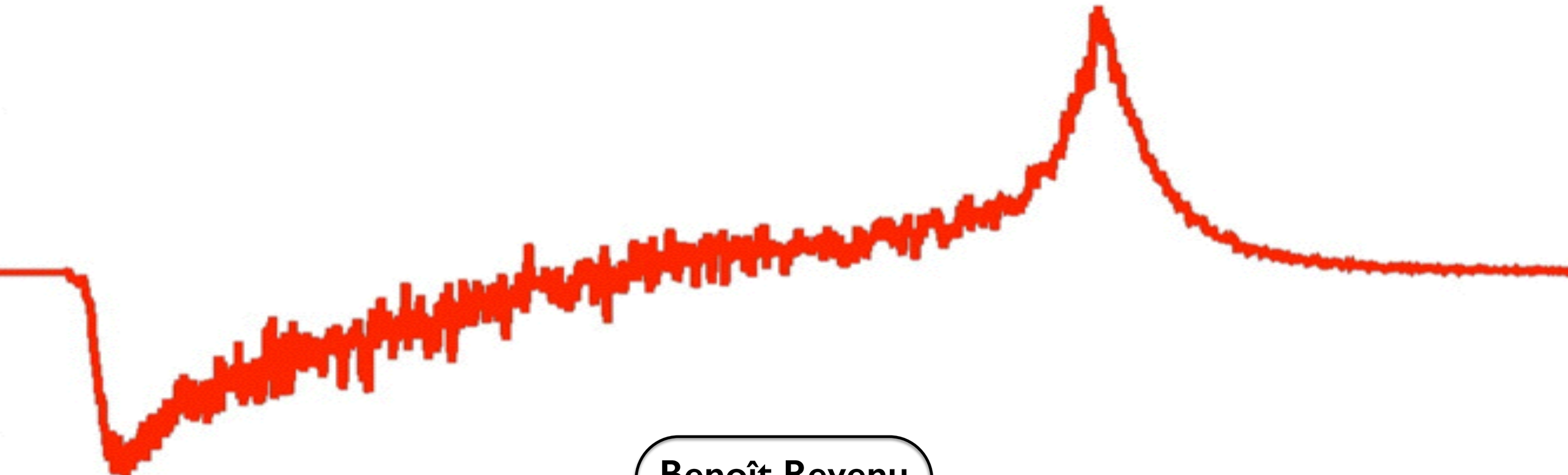
Study of ultra-high energy cosmic rays through their radio signal in the atmosphere



Benoît Revenu
SUBATECH
École des Mines de Nantes
Université de Nantes
CNRS/IN2P3

Outline

1. Physics and astrophysics of ultra-high energy cosmic rays
2. The extensive air showers
   a. Contents of a shower
   b. Detection by a surface detector
   c. Detection by a fluorescence detector
3. The radio signal
   a. Theoretical computation
   b. Contribution of two mechanisms
   c. Up to GHz frequencies
   d. Down to kHz frequencies: the sudden death signal
4. Detection of the radio signal
   a. The antennas and amplifiers
   b. Deconvolution of the antenna and electronics responses
   c. External triggering, self-triggering, background
   d. Arrays of radio stations: experimental status
5. Primary cosmic ray characteristics reconstruction
   a. Arrival direction
   b. Energy
   c. Composition
6. Summary and perspectives

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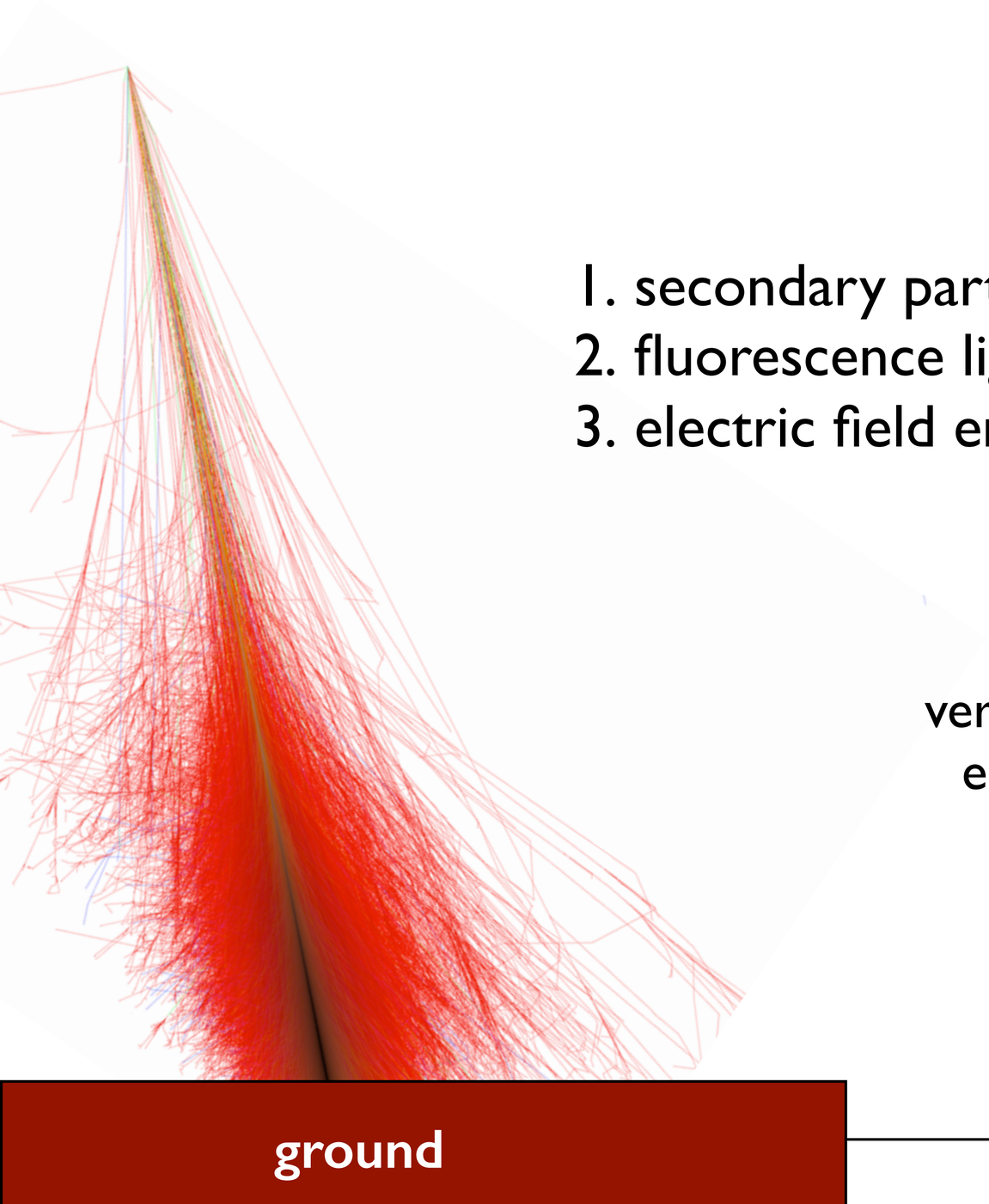
The radio signal



<u>three observables:</u>

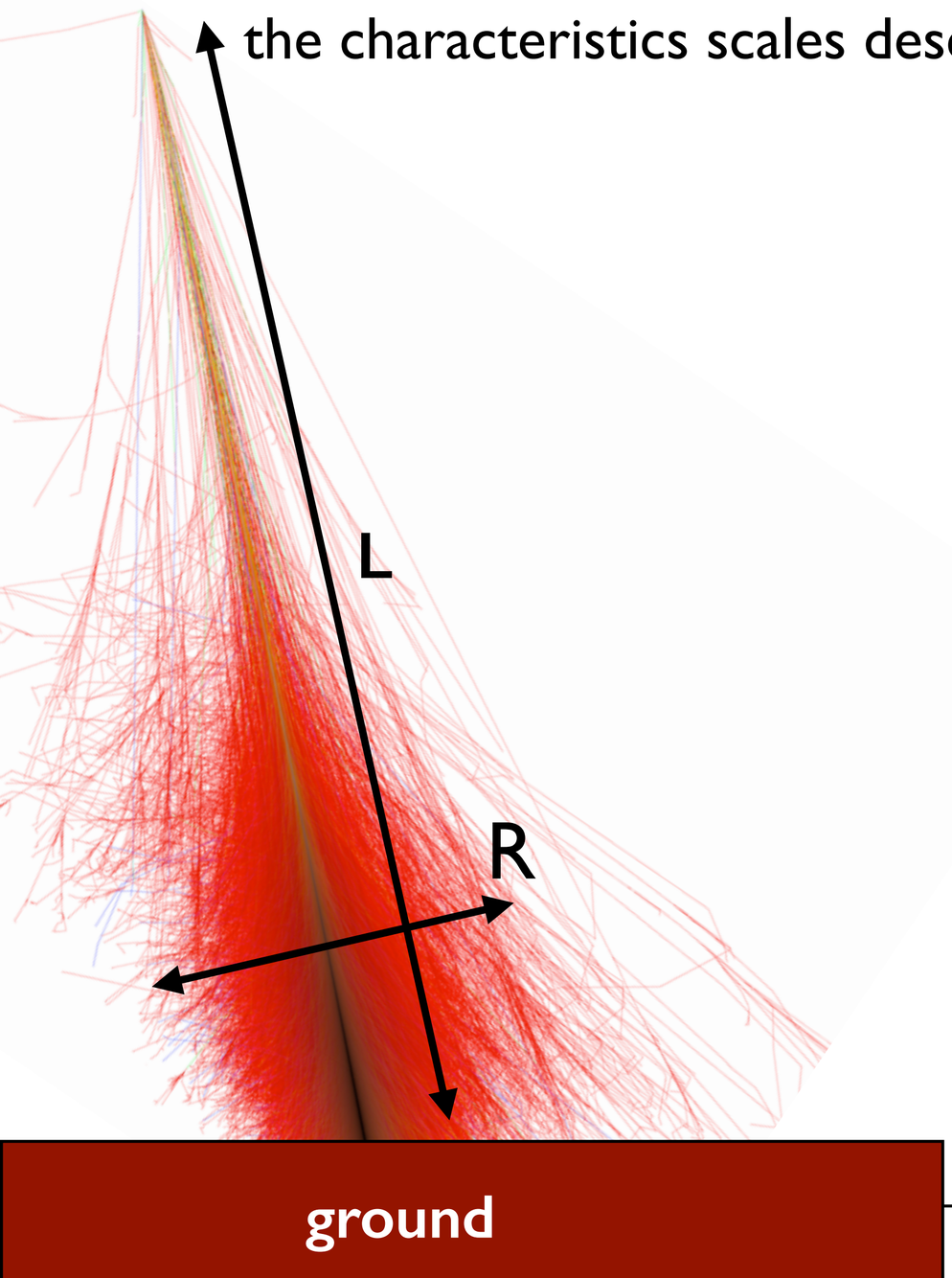
1. secondary particles reaching the ground level (SD)
2. fluorescence light (FD)
3. electric field emitted by all e^+/e^-: **radio waves**!

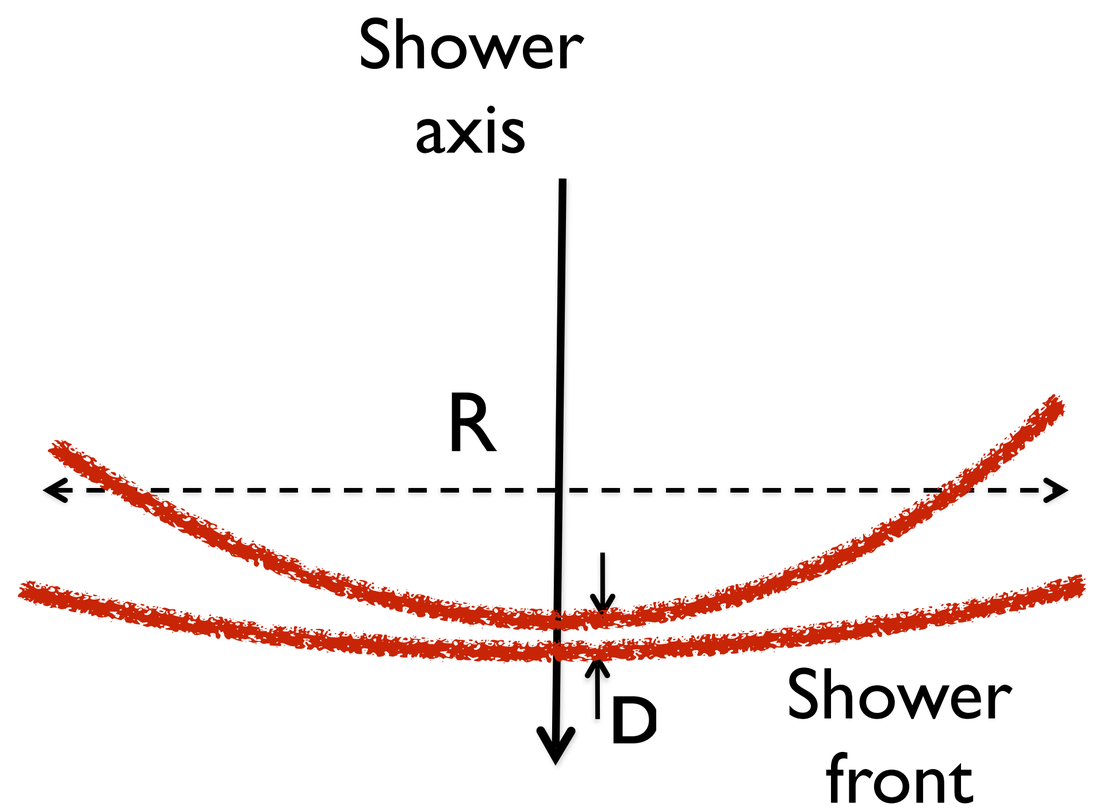
very interesting because probes specifically the electromagnetic component of the shower!
<u>important for composition studies</u>

The radio signal: interference, coherence

Source of the radio signal: the e^+ and e^- of the shower

the characteristics scales describing the shower have a role in the observed signal





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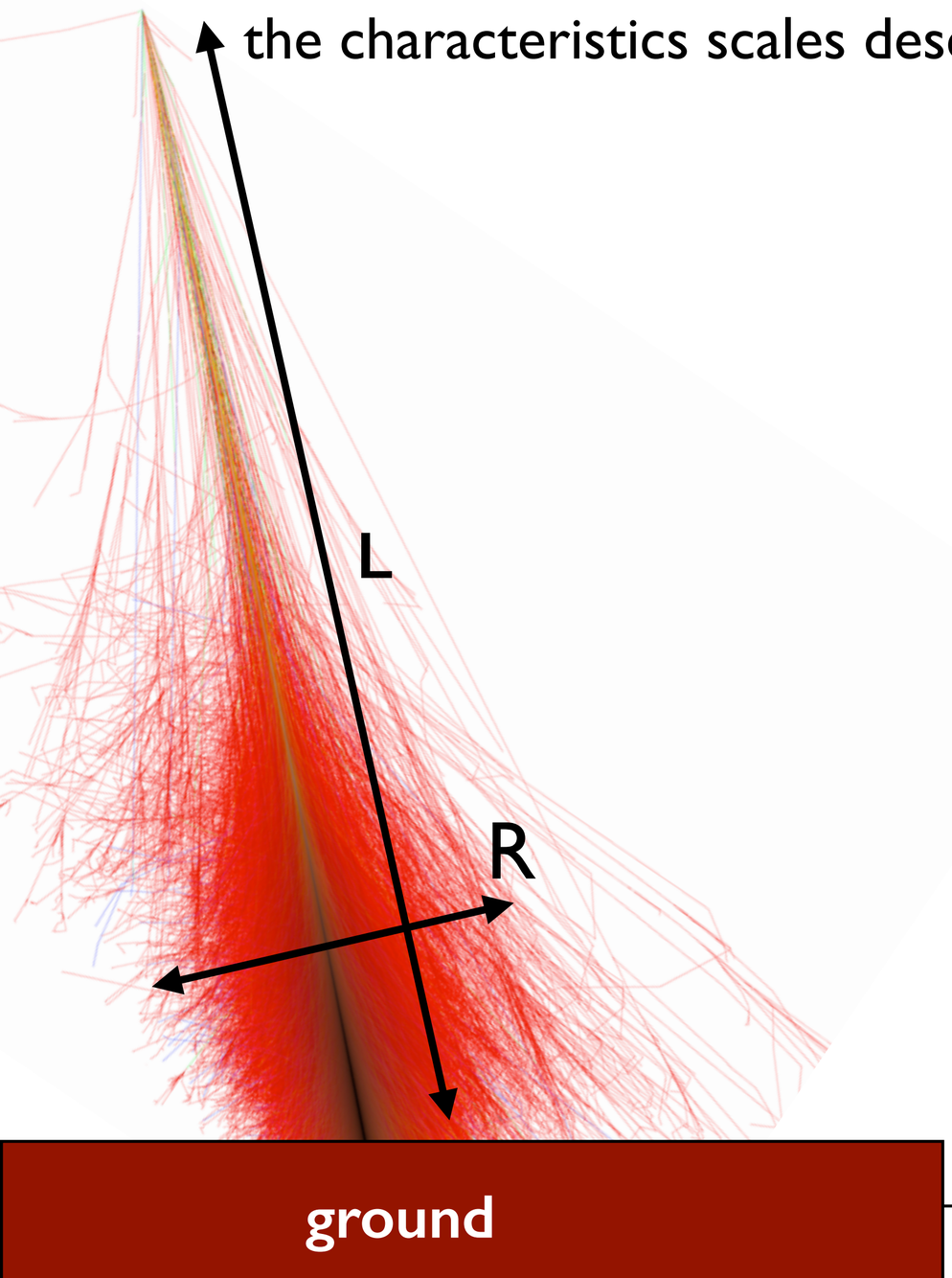


$\lambda \gg$ shower dimensions

fields add up with the same phase

coherence: constructive interference

total field α $N_{particles}$ α $E_{primary}$

$\lambda \ll$ shower dimensions

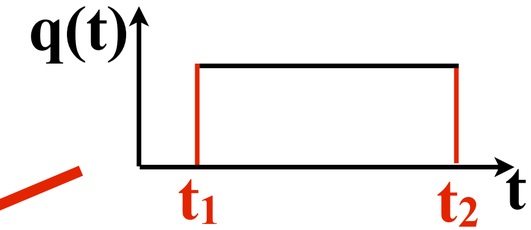
fields add up with random phases

incoherence: destructive interference

➔ cut-off in the frequency spectrum

(see also J. Alvarez-Muniz, ARENA2014)

The radio signal (modern computation)



For a single particle of charge q and a finite lifetime

Charge density $$\rho(\boldsymbol{x}', t') = q[\theta(t' - t_1) - \theta(t' - t_2)]\delta^3(\boldsymbol{x}' - \boldsymbol{x}_0(t'))$$

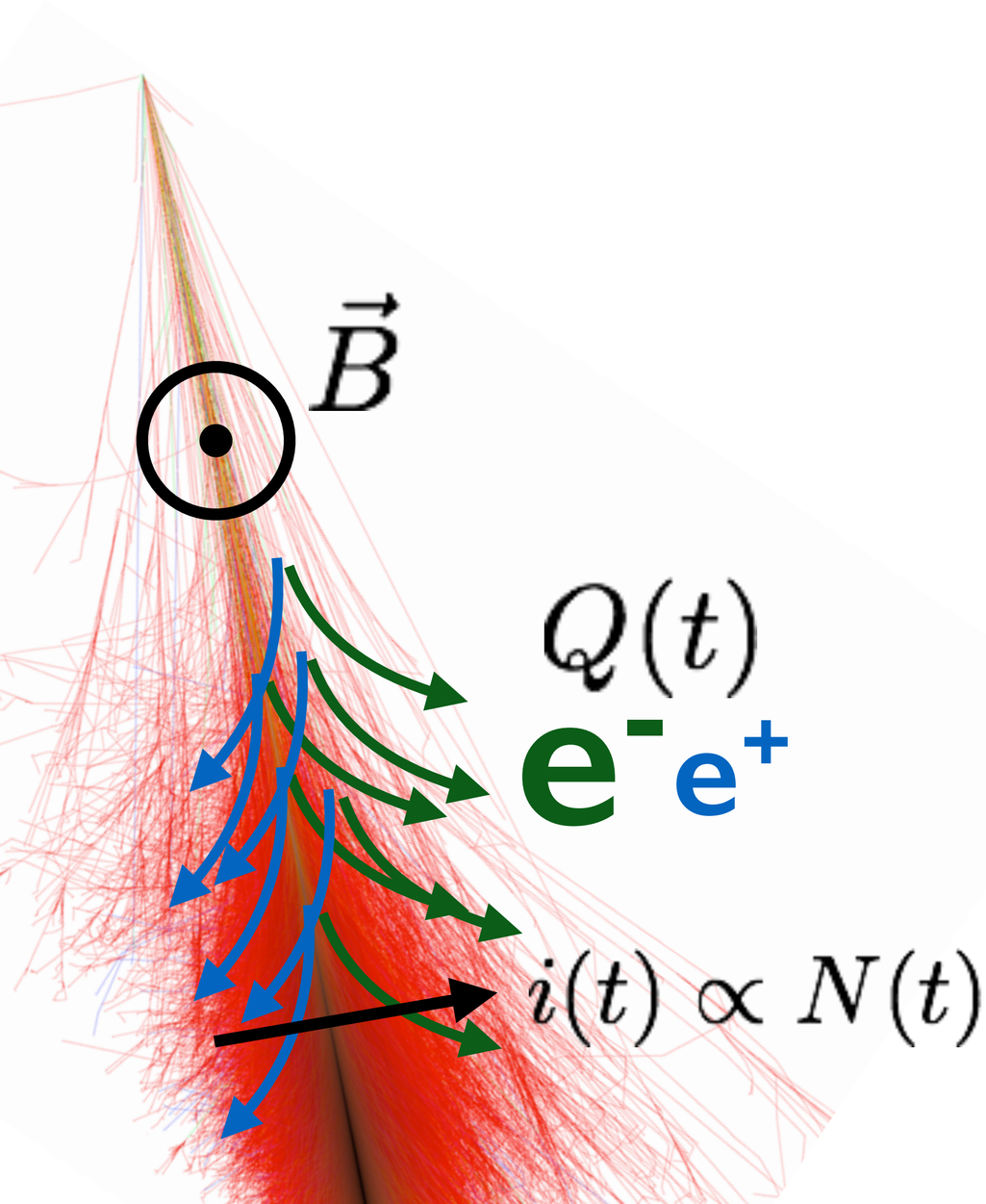
Current density $$\boldsymbol{J}(\boldsymbol{x}', t') = \rho(\boldsymbol{x}', t')\boldsymbol{v}(t')$$

Solution of Maxwell equations in Lorenz gauge:

$$\vec{E}(\vec{x}, t) = \frac{1}{4\pi\varepsilon_0} \int \mathrm{d}^3x' \mathrm{d}^3t' \frac{1}{R} \left(-\nabla'\rho - \frac{1}{c^2}\frac{\partial J}{\partial t'} \right)_{\mathrm{ret}} \delta\left(t' - \left(t - \frac{|x - x'|}{c/\eta} \right) \right)$$

$$\boxed{\vec{E}(\vec{x}, t) = \frac{1}{4\pi\varepsilon_0} \left(\frac{q\,\vec{n}}{R^2(1 - \eta\vec{\beta}\cdot\vec{n})} + \frac{1}{c}\frac{\partial}{\partial t}\frac{q\,\vec{n}}{R(1 - \eta\vec{\beta}\cdot\vec{n})} - \frac{1}{c}\frac{\partial}{\partial t}\frac{q\,\vec{\beta}}{R(1 - \eta\vec{\beta}\cdot\vec{n})} \right)_{\mathrm{ret}}}$$

The total radio signal



$$\vec{E}(\vec{x},t) = \frac{1}{4\pi\varepsilon_0}\left(\sum_{i=1}^{N} \frac{q_i\,\vec{n}_i}{R_i^2(1-\eta\vec{\beta}_i\cdot\vec{n}_i)} \right.$$

Coulombian contribution

$$+ \frac{1}{c}\frac{\partial}{\partial t}\sum_{i=1}^{N} \frac{q_i\,\vec{n}_i}{R_i(1-\eta\vec{\beta}_i\cdot\vec{n}_i)}$$

Charge excess contribution

$$\left. - \frac{1}{c}\frac{\partial}{\partial t}\sum_{i=1}^{N} \frac{q_i\,\vec{\beta}_i}{R_i(1-\eta\vec{\beta}_i\cdot\vec{n}_i)} \right)$$

Transverse current contribution

$$-\frac{1}{c}\frac{\partial}{\partial t}\sum_{i=1}^{N}\frac{q_i\,\vec{\beta}_i}{R_i(1-\eta\vec{\beta}_i\cdot\vec{n}_i)}$$

(Kahn & Lerche 1967)

Transverse current contribution

dominant contribution!
linear polarization!
independent on the observer's location!

$$\frac{\partial}{\partial t}\vec{\beta}_i \propto \vec{\beta}_i \times \vec{B} + \text{random deviations}$$

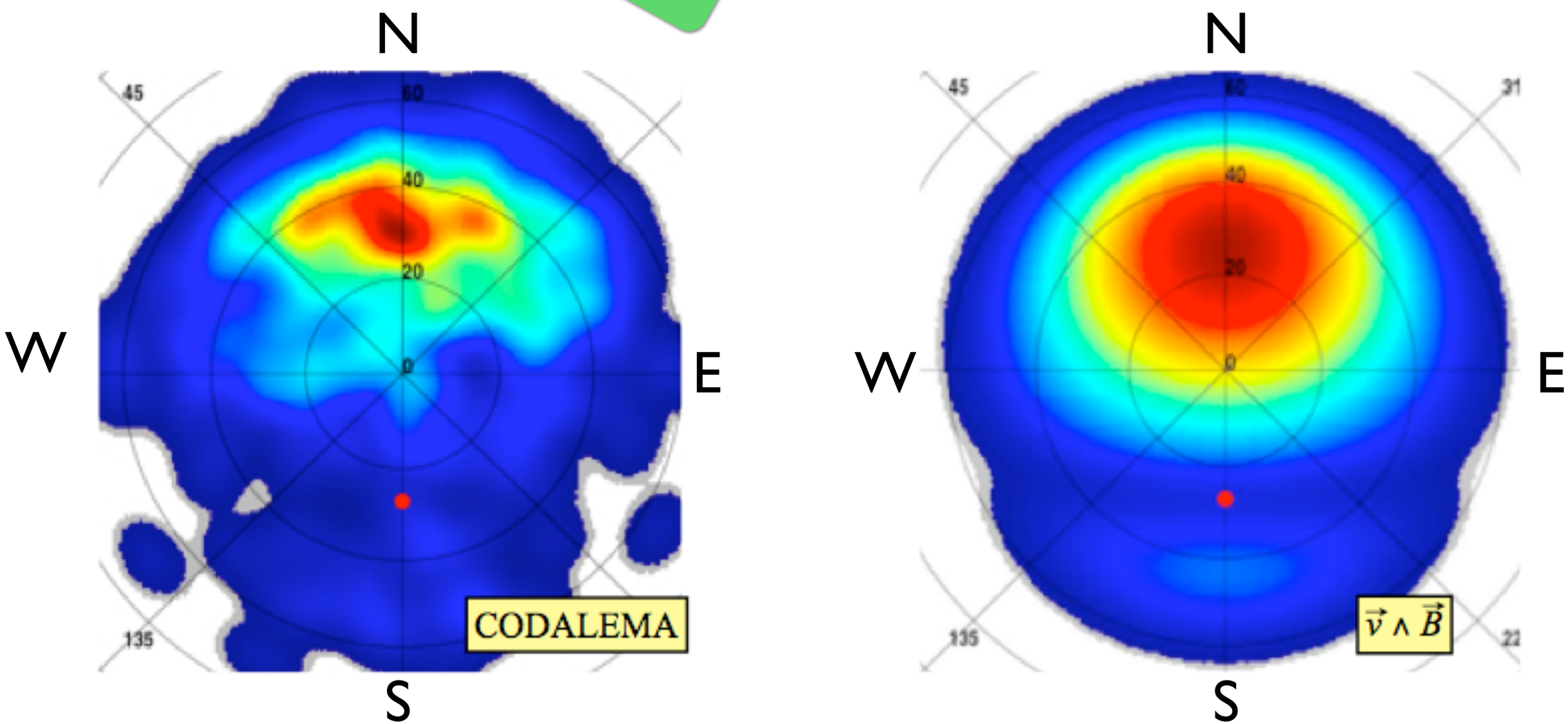
geomagnetic field

almost same direction as the shower axis

the electric field due to this mechanism should be higher when the shower incoming direction is perpendicular to the geomagnetic field

$$-\frac{1}{c}\frac{\partial}{\partial t}\sum_{i=1}^{N}\frac{q_i\,\vec{\beta}_i}{R_i(1-\eta\vec{\beta}_i\cdot\vec{n}_i)}$$

Transverse current contribution



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Transverse current contribution

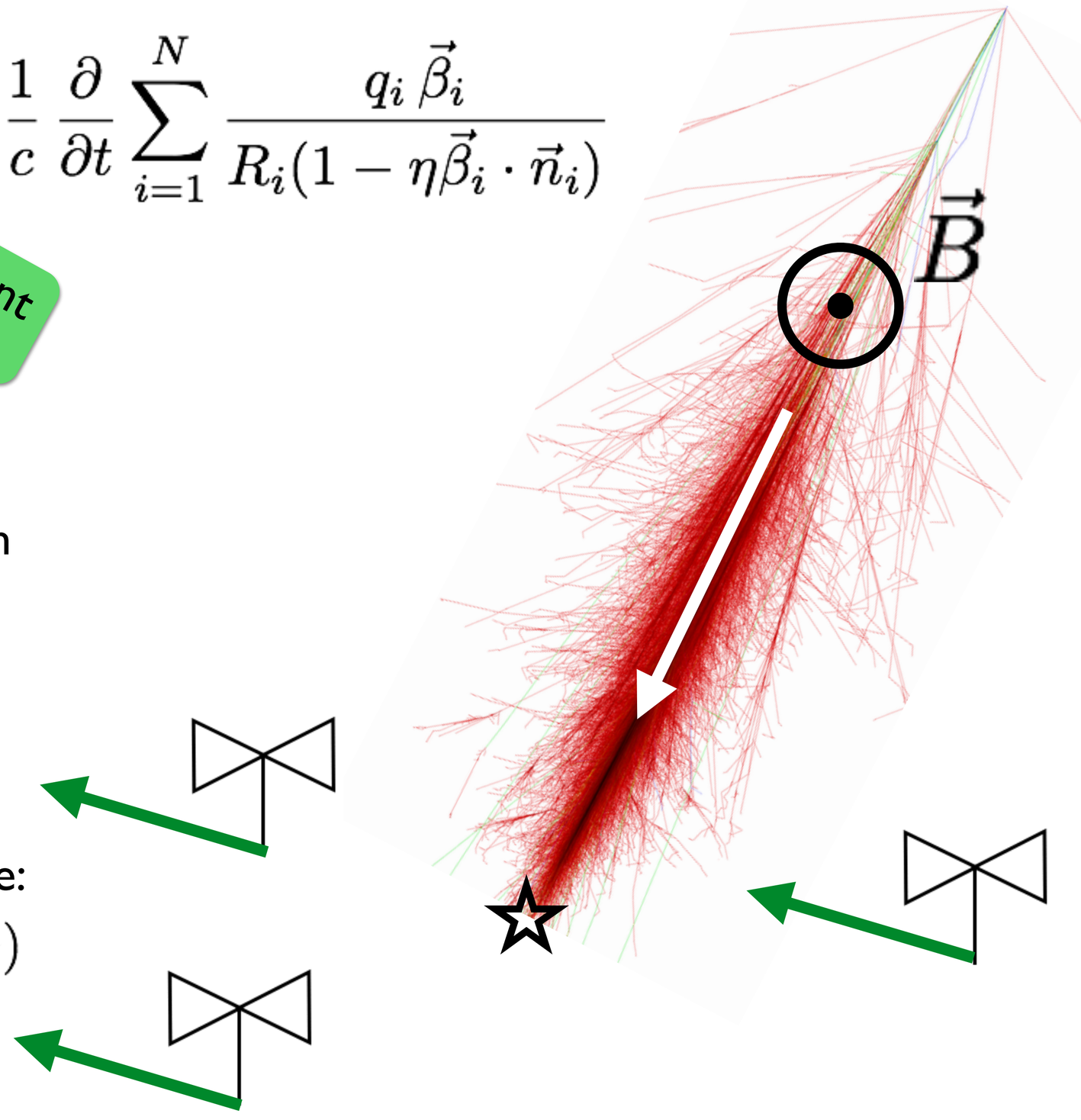
$$\vec{E}_{\rm geo} \propto \vec{\beta}\times\vec{B}$$

from **measurements** of the electric field in the EW and NS polarization, we can compute the polar. angle:

$$\phi_{\rm mes} = \arctan(E_{\rm NS}/E_{\rm EW})$$

and compare it to the **expected** polar. angle:

$$\phi_{\rm exp} = \arctan((\vec{\beta}\times\vec{B})_{\rm NS}/(\vec{\beta}\times\vec{B})_{\rm EW})$$



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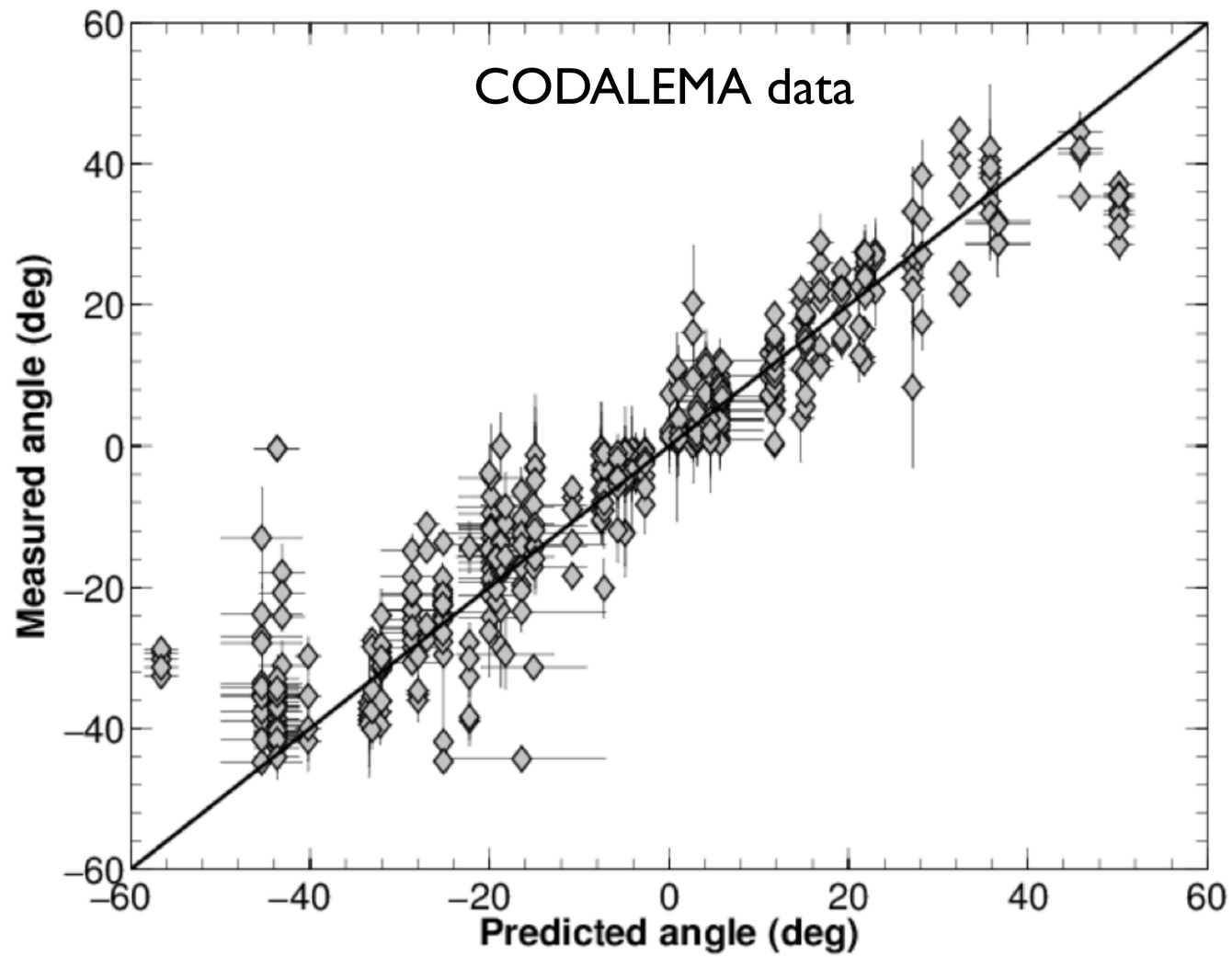

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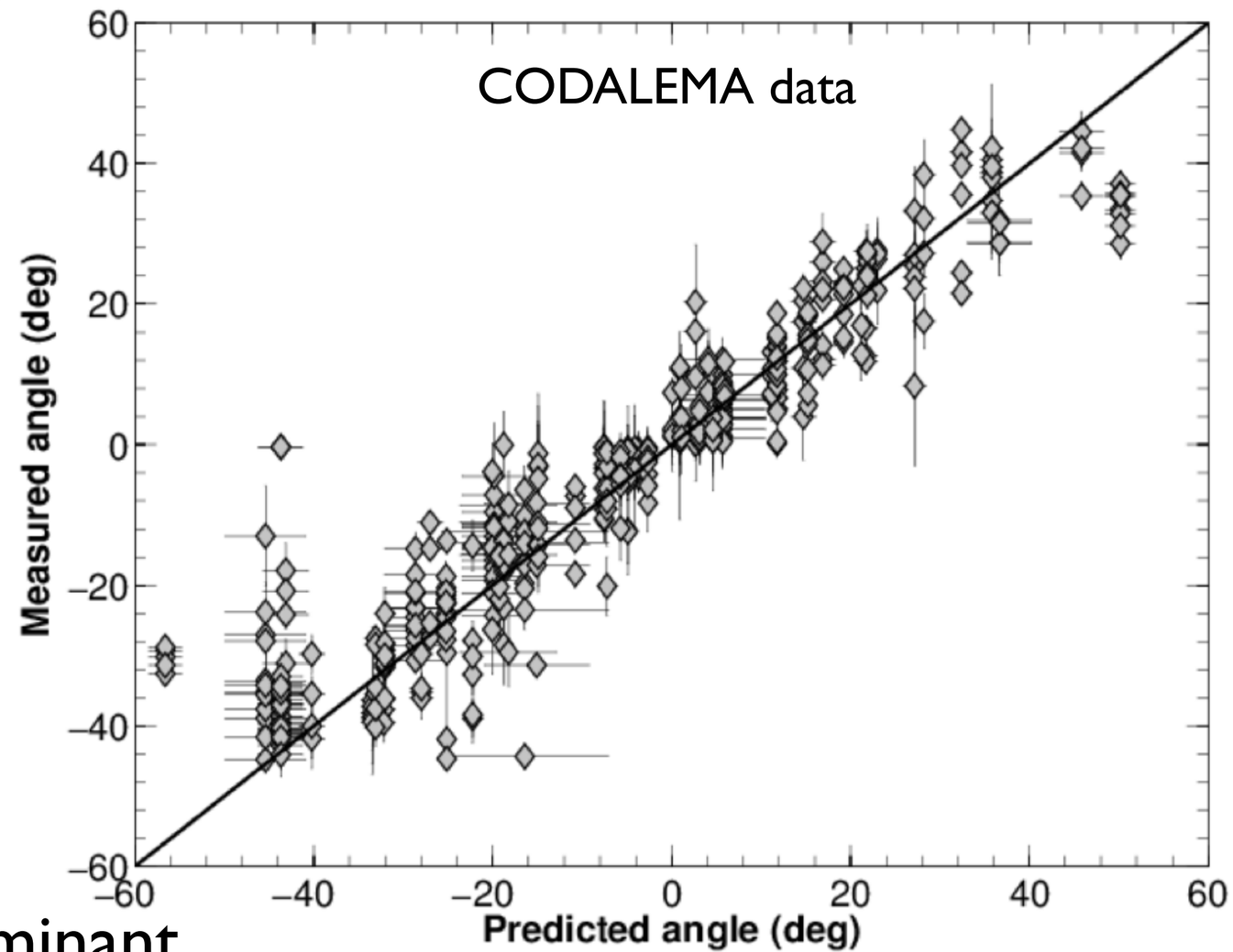


The geomagnetic contribution is dominant

$$+ \frac{1}{c}\frac{\partial}{\partial t}\sum_{i=1}^{N}\frac{q_i\,\vec{n}_i}{R_i(1-\eta\vec{\beta}_i\cdot\vec{n}_i)}$$

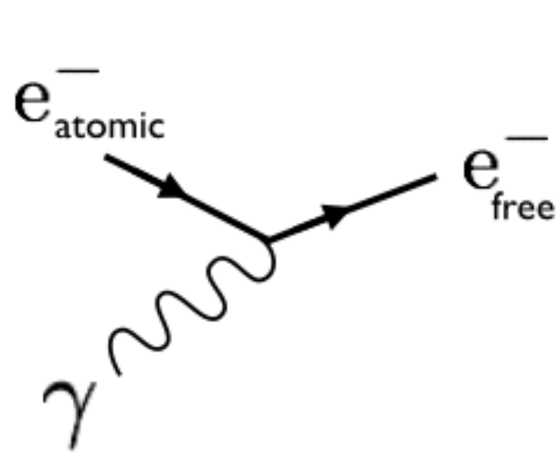
(Askaryan 1962, 1965)

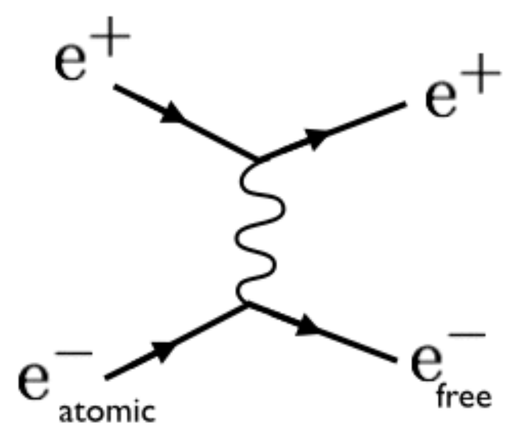
Charge excess contribution

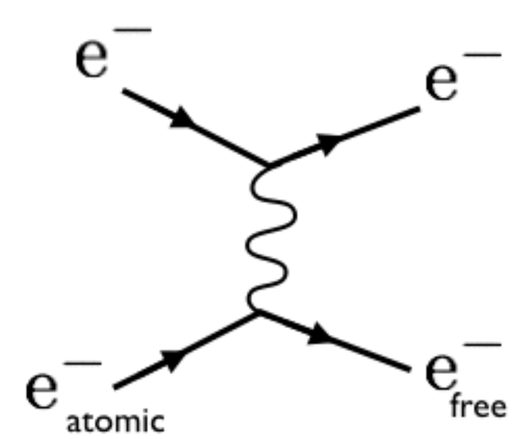
No net electric field if $n_{e+} = n_{e-}$

but $n_{e+} < n_{e-}$ because:

- in flight e+ annihilation
- electrons are extracted from the medium (Compton, Bhabha, Moeller)







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- electrons are extracted from the medium (Compton, Bhabha, Moeller)

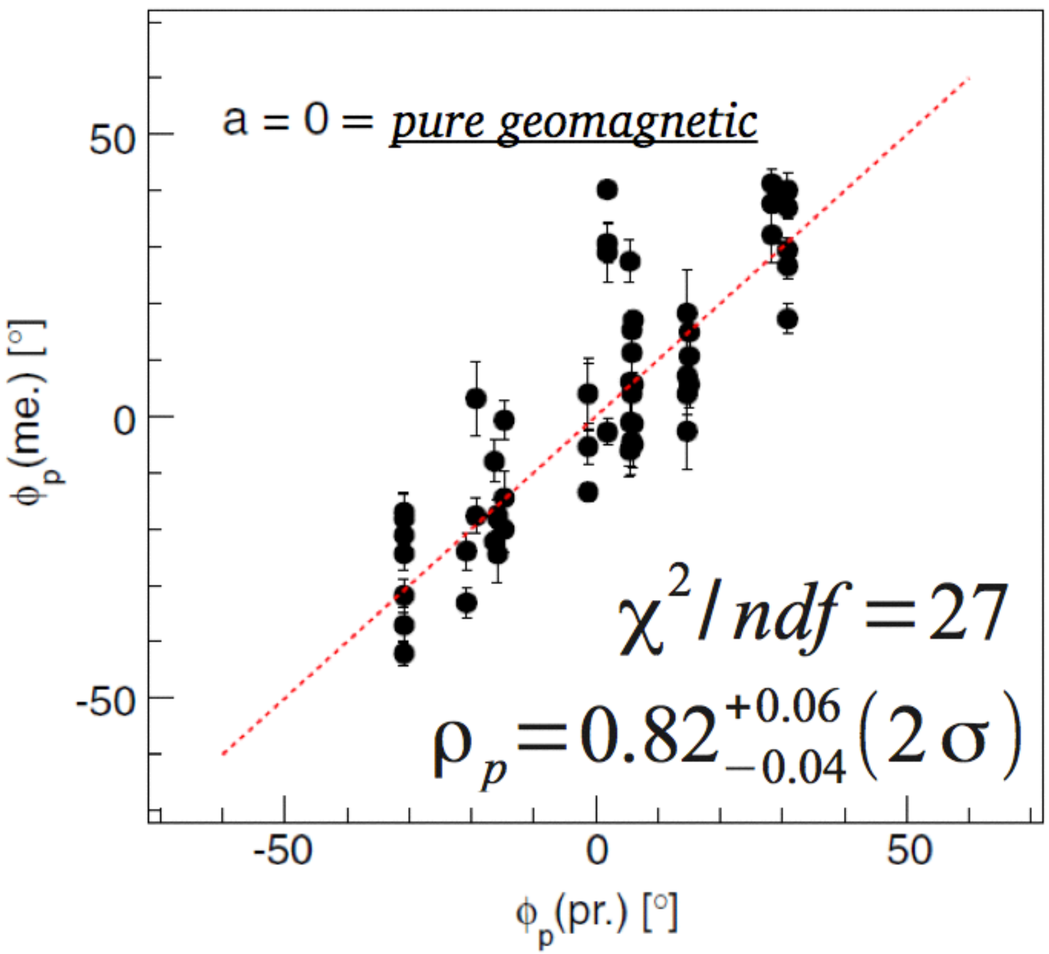
this excess of electrons leads to a

- **net electric field**
- **with a radial polarization pattern**
- **depends on the observer's location**

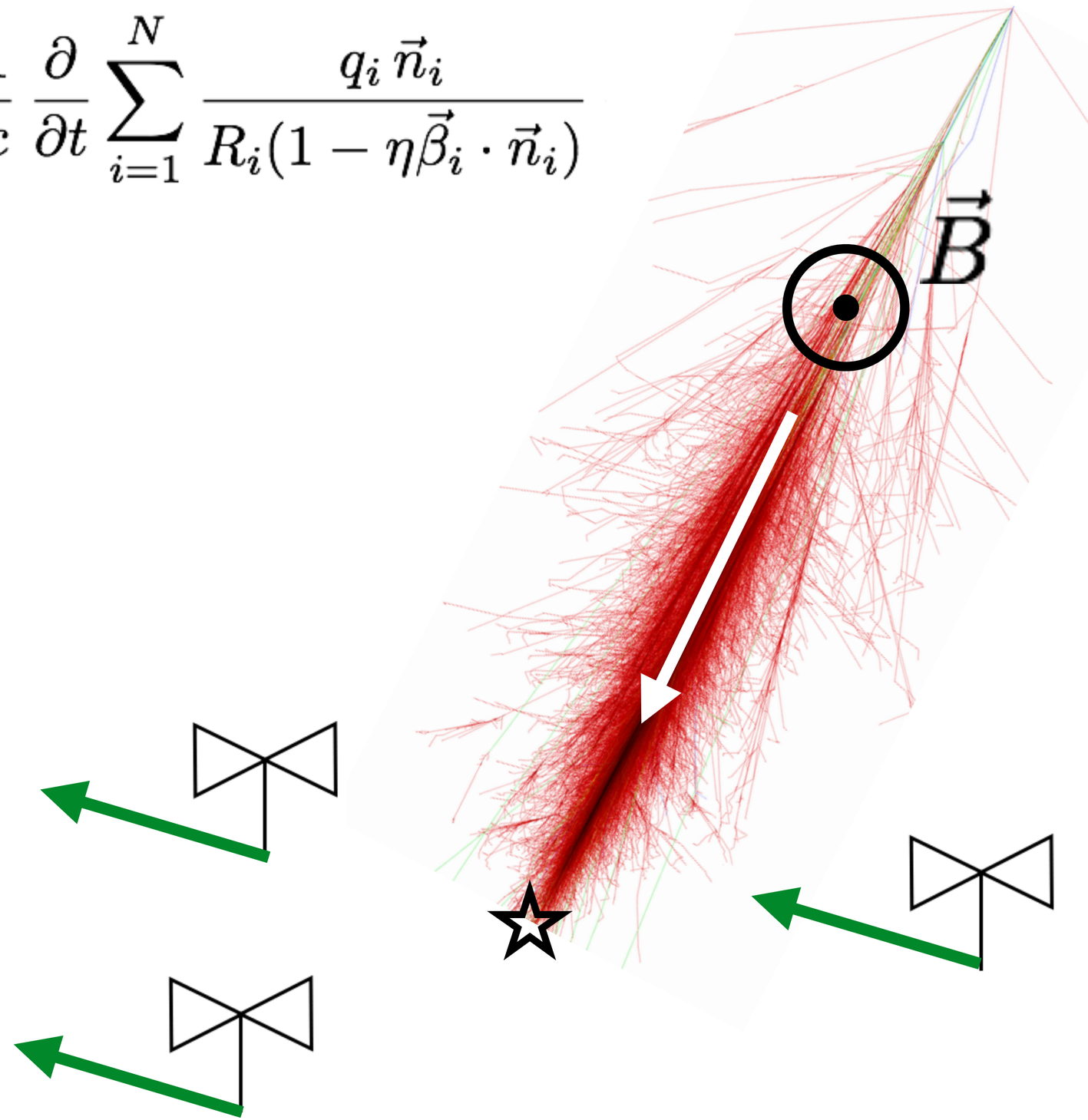
$$+\frac{1}{c}\frac{\partial}{\partial t}\sum_{i=1}^{N}\frac{q_i\,\vec{n}_i}{R_i(1-\eta\vec{\beta}_i\cdot\vec{n}_i)}$$

Charge excess contribution

AERA data



The Pierre Auger Collaboration, Phys. Rev. D 89, 052002 (2014)



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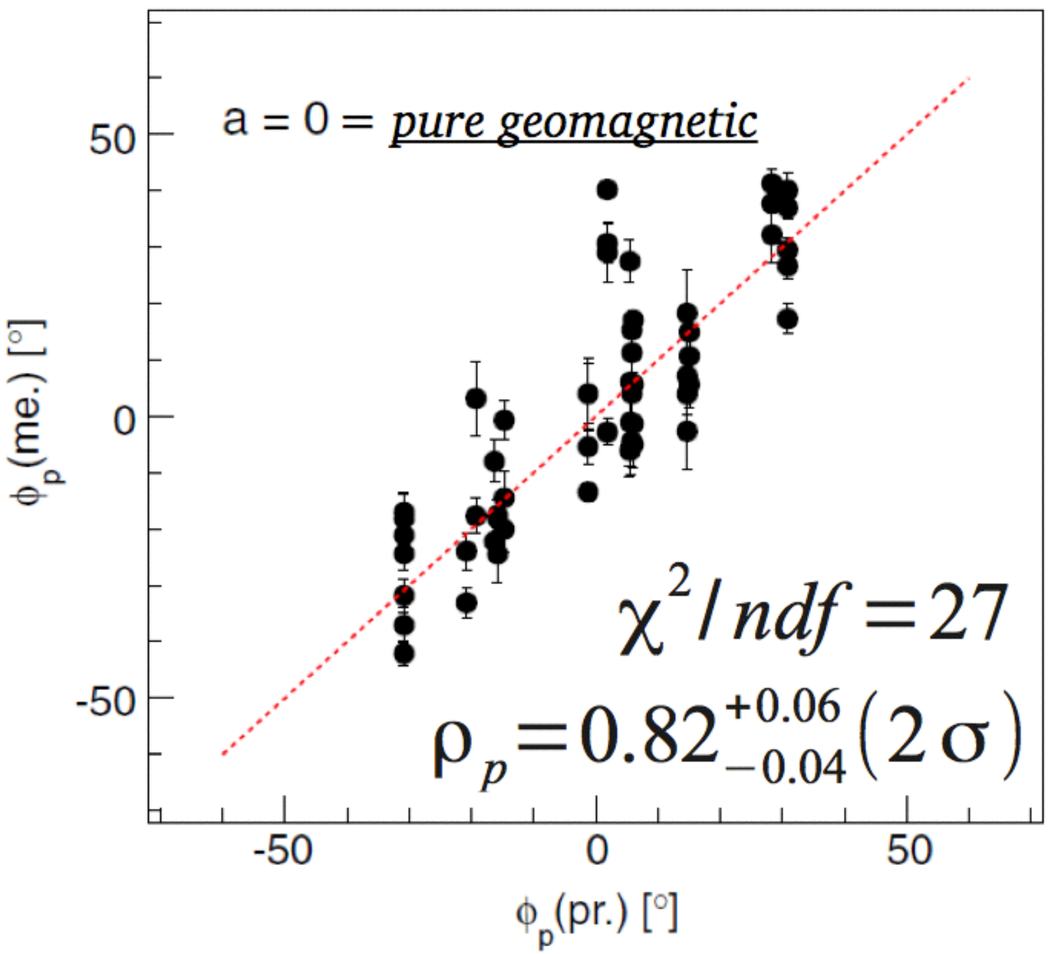

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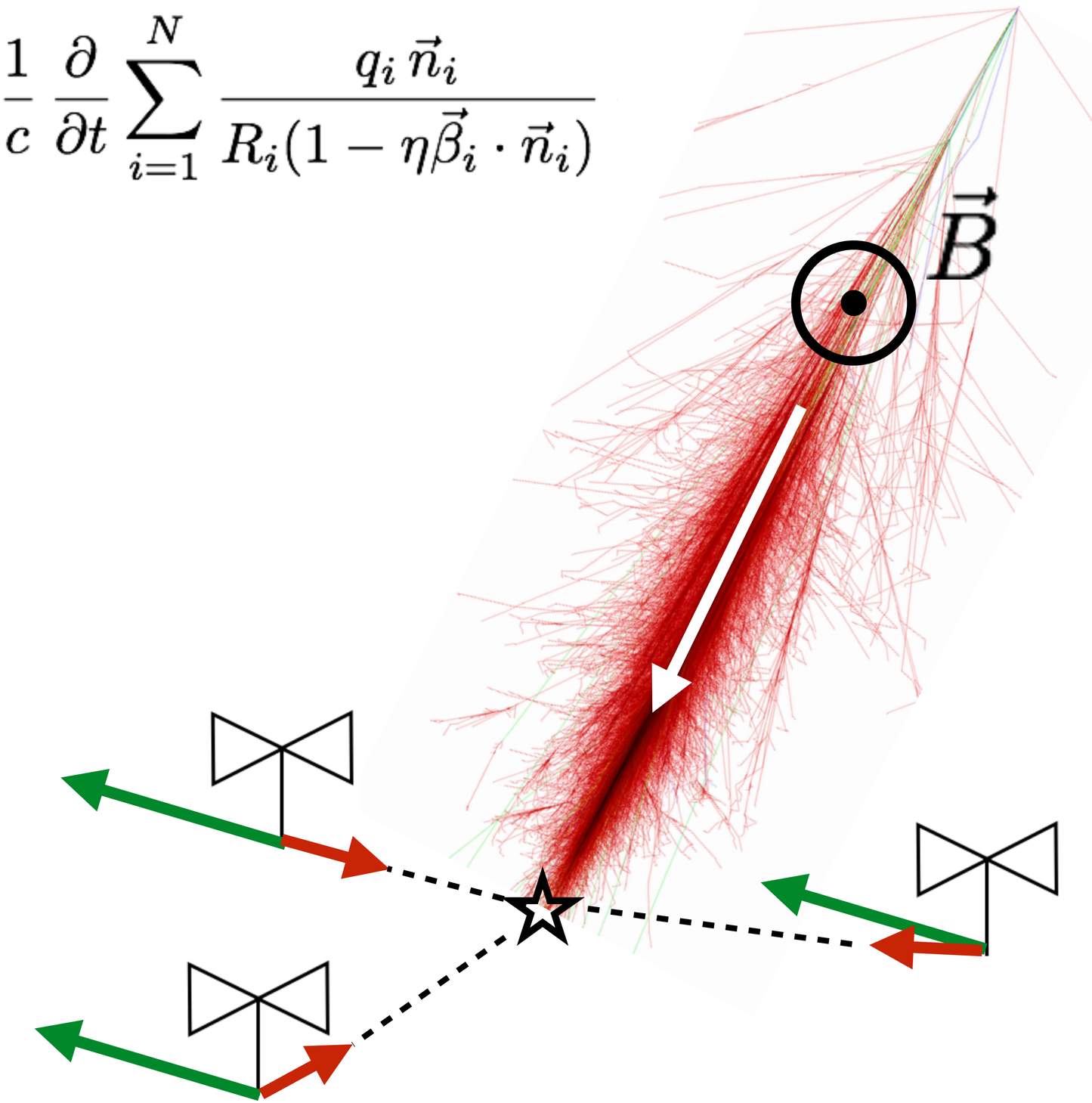

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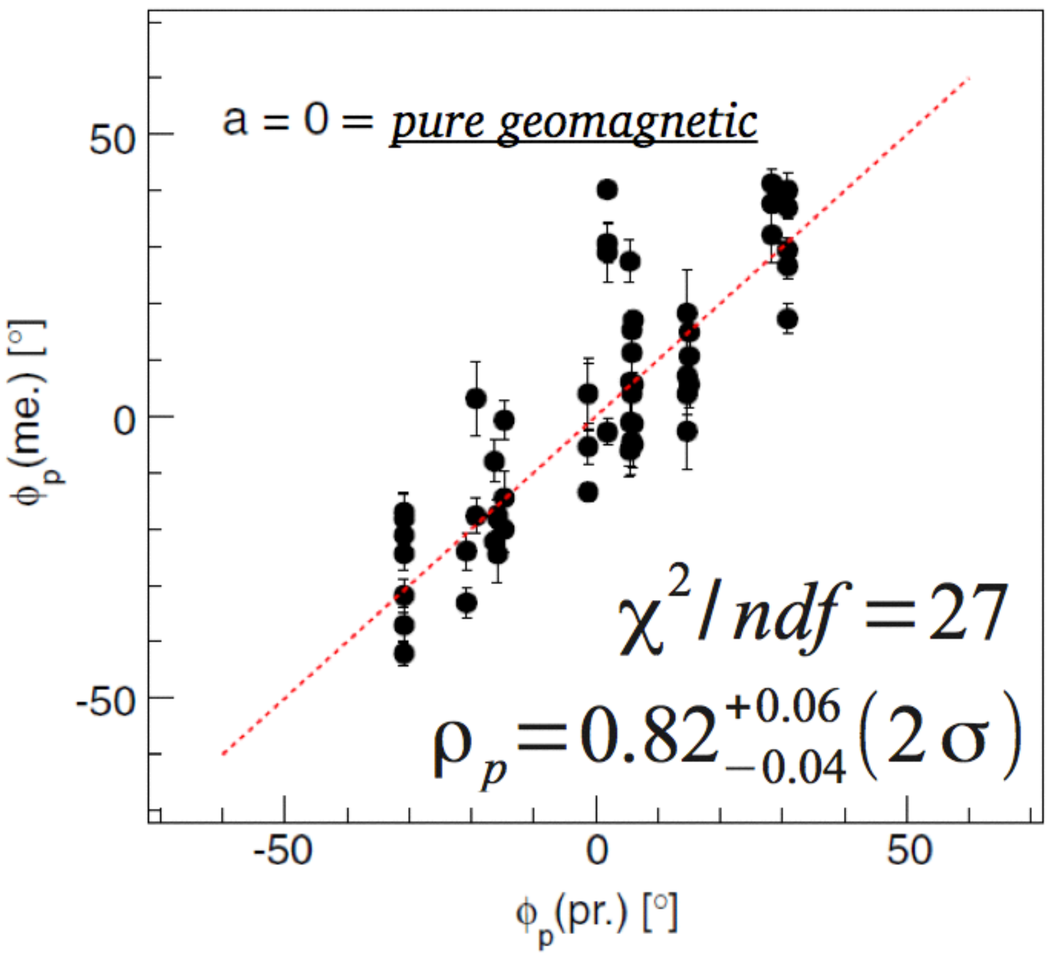

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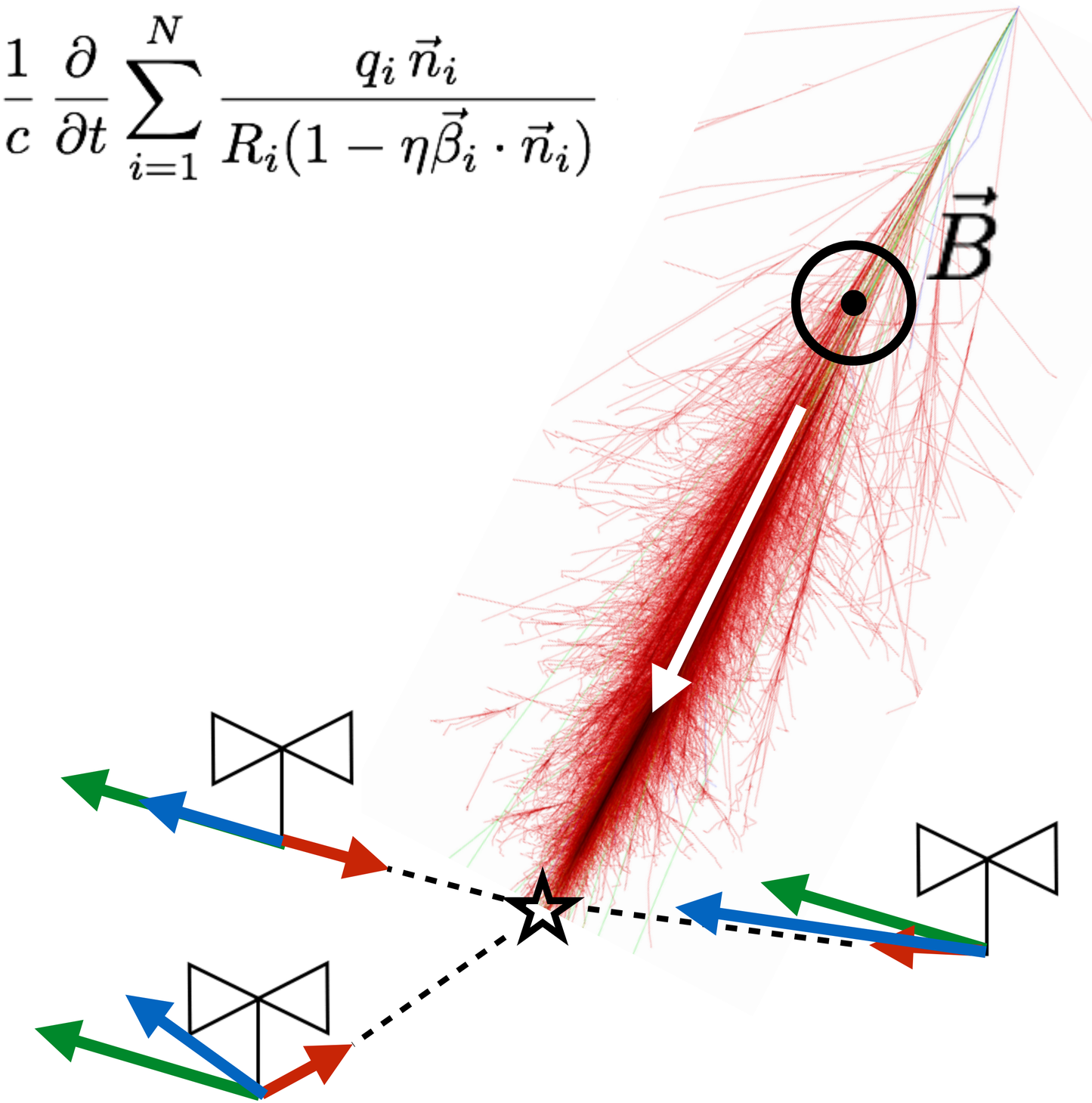

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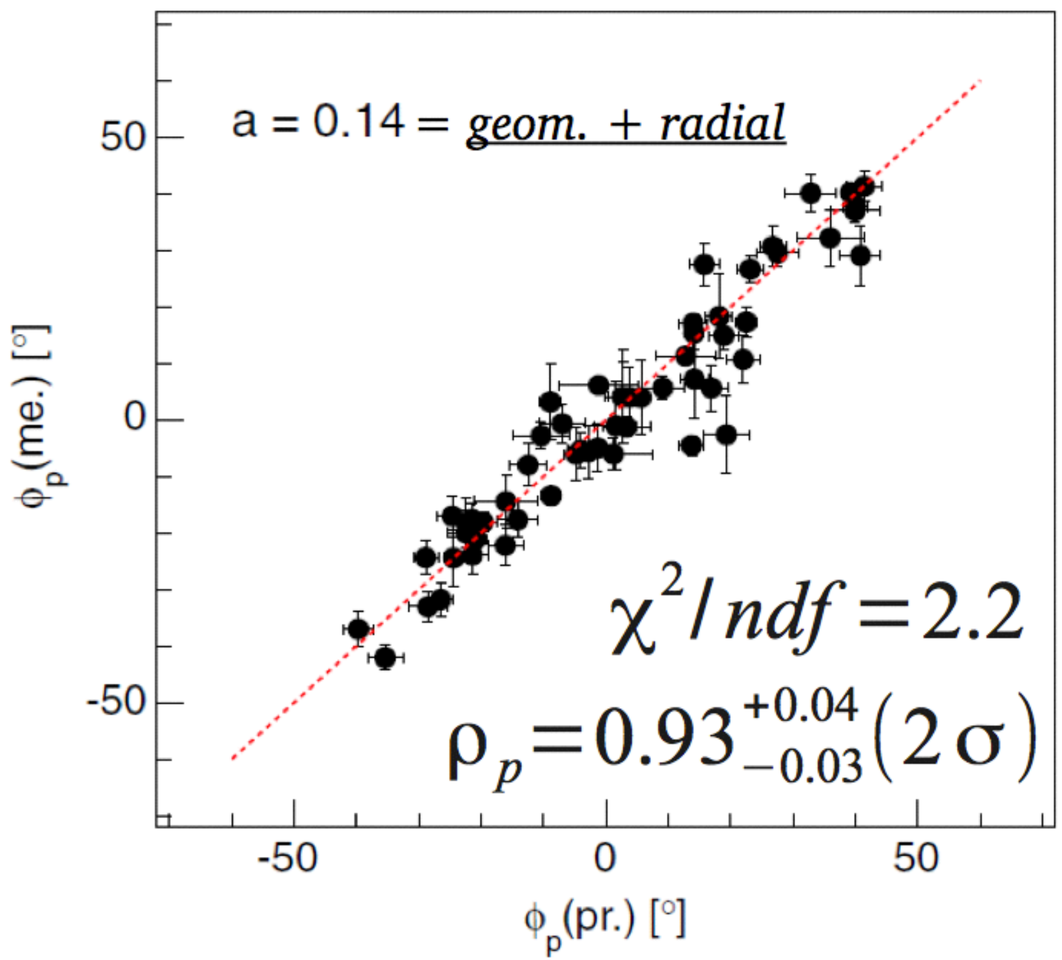

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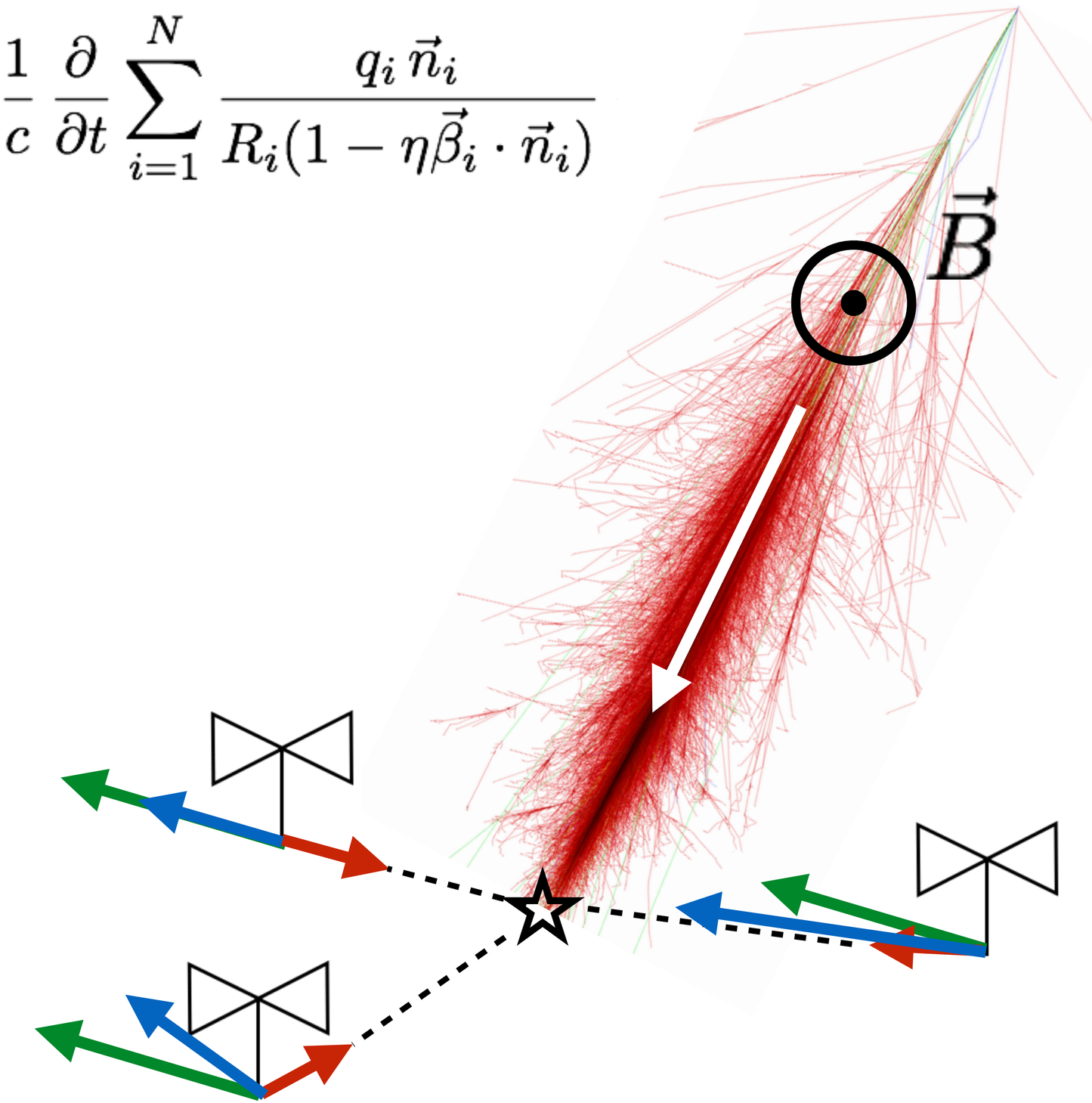

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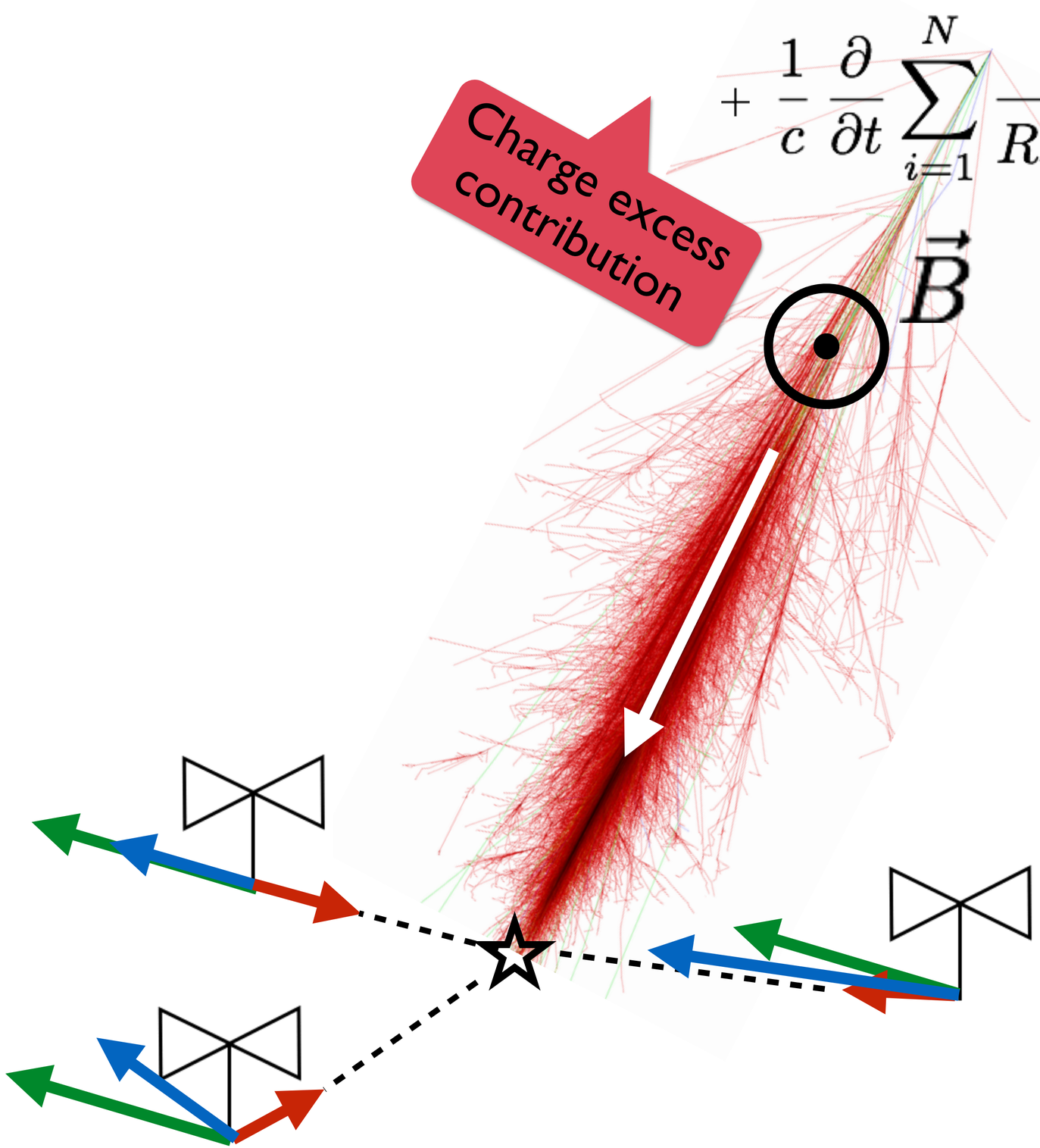

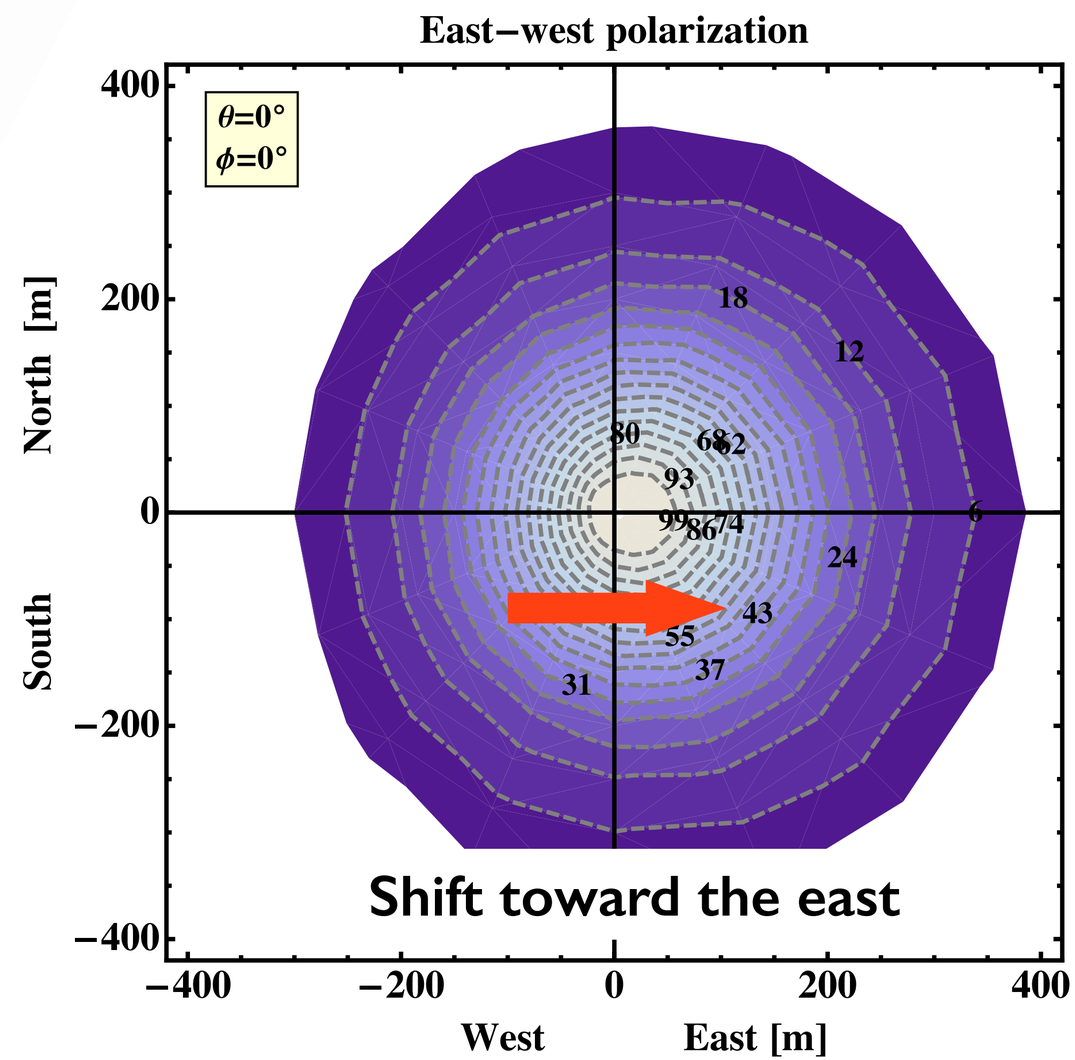

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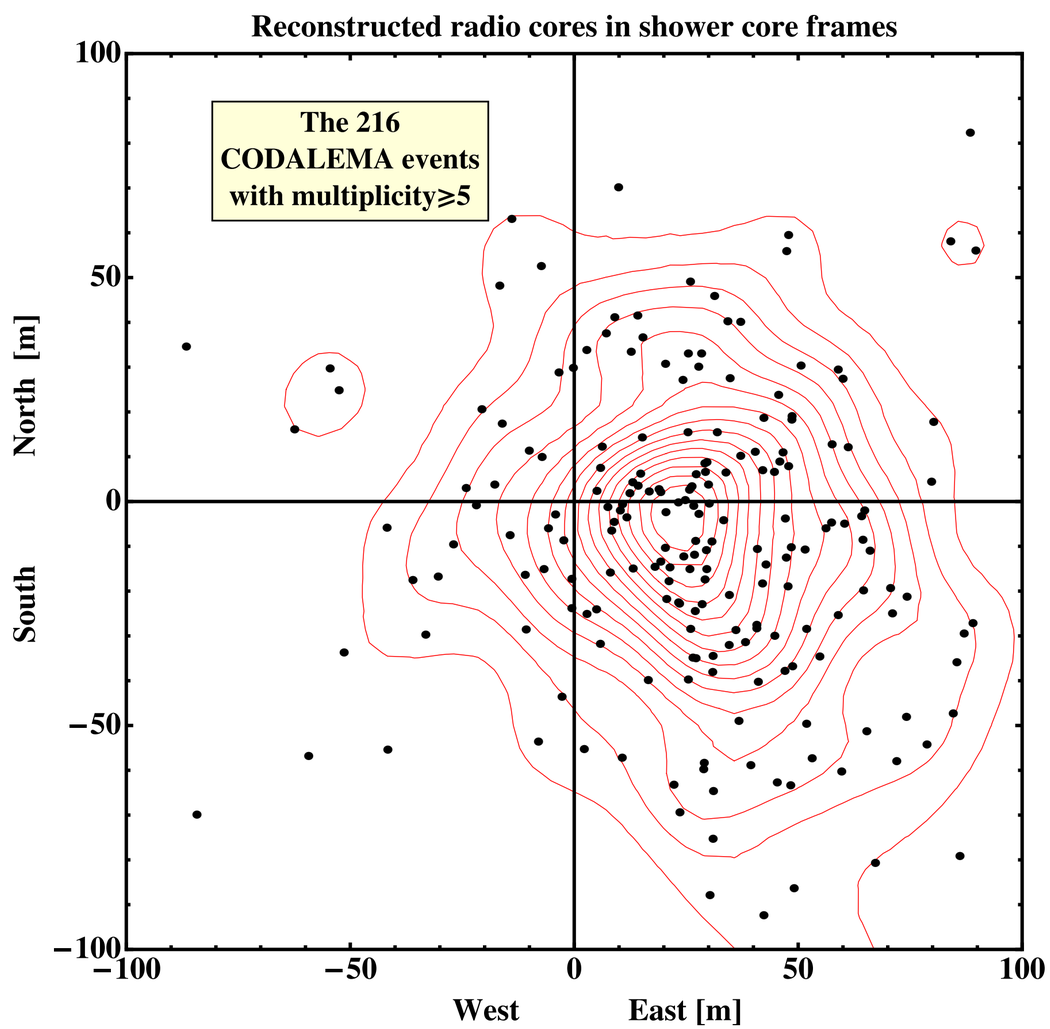

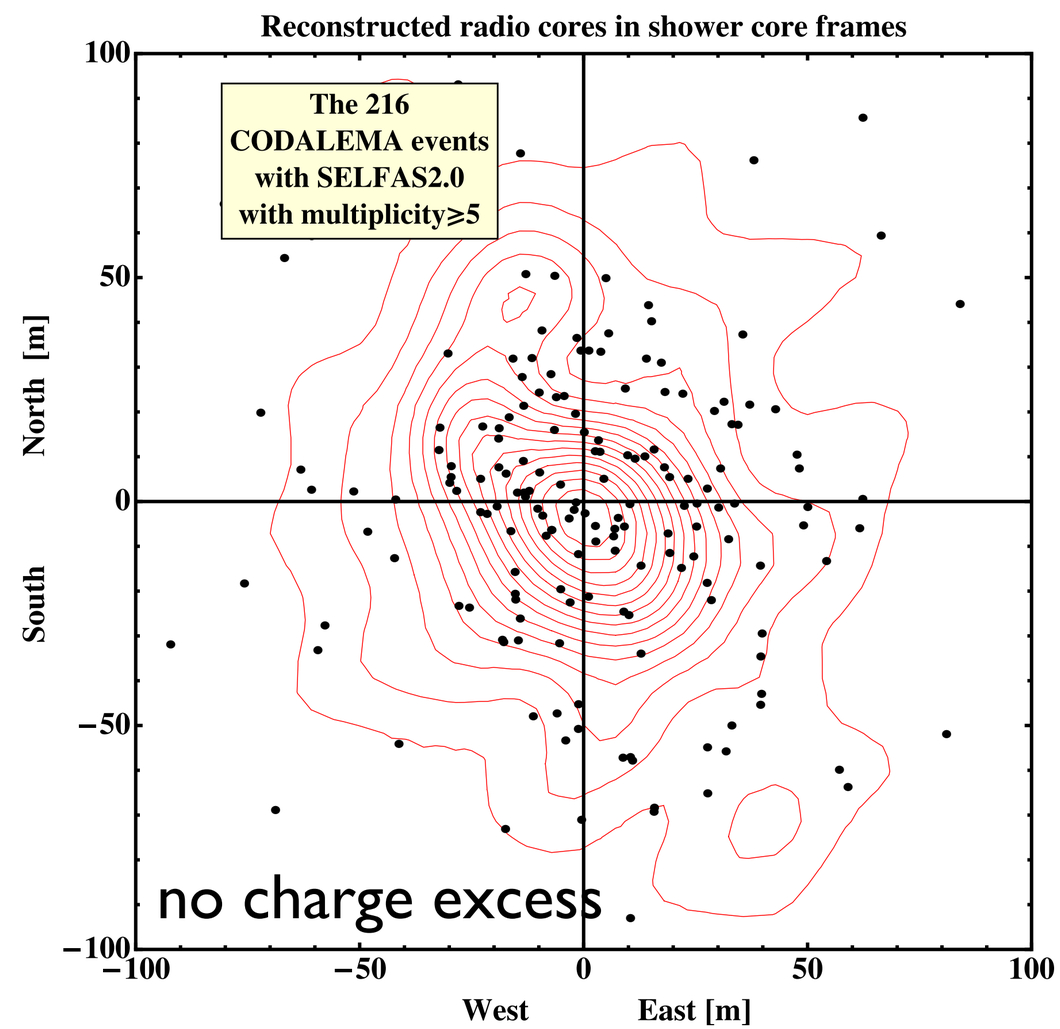

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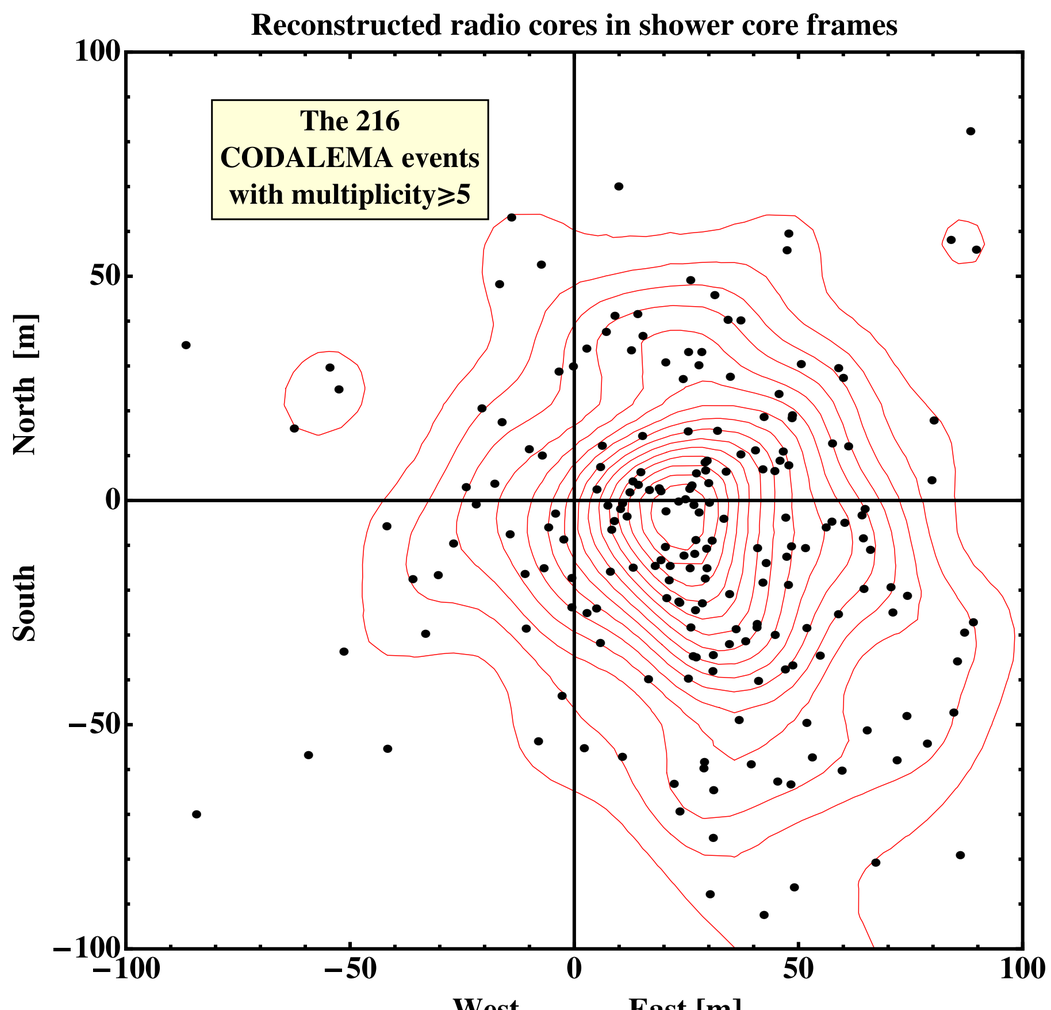
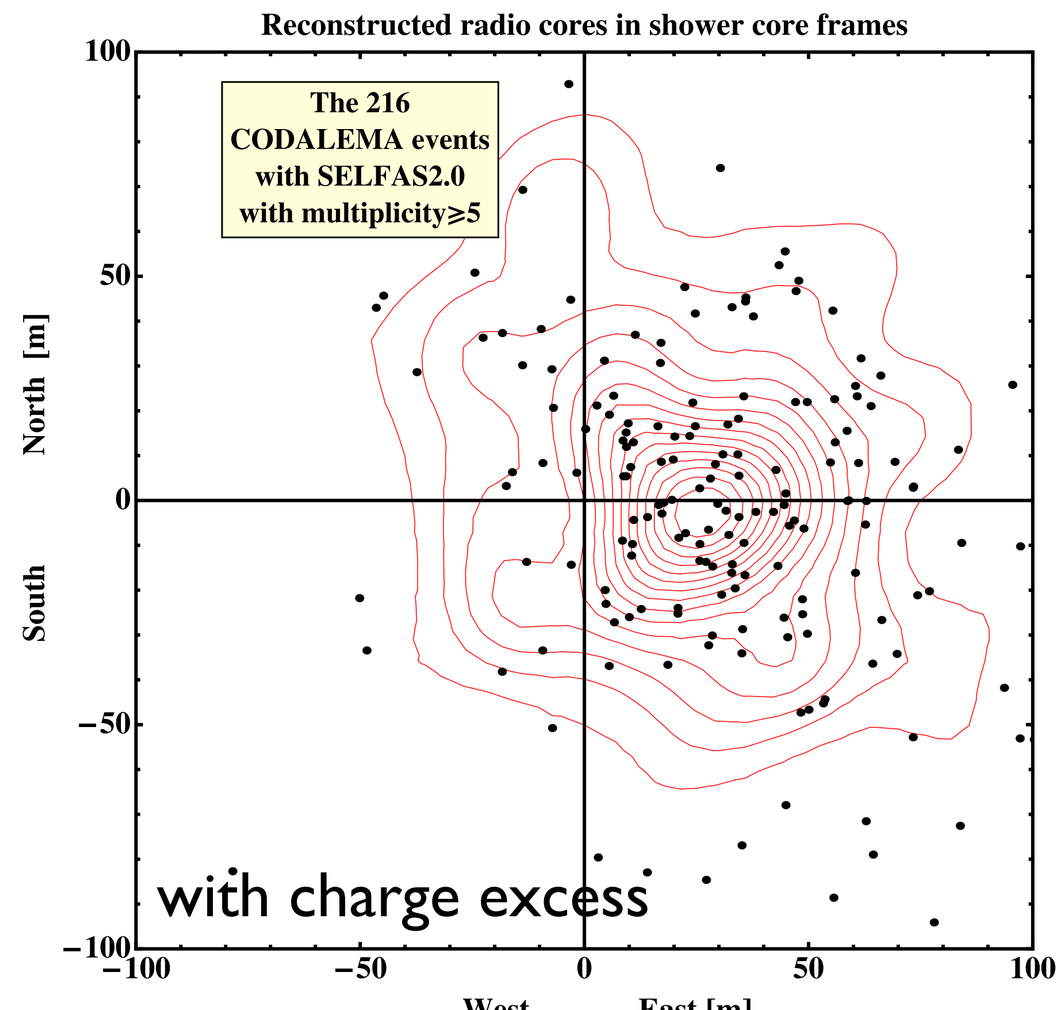
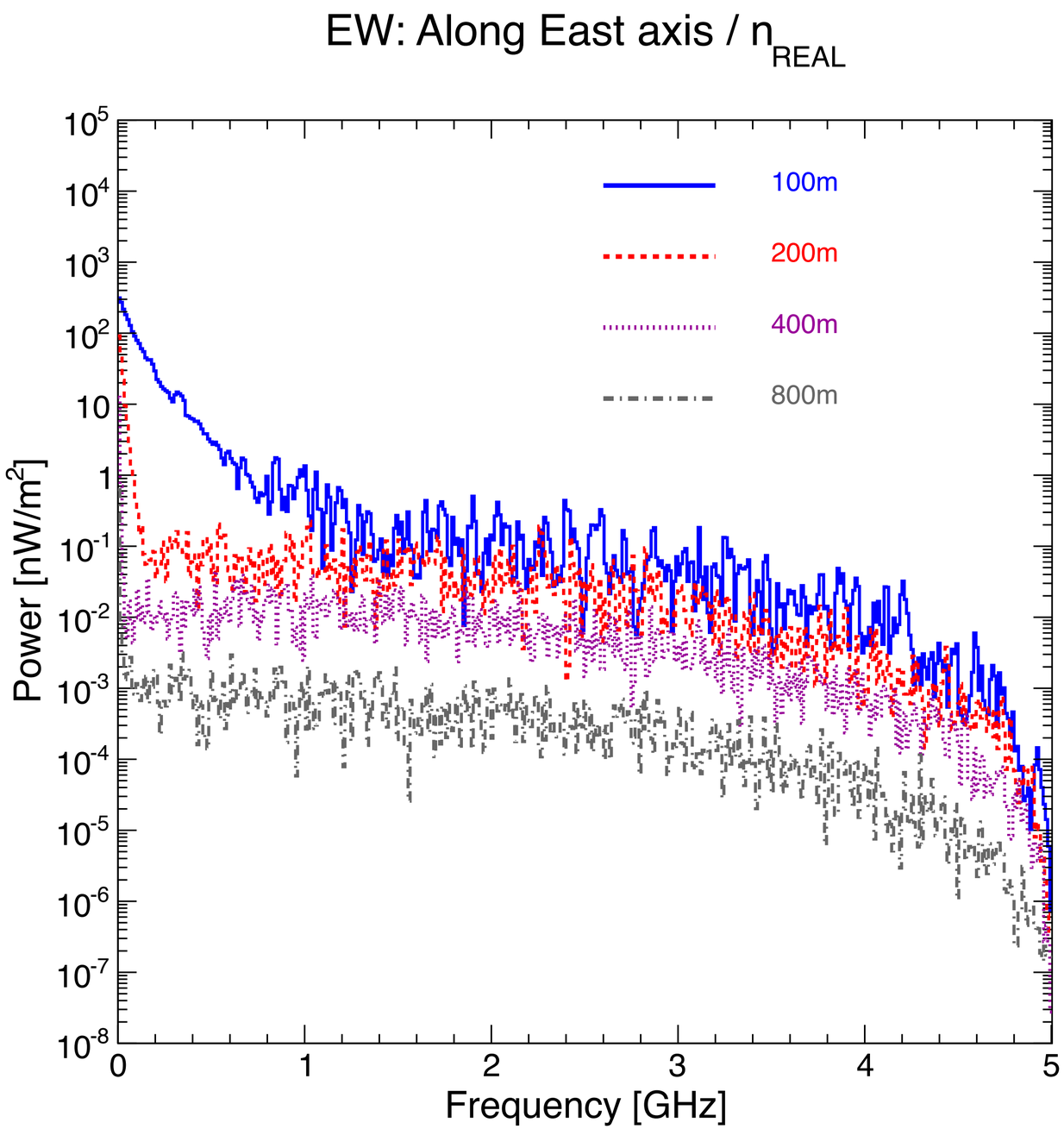


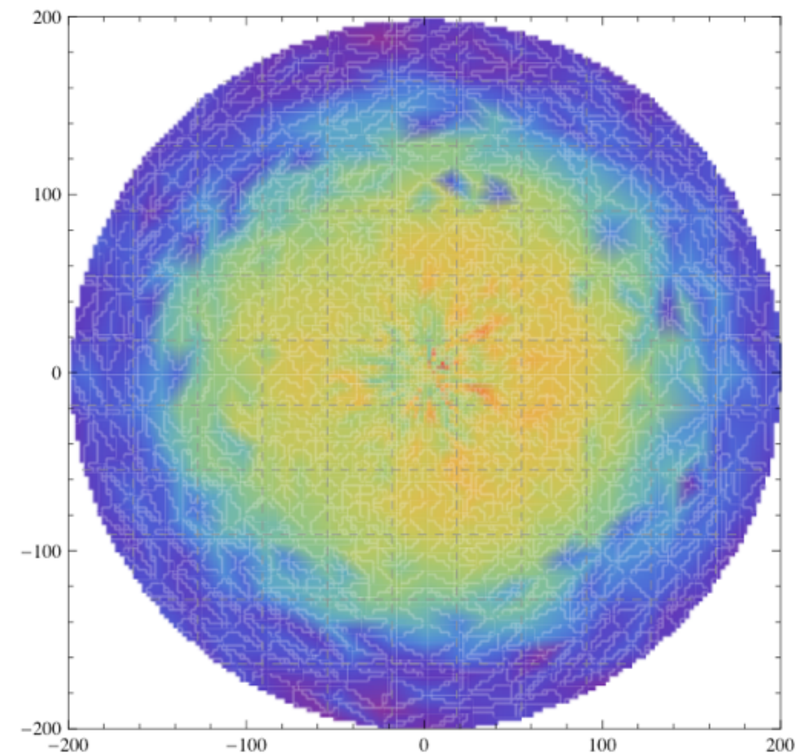


Up to some GHz



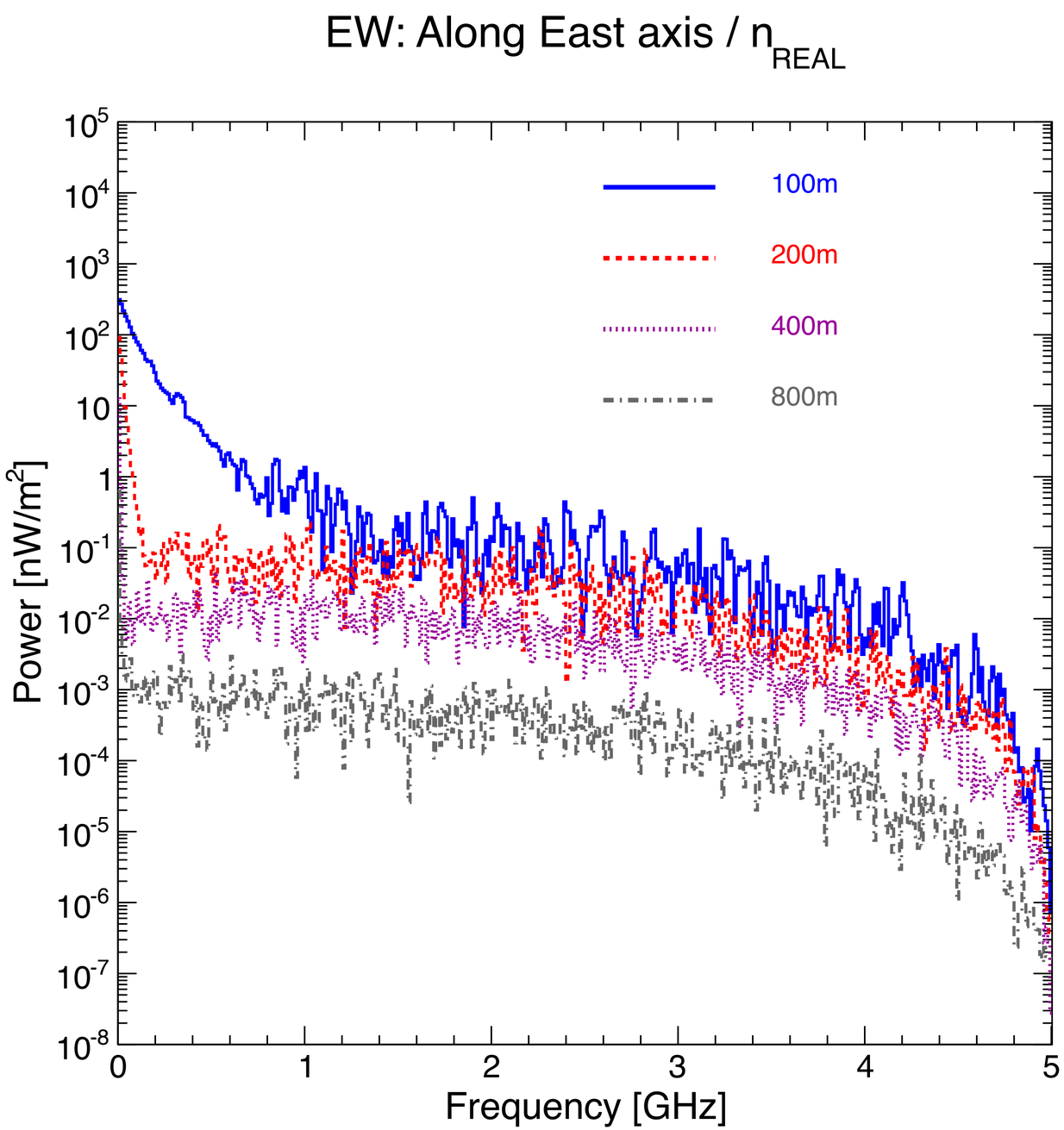
extend the mechanisms observed in the MHz domain to the GHz domain
take into account the effect of a realistic refractive index

Proton



300 MHz - 1.2 GHz

Up to some GHz



extend the mechanisms observed in the MHz domain to the GHz domain
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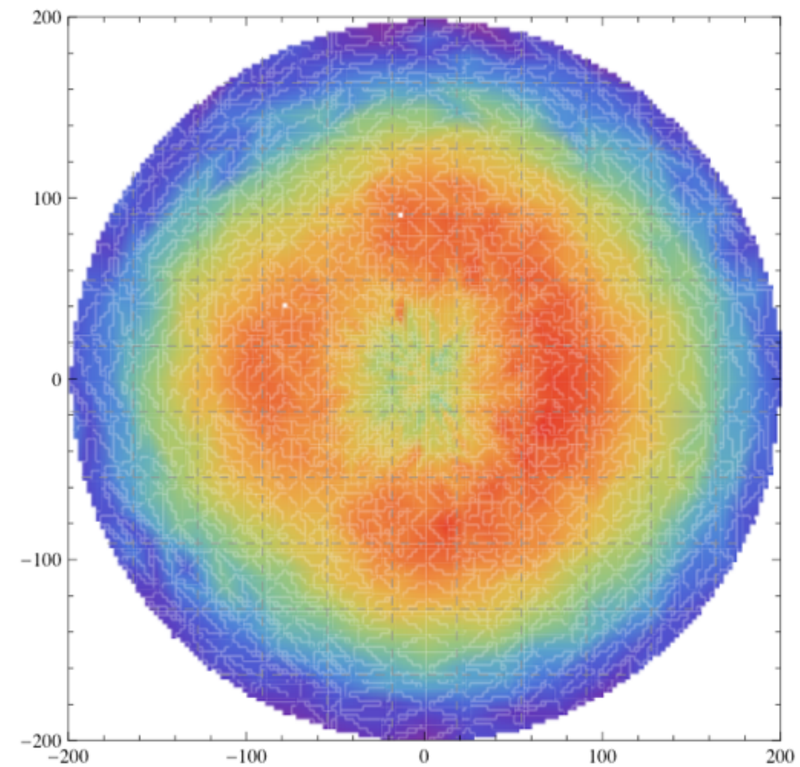
Iron



300 MHz - 1.2 GHz

No MBR evidence in the GHz signal

Down to some kHz

Predicted mechanisms:

usual geomagnetic and charge excess contributions during the shower development in the air
+
the transition radiation when the shower front hits the ground
+
the coherent Bremsstrahlung of e^+/e^- when they reach the ground level
[B. R. ICRC2013, Rio]

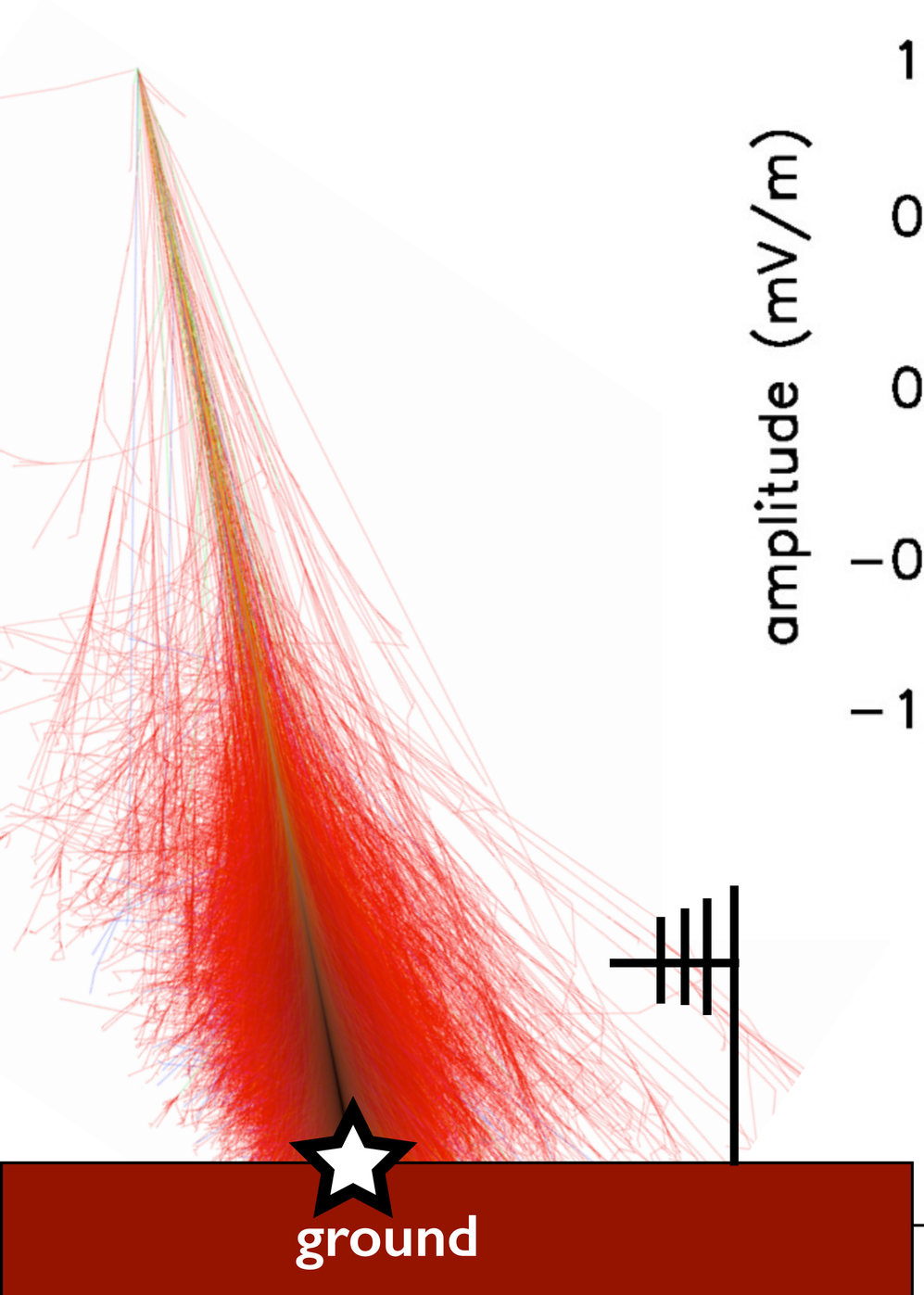
} **sudden death** of the shower

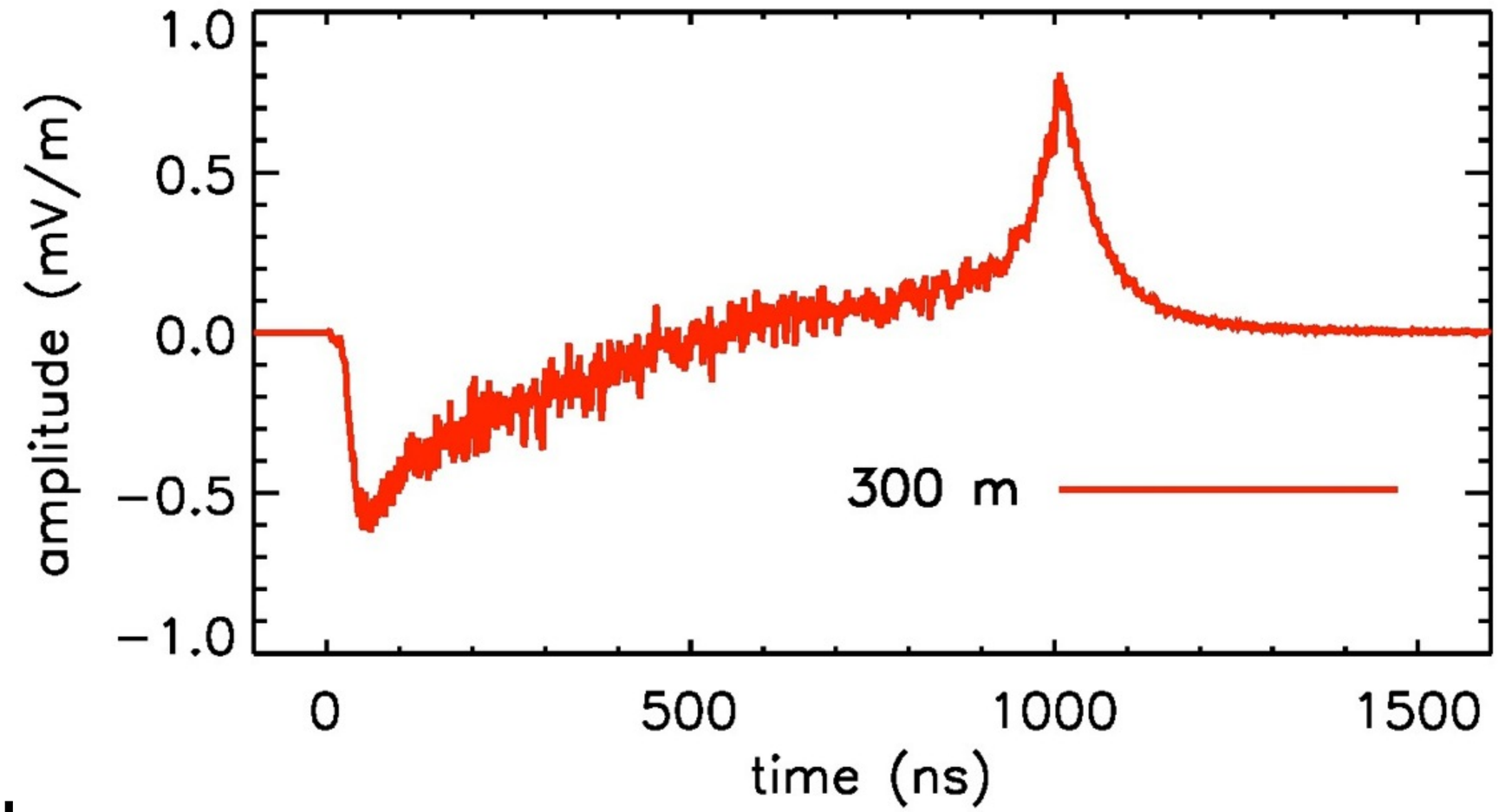
$$\vec{E}(\vec{x},t) = \frac{1}{4\pi\varepsilon_0\, c}\frac{\partial}{\partial t}\sum_{i=1}^{N} q_i \left(\frac{\vec{\beta}_i - (\vec{n}_i\cdot\vec{\beta}_i)\,\vec{n}_i}{R_i(1-\eta\vec{\beta}_i\cdot\vec{n}_i)}\right)_{\mathrm{ret}}$$

(Coulomb gauge)

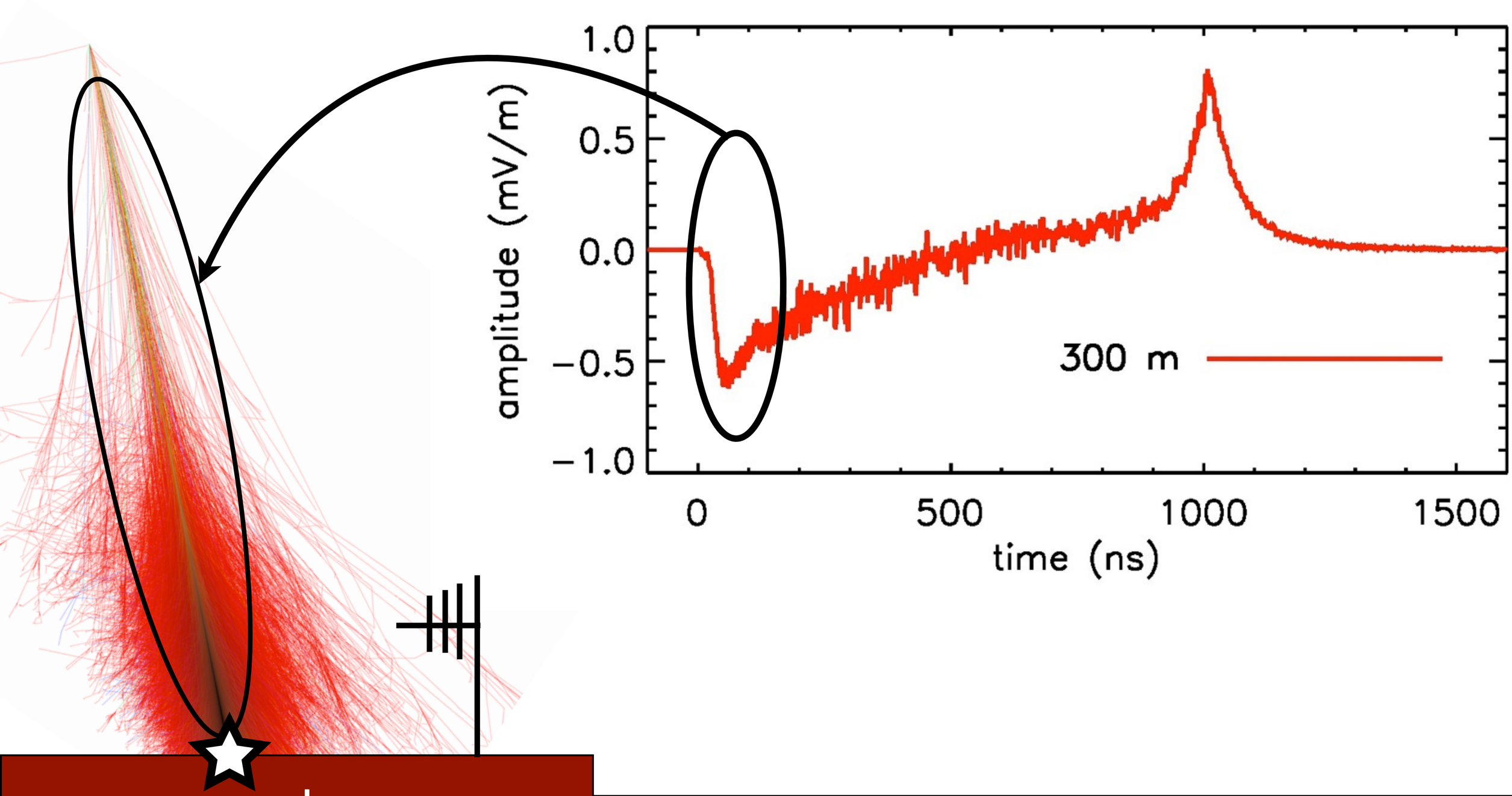
New contribution below 20 MHz, **vertical** polarization,
monopolar pulse with amplitude decreasing with **$1/d_{core}$**
(as already observed in the past by AGASA, Gauhati group, EAS-radio…)

Down to some kHz

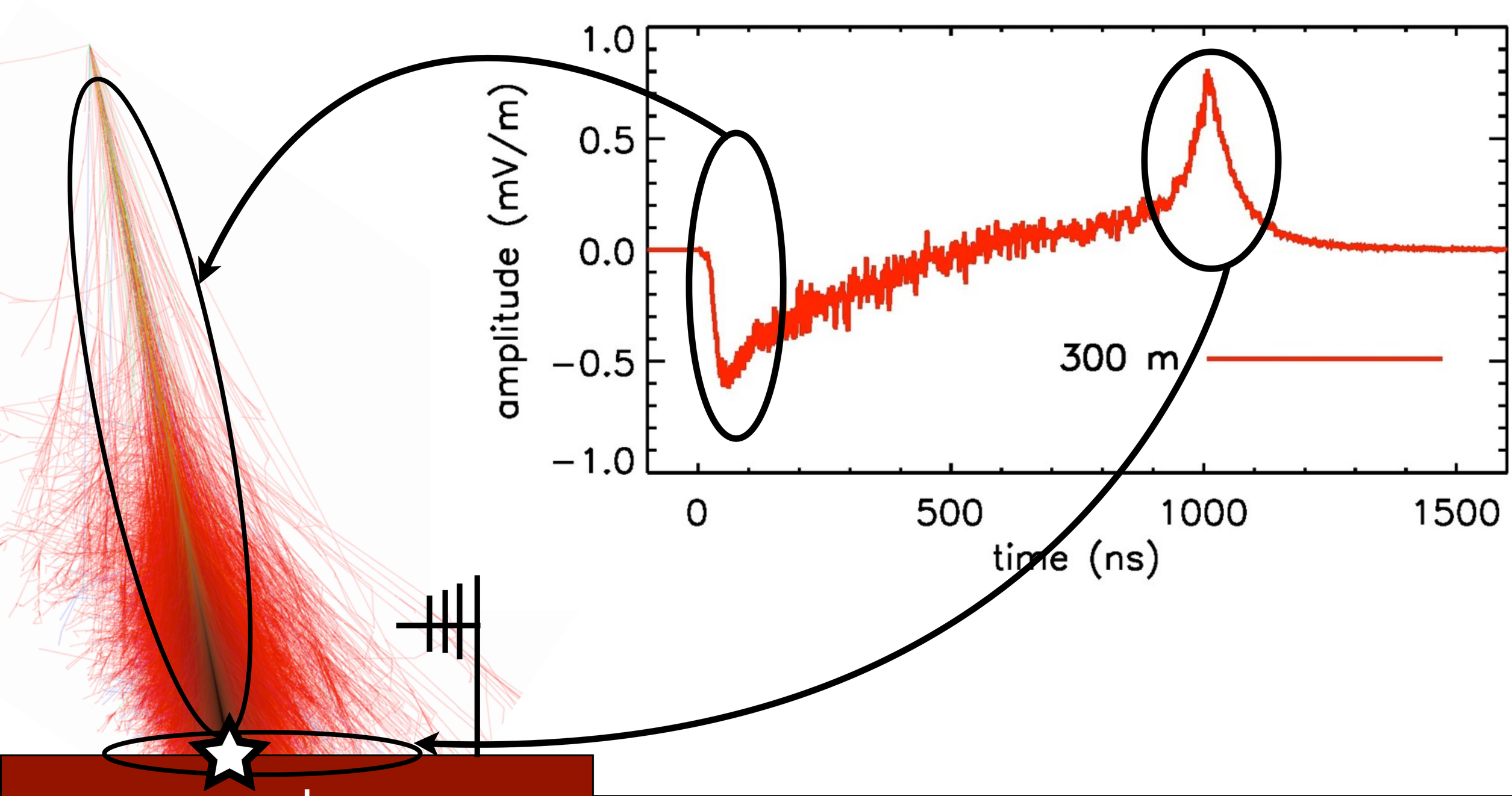




Down to some kHz



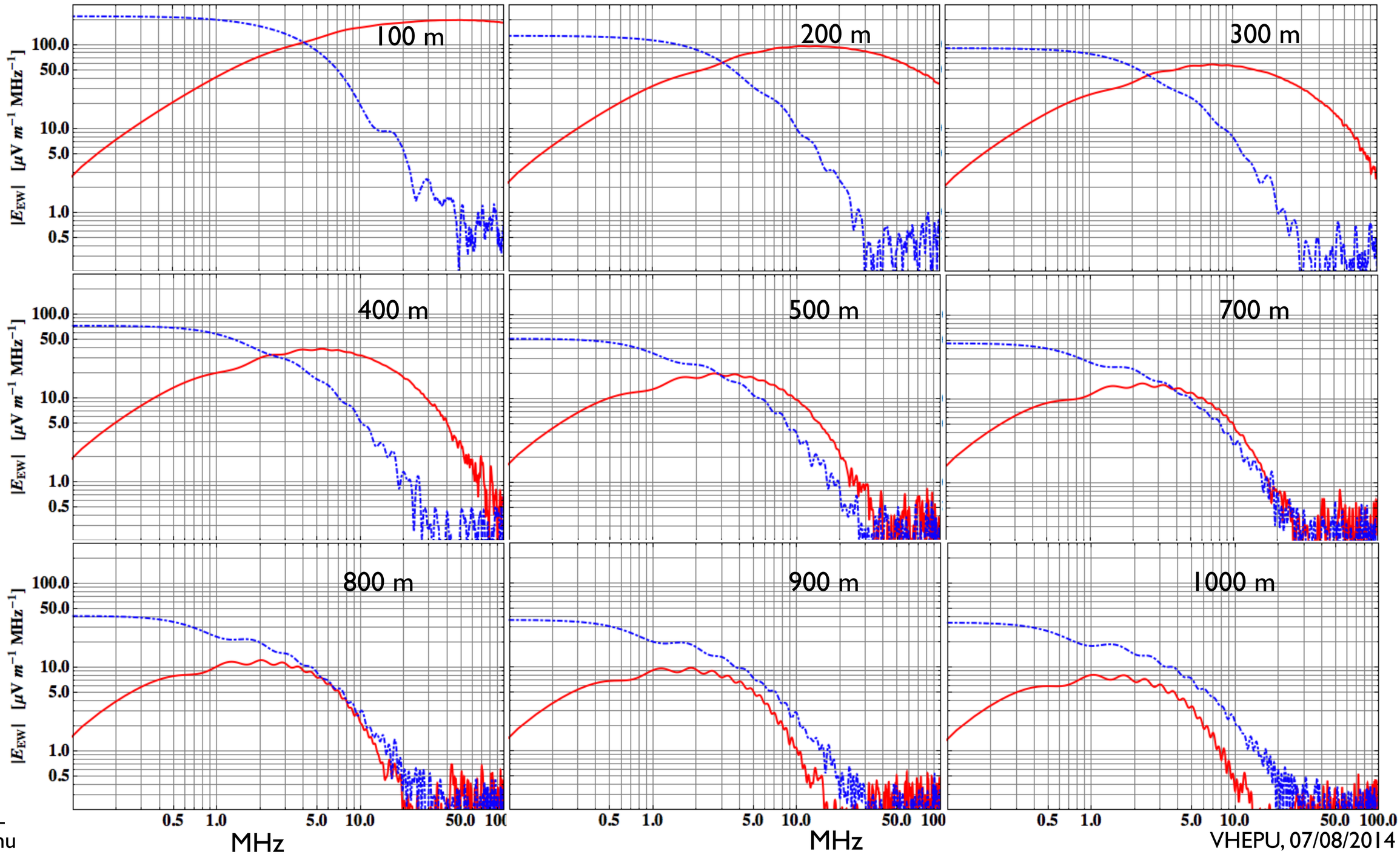
Down to some kHz



ground contribution
development in the air

Down to some kHz

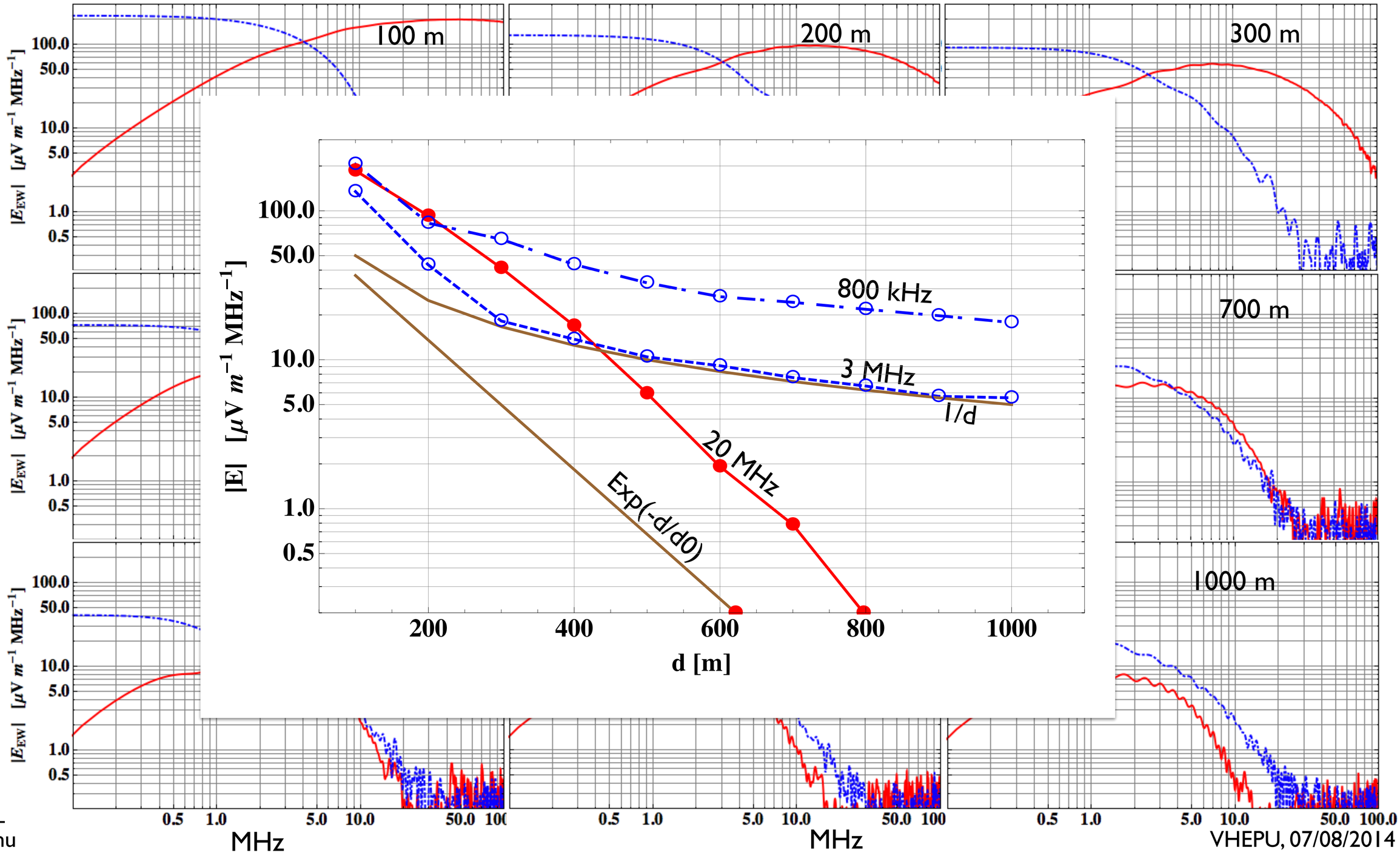
(SELFAS simulations)



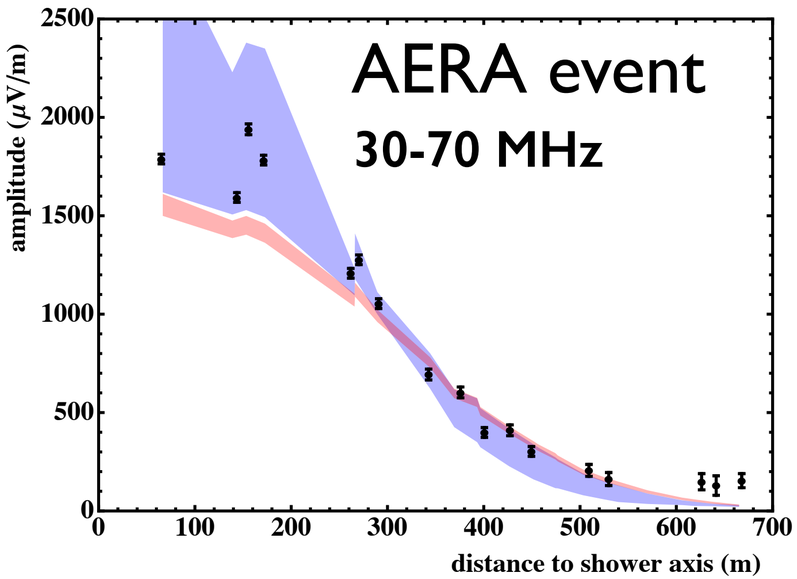
ground contribution
development in the air

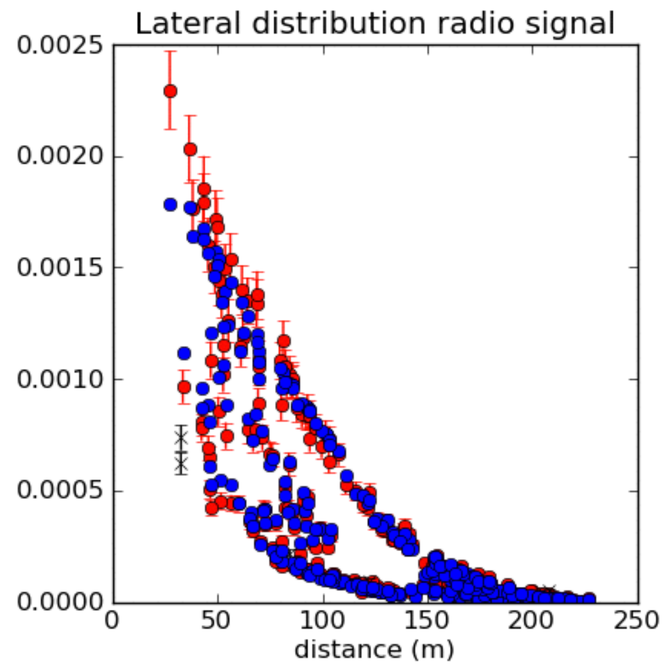
Down to some kHz

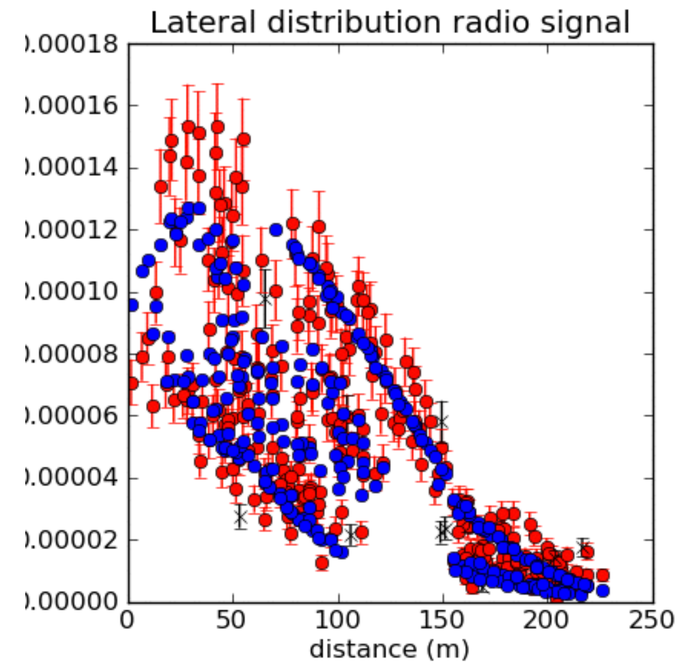
(SELFAS simulations)

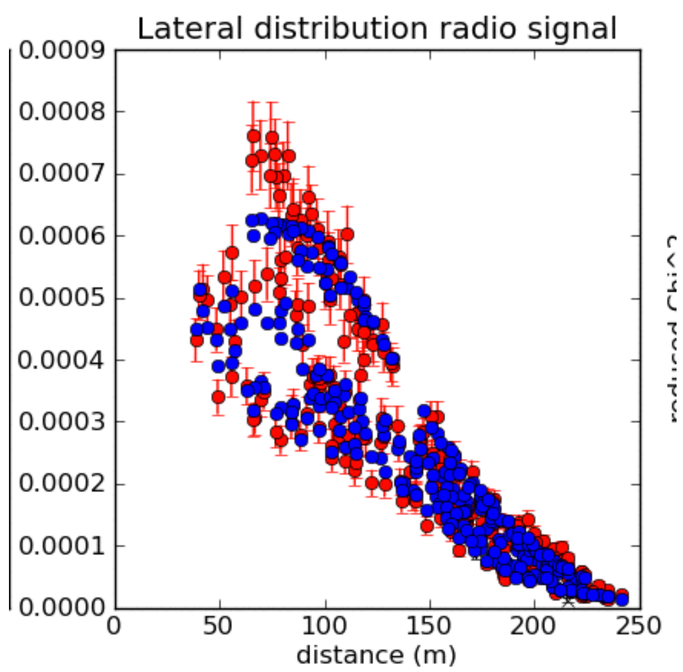


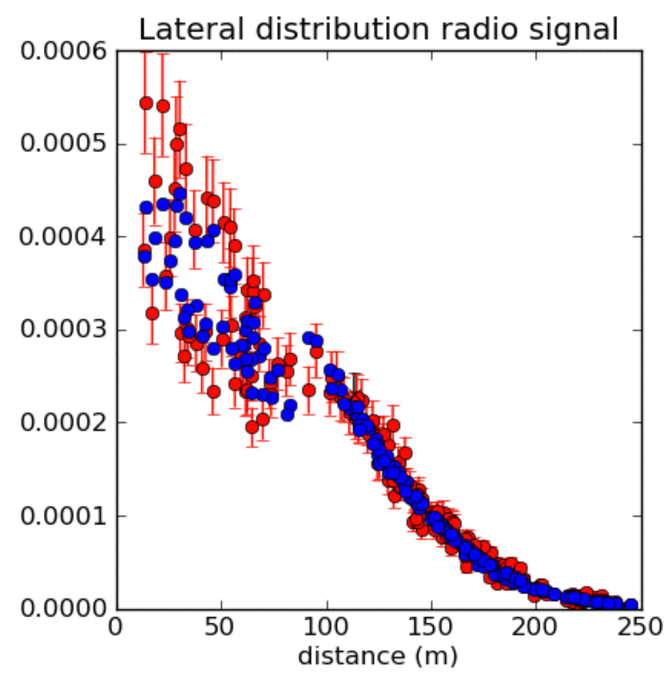
Event-by-event comparison with simulations

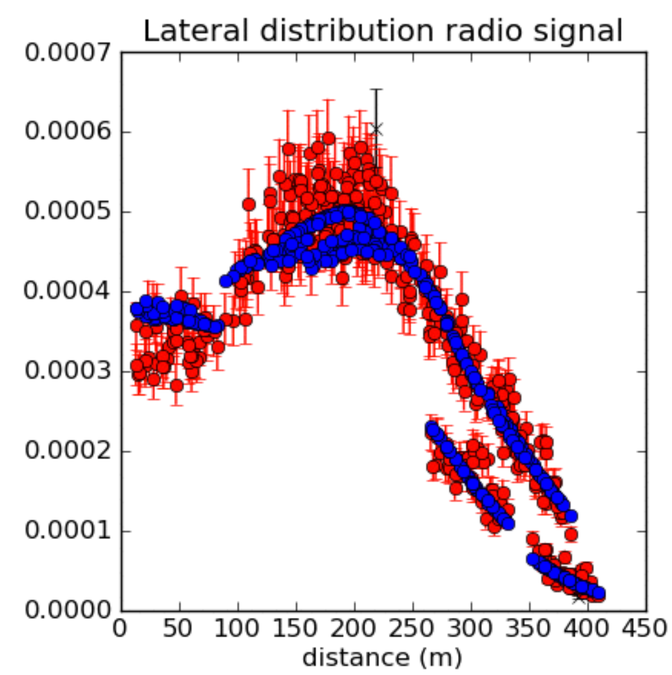












(LOFAR plots by S. Buitink)

Summary

- the radio signal is understood at a high level of accuracy (since beginning of 2014 only!) ➔ this closes a 50 years old debate!

- two mechanisms are involved, both of them are clearly observed, explain all data from 20 MHz to 4 GHz (no MBR signal detected up to now)

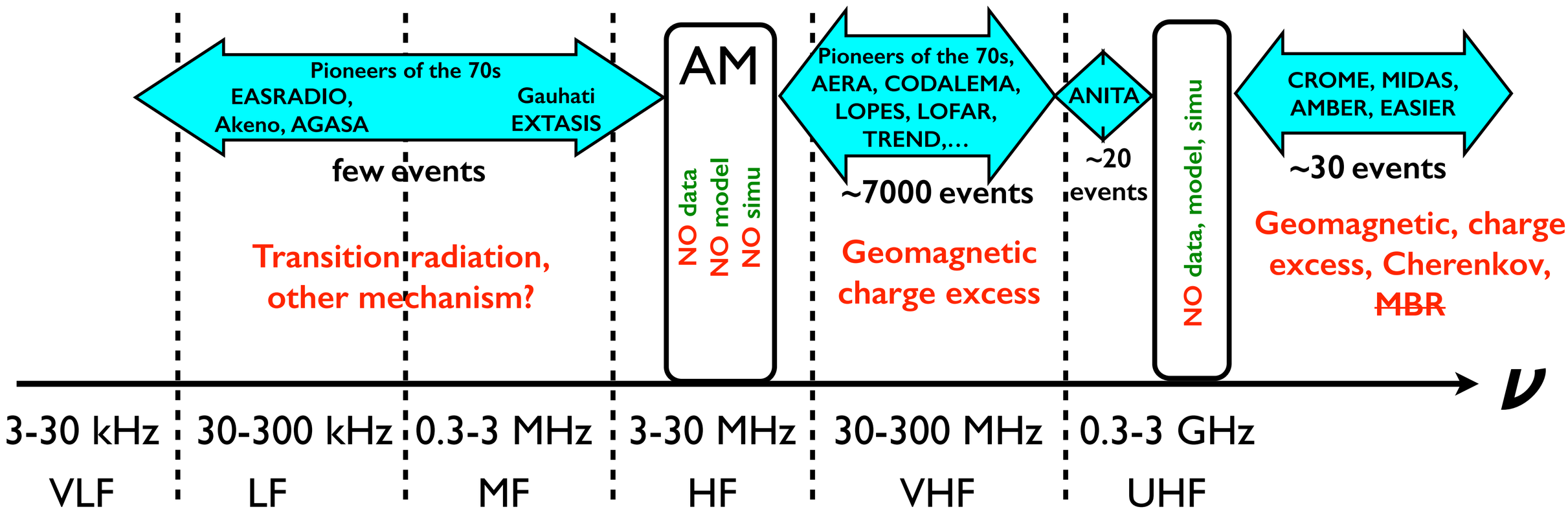
- hint for a new mechanism at low frequencies (below 20 MHz): sudden death signal ➔ will be investigated by the **EXTASIS** experiment (Nançay, France)

the radio signal (30-80 MHz) permits to:

- reconstruct the arrival direction of the primary cosmic ray with high resolution (< 0.5°)
- estimate the primary energy at a level of ~25%
- estimate the shower maximum with an uncertainty around 20 g/cm^2 (LOFAR team, submitted), similar to the fluorescence technique but with ~100% duty cycle instead of 14%

➔ the radio signal allows a **full reconstruction of the primary cosmic ray**

Summary



- R&D
- sudden death mechanism
- large range
- few unexplained events (from old experiments)

- in production
- many events
- limited range (large for inclined showers)

- R&D but decreasing interest
- few events
- very limited range
- small amplitude

Future and perspectives

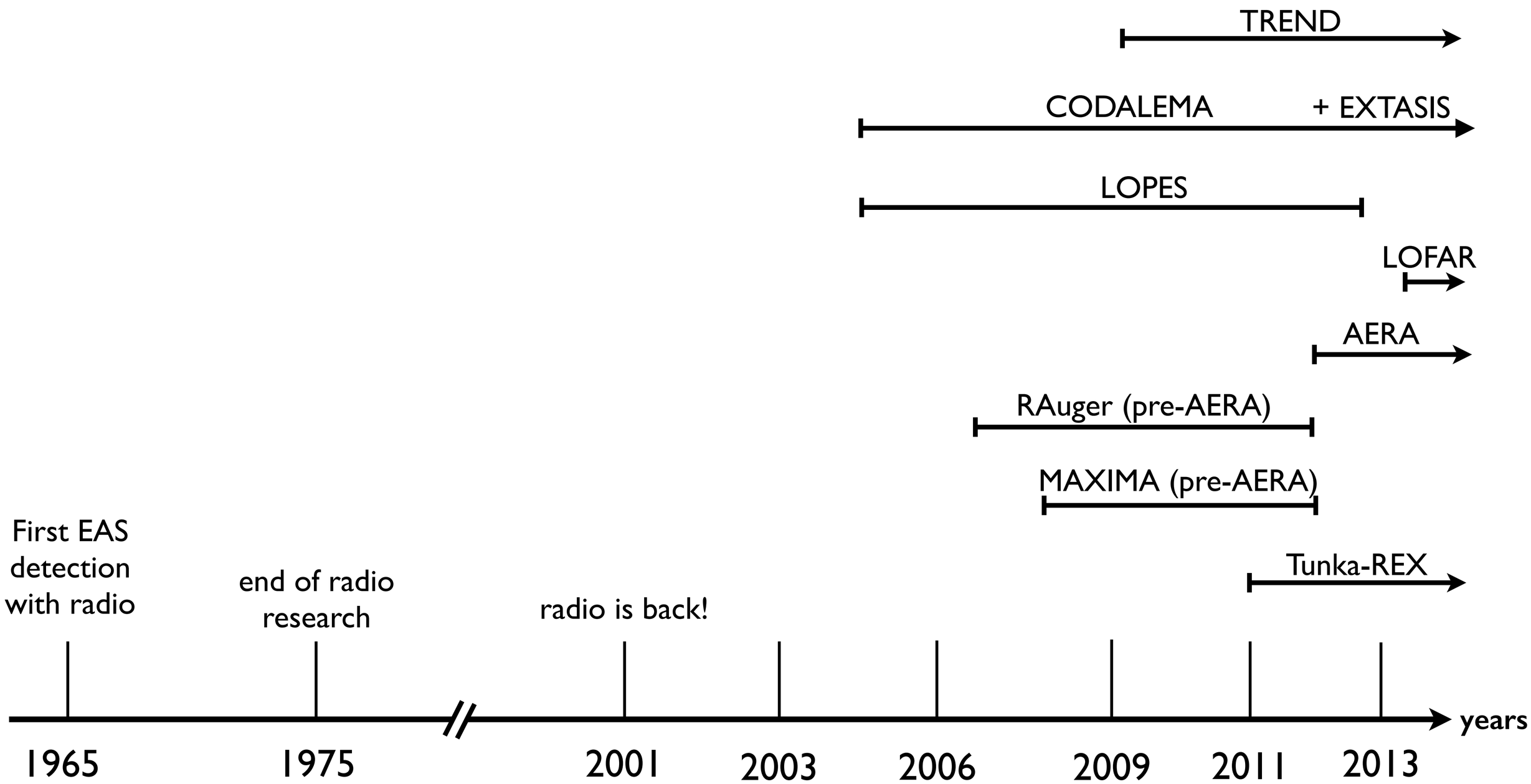
Upcoming and running experiments:

- LOFAR: low energy, very dense array, good for detailed analysis
- AERA, in Auger: high energy, correlation with fluorescence and particles
- TREND: low energy, inclined showers
- EXTASIS (former CODALEMA): sudden death signal at low frequencies, large range
- Tunka-REX: correlation with optical Cherenkov data

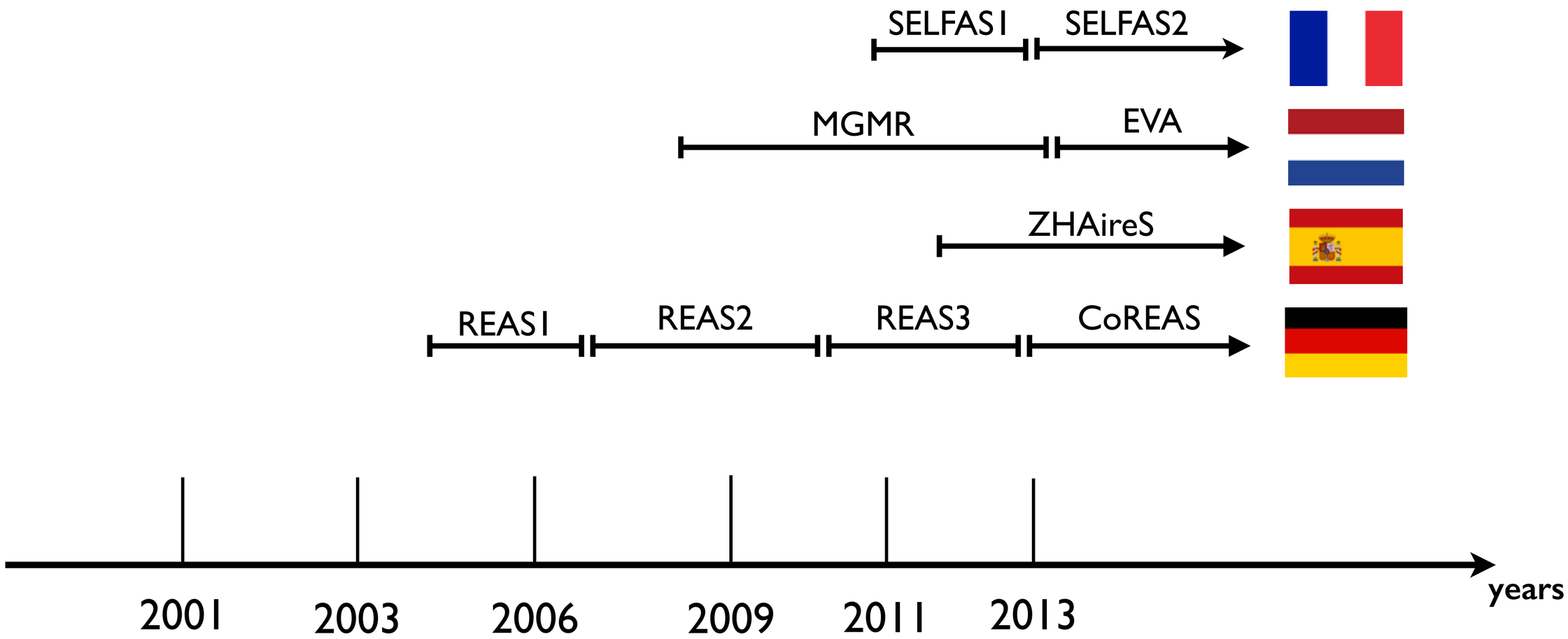
Limited range in 30-80 MHz:

- the idea to have a huge radio array only seems outdated (would need dense array, expensive)
- investigate inclined showers
- go down to ~MHz domain
- hybrid analysis with another UHECR detector (case of AERA)

Experimental summay



Simulation efforts summay



Simulation efforts summay

REAS1: microscopic, geosynchrotron, shower from analytical parameterizations
REAS2: microscopic, geosynchrotron, shower from CORSIKA histograms
REAS3: microscopic, end-points formalism, shower from CORSIKA histograms
CoREAS: microscopic,end-points formalism, integrated in CORSIKA directly

since the end-points formalism, the radiation from the variation of charge and current are taken into account

MGRM: macroscopic, use charge and current distributions + Maxwell, 1D shower (no lateral dispersion), pancake thickness modelled, fixed index of refraction
EVA: macroscopic, use charge and current distributions + Maxwell, full 3D shower (CONEX), variable index of refraction

SELFAS1: microscopic, no lifetime limit to the particles, fixed index of refraction, 3D shower from universality
SELFAS2: microscopic, lifetime limited particles, variable index of refraction, 3D shower from universality

ZHAireS: microscopic, lifetime limited particles, variable index of refraction, full 3D shower (AIRES)