Extracting the meter-scale structure of lightning plasma with the LOFAR telescope

Brian Hare
& LOFAR Lightning collaboration

European Research Council
Established by the European Commission

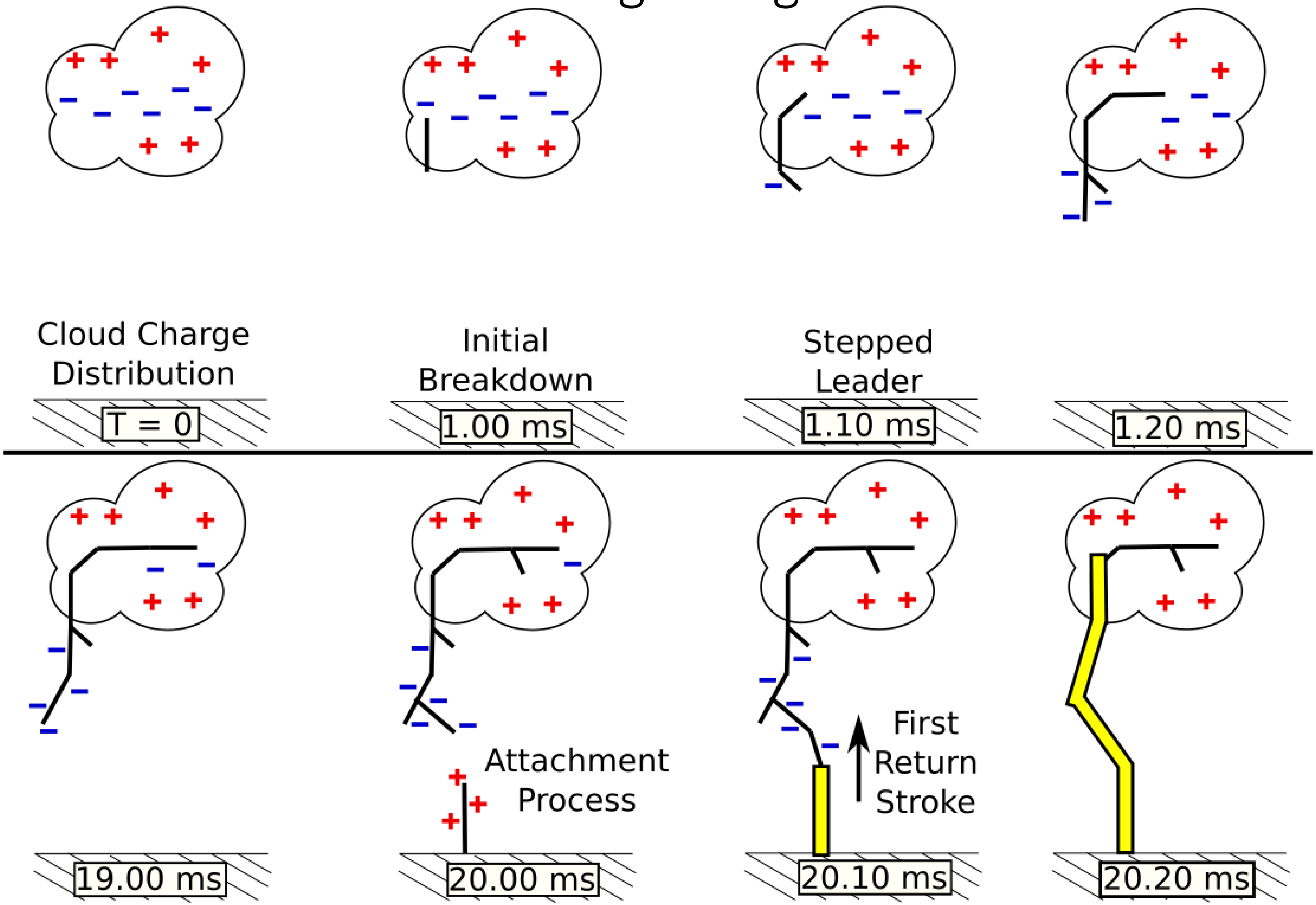
university of groningen

University of New Hampshire

VRIJE UNIVERSITEIT BRUSSEL

ASTRON
Netherlands Institute for Radio Astronomy

The Basic Lightning Processes



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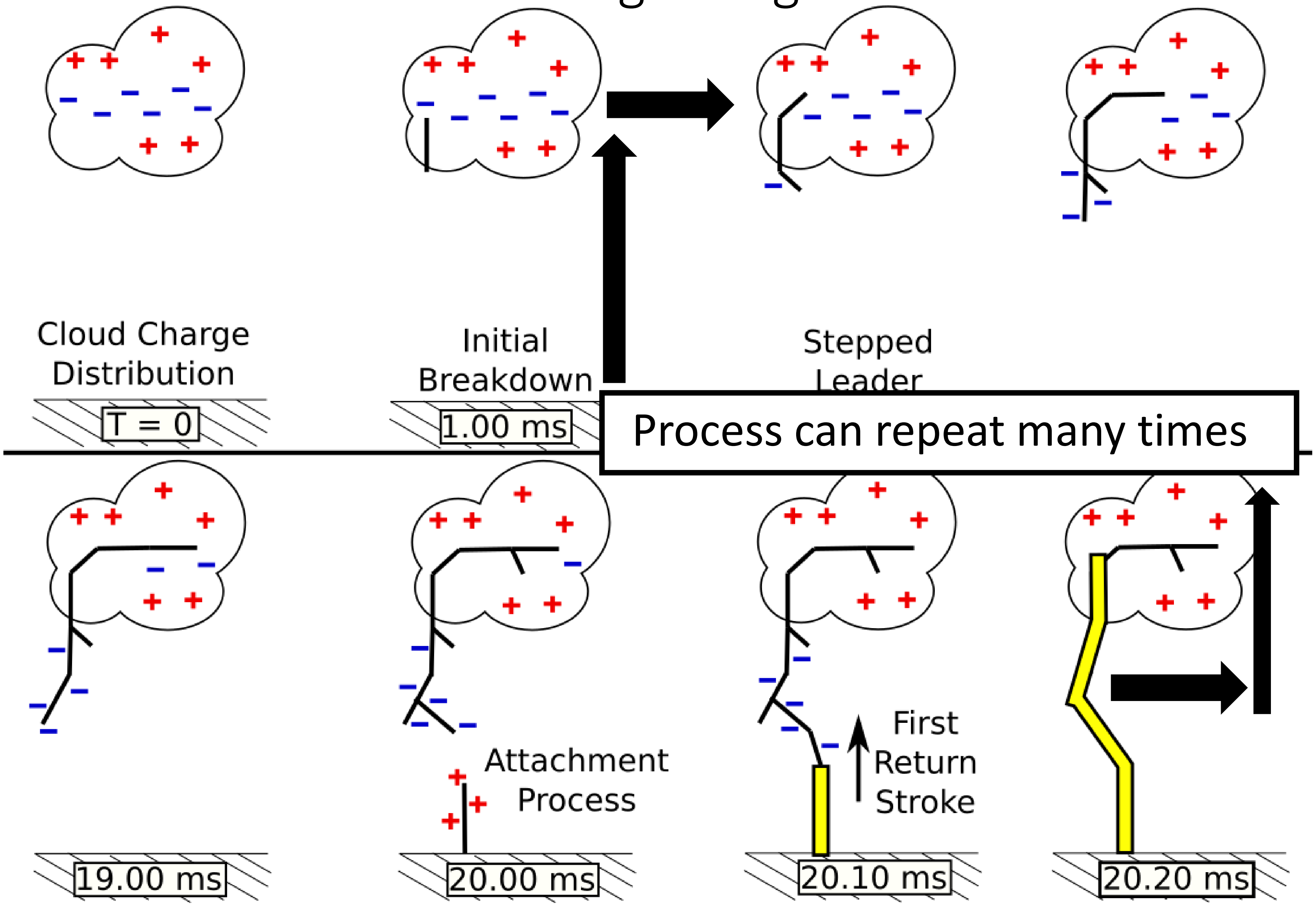
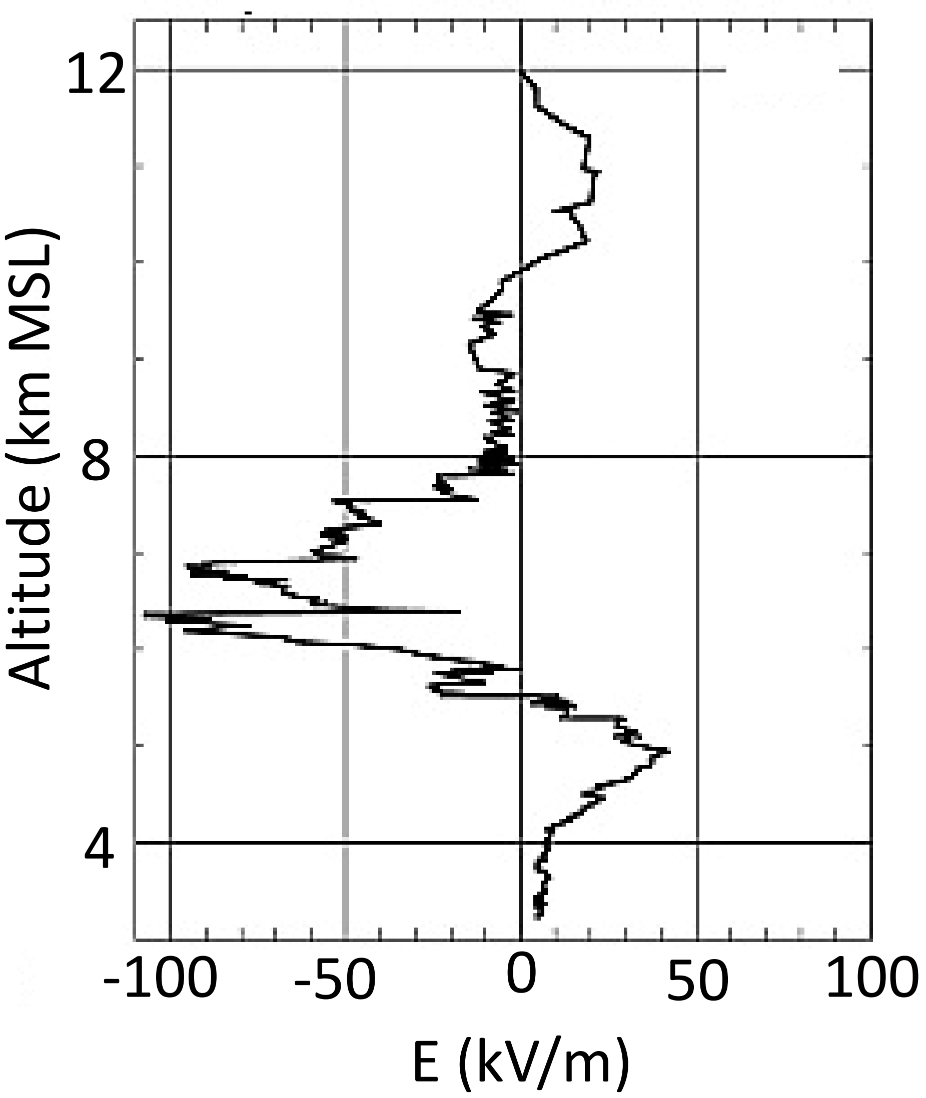


Lightning Initiation

balloon-borne electric field measurement



Dielectric strength of air is 3000 kV/m

Order-of-magnitude higher then measured thunderstorm electric fields

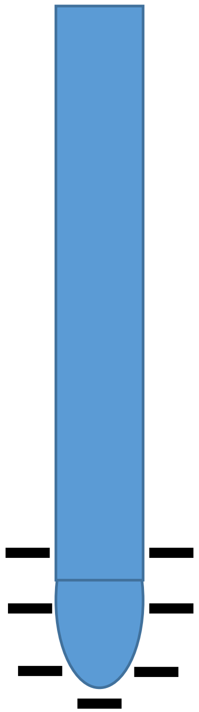
Two current major hypothesis:

-Cosmic Ray Air Showers

-Electric field amplification by hydrometeors

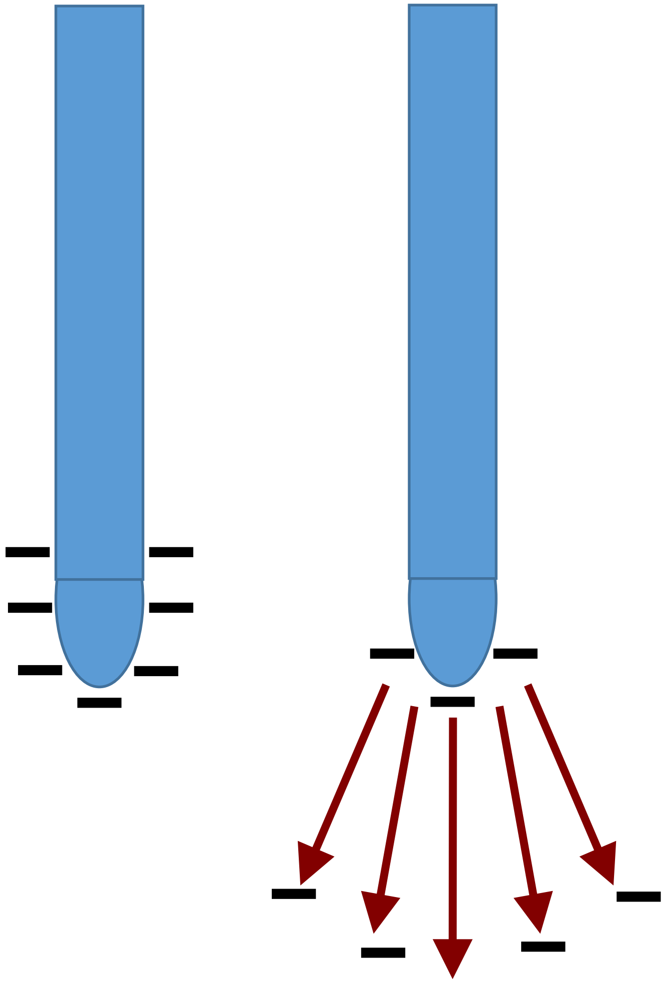
-There are others

Negative Leader Propagation



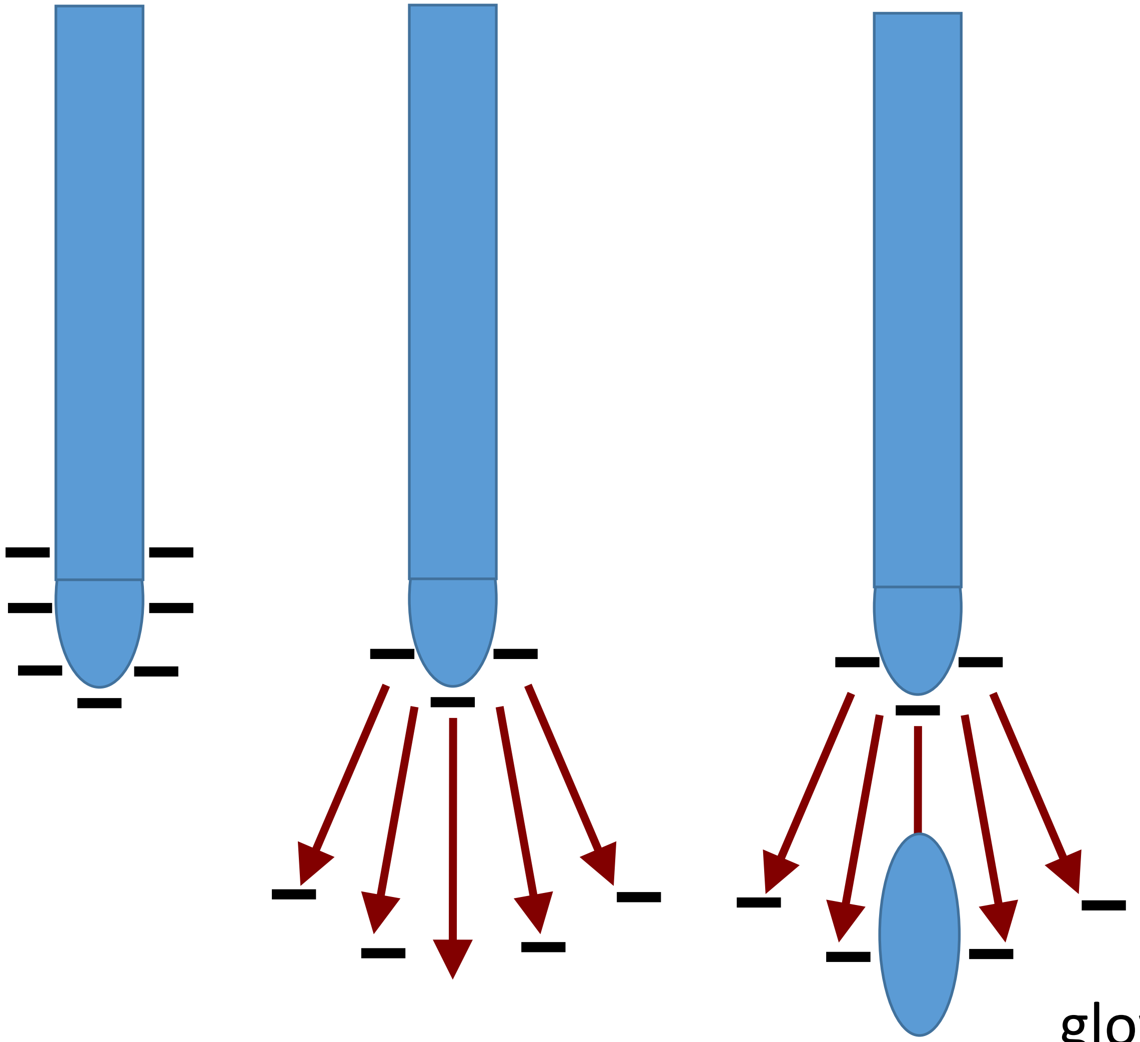
Start with existing channel

Negative Leader Propagation



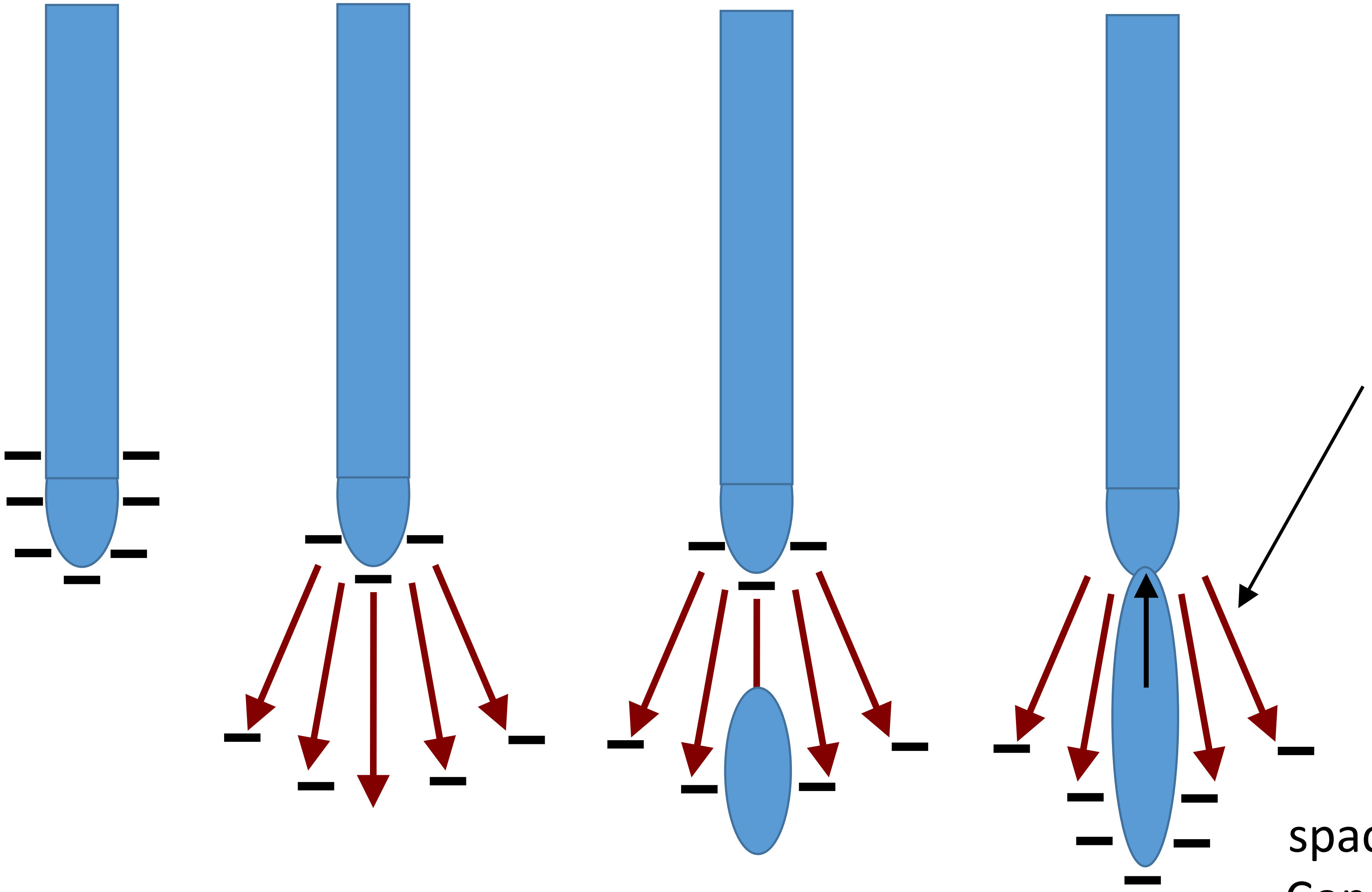
Corona Burst
cold plasma surges forward

Negative Leader Propagation



glowing thing forms
called space stem
assumed conductive

Negative Leader Propagation

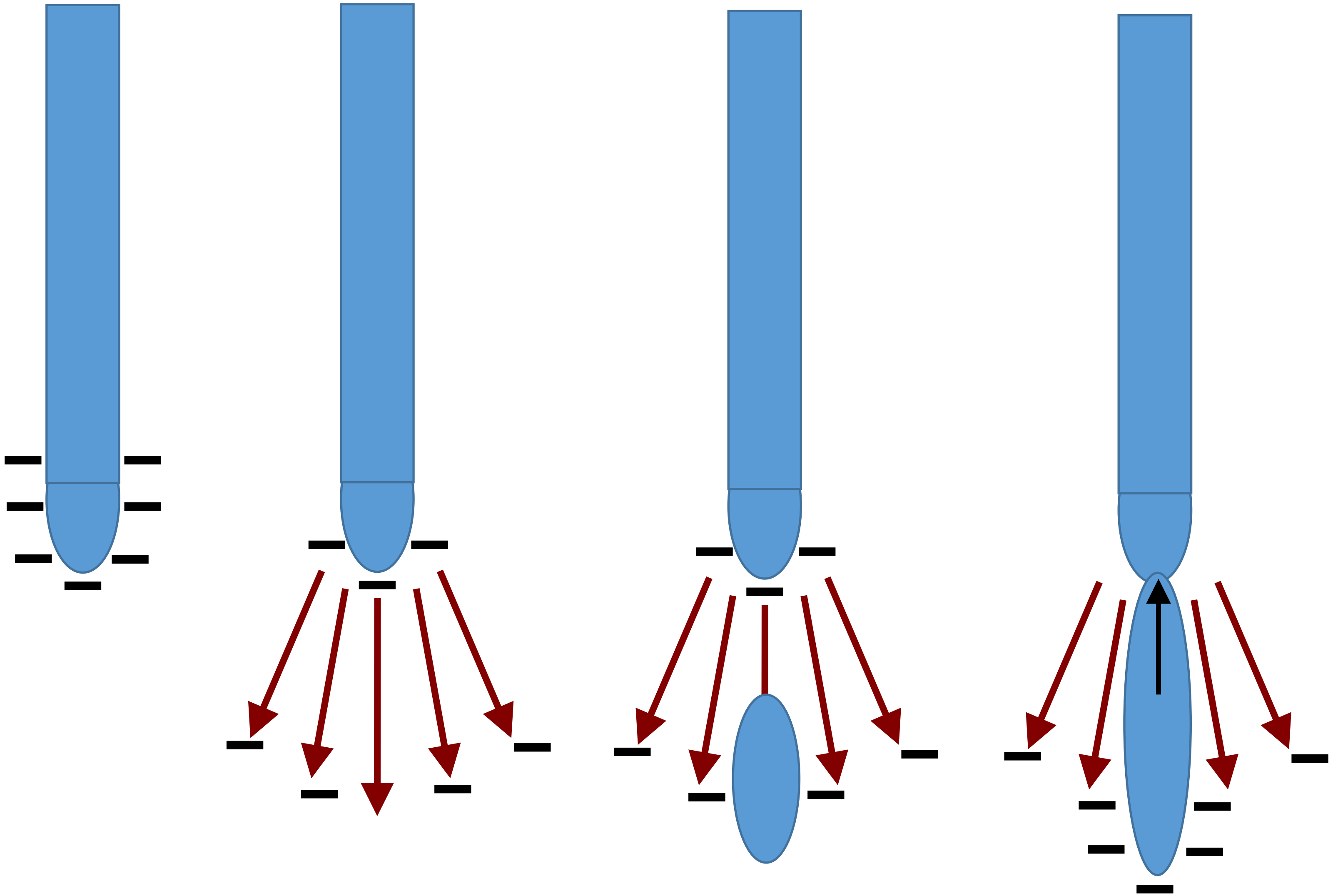


Leftover streamers create region of cold plasma

Called corona sheath

space stem grow backwards
Connects with main channel
Creates current pulse

Negative Leader Propagation



- Pieced together from camera observations and long lab sparks
- Cannot be modeled
- What part emits VHF
- What is a space stem?

Terrestrial Gamma Ray Flashes

Credit: NASA/Goddard Space Flight Center/J. Dwyer/Florida Inst. of Technology

- Intense bursts of gamma radiation from lightning
  - Energies up to 20 MeV

  - Produced around 10 km altitude
  - Intense flux saturates orbiting gamma-ray observatories

The Big Questions in Lightning

- How does lightning get started?
  - Measured electric fields are too small to make a spark via typical mechanisms
- How does lightning grow?
  - The plasma physics is extremely complex, and too complicated for current computers to model
- How does lightning emit gamma rays?
  - This strongly depends on how the lightning grows

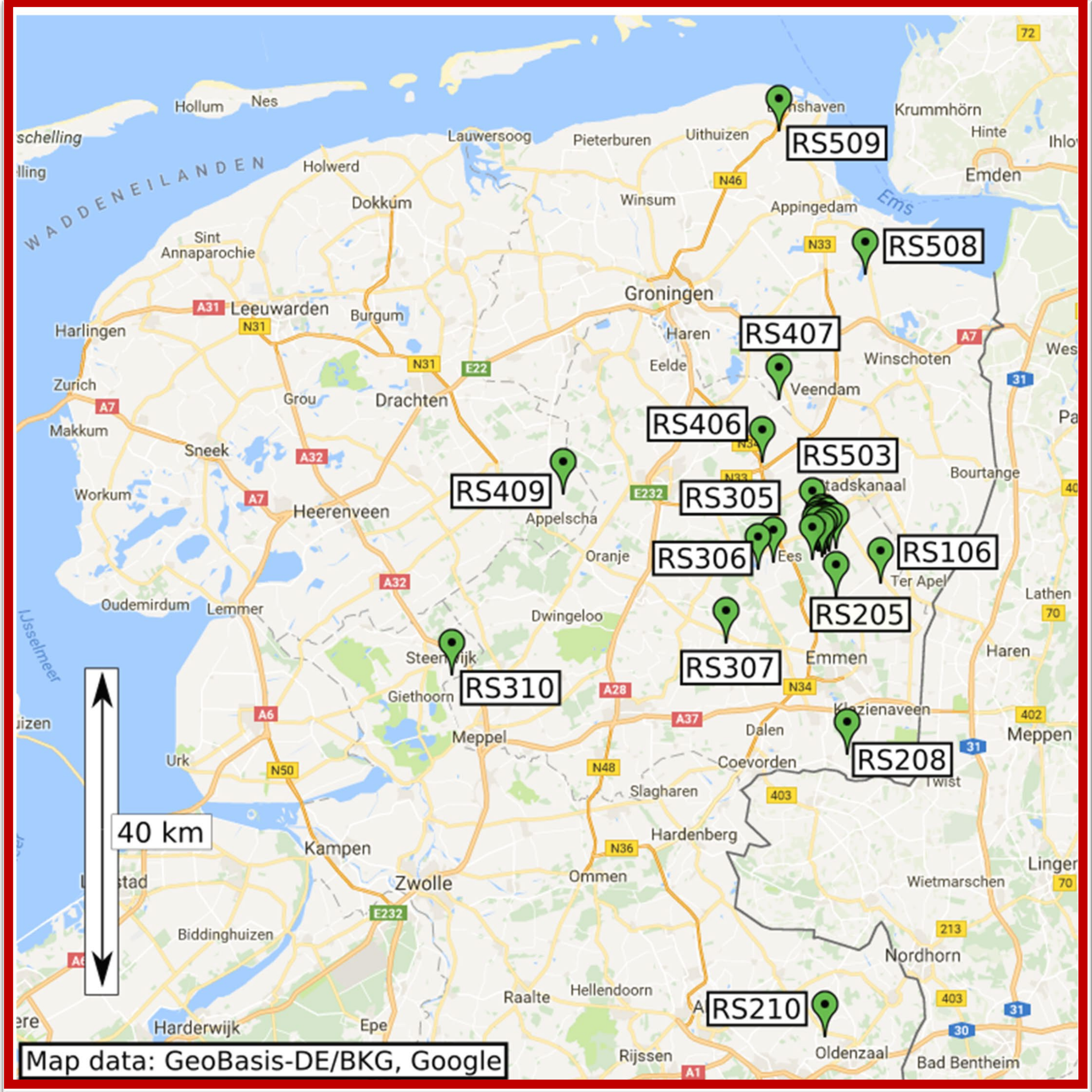
Dutch LOFAR

- 24 “core” stations
- 14 “remote” stations
- 3200 km^2 enclosed area

Per Station:

- 96 low-band antennas
  - 10 – 90 MHz
  - 48 dual-polarized pairs
  - We use 6 dual-polarized pairs out of the 48 pairs
- 20 high-band antennas
  - 110-250 MHz
  - presently not utilized

Also shown in Hare et al. [2018], *JGR*

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Uithuizen
Hinte
Emden
Ems
Appingedam
Groningen
Haren
Eelde
Winschoten
Veendam
Bourtange
Oranje
Ter Apel
Lathen
Emmen
Haren
Meppen
Slagharen
Twist
Wietmarschen
Ommen
Nordhorn
Oldenzaal
Rijssen
Bad Bentheim
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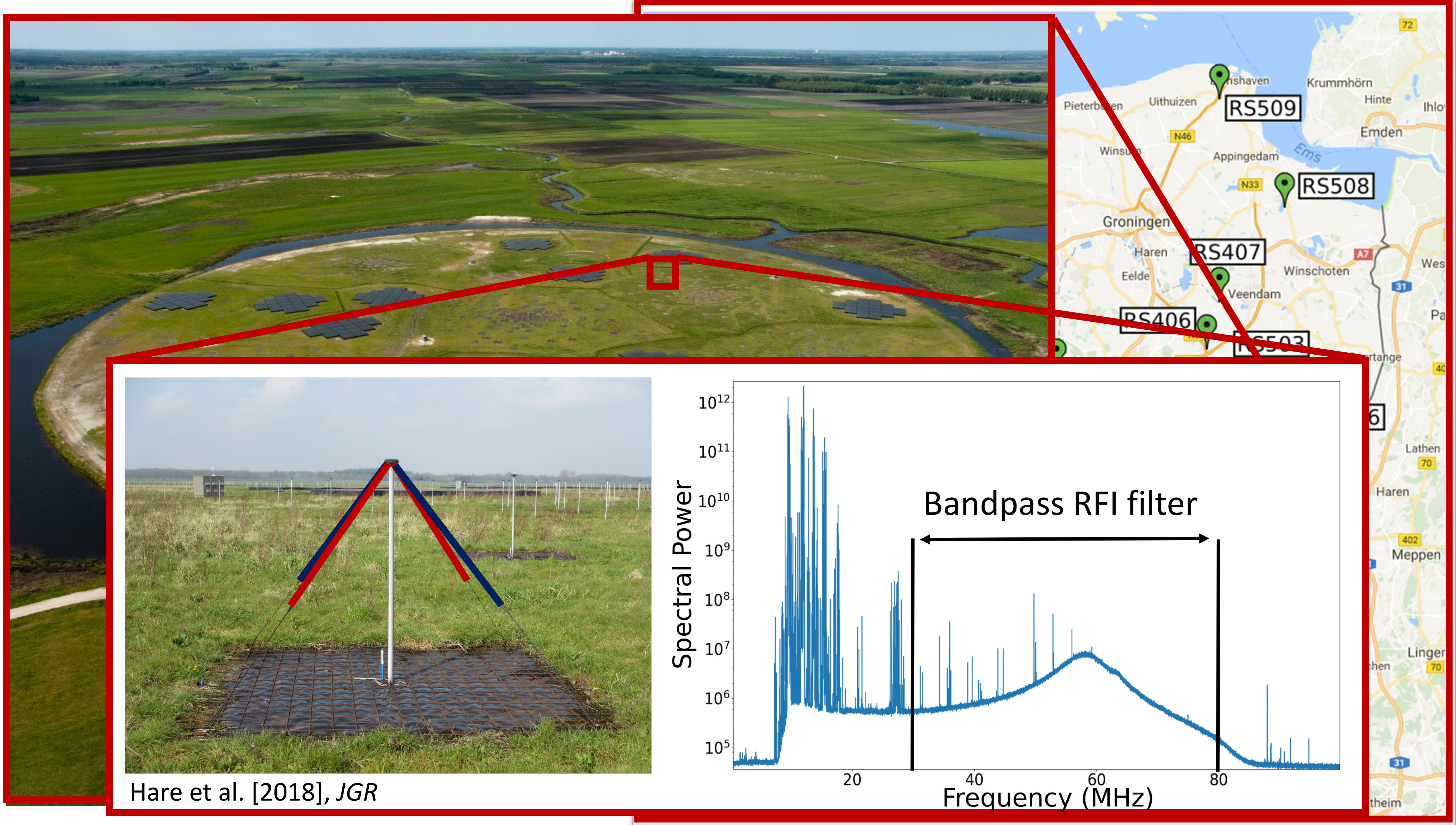
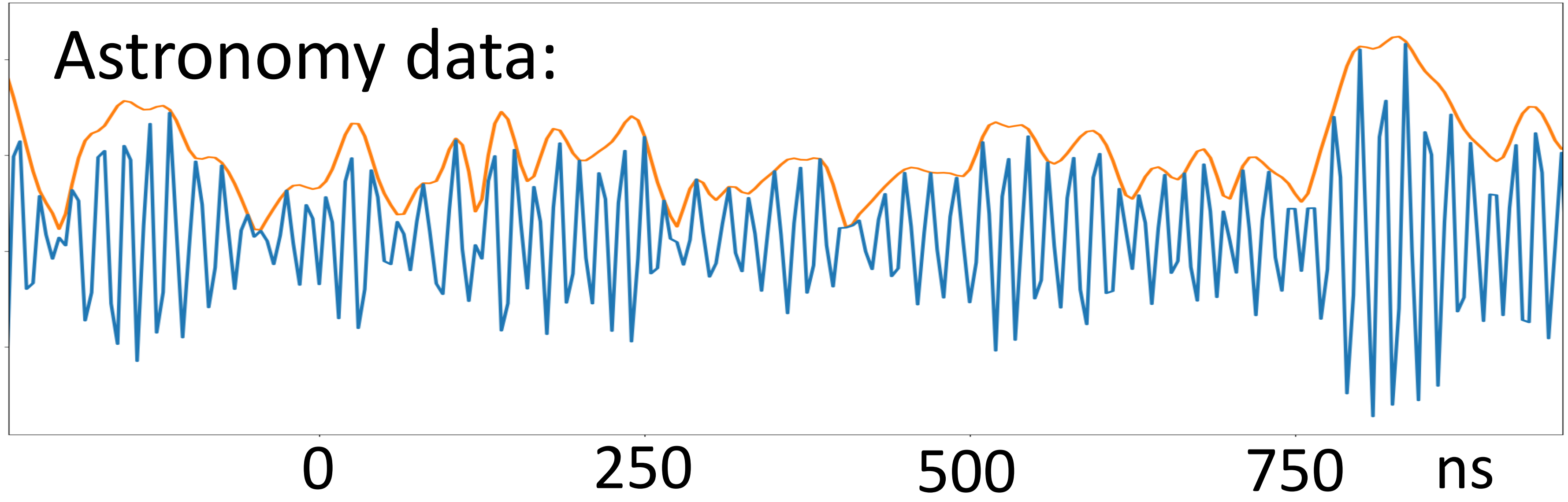


Hare et al. [2018], *JGR*

Lightning vs Astronomy Transient Buffer Data



- Looks like noise
- Need Beamforming

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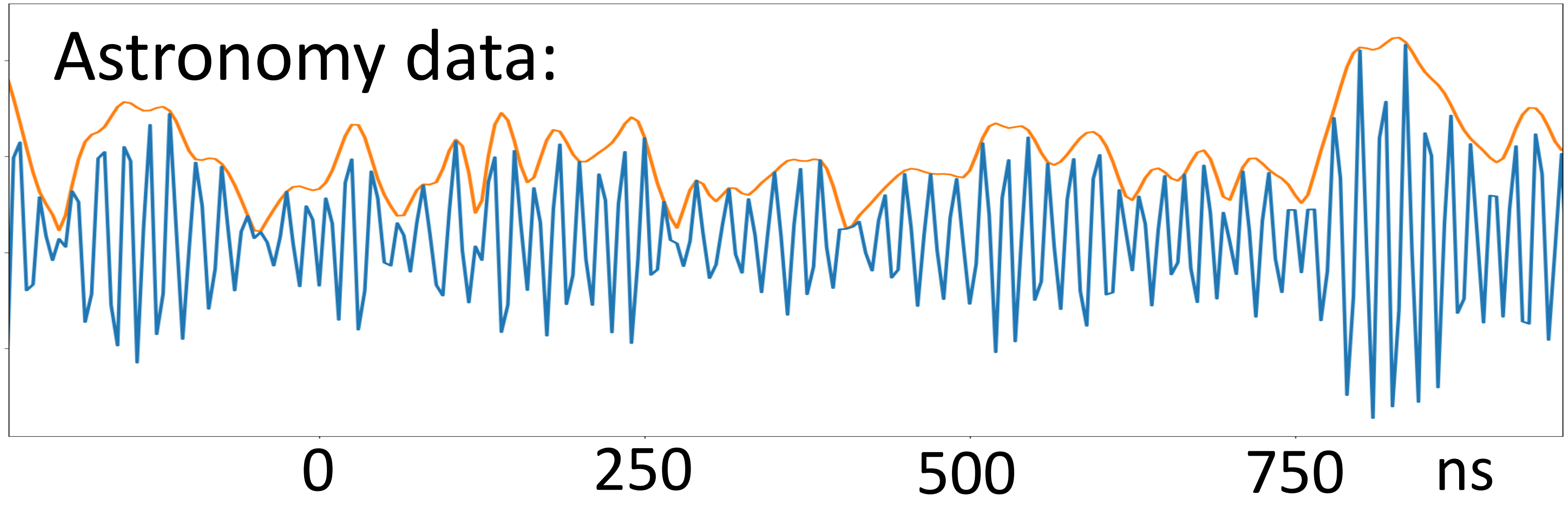

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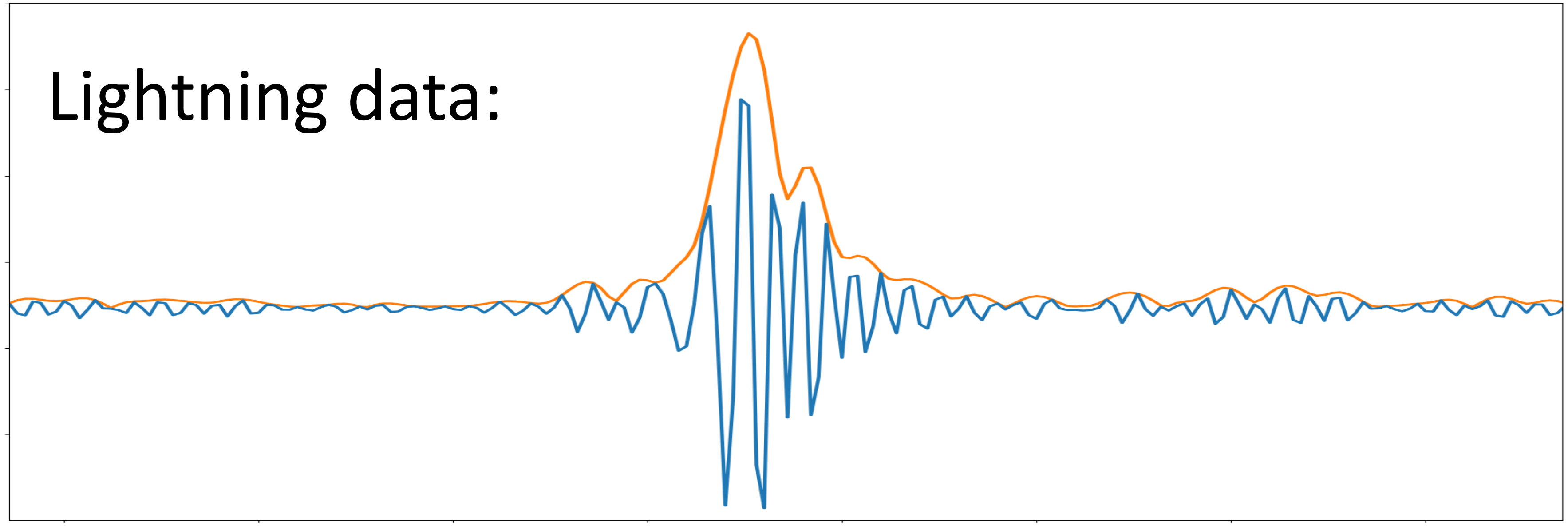

- Discrete Pulses
- Easy to get time-of-arrival
- Beamforming not required

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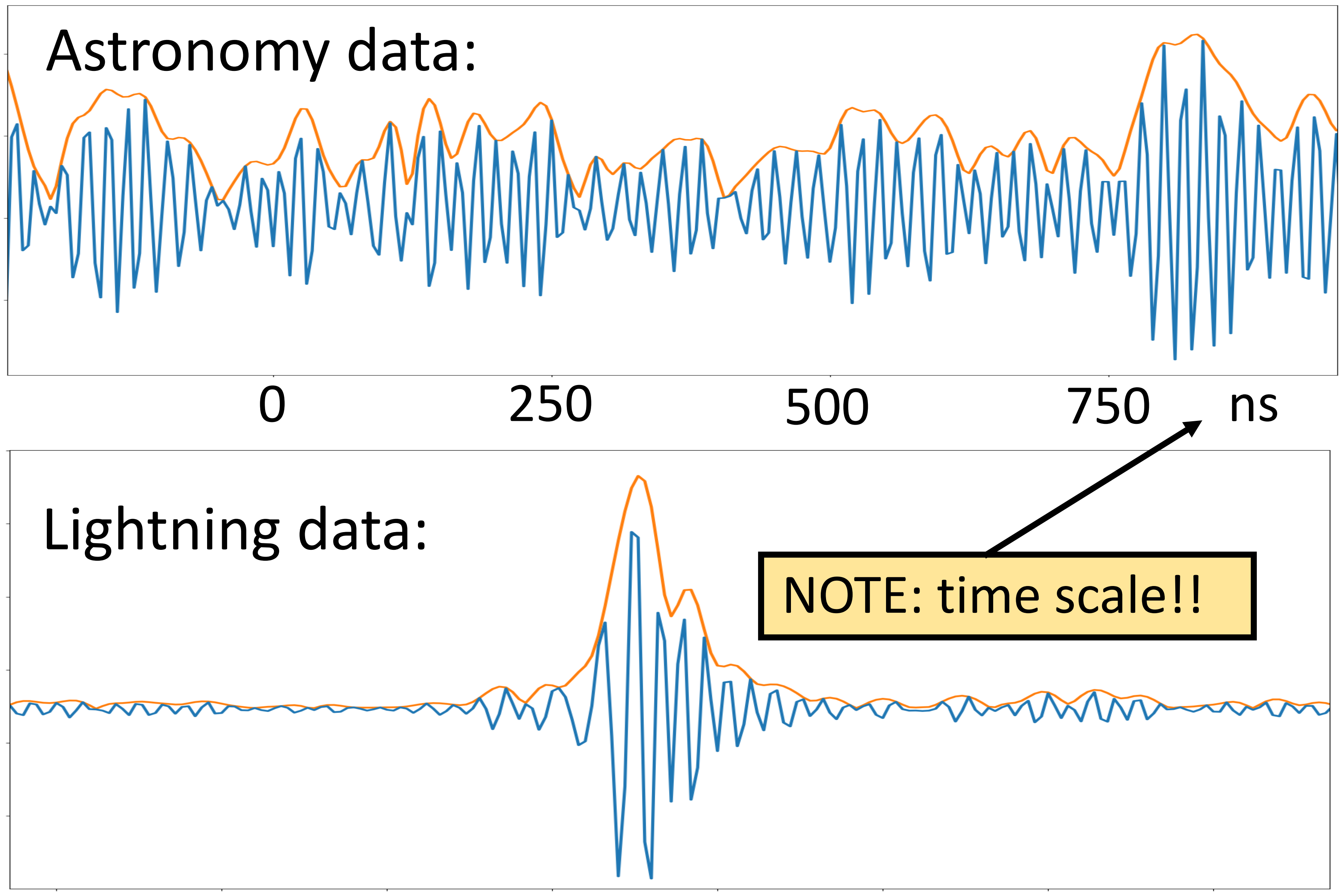

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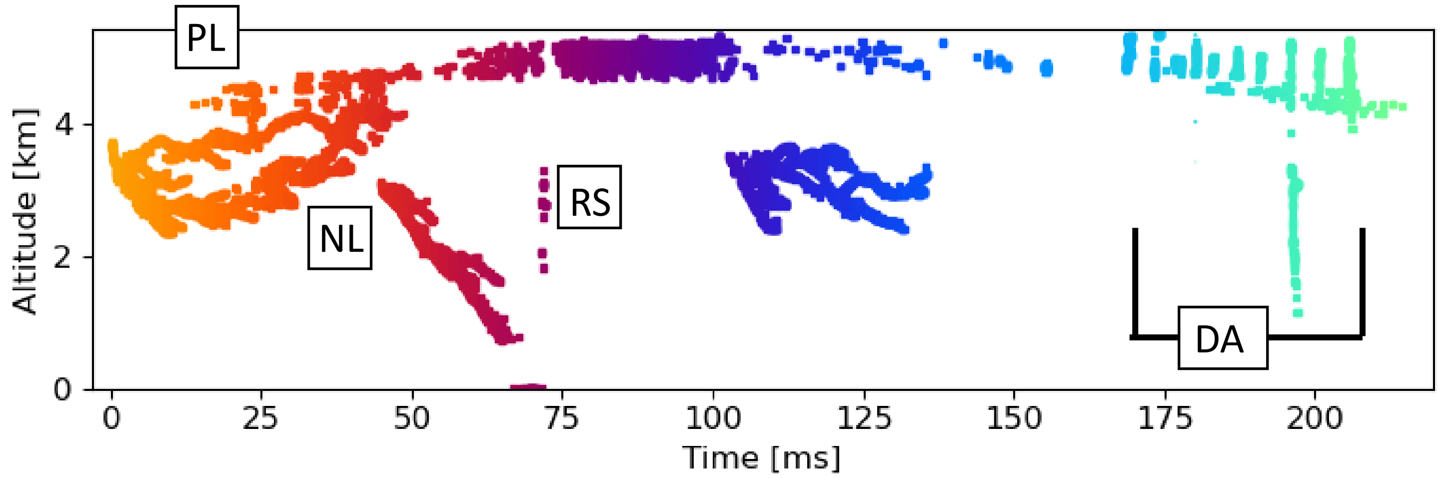
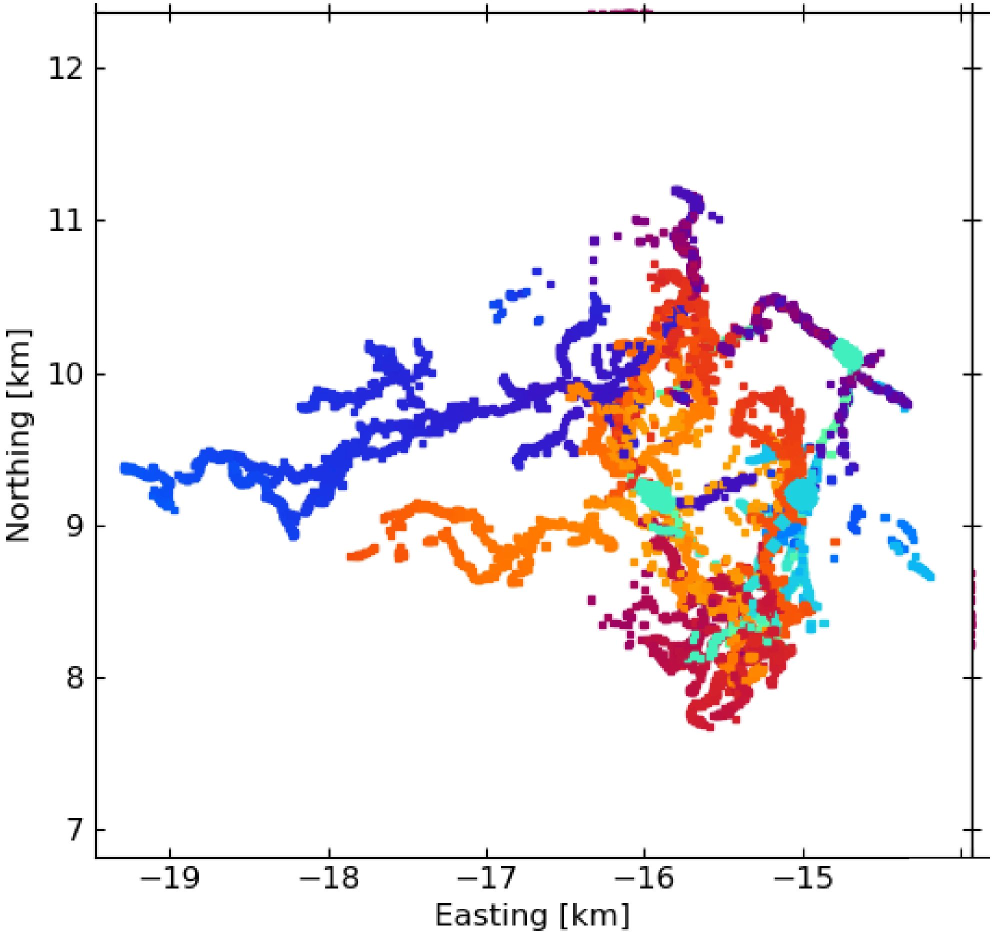


PL - positive leader
NL - negative leader
RS - return stroke
DA - dart leader



Lightning flash imaged with “impulsive techniques” (TOA)

-CPU efficient, not as good as interferometry

65,200 sources after cuts

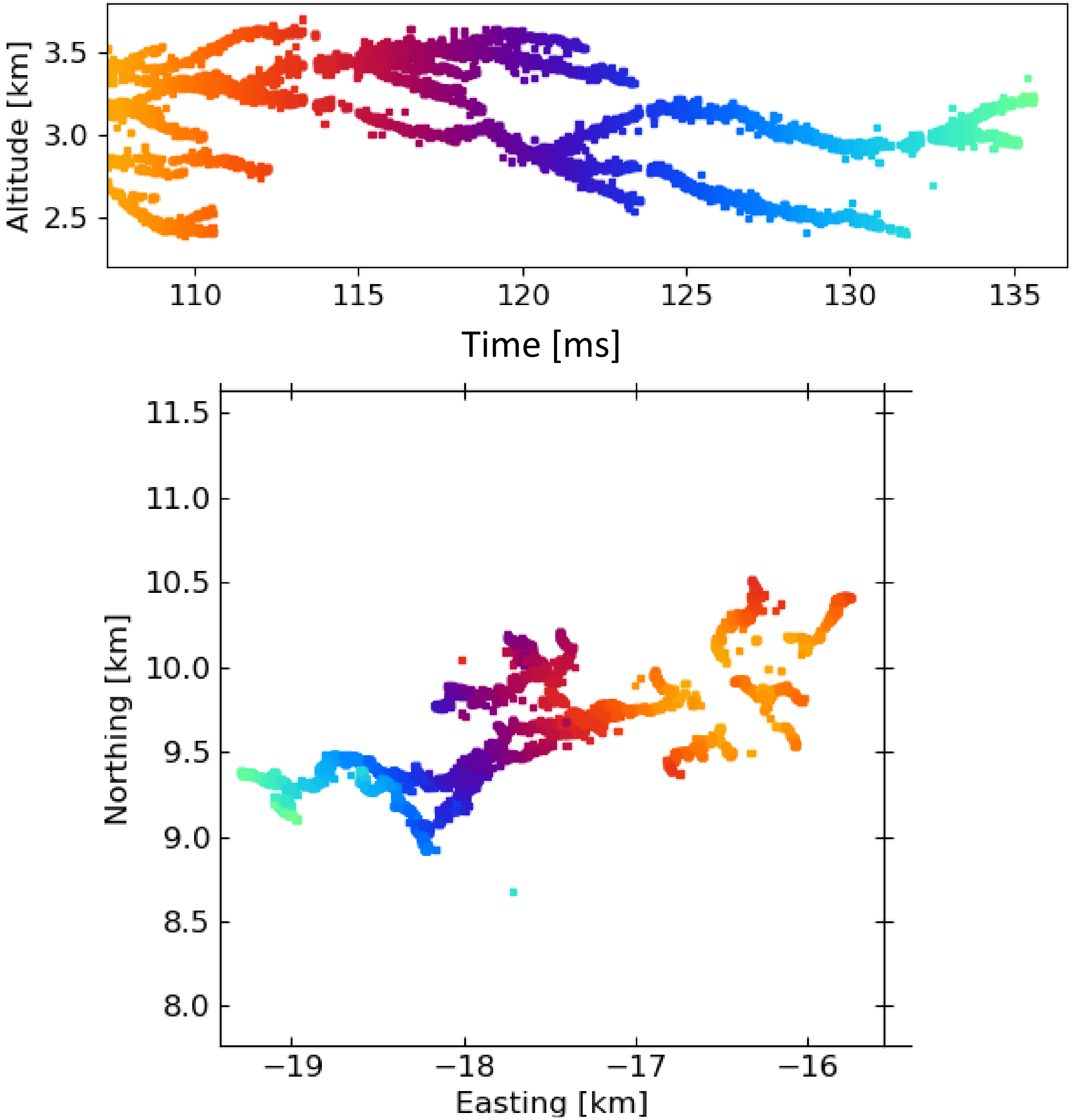
≈ 300 sources per ms

Horizontal accuracy around 1 m

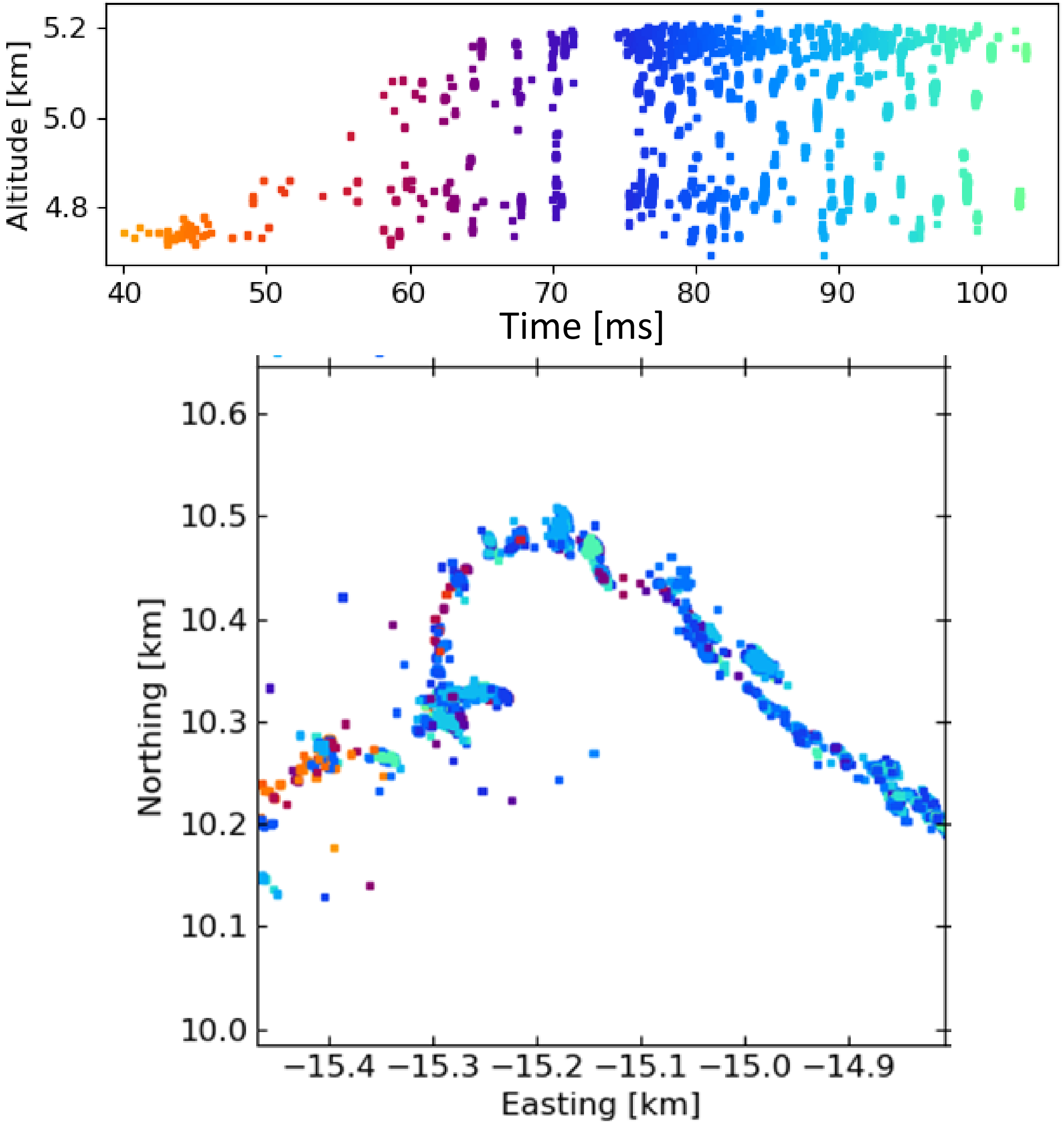
-limited by source-confusion

Positive vs Negative Charged Channels

Negative Lightning Channels



Positive Lightning Channels



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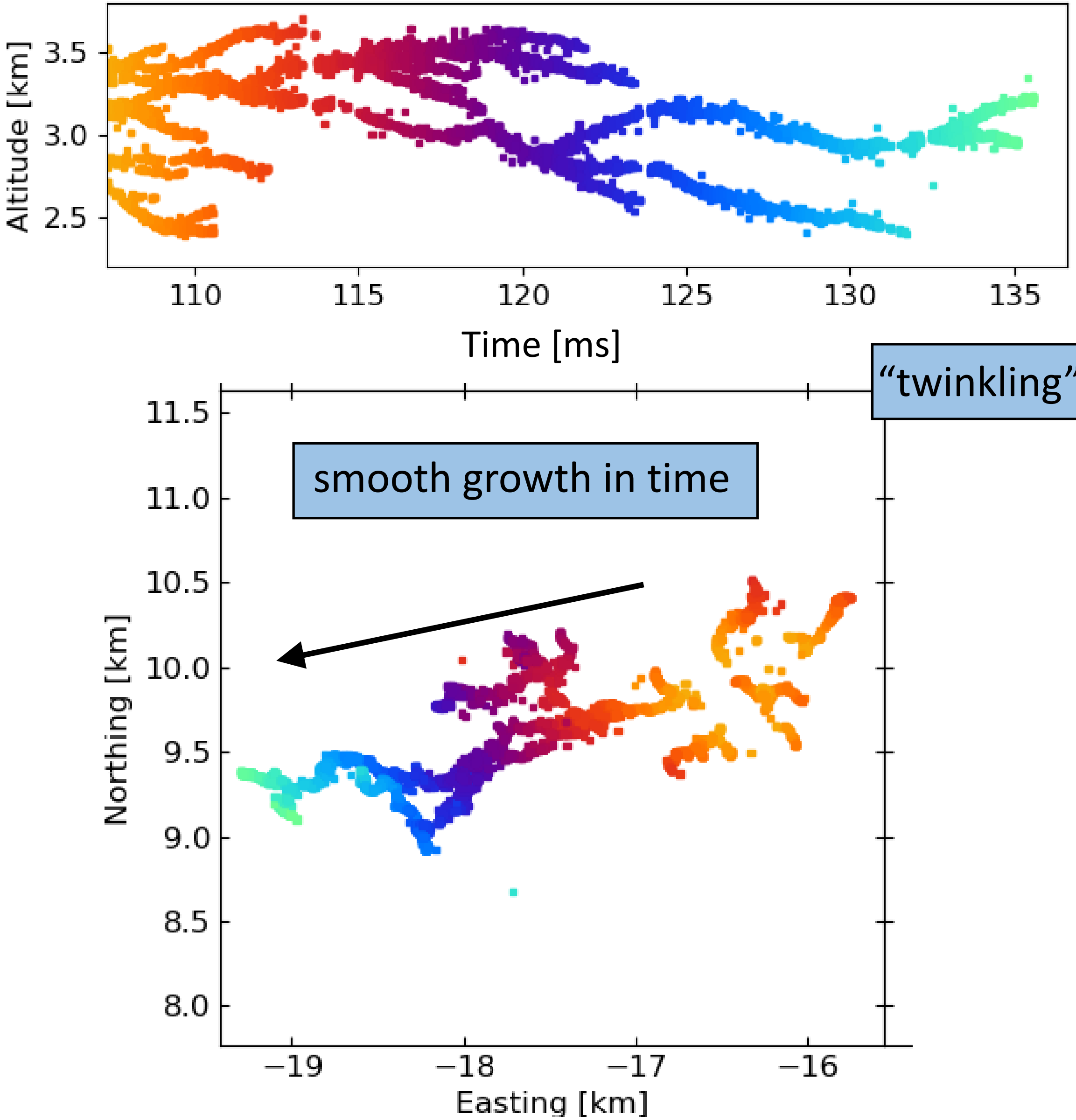

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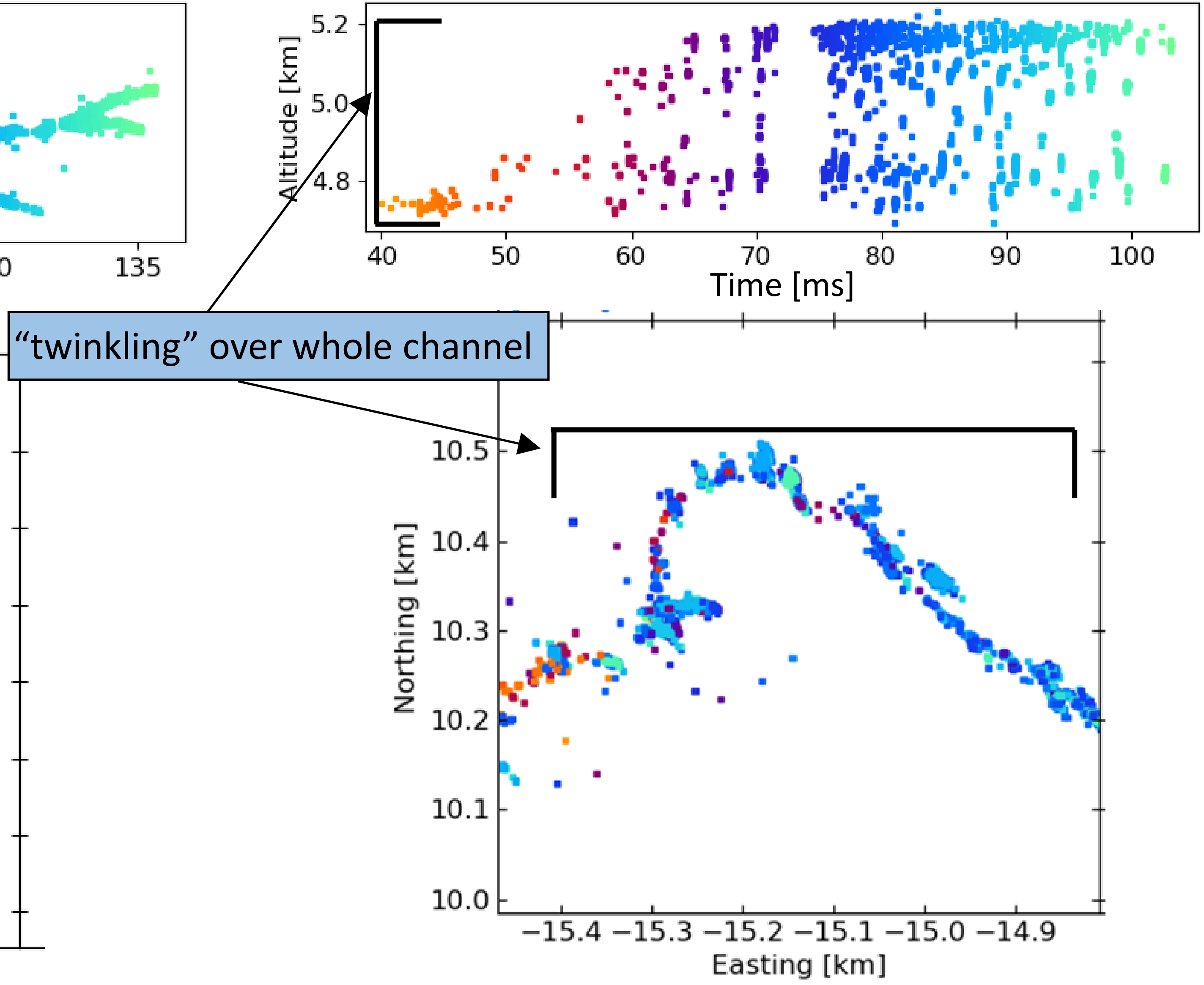

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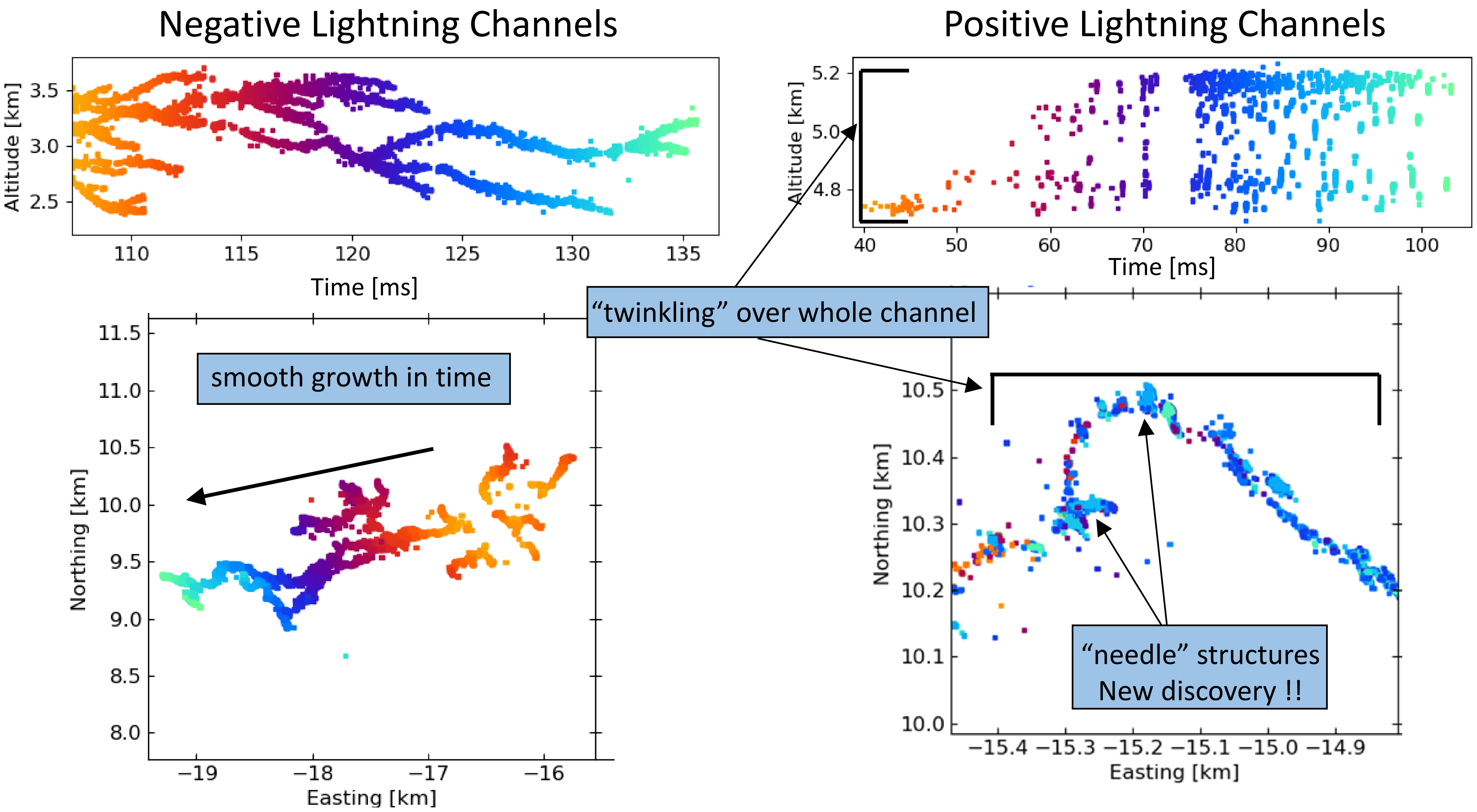

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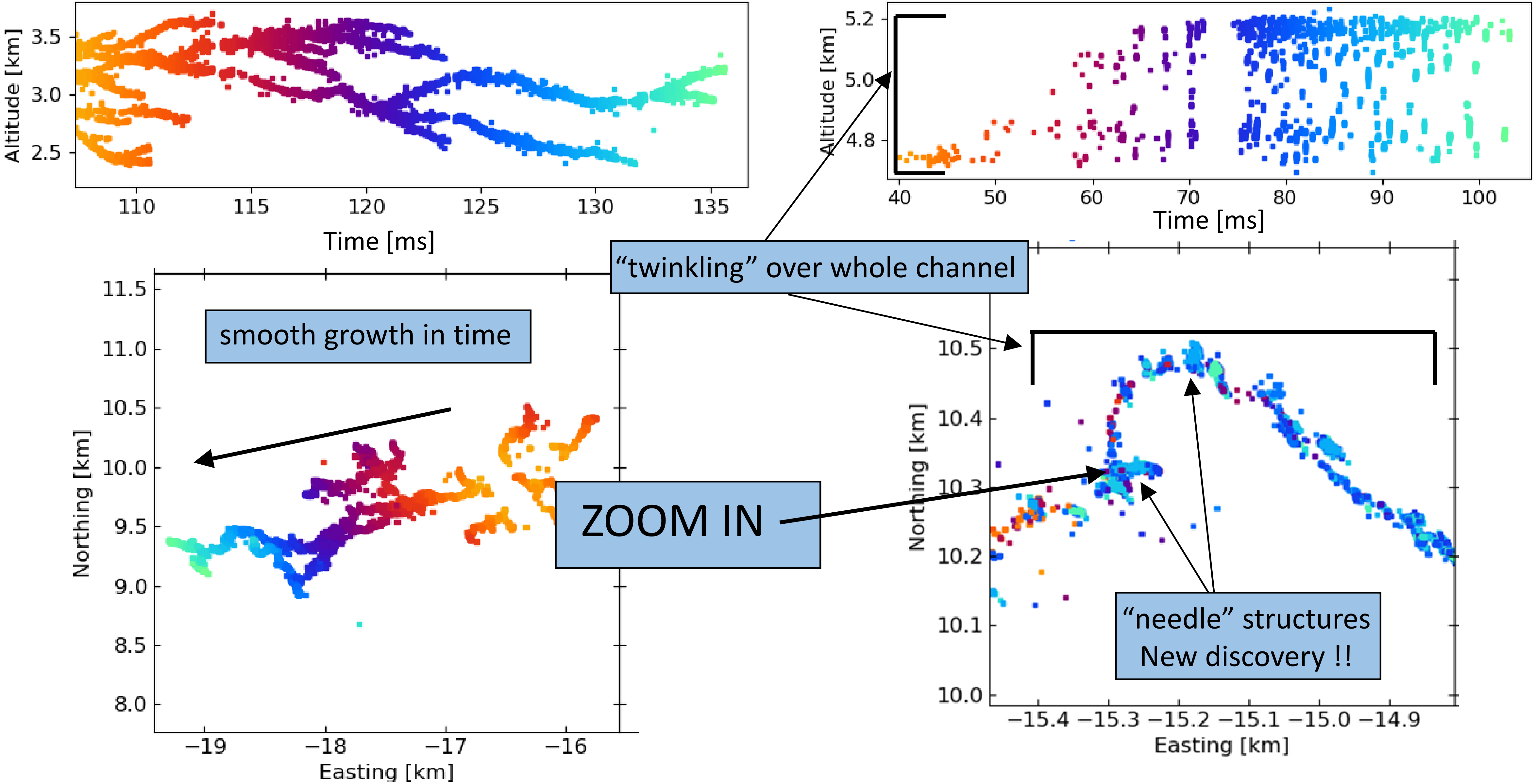
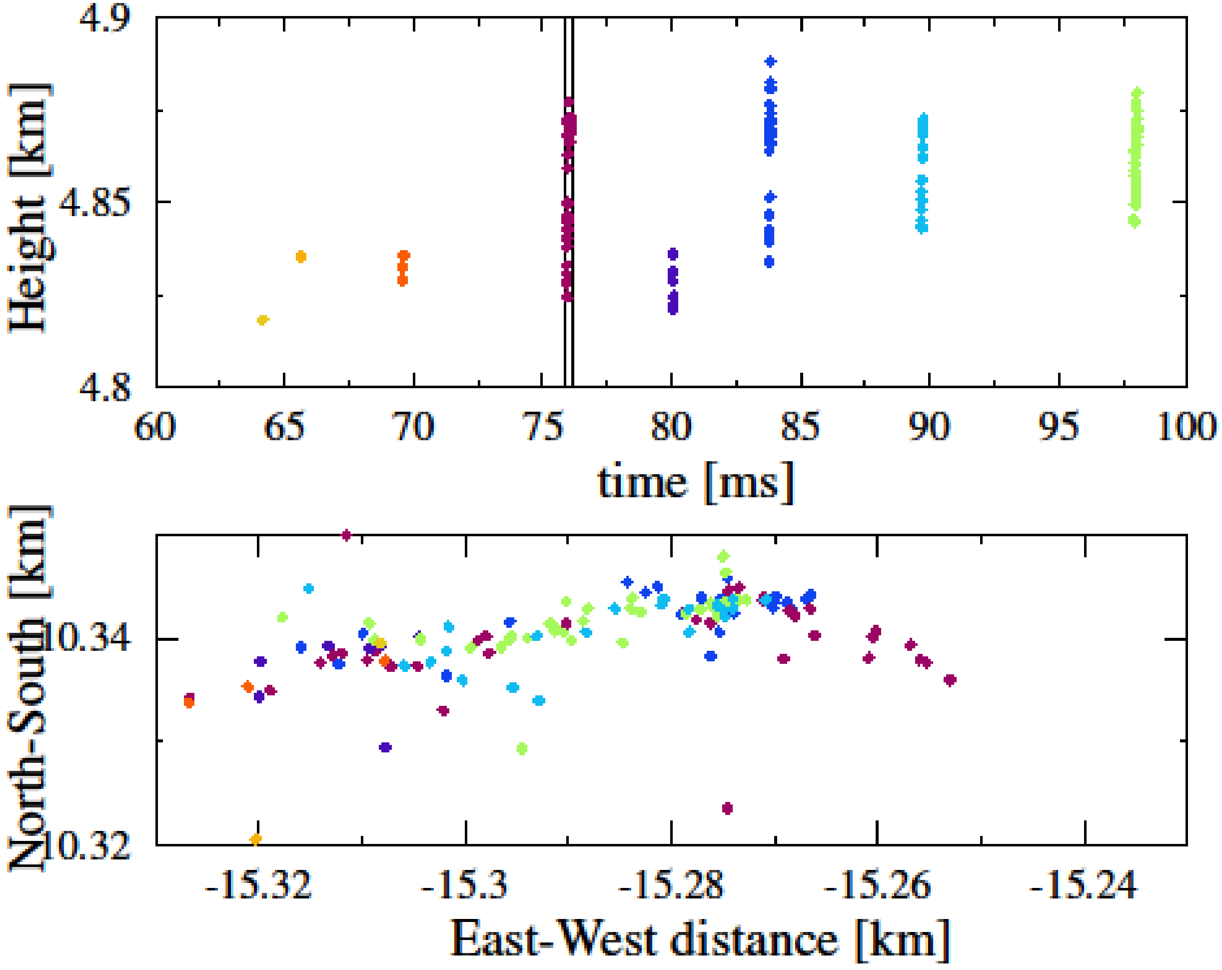
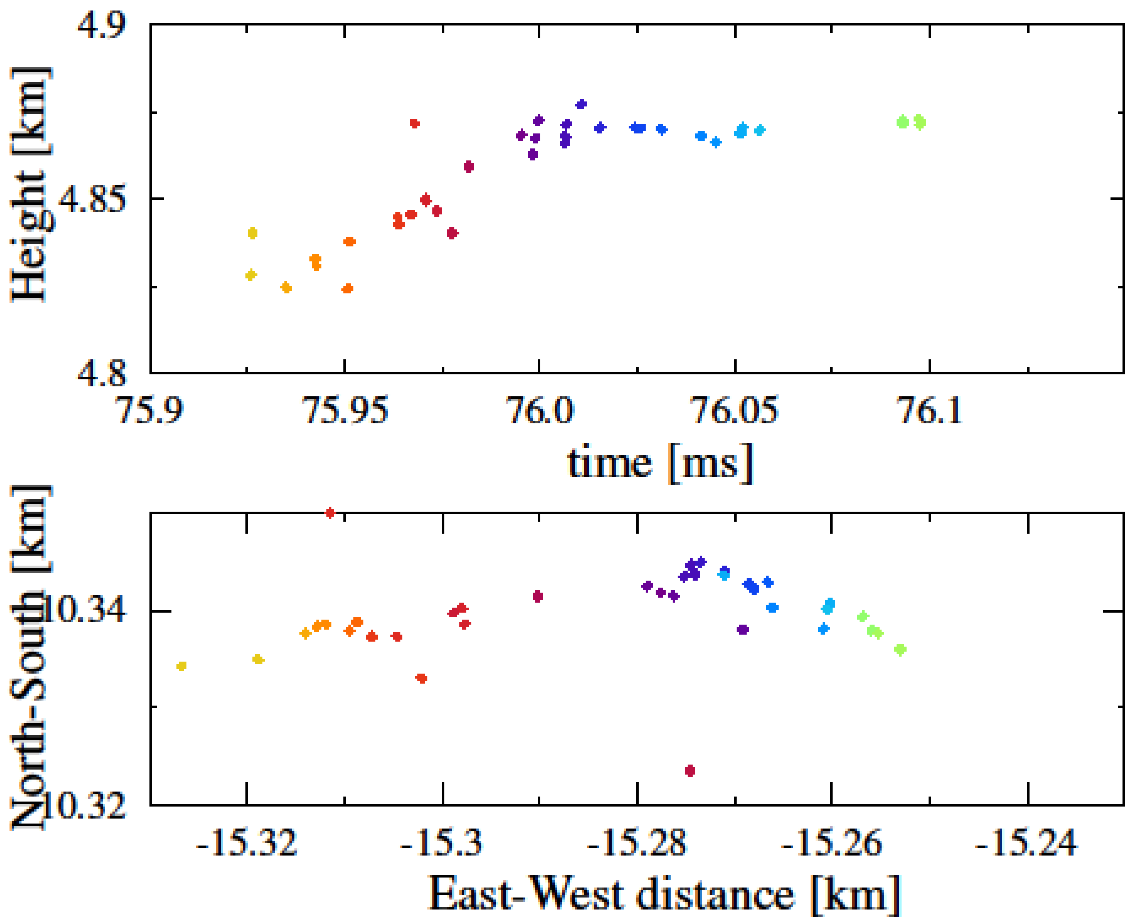


One flickering positive leader structure



Time zoom-in



← Positive Leader channel to the West ←

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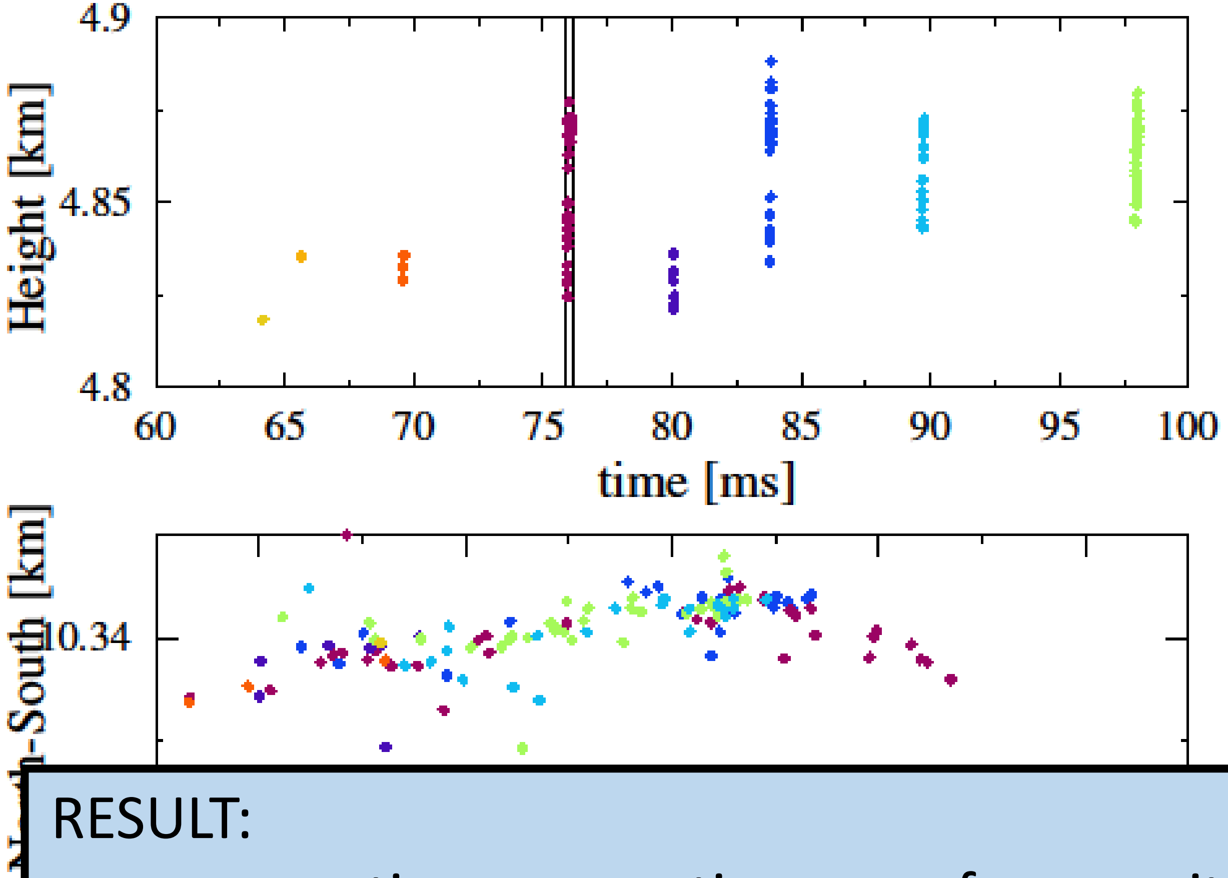

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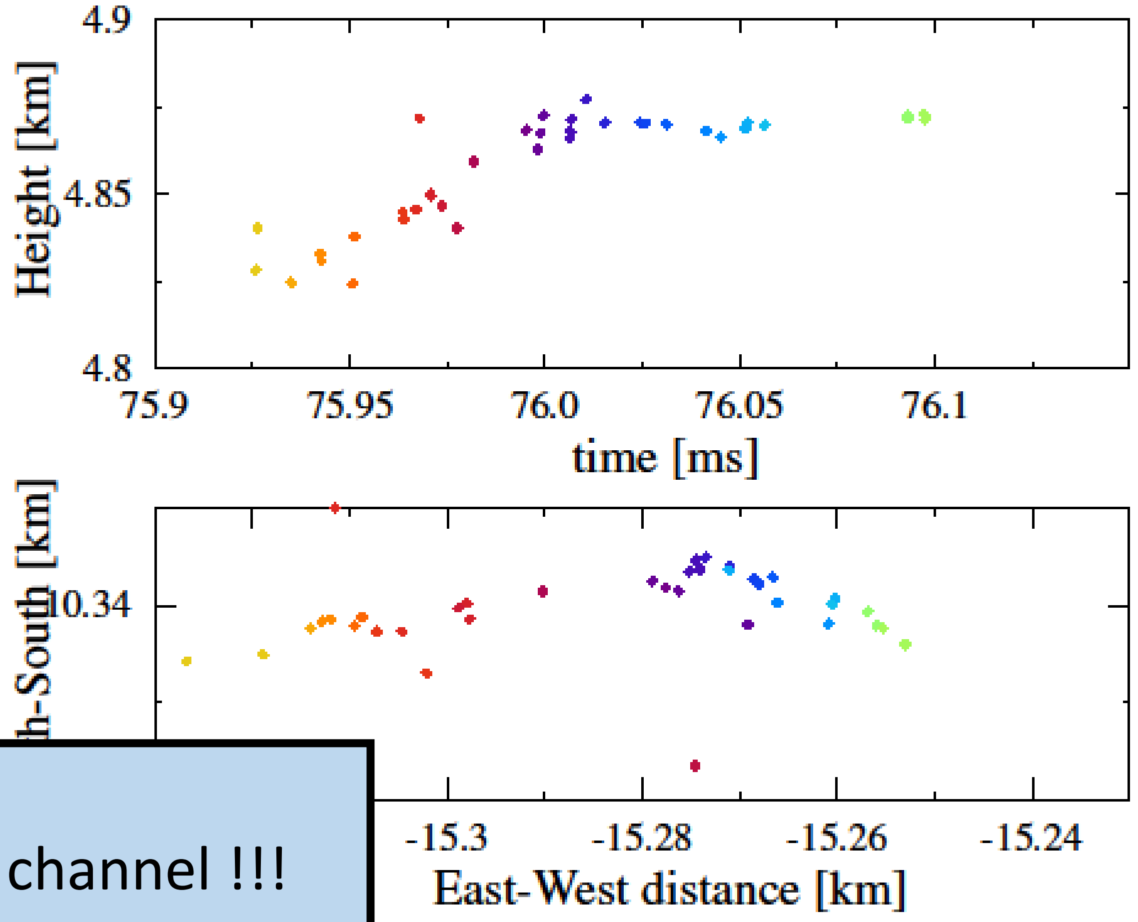


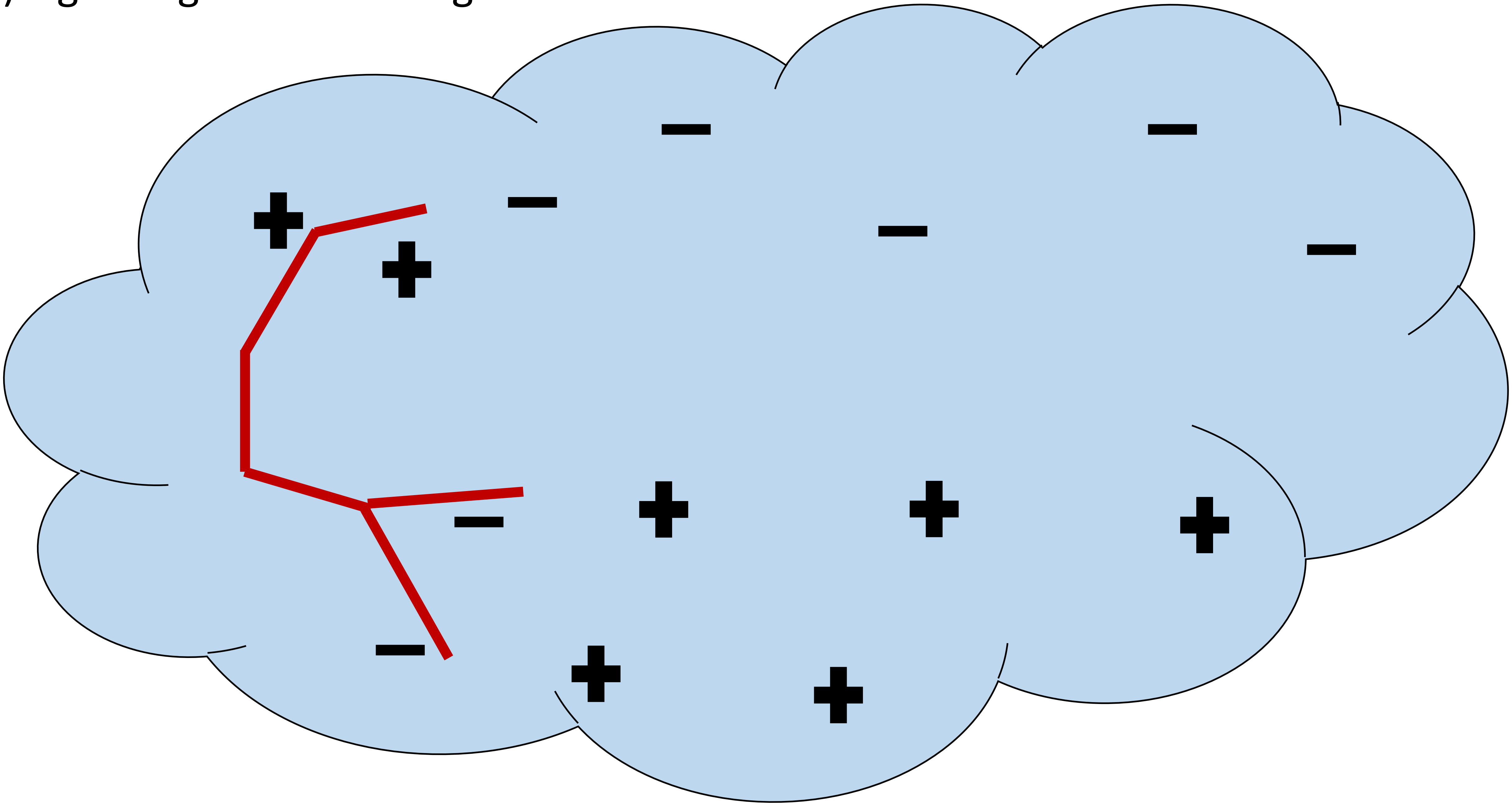
RESULT:

negative propagation away from positive channel !!!

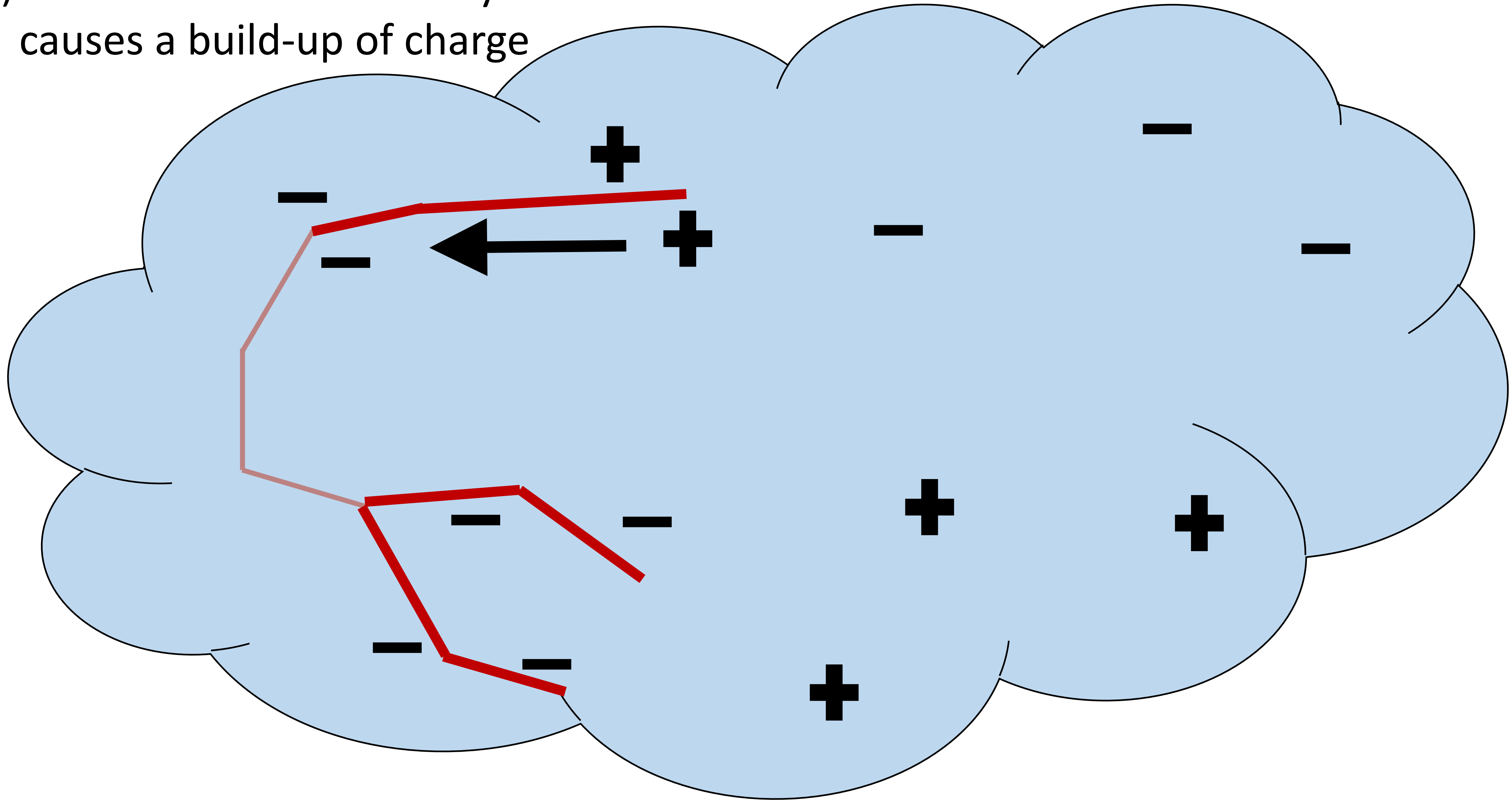
Published in Nature

← Positive Leader channel to the West ←

1) Lightning initiates and grows < 10 ms

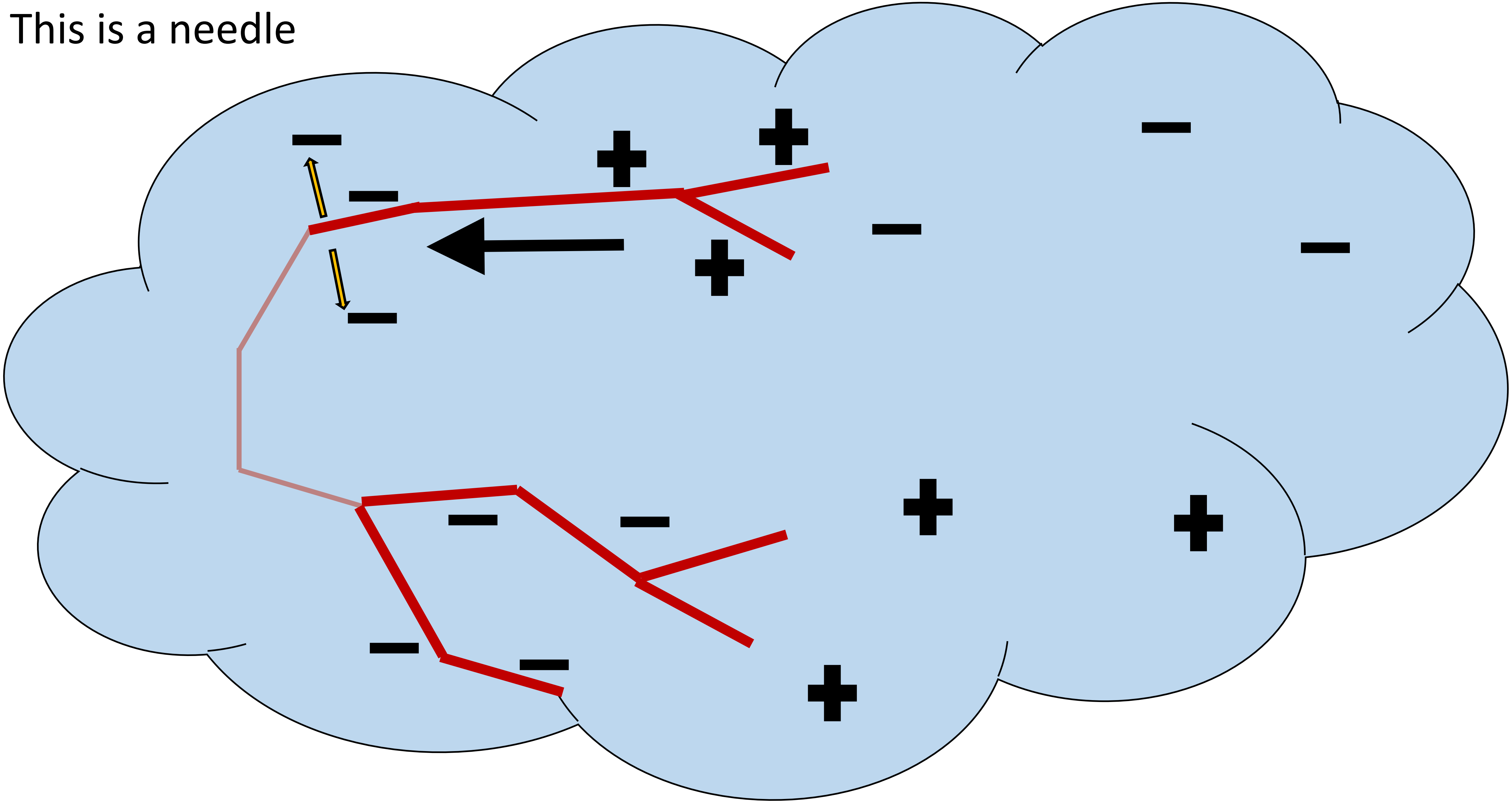


2) Leader loses conductivity ≈20 ms
causes a build-up of charge

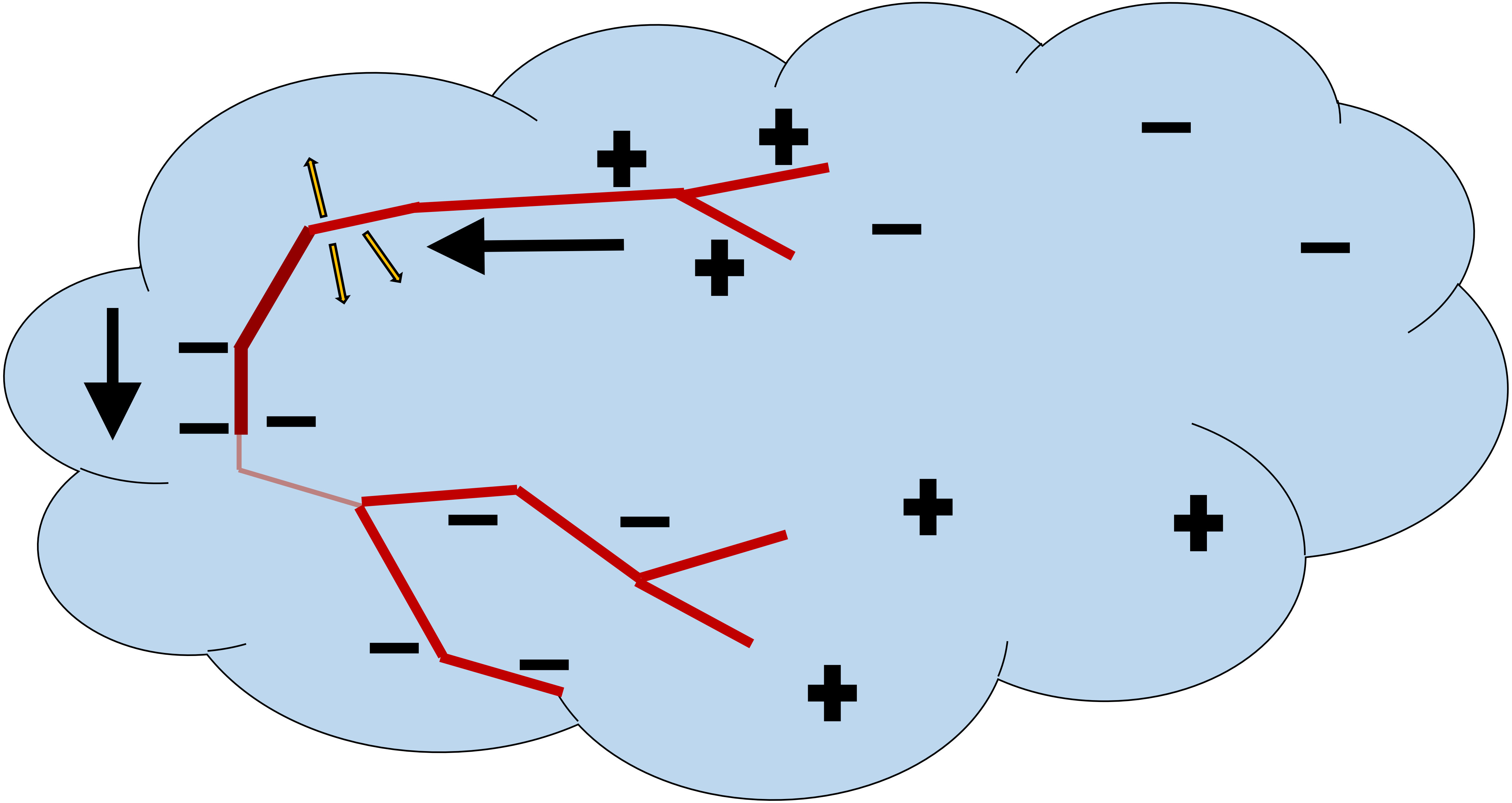


3) Soon, there is dielectric breakdown   > 20 ms

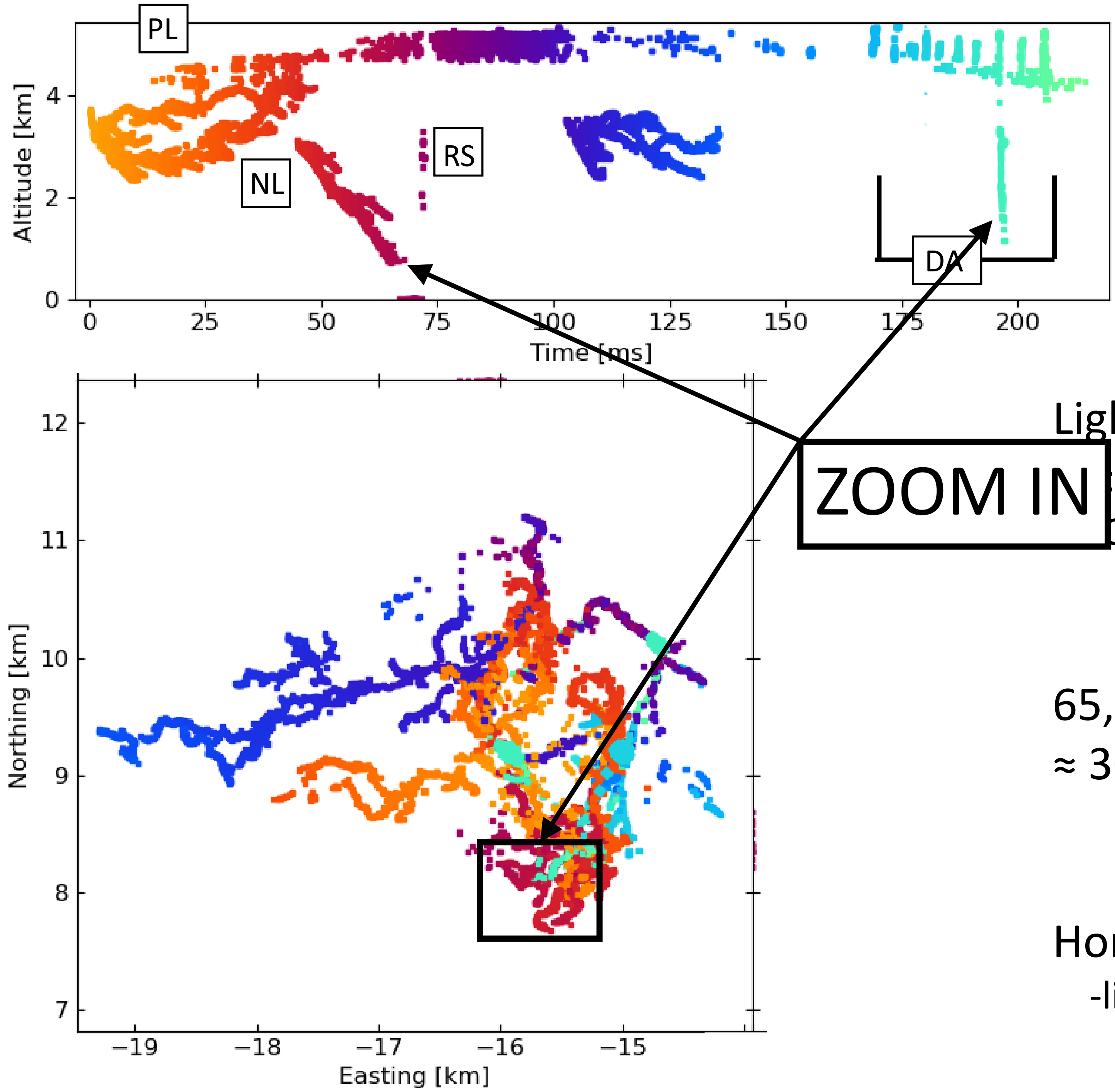
This is a needle



4) Eventually, the charge is sent back down the channel ≈100 ms



Current work: Dart Leaders



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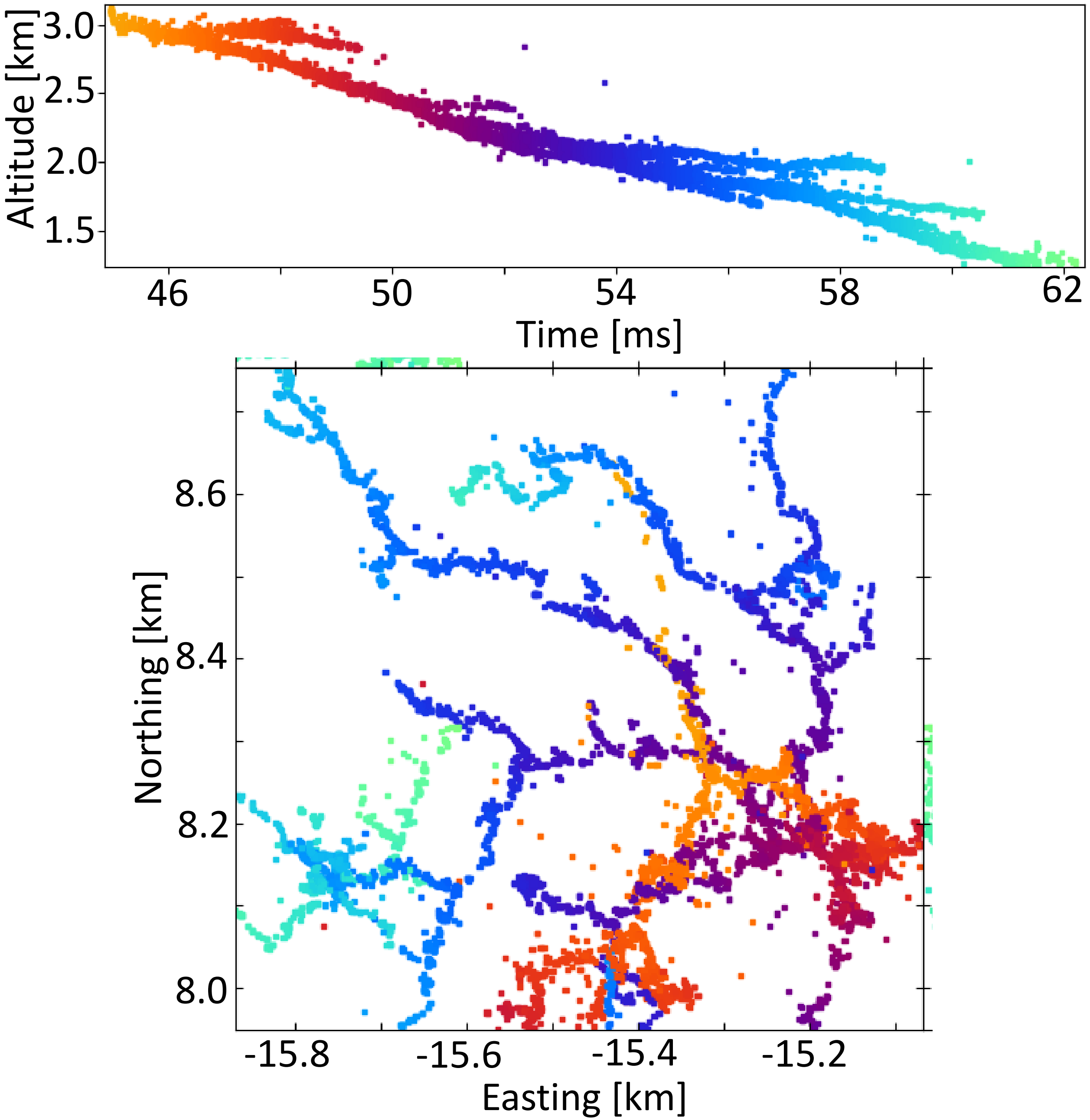
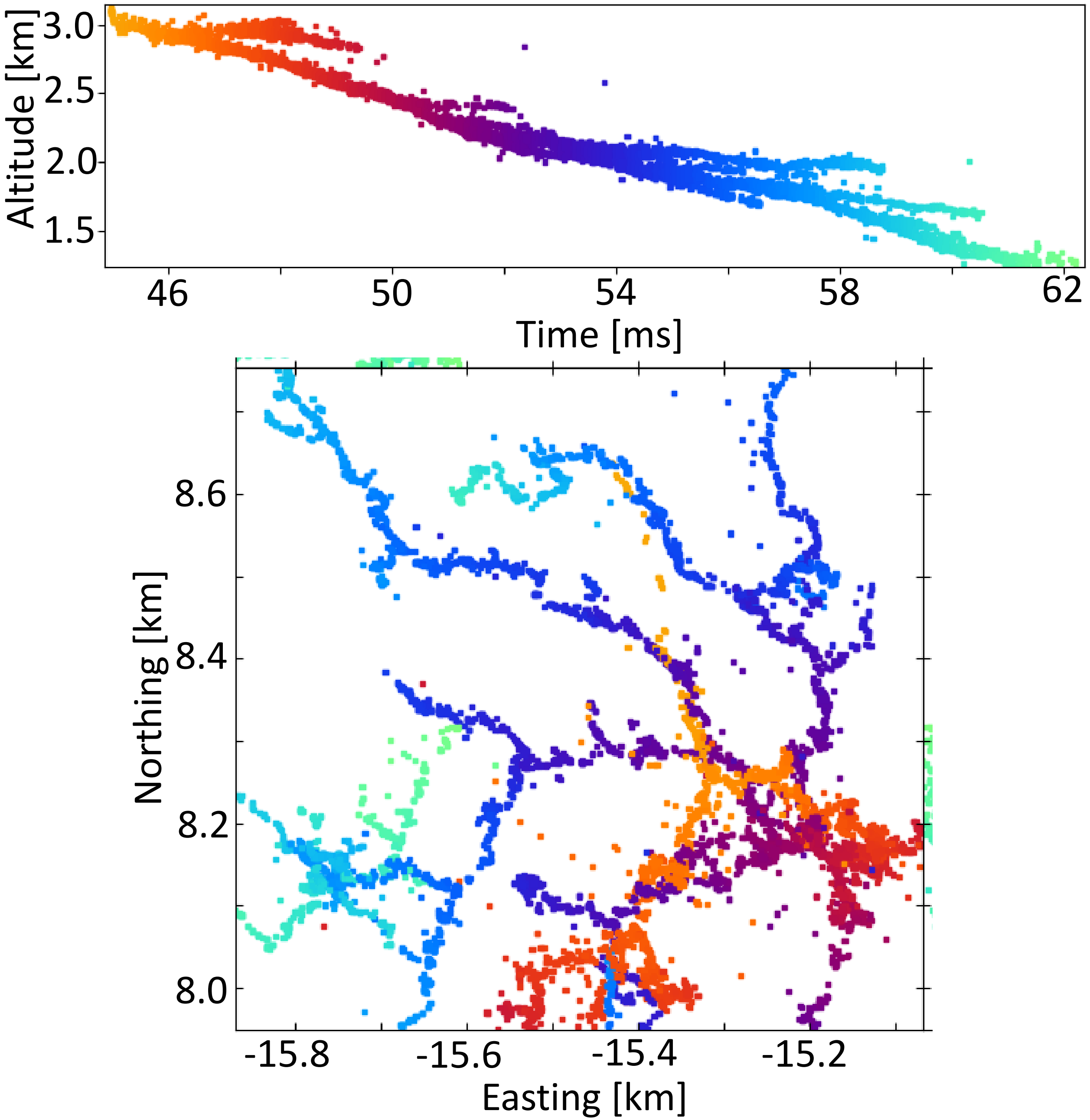
Negative Leader



Dart Leader over same spot

Negative Leader



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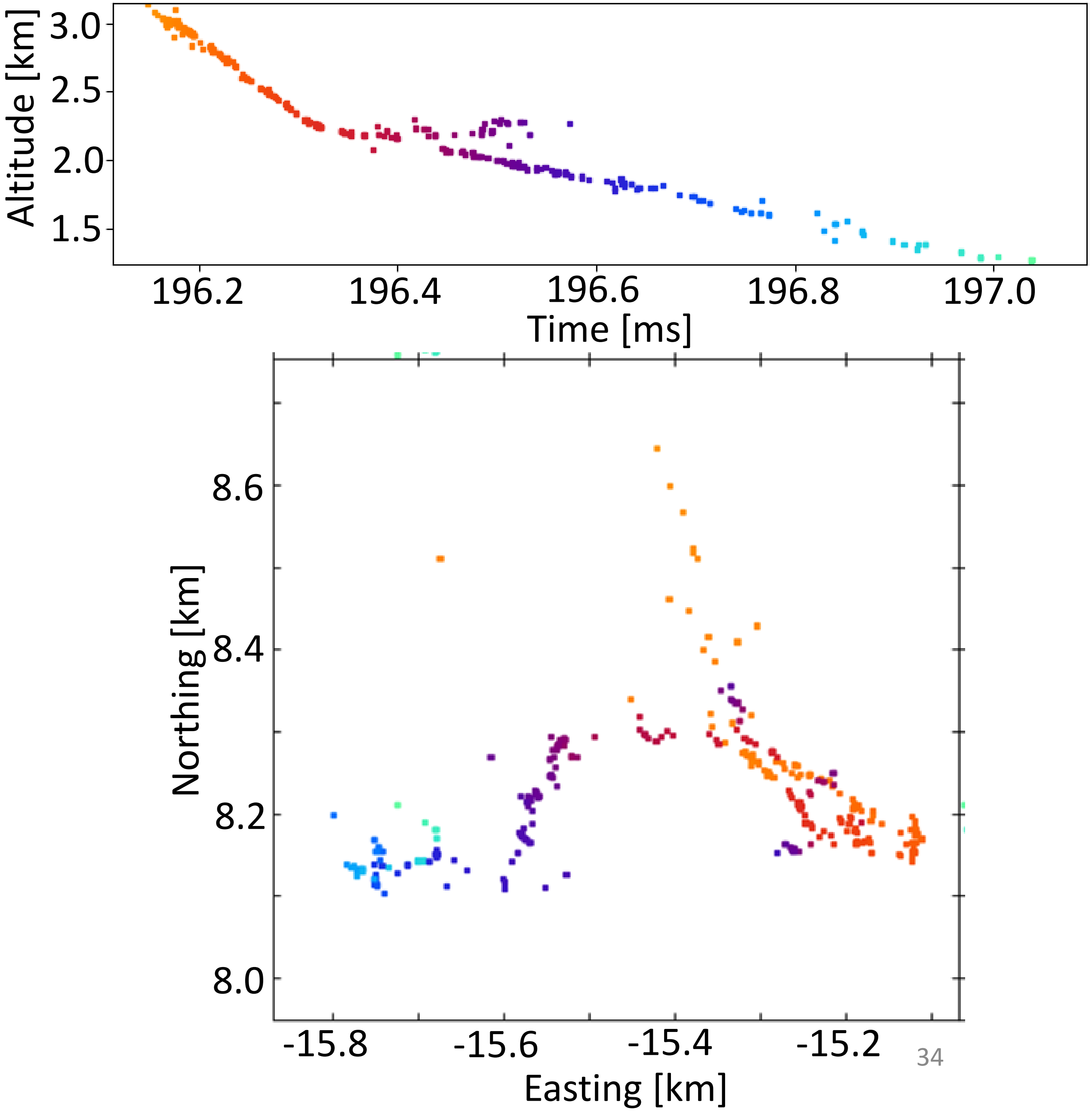
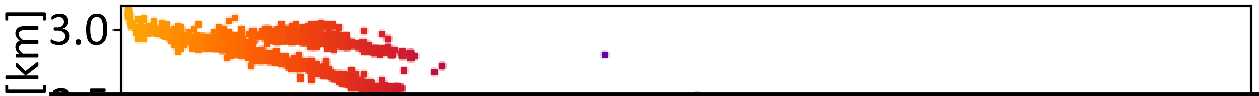
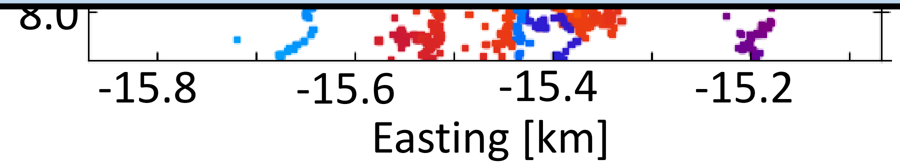


Negative Leader



- study meter-scale structure of dart leaders
  - Good challenge
  - Not well understood
  - Insight into lightning plasma
- Impulsive TOA imaging not so good for recoils
- Need 3D beamforming
  - Which needs 3D polarization
    - Polarization could give direction of streamers, thus structure of plasma



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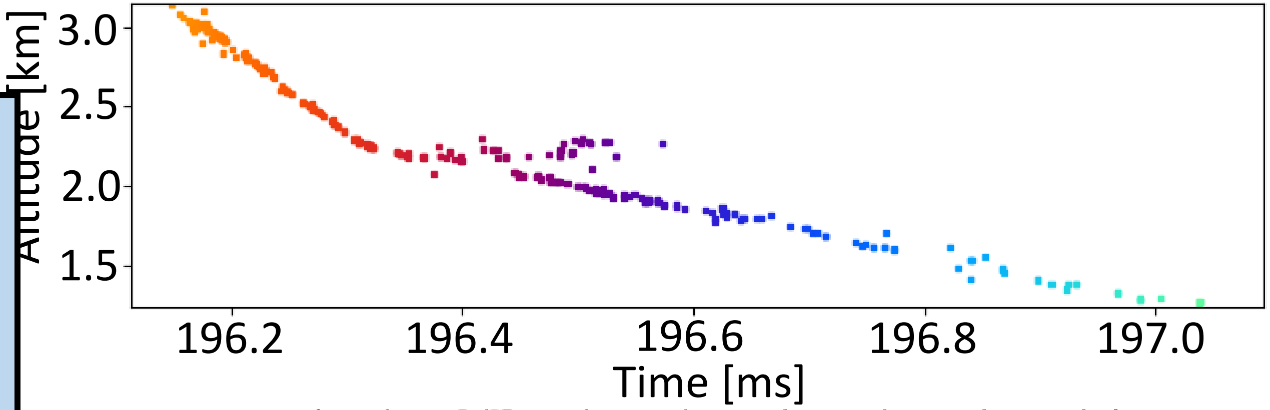
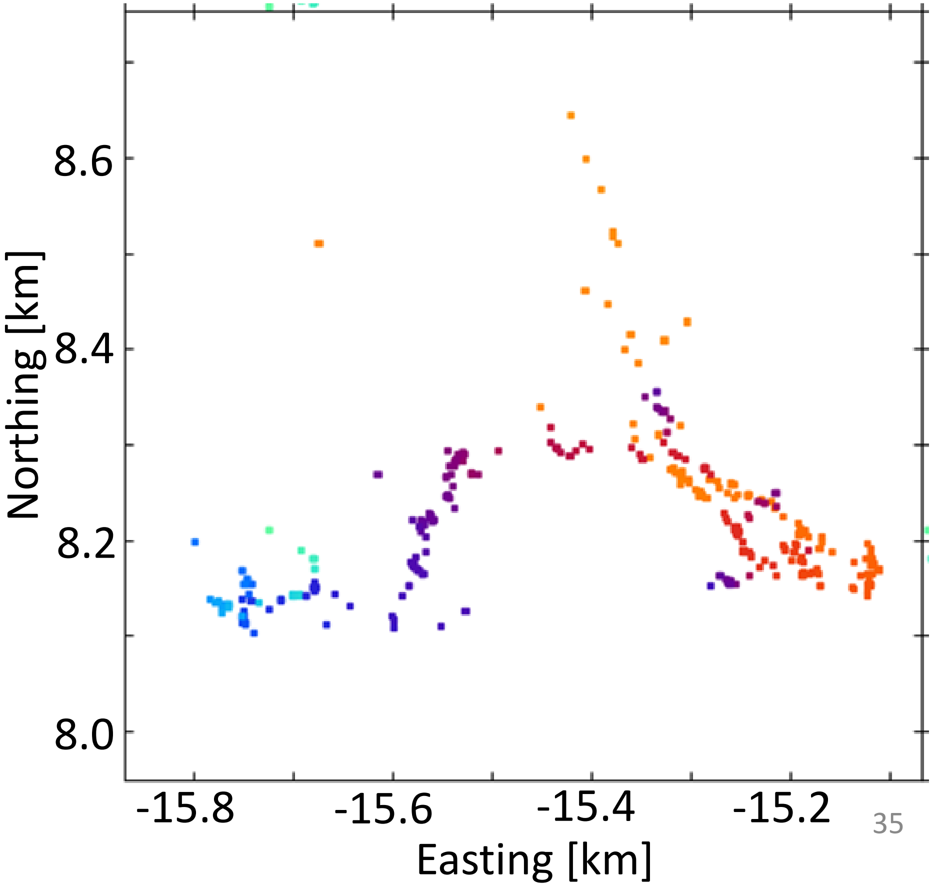
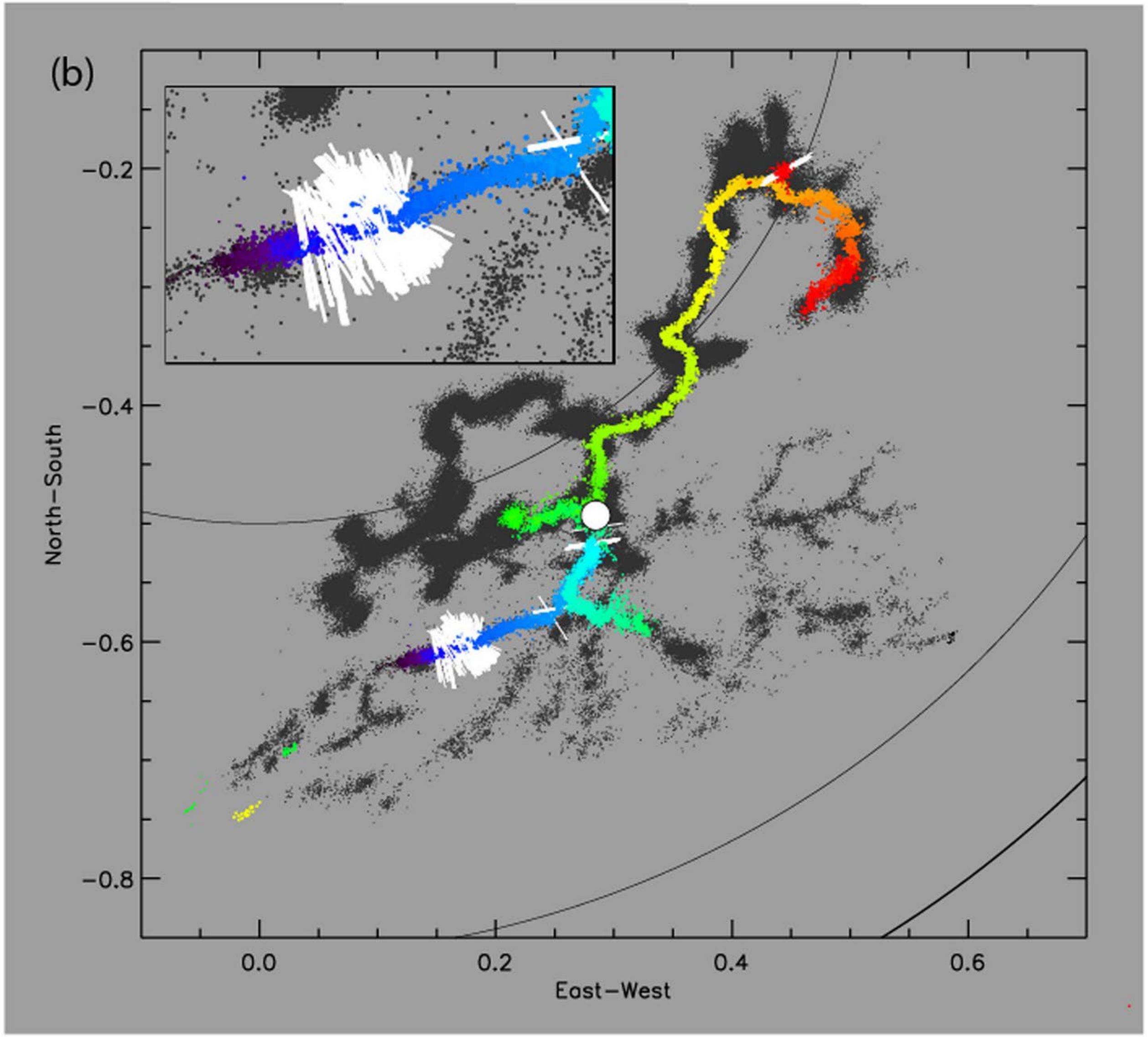




A Previous Work



X.M Shao (2018), JGR-Atmospheres

- Studied recoil leaders with 2D radio imaging
  - 1 μs integration time
  - 100 m resolution
- Extracted 2D polarization
- Black dots are whole flash
- Colored dots are a dart leader
- White lines is linear polarization direction
- RESULT:
  - Polarization is perpendicular to propagation
  - Implies dart strongly interacts with corona sheath around plasma channel

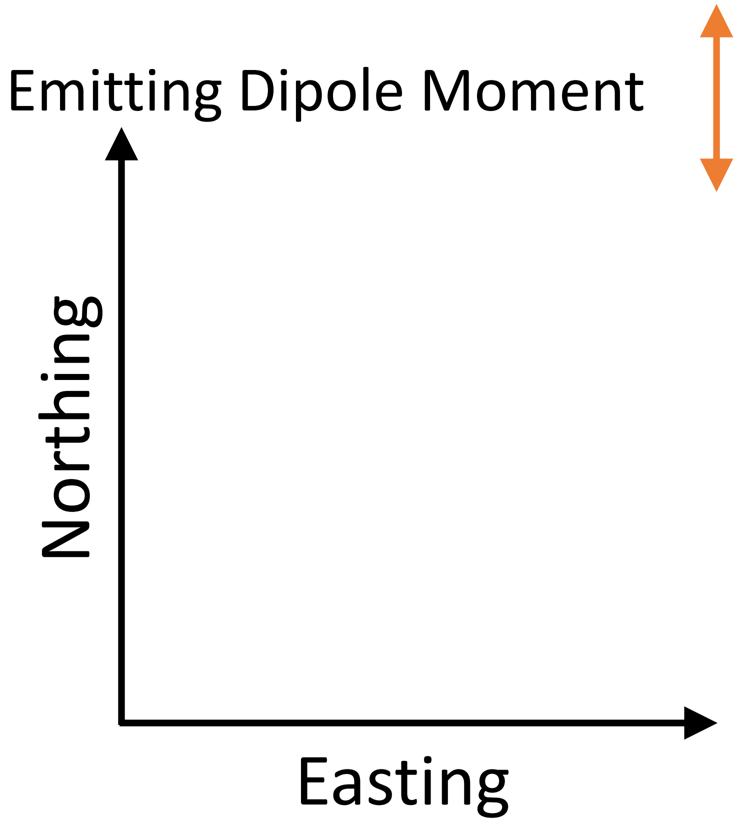
3D Beamforming

Impulsive imaging techniques struggle with interfering sources, which we want to improve by using beamforming

Challenges for 3D:

- Curved wave front
  - Solution: replace plane wave model with 3D point sources
- Curse of dimensionality (3D+time vs 2D)
  - Want integration times of 100 ns
  - Solution: only image small sections, not entire flash
- Polarization
  - This one is hard

The Polarization Problem



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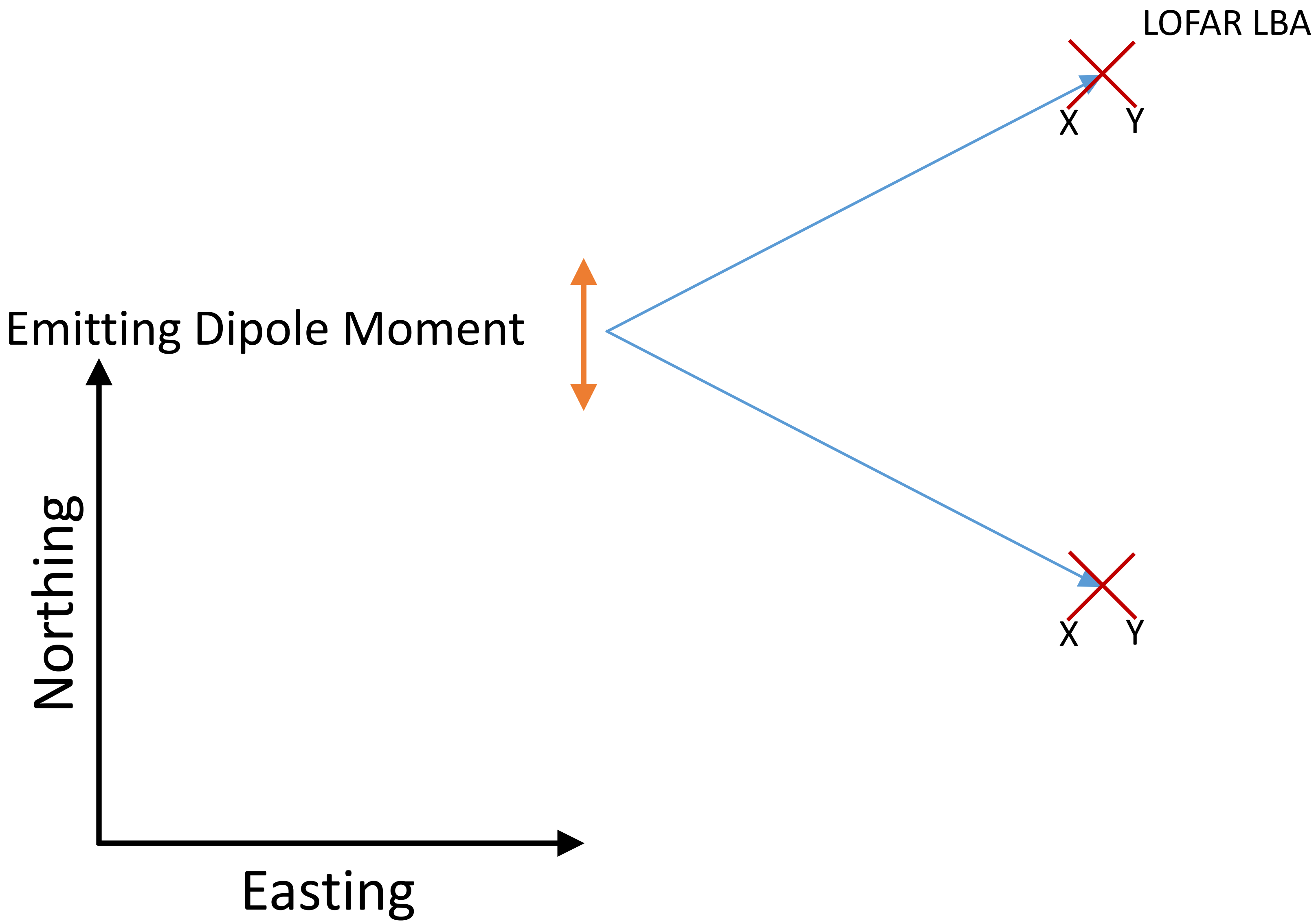

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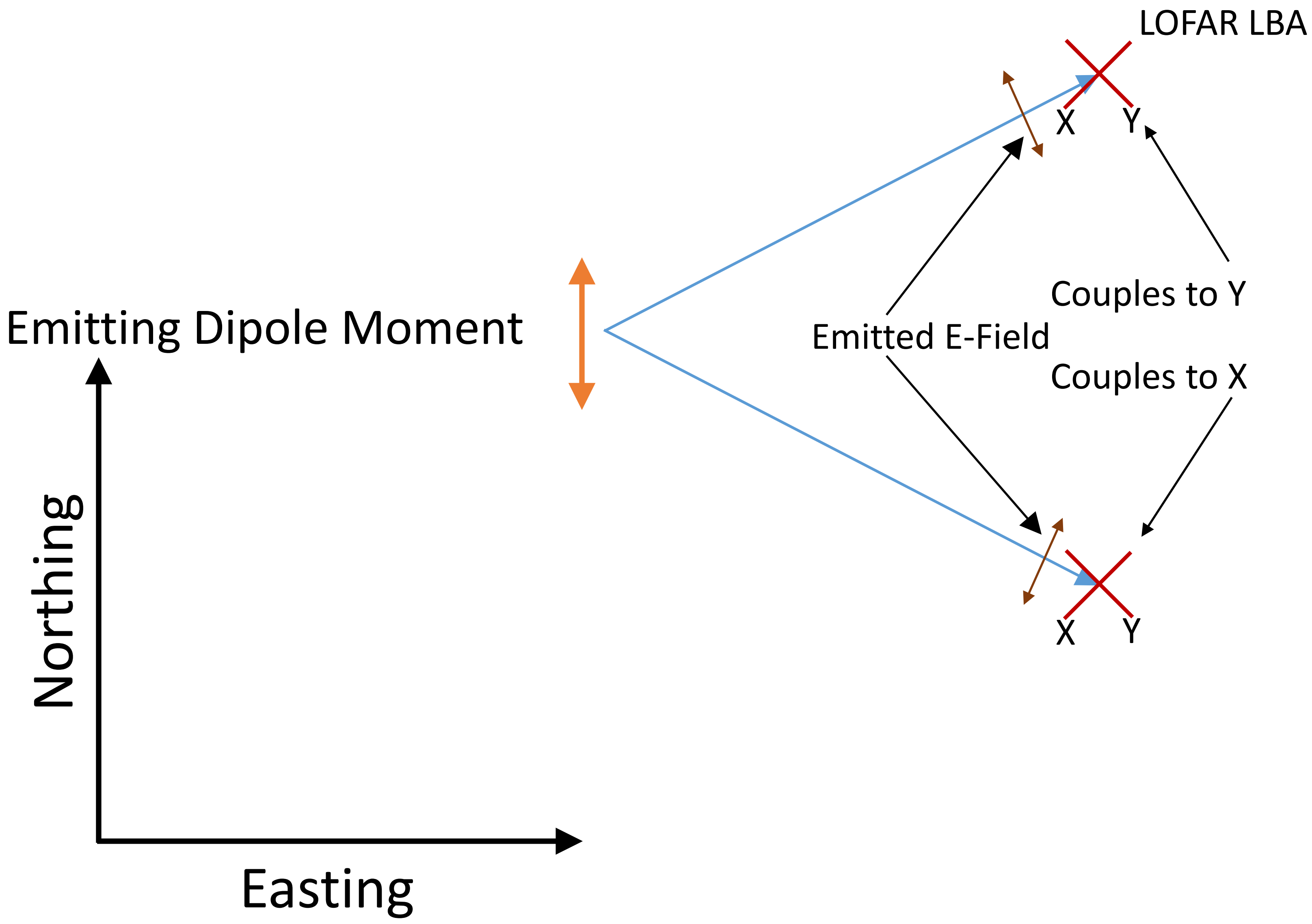

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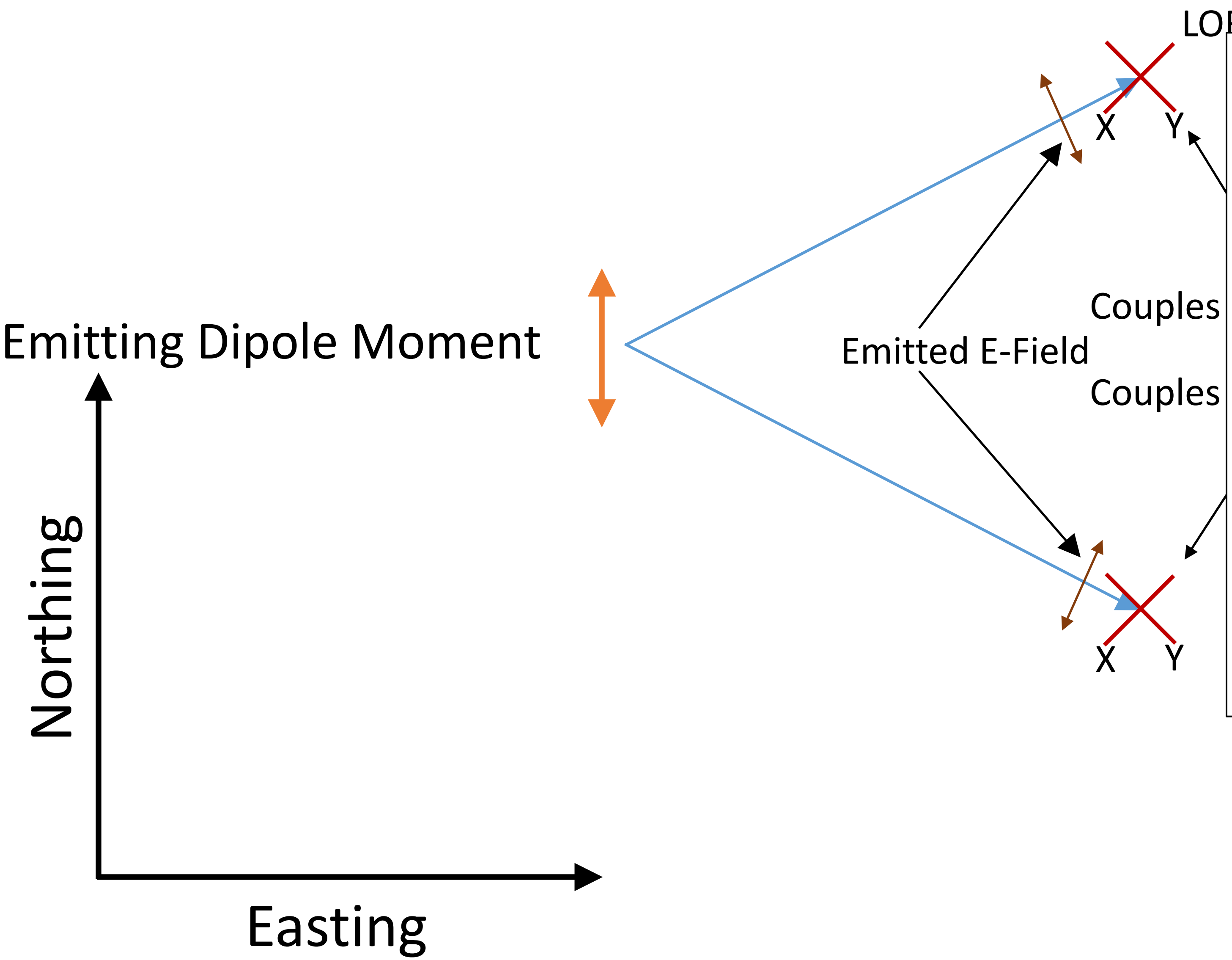
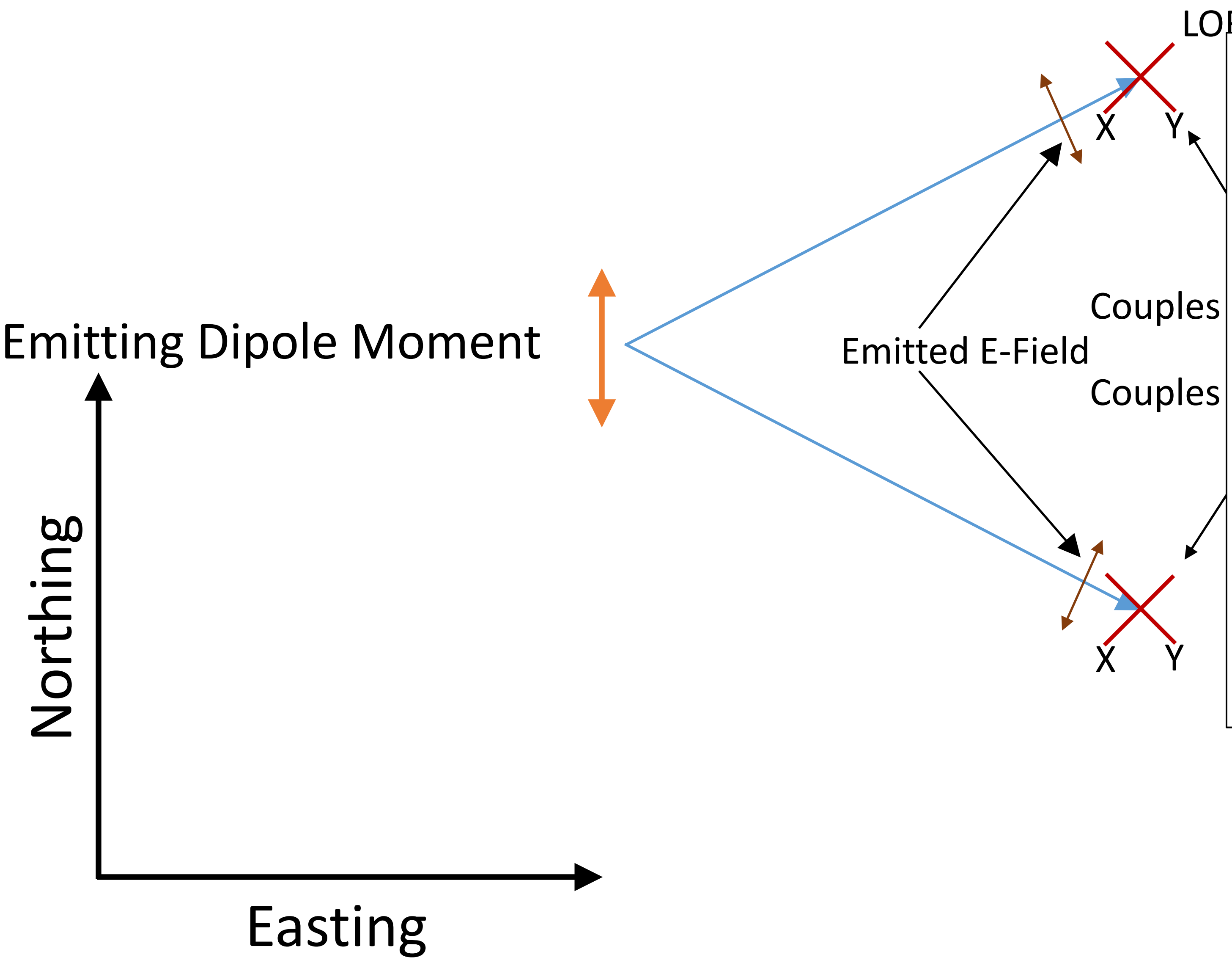


In 2D beamforming:

- 2 polarizations entirely orthogonal
- easily handled at any point in pipeline

The Polarization Problem



In 2D beamforming:

- 2 polarizations entirely orthogonal
- easily handled at any point in pipeline

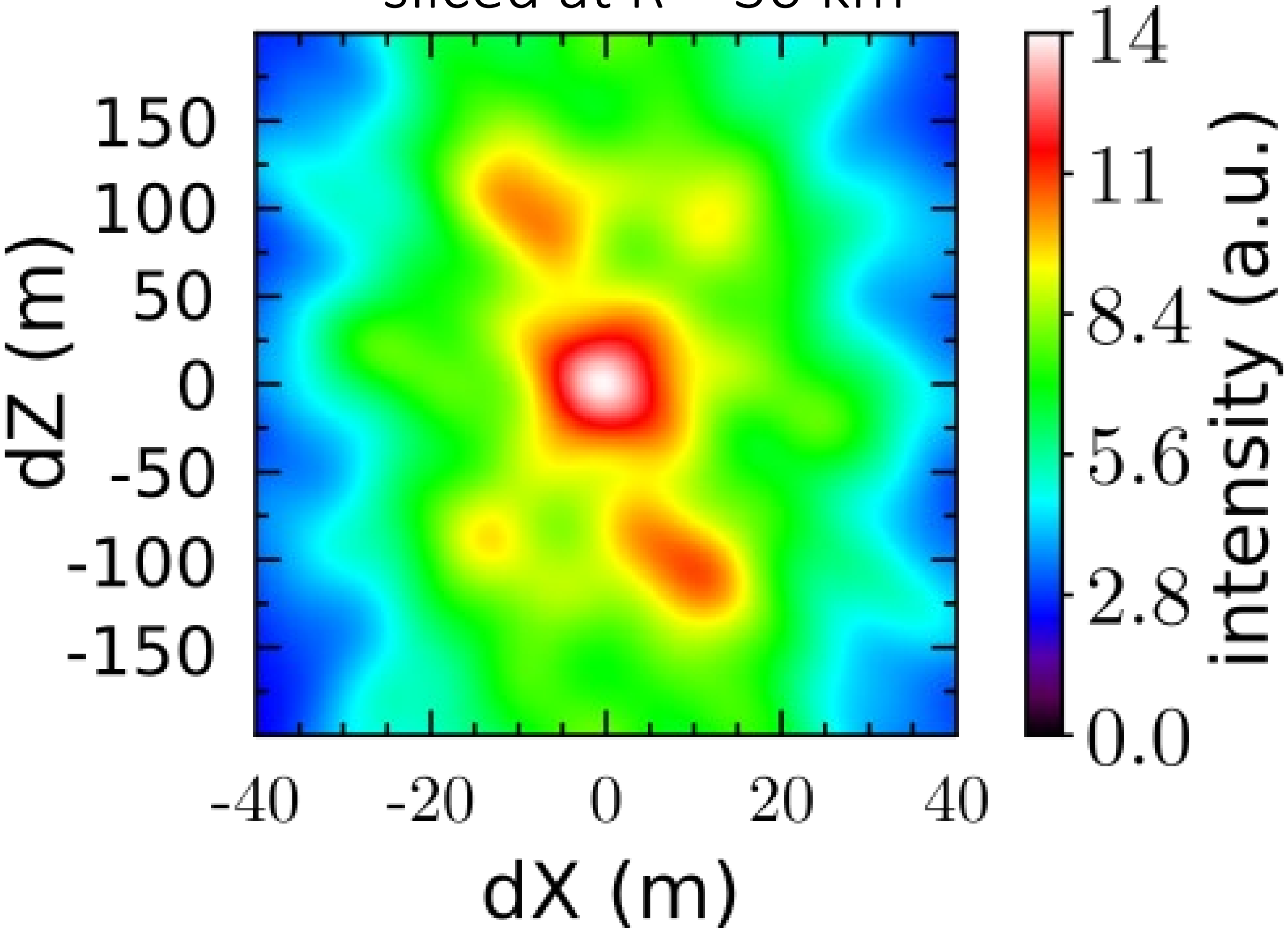
3D beamforming:

- Antennas on all sides of the source
- Different antennas see different polarization
- Different polarizations create phase shifts
- Polarization + antenna function must be accounted for early in imaging

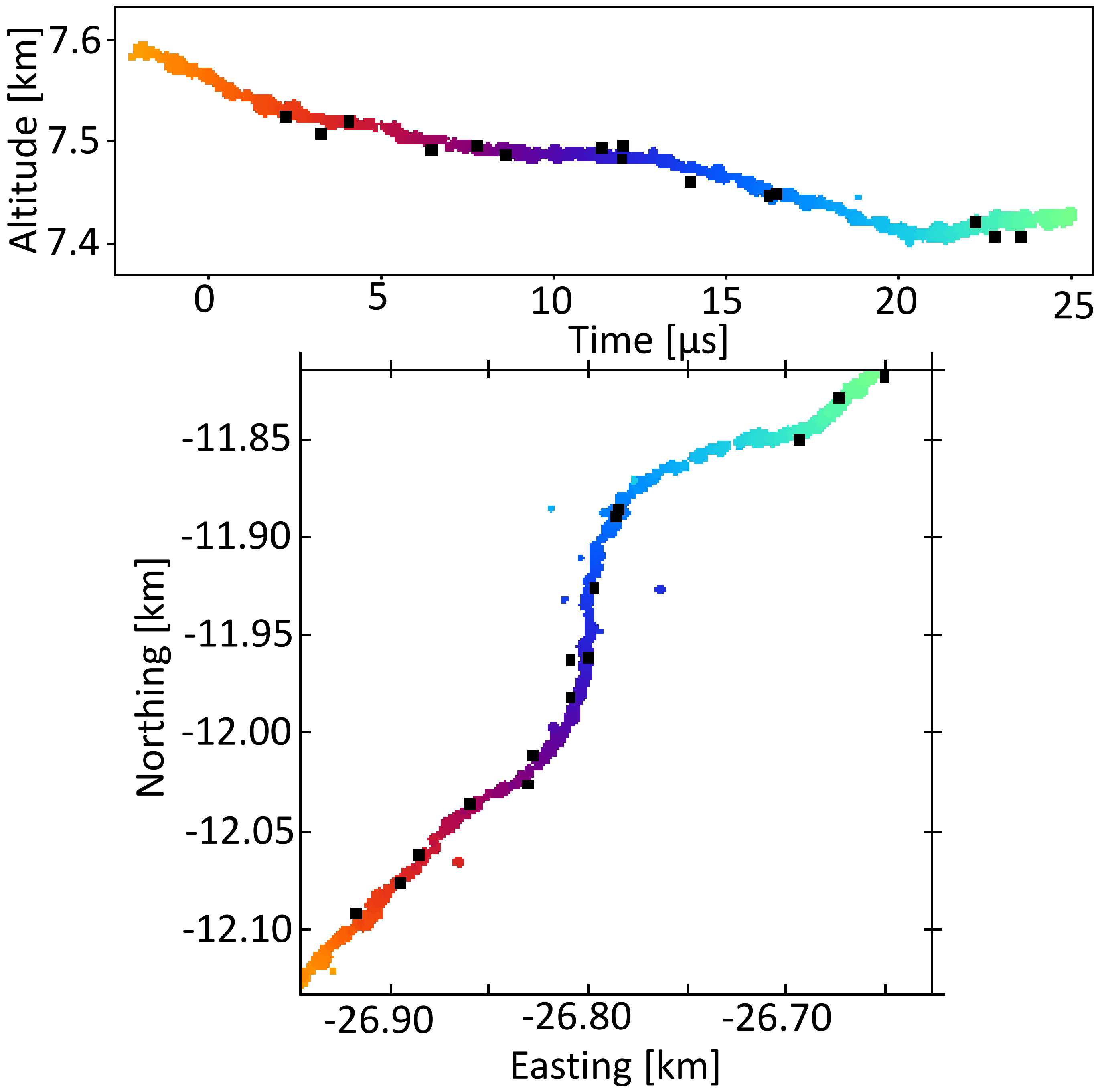
NEW 3D Lightning Beamforming

Resulting Image

sliced at R = 30 km

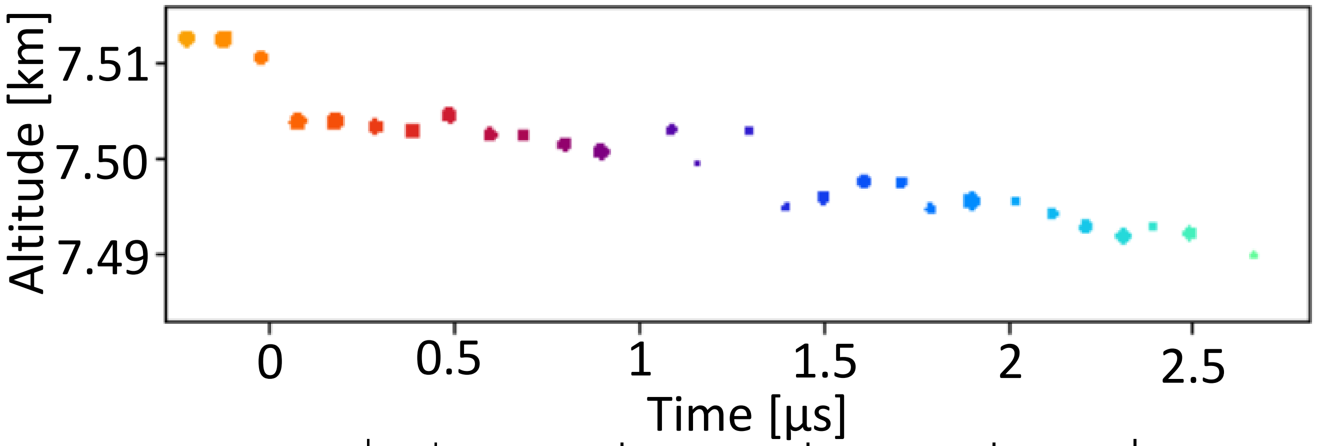


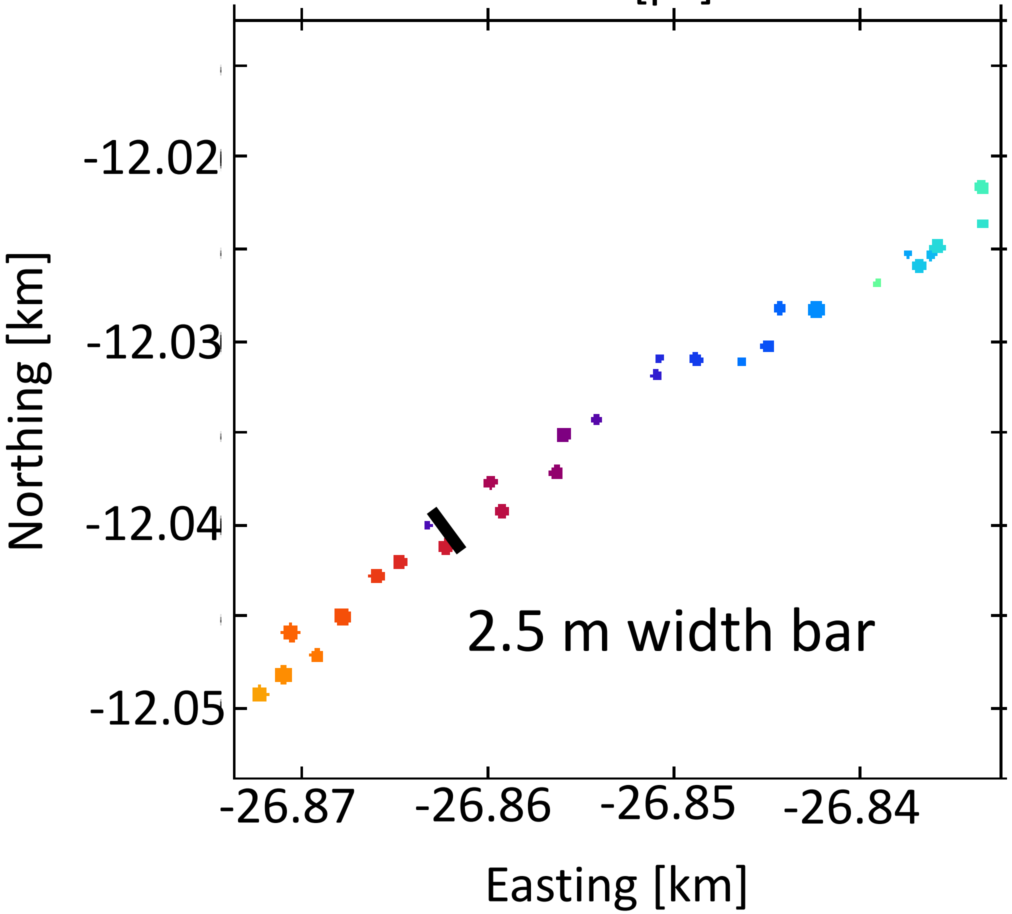
- Accounts for full 3D polarization
- Full 3D Image
  - Integrate over 100 ns
- Pick location of max. intensity as location of source
  - No deconvolution yet
- Repeat this over many time-slices



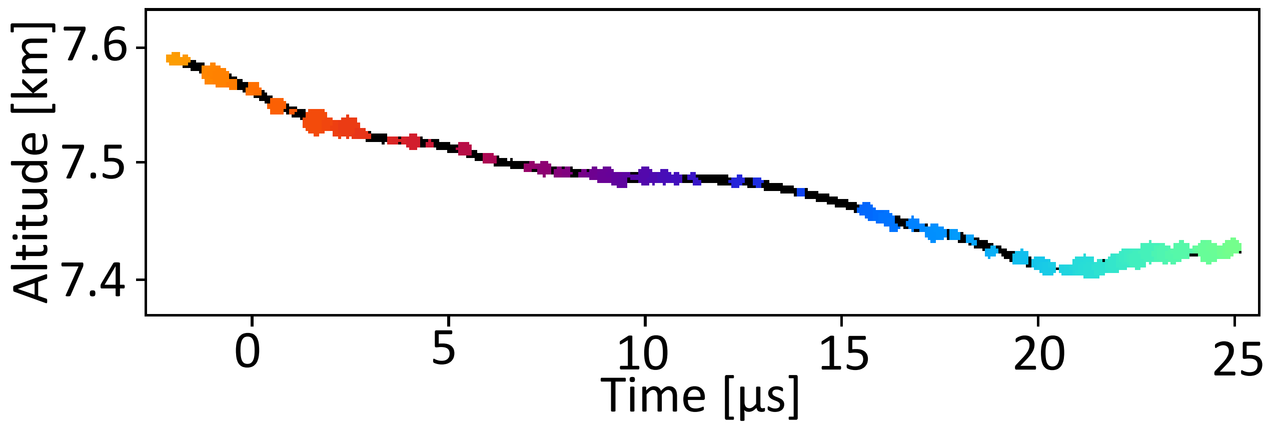
Small Section of Dart

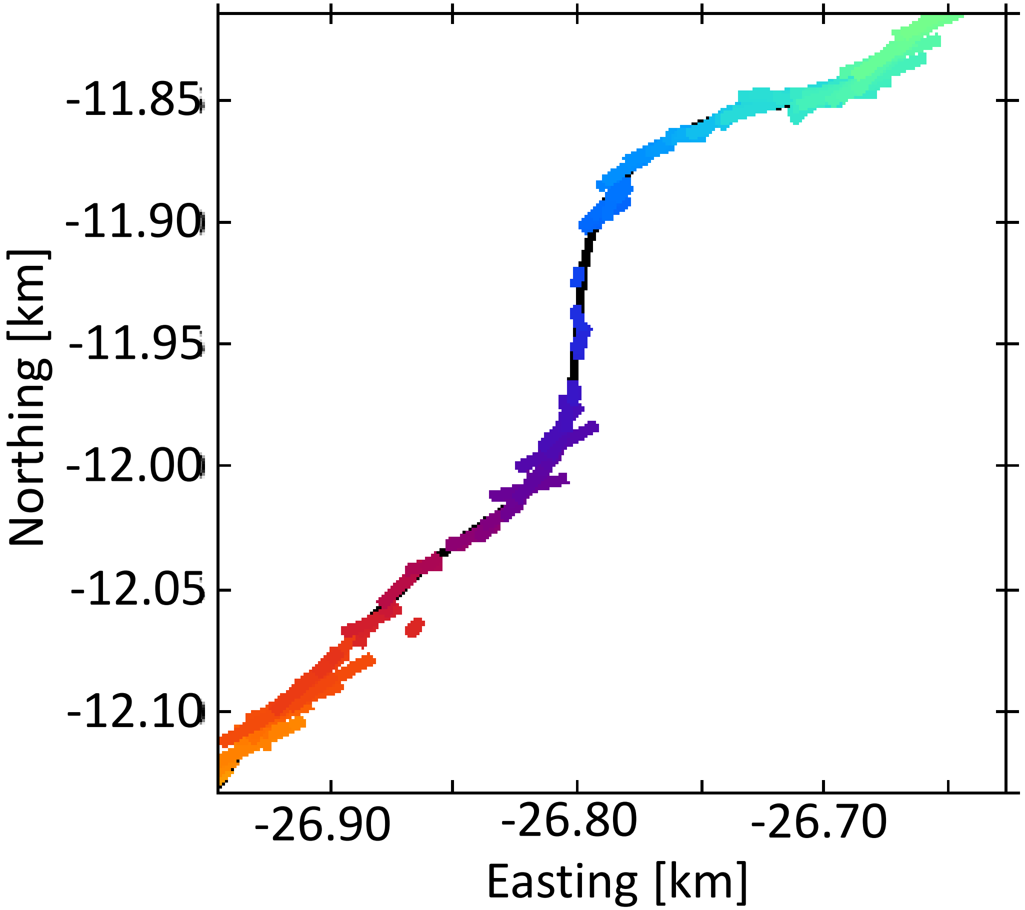
- Black data are previous imager
- Colored dots are new Interferometry
- One of cleanest events
- Tremendous detail
  - Physics results: very smooth



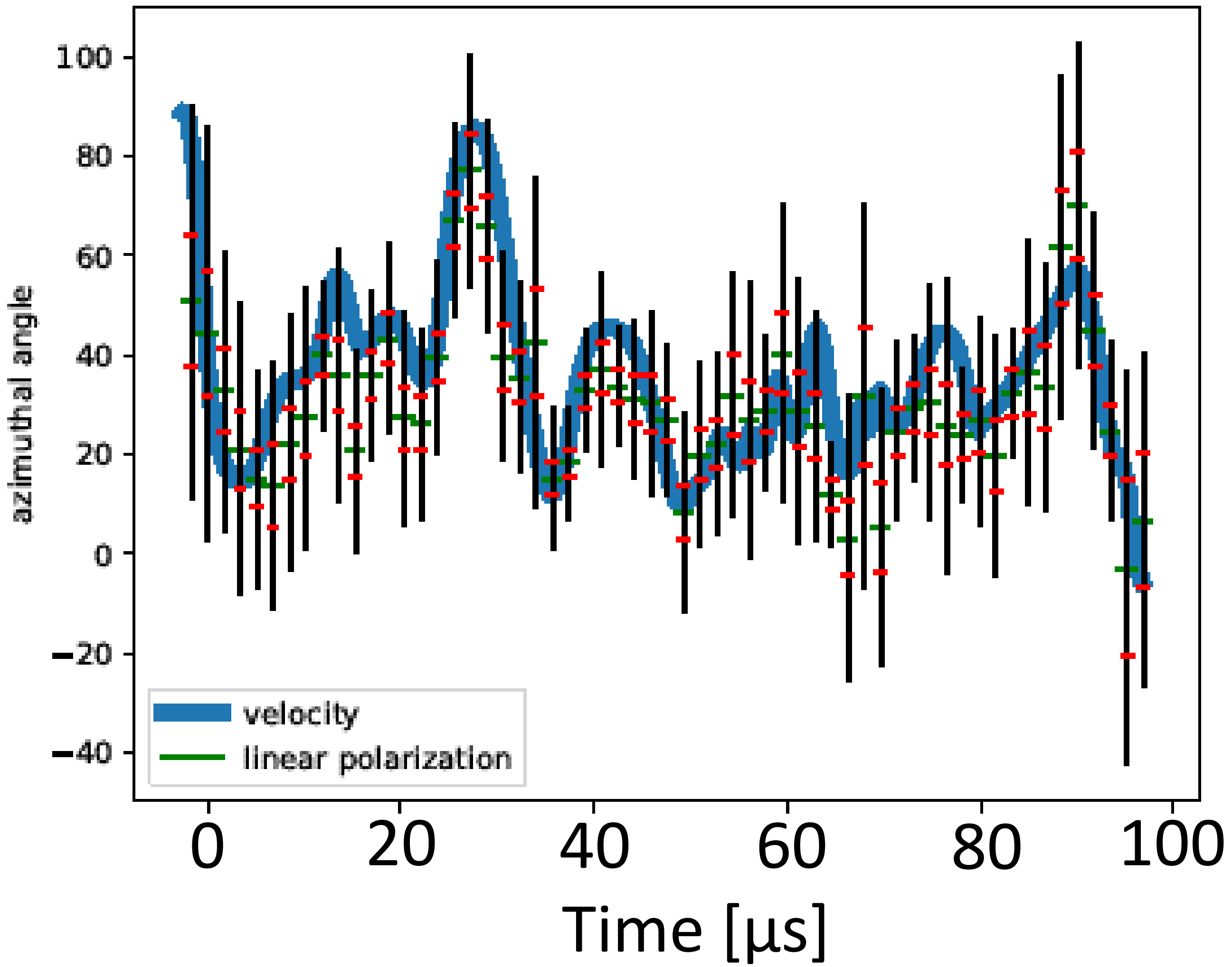


- Zoom-in to previous plot
- VHF-emitting region is about 2 m wide
  - Due to resolution
- Lightning channel have
  - Thin hot core (cm in size)
  - Cold corona sheath (20 m size)
- Thus VHF from hot core
  - Surprising!!





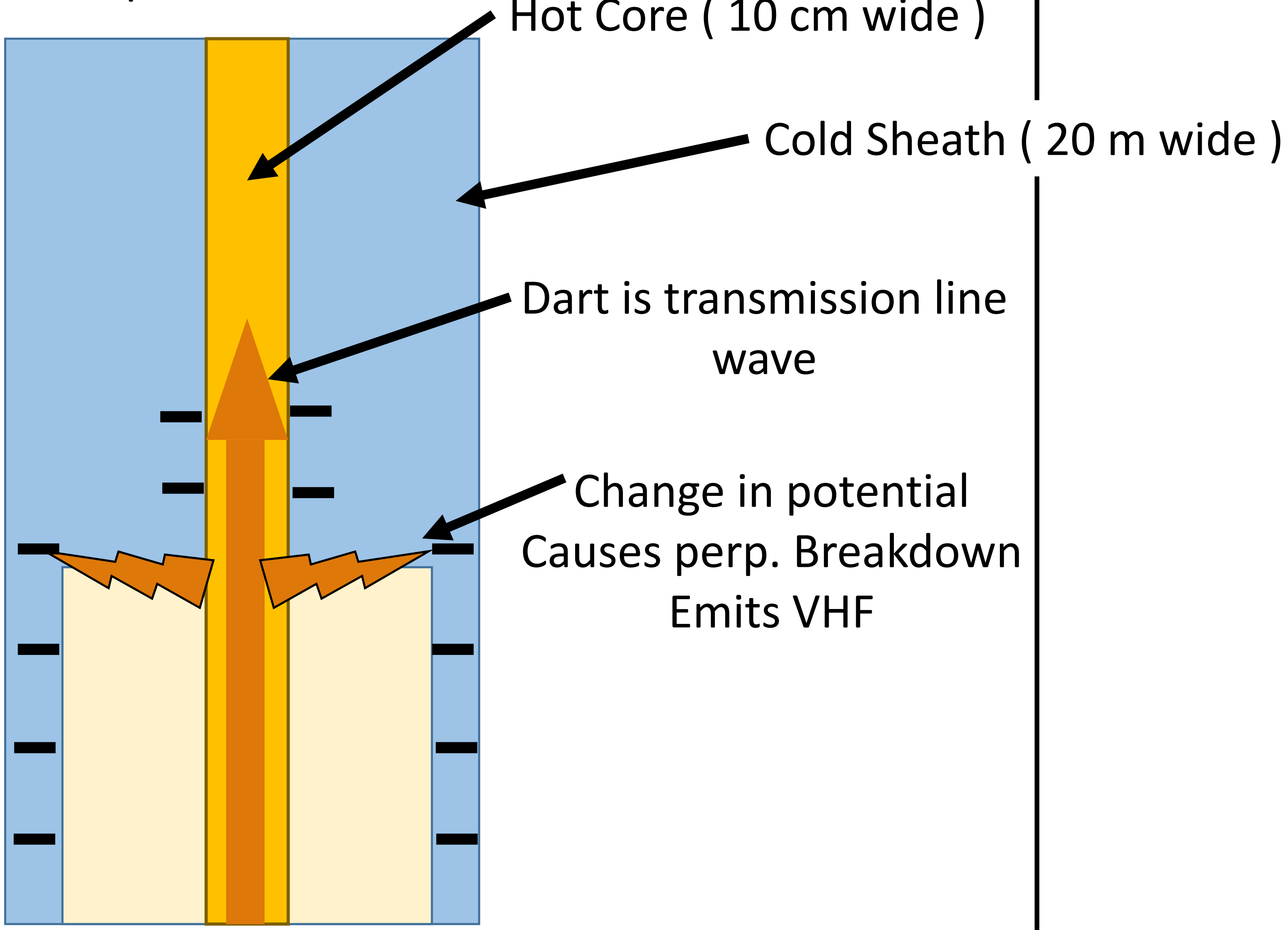
- Lines show linear polarization
  - Of strongest pulses
- Polarization is parallel leader track
  - Different from previous results
- But this type of plot can be misleading
  - Better statistical analysis next slide



- Blue line : direction of propagation
- Black bars : linear polarization
  - Center shows average
  - Width shows standard deviation
- Confirms previous plot
  - Polarization follows propagation

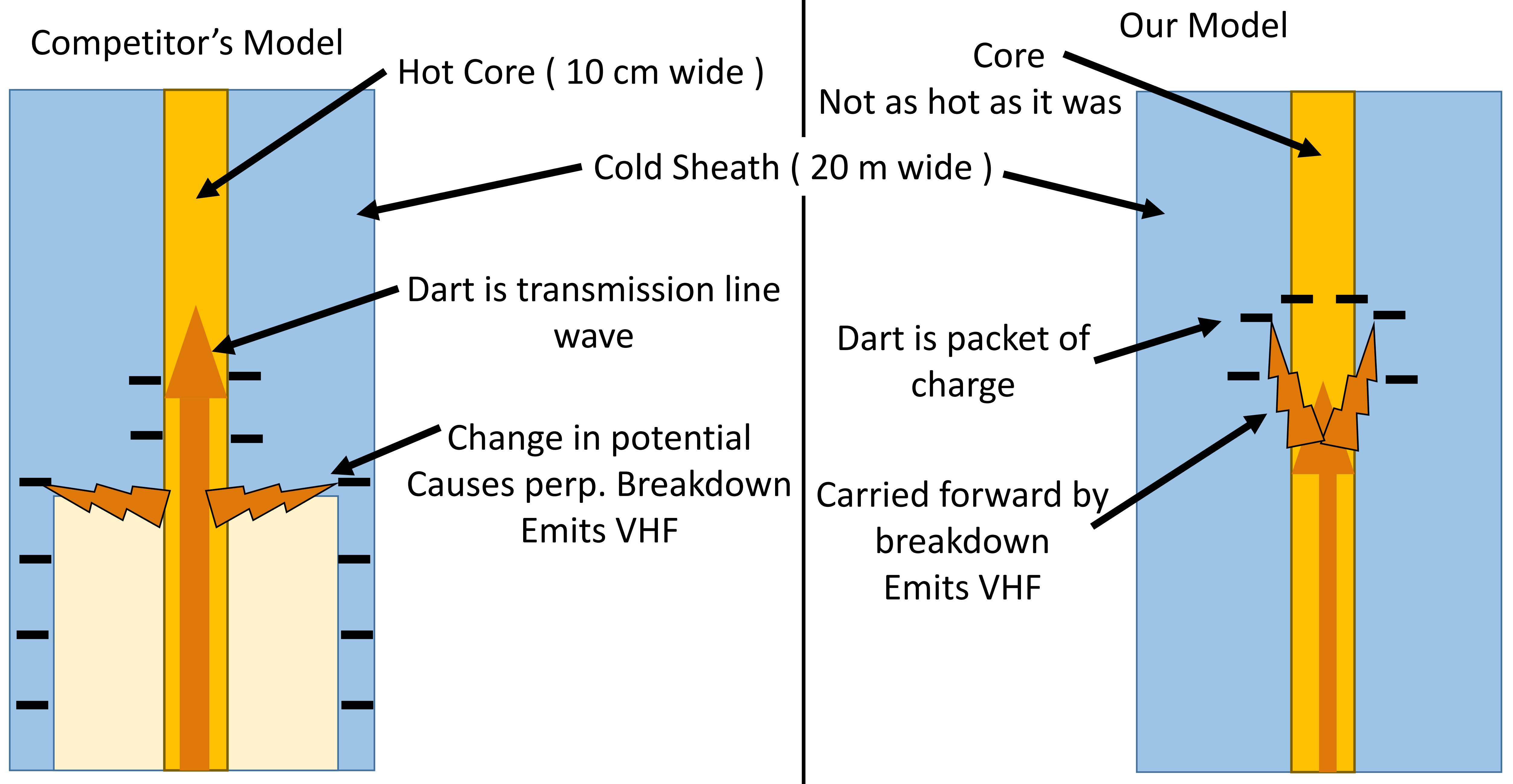
Dart Conclusions

Competitor's Model



Our Model

Dart Conclusions



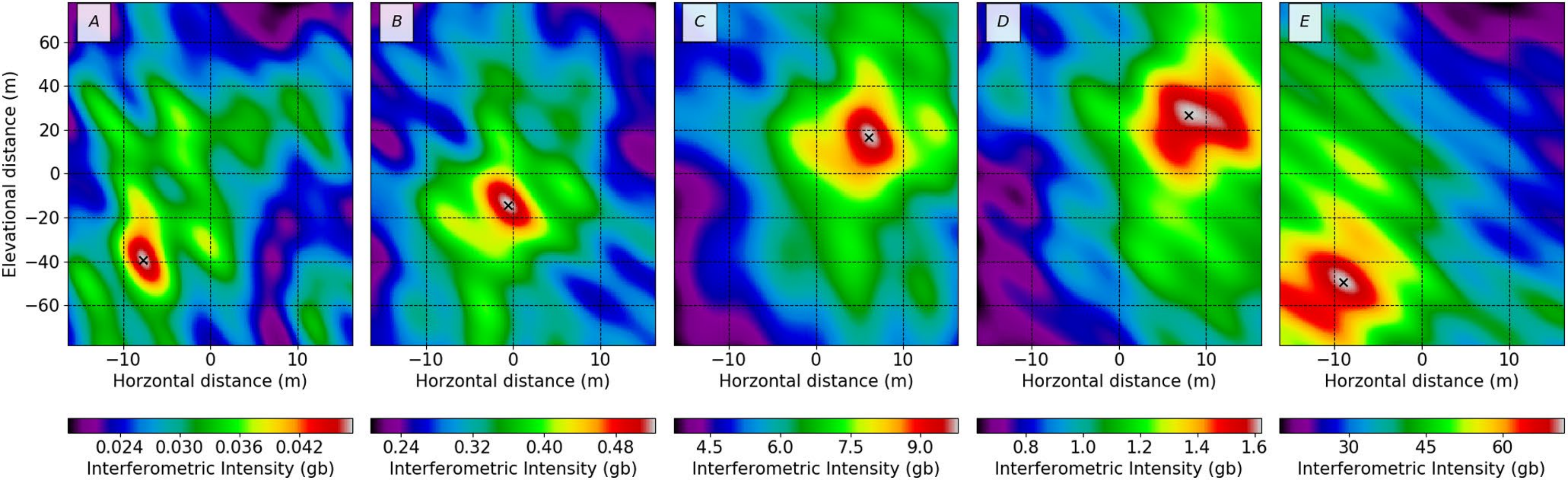
Initiation

New interferometry allows imaging weakly emitting processes

Initiation

New interferometry allows imaging weakly emitting processes

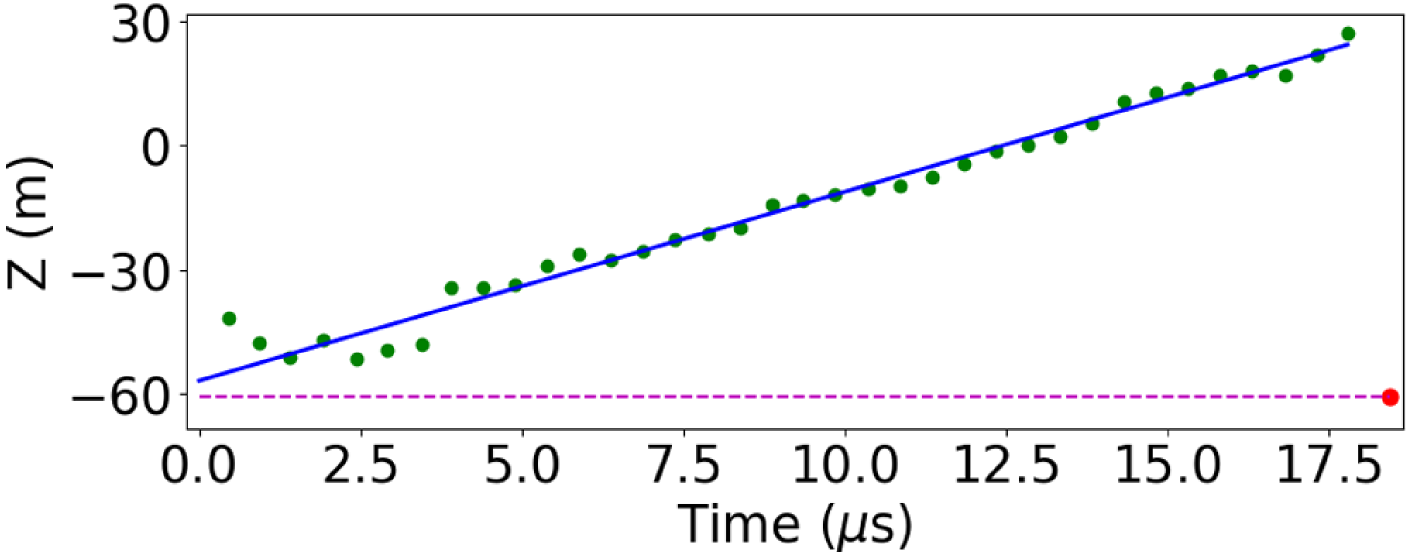
First Image of first process in lightning



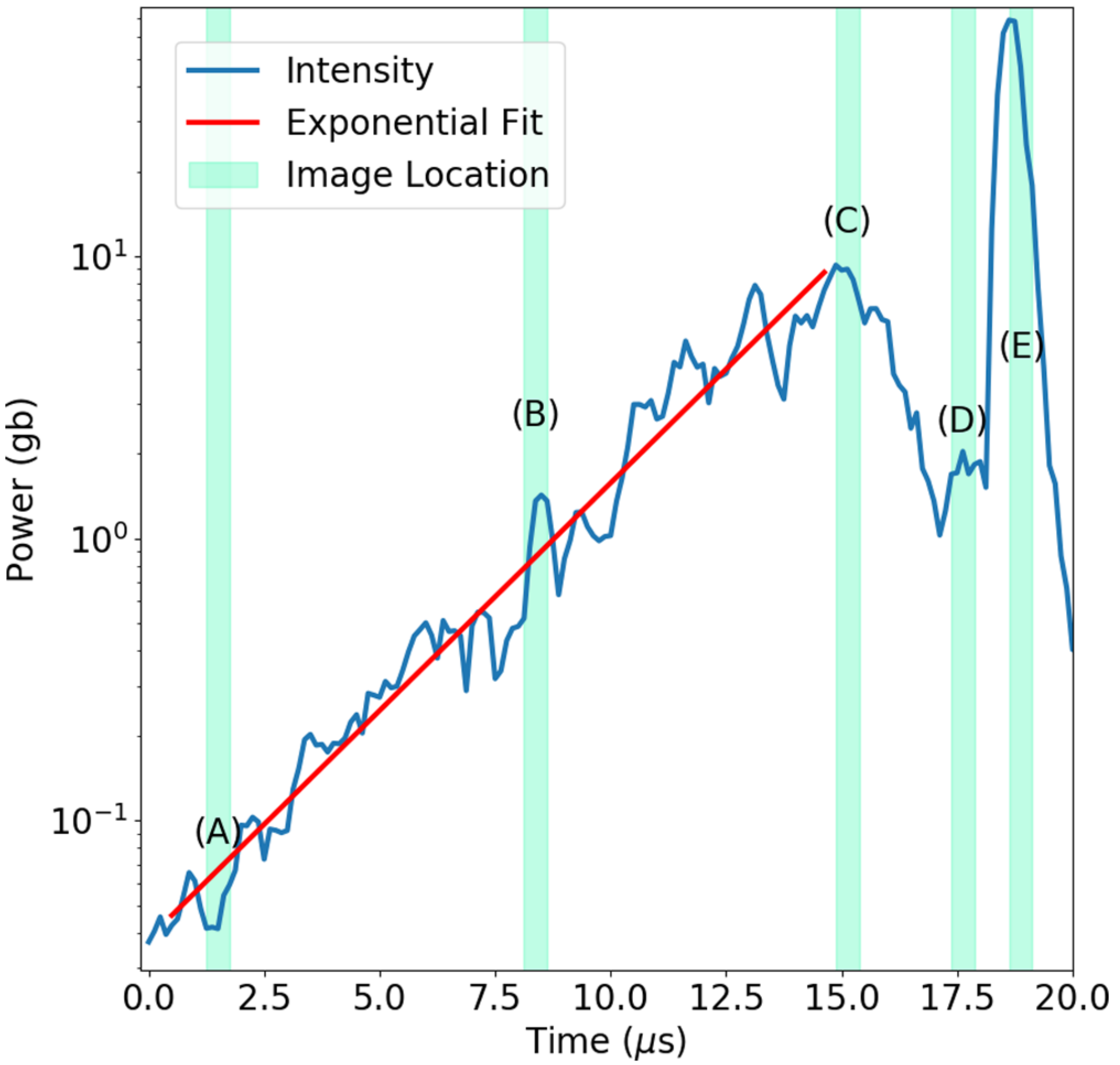
A) Process goes UP then back DOWN

B) VHF power increases exponentially

Location VS Time
(is linear!)



Radio Power VS Time
(is exponential!)

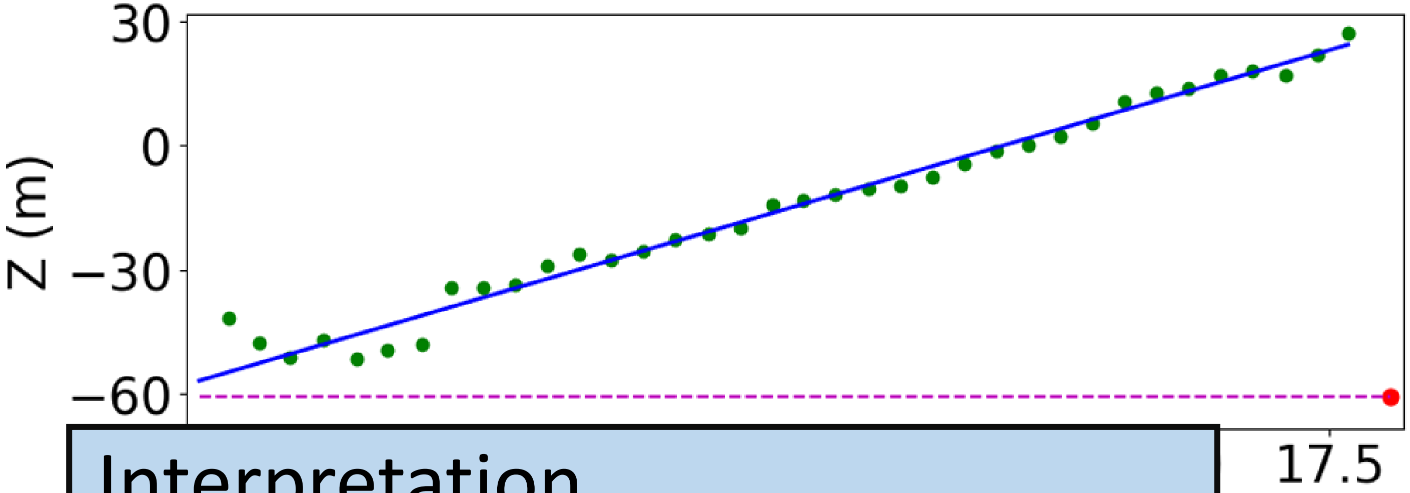


1) Constant upward speed
   - Means propagation is positive charged

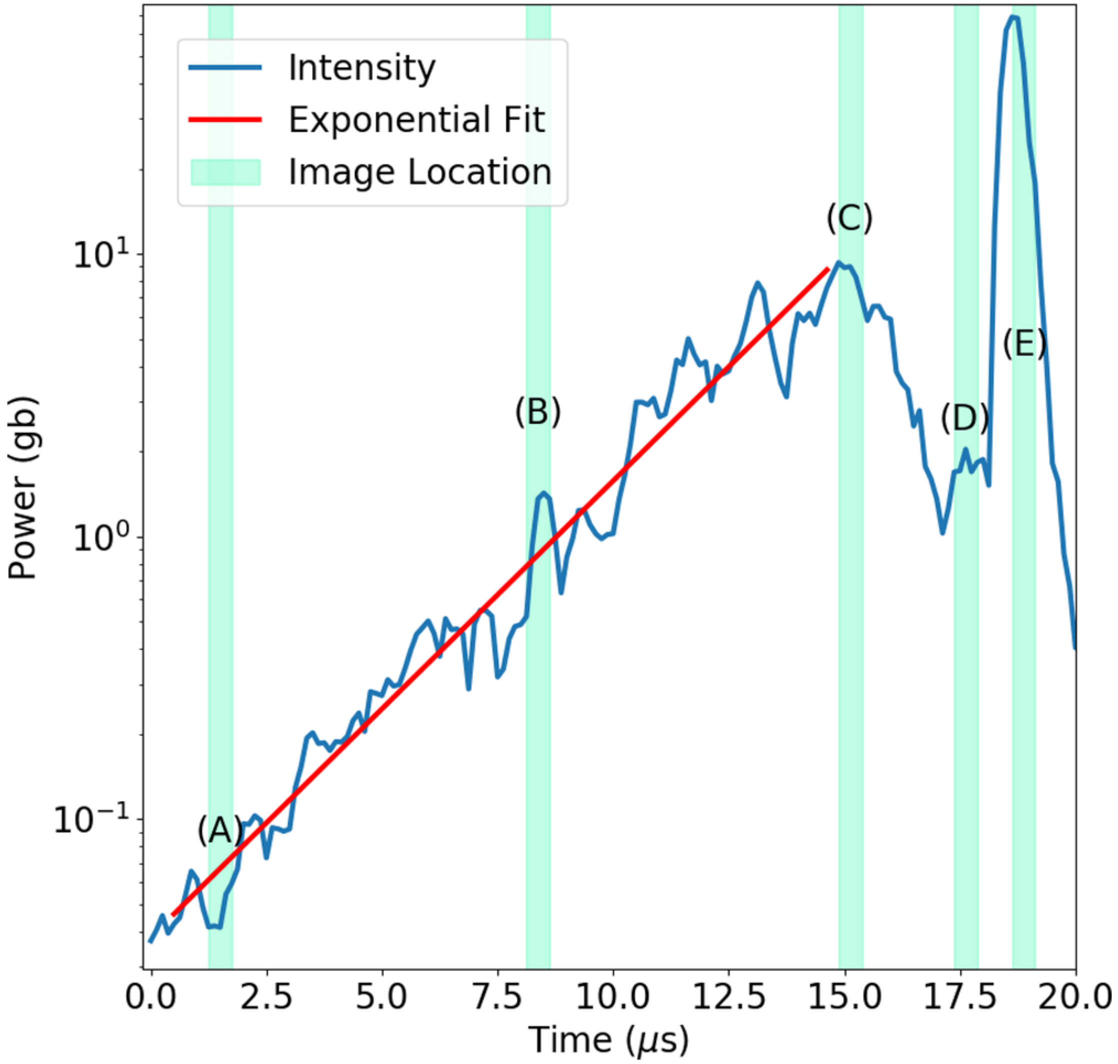
2) Final source at bottom (T=18 us) is start of negative leader

3) Power increase exponential
   - How is speed constant but power exponential?

Location VS Time
(is linear!)



Radio Power VS Time
(is exponential!)



Interpretation

Positively charged streamers
  Essentially cold plasma

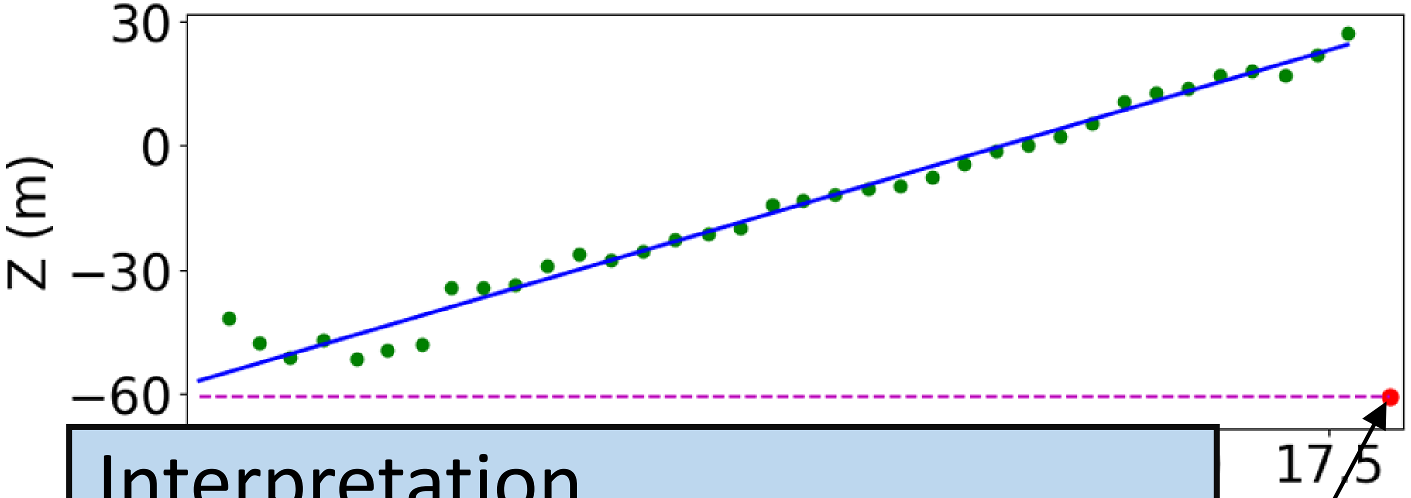
Streamers branch as propagate
  Exponential increase in power
  How is speed constant?

1)

2) … tive
le…

3) … ?

Location VS Time
(is linear!)



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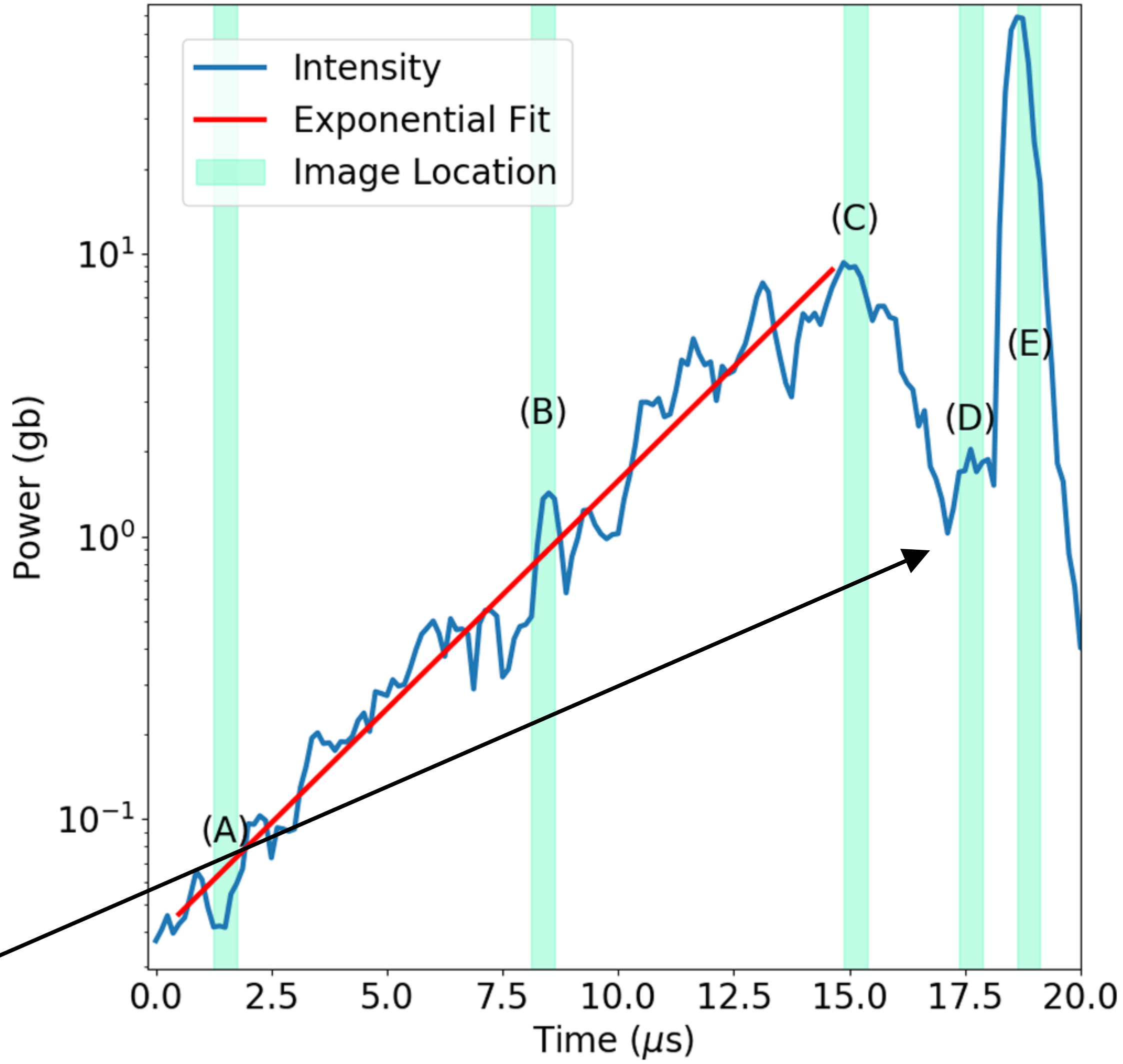

1)

2) tive

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3)

?

Interpretation

Positively charged streamers
  Essentially cold plasma

Streamers branch as propagate
  Exponential increase in power
  How is speed constant?

Afterwards, the negative leader starts

Conclusion

- LOFAR is probing fundamental lightning questions
  - Discovering new lightning phenomena (needles)
  - Exploring how lightning propagates (dart leaders)
  - Imaging lightning initiation

EXTRA

Kalman-Inspired Iterative Solution

- For each pulse to locate:

1) Use 1 LOFAR station
   - Get initial direction

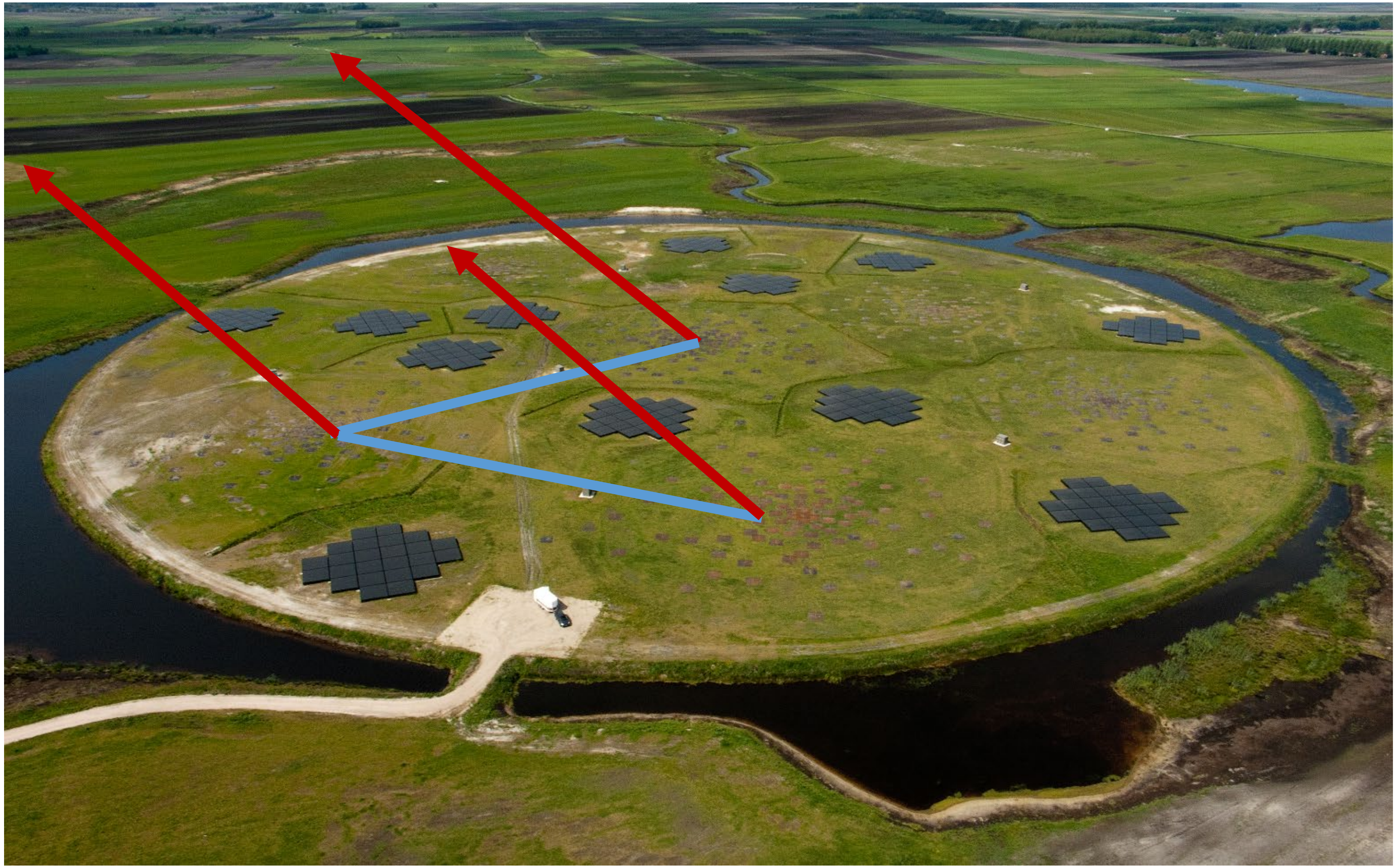
Kalman-Inspired Iterative Solution

- For each pulse to locate:

1) Use 1 LOFAR station
   - Get initial direction

2) Select next station
   - Guess which pulse
   - Improve location guess

Kalman-Inspired Iterative Solution



- For each pulse to locate:

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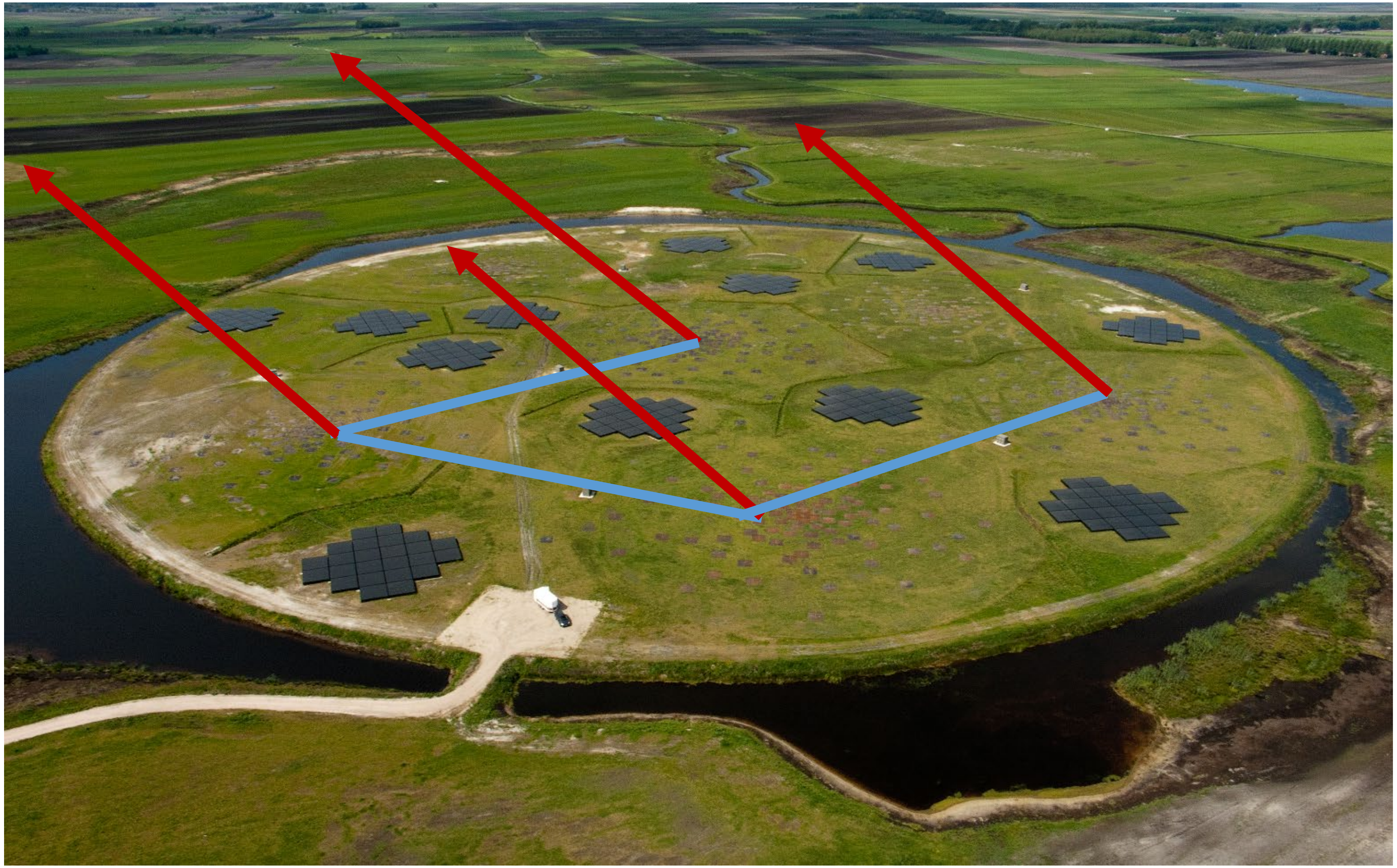
   - Improve location guess

3) Repeat for all LOFAR stations

Kalman-Inspired Iterative Solution



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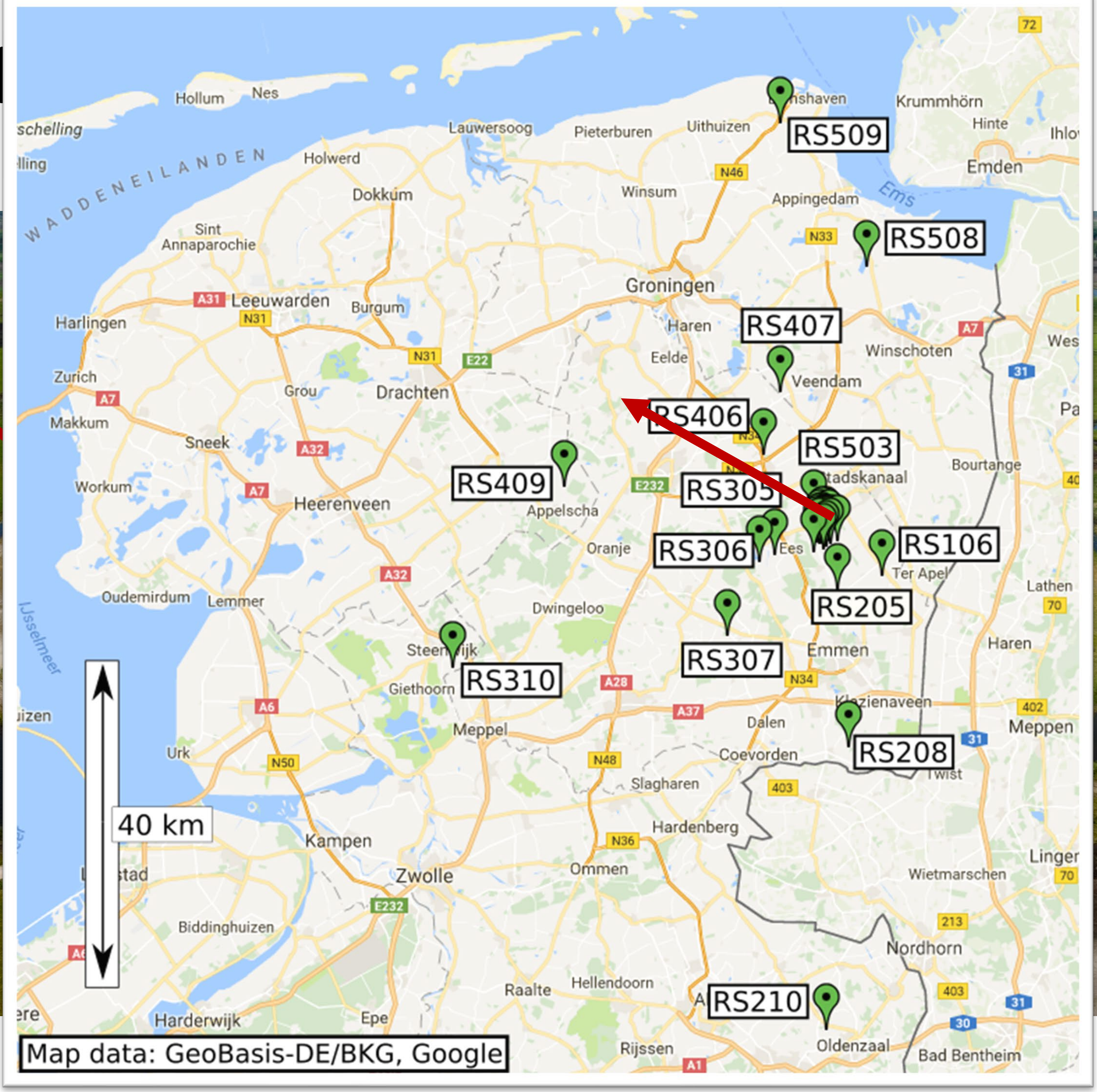

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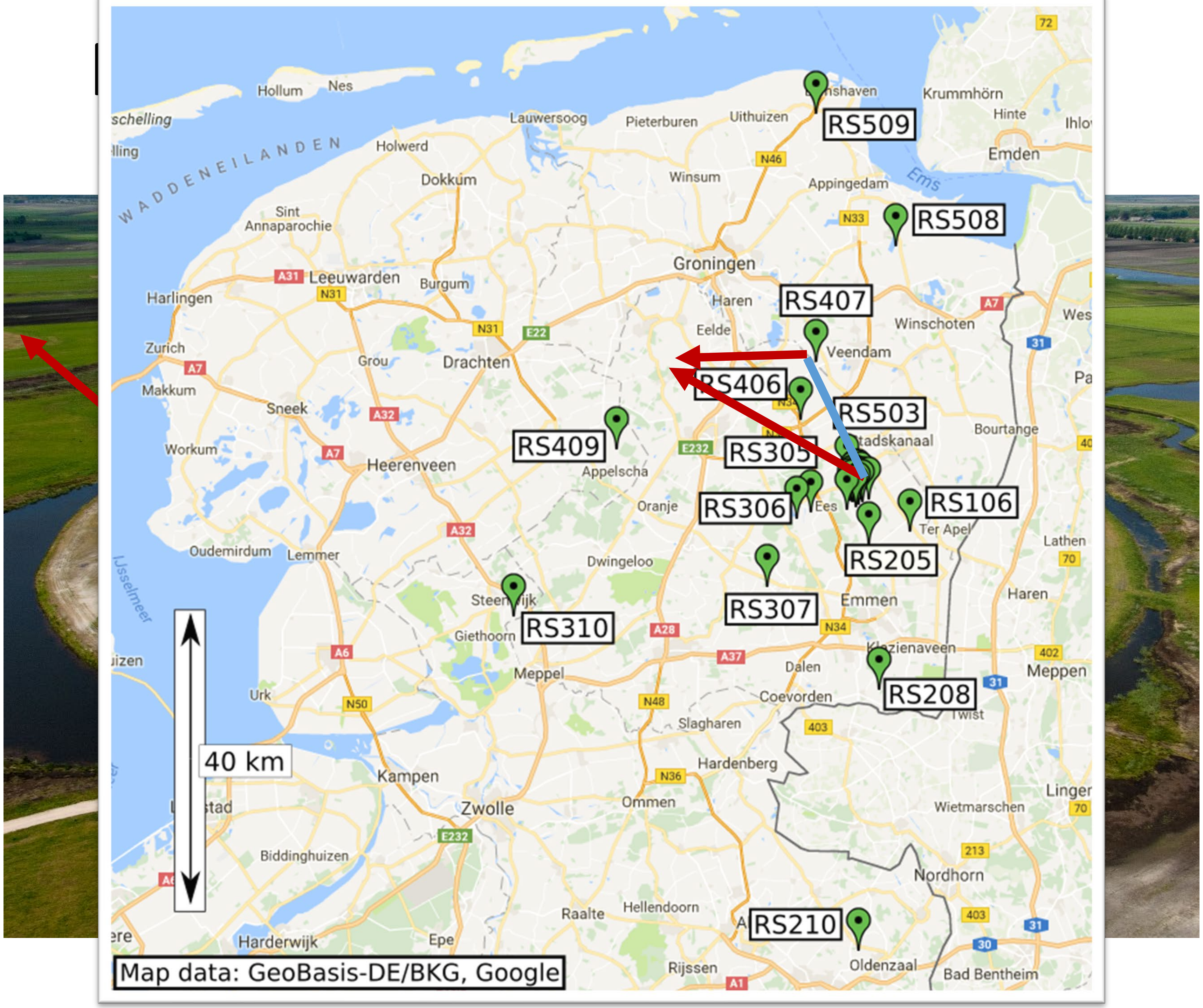
3) Repeat for all LOFAR stations

(include remote stations)



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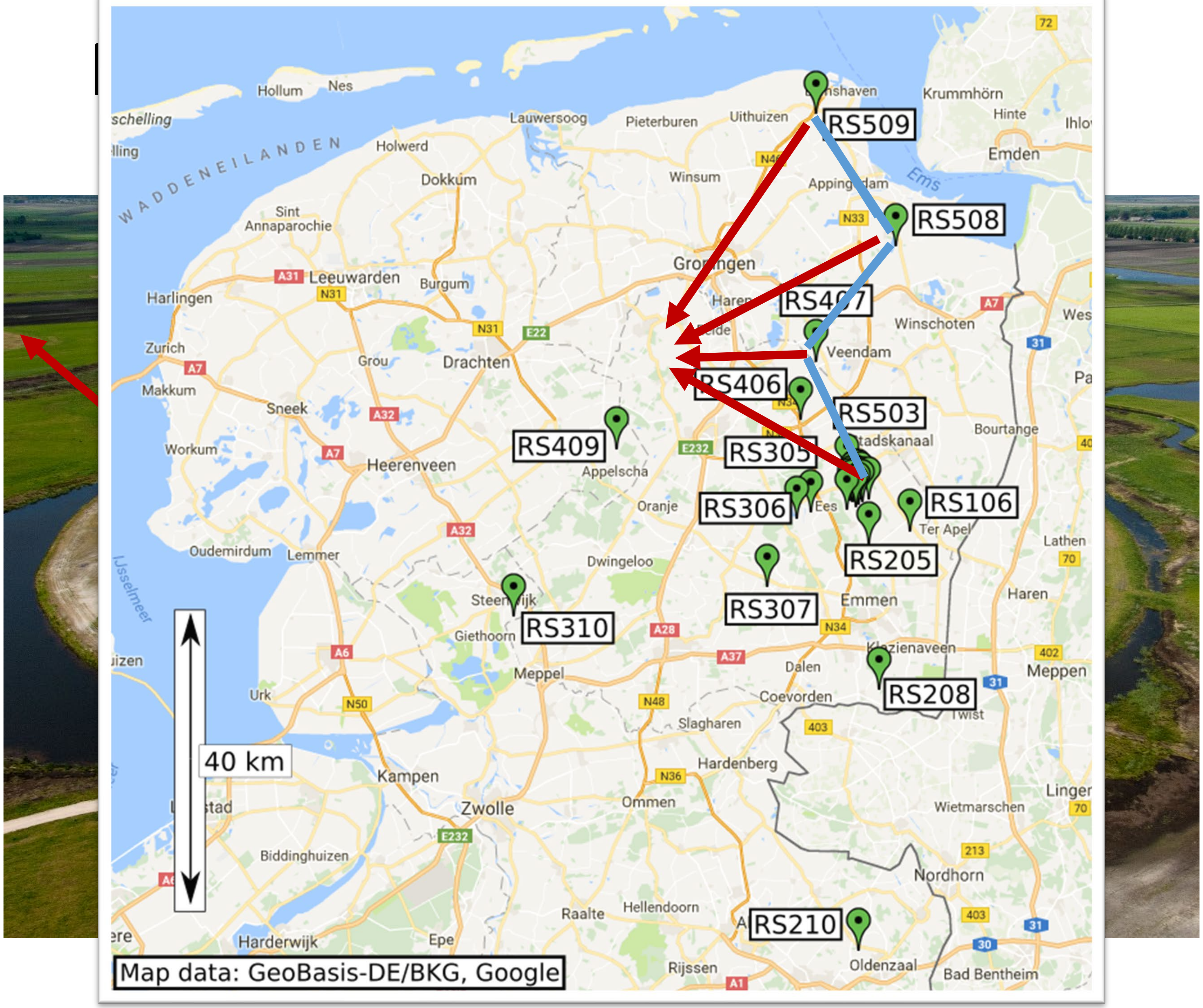

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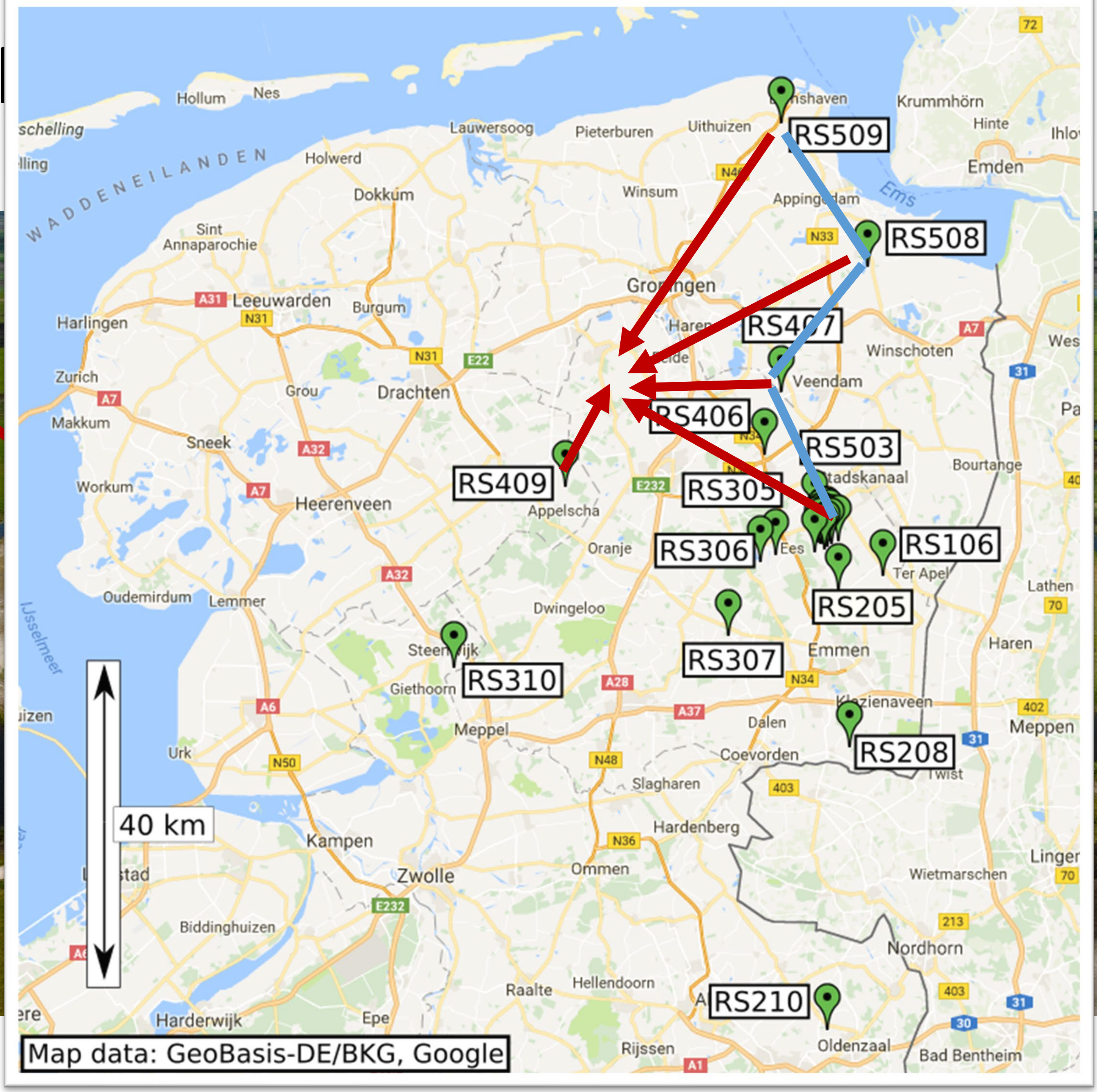

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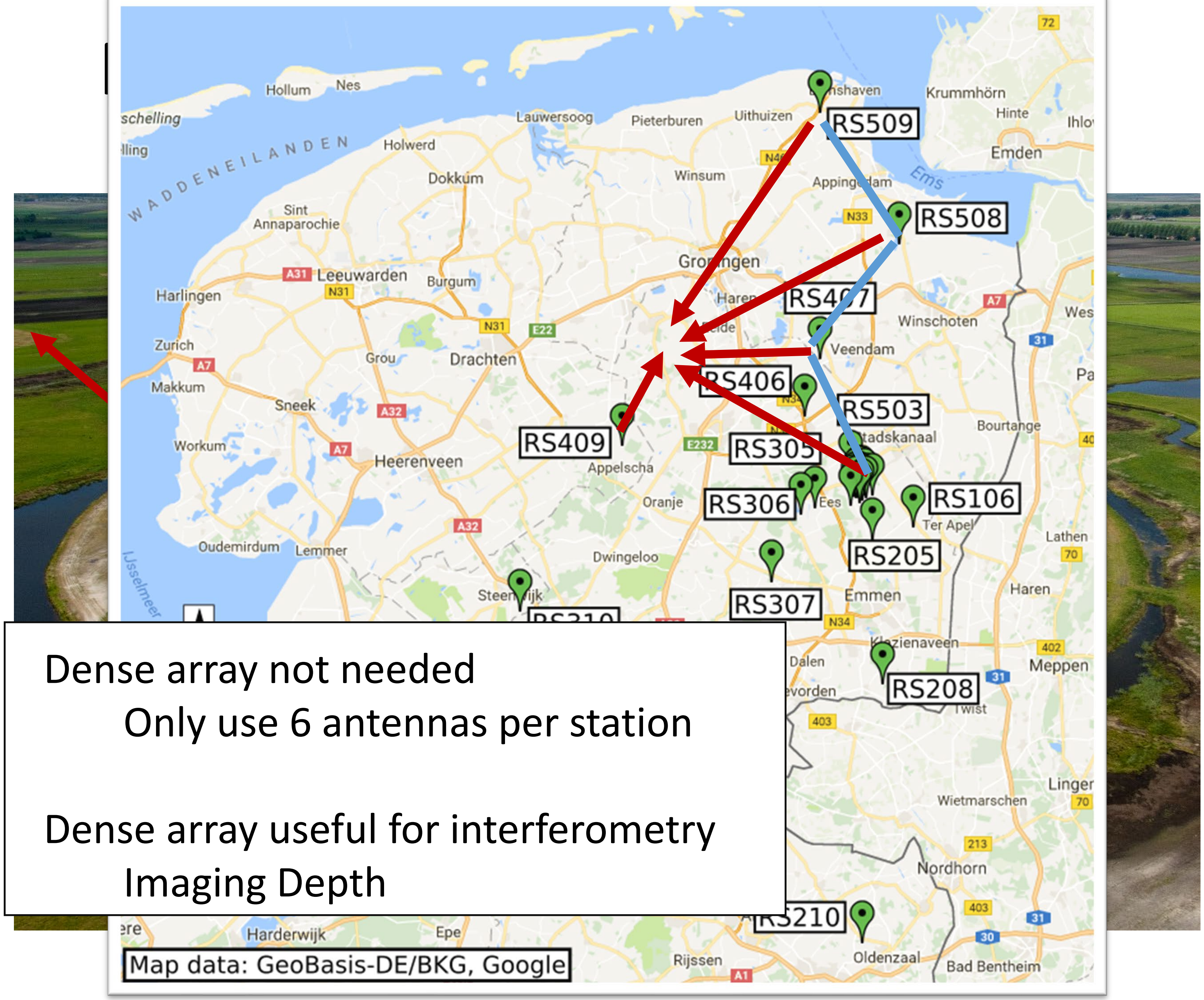


Dense array not needed

Only use 6 antennas per station

Dense array useful for interferometry

Imaging Depth

- For each pulse to locate:

1) Use 1 LOFAR station
   - Get initial direction

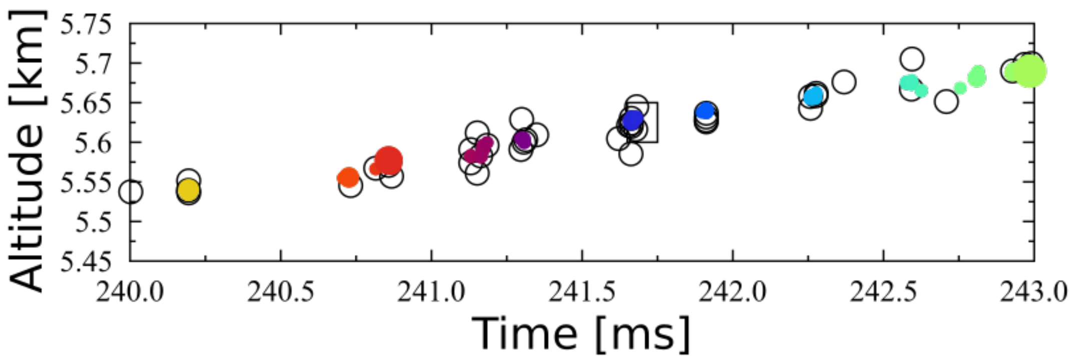
2) Select next station
   - Guess which pulse
   - Improve location guess

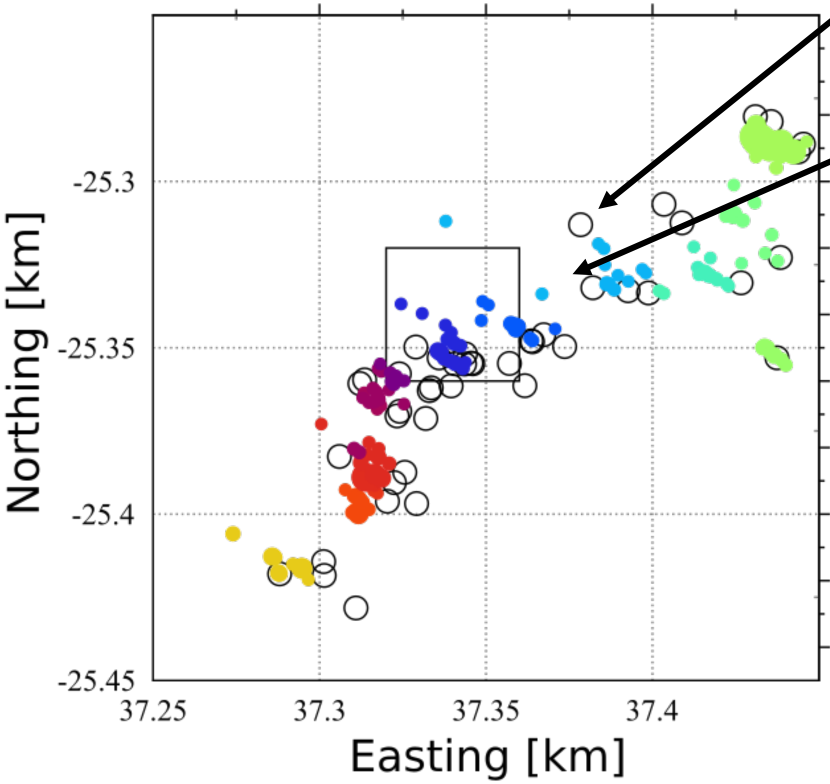
3) Repeat for all LOFAR stations

(include remote stations)

Negative Leader

Negative Leader Section

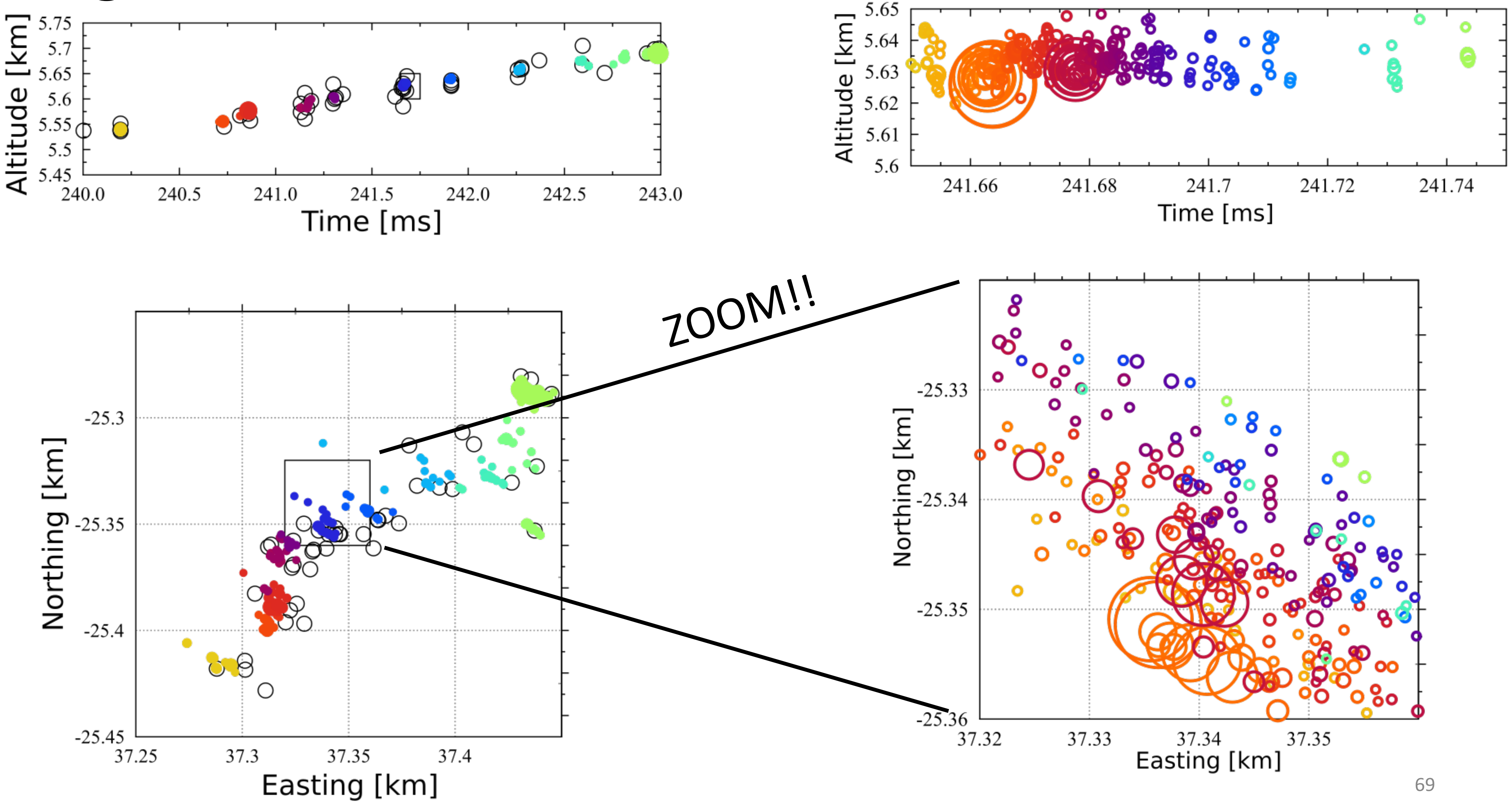




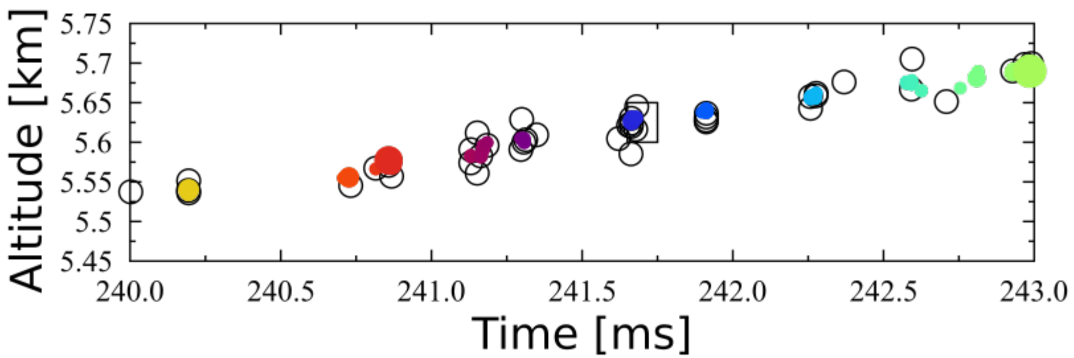
Open circles : Impulsive Imager

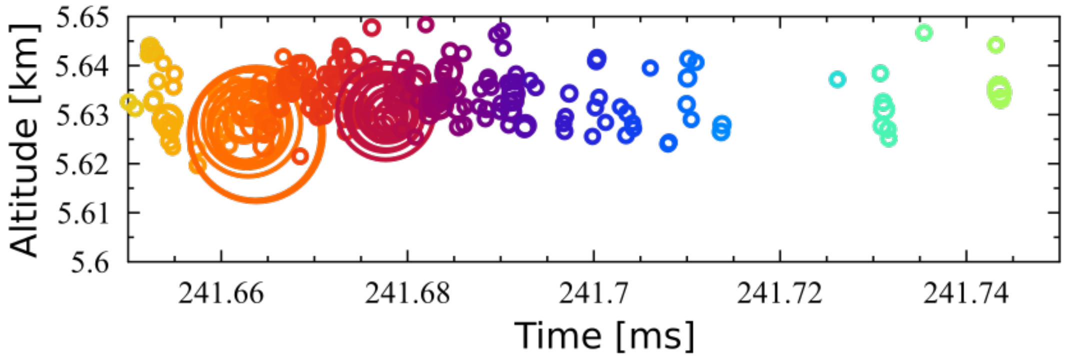
Colored circles : New Imager
Significant clearer bursts

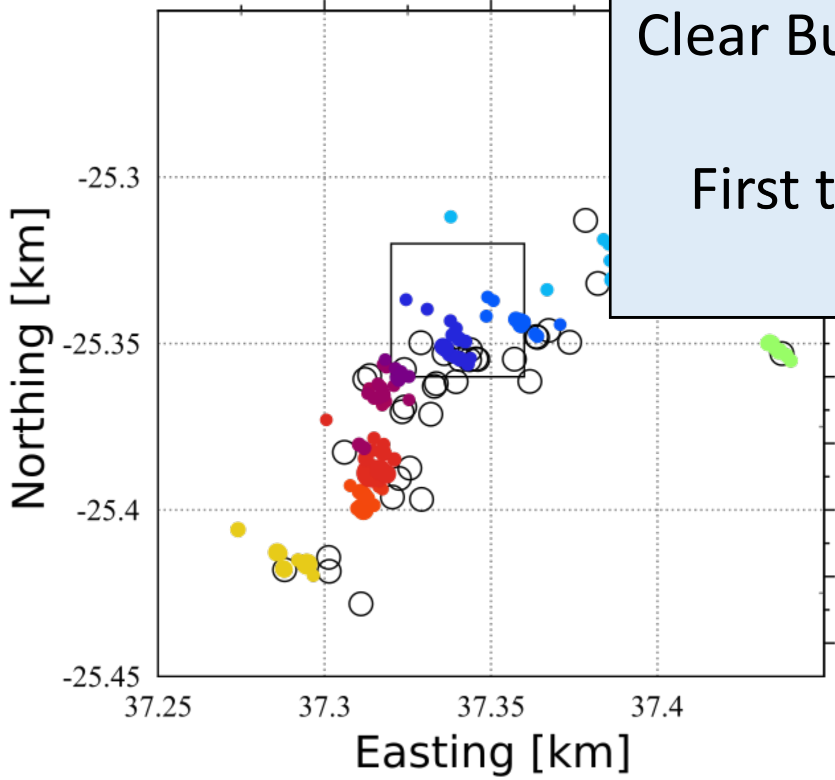
Negative Leader Section



Negative Leader Section

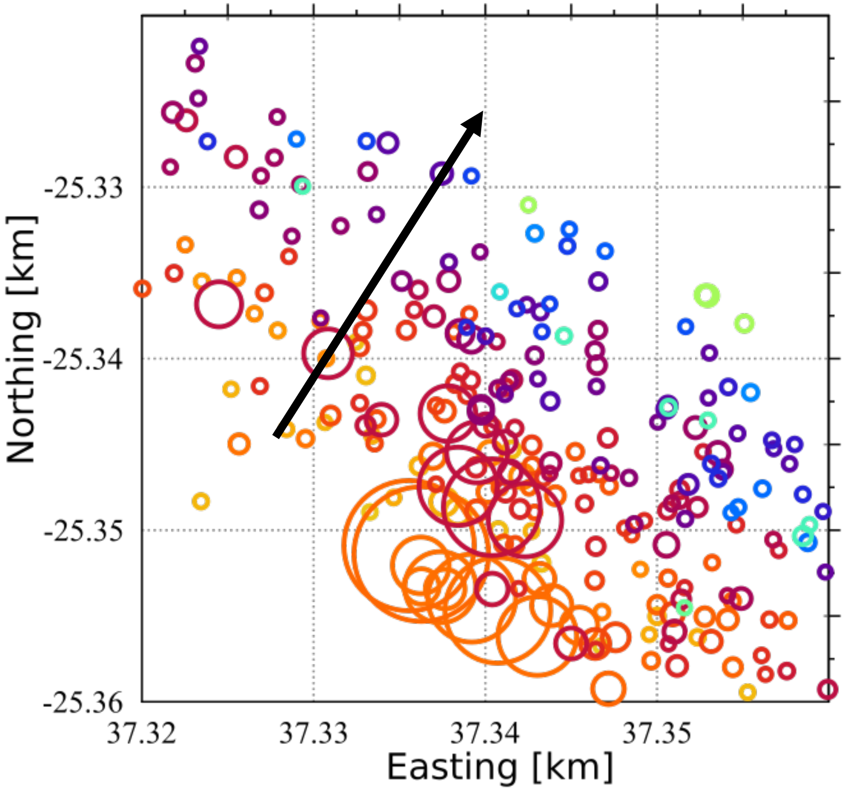






Clear Burst Propagation!

First time imaging in nature!!



Polarization problem