
LOFAR SCIENCE
R. F. Pizzo
ASTRON
ASTRON, September 5th 2016
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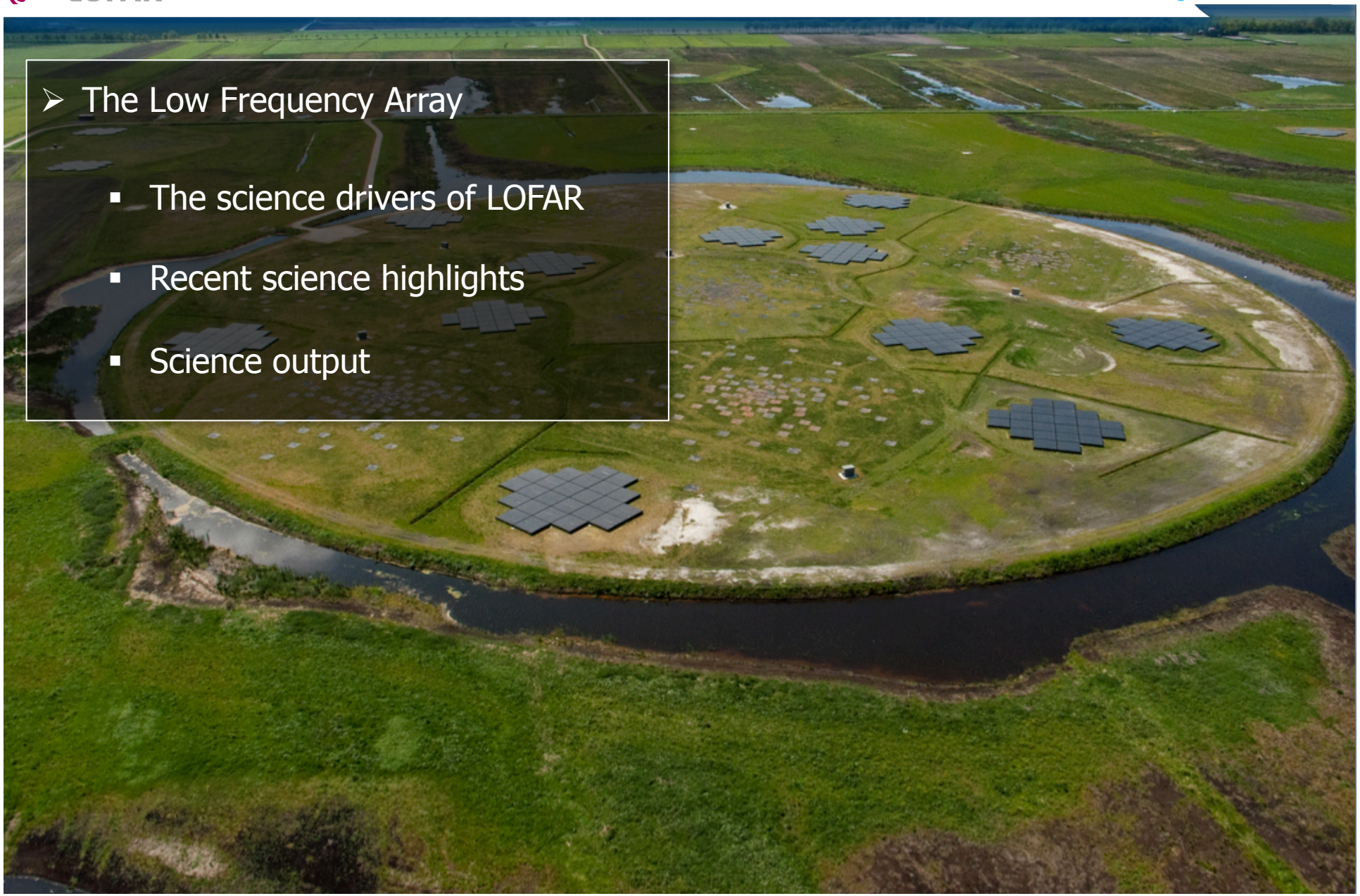
OUTLINE



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

LOFAR SCIENCE DRIVERS

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Key Science Projects

Epoch of Reionization

Transients and Pulsars

High Energy Cosmic Rays

Surveys and Distant Universe

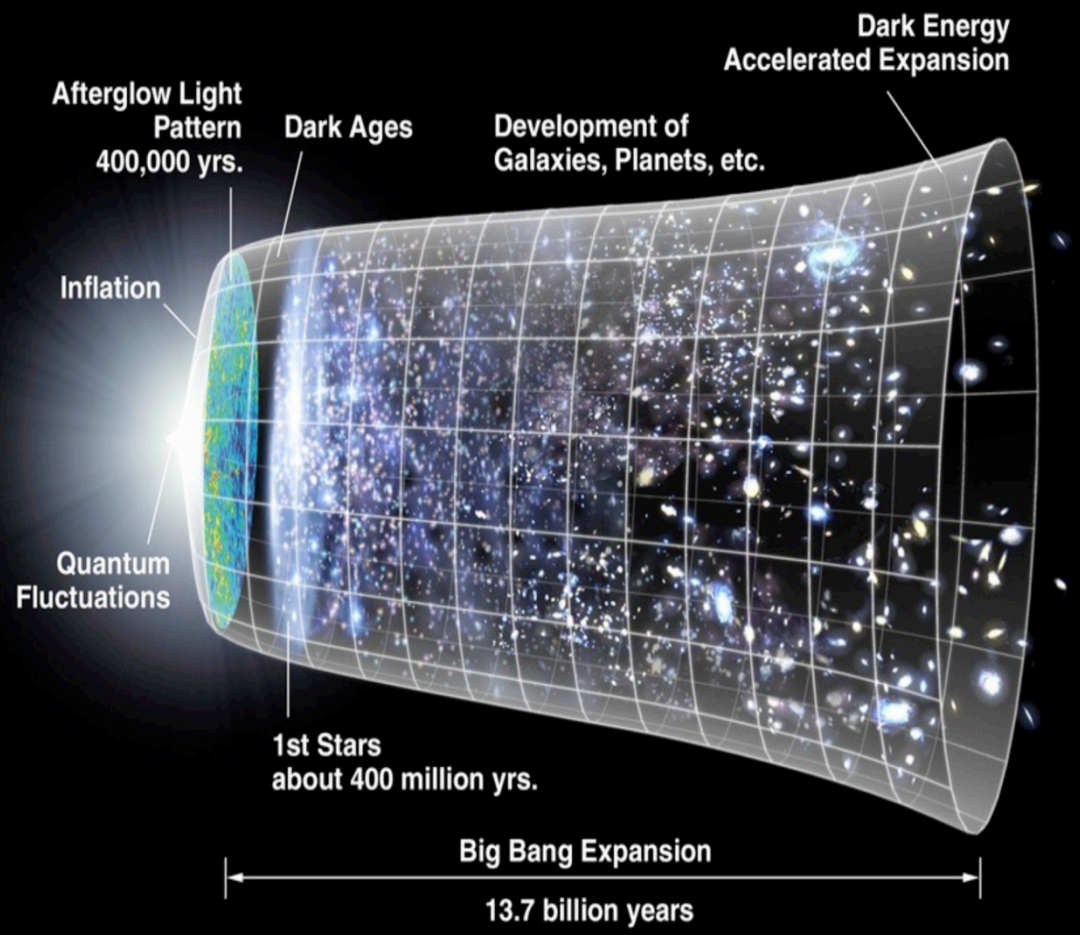
Cosmic Magnetism

Solar Physics and Space Weather

International membership from countries all over the World

Constribute 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

$z = 6.7 \Rightarrow 185$ MHz

$z = 8.5 \Rightarrow 150$ MHz

$z = 11.4 \Rightarrow 115$ MHz

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

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

EoR DEEP FIELDS – FIRST RESULTS

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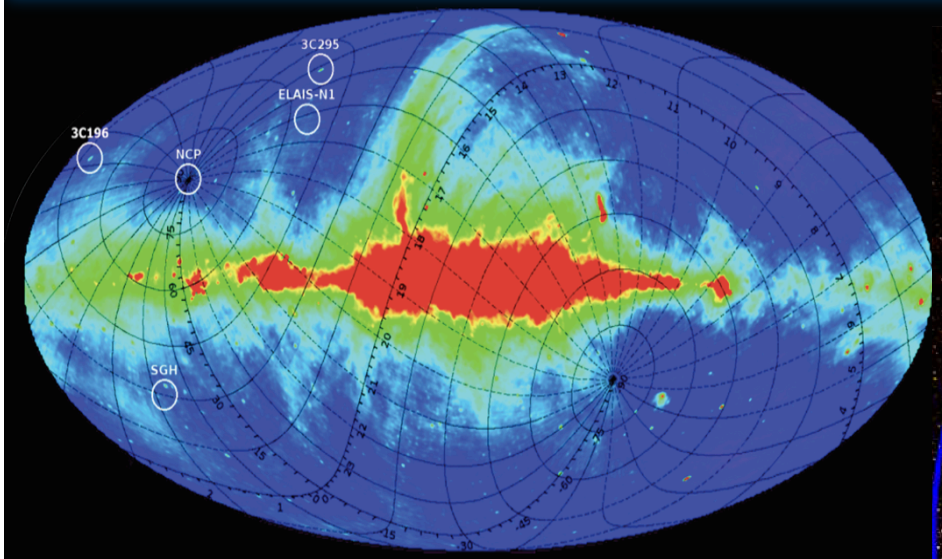
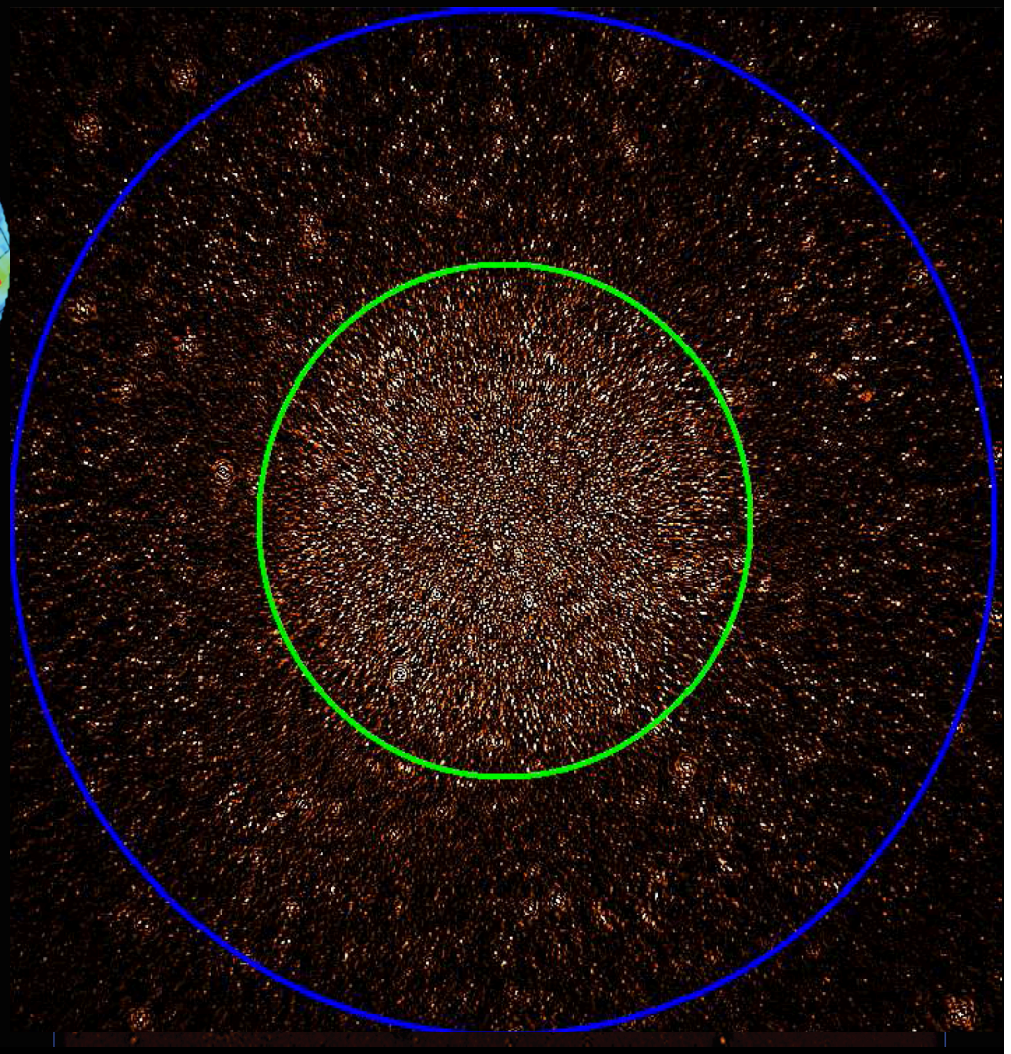




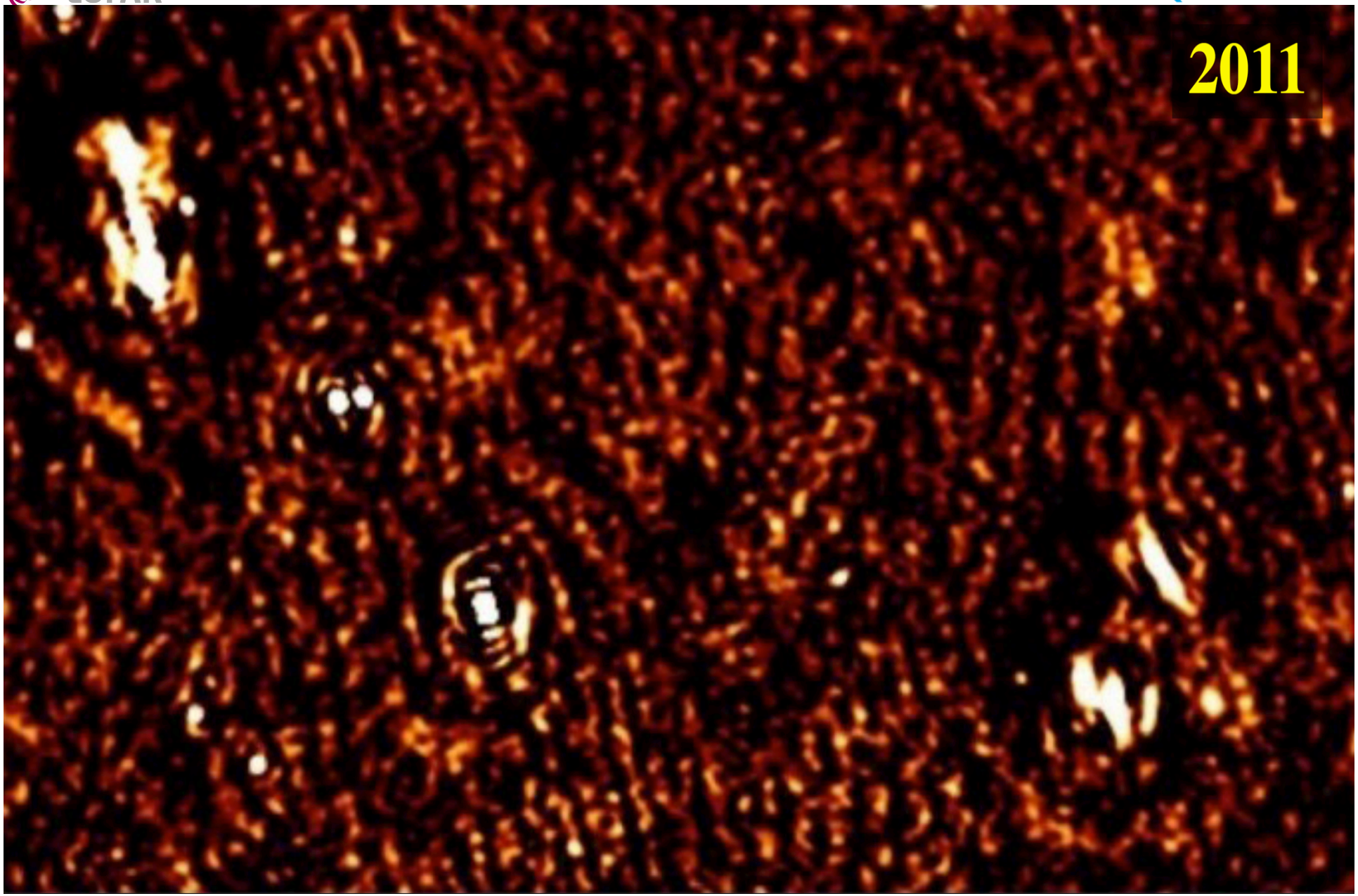
- Total 2000+ hours allocated
- Focus on 2 distinct fields
- Custom processing on EoR clusters

  σ = <50 μJy θ ~ 5″

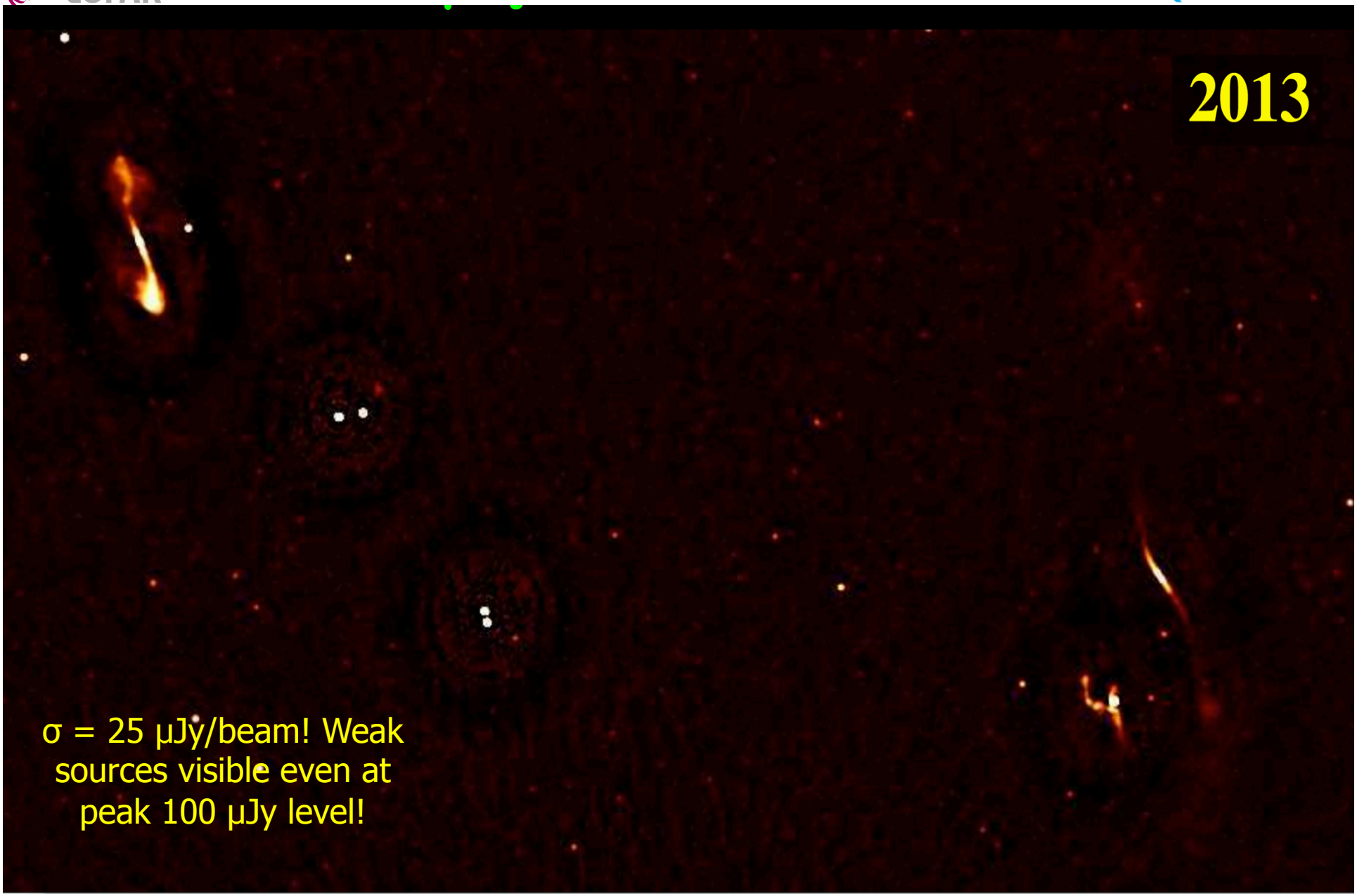
- 60 MHz bandwidth
- 20 deg x 20 deg

(courtesy S. Yatawatta and the EoR KSP Team)

EoR DEEP FIELDS – FIRST RESULTS



EoR DEEP FIELDS – FIRST RESULTS



EoR DEEP FIELDS – 3C196

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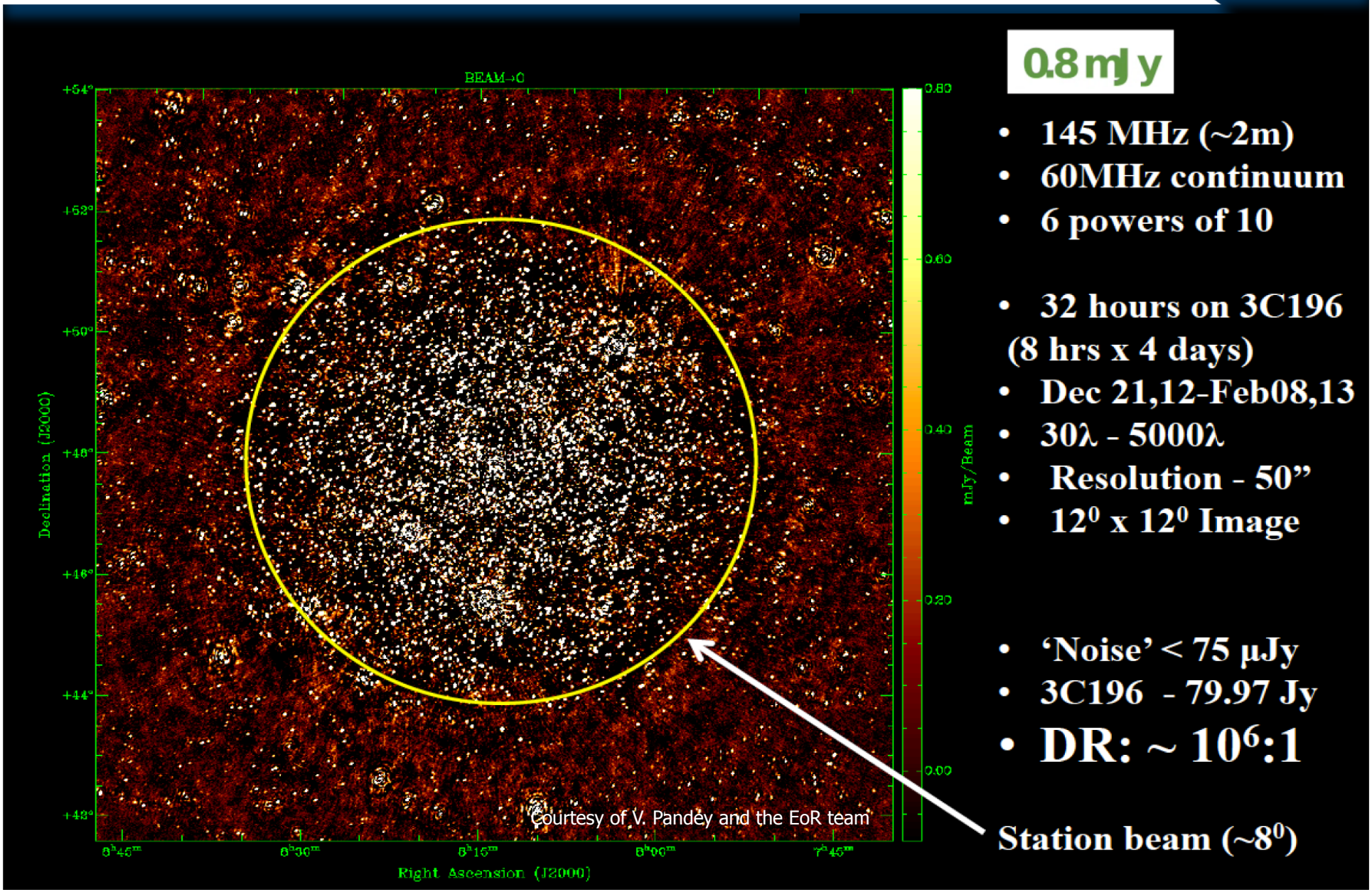

SURVEYS KSP - DEEP SURVEYS

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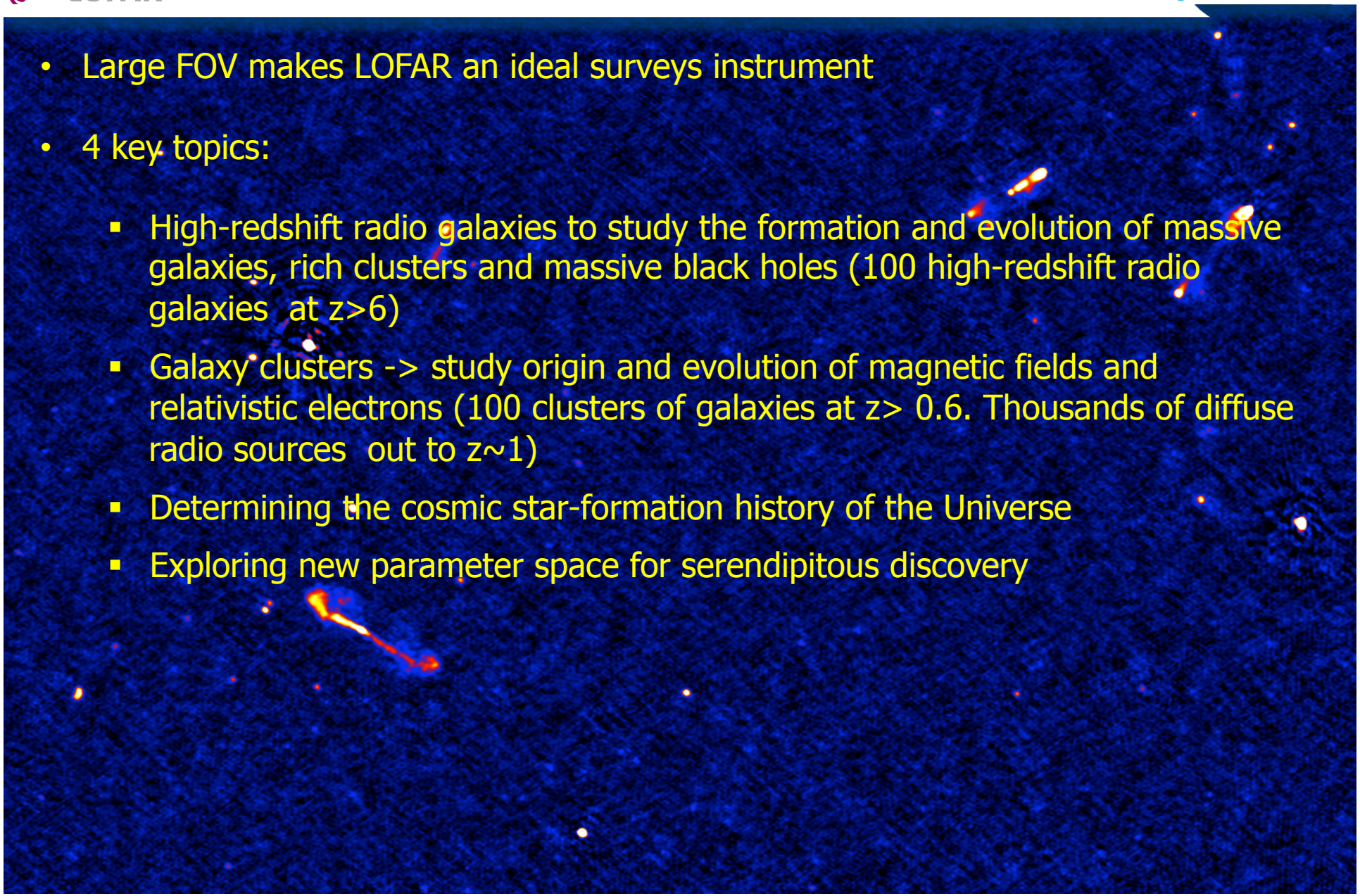
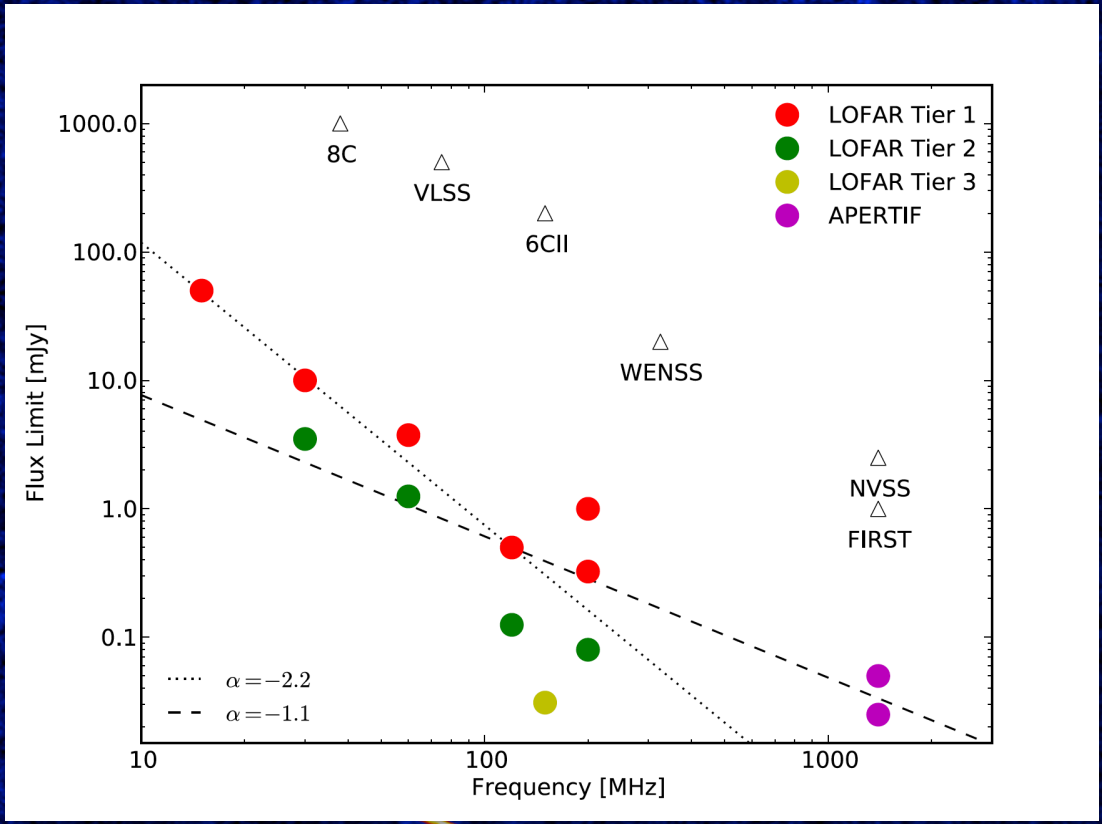


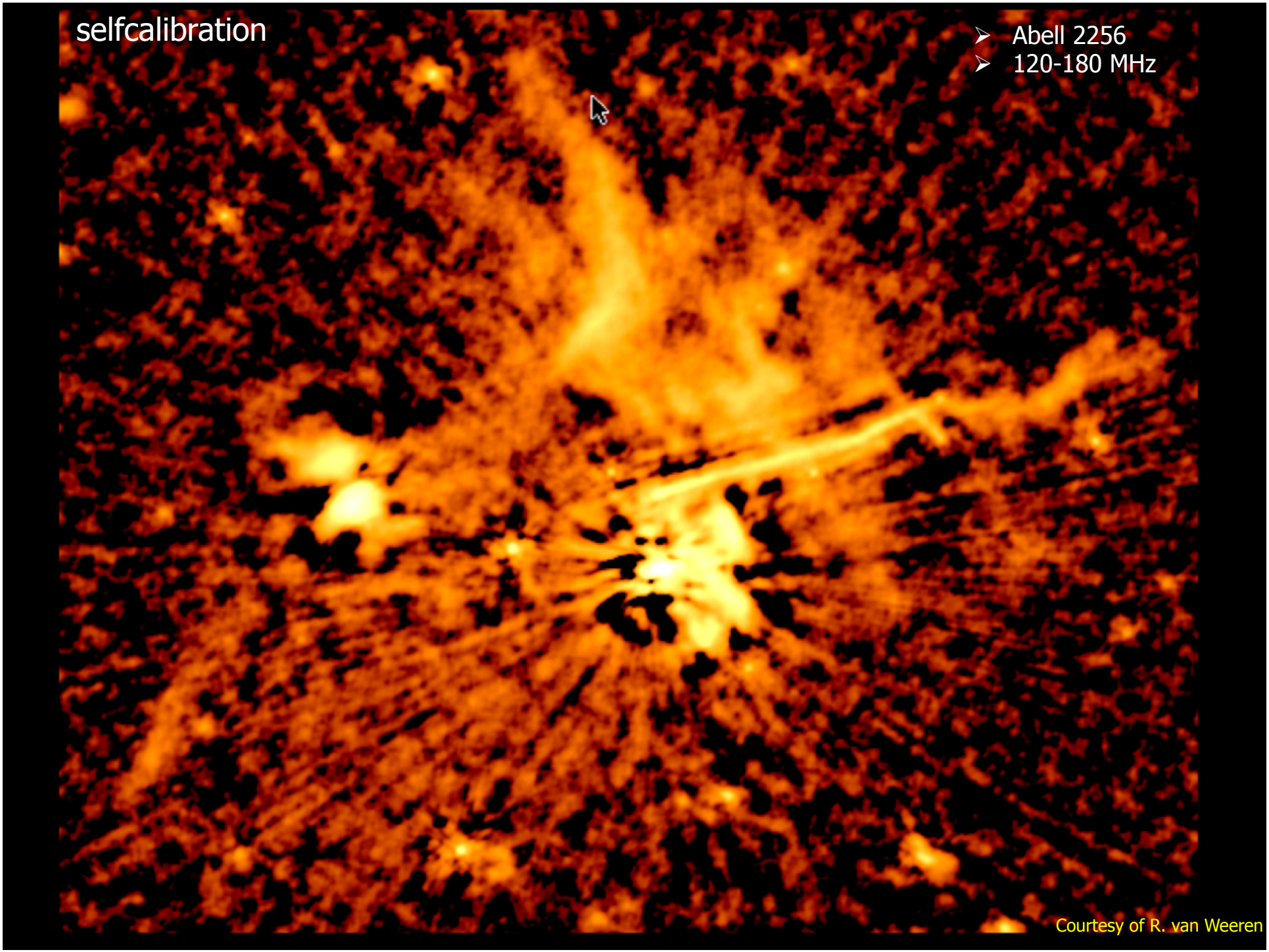
- Large FOV makes LOFAR an ideal surveys instrument
- 4 key topics:
  - High-redshift radio galaxies to study the formation and evolution of massive galaxies, rich clusters and massive black holes (100 high-redshift radio galaxies at z>6)
  - Galaxy clusters -> study origin and evolution of magnetic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

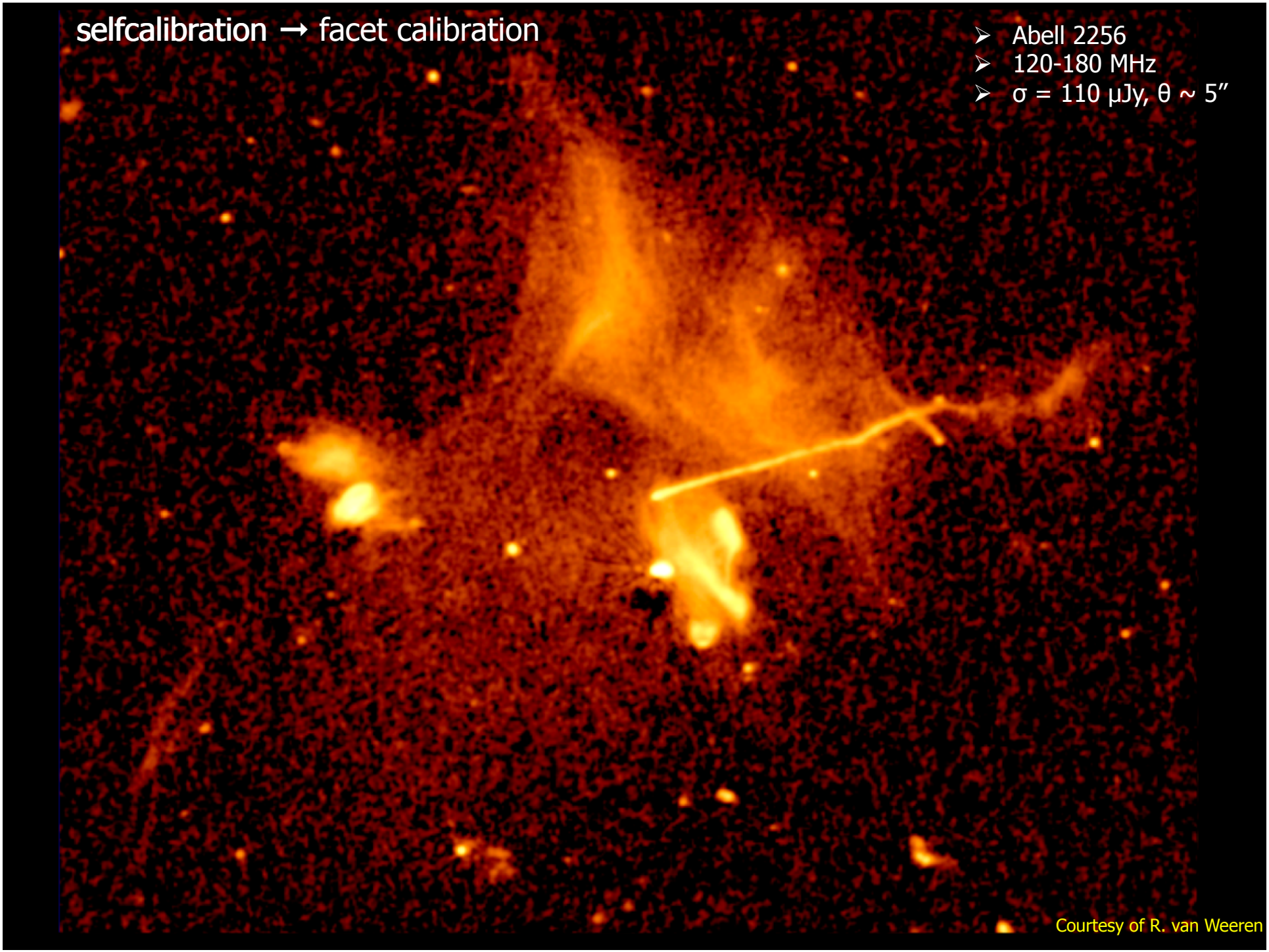
SURVEYS KSP - DEEP SURVEYS

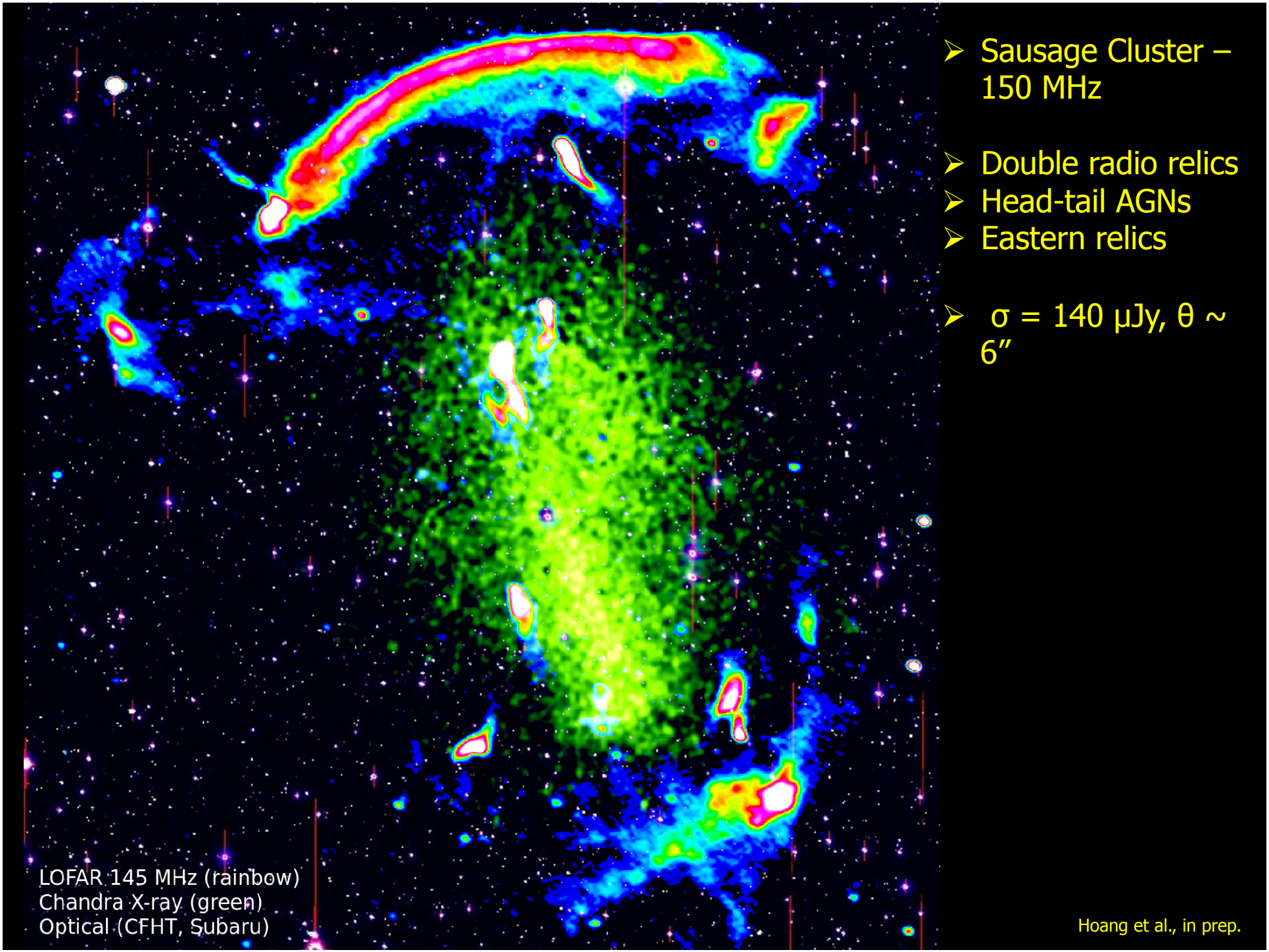


- Tier 1: 'large area' 2π steradian surveys – HBA (σ = 0.07 mJy) + LBA (σ = 1-2 mJy)
- Tier 2: the 'deep' surveys – HBA (500 deg², σ = 15 μJy)+ LBA (1000 deg², σ = 0.3 mJy)
- Tier 3: the 'ultra-deep' survey – 5 fields in HBA -> σ = 7μJy -> detect 50 proto-clusters at z>2

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

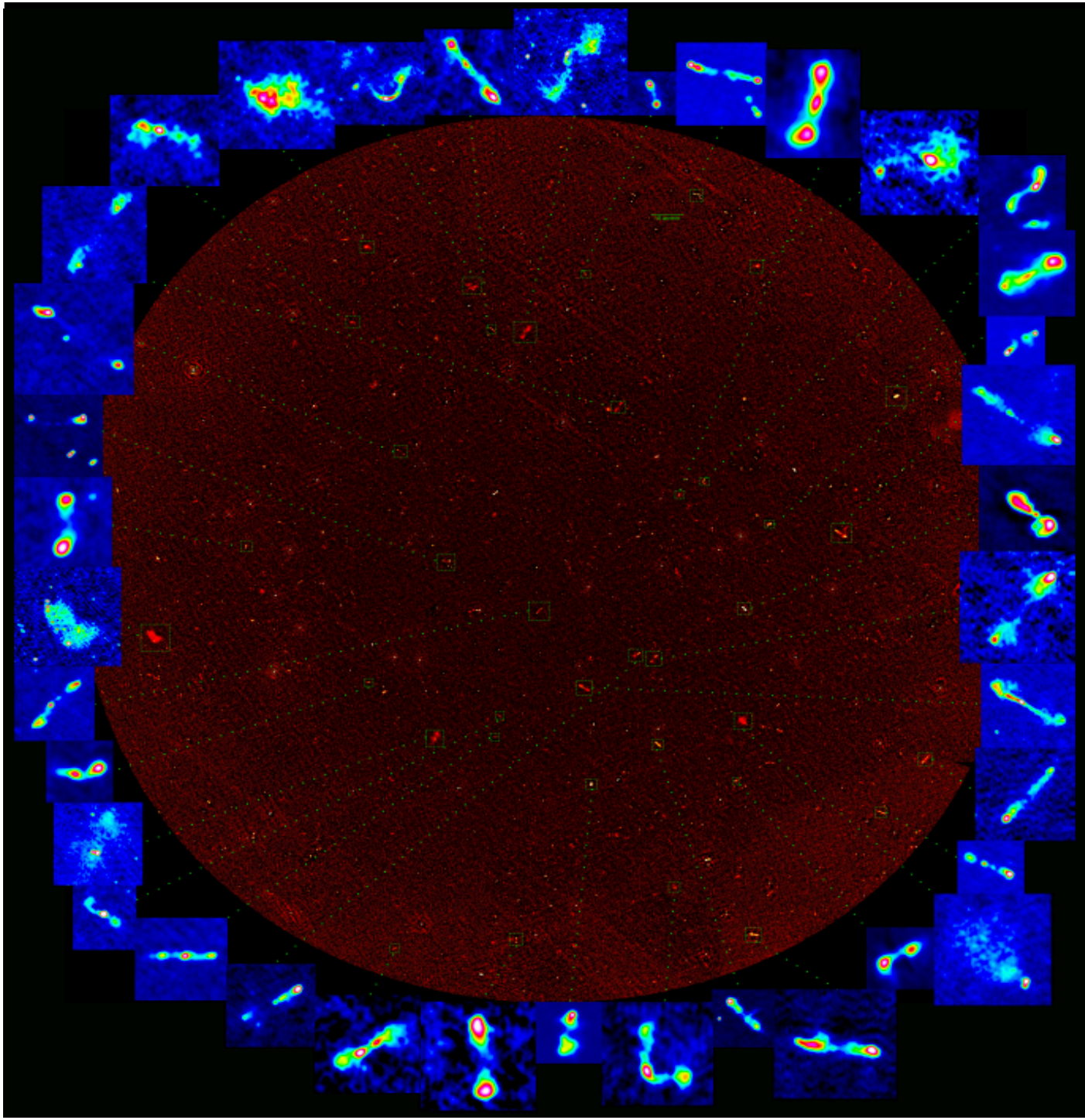

selfcalibration
Abell 2256
120-180 MHz
Courtesy of R. van Weeren


selfcalibration → facet calibration
Abell 2256
120-180 MHz
σ = 110 μJy, θ ~ 5″
Courtesy of R. van Weeren



- Sausage Cluster – 150 MHz
- Double radio relics
- Head-tail AGNs
- Eastern relics
- σ = 140 μJy, $\theta \sim$ 6″

Hoang et al., in prep.



- 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
- σ = 120 μJy, $\theta \sim$ 6”

Williams et al. 2016

IMAGING WITH THE INTERNATIONAL STATIONS

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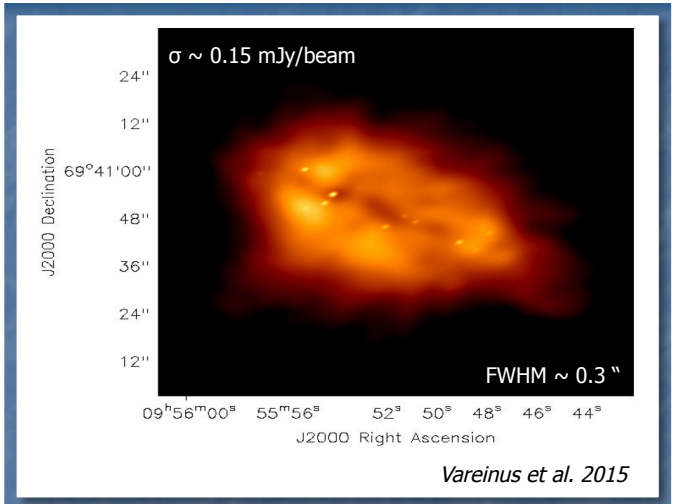
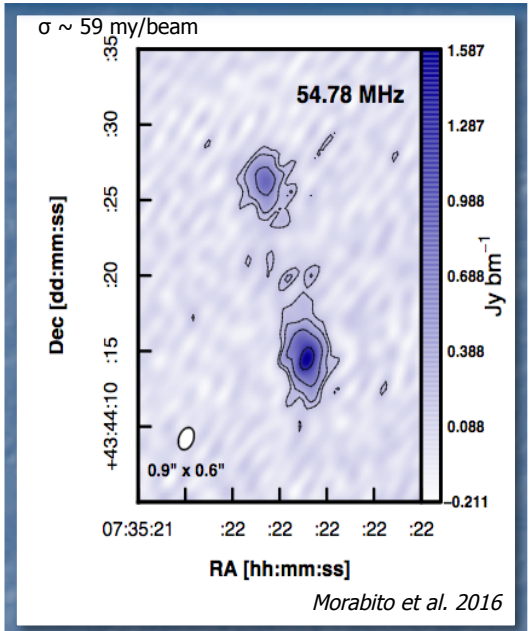


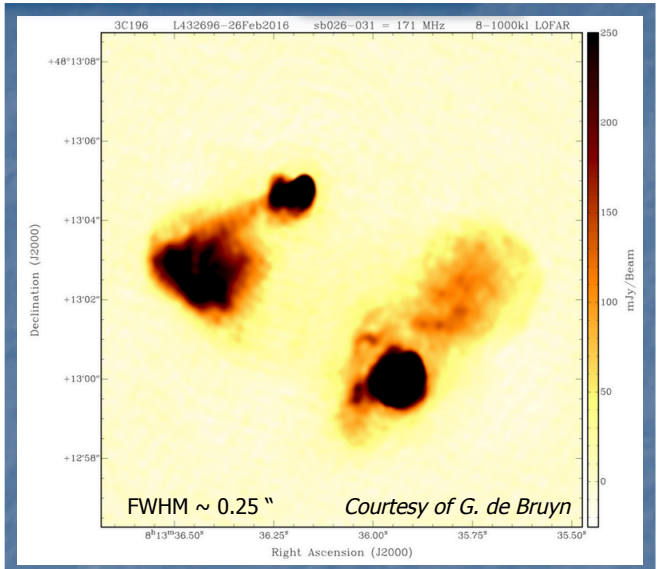
Vareinus et al. 2015

- 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



Morabito et al. 2016

- 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!!

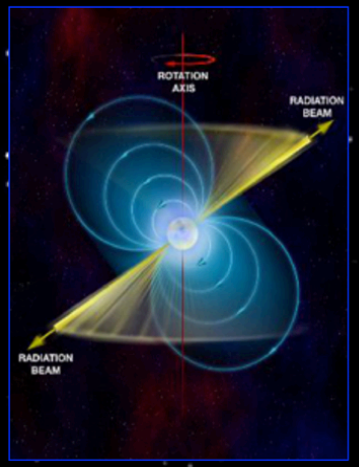


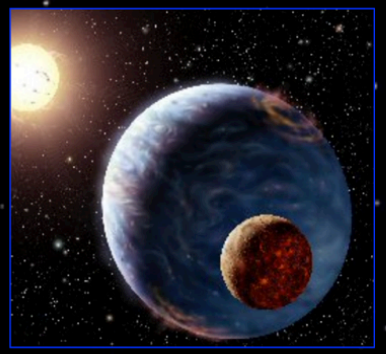
- It includes the Polish stations – maximum baseline > 1300 km!

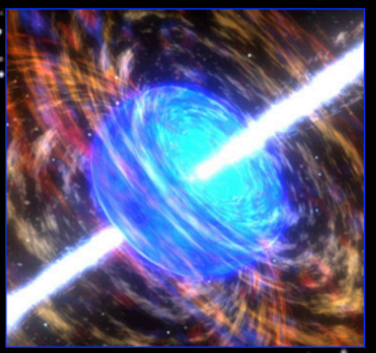
see J. Moldon's lecture on Thursday

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

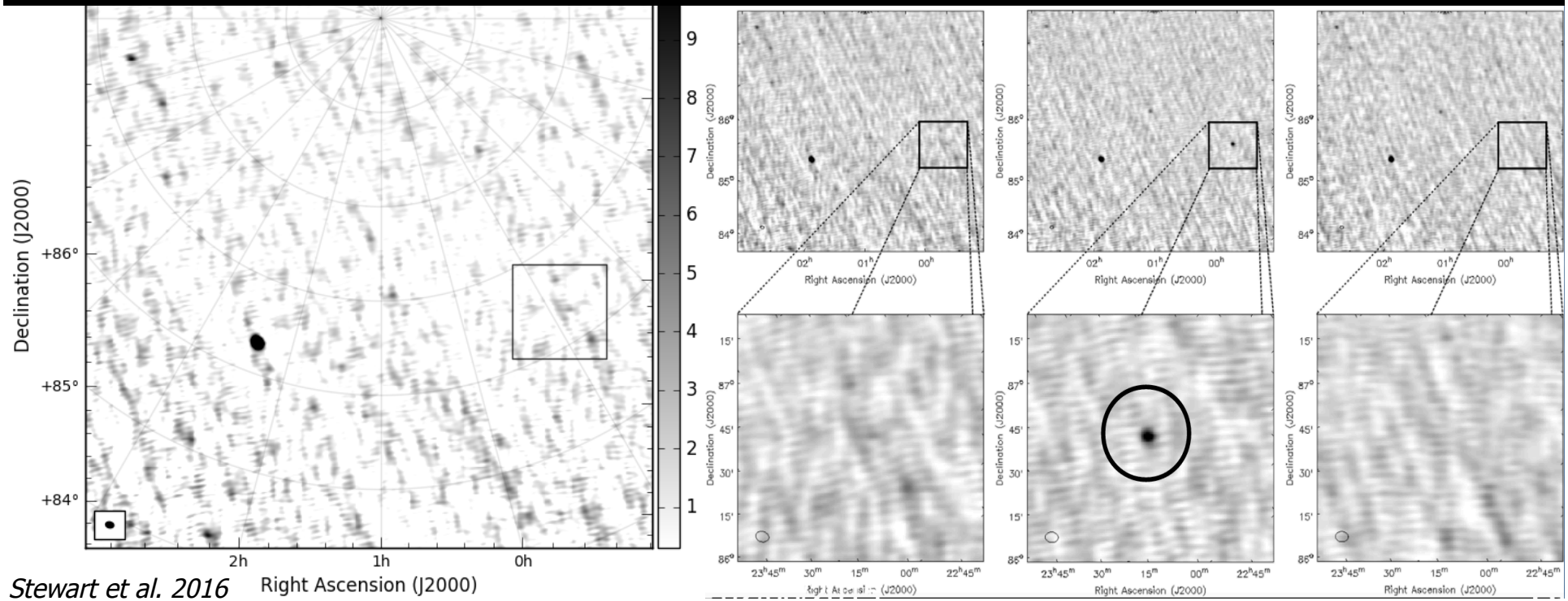






Adam's transient

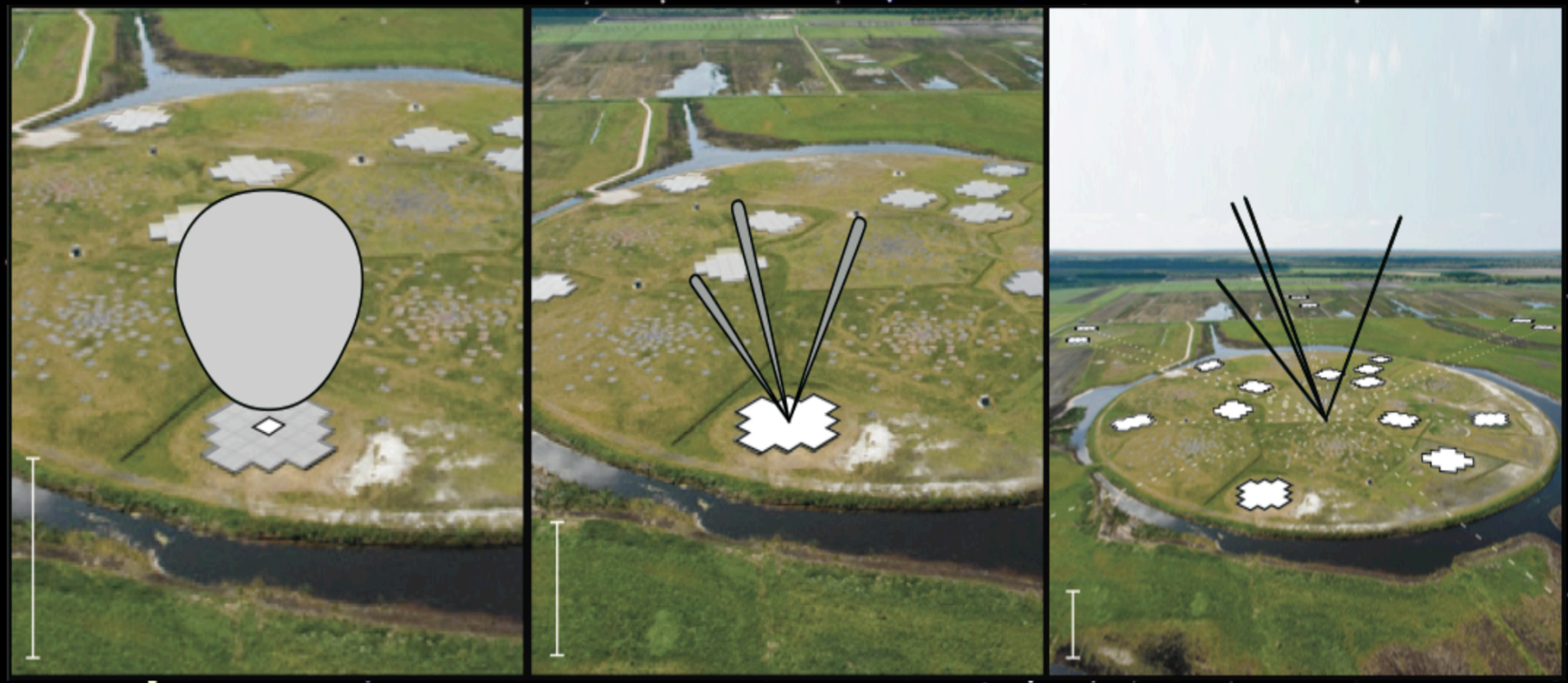
- NCP monitoring project during MSSS-LBA
- Transient seen in one, 11 min snapshot at 60 MHz
- Brightness of 15-20 Jy
- Passed exhaustive validity tests
- No counterpart at higher frequencies
- At present the origin is unknown - attempt to find more events, using data from Cycles 2 & 3.



Stewart et al. 2016

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***

LOFAR TIED-ARRAY ALL-SKY SURVEY (LOTAAS)

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- Deepest low-frequency Pulsar Survey ever performed

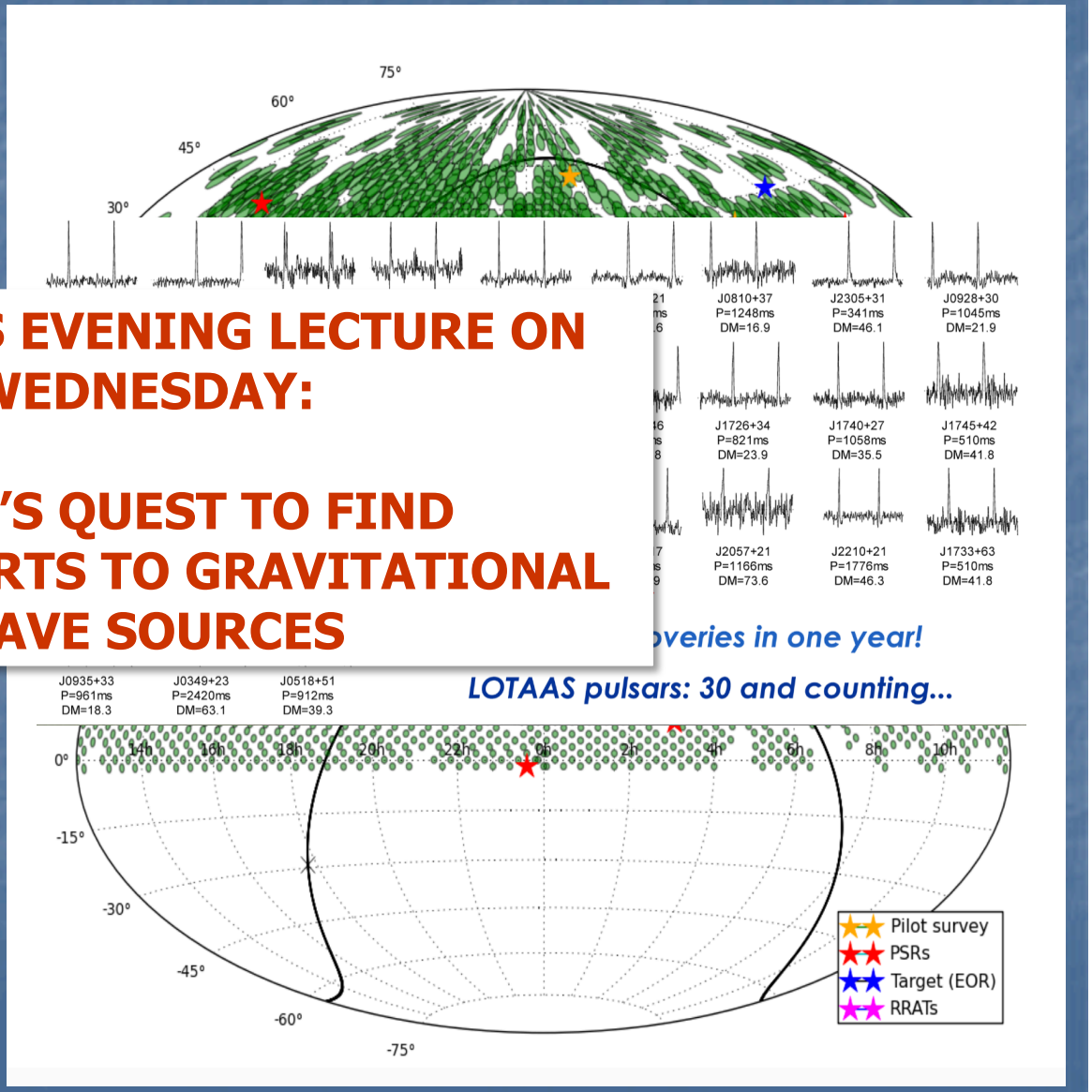
1. Discover exotic pulsar systems to use for testing gravity in the strong-field regime, constraining the physics of dense matter, and probing the pulsar emission mechanism
2. Characterize the transient radio sky on timescales and determine what fraction of radio pulsars are transient

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

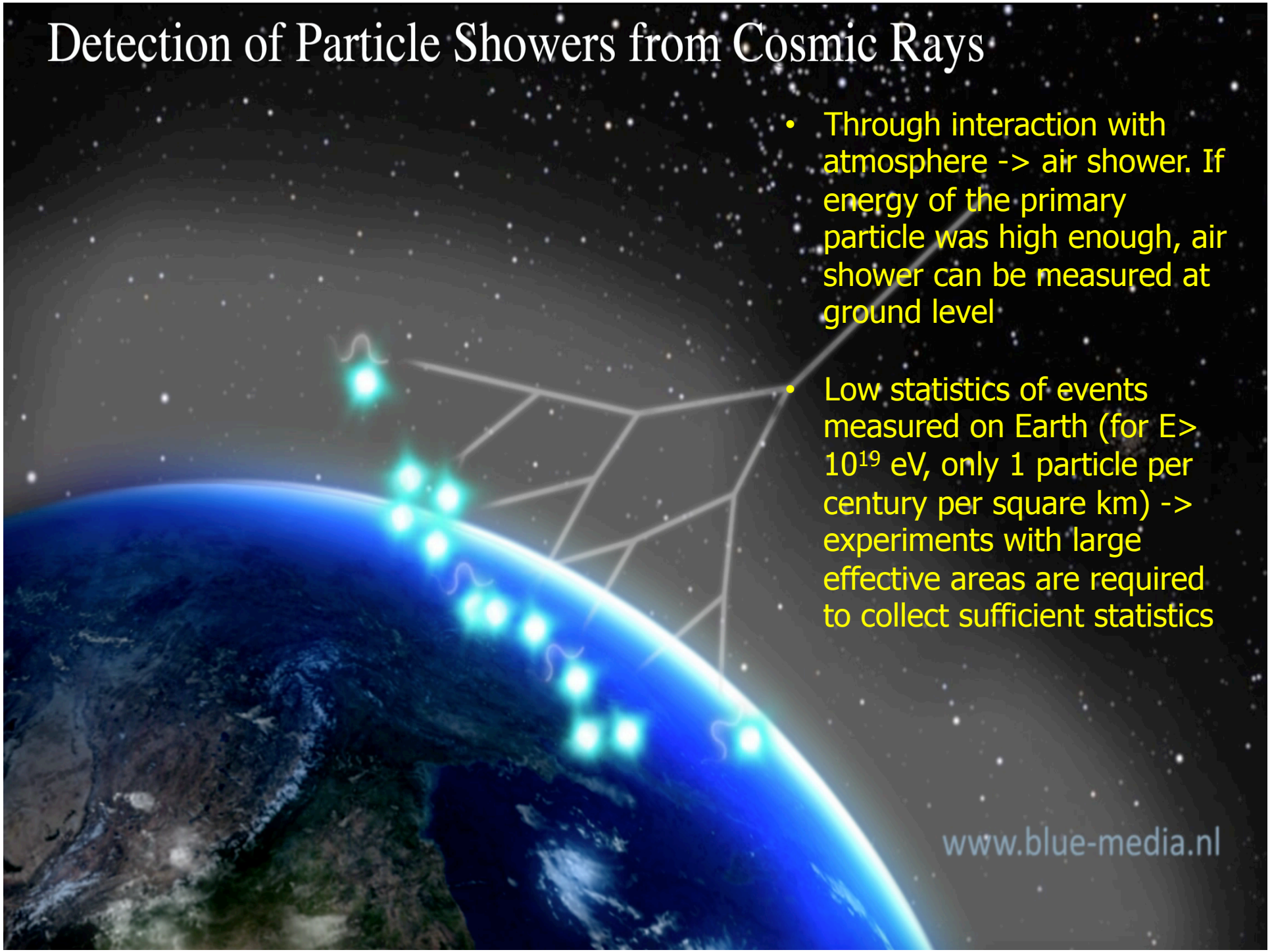
see R. Oonk & S. ter Veen's lecture on Thursday

DON'T MISS EVENING LECTURE ON WEDNESDAY:

LOFAR'S QUEST TO FIND COUNTERPARTS TO GRAVITATIONAL WAVE SOURCES



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

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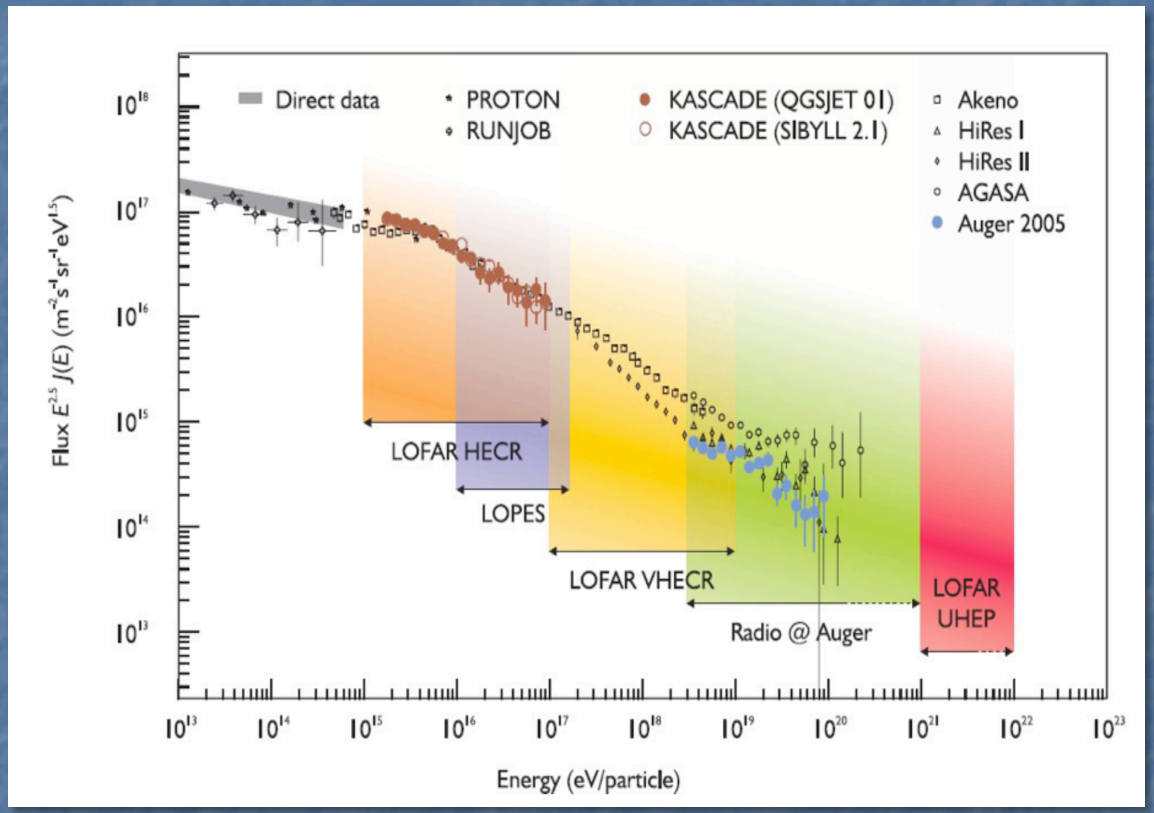

- Spectrum of CR flux is smooth and follows a power low
- At E ~ 5 x 10^{15} eV -> turnover (knee). Above the knee, composition of CR is not yet understood
- Composition crucial for understanding of acceleration and propagation mechanisms
- LOFAR will observe CR above 10^{16} eV up to 10^{19} eV.

COSMIC RAY PRECISION COMPOSITION MEASUREMENTS

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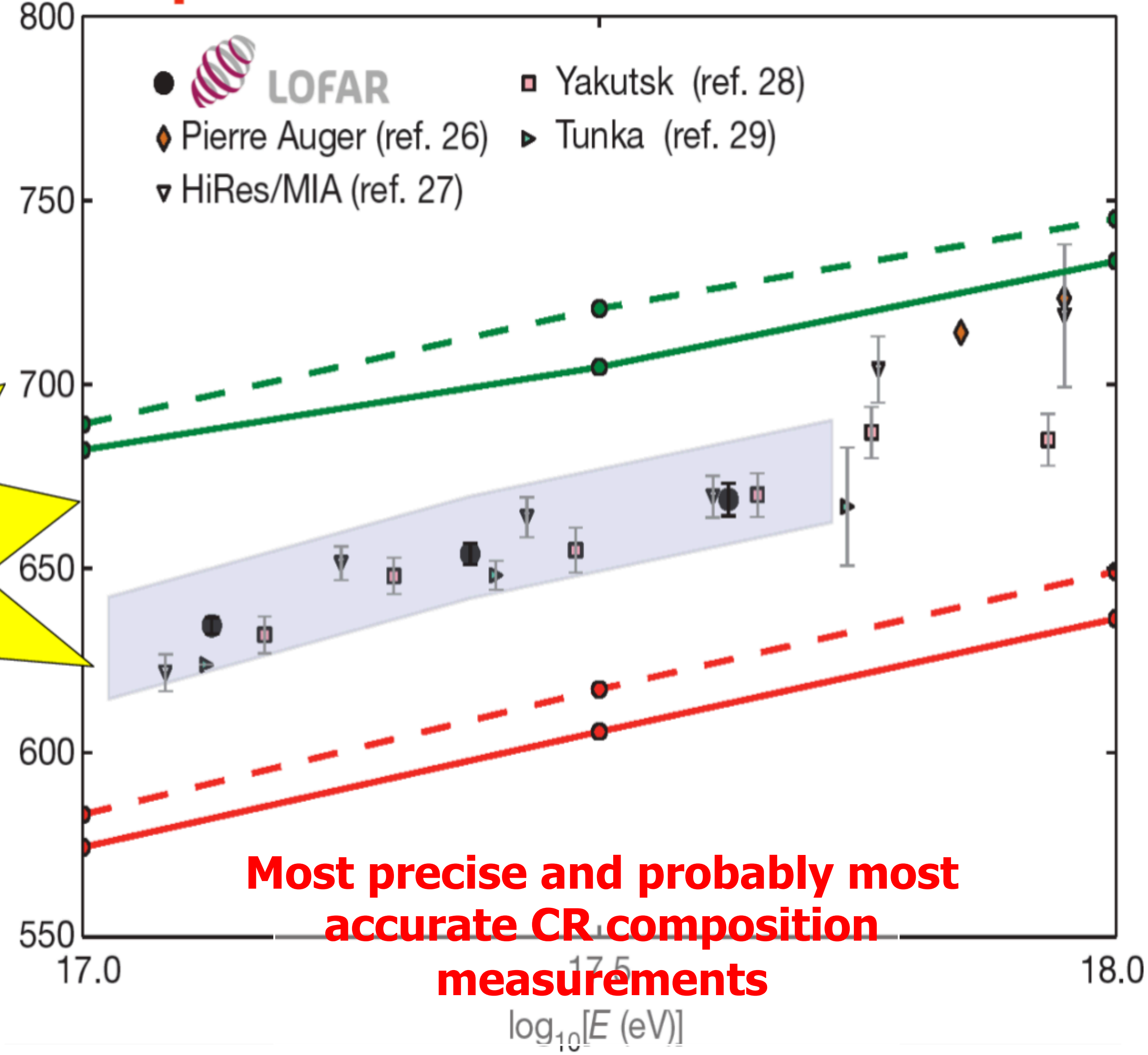
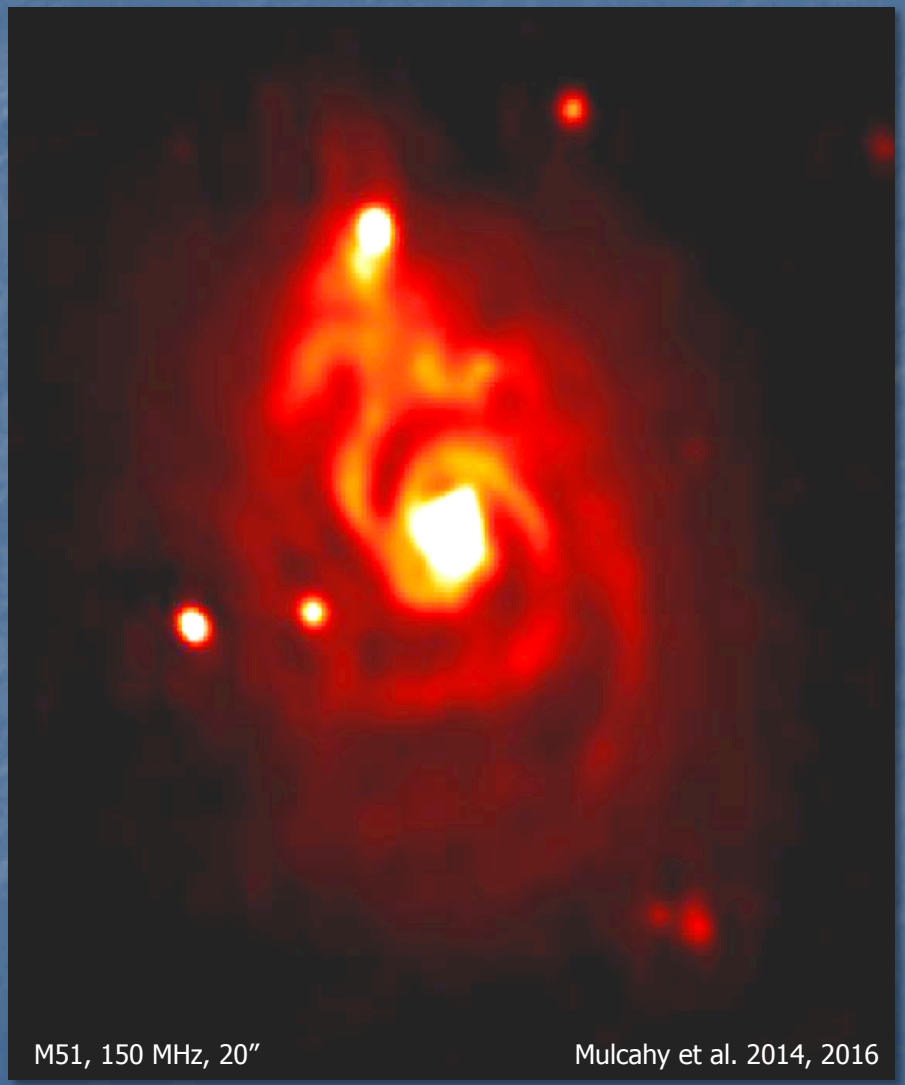
Depth of the shower maximum



S. Buitink et al., Nature (2016)

COSMIC MAGNETISM

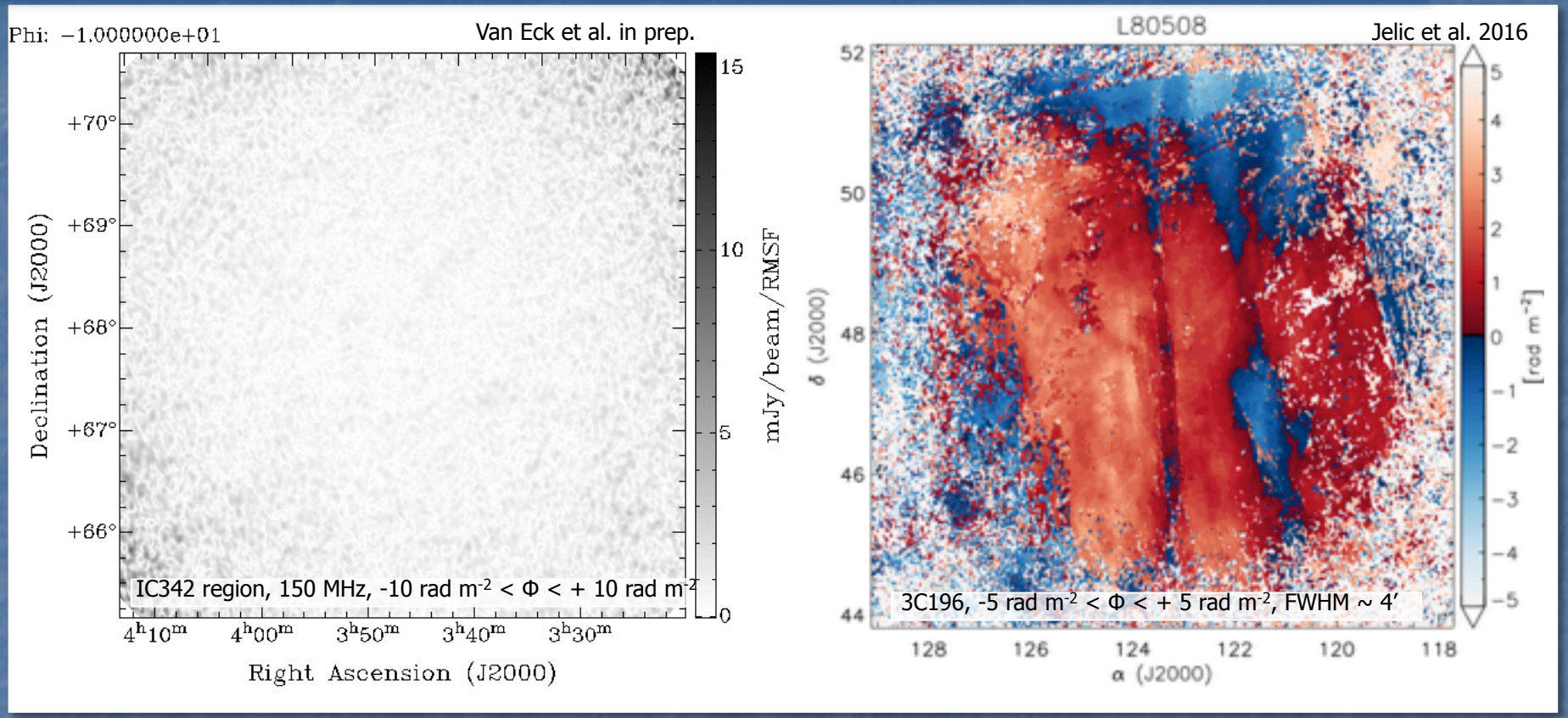


M51, 150 MHz, 20”

Mulcahy et al. 2014, 2016

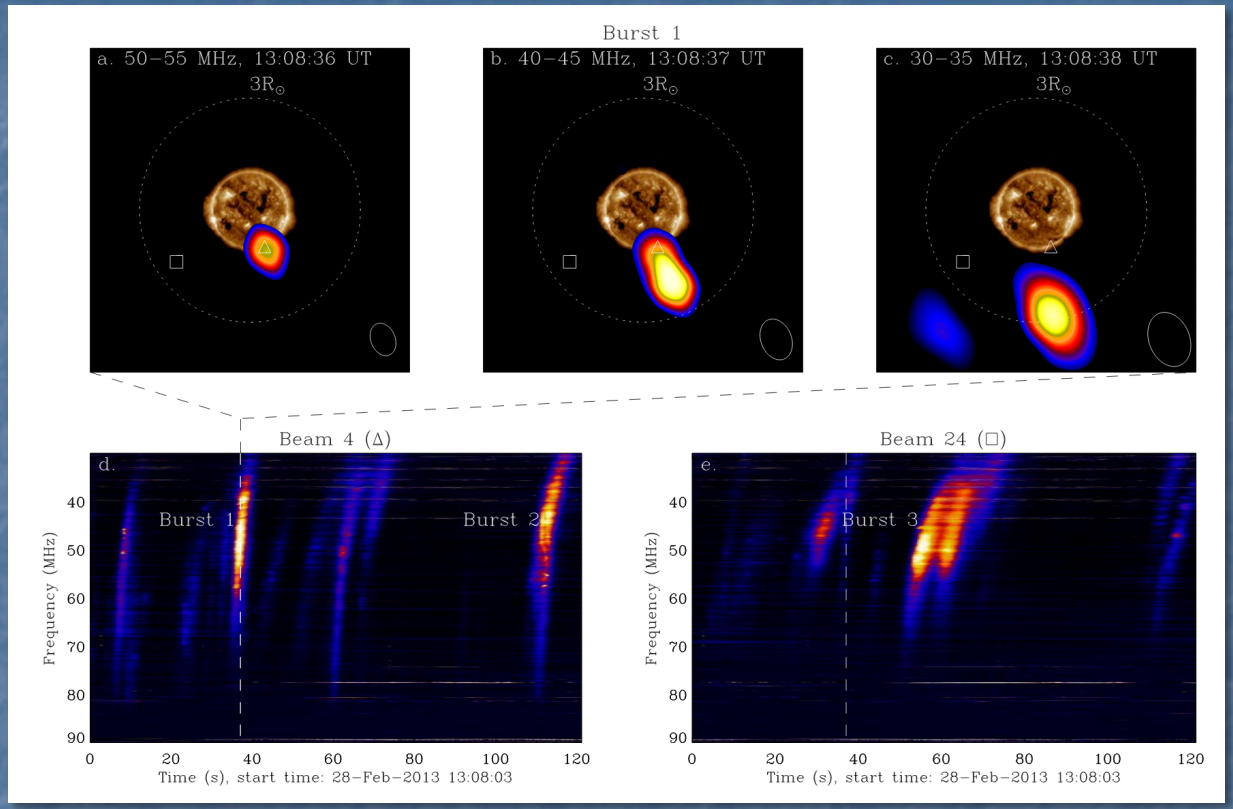
- Magnetic fields are ubiquitous in the Universe – their origin, evolution and structure still remain open fundamental problems
- Synchrotron radiation produced by relativistic electrons -> total field strength, orientation and degree of ordering in the plane of the sky and component of ordered fields 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 fro CR acceleration sites
  - Trace weak magnetic fields through Faraday rotation studies (RM synthesis)
- See M. Iacobelli’s lecture on Thursday

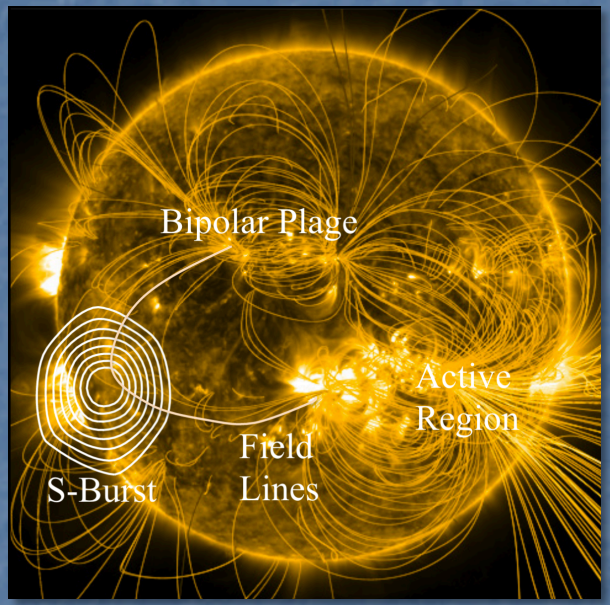
GALACTIC FOREGROUNDS: FAN REGION & 3C196



- 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

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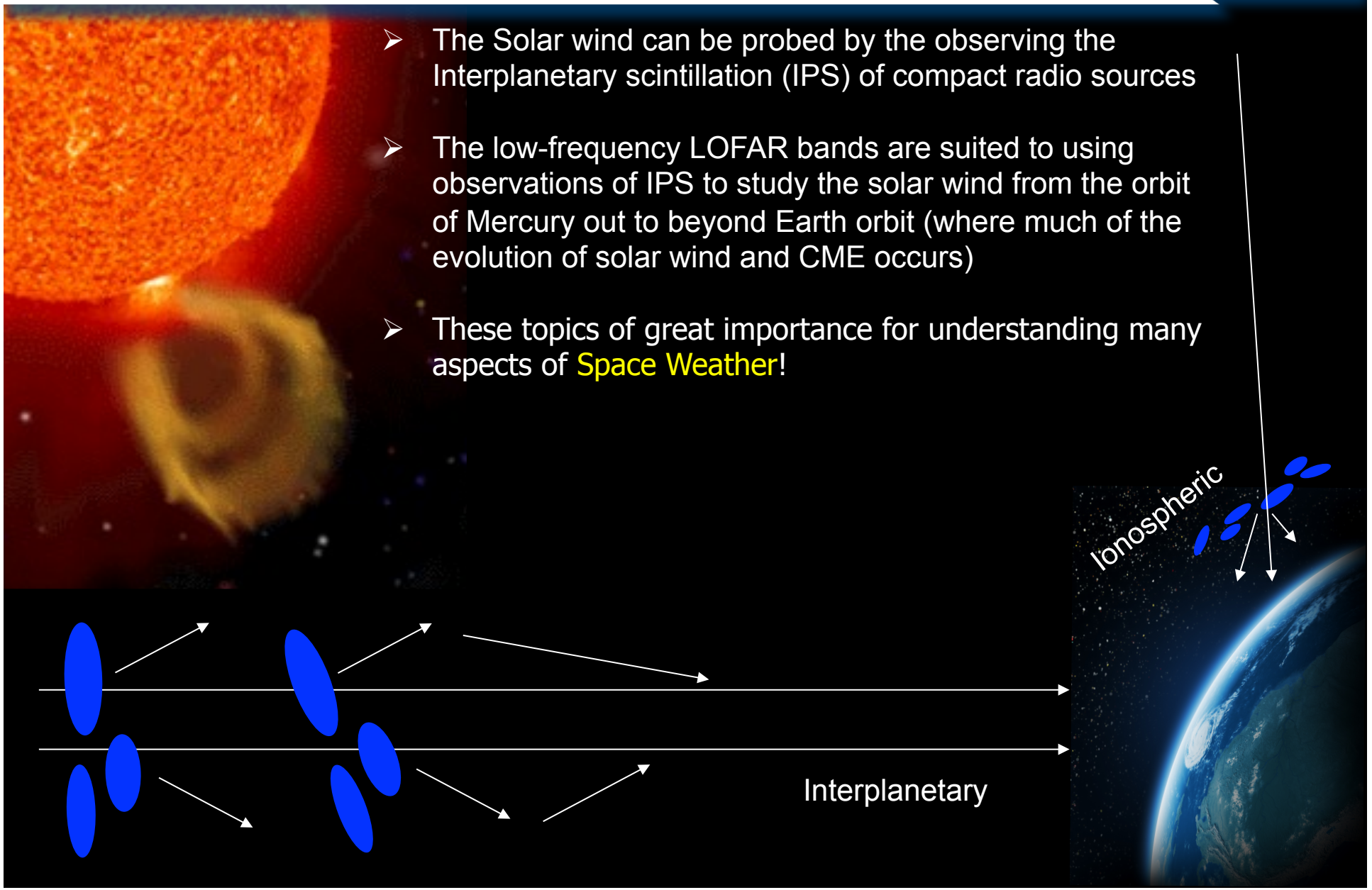

SOLAR PHYSICS AND SPACE WEATHER

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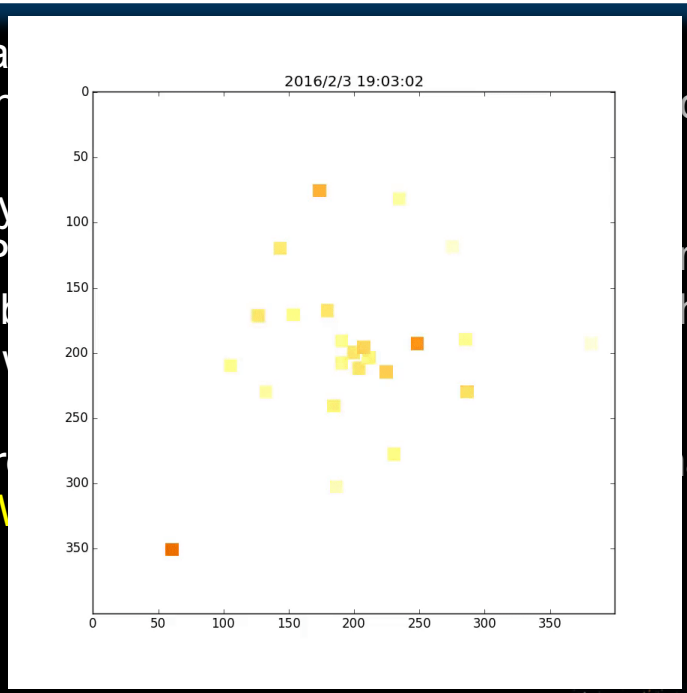
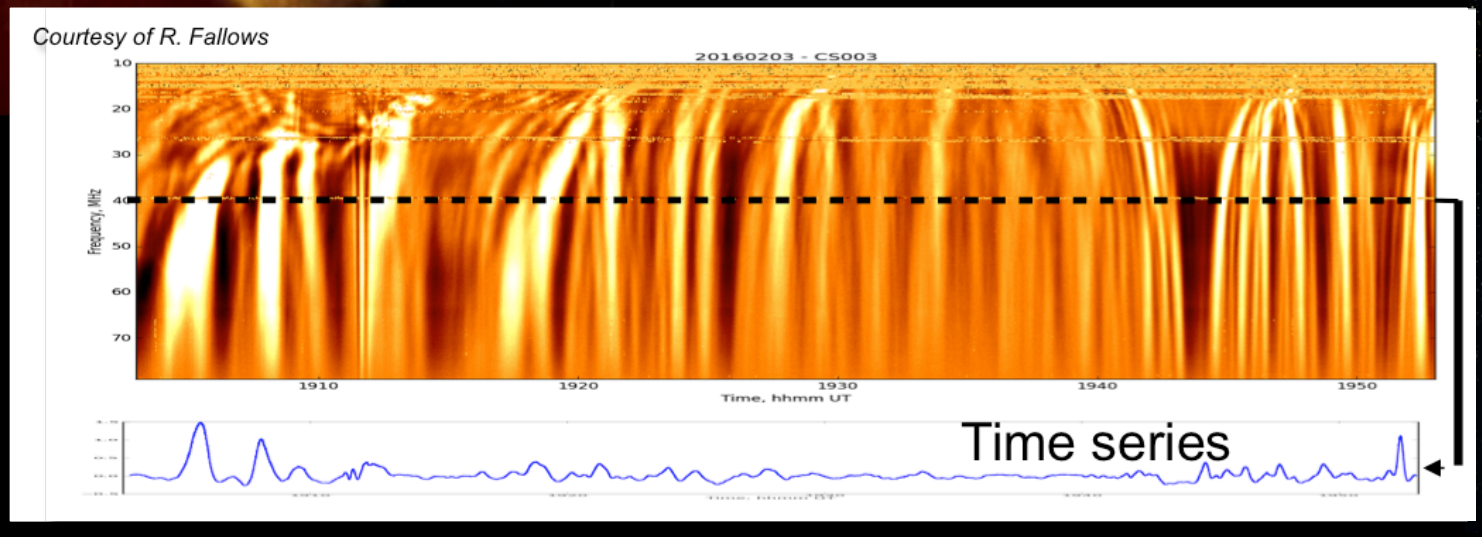
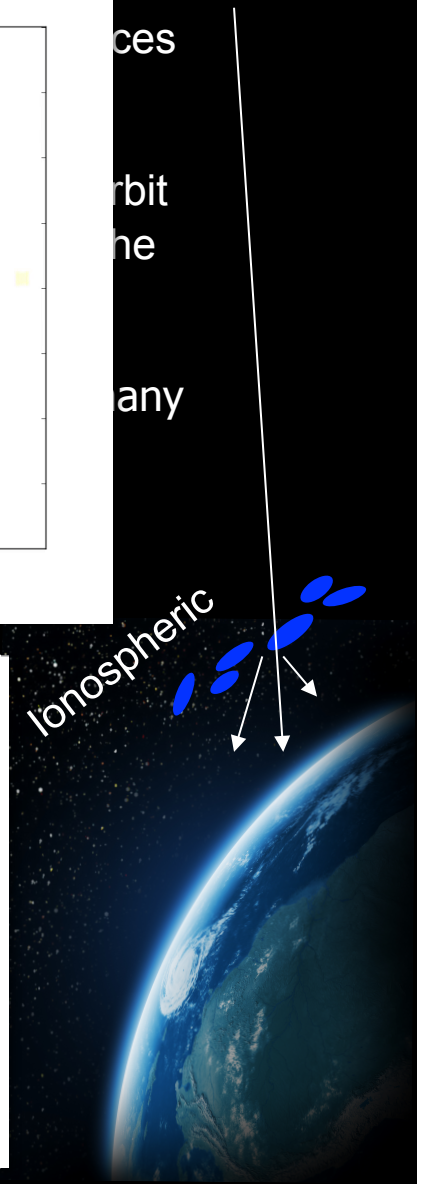
- The Solar wind ca… Interplanetary scir… …ces
- The low-frequency… observations of IP… …rbit of Mercury out to … …he evolution of solar …
- These topics of gr… …any aspects of Space …







MULTIFREQUENCY SNAPSHOT SKY SURVEY: MSSS

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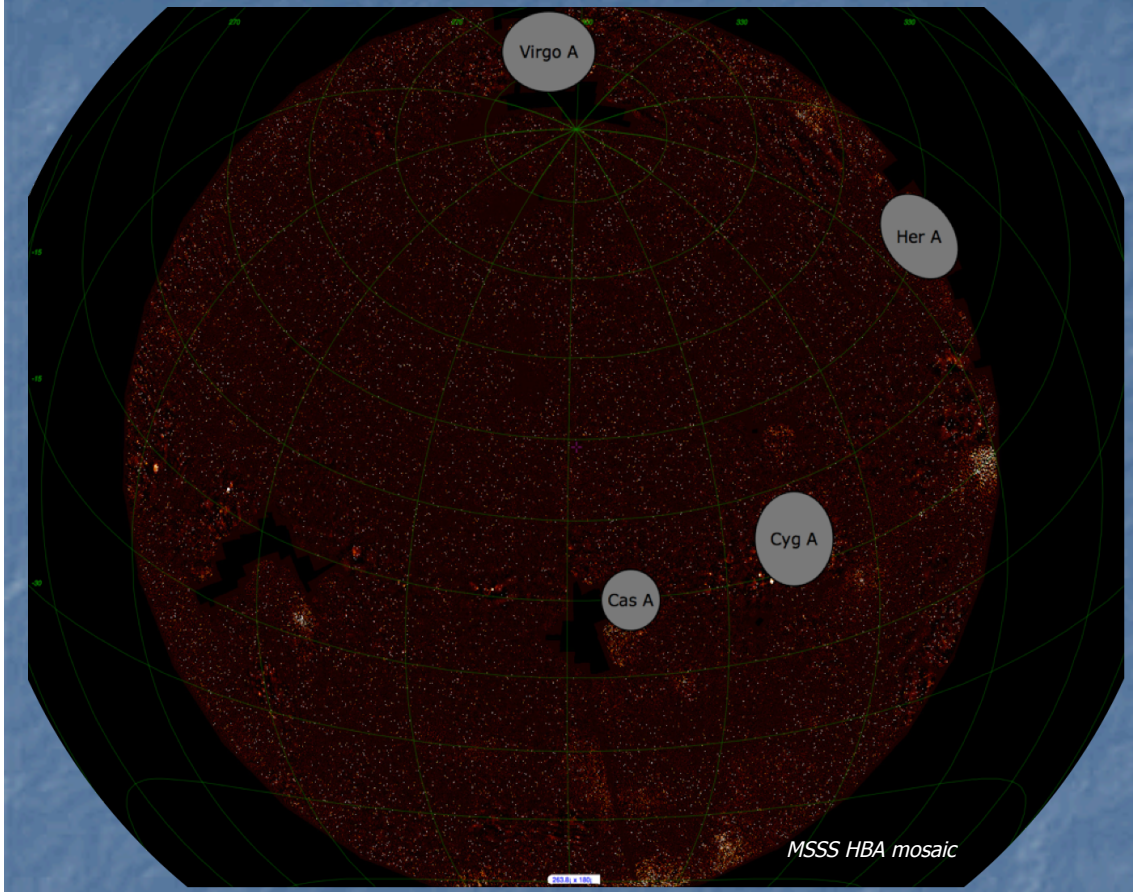
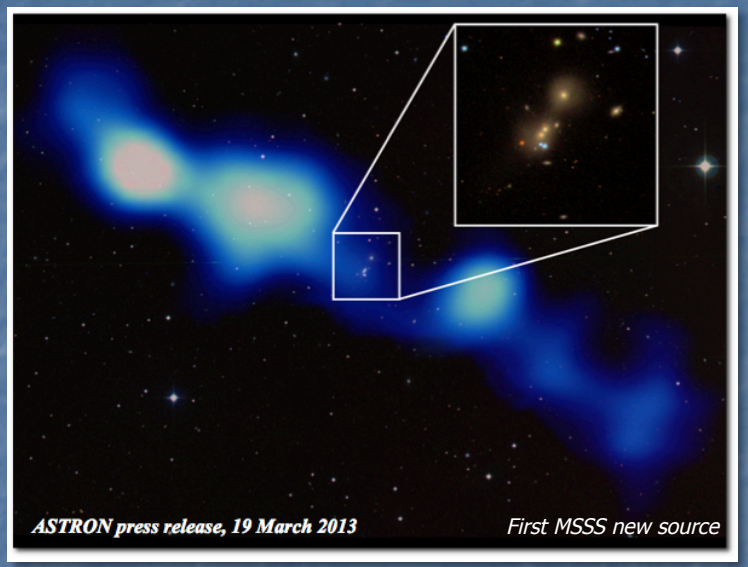
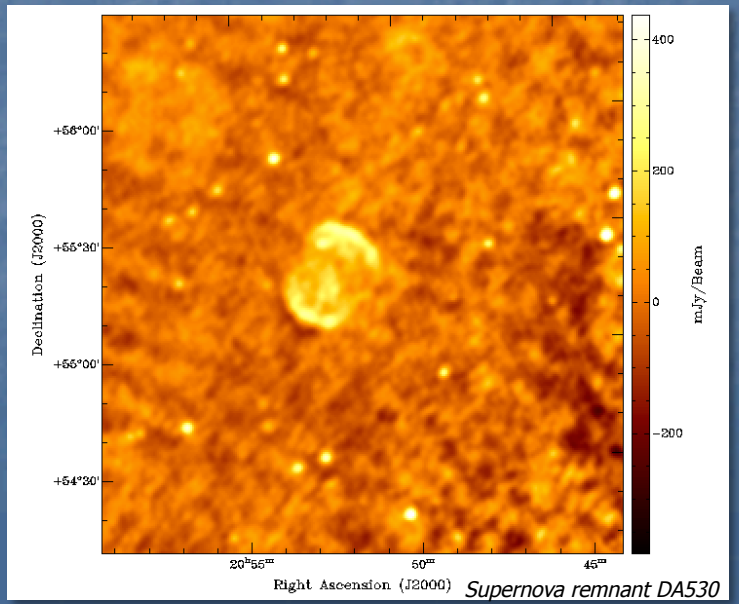


MSSS HBA mosaic



First MSSS new source

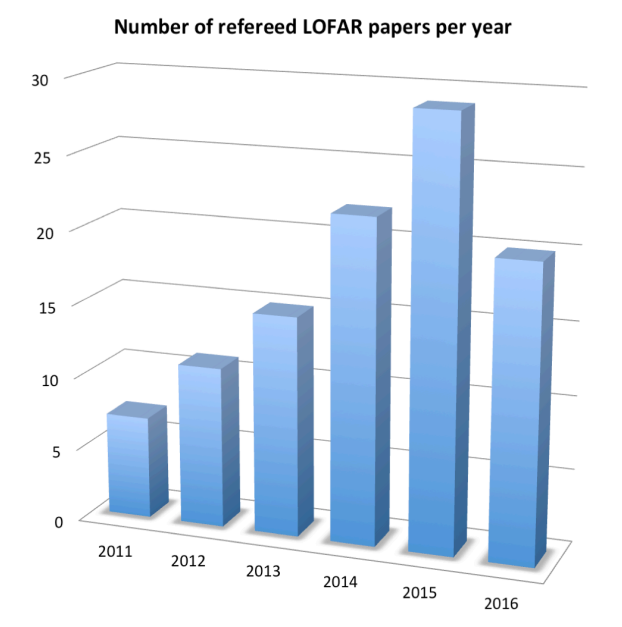


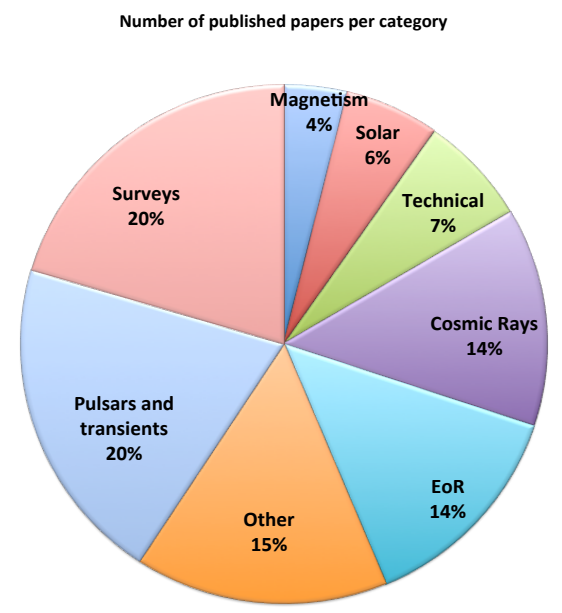
Supernova remnant DA530

- 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
Hermsen 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!!!

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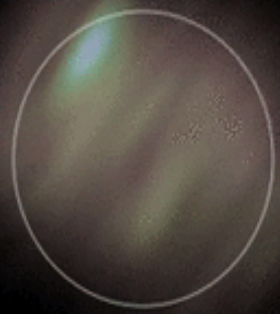
Netherlands Institute for Radio Astronomy

Solar Eclipse – March 2015

LOFAR, HBA

08:25 CET



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Courtesy of M. Brentjens

THANKS