



LOFAR SCIENCE

R. F. Pizzo

OUTLINE



- The Low Frequency Array
 - The science drivers of LOFAR
 - Recent science highlights
 - Science output



LOFAR SCIENCE DRIVERS



Key Science Projects

Epoch of Reionization

Transients and Pulsars

High Energy Cosmic Rays

Surveys and Distant Universe

Cosmic Magnetism

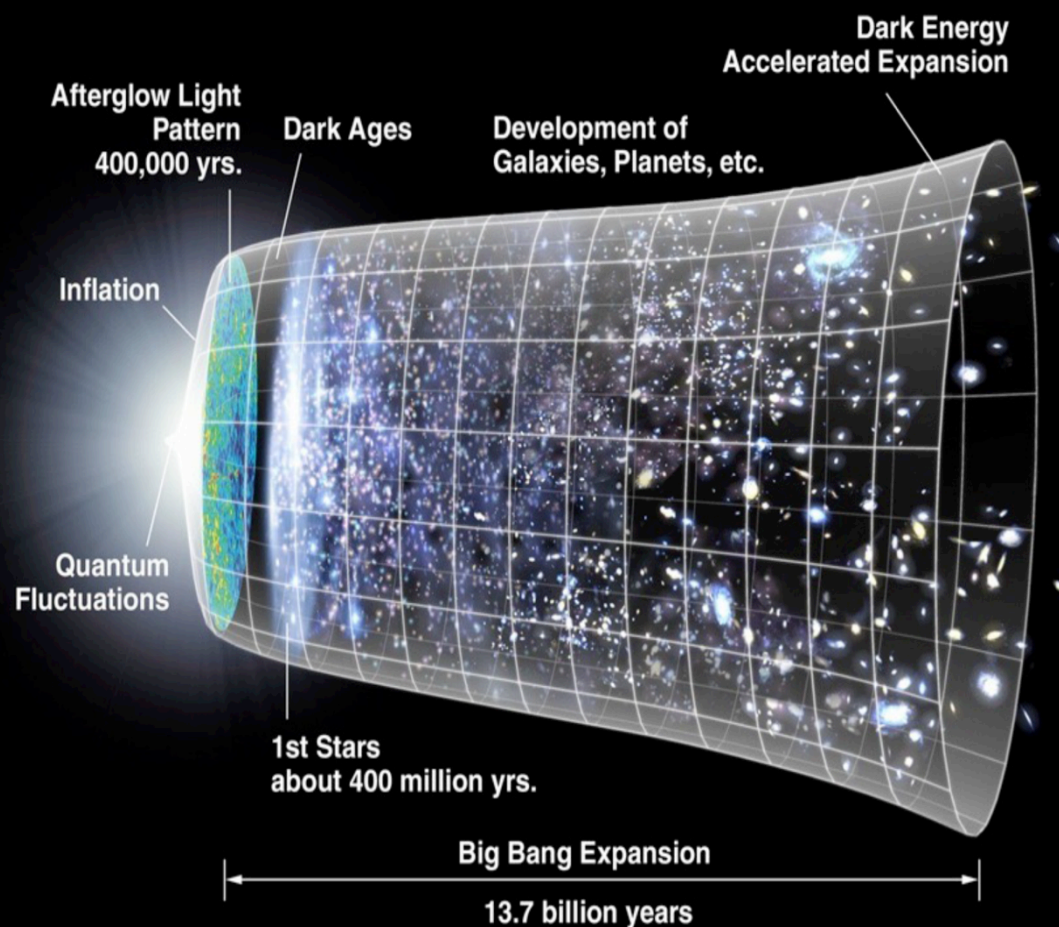
Solar Physics and Space Weather

International membership from countries all over the World

Contribute development and commissioning resources

The LOFAR Epoch of Reionization

Key Science Project



- When was the Universe reionized ?
- How (fast) did reionization proceed ?
- Which objects were responsible ?
stars/galaxies , QSOs, or ...

Redshifted HI to frequency mapping

$z = 6.7 \Rightarrow 185 \text{ MHz}$

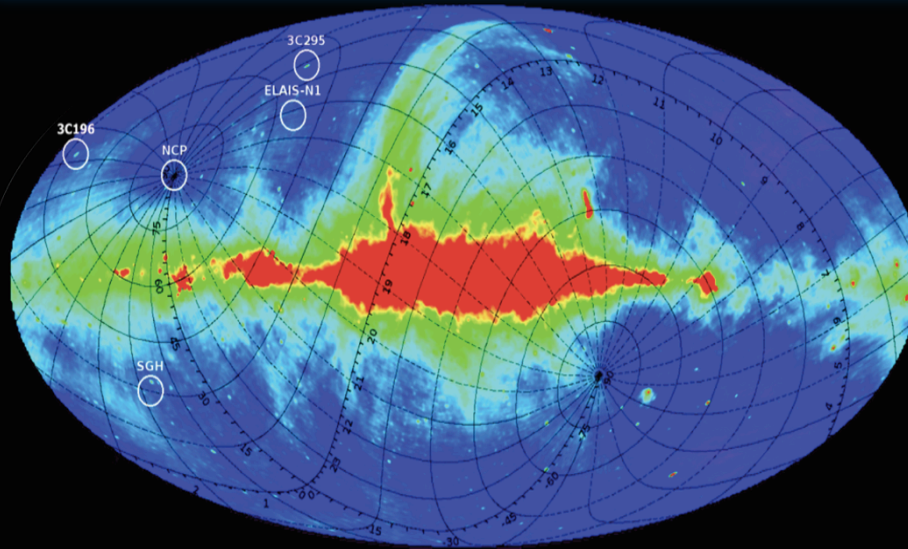
$z = 8.5 \Rightarrow 150 \text{ MHz}$

$z = 11.4 \Rightarrow 115 \text{ MHz}$

Goal: Detect cosmological 21cm signal ($z \sim 6-10$) from the Epoch of Reionization

$\Rightarrow 1.5 \text{ Pbytes and } 10^{21}\text{-}10^{22} \text{ FLOP to extract signal!}$

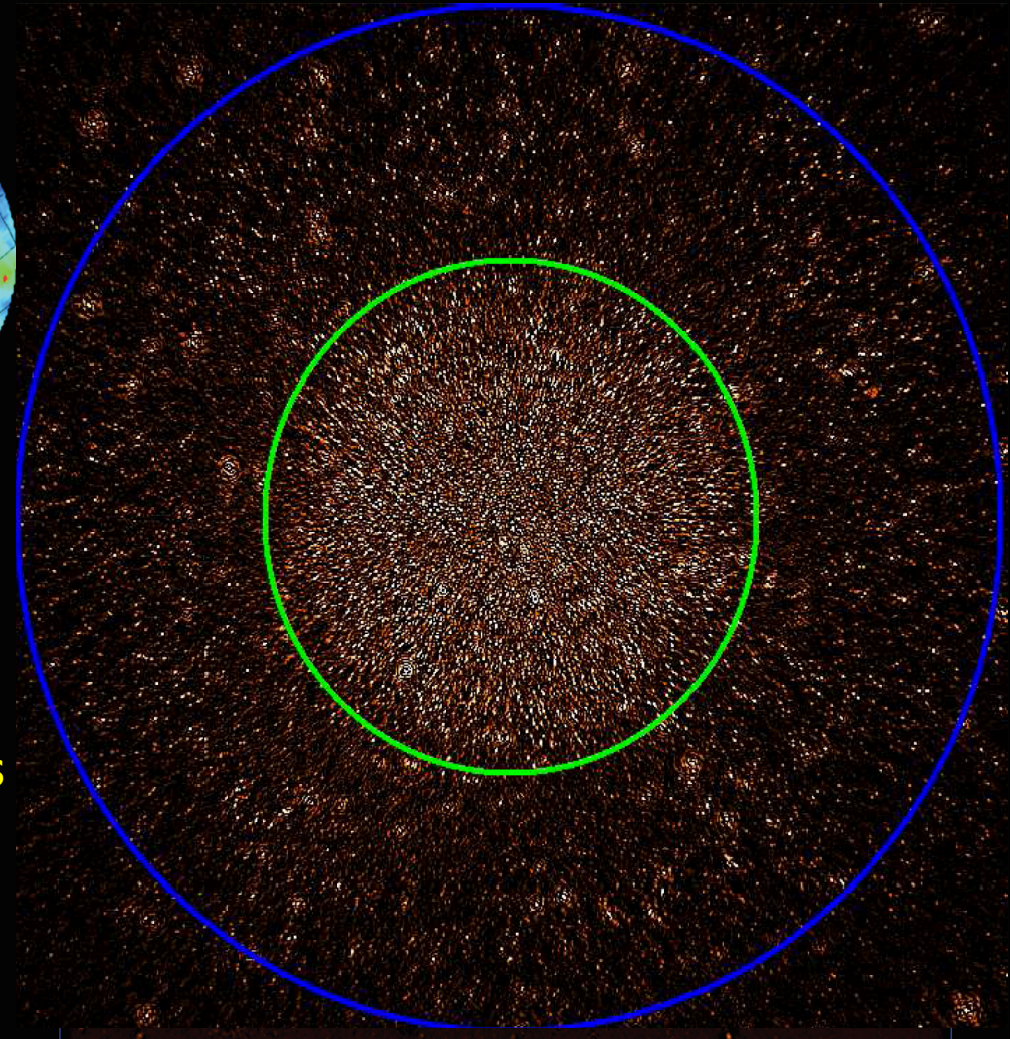
EoR DEEP FIELDS – FIRST RESULTS



- Total 2000+ hours allocated
- Focus on 2 distinct fields
- Custom processing on EoR clusters

$$\sigma = <50 \mu\text{Jy} \quad \theta \sim 5''$$

- 60 MHz bandwidth
- 20 deg x 20 deg

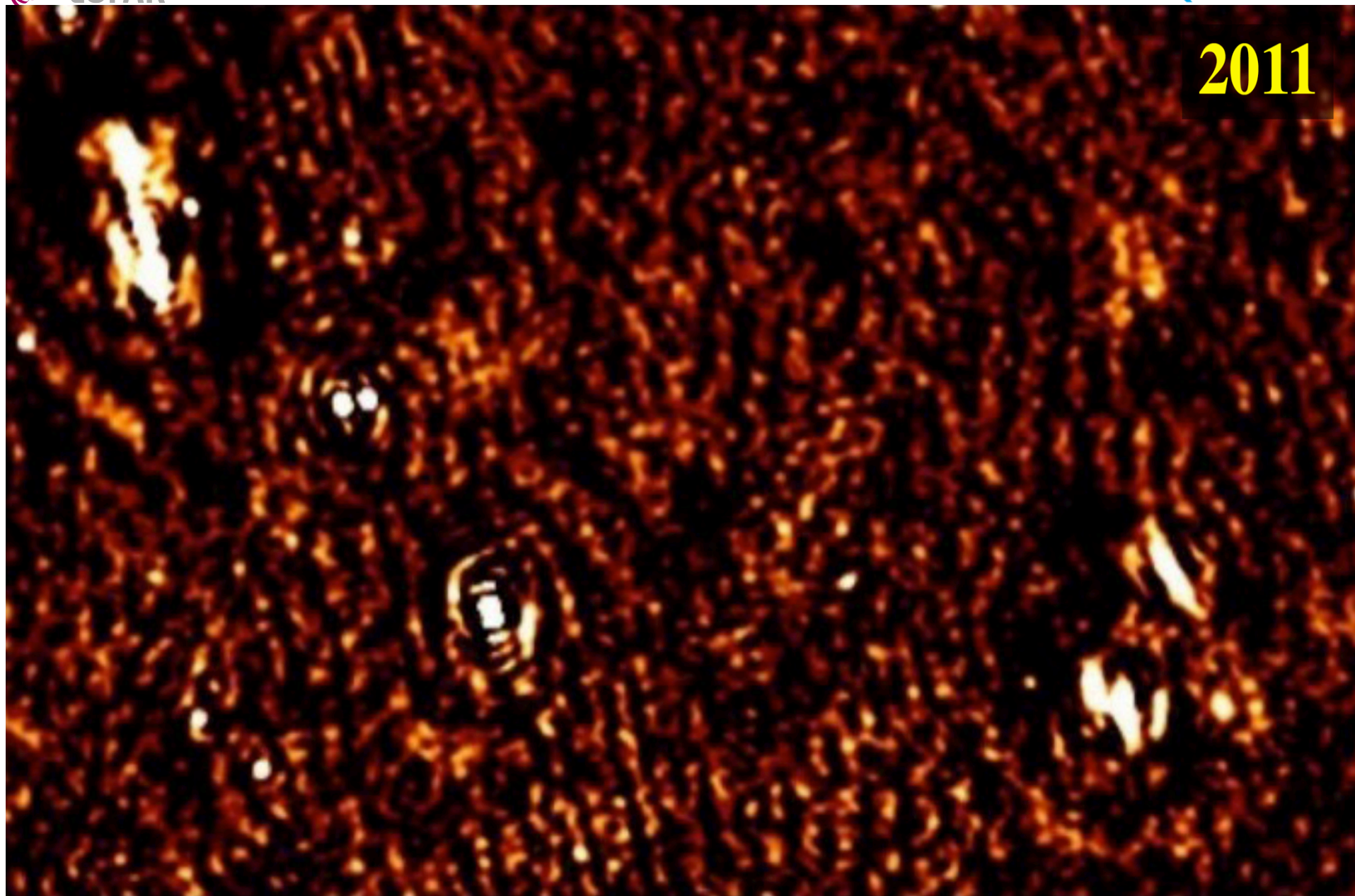


(courtesy S. Yatawatta and the EoR KSP Team)

EoR DEEP FIELDS – FIRST RESULTS



2011



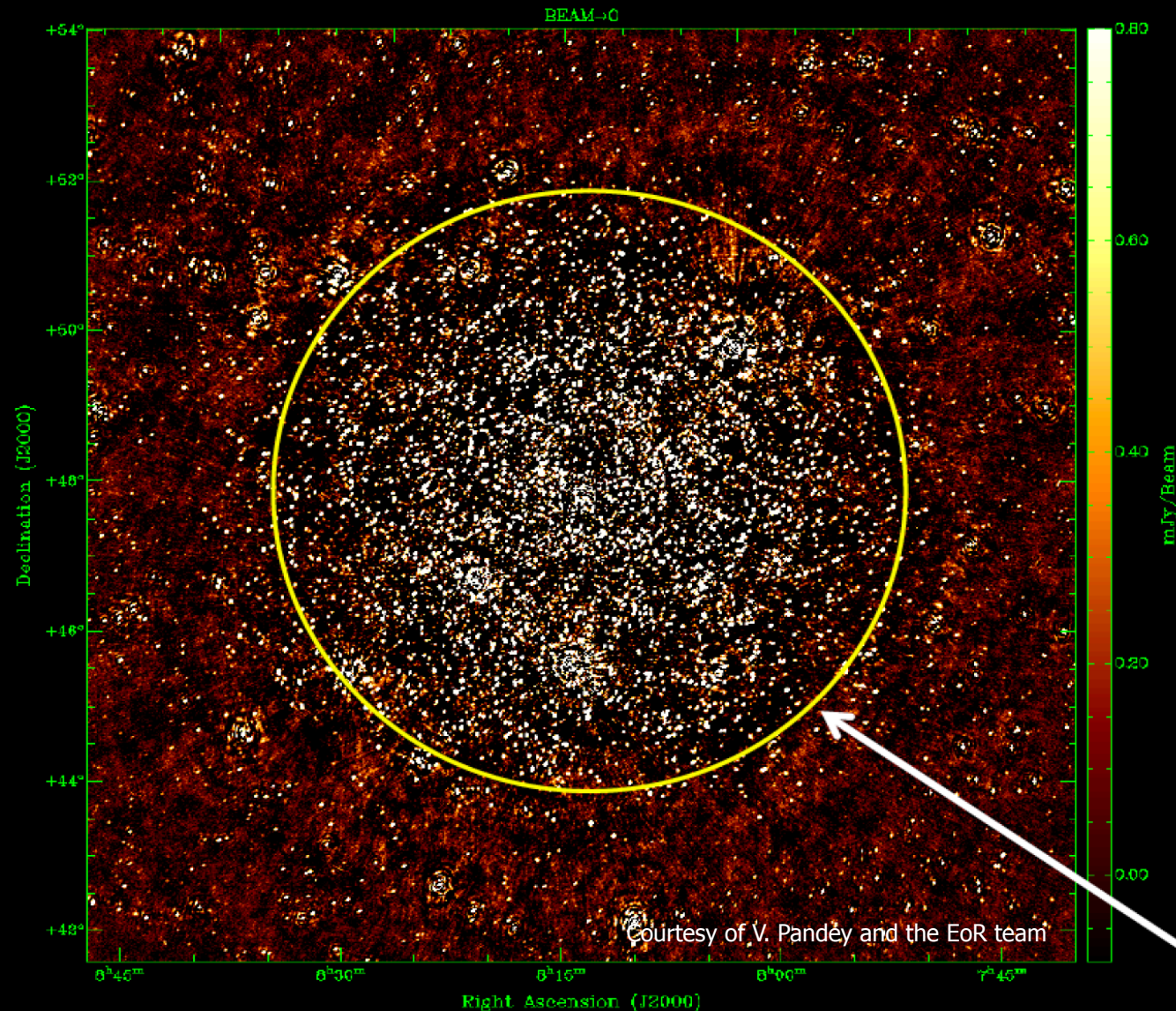
EoR DEEP FIELDS – FIRST RESULTS



2013

$\sigma = 25 \mu\text{Jy}/\text{beam}$! Weak
sources visible even at
peak 100 μJy level!

EoR DEEP FIELDS – 3C196



0.8 mJy

- 145 MHz (~2m)
- 60MHz continuum
- 6 powers of 10
- 32 hours on 3C196 (8 hrs x 4 days)
- Dec 21,12-Feb08,13
- 30 λ - 5000 λ
- Resolution - 50''
- 12 $^{\circ}$ x 12 $^{\circ}$ Image
- 'Noise' < 75 μ Jy
- 3C196 - 79.97 Jy
- DR: $\sim 10^6:1$

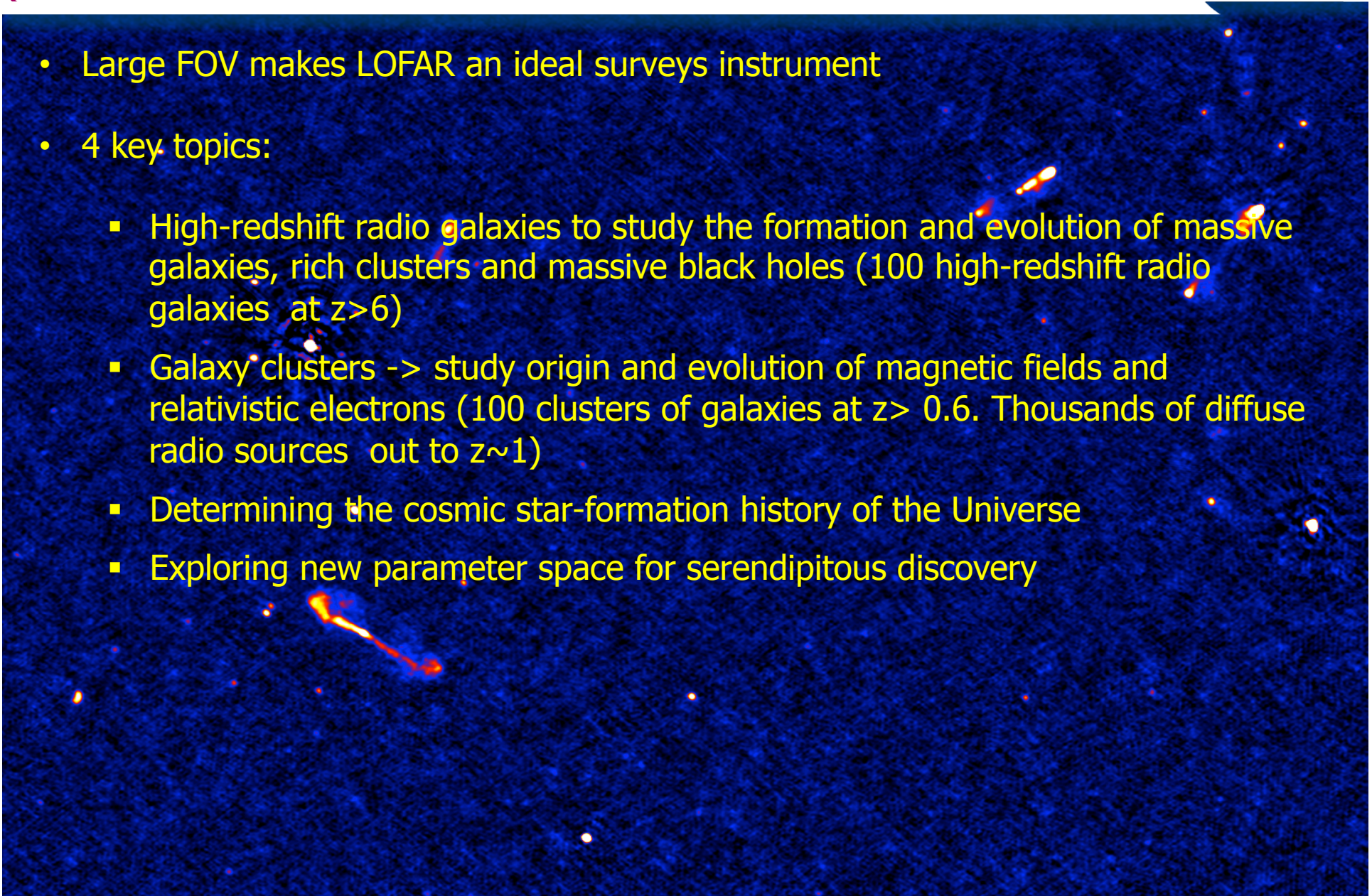
Station beam ($\sim 8^{\circ}$)

Courtesy of V. Pandey and the EoR team

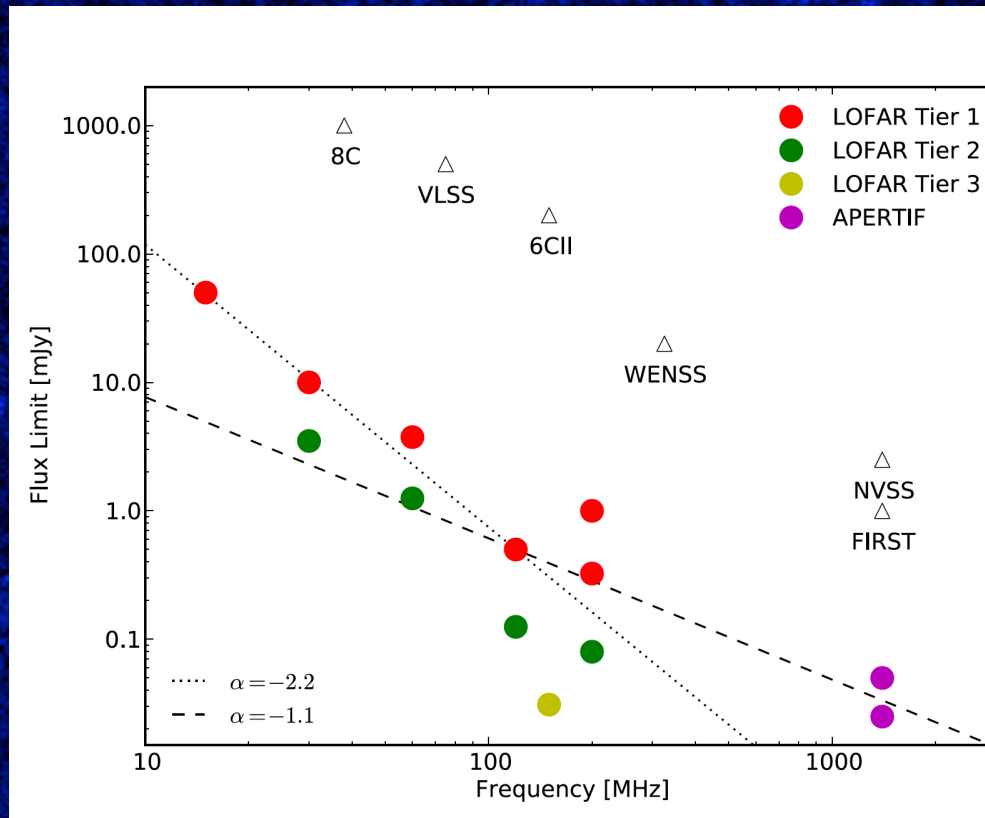
SURVEYS KSP - DEEP SURVEYS



- Large FOV makes LOFAR an ideal surveys instrument
- 4 key topics:
 - High-redshift radio galaxies to study the formation and evolution of massive galaxies, rich clusters and massive black holes (100 high-redshift radio galaxies at $z > 6$)
 - Galaxy clusters -> study origin and evolution of magnetic fields and relativistic electrons (100 clusters of galaxies at $z > 0.6$. Thousands of diffuse radio sources out to $z \sim 1$)
 - Determining the cosmic star-formation history of the Universe
 - Exploring new parameter space for serendipitous discovery



SURVEYS KSP - DEEP SURVEYS

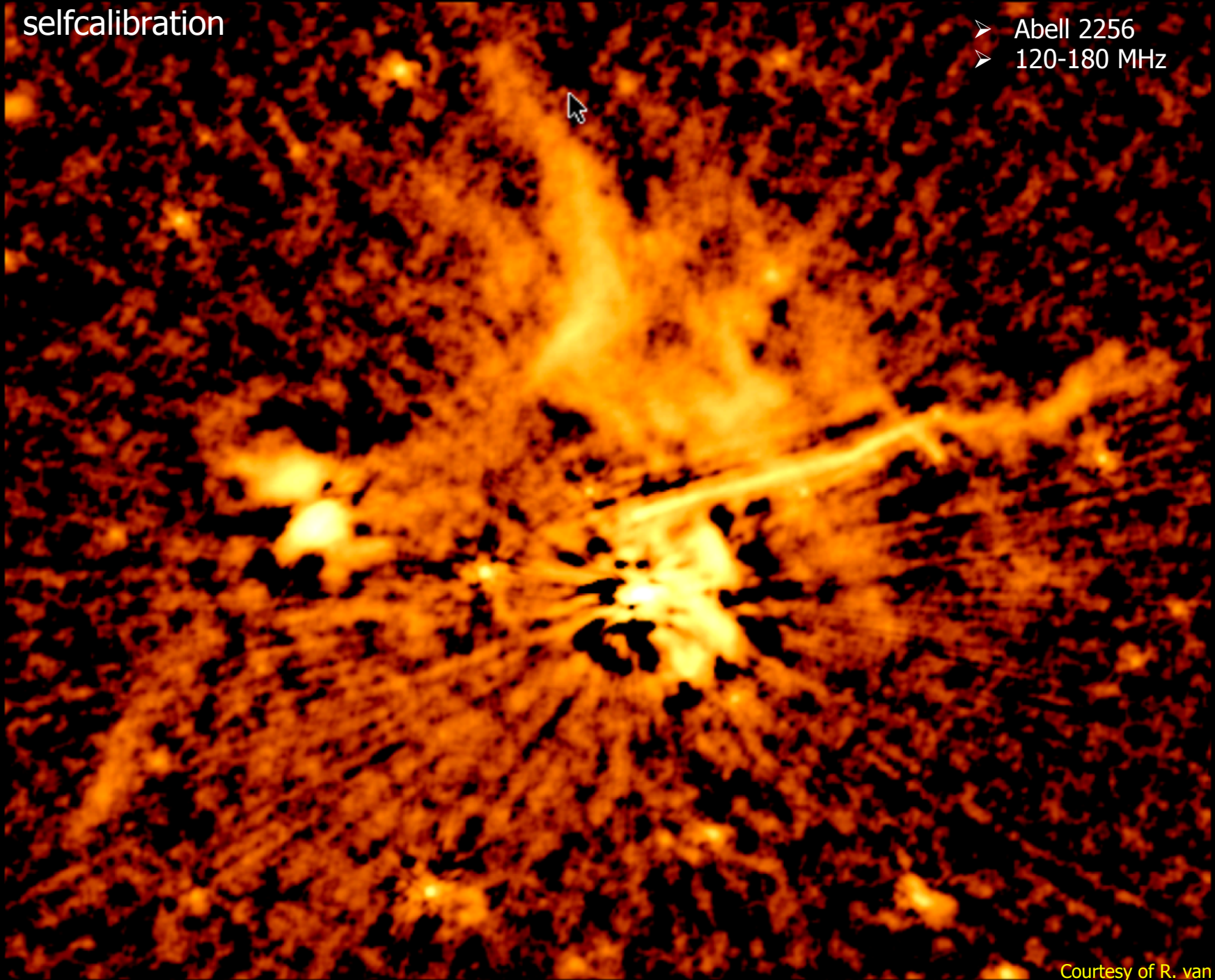


- Tier 1: 'large area' 2π steradian surveys – HBA ($\sigma = 0.07$ mJy) + LBA ($\sigma = 1-2$ mJy)
- Tier 2: the 'deep' surveys – HBA (500 deg^2 , $\sigma = 15 \mu\text{Jy}$) + LBA (1000 deg^2 , $\sigma = 0.3$ mJy)
- Tier 3: the 'ultra-deep' survey – 5 fields in HBA $\rightarrow \sigma = 7 \mu\text{Jy} \rightarrow$ detect 50 proto-clusters at $z > 2$

The LOFAR surveys will reach 2–3 orders of magnitude deeper in sensitivity than existing large-sky radio surveys

selfcalibration

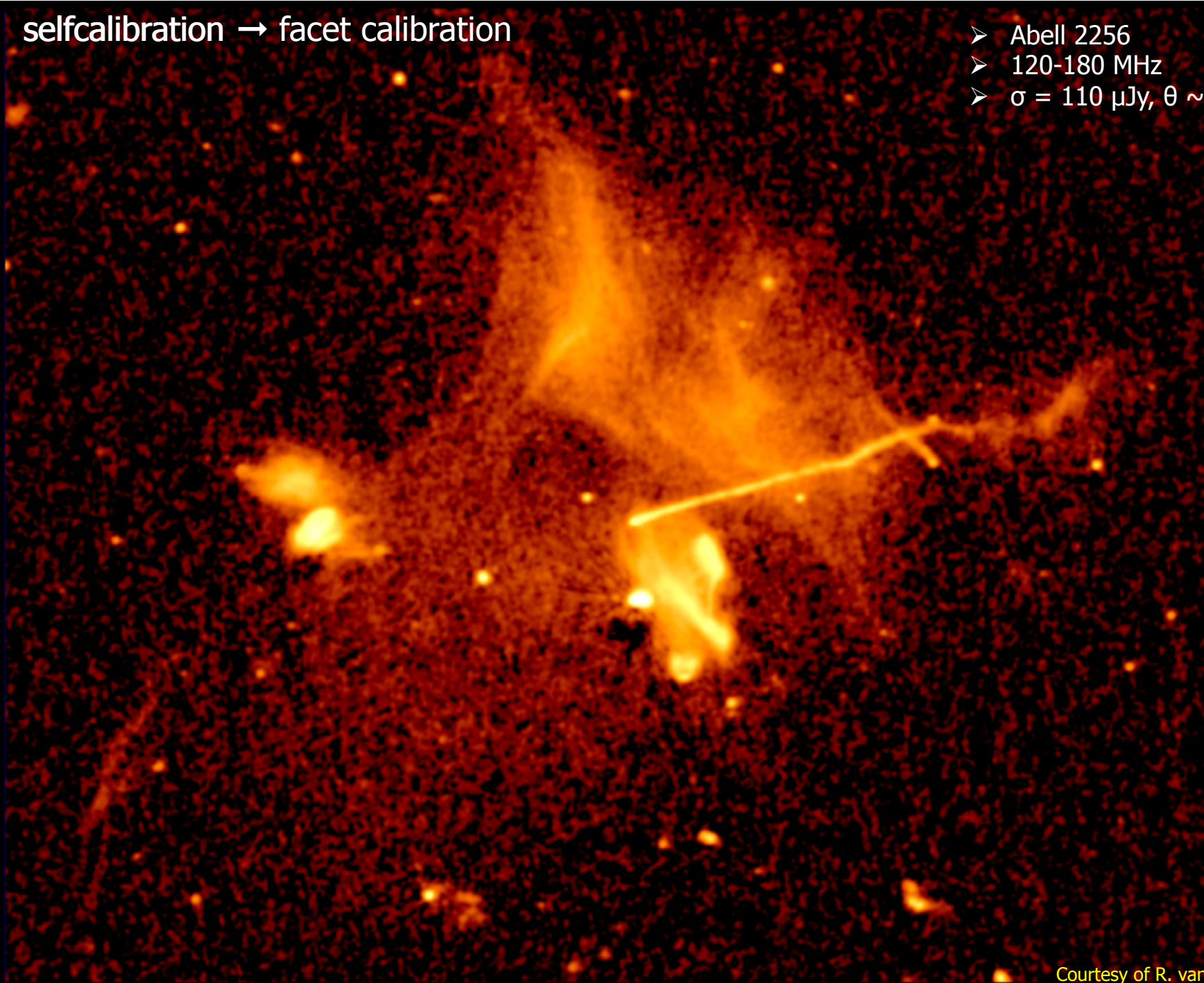
- Abell 2256
- 120-180 MHz



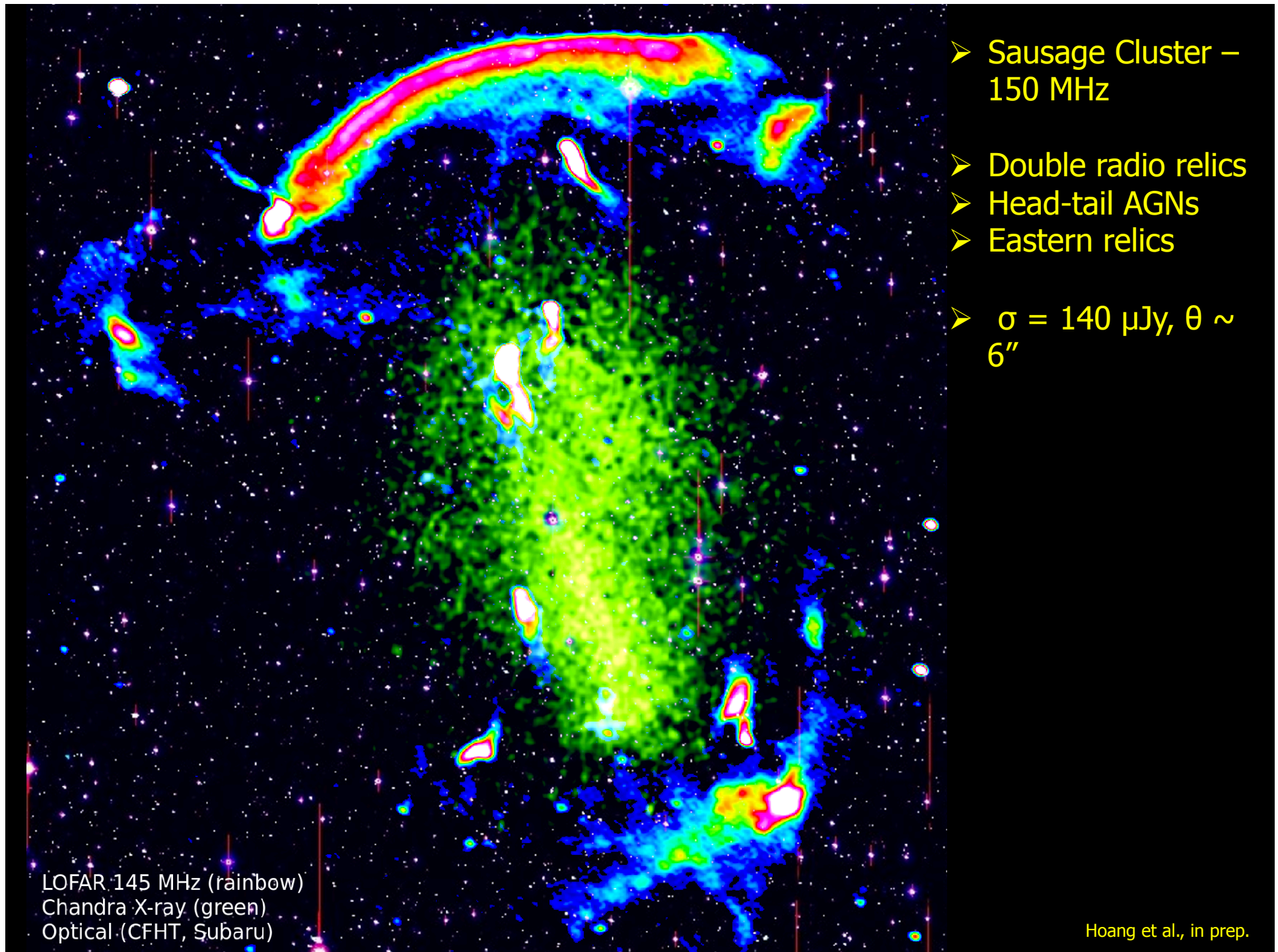
Courtesy of R. van Weeren

selfcalibration → facet calibration

- Abell 2256
- 120-180 MHz
- $\sigma = 110 \mu\text{Jy}$, $\theta \sim 5''$



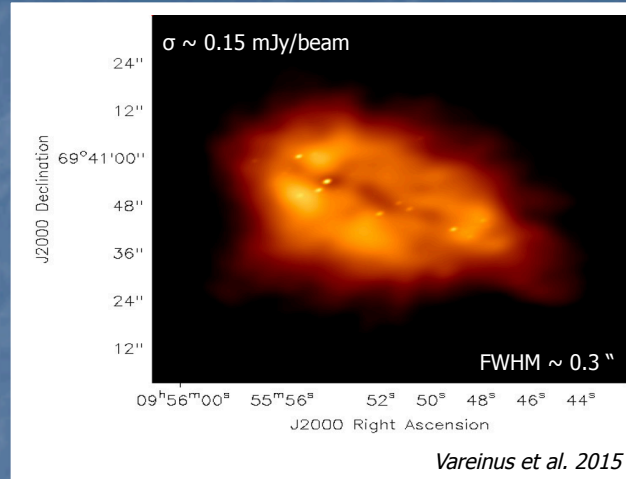
Courtesy of R. van Weeren



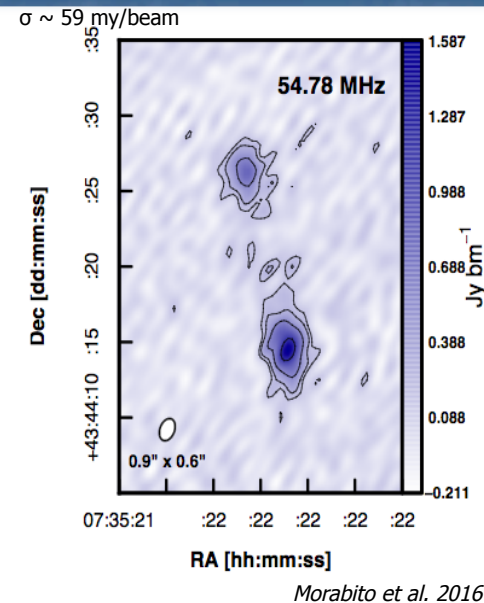
- Sausage Cluster – 150 MHz
- Double radio relics
- Head-tail AGNs
- Eastern relics
- $\sigma = 140 \mu\text{Jy}$, $\theta \sim 6''$

- Bootes field, 150 MHz
- catalogue of 6276 radio sources in an area 10x the size of the full Moon
- Differential source counts reaching an order of magnitude deeper in flux density than previously achieved at these low frequencies
- $\sigma = 120 \mu\text{Jy}$, $\theta \sim 6''$

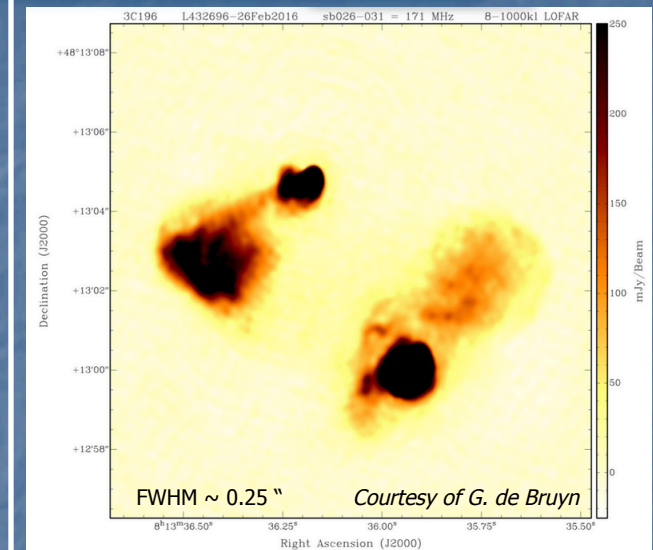
IMAGING WITH THE INTERNATIONAL STATIONS



- M82: population of compact Supernova Remnants embedded in diffuse emission
- First weak extended object to be imaged by the full European wide network of LOFAR stations; the resulting image is a new record in terms of image resolution at low frequencies



- The first spatially resolved studies at frequencies below 100 MHz of the $z = 2.4$ radio galaxy 4C 43.15
- LB imaging with the LBA!!

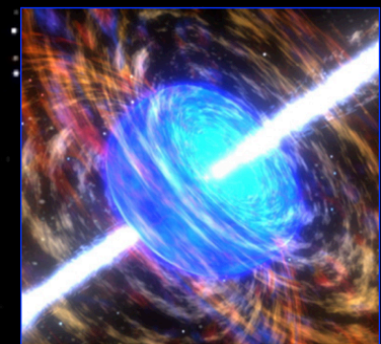
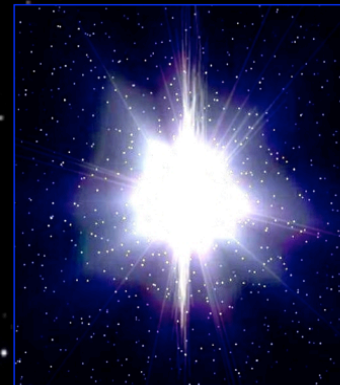
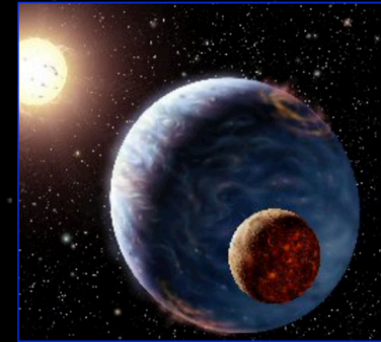
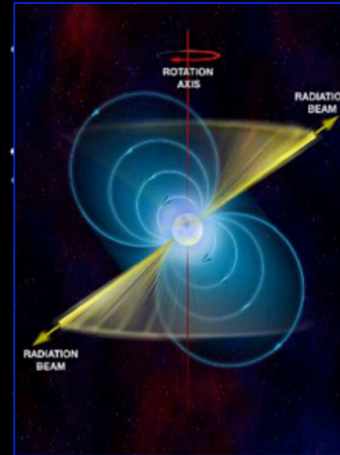


- It includes the Polish stations – maximum baseline > 1300 km!

see J. Moldon's lecture on Thursday

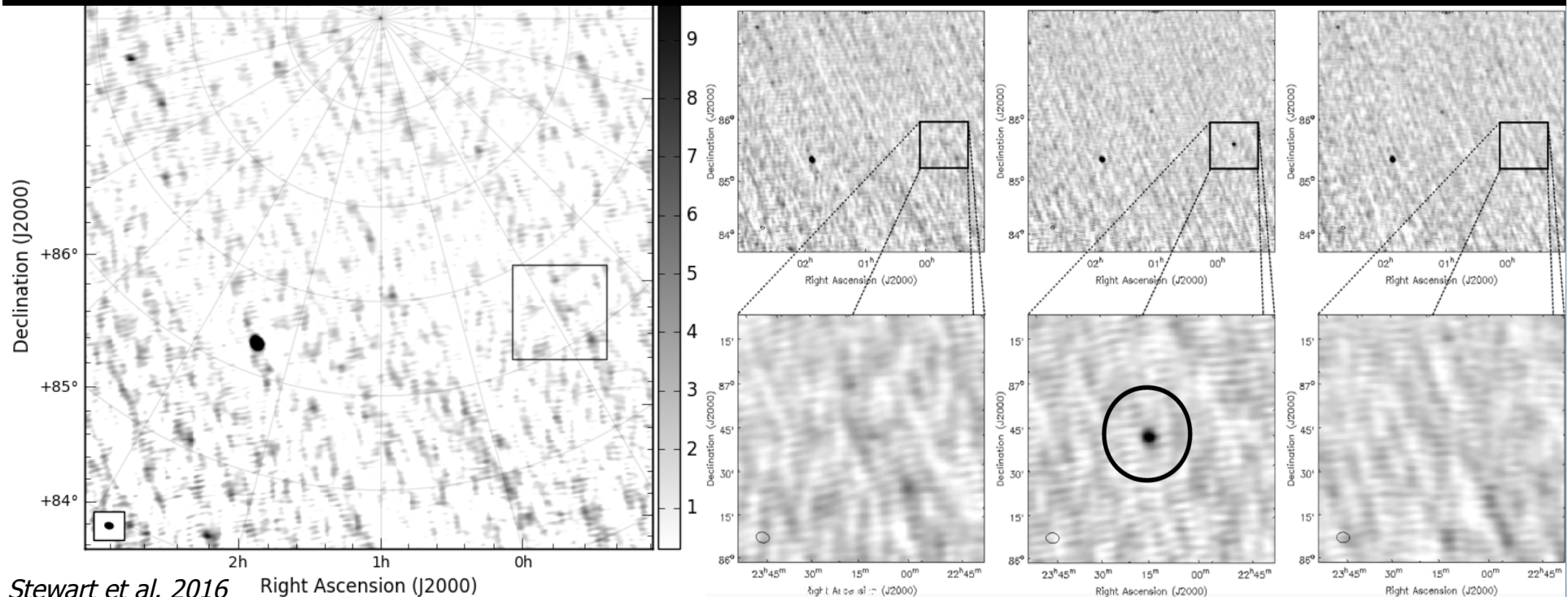
Transient and Pulsar Science Case

- Time variability of most extreme objects - e.g. accreting black-holes and neutron stars, gamma-ray bursts, and supernovae
- Radio provides an important complement to X-ray and γ -ray observations
- LOFAR's FoV is critical to catch up with high-energy monitoring for rare events
- Probe timescales from secs to years



Adam's transient

- NCP monitoring project during MSSS-LBA
- Transient seen in one, 11 min snapshot at 60 MHz
- Brightness of 15-20 Jy
- Passed exhaustive validity tests
- No counterpart at higher frequencies
- At present the origin is unknown - attempt to find more events, using data from Cycles 2 & 3.



Pulsar Surveys with LOFAR

Flexible beam-forming



Element beam

Stations beams

Tied-array beams

⇒ *Roughly speaking, beam-formed modes trade spatial resolution for time resolution*

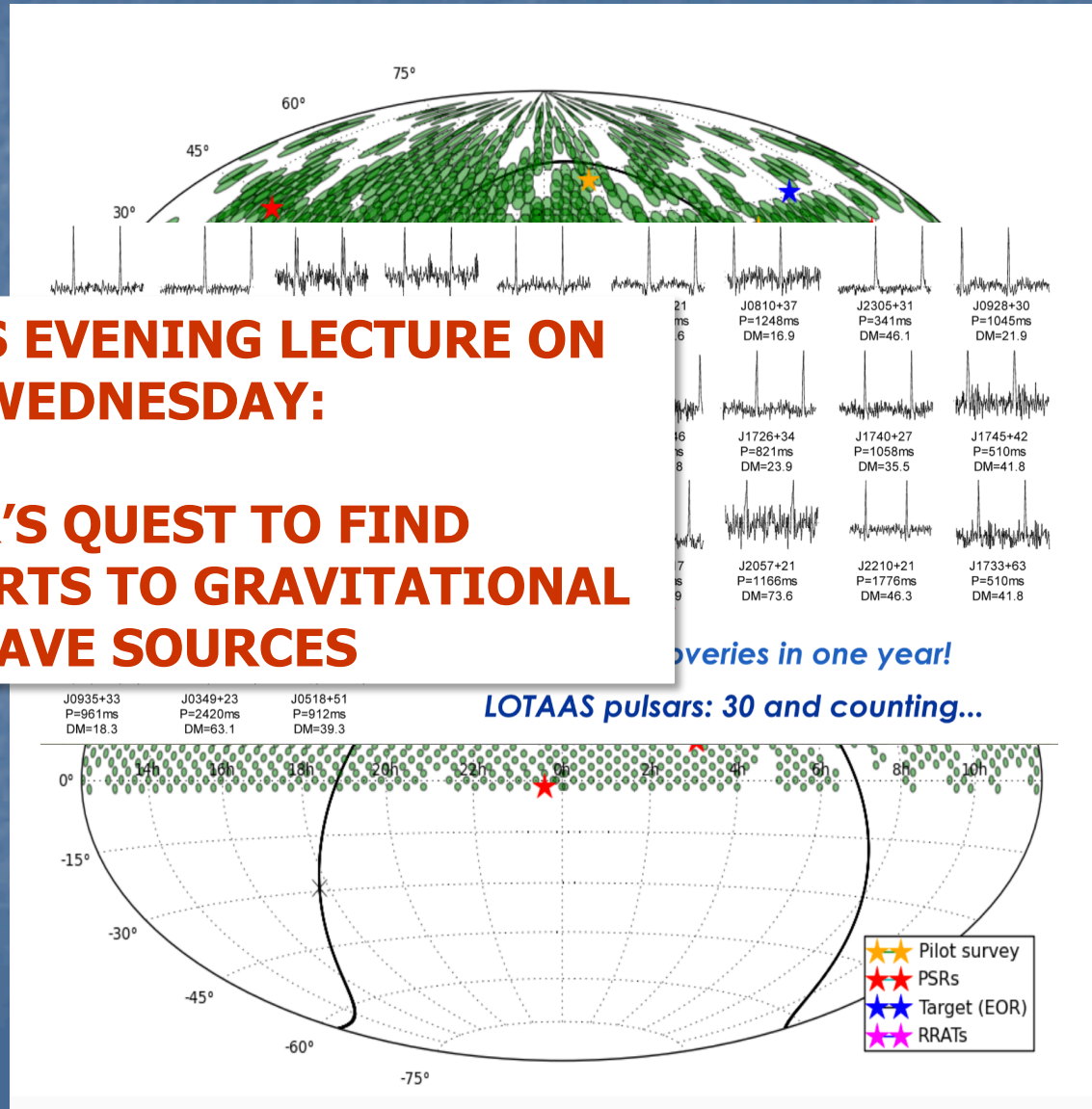
- Deepest low-frequency Pulsar Survey ever performed
- 1. Discover exotic pulsar systems to use for testing gravity in the strong-field regime, constraining the physics of dense matter and probing the pulsar emission mechanism
- 2. Characterize the transient radio sky on timescales and on a fraction of radio stars are transients

DON'T MISS EVENING LECTURE ON WEDNESDAY:

LOFAR'S QUEST TO FIND COUNTERPARTS TO GRAVITATIONAL WAVE SOURCES

- ~1000 h observed – 45 new pulsars discovered!
- Potential to be one of the most successful Pulsar surveys *at any frequency*

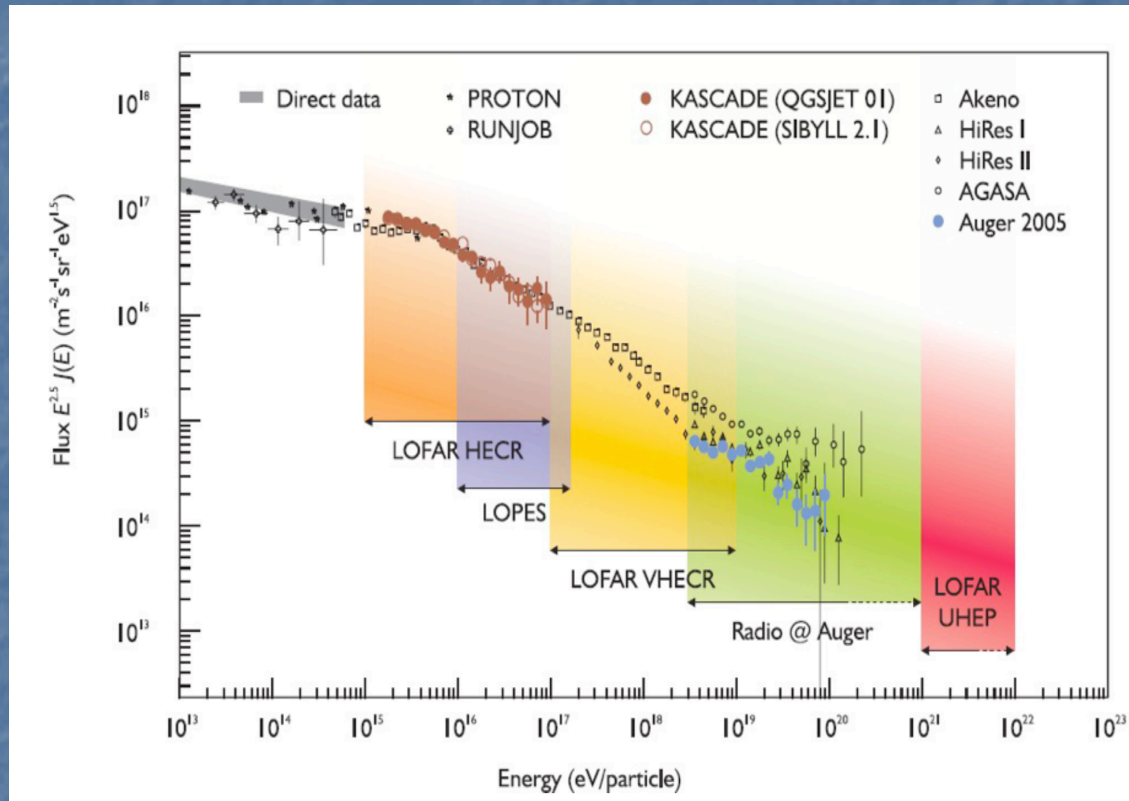
see R. Oonk & S. ter Veen's lecture on Thursday



Detection of Particle Showers from Cosmic Rays

- Through interaction with atmosphere -> air shower. If energy of the primary particle was high enough, air shower can be measured at ground level
- Low statistics of events measured on Earth (for $E > 10^{19}$ eV, only 1 particle per century per square km) -> experiments with large effective areas are required to collect sufficient statistics

COSMIC RAY ENERGY SPECTRUM



- Spectrum of CR flux is smooth and follows a power law
- At $E \sim 5 \times 10^{15}$ eV \rightarrow turnover (knee). Above the knee, composition of CR is not yet understood
- Composition crucial for understanding of **acceleration and propagation mechanisms**
- LOFAR will observe CR above 10^{16} eV up to 10^{19} eV.

COSMIC RAY PRECISION COMPOSITION MEASUREMENTS



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LETTER

doi:10.1038/nature16976

A large light-mass component of cosmic rays at 10^{17} – $10^{17.5}$ electronvolts from radio observations

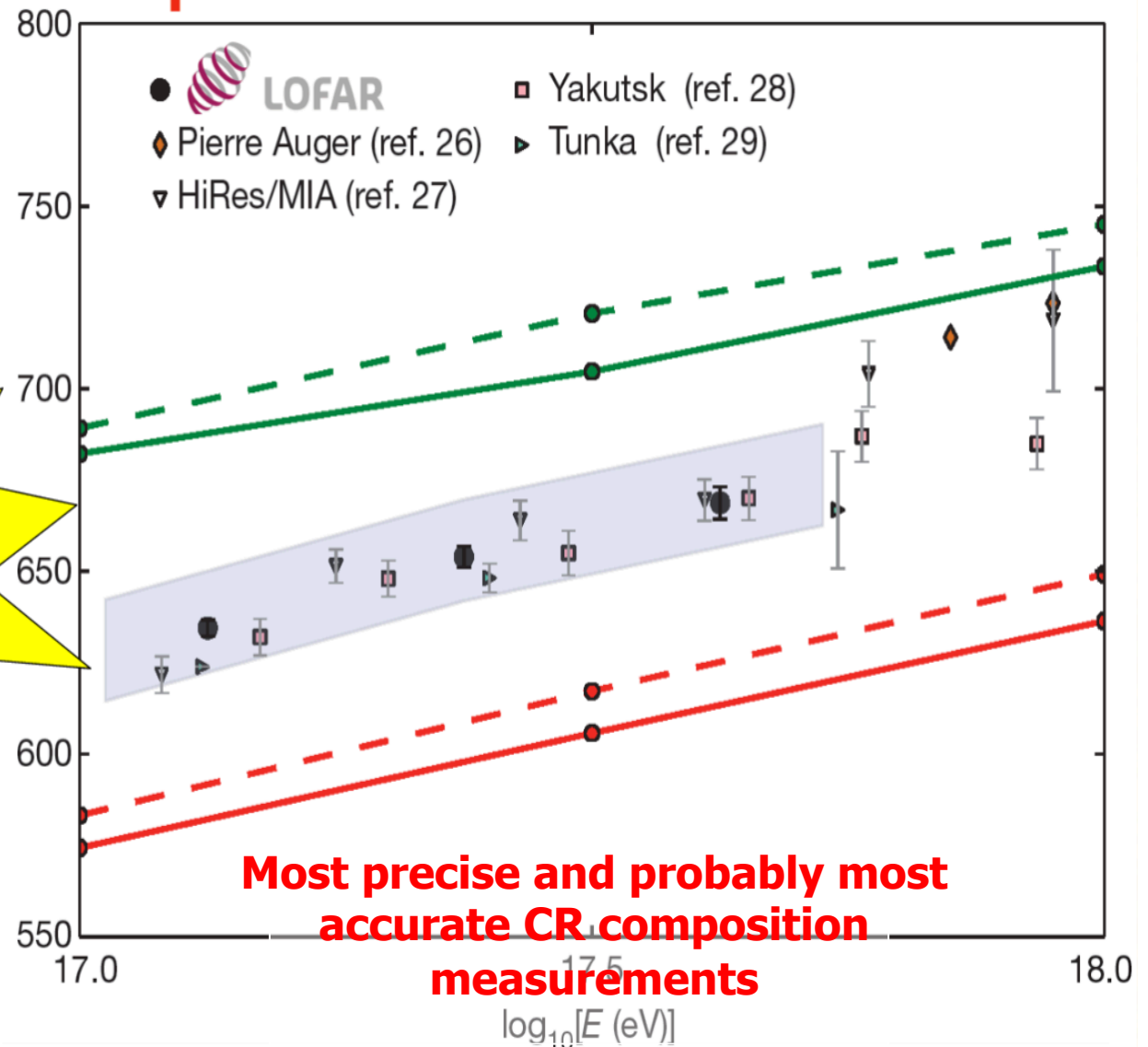
S. Buitink^{1,2}, A. Costantini³, H. Falcke^{3,4,5}, J. R. Hörandel^{1,4}, T. Haege⁶, A. Nelles^{7,2}, J. P. Rachen⁸, L. Rossetto⁹, P. Schellart¹, O. Scholten^{1,2}, S. ter Veen¹, S. Thoudam¹, T. N. G. Trinh¹, J. Anderson¹⁰, A. Angelkar¹¹, J. M. Arruch¹², M. E. Bell¹³, M. J. Beusterius¹⁴, G. Bernardi^{15,16}, P. Best¹⁷, A. Bonafede¹⁸, F. Brückling¹⁹, J. W. Brückner²⁰, W. N. Brown^{21,22}, M. Brüggen²³, H. E. Butler²⁴, D. Carbone²⁵, B. Ciardi²⁶, J. E. Conway²⁷, F. de Gasparis²⁸, E. de Gouveia²⁹, A. Deller³, R.-J. Dettmar³, G. van Diepen³, S. Duscha³, J. Eisküpper³⁰, D. Engels³¹, I. E. Enriquez³², R. A. Fallows³³, R. Fender³⁴, C. Ferrari³⁵, W. Friesswijk³, M. A. Garrett^{36,37}, J. M. Grielenker^{38,39}, A. W. Gunst⁴⁰, M. E. van Haaren⁴¹, T. E. Hassall⁴², G. Heald⁴³, J. W. T. Hessels⁴⁴, M. Hoef⁴⁵, A. Horneffer⁴⁶, M. Isacbell⁴⁷, H. Irtens^{48,49}, E. Juetten⁵⁰, A. Karastergiou⁵¹, V. I. Kondratiev^{52,53}, M. Kramer^{54,55}, M. Kuniyoshi⁵⁶, G. Kuper⁵⁷, J. van Leeuwen⁵⁸, G. M. Loefer⁵⁹, P. Maat⁶⁰, S. Markoff⁶¹, R. McFadden⁶², D. McKay-Bukowski⁶³, J. P. McKean⁶⁴, M. Mevius⁶⁵, D. D. Mulcahy⁶⁶, H. Munk⁶⁷, M. J. Norden⁶⁸, E. Orru⁶⁹, H. Pais⁷⁰, M. Pandey-Punnam⁷¹, V. N. Pandey⁷², M. Perle⁷³, R. Fitz⁷⁴, A. G. Polstad⁷⁵, W. Reich⁷⁶, H. J. A. Röttgering⁷⁷, A. M. M. Scaife⁷⁸, D. I. Schwartz⁷⁹, M. Serylak⁸⁰, J. Shuman⁸¹, O. Smirnov^{82,83}, R. W. Stappers⁸⁴, M. Steinmetz⁸⁵, A. Stewart⁸⁶, J. Swinbank^{87,88}, M. Tagger⁸⁹, V. Tanzi⁹⁰, C. Tasse^{91,92}, M. C. Toribio⁹³, R. Vermeulen⁹⁴, C. Vogt⁹⁵, R. I. van Weeren⁹⁶, R. A. M. I. Wijers⁹⁷, S. J. Wijnholds⁹⁸, M. W. Wise⁹⁹, O. Wucknitz¹⁰⁰, S. Yatawatta¹⁰¹, P. Zarka¹⁰² & J. A. Zensus¹⁰³

Cosmic rays are the highest-energy particles found in nature. Measurements of the mass composition of cosmic rays with energies of 10^{17} – $10^{17.5}$ electronvolts are essential to understanding whether they have galactic or extragalactic sources. It has also been proposed that the astrophysical neutrino signal comes from accelerators capable of producing cosmic rays of these energies. Cosmic rays initiate air showers—cascades of secondary particles in the atmosphere—and their masses can be determined from measurements of the atmospheric depth of the shower maximum. Observations of the air shower when it contains the largest number of the composition of shower particles reaching the detector. Current measurements have other high uncertainties, and a high energy threshold. Radio detection is a rapidly developing technique for determining the mass composition of cosmic rays with a duty cycle of, in principle, nearly 100 per cent. It is generated by the separation of relativistic electrons in the geomagnetic field and a negative charge excess in the front. Here we report radio measurements of the mass composition of 16 grams per square centimetre of cosmic rays initiated by cosmic rays with energies of 10^{17} – $10^{17.5}$ electronvolts. This high resolution in X_{max} enables us to detect the mass spectrum of the cosmic rays; we find a mixed composition, with a light-mass fraction (protons and helium nuclei) of about 80 per cent. Unless contrary to current expectations, the galactic component of cosmic rays contributes substantially below $10^{17.5}$ electronvolts, our measurements indicate the existence of an additional cosmic component measured in the 10^{17} – $10^{17.5}$ electronvolt range. LOFAR is a radio telescope with the largest number of antennas of the world, built in the Netherlands and in several other countries.

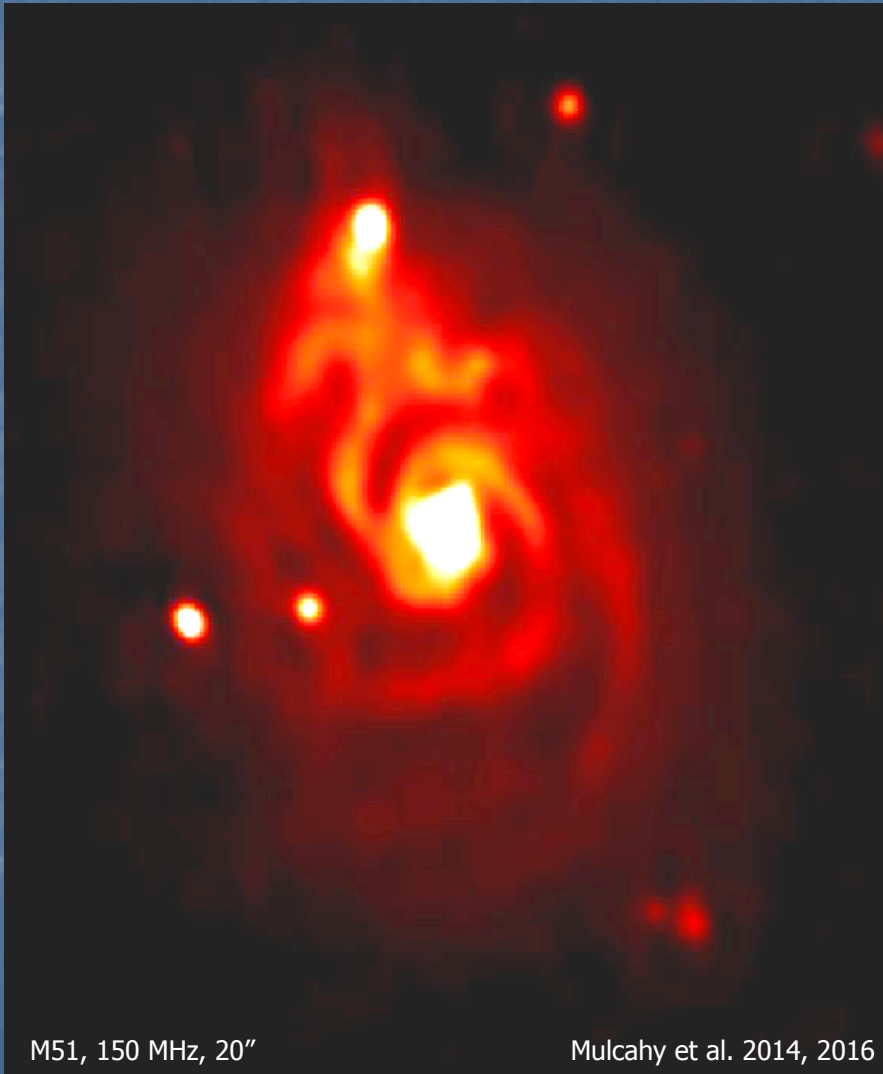
published in nature

Nature

Depth of the shower maximum



COSMIC MAGNETISM



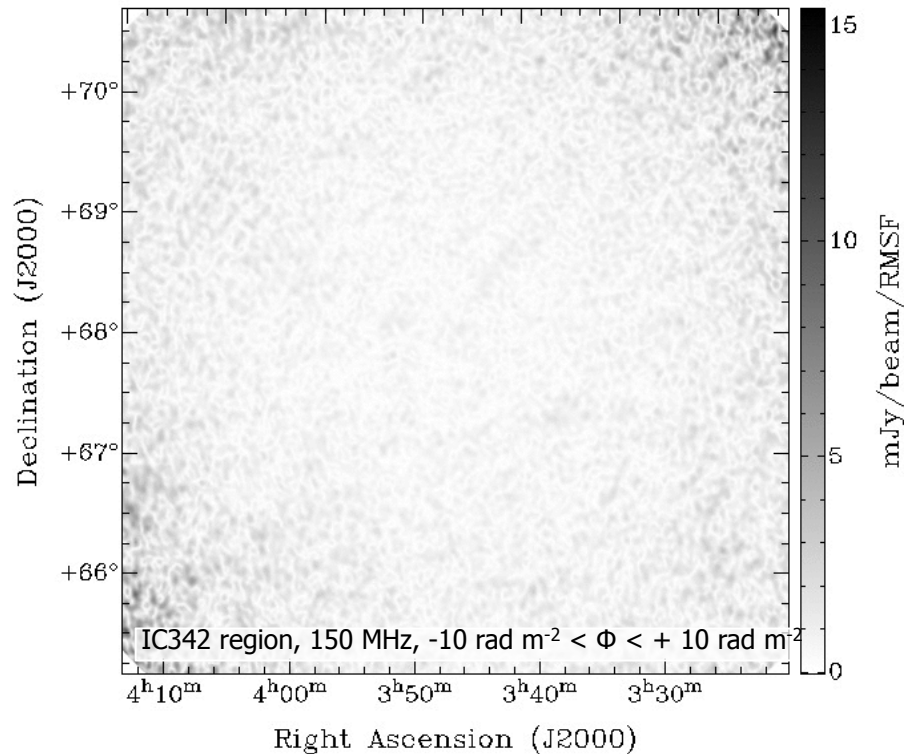
- Magnetic fields are ubiquitous in the Universe – **their origin, evolution and structure still remain open fundamental problems**
- Synchrotron radiation produced by relativistic electrons -> total field **strength, orientation and degree of ordering** in the plane of the sky and component of ordered fields along the line of sight
- Due to its wide bandwidth at low frequency, LOFAR can:
 - Provide info on **spectral properties of the synchrotron radiation**
 - **Trace magnetic fields far away from CR acceleration sites**
 - **Trace weak magnetic fields through Faraday rotation studies (RM synthesis)**
- See M. Iacobelli's lecture on Thursday

GALACTIC FOREGROUNDS: FAN REGION & 3C196



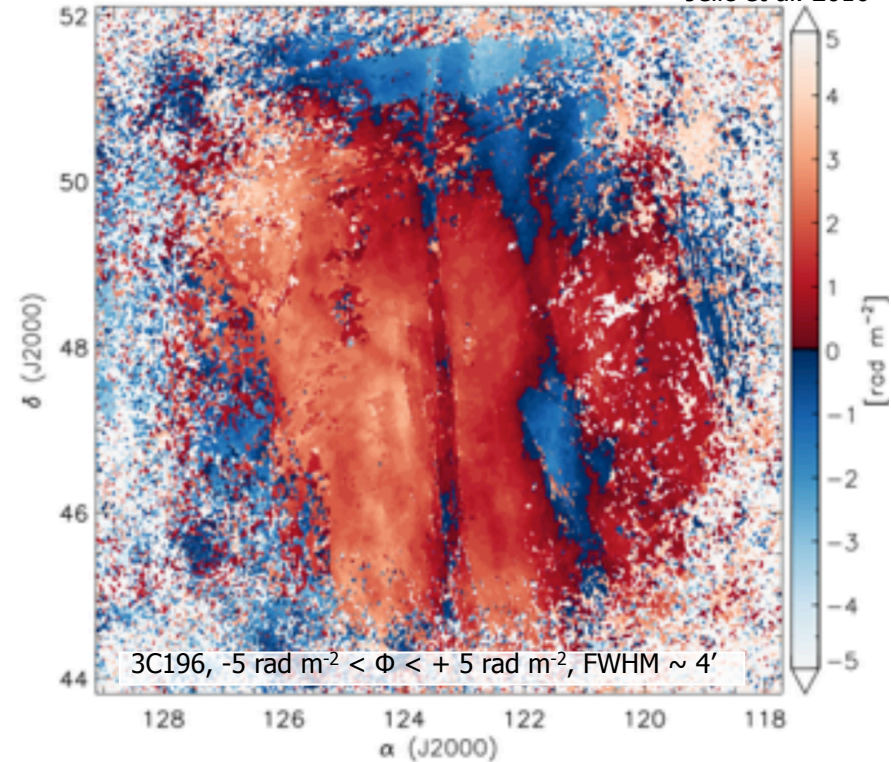
ASTRON

Phi: $-1.000000e+01$ Van Eck et al. in prep.



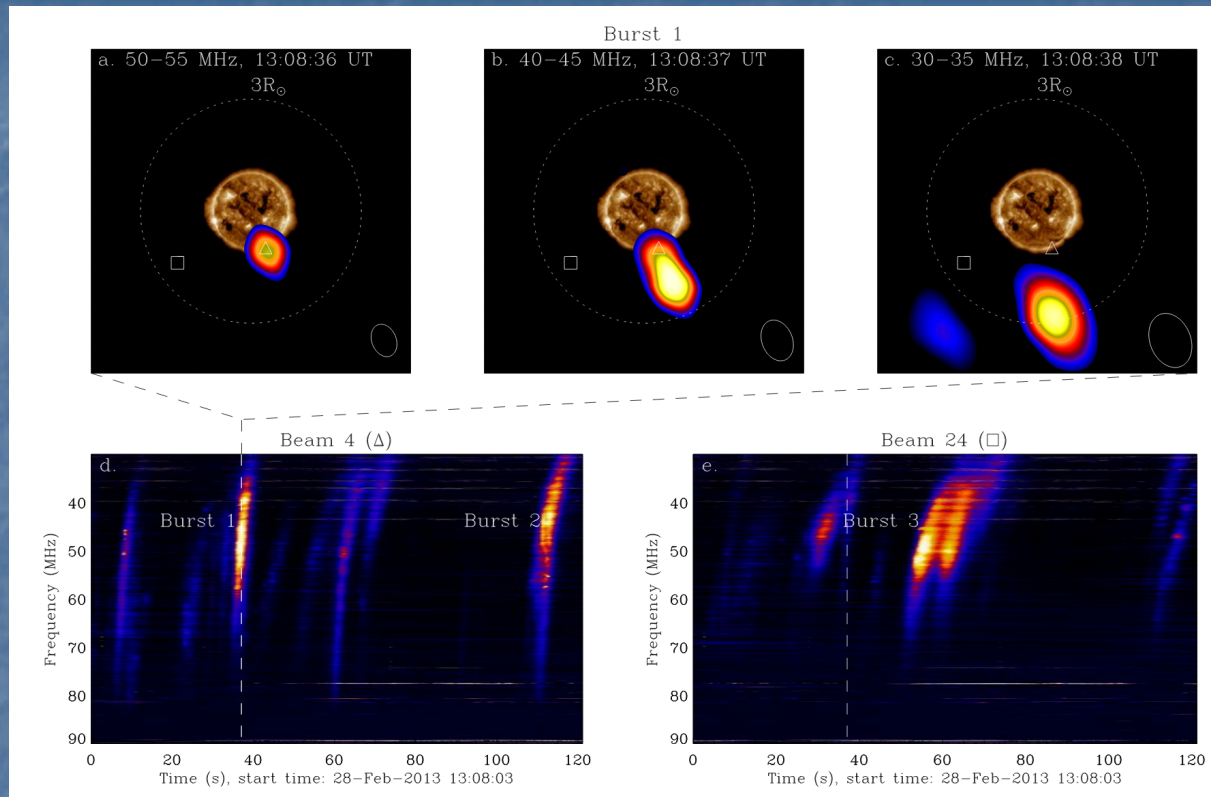
L80508

Jelic et al. 2016



- Rich morphology of polarized emission detected with LOFAR (115 - 175 MHz)
- Discovery of many filamentary structures and linear depolarization canals (thermal instabilities with anisotropic conduction; trails of stars,...)
- Probed ISM mostly close by (<200 pc), within the Local Bubble

SOLAR PHYSICS AND SPACE WEATHER

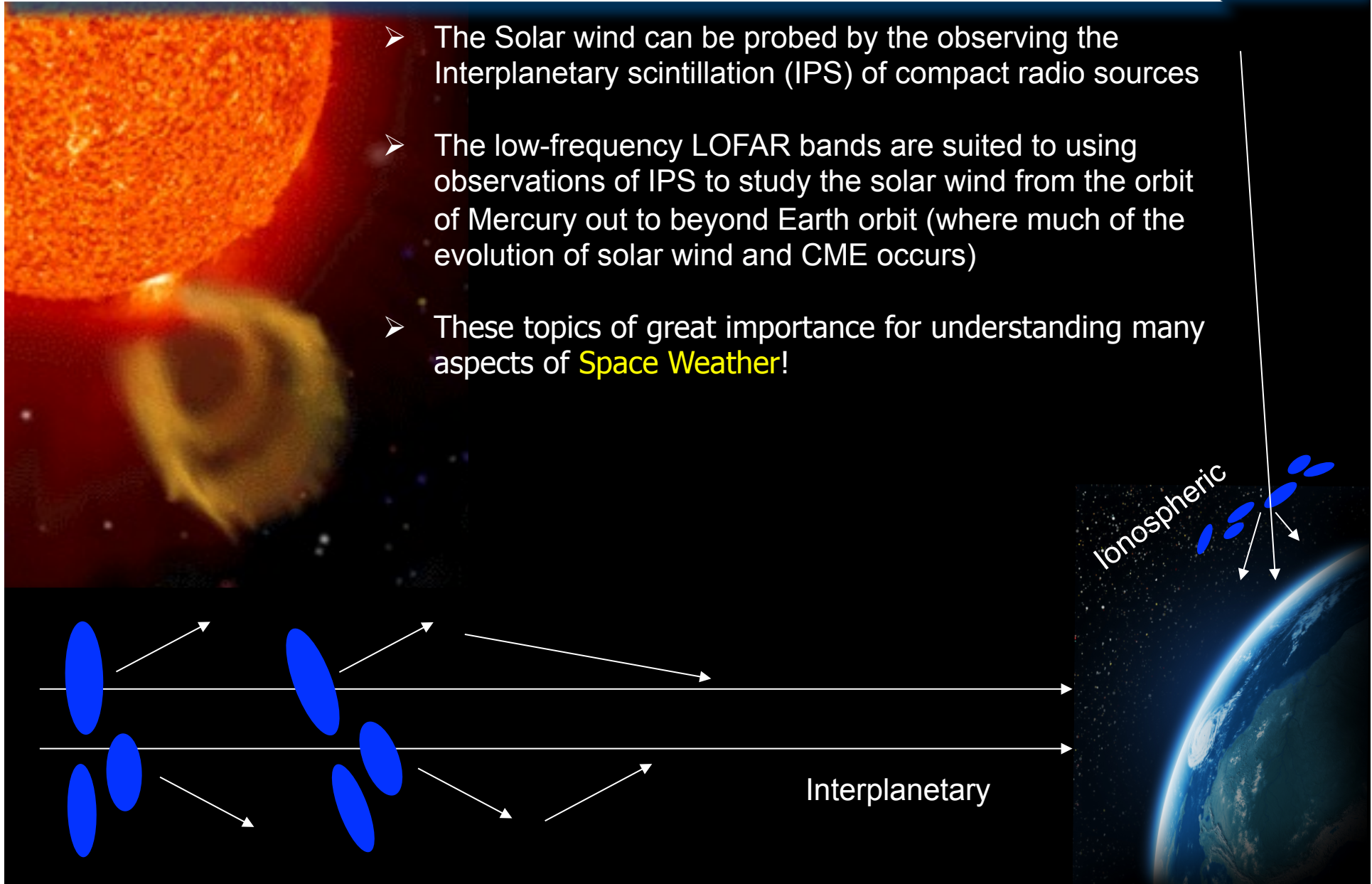


- Thermal radiation of the quiet Sun interspersed with intense radio bursts (flares and CMEs)
- LOFAR serves as a dynamic spectroscopic radio imager – wide bandwidth and high resolutions make LOFAR a powerful tool for probing previously unexplored solar coronal structures
- Several type I-II-III radio bursts detected since 2011 (see e.g. Morosan et al. 2014)

SOLAR PHYSICS AND SPACE WEATHER



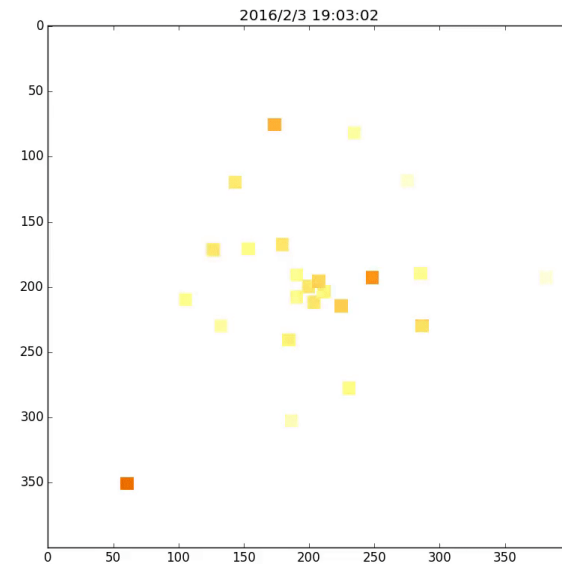
- The Solar wind can be probed by the observing the Interplanetary scintillation (IPS) of compact radio sources
- The low-frequency LOFAR bands are suited to using observations of IPS to study the solar wind from the orbit of Mercury out to beyond Earth orbit (where much of the evolution of solar wind and CME occurs)
- These topics of great importance for understanding many aspects of **Space Weather**!



SOLAR PHYSICS AND SPACE WEATHER



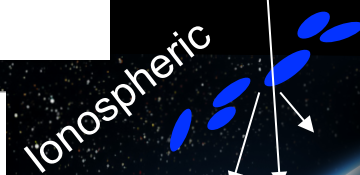
- The Solar wind can be observed by Interplanetary spacecraft
- The low-frequency observations of IP spacecraft of Mercury out to the edge of the evolution of solar wind
- These topics of great interest are aspects of Space Weather



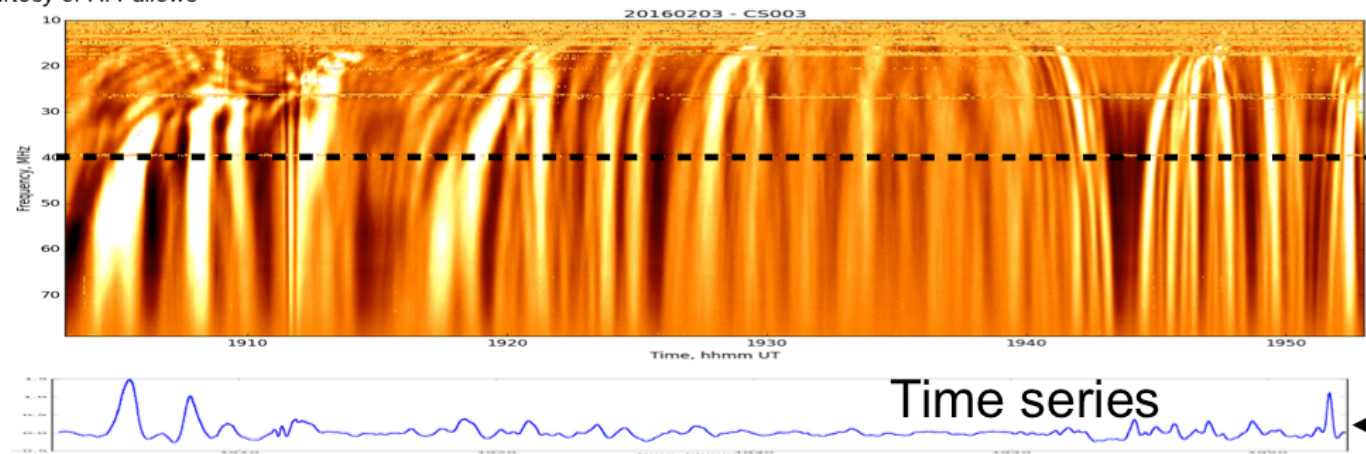
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orbit
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Courtesy of R. Fallows

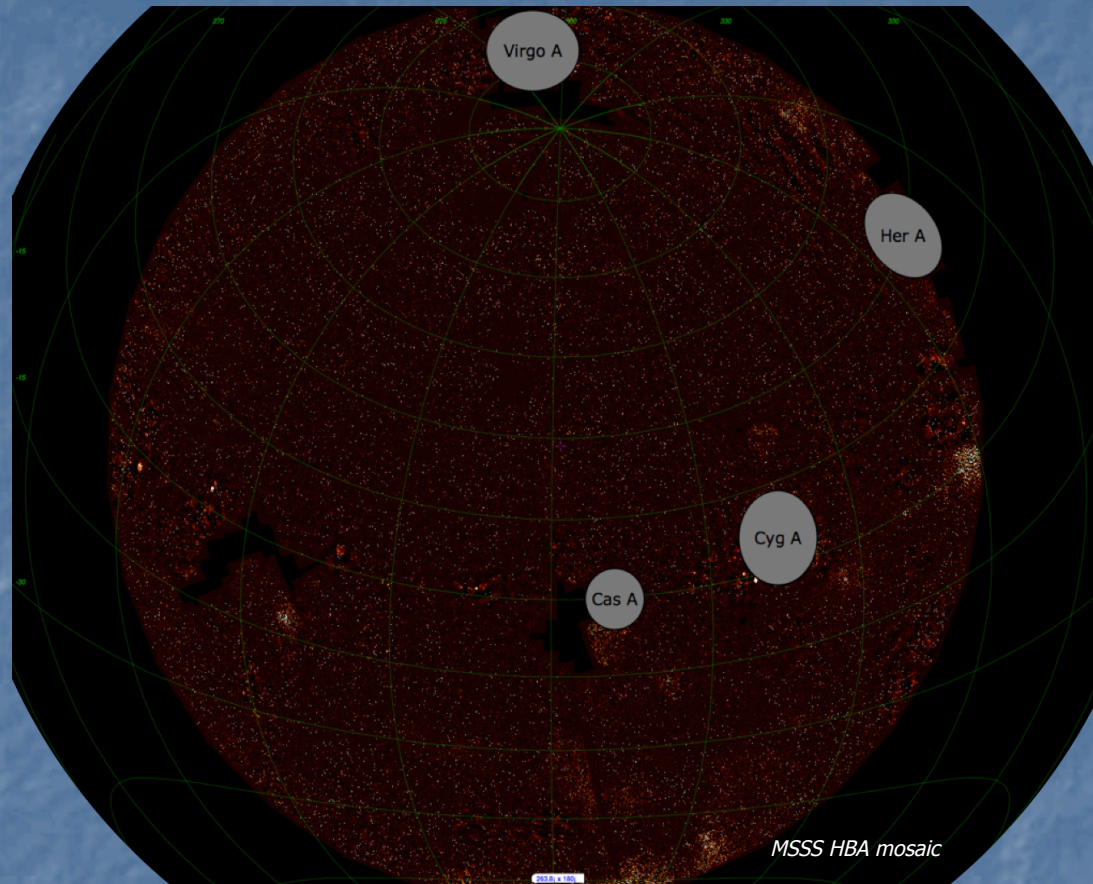


Time series

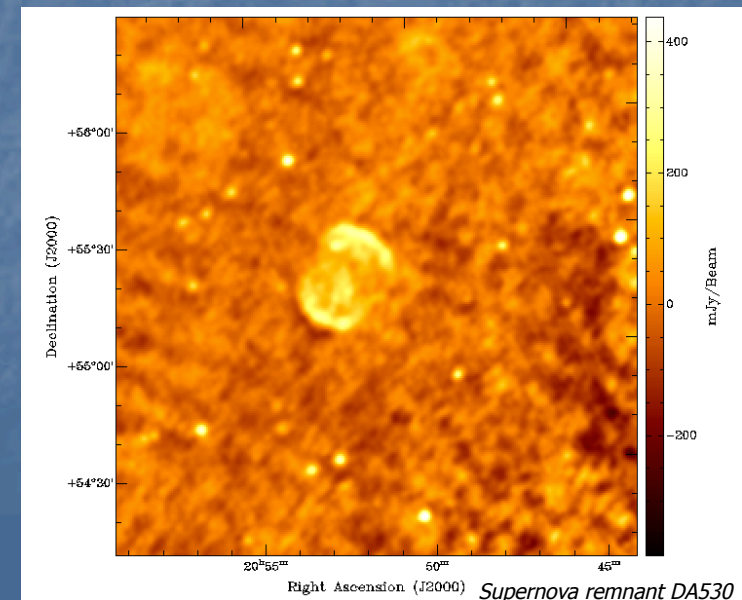
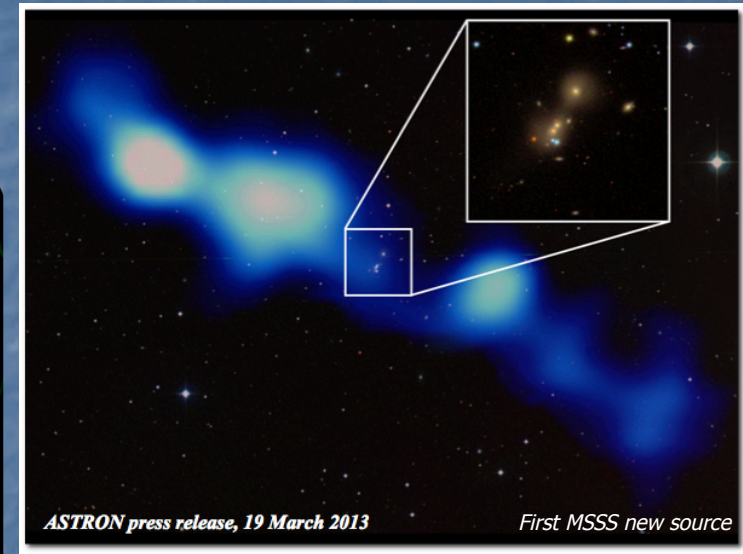
MULTIFREQUENCY SNAPSHOT SKY SURVEY: MSSS



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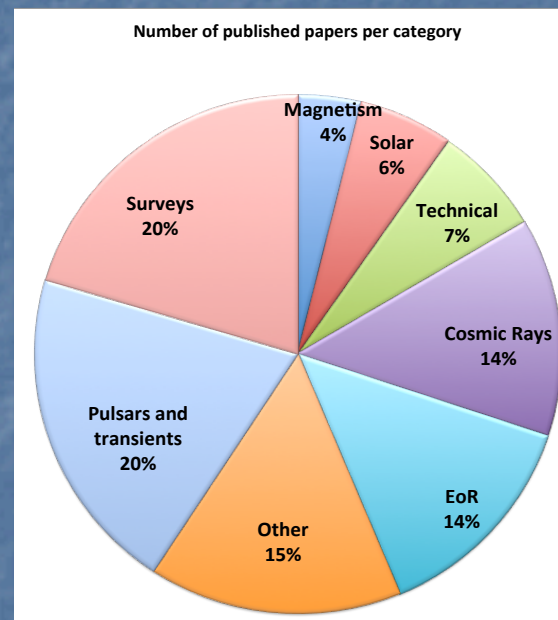
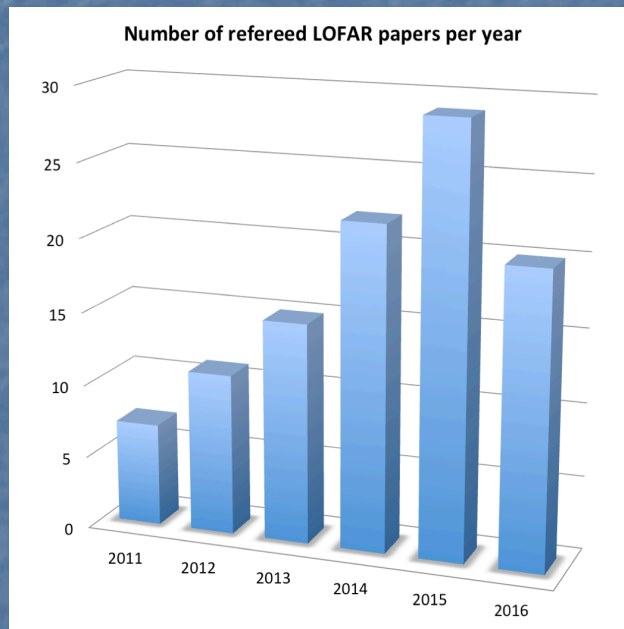
- See E. Orru's lecture on Tuesday
- HBA completed
- Initial catalogue to be released soon



LOFAR SCIENCE OUTPUT



- 104 refereed papers to date



Paper	2014	2016
Van Haarlem et al. 2013	53	357
Stappers et al. 2011	67	118
Hermesen et al. 2013	23	44

Top cited papers (2014 -> 2016)

- Papers mentioning LOFAR:

936

SUMMARY

- **LOFAR is up and running and generating great scientific data**
- **LOFAR provides several unique scientific capabilities**
- **NEW EXCITING DISCOVERIES ARE THERE FOR YOU TO MAKE!!!**

ASTRON

Netherlands Institute for Radio Astronomy

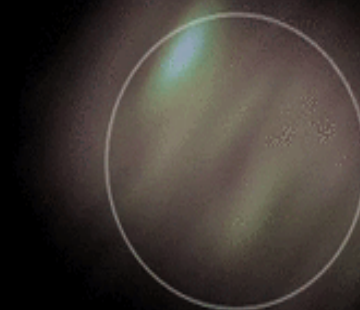
Solar Eclipse – March 2015

LOFAR, HBA

08:25 CET



LOFAR



Courtesy of M. Brentjens

THANKS