

Extragalactic Science with ALMA

First results from Cycle 0 Early Science and from Science Verification



North American ALMA Science Center

Carol Lonsdale

Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Large Baseline Array



Science Verification Data ALMA

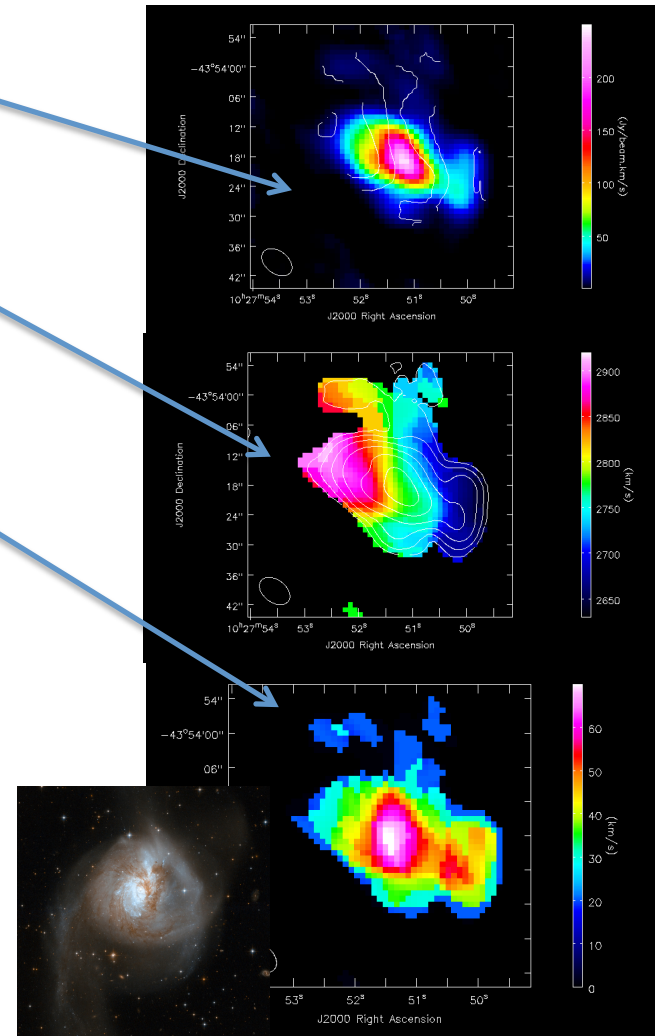
- ALMA data released for:

NGC 3256* BAND 3, CO (1-0) MAP,
DISPERSION, VELOCITY FIELD

M100

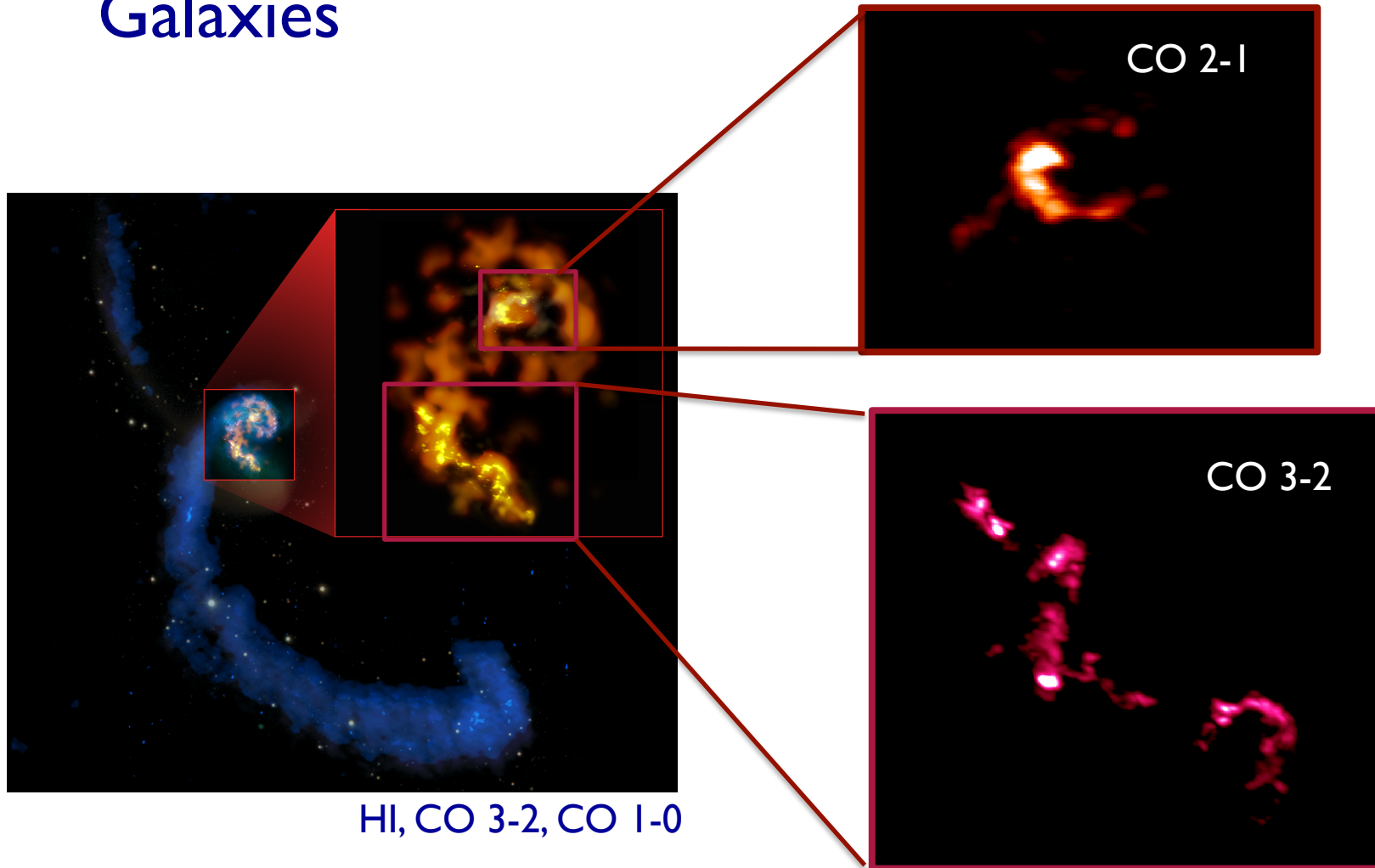
THE ANTENNAE GALAXIES*

- download from ALMA Science Portal
<http://almascience.org/>
- Calibrated & uncalibrated data, images.
 - * - CASA guide available at
<http://casaguides.nrao.edu>



ALMA Images Nearby Galaxies

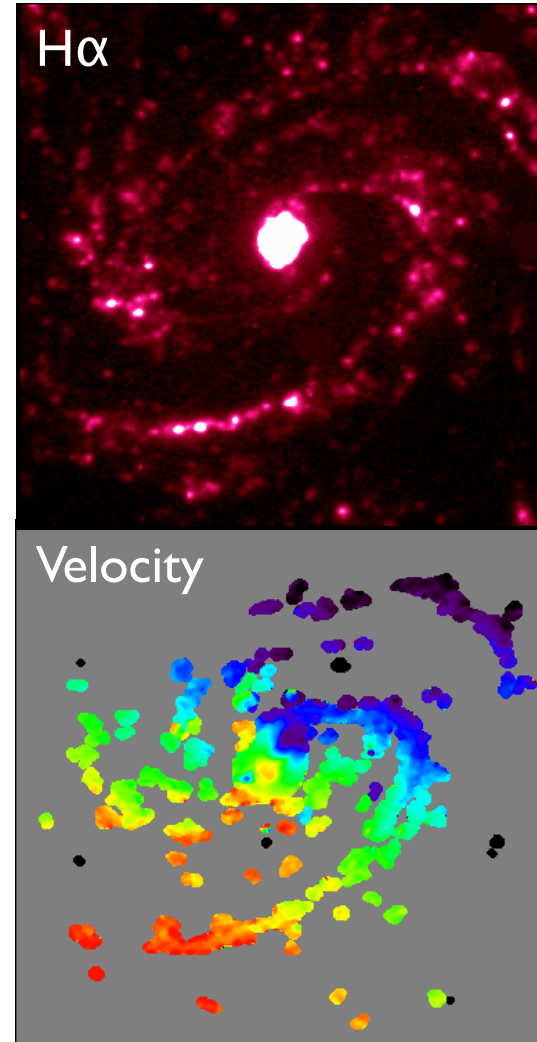
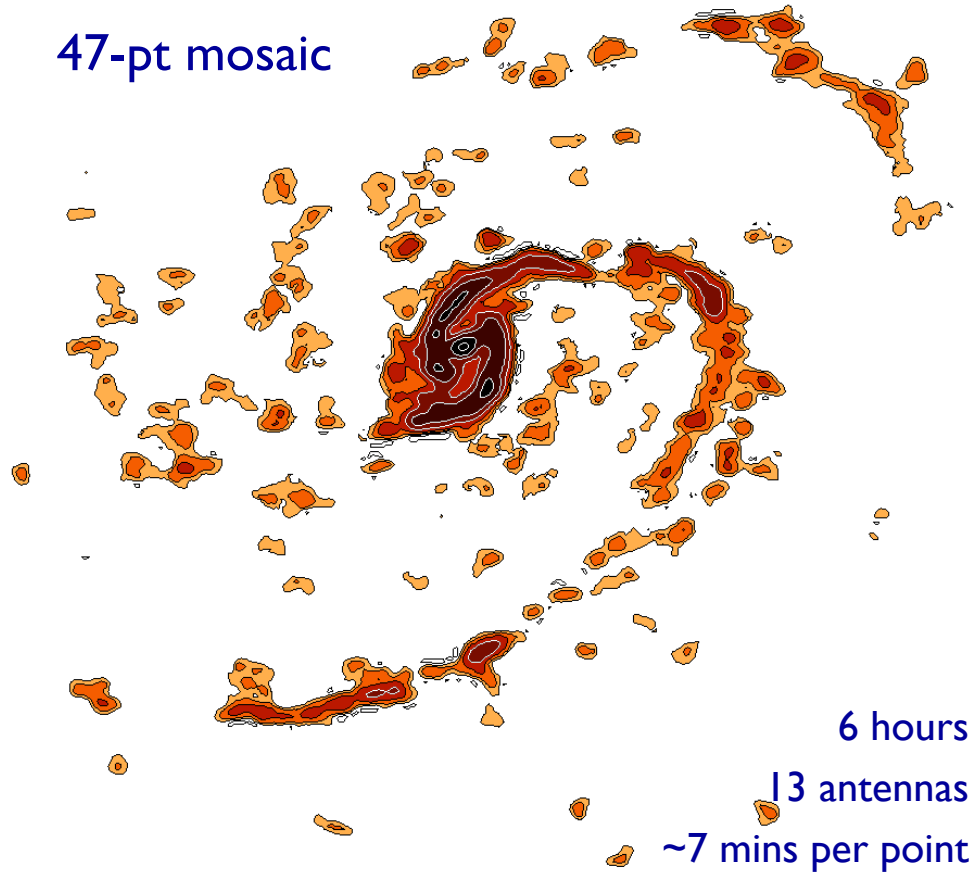
- Science verification imaging of the Antennae Galaxies



ALMA Images Nearby Galaxies

- Science verification imaging of M100

CO I-0
47-pt mosaic



ALMA Cycle 0 Underway

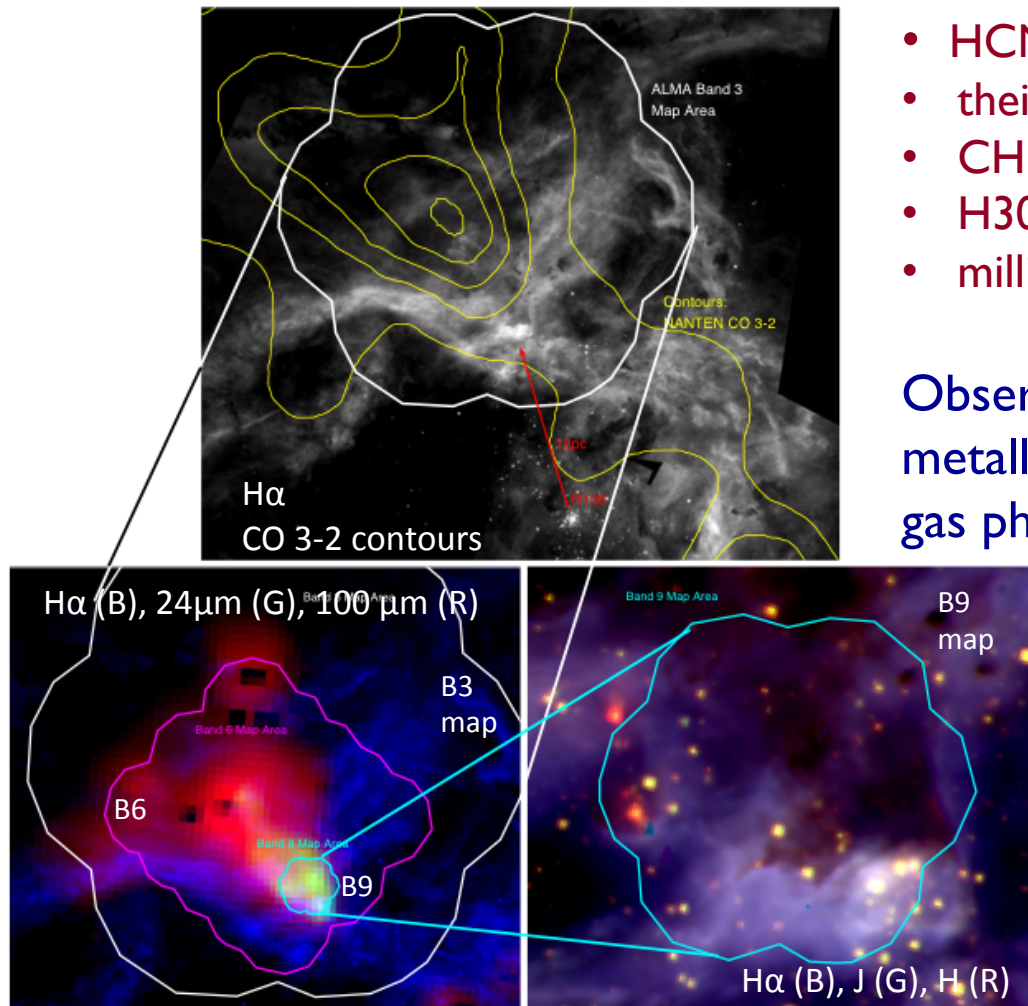
- Observations of fine structure lines at high redshift.
RESOLVE AND DETECT [CII] OUT TO $z > 6$, CONTRAST WITH [NII], REACH 300 PC RESOLUTION
- Detailed physical conditions at high resolution in local galaxies.
 - Starbursts & Mergers: ARP 220, ANTENNAE, II ZW 96, NGC 253, NGC 6240, NGC 1068
 - Galactic Nuclei: CEN A, NGC 1266, SOMBRERO, NGC 1433 & 1566, NGC 1097
 - Brightest Cluster Galaxies
 - Dwarfs and Normal Spirals: M83, SBS 0335-052
 - Our Closest Neighbors: Super star cluster 30 DOR
- Measuring the gas in normal galaxies at intermediate redshift.
- Exploring new populations.
SPT SOURCES, WISE QSOs, BLIND SURVEY BEHIND A LENSED CLUSTER, LOCALIZING SMGs

Indebetouw et al.: The Subparsec Scale Environment of the Super Star Cluster 30 Doradus

Matched 1-2'' tiered Band 3, 6, & 9 imaging:

- HCN, HCO+, and CS
- their isotopologues
- CH₃OH
- H30 α and H40 α recombination lines
- millimeter continuum

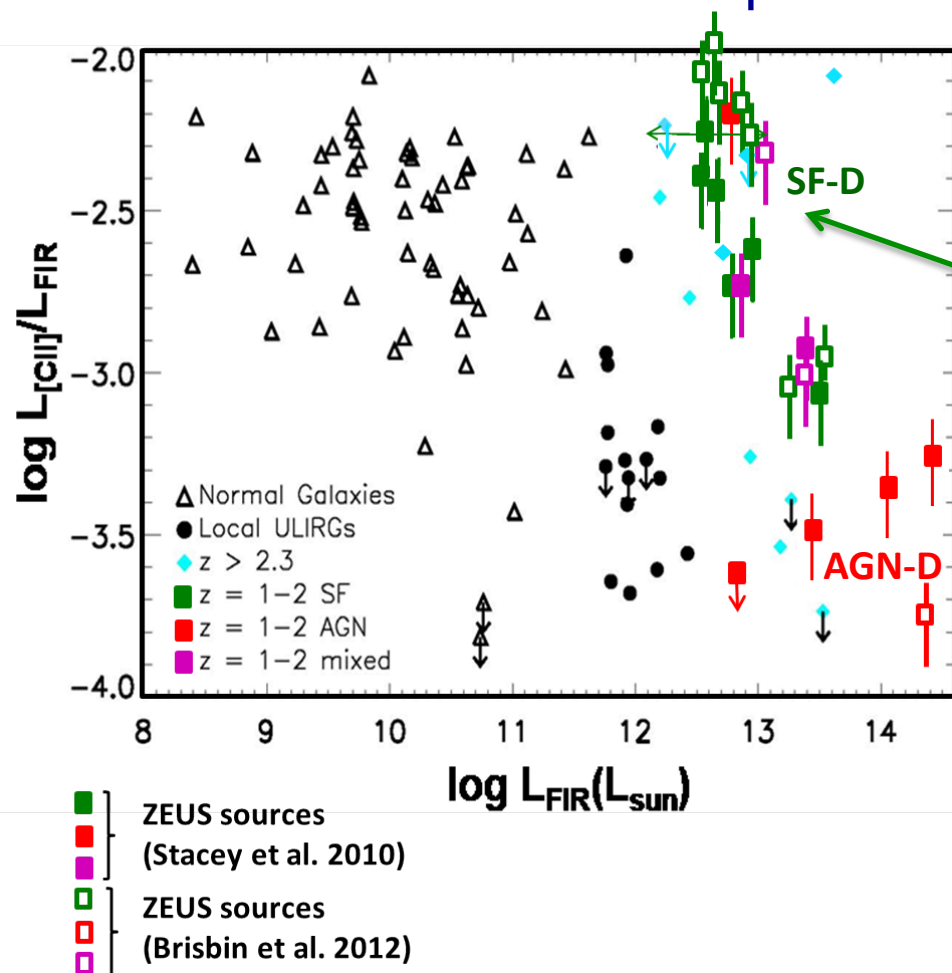
Observing sub-parsec scale clumps in low metallicity starburst PDR, tracing different gas phases



G.J Stacey, S. Hailey-Dunsheath et al.

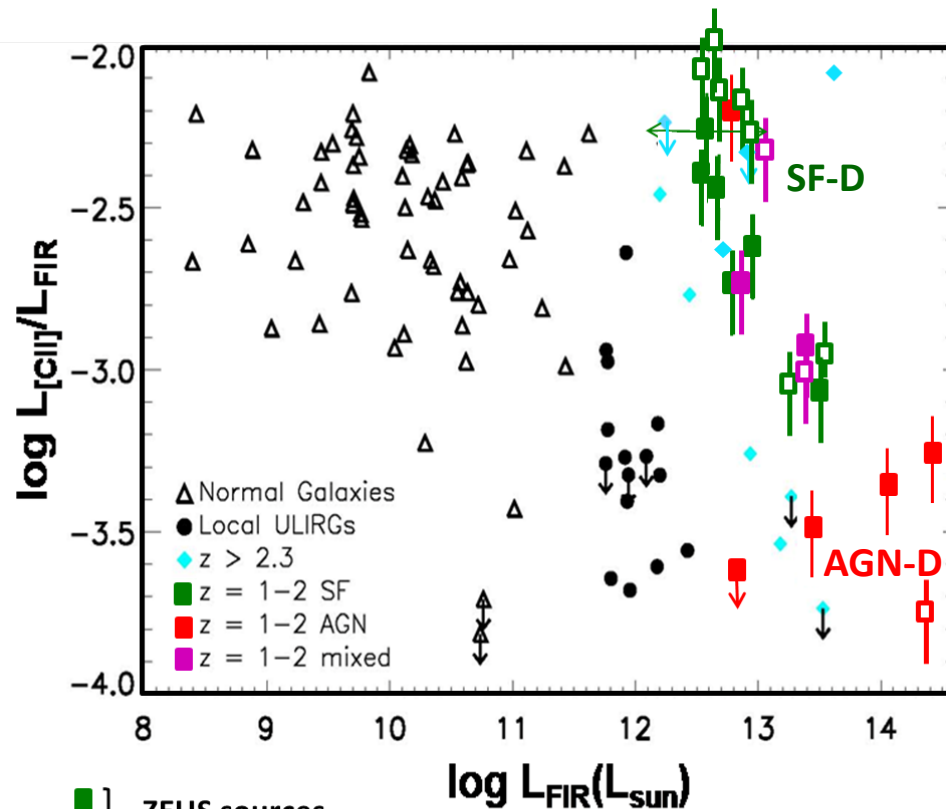
ALMA Imaging of the Star Formation Process at the Historic Peak

Builds on ZEUS-CSO study of 23 galaxies in 158 μ m [CII] line at $z \sim 1-2$
 – the historic peak of star formation activity



- [CII]/far-IR luminosity ratio, R traces strength of far-UV fields, G_0
- Large R for star formation dominated (SF-D) systems
 - Far-UV fields and molecular cloud densities like local starbursts (e.g. M82) **BUT kpc in size**
 - **Unlike** the collision-induced, confined and very intense **local ULIRG starbursts**
 - Likely reflects the enormous gas reservoirs at this epoch – and **continuous-mode star formation**

G.J Stacey, S. Hailey-Dunsheath et al. ALMA Imaging of the Star Formation Process at Historic Peak



- G_0 is $8 \times$ larger in AGN-D
 - Collision-induced ULIRG-like starbursts *on much larger scales*, or
 - younger starbursts than SB-D systems

- ZEUS sources (Stacey et al. 2010)
- ZEUS sources (Brisbin et al. 2012)

ALMA Imaging of the Star Formation Process at the Historic Peak

ALMA Science Goals

Image [CII] and far-IR in 3 representative sources:

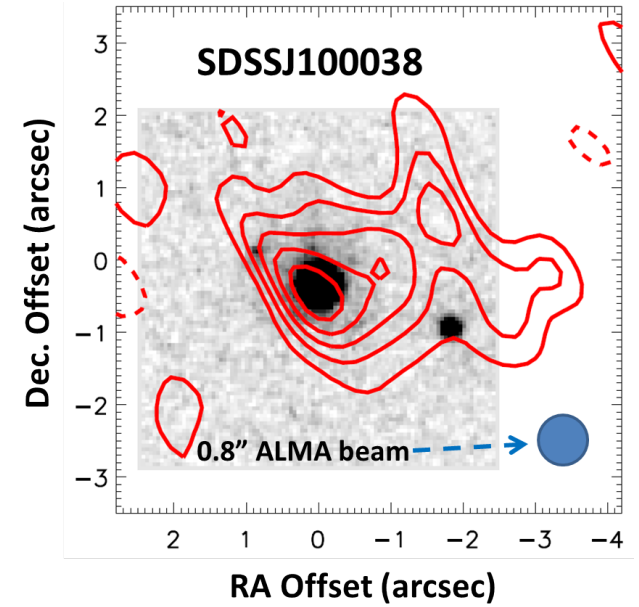
PKS 0215 (AGN-D), SDSS J100038 (SF-D), RX J094144 (mixed)

Traces the far-UV field strength and star formation activity across these galaxies:

- relative importance of collision-induced over continuous-mode star formation
- AGN/starburst link at $z \sim 2$ – the epoch of peak star formation activity in the Universe.

Expectation are:

1. Similar distributions to CO(4-3) for SDSS J100038
2. Extended emission plus a nuclear spike? ([CII] and/or far-IR) for RX J094145
3. Strong nuclear (AGN/XDR associated) emission in both [CII] and the far-IR from the Blazar PKS 0215



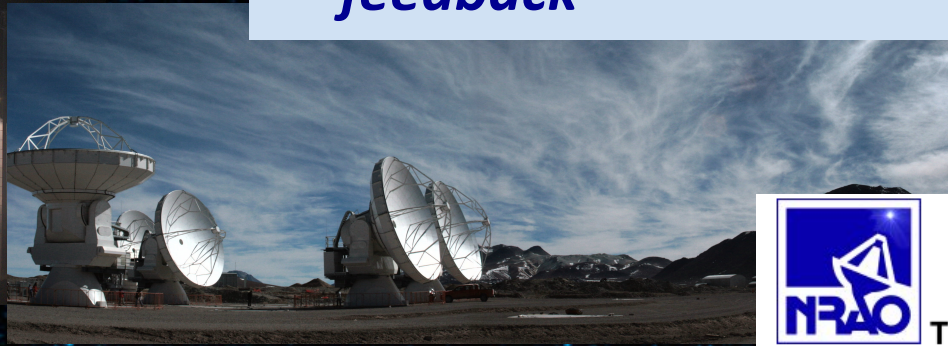
PdBI CO(4-3) overlaid on HST I-band image (Hailey-Dunsheath et al. in prep.)

Lonsdale et al: The most luminous obscured quasars in the universe: the role of radio feedback

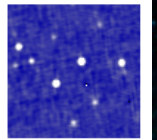
Carol J Lonsdale, NRAO
Amy Kimball, NRAO
Jim Condon, NRAO
Minjin Kim, Korea
Mark Lacy, NRAO
Tom Jarrett, IPAC
Andrew Blain, U. Leicester
Dominic Benford, Goddard
Frank Masci, IPAC
Dan Stern, JPL
Chao-Wei Tsai, IPAC

49 obscured quasars

1. Bright at $22\mu\text{m}$ and very red MIR-optical colors from **WISE**
2. Radio-intermediate, compact, from **NVSS**: AGN is present
3. **ALMA**: measure **starburst**/AGN flux ratio to find sources in early stages of turning off star formation via **radio-mode feedback**



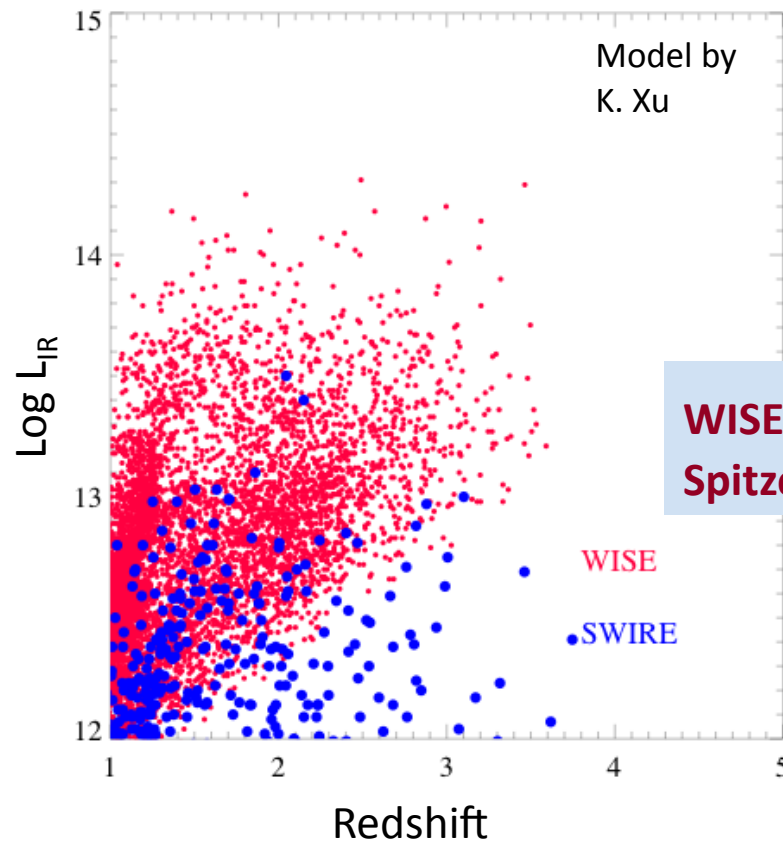
The NRAO VLA Sky Survey



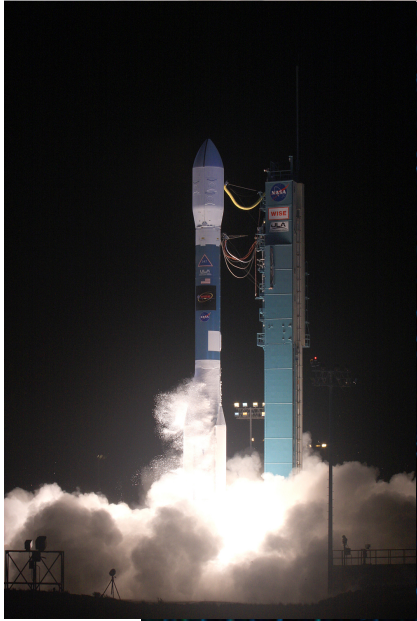
WISE Excels at Discovering Obscured QSOs

WISE finds the most luminous ULIRGs and obscured QSOs to $z > 3$

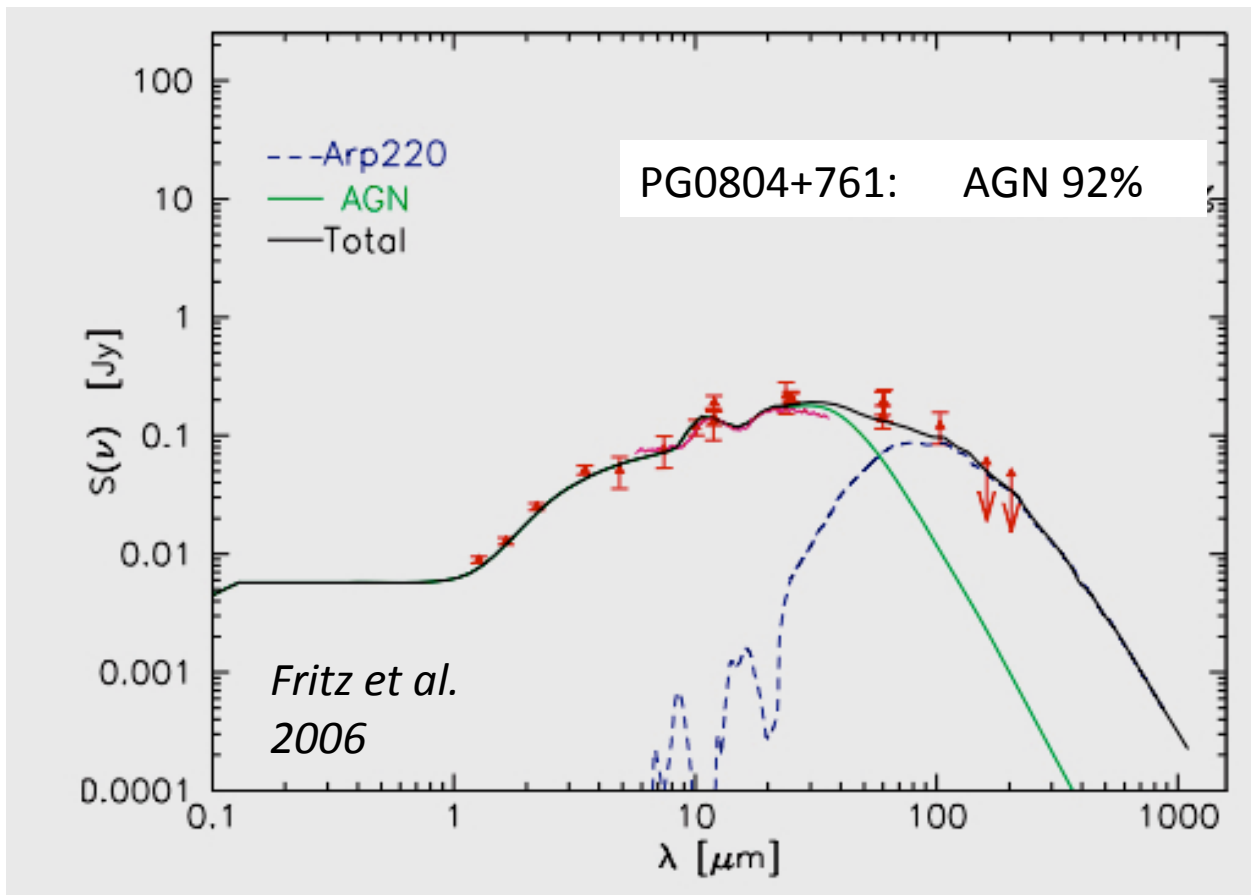
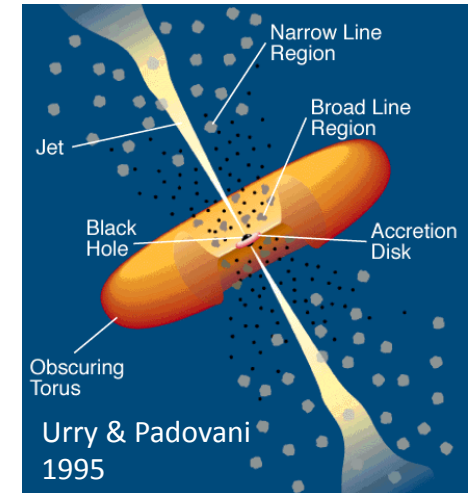
NGC 253



WISE: all sky
Spitzer surveys: $\sim 0.2\%$ of the sky



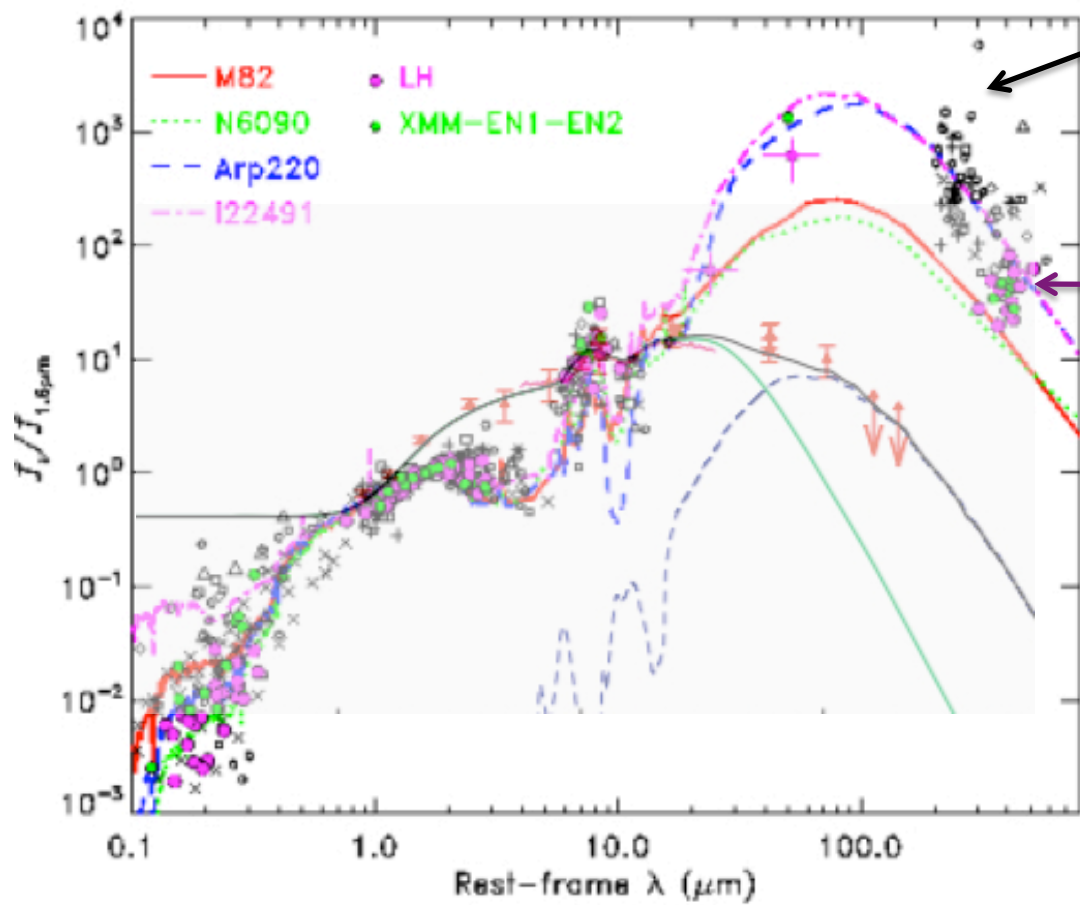
Warm dust from AGN-heated dust peaks in mid-IR



Radio jet can interact mechanically with ISM

- halt infall
- halt starbursting
- eject matter

In contrast: starburst-dominated $z \sim 2$ ULIRGs



SMGs, 850 μ m

Spitzer starburst-
dominated ULIRGs
Lonsdale et al.
(2009),
Mambo 1.2mm

Much larger submm/
24 μ m ratios than
MIR-selected AGN

Merger Sequence, Hopkins et al. (2008)

d: Peak SFR.
FIR
dominated

d-e: Peak QSO.
Mid-IR
dominated

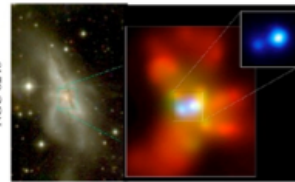
e: Blowout
phase / AGN
feedback
Radio jet

(c) Interaction/"Merger"



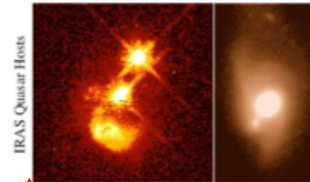
- now within one halo, galaxies interact & lose angular momentum
- SFR starts to increase
- stellar winds dominate feedback
- rarely excite QSOs (only special orbits)

(d) Coalescence/(U)LIRG



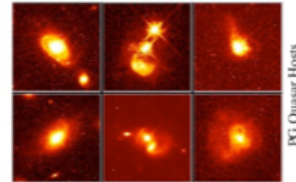
- galaxies coalesce: violent relaxation in core
- gas inflows to center: starburst & buried (X-ray) AGN
- starburst dominates luminosity/feedback, but, total stellar mass formed is small

(e) "Blowout"



- BH grows rapidly: briefly dominates luminosity/feedback
- remaining dust/gas expelled
- get reddened (but not Type II) QSO: recent/ongoing SF in host
- high Eddington ratios
- merger signatures still visible

(f) Quasar



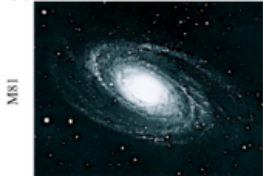
- dust removed: now a "traditional" QSO
- host morphology difficult to observe: tidal features fade rapidly
- characteristically blue/young spheroid

(b) "Small Group"

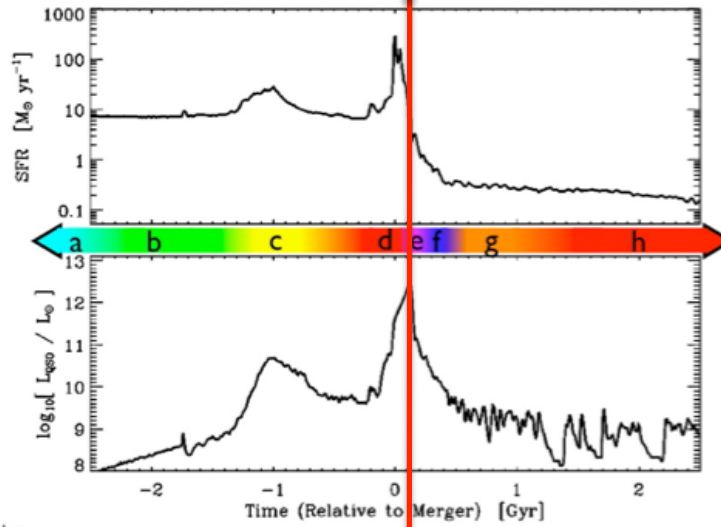


- halo accretes similar-mass companion(s)
- can occur over a wide mass range
- M_{halo} still similar to before: dynamical friction merges the subhalos efficiently

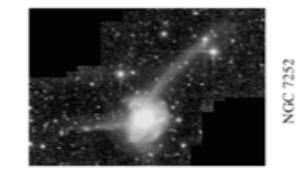
(a) Isolated Disk



- halo & disk grow, most stars formed
- secular growth builds bars & pseudobulges
- "Seyfert" fueling (AGN with $M_{\text{BH}} > 23$)
- cannot redden to the red sequence



(g) Decay/K+A



- QSO luminosity fades rapidly
- tidal features visible only with very deep observations
- remnant reddens rapidly (E+A/K+A)
- "hot halo" from feedback
- sets up quasi-static cooling

(h) "Dead" Elliptical



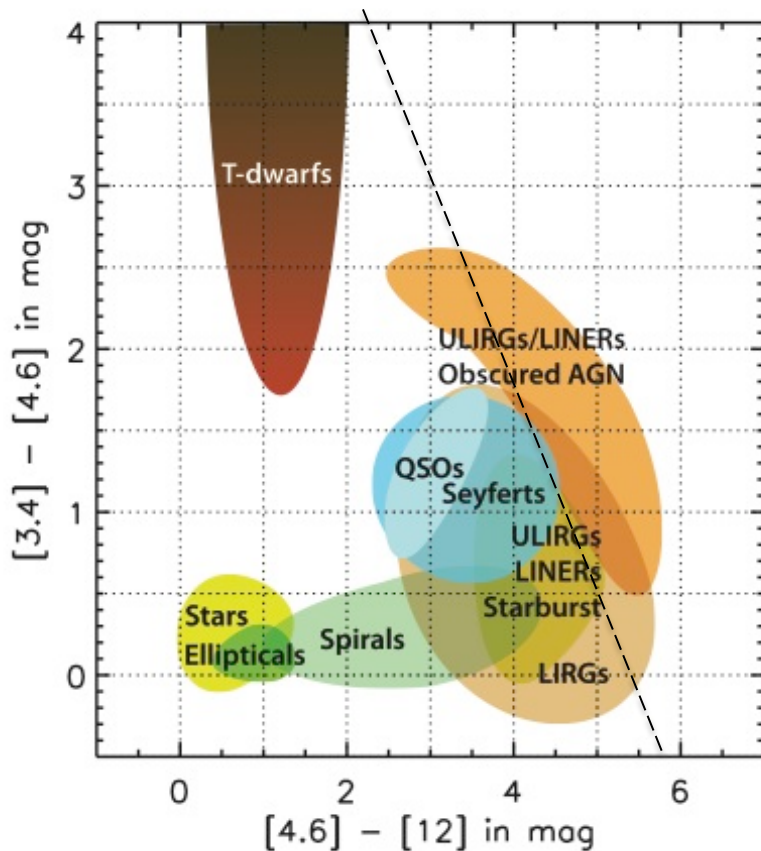
- star formation terminated
- large BH/spheroid - efficient feedback
- halo grows to "large group" scales: mergers become inefficient
- growth by "dry" mergers



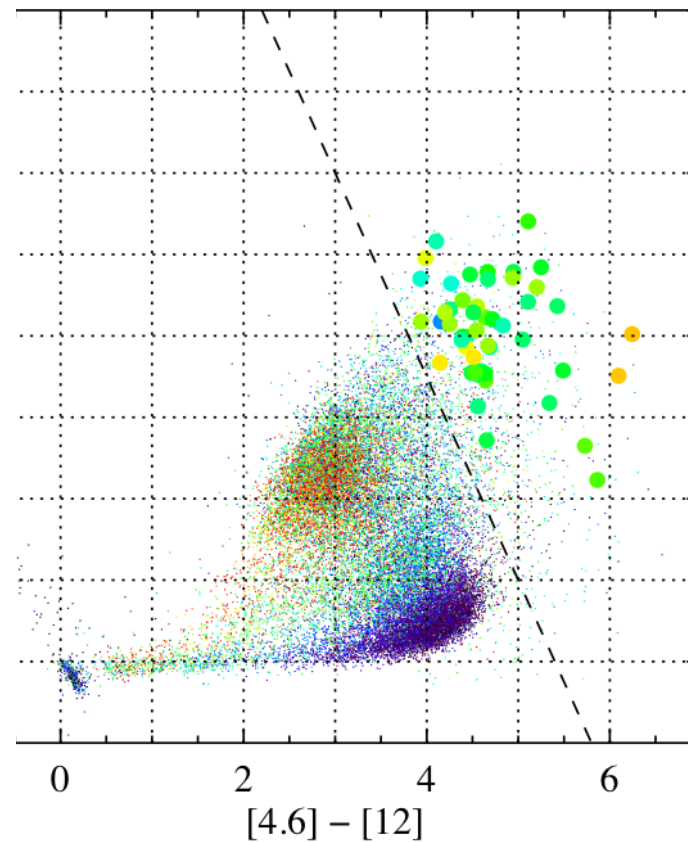
ALMA Sample

49 extremely red WISE sources

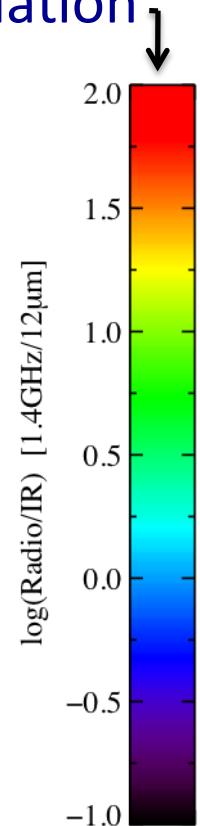
Moderately radio-loud from Ibar et al (2008) 1.4GHz/24 μ m relation



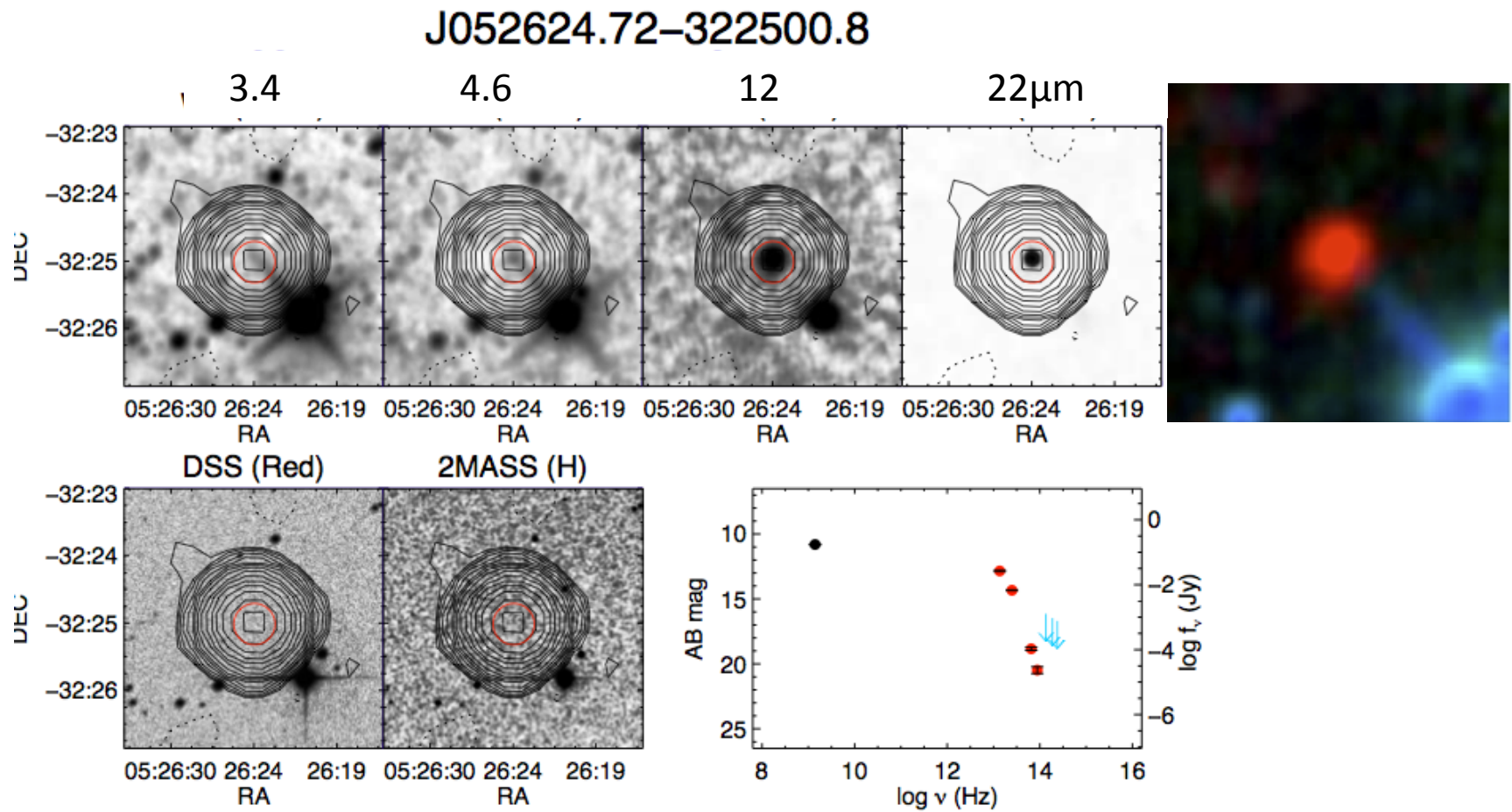
Wright et al. (2011); Jarrett et al. (2011)



Lonsdale et al. (2012)

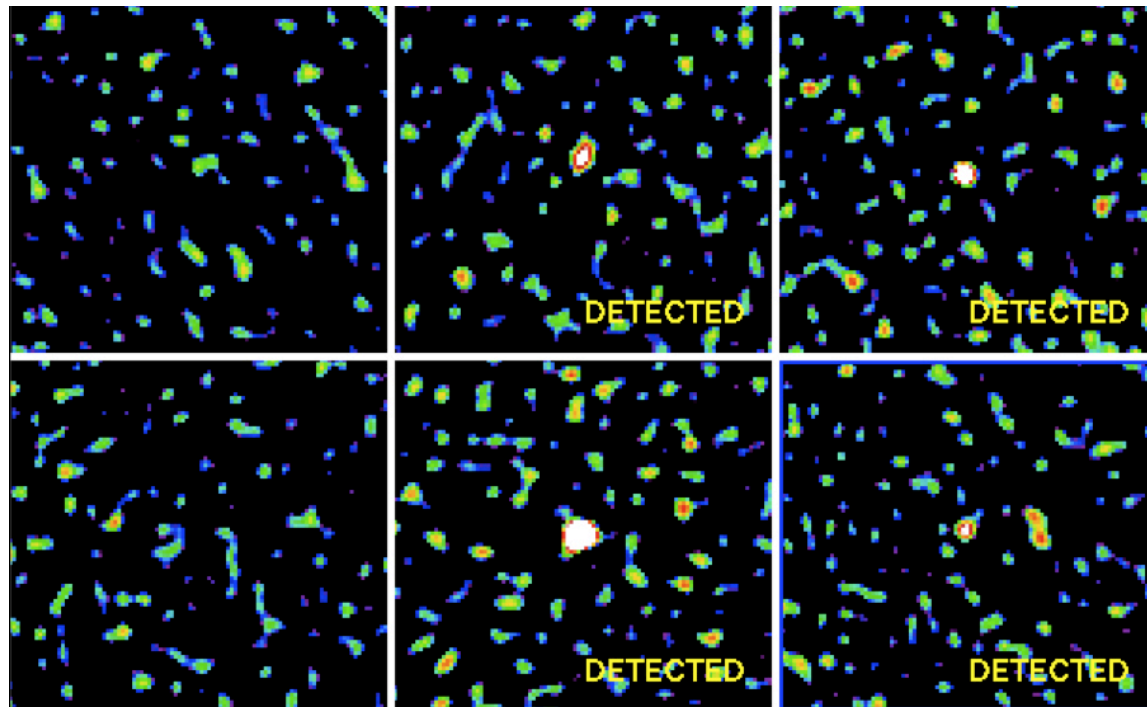


WISE images and NVSS contours.



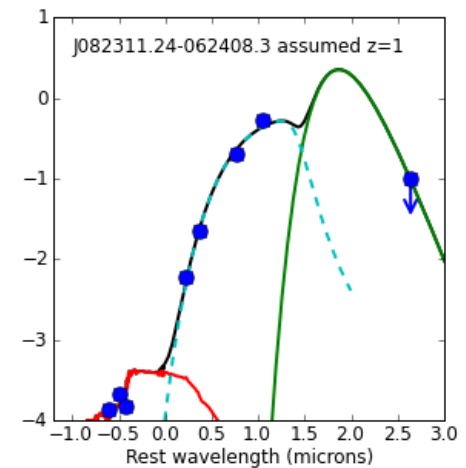
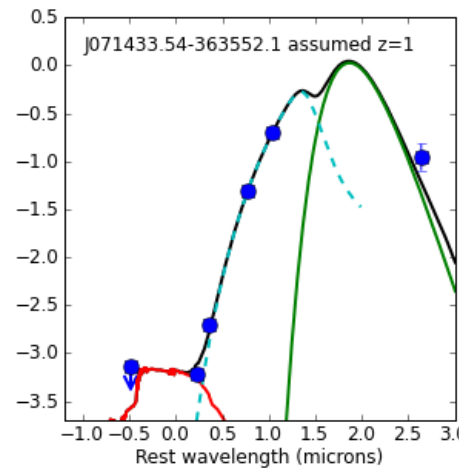
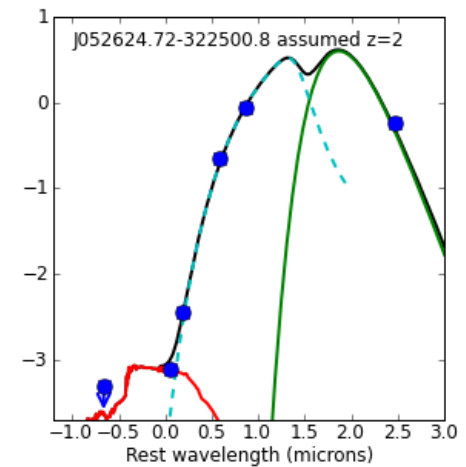
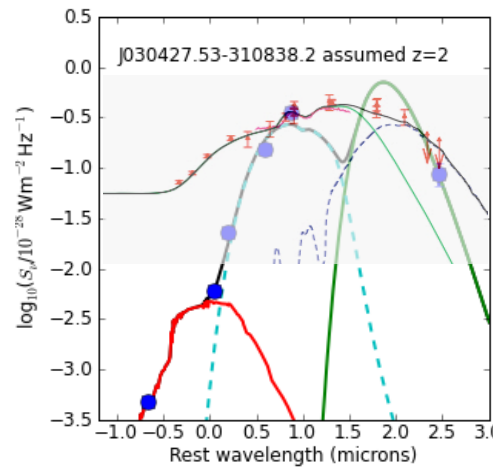
First ALMA Results

- > 50% detections at 870 μ m (Band 7).
 - 0.5 mJy rms, 90 secs, 16 antennas, Cycle 0 compact array
 - 26 more to be observed



ALMA Results

- All fall well below expected color for starburst-dominated phase
- Likely to be in **post-starburst, radio feedback phase**
- Upcoming EVLA study of 150 sources will determine radio shape, size.
- Spectroscopy at SOAR late January



Modeling by M Lacy

Stellar population ————
Modified BB ————
AGN torus - - - -