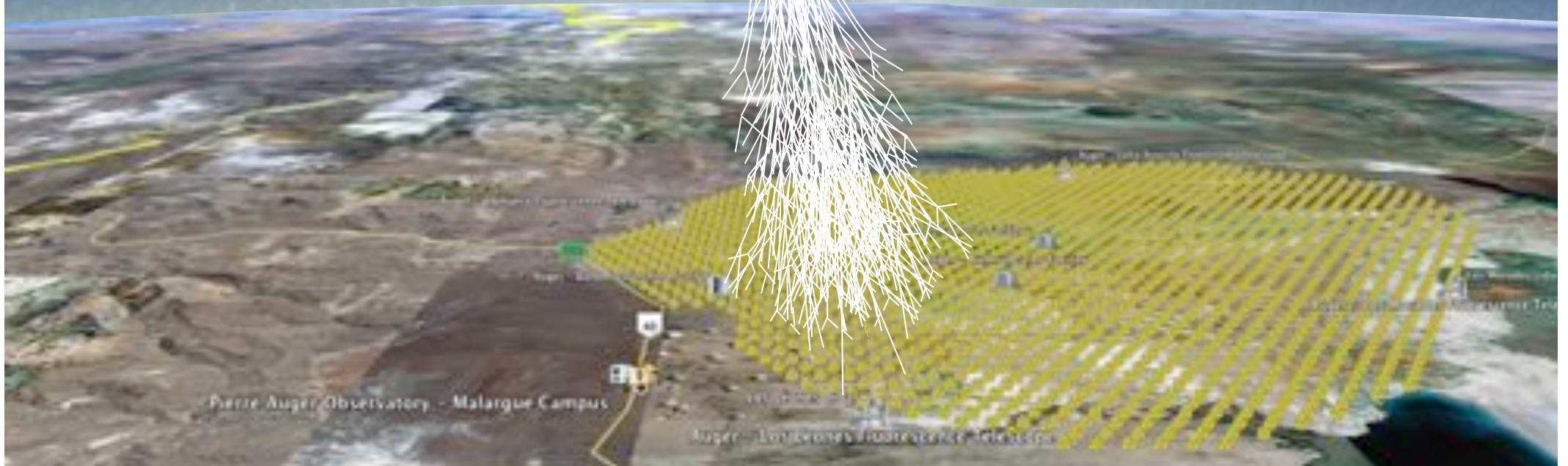
ECOLE DES MINES DE NANTES



UNIVERSITÉ DE NANTES

Vincent Marin

*Nantes
01/07/2010*





A simple case

Electron-positron example,
Electromagnetic emission,
Methodology.

Application to air shower

Geometrical description,
Monte-Carlo simulation,
First results and analysis,
Conclusion.

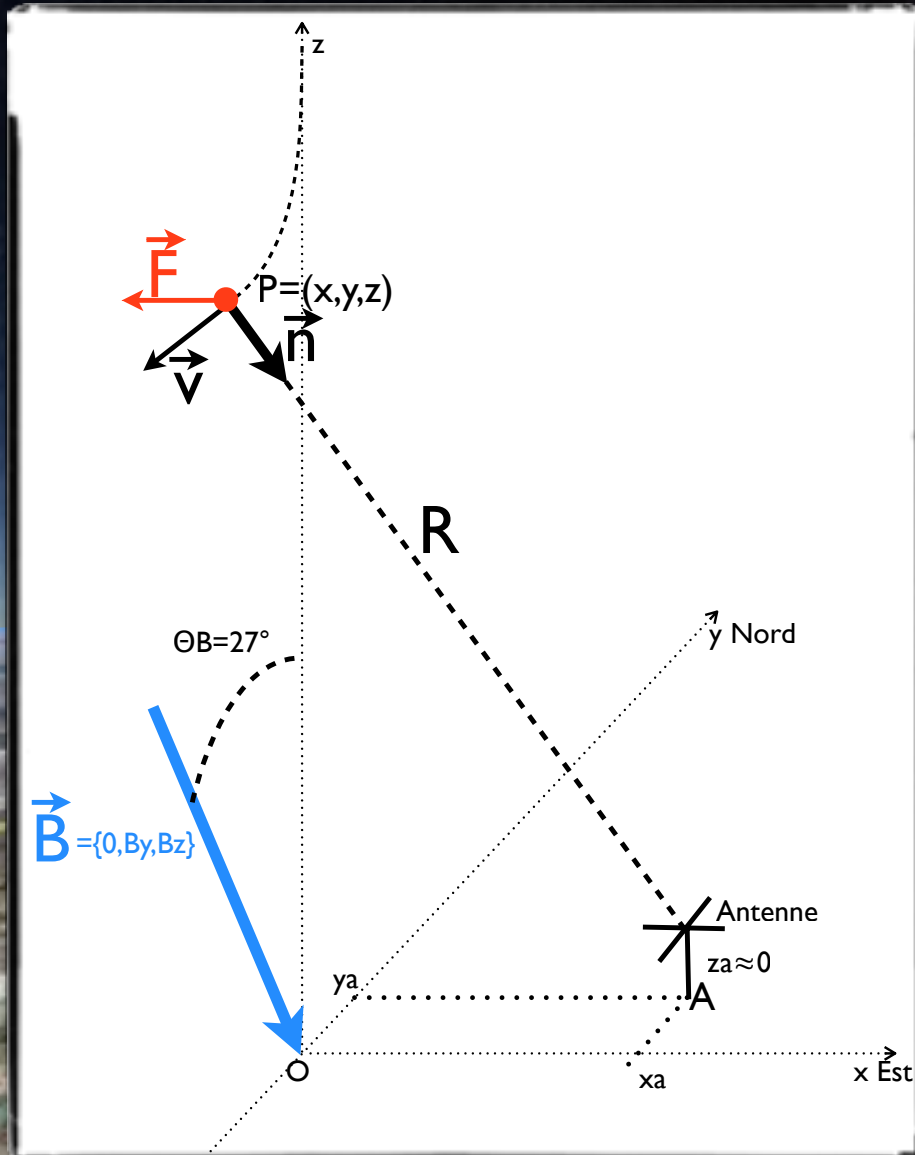
An aerial photograph of the Pierre Auger Observatory in Malargue, Argentina, showing a vast grid of yellow detector stations. A white particle shower visualization is overlaid on the grid, showing a central point from which numerous white lines radiate outwards, representing the path of particles in a cosmic ray shower. A single white line extends from the top of the frame down to the shower's origin. A large black rectangular box is superimposed over the center of the image, containing text.

A simple case

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Simple case

Electron-positron pair



$$\frac{d\vec{\beta}}{dt} = \frac{e}{\gamma mc} \vec{\beta} \wedge \vec{B}$$

Motion in the geomagnetic field

One mean free path 36.62 g cm^2

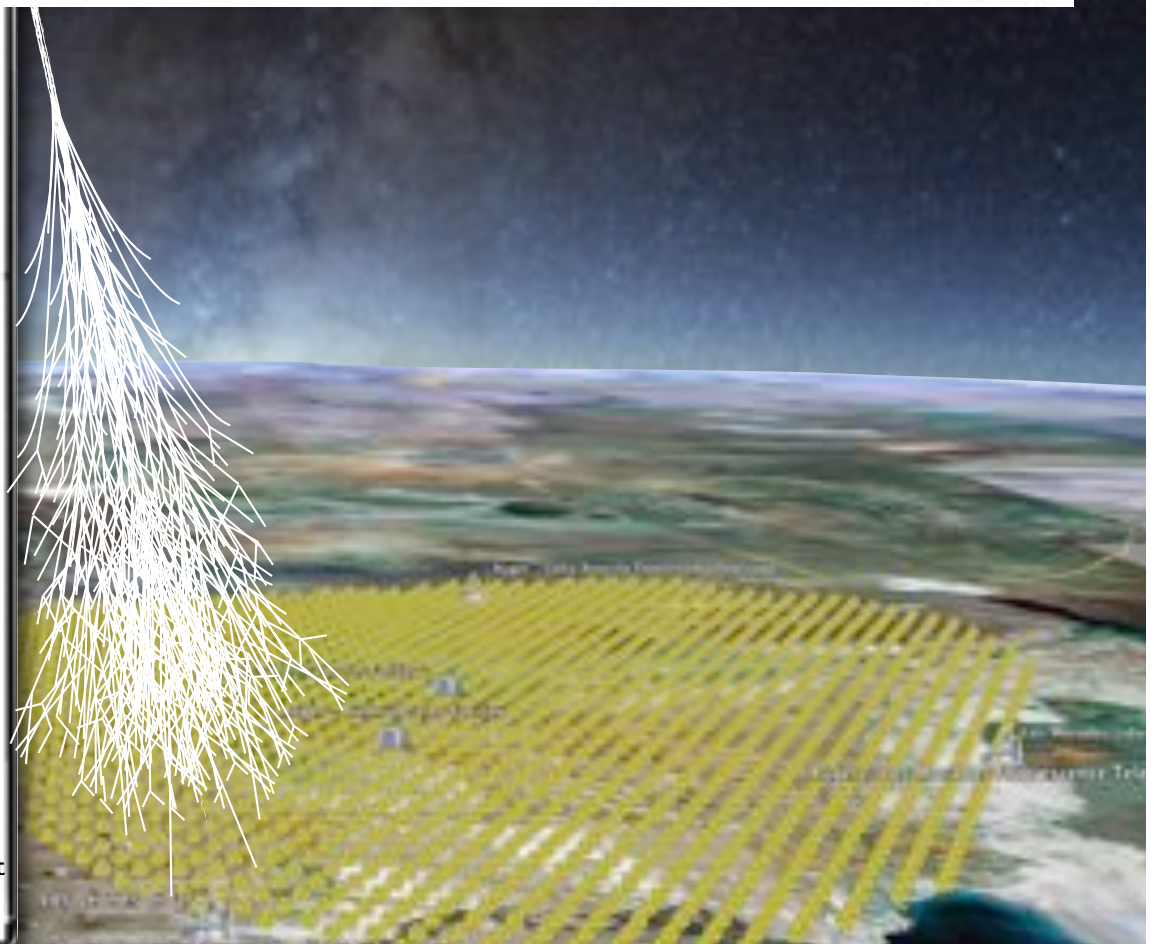
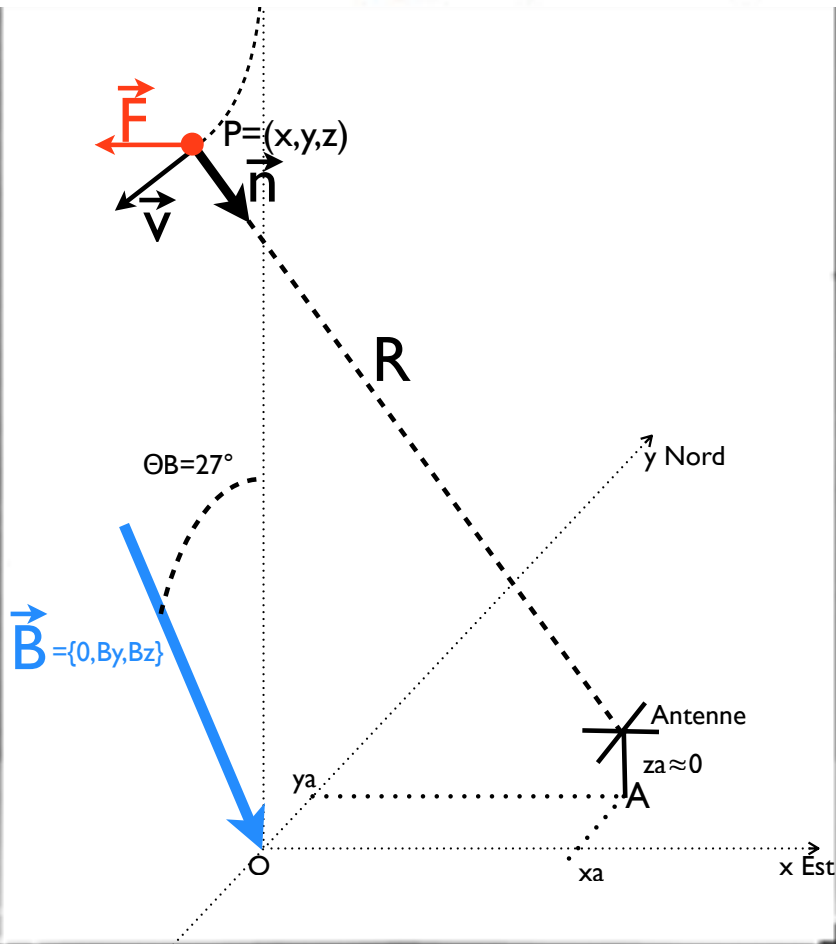
The trajectory of each particle is divided into small segments to compute energy losses

Scattering not included for the moment

Electric field

Electric field emitted by relativistic particles

$$\vec{E}(A, t) = \frac{q}{4\pi\epsilon_0} \left(\left[\frac{\vec{n} - \vec{\beta}}{\gamma^2 (1 - \vec{\beta} \cdot \vec{n})^3 R^2} \right] + \frac{1}{c} \left[\frac{\vec{n} \wedge \left\{ (\vec{n} - \vec{\beta}) \wedge \dot{\vec{\beta}} \right\}}{(1 - \vec{\beta} \cdot \vec{n})^3 R} \right] \right)_{\text{retardé}}$$

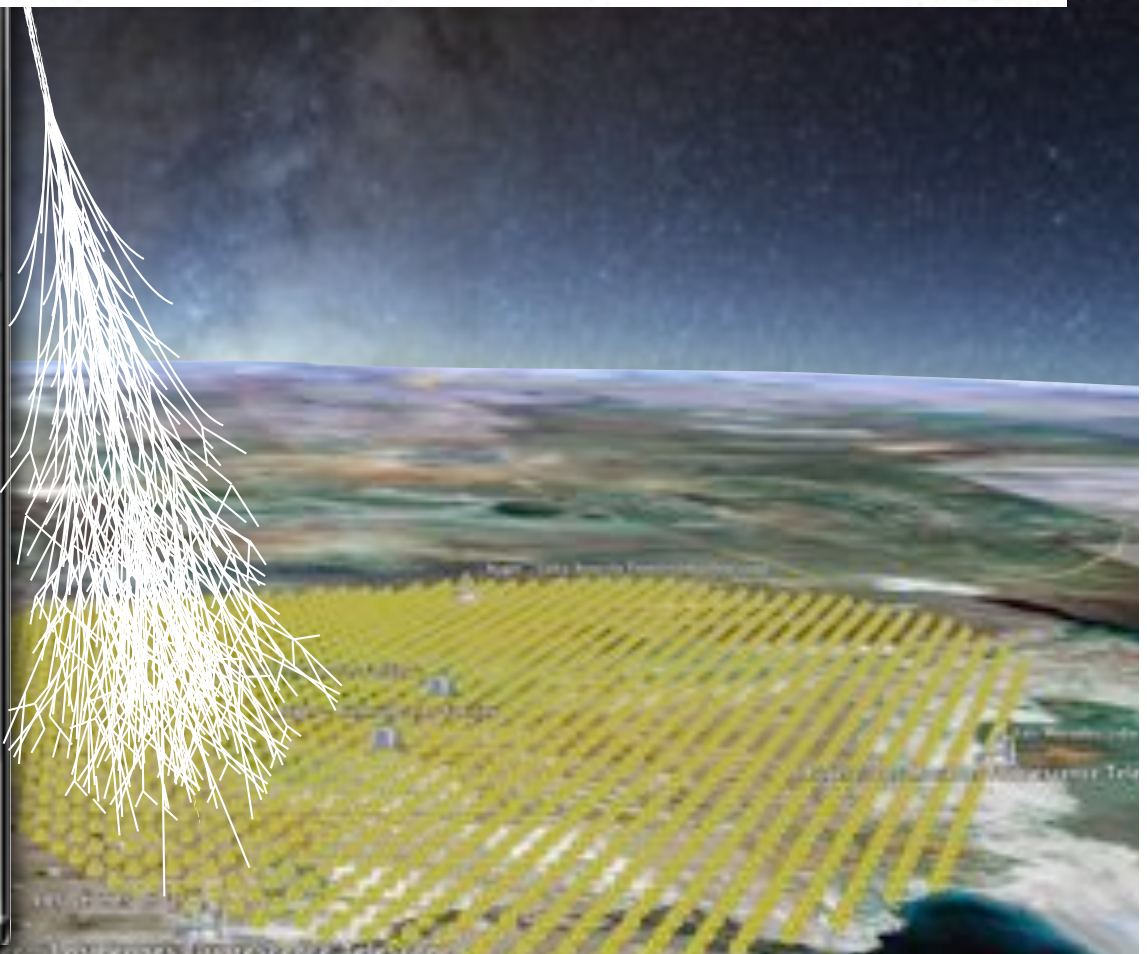
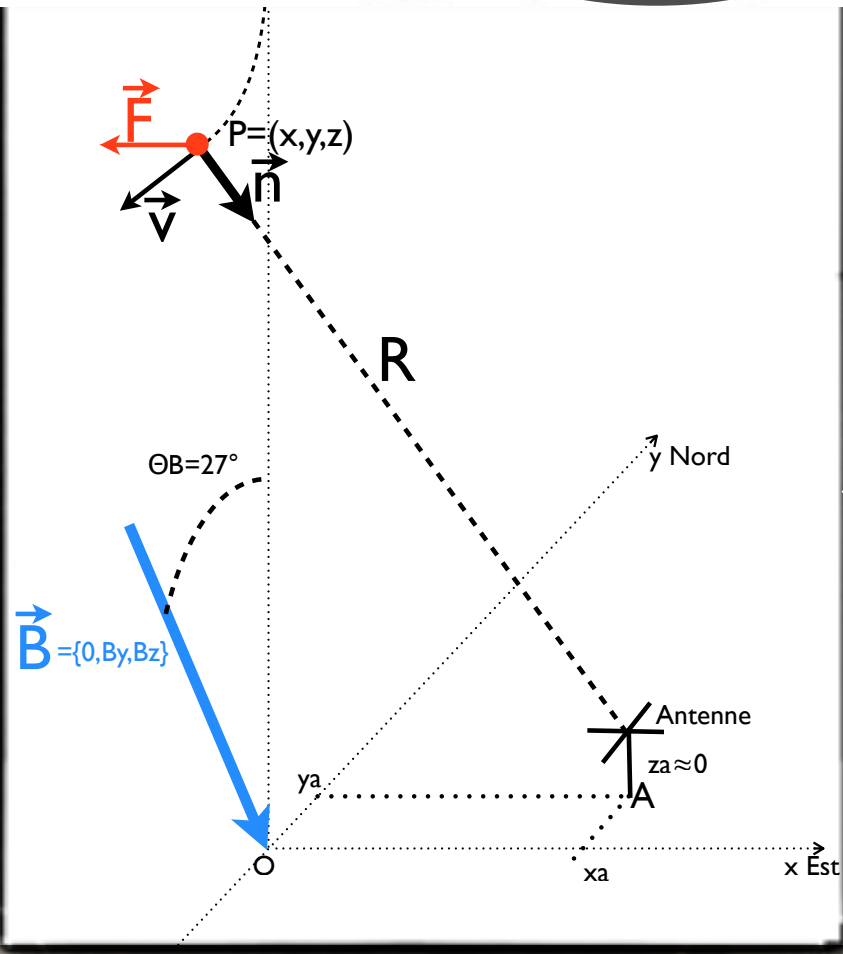


Electric field

Electric field emitted by relativistic particles

$$\vec{E}(A, t) = \frac{q}{4\pi\epsilon_0} \left(\left[\frac{\vec{r}}{\gamma^2 (1 - \vec{\beta} \cdot \vec{n})^3 R^2} \right] + \frac{1}{c} \left[\frac{\vec{n} \wedge \left\{ (\vec{n} - \vec{\beta}) \wedge \dot{\vec{\beta}} \right\}}{(1 - \vec{\beta} \cdot \vec{n})^3 R} \right] \right)_{\text{retardé}}$$

Coulombian part
Neglected

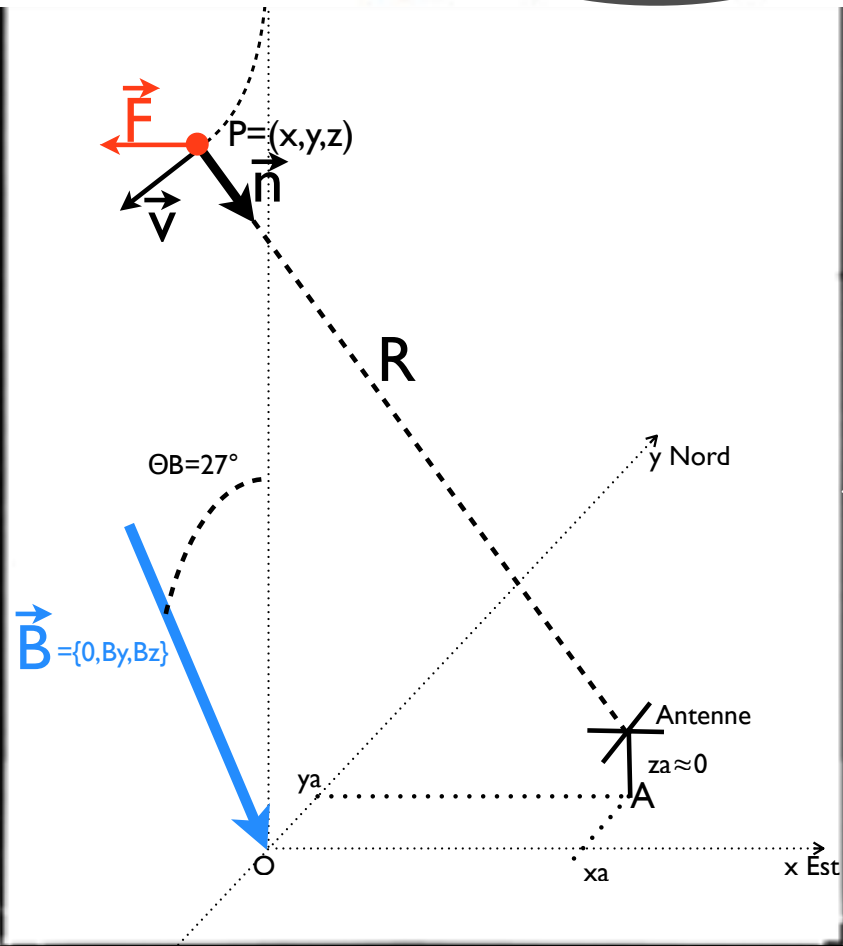


Electric field

Electric field emitted by relativistic particles

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Coulombian part
Neglected



- \vec{a} Acceleration
- \vec{v} Velocity
- \vec{r} Position
- R Part-ant distance
- \vec{n} Part-ant vector

Electric field

Electric field emitted by relativistic particles

$$\vec{E}(A, t) = \frac{q}{4\pi\epsilon_0} \left(\left[\frac{\vec{r}_2 - \vec{r}_1}{\gamma^2 (1 - \vec{\beta} \cdot \vec{n})^3 R^2} \right] + \frac{1}{c} \left[\frac{\vec{n} \wedge \left\{ (\vec{n} - \vec{\beta}) \wedge \dot{\vec{\beta}} \right\}}{(1 - \vec{\beta} \cdot \vec{n})^3 R} \right] \right)_{\text{retardé}}$$

Coulombian part
Neglected

delayed time for reception

$$t_{\text{reception}} = t_{\text{emission}} + R/c$$

To avoid time consuming procedure of signal interpolation for each reception time bin, we solve:

$$t_{\text{reception}} = f(t_{\text{emission}})$$

to obtain $t_{\text{emission}} = f(t_{\text{reception}})$

$\vec{\beta} \cdot \dot{\vec{\beta}}$
 $\vec{\beta}$
 \vec{P}
 O
 R
 \vec{n}

Acceleration

Velocity

Position

Part-ant distance

Part-ant vector

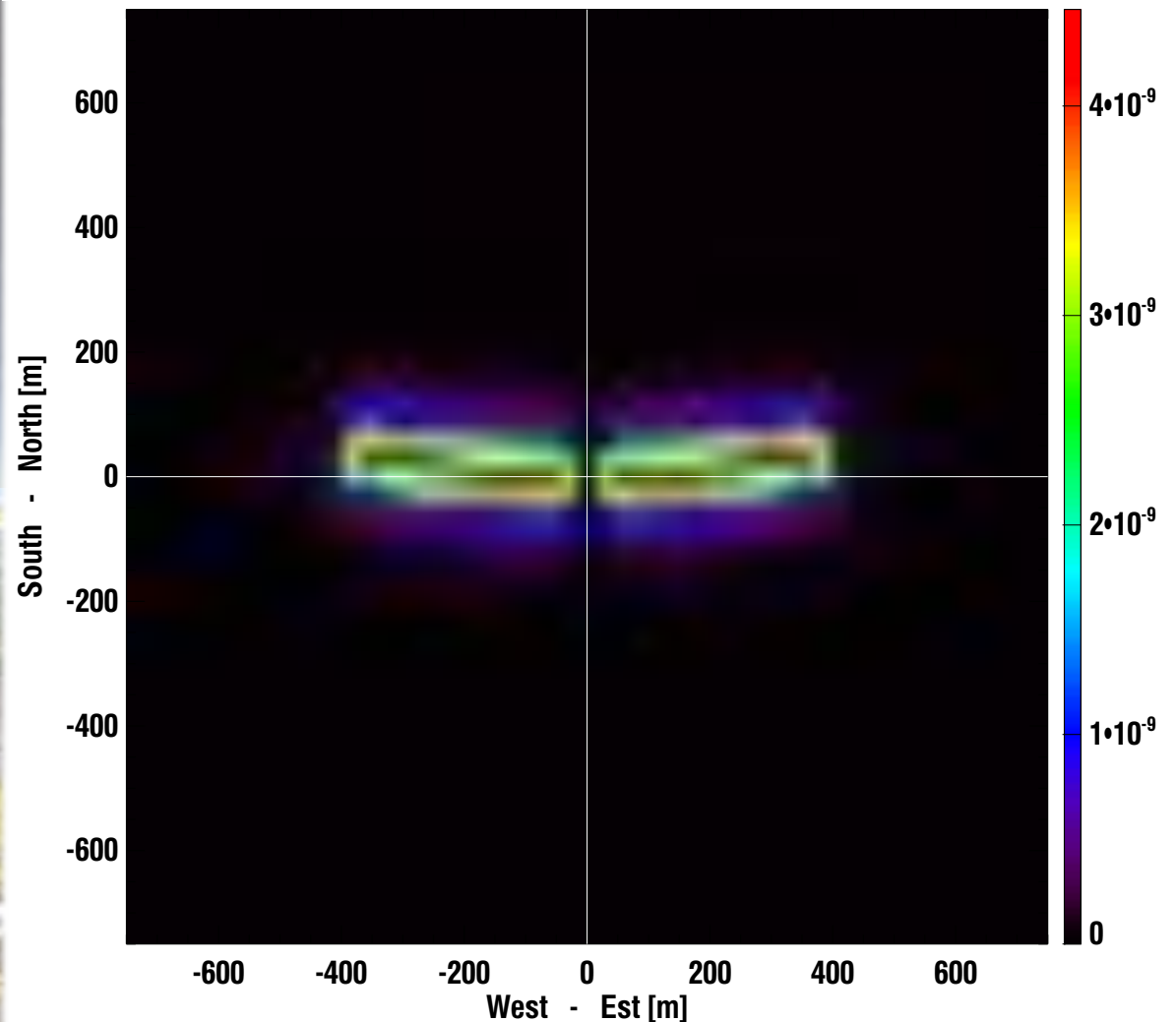
Electron-positron pair example

Ground footprint of
 $\text{Max } |E_{EW}(t)|$

generated by
electron/positron pair

initially injected in (0,0,4000 m)
vertical initial velocity $p = 30 \text{ MeV}$
travel length : 1500 m

EW component of the electric field emitted by an
electron-positron pair



Electron-positron pair example

Ground footprint of
 $\text{Max } |E_{EW}(t)|$

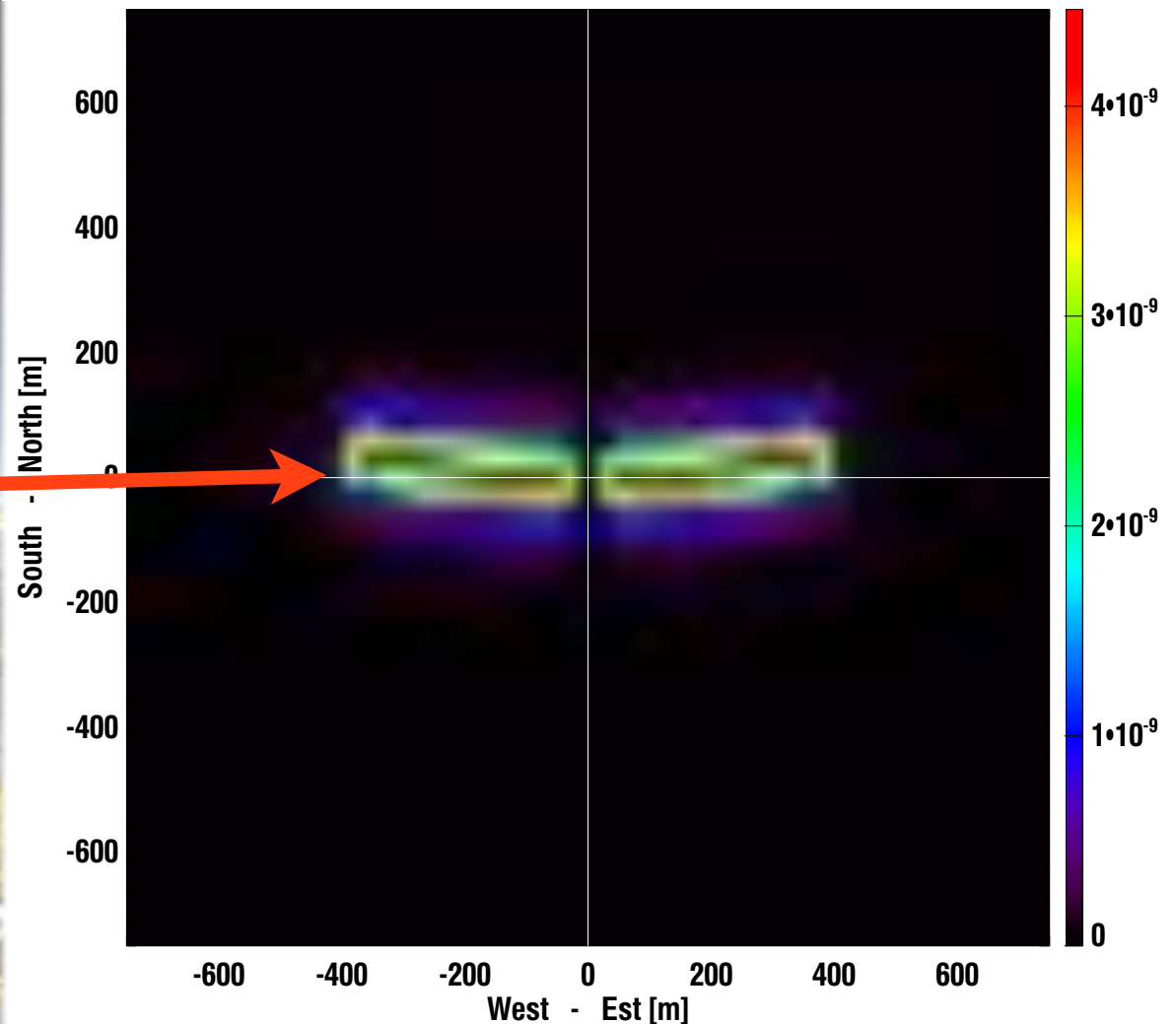
generated by
electron/positron pair

initially injected in (0,0,4000 m)
vertical initial velocity $p = 30 \text{ MeV}$
travel length : 1500 m

Narrow band

Synchrotron radiation
strongly confined in a
emission cone.
Used to accelerate
computations.

EW component of the electric field emitted by an
electron-positron pair





A simple case

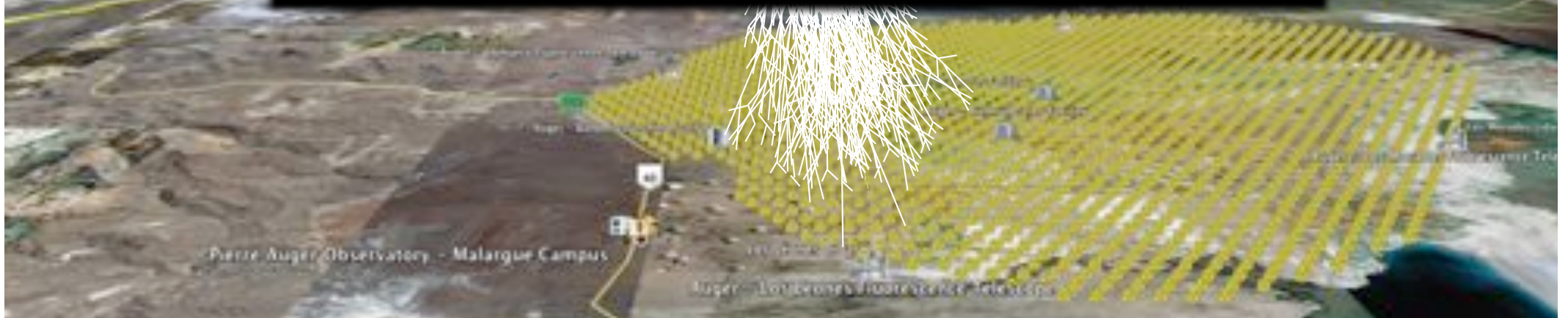
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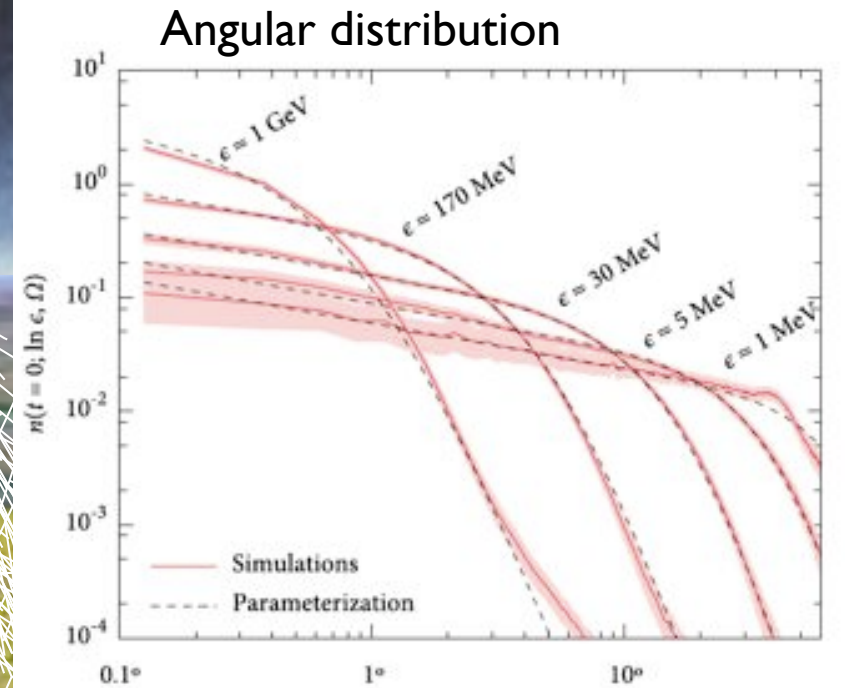
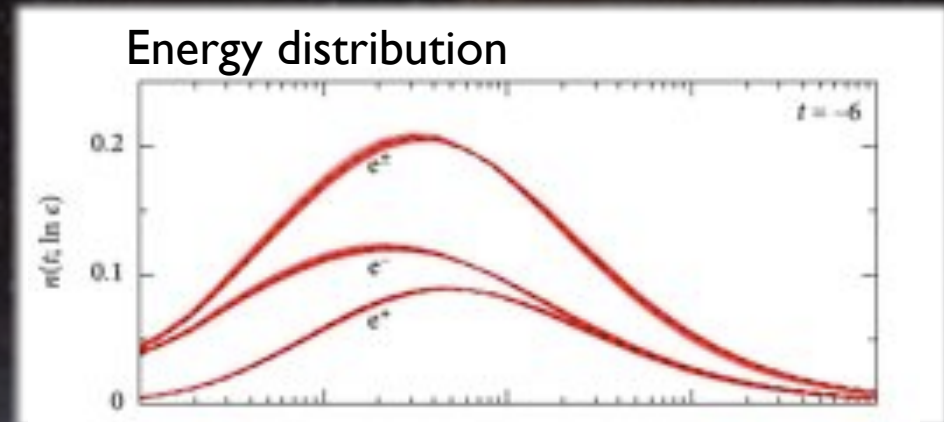
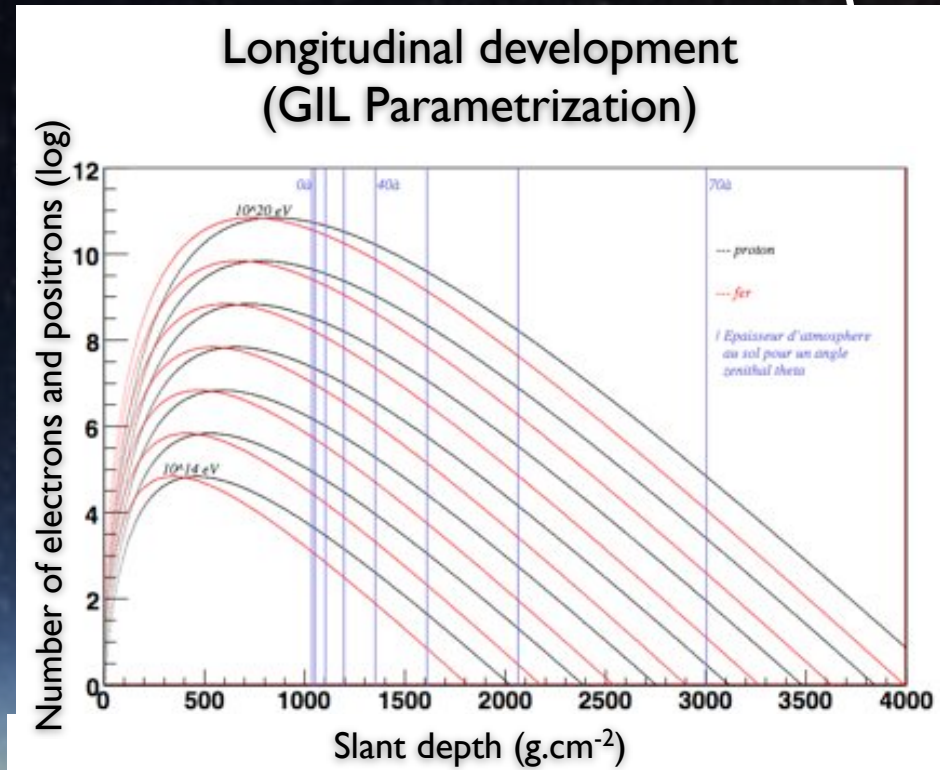
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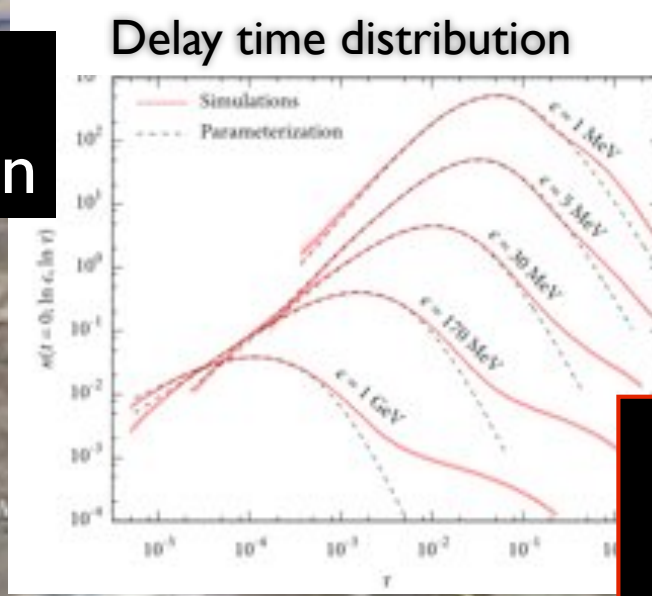


Air shower geometrical description

What we need :



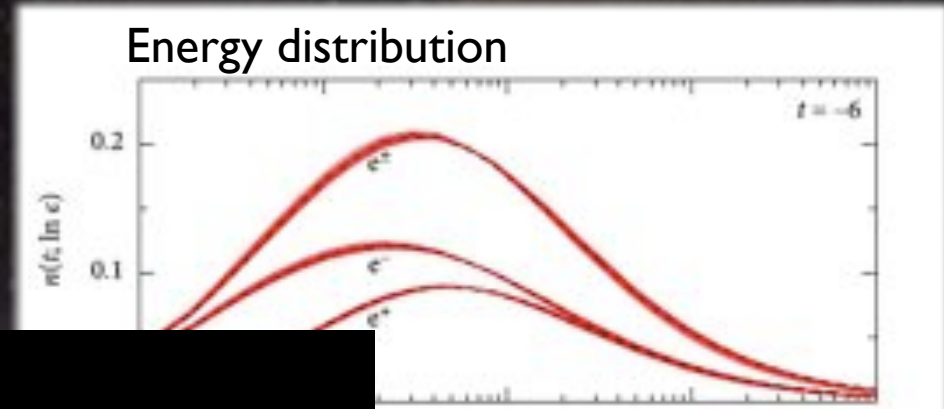
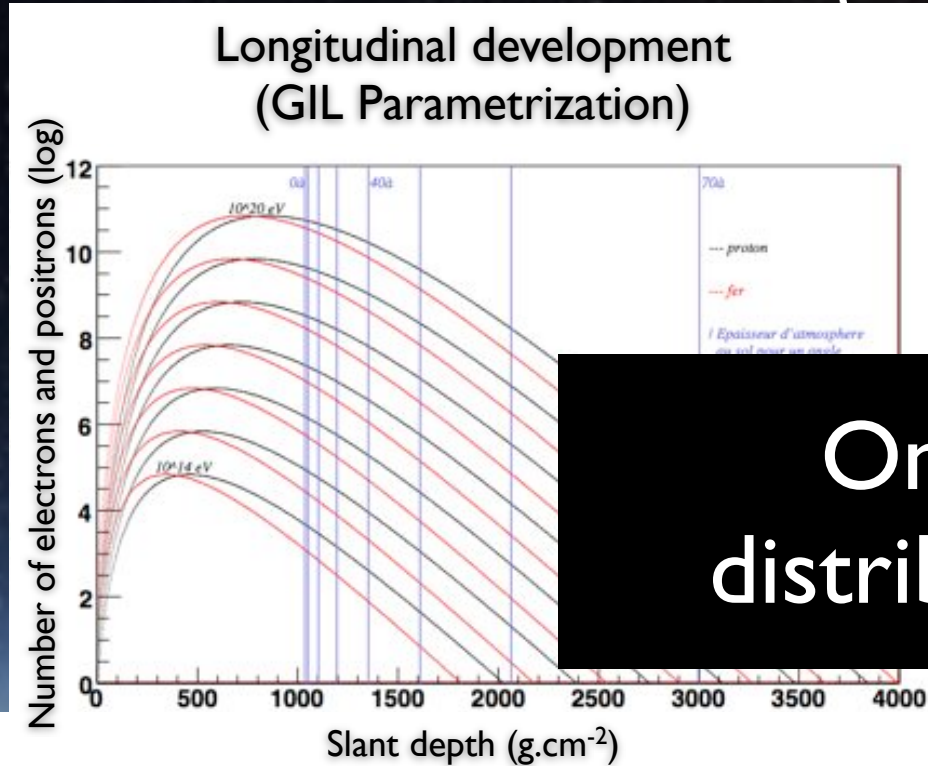
Pancake description



Well described in :
arXiv:0902.0548v1 Lafebre et al

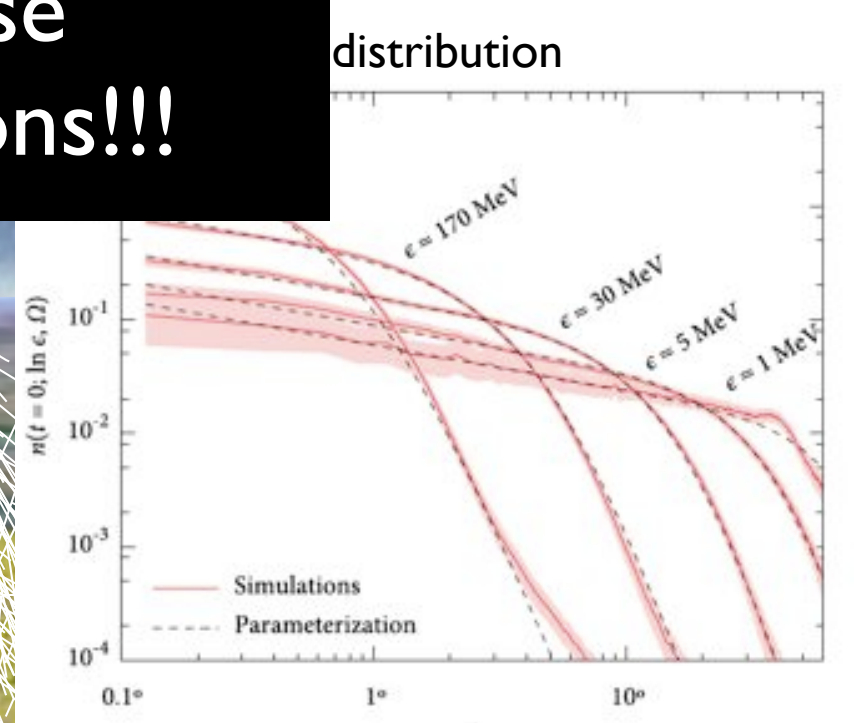
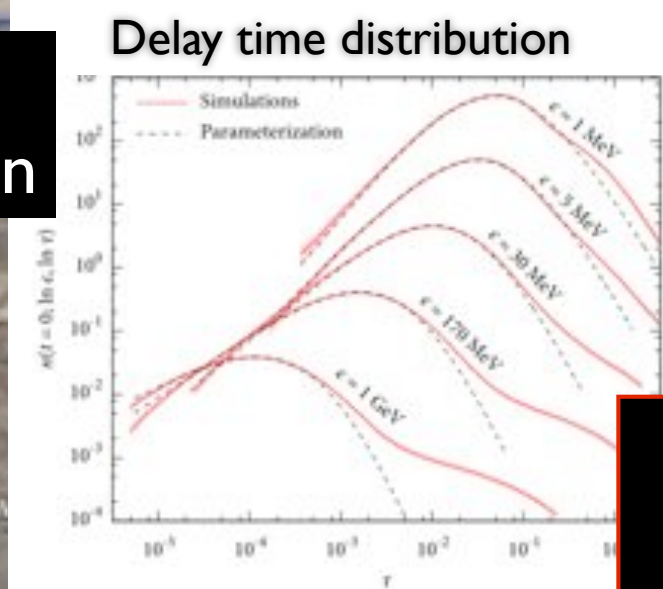
Air shower geometrical description

What we need :



Only use
distributions!!!

Pancake
description



Well described in :
arXiv:0902.0548v1 Lafebre et al

Assumptions :

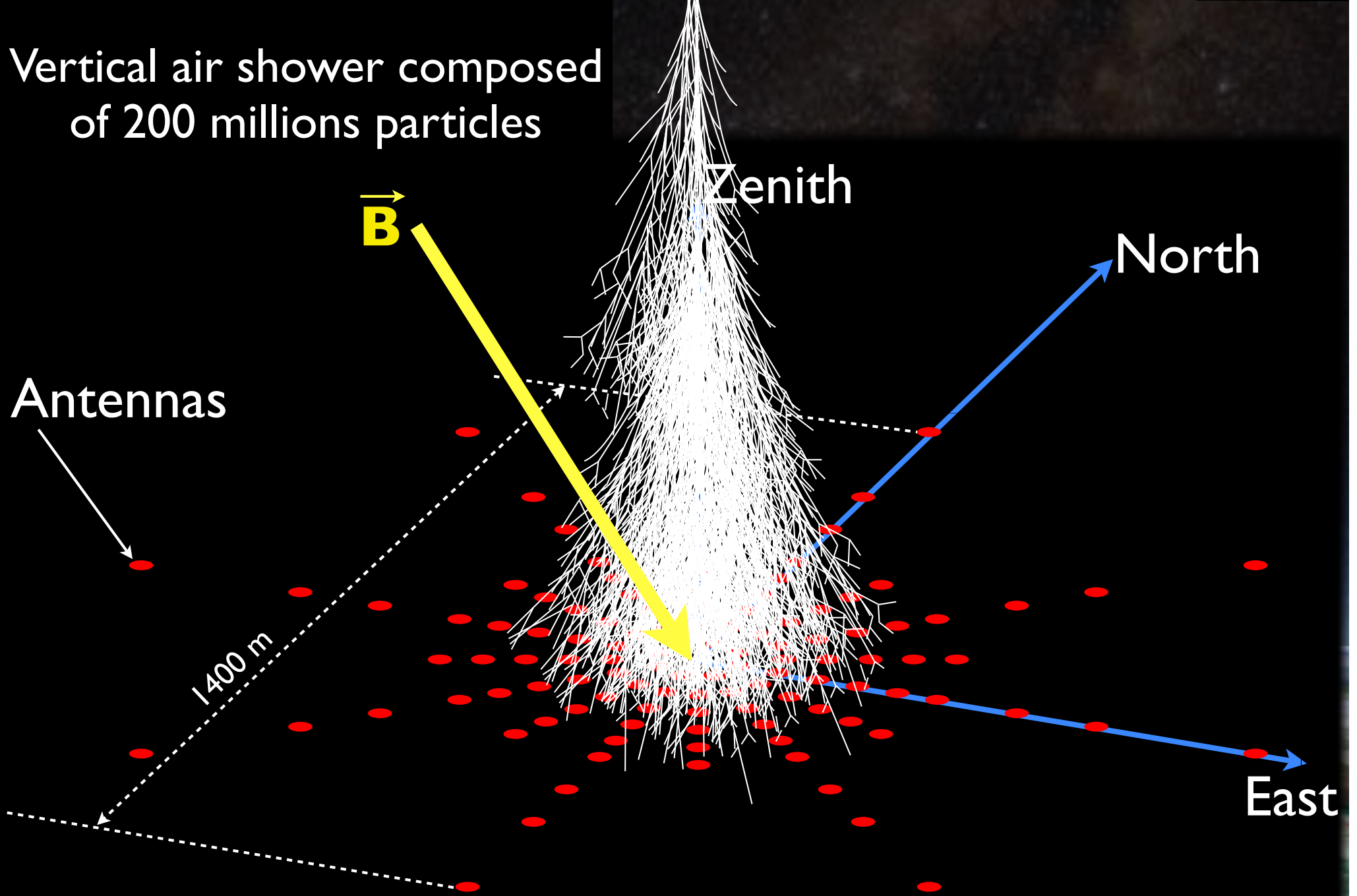
Same random initial conditions for electrons and positrons of the same pair,

Scattering (coulombian diffusions) not taken into account,

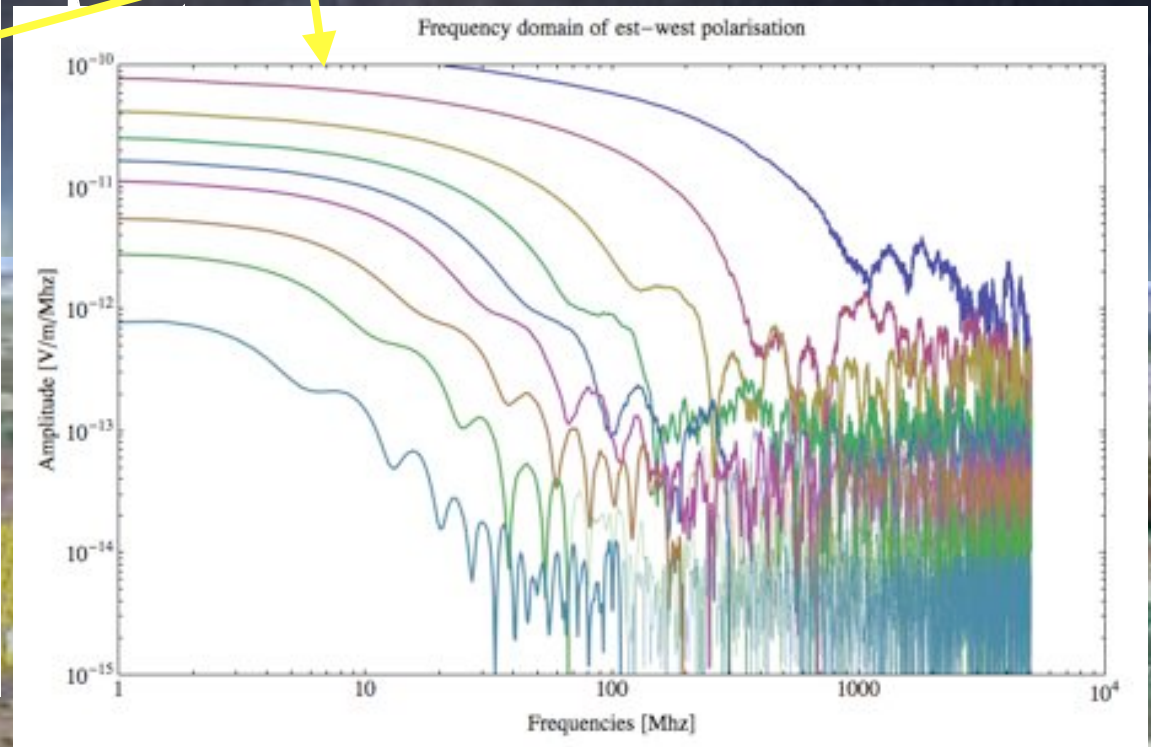
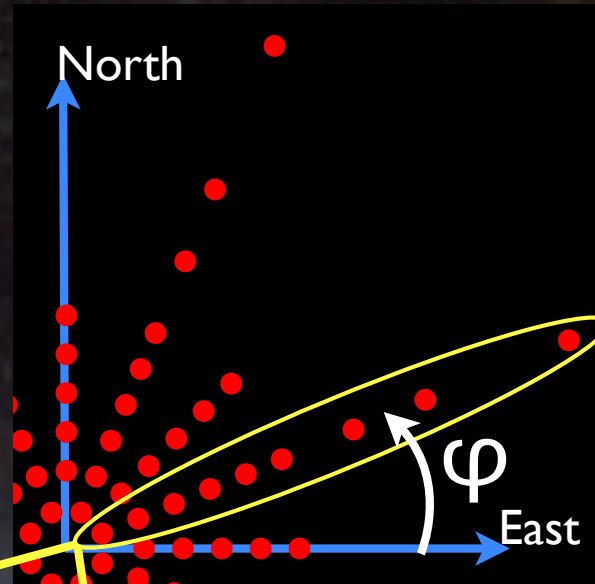
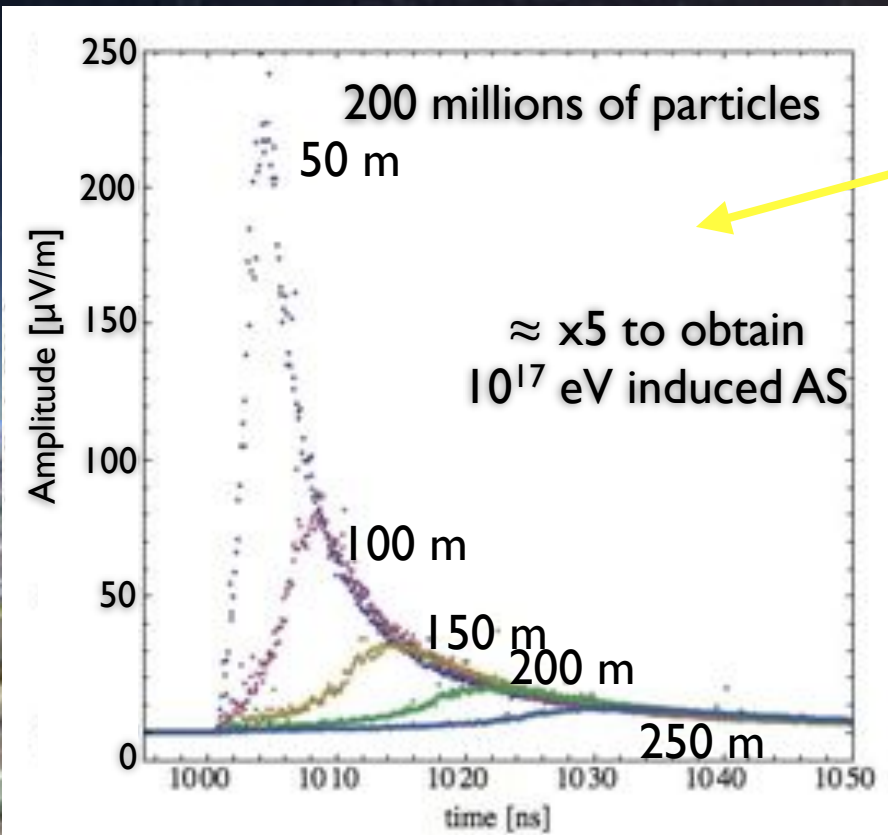
Mean free path of particle $X_0=36.62 \text{ g cm}^{-2}$
(air density changing with altitude),

Air refractive index equal to 1,
(no Cerenkov radiations).

Vertical air shower composed
of 200 millions particles

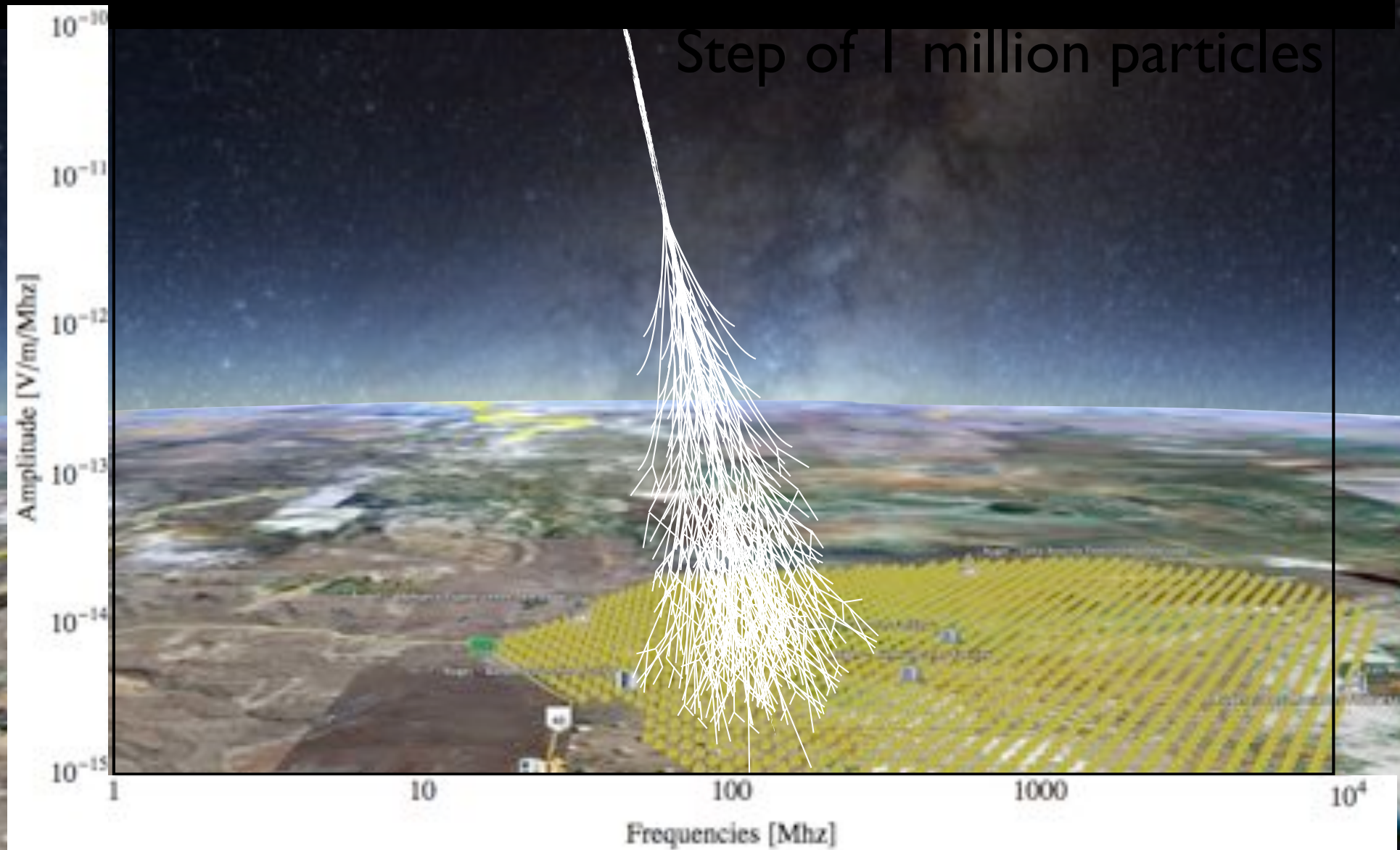


Different impulsions for different distances from air shower axis:



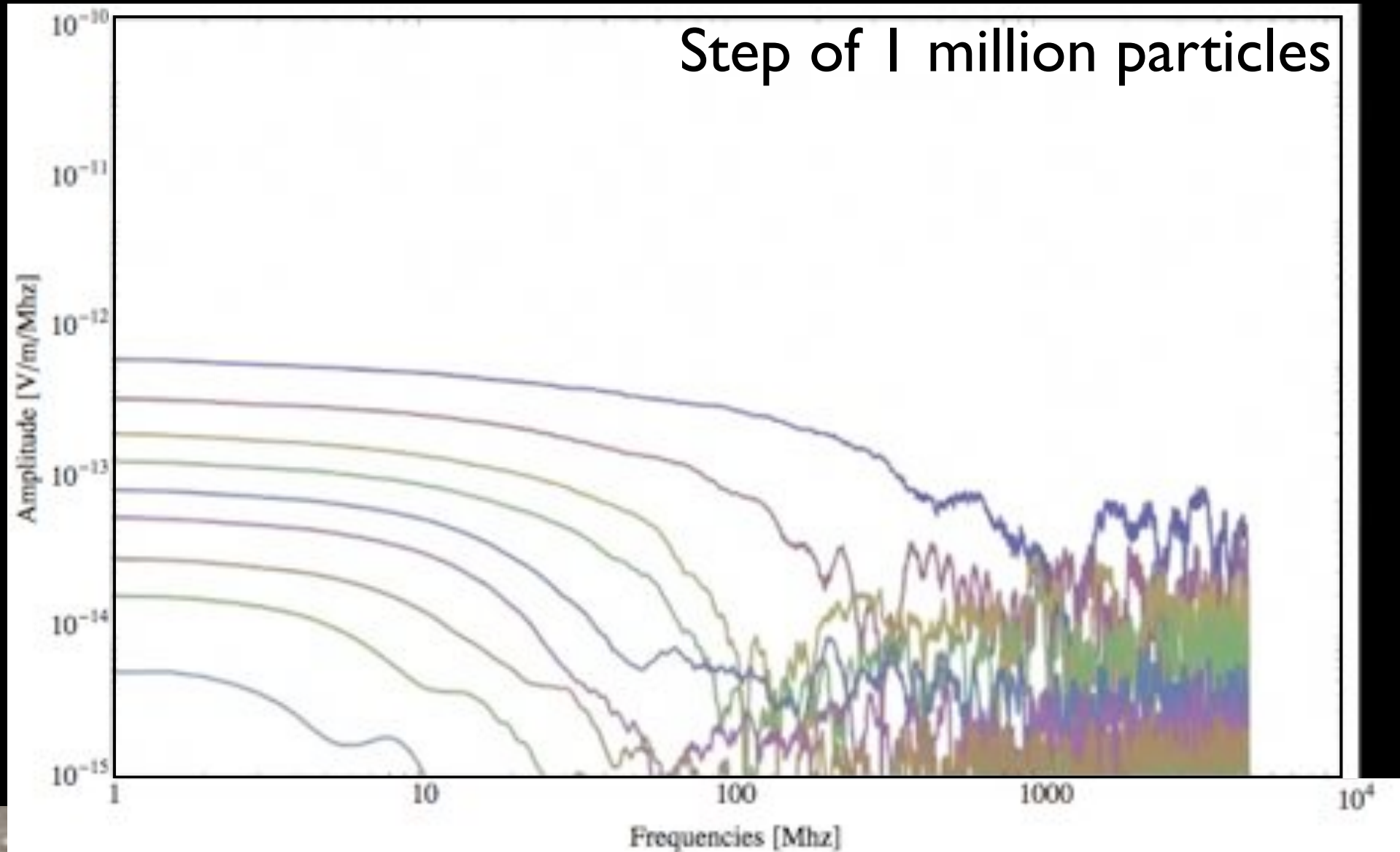
Analysis

Power deposited in function of particles number:
Evolution of spectra with particles number,
from 1 million to 200 millions.



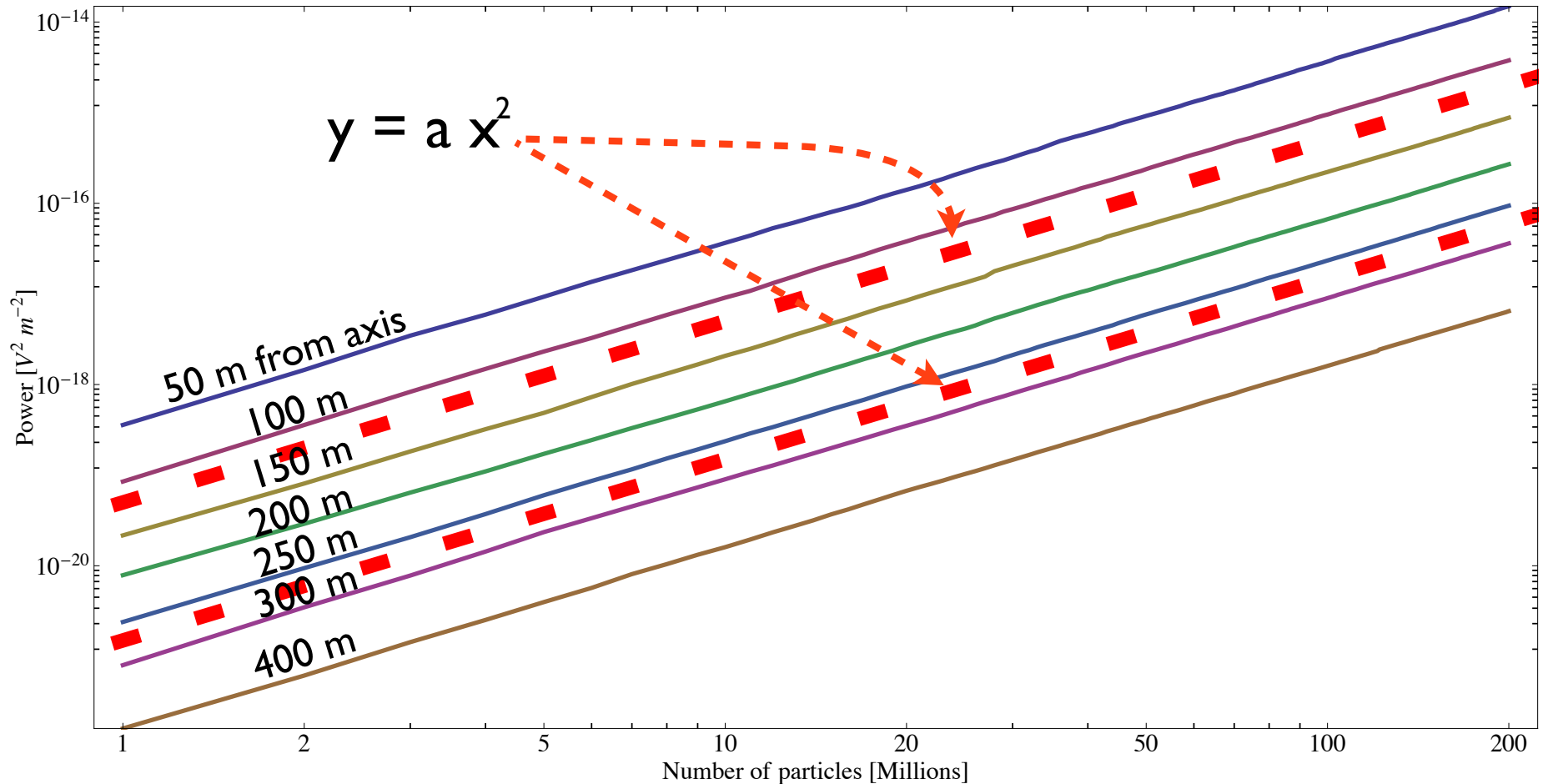
Analysis

Power deposited in function of particles number:
Evolution of spectra with particles number,
from 1 million to 200 millions.



Analysis

Integral of spectra between 1 and 50 MHz



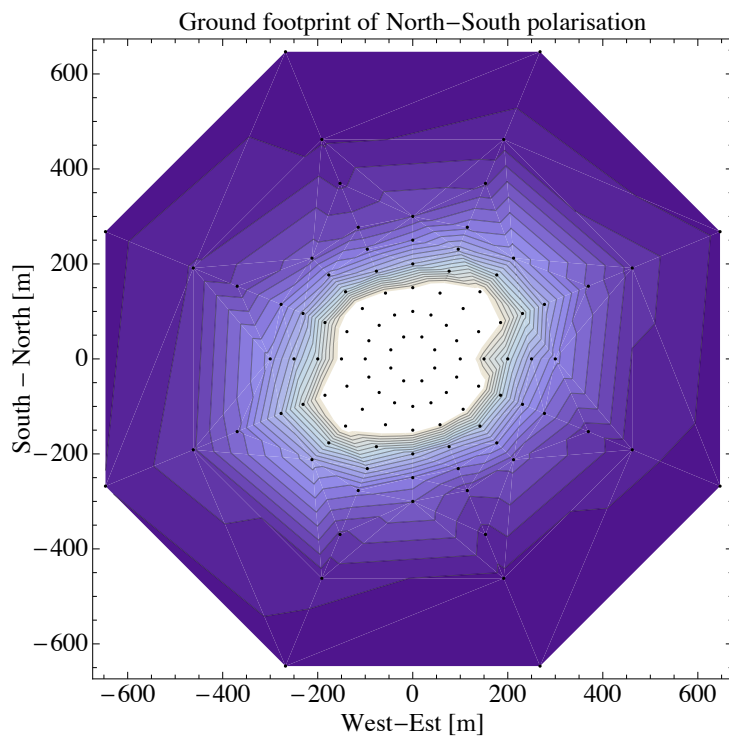
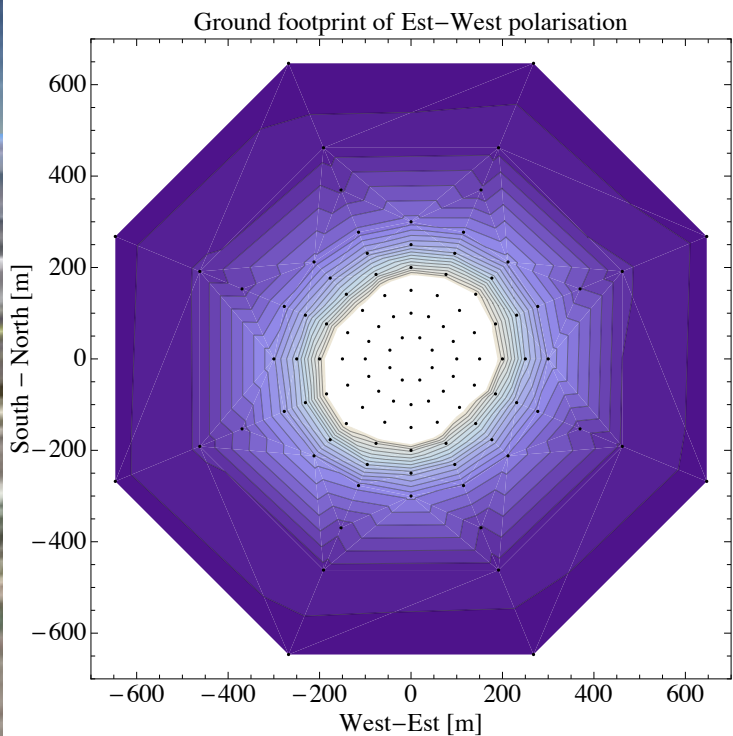
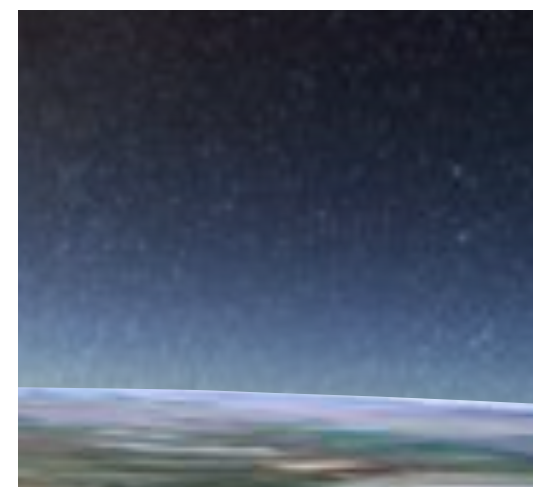
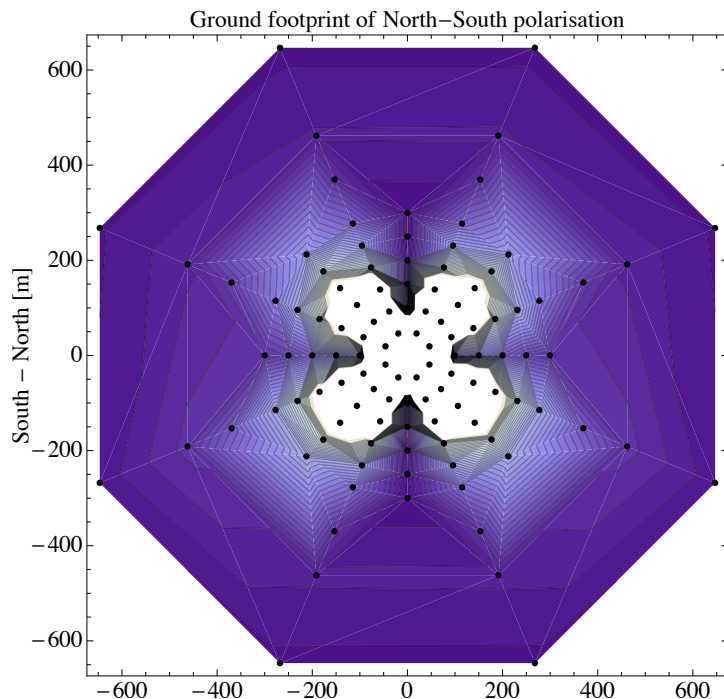
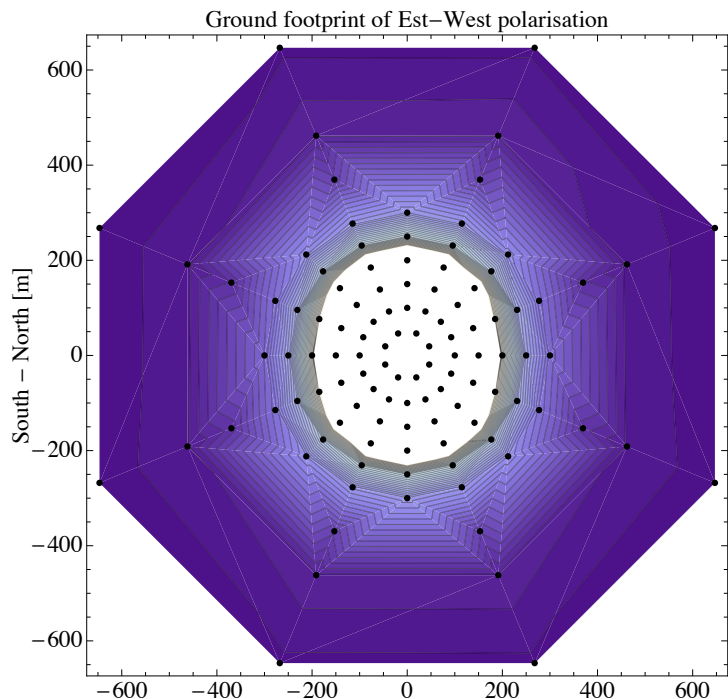
This behavior could give us directly a theoretical law between primary energy and signal observed.

East-West polarisation

North-South polarisation

Ground footprint

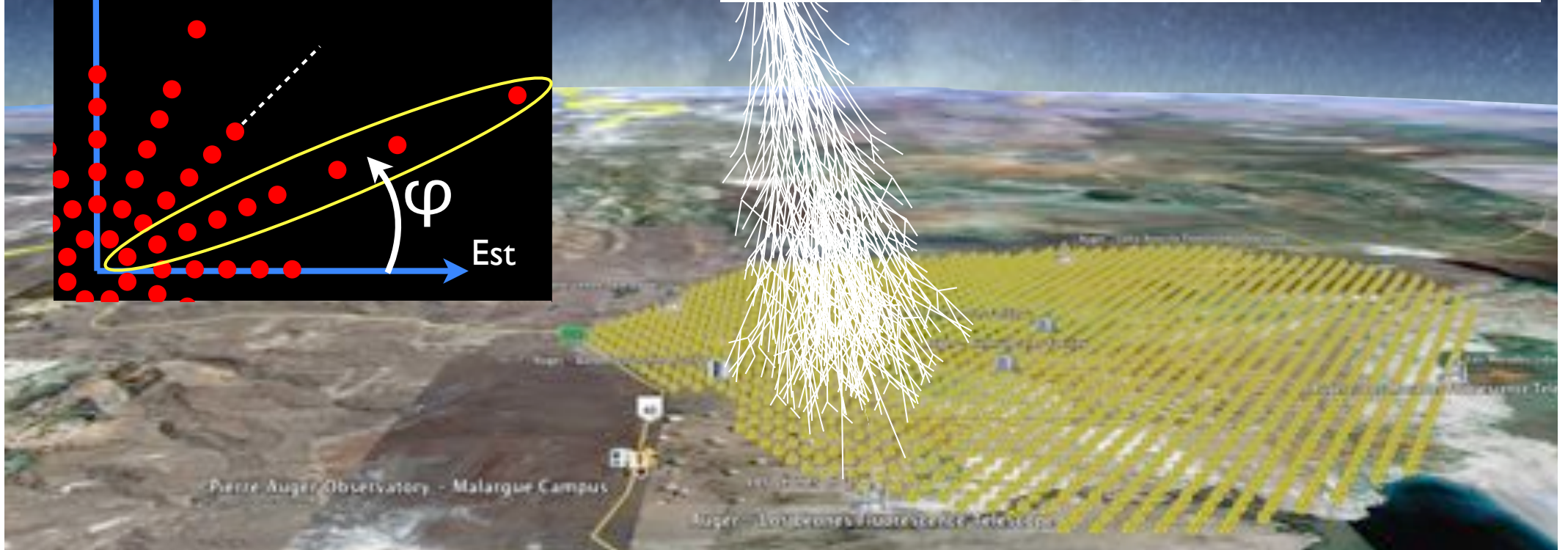
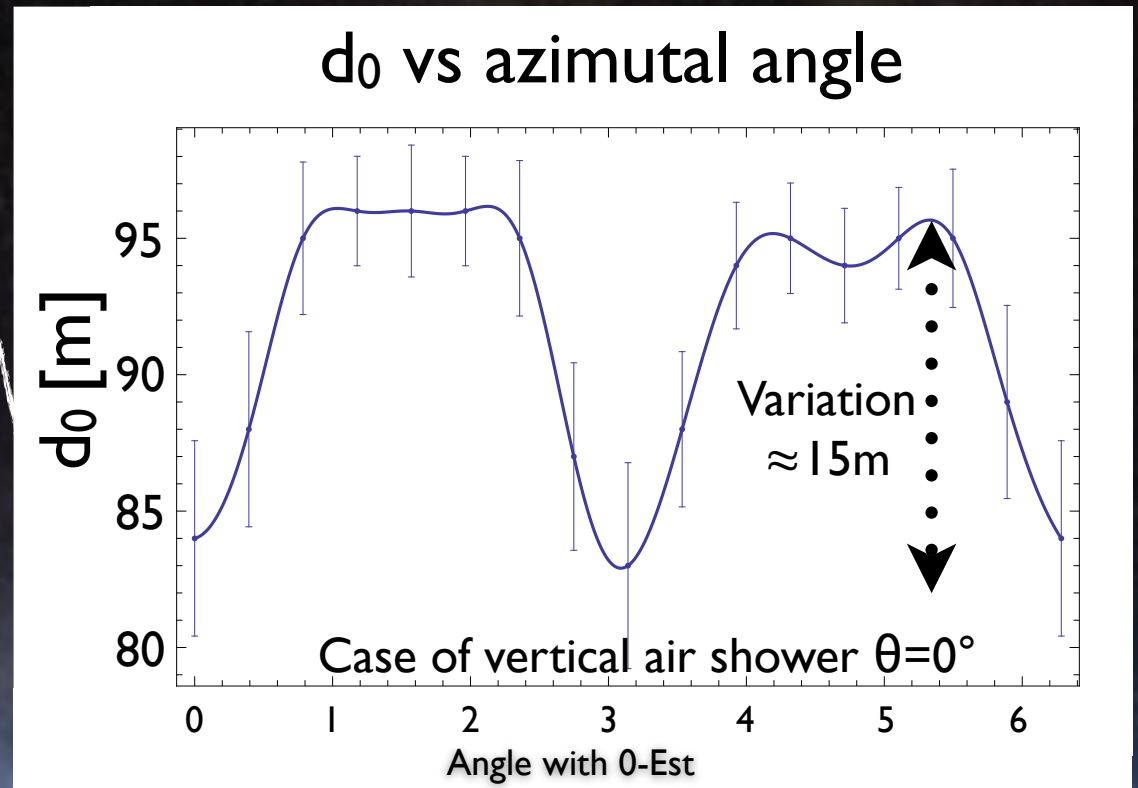
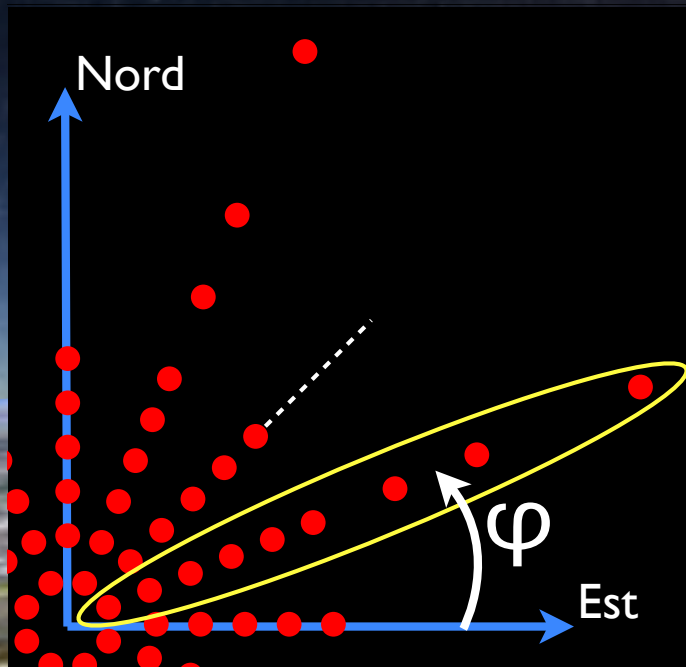
Vertical AS
 $\theta=0^\circ$ $\varphi=0^\circ$



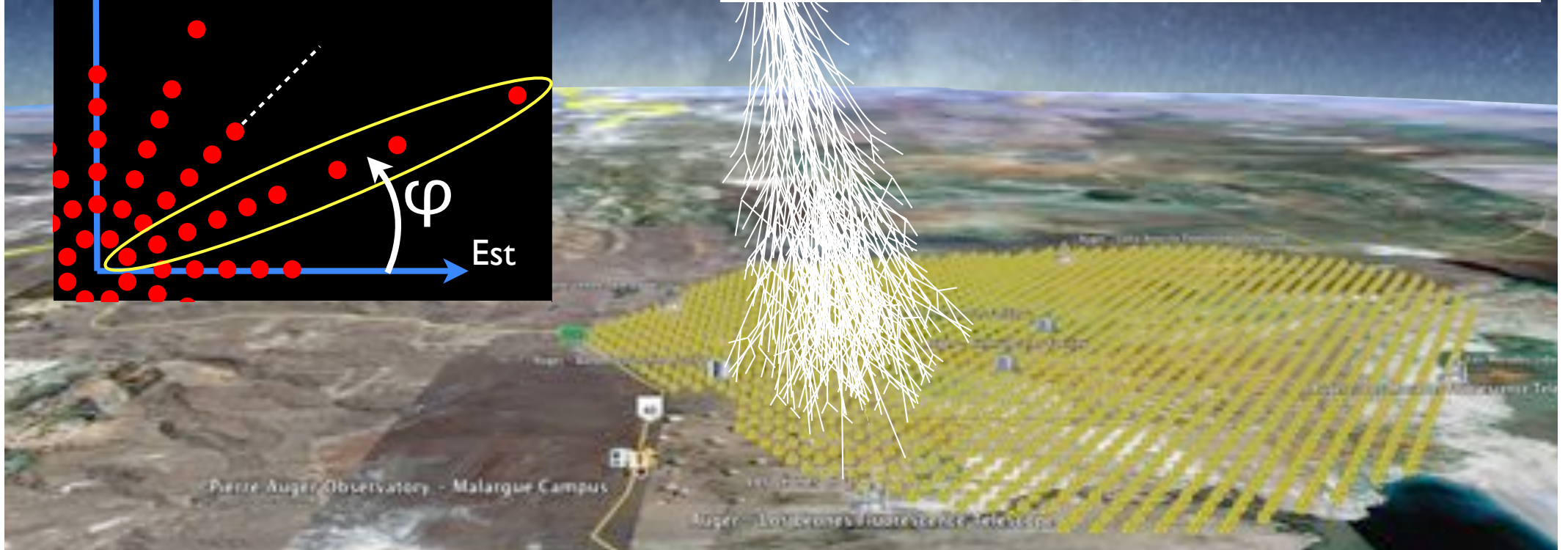
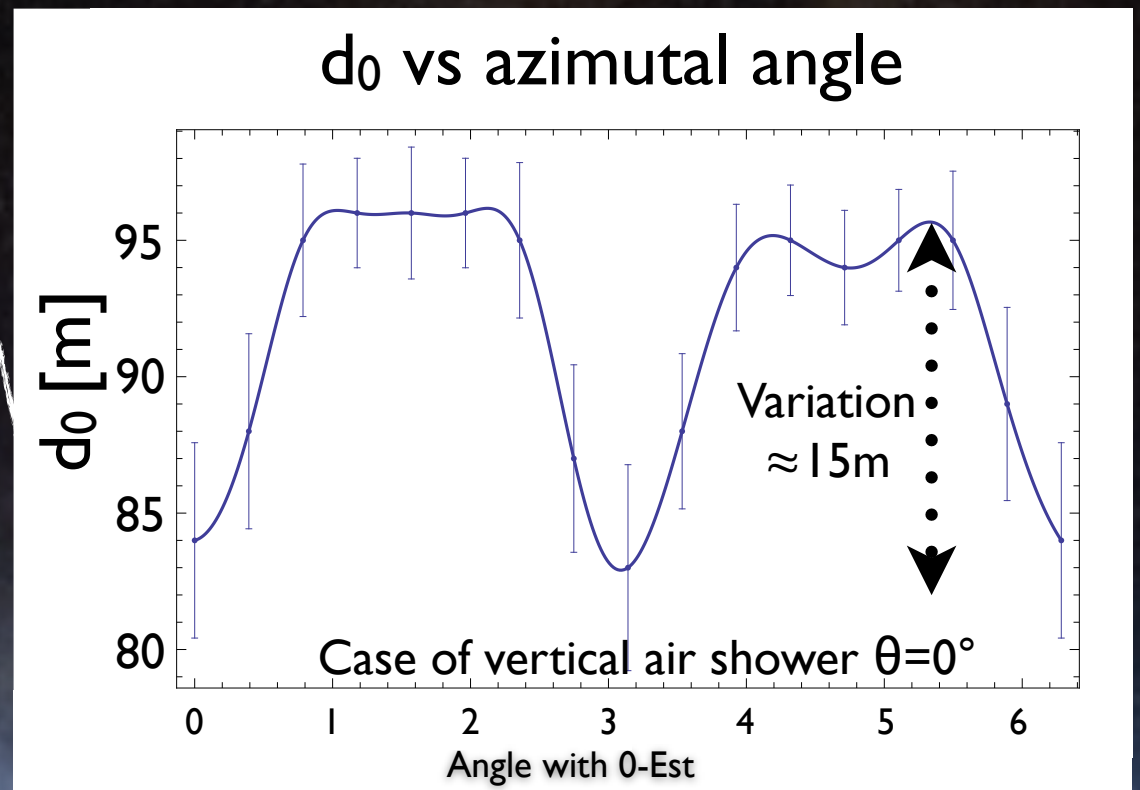
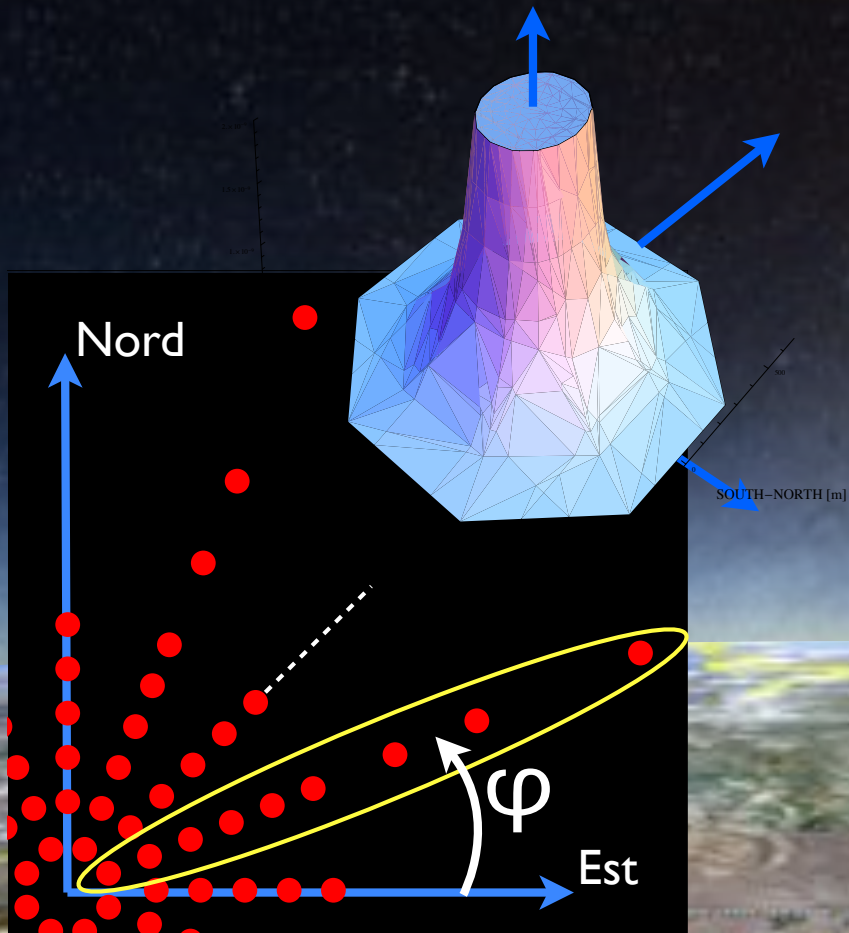
Inclined AS
 $\theta=40^\circ$ $\varphi=45^\circ$



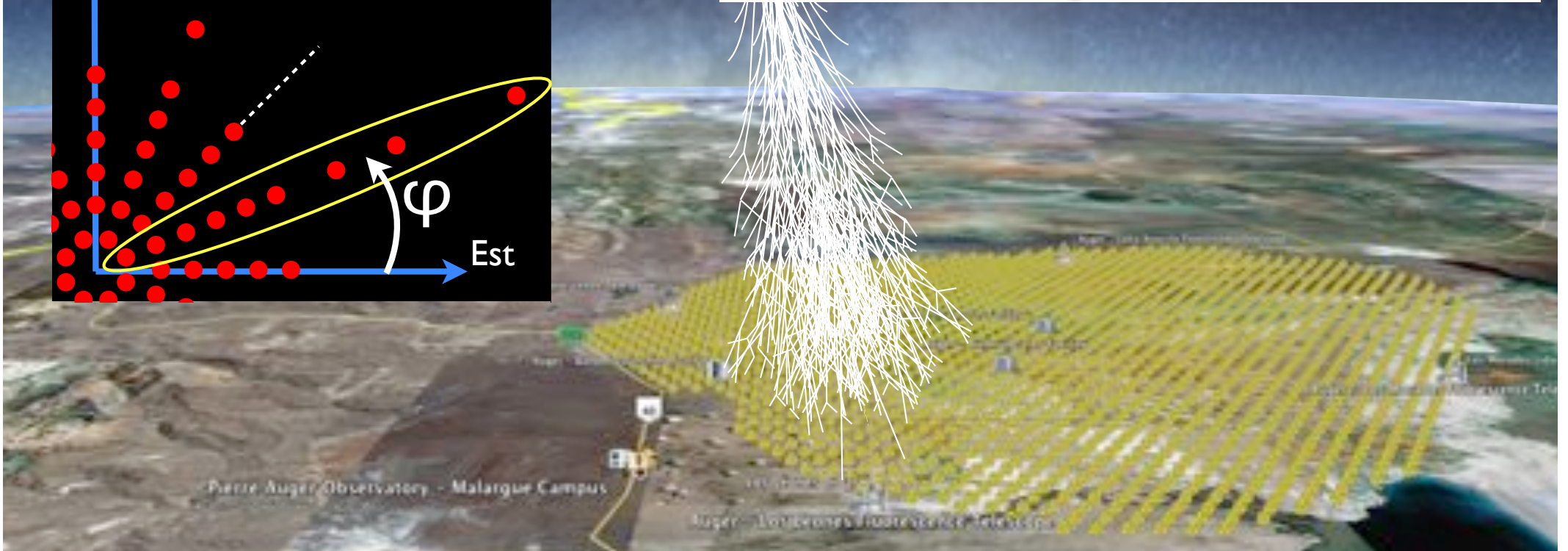
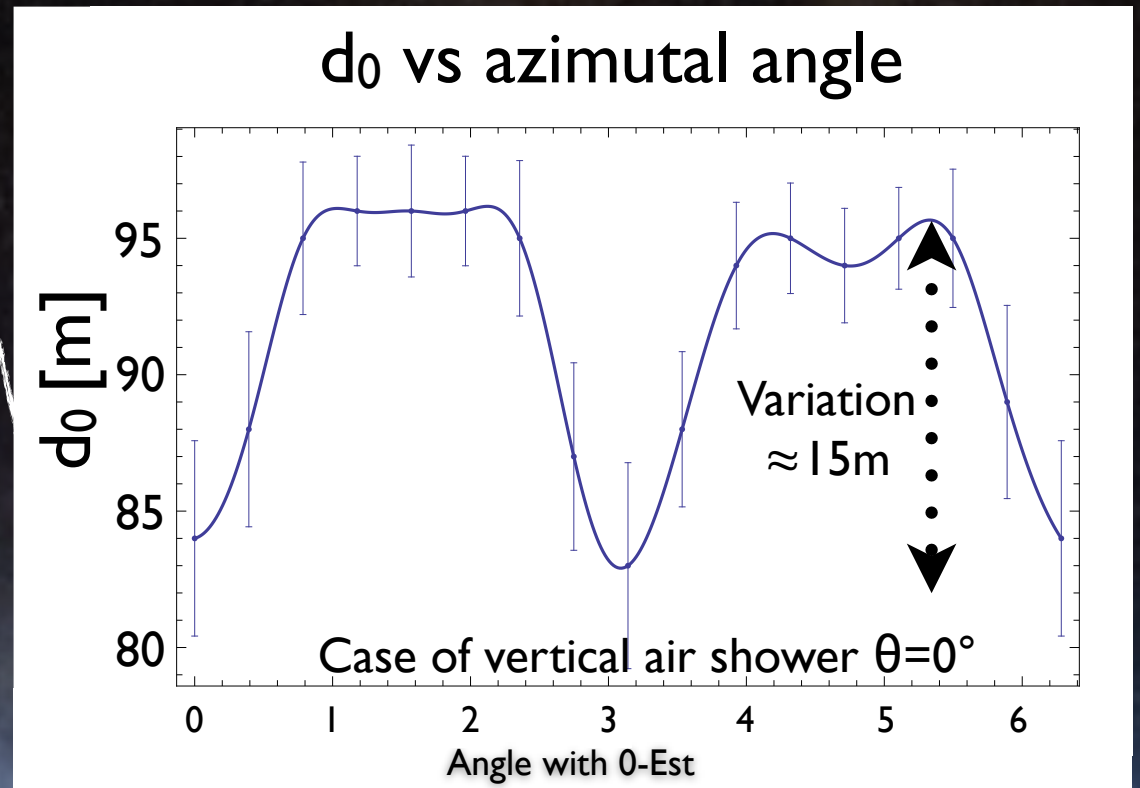
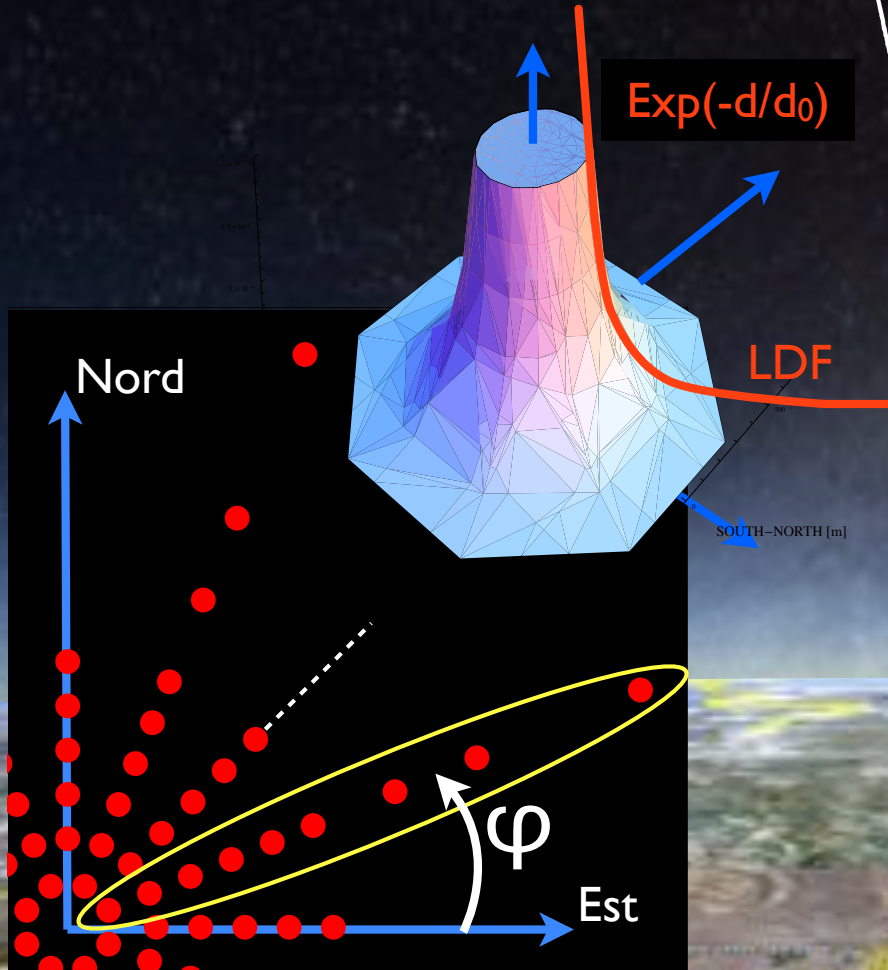
First Analysis



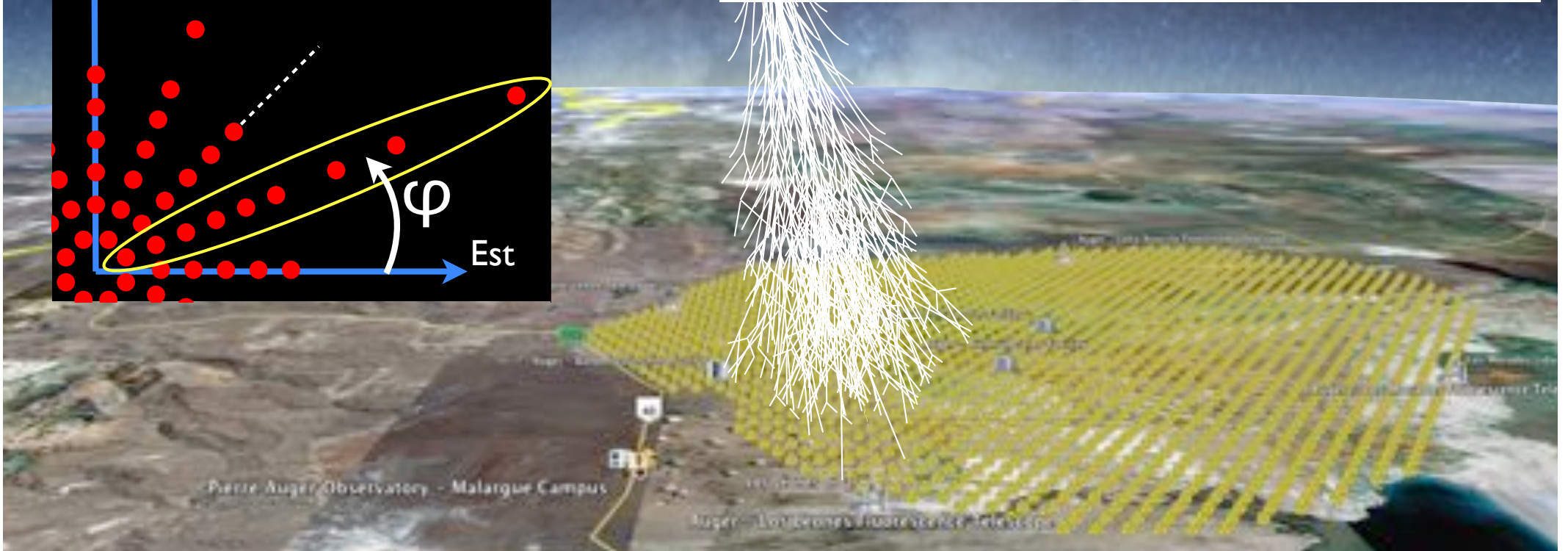
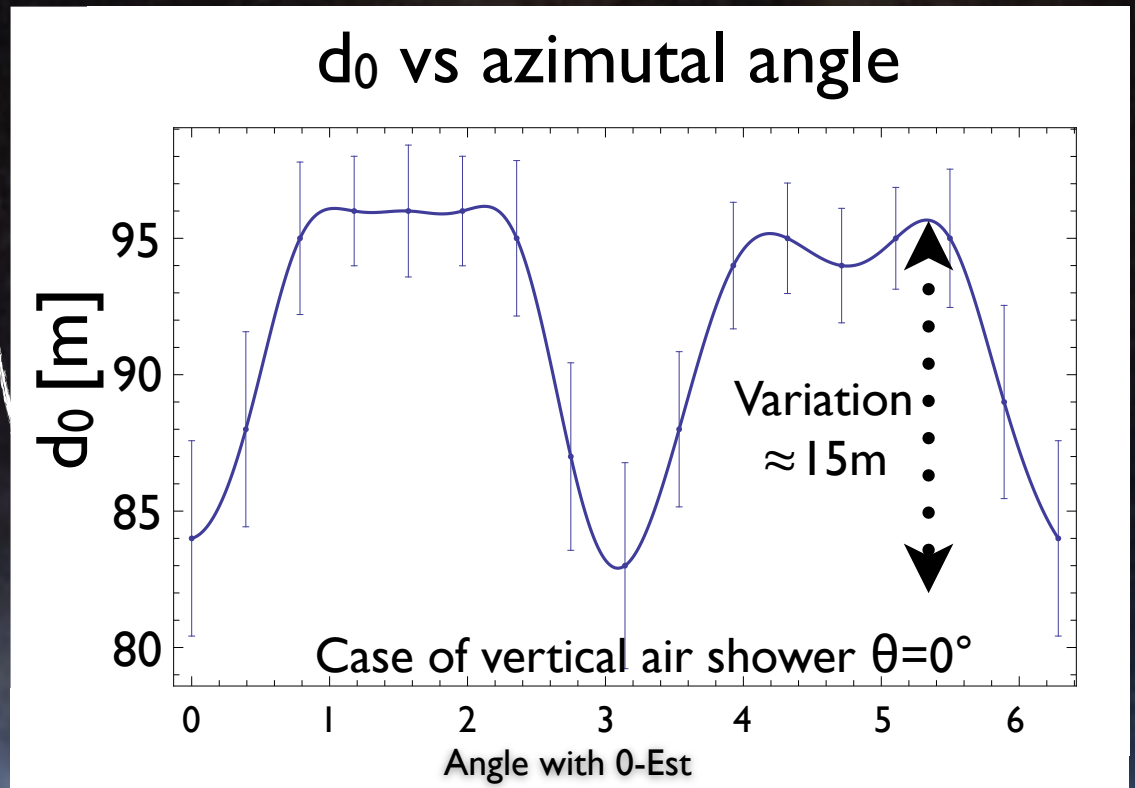
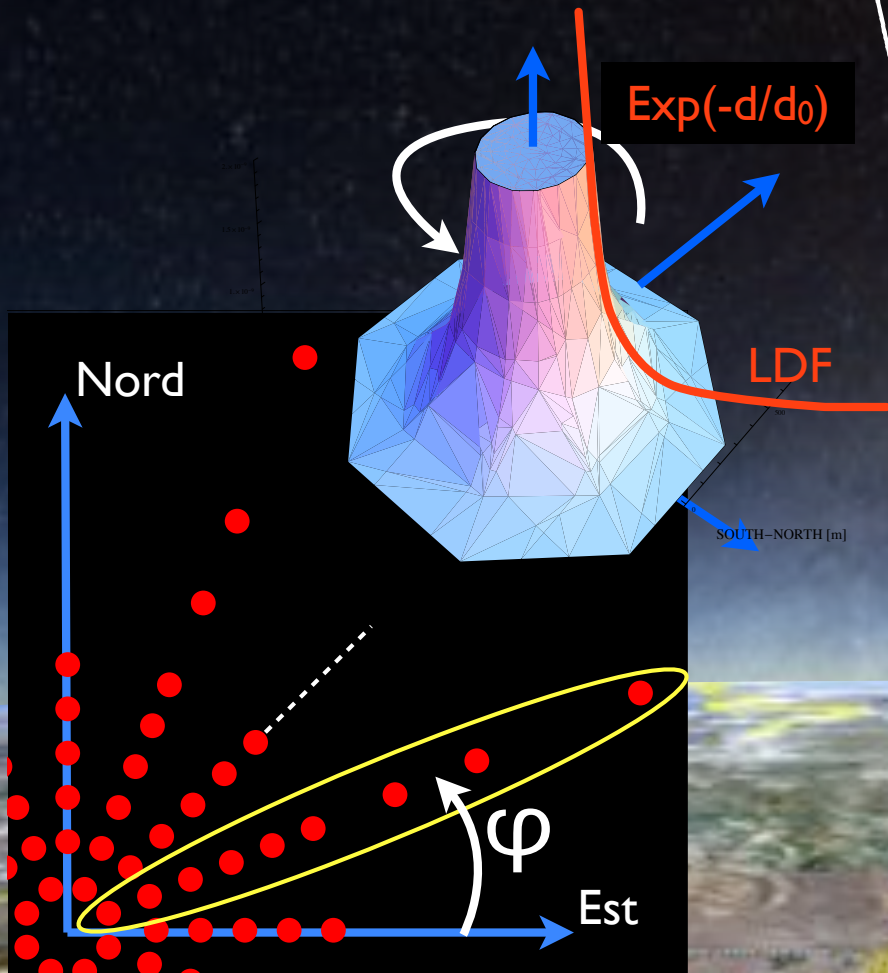
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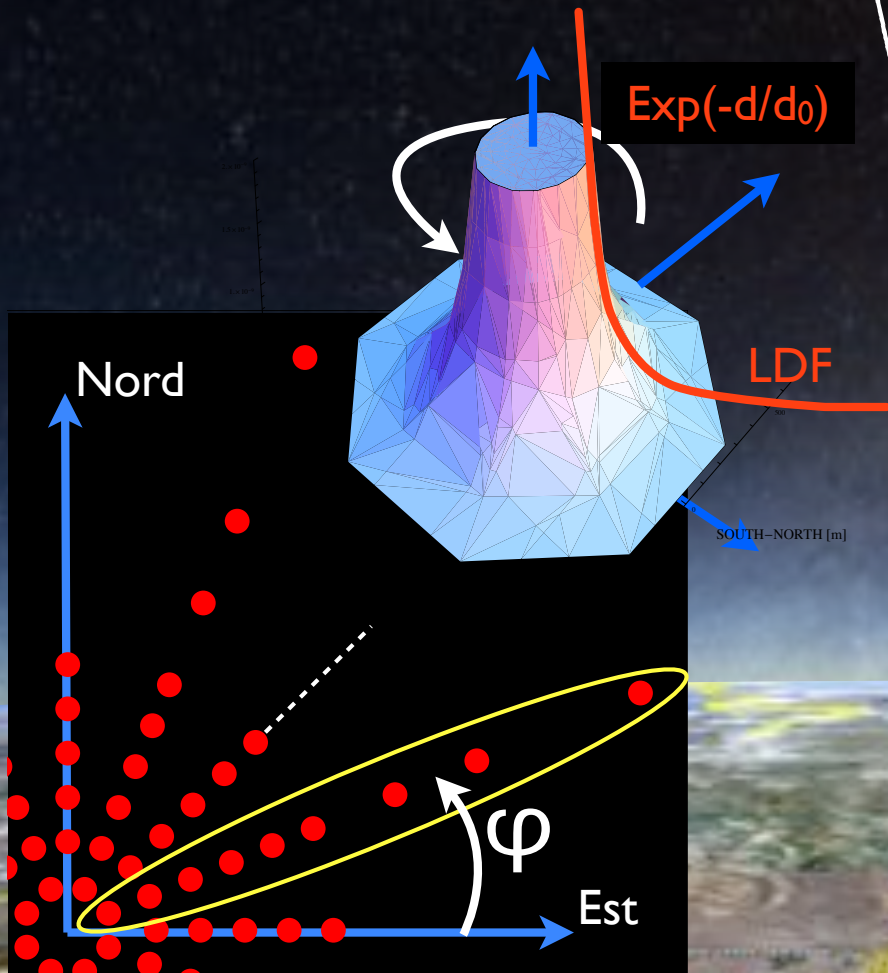
First Analysis



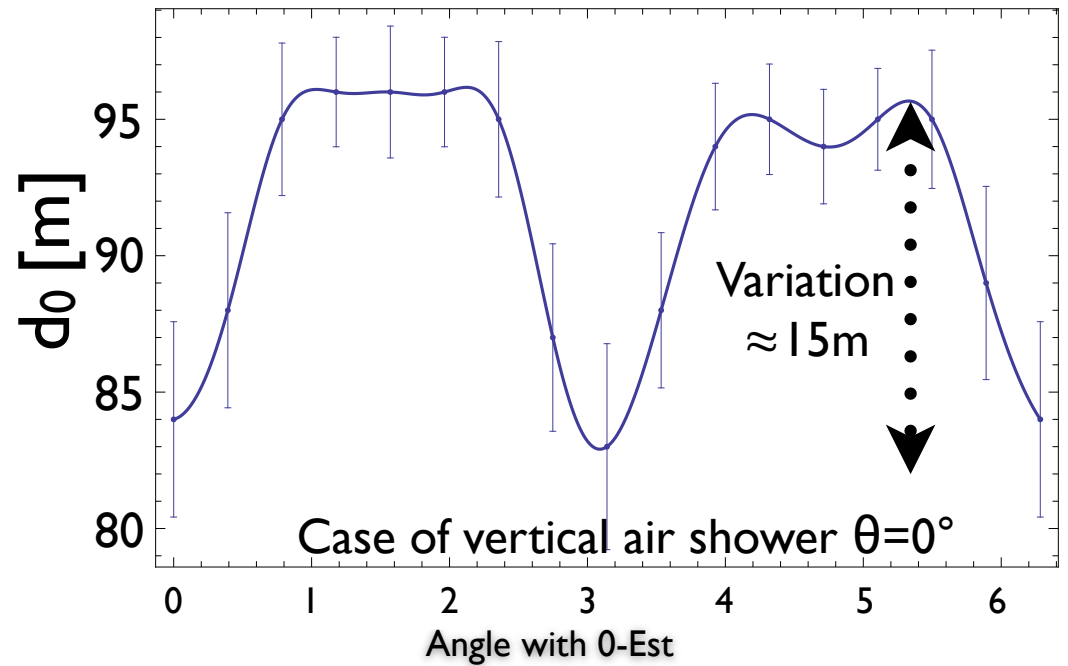
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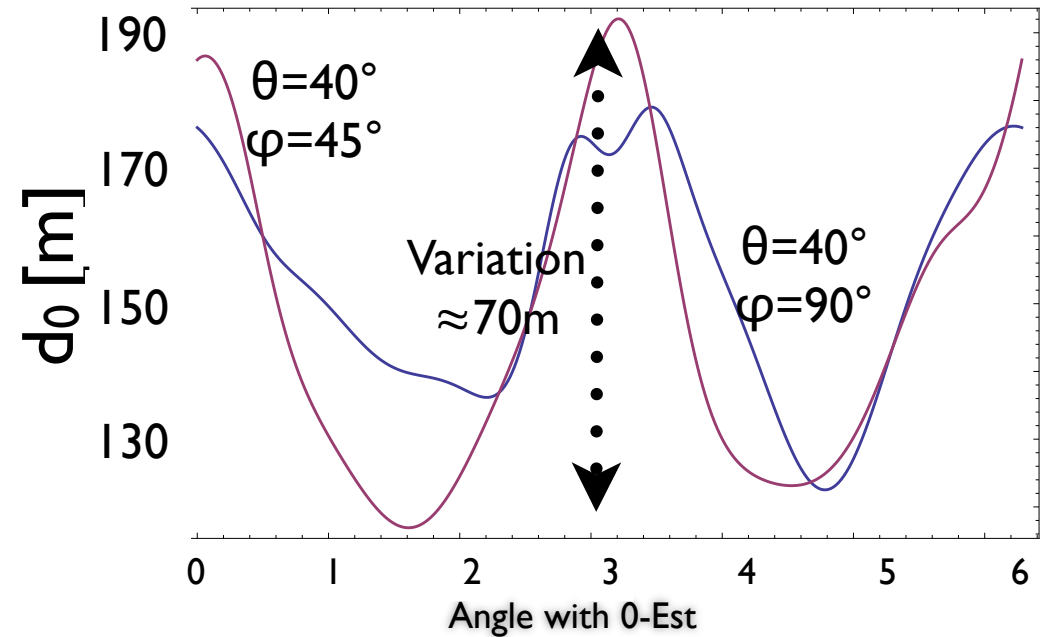
First Analysis



d_0 vs azimuthal angle

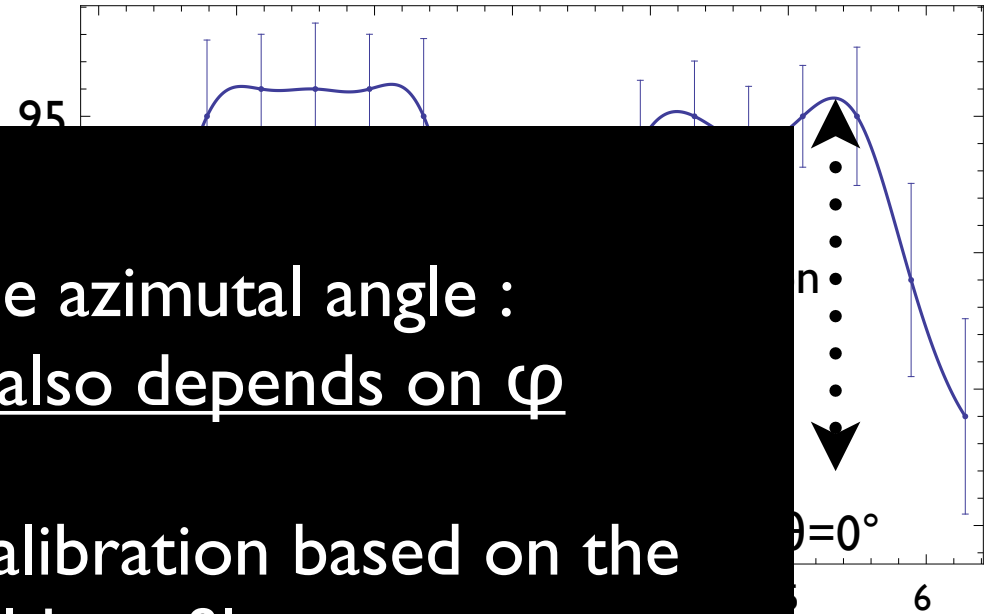


Case of inclined air Showers $\theta=40^\circ$



First Analysis

d_0 vs azimuthal angle



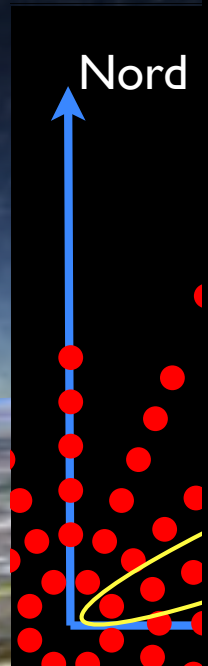
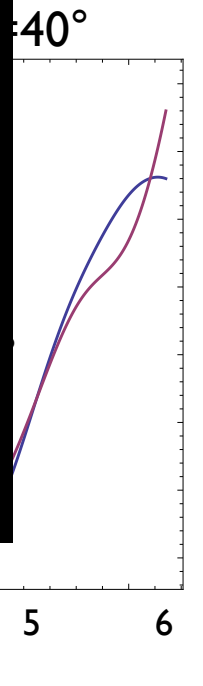
d_0 depends on the azimuthal angle :
 $d_0(\varphi) \longrightarrow$ LDF also depends on φ

CODALEMA energy calibration based on the electric field profile :

$$E_i = E_0 \exp(-d_i/d_0), E_0 = f(E_{CIC})$$

Energy estimation should therefore include the azimuthal dependence of the profile

$$E_i = E_0(\varphi) \exp(-d_i/d_0(\varphi))$$



Conclusion

Strategy adopted for computation allows a large number of particles without excessive effort :

for one antenna => 1 million of particles in 7 min (2.66 GHz intel)

The code «SEIFAS» is written in C and could be shared soon
SEIFAS=Simulation Electric Field Air Shower

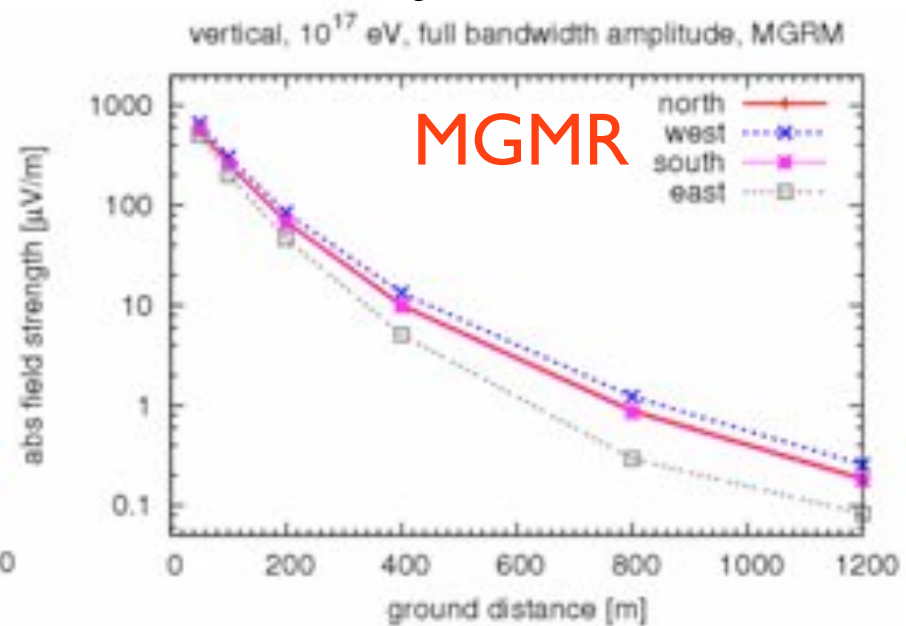
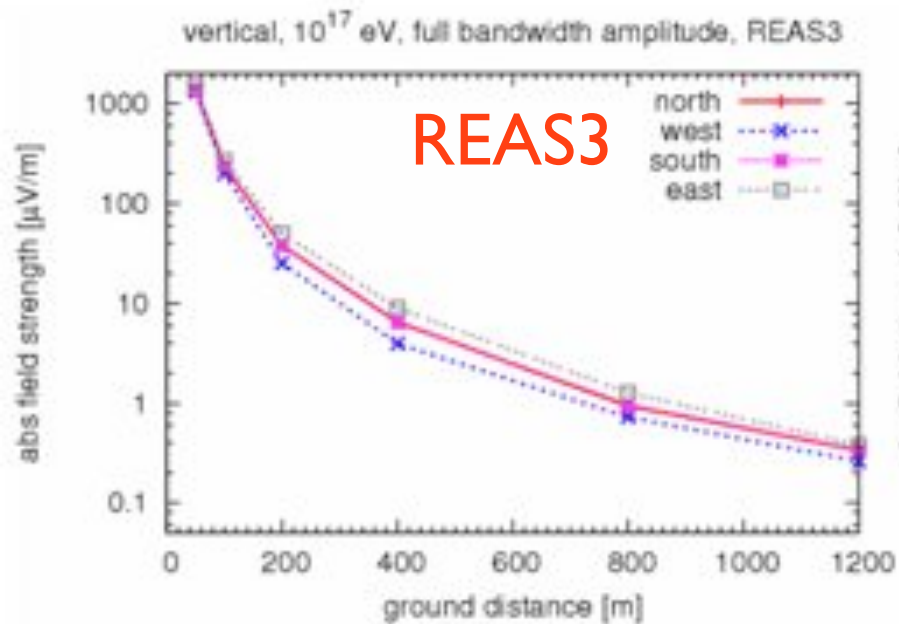
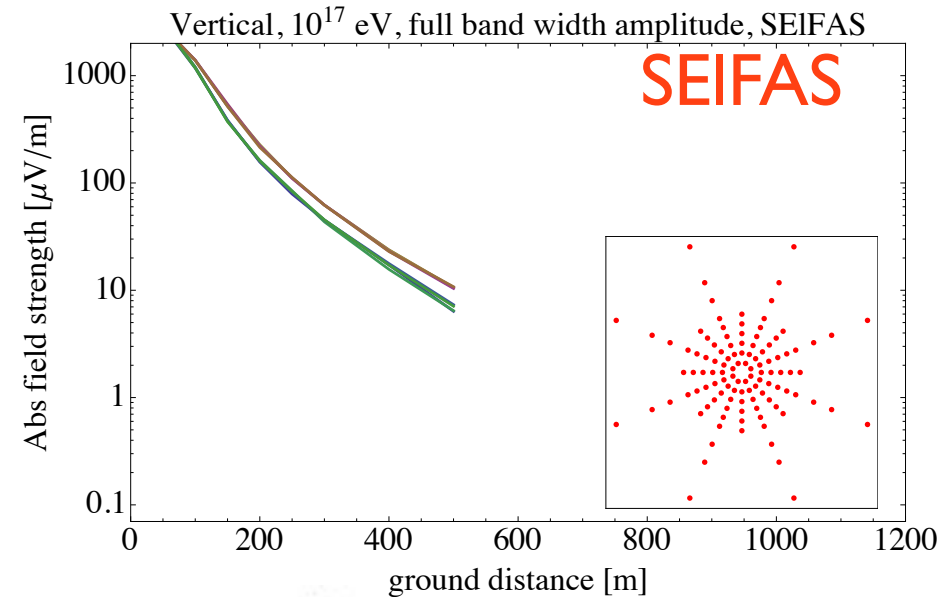
Work on the analysis of results given by the simulation in particular:

Comparison with other models like REAS and MGRM...



Conclusion

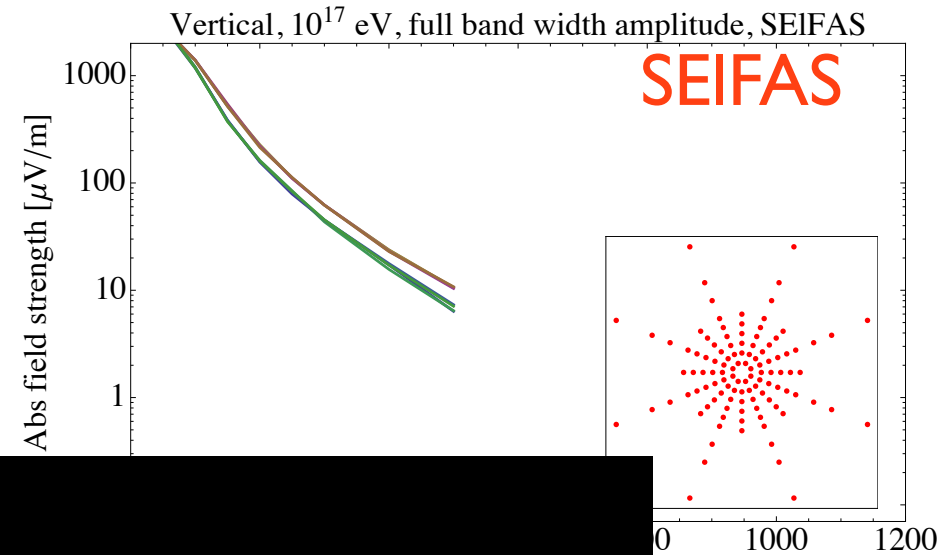
Nancy
magnetic field
 $B=0.50$ Gauss
 $\theta=27^\circ$



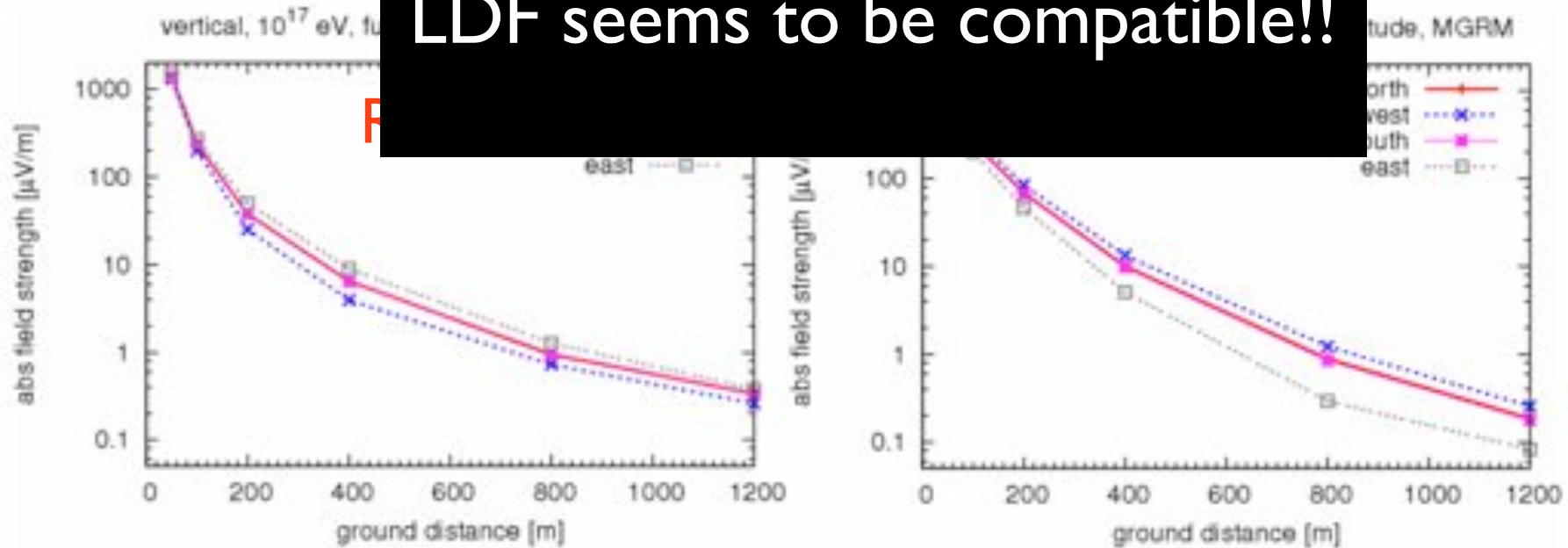
Auger $B=0.23$ Gauss $\theta=58^\circ$

Conclusion

Nancy
magnetic field
 $B=0.50$ Gauss
 $\theta=27^\circ$



LDF seems to be compatible!!



Auger $B=0.23$ Gauss $\theta=58^\circ$

Conclusion

Lateral distribution function is φ -dependent

SEIFAS verify coherent-incoherent behavior

Extract a theoretical law between primary energy and measured signal

Other work in progress

Establish a more realistic model with:

«Vector-potential point of view»

Cerenkov radiation (Cf A. Romero-Wolf talk)

(bipolarity of the pulse)

Scattering effect

Effect of asymmetry between electrons and positrons

All these improvements are easily implementable in SEIFAS

An aerial photograph of the Pierre Auger Observatory in Argentina, showing a vast grid of yellow fluorescence detector stations. A visualization of a particle shower is overlaid on the image, consisting of a single white line descending from the top of the frame that branches out into a dense, fan-like structure of white lines as it reaches the detector array. The background shows the dark, starry night sky and the horizon of the Earth.

Thanks...

Pierre Auger Observatory - Malargue Campus

Auger - 100 square kilometers of detectors