Science Highlights of LOFAR: From Cosmic Rays to the Early Universe

Heino Falcke

Radboud University Nijmegen
ASTRON, Dwingeloo
MPIfR Bonn

International LOFAR Telescope (ILT)

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- *50 operational stations completed*
- *38 NL stations, 12 international stations*
- *Includes 3 new stations in Poland*
- *Ireland station coming this year*

Yesterday Irish minister announced 1.4 M€ for Irish LOFAR station!!

LOFAR core from space

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LOFAR core from Space

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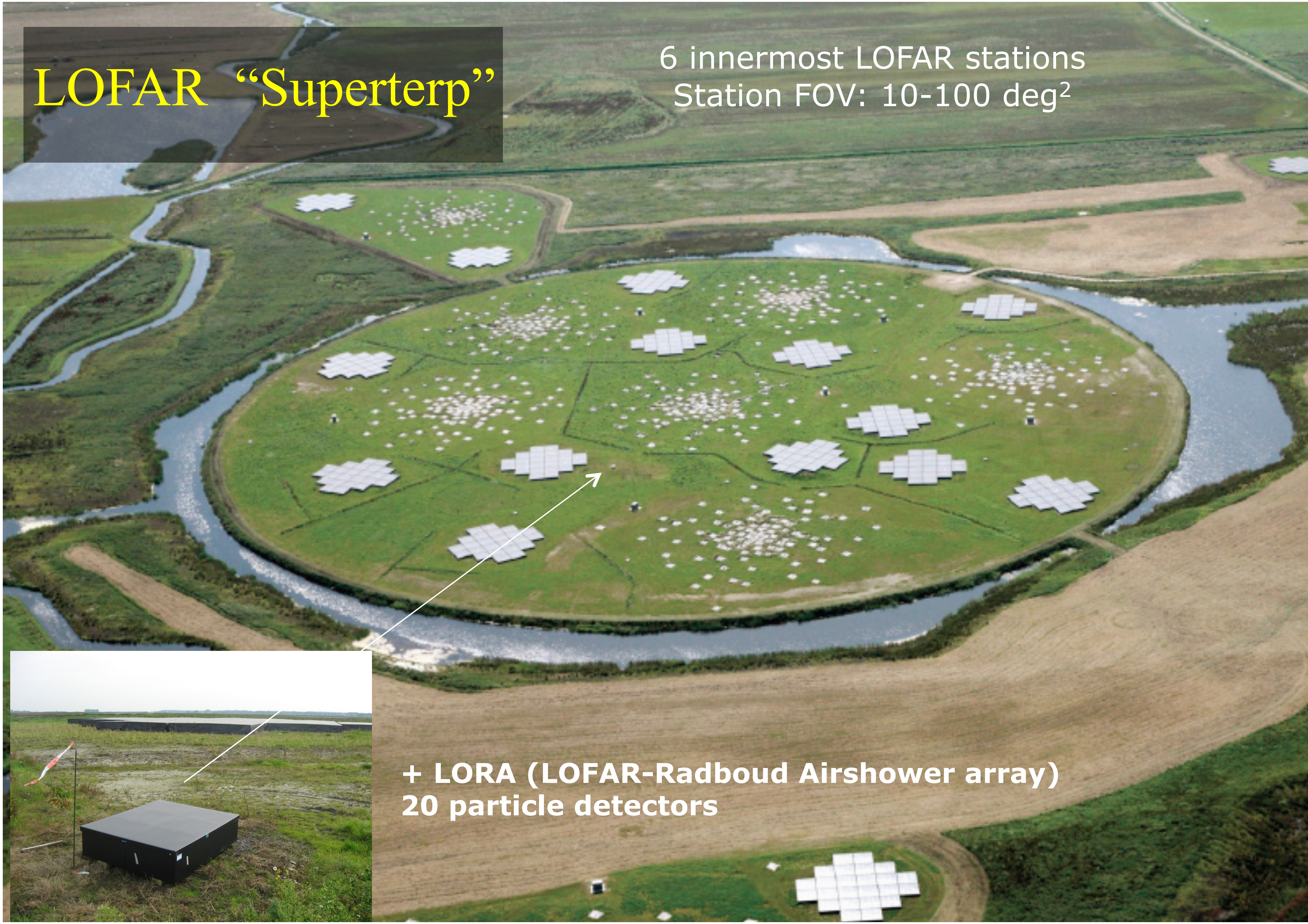
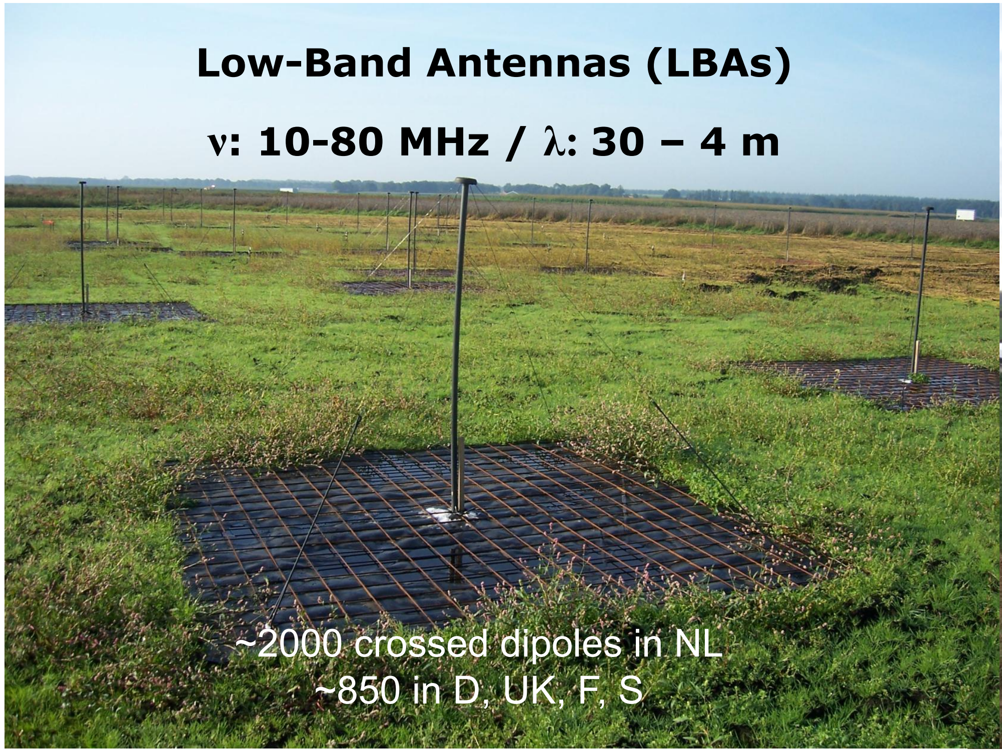
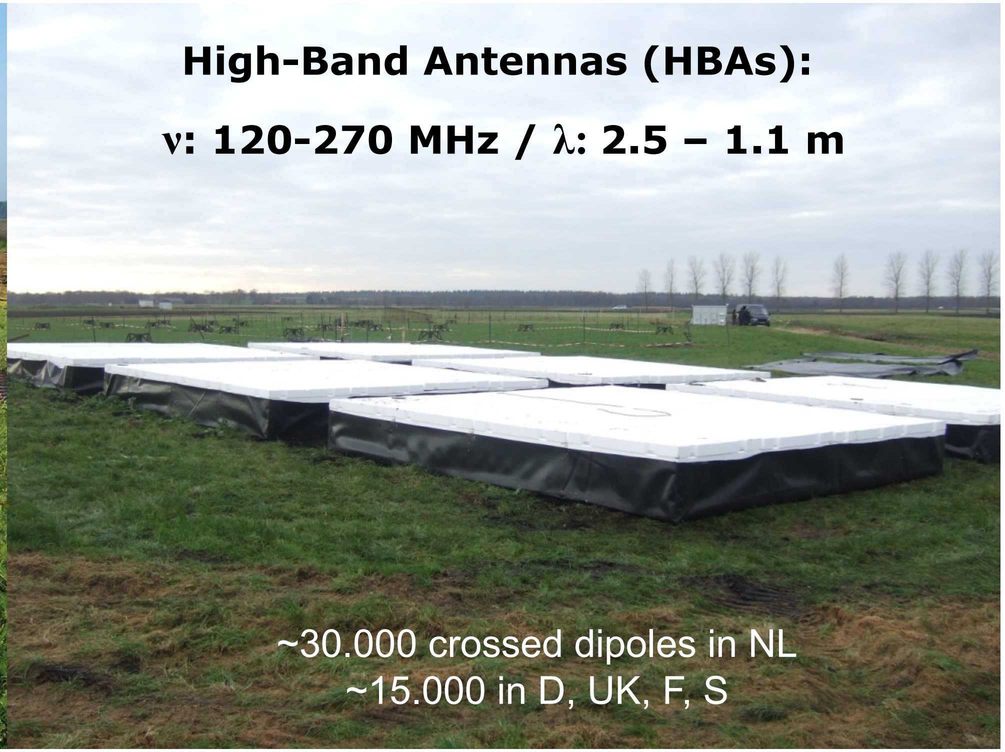
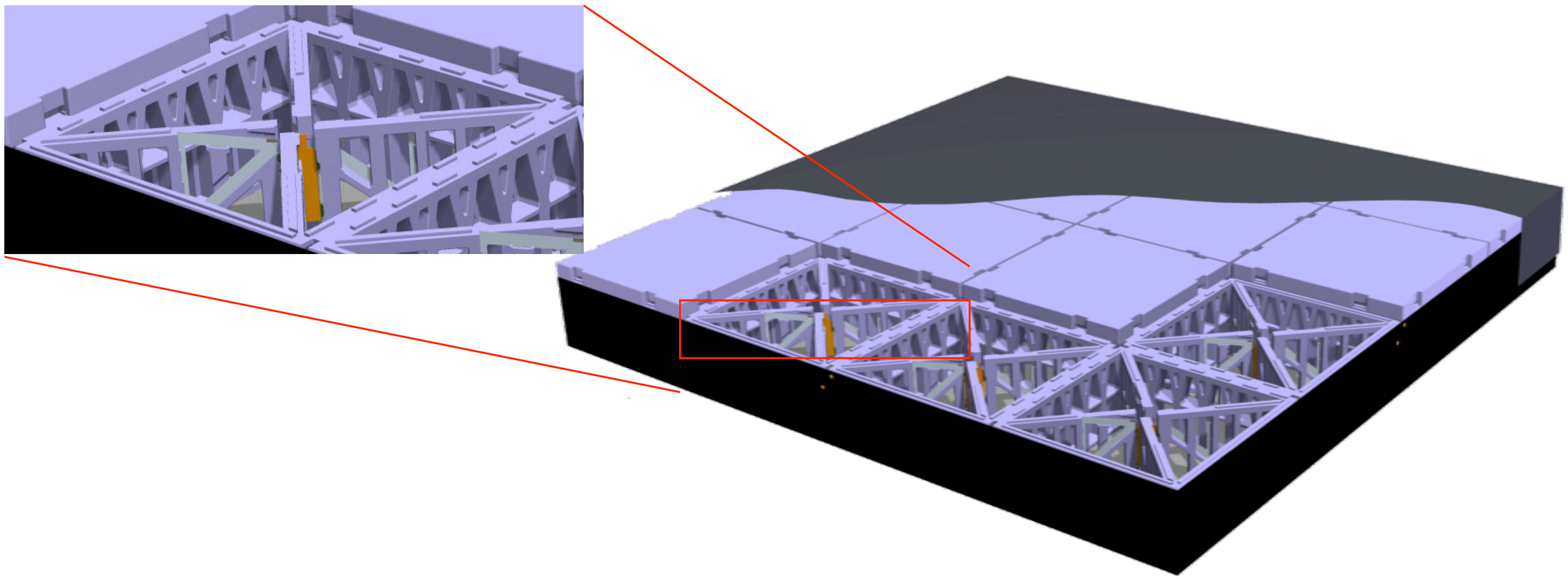

LOFAR “Superterp”
6 innermost LOFAR stations
Station FOV: 10-100 deg²
+ LORA (LOFAR-Radboud Airshower array)
20 particle detectors


Low-Band Antennas (LBAs)
ν: 10-80 MHz / λ: 30 – 4 m
~2000 crossed dipoles in NL
~850 in D, UK, F, S


High-Band Antennas (HBAs):
ν: 120-270 MHz / λ: 2.5 – 1.1 m
~30.000 crossed dipoles in NL
~15.000 in D, UK, F, S



Hamburg/Norderstedt

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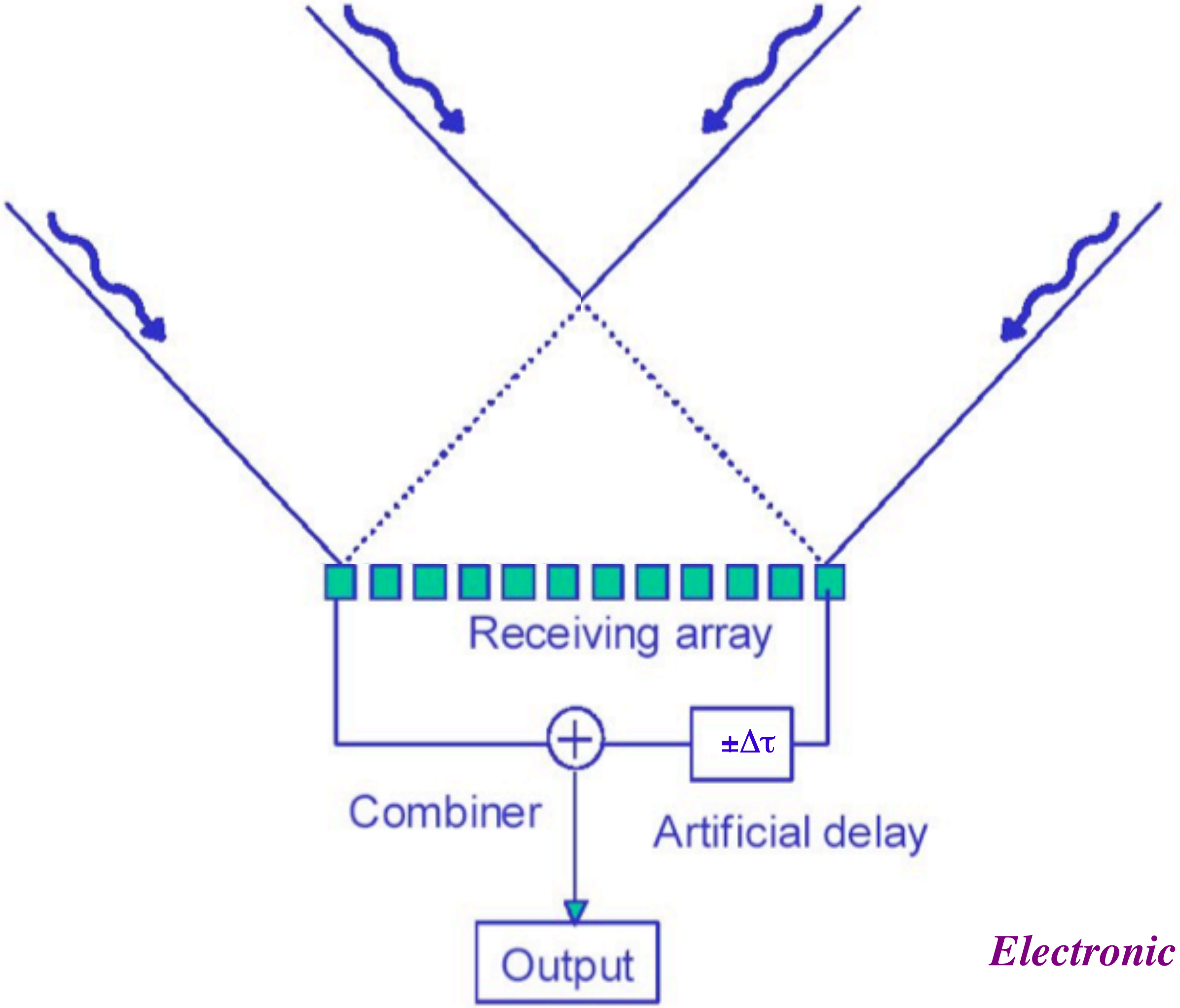
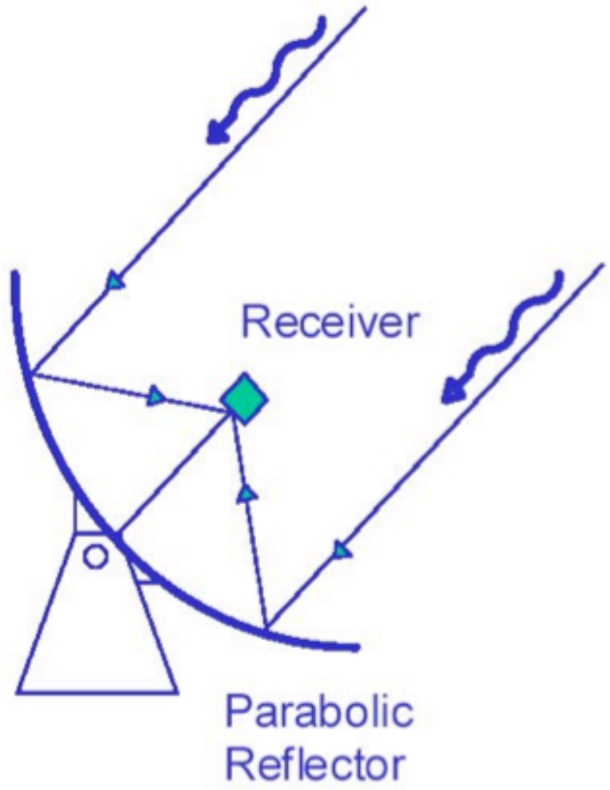
LOFAR: A "Phased Array"





Electronic beam steering

Inteferometer Principle

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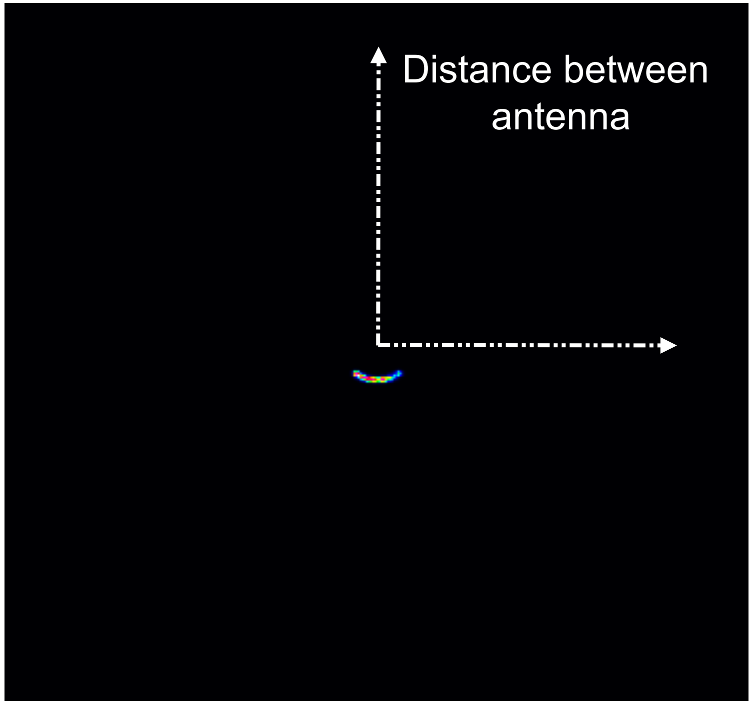
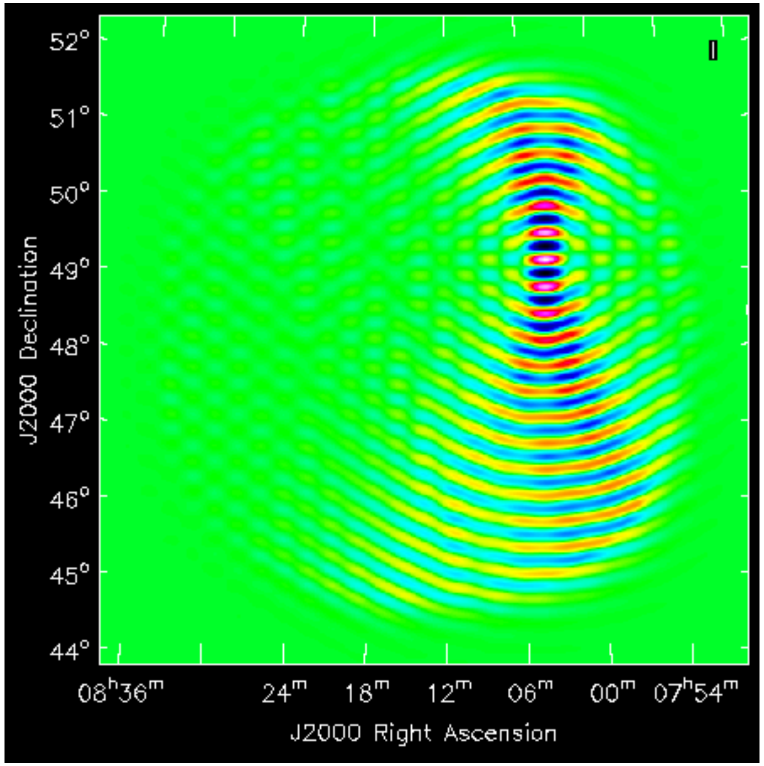
- Each antenna-antenna baseline "draws" a ring on the sky
- Interference between signals produces interferometry fringes
- The superposition of the information of many baselines (fringes) "draws" the image.





Slide: C. Tasse

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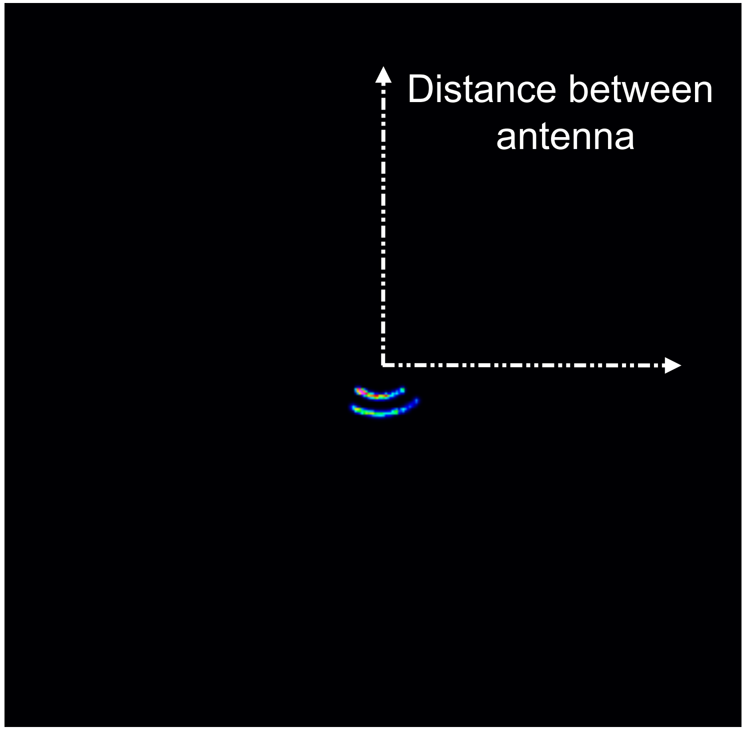

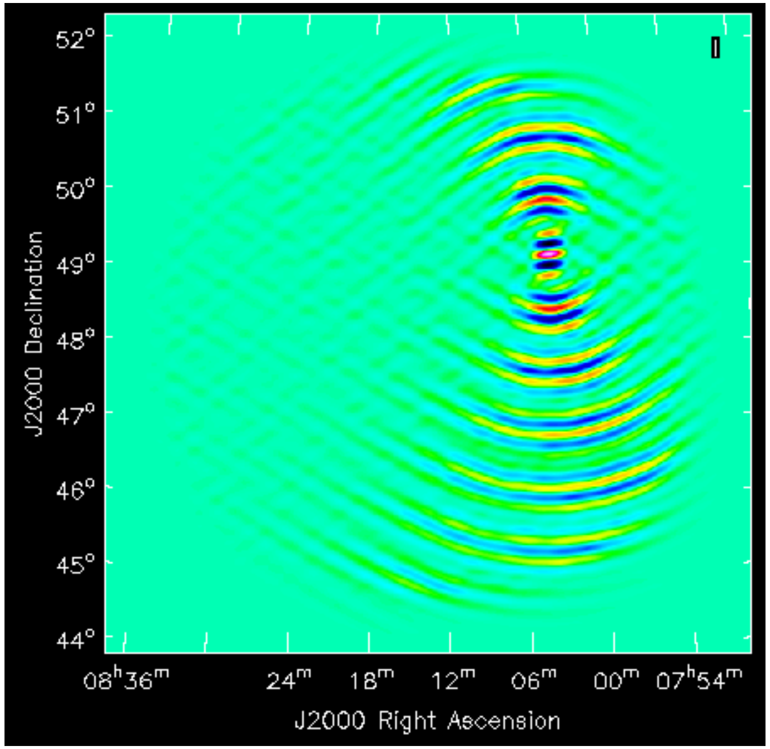

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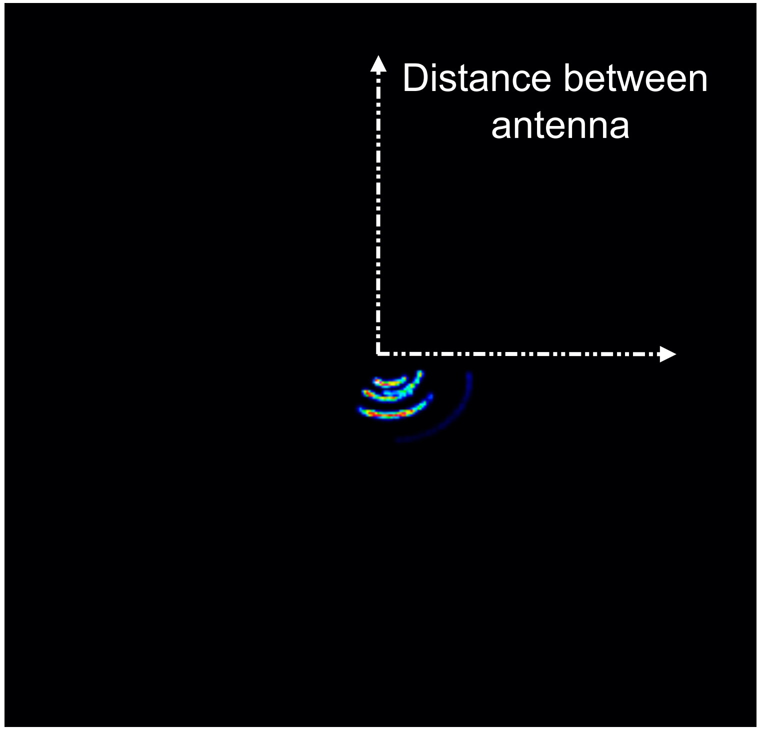

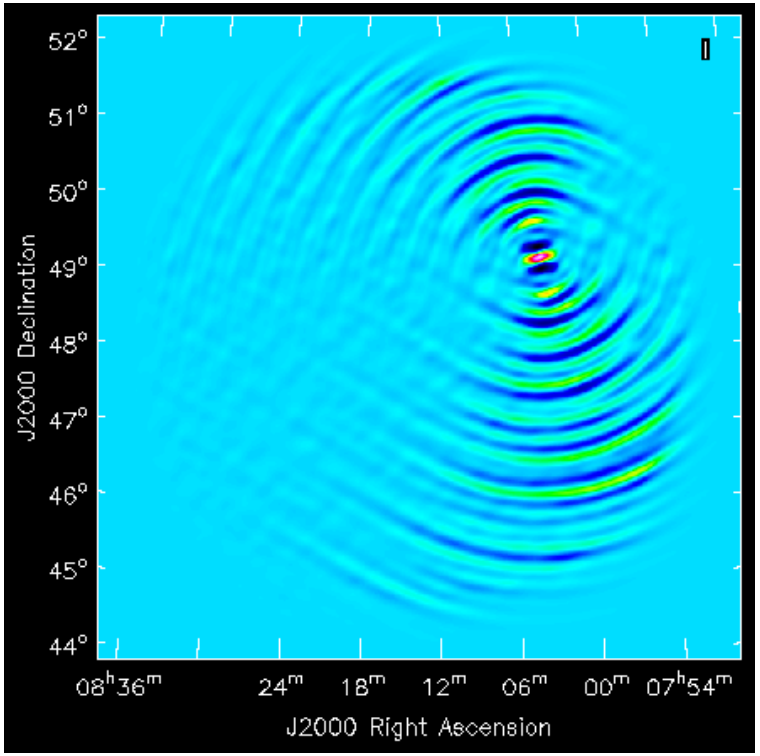

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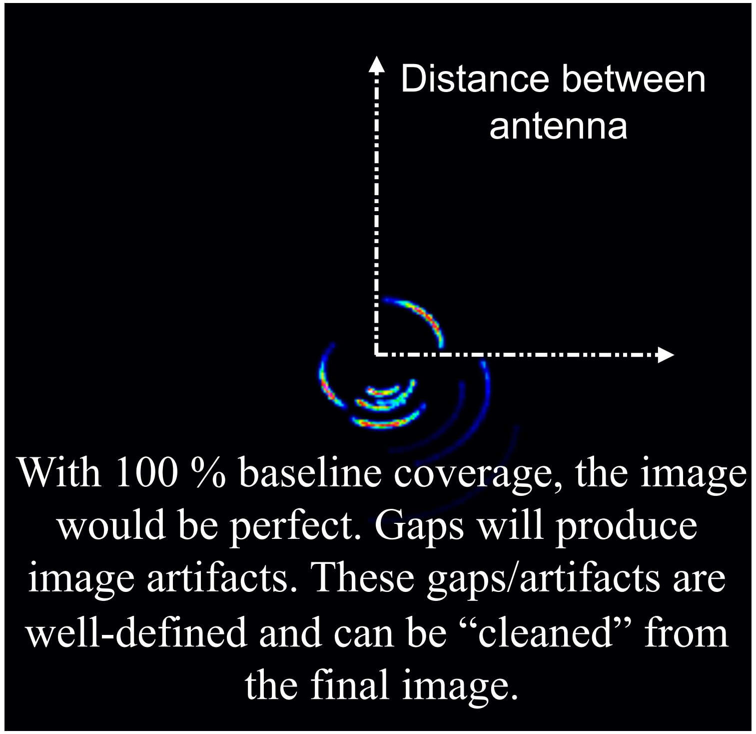

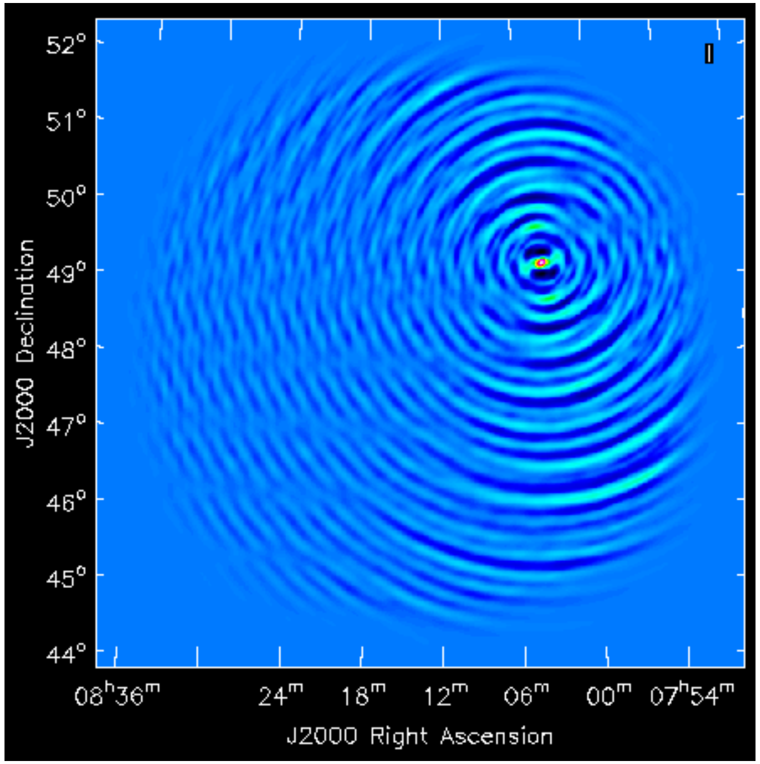

Slide: C. Tasse

The Enemy: Interference

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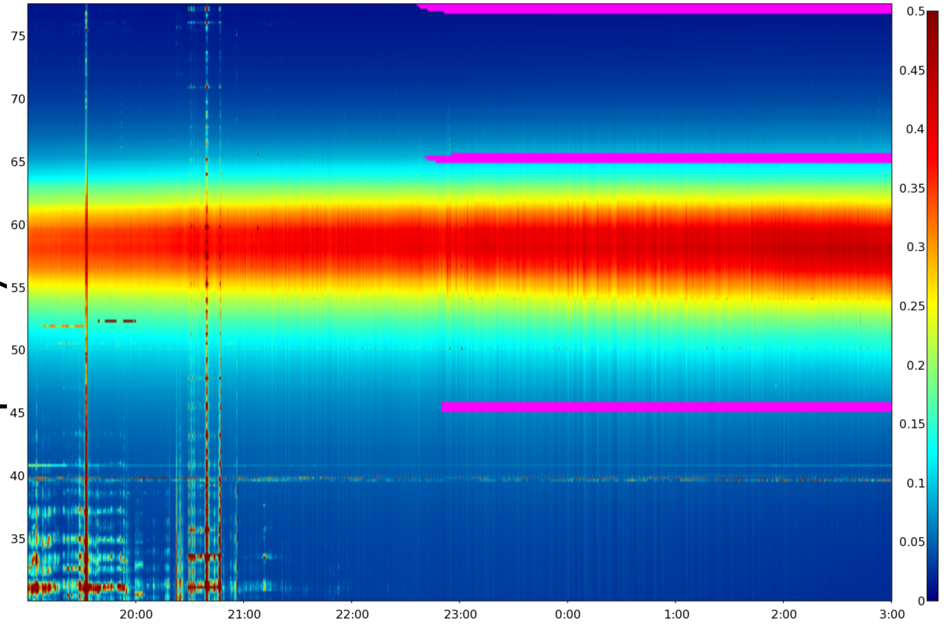
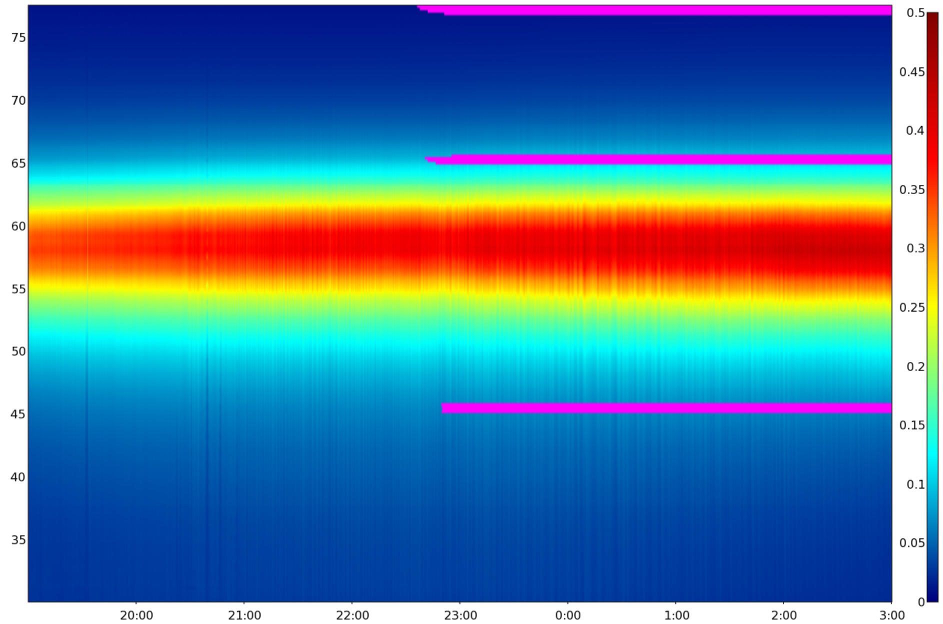
Before …

… and after interference removal

Frequency ↑





Time →

Offringa et al. (2012)

LOFAR RFI environment

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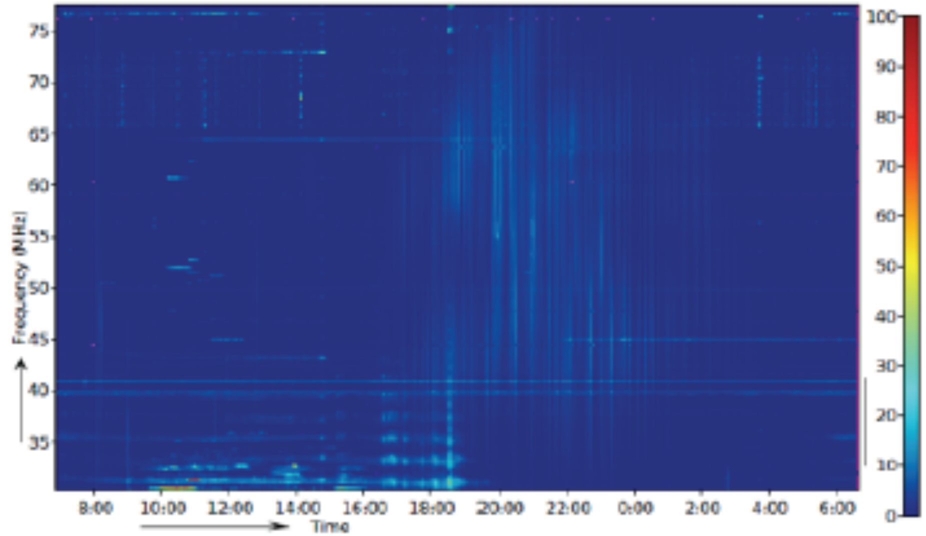
Offringa et al. 2013

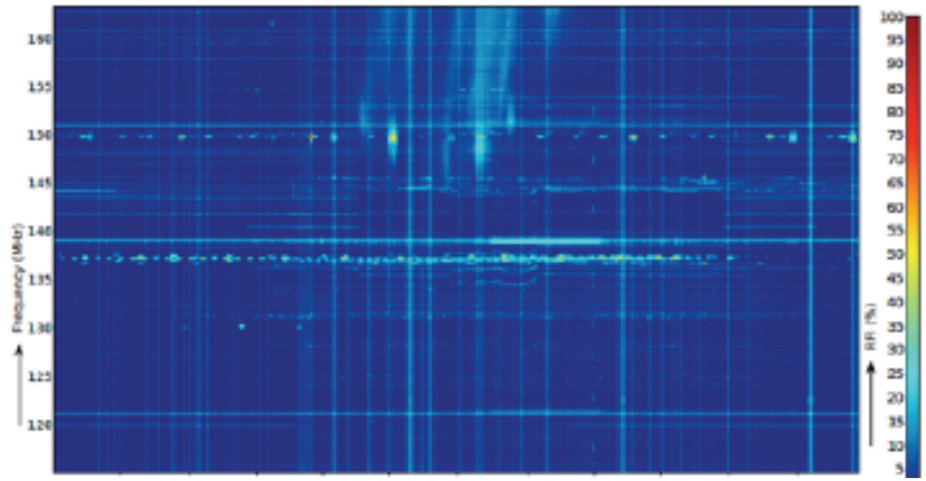
LBA 24h (1s, 0.76 kHz)
Only 1.8% RFI

33 stations 9 Oct 2011



HBA 24h (1s, 0.76 kHz)
Only 3.2 % RFI

13 stations 27 Dec 2010



The Enemy: Ionosphere

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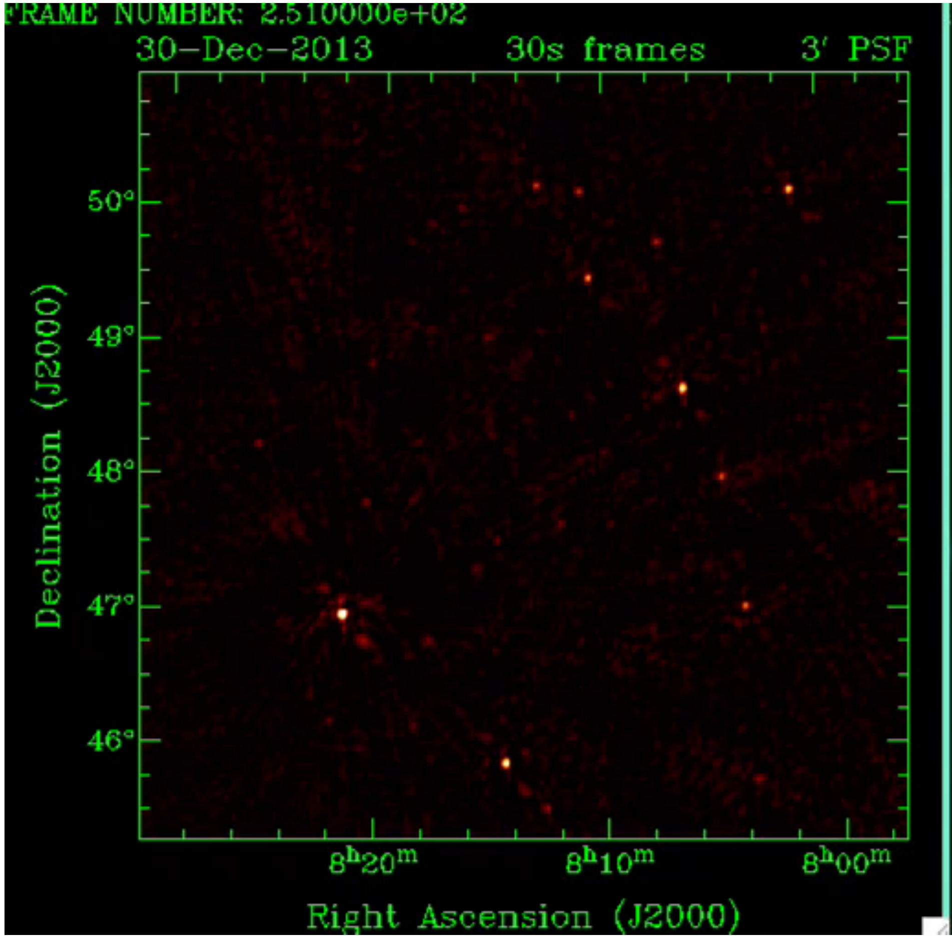
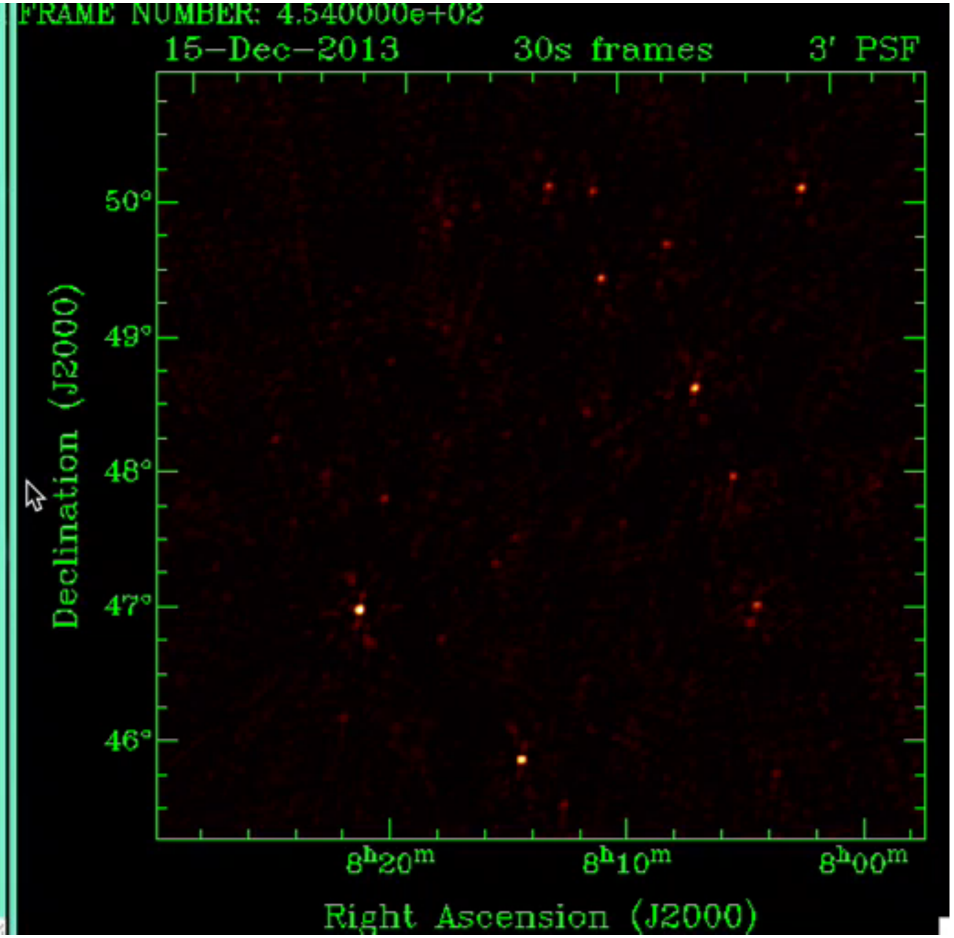
Without ionospheric calibration



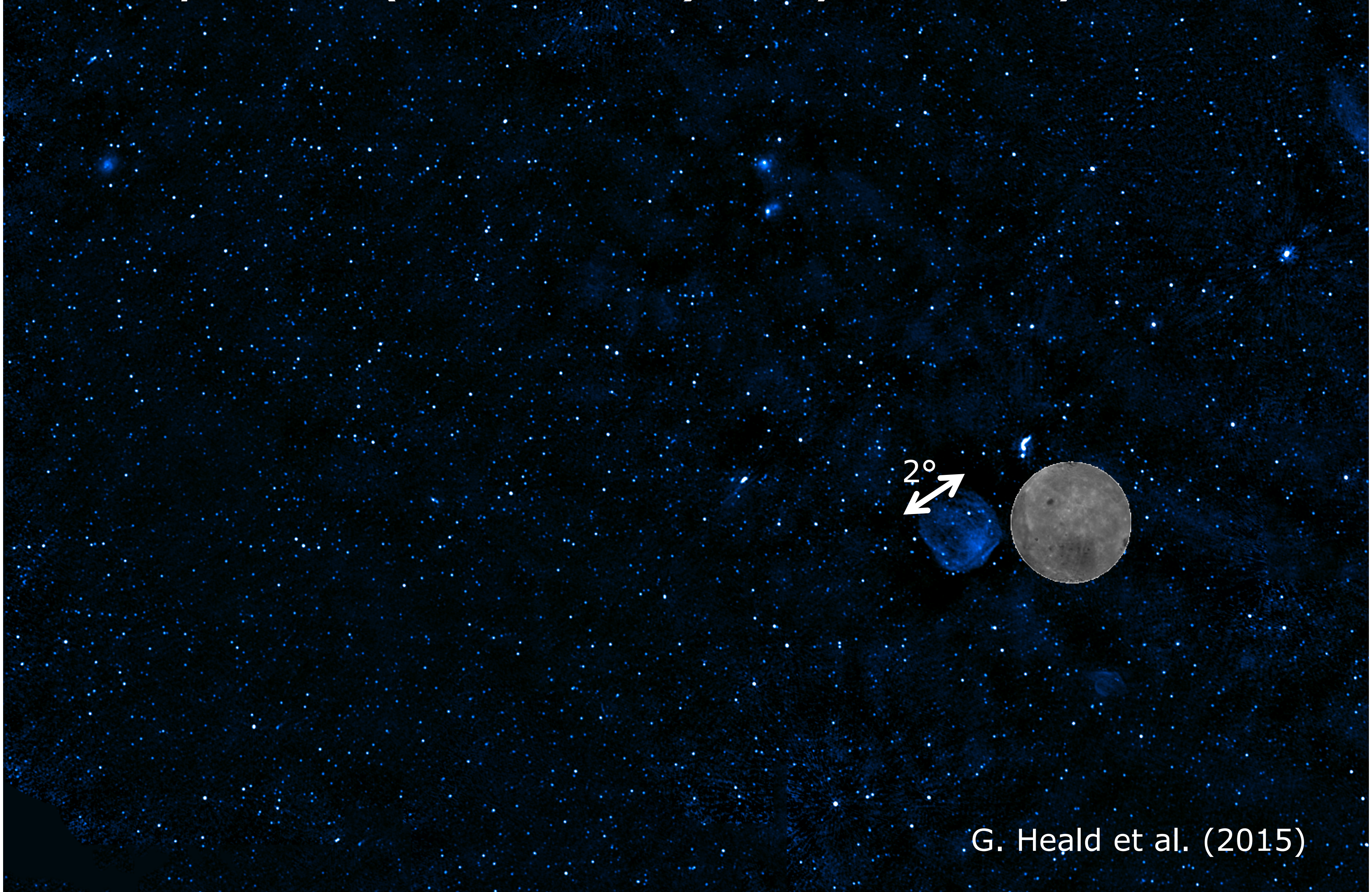
With ionospheric calibration



Science Topics

- Pulsars
- ISM and magnetic fields
- **Radio Galaxies & Surveys**
- Epoch of Reionization
- Ultra-High Energy Cosmic Rays

LOFAR MSSS: Multifrequency Snapshot (Northern) Sky Survey



Galaxy Clusters with LOFAR

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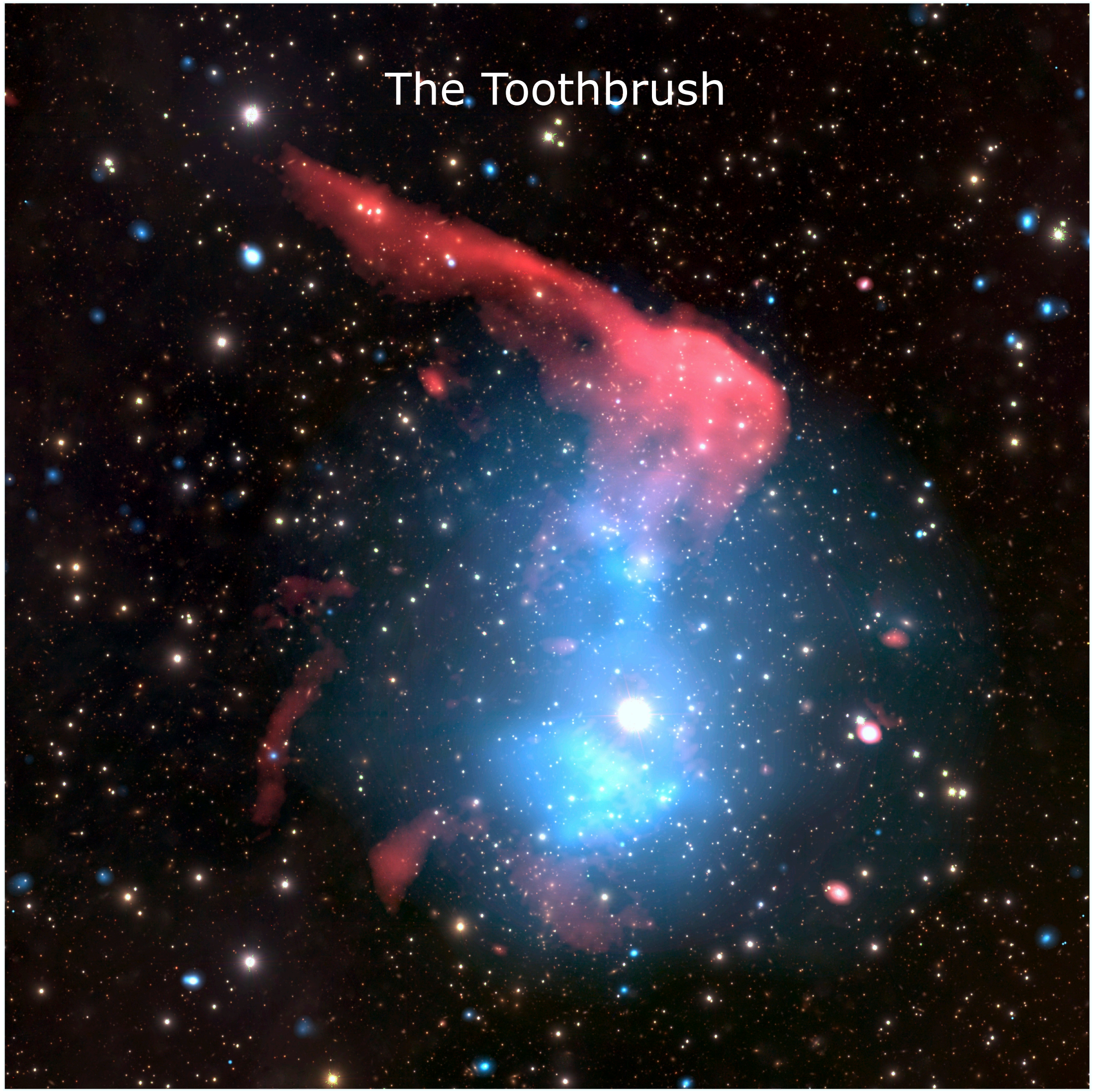

LOFAR HBA: Red
Chandra: Blue
Subaru: optical

LOFAR survey KSP
(Rottgering et al.)
and Magnetism KSP
(Brüggen et al.)

Reinout van Weeren

Galaxy Cluster with LOFAR

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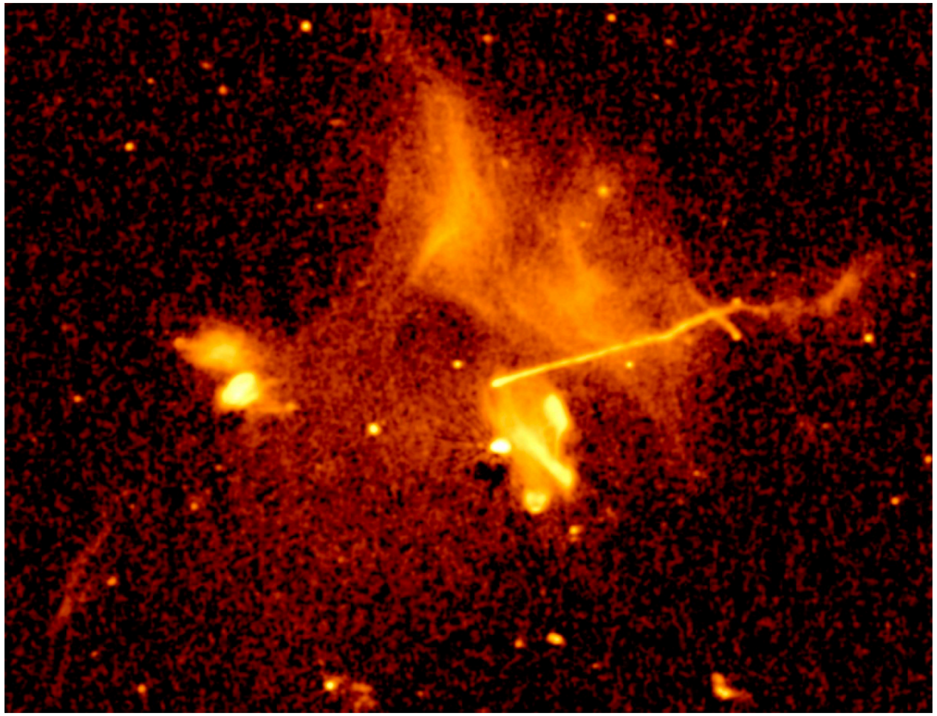
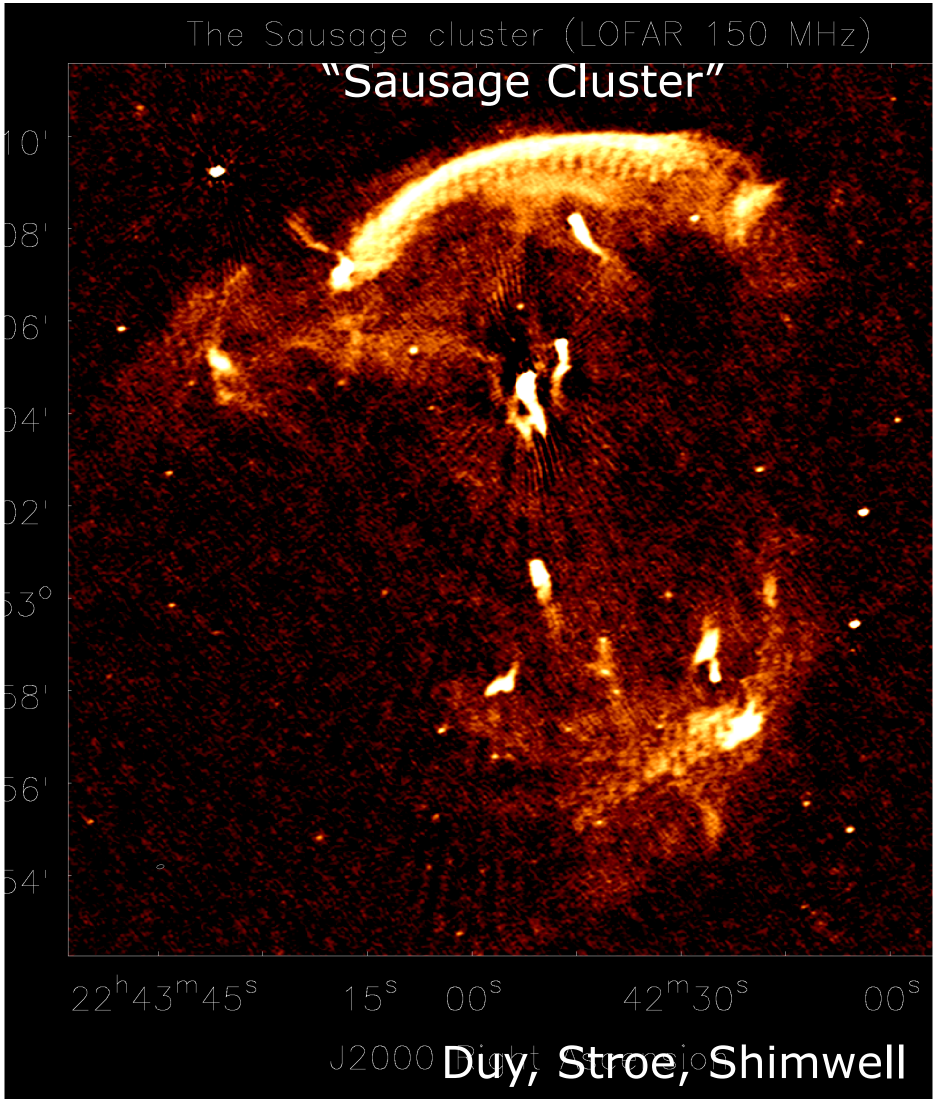
A2256



Reinout van Weeren



Duy, Stroe, Shimwell

Part of a "random" empty field after 4 hr integration

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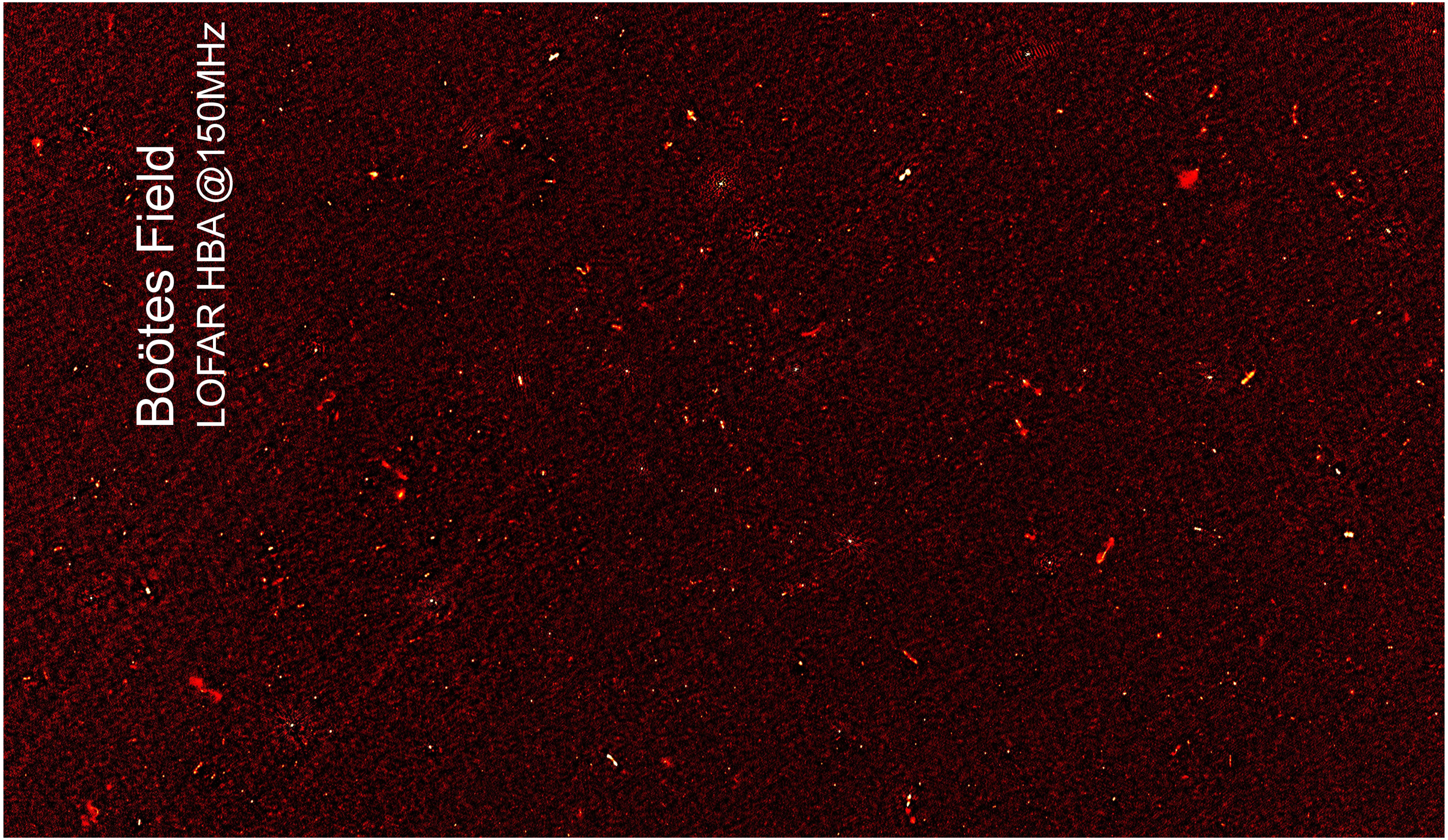

Williams, Rottgering et al. (2015)

Bootes Field: cut-outs from 3° × 3° single pointing

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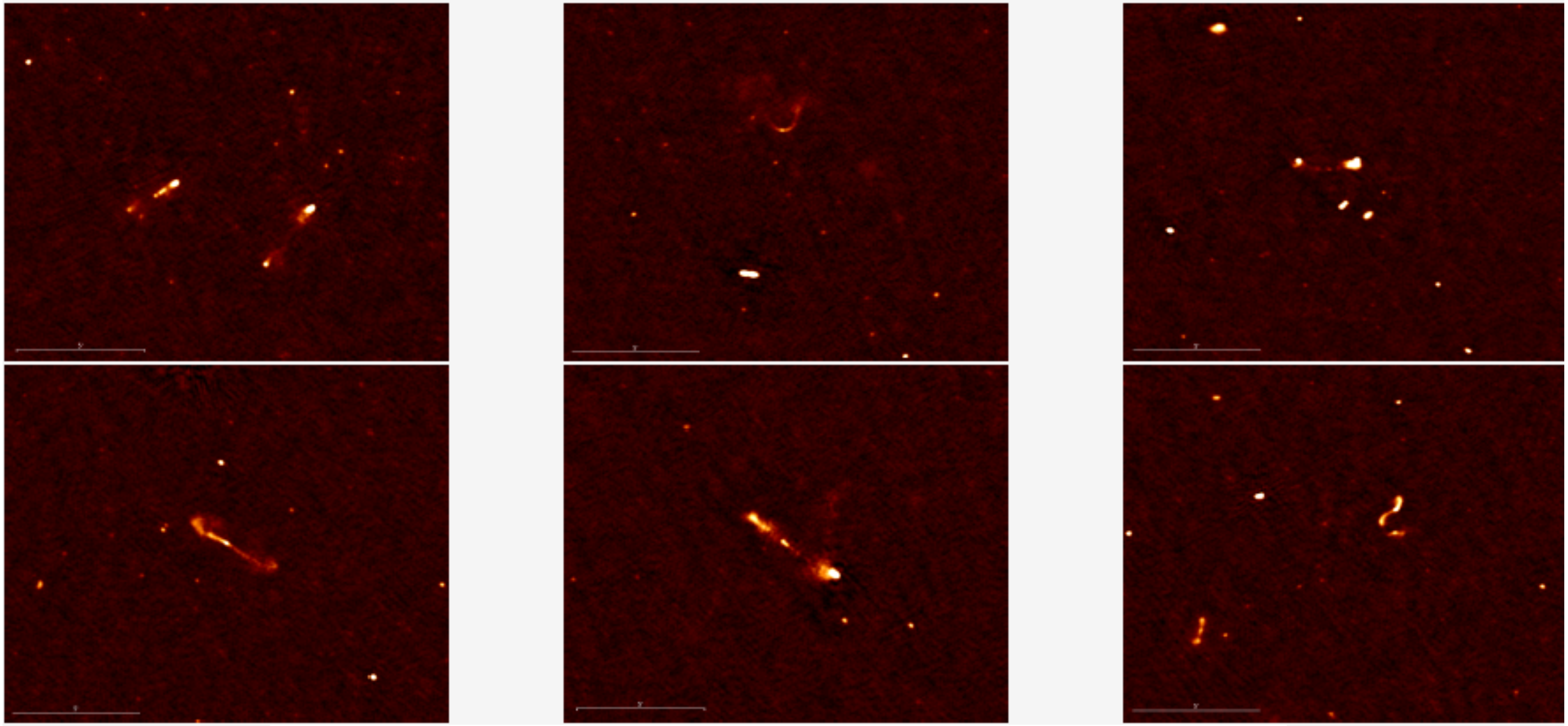
Selected zooms into sub-regions



120 μJy RMS, 5×7 arcsec resolution
4 hrs integration – thermal noise limited

Wendy Williams et al. (2015, LOFAR Survey KSP)

LOFAR Long Baselines

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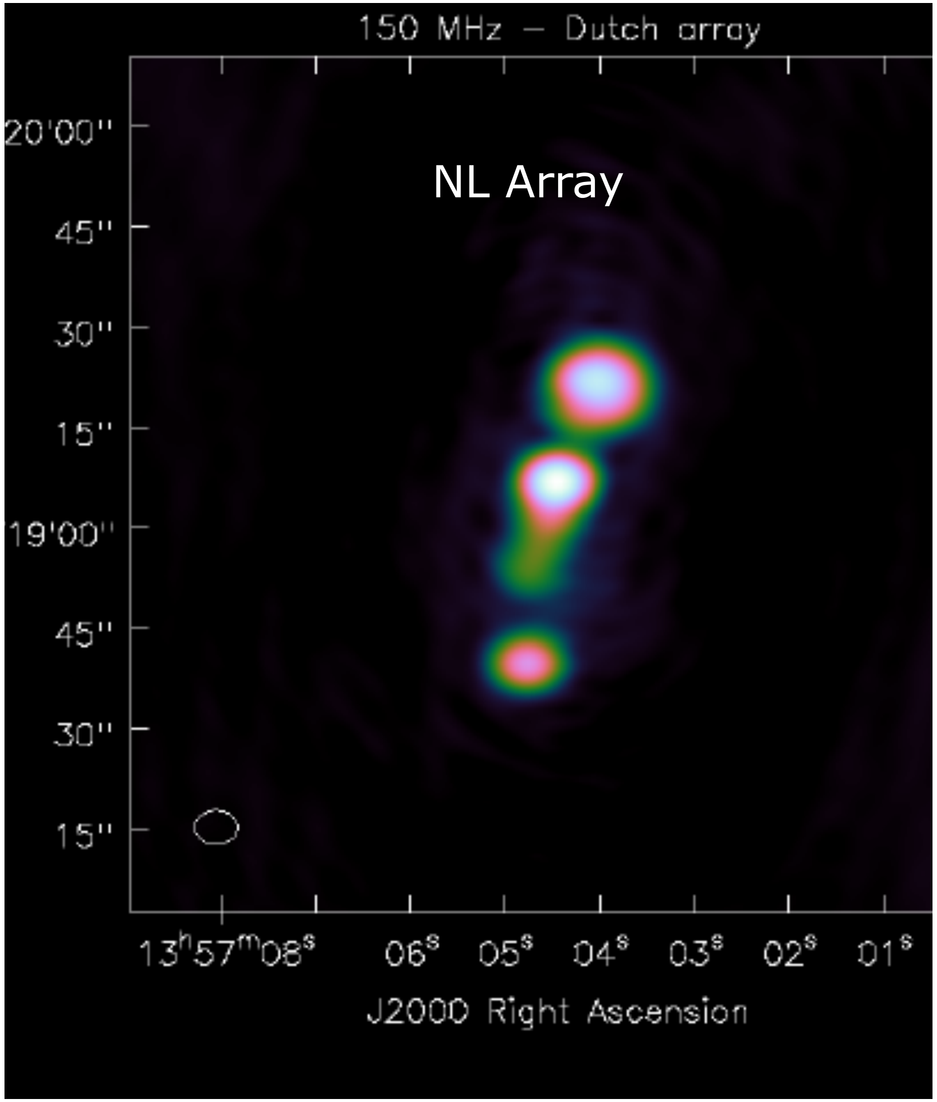
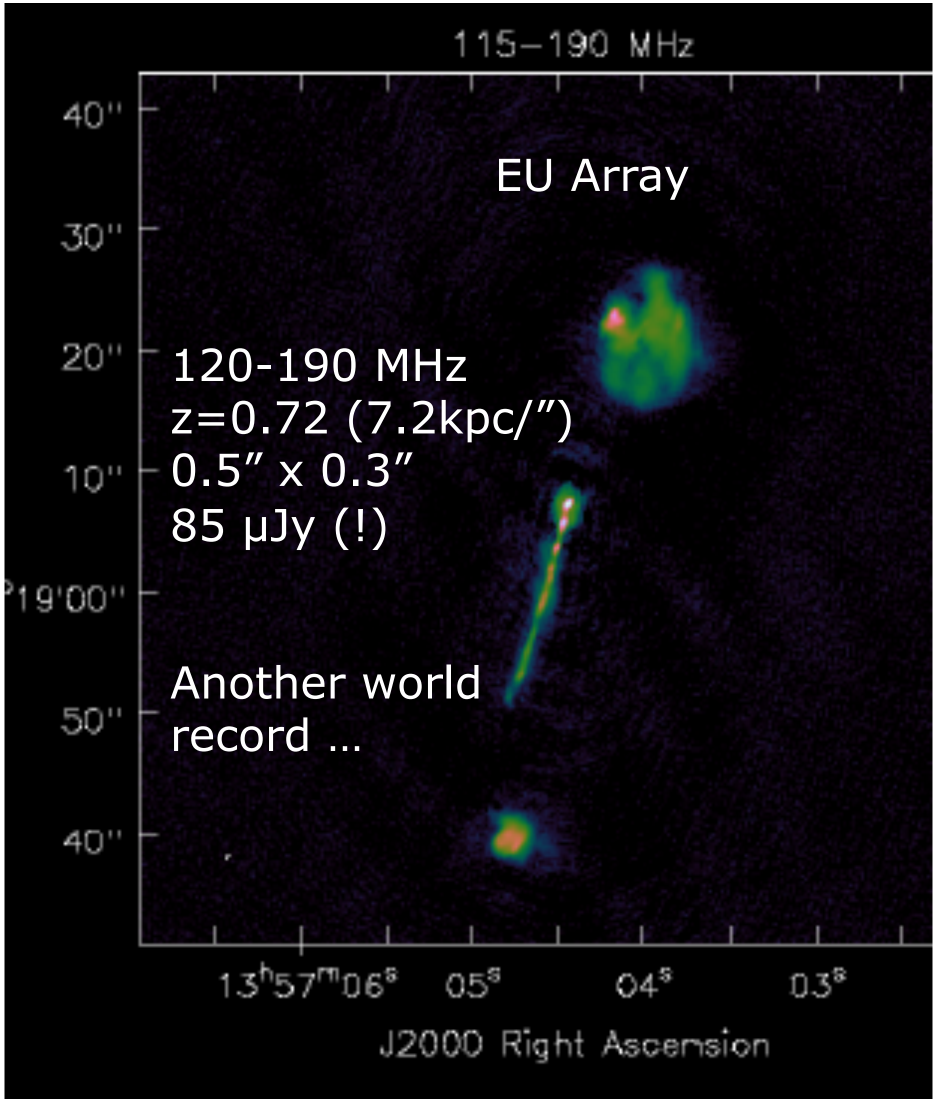
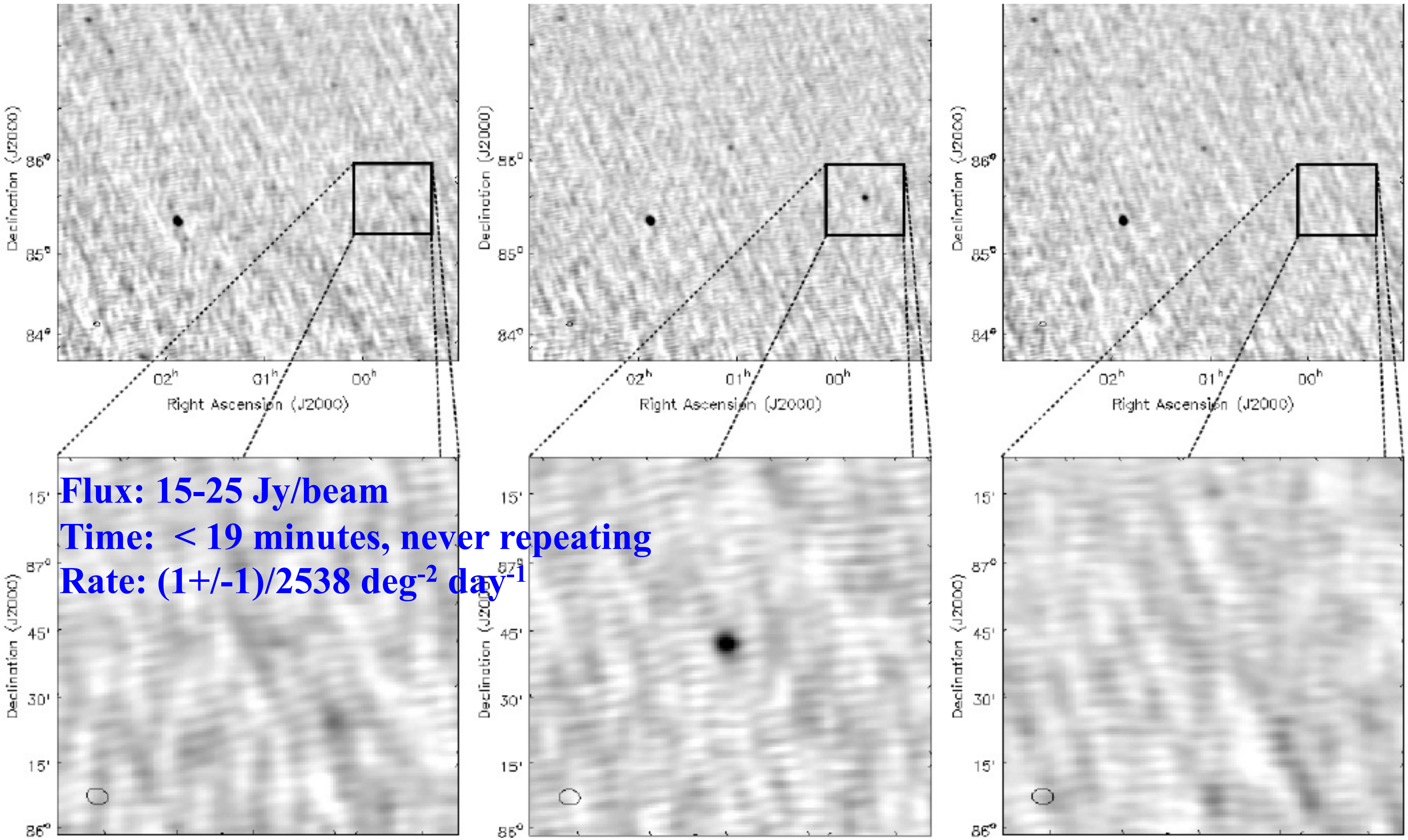




Transients



Flux: 15-25 Jy/beam

Time: < 19 minutes, never repeating

Rate: (1+/-1)/2538 deg^{-2} day^{-1}

Stewart et al. (2015)

Science Topics

- Pulsars
- ISM and magnetic fields
- Radio Galaxies & Surveys
- **Epoch of Reionization**
- Ultra-High Energy Cosmic Rays

Epoch of Re-ionization
HI at z~9

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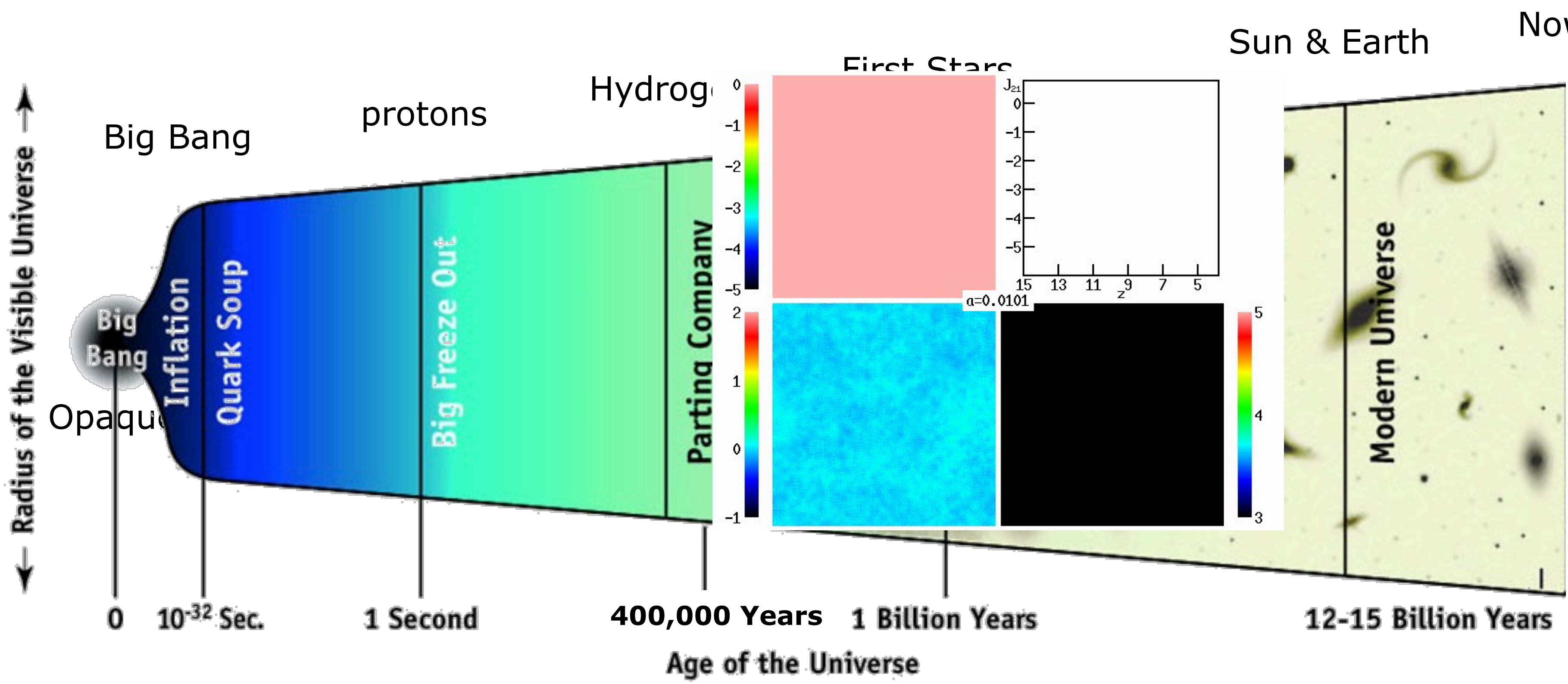
HI 21cm line: spin-flip of
electron in hydrogen atom

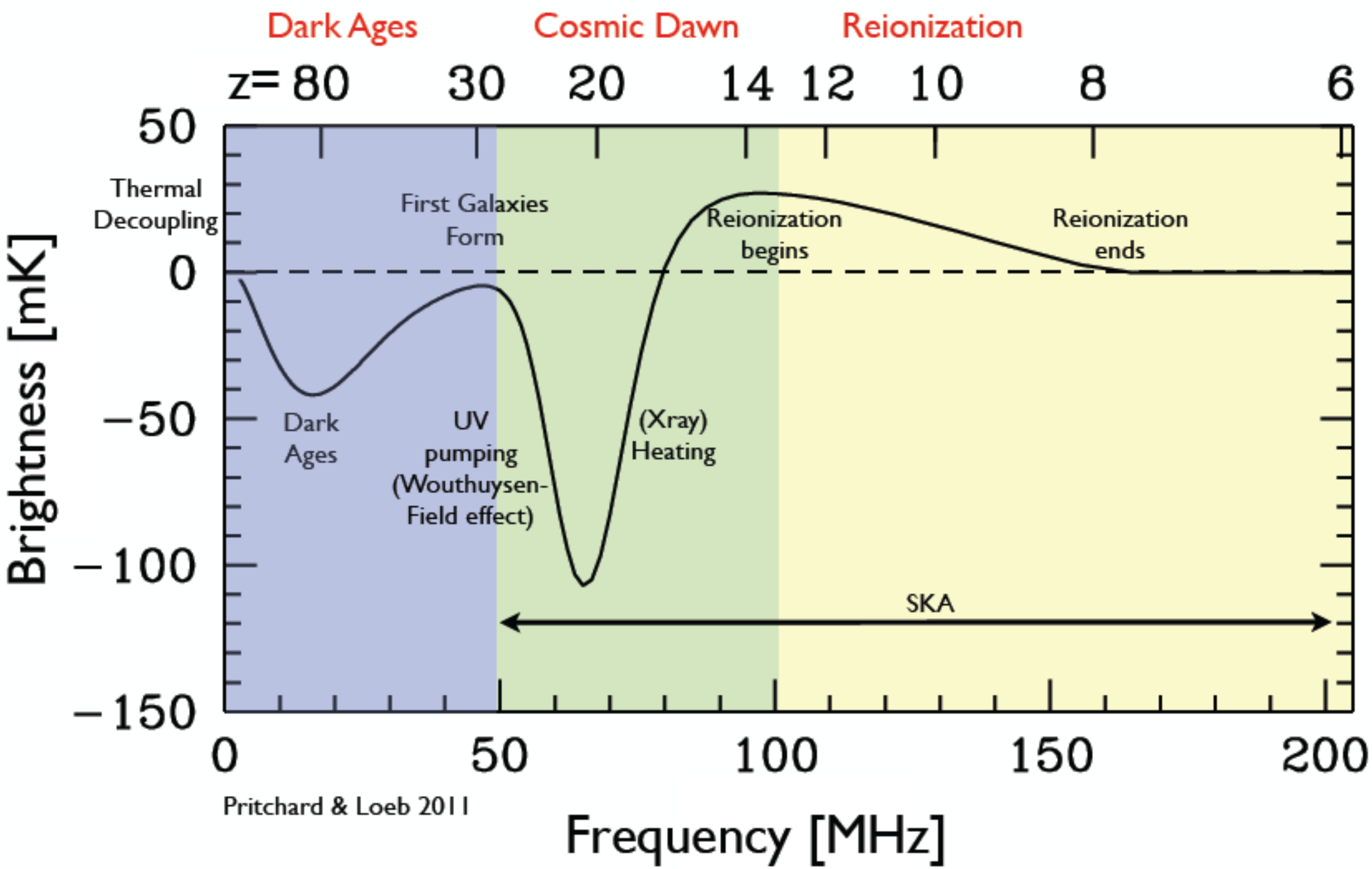
Cosmological Redshift -
Hydrogen line is seen at:

1.4 MHz
14 MHz
140 MHz
1.4 GHz

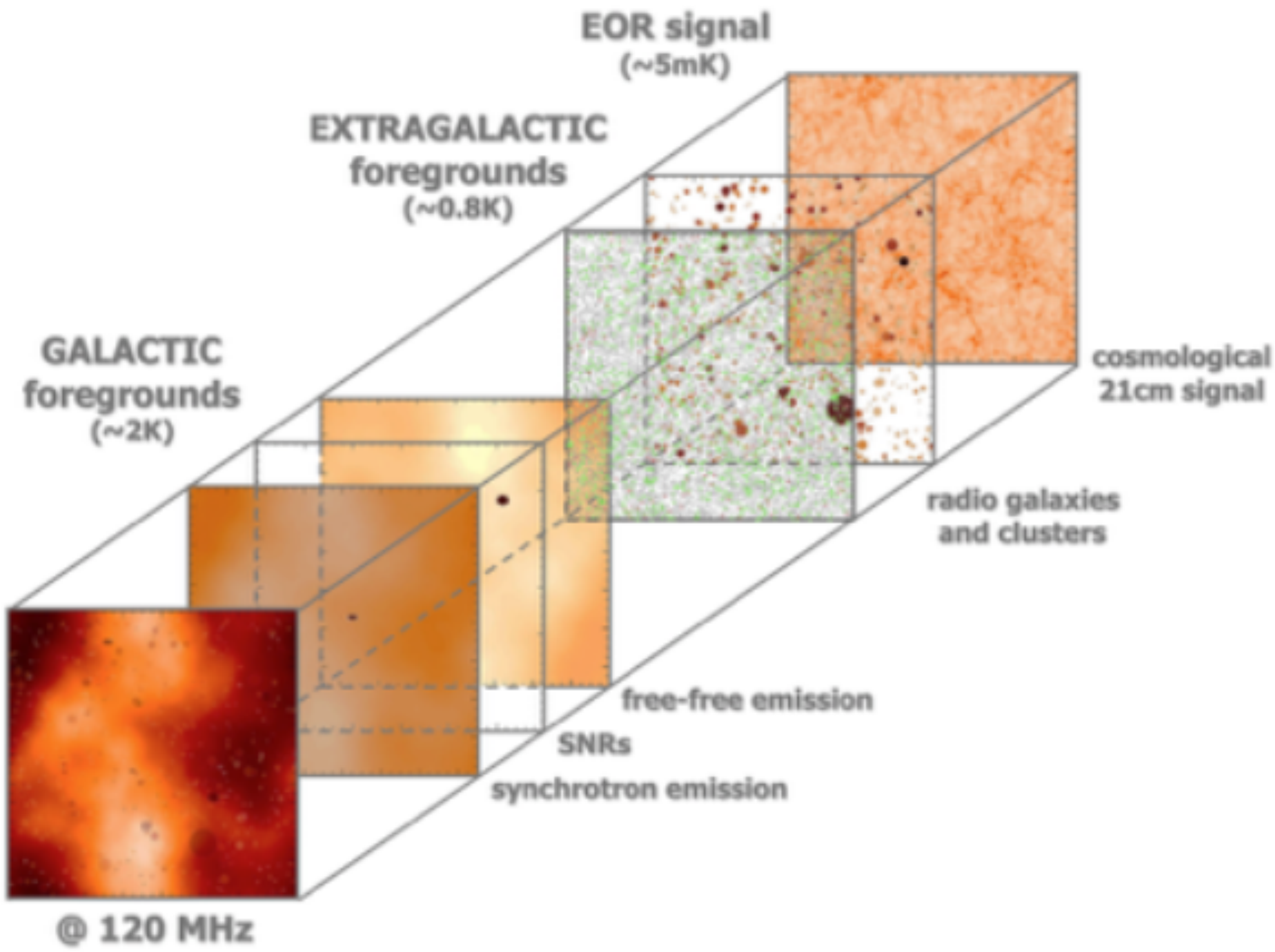


Hydrogen Brightness Temperature

Global Signal



Foregrounds



Galactic Imaging
Cygnus Region

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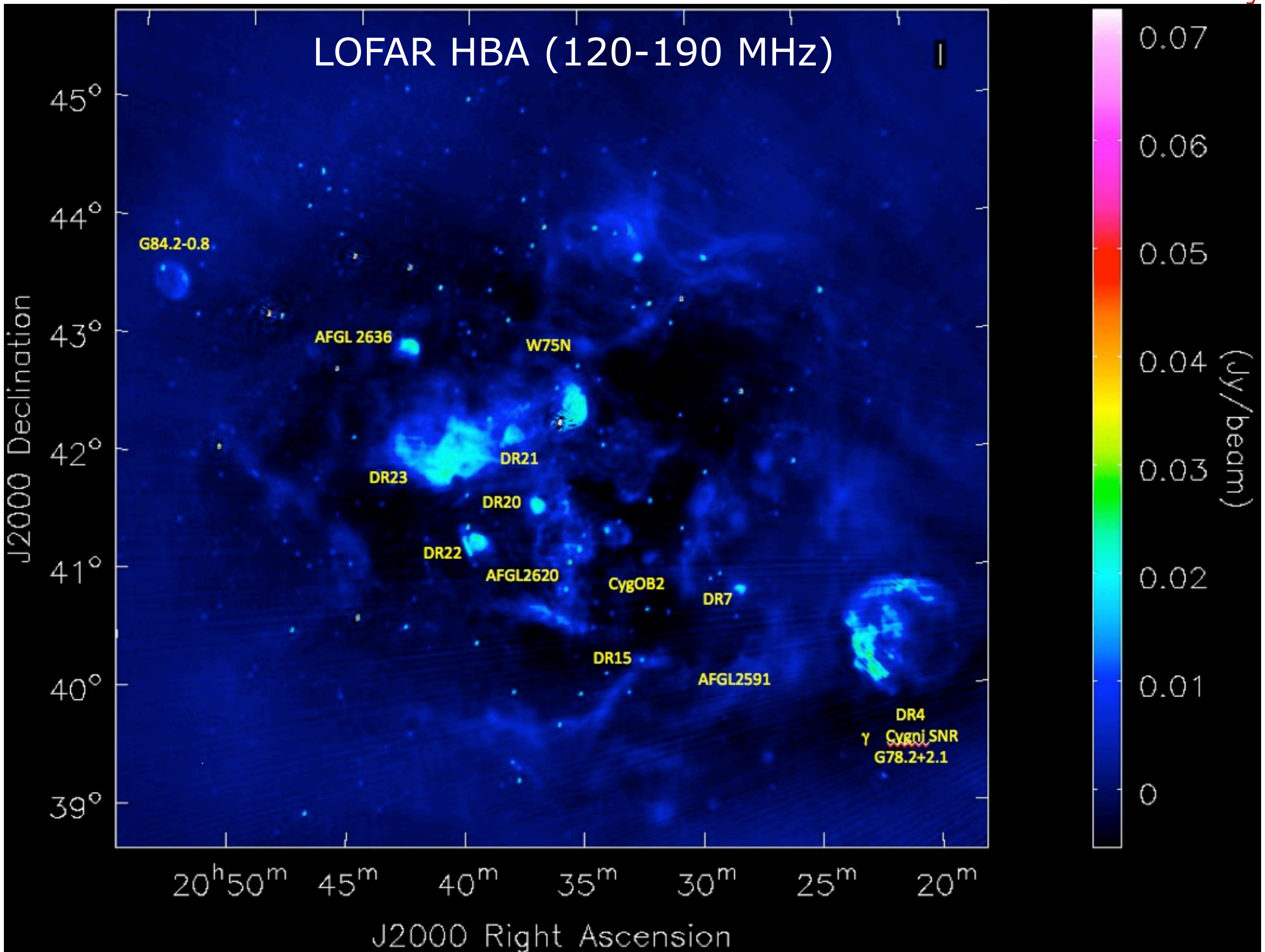

Glenn White

Spectroscopy of Rydberg Atoms: Radio Recombination Lines (RRLs) probing the Cold Neutral Medium (CNM)

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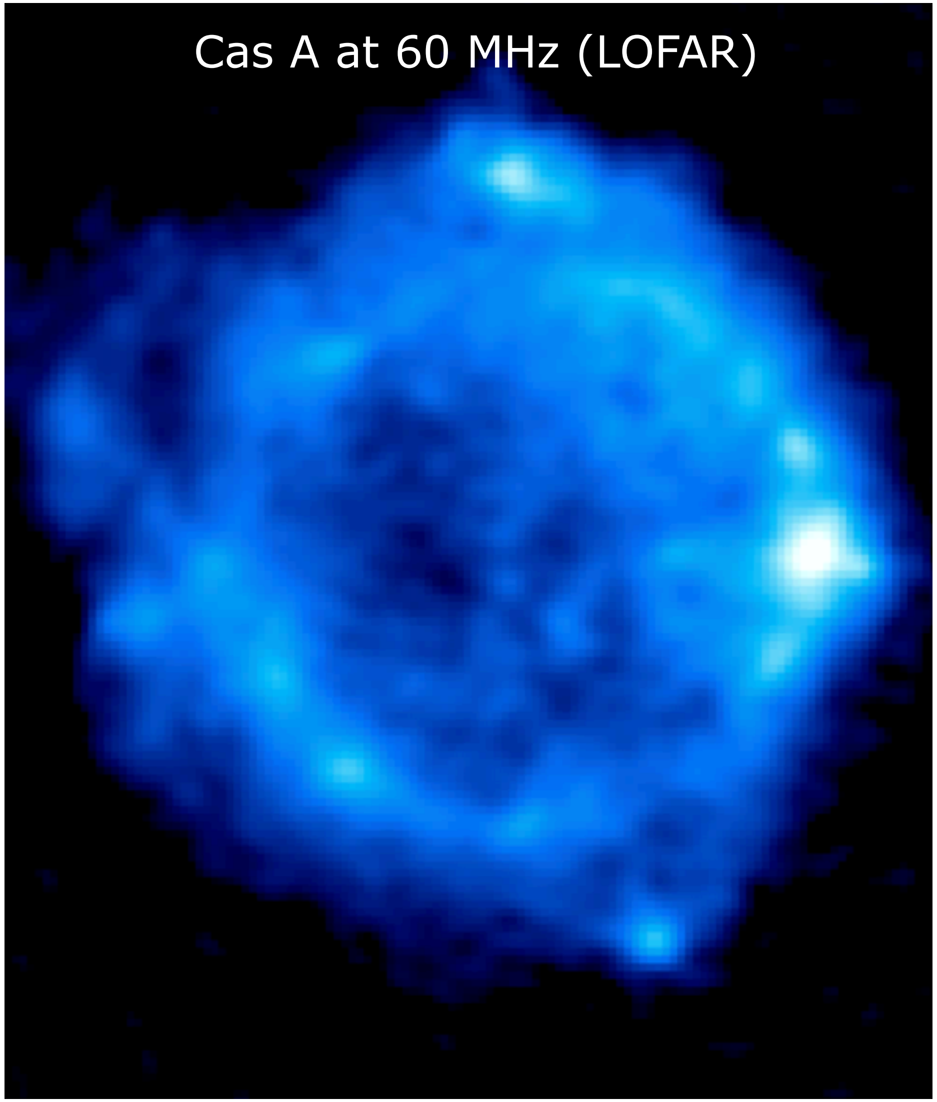
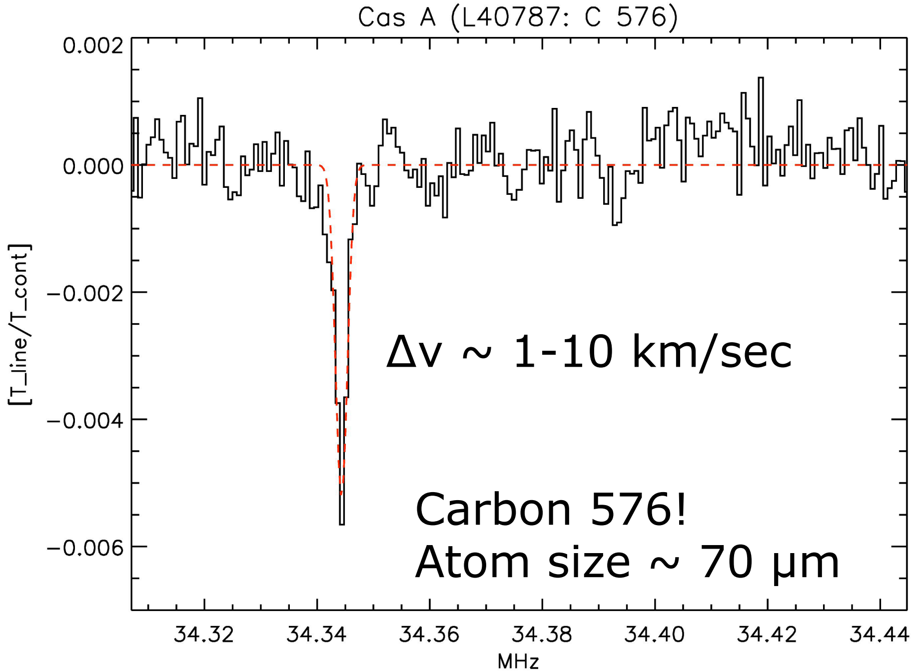


van Weeren et al. (2013)

LOFAR spectrum towards Cas A



C-RRLs actually seen throughout Galaxy!

Asgekar, Oonk, et al. (2013/2014)

First extragalactic detection in M82 by Morabito et al. (2014)!

Faraday Rotation Measure Cubes: Interstellar Medium Structures

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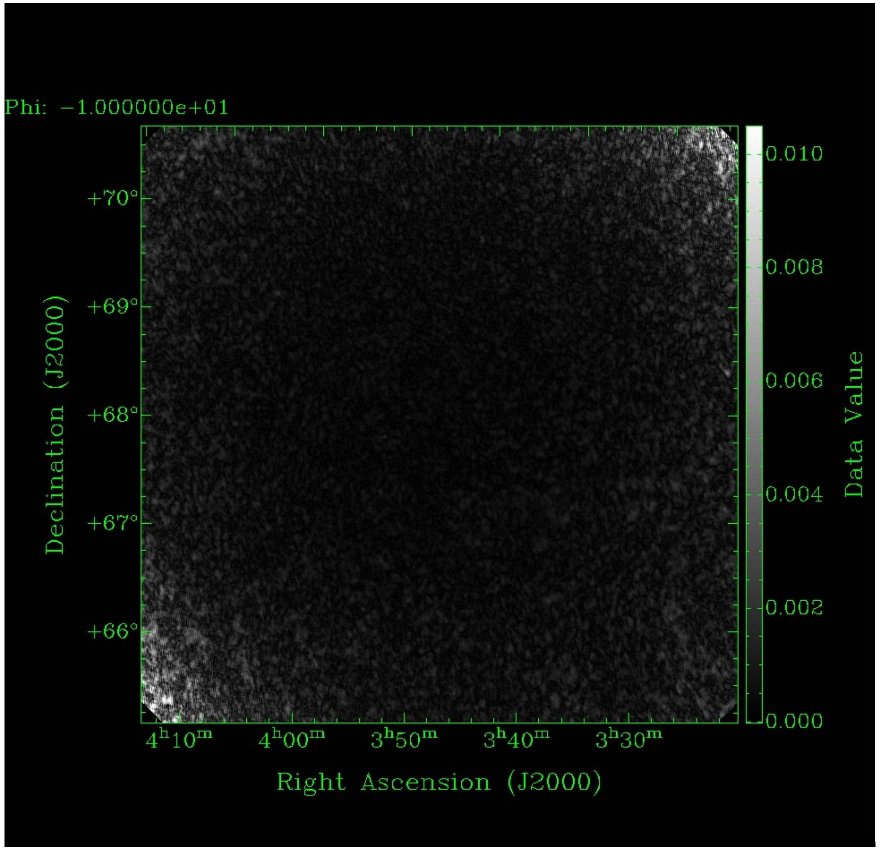
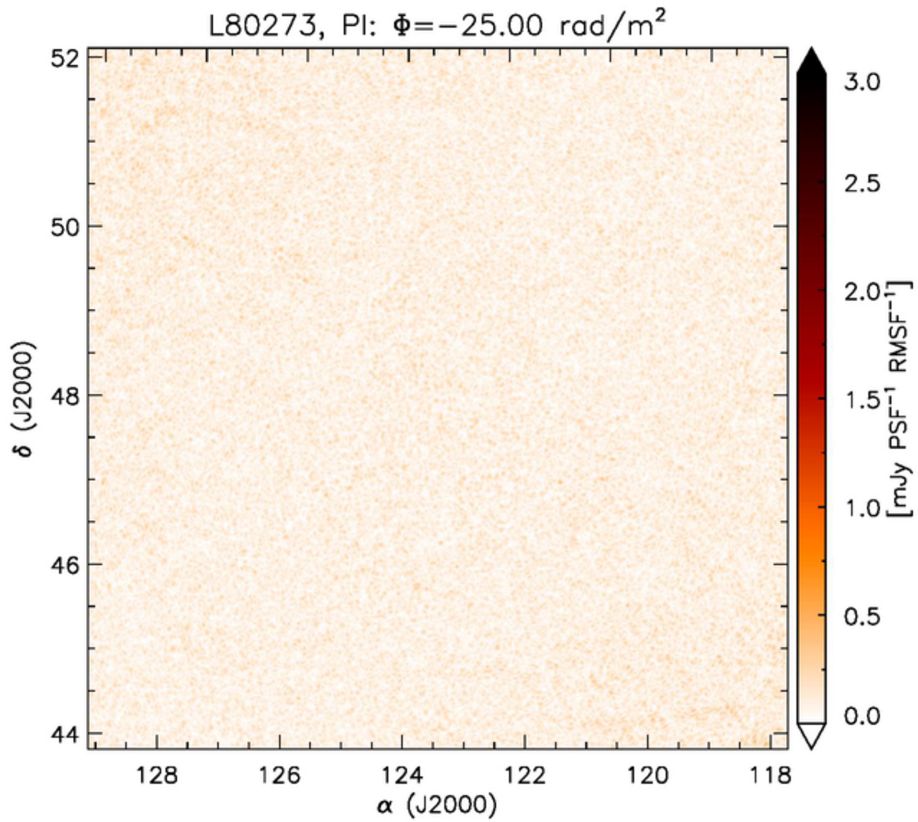
Slices through different Faraday depth (RM) with LOFAR
~ distances



Cameron van Eck
(Magnetism KSP team)



Vibor Jelić
(EOR KSP team)

Planck Dust Polarization

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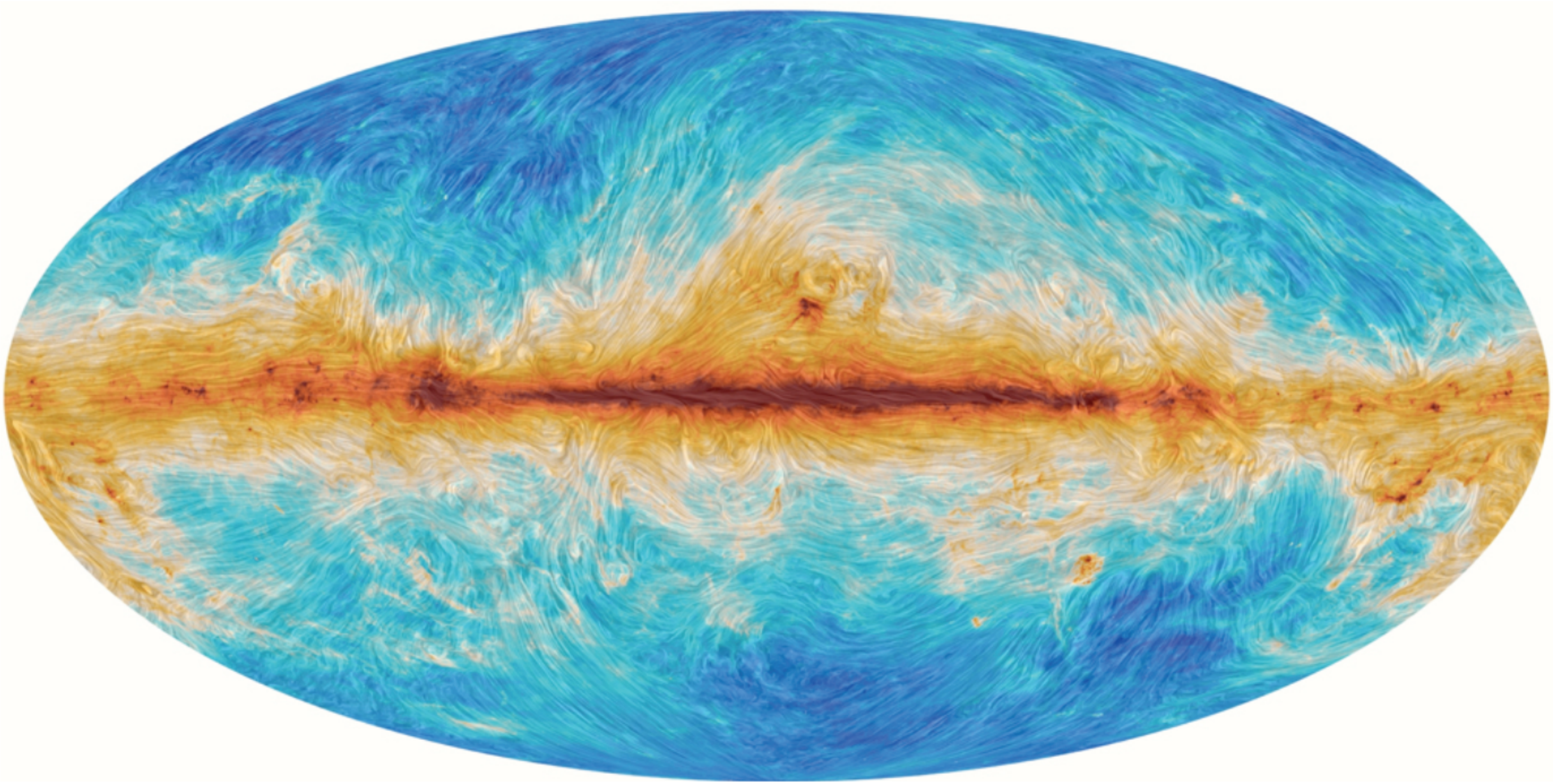

LOFAR features align with Planck Dust Map

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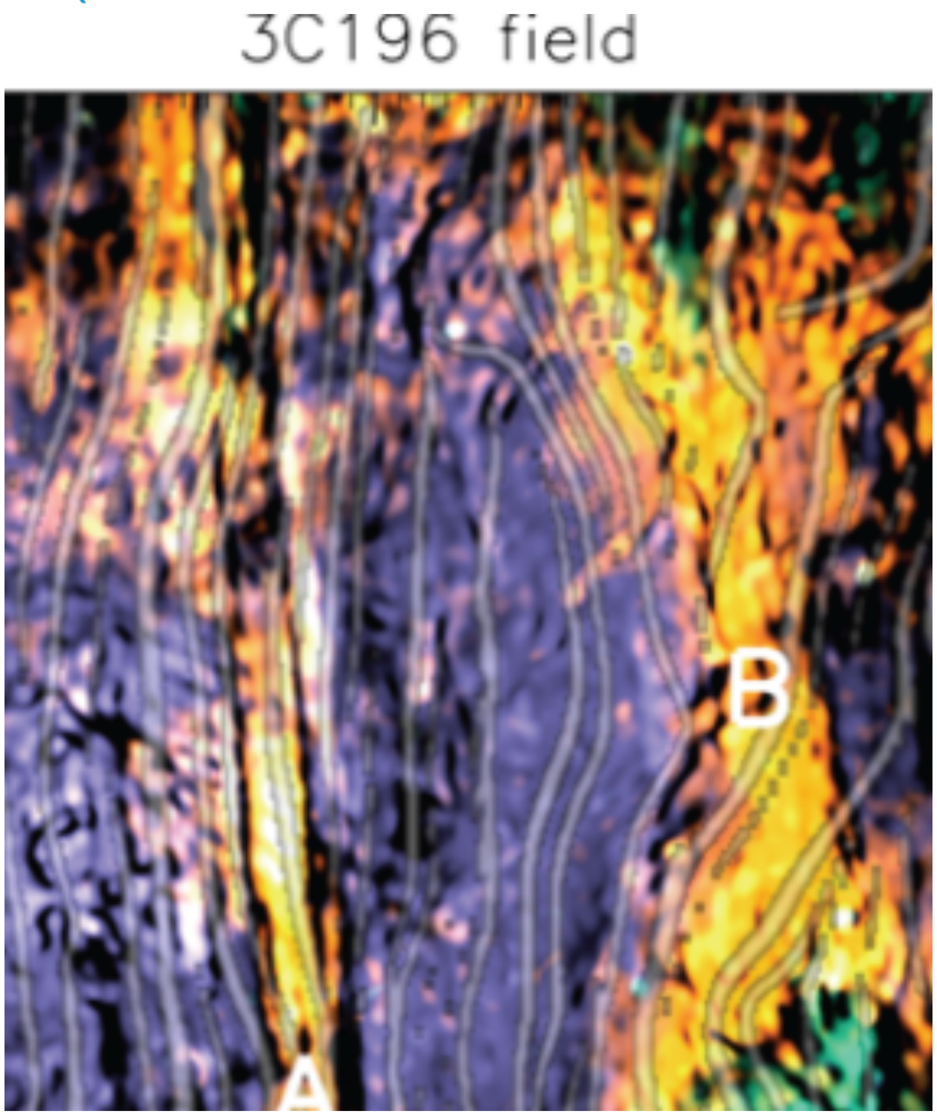

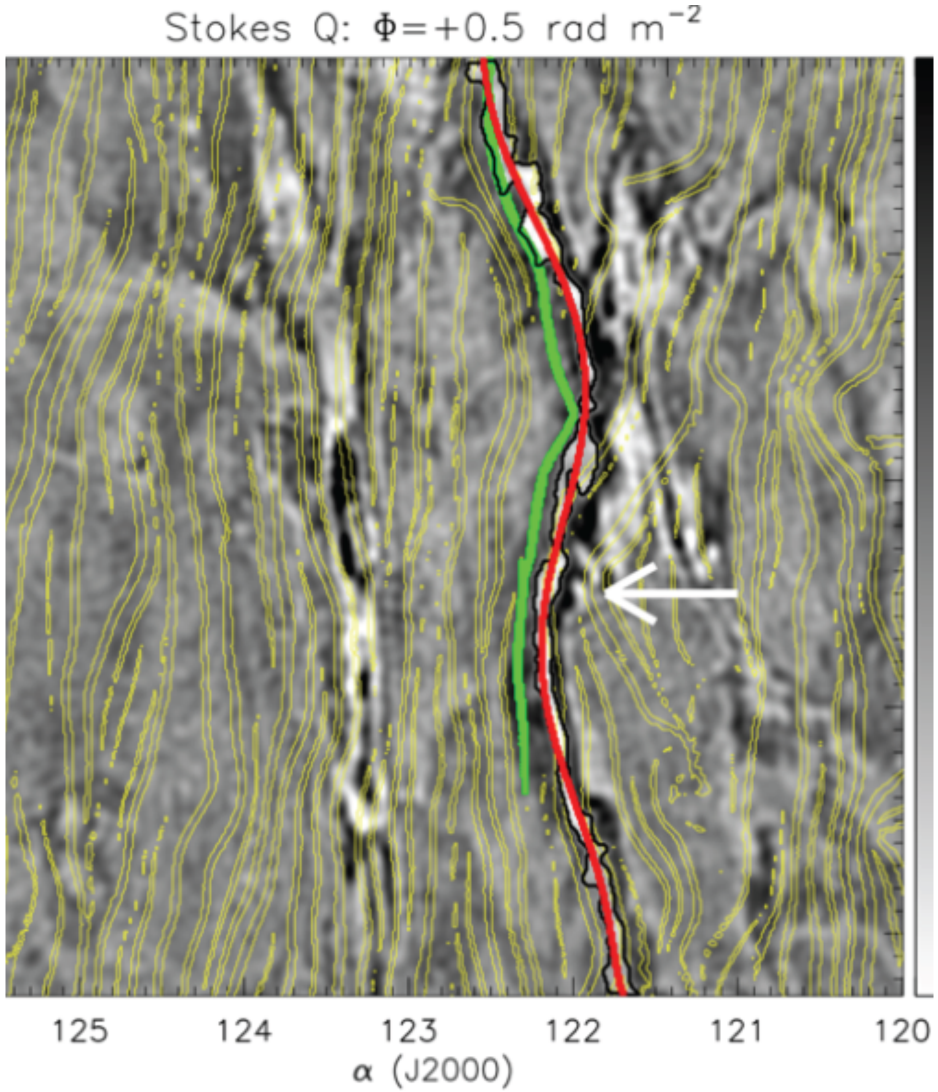

Jelic et al. (2015), Zaroubi et al. (2015)

The EoR windows

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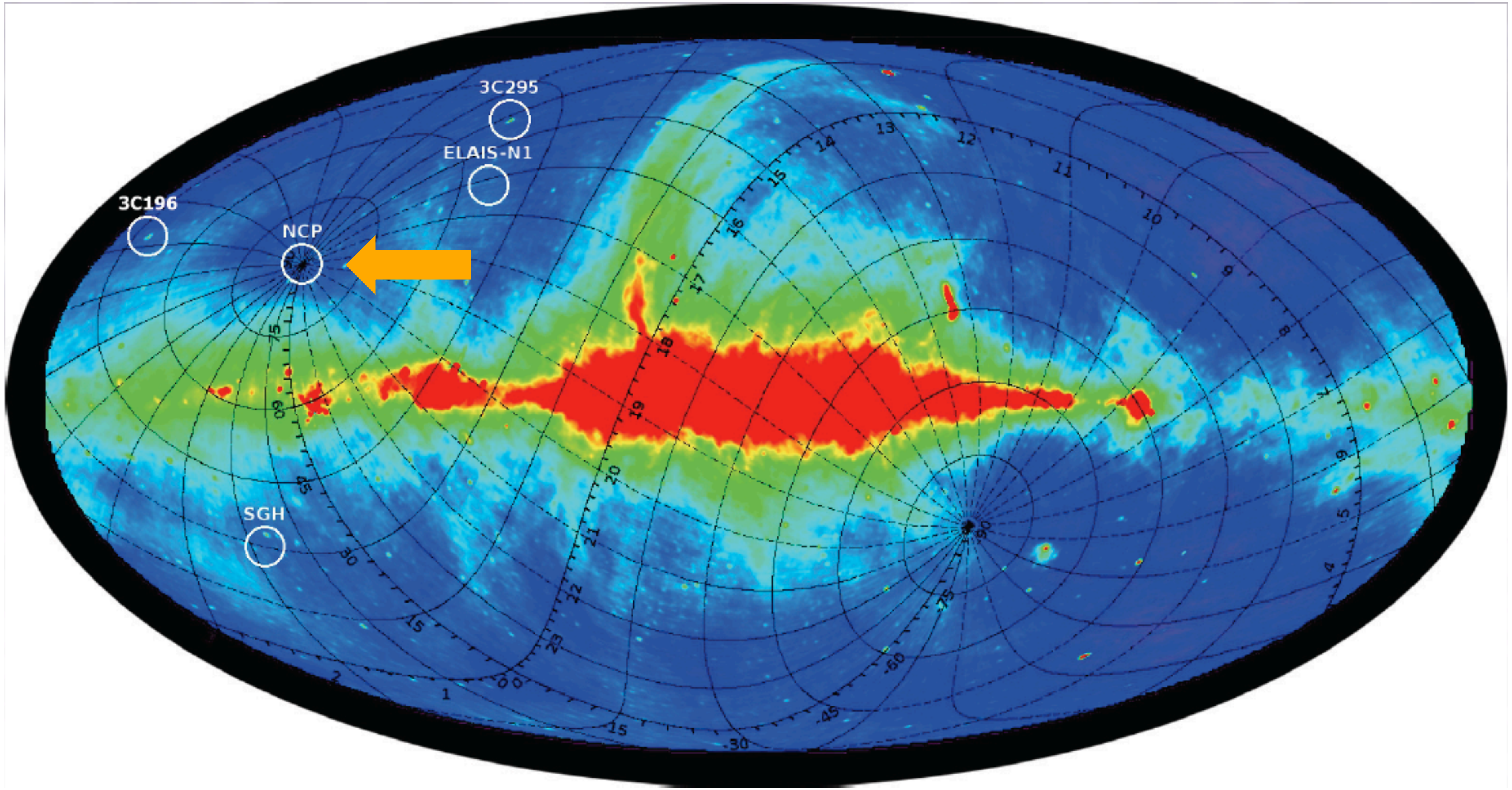

EOR KSP: de Bruyn, Koopmans, et al.

EoR Window – North Celestial Pole (NCP) 155 hrs

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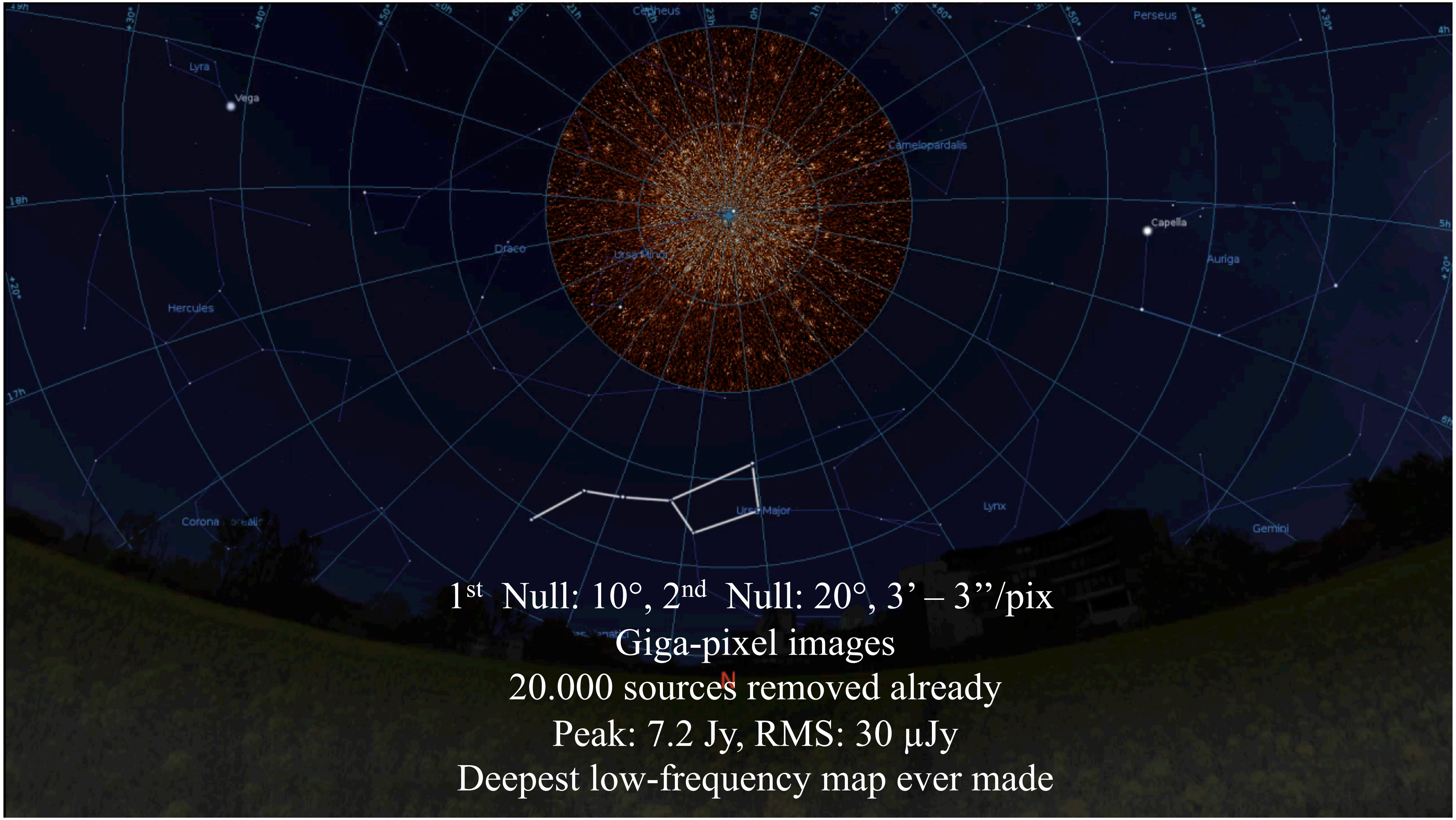

1st Null: 10°, 2nd Null: 20°, 3' – 3''/pix

Giga-pixel images

20.000 sources removed already

Peak: 7.2 Jy, RMS: 30 μJy

Deepest low-frequency map ever made

LOFAR EOR: Current Upper Limits

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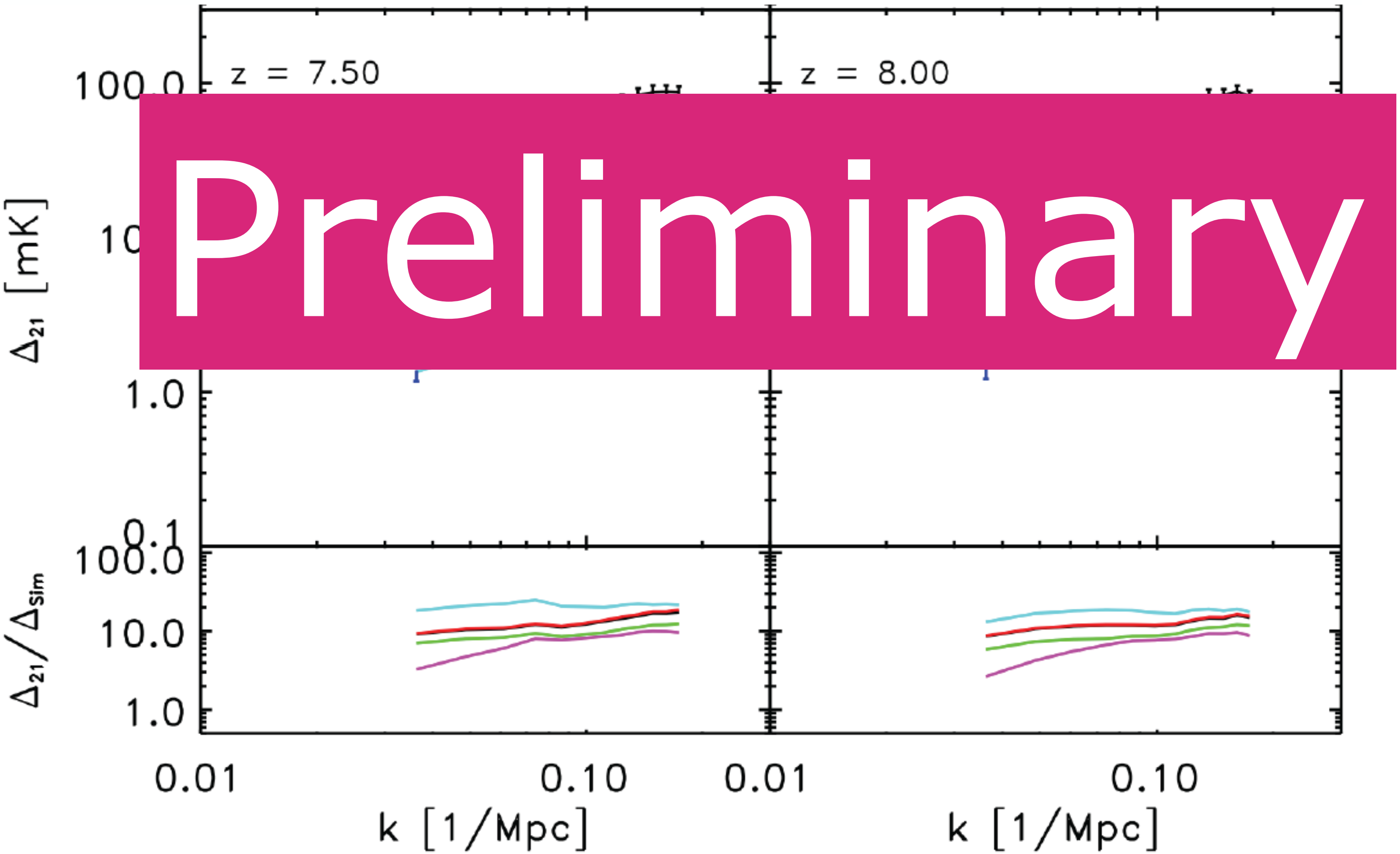

Zaroubi et al. (2016, in prep.)

EoR Status

- Current EoR limits (155h) at z=7.5 to z=10 are at ~20 mK levels at k ~ 0.05 Mpc-1
- Already order of magnitude improvement
- Signal expected between few-10 mK; thermal noise PS is already at/below the signal level !!
- After Cycle 5: 2000 hours of data (NCP, 3C196) of which 900+700 = 1600 h of good quality
- Now processing about one NCP-night/week; as of 1 Dec 2015 a new ERC-funded cluster (Koopmans) is operational, 5-10 x faster
- 2014/15, learning years: discovering ‘systematics’, improved wide-field broad-band calibration
- 2016 and 2017: Years to harvest and hope for first detection of HI from the EoR!

LOFAR EOR KSP: Koopmans, der Bruyn, Zaroubi et al.

Science Topics

- Pulsars
- ISM and magnetic fields
- Radio Galaxies & Surveys
- Epoch of Reionization
- **Ultra-High Energy Cosmic Rays**

PI: Hörandel (Radboud)
Co-PI: Buijtink (Brussels)

Cosmic Ray Spectrum ($\times E^3$)

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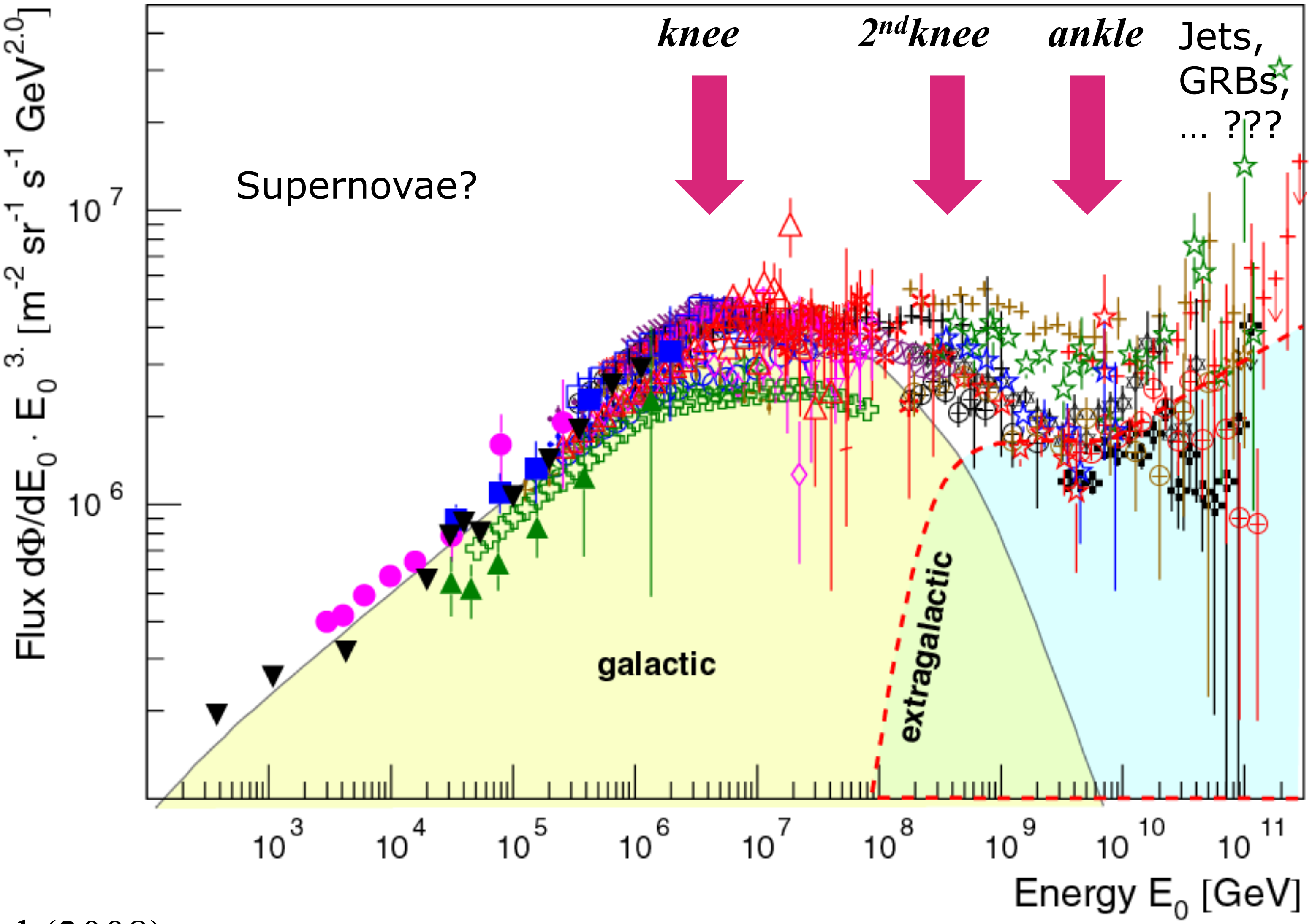
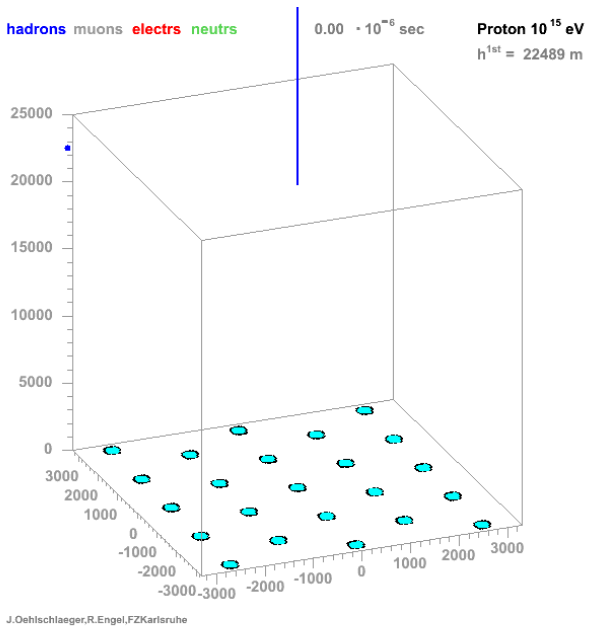
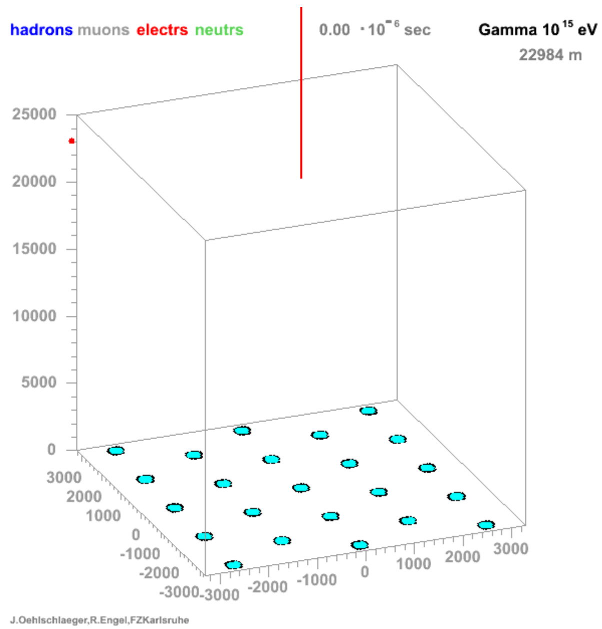


Hörandel (2008)

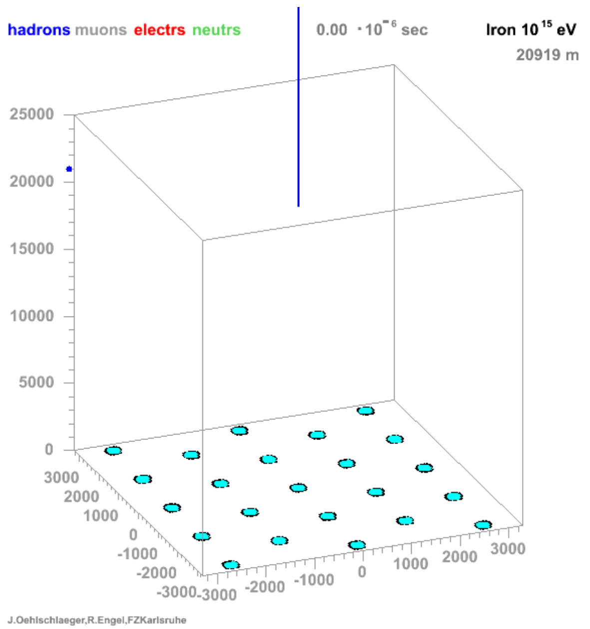
Air showers: simulations



proton



photon



iron nucleus

Coherent Geosynchrotron Radio Pulses in Earth Atmosphere

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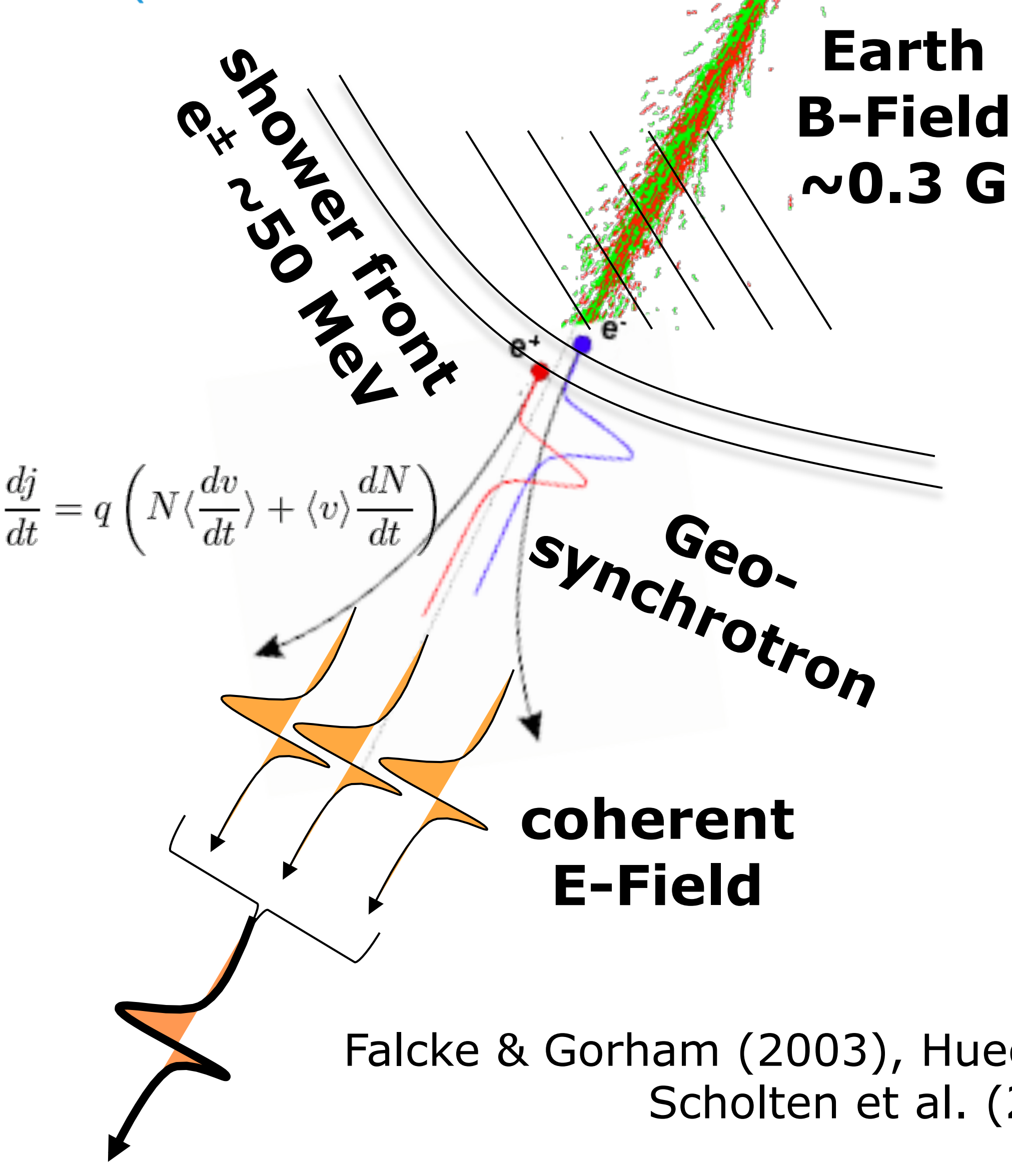


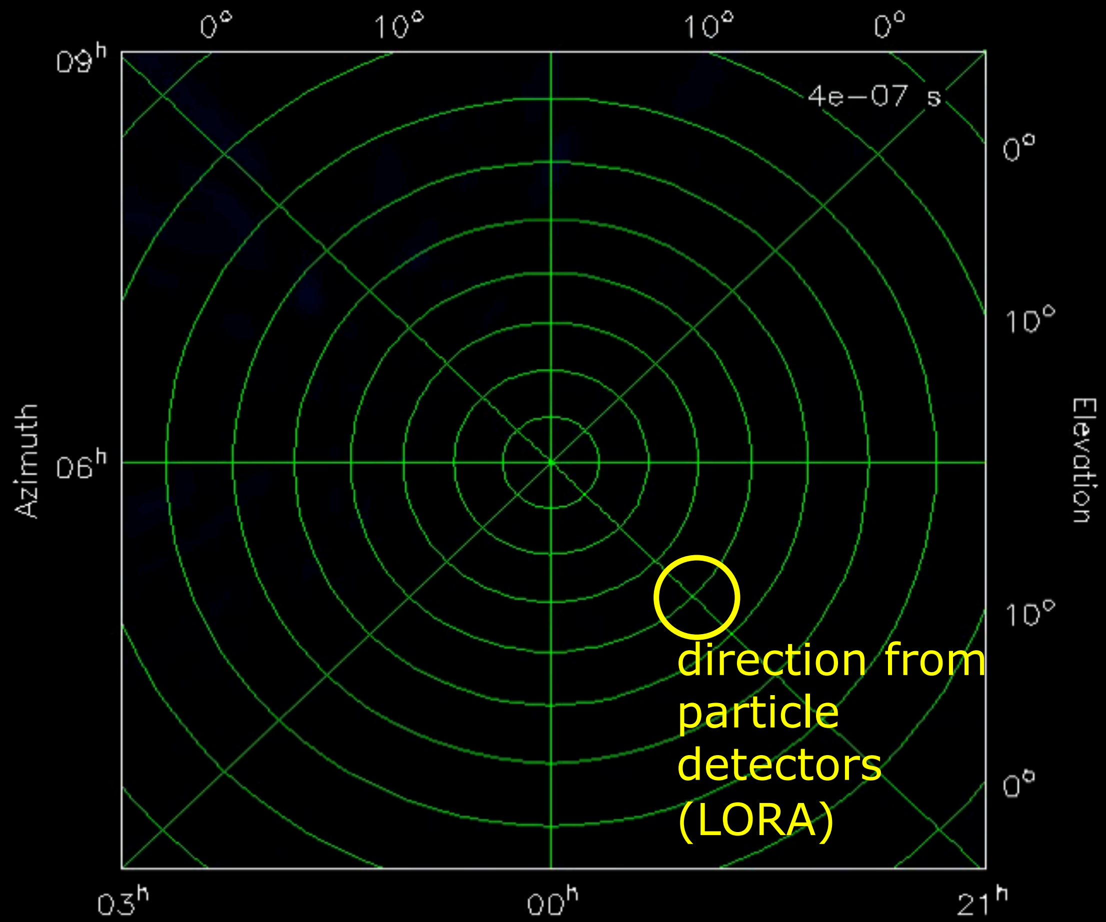
- UHECRs produce particle showers in atmosphere
- Shower front is ~2-3 m thick ~ wavelength at 100 MHz
- $e^{\pm}$ emit synchrotron in geomagnetic field
- Emission from all $e^{\pm}$ (N_e) add up coherently
- Radio power grows quadratically with N_e

⇒ $E_{total}=N_e*E_e$
⇒ Power $\propto E_e^2 \propto N_e^2$
⇒ GJy flares on 20 ns scales

Falcke & Gorham (2003), Huege & Falcke (2004,2005), Scholten et al. (2007-2011)

Imaging Nanosecond Radiopulses

Cosmic ray radio signal imaged with data from single LOFAR station



Footprint of an air shower

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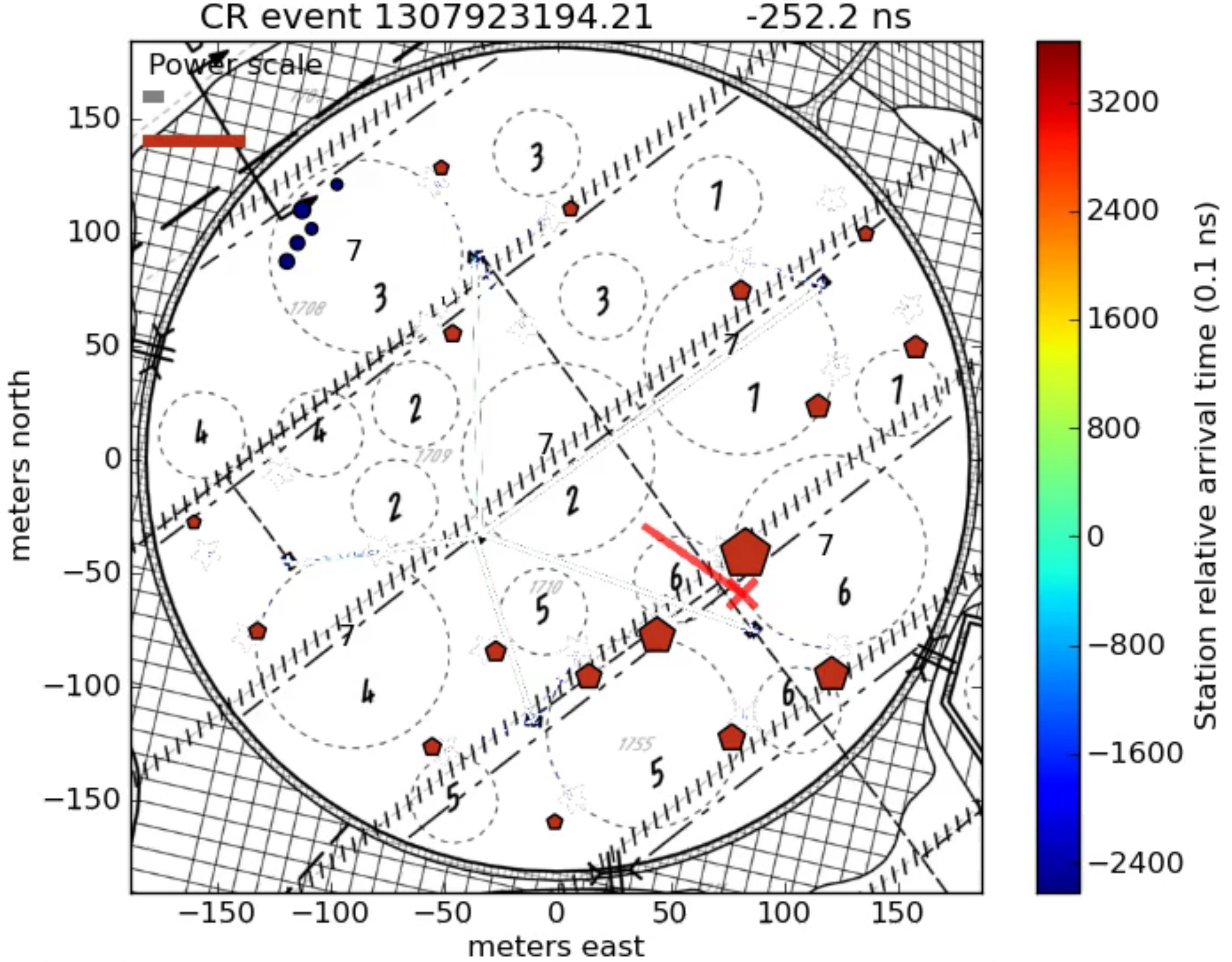
Most densely instrumented measurements of air shower radio emission!



Circles: LOFAR antennas, Pentagons: LORA particle detectors, size denotes signal strength

S. ter Veen

Monte Carlo simulation of radiation processes: The endpoint formalism

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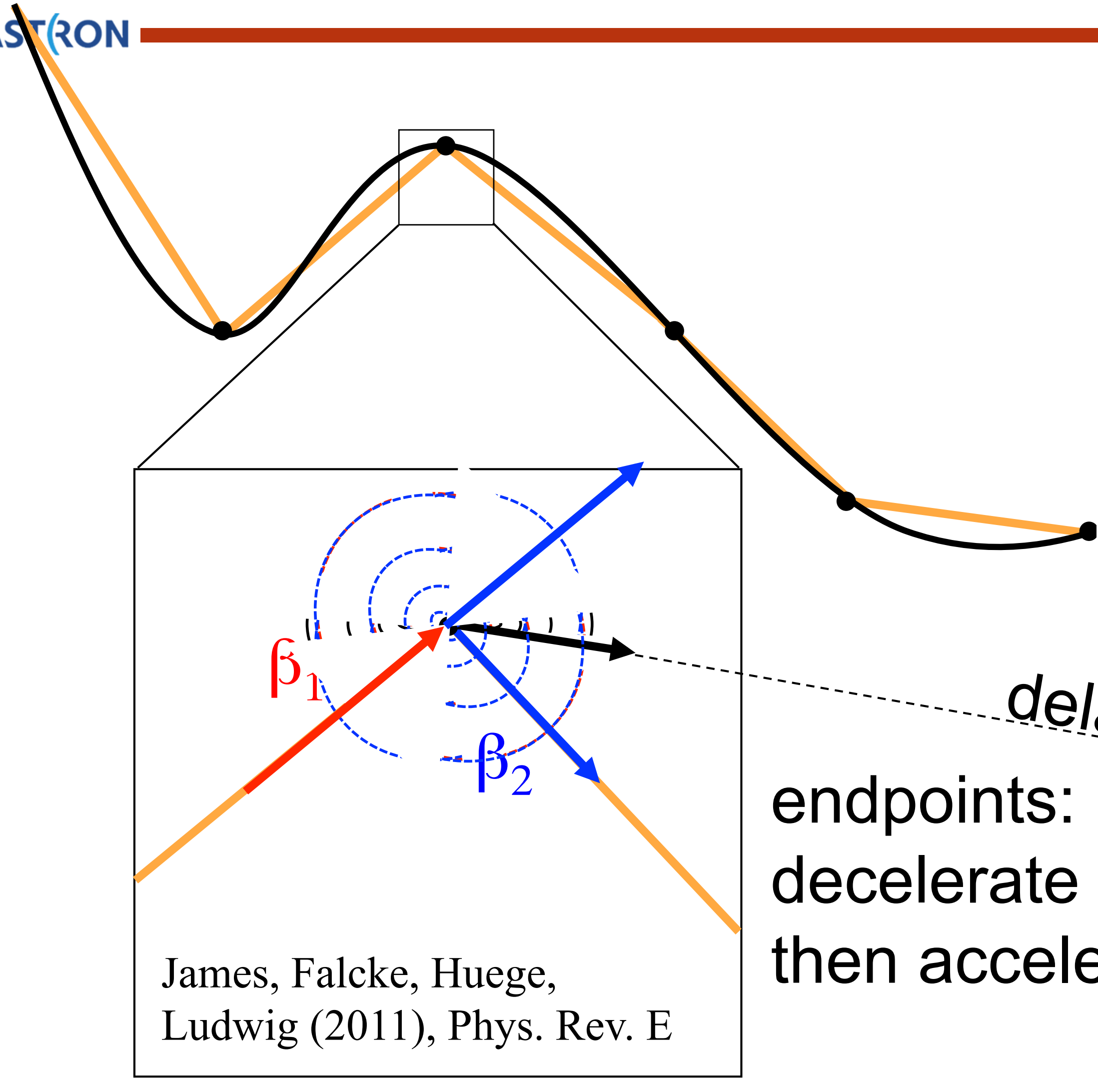
IN·DEI·NOMINE·FELICITER



- discrete formulation for arbitrarily complex motion
- radiation *only* from endpoints
- Coupled to CR Monte Carlos codes

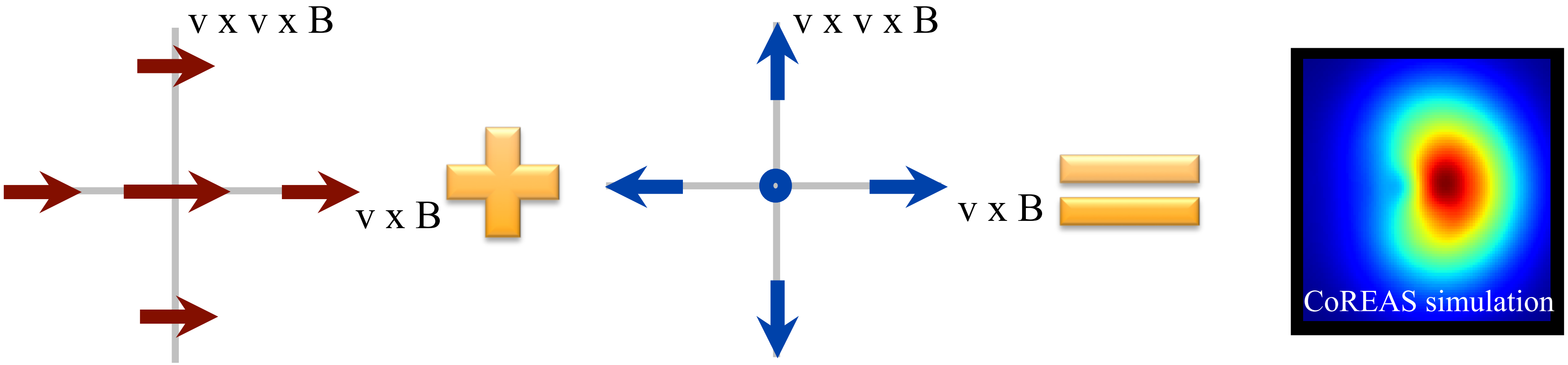
delay: R/c

endpoints:
decelerate from β_1 to rest
then accelerate from rest to β_2

antenna

Couple this to CORSIKA air shower code and predict Radio Emission from Extensive Airshowers
→ **CoREAS code** (Huege et al. 2011,2013)

Radio Emission Pattern inherently 2D



E-field vectors
geomagnetic

E-field vectors
charge excess

- vector sum of geomagnetic and charge excess component
- relativistic beaming
- Cherenkov-like propagation effects ($n \neq 1$)

All radiation effects covered in simulations automatically by endpoint-method!

Emission Pattern at Low Frequencies: Theory & Observation

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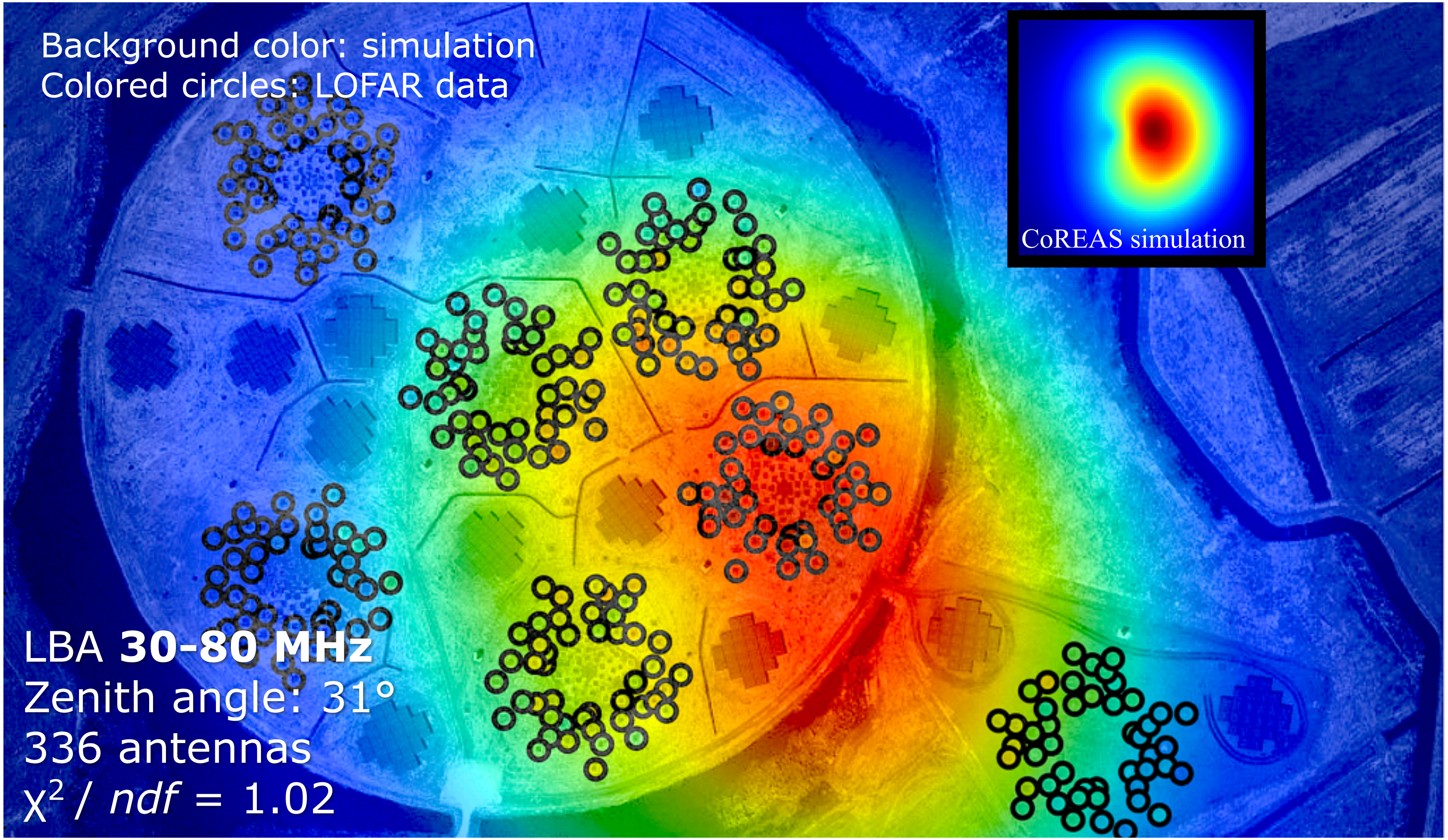

Emission Pattern at High Frequencies: Cherenkov-Like Ring

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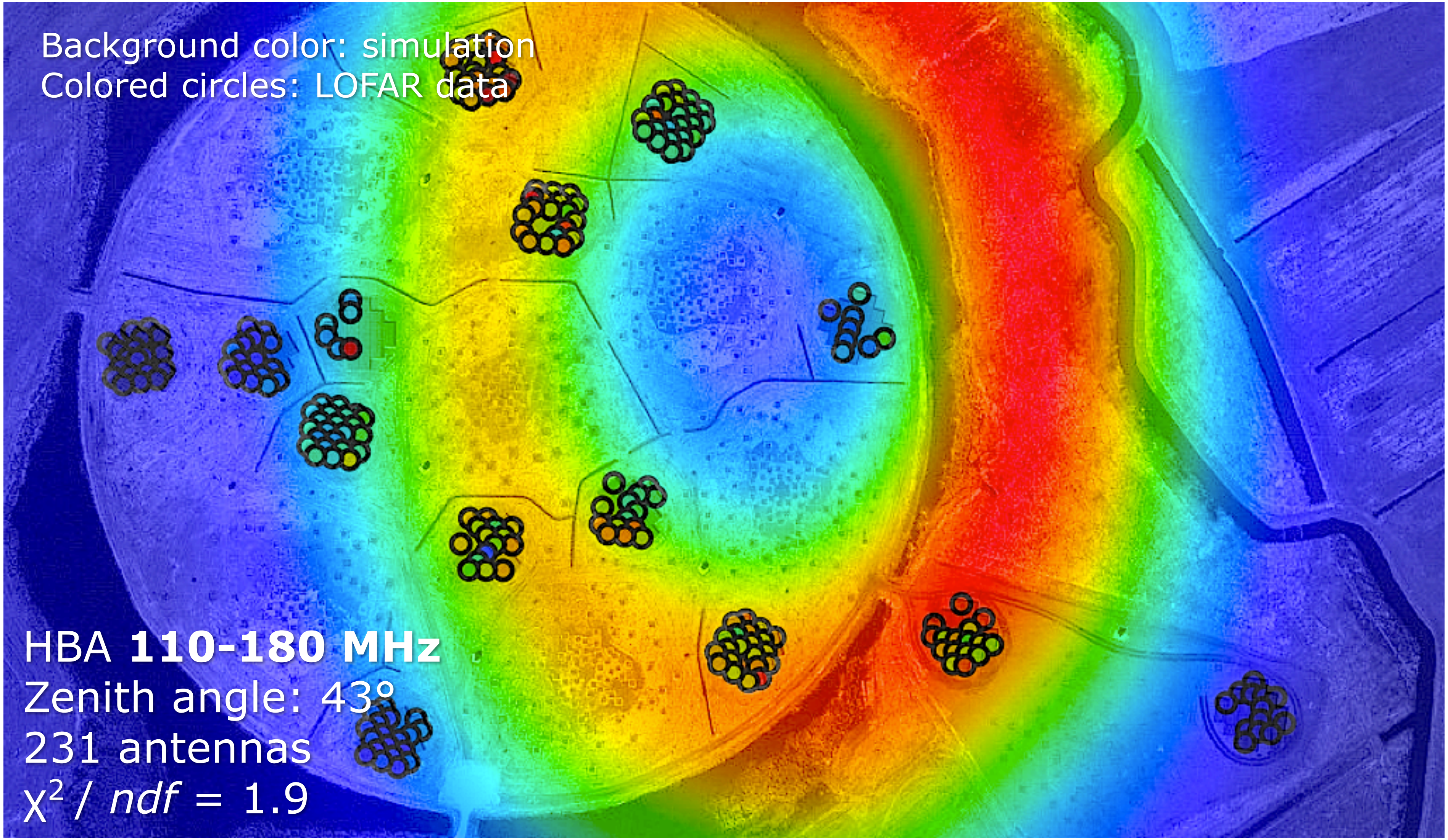

Nelles et al. (2014), Astropart. Phys., subm.

Radio Lateral Distribution Function (LDF)

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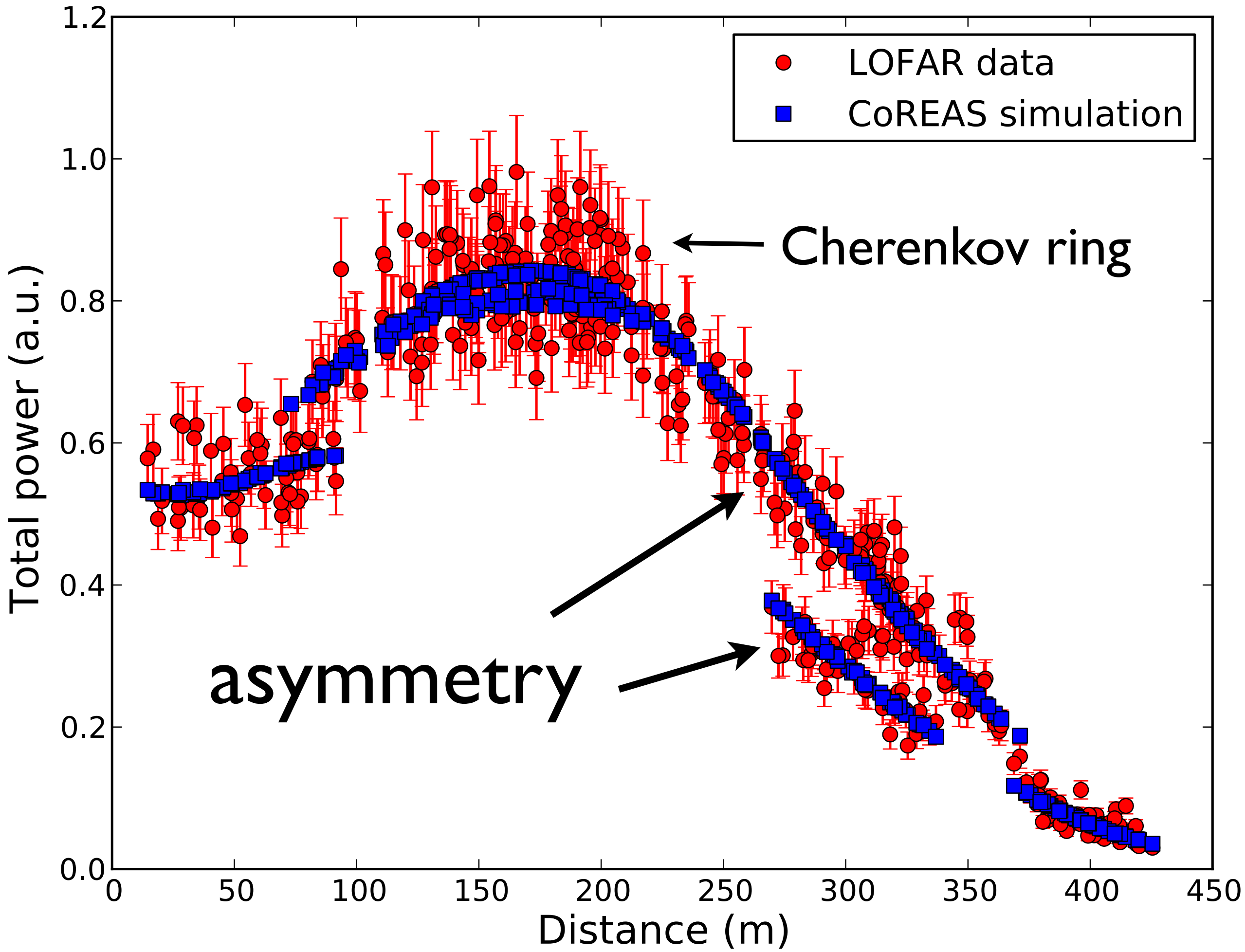

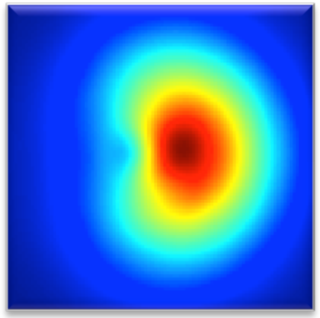

Model vs Data

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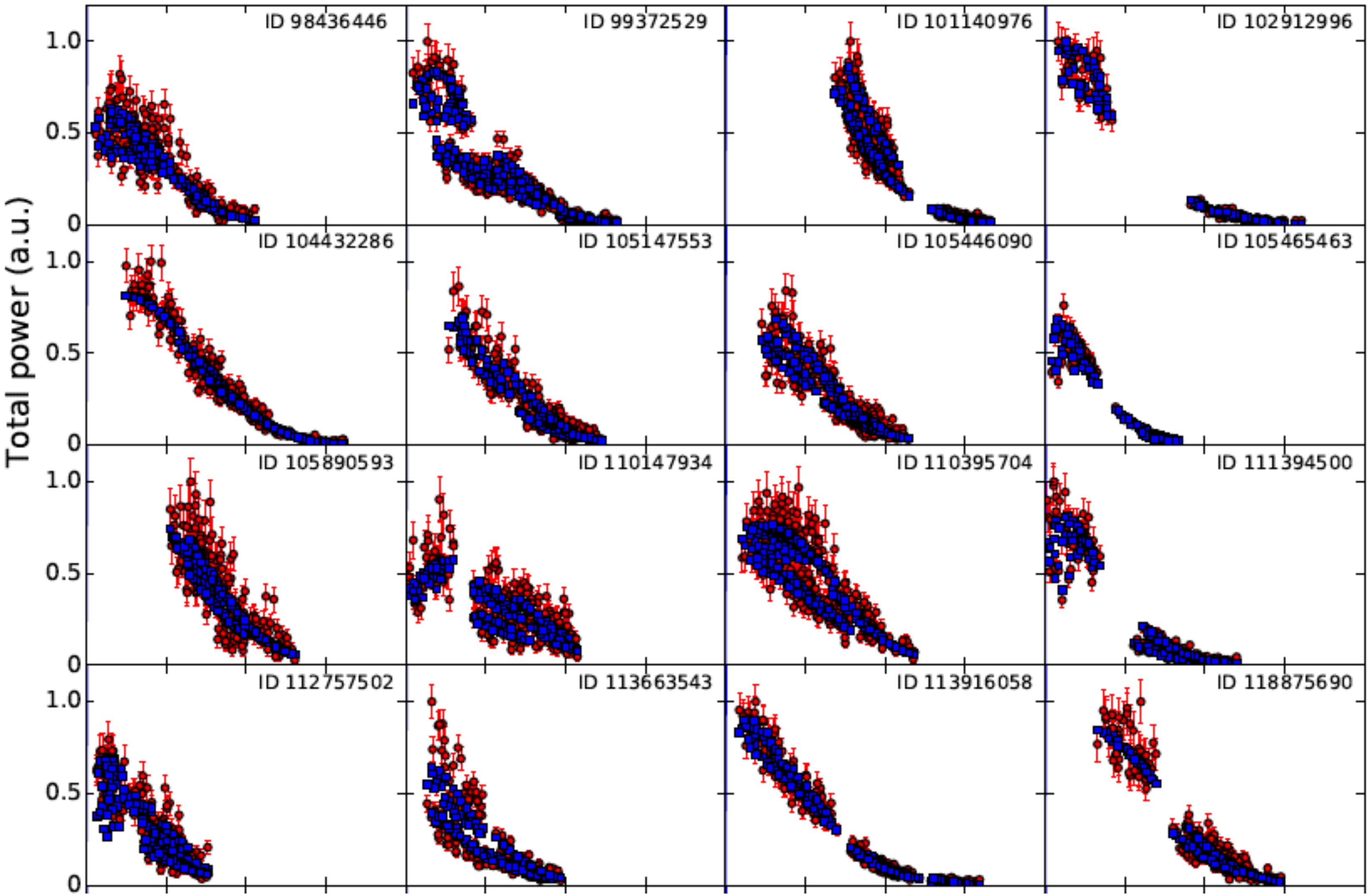

Buitink et al. (2015, Nature, accepted)

X_{max} from LOFAR

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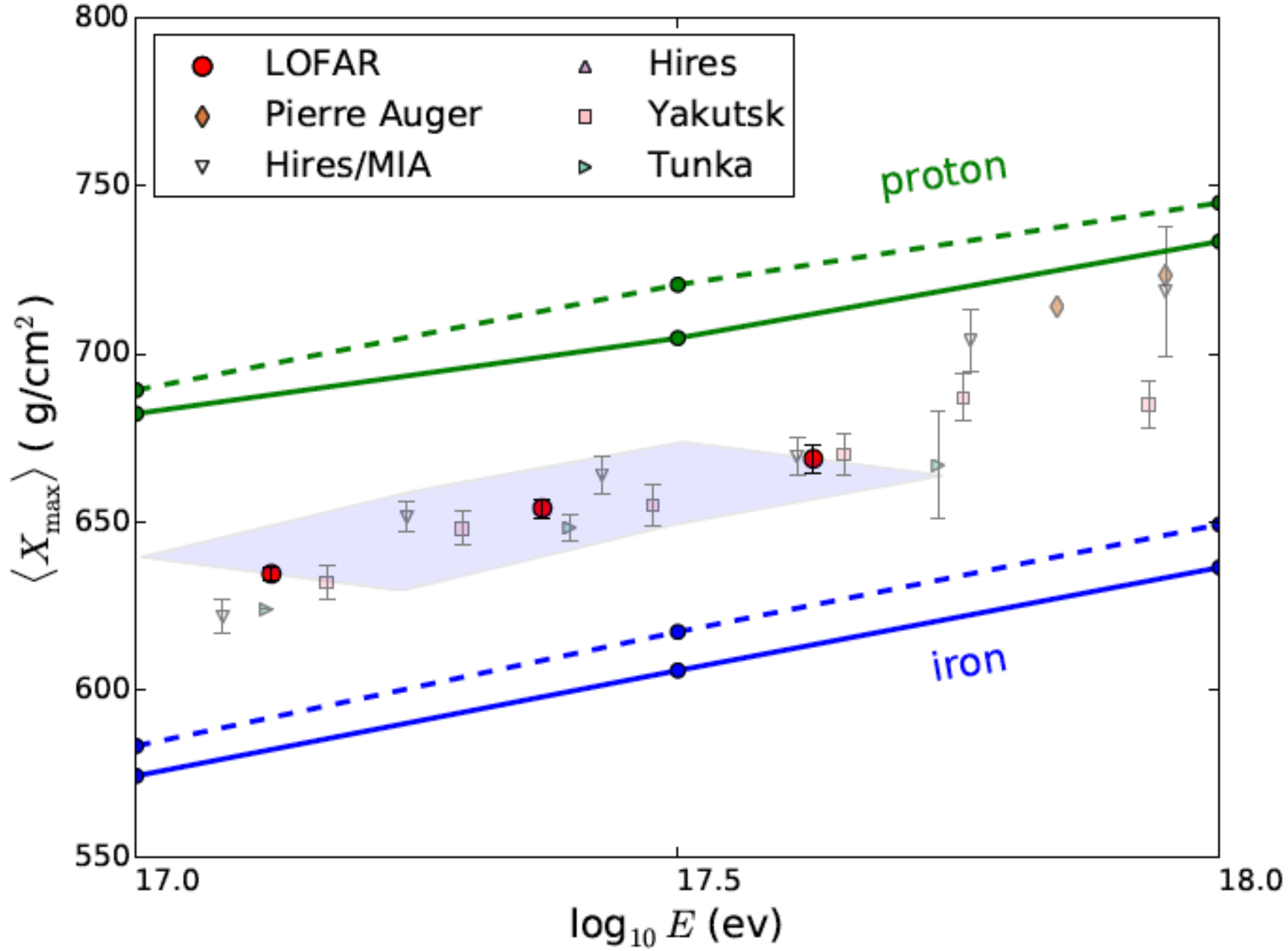

Buitink et al. (2016, Nature, accepted)

Unbinned Composition Analysis

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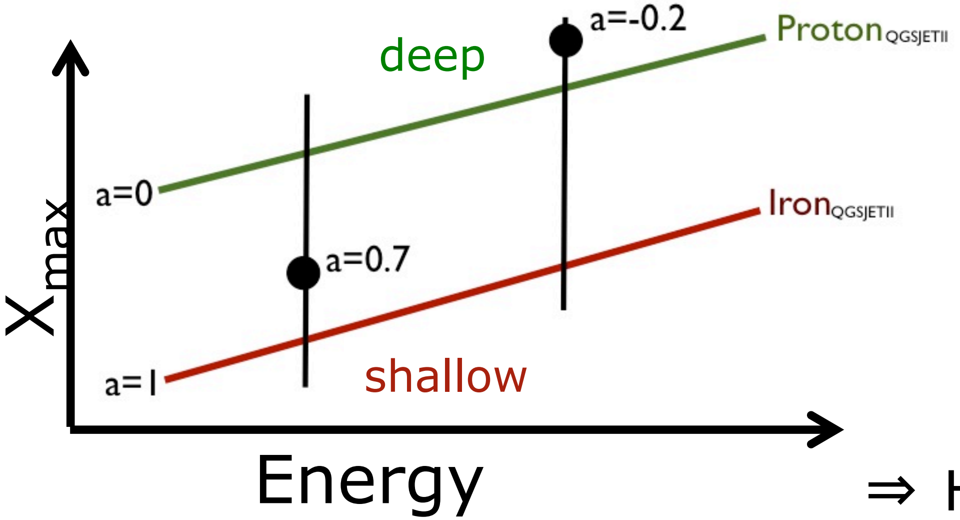
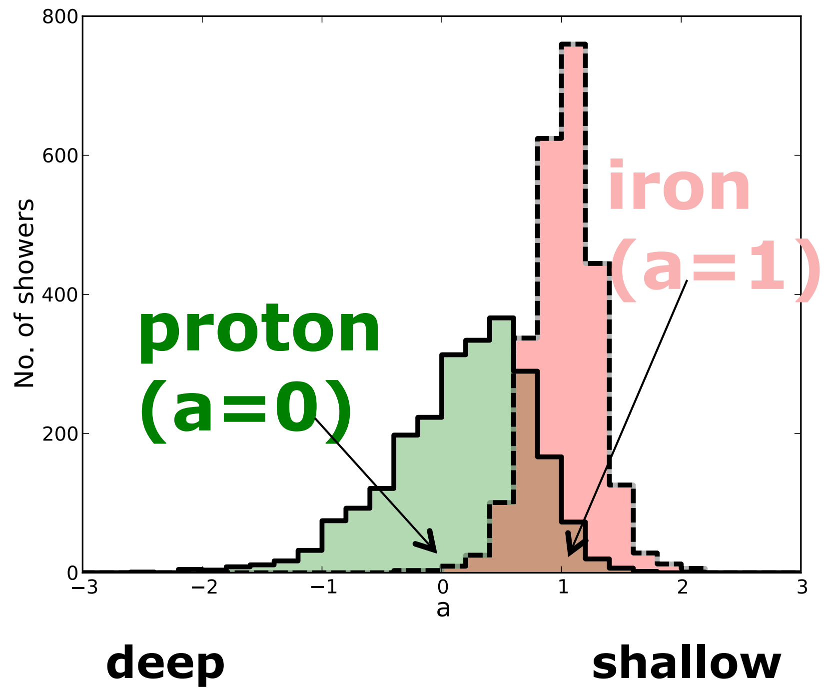
Calculate energy-independent mass parameter *a* for each event.

$$a = \frac{\langle X_{\text{proton}} \rangle - X_{\text{shower}}}{\langle X_{\text{proton}} \rangle - \langle X_{\text{iron}} \rangle}$$



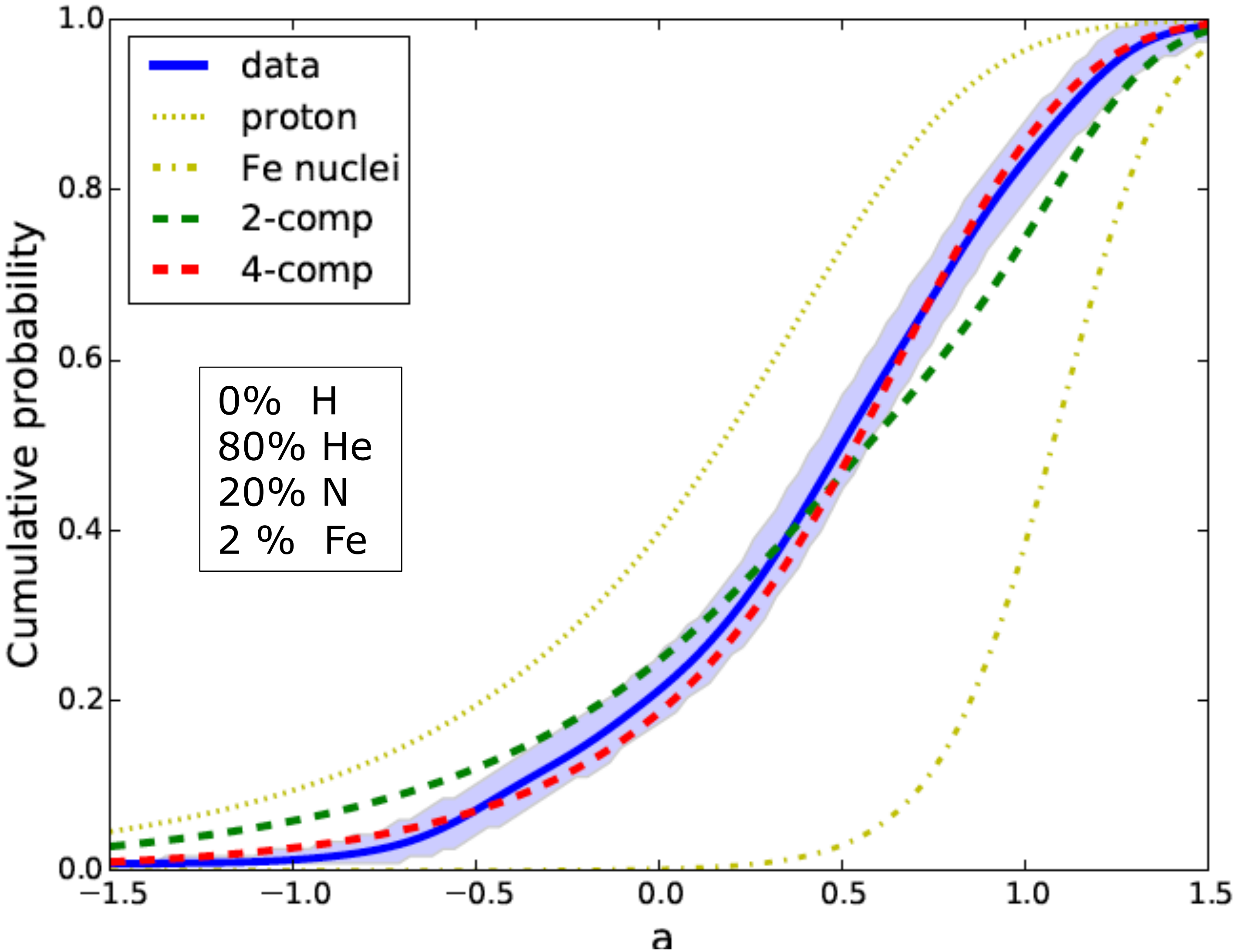
Buitink et al. (2014, PRD)

Simulated distribution of iron and proton showers for LOFAR resolution



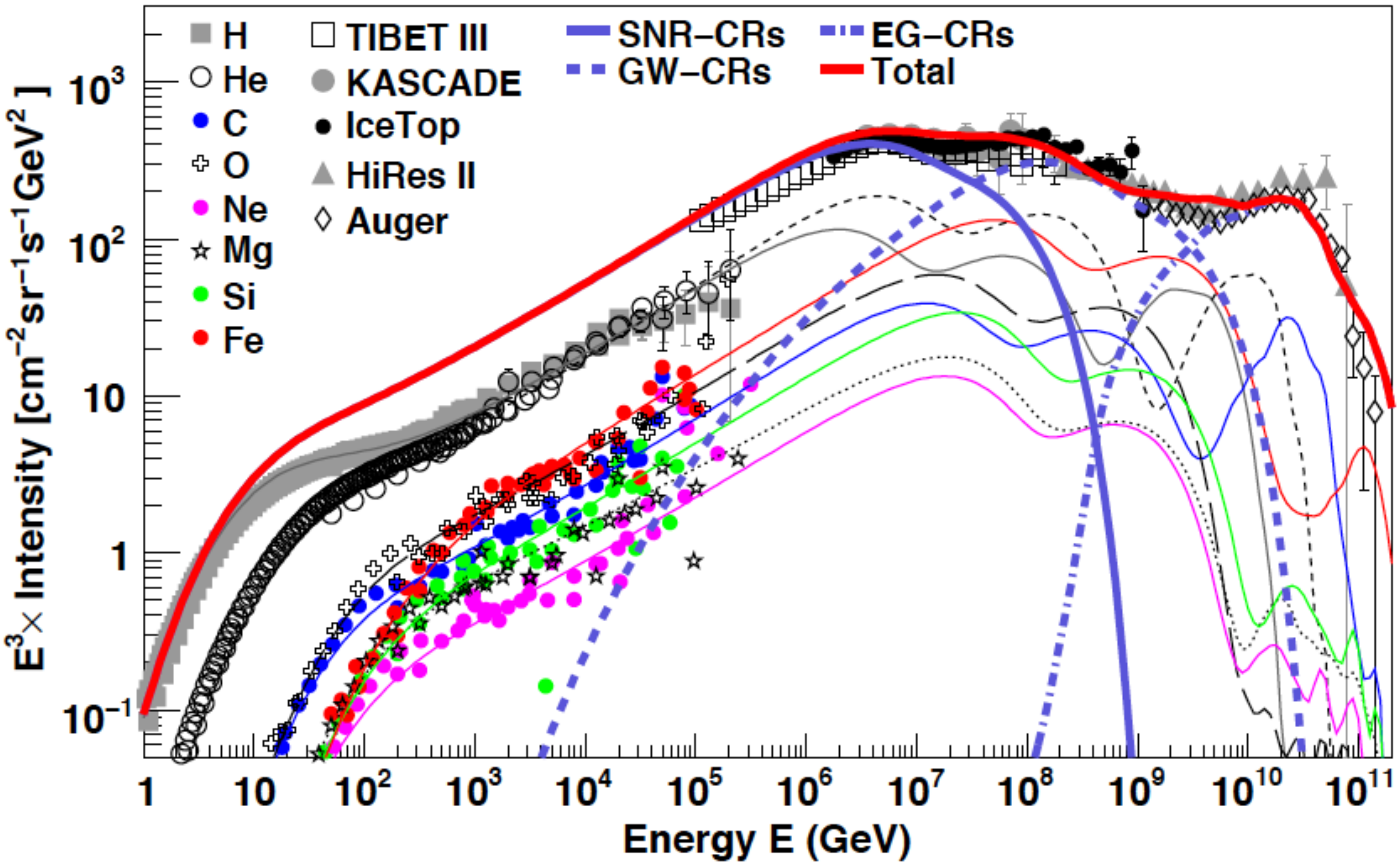
⇒ High X_{max} resolution allows distinction between pure iron, pure proton, or mixed composition!

LOFAR Composition Fit



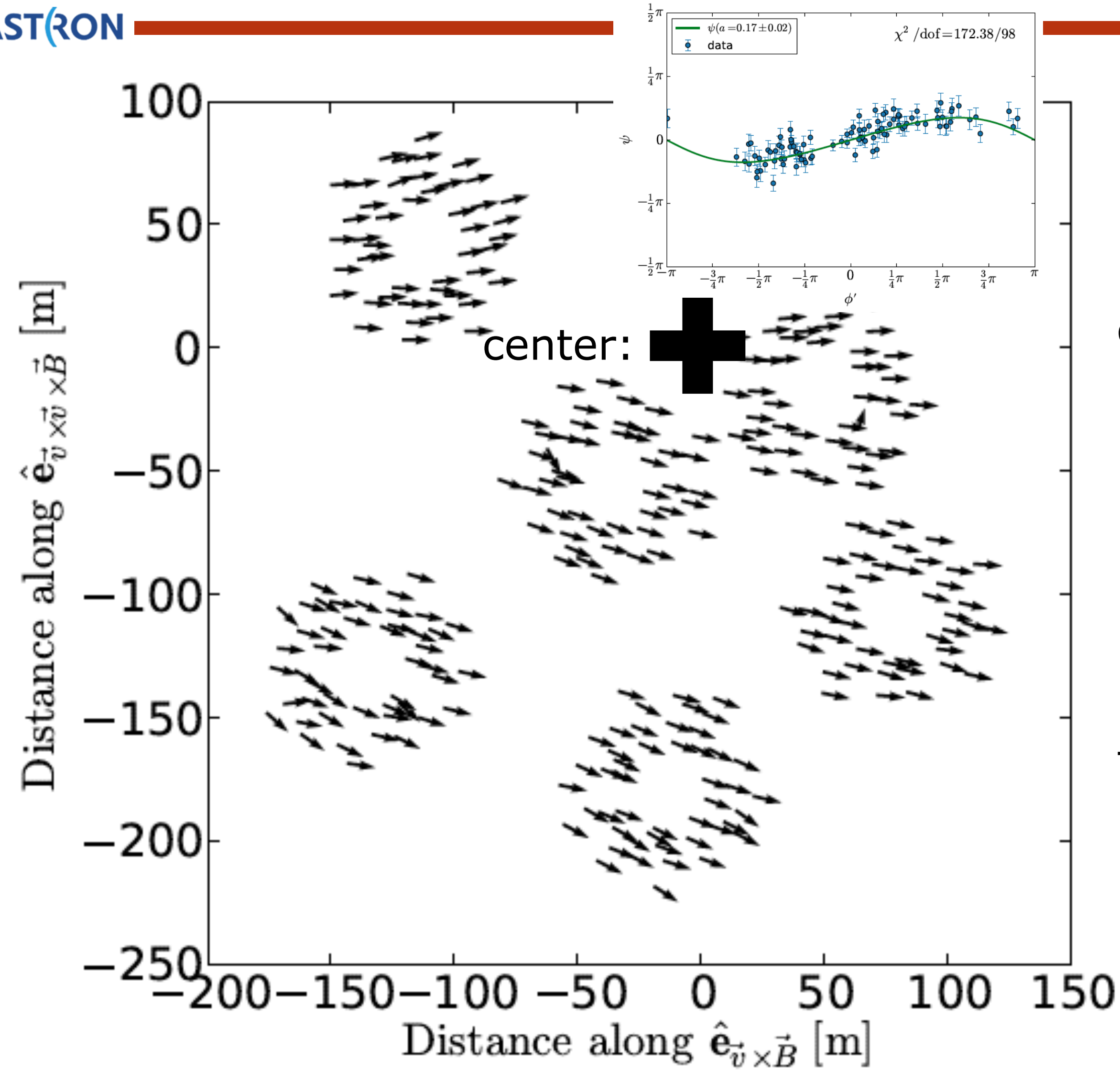
Buitink et al. (2015, Nature, accepted)

The Cosmic Ray Spectrum



Thoudam et al. (2016, in prep.)

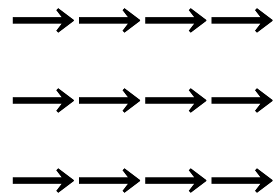
Air Shower Polarization



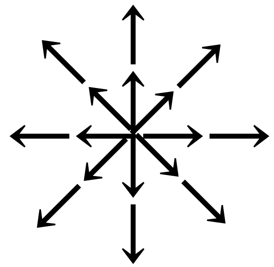
Schellart et al. (2014)

Polarization very regular:

100% polarization in **v** x **B** plane due to dominant geosynchrotron radiation



plus some radial contribution from charge-excess radiation



Polarization – Thunderstorms and Geoelectric Fields

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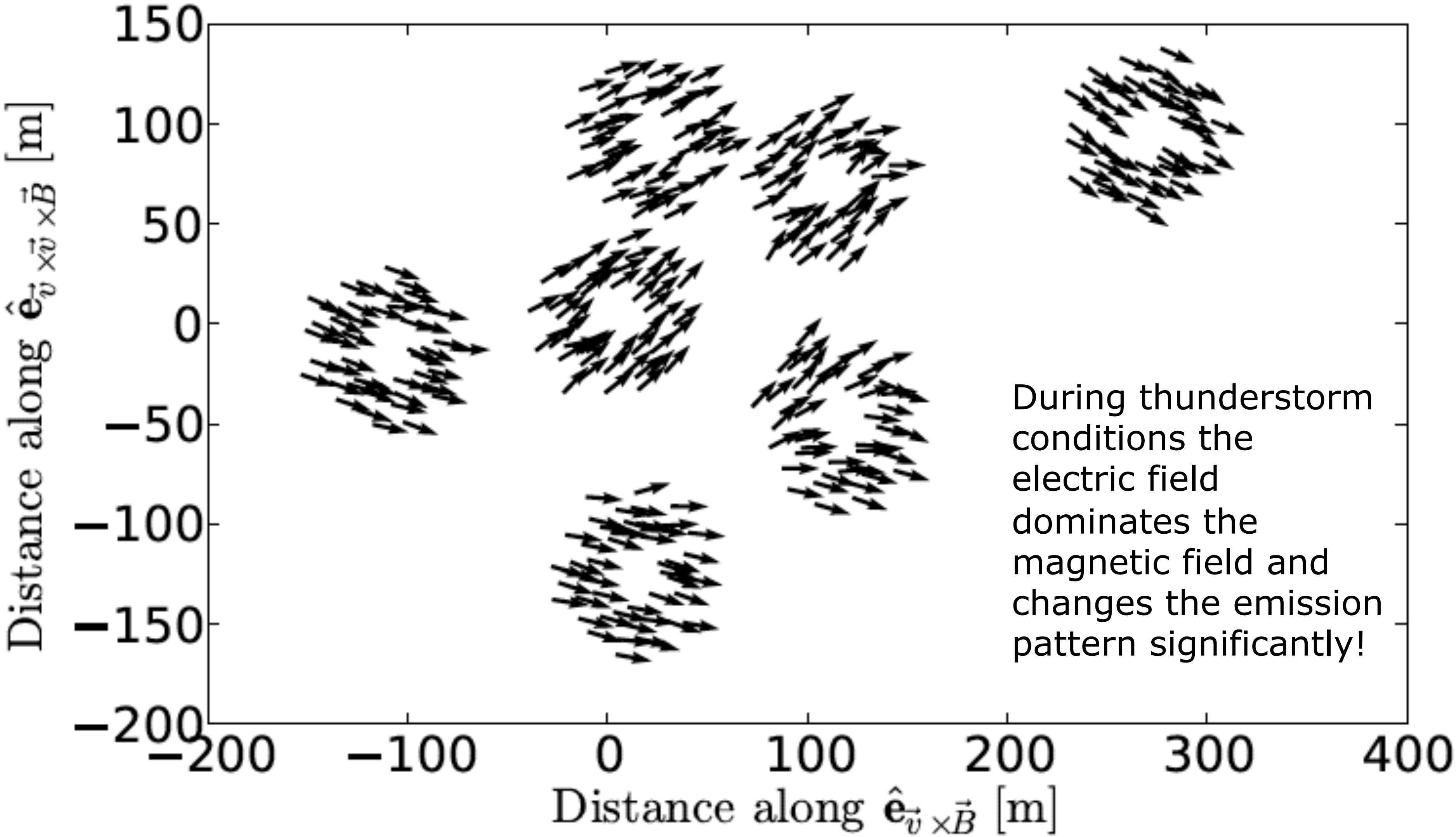

Schellart et al. (2015, PRL)

Lightning & Cosmic Rays: Astroparticlegeophysics

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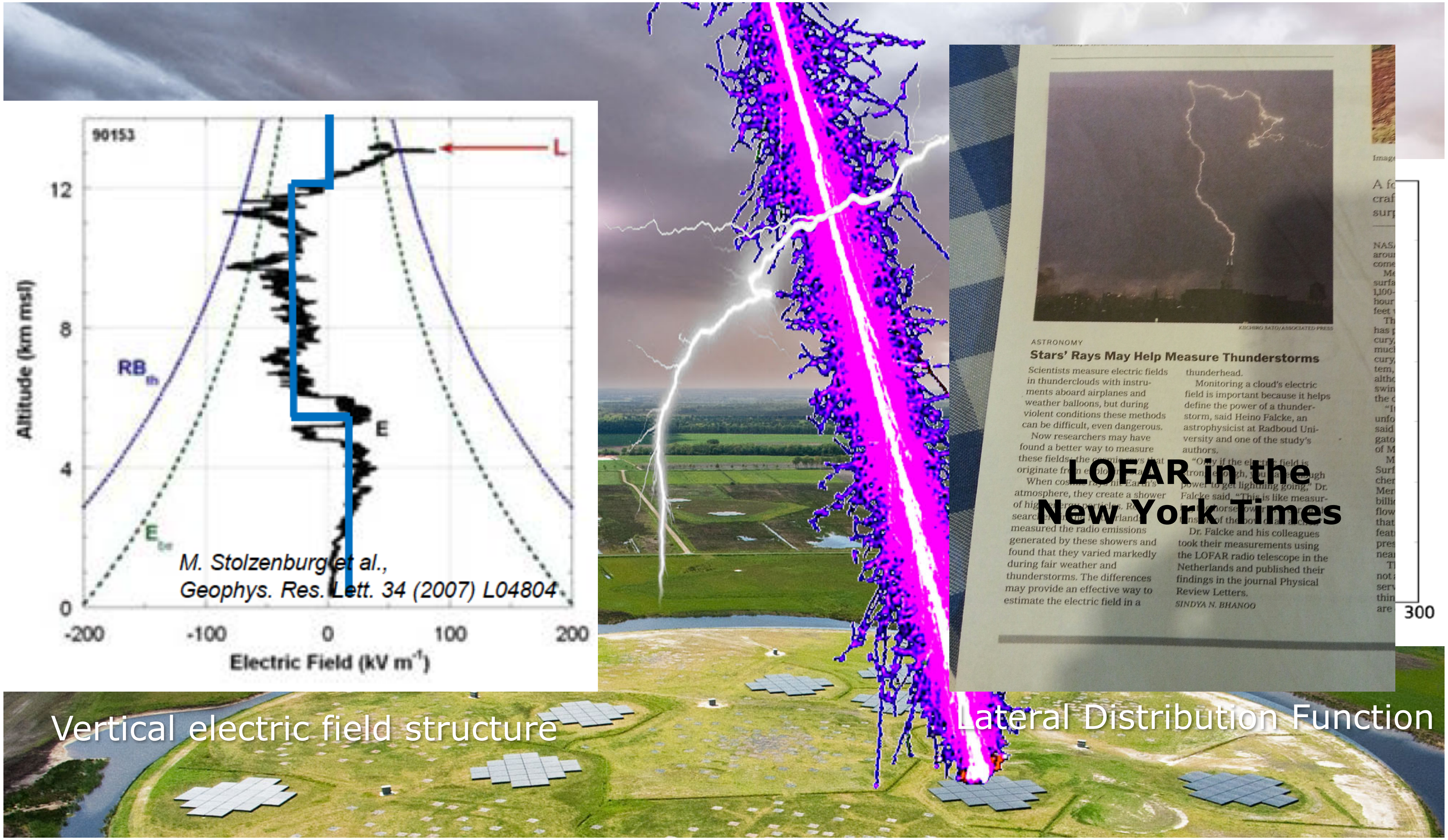

Schellart et al. (2015, PRL), Tran et al. (2016, PRD)

Conclusion

- LOFAR works (better every week ☺)
- Shattered all world records at low frequencies:
  - Highest resolution, highest sensitivity, highest dynamic range, densest air shower measurements
- A lot of diverse and exciting science coming up:
  - Pulsars: Discovery, Follow-up, Interstellar medium
  - Interstellar medium: Radio-Recombination Lines, magnetic fields
  - Multi-frequency radio surveys: Black holes, supernovae, transients
  - Epoch of Reionization: order of magnitude improved limits, on track for discovery
  - Cosmic Rays: composition and energy (also at Auger!!)
- Future: LOFAR2.0, SKA, and … LOFAR on the moon!