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

Measuring Star-formation in the Radio, Millimetre & Sub-millimetre

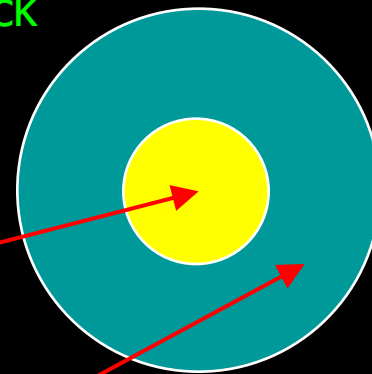Tom Muxlow & Nick Wrigley JBCA Manchester for the e-MERGE Consortium

JBCA   24th July 2017

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

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

~200mas – detailed investigation of SF activity / AGN feedback

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

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

In full 30' field ~5000 sources complete to local ~6σ [2019]

Q3 2017 → First consortium data and image release [DR-1]:

L-Band: JVLA 30' field, beam~2", 1σ~1.8µJy/bm   ✓
   + e-MERLIN(130hrs)+JVLA 12' field , beam ~200mas, 1σ~1.5µJy/bm *–Soon!!*
C-Band: JVLA mosaic of 12', beam ~500mas, 1σ~3µJy/bm   ✓
                                                             ✓
[+EVN L-Band12' field (72-hrs), beam ~5mas, 1σ~3µJy/bm]   *30%*
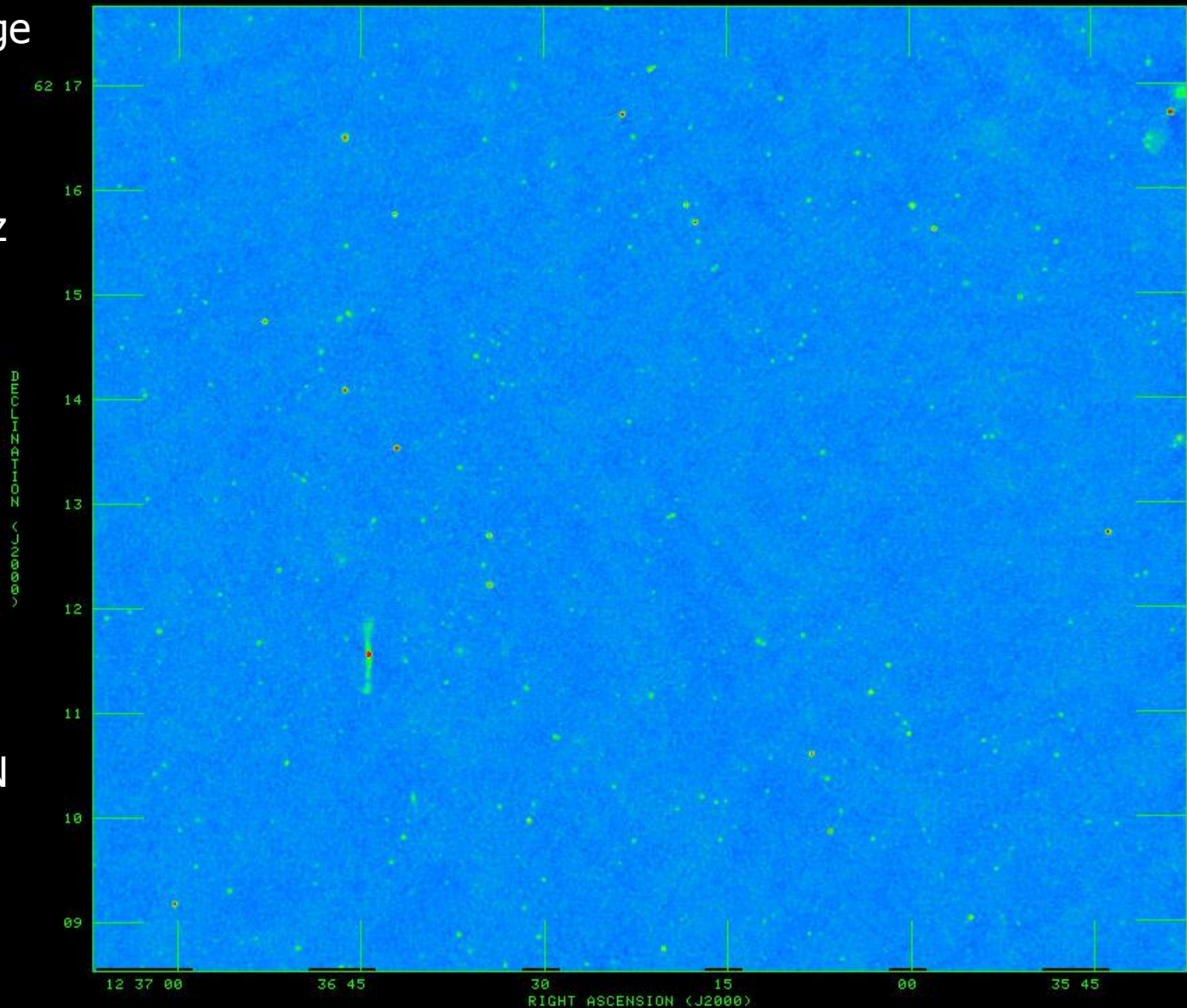
→ Detailed investigation of >500 SFGs and AGN in 12' field

Central 12 Arcminute Field

JVLA L-Band image
of GOODS-N .
Full image to 30'

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

Few classical AGN
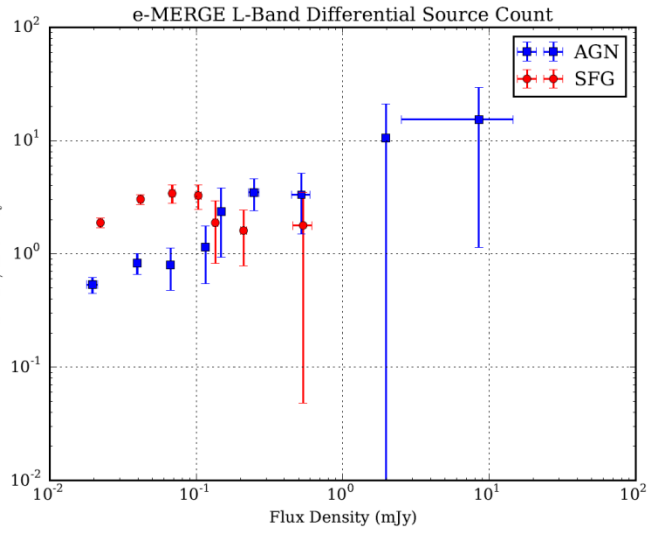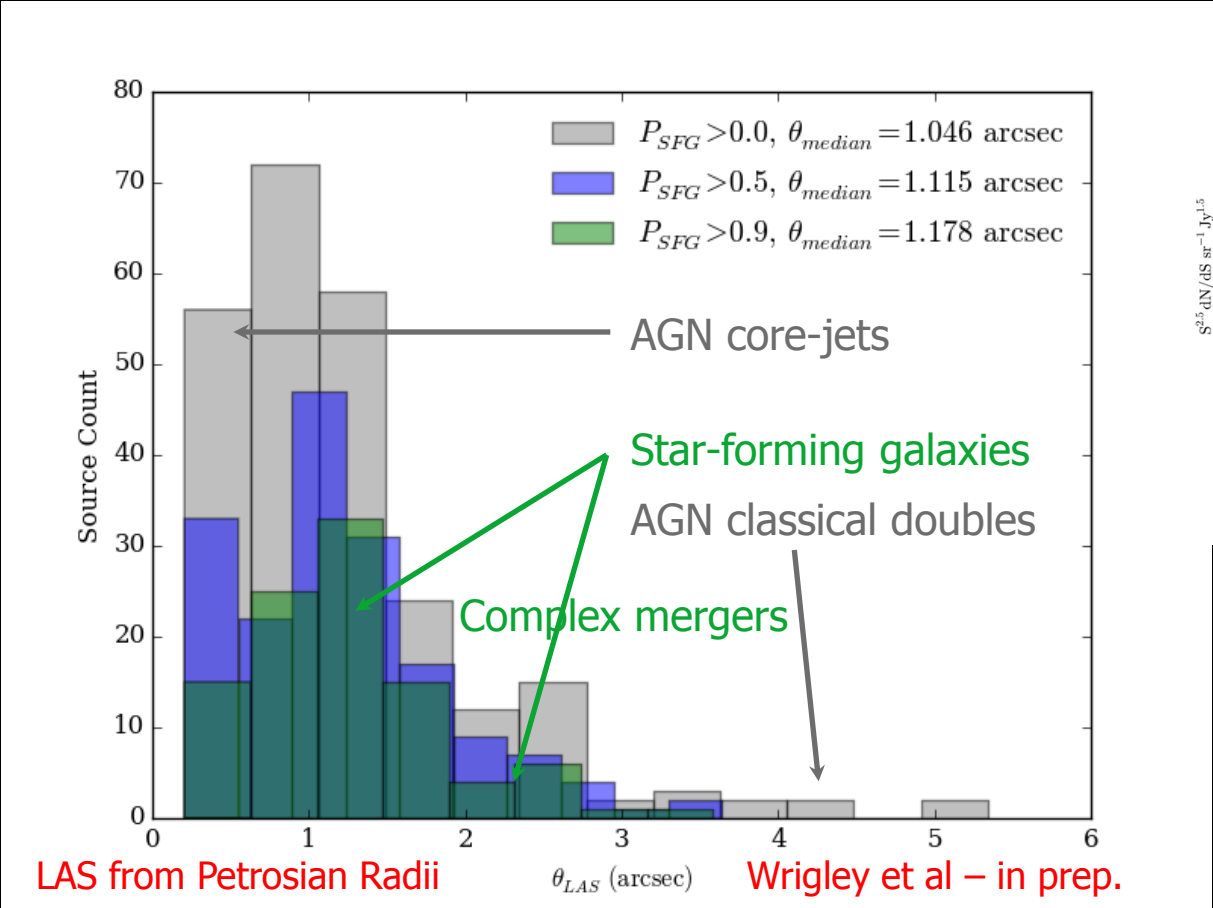double structures
seen – mostly
small core-jet
structures

– LAS & SFG/AGN assignment from Nick Wrigley

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...

$P_{SFG} > 0.0$, $\theta_{median} = 1.046$ arcsec
$P_{SFG} > 0.5$, $\theta_{median} = 1.115$ arcsec
$P_{SFG} > 0.9$, $\theta_{median} = 1.178$ arcsec

AGN core-jets

Star-forming galaxies

AGN classical doubles

Complex mergers

LAS from Petrosian Radii

Wrigley et al – in prep.

Machine-learning (SVM – Support Vector Machine)

e-MERGE L-Band Differential Source Count

Differential Source Counts:

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

– Study extended to detailed SFG radio structures

Star-forming Galaxies

Star-forming Galaxies:
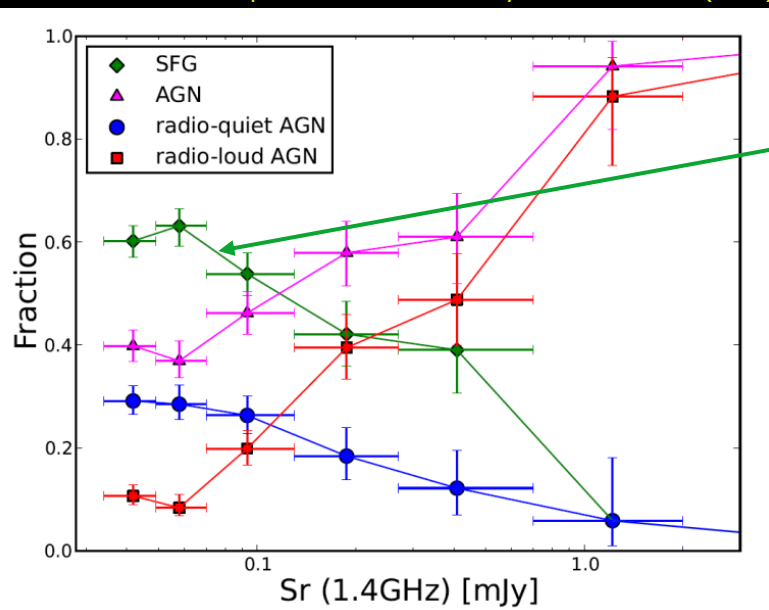
Typical example – J123708+621056 – steep-spectrum starburst ($S_{1.5} = 45\mu Jy$)
Emission across central region of $10^{10}\,M_\odot$ dust-obscured irregular galaxy at z=0.422
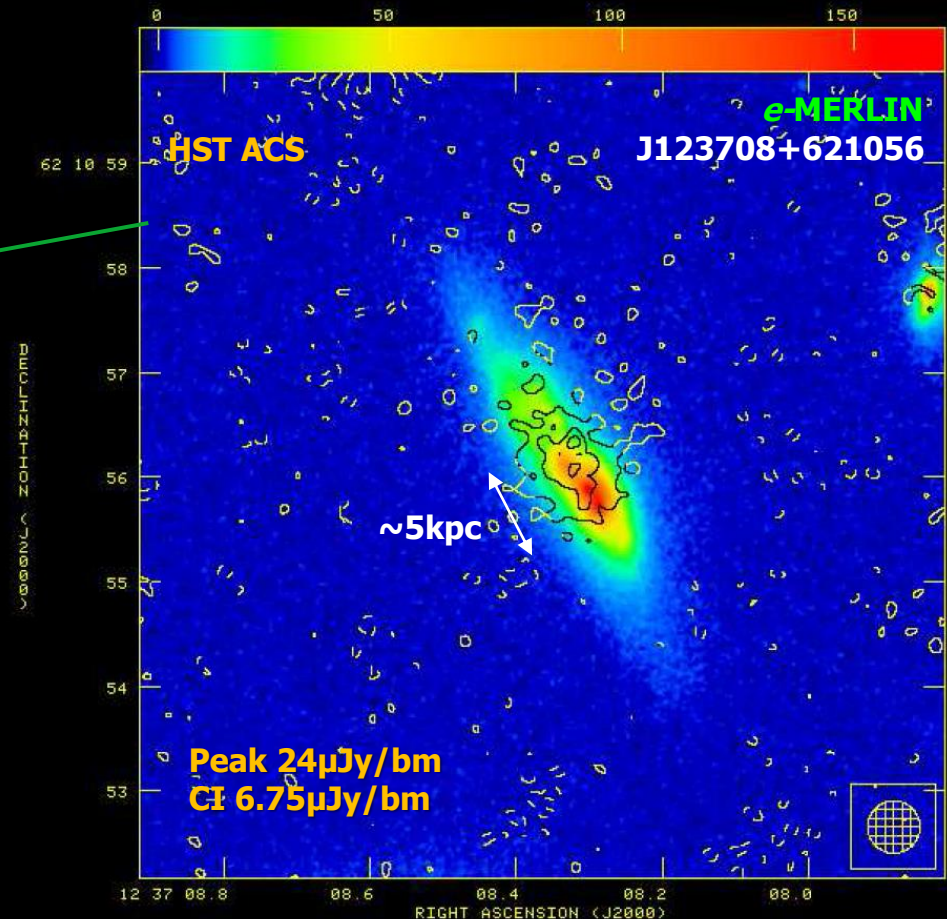**S-F rate 20 $M_\odot$/yr** (0.1 - 100 $M_\odot$ assuming Kroupa IMF)

~5x linear size of M82

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

Radio population dominated by S-F galaxies below $S_{1.4}$~100μJy

HST ACS

e-MERLIN
J123708+621056

~5kpc

**Peak 24μJy/bm
CI 6.75μJy/bm**

# Nuclear Activity within Star-forming Galaxies

SFGs with z>0.5:

Tend to contain centrally condensed nuclear starbursts + extended star-formation

Many found in galaxies with AGN visible only in other wavebands

$10^{11} M_\odot$ Seyfert-2 galaxy z=0.5186

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

S-F rate 88 M$_\odot$/yr

HST ACS

e-MERLIN
J123641+620948

$10^{11} M_\odot$ Seyfert-2 galaxy
z=0.5186

Peak 35μJy/bm
CI 6.75μJy/bm
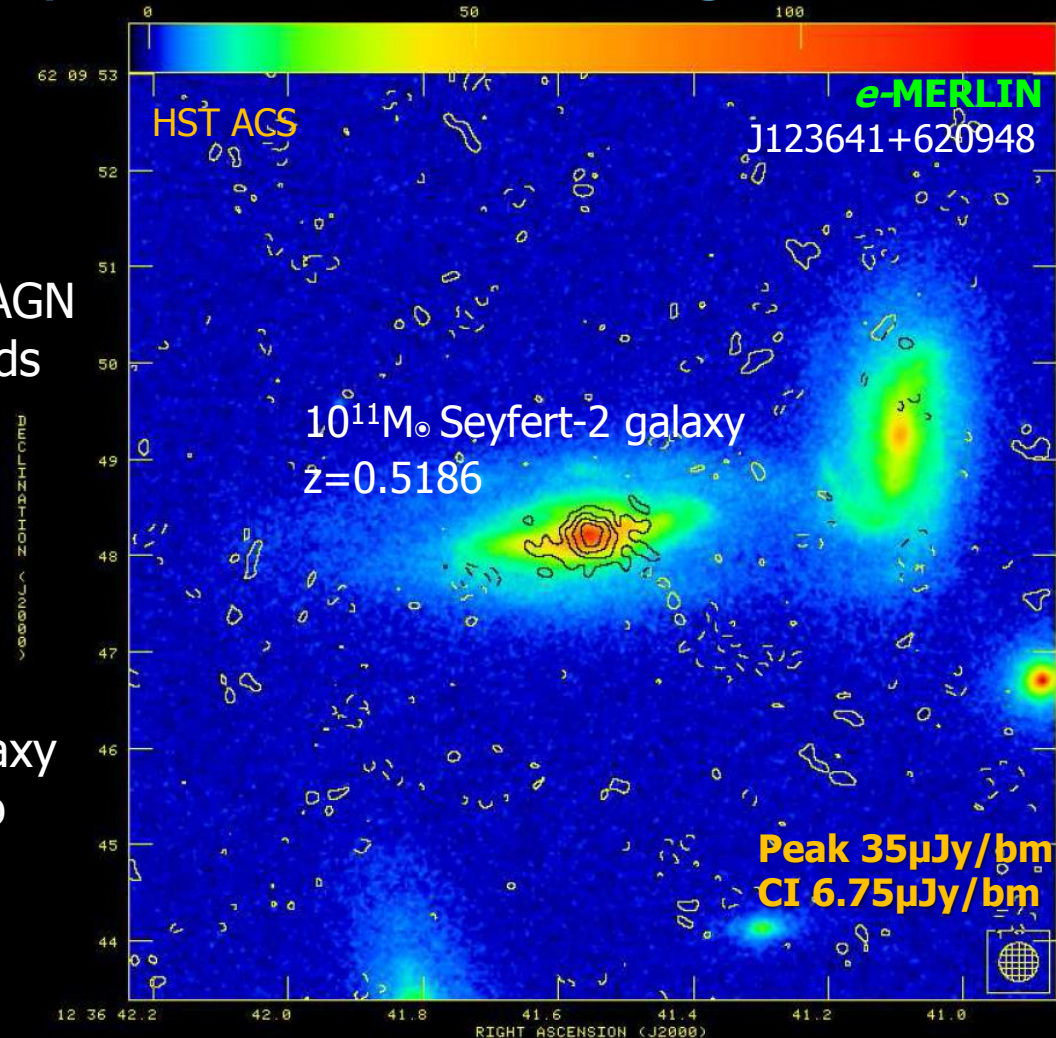
AGN or nuclear starburst?
Resolved by e-MERLIN (~370mas), no VLBI detection to 8μJy → Nuclear starburst
Need deep 5.5GHz e-MERLIN (+EVN 1.4GHz) to image in detail   (Beam 5→50mas)

SFGs Radio Structures

The proportion of SFGs with nuclear starbursts are seen to increase with redshift
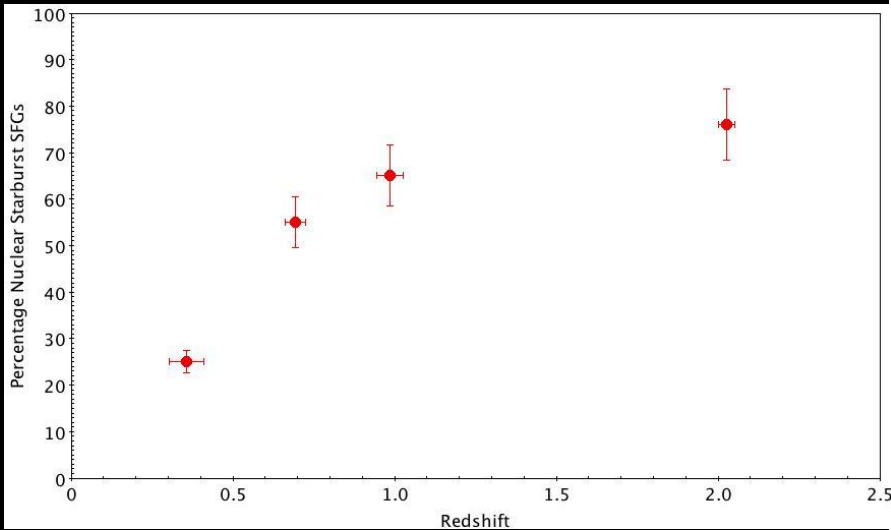
At high redshifts the proportion with nuclear starburst ~ 70%.
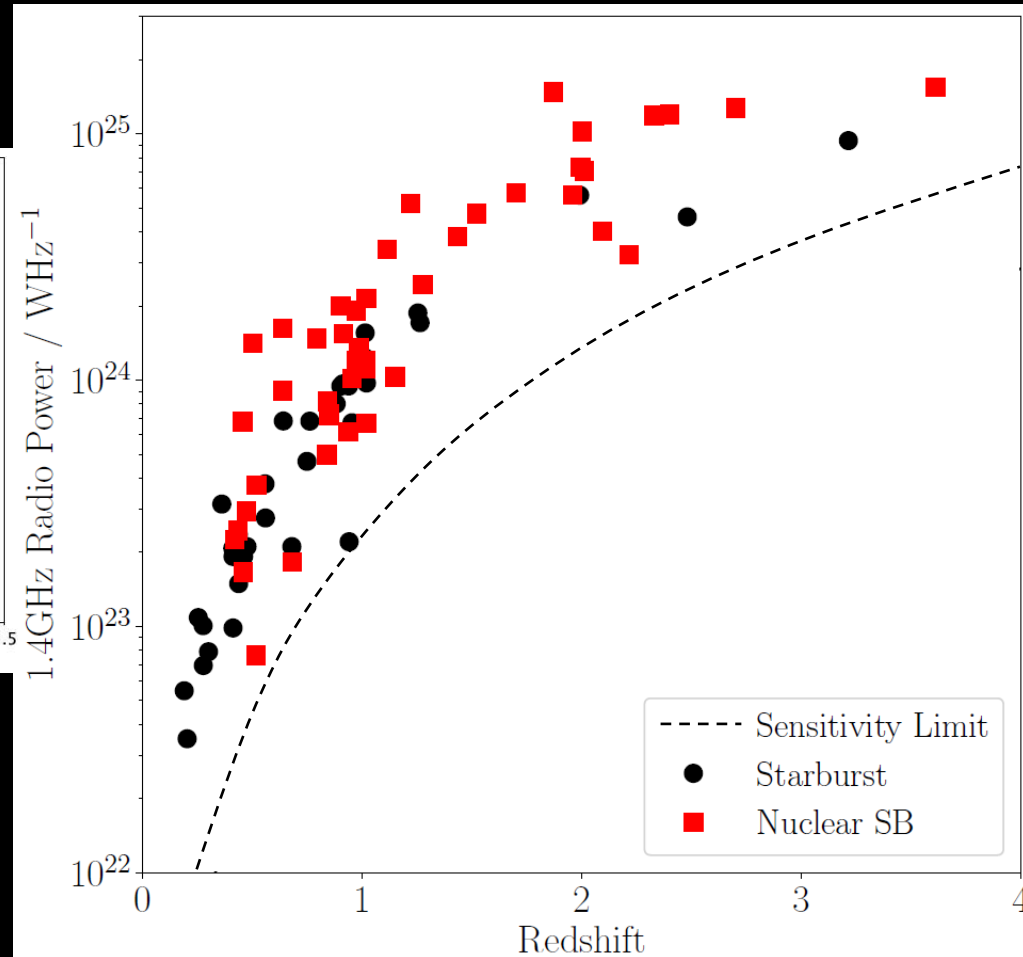
Malmquist bias since SFGs containing nuclear starbursts are more luminous systems – although some extended only SFGs are still found in high redshift systems

80 SFGs with spectroscopic redshifts

Imaging SFG Radio Structures
Strongly dependent on spectral properties...

HST ACS

SMMJ123635.6+621424
I=23.3^{mag} Seyfert-2 galaxy z=2.015
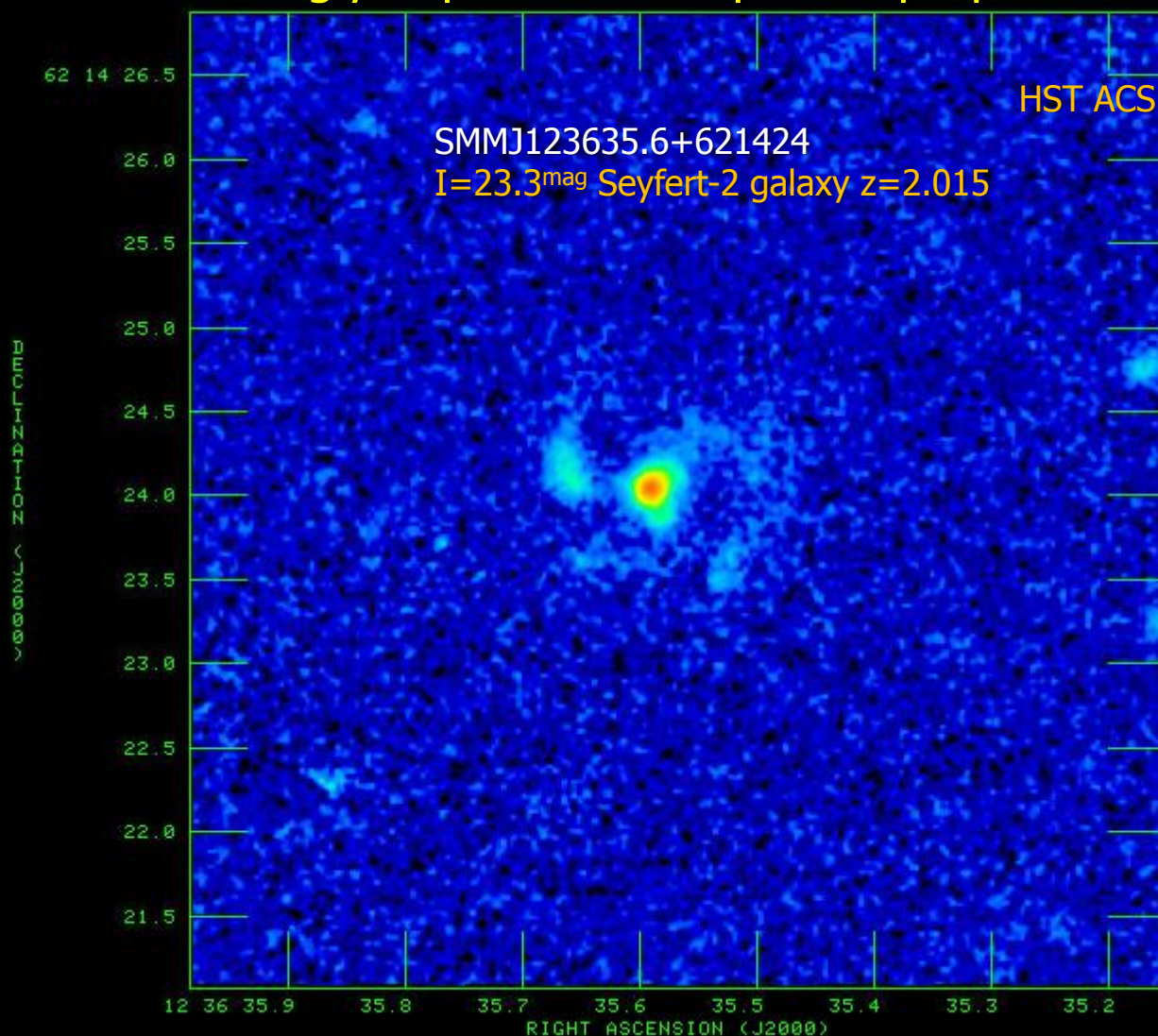
Eric Murphy+ 2017

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

Beam 0.22"
FOV ~4.25'
38 detections (32+6)
1σ = 572nJy/bm

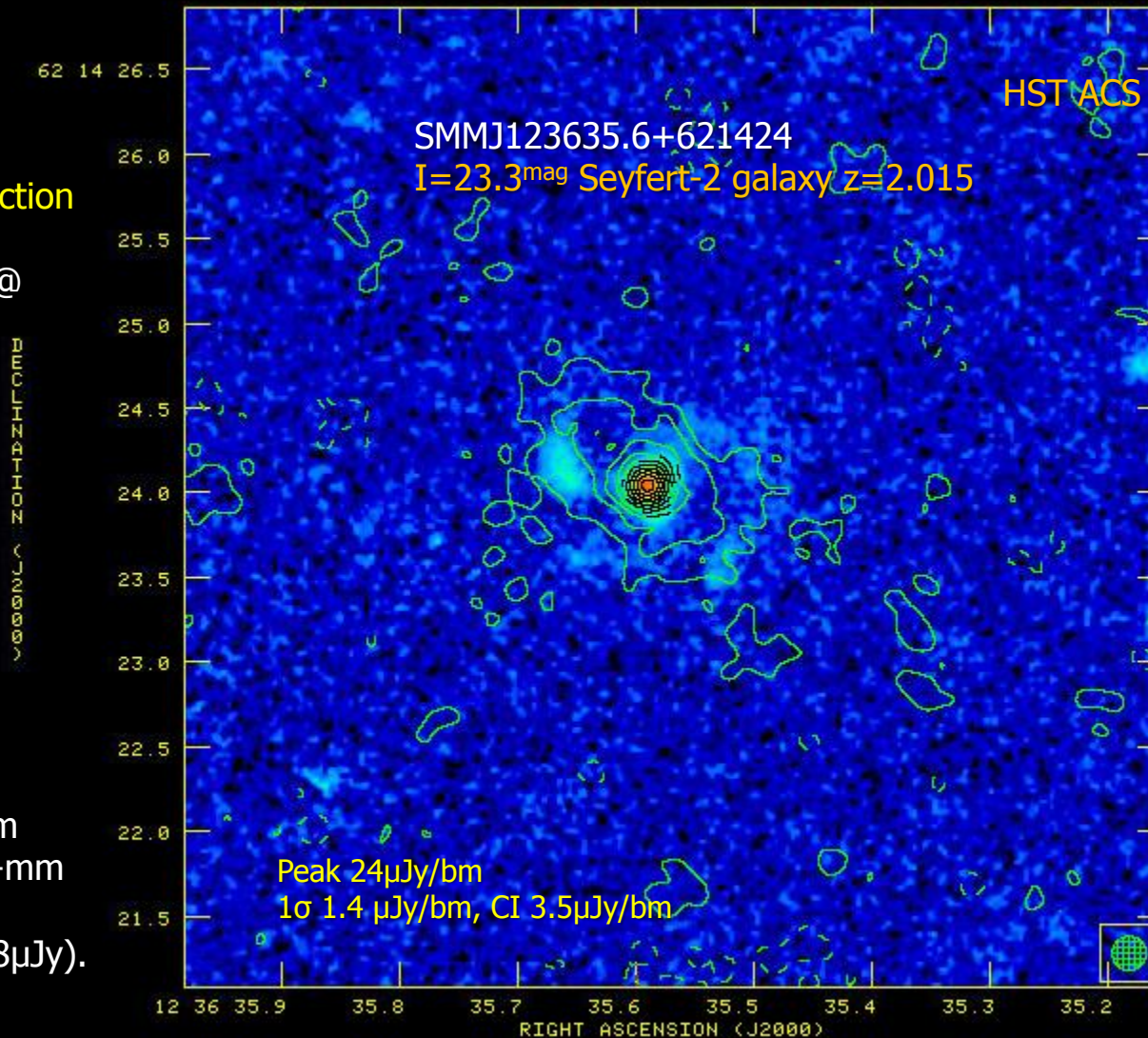Comparison of 15 GOODS-N radio structures seen by both e-MERGE at 1.5GHz and JVLA at 10GHz

e-MERLIN+JVLA 1.5GHz image of a high z Sub-mm SFG

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

36μJy nuclear starburst
EVN non-detection
Fitted size
250x160mas @
PA+165°

SF ~ equally distributed between nuclear and extended components

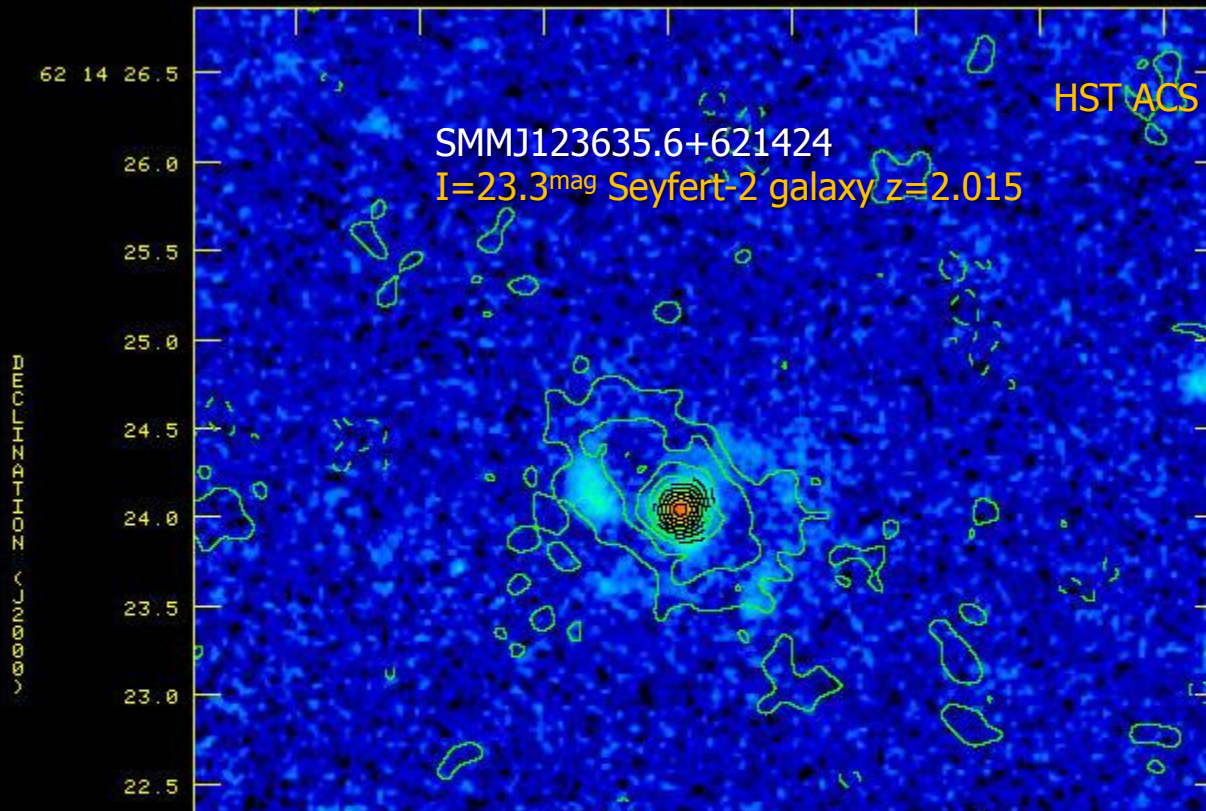Steep-spectrum ($\alpha<-0.87$) sub-mm source.
(Total $S_{1.5}$ = 88μJy).

HST ACS

SMMJ123635.6+621424
I=23.3^{mag} Seyfert-2 galaxy z=2.015

Peak 24μJy/bm
1σ 1.4 μJy/bm, CI 3.5μJy/bm

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

e-MERLIN+JVLA 1.5GHz image of a high z Sub-mm SFG   + JVLA 10GHz
– shows nuclear starburst + fainter emission extending across face of Seyfert-2 galaxy

HST ACS

SMMJ123635.6+621424
I=23.3^{mag} Seyfert-2 galaxy z=2.015

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

J123635+621424

bzH   F336W   log(M)   β−slope (SED)   log(SFR,SED)   log(LUV)
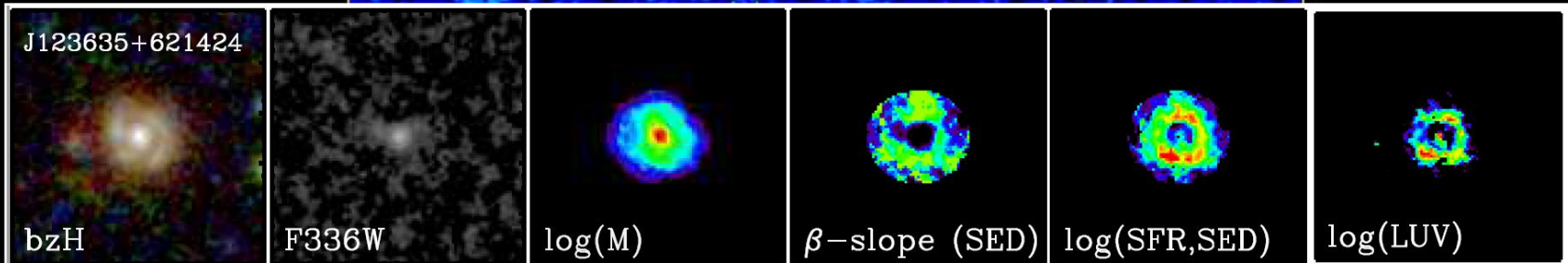
Anna Cibinel (Sussex) – private communication – multiband star-formation mapping

e-MERLIN+JVLA 1.5GHz image of a high z Sub-mm SFG   + JVLA 10GHz
– shows nuclear starburst + fainter emission extending across face of Seyfert-2 galaxy
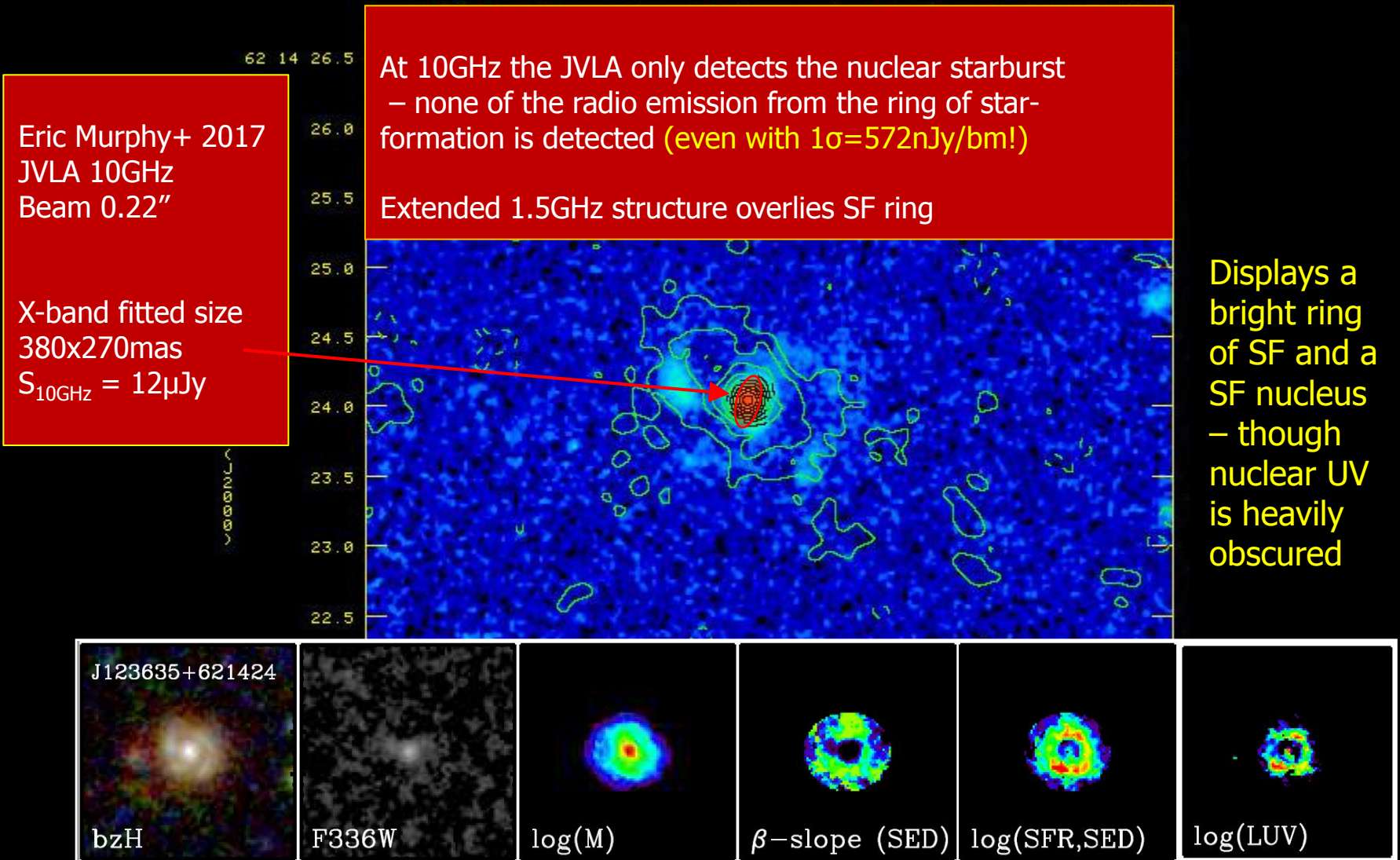
Eric Murphy+ 2017
JVLA 10GHz
Beam 0.22"

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

At 10GHz the JVLA only detects the nuclear starburst
 – none of the radio emission from the ring of star-
formation is detected (even with 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

J123635+621424

bzH   F336W   log(M)   β−slope (SED)   log(SFR,SED)   log(LUV)

Anna Cibinel (Sussex) – private communication – multiband star-formation mapping
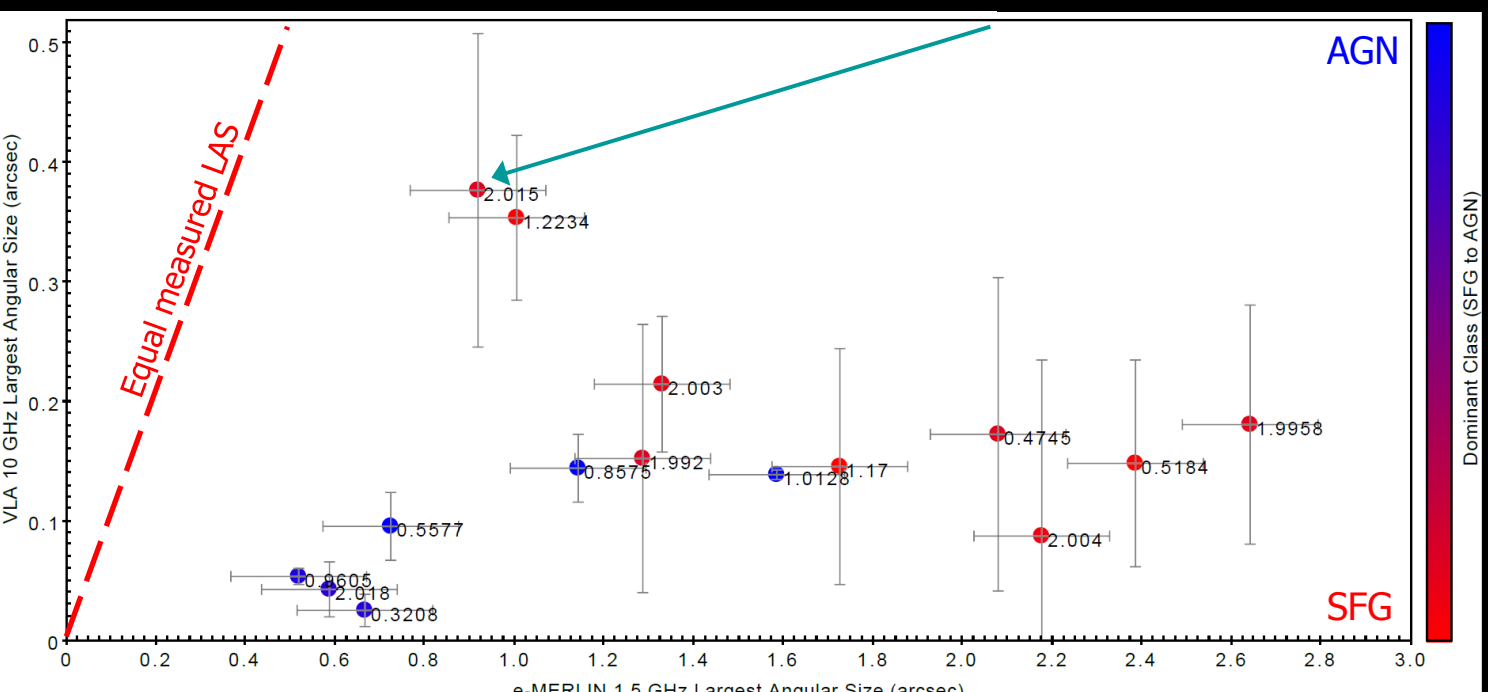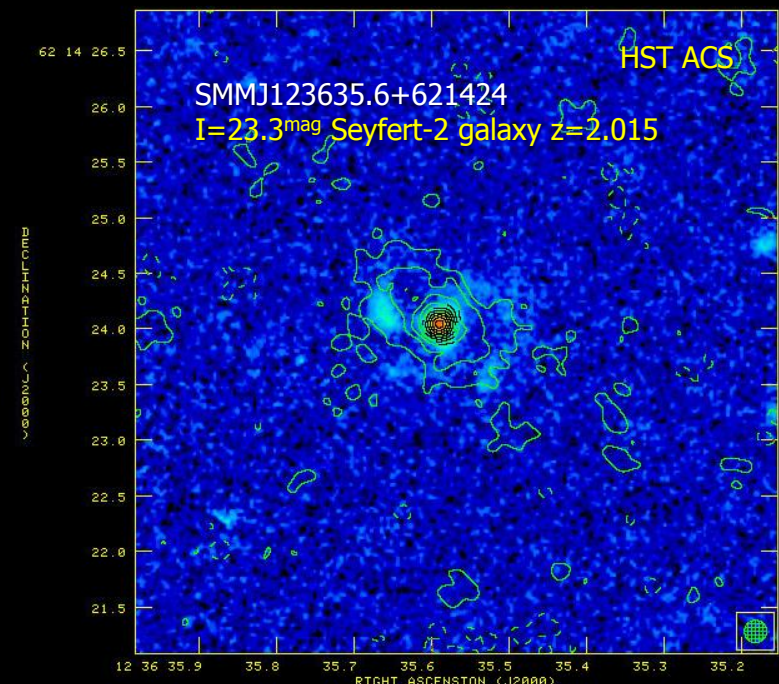
Matched Resolution Imaging of SFGs at 1.5 GHz and 10GHz...

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

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

JVLA LAS at 10GHz are up to an order of magnitude smaller than e-MERGE at 1.5GHz (Median ~170mas)

- also significantly smaller than 3GHz sizes of 115 SMGs in COSMOS (median FWHM ~0.54")
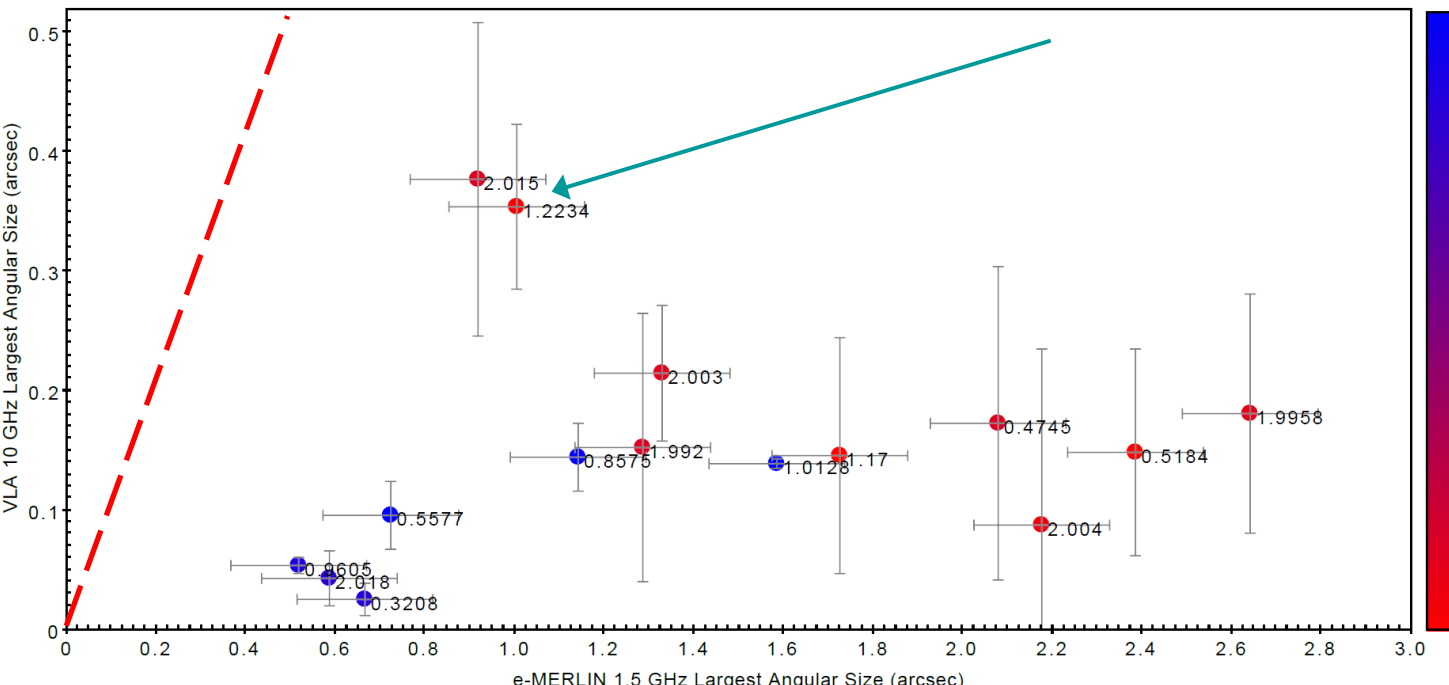Miettinen+ 2017

SMMJ123635.6+621424
I=23.3^{mag} Seyfert-2 galaxy z=2.015

HST ACS

Matched Resolution Imaging of SFGs at 1.5 GHz and 10GHz...

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

10GHz · z = 1.2234 · 1"

HST/F850LP · Murphy+ (2017) · 1"

HST/F160W · 1"
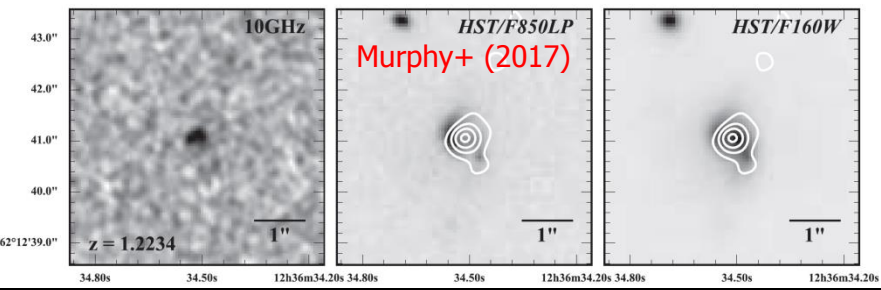
Merging Scd sub-mm galaxy with tidal tail
- High redshift version of the 'Antennae'

S-F rate ~960 M☉/yr
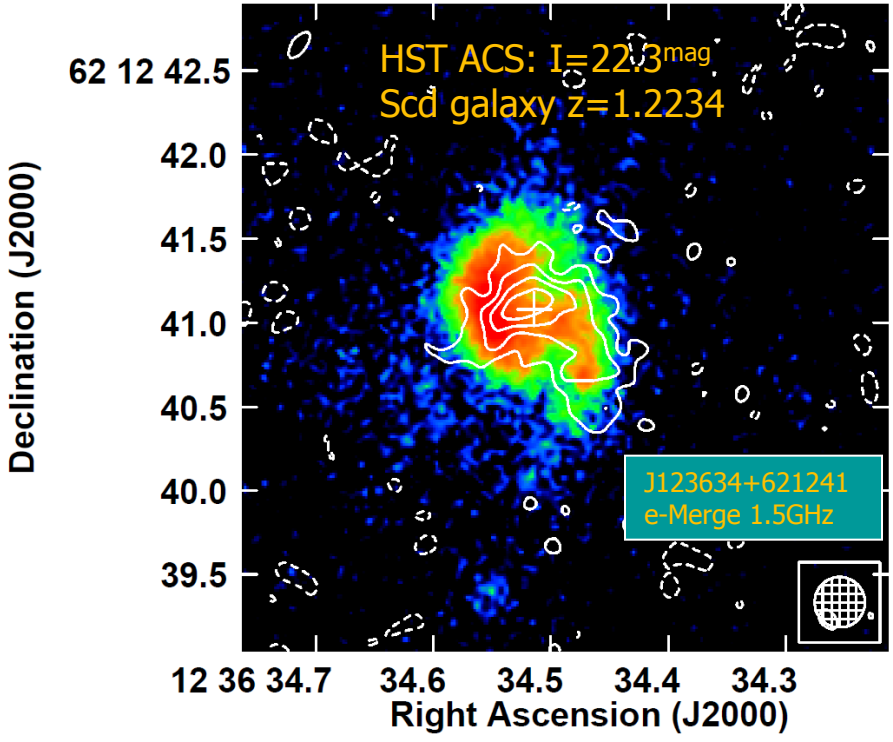
HST ACS: I=22.3^{mag}
Scd galaxy z=1.2234

J123634+621241
e-Merge 1.5GHz

JVLA at 10GHz detects only the central nuclear starbursts / merging cores in star-forming galaxies
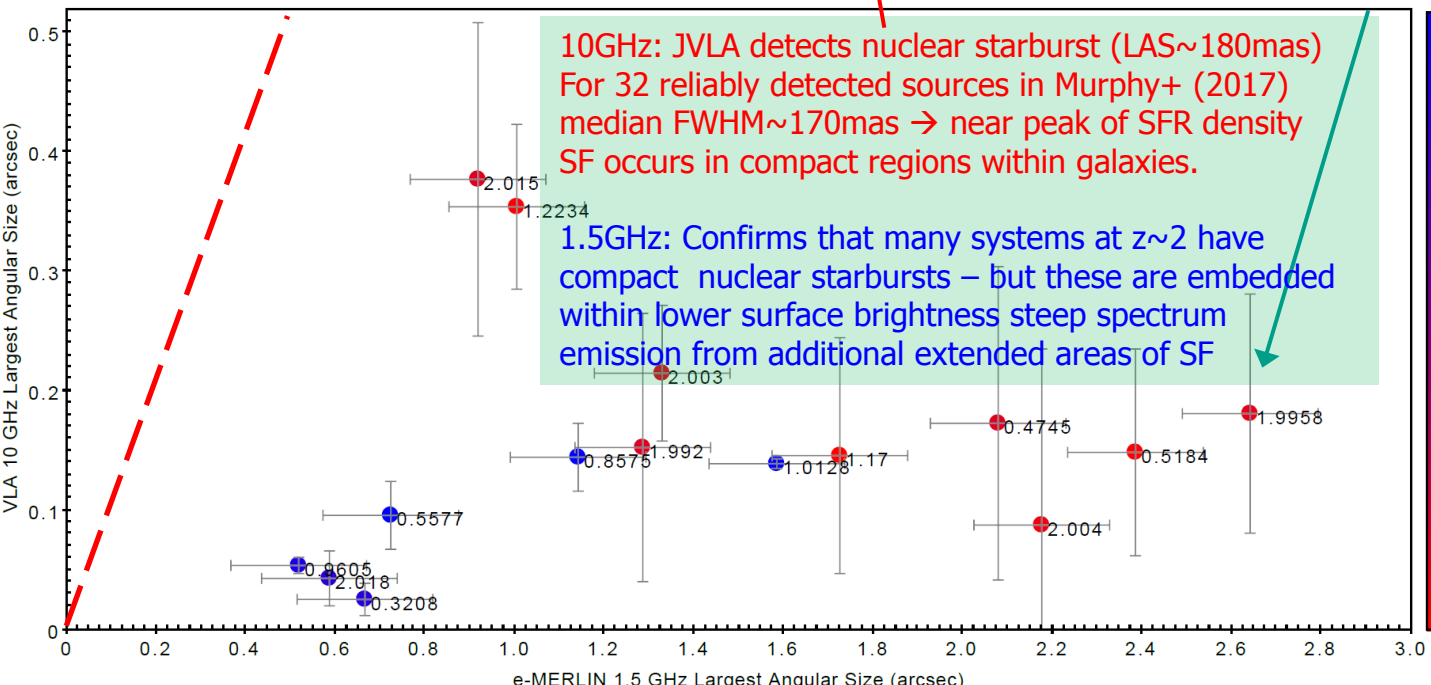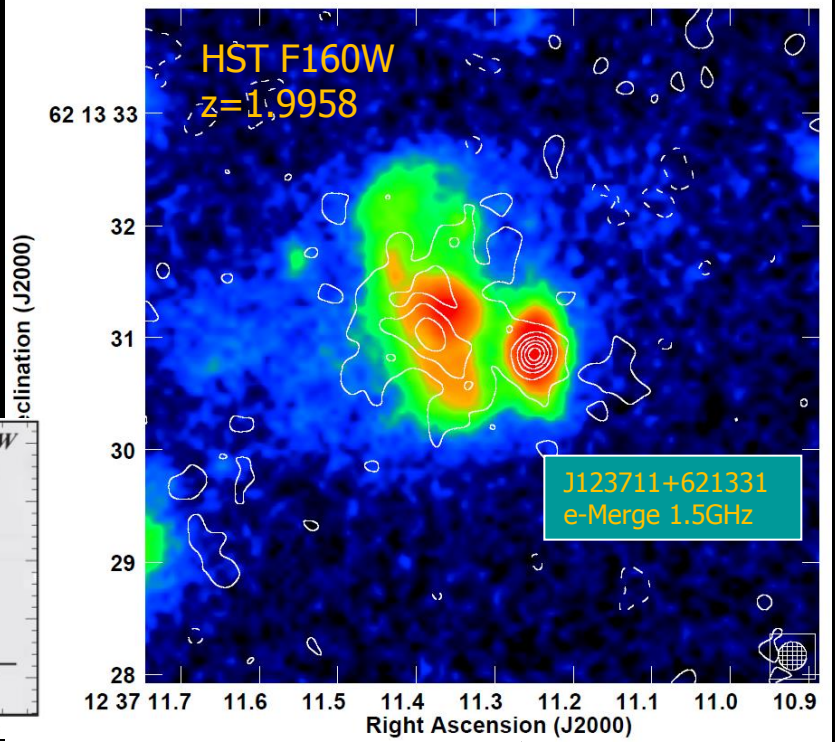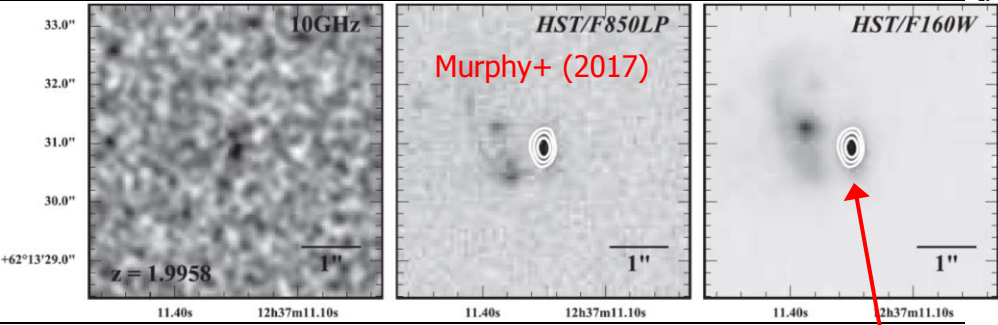
- and the inner core-jet structures in AGN systems

Matched Resolution Imaging of SFGs at 1.5 GHz and 10GHz…

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

Unusual merging system with star-formation + nuclear starburst (No VLBI detection)

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

10GHz   z = 1.9958

HST/F850LP
Murphy+ (2017)

HST/F160W

HST F160W
z=1,9958

J123711+621331
e-Merge 1.5GHz

10GHz: JVLA detects nuclear starburst (LAS~180mas)
For 32 reliably detected sources in Murphy+ (2017)
median FWHM~170mas → near peak of SFR density
SF occurs in compact regions within galaxies.

1.5GHz: Confirms that many systems at z~2 have
compact nuclear starbursts – but these are embedded
within lower surface brightness steep spectrum
emission from additional extended areas of SF

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

- For z~2 spectral
deconvolution →
nuclear SBs at 10GHz
have~50% thermal
from HII regions

VLA 10 GHz Largest Angular Size (arcsec)

e-MERLIN 1.5 GHz Largest Angular Size (arcsec)

Dominant Class (SFG to AGN)

2.015
1.2234
2.003
0.4745
1.9958
0.8575 1.992
1.0128 1.17
0.5184
2.004
0.5577
0.8605
2.018
0.3208

Some Concluding Thoughts on SMGs...

- Classical extended starbursts dominate at z<0.5

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

- High-frequency imaging at high redshifts is insensitive to synchrotron emission from extended regions of SF & may detect only nuclear starbursts – however high frequency images can separate and image the thermal emission from embedded HII regions
  – very deep images will be required to recover the steep spectrum extended structure!!

- Extended starburst regions may contain substantial SF

- Deep C-Band e-MERLIN+JVLA (50mas beam) + full depth L-Band EVN/e-MERLIN/JVLA combination imaging (5-500mas beam) will investigate nuclear starbursts in detail

- Some nuclear starbursts contain AGN visible in other wavebands – Are these young systems where the AGN activity has not yet quenched SF?

- Are the nuclear starbursts recently triggered and younger than the extended star-formation seen on larger scales?