The Mechanism of the Origin and Development of Lightning from Initiating Event to Initial Breakdown Pulses

arXiv:1906.01033 [physics.ao-ph], [v1] Mon, 3 Jun 2019

Alexander Yu. Kostinskiy

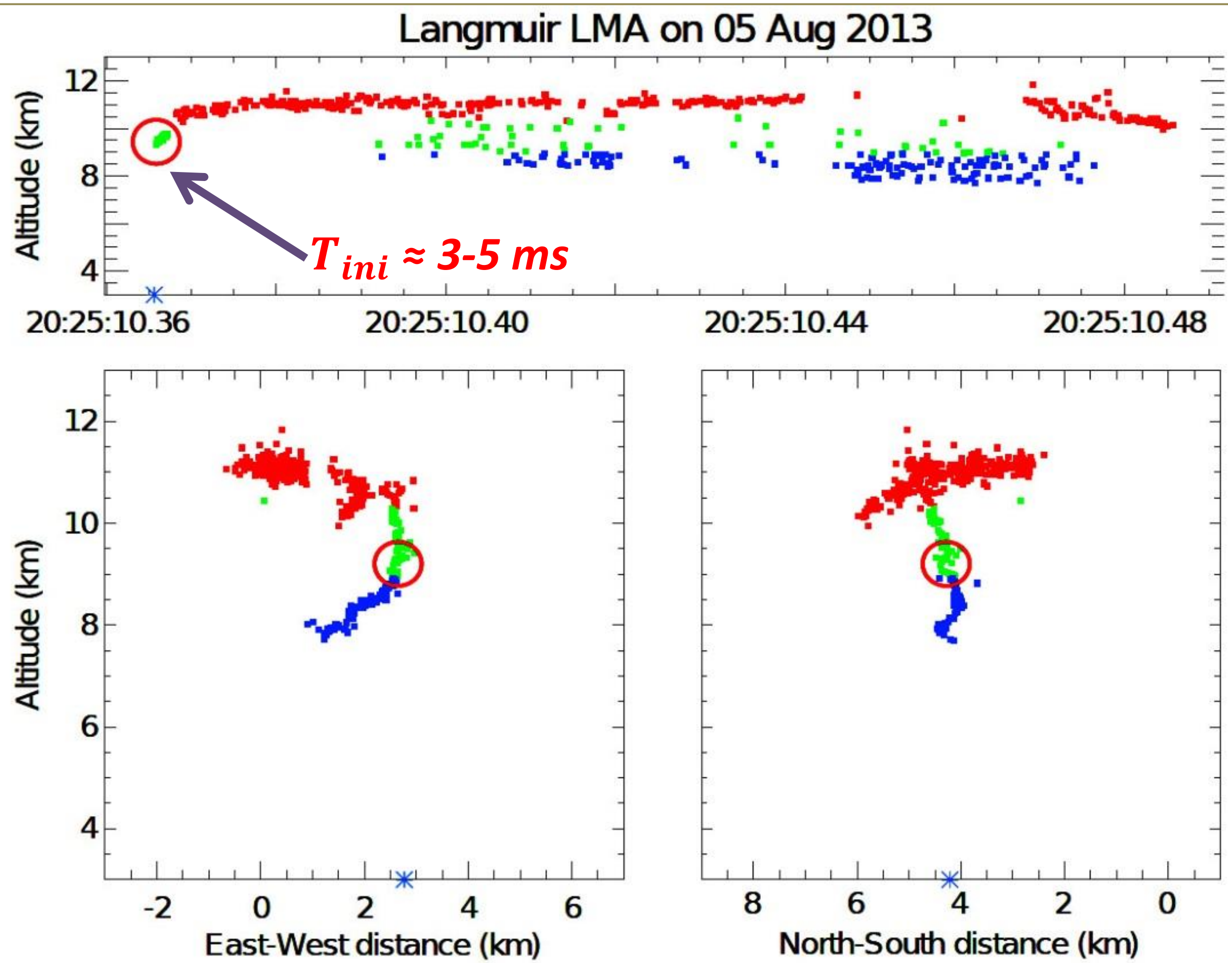
Moscow Institute of Electronics and Mathematics NRU HSE, Moscow, Russia

Thomas C. Marshall, Maribeth Stolzenburg

Department of Physics and Astronomy, University of Mississippi, University, Mississippi, USA

TEPA 2019, October 15, Nor Amberd

NBE(CID) initiates lightning, $T_{total} \approx 120$ ms (NBE2, Rison et al., 2016)



Supplementary Figure 4: LMA observations for the NBE2 flash. Same as Fig.1b, except showing the first 120 ms of the bilevel IC flash initiated by NBE2. Like NBE1, NBE2 (red circle) occurred at the base of the upward negative leader of the flash (green sources). The E-W and N-S vertical projections show that the negative leader was primarily vertical, consistent with the NBE also being vertical.

The Mechanism

arXiv:1906.01033 [physics.ao-ph], [v1] Mon, 3 Jun 2019

1. **We propose a mechanism for the appearance of lightning after initiation by NBEs (narrow bipolar events) or weaker initiating events (IE), in a turbulent cloud with strong local electric fields**
2. **These IE are a volume of positive streamer flashes initiated by the relativistic particles and gamma photons**

PB = Initial Breakdown Pulses = IB-IBPs

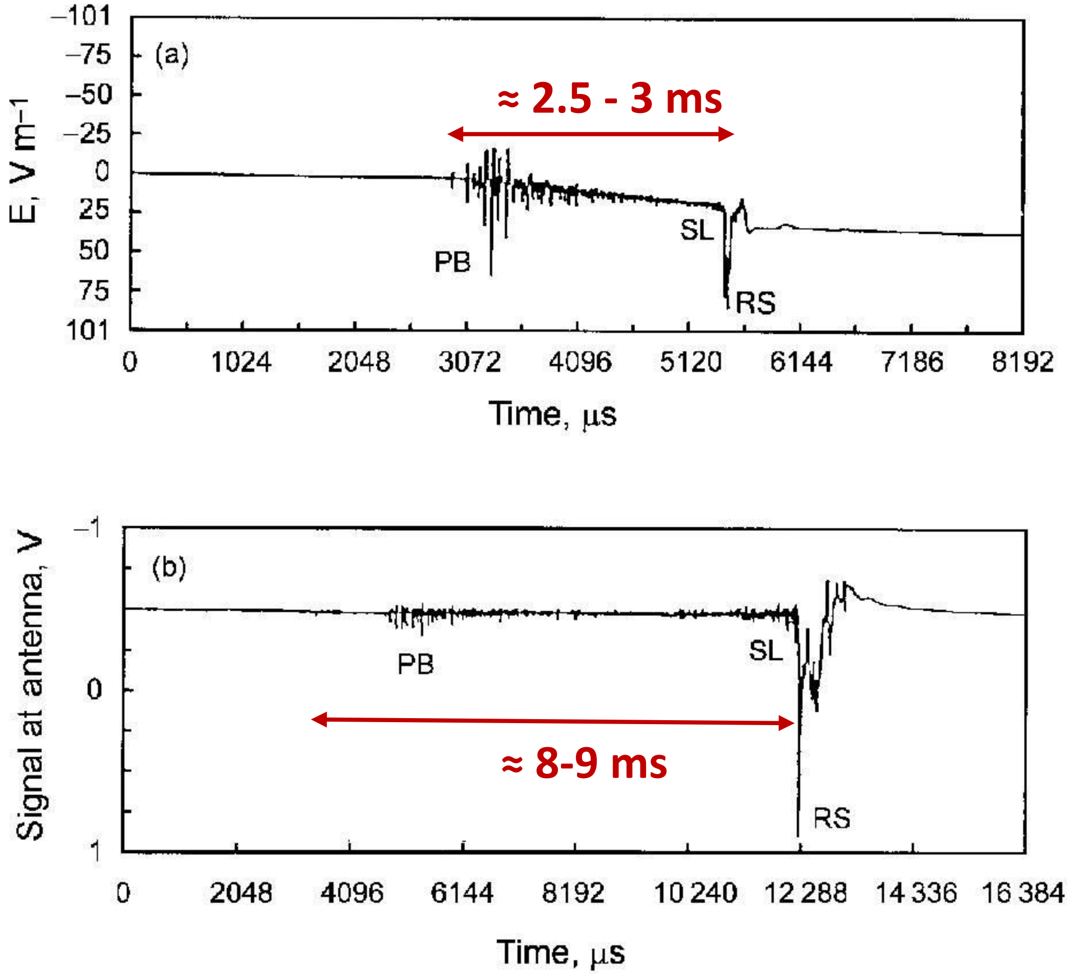
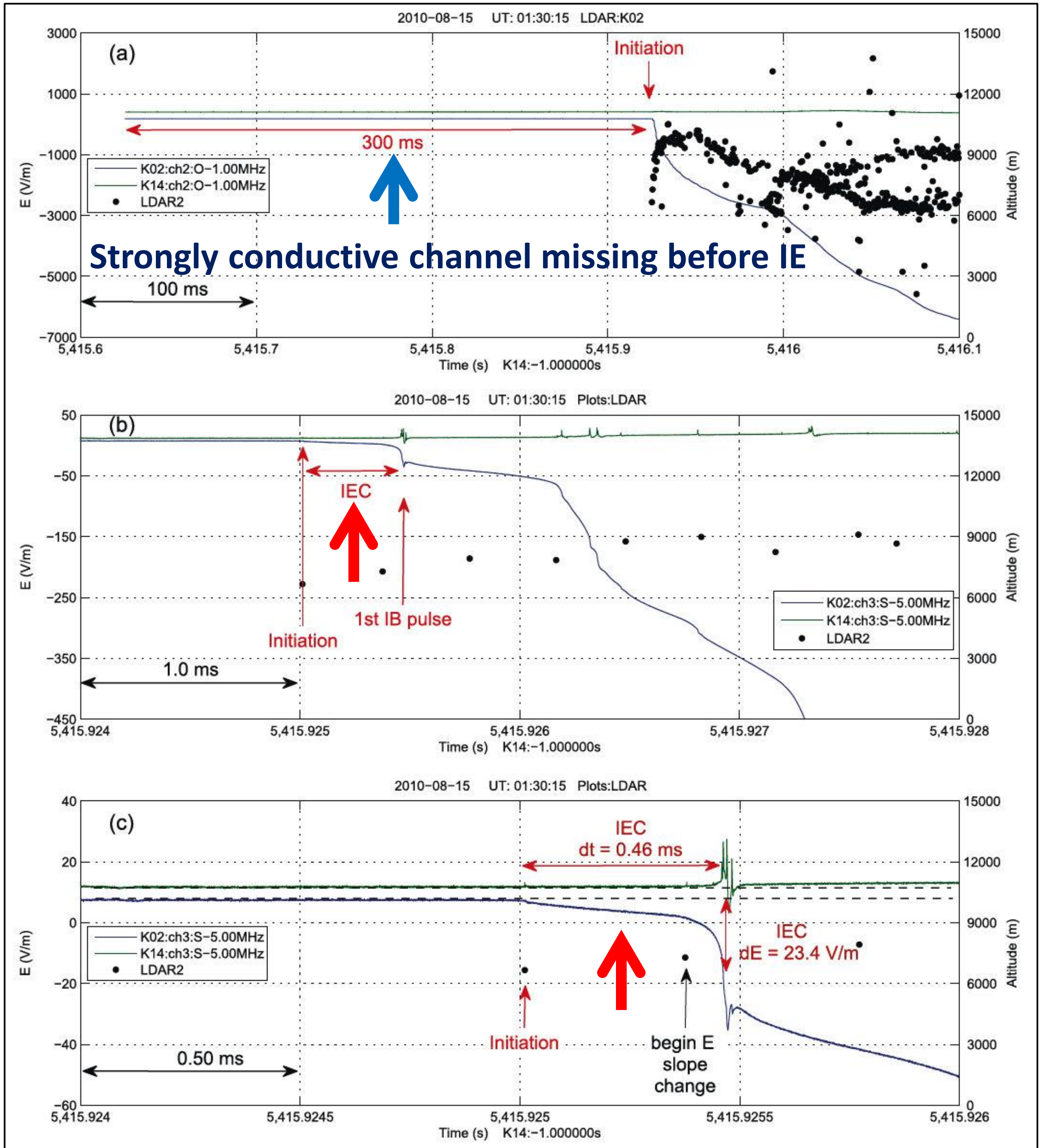


Fig. 4.11. Examples of electric fields due to negative first strokes in cloud-to-ground lightning: (a) winter lightning at about 25 km, (b) summer lightning at an unknown distance. PB stands for preliminary breakdown, SL for stepped leader (just prior to its attachment to ground), and RS for return strokes. The overall time scales in Figs. 4.11a, b are about 8.2 and 16.4 ms, respectively. Note that the separation between PB and RS, the duration of the stepped leader, is smaller than usual, particularly in Fig. 4.11a. The atmospheric electricity sign convention (subsection 1.4.2) is used here. Adapted from Brook (1992).

IEC (an Initial Electric-field Change), *Marshall et al. (2014a)*



IBPs (the visible light), *Stolzenburg et al. 2013*

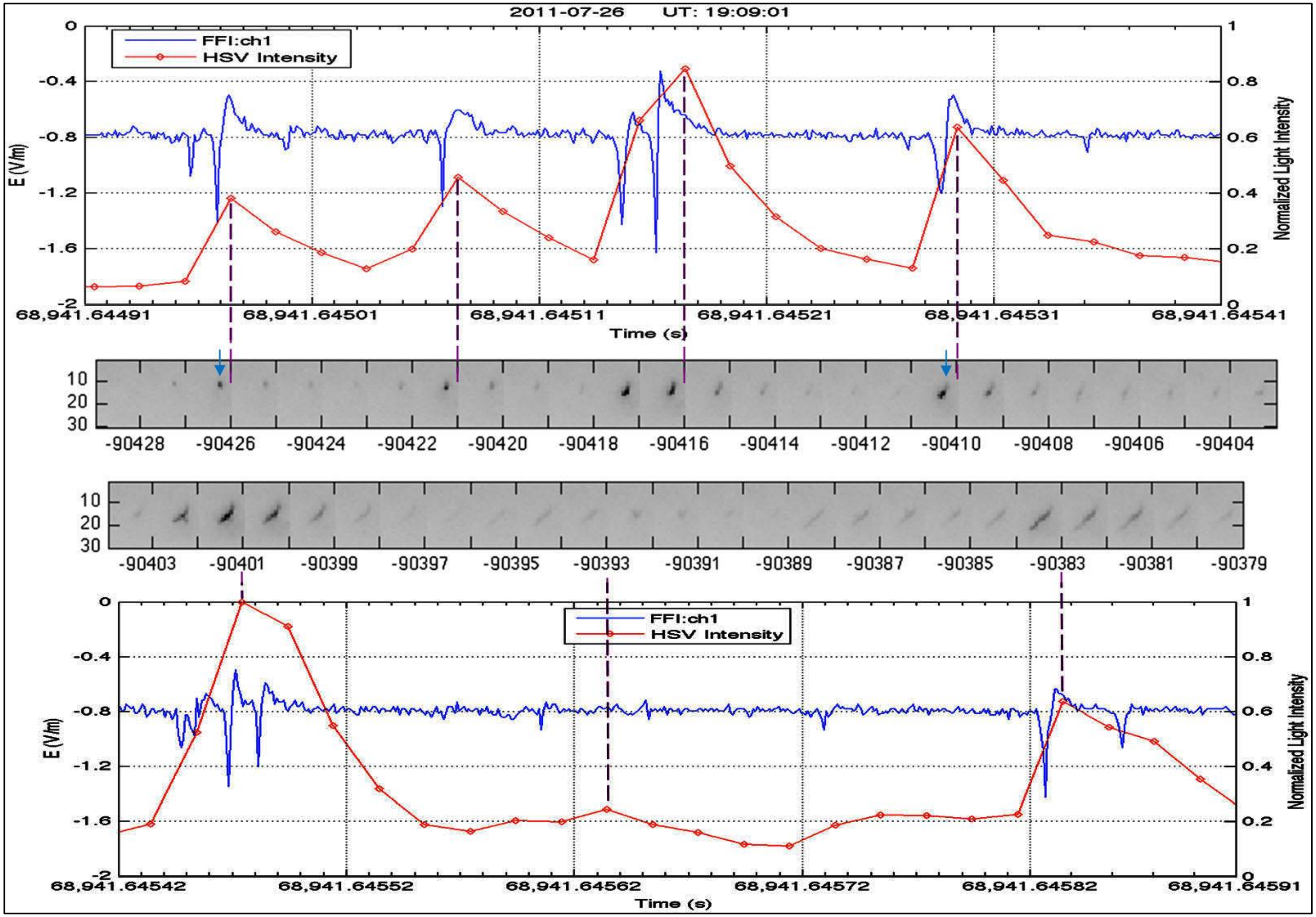
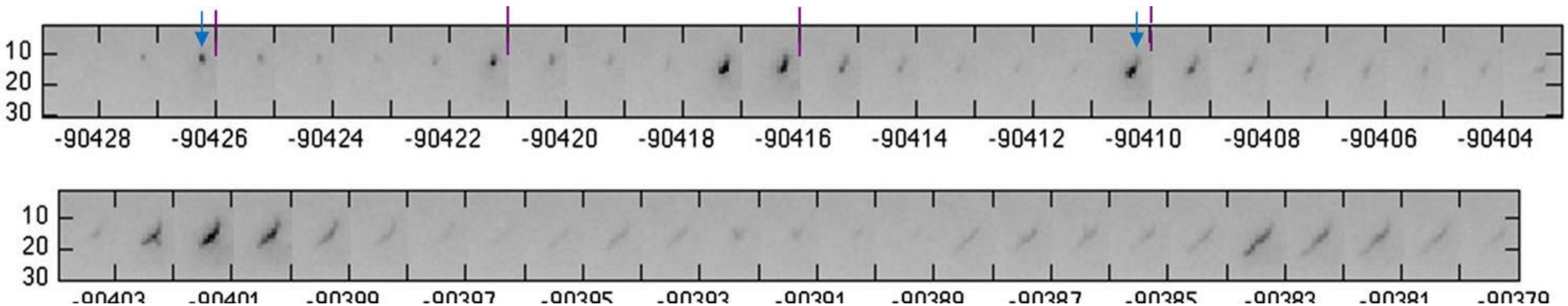


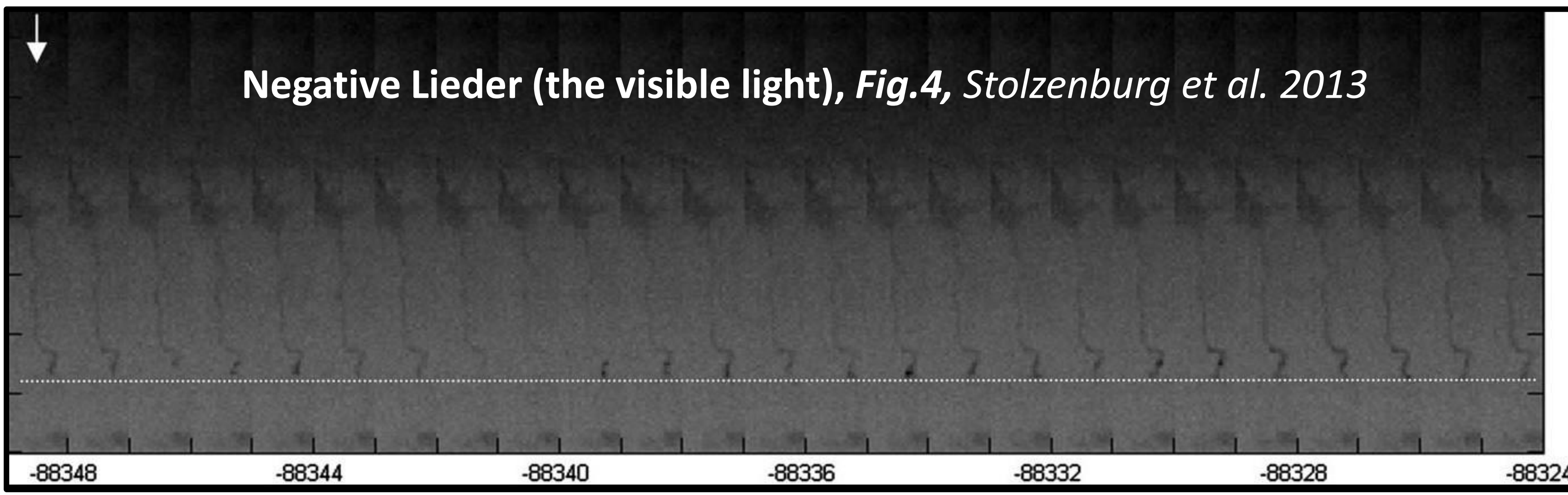
Figure 3. Two portions of E-change data and normalized video intensity (top and bottom graphs), as in Figure 2b, each time-aligned with a sequence of 25 intensity-inverted video frames (middle two panels) for Example 1. Video data shown start at 1909:01.644934 (frame end time) on 26 July 2011 and continue for 1 ms during the IB stage. Each full frame is cropped to 20 pixels wide by 31 pixels high and plotted adjacent to the following frame; image number is given along horizontal axes (alternate ticks labeled at right edge of respective frame). Area shown in each cropped frame is approximately 482 m wide 747 m high, and the first burst is at 4.6 km altitude. Blue arrows on frames 90426 and 90410 indicate same location as in Figures 1a and 1c. Vertical dashed lines between panels indicate several corresponding frame end times and markers on the intensity curve, for reference.

The visible light: *IBPs vs Negative Lieder*

Stolzenburg et al., 2013



IBPs (the visible light), *Fig.3,* *Stolzenburg et al. 2013*



Negative Lieder (the visible light), *Fig.4,* *Stolzenburg et al. 2013*

IBP (Initial Breakdown Pulse)

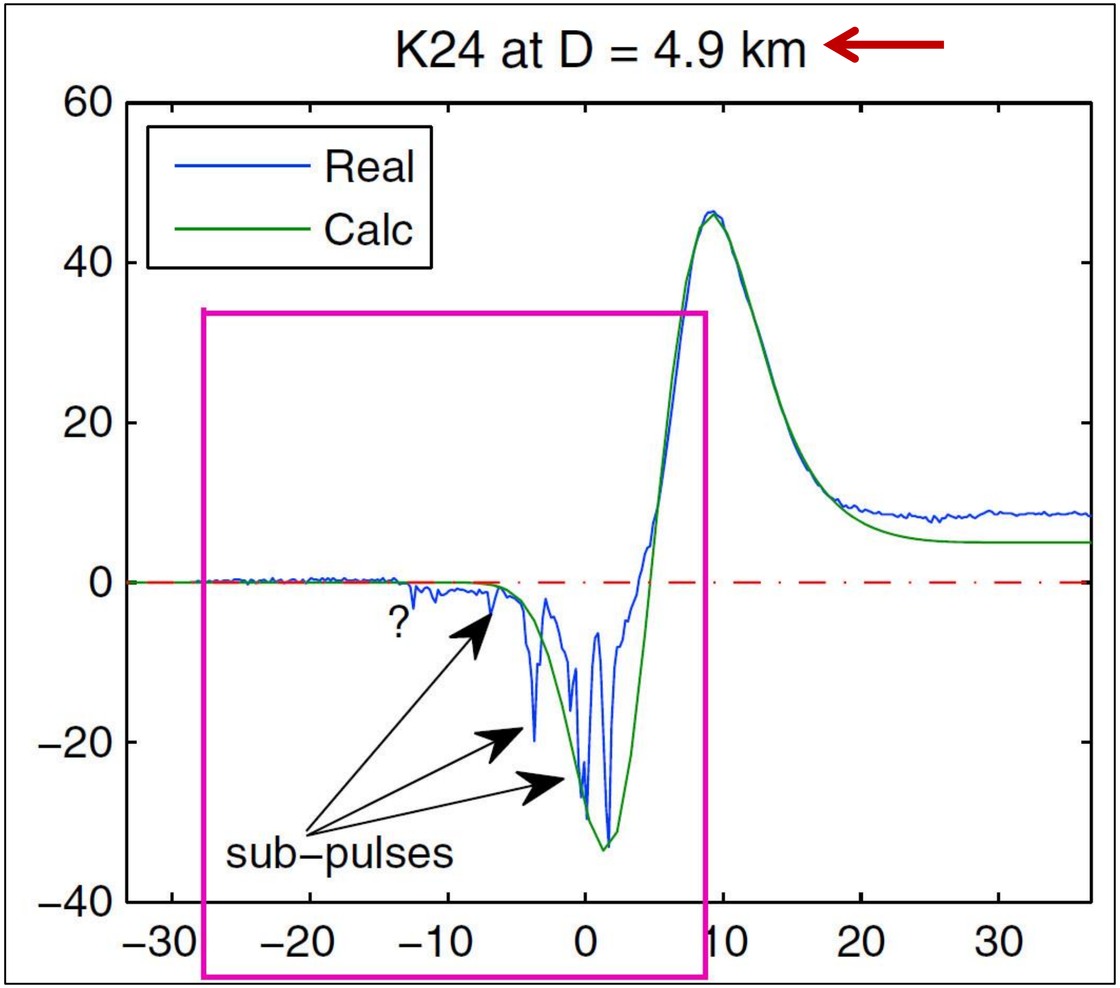


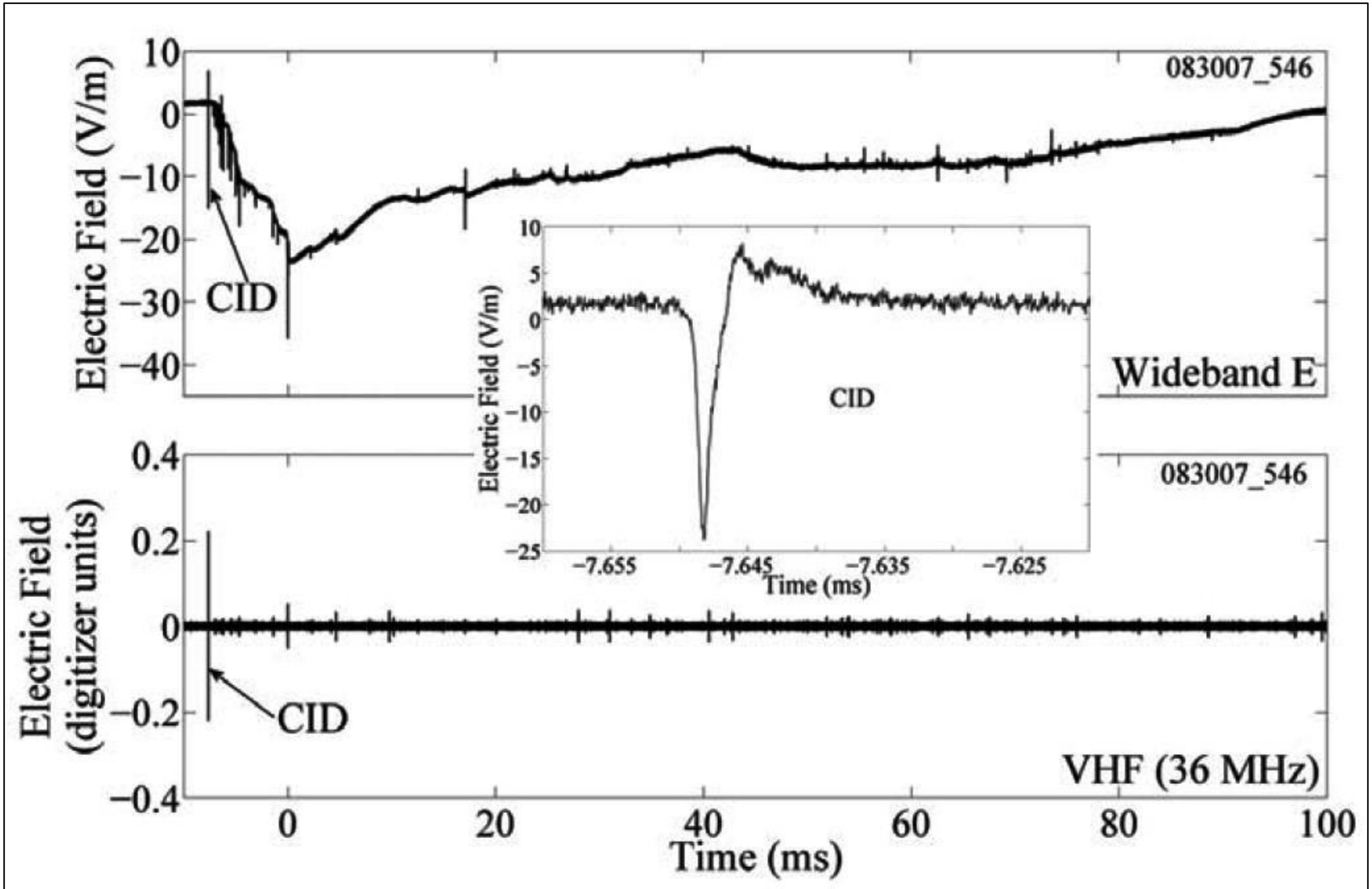
Fig.6, Karunarathne, Marshall et al., 2014

Total charge *Q* (C)

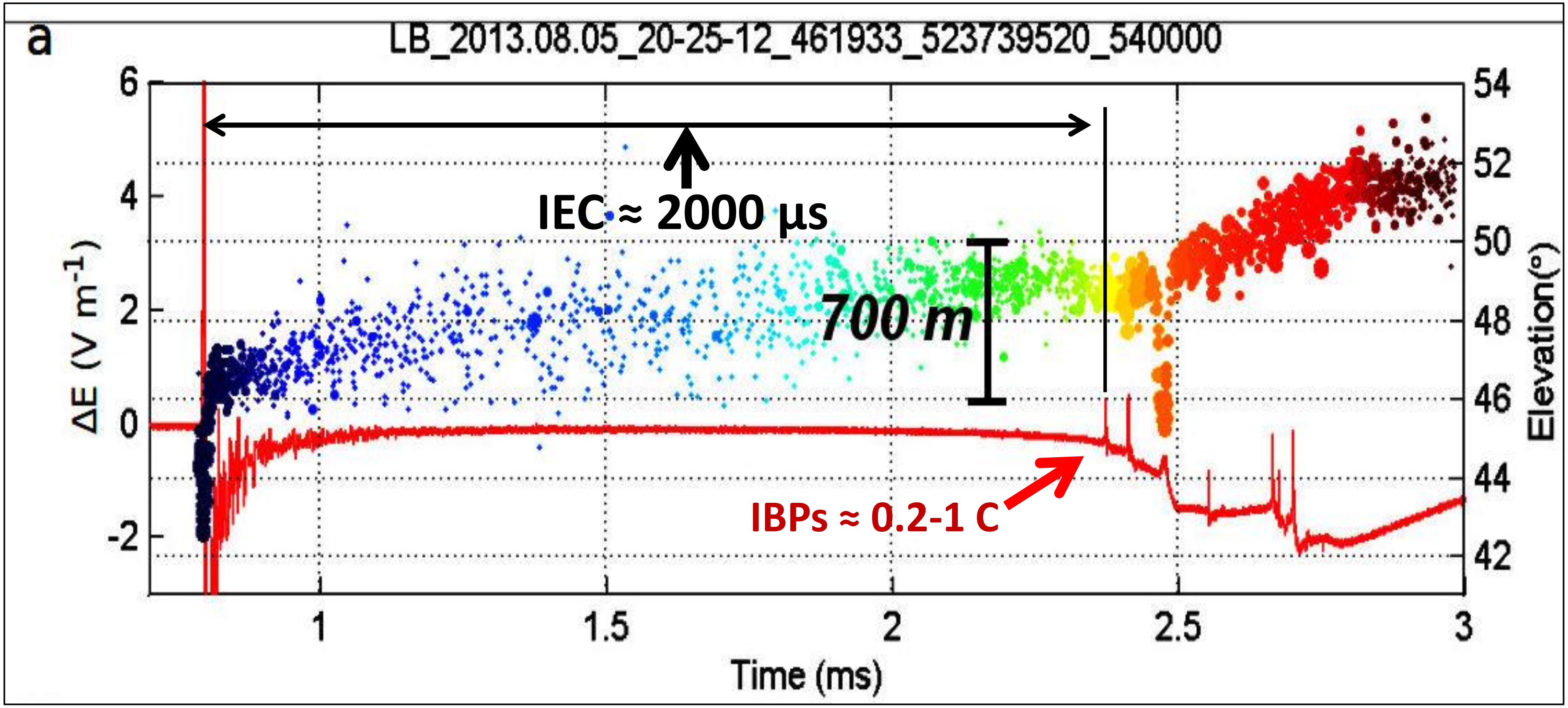
Min: –0.12 C, Max: –1.7 C, Mean: (0.44 ± 0.40) C

CID (NBE) initiates lightning

Nag, Rakov et al., 2010



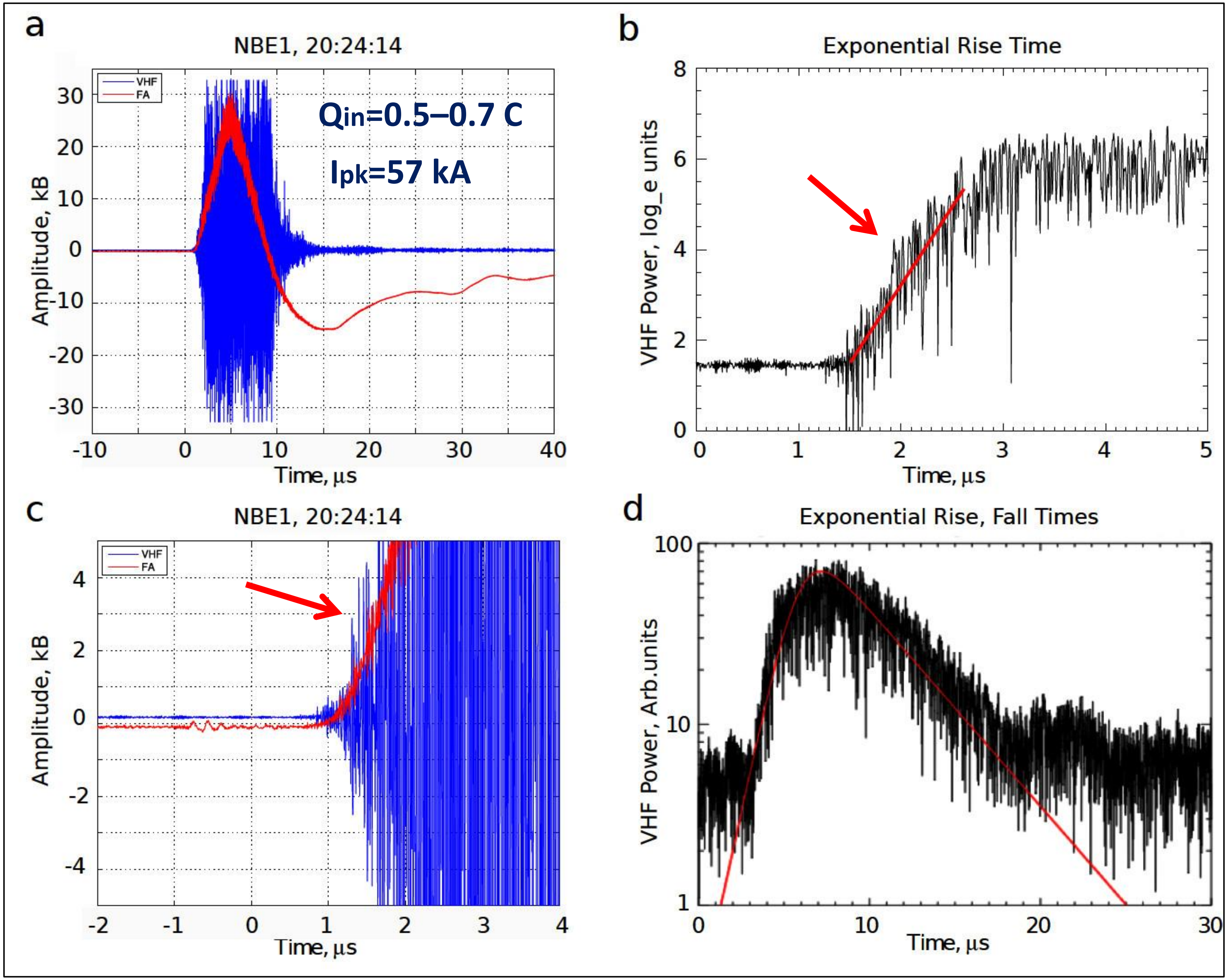
NBE(CID) initiates lightning; *NBE2, Rison et al., 2016, Tini ≈ 3 ms*



Supplementary Figure 6: Initial activity of the NBE2 flash. a, Detailed INTF and FA observations for the first 2 ms of the IC flash initiated by NBE2, illustrating the two-stage nature of the negative breakdown: i) gradual upward development during the 1.5 ms-duration initial electric field change (IEC), ii) the fine structure of the first initial breakdown pulse (IBP) following the IEC, iii) the occurrence of the second NBE (downward orange sources) at the beginning of the IBP, and iv) the accelerated upward development associated with the IBP. The IEC (blue and green sources) extended the discharge 500 m at an estimated speed of 3·10^5 m/s, and the IBP (yellow and red sources) extended the discharge a similar additional distance at 1 · 10^6 m/s. In this and other figures, the INTF sources are coloured by time and and sized logarithmically by power.

Rison et al. (2016), Observations of narrow bipolar events reveal how lightning is initiated in thunderstorms, Nature Comms. 7:10721, doi:10.1038/ncomms10721.

VHF-Rise Time, NBE1 (CID), *Rison et al. (2016)*

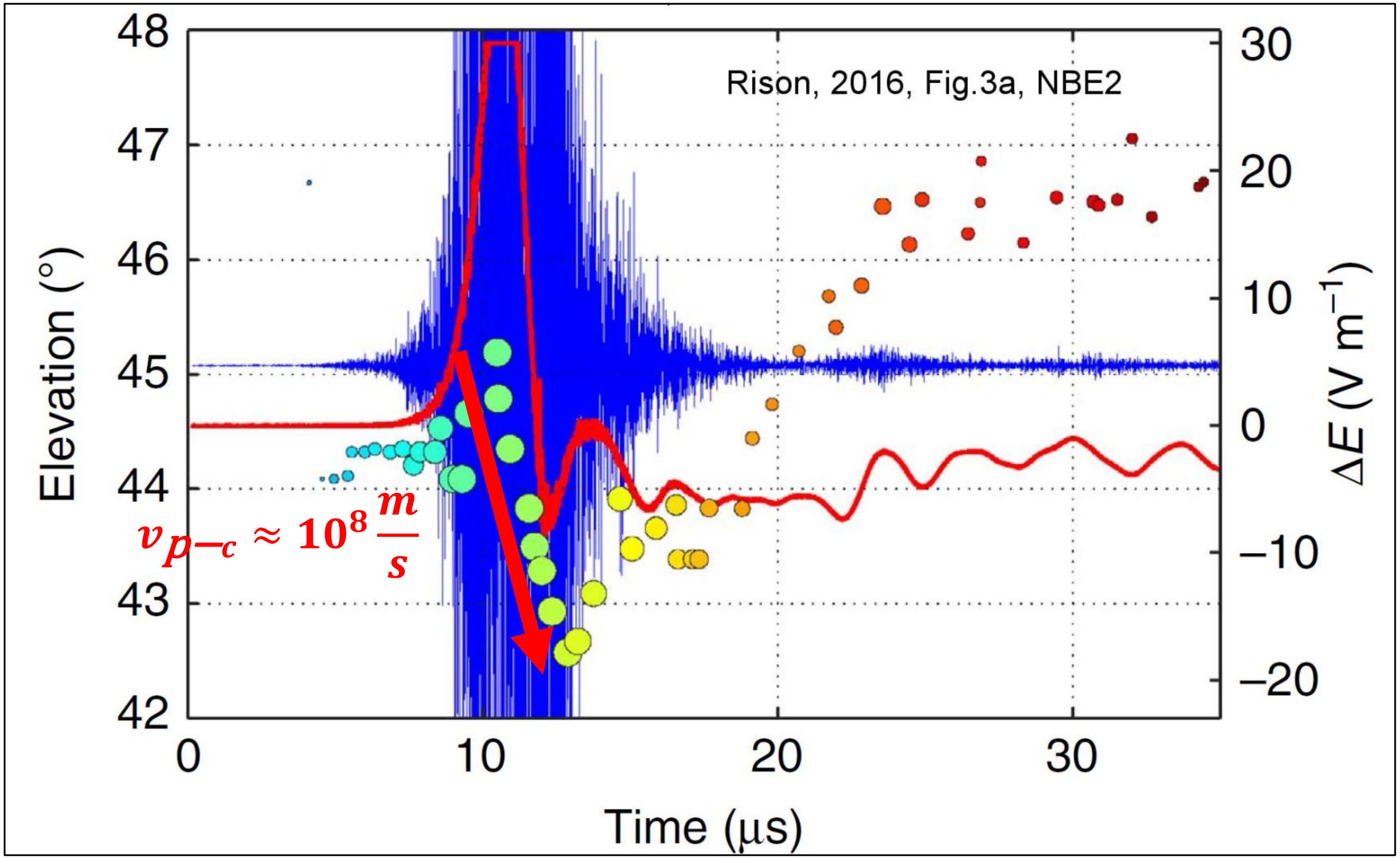


Speed of bright VHF-sources (points or centroids)

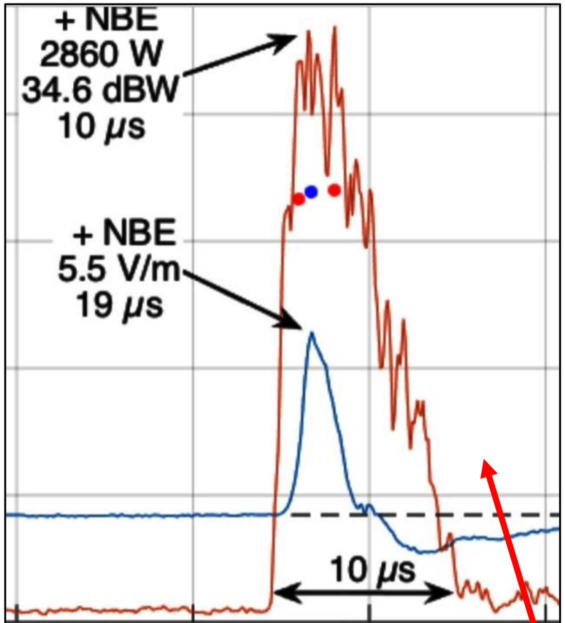
NBE2, Rison et al. (2016)

Q_{in}=0.5–0.7 C

I_{pk}=57 kA



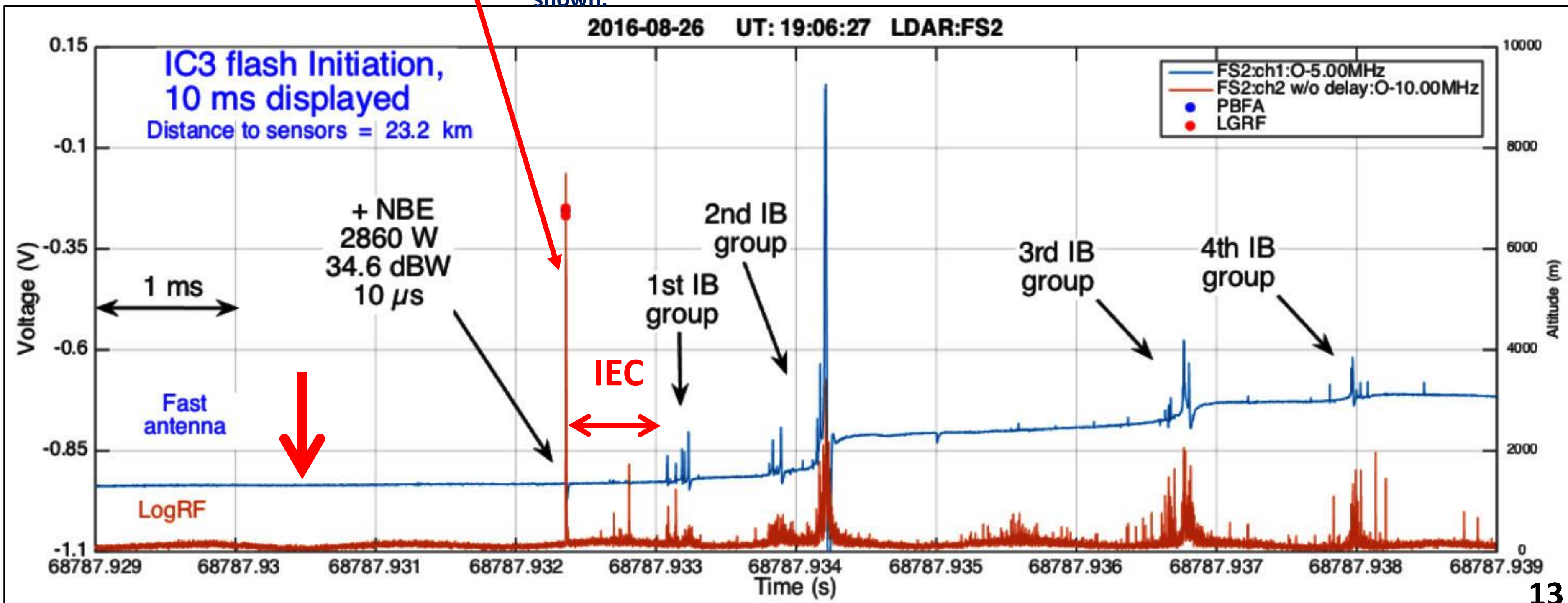
Подписи



NBE (CID) initiates lightning,

Marshall et al., 2019

Fig. 2 (a). (*from Marshall et all., 2019)* First 10 ms of lightning data of IC1, an IC flash on 5 August 2016 plotted versus time in seconds from midnight. Data from the IH sensors at a horizontal range of 19.0 km from the initiation events shown. The upper (blue) curve shows the Fast Antenna (FA) data (uncalibrated linear scale in volts, left axis); lower (red) LogRF curve shows VHF power (uncalibrated logarithmic scale in volts, left axis). PBFA locations of some FA pulses and LGRF locations of some LogRF pulses are plotted as altitude (right axis) versus event arrival time at the IH sensor. The initiation event along with its LogRF power and duration are indicated with an arrow. The first classic IB pulse along with its range-normalized amplitude (RNA, relative to 100 km) and duration are also shown.



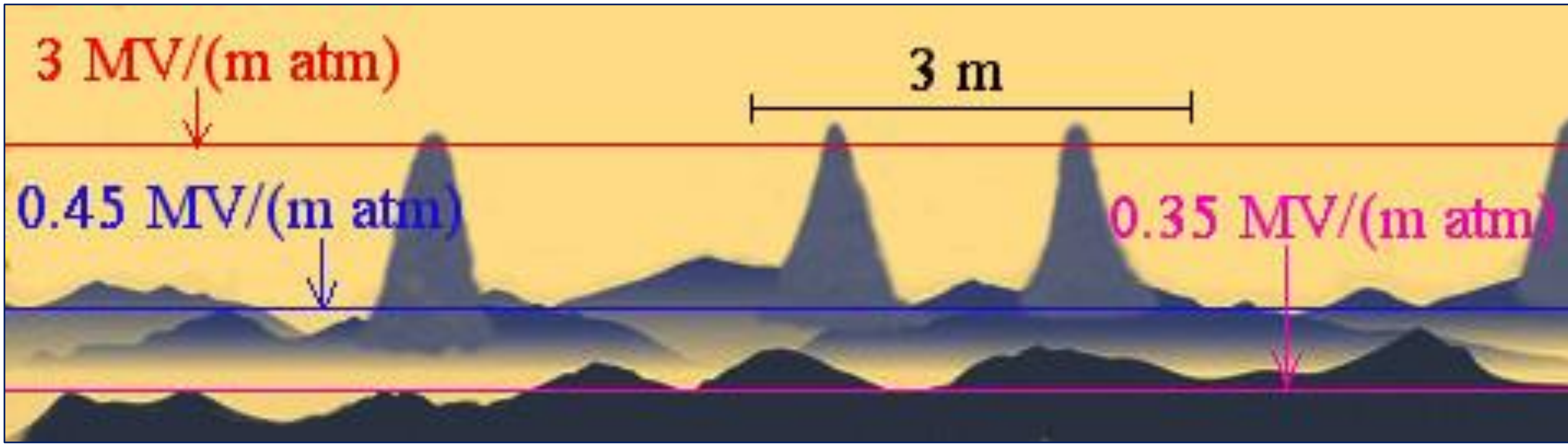
The requirements of the Mechanism of the birth of lightning

Kostinskiy, Marshall, Stolzenburg, 2019, arXiv:1906.01033

The origin of streamer flashes requires:

- Areas of 2-10 cm in size (from Meek's criterion) with fields E≥ 3 MV/(m·atm) are required (***initiation of streamers***, **"air electrode"**, E_{th}*-volume*)
- Areas of 10–100 m in size with electric fields Em ≥ 0.45–0.5 MV/ (m·atm) are needed. ***Maintain movement of streamers***
- We need the ***first electrons*** that create cosmic rays at an altitude of 5-20 km
- *Without a conductive plasma channel, only* ***relativistic particles*** *can provide a speed of* $0.5 - 1 \cdot 10^8 \, \frac{m}{s}$

The landscape of the electric field, which will provide a lot of streamer flashes in about 1 μs (NBE-CID)



Hydrodynamic and statistical processes in a thundercloud can create such an electric field landscape
(*Colgate, 1967; Trakhtengerts, 1989; Trakhtengerts et al., 1997; Mareev et al., 1999; Iudin et al., 2003; Iudin, 2017; Brothers et al., 2018*)

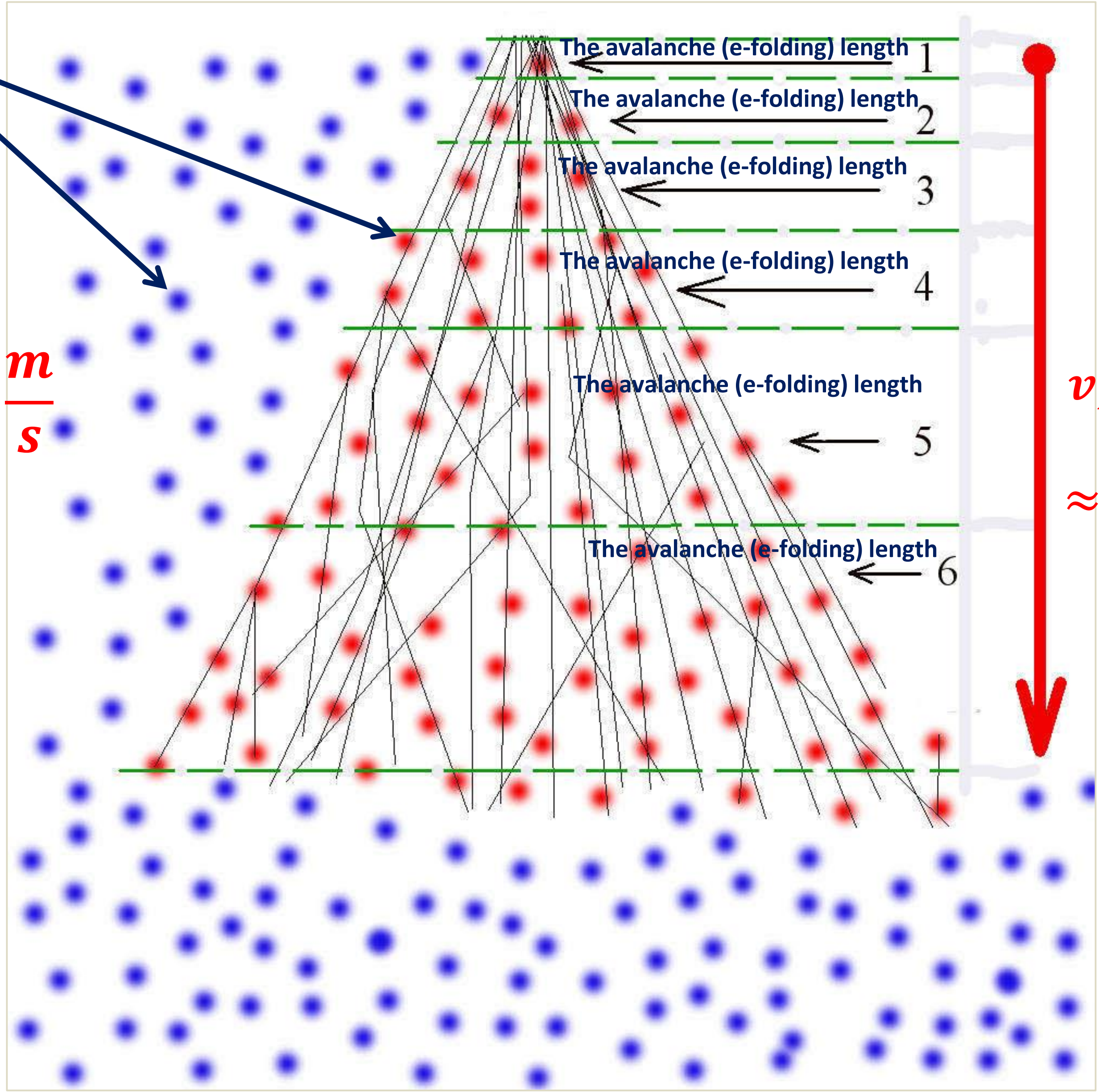
“Ignition” of the phase wave of streamer flashes by relativistic particles with a speed of $\approx 10^8\ m/s$ (fragment)

Kostinskiy, Marshall, Stolzenburg, 2019, arXiv:1906.01033

$$E_{th} \geq 3\ \frac{MV}{m \cdot atm}$$

$$v_{str} \approx 10^6 \frac{m}{s}$$

$$v_{NBE-FPB} \approx 10^8\ \frac{m}{s}$$



$$v_{NBE-FPB} \approx 10^8\ \frac{m}{s}$$

Estimation of the number of relativistic particles required for «ignition»

Kostinskiy, Marshall, Stolzenburg, 2019, arXiv:1906.01033

- Volume of strong turbulence area of a thundercloud ≈ $1\ km^3$ ≈ $10^9\ m^3$ *(E_{re}> 284 kV/(m·atm)*

- The relativistic particles cross all possible volumes with a breakdown field $\mathrm{E_{th}}$ with a diameter of 10 cm: $\mathrm{V} \approx 0.001\ \mathrm{m}^3 \cdot 1000 = 1\ \mathrm{m}^3$

- If we take into account the intersection of the trajectories of particles, the fall of the flow at an angle, statistical processes, then we can accept the estimate from above $10^{10}\ \mathrm{km}^{-3}$

- The lower estimate gives the number of particles (≈ $3 \cdot 10^4$), which initiates a cosmic particle with a "small" energy 10^{13}eV at altitudes of 5-15 km (*Anchordoqui et al. 2000, arXiv:astro-ph/0006141v2*)

$$\lambda = \frac{7300\ kV}{\left(E-(276\ kV/m)\cdot\frac{n}{n_0}\right)}, E = 300 - 2600\ kV/m$$

(*Dwyer, J.R., A fundamental limit on electric fields in air, GRL 30 (2003) 2055*)

If the external mean field at a height of 6 km is 294 kV/m, then by Dwyer's formula λ=46 m, considering that the ionizing relativistic particles are $3 \cdot 10^4$

$$N = 3 \cdot 10^4 \cdot \exp\left(\frac{600\ m}{46\ m}\right) \approx 1.4 \cdot 10^{10}$$

The Mechanism

1. We propose a mechanism for the appearance of lightning after initiation by NBEs (narrow bipolar events) or weaker initiating events (IE), in a turbulent cloud with strong local electric fields
2. These initial events are a volume of positive streamers initiated by the phase wave of relativistic particles and gamma photons
3. **Due to ionization-heating instability, unusual plasma formations (UPFs) appear along the trajectory of streamers, which are combined into long hot plasma channels**

Unusual Plasma Formations (UPFs)

Positive Streamers Transition to UPFs, which include a network of hot channels

(Kostinskiy et al., 2019)

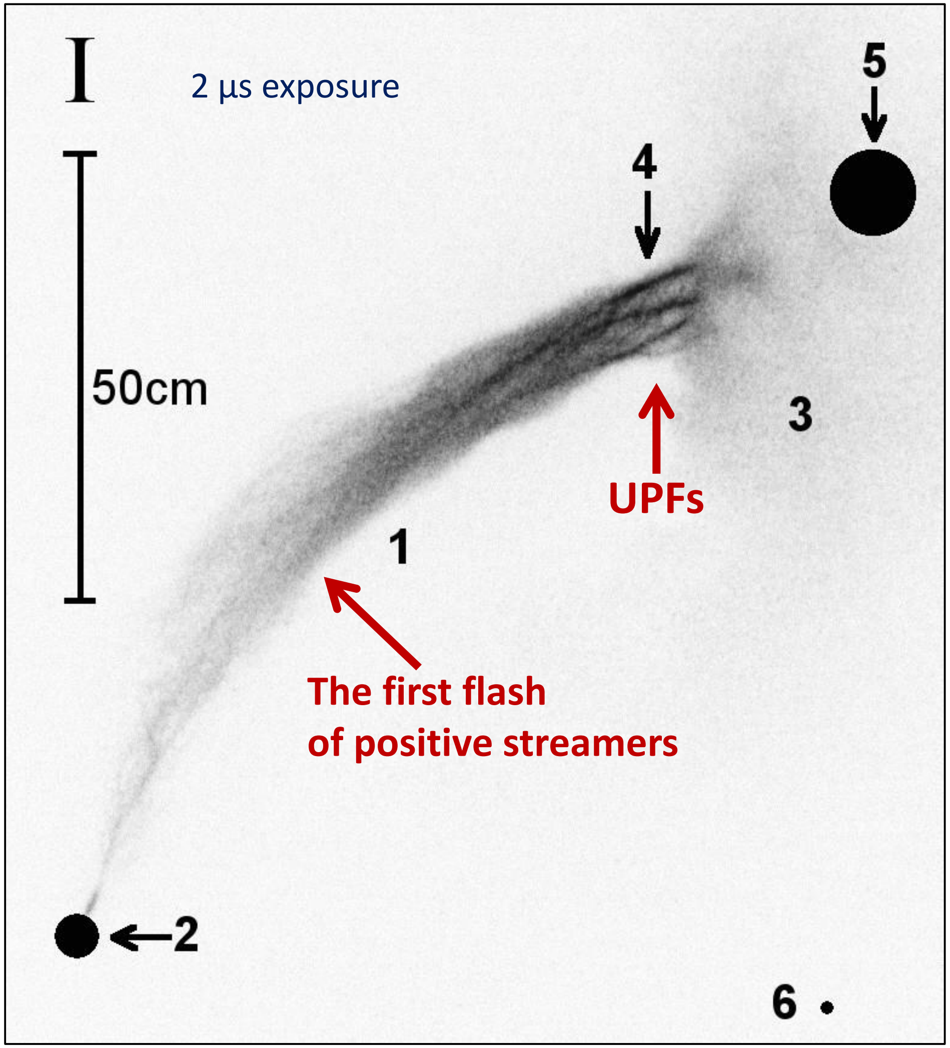
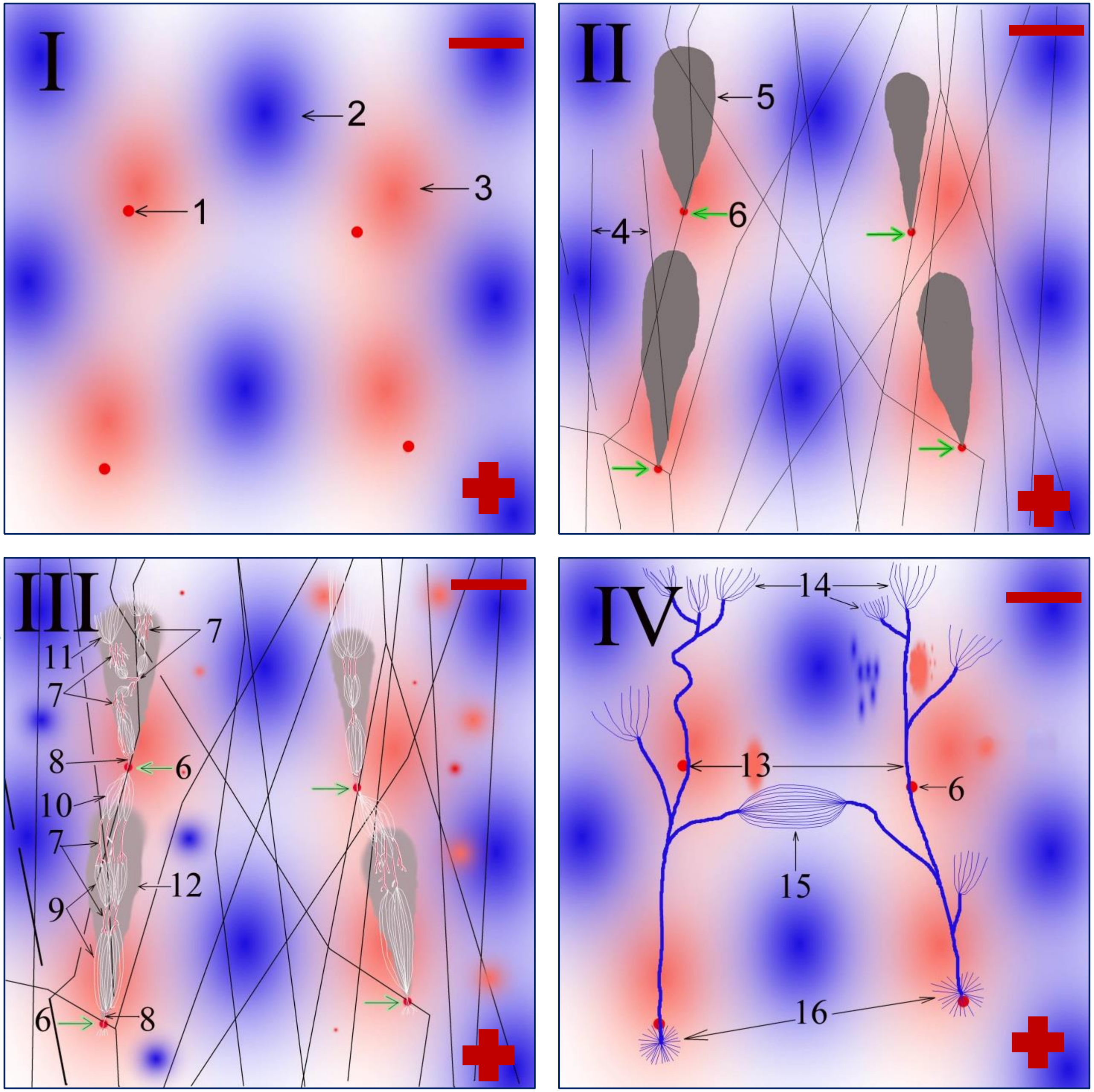


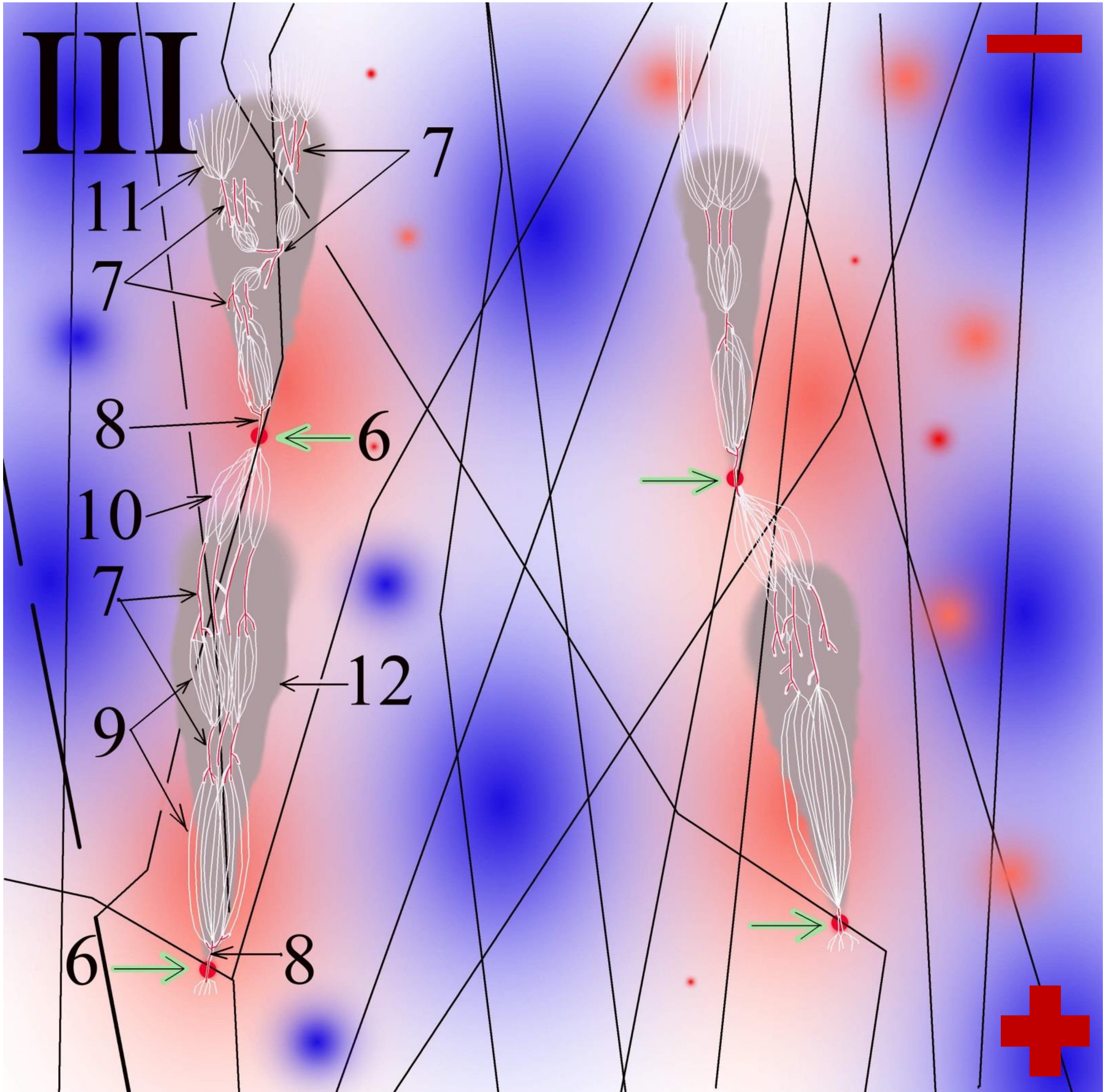
Figure 2b. (2015-12-04_03). The streamer flash started from a grounded electrode (2) in the electric field of a charged aerosol cloud. The two image were taken with a 4Picos camera with image enhancement: Numbered features: 1 - the first flash of positive streamers; 2 — 5 cm grounded sphere equipped with current-measuring shunt; 3 — cloud of charged water droplets; 4 — UPFs; 5 — the area of passage of the microwave beam; 6 — the center of the grounded plane where the nozzle is located; 7 — upward positive leader; 8 — streamer crown of a positive leader *(Kostinskiy et al., 2019).*

Lightning initiation mechanism due to NBE (CID) (fragment)

Kostinskiy, Marshall, Stolzenburg, 2019, arXiv:1906.01033

1,6 - area with Eth≥ 3 MV/(m·atm)
2 - area with E< 0.45-0.5 MV/(m·atm)
3 - area with Em ≥ 0.45-0.5 MV/(m·atm)
4 - runaway electron trajectories;
5 - positive streamer flashes;
7,8 - UPFs
9 - secondary streamer positive crowns connecting UPFs
10 - secondary streamer crowns connecting UPFs of two different streamer flashes
11 - positive crown before UPFs
12 - the trace of the first streamer flash
13 - hot highly conductive plasma channels
14 - streamer crowns of positive leaders
15 - streamer corona of two interacting large plasma channels
16 - flash negative leader crown




III
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Estimate of the number of breakdown areas to ensure NBE (CID) *charge* and *current*

Kostinskiy, Marshall, Stolzenburg, 2019, arXiv:1906.01033

- NBEs in *Rison et al. (2016)* were ***Q=0.5, 0.7 and 1.0 C***

- an "air electrode" of about (0.001 m^3), $E_{th} \geq 3\ \frac{MV}{m \cdot atm}$, $\boldsymbol{q_{str-fl} \approx 10^{-7} - 10^{-8} C}$

- *EE-volume of 1000x1000x1000 m into* $\boldsymbol{10^7 - 10^8}$ *equal volumes that are 100 m^3 (≈ 4.6 x 4.6 x 4.6 m), 10 m^3 (≈ 2.2 x 2.2 x 2.2 m)*

- *For a maximum current of NBE(CID) ≈ 50-100 kA with a flash current of 1 A, we need ≈ 10^5 (0.1 A, we need ≈ 10^6) "air electrode"*

The Mechanism

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3. Due to ionization-heating instability , unusual plasma formations (UPFs) appear along the trajectory of streamers, which are combined into long hot plasma channels
4. **Interaction of plasma channels that are formed close to each other leads to formation of three-dimensional plasma networks**
5. **Interaction of three-dimensional plasma networks leads to a series of breakdowns that are the source of initial breakdown pulses (IBPs)**

The need for three-dimensional parallel development of the initial channels of lightning

Kostinskiy, Marshall, Stolzenburg, 2019, arXiv:1906.01033

The charge of the IBPs must be stored in the corona sheaths of the initial channels

- **For an IBP charge of 0.44 C, and a charge/length of 0.1-0.2 mC/m, then need a total channel length of 2.2-4.4 km**

Note that this charge must be developed during the IEC which is only ≈ 200 µs for CG flashes. In this extremely short time, the bidirectional leader, even at a speed of $2 \cdot 10^5 \frac{m}{s} \left(0.2\ \frac{m}{\mu s}\right)$***, will only collect a maximum of 0.008 C***

- **Therefore, our mechanism assumes many short, “parallel” channels with a total length of 2.2-4.4 km rather than one long channel**

First IBP (IBP#1)

Kostinskiy, Marshall, Stolzenburg, 2019, arXiv:1906.01033

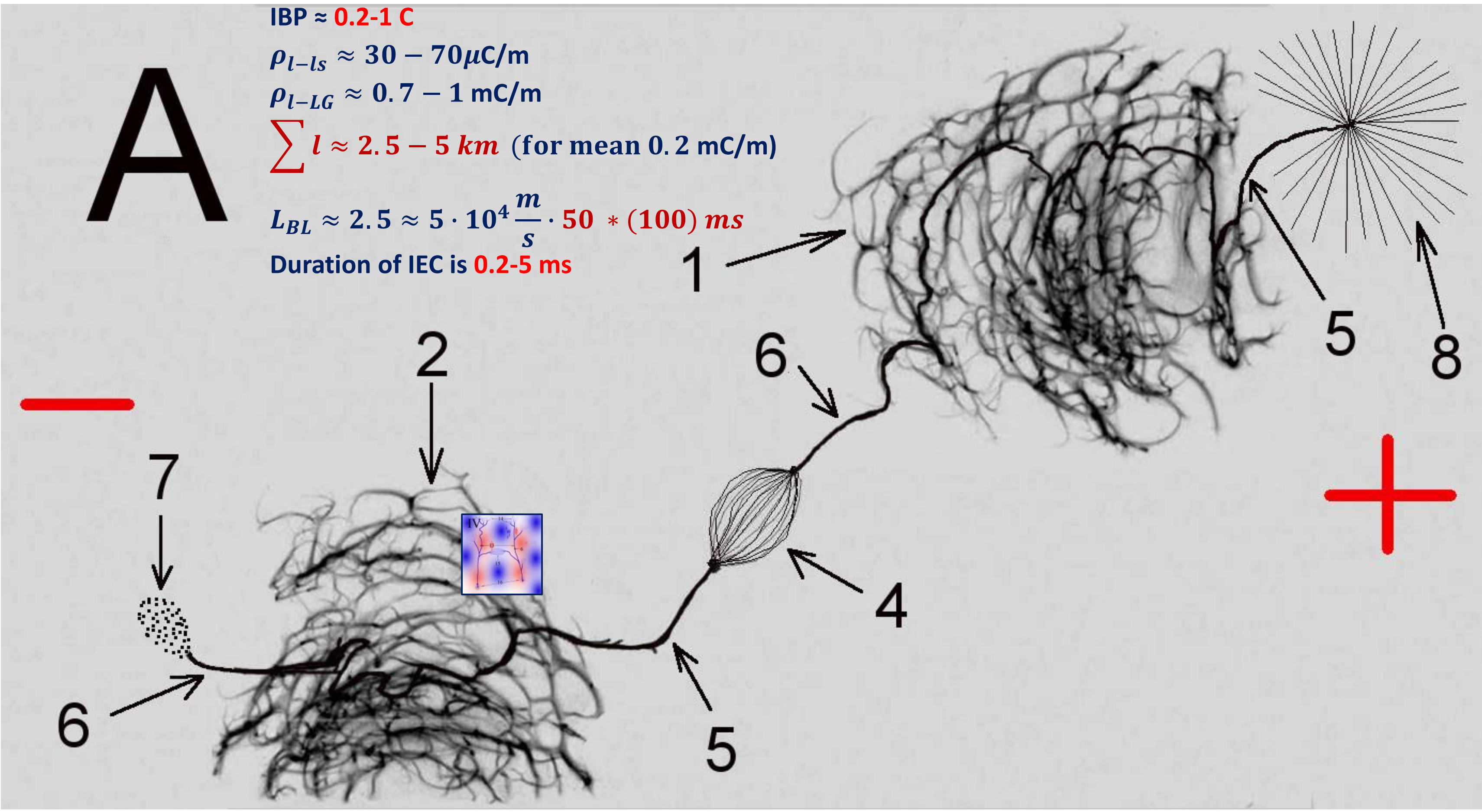
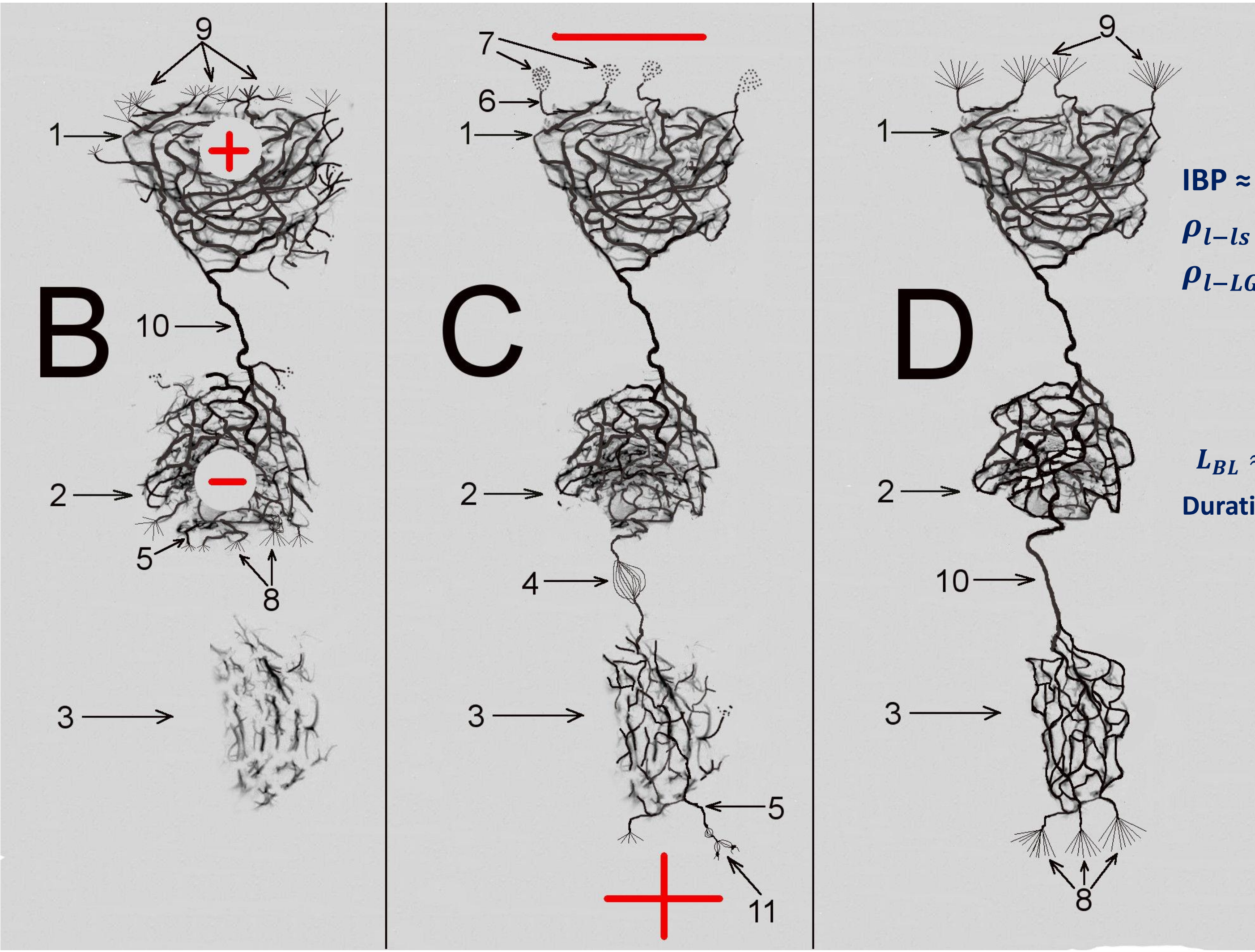


Figure 9 (sketch). A. Two plasma networks formed after the merger of UPFs interact with each other (the breakthrough phase of IBP#1). 1 - first plasma network, which was formed by the junction of many UPFs; 2 - second plasma network; 4 - the breakthrough phase contact of plasma networks; 5 - the negative leader; 6 - the positive leader; 7 - the streamer crown of the positive leader; 8 - flash of the streamer crown of the negative leader

Second IBP (IBP#2)



IBP ≈ 0.2-1 C

$\rho_{l-ls} \approx 30 - 70\mu\mathrm{C/m}$

$\rho_{l-LG} \approx 0.7 - 1\ \mathrm{mC/m}$

$$\sum l \approx 2.5 - 5\ km$$

(for mean 0.2 mC/m)

$L_{BL} \approx 2.5 \approx 5 \cdot 10^4 \frac{m}{s} \cdot 50 * (100)\ ms$

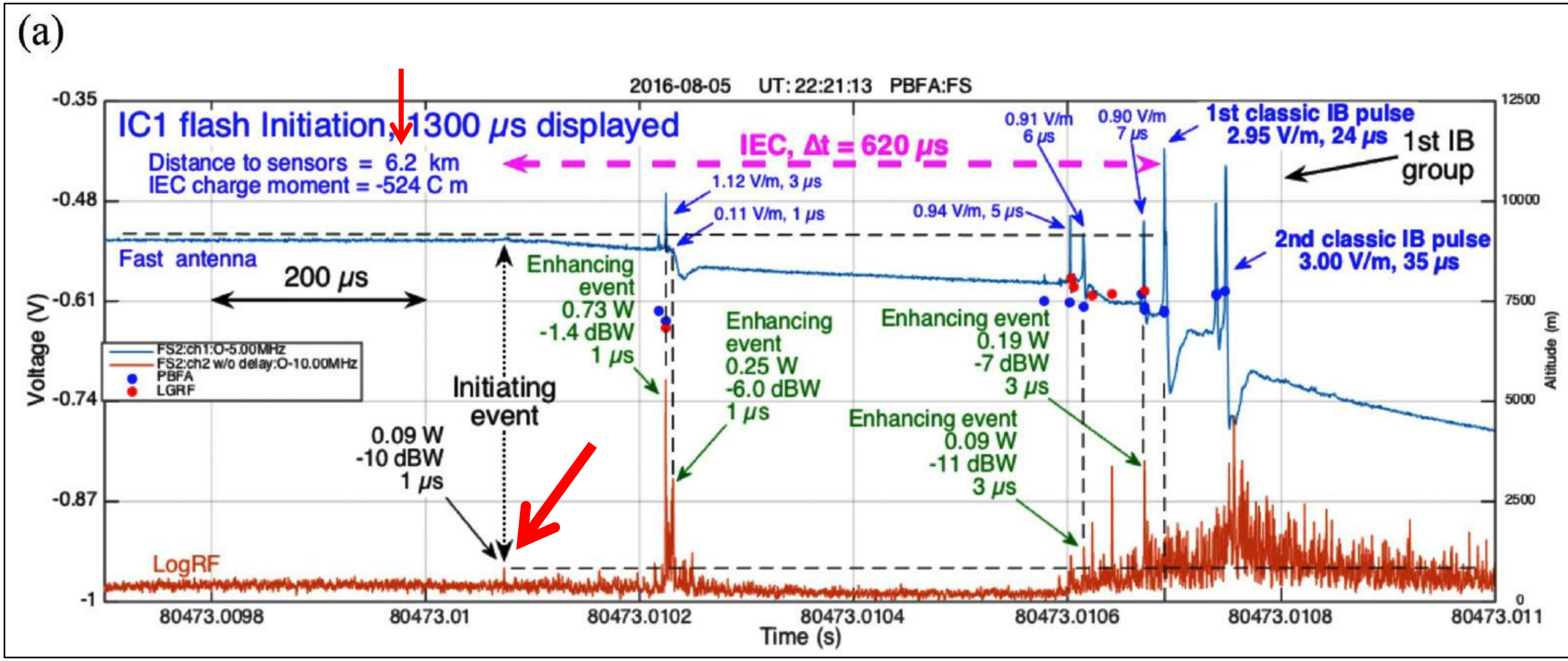
Duration of IEC is 0.2-5 ms

Kostinskiy, Marshall, Stolzenburg, 2019, arXiv:1906.01033

Figure 9 (sketch). B. The “return stroke” phase of IBP#1 at which two plasma networks merge. C. The breakthrough phase of IBP#2. D. The “return stroke” phase of IBP#2. Numbered features: 1 - first plasma network, which was formed by the junction of many UPFs; 2 - second plasma network; 3 - third plasma network; 4 - the breakthrough phase contact of plasma networks; 5 - the negative leader; 6 - the positive leader; 7 - the streamer crown of the positive leader; 8 - flash of the streamer crown of the negative leader; 9 - flash of the streamer crown of the positive leader; 10 - the plasma channel of the “return stroke” phase; 11 - the streamer crown of the negative leader

Weak event triggers lightning (Initiating Event) ≈ 88% IC and 96% CG

Marshall et al.(2019)



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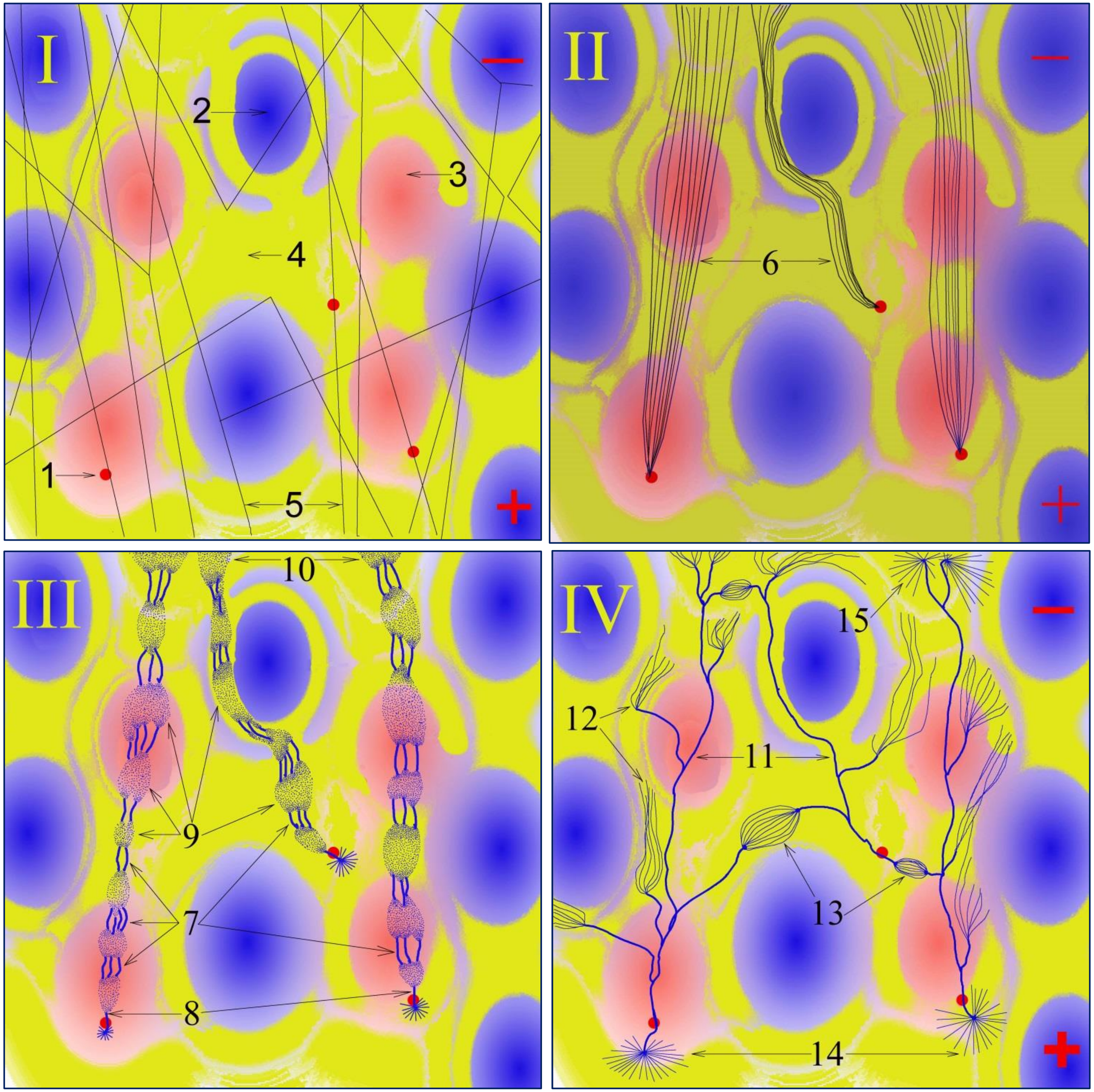
The IE initiates a lightning (fragment)

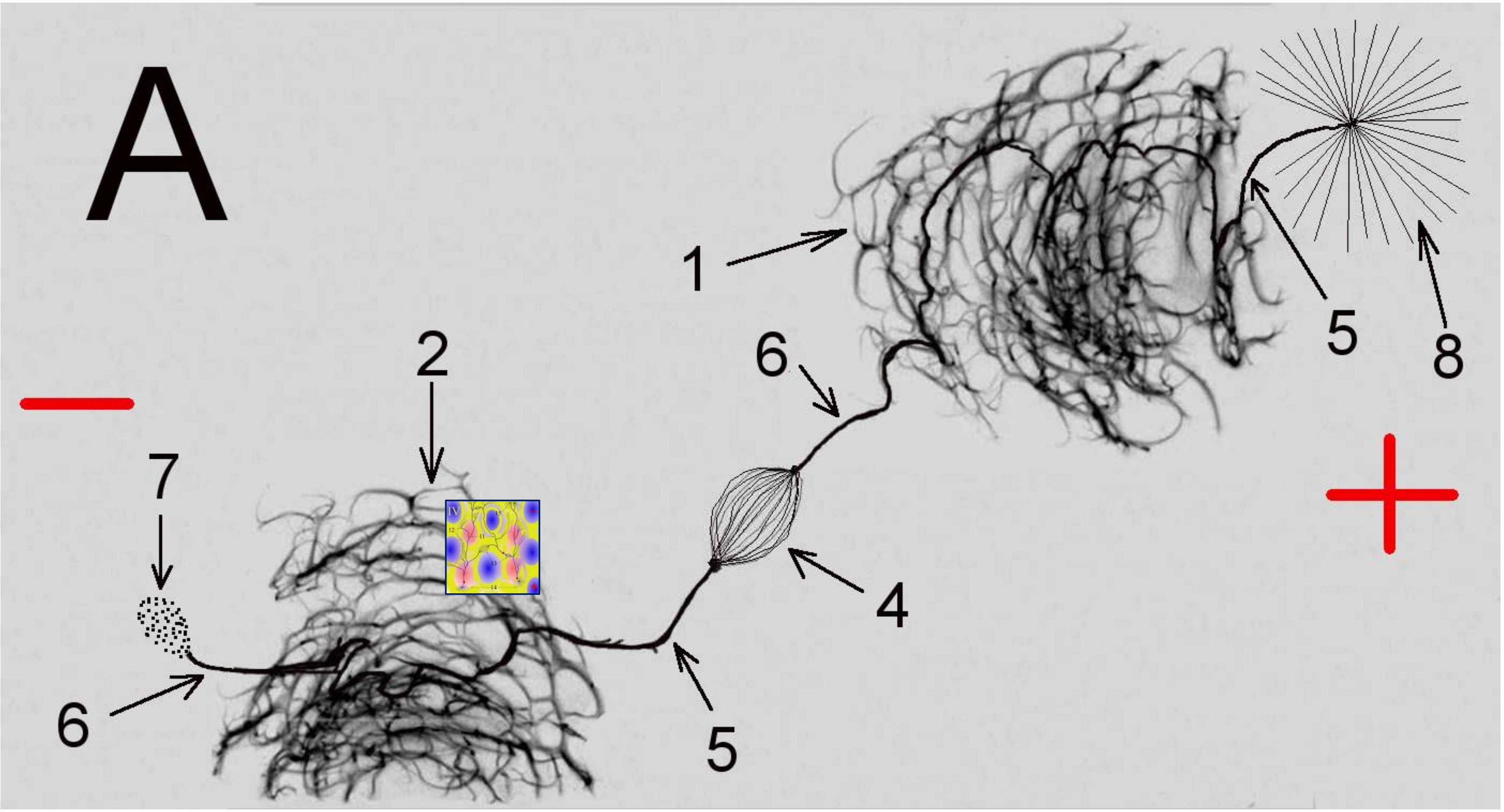
Kostinskiy, Marshall, Stolzenburg, 2019, arXiv:1906.01033

Figure 10 (sketch):
1 - area with E≥ 3 MV/(m· atm)
2 - area with E< 0.45-0.5 MV/(m·atm)
3 - area with E ≥ 0.45-0.5 MV/(m·atm)
4 - area with E≈ 0.45-0.5 MV/(m·atm)
5 - runaway electron trajectories
6 - long positive streamer flashes
7,8 – UPFs
9 - secondary streamer crowns connecting UPFs
10 - positive crown ahead of UPF
11 - hot highly conductive plasma channels
12 - positive streamer crowns of positive leaders
13 - positive streamer corona of two interacting large plasma channels
14 - negative leader crown flash
15 - positive leader crown flash



First IBP (IBP#1)

Kostinskiy, Marshall, Stolzenburg, 2019, arXiv:1906.01033



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4. Interaction of plasma channels that are formed close to each other leads to formation of three-dimensional plasma networks
5. Interaction of three-dimensional plasma networks leads to a series of breakdowns that are the source of initial breakdown pulses (IBPs)
6. **Successive breakdowns along the extending path eventually make a conductive channel that can support a stepped leader process**

Questions?

Distances between plasma objects (NBE/CID)

Bandara, Marshall et al., 2019

v_L - *Leader velocity*

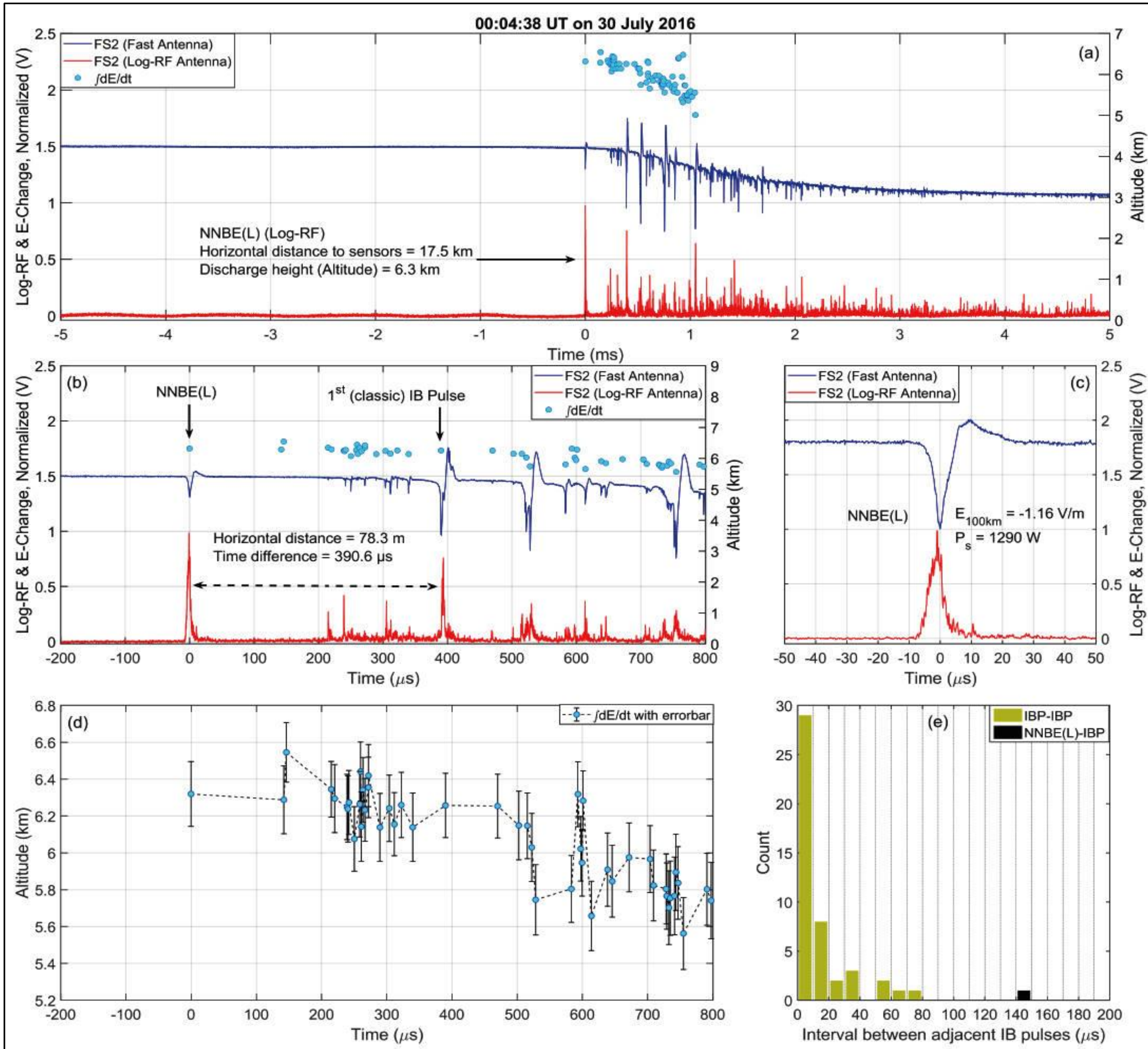
$$v_L \approx 0.02 - 0.1\ \frac{m}{\mu s}$$

$v_{L_{br}}$ - *Leader velocity in the breakthrough phase*

$$v_{L_{br}} \approx 0.1 - 0.3\ \frac{m}{\mu s}$$

D_{ch} - *distance between plasma channels*

$$D_{ch-NBE} \approx 0.1\ \frac{m}{\mu s} \cdot (10 - 100)\mu s \approx (1 - 10)\ m$$



Distances between plasma objects (IE)

Bandara, Marshall et al., 2019

v_L - *Leader velocity*

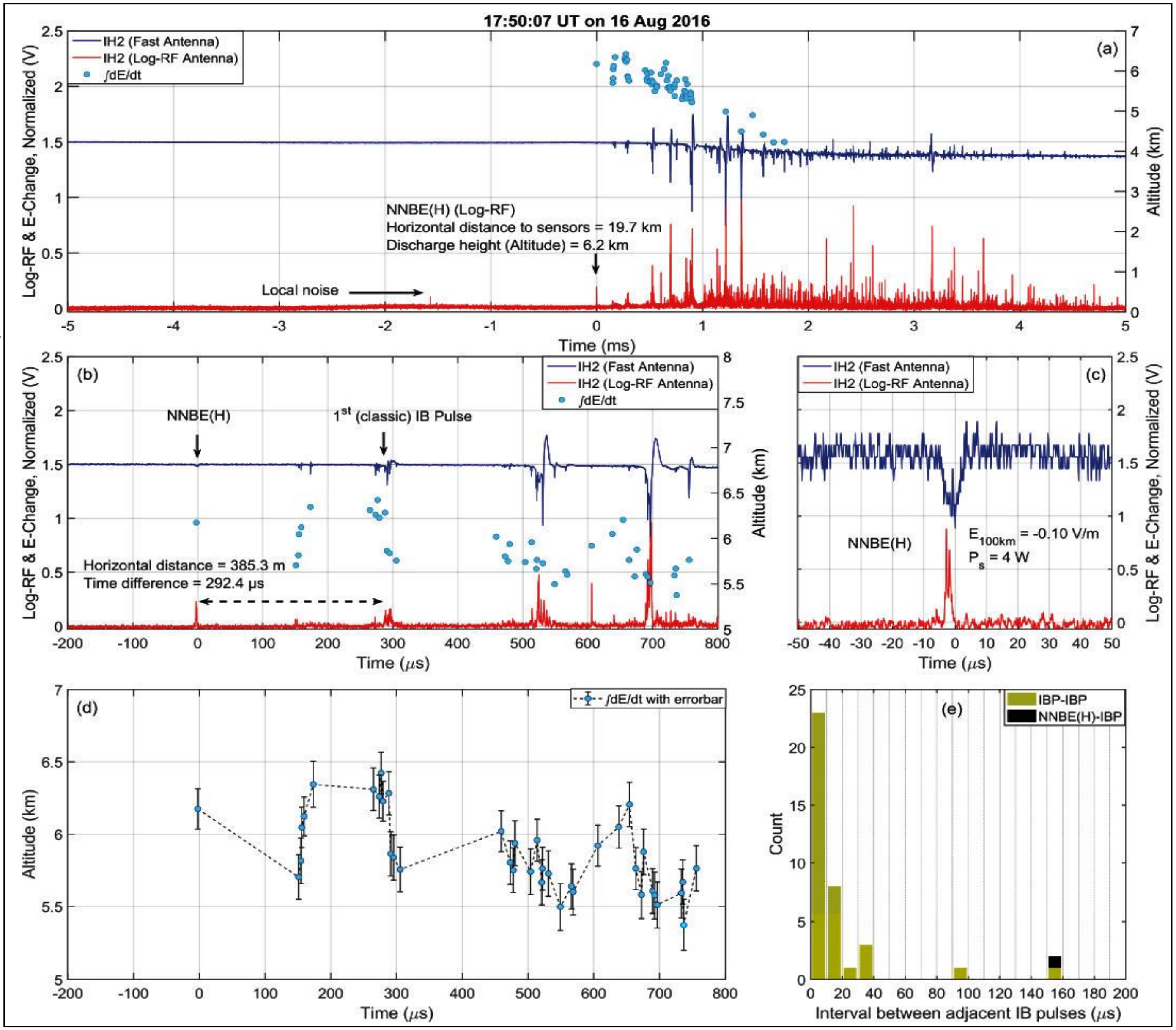
$$v_L \approx 0.02 - 0.1\ \frac{m}{\mu s}$$

$v_{L_{br}}$ - *Leader velocity in the breakthrough phase*

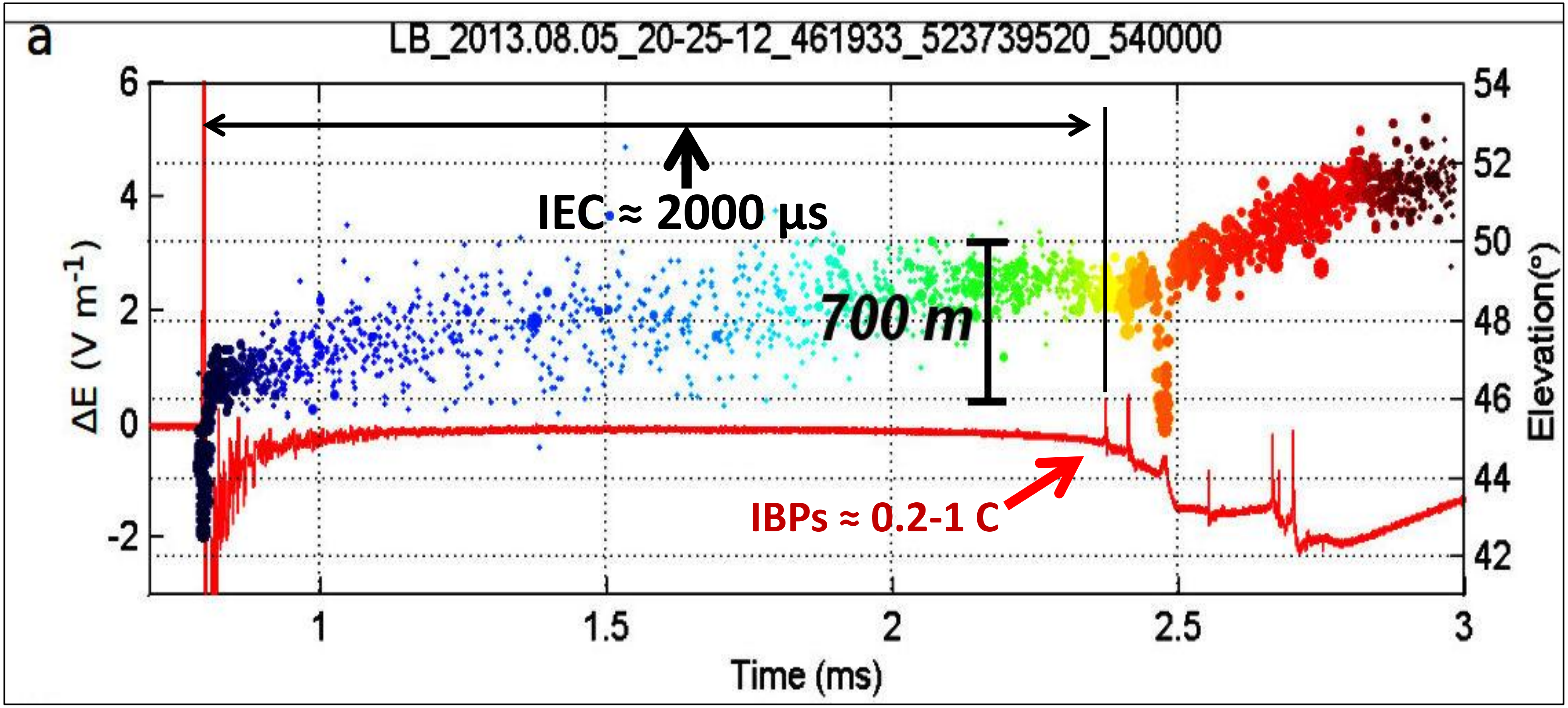
$$v_{L_{br}} \approx 0.1 - 0.3\ \frac{m}{\mu s}$$

D_{ch} - *distance between plasma channels*

$$D_{ch-IE} \approx 0.1\ \frac{m}{\mu s} \cdot (10 - 150)\mu s \approx (1 - 15)\ m$$



Many 3D VHF events in volume during IEC, 2000 μs NBE(CID) initiates lightning; *NBE2, Rison et al., 2016*



Supplementary Figure 6: Initial activity of the NBE2 flash. a, Detailed INTF and FA observations for the first 2 ms of the IC flash initiated by NBE2, illustrating the two-stage nature of the negative breakdown: i) gradual upward development during the 1.5 ms-duration initial electric field change (IEC), ii) the fine structure of the first initial breakdown pulse (IBP) following the IEC, iii) the occurrence of the second NBE (downward orange sources) at the beginning of the IBP, and iv) the accelerated upward development associated with the IBP. The IEC (blue and green sources) extended the discharge 500 m at an estimated speed of 3·10^5 m/s, and the IBP (yellow and red sources) extended the discharge a similar additional distance at 1 · 10^6 m/s. In this and other figures, the INTF sources are coloured by time and and sized logarithmically by power.

Rison et al. (2016), Observations of narrow bipolar events reveal how lightning is initiated in thunderstorms, Nature Comms. 7:10721, doi:10.1038/ncomms10721.

Many 3D VHF events in volume during IEC, 230 μs

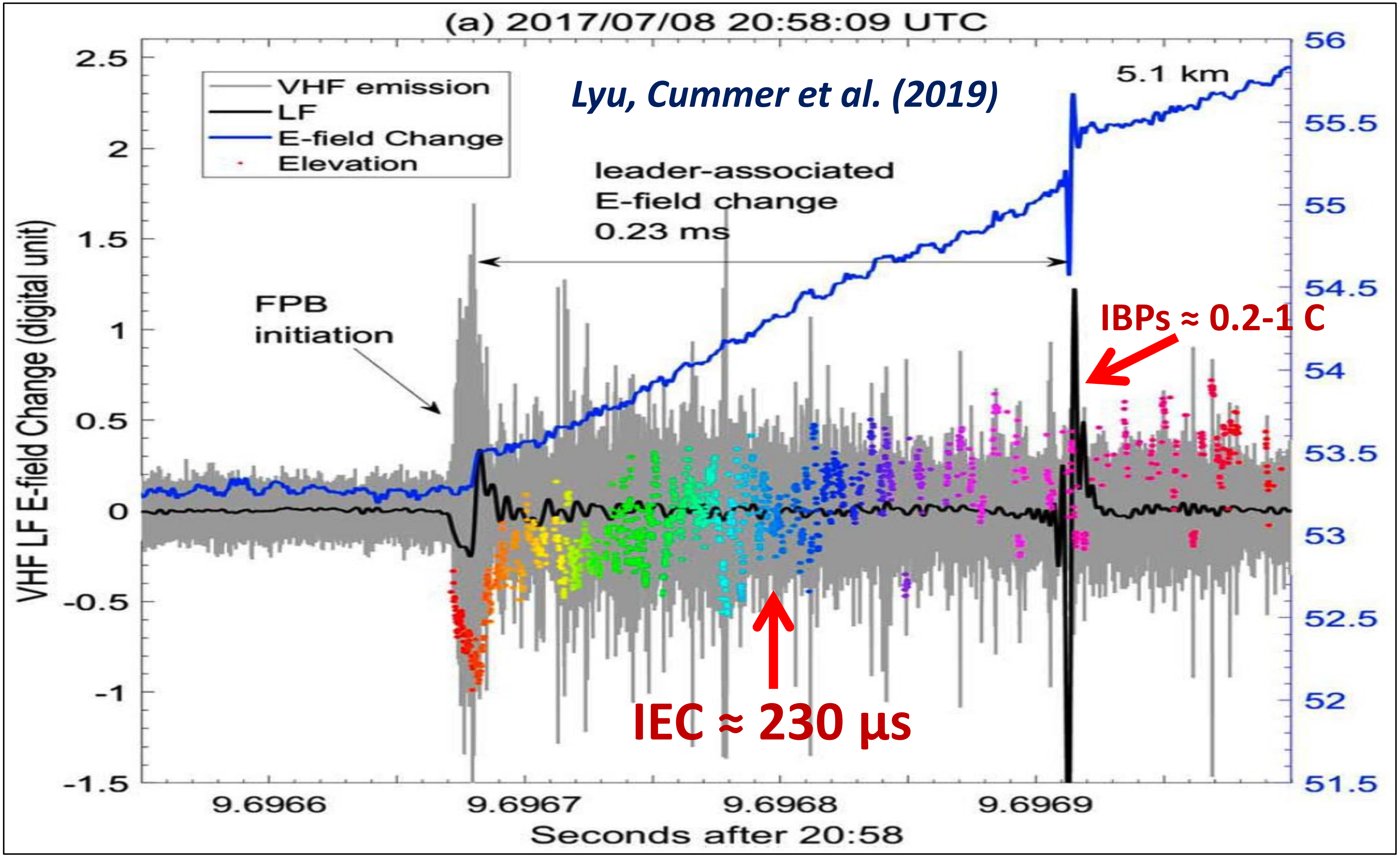


Figure ***6a (Lyu, Cummer et al., 2019)*****. Two examples of electric field change associated with the very high frequency (VHF) initiation events. The VHF emission (gray), low-frequency (LF) magnetic field emission (black), electric field change waveform (blue), and the VHF source elevation (colored dots starting with red) of the initial breakdown process from two flashes occurred at close range are illustrated. Panel (a) show an IC initial leaders started with a relatively weaker fast positive breakdown (FPB) event. Panel (b) shows IC initial leader started with the newly identified short duration VHF event. The two magenta dashed lines in panel**

The Mechanism

arXiv:1906.01033 [physics.ao-ph], [v1] Mon, 3 Jun 2019

1. We propose a mechanism for the appearance of lightning after initiation by NBEs (narrow bipolar events) or weaker initiating events (IE), in a turbulent cloud with strong local electric fields
2. These initial events are a volume of positive streamers initiated by the phase wave of relativistic particles and gamma photons
3. Due to ionization-heating instability , unusual plasma formations (UPFs) appear along the trajectory of streamers, which are combined into long hot plasma channels
4. Interaction of plasma channels that are formed close to each other leads to formation of three-dimensional plasma networks
5. Interaction of three-dimensional plasma networks leads to a series of breakdowns that are the source of initial breakdown pulses (IBPs)
6. **Successive breakdowns along the extending path eventually make a conductive channel that can support a stepped leader process**

Simple estimates: the need to “ignite” ordinary streamer flashes with relativistic particles

Kostinskiy, Marshall, Stolzenburg, 2019, arXiv:1906.01033

<u>Conditions for the occurrence of NBE (CID):</u>

- **A conductive plasma channel does not exist prior to the start of a NBE (CID)**
- The NBE (CID) should emit weak light in the visible range
- Total charge NBE (CID): 0.3-1 C
- Powerful VHF signal (Without conductive hot channel presence)

lightning strikes cannot provide it either

- VHF-Rise Time ≈ 0.5-2 μs
- Speed of bright VHF-sources (points or centroids) $v \approx 0.5 - 1 \cdot 10^8 \frac{m}{s}$
- At pressures p ≈ 0.3-1 atm and electric fields $E \leq 4 \frac{MV}{m}$

streamer speed $v_{str} \leq 6 \cdot 10^6 \frac{m}{s}$

The need for three-dimensional parallel development of the initial channels of lightning

The charge that discharges lightning is in the covers of the leaders

Kostinskiy, Marshall, Stolzenburg, 2019, arXiv:1906.01033

The required length of the channels, which will ensure the transfer of charge IBPs:

- **Total charge IBPs = 0.2-1 C**
- **Linear charge density of a long spark,** $\rho_{l-ls} = 0.03 - 0.07$ **mC/m**
- **Linear charge density of the negative leader of advanced lightning,** $\rho_{l-LG} = 0.7 - 1$ **mC/m**
- **The required channel length is equal to** $\sum l = 2.5 - 5\ km$ (for mean 0.2 mC/m)
- **The time required for accumulation of charge**

$$L_{BL} = 2.5 - 5\ km = 5 \cdot 10^4 \frac{m}{s} \cdot 50\ (100)\ ms$$

- **Duration of IEC is 0.2-5 ms**

"Normal" streamer flash E_{el}= 4.17 MV/m

Maximum experimental speeds(p=0.3-1 atm)

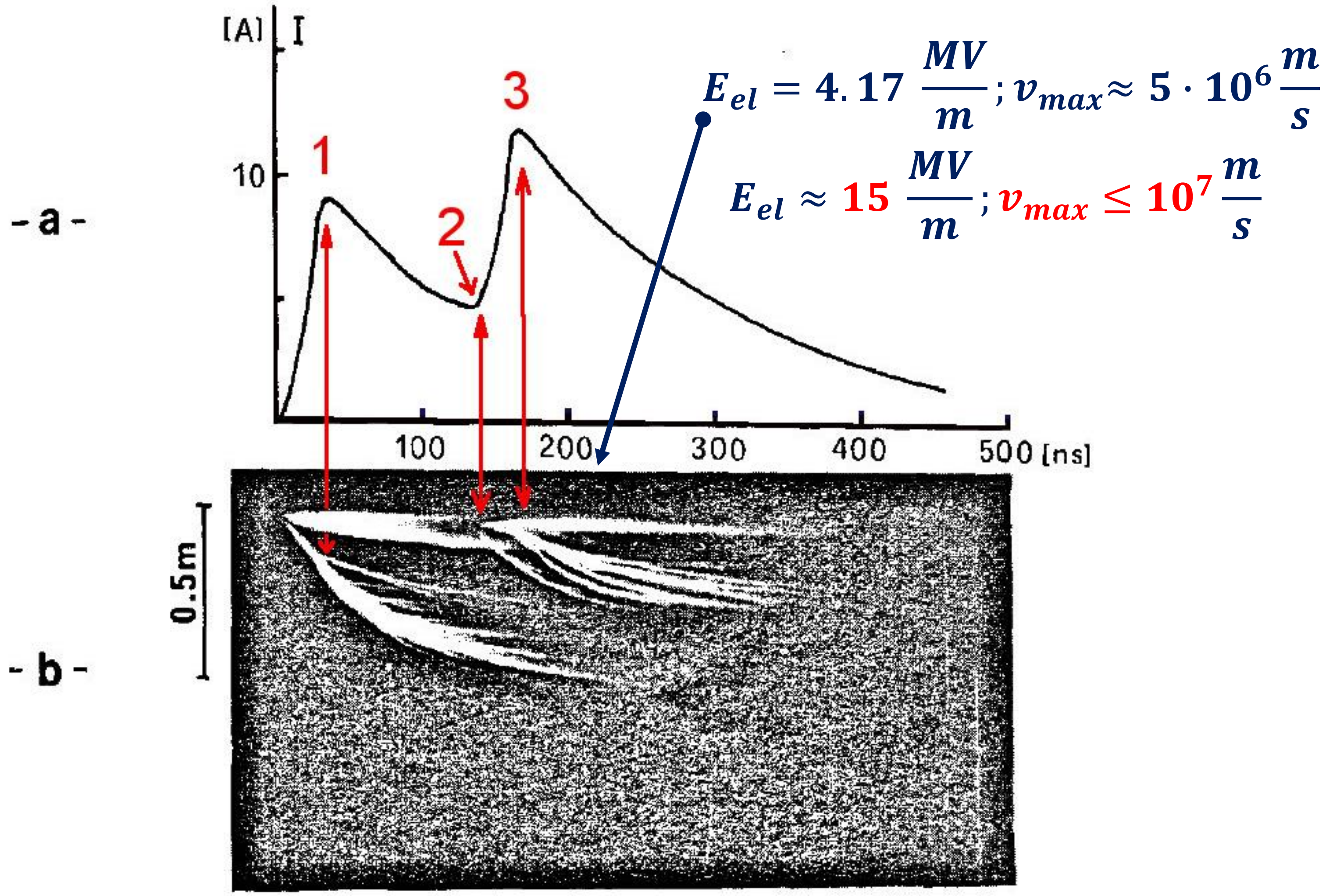


Figure 1. **A typical streamer flash starting from a metal electrode. Overvoltage leads to an electric field of 4.17 MV/m on the electrode surface at the start of a streamer flash. The diameter of the electrode is 25 cm. The voltage front is 200 µs, the rod-plane gap is 4 m. (a) current at the HV electrode; (b) simultaneous image-converter picture, total sweep: 500 ns** *(Les Renardières Group, 1977, Figure 3.4, p.41)*

Длинная тримерная вспышка вверху

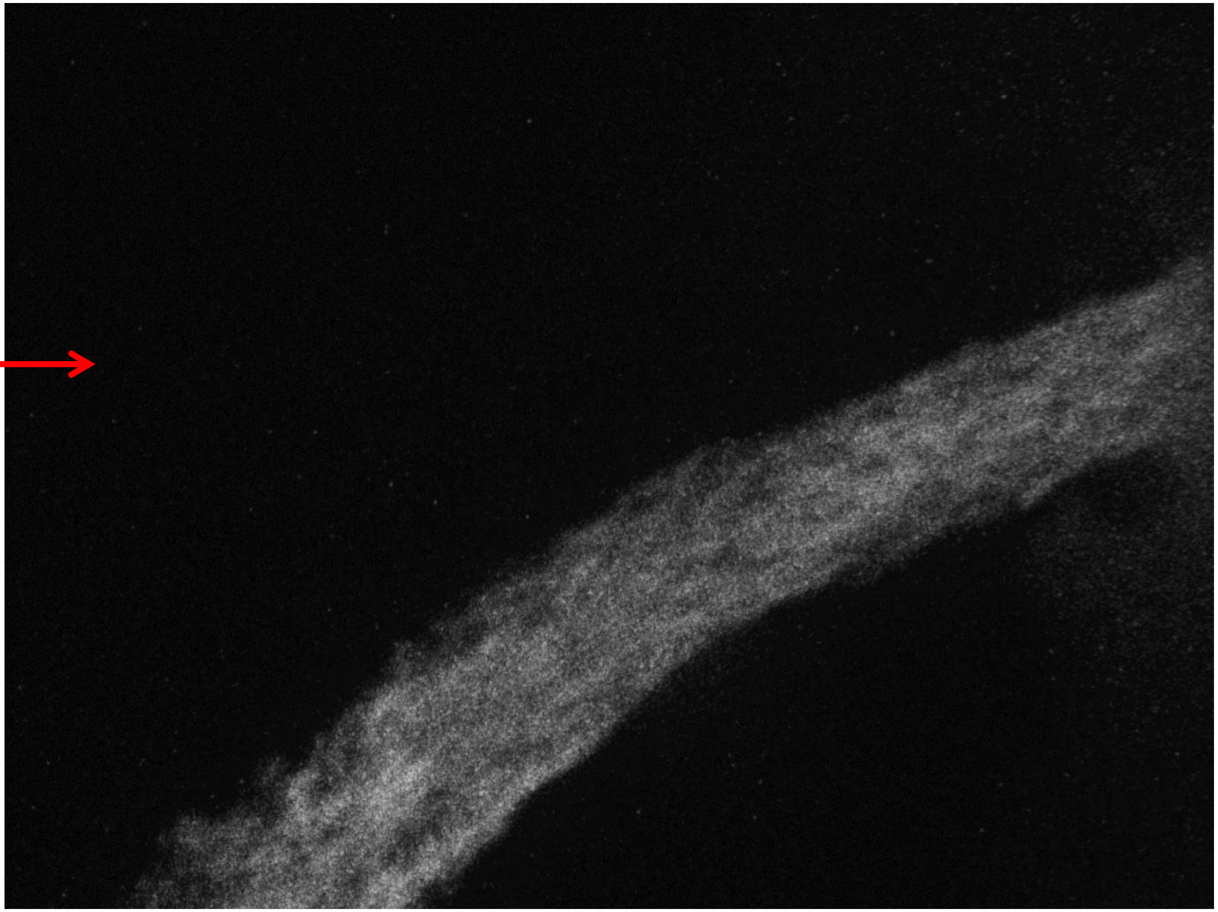
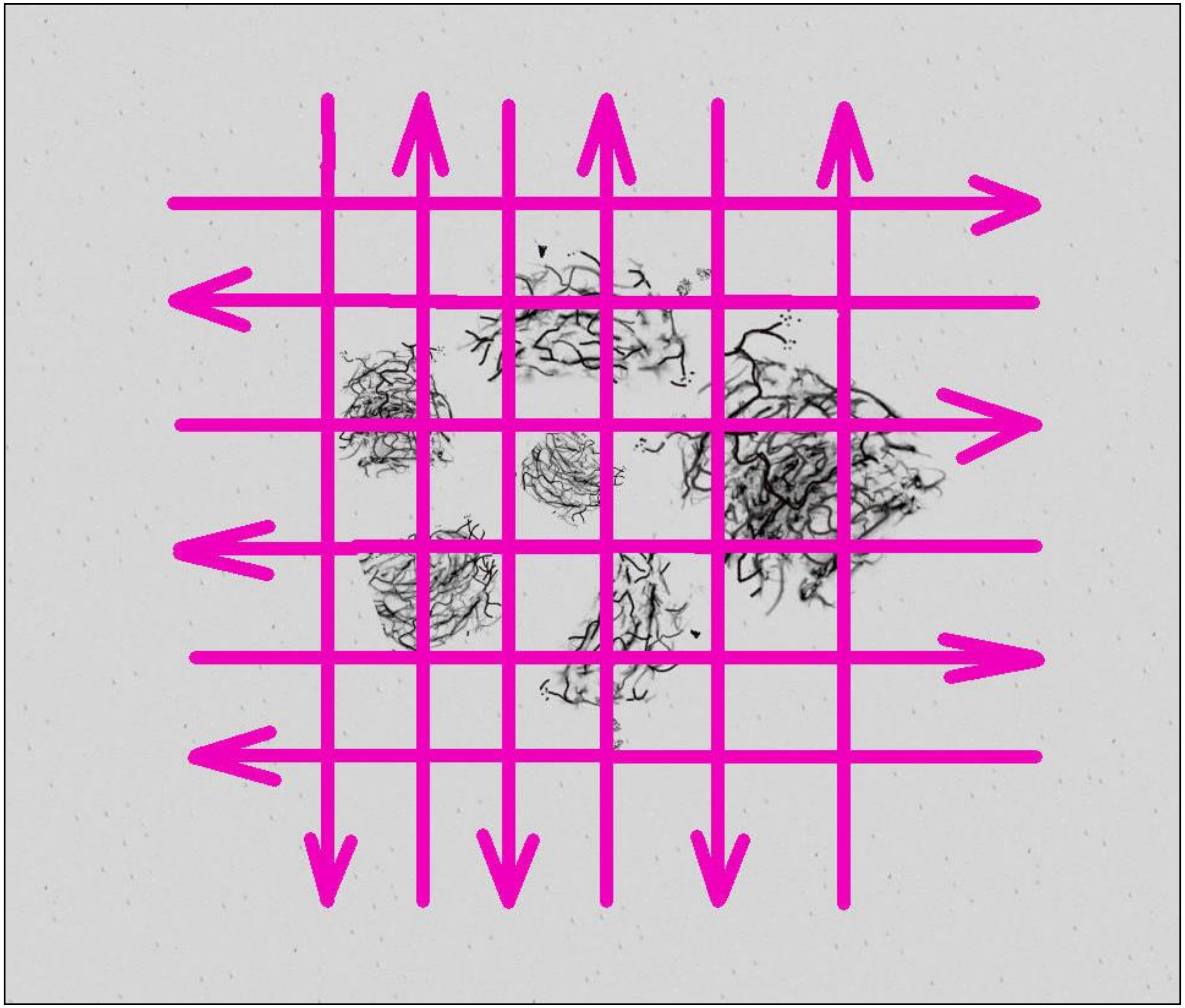
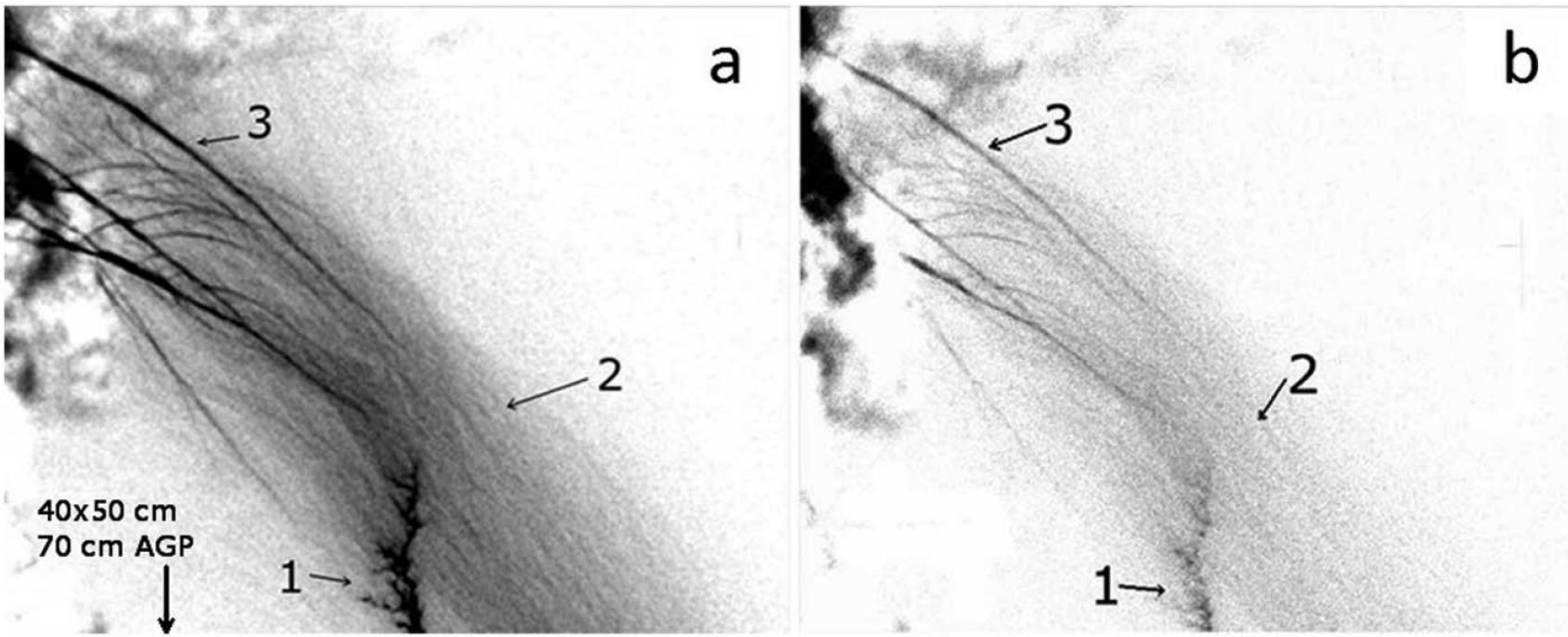


Рис. 16 (21-2014-03-05-Picos-0-100нс) задержка от начала разряда составляет 2,5 мкс, то даже при выдержке 100 нс

Experimental verification of the Mechanism with LMA and Active Phased Array Antennas (AFAA-AFAR)



Unusual Plasma Formations (UPFs)
Positive Streamers Transition to UPFs, which include a network of hot channels



re 2. Two consecutive infrared images (negatives) obtained with 6.7 ms exposure and separated by 2 ms that s
ıus discharge processes inside the cloud. Only flashes of scattered light, as opposed to distinct channels, were
ːrved during this event in the visible range. 1: upper part of the upward positive leader (its lower part, developin
' air, is outside the field of view of the IR camera), 2: streamer zone, 3: unusual plasma formation (UPF). AGP stand
ve the grounded plane."

Плотность гидрометеоров

	Reflect. dBZ	Liquid H_2O ?	Small ice 25-1000 μm	ice > 1 mm	ice > 3mm	Max. diam.
Weak core (Dye 1986)	40	yes	$2000/m^3$	$200/m^3$	$4/m^3$	7 mm
Anvil (Dye 2007)	12	no	$200{,}000/m^3$	$1000/m^3$	$10/m^3$	4 mm (?)

Идеальные точки Нью-Мехико-тим