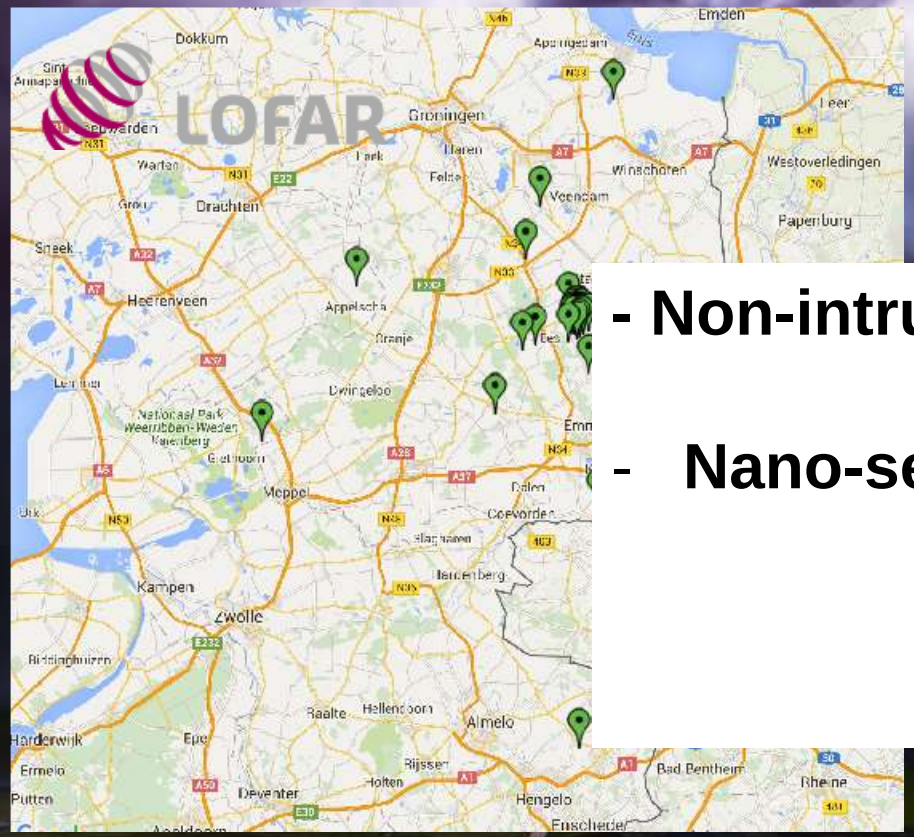
Precision Lightning Imaging with LOFAR



- **Non-intrusive E-field determination,**
  - **Gia Trinh +, accepted JGR 20**
- **Nano-second LMA**
  - **Brian Hare +, JGR 2018**
  - **Brian Hare +, Nature 2019**
  - **Brian Hare +, Phys Rev Lett 2020**

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University of New Hampshire

& LOFAR Cosmic Ray KSP

LOFAR

Low-Frequency Array
New generation radio-telescope
High resolution= long baseline
omnidirectional

6 stations on Superterp
+ 18 Core Stations (<2 km from Superterp)
+ 14 Dutch Remote Stations (<70 km from Superterp)
+ 12 European Stations (<1000 km from Superterp)

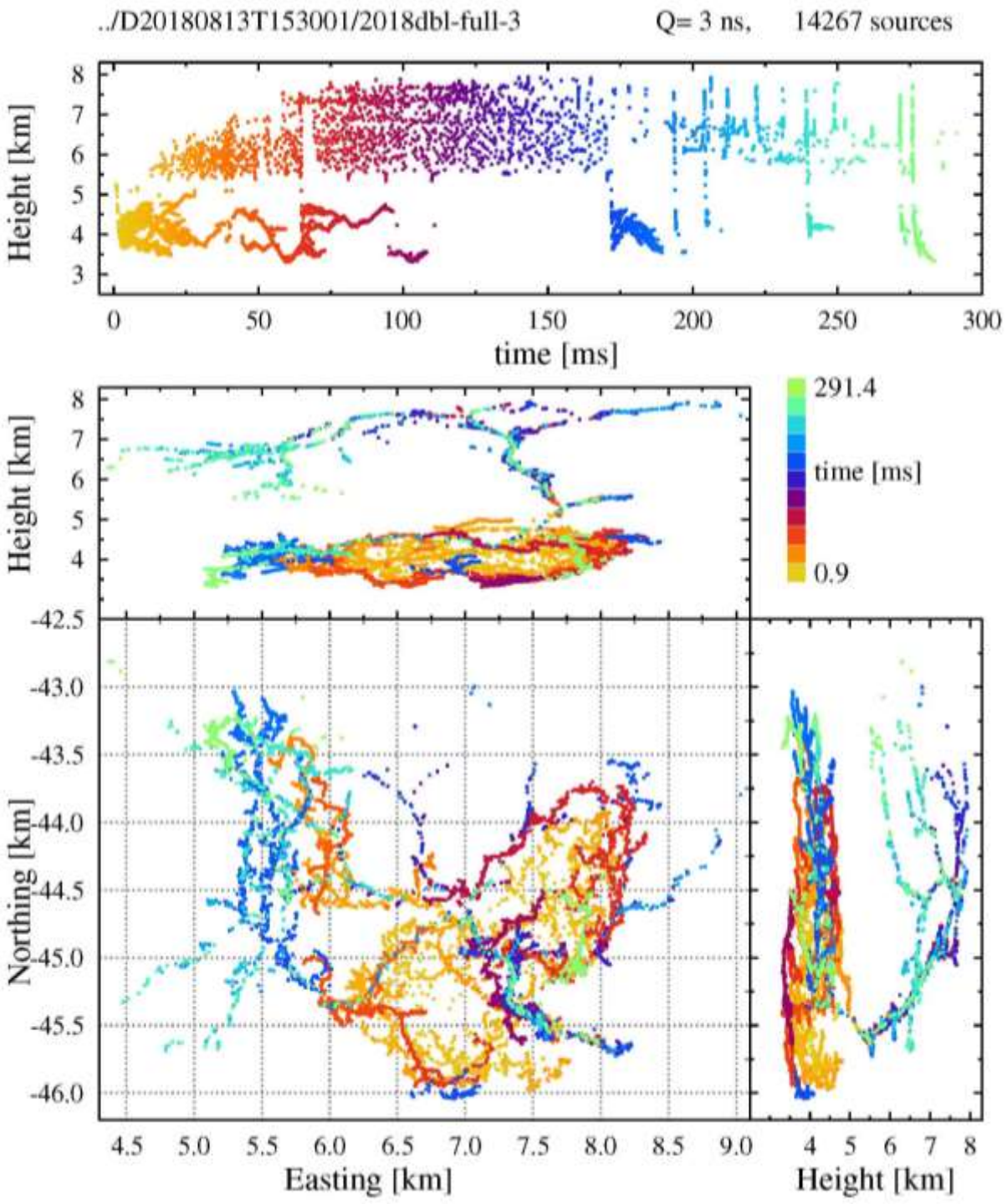
LOFAR

Imaging Procedure

Most important concepts & steps

Improved procedure from Hare+, Nature 2019

- **LOFAR: 30-80 MHz band:**
  - **dual polarized antennas, 200 MHz sampling**
  - **300 – 1000 antennas per lightning observation, up to 100 km baselines, Dutch stations**
  - **full time traces, 5 sec max, for off-line processing**
- **RFI mitigation:**
  - **software notch filters for radio & TV stations**
- **Antenna calibration, most time consuming:**
  - **select several (~20) 'easy' pulses spread over the flash**
  - **bootstrap procedure combining source locations and antenna timing (similar as for source finding)**
  - **reach ~1 ns calibration accuracy for all antennas, source location to ~1 m**
- **Source finding:**
  - **locate strongest (=candidate) pulses in time-trace reference antenna (condition spacing)**
  - **locate peak in cross correlation of candidate pulse with other antennas**
    - **use educated guess for pulse location (inspired by Kalman filter)**
  - **find source location by minimizing RMS time difference**
  - **repeat for every candidate for increasing number antennas**
- **Image construction:**
  - **apply quality criteria to calculated error in height [sigma(h)], RMS, & excluded antennas [N_{ex}]**

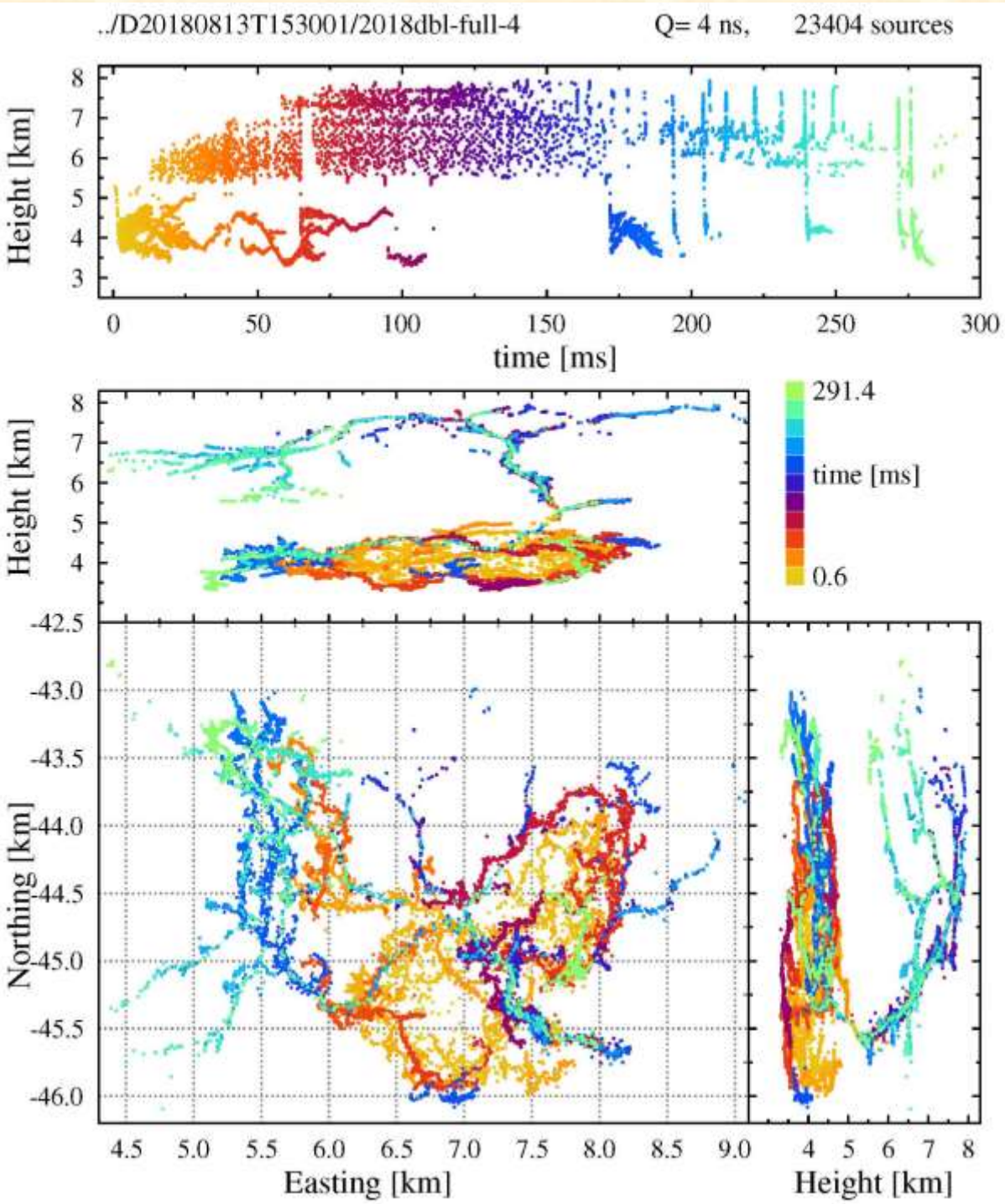


Flash D20180813T153001 (typical)

Quality Criteria:
σ(h) < 3.5 m; RMS < 3 ns; N_{ex} < 10 (out of 265)
14267 sources pass all criteria (300 ms flash)

Typical (small) Dutch summer thunderstorm

- **Initiation at 5km, just below negative charge layer**
- **Twinkling positive leaders 5-8 km height**
- **Extensive network of negative leaders below 5 km**
- **Several K-changes all flowing through initiation point (‘neck’)**

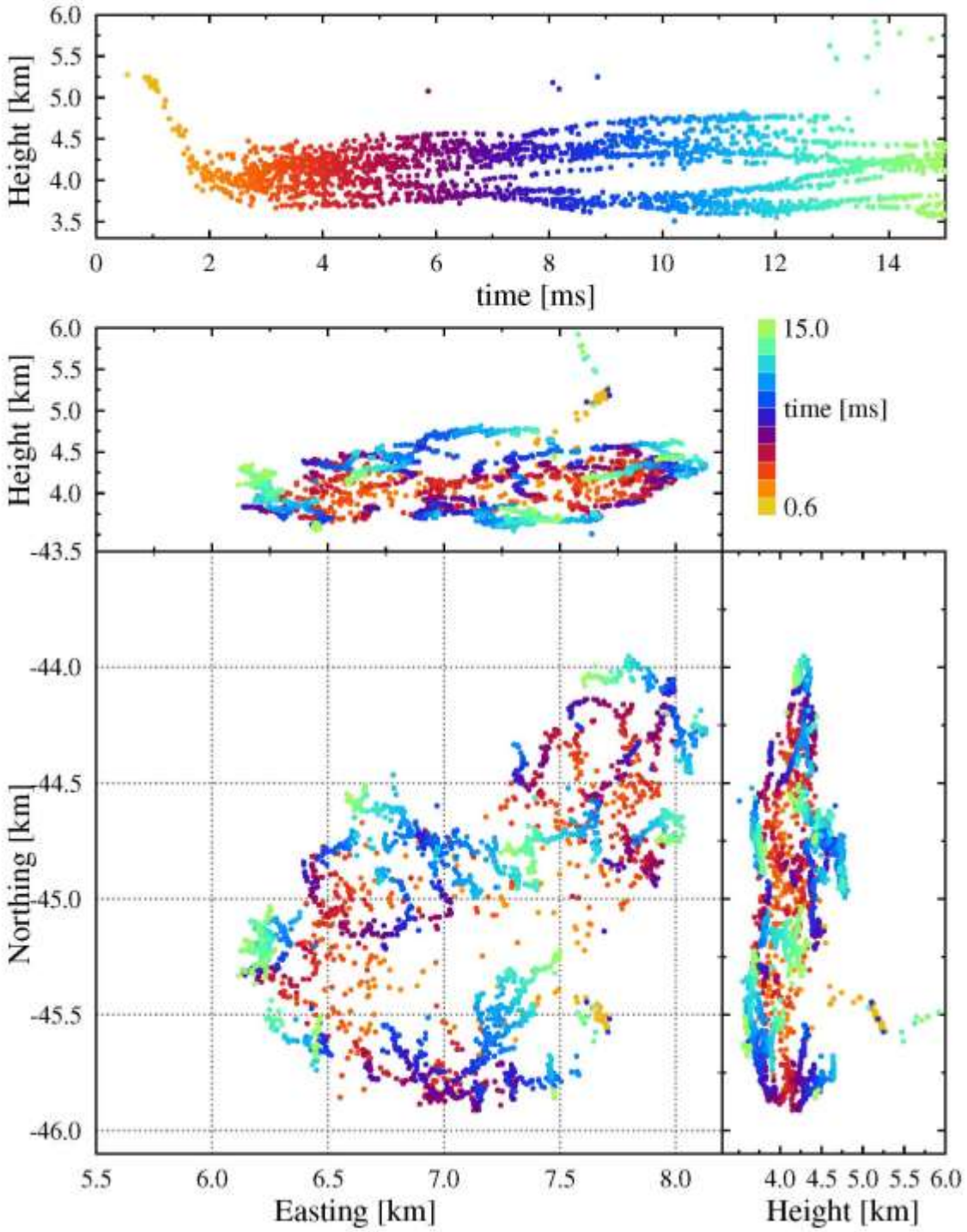


Somewhat more relaxed quality

Quality Criteria:
σ(h) < 3.5 m; RMS < 4 ns; N_{ex} < 20 (out of 265)
23404 sources pass all criteria (300 ms flash)

Almost twice as many sources
- **details more enhanced**

Almost the same sharpness



Zoom in on initial stage - I

Quality Criteria:
$\sigma(h) < 3.5$ m; RMS < 4 ns; $N_{ex} < 20$ (out of 265)
2962 sources pass all criteria (first 15 ms of flash)

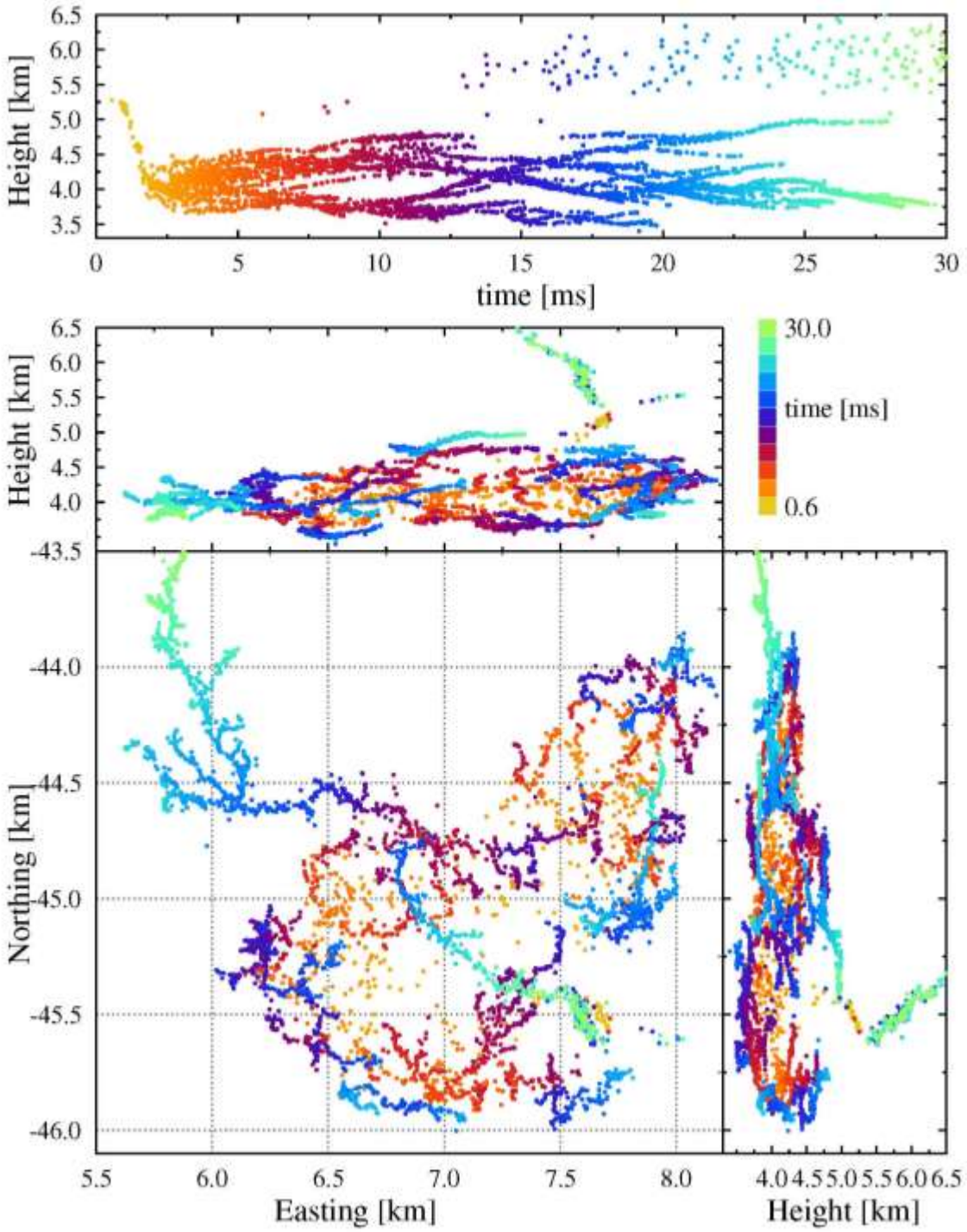
We see:

Flash initiates at 5.25 km height,
at bottom negative charge layer

Develops Primary Initial Leader

A multitude of negative leaders is triggered
in a very limited area

It takes 14 ms to see first sign of positive leader



Zoom in on initial stage - II

Quality Criteria:
$\sigma(h) < 3.5$ m; RMS < 4 ns; $N_{ex} < 20$ (out of 265)
5776 sources pass all criteria (first 30 ms of flash)

We see:

Between 20 - 25 ms most negative leaders stop

At 30 ms a single one is continue to propagate

Copious positive leader twinkling starts after 15 ms

Summary

With LOFAR we have the perfect instrument for lightning imaging.

We are geared up to make high-resolution images of lightning flashes
- Typical details: close to 1 meter
- Source density: proven capability of 200 per ms flash = 200k sources per second

We see: Most amazing details, paper in preparation