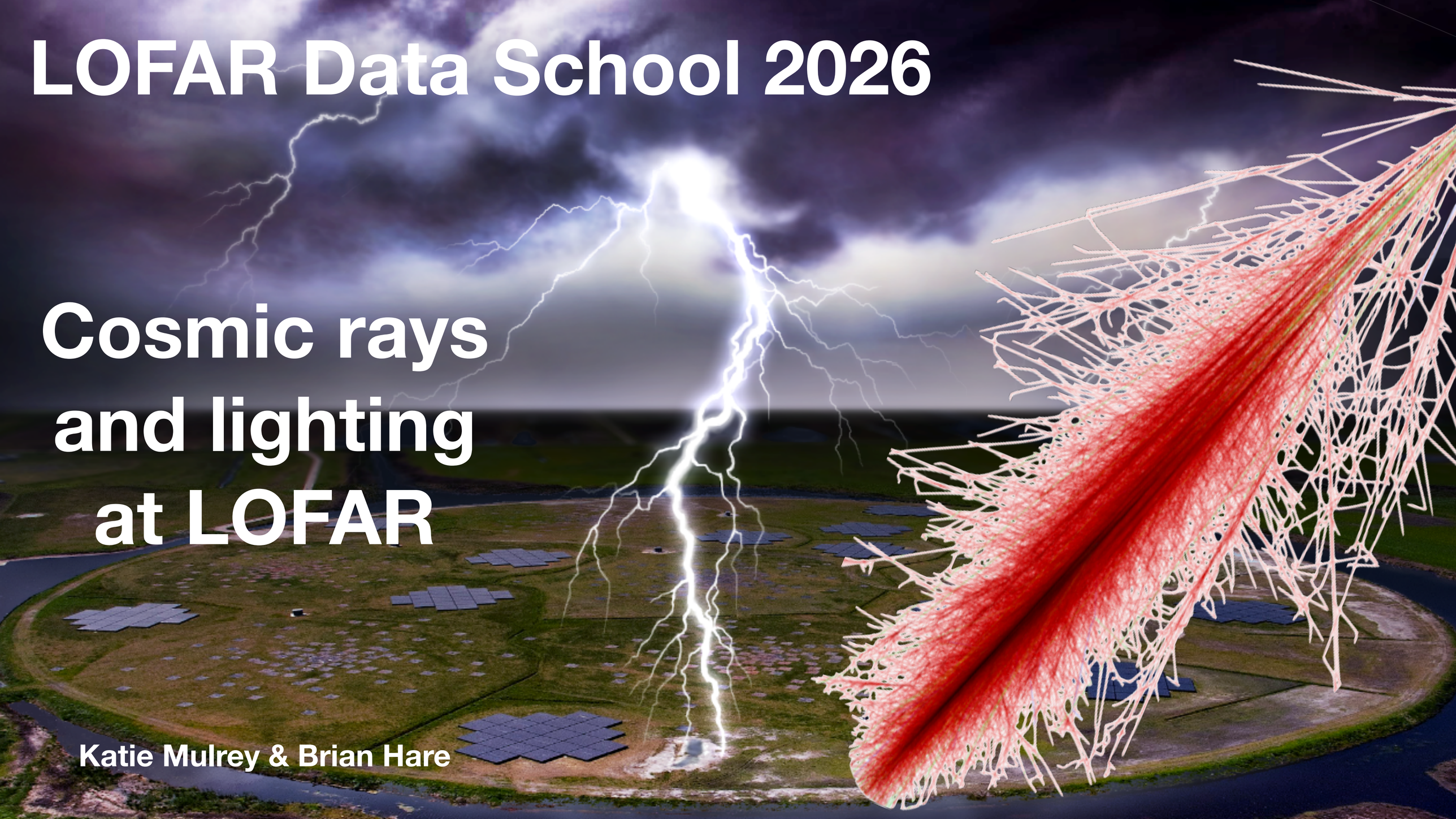
LOFAR Data School 2026



Cosmic rays and lighting at LOFAR

Katie Mulrey & Brian Hare

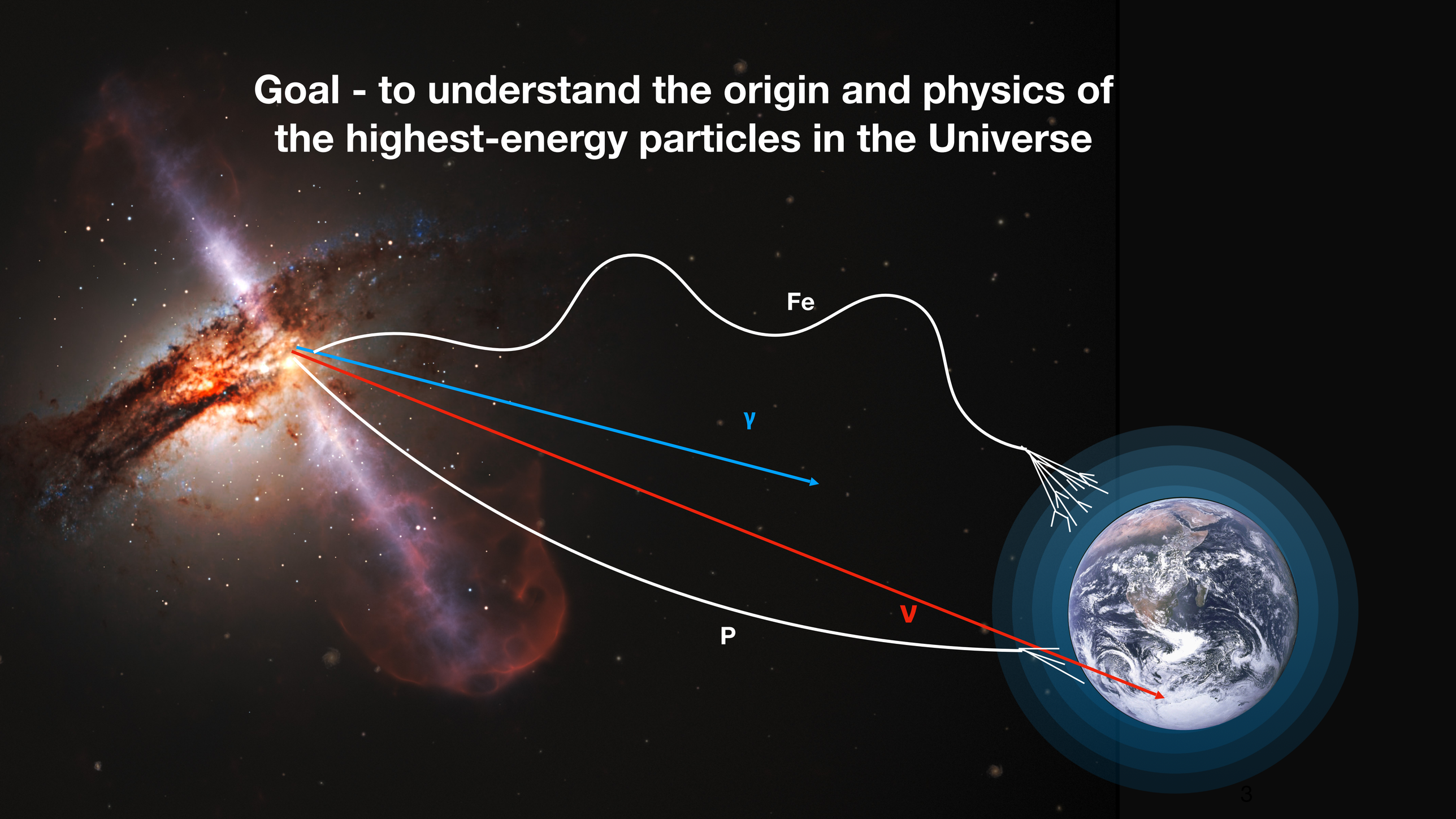
LOFAR Data School 2026

Cosmic rays and lighting at LOFAR

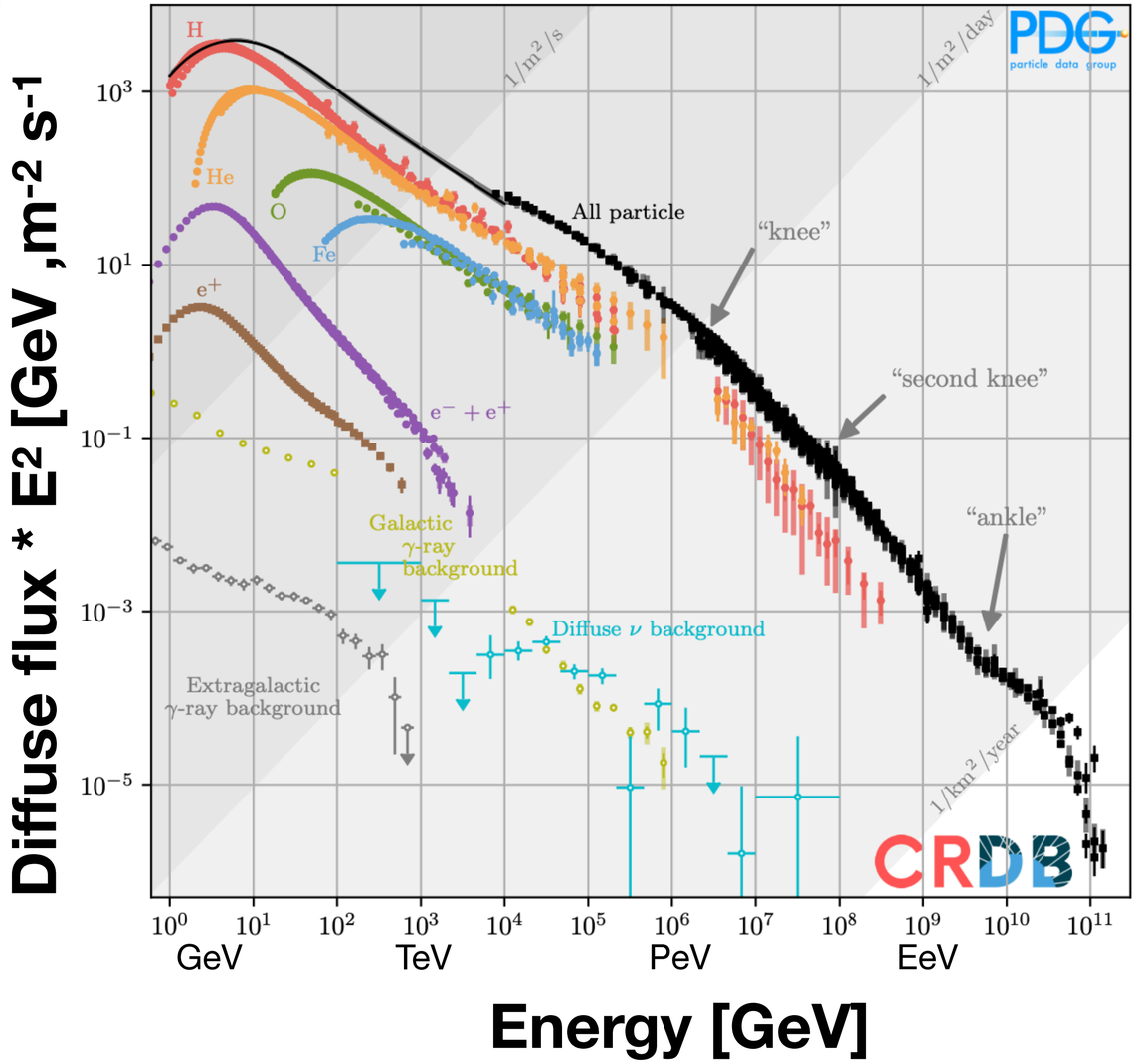


Katie Mulrey & Brian Hare

Goal - to understand the origin and physics of the highest-energy particles in the Universe

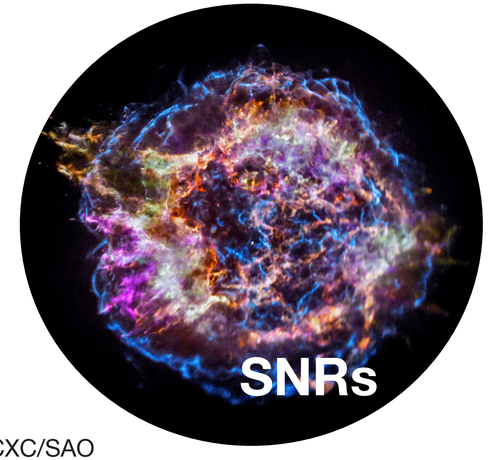


Cosmic ray landscape

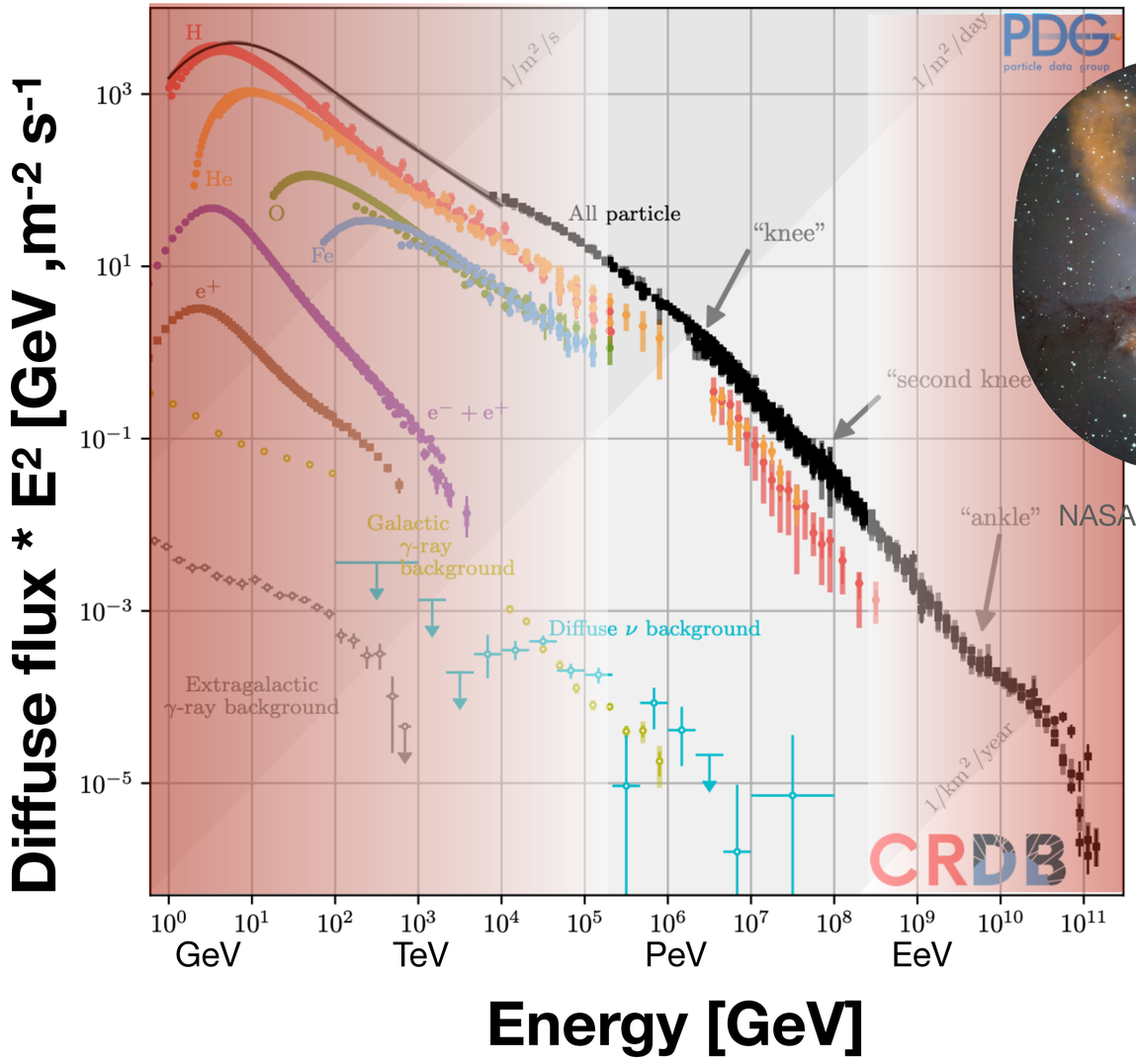


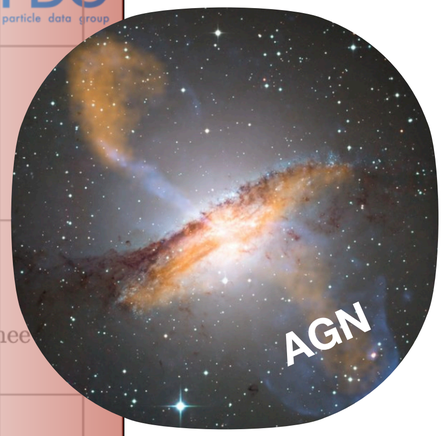
Cosmic ray landscape

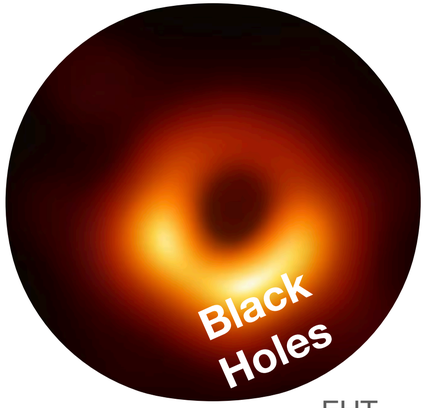
Galactic



NASA/CXC/SAO







EHT

NASA / ESO/MPIfR

extragalactic



NASA / ESA

Cosmic ray landscape

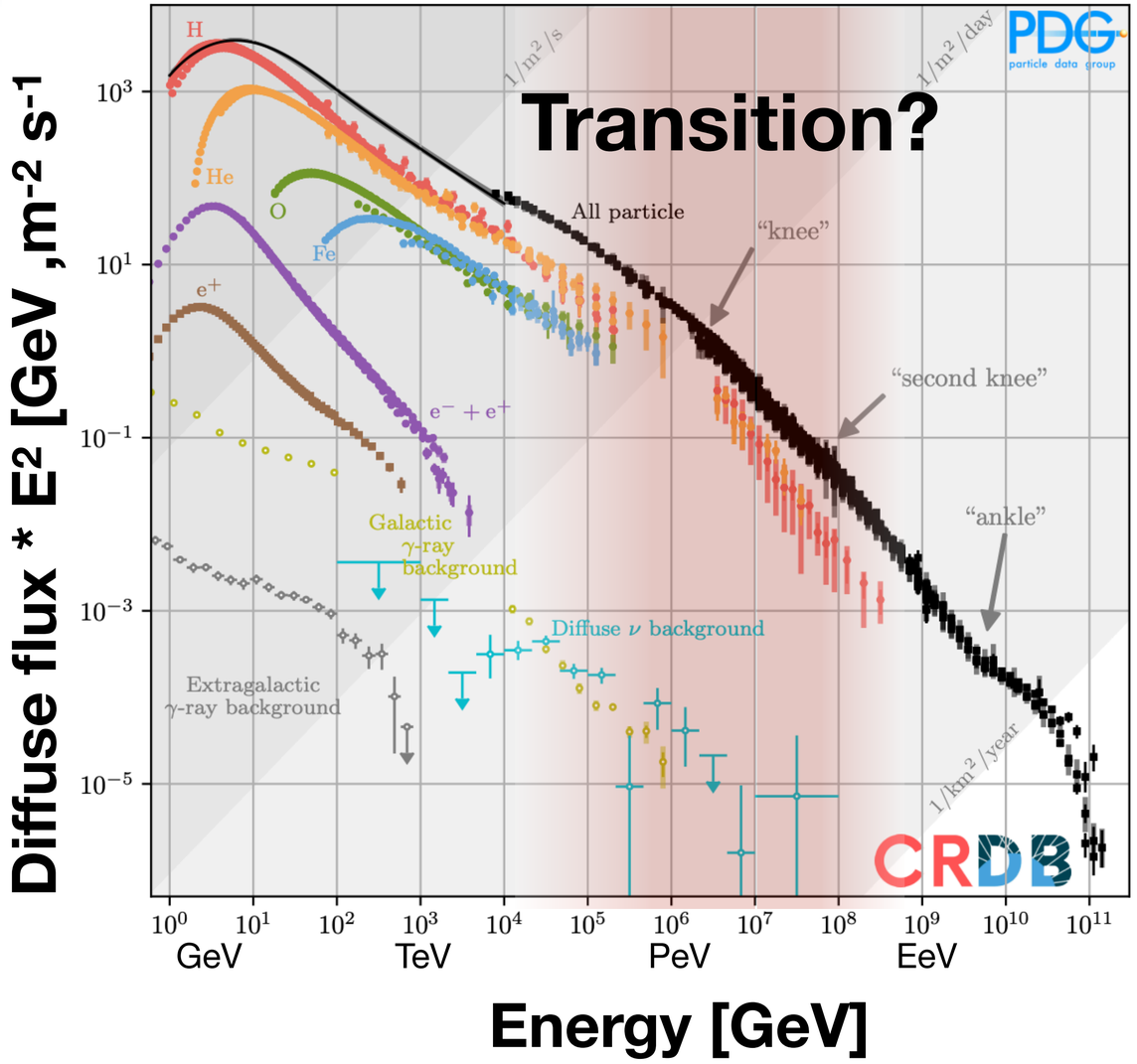




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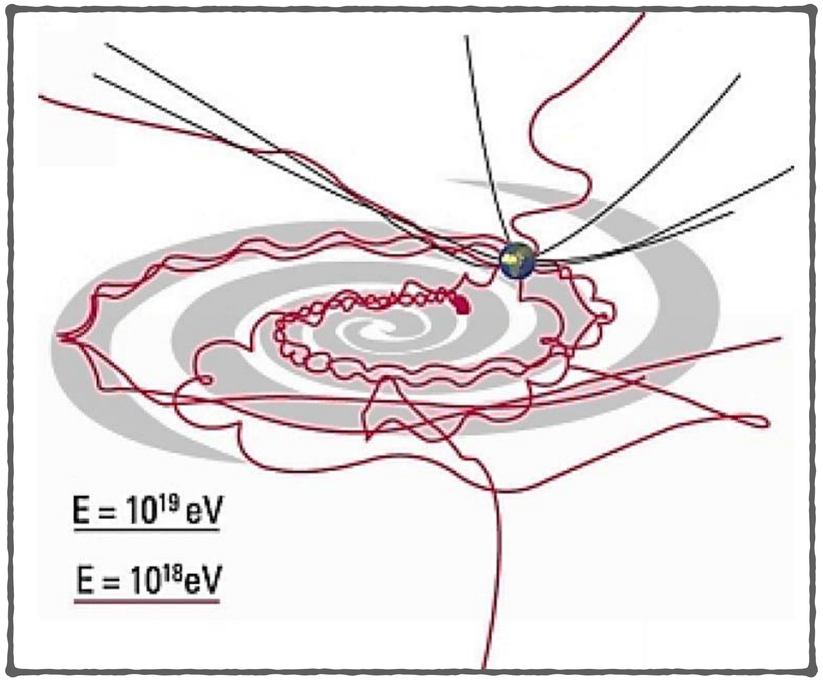
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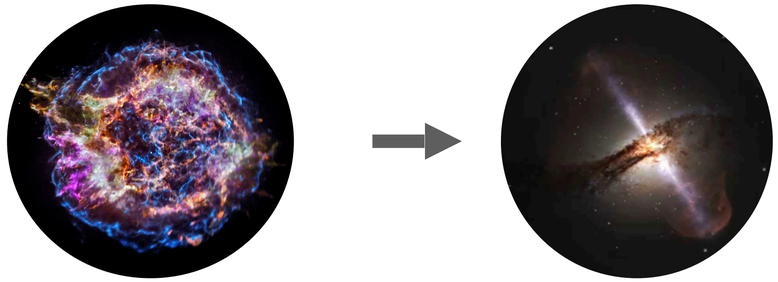


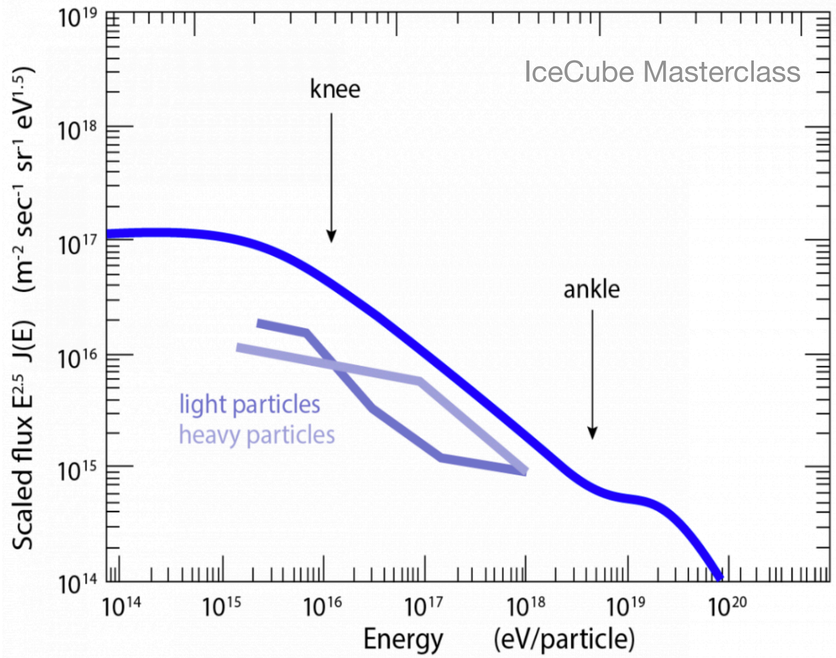
- Second Galactic CR component?
- Influence of Galactic and extragalactic magnetic fields?
- Hadronic physics at energies beyond the reach of the LHC?
- Connections to other cosmic messengers (PeVatrons)?

Cosmic ray landscape

Challenge: CR trajectories are scrambled in magnetic fields







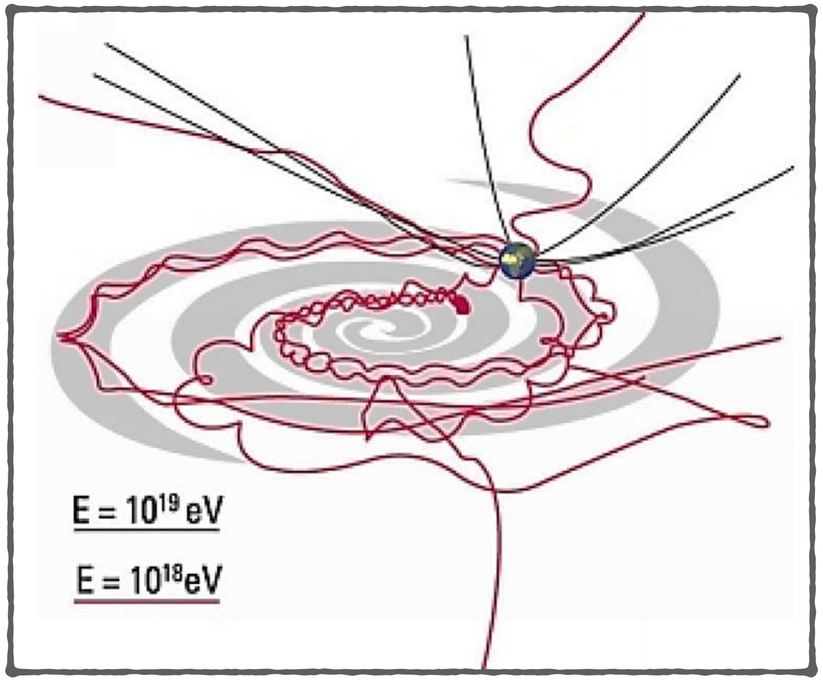
$$\mathrm{E_{max}} \propto Z\ e\ B\ r$$

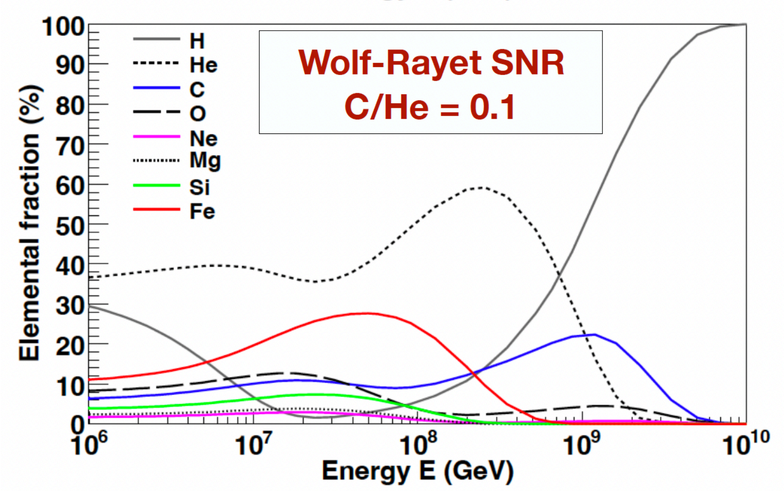
$$\mathrm{E_{Fe,\ max}} = 26 \times E_{\mathrm{p,\ max}}$$

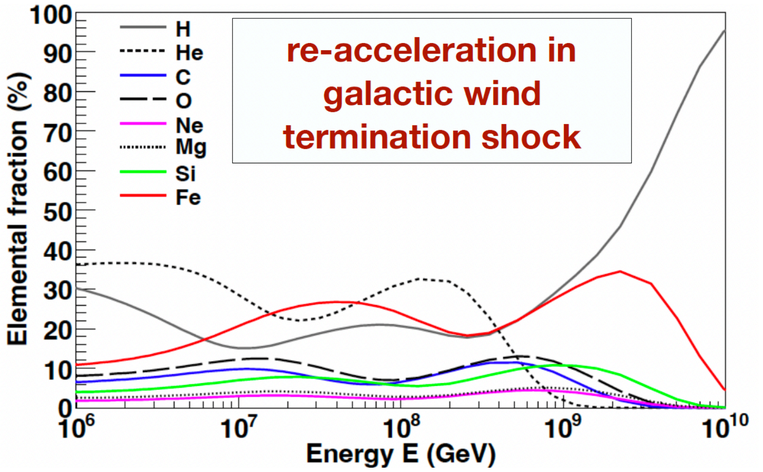
energy & composition

Cosmic ray landscape

Challenge: CR trajectories are scrambled in magnetic fields



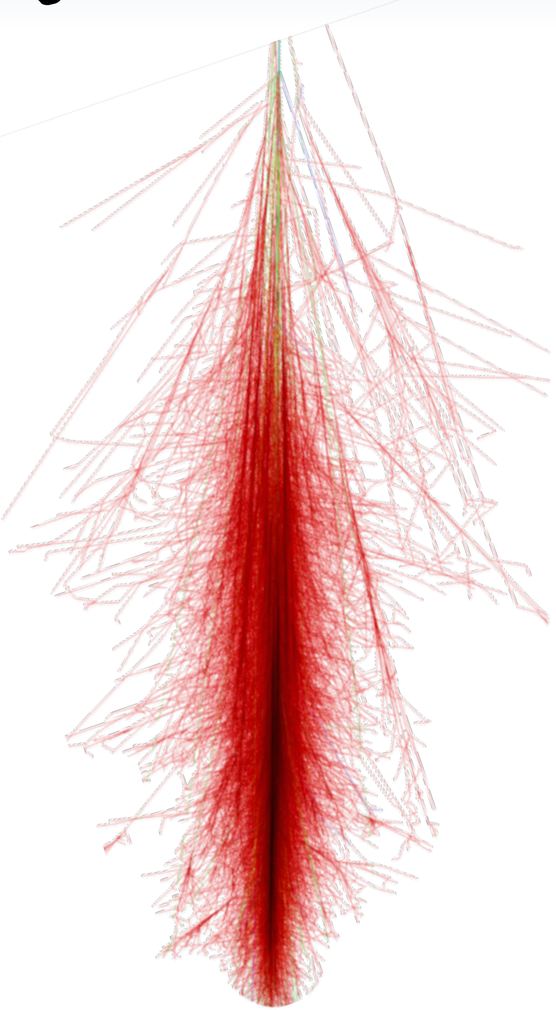


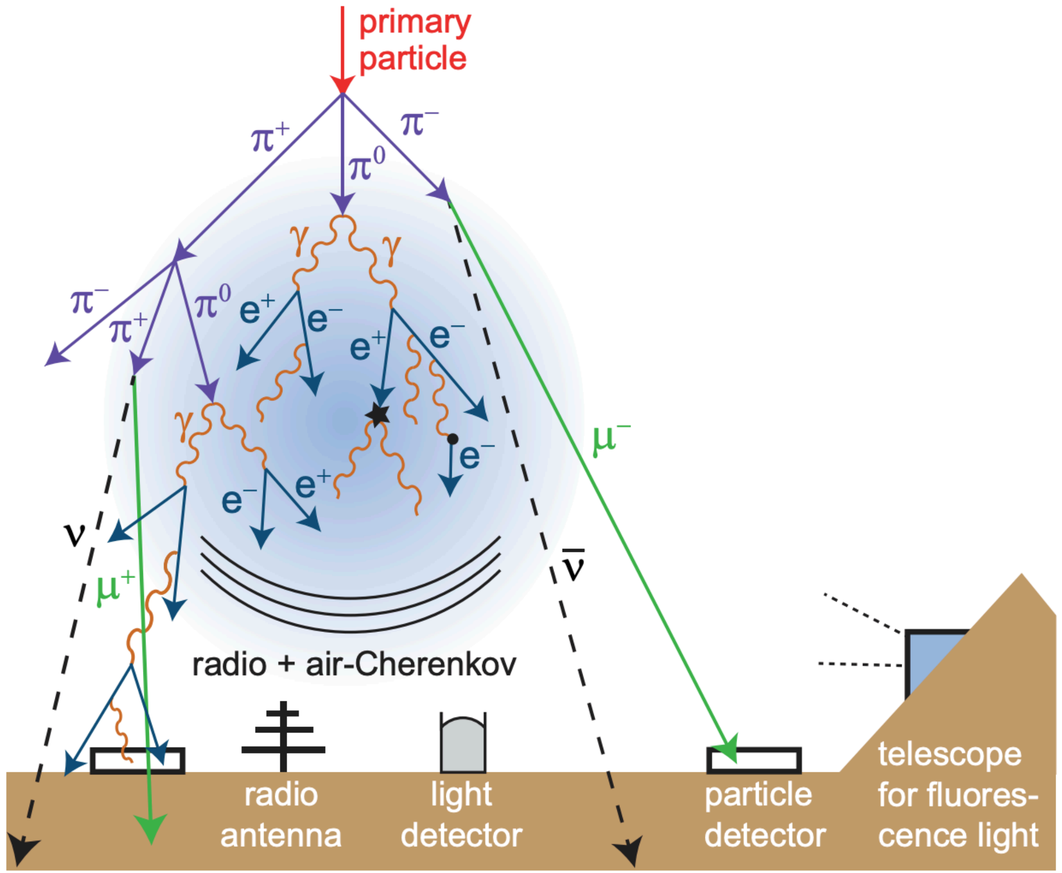


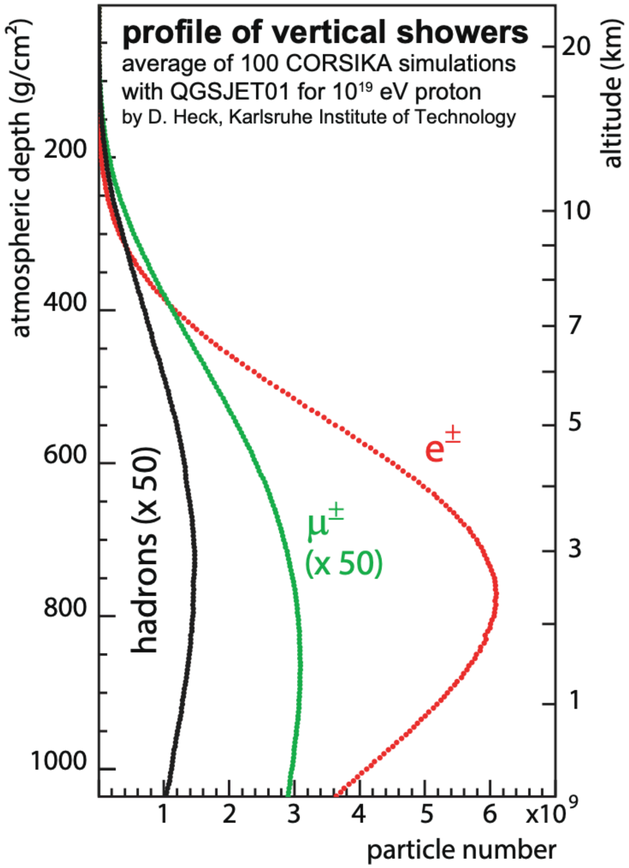
Source - specific composition signatures

S. Thoudam et al, A&A 2016.

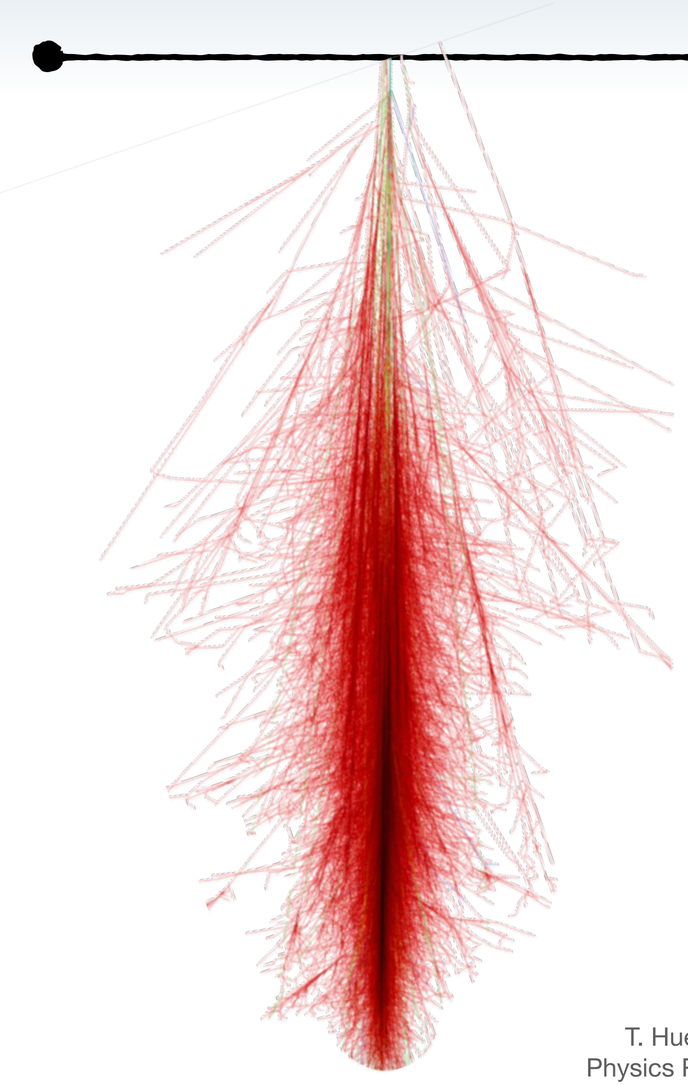
Cosmic ray air showers

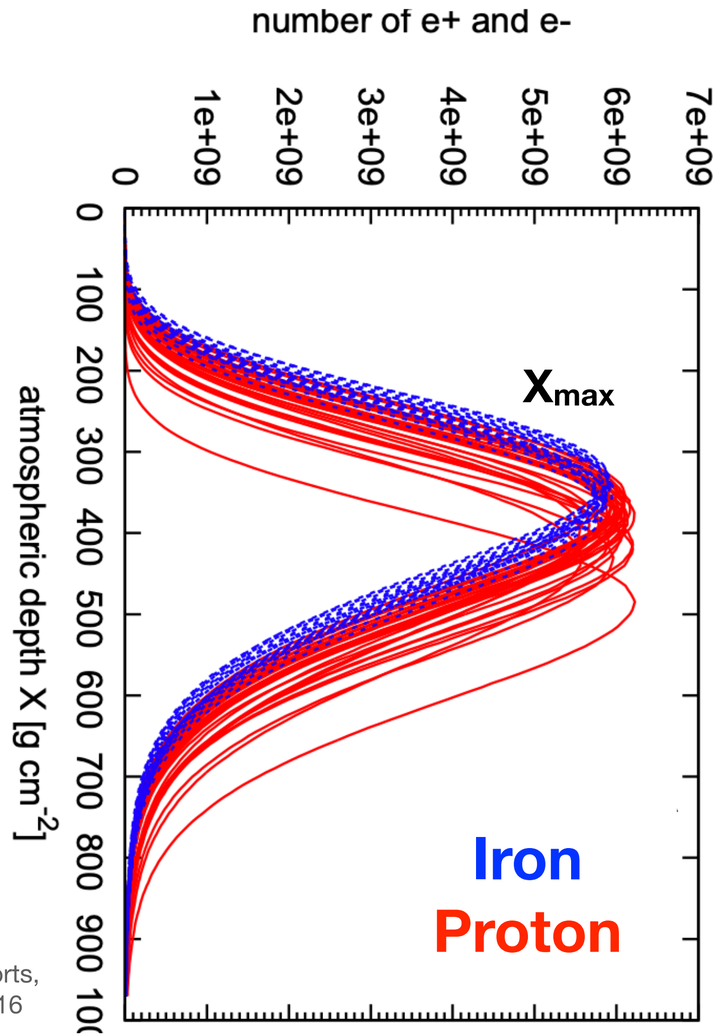




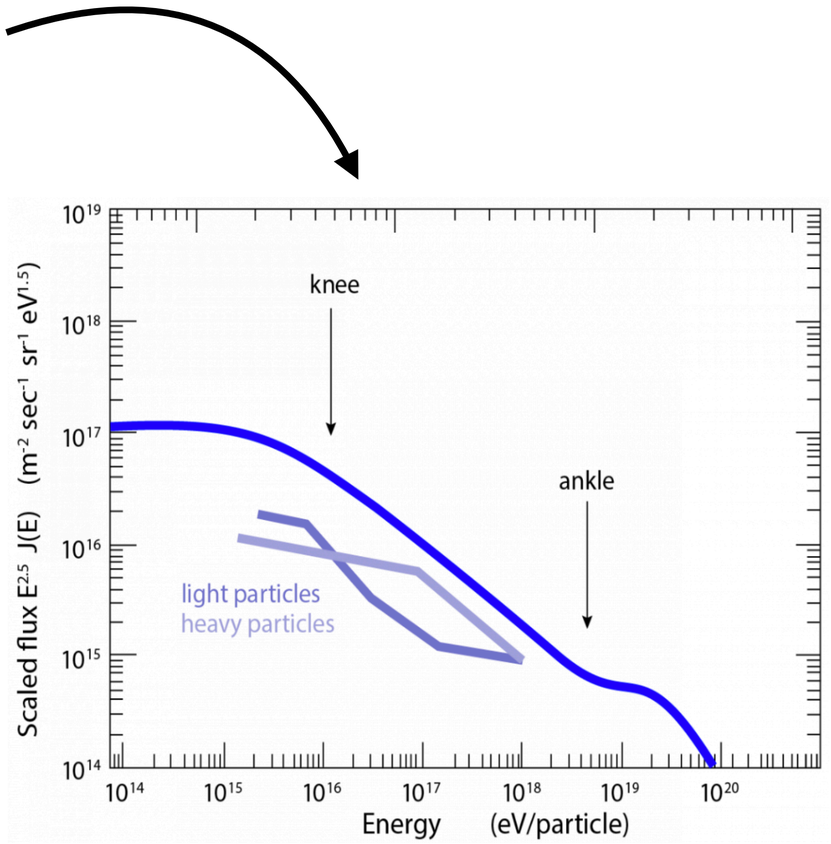


Cosmic ray air showers

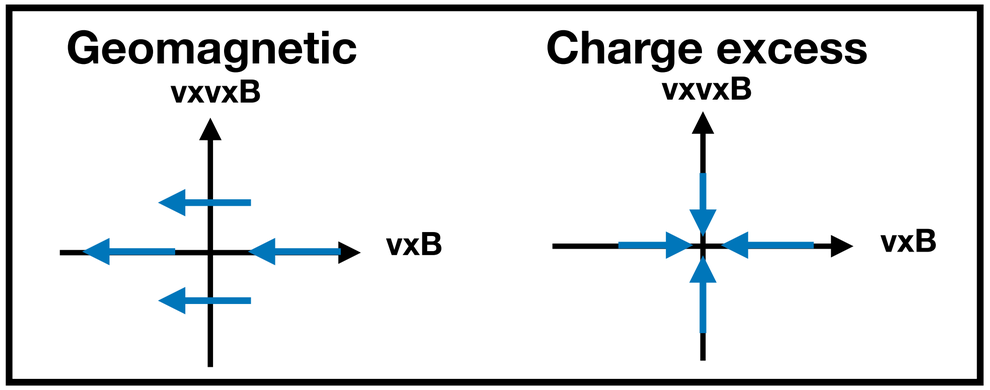


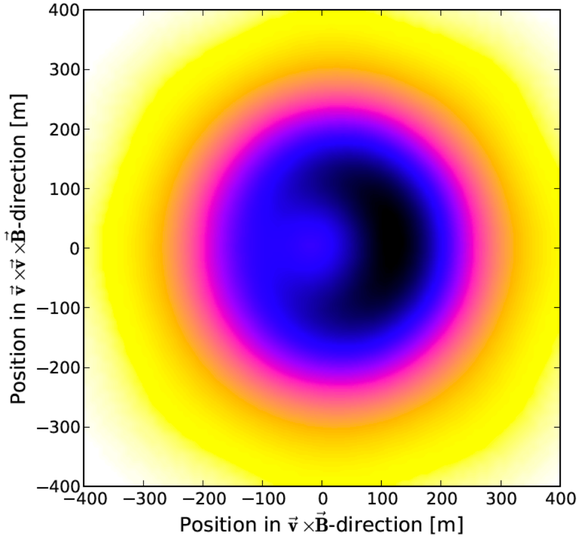


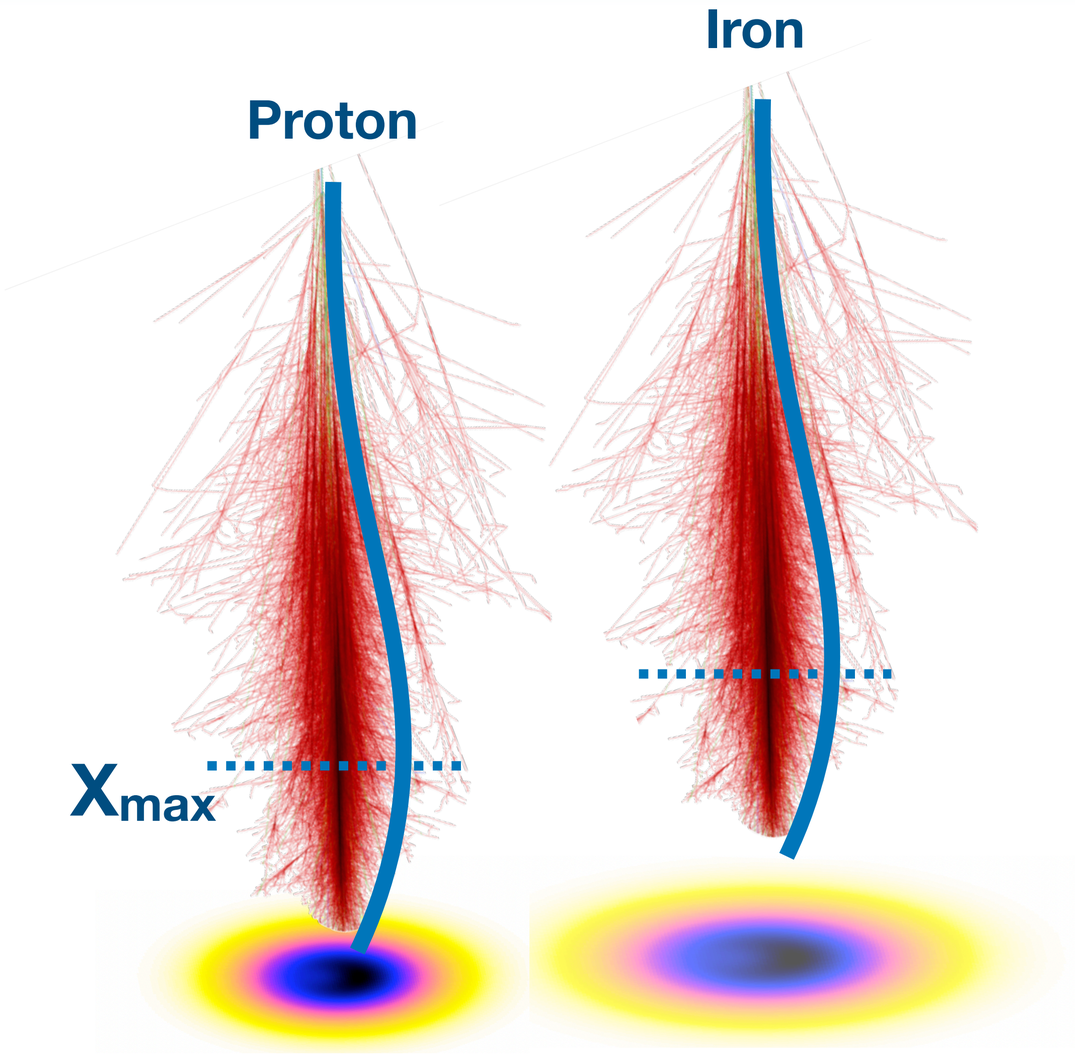
T. Huege.
Physics Reports,
620:1-52,2016



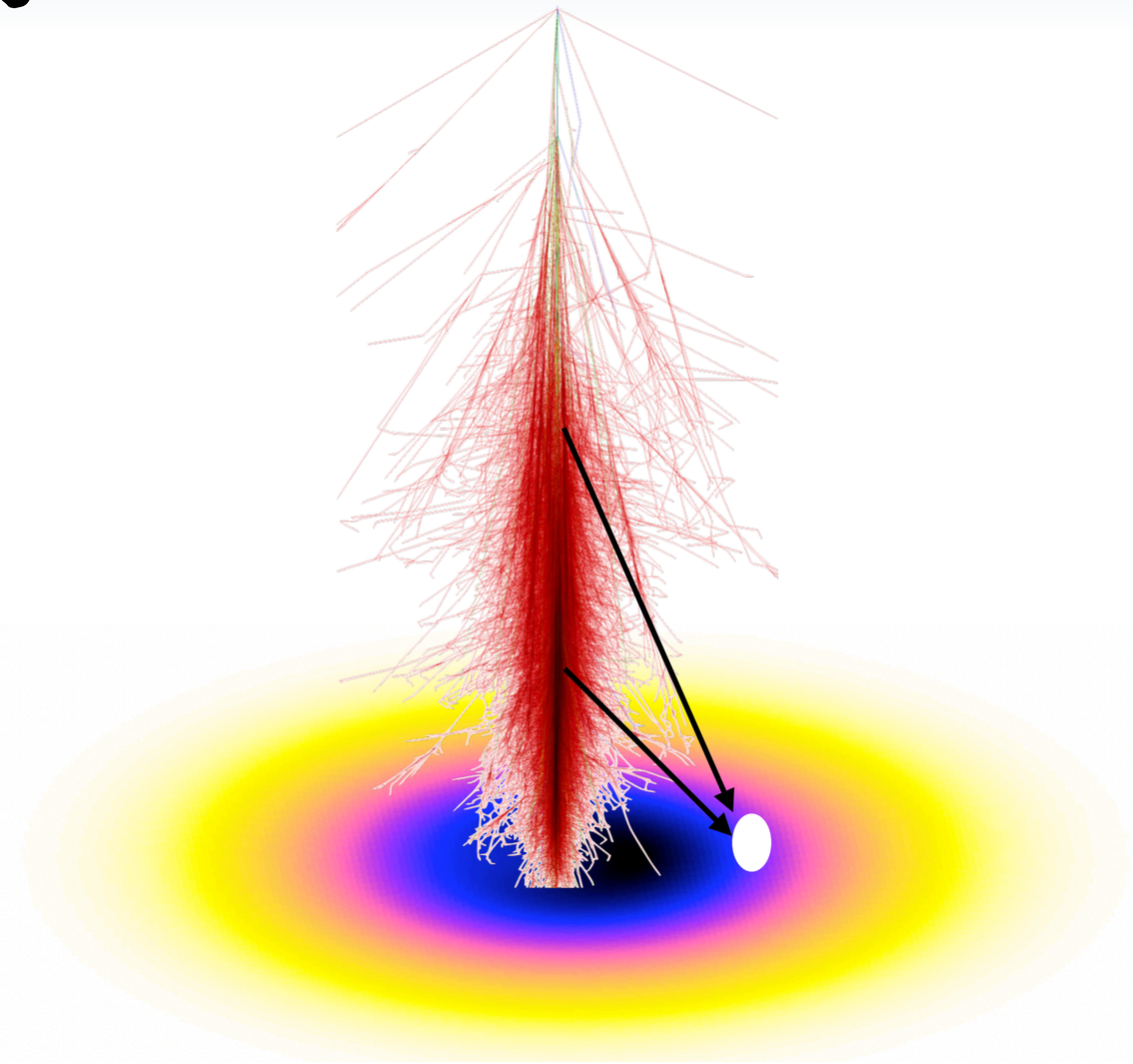
Radio emission from air showers



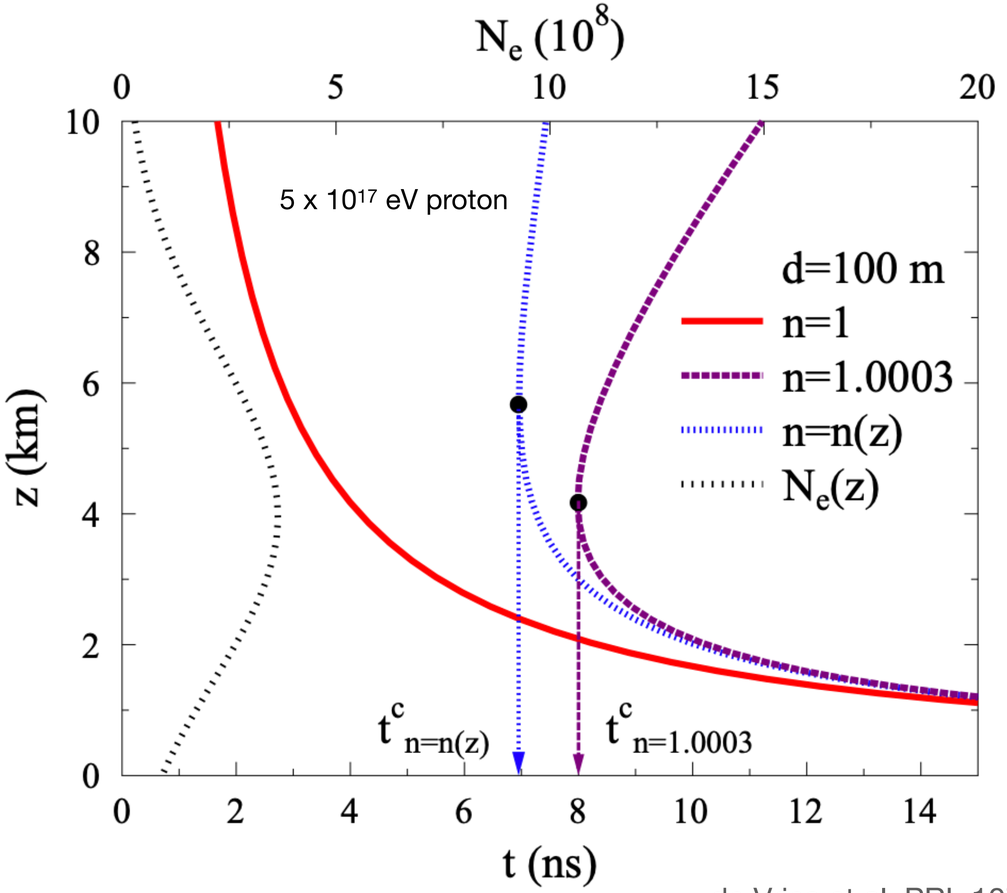




Radio emission from air showers



“Cherenkov-like” effects: signal coherence



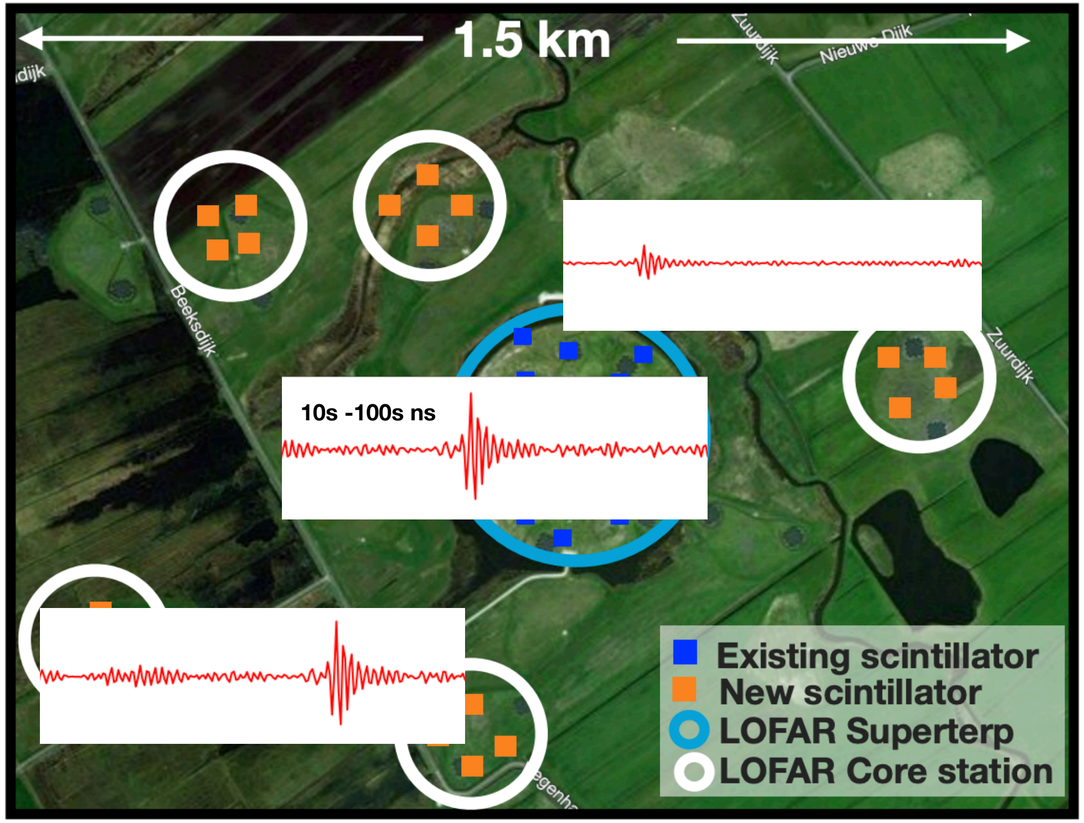
de Vries et al. PRL 107:061101,2011

Cosmic rays at LOFAR

Low band (30-80 MHz)



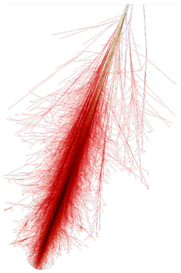
~ 100s of antennas per event



Particle detector for triggering

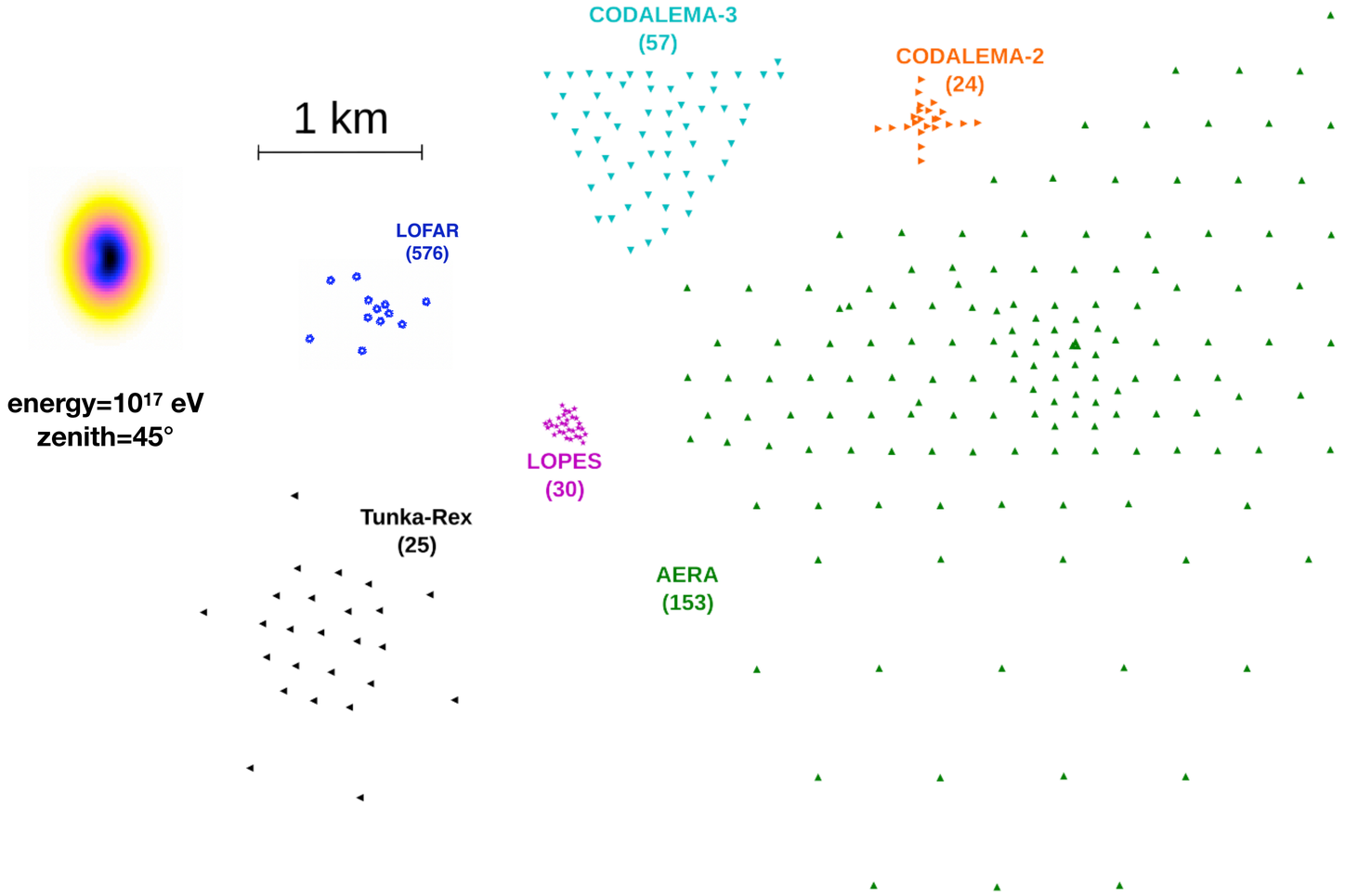


P. Schellart et al., A&A 560, 98 (2013)



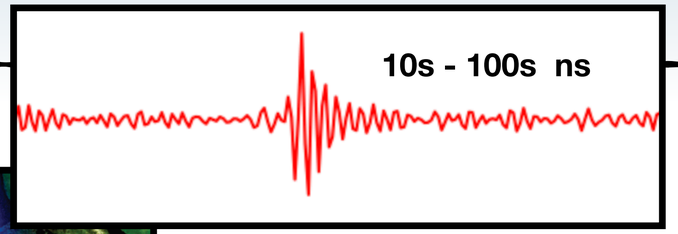
CR event → **particle trigger** → **radio buffer readout** → **offline analysis**

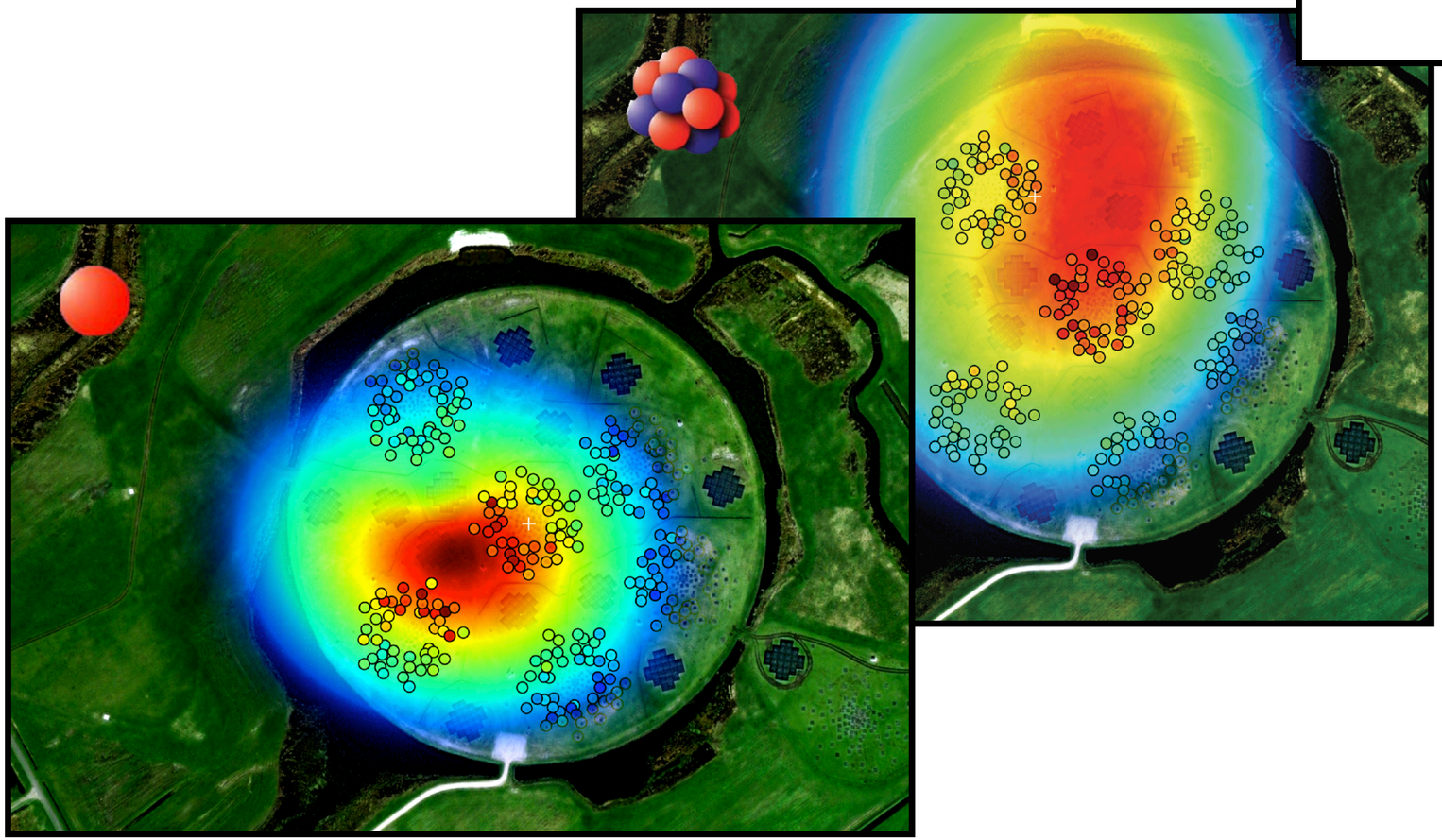
Cosmic rays at LOFAR

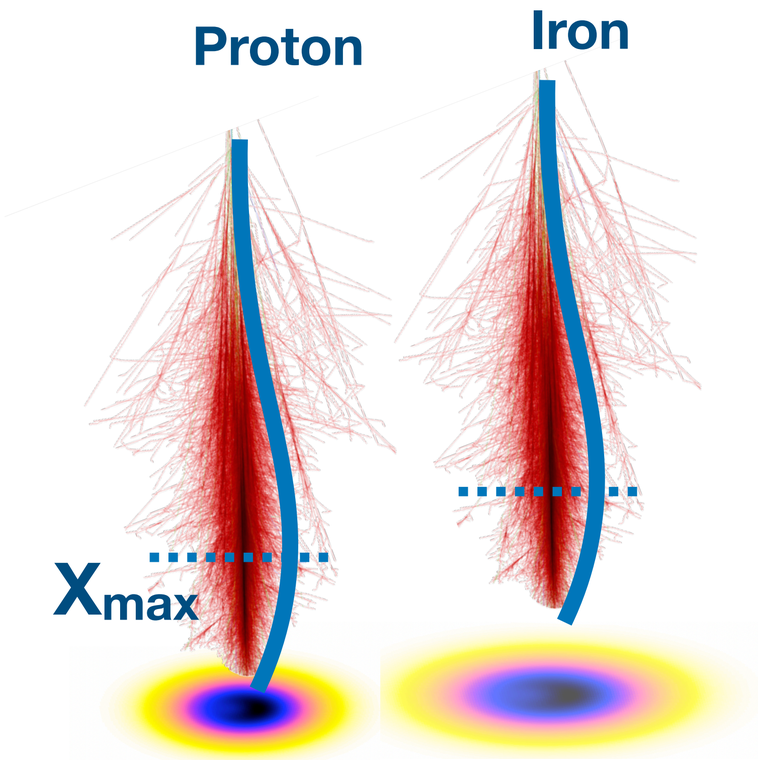


T. Huege. Physics Reports, 620:1-52, 2016.

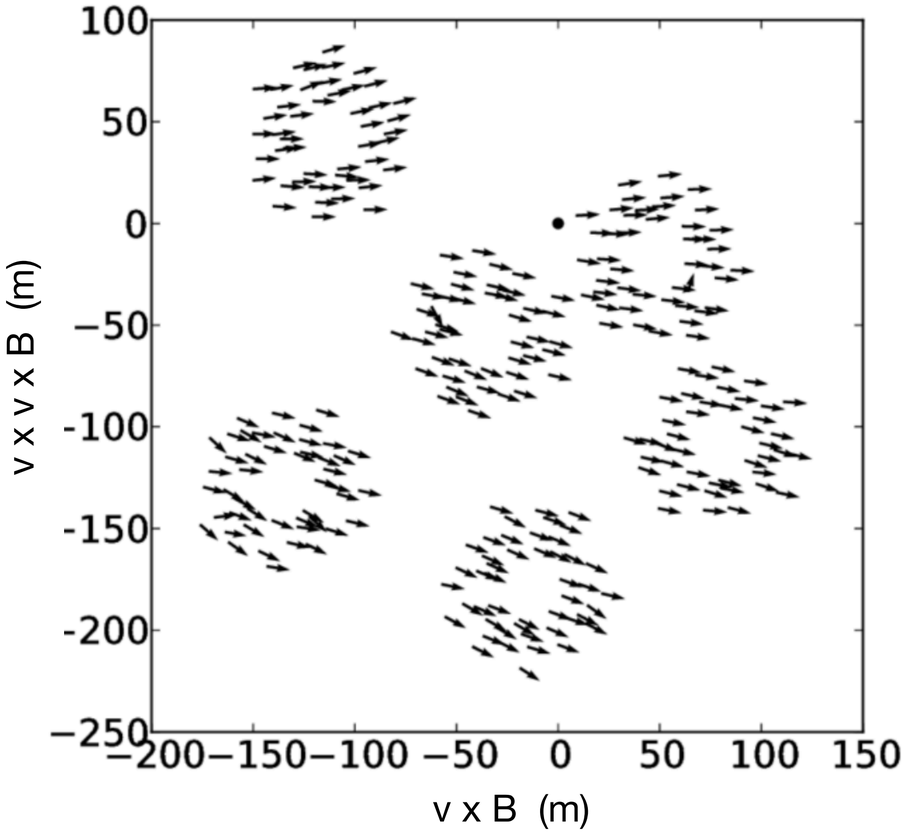
Cosmic rays at LOFAR



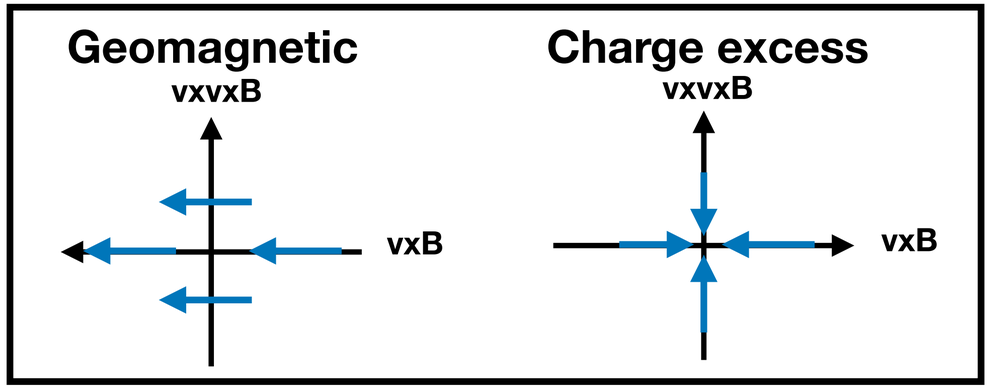


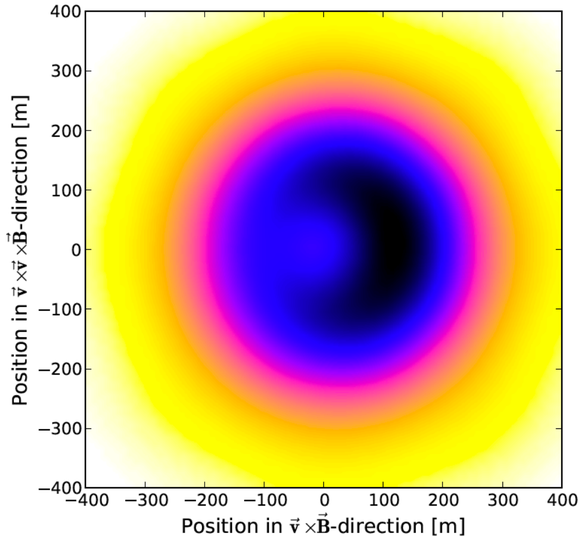


Cosmic rays at LOFAR

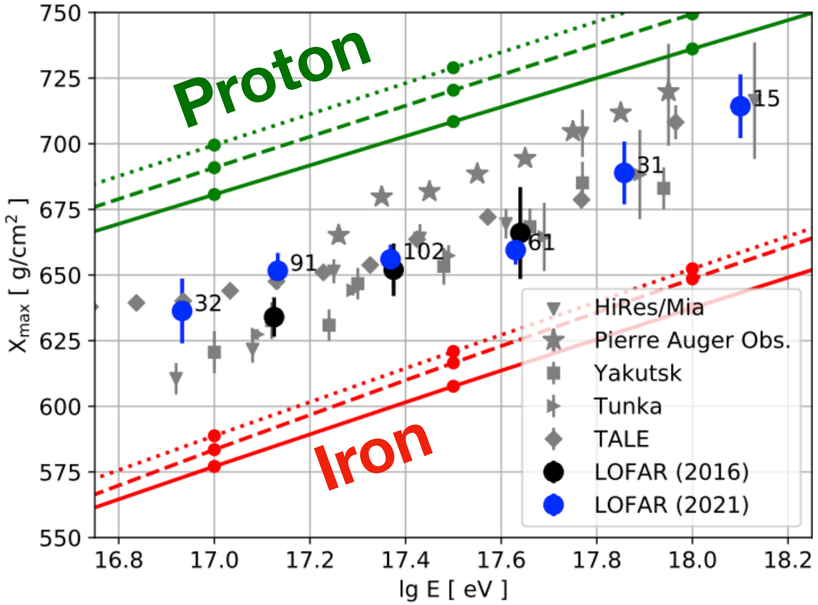


Schellart et al. JCAP, 2014.





Cosmic rays at LOFAR - Scientific highlights

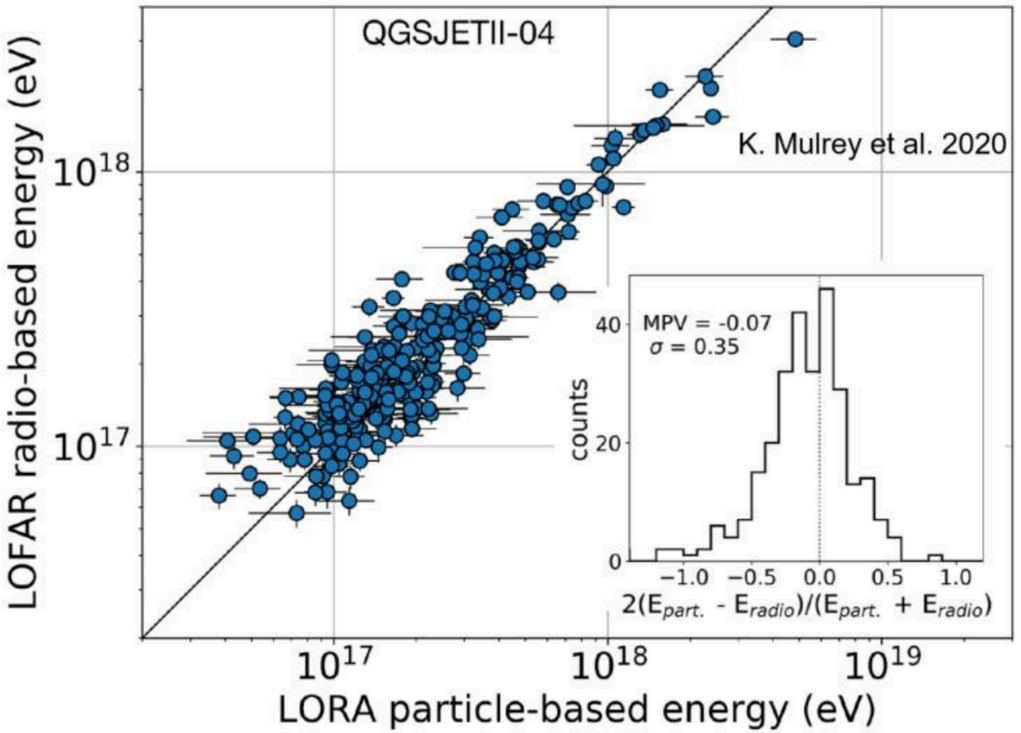


- First radio-based X_{max} reconstruction and cosmic ray composition studies - LOFAR shows a second light component of Galactic cosmic rays

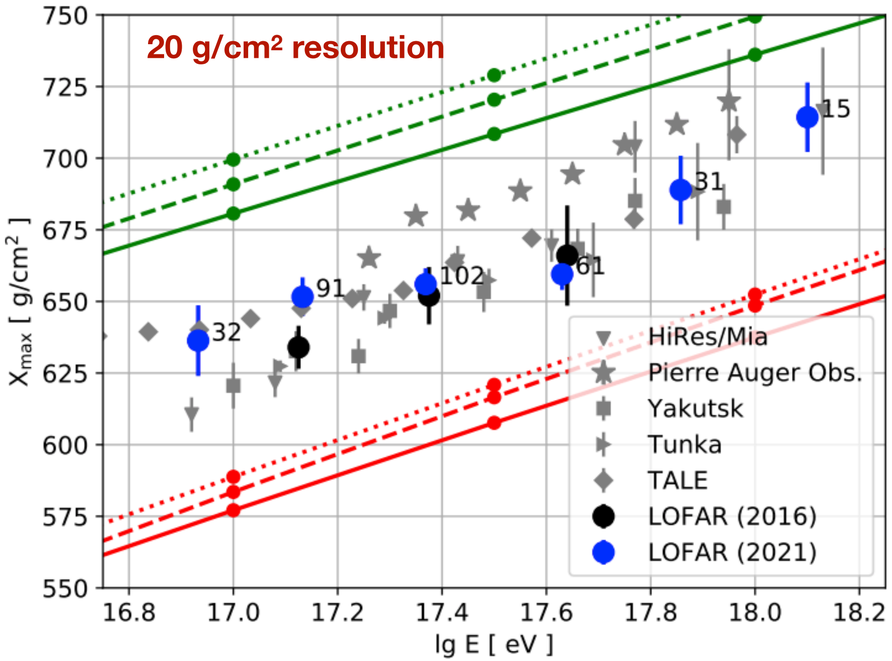
Buitink et al. Phys. Rev. D, 2014.
Buitink et al. Nature, 2016.
Corstanje et al. Phys. Rev. D. , 2021.
Mitra et al. APP, 2020.

- Radio-based energy scale derived from LOFAR observations! These have been shown to be consistent with other observatories

Mulrey et al. APP, 2019.
Mulrey et al. JCAP, 2020.



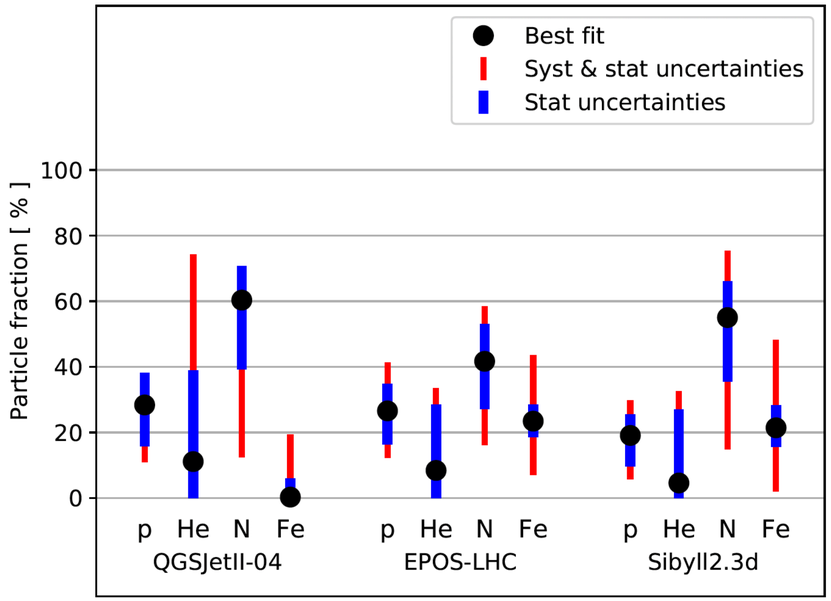
Cosmic rays at LOFAR



Buitink et al. Phys. Rev. D, 2014.

Buitink et al. Nature, 2016.

Corstanje et al. Phys. Rev. D. , 2021.



- large light mass component above SNR cutoff?
- high dependency on hadronic interaction model

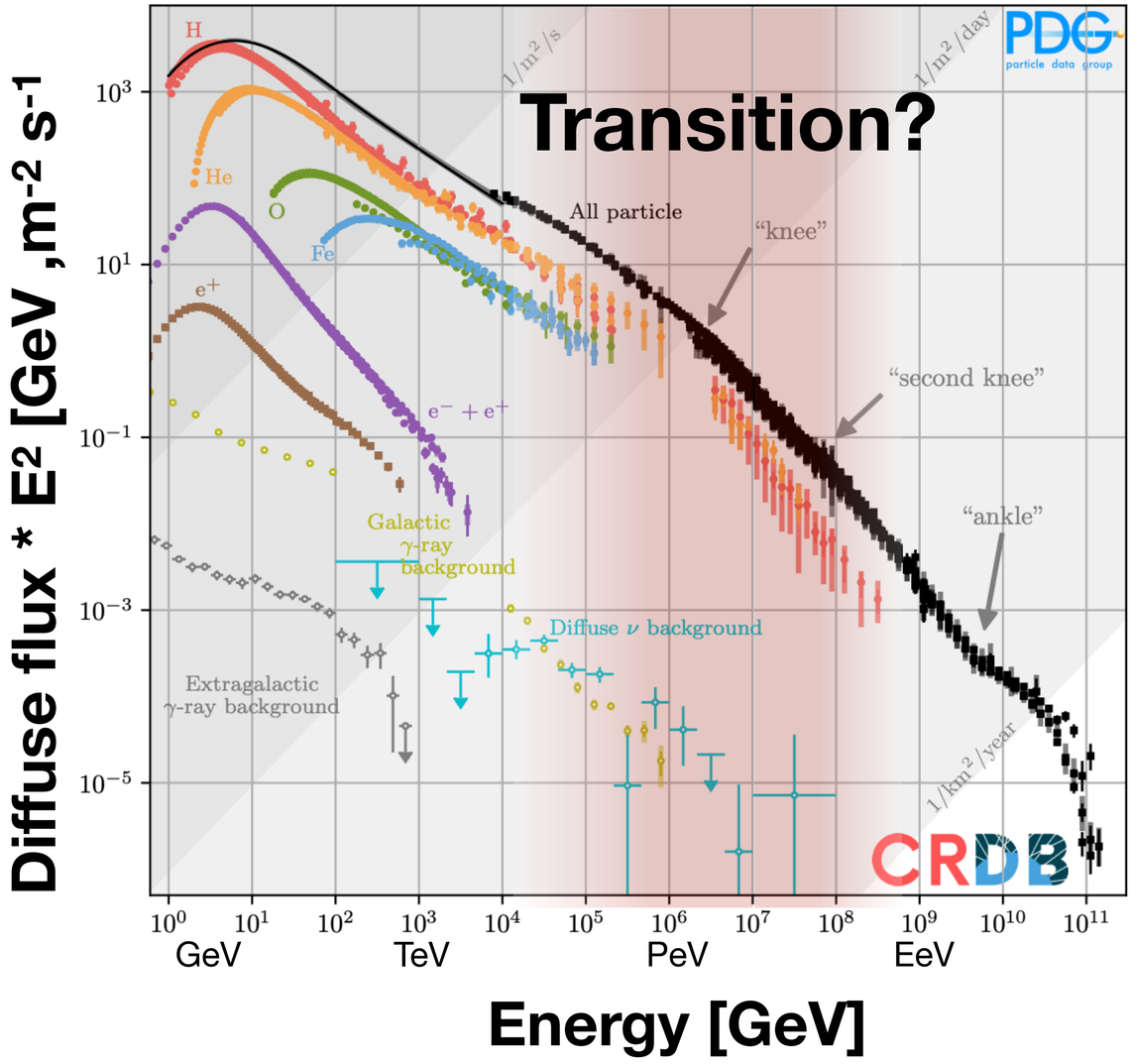
Cosmic rays at LOFAR

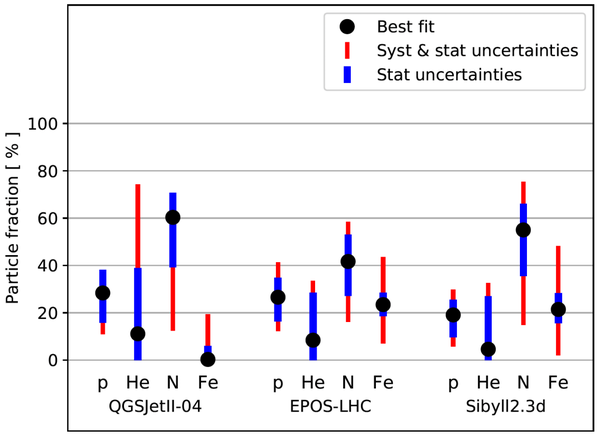




?

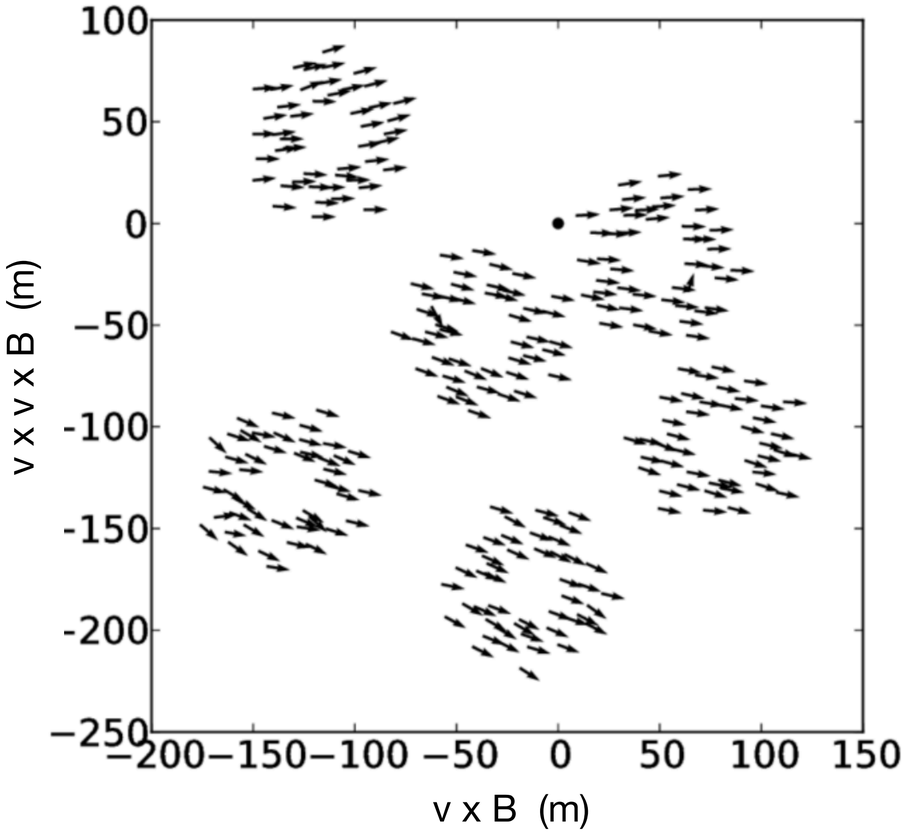




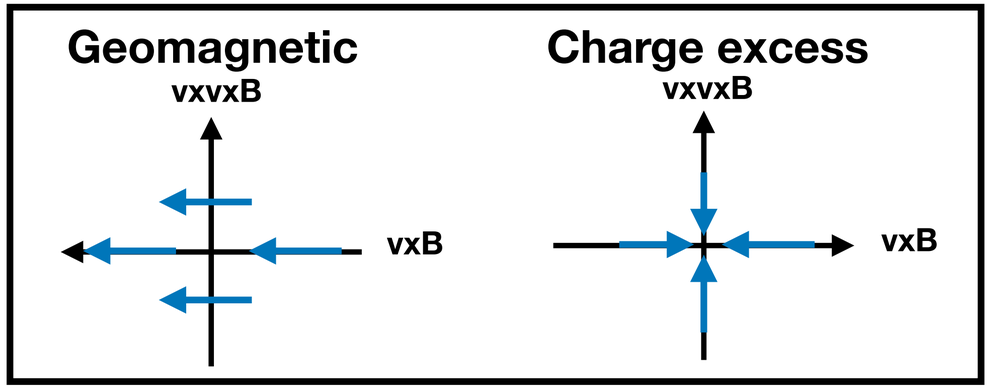


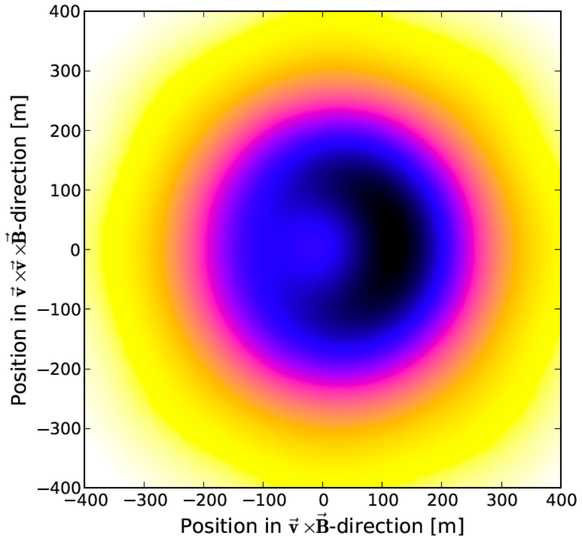
Evidence of 2nd Galactic cosmic ray component

Cosmic rays at LOFAR

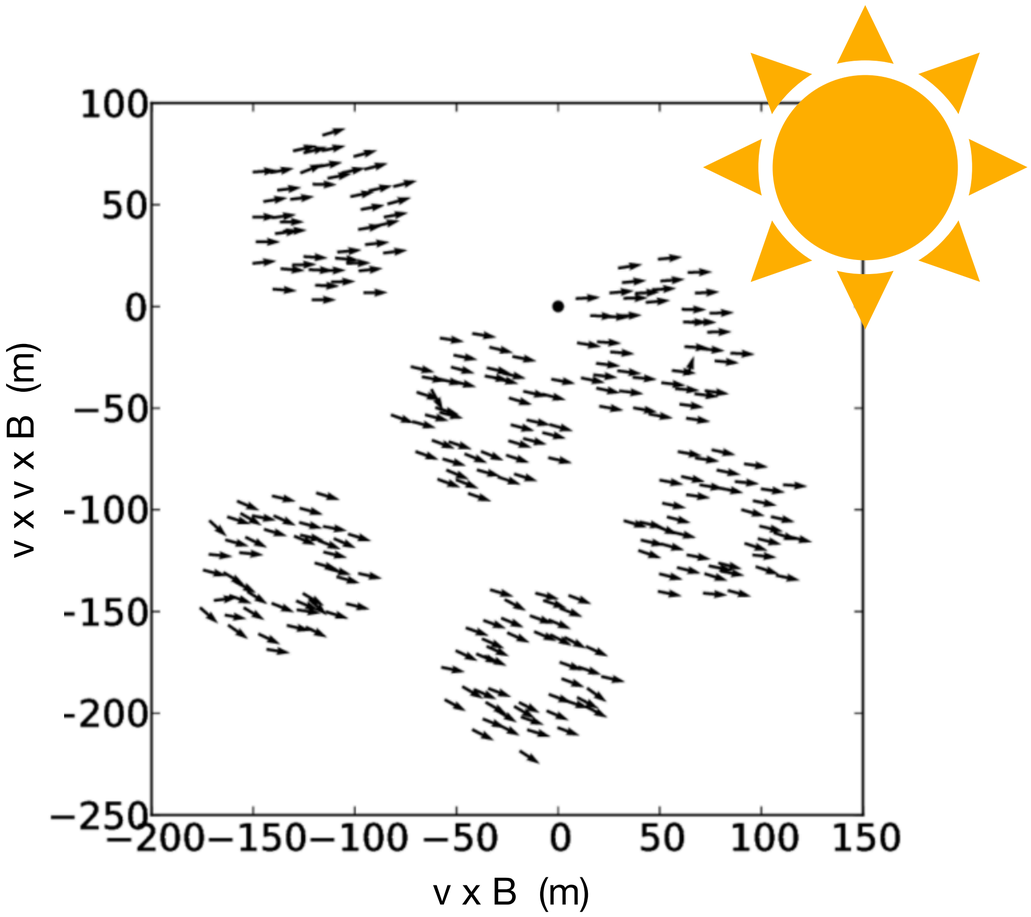


Schellart et al. JCAP, 2014.

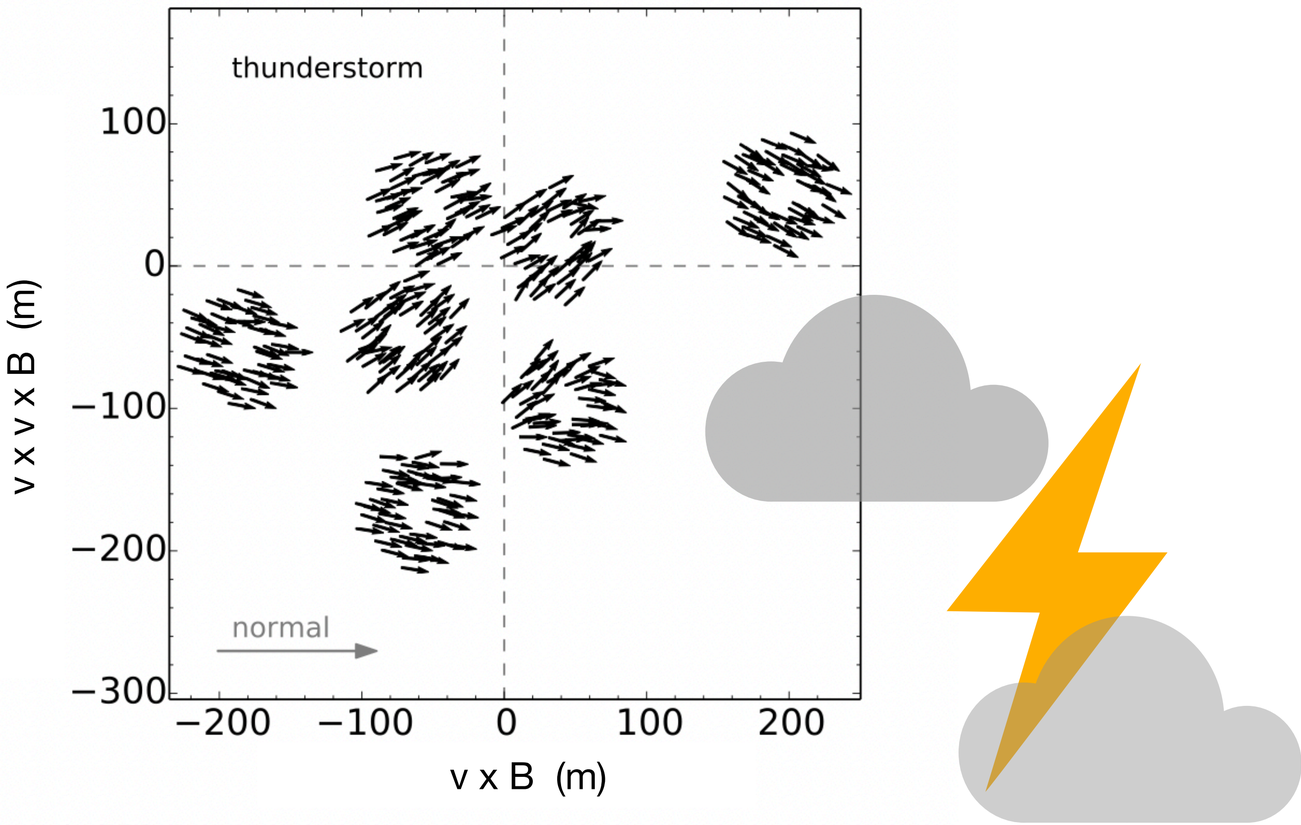




Cosmic rays at LOFAR

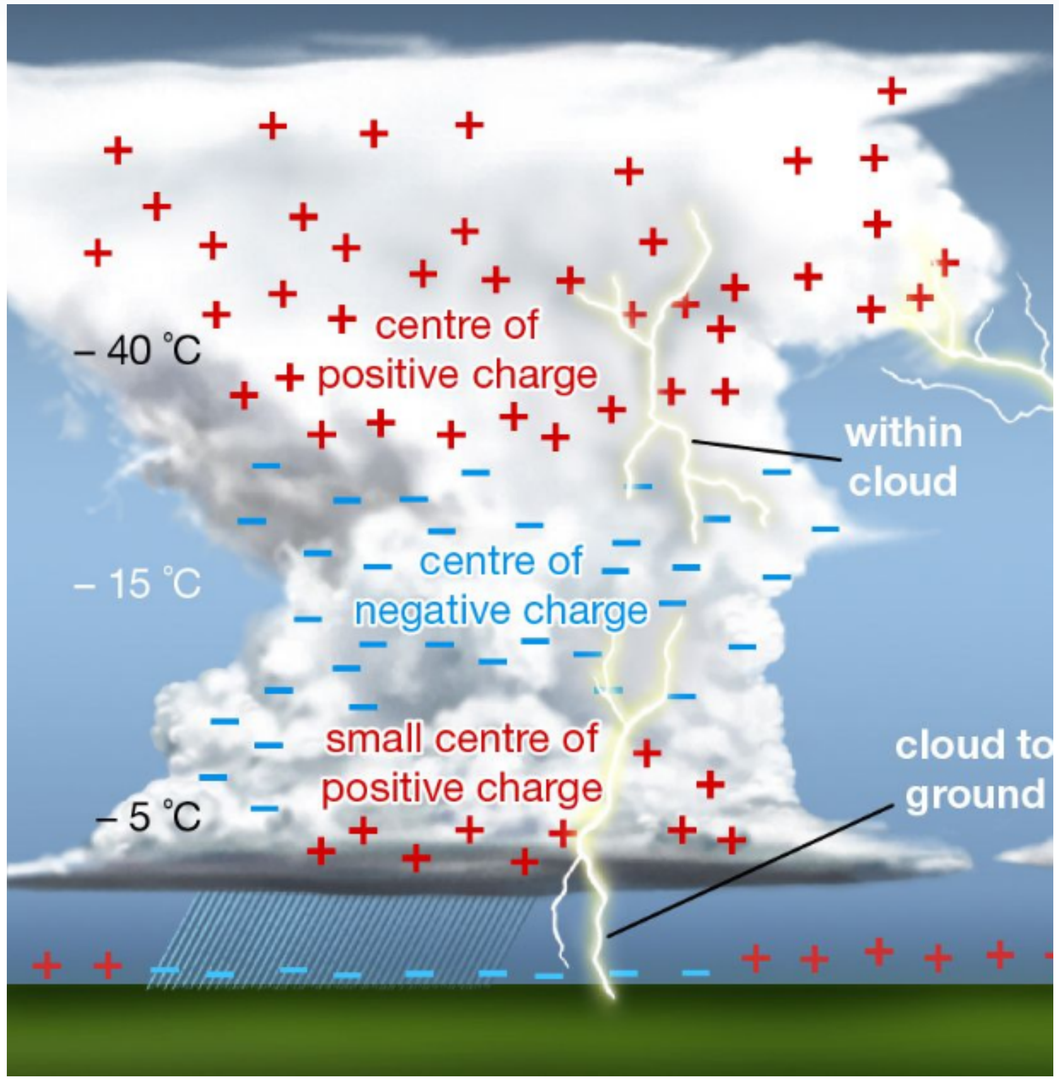


Schellart et al. JCAP, 2014.



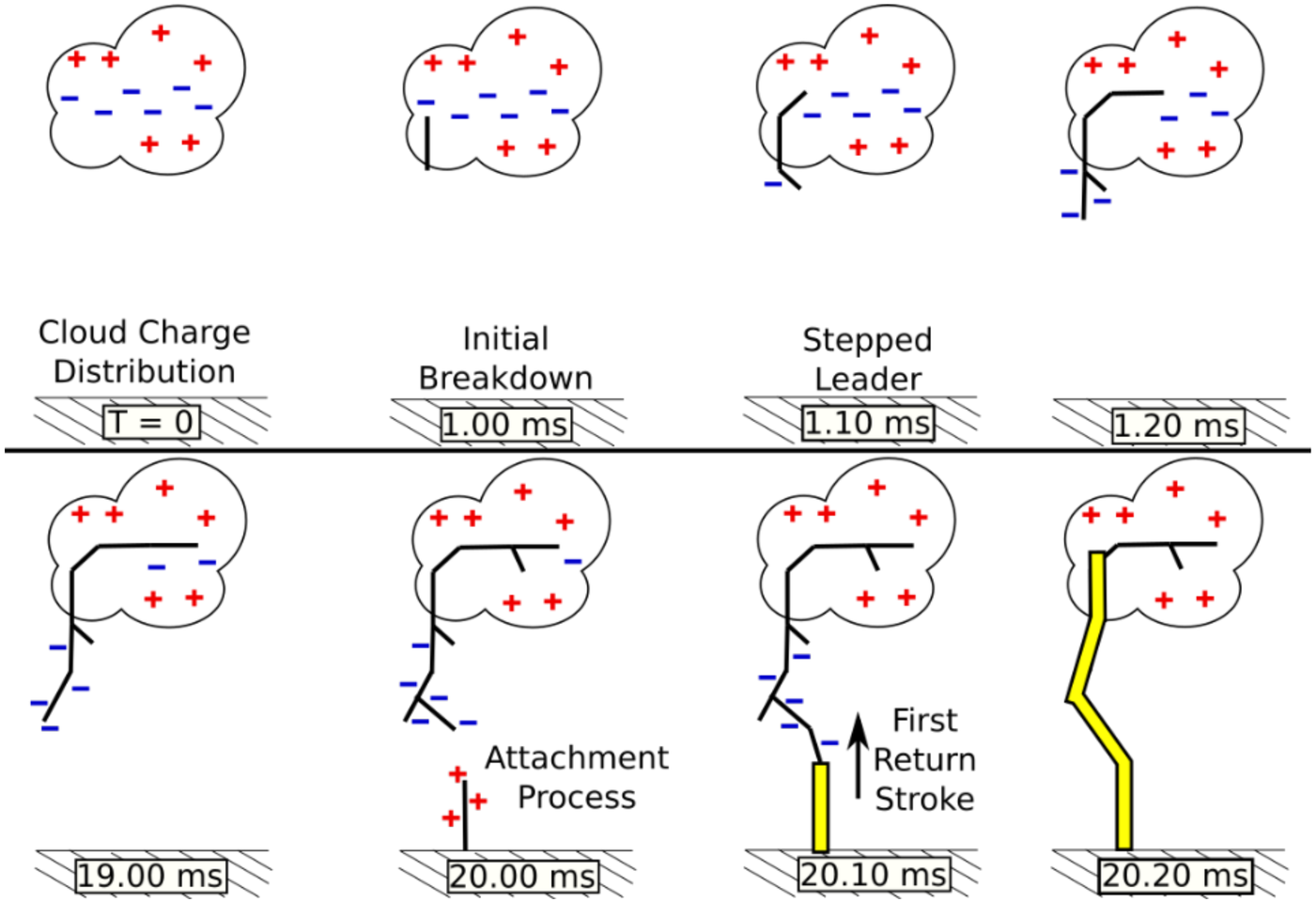
G. Trinh et al., PRD **95** 083004 (2017)

Thundercloud Structure

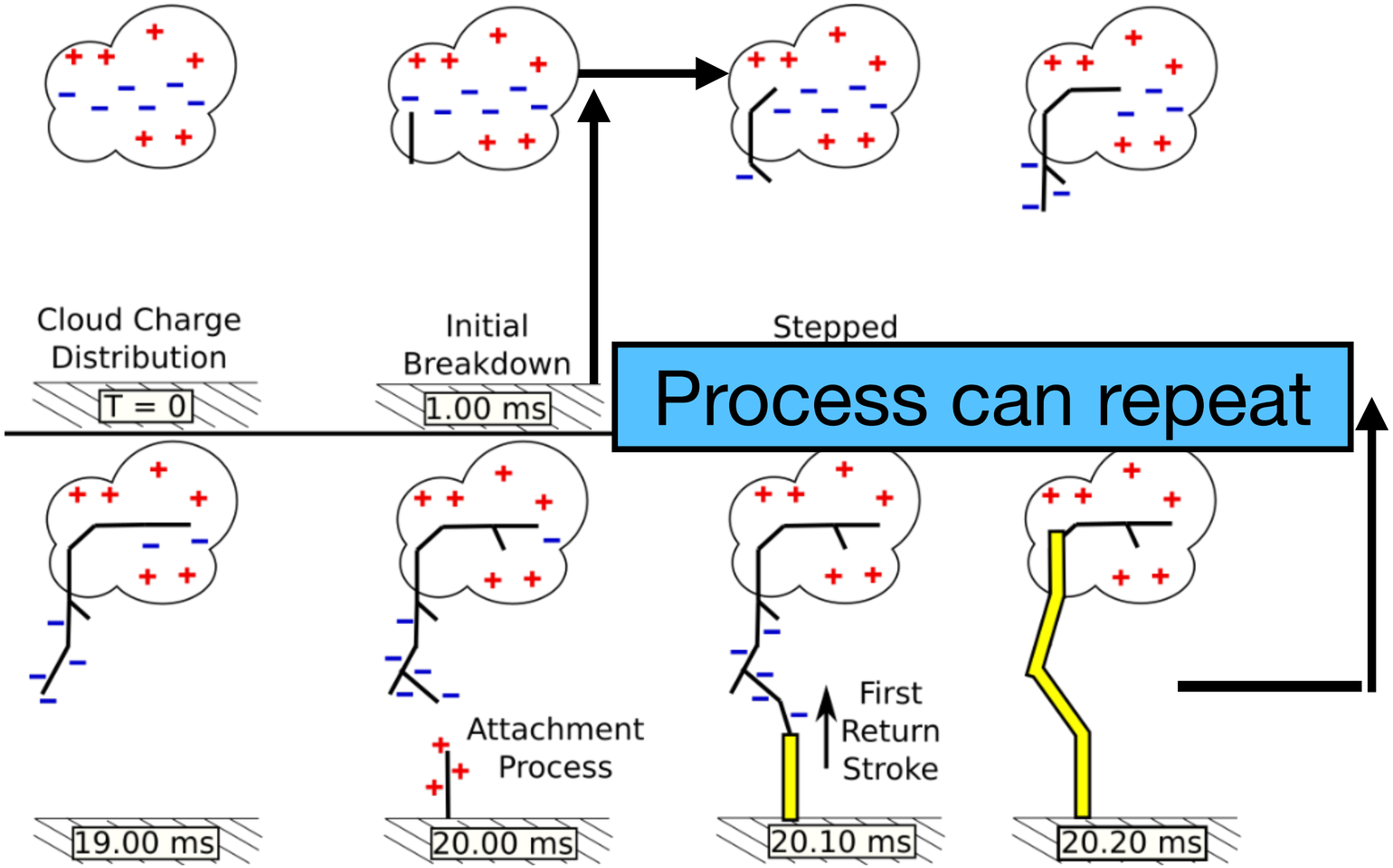


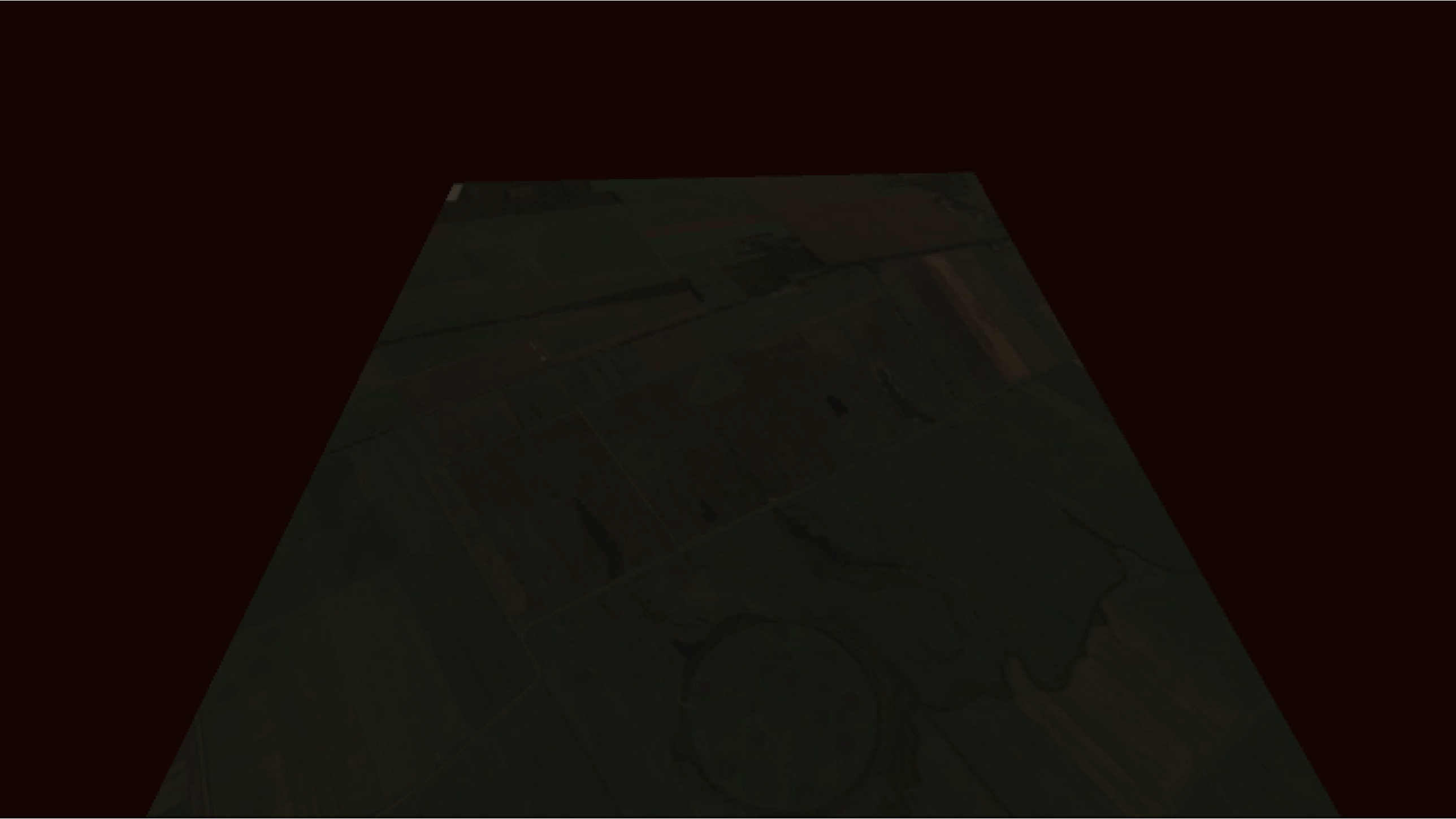
- Charge in thundercloud forms a tri-pole structure
  - Strong upper positive
  - Strong center negative
  - Weak/ non-extant lower positive
- Dutch Storms are upside-down
  - Weak/ non-extant *upper* positive
  - Strong *lower* positive
- Two main categories of lightning
  - IC
    - Does not go to ground
    - 80-90% of all lightning
  - CG
    - Cloud to ground
    - 10-20% of all lightning
- Dutch thunderstorms *probably* has higher fraction IC lightning

Lightning initiation

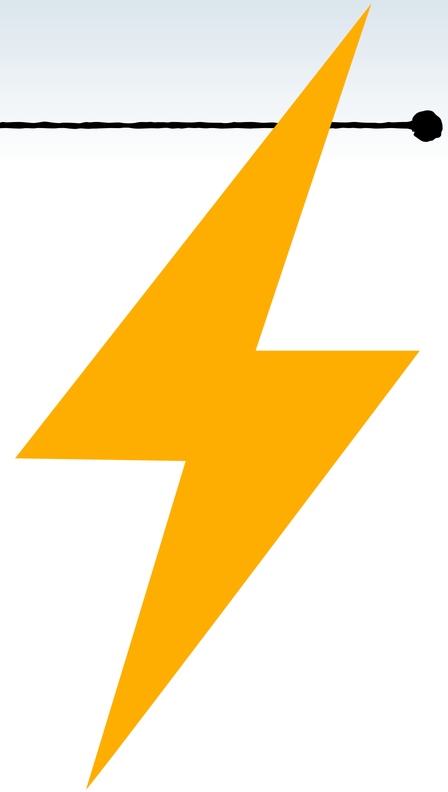


Lightning initiation



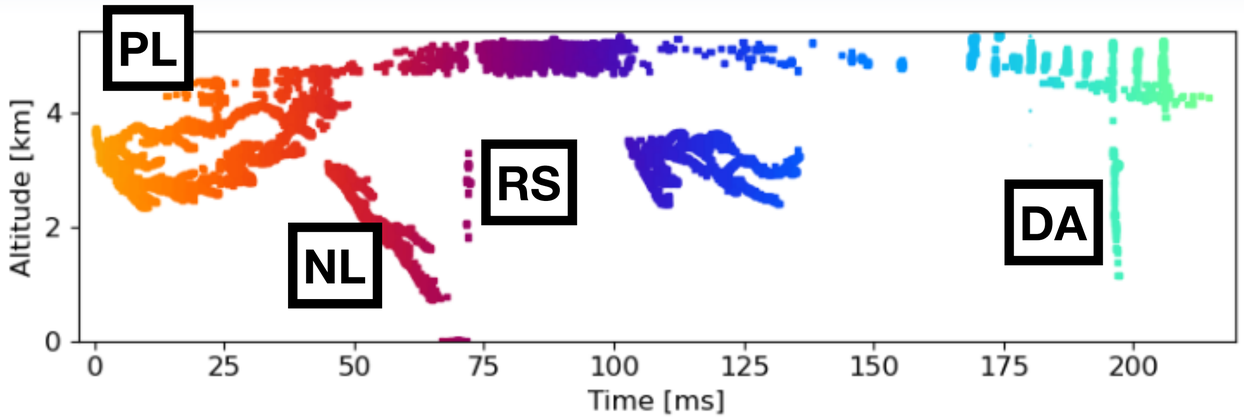


The Big Questions in Lightning

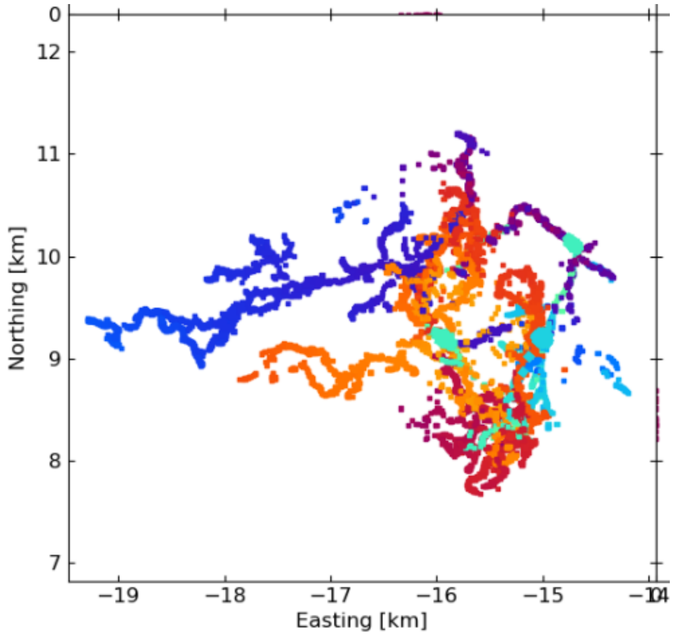


- How does lightning get started?
  - Measured electric fields are too small to make a spark via typical mechanisms
- How does lightning grow?
  - The plasma physics is extremely complex, and too complicated for current computers to model
- How does lightning emit gamma rays?
  - This strongly depends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

Lightning imaging with LOFAR



PL - Positive leader
NL - Negative leader
RS - Return stroke
DA - Dart leader



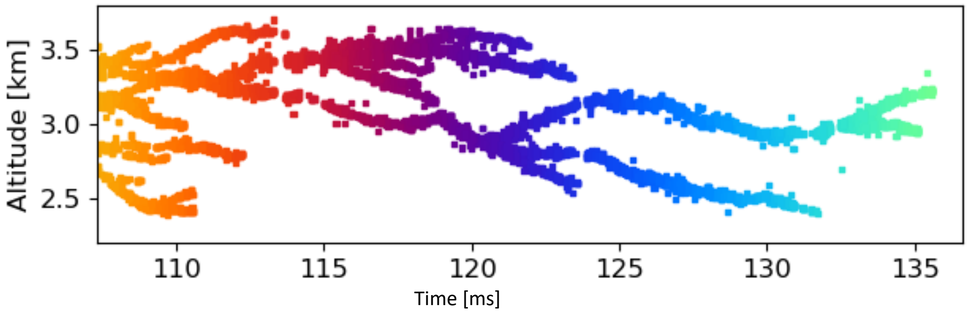
Lightning flash imaged with “impulsive techniques” (TOA)
-CPU efficient, not as good as interferometry

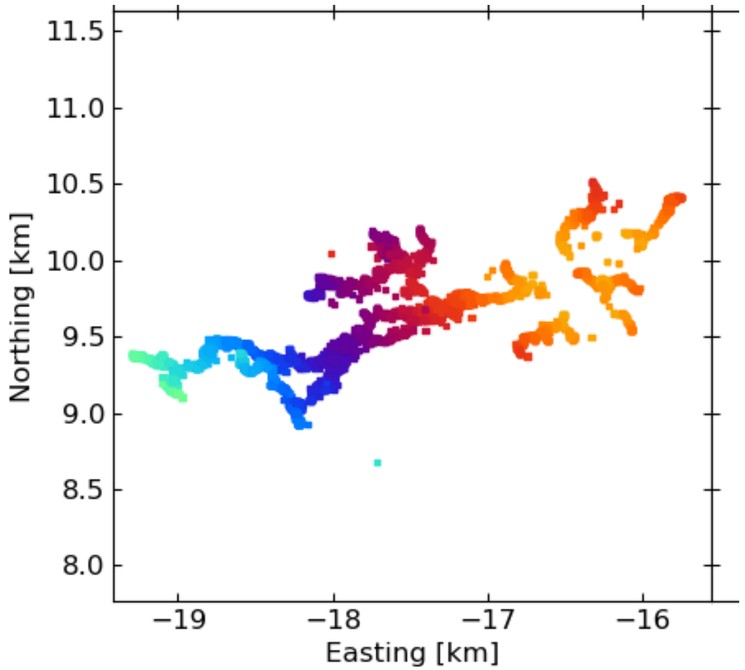
65,200 sources after cuts
≈ 300 sources per ms

Horizontal accuracy around 1 m
-limited by source-confusion

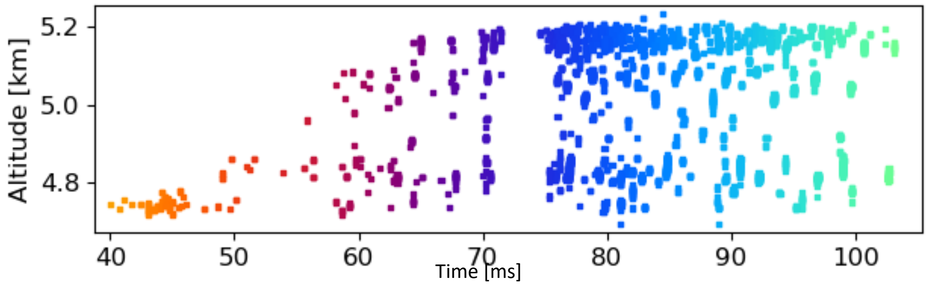
Positive vs Negative Charged Channels

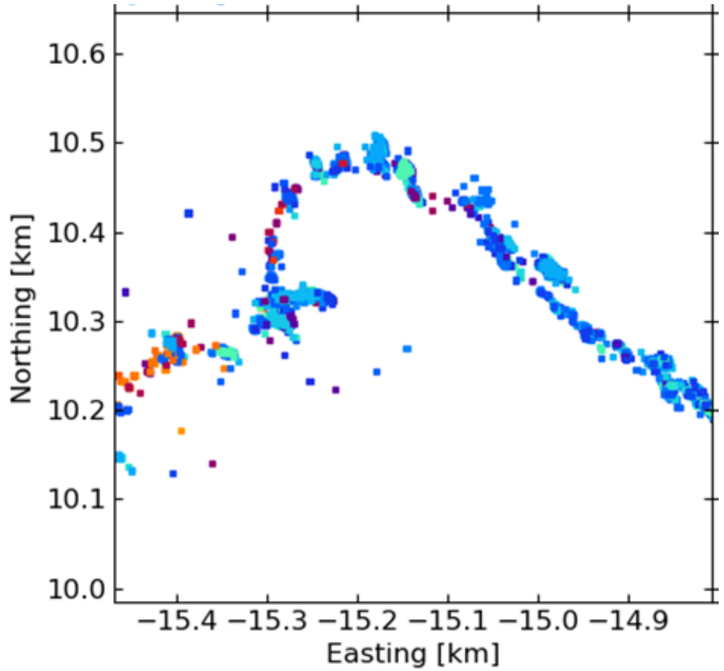
Negative Lightning Channels





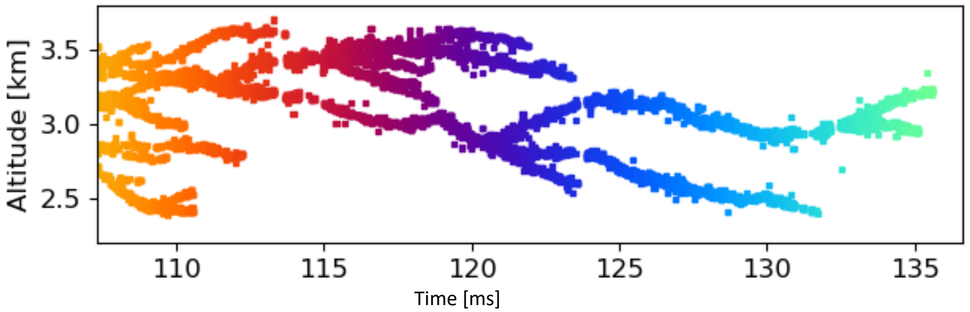
Positive Lightning Channels

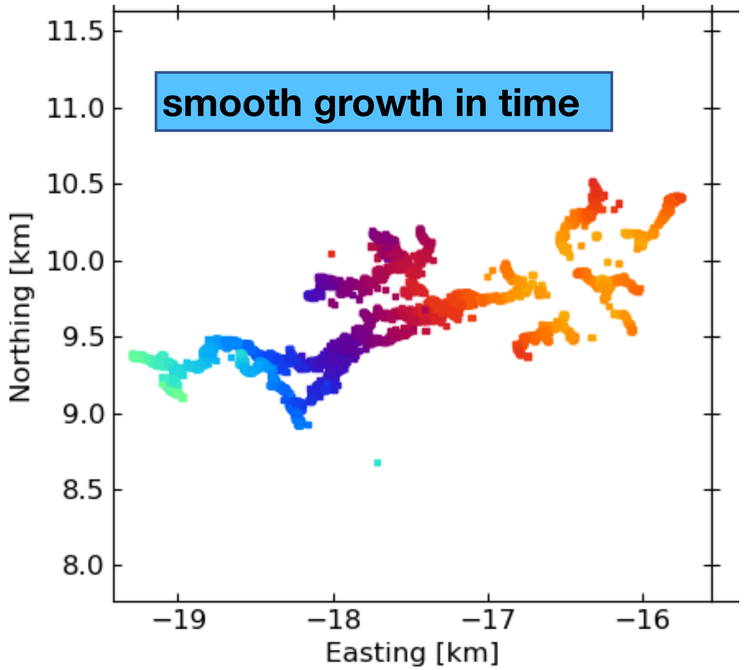




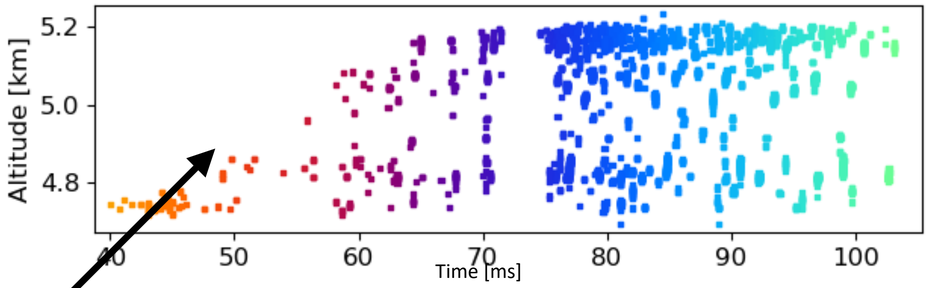
Positive vs Negative Charged Channels

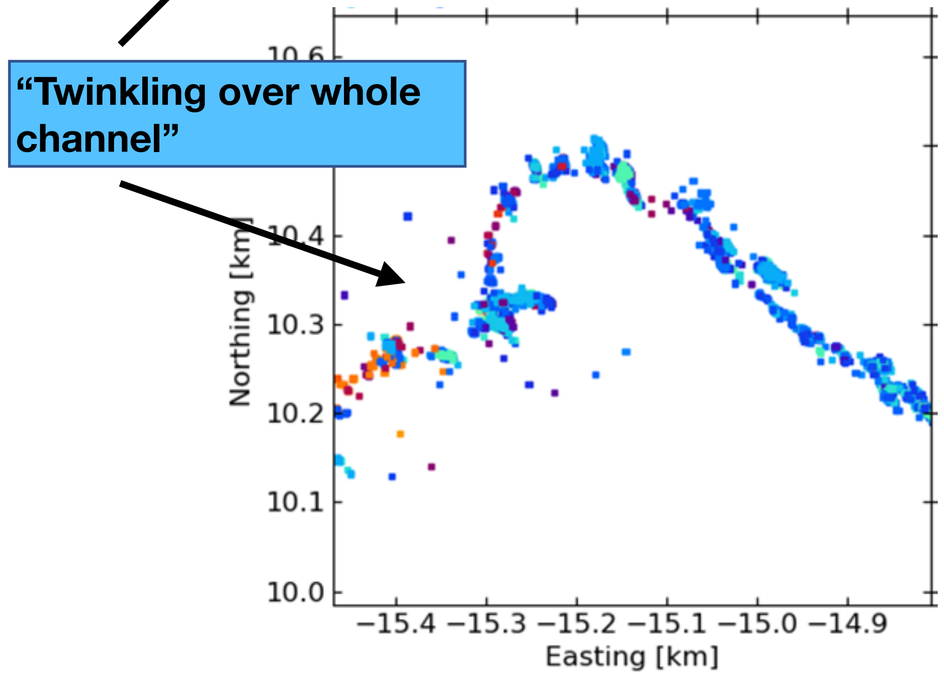
Negative Lightning Channels





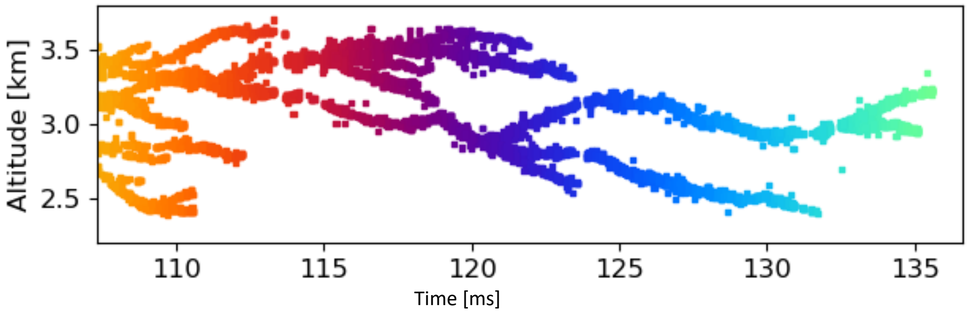
Positive Lightning Channels

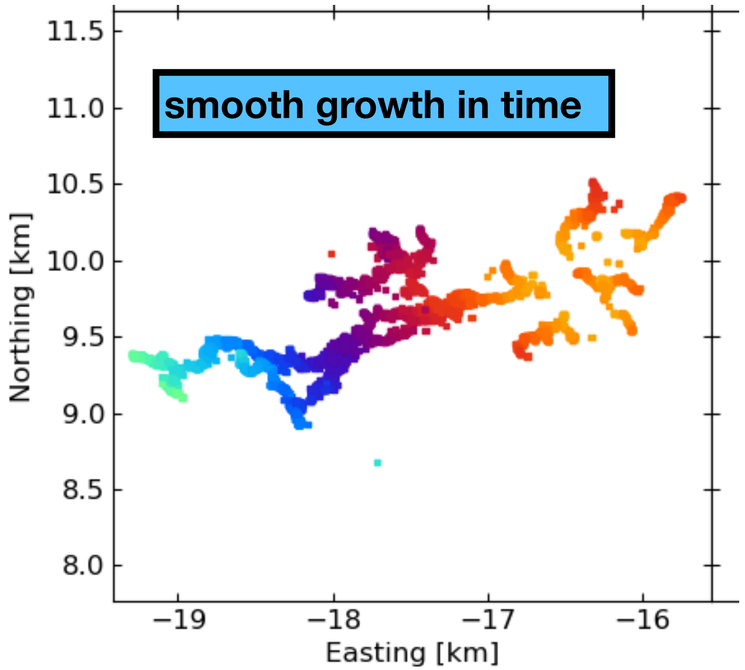




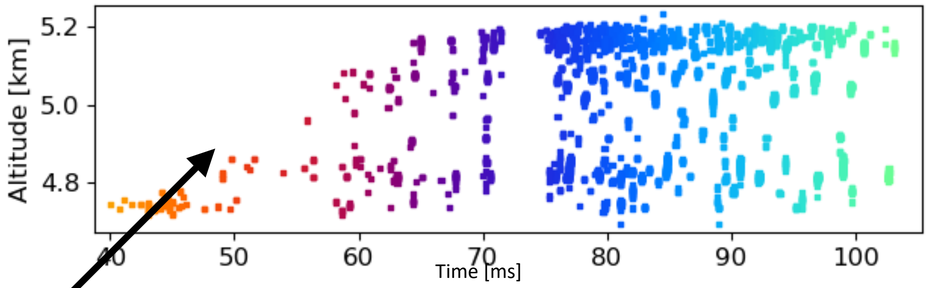
Positive vs Negative Charged Channels

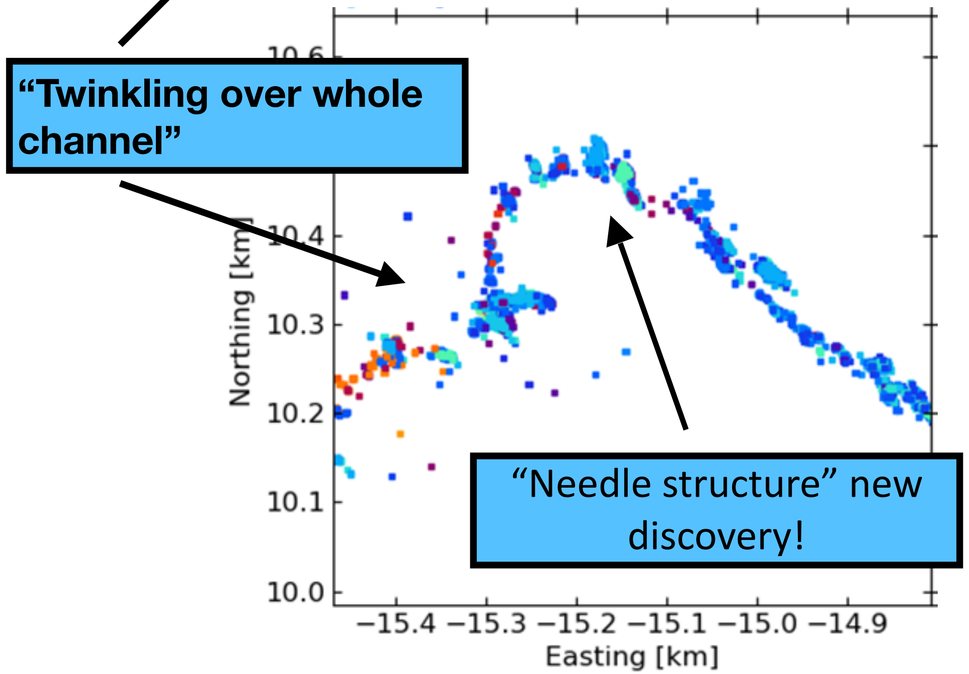
Negative Lightning Channels





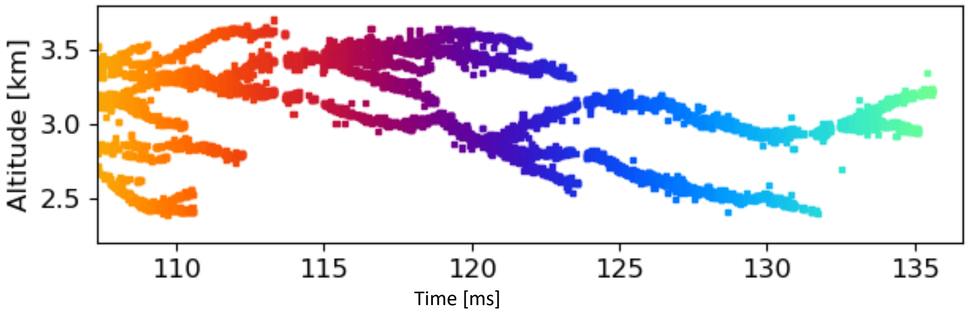
Positive Lightning Channels

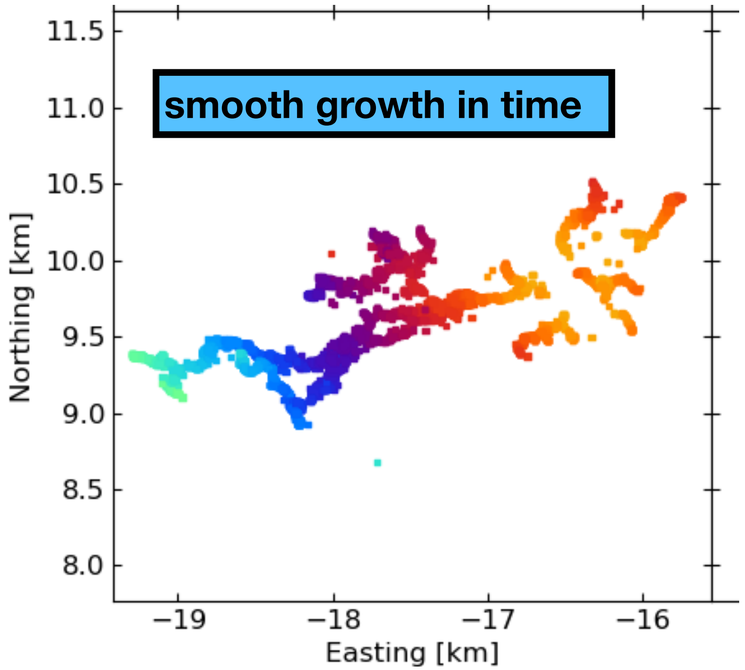




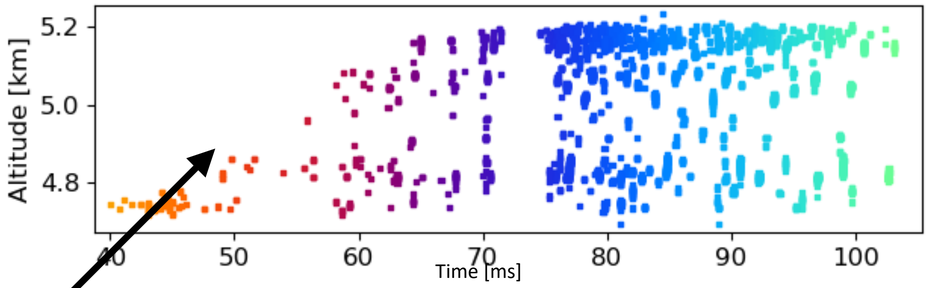
Positive vs Negative Charged Channels

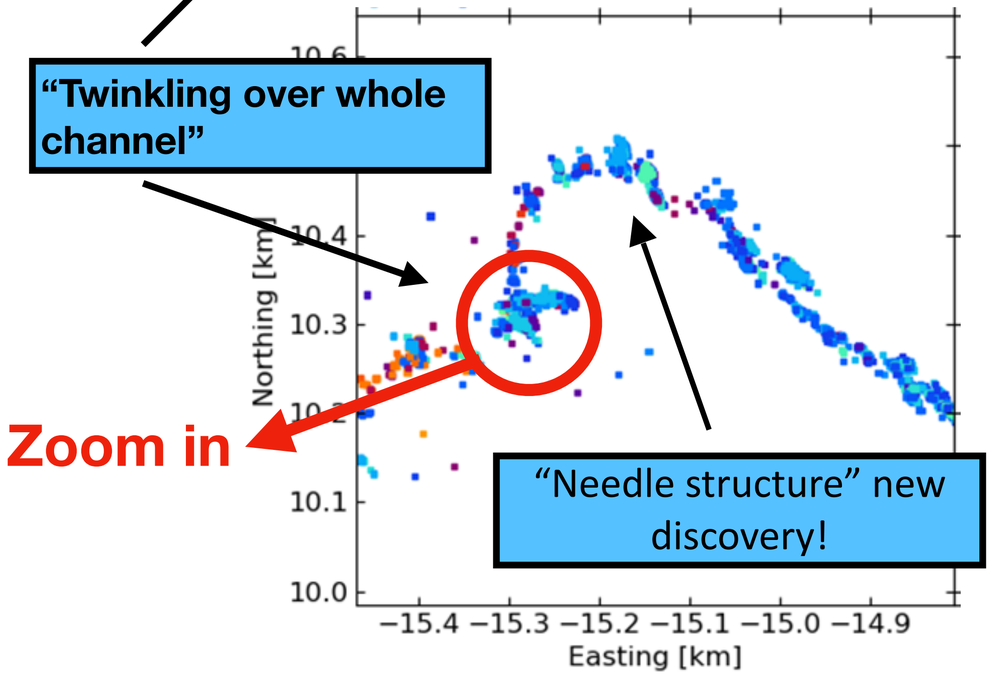
Negative Lightning Channels





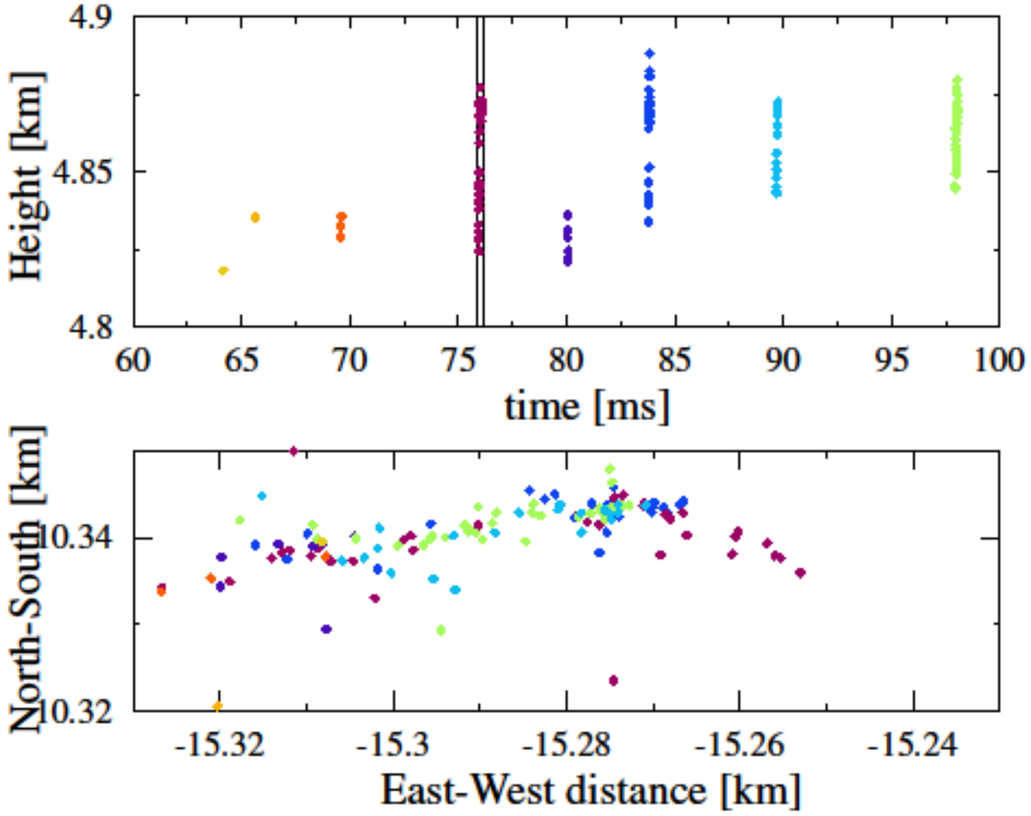
Positive Lightning Channels



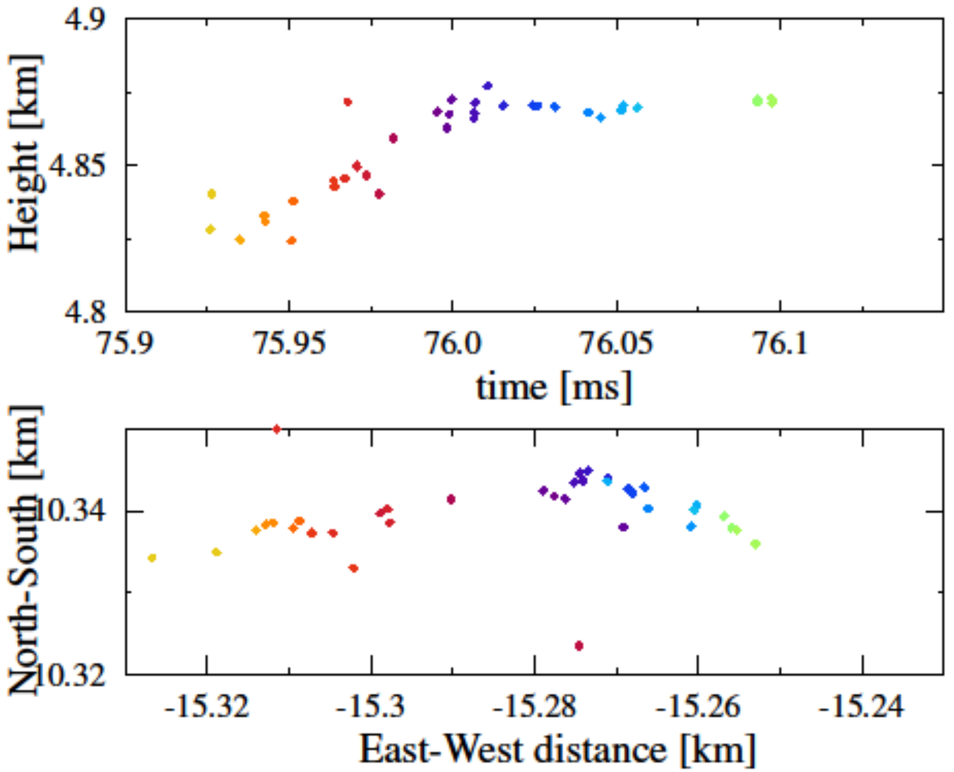


Positive vs Negative Charged Channels

One flickering positive leader structure



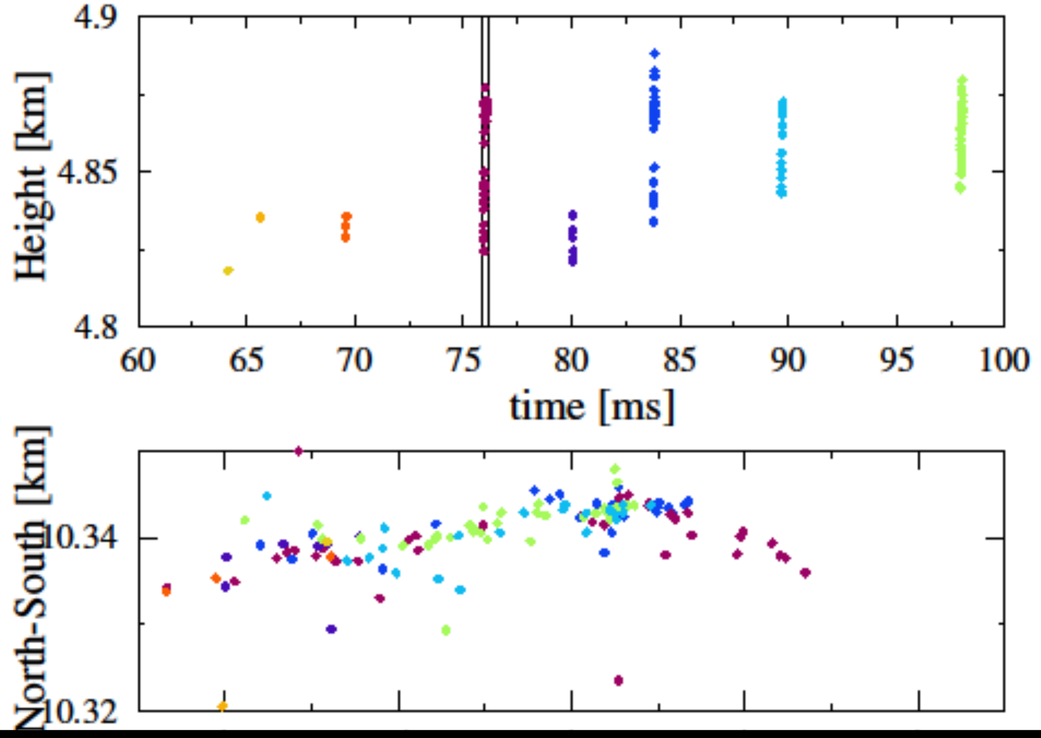
Time zoom-in



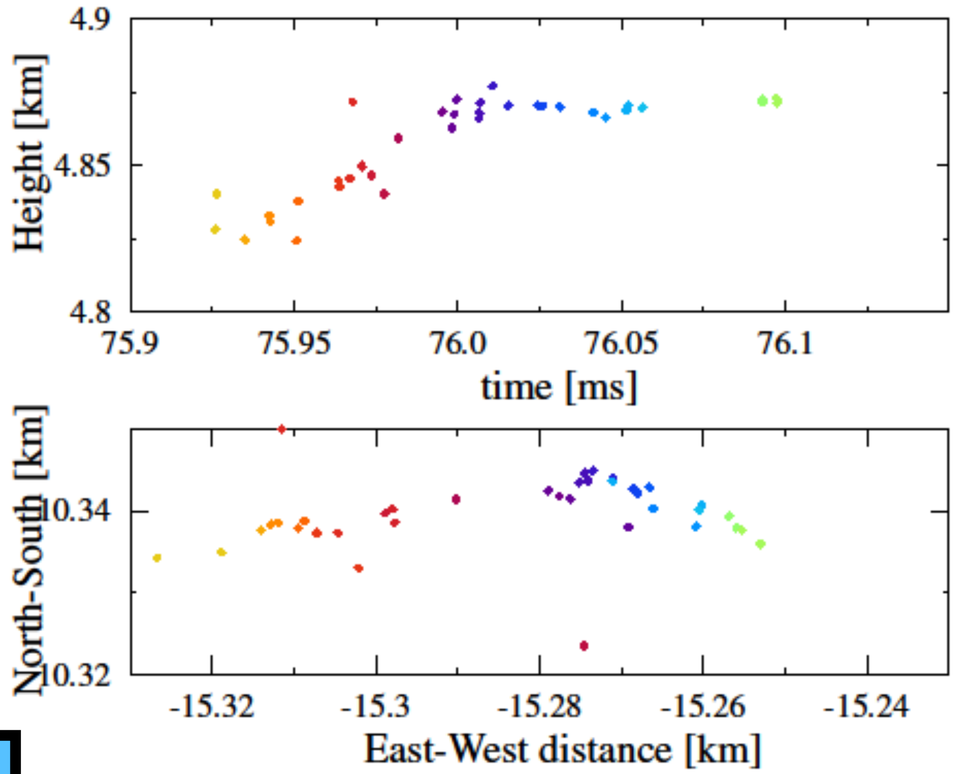
Positive Leader channel to the West

Positive vs Negative Charged Channels

One flickering positive leader structure



Time zoom-in

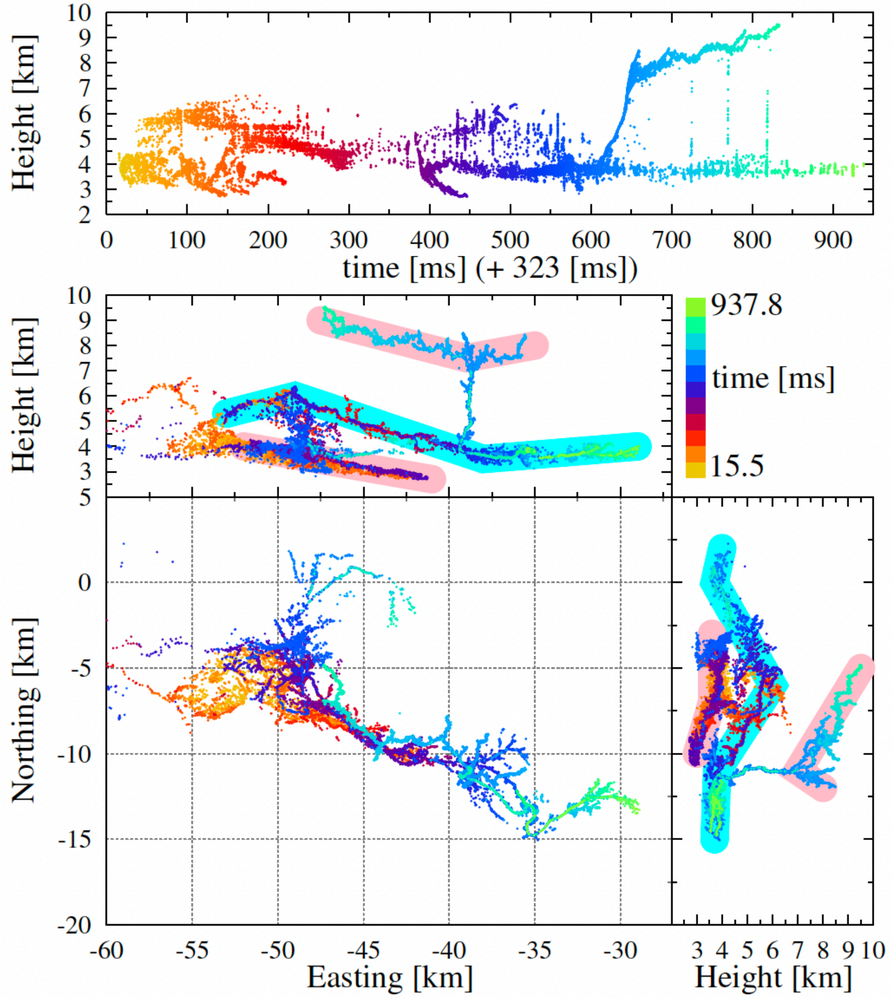


RESULT:
negative propagation away from positive channel !!!

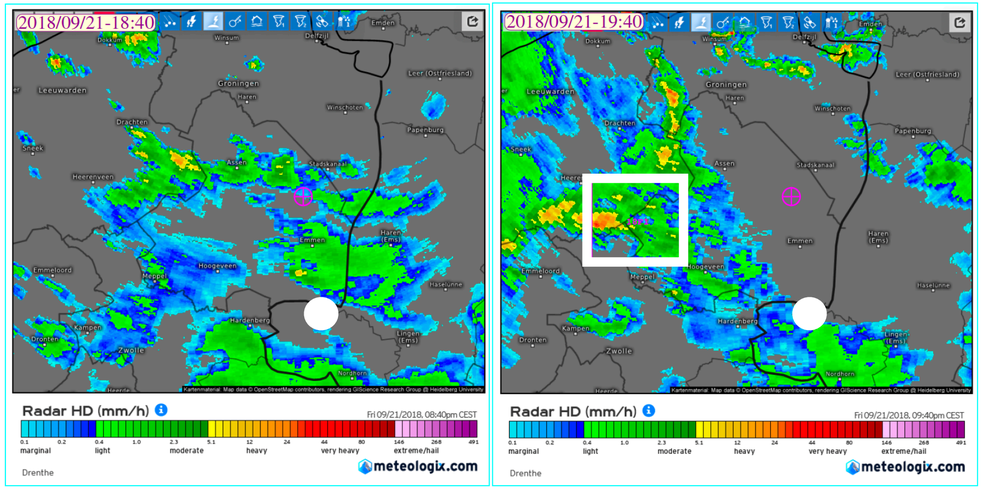
Published in Nature

l to the West ←

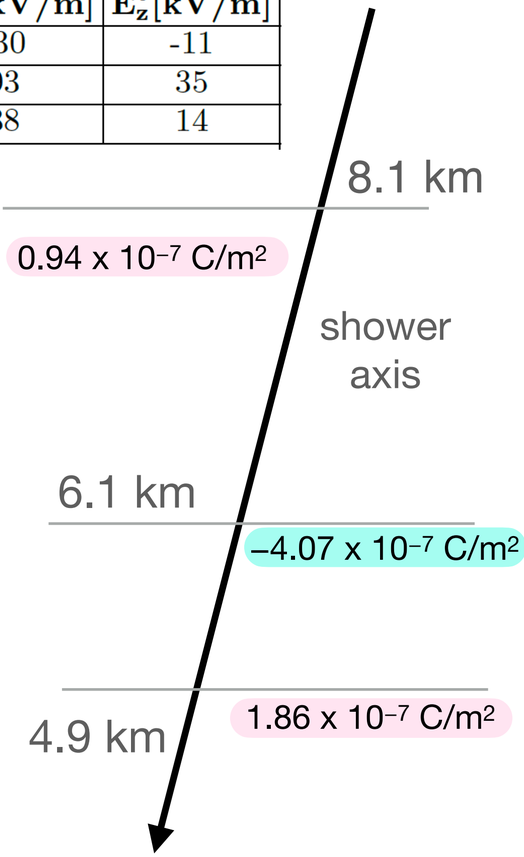
Cosmic rays at LOFAR … & lightning



Layer	h [km]	E [kV/m]	E_{vxz} [kV/m]	$E_{vx[vxz]}$ [kV/m]	E_z^m [kV/m]	E_z^0[kV/m]
1	8.1	45	41	18	-30	-11
2	6.1	58	-12	-57	93	35
3	4.9	52	-47	-23	38	14



T.N.G. Trinh et al., in prep (2024)



Cosmic rays at LOFAR … & lightning

Next topic: how do we process buffered data to do cosmic ray and lightning analyses?

