The University of Manchester
Jodrell Bank
Observatory

MANCHESTER 1824

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

The Broad Impact of (Relatively) Low Frequency Observing…

Tom Muxlow JBCA Manchester for the e-MERGE Consortium

Bologna 22th June 2017

- An interloper from the dark side of the 1GHz divide…

For steep spectrum emission there is no substitute for low frequency imaging on long baselines…

Science & Technology Facilities Council

EUROPEAN VLBI NETWORK

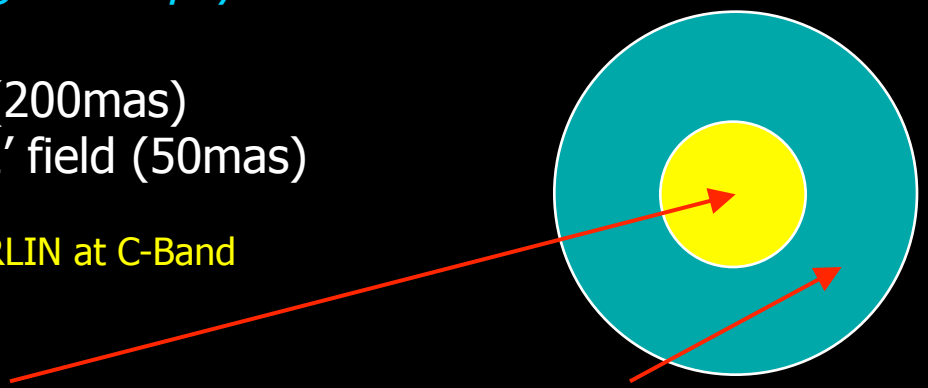
The e-MERGE Survey (e-MERLIN+JVLA)

Don't just count them – Image them in detail to find out what's happening…

Tier 1: *Deep high resolution imaging of the μJy radio sources in GOODS-N*

Deep L-Band imaging of 30′ field (200mas)
Deep C-Band mosaic of the inner 12′ field (50mas)

L-Band complete. Awaiting 380 hrs of e-MERLIN at C-Band



L-Band – Central 12′ 1σ ~500nJy/bm Outer 30′ annulus 1σ ~1μJy/bm

In full 30′ field ~1500 AGN and ~3100 S-F galaxies complete to local ~6σ [2019]

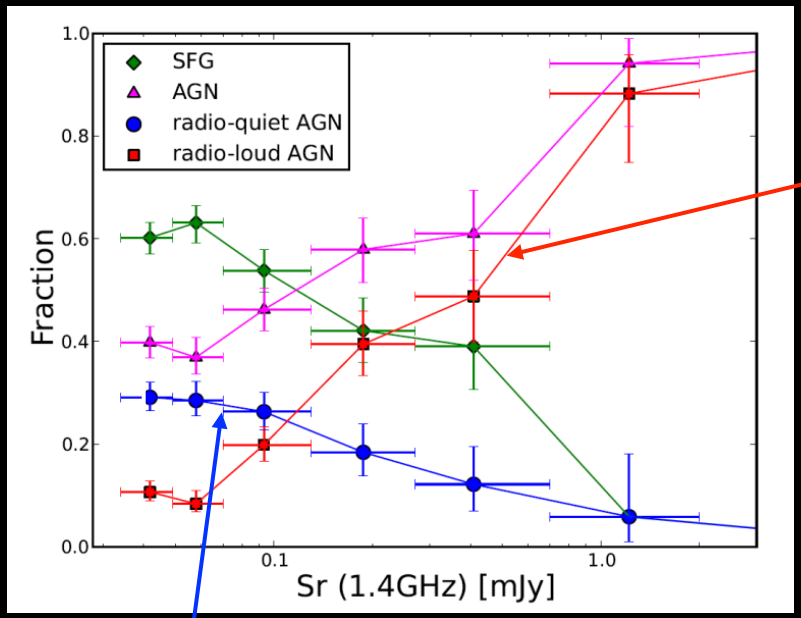
Q3 2017 → Interim consortium data and image release [DR-1]:
L-Band: JVLA 30′ field, beam~2″, 1σ ~1.8μJy/bm ✓
+ e-MERLIN(25%)+JVLA 12′ field , beam ~200mas, 1σ ~1.5μJy/bm *–Soon!!*
C-Band: JVLA mosaic of 12′, beam ~500mas, 1σ ~3μJy/bm ✓
+EG078 EVN L-Band image of 12′ field (72-hrs), beam ~5mas, 1σ ~3μJy/bm
→ Detailed investigation of >500 SF galaxies and AGN in 12′ field

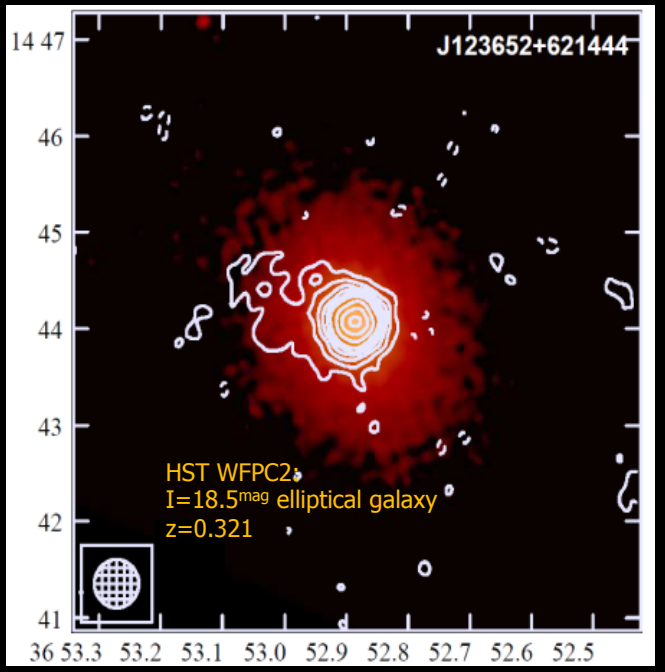
Interim L-Band e-MERLIN+JVLA Images presented from 12′ field 1σ ~2μJy/bm

Radio-Loud Classical AGN Systems

Radio-loud AGN: Very few classical double structures found.
Nearly all are small core-jet structures
J123652+621444 MERLIN+VLA Flat spectrum core + jet
Compact cores confirmed by deep VLBI imaging

Extended Chandra Deep Field South VLA Survey – Padovani et al (2014)





'Radio-Quiet' dominate AGN population below $S_{1.4}$~100μJy

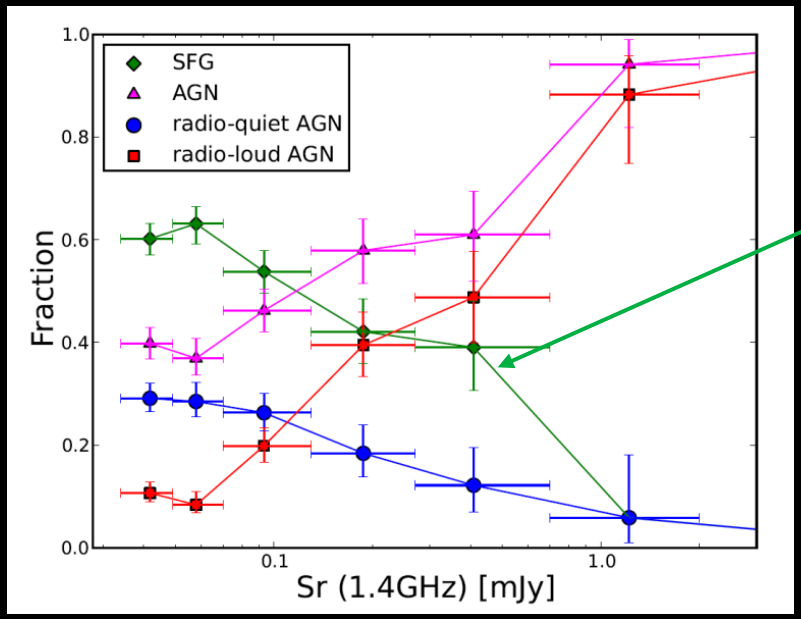
Luminous Classical Star-forming Galaxies

Classical Star-forming Galaxies: Typical example – J123708+621056 Extended radio emission across central region of 10^{10} M⊙ dust obscured irregular galaxy at z=0.422

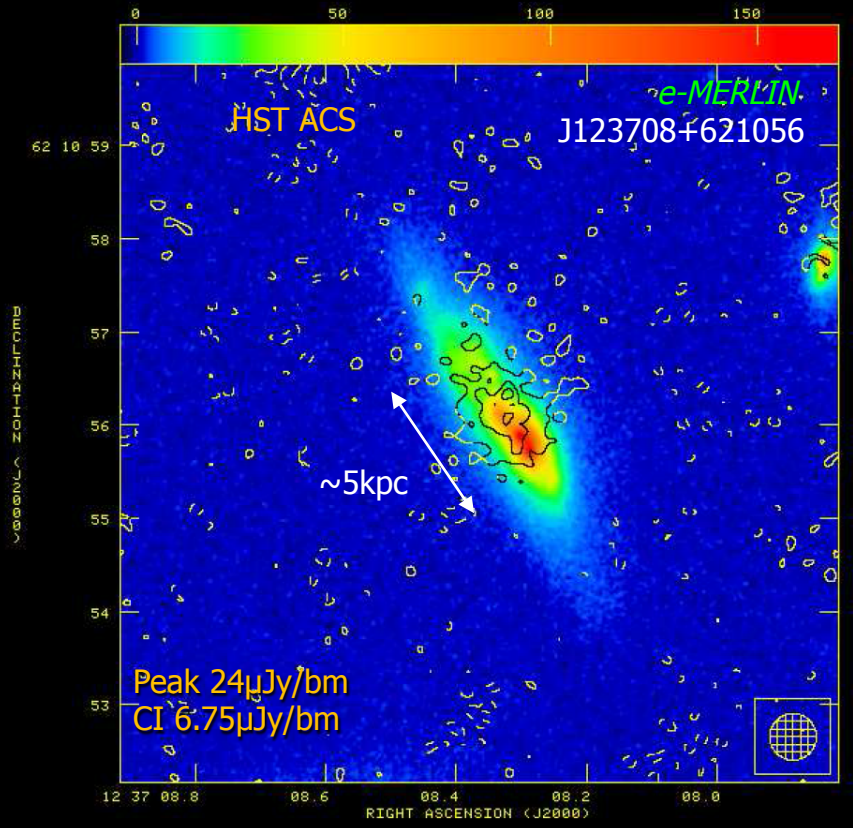
$L_{1.4}$ =3.8x10^{22} W/Hz → Star-formation rate 9 M⊙/yr

(>5 M⊙ assuming Salpeter IMF)

Extended steep-spectrum starburst ($S_{1.5}$ = 45 μ Jy) ~5x linear size of M82



<100μJy population dominated by star-forming galaxies

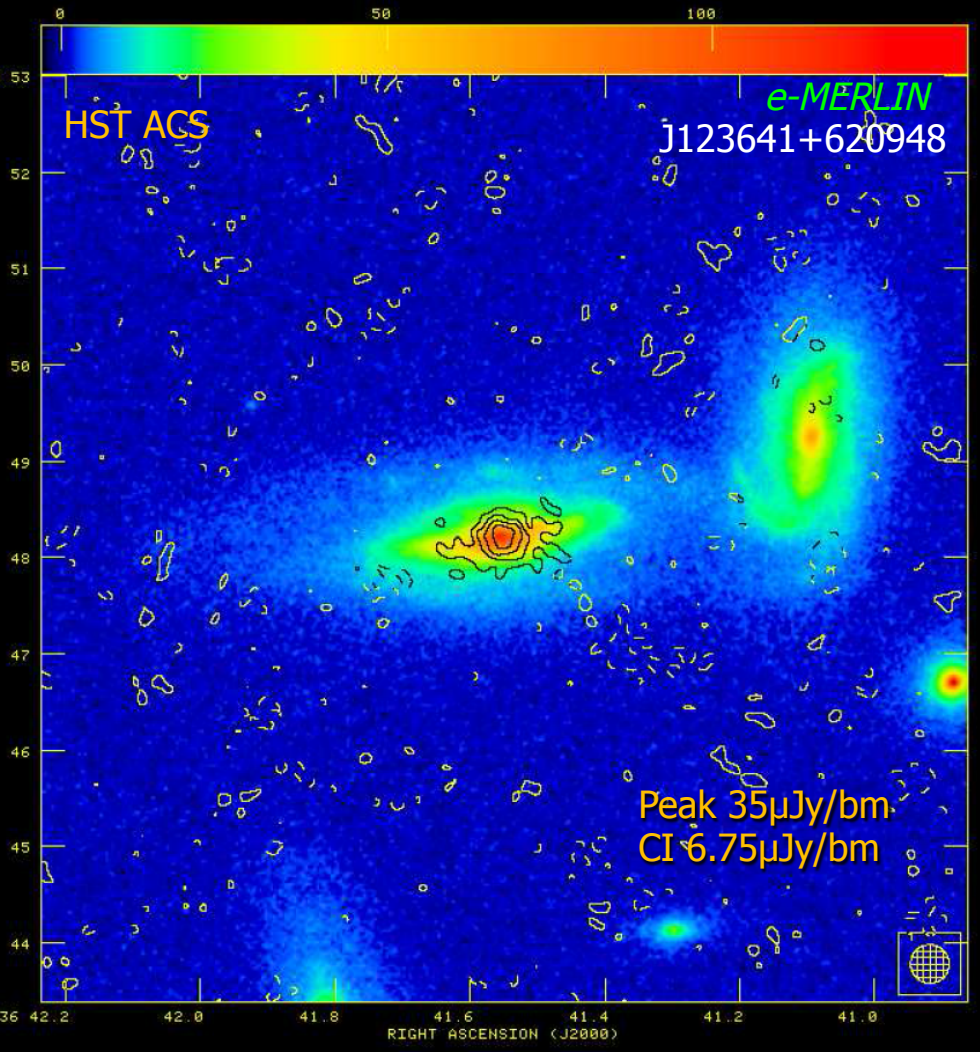


Role of AGN within Starbursts

Many starbursts at z>0.5 are found in galaxies with active AGN visible in other wavebands and contain nuclear starbursts

Steep-spectrum (α<-0.56) starburst extended along galaxy major axis with nuclear radio emission ($S_{1.5}$ = 76 μ Jy).

10^{11}M⊙ Seyfert-2 galaxy
z=0.5186

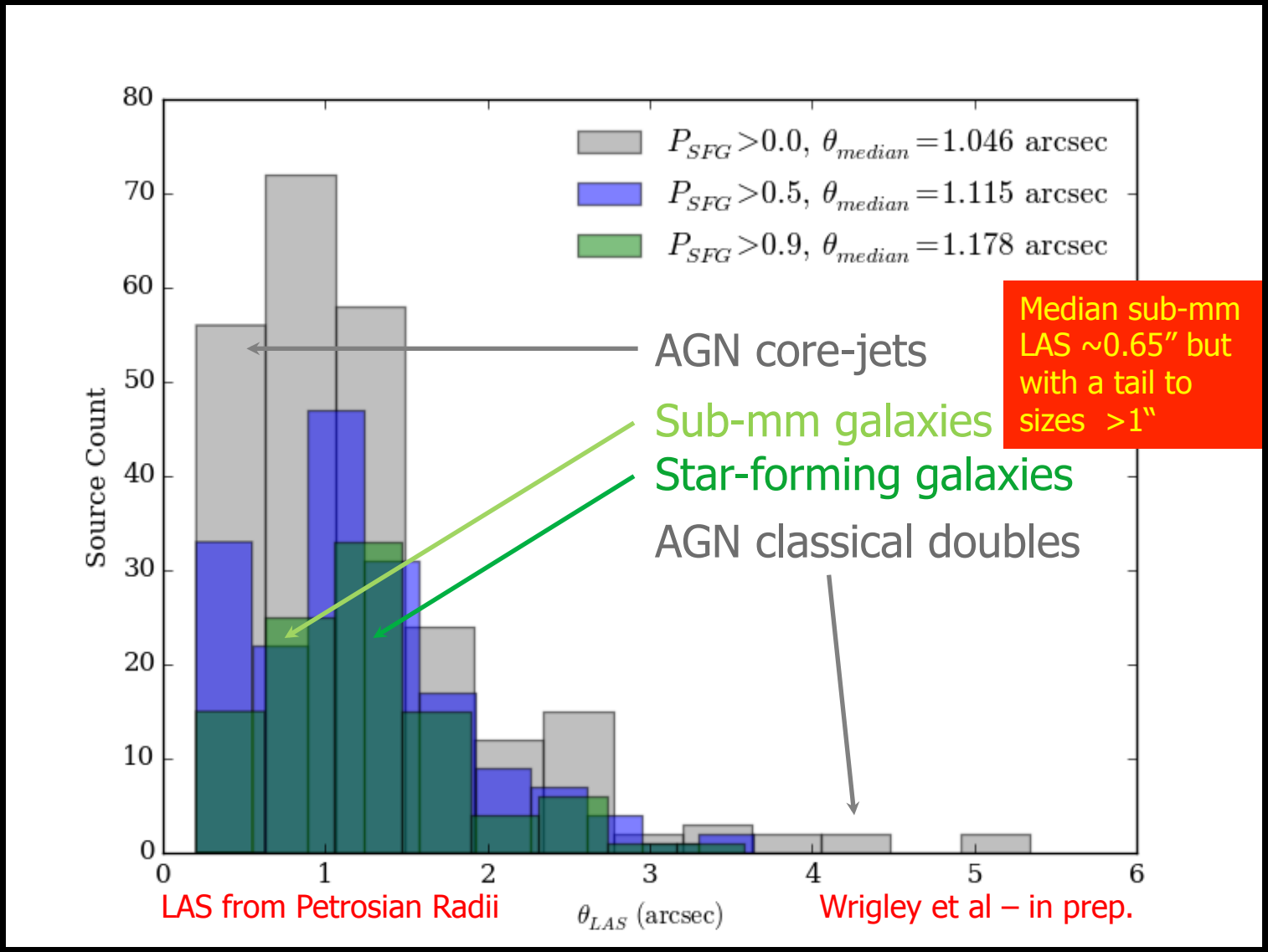


$L_{1.4}$ =1.7x10^{23} W/Hz
→ Star-formation rate 42 M⊙/yr
AGN or nuclear starburst?
Resolved by e-MERLIN (~370mas), no VLBI detection → Nuclear starburst
Radio-quiet AGN ? Radio is SF dominated. AGN seen only in other wavebands

Initial Results From Interim Images:

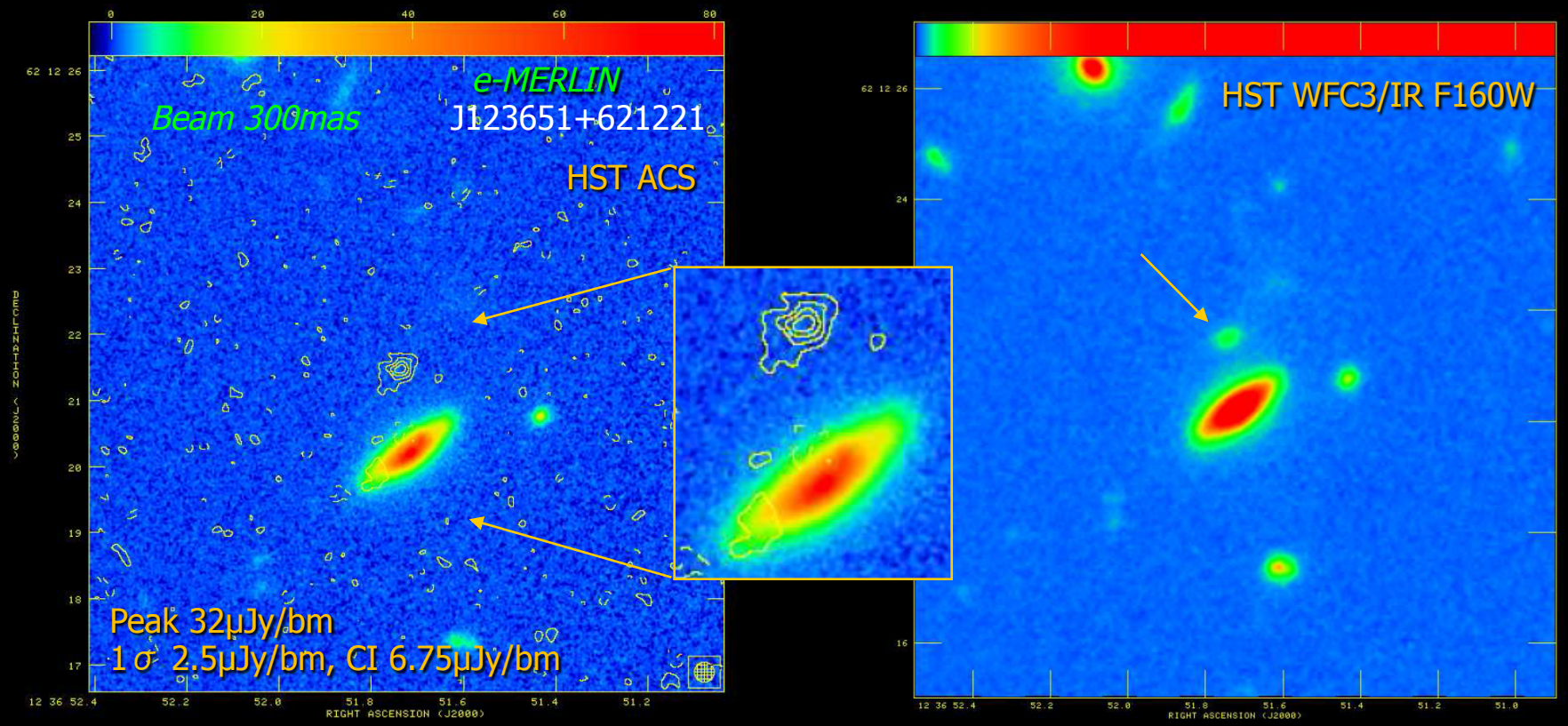
Sample of 248 detected sources within central 12′ field from ~90 hrs of data.

Assign probabilities of being AGN or SF from radio structures and spectral properties…



Machine-learning (SVM – Support Vector Machine)

Sub-mm Starburst Sizes



Central 12′ field contains 43 identified SMGs to 5xlocal beam corrected noise level

J123651+621221 typical with LAS~0.7″ containing a compact 0.3″ nuclear starburst

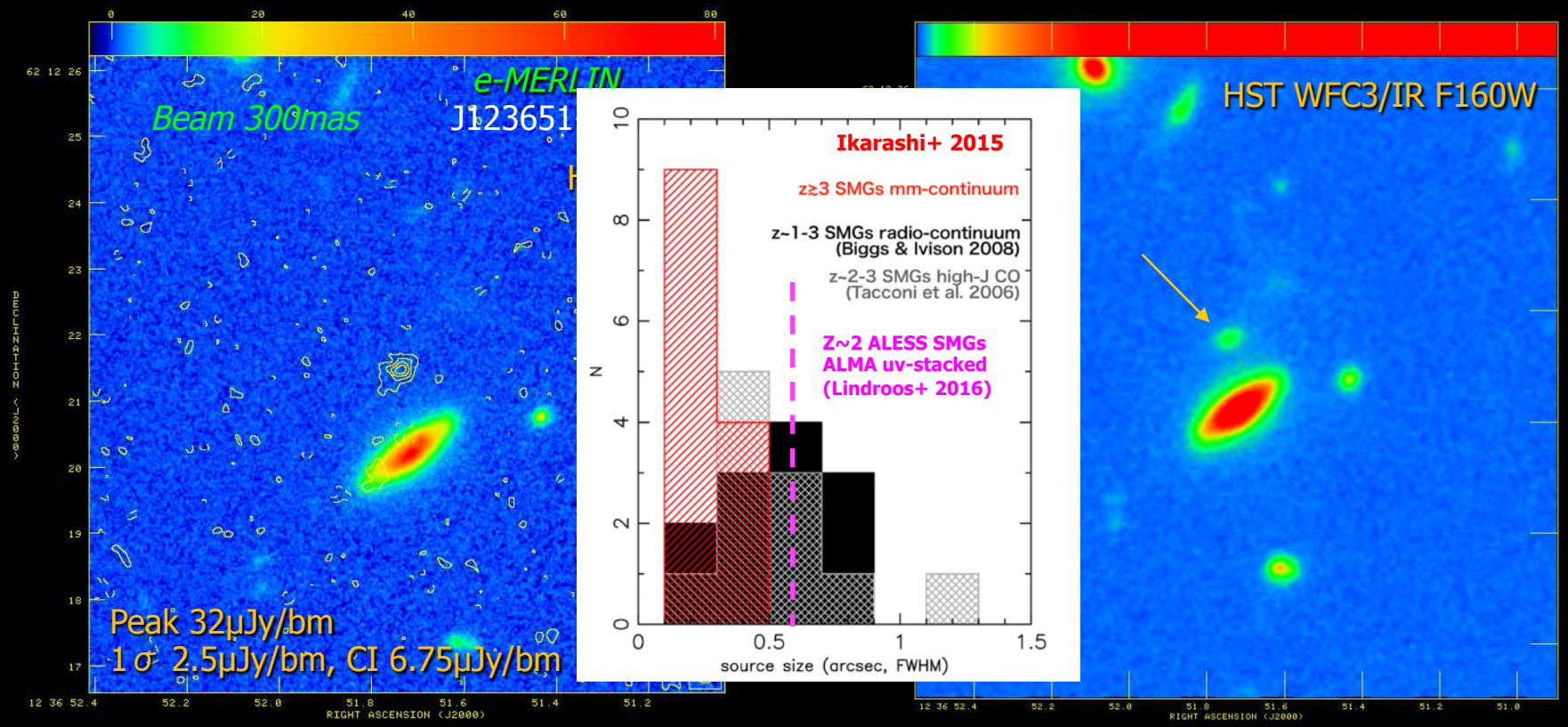
Not detected in visible bands. Faint very red object detected in F160W (1.6μm IR)

1.3mm SMA detection → S-F rate >1000 M⊙/yr

ISO detection → dust obscured starburst at z~3

Hard Chandra X-rays → obscured QSO at z=2.7

Sub-mm Starburst Sizes



Median radio LAS Lockman Hole z=1-3 sub-mm sources ~0.65" (Biggs & Ivison, 2008)

uv-stacking on 344 GHz ALMA observations on sub-mm galaxies in the LABOCA ECDFS sub-mm Survey (ALESS) at $z \approx 2$ with $M_* \approx 5 \times 10^{10} M_\odot$ → LAS ~0.6" (Lindroos+ 2016)

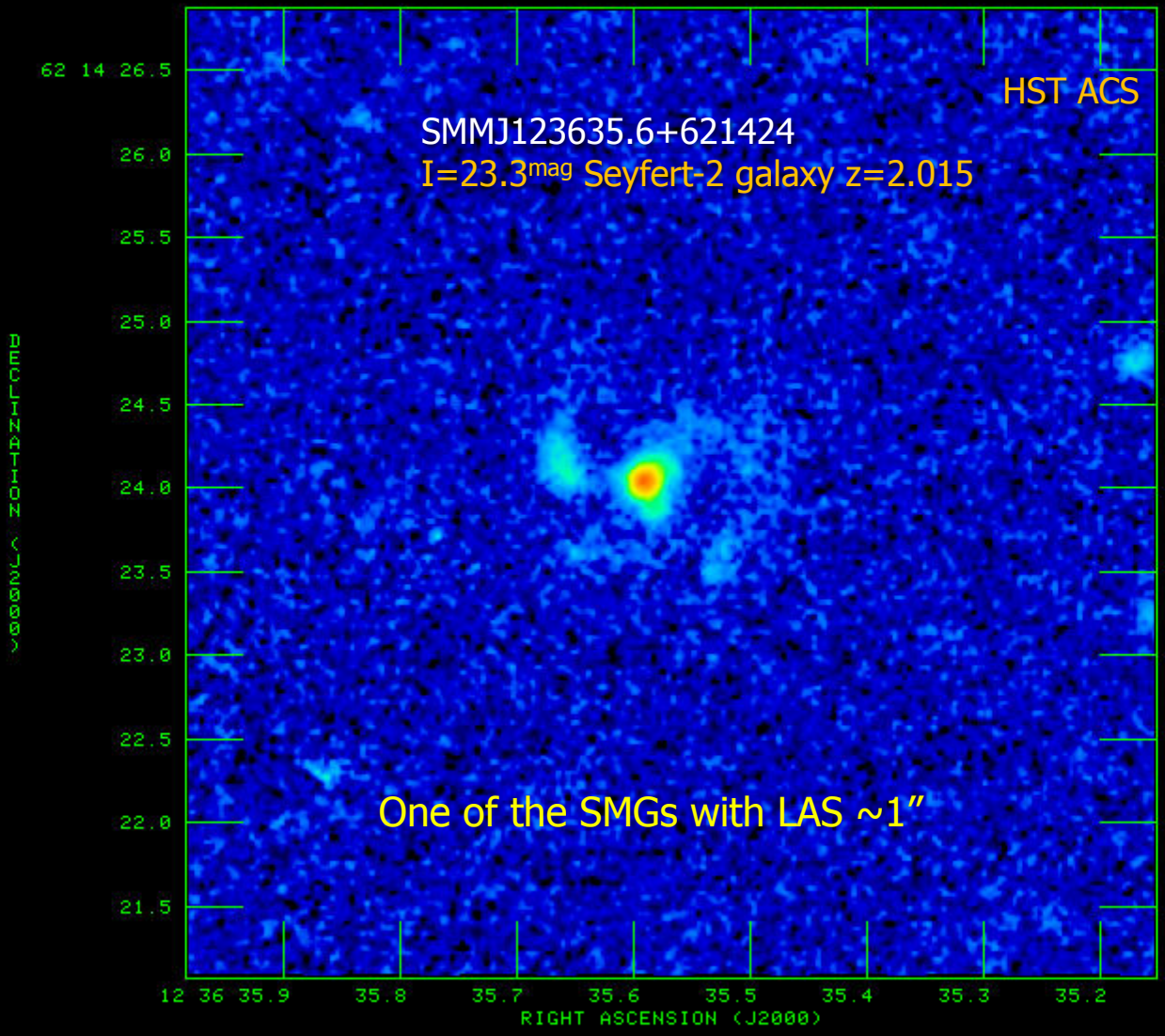
ALMA 1100μm dust continuum for high redshift z>3 SMGs are ~2x smaller (Ikarashi+ 2015)

For z~1->3 LAS ~0.65" LAS smaller for SMGs with z>3

At 1.5GHz there is a tail to the distribution with some LAS>1"

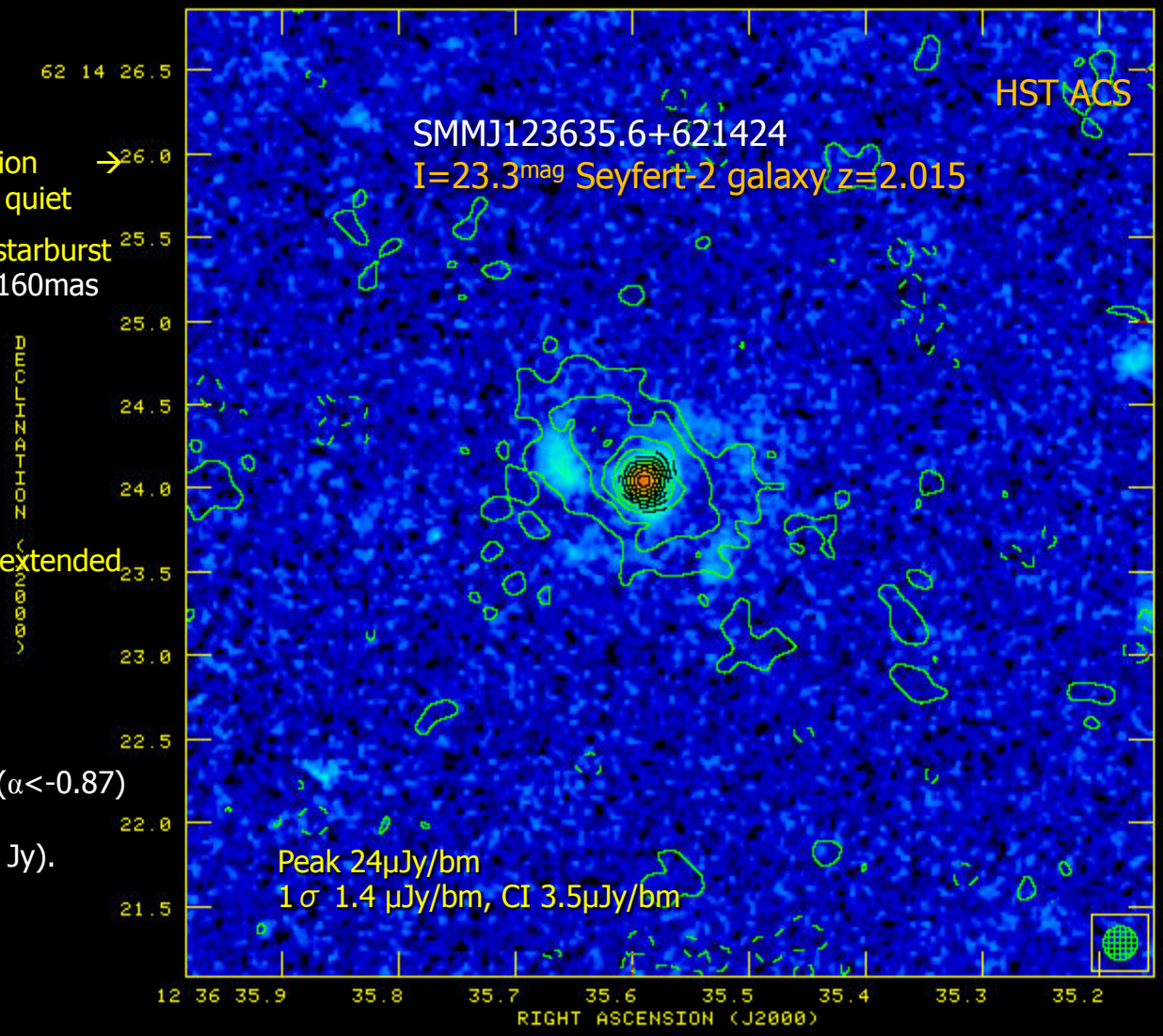
Measuring Source Sizes

Depends on what you can detect….



Multi-scale restoration e-MERLIN+JVLA L-Band

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



VLBI non-detection → AGN – but radio quiet

36 μJy nuclear starburst
Fitted size 250x160mas
@ PA+165°

SF ~ equally distributed between nuclear and extended components

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

S_{850}=5.5mJy. Radio + IR flux densities → S-F rate ~1500 M⊙/yr

Multi-scale restoration e-MERLIN+JVLA L-Band

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

Eric Murphy+ 2017

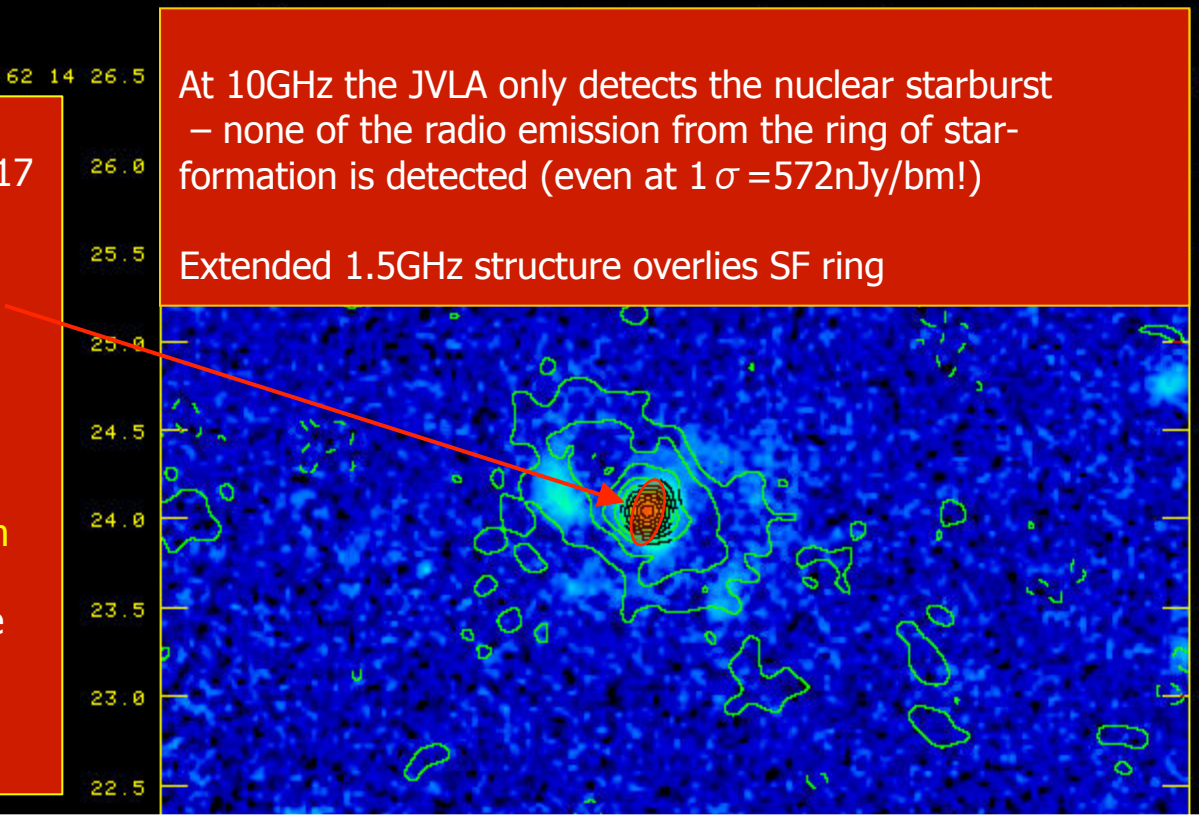
JVLA A+C-array
8-12GHz
23hrs (A) +
1.5hrs (C)

Beam 0.22″
1σ = 572nJy/bm

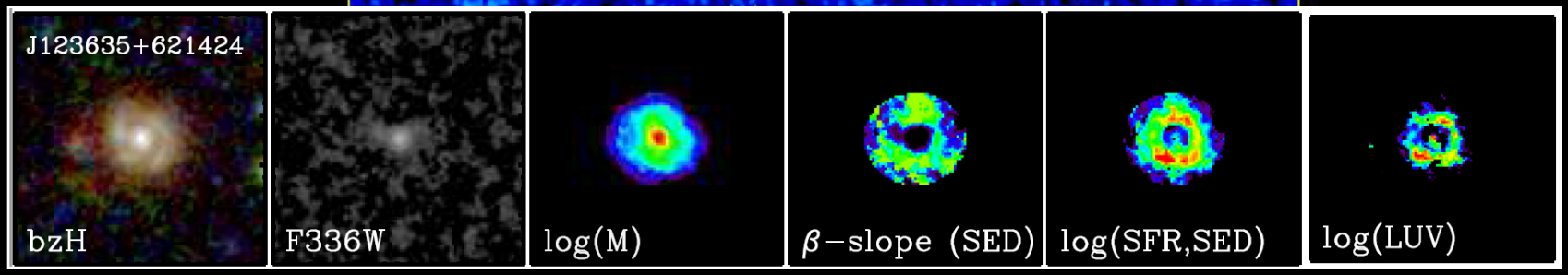
X-band fitted size
380x270mas
S_{10GHz} = 12 μ Jy

At 10GHz the JVLA only detects the nuclear starburst – none of the radio emission from the ring of star-formation is detected (even at 1σ =572nJy/bm!)

Extended 1.5GHz structure overlies SF ring



Displays a bright ring of SF and a SF nucleus – though nuclear UV is heavily obscured



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

High frequency Observing for Angular Resolution with Intermediate Baselines…

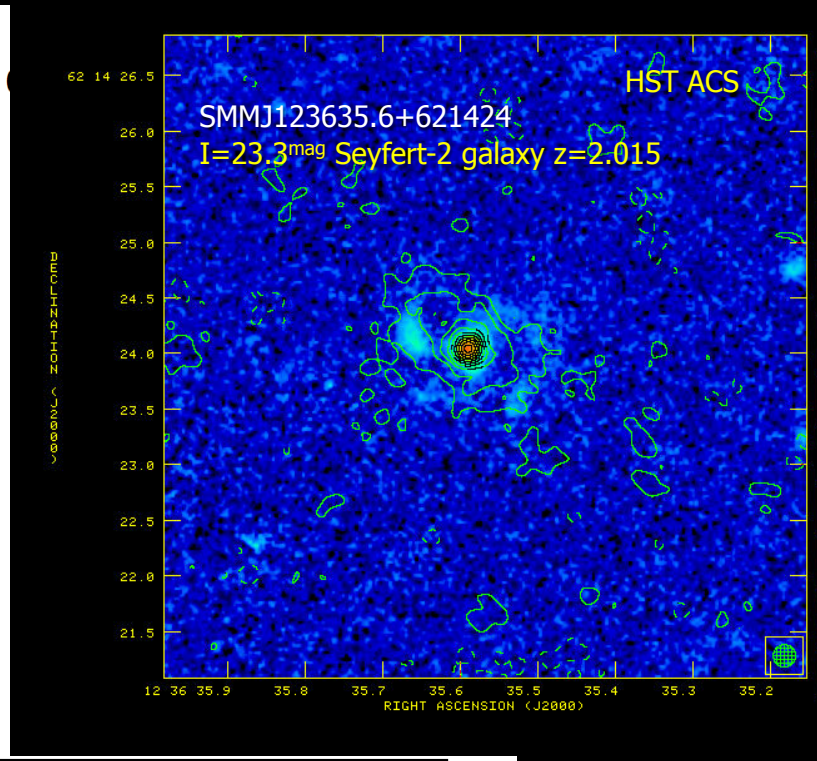
JVLA 10GHz v e-MERLIN 1.5GHz (Beam~200mas)

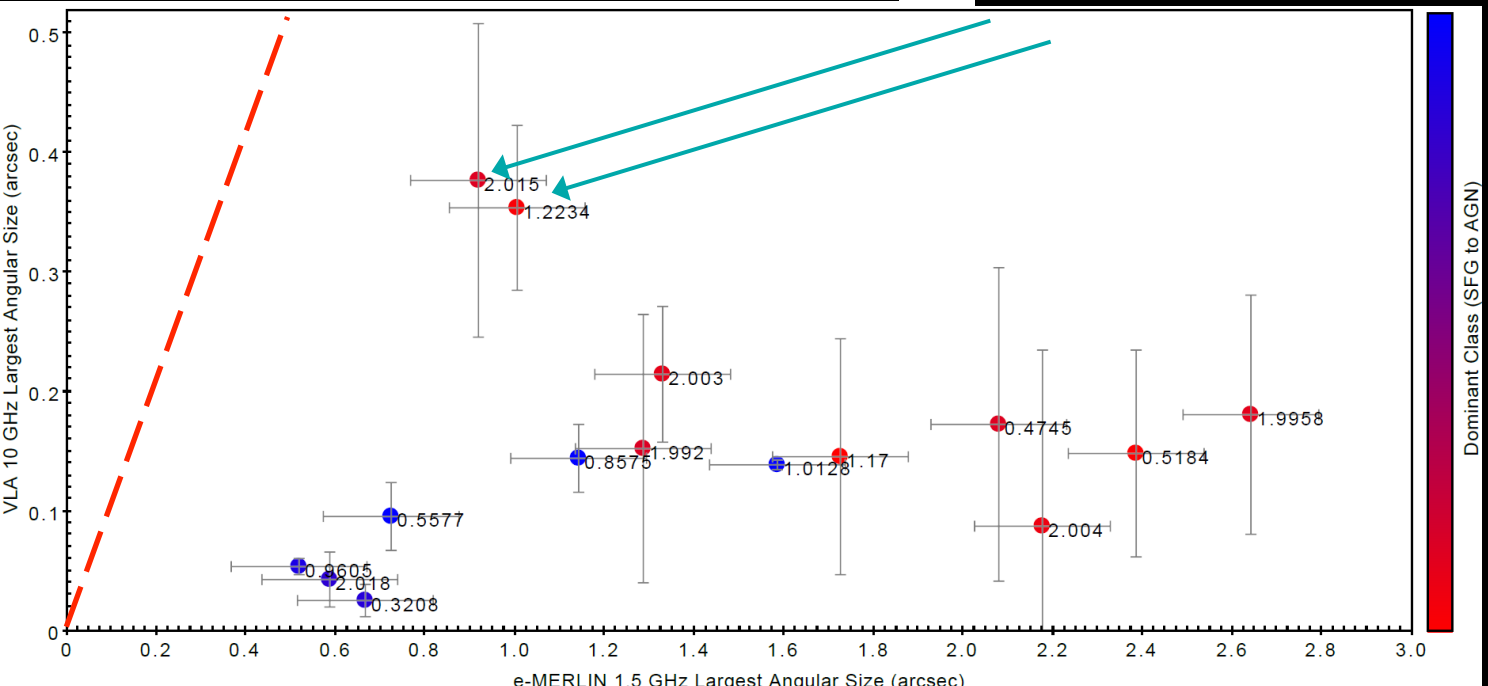
Steep-spectrum (α=-0.74) starburst.
ISO detection

$S_{1.5GHz}$ = 230 μ Jy S_{10GHz} = 28 μ Jy

→ Star-formation rate ~960 M◉/yr

Merging Scd sub-mm galaxy with tidal tail
- High redshift version of the 'Antennae'



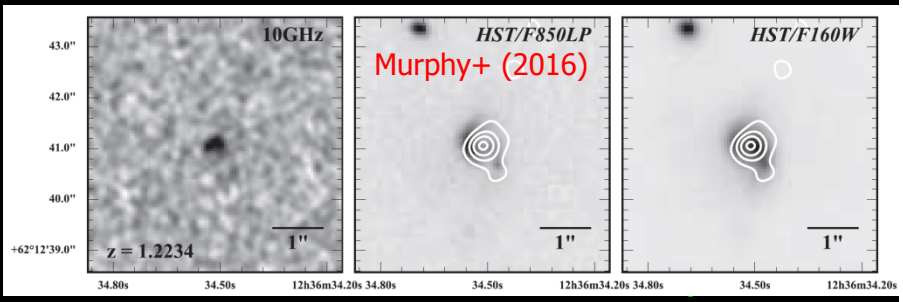


For 15 sources common to both e-Merge and Murphy+ 2017:

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

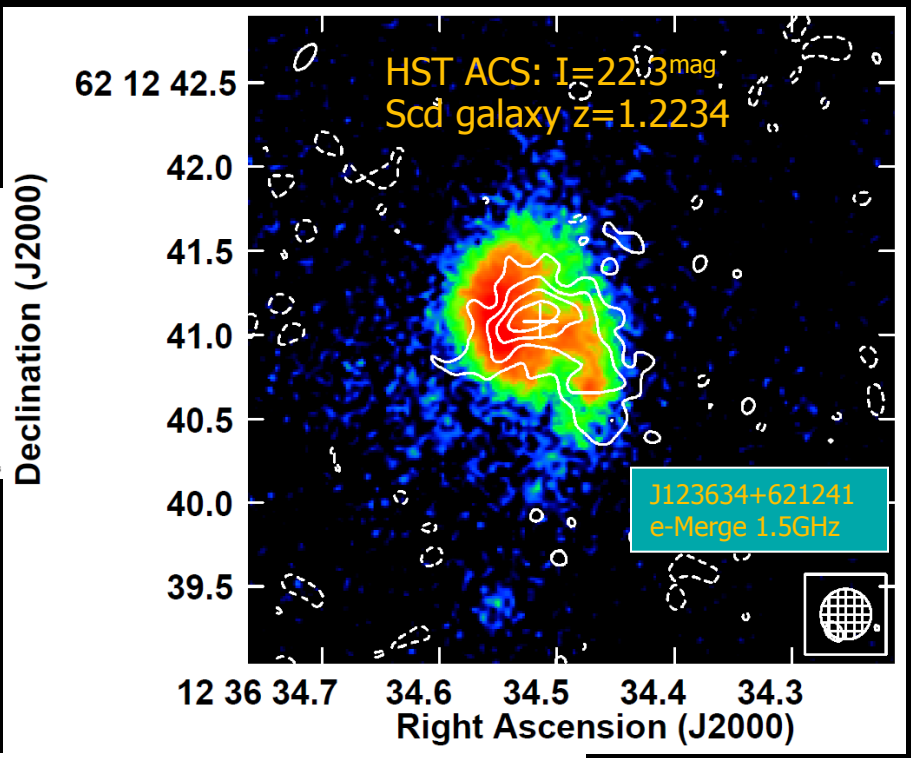
High frequency Observing for Angular Resolution with Intermediate Baselines...

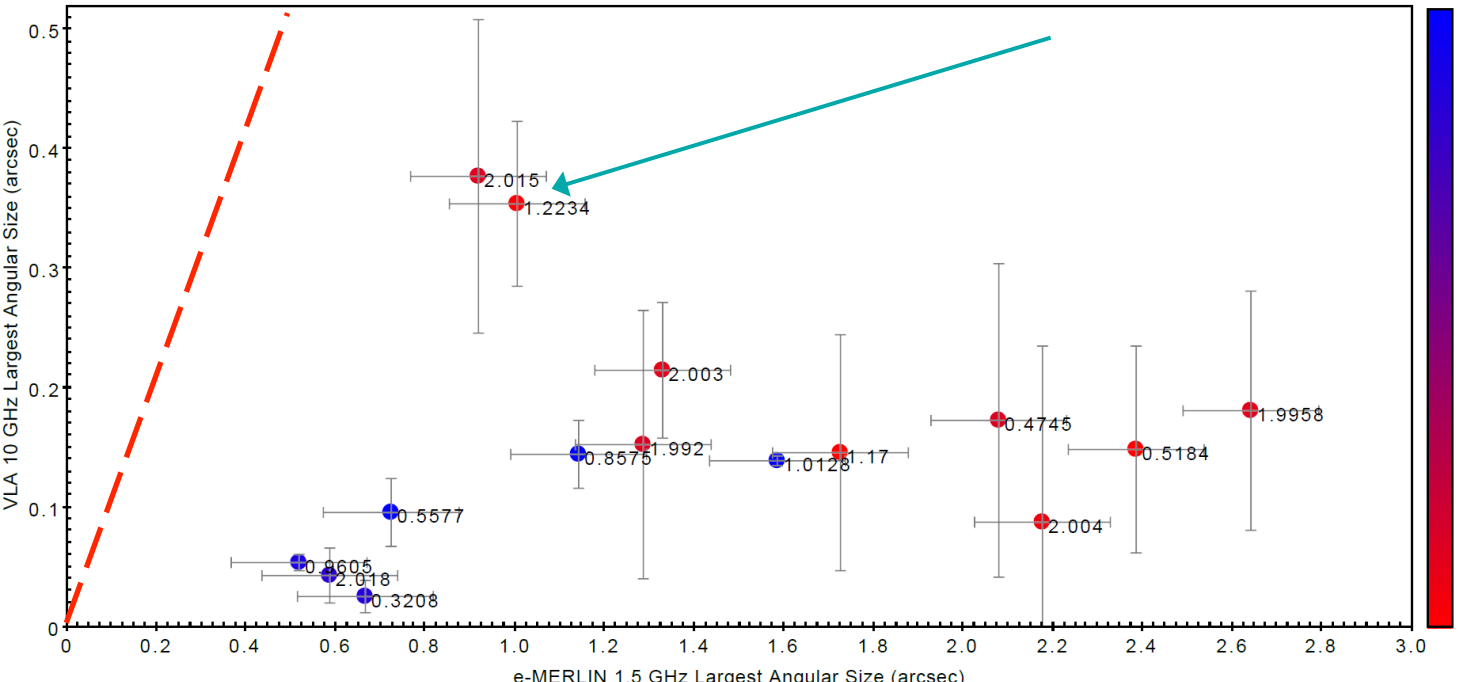
JVLA 10GHz v e-MERLIN 1.5GHz (Beam~200mas)



Merging Scd sub-mm galaxy with tidal tail

- High redshift version of the 'Antennae'





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

- and the inner core-jet structures in AGN systems

High frequency Observing for Angular Resolution with Intermediate Baselines...

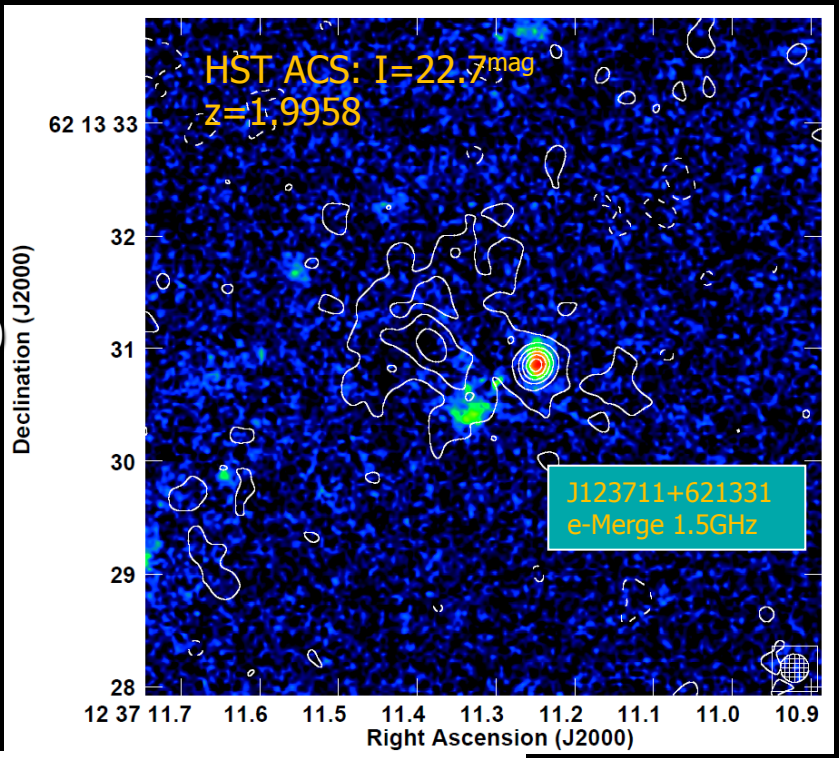
JVLA 10GHz v e-MERLIN 1.5GHz (Beam~200mas)

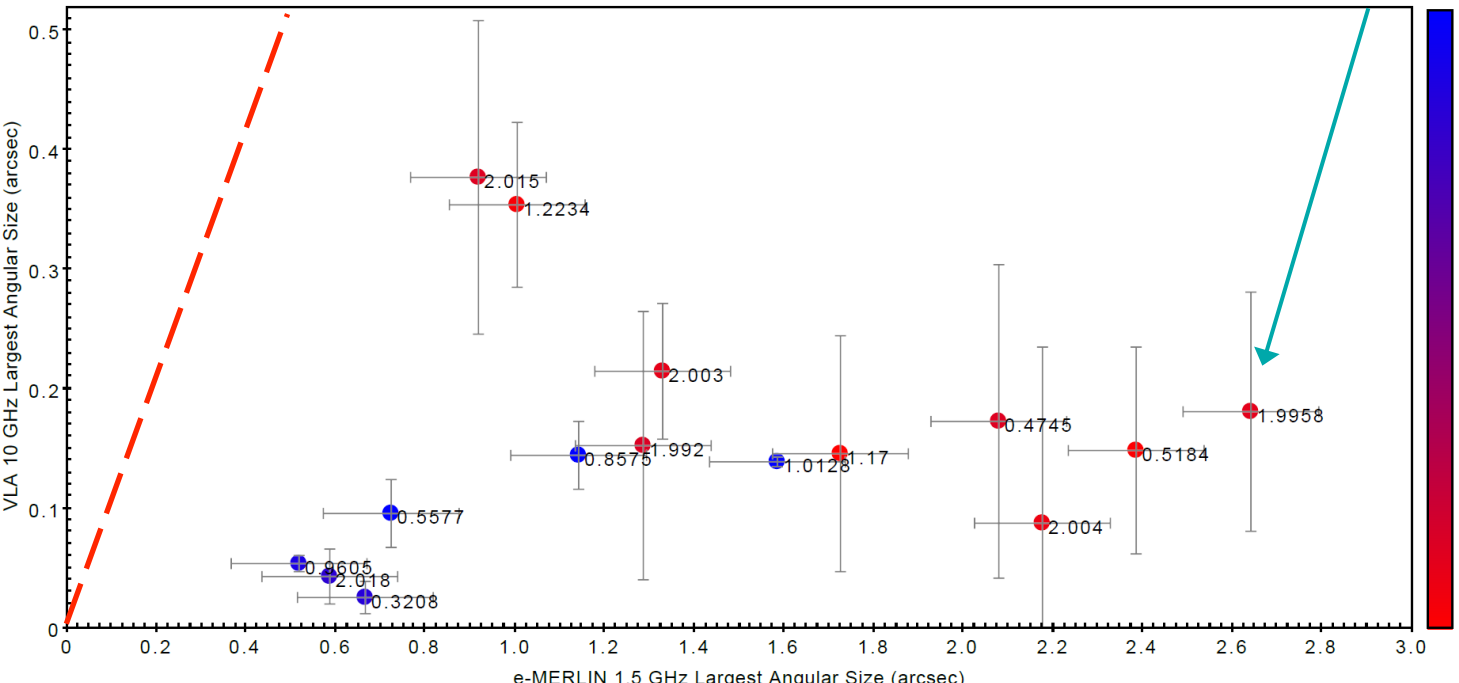
Steep-spectrum (α=-0.69) merging system with star-formation + a nuclear starburst (160x90mas)

$S_{1.5GHz}$ = 130 μ Jy S_{10GHz} = 8 μ Jy

Peculiar extended radio structure overlies a very red galaxy companion seen better in the IR

- Major size difference between 10GHz & 1.5GHz





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

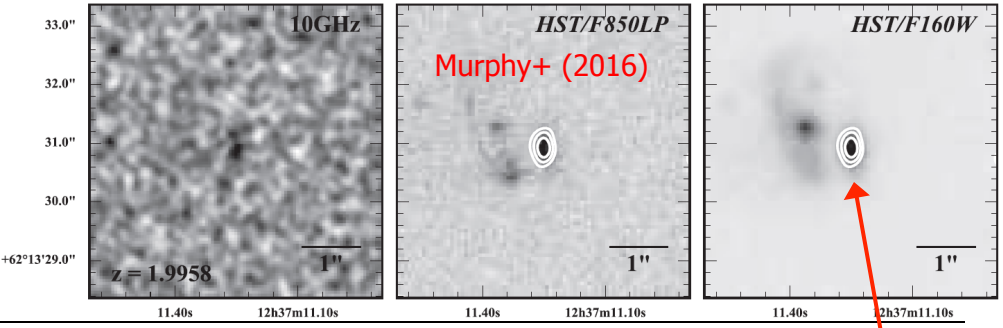
- and the inner core-jet structures in AGN systems

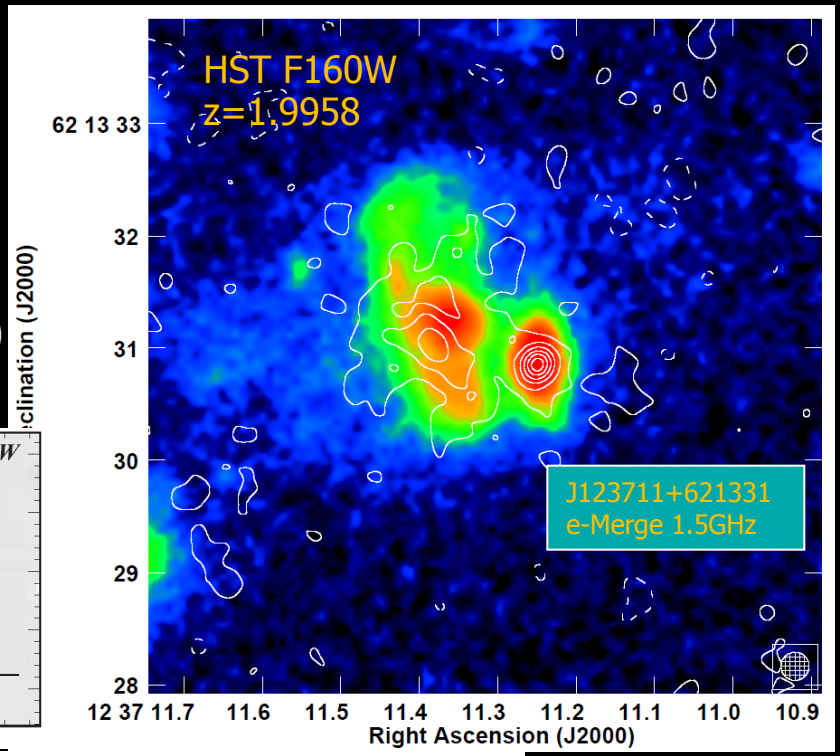
High frequency Observing for Angular Resolution with Intermediate Baselines…

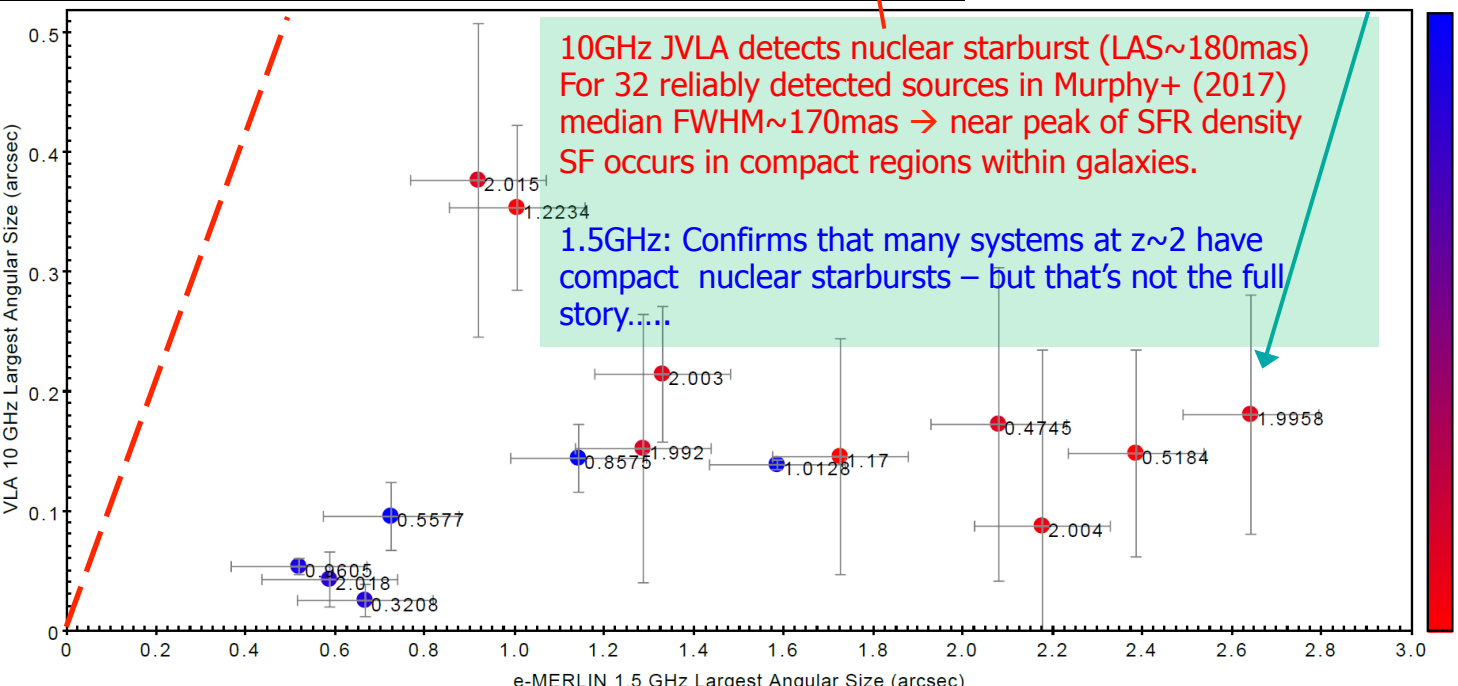
JVLA 10GHz v e-MERLIN 1.5GHz (Beam~200mas)

Steep-spectrum (α=-0.69) merging system with star-formation + a nuclear starburst (160x90mas)

$S_{1.5GHz}$ = 130 μ Jy S_{10GHz} = 8 μ Jy







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

- and the inner core-jet structures in AGN systems

Some Concluding Thoughts…

•Most radio-loud AGN are simple core-jets.
Classical extended starbursts dominate at $z<0.5$

•For $z>0.5$ nuclear starbursts start to become more common

•Typical sub-mm sizes for $z=1 \rightarrow 3$ are around 0.6″ (but some have radio emission on scales >1″). For $z>3$ sizes may be smaller

•Some nuclear starbursts in R-Q AGNs show high SF rates – Are these young systems where the AGN activity has not yet quenched SF?

•No faint embedded radio AGN cores yet seen in R-Q AGNs – Need deep C-Band e-MERLIN+JVLA (50mas beam) + deep L-Band EVN (5mas beam) to confirm

•At higher redshifts star-formation in intense nuclear starbursts is common – but extended star-formation is also present

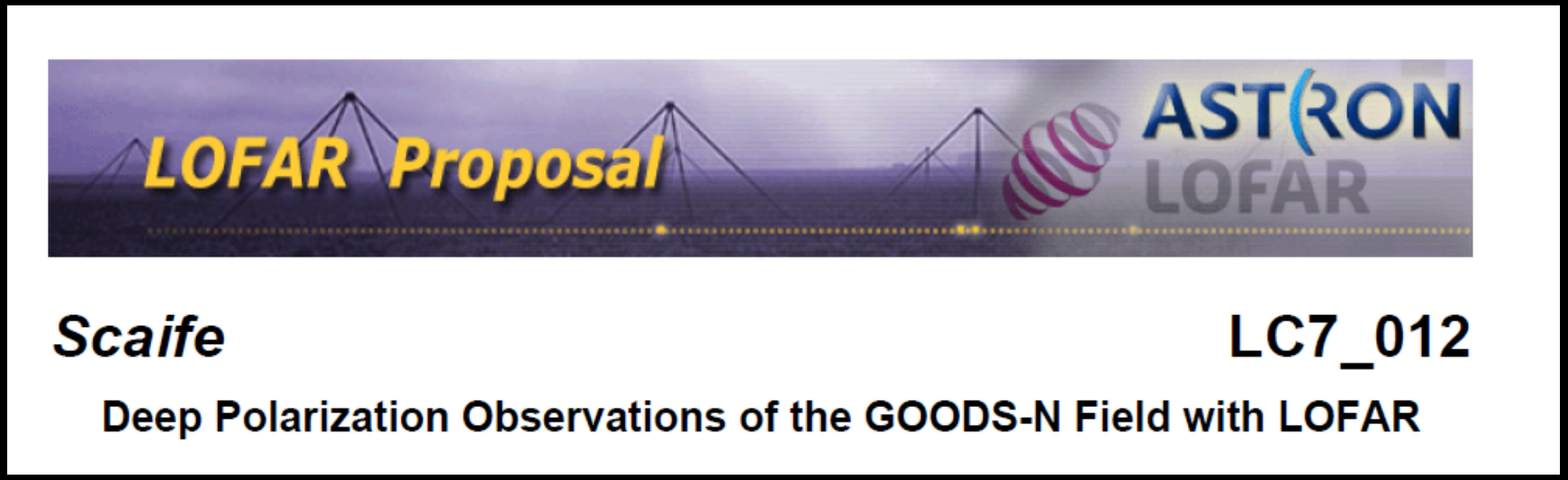
•At higher redshifts, high-frequency imaging (e.g. X-Band) with intermediate length baselines is insensitive to steep spectrum emission from extended regions of SF & detects only the nuclear starbursts – very deep images will be required to recover this!!

→ Full analysis to follow from DR-1 release on ~500 sources.

For steep spectrum emission there is no substitute for low frequency imaging on long baselines…

What are we missing?...

Ultra steep spectrum objects?



250 hours of observing requested - 60 hours within Cycle 7 at 150MHz with international baselines ~matching resolution to e-MERLIN+JVLA L-Band image

This is completely separate (non e-MERGE) programme to image polarized emission from GOODS-N

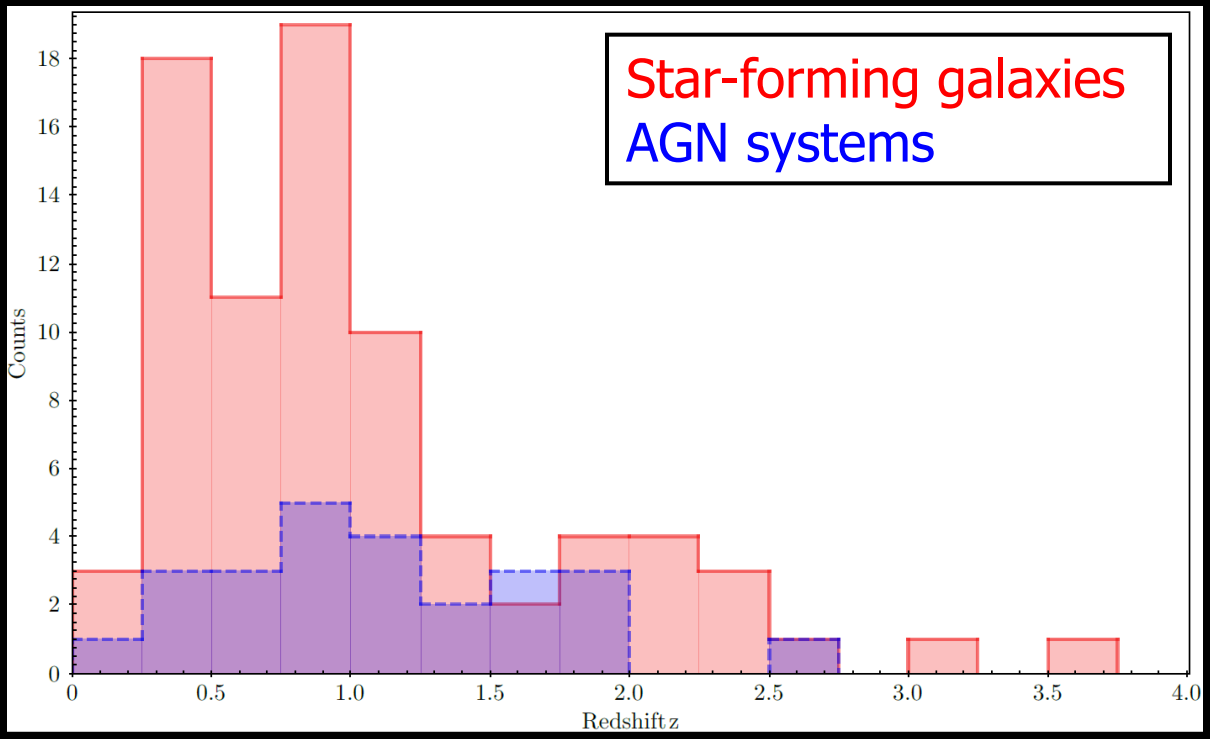
PI is a member of e-MERGE – after all the polarization studies have been completed, they can tell us of any additional sources which we have missed….

Some Initial Test Results:

107 of the 248 sources have spectroscopic redshifts.
Early dataset – small number statistics & missing spectroscopic redshifts >2…

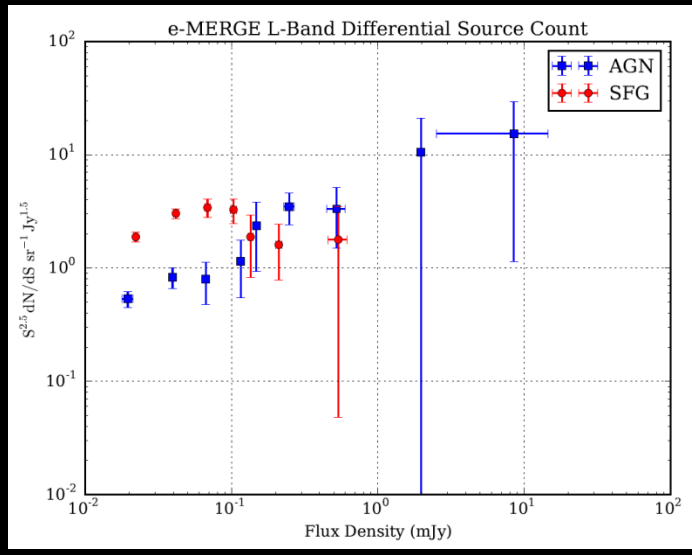
Redshift Distribution:

81 SFG Mean z = 1.03 +/- 0.08 Median z ~0.8
26 AGN Mean z = 1.24 +/- 0.17 Median z ~1.0
cf Murphy+2017 10GHz Median z ~1.24



Differential Source Counts:

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



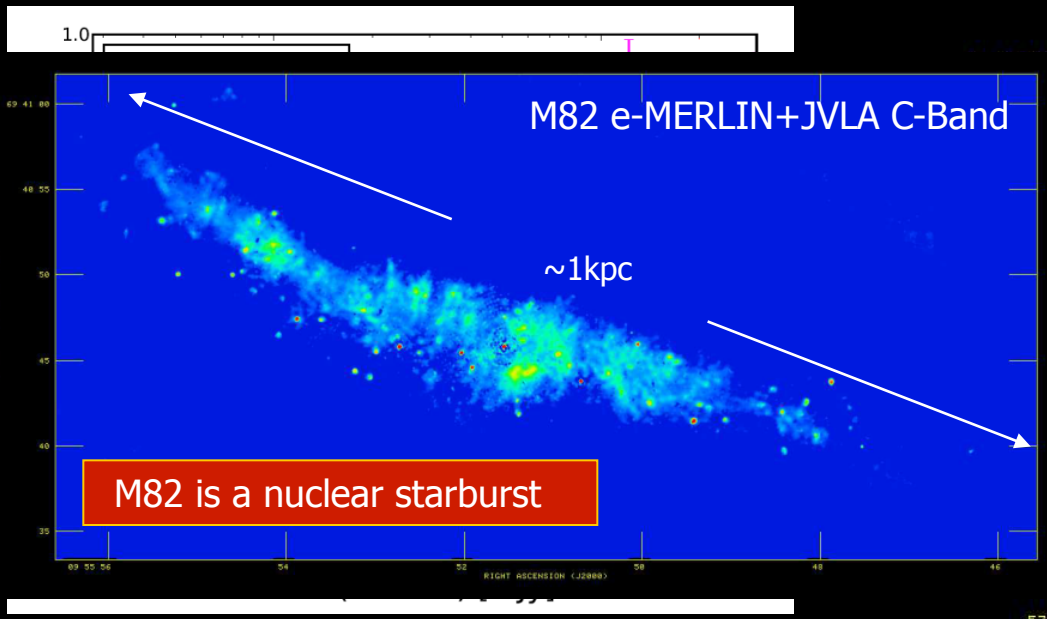
Luminous Classical Star-forming Galaxies

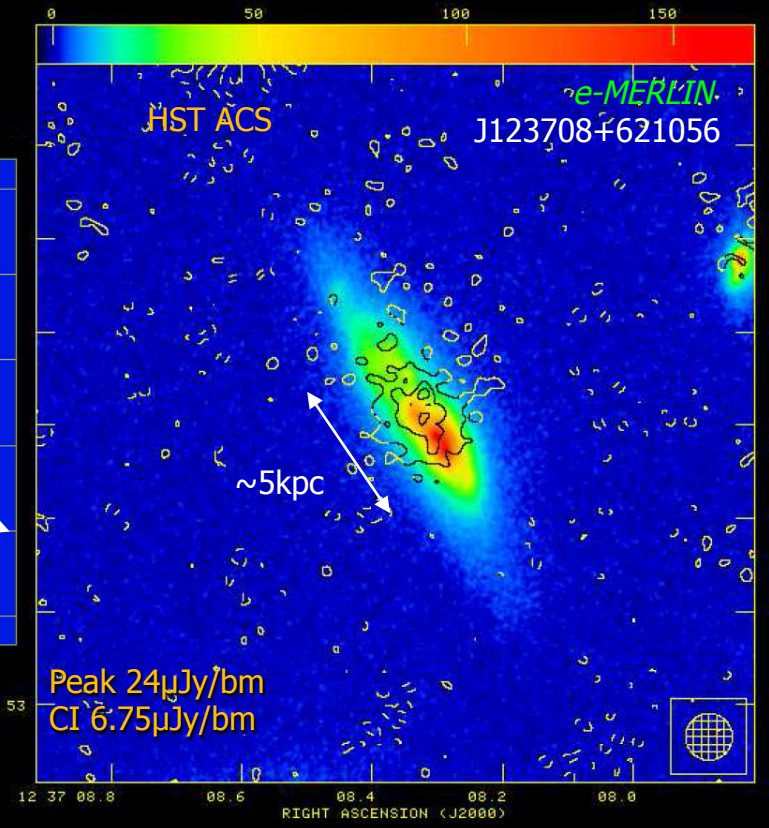
Classical Star-forming Galaxies: Typical example – J123708+621056 Extended radio emission across central region of 10^{10} M⊙ dust obscured irregular galaxy at z=0.422

$L_{1.4}$ =3.8x10^{22} W/Hz → Star-formation rate 9 M⊙/yr

(>5 M⊙ assuming Salpeter IMF)

Extended steep-spectrum starburst ($S_{1.5}$ = 45 μ Jy) ~5x linear size of M82





<100μJy population dominated by star-forming galaxies

Radio-Loud Classical AGN Systems

JVLA L-Band image of the central part of GOODS-N .
38 hrs, BW 1GHz
$1\sigma \sim 1.8\,\mu$Jy/bm

~600 detections in the inner 12′ field to 5x local noise level.
Complete to 9μJy

Very few classical AGN double structures seen – confined to the brighter mJy sources