Galaxy Evolution 1

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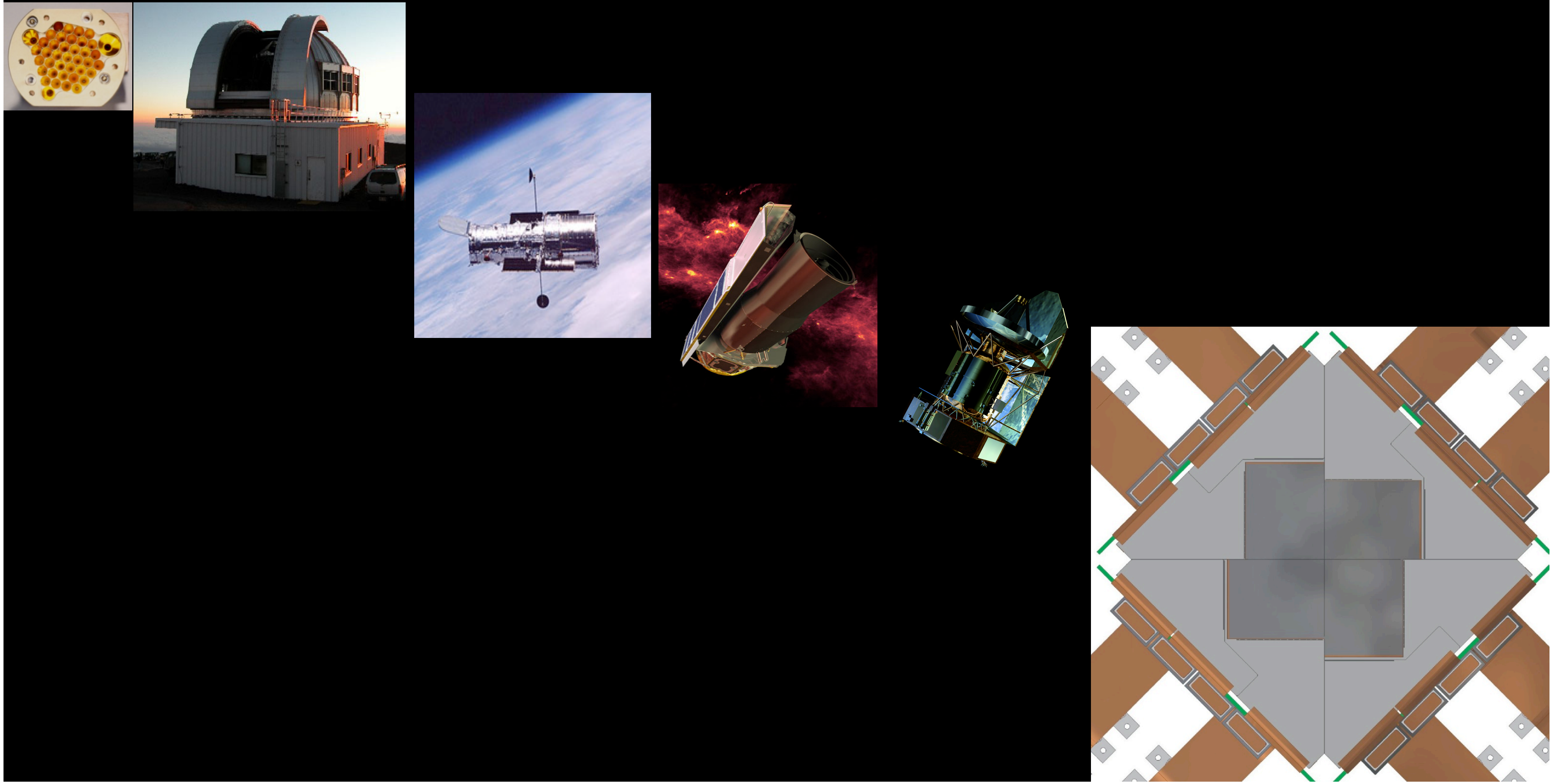


I will focus on

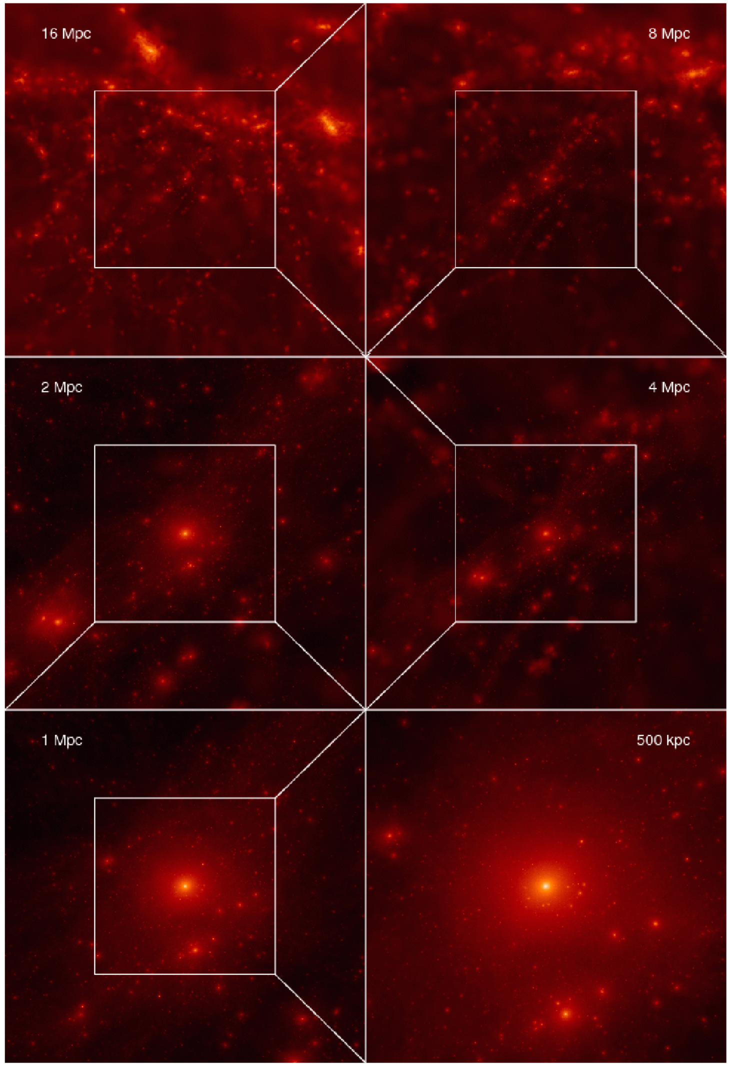
- Motivation
- Continuum imaging at mm/sub-mm wavelengths
- Multi-frequency exploitation & connection

I will say little or nothing about

- CO and C+ spectroscopy
- Clustering
- Detailed studies of lensed sources

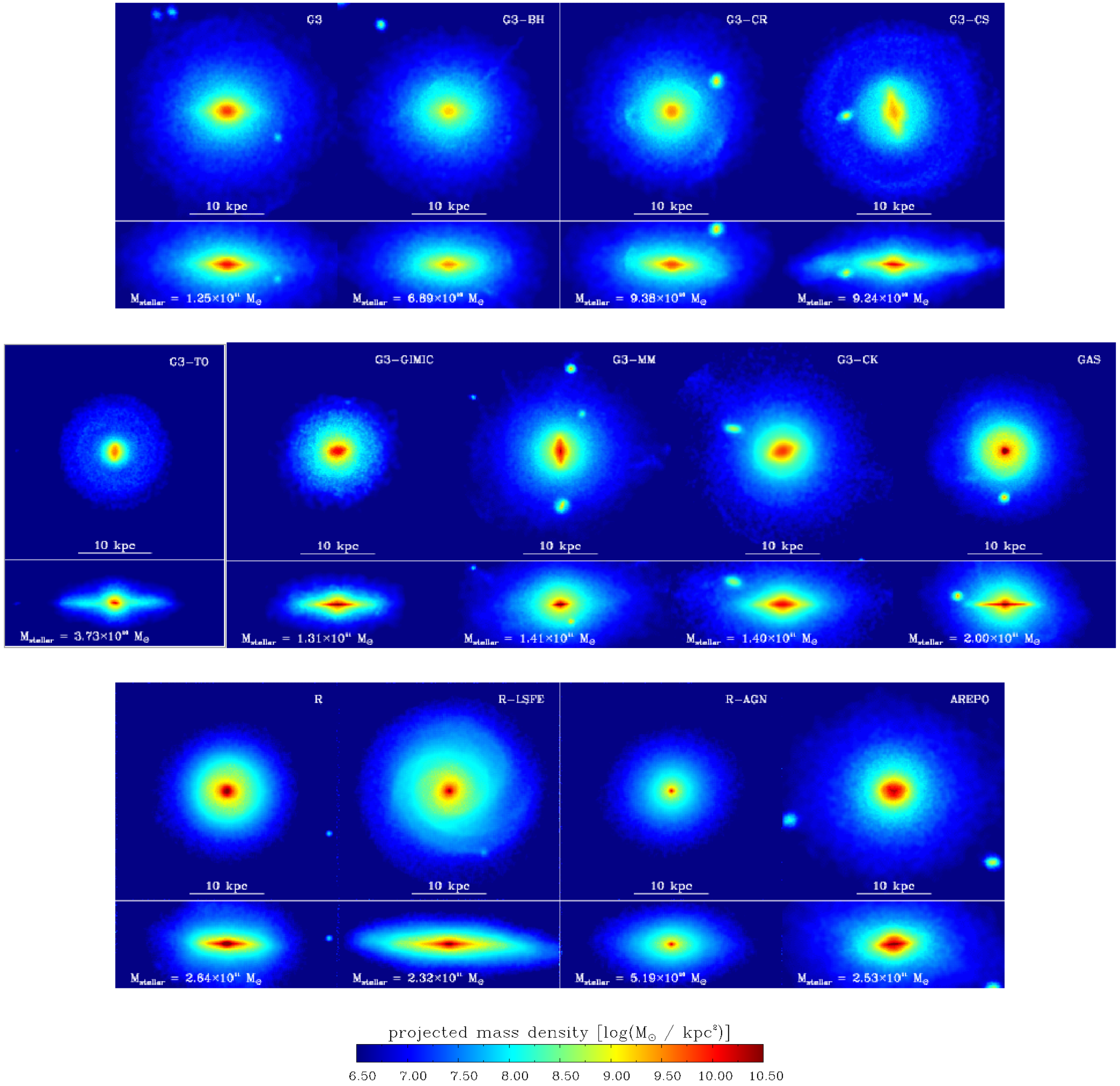
Problems with gas-dynamical models of galaxy formation

Scannapieco et al. 2011 arXiv:1112.0315 (Aquila comparison project)



Problems with hydrodynamic models of galaxy formation

Scannapieco et al. 2011 arXiv:1112.0315 (Aquila comparison project)



Problems with hydrodynamic models of galaxy formation

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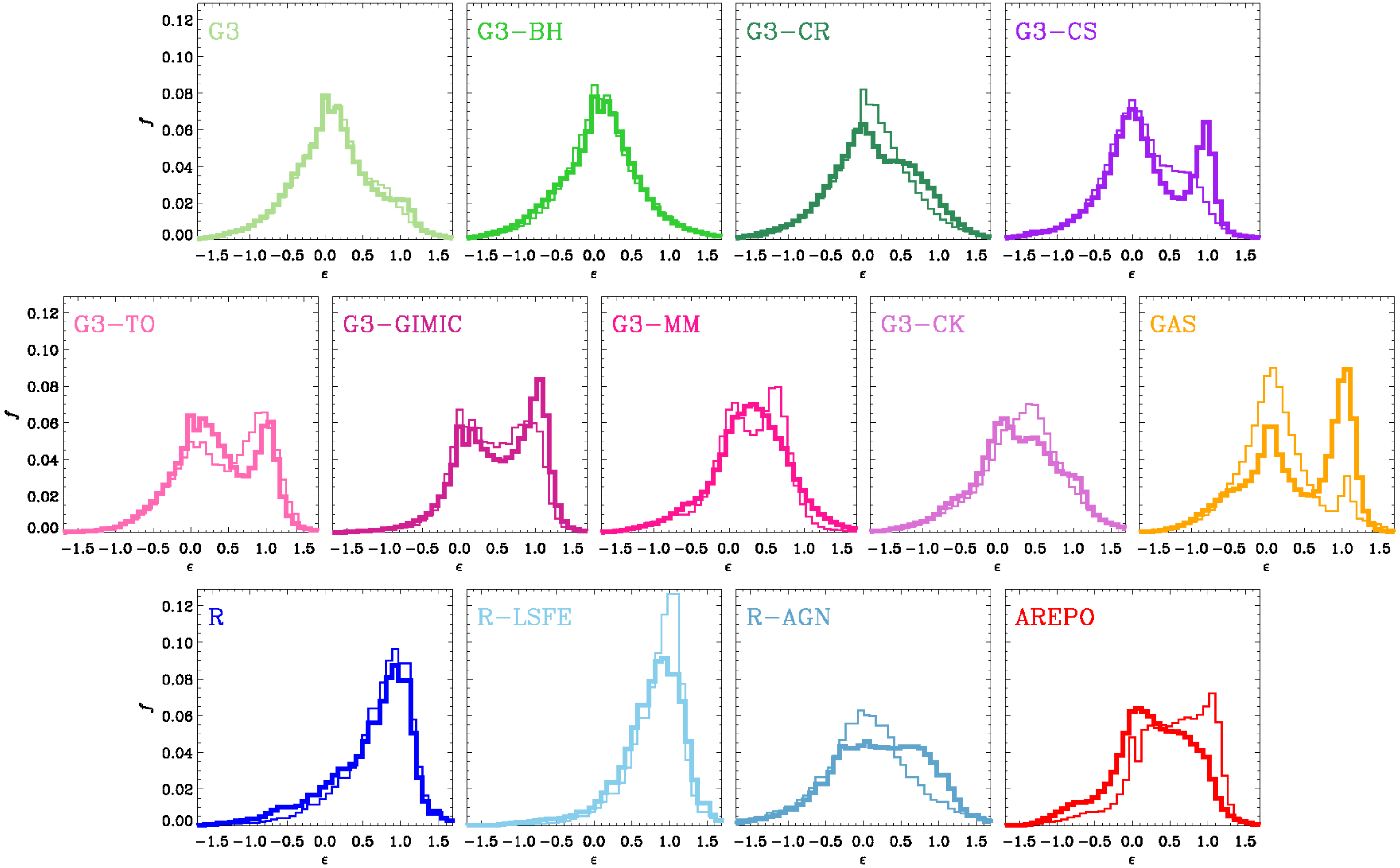

Problems with hydrodynamic models of galaxy formation

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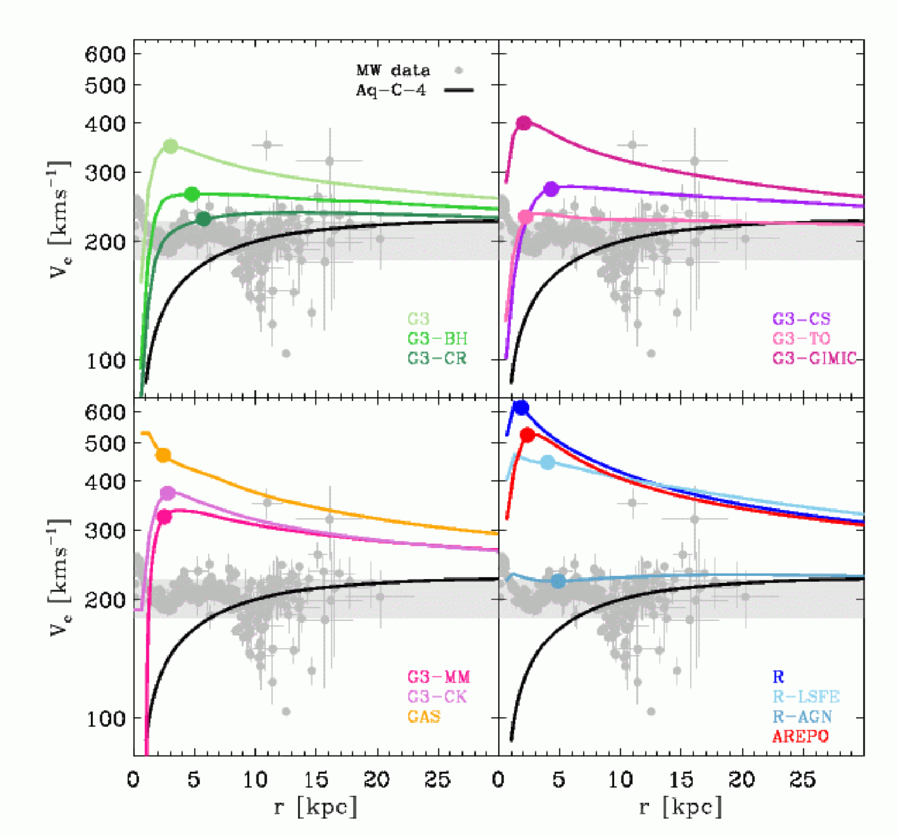
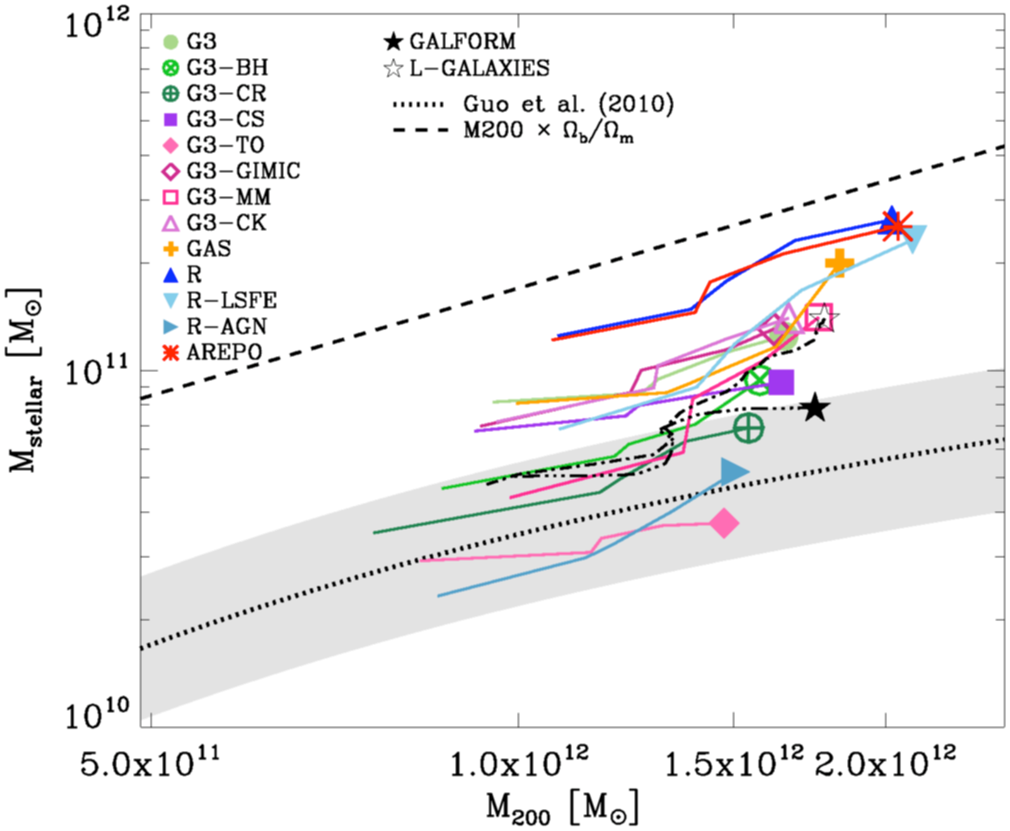




The big issue is feedback

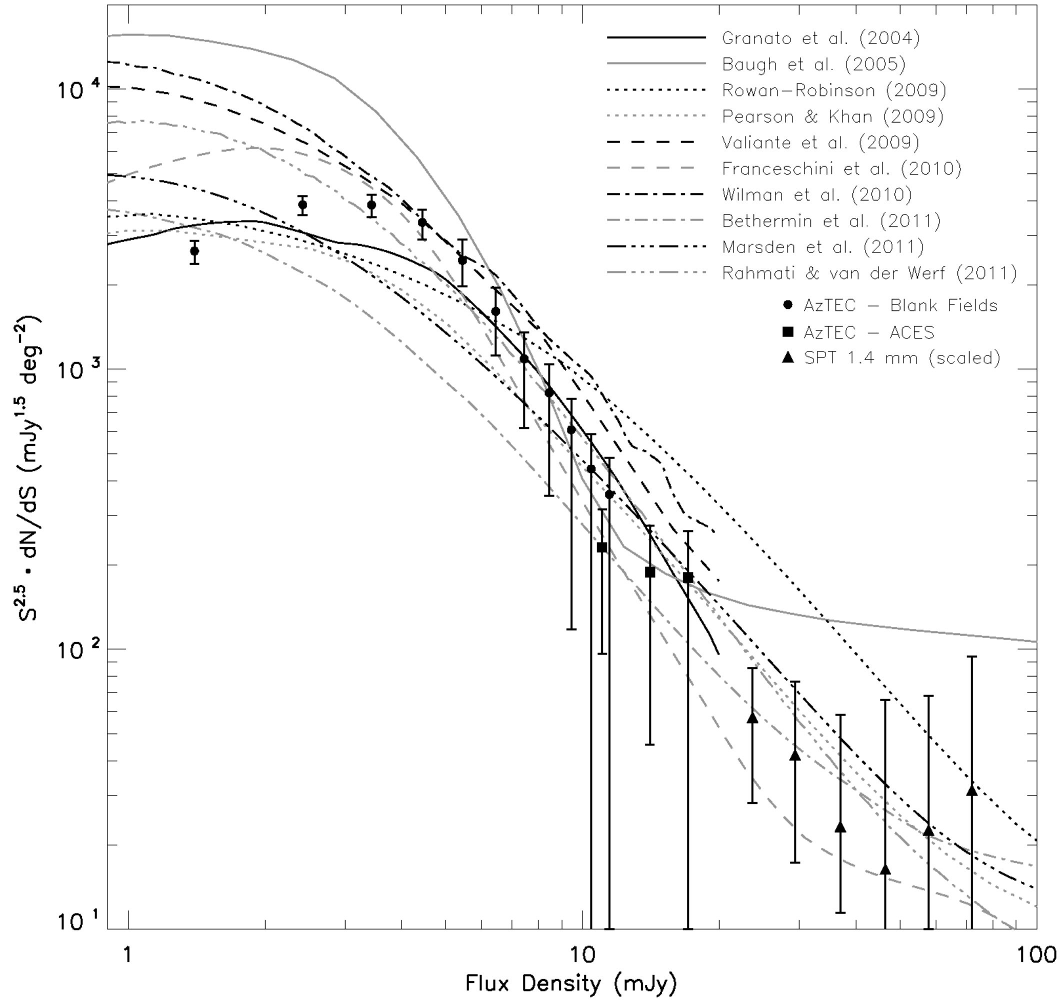
- better observational constraints over cosmic time needed
- as well as a better understanding of milky-way star formation

Problems with semi-analytic & phenomenological models

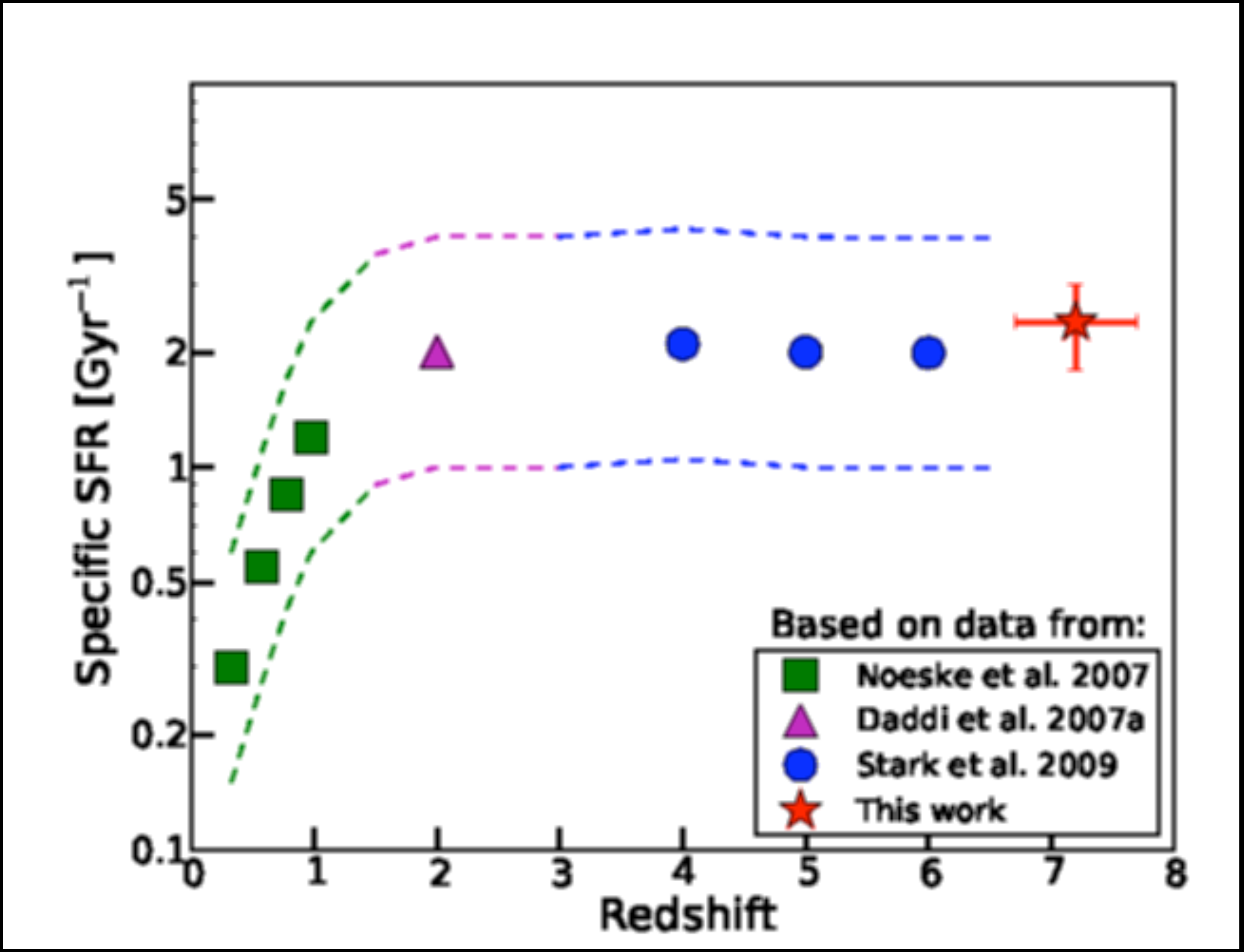
Well known that mm/sub-mm data set demanding constraints

e.g. Number counts from 1.6 sq degree of AzTEC 1.1 mm surveys

Scott et al. 2012



Broader observational context: Cosmic history of sSFR



Gonzalez, V., et al. 2010

How can future mm/sub-mm observations help?

Better constraints on demographics

- More dynamic range in number counts
- Covering representative cosmological volumes
- With decent redshift information
- Extending to redshifts not well sampled by Herschel
- Reaching sufficient depth to detect “normal” high-z galaxies

Better information on basic physical properties

- Bolometric luminosities – disentangling Herschel-SPIRE imaging
- Stellar masses, and specific star-formation rates
- Clustering – halo masses – duty cycles
- Morphologies – no orientation selection bias
- Role within mass-selected samples

Better understanding of star formation & feedback mechanisms

- Importance of molecular hydrogen versus basic gas density
- Ionizing radiation and cosmic ray heating of molecular clouds
- Galaxy black-hole connection

Example - 2 alternative views of sub-mm galaxies

1. Sub-mm galaxies are high-z versions of local ULIRGS
   - moderate mass
   - major mergers
   - compact starburst
   - extreme Specific Star Formation Rate (sSFR=SFR/Mass)

   (e.g. Gonzalez, J. et al. 2010; Hainline et al. 2011; Engel et al. 2010)

2. Sub-mm galaxies are simply the high-mass end of normal star-forming galaxies at z = 2 – 3
   - high mass
   - high gas supply/reserve
   - spatially extended “normal” star-formation – in discs?
   - standard sSFR - what does this mean?

   (e.g. Dave et al. 2010; Targett et al. 2011; Rujopakarn et al. 2011)

This requires a near-IR to mm perspective…

HST WFC3 (~ 1 micron) - morphologies

Spitzer IRAC (~ 5 micron) - stellar masses

BLAST/Herschel (~100 micron) - T, star-formation rate

SCUBA/Laboca/AzTEC (~1mm) - dust mass, SFR

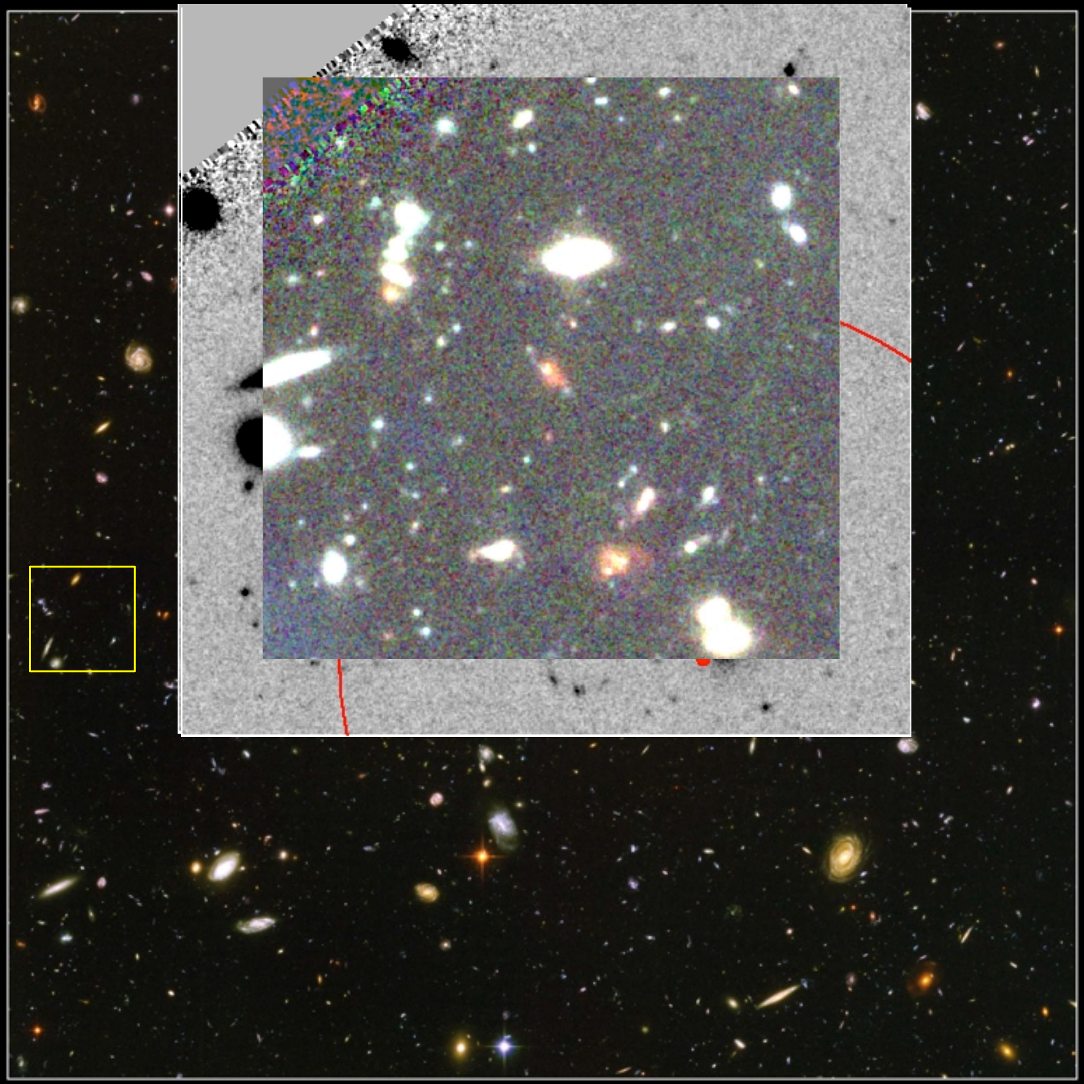
IRAM PdB/EVLA (mm-cm) - gas/dynamical mass

Problem: angular resolution dynamic range of ~500

The sub-mm source in the HUDF

Dunlop 2011, arXiv:1108.5679

HUDF



BLAST 250 micron

AzTEC 1100 micron

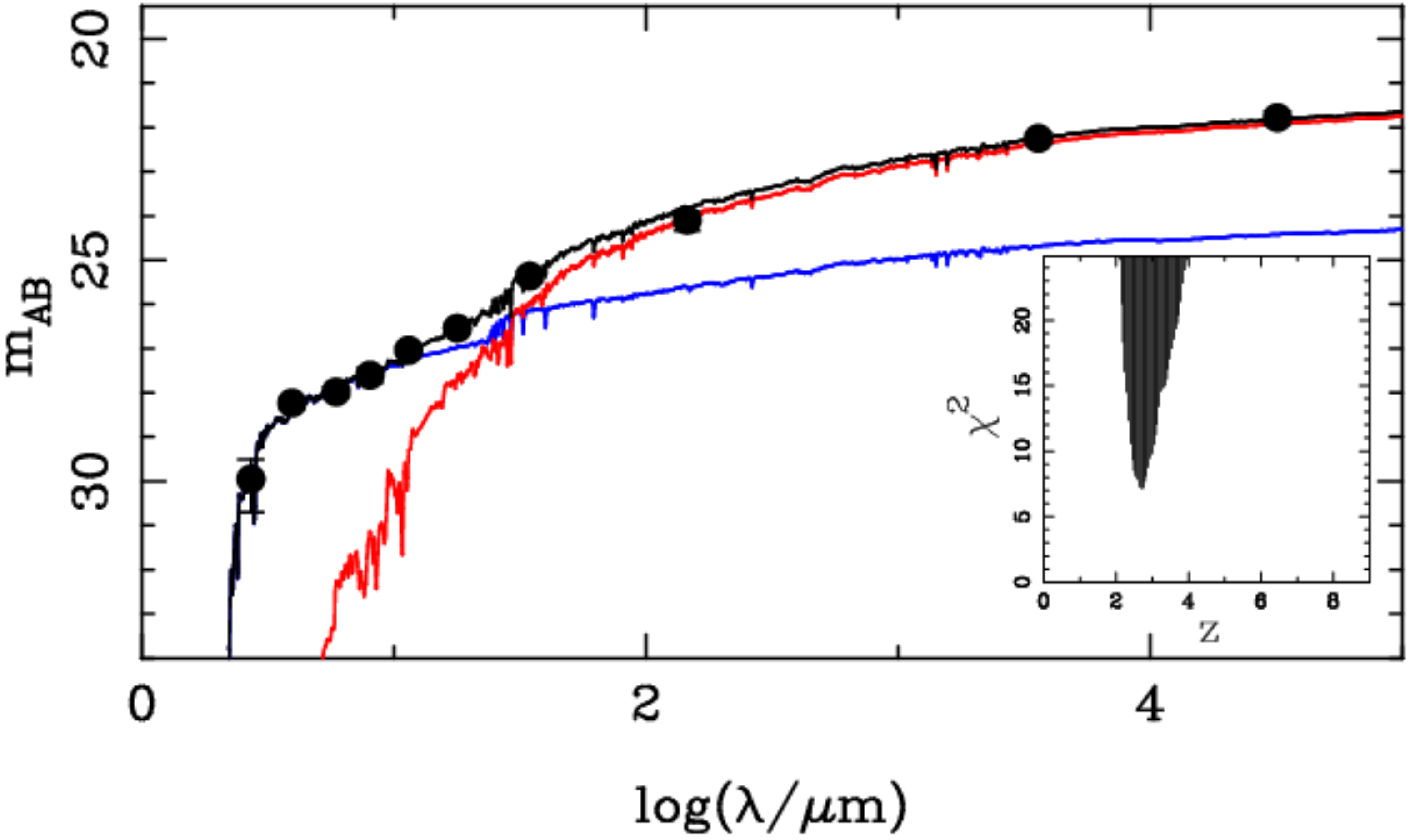
Laboca 870 micron

VLA 1.4 GHz

Y,J,H HST WFC3

2-component SED fit to world's best photometry

z = 2.97, stellar mass $M_* = 2.5 \times 10^{11}\ M_{sun}$ (Chabrier IMF)



Stellar Masses

Even assuming accurate z and good optical-IRAC photometry, there are several issues:

1. Single or double component

2. Maraston or BC2003 models

3. Chabrier or Salpeter IMF

Stellar Masses

Even assuming accurate z and good optical-IRAC photometry, there are several issues:

1. ~~Single~~ or double component – need double-component fits

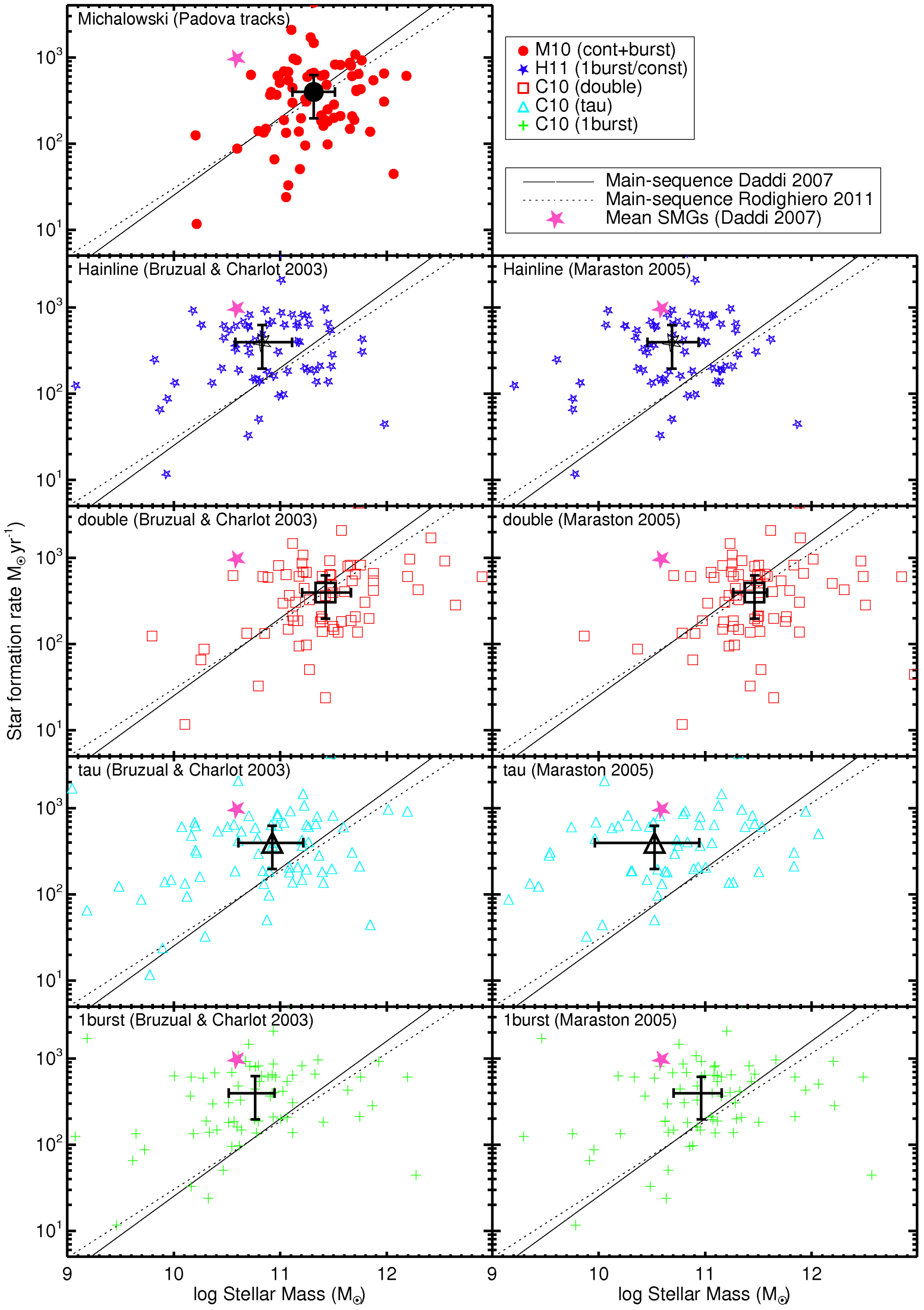
2. ~~Maraston~~ or BC2003 models – Maraston now ~ ruled out

3. Chabrier or ~~Salpeter~~ IMF – Salpeter seems to give excessively large masses

Gives average $M_* \sim 2 \times 10^{11}\ M_{sun}$

(e.g. Michalowski et al. 2011; Schael et al. 2011)

cf $M_* \sim 5 \times 10^{10}\ M_{sun}$ (e.g. Hainline et al. 2011; Bussmann et al. 2011)


Michalowski (Padova tracks)
Hainline (Bruzual & Charlot 2003)
Hainline (Maraston 2005)
double (Bruzual & Charlot 2003)
double (Maraston 2005)
tau (Bruzual & Charlot 2003)
tau (Maraston 2005)
1burst (Bruzual & Charlot 2003)
1burst (Maraston 2005)
● M10 (cont+burst)
★ H11 (1burst/const)
□ C10 (double)
△ C10 (tau)
+ C10 (1burst)
Main-sequence Daddi 2007
Main-sequence Rodighiero 2011
★ Mean SMGs (Daddi 2007)
Star formation rate $M_{\odot} yr^{-1}$)
10^1
10^2
10^3
9
10
11
12
log Stellar Mass ($M_{\odot}$)

Dynamical Masses

CO 3-2 work has yielded $v \sim 300\ \mathrm{km\ s^{-1}}$, $r \sim 2$ kpc

$\Rightarrow M_{dyn} = 2 \times 10^{11}\ M_{sun}$ (e.g. Tacconi et al. 2008)

But recent CO 1-0 results suggest $v \sim 400\ \mathrm{km\ s^{-1}}$, $r \sim 6$kpc

$\Rightarrow M_{dyn} \sim 5 \times 10^{11}\ M_{sun}$ (e.g. Ivison et al. 2010)

Gas Masses

Who knows…..

But dynamical masses can probably now accommodate ~50:50 split between stars and molecular mass, i.e.

$\Rightarrow M_{gas} \sim 2 \times 10^{11} M_{sun}$

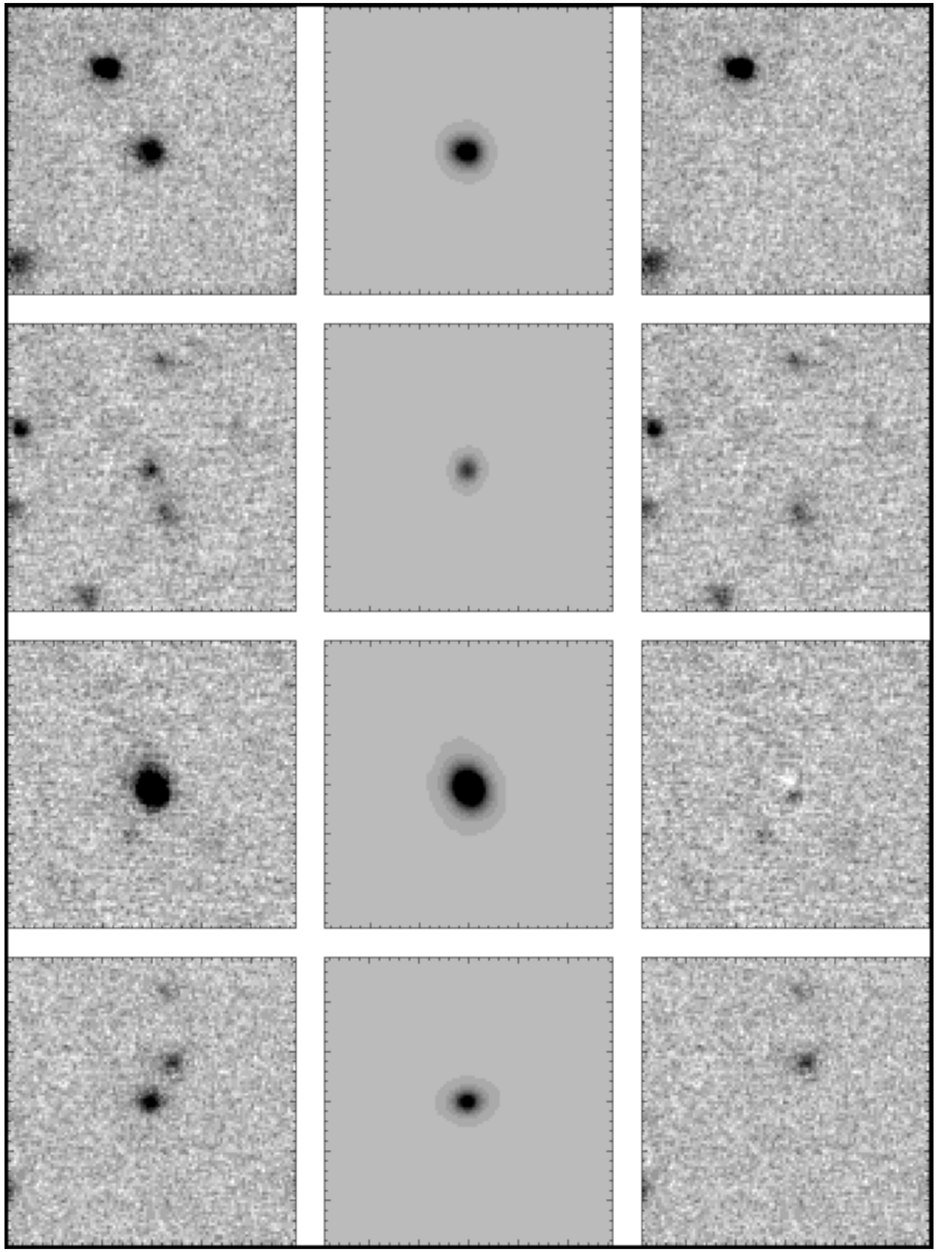
Comparison with CO luminosities could then be consistent with CO to H_2 conversion ratio of ~5 as in the Milky Way, rather than 0.8 as assumed for ULIRGS (bi-model X_{CO} idea now discredited anyway – e.g. Krumholtz et al. 2011)

Morphologies

Some objects do seem to look like mergers, but Targett et al. (2011) found most sub-mm galaxies to have a dominant disc galaxy with $r_{1/2} \sim 3$ kpc.

But this result is based on ground-based K-band imaging (albeit with ~0.4 arcsec seeing)

Somewhat different conclusions have been reported from HST ACS and NICMOS imaging (e.g. Swinbank et al. 2011; Ricciardelli et al. 2010)



K-band imaging/modelling

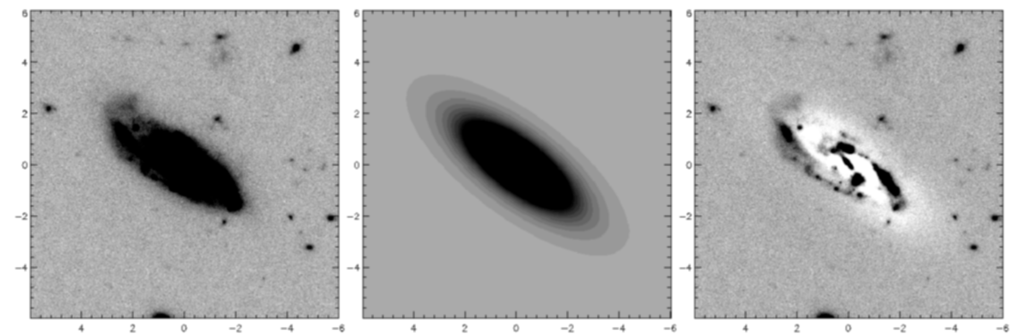
But now we have WFC3/IR……….

Back to the sub-mm galaxy in the HUDF

Low-redshift control – disc galaxy at z = 0.345

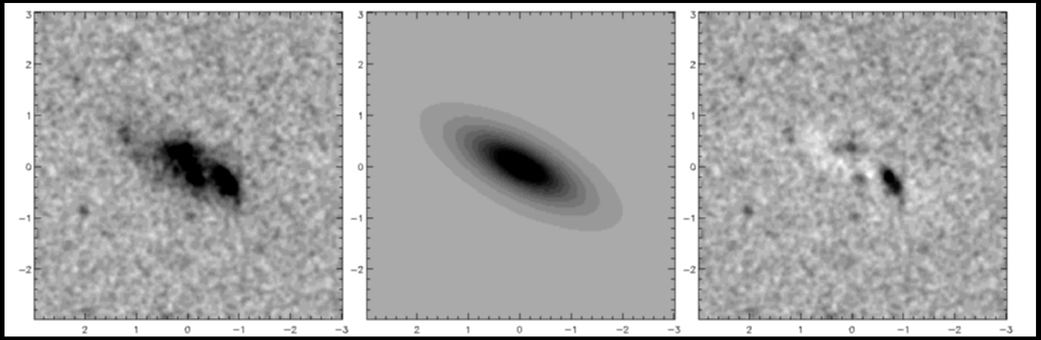
Galaxy Model fitting

Control galaxy
z = 0.345
ACS B-band



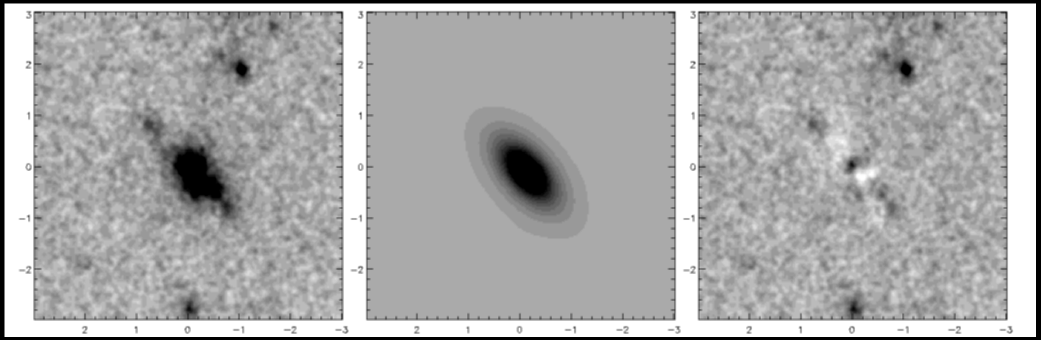
Disc galaxy
Re = 8 kpc

Control galaxy
z = 3 simulated
WFC3 H-band



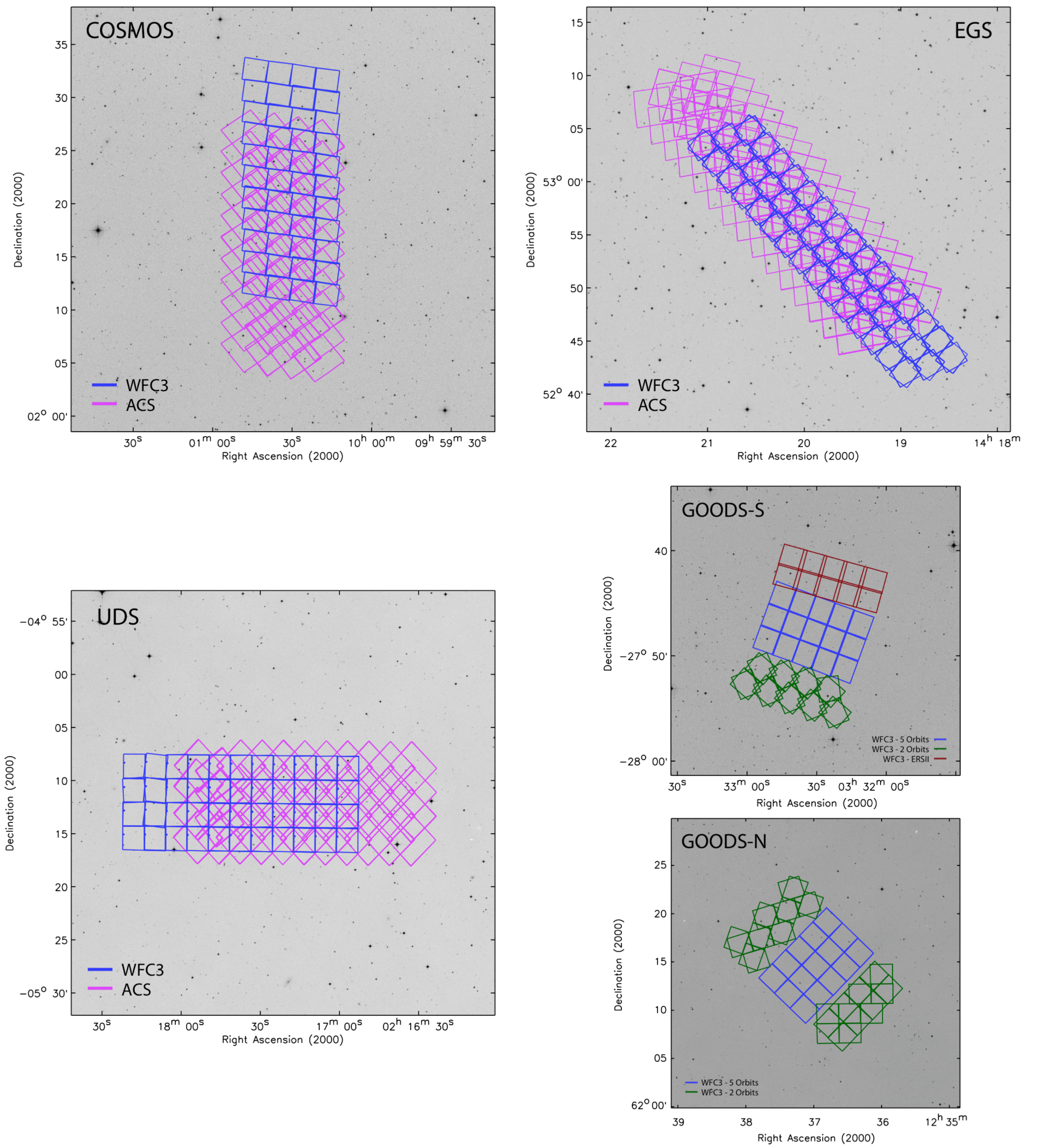
Disc galaxy
Re = 8 kpc

Real z = 3
submm galaxy
WFC3 H-band

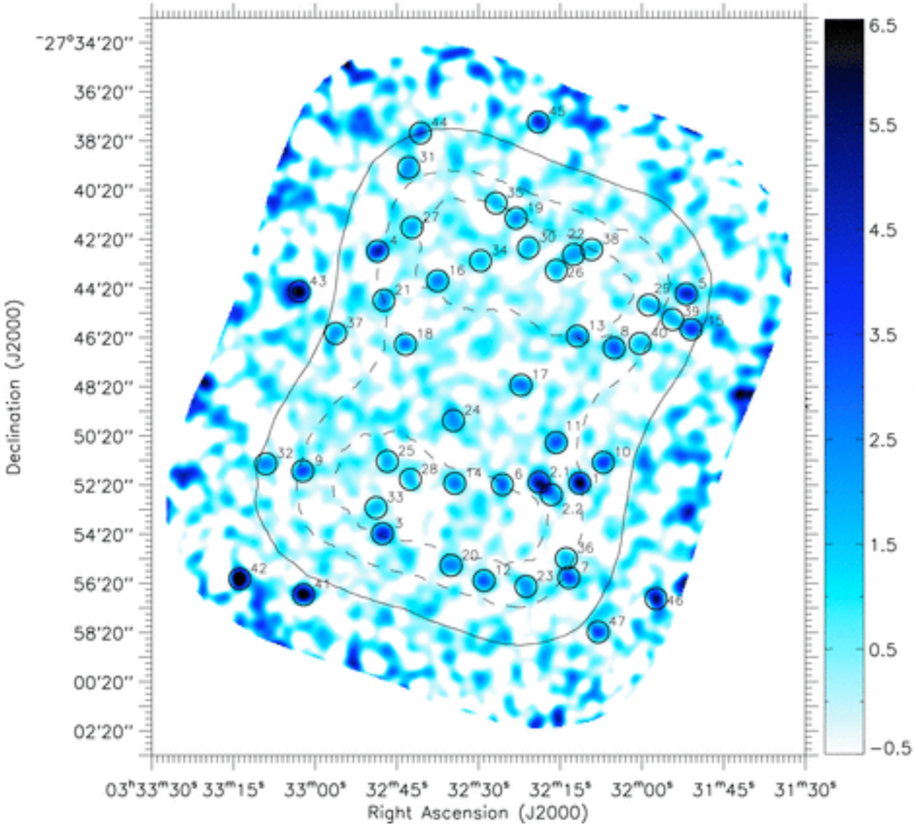


Disc galaxy
Re = 5 kpc

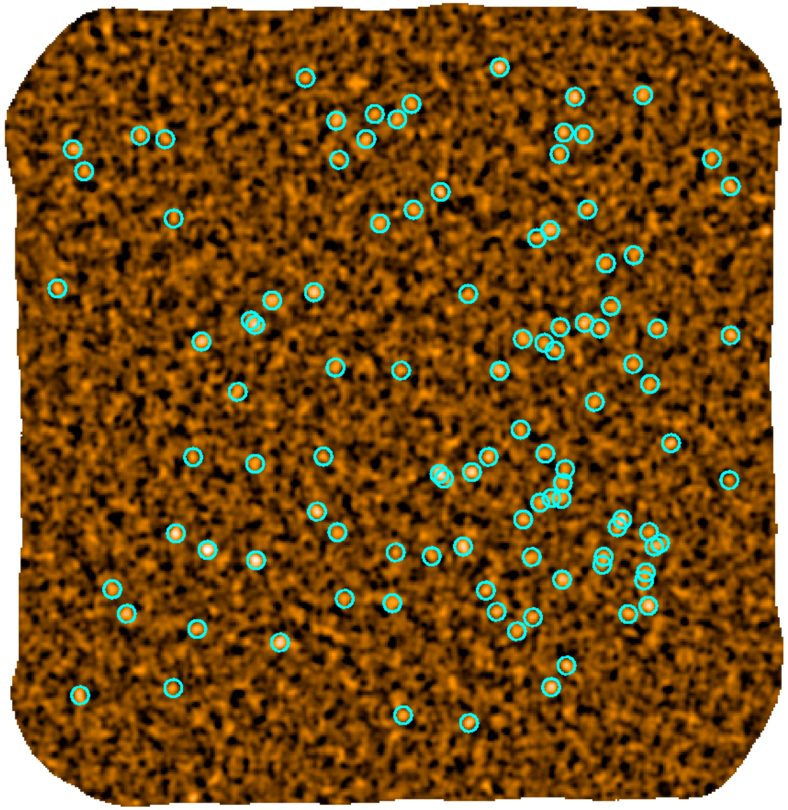
And now we have CANDELS………



GOODS-South sub-mm sources



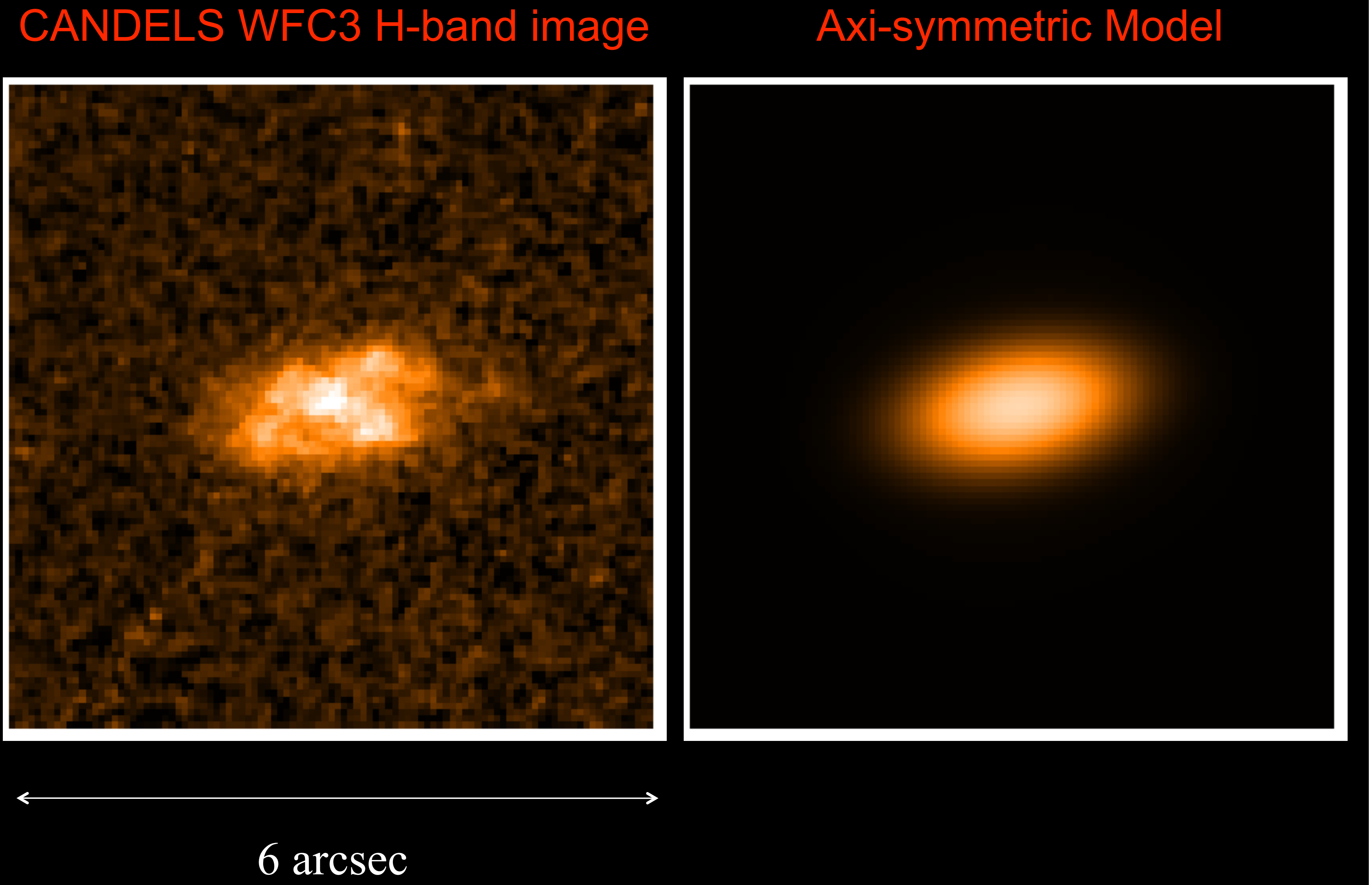
AzTEC 1.1 mm (Scott et al. 2010)
26' x 20' field



LABOCA 870 μm (Weiss et al. 2009)
30' x 30' field

25 sources in CANDELS area – only 1 LABOCA source not in AzTEC map

AzTEC.GS08 – clumpy disc?

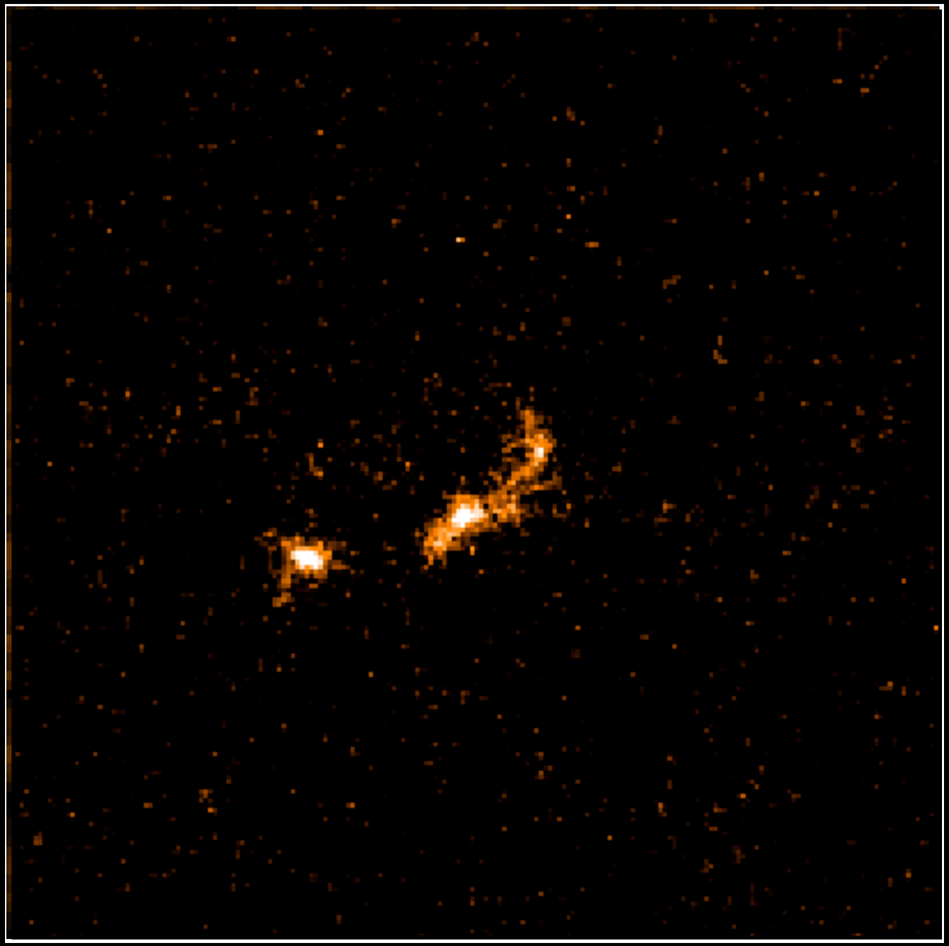


CANDELS WFC3 H-band image

Axi-symmetric Model

LESSJ033243 – merger or very clumpy disc?

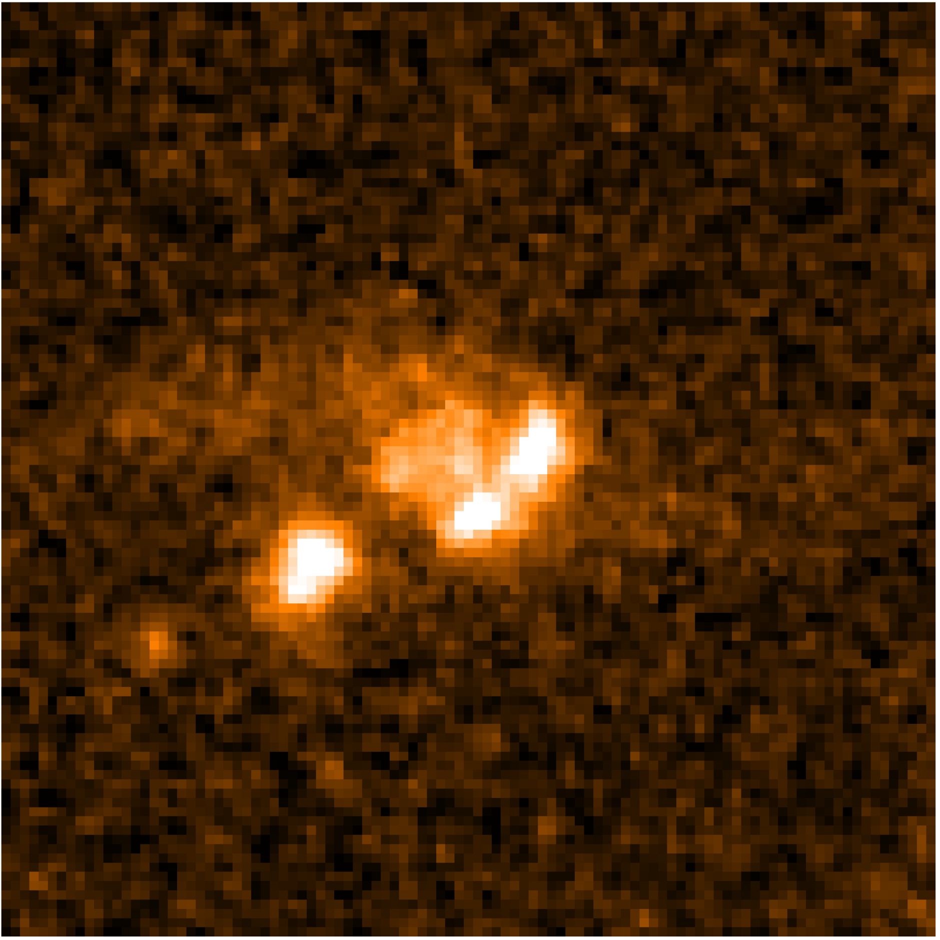
ACS I-band



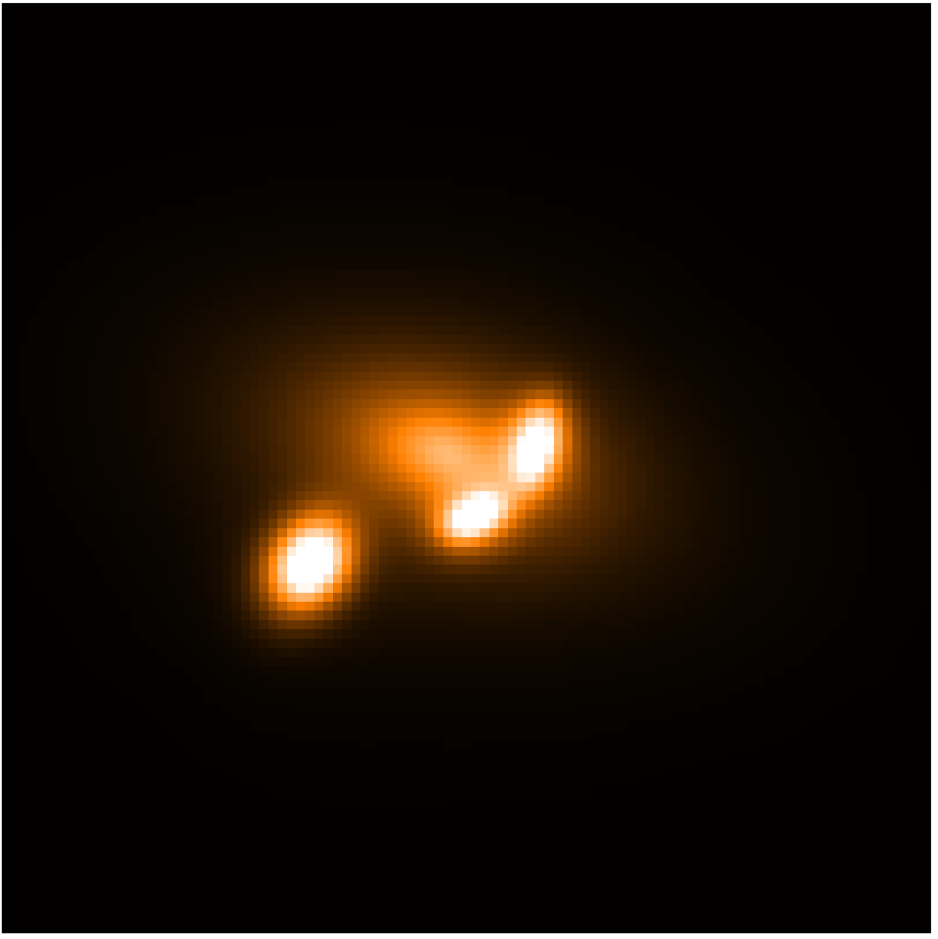
Shallow H-band

So no great surprise NICMOS imaging seems to agree with ACS

LESSJ033243 – merger or very clumpy disc?



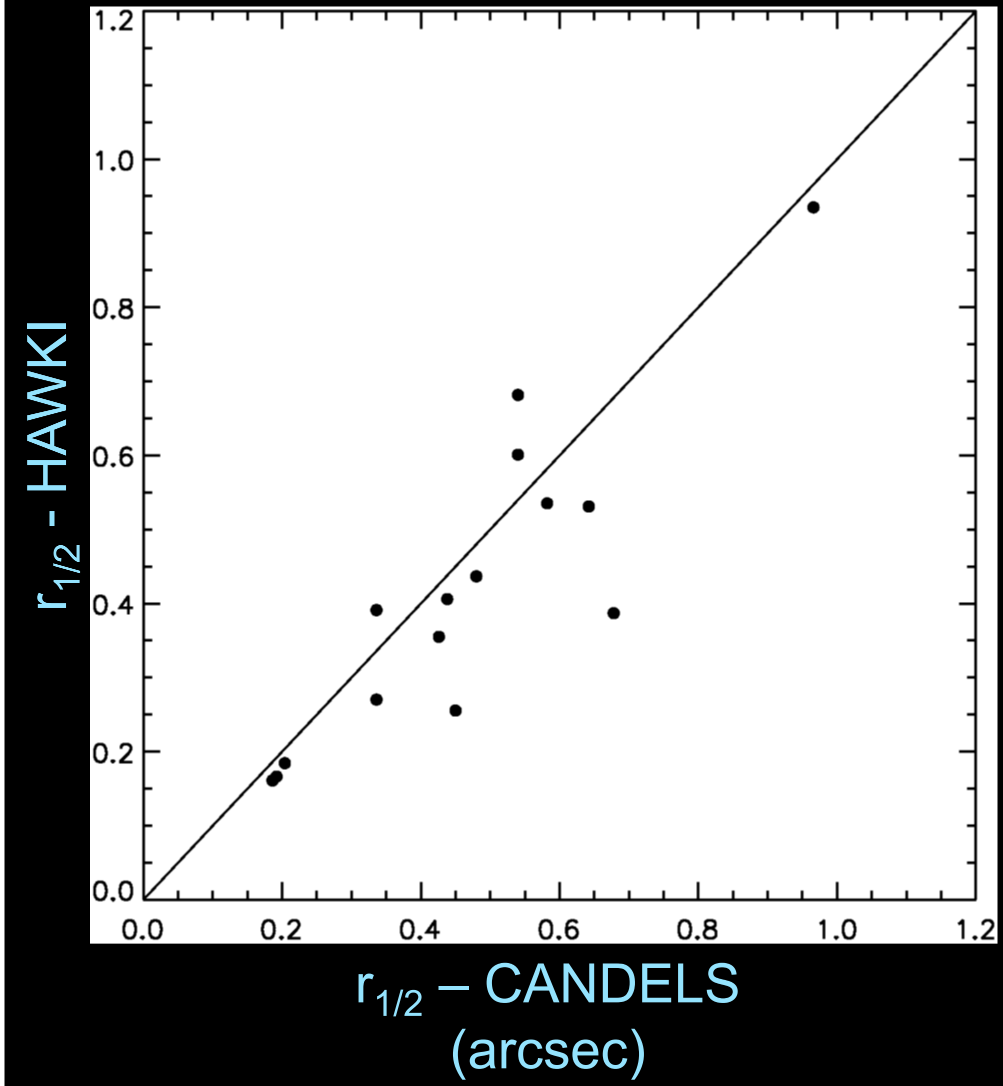
CANDELS WFC3 H-band image

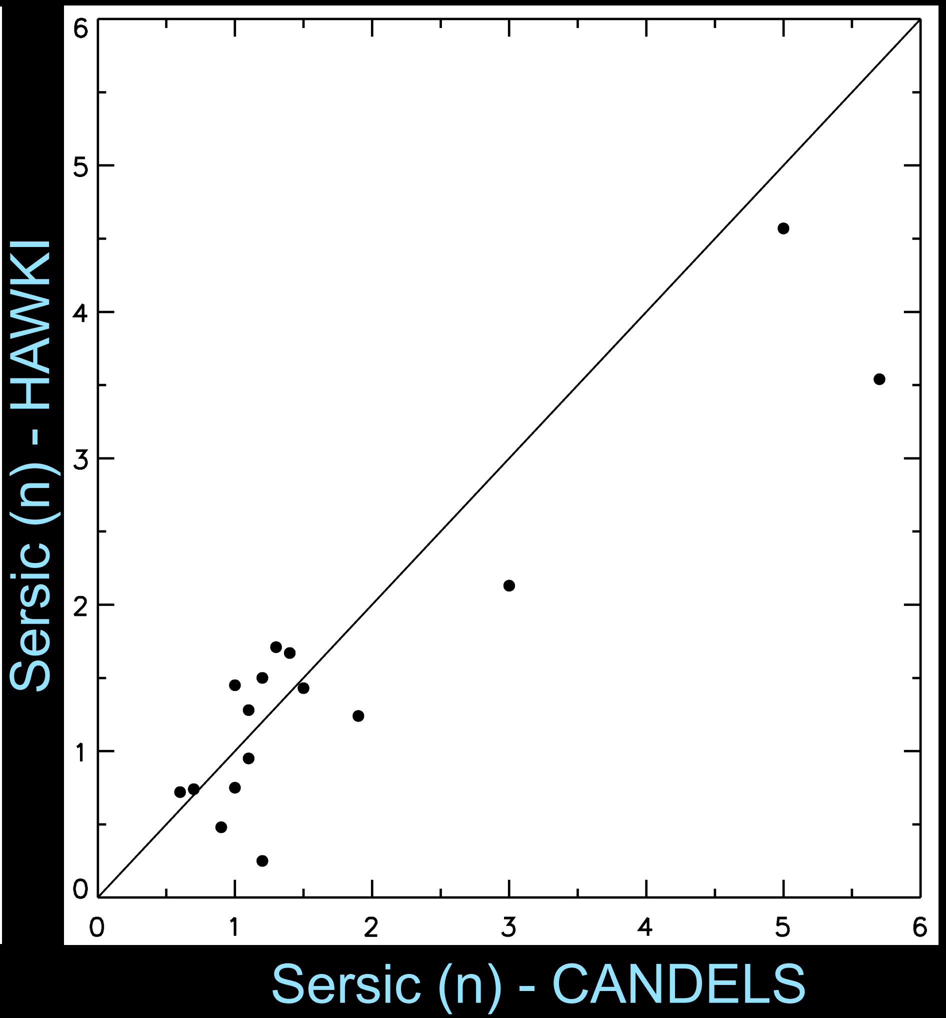


4-component Model

Space based versus Ground based

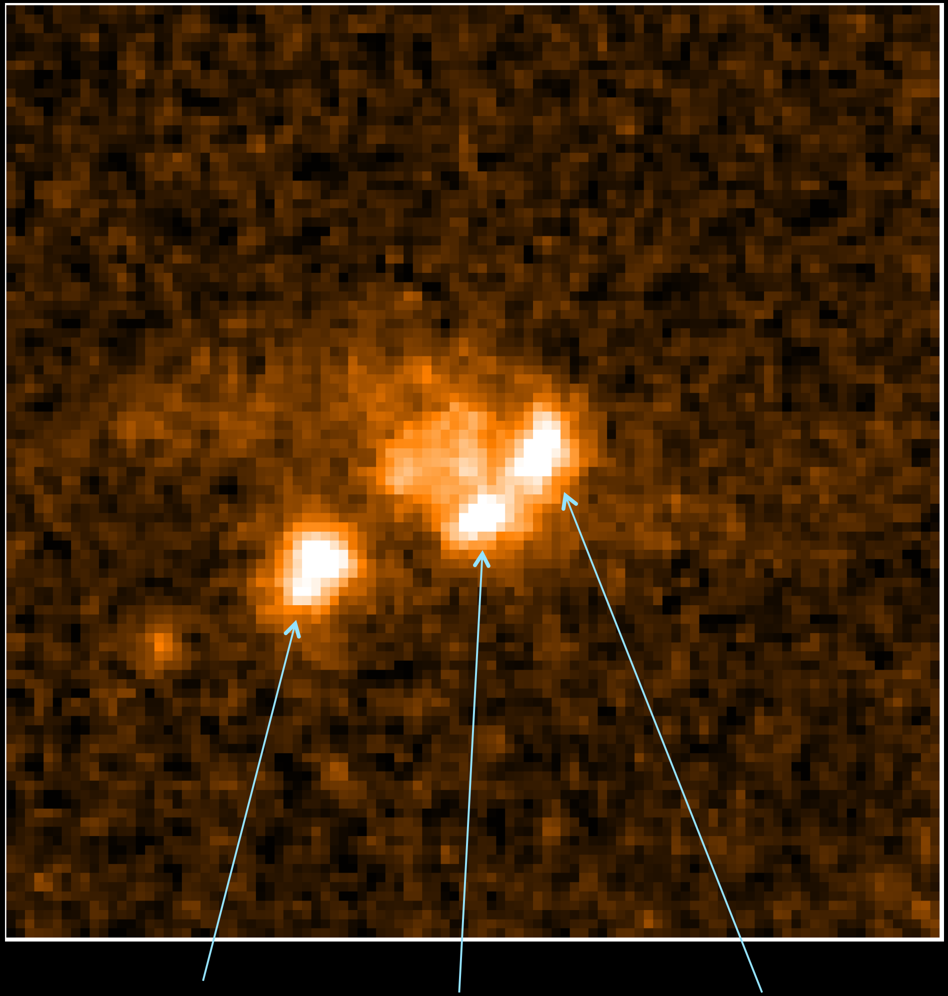
Ground-based K-band results are pretty good!





But WFC3 exposes the details & the underlying disc galaxy

High surface-brightness clumps ?

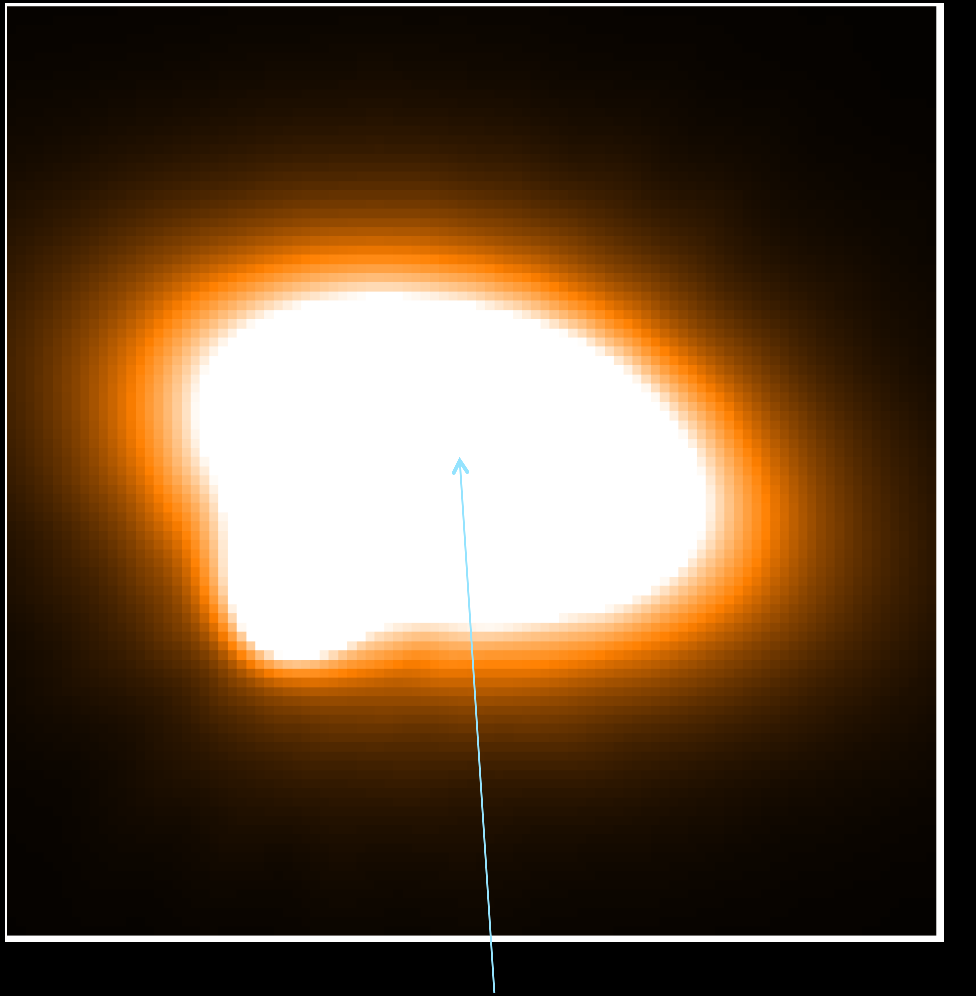


1.5 kpc
n = 0.8

1.1 kpc
n = 0.4

1.4 kpc
n = 0.4

Big underlying disc

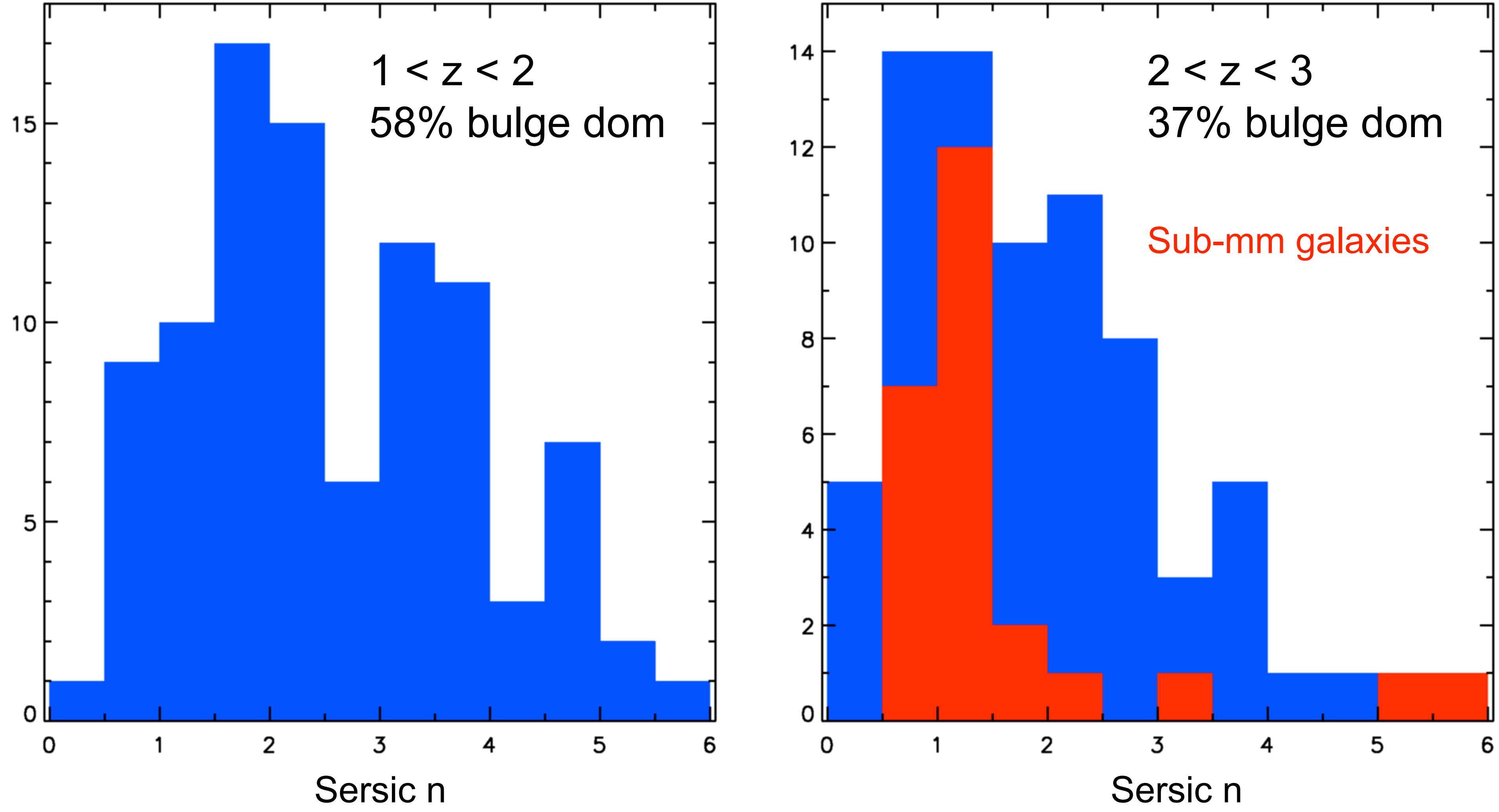


7.3 kpc
n = 1.1

Morphological results in context

Detailed study of all ~220 galaxies in CANDELS UDS field with $1 < z < 3$ and $M_* > 10^{11} M_{sun}$

Bruce et al. (2012)



Morphological results in context

~ All sub-mm galaxies at z ~ 1.5 – 3 are massive discs

~ 10% of massive galaxies at z ~ 1.5 – 3 are sub-mm galaxies

~ 50% of massive discs at z ~ 1.5 – 3 are sub-mm galaxies

In summary, the archetypal “8-mJy” sub-mm galaxy…..

- is a “mature” star-forming disc galaxy at $z = 1.5 - 3$
- is forming stars at ~500 solar masses per year
- has stellar mass $M_* \sim 2 \times 10^{11}\ M_{\mathbf{sun}}$
- has a gas mass $M_g \sim 0.5 - 2 \times 10^{11}\ M_{\mathbf{sun}}$
- has dynamical mass $M_d \sim 5 \times 10^{11}\ M_{\mathbf{sun}}$
- has implied halo mass $M_h \sim 1 \times 10^{13}\ M_{\mathbf{sun}}$

cf HeRMES clustering result

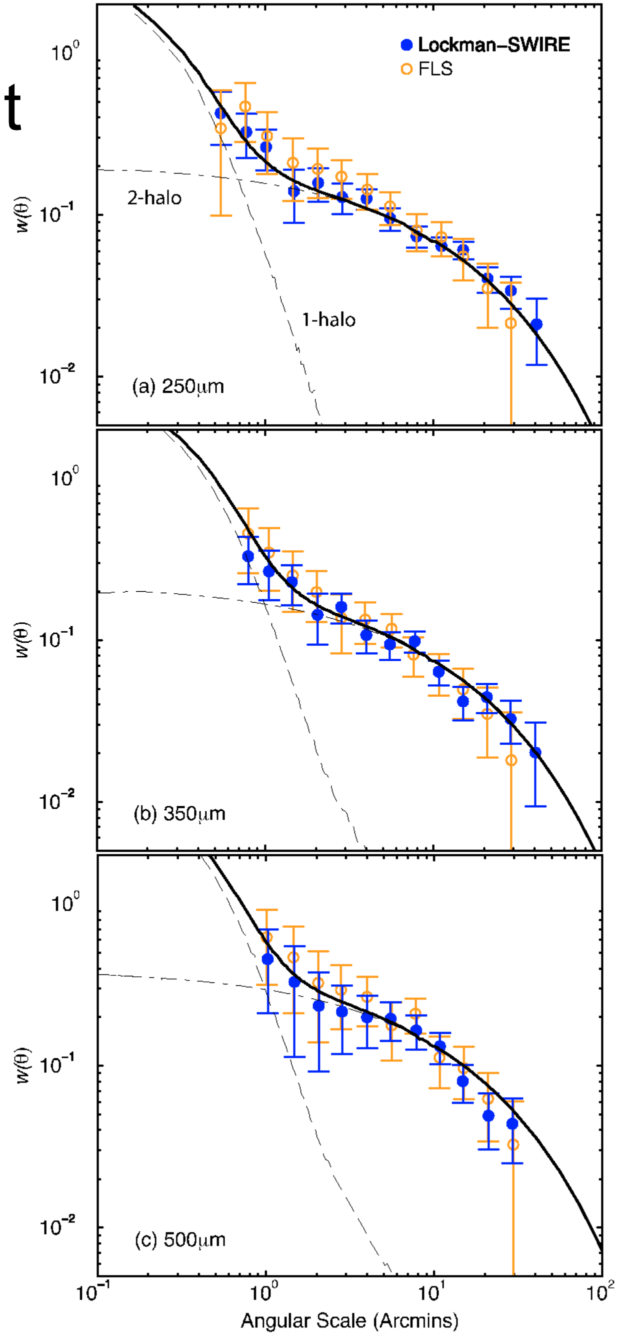
- has $r_{1/2} \sim 3$ kpc
- has sSFR ~ 2.5 per Gyr
- is “expected” at these redshifts…………

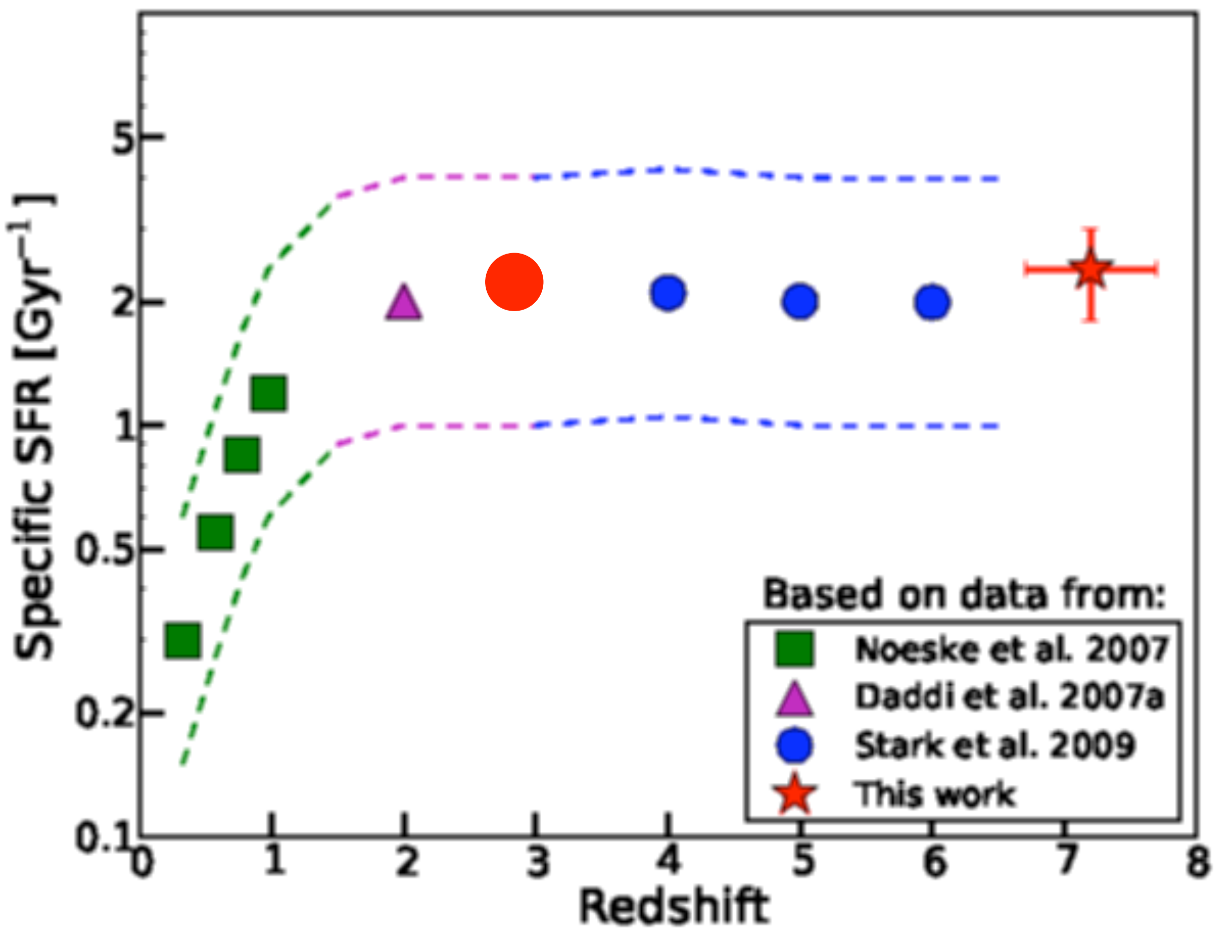
Herschel HerMES clustering measurement

Cooray et al. 2011

500 micron sources live in halos with
$M_d \sim 10^{13}$ solar masses

consistent with
$M_* \sim 2 \times 10^{11}$ solar masses





Independent number – from Ricciardelli et al. 2010
<z=2.3> and <SSFR = 2.2>

What next on the mm/sub-mm imaging front?

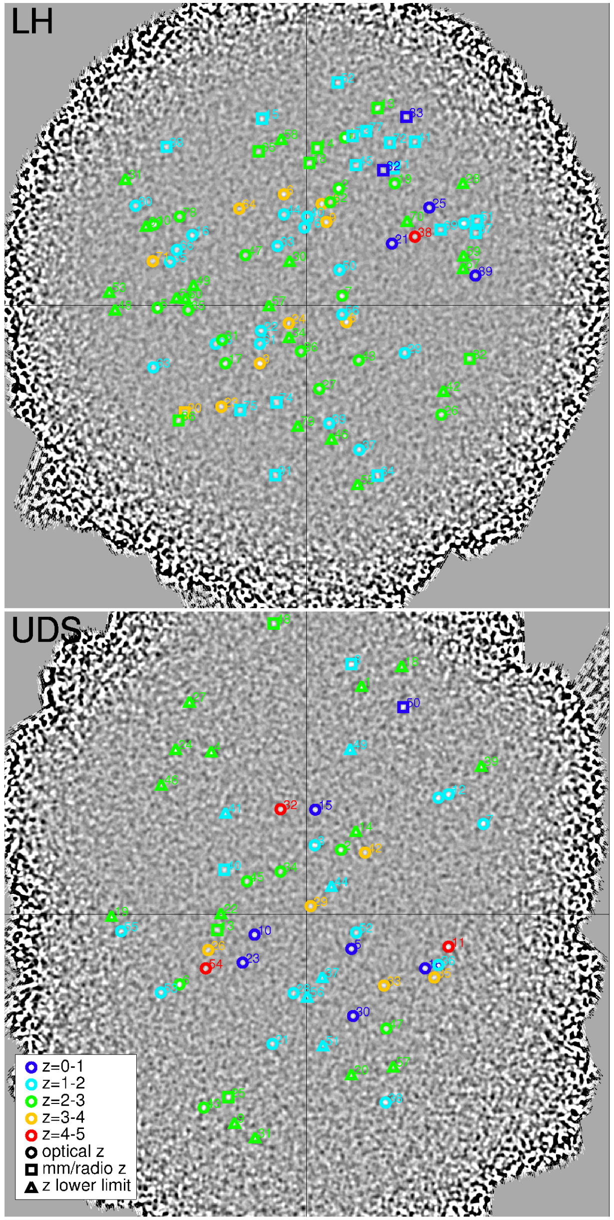
SCUBA2 850 micron imaging of ~ 10 sq degrees

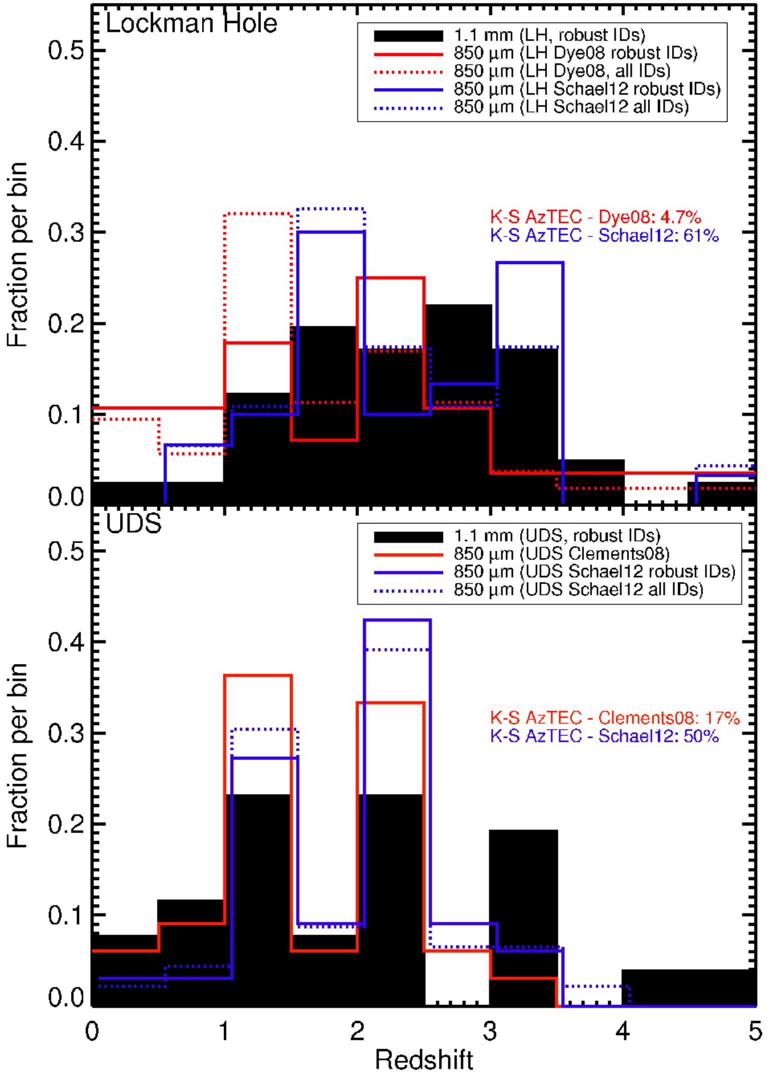
Deep SCUBA2 450/850 micron imaging of all CANDELS fields

Ultra-deep ALMA imaging of HUDF and GOODS fields

Need more area at bright end - e.g. SHADES-AzTEC fields

Michalowski, Dunlop et al., 2011

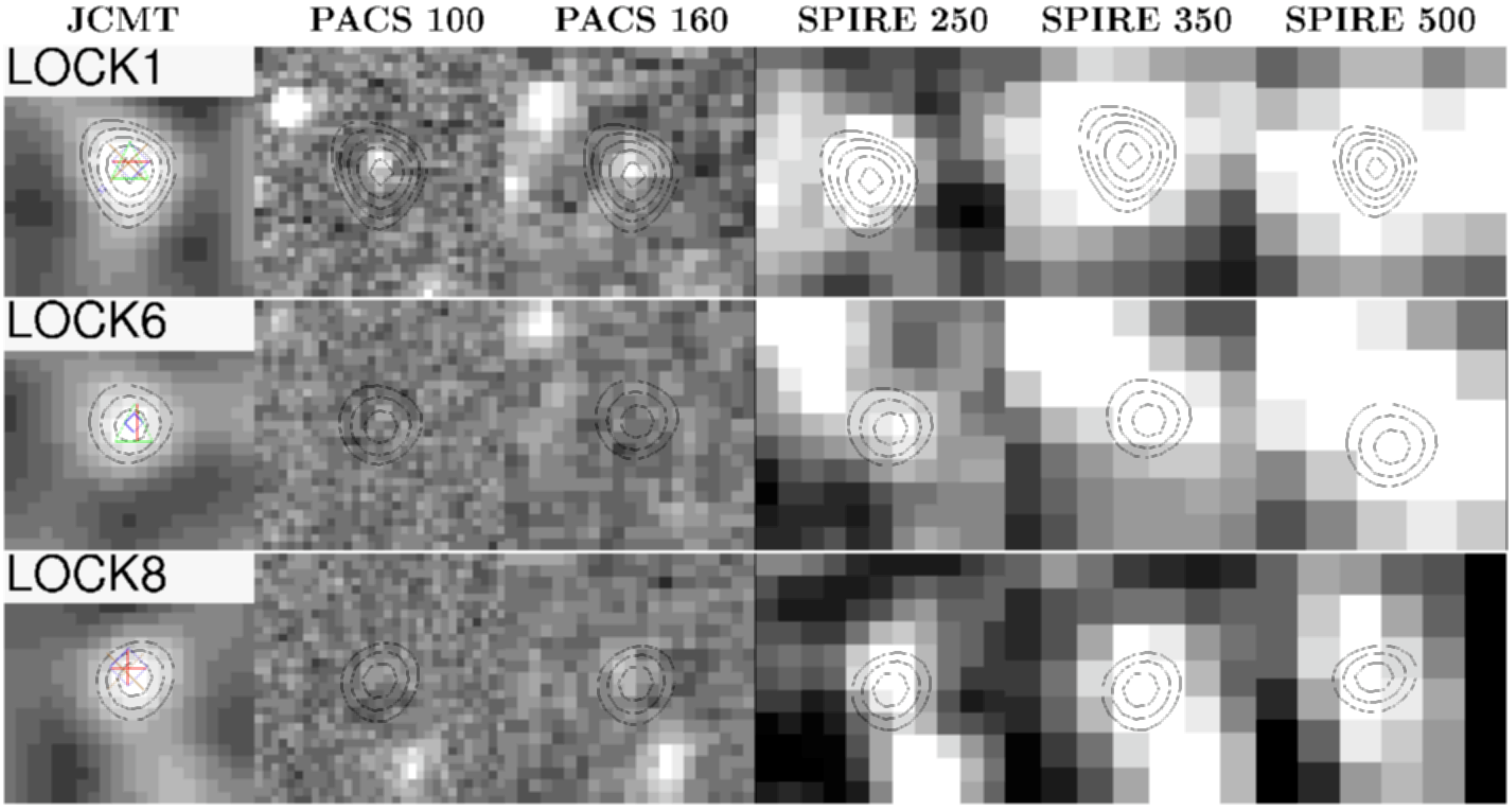




But hasn’t Herschel covered plenty area?

Yes – but we need to properly milk the PACS+SPIRE dataset

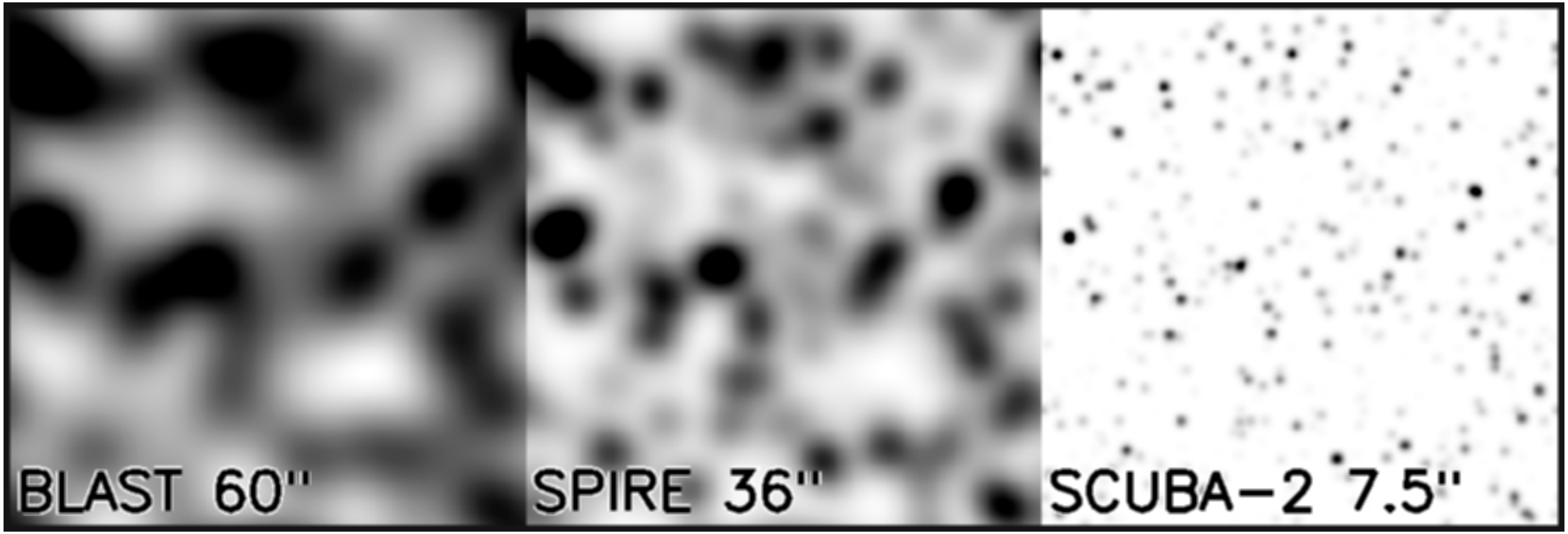
Combining JCMT and Herschel observations



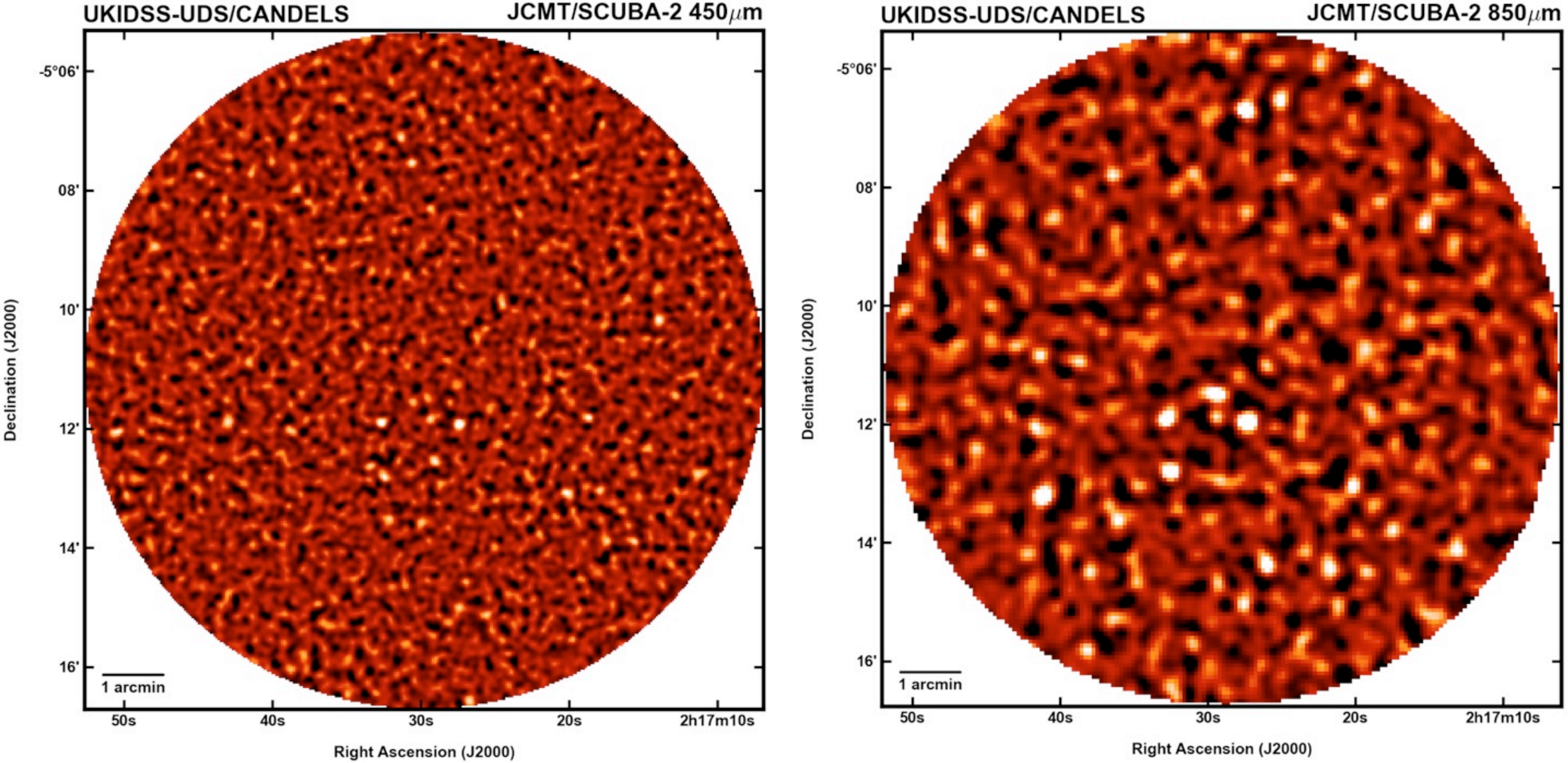
SCUBA2 - why do we still care about the JCMT?

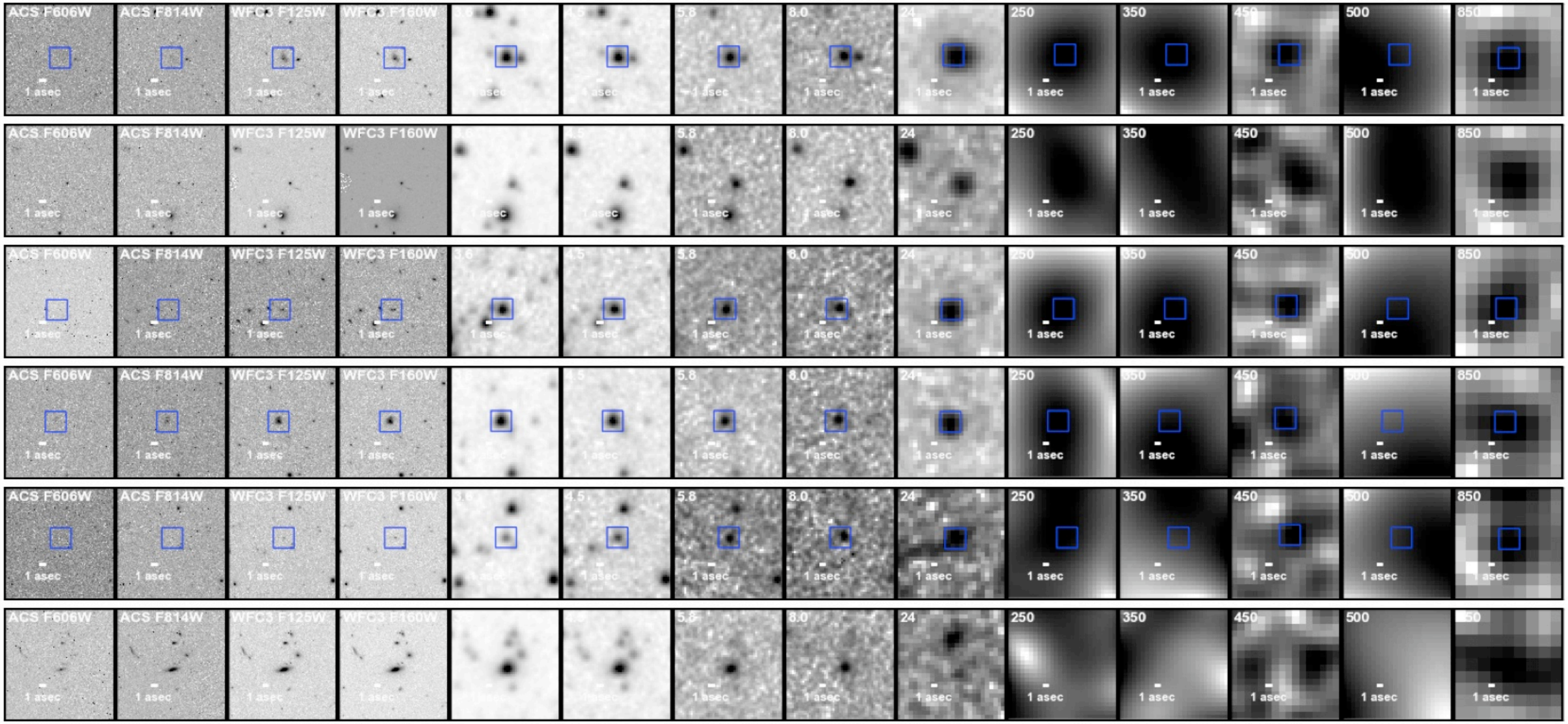
Because it is 15 m wide

Resolution comparison of BLAST, Herschel and JCMT at 500/450 microns
50 square arcmin simulation based on BLAST counts



SCUBA2 needed to fully exploit Herschel maps (especially at high-z) to establish secure galaxy counterparts, and robust SEDs/SFRs


UKIDSS-UDS/CANDELS
JCMT/SCUBA-2 450μm
-5°06'
08'
10'
12'
14'
16'
Declination (J2000)
1 arcmin
50s
40s
30s
20s
2h17m10s
Right Ascension (J2000)
UKIDSS-UDS/CANDELS
JCMT/SCUBA-2 850μm
-5°06'
08'
10'
12'
14'
16'
Declination (J2000)
1 arcmin
50s
40s
30s
20s
2h17m10s
Right Ascension (J2000)


ACS F606W
ACS F814W
WFC3 F125W
WFC3 F160W
3.6
4.5
5.8
8.0
24
250
350
450
500
850
1 asec

Wide 850-μm survey: This component of the survey would be carried out when the opacity at zenith is in the range $0.05 < \tau_{CSO} < 0.10$. Using the SCUBA-2 ITC we calculate that mapping 1 degree^2 to a depth of $\sigma_{850} = 1.2$ mJy requires $\sim$ 150 hours (using the opacity-weighted area for our survey and assuming a mean opacity of 0.08). Therefore the total time necessary to carry out the 10 deg^2 survey is 1497 hours over 2.5 years.

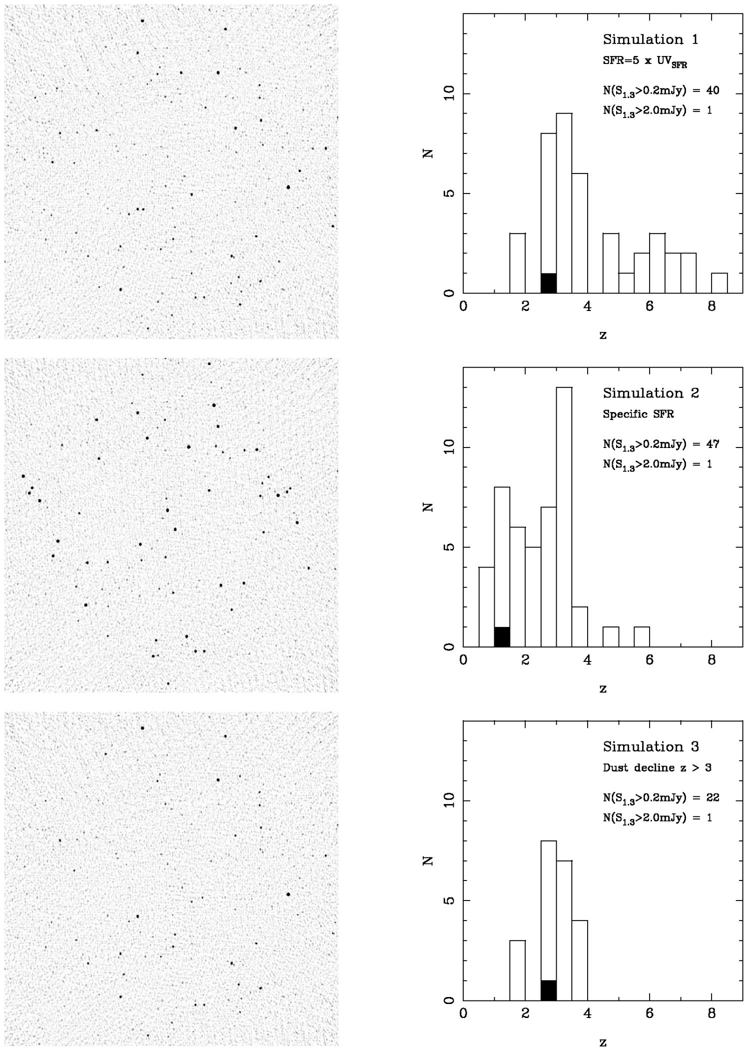
Deep 450-μm survey: The Deep survey strategy uses the time when the weather conditions are suitable for high-frequency work: we propose confining data collection to $\tau_{CSO} \leq 0.05$. The aim is to achieve 3.75-σ detections of SMGs with $S_{450} = 4.5$ mJy. Using the ITC, the time required to map a 0.0625 deg^2 field to $\sigma_{450} = 1.2$ mJy is $\sim$ 260 hours (again for our mean area-weighted opacity, assuming $\tau_{CSO} = 0.045$). Thus, as detailed below, to cover all five CANDELS fields we require 1156 hr with $\tau_{CSO} \leq 0.05$.

TABLE 1: FIELDS, DEPTHS, AND REQUESTED INTEGRATION TIMES FOR 2.5-YEAR S2CLS PROGRAMME

Survey	Field	RA (J2000)	DEC (J2000)	Depth (mJy)	τ range	2.5-yr Area (deg^2)	2.5-yr Time (hours)	Notes
Wide	UDS+VVDS/XMM	02 18 00	−05 00 00	$\sigma_{850} = 1.2$	0.05–0.10	4.0	612	HerMES Level-3/4/5
Wide	ECDFS	03 32 00	−28 16 00	$\sigma_{850} = 1.2$	0.05–0.10	0.25	48	HerMES Level-2
Wide	COSMOS	10 00 29	+02 12 00	$\sigma_{850} = 1.2$	0.05–0.10	2.0	293	HerMES Level-2
Wide	LH-East	10 52 43	+58 28 48	$\sigma_{850} = 1.2$	0.05–0.10	0.50	80	HerMES Level-3/5
Wide	LH-North	10 46 00	+59 01 00	$\sigma_{850} = 1.2$	0.05–0.10	0.50	80	HerMES Level-3/5
Wide	GOODS-N	12 36 46	+62 13 58	$\sigma_{850} = 1.2$	0.05–0.10	0.25	43	HerMES Level-2/3
Wide	Bootes	14 32 06	+34 16 48	$\sigma_{850} = 1.2$	0.05–0.10	1.25	160	HerMES Level-5
Wide	EGS	14 19 18	+52 49 30	$\sigma_{850} = 1.2$	0.05–0.10	1.25	181	HerMES Level-3/5
					0.05–0.10	10.0	1497	
Deep	UDS	02 18 00	−05 00 00	$\sigma_{450} = 1.2$	< 0.05	0.057	208	CANDELS
Deep	GOODS-S	03 32 28	−27 48 30	$\sigma_{450} = 1.2$	< 0.05	0.041	285	CANDELS-Wide
Deep	COSMOS	10 00 29	+02 12 00	$\sigma_{450} = 1.2$	< 0.05	0.056	186	CANDELS
Deep	GOODS-N	12 36 46	+62 13 58	$\sigma_{450} = 1.2$	< 0.05	0.044	250	CANDELS-Wide
Deep	EGS	14 19 18	+52 49 30	$\sigma_{450} = 1.2$	< 0.05	0.054	227	CANDELS
					< 0.05	0.252	1156	

Total time request: This yields a total time request of: 2653 hr with $\tau_{CSO} \leq 0.1$ of which 1156 hr require $\tau_{CSO} \leq 0.05$.

ALMA can connect us to “normal” galaxies



What we should be doing……

Facing a ~10 year hiatus in new space facilities

- Need/duty to exploit legacy of HST, Spitzer, Herschel, Chandra/XMM
- Need to prepare for JWST, EUCLID, IXO

This means the near-term focus should be to ensure that we:

- Fully exploit UK ALMA membership for deep continuum and spectroscopy
- Carry out wide-area (50-100 sq degree) imaging surveys with SCUBA2 and/or something else – e.g. in EUCLID Deep fields
- Further develop connections with radio surveys – EVLA, LOFAR etc

How can future mm/sub-mm observations help?

Better constraints on basic demographics

- More dynamic range in number counts
- Covering representative cosmological volumes
- With decent redshift information
- Extending to redshifts not well sampled by Herschel
- Reaching sufficient depth to detect “normal” high-z galaxies

Better information on physical properties over cosmic time

- Bolometric luminosities – disentangling Herschel-SPIRE imaging
- Stellar masses, and specific star-formation rates
- Clustering – halo masses – duty cycles
- Morphologies – no orientation selection bias
- Role within mass-selected samples

Better understanding of star formation & feedback mechanisms

- Importance of molecular hydrogen versus basic gas density
- Ionizing radiation and cosmic ray heating of molecular clouds
- Galaxy black-hole connection