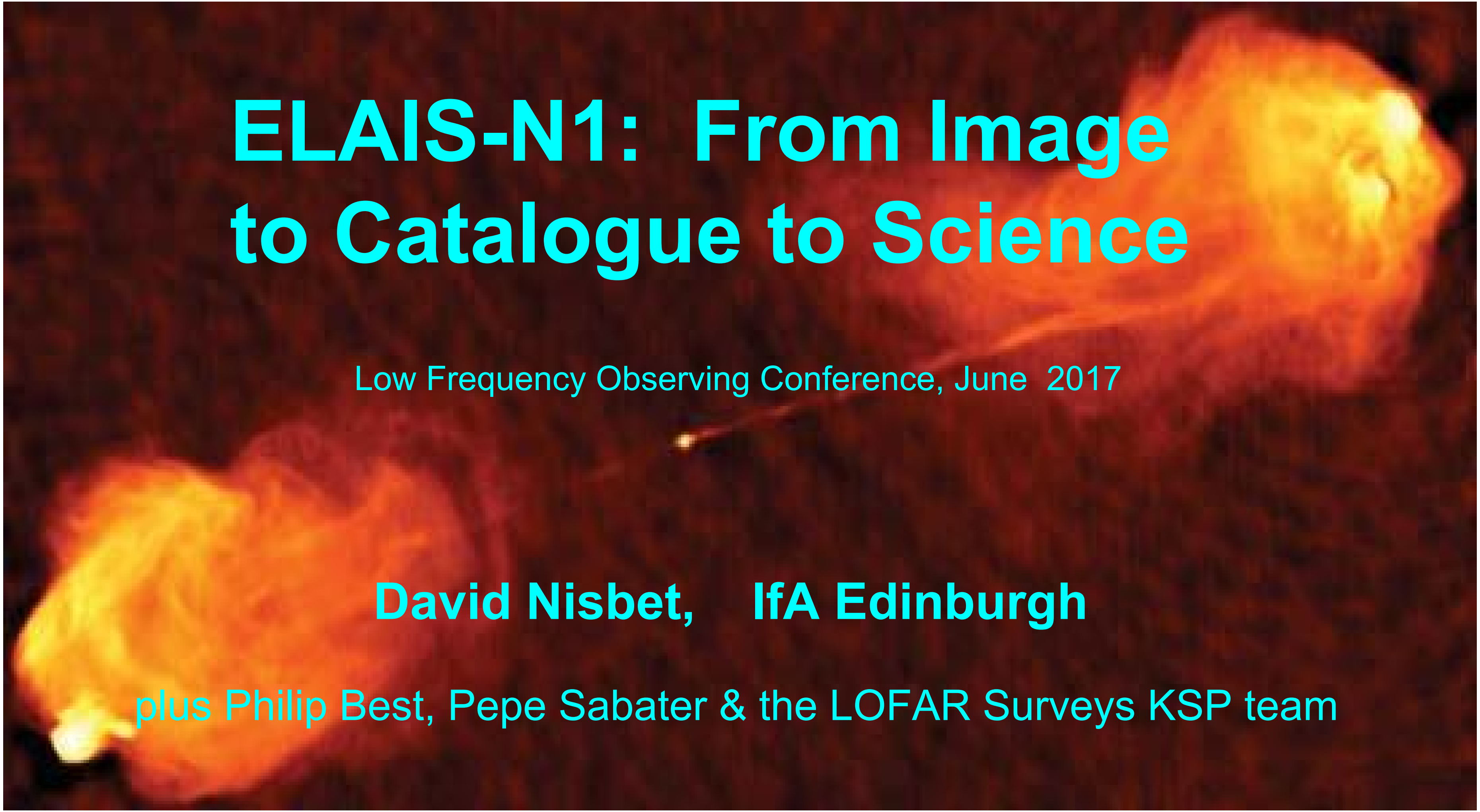


ELAIS-N1: From Image to Catalogue to Science

Low Frequency Observing Conference, June 2017

David Nisbet, IfA Edinburgh

plus Philip Best, Pepe Sabater & the LOFAR Surveys KSP team

Outline of Talk

- Why ELAIS-N1?
- Observations and Calibrations
- Identification of Host Galaxies
- Refinement to Maximum Likelihood Analysis
- Early Science Results
- Science Goals and Opportunities

Why ELAIS-N1?

- Low column of foreground material.
- High ecliptic latitude.
- Extensive, deep multiband data over several square degree area (matched to LOFAR primary beam).
- Extensive spectroscopic data.

Survey / Telescope	Wavebands
GALEX	fuv and nuv
SDSS	u, g, r, i and z
INT	u, g, r, i and z
PanSTARRS Medium Deep	g, r, i, z and y
UKIDSS DXS	J and K
2MASS	J, H and K
SWIRE	3.6, 4.5, 5.8 and 8.0 microns
SERVS	3.6 and 4.5 microns
WISE	3.4, 4.6, 12.0 and 22.0 microns
MIPS	24, 70 and 160 microns
Herschel HERMES	250, 350 and 500 microns
FIRST	21 cm

ELAIS-N1 Observations and Reduction

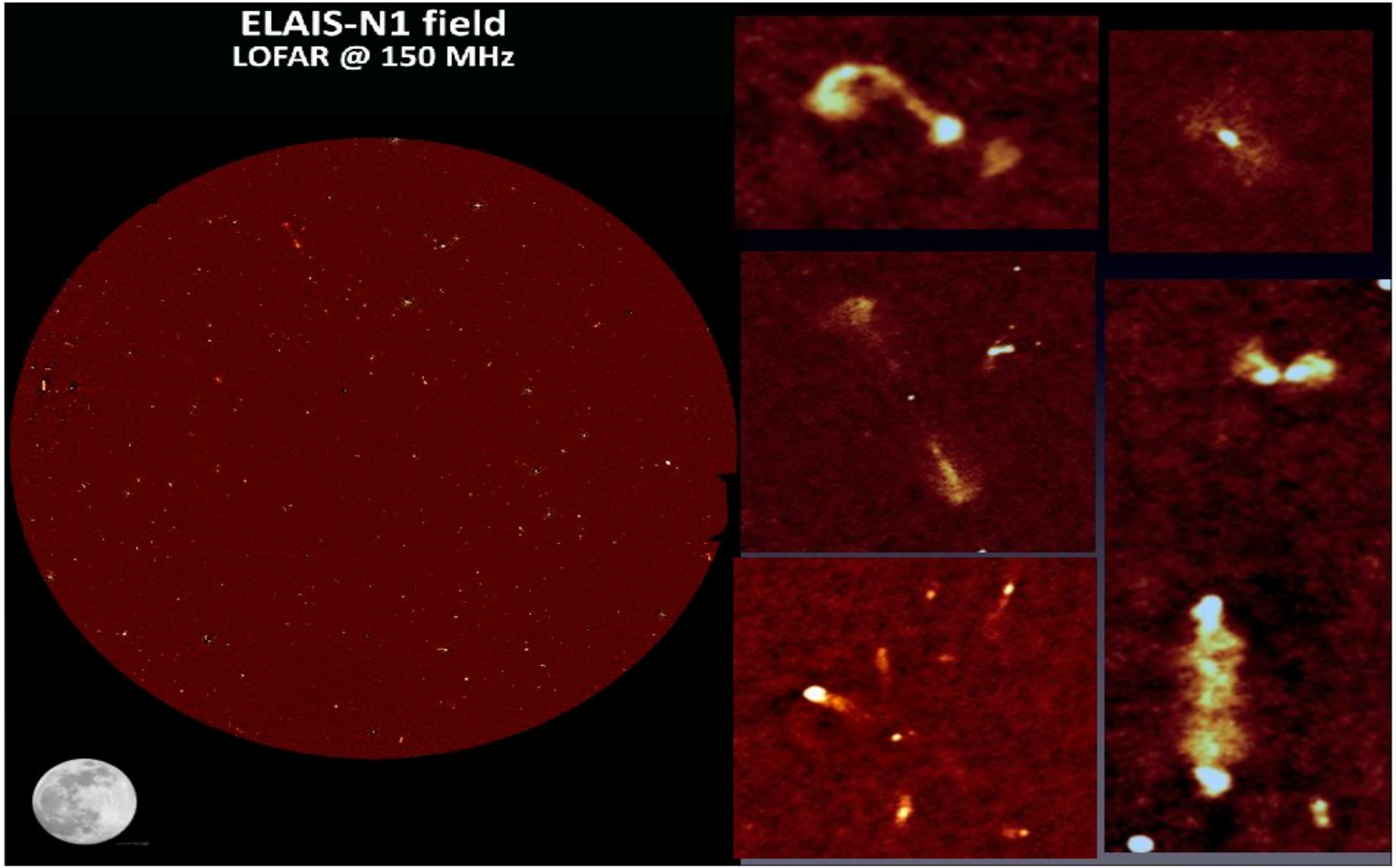
- ~ 250 hours of LOFAR (HBA) observations.
- Central Frequency 150 MHz.
- Direction-dependent facet calibration (see earlier talks).
- 3 x 8 hour observation sets reduced.
- This talk based on one 8-hour run.
- Calibration continuing on the cloud, see: "Calibration of LOFAR data on the cloud", Sabater et al,. Astronomy and Computing 2017, Volume 19, Pages 75–89.

ELAIS-N1 Images

Resolution = 5 arcseconds

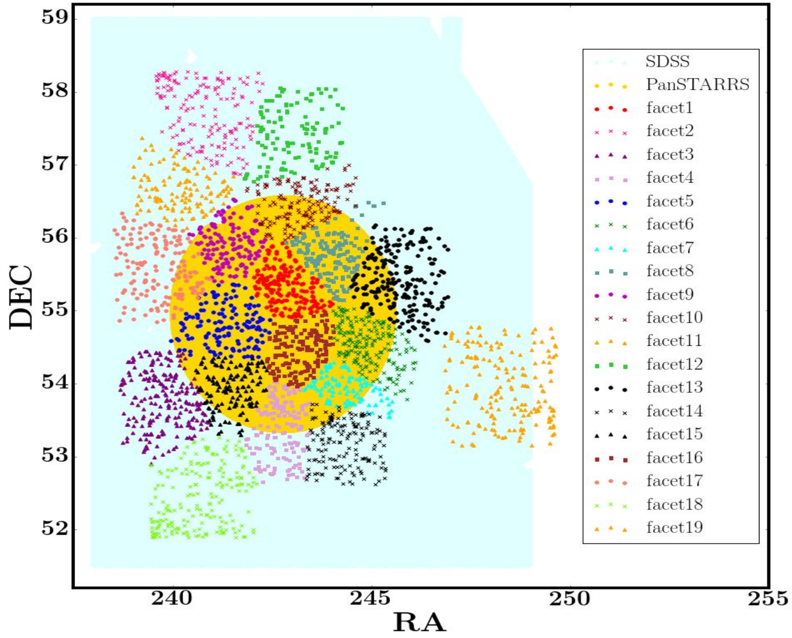
Noise = 135 micro Jy/beam

Sources extracted using PyBDSM

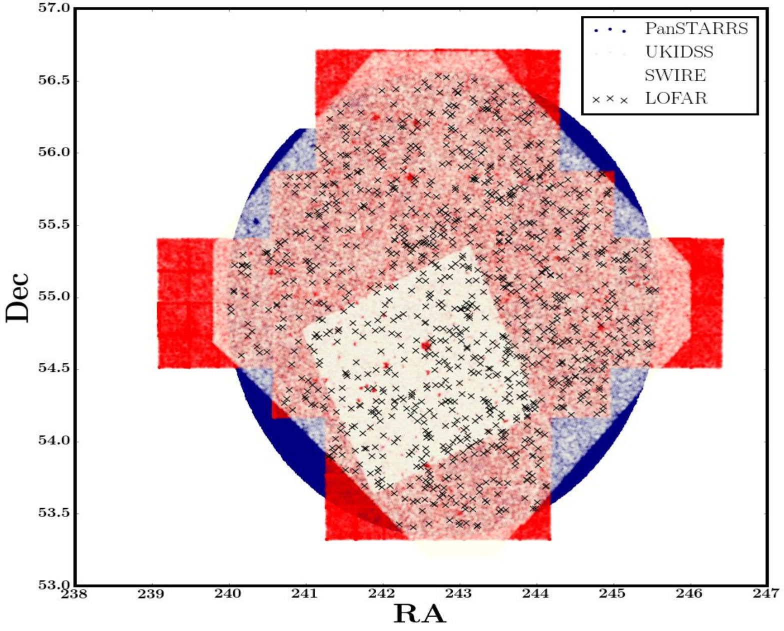


The LOFAR Sources

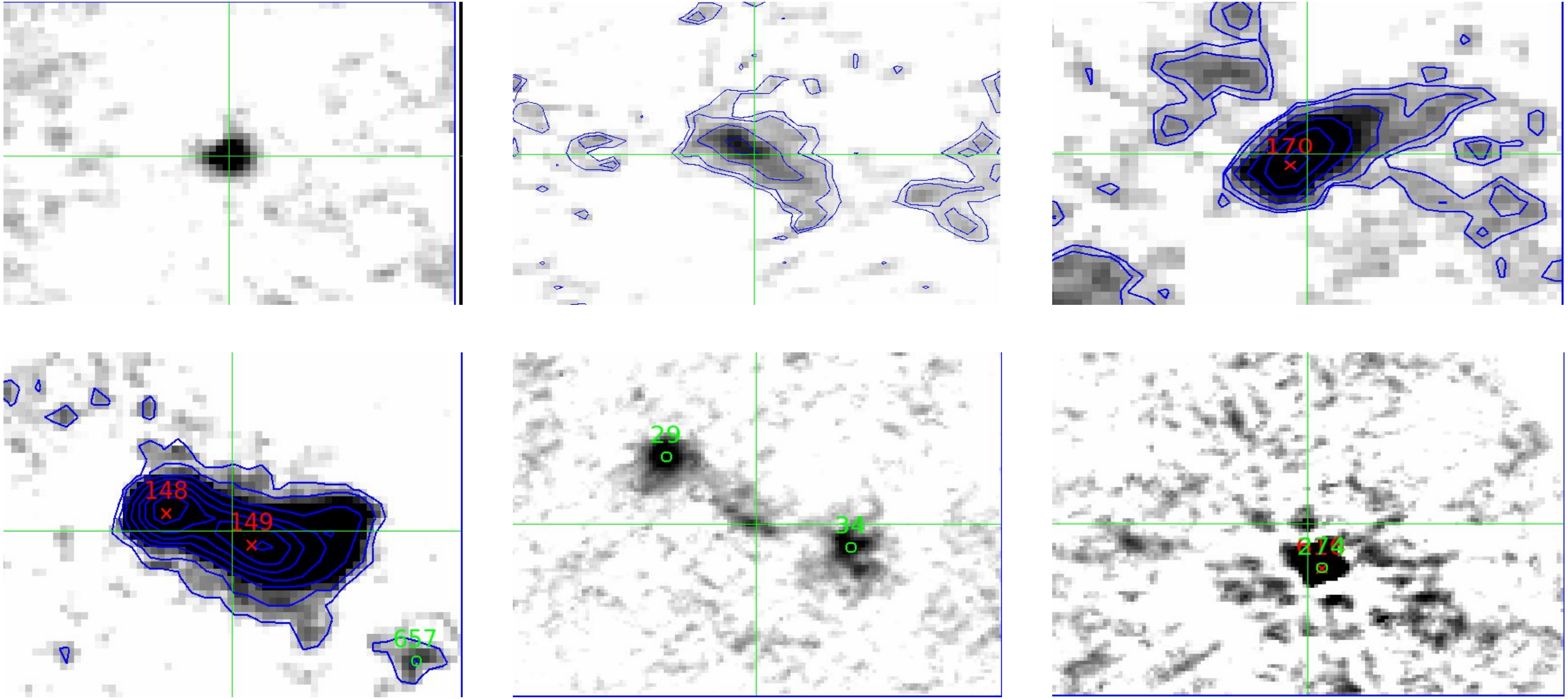
3176 sources



1357 sources



Single, Extended, Double and Spurious Sources



Procedure to Identify the Host Galaxy

- Correct the Astrometry on facet-by-facet basis, using PanSTARRS data.
- Combine the multiband data (here, g, i, K and 3.6 micron wavebands) to create catalogue of possible galaxy hosts.
- Separate out the LOFAR sources requiring visual matching.
- Match the remainder using Maximum Likelihood Analysis.
- Visual inspection of low-likelihood and close-likelihood matches.

Traditional Maximum Likelihood Analysis

Likelihood Ratio = f(r) q(m) / n(m)

f(r) = probability distribution of offset, r, between radio and optical positions
Gaussian, using positional errors projected to optical candidate

n(m) = magnitude distribution of underlying full population
cumulative distribution per arcsecond^2

q(m) = magnitude distribution of true counterparts
cumulative distribution scaled to Q_0 *at faintest magnitudes*

Q_0 = fraction of sources for which a match is expected

Estimating Q_0

Traditional Approach

- Count optical sources around the radio sources and in blank sky regions.
- This over-estimates Q_0 due to galaxy clustering.

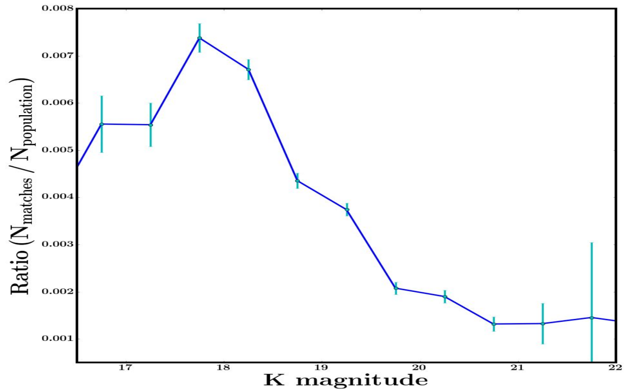
Refinement by Fleuren et al (2012)

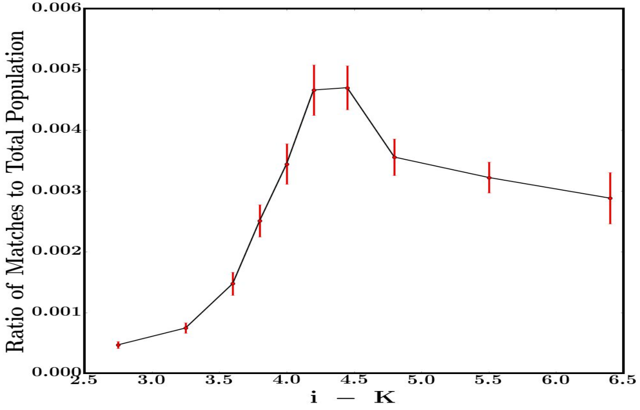
- Use comparison of numbers of blank fields around radio sources and at random locations.
- Search out to radius r.
- U_{obs} = fraction of blank targets; U_{rand} = fraction of blank randoms.
- $Q_0(r)$ = fraction of all matches expected within radius r.
- $U_{obs} / U_{rand} = 1 - Q_0(r)$

Incorporate Colour Information

LR = f(r) q(m, c) / n(m, c)

- For LOFAR sources, trends with colour can be (at least) as strong as those with magnitude.
- Easier to incorporate limits for non-detections into the analysis.
- Produces better results.





Problem: Q_0 calculation with colour

Blank field technique of Fleuren et al no longer works:

- A LOFAR source may have a host galaxy of colour “c”; clustering increases the probability of other galaxies of different colours within the search radius.
- Hence, this will not be a blank field at those other colours.
- Hence, Q_0 will be over-estimated for those other colours.

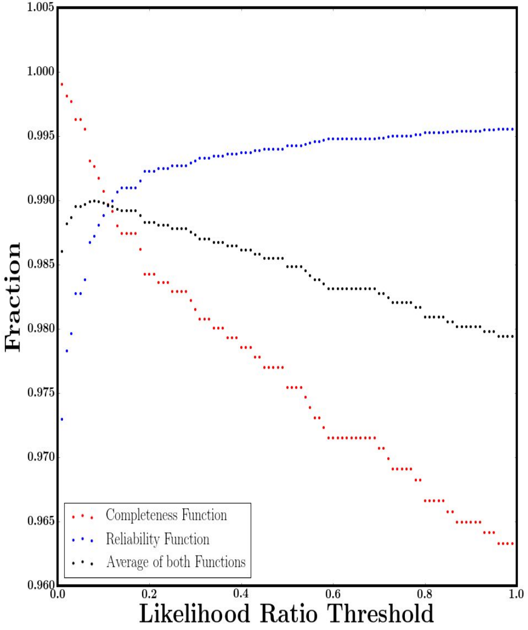
Revised Approach:

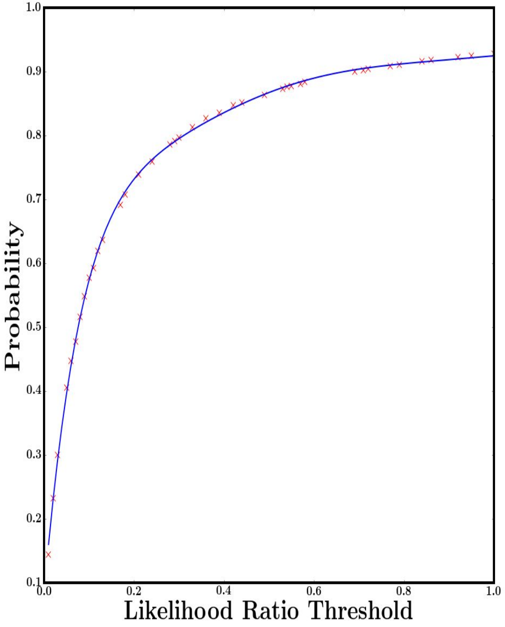
- Apply magnitude-only maximum likelihood analysis.
- This provides a first set of matched galaxies.
- Split these by colour to derive first-pass $Q_0(c)$ and $q(m,c)$.
- Apply magnitude and colour maximum likelihood analysis.
- Re-derive $Q_0(c)$ and $q(m,c)$.
- Iterate until convergence.

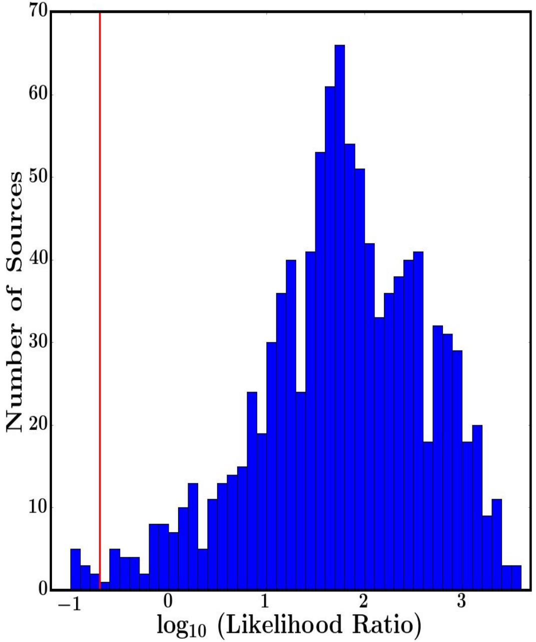
Q_0(c) Factors by Colour Category

	All giK groupings				K only, Ks only
Category	i - K	g - i Midpoint	Blue Half	Red Half	
1	< 3.0	1.04	0.031	0.002	
2	3.0 - 3.5	1.08	0.027	0.017	
3	3.5 - 3.7	1.19	0.023	0.025	0.004
4	3.7 - 3.9	1.32	0.044	0.035	
5	3.9 - 4.1	1.44	0.039	0.058	
6	4.1 - 4.3	1.53	0.051	0.057	0.001
7	4.3 - 4.6	1.58	0.072	0.075	0.003
8	4.6 - 5.0	1.65	0.052	0.057	0.012
9	5.0 - 6.0	1.80	0.073	0.054	0.030
10	> 6.0	1.63	0.014	0.011	0.019
gi only, g only, i only			0.001		
s only			0.012		

Completeness Analysis







Final Catalogue

Source Type	Classification Method	Number	Number of Optical IDs	ID Fraction
Isolated Singles	Maximum Likelihood	1062	1030	97%
Singles	ML / Visual	23	23	100%
Extended Singles	Visual	105	98	93%
Multi-Components	Visual	32	29	91%
Total		1222	1180	97%

(after excluding lobes and spurious sources)

What LOFAR Sources are suitable for ML Analysis?

Tier 1 survey will identify ~10 million radio sources. Need to restrict the number requiring visual analysis. Used ELAIS-N1 results to investigate.

Relevant Factors:

- Size of Source
- Distance to Nearest Neighbour
- Single or Multi-Gaussian Source
- Properties of Gaussians
- Results of ML Analysis

Possible Strategy:

Single Gaussian

- Send to ML if deconvolved size < 15 arcseconds and distance to nearest neighbour > 30 arcseconds

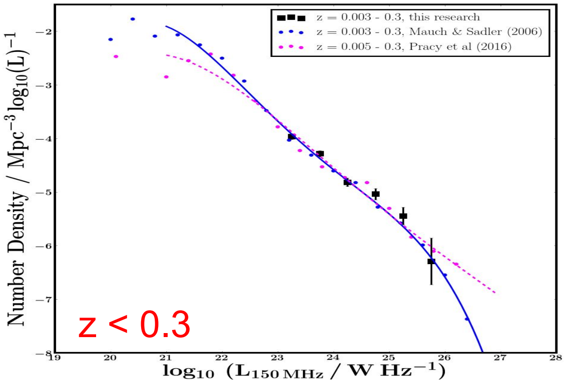
Multi-Gaussians

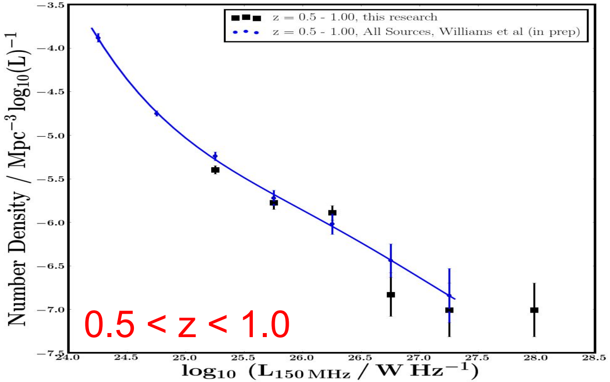
- Perform ML analysis on source and on each Gaussian component.
- If ID for source coincides with ID for the Gaussian with the highest LR, accept ID.

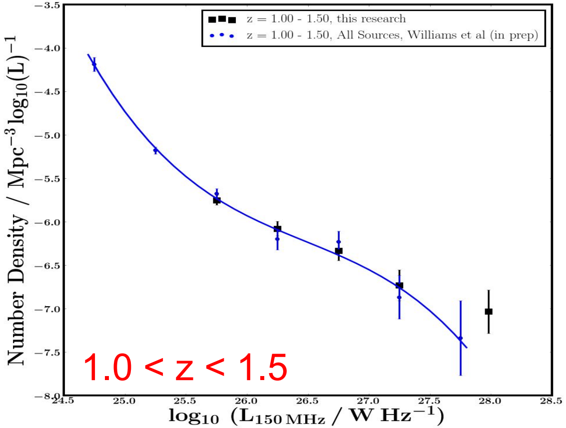
What LOFAR Sources are suitable for ML Analysis?

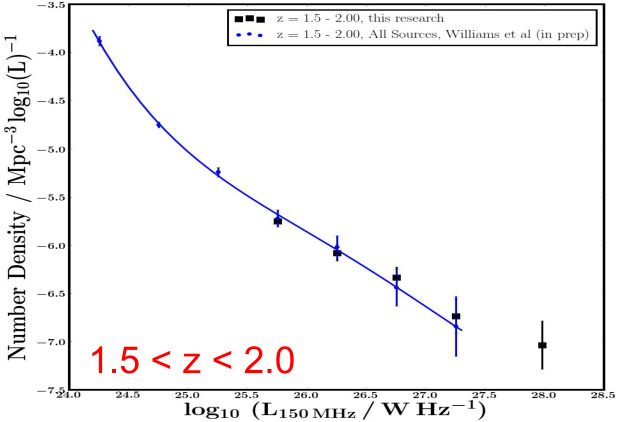
		Maximum Likelihood			Visual
	Total Number	Total	Correct	Wrong	
Single-Gaussian	78.2%	70.4%	69.2%	1.2%	7.8%
Multi-Gaussian:					
LR IDs coincide	12.3%	12.3%	12.2%	0.1%	
Don’t coincide	9.5%	-	-	-	9.5%
Total	100.0%	82.7%	81.4%	1.3%	17.3%

Luminosity Functions



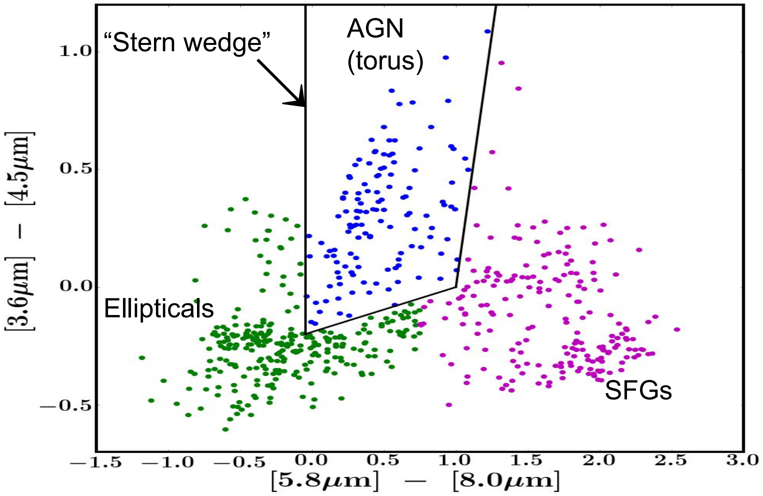


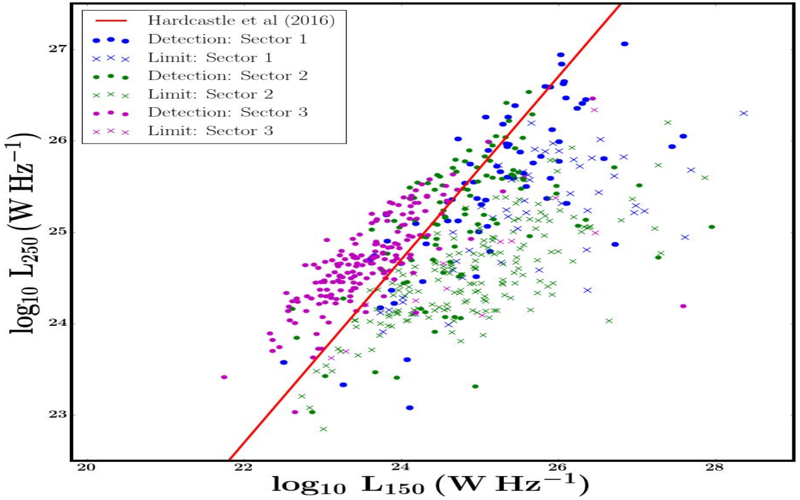




Separating HERGs, LERGs and SFGs

- Work in progress.
- Multiband datasets offer opportunity for accurate classification, as illustrated by these example plots.





Science Opportunities

Using just 3% of observations:

- >1200 radio sources
- 97% identification fraction.

Roughly equal mix of SFGs and jet-mode radio AGN.

Trace jet-mode cosmic evolution to z~2.

Improve understanding of jet-mode feedback.