Galaxy formation & evolution: the far-infrared/sub-mm view

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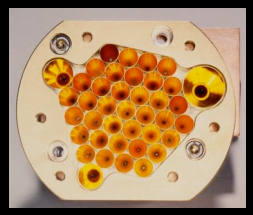
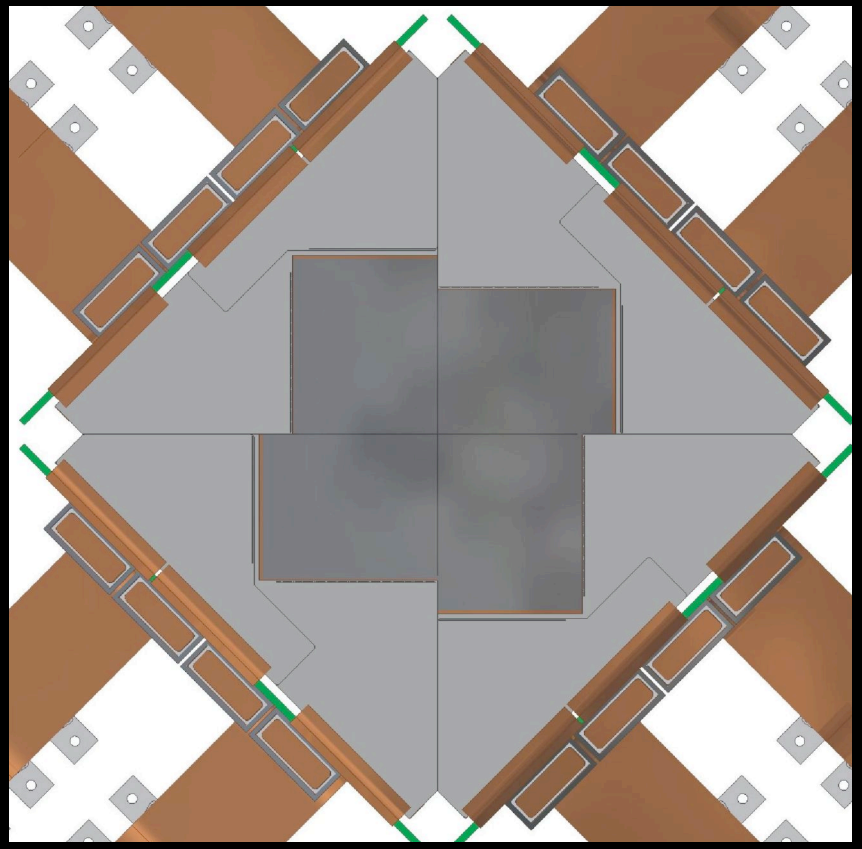
University of Edinburgh



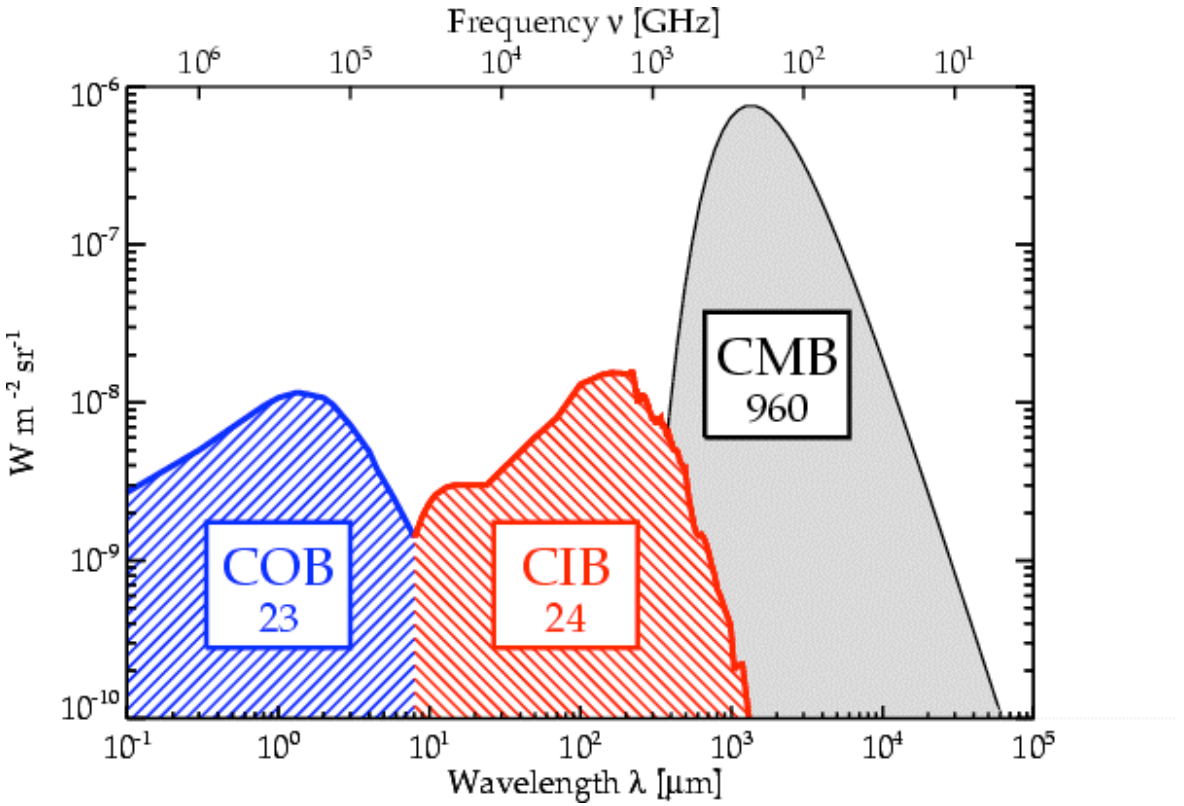


Outline

0. Why?
1. Surveys and number counts
2. Identifications and redshifts
3. Sizes, morphologies and masses
4. The nature of sub-mm galaxies
5. Future prospects

0. Motivation for sub-mm/mm studies

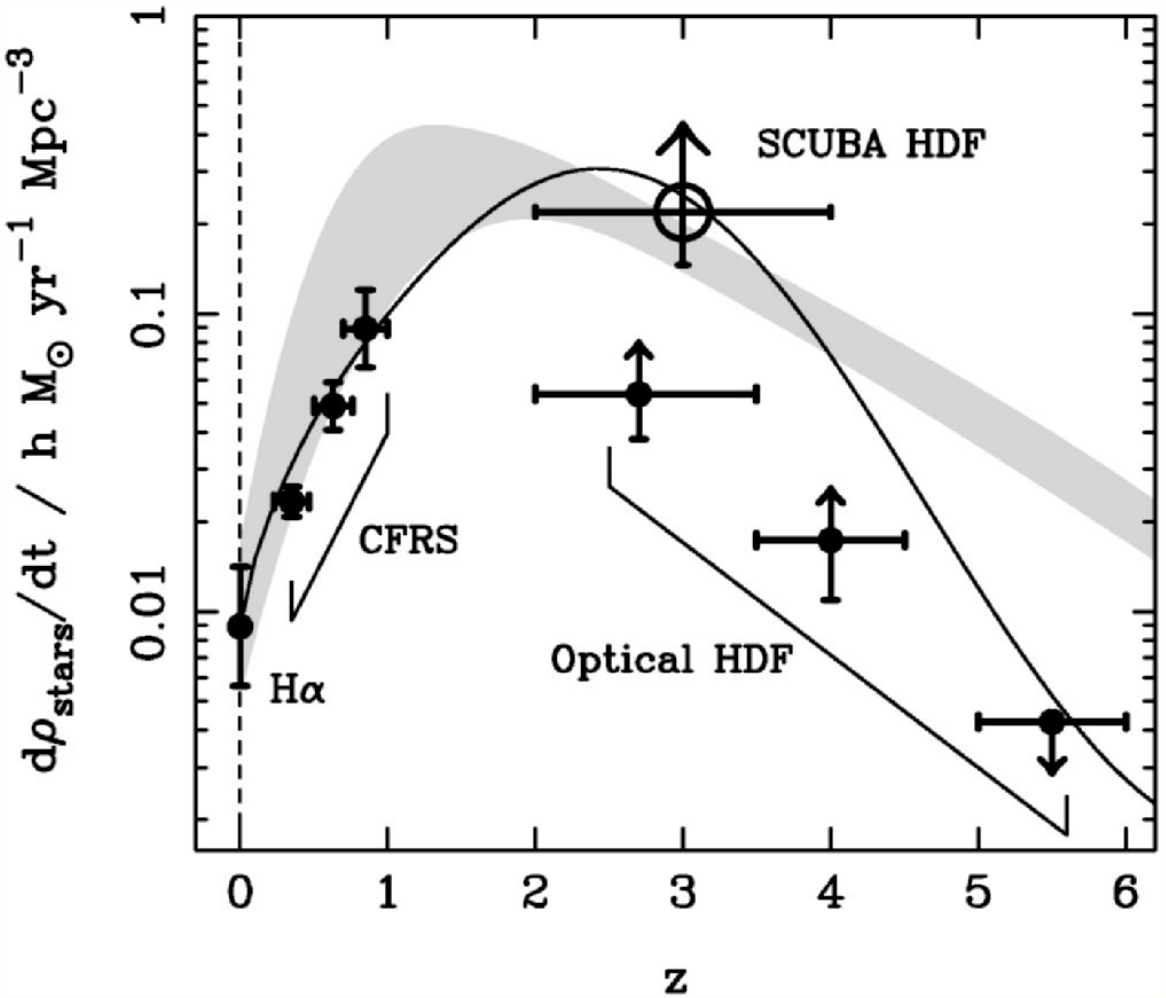
The Cosmic Infrared Background (CIB) contains as much energy as the integrated optical background



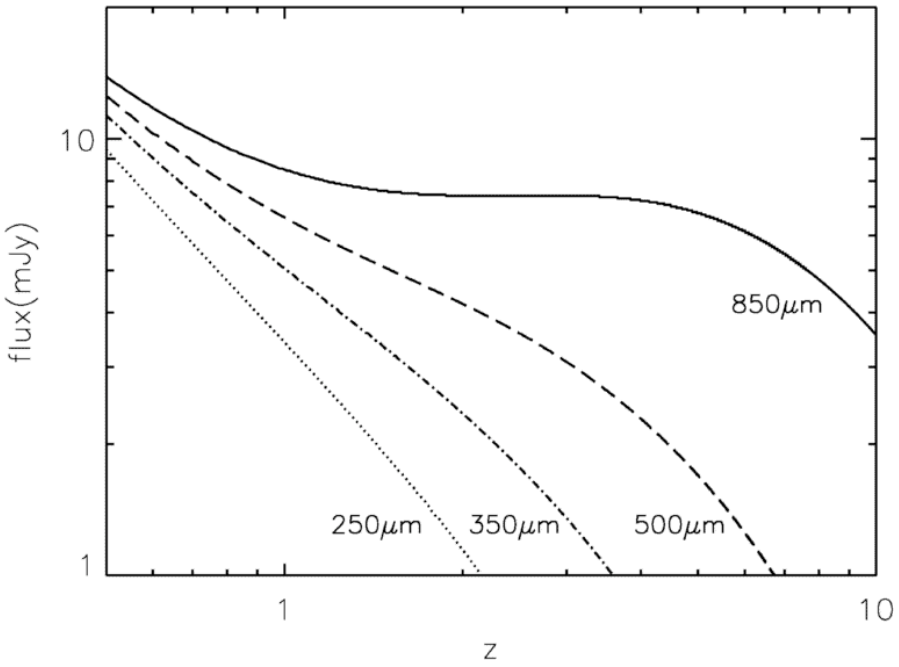
Dole et al. (2006)

~80% of cosmic star formation history is obscured

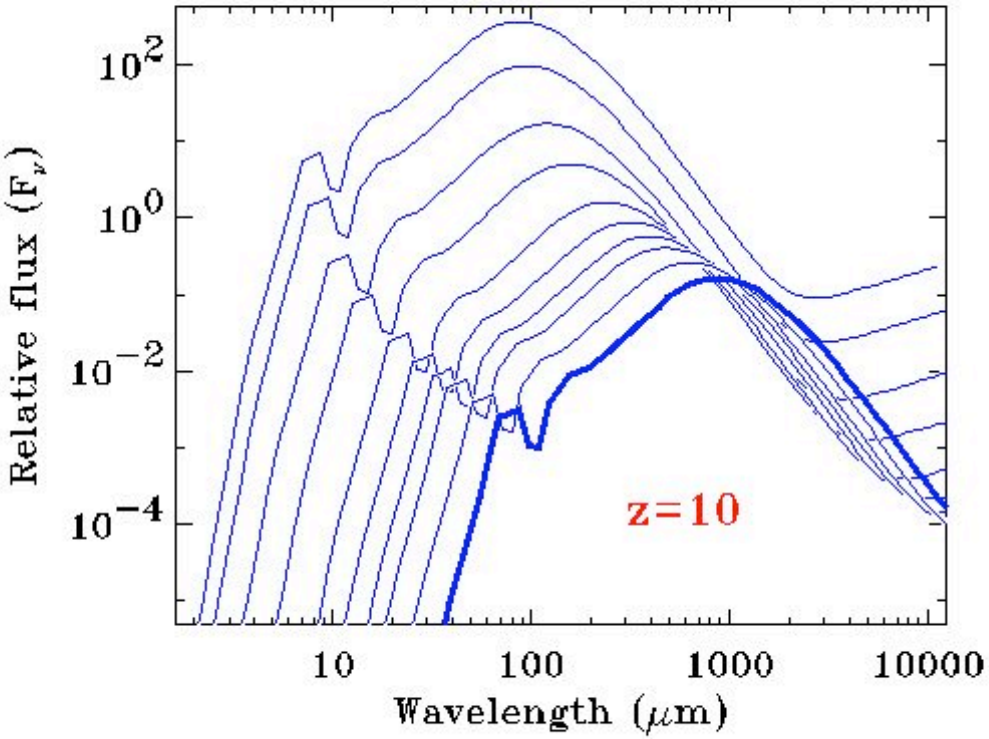
Hughes et al. (1998) Nature, 394, 241



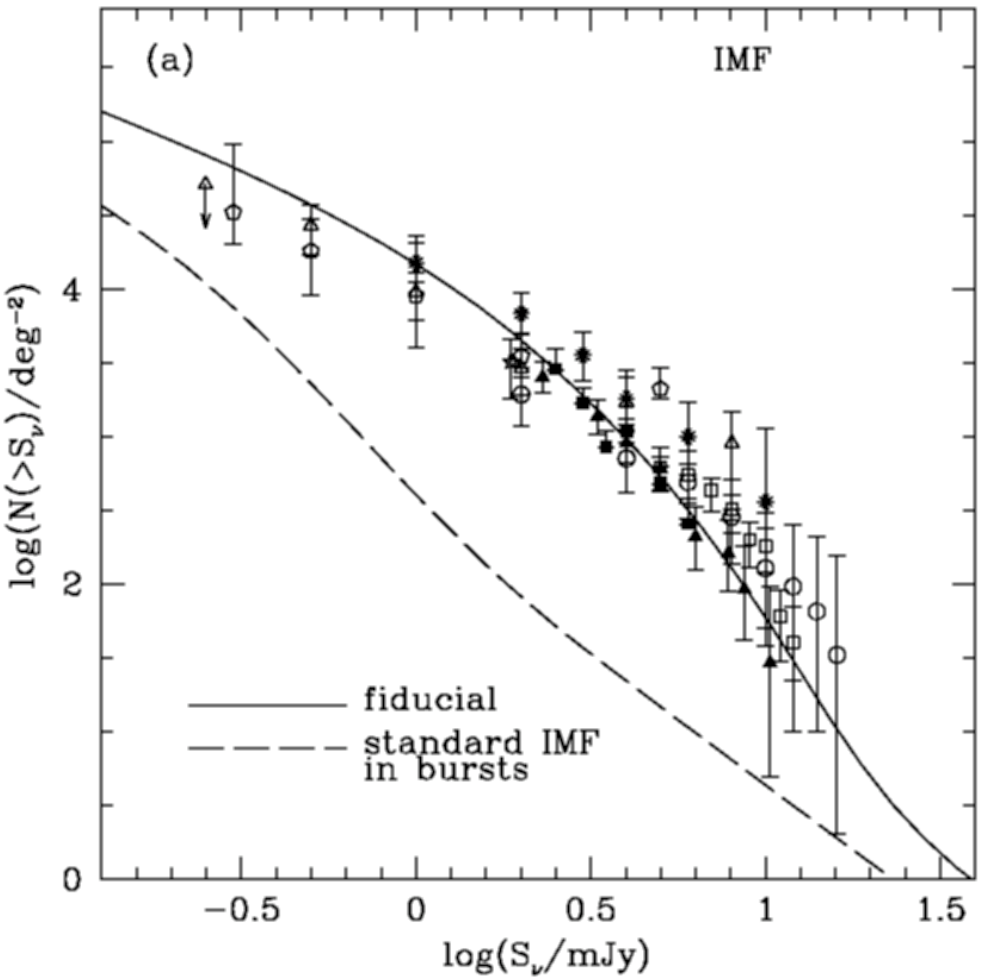
A clear view from z = 1 to z = 8 (reionization?)



Galaxy spectrum at progressively higher redshifts



A challenge to models of galaxy formation



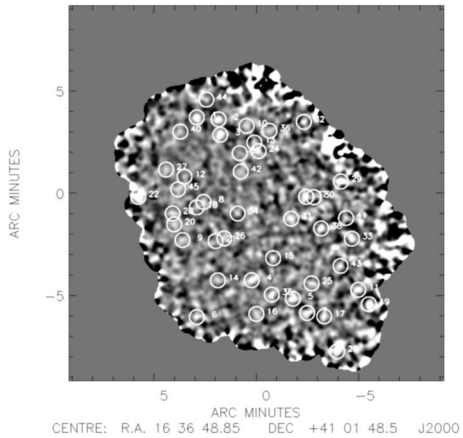
Baugh et al. (2005)

1. Surveys and number counts

Early sub-mm / mm surveys

- Clusters – Smail et al. (1997)
- HDF – Hughes et al. (1998)
- Canada-UK Deep Submm Survey (CUDSS) – Eales et al. (2000)
- Hawaii Flanking Fields survey – Barger et al. (1998)
- 8-mJy survey – Scott et al. (2002)
- 8-mJy IRAM Mambo follow-up – Greve et al. (2004)

Combined reanalysis of the blank-field SCUBA surveys published in Scott, Dunlop & Serjeant et al. (2006)



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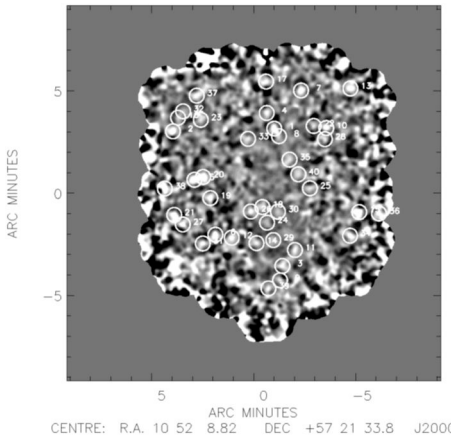

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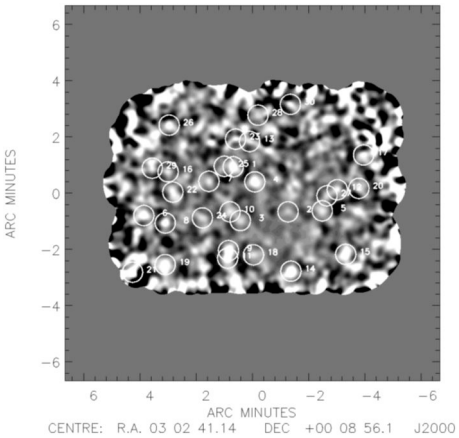

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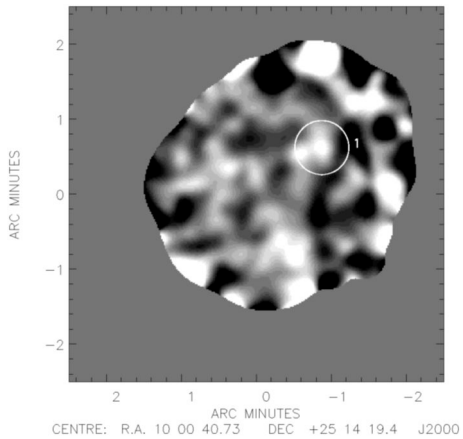

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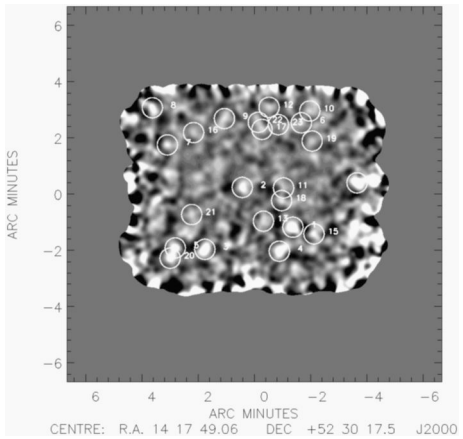

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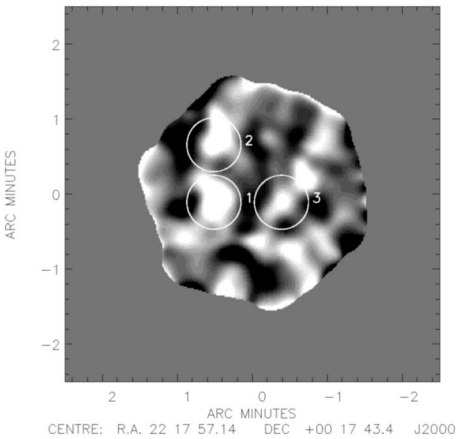

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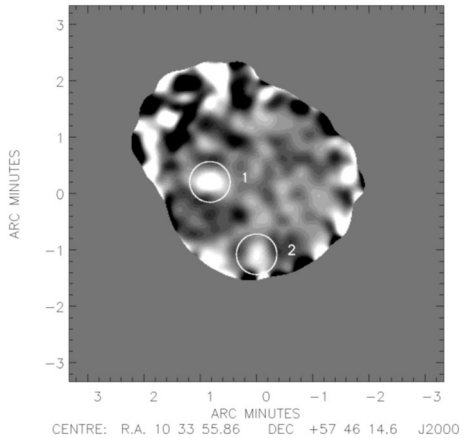

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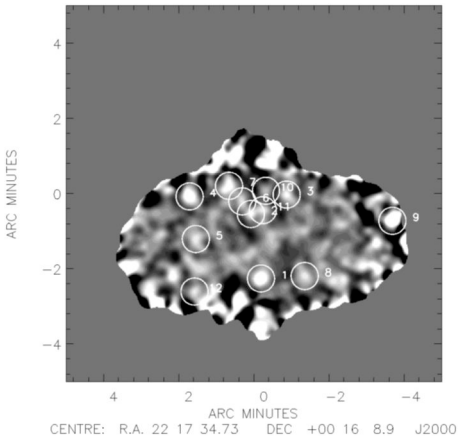

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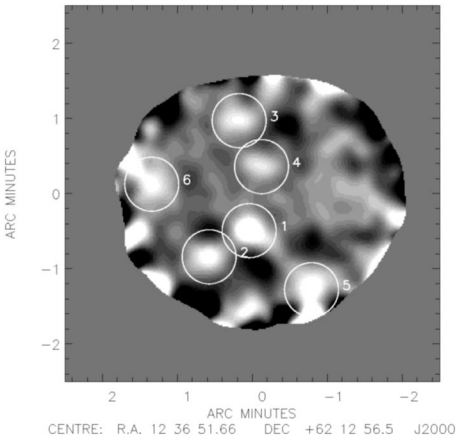

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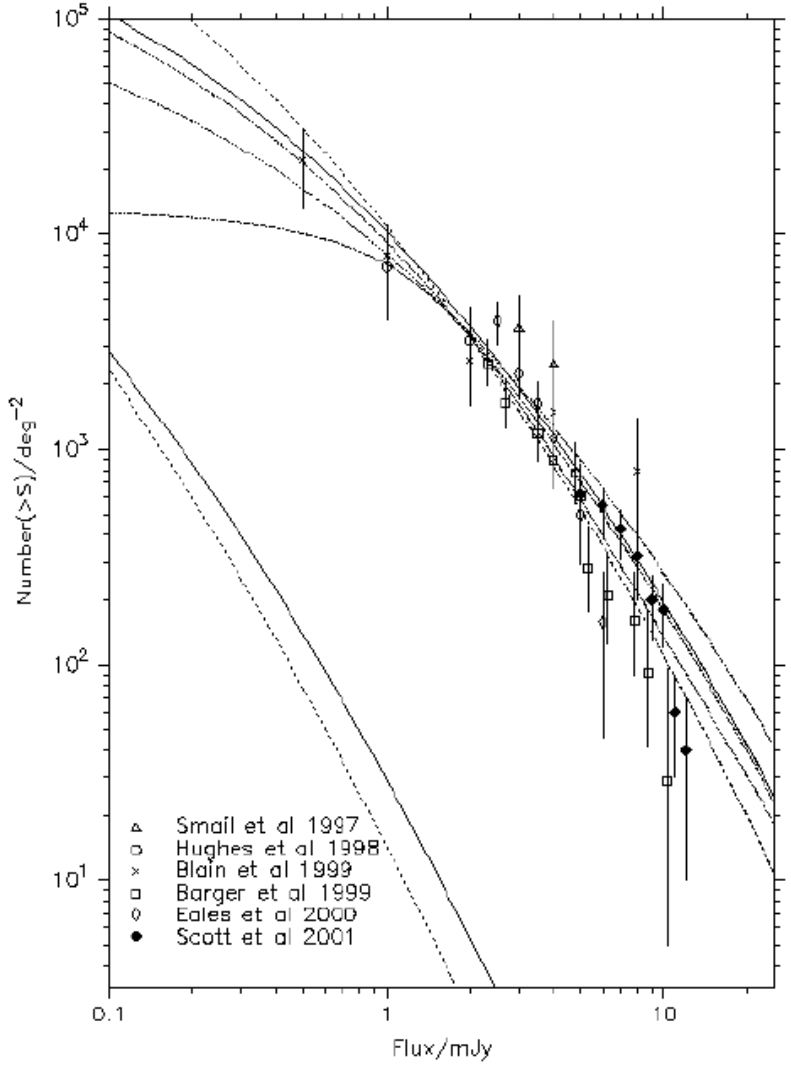
Number counts & comoving no. density

Surface density of bright SCUBA sources from 8mJy survey
(Scott et al. 2002)



Assuming most of these lie at z ~ 2

co-moving number density of things
forming ~ 1000 solar masses
of stars per year

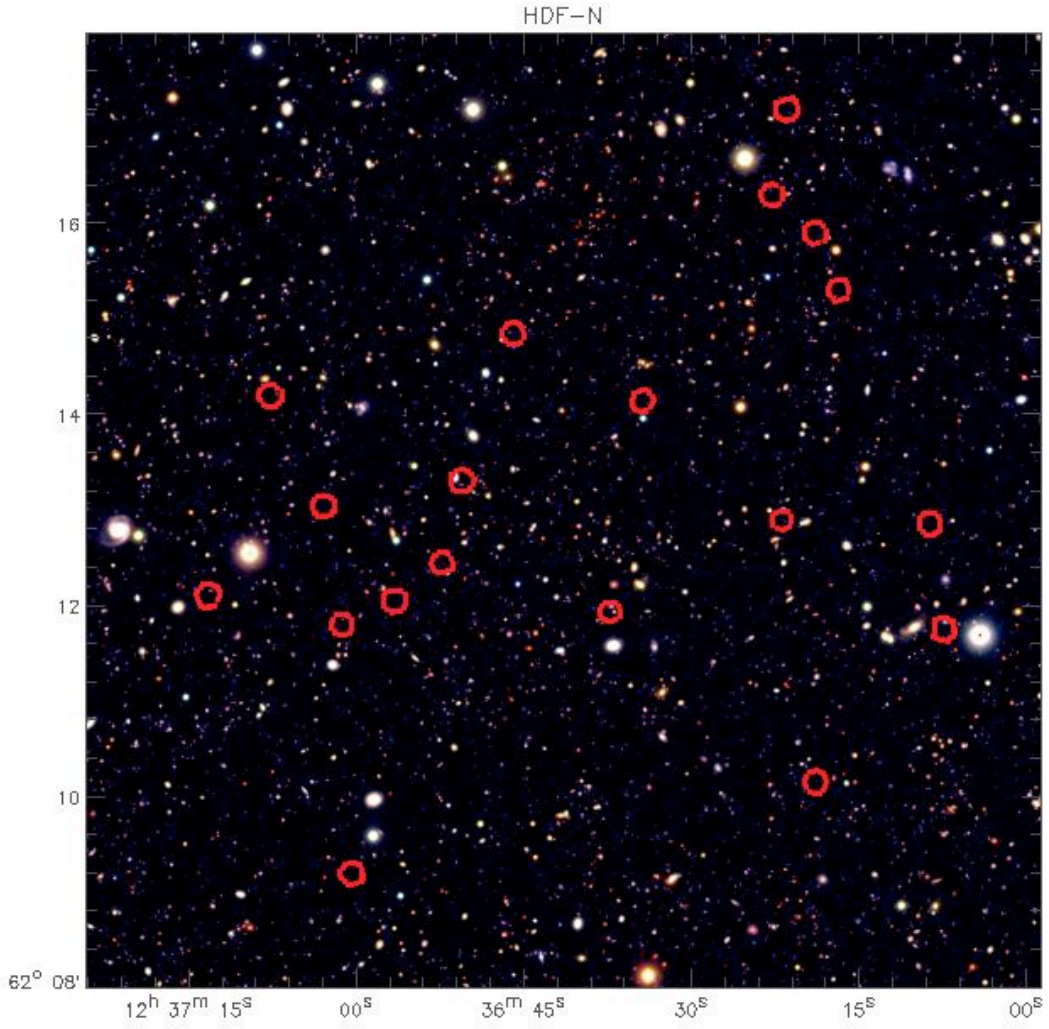
= 1 - 3 x 10^{-5} Mpc^{-3}

Comparable to number density of
2-3 L* ellipticals today

HDF supermap – 19 sources - Borys et al. (2003)

Messy sub-mm map, but

excellent existing supporting multi-frequency data



See also:

Borys et al. (2004)

Pope et al. (2005)

Pope et al. (2006)

SHADES

An attempt to put extragalactic sub-mm astronomy on a solid footing.

The first complete, unbiased, large area, sub-mm survey

Aim to determine number counts, redshift distribution, clustering, and other basic properties of the bright (~8 mJy) sub-mm population

RATIONALE

Available dynamic range with JCMT is limited

So stay bright – 8 mJy
unconfused
maximum chance of effective follow-up
massive starbursts = big challenge to theory

SHADES

DATA

3 years observing with an increasingly ill SCUBA

- SCUBA 850-micron map of ~1/4 sq. degrees
- 850 rms ~2 mJy
- Two fields – Lockman Hole & SXDF
- Major multi-frequency follow-up

  VLA, GMRT, UKIRT, Spitzer, Subaru, Keck, Gemini, VLT, AAT,

  XMM, Chandra, SMA, AzTEC

SHADES www.roe.ac.uk/ifa/shades

Dunlop 2005, astro-ph/0501419

van Kampen et al. 2005, MNRAS, 359, 469

Mortier et al. 2005, MNRAS, 363, 563

Coppin et al. 2006, MNRAS, 372, 1621

Ivison et al. 2007, MNRAS, in press (astro-ph/0702544)

Aretxaga et al. 2007, submitted (astro-ph/0702509)

Takagi et al. 2007, in press

Coppin et al. 2007, submitted

Dye et al. 2007, in prep

Clements et al. 2007, in prep

Serjeant et al. 2007, in prep

Van Kampen et al. 2007, in prep

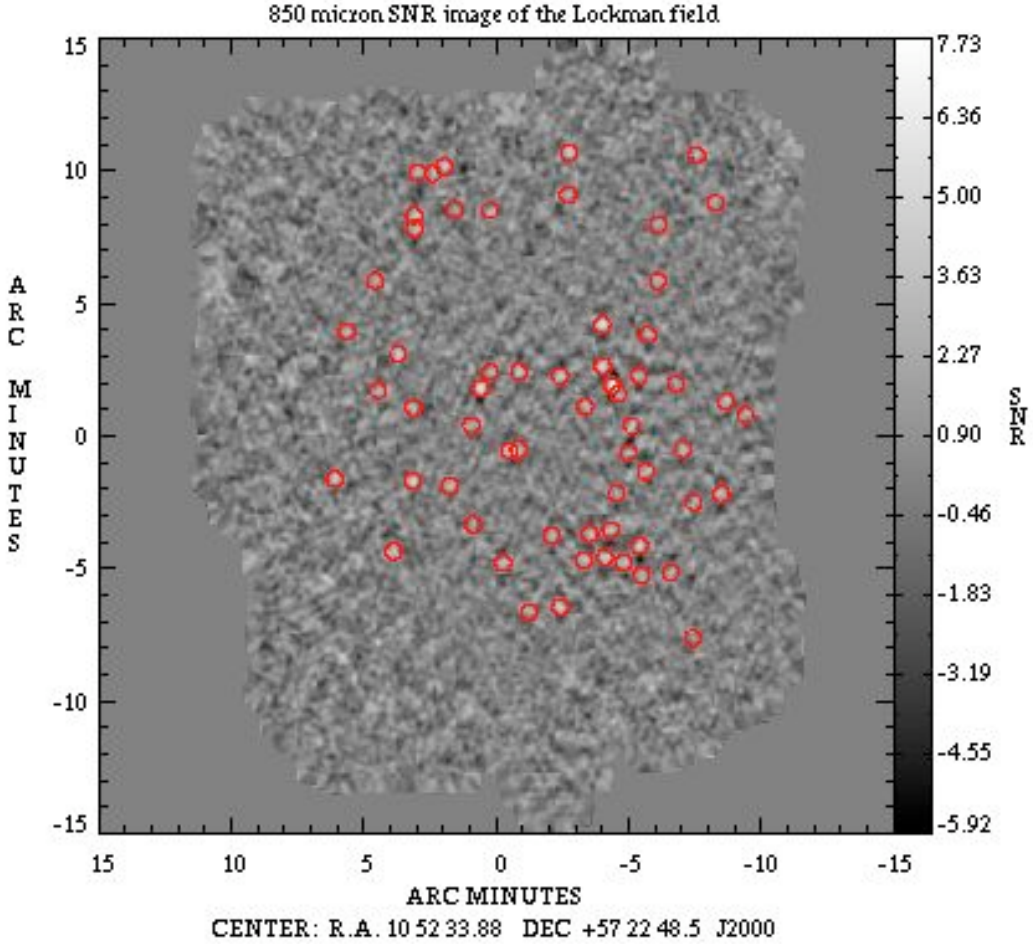
+ AzTEC papers to follow

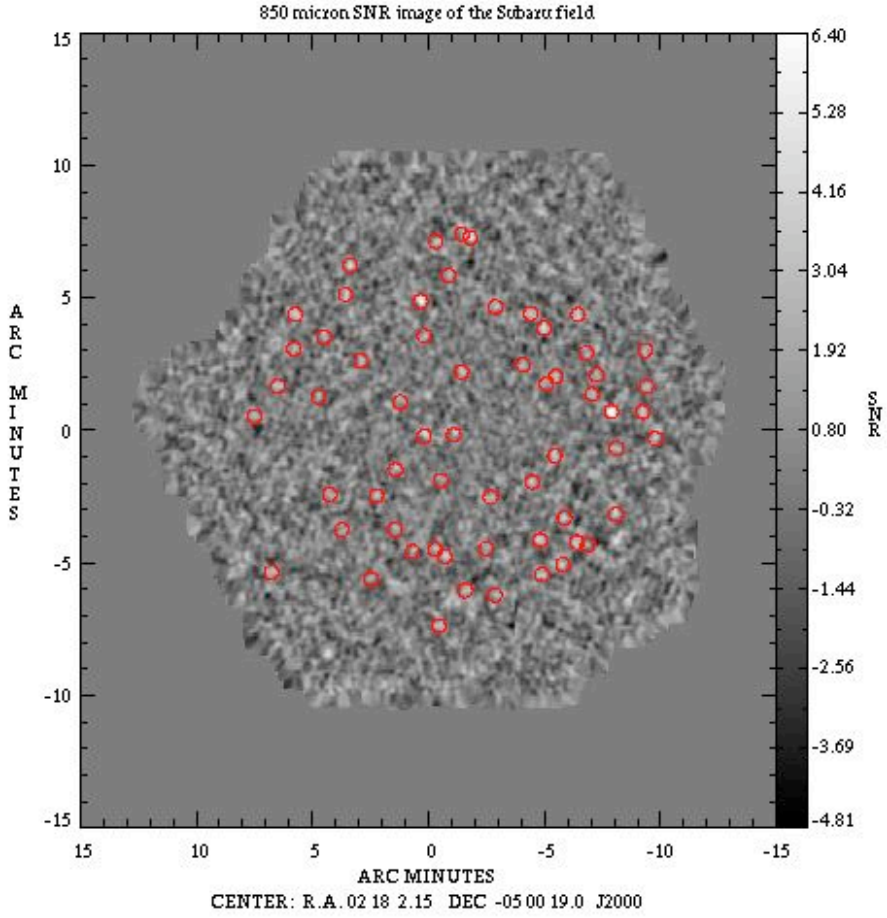
SHADES SCUBA 850-micron maps

2 fields – Lockman Hole & SXDF/UDS

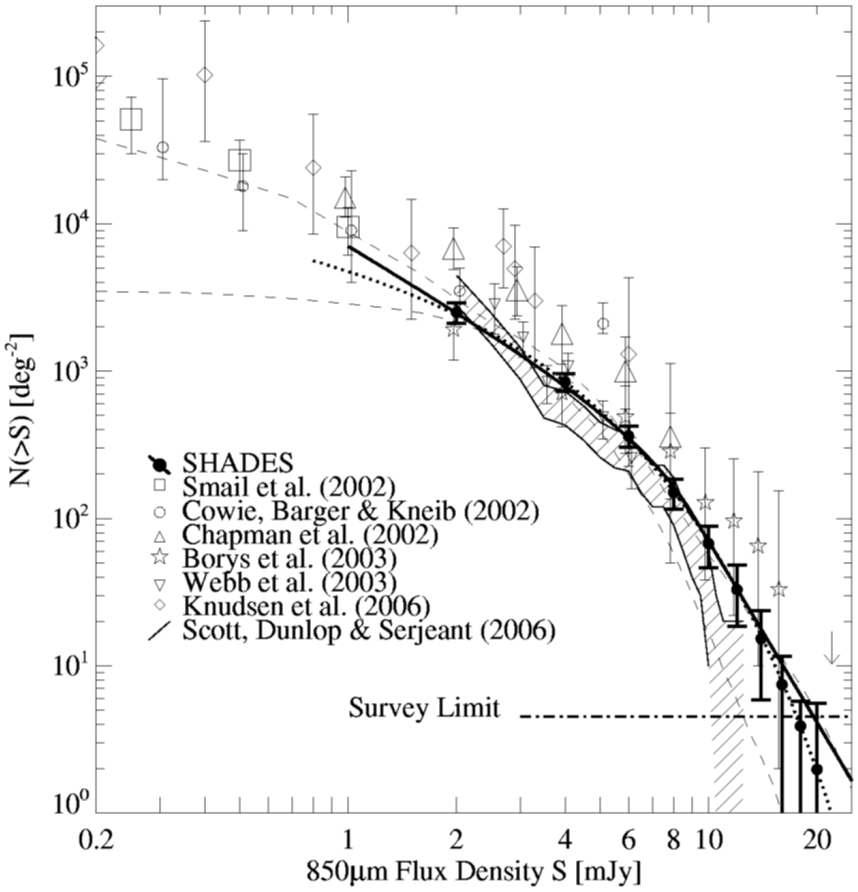
4 independent reductions combined to produce one SHADES catalogue

120 sources with unbiased (deboosted) flux densities





Number counts

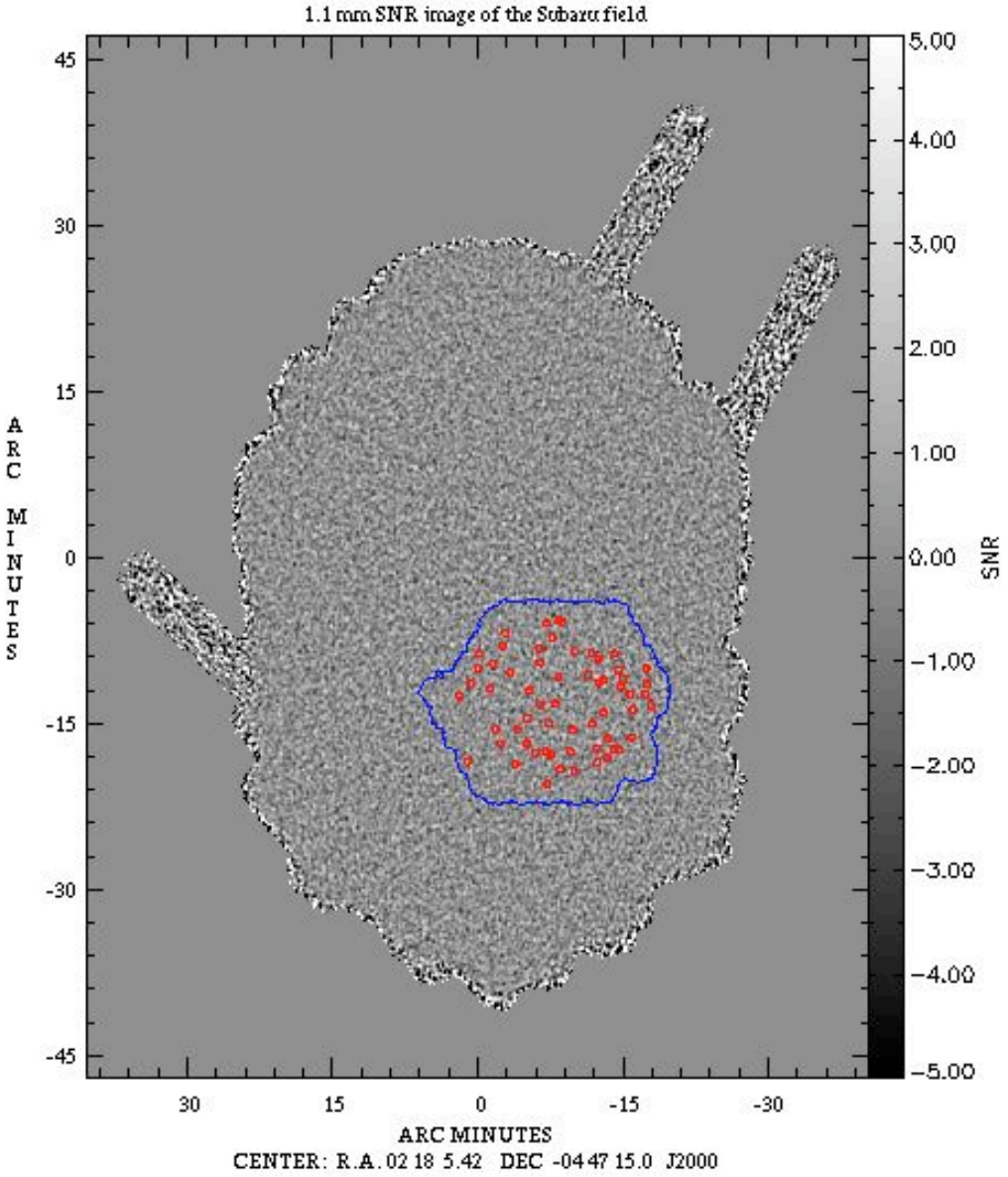


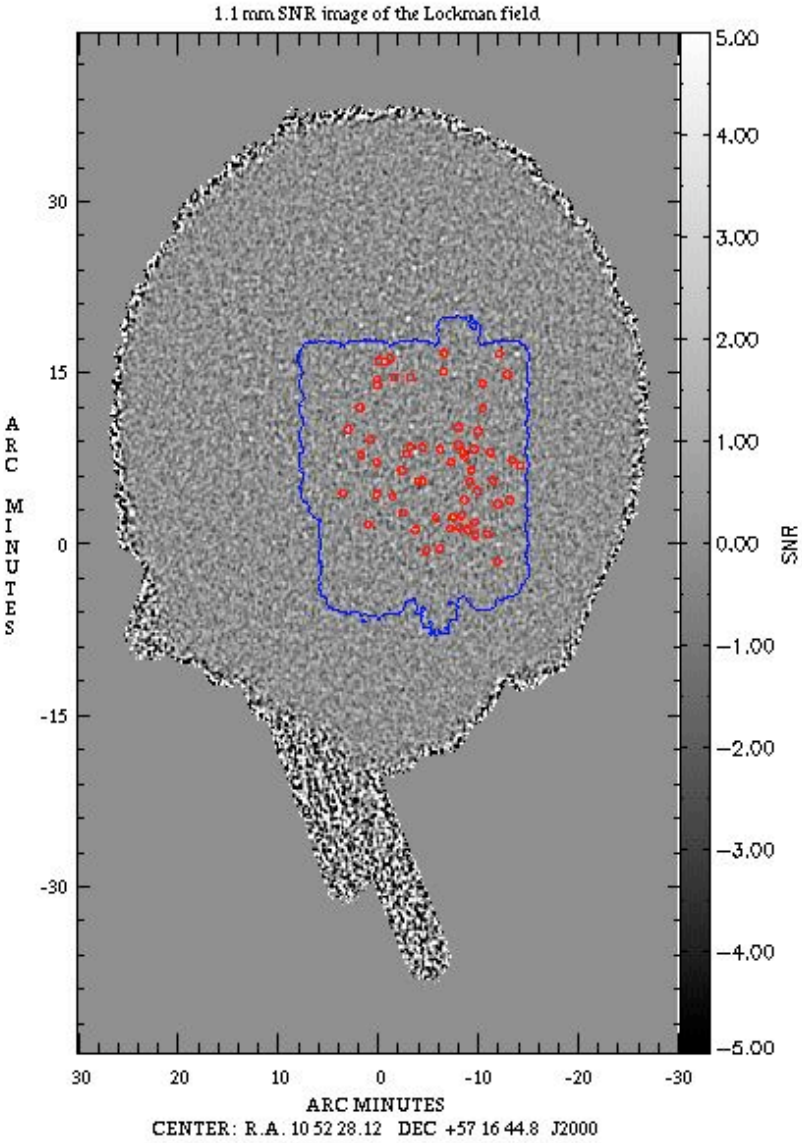
Coppin et al. 2006

Estimated background of sources >2mJy is ~9700 mJy/deg²
>20-30% of FIRB resolved

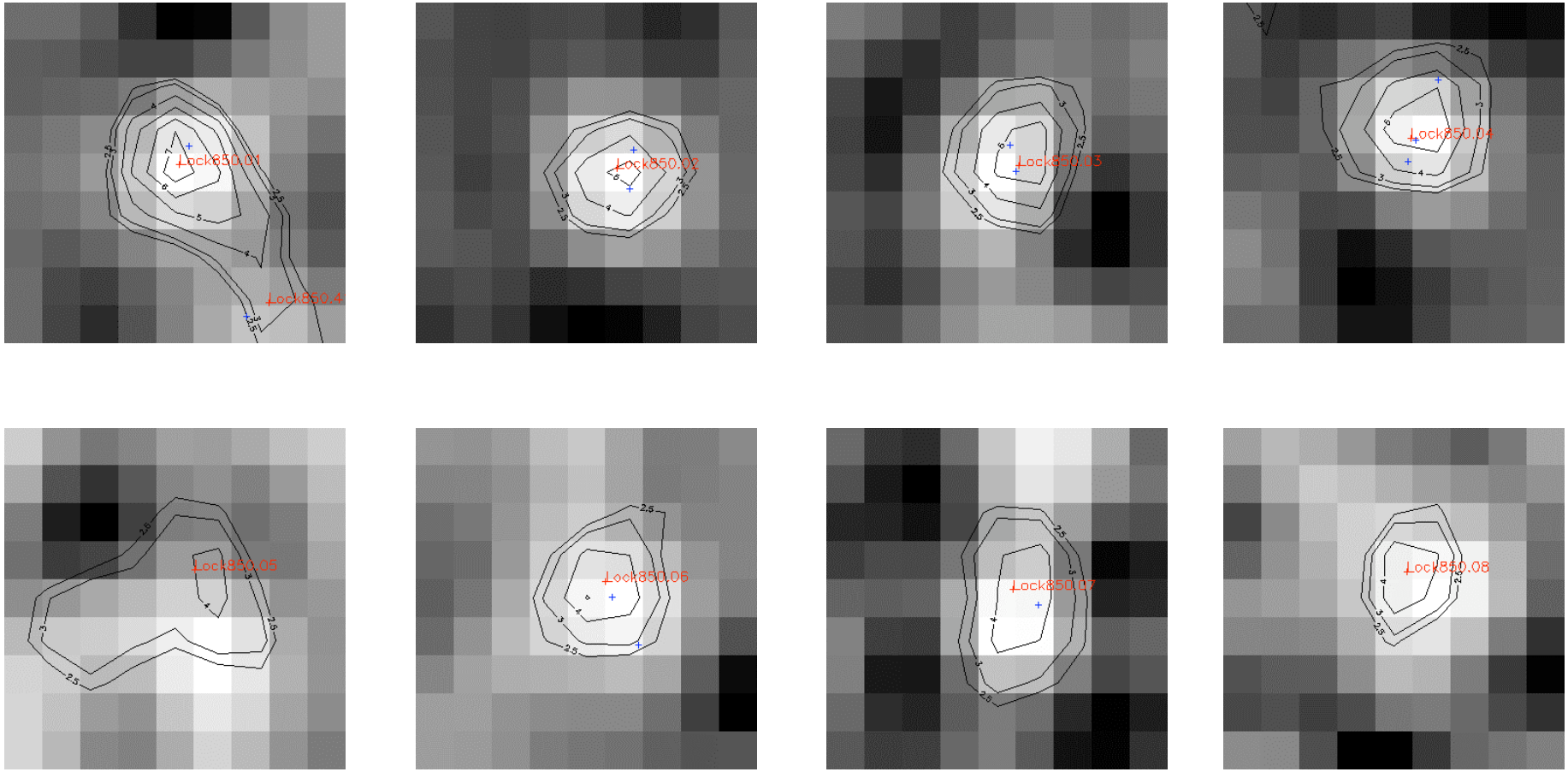
New SHADES AzTEC 1.1mm maps

(SNR maps shown here produced by Jason Austerman)





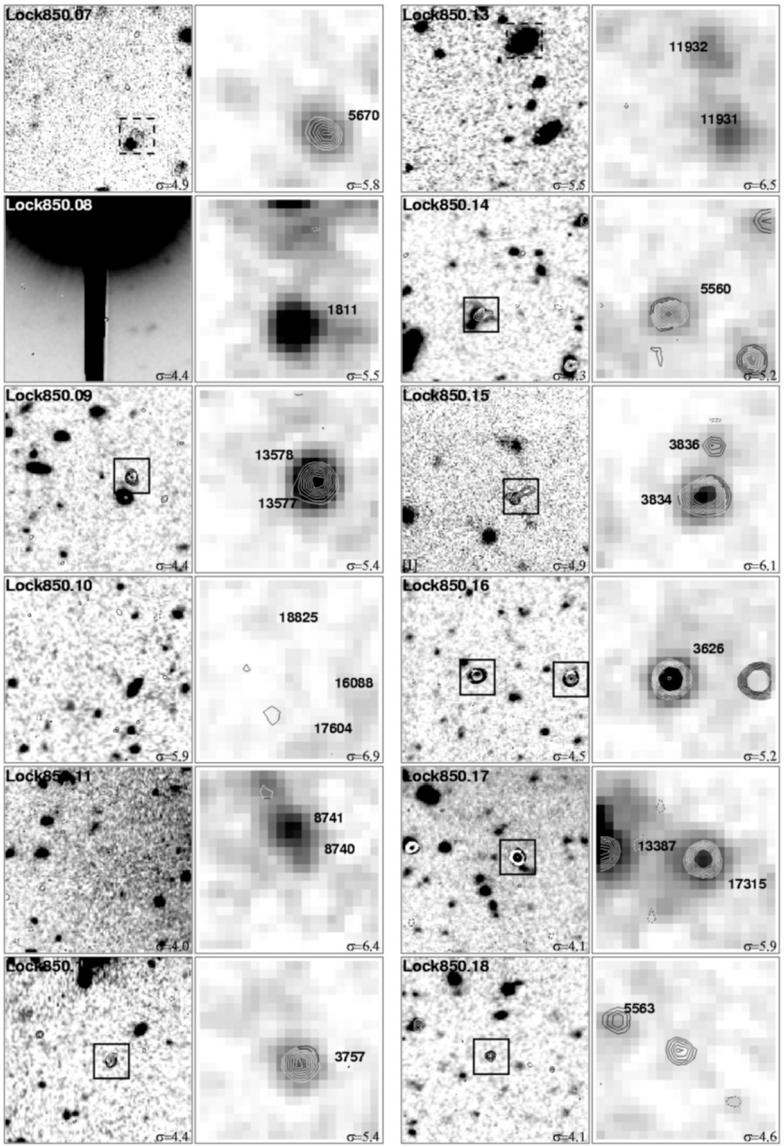
850-micron contours on 1.1mm greyscale



Joint SCUBA+AzTEC source extraction now being explored

2. Identifications and redshifts

Radio and mid-infrared



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Ivison et al., 2007, MNRAS, in press (astro-ph/0702544)

25 x 25 arcsec stamps

VLA radio contours on

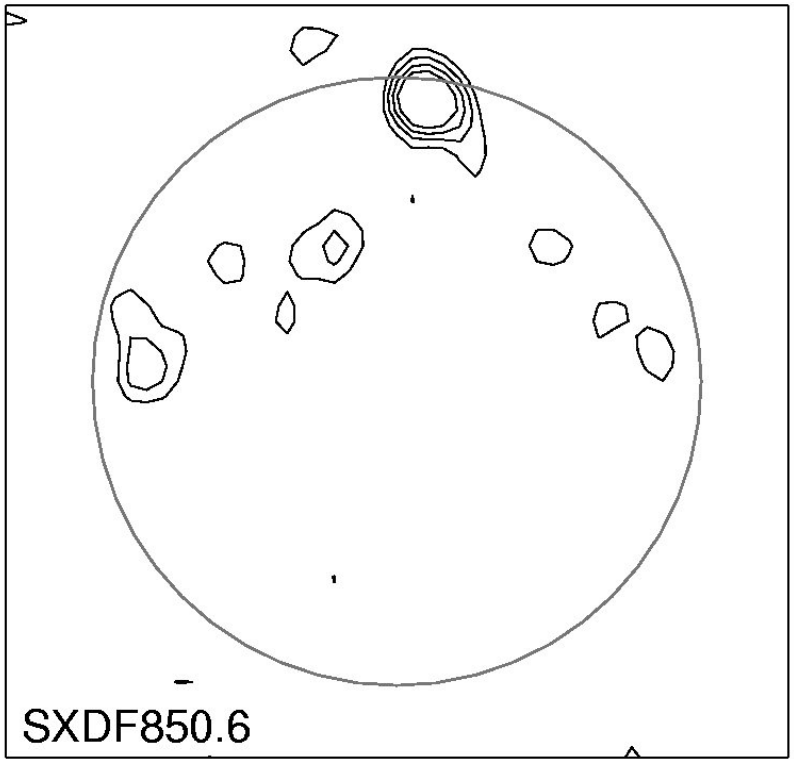
R-band Subaru image, and

Spitzer 24-micron image

85-90% of the 120 sources identified via VLA and/or Spitzer

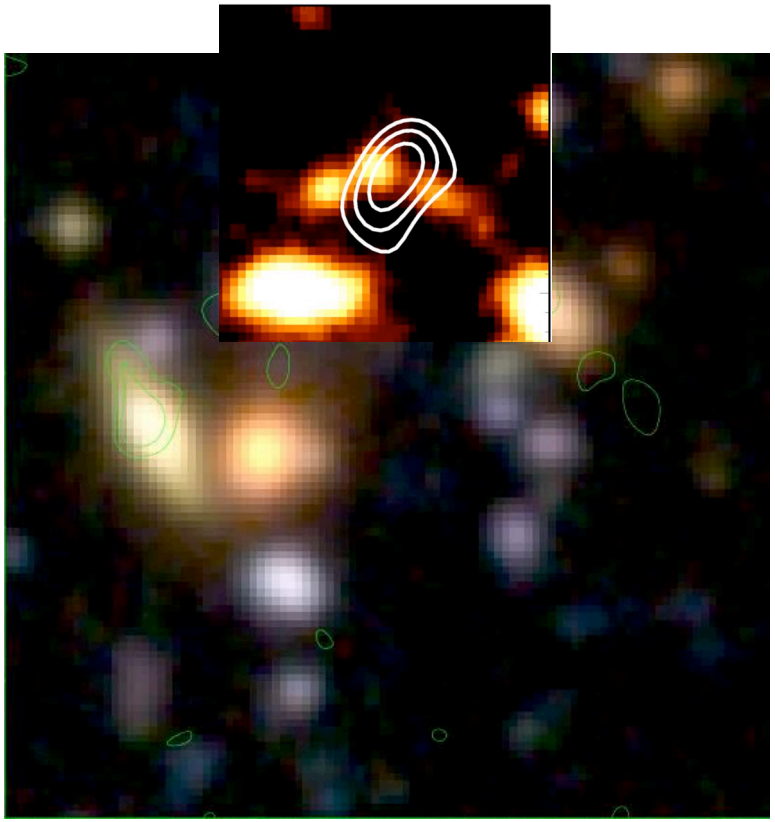
Sometimes identification can be tricky

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



VLA 1.4 GHz

SMA

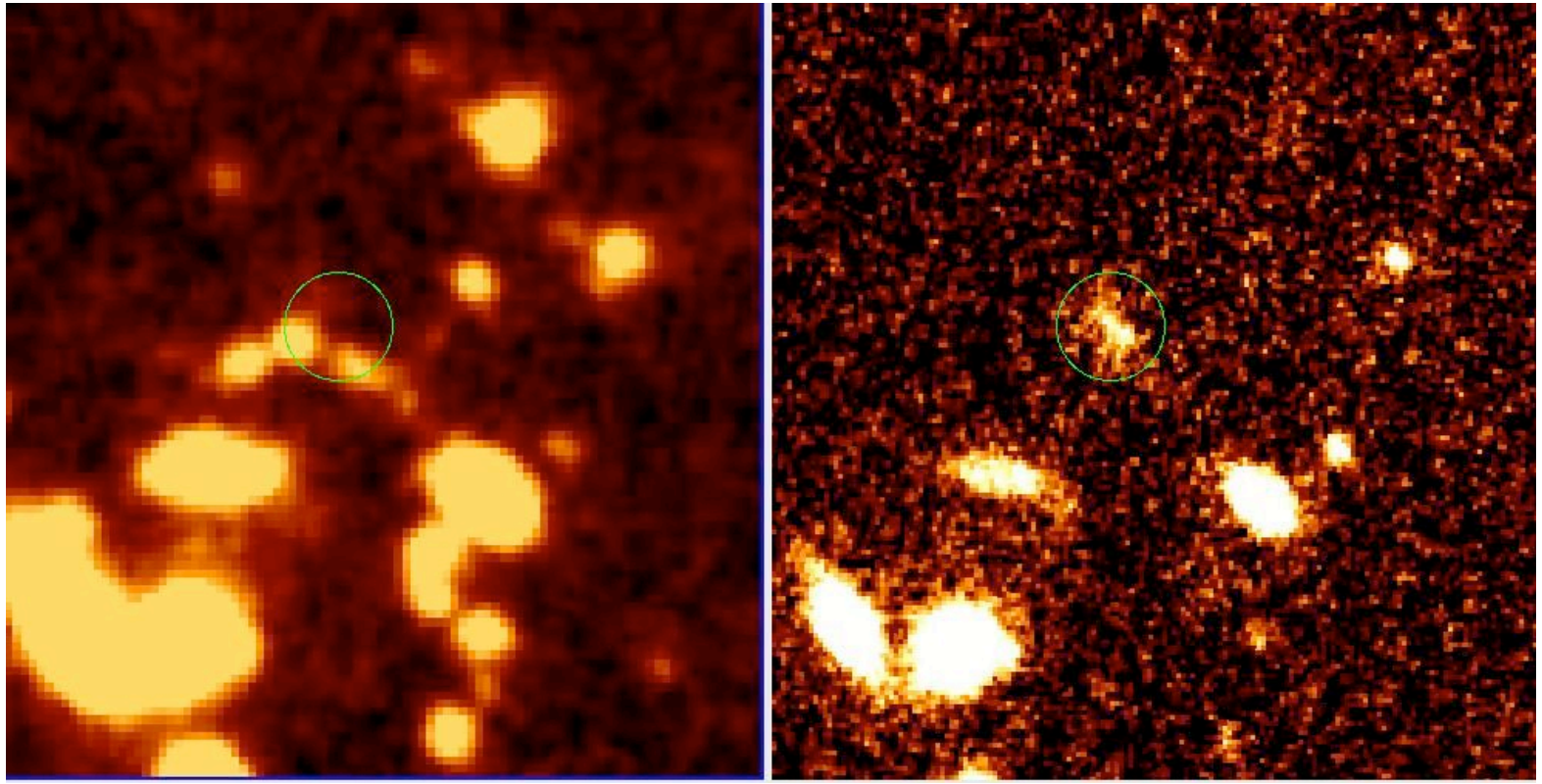


Optical - Subaru

Finally …….unambiguous K-band ID

SMA on optical

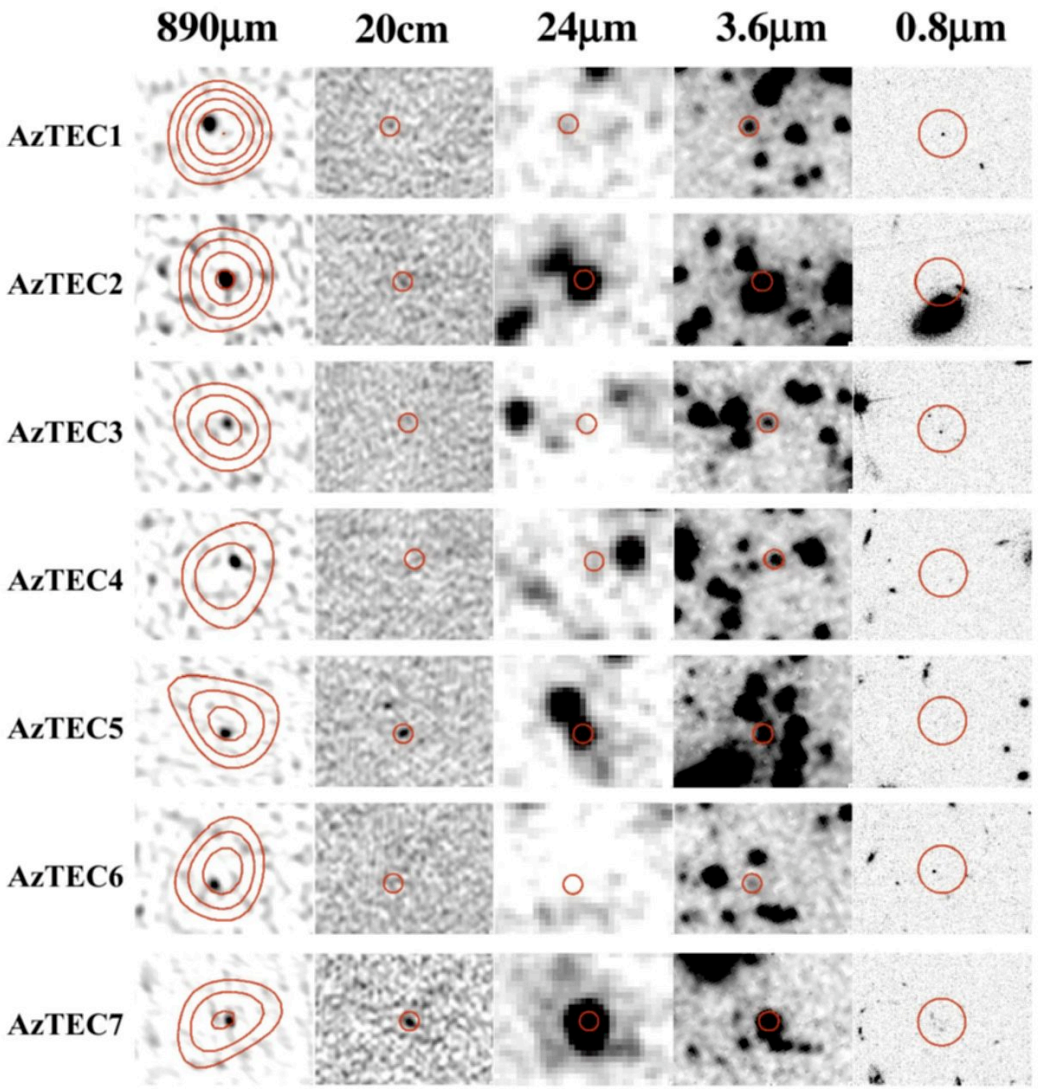
SMA on K-band



Demonstrates

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

SMA – a glimpse of ~1 arcsec sub-mm astronomy



Younger et al. (2007)

Redshifts

Redshifts

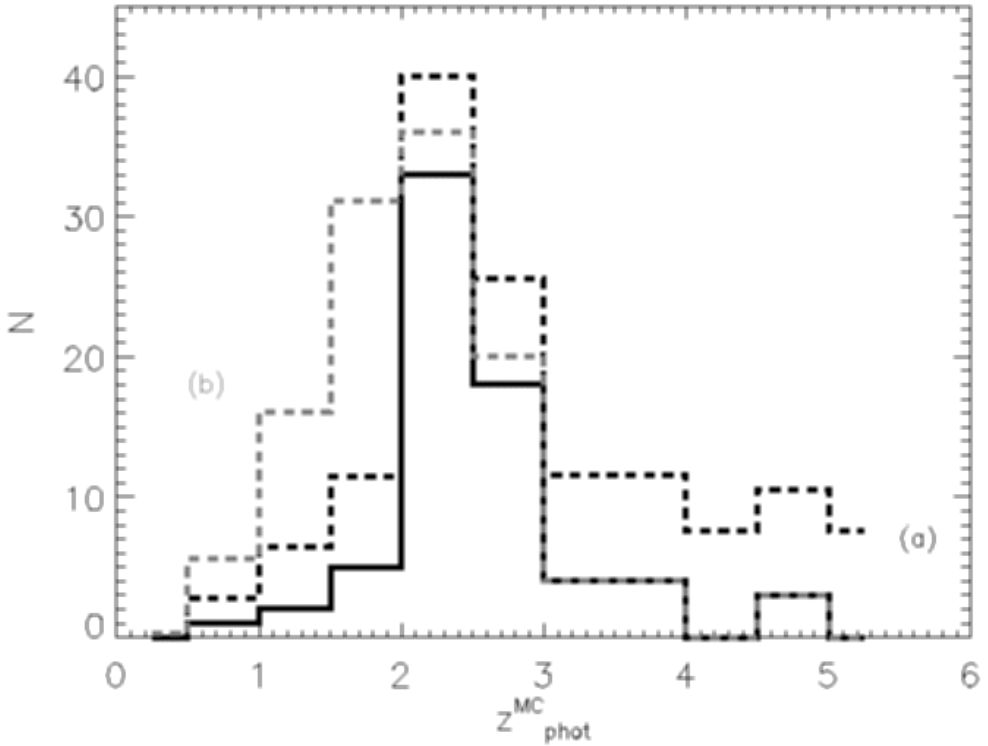
4 different forms of redshift information:

- 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.

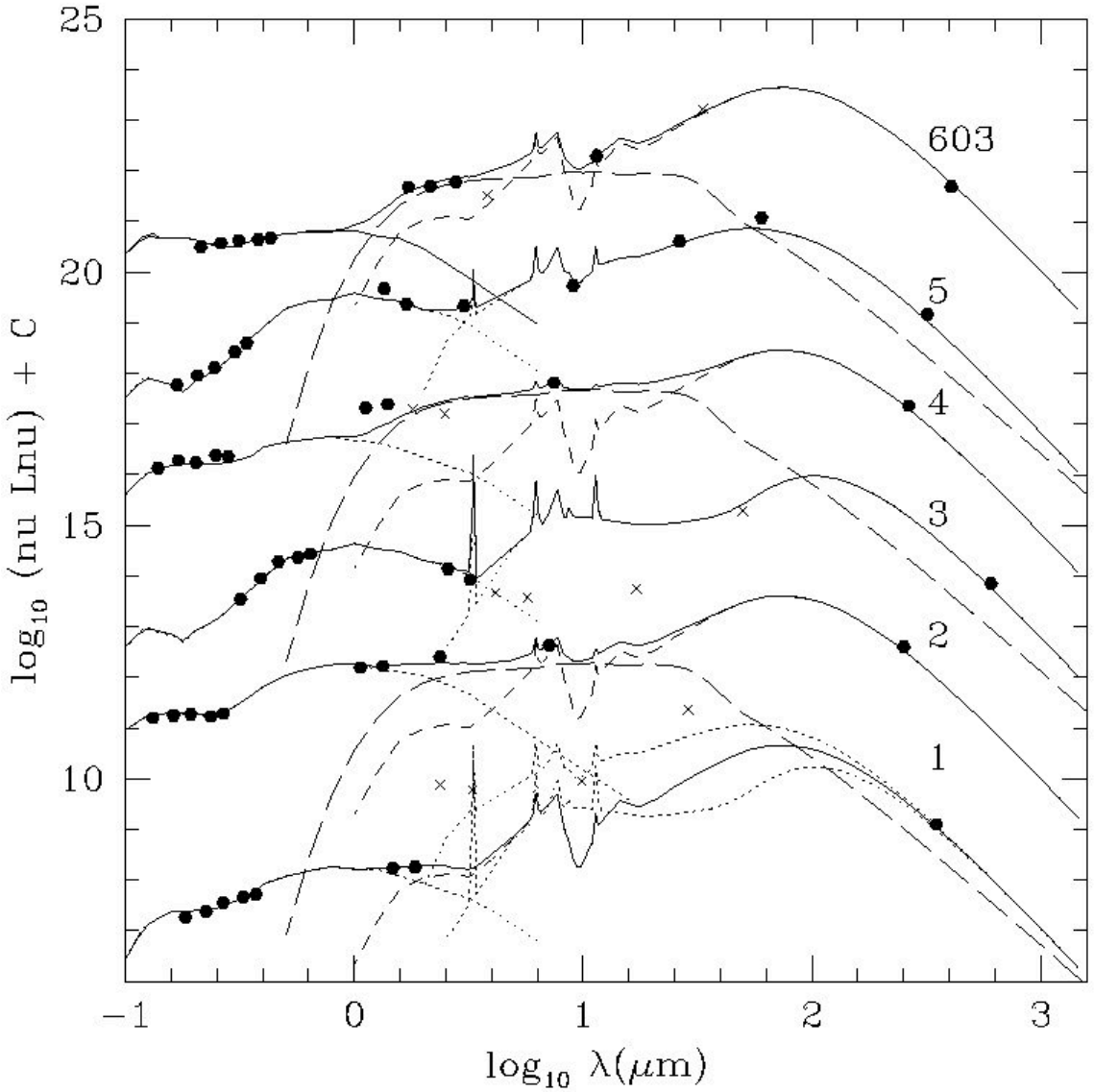
In SHADES only ~12 (ie 10%) of sources currently have an unambiguous spectroscopic z

Current estimates of z distribution

– Aretxaga et al.,2007, MNRAS, in press (astro-ph/0702509)



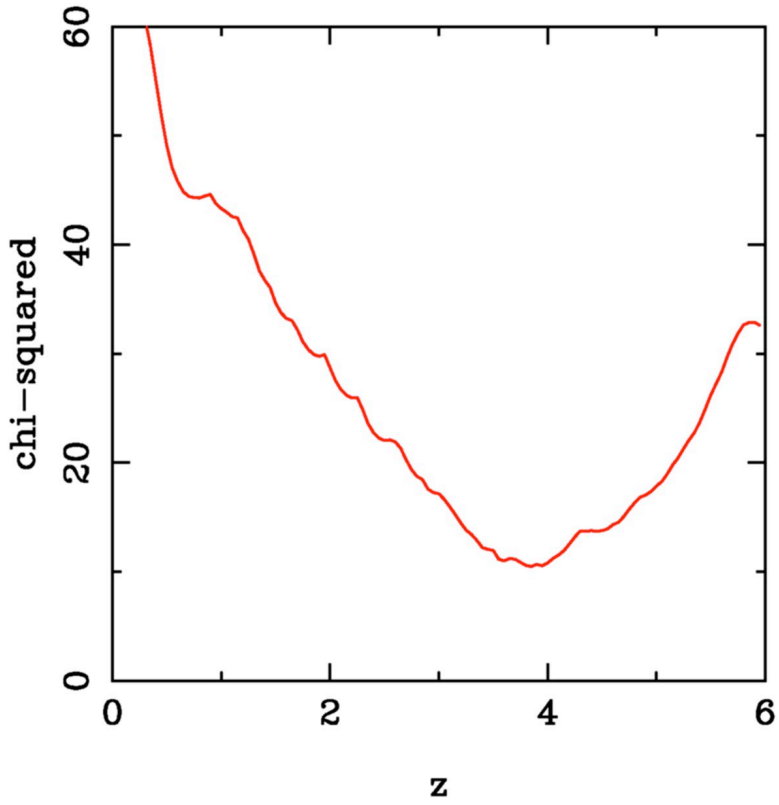
Aiming to use other photo-z info to refine this



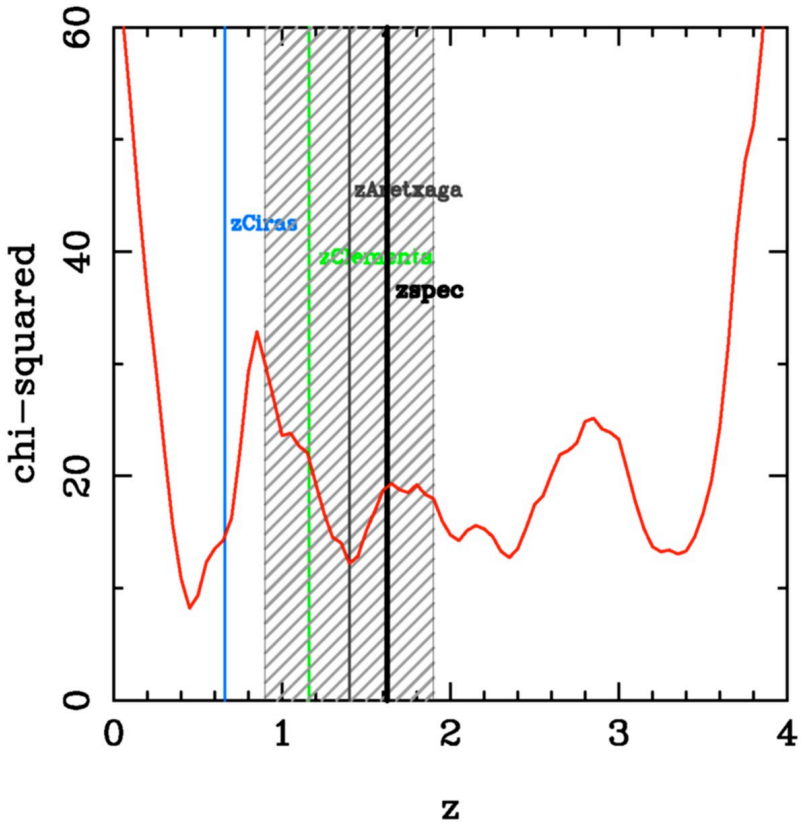
e.g. Clements et al. (2007)

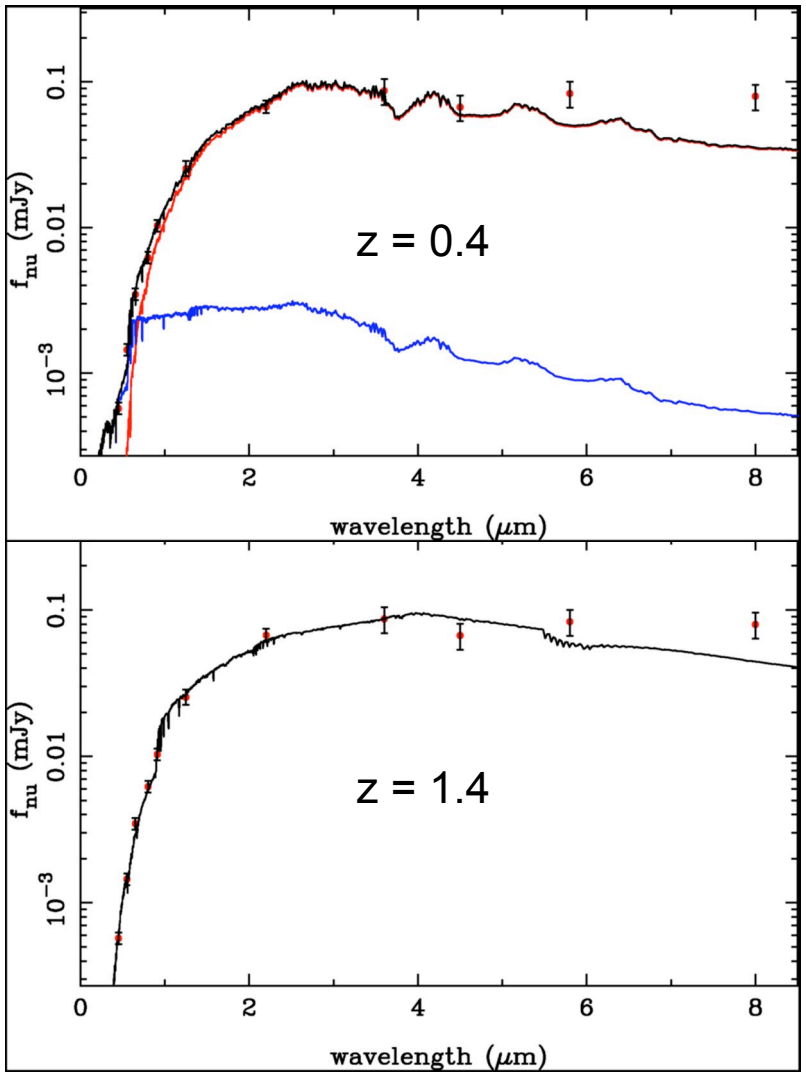
Sometimes redshift estimation fairly clean

e.g. GN20 – brightest HDF source



But sometimes complicated….





Currently exploring how to combine independent redshift estimates

Some evidence of down-sizing:

brightest sources have highest redshifts

Clear that the comoving number density of bright (~5-10 mJy) sub-mm sources peaks in redshift range $2 < z < 3$

3. Sizes, morphologies, masses

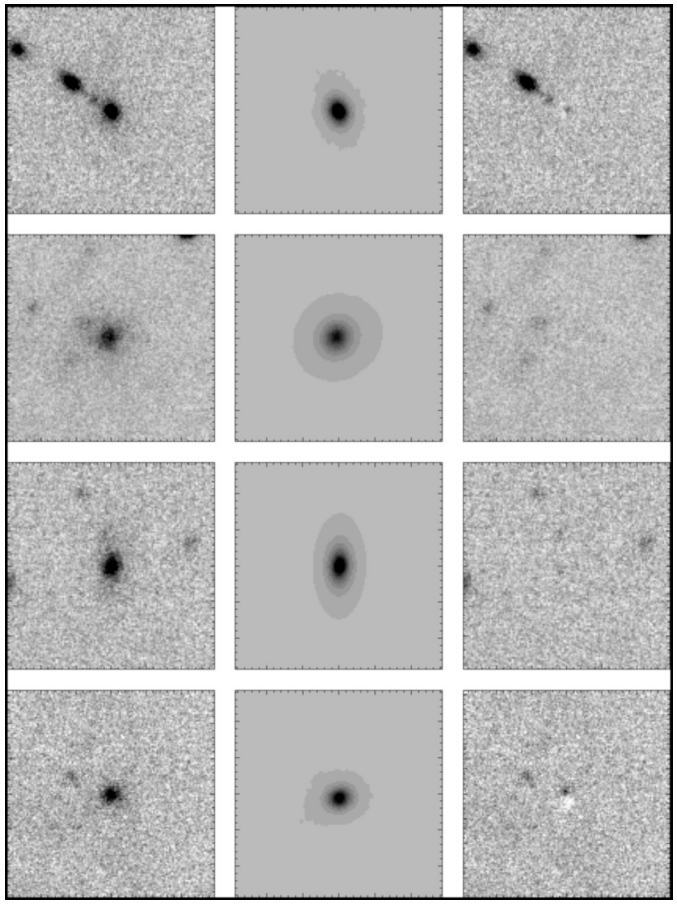
Some new results from

Targett, Dunlop, et al. (2007)

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

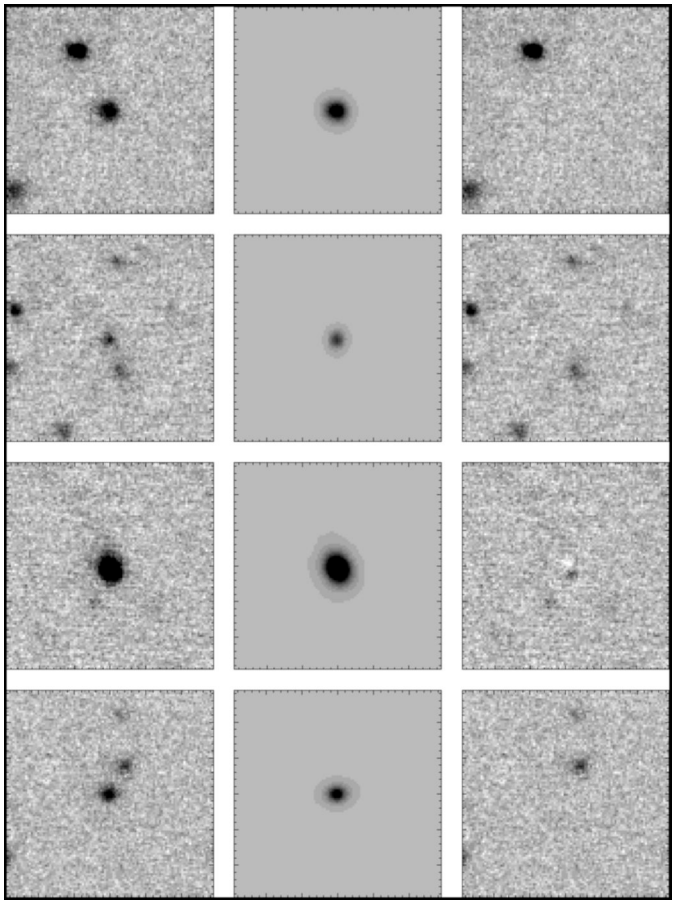
Radio galaxies

= known elliptical progenitors

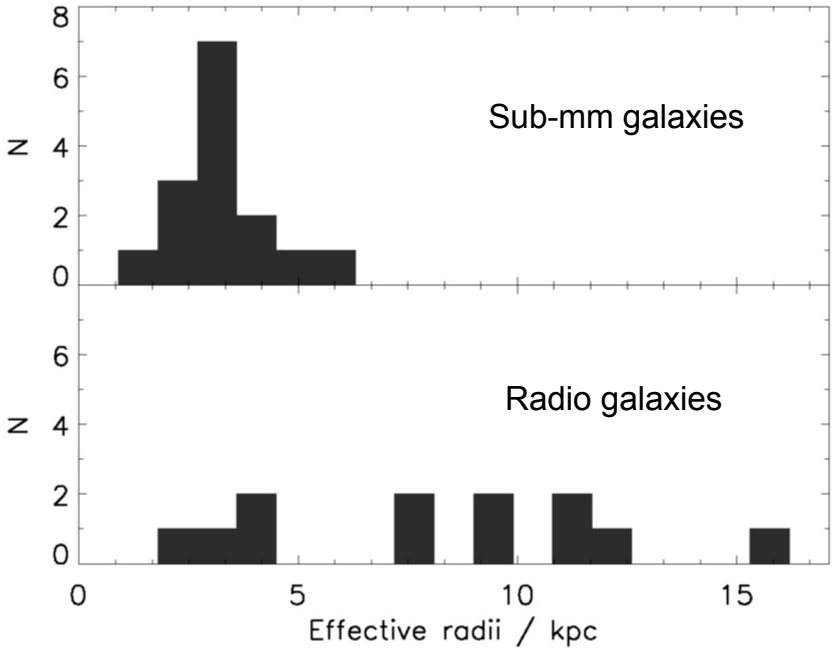


Sub-mm galaxies

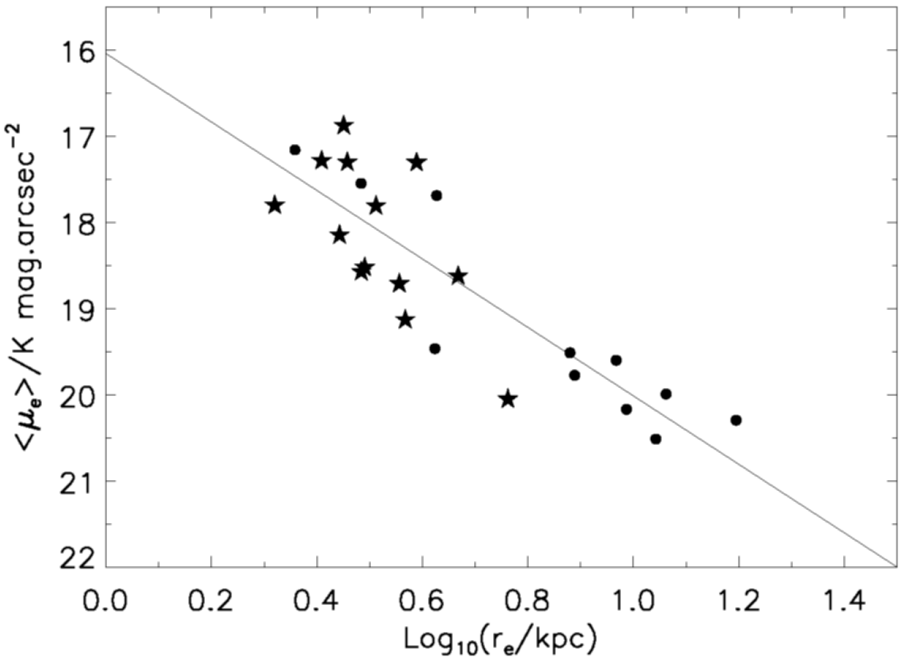
= possible elliptical progenitors



Results from galaxy model fitting

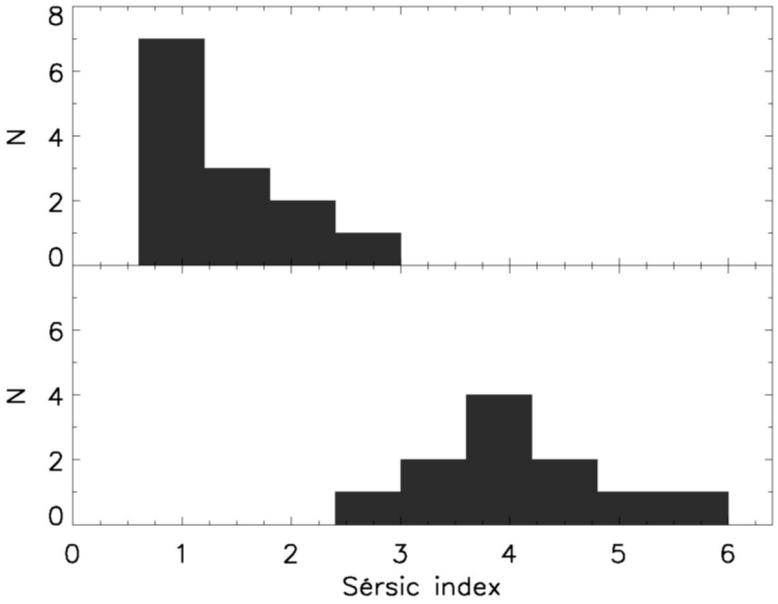


Sizes



Kormendy relation at z = 2

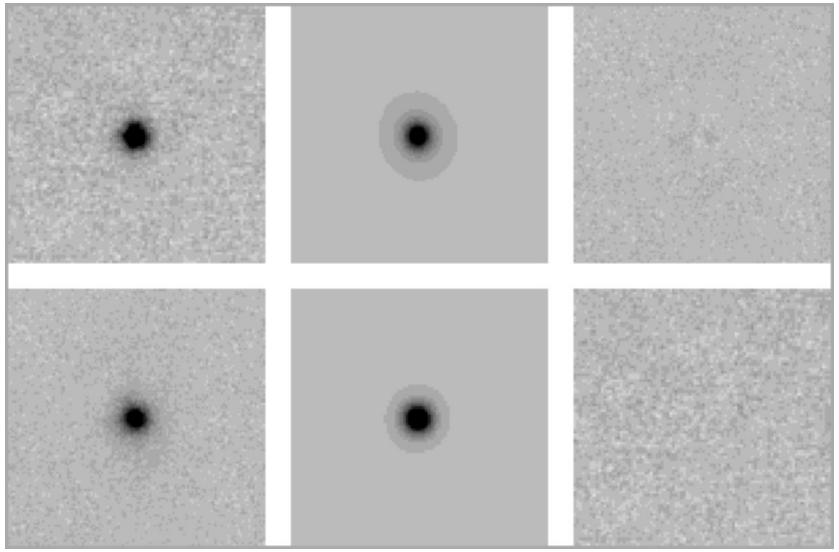
Morphologies



Sub-mm galaxies are mainly discs

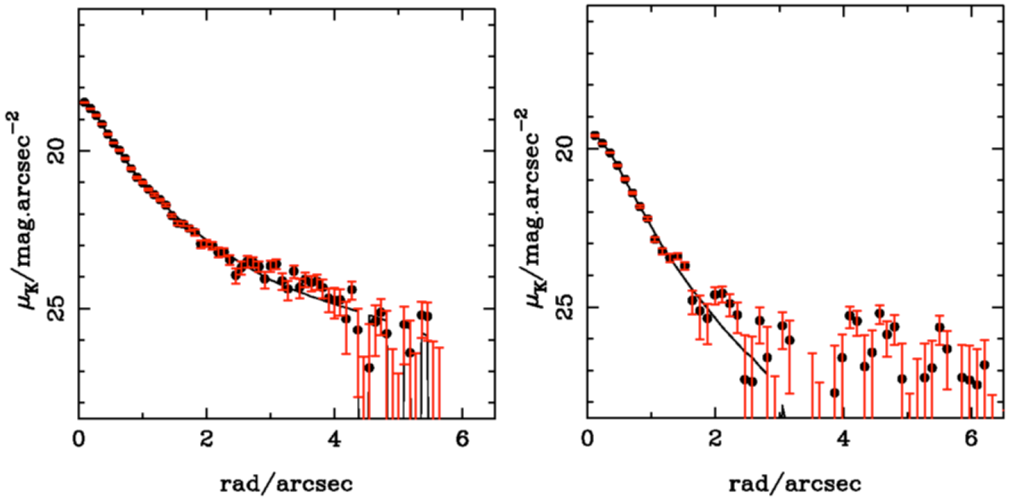
Radio galaxies are $r^{1/4}$ spheroids

Image Stack



~50 hr UKIRT image of
z = 2 radio galaxy

~20 hr Gemini image of
z = 2 submm galaxy



Masses

Await decent clustering measurements to characterize typical CDM halo masses of submm galaxies

CO dynamical masses suggest

~10^{11} M_{sun} within r ~ 2 kpc (Tacconi et al. 2006)

We find typical stellar masses

~ 3 x 10^{11} M_{sun} and typical $r_{0.5}$ = 2-3 kpc

4. The nature of sub-mm galaxies

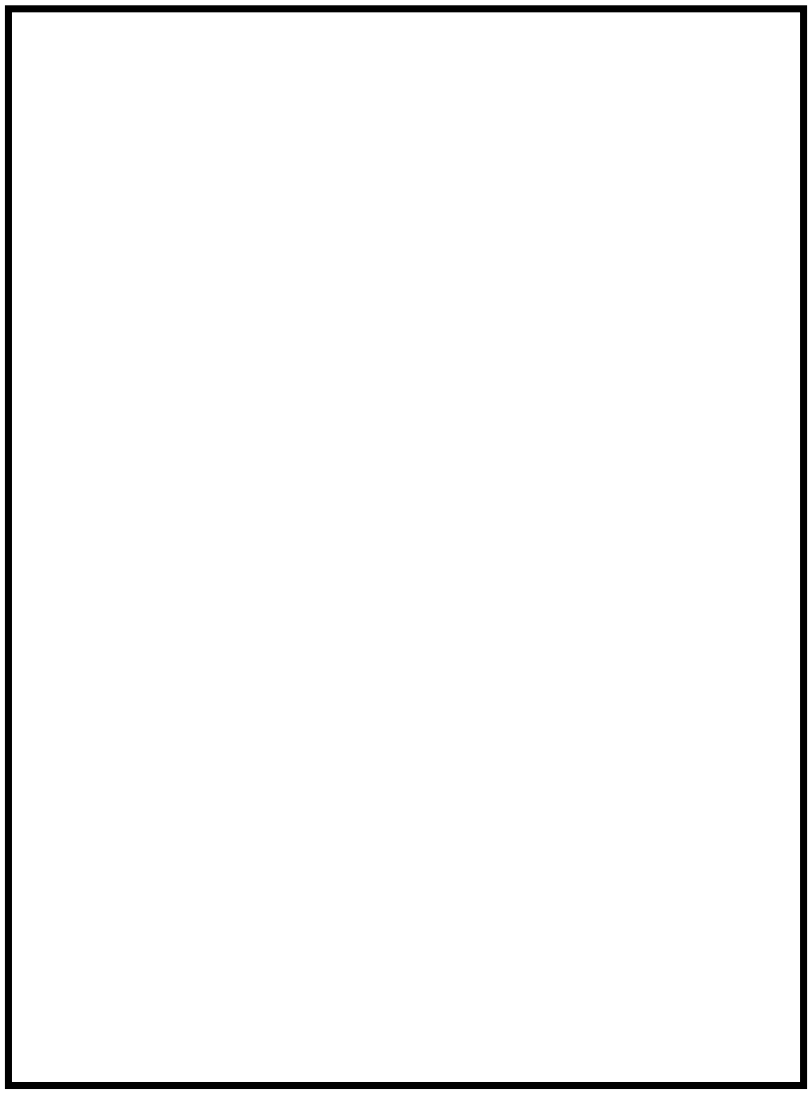
4. The nature of sub-mm galaxies

Sometimes claimed that sub-mm galaxies are bizarre objects in a very unusual phase/mode of star formation

But….

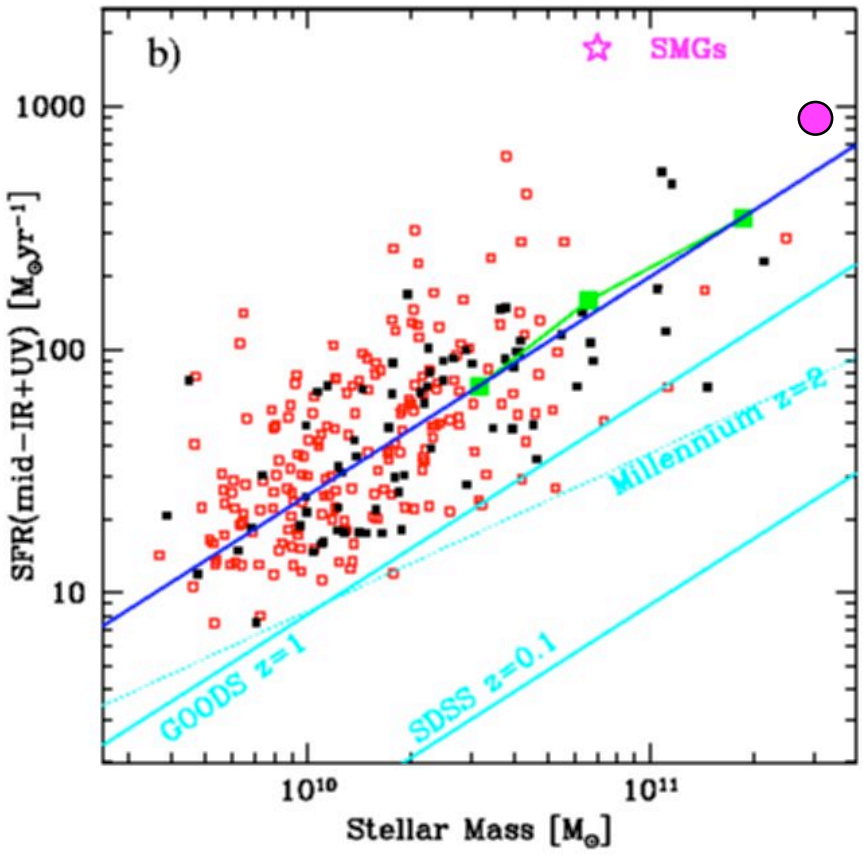
10^{11} M_{sun} of gas within r ~ 1 kpc would be expected to produce 1000 M_{sun} of stars per yr

Schmidt-Kennicutt Law



Bouche et al. (2007)

You'd expect such a big starburst to be hosted by an already massive galaxy



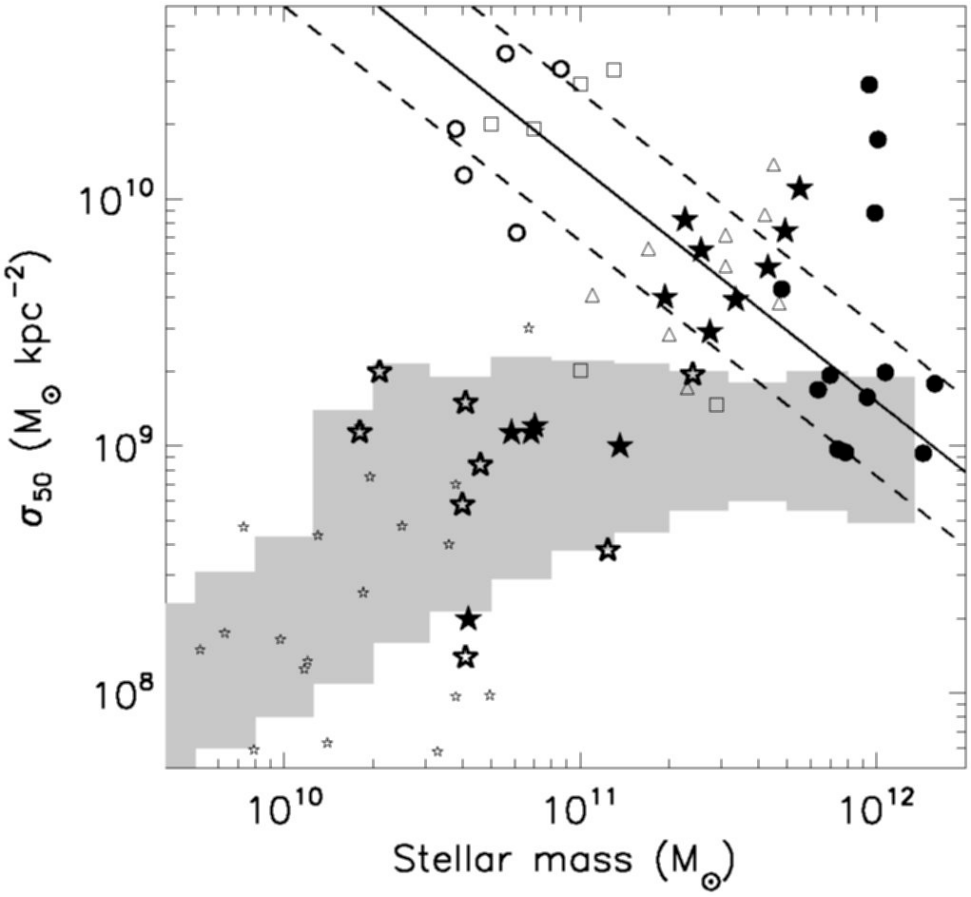
Daddi et al. (2007)

SFR v stellar mass relation at z = 2

…. and the massive host galaxy has a very high stellar mass density

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

- following Zirm et al. (2006)



Targett, Dunlop et al. (2007)

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?).

5. Future prospects

Larger, deeper samples with complete SEDs

- BLAST, SCUBA2, Herschel, LMT, CCAT

Complete IR identifications, redshifts, masses

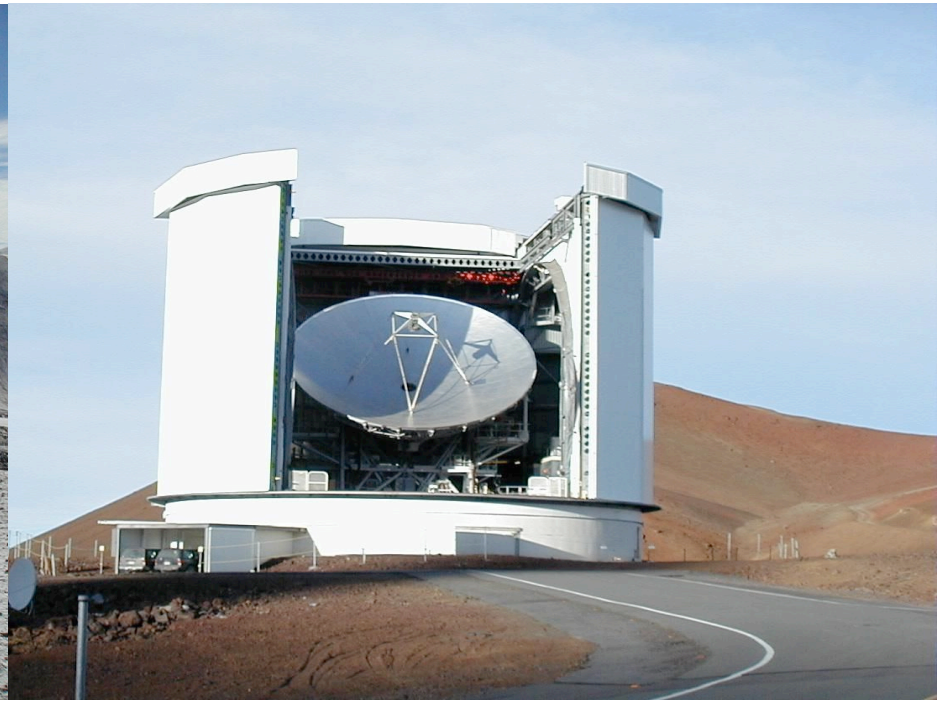
- UKIDSS, Ultra-VISTA, Spitzer, FMOS, KMOS

Detailed high-resolution spectroscopy

- ALMA, JWST

Cosmology Legacy Survey

Jim Dunlop University of Edinburgh
+ Ian Smail (Durham), Mark Halpern (UBC), Paul van der Werf (Leiden)



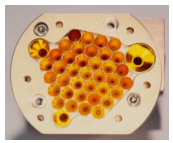
Cosmology Legacy Survey

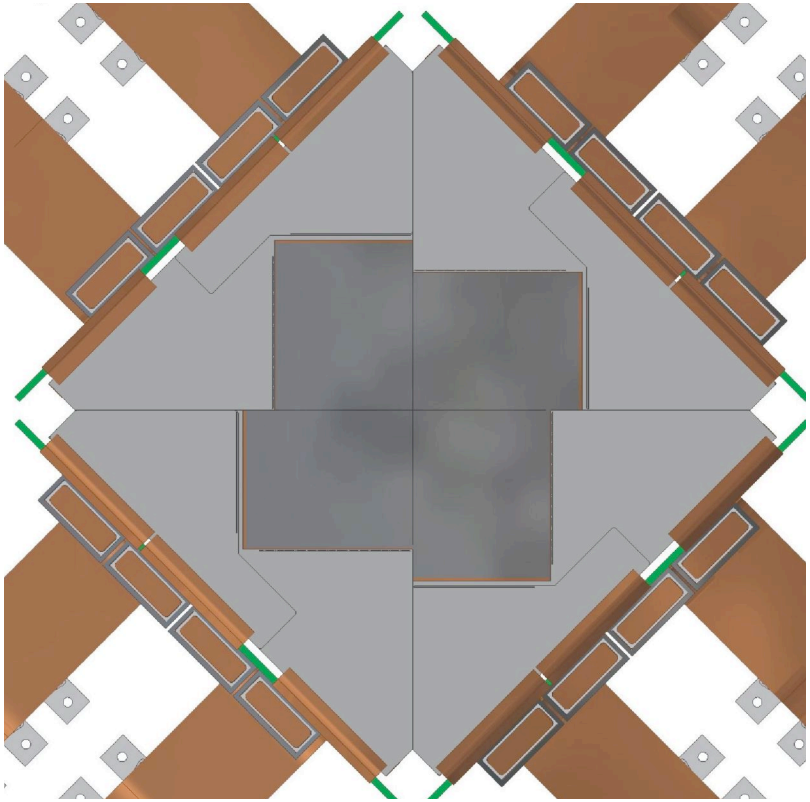
SCUBA-2 is a new CCD-style imager for the JCMT

50 sq arcmin FOV ~ 10 x SCUBA FOV

Fully sampled imaging

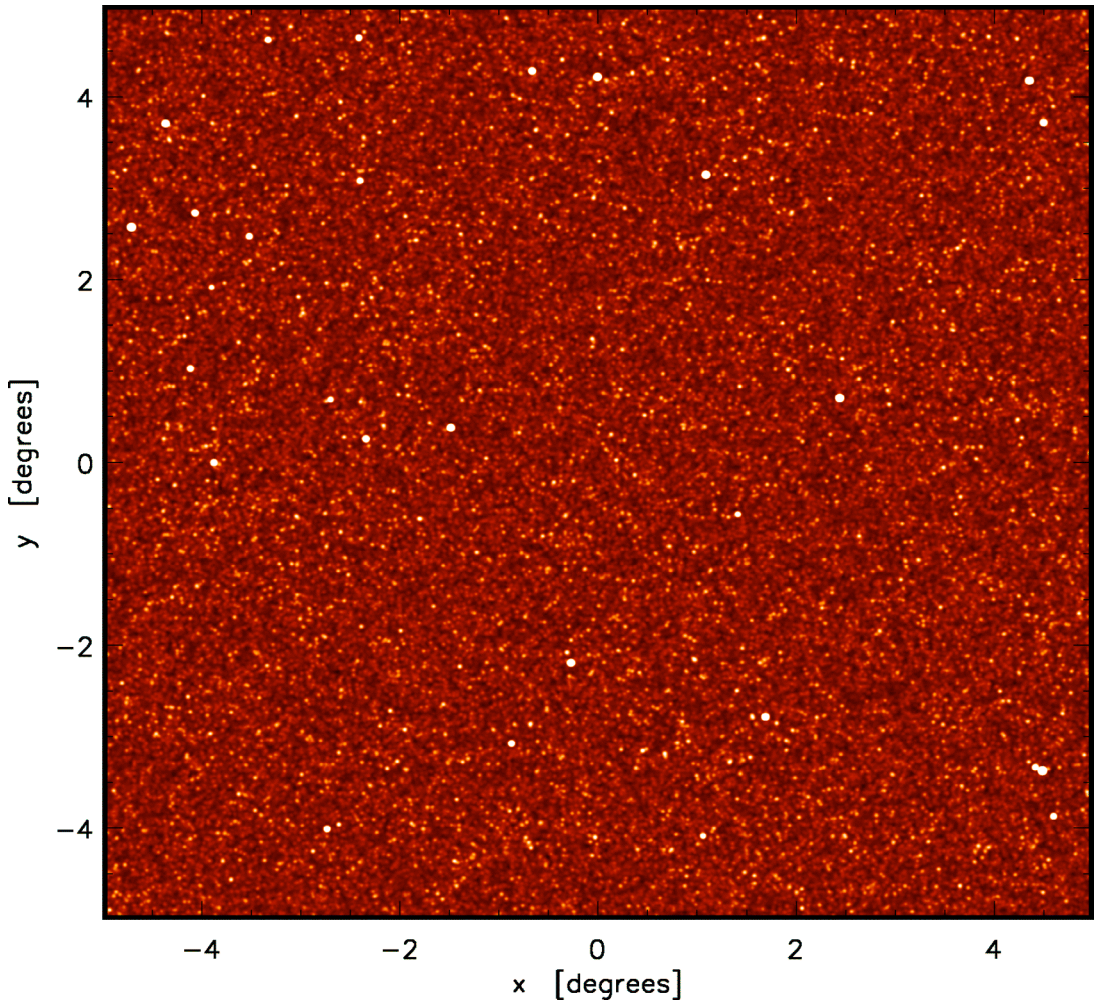
New TES detectors





Cosmology Legacy Survey

SCUBA2 Survey Strategy



Wide 850 survey – "Super SHADES"

20 sq degrees, σ_{850} = 0.7 mJy ~10,000 sources with S/N > 10

- ~Schmidt plate in area, to the depth of the SCUBA HDF image
- Accurate measurements of clustering and redshift distribution
  – placing luminous starbursts within ΛCDM
- Observing proto Coma clusters
- The bright source counts – extreme objects
- Bulge and black-hole formation
- Intermediate and low-redshift sources
- The SZ effect

Deep 450 micron survey

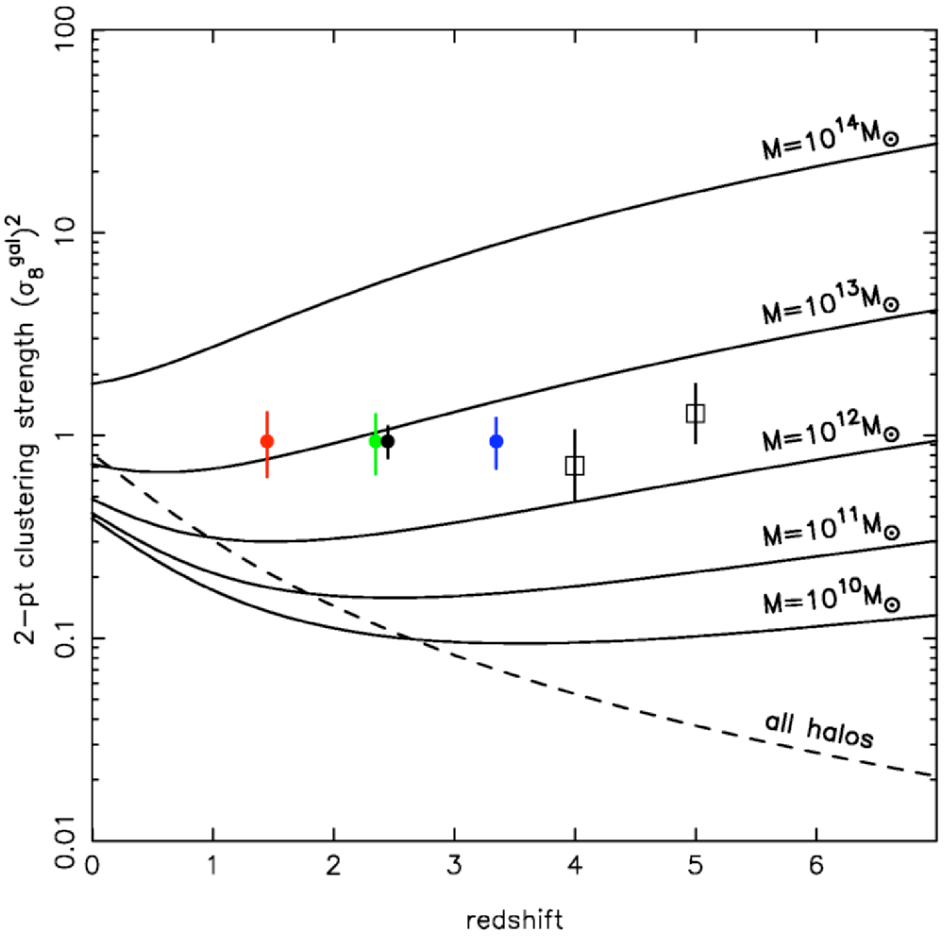
0.6 sq degree, σ_{450} = 0.5 mJy, ~10000 sources

- Bolometric output of the 850 micron population
- Determining the source populations dominating the 450 micron background
- Exploiting high-resolution to beat down the confusion limit
- Exploiting high resolution to better identify the 850 micron sources + connect with Herschel and Spitzer data

Cosmology Legacy Survey

1. Sub-mm galaxies and Structure Formation

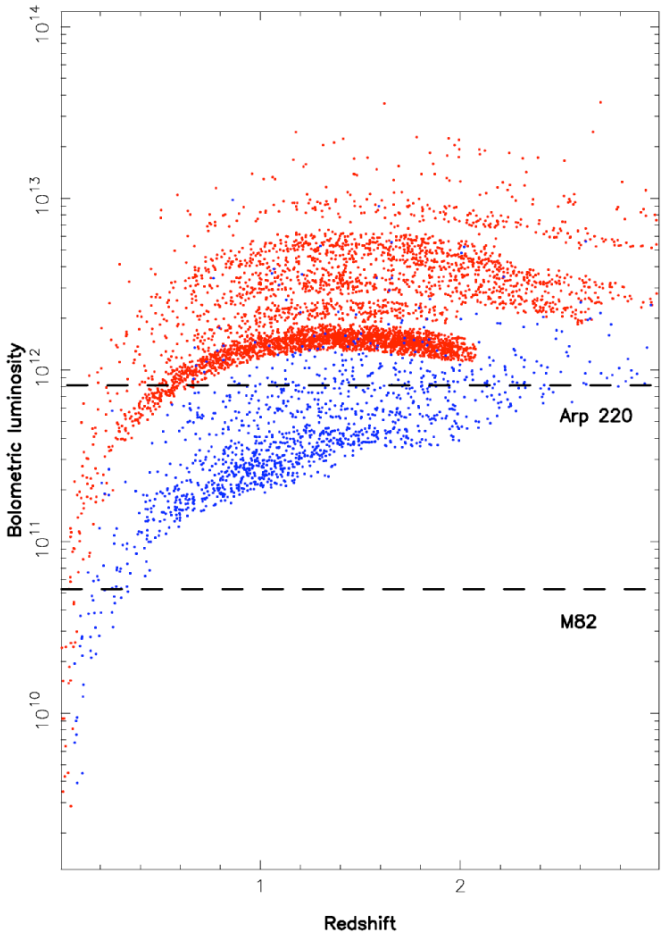
- placing sub-mm galaxies in the Lambda-CDM framework



Cosmology Legacy Survey

2. Sub-mm galaxies and Cosmic Star Formation History

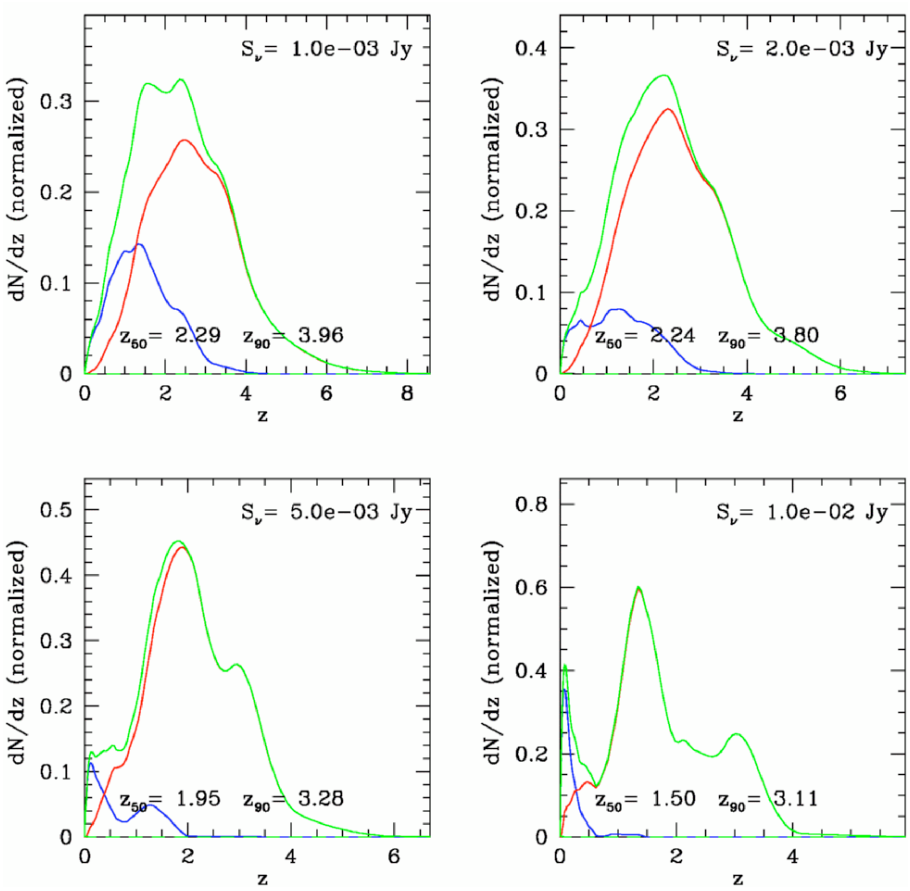
- constructing the evolving sub-mm luminosity function

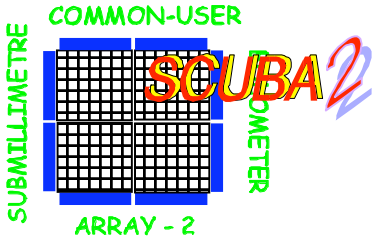


Cosmology Legacy Survey

3. Towards a detailed understanding of galaxy formation

- testing semi-analytical, semi-numerical, and hydrodynamical models





Cosmology Legacy Survey

Survey Status

Survey approved in July 2005

490 hrs of band-1 time awarded to the 450 micron survey
in semesters 08A,08B,09A,09B (=90% of all band-1 time)

630 hrs of band-2/3 time awarded to the 850 micron survey
in semesters 08A,08B,09A,09B

SCUBA2 should head to Hawaii by end of 2007