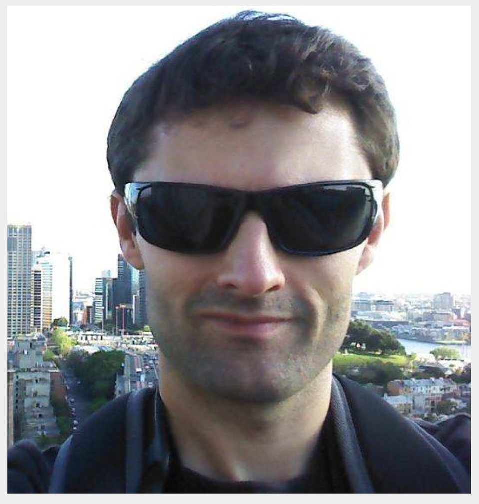
The complex multi-frequency radio properties of ALMA-identified z>2 starburst galaxies



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The big issue

High-frequency (υ_{rest}~20GHz) radio observations of ten ALMA SMGs show a lack of high-frequency flux relative to power-law extrapolations from 1.4GHz – why? Is synchrotron or free-free emission suppressed?

1. Background

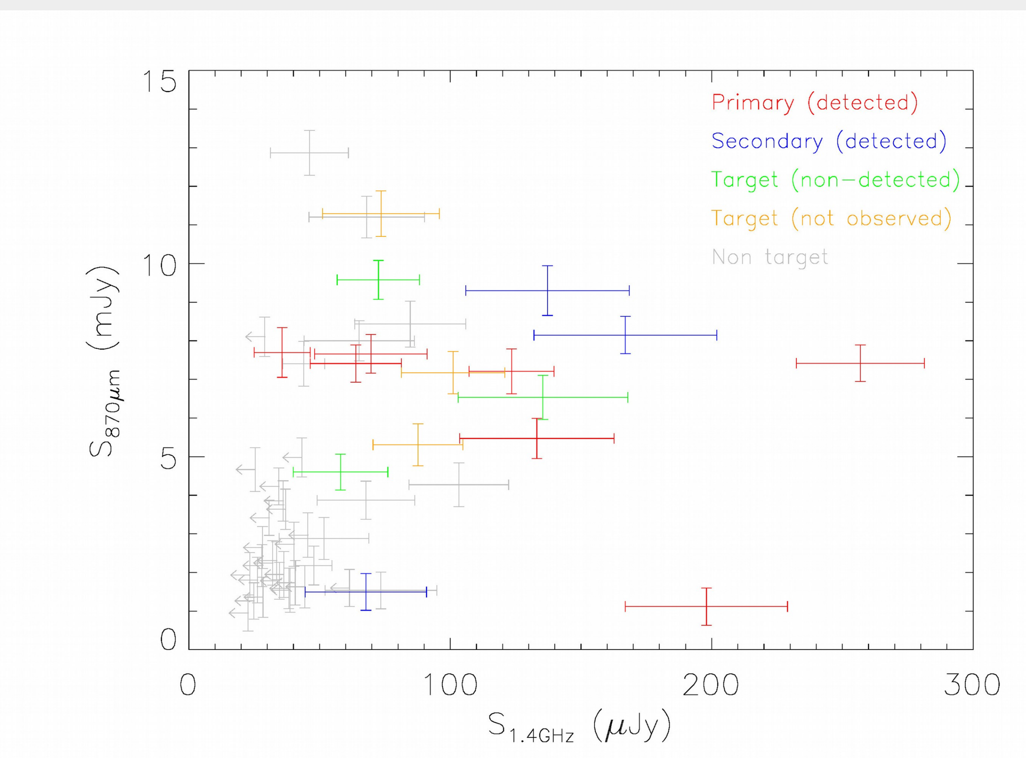
The radio spectra of star-forming galaxies are thought to arise primarily from two power law components; *synchrotron* emission (which traces the energy loss of electrons shocked to relativistic speeds by supernovae in the galaxy's magnetic fields; Ibar et al., 2010) and *free-free* emission, which traces the scattering of free-electrons off ionized gas in HII regions around young, massive stars (Condon, 1992).

The first process produces steep-spectrum (α_{sync} ~ -0.8) emission, and dominates the radio power at low frequencies (υ<10GHz), while the second has a flatter spectrum (α_{FF} ~ -0.1) and becomes dominant at higher frequencies.

Here we present an analysis of the multi-frequency radio properties of a sample of 870µm-identified submillimetre galaxies (SMGs) from our ALMA follow-up (AS2UDS; Simpson et al., 2015a,b) to the deep, single-dish SCUBA-2 survey of the UDS field (S2CLS Geach et al., 2017). Using the VLA at 6GHz in A-array, we probe rest-frame ~20GHz emission in these z~2 SMGs, and achieve an angular resolution comparable to that of the ALMA dust continuum maps. This allows us to perform a quantitative comparison of the sizes of the dust/radio emission, while 1.4GHz VLA data (Arumugam et al, in prep) and 610MHz GMRT imaging of the field (Ibar et al., 2010) allow us to decompose the radio emission into its constituent power laws, isolating the free-free component .

Free-free emission is an excellent, dust-free tracer of star-formation (Murphy et al., 2015), and provides an important check on SFR_{IR}, which may be contaminated by dust-heating due to AGN activity.

Fig 1: *In pointings centred on 30 SCUBA-2 sources, Simpson et al. (2015a) identified 52 ALMA SMGs. We selected a 1.4GHz-bright sub-sample for follow up with VLA at 6GHz*



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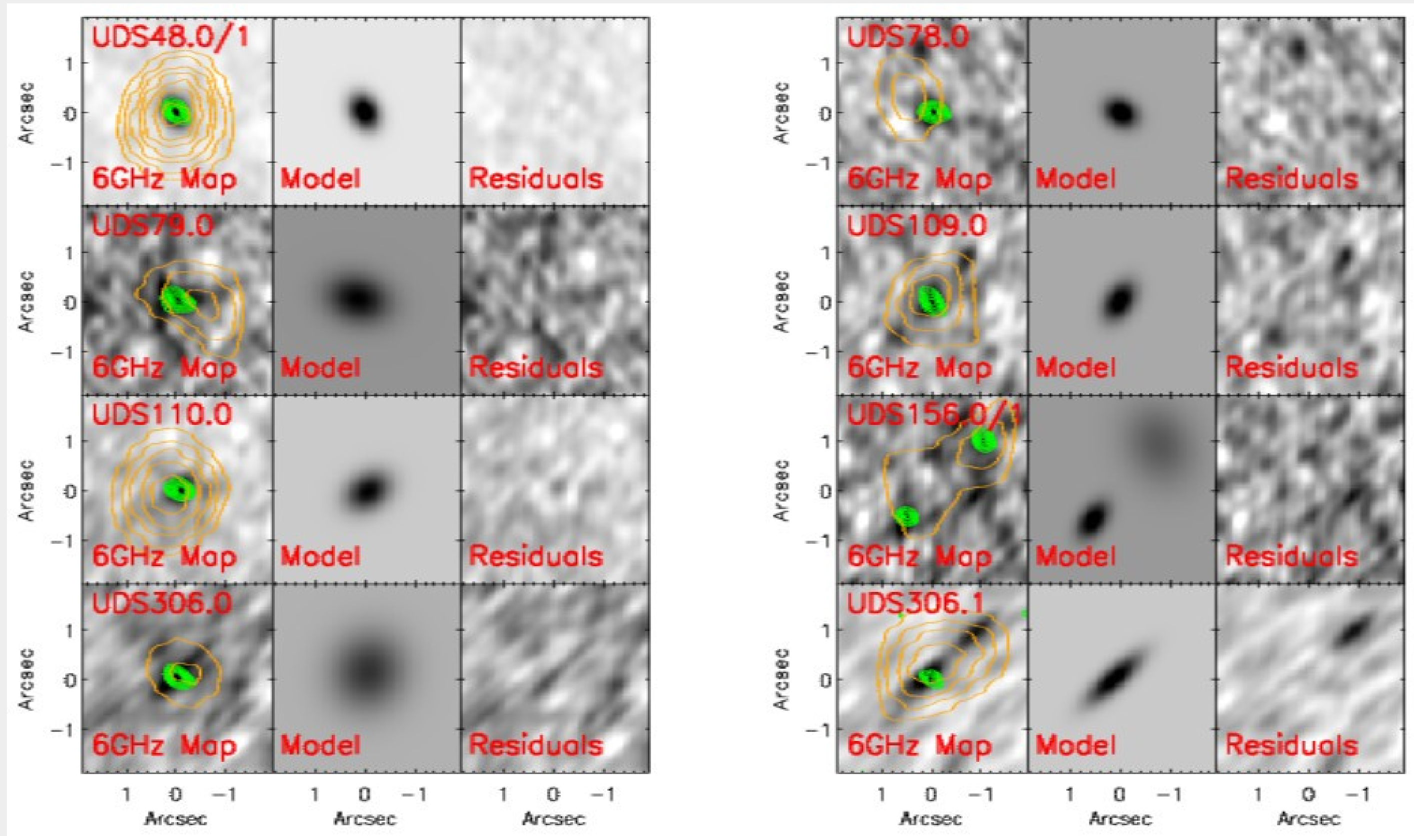
2. Dust/radio size comparison

In Figure 2, I show thumbnails consisting of 1.4GHz and 870µm contours (orange and green, respectively), along with greyscales of the 6GHz emission. The 1.4GHz beam is ~1.7", the 6GHz beam is ~0.5" and the 870µm beam is ~0.3". Emission in all three bands is fit with 2D Gaussians in CASA to measure flux densities and sizes. The dust emission traces a region 1-2kpc in size (Simpson et al. 2015a), while the 6GHz emission is somewhat more extended (~3-4kpc).

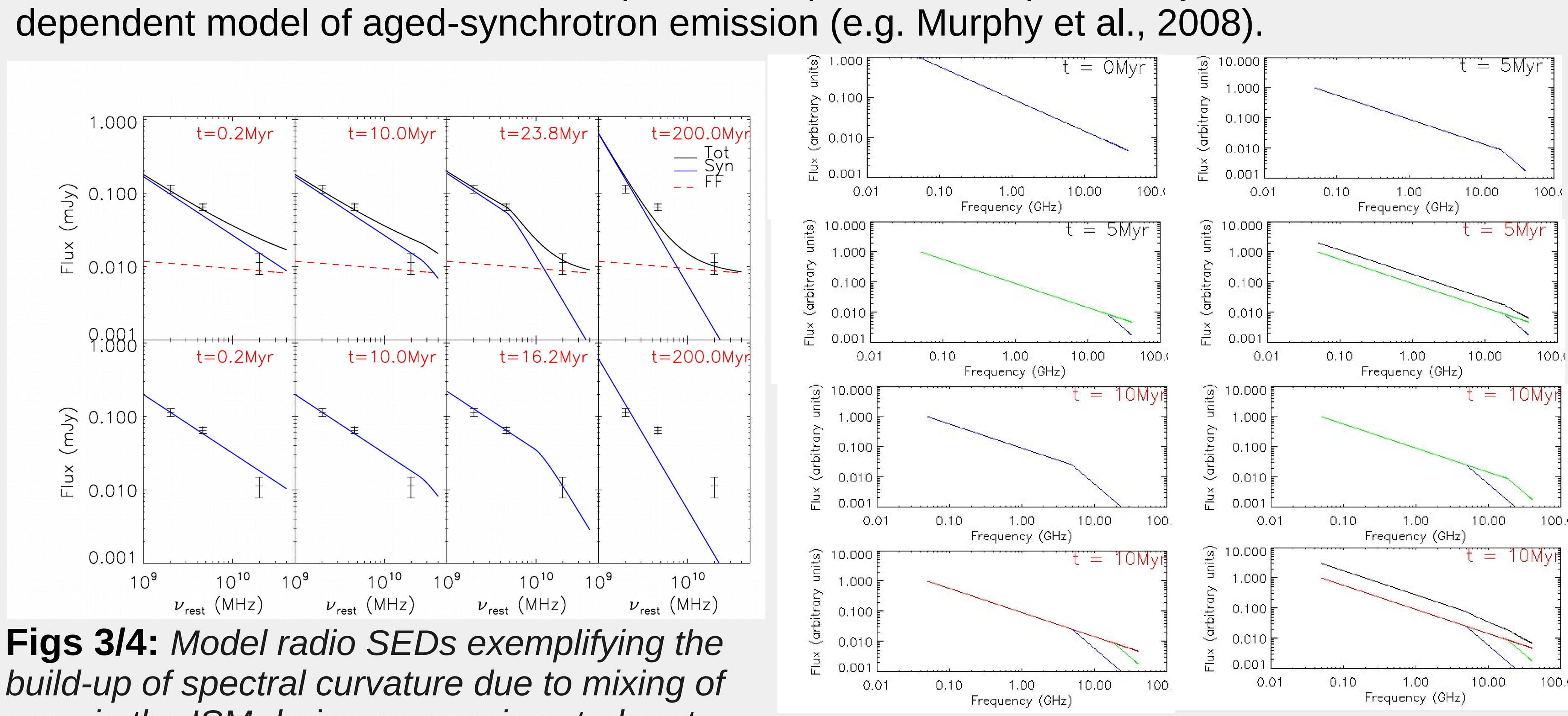
Fig 2: *VLA 6GHz thumbnails of our targets (greyscale) with ALMA 870µm contours (green) and VLA 1.4GHz contours (orange). We model the SMGs in each band with 2D Gaussians using CASA to measure their fluxes and sizes. Model and residual images for the 6GHz observations are shown. Our measured 6GHz sizes are ~2.5x larger than the dust continuum sizes*



At 1.4GHz, one SMGs (UDS306.0) is unresolved, while three others (UDS156.0, 156.1 and 306.1) have sizes that cannot be reliably measured due to blending with nearby sources. The remaining 6 SMGs have 1.4GHz sizes (deconvolved from the beam) of ~8kpc, 4x larger than the dust emission and 2x larger than the 6GHz sizes. One possible explanation for this curious mis-match in spatial scales traced at each wavelength is that the rest-frame 280µm dust continuum misses a significant star-forming component seen in the radio; alternatively, the radio emission may trace an enlarged synchrotron "halo", surrounding a central, dusty starburst.

3. A mechanism for radio spectral steepening

Our sample has a median $S_{1.4GHz}$~133µJy, and was expected – given a synchrotron spectral index α_{sync} ~ -0.8, plus a flatter (α_{FF} ~ -0.1) free-free component proportional to the high SFR_{IR} – to have S_{6GHz} ~70µJy. Instead, we see surprising evidence of spectral *steepening,* wherein the 6GHz flux densities are around half as bright as expected. This suggests either suppression of the free-free component, or losses of synchrotron emission. We find that this curious spectral shape can be explained by a SFH-dependent model of aged-synchrotron emission (e.g. Murphy et al., 2008).



Figs 3/4: *Model radio SEDs exemplifying the build-up of spectral curvature due to mixing of ages in the ISM during an ongoing starburst.*

A single burst of synchrotron emission in a galaxy will eventually decay due to energy loss of free electrons off the galaxy's *B*-field. High-energy electrons (which produce high-frequency radio waves) have a large cross section, σ_T, and so decay faster than low-energy electrons, inducing a break in the synchrotron spectrum which, over time, moves to lower υ. In an ongoing starburst, new synchrotron emission is continually fed into the ISM via supernovae, ameliorating these losses, but not compensating for them entirely. As the starburst evolves, a curved synchrotron spectrum naturally builds up (which can appear as a sharp break, if there is a large gap in sampling, for instance from υ_{rest}~3-20GHz), whose level of curvature is dependent on the combination of *B*-field strength and age (*t*).

We find that the observed degree of spectral curvature is best-fit, for a constant SFH, with synchrotron ages in the range 20-30Myr (other models, such as an exponentially-decling SFH, are compatible with younger ages). These ages well agree with SMG ages inferred from the far-IR/radio correlation (Bressan et al, 2002; Thomson et al, 2014) and arguments based on the gas depletion timescales (e.g. Huynh et al., 2013).