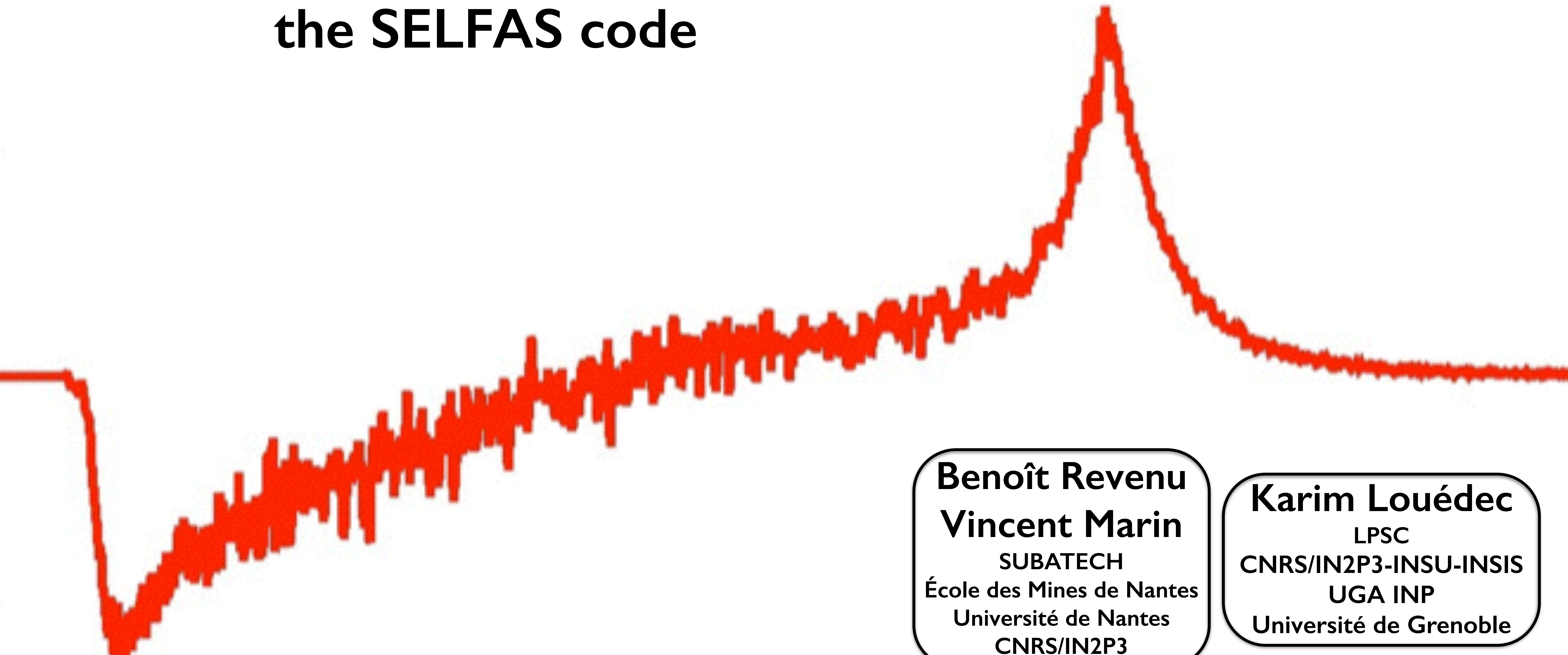
Characterisation of the radio signal emission using the SELFAS code



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Basics

SELFAS computes the electric field emitted by the secondary e^+/e^- in EAS,

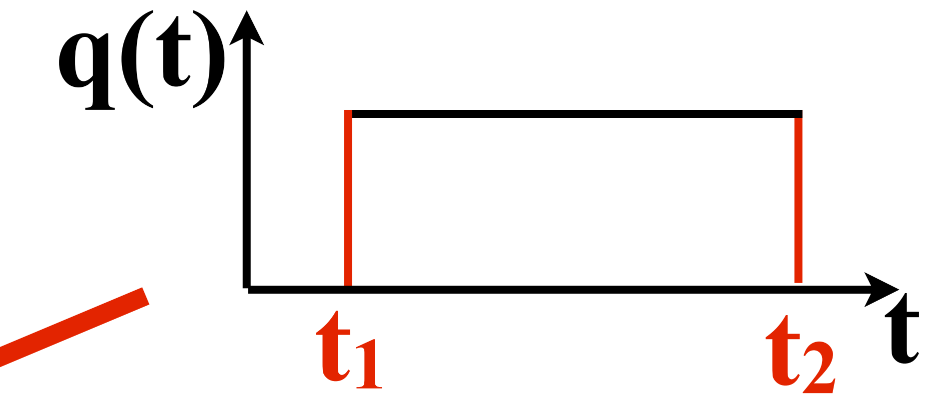
- in a large frequency band (kHz-GHz)
- no full shower simulation needed: based on shower universality concept
  - Longitudinal profile from GIL or CONEX
  - Energy distribution
  - Vertical and horizontal momentum direction
  - lateral distribution
  - Delay time (shower front thickness)

Lafèbre et al
Astropart. Phys., 31(3):243 2009

- track all e^+/e^- along their trajectory and sum up all individual contributions to the observer's location

Frequency	~ 1 MHz	20-200 MHz	~ GHz
Year	**2012**	**2008-2009**	**2012**

Formalism



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

Maxwell equation in Lorentz gauge:

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

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

Shower generation

Input : shower + site configuration
+ antennas location + number of particles

Shower generation

Input : shower + site configuration
+ antennas location + number of particles

Generation of the longitudinal profile

Following GIL parameterization (Greisen-Iljina-Linsley)

or

Using CONEX 2r4.37 (QGSJET-II.04, EPOS — …)

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Particle n : random depth X following the longitudinal profile

Initial conditions
Lafèbre et al
Astropart. Phys., 31(3):243, 2009

- ➤ Energy distribution
- ➤ Angular distribution
- ➤ Lateral distribution
- ➤ Delay time distribution

} **Monte-Carlo**

Air refractive index

$$\eta_i(h) = 1 + (\eta_{h=0} - 1)\frac{\rho_{air}(h)}{\rho_{air}(h=0)}$$

$\eta_{h=0} = 1.000292$

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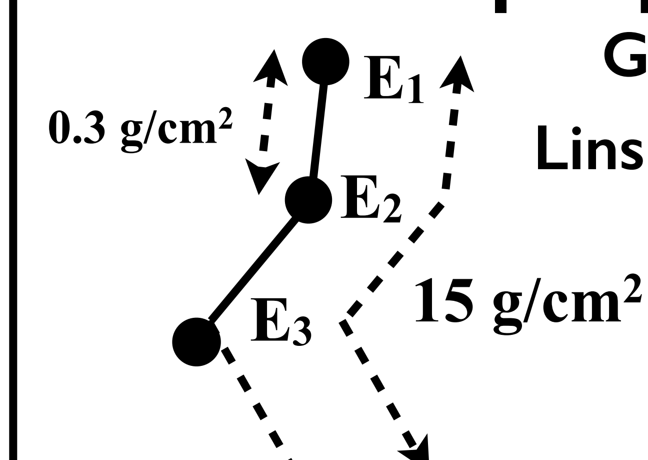
} **Monte-Carlo**

Particle propagation and field calculation



Geomagnetic deviations + scattering deviations

Linsley parameterization of US standard atmosphere

Compute field every 0.3 g/cm^2 along particle trajectory

Air refractive index

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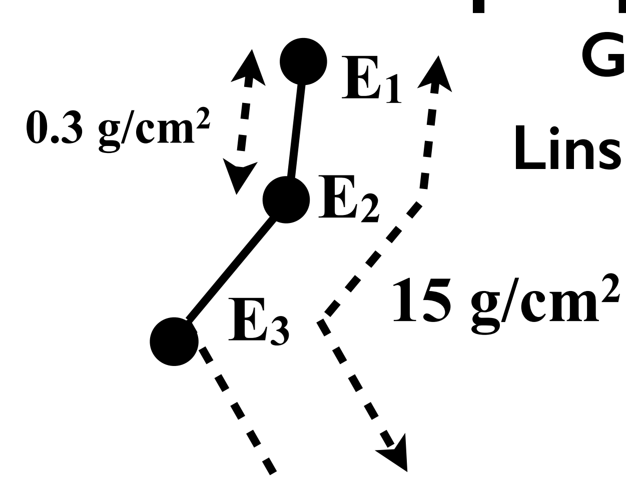


Geomagnetic deviations + scattering deviations

Linsley parameterization of US standard atmosphere

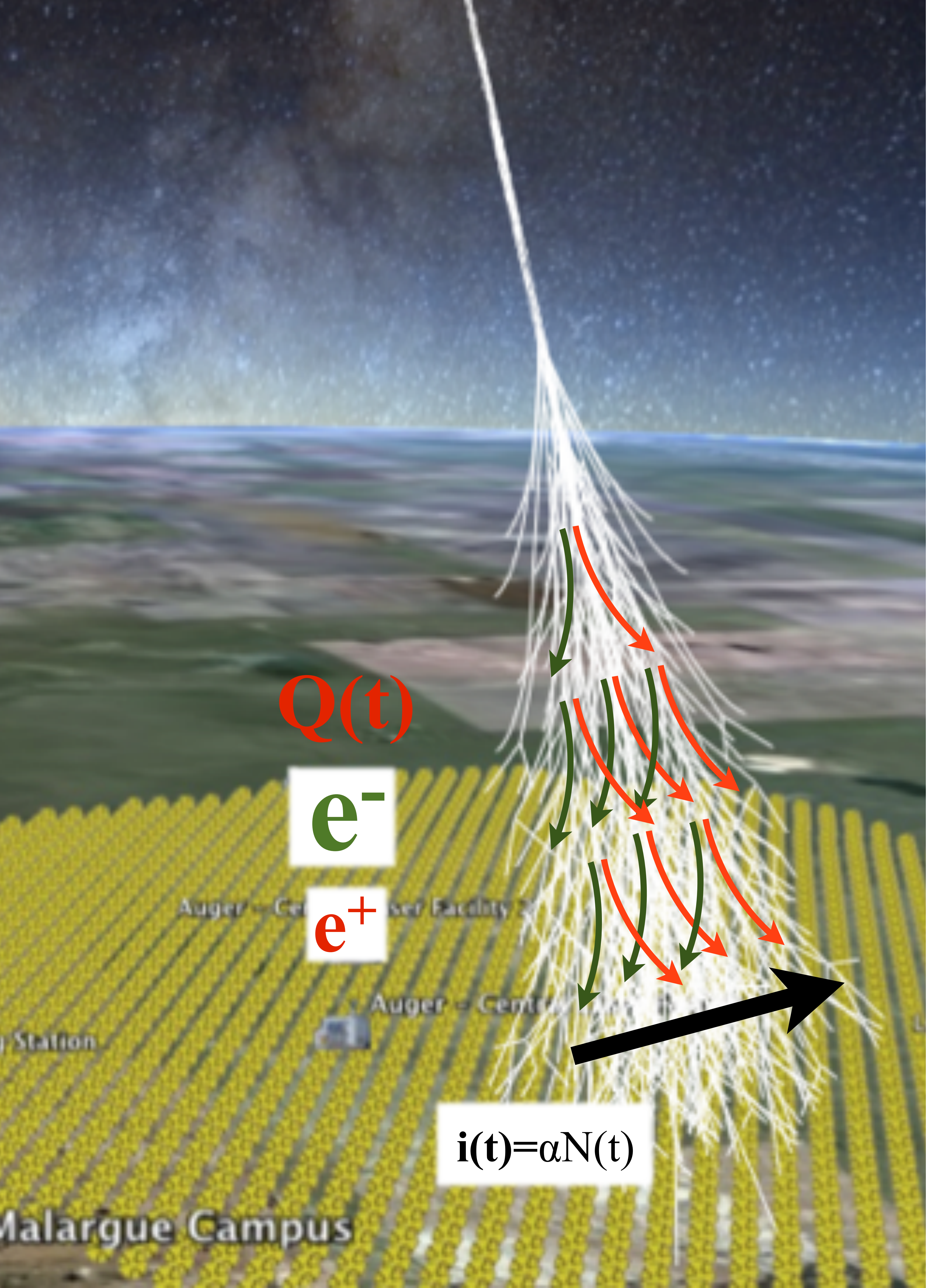
Compute field every 0.3 g/cm^2 along particle trajectory

Particle n+1

Air refractive index

$$\eta_i(h) = 1 + (\eta_{h=0} - 1)\frac{\rho_{air}(h)}{\rho_{air}(h=0)}$$

$\eta_{h=0} = 1.000292$



Shower generation

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

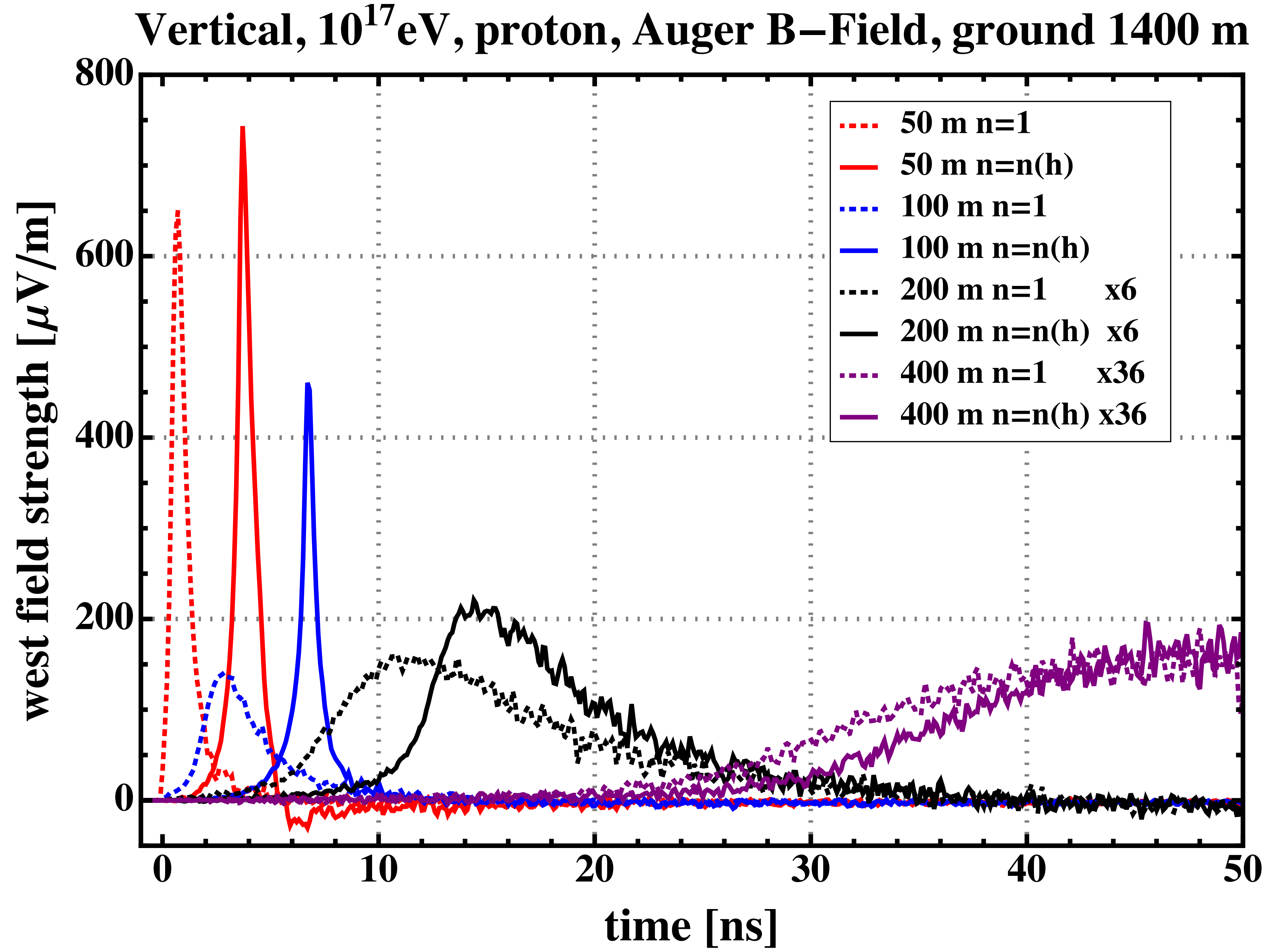
Coulombian contribution

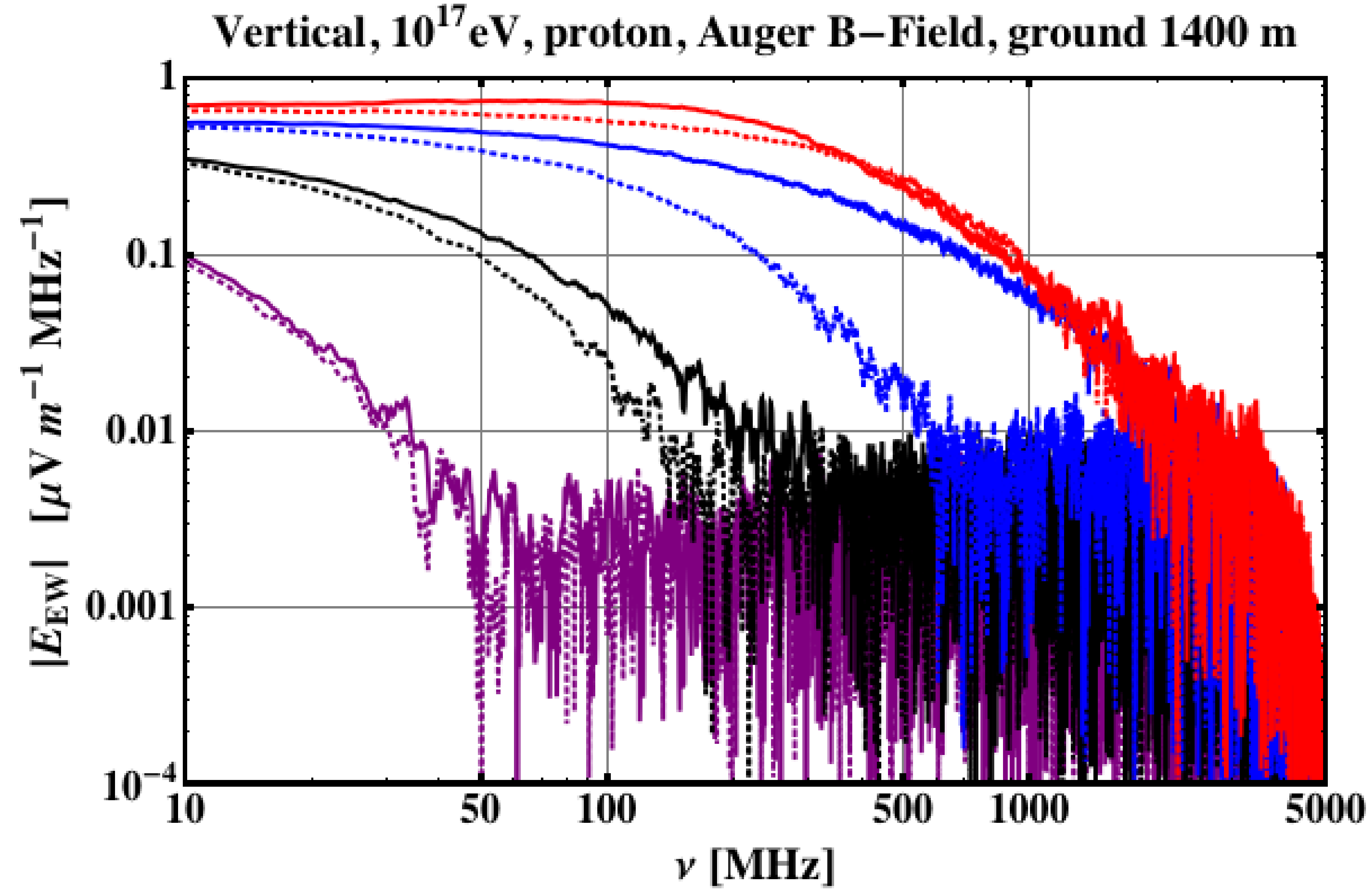
$$+ \frac{1}{c}\frac{\partial}{\partial t}\sum_{i=1}^{N}\frac{q_i\,\vec{n}_i}{R_i(1-\eta\vec{\beta}_i\cdot\vec{n}_i)}$$

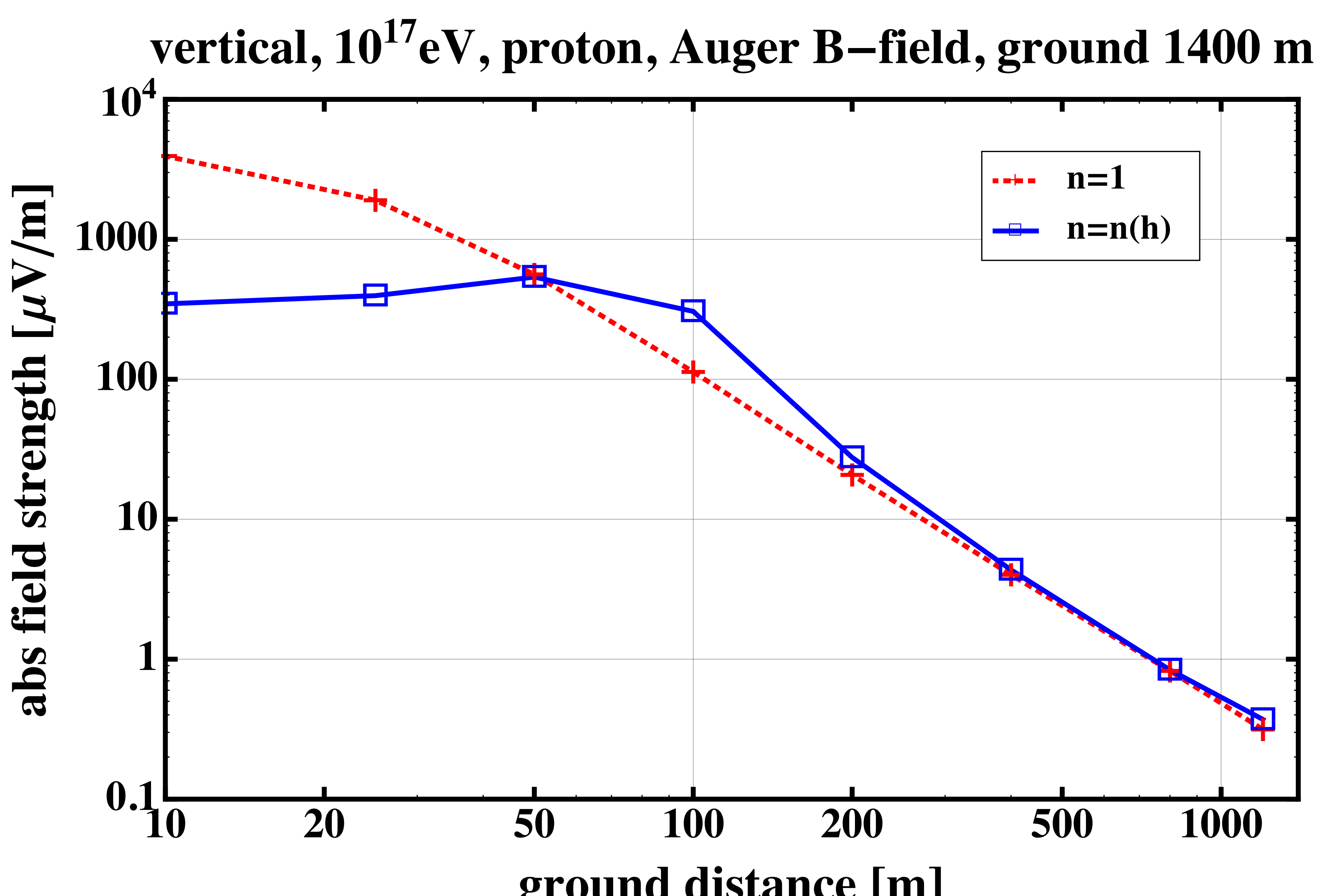
Charge excess contribution

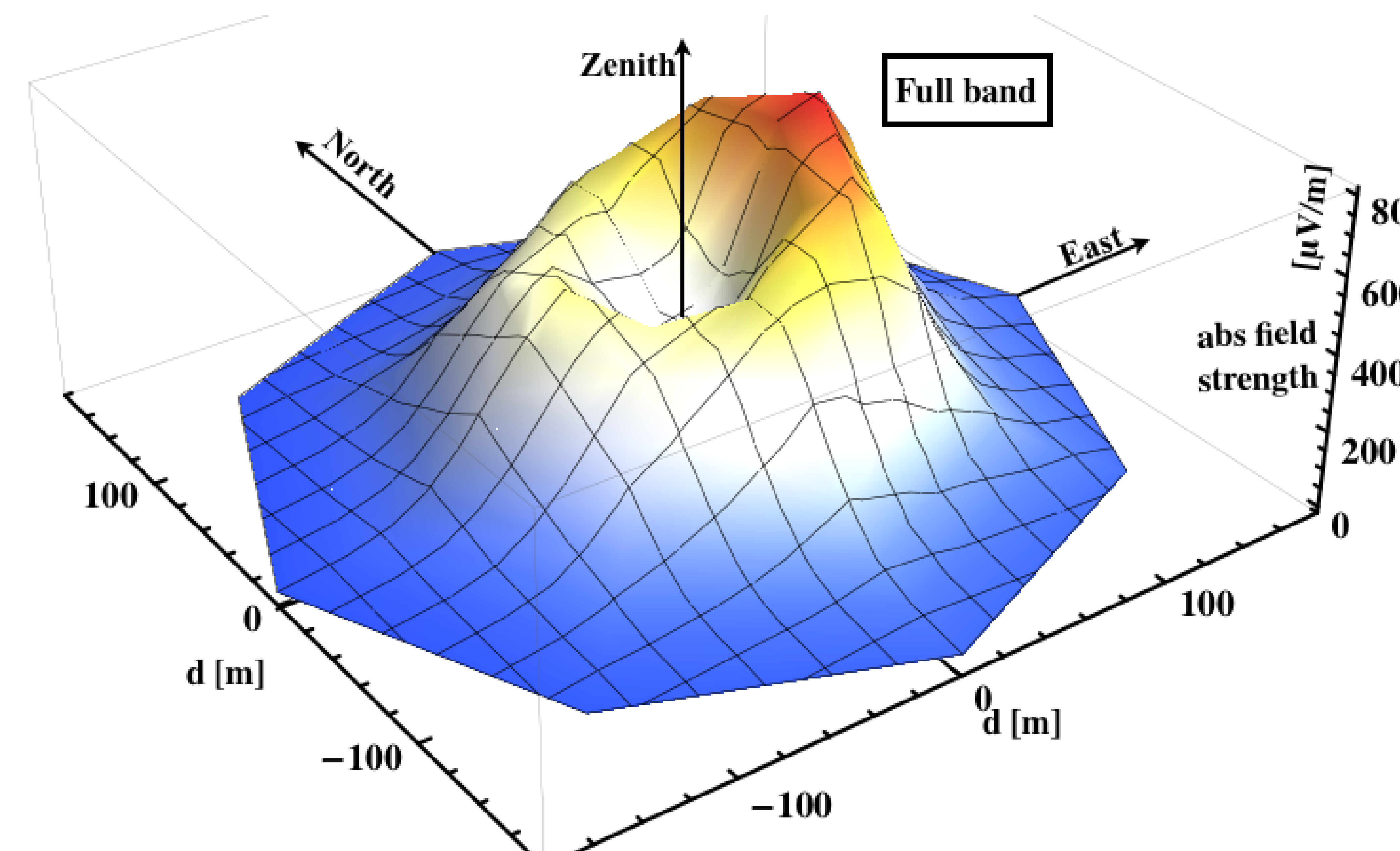
$$\left. - \frac{1}{c}\frac{\partial}{\partial t}\sum_{i=1}^{N}\frac{q_i\,\vec{\beta}_i}{R_i(1-\eta\vec{\beta}_i\cdot\vec{n}_i)} \right)$$

Transverse current contribution


Vertical, 10^{17}eV, proton, Auger B−Field, ground 1400 m
west field strength [μV/m]
time [ns]
50 m n=1
50 m n=n(h)
100 m n=1
100 m n=n(h)
200 m n=1 x6
200 m n=n(h) x6
400 m n=1 x36
400 m n=n(h) x36
0
200
400
600
800
0
10
20
30
40
50


Vertical, 10^{17}eV, proton, Auger B−Field, ground 1400 m
$|E_{EW}|$ [$\mu V\, m^{-1}$ MHz^{-1}]
ν [MHz]
1
0.1
0.01
0.001
10^{-4}
10
50
100
500
1000
5000

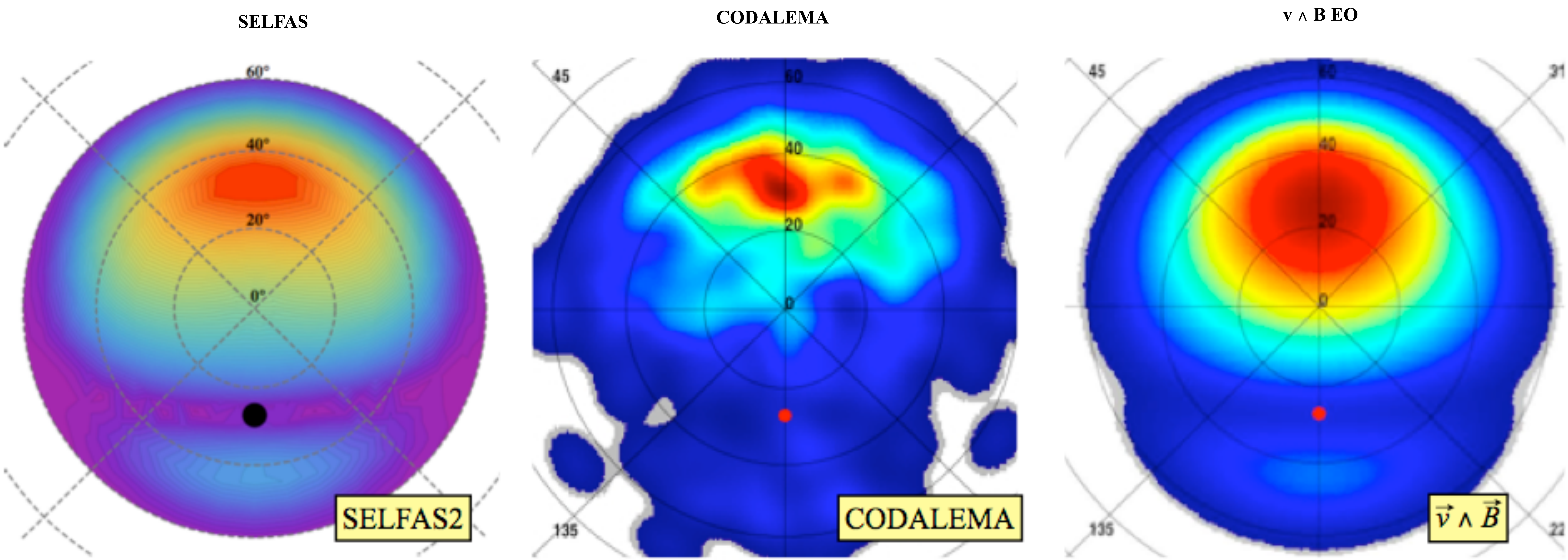

vertical, 10^{17}eV, proton, Auger B−field, ground 1400 m
abs field strength [μV/m]
ground distance [m]
n=1
n=n(h)
10^4
1000
100
10
1
0.1
10
20
50
100
200
500
1000


Zenith
Full band
North
East
[μV/m]
abs field strength
800
600
400
200
0
100
0
−100
d [m]
100
0
d [m]
−100

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

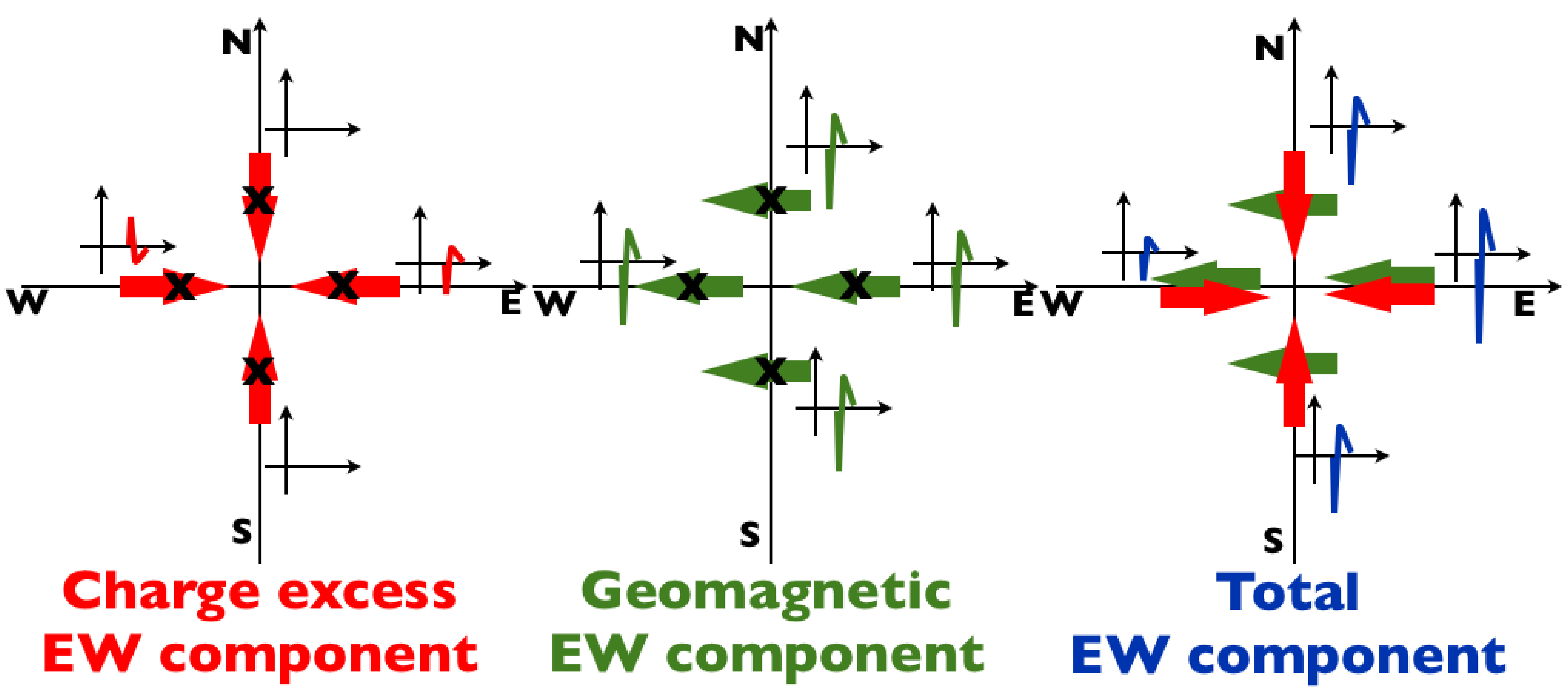
Transverse current contribution

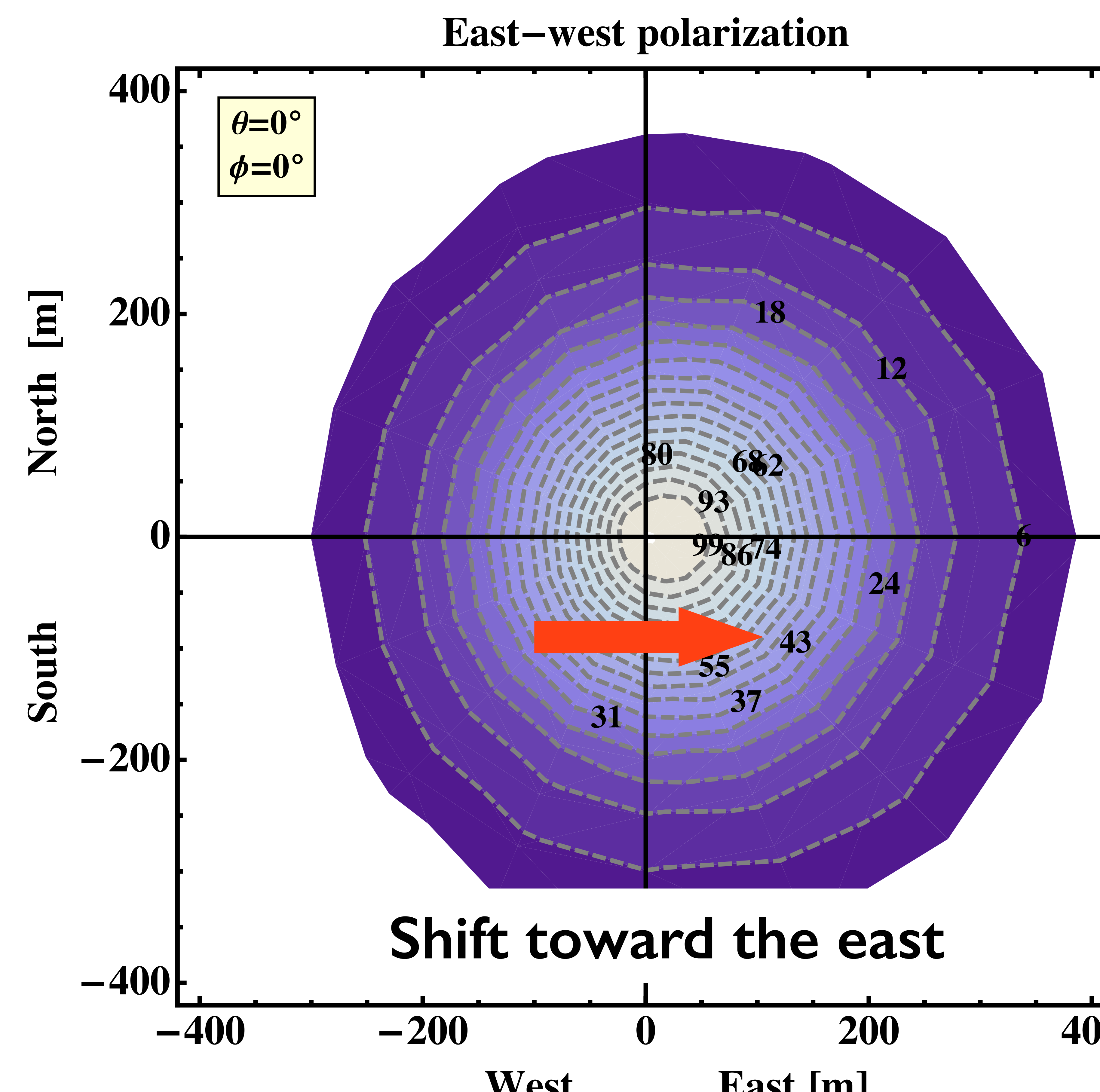
dominant contribution!



Charge excess contribution

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

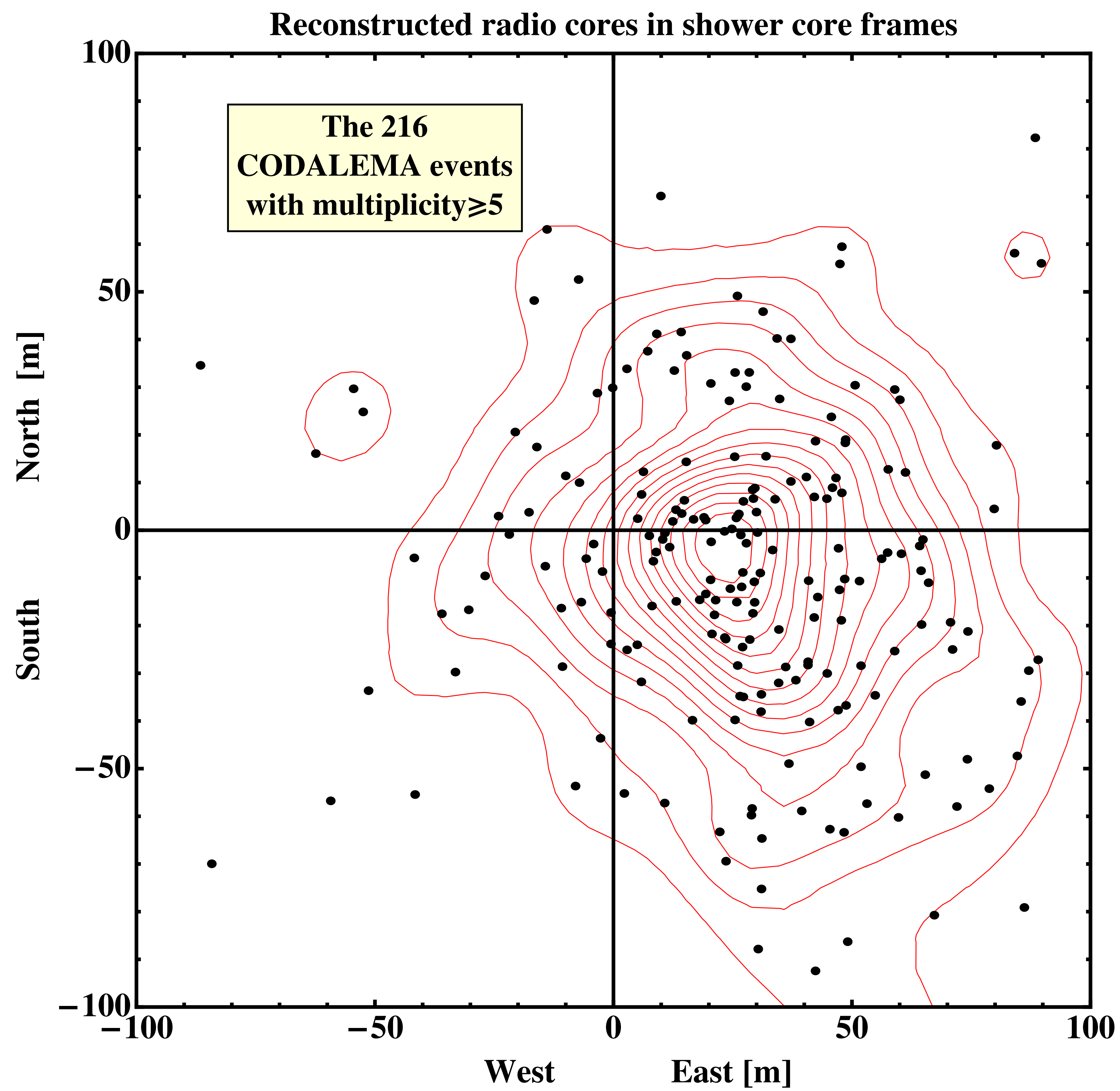


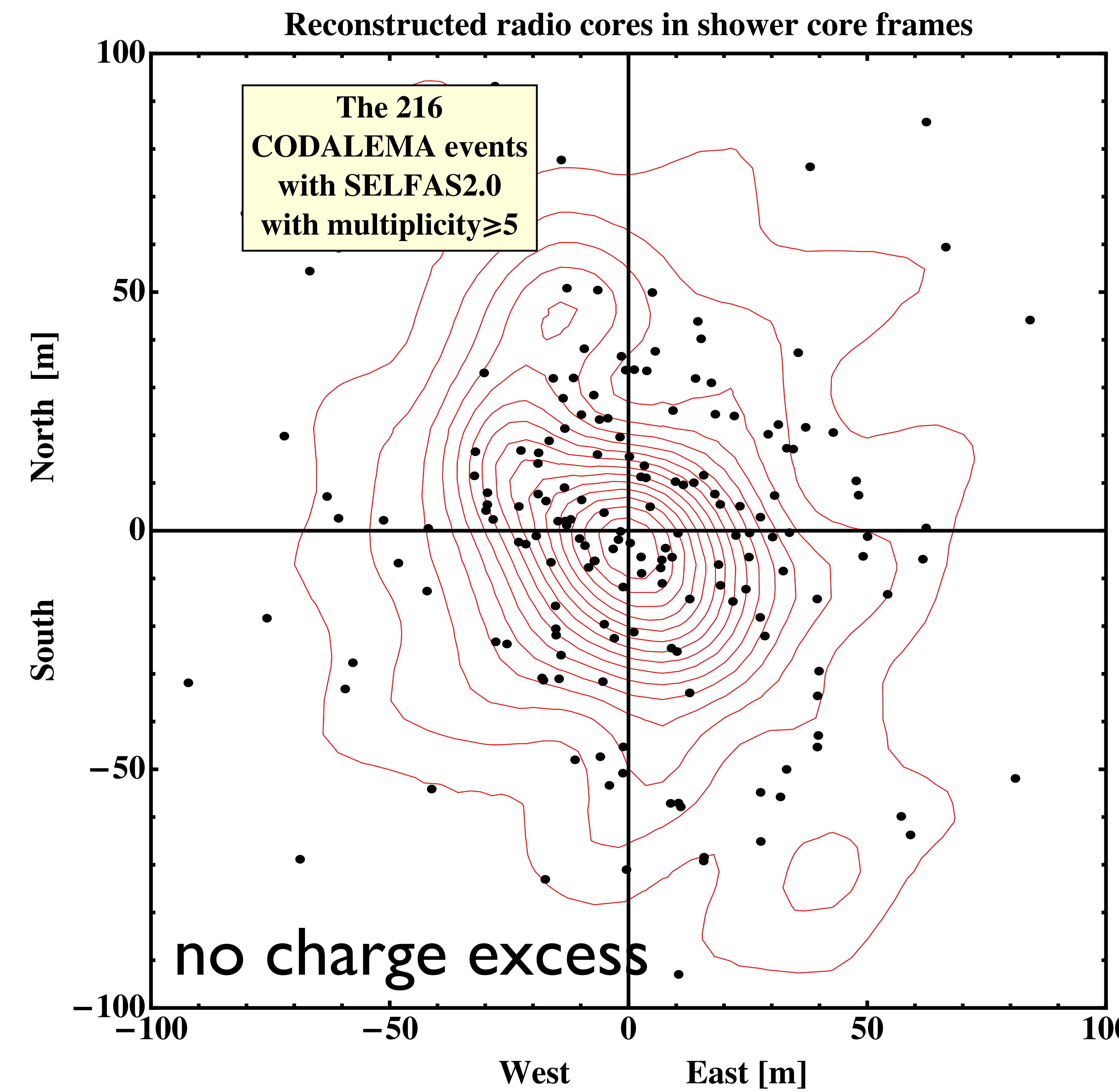


(+R-analysis, a-analyis by Tim this morning)

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

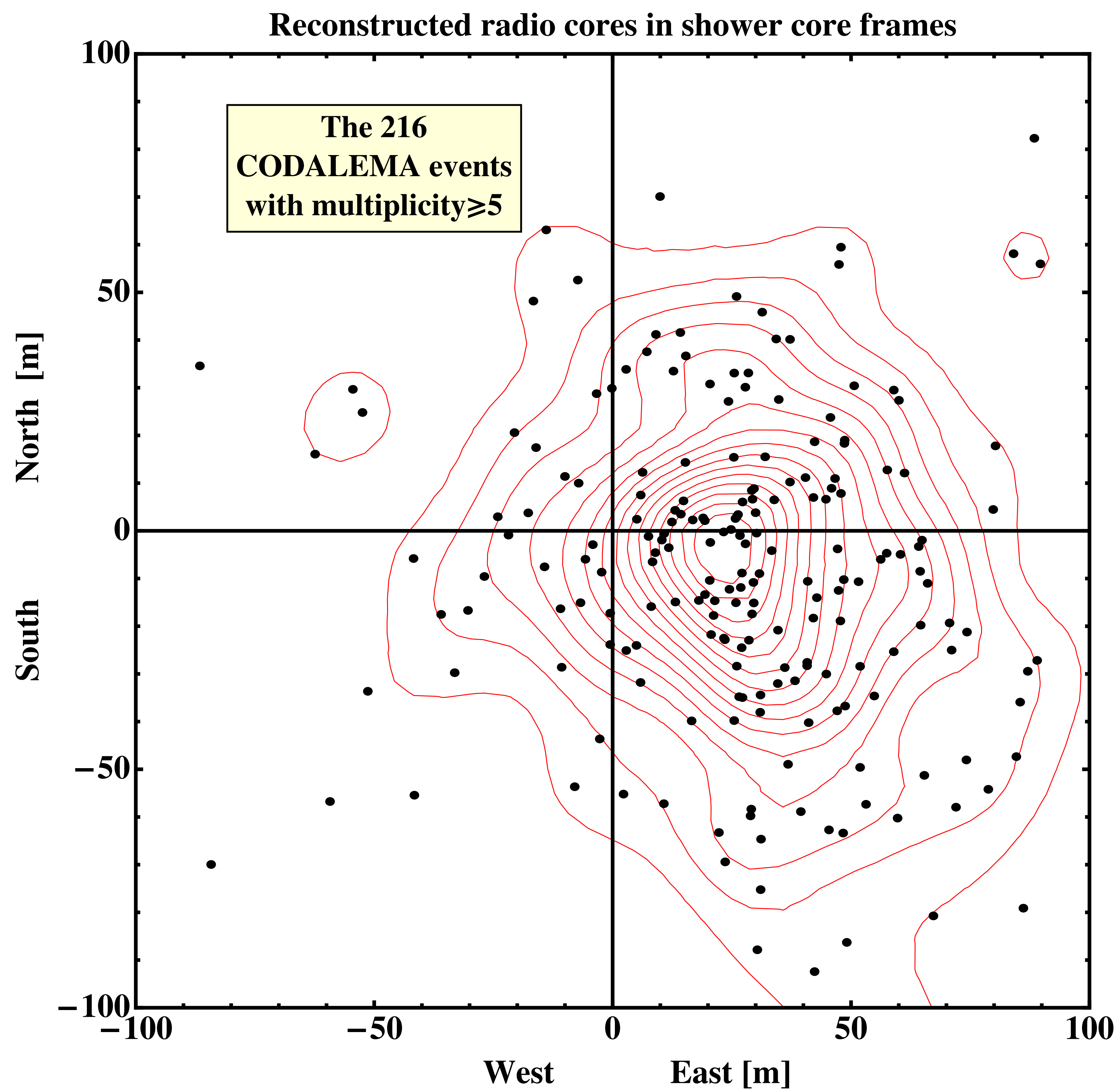
Charge excess contribution

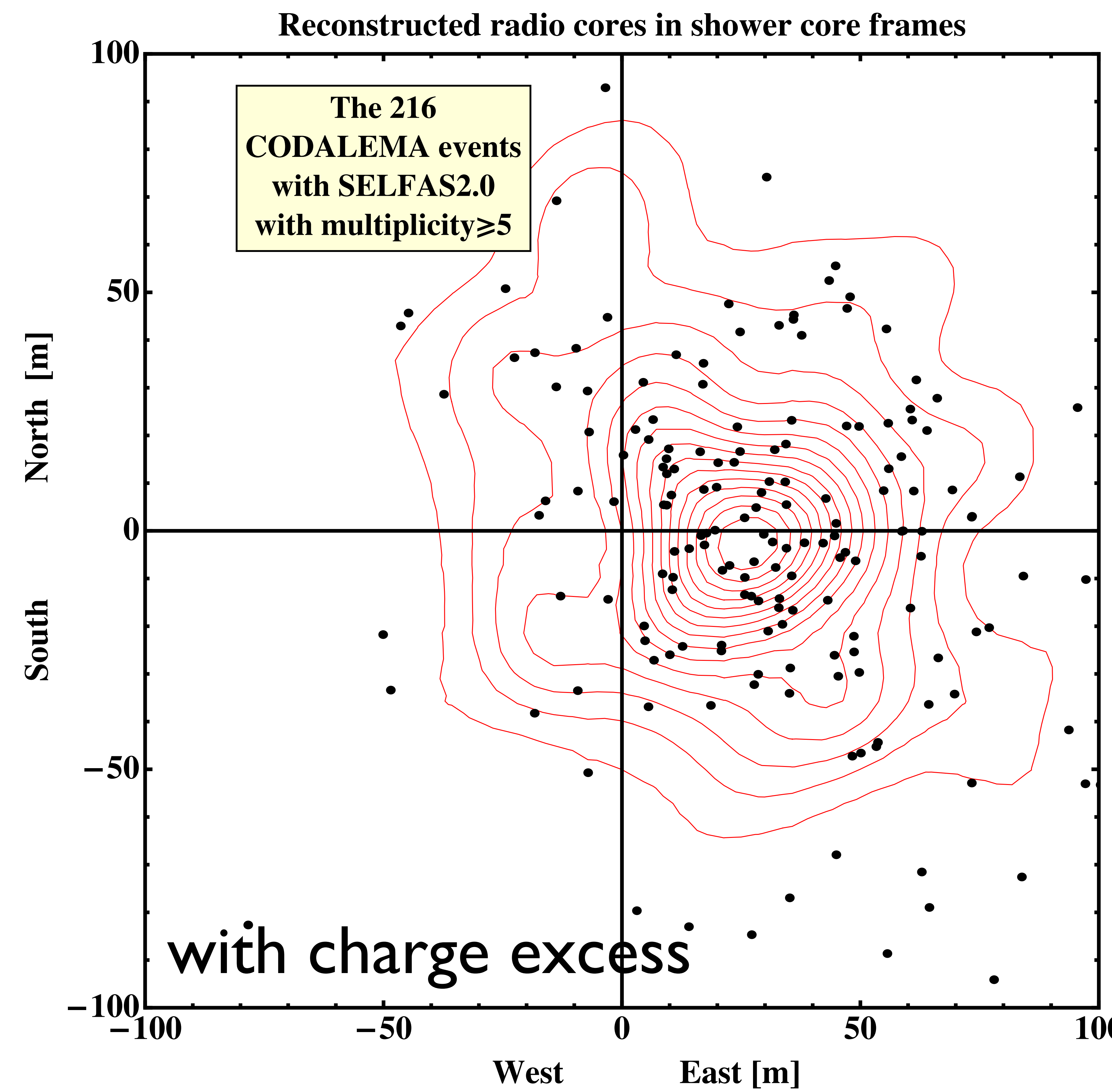




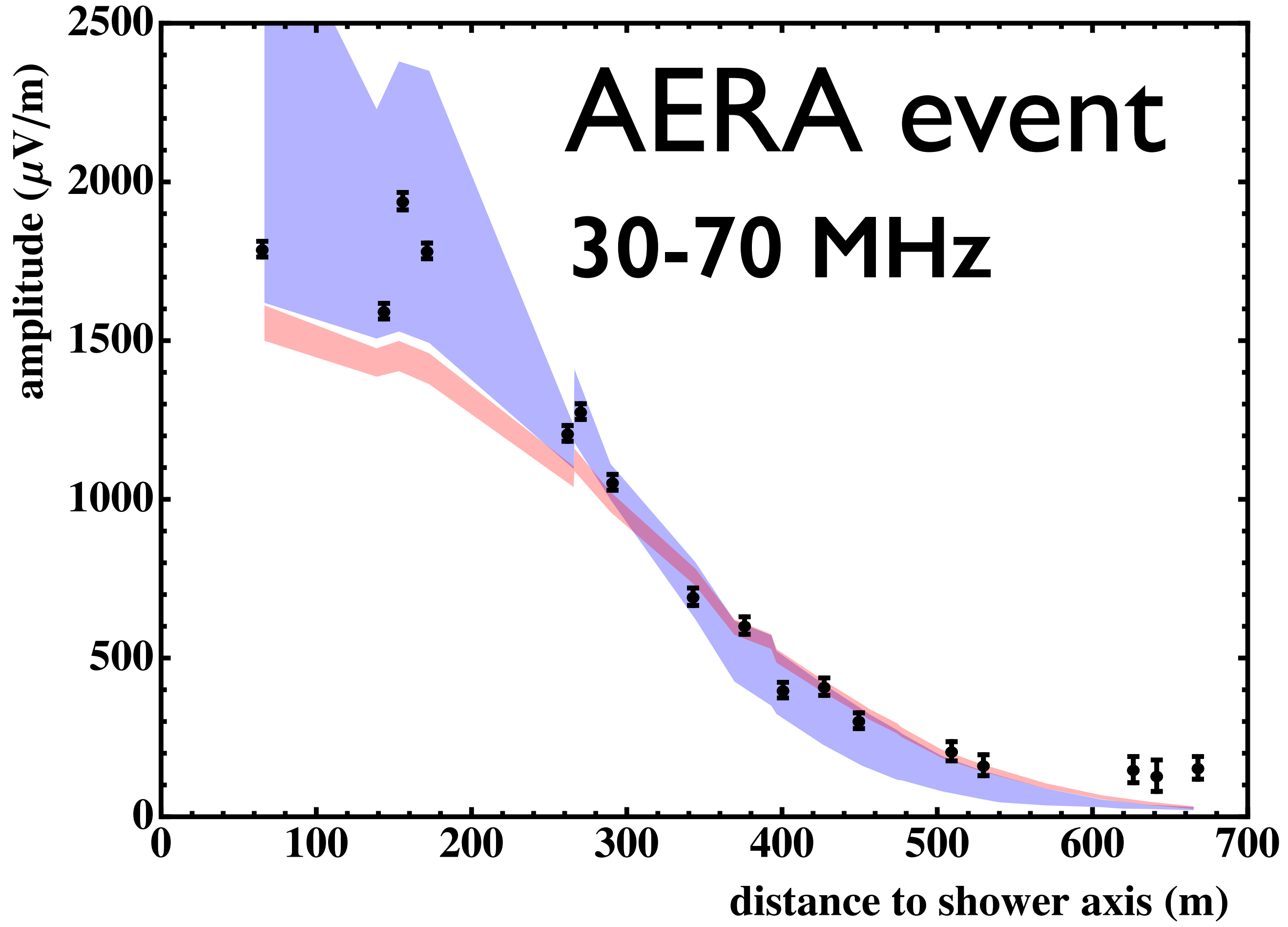
$$+\frac{1}{c}\frac{\partial}{\partial t}\sum_{i=1}^{N}\frac{q_i\,\vec{n}_i}{R_i(1-\eta\vec{\beta}_i\cdot\vec{n}_i)}$$

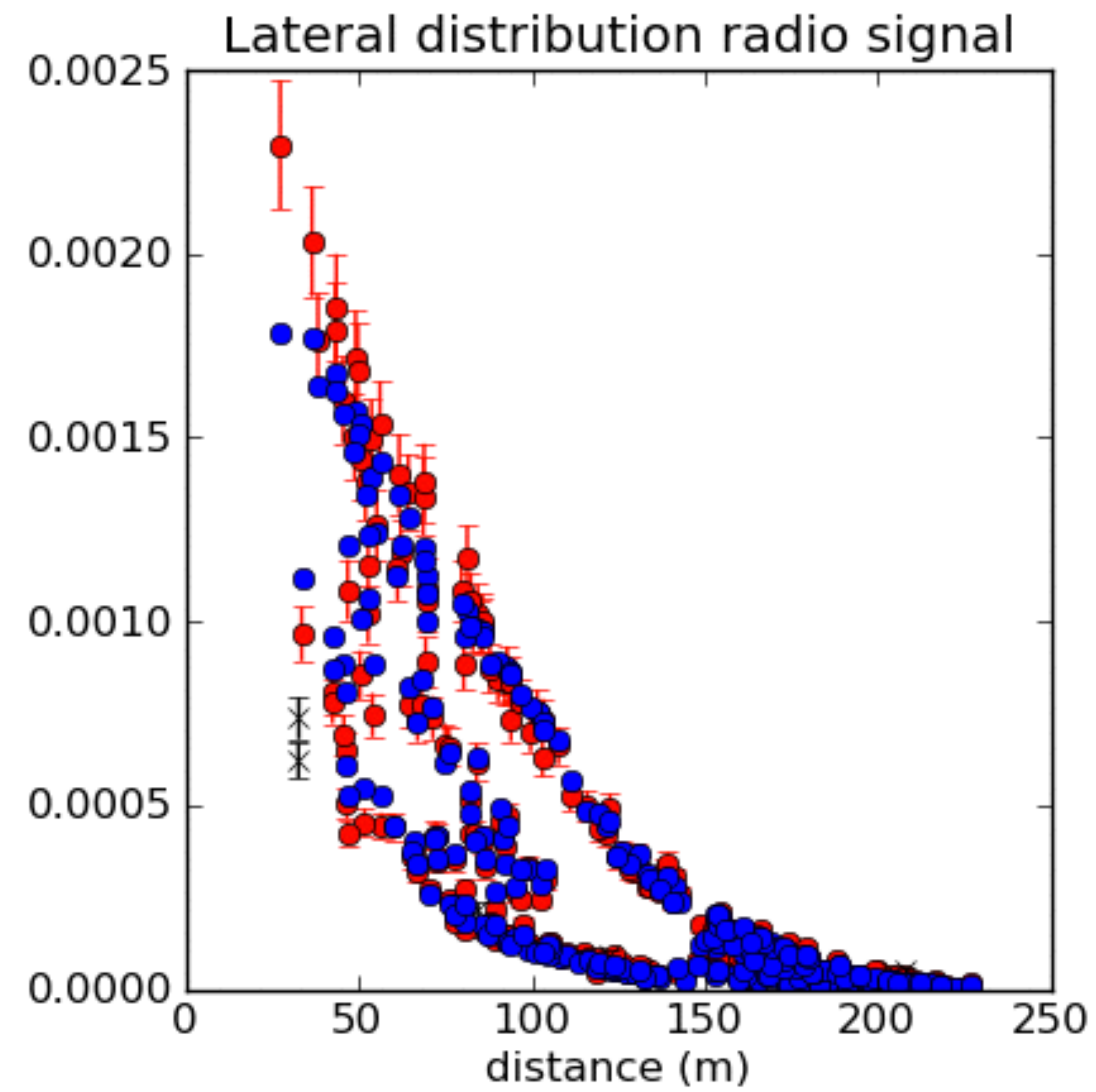
Charge excess contribution

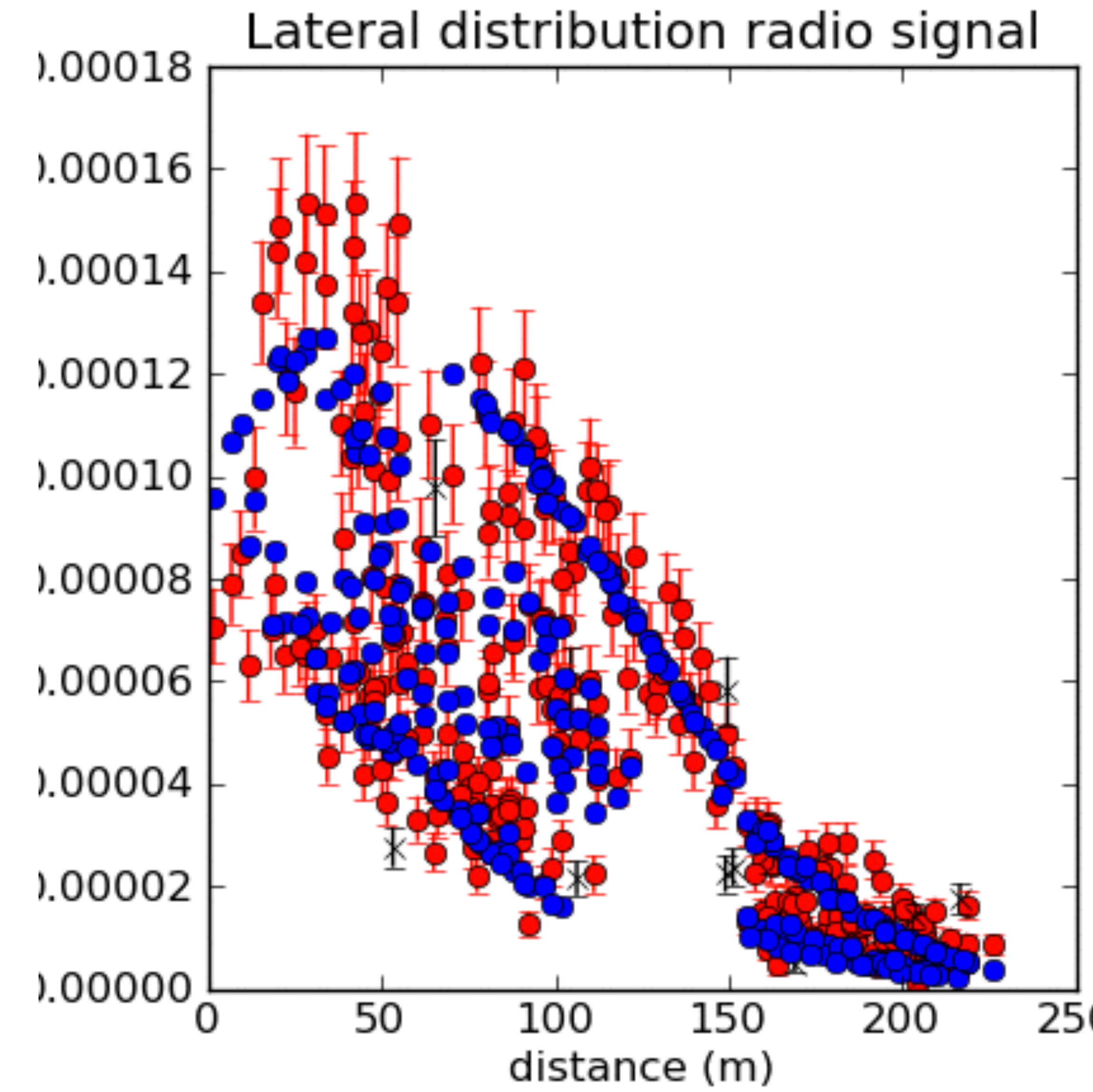


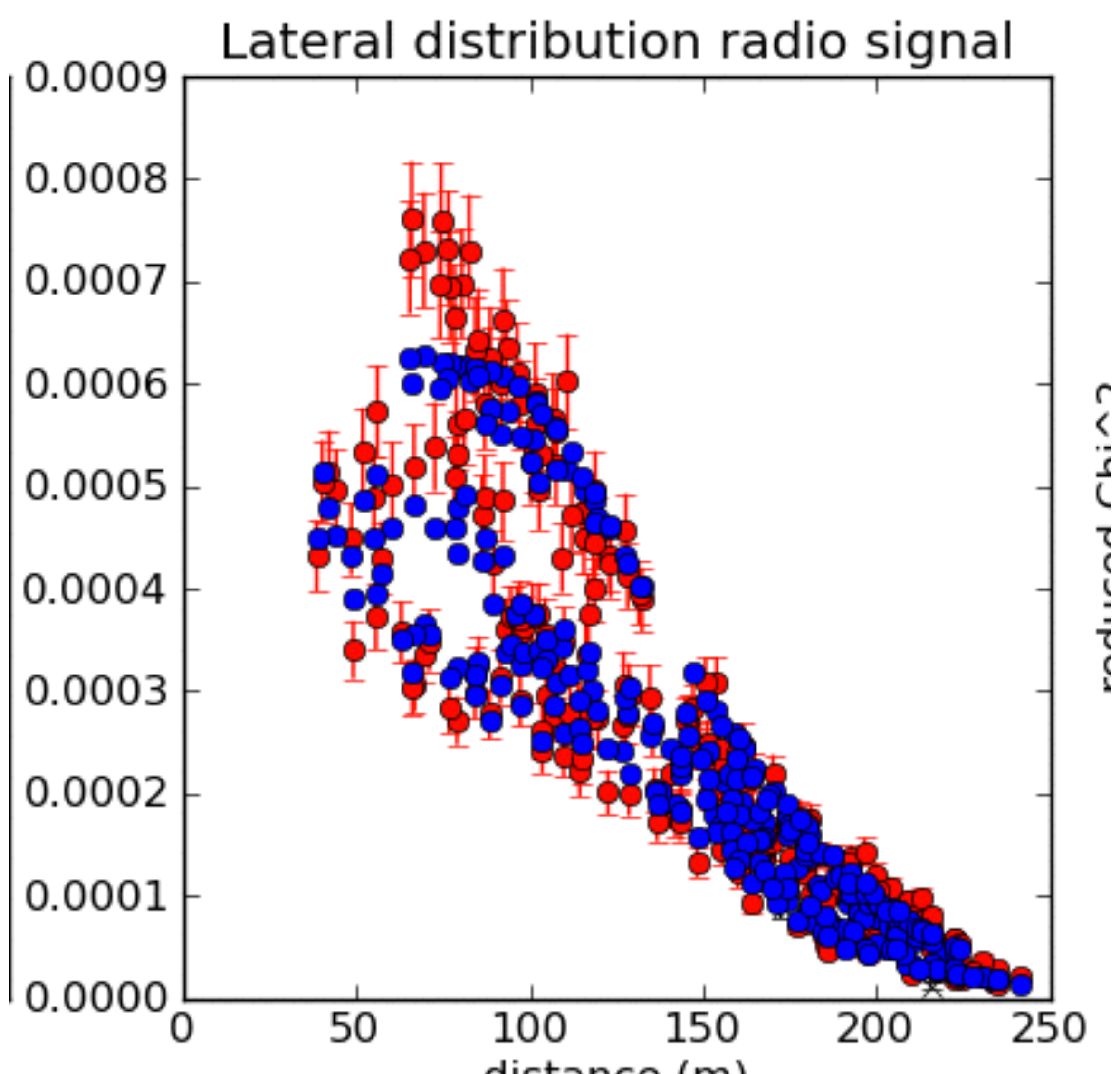


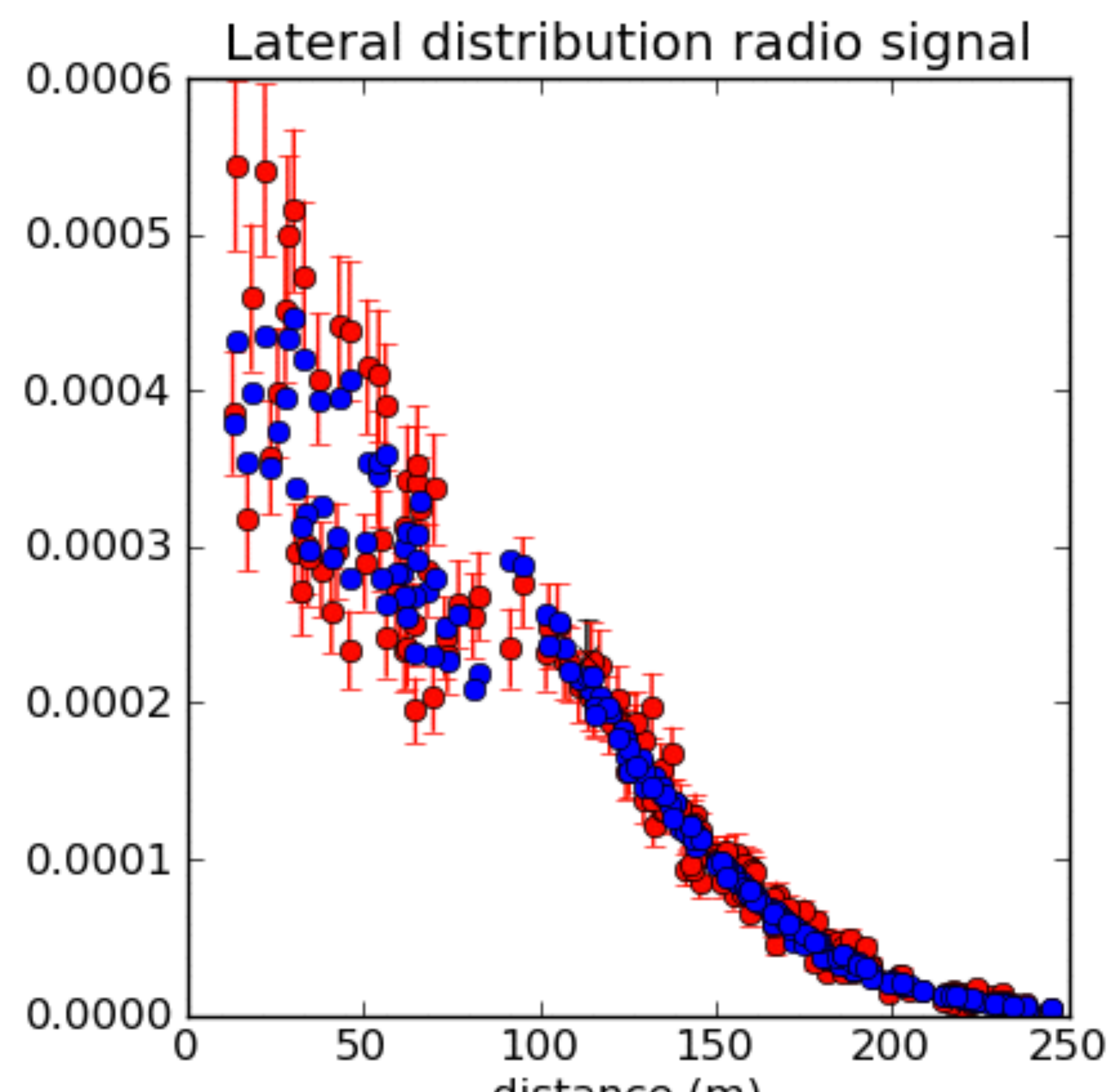
Comparison with single events

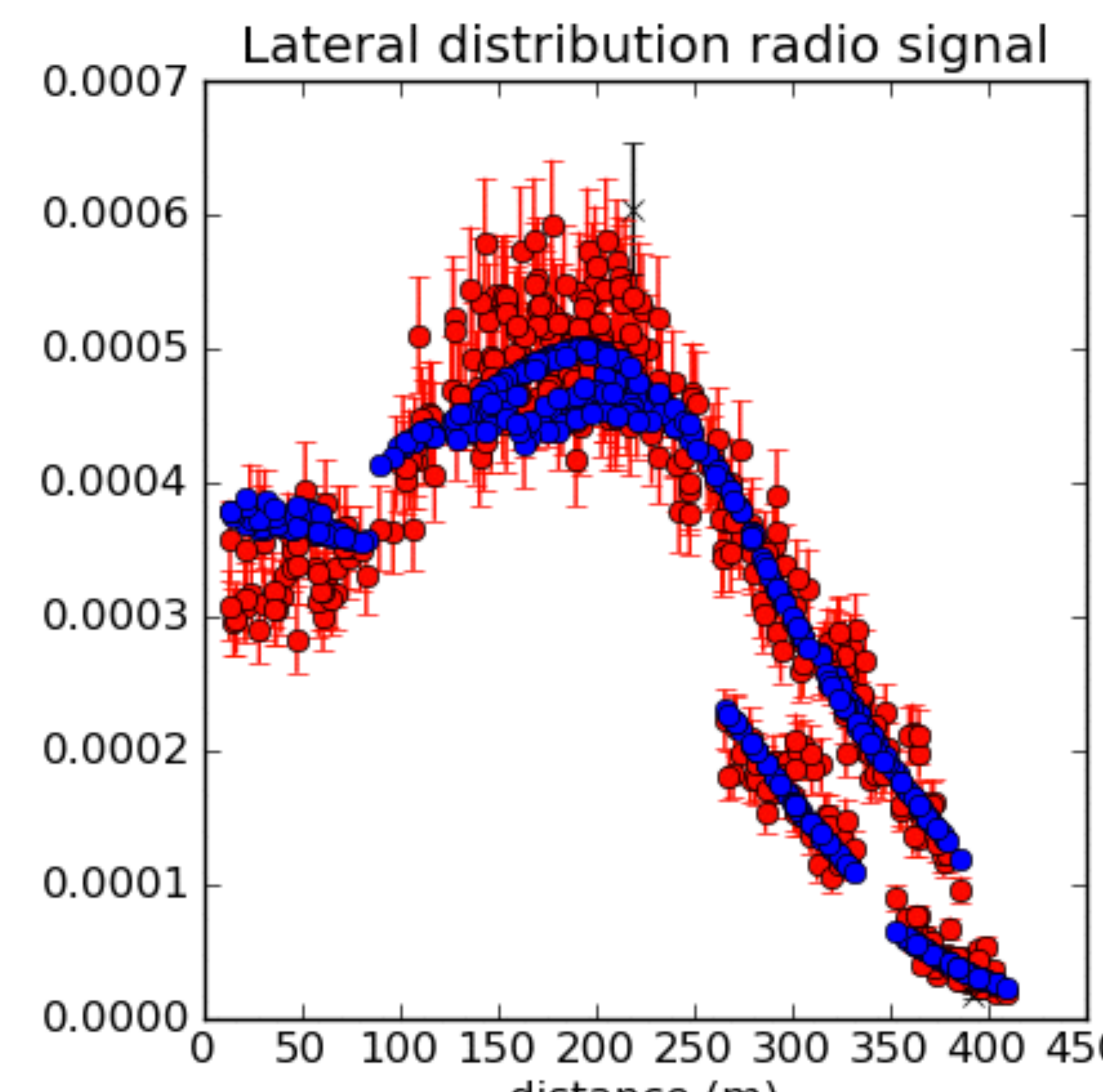






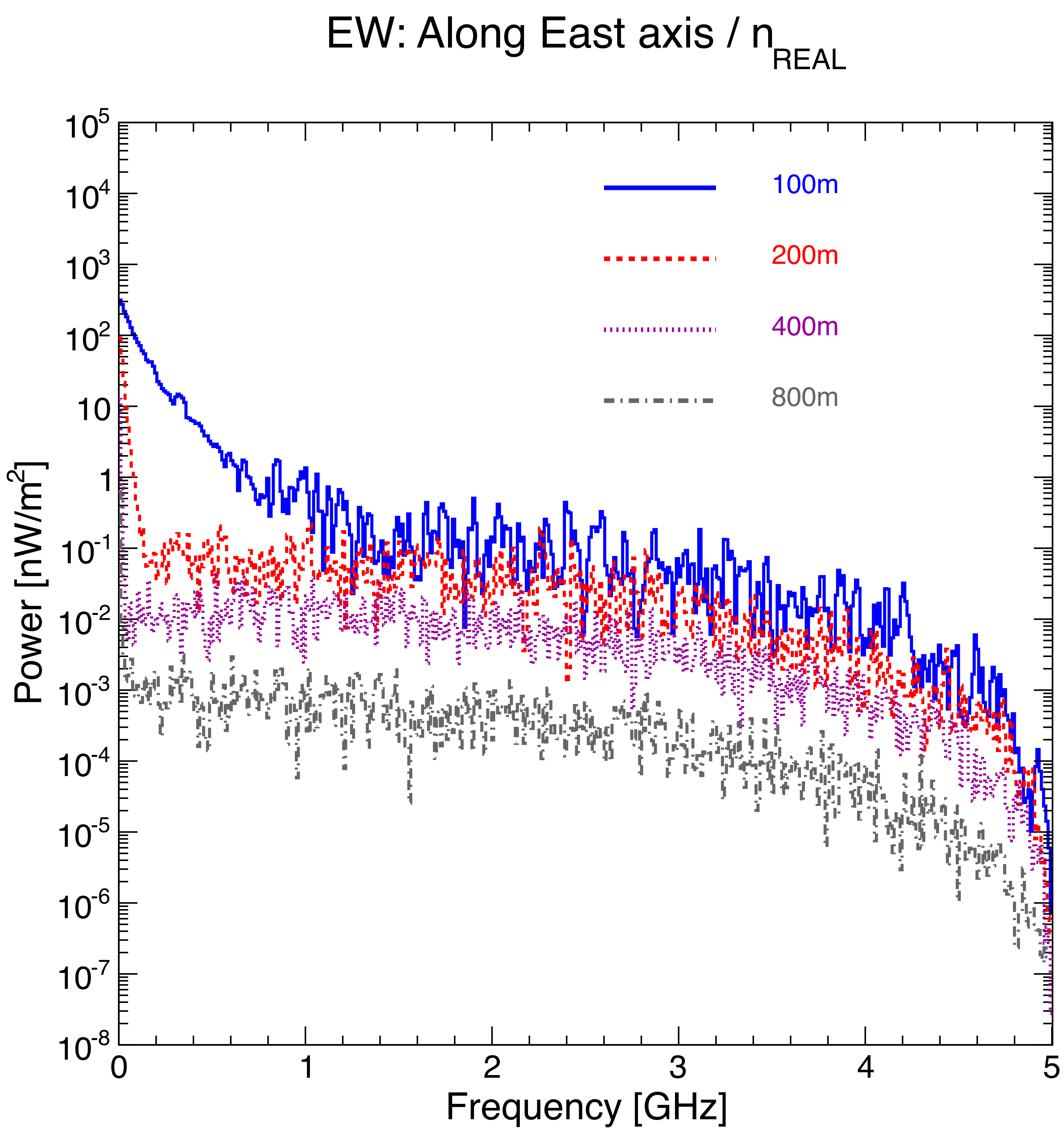






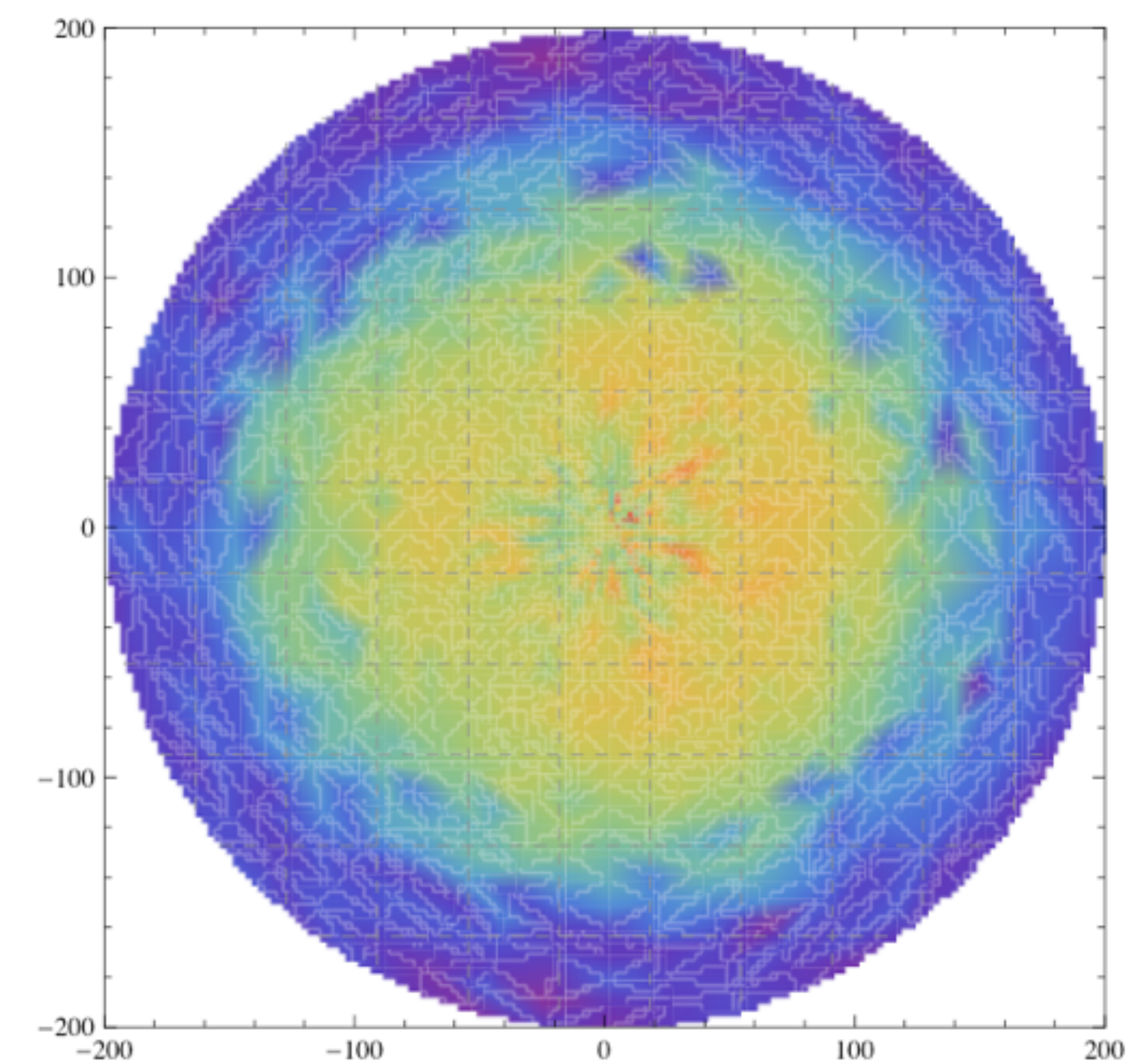
(LOFAR plots by S. Buitink)

Up to some GHz



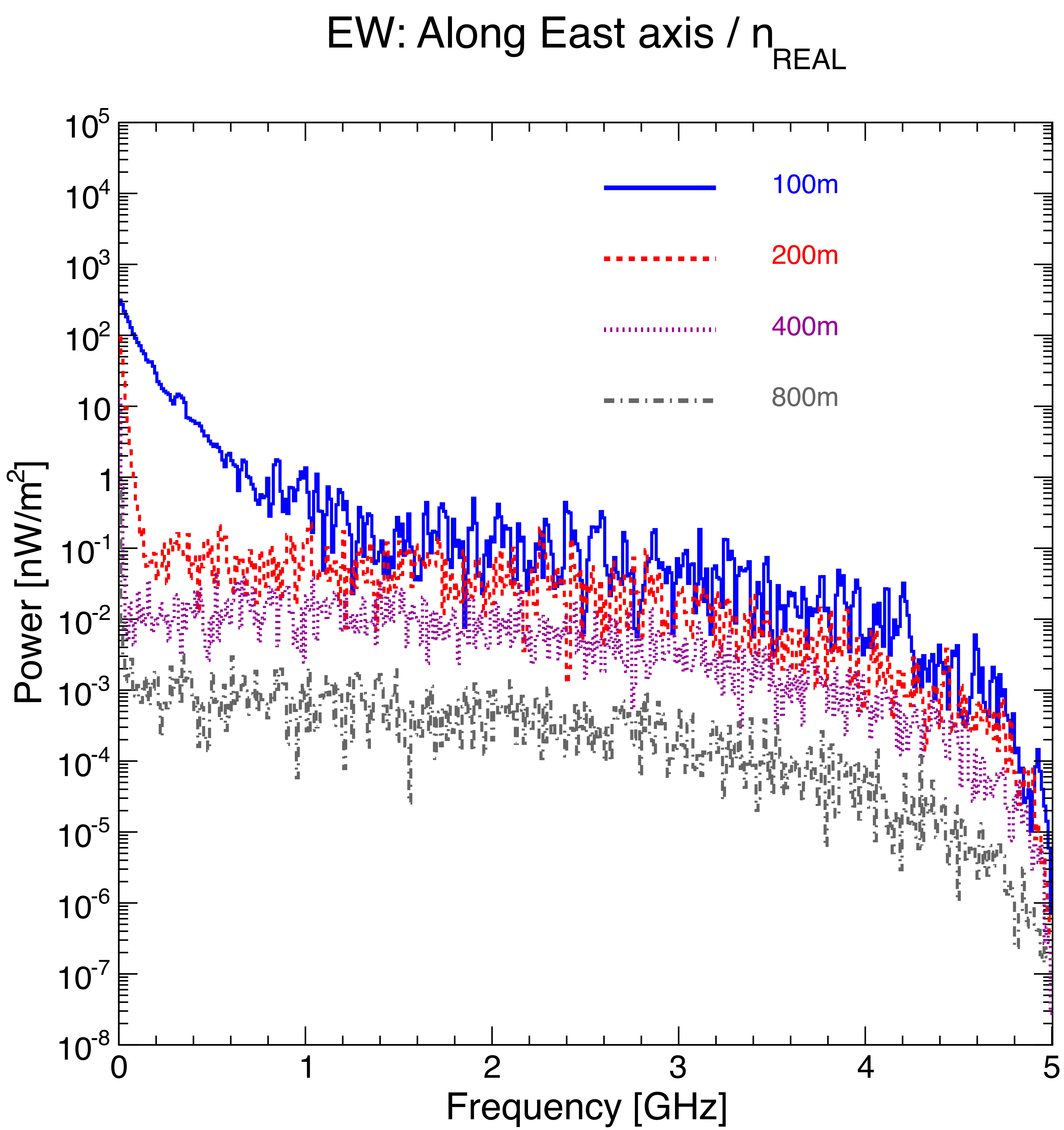
extend the mechanisms observed in the MHz domain to the GHz domain
take into account the effect of a realistic refractive index

Proton



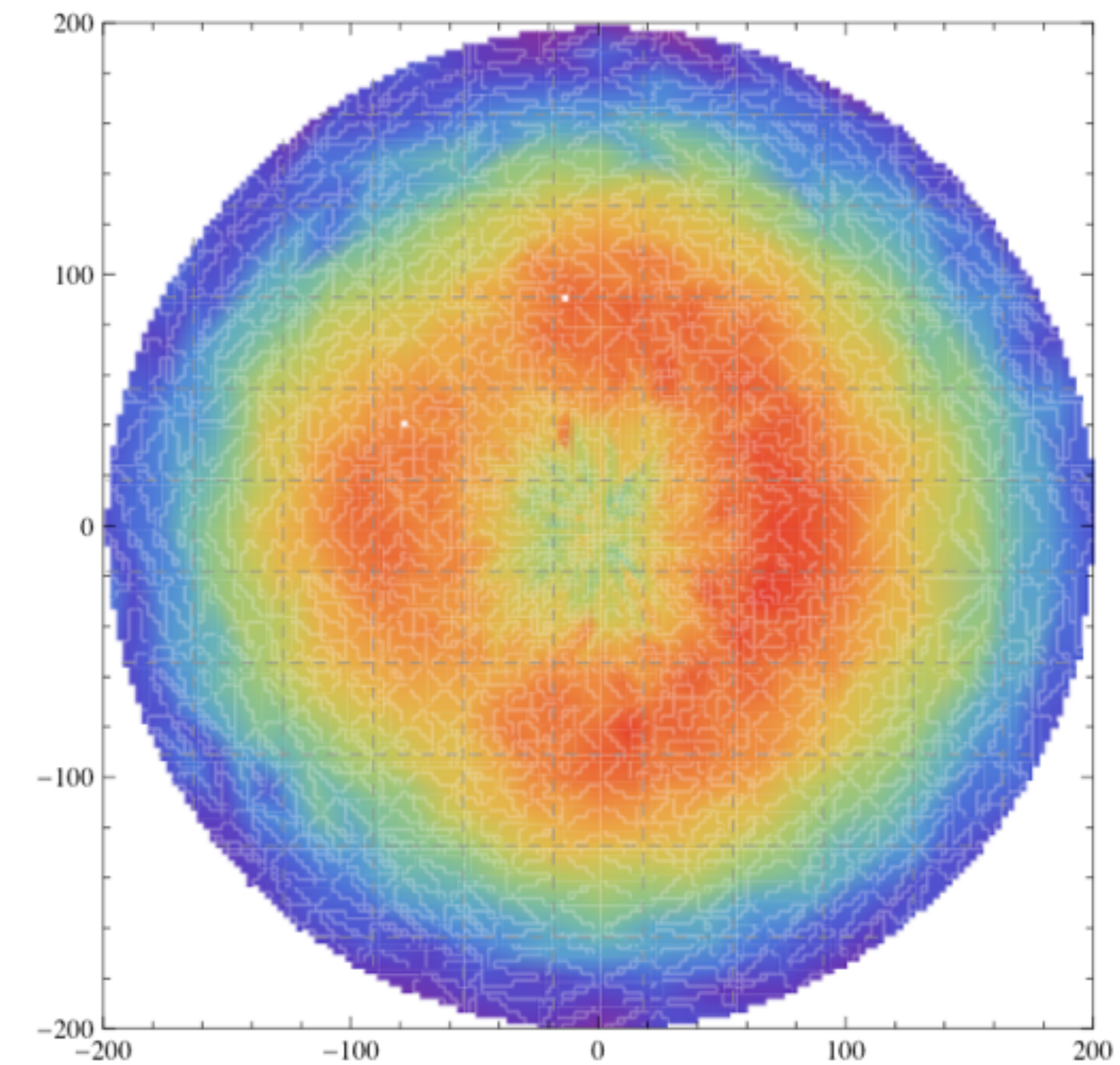
300 MHz - 1.2 GHz

Up to some GHz



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

Iron



300 MHz - 1.2 GHz

No MBR evidence in the GHz signal

Down to some kHz

Predicted mechanisms:

contribution of the 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
[Revenu ICRC2013, Rio]

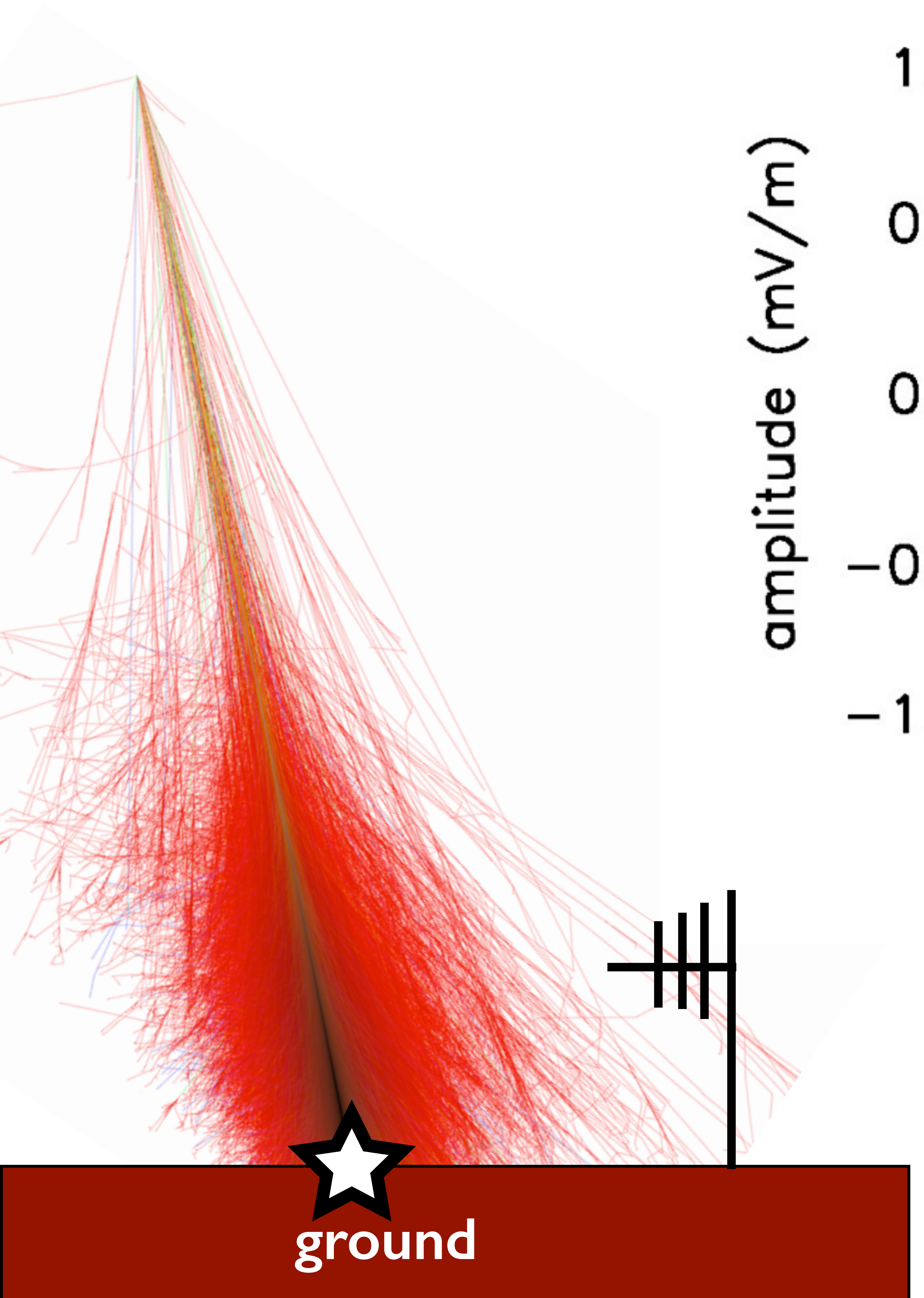
} **sudden death** of the shower

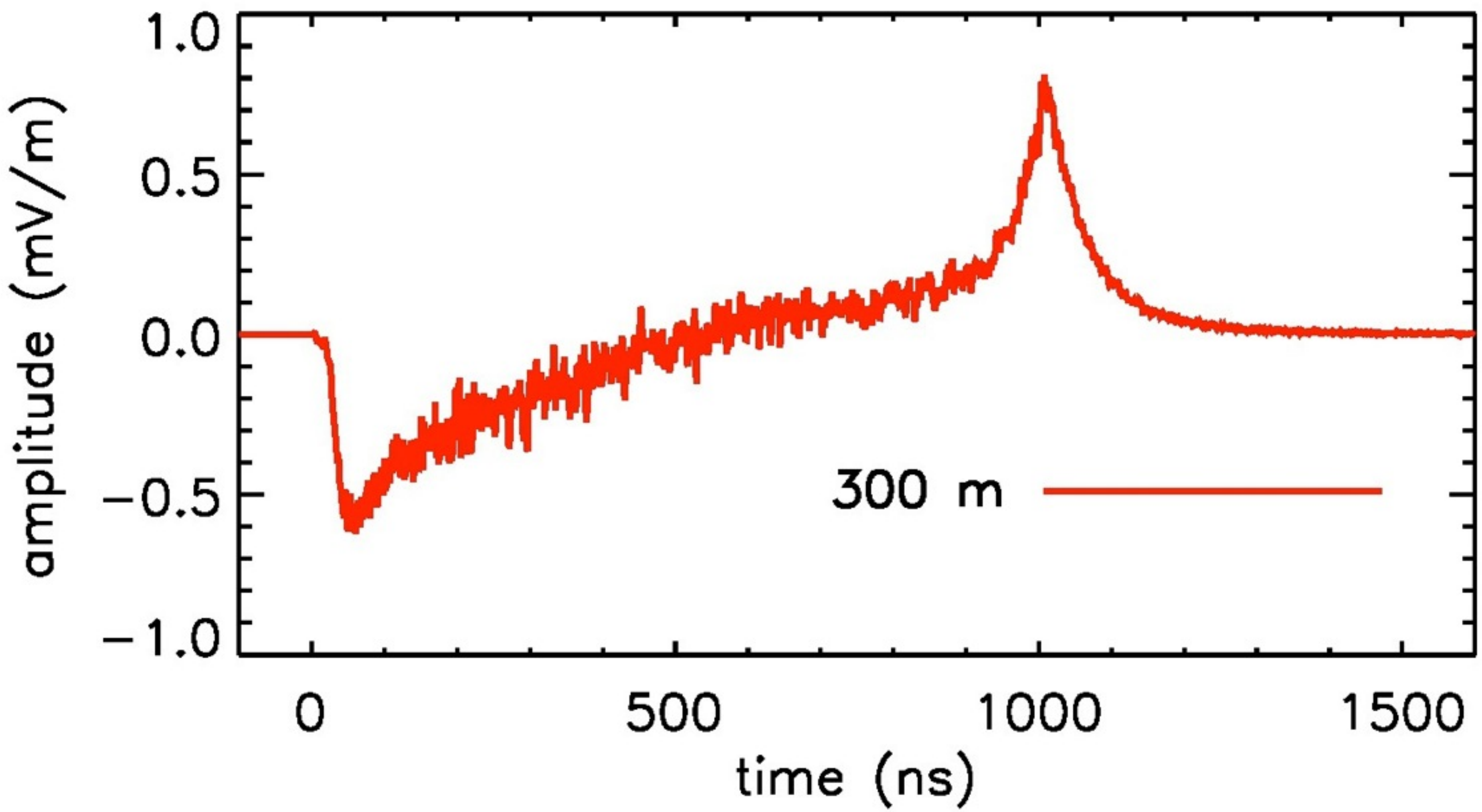
$$\vec{E}(\vec{x},t) = \frac{1}{4\pi\varepsilon_0\, c}\frac{\partial}{\partial t}\sum_{i=1}^{N} q_i \left(\frac{\vec{\beta}_i - (\vec{n}_i\cdot\vec{\beta}_i)\,\vec{n}_i}{R_i(1-\eta\vec{\beta}_i\cdot\vec{n}_i)}\right)_{\mathrm{ret}}$$

(Coulomb gauge)

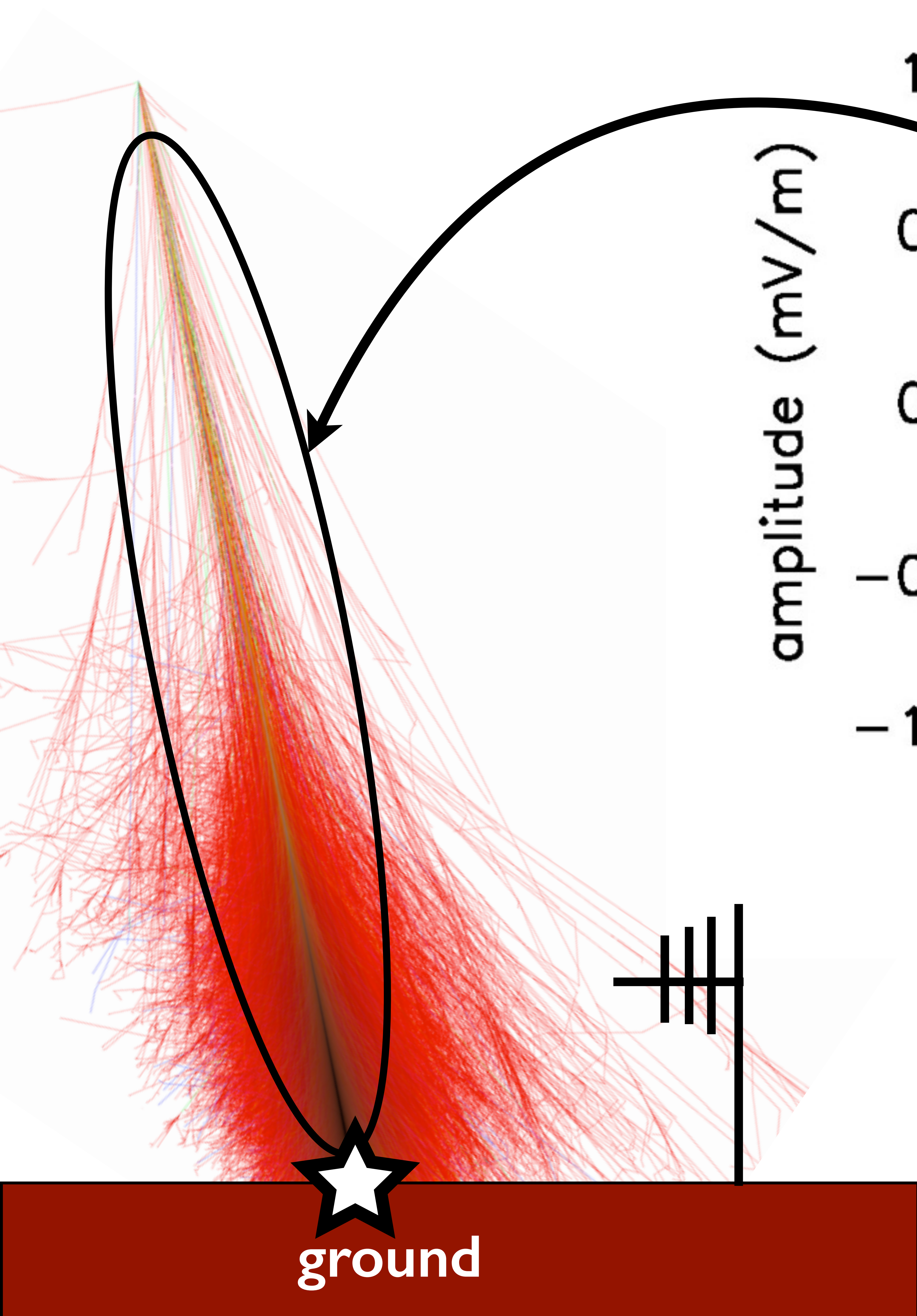
New contribution below 20 MHz, **vertical** polarization,
monopolar pulse with amplitude decreasing with **$1/d_{core}$**
(as already observed in the past by AGASA, Gauhati group, EAS-radio…)

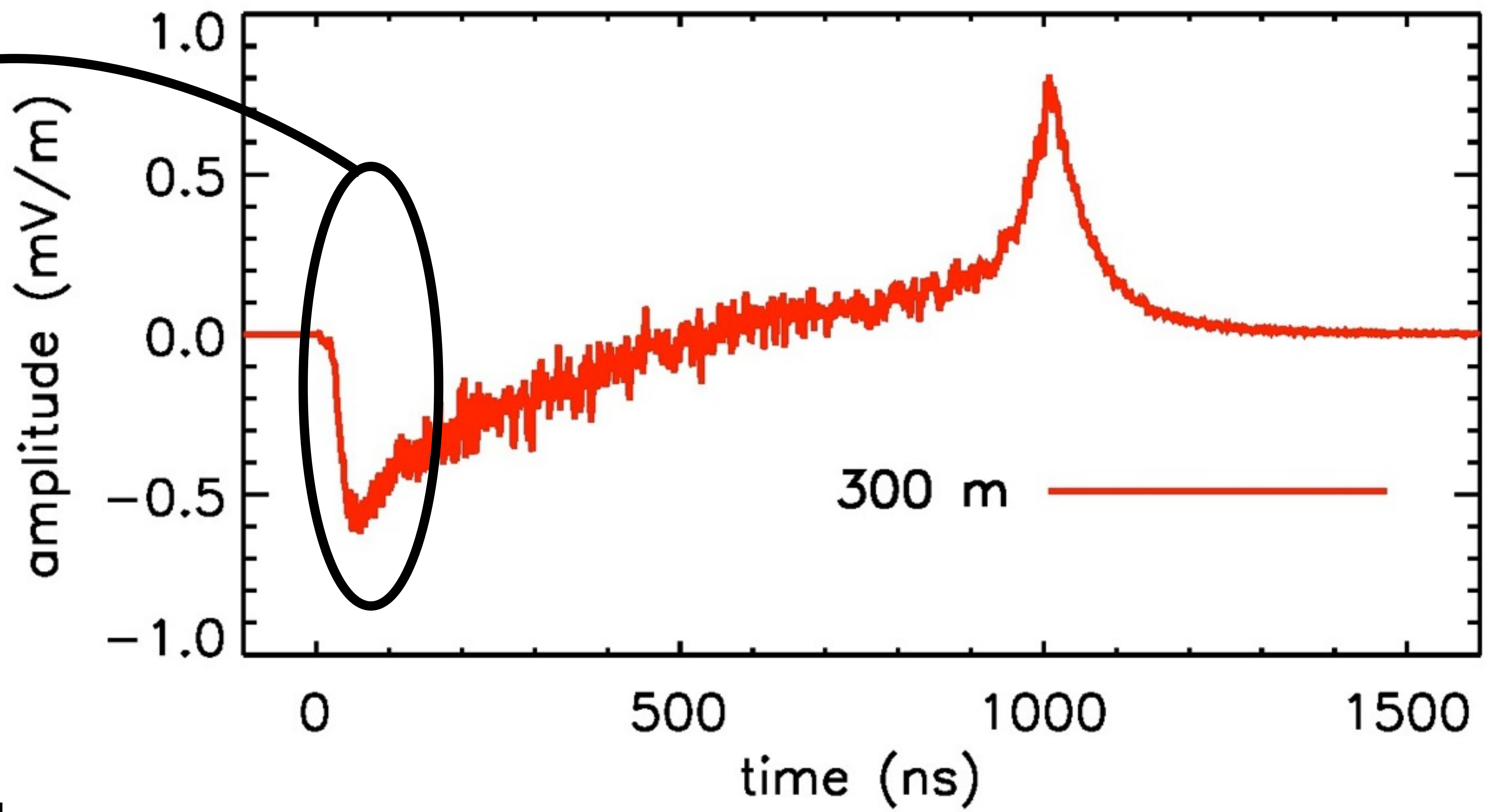
Down to some kHz



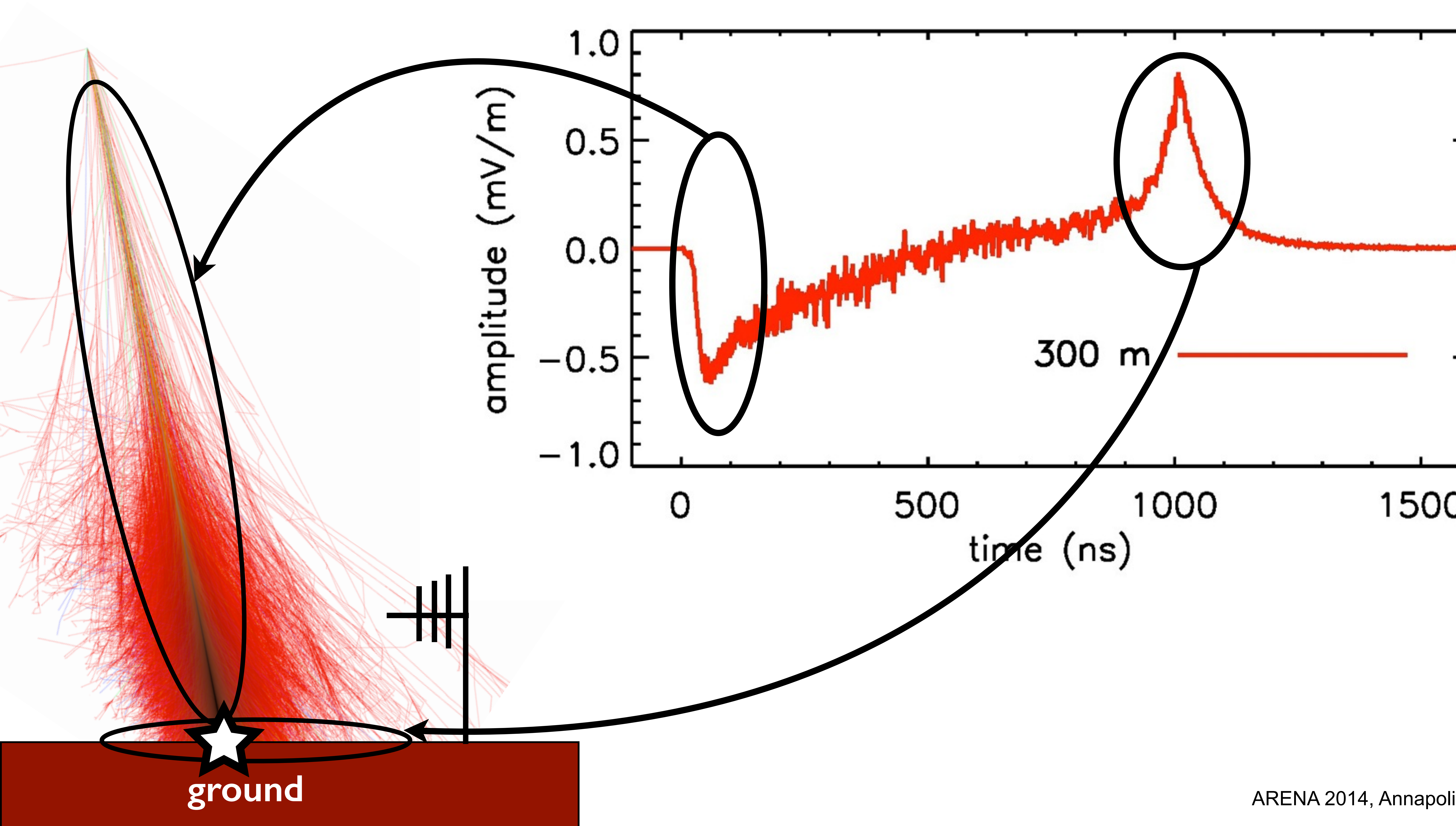


Down to some kHz



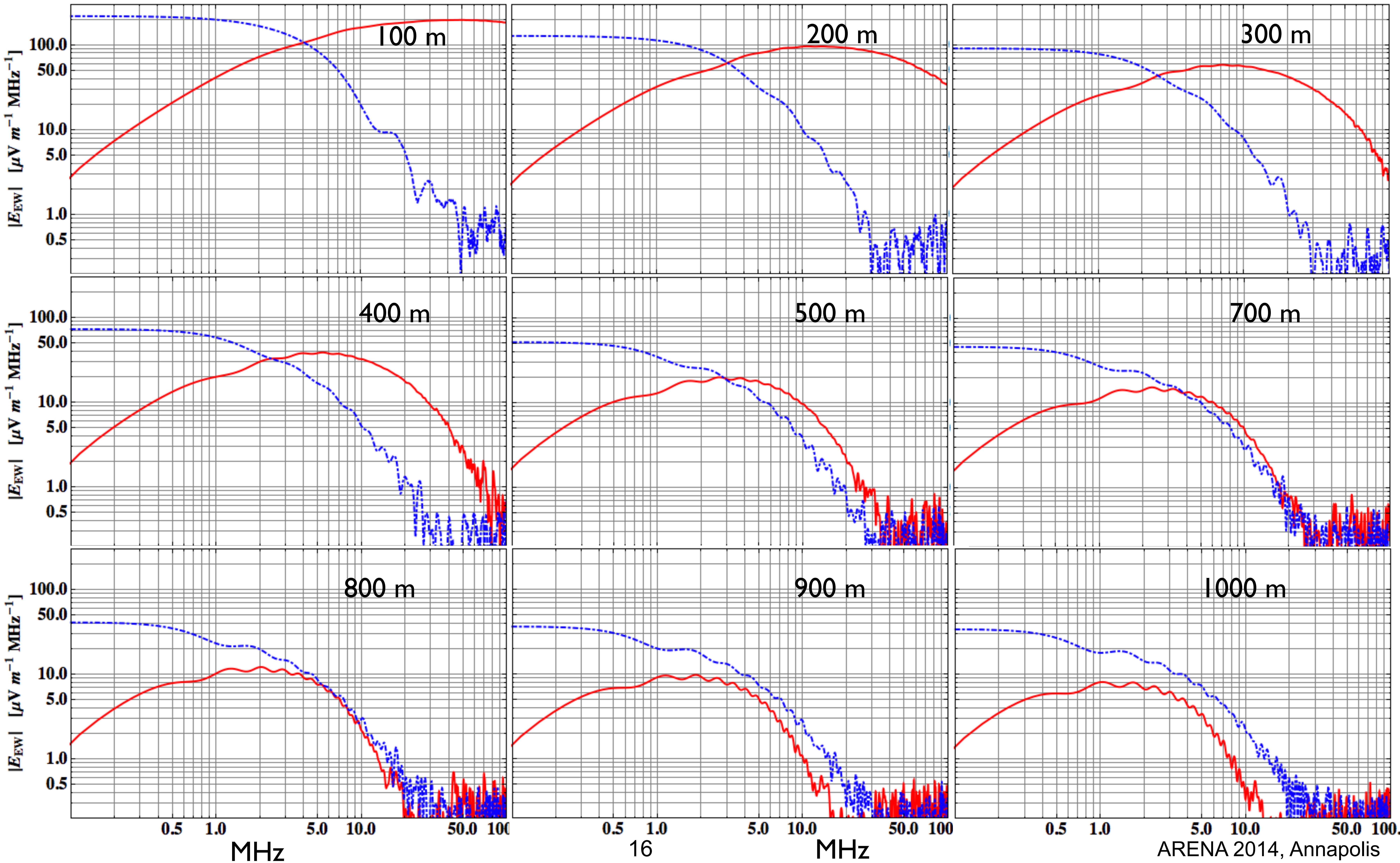


Down to some kHz



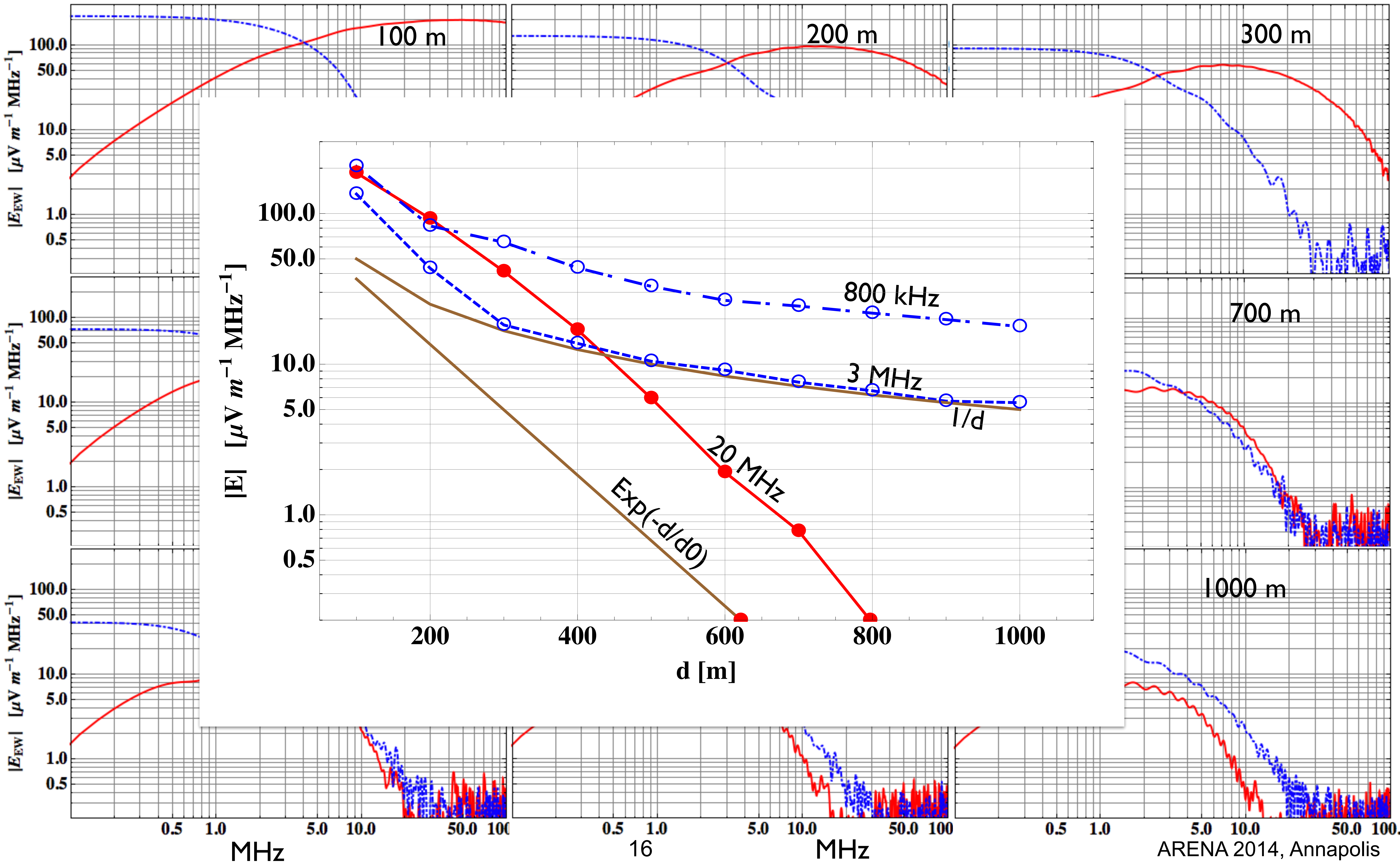
Down to some kHz

ground contribution
development in the air



ground contribution
development in the air

Down to some kHz



Conclusion

- SELFAS is a simple code, easy to use and fast: good for extensive use event by event
- it describes well the data (RAuger, CODALEMA, AERA, LOFAR…) in the range 20-200 MHz
- CONEX is used to generate the longitudinal profile
- the radio emission is now well understood
- at lower frequencies, a new phenomenon appears: the electric field emission by the shower sudden death when reaching the ground
  EXTASIS is a dedicated experiment in Nançay, inside CODALEMA, under progress