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e-MERLIN

e-MERLIN

Rob Beswick
(on behalf of e-MERLIN team)

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e-MERLIN

- Major project to transform sensitivity & capabilities of old MERLIN
- 150 -10 mas resolution at L, C and K-band
- Increase bandwidth to 0.5/2 GHz

  → uJy sensitivity
- First semester of Legacy/Open time observations finished
- S. Garrington, R. Beswick, T. Muxlow P. Harrison, A. Richards, R. Noble, M. Bentley, C. Shenton, J. Edgley, E. Blackhurst, P. Diamond, R. Spencer, R. Davis, N. Roddis, et al

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The e-MERLIN Project

Goals

- Increase bandwidth to
  - 0.5 GHz (L-band)
  - 2 GHz (C & K -band)
- Include Lovell Telescope at C-band
- New telescope optics,feeds, receivers, IF, samplers
- Digital transmission system: 30 Gb/s from each telescope
- Dedicated optical fibre network
  - 100 km installed; 600km leased

  (total ~700km)
- H-maser freq (1 part in 10^{14})std over optical fibre network
- New correlator: wide field imaging; simultaneous line & continuum observations
- EVN recording/transmission for multiple telescopes

Capabilities

150, 40, 10 mas **resolution**

~3 uJy **sensitivity** in typical runs

20-30 x better than MERLIN performance

< uJy deep fields

Wide fields

[~7,27 arcmin]

Spectroscopy

Up to 16 sub-bands;>512 chan/pol;
(More with Recirculation)
Mix line and continuum

Much improved aperture coverage

Via frequency coverage

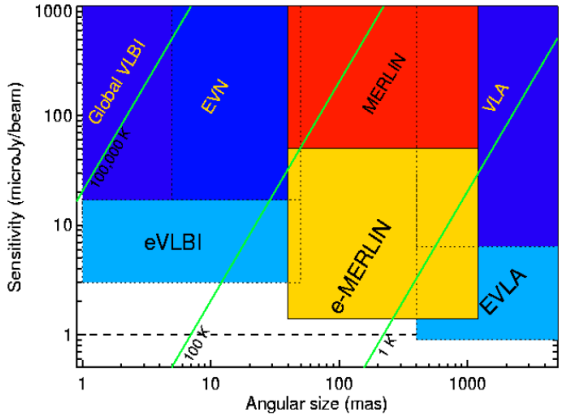
Spectral mapping

1.3-1.7; 5-7/4-8 GHz

Polarization (L,R → IQUV)

Astrometry

Goal is < 1 mas wrt ICRF



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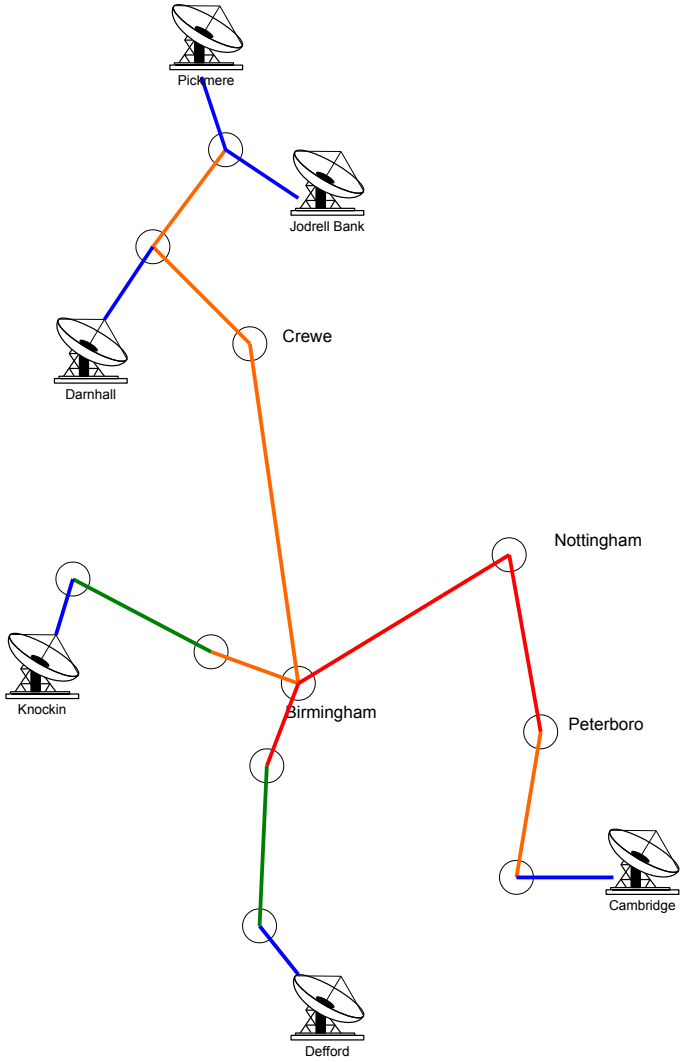
e-MERLIN

Data Transmission Network Solution

- 7tels * 30 Gb/s sustained data rate from each telescope
  - (=5M homes @ 10GB/month)
- Private fibre network to connect remote telescopes in rural locations
- Installed & tested 90km new fibre alongside minor roads to connect to…
- 600 km Dark Fibre trunks leased from UK telecoms providers
- Use e-MERLIN/JVLA/ALMA data transmission system
- Amplifiers/Regeneration at Peterborough, Nottingham, Birmingham, Crewe, designed and installed by JBO



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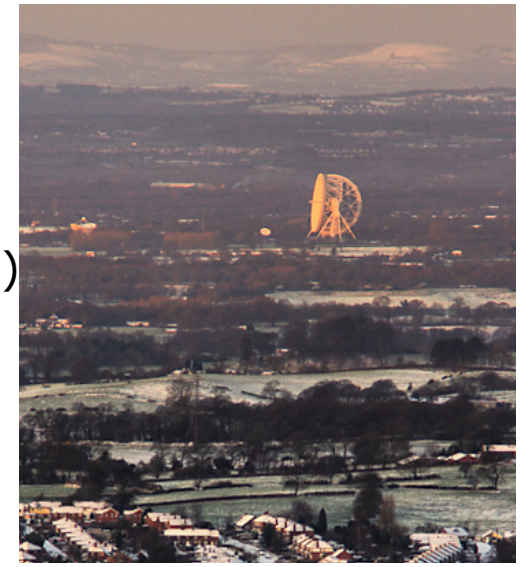
e-MERLIN

Progress & Status

- Whole system complete & operational
  (except for 4 Gs/s boards – coming soon)
- Over the last couple of years...
  - Completed & commissioned 4-8 GHz
    (0.5 GHz b/w currently – expanding to 2GHz soon)
  - Completed & commissioned 1.25 – 1.75 GHz
  - Incorporated Lovell Telescope at L, C-band
  - Entire IF replacement
  - H-maser synchronisation over optical fibre
  - Complete new operational s/w
  - Successful e-VLBI tests with multiple telescopes
- Science continued at some level throughout development – *get scientists involved with early data*
- Started *Legacy* Programme observations
- Cycle-0 call & observations for open time (last year)
- Cycle-1 – commences in Autumn 2013
  - Oversubscribed ~3:1 (all time), ~6:1 (requests requiring Lovell telescope)



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e-MERLIN

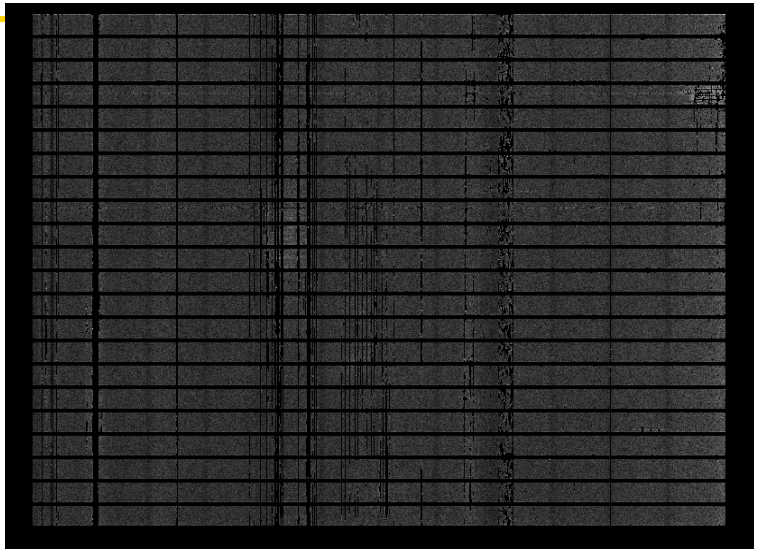
L-band performance

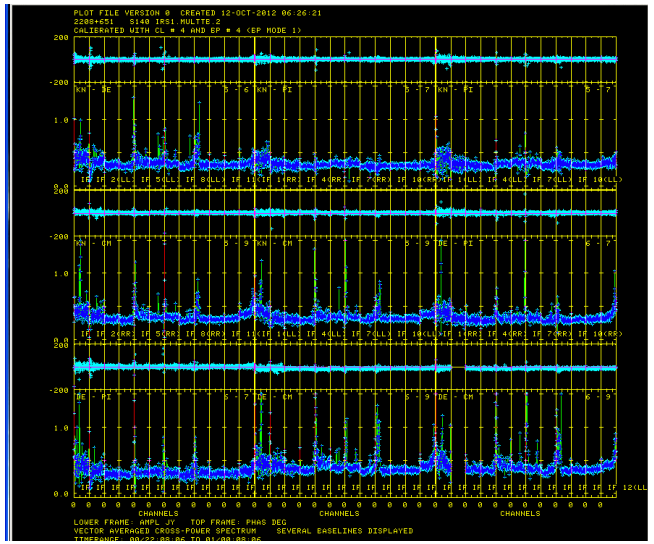
- Accessible band constrained by RFI
  - Radars etc below 1.2 GHz
  - Cell phones above 1.7 GHz
- High-performance filters → band (1.25 – 1.75 GHz)
  - Front ends & IF linear (8-bit sampling)
- Use narrower sub-bands than c-band
  - 8 x 64 MHz (512 ch/sub-band/pol)
- Auto-flaggers essential
  - SERPent (developed for e-MERLIN Peck & Fenech [UCL]) – see poster.

  ~90% data useable is norm.

  Interference from fixed links, CCTV camera, computers, wifi etc etc
- Typical image noise

  ~ <10 uJy/beam, Lovell





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Wide-field & wide-band imaging

- Default correlator configuration allows full primary beam imaging
- At L-band N(>2.5 mJy) ~ 15; 30% compact

  SNR/tel ~ 10 in 100s using full 500 b/w

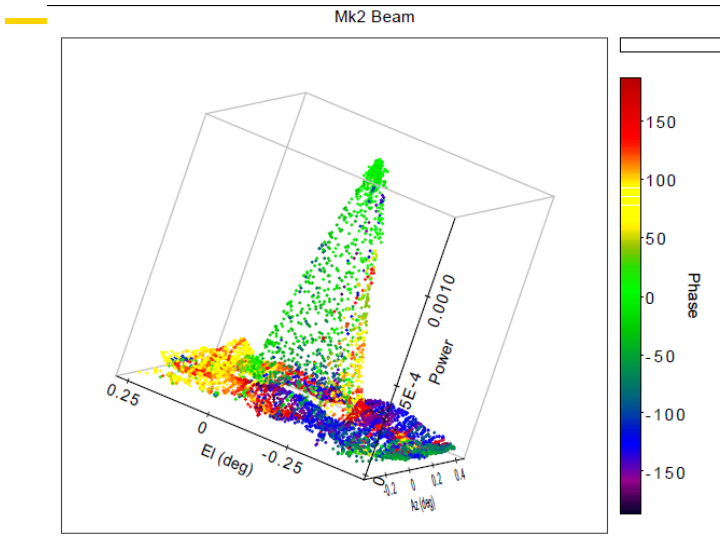
→ In-beam self-calibration routine at L-band

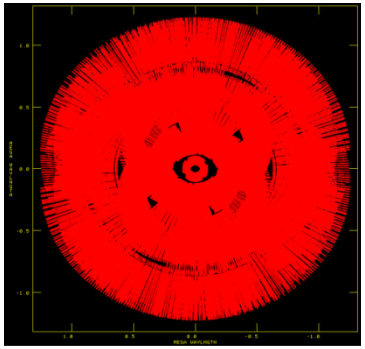
→ To achieve uJy sensitivity need to subtract these sources with DR ~10,000:1

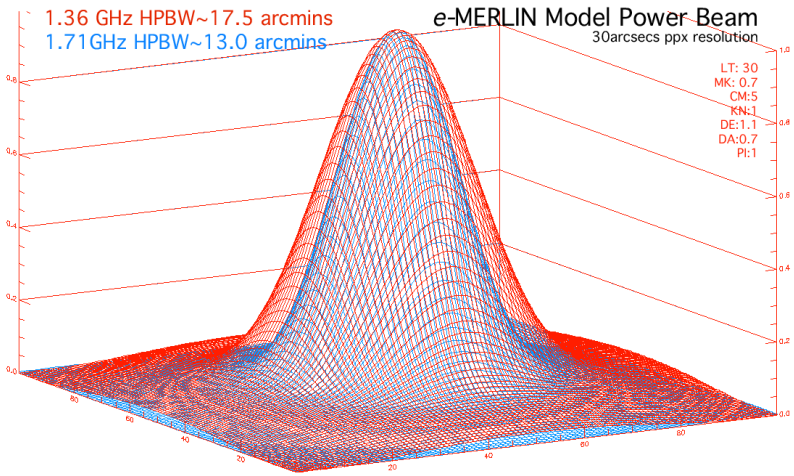
→ Need detailed map/model of primary beam

  ... For each telescope

- Direction dependent calibration (ALBiUS)
- 30% fractional bandwidth → MF deconvolution







N. Wrigley (part of his PhD)

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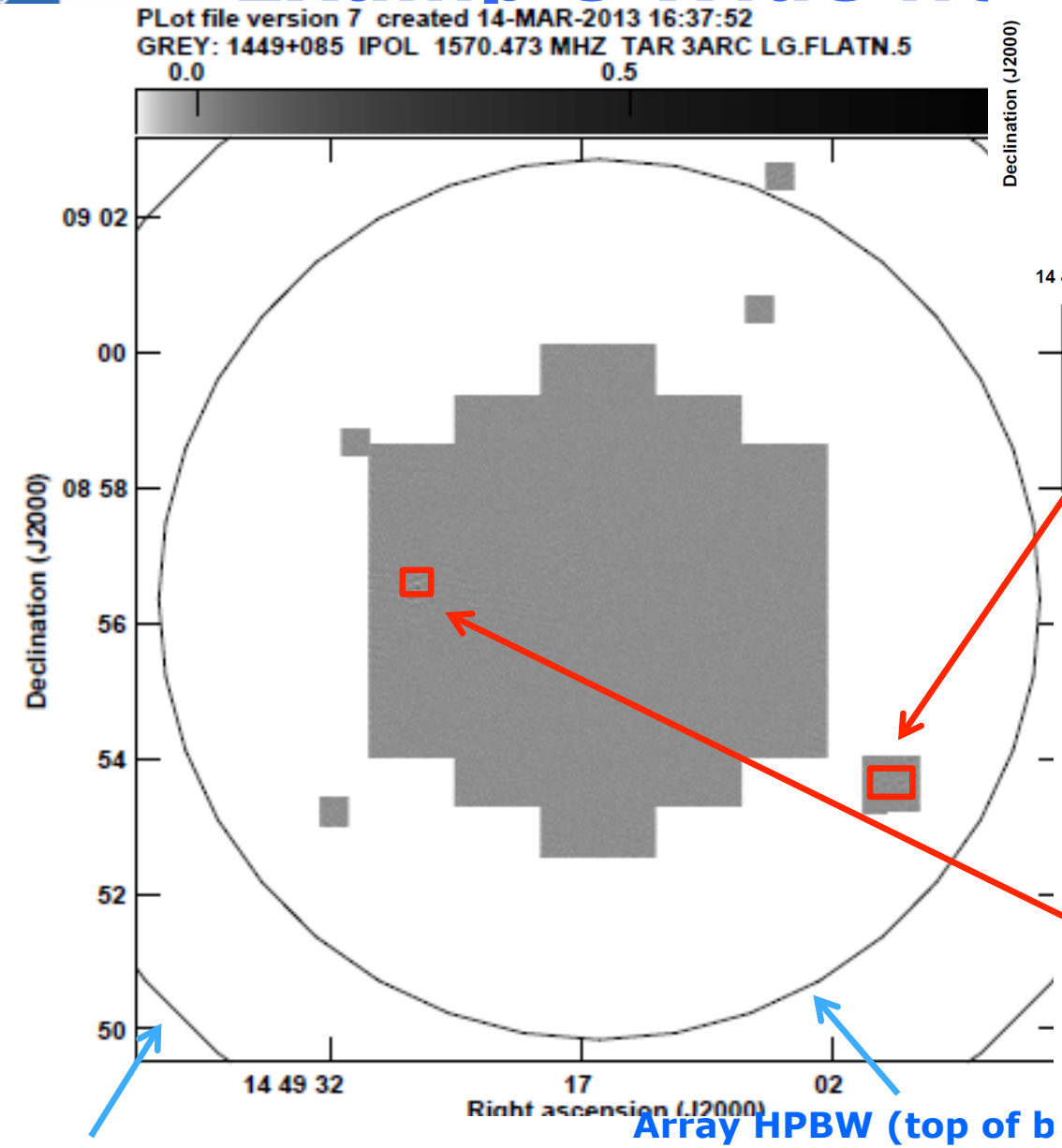
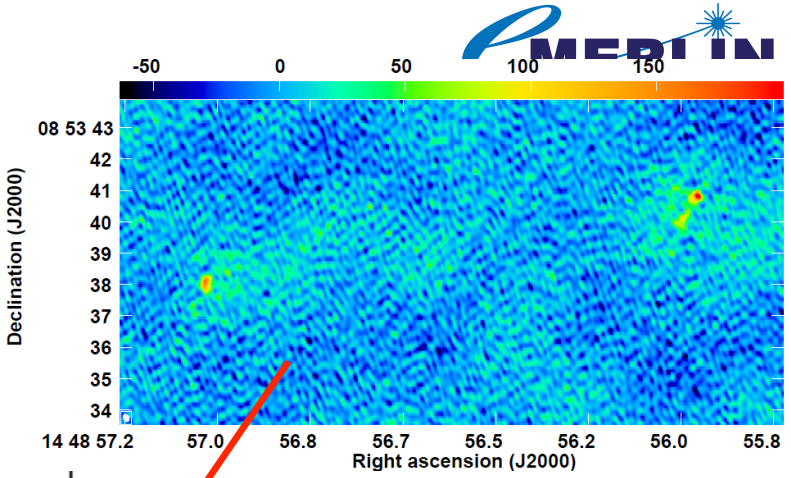
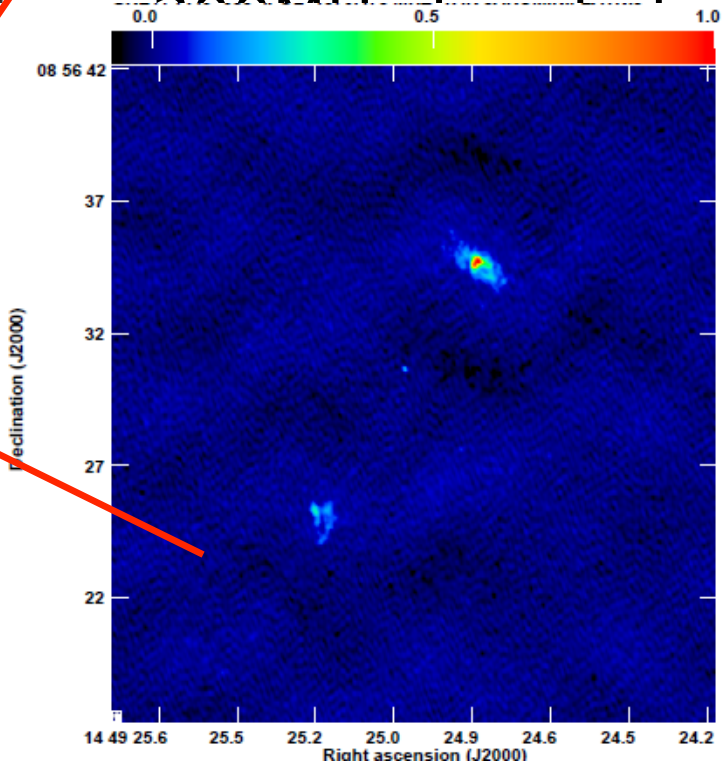
Example Wide fie





(with LT) ~13uJy/ bm noise



Array HPBW (bottom of band)

Array HPBW (top of b

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e-MERLIN

e-MERLIN observing

- e-MERLIN is open to all users
  - Open-time Cycle-0 observations (complete)
  - Cycle-0 period (3-way-split = open-time shared-risk/ ongoing instrument commissioning/legacy test observations)
  - Cycle-1 starting Autumn 2013.
    - Oversubscribed ~3:1 (all time), ~6:1 (requests requiring Lovell telescope)
- Alongside open-time, 50% of time in first ~5 semesters is allocated to large 'key' science [Legacy] programmes.
  - Legacy projects targeting key science areas and provide long term legacy data products.
  - Large consortia teams.
- Legacy observations now underway (observing)

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e-MERLIN

e-MERLIN legacy programme

- Defined key science programme before instrument ready

Large projects covering planet formation → cosmology

Full project proposals available http://www.e-merlin.ac.uk/legacy/

GALACTIC PROJECTS:

• eTT - Pulsar astrometry – Vlemmings/Stappers et al.	160hrs **
• PEEBLES – planet formation - Greaves et al.	72hrs **
• Feedback processes in Massive SF – Hoare/Vlemmings et al.	450hrs
• Thermal jets from low mass stars - Rodriguez et al	180hrs
• COBRaS – wide-field deep galactic survey - Prinja et al.	294hrs

EXTRA-GALACTIC PROJECTS:

• LEMMINGS – 300 nearby gals - Beswick/McHardy et al.	810hrs
• LIRGI – LIRGs/ULIRGs - Conway/Perez-Torres et al.	353hrs
• Extragalactic Jets – Laing/Hardcastle et al	375hrs
• AGATE – cluster fields - Simpson/Smail et al	330hrs
• e-MERGE – deep field - Muxlow/Smail/McHardy et al	918hrs
• Gravitational lenses – Jackson/Serjeant et al	228hrs **
• SuperCLASS - weak lensing 1.7deg^2 supercluster Battye et al	832hrs

- **** Remaining 830hrs to be allocated to these projects pending initial results**

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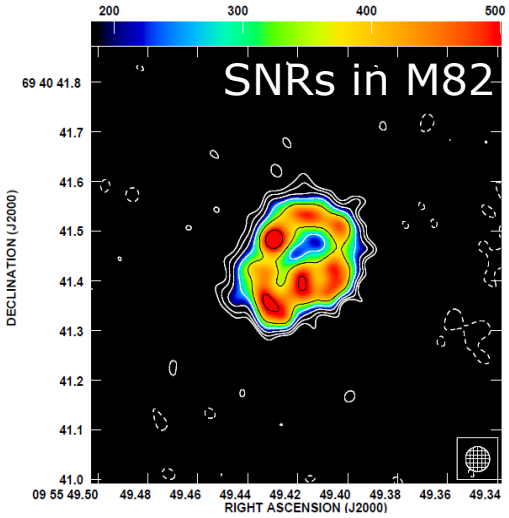
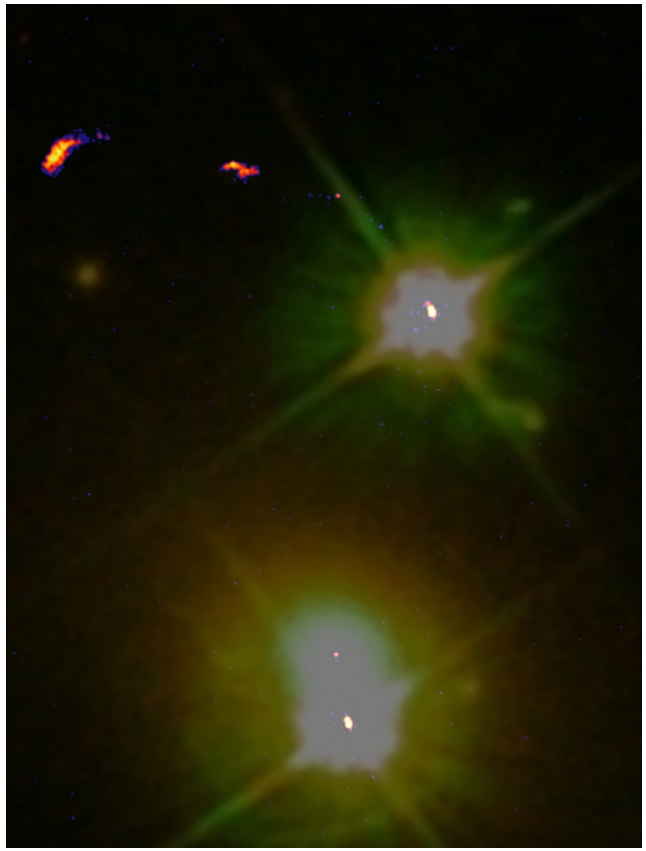
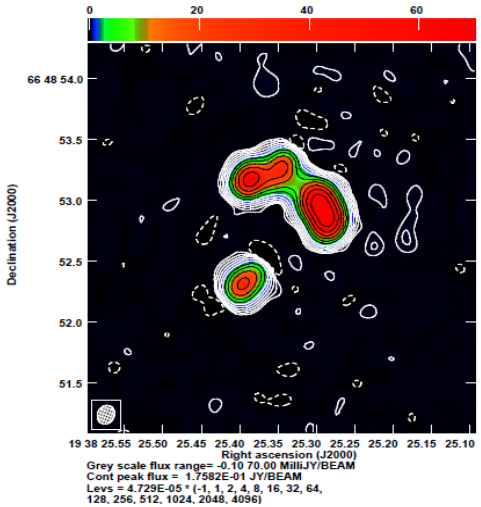
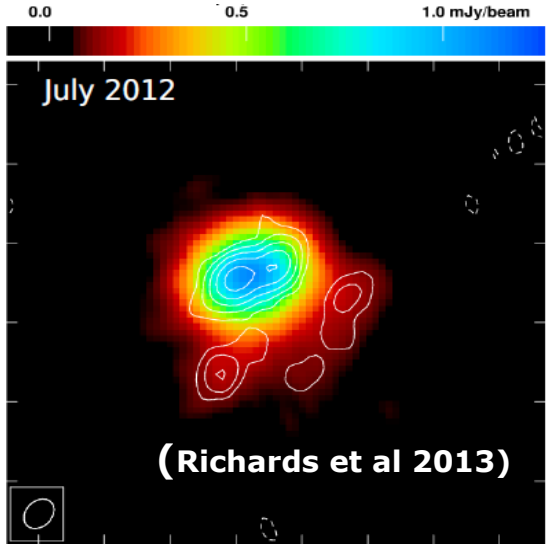
First Science and early results

- Legacy programme
  - 12 projects
  - Proto-planets... Star-formation in distant galaxies
- Open programme (PATT) – 50% of observing time.









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e-MERGE Legacy Survey

A tiered e-Merlin +JVLA Legacy project

– utilising e-Merlin step change in sensitivity & imaging ability

The e-MERlin Galaxy Evolution Survey

Tier 0 – *Imaging radio emission from normal galaxies out to z ~ 5*

Deep imaging around clusters to utilise amplification by lensing

Tier 1 – *A very deep directed survey of the μJy radio source population*

Deep imaging of the μJy radio source population in GOODS-N

The combination of these tiers will ensure a full sampling of the active and star-forming galaxy radio luminosity function out to z~5

Tier 0: Ian Smail [Durham], Tier 1: Tom Muxlow [Manchester] (Deep-narrow) , Tier 2: Ian McHardy [Southampton] (Through PATT time) (Shallow-wide)

Tier 0 – 180hrs e-Merlin (L-band) + JVLA-A

Tier 1 – 360hrs e-Merlin+40hrs JVA-A (L-band)+ 378hrs e-Merlin+ JVLA A/B/C (C-band)

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e-MERLIN

Tier 1: New Ultra-Deep Study of GOODS-N

e-MERLIN will match the depth of the existing (18 day) MERLIN image in just 24 hours of on-source integration.

L-band: Single pointing centre, ~20 days including 76m Lovell telescope.

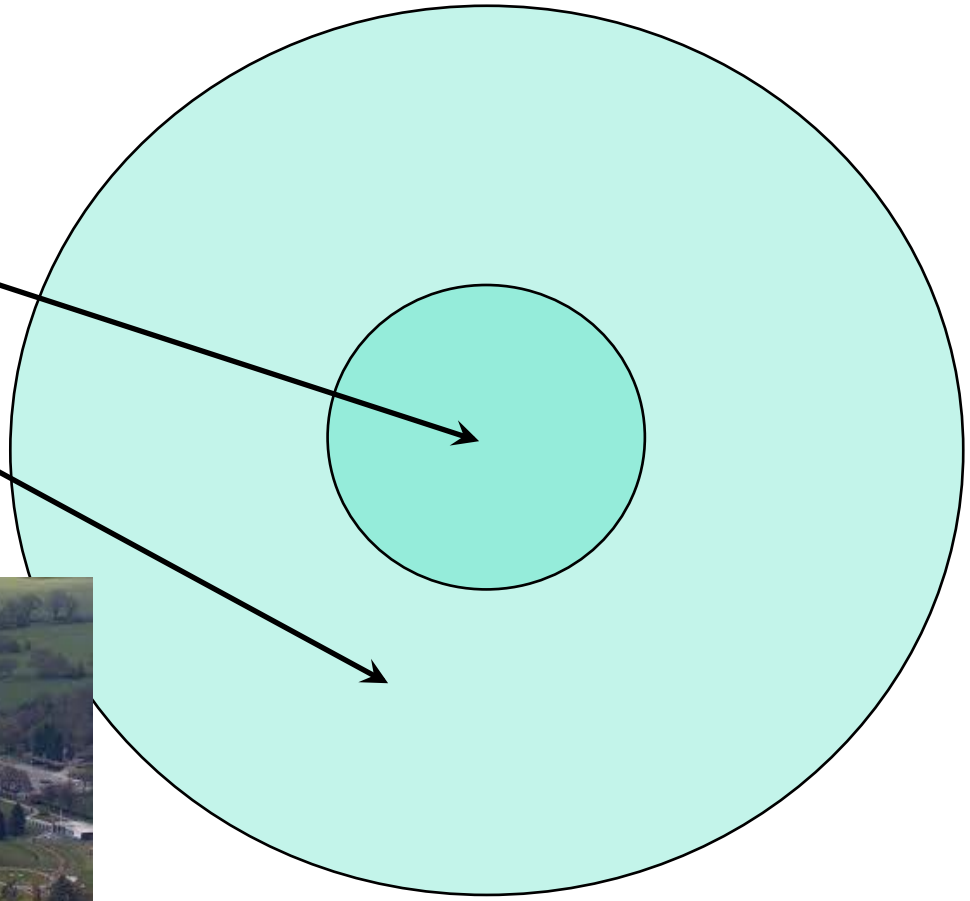
Central 12 arcminute field

1σ ~ 500nJy/beam

(in combination with JVLA)

Outer 30 arcminute field

1σ ~ 1μJy/beam



Tier 1: New Ultra-Deep Study of GOODS-N

e-MERLIN will exceed the depth of the existing MERLIN map in just 24 hours of on-source integration.

L-band: Single pointing centre, ~20 full tracks.

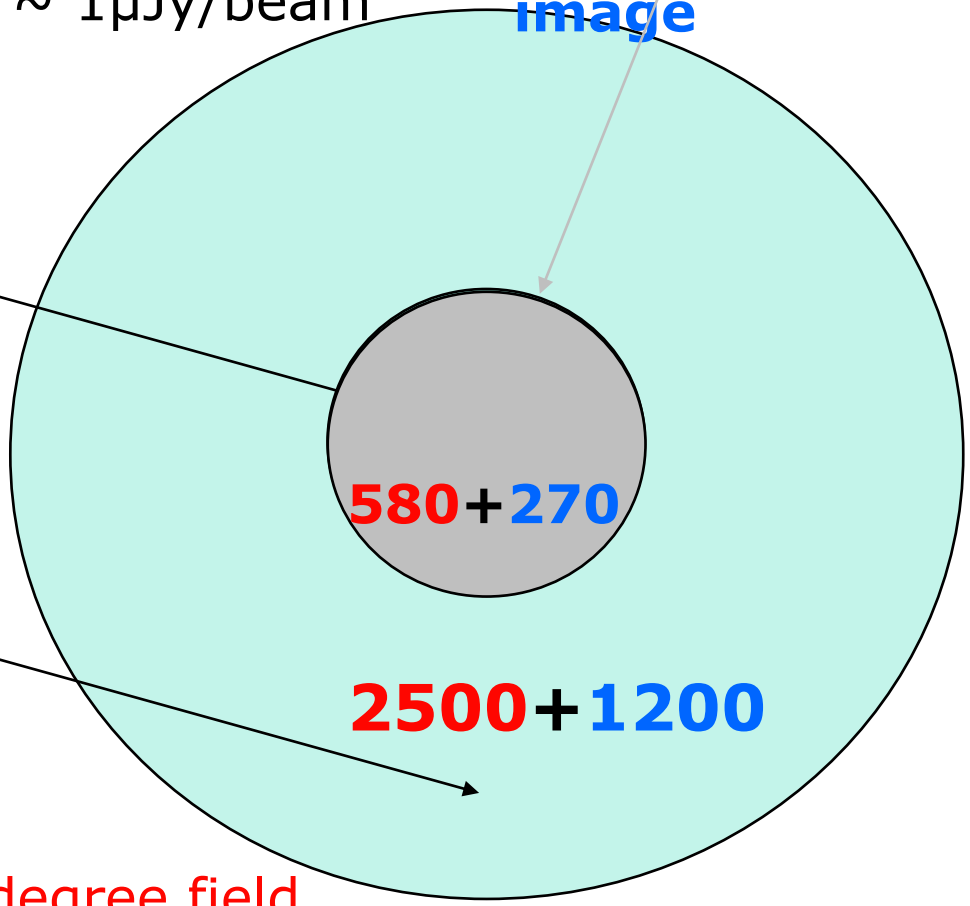
Central 12 arcminute field 1σ ~ 500nJy/beam

Outer 30 arcminute field 1σ ~ 1μJy/beam

e-MERLIN will image ~850 individual starburst and AGN with an angular resolution of ~170 mas, complete to ~3μJy

(>10 times deeper than the 2005 study)

In the surrounding 800 square arcmins, *e*-MERLIN will image ~2500 star-forming galaxies and ~1200 AGN brighter than ~6μJy



>5000 sources in 0.2 square degree field

Tier 1: New Ultra-Deep Study of GOODS-N

New C-band image: 7 pointing centres

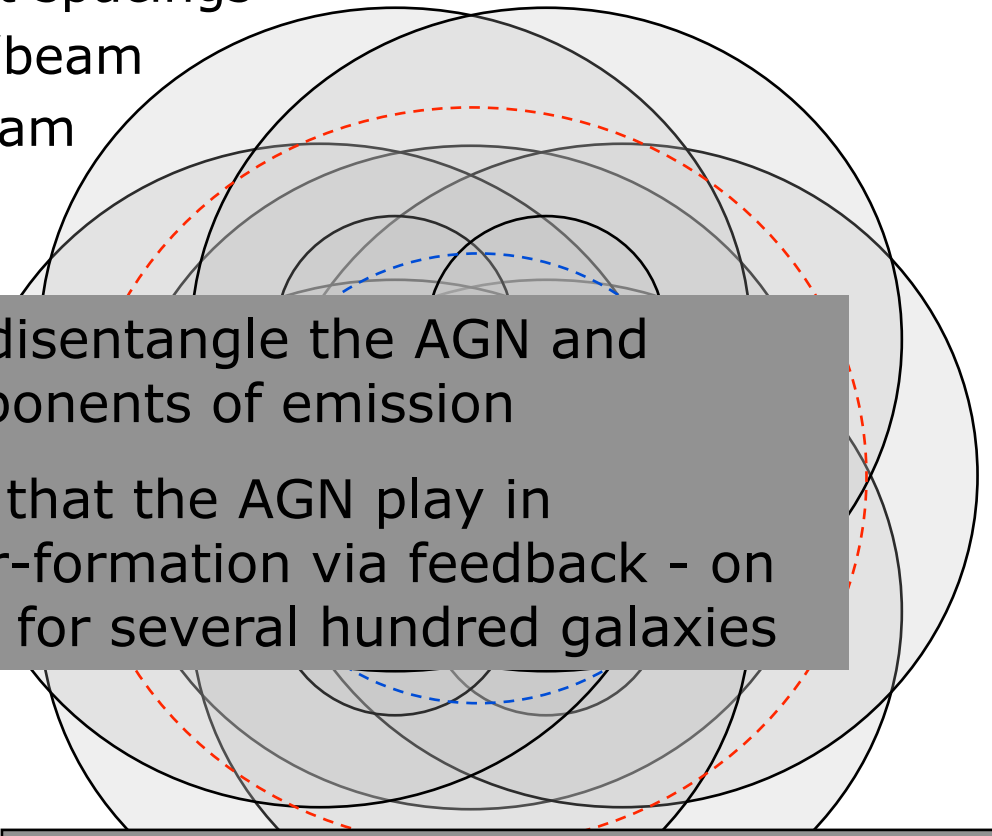
Mosaic pattern set for Lovell - 25m beam

JVLA will provide short spacings

Inner 6′ 1σ ~ 500nJy/beam

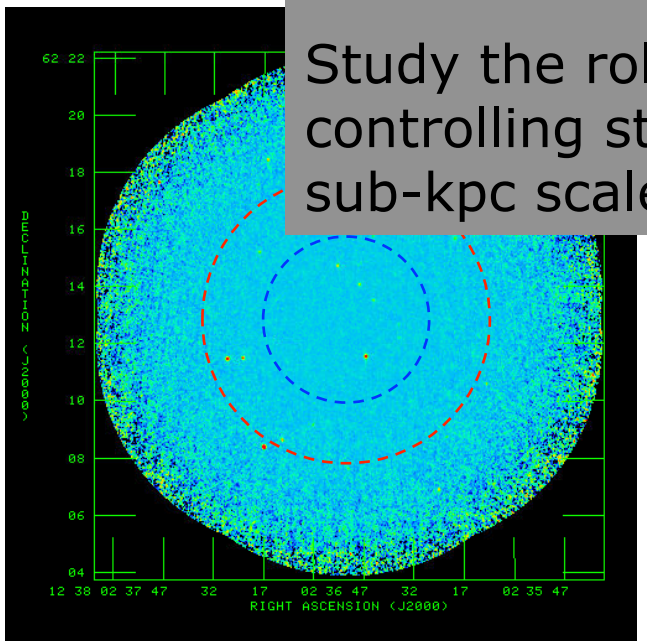
6-12′ 1σ ~ 700nJy/beam

Resolution ~40 mas



Separate and disentangle the AGN and starburst components of emission

Study the role that the AGN play in controlling star-formation via feedback - on sub-kpc scales for several hundred galaxies



JVLA C-array 7 pointing mosaic – for addition to B & A-array data + e-MERLIN

Resolution ~5 arcsec, 1σ noise 5.5μJy/bm

Tier 1: New Ultra-Deep Study of GOODS-N

Recent L-Band e-Merlin test taken and now being processed.

Test data: 26 hours on target → 1σ noise ~6.6μJy/bm

Full spatial frequency coverage: → Superb image fidelity – from just 7 (6) antennas - 1230 MHz – 1740 MHz (34%)

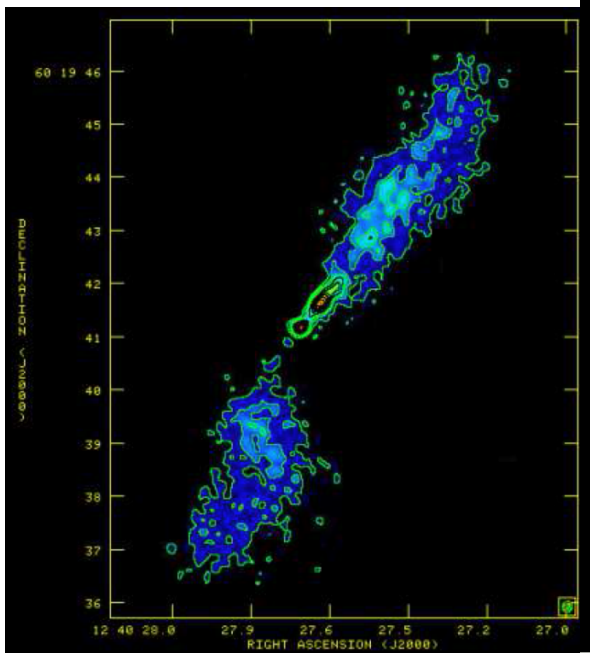
Even reference field deep enough to image interesting confusing sources

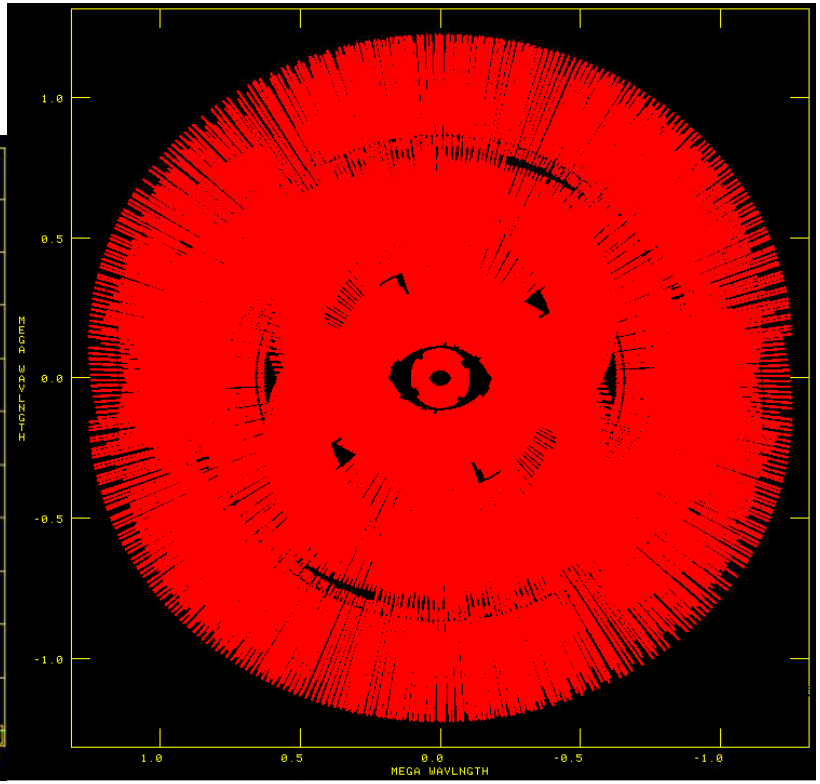
– ~20mJy FR-I

– 8’ offset

– Peak ~926μJy/bm

~3mJy unresolved flux density within central 12 arcmin field is sufficient for ϕ self-calibration

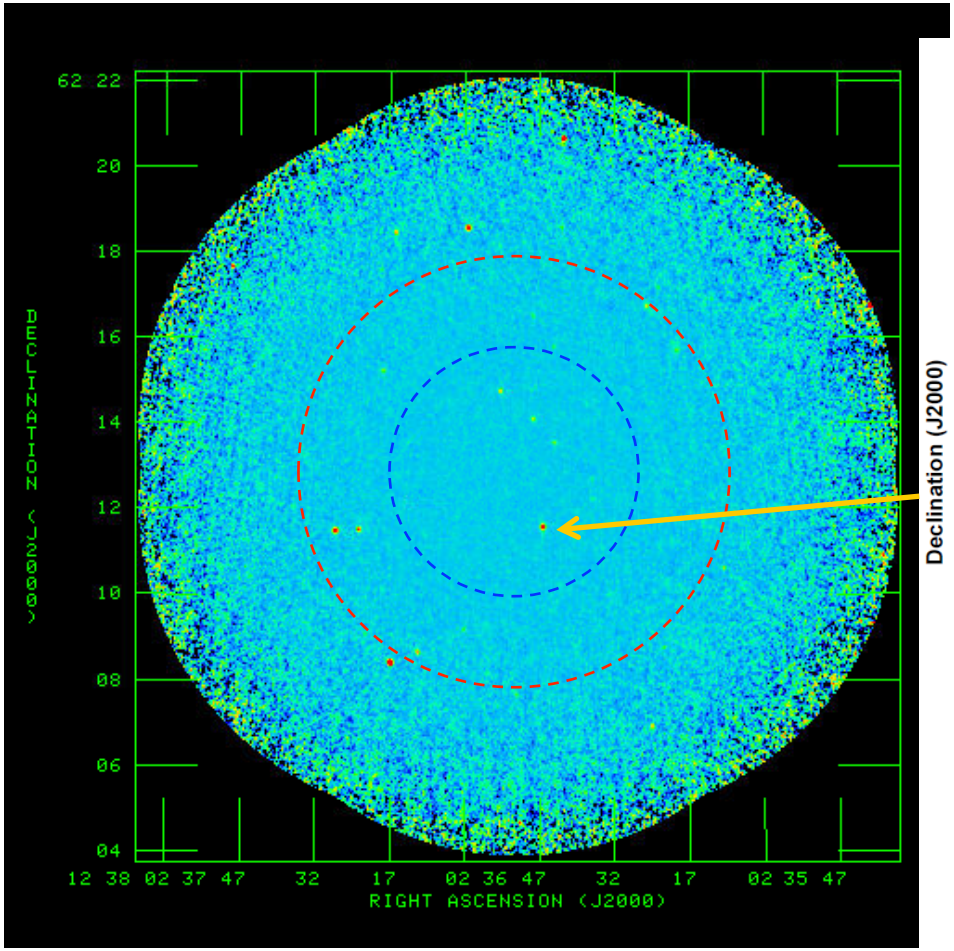


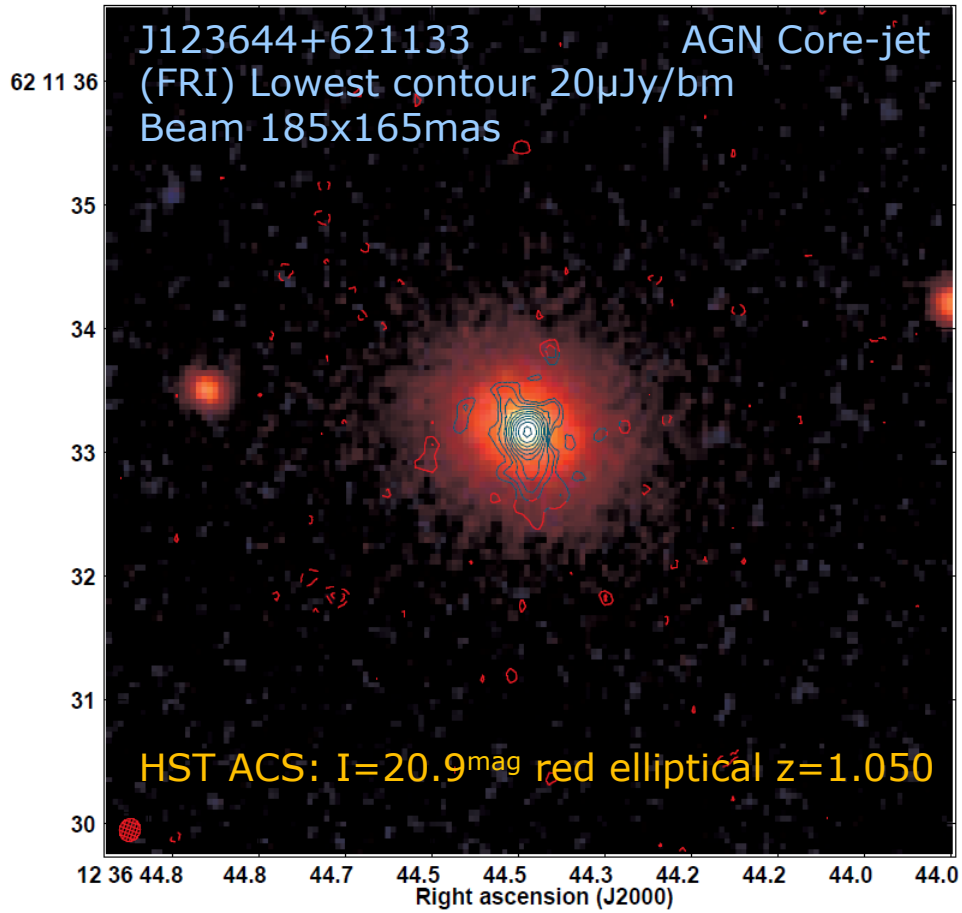


Tier 1: New Ultra-Deep Study of GOODS-N

Test e-MERLIN L-band data: 26 hours on target → 1σ noise ~6.6μJy/bm

Core-jet AGN at nucleus of 11” N-S FR-I (Total 5.96mJy)



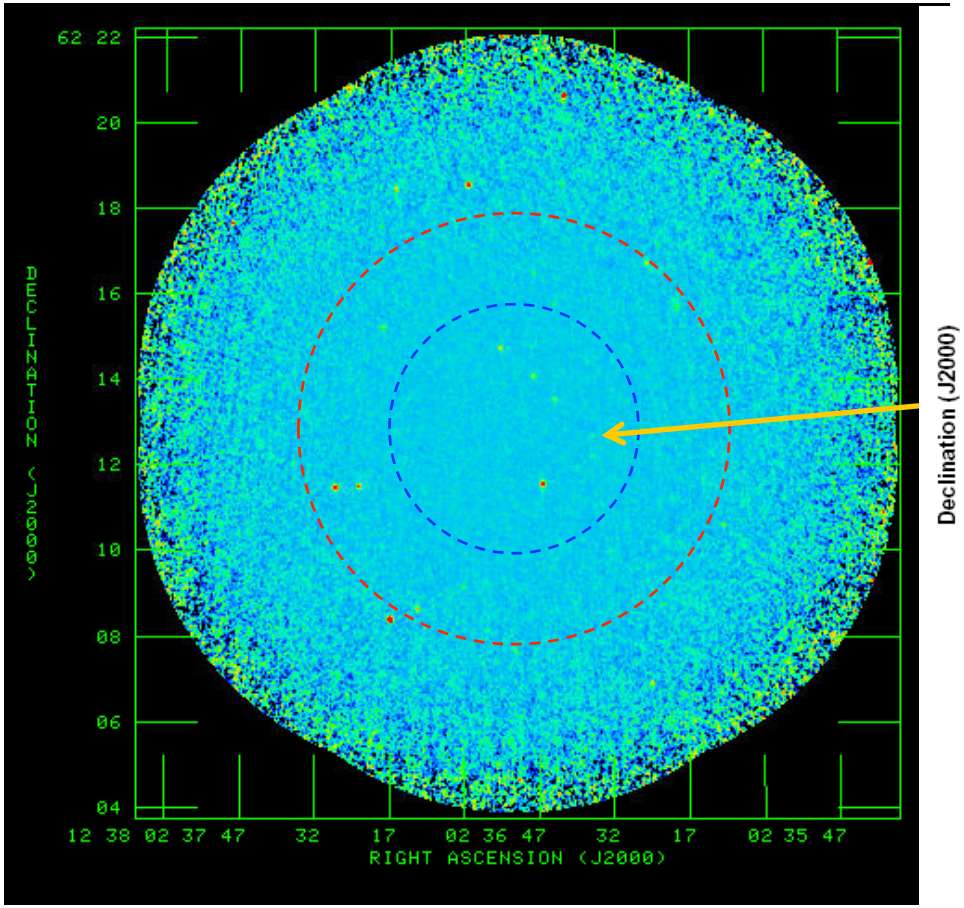


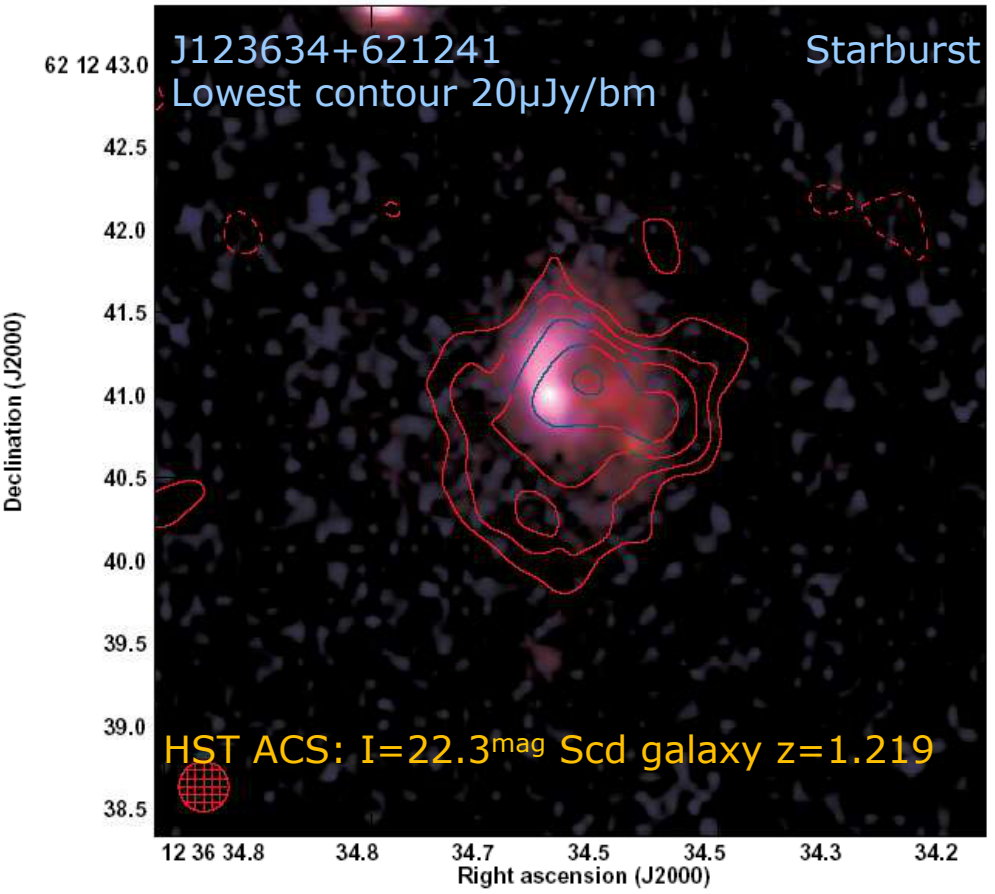
Tier 1: New Ultra-Deep Study of GOODS-N

Test e-MERLIN L-band data: 26 hours on target → 1σ noise ~6.6μJy/bm

Extended steep-spectrum (α=0.74) starburst (Total 230μJy) ISO detection

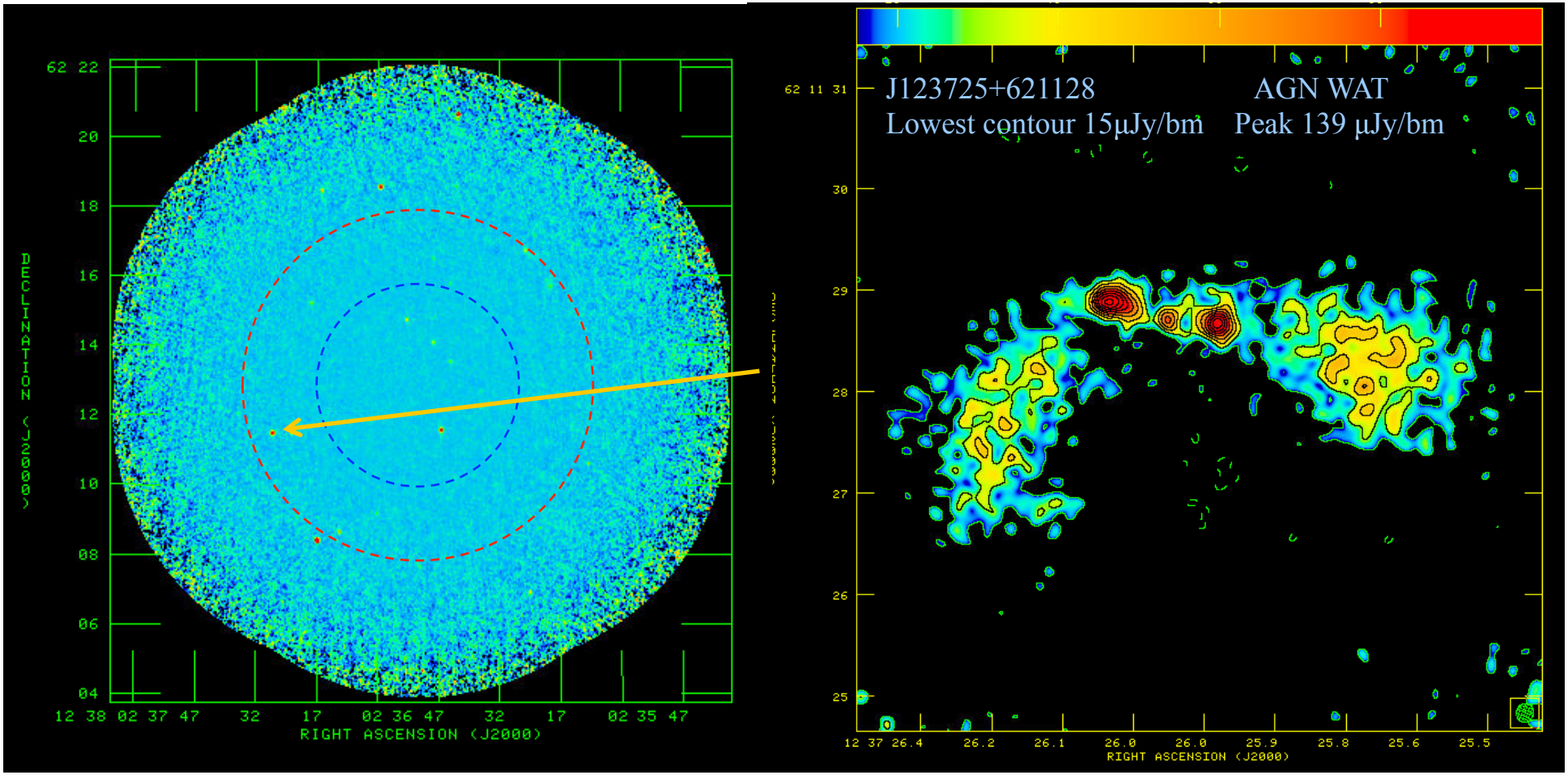
$L_{1.4}$ =4.1x10^{24} W/Hz → Star-formation rate ~960 M⊙/yr (0.1-100M⊙ assuming Salpeter IMF)





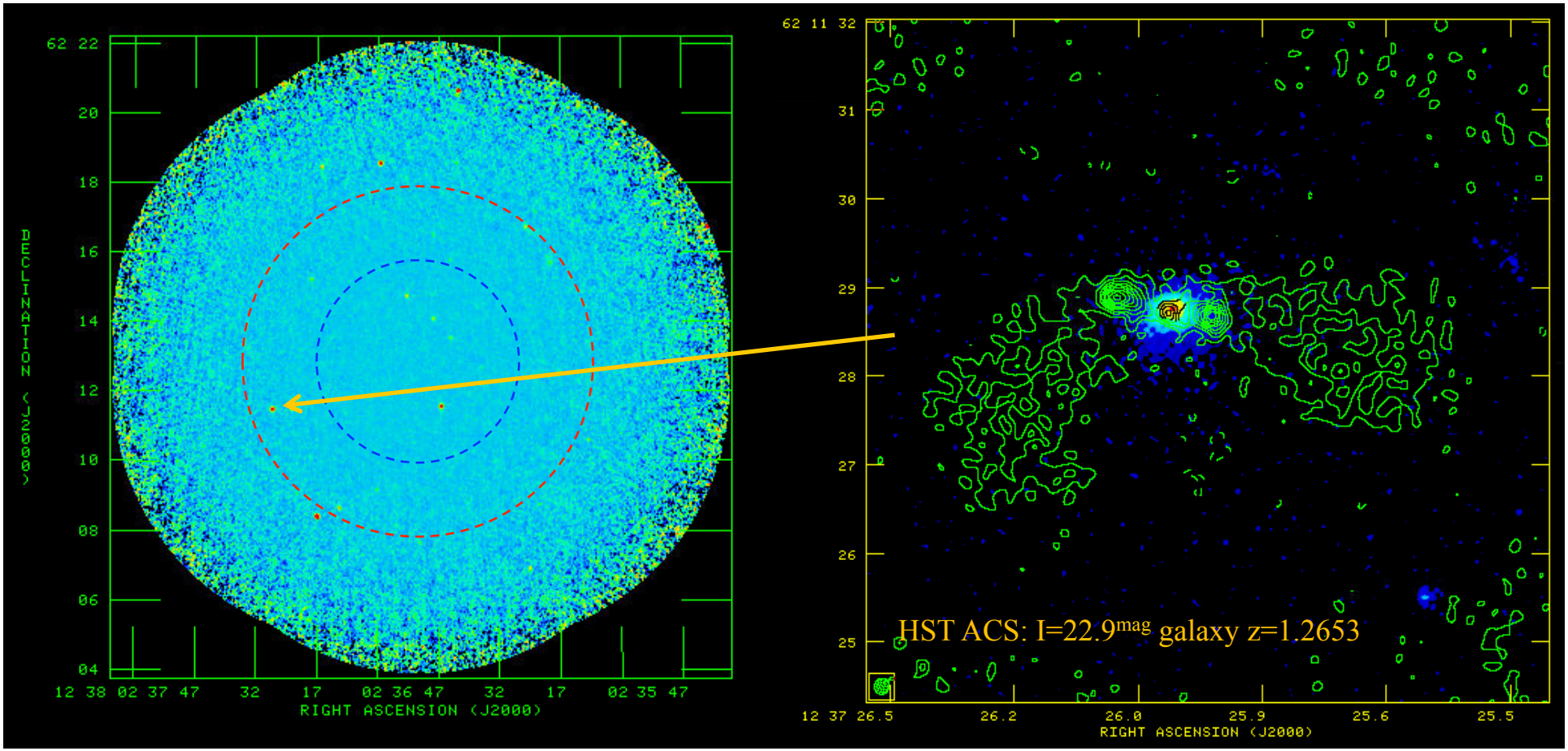
Tier 1: New Ultra-Deep Study of GOODS-N

AGN Wide-angled tail radio galaxy (Total 1.3mJy)



Tier 1: New Ultra-Deep Study of GOODS-N

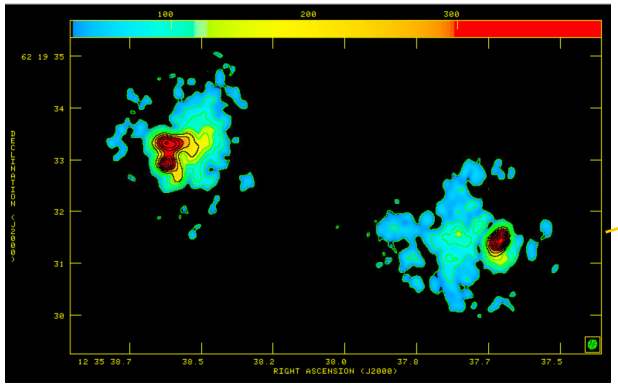
AGN Wide-angled tail radio galaxy (Total 1.3mJy)

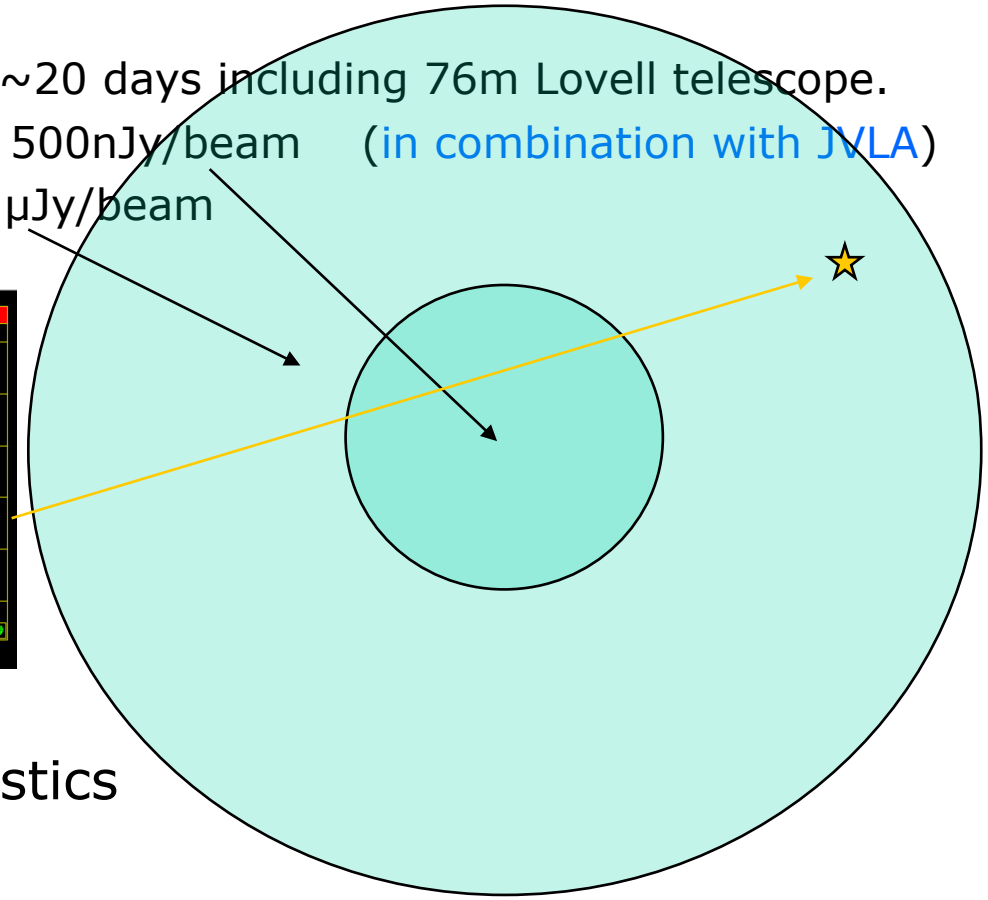


Tier 1: New Ultra-Deep Study of GOODS-N

ide-field data allows imaging to the edge of the outer field:
62mJy FR-II imaged (test data) – 10.4 arcminutes from field centre

L-band: Single pointing centre, ~20 days including 76m Lovell telescope.
Central 12 arcminute field 1σ ~ 500nJy/beam (in combination with JVLA)
Outer 30 arcminute field 1σ ~ 1μJy/beam





Target of field source count statistics free from sample variance, over small but deep region

Tier 1: New Ultra-Deep Study of GOODS-N

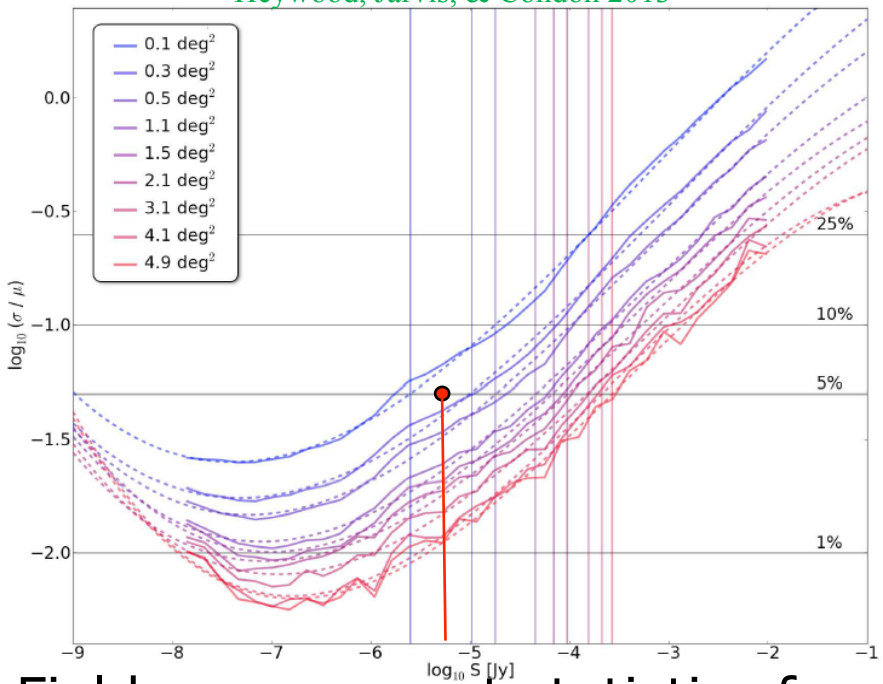
30′ field ~0.2 deg² – Complete to 6μJy → source count scatter imposed by sample variance ~5% of the mean & sources ~unresolved to JVLA

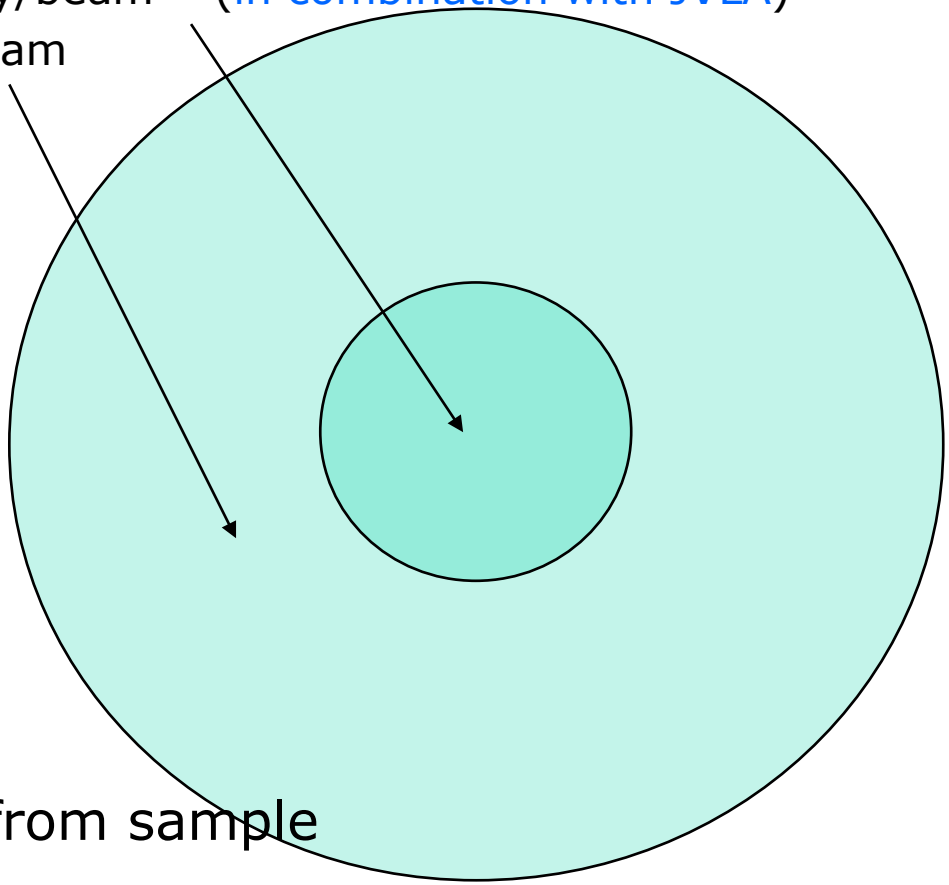
L-band: Single pointing centre, ~20 days including 76m Lovell telescope.

Central 12 arcminute field 1σ ~ 500nJy/beam (in combination with JVLA)

Outer 30 arcminute field 1σ ~ 1μJy/beam

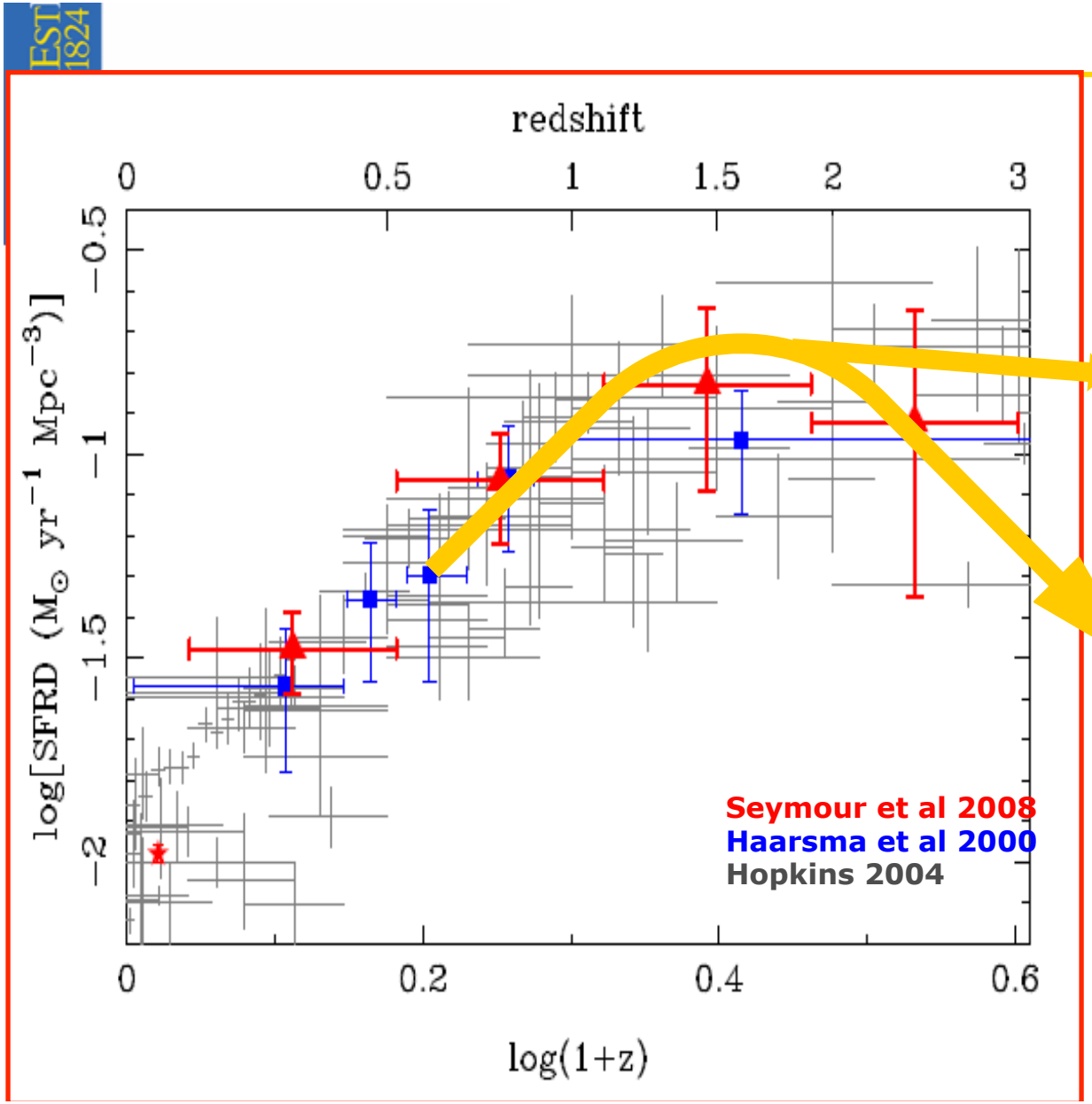
Heywood, Jarvis, & Condon 2013





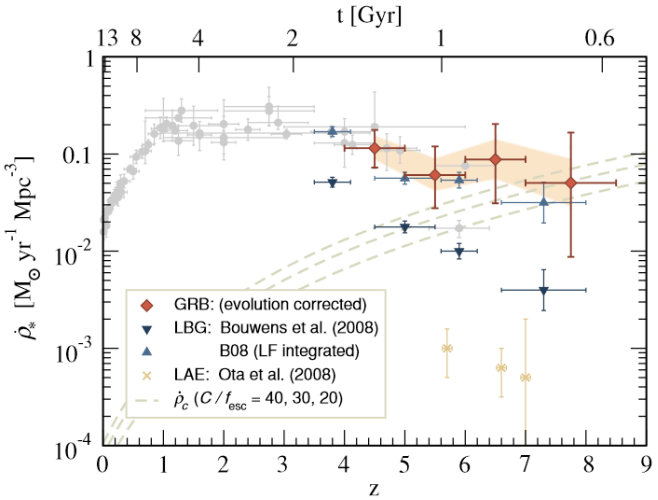
Field source count statistics free from sample variance

Star-formation History of the Universe - from Starburst Luminosities



The co-moving Star-Formation Rate Density of the Universe from L-Band radio studies by Seymour et al (2008), Haarsma et al (2000), & UV, Hα, Far-IR… Hopkins (2004)

L-Band results from the eMERGE survey will provide data for several thousand more sources



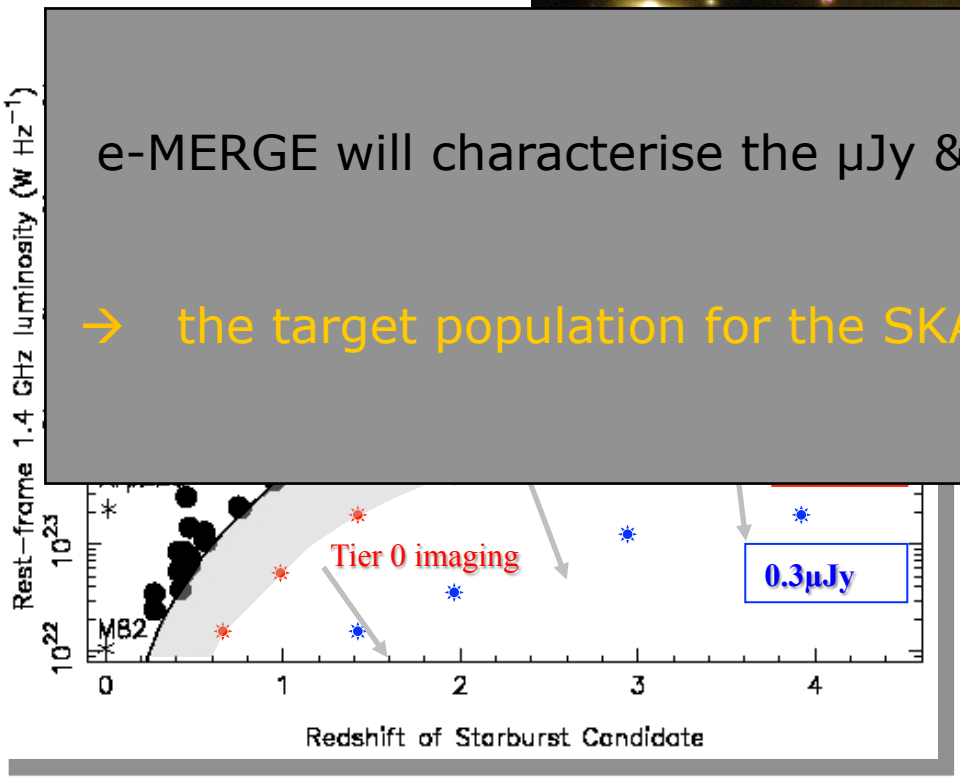
Star-formation from GRB studies – Kistler et al 2009

Tier 0: Imaging sub-μJy galaxies

A single L-band pointing on a strongly lensing cluster A2218 (z=0.18).

e-MERGE will characterise the μJy & sub-μJy radio source population

→ the target population for the SKA in future high redshift SF studies



Measure faint radio counts

May include SF galaxies with SFR~200M◉/yr to z~5

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e-MERLIN

Summary

- e-MERLIN is full operational
  - Unique capabilities of uJy and sub-arcsecond imaging
  - Simultaneous spectral line modes
  - Wide range of science
  - wide-ranging key-science programme
    - driving science & operational developments.
  - Further developments coming soon
    - 2GHz b/w at C-band, improved 22GHz sensitivity .....
- Few hundred km baseline SKA pathfinder.
  - Resolution key for much of e-MERLIN astrophysics & continuum science.
  - Typical moderate redshift galaxy size is ~<1arcsec
- Communications with users critical.
  - Early science helps keep users involved & contributing

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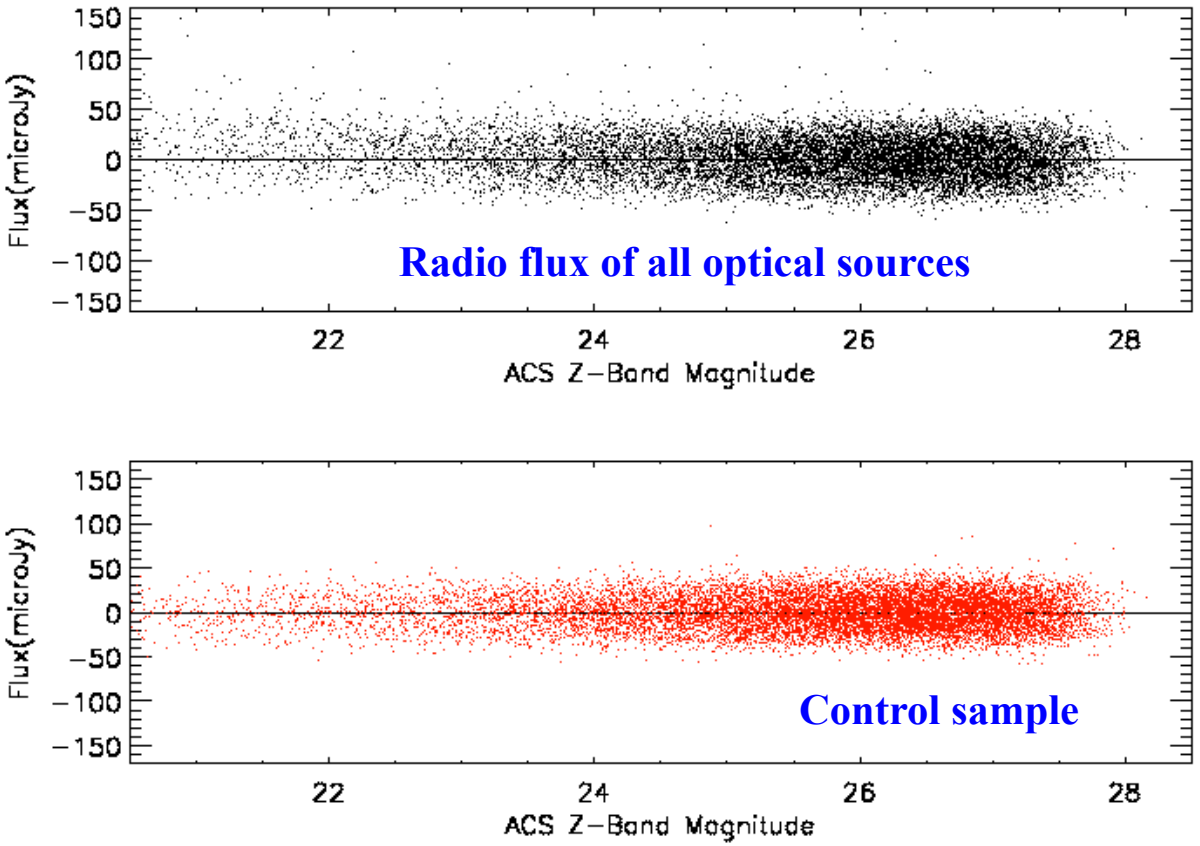
Stacking of deep MERLIN data: GOODS – ACS data

- **~13030** galaxies above mag 28.3 mag in *z*-band (just in 8.5 arcmin^2 field)
- ACS images aligned with MERLIN radio image to <0.05 arcsec rms.



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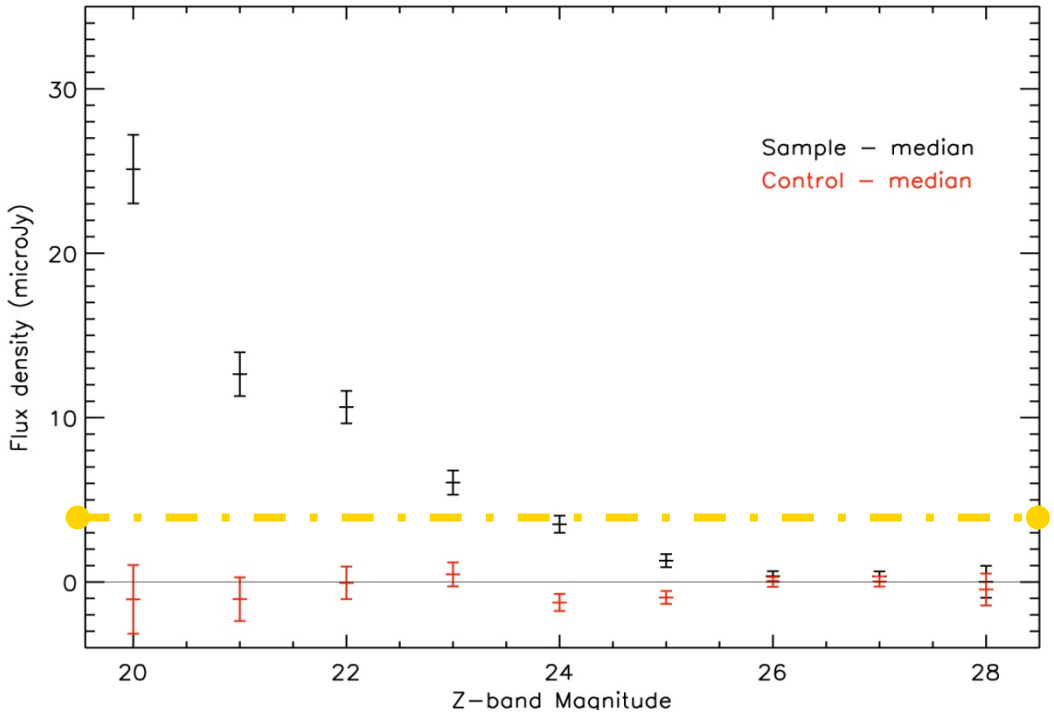
Radio census of ACS sources

- Radio flux within 0.75arcsec of all z-band optical galaxies.

(Note excluding all bright radio sources (>20μJy pixel))



Median values are not statistically different from means implying that of the ~2700 galaxies brighter than Z=24mag, around 1400 will have radio flux densities of ~4μJy or greater (~8σ for a deep *e*-MERLIN/EVLA image)

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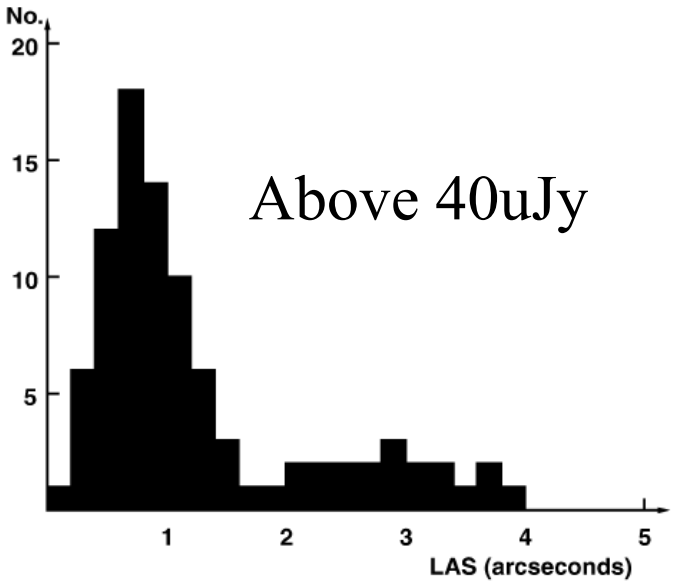
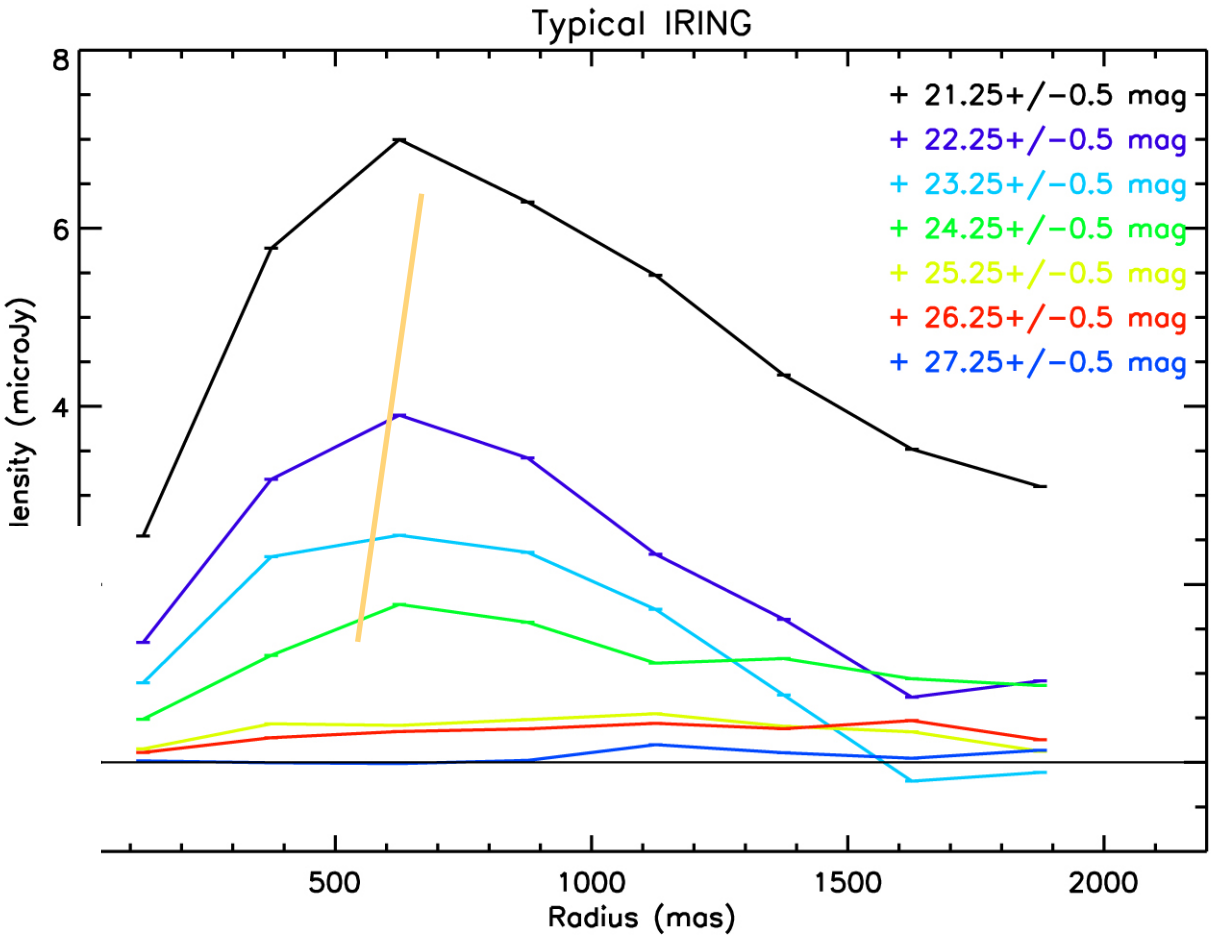
Radio source sizes:

very weak (sub-20uJy) radio sources

Average source sizes range from r~0.75arcsec (21.25^{mag} [~12μJy]) to



Above 40uJy



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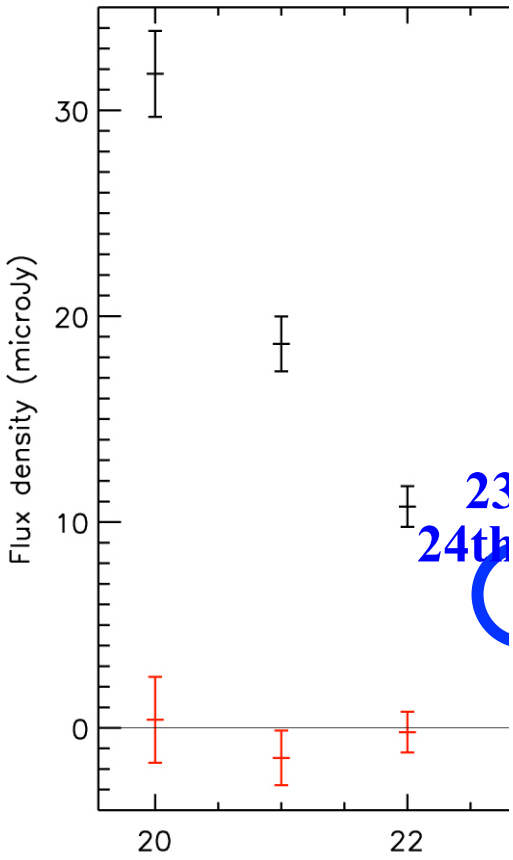
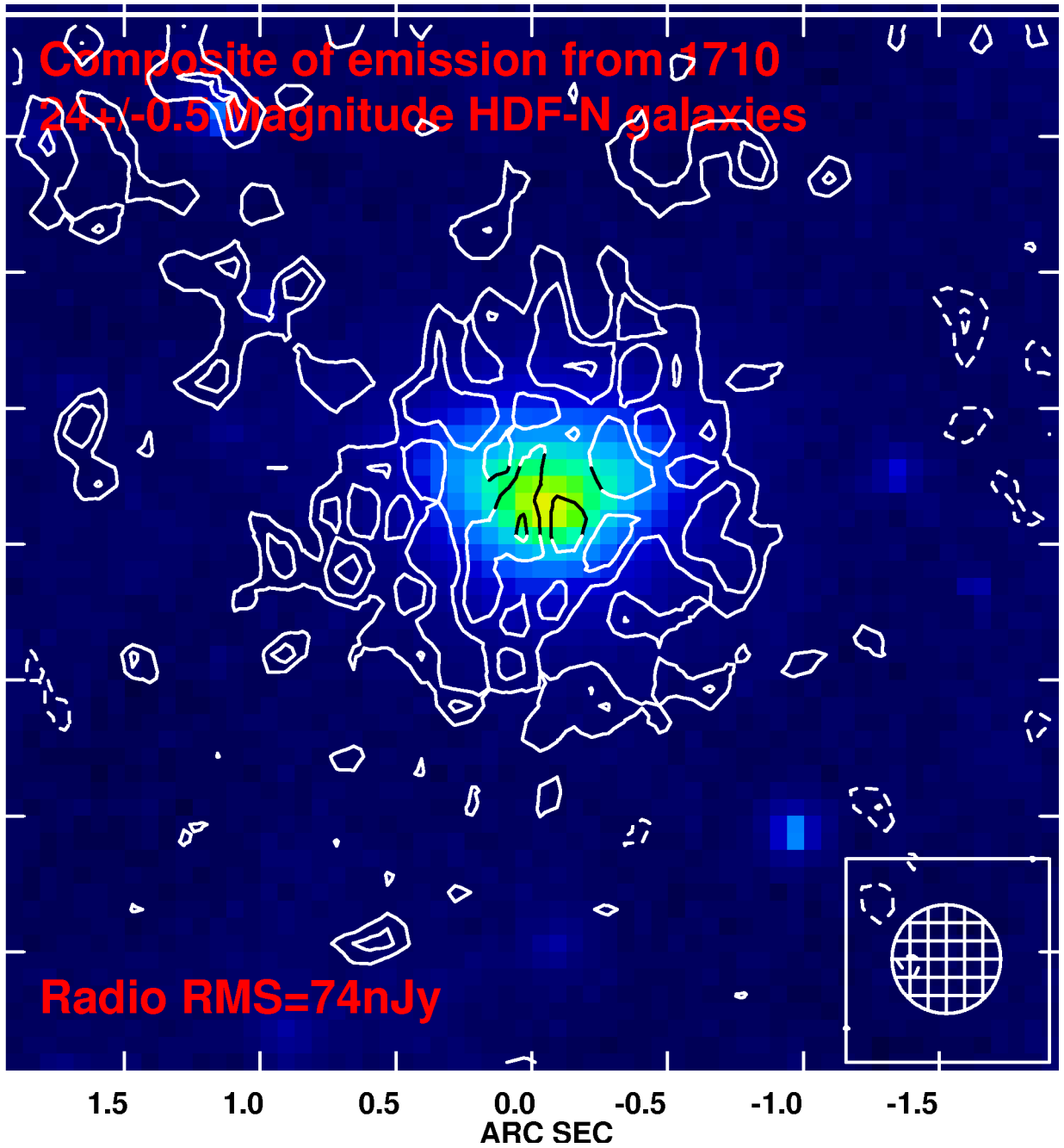
Average im





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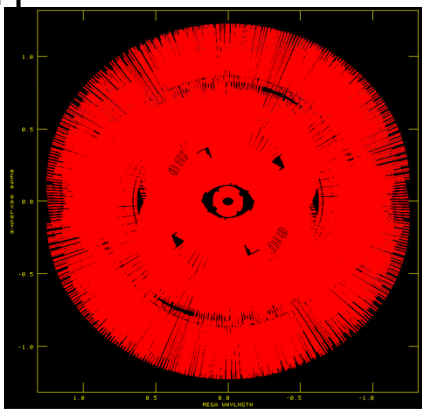
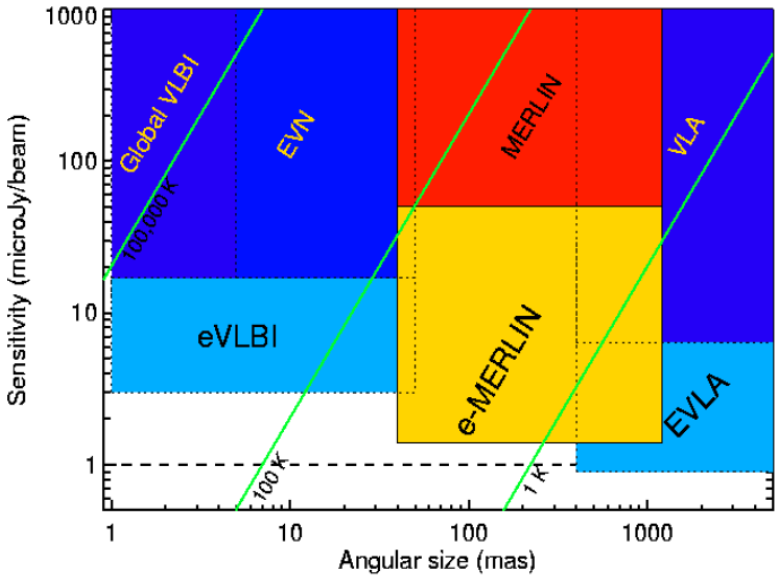
Capabilities

- 150, 40, 10 mas resolution at L[20cm],C[6cm],K[1.3cm]
- ~2 uJy sensitivity in typical runs
  - <uJy in deep fields
  - ~30 uJy in ~1 min
- Wide fields
  - Out to HPBW of 25-m [7,27 arcmin]
- Spectroscopy
  - 16 placeable sub-bands;>512 channels/pol; recirculation
  - Can mix/trade bandwidths; no. of channels, polarisations
- Much improved aperture coverage
  - Via frequency coverage
  - May help snapshots too
- Spectral mapping
  - 1.3-1.7; 5-7/4-8 GHz
- Polarization (L,R → IQUV)
- Astrometry
  - Goal is < 1 mas wrt ICRF: using GPS measurements of troposphere delay (5cm error -> 5mm); closer calibrators





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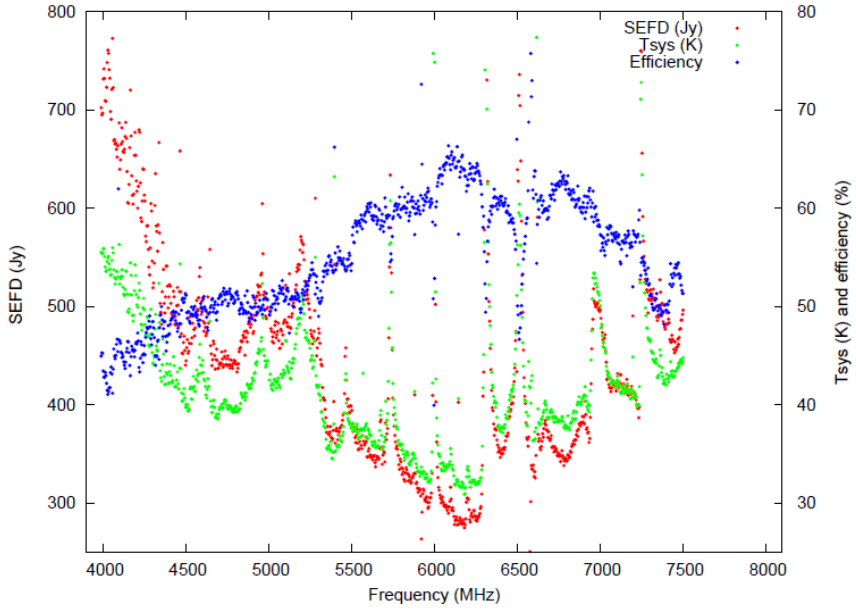
C-band Performance

- C-band – on telescope
  - Tsys: ~34K over 512 MHz
    ~38K over 2 GHz
    SEFD (25-m) 300, 340Jy
- C-band noise measuremer
  - 10-15% higher (low elevatio
- Image noise measuremen
  - ~ 15 uJy/beam, 512 MHz, no Lovell
- RFI – time consuming
  - Groups working on auto-flaggers
  - Not a major impact on C-band performance



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e-MERLIN

Optical fibre synchronisation

- Single H-maser at Jodrell Bank
- 2-way transmission system
- Local frequency standard at telescopes

- Now fully implemented on optical fibre network on separate fibre or additional DWDM wavelengths
- Improved short term stability
- Diurnal drifts – incorporated into delay model