Overview of Selected Recent Lightning Advancements

Brian Hare,
Lightning Group,
& CR group

European Research Council
Established by the European Commission

ASTRON
Netherlands Institute for Radio Astronomy

university of groningen

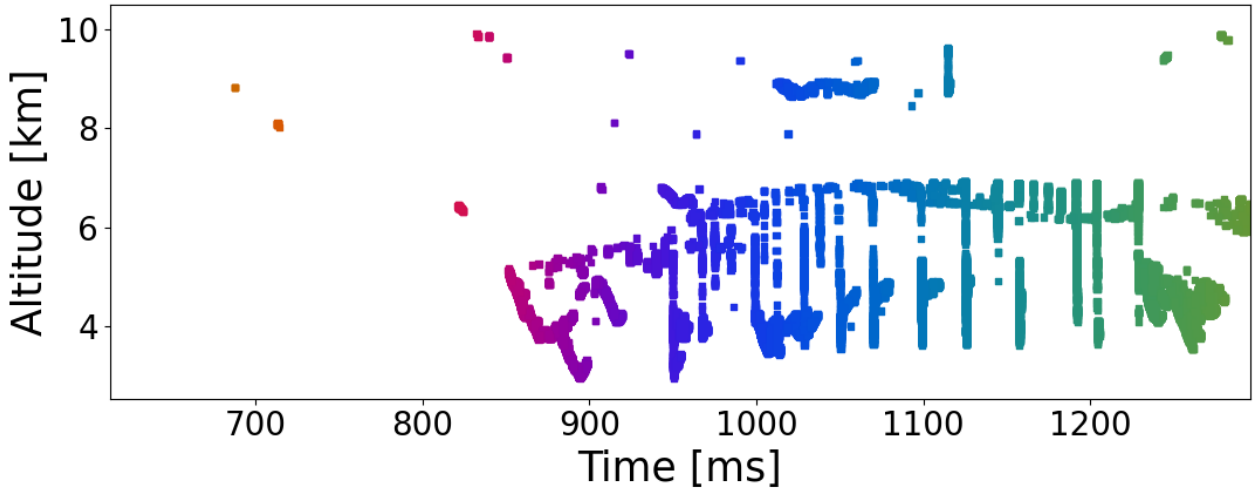
Duke UNIVERSITY

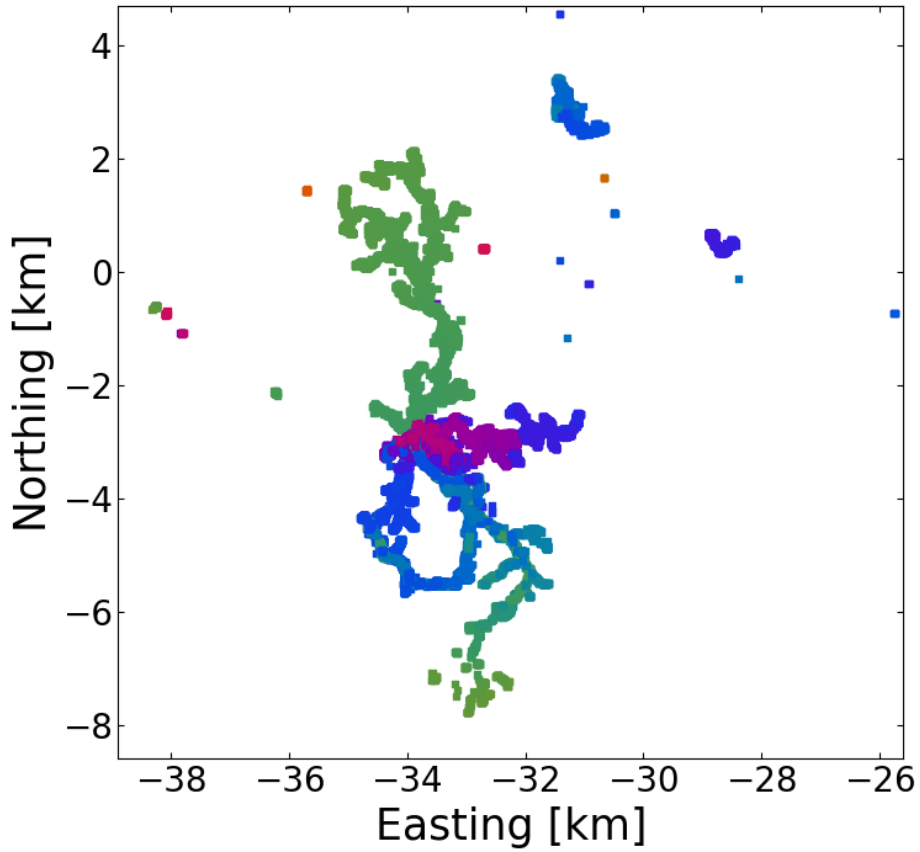
University of New Hampshire

Two Imaging Techniques

- Impulsive Imager
  - Time of Arrival Differences
  - Entire flashes
  - See plot right

- TRI-D
  - Nearfield Beamforming Imager
  - Small sections with extreme precision
  - Next Talk





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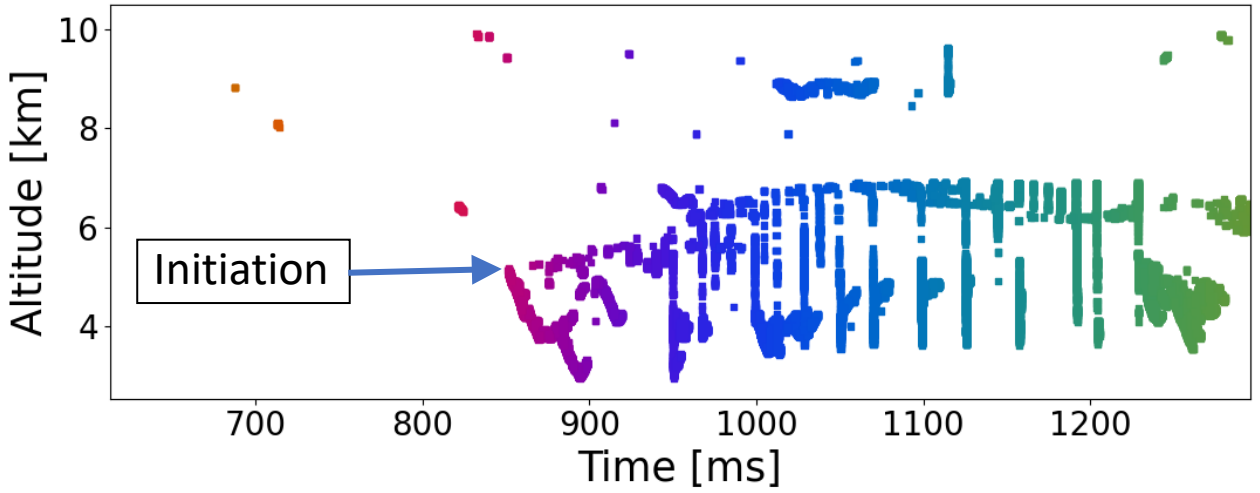

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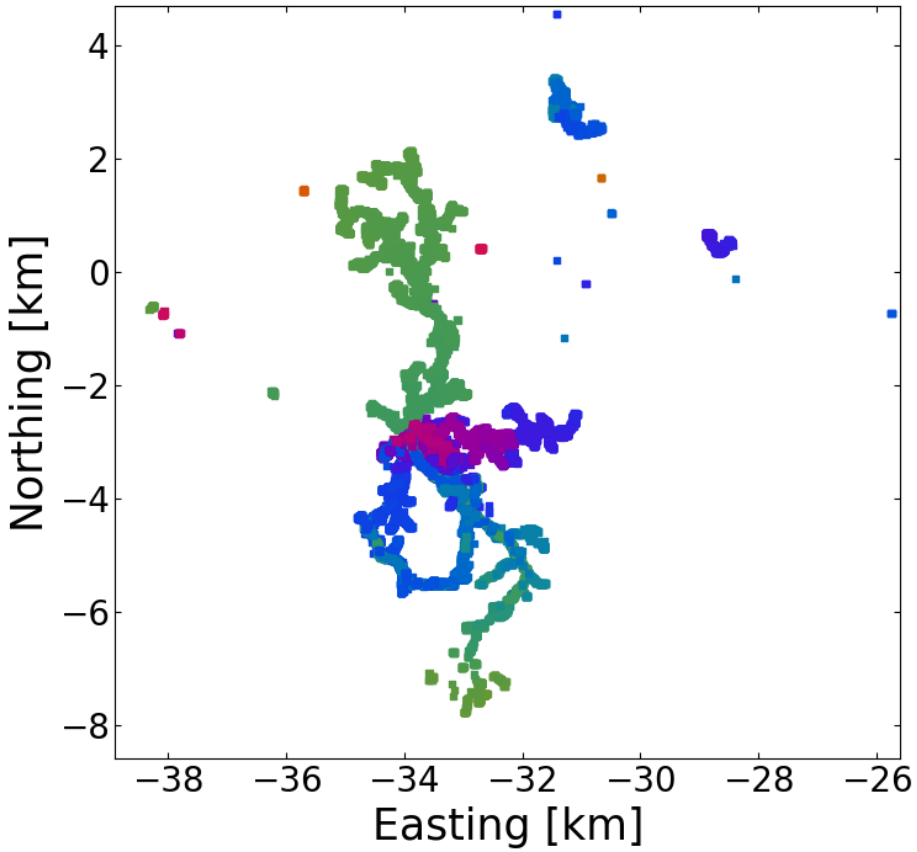

Selected Science

- Initiation
  - See next talk

Two Imaging Techniques

- Impulsive Imager
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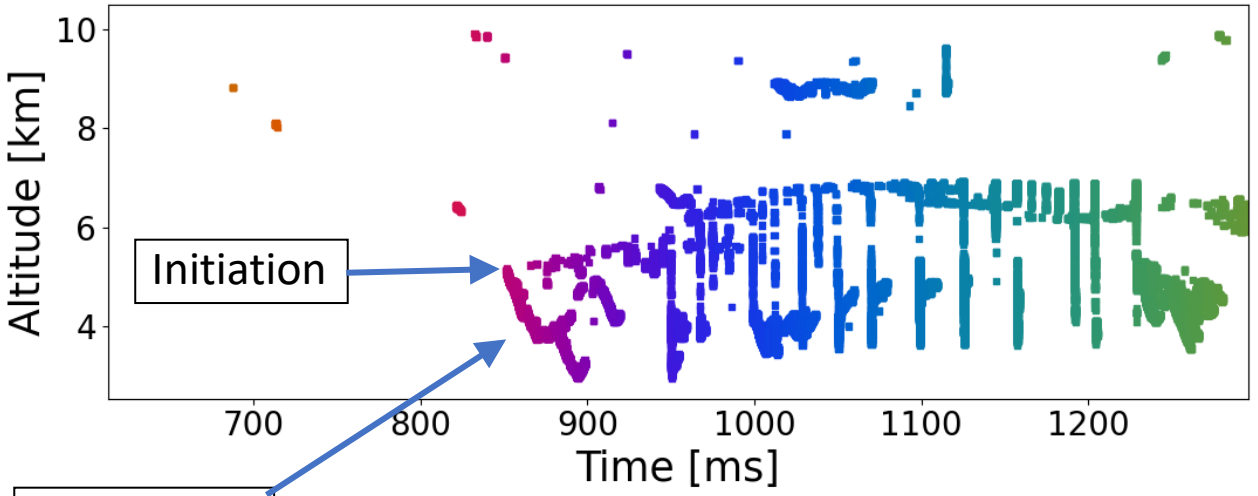
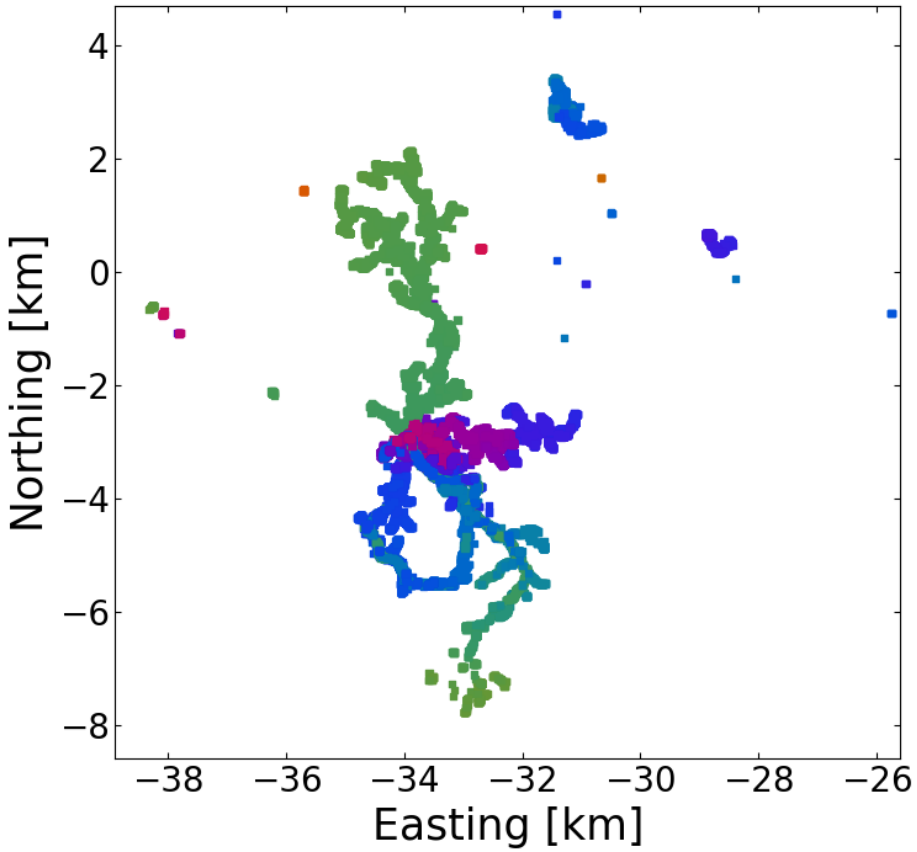


Negative Propagation goes ***down*** Is weird

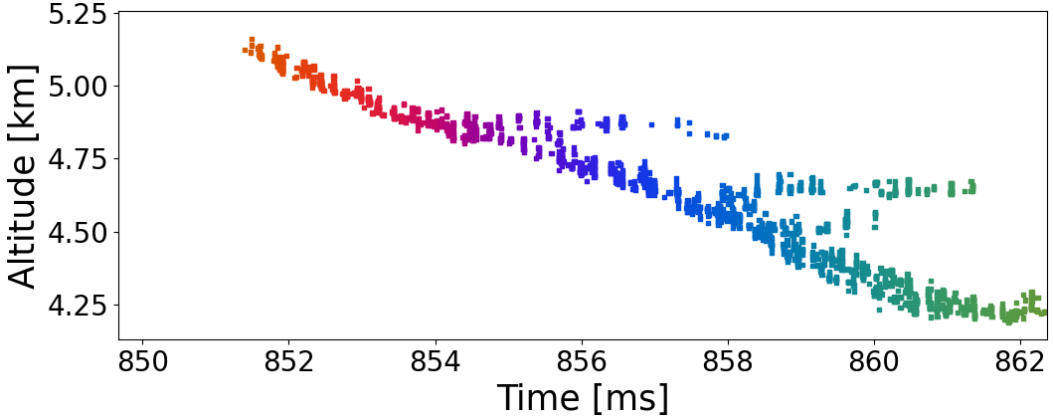


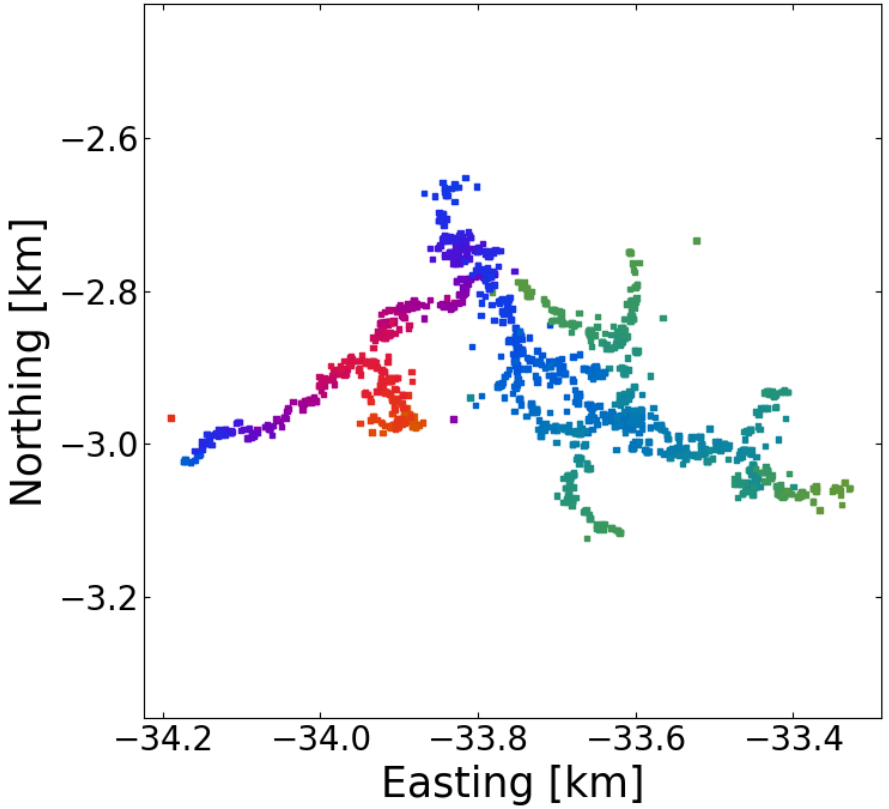
Selected Science

- Initiation
  - See next talk

- Upside-down lightning

LOFAR-observed Initial Stage Goes *Down*





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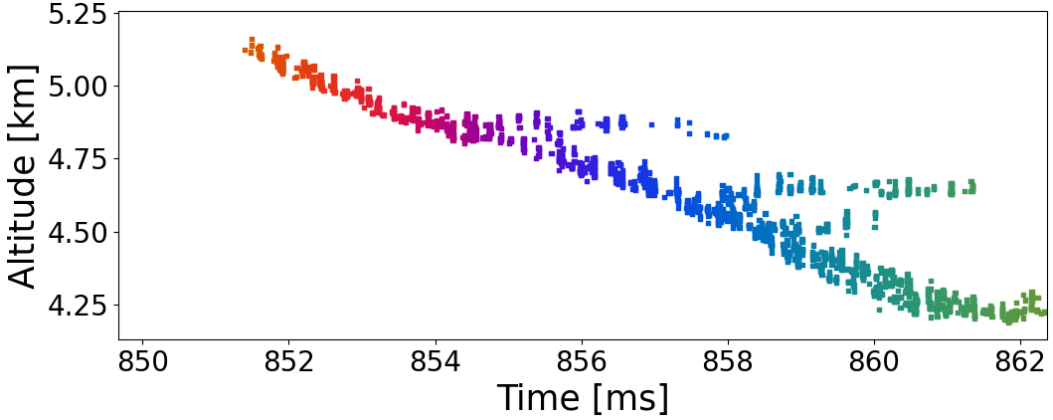
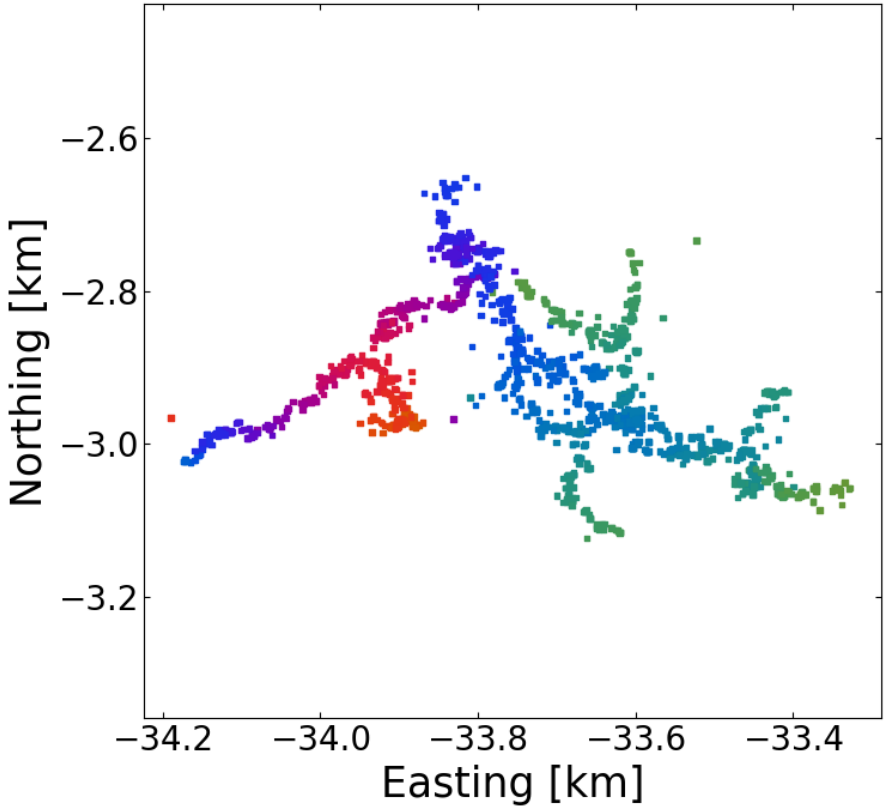
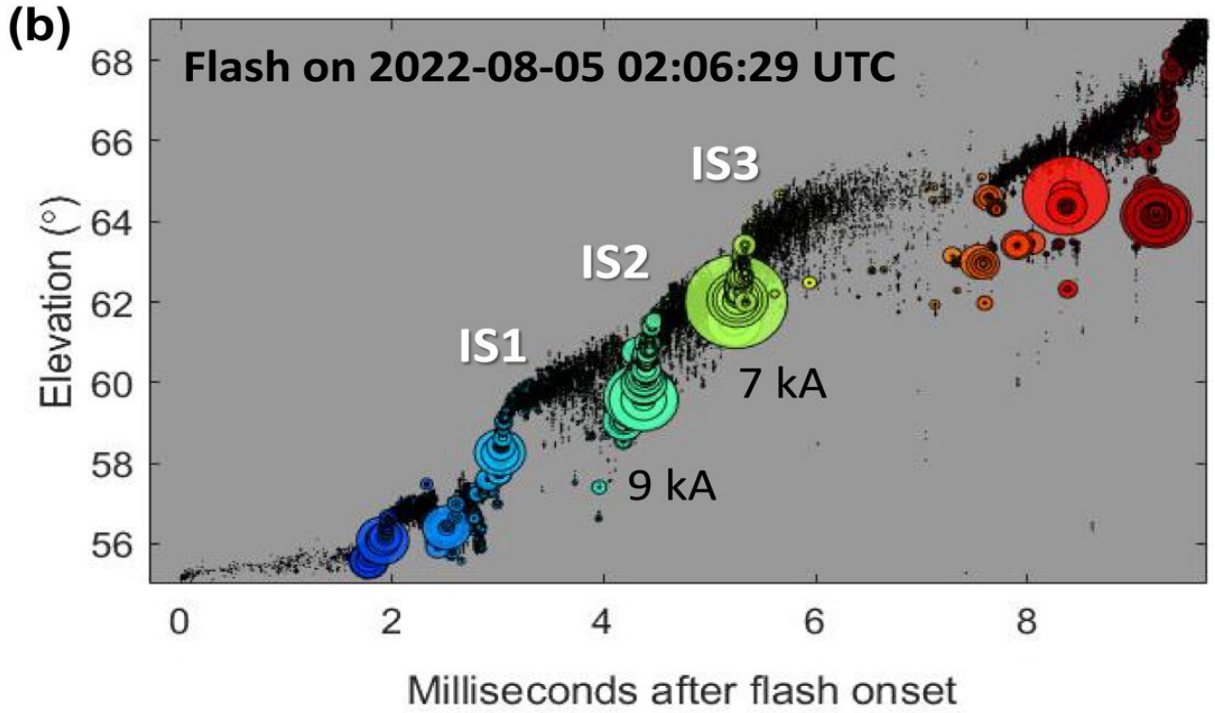


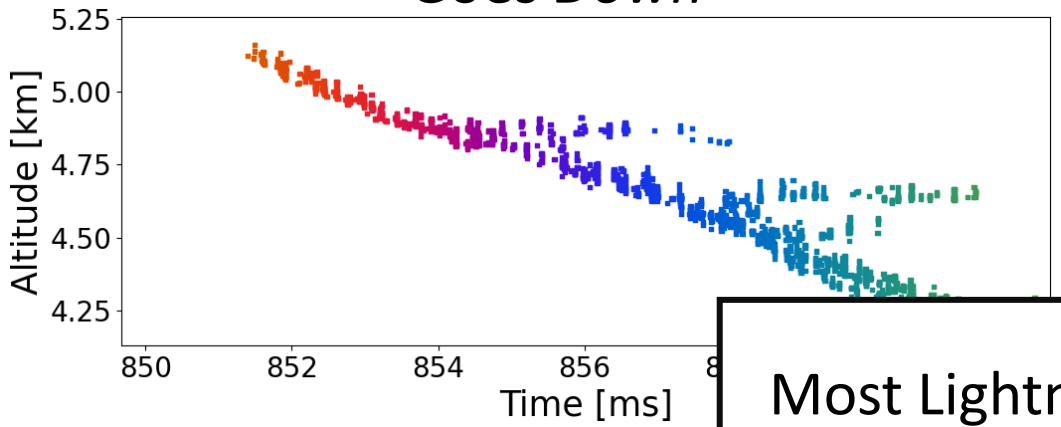


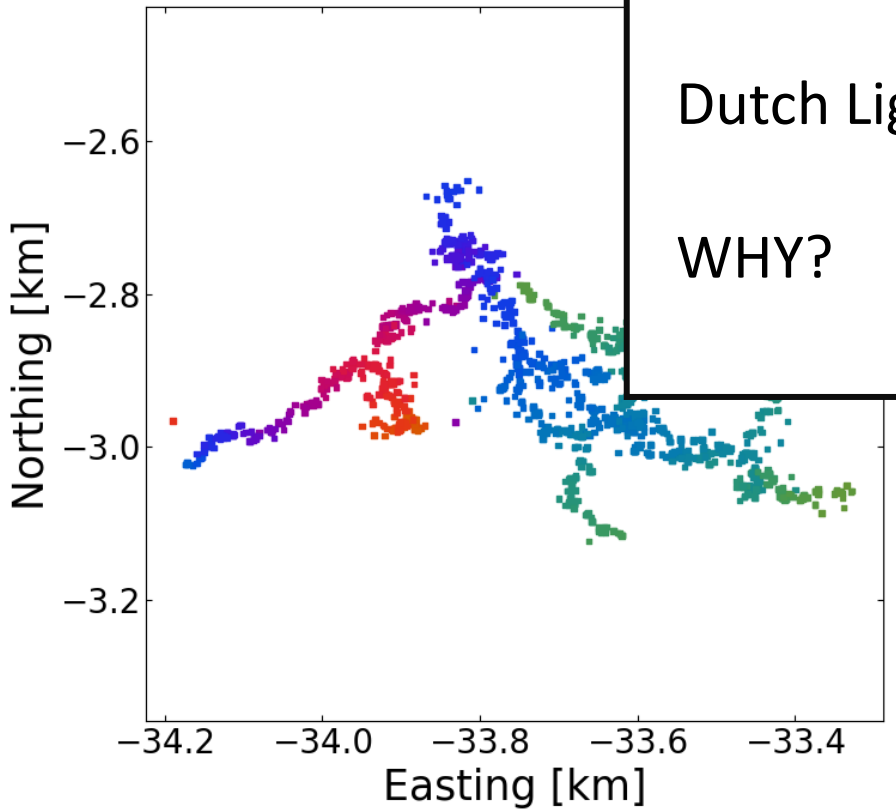
Typical intra-cloud lightning Initial Stage Observed in USA Goes *UP*



* Pu, Cummer (2024), *GRL*

LOFAR-observed Initial Stage Goes *Down*



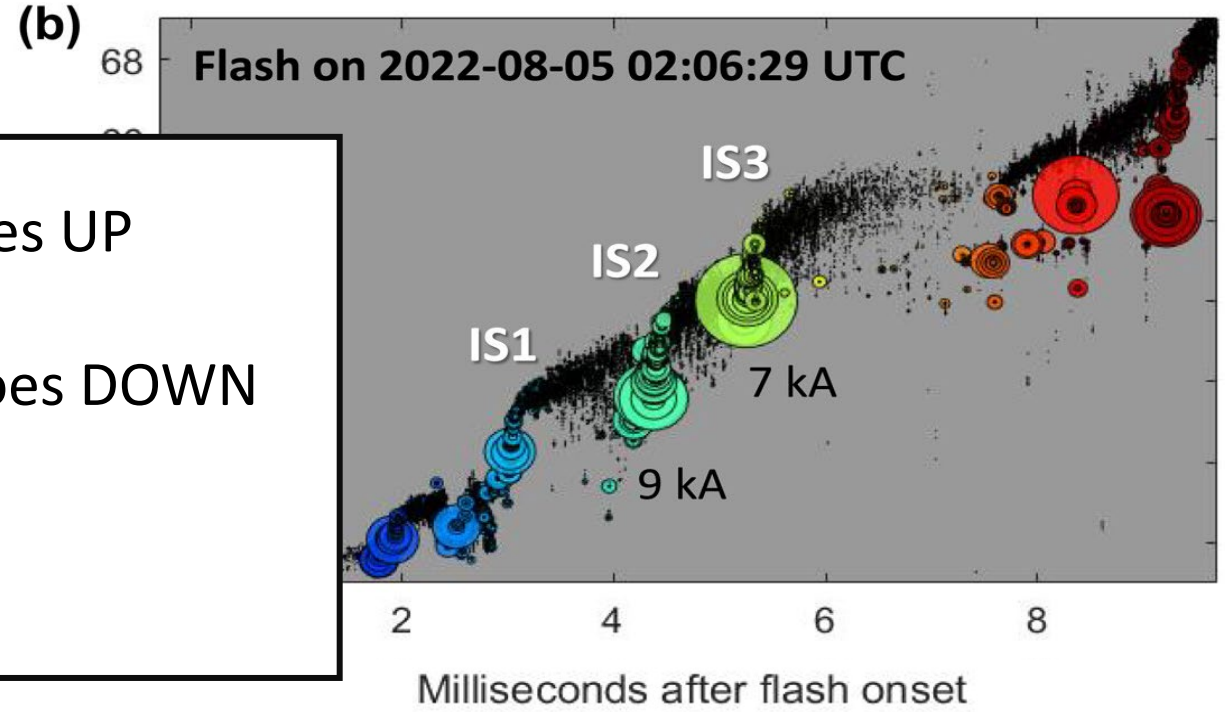


Most Lightning goes UP

Dutch Lightning goes DOWN

WHY?

Typical intra-cloud lightning Initial Stage Observed in USA Goes *UP*



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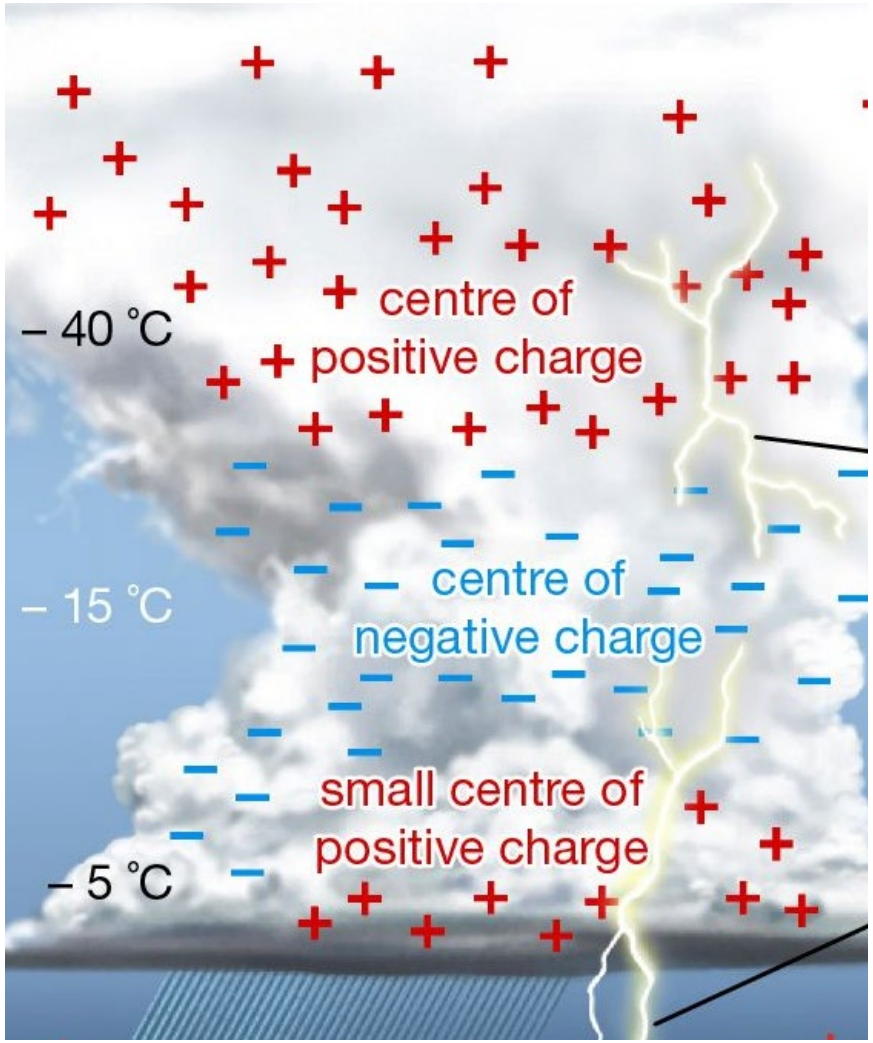
Hypothesis:
Dutch *Thunderstorms* are upside-down

Typical Thunderstorm Structure



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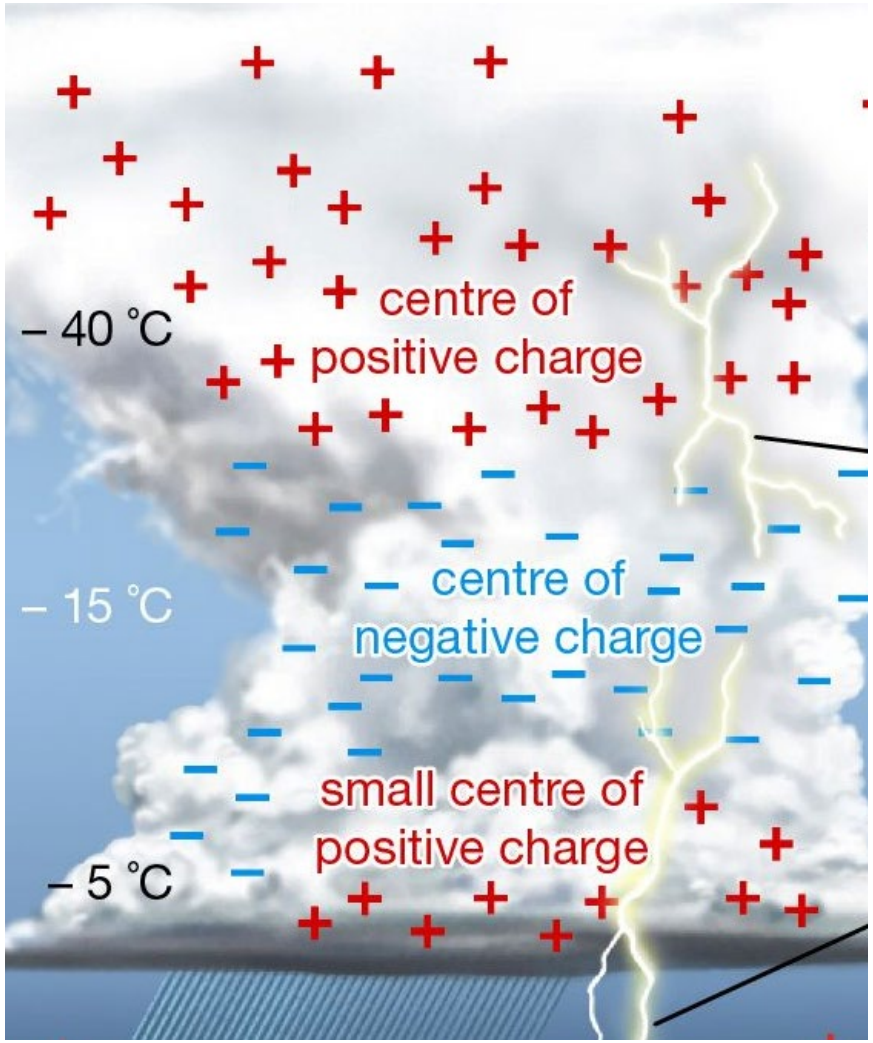

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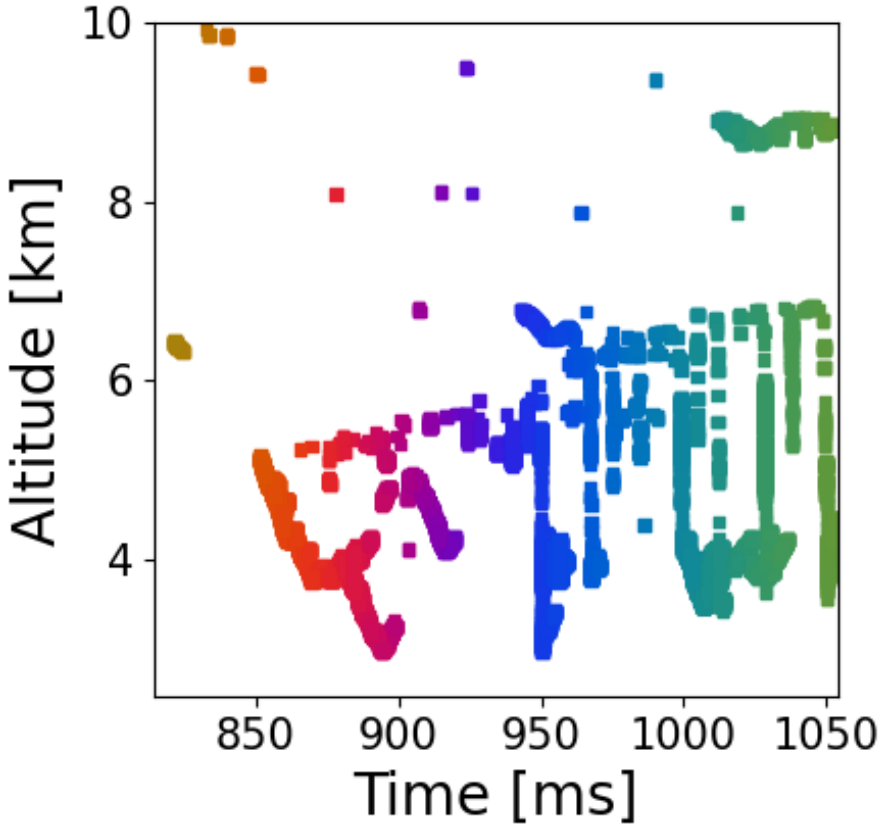

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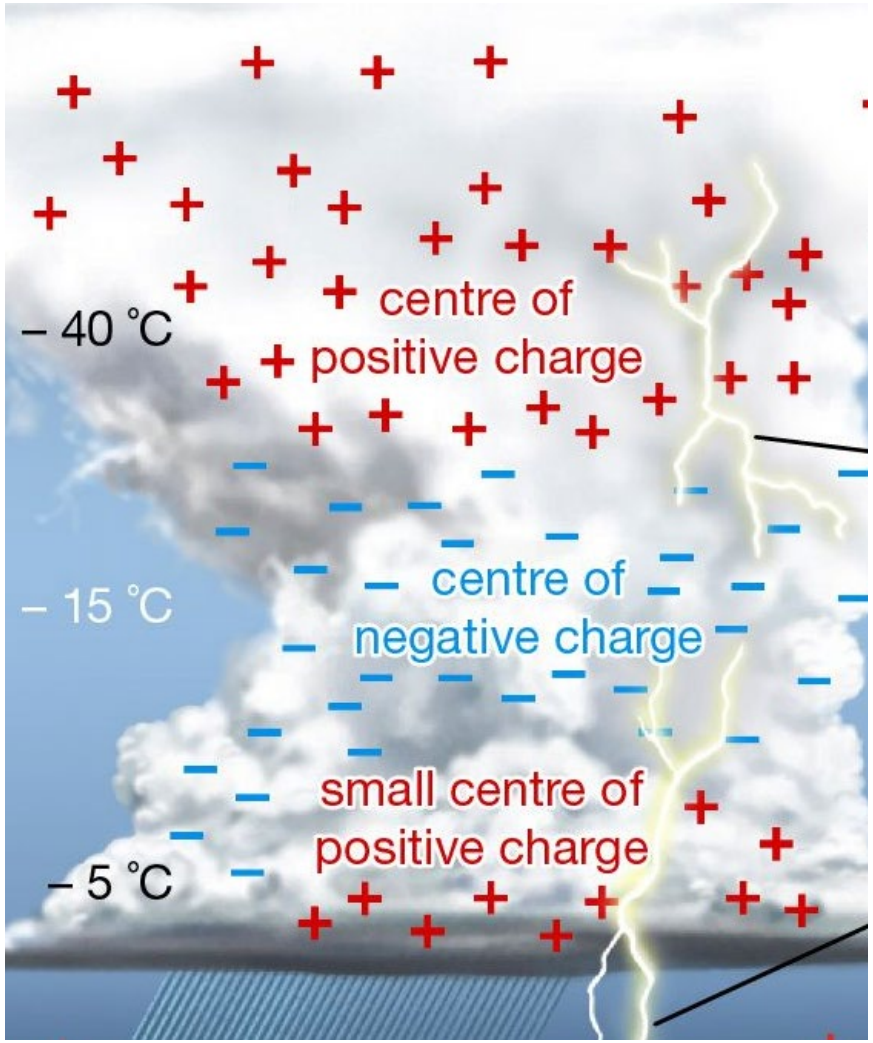

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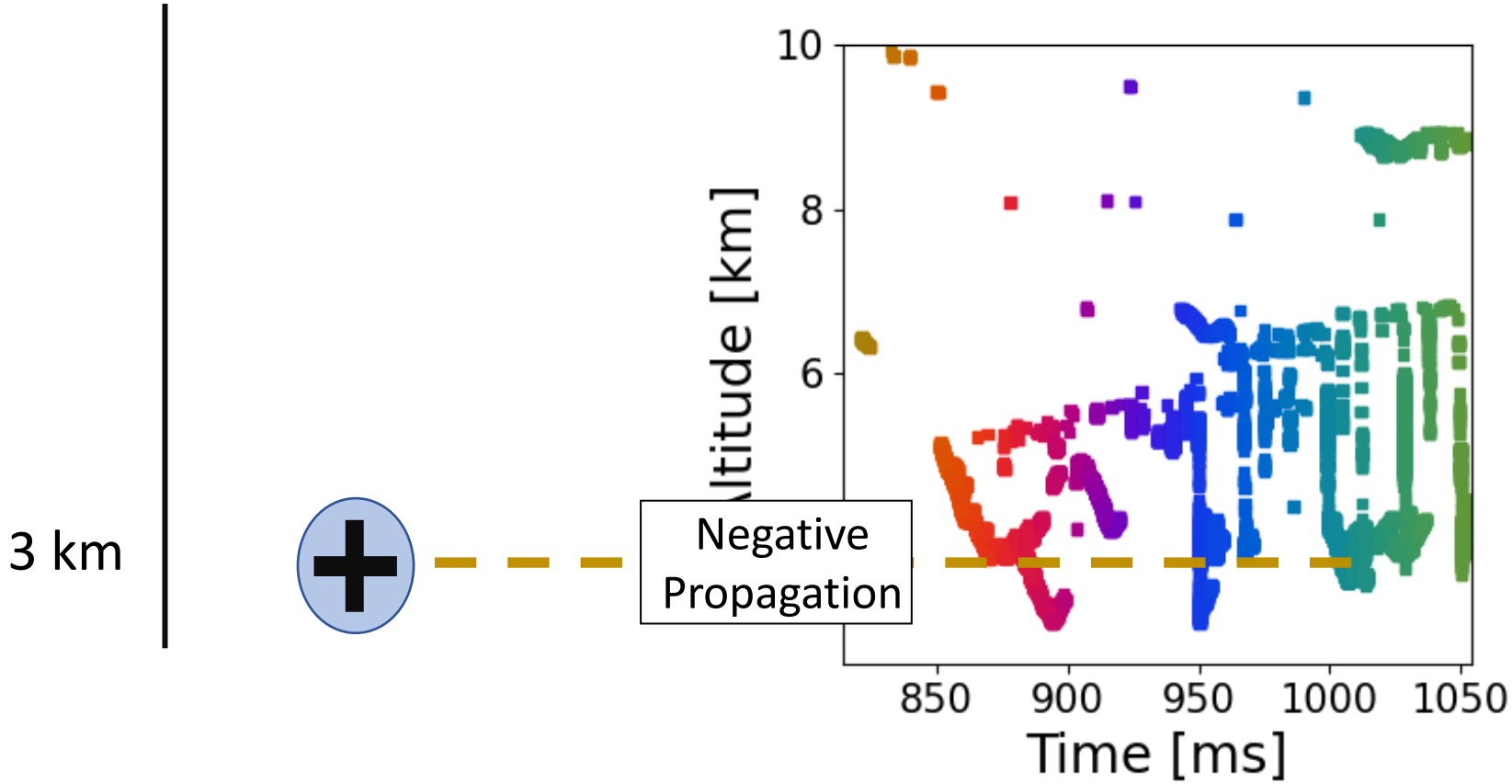

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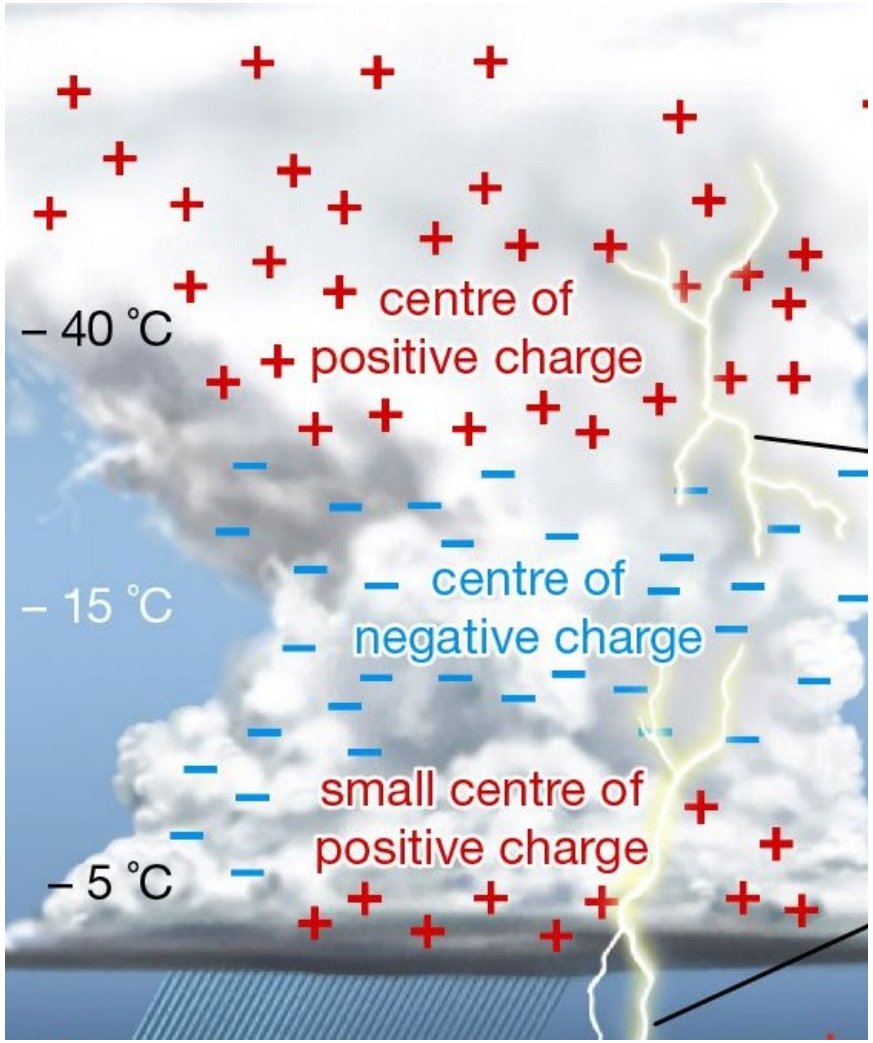

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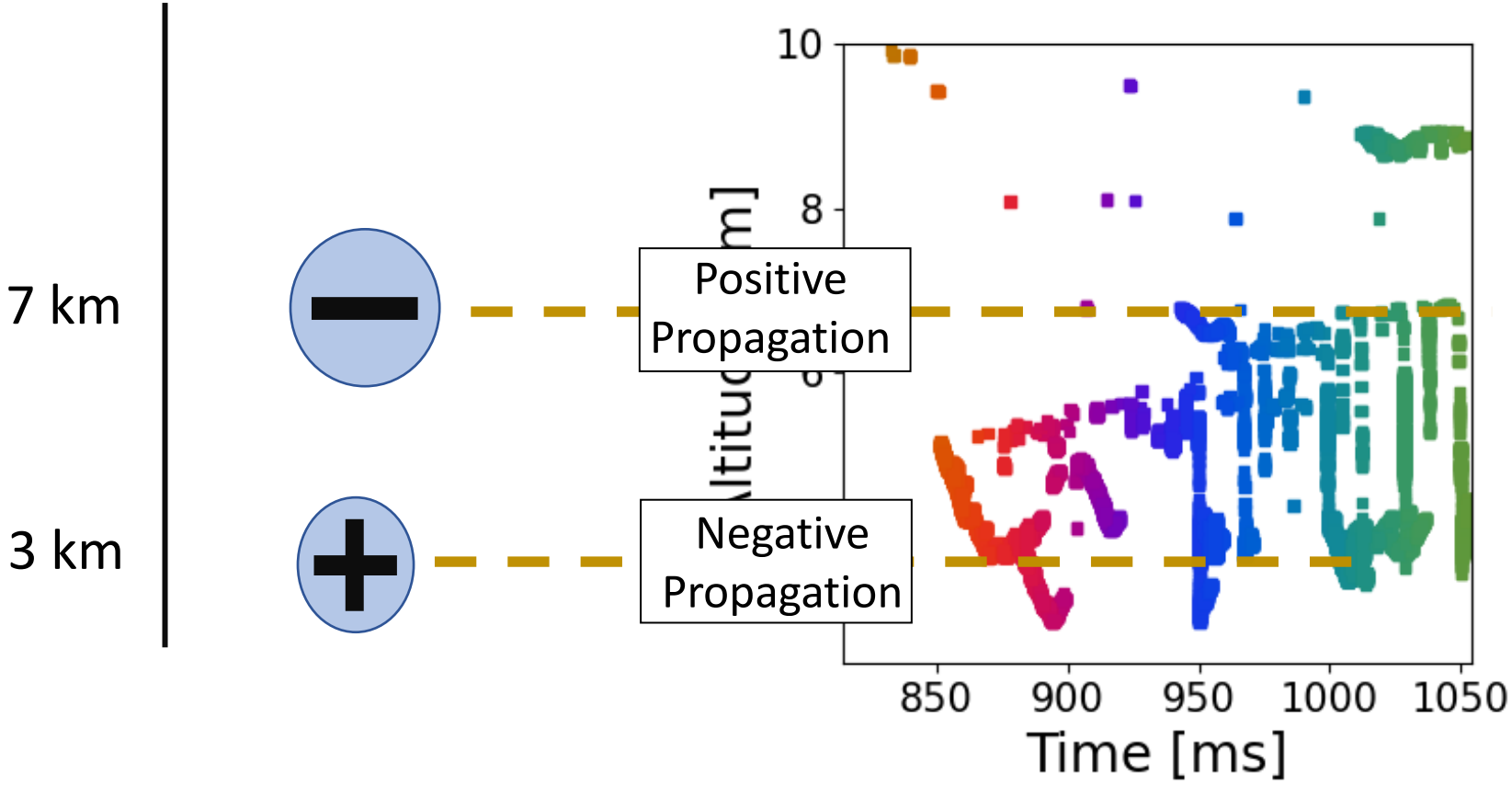

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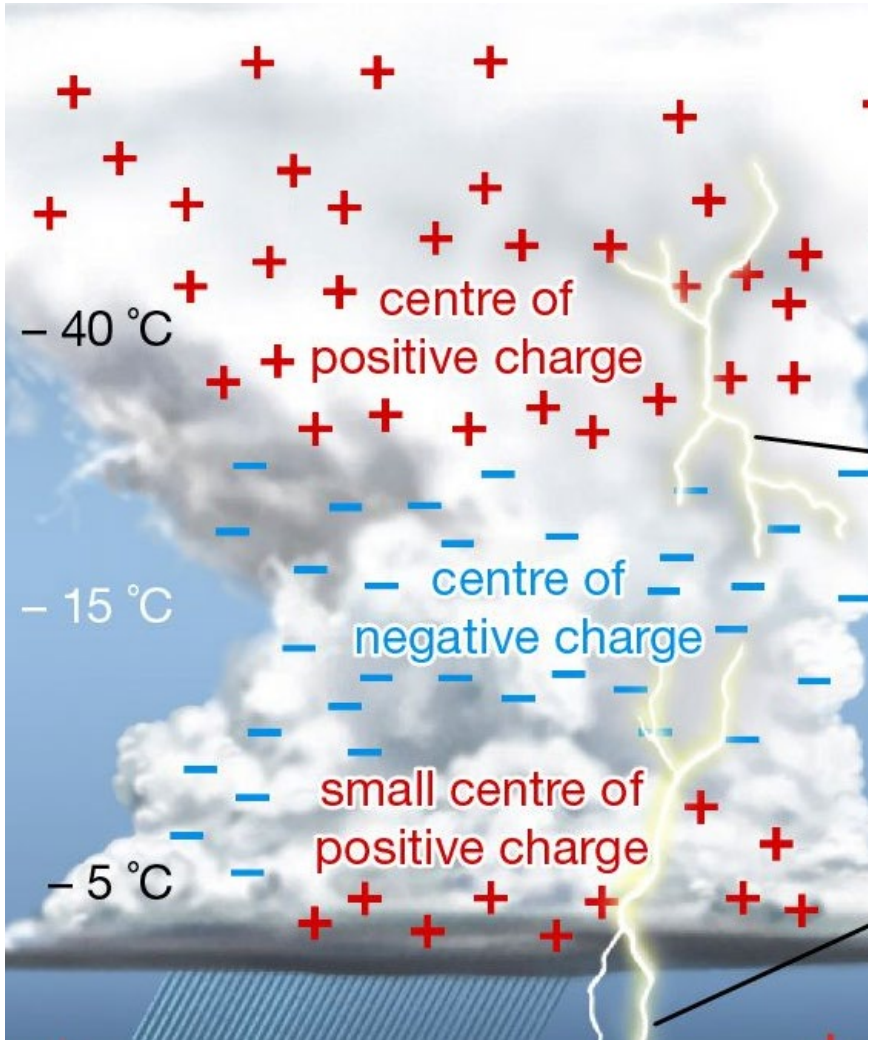

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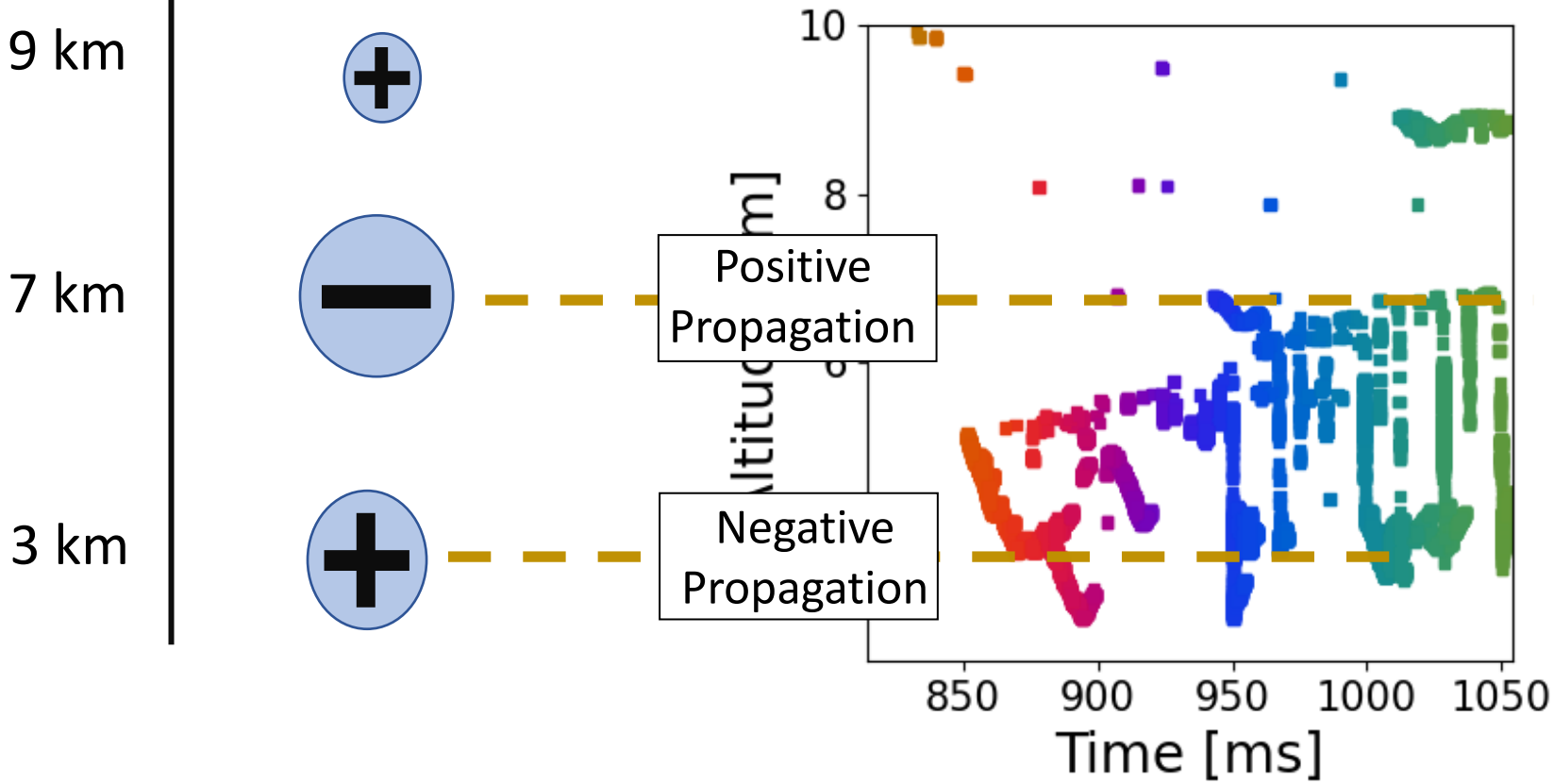
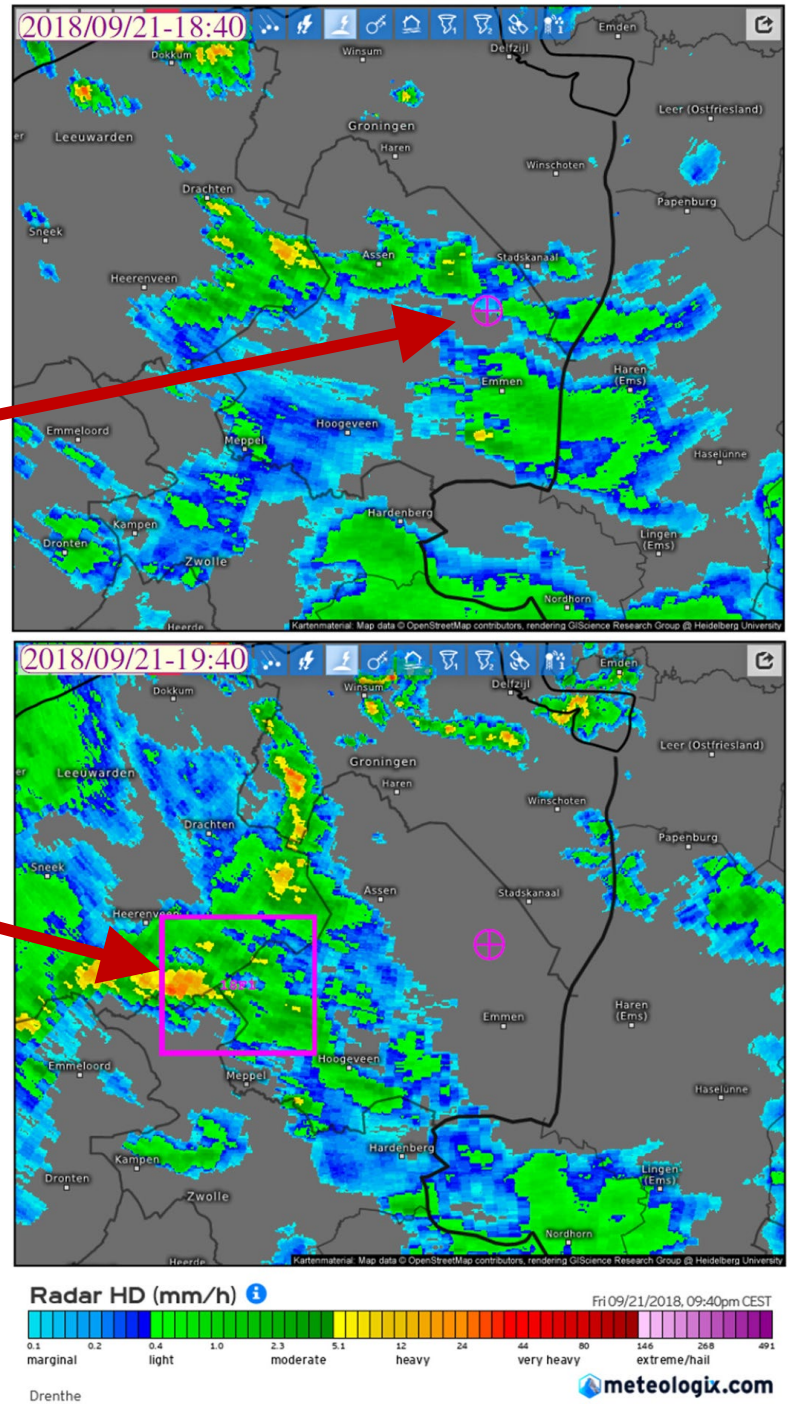


Test Hypothesis:
Measure charge with cosmic rays!

Trinh et al. (2025), *GRL*

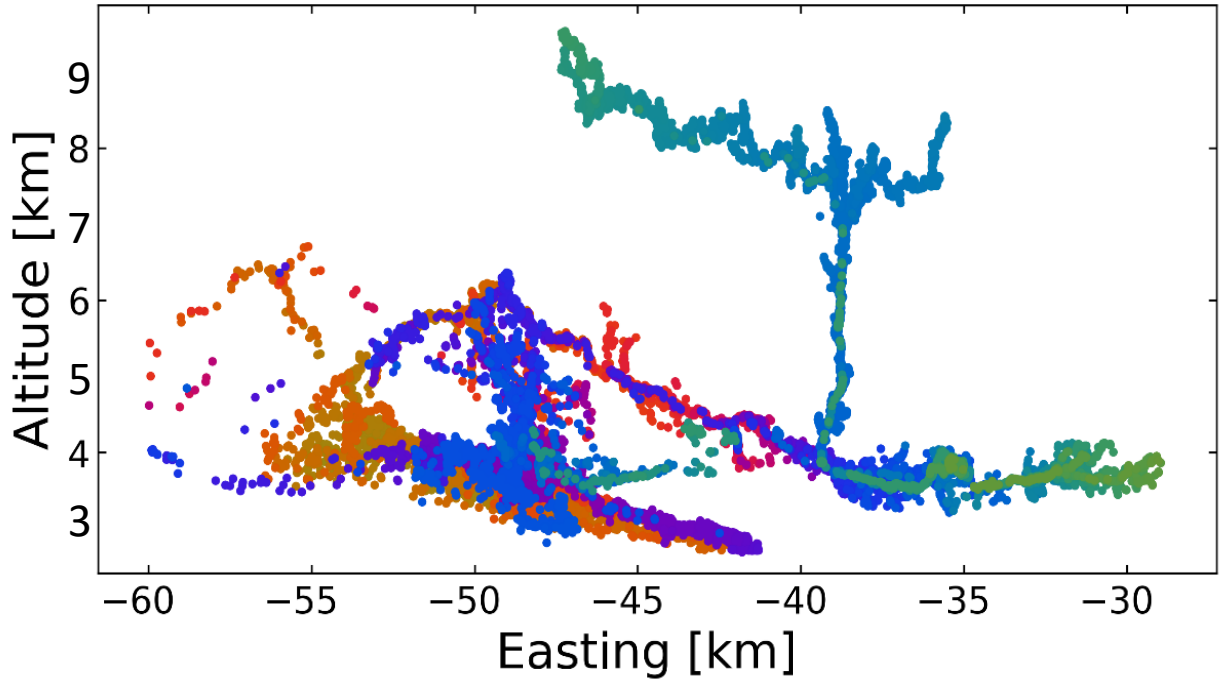
- Measure cosmic ray air shower at LOFAR core
- Image a lightning flash here
  - ~ 40 km from core
  - 1 hour later
  - *Is same storm cell!*
- Compare structure of results



Results

Trinh et al. (2025), *GRL*

Observed Lightning Flash
estimate location/size of charge layers



Small + layer : ≈6.5 km

Main - layer : ≈5 km

Main + layer : ≈3 km

Results

Trinh et al. (2025), *GRL*

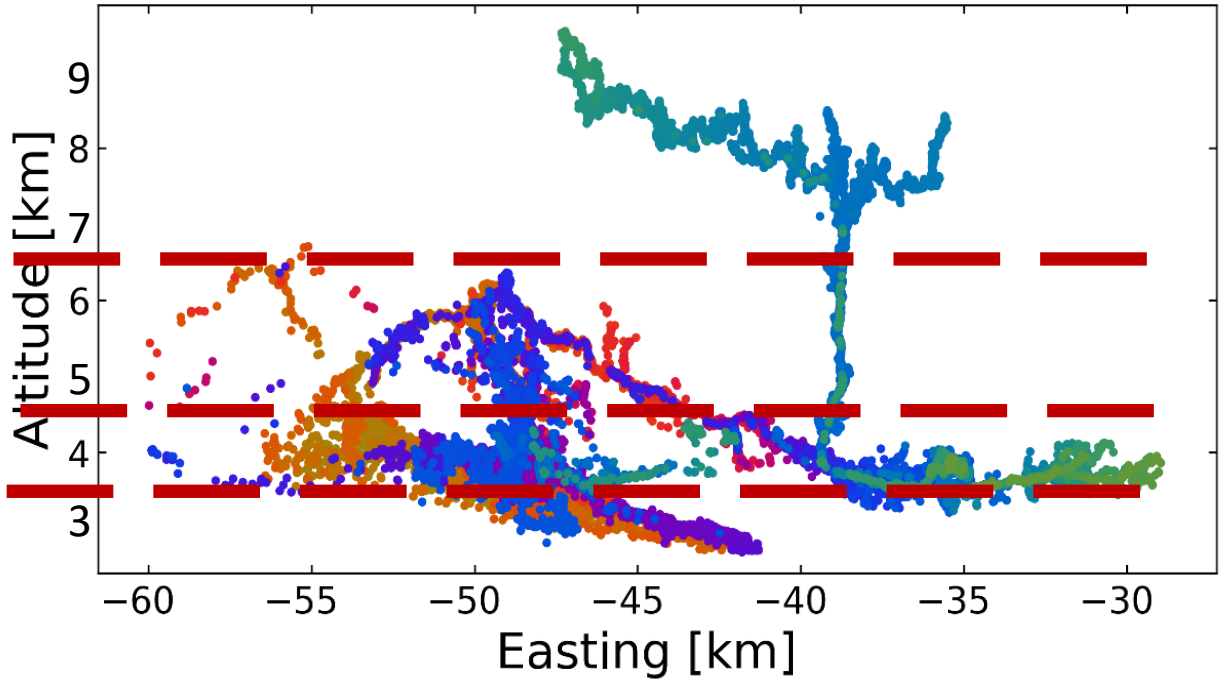
CR Results

Z=6.5 km σ = .1 μC/m²

Z=4.5 km σ = -.6 μC/m²

Z=3.5 km σ = .3 μC/m²

Observed Lightning Flash
estimate location/size of charge layers



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Cosmic Ray Conclusions

Trinh et al. (2025), *GRL*

- Cosmic Ray measured charge distributions
- Consistent with lightning structure
- Confirmed Hypothesis!
  - Lower Positive Layer is stronger than Upper Layer
  - Upside down from “normal” thunderstorms
- Why are Dutch thunderstorms upside down?
  - To be explored
- FUTURE WORK
  - Joint observation campaign with mobile research radar and LOFAR
  - Better explore thunderstorm meso-scale structure

Lightning Propagation

ongoing work, M. Lourens

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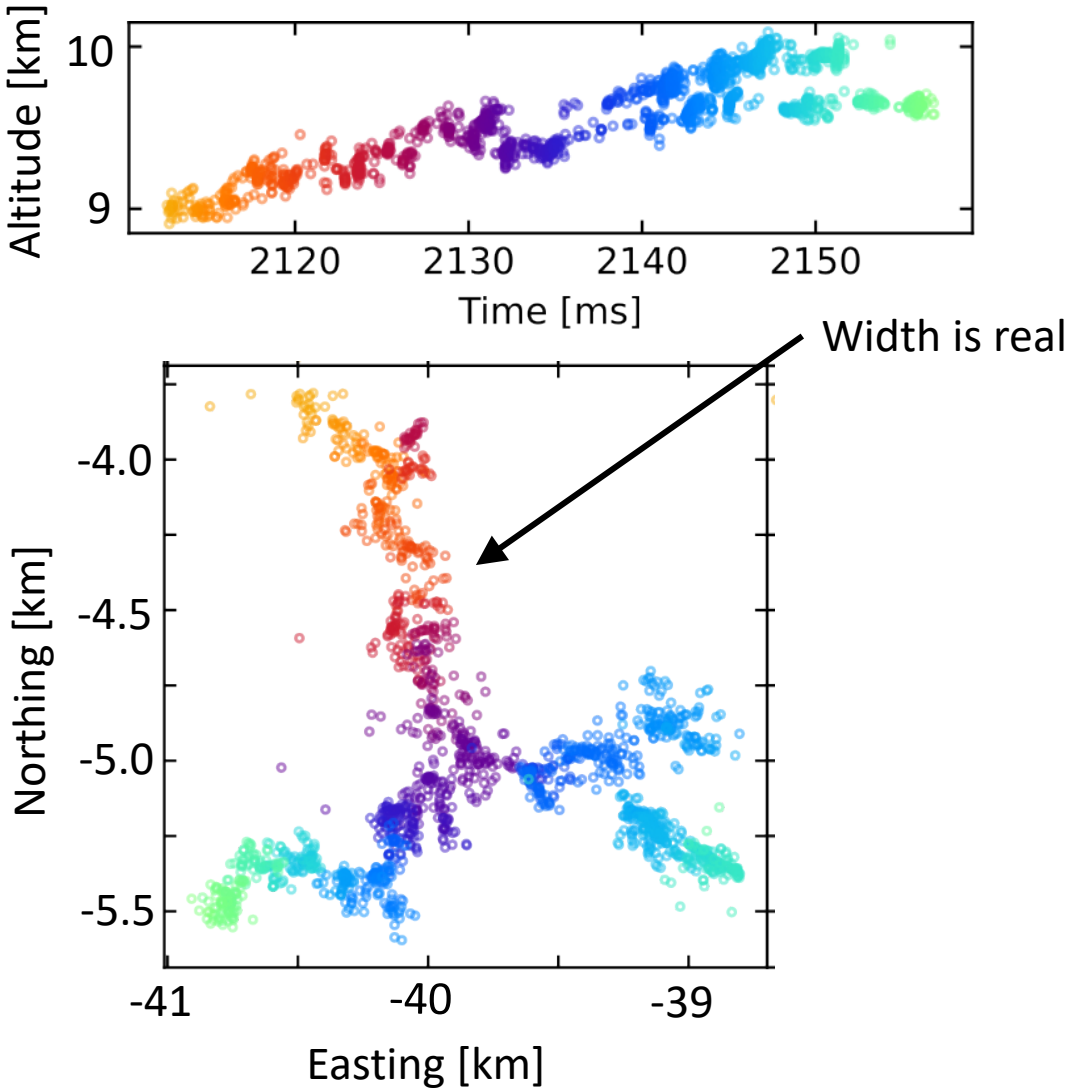
Negative Plasma Channel (Leader)



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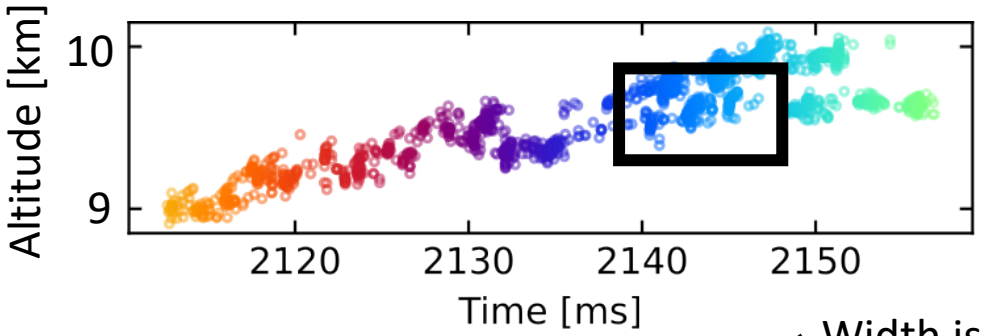
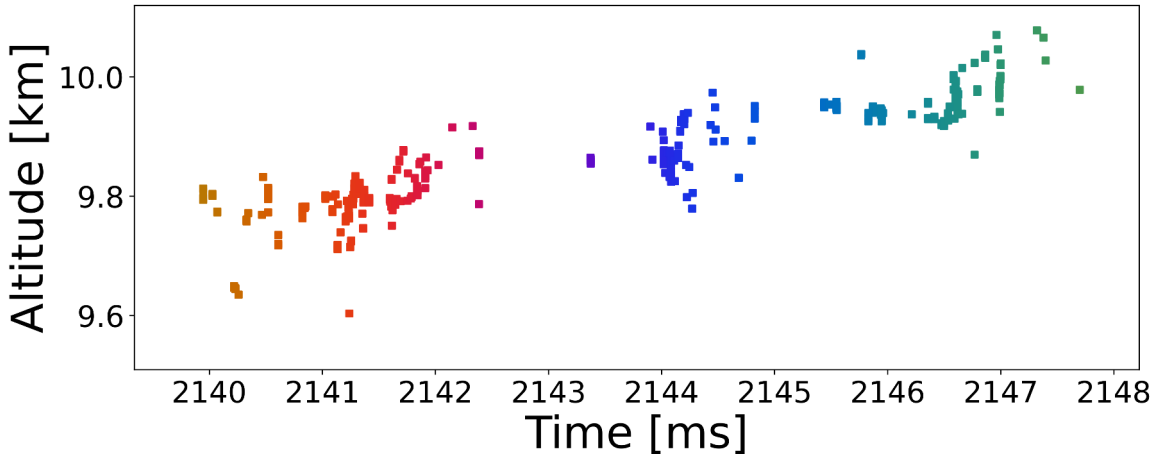
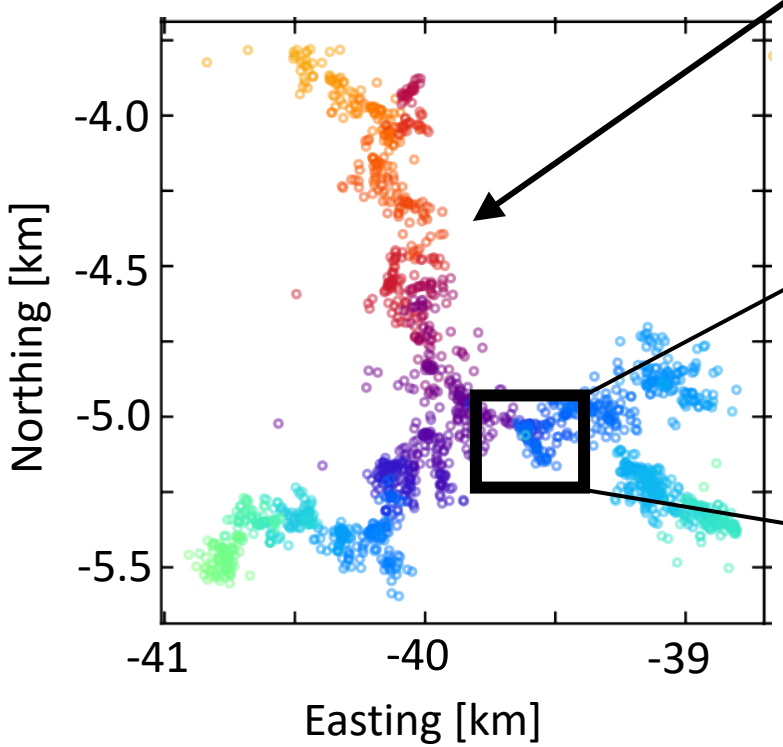
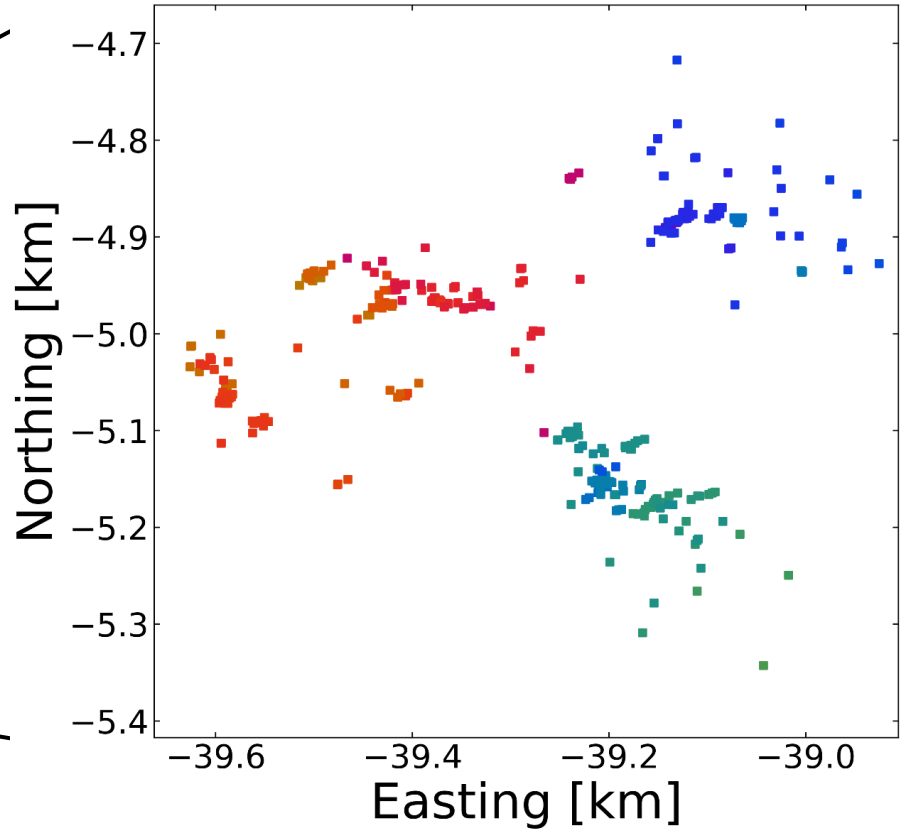




Width is real





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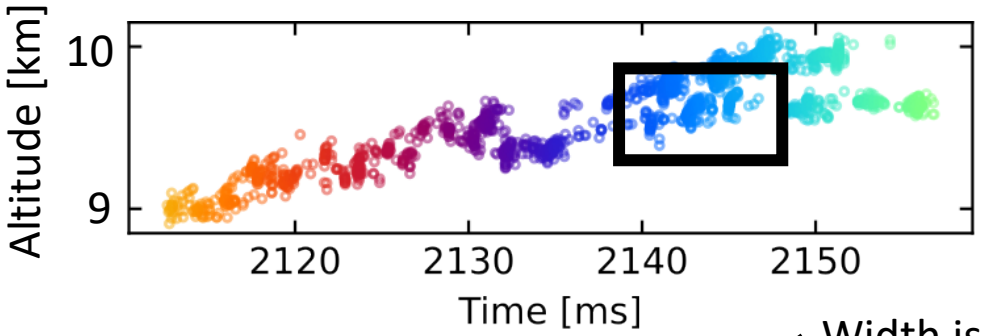

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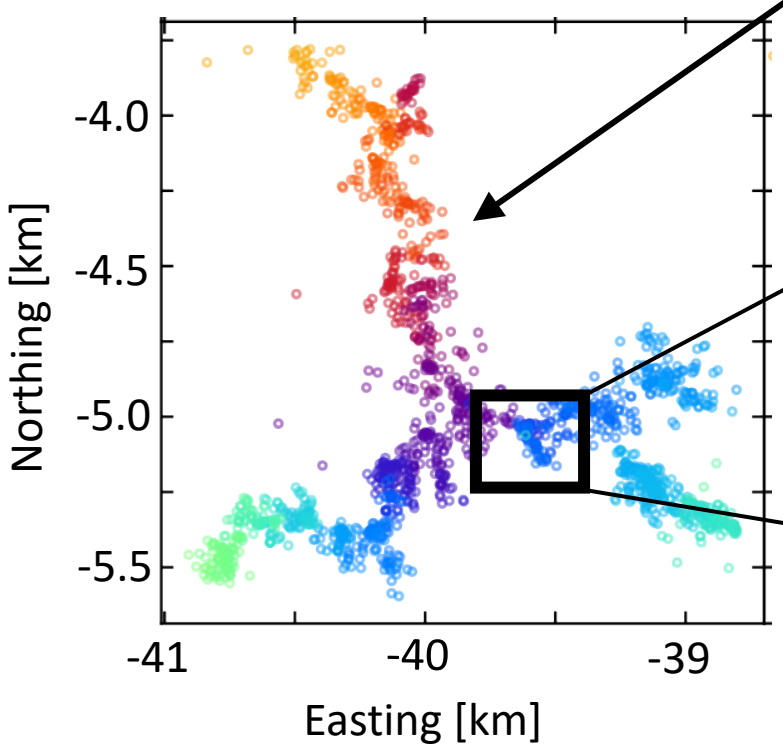

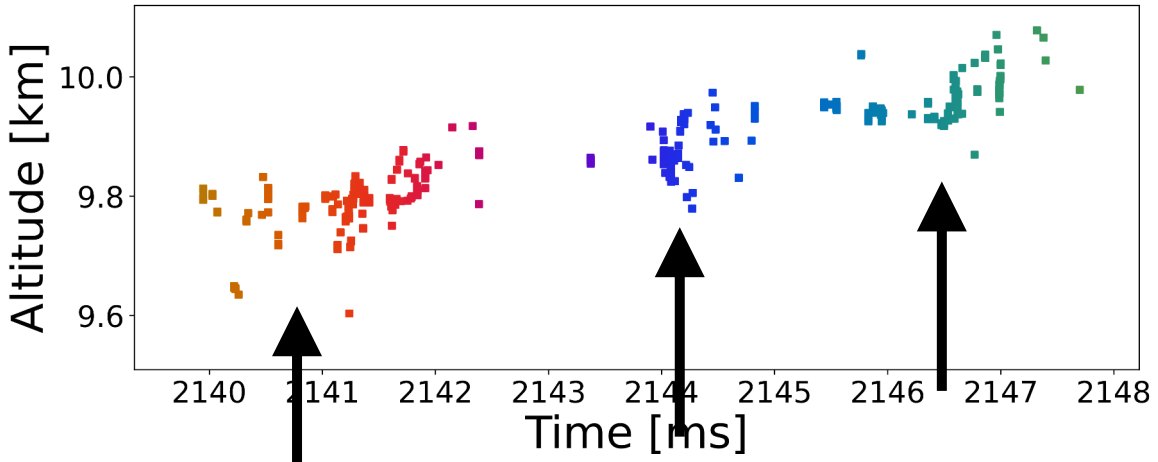

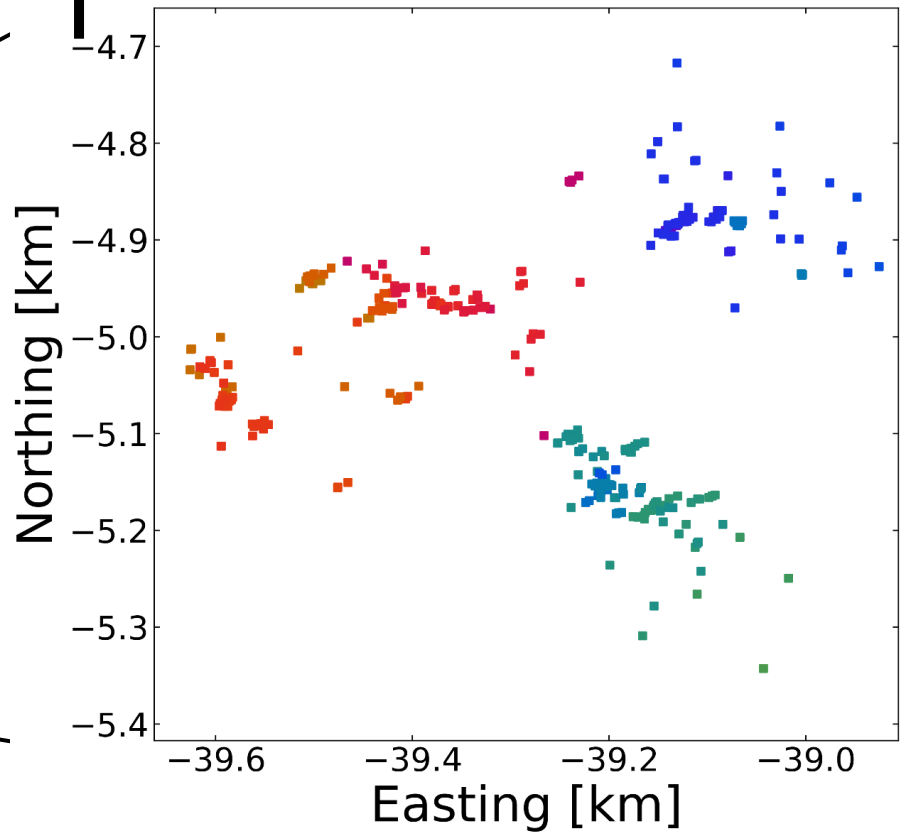

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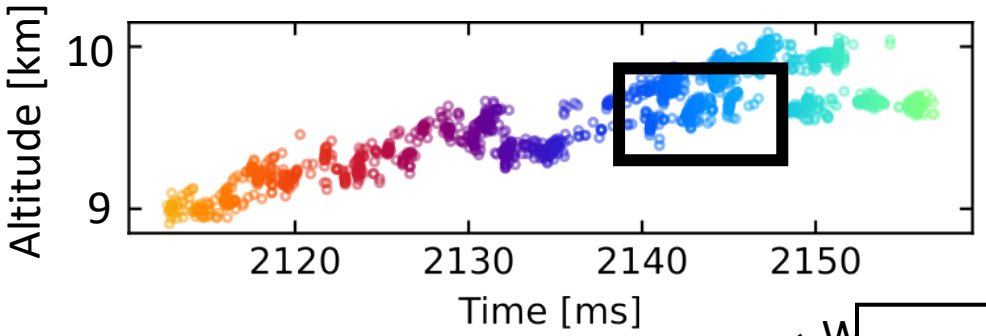
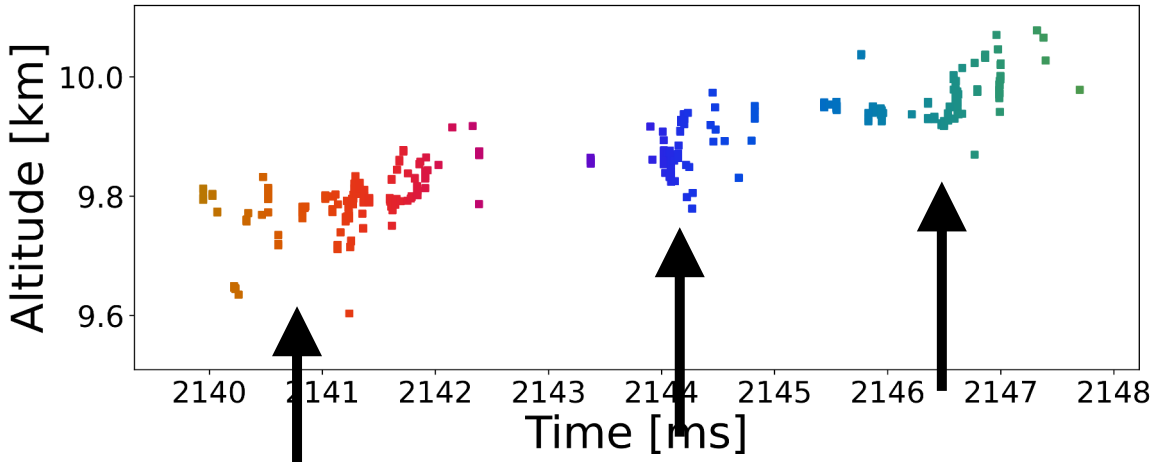
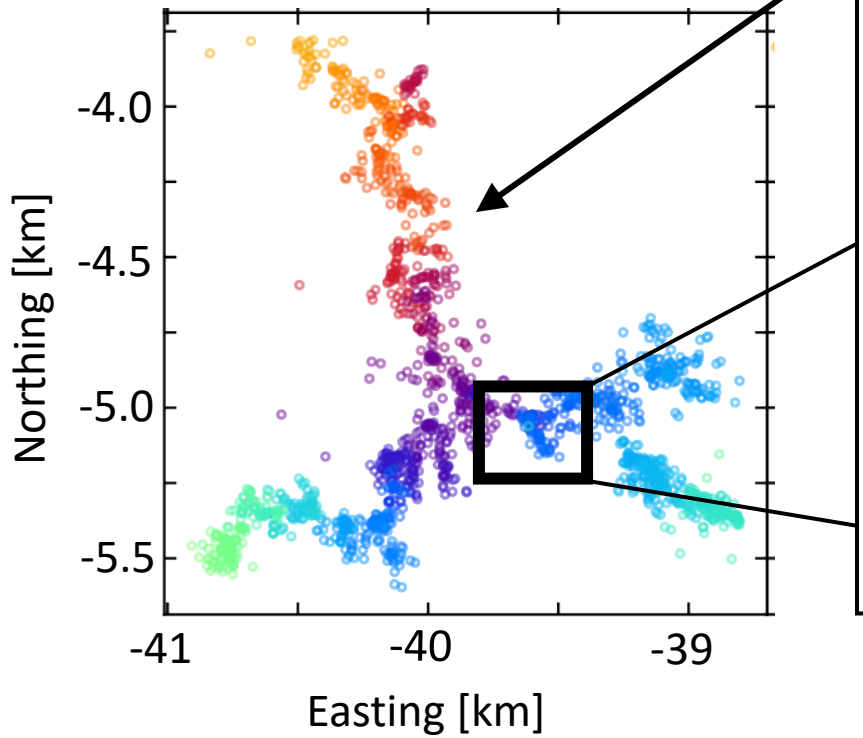




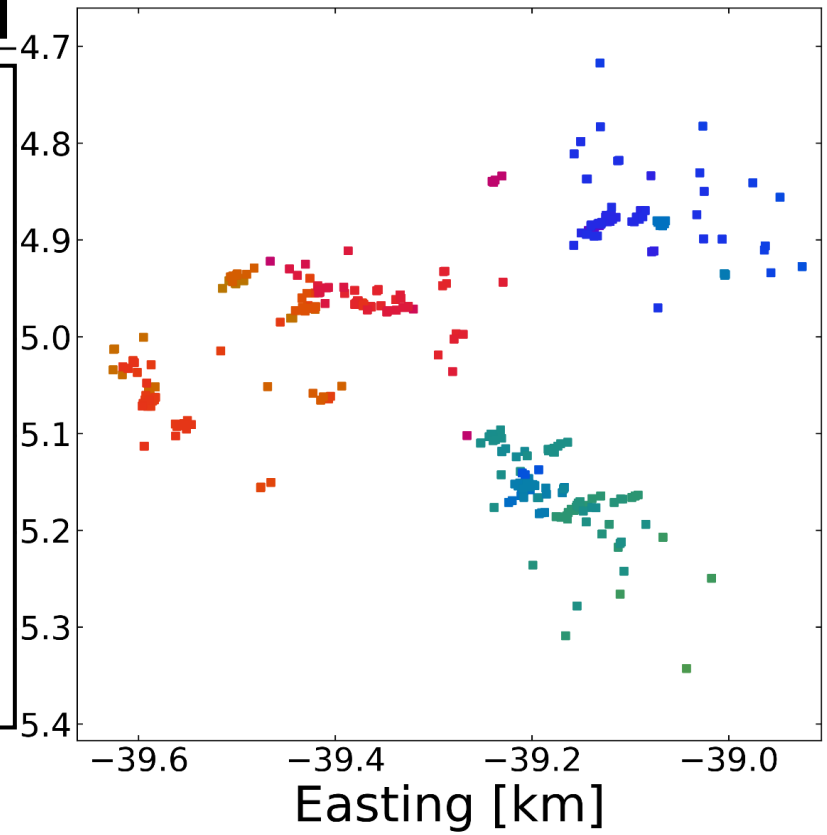


Bursts!

Existence well known

Only LOFAR can resolve in radio

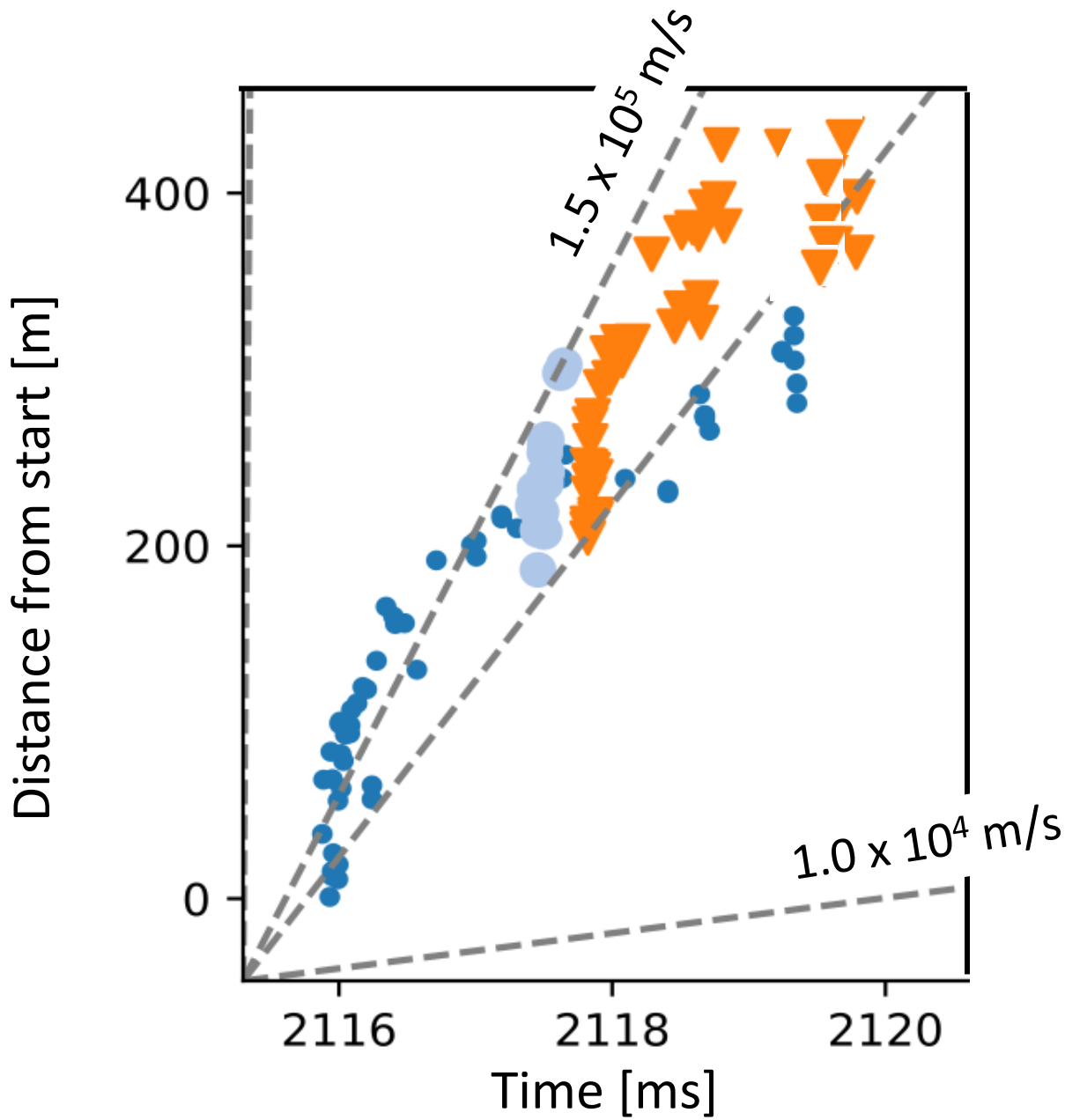
Only radio can resolve fast enough time scales!



Speed of Three Bursts

Speed of bursts is never measured

- Separate bursts by hand
- Plot distance vs time



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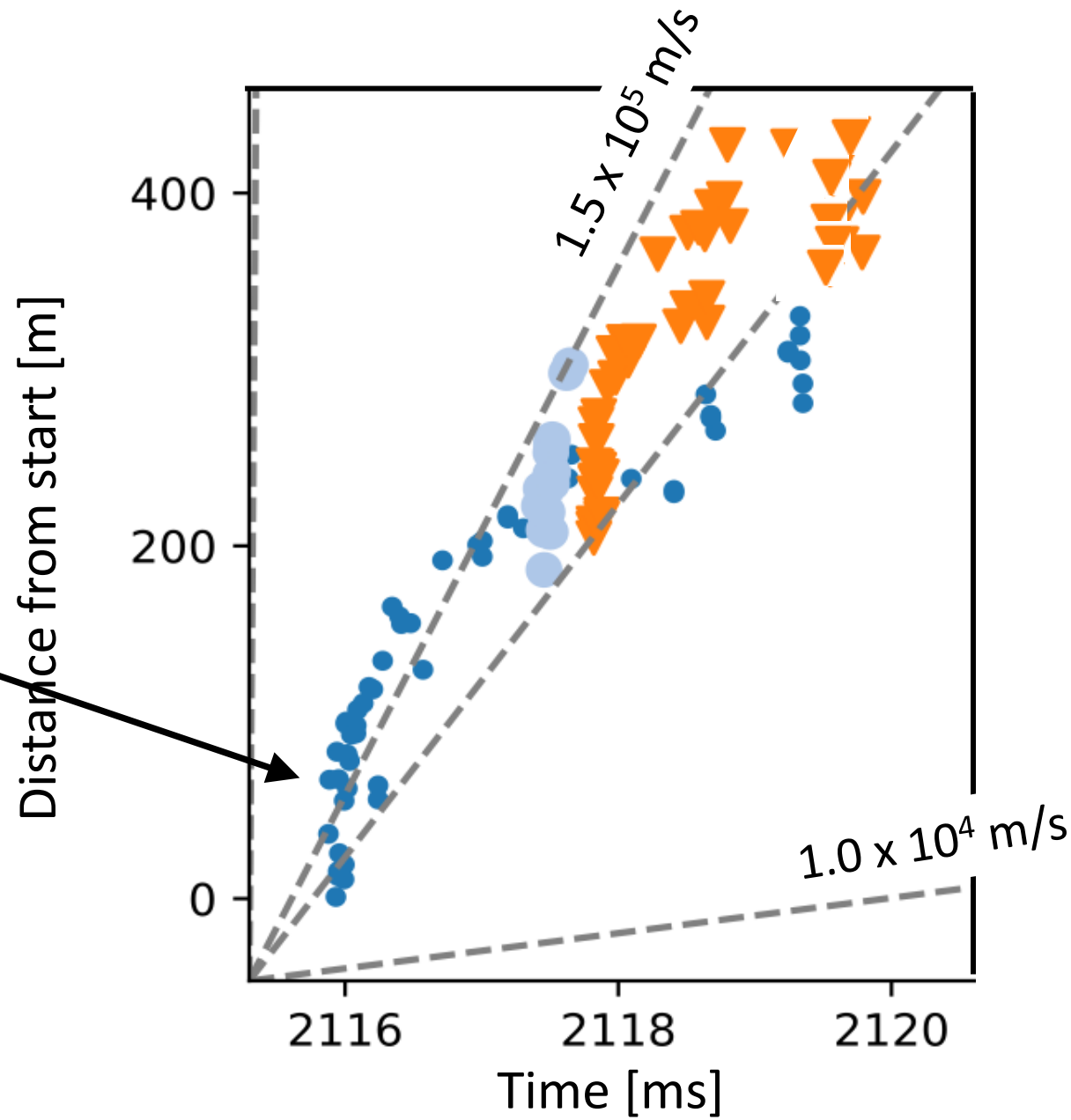
Results:

- Start Fast
  - ~ 5×10^6 m/s



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Speed of bursts is never measured

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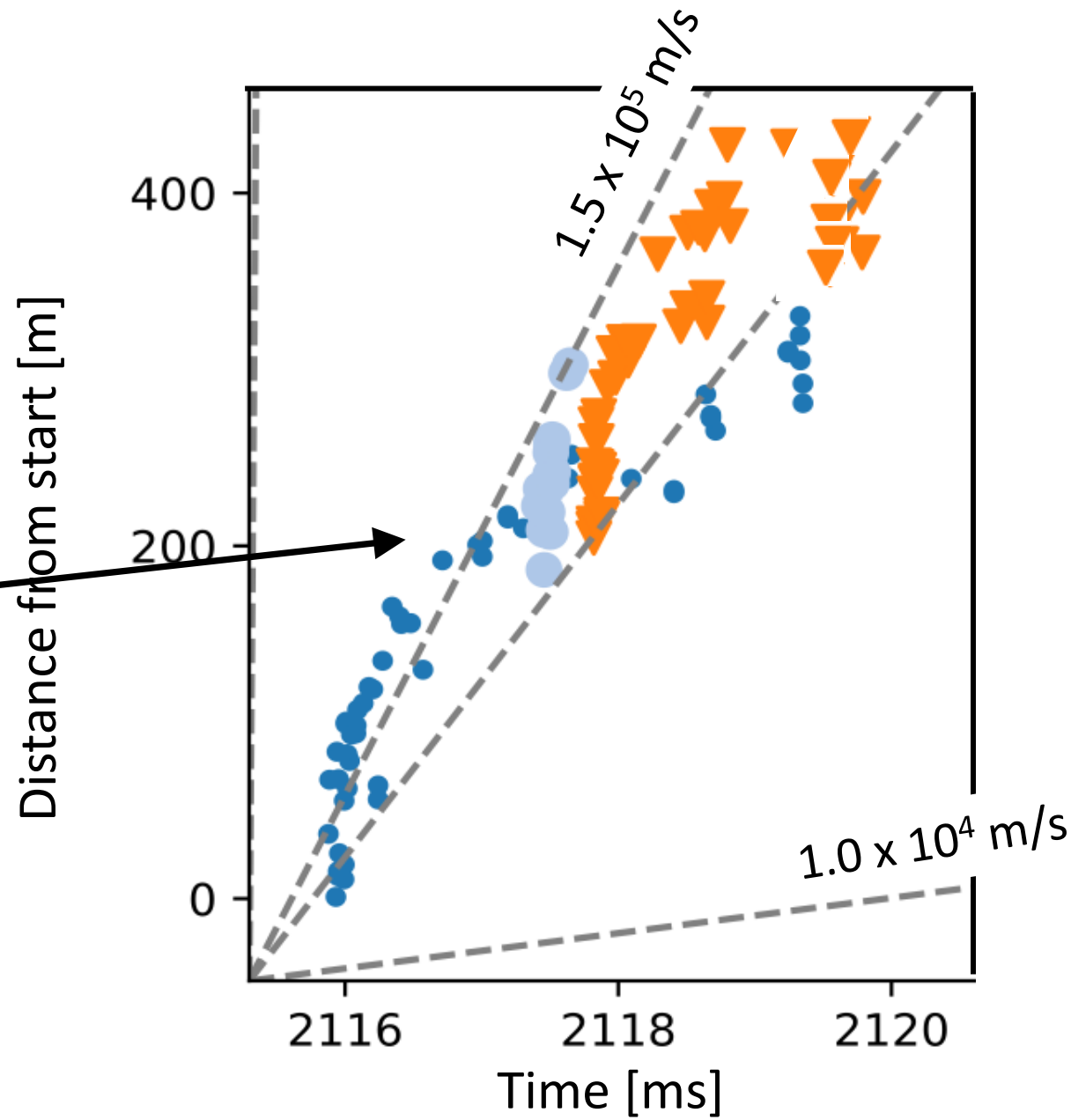
Results:

- Start Fast
  ~ 5×10^6 m/s
- Then slows down
  ~10^4 m/s



Speed of Three Bursts

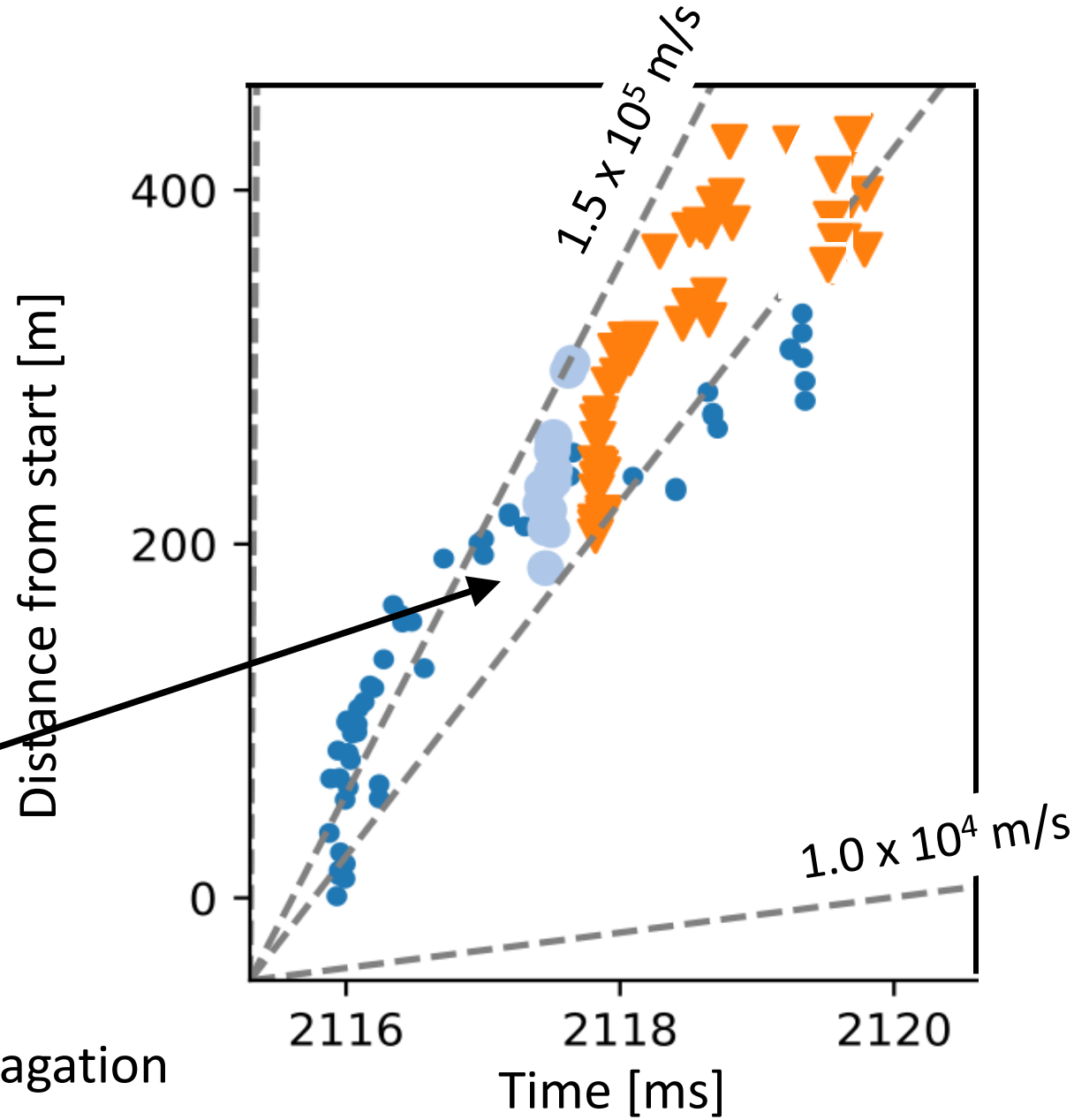
Speed of bursts is never measured

- Separate bursts by hand
- Plot distance vs time

Results:

- Start Fast
  ~ 5×10^6 m/s
- Then slows down
  ~10^4 m/s
- Next burst
  - Starts INSIDE previous

None of this observed before, in typical propagation



Conclusions and Future Plans

- Lightning Science with LOFAR is continuing to grow
  - Thunderstorm Structure
  - Lightning Propagation
  - Lightning Initiation (Next Talk!)

- Future:
  - LOFAR 2.0
    - Simultaneous LBA / HBA
    - Easier Calibration / White Rabbit
  - Joint Observation Campaigns in Planning
    - Radar
    - Balloons
    - Particle Scintillators