Radio-optical synergies: Extracting multi-wavelength science

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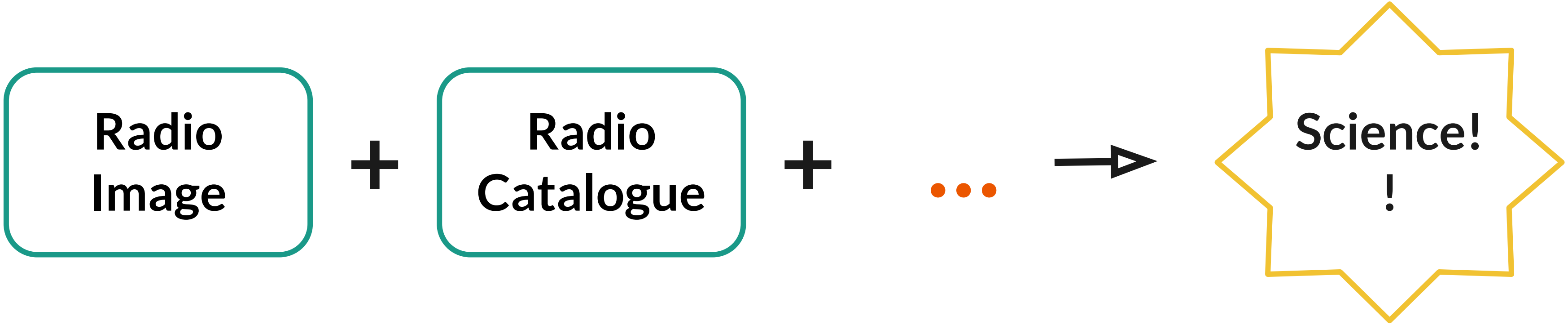
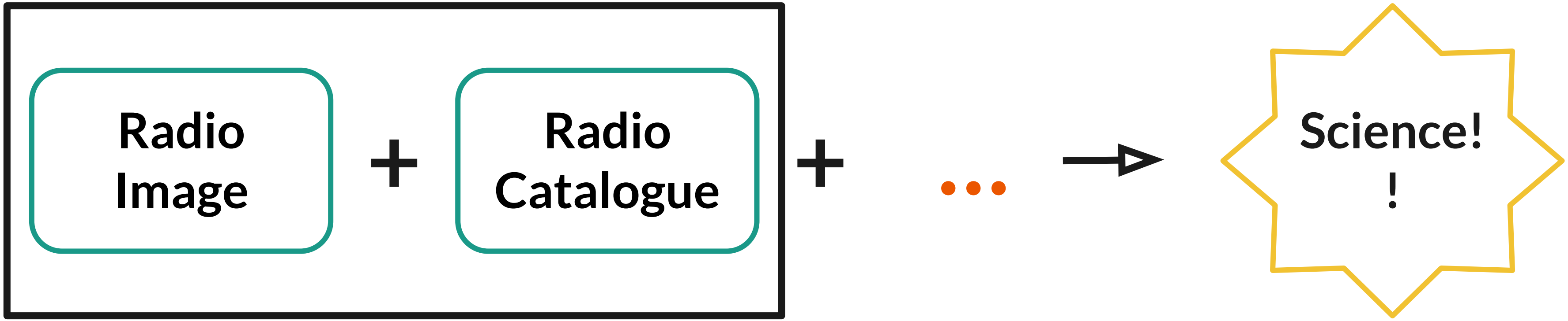
Motivation

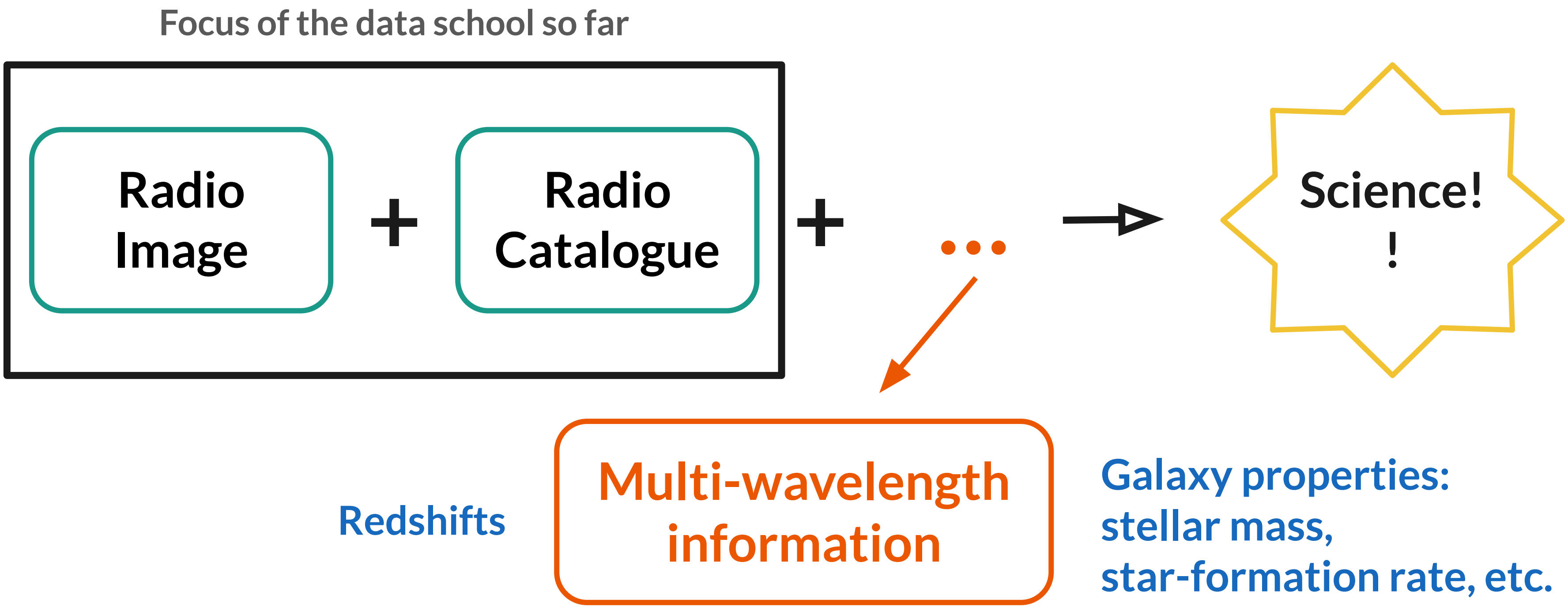


Motivation

Focus of the data school so far



Motivation


Focus of the data school so far
Radio Image
+
Radio Catalogue
+
...
Science!!
Redshifts
Multi-wavelength information
Galaxy properties: stellar mass, star-formation rate, etc.

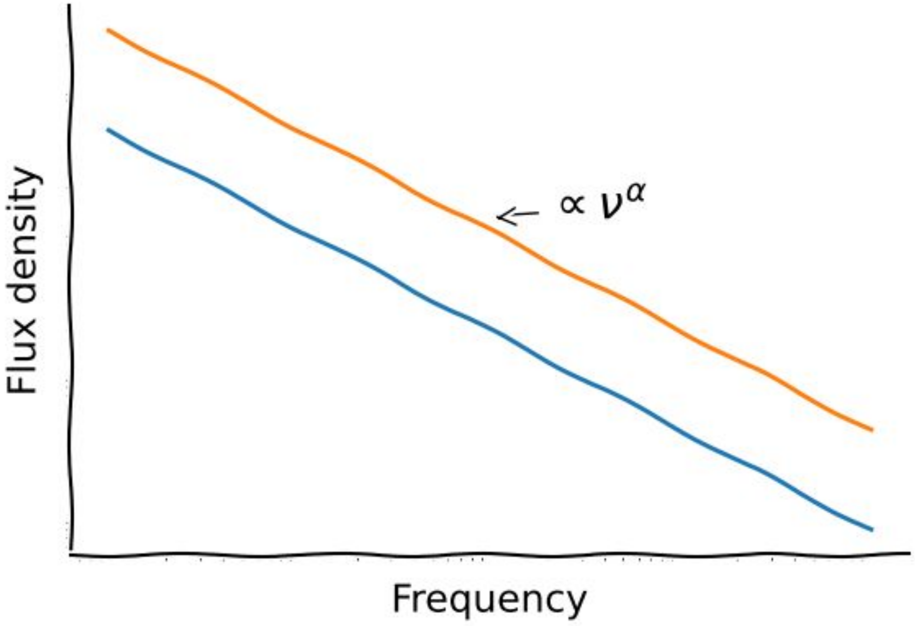
Motivation

Radio spectrum is ~ a power law

Redshift completely unconstrained

Radio data alone offers limited scientific value

Need multi-wavelength information to maximise the scientific potential



Motivation and Overview

Radio alone offers limited scientific use -> need to extract multi-wavelength properties

- Host-galaxy (or multi-wavelength counterpart) identification
- (Photometric) redshift estimation
- A demonstration/example use case on a LOFAR dataset

* Colloquially: “opical” = wavelengths other than radio

* Caveat: A focus on galactic/extragalactic science, but applicable to other cases

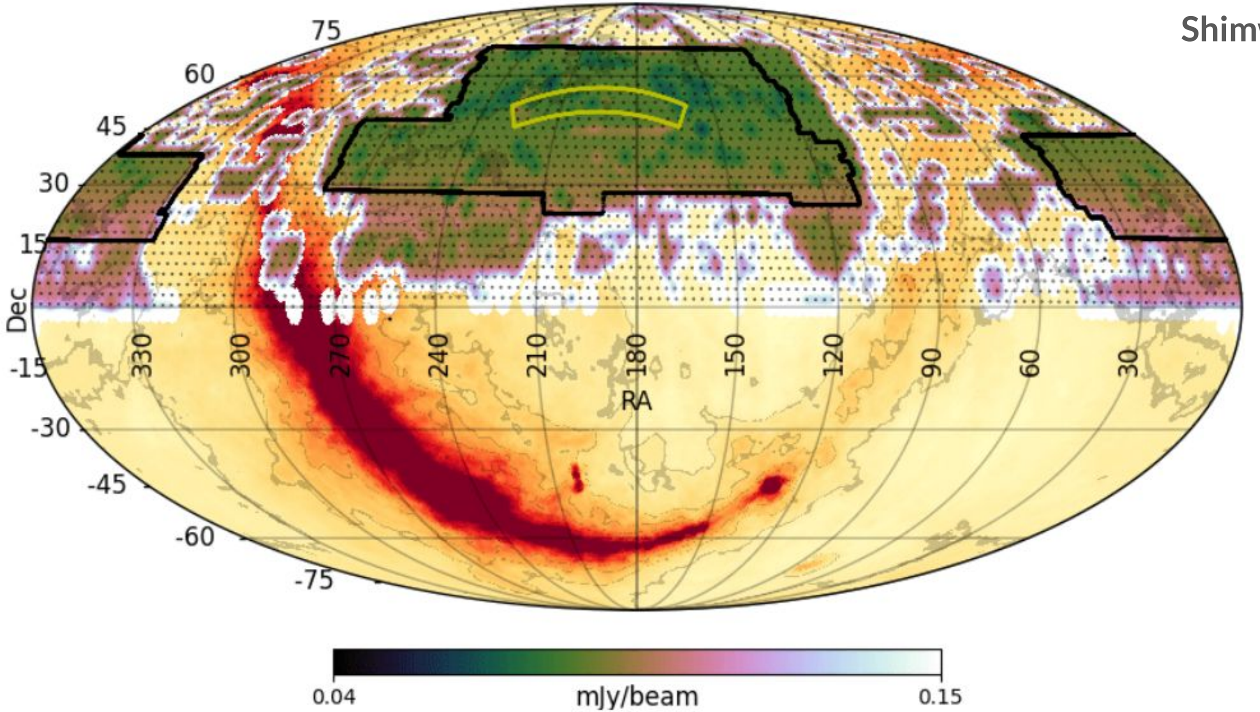
Radio-optical cross-match

The LOFAR surveys

LOFAR Two-meter Sky Survey (LoTSS) DR2

See Tim's talk!

Shimwell et al. 2022



Aims to survey all Northern sky at 150 MHz, ~100 uJy/beam

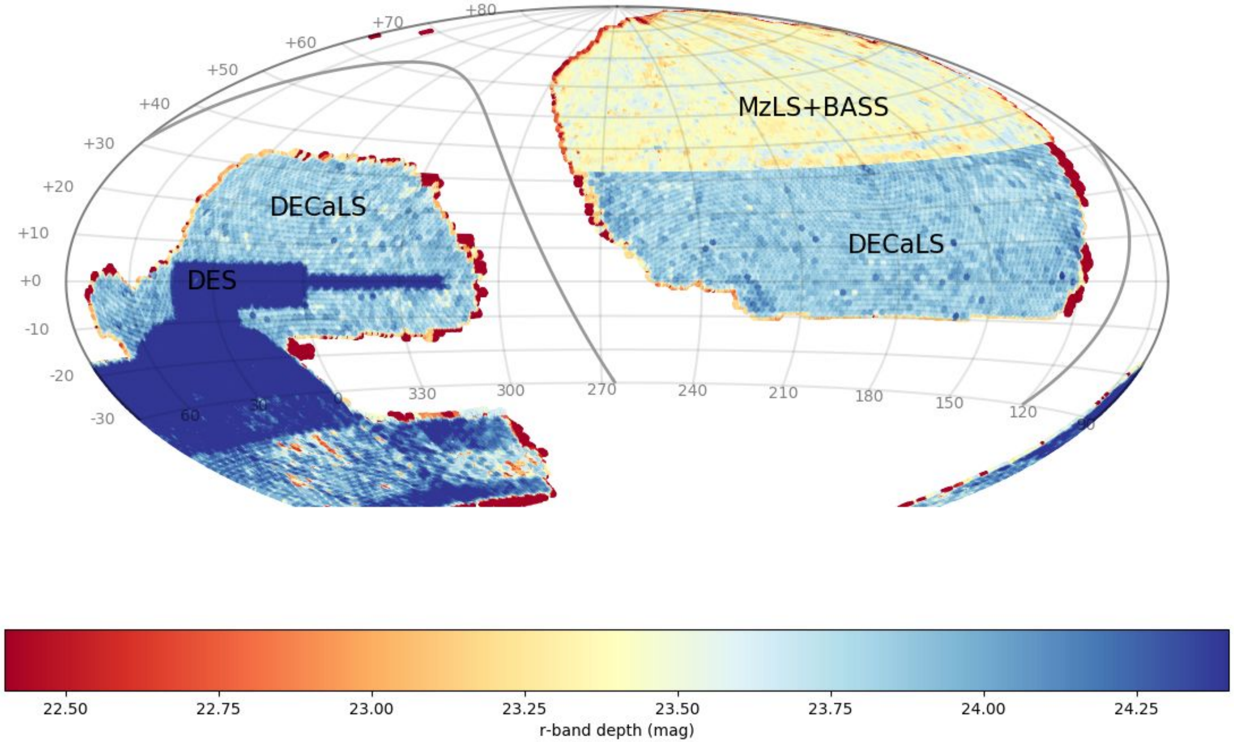
Data release 2: > 4 million radio sources! Covering > 5500 deg^2

LoTSS DR2 - Multi-wavelength datasets

DESI Legacy Imaging Surveys:

Optical g, r, z photometry

+unWISE IR deblended photometry



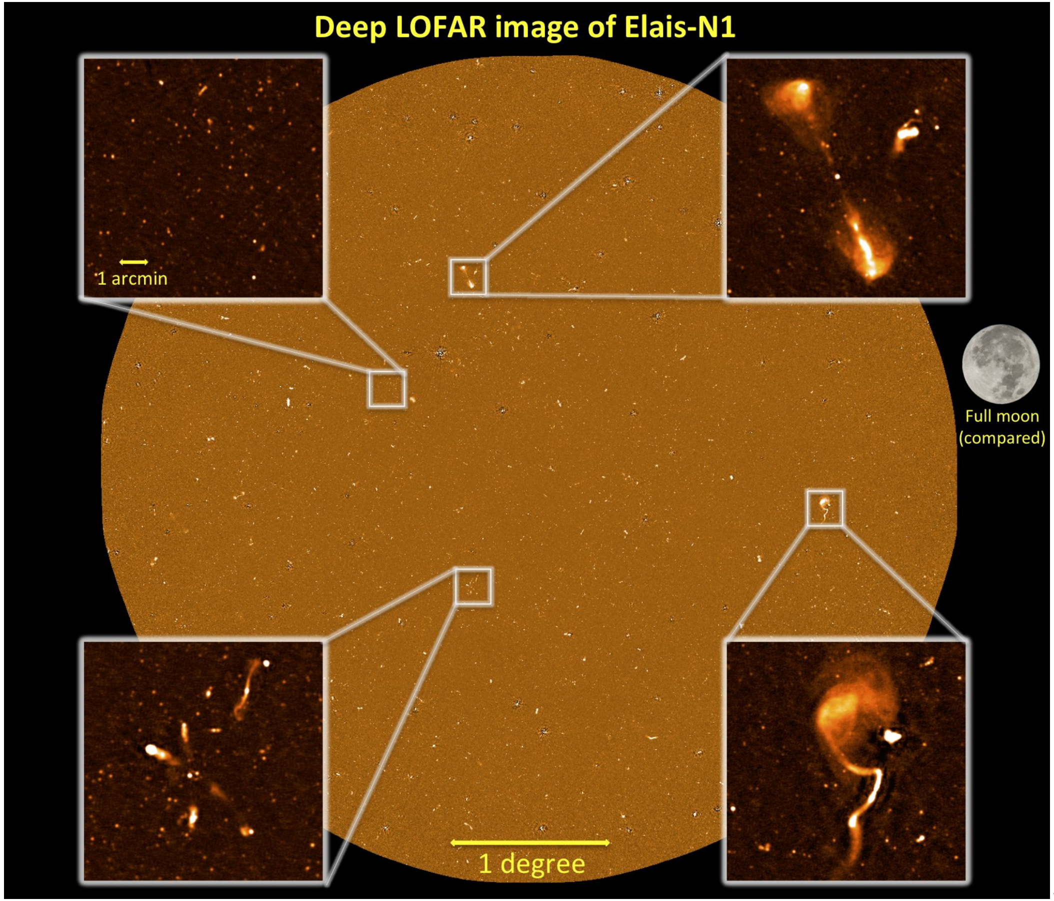
https://www.legacysurvey.org/

Hardcastle et al. 2023

LoTSS Deep Fields (DR1)

- **Deepest wide-field radio continuum survey** to date at low frequencies
- 100s hrs of radio imaging **over 25 sq. deg.**
- **3 fields: ELAIS-N1, Lockman Hole, Bootes**

Tasse et al. 2021; Sabater et al. 2021 Kondapally et al. 2021; Duncan et al. 2021; Best et al. 2023



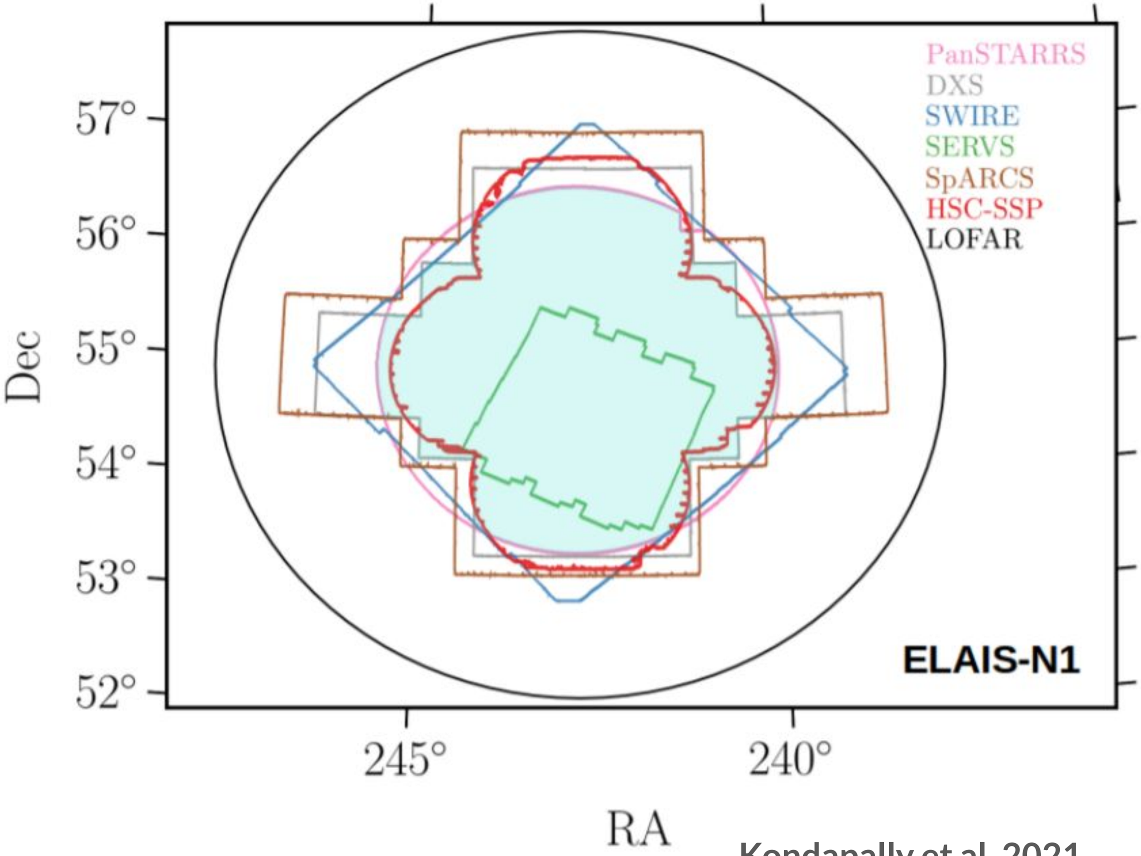
LoTSS Deep Fields

ELAIS-N1

Excellent deep, wide-area coverage from UV to far-IR (~2 million sources)

+ radio (~30,000 sources)

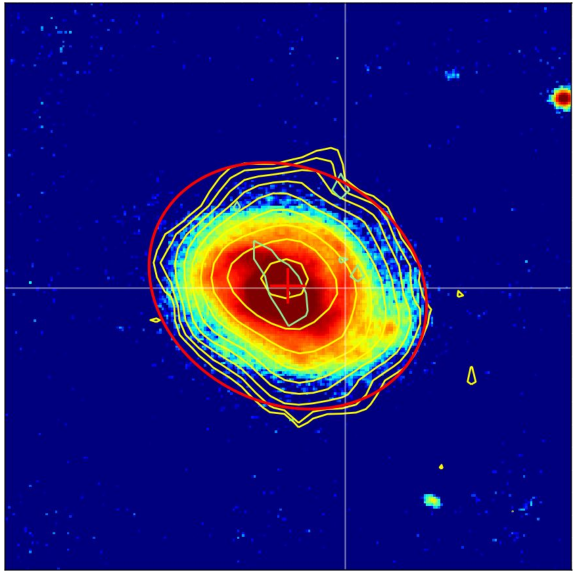
~ 7 deg^2 of overlap

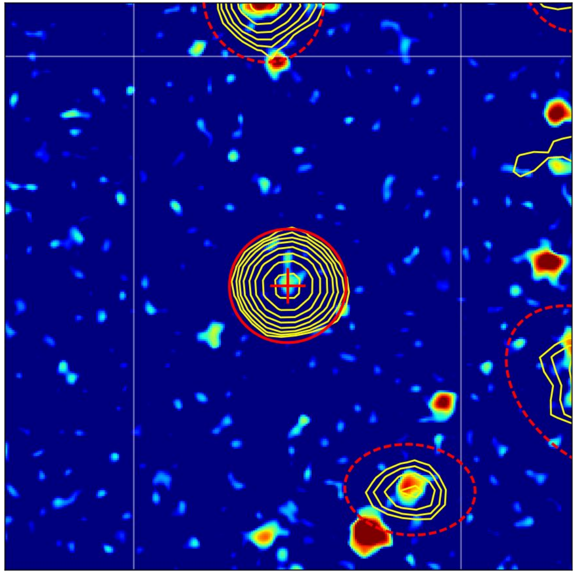


Kondapally et al. 2021

Cross-matching: a challenging endeavour

Fairly straight-forward ***if sources are compact/unresolved***





However…

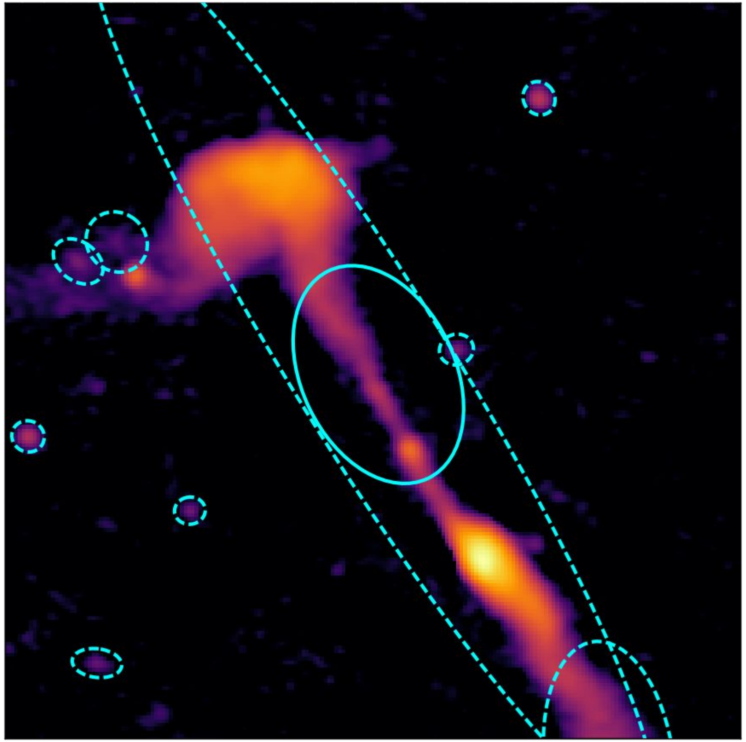
Cross-matching: a challenging endeavour

Radio source population is diverse, with **complex emission and morphologies** -> **difficult to simply use NN methods**

Source detection software don't know astrophysics!

- Complex emission -> ***physical*** sources **not correctly identified** -> **requires manual intervention**

Radio image with PyBDSF sources

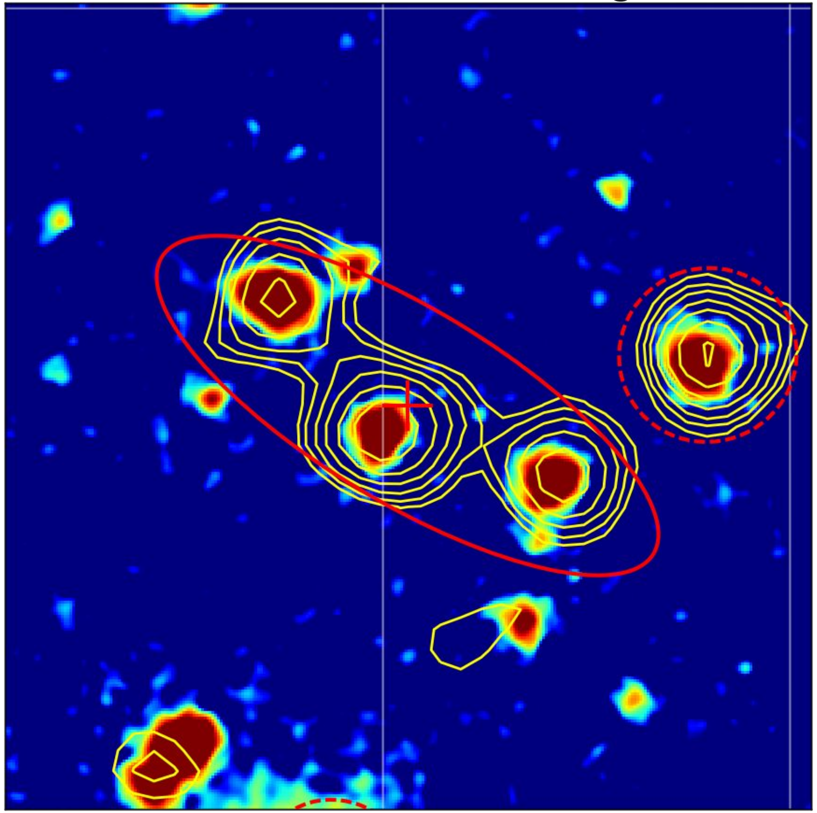


Cross-matching: a challenging endeavour

Source blending is also an issue (esp. for deep surveys)

Image: **three distinct physical sources**, categorised as a ***single* PyBDSF source**

Radio contours + IR image



Williams et al. 2019; Hardcastle et al. 2023

Cross-matching: a hybrid approach

Combination of statistical (automated) method for simple sources and visual classification for complex sources

Statistical Likelihood Ratio method

Probability of a galaxy to be the genuine counterpart to given radio source

$$LR = \frac{f(r)\ q(m,c)}{n(m,c)}$$

Visual Classification

Visual classification used for more complex sources

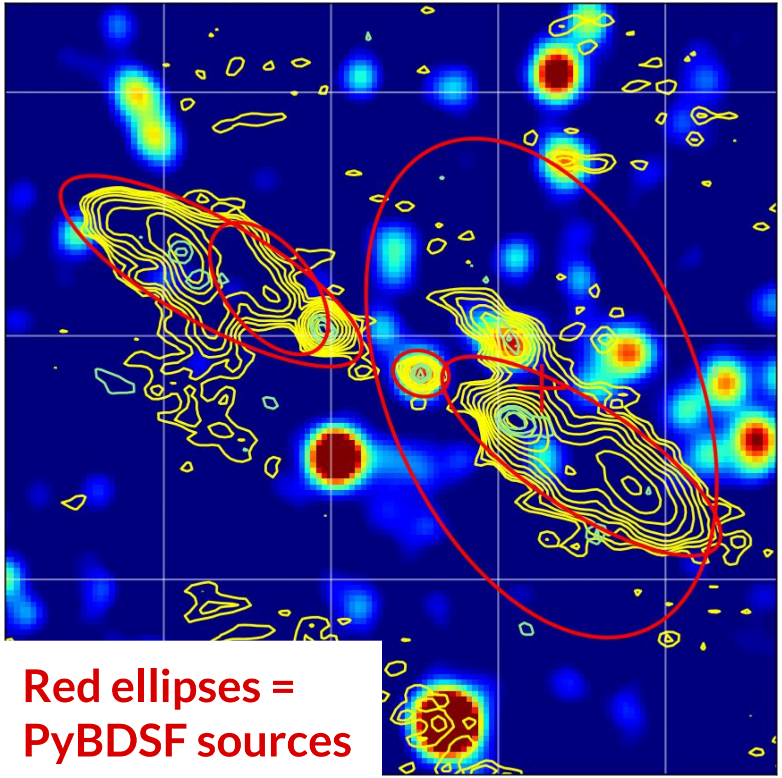
Both host-galaxy identification and source association

Using the Zooniverse framework

Consensus decision from at least 5 astronomers

*** Different process for LoTSS DR2**

Radio contours + IR image



Red ellipses = PyBDSF sources

Williams et al. 2019; Hardcastle et al. 2023

When to use LR versus visual classification?

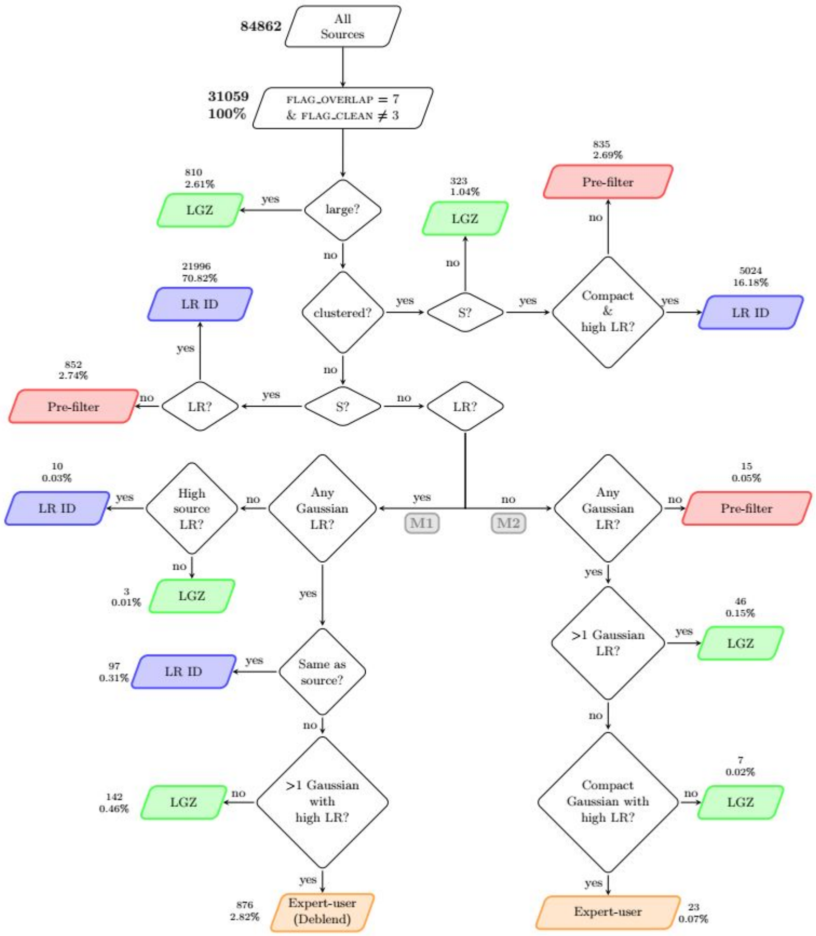
Use a **decision tree** to identify when to use LR versus visual classification

In LOFAR Deep Fields:

Counterparts found for > 97% of radio sources

LR: 85% of radio sources

Visual classification: 15%



Kondapally et al. 2021

Science applications utilising multi-wavelength information

Spectroscopy provides most robust measure of redshifts and many other galaxy properties

Template Fitting

EAZY
Brammer et al. (2008)

LePhare
Arnouts et al. (1999)
Ibert et al. (2006)

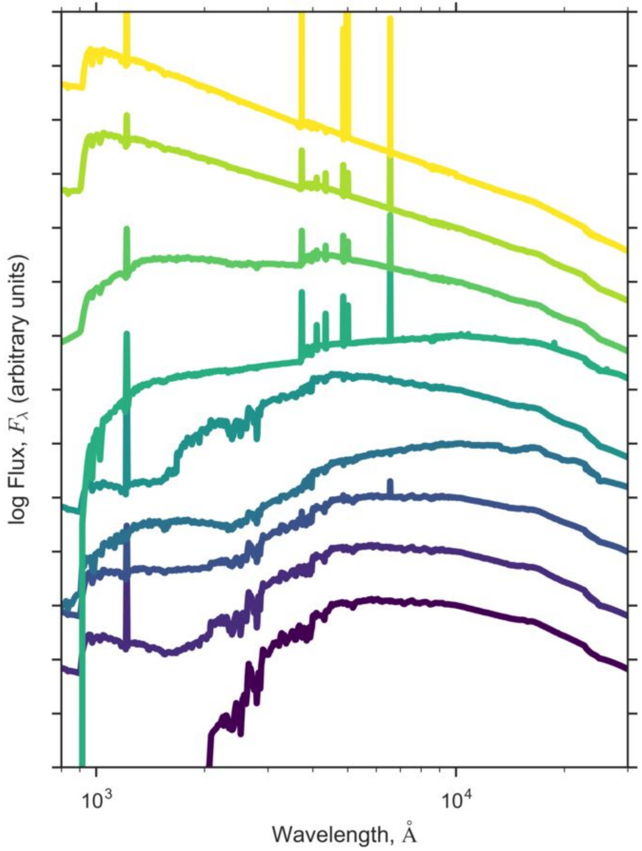
PhotoZ
Bender et al. (2001)

Hyper-Z
Bolzonella et al. (2000)

ZEBRA
Feldmann et al. (2006)

Mizuki
Tanaka et al. (2015)

BPZ
Benitez (2000)



Photometric Redshifts - two ways

Machine Learning

Radial basis function networks

Generalized Linear Models

Naive Bayes

Self-organizing Maps (SOMs)

Bayesian Network

Gaussian Processes

Neural Networks

Deep learning

k-Nearest Neighbour

Randomised Forests

Relevance vector machines

Boosted Decision Trees

Normalised inner product nearest neighbour

Support Vector Machines (SVM)

Directional neighbourhood fitting

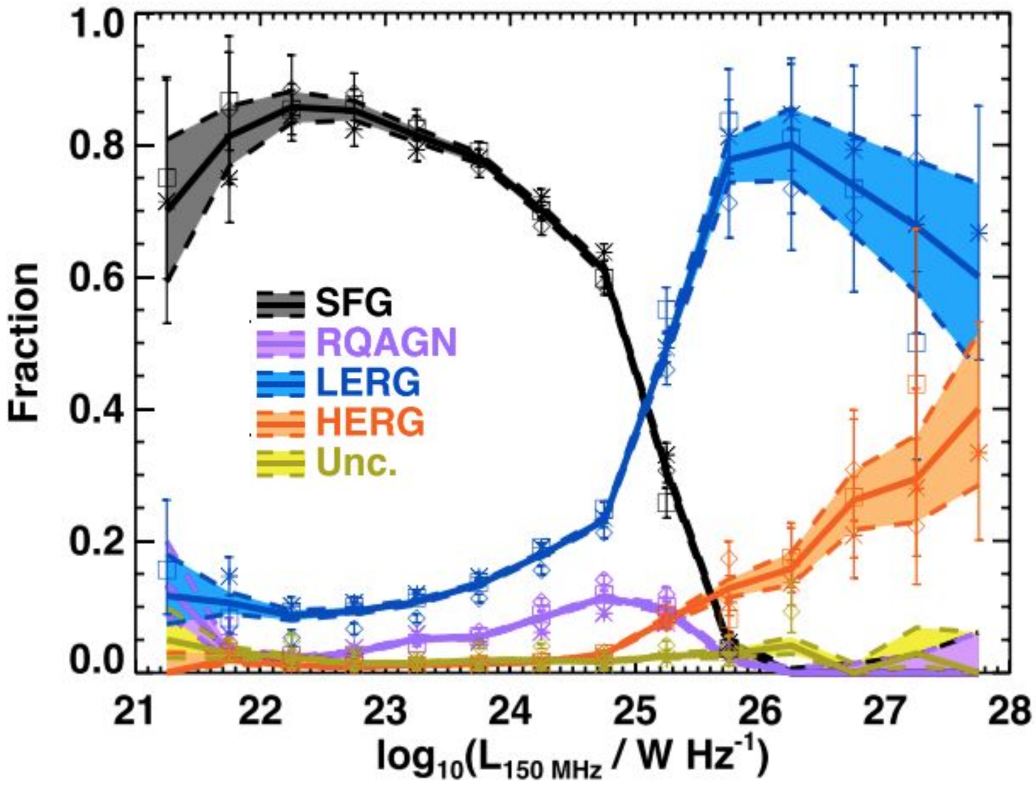
Non-conditional density estimation

Voronoi tesselation density estimator

Diverse radio source population

Diverse nature of the radio source population

-> Single approach may not be most suitable

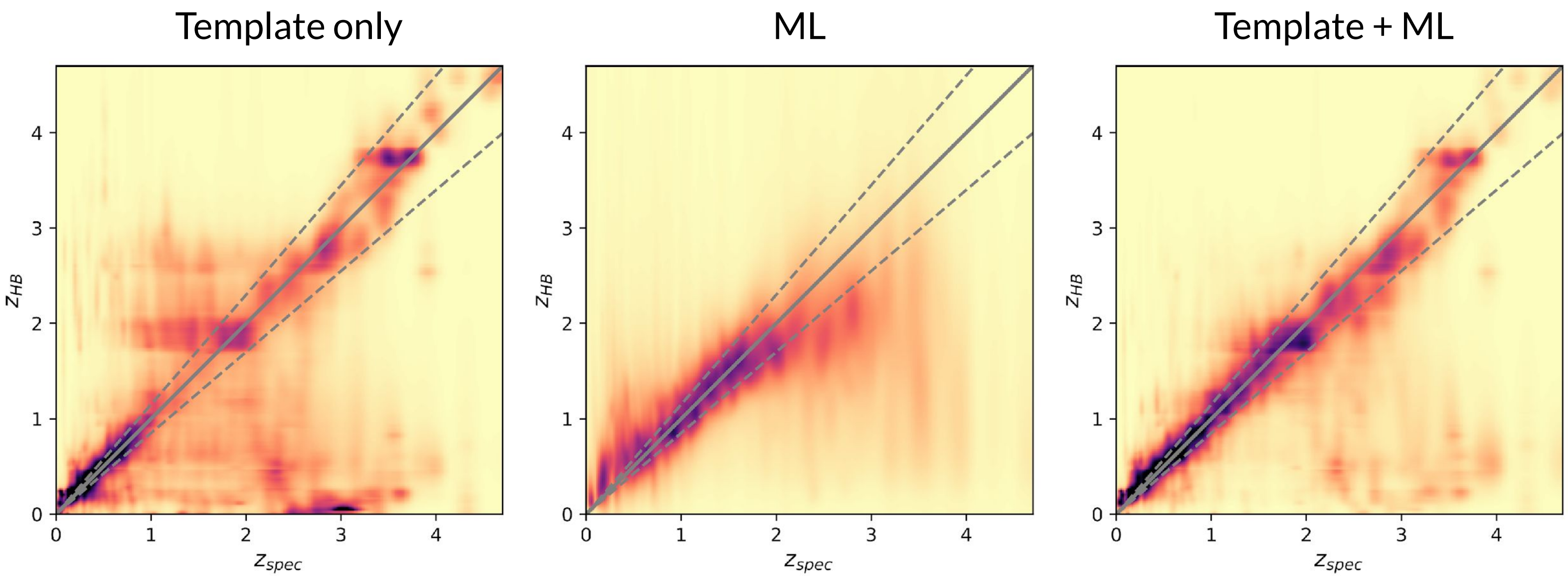


Best et al. 2023

Photometric Redshifts: a hybrid approach

A hybrid approach within LOFAR surveys for photo-z's – led by **Ken Duncan**

Fitted z



Spectroscopic z (gold standard; "ground truth")

Duncan et al. 2018a,b;
Duncan et al. 2021;
Duncan 2023

The future: new spectroscopic redshift surveys

WHT 4.2m Telescope
370-960nm wavelength coverage
960 fibres @ R~5000
Northern hemisphere
Starting Q2 2024

VISTA 4m Telescope
370-960nm wavelength coverage
~1400 fibres @ R~5000
Southern hemisphere
Starting 2025

Mayall 4m Telescope
360-980nm wavelength coverage
5000 fibres @ R~2-5000
Northern hemisphere
Started 2022-23

Subaru Telescope
0.38-1.2micron coverage
2400 fibres @ R~2-5000
Northern hemisphere
Starting >2024

VLT 8m Telescope
0.68-1.8micron coverage
~1000 fibres @ R~4-6000
Southern hemisphere
Starting ~Q2 2025

WEAVE-LOFAR (1.3m fibre hours)
WEAVE-Apertif (Resolved spectroscopy of HI sources)

WAVES (GAMA Mrk.2)
Cosmology Redshift Survey
AGN Survey (eROSITA sources)
Cluster survey
ORCHIDDS (Optical Radio and HI Deep Spectroscopic Survey; PI Duncan)

Cosmology survey:
'Bright galaxies' at $z < 0.4$
Luminous Red Galaxies
Emission line galaxies (ELGs)
Quasars

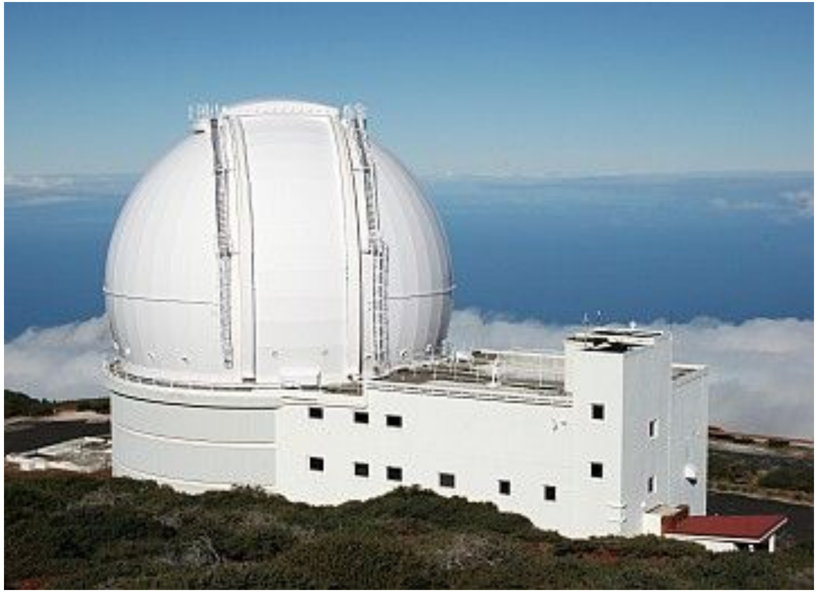
Cosmology: ELGs at $0.6 < z < 2.4$
Galaxies: near-IR selected deep fields

Deep near-IR selections
(e.g. COSMOS/CDFS etc)
Some MIGHTEE follow-up (TBC)

WEAVE

WHT Enhanced Area Velocity Explorer

- WEAVE is a ~1000 fibre multi-object spectrograph going on the 4.2m WHT
- 2 deg diameter field of view
- Complete wavelength coverage from 370–960nm at R=5000
- **Starting Q2 2024!**



WEAVE-LOFAR

Spectroscopic follow-up of large numbers of LOFAR-selected sources in three tiers, to get a complete picture of SF and AGN co-evolution.

> 1 million fibre hours allocated

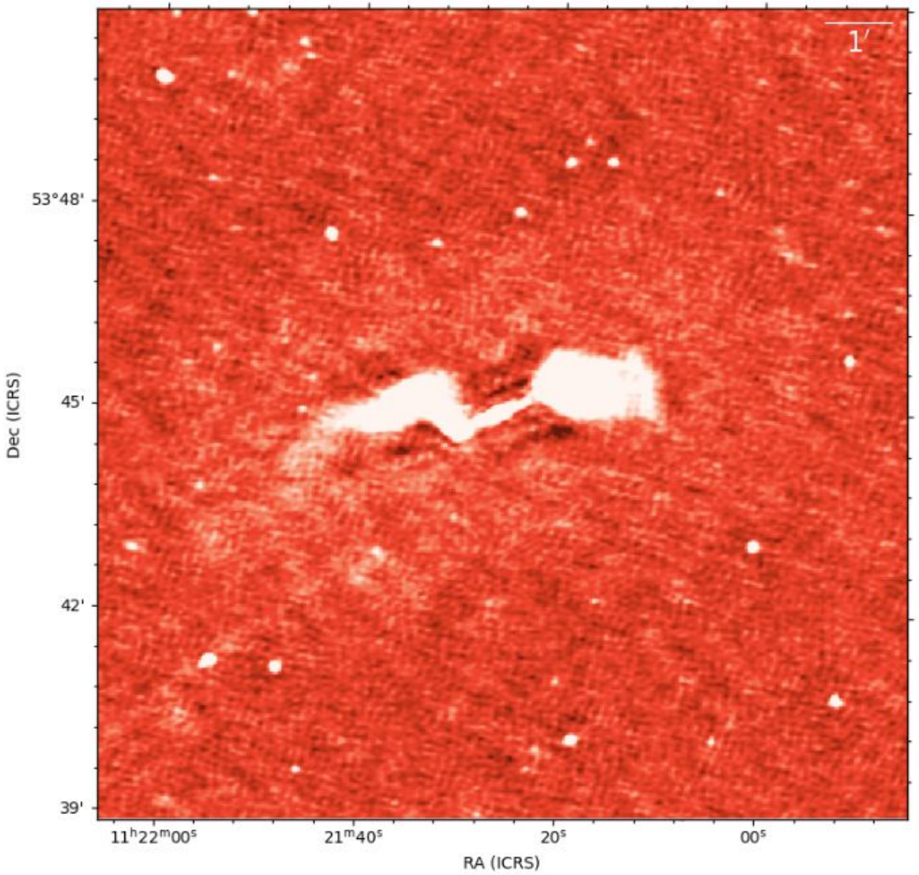
Deep (up to 100 deg^2) — Targets > 100 uJy

Mid (1,250 deg^2) — Targets > 1 mJy

Wide (up to 10,000 deg^2) — Targets > 10 mJy

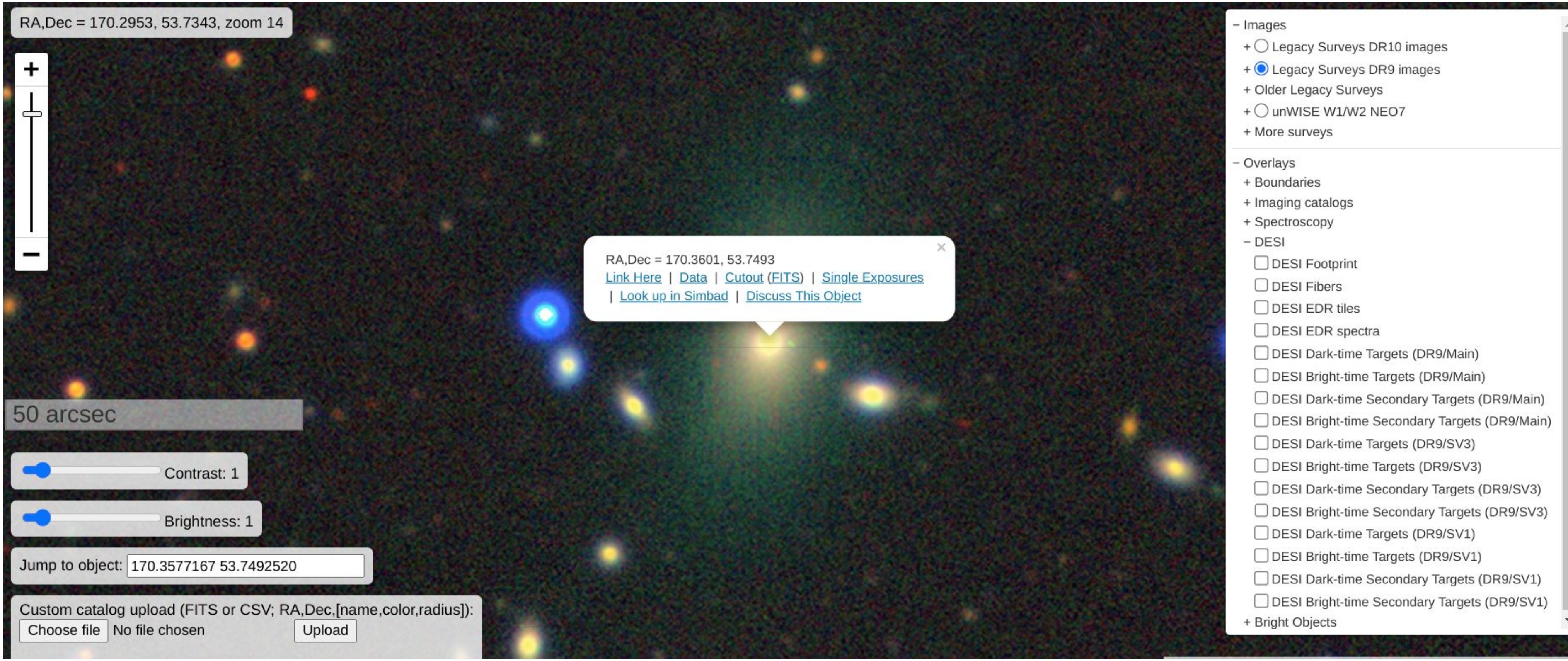
Demonstration of combining radio and multi-wavelength datasets

A giant radio galaxy example



Legacy Survey Viewer + Catalogue

https://www.legacysurvey.org/viewer



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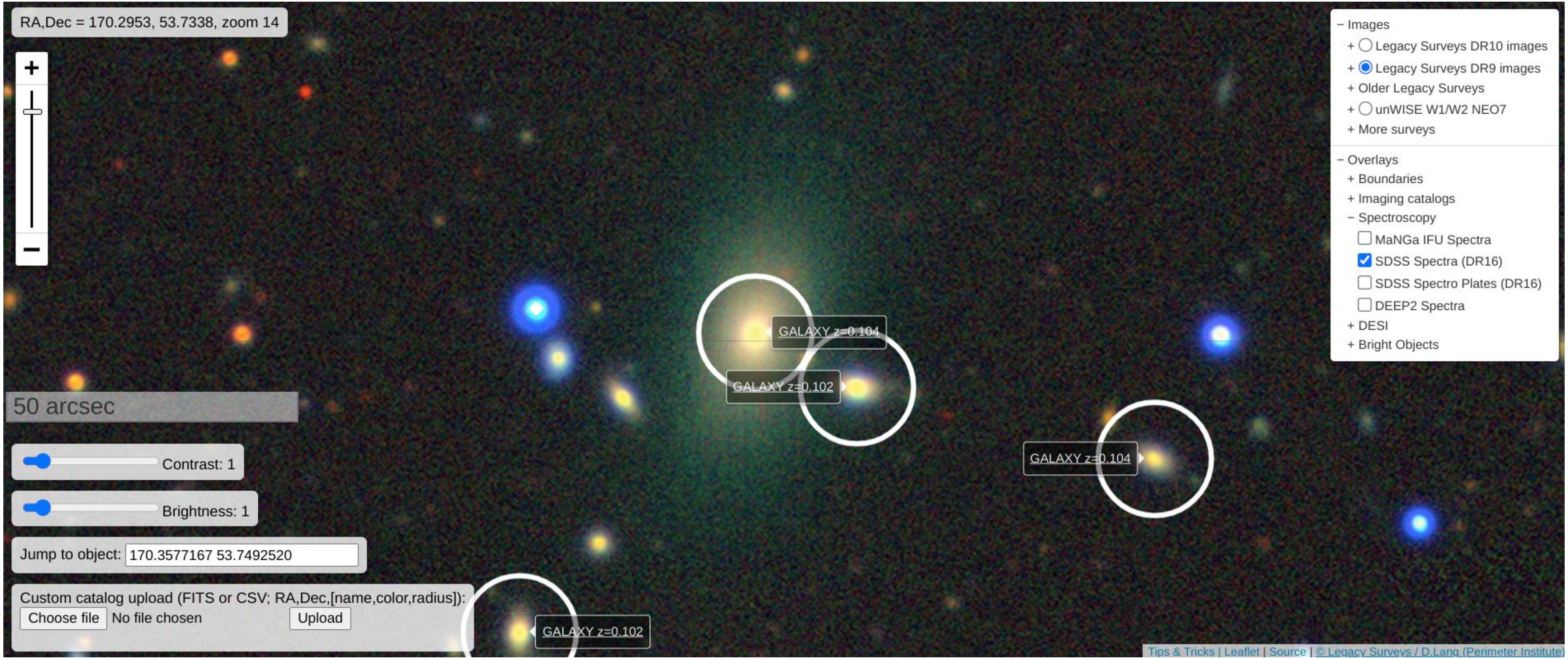
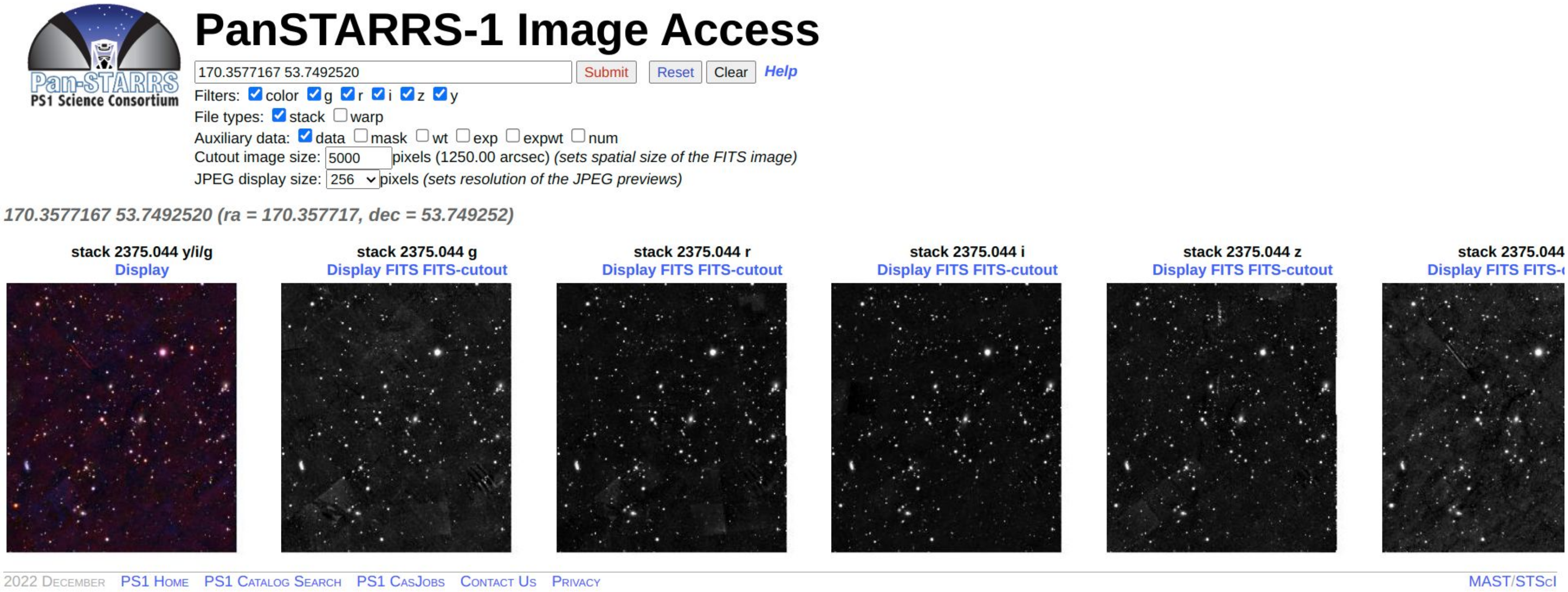


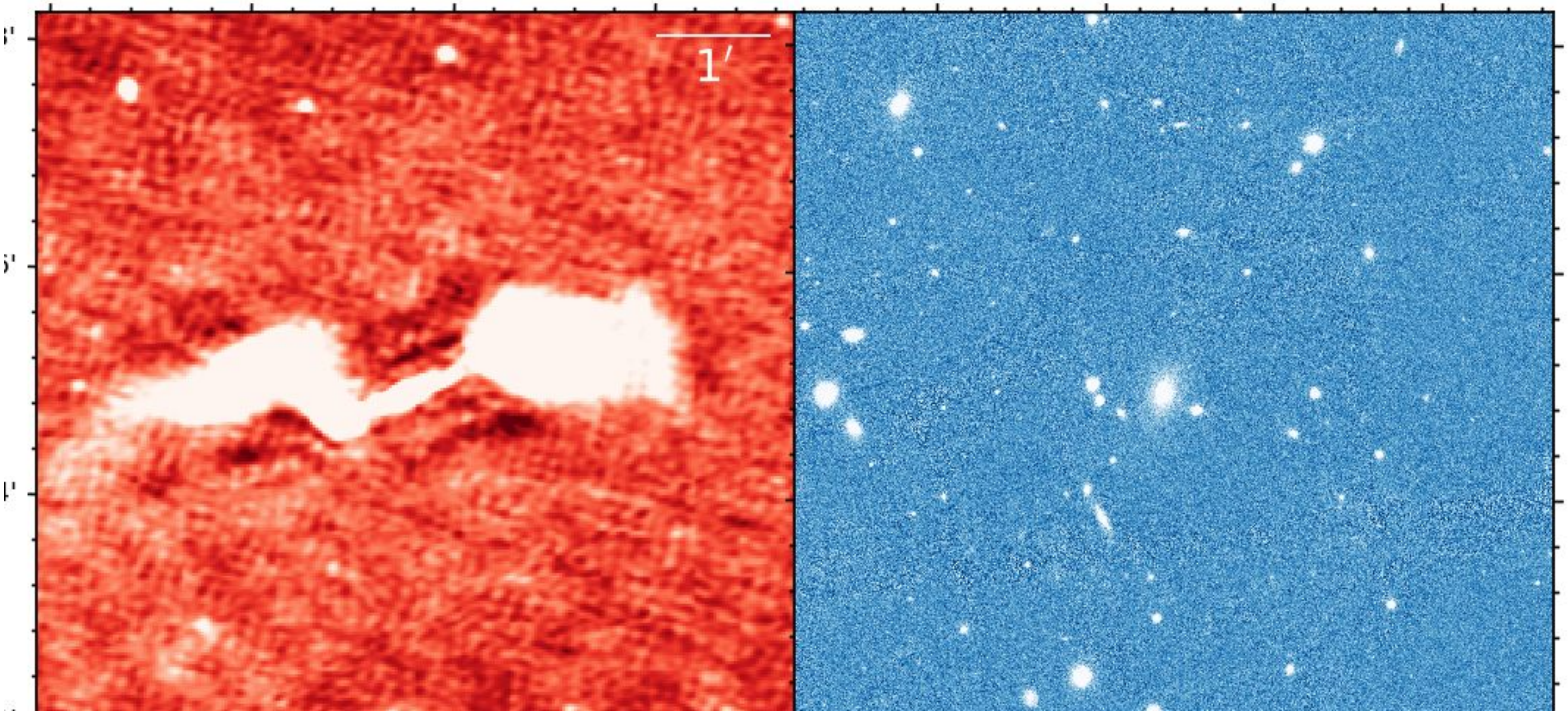
PanSTARRS Image Cutout Service

https://ps1images.stsci.edu/cgi-bin/ps1cutouts



LOFAR 150 MHz

PS1 (g-band)



Conclusions

- Need to incorporate multi-wavelength data to maximise scientific potential from radio surveys
- Methods of cross-matching radio and optical surveys
- Estimating photometric redshifts
- Useful resources for finding and obtaining multi-wavelength datasets for your radio data

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Radio-optical analysis: useful resources

Radio-optical analysis: useful resources

PanSTARRS (PS1) DR1 and DR2

Optical g,r,i,z,y bands

Images and catalogues: https://outerspace.stsci.edu/display/PANSTARRS/

Legacy Surveys (DR10 latest)

g,r,z bands (deeper than PS1) + unWISE (IR) de-blended photometry

Measurements of redshifts, simple galaxy profiles/sizes

Images and catalogues: https://legacysurvey.org

SDSS

Large optical spectroscopic data

Many data releases, (mostly) local Universe, spec-z's, galaxy properties

https://www.sdss4.org/

Radio-optical analysis: useful resources

Access to large IR datasets
NASA IR Science Archive (IRSA):
https://irsa.ipac.caltech.edu/

Interactive sky viewer with many overlays and easy data access functionality
Legacy Sky Viewer:
https://www.legacysurvey.org/viewer

Large public catalogue repository with flexible access, searching, cross-match **Vizier/CDS:**
https://vizier.cds.unistra.fr/viz-bin/VizieR

Interactive viewer for **(most)** public data
ESA Sky: **https://sky.esa.int/esasky/**

Space telescopes archive
MAST: https://archive.stsci.edu/

NASA Extragalactic Database (NED):
https://ned.ipac.caltech.edu/