Radio & Sub-mm Galaxies

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Outline

1. UKIRT and Radio Galaxies –
   a 30 year relationship

2. Sub-mm galaxies –
   identifications and redshifts

3. Sizes, morphologies and masses –
   a comparison with radio galaxies

4. The future – the crucial role of UKIRT

1. UKIRT and Radio Galaxies

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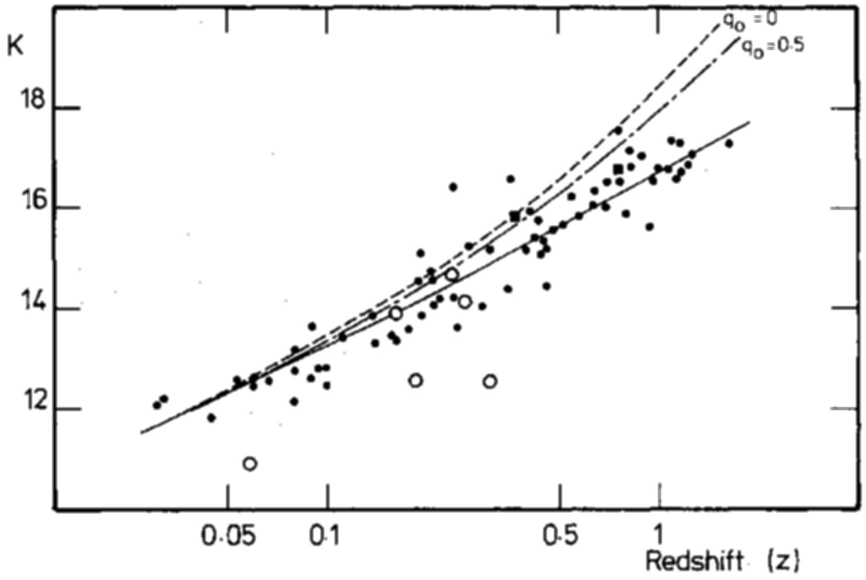

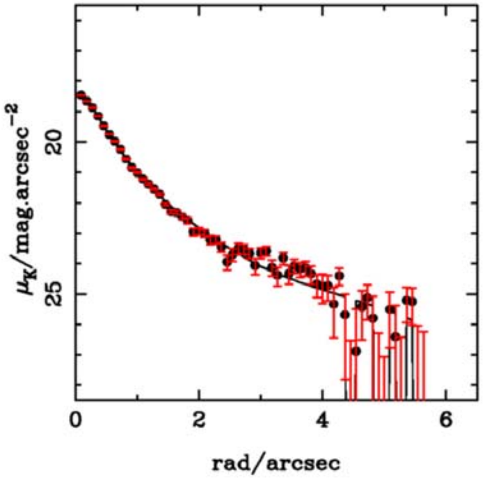

Leverage value of UKIRT

Redshift cutoff in radio LF: Dunlop & Peacock (1990)
Relied on UKT9 photometry and the K-z relation

A 3.5 Gyr old galaxy at z = 1.55: Dunlop et al. (1996)
UKIRT data isolated old galaxy and levered Keck

Radio galaxies and quasar hosts: Dunlop et al. (1993,2003)
IRCAM imaging revealed massive hosts & levered major HST programme

Sub-mm studies – 8mJy to SHADES to SCUBA2: Dunlop et al (2009)
UFTI and WFCAM data crucial for IDs, estimated redshifts and masses

Galaxies at z = 5 – 9: Dunlop et al. (2007), McLure et al. (2008,2009,2010)
Ongoing UKIDSS UDS work has led directly to work with WFC3 on HST

Galaxies at z = 6 – 9 from the WFC3/IR imaging of the HUDF

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Accepted ... ; Received ... ; in original form ...

ABSTRACT

We present the results of a systematic search for galaxies in the redshift range $z = 6-9$, within the new, deep, near-infrared (Y, J, H) imaging of the Hubble Ultra Deep Field provided by the Wide Field Camera 3 (WFC3) on the Hubble Space Telescope. We have performed full spectral energy distribution fitting to the optical+infrared photometry of all high-redshift galaxy candidates detected at $\geq 5\sigma$ significance in at least one of the WFC3/IR broad-band filters. After careful rejection of contaminants, the result is a sample of 49 galaxies with primary photometric redshift solutions $z > 5.9$, within the 4.5 arcmin^2 field covered by the new near-infrared imaging. Our sample, selected without recourse to specific colour cuts, re-selects all but the faintest one of the 16 z_{850}-drops selected by Oesch et al. (2009), recovers all 5 of the Y_{105}-drops reported by Bouwens et al. (2009), and adds a further 29 equally plausible galaxy candidates, of which 12 lie beyond $z \simeq 6.3$, and 4 lie beyond $z \simeq 7.0$. However, we also present confidence intervals on our photometric redshift estimates, including alternative secondary redshift solutions. As a result of this analysis we caution that acceptable low-redshift $(z < 2)$ solutions exist for 28 out of the 37 galaxies at $z > 6.3$, and in particular for all 8 of the galaxy candidates reported here at $z > 7.5$. Nevertheless, we note that the very highest redshift candidates appear to be strongly clustered in the field. Based on our photometric redshift analysis we derive new estimates of the ultraviolet galaxy luminosity function at $z \simeq 7$ and $z \simeq 8$. Where our results are most robust, at a characteristic luminosity $M_{1500} \simeq -19.5(AB)$, we find that the comoving number density of galaxies declines by a factor of $\simeq 2.5$ between $z \simeq 6$ and $z \simeq 7$, and by a further factor of $\simeq 2$ by $z \simeq 8$. These results suggest that it is difficult for the observed population of high-redshift star-forming galaxies to achieve reionisation by $z \simeq 6$without a significant contribution from galaxies well below the detection limits, plus alterations in the escape fraction of ionising photons and/or continued vigorous star formation at $z > 15$.

Key words: cosmology: observations - galaxies: evolution - galaxies: formation - galaxies: high-redshift

1 INTRODUCTION

A key goal of modern observational cosmology is to discover and study the first galaxies, and to quantify their role in the reionisation of the neutral universe at redshifts $z > 7$ (Dunkley et al., 2009). Studies of quasars have now reached beyond $z \simeq 6$ (e.g. Fan et al. 2006) and indicate that the Gunn-Peterson (1965) optical depth due to neutral hydrogen in the intergalactic medium (IGM) increases significantly at these redshifts. Whatever the precise implications for reionisation physics, the increased strength of the Lyman-break produced by this enhanced optical depth should make it relatively straightforward to select still higher-redshift objects via the Lyman-break technique (e.g. Steidel et al. 1996), given sufficiently sensitive broad-band imaging.

Over recent years, galaxy evolution studies have indeed been successfully extended to redshifts $z > 6$, via both ground-based and *Hubble Space Telescope* (HST) searches for objects with either strong Lyman breaks and/or strong Lyman-α emission at observed wavelengths $\lambda_{obs} > 8500$Å (e.g. Bouwens et al. 2004; Yan

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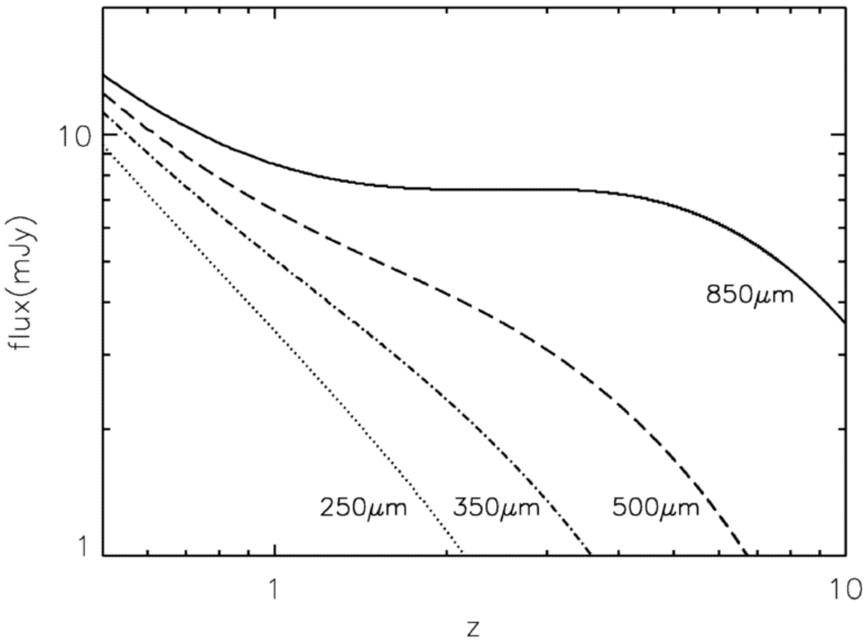
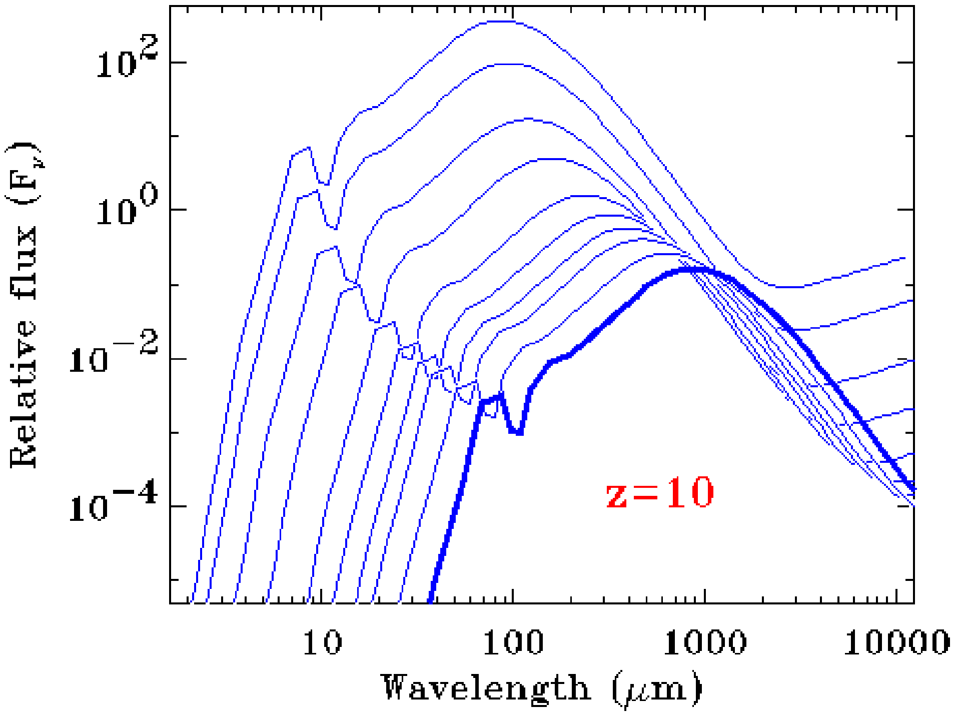
2. Sub-mm galaxies

Example of UKIRT+JCMT synergy

Sub-mm offers a clear view from z = 1 to z = 8 (reionization?)



Galaxy spectrum at progressively higher redshifts

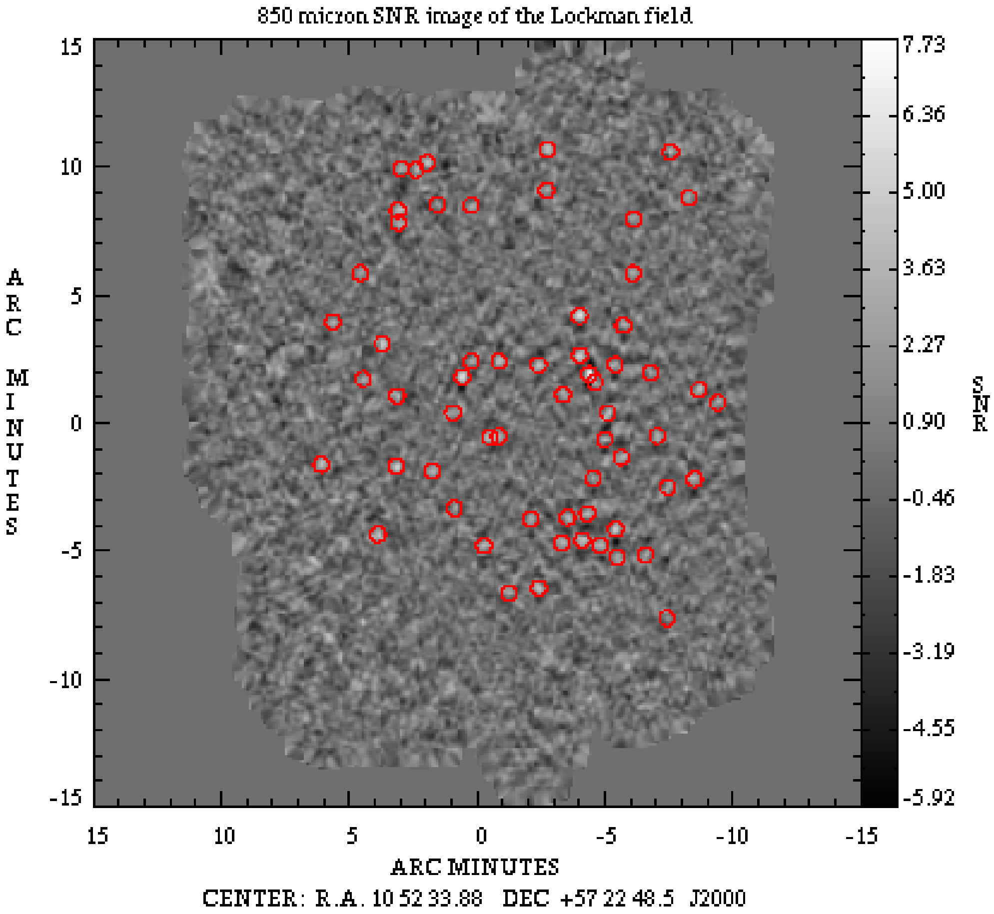


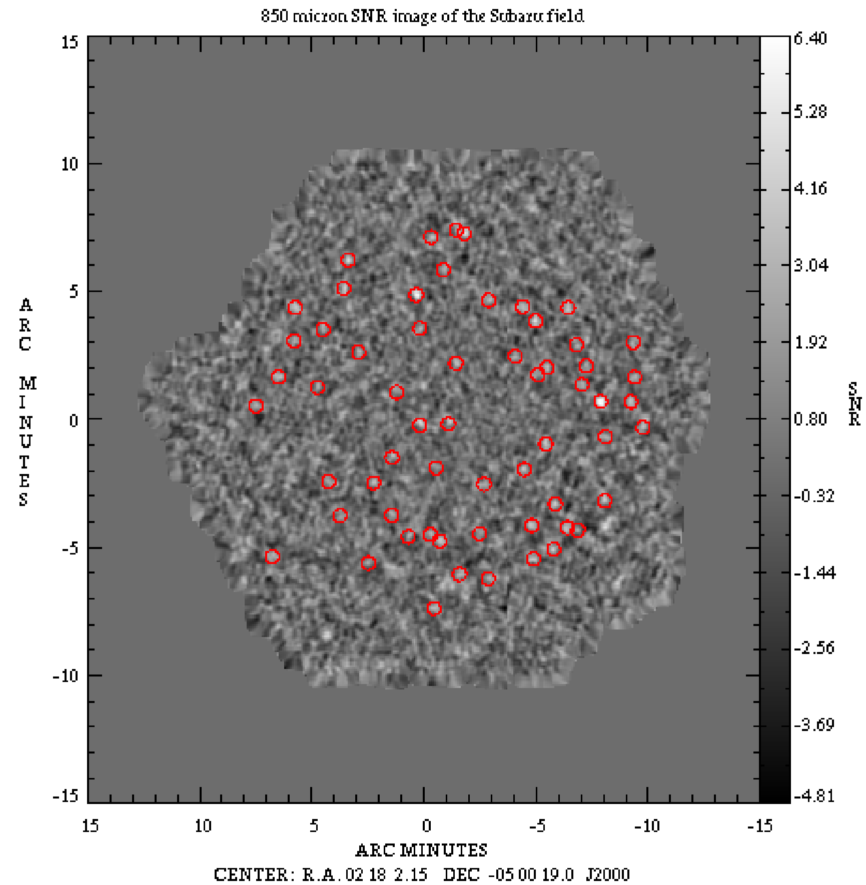
SHADES SCUBA 850-micron maps

2 fields – Lockman Hole & SXDF/UDS

4 independent reductions combined to produce one SHADES catalogue

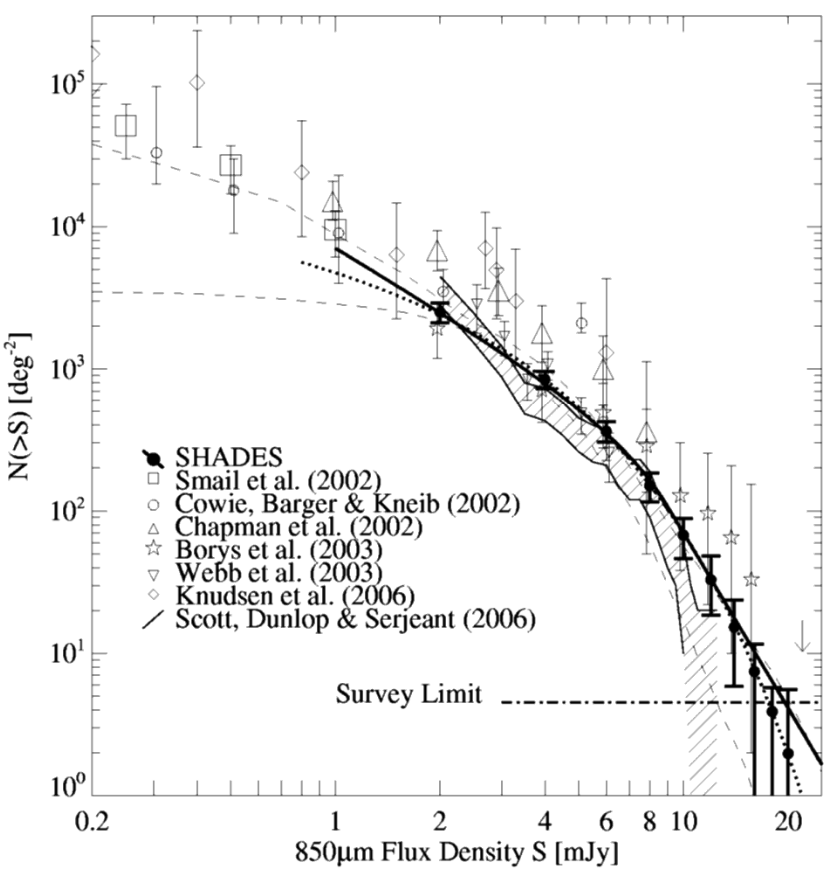
120 sources with unbiased (deboosted) flux densities





Number counts

28 *Coppin et al.*



Coppin et al. 2006

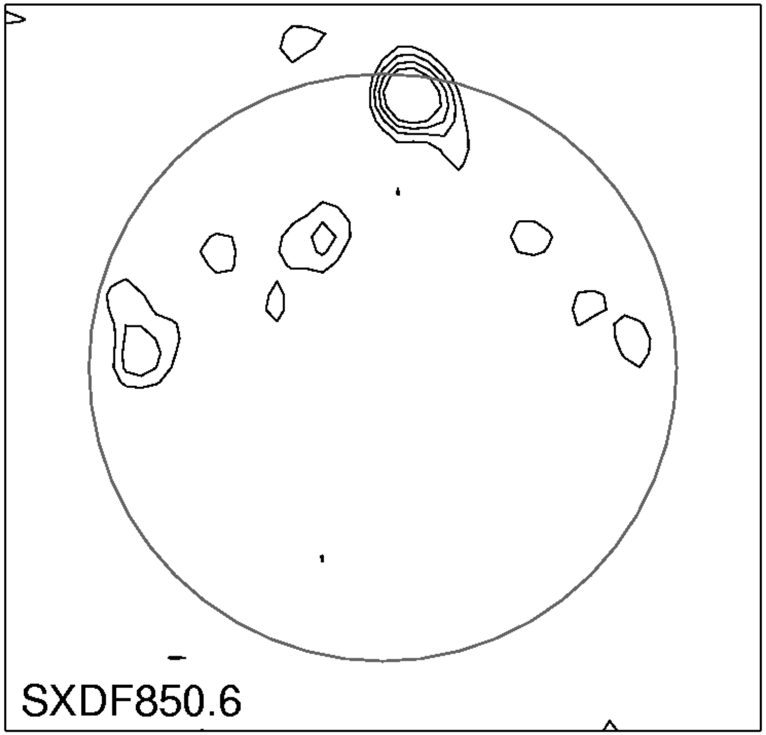
Estimated background of sources >2mJy is ~9700 mJy/deg^2

>20-30% of FIRB resolved

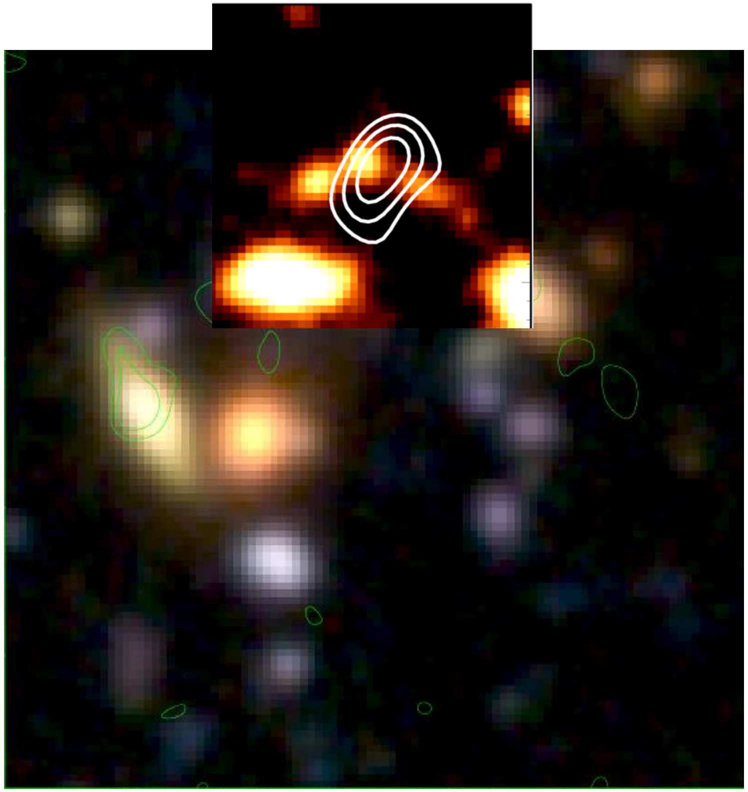
Identifications and redshifts

Sometimes identification can be tricky

e.g. SMA follow-up of SXDF850.6 Iono et al. (2007)



VLA 1.4 GHz

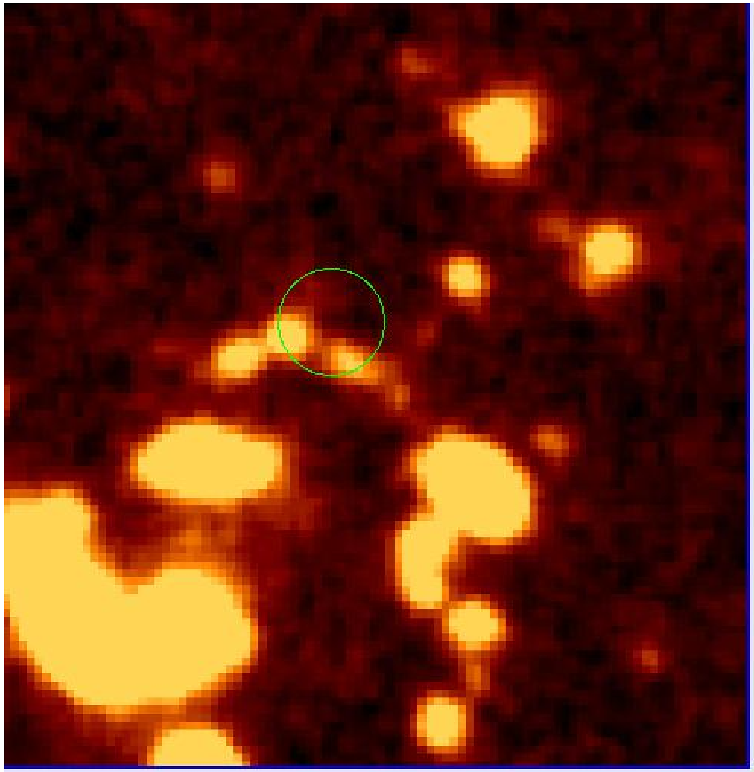


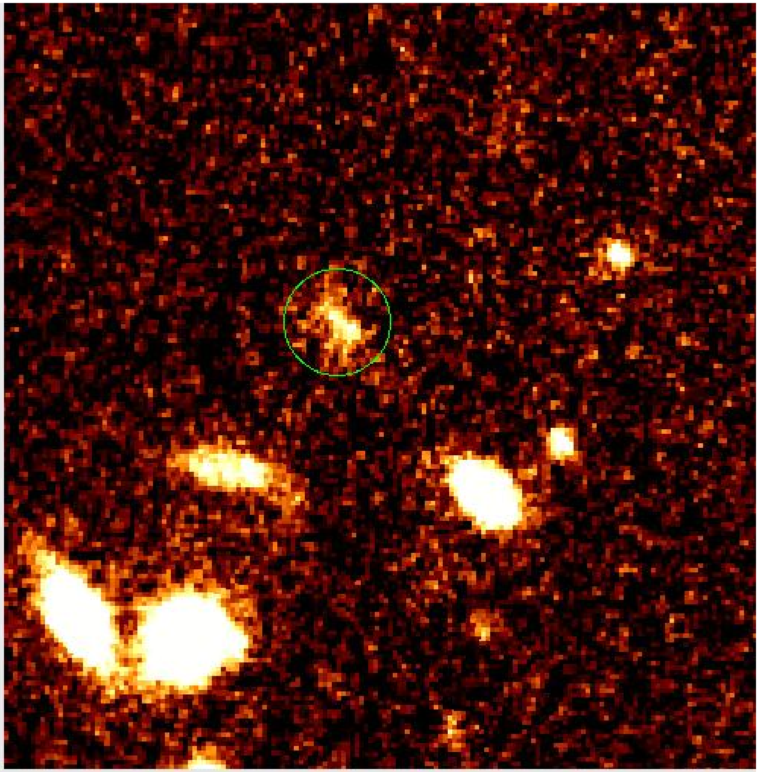
Optical - Subaru

Finally …….unambiguous K-band ID

SMA on optical

SMA on K-band





Demonstrates

1. power of sub-mm interferometry
2. importance of near-IR data identification & study of host galaxy

Redshifts

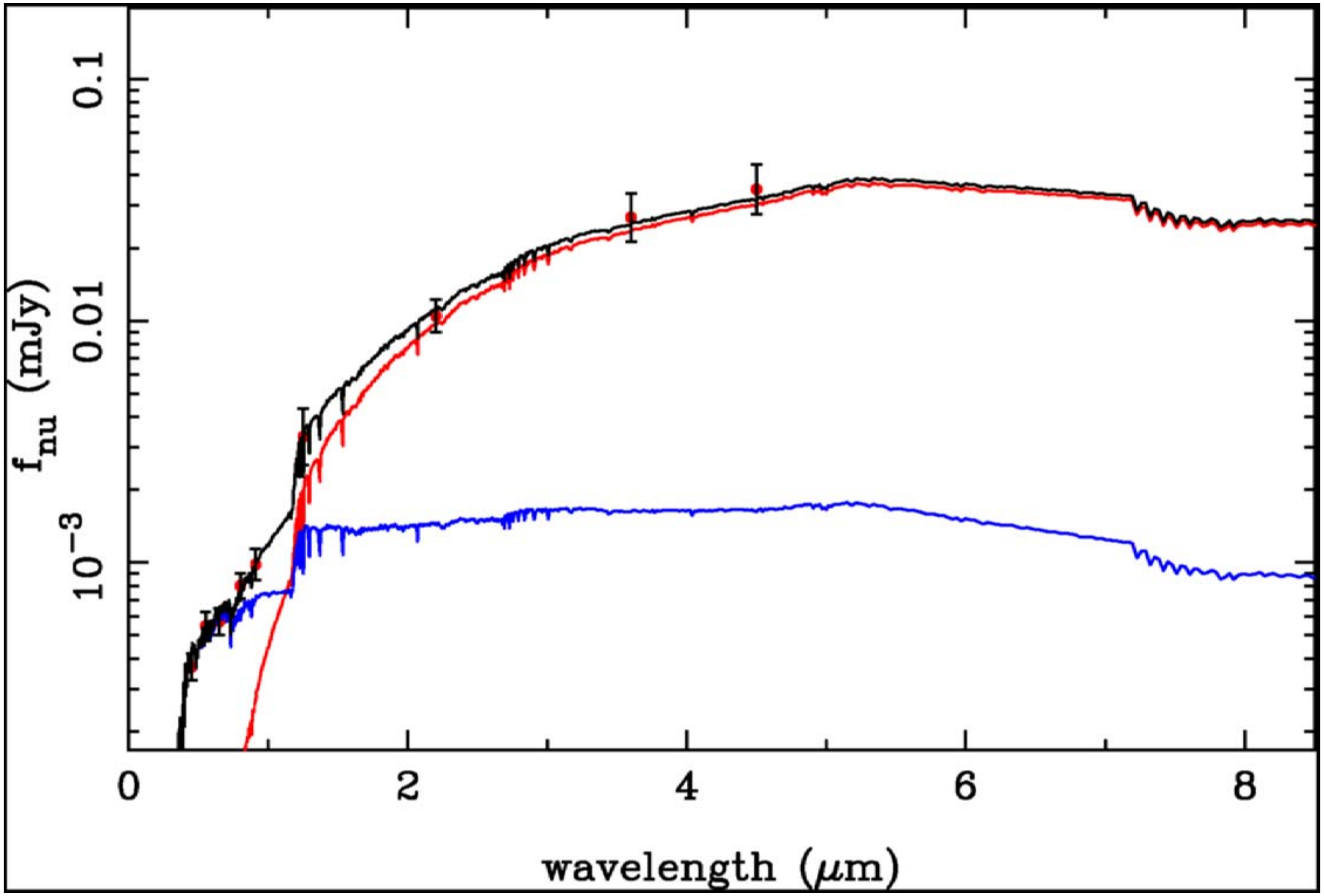
Redshifts

4 different forms of redshift information:

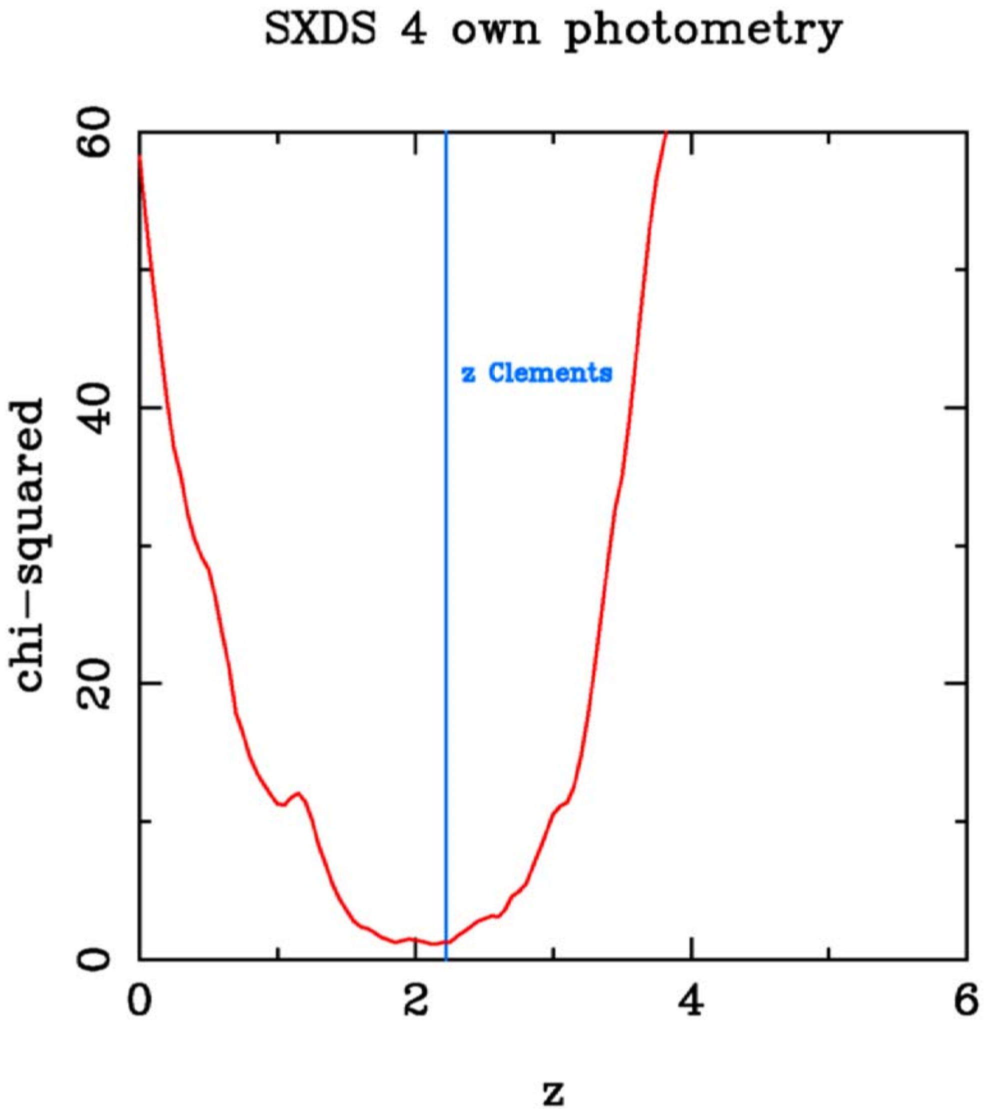
- Spectroscopic – Chapman et al., Stevens et al.
- Far-infrared to radio – Carilli & Yun, Aretxaga et al.
- Optical – near-infrared – Dye et al., Clements et al.
- Spitzer – Pope et al.

In SHADES only ~15 (i.e. 12%) of sources currently have an unambiguous spectroscopic z

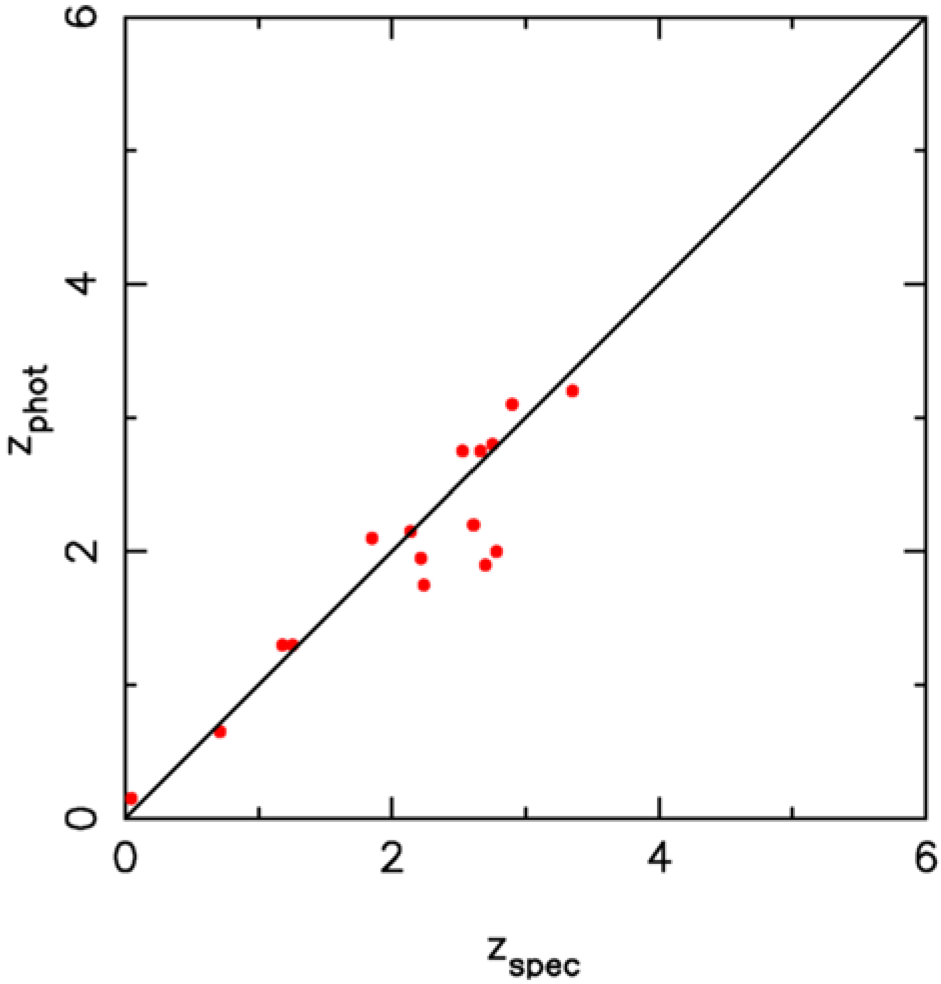
Near-infrared data crucial for photometric redshifts



Near-infrared data crucial for photometric redshifts

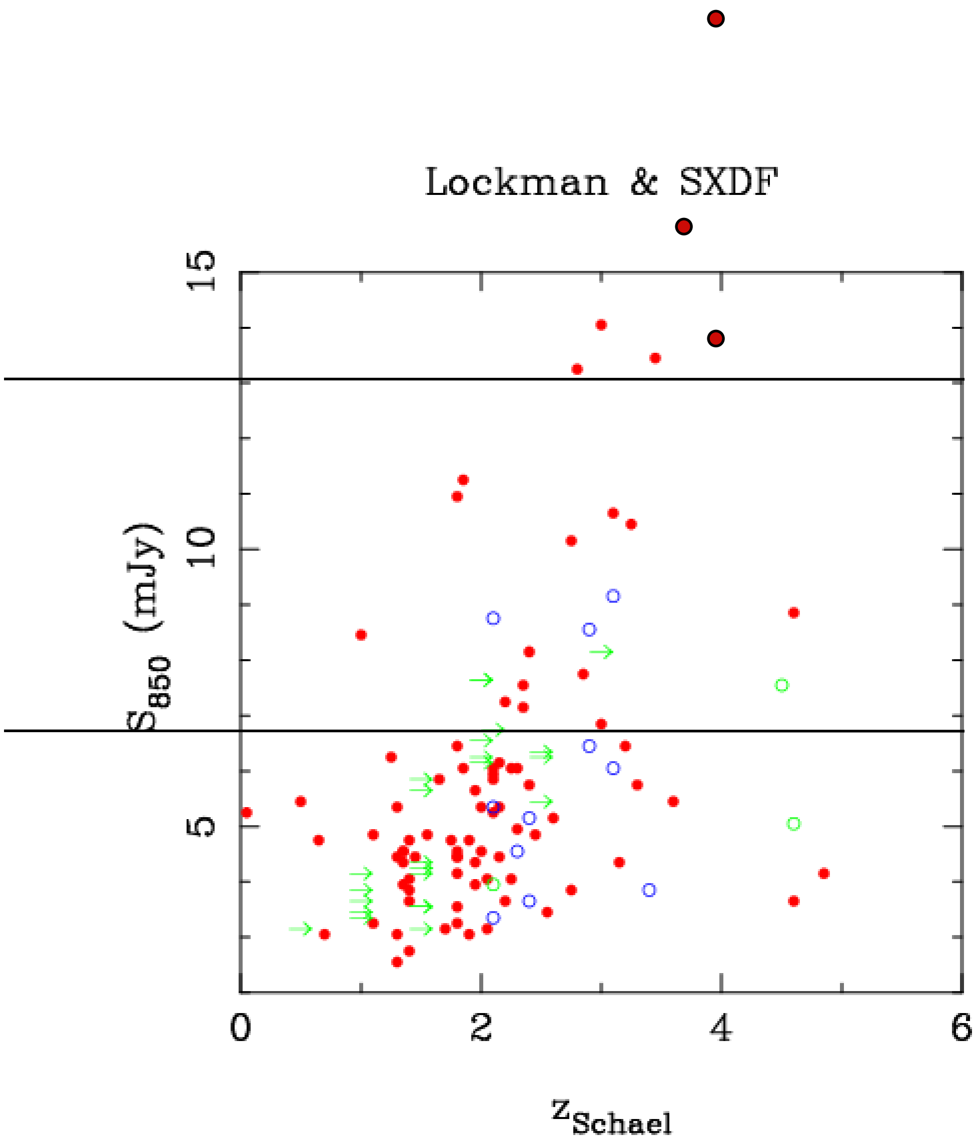


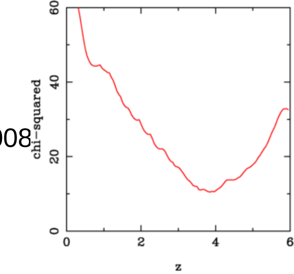
Accuracy of new optical-IR photo-zs – Schael et al. 2009



SFR > 2000 M_{sun} yr $^{-1}$

SFR > 1000 M_{sun} yr $^{-1}$





GN20 –
Iono et al. 2006
Younger et al. 2008

COSMOS AzTEC 1 –
Younger et al. 2007

GOODS 850.5 –
Wang et al. 2008

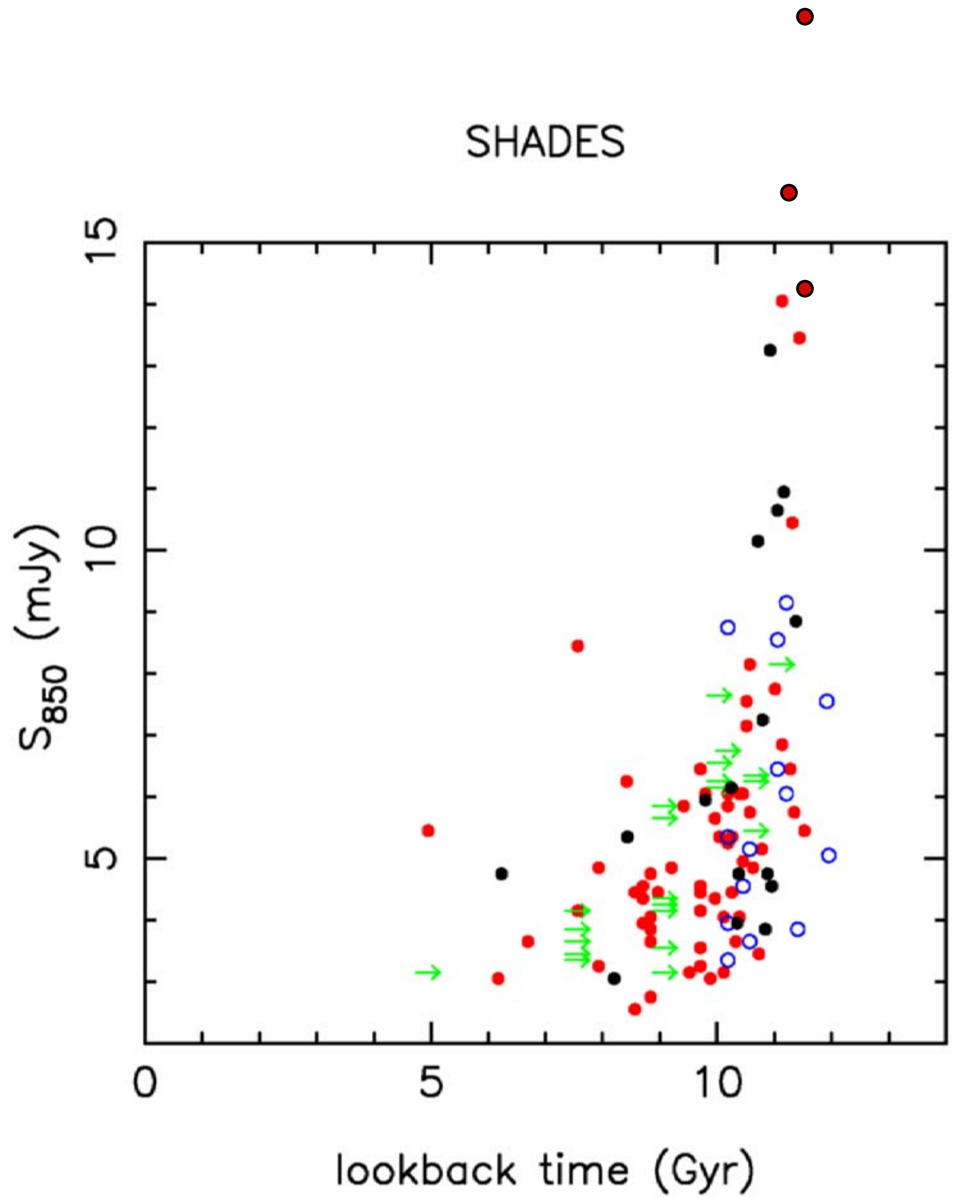
Evidence of down-sizing:

Clear that the comoving number density of > 5 mJy sub-mm sources peaks in redshift range $2 < z < 3$

Brightest (>12 mJy) sources lie at $3 < z < 4$

< 5mJy sources span much wider z range

SFR versus cosmic time – epoch of massive galaxy formation



Number densities at $2 < z < 3$

$M_{star} > 10^{11}\ M_{sun}$:	$1 \times 10^{-4}\ Mpc^{-3}$
$SFR > 500\ M_{sun}\ yr^{-1}$:	$2 \times 10^{-5}\ Mpc^{-3}$
$SFR > 1000\ M_{sun}\ yr^{-1}$:	$3 \times 10^{-6}\ Mpc^{-3}$
$SFR > 2000\ M_{sun}\ yr^{-1}$:	$1 \times 10^{-6}\ Mpc^{-3}$

3. Sizes, morphologies, masses

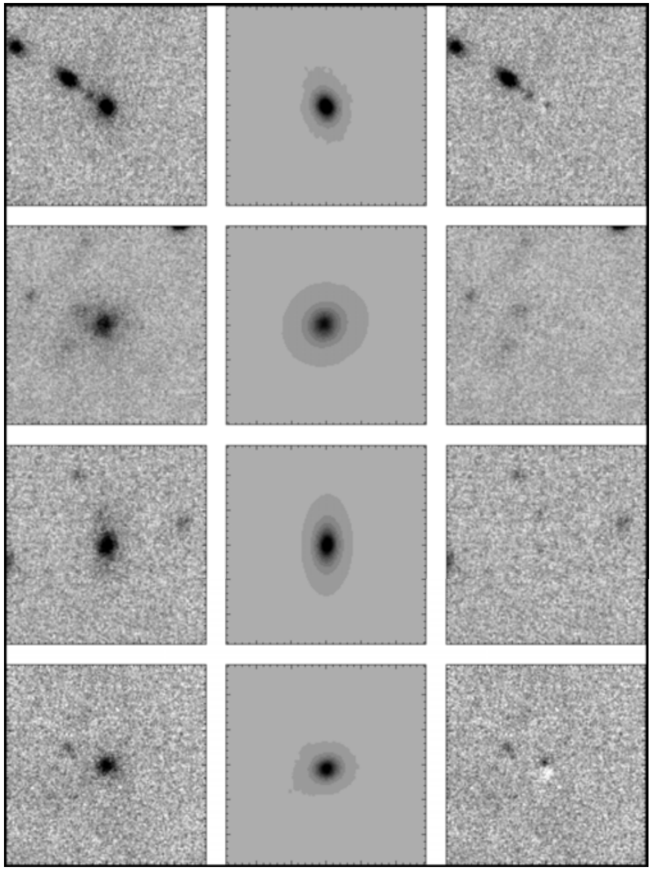
New results from Targett, Dunlop, et al. (2009)

Nice demo of the power of UKIRT to perform high-resolution imaging, and of the virtues of flexible scheduling

Deep, high-resolution (0.5 arcsec) K-band imaging of
13 radio galaxies and 15 8-mJy sub-mm galaxies at z ~ 2

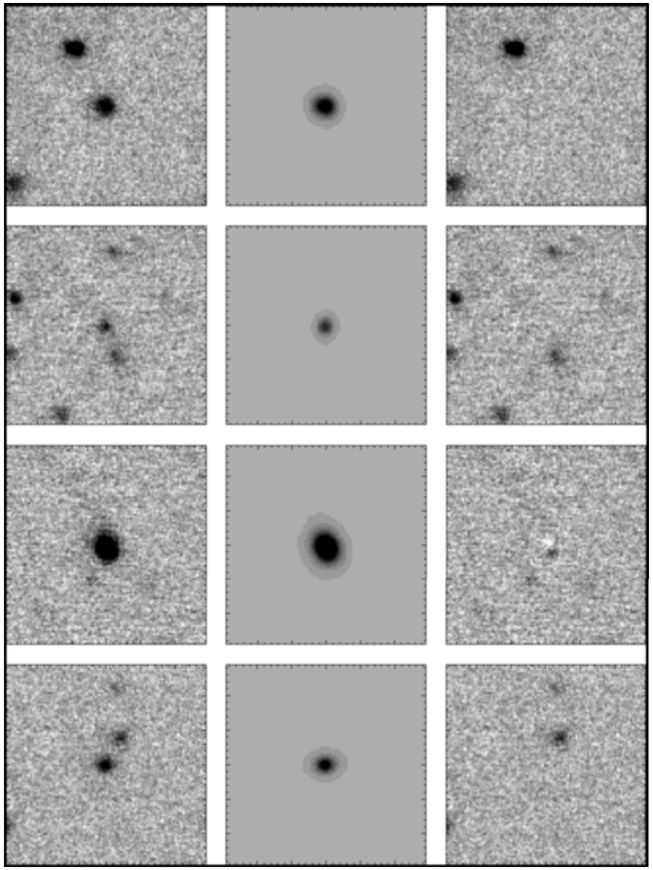
Radio galaxies

= known elliptical progenitors

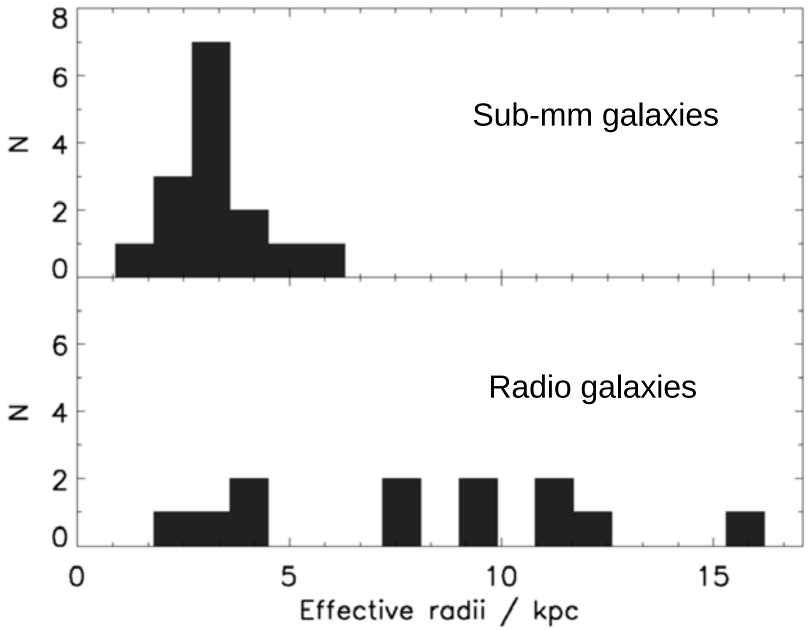


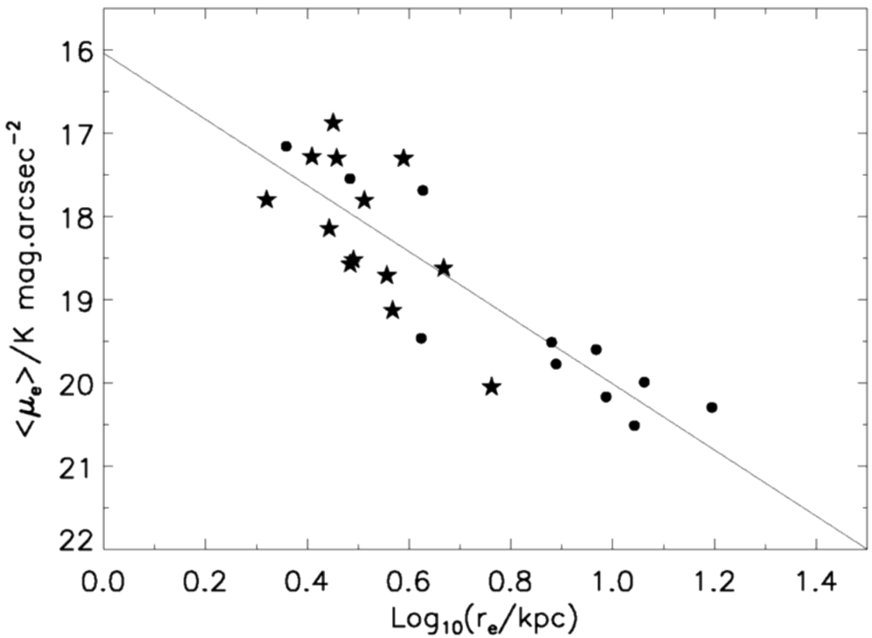
Sub-mm galaxies

= possible elliptical progenitors



Results from galaxy model fitting

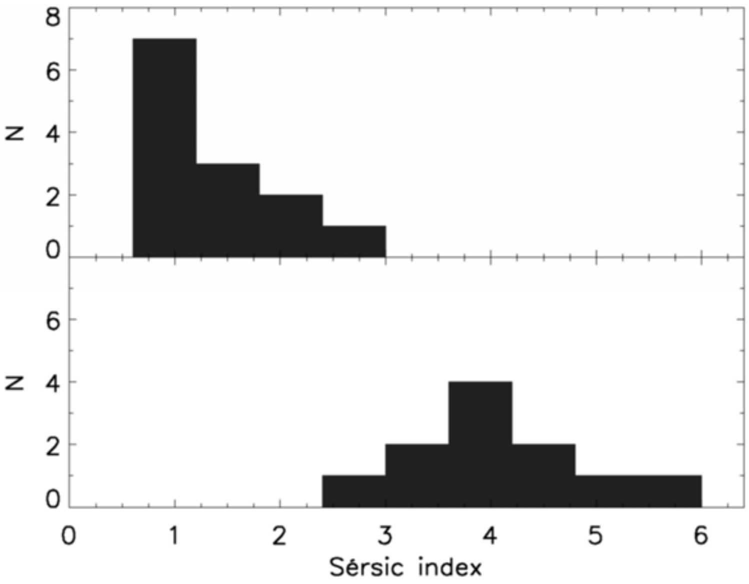




Sizes

Kormendy relation at z = 2

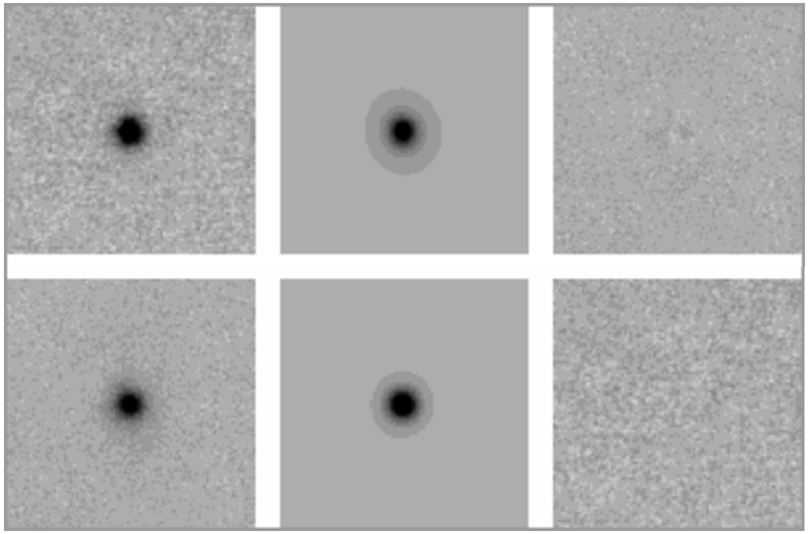
Morphologies



Sub-mm galaxies are mainly discs

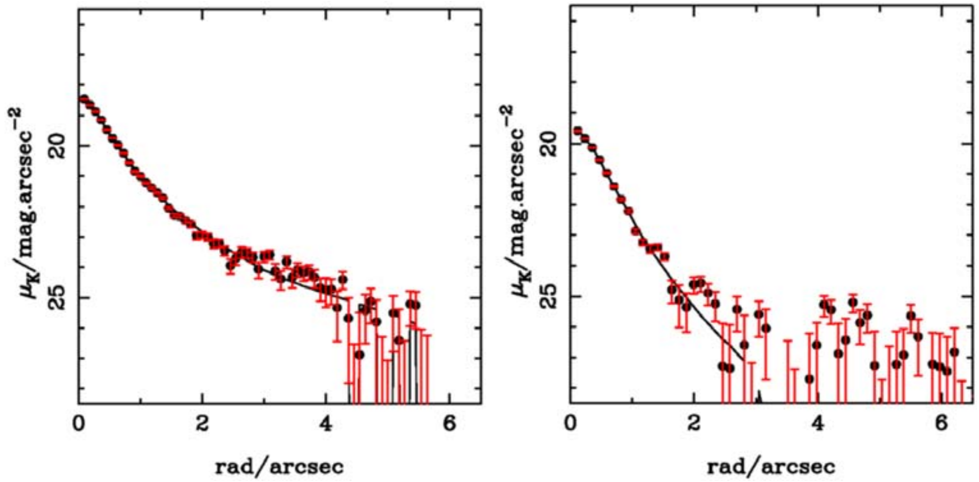
Radio galaxies are $r^{1/4}$ spheroids

Image Stack

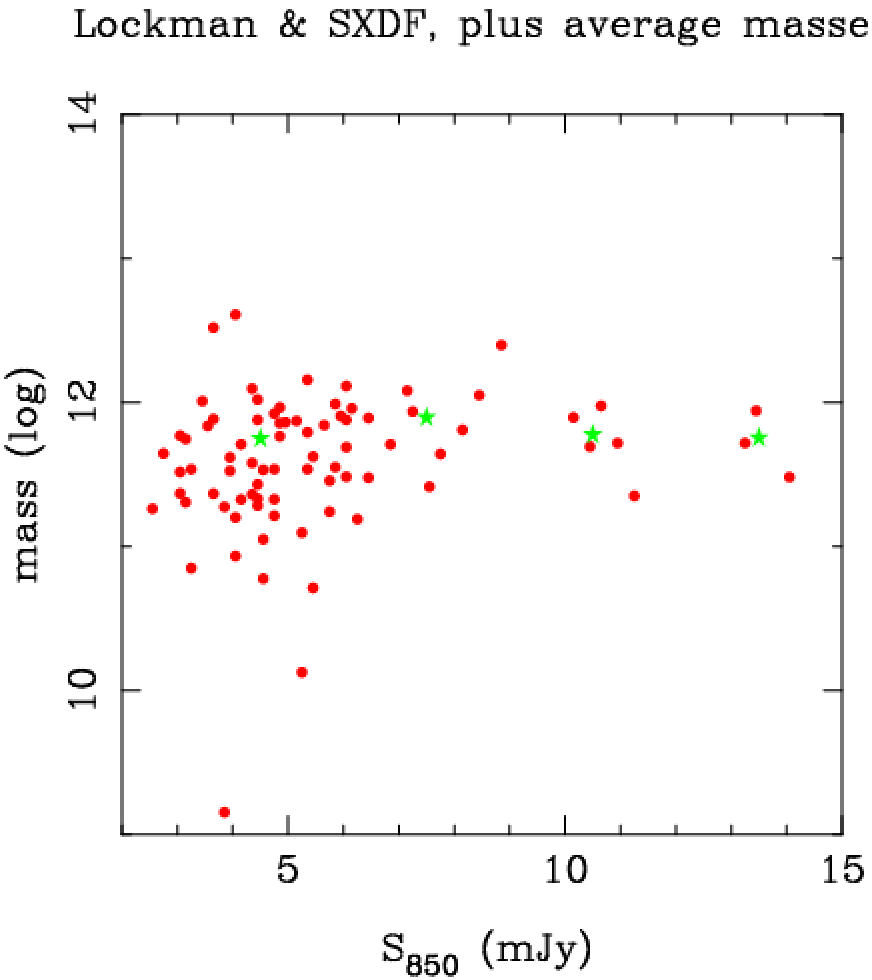


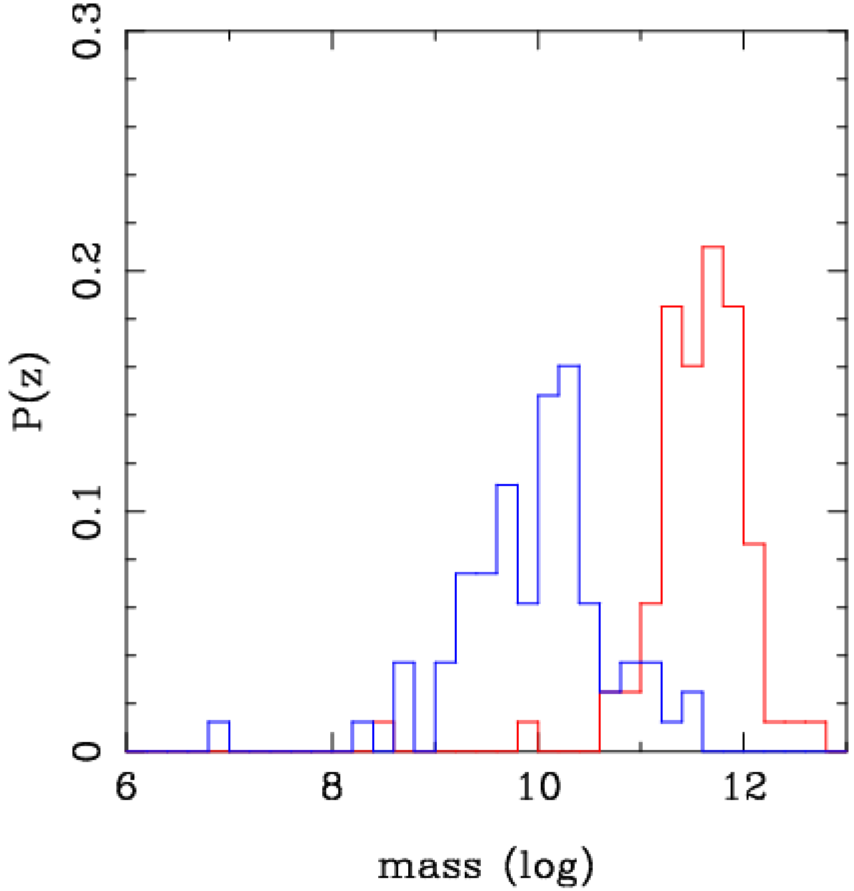
~50 hr K-band image of z = 2 radio galaxy

~50 hr K-band image of z = 2 submm galaxy

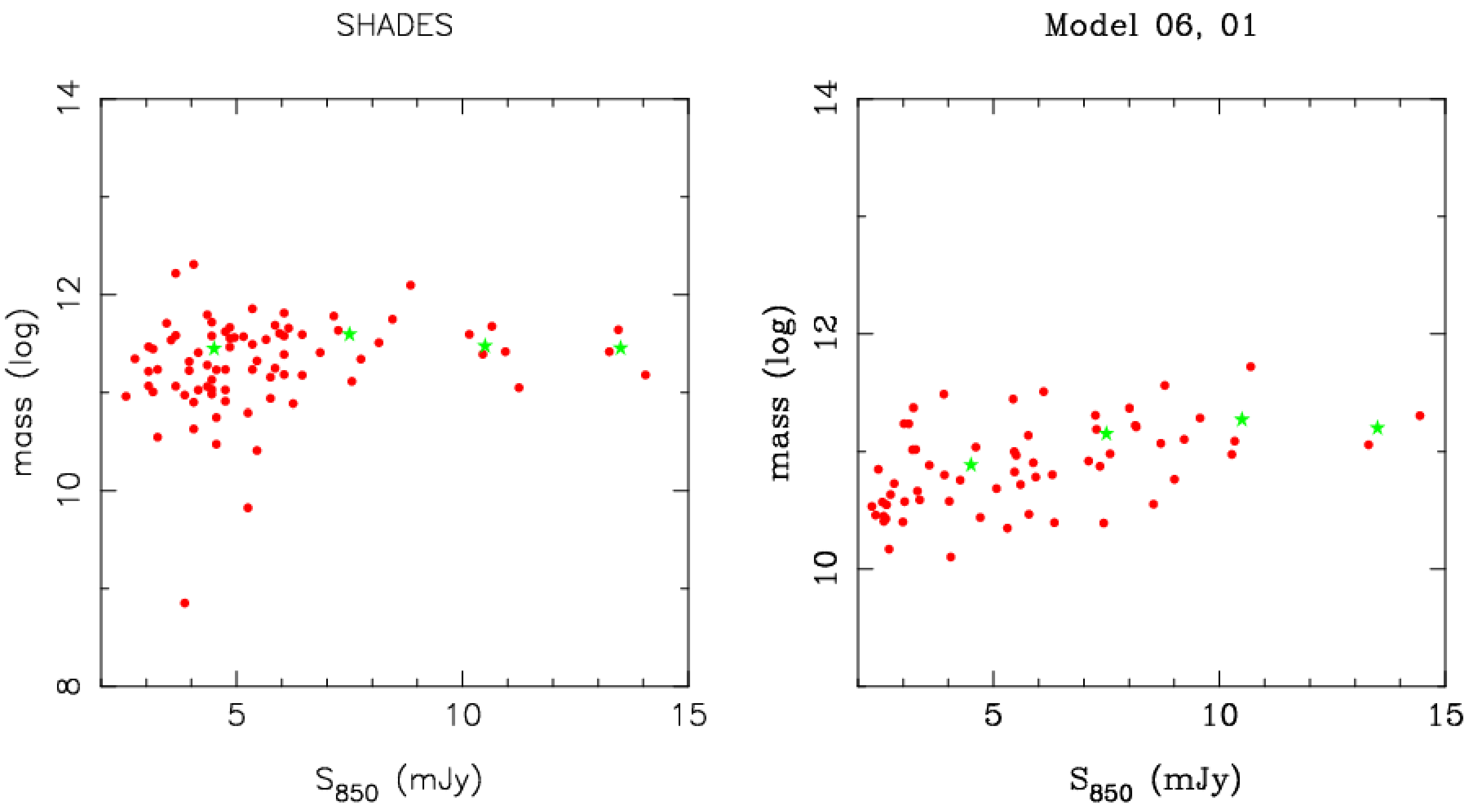


Stellar masses from 2-comp fitting





Comparison with models – stellar mass



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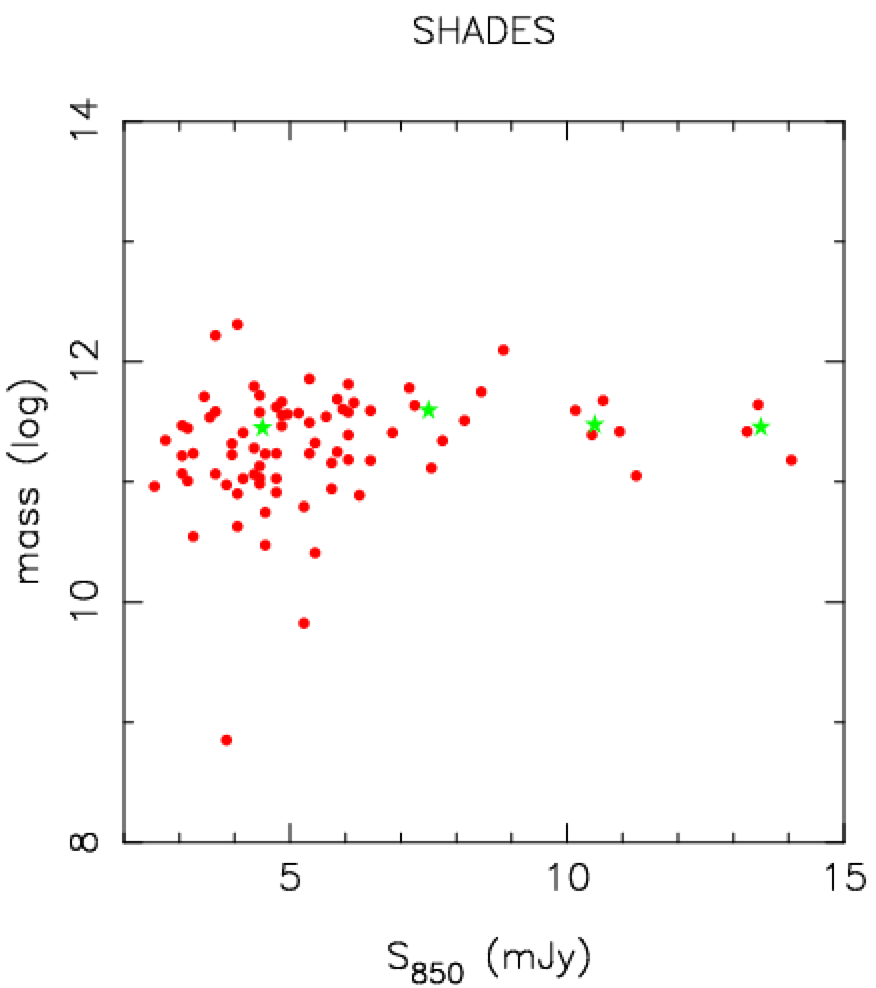
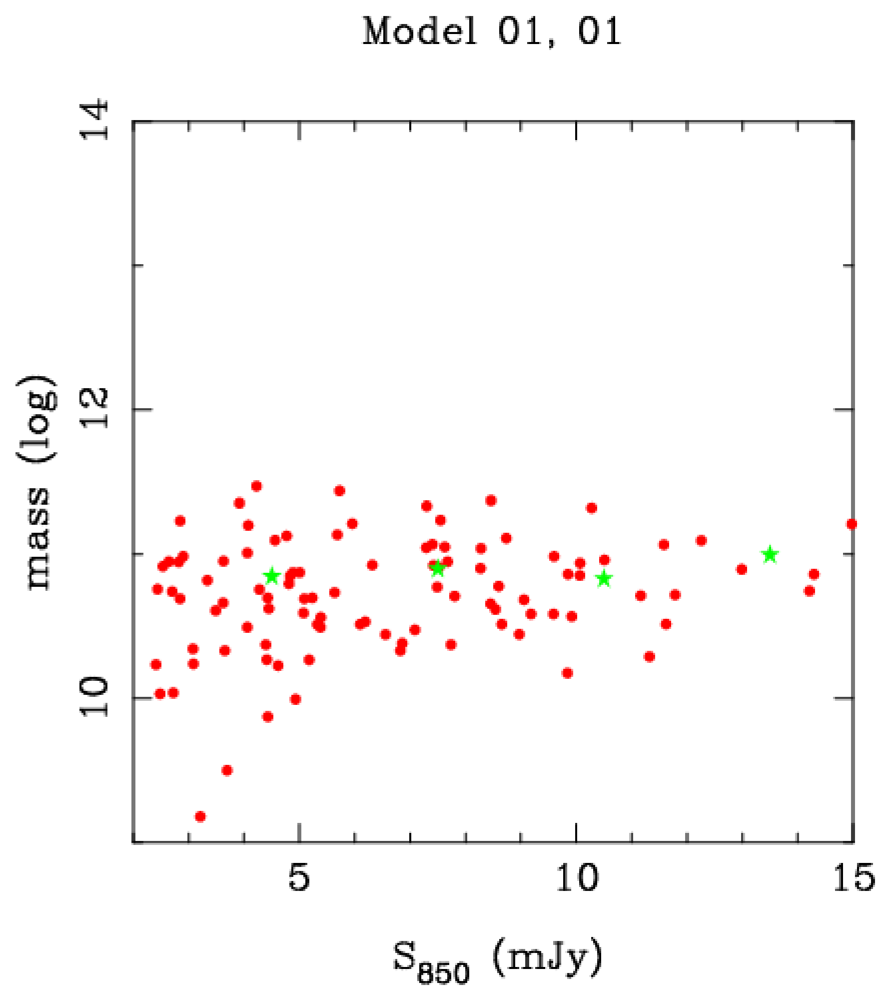
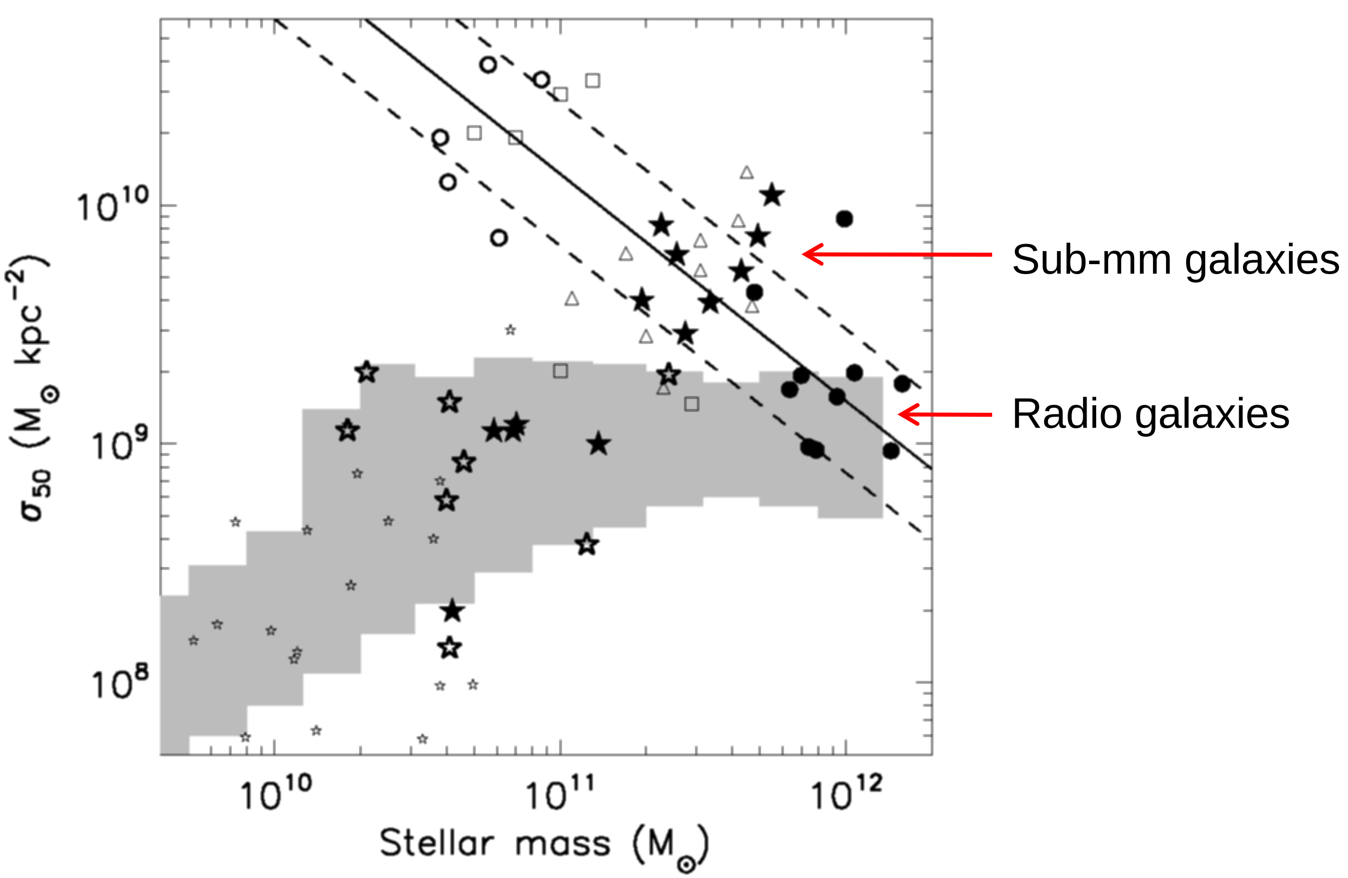




Sub-mm and radio galaxies in the mass-density : mass plane

- following Zirm et al. (2006)



Sub-mm galaxies appear to be massive gas rich discs completing the formation of their cores.

But in terms of density, they are much more like ellipticals/bulges than present-day star-forming discs

They seem destined to evolve into the massive ellipticals, awaiting relaxation and further extended mass growth by a factor ~ 2 (via dryish mergers?).

4. The future

UKIRT remains essential for exploiting SCUBA2, Herschel, PanSTARRS, Spitzer Warm etc…..

Photo-zs will remain crucial, and near-infrared data essential at high-redshift – consider medium band filters in WFCAM?

Deeper broad-band surveys – J= 26-27 (AB) mag is achievable over a few sq degrees – c.f. a few sq. arcmin with HST or indeed JWST.