The LOFAR Surveys Deep Fields

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In collaboration with the LOFAR Surveys KSP

Special credits:

- (Radio) Cyril Tasse, Tim Shimwell, Pepe Sabater, Martin Hardcastle
- (Multi-wavelength) Rohit Kondapally, Ken Duncan

LOFAR Surveys: Multi-tiered approach

Tier 1: “Large Area” (LoTSS / LoLSS; Shimwell, de Gasperin):

- all northern sky at 60 and 150 MHz, to S_{150MHz} < 100μJy/bm rms
  - finding rare objects (e.g. z>7 RGs, cluster halos, strong lenses)
  - large samples of nearby AGN/SFGs
  - cosmology (e.g. Integrated Sachs-Wolfe effect, weak lensing)

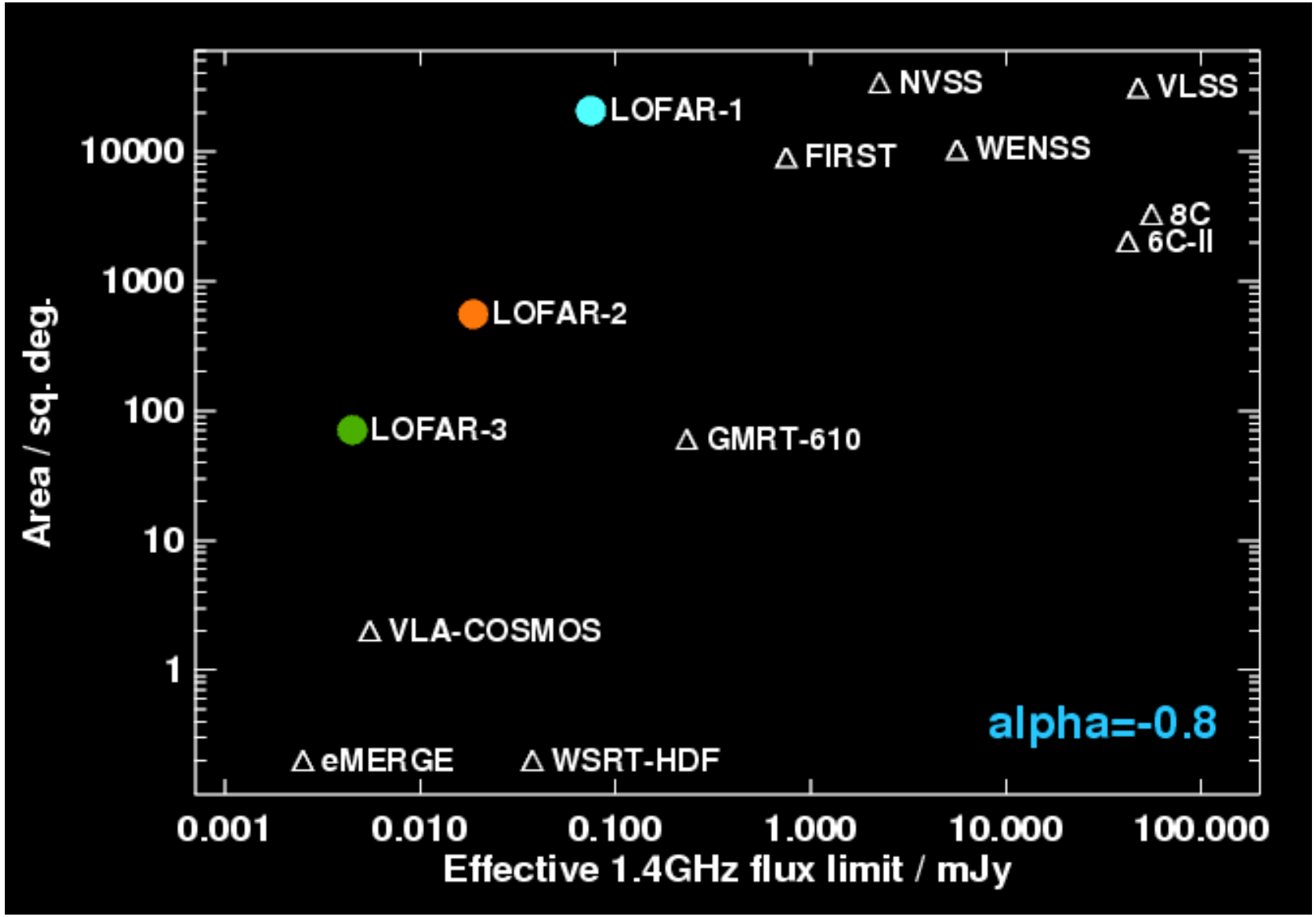
Tier 2: “Medium Deep”:

- few 100 sq. deg at 60 and 150 MHz to S_{150MHz}~ 25μJy/bm rms
  - properties & evolution of SF galaxies, radio-loud & radio-quiet AGN
  - localise & identify sources from Herschel, SCUBA-2, Spitzer, etc
  - deep studies of nearby galaxies and clusters

Tier 3: “Ultra-deep”:

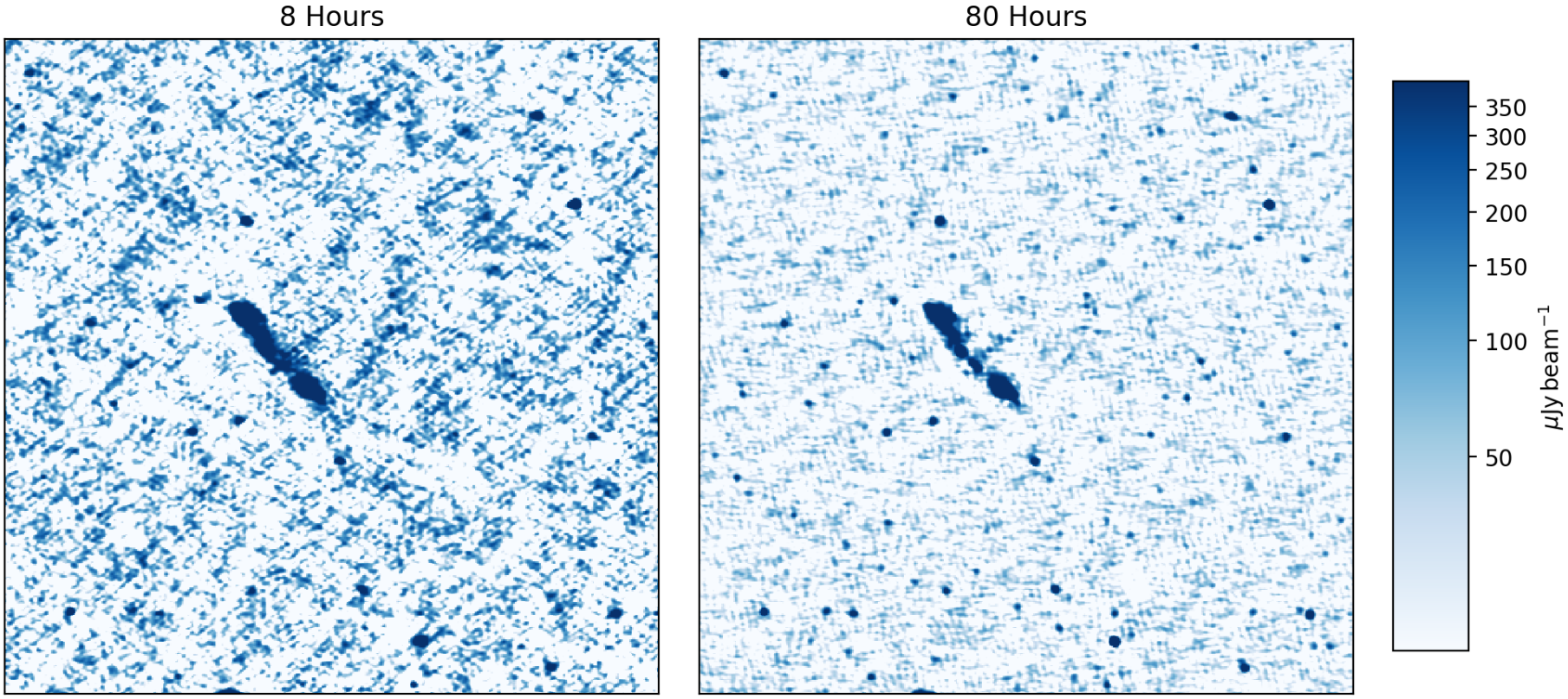
- ~70 square degrees, 150MHz only, to ~10μJy rms
  - deep SF & RQ AGN studies; variation with z, environment, host gal
  - sufficient sky area to sample all environments at high-z.

LOFAR HBA compared to other surveys



Progress to Tier 2/3 in ‘famous fields’

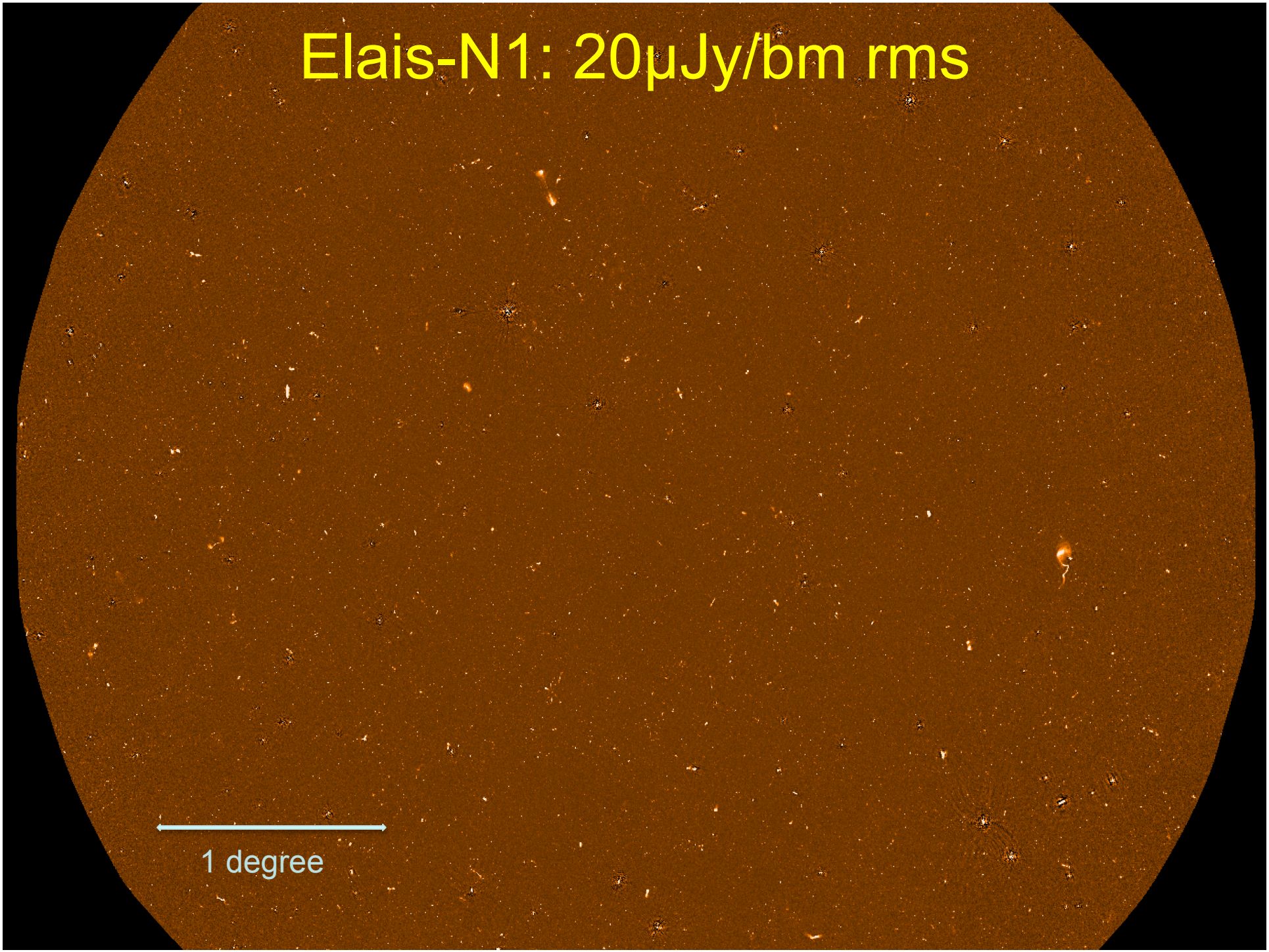
- Continuing to progress towards deeper Tier 2/3 depth data in the extragalactic fields with best degree-scale multi-wavelength data
  - Elais-N1, Bootes, Lockman Hole
- Calibration quality still good: noise decreasing as sqrt(t).

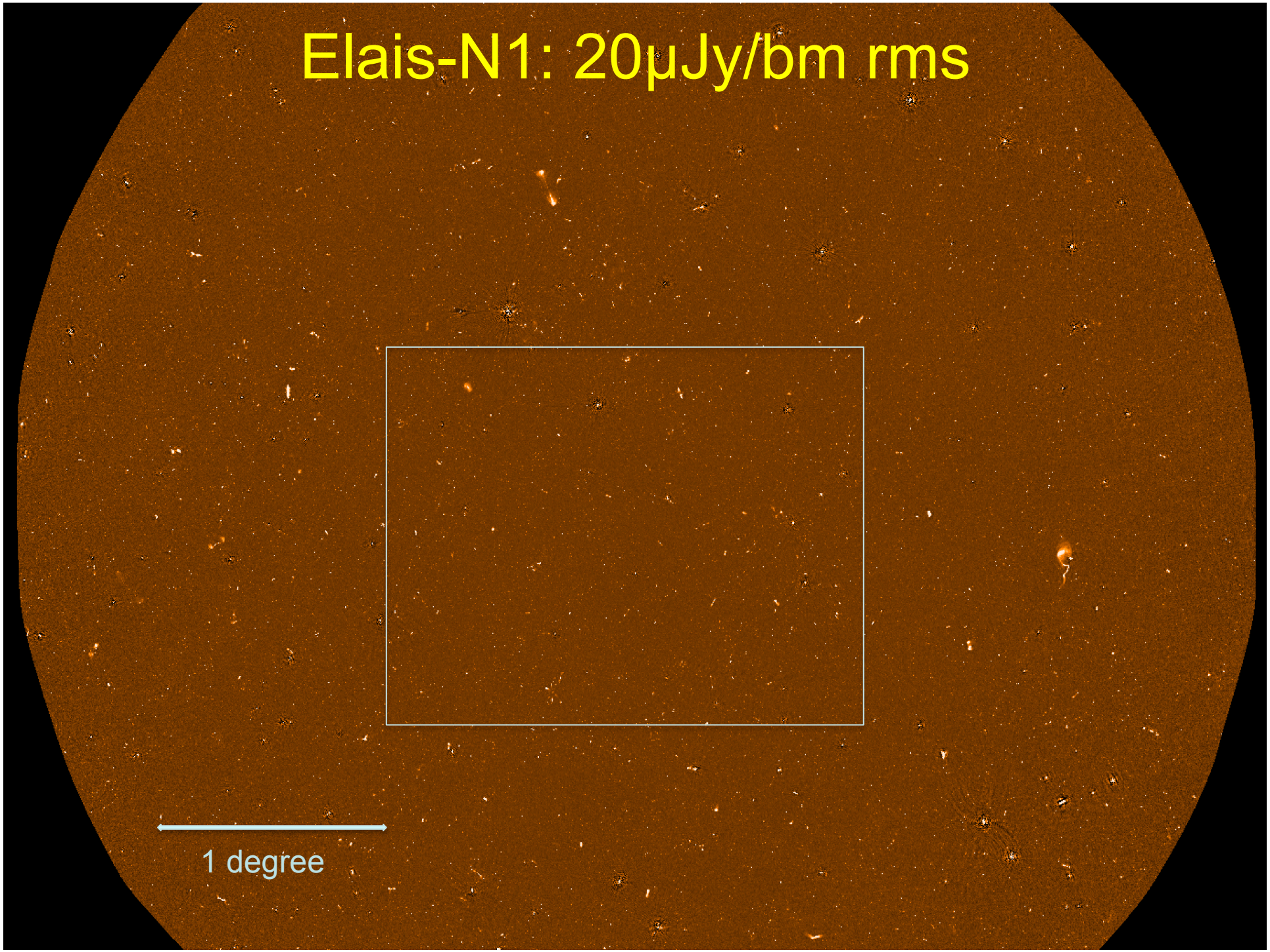


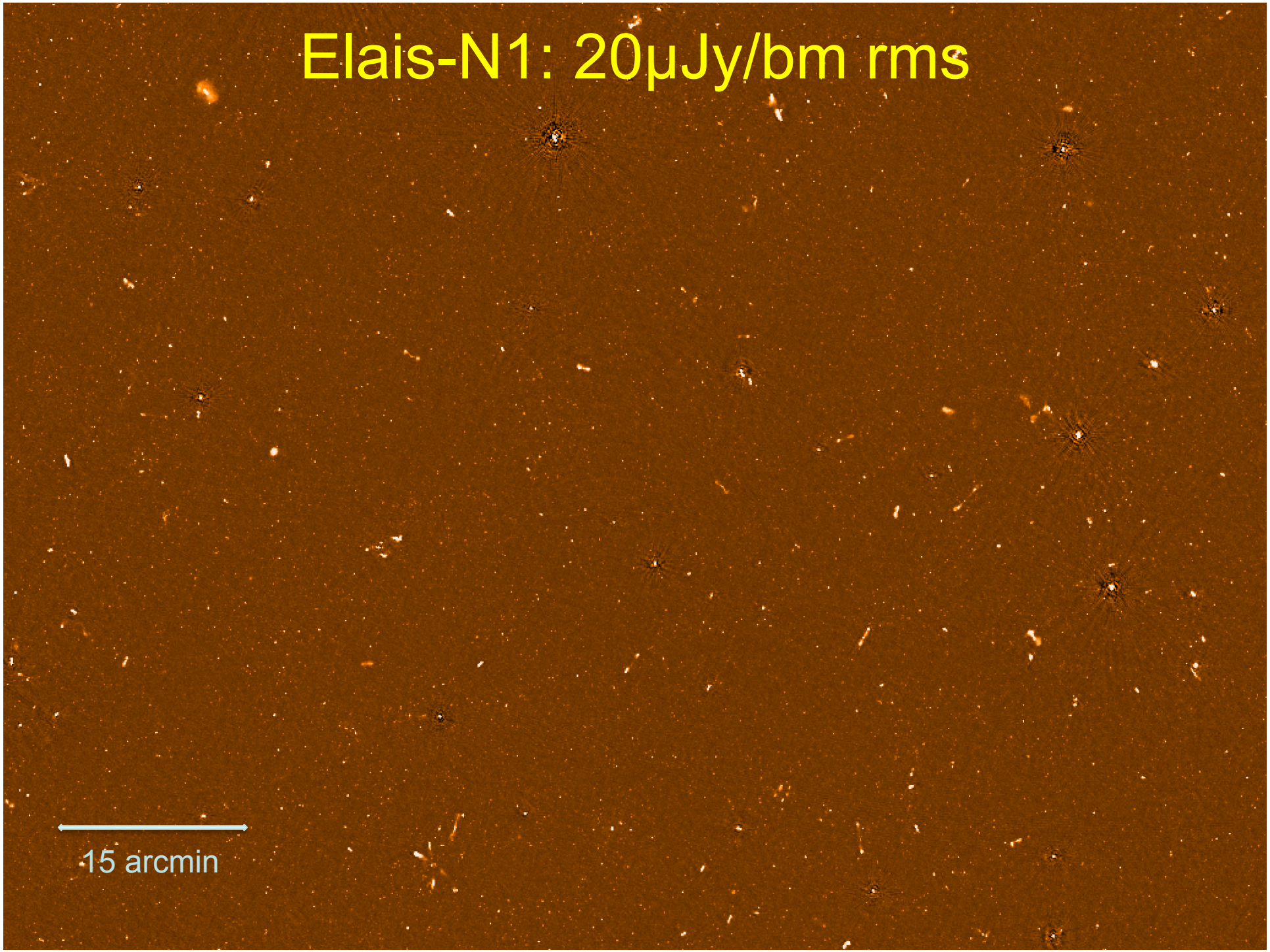
Data acquisition in deep fields

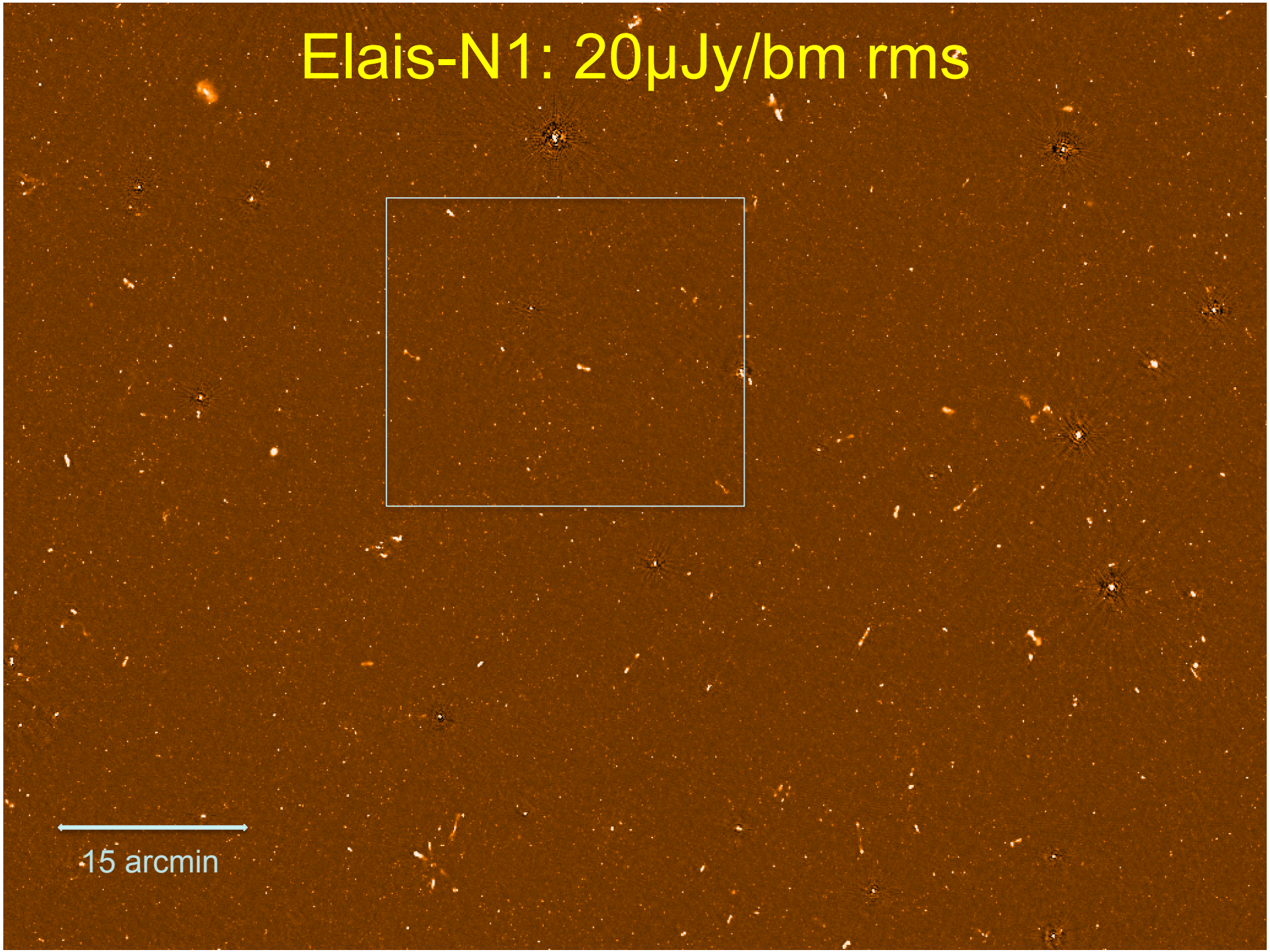
Field	Data before Cycle 10	Allocated time Cycle 10-13	Analysed for Data Release 1	Depth (μJy/bm)
Boötes	80 hrs	80 hrs	80 hrs	~37
Elais-N1	180 hrs	160 hrs	170 hrs	~20
Lockman Hole	72 hrs	80 hrs	112 hrs	~25

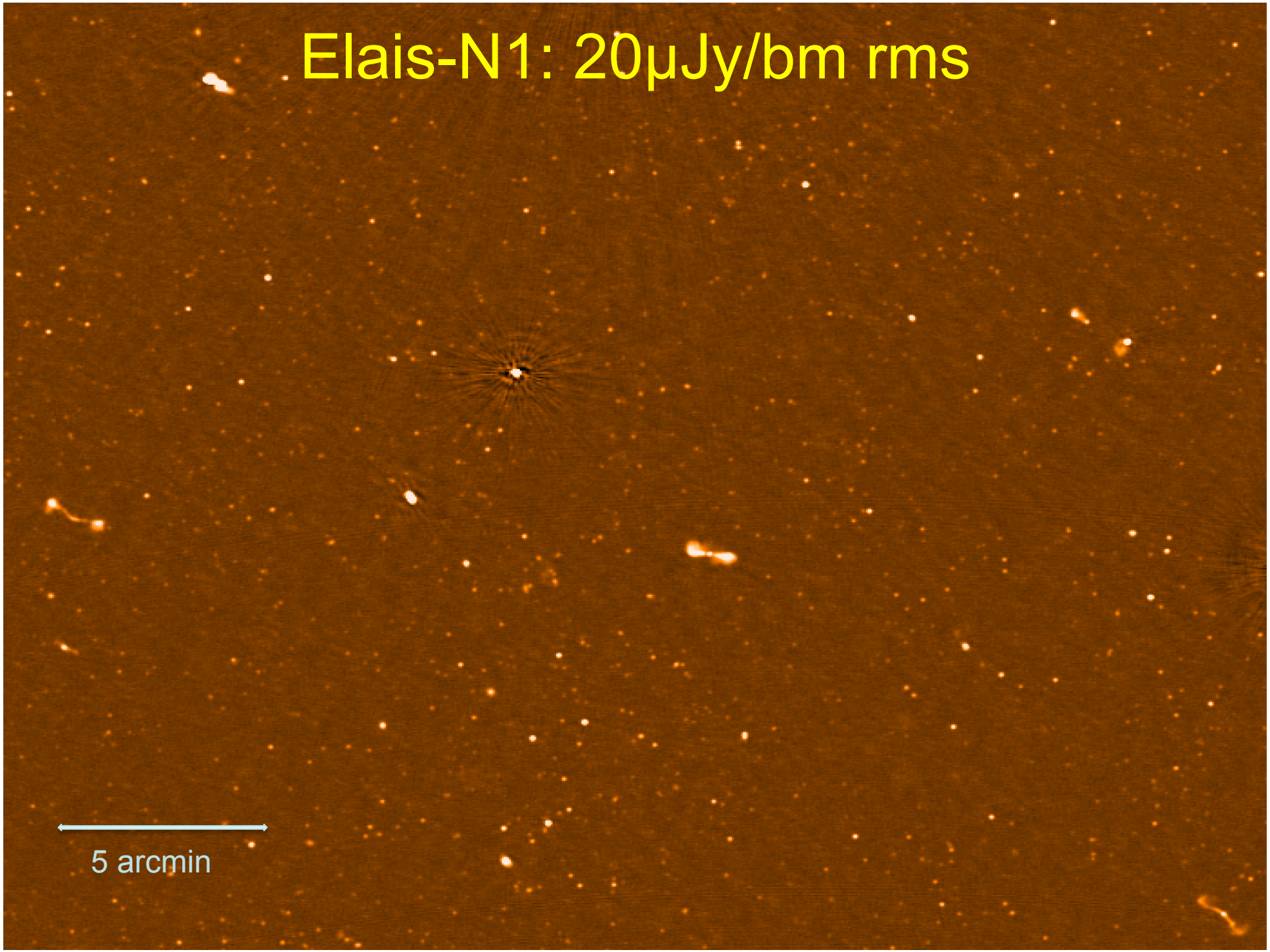
Imaging in Elais-N1 detects 33k objects over central 7 deg^2 of field (nearly 5000 per deg^2) – seven times the LoTSS source density!

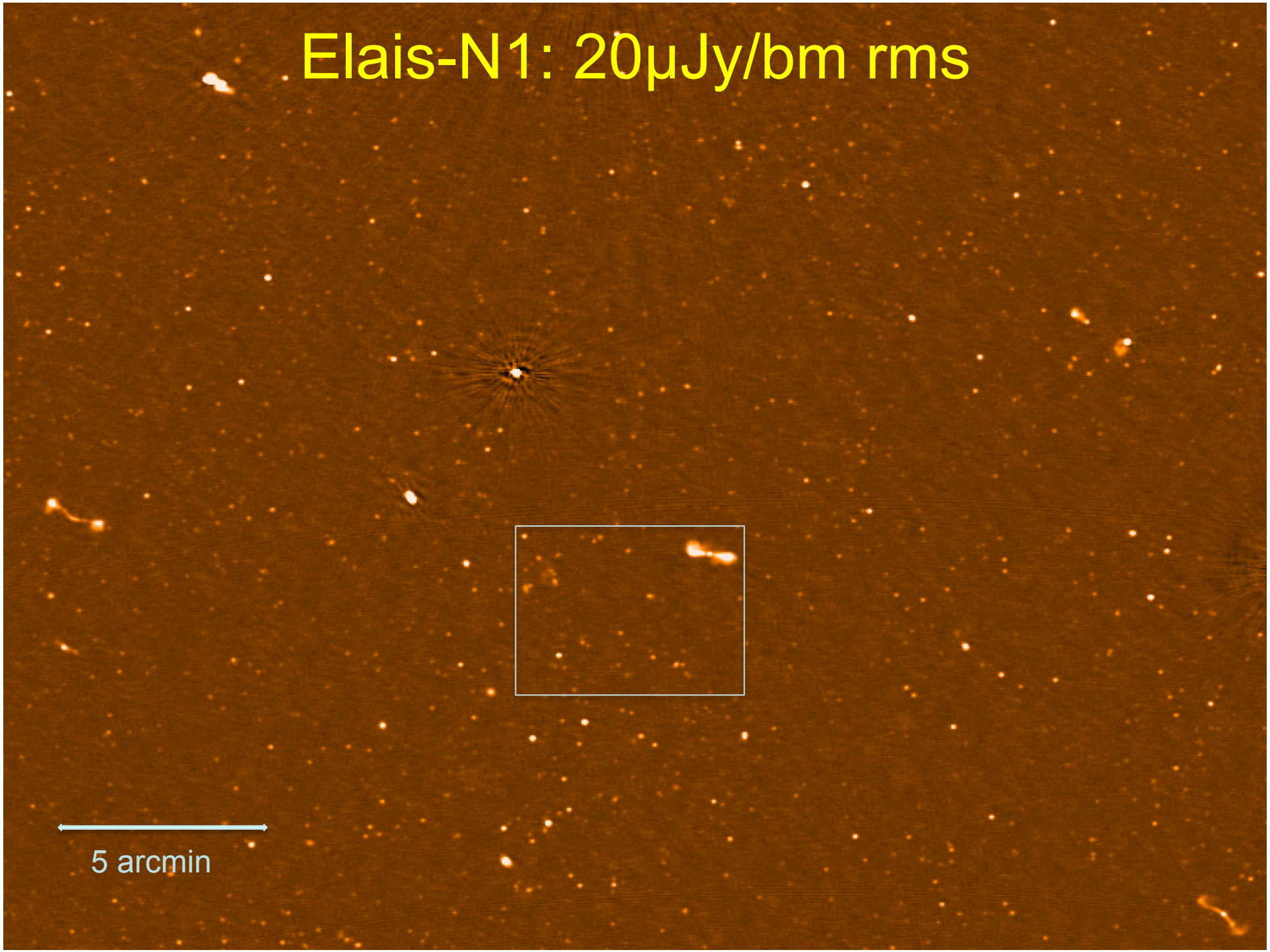

Elais-N1: 20μJy/bm rms
1 degree

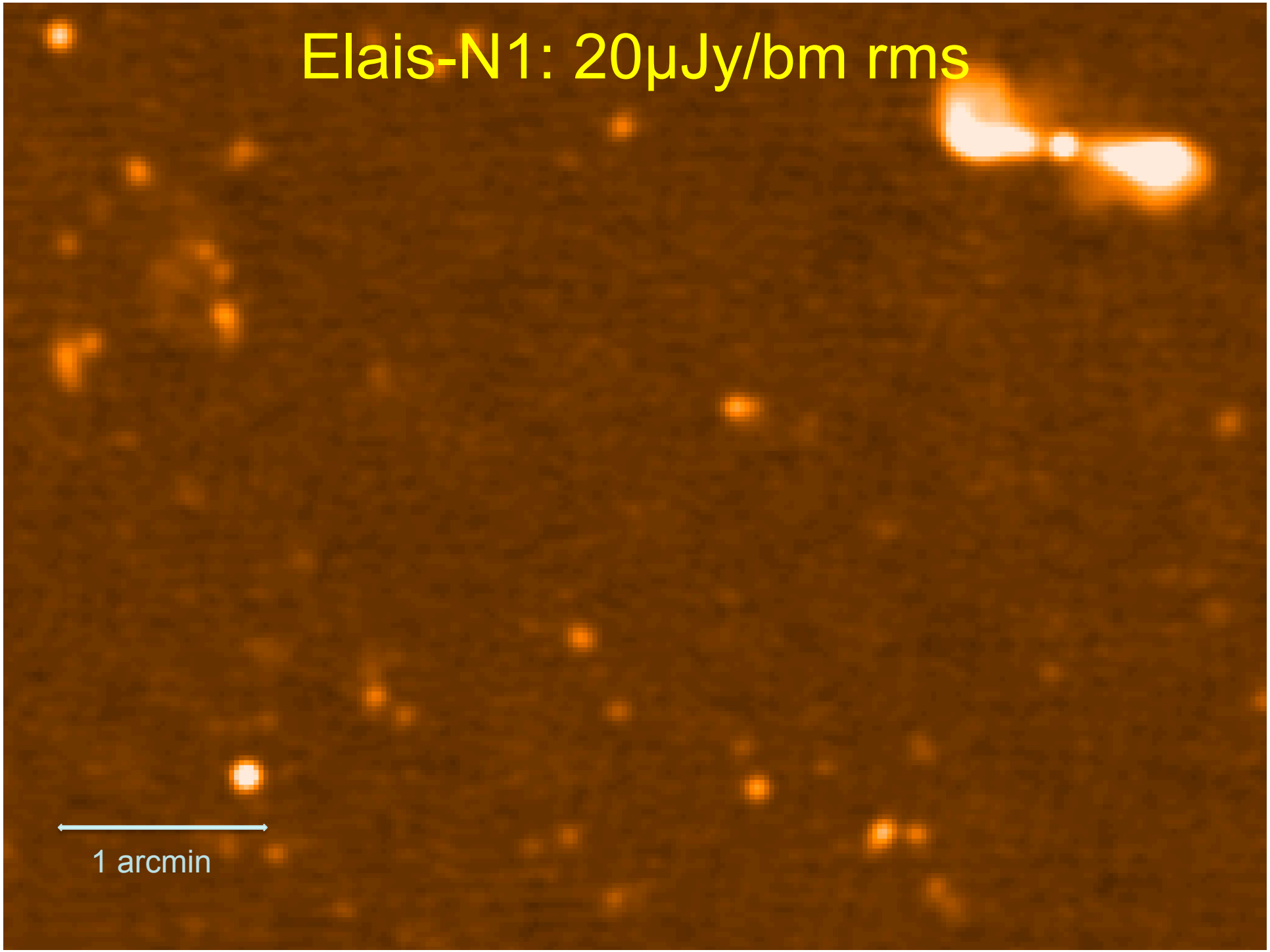

Elais-N1: 20μJy/bm rms
1 degree


Elais-N1: 20μJy/bm rms
15 arcmin


Elais-N1: 20μJy/bm rms
15 arcmin

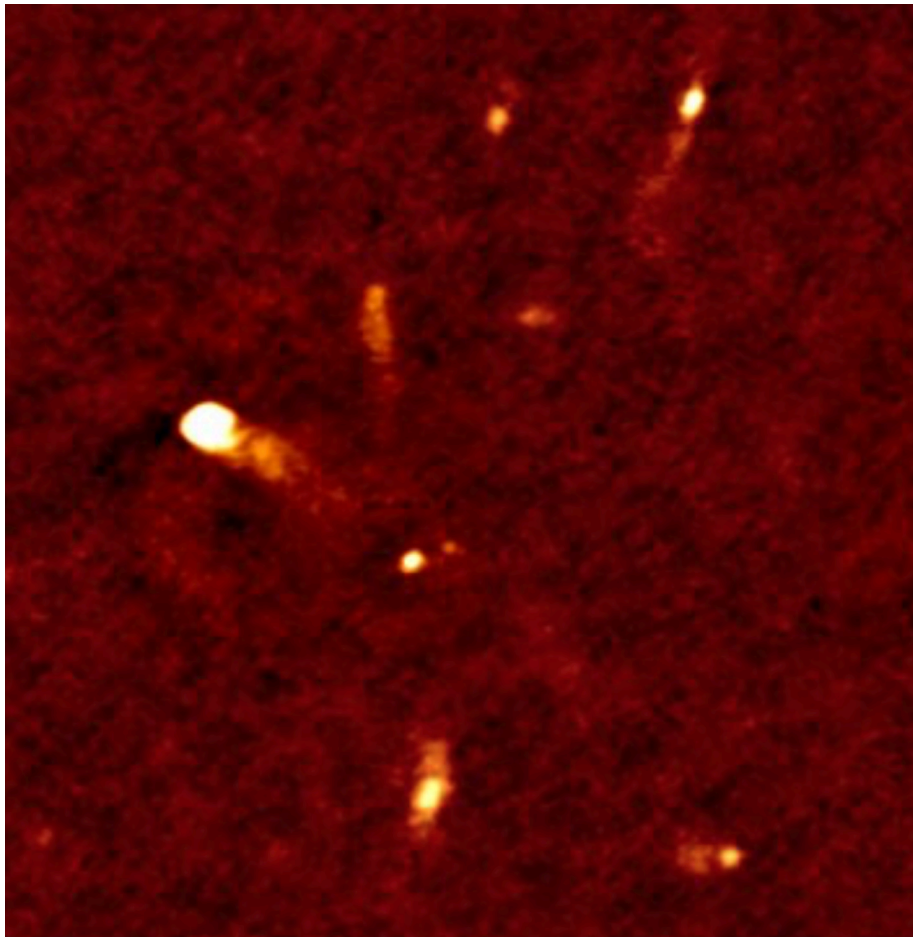

Elais-N1: 20μJy/bm rms
5 arcmin


Elais-N1: 20μJy/bm rms
5 arcmin


Elais-N1: 20μJy/bm rms
1 arcmin

‘Fireworks’ region

Previous image (8 hrs)



‘Fireworks’ region

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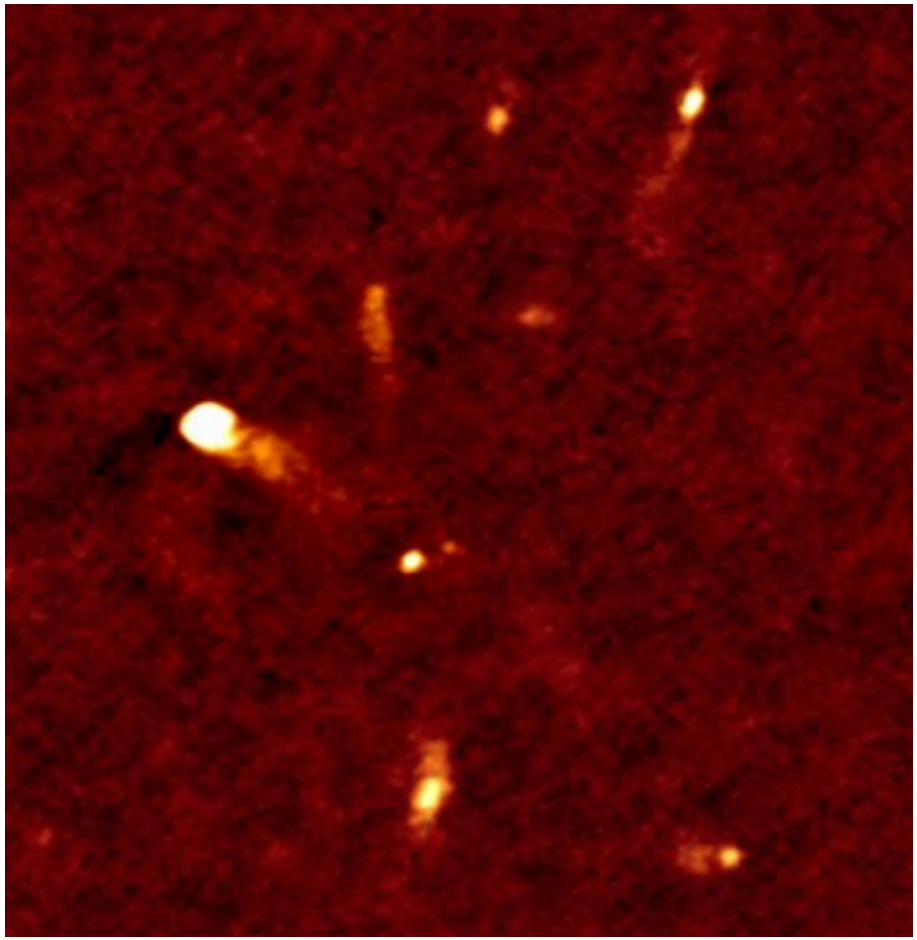
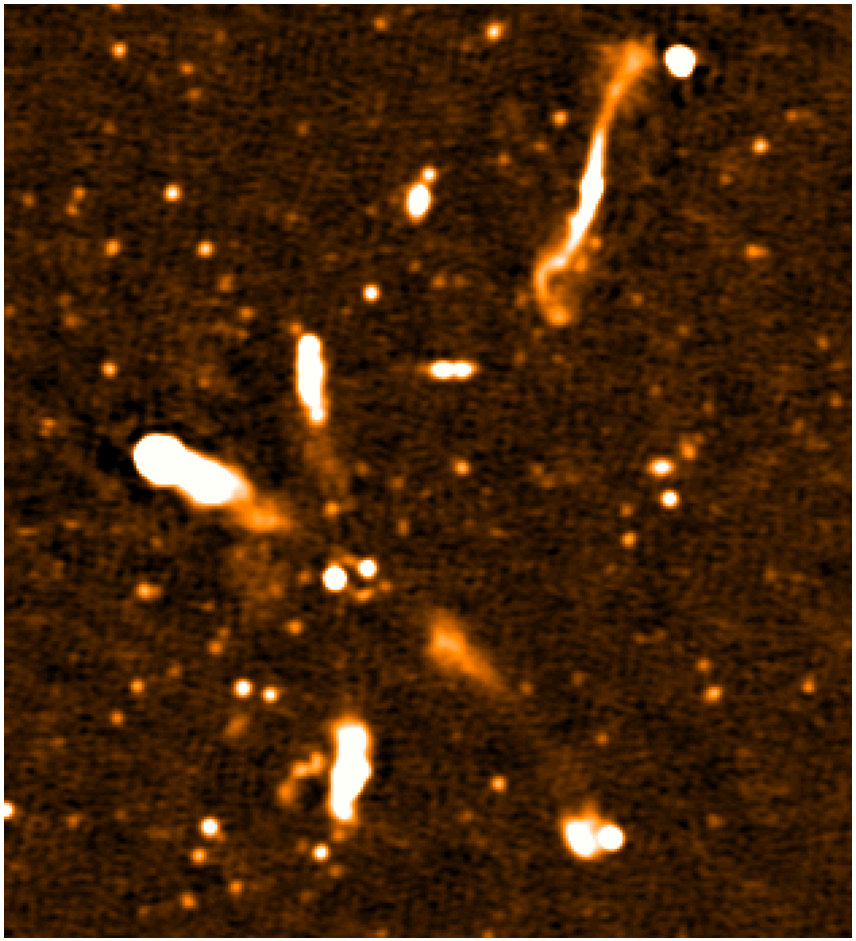


New image



Optical & multi-wavelength data

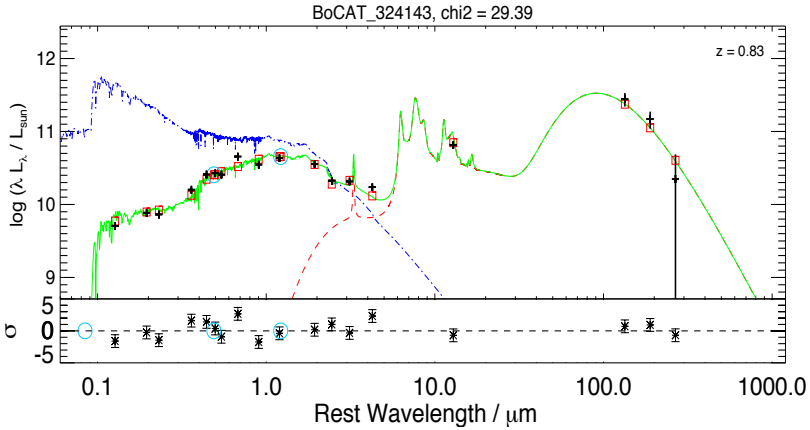
Radio data alone provides limited science.

Critically dependent on multi-wavelength data to provide:

- host galaxy identifications
- source classifications (AGN/SF/etc)
- photometric redshifts
- galaxy properties (mass, SFR, etc)

Elais-N1, Boötes and Lockman hole have deep multi-wavelength data over ~10 deg^2 regions

- optical (e.g. ugrizy bands)
- near-infrared (J,K, 3.6μm, 4.5μm)
- mid-infrared (5.8μm, 8μm, 24μm)
- far-infrared (Herschel bands)



We have performed matched-aperture forced photometry

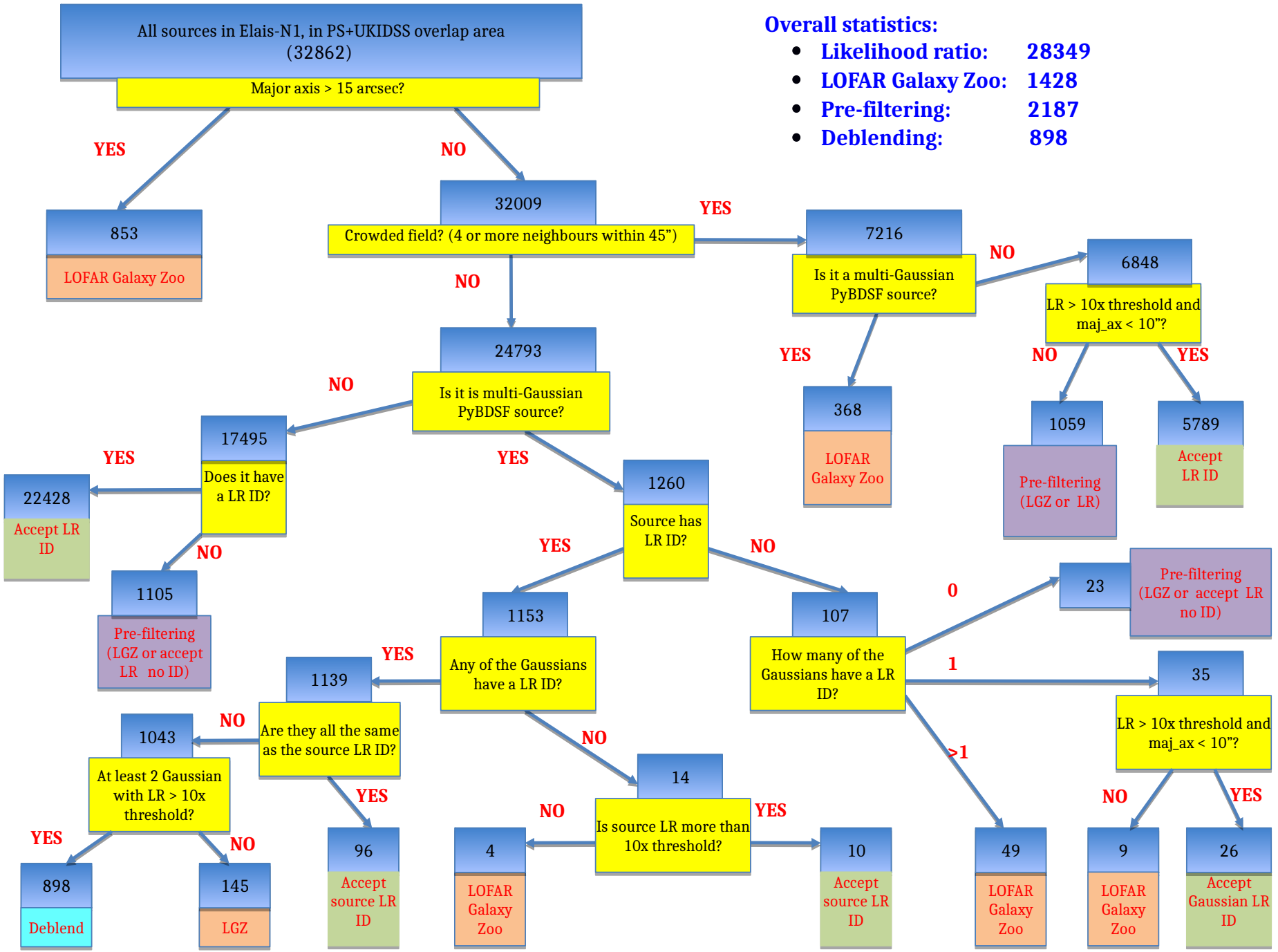
Host galaxy identification

Follow an adapted process from LoTSS DR1: (Wendy's talk)

- use automated statistical techniques where possible
  - likelihood ratio, including magnitude and colour terms
- where not possible, use internal LOFAR Galaxy Zoo
  - at least 5 people view each source
  - in progress: more volunteers welcome!
- also identify many potential blended sources that need inspection

Deep multi-wavelength data means that LR techniques identify the host galaxy for over 96% of the sources in Elais-N1

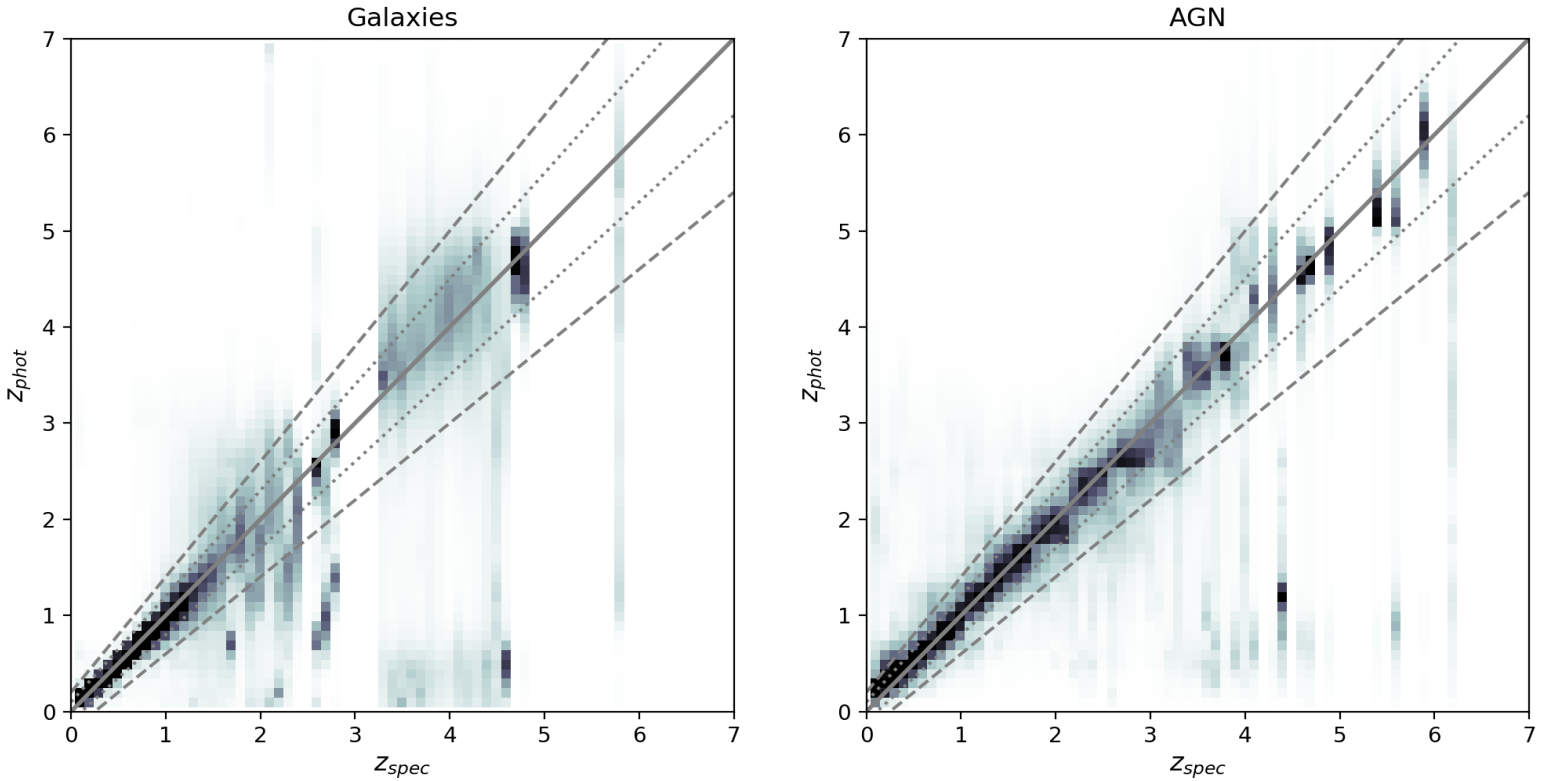
- Compared to 72% in HETDEX, it's clear this enables a vast array of additional science
- *Every* object that doesn't get a LR ID is visually inspected to ensure a robust outcome.


All sources in Elais-N1, in PS+UKIDSS overlap area (32862)
Major axis > 15 arcsec?
YES
NO
853
LOFAR Galaxy Zoo
32009
Crowded field? (4 or more neighbours within 45")
YES
7216
Is it a multi-Gaussian PyBDSF source?
NO
6848
LR > 10x threshold and maj_ax < 10"?
NO
YES
1059
Pre-filtering (LGZ or LR)
5789
Accept LR ID
YES
368
LOFAR Galaxy Zoo
NO
24793
Is it is multi-Gaussian PyBDSF source?
NO
17495
Does it have a LR ID?
YES
22428
Accept LR ID
NO
1105
Pre-filtering (LGZ or accept LR no ID)
YES
1260
Source has LR ID?
YES
NO
1153
Any of the Gaussians have a LR ID?
YES
1139
Are they all the same as the source LR ID?
NO
1043
At least 2 Gaussian with LR > 10x threshold?
YES
NO
898
Deblend
145
LGZ
YES
96
Accept source LR ID
NO
14
Is source LR more than 10x threshold?
NO
YES
4
LOFAR Galaxy Zoo
10
Accept source LR ID
107
How many of the Gaussians have a LR ID?
0
23
Pre-filtering (LGZ or accept LR no ID)
1
35
LR > 10x threshold and maj_ax < 10"?
>1
49
LOFAR Galaxy Zoo
NO
YES
9
LOFAR Galaxy Zoo
26
Accept Gaussian LR ID
Overall statistics:
Likelihood ratio: 28349
LOFAR Galaxy Zoo: 1428
Pre-filtering: 2187
Deblending: 898

Photometric redshifts

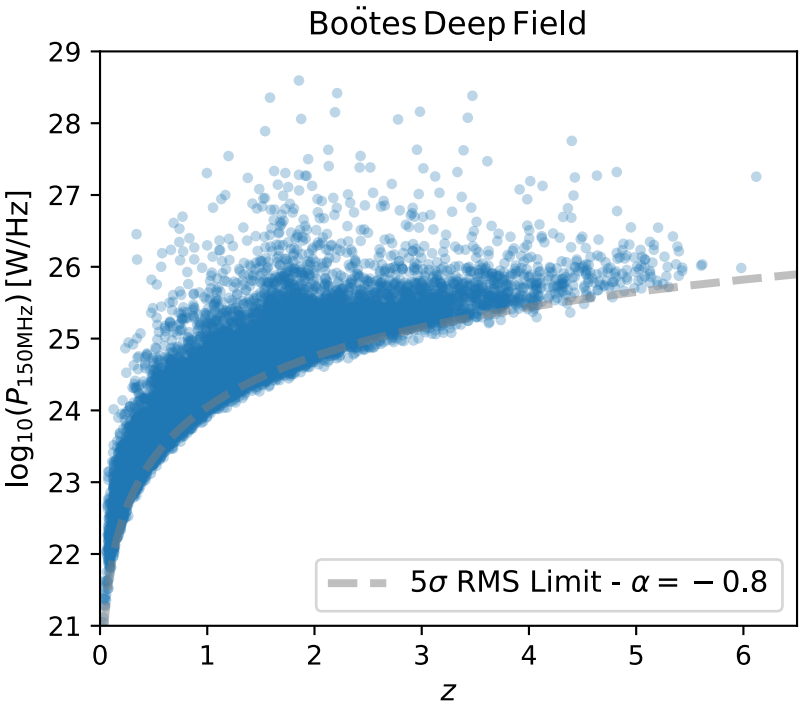
(Courtesy Ken Duncan)

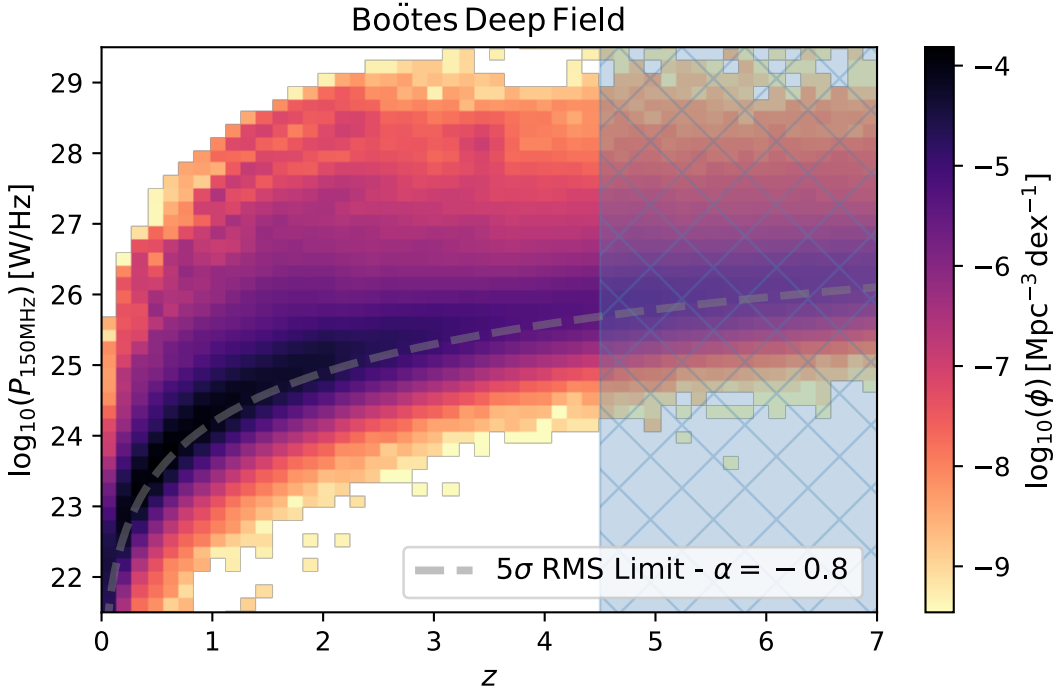
- accurate photo-z's for all sources in the field
  - optimised hybrid of template models & machine learning approach
- reliable to z~1.5 for galaxies and z>3 for AGN



Photometric redshifts

- In Boötes, best-fit photo-z's reach out to z~6 (a known quasar).
- Using the full probability distribution for photo-z's, it's clear that there's a large region of luminosity-redshift space to be probed

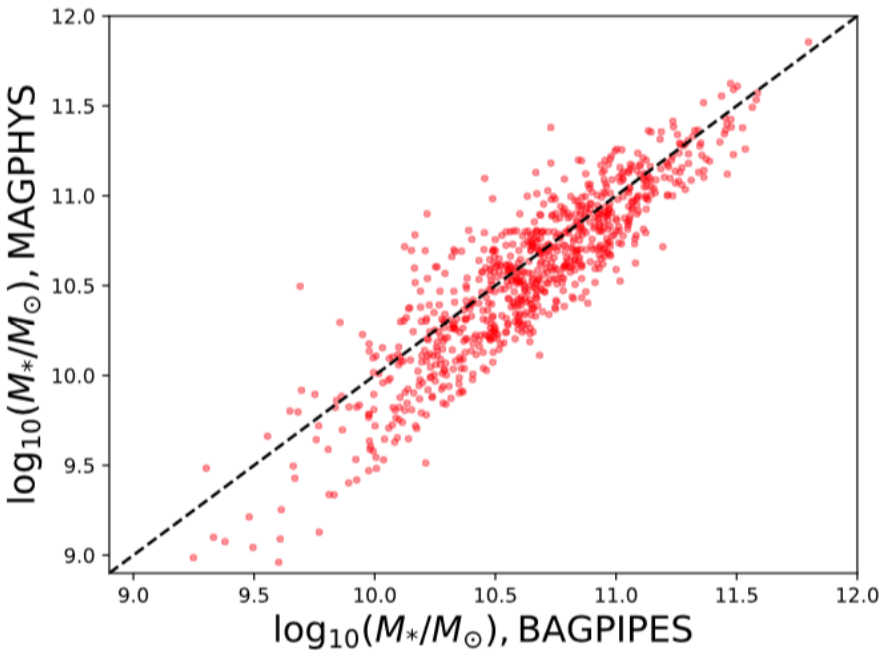


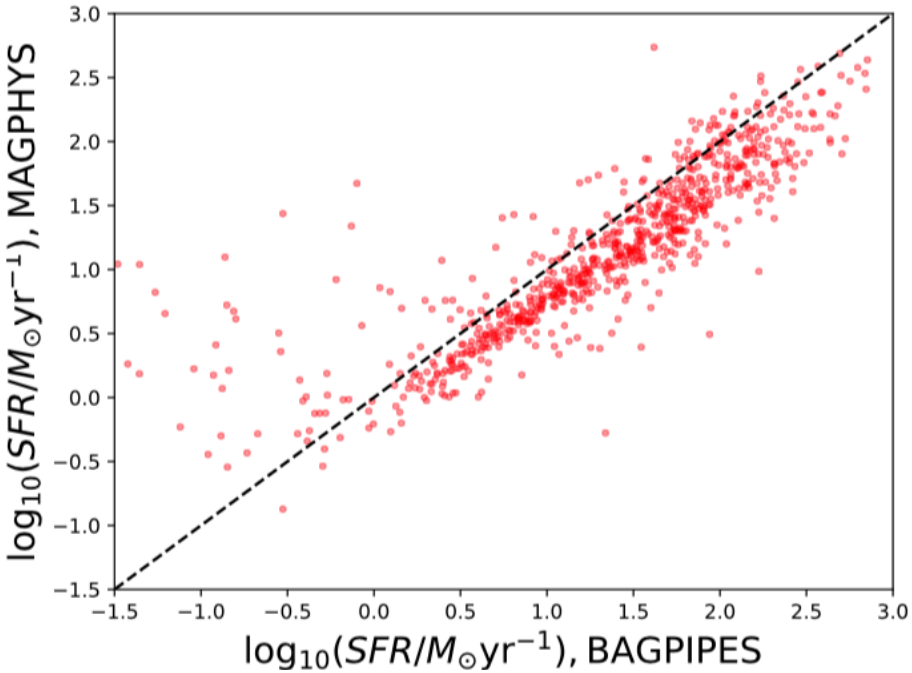


Source classification

Source classification (AGN/SF) and extraction of host galaxy properties is in progress

- using well-known diagnostic plots, plus spectral-energy distribution fitting packages MagPHYS, CIGALE, BAGPIPES and AGNfitter
- testing on 1000-source sample in Boötes
- good agreement between SED fits where no strong AGN component





Deep Fields Data Release 1

Focus to date has been on total intensity (Stokes I):

- radio images and catalogues (low and high resolution)
- source associations and host galaxy identifications
- photometric redshifts
- AGN/SF classifications
- host galaxy properties

Also working to produce additional radio data products

- in-band spectral indices
- Stokes V images
- Together with Magnetism KSP, deep Stokes Q & U
- Series of nightly images
- Dedicated re-processing of extended and variable images
- … let us know if you need something else …
- (Longer-term: inclusion of international station data)

Deep Fields Data Release 1

Initial data products already released to LOFAR Surveys KSP

Intention is to release this publically in late 2019 / early 2020, in conjunction with a series of science papers (as for LoTSS DR1)

- currently have 34 proposed papers for the paper splash
- topics include:
  - Star formation: cosmic star formation history; dusty starbursts; environmental effects on galaxies
  - AGN: radio-loud AGN evolution; radio emission in radio-quiet quasars; AGN morphologies
  - diffuse emission from the cosmic web; halo and relic sources
  - low surface brightness background radiation
  - deep field magnetism
  - nearby stellar systems
  - and more

Conclusions & outlook

- We have shown that LOFAR is capable of imaging to great depths with HBA observations
  - 20μJy/bm rms already, and still going deeper...
- The LOFAR Deep Fields, in the best-studied multi-wavelength regions of the northern sky, will open a vast science potential
- The data will be public soon – but if you are interested, get in touch and we can collaborate already

- Longer term, the WEAVE-LOFAR spectroscopic survey will begin next year
  - will take spectra for *all* sources in the LOFAR Deep Fields, adding yet more science.