The University of Manchester
Jodrell Bank Observatory

MANCHESTER 1824

EUROPEAN VLBI NETWORK

Planned future high-resolution radio observations of the GOODS-N field

A very deep directed survey of the μJy radio source population (e-MERLIN Legacy)

Tom Muxlow

Bologna, 24th September 2008

Science & Technology Facilities Council

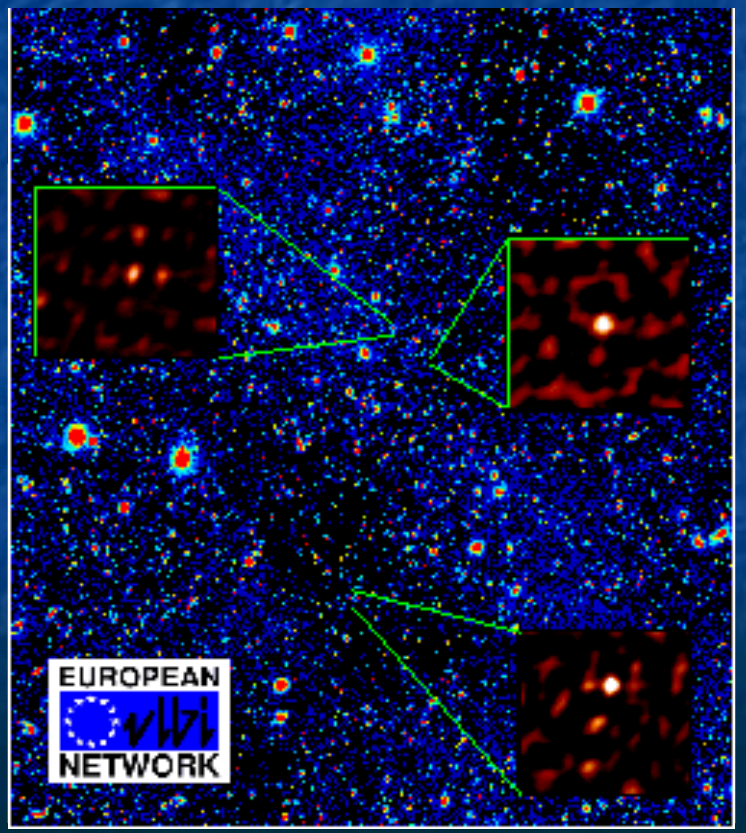
JIVE JOINT INSTITUTE FOR VLBI IN EUROPE

Outline

- The Original MERLIN / VLA / EVN study
- Developments from the original study
  – enabled by Astrogrid access [Anita Richards, Paul Harrison]
  - Statistical properties of the radio source population to a few μJy
  - Embedded AGN and star-formation activity in the sub-mm source population
- The proposed new ultra-deep *e*-MERLIN / EVLA study of the GOODS-N field and the role of the EVN in this investigation

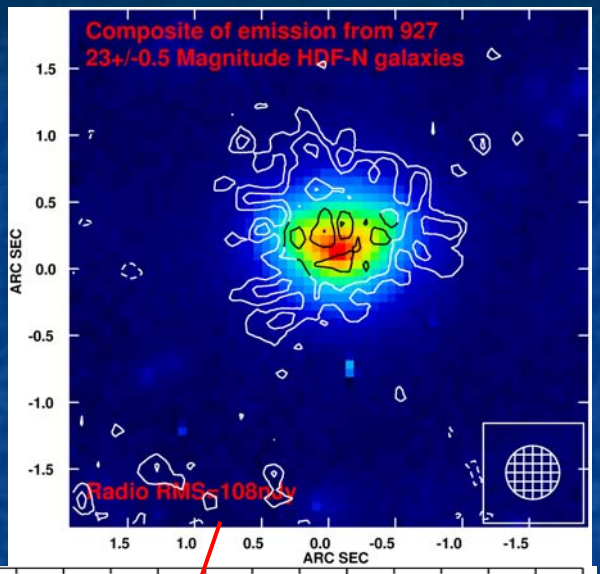
The Original Study [Muxlow et al. 2005]

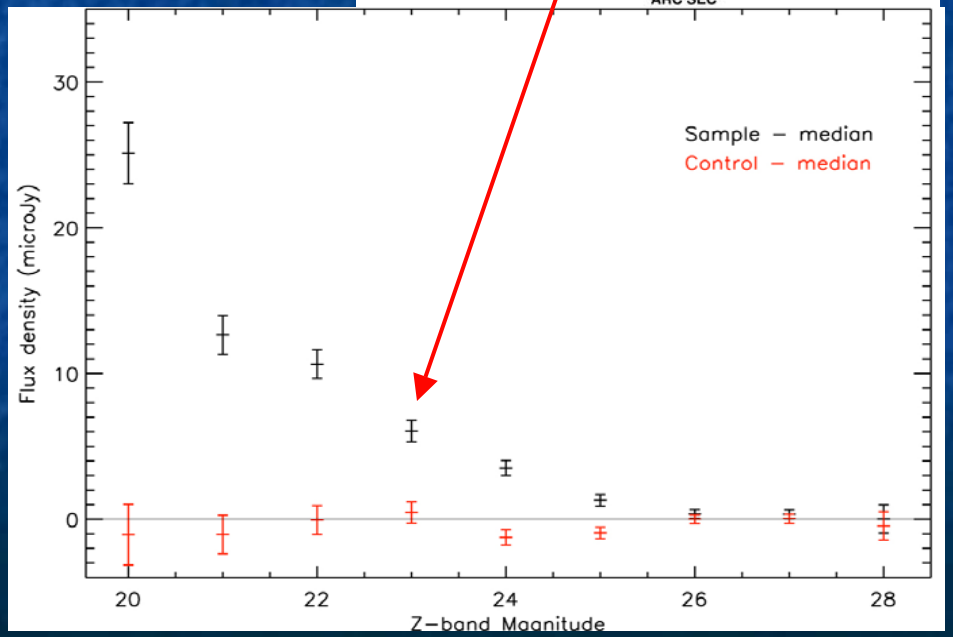
- Within a 10×10 arcmin field centred on the Hubble Deep Field North, 92 radio sources were detected by the VLA at L-Band above a completeness limit of 40μJy. Data date from mid 90's
- Combination L-Band MERLIN/VLA observations can morphologically distinguish AGN from starburst systems
- Below ~70μJy the radio population becomes dominated by powerful star-forming galaxies typically at z<1.5 and with SF rates of many times those seen in nearby star-forming galaxies
- Around 15% of the population lie at higher redshifts, many of which are also identified as sub-mm sources.
- Some of the most luminous starburst systems also show evidence for powerful embedded AGN (VLBI data)



Recent Developments - 1

- Utilising ancillary data from GOODS-N, radio emission at the level of a few μJy has been statistically detected associated with ACS galaxies brighter than a z-band magnitude of 26
- Identified as extended starburst systems with average properties similar to those star-forming galaxies studied individually at higher flux densities
- Evolution of the infrared-radio correlation seen at very low flux densities (Beswick et al 2008)





Radio emission with 0.75" of 13030 z-band galaxies – excluding bright sources and close galaxy pairs

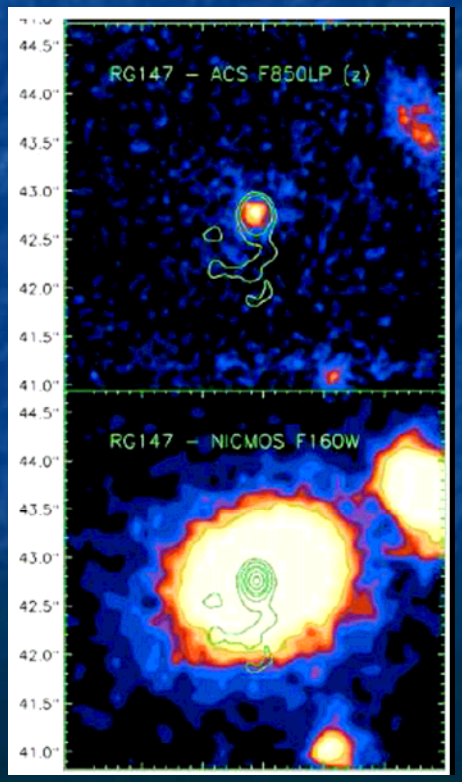
Muxlow et al 2007

Recent Developments - 2

- High-resolution radio imaging is a powerful diagnostic tool and has been used to discriminate between AGN and star formation in the diverse sub-mm galaxy (SMG) populations at z~2. (IoA group)
- Two thirds of the SMGs show resolved radio morphologies extending to ~1" → bolometric output arises in extended, faint, dust obscured regions that are forming stars at close to their Eddington limit (Chapman et al 2008)
- MERLIN +VLA imaging have identified some sub-mm faint radio galaxies within GOODS-N as part of the radio-AGN population – previously misidentified as starbursts at other wavelengths (Casey et al. 2008)

z=1.92 radio source initially identified as a starburst, but revealed by MERLIN as an AGN core-jet.

Optical imagery [top] reveals a compact source characterized as a starburst from Keck spectroscopy, while near-IR imagery [bottom] reveals a giant Elliptical galaxy.



New Ultra-Deep Study of GOODS-N

- Part of a tiered *e*-MERLIN Legacy proposal – the *e*-MERGE Survey is designed to study the formation and evolution of star-forming galaxies and AGN out to redshifts > 5

  – 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*
  - Tier 2 – *A reliable cosmic census of starburst and AGN populations*
    - *Medium depth imaging over a number of fields (total area ~2 sq. degrees)*

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

>60 CO-Is from 9 countries

Tier 0: Ian Smail [Durham], Tier 1: Tom Muxlow [Manchester] Tier 2: Ian McHardy [Southampton]

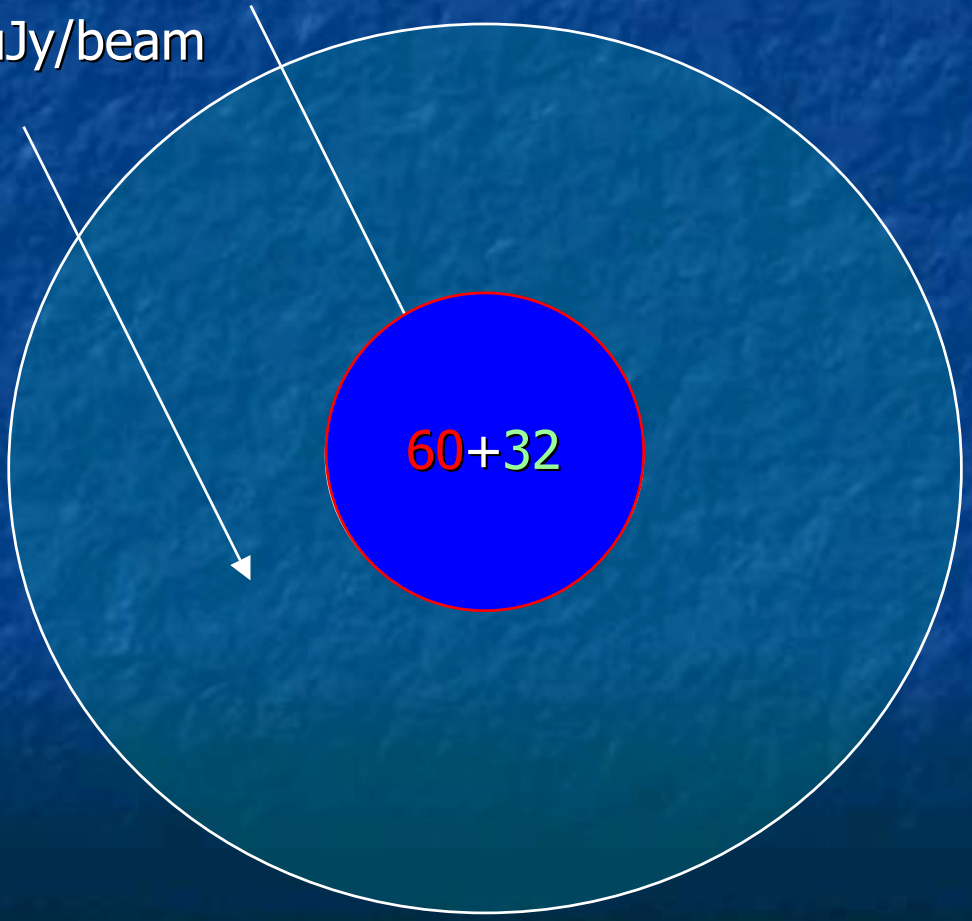
~2400 hours of *e*-MERLIN time proposed

New Ultra-Deep Study of GOODS-N

- A very deep survey of some of the faintest radio starburst galaxies and AGN systems in the GOODS-N region – designed to directly address the following key science drivers:
  - To extend the star-formation (SF) density history to redshifts >5 and thus trace the evolution of star-formation through cosmic time.
  - To determine the contribution of AGN to activity in the distant galaxy population and separate AGN from starbursts by high resolution multi-frequency observations.
  - To determine the role of AGN in driving and controlling the SF processes
  - To statistically characterize the nature of the sub-μJy radio population – the target objects for the SKA

New Ultra-Deep Study of GOODS-N

- *e*-MERLIN will exceed the depth of the existing MERLIN combination map in just 24 hours of on-source integration.
- L-Band: Single pointing centre, 20 full tracks including Lovell telescope.
- Central 10 arcminute field $1\sigma \sim 500$nJy/beam
- Outer 30 arcminute field $1\sigma \sim 1\mu$Jy/beam



- cf – Original study:18 full tracks +42 hours VLA A-array
- Central 10 arcminute field only
- $1\sigma \sim 3.3$ μJy/beam

- 92 sources >40μJy
- 60 starburst galaxies
- 32 AGN systems

New Ultra-Deep Study of GOODS-N

+ matching EVLA L-Band A-array data (~ 40 hrs)

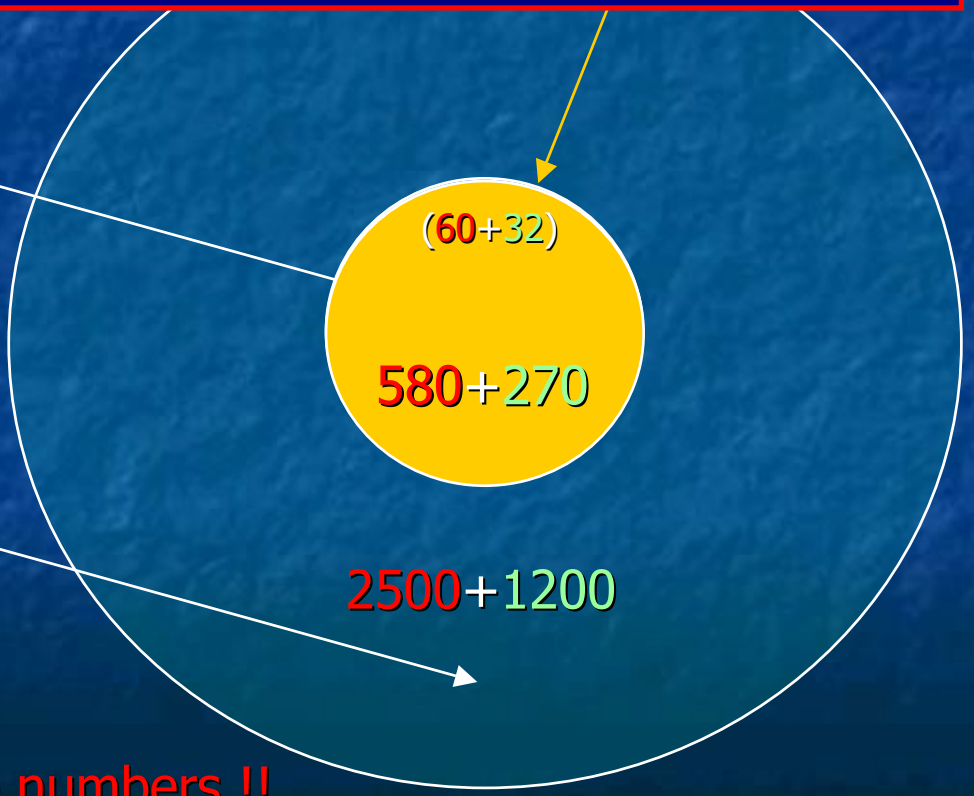
→ short-spacing coverage for very extended source recovery

→ reduces noise by ~ 1.5 → ~ 330 & 670 nJy/beam

- *e*-MERLIN will image ~850 individual starburst and AGN with an angular resolution of ~200 mas, complete to ~3μJy

  (>10 times deeper than the original study)

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



- 5250:92 >50x increase in source numbers !!

New Ultra-Deep Study of GOODS-N

The ultra-deep C-Band image will:

Map the star-forming regions in great detail

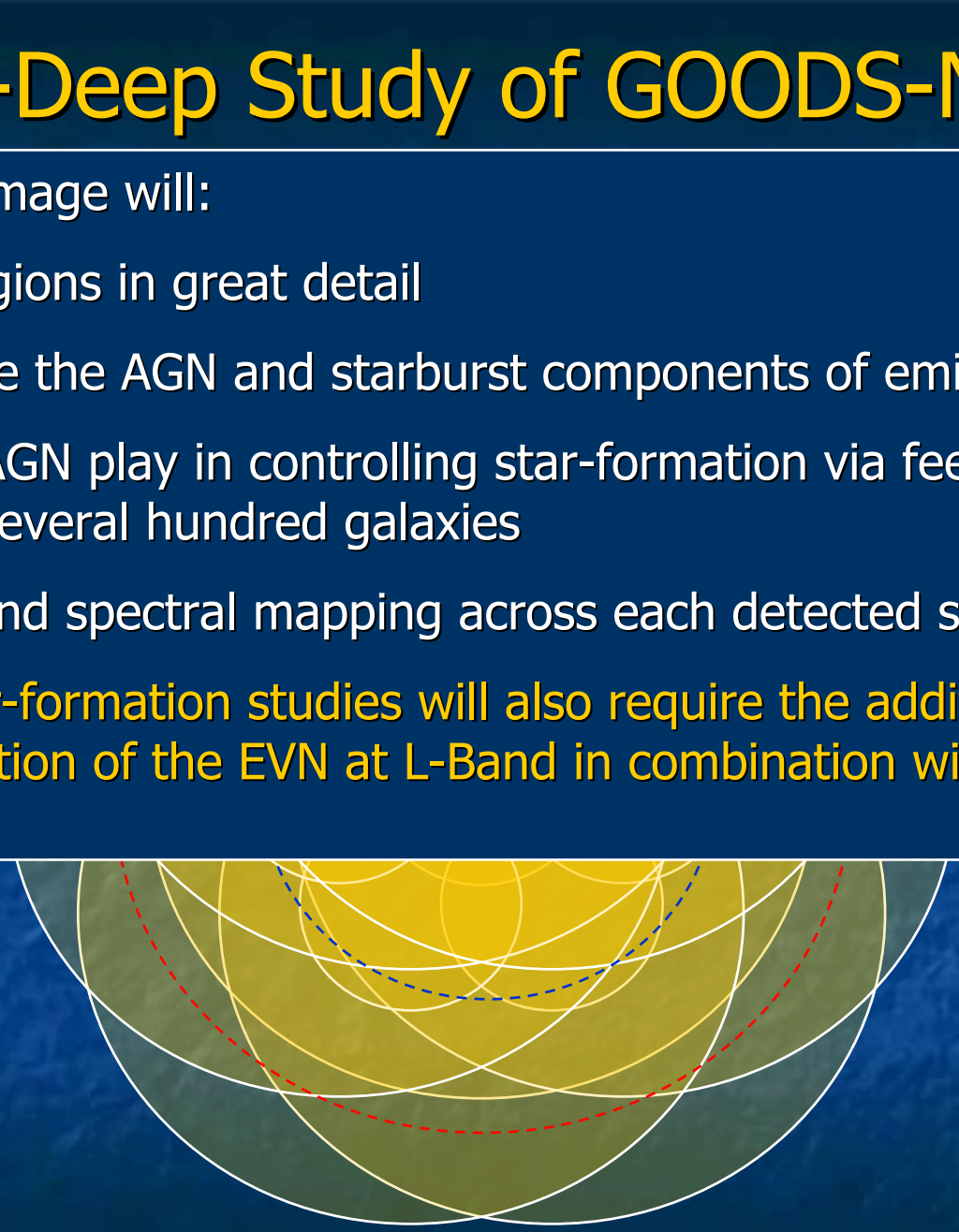
Separate and disentangle the AGN and starburst components of emission

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

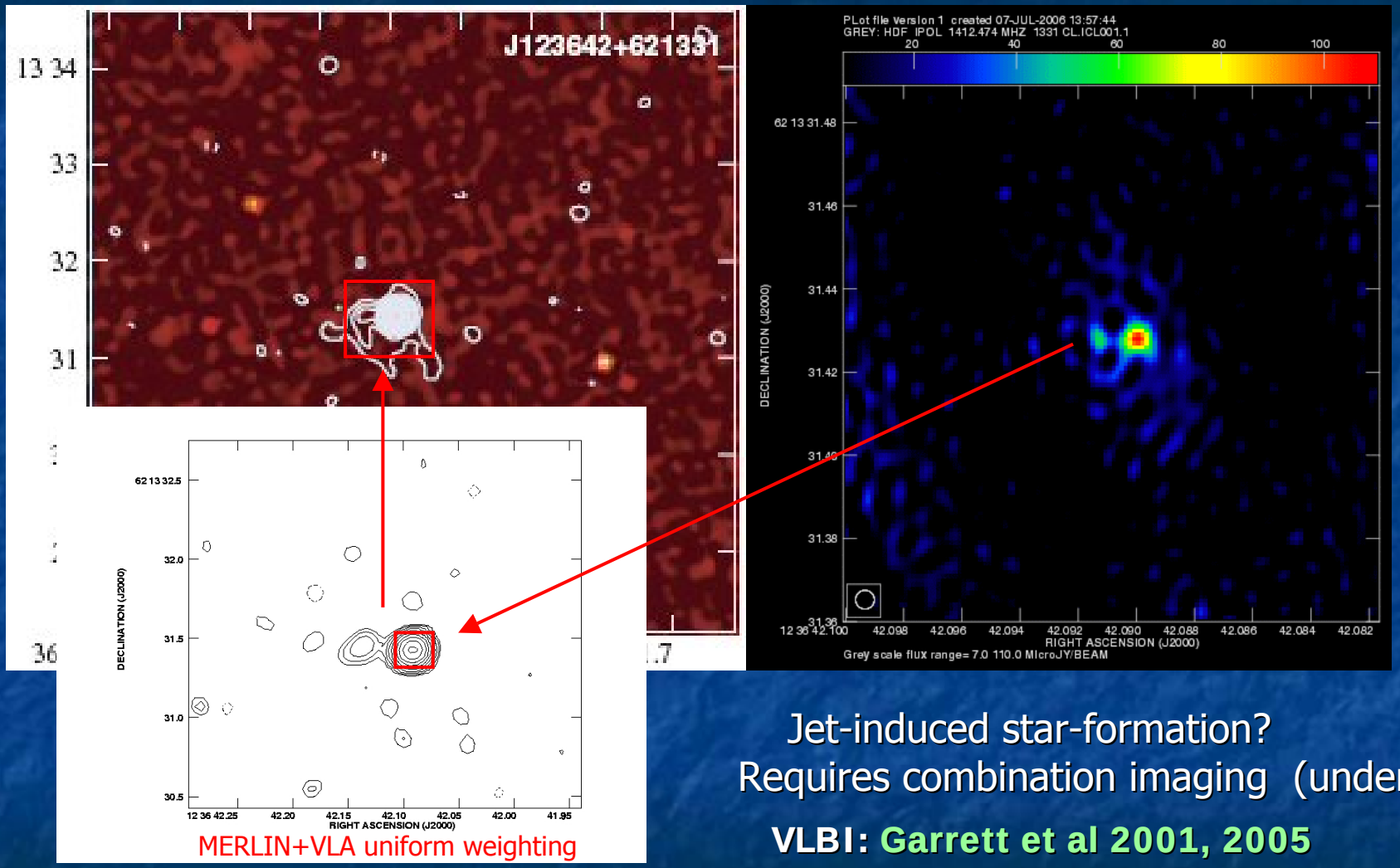
Produce total intensity and spectral mapping across each detected system

Detailed jet-induced star-formation studies will also require the additional very high angular resolution of the EVN at L-Band in combination with *e*-MERLIN

factor~1.5 and adds short-spacing *uv*-coverage to recover the very heavily resolved radio structures with sizes > 1.2 arcseconds



An example from existing data:
J123642+621331 – A Starburst with an Embedded AGN at z=4.424



Jet-induced star-formation?
Requires combination imaging (under way)

VLBI: Garrett et al 2001, 2005

Seungyoup Chi

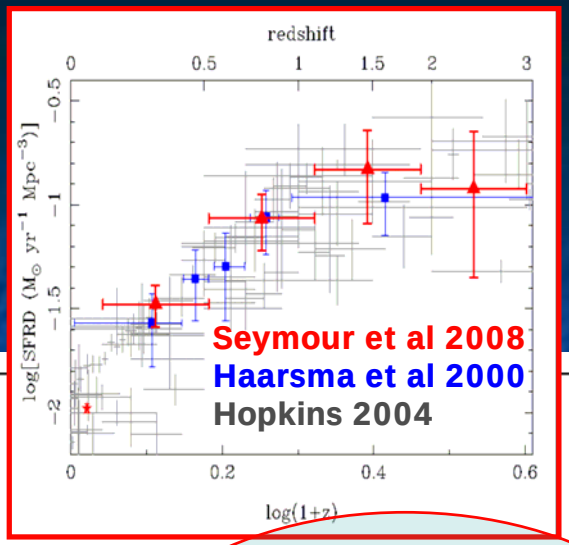
MERLIN+VLA

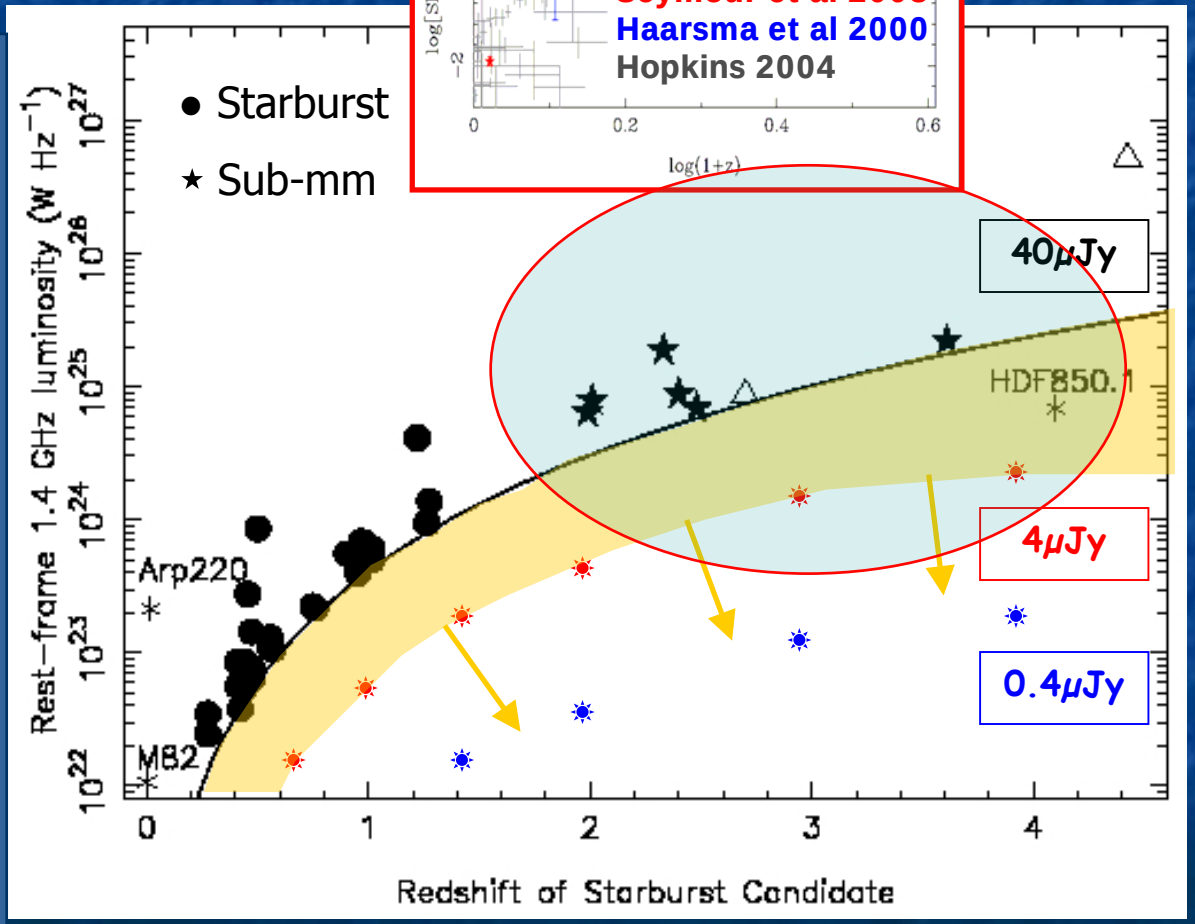
Star-formation History from Starburst Luminosities

For those weak

Sub-mm starburst systems at high redshift show evidence for substantial AGN activity

The EVN will play a pivotal role in probing the role of AGN/jets in such systems and in estimating the AGN contamination to the radio emission from the starburst





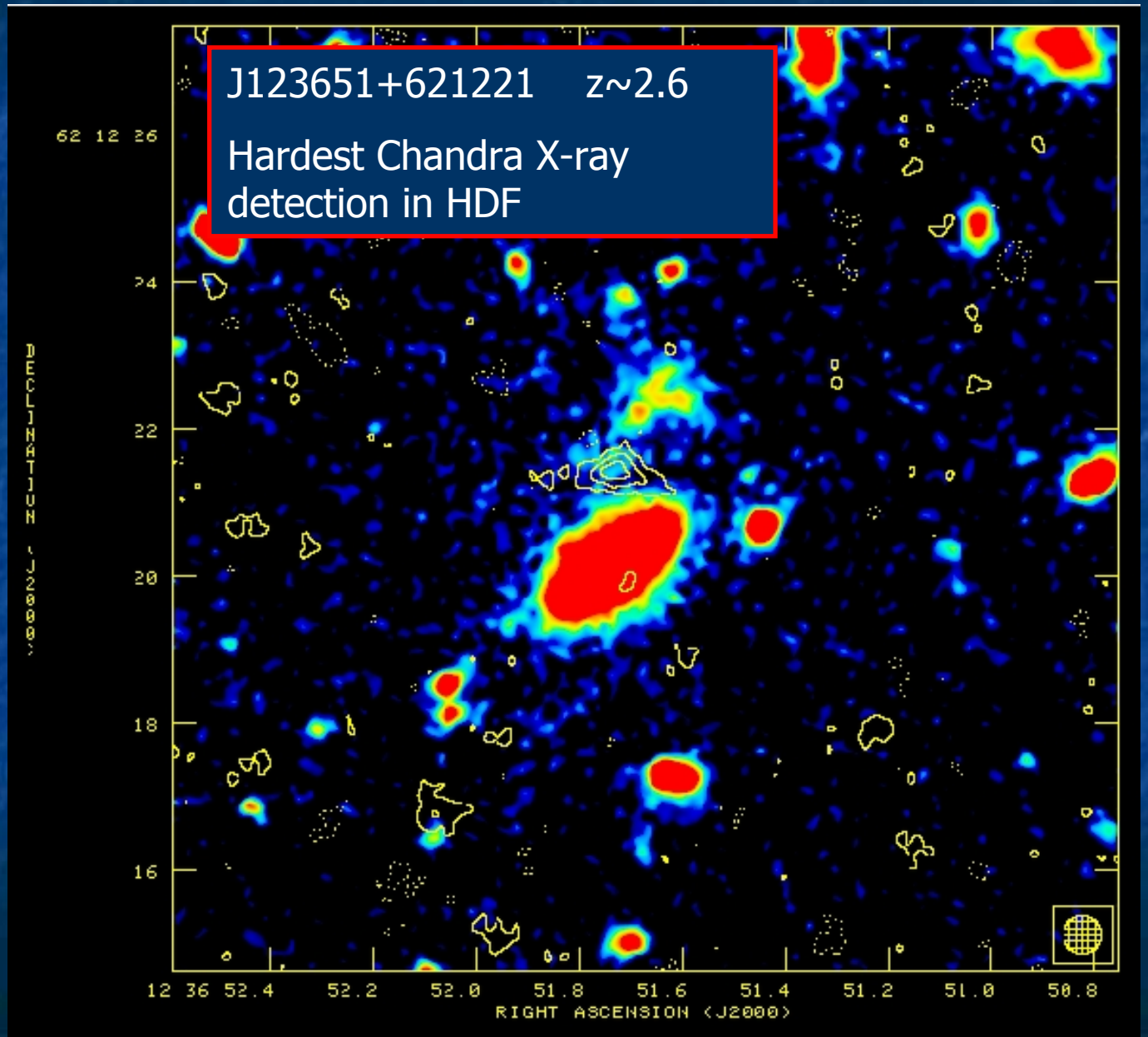
Summary

- If approved, observations will require full specifications for *e*-MERLIN → scheduling will not be before ~ 2010
- Complimentary A-array EVLA data will be sought
- New ultra-deep EVN observations are planned
- Results likely to be made public in a series of staged releases – the full sensitivity over the complete area will take time to achieve

References:

Beswick, R., et al., 2008, MNRAS, 385, 1143
Casey, C. M., et al., 2008, ApJS, 177, 131.
Chapman, S. C., et al., 2004, ApJ, 611, 732.
Garrett, M. A., et al., 2001, A&A, 366, L5
Garrett, M. A., et al., 2001, A&A, 366, L5
Hopkins, A. M., 2004, ApJ, 615,209.
Muxlow, T. W. B., et al., 2005 MNRAS, 358, 1159
Muxlow, T. W. B., et al., 2007, ASPC 380, 199.

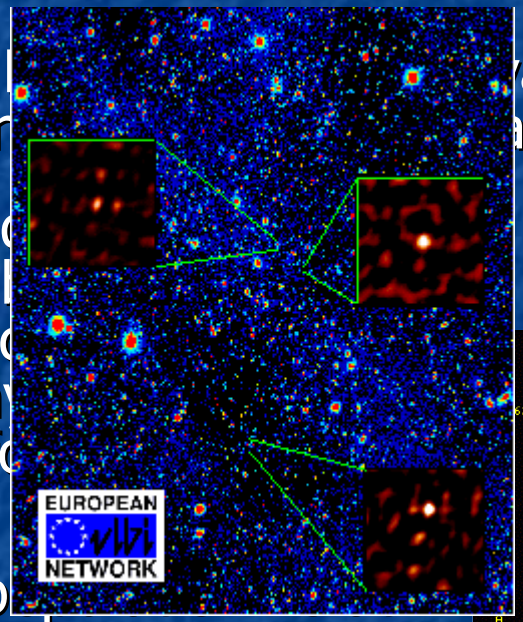
Contours: Radio linear CI=10μJy/bm Image: Optical colour

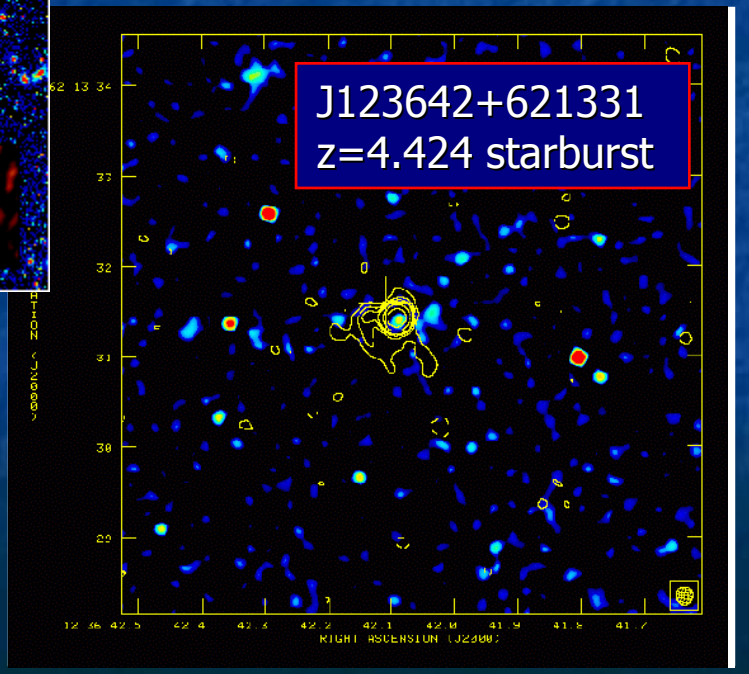


- To date, most distant starbursts show no discernible evidence of significant AGN activity
- Some emit hard X-rays indicating an active AGN – but no compact radio source is as yet detected.
- Some of the highest-redshift star-forming systems do show embedded compact radio cores
- *e*-MERLIN + EVN deep combination imaging will study jet-induced star-formation in such systems.

The Original Study [Muxlow et al. 2005]

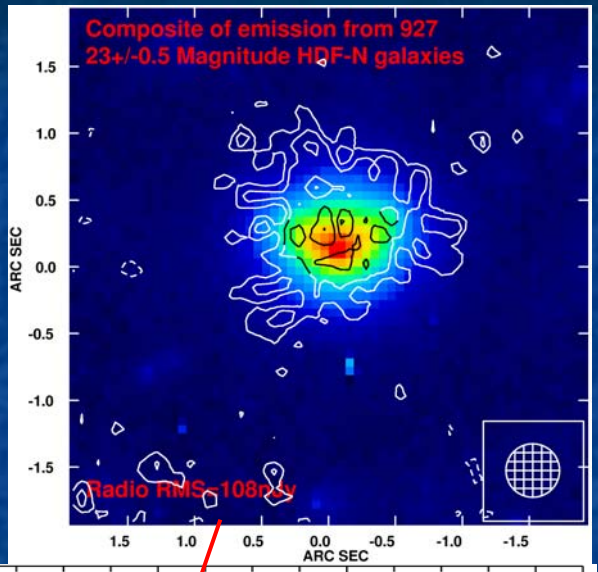
- Within a 10×10 arcmin field centred on the Hubble Deep Field North, 92 radio sources were detected by the VLA at L-Band above a completeness limit of 40μJy/beam. Data from ~1996
- Combination L-Band I … vations could morphologically distin… arburst systems
- Below ~70μJy the ra… becomes dominated … forming galaxies typic… with s-f rates of many … seen in nearby star-fo…
- Around 15% of the p… higher redshifts, many of which are also identified as sub-mm sources.
- Some of the most luminous starburst systems also show evidence for powerful embedded AGN (VLBI data)



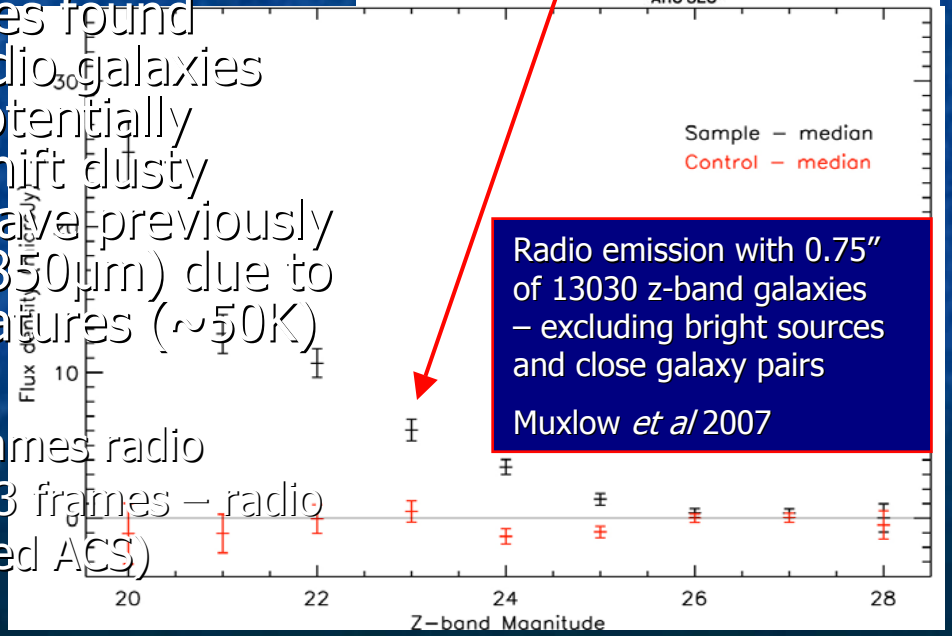


Recent Developments - 1

- Utilising ancillary data from GOODS-N, radio emission at the level of a few μJy is statistically detected associated with ACS galaxies brighter than a z-band magnitude of 26 – identified as extended starburst systems with average properties similar to those star-forming galaxies studied individually



- The extended radio morphologies found associated with star-forming radio galaxies (SFRGs) show that there is a potentially significant number of high redshift dusty ultra-luminous galaxies which have previously escaped notice (undetected at 850μm) due to their relatively hot dust temperatures (~50K)



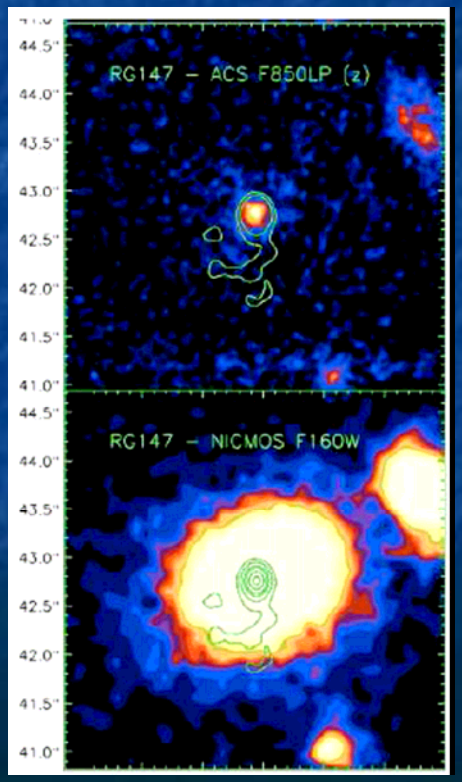
Radio emission with 0.75" of 13030 z-band galaxies – excluding bright sources and close galaxy pairs

Muxlow *et al* 2007

Sample shown from GOODS-N (first 5 frames radio contoured over ACS) and Lockman (last 3 frames – radio contoured over SUBARU & coarsely binned ACS) [Casey et al in preparation]

Recent Developments - 2

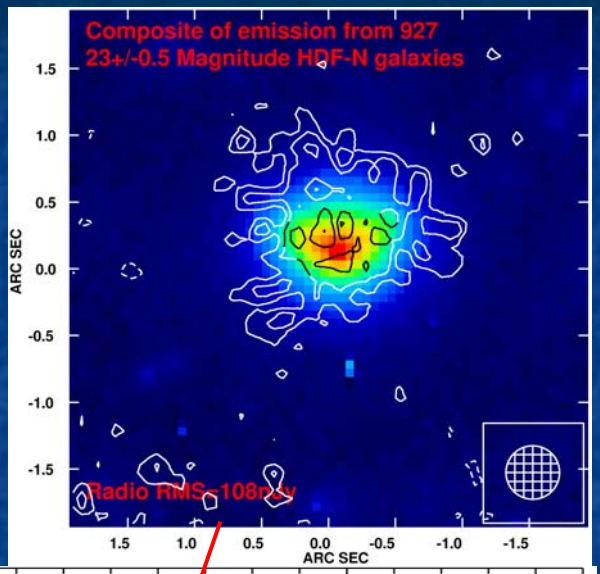
- The resolved MERLIN radio morphologies of luminous z~2 sub-mm galaxies (SMGs) have revolutionized our understanding of this important high-redshift ULIRG population
- Two thirds of the SMGs show resolved radio morphologies extending to ~1" → bolometric output arises in extended, faint, dust obscured regions that are forming stars at close to their Eddington limit
- MERLIN+VLA observations of a sample of sub-mm faint radio galaxies within GOODS-N were critical in morphologically identifying the galaxies as part of the radio-AGN population – misidentified as starbursts at other wavelengths (Casey et al. 2008)
- VLBI investigations (Garrett et al., 2001, Chi et al., in prep) indicated that some of the brightest examples of the SMG population may contain substantial AGN components



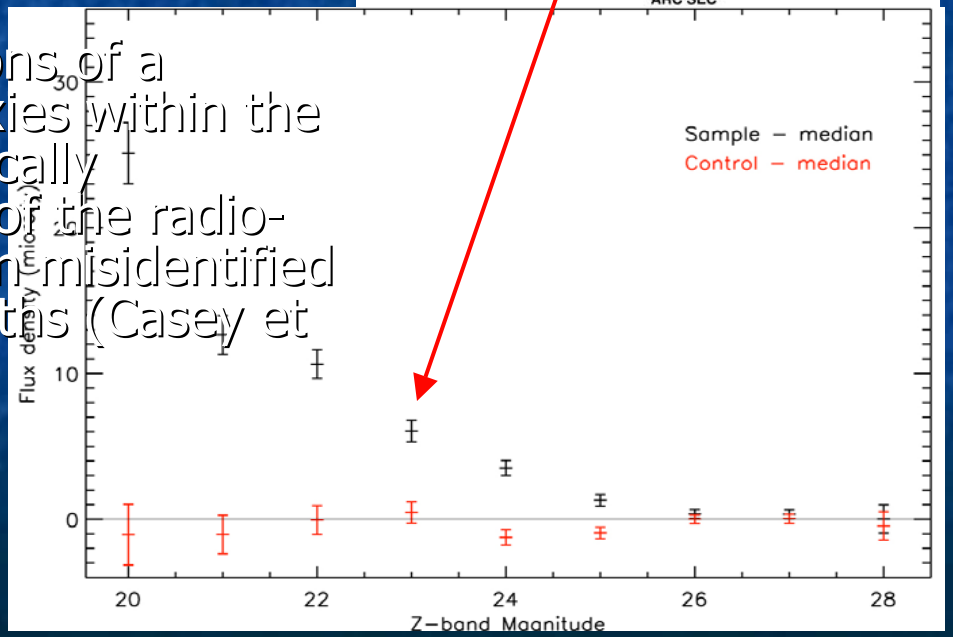
A z=1.92 radio source thought initially to be a starburst, But revealed by MERLIN as an AGN. MERLIN 1.4GHz Contours show a compact source (<65mas, <400pc at z=1.92) with a jet-like extent to the South. Optical imagery [top] reveals a compact source characterized as a starburst from Keck spectroscopy, while near-IR imagery [bottom] reveals a giant Elliptical galaxy. **[Casey, Chapman et al in prep]**

Recent Developments

- Utilising ancillary data from GOODS-N, radio emission at the level of a few μJy was statistically detected associated with ACS galaxies brighter than a z-band magnitude of 26 – identified as extended starburst systems with average properties similar to those star-forming galaxies studied individually by Muxlow et al. (2005), but with average flux densities of just $S_{1.4GHz}$ ~ a few μJy



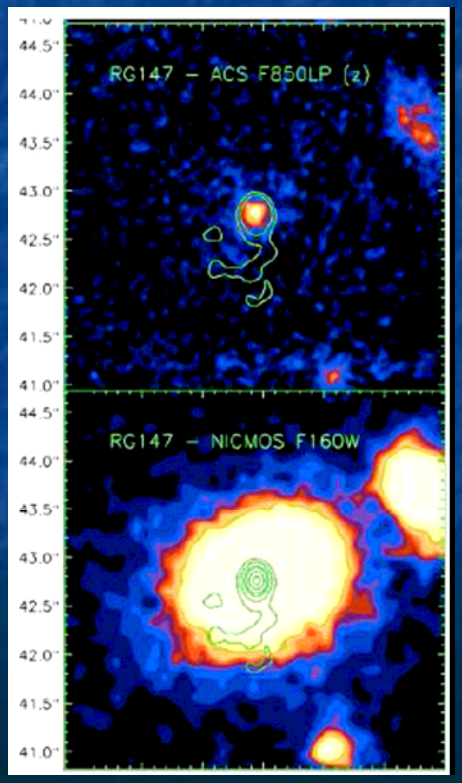
- These MERLIN +VLA observations of a sample of luminous z~1.5 galaxies within the field were critical in morphologically identifying the galaxies as part of the radio-AGN population – they had been misidentified as starbursts at other wavelengths (Casey et al. 2008)



Recent Developments - 2

- The resolved MERLIN radio morphologies of luminous z~2 sub-mm galaxies (SMGs) have revolutionized our understanding of this important high-redshift ULIRG population
- Two thirds of the SMGs show clearly resolved radio morphologies extending to ~1”, and crucially demonstrate that their bolometric output arises in extended, optically faint, dust obscured regions that are forming stars at close to their Eddington limit
- MERLIN+VLA observations of a sample of sub-mm faint radio galaxies within GOODS-N were critical in morphologically identifying the galaxies as part of the radio-AGN population – they had been misidentified as starbursts at other wavelengths (Casey et al., 2008)
- VLBI investigations (Garrett et al., 2001, Chi et al., in prep) indicated that some of the brightest examples of the SMG population may contain substantial AGN components

Characterizing the weak-z~2 µJy SMG population. A z=1.92 radio source, thought initially to be a starburst, but revealed by MERLIN as an AGN. MERLIN 1.4GHz contours show a compact source (<65mas, <400pc at z=1.92) with a jet-like extent to the South. Optical imagery [top] reveals a compact source characterized as a starburst from Keck spectroscopy, while near-IR imagery [bottom] reveals a giant Elliptical galaxy.



New Ultra-Deep Study of GOODS-N

- Part of a tiered *e*-MERLIN Legacy proposal – the *e*-MERGE Survey is designed to study the formation and evolution of star-forming galaxies and AGN out to redshifts > 5

  – The *e*-MERlin Galaxy Evolution Survey

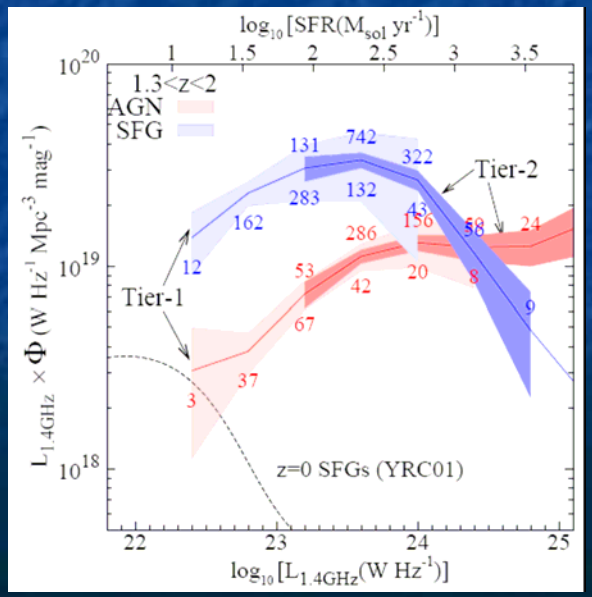
  - Tier 0 – *Imaging radio emission from normal galaxies out to z ~ 5*
    - *Deep imaging around clusters to utilise amplification by lensing*
  - Tier 1 – *A very deep directed survey of the μJy radio source population*
    - *Deep imaging of the μJy radio source population in GOODS-N*
  - Tier 2 – *A reliable cosmic census of starburst and AGN populations*
    - *Medium depth imaging over a number of fields (total area ~2 sq. degrees)*

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

  >60 CO-Is from 9 countries

  Tier 0: Ian Smail [Durham] Tier 1: Tom Muxlow [Manchester] Tier 2: Ian McHardy [Southampton]

  ~2400 hours of *e*-MERLIN time proposed



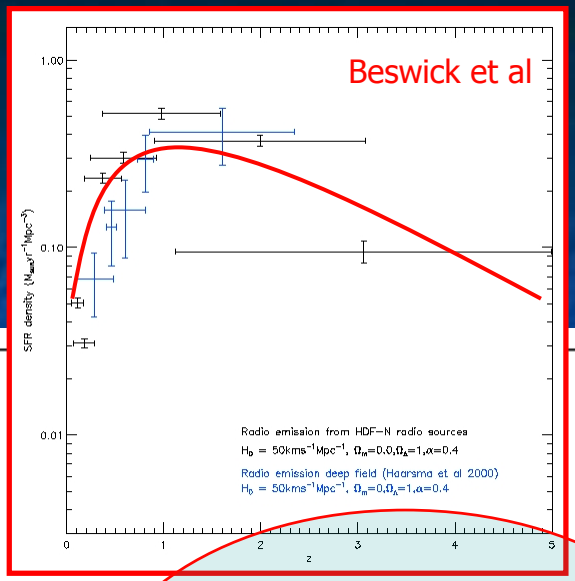
Simulated L-band luminosity density function of SFGs (blue) and AGN (red) expected in the *e*-MERGE survey, for redshifts 1.3 < z < 2. Symbols show the input from the models of Wilman et al. (2008). Shaded areas indicate the predicted constraints on the luminosity function from Tier-1 (light shading) and Tier-2 (darker shading)

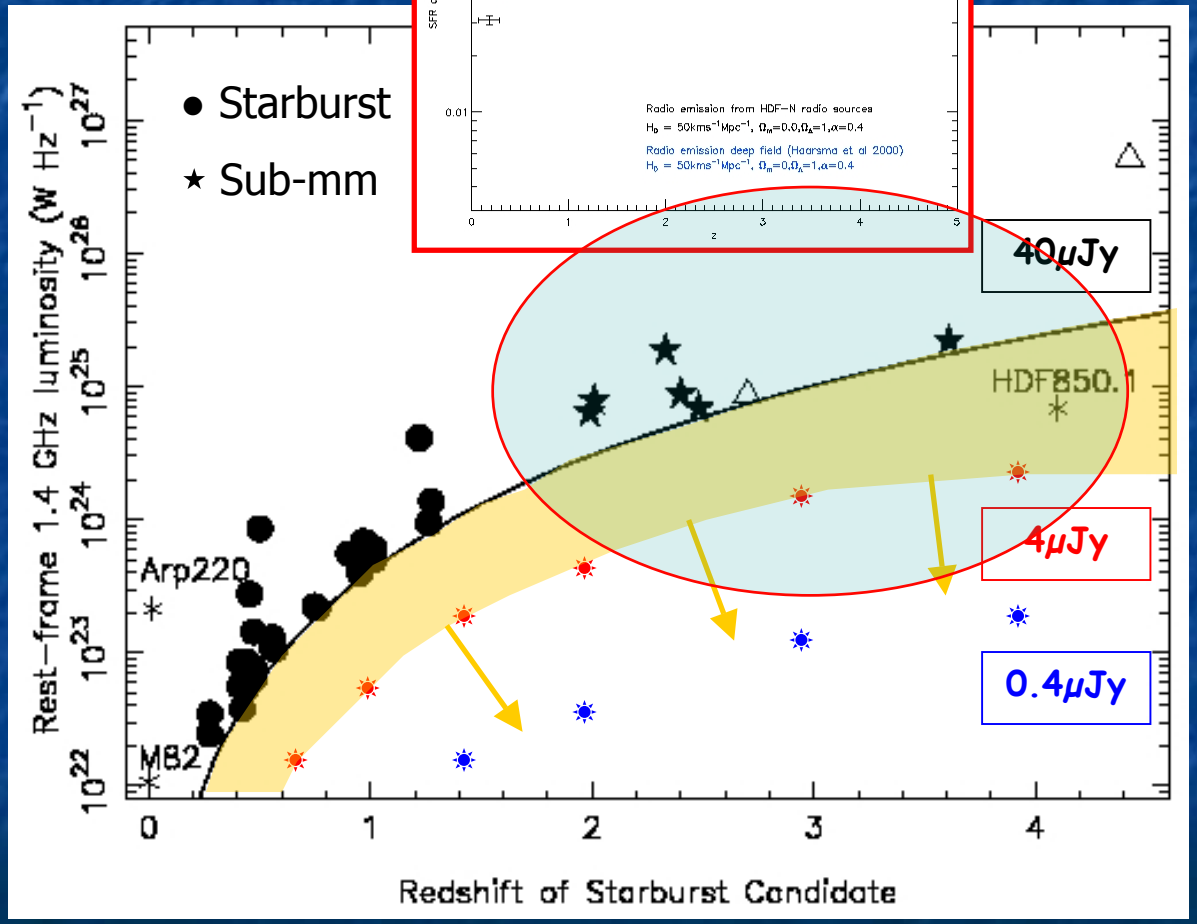
Star-formation history from starburst luminosities

For those weak

Sub-mm Starburst systems at high redshift show evidence for substantial AGN activity

The enhanced EVN will play a pivotal role in probing the role of AGN in such systems and estimating the AGN contamination to the radio emission from the starburst





The EVN in 2015

- Technical specification from Cormac and Huib
- + Routine joint observations with *e*-MERLIN

  - Sub μJy sensitivity for full continuum imaging runs
  - mas angular resolution
  - Wide-field of view
  - High fidelity imaging with full *uv* – coverage
  - Simultaneous spectral and spatial imaging with MFS

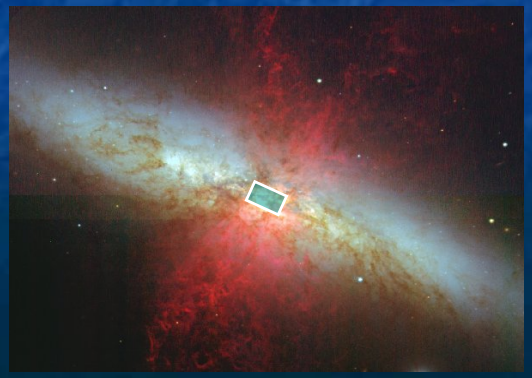
- What are the outstanding questions in starburst galaxy research and will the EVN be the instrument of choice to investigate these ?

How well do we understand the starburst phenomenon?

- What triggers a starburst?
- What fuels the starburst?
- What is the star-formation history of the Universe?
- How do individual supernovae evolve into remnants?
- Does every supernova produce a visible remnant?
- What are the expansion velocities of supernova remnants?
- What is the detailed interaction of the ejecta with the surrounding medium?
  - How do remnants slow with time?
  - What are the effects of a clumpy medium?
  - What are the properties of the medium?
- SN rate and star-formation rate – do we see all the SN?
- What are the transient radio sources?
- Late-stage GRB afterglows in nearby starburst galaxies?

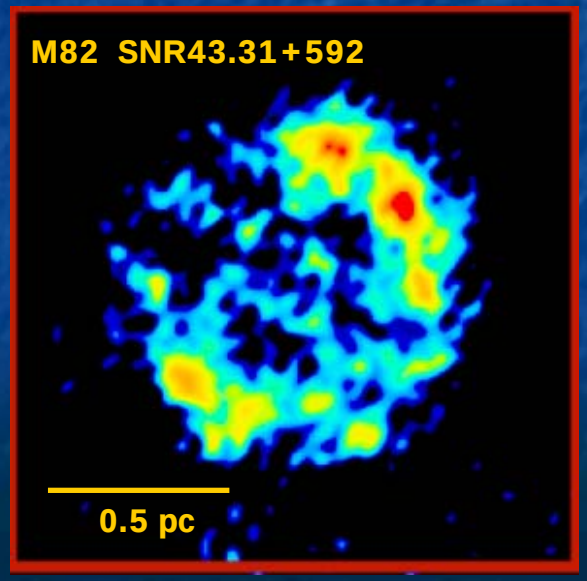
Synergy between new generation radio instruments:
ALMA, EVLA, *e*-MERLIN, enhanced EVN

The high angular resolution and continuum sensitivity of the EVN in 2015 is likely to make a major contribution in these areas



Existing VLBI Imaging of SNR - in M82 and other nearby starburst galaxies

- **Measure expansion velocities and deceleration**
  - **Have begun to probe the nature of the environment – thought to be extremely clumpy**
  - **Have started to investigate how the ejecta interact with the environment and eventually move into the Sedov phase of expansion**
  - **Do SN in environmental voids produce no observable remnant? In M82, SFR → SN rate of 1 every ~12 years (cf observed SNR rate of 1 every ~30 years)**
  - **Transients seen (t<6 months) – nature unknown**



Investigation is statistical in nature – need to expand the study sample by at least an order of magnitude

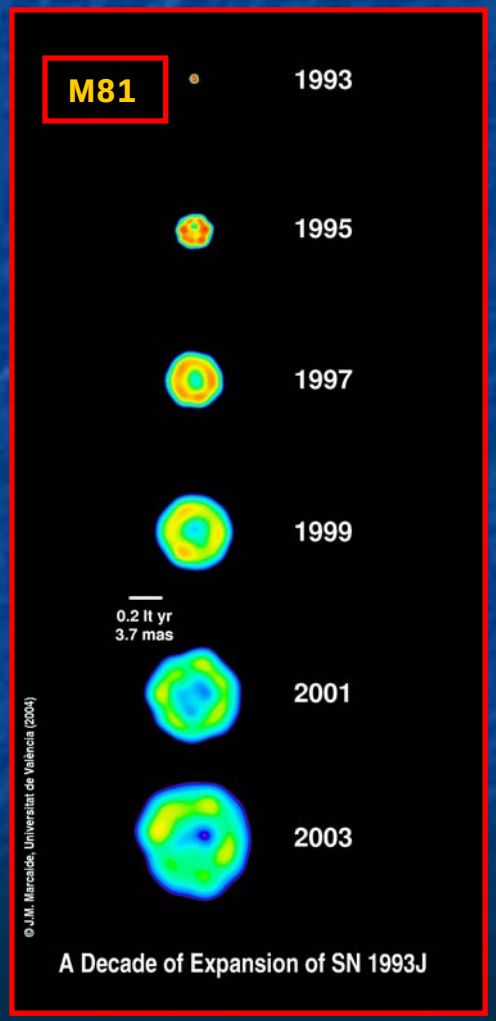
SN43.31+592:

Beswick et al 2006

SN1993J:

Marcaide et al

Bietenholz, Bartel, Rupen et al

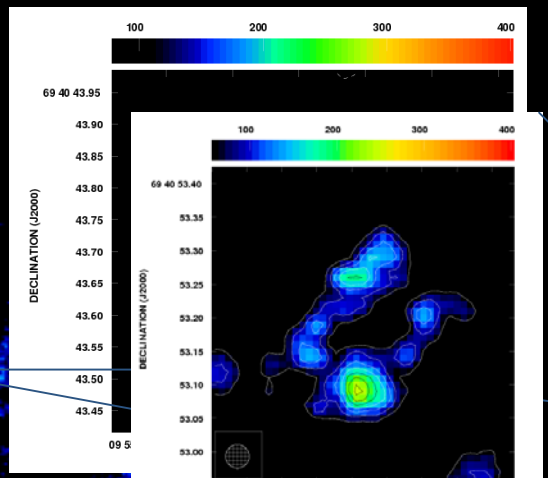


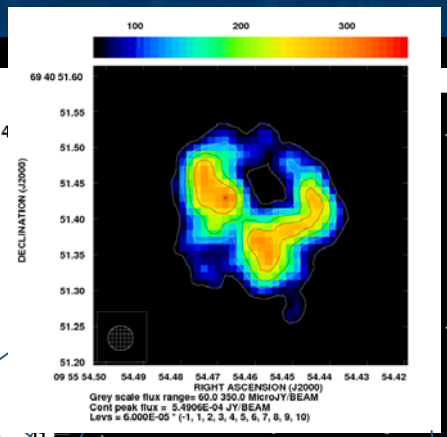
EVN in 2015 will give us much deeper images with high fidelity structural detail. In combination with EVLA & *e*-MERLIN:

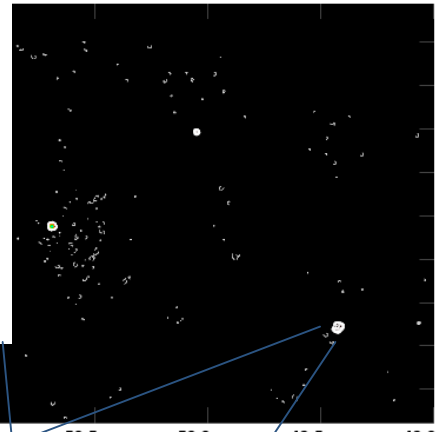
- Extend the SNR study to older fainter remnants.
- Extend the study to more distant starburst galaxies. (d<30Mpc, ~30 galaxies) [SNR~50μJy, d~30mas].
- Use the high image fidelity and spatial frequency filtering to extract the faint remnants from any extended background.
- Use spectral/structural information to separate weak SNR from HII regions
- Compare matched resolution high fidelity images at L and C-band to investigate the medium on the sub-pc scale size by studying variable free-free absorption across the face of the SNR
- Investigate the magnetic field strength in the medium from the rotation measure of any linearly polarized emission detected in SNR
- Try to detect and resolve recent radio transients – what are they?
- Late-stage GRBs - Is 41.95+595 an afterglow from ~100 yr old GRB? How many others are there in other nearby starburst galaxies?

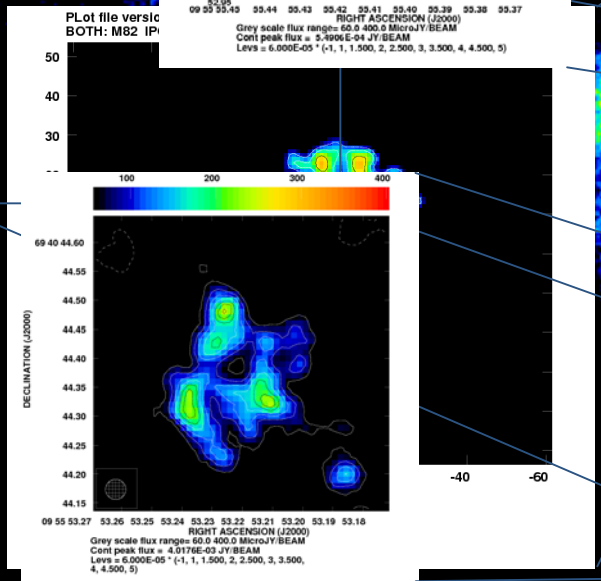
Present day combination imaging

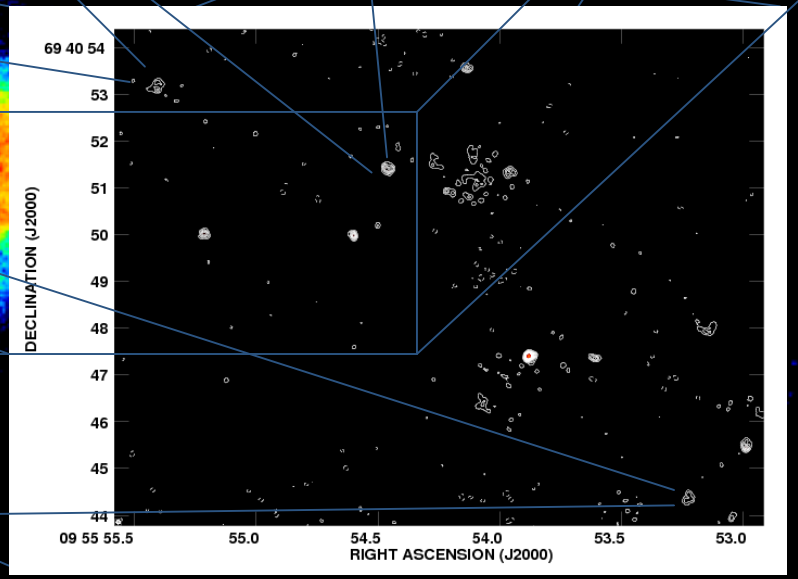
MERLIN+VLA (5GHz) & EVN+MERLIN (1.6GHz)









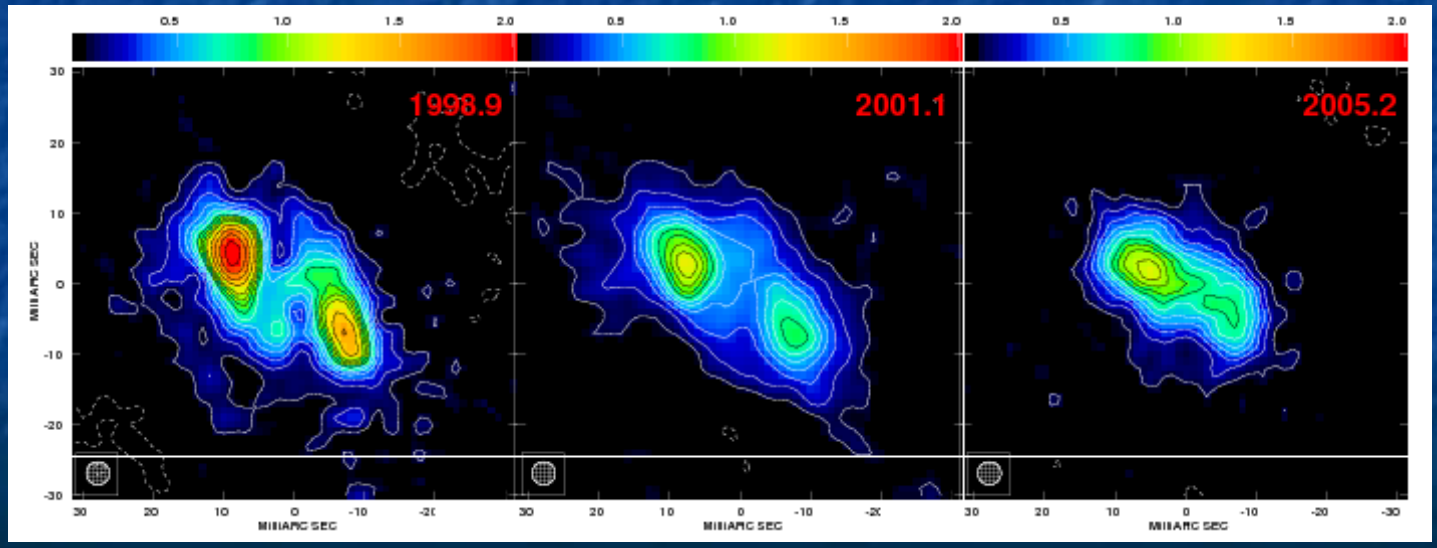


MERLIN+VLA 5GHz

Danielle Fenech PhD 1.6GHz

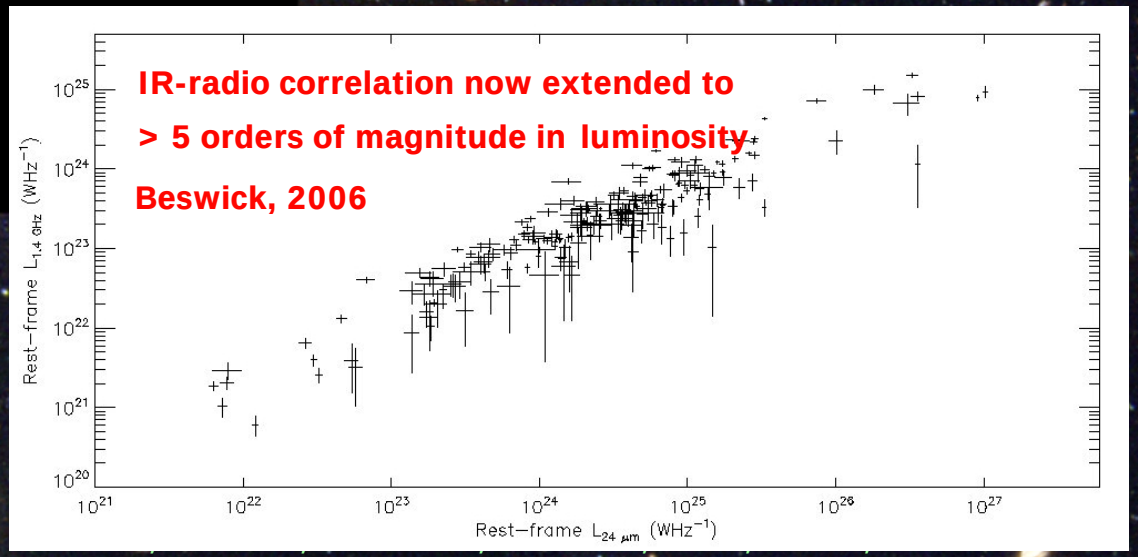
Local late-stage GRB afterglows

- Most compact source in M82 [41.95+57.5]
- Peak flux decreasing by ~8.5% per year [dominates flux in 1960s]
- Bi-polar structure not typical of an SNR
- Slow expansion at ~1500km/s, sits in HII bubble with r~100 ly
- Is this ~100 yr old (non-aligned) GRB afterglow at a distance of 3Mpc?
- How many more are there within 30 Mpc?
- We can only study this type of object locally ~100 yrs after outburst



Star-formation at High Redshift

HDF (N)



- How does the star-formation density vary with cosmic epoch ?
- What are the best extinction-free measures of star-formation rate at high redshift ?
- How does AGN activity (feedback) effect star-formation ?

Contribution of EVN in 2015 to starburst galaxy research?

- Extend the SNR study to older fainter remnants.
- Extend the study to more distant starburst galaxies. (d<30Mpc, ~30 galaxies) [SNR~50μJy, d~30mas].
- Use the high image fidelity and spatial frequency filtering to extract the faint remnants from any extended background.
- Use spectral/structural information to separate weak SNR from HII regions
- Compare matched resolution high fidelity images at L and C-band to investigate the medium from the scale size of free-free absorption across the face of the SNR
- Investigate the magnetic field strength in the medium from the rotation measure of any linearly polarized emission detected in SNR
- Try to detect and resolve recent radio transients – what are they?
- GRBs - Is 41.95+595 an afterglow from ~100 yr old GRB? How many others are there in other nearby starburst galaxies?
- Investigate the role of AGN activity in high-redshift starburst galaxies. Feedback? Jet-induced star-formation?
- Separate AGN and starburst radio emission in such high-redshift systems and thus help derive the star-formation rate history of the Universe