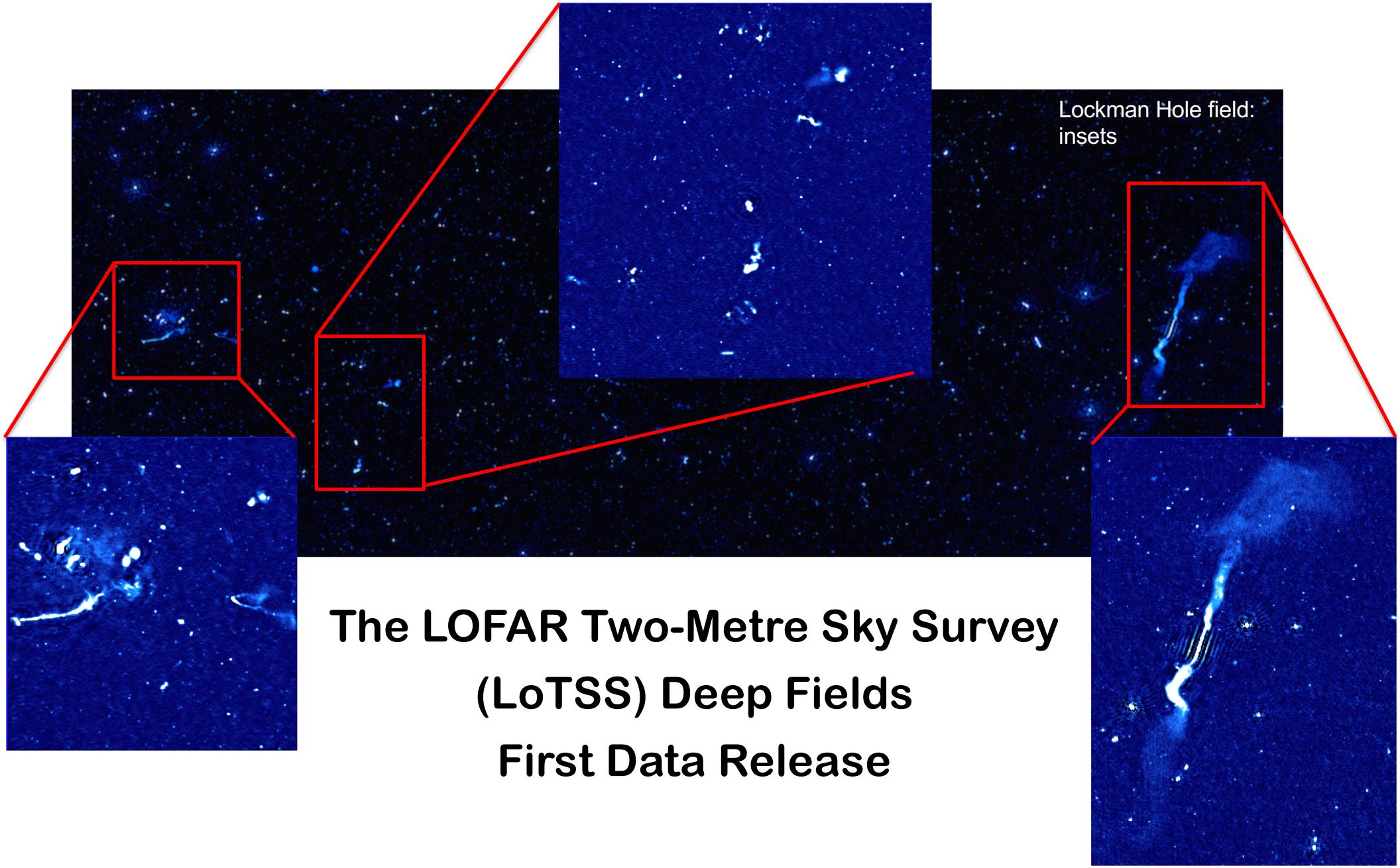


The LOFAR Two-Metre Sky Survey (LoTSS) Deep Fields First Data Release

Isabella Prandoni

Outline

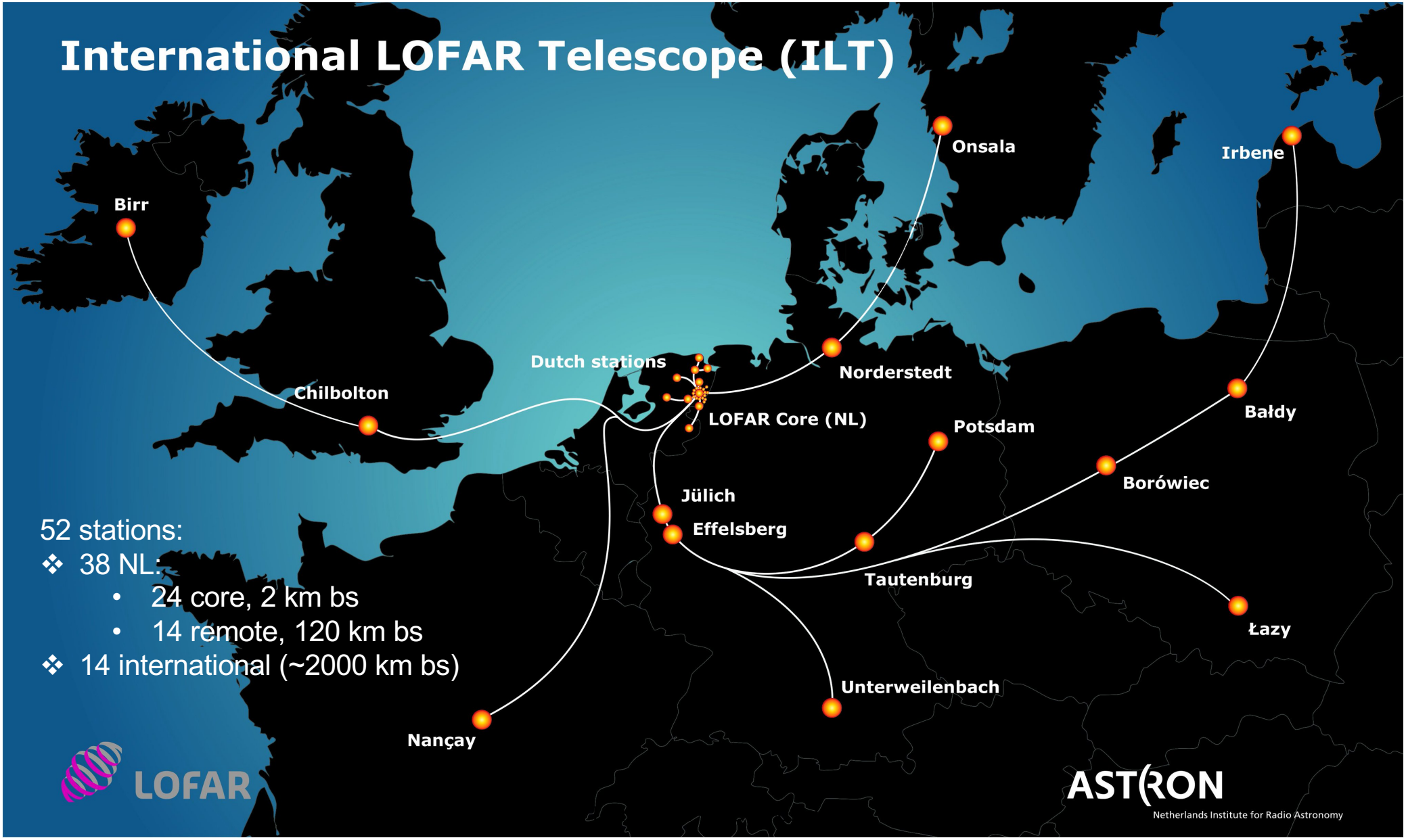
- **Introduction**
  - LOFAR
  - LOFAR Survey KP
  - LoTSS / LoTSS Deep

- **LoTSS Deep Fields DR1: Data Products**
  - Imaging & Source extraction
  - opt/IR identifications and catalogue post-processing
  - Multi-band photometry, photometric redshifts

- **LoTSS Deep DR1: Science Highlights**
  - A&A Special Issue

- **Future Perspectives**

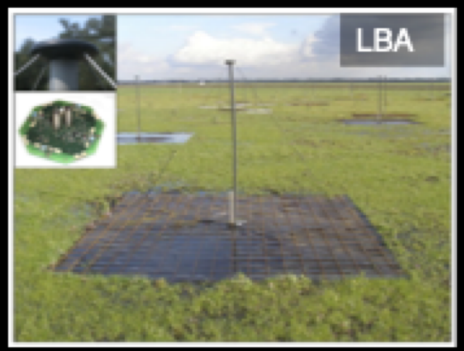
The International LOFAR Telescope

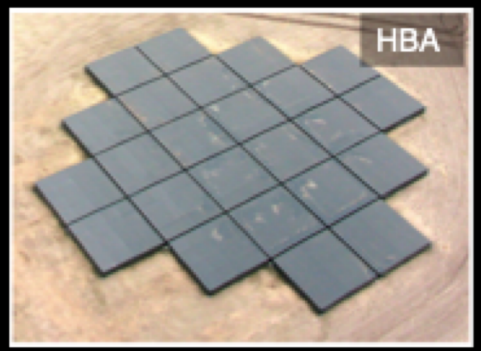


The International LOFAR Telescope

Adapted from R. Pizzo

- Soon station also in Italy (2022)
- 10-250 MHz
- LBA: 10-90 MHz (4800 dipole pairs, 96 LBA per station), 1 mJy/b rms in 8h
- HBA: 110-250 MHz (47616 dipole pairs, 48/96 tiles per station in NL/EU),), 0.1 mJy/b rms in 8h
- Several observing modes – 96 MHz bandwidth (multi-beam option)
- 8 years of operations

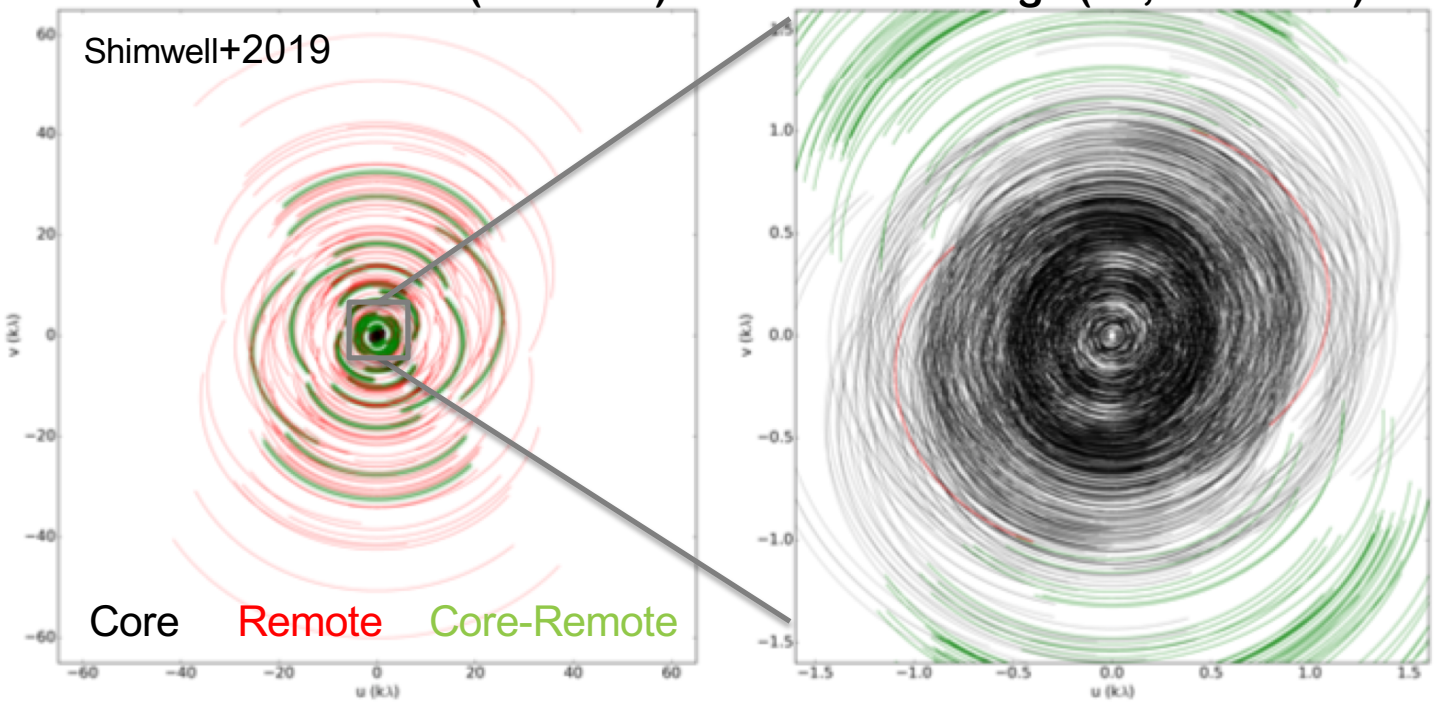




LOFAR: A Survey Telescope

Field of View @150 MHz: ~2.5 deg FWHM
Spatial Resolution @150 MHz: 6″ NL stations / 0.3″ incl. international stations
Sensitivity @150 MHz: ~0.1 mJy/b (6″ resolution) for 8 hours integration

Monochromatic (150 MHz) UV-Plane Coverage (8h, +55 Decl.)



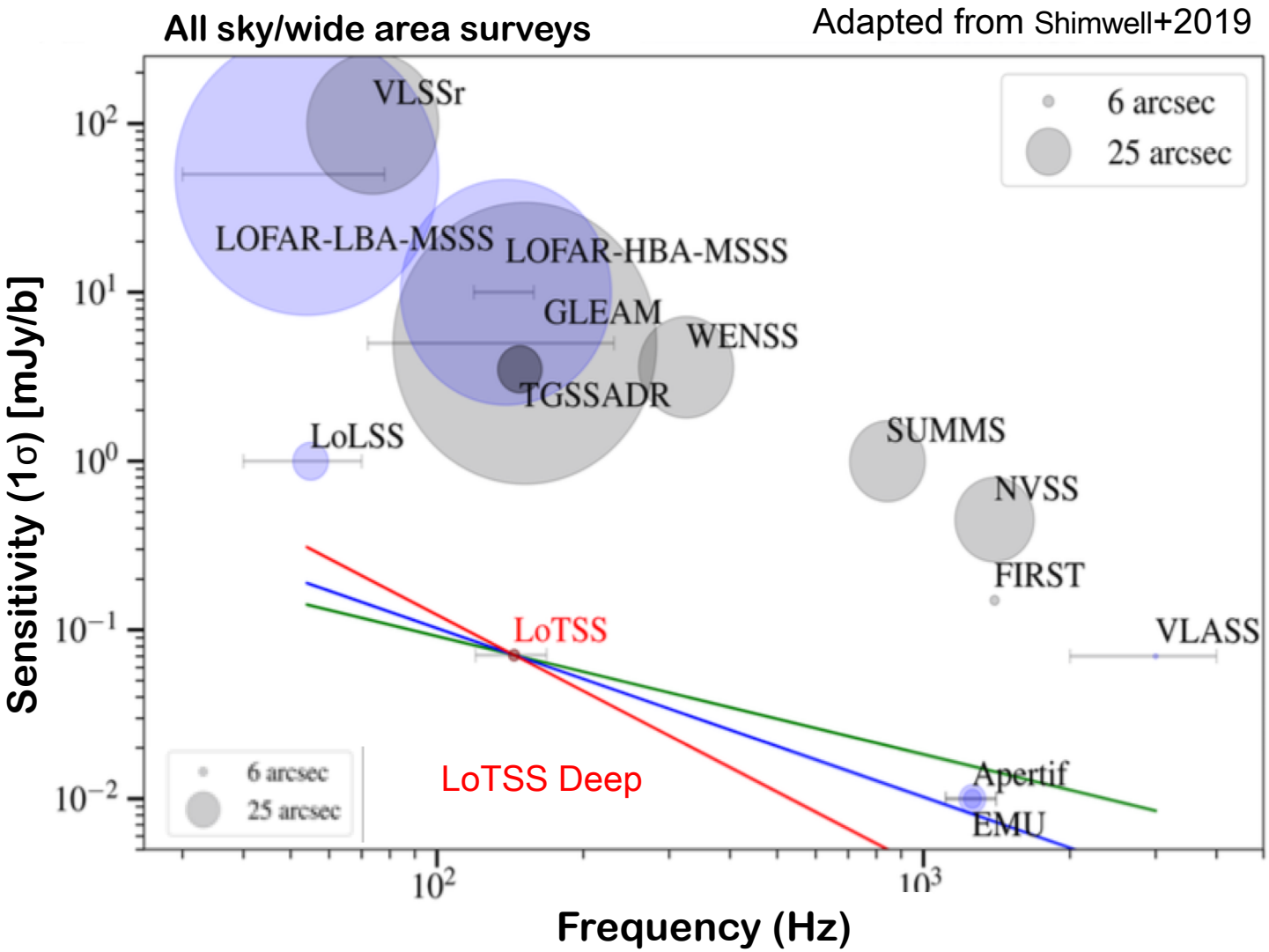
Dense uv coverage + arcsec-scale resolution → Excellent surface brightness sensitivity + image fidelity

The LOFAR Survey KP

Ongoing LOFAR Surveys:

HBA: LoTSS
- All-sky Dec.>0
  100 uJy/b rms @ 6″ res.
  8hr / pointing → 14,000h
- Deep fields:
  10 uJy/b rms
  ~500h / pointing

LBA: LoLSS
(PDR: de Gasperin+2021)
- All-sky Dec.>0
  1 mJy/b rms @15″ res.
  8hr / pointing



The LOFAR Survey KP

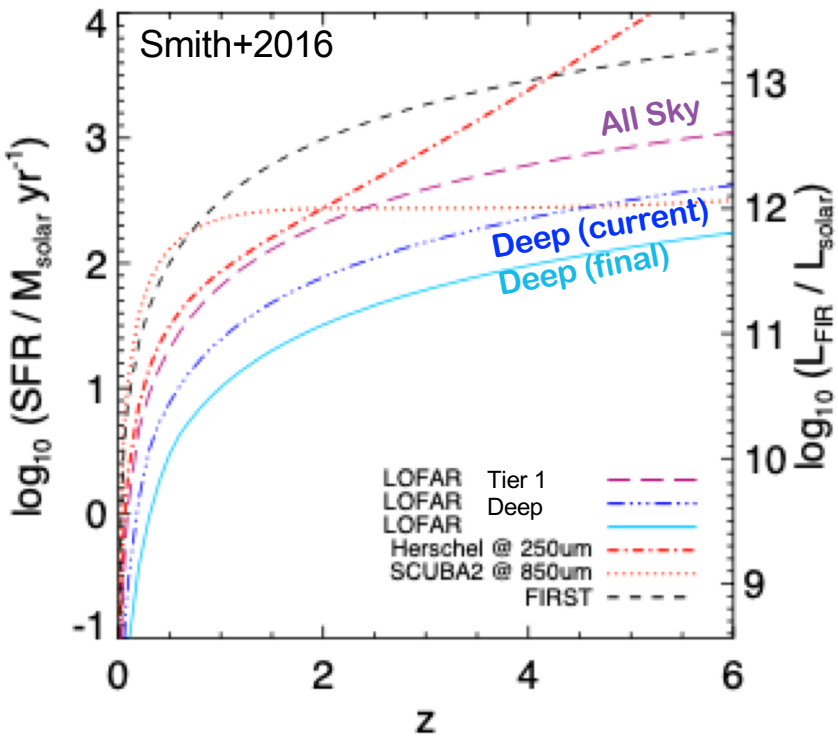
Original Scientific Aims (Röttgering+2011):

- Detect 100 Radio Galaxies at z>6
- Detect diffuse radio emission in 100 galaxy clusters at z>0.6

GO WIDE ➔ All Sky (LBA+HBA)

- Detect MW-like galaxies to z~1
- Detect SB to z~6
- Map sufficiently large sky area to probe different environments and build statistics

GO DEEP ➔ Deep Fields (HBA)



The LOFAR Survey KP: Science

Main Science Drivers:

I. **Galaxy/AGN co-Evolution:** SF History & Role of AGN Feedback

II. **Formation of Massive Galaxies and Protoclusters**: massive RGs at z>2 as sign-post for proto-clusters

III. **Epoch of Reionization:** IGM through HI abs. studies against z>6 RL-QSO

IV. **RL AGN:** Physics & Duty cycles (new-born, mature, dying)

V. **Clusters' dynamics and micro-physics:** Radio Halos & Relics

VI. **LSS**: traced through RC and RM

VII. **Cosmology tests:** clustering, ISW Effect, etc.

VIII. **Resolved studies of nearby galaxies:** Magnetic Fields, ISM, FIR/Radio Correlation

IX. **...**

<u>Close collaborations with EoR, Magnetism and Transients KPs</u>

The LOFAR Survey KP: Structure

PI: H. Rottgering

Survey Team: ~200 members from ~30 Institutions

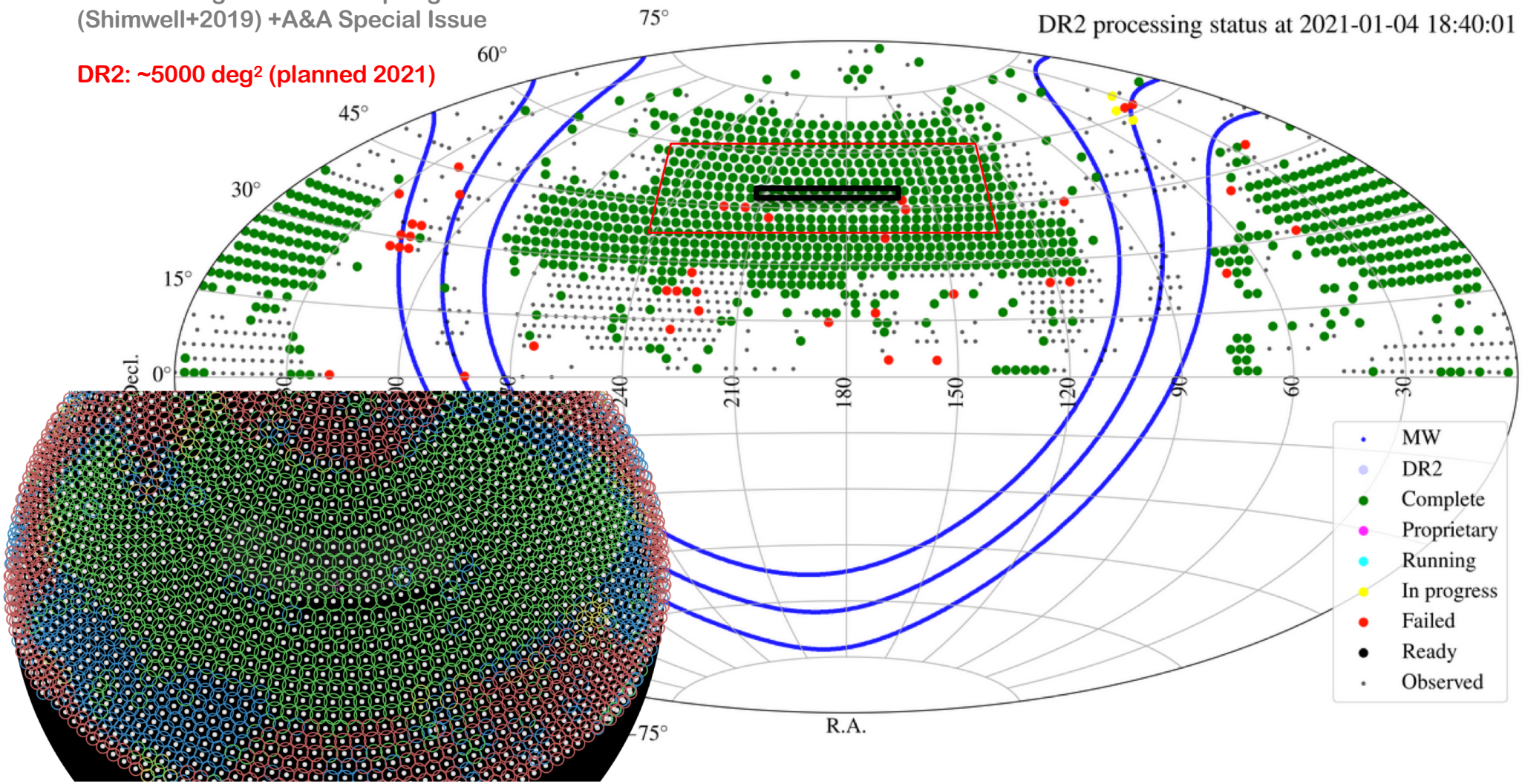
Science WGs and Coordinators:

1. The highest redshift radio galaxies (G. Miley)
2. Clusters and cluster halo sources (G, Brunetti, M. Brüggen)
3. Evolution of AGN and star-forming galaxies (P. Best)
4. Detailed studies of low-z AGN (R. Morganti)
5. Nearby galaxies (K. Chyzy, J. Conway)
6. Galactic radio sources (G. White, M. Haverkorn)
7. Gravitational Lensing (N. Jackson)
8. Cosmological studies (M. Jarvis)

LoTSS - All-Sky: Current Status

DR1: 424 deg² in HETDEX Spring field
(Shimwell+2019) +A&A Special Issue

DR2: ~5000 deg² (planned 2021)



Processed Observed Scheduled Not started

LoTSS Deep Fields: Current Status

- **Several 'famous' extragalactic fields targeted, incl. equatorial fields (COSMOS, XMM-LSS)**

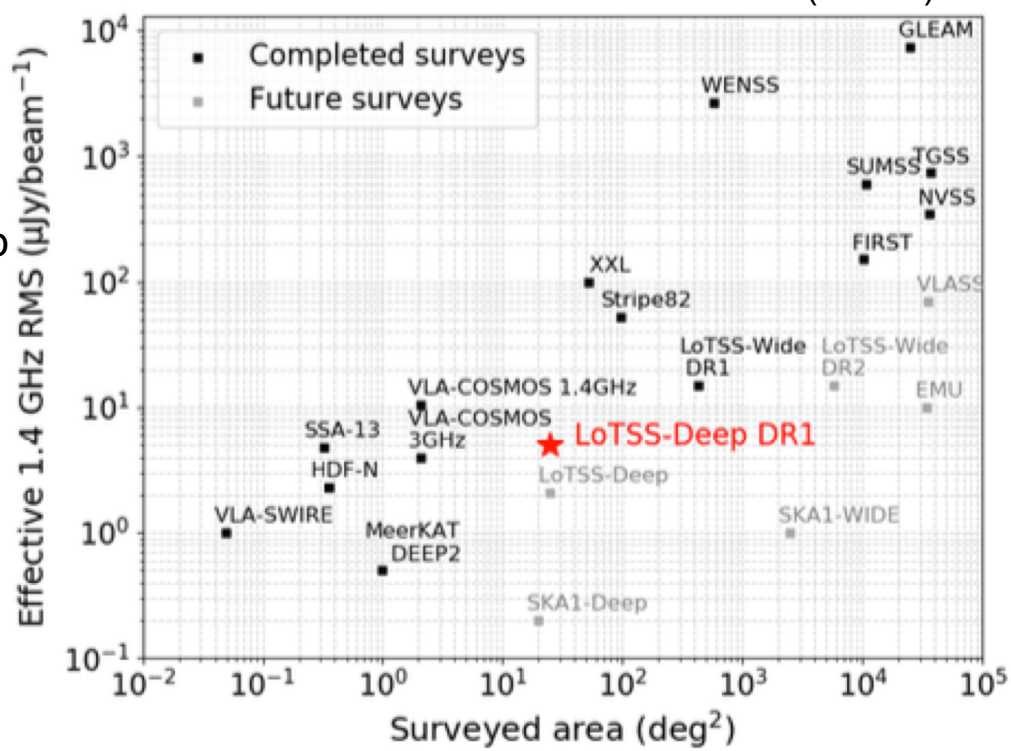
- **Observational setup (LoTSS):**
  - HBA DUAL-INNER Mode (24 tiles sub-stations)
  - Intl baselines included (but not processed)
  - Bandwidth: 48 MHz (x2 beams)

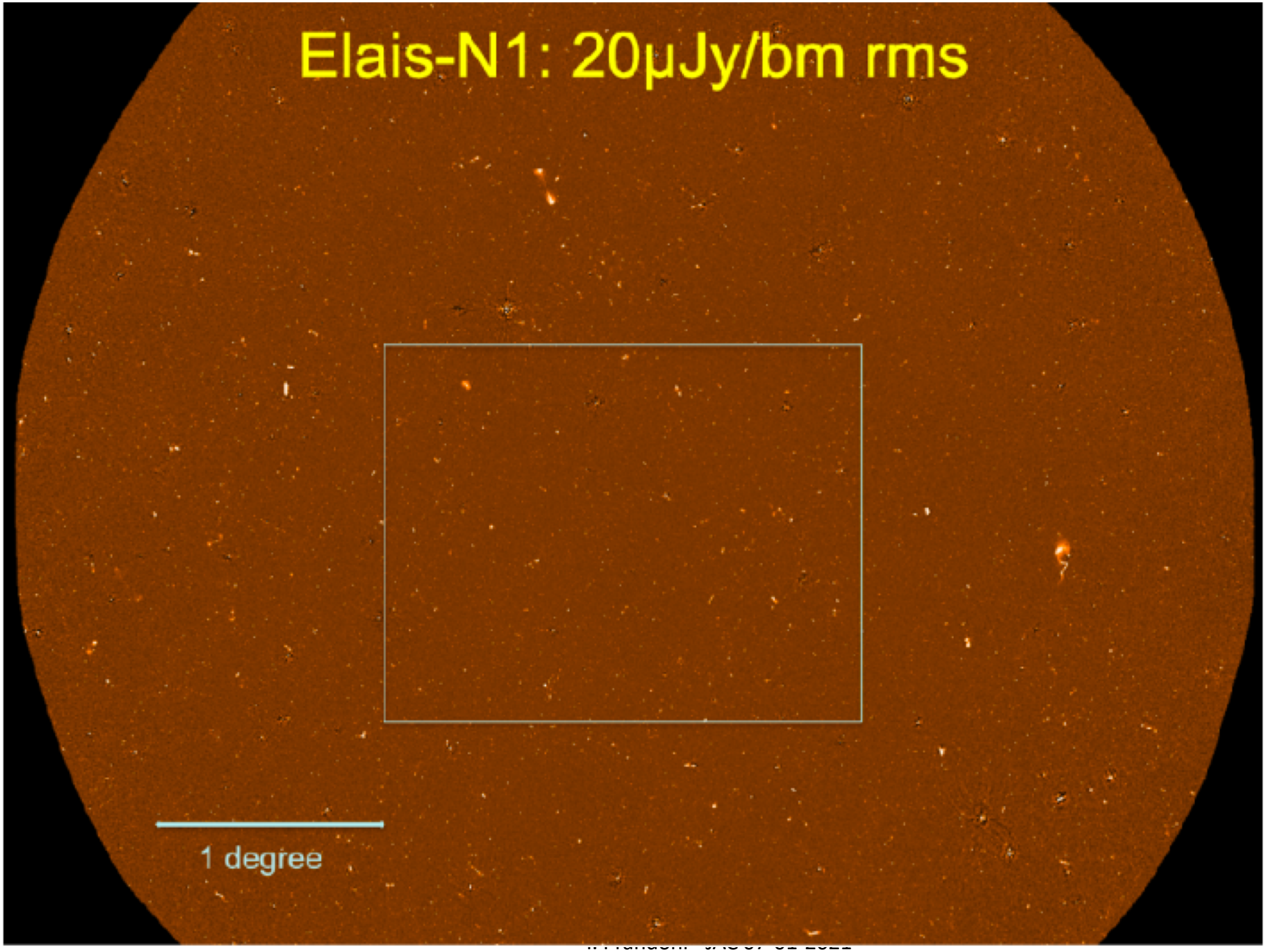
- **DR1: Focus on three fields at high declination:**
  - ELAIS-N1 (Decl. +55 deg): 164 hrs, σ_c ~17 uJy/b
  - Lockman: (Decl. +58 deg): 112 hrs, σ_c ~22 uJy/b
  - Bootes (Decl. +34 deg): 80 hrs, σ_c ~32 uJy/b

Data products: https://lofar-surveys.org/

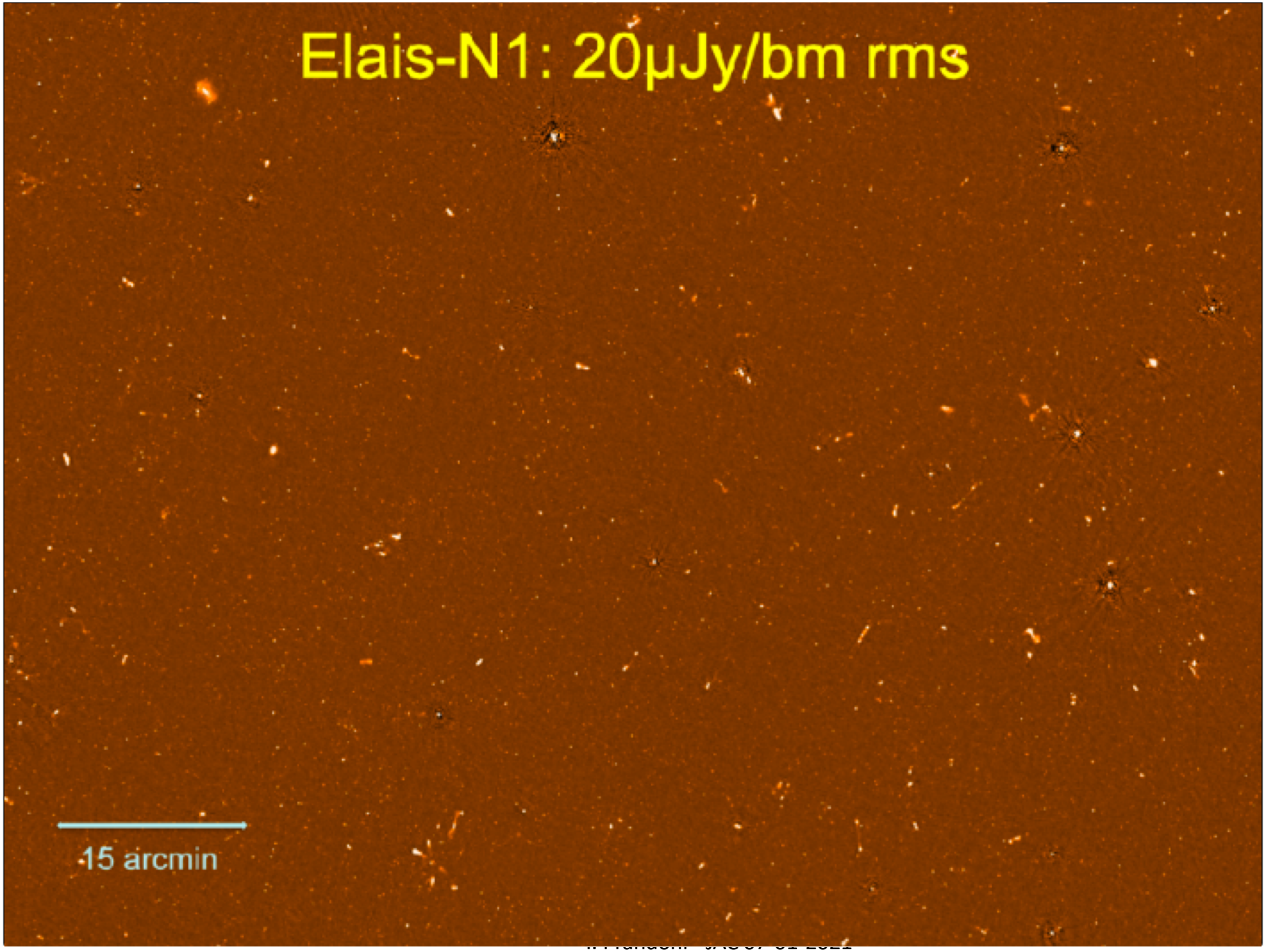
A&A Special Issue: 14 papers
- 10 accepted + 4 under revision

Tasse+2021 (α=-0.7)

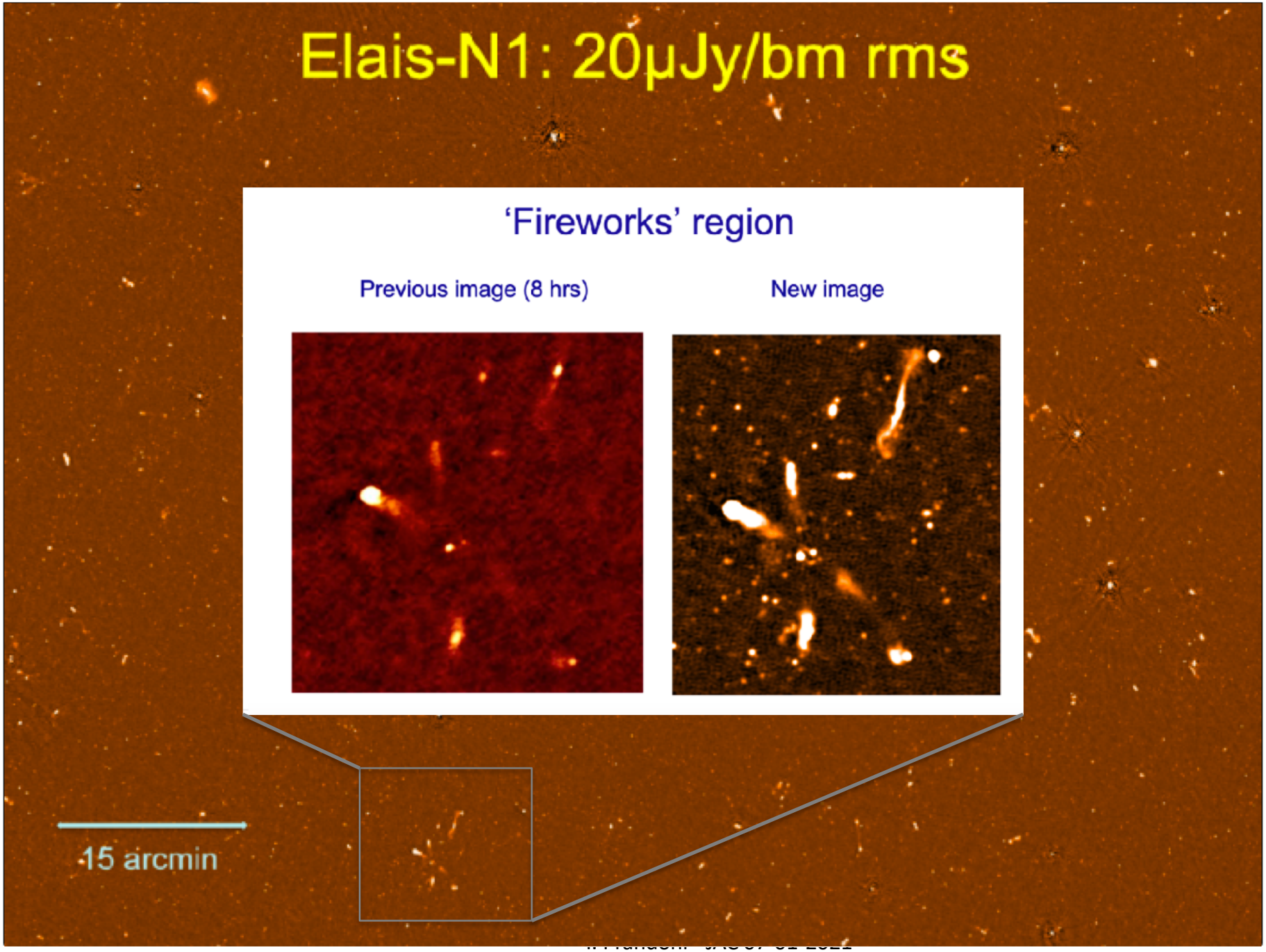




Courtesy T. Shimwell



Courtesy T. Shimwell



Courtesy T. Shimwell

LoTSS Deep Fields DR1: Data Products

Main data products:

- **Radio images & catalogues**
- **Noise maps**
- **Value-added catalogues** (opt/IR, photo-z, M_*)

Data papers:

- **Tasse+2021:** Imaging pipeline + LH and Boo datasets (images + initial radio catalogue)
- **Sabater+2021:** EN1 dataset (incl. EoR obs.)
- **Kondapally+202!:** value-added catalogues, opt/IR identifications, final radio catalogues
- **Duncan+2021:** photometric redshifts for optically-selected sample, stellar masses

Ancillary radio data:

- **I and V Stokes low res. Images** (20″) + **QU cubes** (20″ / 4.3’ res., ~1 MHz channels) – QUV not deconvolved
- **I-Stokes images for three frequency chunks**

LoTSS Deep Fields: Calibration & Imaging

Hard and computationally expensive!

Main Data Reduction Steps:

- **Initial data processing:** data quality assessment, RFI flagging (AOFlagger, Offringa+2012), frequency and time averaging; if required, subtracting A-team sources outside the field of view (demixing) [80 TB → 12 TB]
- **PreFactor pipeline:** solve for direction-independent (DI) effects: polarization misalignments, ionospheric Faraday rotation, amplitude bandpass response, clock offsets, etc. [12 TB → 4TB]
- **DDF pipeline** (based on kMS solver and DDFacet imager**):** solve for direction dependent effects (ionospheric distortions, complex primary beam shapes of phased arrays), while imaging. DI-calibrated image divided in facets containing bright sources, which are then used for various cycles of (phase only/phase+ampl.) self-cal and deconvolution. [0.9 TB MS & 1.5 GB image]

LoTSS Deep Fields: Calibration & Imaging

Hard and computationally expensive!

Main Data Reduction Step

- **Initial data process**
  Offringa+2012), frequen
  outside the field of view
- **PreFactor pipeline:**
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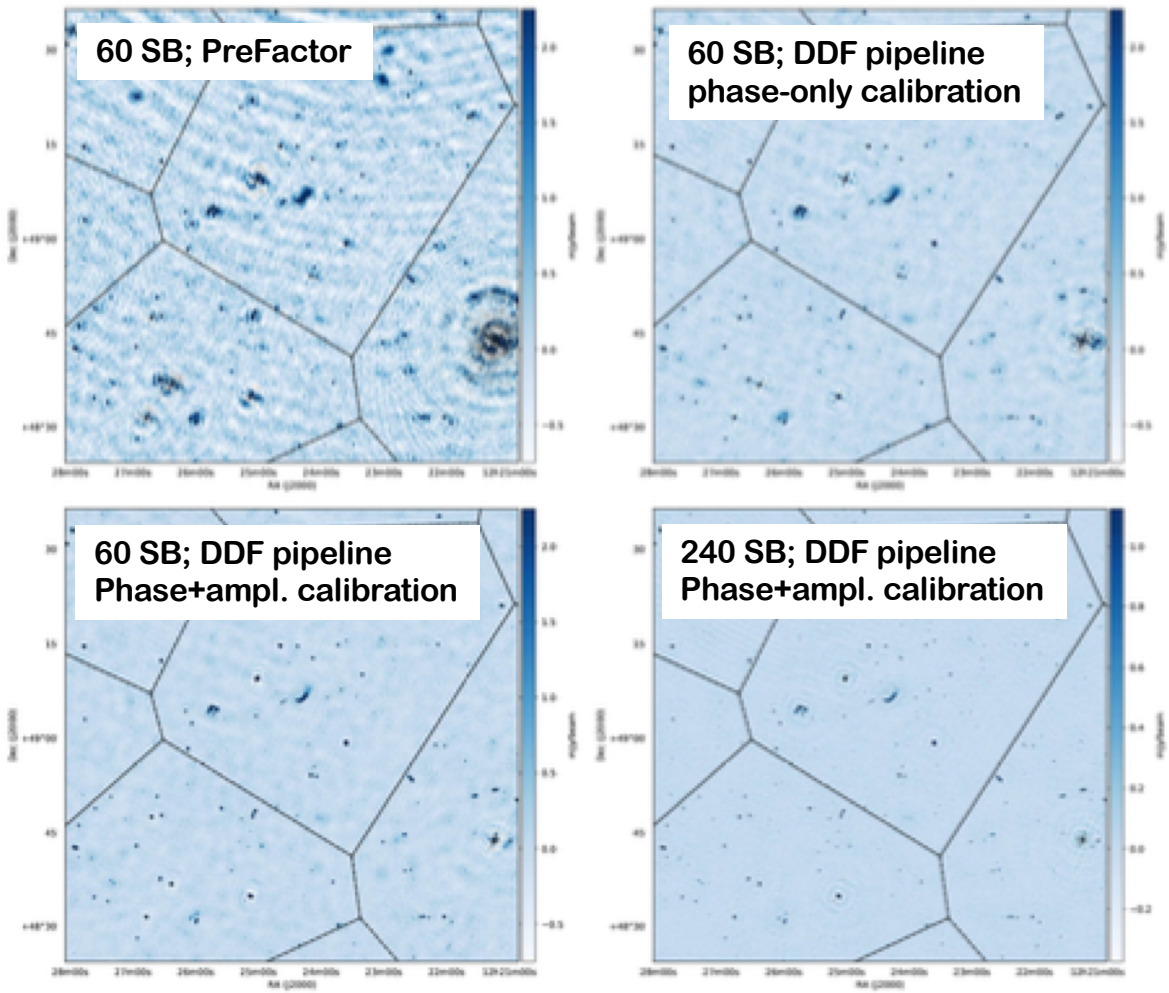
  etc. [12 TB → 4TB]
- **DDF pipeline** (based or
  effects (ionospheric dist
  imaging. DI-calibrated ir
  used for various cycles c

Shimwell+2019

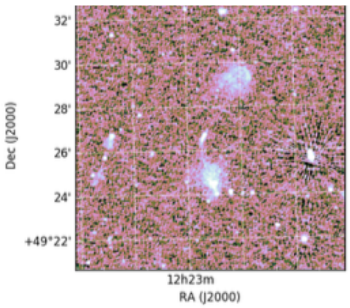


LoTSS Deep Fields: Calibration & Imaging

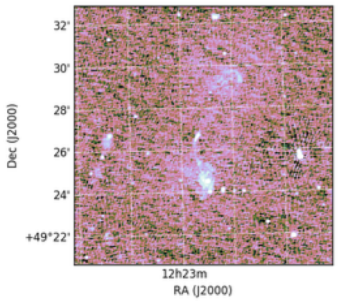
The Evolution of the DDF pipeline (Tasse+2021):

- **DDF pipeline v2 (Alg. 1)**: LoTSS-All sky DR2
  Improve wrt DDF pipeline v1 (Alg.0) on:
  - limited dynamic range: DI+DD self-cal loops using as sky model the bright sources in facets (6 arcsec res.)
  - Artificial diffuse halos and holes: shorter uv-distance cut & better deconvolution; longer solution intervals

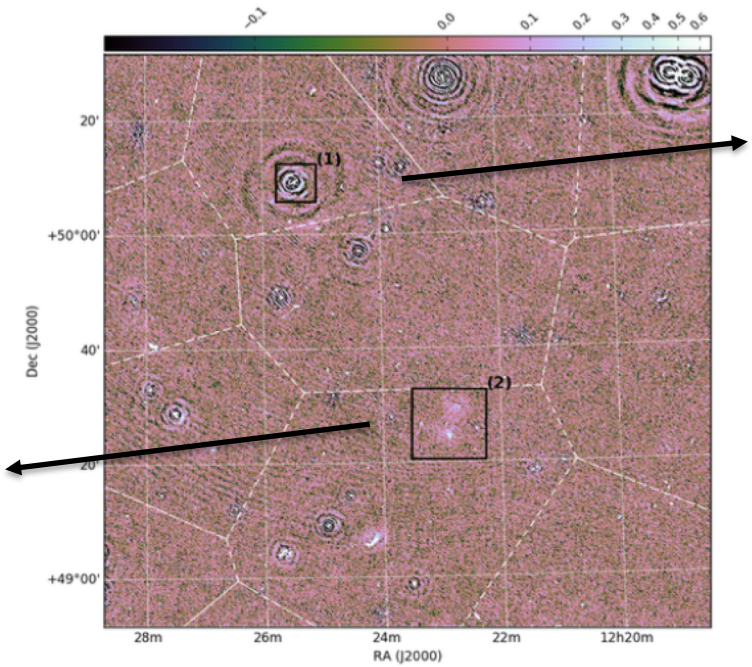
Tasse+2021



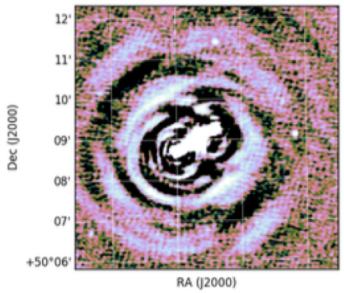
(f) Region (2) as imaged by Alg. 1



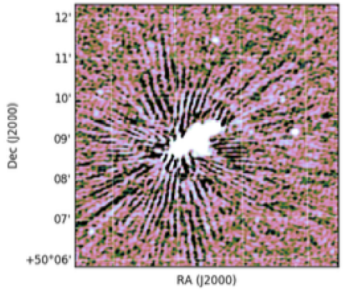
(e) Region (2) as imaged by Alg. 0



(a) The central part of the P26HETDEX03 8 hours LOFAR-HBA scan as imaged by Alg. 0.



(b) Region (1) as imaged by Alg. 0



(c) Region (1) as imaged by Alg. 1

LoTSS Deep Fields: Calibration & Imaging

The Evolution of the DDF pipeline (Tasse+2021):

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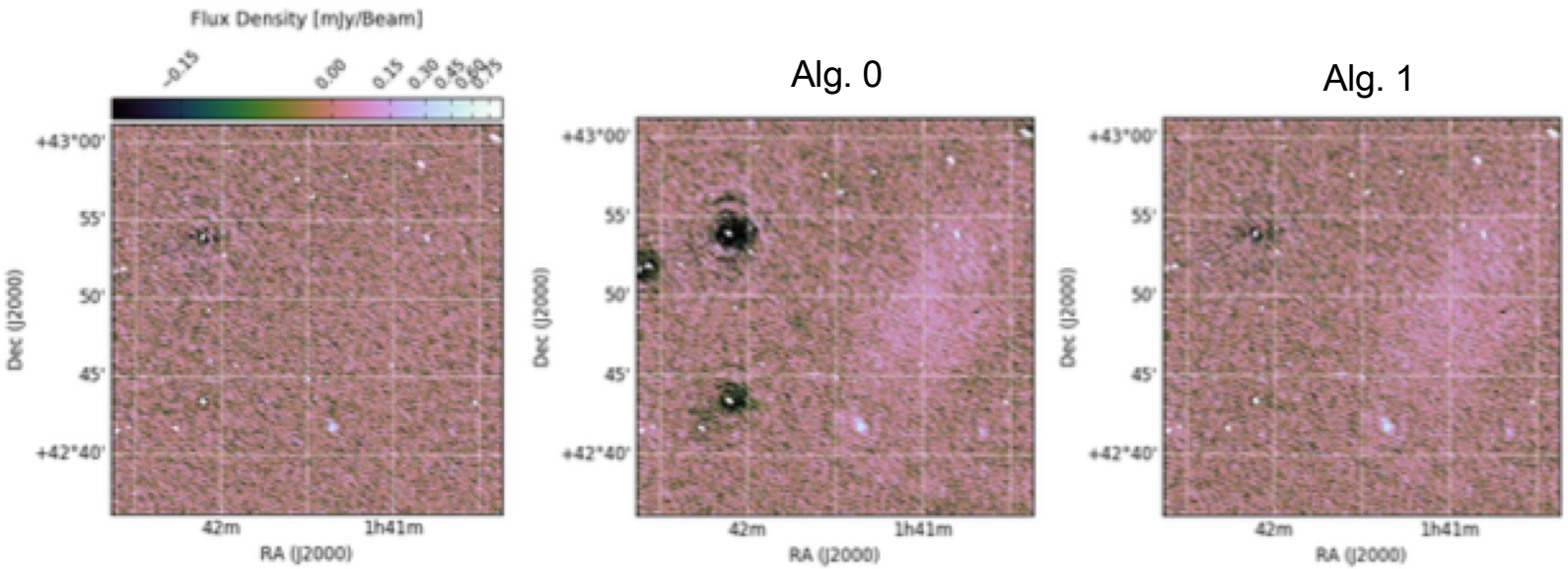
  Improve wrt DDF pipeline v1 (Alg.0) on:
  - limited dynamic range: DI+DD self-cal loops using as sky model the bright sources in facets (6 arcsec res.)
  - Artificial diffuse halos and holes: shorter uv-distance cut & better deconvolution and longer solution intervals



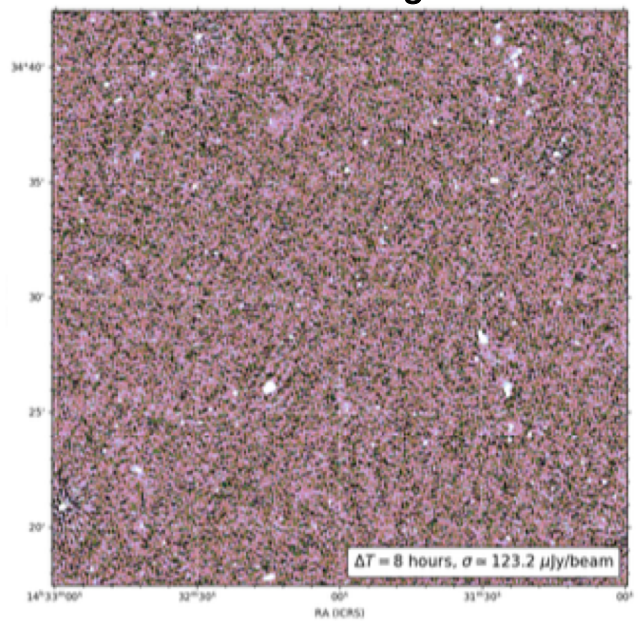
Tasse+2021

LoTSS Deep Fields: Calibration & Imaging

The Evolution of the DDF pipeline (Tasse+2021):

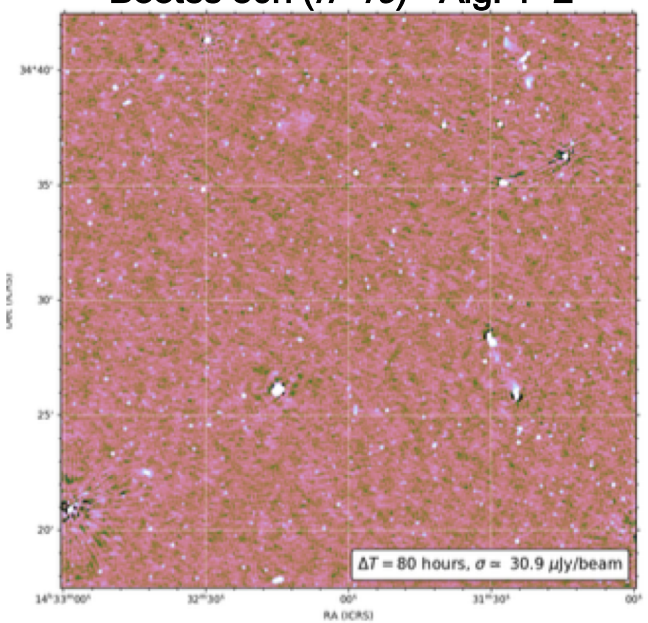
- **DDF pipeline v2 (Alg. 1+2)**: LoTSS-Deep DR1
  - Build a wide-band DI+DD self-calibrated sky model from a single wide band (240 SB) ~8 hours observation using **Alg. 1**.
  - This model is applied to all others 8h runs. All *n* runs are then jointly DI+DD calibrated and imaged (**Alg. 2**)

Bootes 8h - Alg. 1



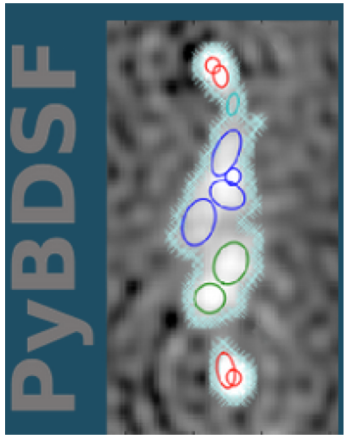
Tasse+2021

Bootes 80h (*n=10*) - Alg. 1+2



LoTSS Deep Fields: Source finder & flux scale

Source extraction using PyBDSF tool (Python Blob Detector and Source Finder**)**



- sources that can be composed of either individual or multiple Gaussians
- diffuse emission on different scales recovered by using wavelets
- local variations of the noise are accounted for (rms maps)

Parameters optimized for LOFAR images through tests and Simulations

Parameter	value
rms_box	(150, 15)
adaptive_rms_box	True
rms_box_bright	(60, 15)
thresh_isl	4.0
thresh_pix	5.0
adaptive_thresh	150
atrous_do	True
atrous_jmax	4
flag_maxsize_fwhm	0.5
ini_method	'intensity'
mean_map	'zero'
group_by_isl	False
group_tol	10
rms_map	True
output_all	True
output_opts	True
flagging_opts	True

Initial PyBDSF catalogues used to calibrate image flux scale **(Sabater+2021)**

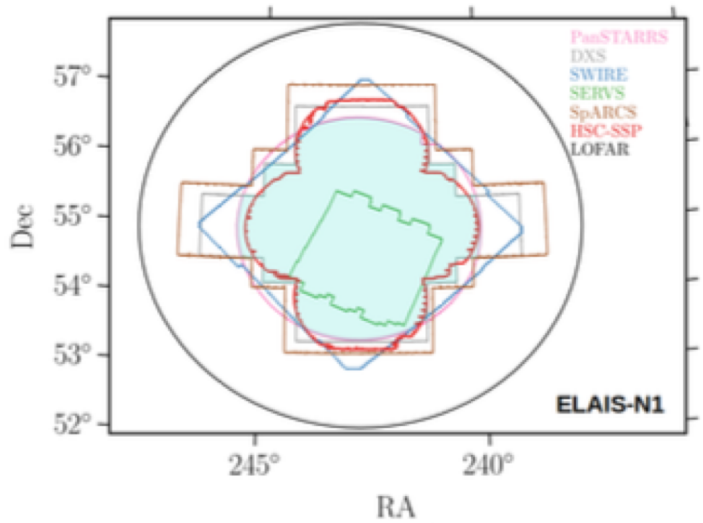
EN1: 0.796 ± 0.024
LH: 0.920 ± 0.040
Bootes: 0.859 ± 0.035

LoTSS Deep Fields: Value-added catalogues

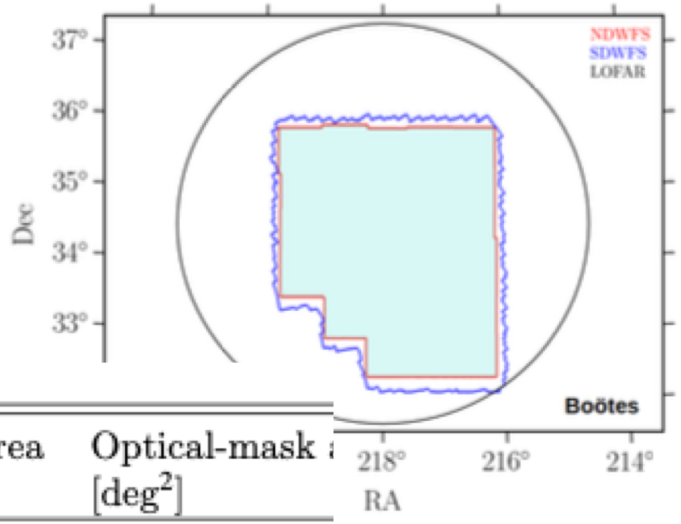
Dense ancillary multi-band opt/IR coverage

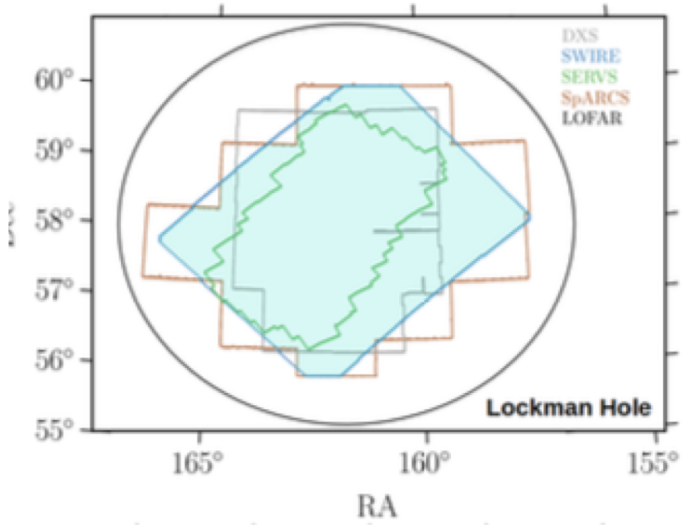
Value-added cat. produced for masked regions (highlighted in light blue), i.e. overlap between SWIRE and 'best' optical surveys:

- EN1: HSC-SSP (Hyper-Suprime Cam Subaru)
- LH: SPARCS-r band (CFHT-MegaCAM)
- Bootes: NDWFS (NOAO)



(Kondapally+2021)





Additional masking around bright stars

Field	Spitzer-mask area [deg^2]	Optical-mask [deg^2]
ELAIS-N1	0.40	0.61
Lockman Hole	0.31	0.85
Boötes	0.87	1.18

LoTSS Deep Fields: Value-added catalogues

- **Pixel-matched images (0.2″/px)** common astrometric projection and flux scale
- **Coadded mosaics for each filter,** pixels weighted for relative sensitivity

(Kondapally+2021)

- **Matched-aperture multi-band catalogues (from UV to mid-IR) obtained with SExtractor (dual mode)**

➢ detection on deep χ^2 images + forced photometry for all filters
➢ Opt./NIR and Spitzer separately
➢ Varying PSF accounted for through aperture corrections
➢ Catalogues cleaned for artefacts & low significance detections
➢ corrected for Galactic extinction

➢ Opt/NIR and Spitzer cat. Merged (Spitzer only sources ~4-5%)

Field/Survey	Band	Vega-AB [mag]	PSF [arcsec]	3σ depth [mag]	$A_{band}/E(B-V)$	Area [deg^2]
ELAIS-N1						
SpARCS						11.81
	u	-	0.9	25.4	4.595	
PanSTARRS						8.05
	g	-	1.2	25.5	3.612	
	r	-	1.1	25.2	2.569	
	i	-	1.0	25.0	1.897	
	z	-	0.9	24.6	1.495	
	y	-	1.0	23.4	1.248	
HSC						7.70
	G	-	0.5	25.6	3.659	
	R	-	0.7	25.0	2.574	
	I	-	0.5	24.6	1.840	
	Z	-	0.7	24.2	1.428	
	Y	-	0.6	23.4	1.213	
	NB921	-	0.6	24.3	1.345	
UKIDSS-DXS						8.87
	J	0.938	0.8	23.2	0.797	
	K	1.900	0.9	22.7	0.340	
SWIRE						9.32
	3.6 μm	2.788	1.66	23.4	0.184	
	4.5 μm	3.255	1.72	22.9	0.139	
	5.8 μm	3.743	1.88	21.2	0.106	
	8 μm	4.372	1.98	21.3	0.075	
SERVS						2.39
	3.6 μm	2.788	1.66	24.1	0.184	
	4.5 μm	3.255	1.72	24.1	0.139	

LoTSS Deep Fields: Value-added catalogues

- **Pixel-matched images (0.2″/px)** common astrometric projection and flux scale
- **Coadded mosaics for each filter,** pixels weighted for relative sensitivity

(Kondapally+2021)

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➢ Opt./NIR and Spitzer separately
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➢ corrected for Galactic extinction

➢ Opt/NIR and Spitzer cat. merged (Spitzer only sources ~4-5%)

Field/Survey	Band	Vega AB	PSF	3σ depth	$A_\lambda/E(B-V)$	Area
	$3.6\,\mu$m	2.788	1.66	24.1	0.184	
	$4.5\,\mu$m	3.255	1.72	24.1	0.139	

Science-ready catalogues for optically selected sample (~7 million sources):

- multi-band photometry
- spectro/photometric(*) redshifts
- Stellar masses (z<1.5)

(Duncan+2021)

(*) Robust up to z = 1.5 for galaxies (σ_{NMAD} = 1.48xmedian($|\Delta z|/(1+z_{spec})$) = 0.02; OLF~1.5-1.8%), and up to z=4 for AGN (σ_{NMAD} =0.064; OLF~18-22%)

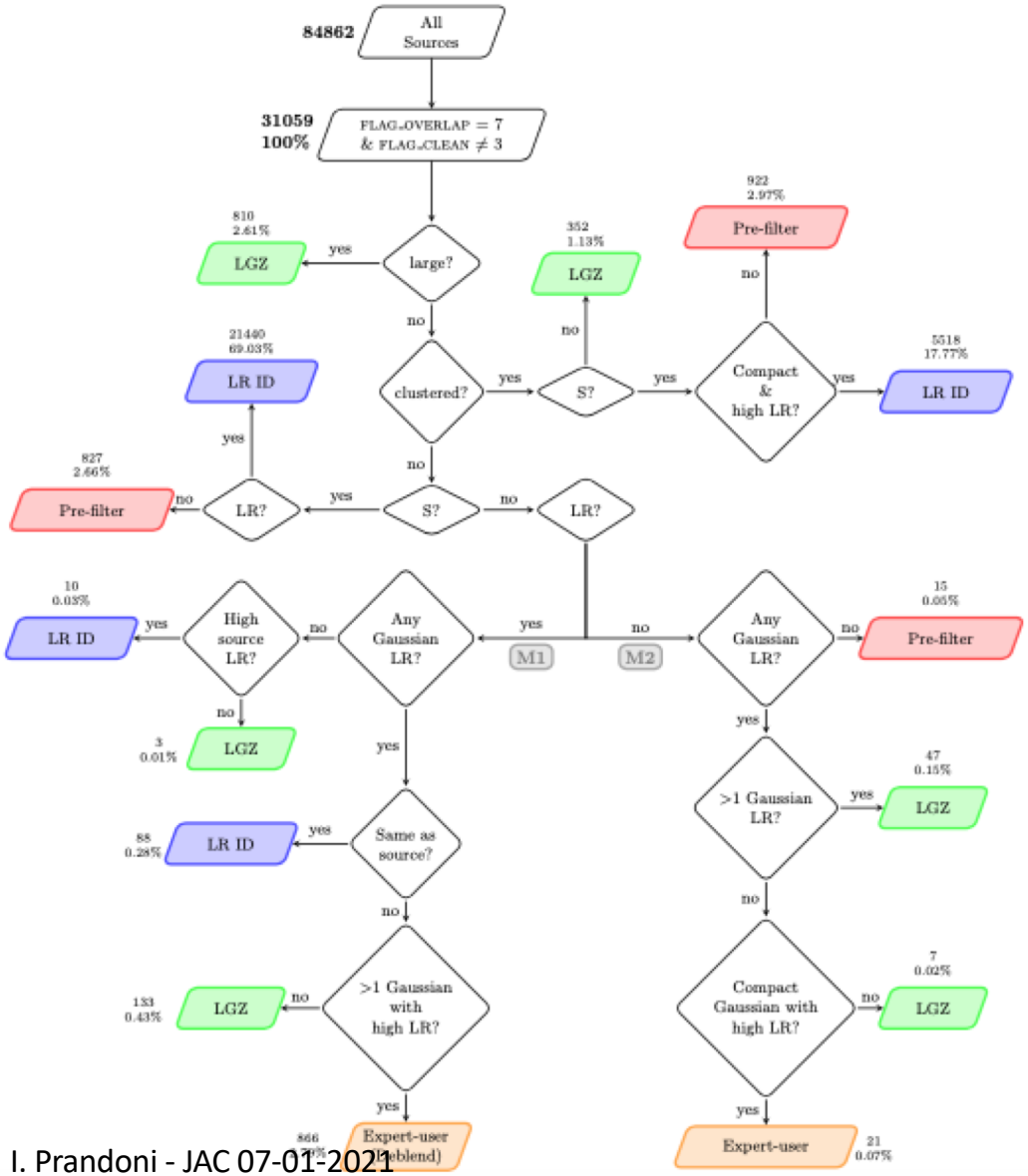
LoTSS Deep Fields: Radio-opt/IR cross-id

- **Value-added catalogues used to find radio source counterparts**
- **Improve PyBDSF radio catalogues**

  (Kondapally+2021)

➢ Mix of LR analysis (incl. magnitude and <u>colour</u> information) and visual inspection

➢ Visual inspection (LGZ) for:
  - Very extended sources
  - Clustered sources
  - Sources with no reliable LR id
  - Multiple/Complex sources



LoTSS Deep Fields: Radio-opt/IR cross-id

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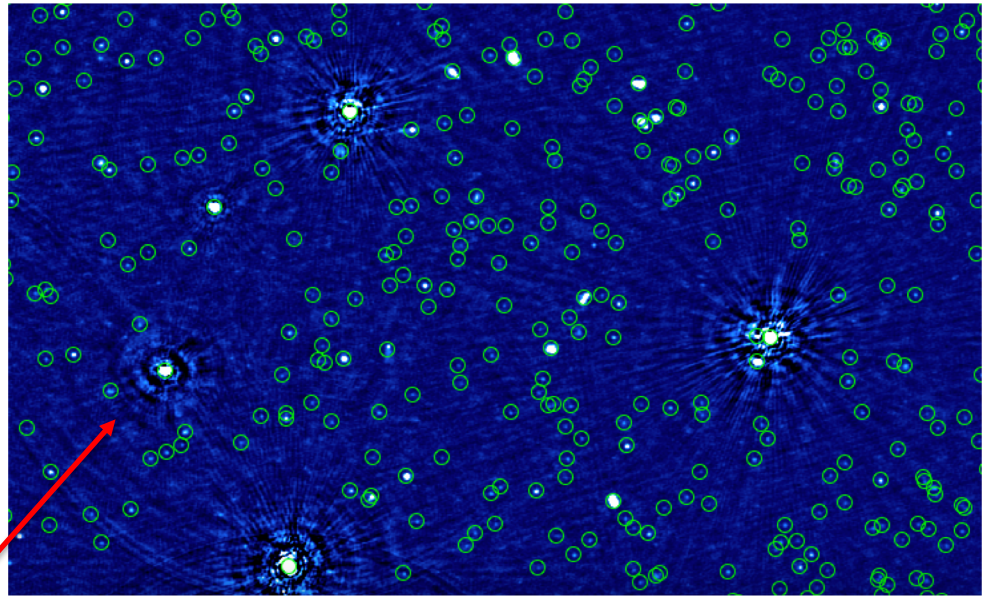
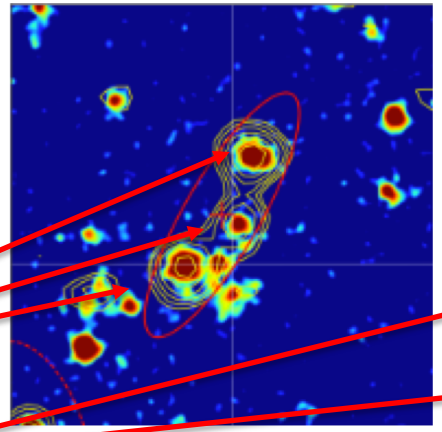
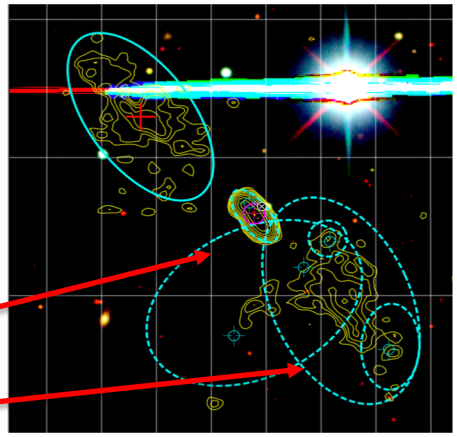
Improve PyBDSF radio catalogues

(Kondapally+2021)







- Mix of LR analysis (incl. magnitude and colour information) and visual inspection

- Visual inspection (LGZ) for:
  - Very extended sources
  - Clustered sources
  - Sources with no reliable LR id
  - Multiple/Complex sources

- Clean radio catalogue from artefacts
- Deblend confused sources
- Associate components belonging to multiple radio galaxies
- Increase id rate (≥ 97%)

LoTSS Deep Fields: DR1

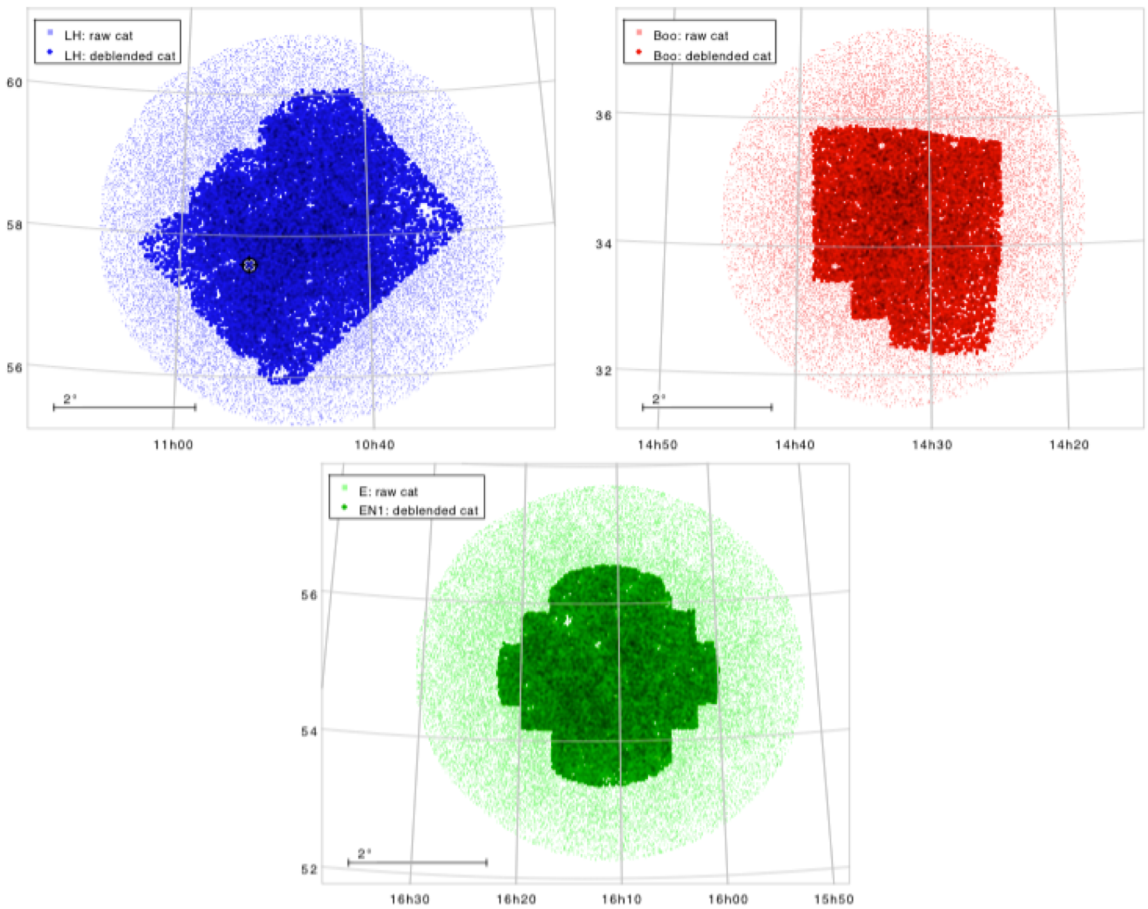
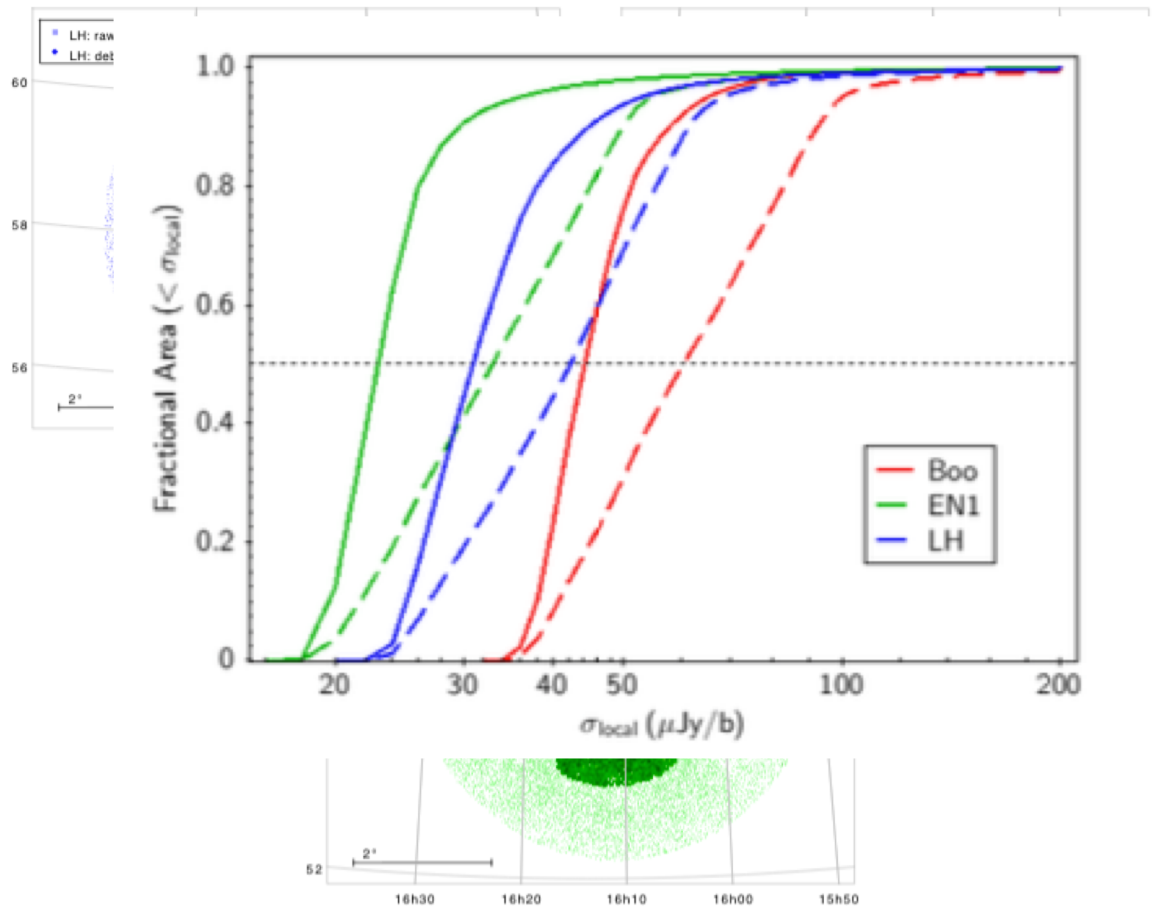


Table 1. An overview of the statistical properties of the three LoTSS Deep Fields.

Field	R.A. (hh:mm:ss)	DEC. (dd:mm:ss)	Obs. Time (hr)	σ_c (μJy beam^{-1})	Area^{full} (deg^2)	N_S^{raw}	σ_{med}^{full} (μJy beam^{-1})	Area^{masked} (deg^2)	N_S^{final}	σ_{med}^{masked} (μJy beam^{-1})
LH	10:47:00.0	+58:04:59.0	112	22	25.0	50112	42	10.3	31162	31
Boo	14:32:00.0	+34:30:00.0	80	32	26.5	36767	60	8.6	19179	44
EN1	16:11:00.0	+55:00:00.0	164	17	24.3	69954	33	6.7	31610	23

LoTSS Deep Fields: DR1

Visibility function



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LoTSS Deep Fields DR1: Science

Science demonstration papers (more to come!):

- **Mandal+2021:** deepest 150 MHz radio source number counts to date
- **Hardcastle+2021:** estimate of contribution of LoTSS sources to radio background

- **Wang+2021**: constraints on number density of HLIRG from Herschel samples in all three fields (5-18 /deg^2; higher than predicted by GALFORM)
- **Ramasawmy+2021:** flattening of low-v radio spectra in20% of sub-mm galaxy sample in LH, likely related to free free absorption from clumpy ISM on sub-kpc scales
- **Gloudemans+2021**: defines a robust sub-sample of z=5.7 and z=6.6 LAE candidates in EN1 (from SILVERRUSH) and provides upper limits to SFR of ~50 M_{sun} /yr
- **Smith+2021:** SFR – radio luminosity correlation of NIR-selected galaxies with z<1 in EN1
- **Morganti+2021:** search for remnant/restarted RG through spatially resolved spectral index maps of extended radio galaxies with LOFAR and Apertif in LH

- **Herrera-Ruiz+2021:** catalog of polarized sources in EN1 from stacked 8h images (26 uJy/b rms; 0.6 sources/deg^2)
- **Osinga+2021:** search for diffuse radio emission in Planck, X-ray and X-ray-SZ clusters in all three fields; report discovery of new RH in X-ray cluster at z=0.77 with M ~3.3 10^{14} M_{sun} and provide upper limits on P_{Halo} in unexplored M<5 10^{14} M_{sun} regime
- **Callingham+2021:** report on longest low frequency monitoring of M-dwarf (6.5 days in 2 block 1-year apart for flare star CR Draconis)

Extremely deep 150 MHz source counts from the LoTSS Deep Fields

S. Mandal*[1], I. Prandoni**[2], M. J. Hardcastle[3], T. W. Shimwell[1,4], H. T. Intema[1,5], C. Tasse[6,7], R. J. van Weeren[1], H. Algera[1], K. L. Emig[1], H. J. A. Röttgering[1], D. J. Schwarz[8], T. M. Siewert[8], P. N. Best[9], M. Bonato[2,10,11], M. Bondi[2], M. J. Jarvis[12,13], R. Kondapally[9], S. K. Leslie[1], V. H. Mahatma[14], J. Sabater[9,15], E. Retana-Montenegro[16], and W. L. Williams[1]

$$N_{\mathrm{eff},i} = r_i\, e_i \sum_{j=1}^{J_i} \left(V_j^{\mathrm{AREA}}\, F^{\mathrm{AREA}}\right)^{-1}$$

r=r(S)=resolution bias

e=e(S)= Eddington bias

V=V(S)=Visibility function

F=Field area

Resolution bias (resolved sources)

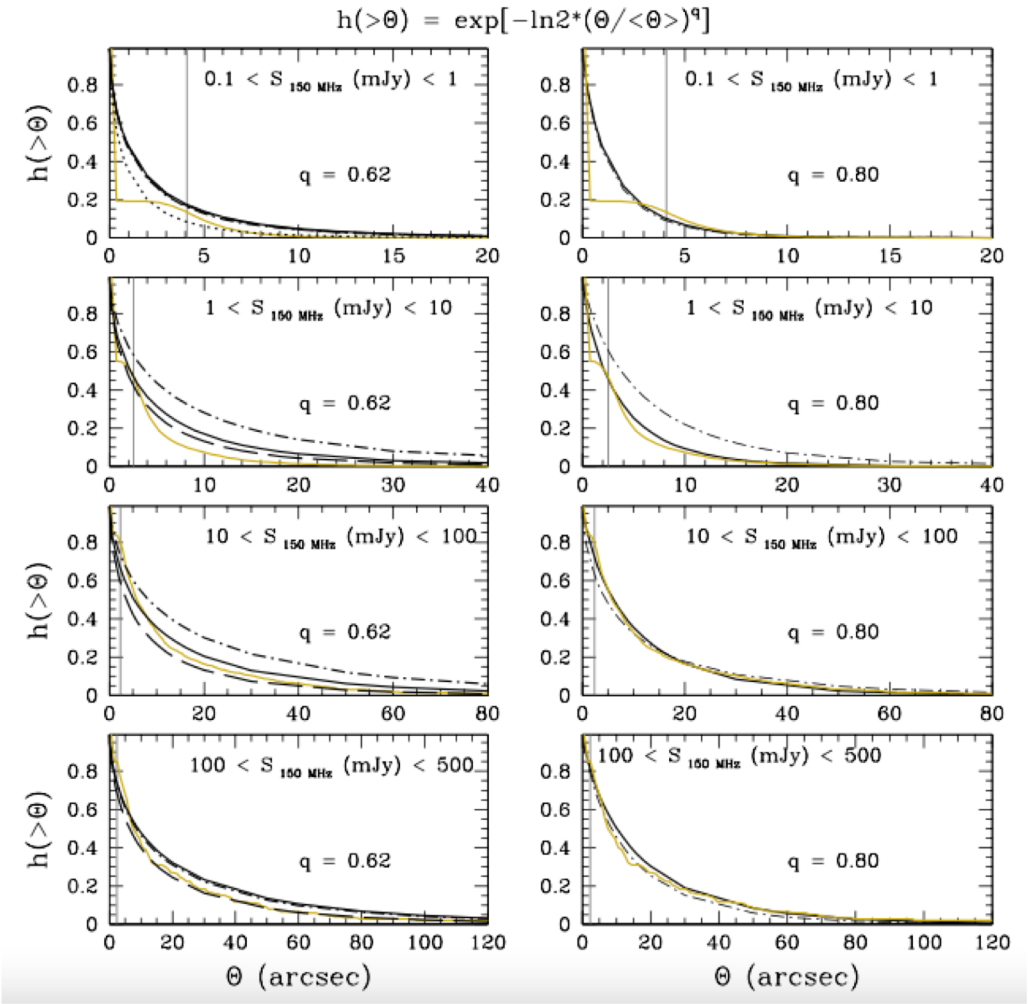
$$\Theta_{\rm max} = \Theta_N \sqrt{(S_{\rm total}/(5\sigma) - 1}$$

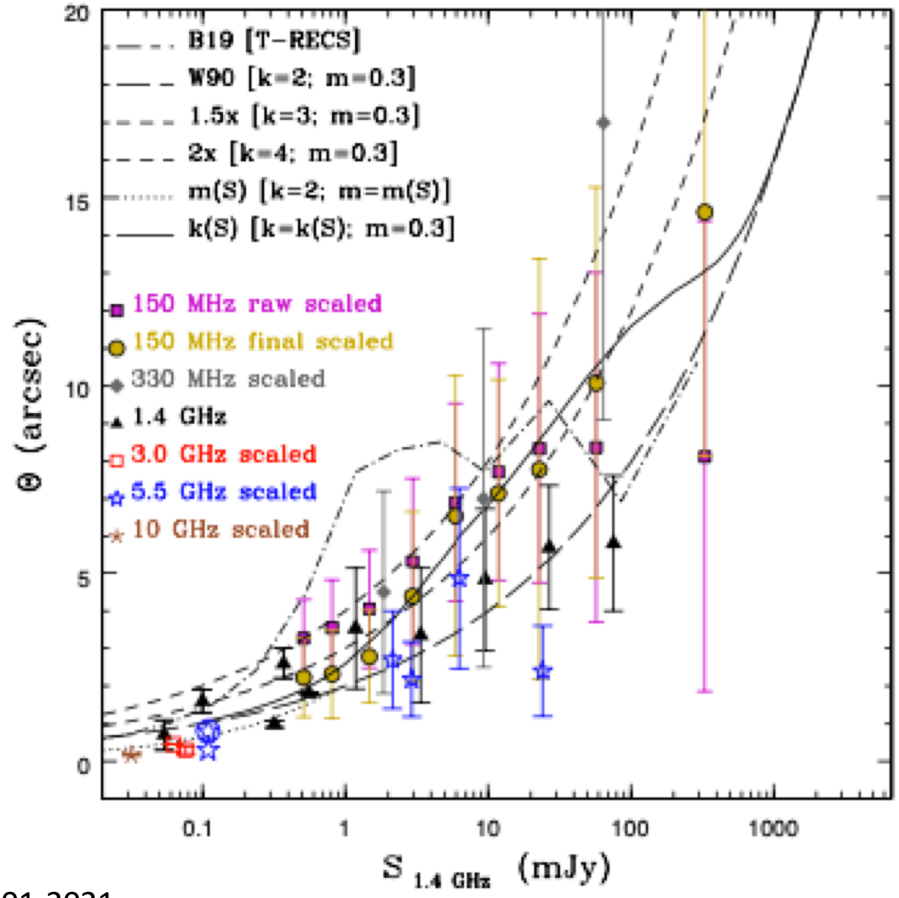
Windhorst+1990 (DC-)size – flux relations ($S_{1.4\ \rm GHz}$ >1 mJy):

$$h(>\Theta) = \exp[-\ln 2\,(\Theta/\Theta_{\rm med})^q]$$

$$\Theta_{\rm med} = k \times (S_{1.4\rm GHz})^m$$

q=0.62
k=2”
m=0.3





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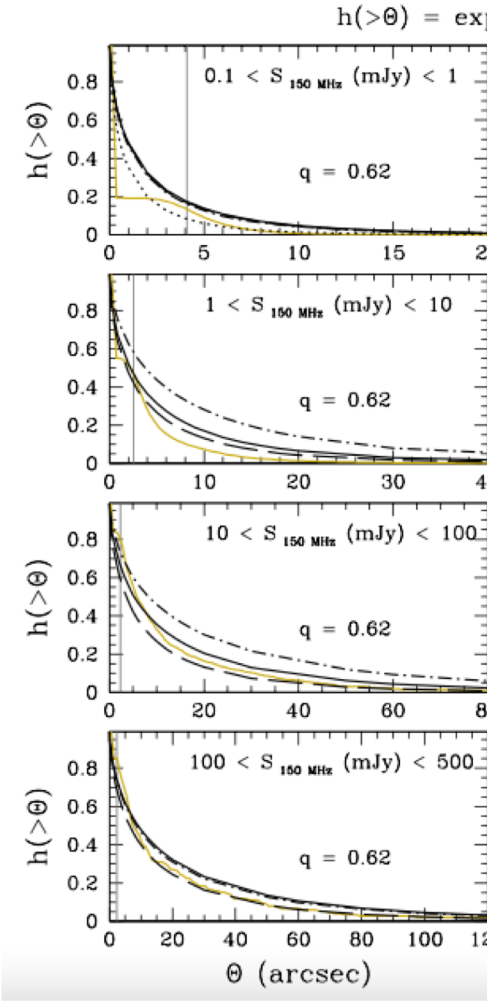
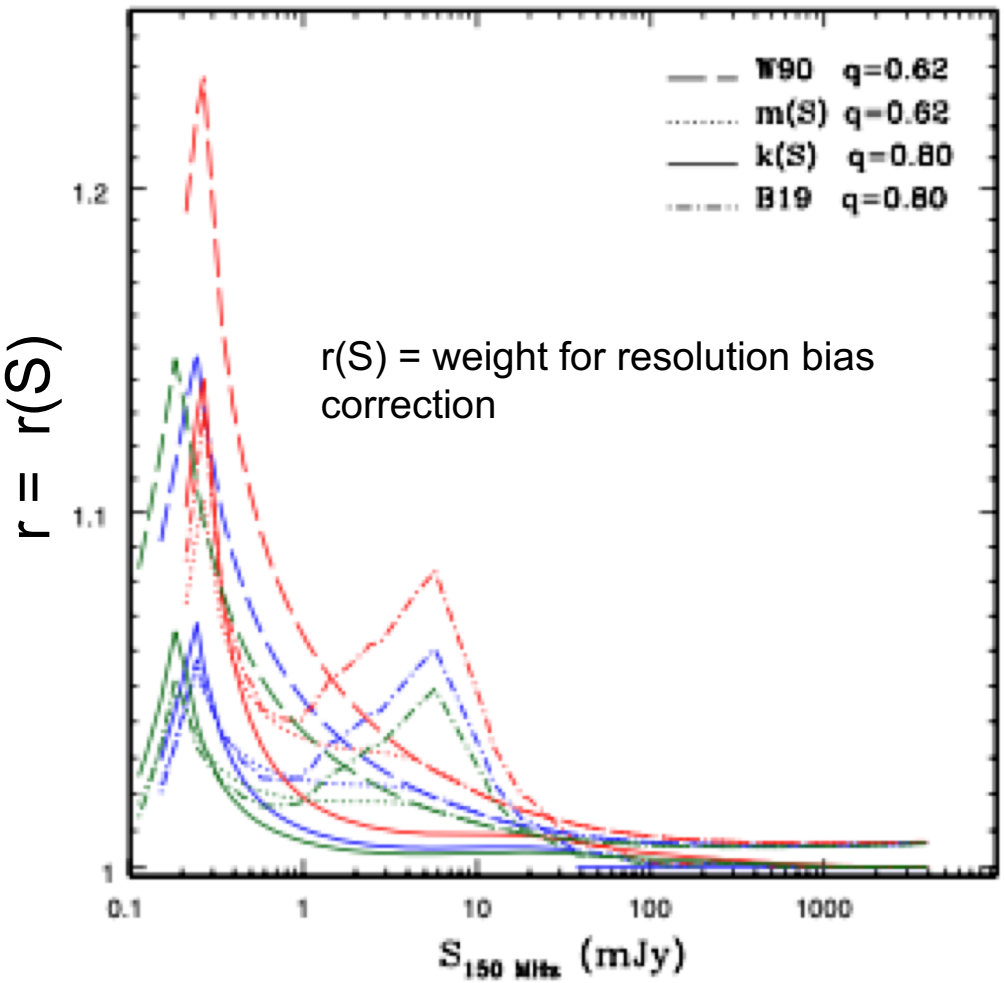
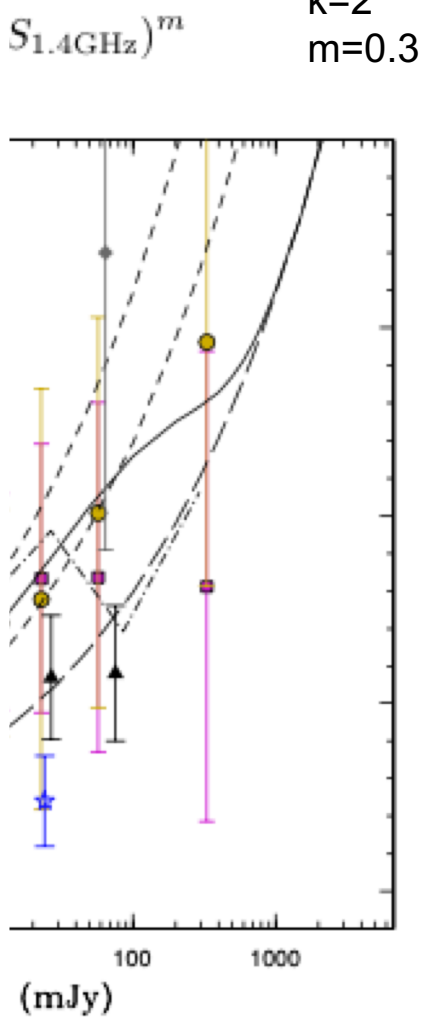
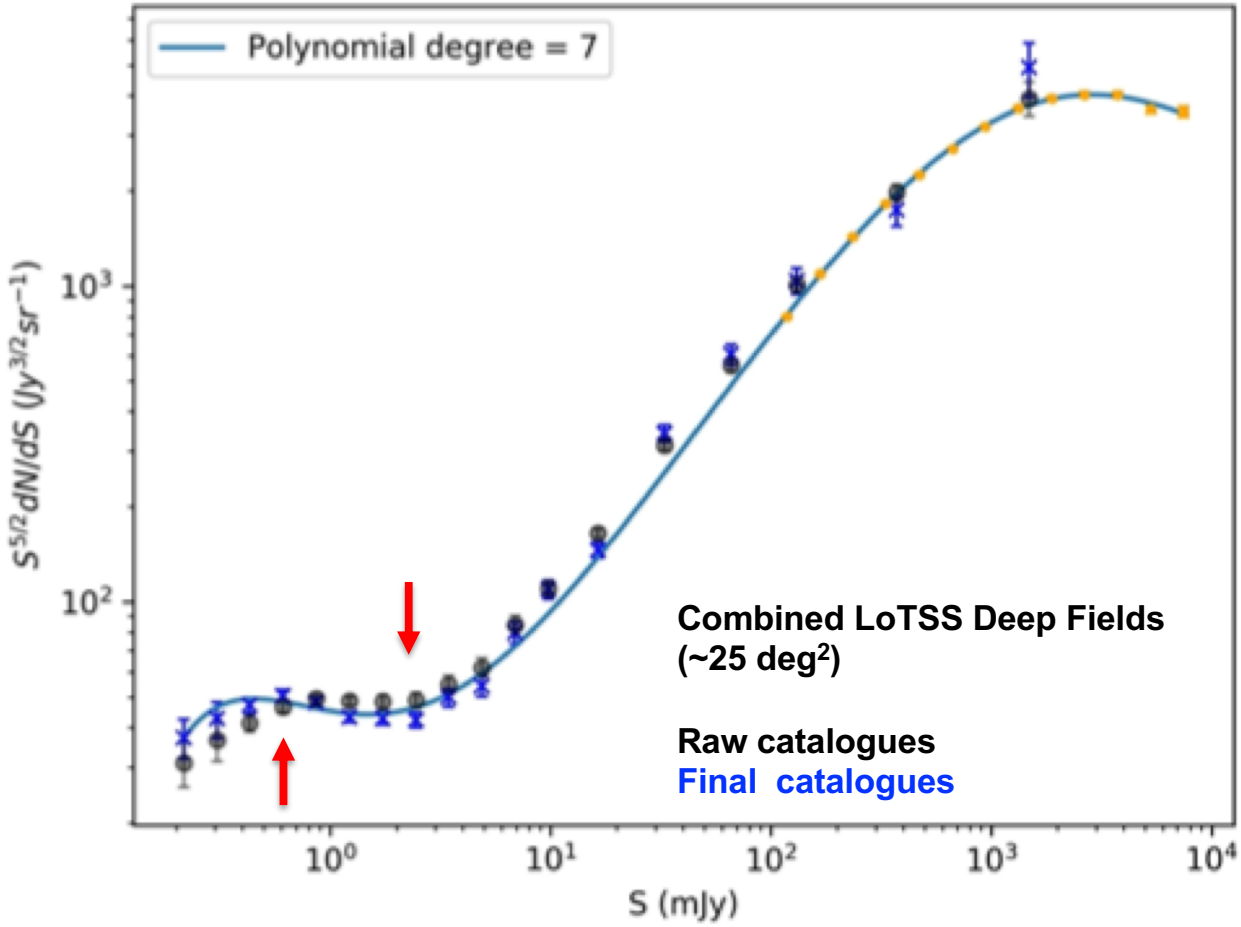


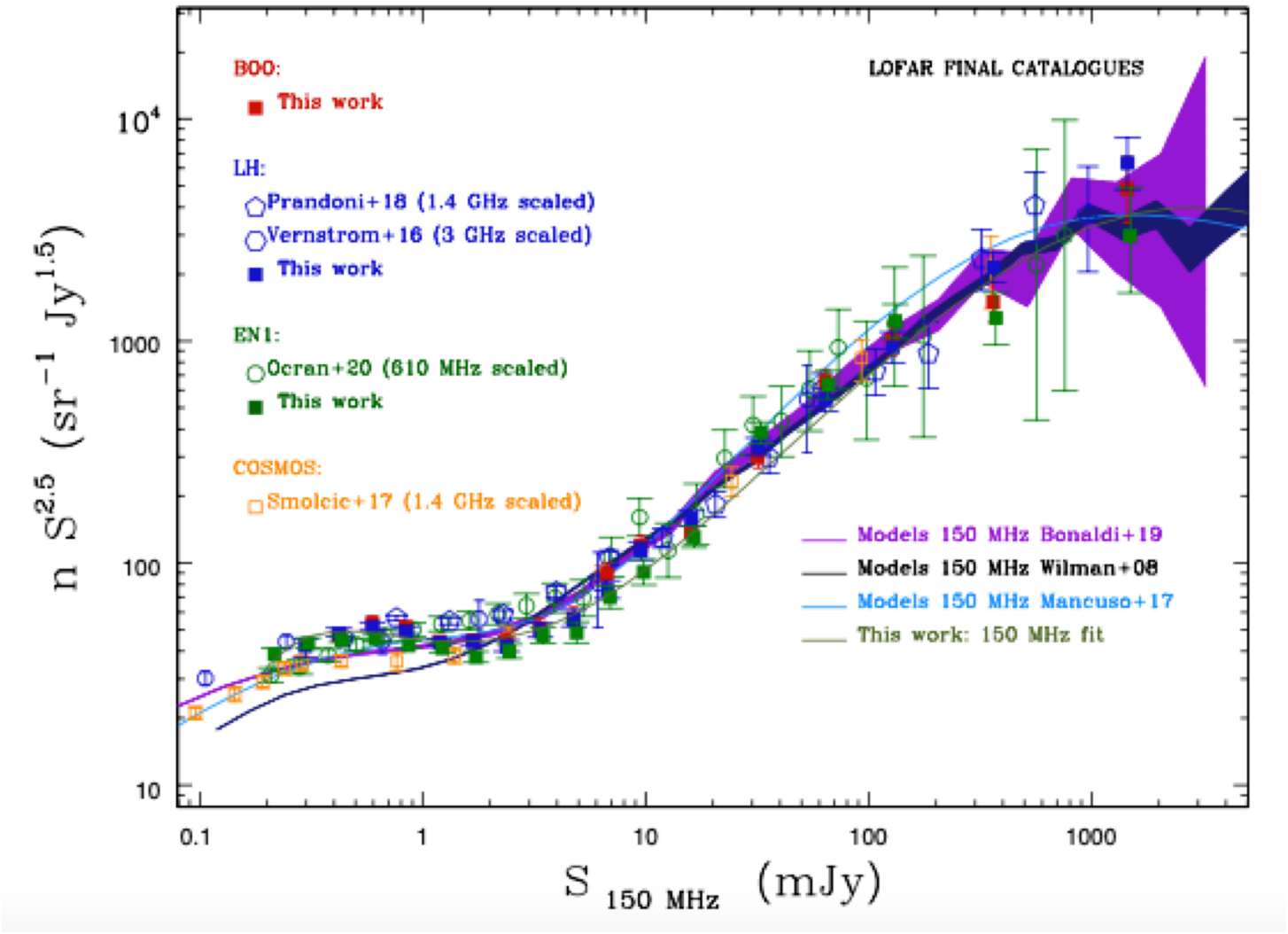




150 MHz Source Counts – deepest to date



Source Counts Comparison



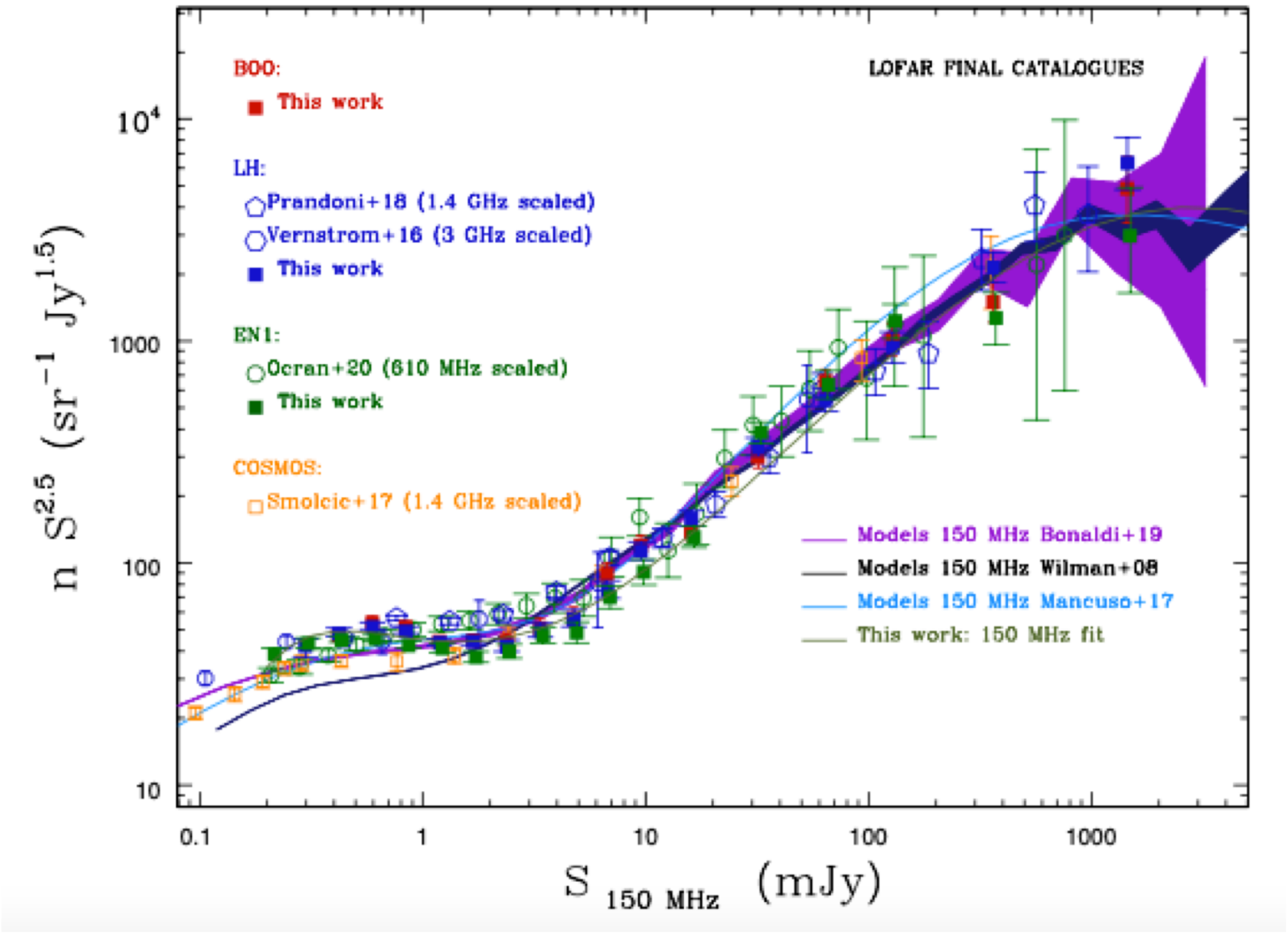
Good agreement with determinations at higher frequencies in the sub-mJy regime (except COSMOS)

More pronounced drop at 2-7 mJy (except COSMOS)

- Sample variance 15-25% at mJy fluxes for < 2 deg^2 samples
- Survey systematics: LoTSS can counts on very complete identifications → more accurate artefact removal?

- Other systematics: extrapolation of higher frequency counts to 150 MHz with α=-0.7

Source Counts Comparison



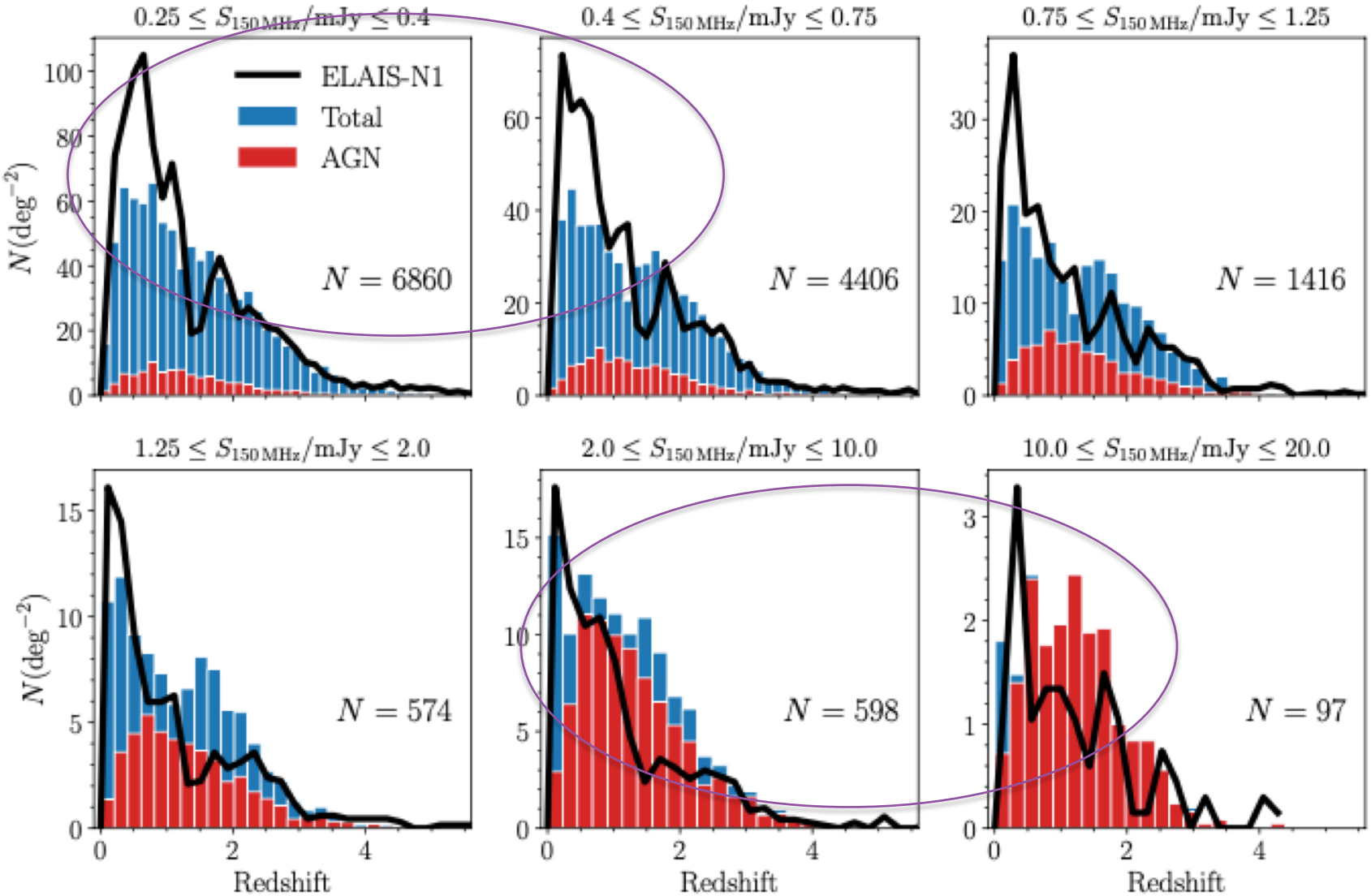
Good agreement with models at bright end (except Mancuso+17)

Good agreement with models at faint end (except Wilman+08)

All models over-estimate counts at 2-20 mJy wrt LoTSS fit (also noticed in LoTSS DR1; Siewert+20)

None of the models can reproduce the bumb at sub-mJy fluxes

Comparison with T-RECS



T-RECS:

Deficiency of low-z (z<1) galaxies/AGN at sub-mJy fluxes

Excess of intermediate redshift (1<z<2) AGN at mJy flluxes

➔ Models may need revision…

The contribution of discrete sources to the sky temperature at 144 MHz

M.J. Hardcastle[1]*, T.W. Shimwell[2], C. Tasse[3,4], P.N. Best[5], A. Drabent[6], M.J. Jarvis[7,8], I. Prandoni[9], H.J.A. Röttgering[10], J. Sabater[5], and D.J. Schwarz[11]

$$N_{\mathrm{eff},i} = r_i \, e_i \sum_{j=1}^{J_i} \left(V_j^{\mathrm{AREA}} \, F^{\mathrm{AREA}} \right)^{-1}$$

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Why LoTSS

Observed radio background (see e.g. Fixsen+11, ARCADE-2 bolometer) too high to be explained with contribution of discrete extra-galactic radio sources (Vernstrom+11; Condon+12)

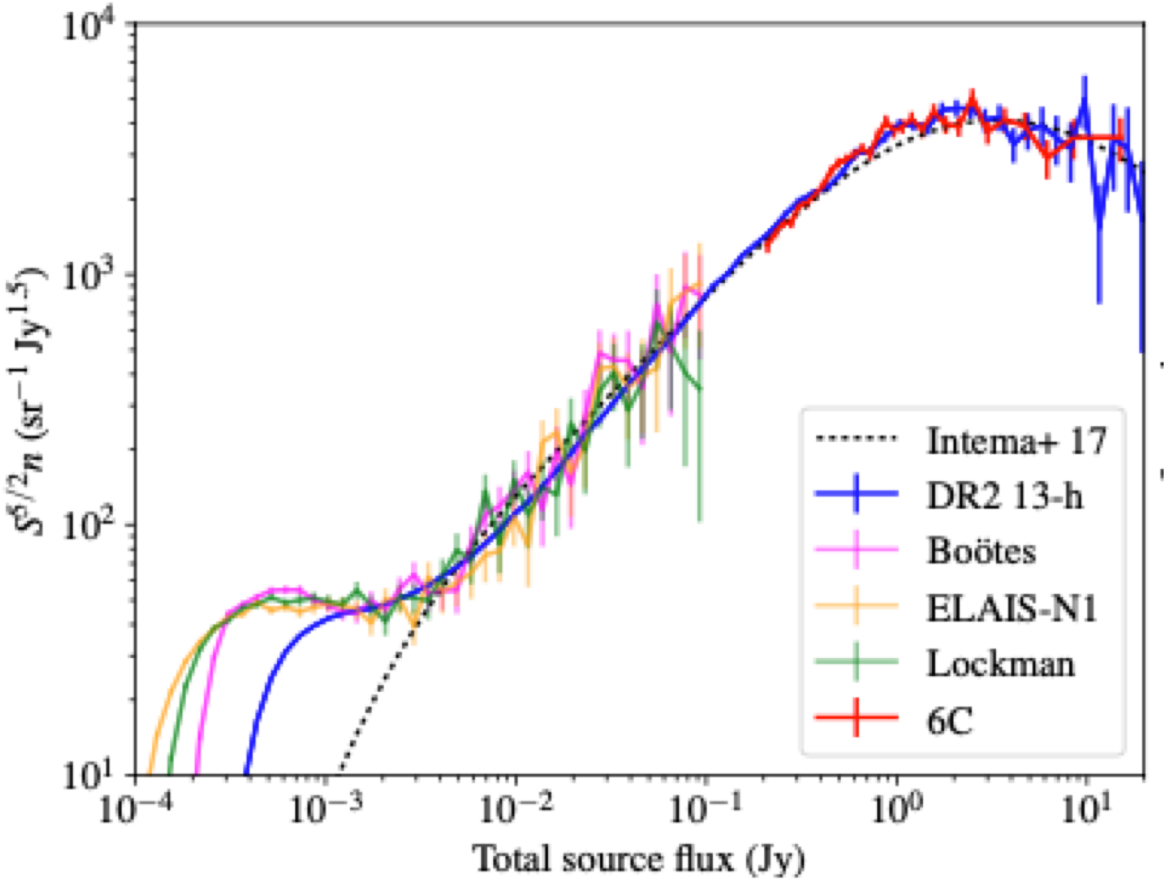
Possible explanations:

1) MW contribution not correctly subtracted → extragalactic background over-estimated
2) higher frequency surveys with more sparse telescopes miss a substantial contribution from diffuse emission associated with extended radio sources
3) Extragalactic background composed of populations of very faint, non-thermal (steep spectrum) sources, yet to be uncovered

LOFAR is best suited for such studies because:
a) It operates at low frequency and can take advantage of the steep spectrum of synchrotron radiation
b) It has an excellent surface brightness sensitivity

This work based on:
LoTSS DR2: preliminary catalogue (**2000 deg^2** centered on HETDEX field at RA=13h)
LoTSS Deep DR1: inner 3 deg^2 only (uniform noise), raw radio catalogues (consistency with LoTSS DR2)

Uncorrected Source Counts



Completeness correction for resolution bias in LoTSS Deep fields:

Injection of simulated sources and re-extraction with PyBDSF

Simulated source population:

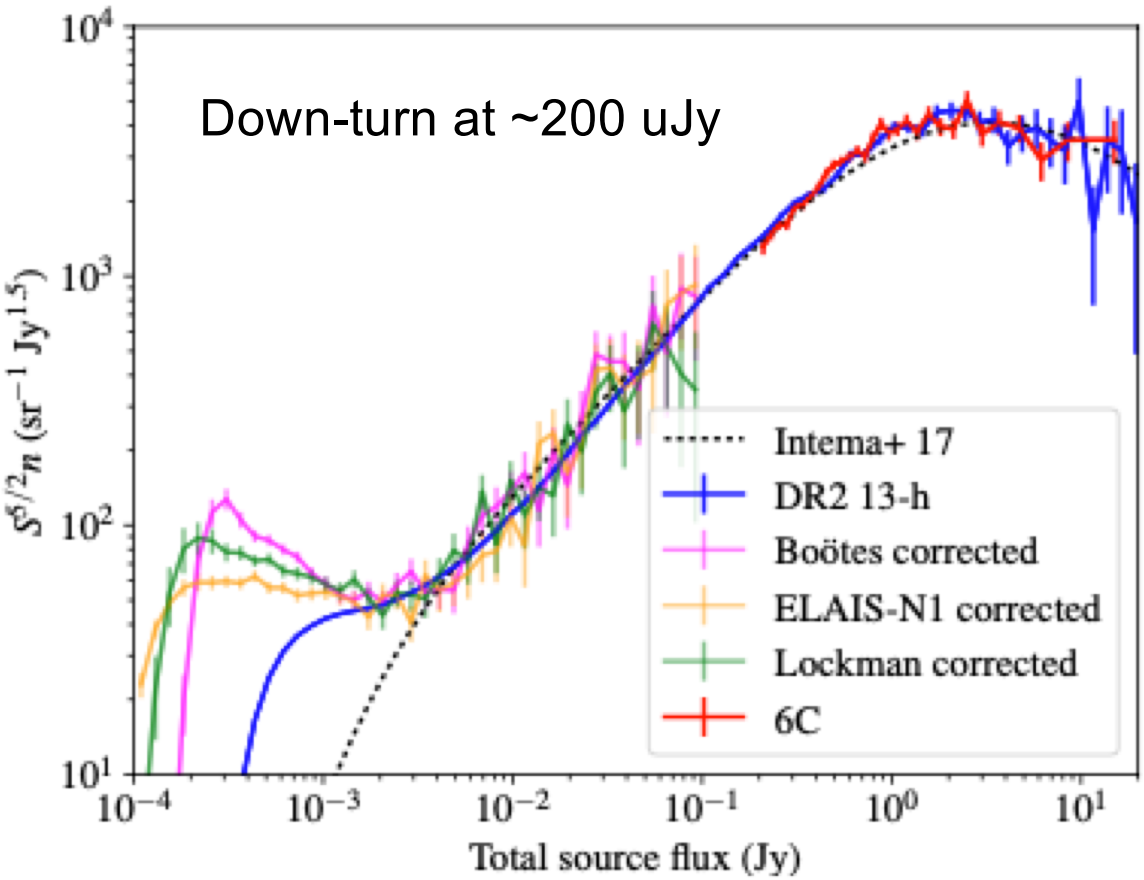
- flux density 0.1<S<5 mJy
- Major/minor axes randomly drawn from DR2 13h sources with S>100 mJy

AGN/RGs dominant at S>100 mJy:

➔ extreme scenario probed

➔ Resolution bias likely over-estimated

Corrected Source Counts



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Total Sky Temperature

The spectral radiance is given by:

$$I_\nu = \frac{\sum S_i}{\Omega} \quad , \qquad (1)$$

where S_i are the flux densities of individual sources in W Hz^{-1} m^{-2} and Ω is the total solid angle covered by the survey in sr. The sky brightness temperature is then given by

$$T_b = \frac{I_\nu c^2}{2k\nu^2} \quad . \qquad (2)$$

Alternatively, we can integrate over the binned number counts to obtain

$$I_\nu = \int S n(S)\, \mathrm{d}S \quad , \qquad (3)$$

44.5 ±3.0 K - Bootes

43.3 ±2.8 K - EN1

45.4 ±3.3 K - LH

[errors include uncertainties on correction]

$\langle T_b \rangle$ = 44.4 ±1.7 K at 144 MHz for sources with S>100 uJy

NB: Effect of correction is 10-20% boosting → conservative estimate: **T_b~40 K**

Comparison with other estimates

Discrete radio sources [$T_b \sim \nu^{-\beta}$ with β=2.7]**:**

- Hardcastle+2021 (LoTSS): **T_b = 44.4 ±1.7 K at 144 MHz**
- Vernostrom+2011 (6C): **T_b ~18 K at 150 MHz ➔ T_b ~20 K at 144 MHz**
- Bridle+1967: **T_b ~30 ±7 K at 178 MHz ➔ T_b ~53 ±12 K at 144 MHz**
- Turtle & Baldwin 1962: **T_b <80 K at 178 MHz ➔ T_b <140 K at 144 MHz**

Background [based on fits to data at 22, 45, 408, and 1400 MHz]:

- Fixsen+2011: **T_b ~110 K at 178 MHz ➔ T_b ~190 K at 144 MHz**

[supported by Dowell & Taylor 2018]

➔ Despite its SB sensitivity, LoTSS can reproduce only ¼ of background T_b
➔ If counts down-turn at 200 uJy real → no extrapolation can make up this discrepancy
➔ Implications for modeling of extragalactic background in EoR experiments

The LOFAR Two-metre Sky Survey Deep fields:

The star formation rate – radio luminosity relation at low frequencies

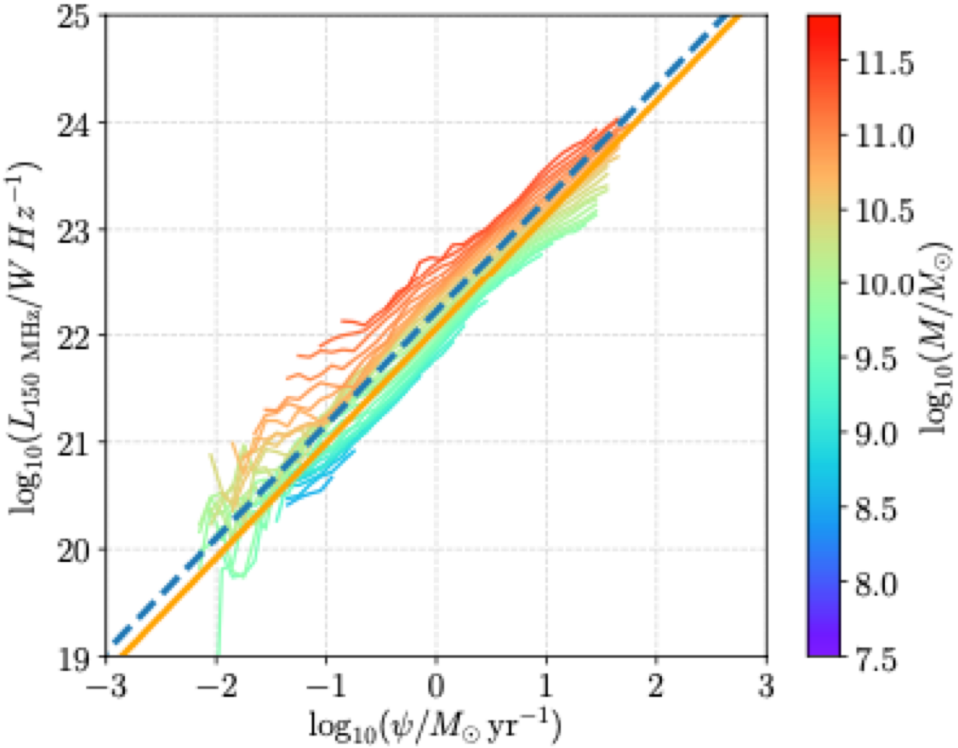
D. J. B. Smith[1], P. Haskell[1], G. Gürkan[2], P. N. Best[3], M. J. Hardcastle[1], R. Kondapally[3], W. Williams[4], K. J. Duncan[4,3], R. K. Cochrane[5], I. McCheyne[6], H. J. A Röttgering[4], J. Sabater[3], T. W. Shimwell[7,4], C. Tasse[8,9], M. Bonato[10,11,12], M. Bondi[10], M. J. Jarvis[13,14], S. K. Leslie[4], I. Prandoni[10], and L. Wang[15,16]

Sample: 118,517 galaxies at 0.05<z<1 from NIR (3.6 um) selected value-added catalogue in EN1 (incl. spectr-/photo-z)

- SFR and stellar masses derived from SED fitting (MAGPHYS), incl. SWIRE MIPS and (deblended) Herschel data
- only 9% of the sources detected in LoTSS ➔ pixel flux density used for the others (ML estimates of 150 MHz flux densities for unresolved sources)
- AGN contamination minimized through a variety of multi-band diagnostics (incl. removing bad MAGPHYS fits and Rex sources)

Scope: provide accurate calibration of SFR based on 150 MHz luminosity to be exploited in SFG studies based on LOFAR deep surveys

SFR – $L_{150\ MHz}$ relation



$L_{150\ MHz} = L_1\ \psi^{\beta}$

Best fit values:

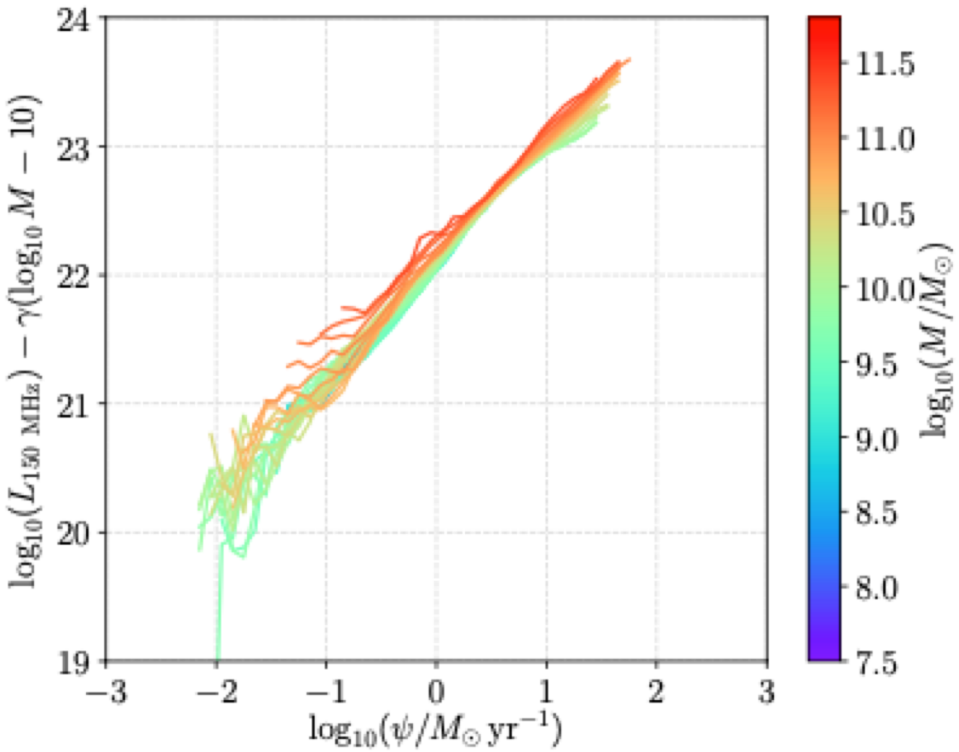
- **Log L_1 = 22.221 ± 0.008**
- **β = 1.058 ± 0.007**

Linear down to ψ~0.01 M_{sun}/yr

[No flattening below ψ~1 M_{sun}/yr (Gurkan+28)]

Mass dependence ?

SFR – $L_{150\ MHz}$ relation



$L_{150\ MHz} = L_C\ \psi^{\beta}\ (M/[10^{10}\ M_{sun}])^{\gamma}$

Best fit values:

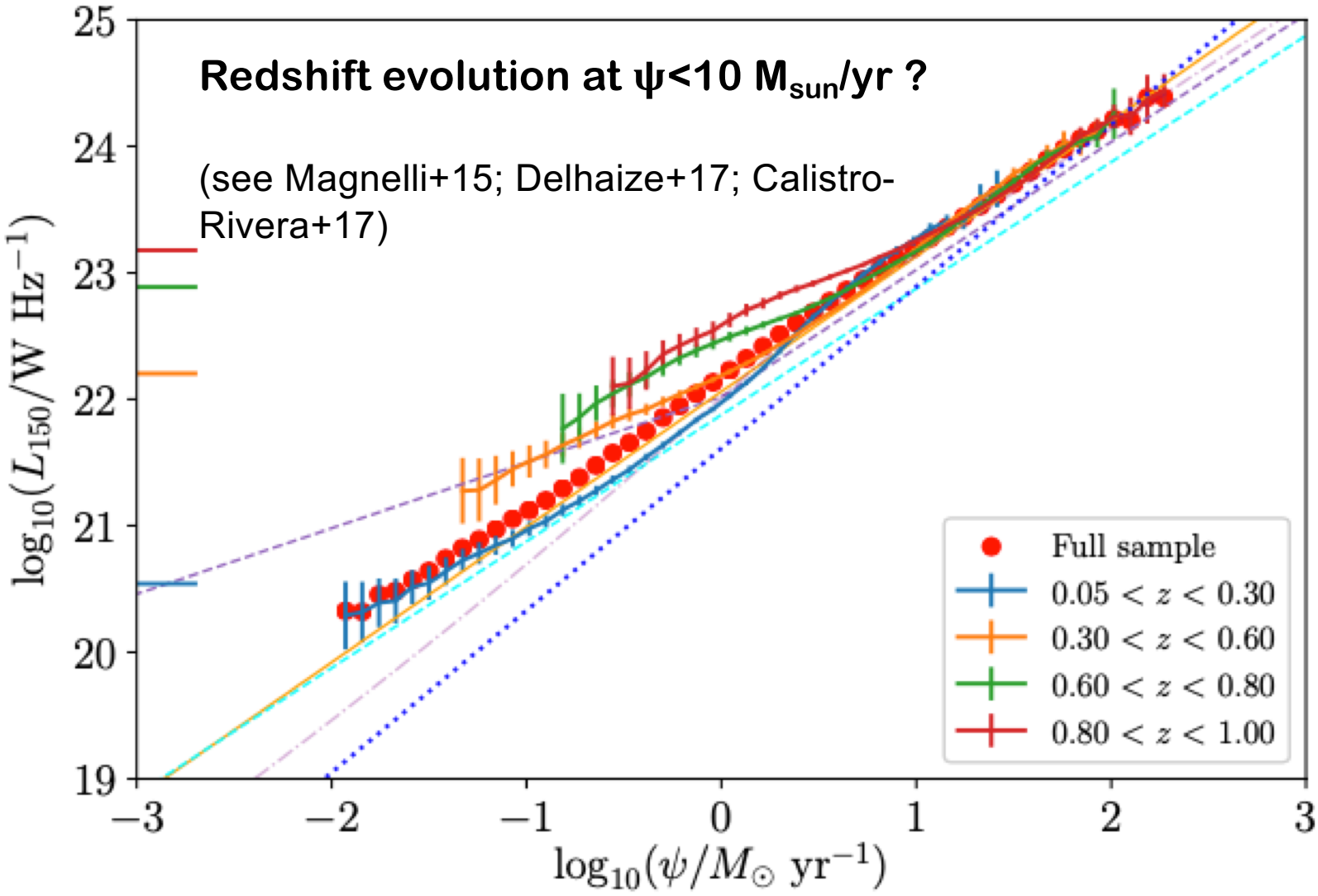
- **Log L_C = 22.218 ± 0.016**
- **β = 0.903 ± 0.012**
- **γ= 0.332 ± 0.037**

Clear dependence on stellar mass

(see also Gurkan+18; Read+19; Delvecchio+21)

AGN contamination canot be ruled out **BUT** mass dependence extend down to very low masses

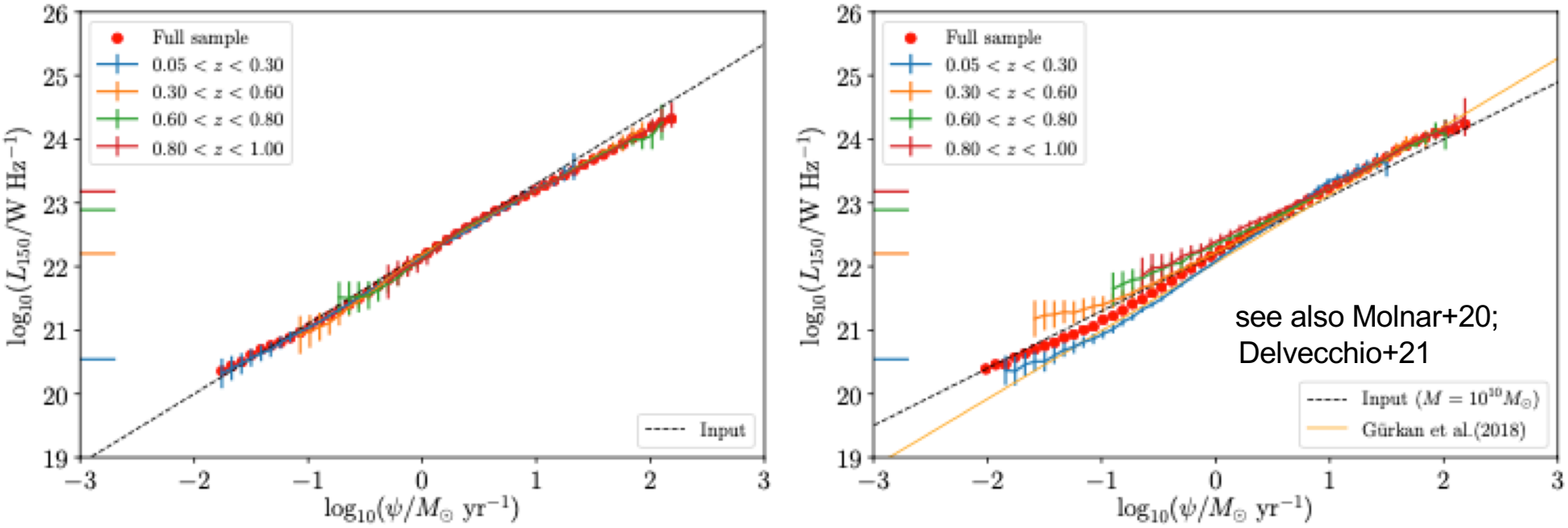
SFR – $L_{150\ MHz}$ relation



SFR – $L_{150\ MHz}$ relation

Redshift evolution at ψ<10 M_{sun}/yr ?

(see Magnelli+15; Calistro-Rivera+17



(a) Mass independent model

(b) Mass-dependent model

see also Molnar+20; Delvecchio+21

Set of simulations incl. a variety of selection effects

Possible Interpretations

Mass dependence real?

Radio AGN incidence in galaxies increases dramatically with stellar mass (Sabater+19)

- Radio AGN with $L_{150\ MHz} > 10^{21}$ W/Hz go from 10% at $M \sim 10^{10.5}$ M_{sun}/yr to 100% at $M \sim 10^{11}$ M_{sun}/yr

→ Radio AGN contamination could mimic a mass dependence
(see also Molnar+18 for similar dependence based on galaxy morphology)

AGN contamination cannot be ruled out **BUT** mass dependence observed down to $M < 10^{10}$ M_{sun}/yr

If real:

could be explained by a mass-dependent cosmic ray escape fraction

- c.r. can escape the galaxy before their energy is radiated away at radio frequencies, especially in lower mass normal galaxies

- See Delvecchio et al. for a more extensive discussion of possible explanations

Future Perspectives

Additional fields:

- EDF-North (NEP): now ~72h (perhaps mosaic to get uniform noise on entire Euclid area)

Towards goal sensitivity (500h)

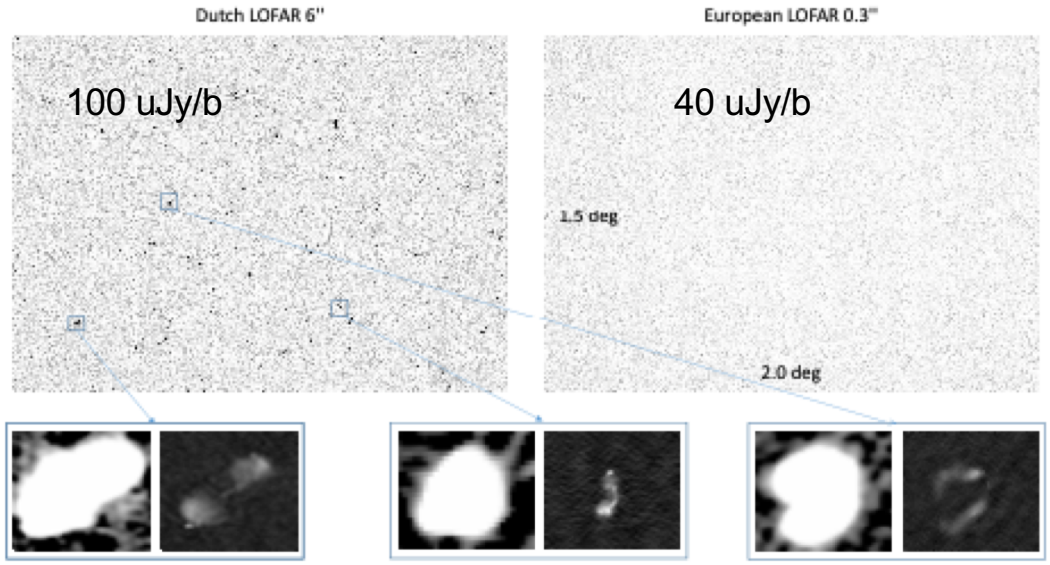
- More observations taken/allocated: will reach 500h on EN1 & 250h on LH by mid-2022
- Cycle 16/17: will likely focus on EDF

Include intl baselines:

- High priority on EDF, to match Euclid spatial resolution

Weave LOFAR on WHT:

- Spectrocopy for a million LOFAR sources (starting 2021?)



LH: Sweijen+

Synergies with APERTIF:

- APERTIF 1.4 GHz surveys started: commissioning field LH

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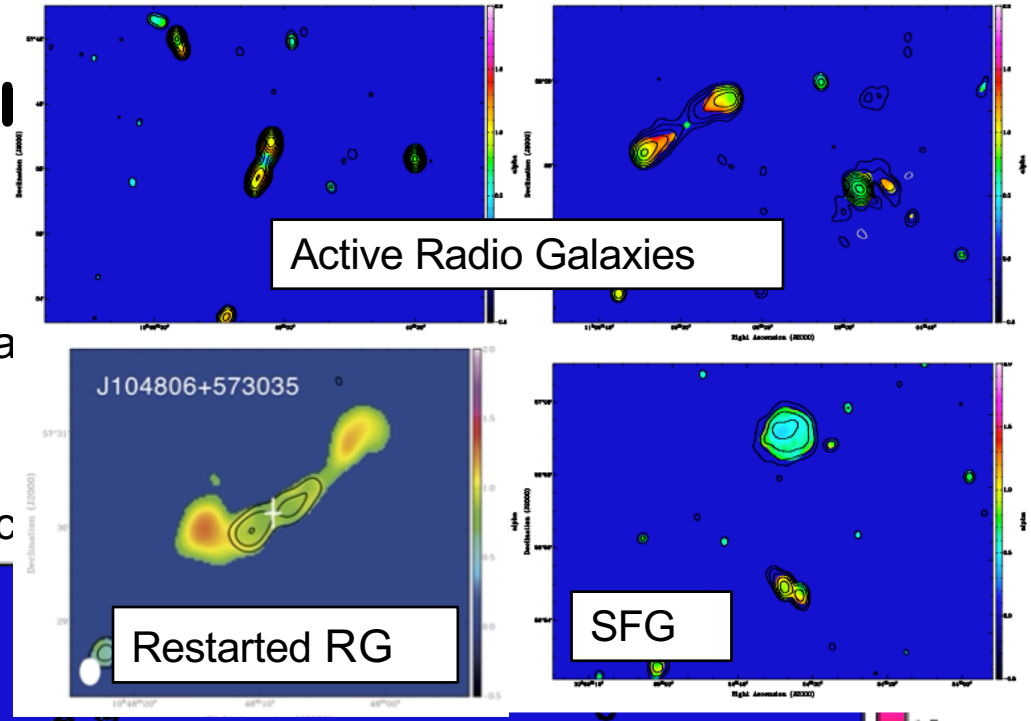

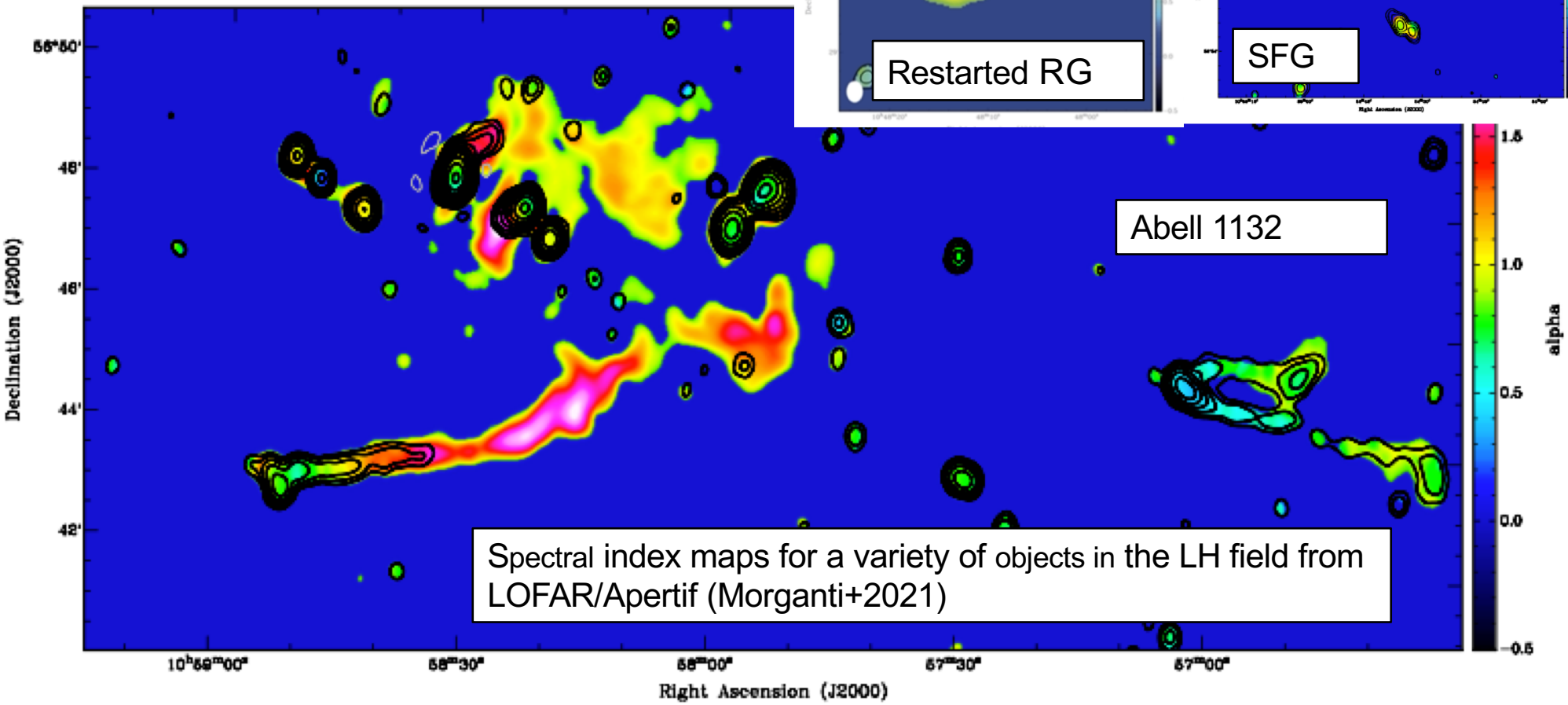

Spectral index maps for a variety of objects in the LH field from LOFAR/Apertif (Morganti+2021)