Near-field radio emission induced by extensive air showers

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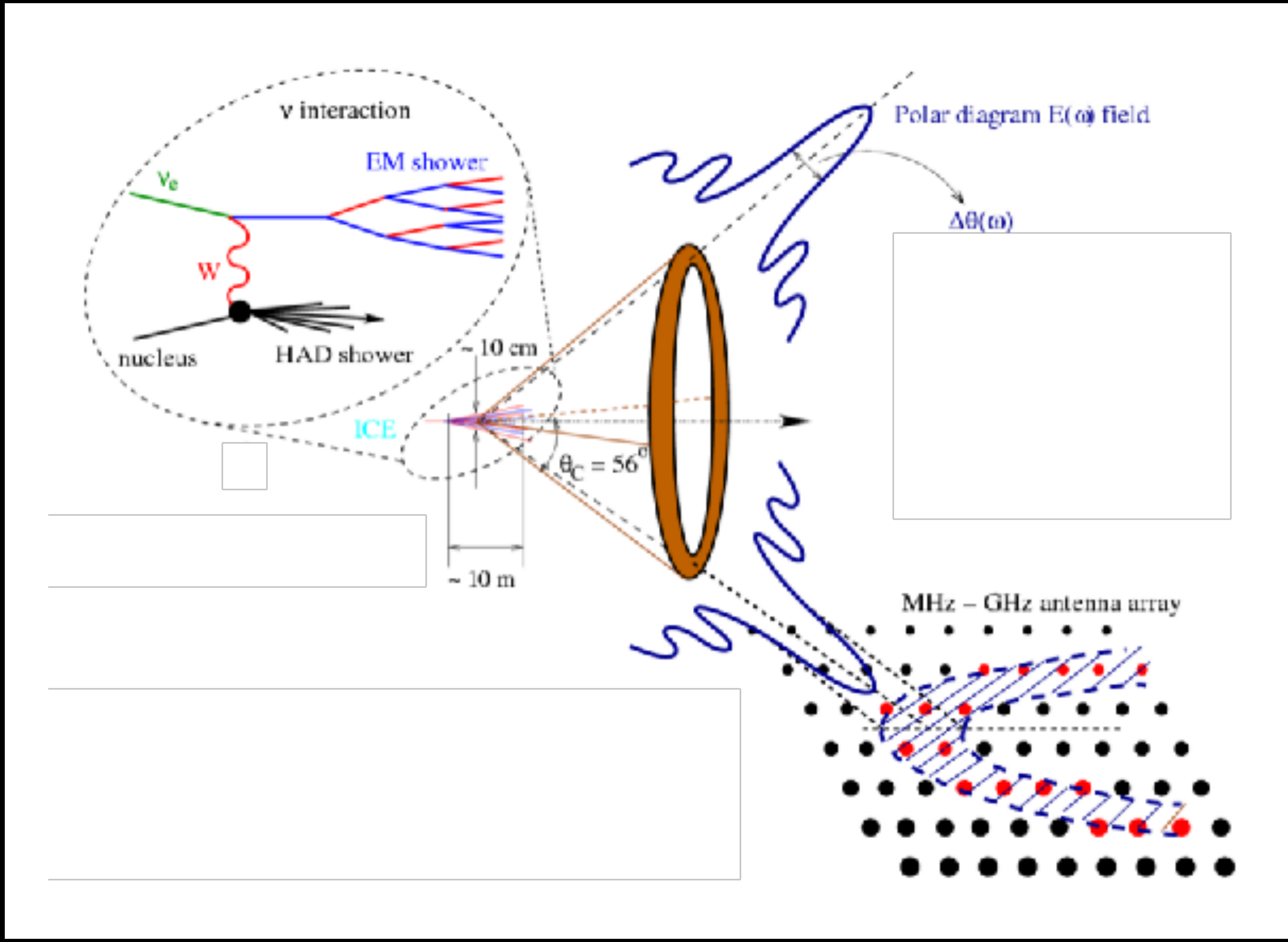
Take-home message

- Low frequency (< 10 MHz) radio emission of EAS needs a new treatment including near-field effects (d~λ)
- We expect the existence of a new signal called the sudden death pulse (SDP)
- We present a formula suitable for the calculation of the low-frequency electric field

Radio detection of cosmic rays (or neutrinos)

- A primary particle creates an EAS
- Charged particles in the EAS create electric field
- Electric field is measured (usually > 20 MHz)



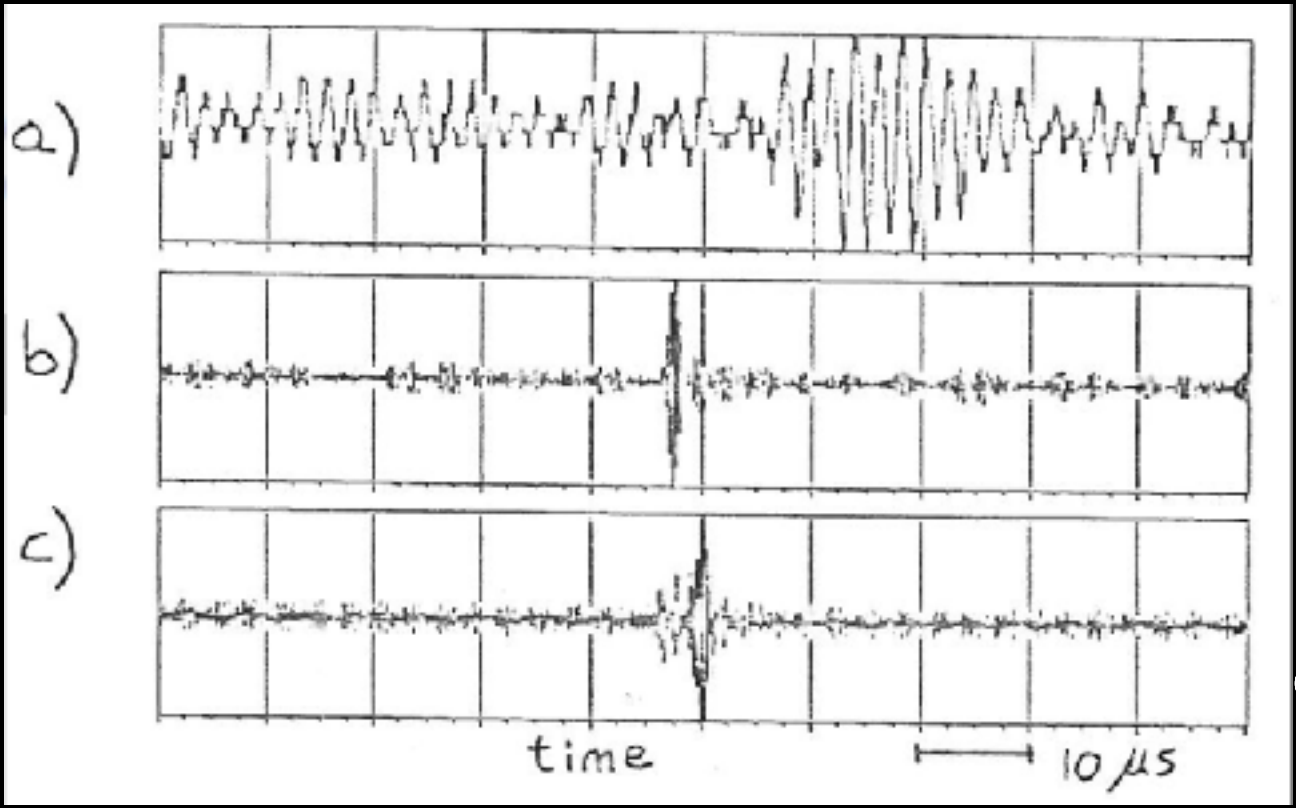
Why low frequency?

- Several experiments (EASTOP, Akeno) have measured a large low-frequency emission (C. Castagnoli et al., 22nd ICRC, 363. // K. Nishi, K. Suga. Proc. 20th ICRC (1987) 125)
- Simulations and measurements (see A. Escudie, [CRI102]) indicate an emission at low frequency with a larger detection range
- We expect a new kind of signal, the sudden death pulse

450 - 500 kHz

2.3 - 2.9 MHz

3.1 - 4.1 MHz



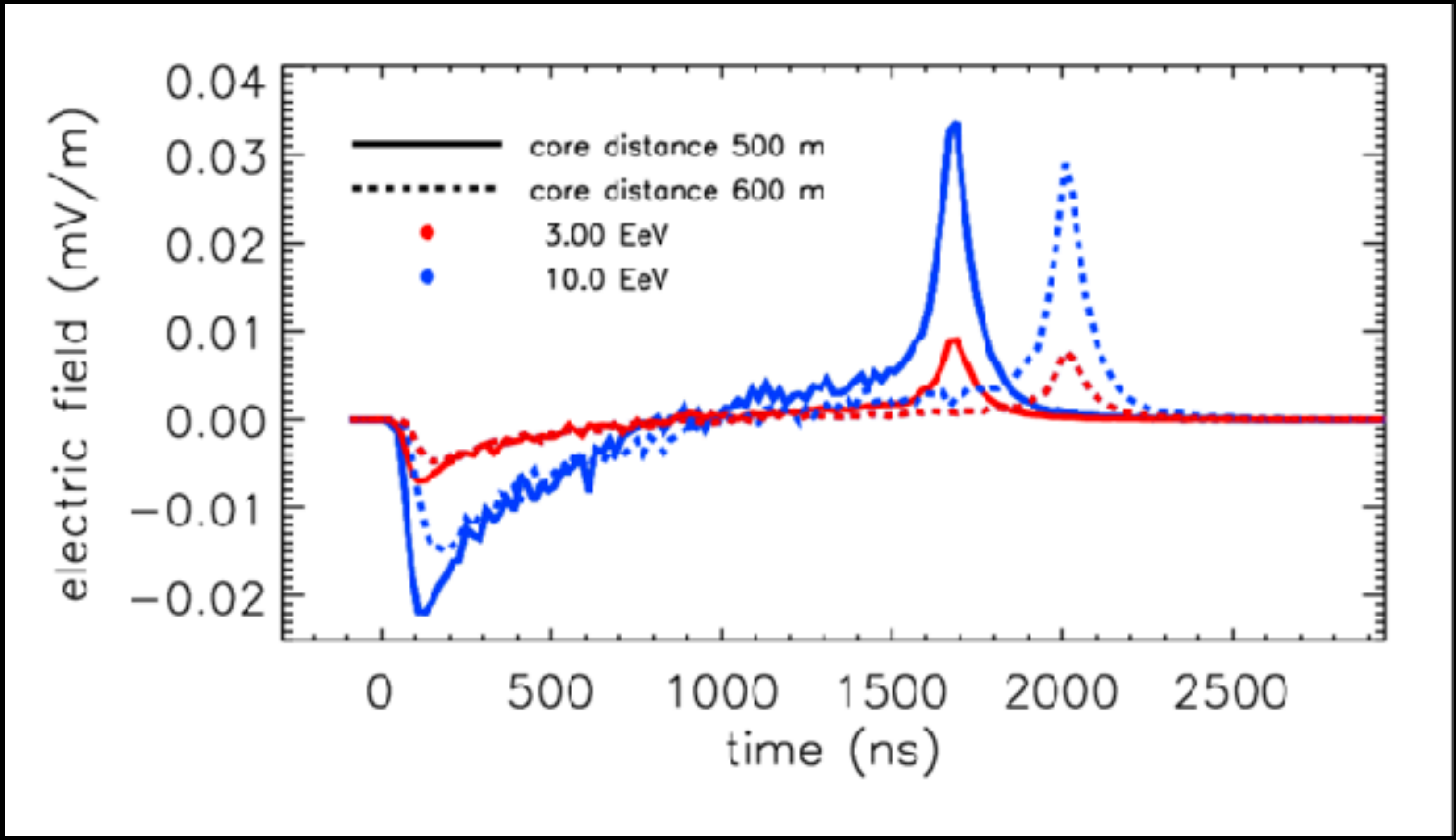
EASRADIO (EASTOP)
Vertical polarisation

Castagnoli et al., 22nd ICRC, 363

Sudden Death Pulse

- Shower particles are decelerated upon arrival to the ground
- Large shower footprint, but coherence at low frequencies (1 MHz ~ 300 m)
- Pulse at t = d/c after shower core arrival
- Low-frequency pulse

Vertical component



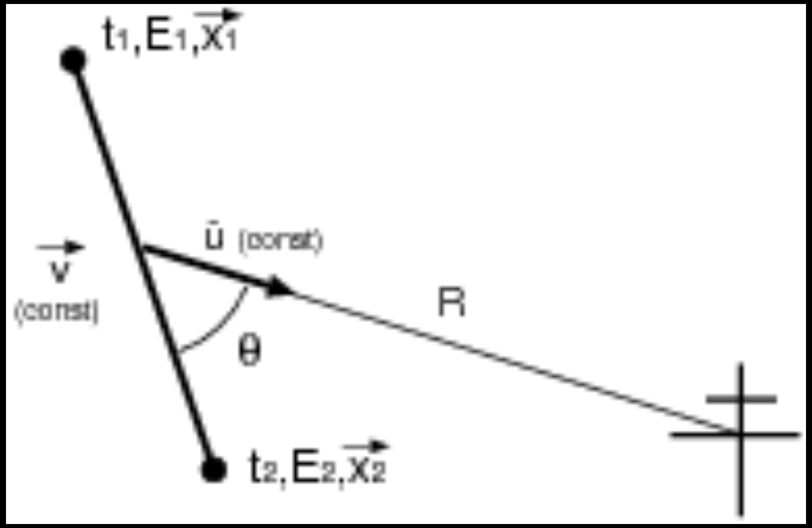
ArXiV:1211.3305

The EXTASIS experiment

- New experiment at the Nançay radio observatory
- Detect the low-freq (1.7 - 3.7 MHz) counterpart to the known EAS field
- Detect the SDP
- See A. Escudie's talk [CRI102]

Electric field for a track

- Codes such as SELFAS, ZHAireS or CoREAS use the far-field approximation (kR >> 1)



- At 1 MHz, and R = 100 m: kR ~ 2. Near field!

- Formula for the field of a particle track at all frequencies:

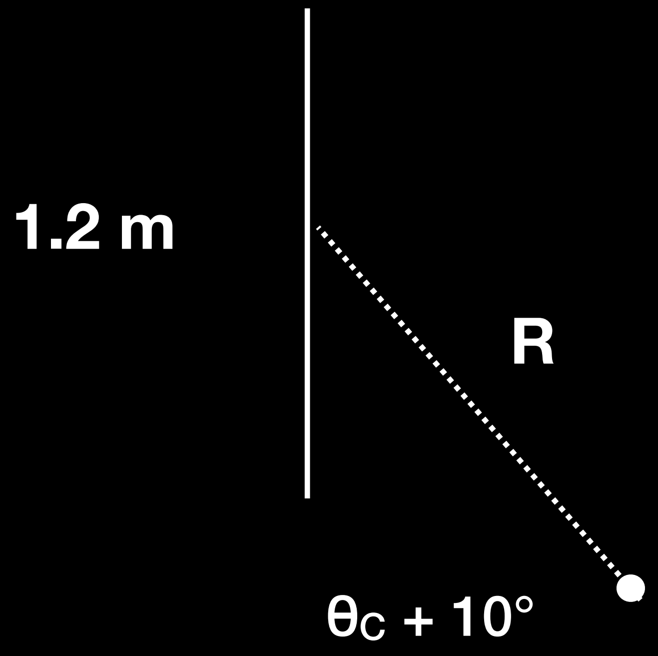
$$\mathbf{E}(\mathbf{x},t) = \frac{1}{4\pi\varepsilon}\int \mathrm{d}^3x' \left\{ \left[\frac{\rho(\mathbf{x}',t_{\mathrm{ret}})\mathbf{r}}{R^2(1-n\beta\cdot\mathbf{r})}\right]_{\mathrm{ret}} + \frac{n}{c}\frac{\partial}{\partial t}\left[\frac{\rho(\mathbf{x}',t_{\mathrm{ret}})\mathbf{r}}{R(1-n\beta\cdot\mathbf{r})}\right]_{\mathrm{ret}} - \frac{n^2}{c^2}\frac{\partial}{\partial t}\left[\frac{\mathbf{J}(\mathbf{x}',t_{\mathrm{ret}})}{R(1-n\beta\cdot\mathbf{r})}\right]_{\mathrm{ret}} \right\}$$

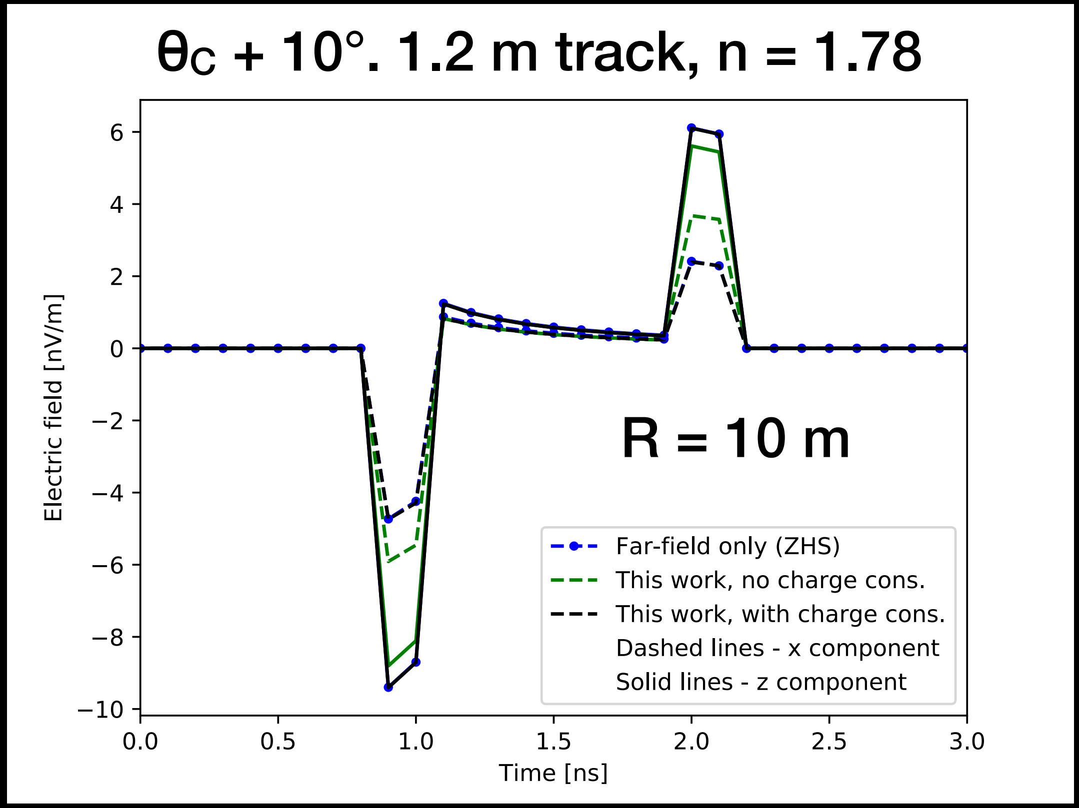
- Caveat: Charge MUST be conserved!

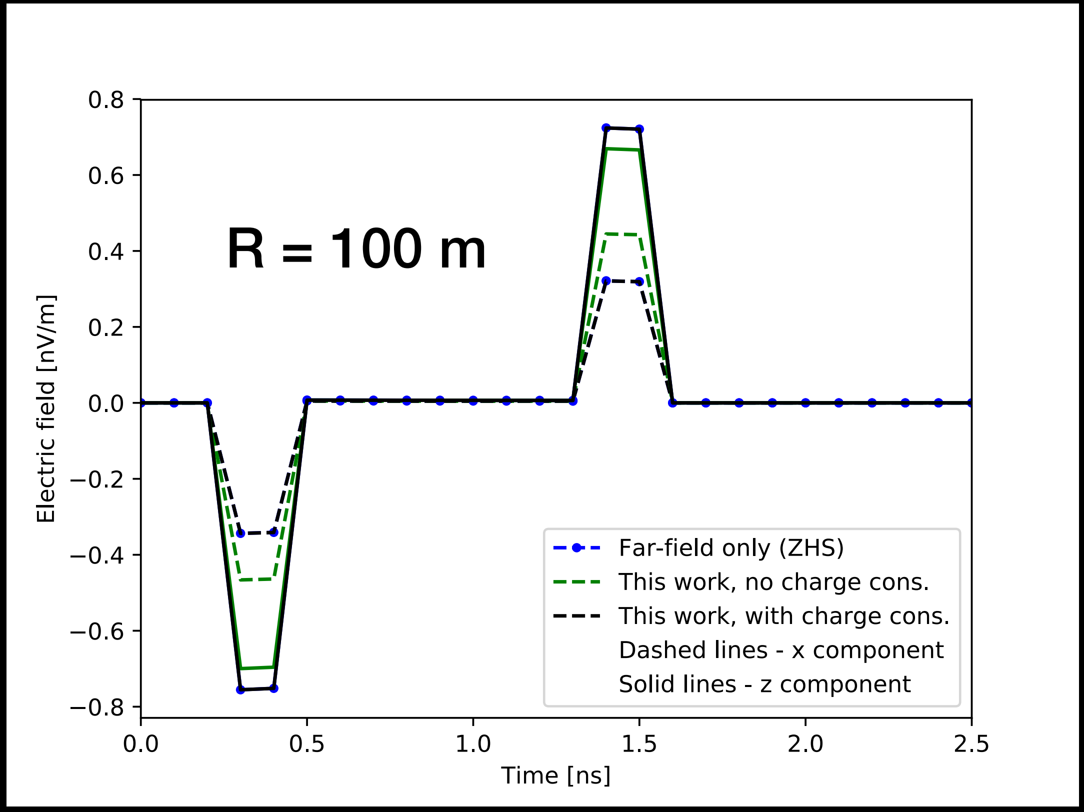
$$\rho(\mathbf{x},t) = q\delta^{(3)}(\mathbf{x}-\mathbf{x}_1)\Theta(t_1-t) + q\delta^{(3)}(\mathbf{x}-\mathbf{x}_1-\mathbf{v}(t-t_1))\Theta(t-t_1)\Theta(t_2-t_1) + q\delta^{(3)}(\mathbf{x}-\mathbf{x}_2)\Theta(t-t_2)$$

Comparison with far-field: ZHS

- Our formula yields the same result as the ZHS formula (far-field). <u>J. Alvarez-Muniz *et al.*</u> Phys. Rev. D 81 (2010) 123009
- If charge is not conserved, pulses from the beginning and end of the track are not well reproduced.



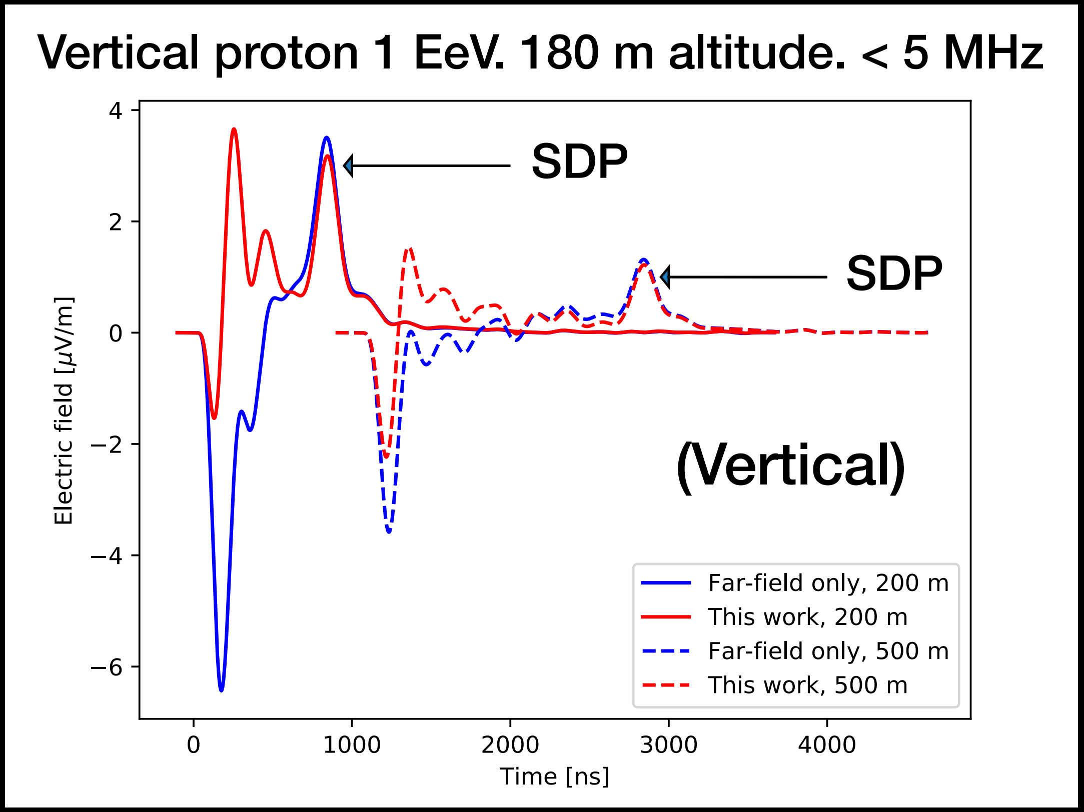


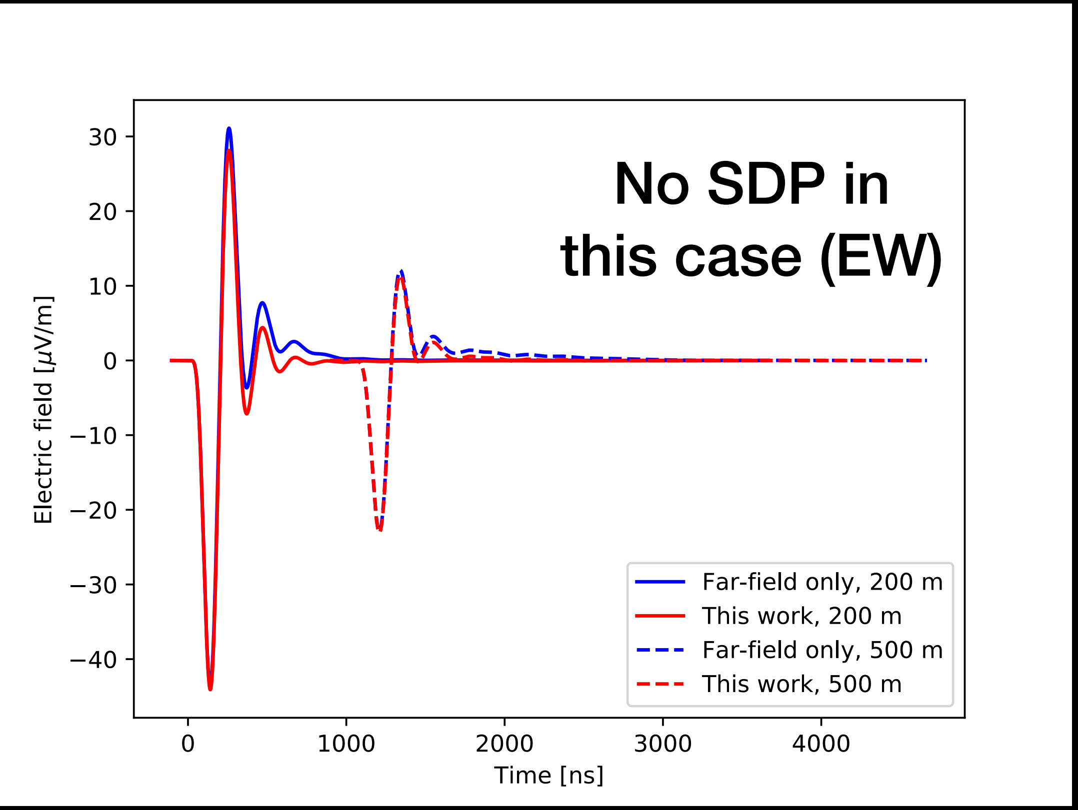


Implementation in SELFAS

- SELFAS (open source) is a MC code that calculates the field of an EAS. It has been upgraded with a state-of-the-art treatment of the atmosphere (see B. Revenu [CRI109])

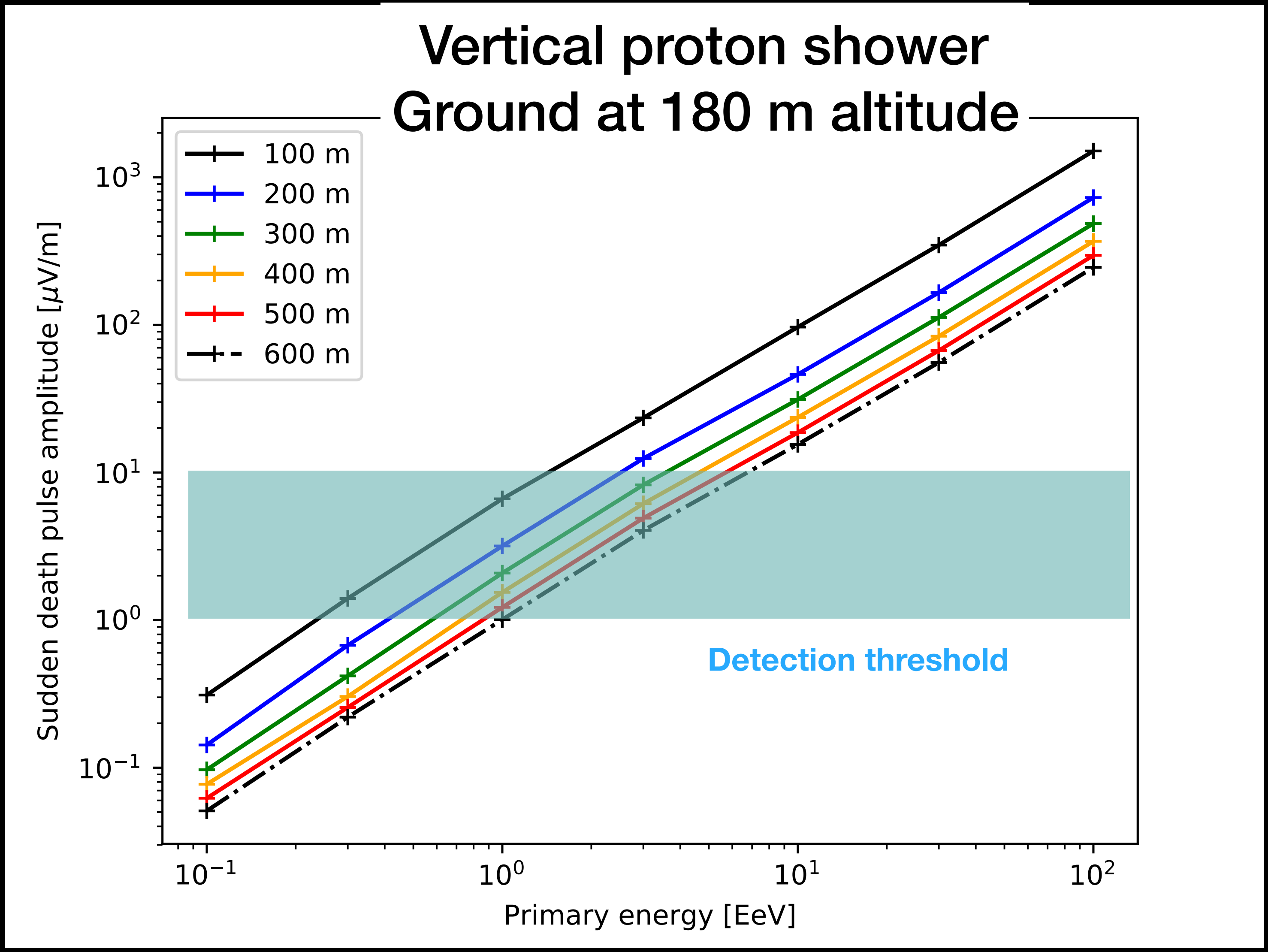
- We have implemented our formula assuming:
  - No static field after shower extinction
  - Particles are suddenly stopped at ground level
  - No reflection (can be taken into account with antenna pattern) or surface wave
  - No transmission (attenuation in soil)





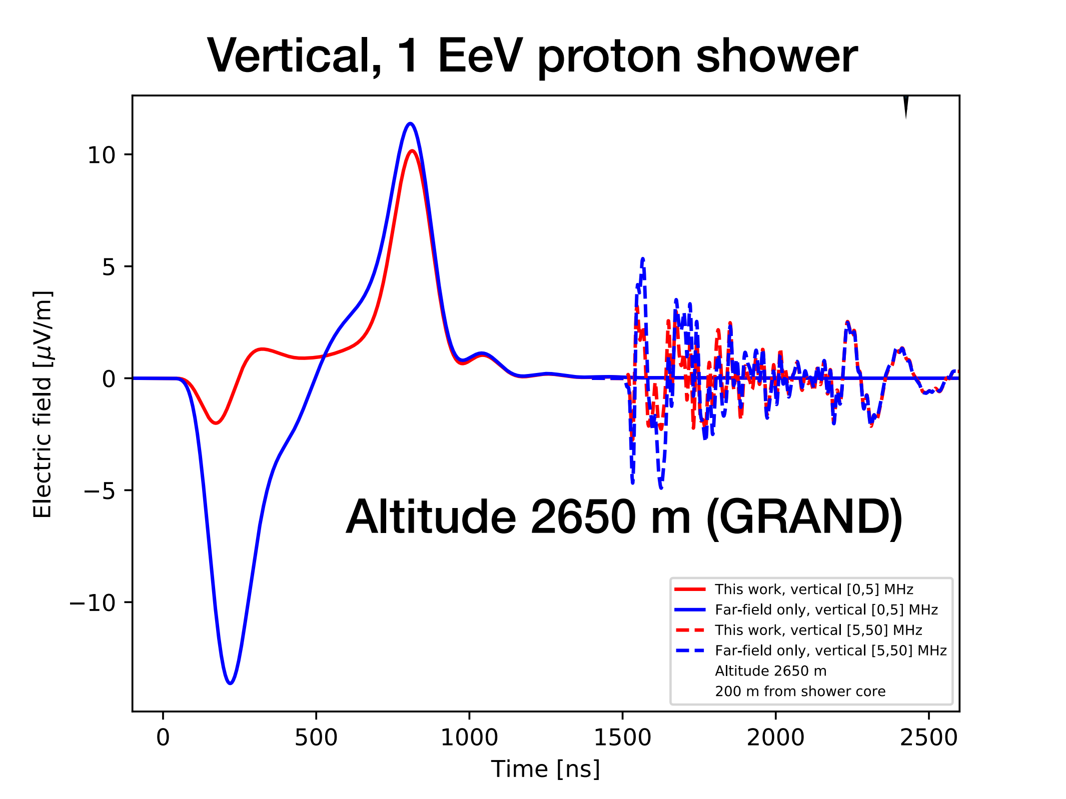
Sudden Death Pulse amplitude

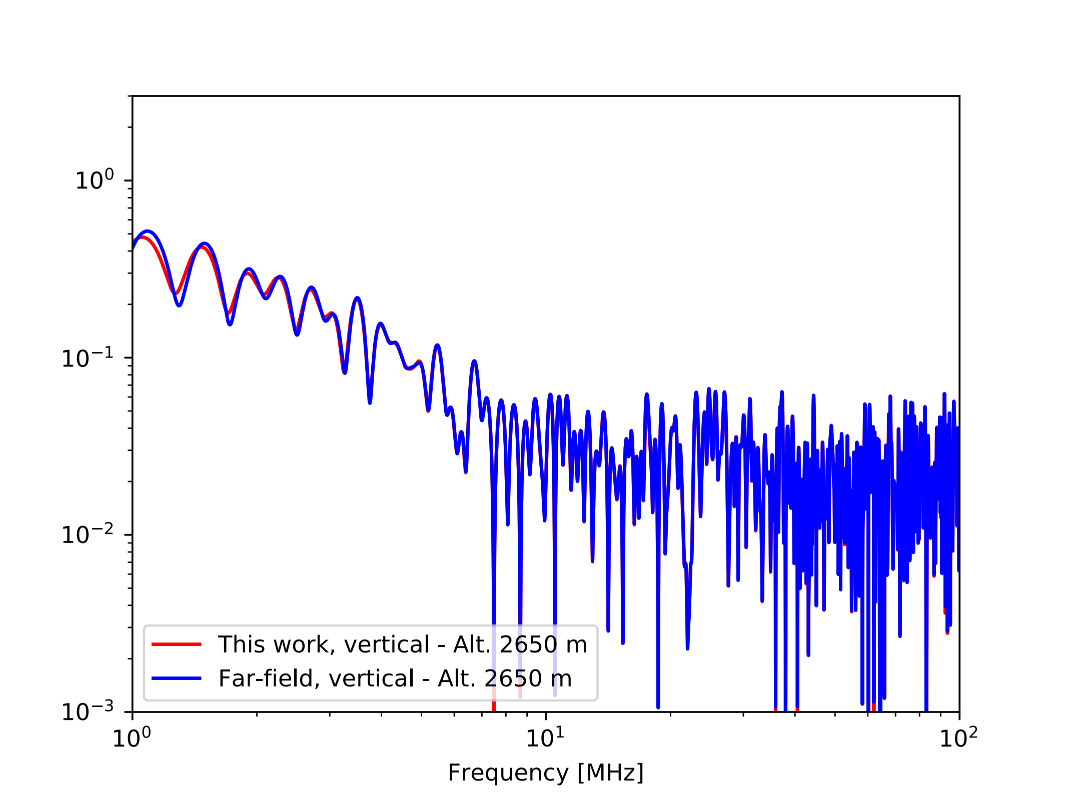
- SDP amplitude calculated as a function of energy and distance (vertical proton shower)
- The amplitude is proportional to the energy (number of particles arriving to the ground)
- At Nançay, we expect detectability between 1 and 10 μV/m



Low frequency emission at high altitude

- The amplitude is proportional to the energy (number of particles arriving to the ground)
- Altitude closer to the shower maximum means larger SDP signal
- More total signal below 10 MHz! See spectrum.





Conclusions

- We have presented an equation for the electric field of a particle track valid for all frequencies (includes near-field effects)
- Correctly taking into account near-field effects is crucial for low frequency measurements (below 10 MHz). That is the case for the EXTASIS experiment.
- We have implemented this formula in the SELFAS Monte Carlo code and checked its consistency with far-field (ZHS) calculations.
- An analysis of the surface wave and the effects of the interface on the field is underway.
- Caveat: we have talked about electric field, not voltage. The response of the antennas in the near field could be complicated; only far-field properties are usually well known.

Thank you
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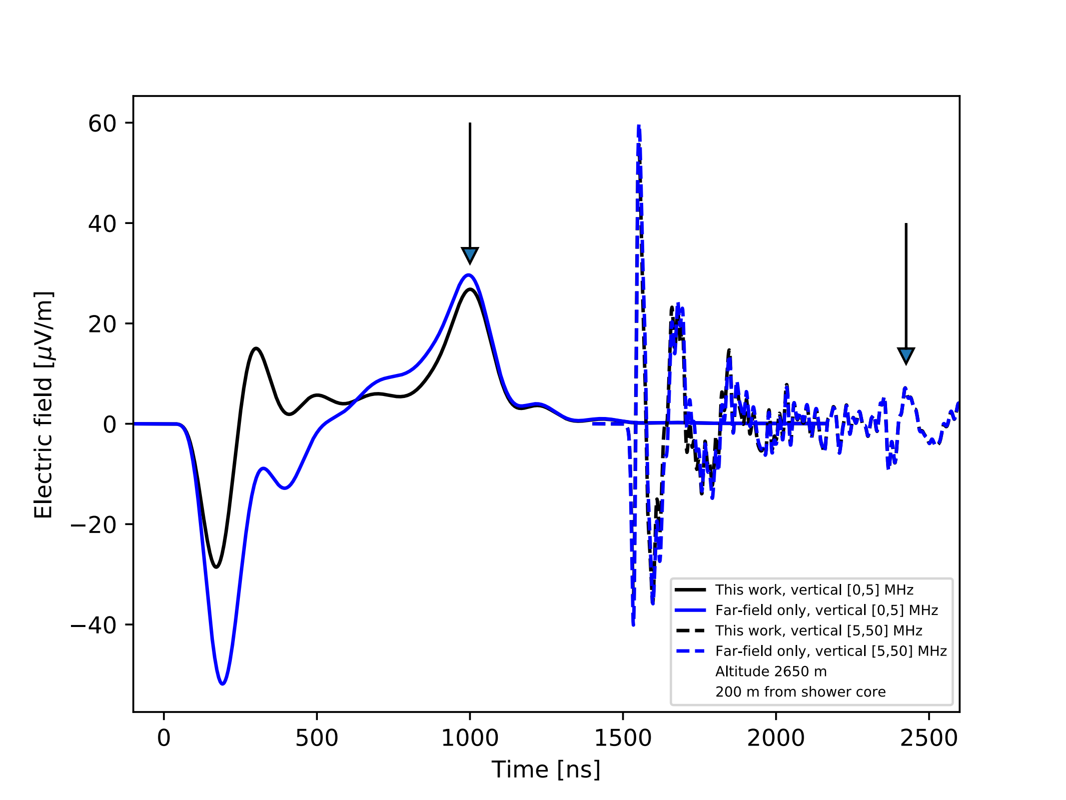
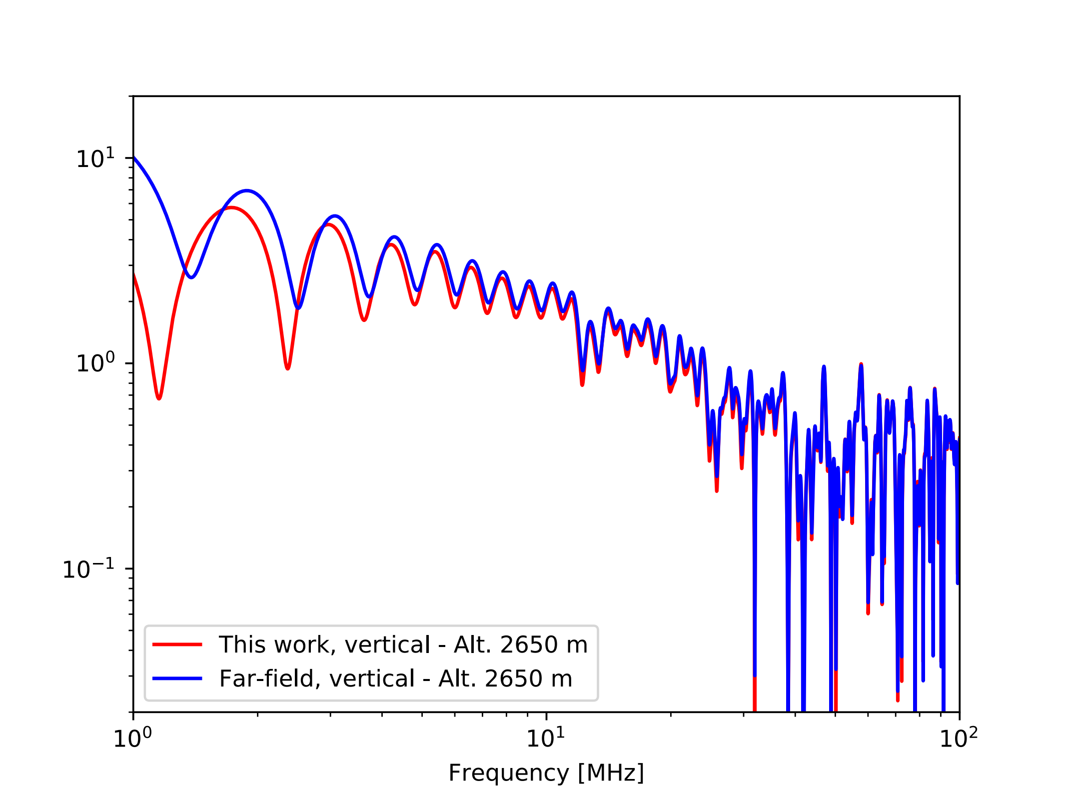
Low frequency emission at high altitude

- The amplitude is proportional to the energy (number of particles arriving to the ground)
- Higher altitude means larger SDP signal
- More total signal below 10 MHz! See spectrum.

Figure: 30 degrees 5 EeV proton shower Ground at 2650 m of altitude





Comparison with exact formula (frequency)

$$\mathbf{E}(\mathbf{x},\omega) = \frac{q}{4\pi\varepsilon}\left\{\int_{t_1}^{t_2} \mathrm{d}t\, e^{i\omega t}\frac{e^{ikR}}{R}\mathbf{r}\left[\frac{1}{R}-\frac{i\omega n}{c}\right] + \sum_{j=1,2}\left[(-1)^j e^{i\omega t_j} e^{ikR_j}\mathbf{r}_j\left(\frac{n}{cR_j}+\frac{i}{\omega R_j^2}\right)\right]\right\} + \frac{i\omega\mu_0 q}{4\pi}\int_{t_1}^{t_2}\mathrm{d}t\, e^{i\omega t}\frac{e^{ikR}}{R}\mathbf{v}$$

- Our formula (above, in frequency domain) yields the same result as the exact formula in frequency domain in Phys. Rev D 87 (2013) 023003.
- Therefore, the formula in time domain reproduces the complete electric field

Figure: Cherenkov angle
1.2 m long track in ice, n = 1.78