Streamer discharges in the atmosphere of Primordial Earth

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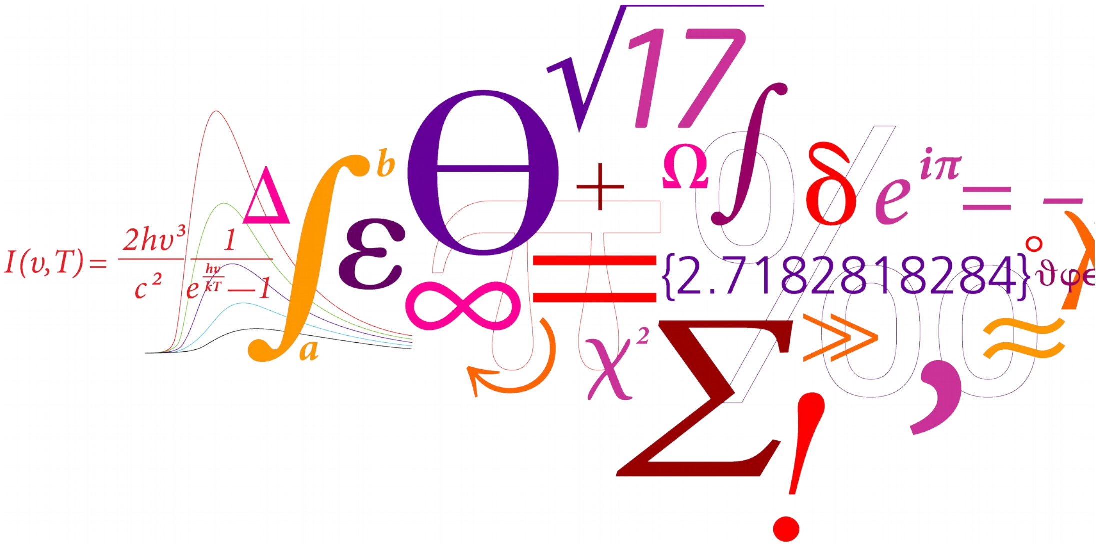

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- Photoionization vs. background ionization
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  - Front velocities
  - Electron energies
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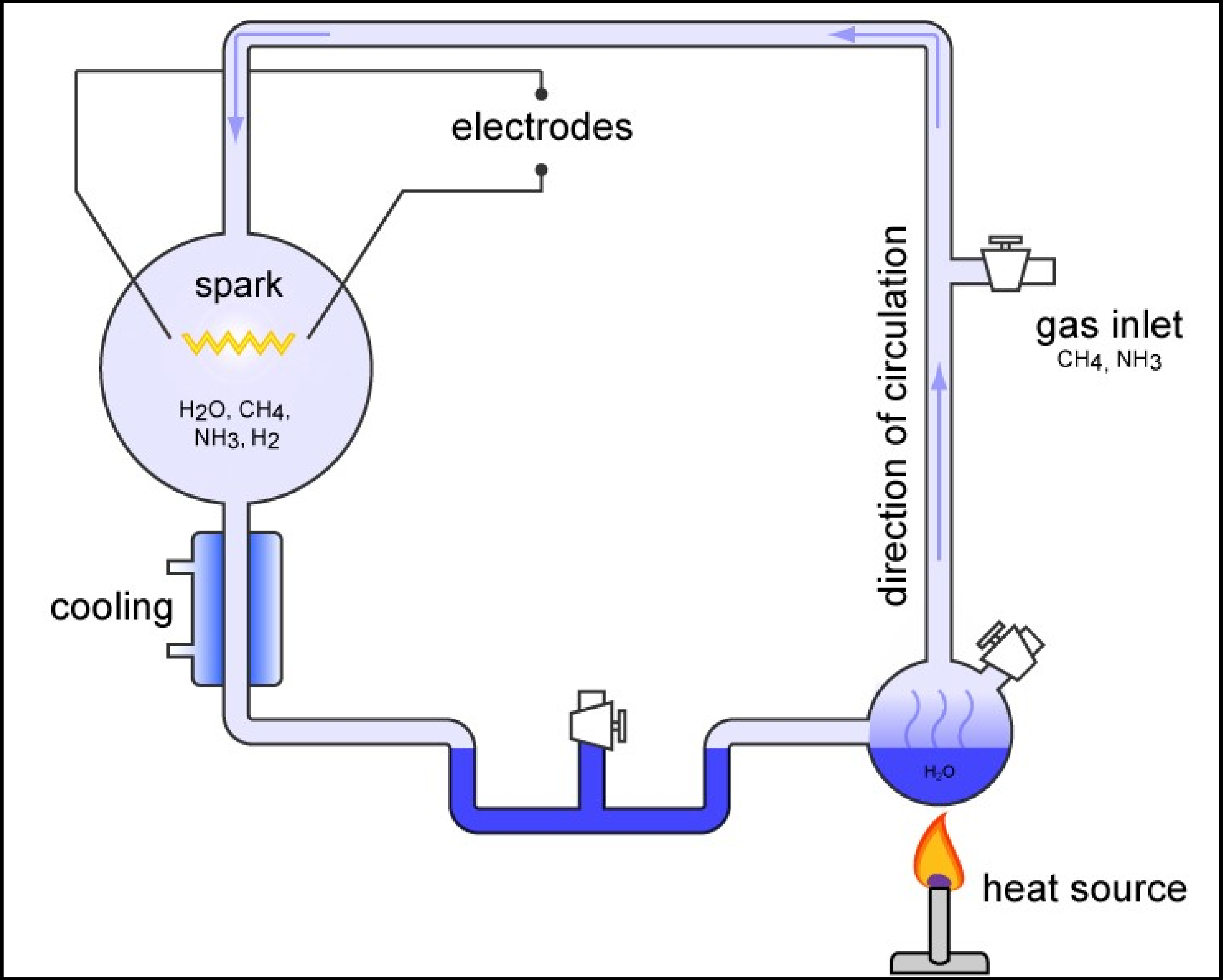
Introduction: Life on Primordial Earth

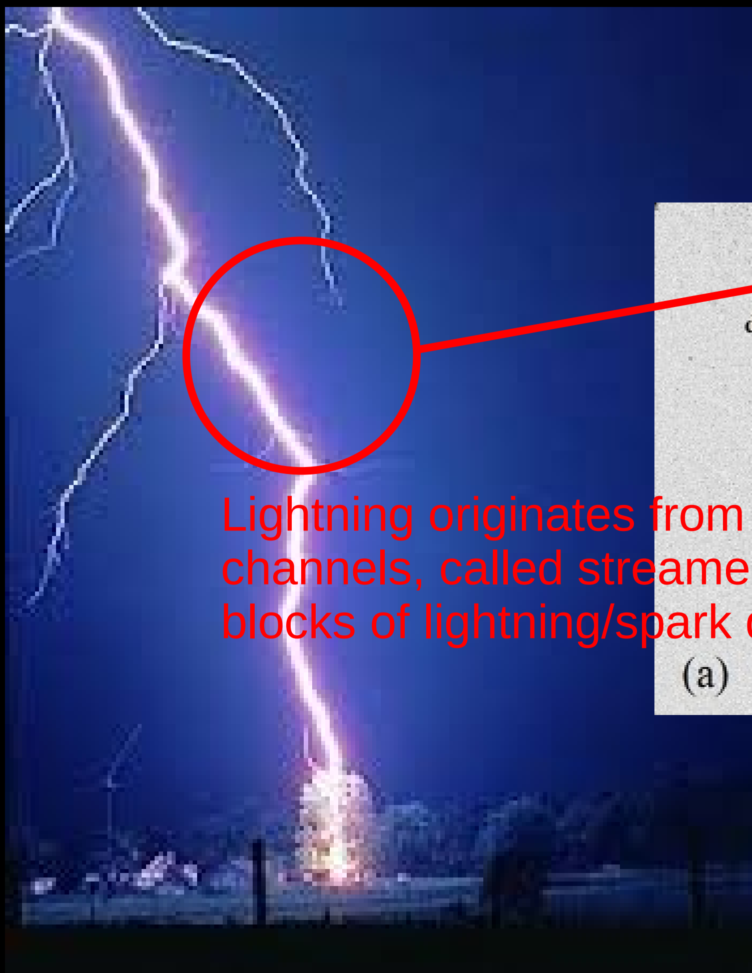


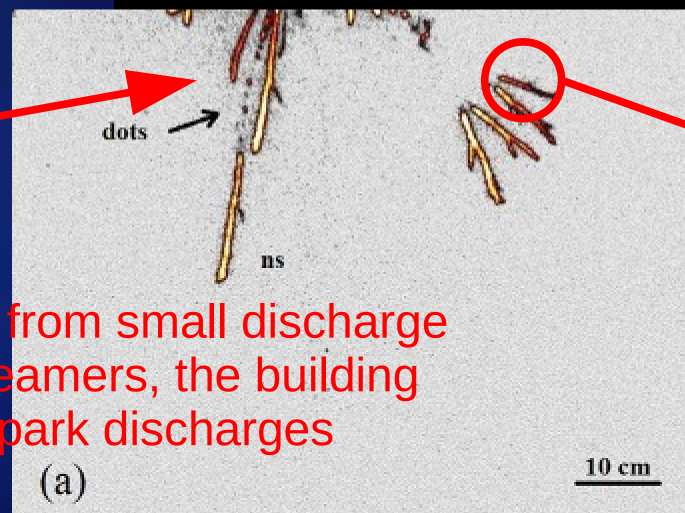
Miller-Urey experiments suggests that the formation of amino and carbon acids was catalyzed by electric discharges (lightning?) in atmosphere

=> what about inception of discharges in the atmosphere of Primordial Earth???

[S. L. Miller and H. C. Urey. Organic Compound Synthesis on the Primitive Earth. Science, 130:3370, pp. 245-251 (1959)]

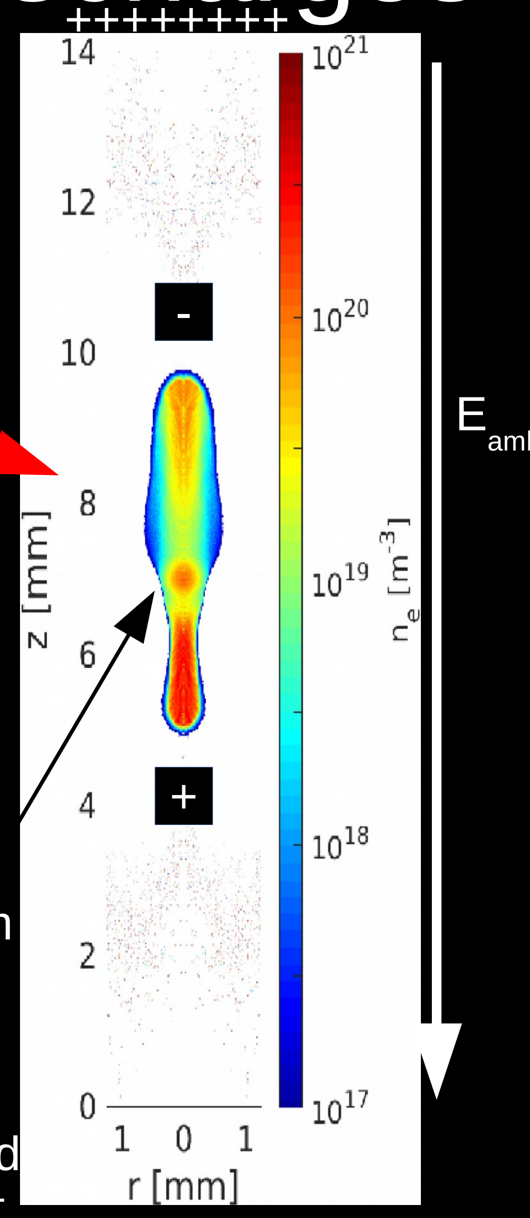
Introduction: Streamer discharges





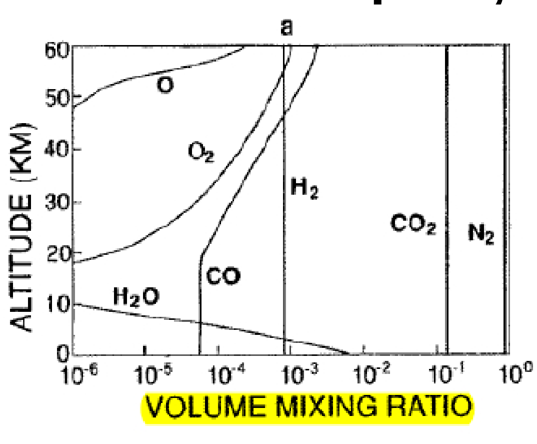
Lightning originates from small discharge channels, called streamers, the building blocks of lightning/spark discharges

Streamers originate from electron-ion patches in an ambient electric field E_{amb} and evolve by electron acceleration and the ionization of ambient gas (high fields at the tips)



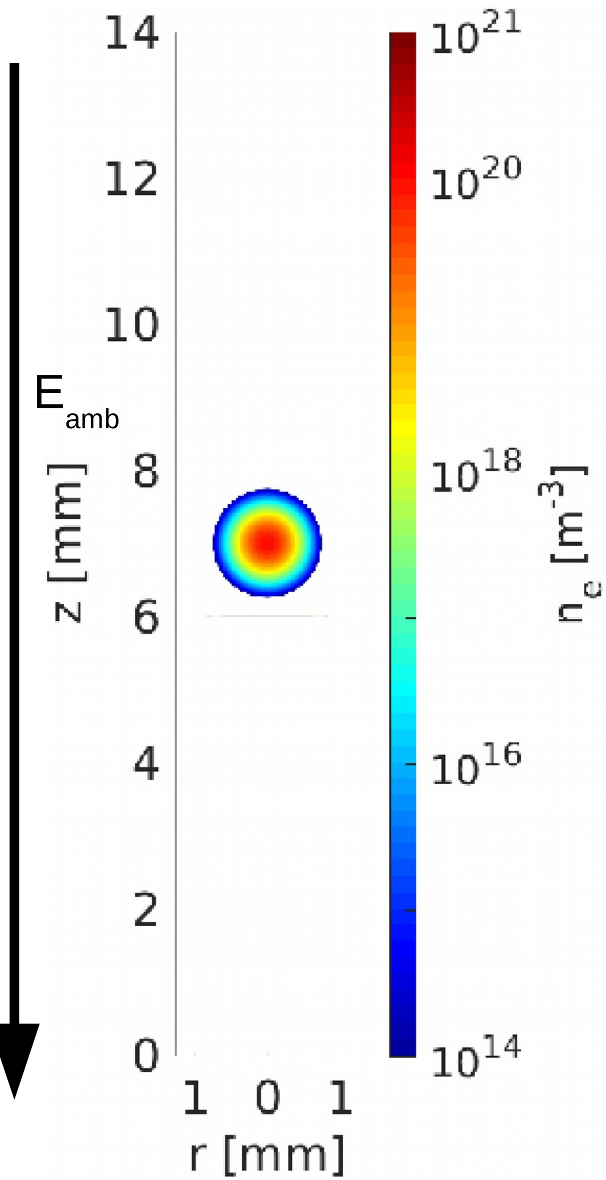
Introduction: Atmospheres on Primordial Earth

- To understand streamers on Primordial Earth and associated chemistry, one needs to know composition of atmosphere
- Miller and Urey used $H_2O:CH_4:NH_3:H_2$= 37.5%:25%:25%:12.5% (reducing atmosphere)
- More recent review [Kasting, 1990.Orig. Life Evol. Biosph., 20, 199–231]:



$N_2:CO_2:H_2O:H_2:CO$= 80%:18.89%:1%:0.1%:0.01% (oxidizing atmosphere)

Modelling of streamers



Ingredients:

- initial electron/ion patch $n_{e,i}(t=0,r,z)=n_{e,0}\,e^{-\frac{r^2+(z-z_0)^2}{\lambda^2}}$ ($n_{e,0}=10^{20}$ m^{-3}, $\lambda=0.2$ mm, $z_0=7$ mm)
- ambient field E_{amb}
- ambient gas mixture (Urey-Miller/UM, Kasting)
- gas pressure/number density of ambient gas (here use $2.5\cdot10^{25}$ m^{-3} as for Modern Earth)

Modelling:

- 2.5D particle code (2D in space, 3D in velocity)
- tracing individual electrons (incl. collision with ambient gas)
- cross section sets as input data for electron scattering in individual gases
- vary mixture and ambient field => study inception of streamer discharges

[O. Chanrion and T. Neubert. A PIC-MCC code for simulation of streamer propagation in air. J. Comp. Phys., 227, pp. 7222-7245 (2008)]

Breakdown fields I

- Electron avalanche/streamer evolution depends on two competing mechanisms (depending on the electric field)
  - Ionization: $A+e^- \rightarrow A^+ + 2e^-$
  - Attachment, e.g. $A+e^- \rightarrow A^-$
- Equilibrium of rates determines the breakdown (or classical) electric field E_k => $\alpha_{ion}(E_k)=\alpha_{att}(E_k)$

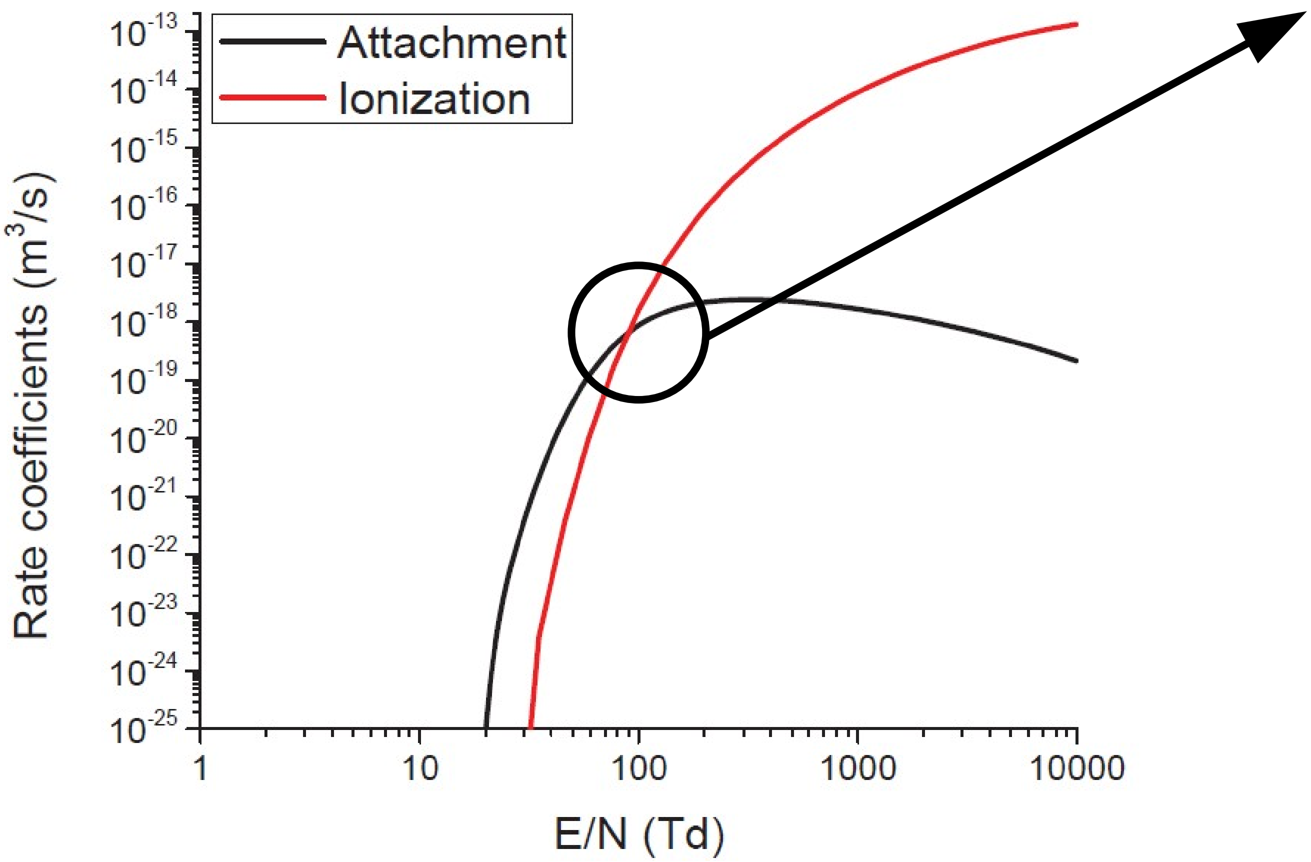
  (α_{ion} : ionization rate

  α_{att}: attachment rate

  E_k: classical electric field indicating (not equal to) field when avalanche-to-streamer transition occurs)

Breakdown fields II

Rates for Kasting's mixture:



$E_{k,Kasting}$=90.3 Td=2.3 MV m^{-1}

Similarly:

$E_{k,UM}$=113.9 Td=2.9 MV m^{-1}

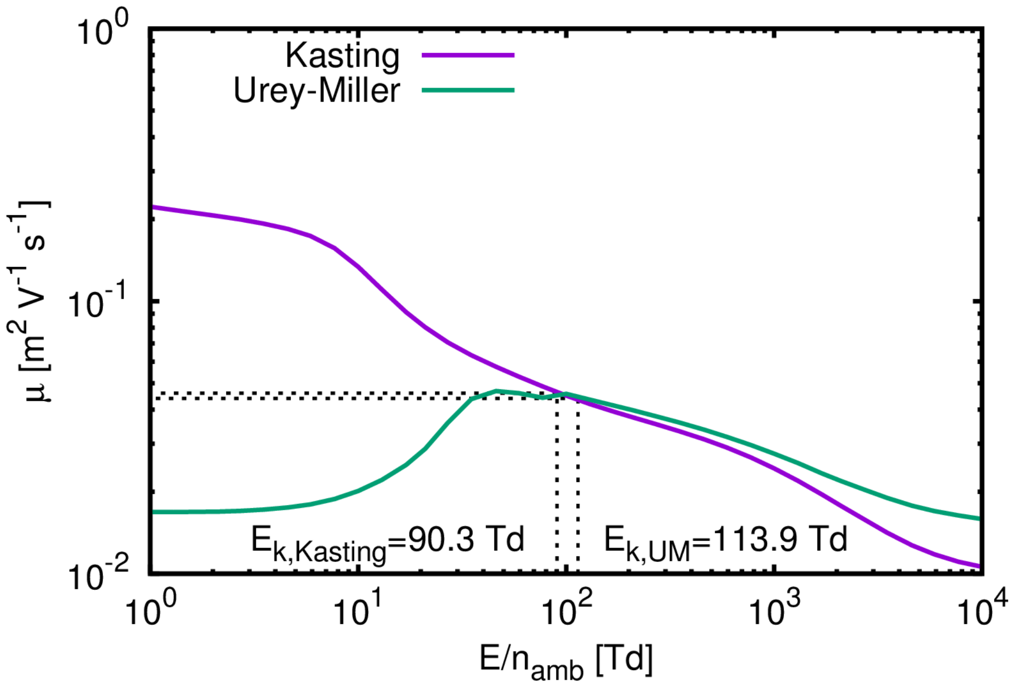
$E_{k, ME}$=125.6 Td=3.2 MV m^{-1}

Reduced electric field [Td] as ratio of electric field and ambient gas density, here $n_{amb}=2.547 \cdot 10^{25}$ m^{-3}

(avalanche/discharge properties scale with gas density)

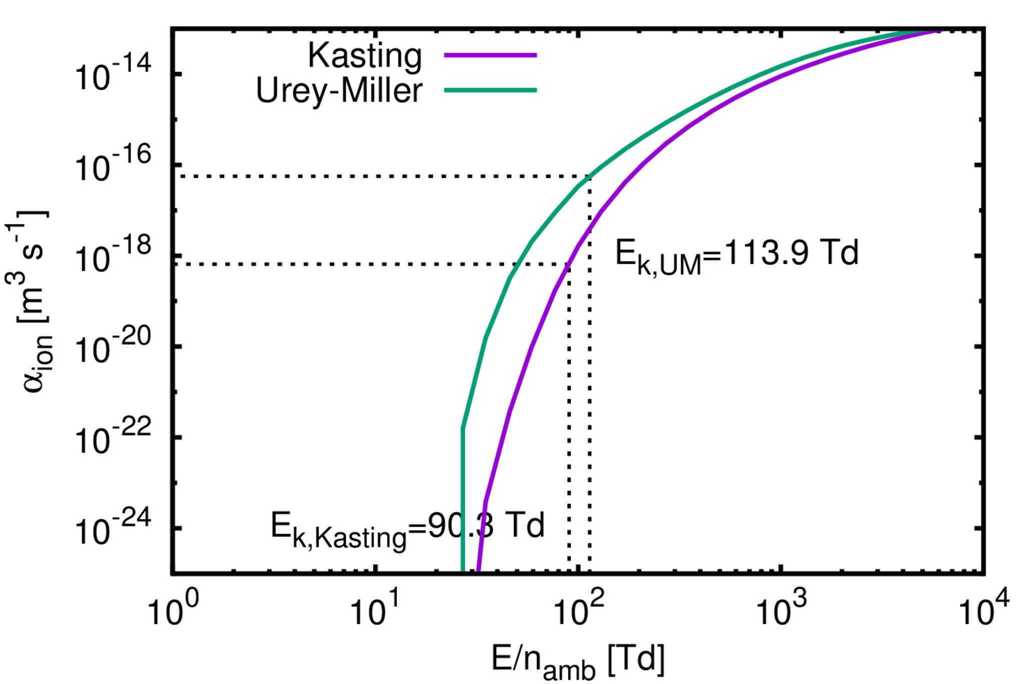
Swarm parameters

Electron mobility



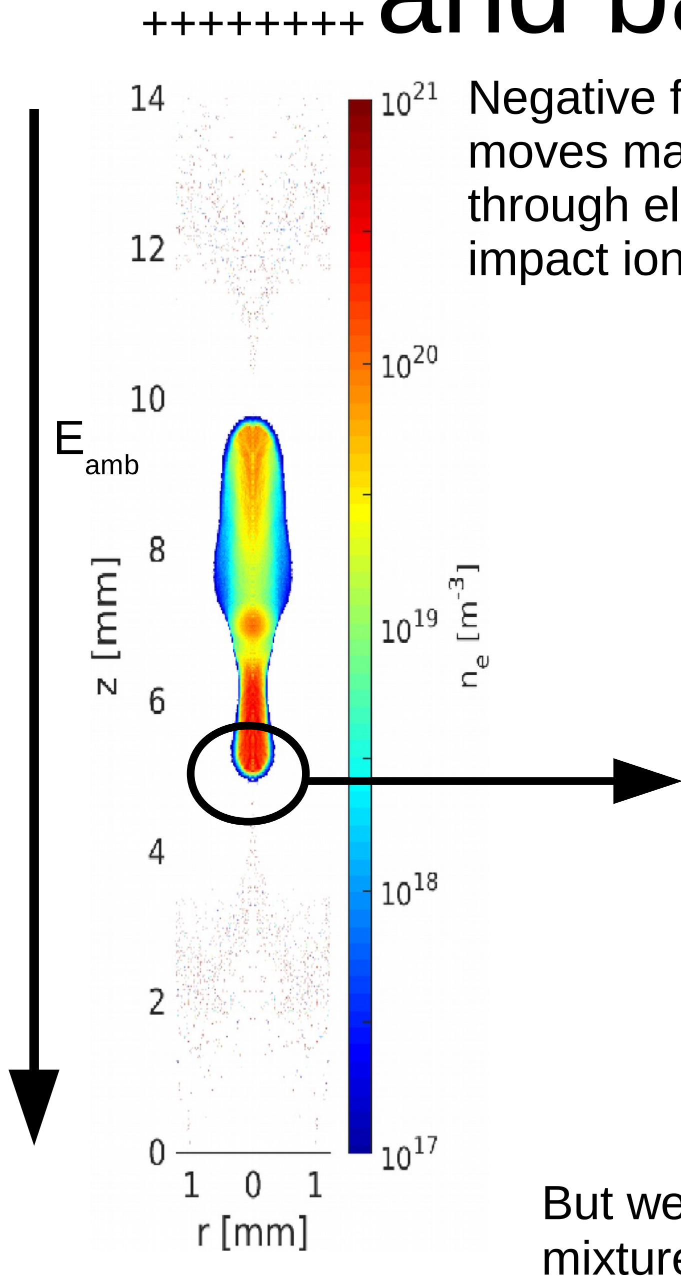
above breakdown: electrons more mobile in Urey-Miller mixture

Ionization rate

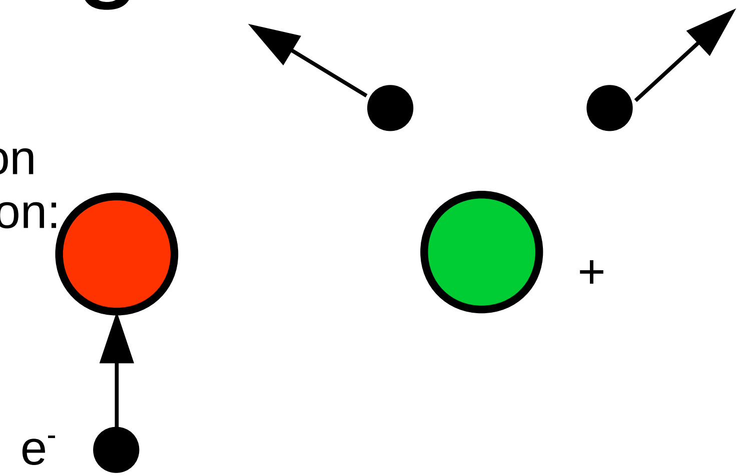


ionization more efficient in Urey-Miller mixture

Sources of ionization: Photoionization and background ionization



Negative front moves mainly through electron impact ionization:



Build-up of space charge => enhance electric field => accelerate electrons further

On the positive side, electrons are dragged into streamer.

? Source of new electrons:

- background ionization (Modern Earth air ≈10^3-10^5 cm^{-3})
- photoionization

In air:

$$N_2 + e^- \rightarrow N_2^* + e^-$$

$$N_2^* \rightarrow N_2 + \gamma_{UV}$$

$$O_2 + \gamma_{UV} \rightarrow O_2^+ + e^-$$

But we do not know how photoionization really works in other gas mixtures: use increased level of background ionization: 10^9 cm^{-3} [A. Bourdon et al.,2010. Plasma Sources Sci. Technol., vol. 19, 034012]

Electron densities I

In Kasting mixture after t=2.85 ns for different ambient fields:

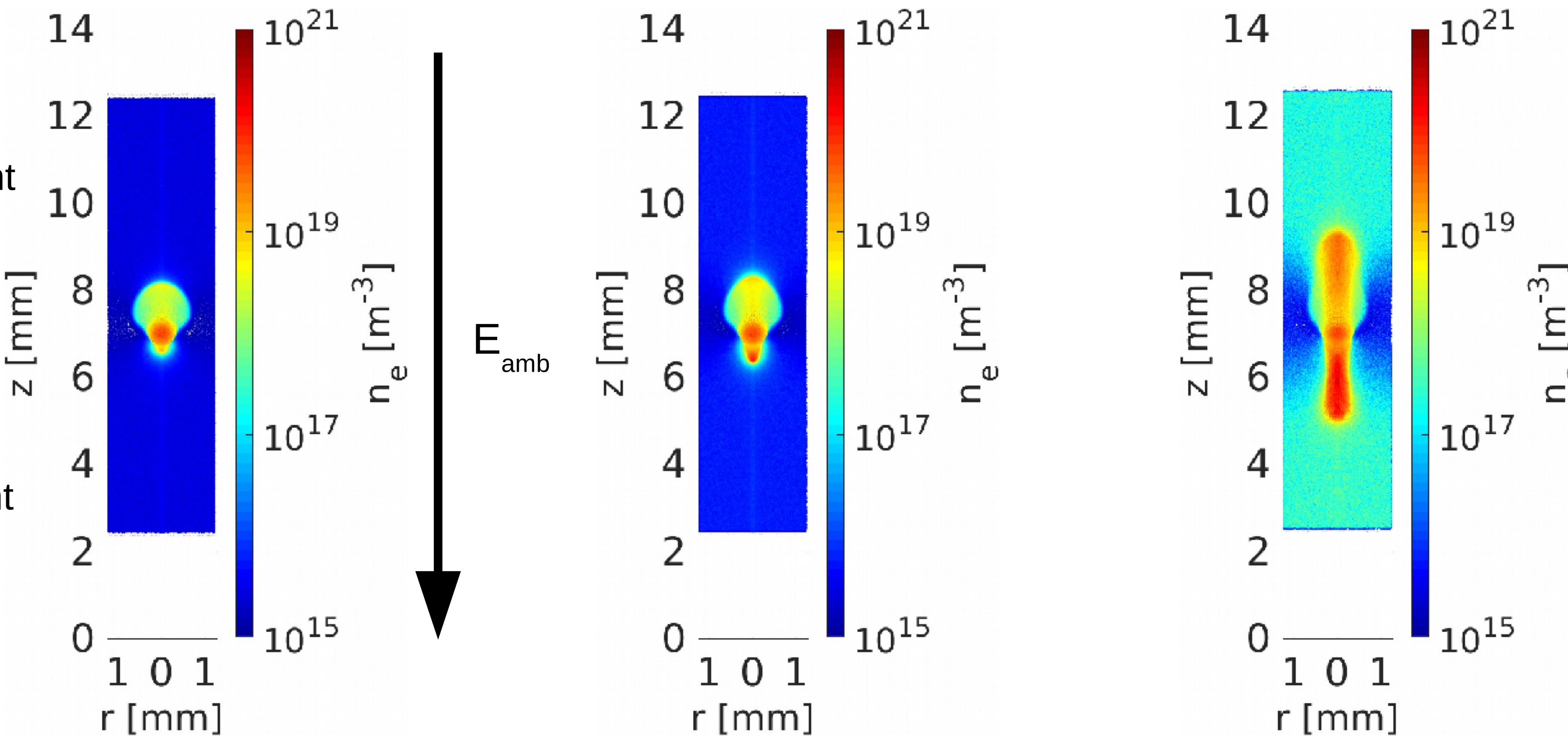
E_{amb}=3.6 MV m^{-1} =141.3 Td

E_{amb}=4.0 MV m^{-1} =157.0 Td

E_{amb}=5.0 MV m^{-1} =196.3 Td

neg. front

pos. front



electron avalanches on both fronts, positive front might turn to streamer

negative front: electron avalanche, but no streamer positive front: avalanche-to-streamer transition

full evolution of positive and negative streamer

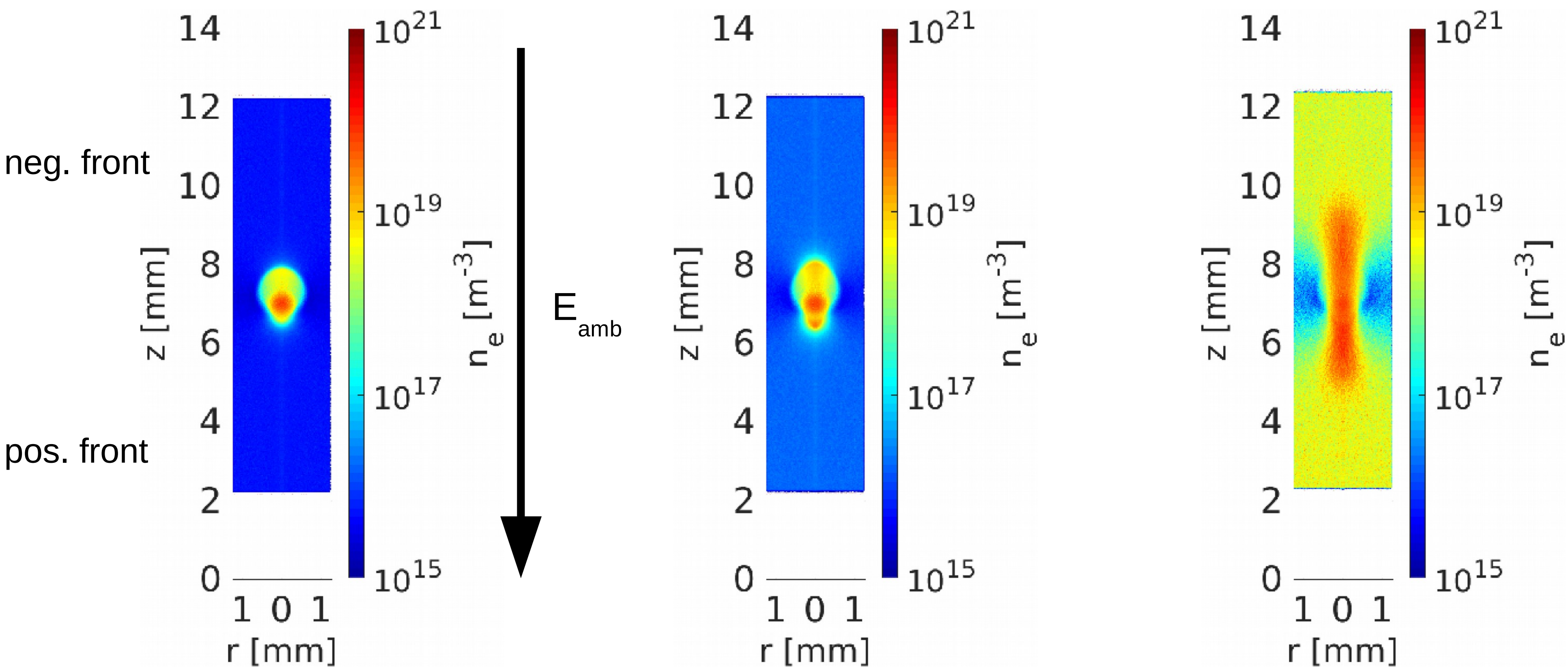
Electron densities II

In Urey-Miller mixture after t=1.81 ns for different ambient fields:

E_{amb}=2.5 MV m^{-1} =98.2 Td

E_{amb}=2.9 MV m^{-1} =113.9 Td

E_{amb}=4.0 MV m^{-1} =157.0 Td



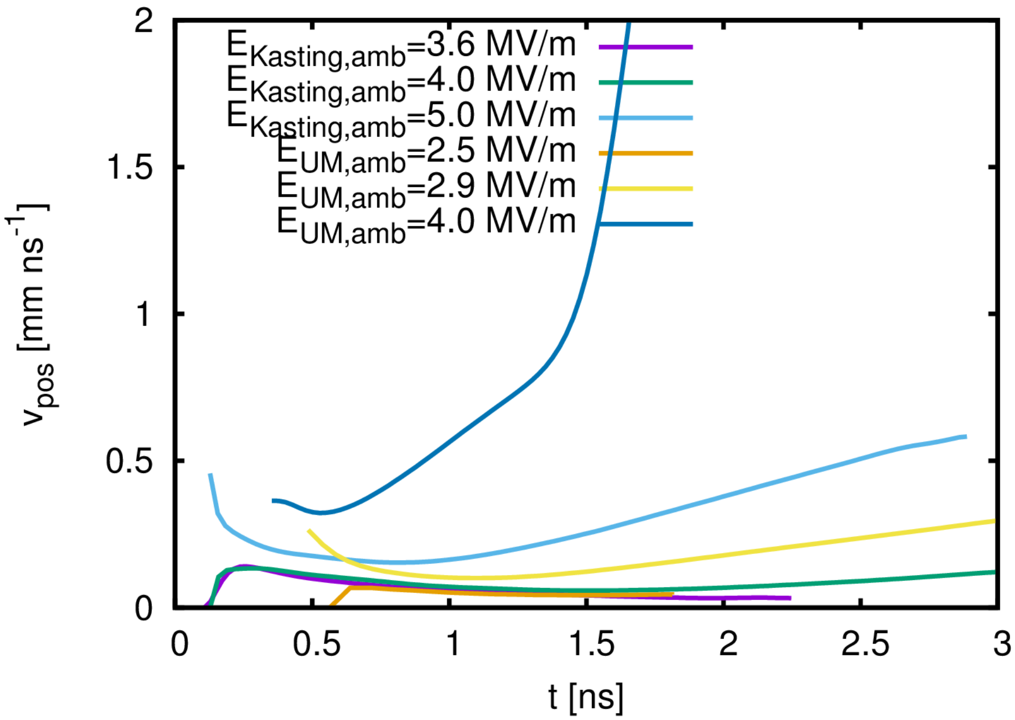
electron avalanches on both fronts

avalanche-to-streamer transition for both polarities

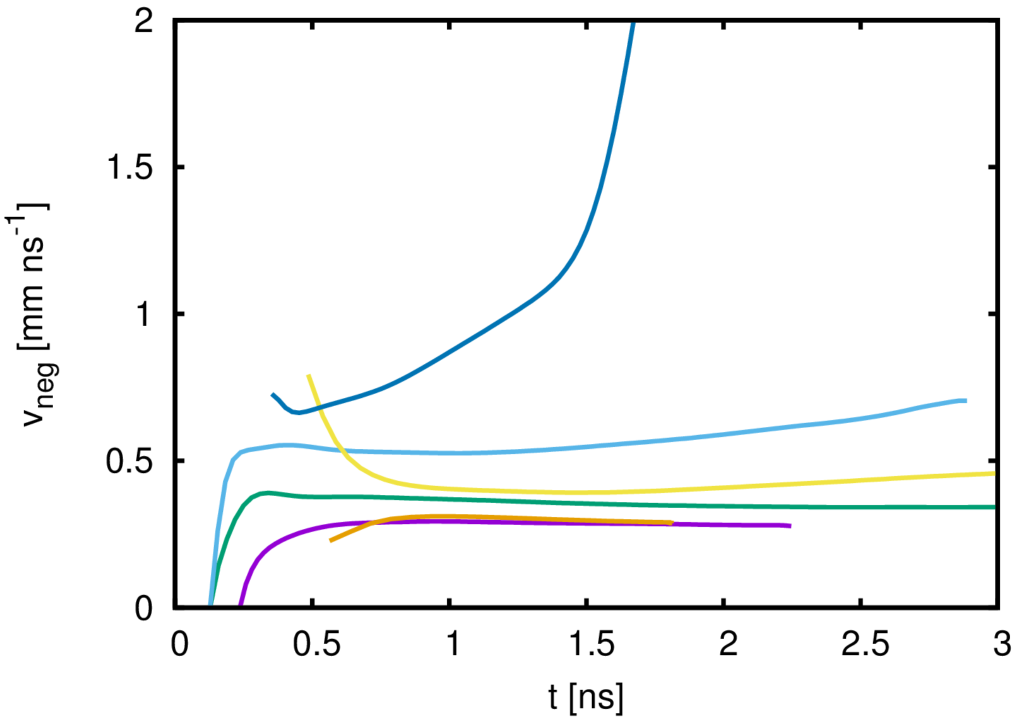
full evolution of positive and negative streamer

Front velocities

positive front:



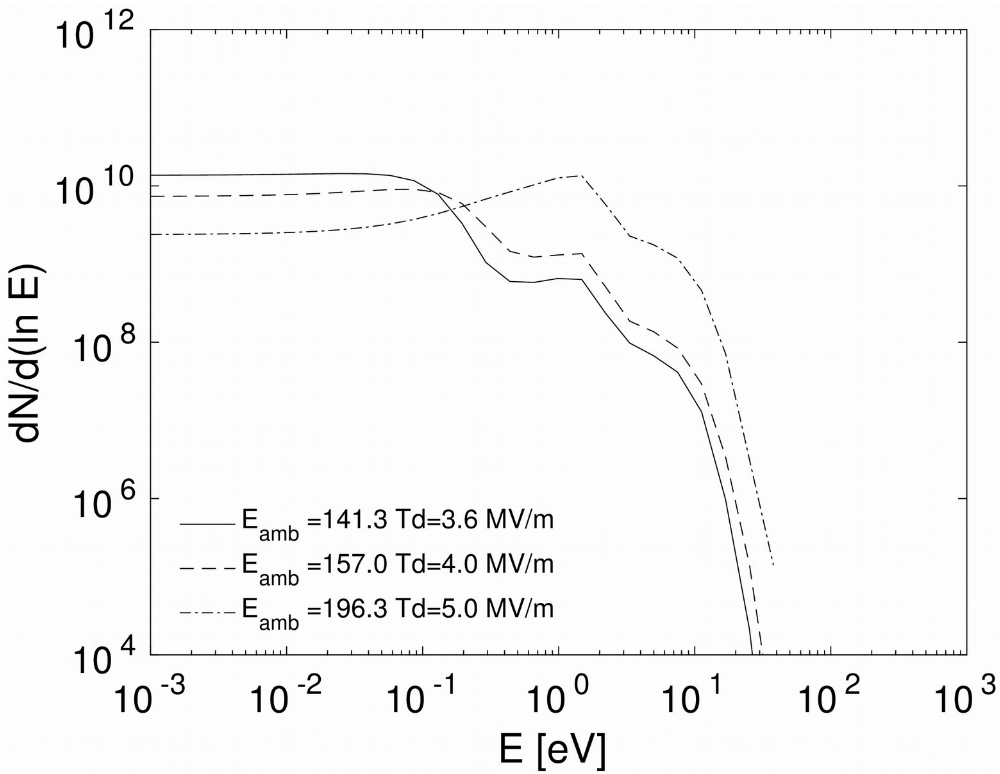
negative front:



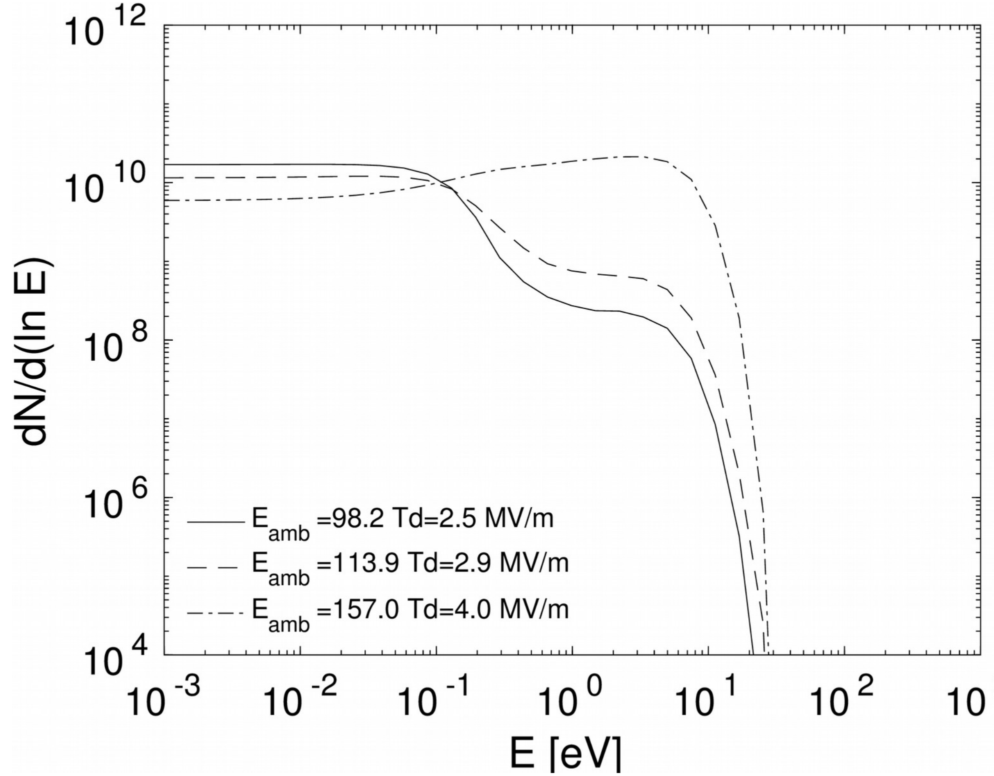
- in Kasting mixture: $v<0.6$ mm ns^{-1}
- velocities in Urey-Miller (in average) larger (although smaller electric fields)
- for comparison: $v_{\text{Modern Earth}} \approx 1\text{-}10$ mm ns^{-1}

Electron energies

Kasting, t=2.85 ns



Urey-Miller, t=1.81 ns



- for 141.3 Td and 157.0 Td E_{max}<30 eV
- for 196.3 Td E_{max}≈40 eV

- for all considered cases E_{max}<30 eV

=> similar electron energies
=> mean ionization energy in Kasting mixture larger than in Urey-Miller mixture
=> discharge inception/evolution less efficient in Kasting mixture

Inception fields

(field when avalanche-to-streamer transition occurs)

Gas mixture	$E_{inc,pos}$ [MV m^{-1}]/[Td]	$E_{inc,neg}$ [MV m^{-1}]/[Td]
Kasting $N_2:CO_2:H_2O:H_2:CO$	3.7/145.3	4.6/180.6
Urey-Miller $H_2O:CH_4:NH_3:H_2$	2.7/106.0	2.7/106.0

(for comparison, on Modern Earth: ≈ 3.2/125.6)

Conclusions and outlook

- Streamer discharge inception in Kasting mixture requires higher fields than in Urey-Miller mixture
- Front velocities in Kasting mixtures smaller than in Urey-Miller mixture
- Comparable energies (<40 eV)

=> Discharges (lightning) inception might be more difficult in the oxidizing Kasting mixture

(does not say anything about local reducing environments)

- Future project: include plasma chemistry of Primordial Earth into streamer code