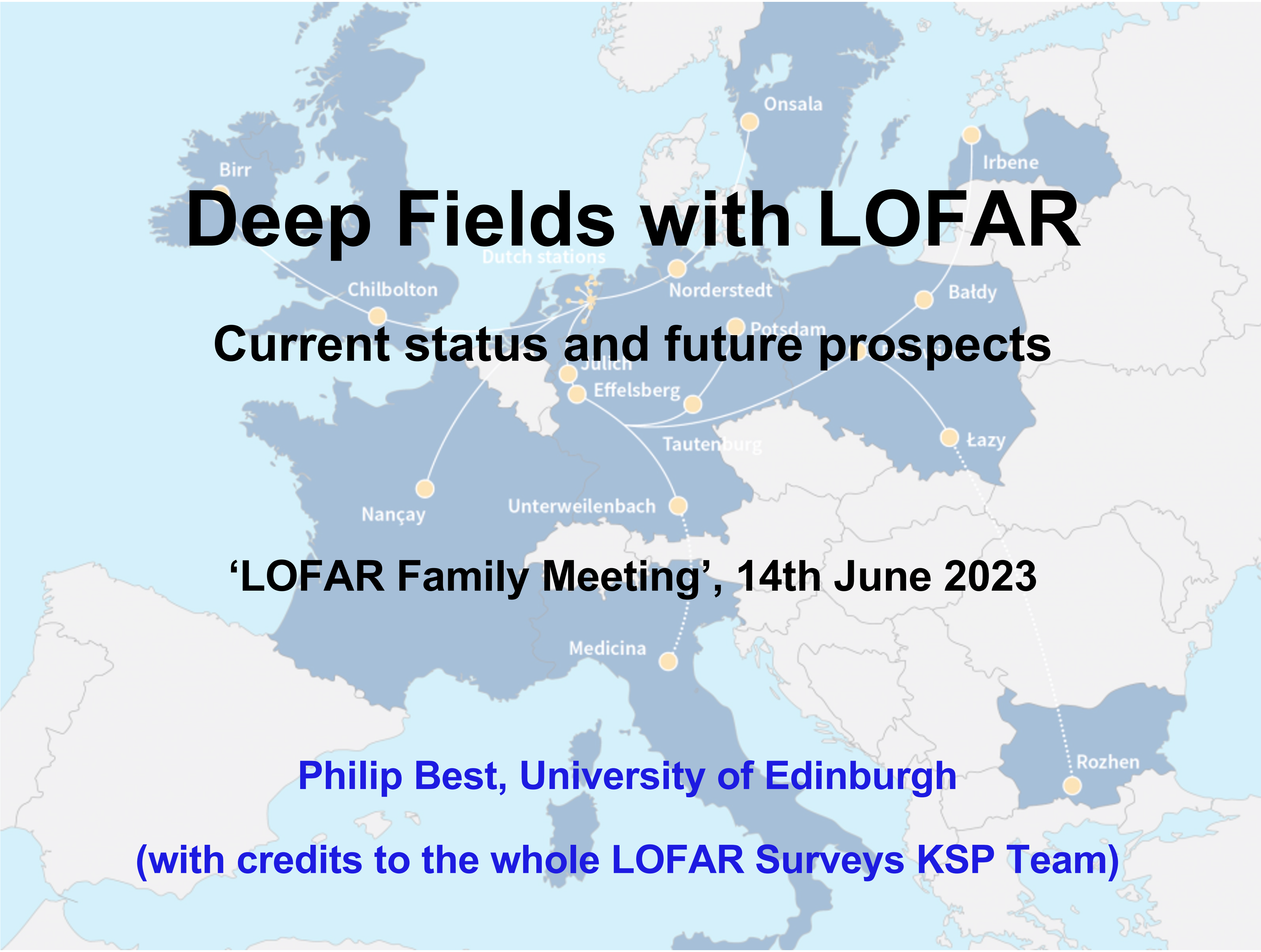
Deep Fields with LOFAR

Current status and future prospects

‘LOFAR Family Meeting’, 14th June 2023

Philip Best, University of Edinburgh

(with credits to the whole LOFAR Surveys KSP Team)



Overview of talk

- The LoTSS Deep Fields survey
  - Overview of survey, and comparison to LoTSS
  - Current survey progress & DR1 release
  - Exploiting the multi-wavelength data
  - Brief science highlights

- Towards LoTSS-Deep DR2 & beyond
  - A 500-hr 150-MHz image of ELAIS-N1
  - Exploiting the international baselines
  - WEAVE-LOFAR

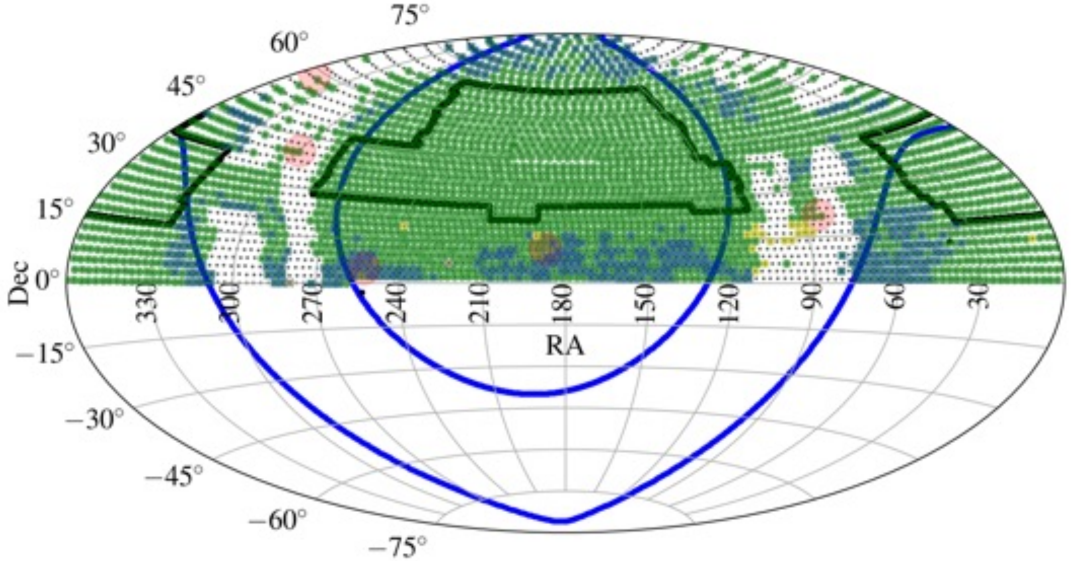
- Deep fields in the LOFAR2.0 era
  - The LOFAR Ultra-Deep Observation: LUDO

LoTSS Surveys: Multi-tiered approach

LOFAR Two-metre Sky Survey, LoTSS (-wide): (see Huub's talk)

- Data Release 1: 424 deg^2, 325k sources (Shimwell et al. 2019)
- Data Release 2: 5600 deg^2, 4.4 million sources (Shimwell et al. 2022)
- all northern sky at 150 MHz, to S_{150MHz} < 100μJy/bm rms
  - finding rare objects (e.g. z>7 RGs, cluster halos, strong lenses)
  - physics of AGN, and SFGs at z<1, using large samples
  - cosmology (e.g. clustering, Integrated Sachs-Wolfe effect)
  - detailed studies of nearby galaxies & nearby AGN
  - and much more!

Right: status of LoTSS survey after end of Cycle 20.



LoTSS Deep Fields

LoTSS-Deep complements LoTSS

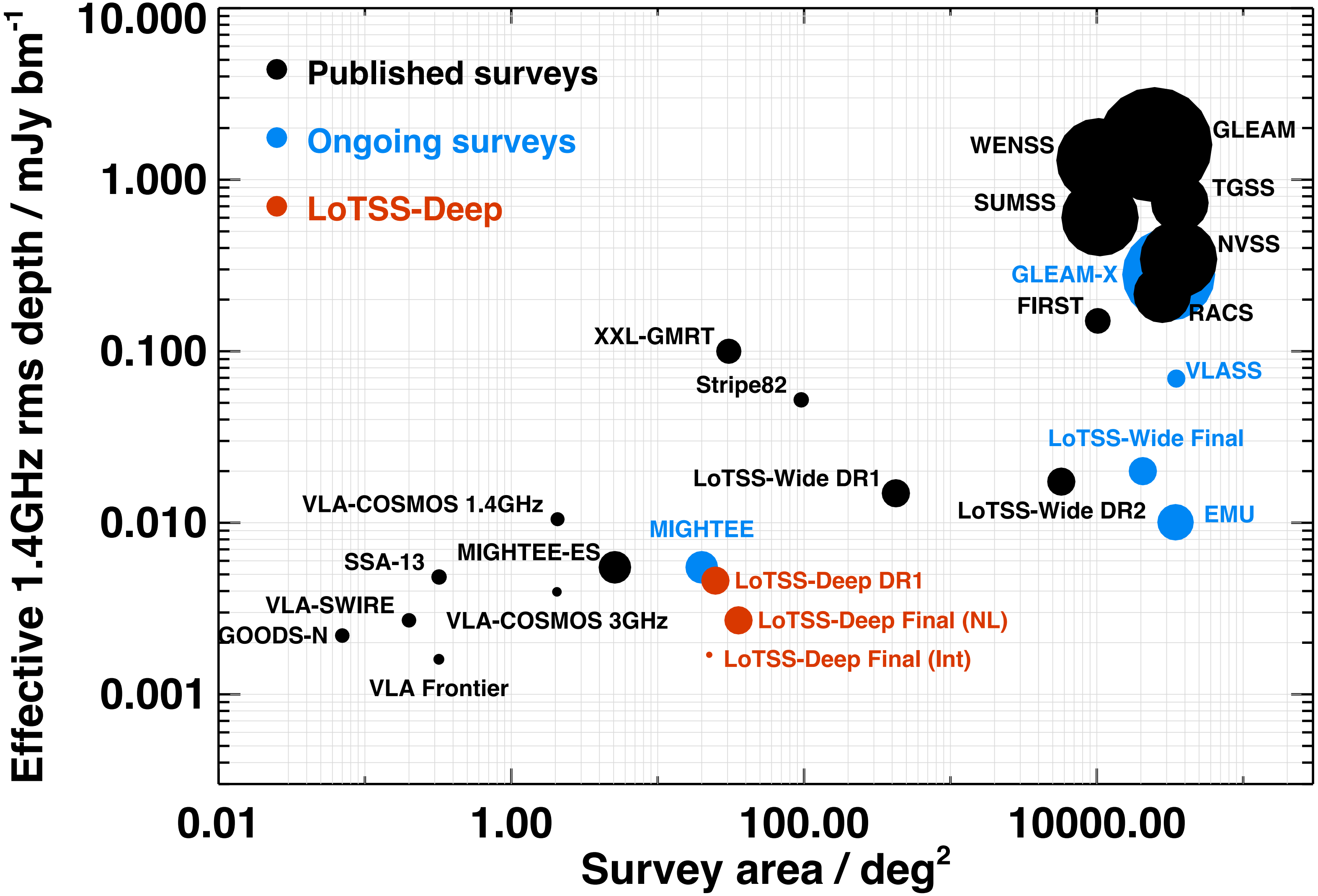
- factor >5x deeper imaging over smaller (but still large) sky area
  - 350–500 hrs integration per pointing (recently completed!)
- 35 square degrees, to 10-15 μJy/bm rms at 150 MHz
  - sufficient sky area to sample all environments at high-z
  - detect Milky Way to z~1; starbursts/AGN across most of Universe
- Targets northern fields with best degree-scale multi-λ data
  - Elais-N1, Lockman Hole, Boötes, North Ecliptic Pole

First data release (DR1-Deep) published in April 2021

(Tasse+ 2021, Sabater+ 2021, Kondapally+ 2021, Duncan+ 2021)

- more than 80k sources over 26 deg^2 of best multi-wavelength data
- reaches 5,000 sources per deg^2 in centre of deepest field
  - new full-depth images reach nearly 10,000 / deg^2

LoTSS-Deep compared with other surveys

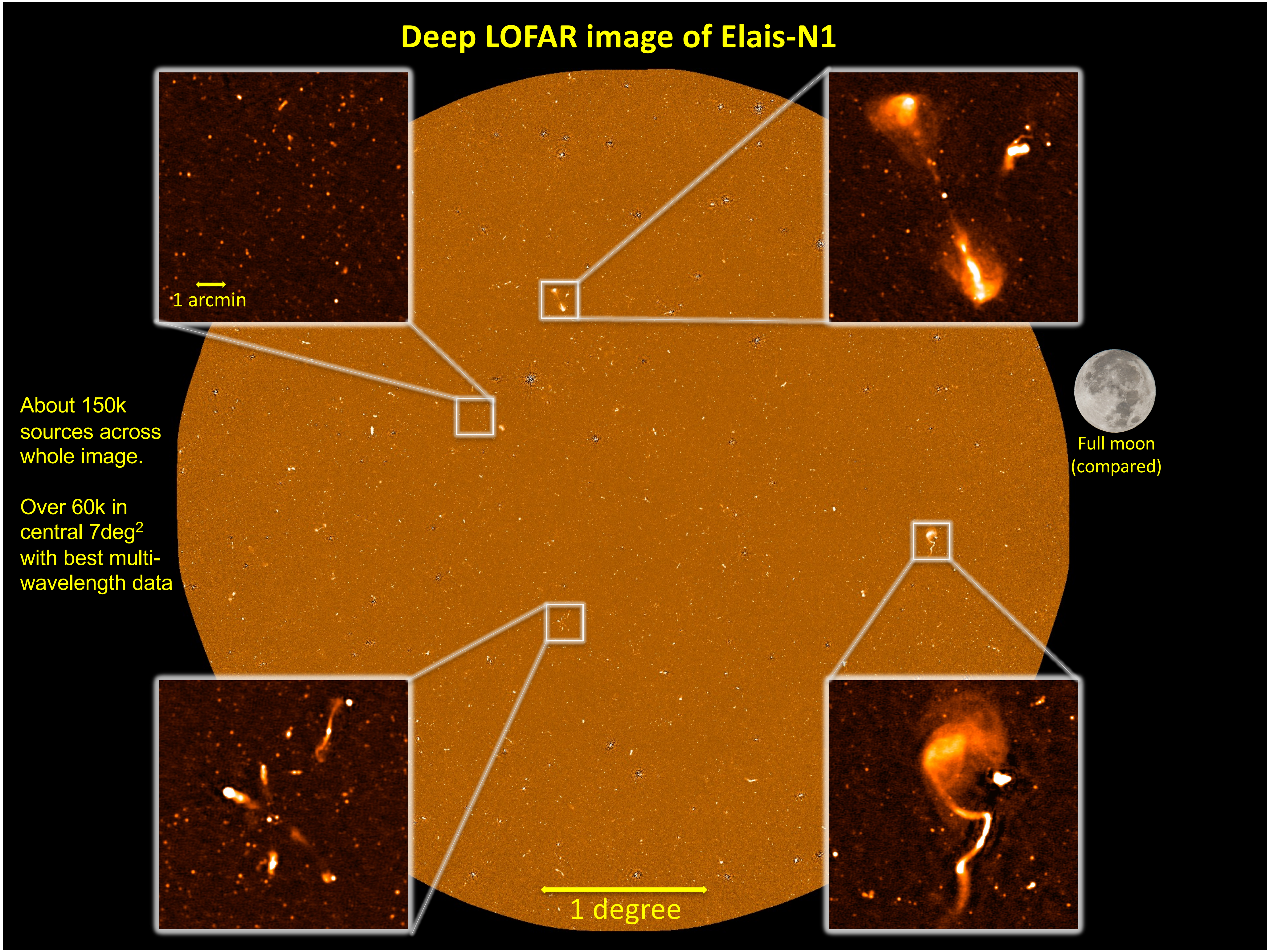


(symbol size is proportional to survey angular resolution)

LoTSS-Deep Fields Status

Field	Ancillary data area (deg^2)	DR1 Int. time	DR1 rms (μJy/bm)	Total time	Status	Final depth (μJy/bm)
Boötes	6.74	80 hrs	~31	300 hrs	All data taken	~16
ELAIS-N1	8.63	164 hrs	~19	500 hrs	Final image	12
Lockman Hole	10.28	112 hrs	~23	350 hrs	All data taken	~13
NEP	10.0	-	-	400 hrs	All data taken	~13

- ELAIS-N1 completed, and final image produced
- Lockman, Boötes & NEP data taken – processing in progress



Deep LOFAR image of Elais-N1
1 arcmin
About 150k sources across whole image.
Over 60k in central 7deg^2 with best multi-wavelength data
Full moon (compared)
1 degree

Multi-wavelength imaging data

Radio continuum data alone provides limited science

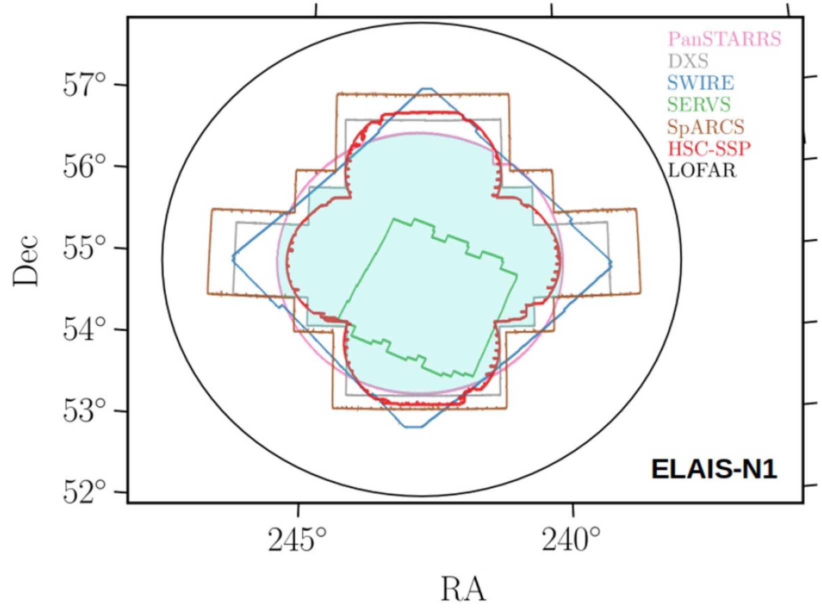
Critically dependent on multi-wavelength imaging data to provide:

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

LoTSS-Deep fields have deep multi-λ 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)

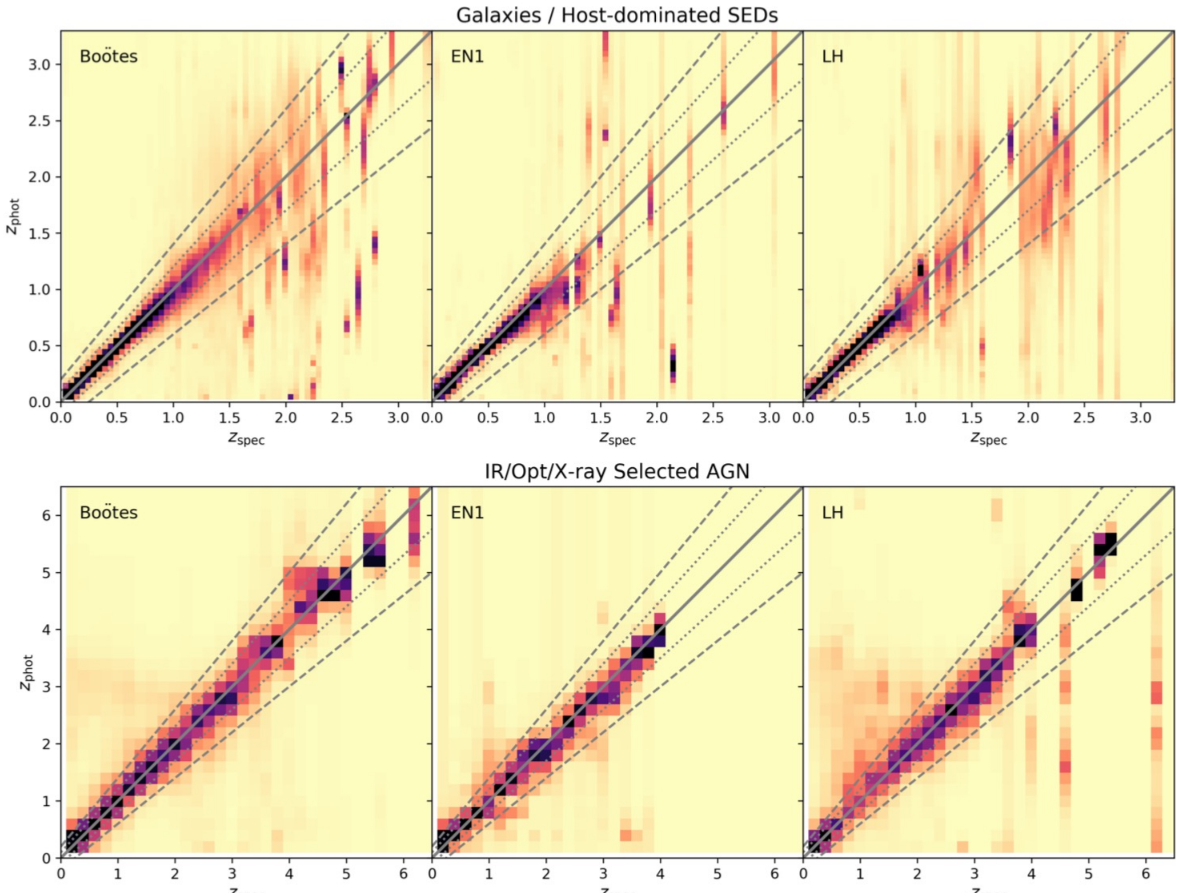
Host galaxy IDs and properties for over 97% of LoTSS-Deep DR1 (Kondapally et al. 2021)

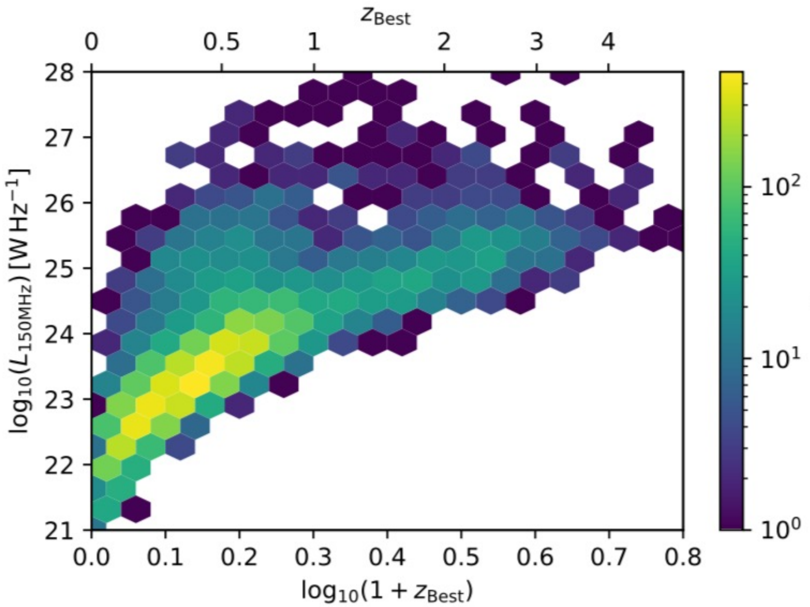


Photometric redshifts

(Duncan et al., 2021)

- 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>4 for AGN





Source classification

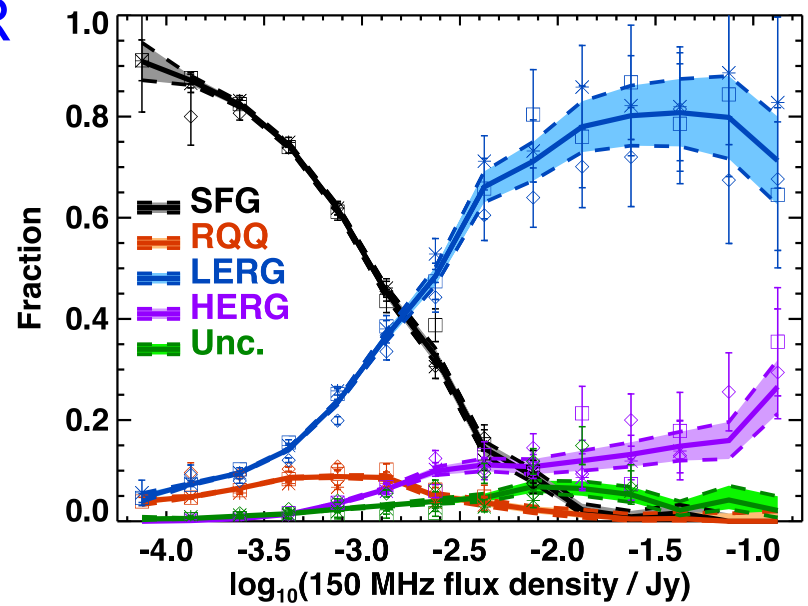
(Best et al. 2023; arXiv:2305:05782)

Source classification and extraction of host galaxy properties

- search for evidence of radiative (quasar-like) AGN (type I or II) using combination of four spectral-energy distribution fitting packages
  - MagPHYS, CIGALE, BAGPIPES and AGNfitter
- derive consensus classifications, masses, SFRs etc.
- identify ‘radio-excess’ AGN with higher radio luminosity than expected from their SFR

Overall in LoTSS-Deep DR1:

- 55,680 SFGs
- 7,442 Radio-quiet AGN
- 1,744 Quasar-like radio-AGN
- 12,749 Jet-mode radio AGN
- 4,336 Unclassified sources



ELAIS-N1 source finding for DR2

credit: Catherine Hale and Rohit Kondapally

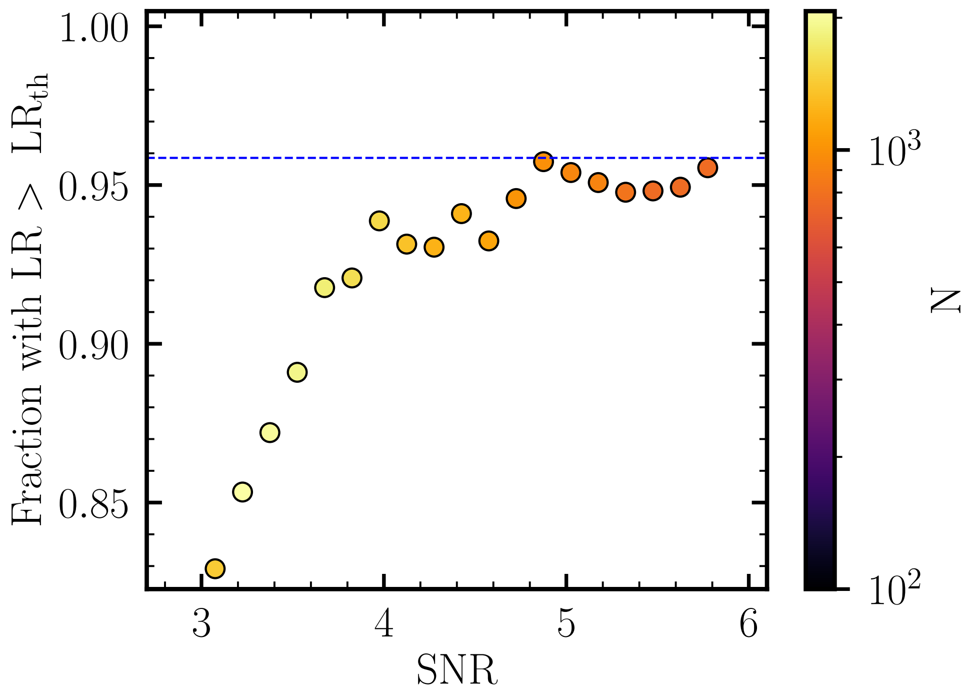
Source confusion leads to PyBDSF over-estimating local noise

- hence many sources fail to reach required S/N threshold
- to overcome, two-stage process developed
  - detect sources and remove them (except bright ones…)
  - calculate rms on residual image and use this in PyBDSF detection

~100% host galaxy detection rate in Deep Fields allows to explore detection threshold selection

- quantify reality of extra sources
  - can go down to S/N=4 with high robustness

Final ELAIS-N1 DR2 sample: 62k sources! (double the 31k in DR1)

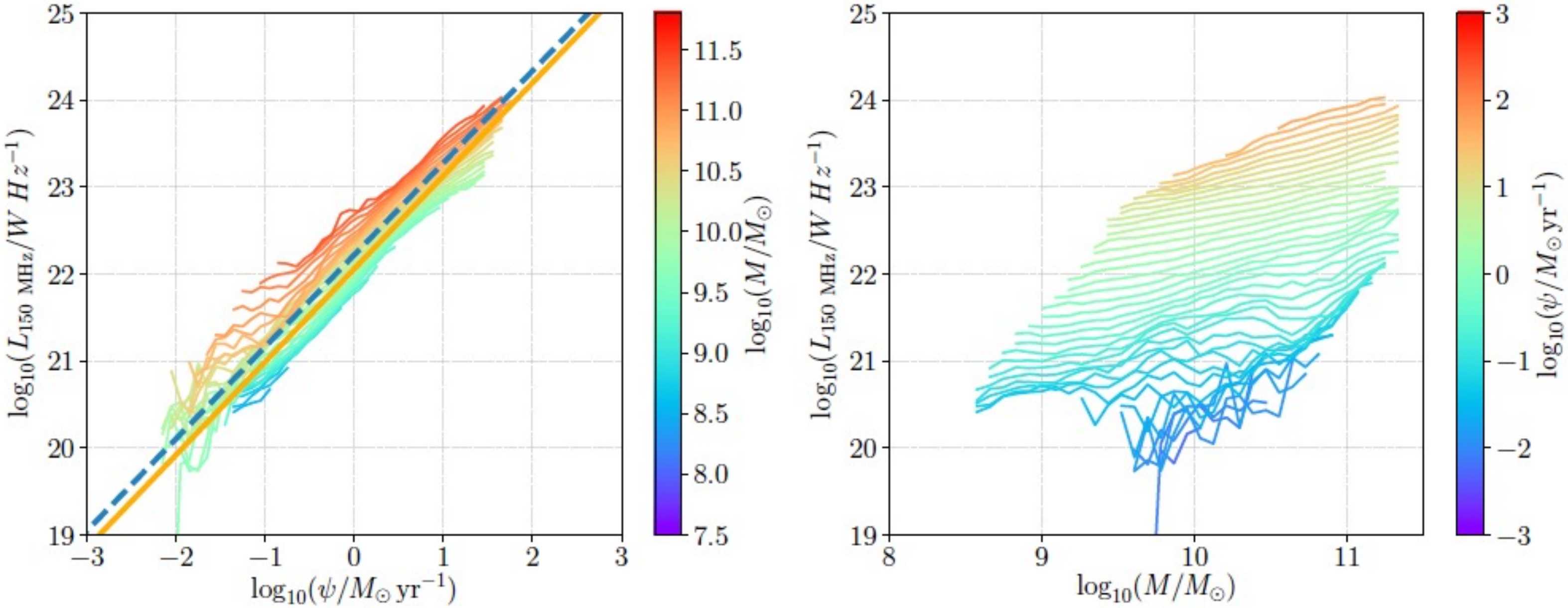


Science highlights using LoTSS-Deep
1. The radio-SFR relation

(Smith et al. 2021)

Radio luminosity vs SFR relation investigated

- Uses ~118k mass-selected galaxies at z<1 from multi-λ catalogue
- Create probability distribution function in L_{radio} vs SFR plane
- Linear, non-evolving relation discovered
- Also strong evidence for a stellar mass dependency

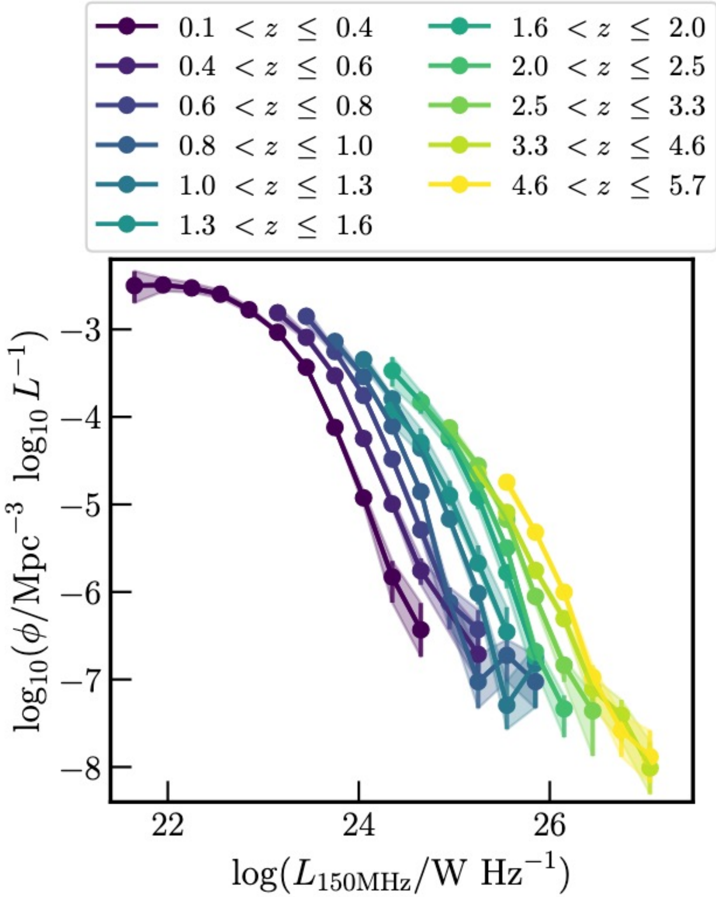


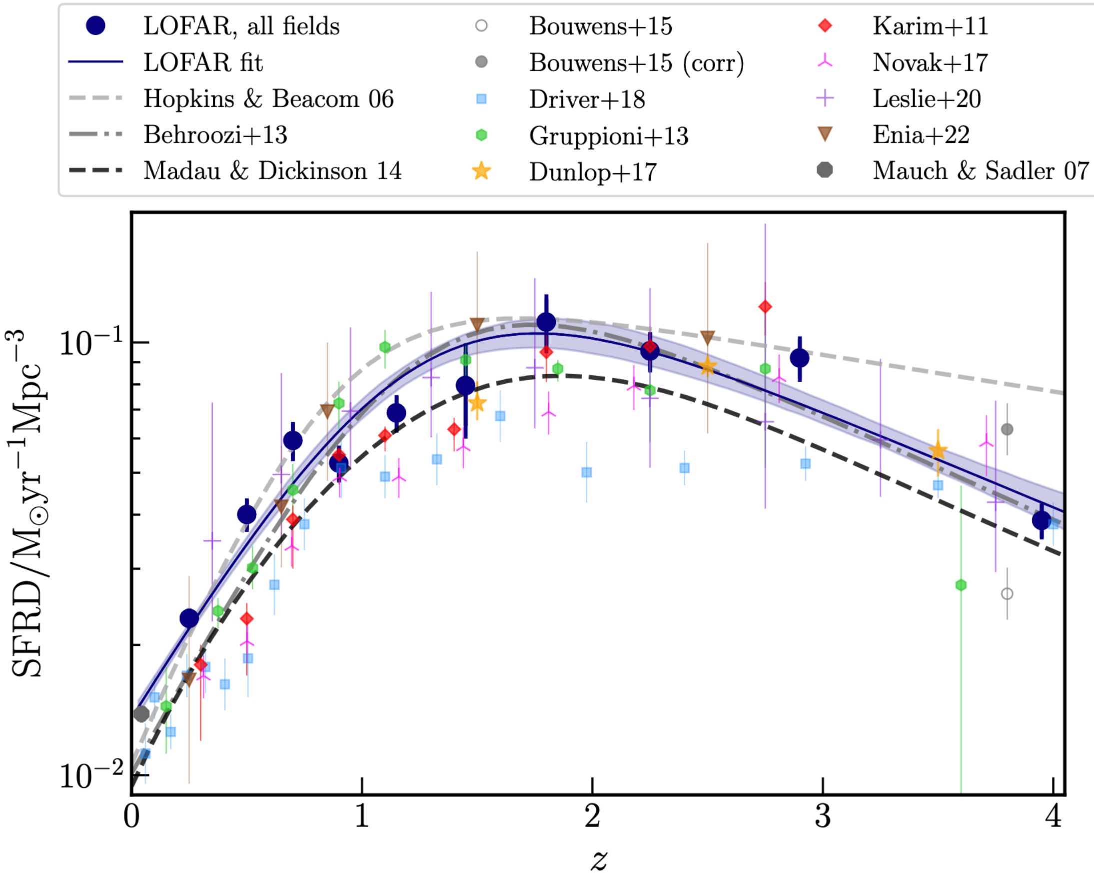
Science highlights using LoTSS-Deep
2. Cosmic SFR density

(Bonato et al. 2021, Cochrane et al 2023)

Dust-independent tracer of cosmic star-formation

- Measure evolution of SF luminosity func. and cosmic SFR density



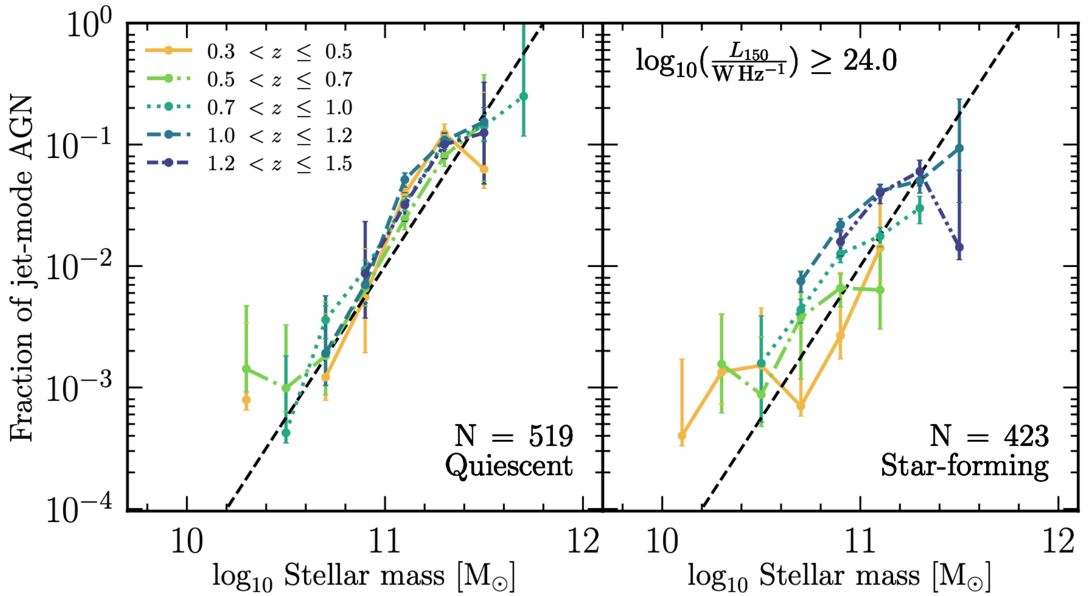


Science highlights using LoTSS-Deep
3. Jet-mode AGN evolution

(Kondapally et al., 2022)

Measure evolution of jet-mode AGN (LERG) population to high-z

- For the first time, split into star-forming & quiescent hosts
- Compare against underlying populations from multi-λ dataset
- Quiescent LERGs show same mass fraction out to at least z~1.5
  - Same fuelling & jet-mode feedback process across cosmic time
- Star-forming LERGs much more common at high-z (more gas)



WEAVE-LOFAR

WEAVE is a multi-object spectrograph currently being commissioned at WHT

- nearly 1000 fibres, 2 deg^2 field-of-view
- 3700-9600Å at spectral resolution R=5000

The WEAVE-LOFAR survey (PI: Dan Smith) will take a million spectra of LOFAR sources

- 5-yr period, 2023-2028

A million spectra gives strong statistical power:

- study the population in detail as a function of parameters & processes of interest
  - mass, SFR, redshift, environment, AGN activity, accretion mode, etc

Why spectroscopy?

Spectroscopic redshifts

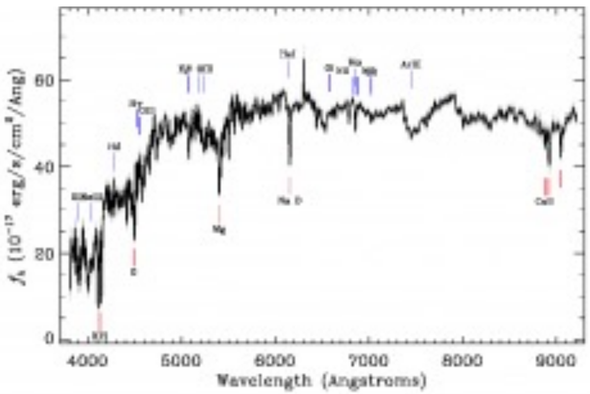
- WEAVE simulations suggest ~100% redshift completeness at z<1
- Into regimes where photometric redshifts are less reliable
- Improved training sets for remaining photo-z's
- Data alignment for stacking, e.g. ORCHIDSS (Ken Duncan's talk)

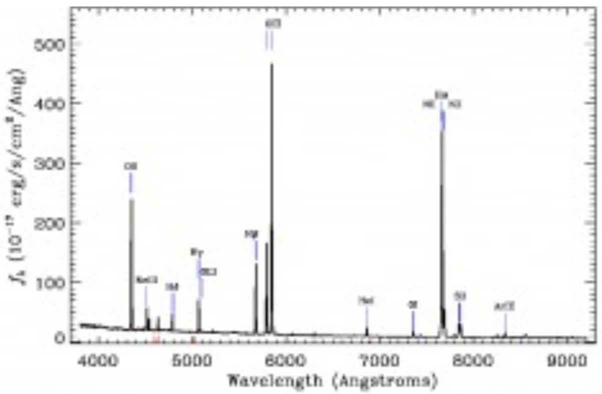
Emission line diagnostics

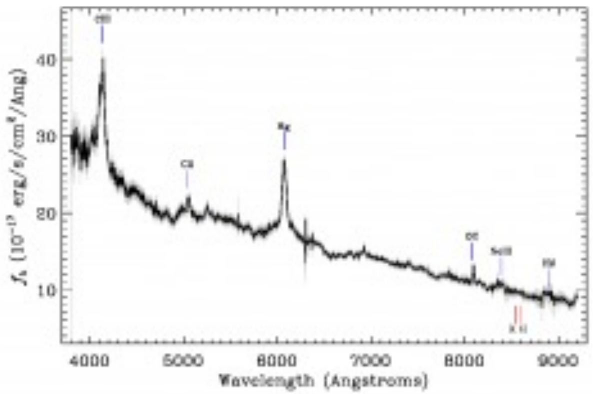
- improved source classification
- emission line luminosities, widths, metallicity, etc

Continuum diagnostics

- e.g. 4000Å break strength; improved SED fitting constraints



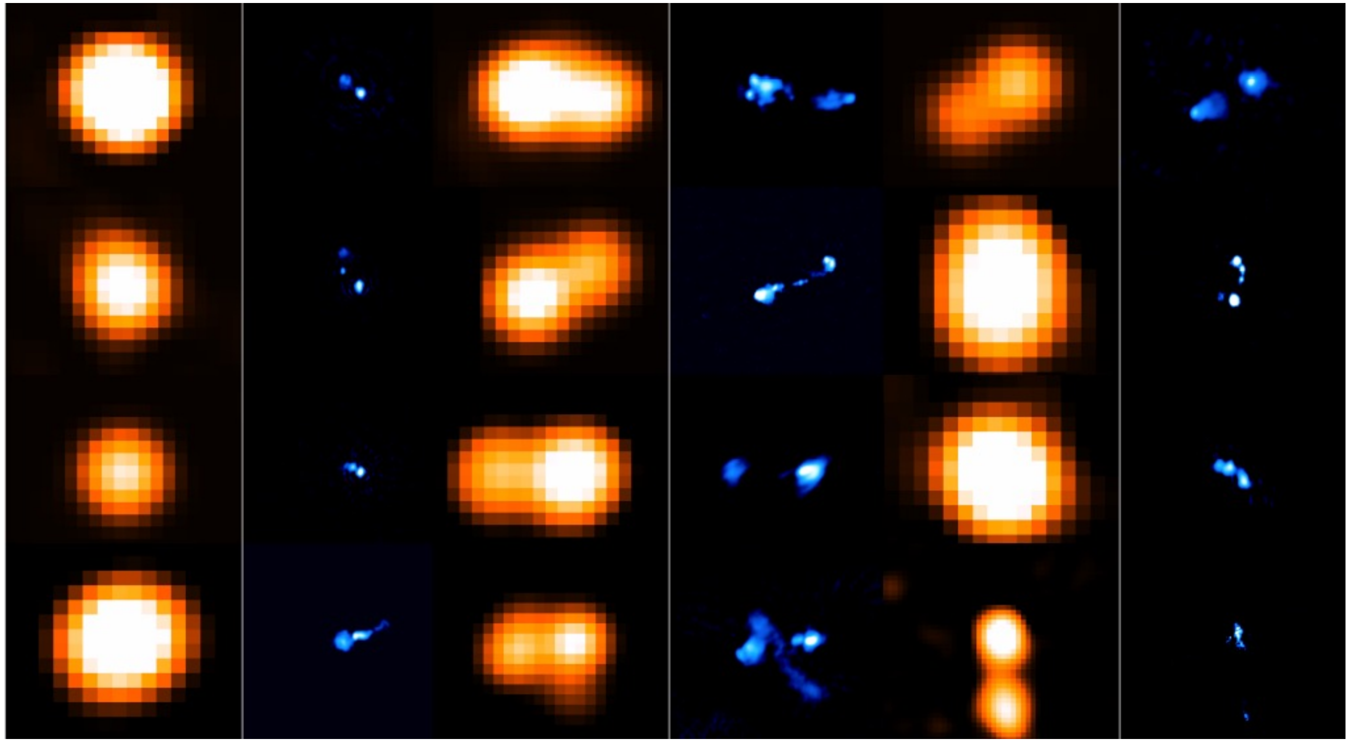




Long-baseline imaging

LoTSS-Deep DR1 images don't include the international stations

- due to additional calibration and computational challenges
- these improve angular resolution to 0.3 arcsec
- also improve point source sensitivity due to extra collecting area



Orange: LoTSS-Deep images at 6" resolution

Blue: Equivalent at 0.3" resolution

For NEP field

(Bondi et al. 2023, in prep)

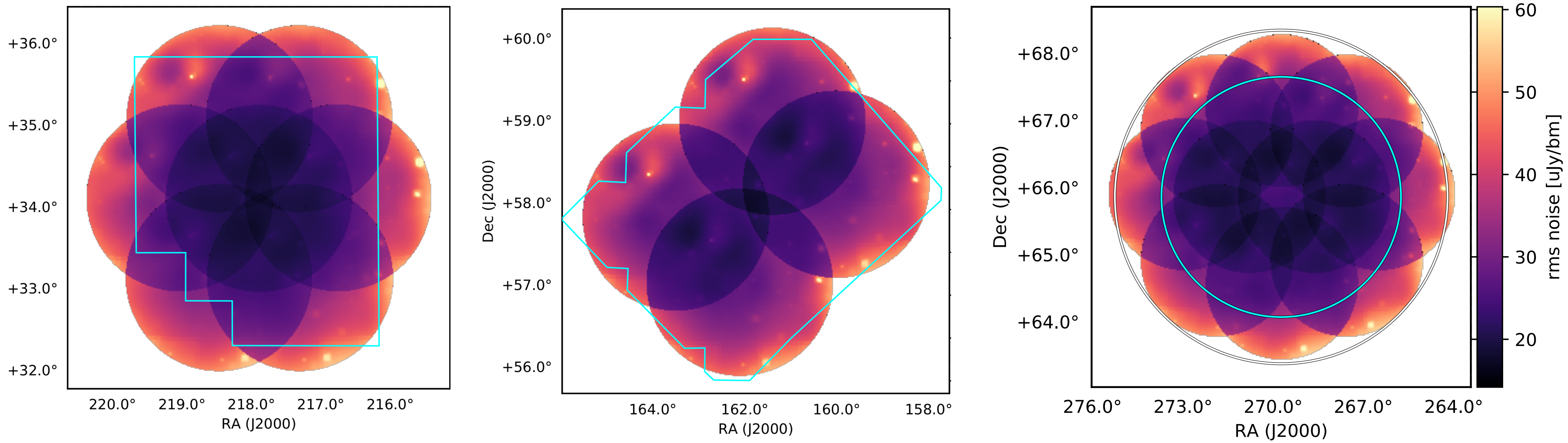
Synergies at high angular resolution

LoTSS-Deep DR1 images don't include the international stations

- due to additional calibration and computational challenges
- but we do have the data, for later re-processing at 0.3” resolution
  - currently ongoing in all fields, including multiple pointings

Bootes, Lockman, NEP have all been observed with tiled pointings

- enable full coverage of multi-wavelength area at full resolution
- retain (nearly) full depth over whole field at NL-resolution



LUDO: LOFAR Ultra-Deep Observation

Expression of Interest for LOFAR2.0 Surveys

- PIs: Best & Morabito

Single ultra-deep LOFAR pointing in North Ecliptic Pole field

- This is EUCLID's Deep Field North
  - EUCLID will provide matched 0.3-arcsec resolution data on ~5 million galaxies over 10 deg^2
- Lots of ground-based follow-up surveys of this key field

LoTSS detects ~1k sources / deg^2, so about 0.2% of EUCLID gals

LoTSS-Deep (nearly 10k/deg^2) detects only ~2%

- LUDO will push this to ~10%

LUDO Science Goals

Star-forming galaxies:

- Detect SF activity across all cosmic time, unbiased by dust
  - Determine the SF-environment connection out to high-z
- Characterise distribution of SF *within* galaxies to beyond z~2
  - e.g. compare stellar mass (near-IR) vs star-formation (radio) distributions within galaxies to trace galaxy growth scenario

AGN:

- Resolve and classify radio-AGN activity to z~6
  - radiatively efficient vs radiatively inefficient AGN
- Accurately trace black hole accretion rate history

Other science

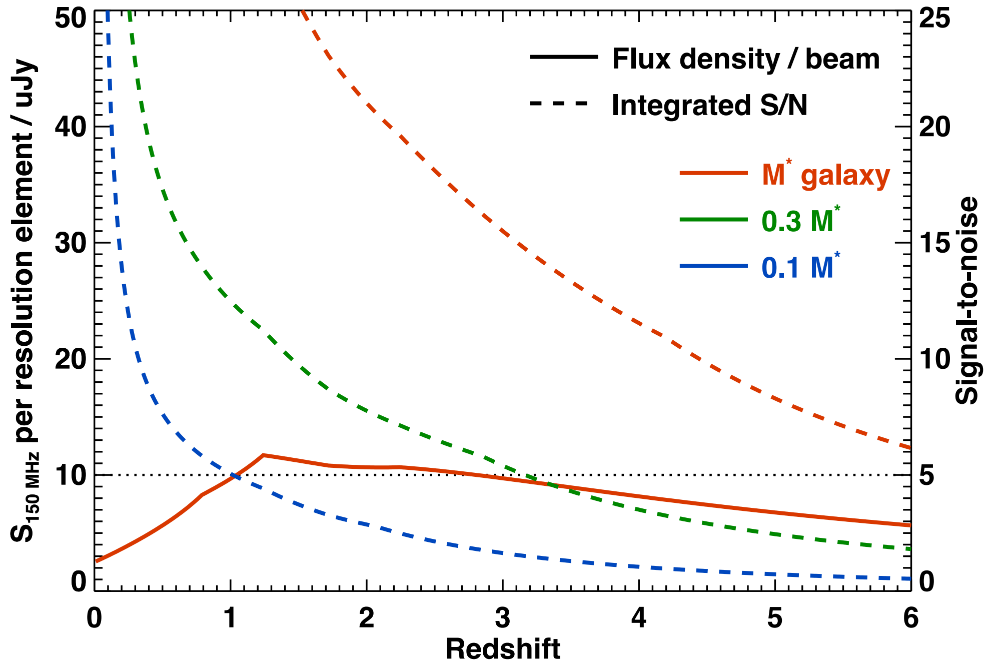
- Huge range of other possibilities opened up by dataset
  - e.g. 400 repeated observations of same sky for transient studies

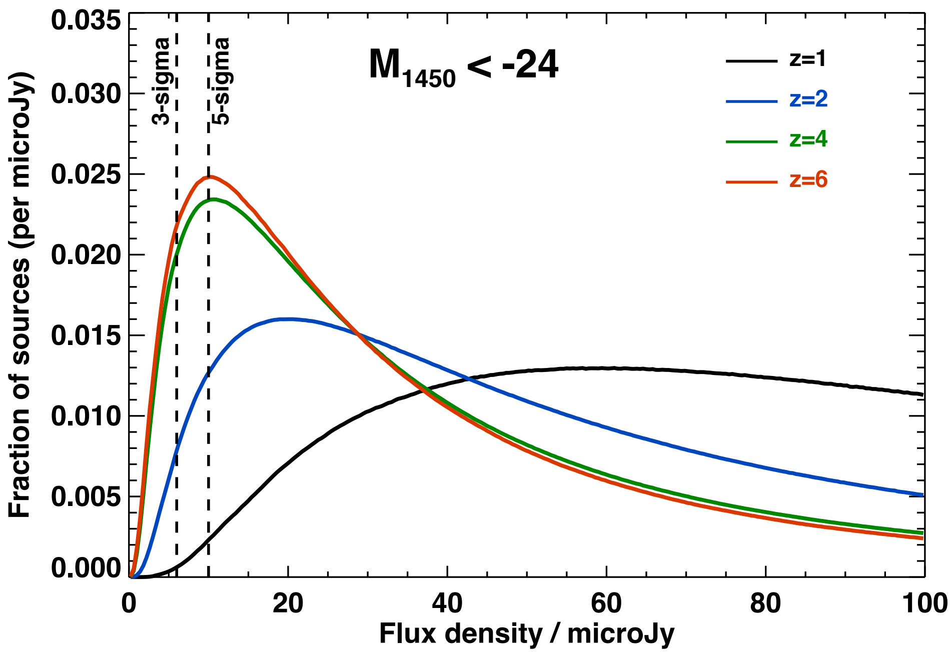
LUDO: target depth

Target depth of LUDO arises from desire to spatially resolve star-forming galaxies

- 2μJy/bm is critical depth to resolve ‘typical’ M^* galaxies from $1<z<3$

This depth is also sufficient to detect the vast majority of all luminous AGN (even radio-quiet ones) out to $z>6$





LUDO: observational requirements

To reach the target 2μJy/bm depth requires 3,200 hrs!

- Assumes international stations, and HBA Dual mode
- Covers 4.8 deg^2 at 0.3” resolution
- Assumes 48 MHz bandwidth: just 25% of LOFAR2.0 bandwidth
  - run in parallel with other projects (iLoTSS, A2255, LBA imaging) effective time is then only 800hrs of full system

- Reference SKA-Mid surveys plan:
  - ‘Mid’ tier, 10 deg^2 to 0.2μJy/bm @ 1.4GHz
  - Equivalent to 10 deg^2 to ~1.5uJy/bm at 150MHz for α=0.7

=> LOFAR / LUDO can deliver SKA science in the pre-SKA era

Conclusions & outlook

- Deep radio continuum surveys offer a powerful probe of key galaxy populations: star-forming galaxies and AGN

- LoTSS Deep Fields are opening a vast science potential
  - the coordinated multi-wavelength surveys are key to this
  - will be further enhanced by WEAVE-LOFAR
  - excellent results already for NL baselines; international baselines making good progress, but much still to be done

- Huge prospects to expand this further in the LOFAR2.0 era:
  - exploit LOFAR – EUCLID synergies
  - can deliver ‘SKA science’ already in the pre-SKA era