# Modelling the production of terrestrial gamma-ray flashes during the final leader step

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# Outline

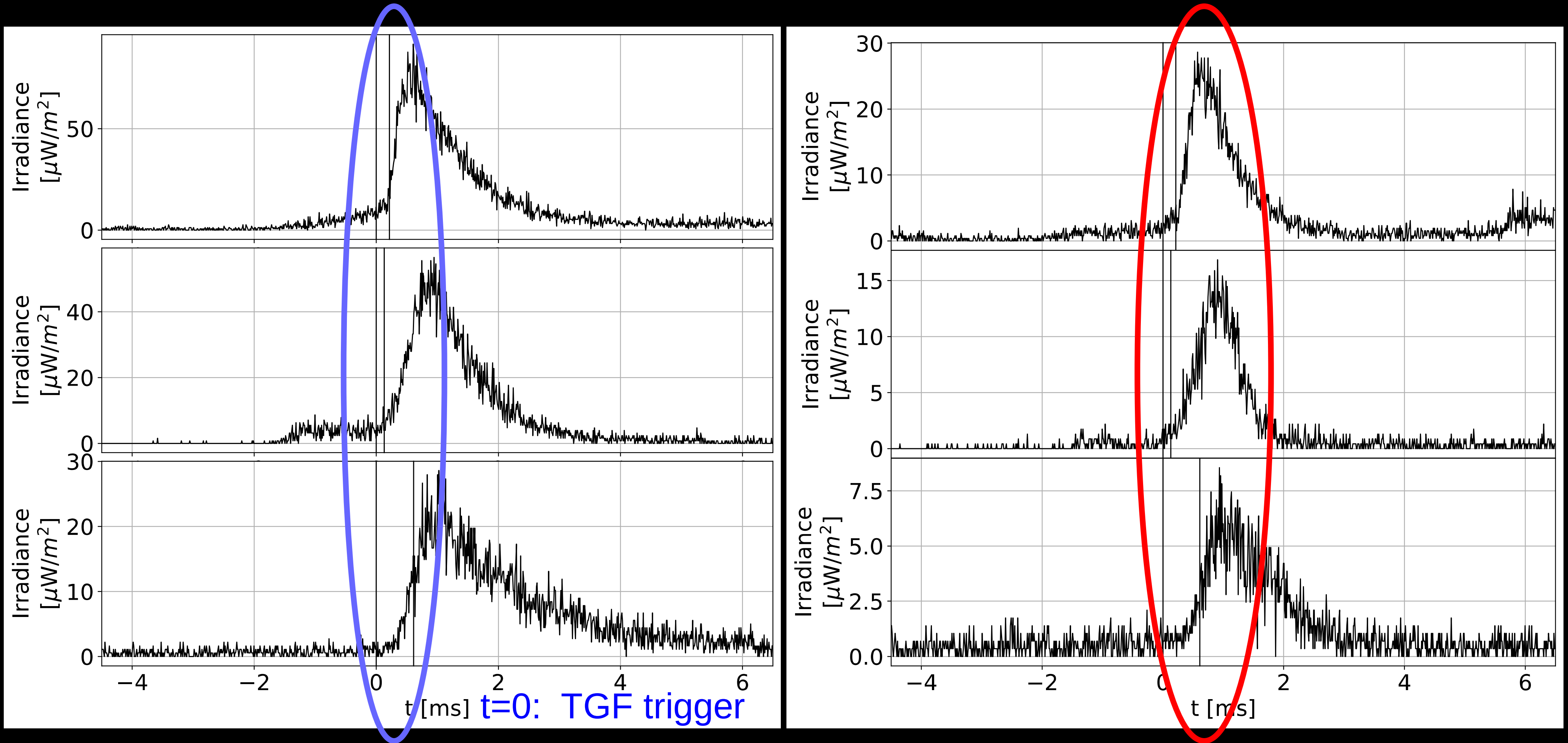
- TGFs, ASIM and ground based measurements
- Length scales in thundercloud
- Monte Carlo simulations
  - Electron motion in lightning leader field
  - Electron acceleration between two colliding streamer coronas
- Simulation results
  - Spatial and energy distribution of electrons and photons
- Parameter study
- Conclusions

# Introduction: ASIM and TGFs

**ASIM on ISS**

# Introduction: ASIM and TGFs

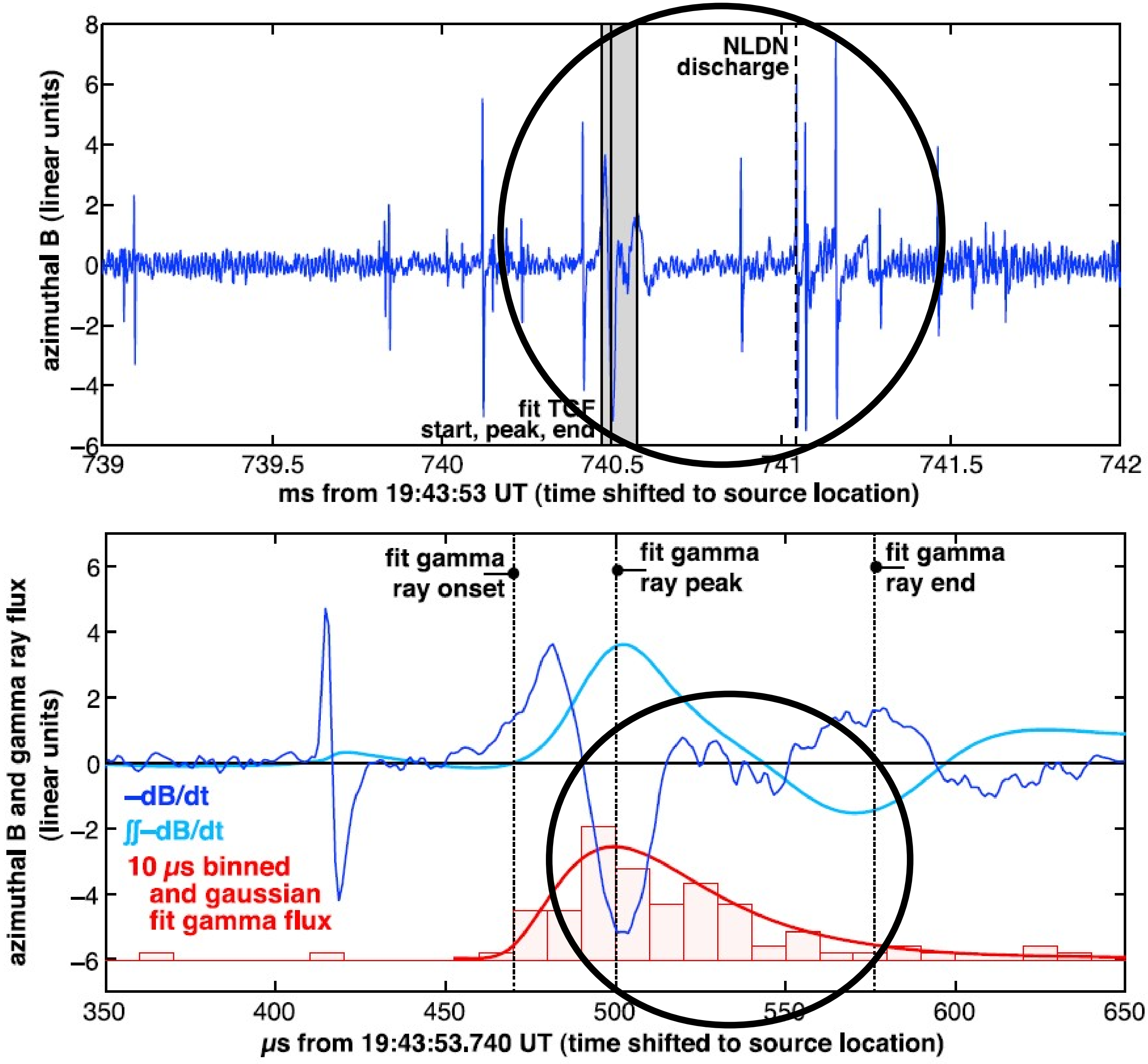
Photometer plots: i) 337 nm associated to streamer activity; ii) 777 nm associated to leader activity (more details on measurements: see presentation EGU2020-2467)




TGF occurs close to onset of streamer activity

Time difference between TGF occurrence and main optical pulse in the order of 100 µs

# Ground-based measurements



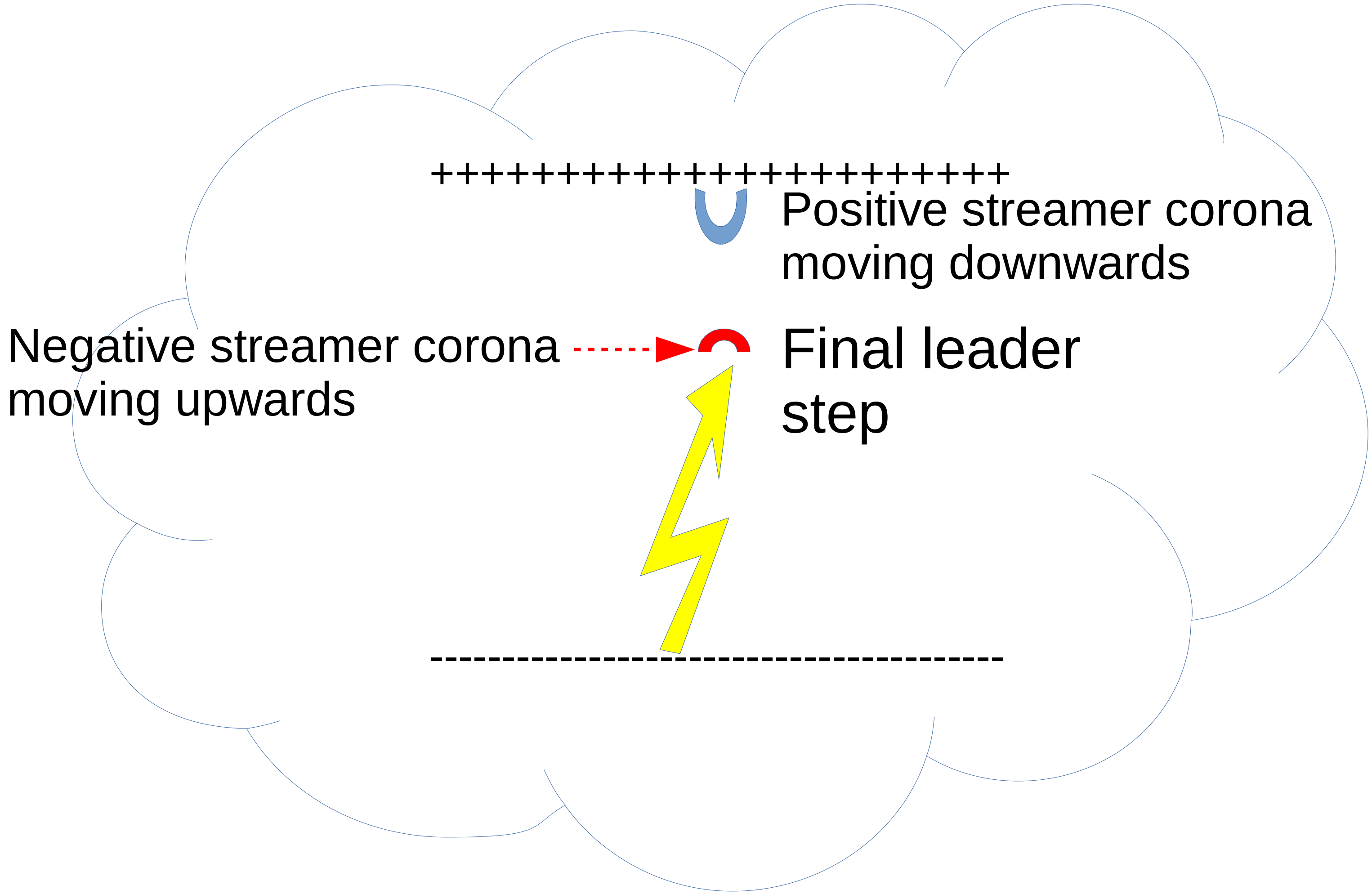

$t_{discharge}$-$t_{TGF}$ ≲500 μs

$\Delta t_{\gamma,onset}$ ≲100 μs

$\Delta t_{\gamma,fit}$ ≲60 μs


[S. Cummer et al., 2011. The lightning-TGF relationship on microsecond timescales. Geophys. Res. Lett., vol. 38, L14810]

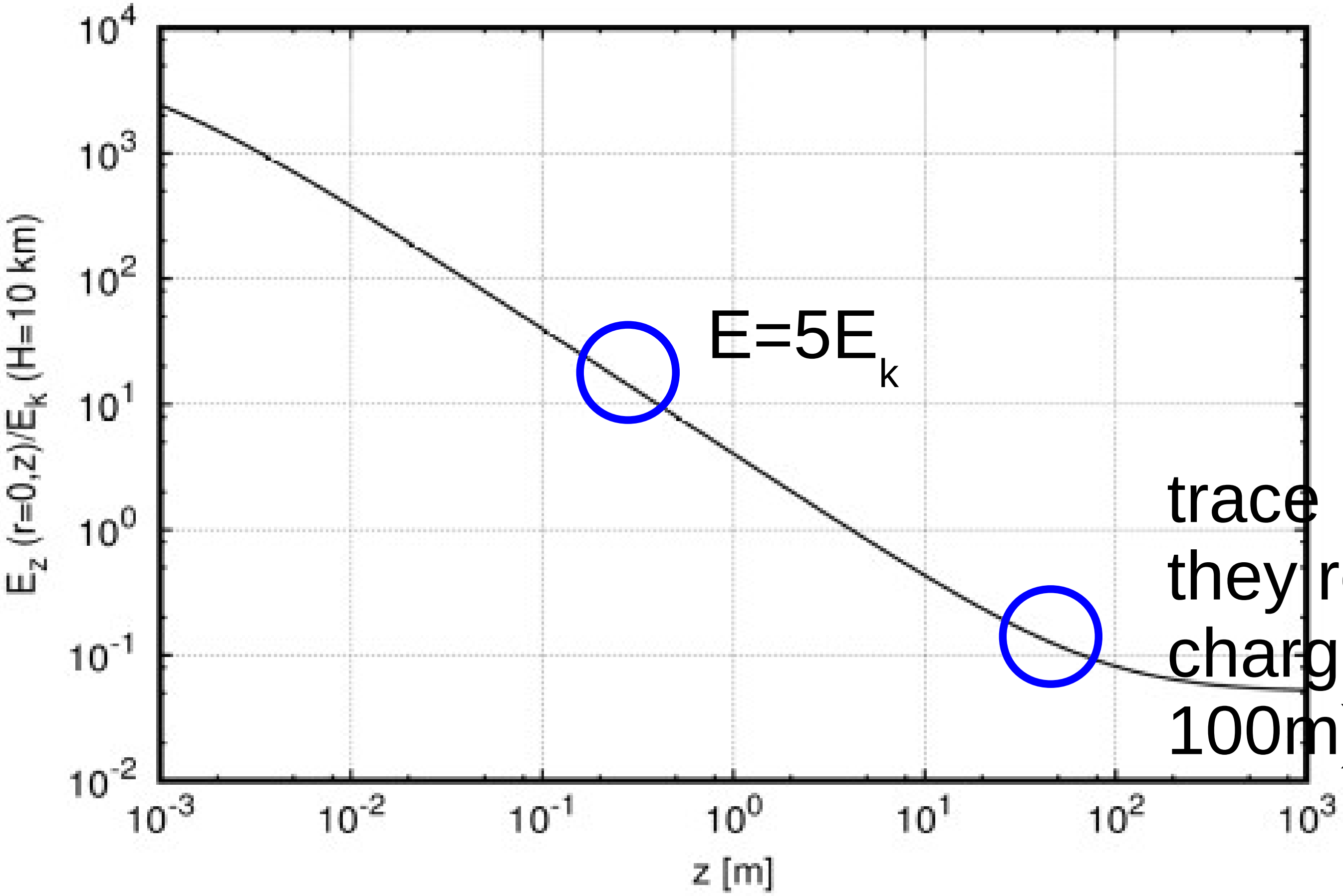
# Characteristic length scales




$\boxed{\Delta t \approx 100\ \mu s}$ => $v_{leader} \approx 10^6\ m\ s^{-1}$ => $L \approx$ 100 m

# Two step simulation

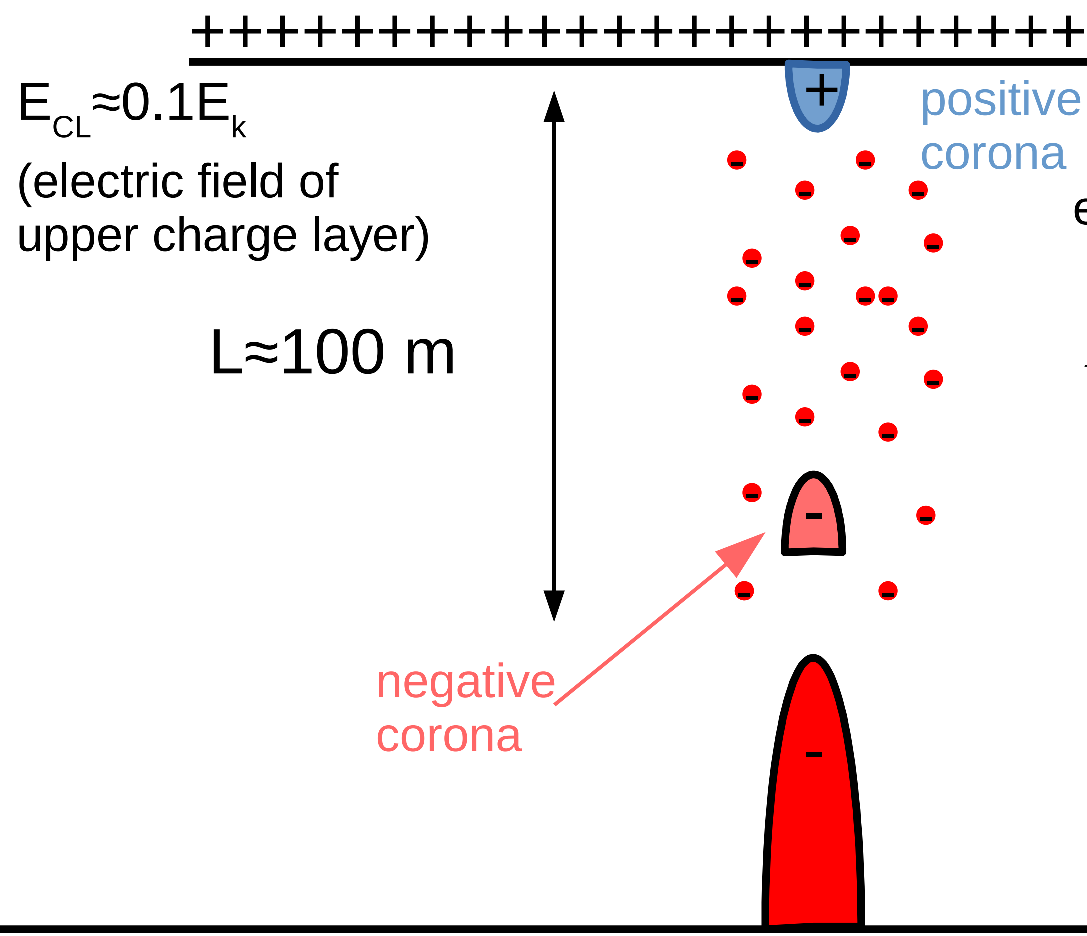
i) inject electrons at $5E_k$ => get spatial and energy distribution of low-energy electrons with MC particle code




trace electrons until they reach the upper charge layer (here at z= 100m)

# Two step simulation

## ii) turn on negative and positive streamer coronae



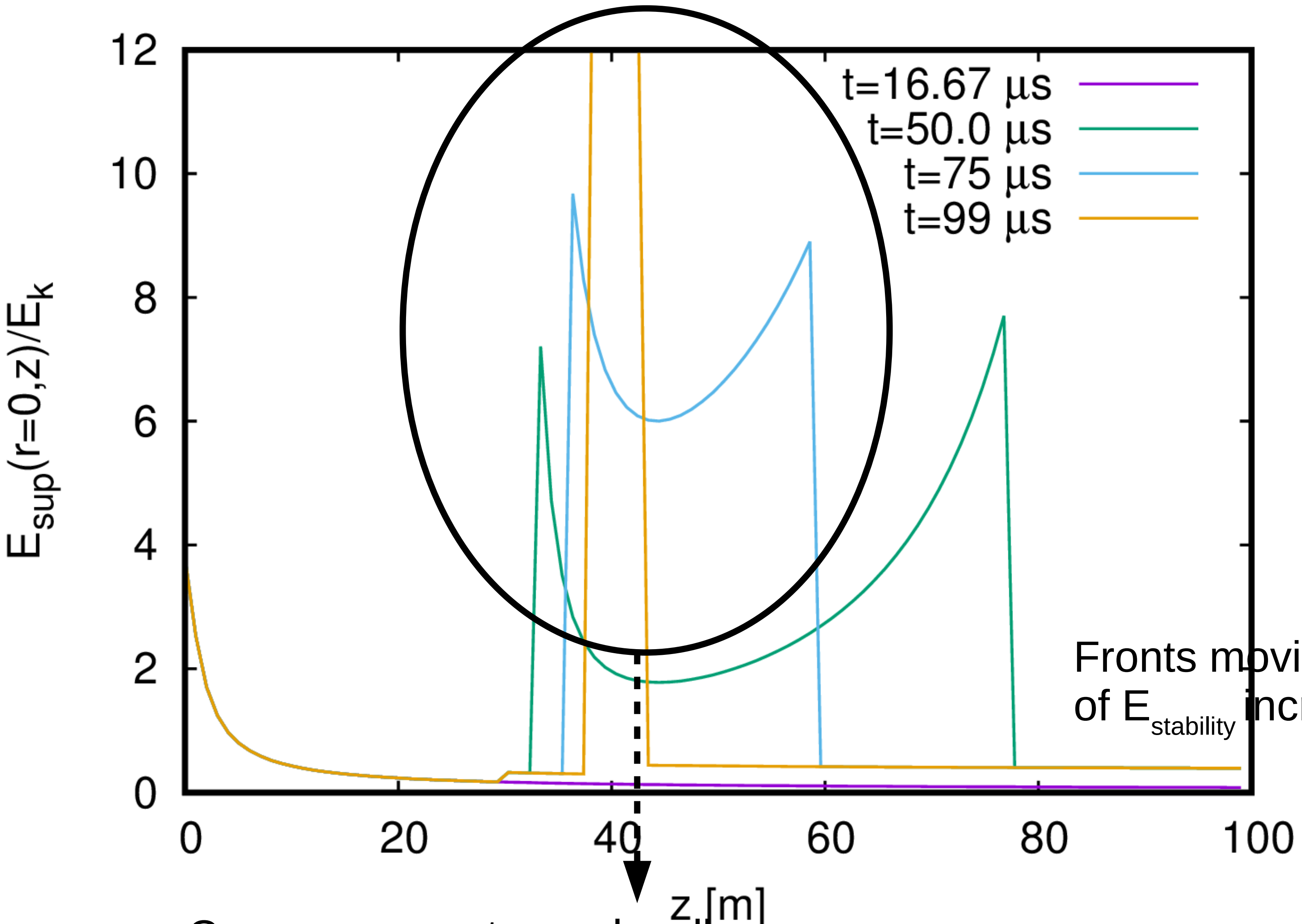

electric field of coronae:

$$E_{coro} \sim \begin{cases} E_0(t)\, 1/r^2, \text{ if outside} \\ E_{stability}, \text{ if inside} \end{cases}$$

(tip field $E_0(t)$ grows linearly in time)

[P. Kochkin, C. Köhn et al., 2016. Analyzing x-ray emissions from meter-scale negative discharges in ambient air. Plasma Sour. Sci. Technol., vol. 25, 044002]

# Evolution of on-axis electric field




Fronts moving => region of $E_{stability}$ increases

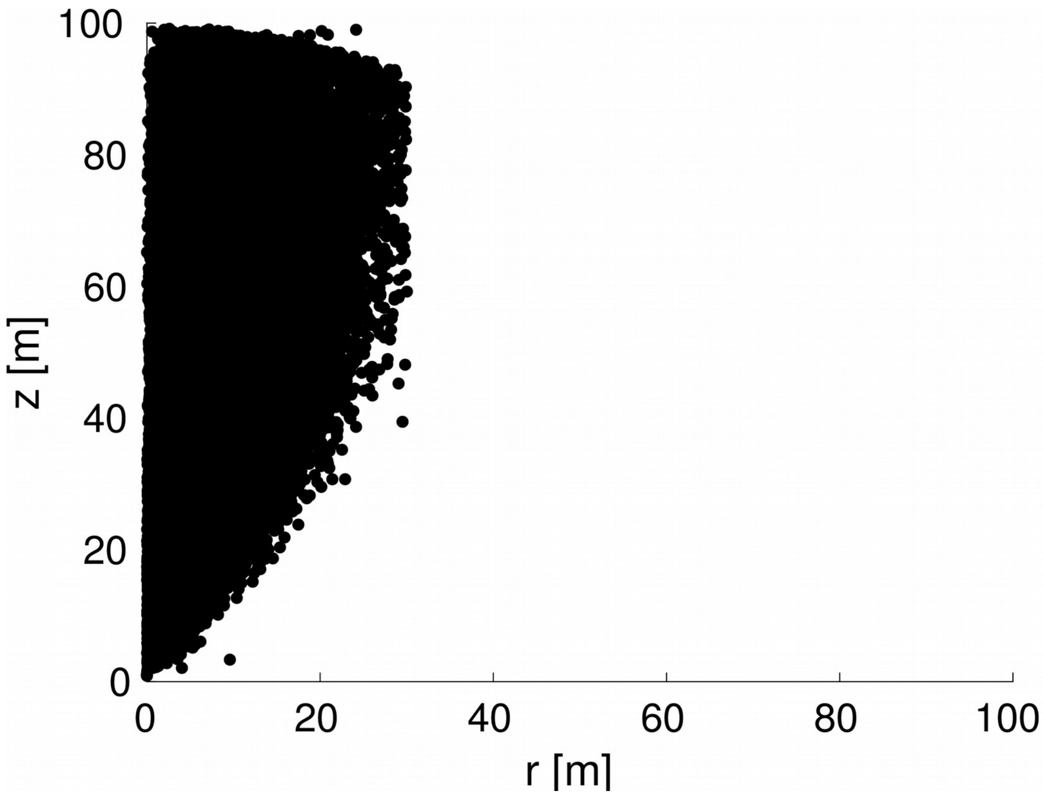
Corona encounter => locally highly enhanced electric field (above $10E_k$)


[V. Cooray et al., 2009. J. Atmos. Sol. Terr. Phys., vol. 71, pp. 1890–1898
M.A. Ihaddadene and S. Celestin, 2015. GRL, vol. 42, pp. 5644–5651
C. Köhn et al., 2017. GRL, vol. 44, pp. 2604–2613
A. Luque et al., 2017. JGR Atmos., vol. 122, pp. 10497–10509]

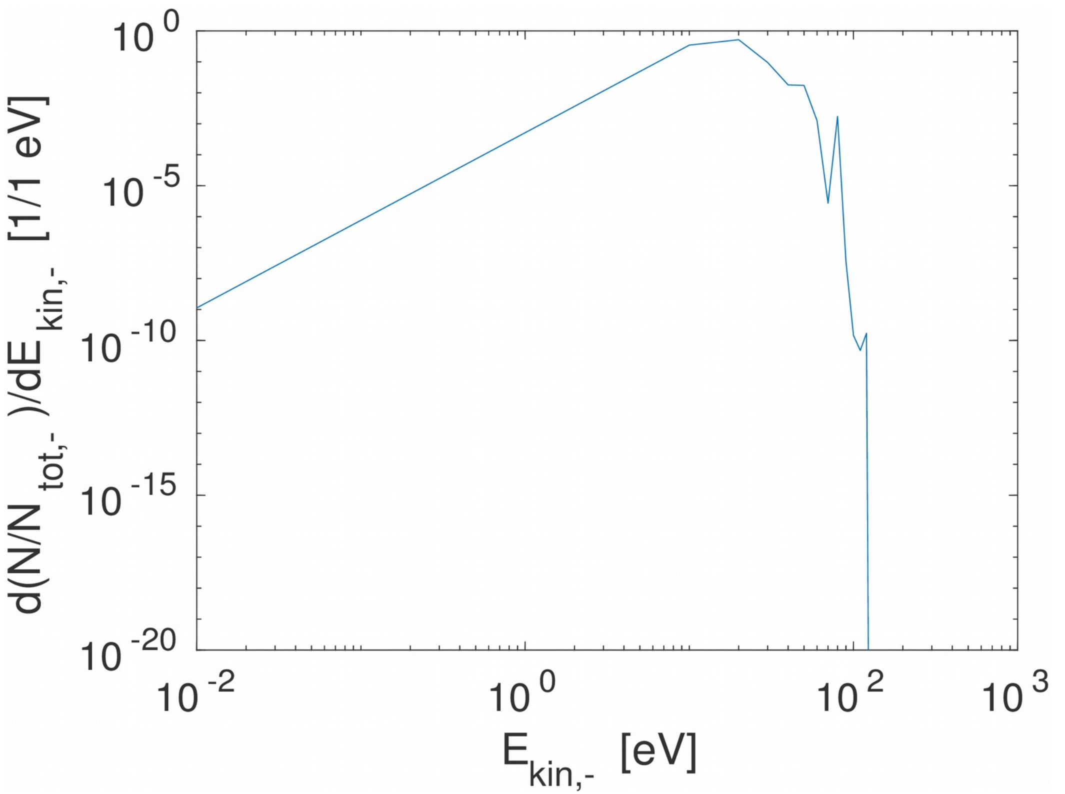
# Spatial and energy distribution of low-energy electrons after 16.7 µs

(before streamer inception)

spatial distribution




energy distribution




Electrons bridge the gap between the leader tip (z=0) and the upper charge layer (z=100)

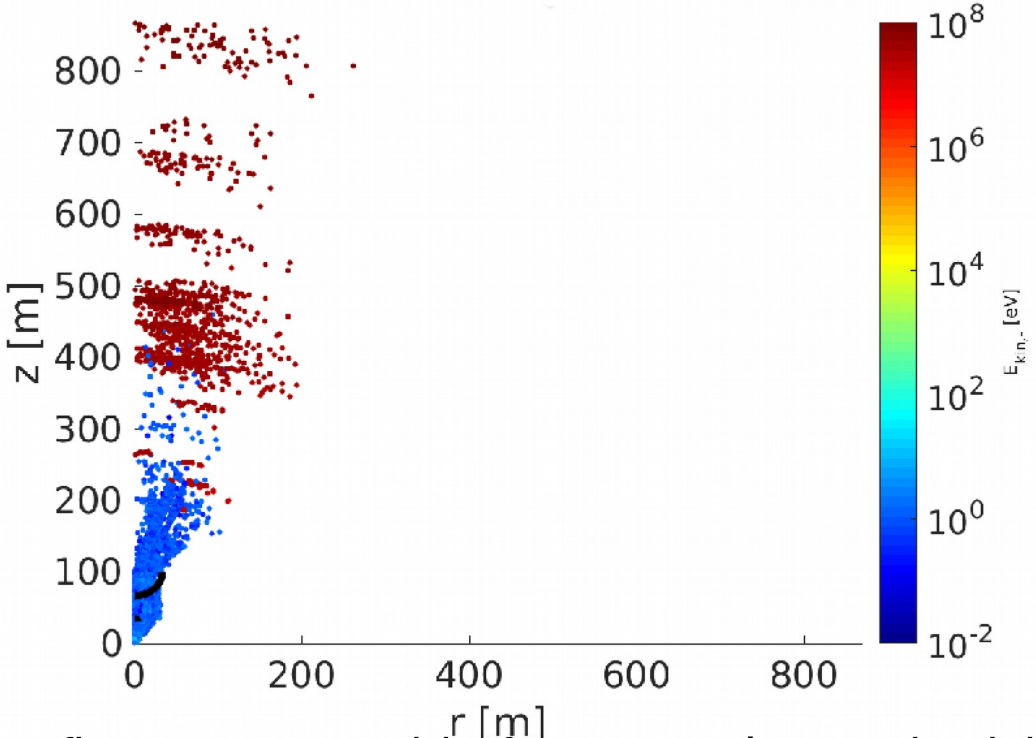
- maximum of energy distribution at ≈ 20 eV
- maximum energy ≈ 100 eV

**=> use these electrons as input for second MC simulation (with streamer coronae)**

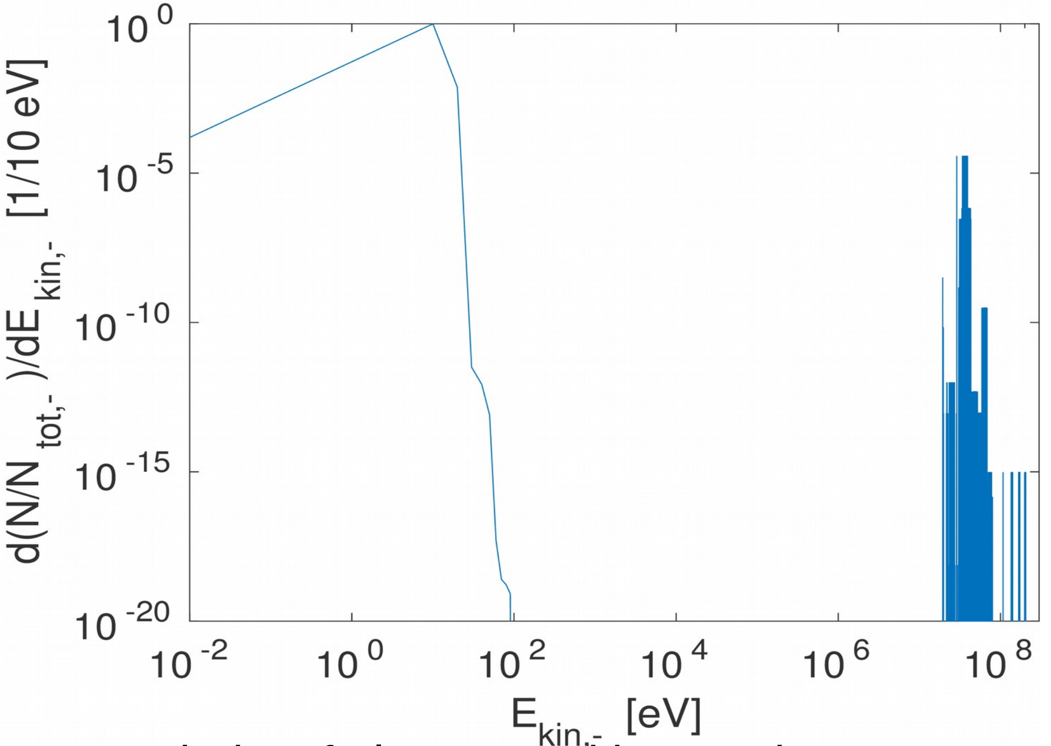
# Spatial and energy distribution of electrons after 65 µs

(after streamer inception)

spatial distribution




energy distribution



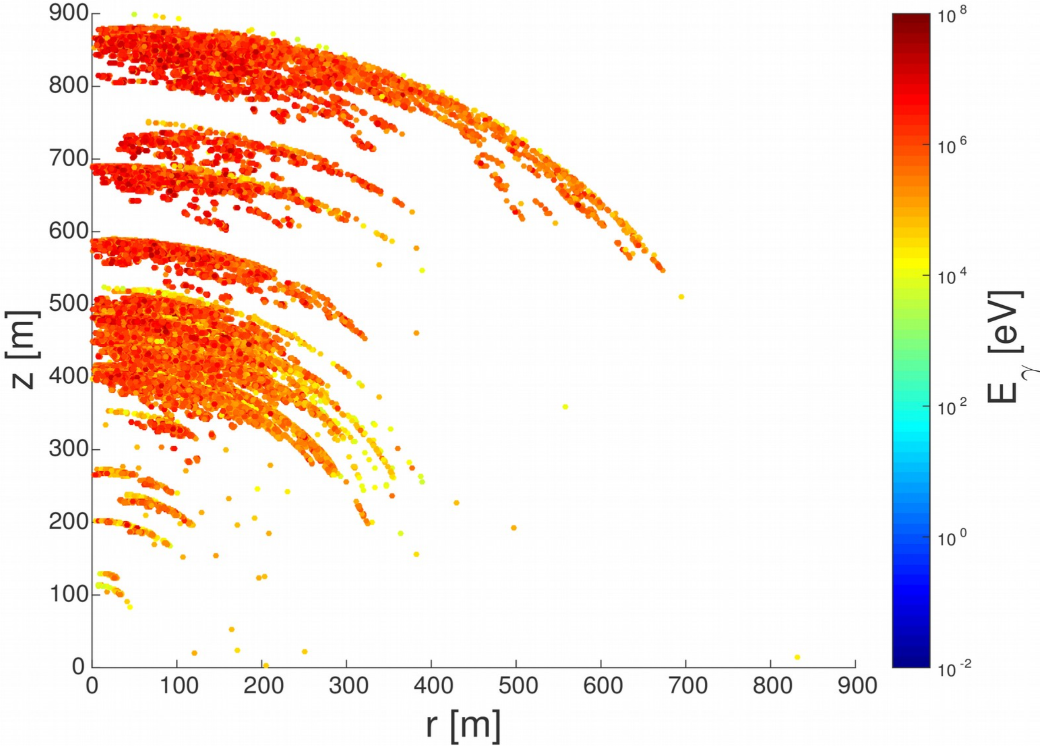

- first appearance(s) of runaway electron (and thus of relativistic beam) random (but probability increases with time/increasing electric field of coronae fronts) => wave-like pattern
- because of growing field, wave smears out (more frequent production of runaway electrons)

- majority of electrons with energies < 100 eV
- some very energetic electrons ($E_{max}$≈300 MeV)
- gap because randomly produced runaway electrons keep getting accelerated

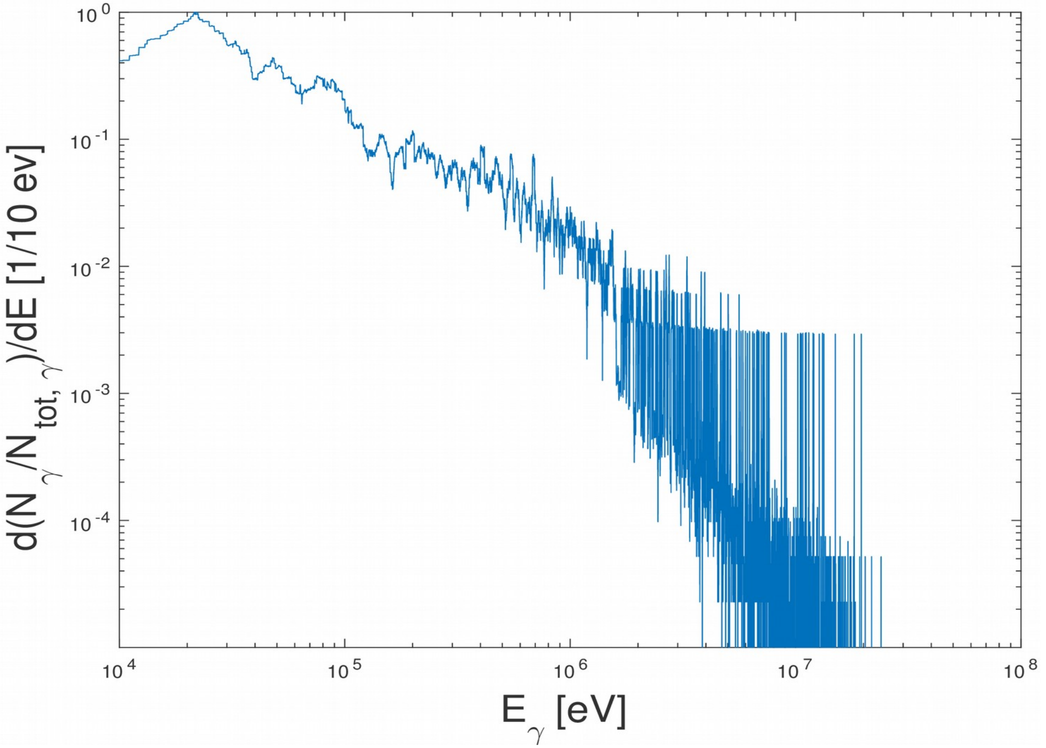
# Spatial and energy distribution of photons after 65 µs

(after streamer inception)

spatial distribution




energy distribution

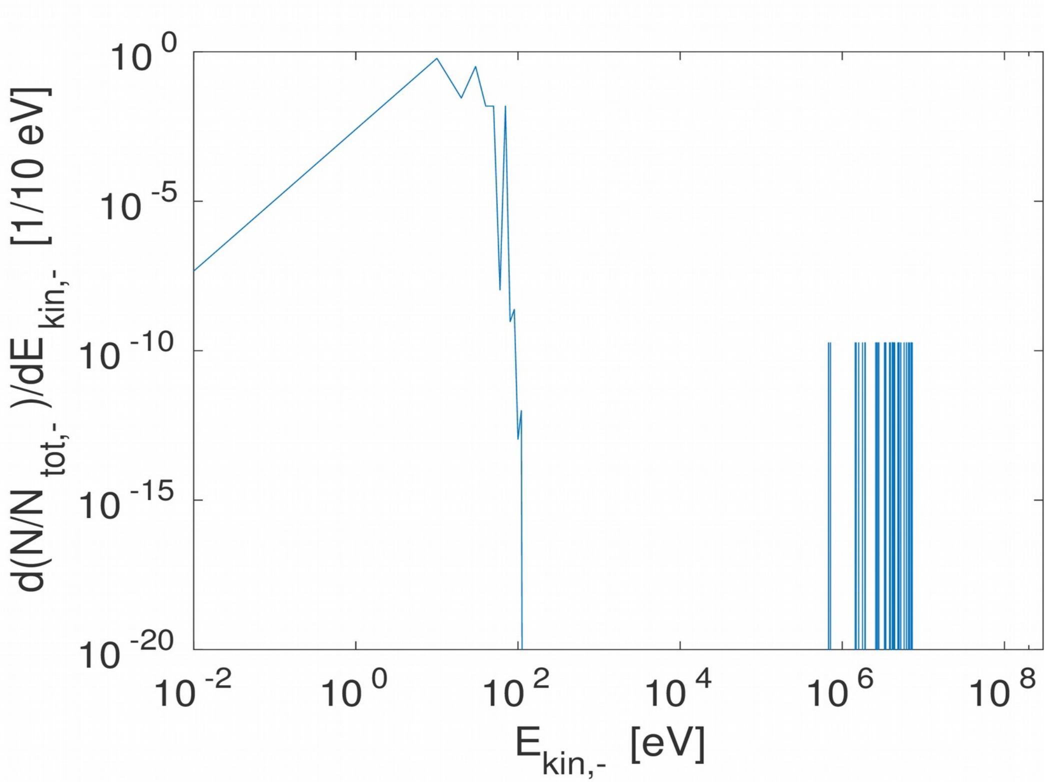



- photon beam follows energetic electrons
- continuous production through Bremsstrahlung => less wave-like pattern than for electrons (beam smeared out)

- maximum photon energy ≈ 40 MeV
- photon distribution can be fitted through $dN_\gamma/dE_\gamma \sim \exp(-E_\gamma/E_{\gamma,0})/E_\gamma$ with $E_{\gamma,0} \approx 5.5$ MeV

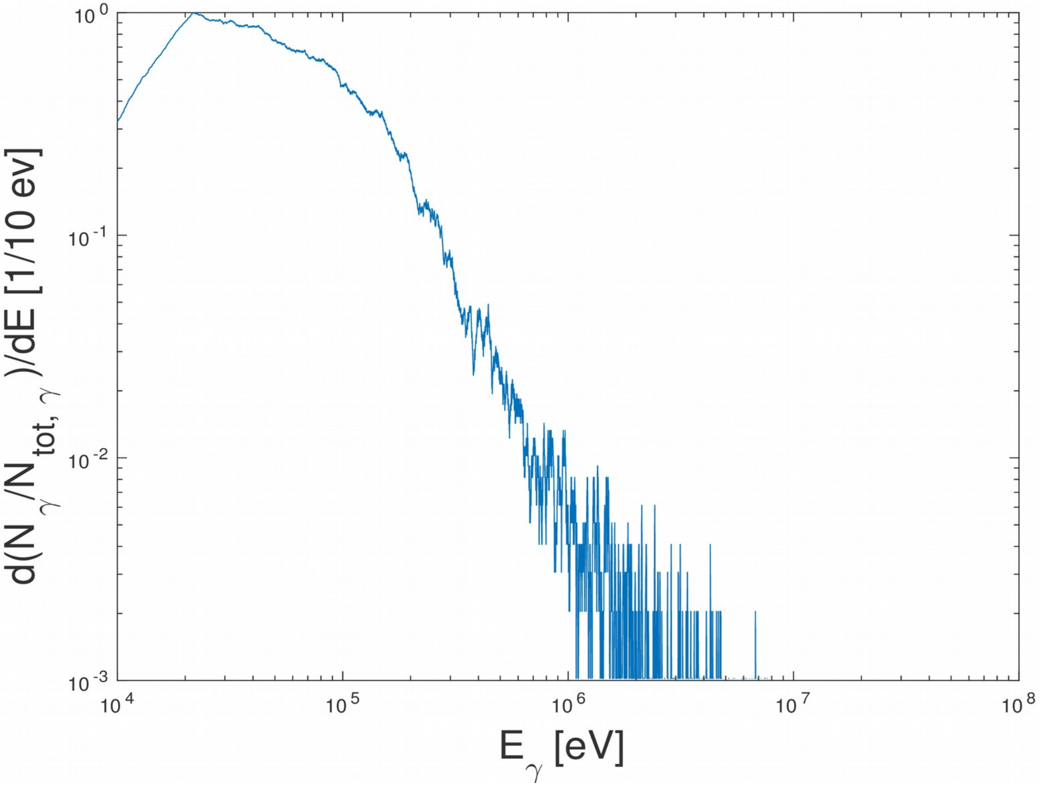
# Energy distribution of electrons and photons without charge layer field

electrons




- similar energy distribution as with charge layer field, but maximum energy ≈ 20 MeV (instead of 300 MeV)

photons




- maximum photon energy ≈ 20 MeV
- photon distribution can be fitted through $dN_{\gamma}/dE_{\gamma} \sim \exp(-E_{\gamma}/E_{\gamma,0})/E_{\gamma}$ with $E_{\gamma,0} \approx 3.2$ MeV

# Parameter study I

- Monte Carlo simulations are time consuming, thus not practical for parameter study
- To get an estimate on maximum electron energy and beam duration, solve set of 1D deterministic differential equations describing electron motion in a given electric field (including friction force) with initial conditions z($t_0$=50 µs)=$z_0$ and v($t_0$=50 µs)=$10^6$ m $s^{-1}$:

$$\frac{dz}{dt}=v$$

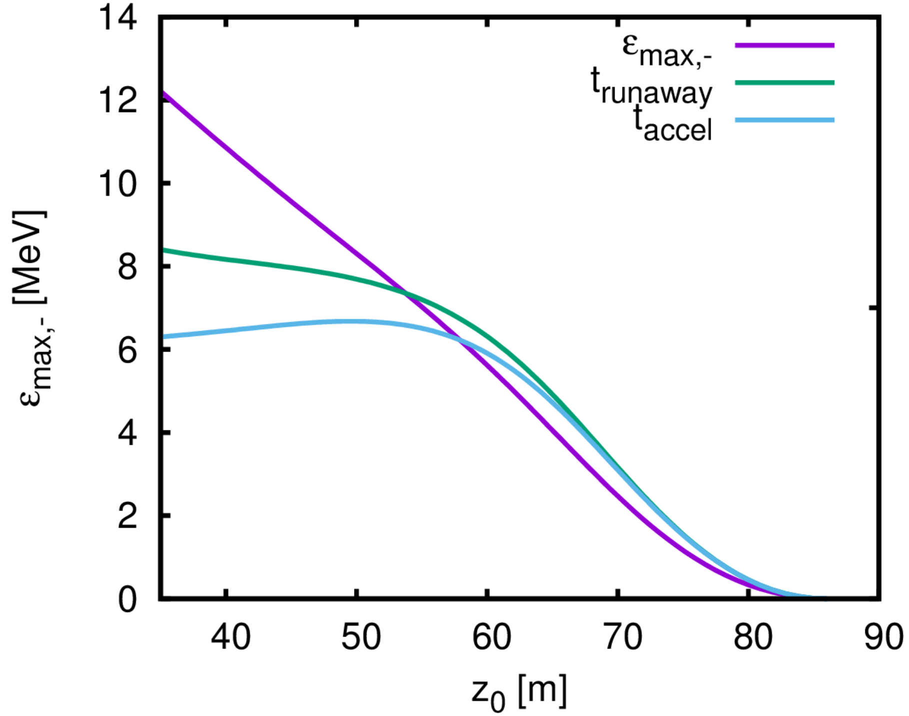
$$\frac{d}{dt}\left(\frac{m_e v}{\sqrt{1-\left(\frac{v}{c}\right)^2}}\right)=e_0\left(\underbrace{E_L(z)}_{\text{Field of lightning leader}}+\underbrace{E_{coro,+}(z,t)+E_{coro,-}(z,t)}_{\text{Electric field of positive and negative streamer corona}}\right)+\underbrace{F_R(v,t)}_{\text{Friction force}}$$

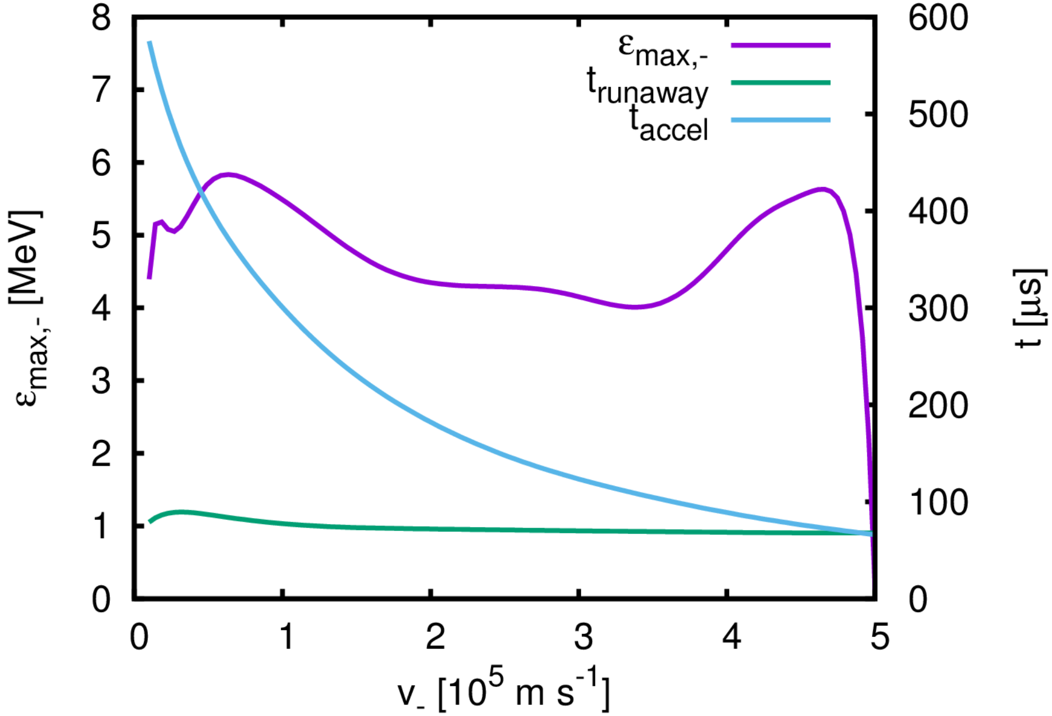
# Parameter study II

maximum electron energy (left y-axis), time $t_{runaway}$ when electron becomes runaway and acceleration duration $t_{accel}$ (right y-axis)

Initial conditions:

| | |
|---|---|
| max. front fields: $E_{max,-} = 8E_k$, $E_{max,+} = 10E_k$ | $E_{max,-} = 8E_k$, $E_{max,+} = 10E_k$ |
| Inception positions: $H_{0,+} = 100$ m, $H_{0,-} = 30$ m | $H_{0,+} = 100$ m, $H_{0,-} = 30$ m |
| front veloc.: $v_+ = 7\cdot10^5$ m s$^{-1}$, $v_- = 10^5$ m s$^{-1}$ | $v_+ = 7\cdot10^5$ m s$^{-1}$, $z_0 = 50$ m (initial $e^-$ position) |




- energies of approx. 10 MeV
- accel. duration of approx 50 µs
- no runaway electrons when $z_0$ too close to $H_{0+}$

- energies of approx. 5 MeV
- accel. duration of approx 50-500 µs
- no runaway electrons when $v_- > 5\cdot10^5$ m s$^{-1}$

# Conclusion

- Simulations confirm relation between production of TGFs and leader-streamer activity (as seen by ASIM)
- TGF duration at least tens of μs
- Maximum photon energy tens of MeV (and typical photon energy distribution)

  => good agreement with current and previous measurements
- Cloud charge layer field determines maximum electron/photon energy
- Parameter study: Need enough space between streamer coronae for electrons to become runaway (otherwise no TGFs)