Star-formation and AGN feedback across cosmic time

High-resolution imaging of the μJy radio source population

e-MERGE – Latest results and planned releases…

Tom Muxlow JBCA Manchester

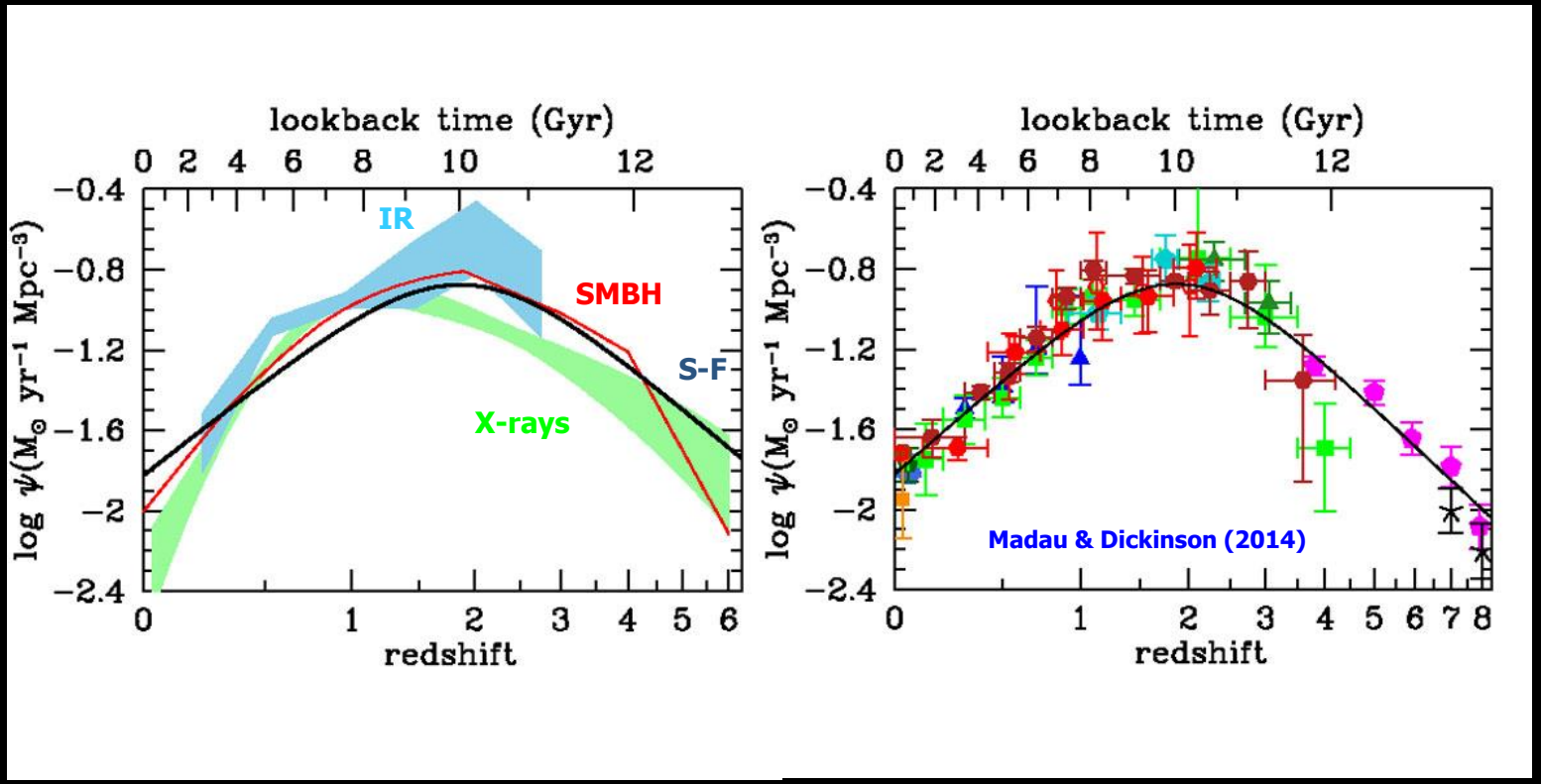
Ian Smail, Ian McHardy, Nick Wrigley, Jack Radcliffe, Alasdair Thompson, Daria Guidetti, & the e-MERGE Consortium

e-MERLIN & JBO:

A radio astronomy facility for the SKA era

JBO 16th September 2016

SMBH and S-F accretion history across cosmic time



Best fit SMBH accretion history from X-rays [*red curve* (Shankar et al. 2009); *green shading* (Aird et al. 2010)] and infrared (*blue shading*) (Delvecchio et al. 2014) data. Co-moving rates of SMBH accretion scaled up by 3,300 to facilitate visual comparison

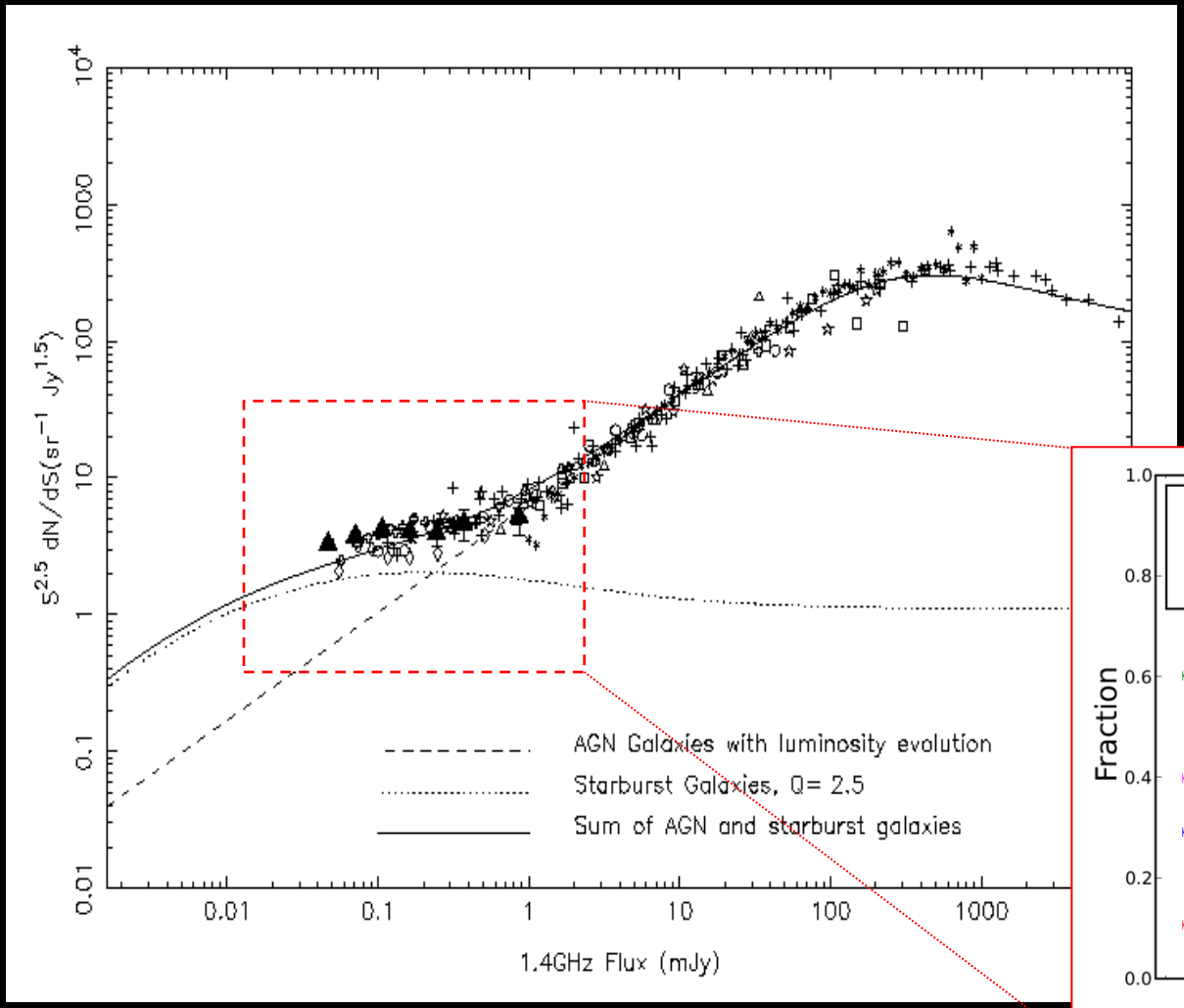
Star-formation and black hole growth are co-evolving and closely linked at all redshifts
Need to study the evolution and interactions in both populations

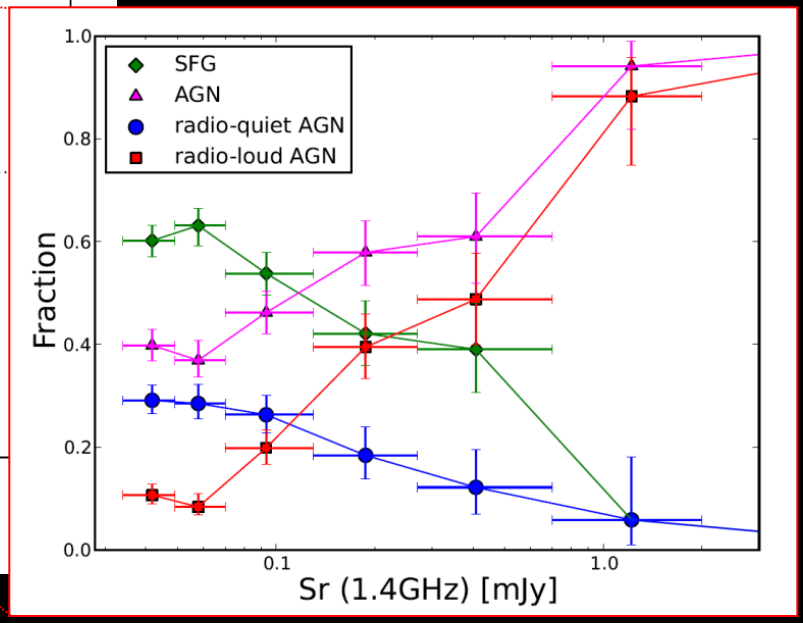
→ Role of AGN in S-F – AGN feedback required to account for observed (bright end) galaxy luminosity function
→ AGN can trigger as well as quench S-F – study feedback from embedded AGN in S-F galaxies
→ S-F rate turn over at z>2 is still problematical – needs to be confirmed by extinction-free S-F tracers
→ Need to separate AGN-jet activity from S-F emission to accurately measure S-F rate in the radio band

The μJy radio source population

Differential radio source counts show an upturn below flux densities of ~1mJy

→ A new population of starburst systems





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

Padovani et al, & others, show AGN population evolves, R-Q AGN dominating over radio-loud AGNs < 100μJy

R-Q AGN properties? Similar to R-Loud AGN but fainter? Starbursts with faint embedded AGN?

Need high resolution, high sensitivity radio imaging to separate AGN-jet from S-F emission…

The e-MERlin Galaxy Evolution survey

A tiered e-Merlin + JVLA + EVN Legacy proposal

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 programme

Tier 2 – *Shallow-wide survey over ~2 square degrees*

May piggyback on another survey ? *[Ian McHardy – Southampton]*

→ full sampling of AGN & S-F galaxy radio luminosity function to z~5

Tier 0 – Observations to follow Tier 1 *[2017→]*

Tier 1 – L-Band: *[Complete, 25% e-M data reduced]*

C-Band: *[e-M 2016/7→, JVLA complete]*

L: Single pointing centre – Central 12′ 1σ ~ 500nJy/beam Outer 30′ 1σ ~ 1μJy/beam

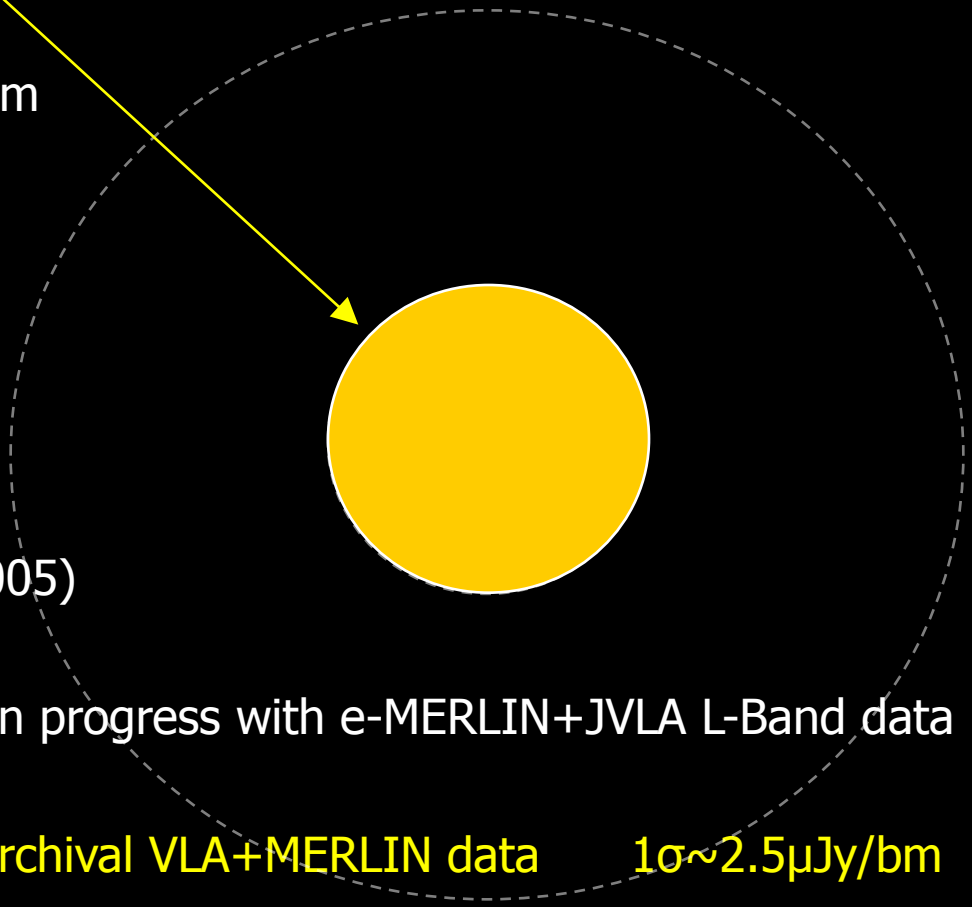
C: Mosaic covering central 12′ field 1σ ~ 700nJy/beam

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

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

→ Interim data release with ~25% e-MERLIN of data processed….

Initial (2016) detailed investigation of several >300 SF galaxies and AGN in central regio
L-Band e-MERLIN/JVLA + EG078 (EVN) + C-Band JVLA mosaic 1σ~1.5μJy/bm
L-Band image 1σ ≤ 2μJy/bm
+EG078 EVN deep wide-field 1σ~3μJy/bm
– Talk by Jack Radcliffe



In progress:
Final assembly/calibration of
e-MERLIN (~110 hrs), JVLA, EVN
datasets for initial combination imaging
(+archival dataset from Muxlow et al (2005)

Wide-field imaging test with WS CLEAN in progress with e-MERLIN+JVLA L-Band data

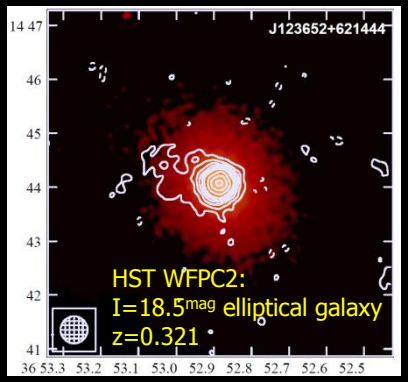
Some recent images from e-MERLIN + archival VLA+MERLIN data 1σ~2.5μJy/bm

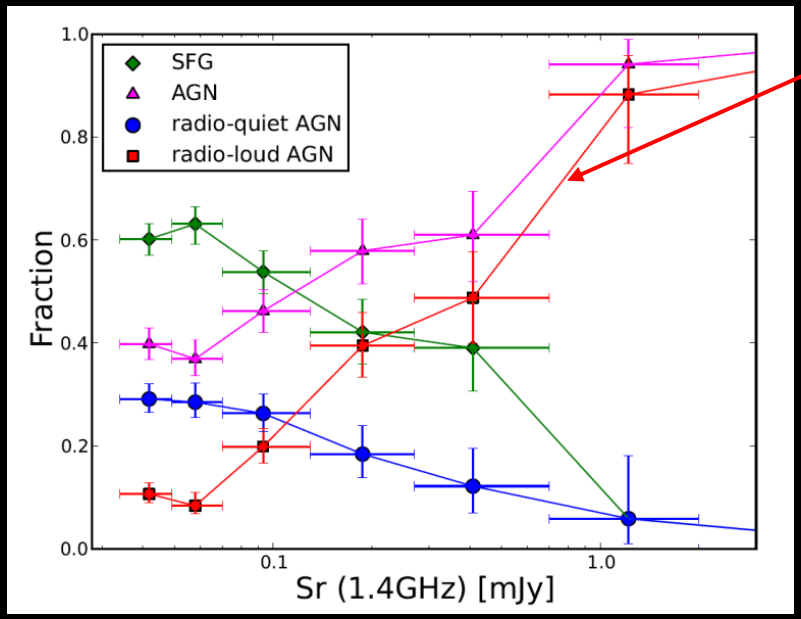
Radio-Loud AGN

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

High angular resolution imaging together with spectral properties can separate populations within the μJy radio source population

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





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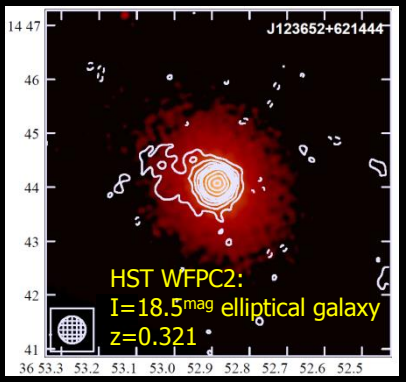
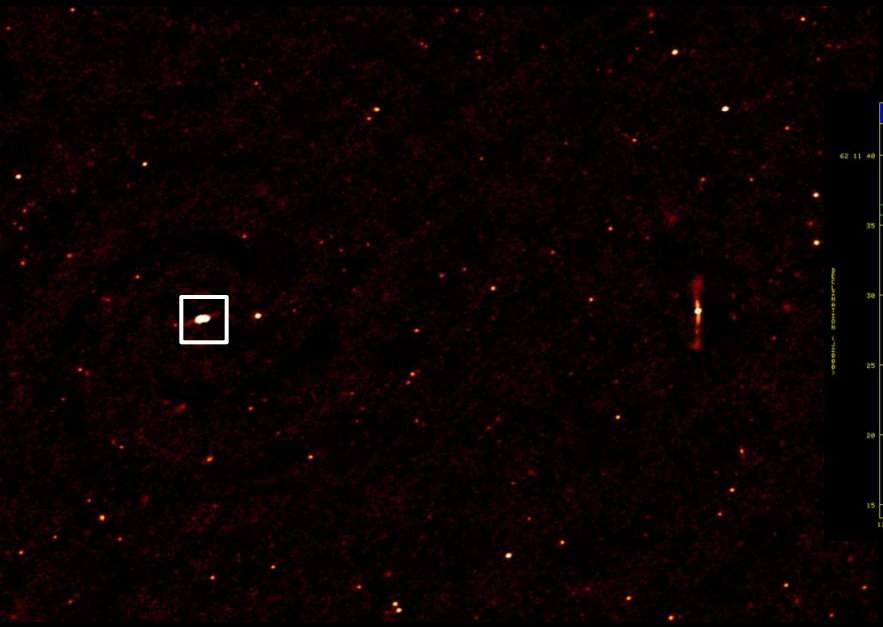
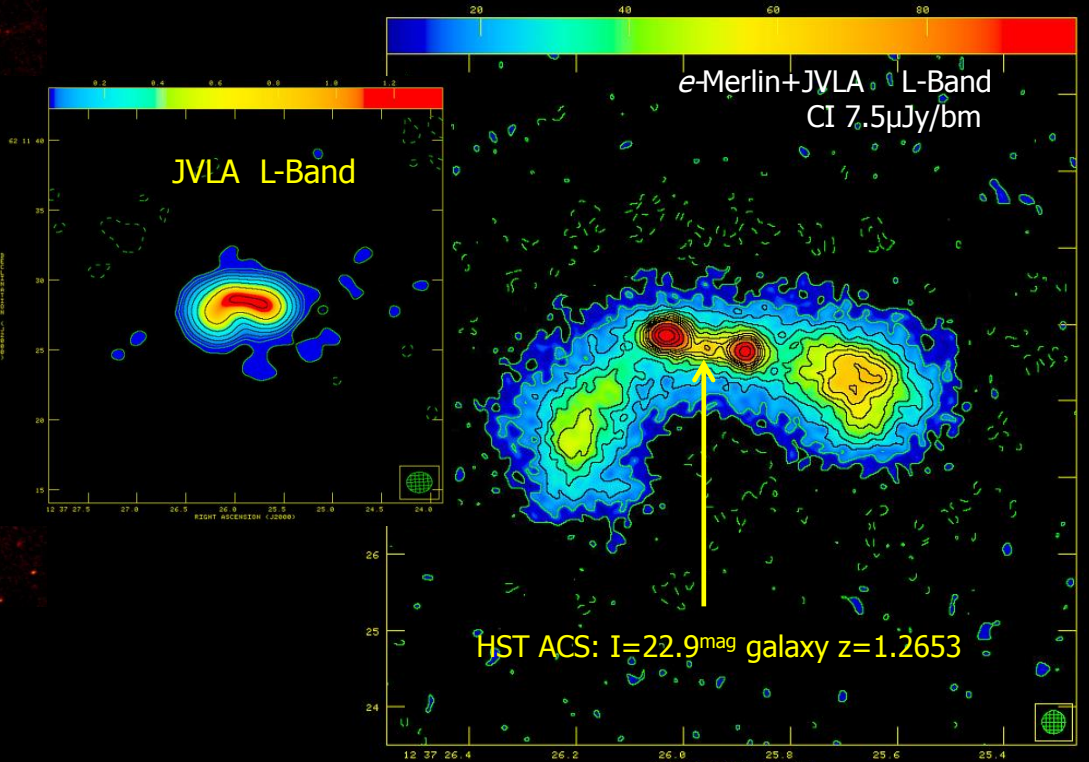






Luminous Starburst

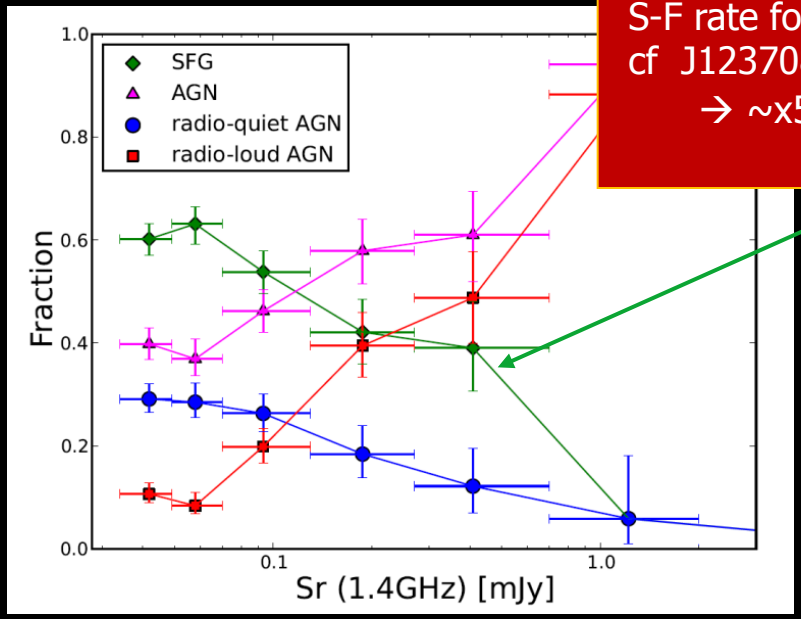
Tier 1: New Ultra-Deep Study of GOODS-N

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

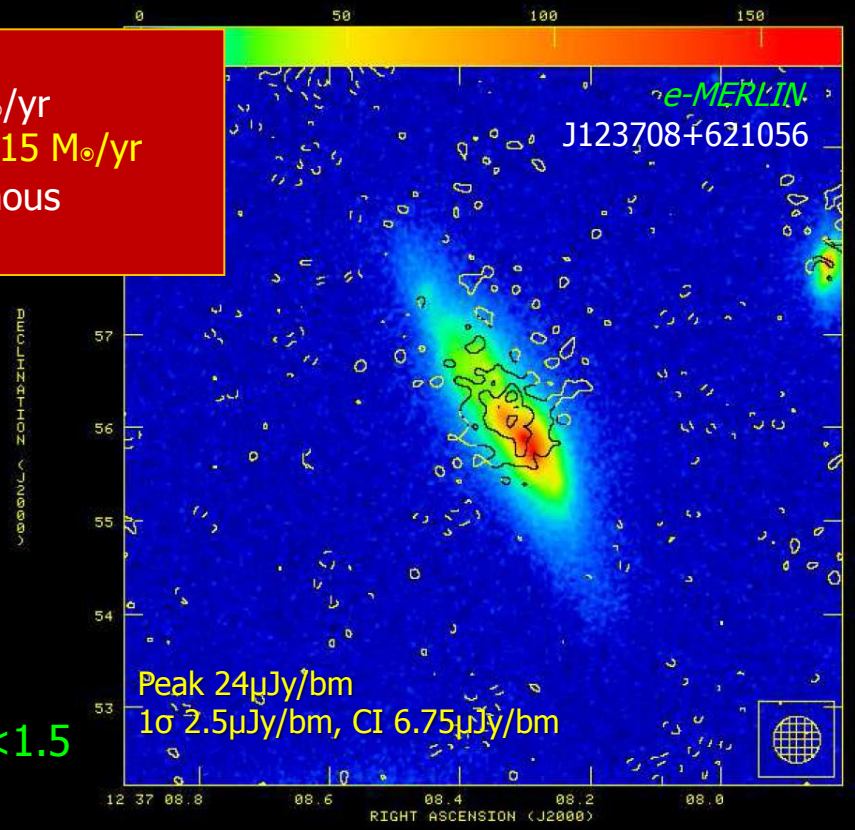
$L_{1.4}$ =3.8x10^{22} W/Hz → Star-formation rate 15 $M_\odot$/yr

(0.1-100$M_\odot$ assuming Salpeter IMF)

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



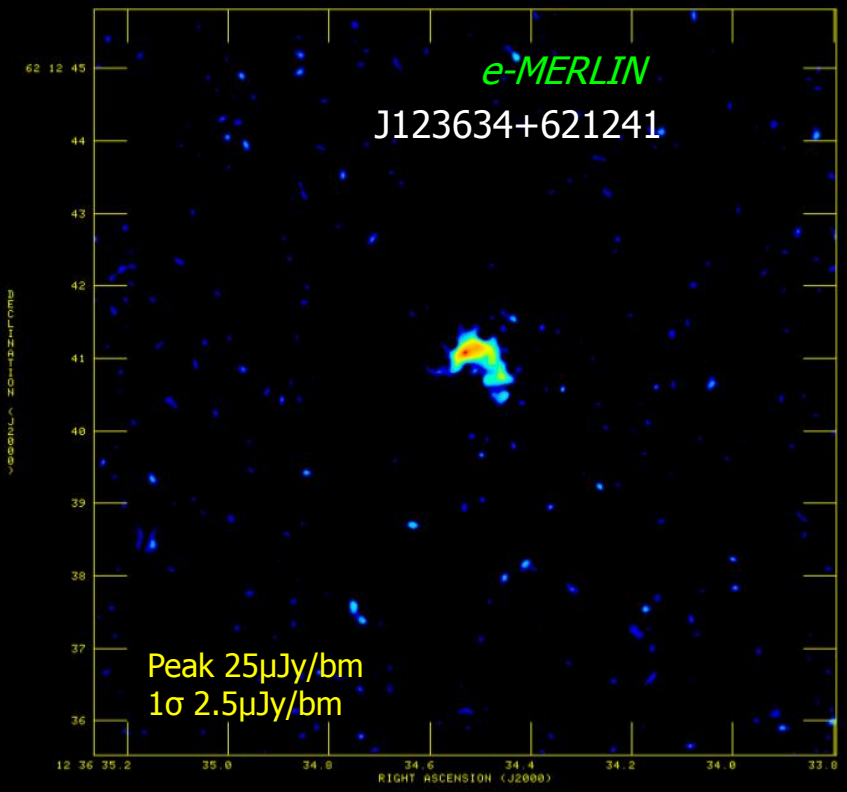
S-F rate for M82 ~3 $M_\odot$/yr
cf J123708+621056 ~15 $M_\odot$/yr
→ ~x5 more luminous

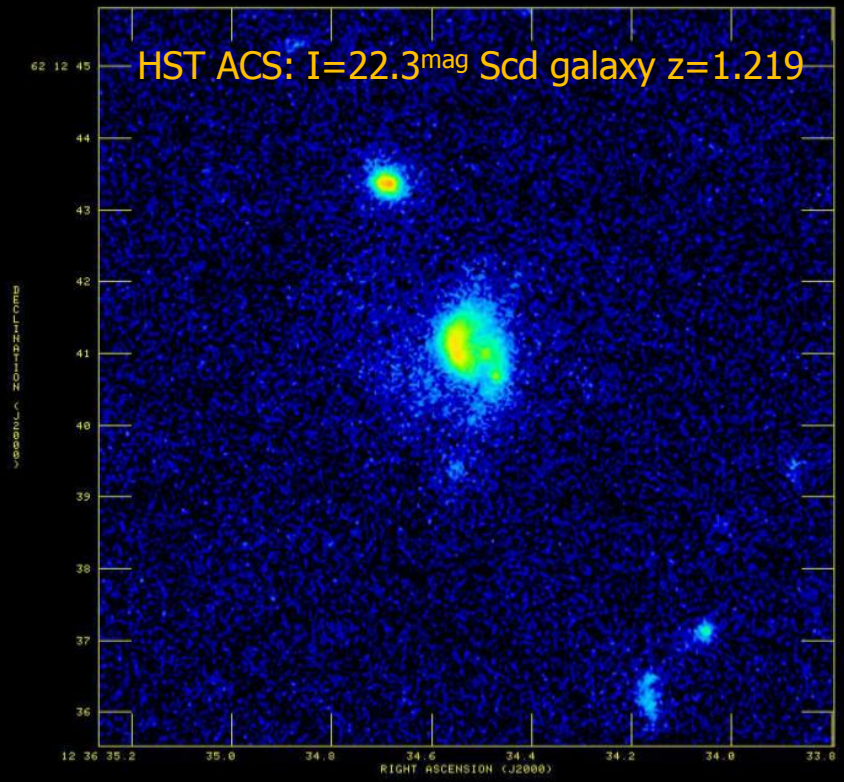


<100μJy population dominated by sfgs typically at z<1.5

Ultra-luminous Starburst

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





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

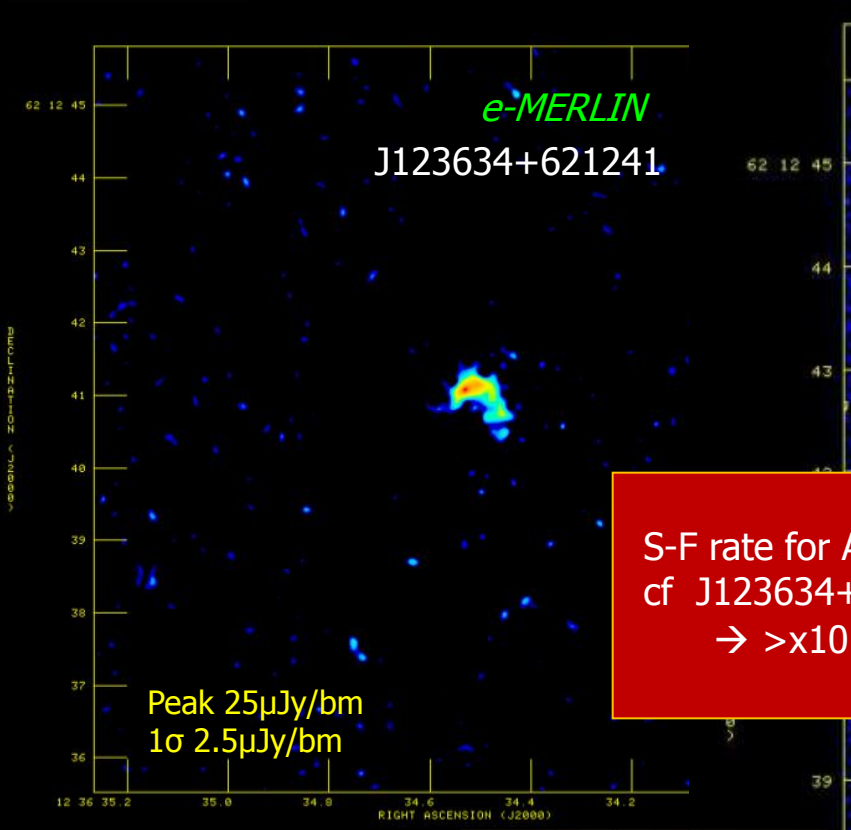
→ Star-formation rate ~960 $M_\odot$/yr

Merging Scd sub-mm galaxy with tidal tail

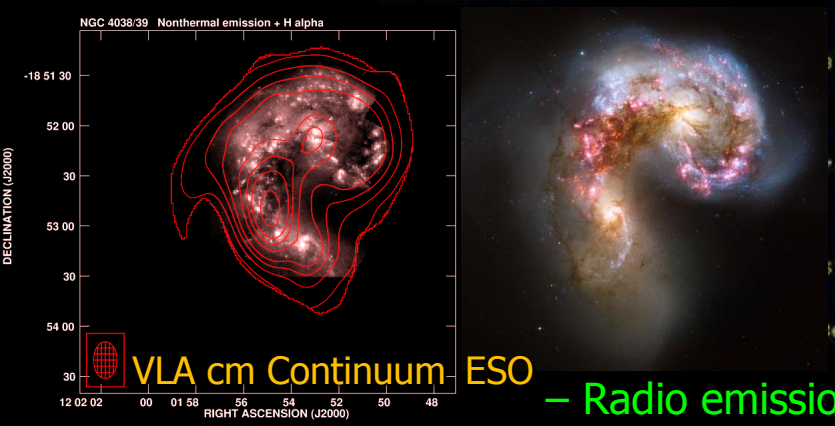
– Radio emission follows merger & extends towards tail (cf 'Antennae')

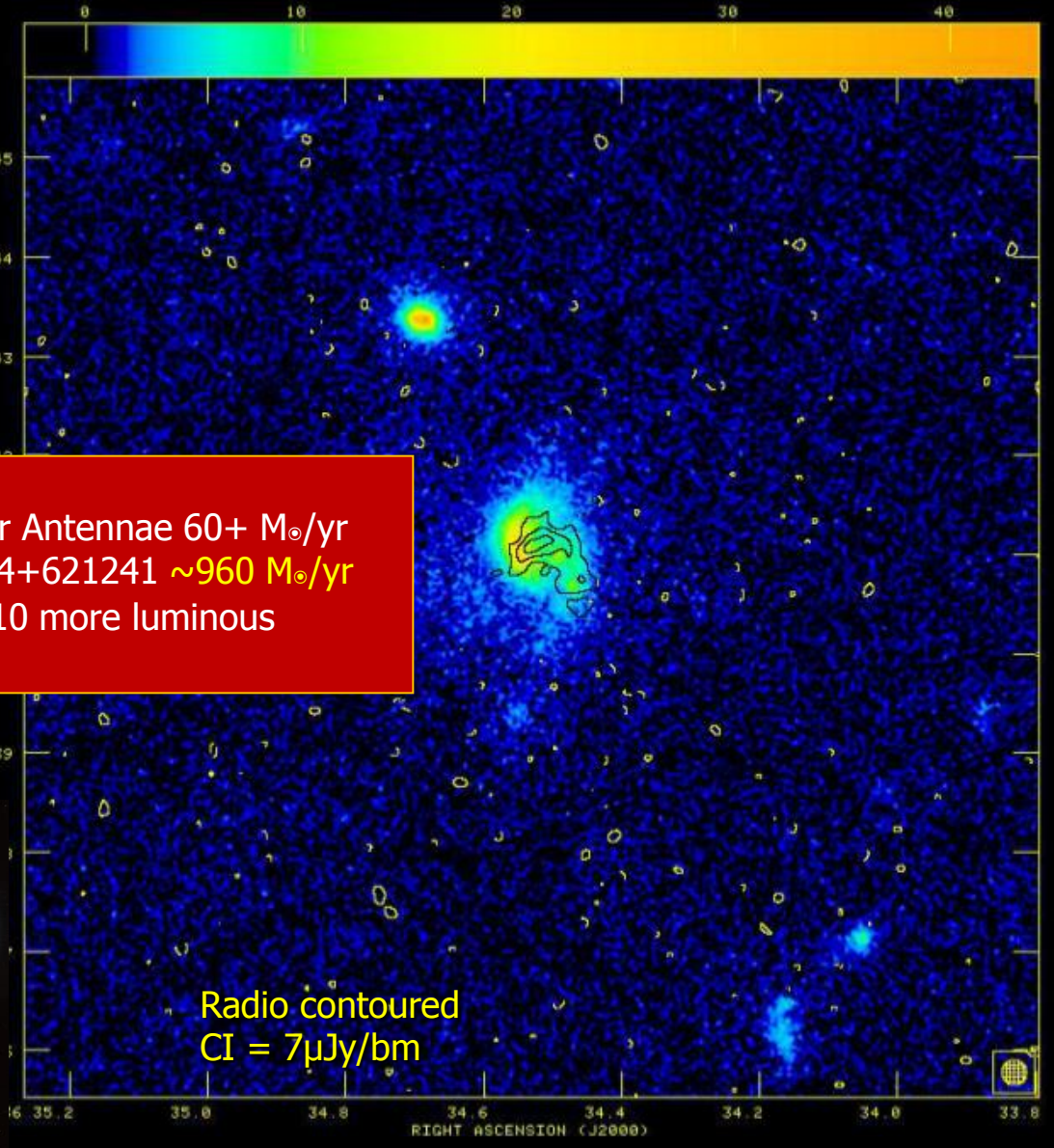
Ultra-luminous Starburst

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



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

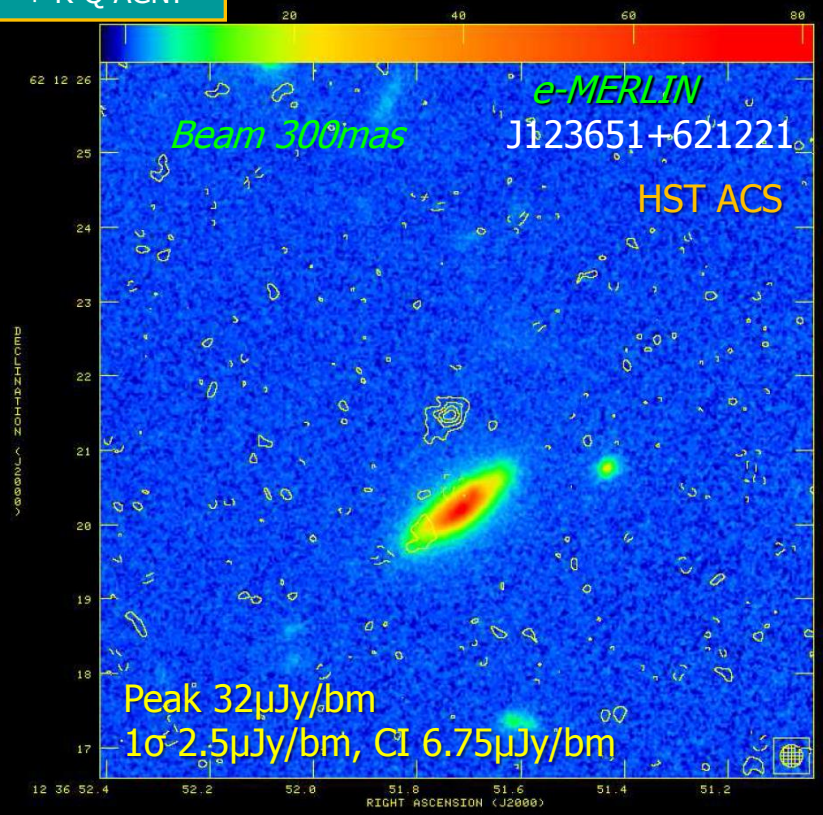


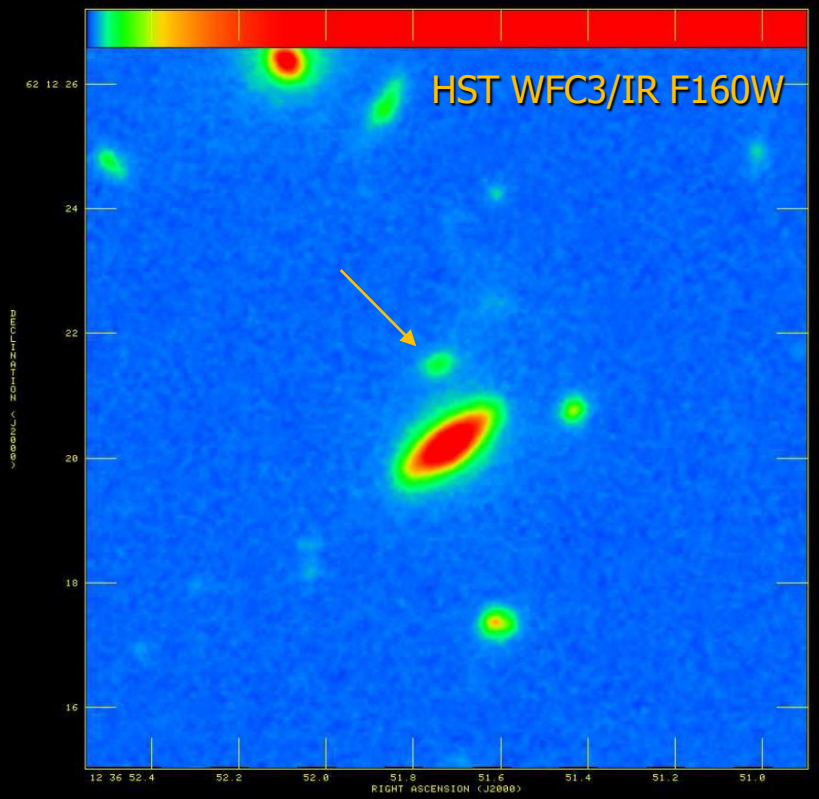


– Radio emission follows merger & extends towards tail (cf 'Antennae')

Sub-mm Starburst + R-Q AGN?

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



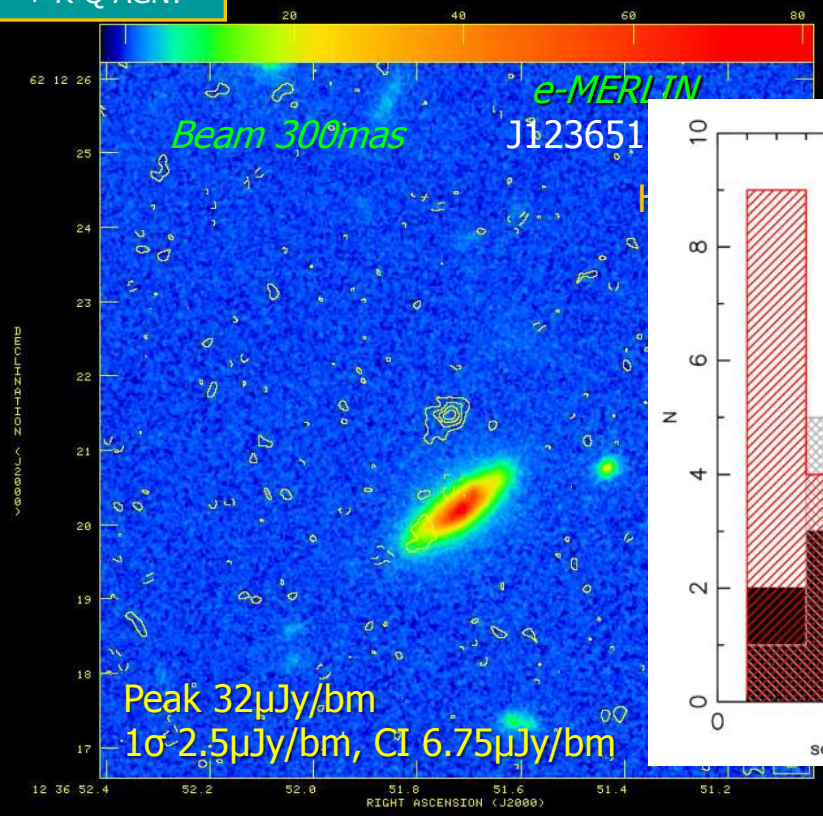


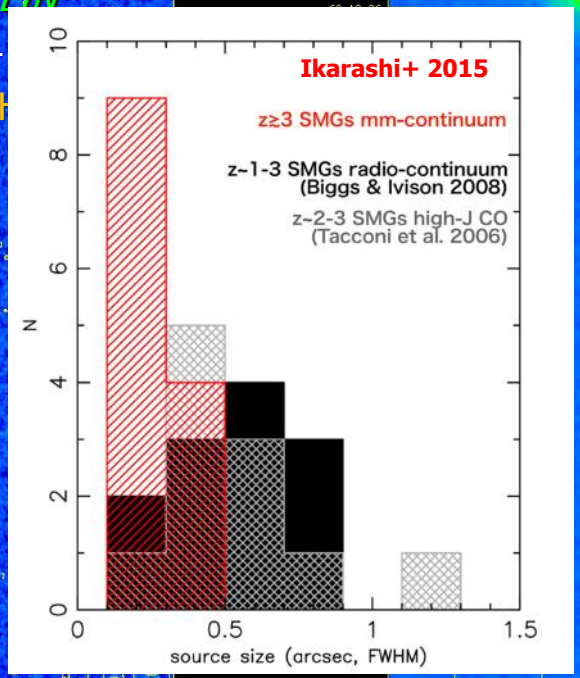
Extended (0.7″) steep spectrum (α>0.71) starburst ($S_{1.4}$ = 49μJy) – No compact emission (VLBI)
No detectable emission in visible bands. Faint very red object detected in F160W (1.6μm IR)

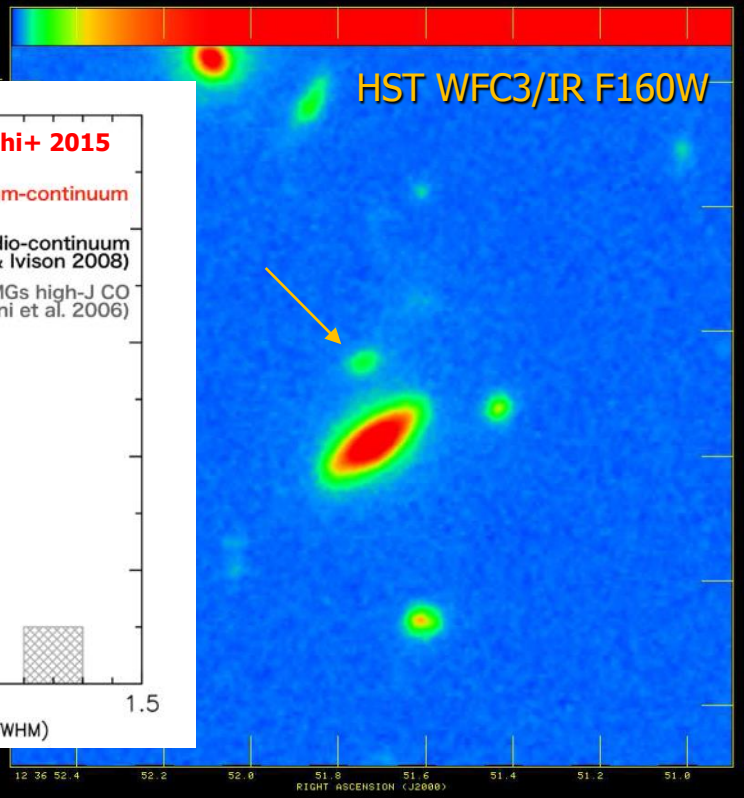
ISO detection → dust obscured starburst at z~3 1.3mm SMA detection → S-F rate ~2000 $M_\odot$/yr
Hard Chandra X-rays → obscured QSO at z=2.7 → Embedded R-Q AGN?

Sub-mm Starburst + R-Q AGN?

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







Central field contains 43 identified SMGs

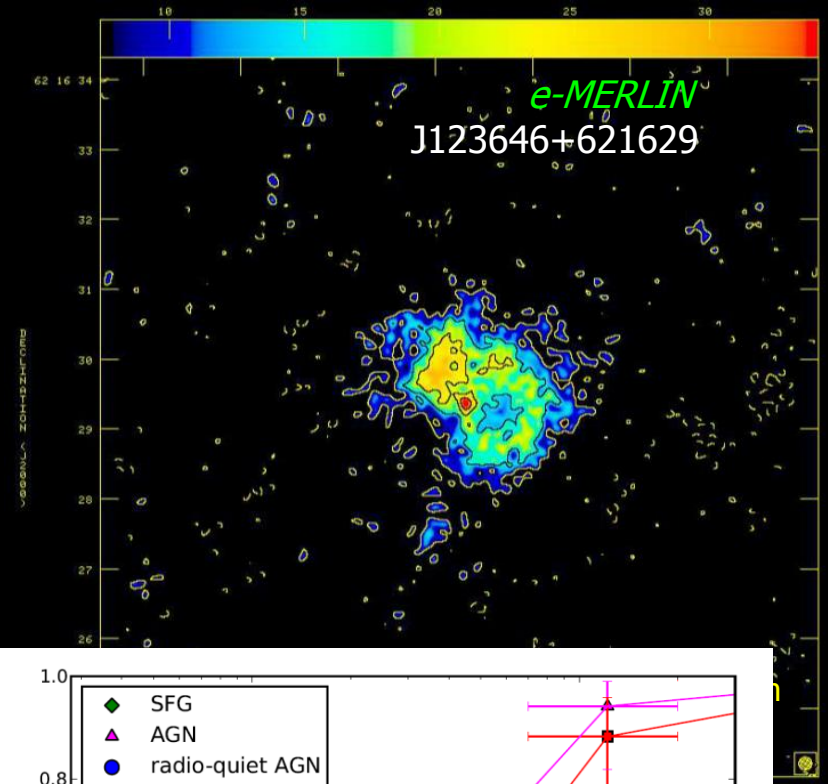
Median radio continuum LAS Lockman Hole z=1-3 sub-mm sources ~0.65" (Biggs & Ivison, 2008)

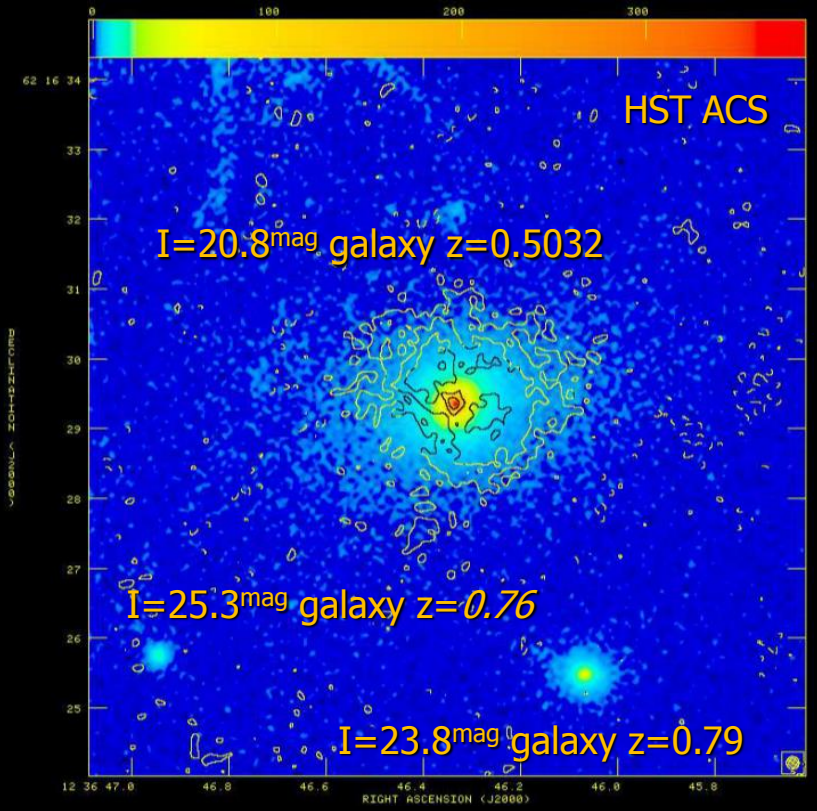
ALMA 1100μm dust continuum for z>3 SMGs are ~2x smaller (Ikarishi+ 2015)

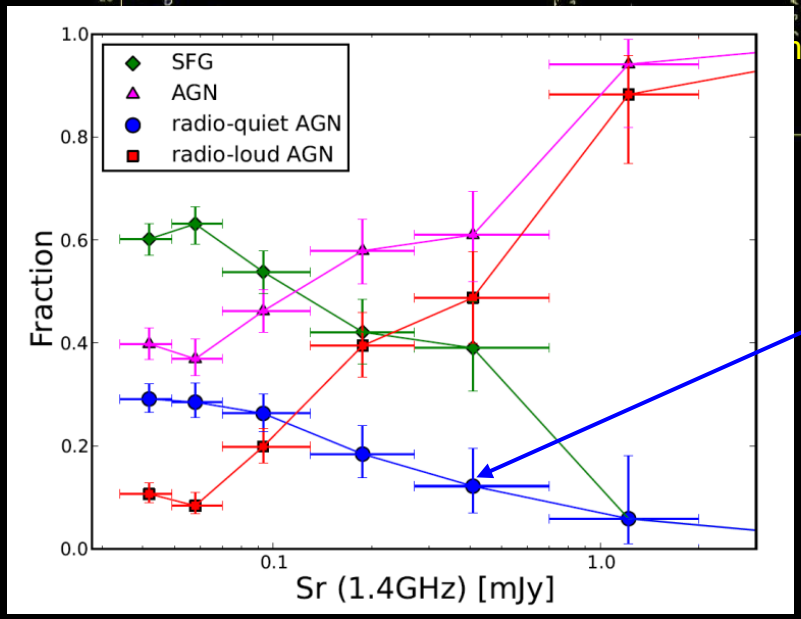
– Talk by Alasdair Thomson

Radio-Quiet AGN

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

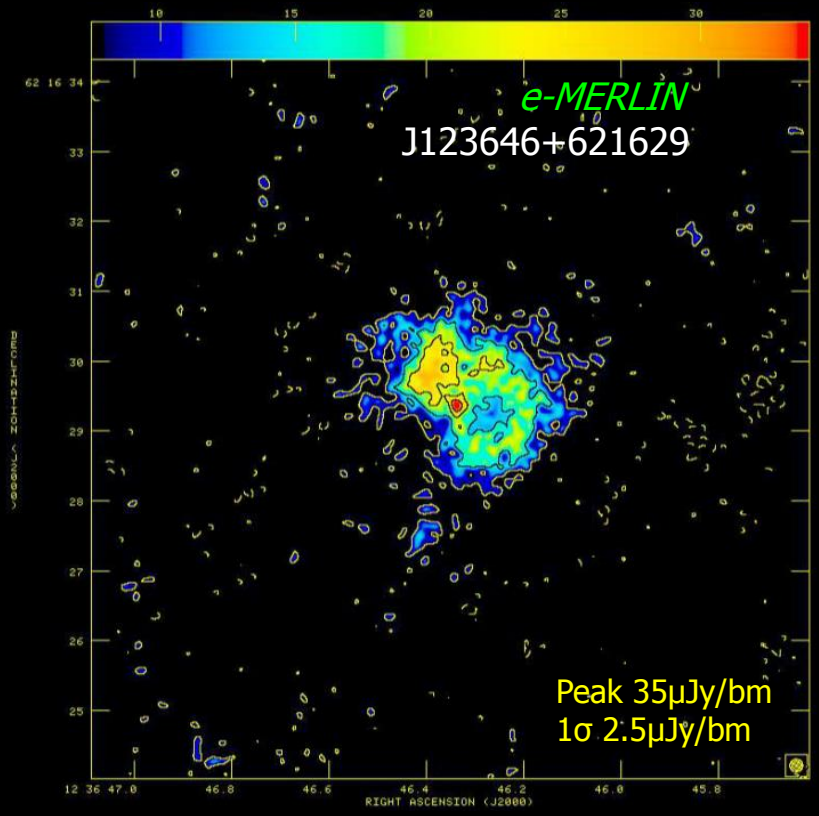


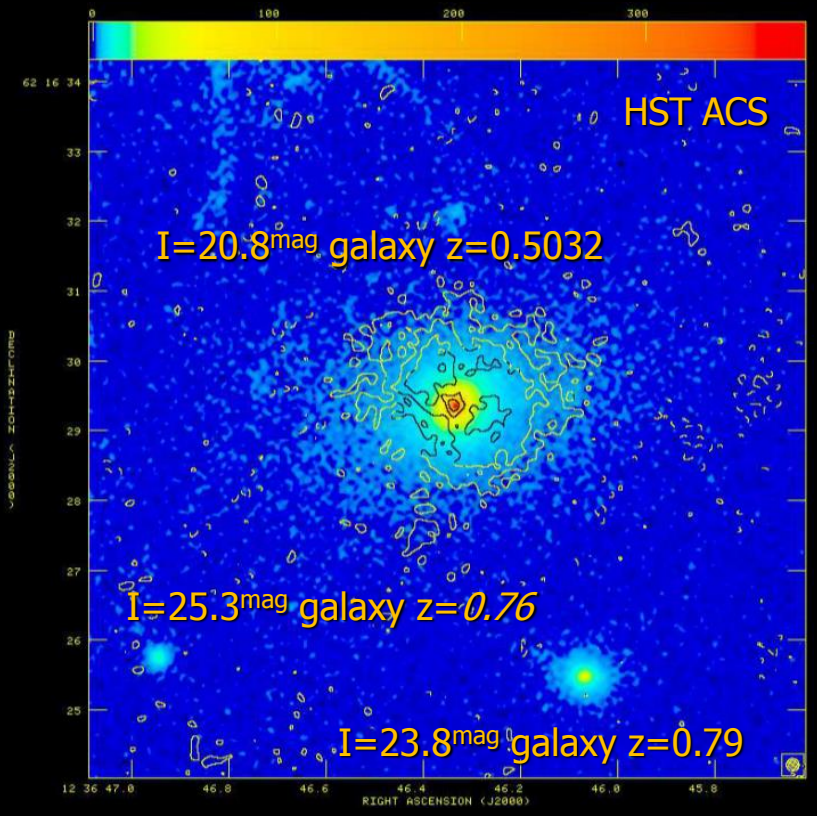


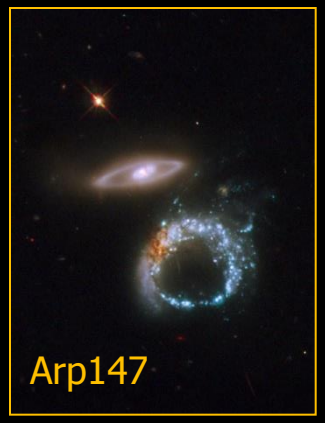


Radio-Quiet AGN

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







Extended steep-spectrum (α>1.62) starburst ($S_{1.4}$ = 393μJy).

→ Ring of star-formation – interacting galaxies? (e.g. Arp147)

Radio emission extends across face of massive spheroidal galaxy

→ Star-formation rate ~200 $M_\odot$/yr

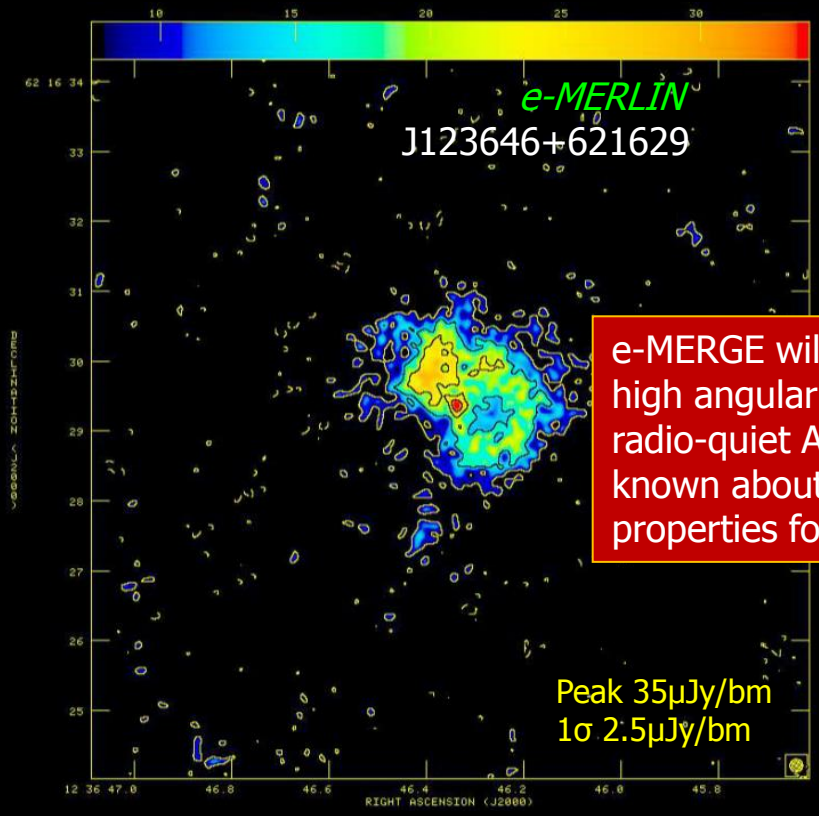
No evidence for galaxy interactions

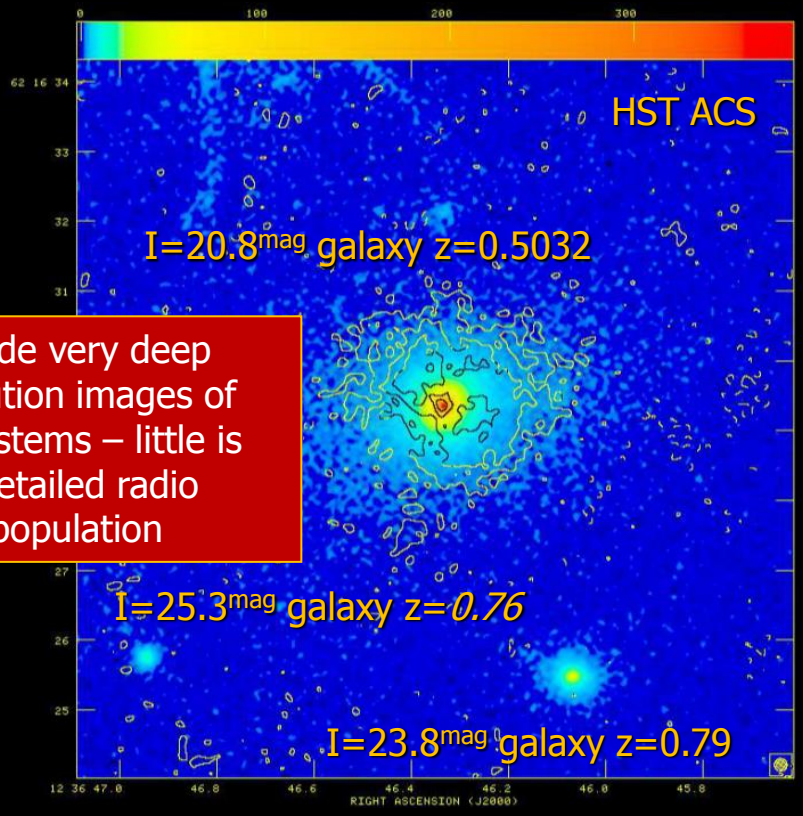
Bright galaxy core shows BL emission → Optical AGN activity

AGN or nuclear starburst? – C-Band/VLBI non-detection – NOT AGN

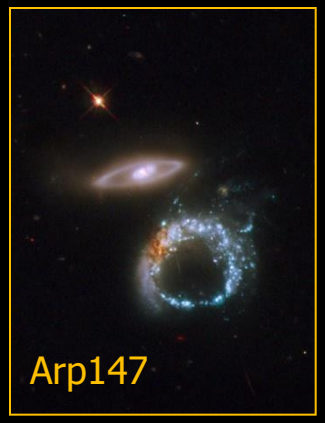
Radio-Quiet AGN

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





e-MERGE will provide very deep high angular resolution images of radio-quiet AGN systems – little is known about the detailed radio properties for this population



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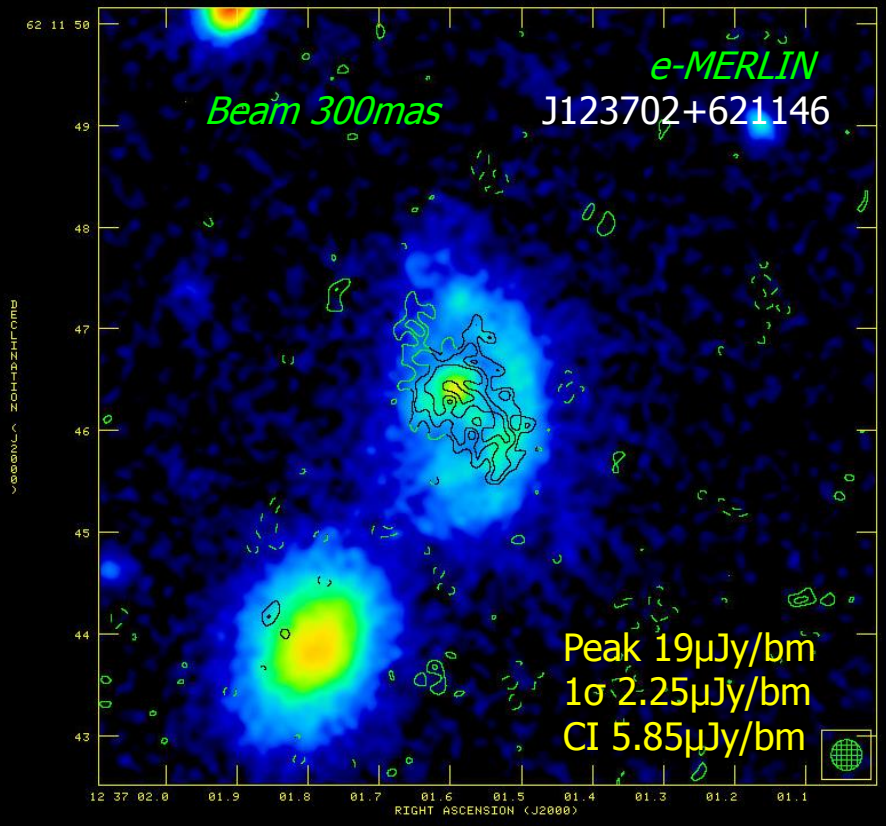
Sub-mm starburst

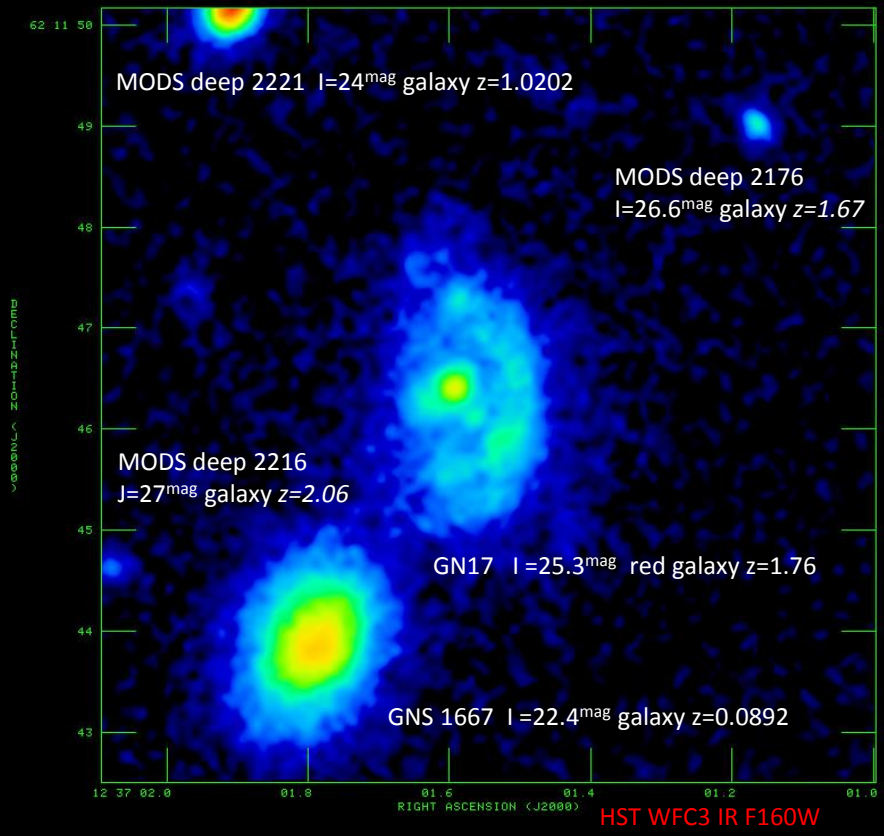
Tier 1: New Ultra-Deep Study of GOODS-N

Extended steep-spectrum (α=0.67) starburst (?) ($S_{1.4}$ = 130μJy). Sub-mm source GN17

Radio emission associated with I=25^{mag} disturbed galaxy at z=1.76 → S-F rate ~670 $M_\odot$/yr

Brightest radio emission aligned over optical nucleus. LAS ~2″





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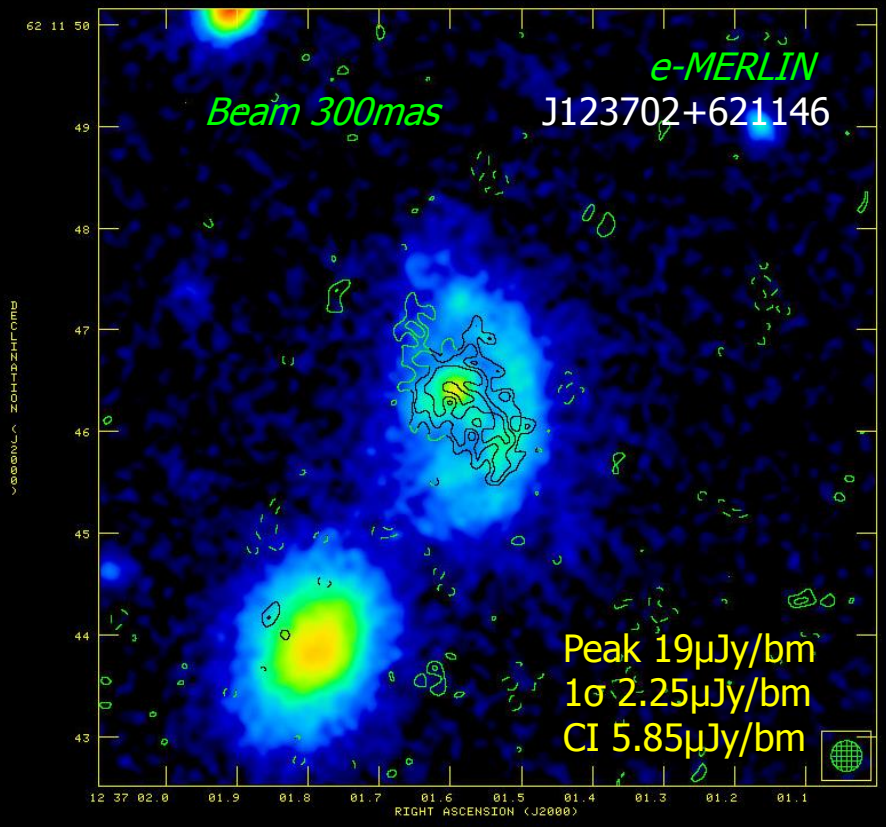
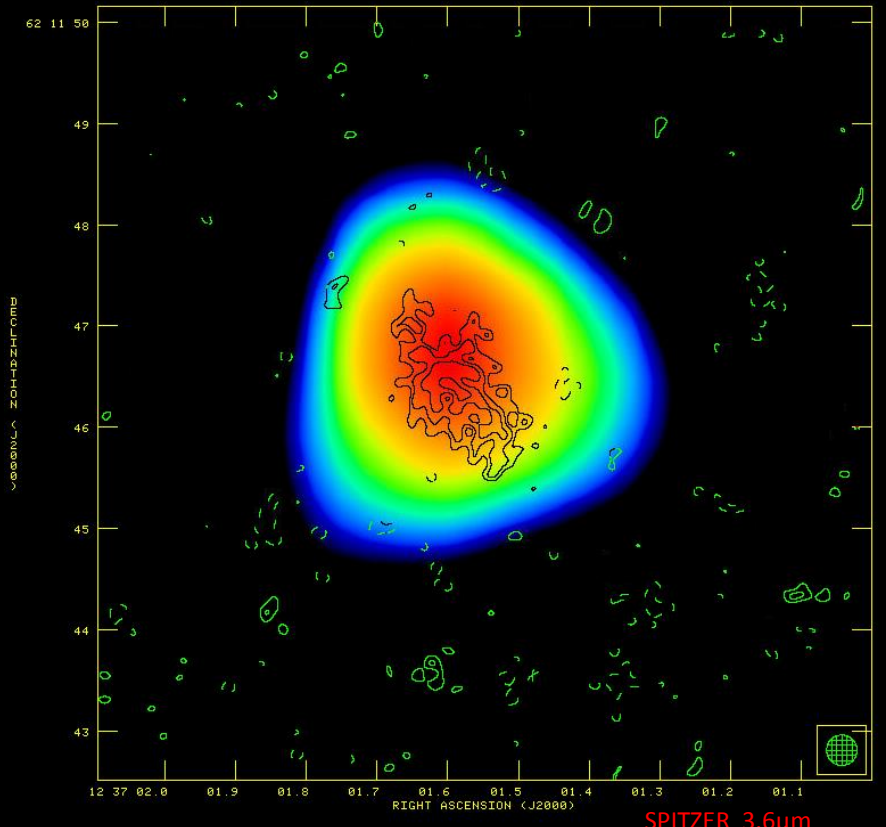
Strong Spitzer 3.6μm detection → Luminous starburst





SPITZER 3.6μm

Sub-mm starburst

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Brightest radio emission aligned over optical nucleus. LAS ~2" - large for a z=1.76 SMM source!

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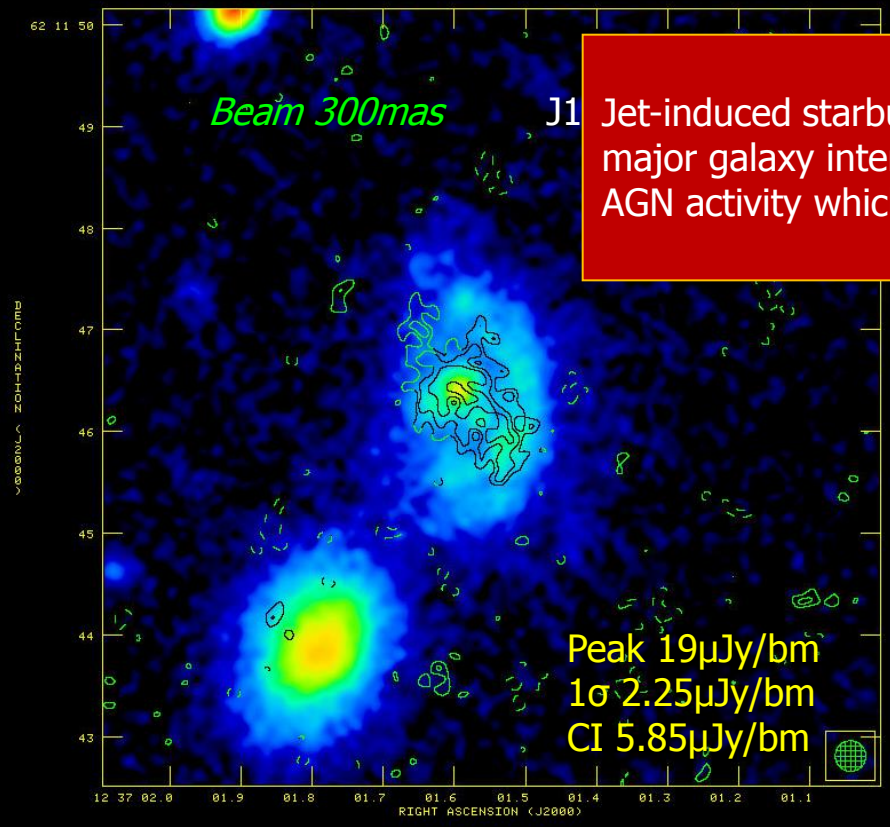
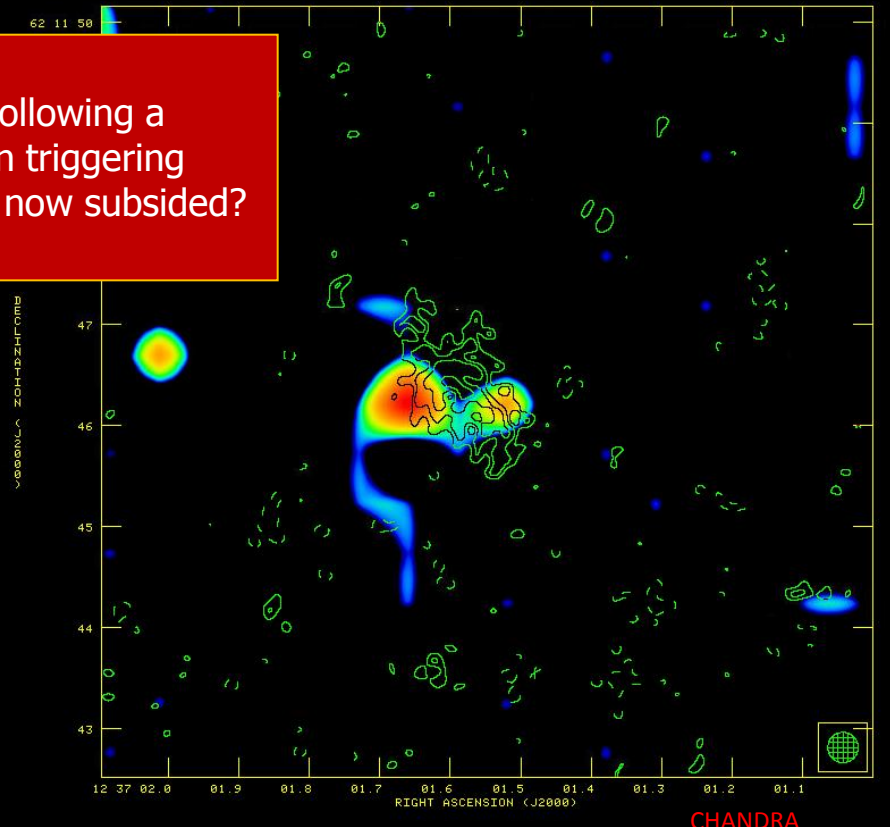
Chandra X-ray consistent with star-formation – but radio emission looks like jet triggering….

Laird et al (2010)

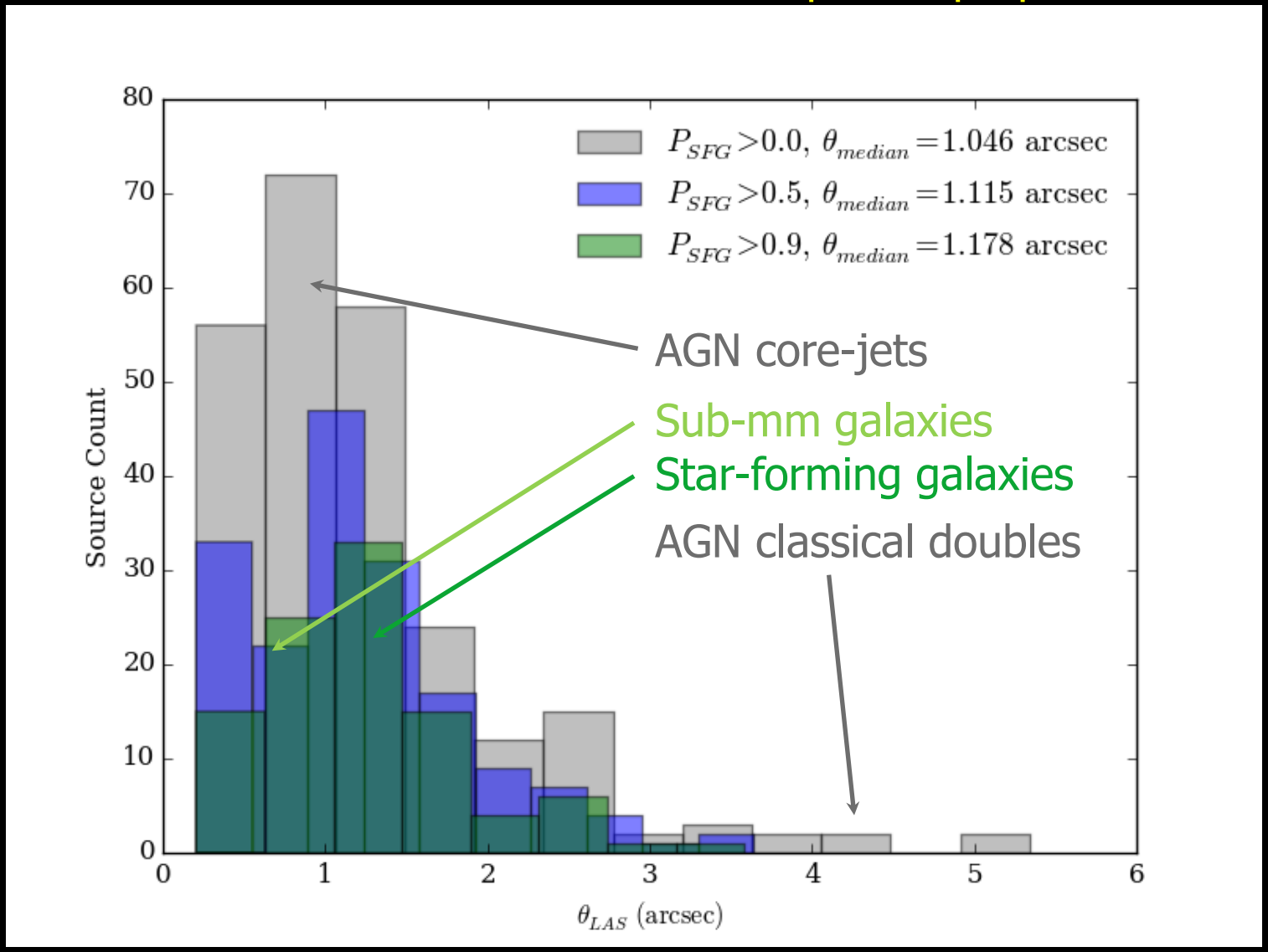


Jet-induced starburst following a major galaxy interaction triggering AGN activity which has now subsided?



Results for 248 detected sources within central 12’ field from ~90 hrs of data

Assign probabilities of emission being due to AGN or star-formation from measured radio structures and spectral properties…



Machine-learning (SVM – Support Vector Machine) Wrigley et al – in prep.

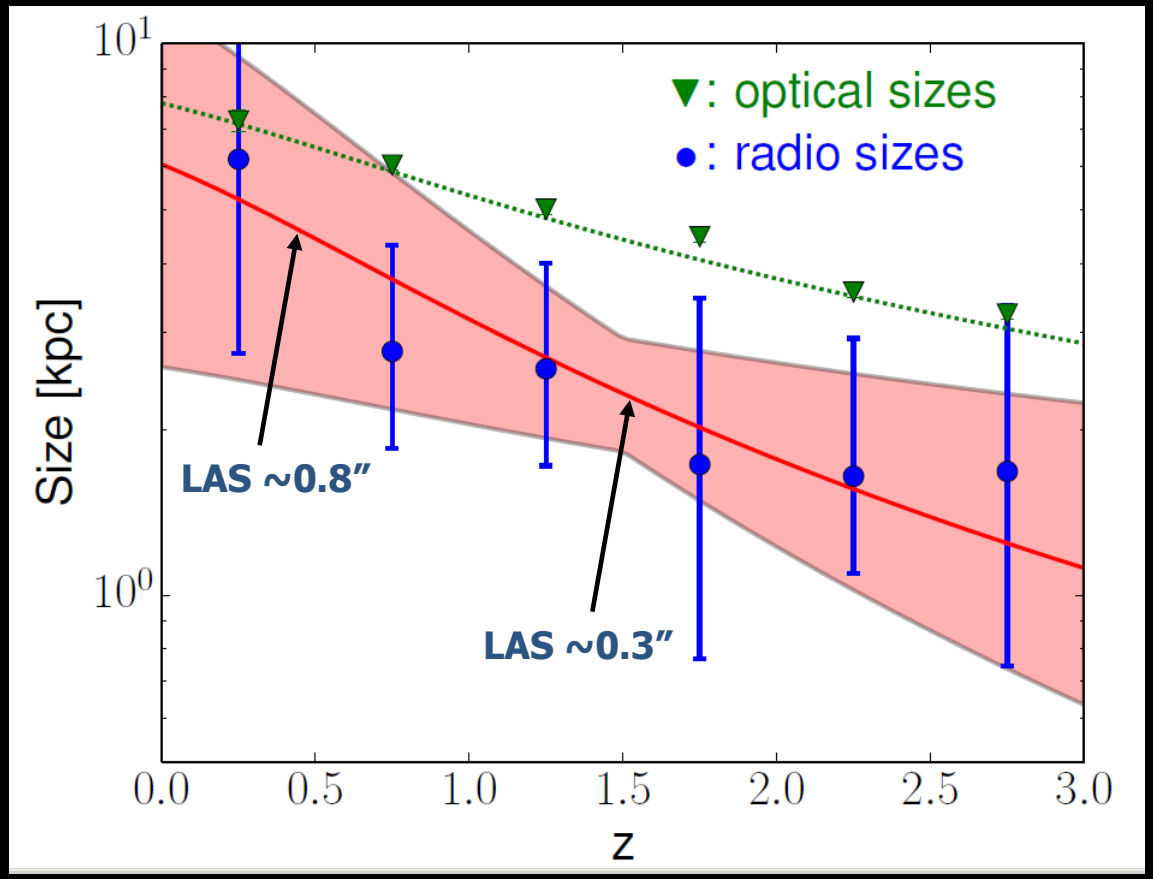
Size evolution of S-F galaxies in radio and optical

Lindroos et al (in prep)

Sized from uv-stacking for ~1000 S-F galaxies with masses 10^{10} – 10^{11} $M_\odot$ in central 12' field using archival MERLIN+VLA data from Muxlow+ 2005.

Sizes derived from model fitting to binned uv data

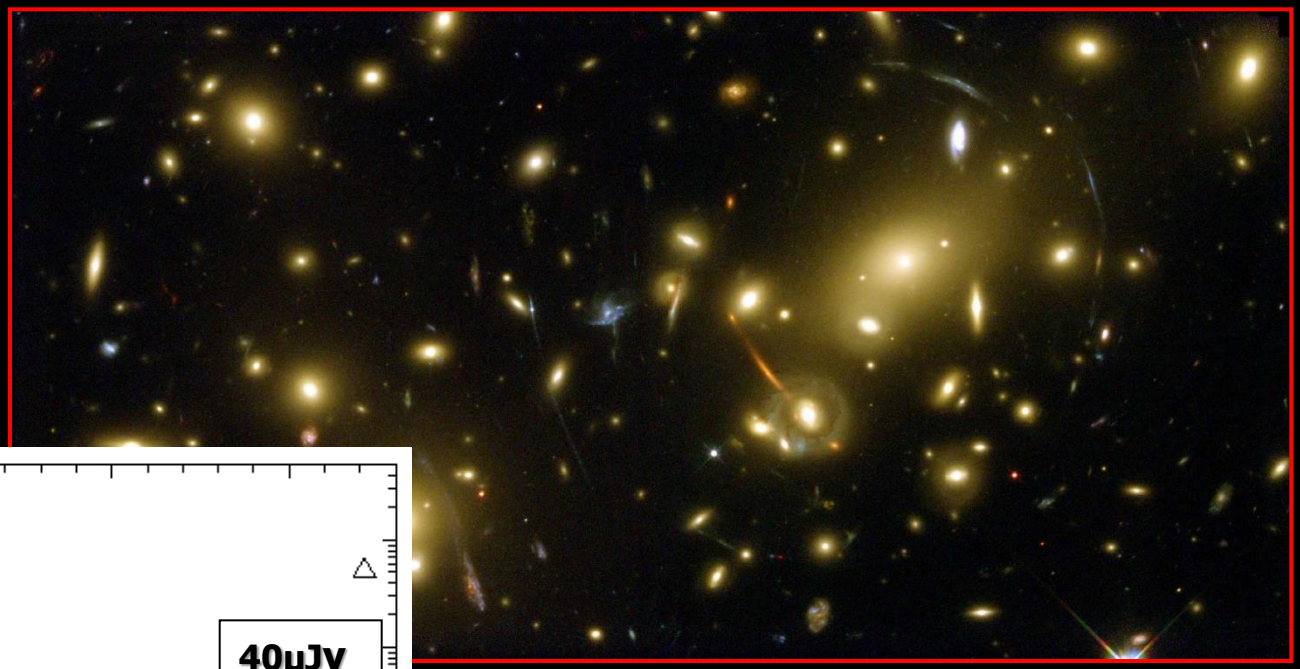
Red area indicates 1σ uncertainties in the fitted model

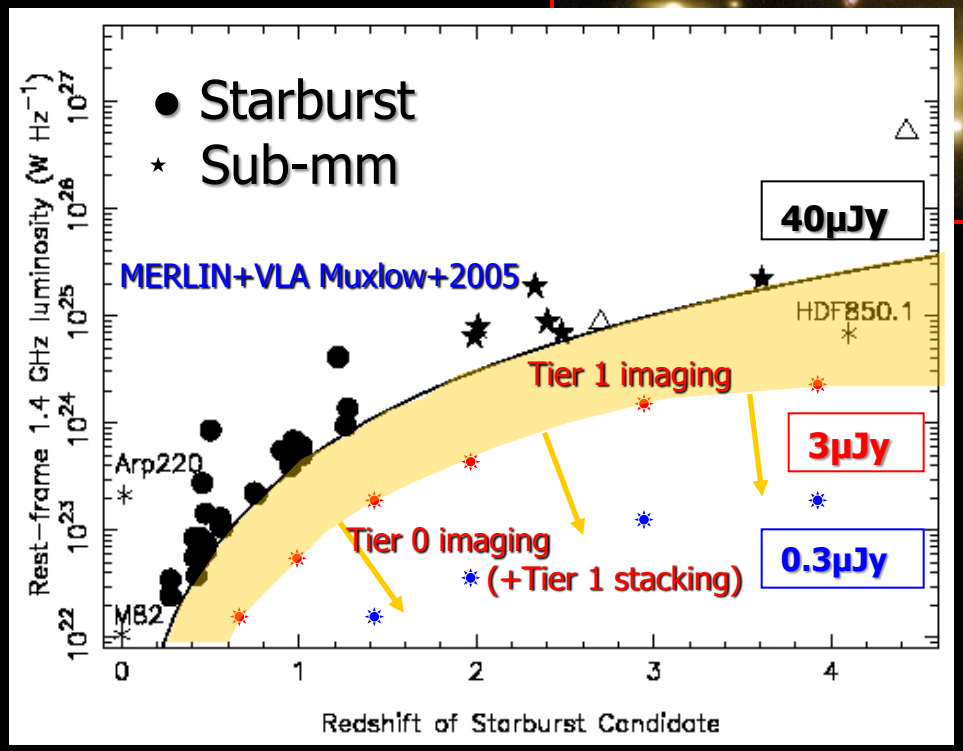


Sizes measured for star-forming galaxies at a stellar mass of $5 \times 10^{10} M_\odot$

Tier 0: Imaging sub-μJy galaxies

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





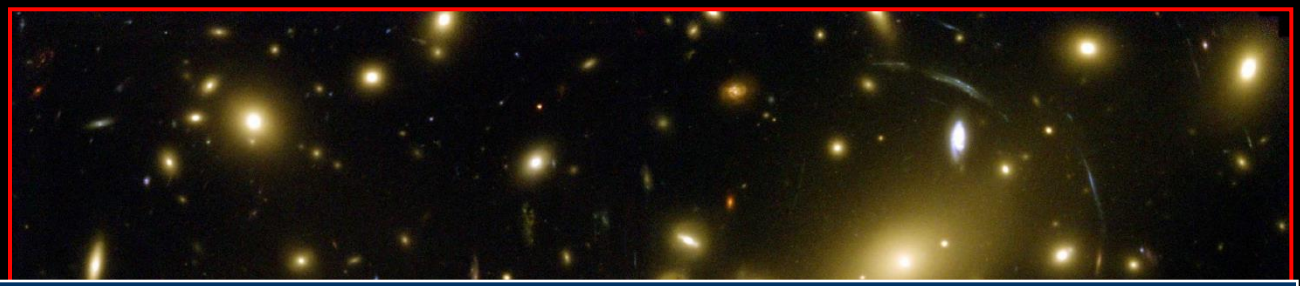
Expect ~50 amplified sources with intrinsic fluxes as faint as 300nJy

Measure faint radio counts

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

Tier 0: Imaging sub-μJy galaxies

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



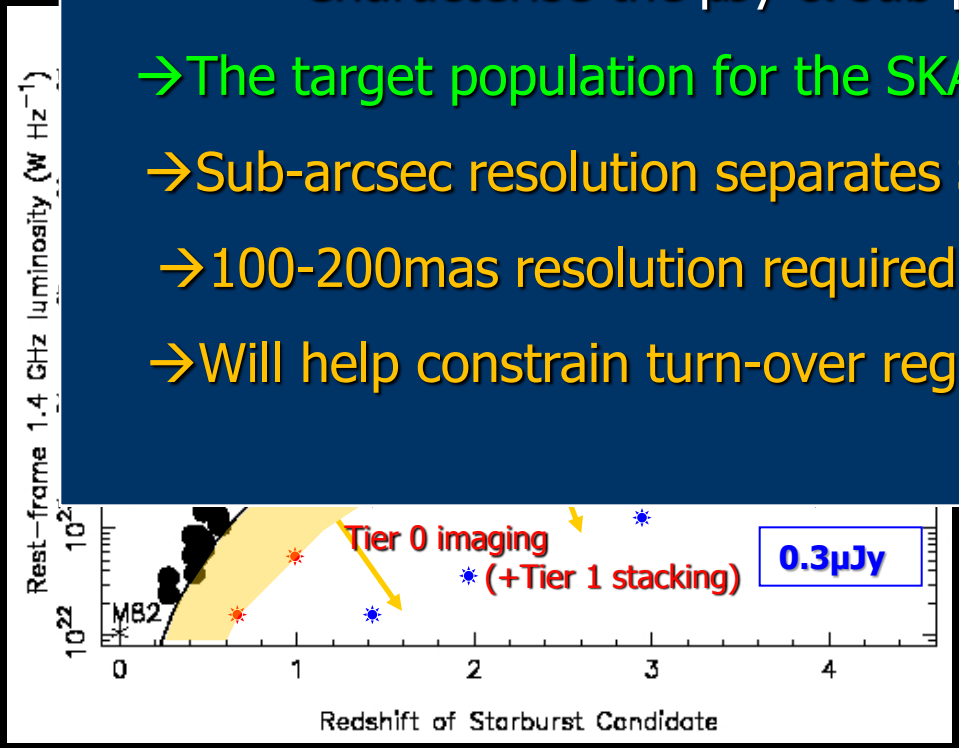
Characterise the μJy & sub-μJy radio source population

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

→Sub-arcsec resolution separates SF and AGN

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

→Will help constrain turn-over region in Madau plot in z=2 - 5 region



Measure faint radio counts

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