The University of Manchester
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Observatory

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e-MERLIN

NRAO

# Star-formation Across Cosmic Time: Initial Results from the e-MERGE Study of the μJy Radio Source Population

## e-MERLIN and the EVN in the SKA Era

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for the e-MERGE Consortium

JBO 11th September 2017

Science & Technology Facilities Council

EUROPEAN VLBI NETWORK

# e-MERGE Survey

Tier 1 – *Deep high resolution imaging of the μJy radio sources in GOODS-N*
→Imaging star-formation in great detail at lower frequencies
→ Precursor of SKA1-Mid deep studies in Band 5……

→ Characterise the μJy radio source population
→ Investigate AGN/S-F interaction and feedback in detail

Addressing STFC Science Challenges A5, A6, D3

Tier 1:

L-Band: Deep 0.2 sq deg – Central 12′ 1σ ~500nJy/bm Outer 30′ annulus 1σ ~1μJy/bm
C-Band: Mosaic of the inner 12′ field (50mas)

In full 30′ field ~1500 AGN and ~3100 S-F galaxies complete to ~6σ

[DR-2] – 2018/2019

2017 → Interim data release [DR-1] with:
L-Band: 25% e-MERLIN data + JVLA over central 12′ field → 1σ~1.5μJy/bm (in prep)
JVLA L-Band 30′ field ✓
C-Band: JVLA mosaic of central region ✓
Detailed investigation of >500 SF galaxies and AGN in 12 arcmin central region
This talk: L-Band images from an interim sample of 248 source complete to 6σ
L-Band images presented from 90 hrs of e-MERLIN data - 12′ field - 1σ~2.5μJy/bm

# Luminous Classical Starbursts

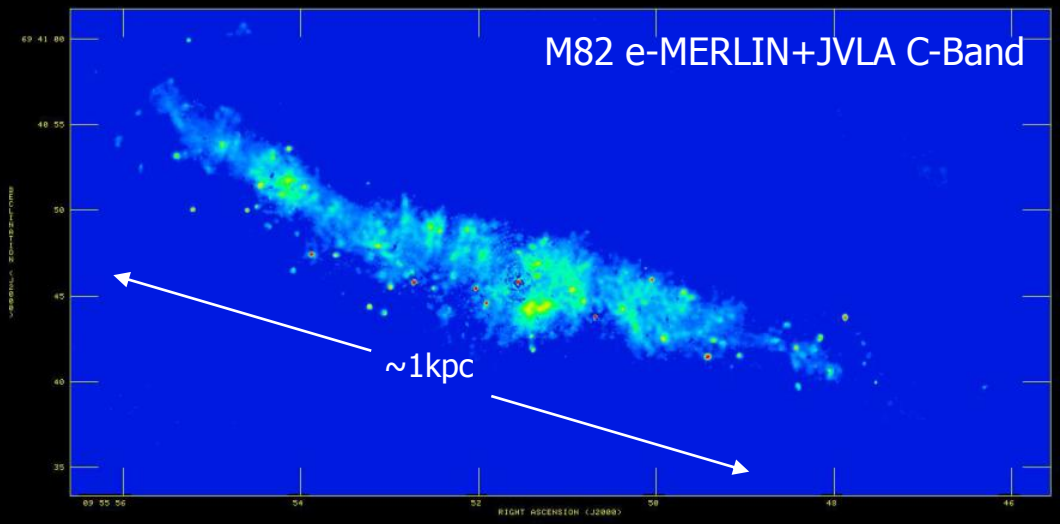
Classical Star-forming Galaxies: Radio emission from central region of $10^{10}$ $M_\odot$ dust obscured irregular galaxy at z=0.422 – No compact emission detected

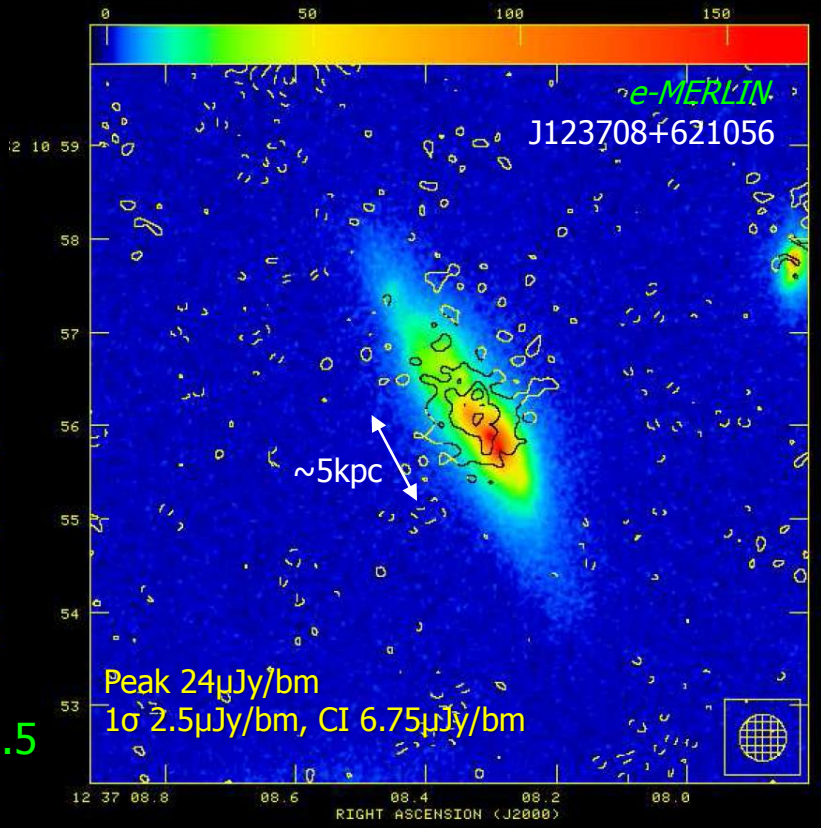
$L_{1.4}$ =3.8x$10^{22}$ W/Hz → Star-formation rate 9 $M_\odot$/yr

(>5 $M_\odot$ assuming Salpeter IMF)

Extended steep-spectrum starburst ($S_{1.4}$ = 45μJy)

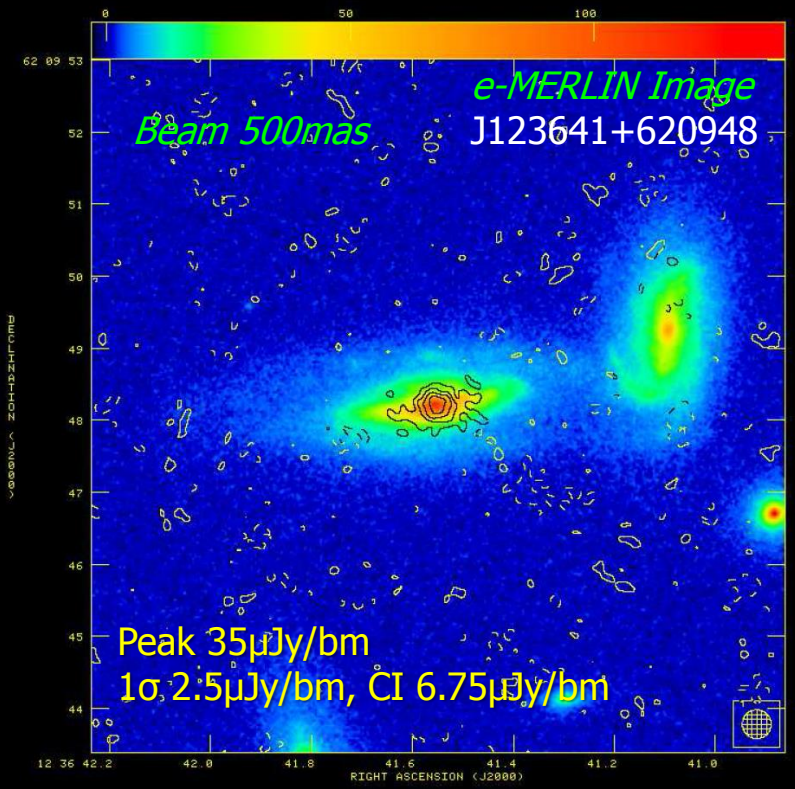
J123708+621056 → ~x4 more luminous than M82



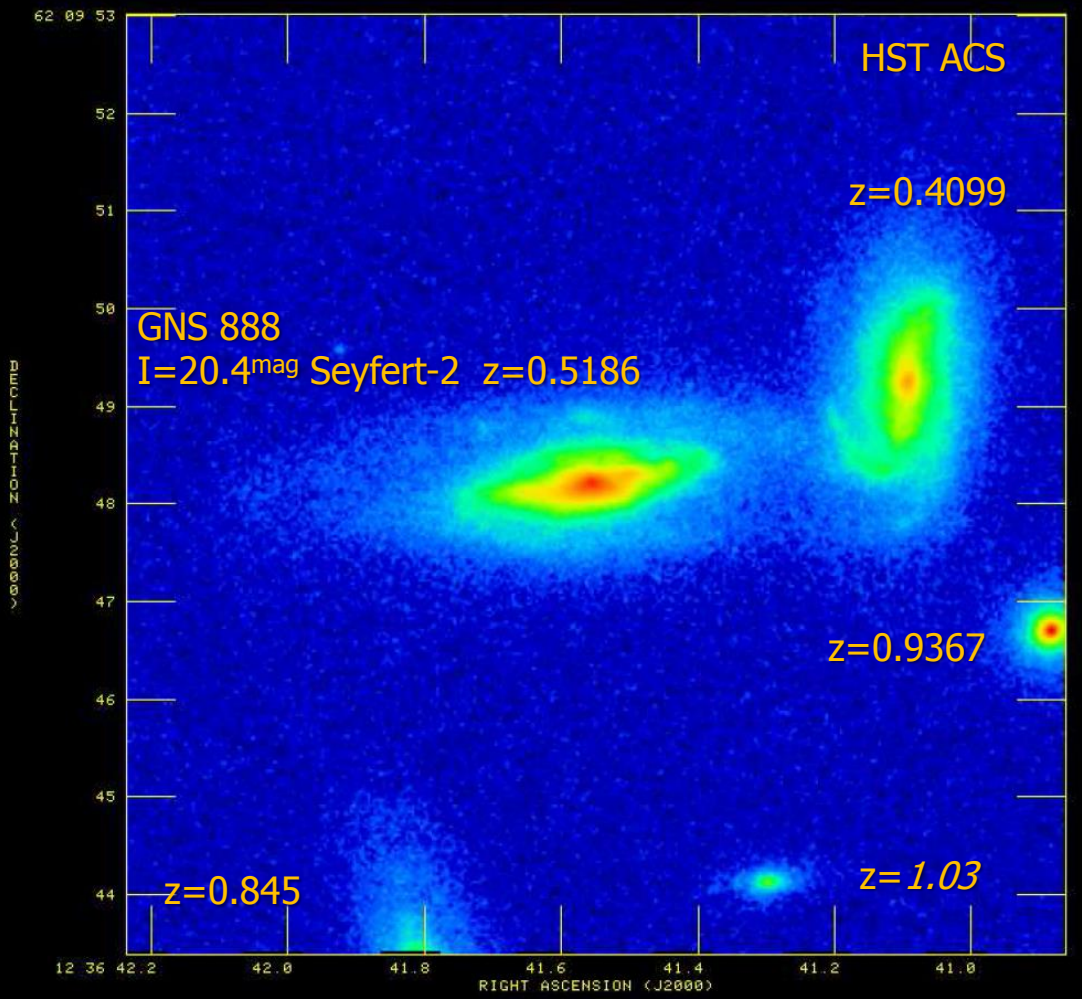




<100μJy population dominated by sfgs typically at z<1.5

# SFG Radio Structures




Steep-spectrum ($\alpha$>0.56) starburst extended along galaxy major axis




Radio emission from central region of $10^{11}M_{\odot}$ Seyfert-2 galaxy – Nuclear emission + extension

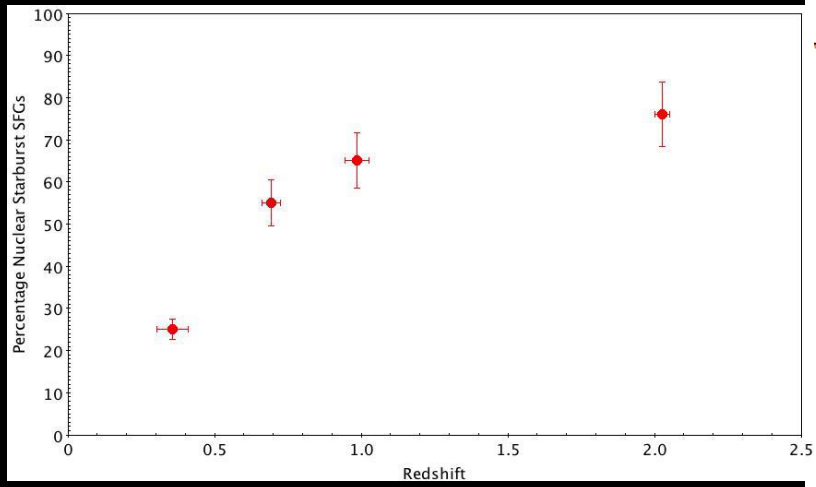
→ Star-formation rate 42 $M_{\odot}$/yr

Seyfert-2 galaxy, faint Chandra detection → AGN – but radio quiet?

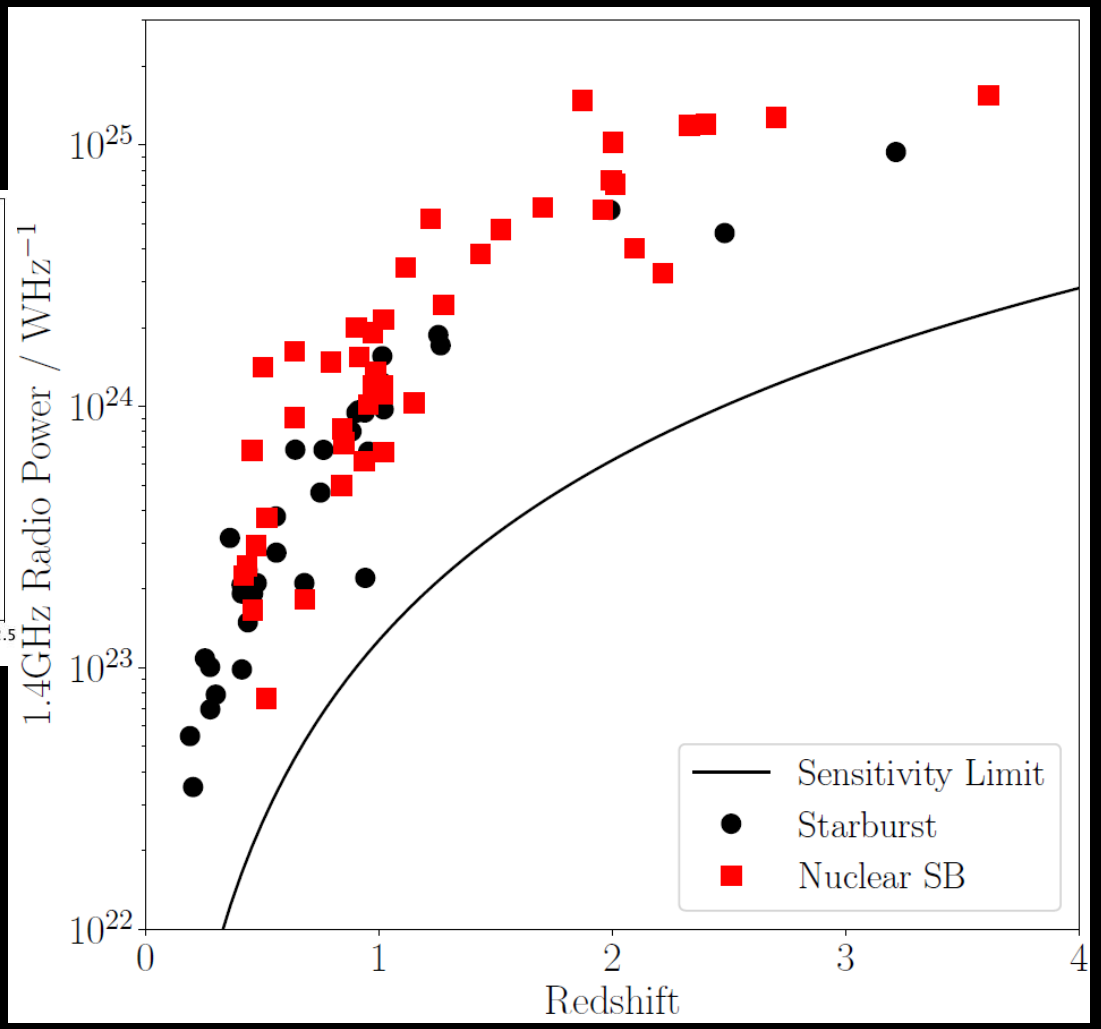
AGN or nuclear starburst? – Resolved by e-MERLIN, no compact component → Nuclear starburst

# SFG Radio Structures

The proportion of SFGs with nuclear starbursts are seen to increase with redshift



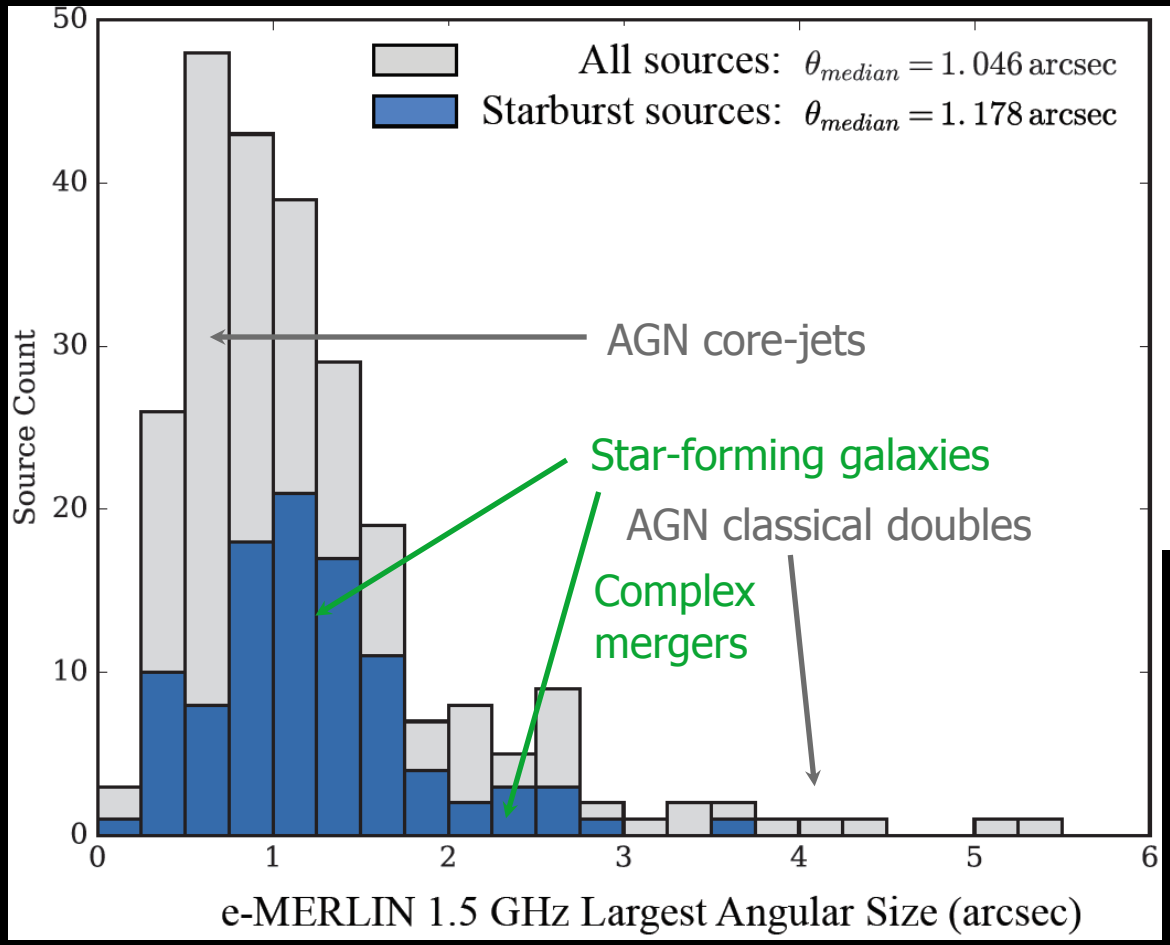

At high redshifts the proportion with nuclear starbursts ~ 70%.



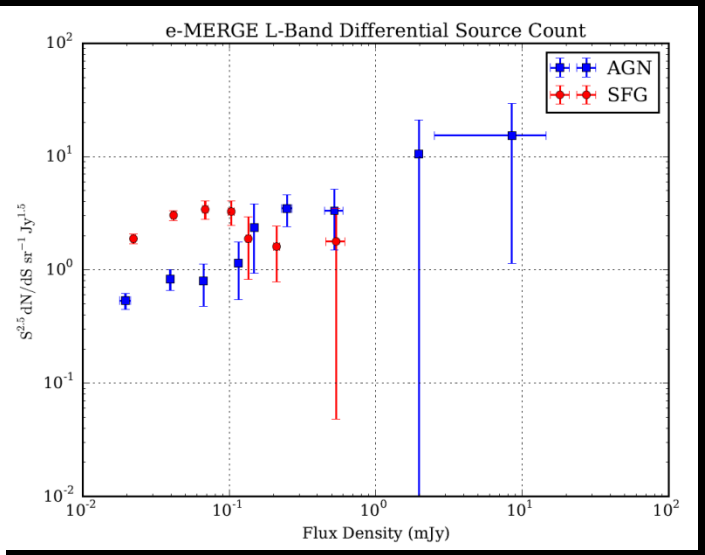

Malmquist bias since SFGs containing nuclear starbursts are more luminous systems – although some extended-only SFGs are still found in high redshift systems

# Initial Results From Interim Images: – From Nick Wrigley's PhD Work

Sample of 248 detected sources within central 12′ field from ~90 hrs of data.
Assign probabilities of being AGN or SF from radio structures and spectral properties…




Machine-learning (SVM – Support Vector Machine)




Differential Source Counts:

Derived from all 248 sources with class assigned by machine learning algorithm (SVM)

26 AGN & 80 SFGs with spectroscopic redshifts

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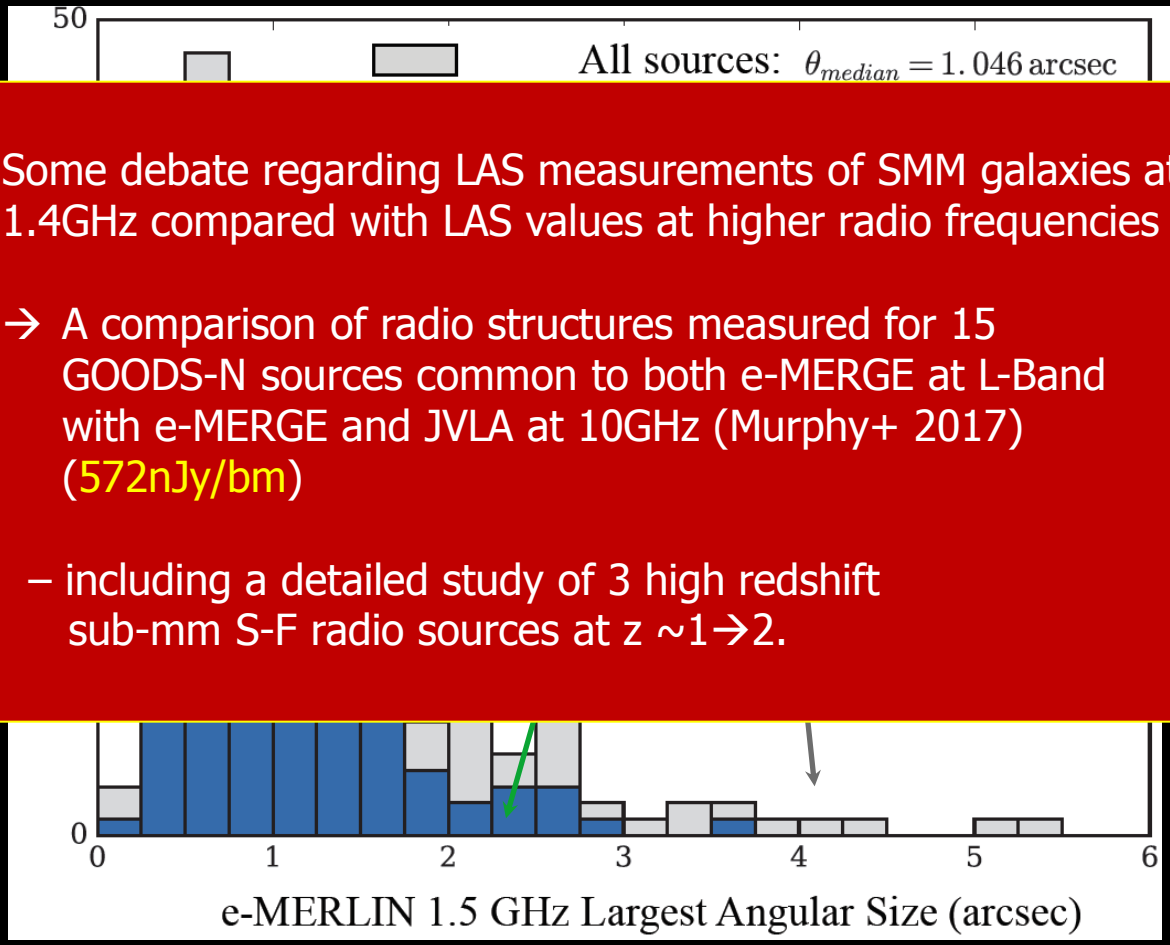
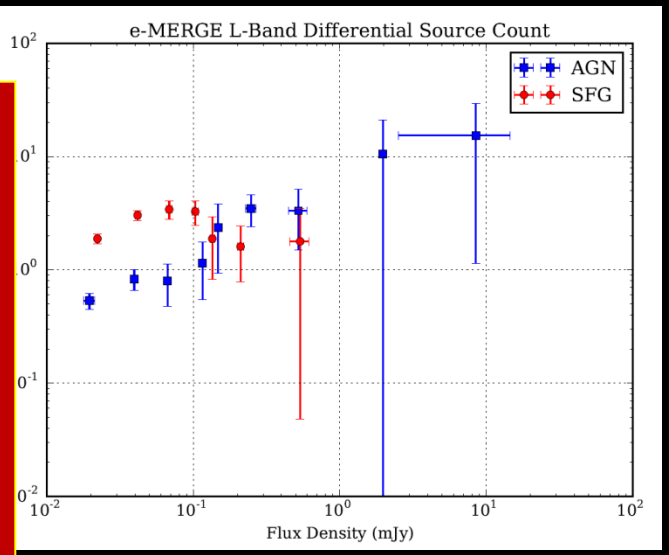



Some debate regarding LAS measurements of SMM galaxies at 1.4GHz compared with LAS values at higher radio frequencies

→ A comparison of radio structures measured for 15 GOODS-N sources common to both e-MERGE at L-Band with e-MERGE and JVLA at 10GHz (Murphy+ 2017) (572nJy/bm)

– including a detailed study of 3 high redshift sub-mm S-F radio sources at z ~1→2.

Machine-learning (SVM – Support Vector Machine)

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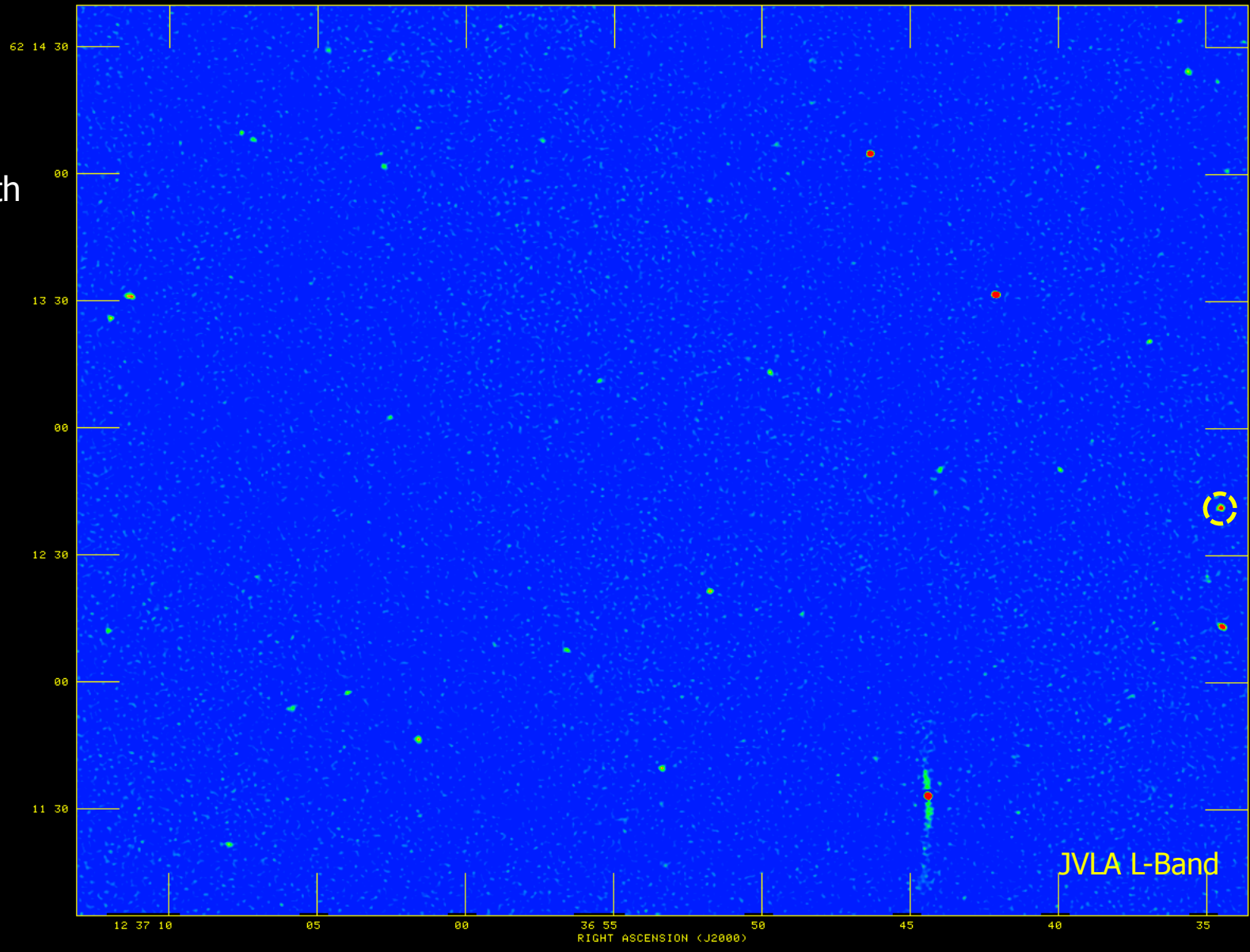
# High frequency Observing for Angular Resolution with Intermediate Baselines…

JVLA 10GHz v e-MERLIN 1.5GHz (Beam~200mas)

Sub-mm source
SMMJ123634+621241
(SCUBA 850.7)

For 15 sources common to both e-MERGE and Murphy+ 2017



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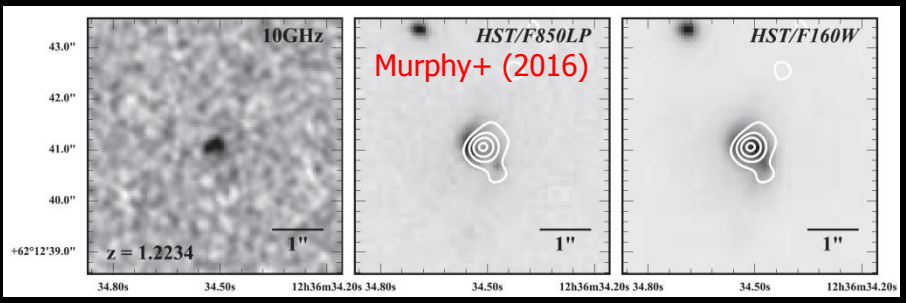
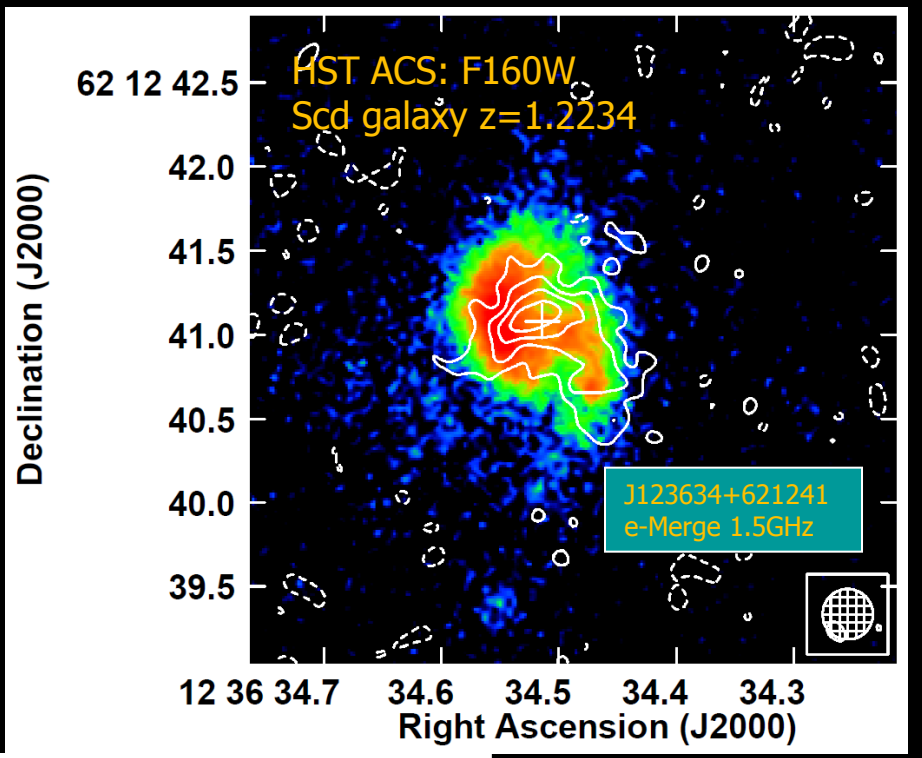
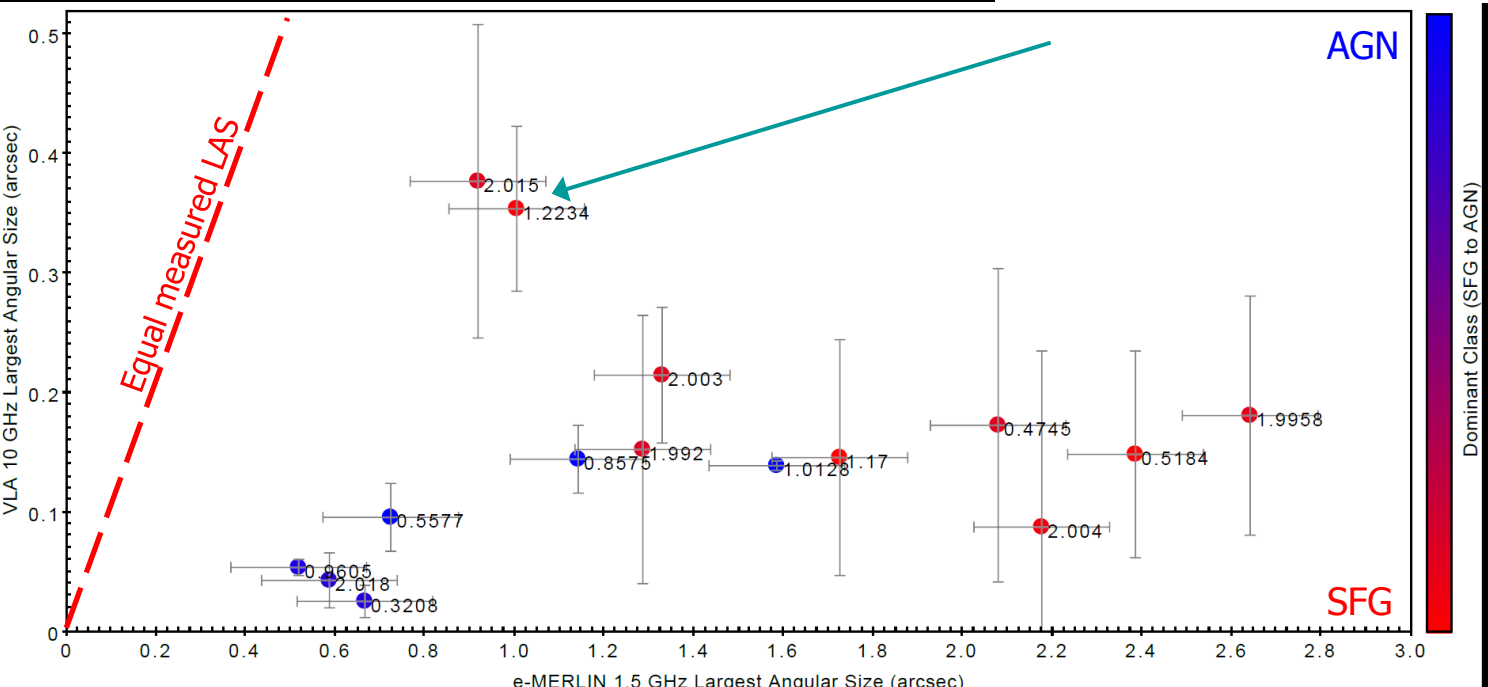



Merging Scd sub-mm galaxy with tidal tail

- High redshift version of the 'Antennae'

JVLA measured sizes at 10GHz are up to an order of magnitude smaller than e-MERLIN at 1.5GHz




→ S-F rate ~960 $M_\odot$/yr

JVLA at 10GHz sees the merging nuclear cores (+ a hint of extension to SW)

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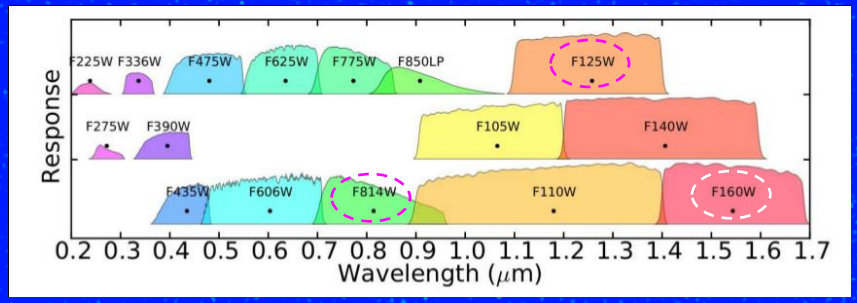
Sub-mm source
SMMJ123635+621424

For 15 sources common to both e-MERGE and Murphy+ 2017

z~2 sub-mm starbursts:
SMMJ123635+621424
SMMJ123637+621331




Three colour composite images derived from a stack of CANDELS epochs 'blue=F814W, 'green'=F125W 'red'=F160W
→ colours ~redshift corrected to emission frame at z=2

JVLA L-Band

62 14 30
00
13 30
00
12 30
00
11 30
DECLINATION (J2000)
12 37 10
05
00
36 55
50
45
40
35
RIGHT ASCENSION (J2000)

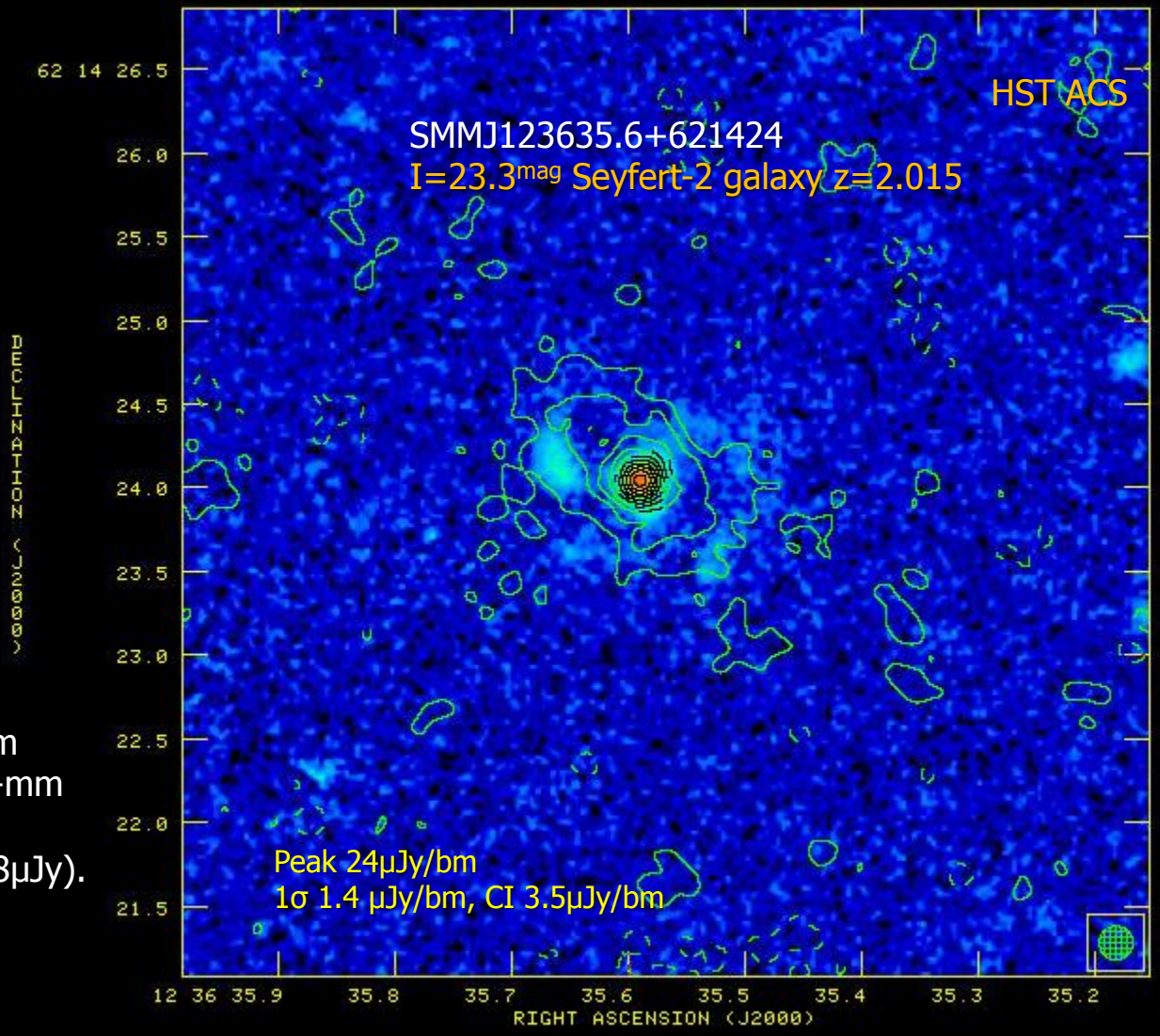
# High frequency Observing for Angular Resolution with Intermediate Baselines…

JVLA 10GHz v e-MERLIN 1.5GHz (Beam~200mas)

e-MERGE L-Band:

– shows nuclear starburst + fainter emission extending across face of Seyfert-2 galaxy

36μJy nuclear starburst
– Fitted size 250x180mas PA+45°




SF ~ equally distributed between nuclear and extended components

Steep-spectrum ($\alpha$<-0.87) sub-mm source.
(Total $S_{1.5}$ = 88μJy).

$S_{850}$=5.5mJy + Radio → S-F rate >1000 $M_\odot$/yr

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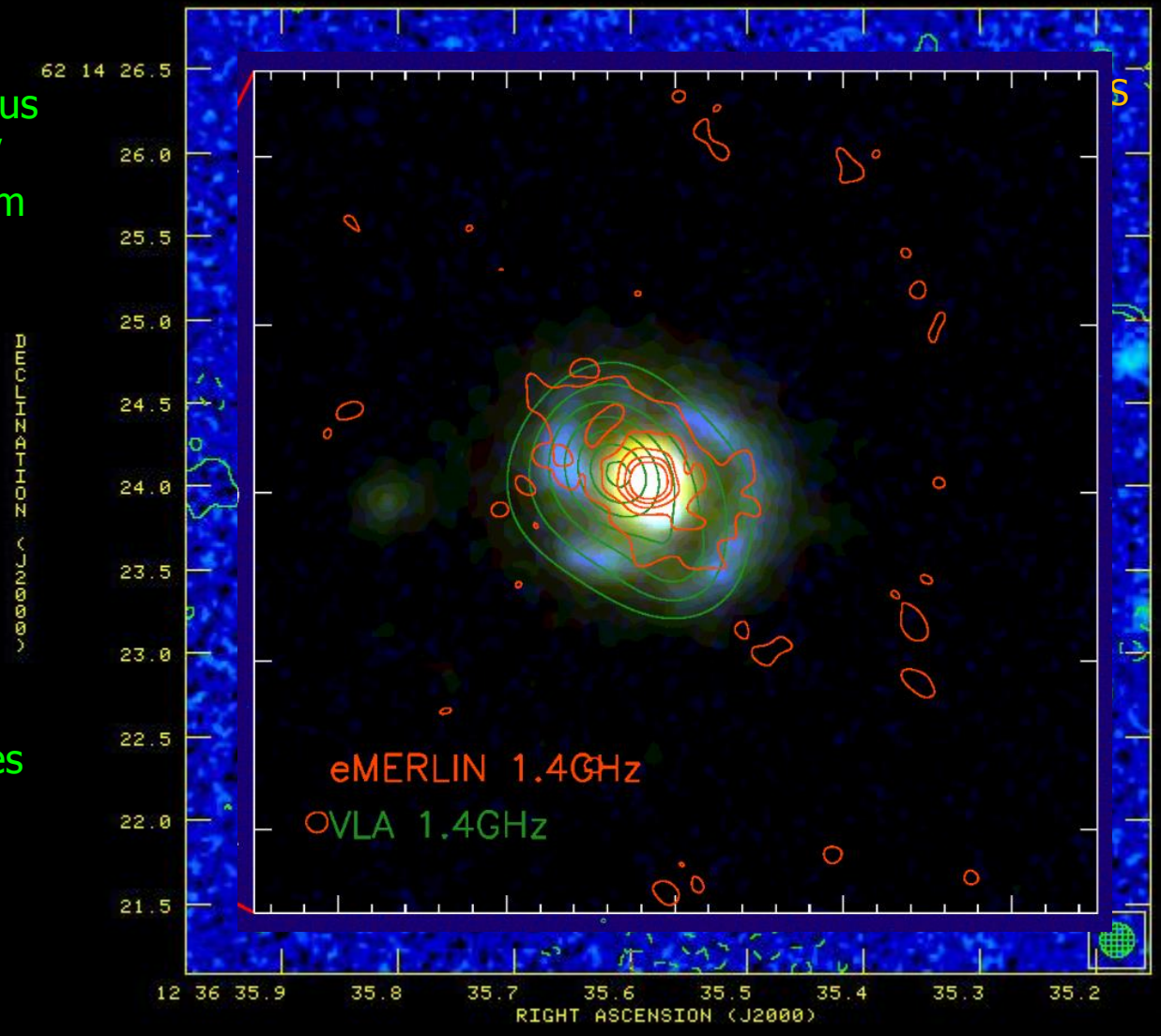
Dusty nucleus with blue UV emission from outer galaxy arms / ring.




Radio overlies galaxy but extended at PA~45°

SF ~ equally distributed between nuclear and extended components

JVLA 1.4GHz image confirms e-MERGE asymmetric structure PA – with peak to NE of central component

$S_{850}$=5.5mJy + Radio → S-F rate >1000 $M_{\odot}$/yr

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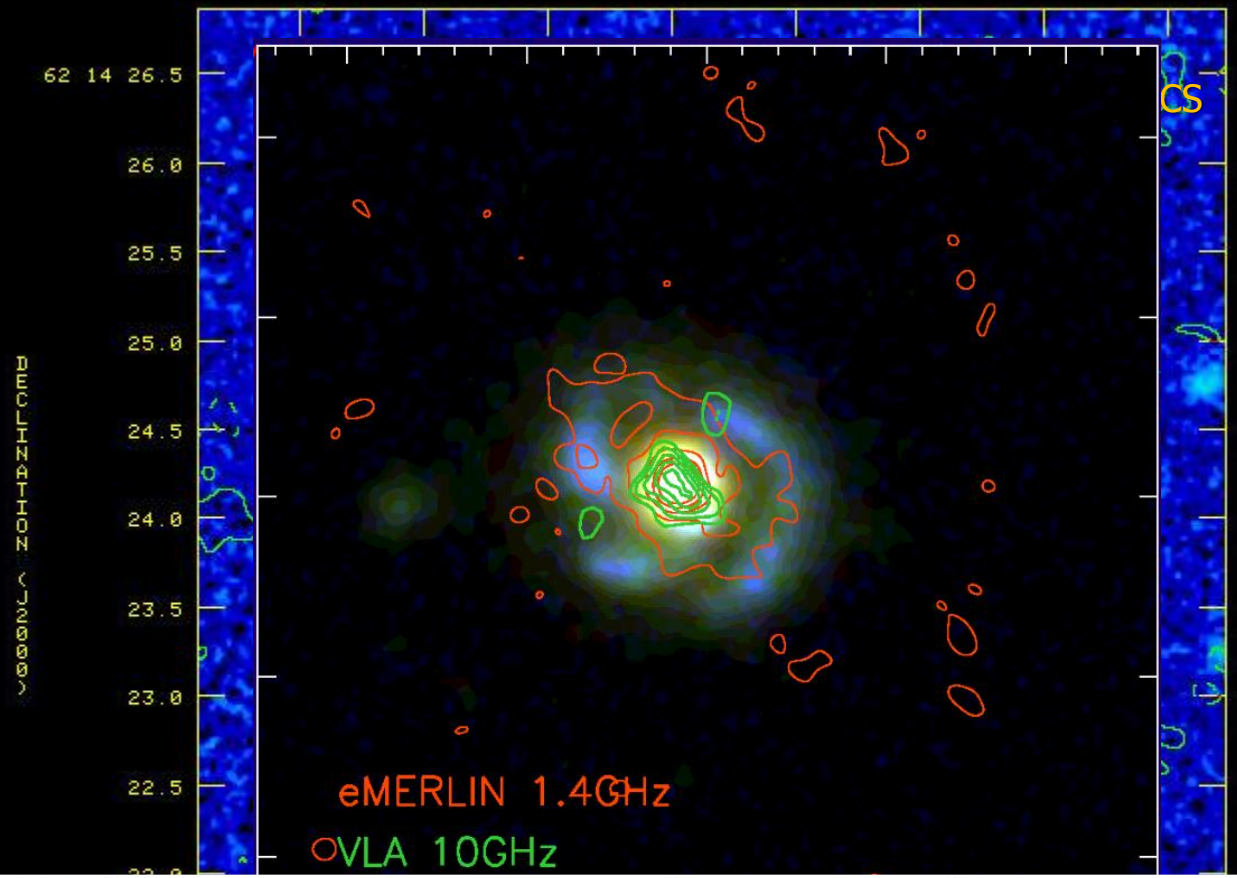
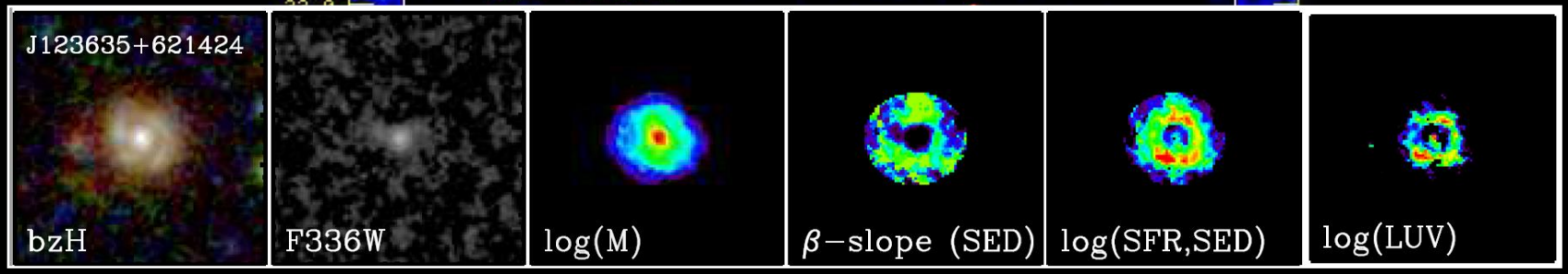



JVLA 10GHz image confirms central star-burst PA agrees with e-MERGE fitted angle – and aligns with outer extended structure

Displays a bright ring of S-F and a S-F nucleus – nuclear UV is heavily obscured

S-F Rate (ring) 320$M_\odot$ /yr




Anna Cibinel (Sussex) – private communication – multiband star-formation mapping

# High frequency Observing for Angular Resolution with Intermediate Baselines…

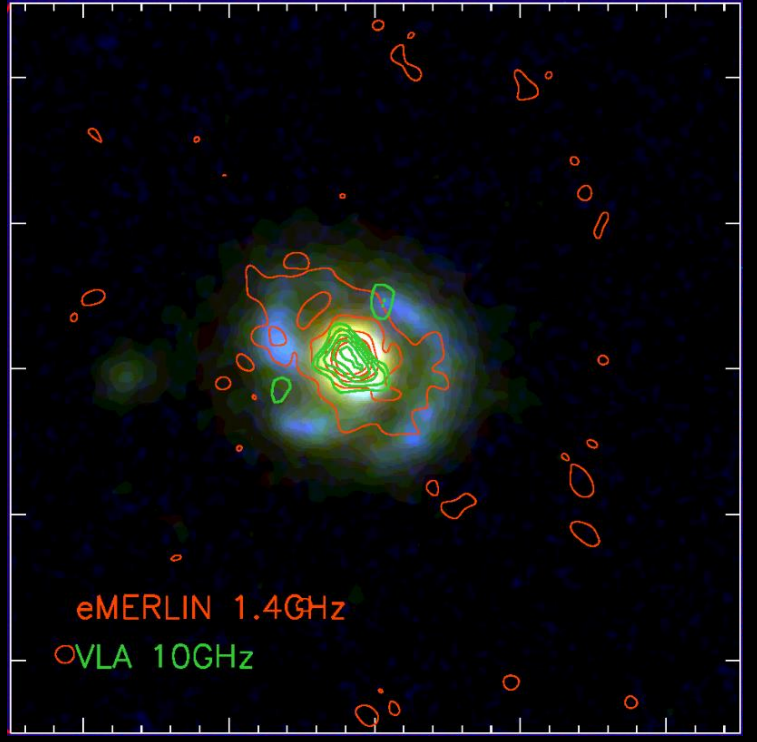
JVLA 10GHz v e-MERLIN 1.5GHz (Beam~200mas)

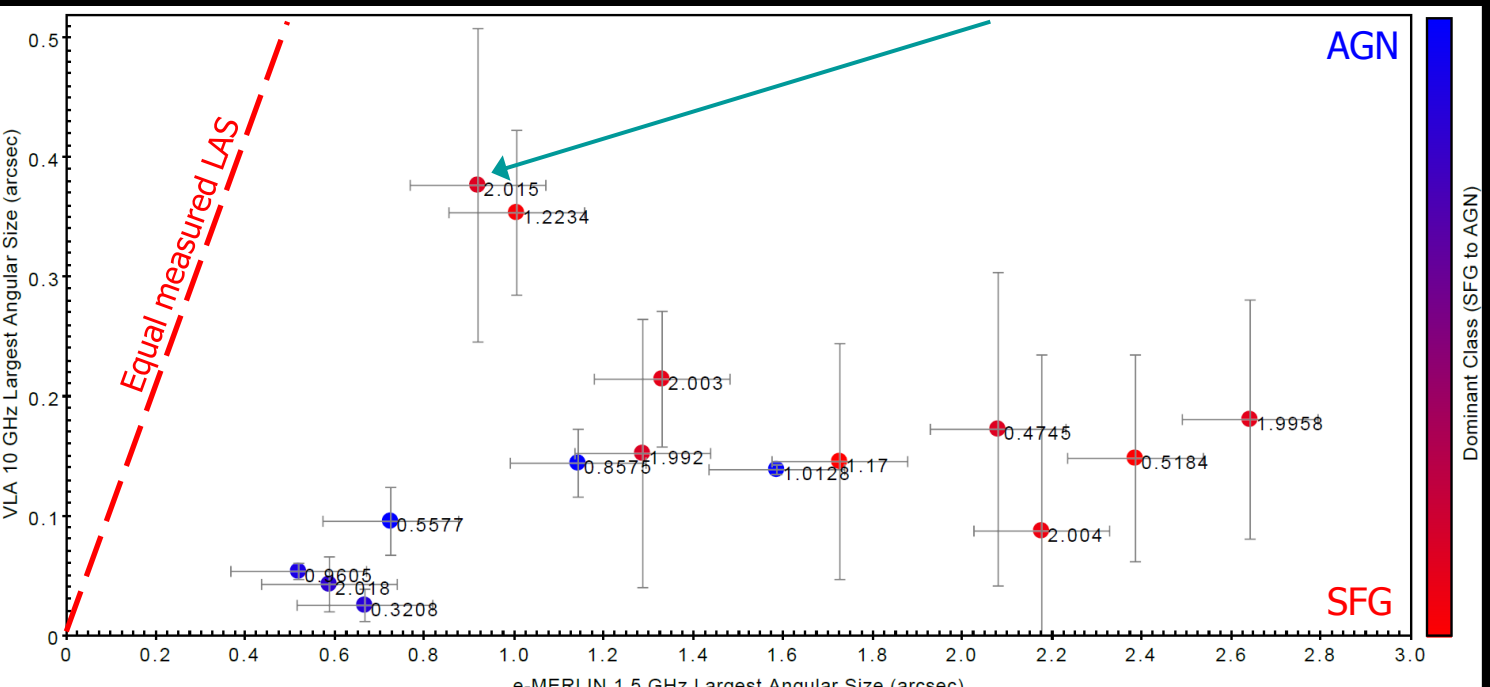
Radio emission not strongly correlated with optical UV?

No compact component → extended nuclear starburst

S-F triggered by previous AGN-jet activity, now ceased?

AGN-jet emission – but must be core-less in the radio?




JVLA at 10GHz detects only the central nuclear starbursts / merging cores in star-forming galaxies

- and the inner core-jet structures in AGN systems

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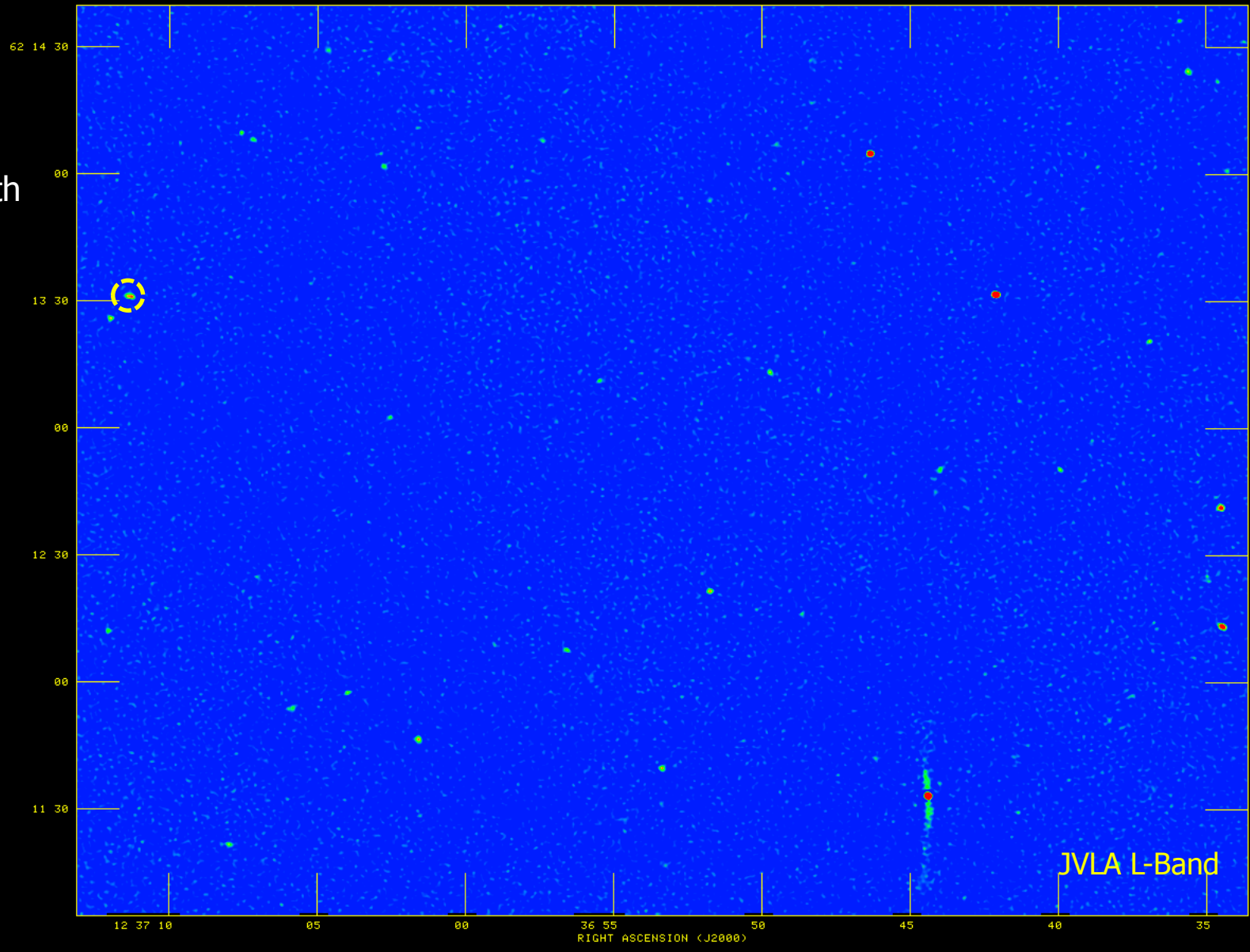


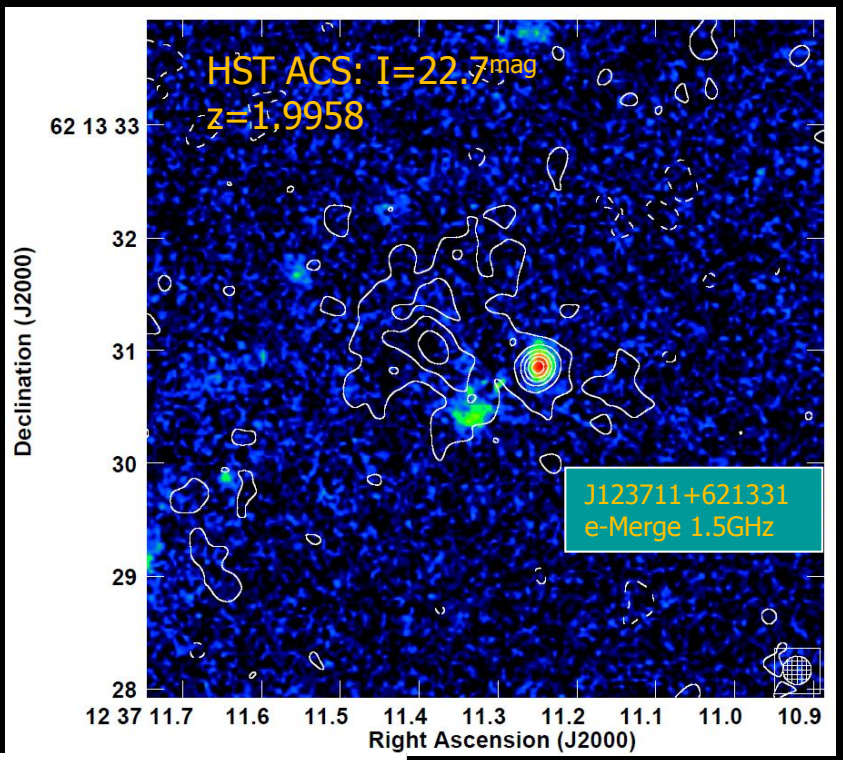
# High frequency Observing for Angular Resolution with Intermediate Baselines…

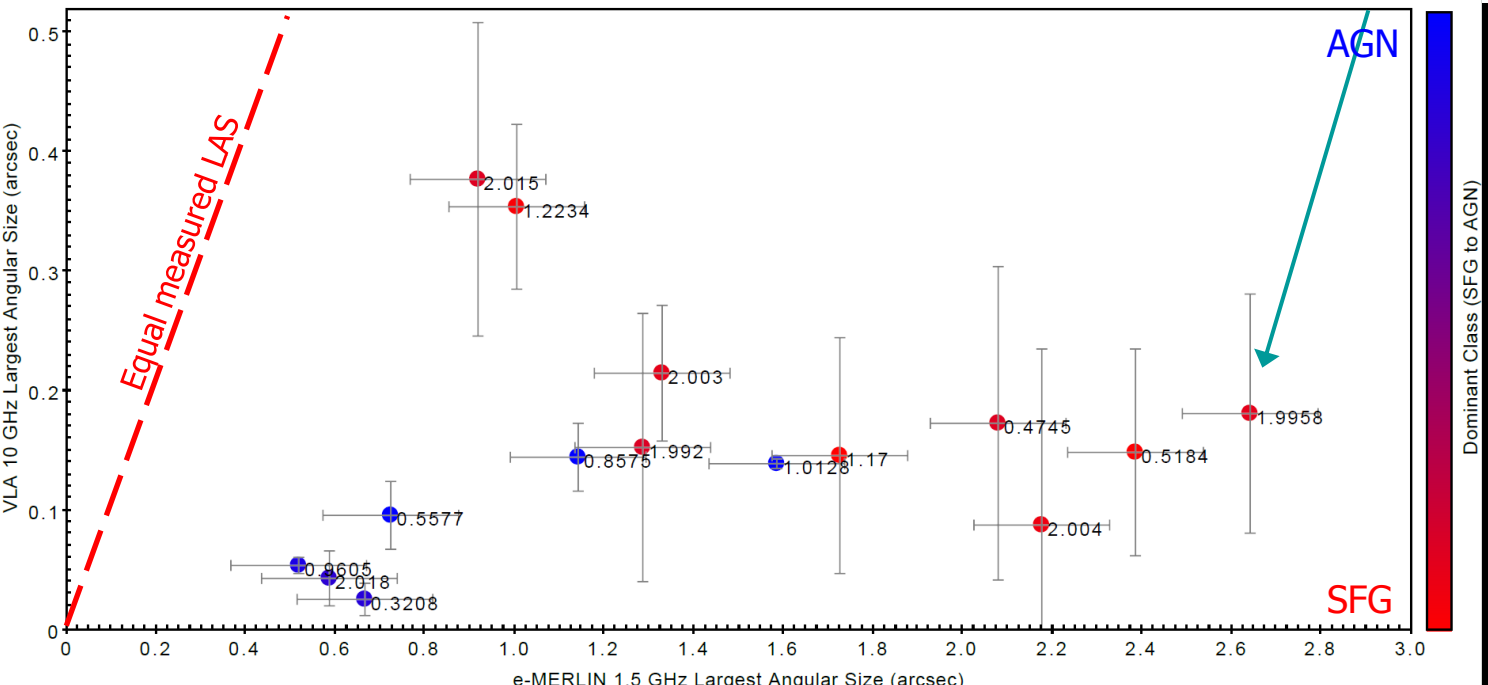
## JVLA 10GHz v e-MERLIN 1.5GHz (Beam~200mas)

Steep-spectrum ($\alpha$=0.75) merging system with star-formation + a nuclear starburst (160x90mas)

$S_{1.5GHz}$ = 130μJy  $S_{10GHz}$ = 8 μJy

Radio → S-F rate >1000 $M_\odot$/yr



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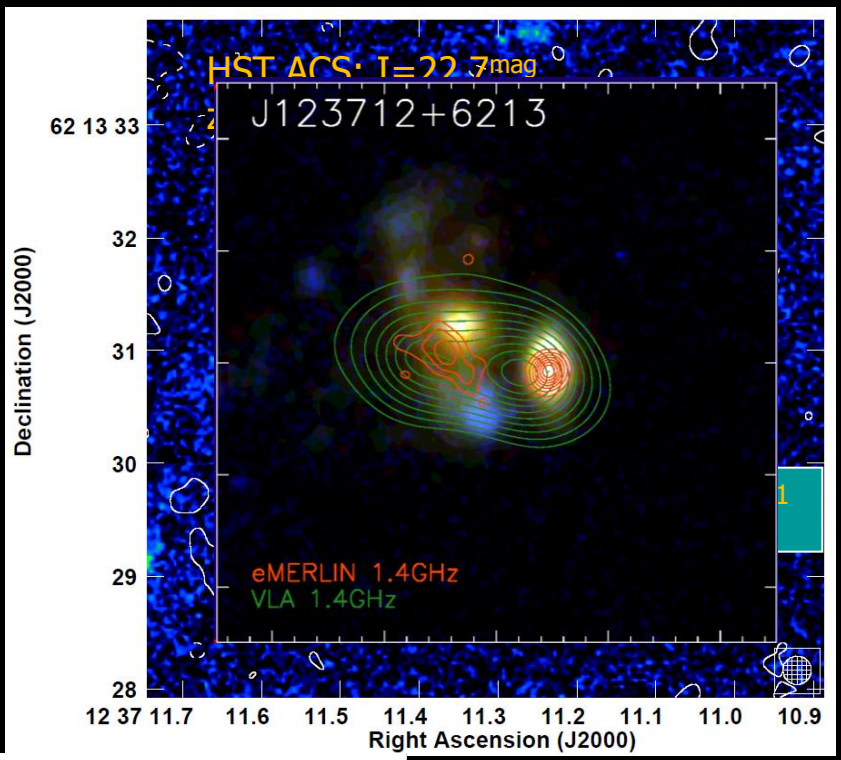
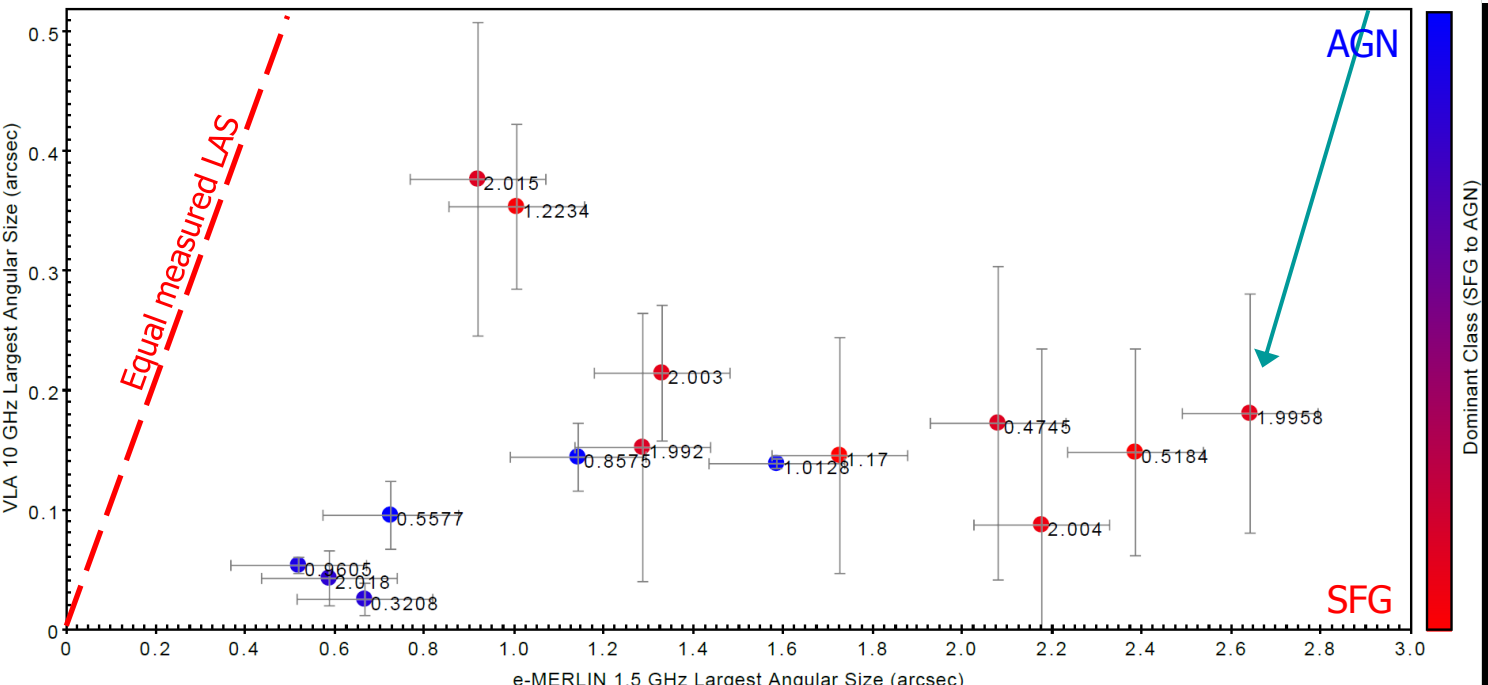
Redshift corrected colours show 2 merging dusty SF galaxies + blue object which may be foreground

Radio → S-F rate >1000 $M_\odot$/yr




JVLA at 1.5GHz confirms e-MERGE structure and LAS

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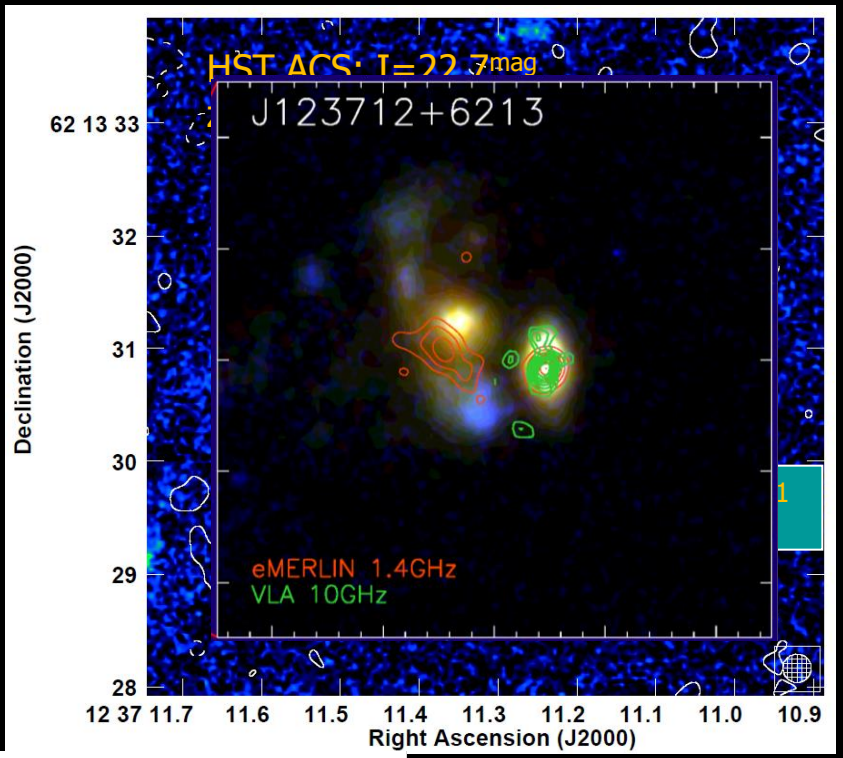


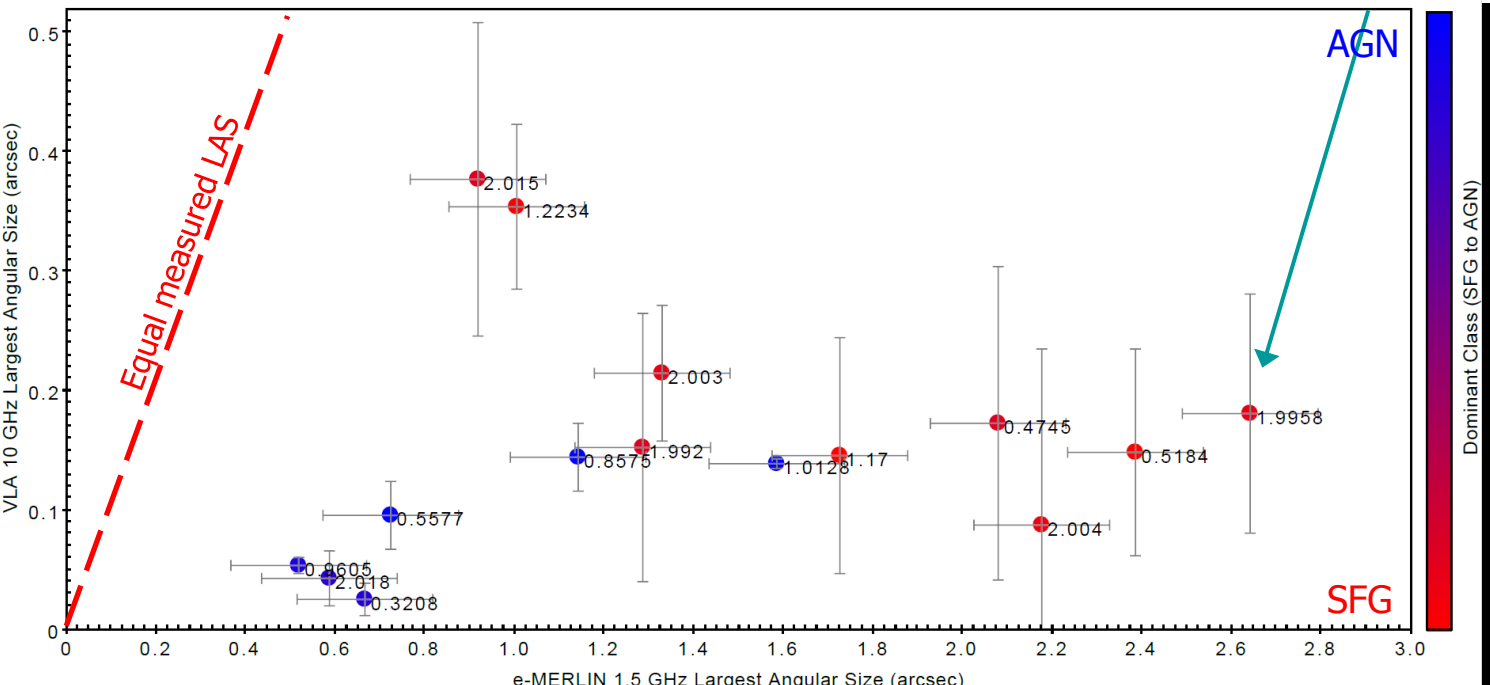


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JVLA at 10GHz detects only the compact nuclear starburst

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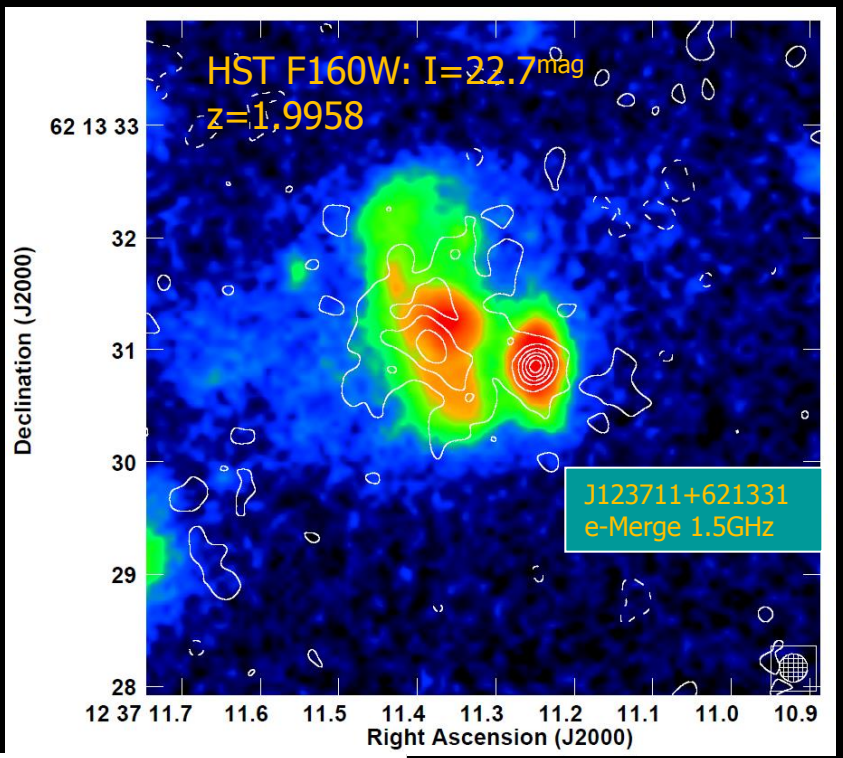


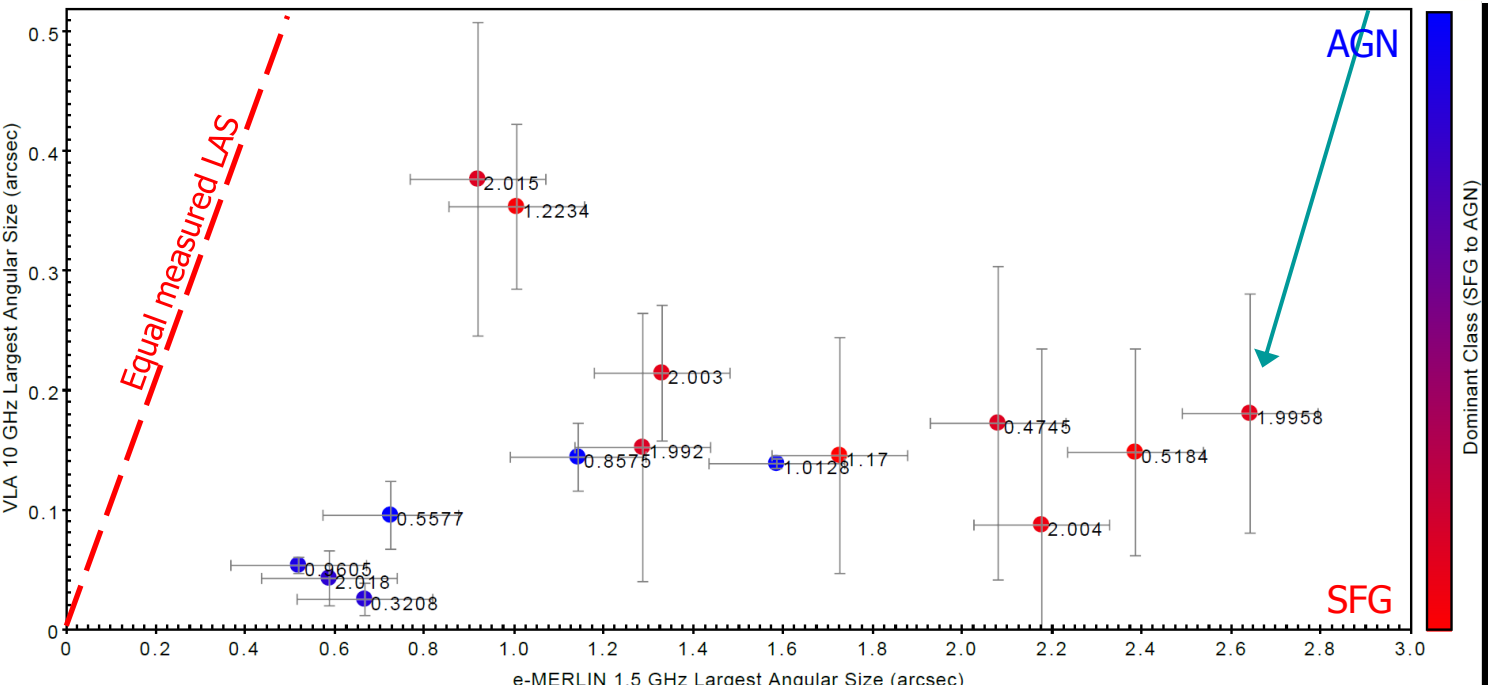


JVLA at 1.5GHz confirms e-MERGE structure and LAS

JVLA at 10GHz detects only the compact nuclear starburst

No spectral steepening found in extended component

# Some concluding thoughts…

→At high z, JVLA 10GHz is insensitive to steep-spectrum extended S-F & needs very deep imaging to compensate.

→At high z, JVLA 10GHz images contain substantial thermal emission

→Low frequency high resolution studies are required to provide the complete picture of high redshift star-formation activity

→1.5GHz images may show older S-F activity
- check for spectral steepening at higher frequencies

→Most radio-loud AGN are simple core-jet systems

→Classical starbursts (Super M82s) dominate at $z<1$ (Median $z\sim0.8$)

→For $z>0.7$ nuclear starbursts appear more common

→Many sub-mm sources show nuclear starbursts + extended emission. No radio AGN cores seen, but do radio structures contain remnant emission from past AGN-jet activity?
- need the initial release deeper study on many more objects