The University of Manchester
Jodrell Bank Observatory

MANCHESTER 1824

EUROPEAN VLBI NETWORK

e-MERLIN

The e-MERGE Legacy Survey
– an e-MERLIN+JVLA Ultra-Deep Survey

High-resolution mapping of the μJy radio source population

Tom Muxlow JBCA Manchester

Ian Smail, Ian McHardy, Nick Wrigley, Alasdair Thompson, Daria Guidetti, & the e-MERGE Consortium

SKA Pathfinder Radio Continuum Surveys

Protea Kruger Gate 1st July 2015

Science & Technology Facilities Council

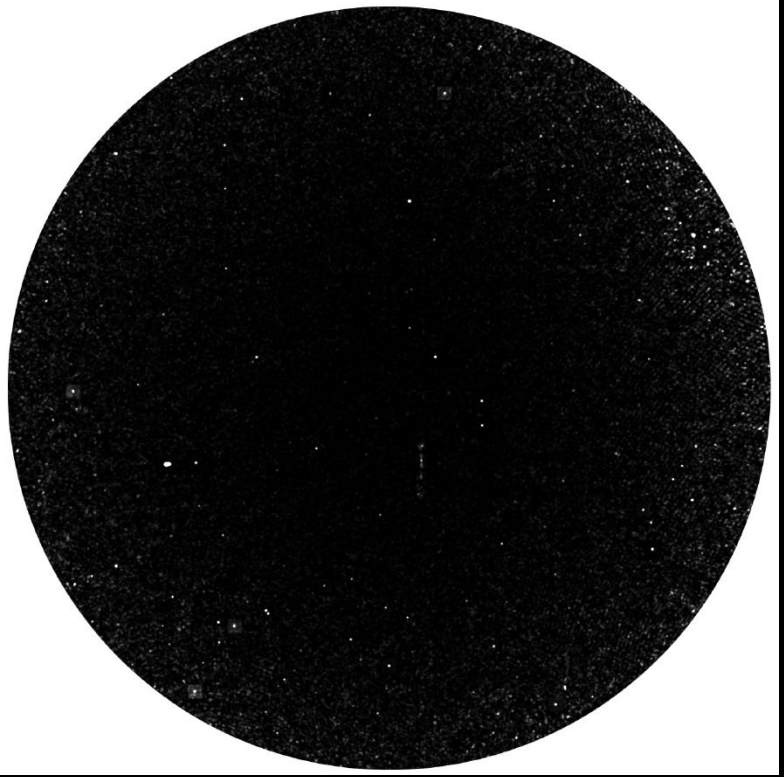
NRAO

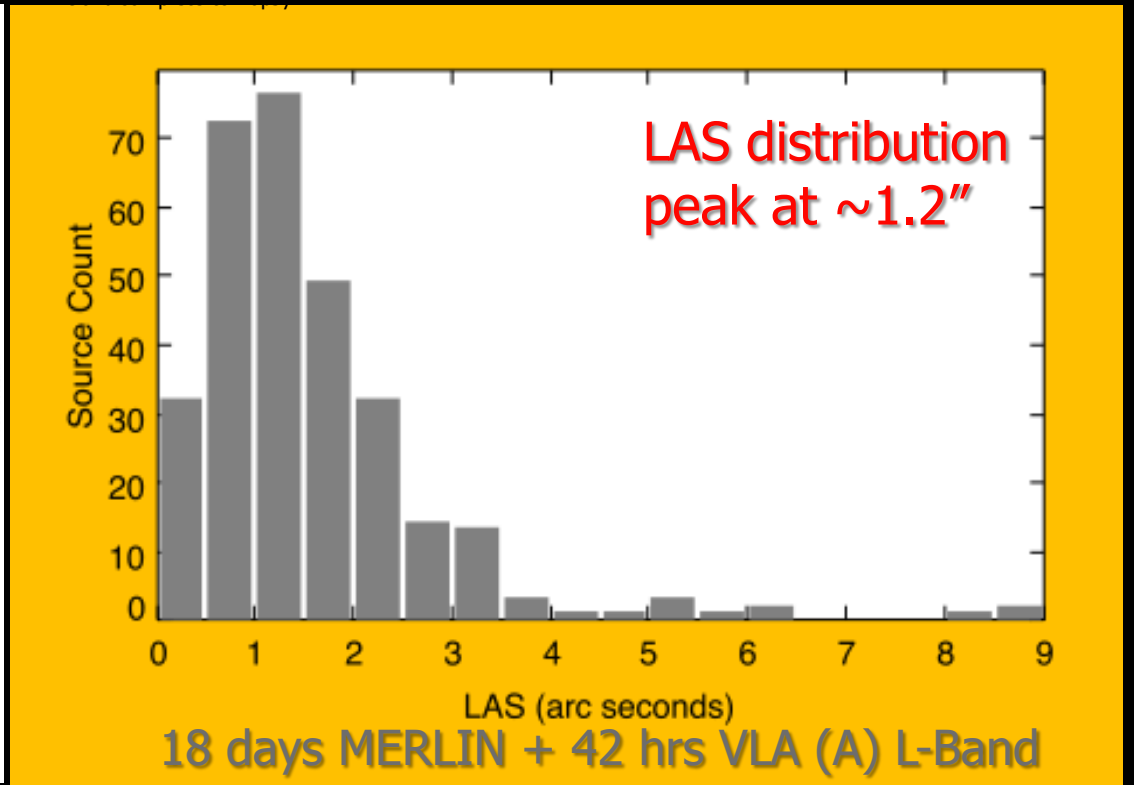
History

Archival MERLIN+VLA study of faint radio sources in GOODS-N

Muxlow et al 2005

10′×10′ L-Band field centred on GOODS-N
92 sources >40μJy Observed 1996-98 Resolution 0.2″ – 0.5″
High resolution imaging can morphologically distinguish AGN & SF
<70μJy population dominated by s-f galaxies typically at z<1.5
Data reworked with enhanced fast imaging: Wrigley et al in prep.
→ 15′ diameter contiguous combination image (cf postage stamp images)
178 sources imaged with flux densities >5σ (beam corrected)





Development

e-MERGE Survey

A tiered e-Merlin + JVLA + EVN Legacy proposal

The e-MERlin Galaxy Evolution Survey

Tier 0 – *Normal galaxies out to z ~ 5* *[Ian Smail – Durham]*
Deep imaging around clusters to utilise amplification by lensing

Tier 1 – *Deep survey of μJy radio sources* *[Tom Muxlow – Manchester]*
Deep imaging of the μJy radio sources in GOODS-N
e-MERLIN Legacy programmes

Tier 2 – *Shallow-wide survey over ~2 square degrees*
[Ian McHardy – Southampton] *Via SuperClass ?*

>60 CO-Is from 9 countries

Tier 0 – [2016→]
Tier 1 – 20 days e-Merlin+40hrs JVA-A (L-band) *[~15% data reduced]* [Complete]
17 days e-Merlin+ JVLA-A/B/C (C-band) *[Q4 2015→]* [Complete]

Tier 2 – [SuperClass] – 2015 → 10% complete

→ full sampling of AGN & s-f galaxy radio luminosity function to z~5

e-MERGE Survey

A tiered e-Merlin + JVLA + EVN Legacy proposal

e-MERGE Goals:

Characterise the radio structures of μJy source population

Investigate AGN – star-formation feedback at high z

Constrain the radio (extinction-free) Madau plot for z<5

Initial publications with part-completed observations in 2015/16

>60 CO-Is from 9 countries

Tier 0 – [2016→]

Tier 1 – 20 days e-Merlin+40hrs JVA-A (L-band) *[~15% data reduced]* *[Complete]*

17 days e-Merlin+ JVLA-A/B/C (C-band) *[Q4 2015→]* *[Complete]*

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→ full sampling of AGN & s-f galaxy radio luminosity function to z~5

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

e-MERLIN matches sensitivity of old (18 days) MERLIN in 24 hrs on source

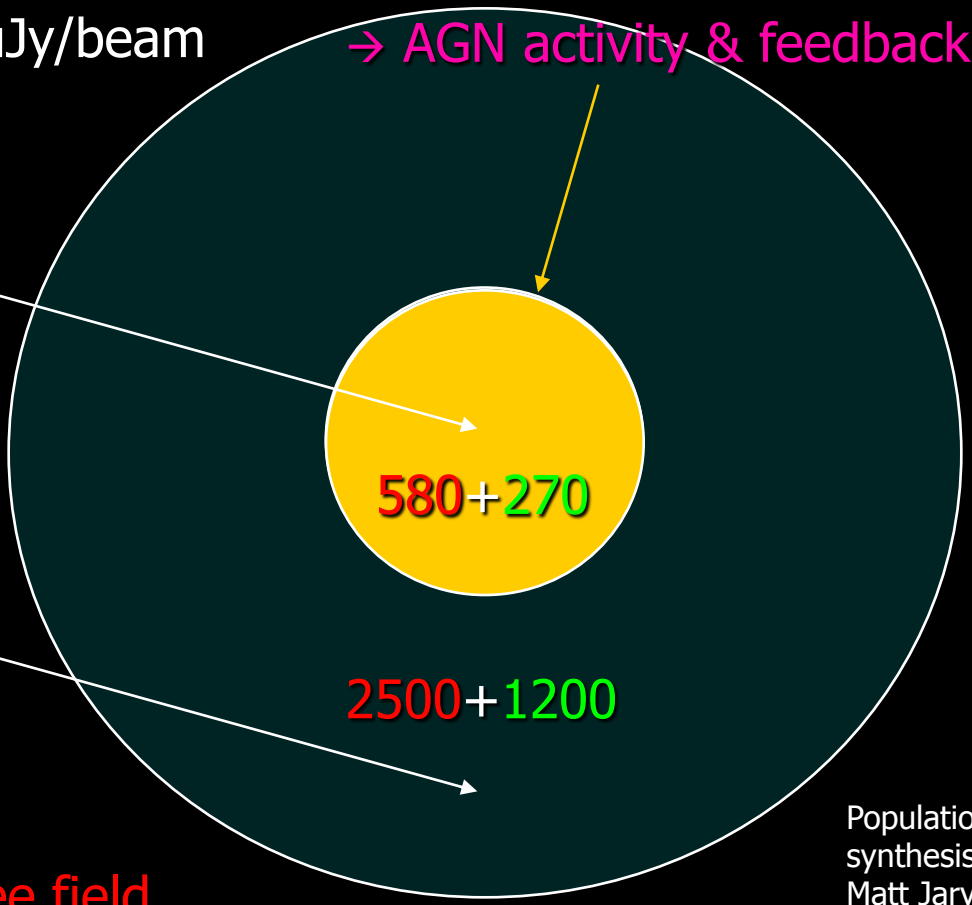
L-band: Single pointing centre, ~20 days
Central 12 arcminute field 1σ ~ 500nJy/beam
Outer 30 arcminute field 1σ ~ 1μJy/beam

Ultra-deep C-band mosaic
+ ultra-deep EVN L-Band
→ AGN activity & feedback

e-MERLIN will image ~580 starbursts and ~270 AGN with an angular resolution of ~200 mas, complete to ~3μJy

(>10 times deeper than the 2005 study)

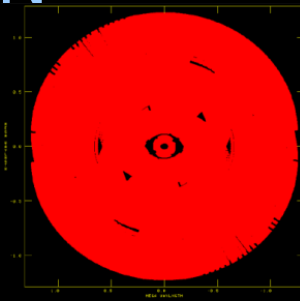
In the surrounding 800 square arcmins, e-MERLIN will image ~2500 star-forming galaxies and ~1200 AGN brighter than ~6μJy



Population synthesis: Matt Jarvis

>5000 sources in 0.2 square degree field

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

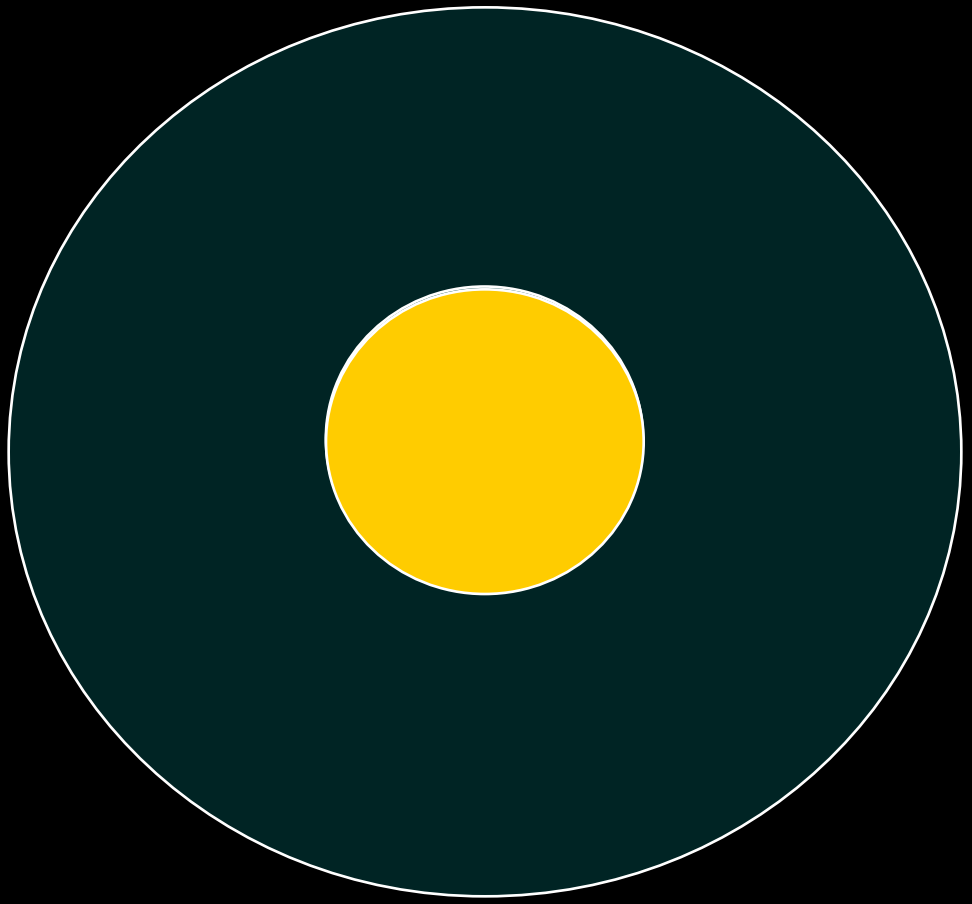


e-Merlin L-band data (1.23-1.74GHz → full *uv* coverage)

→ High fidelity imaging of faint radio structures at full resolution

Initial (2015) detailed investigation of >200 SF galaxies and AGN in central area (L-Band e-MERLIN/JVLA + C-Band JVLA mosaic)

L-Band image 1σ ≤ 2μJy/bm + EG078 - EVN deep wide-field image (72 hrs 1σ ~3μJy/bm)



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

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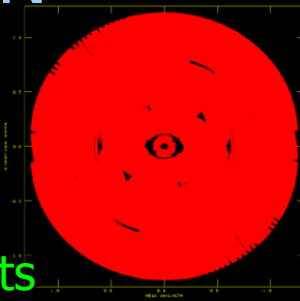
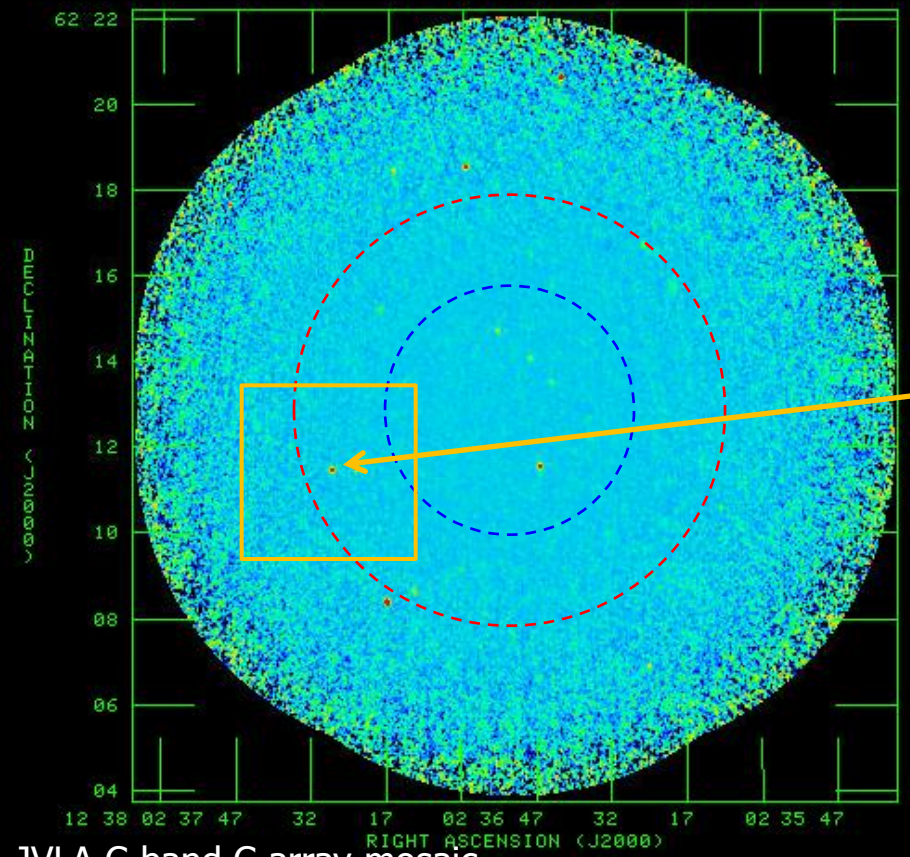
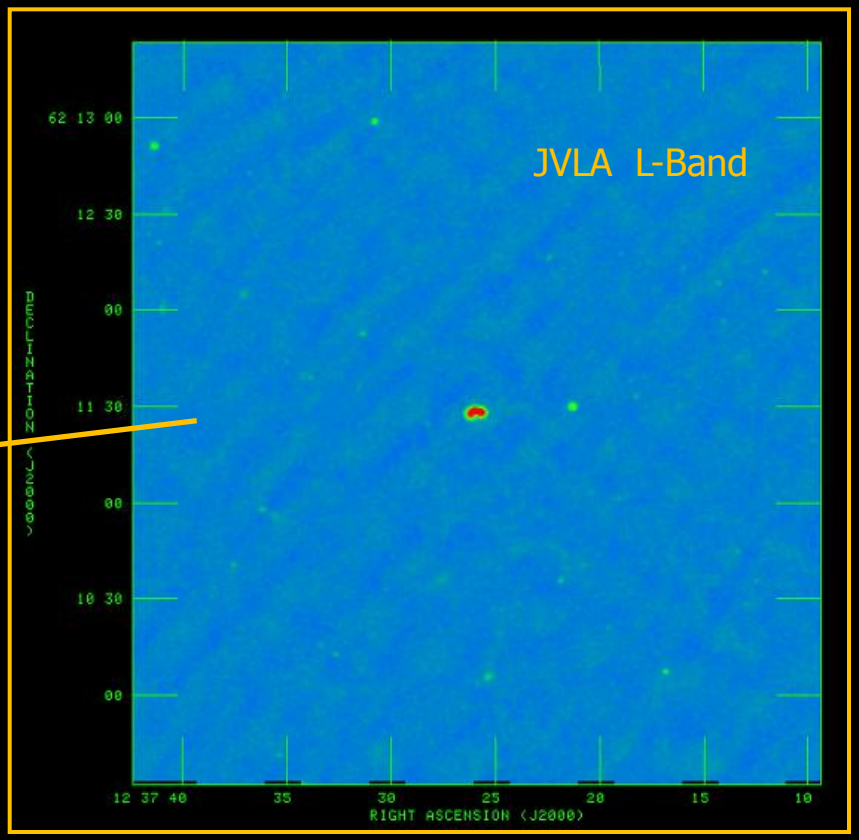


Only a few classical radio galaxy structures – most AGN are small core-jets

AGN Wide-angled tail radio galaxy (Total 5.3mJy)



JVLA C-band C-array mosaic

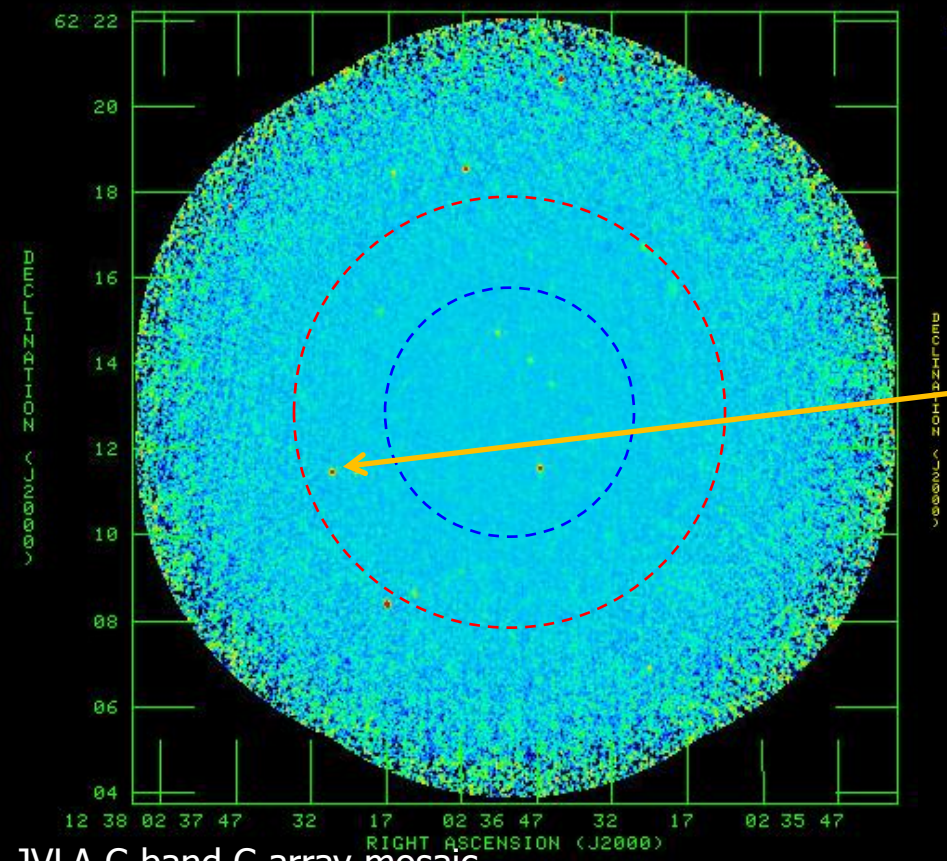


AGN

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

~60 hrs e-Merlin L-band data + 39 hrs JVLA A-array

AGN Wide-angled tail radio galaxy (Total 5.3mJv)



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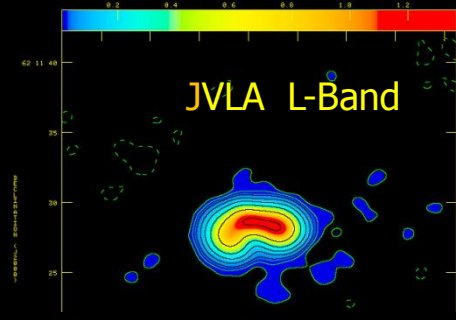
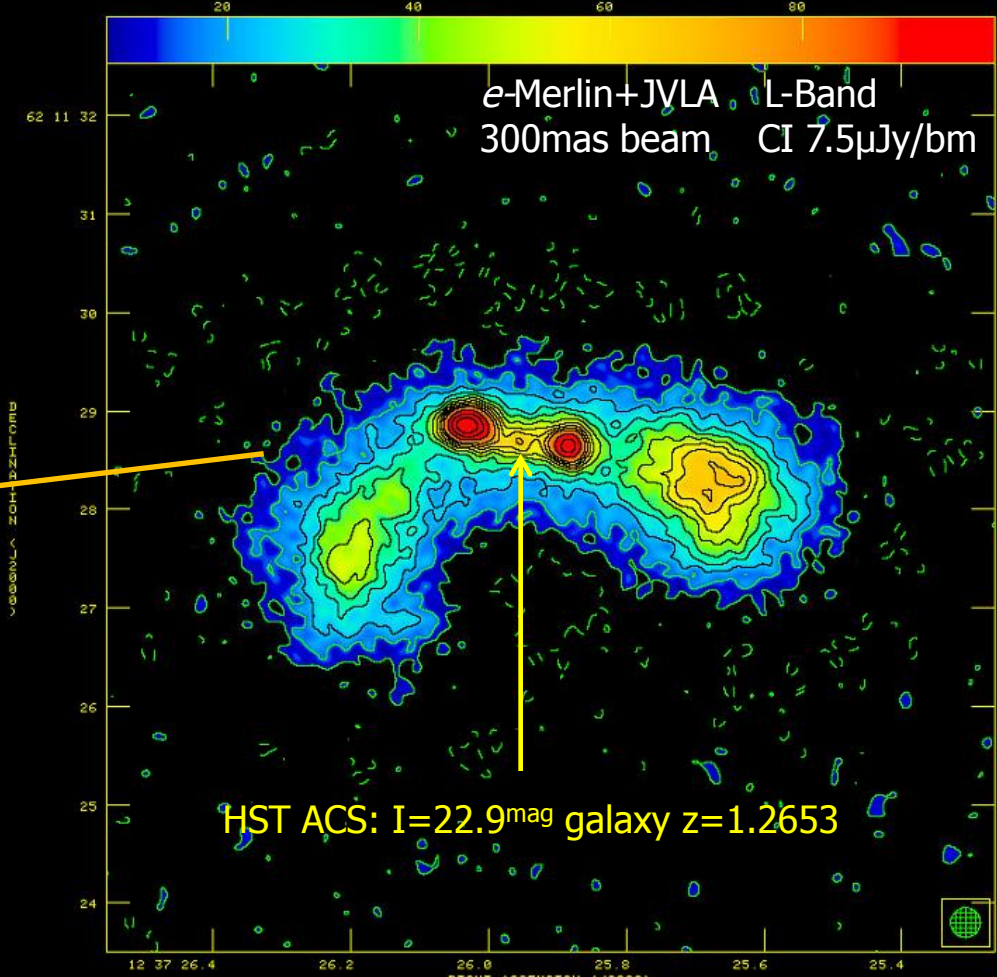
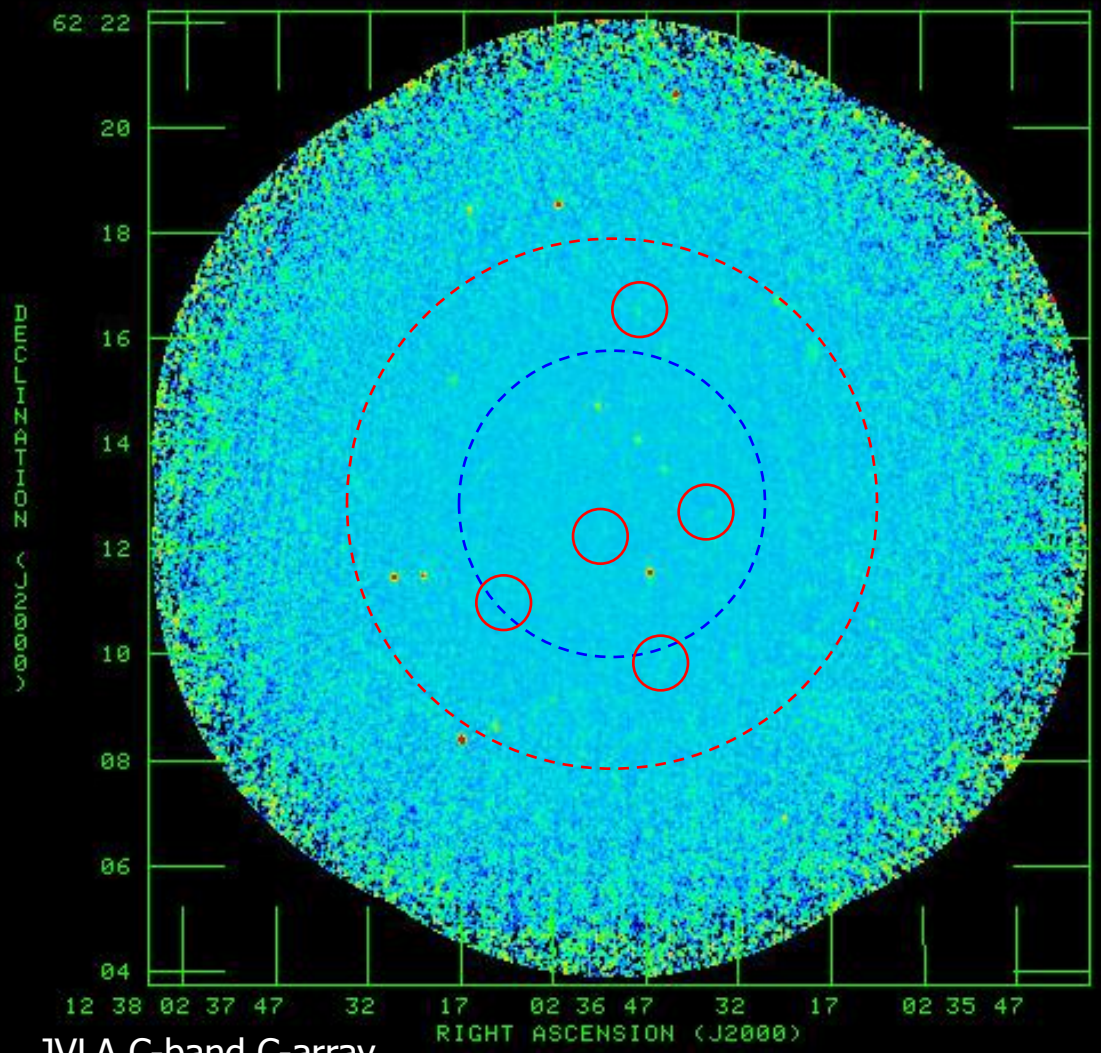




Tier 1: New Ultra-Deep Study of GOODS-N



JVLA C-band C-array

Latest deep high resolution e-MERLIN images of a variety of starburst galaxies:

J123634+621241
J123641+620948
J123646+621629
J123651+621221
J123708+621056

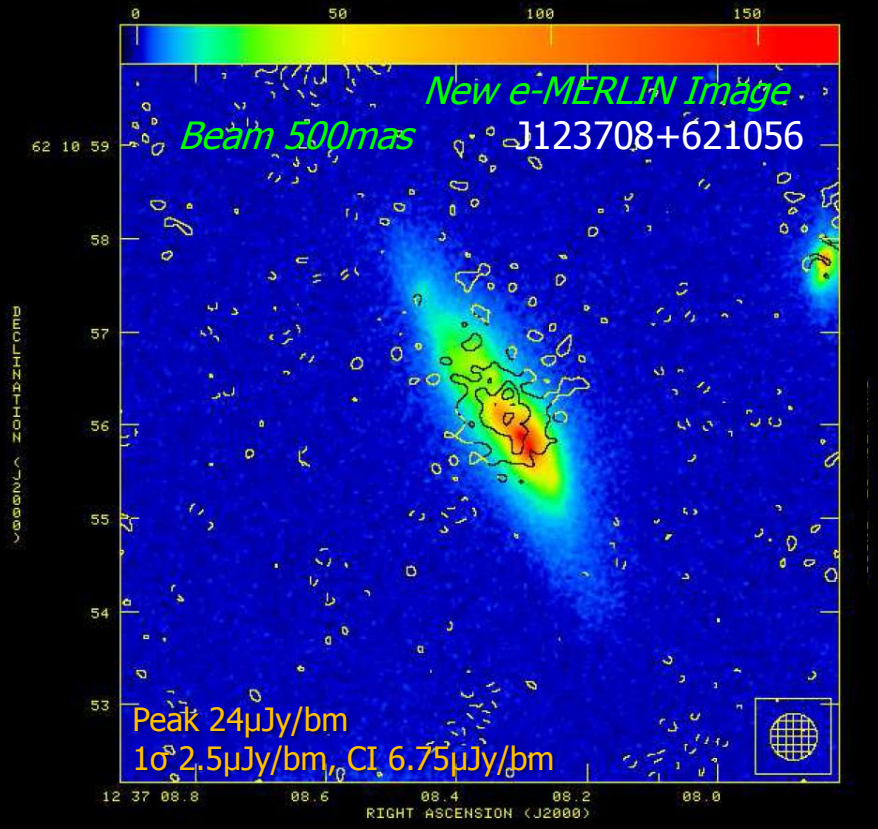
3 e-MERLIN datasets (~60 hrs) + archival MERLIN+VLA σ~2.5 μJy

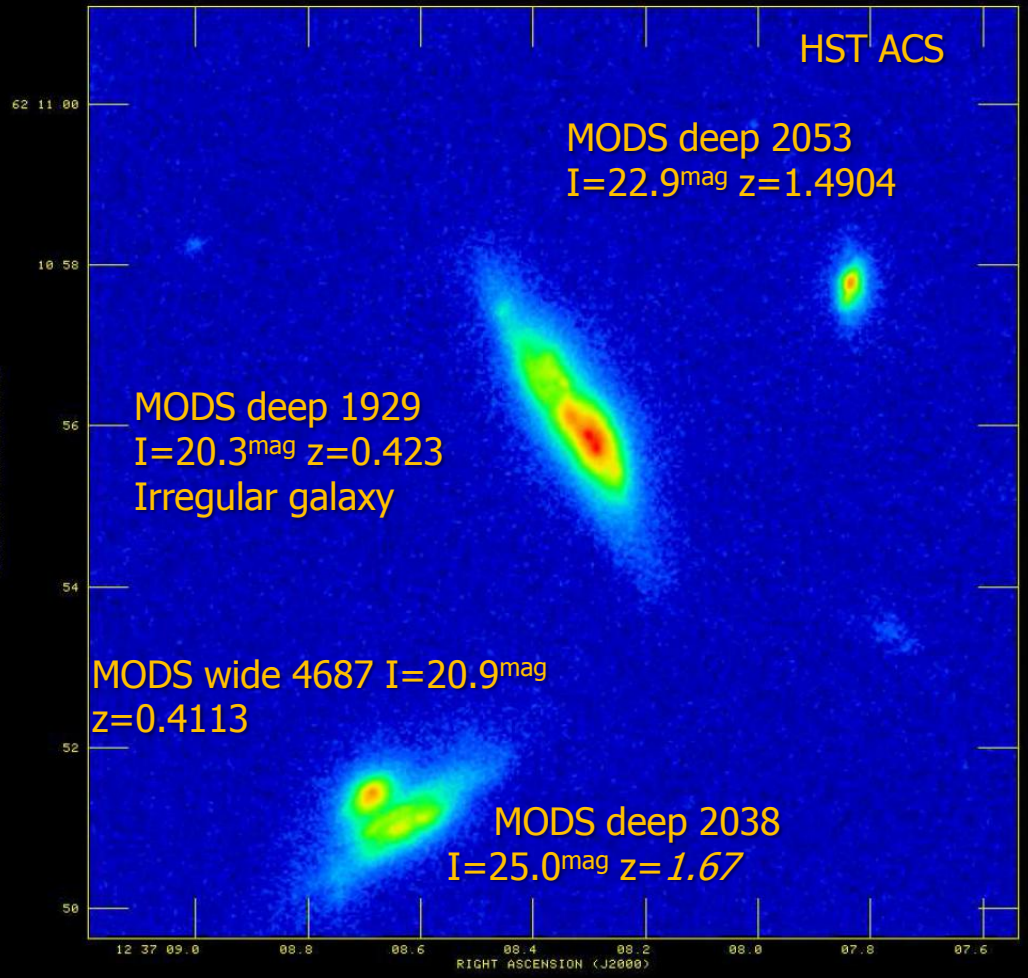
In progress:
Optimising weighting scheme for JVLA L-Band data with sub-set of e-MERLIN dataset → σ~< 2μJy

Classical starbursts – Starbursts + AGN – Sub-mm starbursts – Starbursts in mergers

Classical Starburst

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





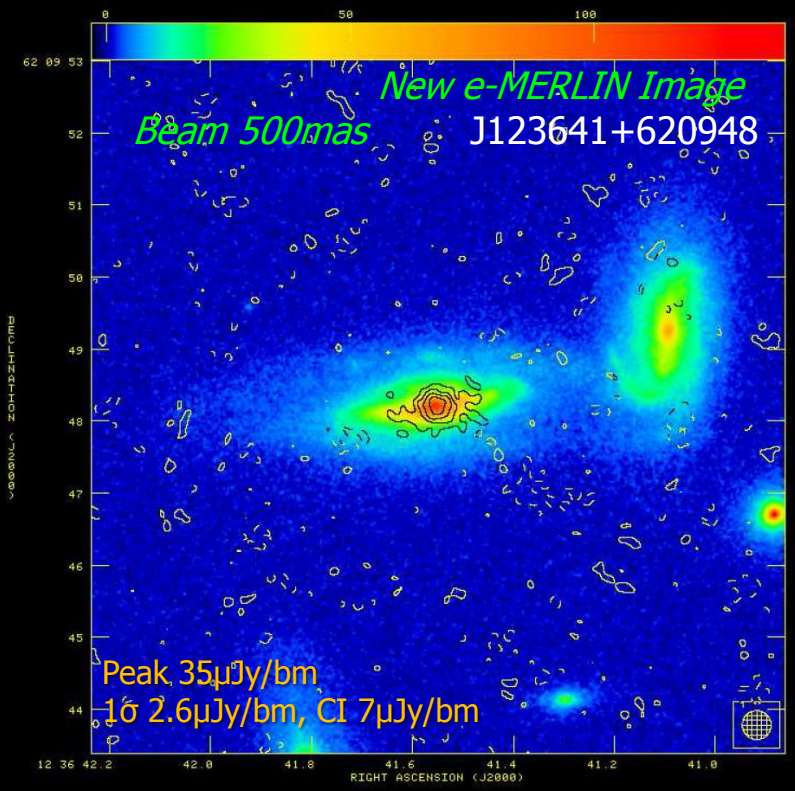
Extended (α>0.35) starburst ($S_{1.4}$ = 45μJy)

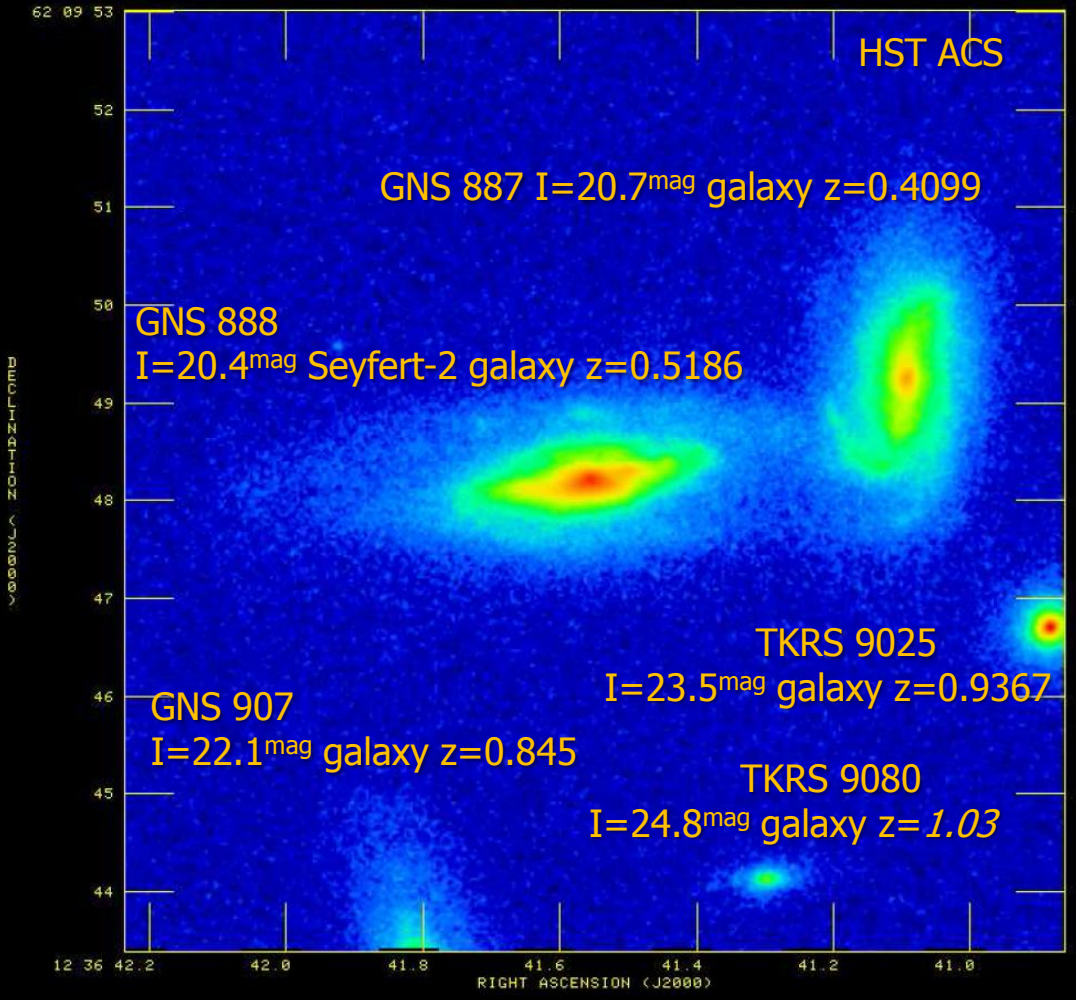
Radio emission from central region of 10^{10} $M_\odot$ Irregular galaxy – No compact emission detected + extension along galaxy major axis. $L_{1.4}$ =3.8x10^{22} W/Hz → Star-formation rate 15 $M_\odot$/yr (0.1-100$M_\odot$ assuming Salpeter IMF)

Extended (1.2") starburst – Central region shows optical obscuration (dust lane?)

Starburst + AGN?

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





Extended steep-spectrum (α>0.56) starburst with embedded AGN? ($S_{1.4}$ = 76μJy). – interacting galaxies?

Emission from central region of 10^{11} $M_\odot$ Seyfert-2 galaxy – Nuclear emission + 1.5″ extension

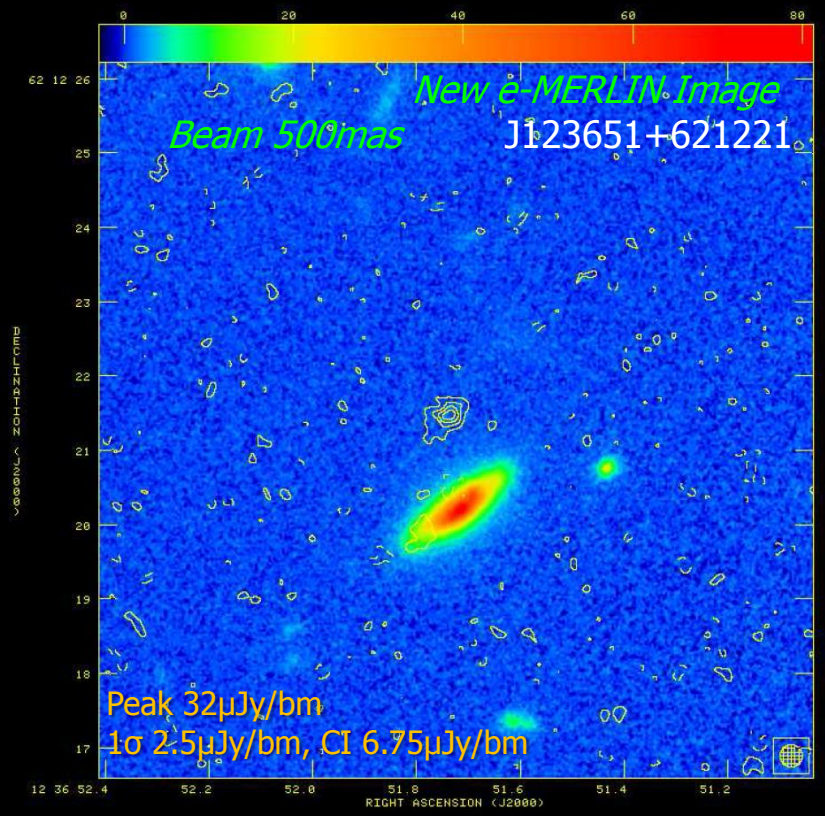
$L_{1.4}$ =1.7x10^{23} W/Hz → Star-formation rate 41 $M_\odot$/yr (0.1-100$M_\odot$ assuming Salpeter IMF)

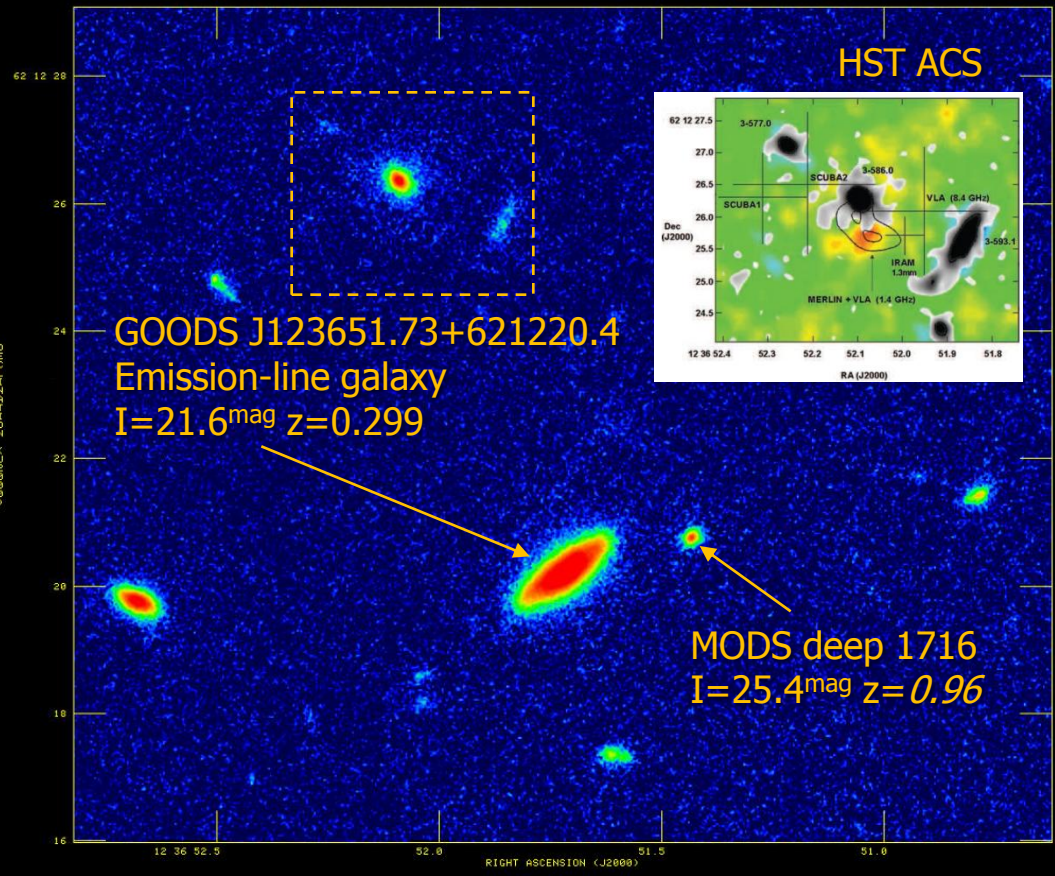
Faint Chandra detection

AGN or nuclear starburst? – VLBI detects no faint radio core to ~8μJy…

Sub-mm Starburst

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





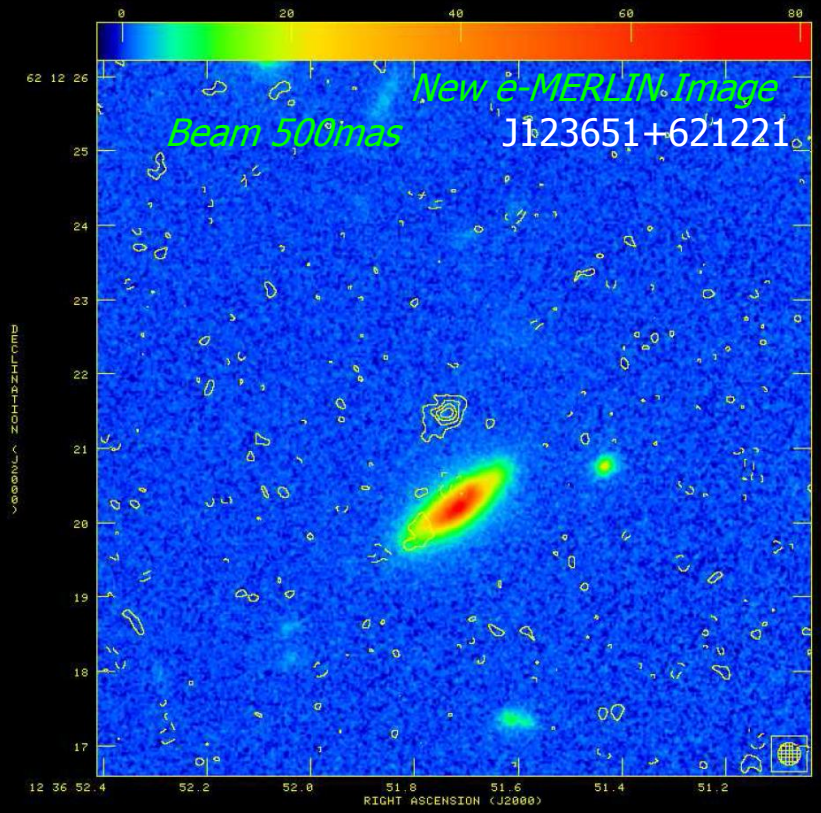
Extended (0.9″) steep spectrum (α>0.71) starburst ($S_{1.4}$ = 49μJy).

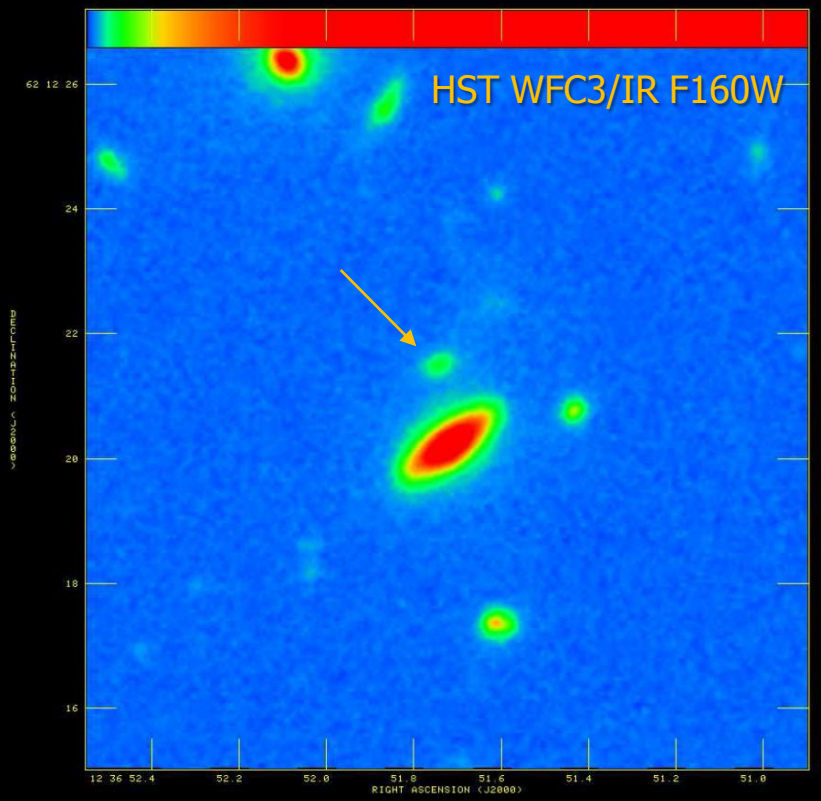
Radio emission lies to north of emission-line galaxy at z=0.299 – No compact emission (VLBI)
No detectable emission in visible bands

Source close to (unrelated) search for galaxy counterpart to SCUBA2 sub-mm detection HDF850.1

Sub-mm Starburst

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





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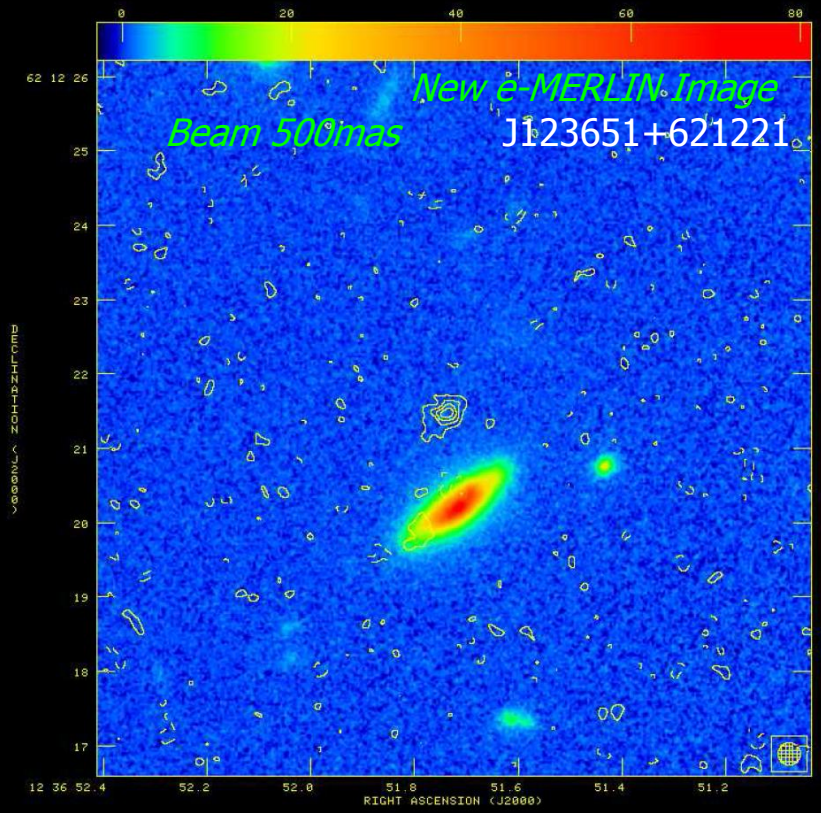
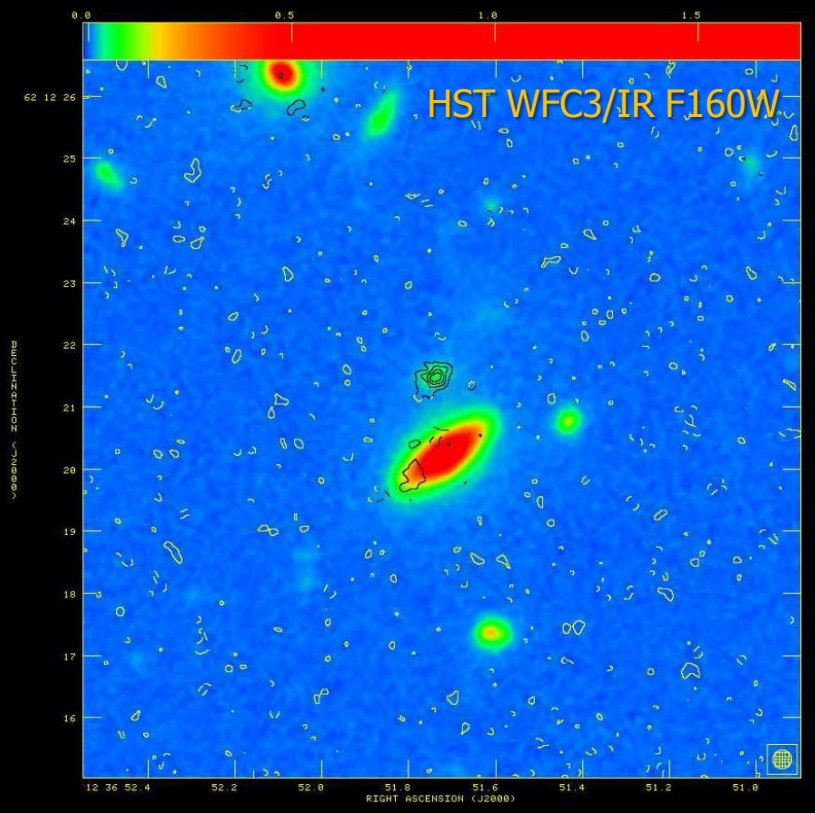
Radio emission lies to north of emission-line galaxy at z=0.299 – No compact emission (VLBI)
No detectable emission in visible bands. Faint very red object detected in F160W (1.6μm IR)
ISO detection → dust obscured starburst at z~3. Hard Chandra X-rays → obscured QSO at z=2.7
SMA detection at 1.3mm

Sub-mm Starburst

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





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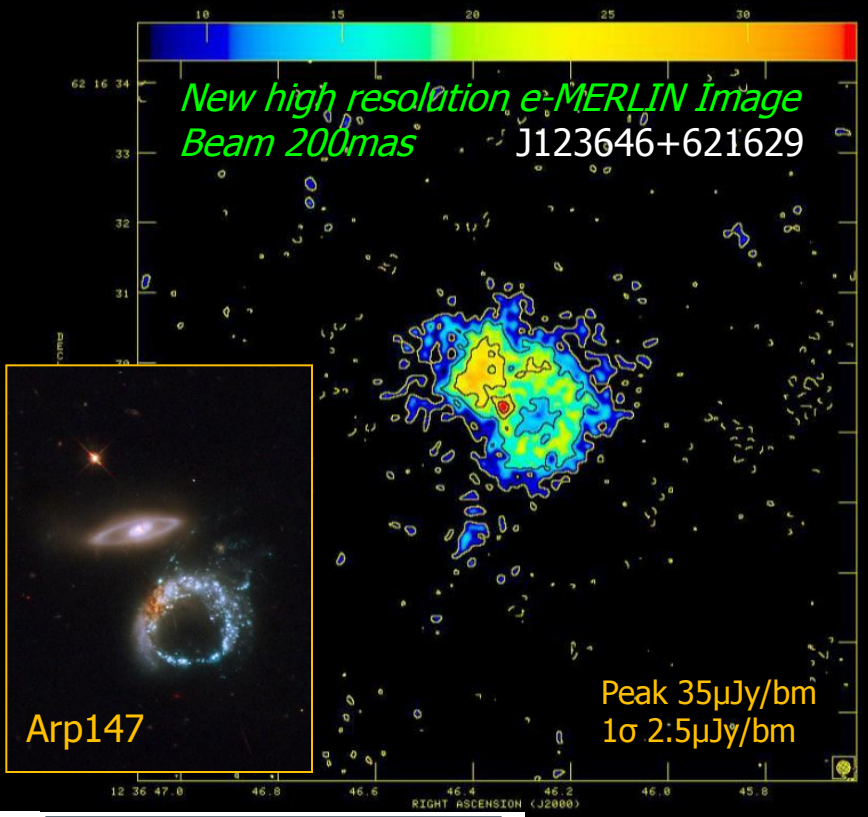
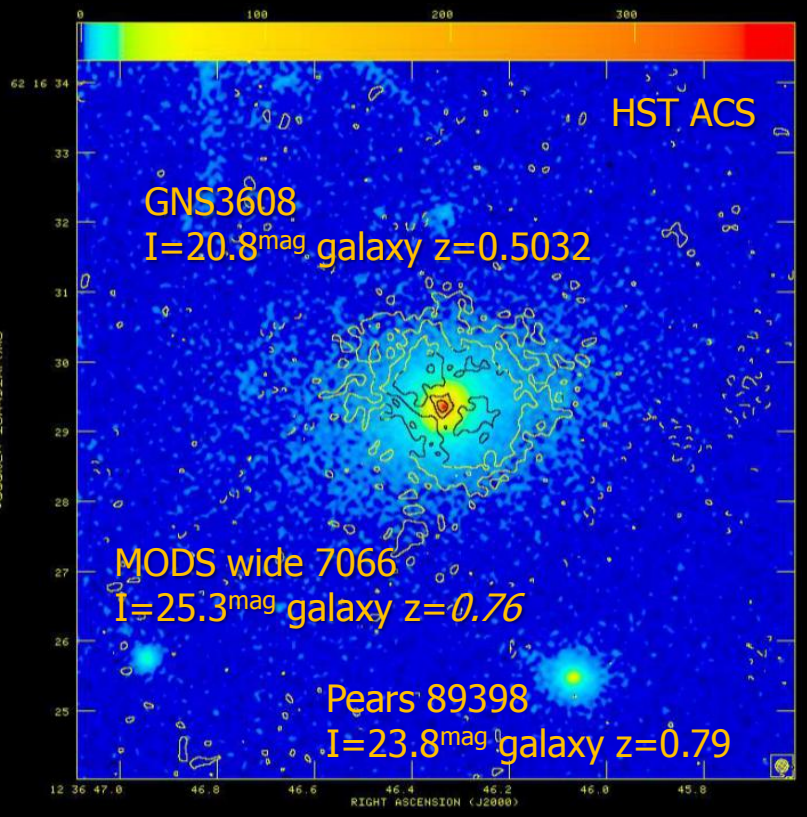
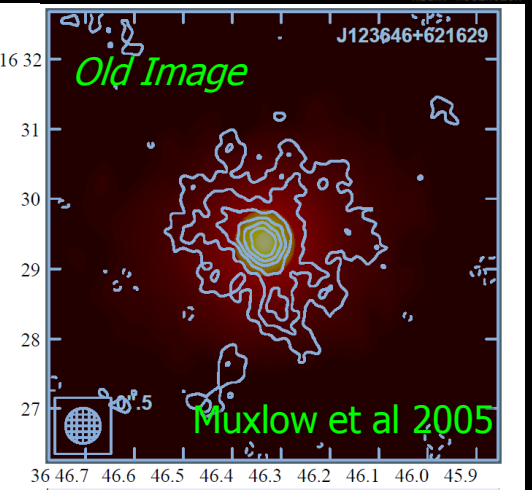
ISO detection → dust obscured starburst at z~3. Hard Chandra X-rays → obscured QSO at z=2.7
SMA detection at 1.3mm
$L_{1.4}$ =8.6x10^{24} W/Hz → Star-formation rate ~2000 $M_\odot$/yr (0.1-100$M_\odot$ assuming Salpeter IMF)

Starburst + AGN?

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







Extended steep-spectrum (α>1.62) starburst with embedded AGN? ($S_{1.4}$ = 393μJy). → Ring of star-formation – interacting galaxies?

Radio emission extends across face of massive spheroidal galaxy

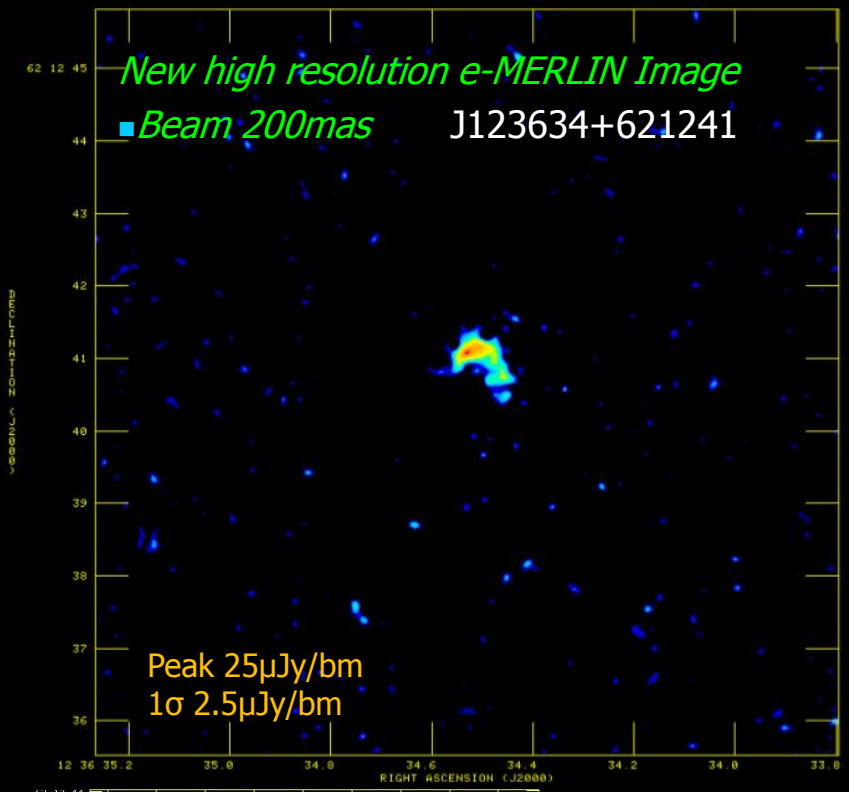
$L_{1.4}$ =8.5x10^{23} W/Hz → Star-formation rate ~200 $M_\odot$/yr (0.1-100$M_\odot$ assuming Salpeter IMF)

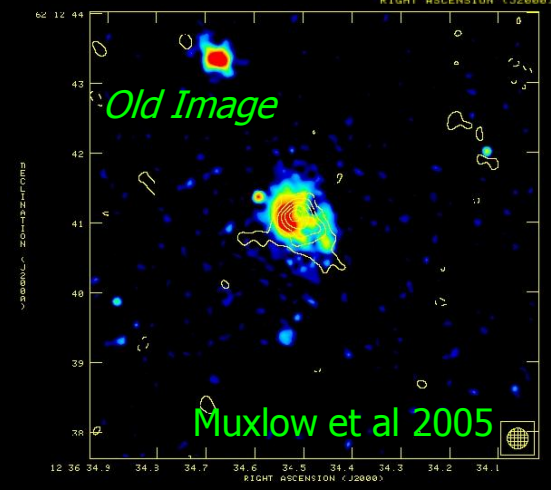
Bright galaxy core shows BL emission → Optical AGN activity

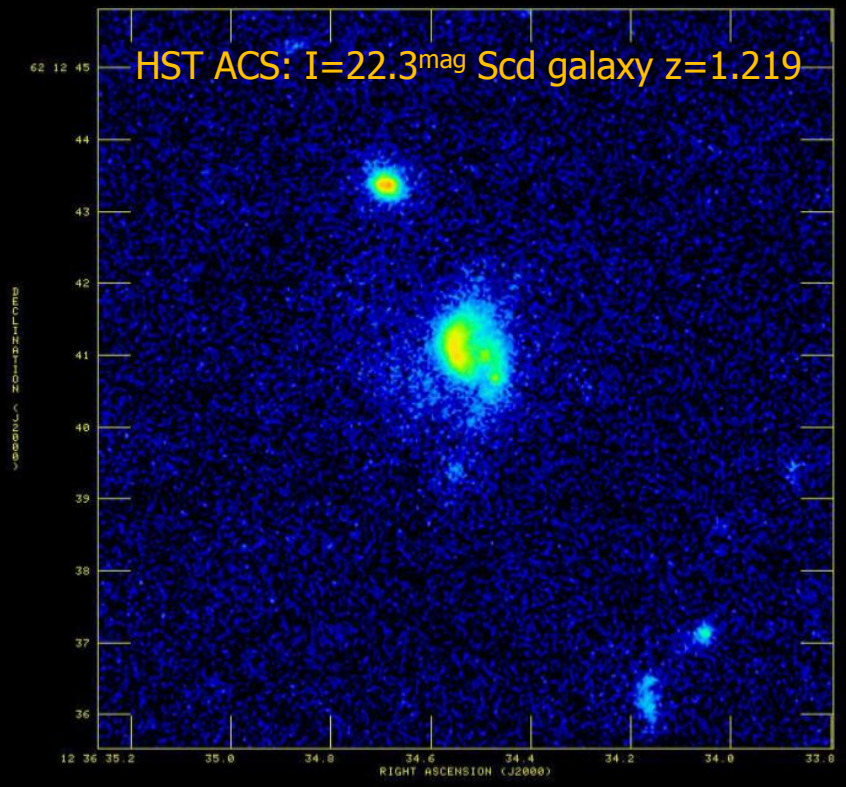
AGN or nuclear starburst? – C-Band/VLBI to look for faint radio core…

Starburst in merger

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







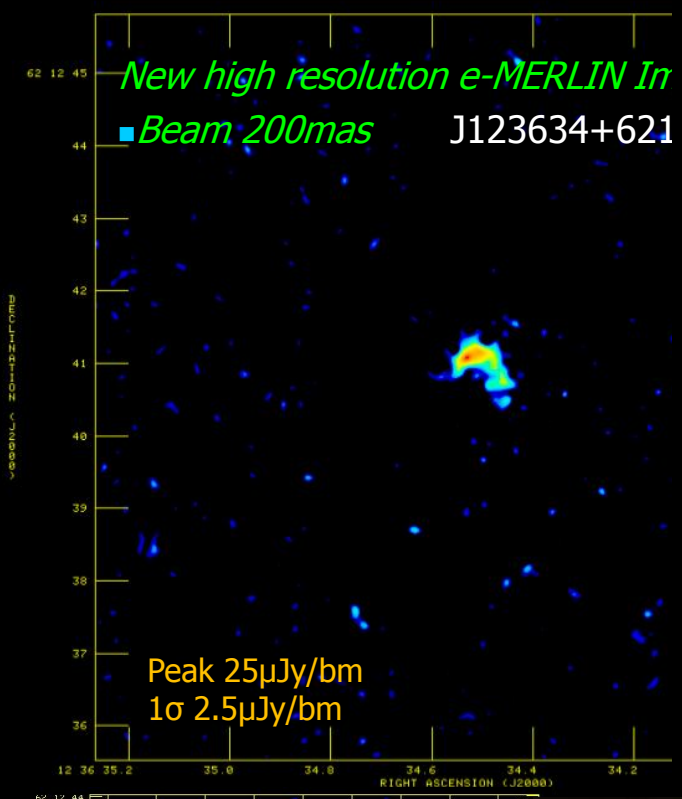
Steep-spectrum (α=0.74) starburst (Total 230μJy) – ISO detection

$L_{1.4}$ =4.1x10^{24} W/Hz → Star-formation rate ~960 $M_\odot$/yr

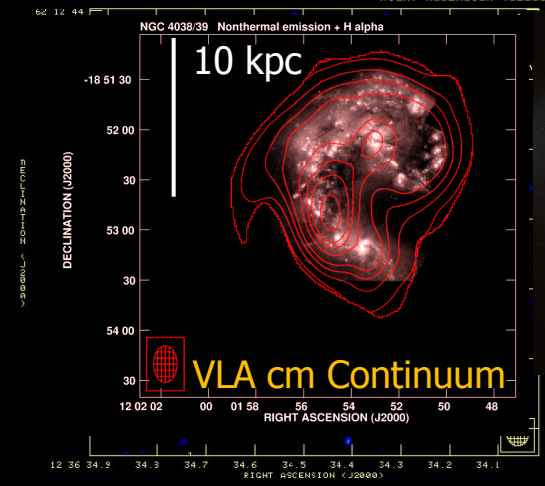
Merging Scd sub-mm galaxy with tidal tail

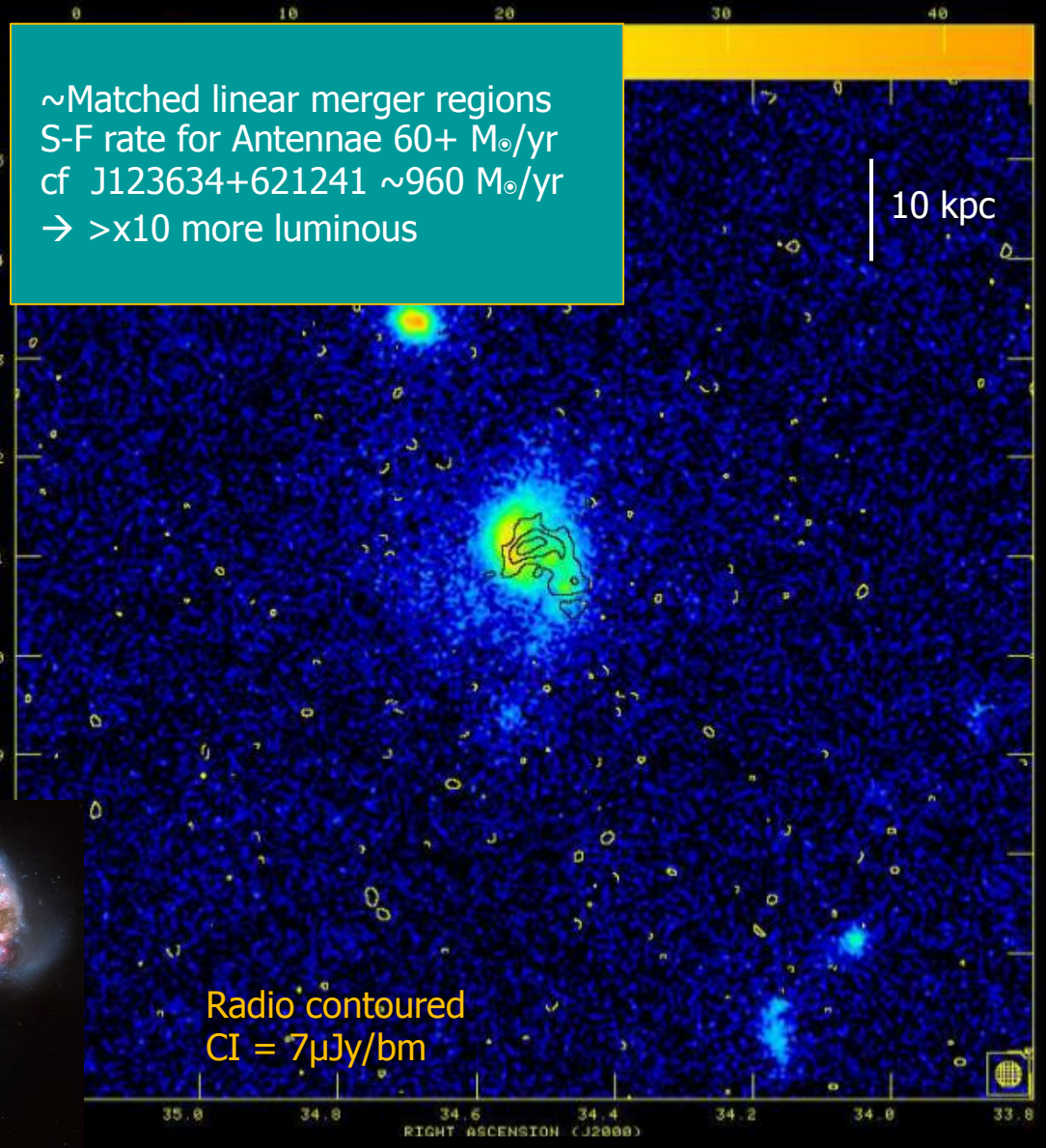
Starburst in merger

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



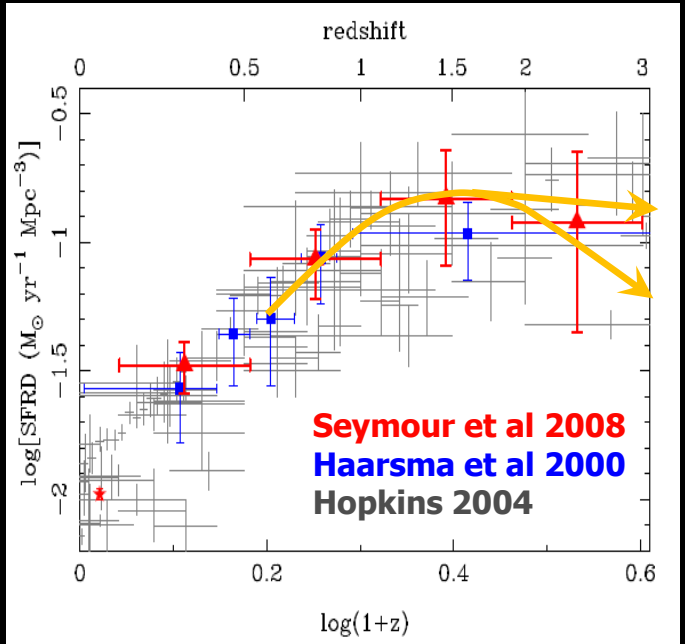
~Matched linear merger regions
S-F rate for Antennae 60+ $M_\odot$/yr
cf J123634+621241 ~960 $M_\odot$/yr
→ >x10 more luminous

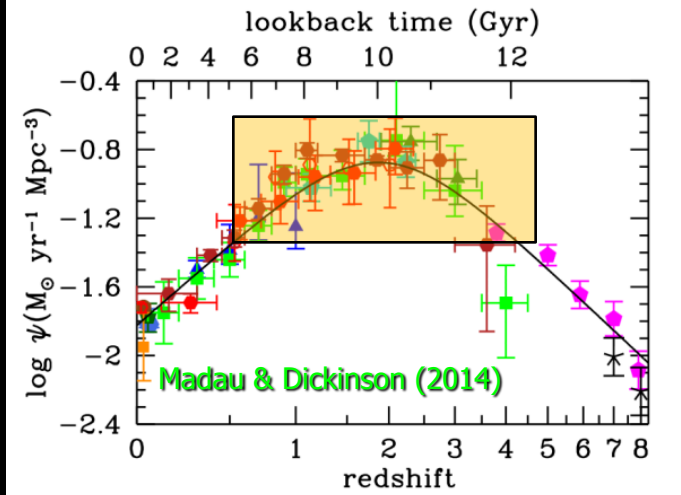




– Radio emission follows merger & extends towards tail (cf 'Antennae')

Star-formation History of the Universe - from Starburst Luminosities

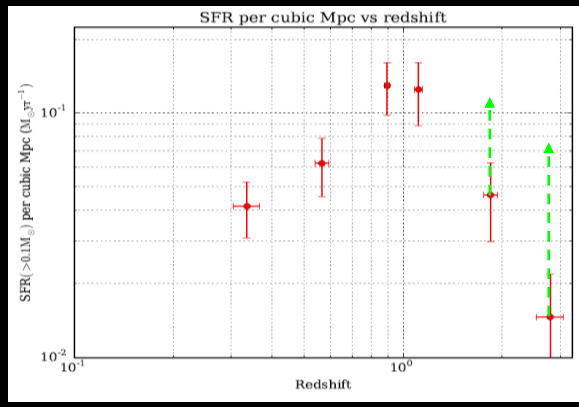




The co-moving Star-Formation Rate Density of the Universe from L-Band radio studies by Seymour et al (2008), Haarsma et al (2000), & UV, Hα, Far-IR... Hopkins (2004)

L-Band results from the e-MERGE survey will provide data for several thousand more sources → tightening the Seymour error bars by a factor ~4 & extending to z~5

Constrain position of maximum from extinction-free SF indicator

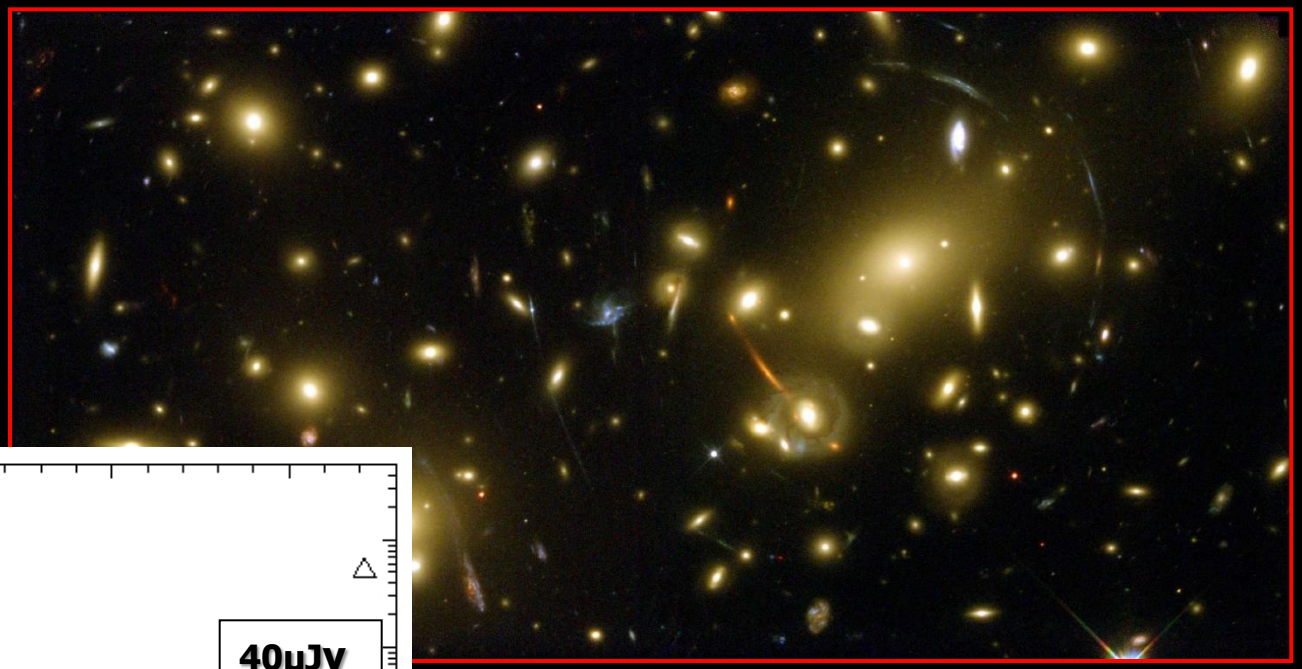


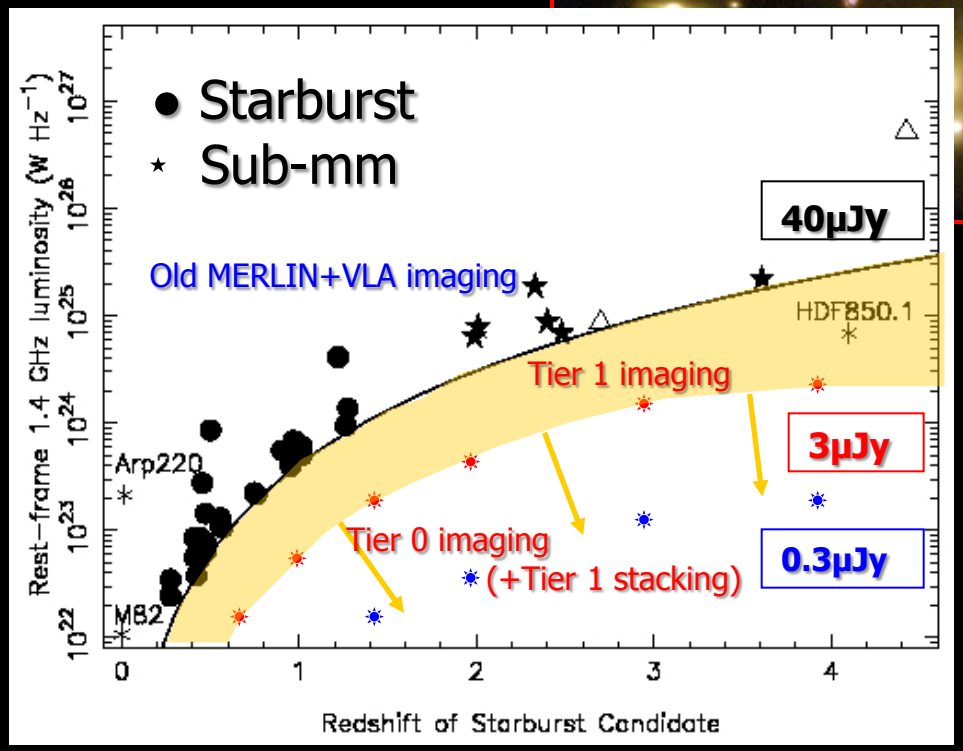
Latest: 196 SF galaxies of 307 sources >3σ

Uncorrected for missing high z redshift measurements – so underestimates SF galaxies at high z

Tier 0: Imaging sub-μJy galaxies

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





Expect ~50 amplified sources with intrinsic fluxes as faint as 300nJy

Measure faint radio counts

May include SF galaxies with SFR~200M$_\odot$/yr to z~5

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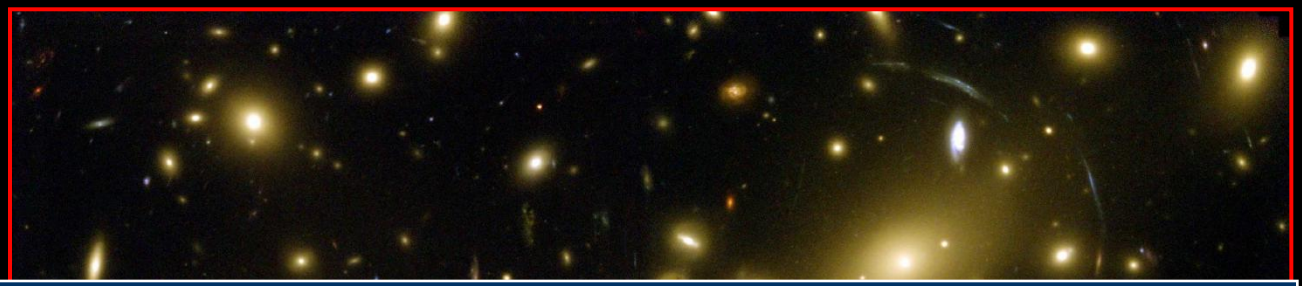
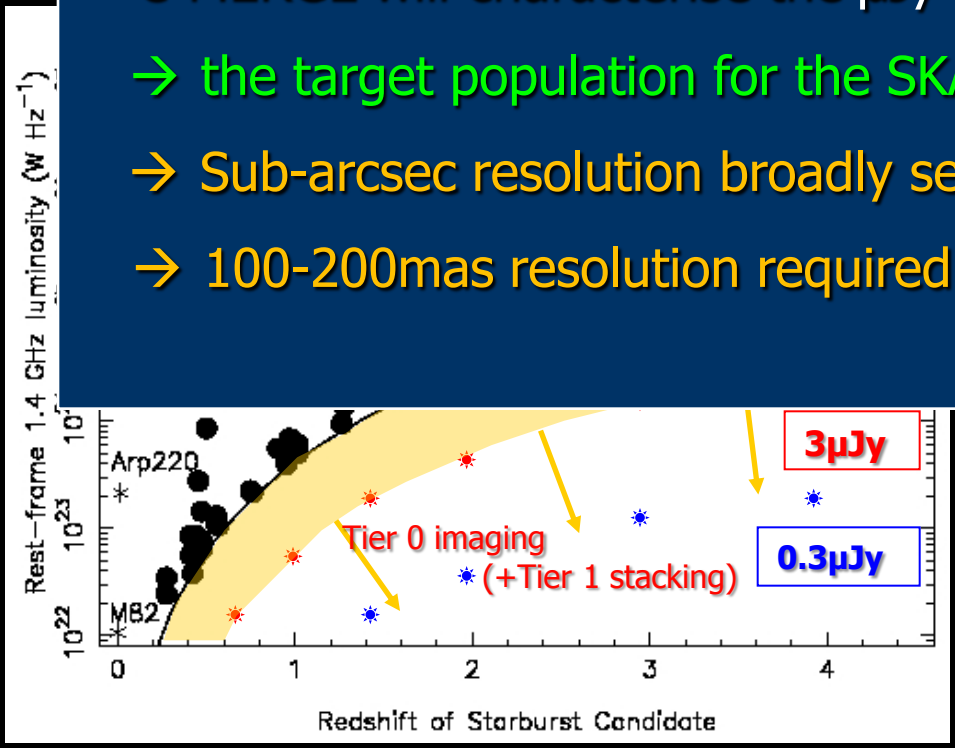


e-MERGE will characterise the μJy & sub-μJy radio source population

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

→ Sub-arcsec resolution broadly separates SF and AGN

→ 100-200mas resolution required to study feedback in faint sources



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