Interpretation of radio emission from particle cascades produced by UHECR.

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+ Klaus Werner (Subatech, Nantes)

Multiple Approaches to understand radio wave emission

- Microscopic:
  - Follow orbit of each electron & positron
    - Add fields of individual particles

Examples: REAS, ZHAireS

- Macroscopic, Emphasize collective aspect
  - Average motion of individual particles
    - Add charges & currents and calculate fields

Easier to interpret basic structure radio signal

Wave phenomenon → determined by length scales

Examples: MGMR, EVA

Consistency

T. Huege et al. ARENA2010, Nantes, France

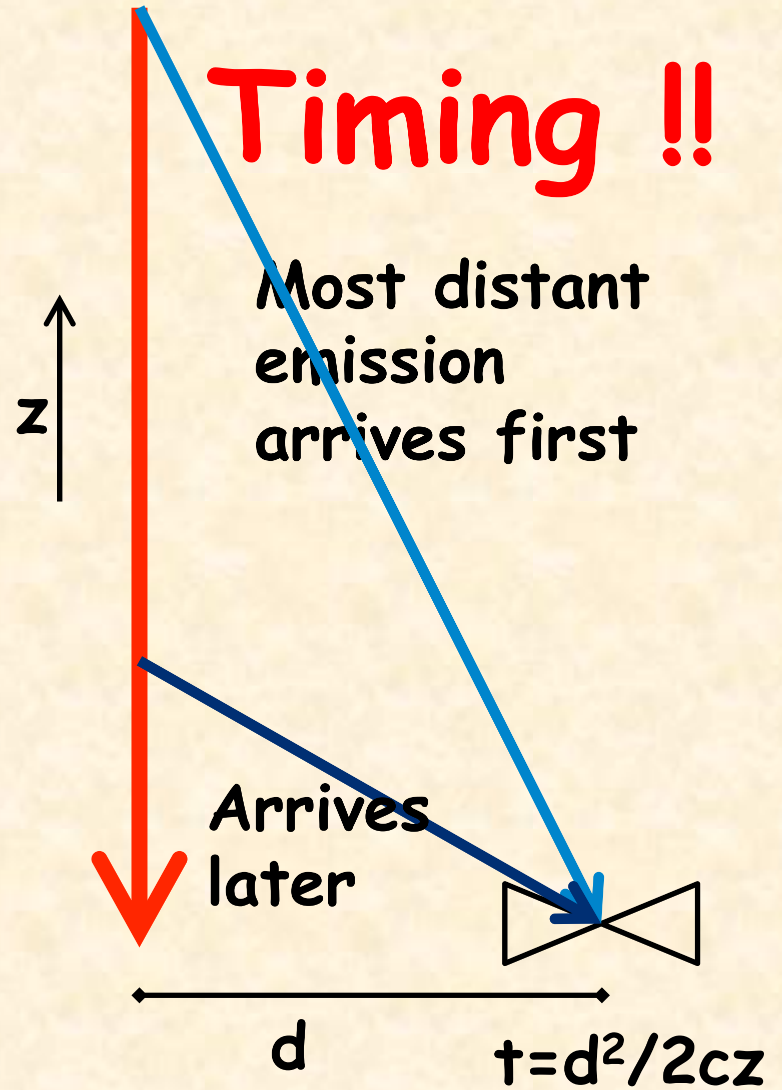
Understanding Radio-wave emission

Basic mantras:

1) **Variation** causes electric currents or charges to emit electromagnetic waves

2) **Coherence** when wavelength is larger than length scale charge distribution

Timing !!



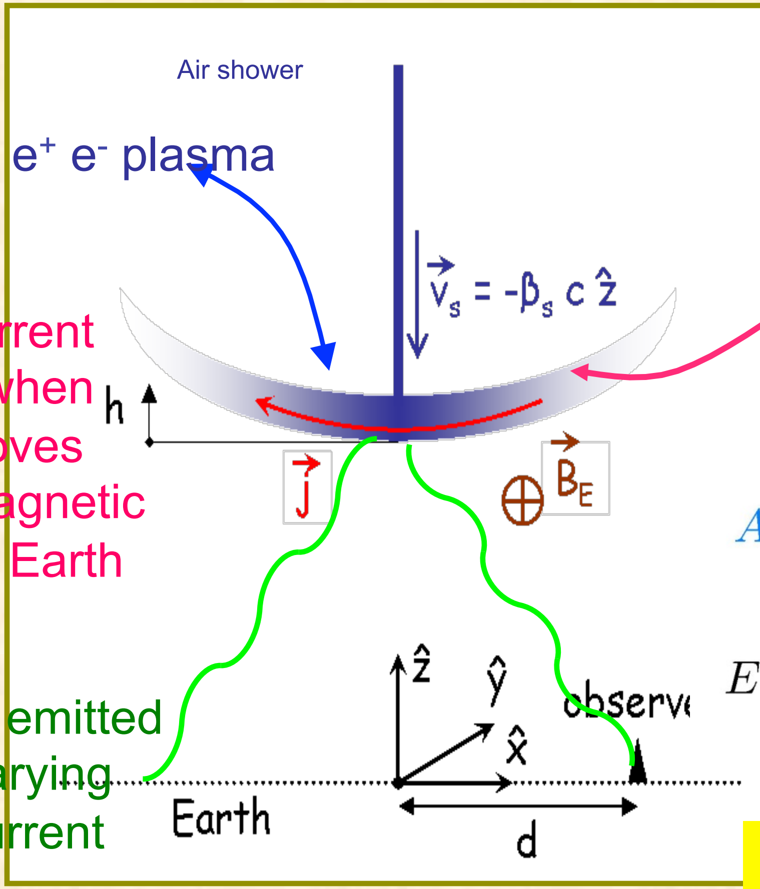
larger distance → broader signal

Macroscopic GeoMagnetic Radiation
> The Basic picture <

Horizontal drift velocity of electrons creates current

Pancake = e^+ e^- plasma

Electric current develops when plasma moves through magnetic field of the Earth



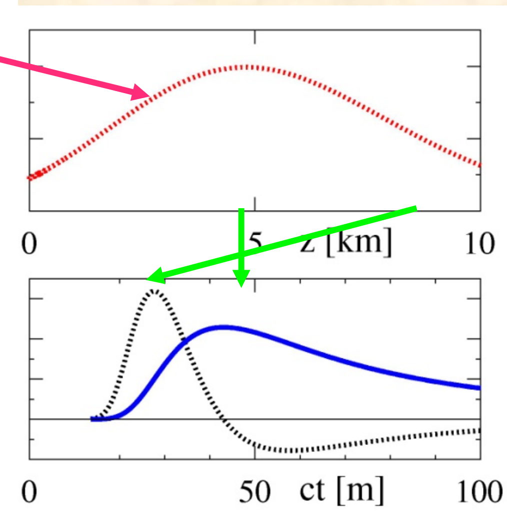
Radiation emitted by time varying electric current

$$j_x(z) = J_0 \rho_e(z)$$

$$z \approx -d^2/2ct$$

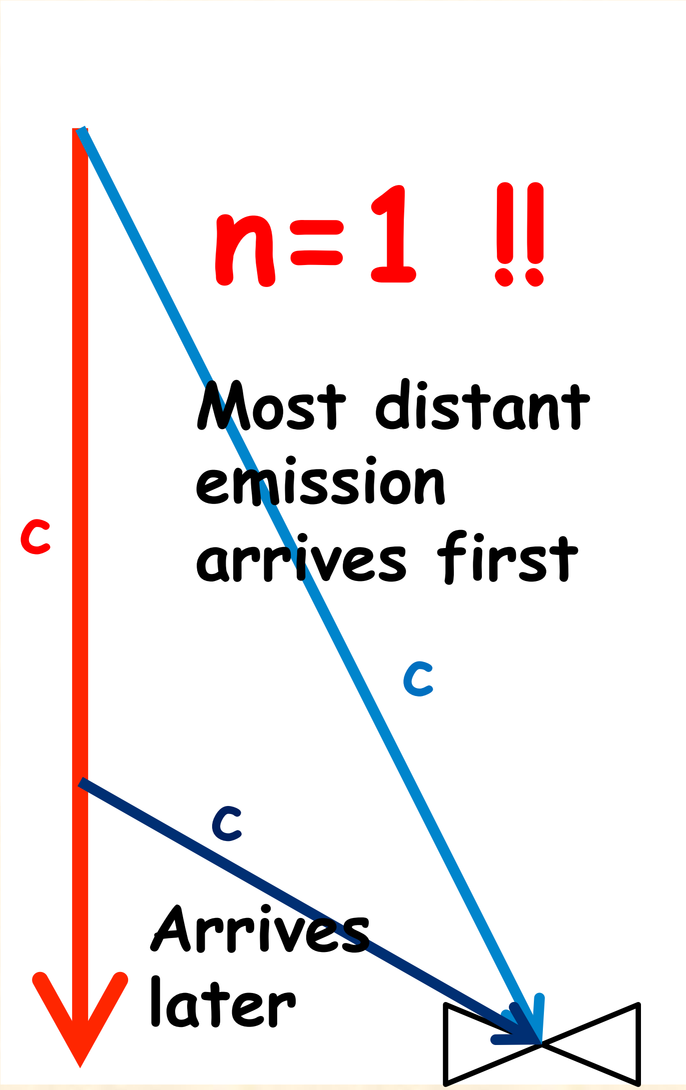
$$A^x(t,d) = \frac{j_x(z)}{\mathcal{D}}\Big|_{ret}$$

$$E^x(t,d) = \frac{d}{dt} A^x(t,d)$$

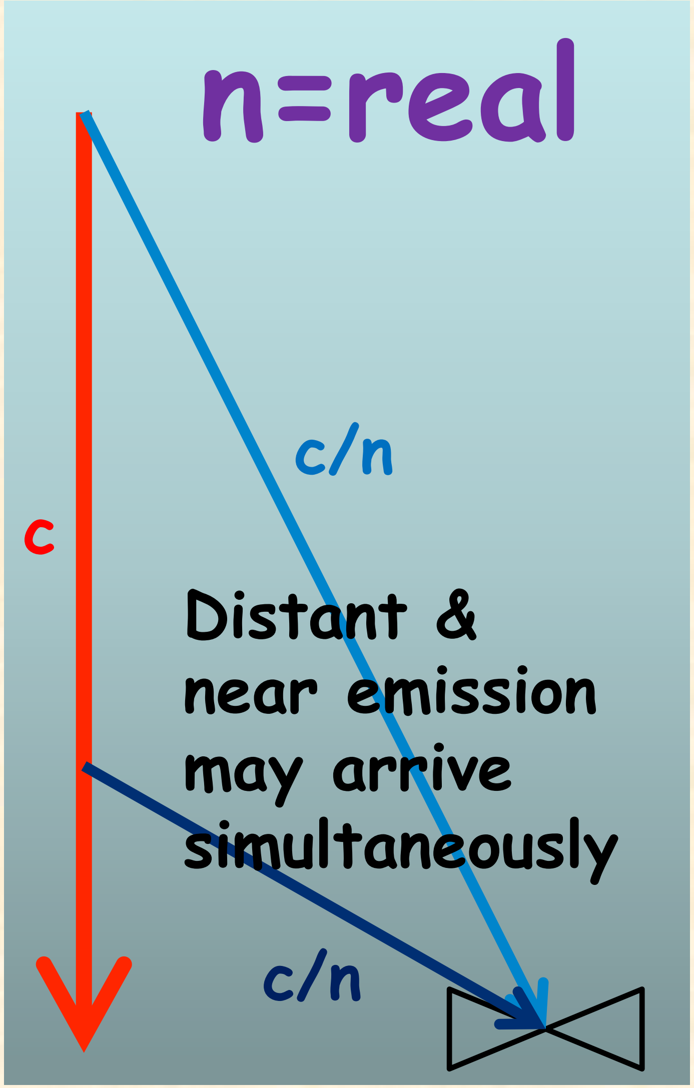


Pulse sensitive to shower development prior to maximum

Timing Radio pulse



$t=d^2/2cz$



Large, sharp pulse

Generic pulse @ Cherenkov distance

A-typical example

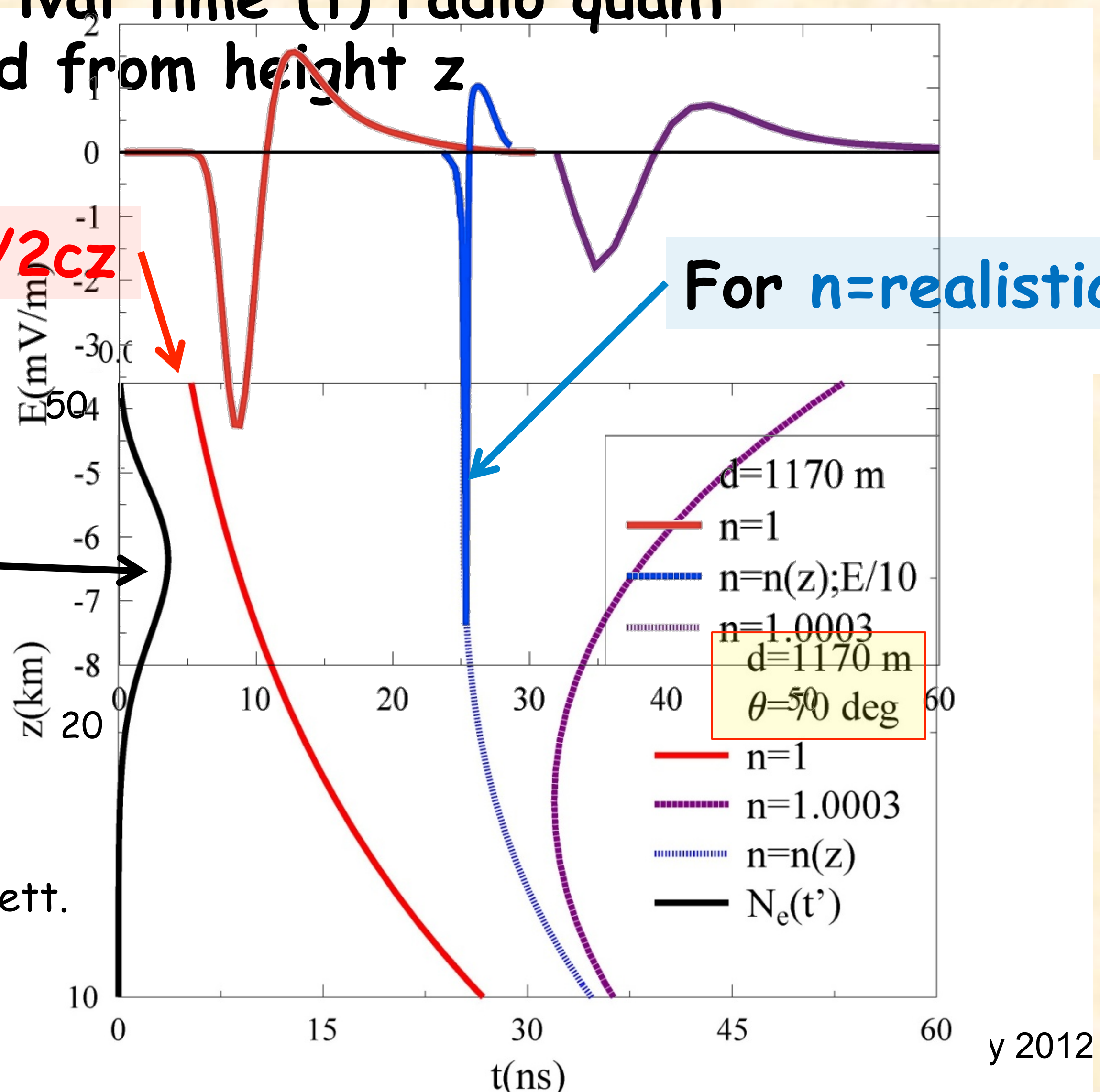
Arrival times reflected in pulse shapes

Calculate arrival time (t) radio quant when emitted from height z

For n=1: $t=d^2/2cz$

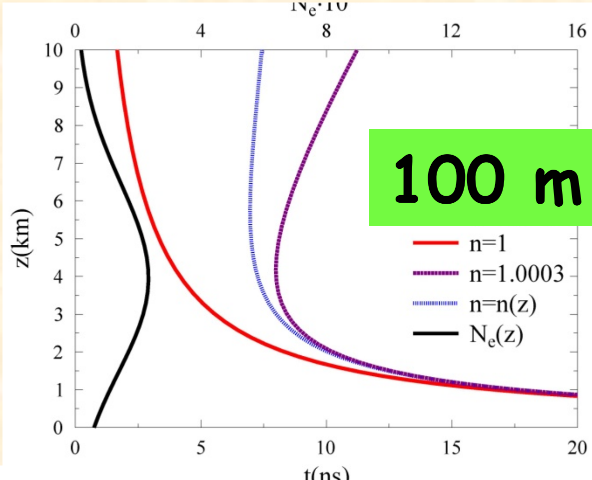
For n=realistic

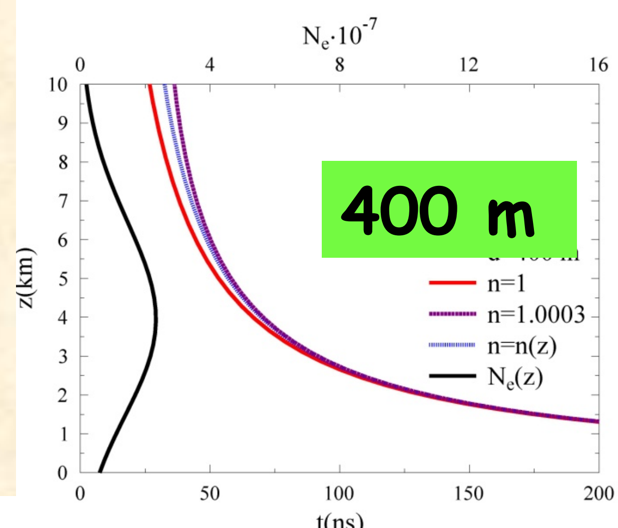
Shower profile



De Vries et al., PhysRevLett. 107, 061101 (2011)

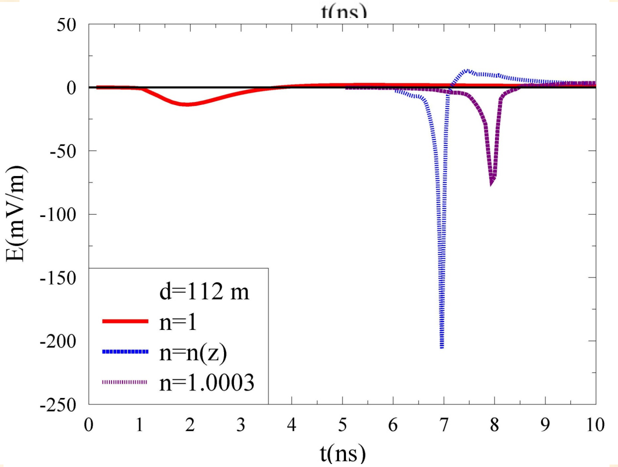
27^0 shower

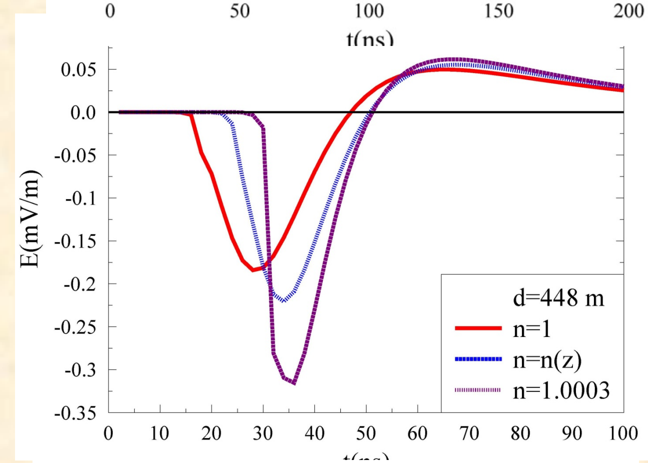




Cherenkov v.s.
'normal'

Timing !



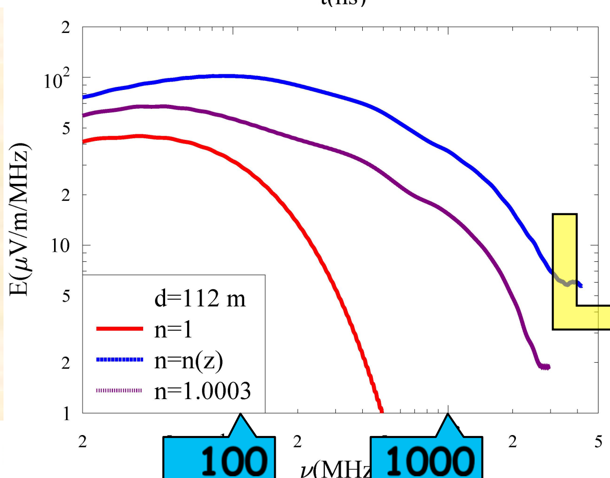


0.1 ns v.s. 10 ns

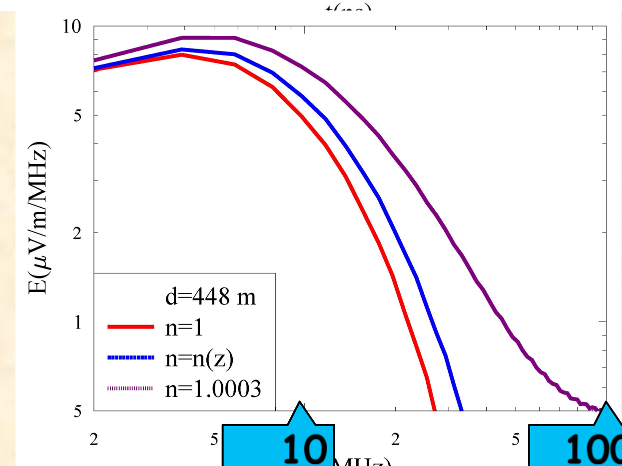
Time spectrum

Frequency spectrum

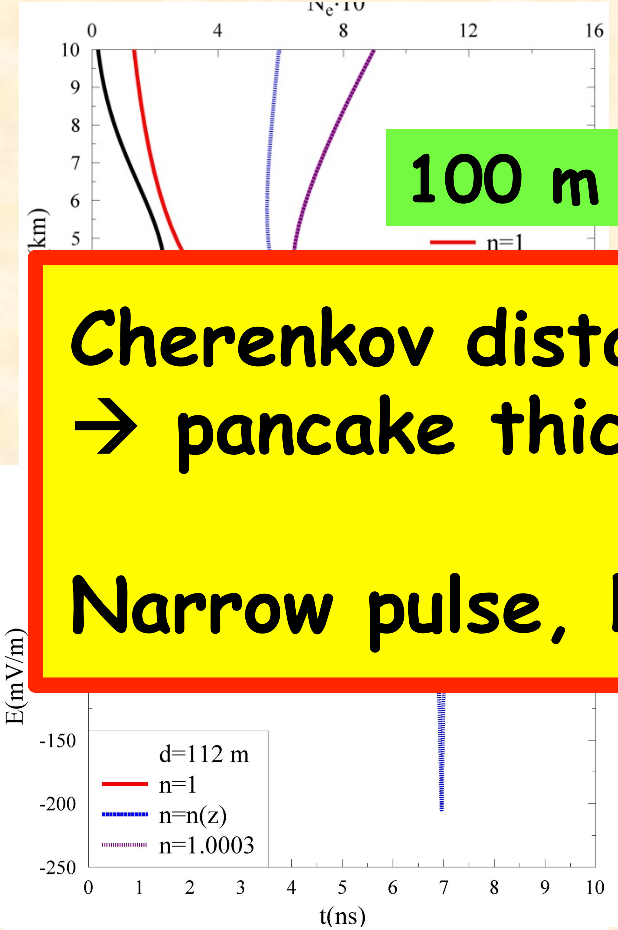
1 GHz v.s. 10 MHz

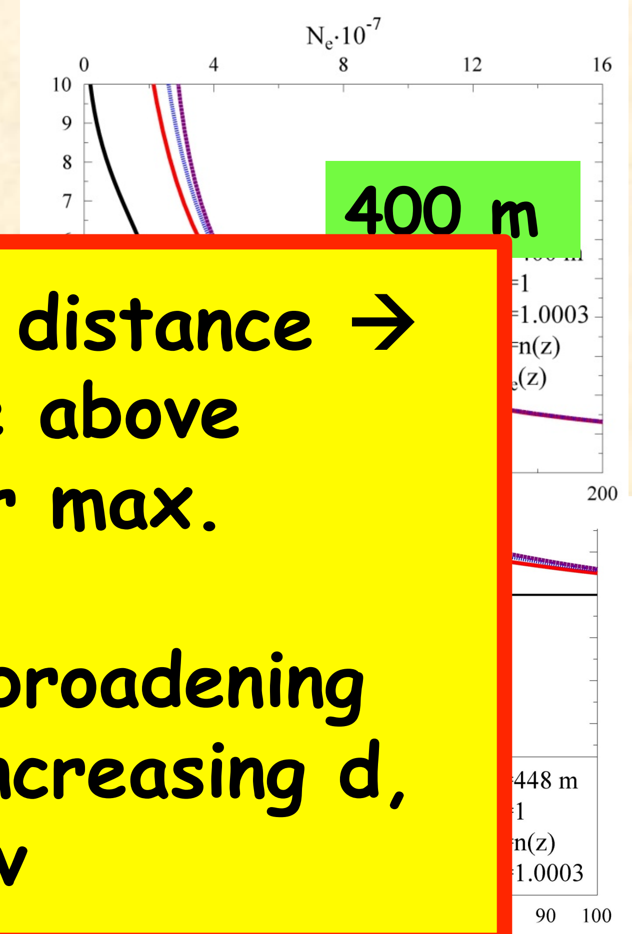


EASIER ?



27^0 shower





Cherenkov

Cherenkov distance → pancake thickness

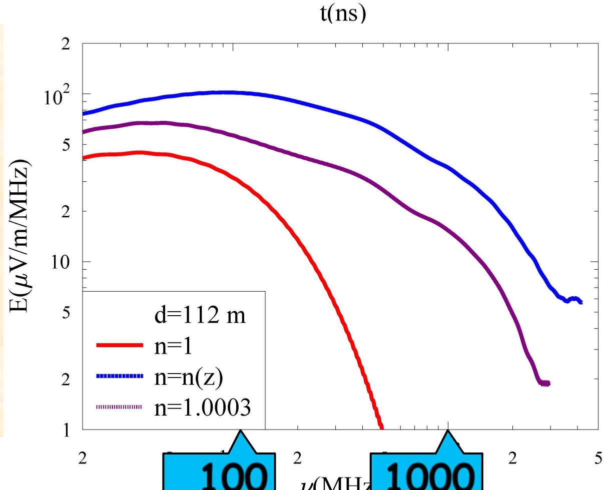
Narrow pulse, high ν

larger distance → profile above shower max.

Pulse broadening with increasing d, lower ν

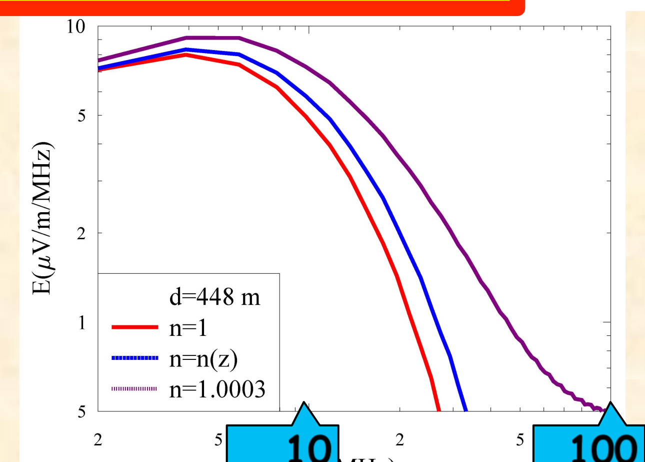
…s v.s

Time spec…



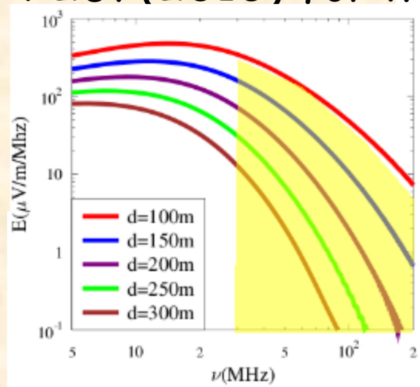
Frequency spectrum

1 GHz v.s. 10 MHz



Chemical composition

K.D. de Vries et al, Astropart.Phys.34:267(2010) for n=1; realistic case to be publ.

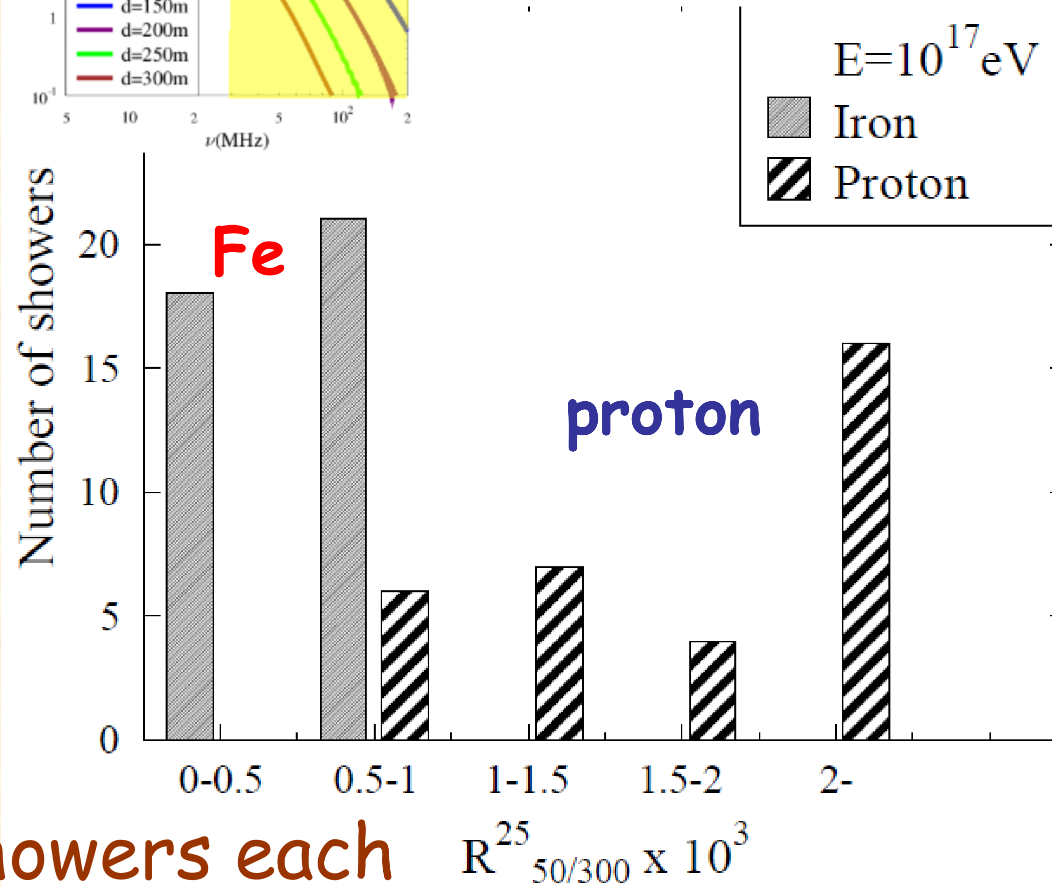


Ratio of power in measuring window for two distances

protons have shower max closer to ground

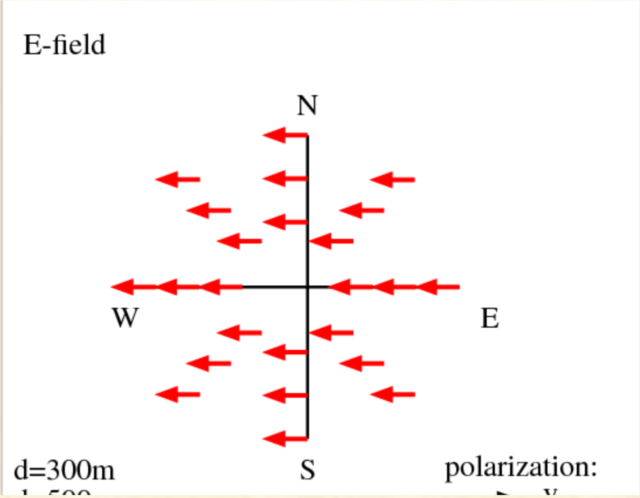
→ lower frequency

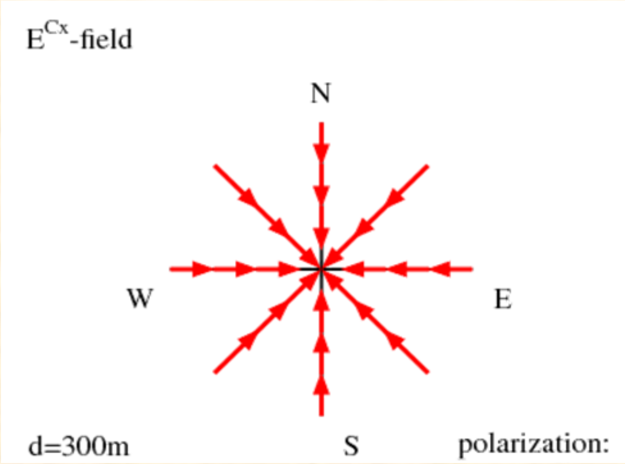
→ sooner out of juice with increasing d



40 showers each

Polarizations at different observer positions





Geomagnetic polarization ~

$\vec{\beta} \times \vec{B}$

Charge excess polarization:

Depending on observer position. Pointing inwards

K. Werner et al.,Astroparticle Physics 29 (2008) 393

Pulse can be understood based on simple geometrical arguments

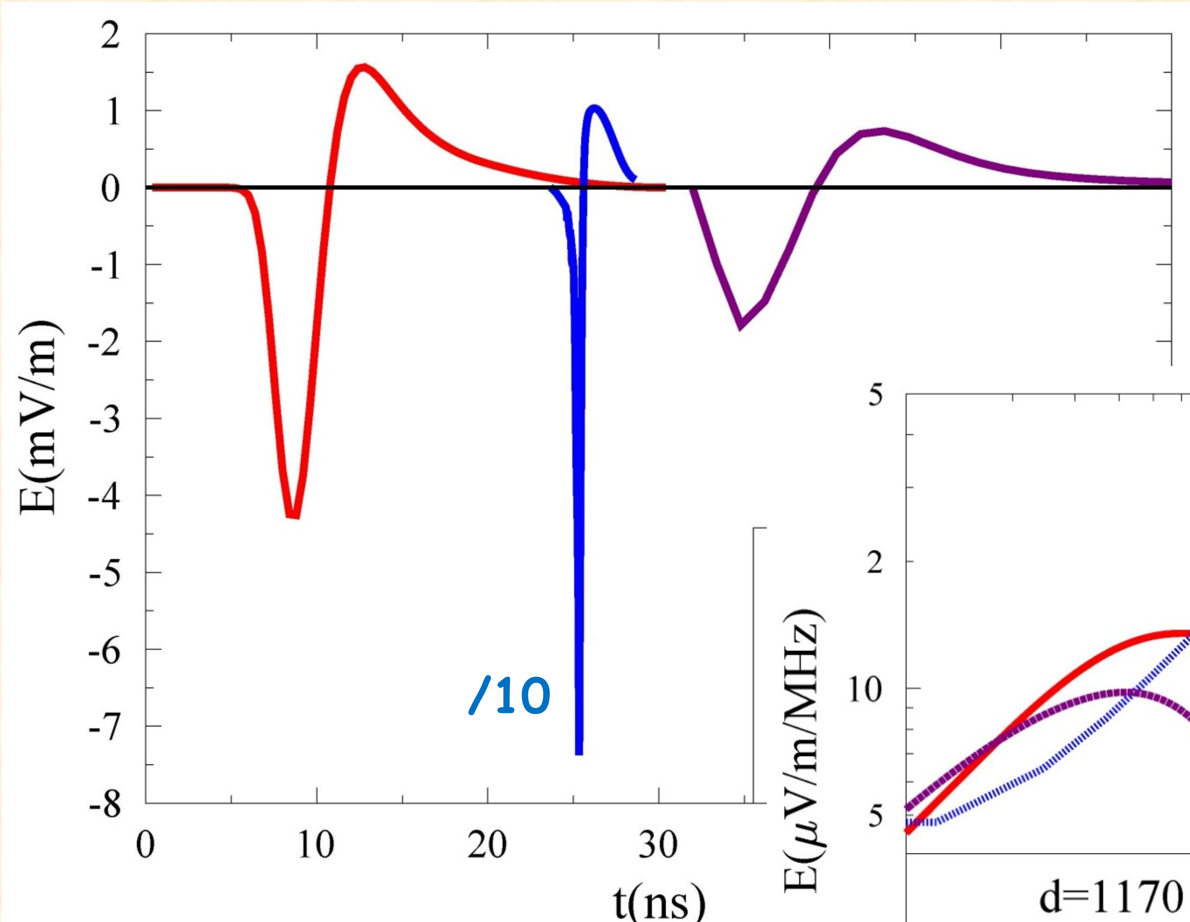
Radio sensitive to **electron content**

Radio provides multiple information of shower evolution:

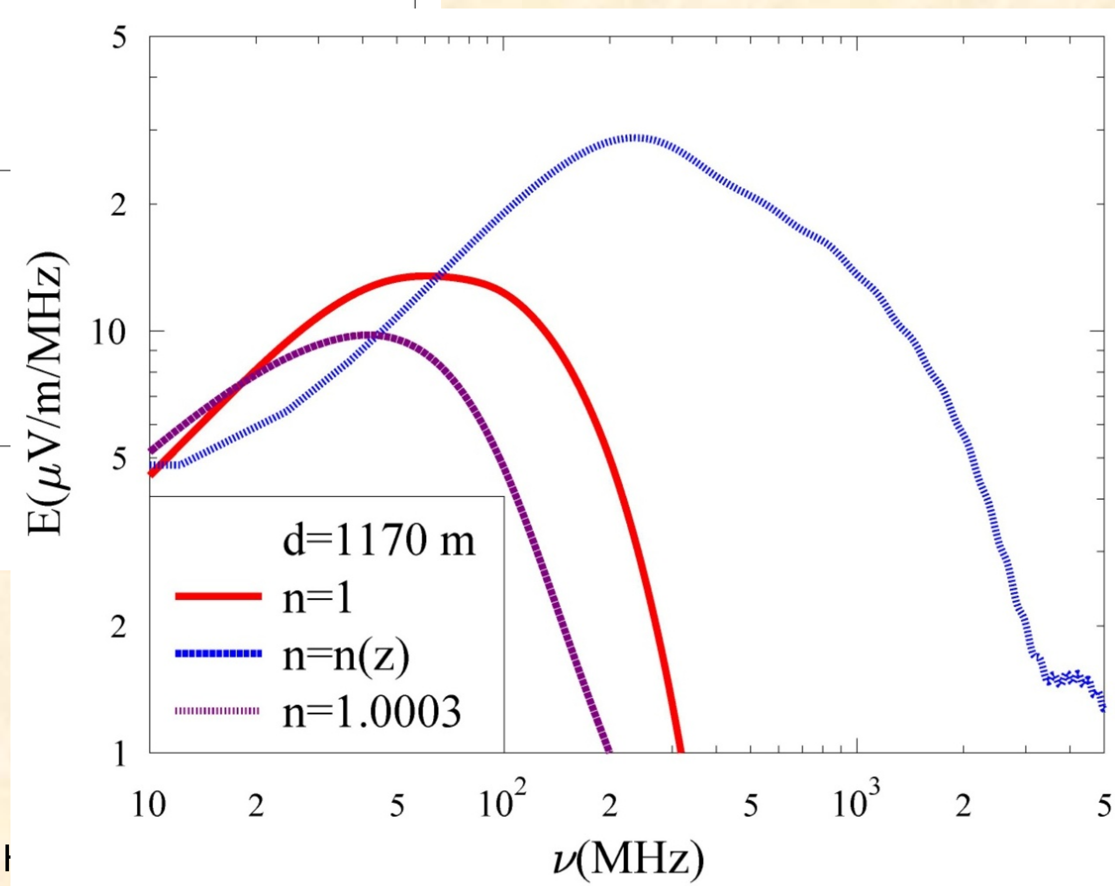
- Cherenkov distance:
  - Shower **pancake thickness** &
  - position **shower maximum**
- Larger distances:
  - **Early shower profile**
- Polarization → **geomagnetic/charge excess**
- **Timing**

Complementary to fluorescence and surface detectors

Pulse details



Sharp pulse → High frequency

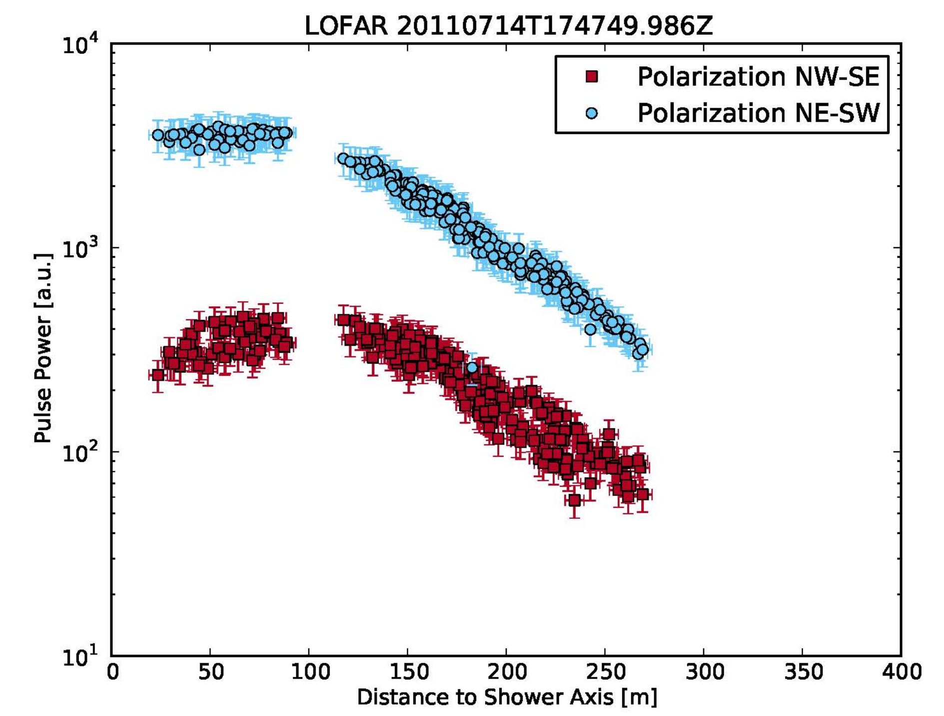


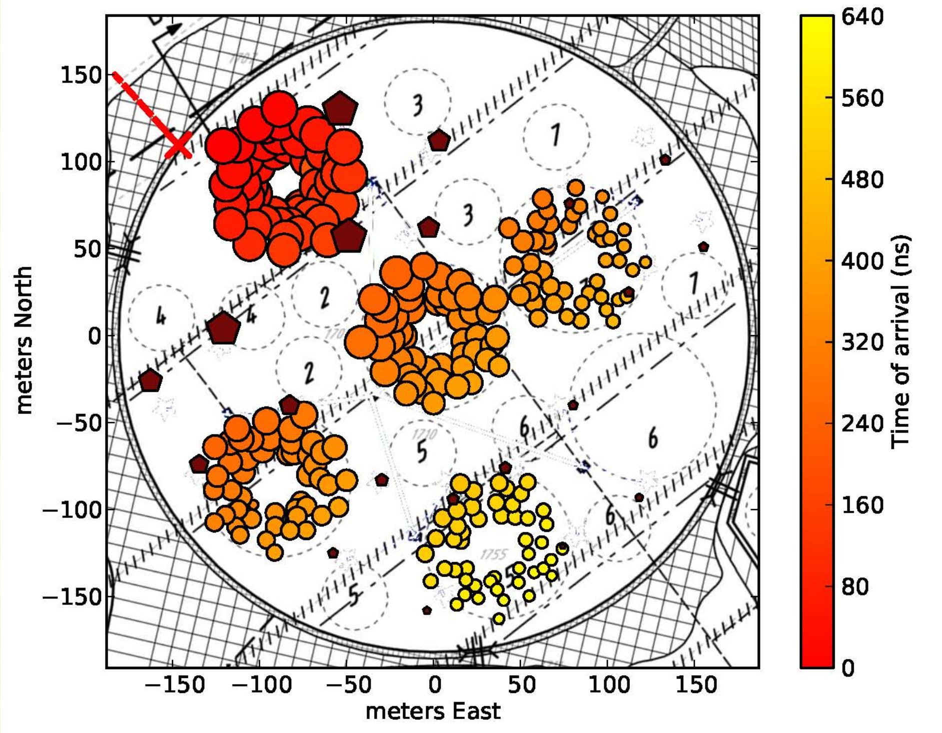
shower max@30 km
(along sh axis)
impact = 400 m, E=5×10^{17}eV

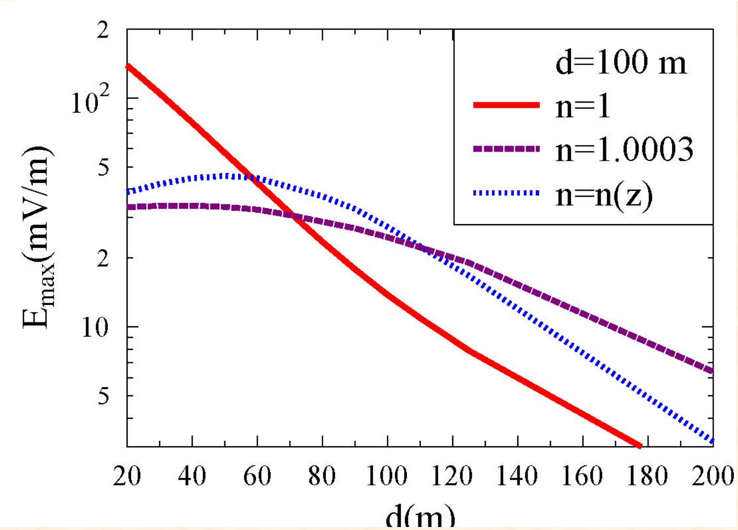
LOFAR

6 x 48 antennas 40-70 MHz

A. Corstanje et al, arXiv:1109.5805v1 [astro-ph.HE] (ICRC)







Movie

De Vries et al., PhysRevLett. 107, 061101 (2011)

Pancake thickness

Determining length scale at Cherenkov distance: distribution of particles near shower front.

Small size → narrow pulse → high frequencies

$$E^i = -\frac{\mu_0 c}{4\pi}\int d^2\vec{r}\int dh \frac{1}{|\mathcal{D}|}\left(\frac{\partial w}{\partial h} J^i_{PL} + w\frac{\partial J^i_{PL}}{\partial t'}\right)$$

Cherenkov, D~0, derivative pancake

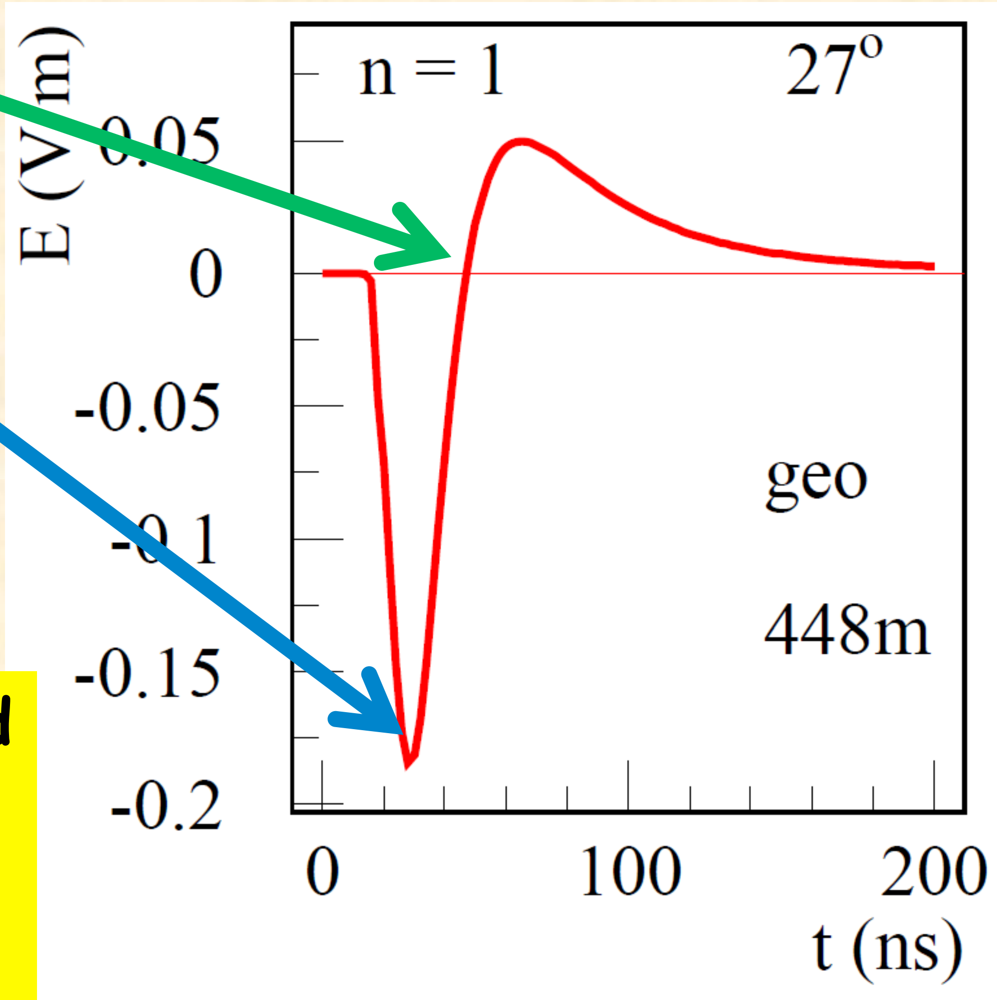
'normal' = derivative longitudinal current

K.D. De Vries et al., PRL 107, 061101 (2011)

Generic pulse @ larger distances

Shower max

pre shower max



Refinements:

- polarization
- Cherenkov effect

Multiple variables determined for a single shower:
- large distance → profile above shower max.
- short distance → pancake thickness