Macroscopic modeling of radio emission from particle cascades

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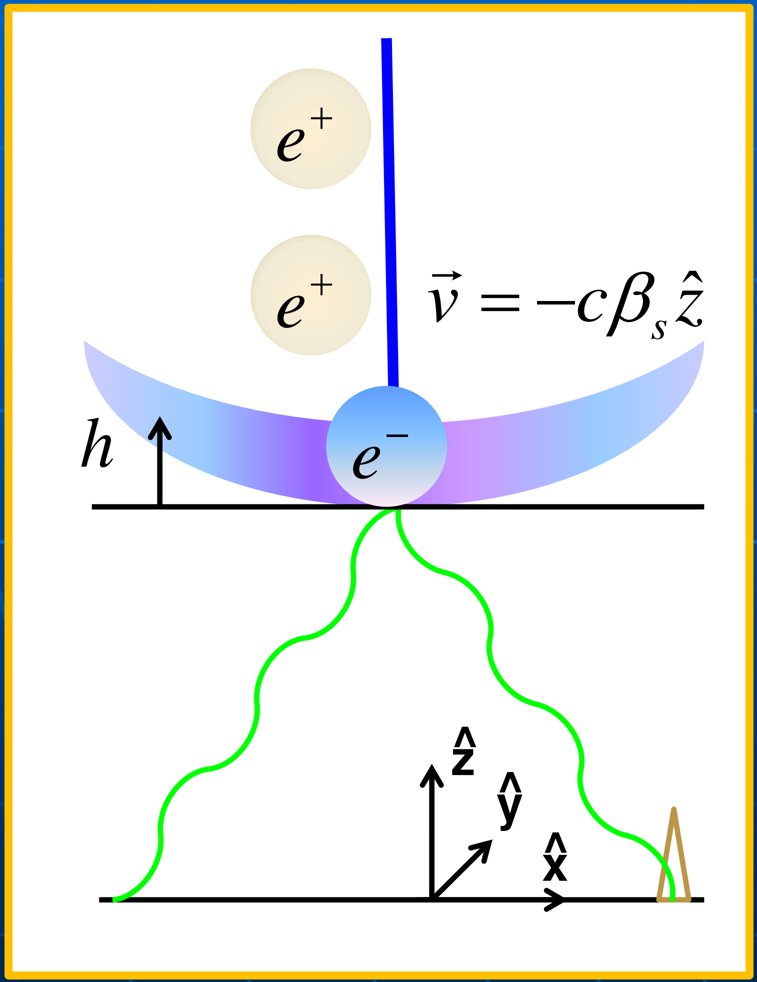
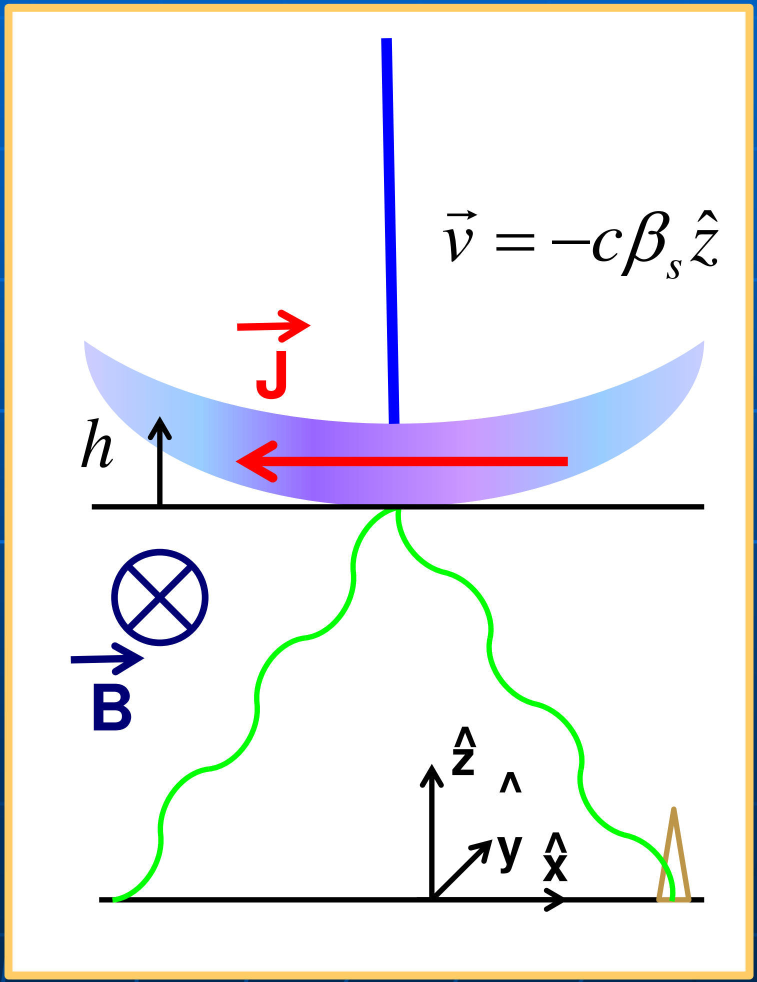
Radio Emission Mechanisms:

Charge excess:



Geomagnetic:



MGMR vs EVA

Ingredients: Particle distributions and Currents

- **MGMR:**

- ***Parameterized*** current and charge distribution

- Lateral particle extent ***ignored***.

- No Cherenkov effects included.

- ***Simulation time:*** Fast! Seconds – Few minutes

- **EVA:**

- ***Full Monte Carlo 3D shower*** information from histograms which are Fitted.

- Cherenkov effects included.

-Simulation time: Air shower simulation: 0.5-4 hours (depends on energy)

Radio emission: Minutes- 2 hours.

The EVA code

K.D. De Vries, Olaf Scholten, Klaus Werner

- ***CX-MC-GEO:*** Full Monte Carlo version of CONEX

- *Provides histograms of the current and charge distributions*

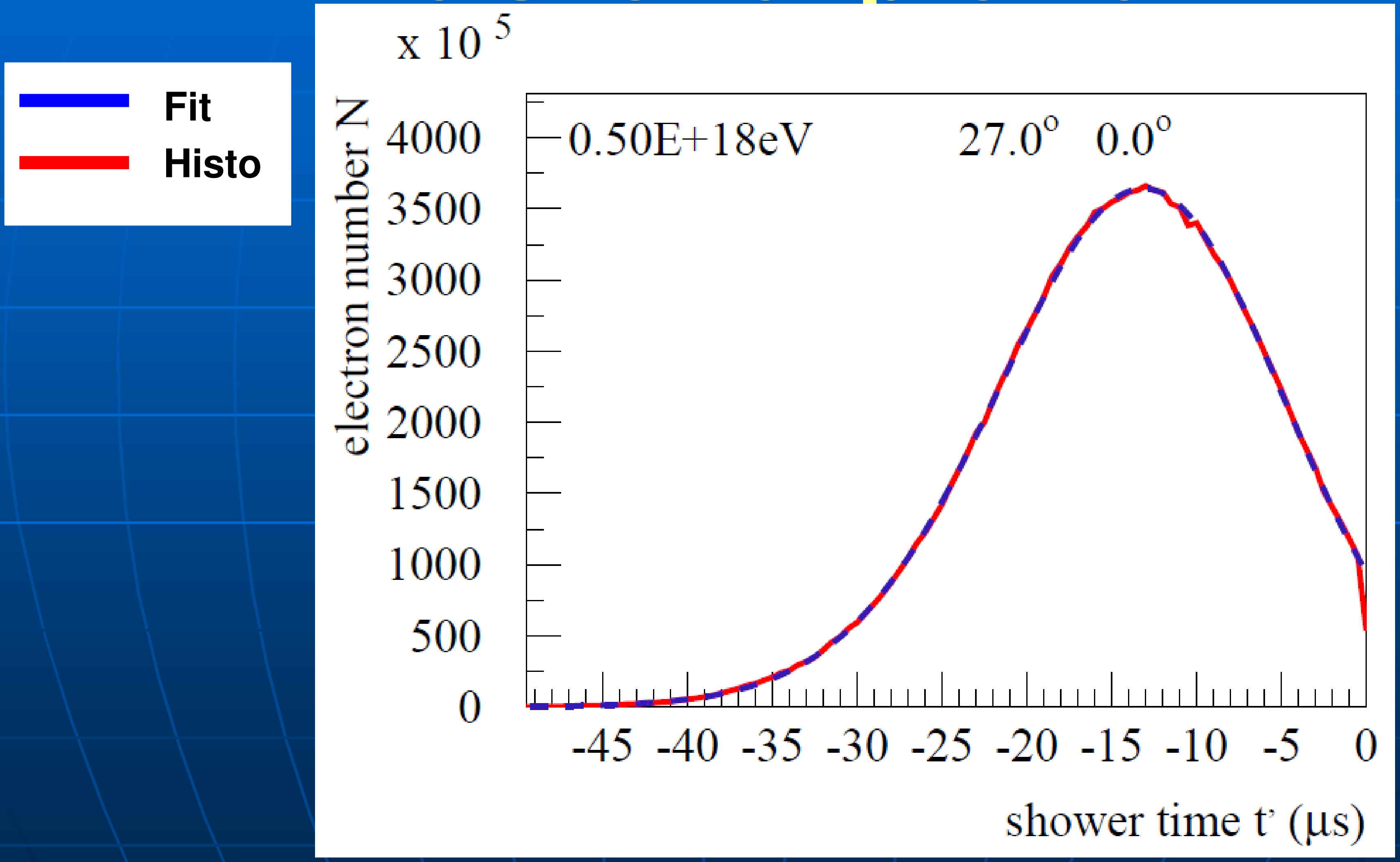
- ***FITMC:*** Fit program

- *Provides analytical expressions for the currents and particle distribution.*

- ***EVA:*** Coherent radio emission from current and charge distributions

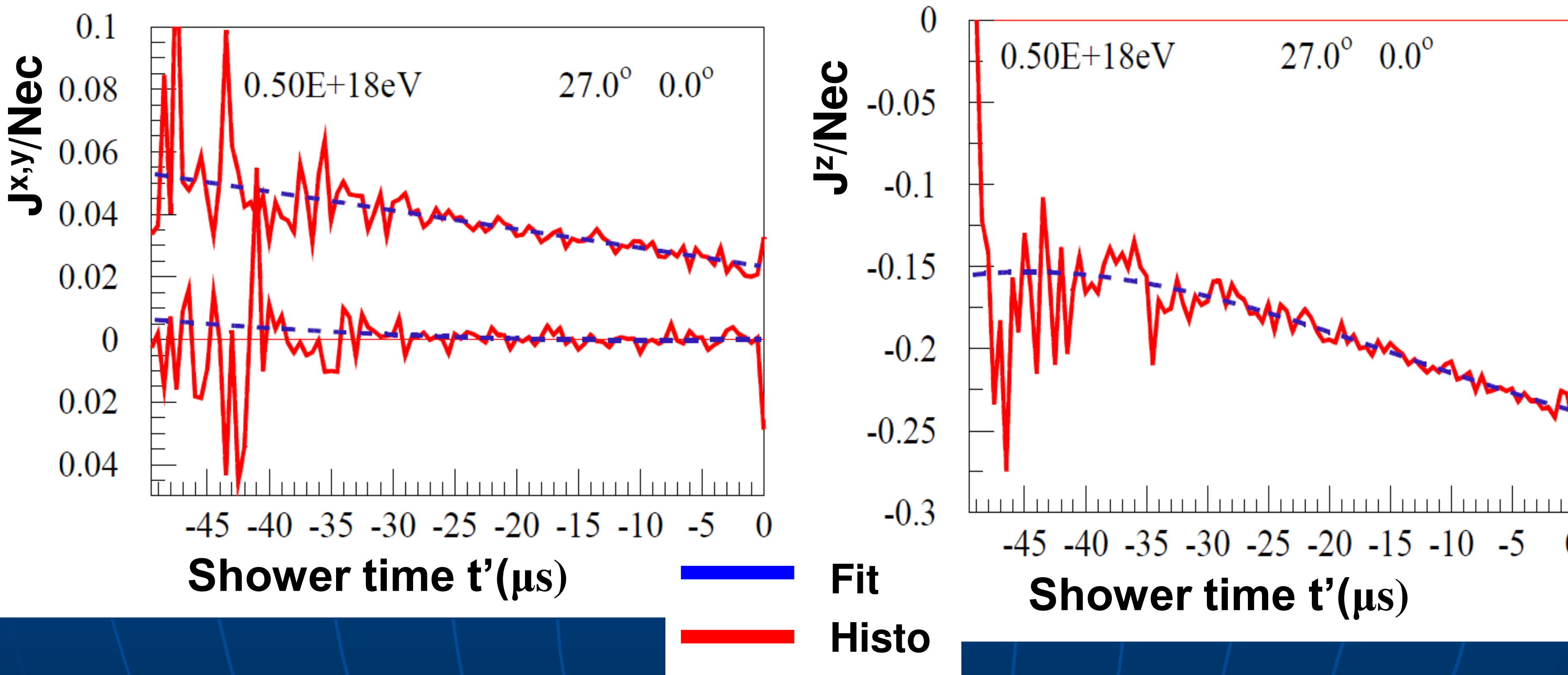
- *Including Cherenkov effects*

CX-MC-GEO+MCFIT: The shower profile



K. Werner, et. al. Astropart. Phys. 37 (2012) 5-16; arXiv:1201.4471

CX-MC-GEO+MCFIT
The Macroscopic currents

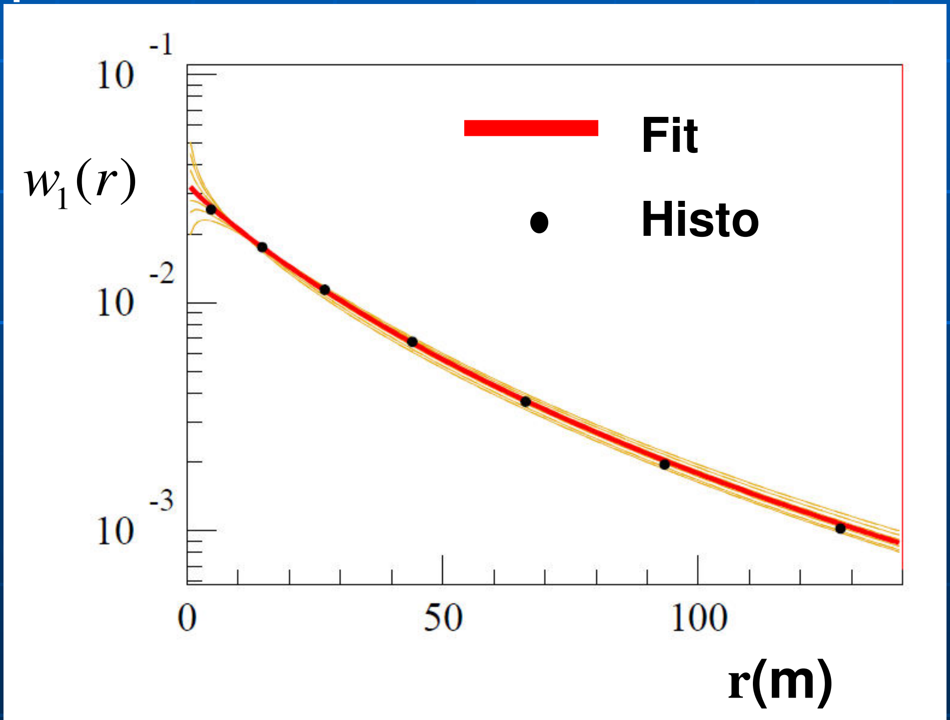


Geomagnetic Current **Charge-excess Current**

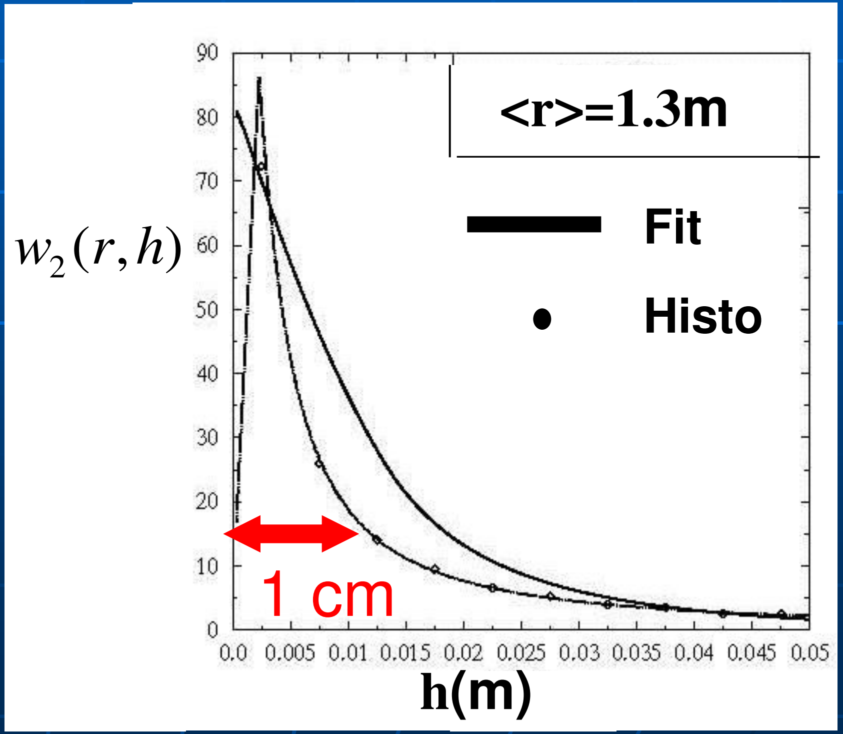
K. Werner, et. al. Astropart. Phys. 37 (2012) 5-16;
arXiv:1201.4471

CX-MC-GEO+MCFIT: The particle distributions in the shower front

Lateral particle distribution in the pancake:



Longitudinal particle distribution close to the shower axis, very sharp!!!



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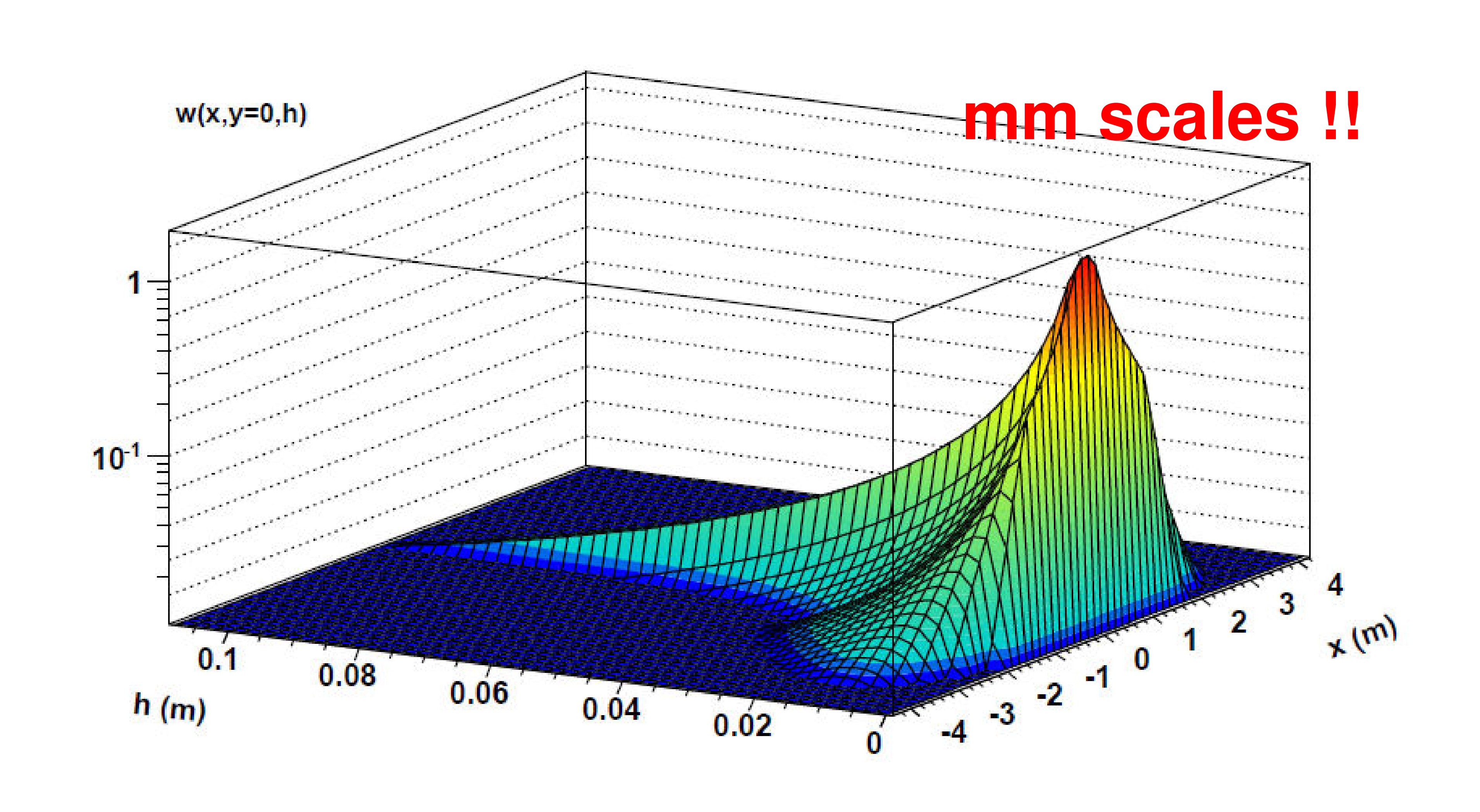
CX-MC-GEO+MCFIT:
The particle distributions in the shower front



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EVA - Emission Mechanisms From Currents to radiation.

$$A^{\mu}(\vec{x},t) = \frac{J^{\mu}(t')}{|D(\vec{x},t)|}$$

$$D = R(1 - n\beta\cos(\theta))$$

$$= R\frac{dt}{dt'}$$

$$\vec{E}(\vec{x},t) =$$

$$-\frac{d}{dt}\vec{A}(\vec{x},t) - \frac{d}{d\vec{x}}A^{0}(\vec{x},t)$$

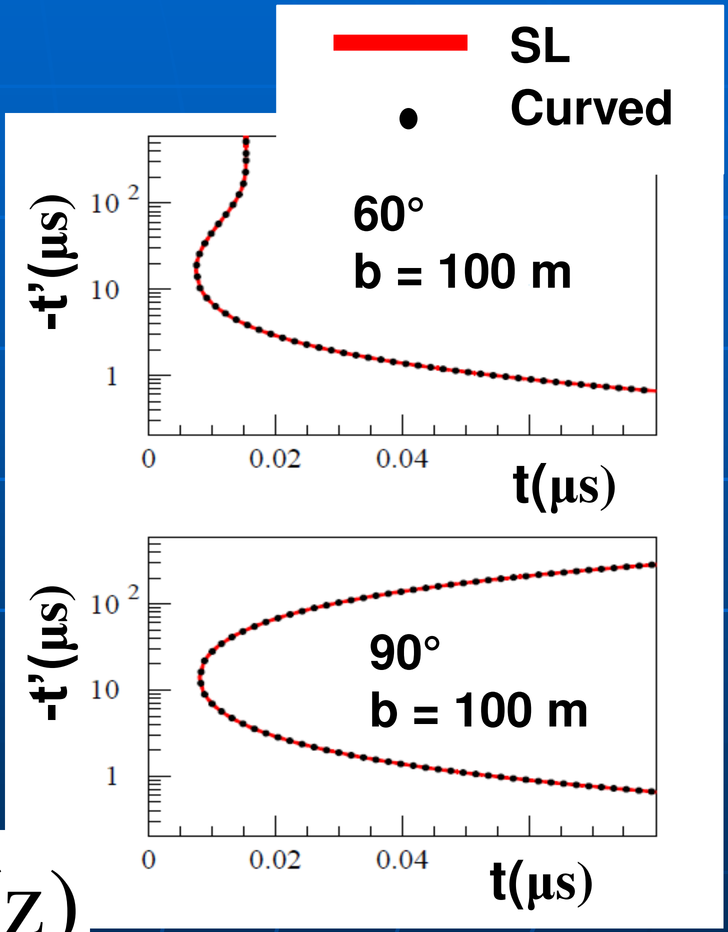
$$\vec{E}(\vec{x},t) \propto \frac{1}{D^2}$$

D can vanish for realistic cases, $n = n(z) \neq 1$ → Cherenkov !

EVA - The Atmosphere and index of refraction

- **The atmosphere** is given by the ***US standard atmosphere***.
- **Ray tracing** possible, shown to be ***not important***.
- **The refractivity** is given by the law of ***Gladstone And Dale:***

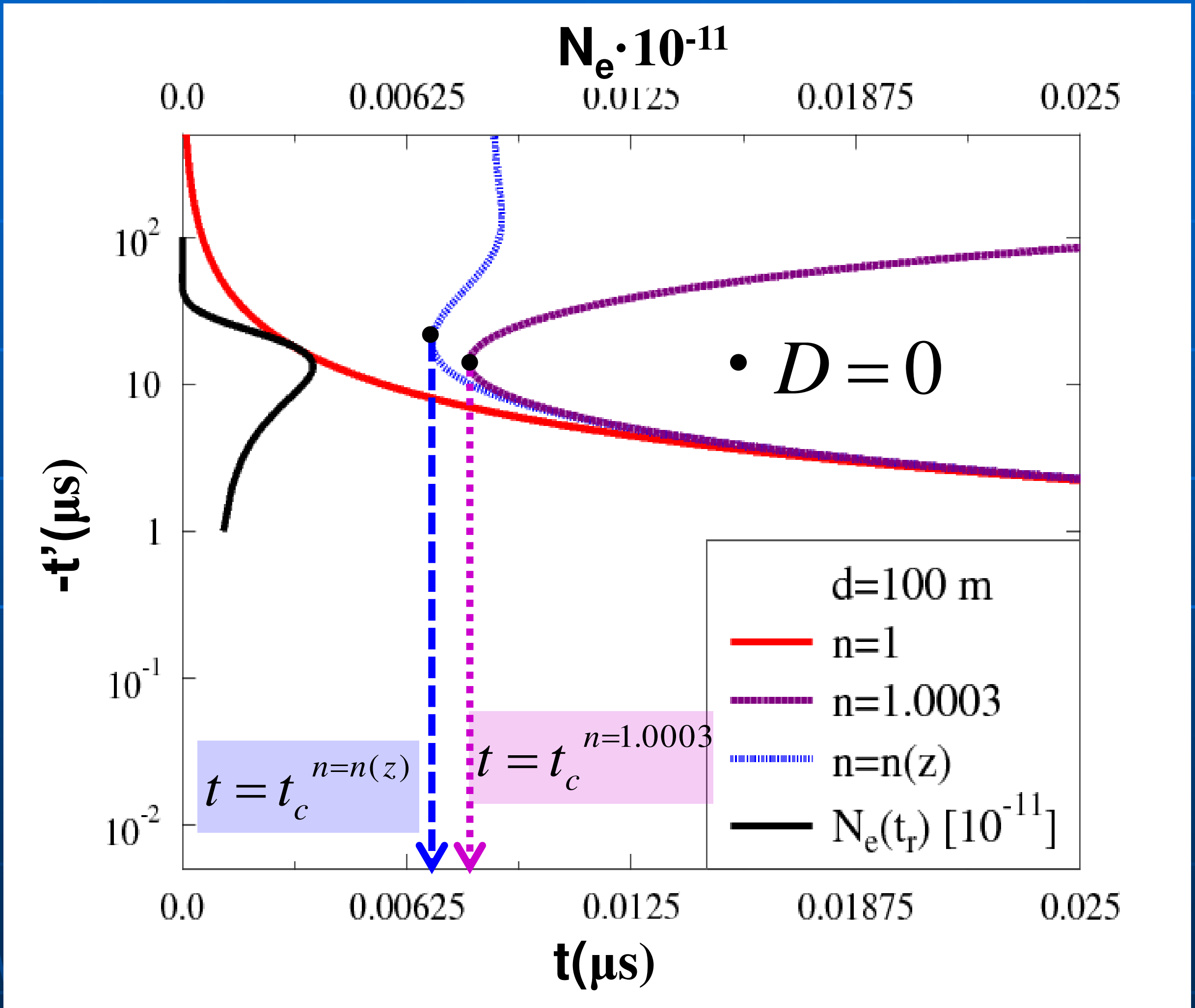
$$N(z) = n - 1 = 0.226\,\mathrm{cm}^3/\mathrm{g}\ \rho(\mathrm{z})$$



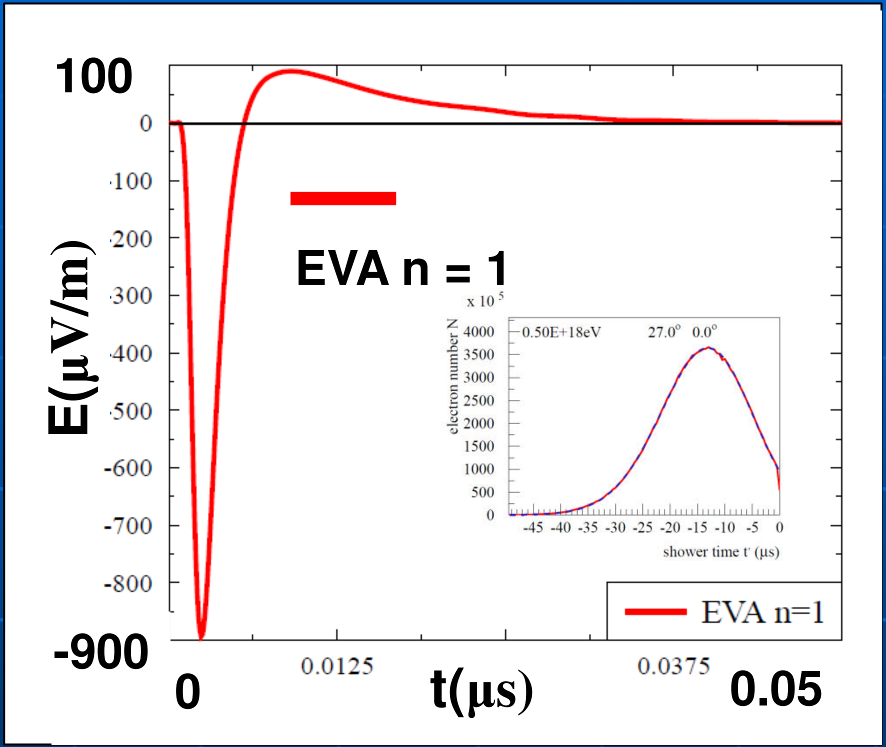
EVA - Retarded distance

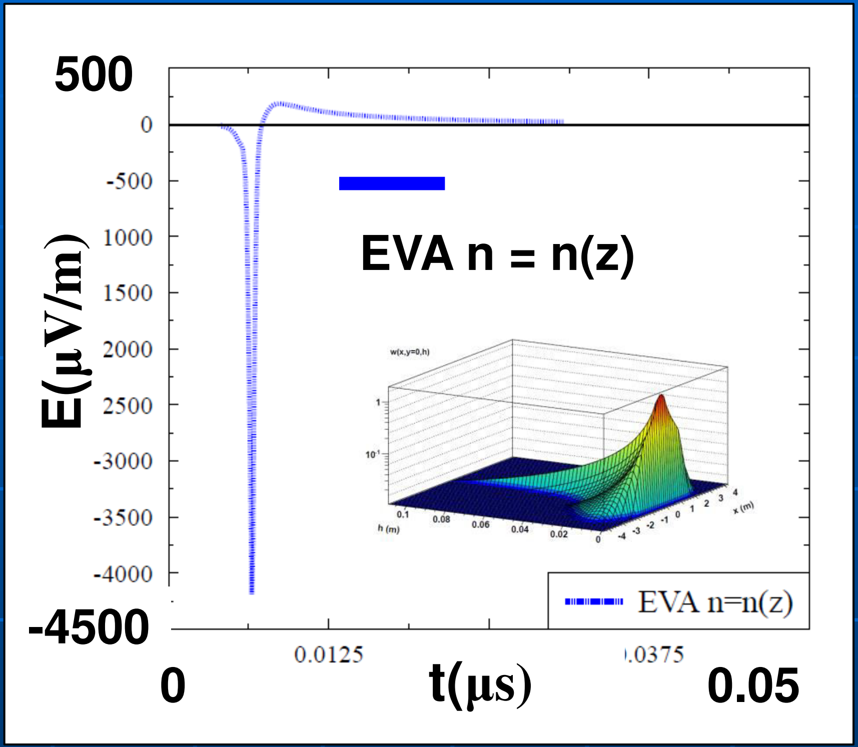
$$\frac{1}{D} = \frac{1}{R}\frac{dt'}{dt}$$

t': emission time
t: observer time



Electric field
100 meters

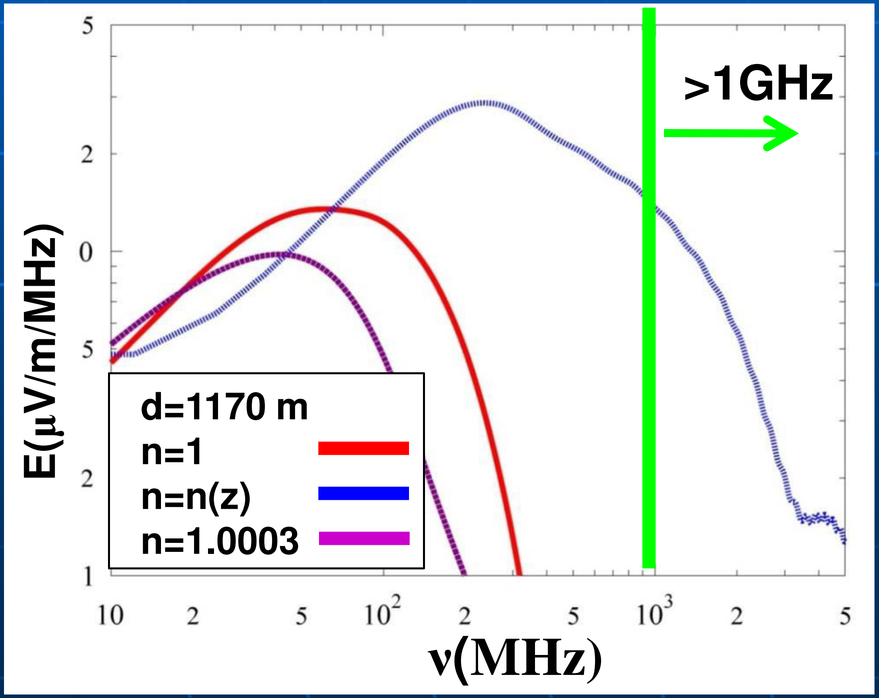




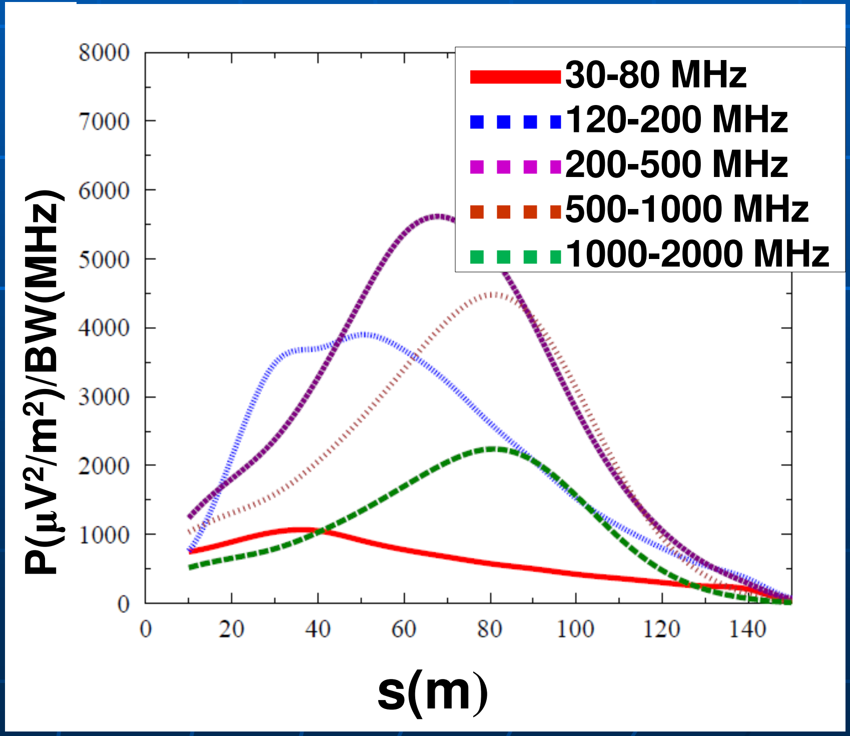
Macroscopic approach:
Finite results due to integration over charge cloud

Signatures of Cherenkov effects:

Emission at very high Frequencies O(GHz)

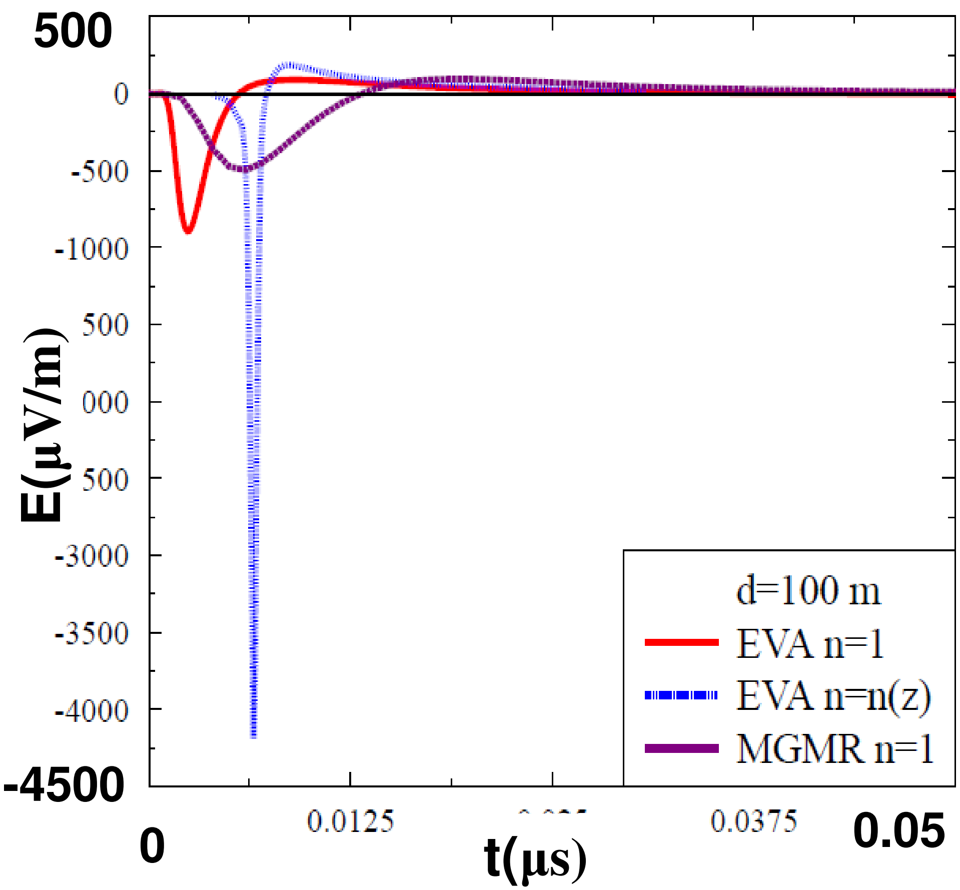


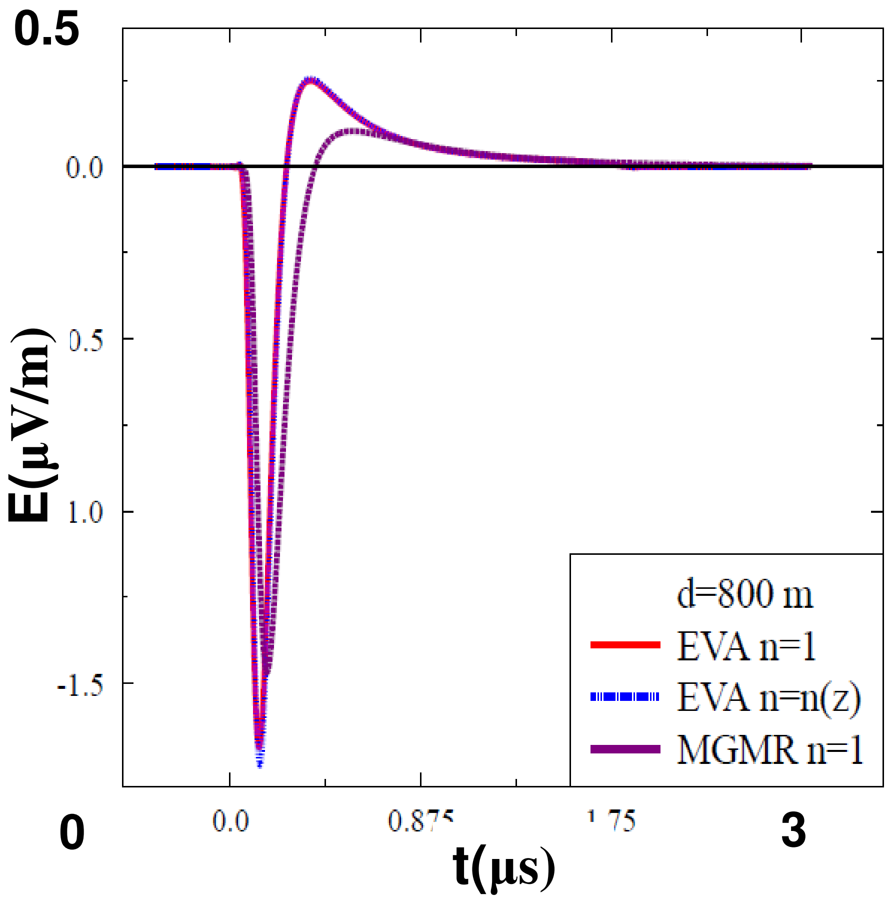
Clear structure in the Lateral Distribution Function



K.D. de Vries et al. Astropart.Phys.45:23-27,2013; arXiv:1304.1321

EVA vs MGMR





d=100 meters

d=800 meters

Recent work: Coherent Transition Radiation

$$\vec{E}(\vec{x},t) = \frac{ex^i}{4\pi\varepsilon_0 c}\lim_{\varepsilon\to 0}\left(\frac{1}{D^2{}_{z_B+\varepsilon}} - \frac{1}{D^2{}_{z_B-\varepsilon}}\right)\delta(z - z_B)$$

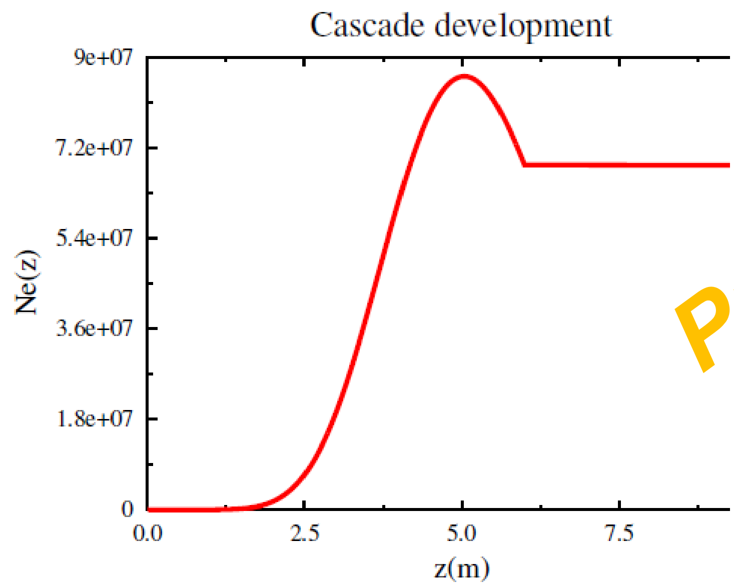
The delta-function can be resolved by considering coherent emission over a macroscopic particle distribution!!!

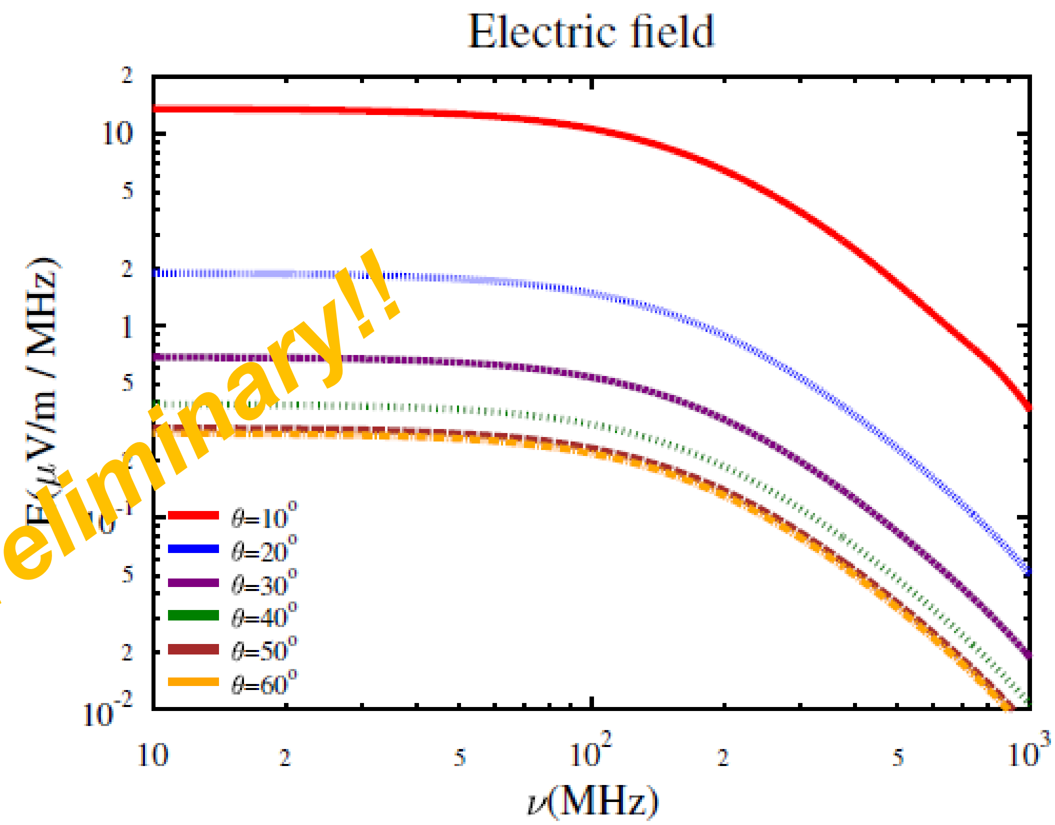
$$\vec{E}(\vec{x},t) = \frac{eN_e(t_r)f(h)x^i}{4\pi\varepsilon_0 c}\left(\frac{1}{D^2{}_{z_B+\varepsilon}} - \frac{1}{D^2{}_{z_B-\varepsilon}}\right)_{h=ct_r-z_B}$$

Coherent Transition Radiation from a Earth skimming neutrino induced particle cascade

$$E_p = 10^{17}\,\mathrm{eV}$$

$$d = 20\,\mathrm{km}$$





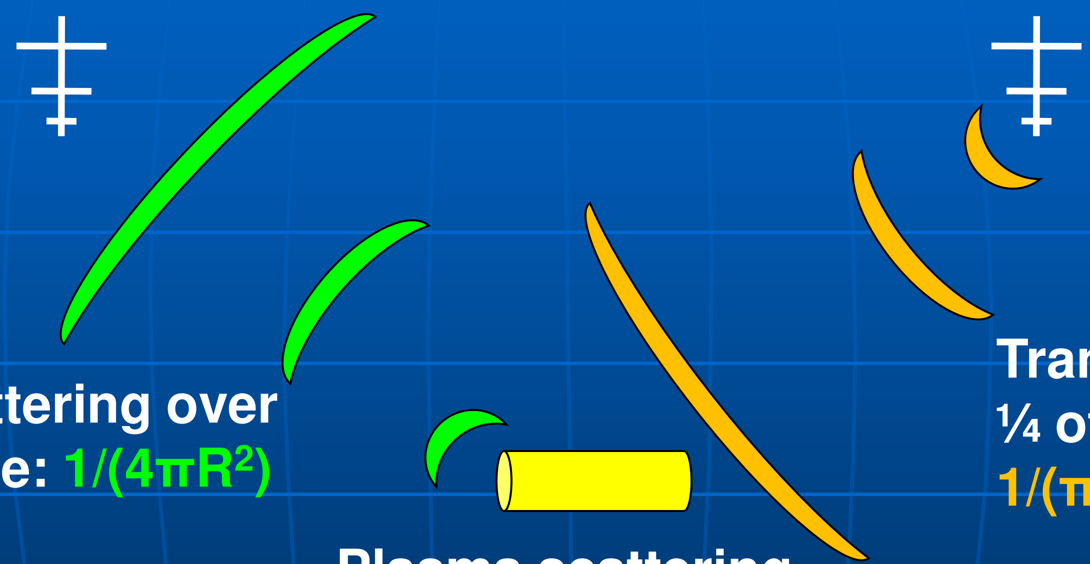
Recent work: RADAR detection of neutrino induced particle cascades in ice

K.D. de Vries, Kael Hanson, Thomas Meures, Aongus O’Murchadha

Bi-static RADAR configuration

Effective area of receiver: A_{eff}

Transmitted power: P_t



Re-scattering over a sphere: $1/(4\pi R^2)$

Transmission over ¼ of a sphere: $1/(\pi R^2)$

Plasma scattering surface: σ_{eff}

Attenuation by the medium

$$P_r = P_t \eta \frac{\sigma_{eff}}{\pi R^2} \frac{A_{eff}}{4\pi R^2} e^{-4R/L_\alpha}$$

Astropart.Phys.60:25-31,2015; arXiv:1312.4331

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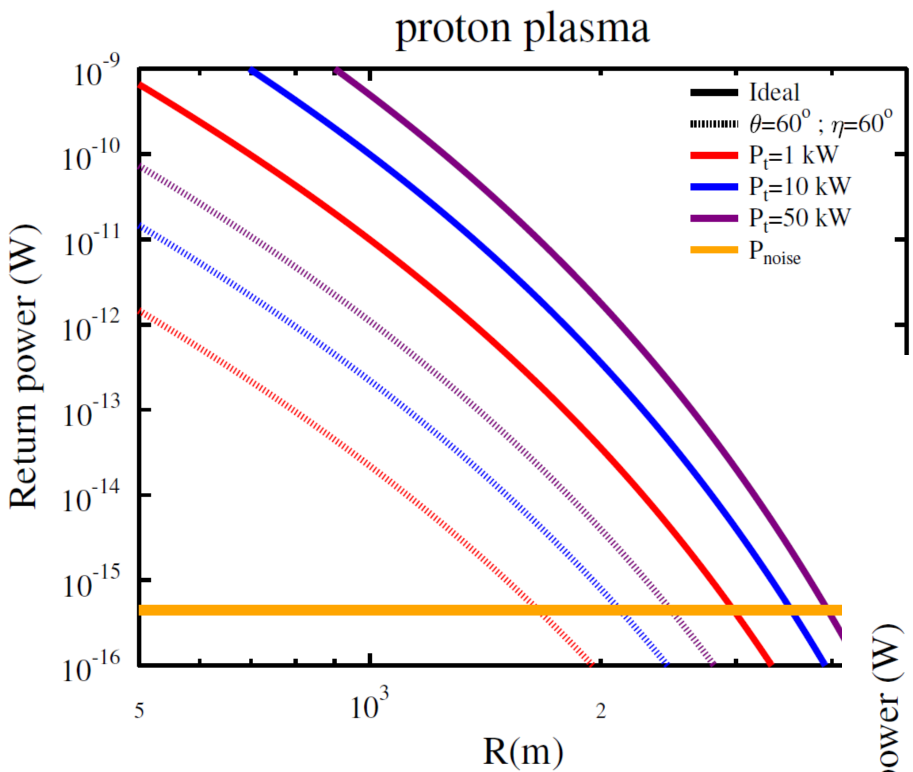
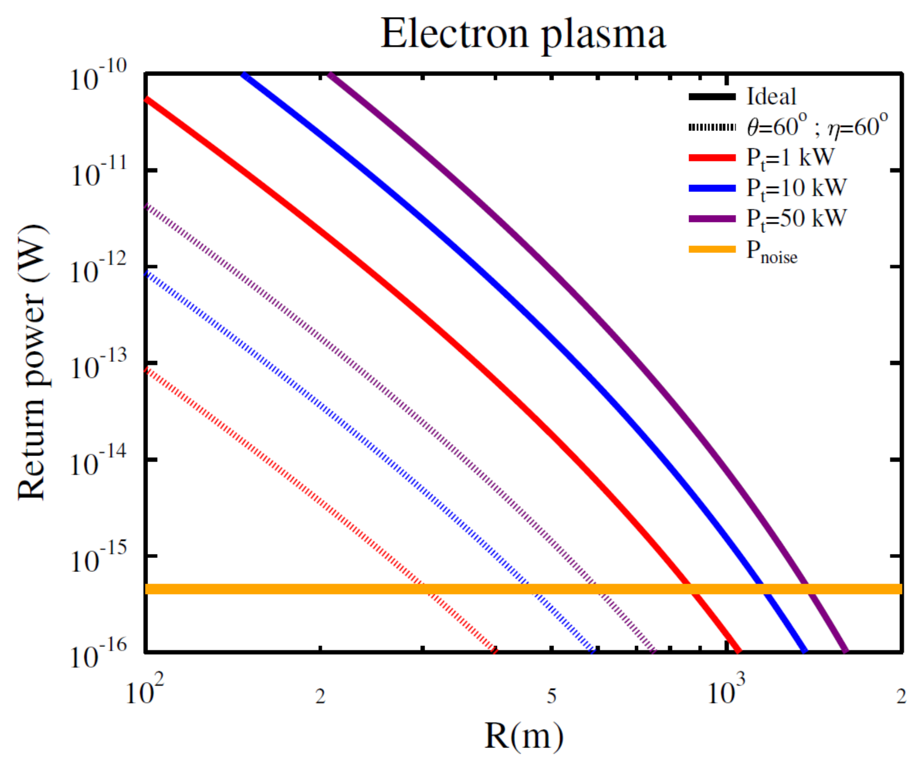


Energy threshold for detection of the over-dense electron plasma: E > 4 PeV



Energy threshold for detection of the over-dense proton plasma: E > 20 PeV

Conclusions

- ***The EVA package is developed:***

\- The code is based on ***Full Monte Carlo air shower simulations***

\- Cherenkov effects can be included due to ***finite extent of the current distributions (particles in the shower front)***

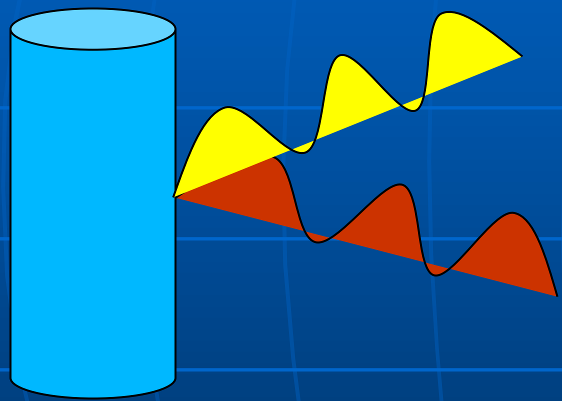
- ***Recent work:***

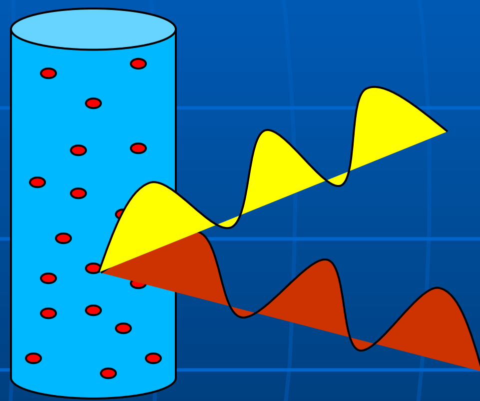
- Coherent transition radiation from particle cascades might be a ***very promising probe*** to detect ***Earth skimming neutrino induced cascades***.

- Modeling the ***RADAR detection*** of high-energy particles cascades shows: ***Low energy threshold ~few PeV. Large detection distance ~ kilometers.***

Scattering regions

- Over-dense scattering:
- Under-dense scattering:





Radar frequency < Plasma Frequency

Reflection from the surface of the plasma tube

Radar frequency > Plasma Frequency

Scattering of the individual charges in the plasma

Over-dense scattering

Two conditions have to be fulfilled:

1) Radar frequency has to be lower than the plasma frequency:

$$\upsilon_{Radar} < \upsilon_{Plasma}$$

2) Lifetime/size of the plasma cloud has to be large enough to make a full oscillation:

$$\upsilon_{Radar} > \begin{cases} 1/\tau_{Plasma} & c_{med}\tau_{\mathrm{e}} < l_c \\ c_{med}/l_c & c_{med}\tau_{\mathrm{e}} > l_c \end{cases}$$

3) Combining these conditions gives:

$$\upsilon_{Plasma} > \begin{cases} 1/\tau_{Plasma} & c_{med}\tau_{\mathrm{e}} < l_c \\ c_{med}/l_c & c_{med}\tau_{\mathrm{e}} > l_c \end{cases}$$

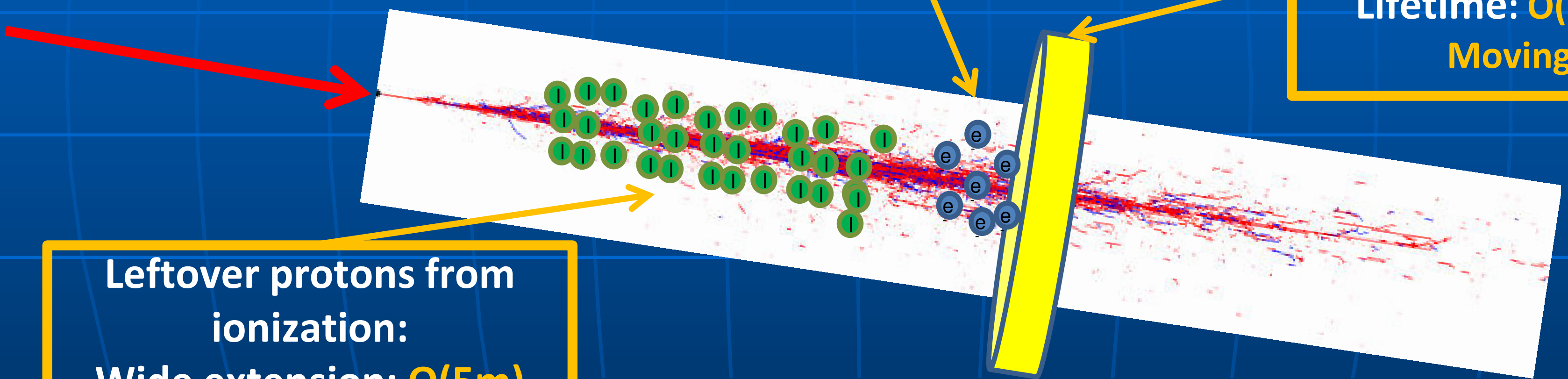
$$\upsilon_{Plasma} \propto \sqrt{n_{Plasma}} \propto \sqrt{E_{primary}}$$

Charge density inside the plasma

Three different types of plasma are considered

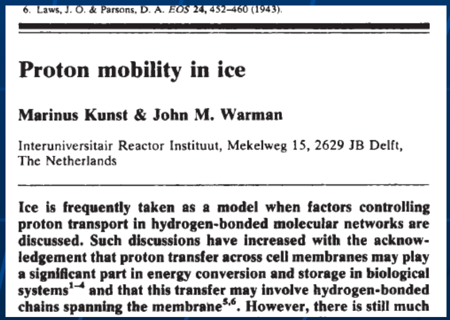
Leftover electrons from ionization:
Extension: O(30 cm)
Lifetime: O(1 ns)

Shower front electrons:
Extension: R_L = O(10 cm)
Lifetime: O(100ns)
Moving!



Leftover protons from ionization:
Wide extension: O(5m)
Lifetime: O(10-100 ns)

Ionization numbers come from Physical Chemistry research!



6. Laws, J. O. & Parsons, D. A. *EOS* **24,** 452–460 (1943).

Proton mobility in ice

Marinus Kunst & John M. Warman

Interuniversitair Reactor Instituut, Mekelweg 15, 2629 JB Delft, The Netherlands

Ice is frequently taken as a model when factors controlling proton transport in hydrogen-bonded molecular networks are discussed. Such discussions have increased with the acknowledgement that proton transfer across cell membranes may play a significant part in energy conversion and storage in biological systems[1–4] and that this transfer may involve hydrogen-bonded chains spanning the membrane[5,6]. However, there is still much

Figure from arXiv:1210.5140v2

Detecting the over-dense plasma

$$\upsilon_e^{Plasma} = 8980\sqrt{n_e}$$

$$\upsilon_p^{Plasma} = \sqrt{\frac{m_e}{m_p}}\upsilon_e^{Plasma}$$

Lower limit!!

$$\tau_e = 1\,\mathrm{ns}$$

$$\tau_p = 10 - 1000\,\mathrm{ns}$$

$$l_c \approx 5\,\mathrm{m}$$

Electron ionization plasma:

$$\upsilon_{Radar} > 1/\tau_{Plasma} > 1\,\mathrm{GHz}$$

$$\upsilon_{Plasma} > 1\,\mathrm{GHz} \Rightarrow \mathrm{E_p} > 4\,\mathrm{PeV}$$

Proton ionization plasma:

$$\upsilon_{Radar} > c_{med} / l_c > 36\,\mathrm{MHz}$$

$$\upsilon_{Plasma} > 36\,\mathrm{MHz} \Rightarrow \mathrm{E_p} > 20\,\mathrm{PeV}$$

RADAR return power estimation (single antenna)

$$P_r = P_t \eta \frac{\sigma_{eff}(\lambda)}{\pi R^2} \frac{A_{eff}(\lambda)}{4\pi R^2} e^{-4R/L_\alpha}$$

$\lambda = 0.18\,\mathrm{m}$

$\sigma_{eff}^{\max} = 0.11\,\mathrm{m}^2$

$\sigma_{eff}(\theta = 60^0, \phi = 60^0) = 1.6 \cdot 10^{-4}\,\mathrm{m}^2$

$L_\alpha = 1\,\mathrm{km}$

$\mathrm{P}_{\mathrm{noise}} = k_b T_{sys} \Delta \nu$

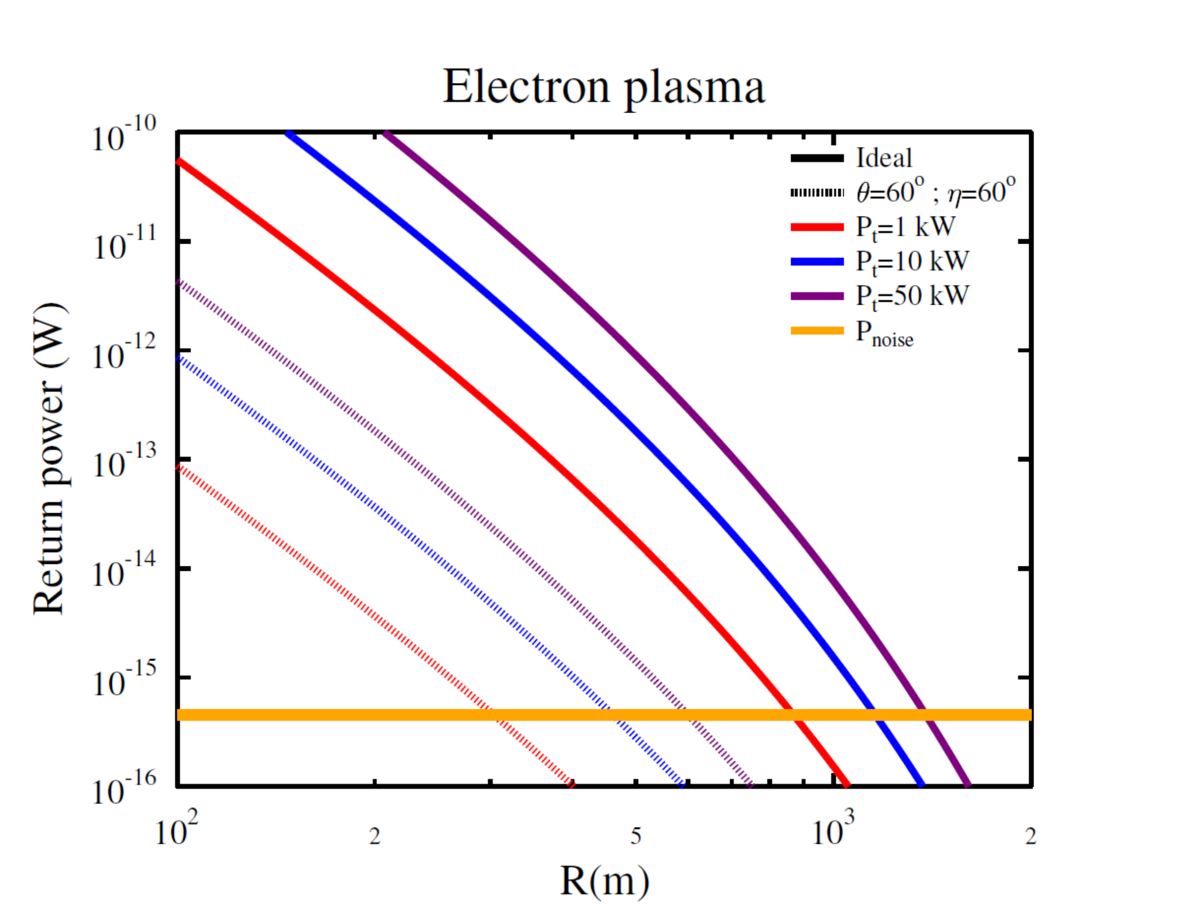
$T_{sys} = 325\,\mathrm{K}$

$\Delta \nu = 100\,\mathrm{kHz}$

N antennas :

$\mathrm{P}_{Noise}(N) = N \cdot P(N=1)$

$\mathrm{P}_{Signal}(N) = N^2 \cdot P(N=1)$



RADAR return power estimation (single antenna)

$$P_r = P_t \eta \frac{\sigma_{eff}(\lambda)}{\pi R^2} \frac{A_{eff}(\lambda)}{4\pi R^2} e^{-4R/L_\alpha}$$

$\lambda = 3.6\,\mathrm{m}$

$\sigma_{eff}^{\max} = 5.5\,\mathrm{m}^2$

$\sigma_{eff}(\theta = 60^0, \phi = 60^0) = 1.2 \cdot 10^{-2}\,\mathrm{m}^2$

$L_\alpha = 1.4\,\mathrm{km}$

$\mathrm{P}_{\mathrm{noise}} = k_b T_{sys} \Delta\nu$

$T_{sys} = 325\,\mathrm{K}$

$\Delta\nu = 100\,\mathrm{kHz}$

N antennas :

$\mathrm{P}_{Noise}(N) = N \cdot P(N=1)$

$\mathrm{P}_{Signal}(N) = N^2 \cdot P(N=1)$