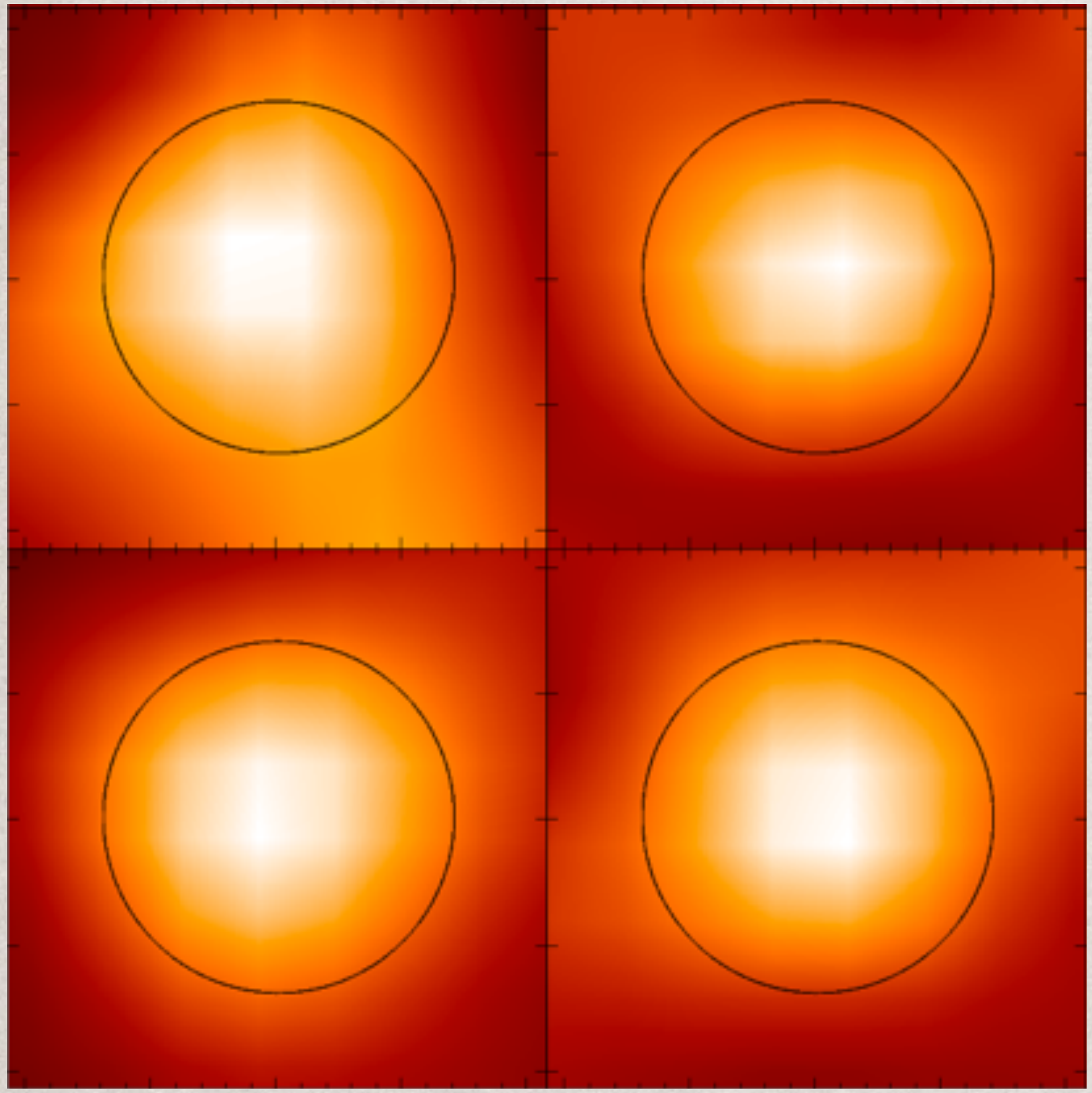
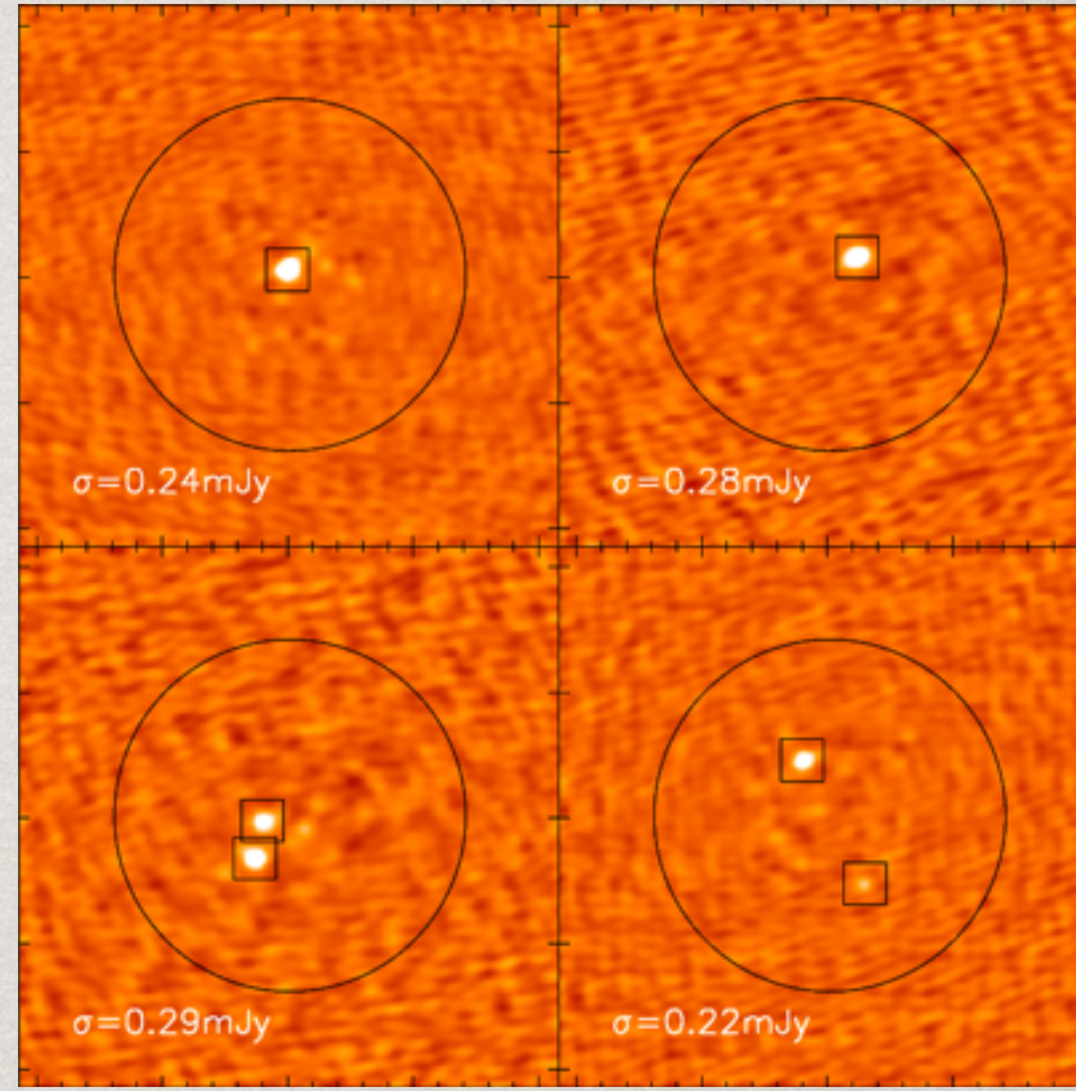
ALMA and Herschel surveys of high-redshift, star-forming galaxies

Mark Swinbank (Durham)

pre-ALMA

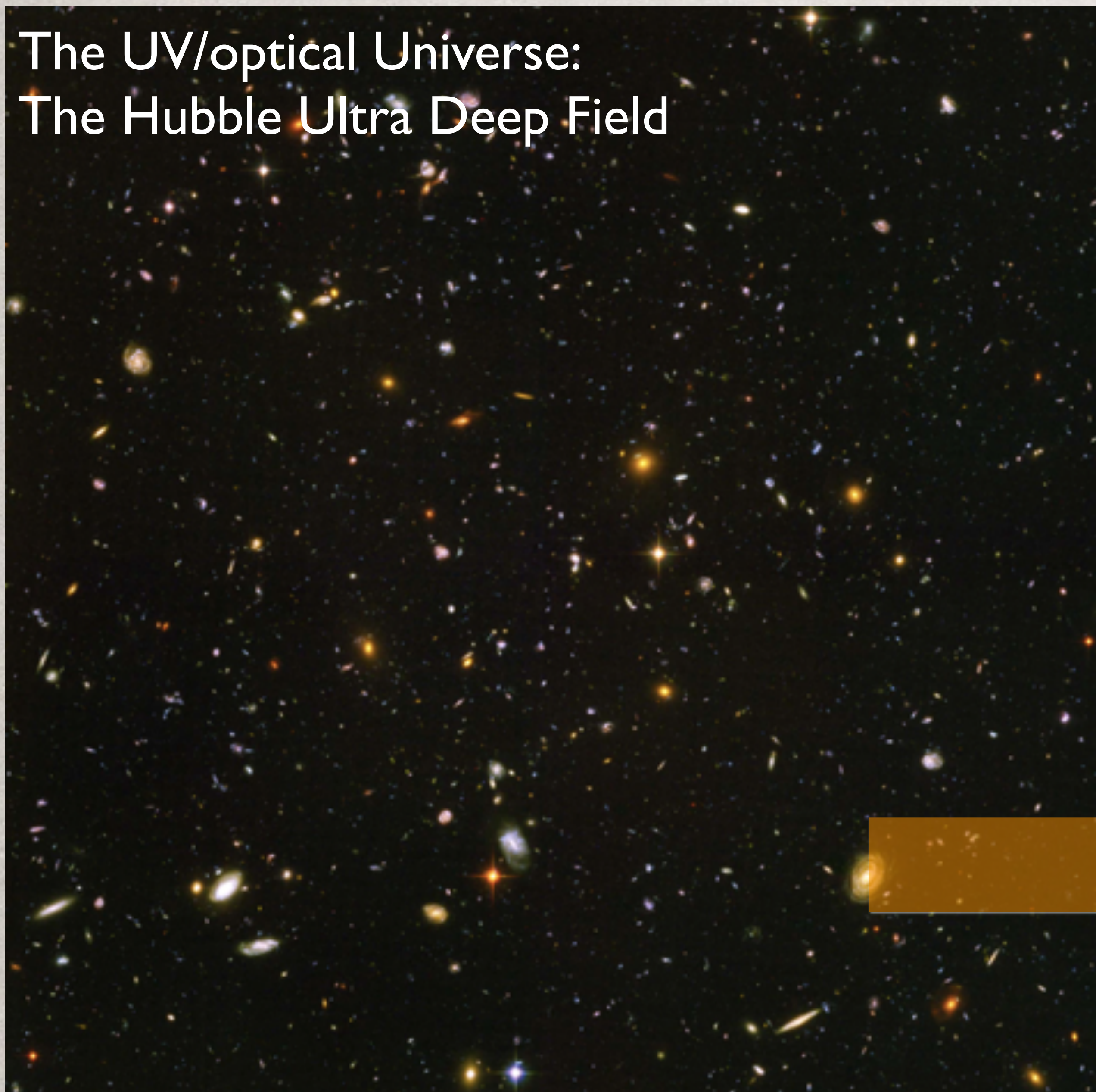


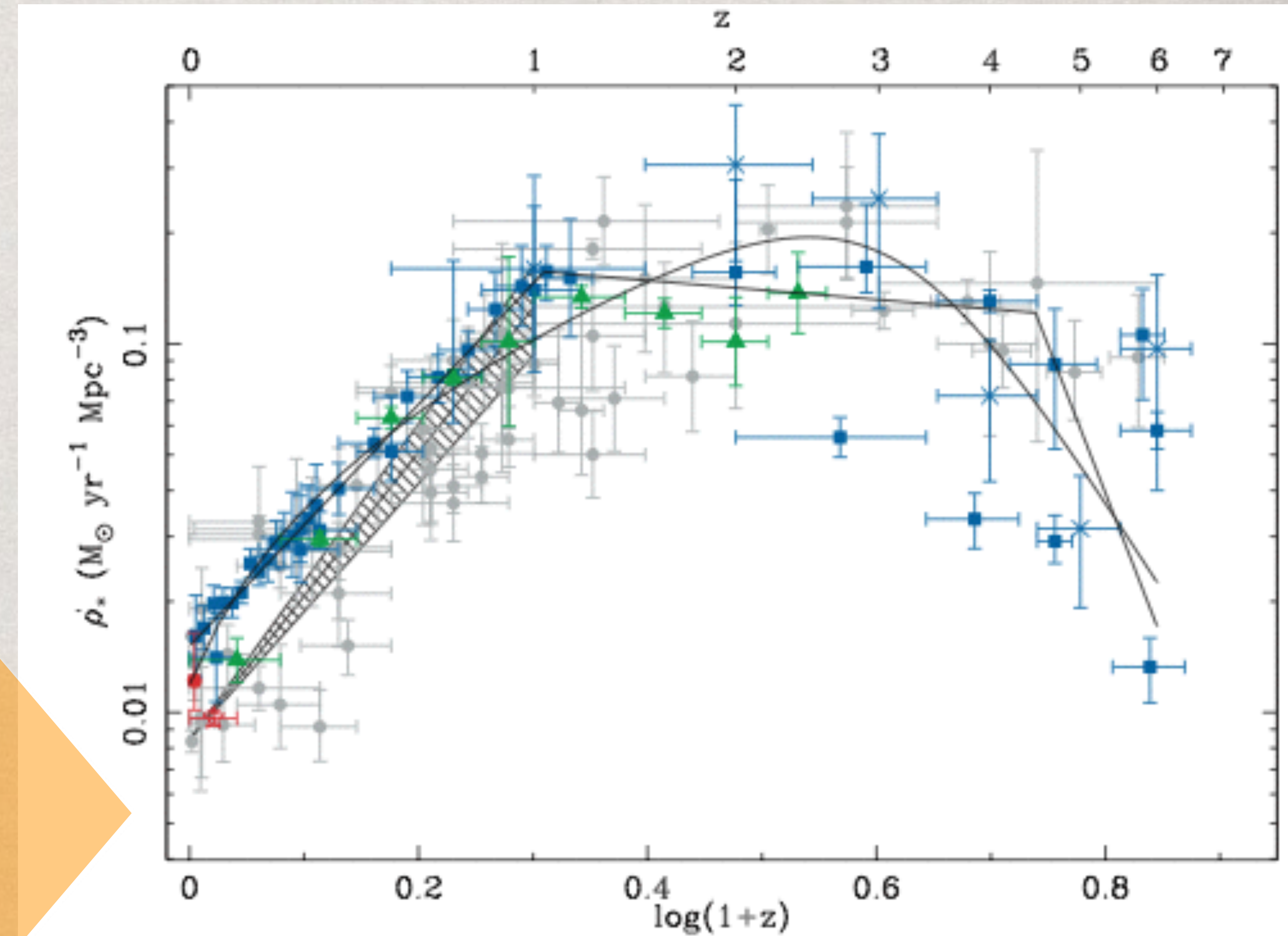
with ALMA



James Simpson, Jackie Hodge, Ian Smail, Alex Karim, Fabian Walter, Rob Ivison, Jim Geach ++ the ALMA-LESS and ALMA-SCUBA-2 CLS consortia

Epoch of Galaxy Formation





Hopkins & Beacom 2006

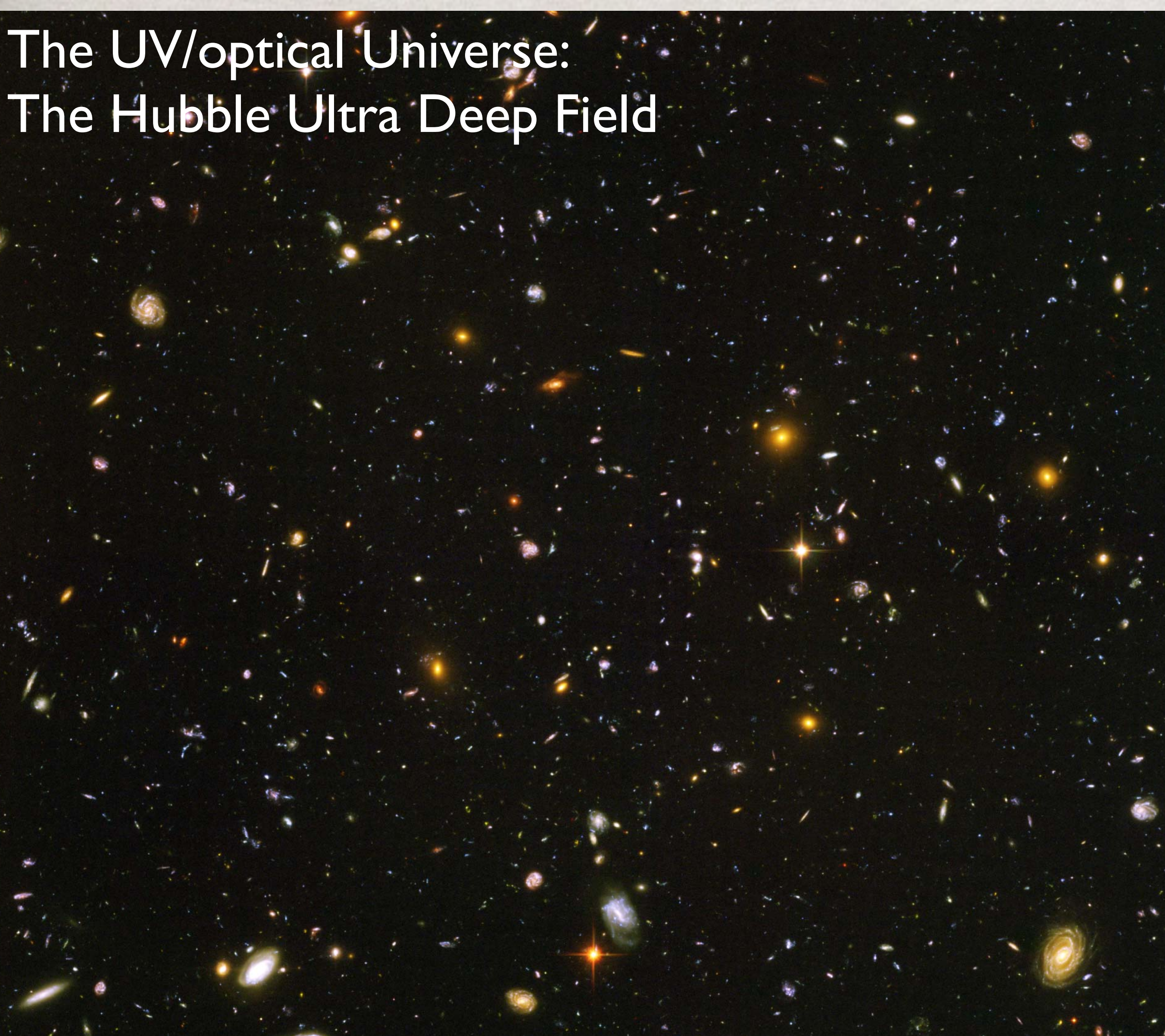
- Background in UV and optical is mainly dominated by stars (rather than AGN)
- Luminosity density can be used to track the evolution of the star-formation with redshift to identify the epoch of galaxy formation

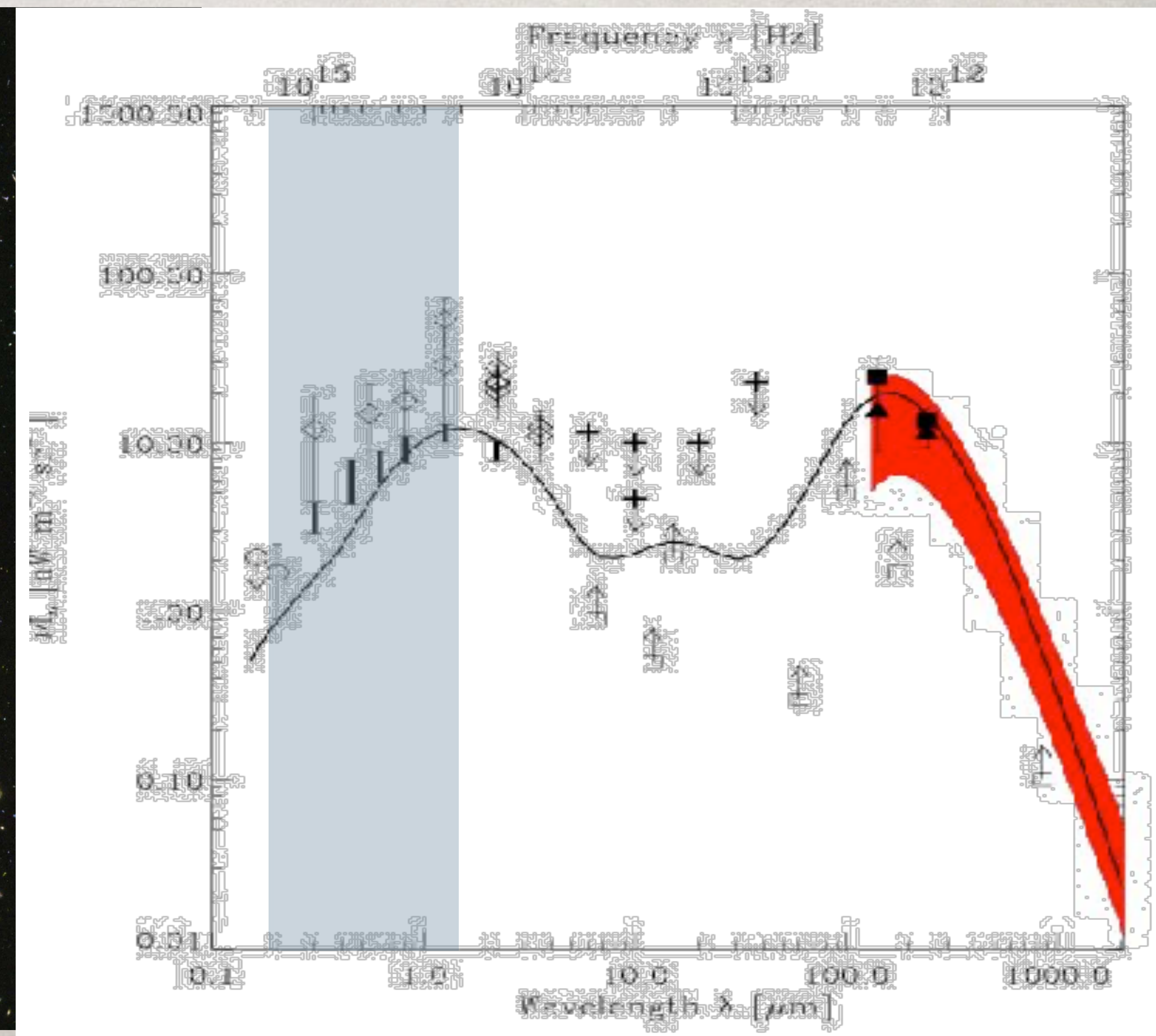
What is special about sub-mm wavelengths?

COBE showed that ~50% of the light produced by extra-galactic objects has been reprocessed by dust and re-emitted in the far infrared and sub-mm.

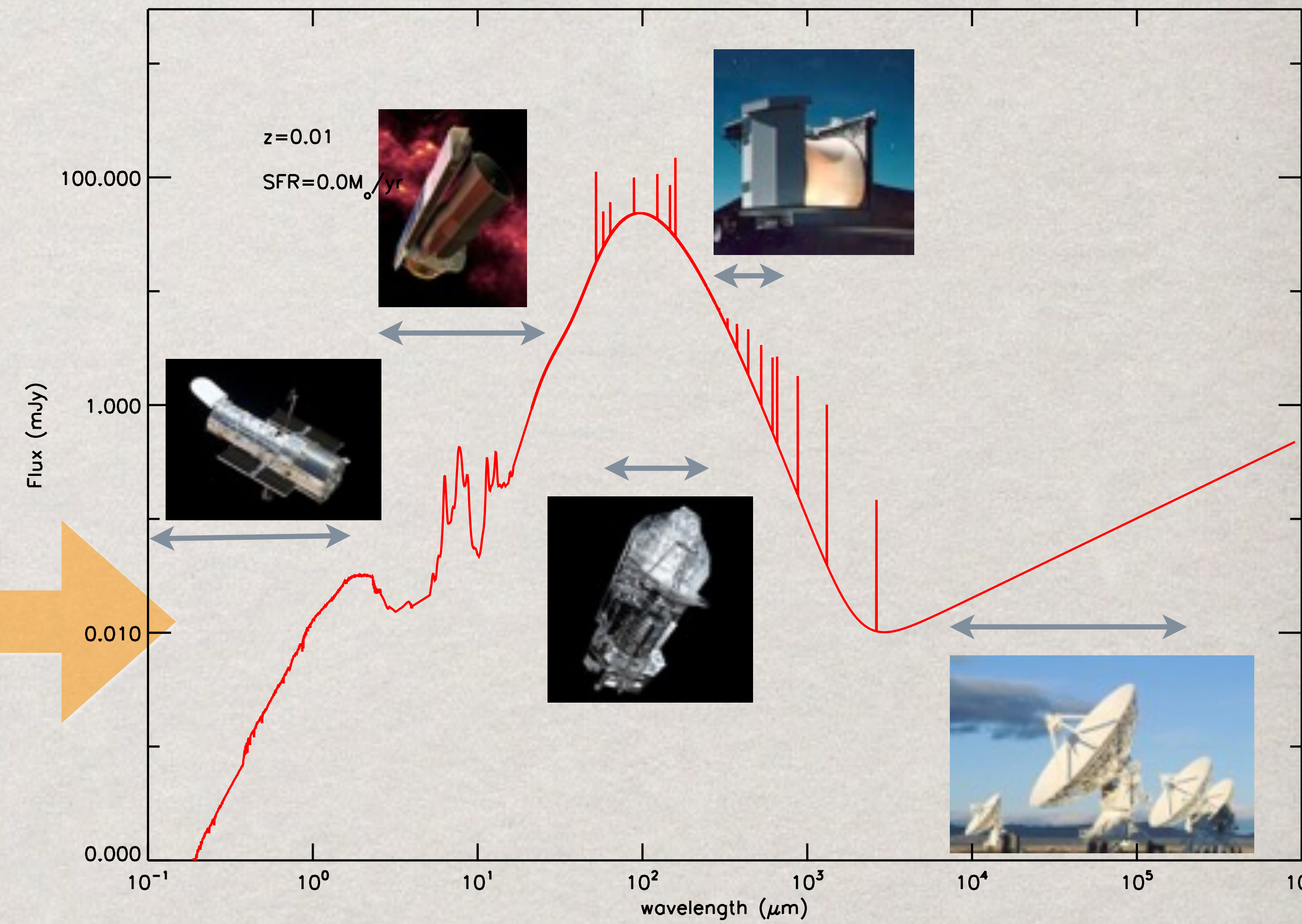
This discovery provides further strong motivation for studying the dust emission from objects at all redshifts and all far infrared wavelengths.

(Puget et al. 1996, Fixsen et al. 1998, Hauser et al. 1998, Lagache et al. 1999)



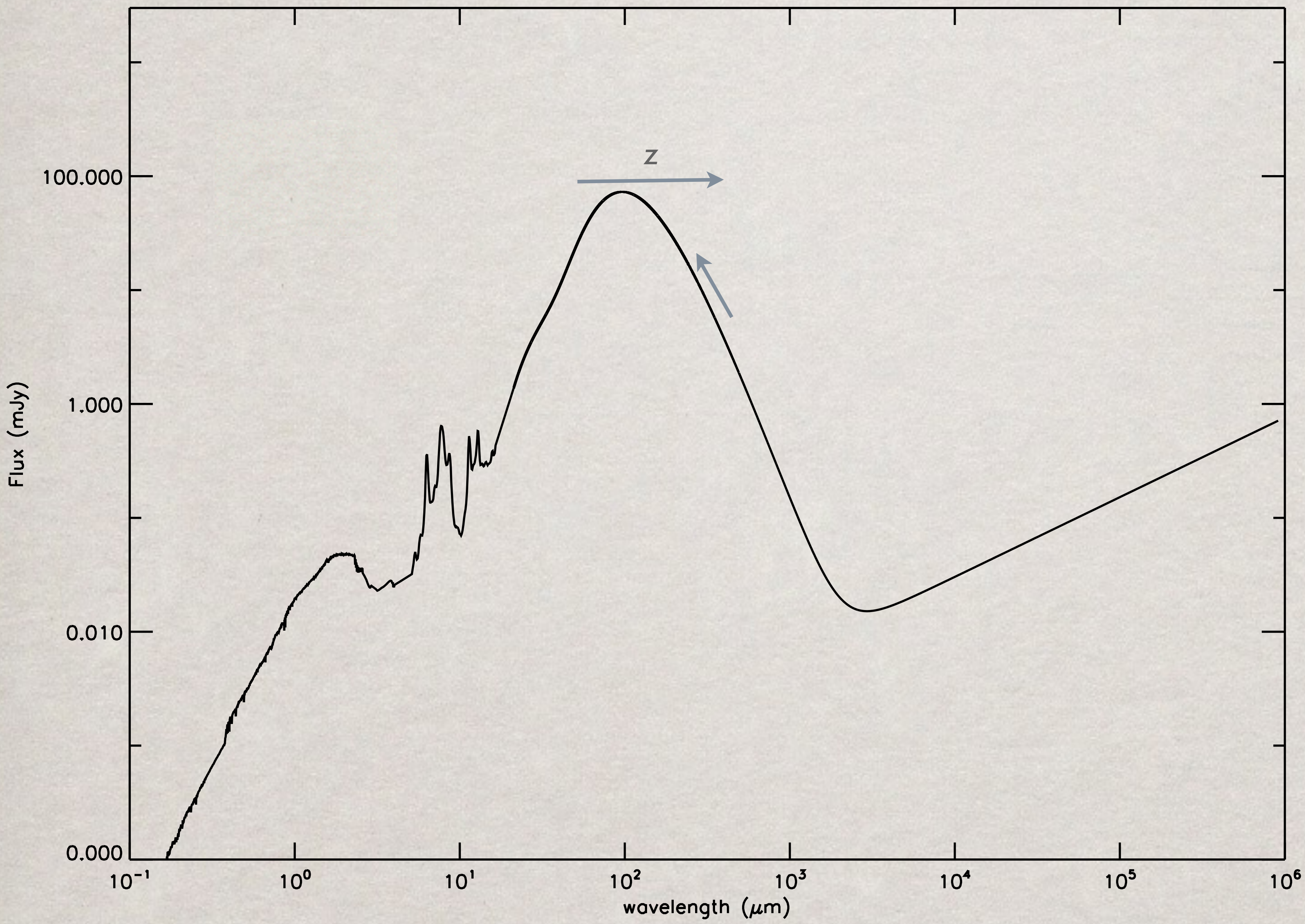


Ultra-Luminous Infrared Galaxies



- Most luminous FIR gals at z~0 are Ultra-Luminous InfraRed Galaxies (ULIRGs)
  - $L_{FIR}>10^{12}L_o$, inferred SFRs 100's M_o/yr
  - >95% Luminosity comes out in FIR (~10-1000um)
- ULIRGs are gas-rich mergers - undergo violent relaxation and produce a pressure-supported stellar system: Elliptical Galaxies
- Host <1% of star formation at z=0 - maybe more important at high-z?
- Ellipticals live in dense regions, if they form in mergers when did they happen?

The negative k-correction in the sub-mm wave-bands

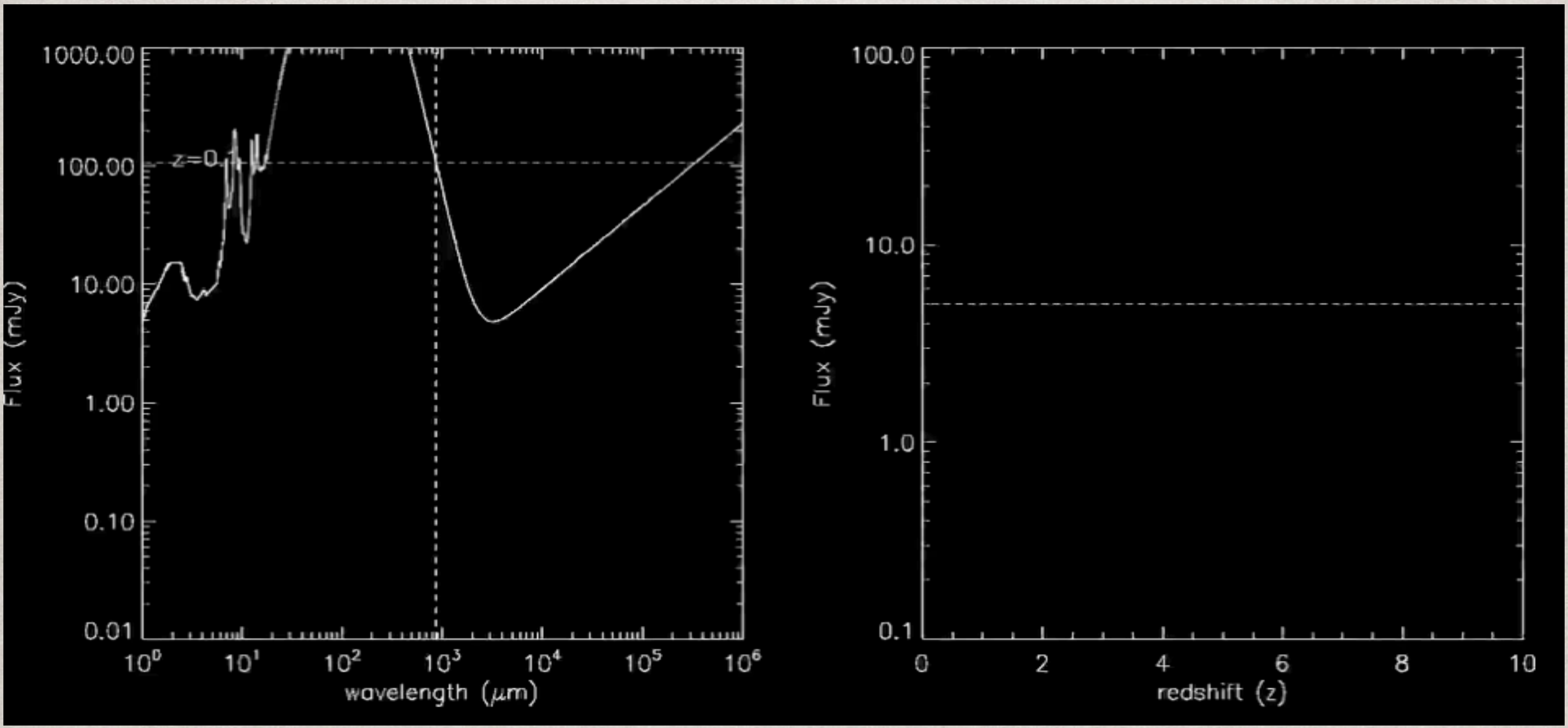


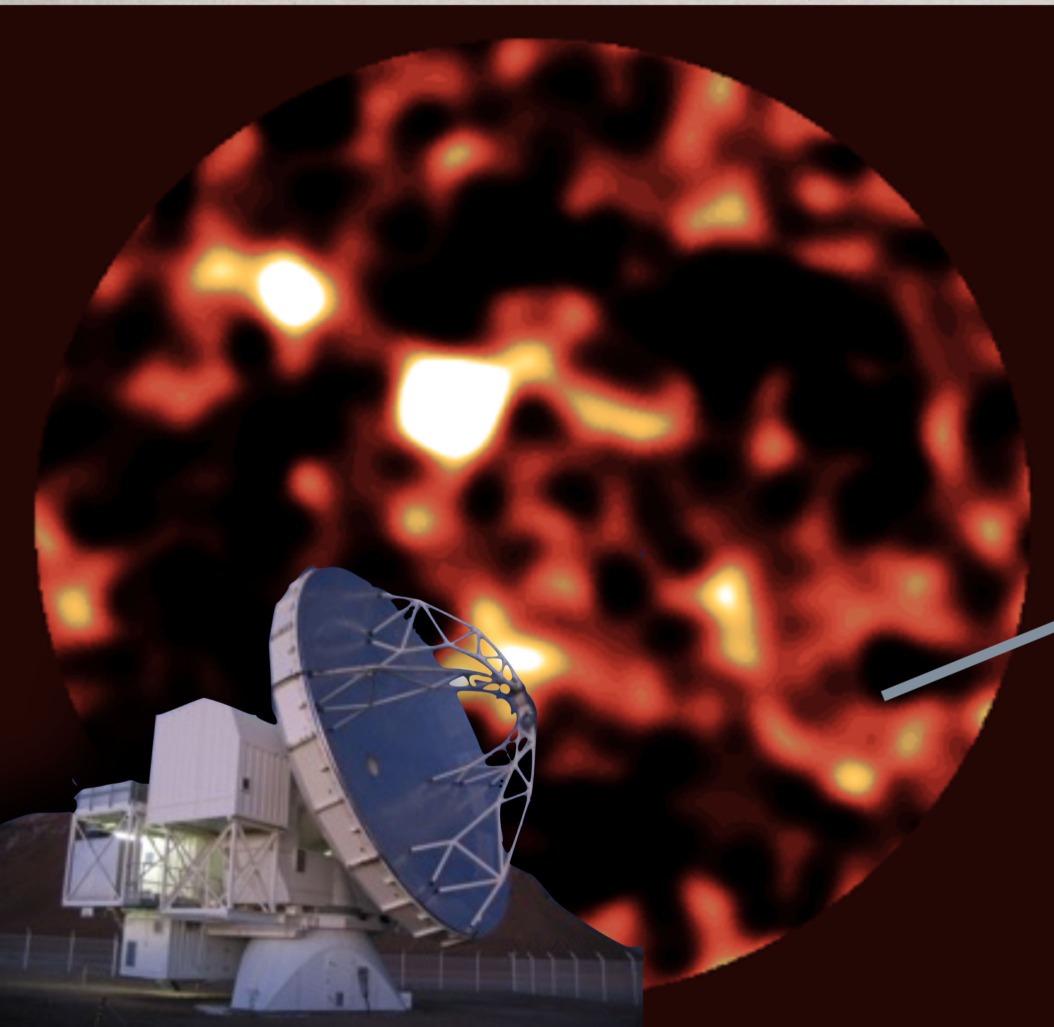
The negative k-correction in the sub-mm wave-bands

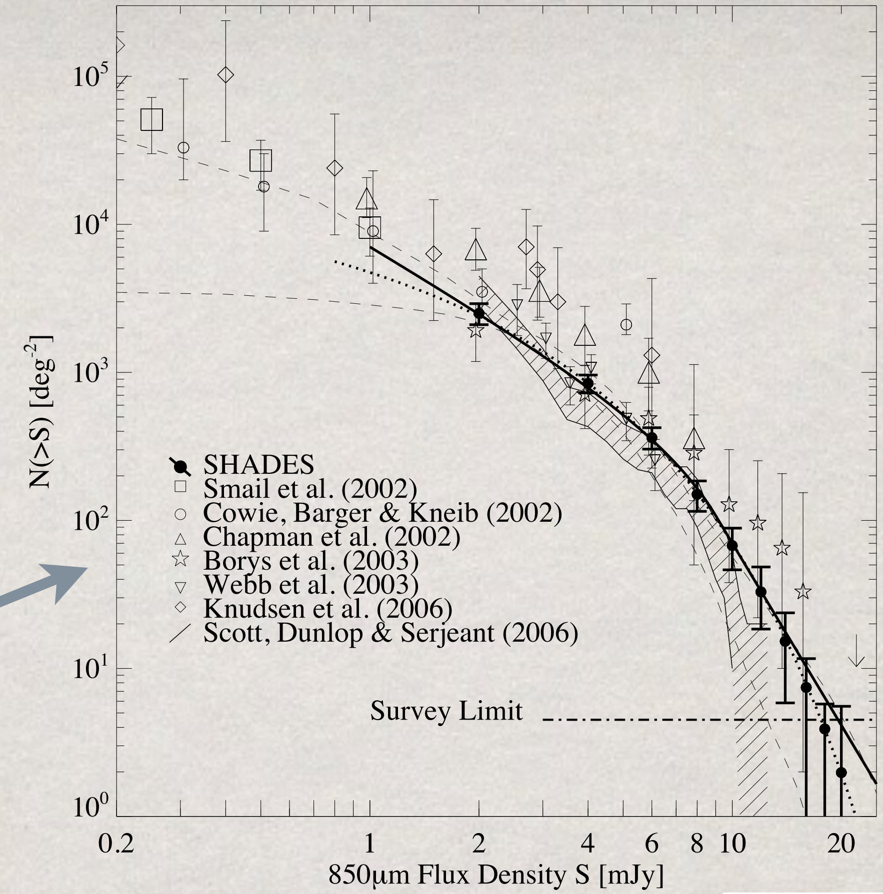
SFR = 500Mo/yr

z = 0.1-10

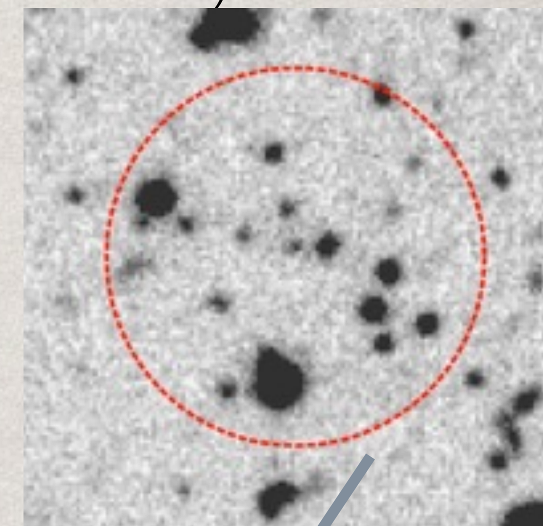
λ_{obs} = 850μm

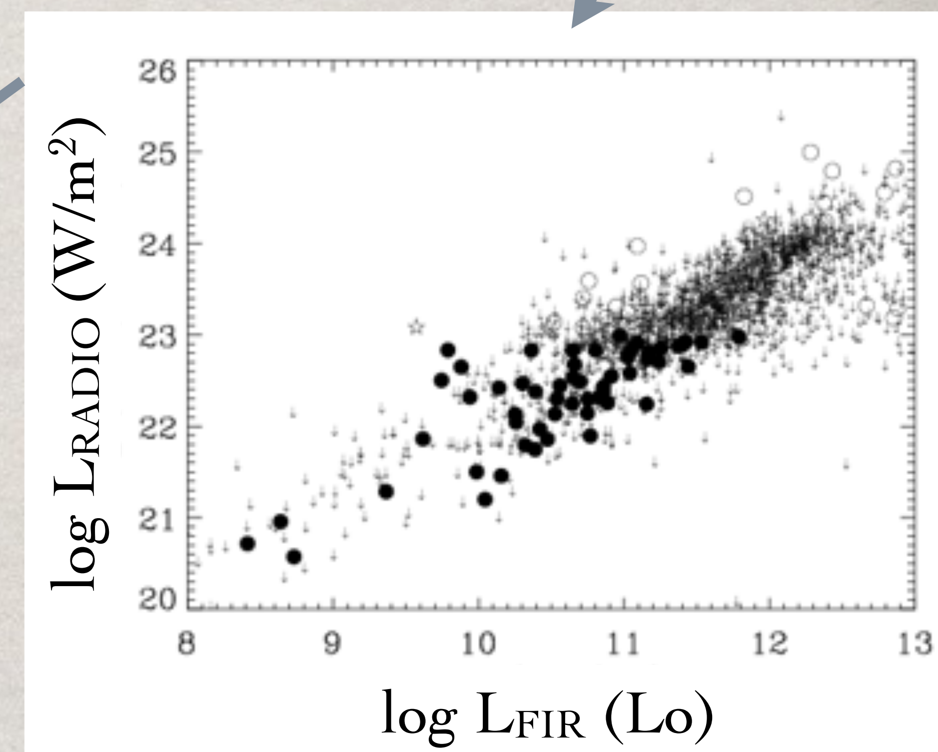


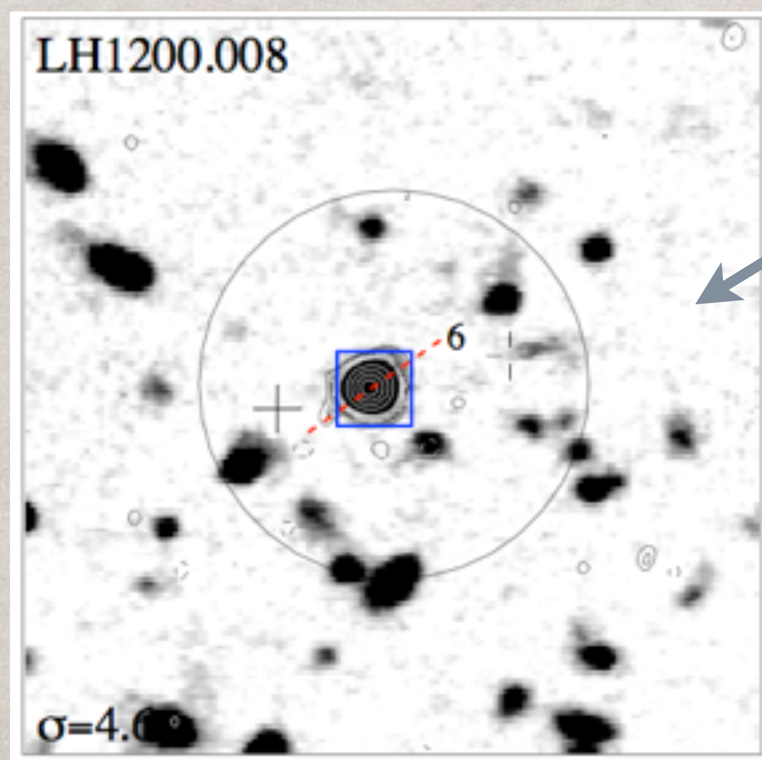




λ/D~18" (so lots of possible counterparts for each sub-mm source)







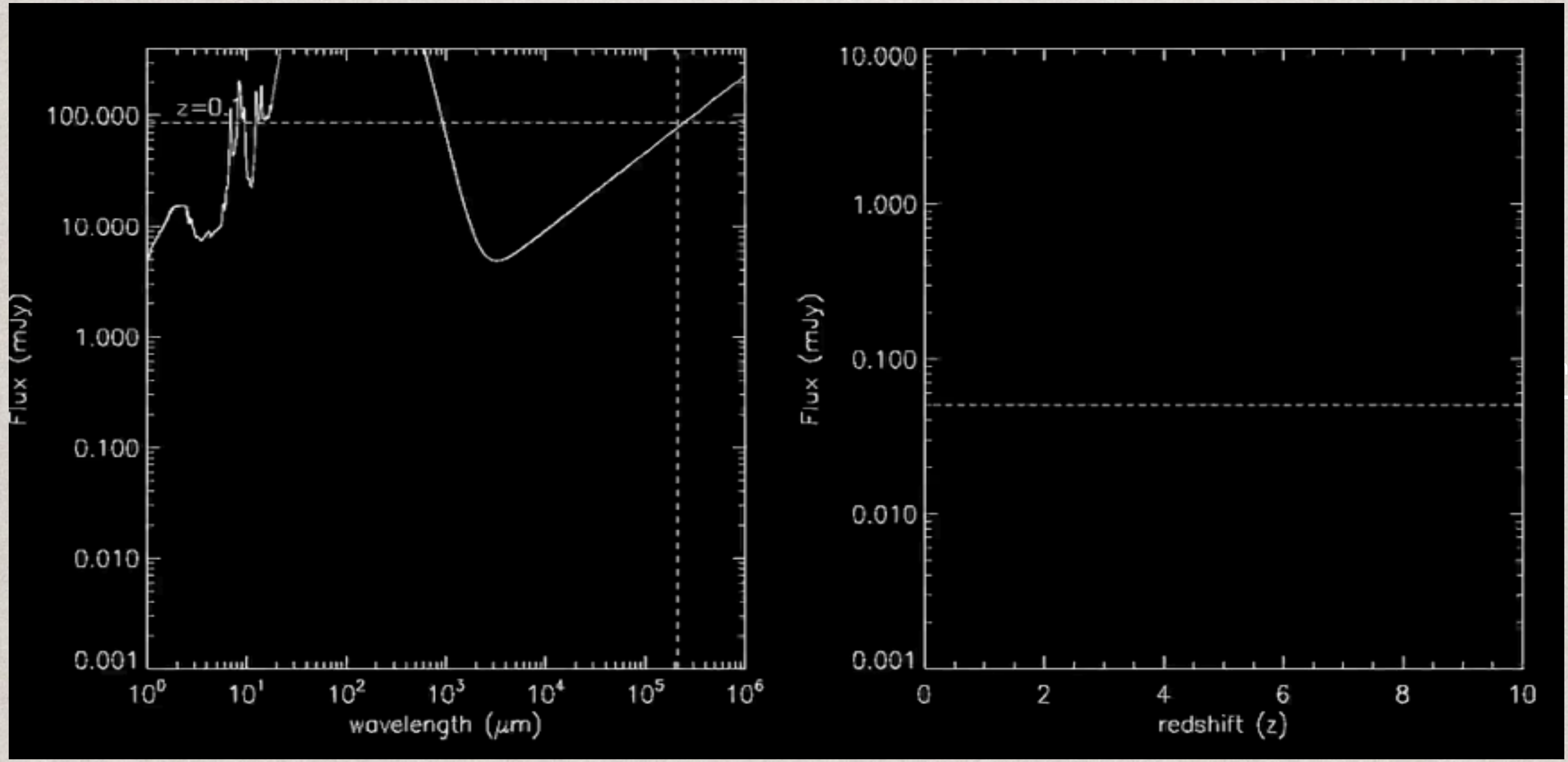
- Exploit correlation between FIR-radio in local star-forming galaxies (radio from CRs accelerated by SNe)
- Use radio to identify SMG then do blind spectroscopy (VLA positions to <0.3")

but there is a positive k-correction in the radio wave-bands

SFR = 500Mo/yr

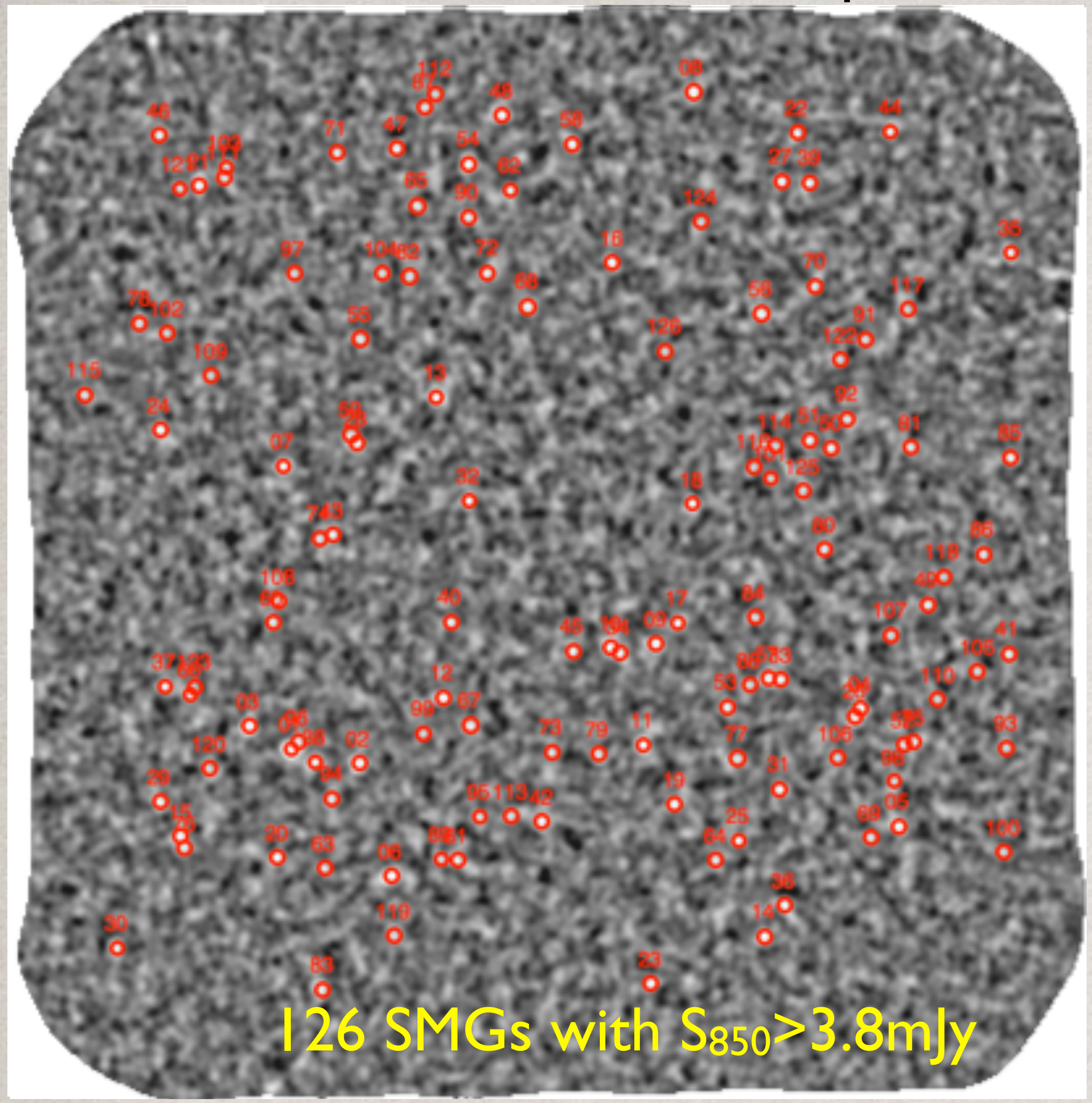
z = 0.1-10

λ_{obs} = 850μm



For most radio surveys, the positive k-correction in the radio means SMGs above z~3 can not be identified (about 50% of the sub-mm sources do not have an ID)

LABOCA Extended Chandra Deep Field South Survey (LESS)

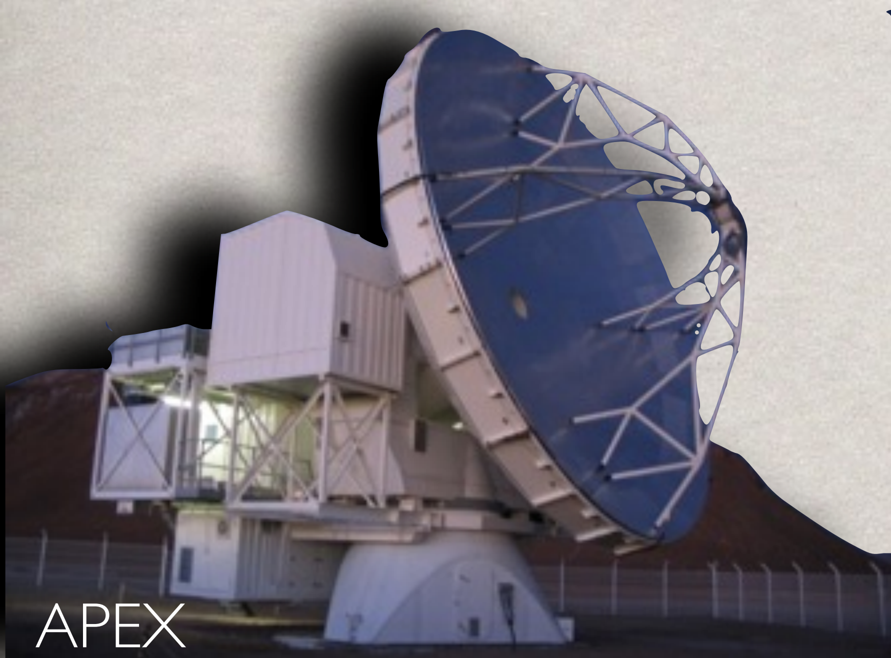


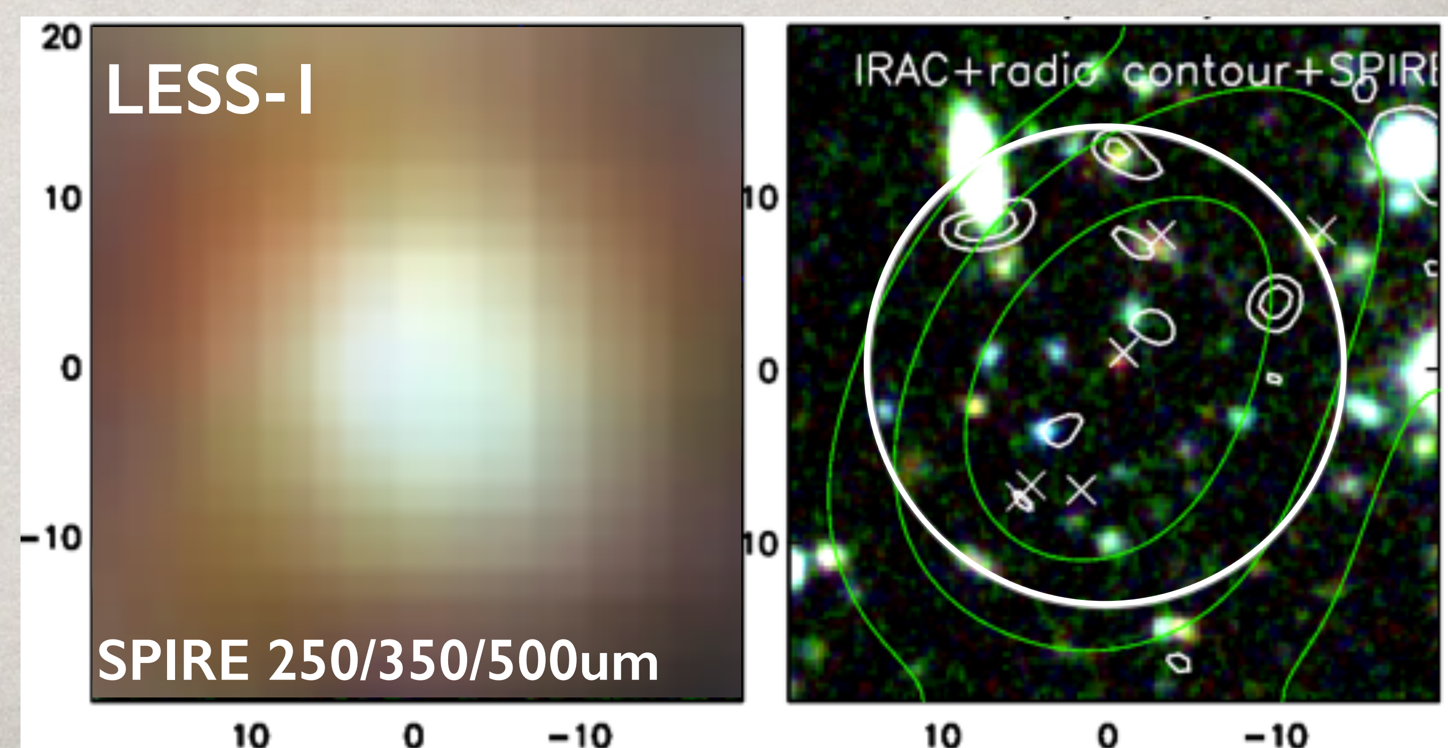
Weiss et al. (2009); Biggs et al. (2010); Coppin et al. (2009, 2011); Dunlop et al. (2010); Greve et al. (2011); Hickox et al. (2011); Wardlow et al. (2011); Chapin et al. (2011); de Breuck et al. (2011); Nagao et al. (2012)

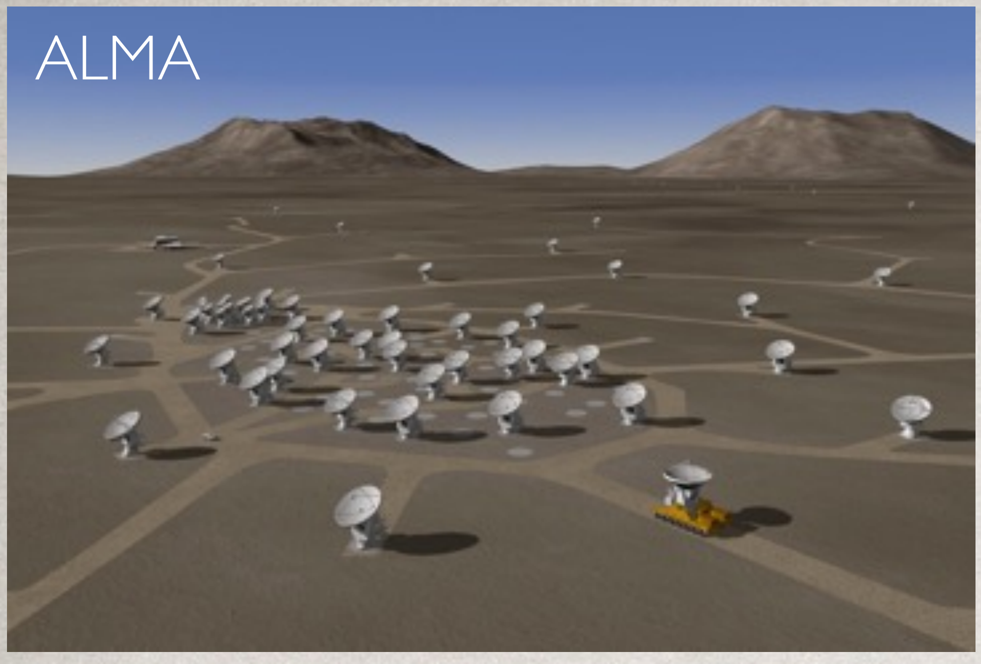
The ECDFS is the prime extra-galactic survey field, with wealth of multi-wavelength data from Chandra X-ray; UV/optical+mid-IR; HSO SPIRE; APEX LABOCA and VLA radio.

LESS reaches uniform 870μm depth of σ_{870} = 1.5mJy over 30 x 30'

Adding Herschel imaging does not improve situation for IDs since resolution is ~15—35''at 250—500μm





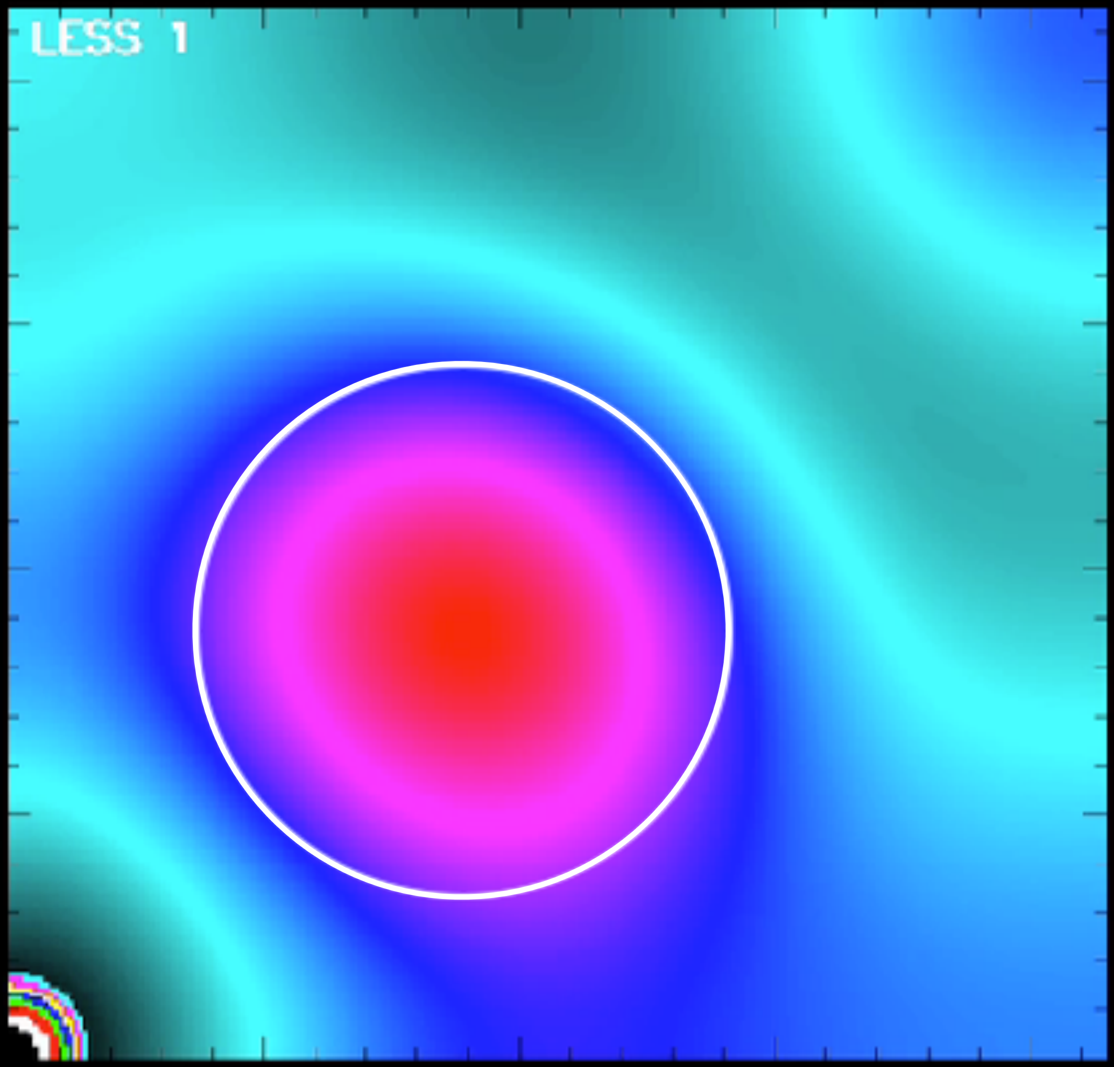


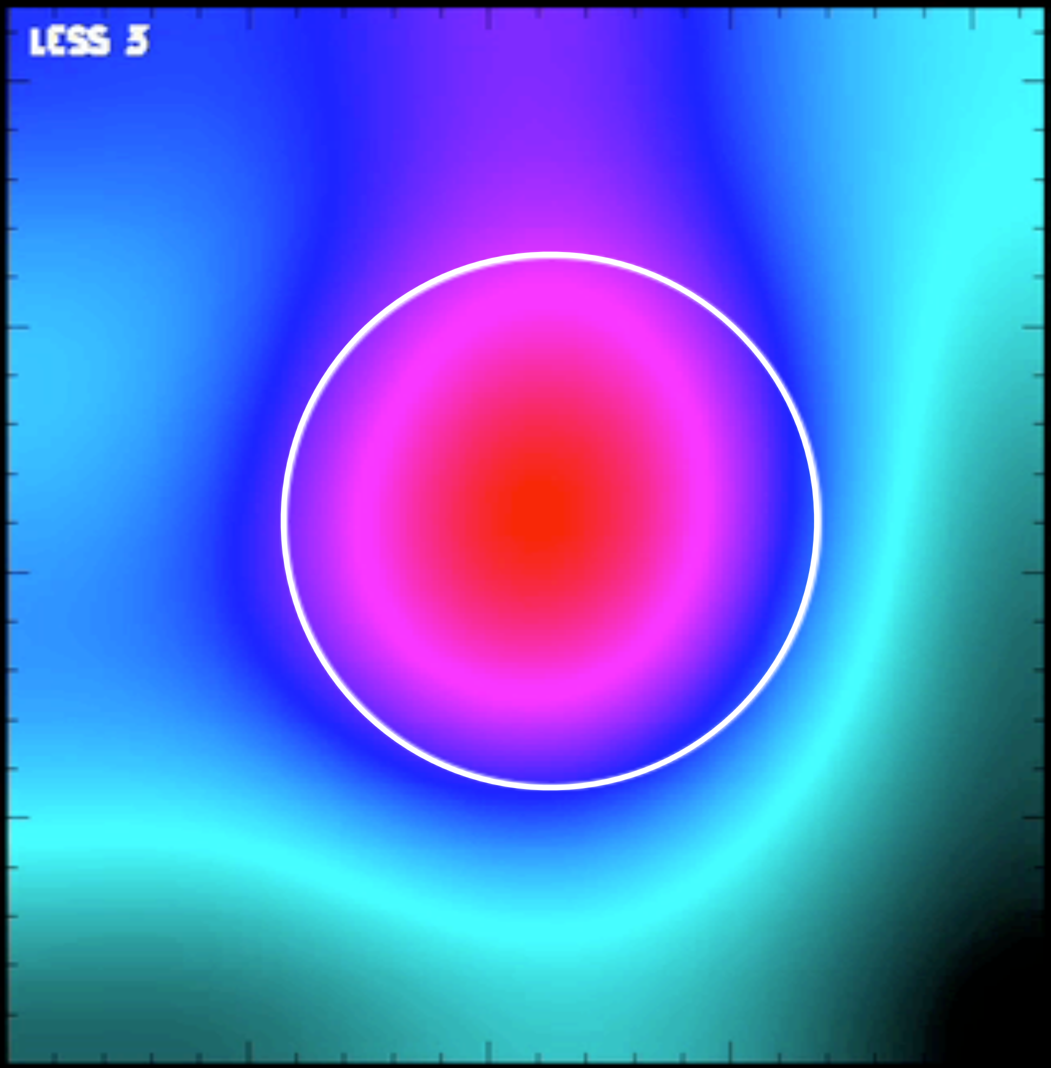
The ALMA LABOCA Extended Chandra Deep Field South Survey (A-LESS)

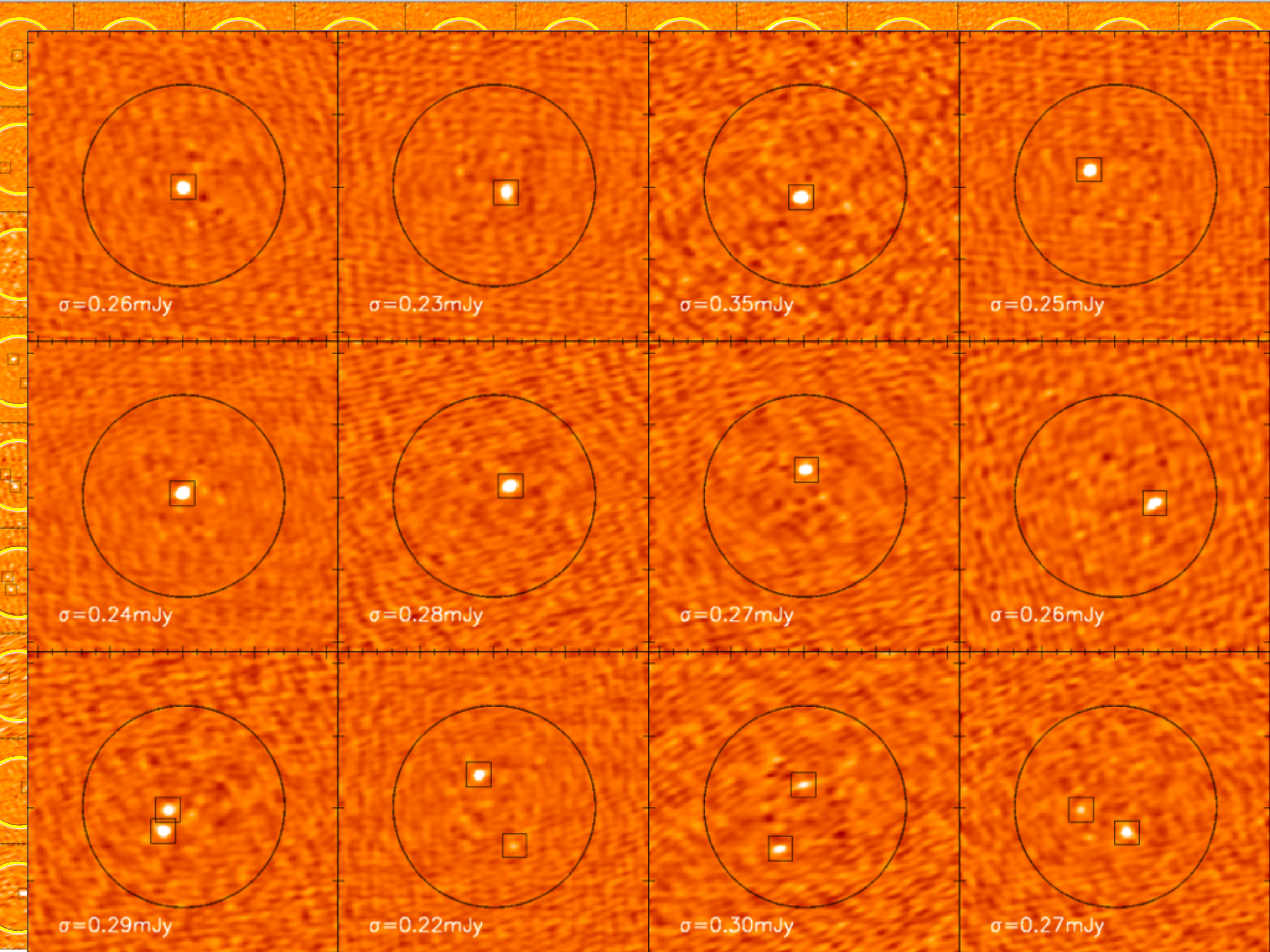
Survey all 126 SMGs in ECDFS at 870mm (345GHz) to depth of 0.3mJy in compact configuration.

5mins/source (c.f. 350hours with APEX to 1.5mJy)

Spacing of 150m means $\theta = \lambda / D = 1.4''$






σ=0.26mJy
σ=0.23mJy
σ=0.35mJy
σ=0.25mJy
σ=0.24mJy
σ=0.28mJy
σ=0.27mJy
σ=0.26mJy
σ=0.29mJy
σ=0.22mJy
σ=0.30mJy
σ=0.27mJy

ALESS: towards a full SMG catalog

ALESS observations

- 122/126 fields around LESS targets observed in Cycle 0
- 8 measurement sets
- 88 (strictly random) maps of homogeneous quality

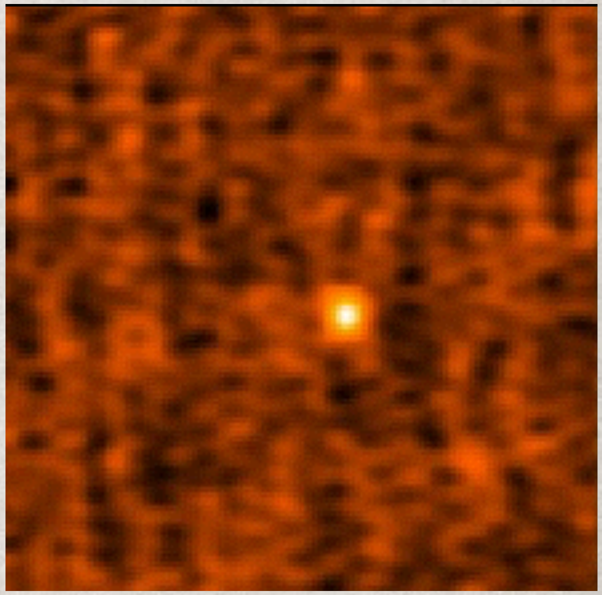
Automated source identification

- Dedicated MCMC code (6/3 parameter source fitter, error estimation, beam deconvolution)
- Initial source catalog (all 122 maps)
- Quality assessment — reduced to 79 maps.

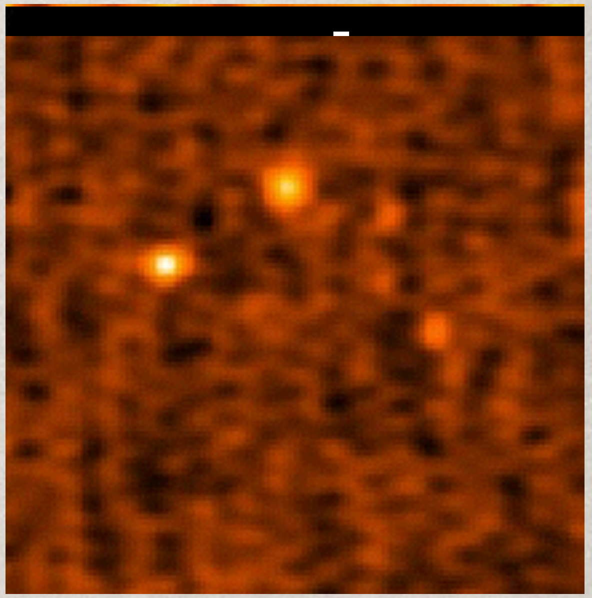
99 SMGs at $>4\sigma$ significance from the “best” maps

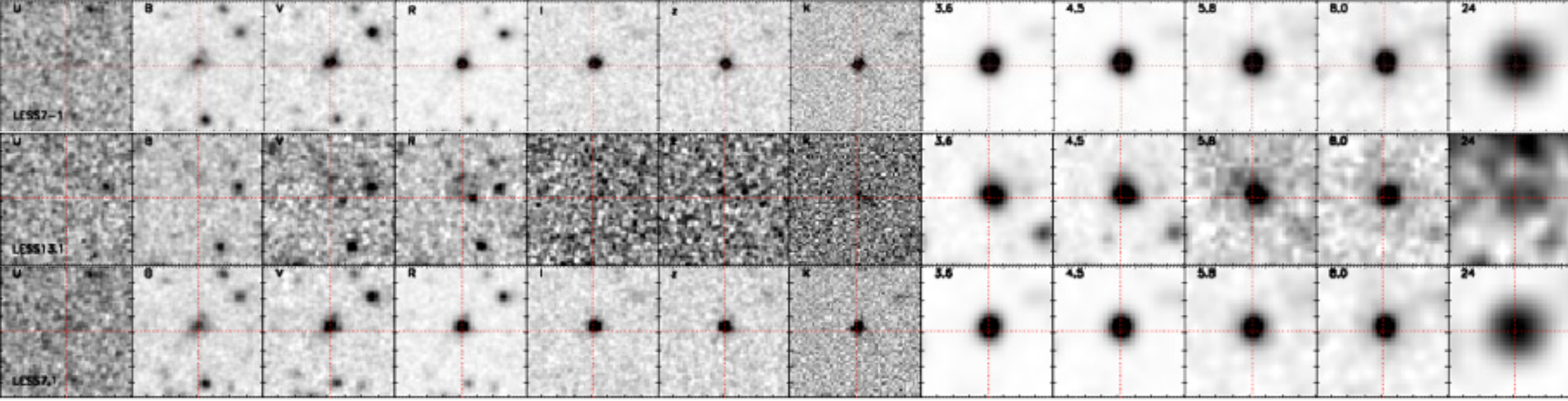
+ 32 SMGs at $>4\sigma$ significance from maps with poorer noise (~3x worse noise AND 3x worse synthesised beam area than requested).

LESS 7

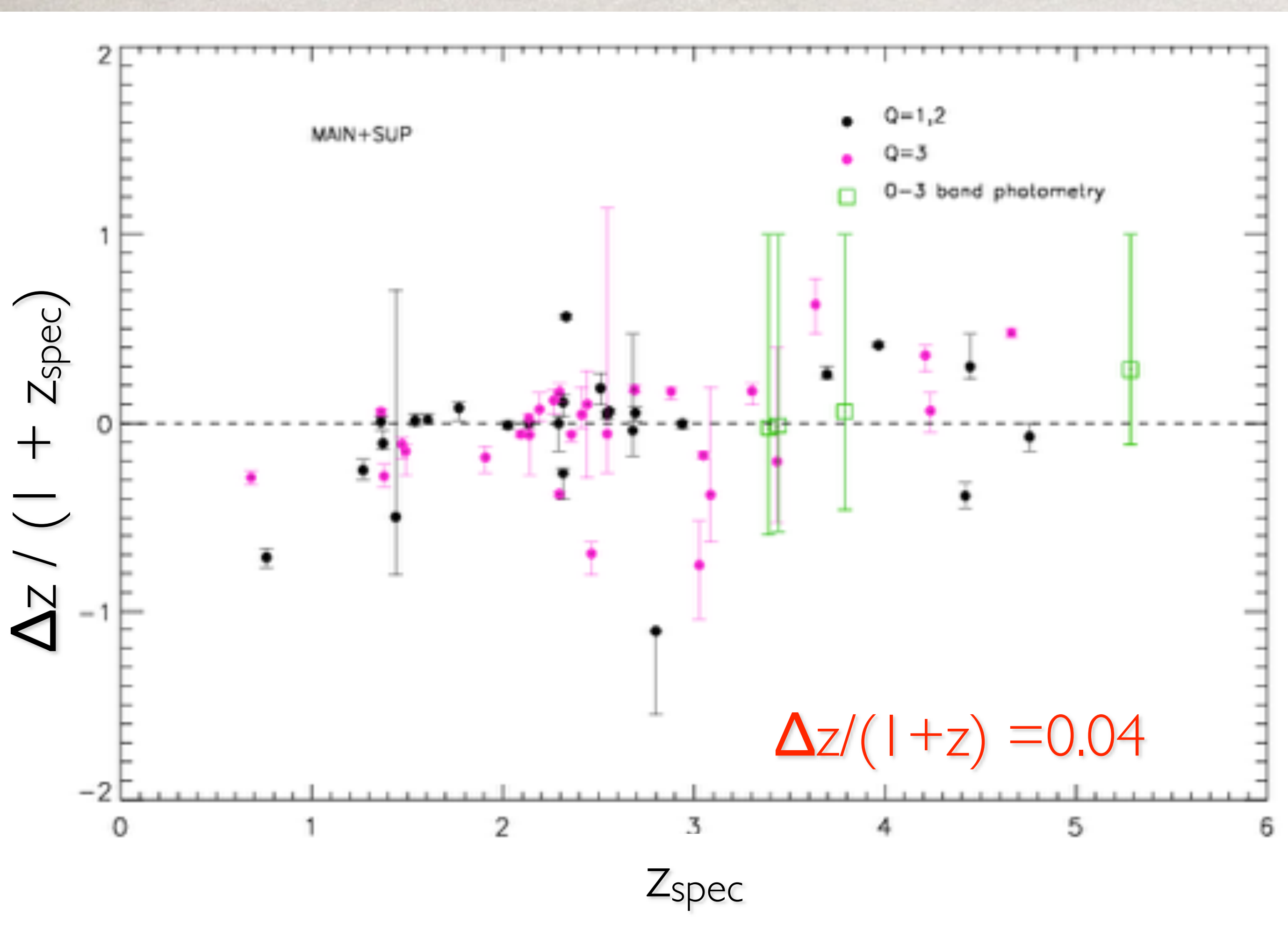


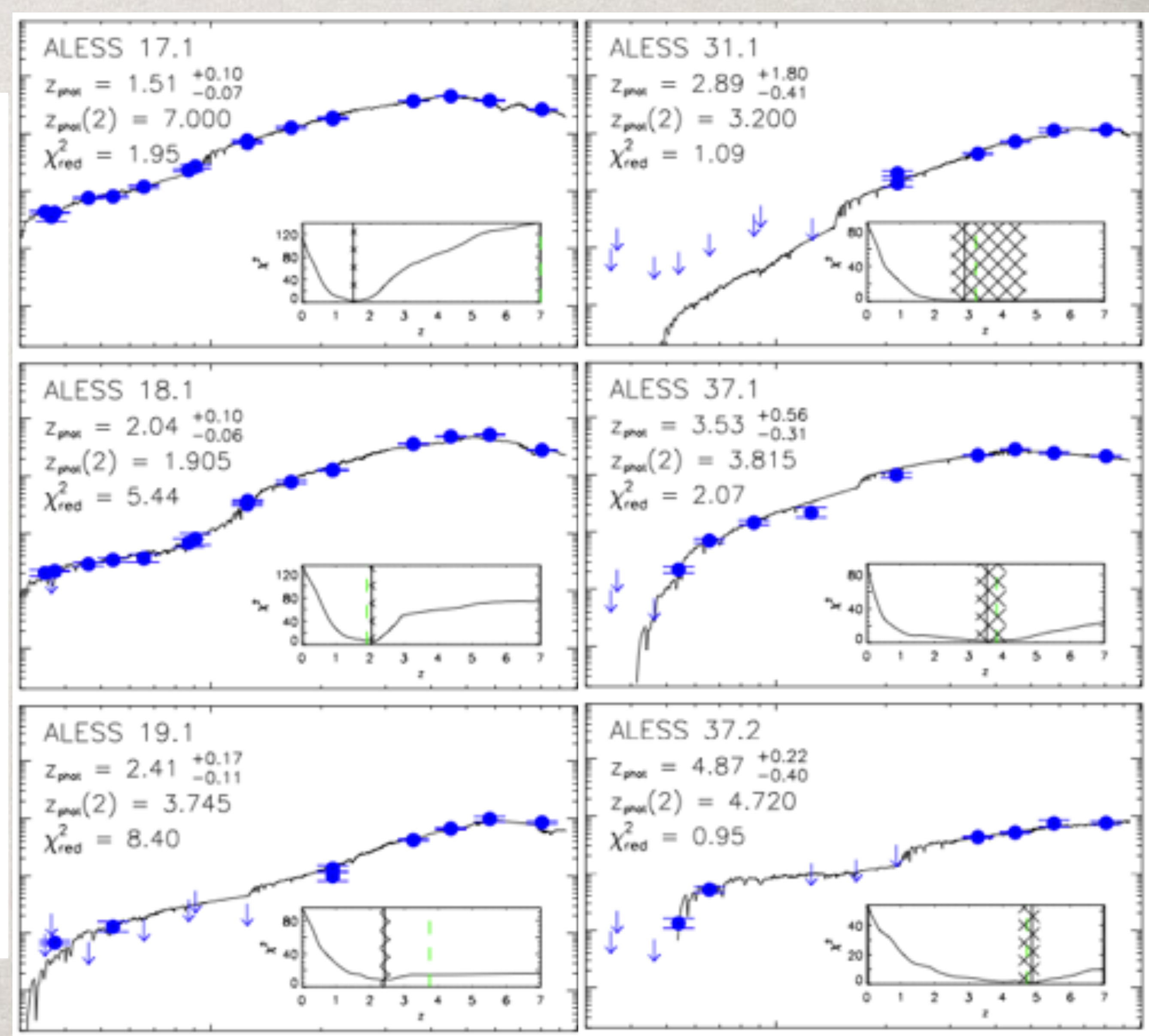
LESS 3





ECDFS deep archival imaging: UBVRIzJHK +IRAC



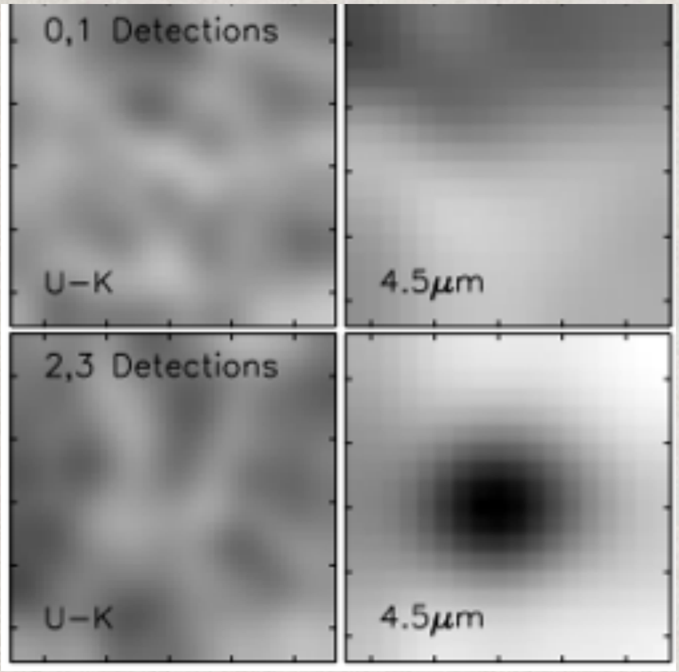


Simpson et al. 2014, Danielson et al. 2015

- 99 ALMA SMGs
- Calibrate against 5900 field galaxies in ECDFS and ~50 SMGs with spec-z's
- Derive photo-z for 76 SMGs with > 4 band photometry

BUT:

- 19 SMGs (20% of sample) have detections in 3 bands (or less) in the UV / optical / NIR / mid-IR bands
- Real or just S/N effects in 870um catalog?



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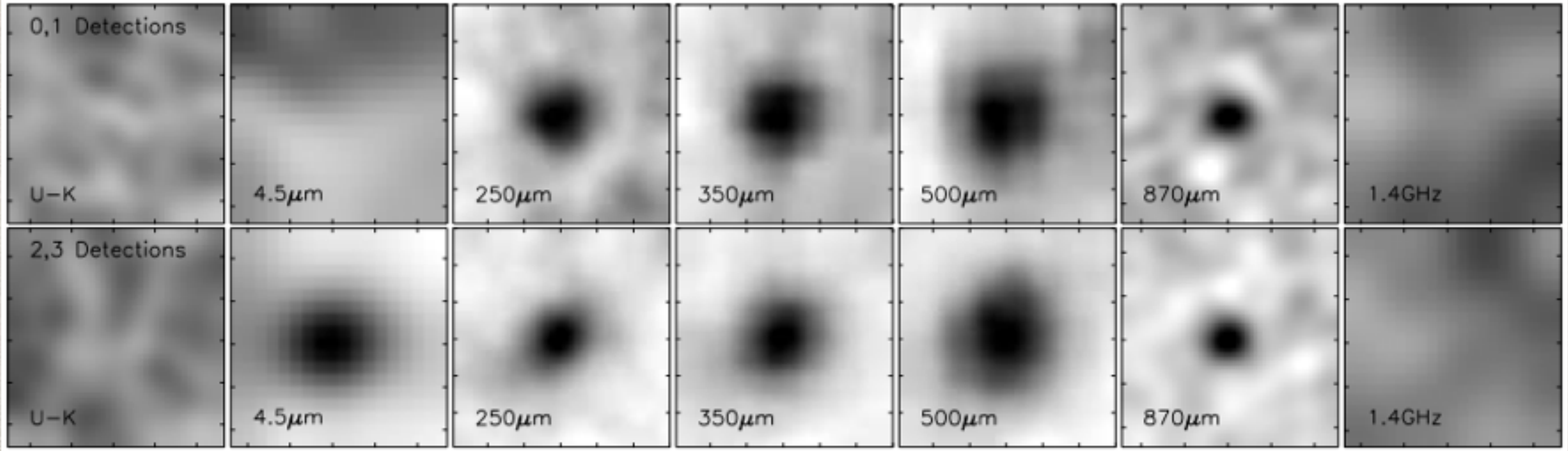
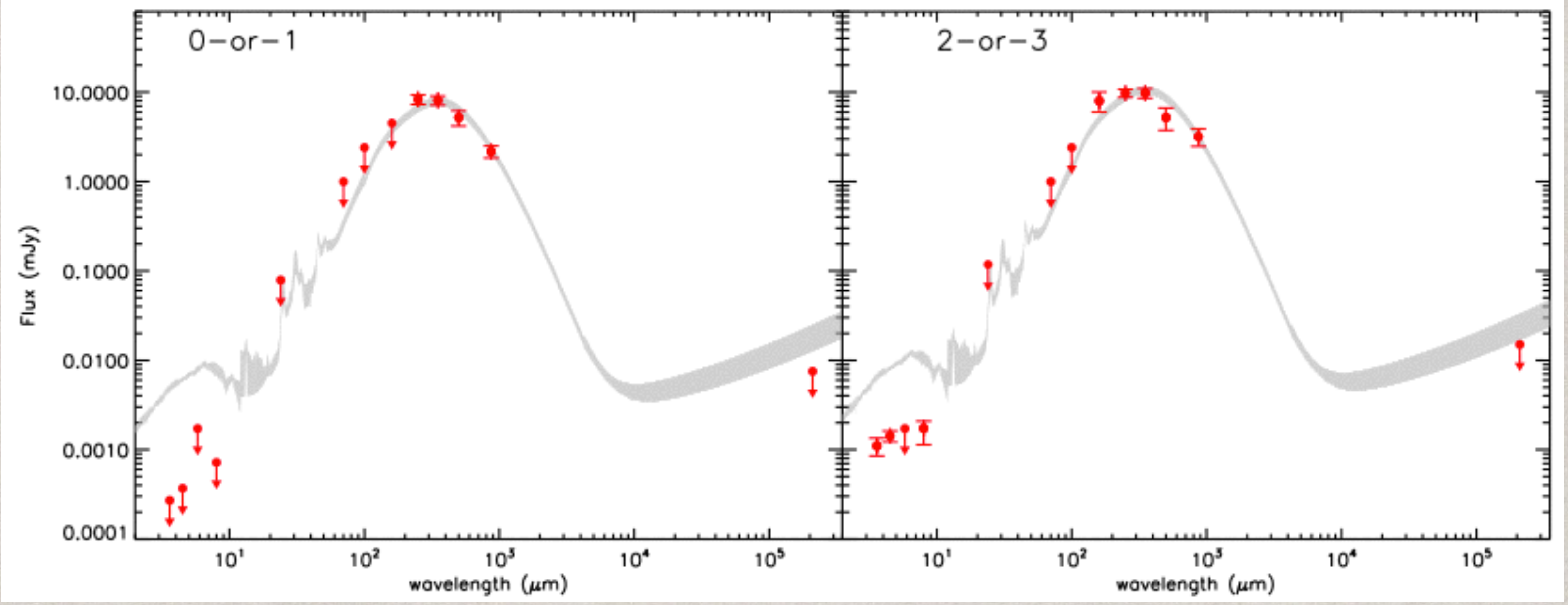
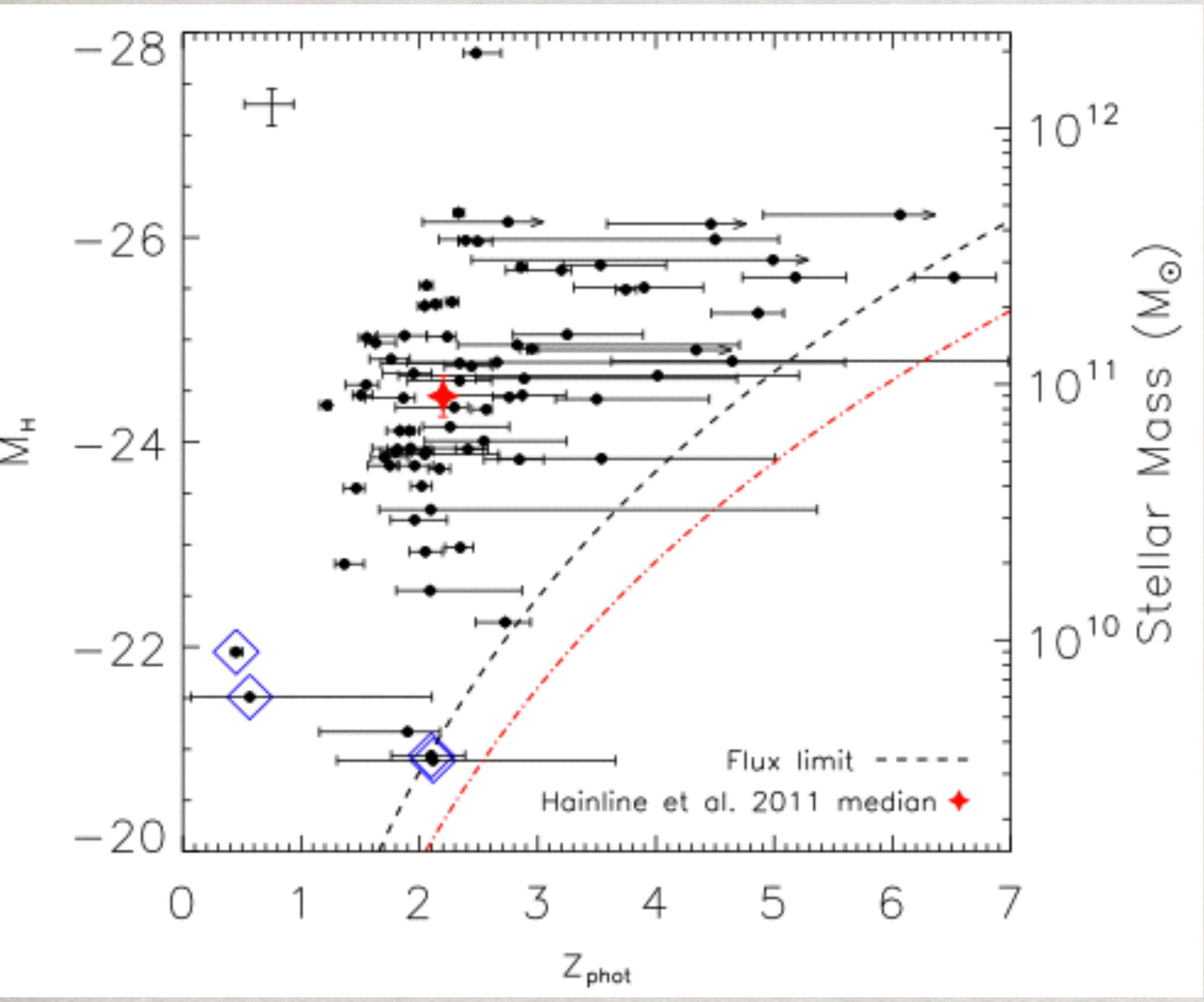




Magnitude distribution & N(z)



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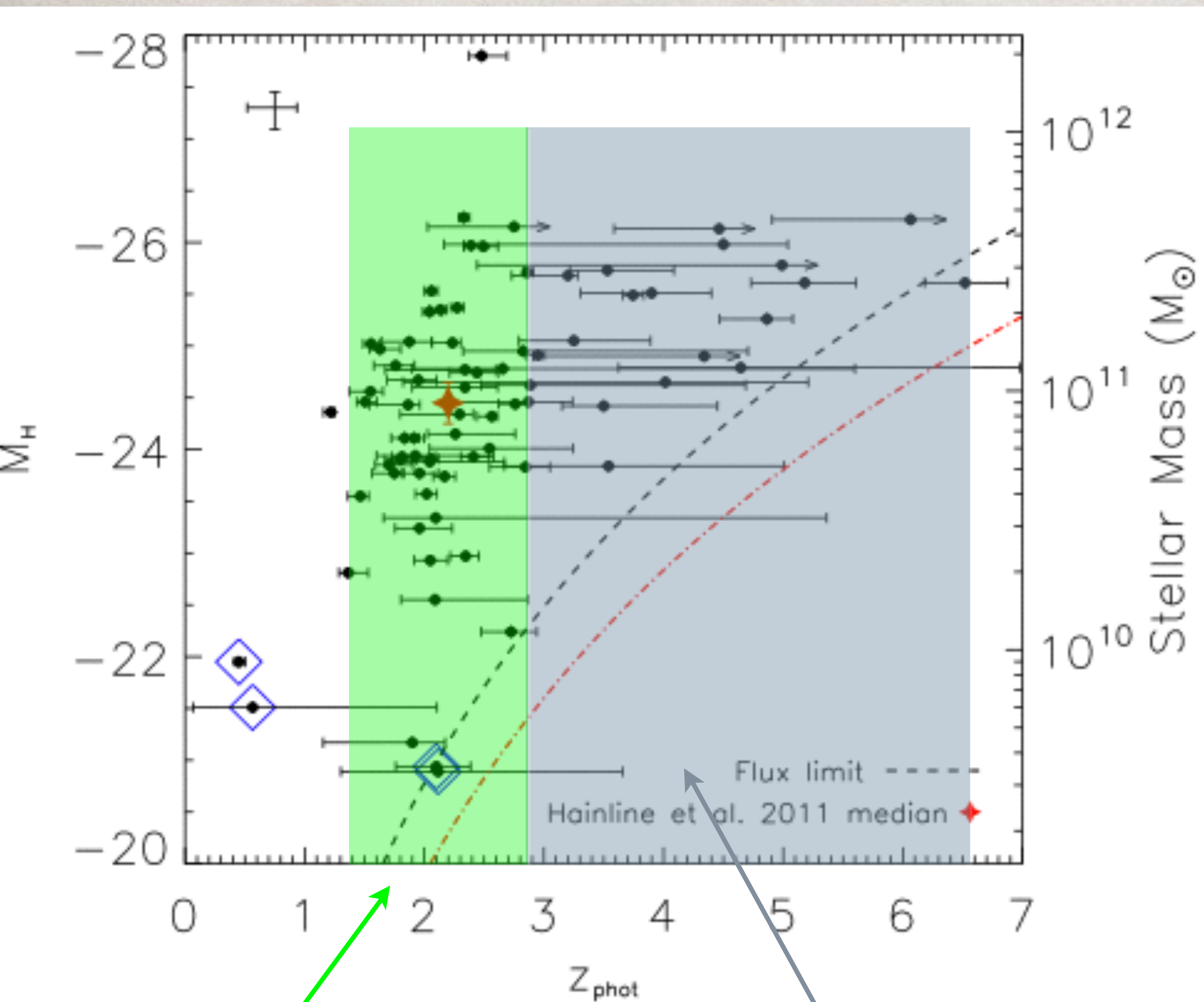
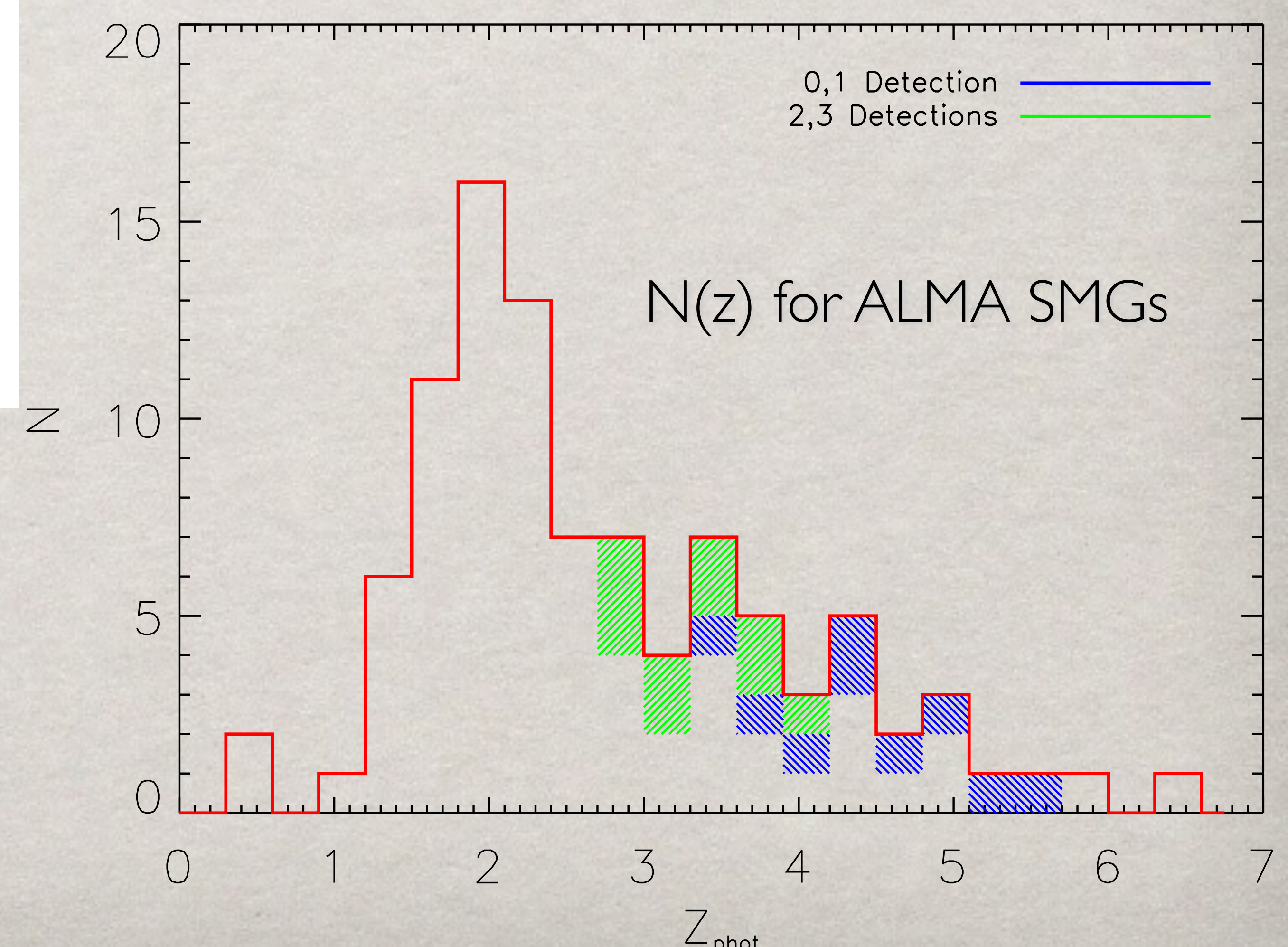
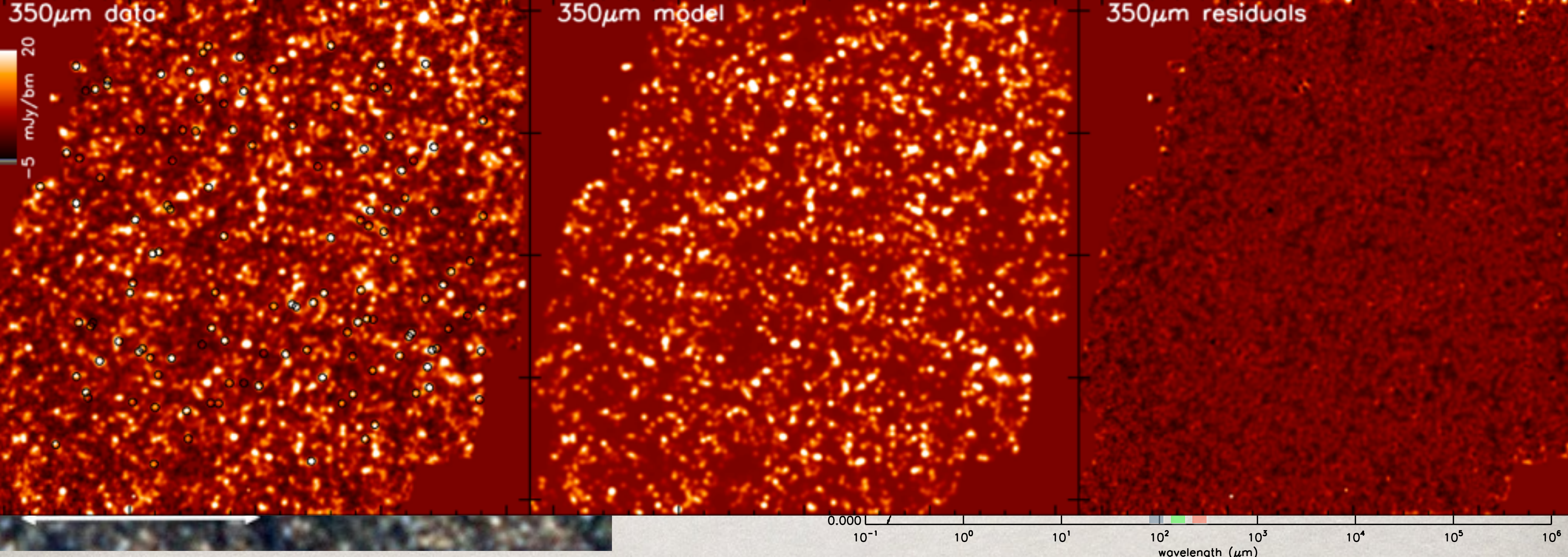
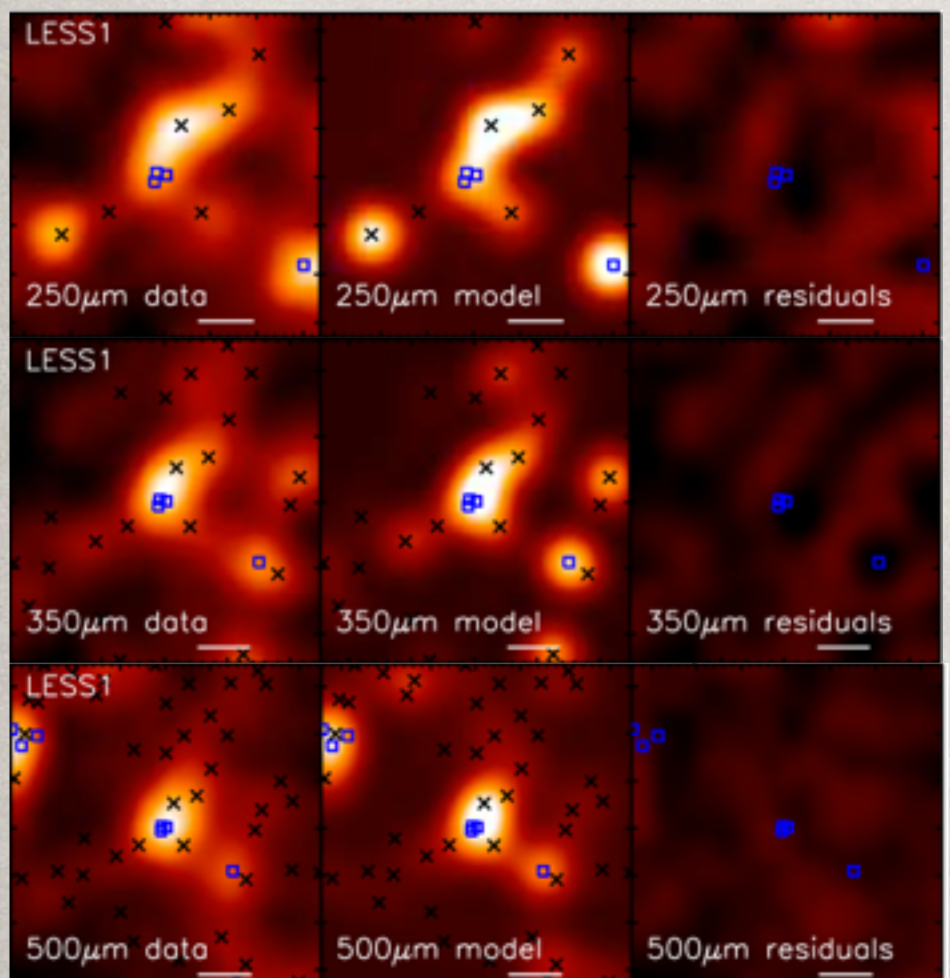


Assume to z=2.8 we have "correct" M_H distribution

MC to derive underlying distribution at z>2.8





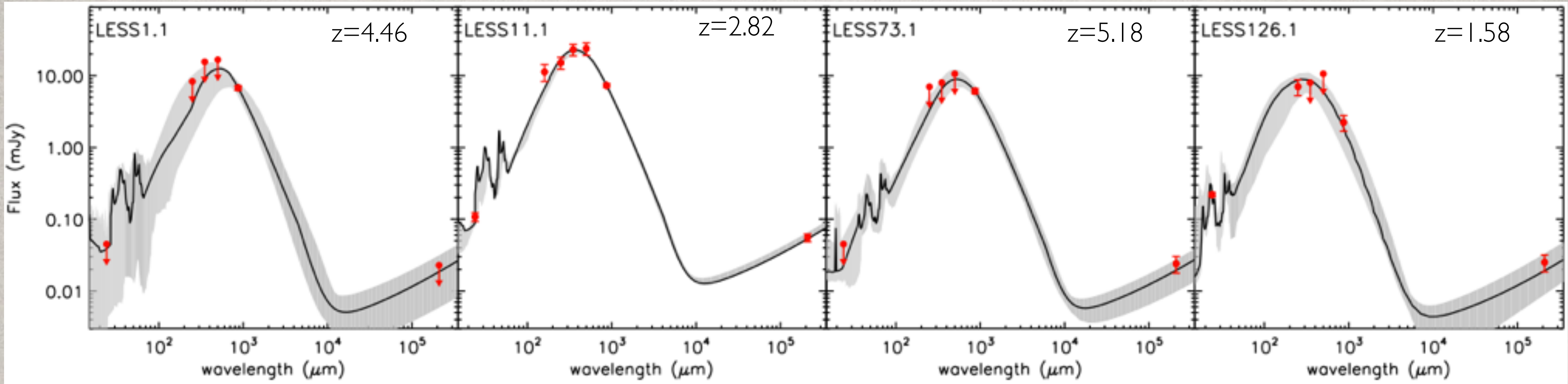


Archival PACS+SPIRE imaging of (E)CDFS

Herschel SPIRE 250, 350, 500μm imaging allows us to improve measurement of far-IR SEDs of ALMA SMGs

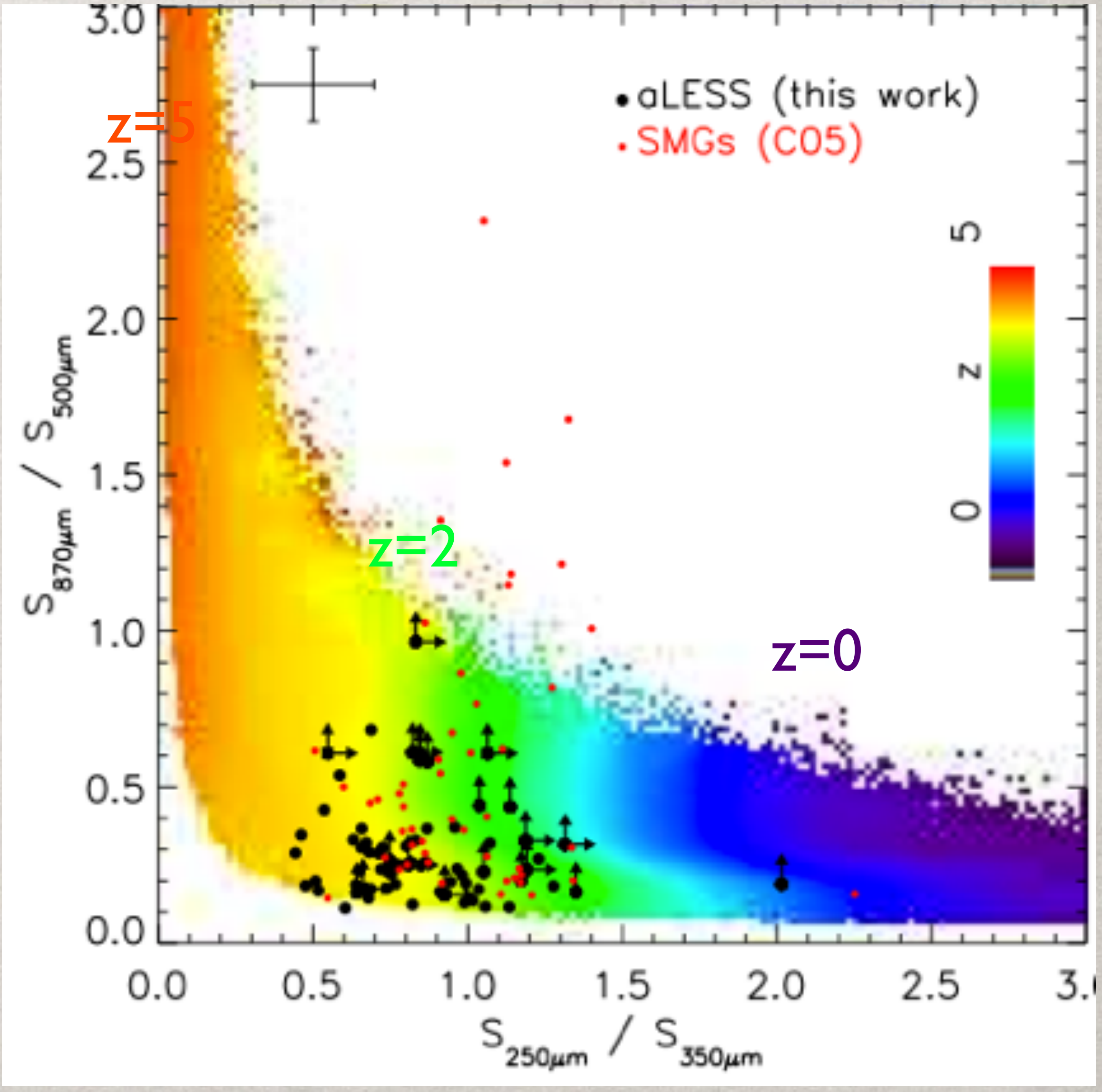
But need to deblend SPIRE maps (use ALMA, 24um and radio imaging as prior catalogs)

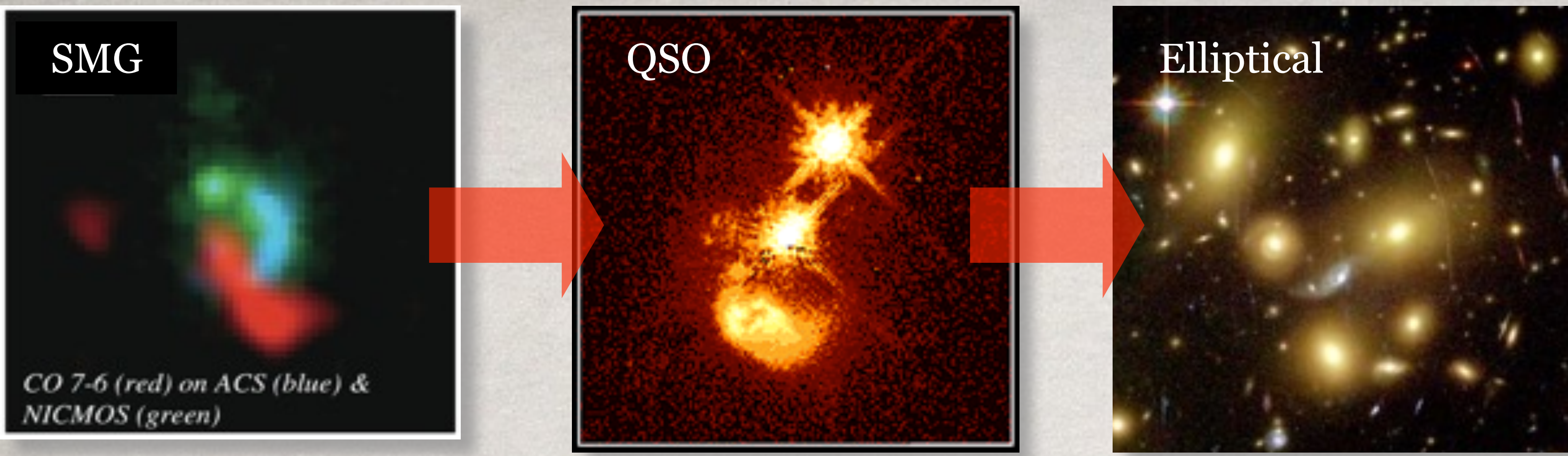
Deconvolve the Herschel maps to investigate SEDs of ALMA-LESS sources

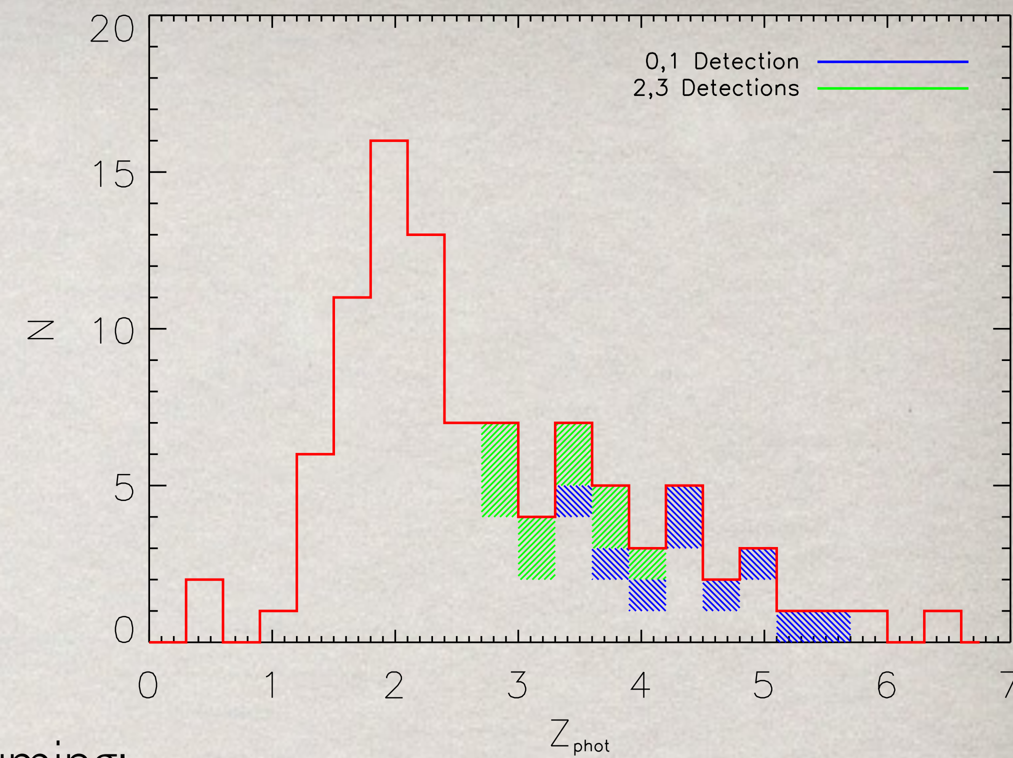


25+/-3 % peak at 250um <z> = 2.1+/-0.3
38+/-3 % peak at 350um <z> = 2.5+/-0.2
37+/-8 % peak at 500um <z> = 3.4+/-0.34

<L> = 2.0 +/- 0.2 x 10^{12} Lo
<SFR> = 300 +/- 30 Mo/yr



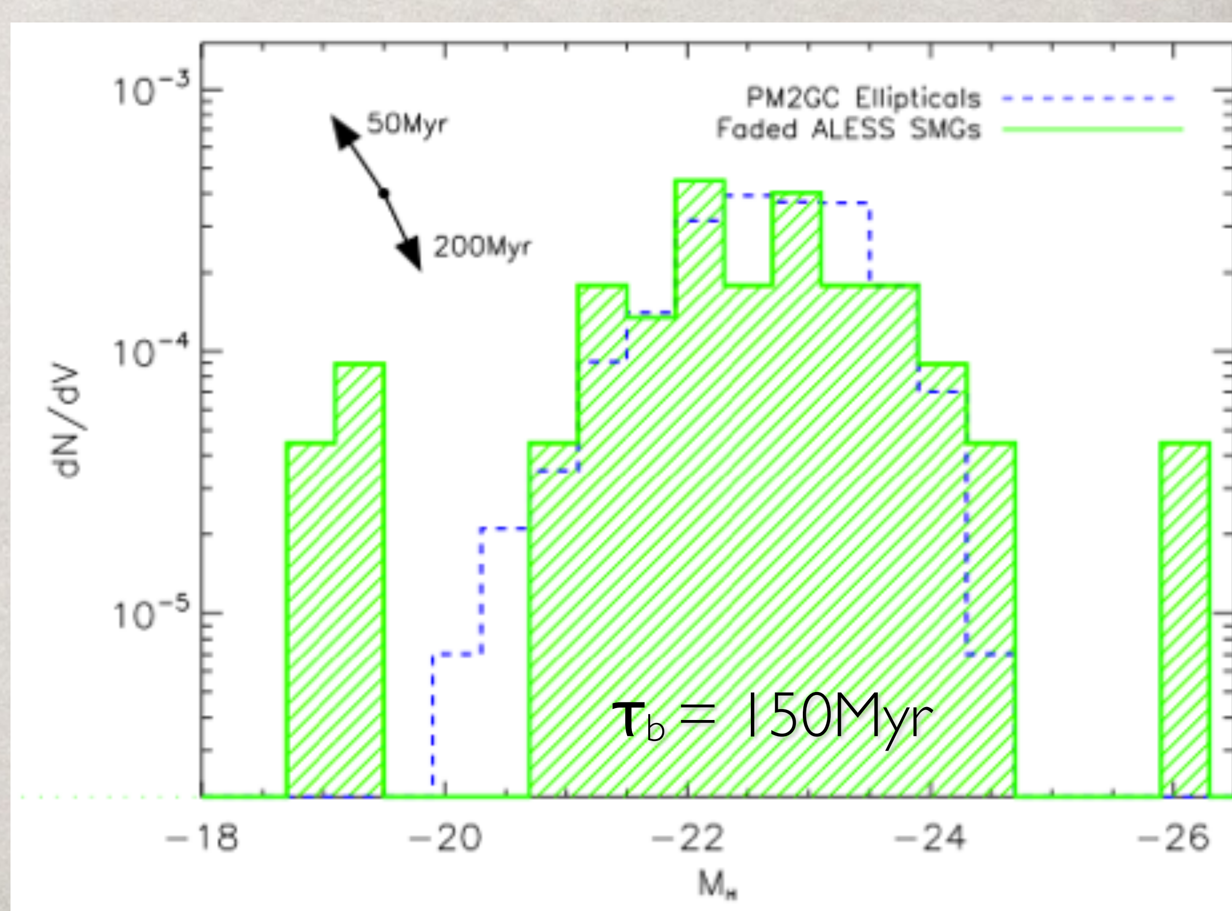




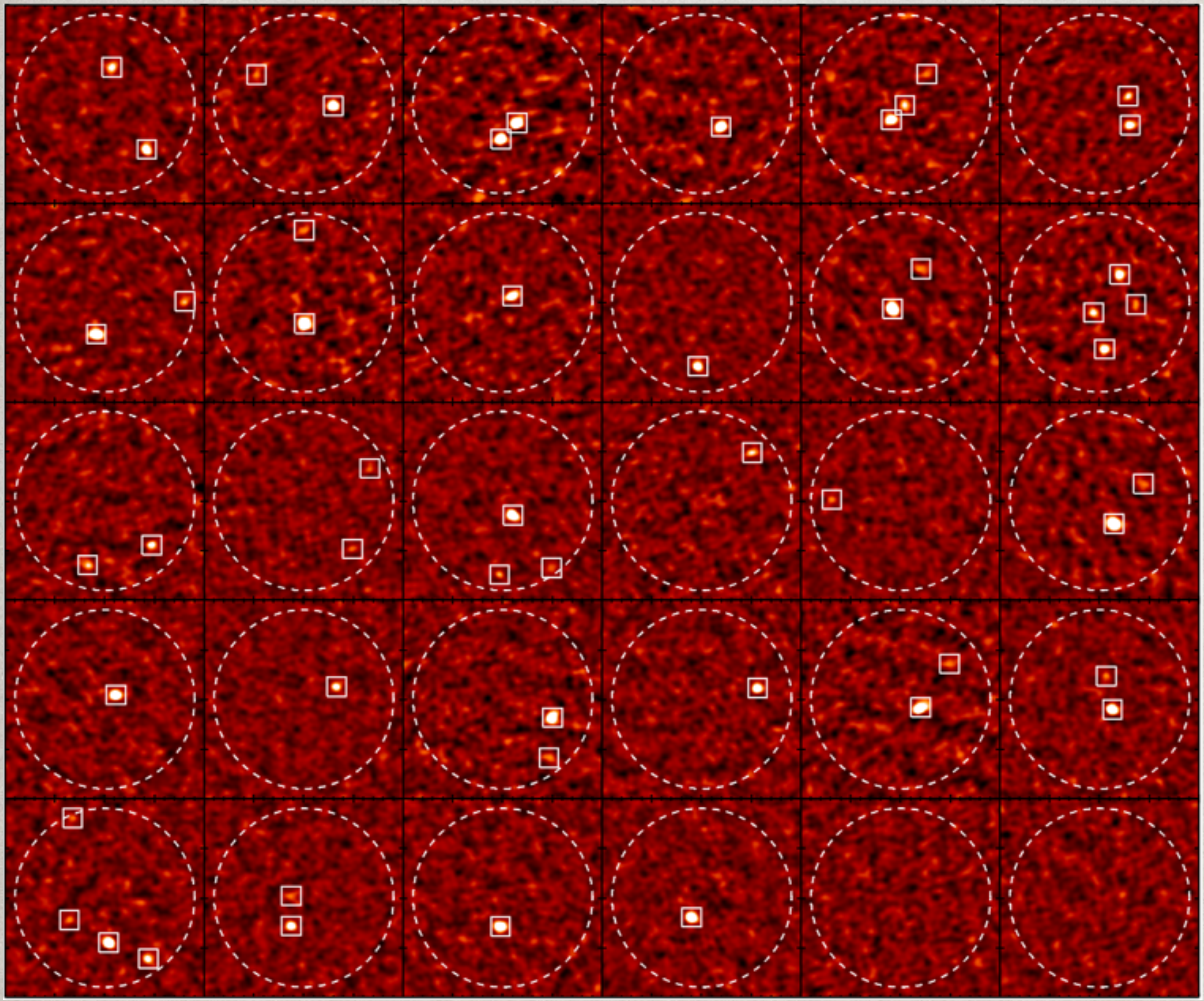
SMG Evolution to z=0

calculate the space density and H-band magnitudes of SMGs at z=0 assuming:

- burst timescale ~150 Myr (M_{H2} / SFR = $3\times10^{10}M_\odot$ / $300M_\odot$/yr)
- only go through one burst
- then the space density and mass weighted ages of the faded descendants are compatible with the whole population of Elliptical galaxies at z=0.



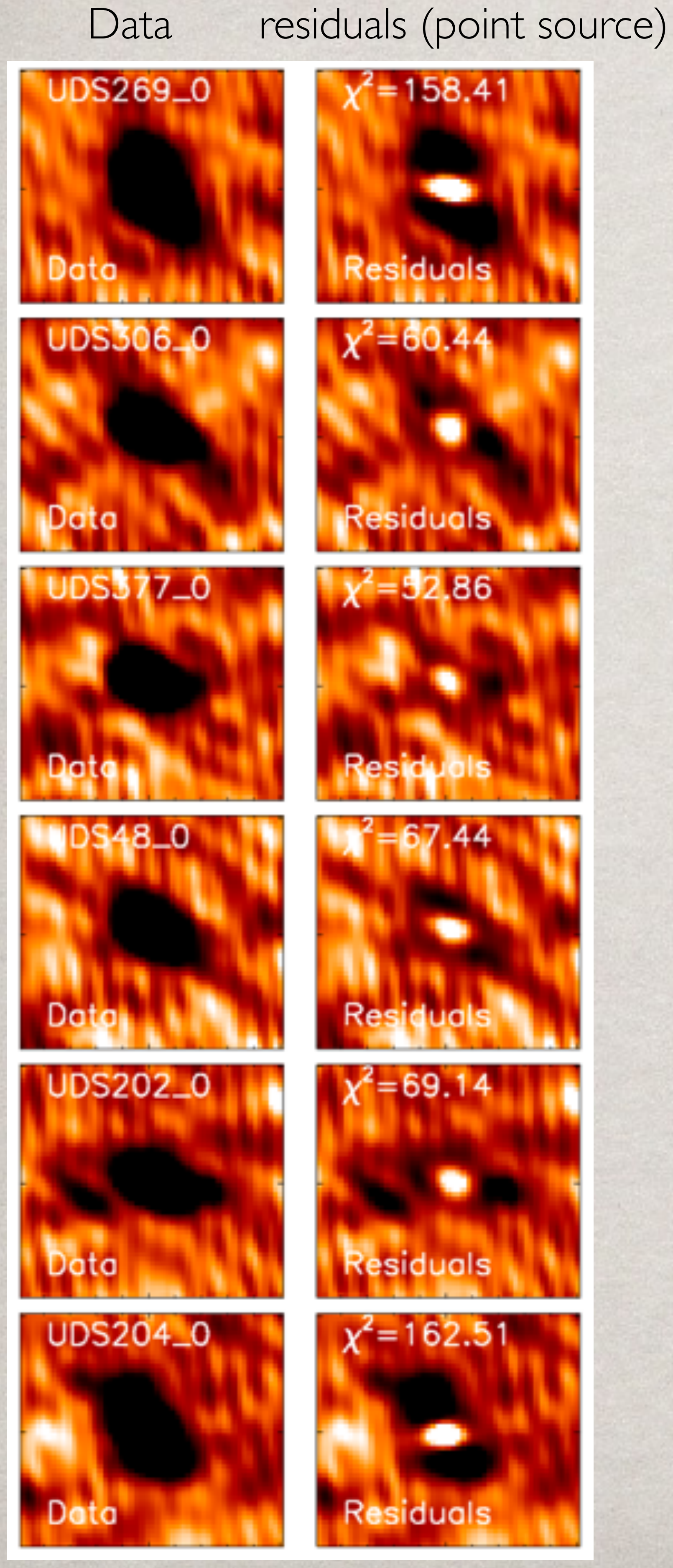
ALMA survey of SMGs from SCUBA-2 Cosmology Legacy Survey (Cycle 1 program)



Higher resolution: ALMA maps have 0.3" FWHM: allows us to investigate morphologies and sizes

Simpson et al. 2015a,b

ALMA survey of S2CLS UDS

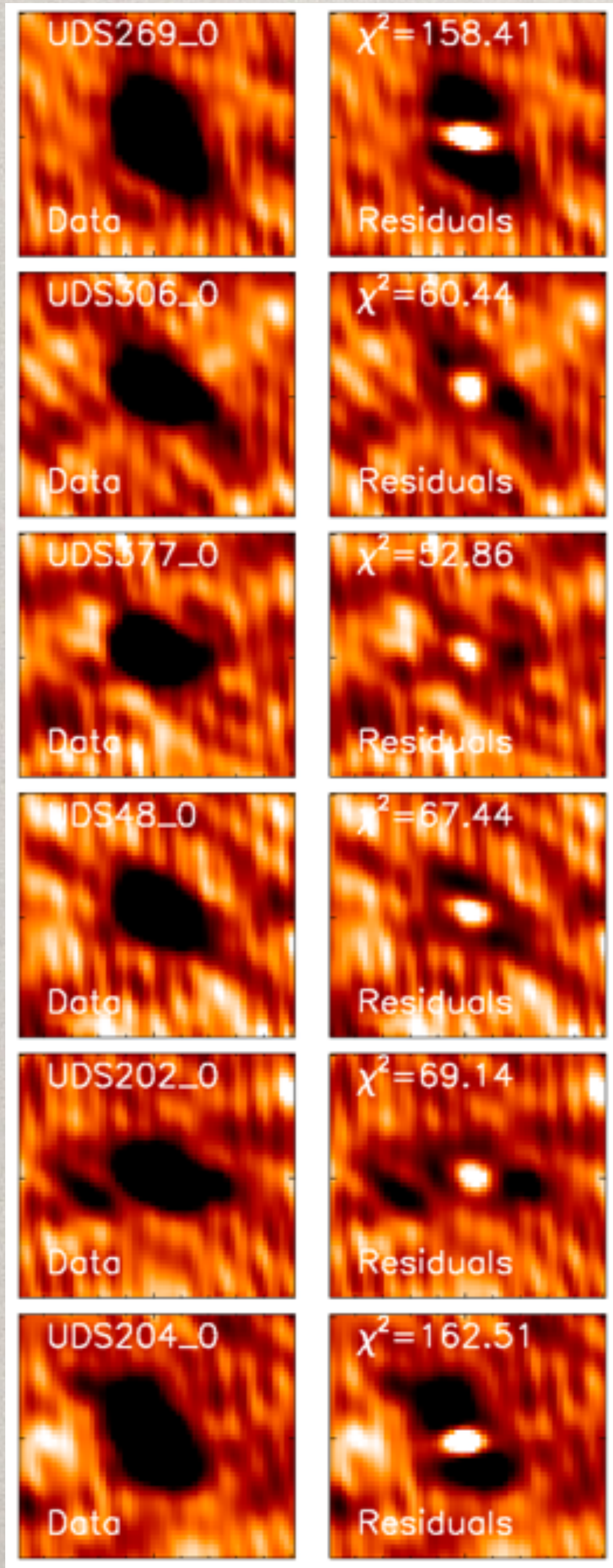


Search for extended emission in new maps
- in image plane (fit beam vs extended source)
- compare total and "peak" fluxes in 0.3" and 0.8" (tapered) maps
- in *uv*-plane

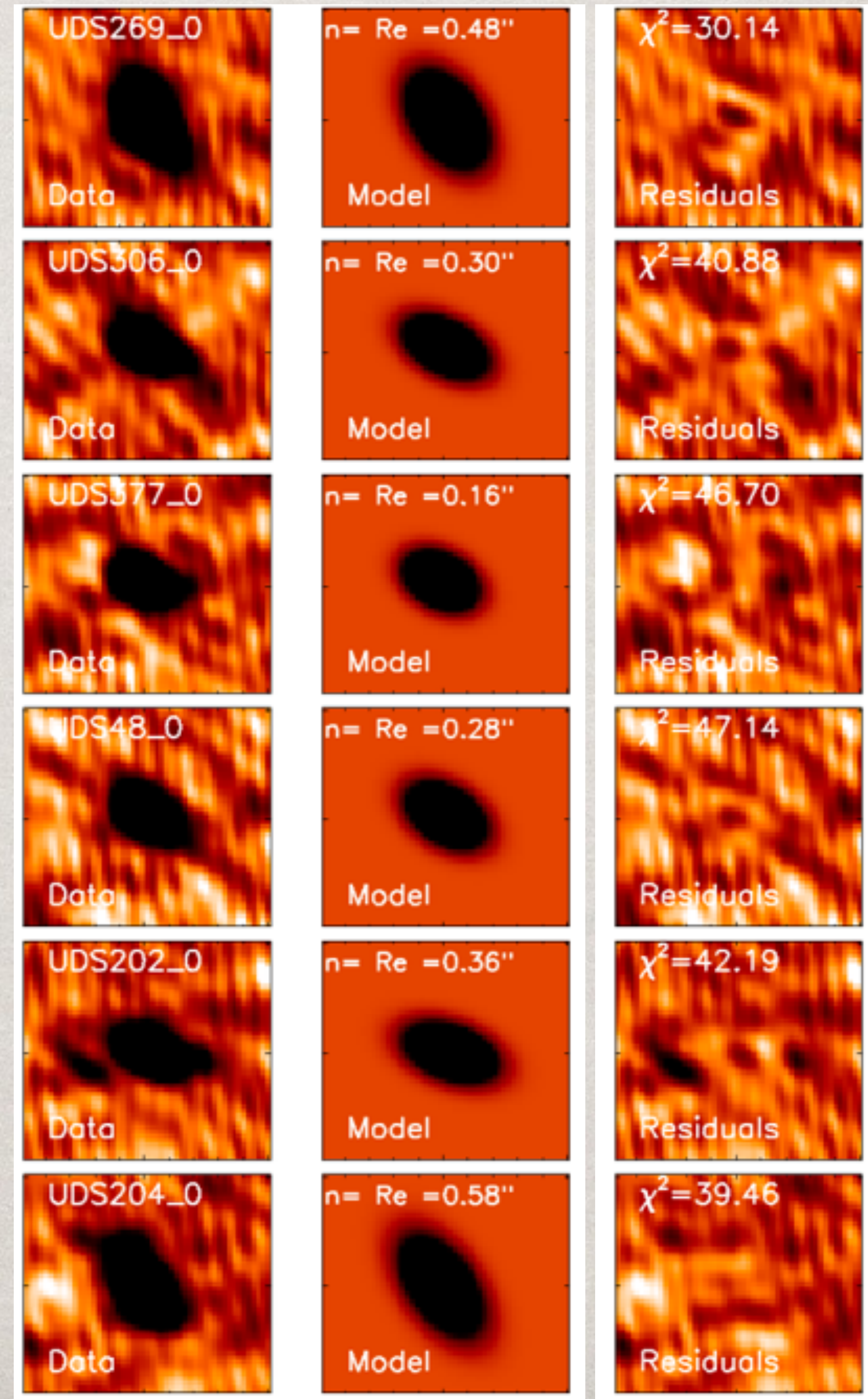
Simpson et al. 2015

ALMA survey of S2CLS UDS

Data residuals (point source)



Data residuals (ext source)

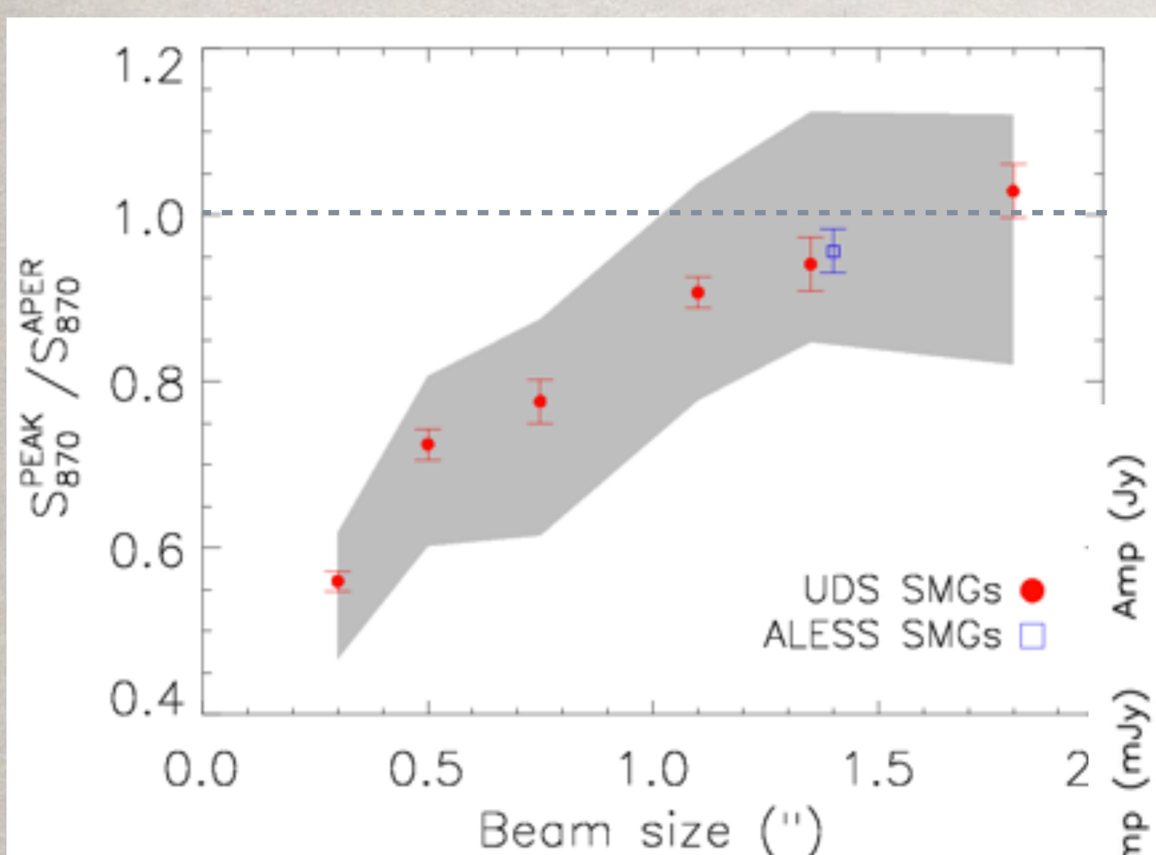


At 0.3" resolution the 870um emission is resolved in 49/52 SMGs

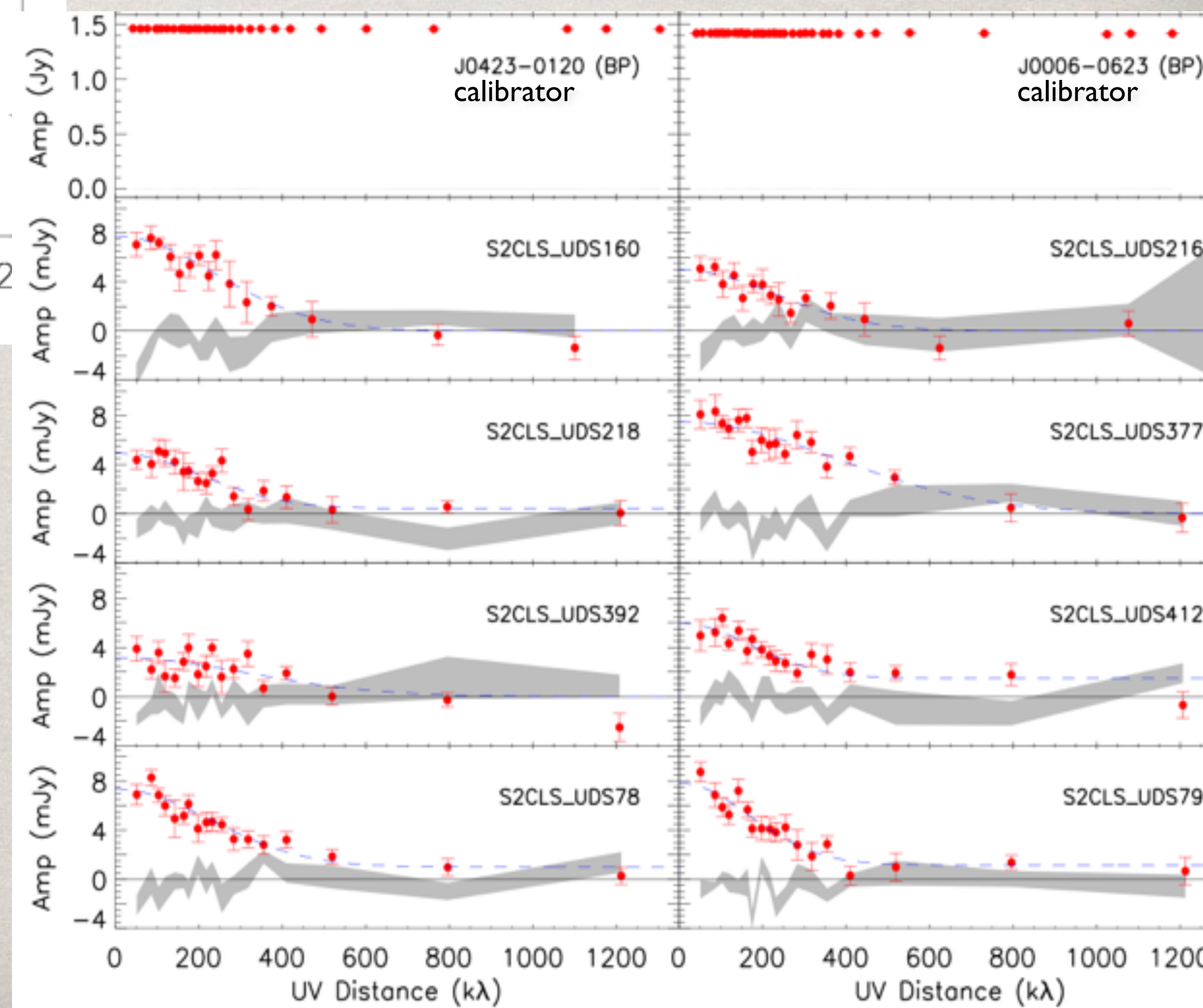
Simpson et al. 2015 ApJ 799 81

ALMA morphologies of SMGs

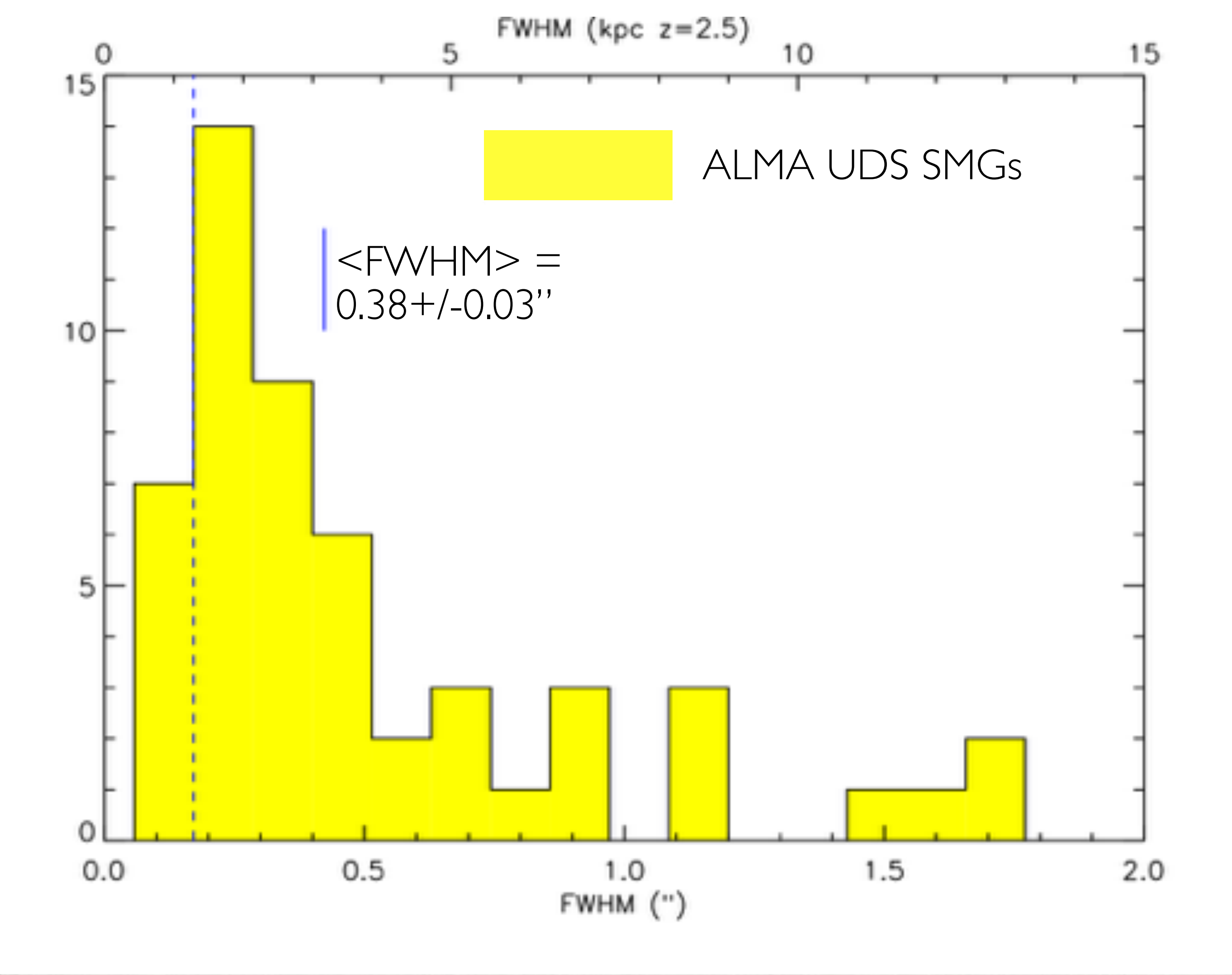
Finally, compare peak flux in 0.8" (tapered) map with peak flux in 0.3" map



and for the more serious radio astronomers…
the real+imaginary visibility components in the *uv*-plane



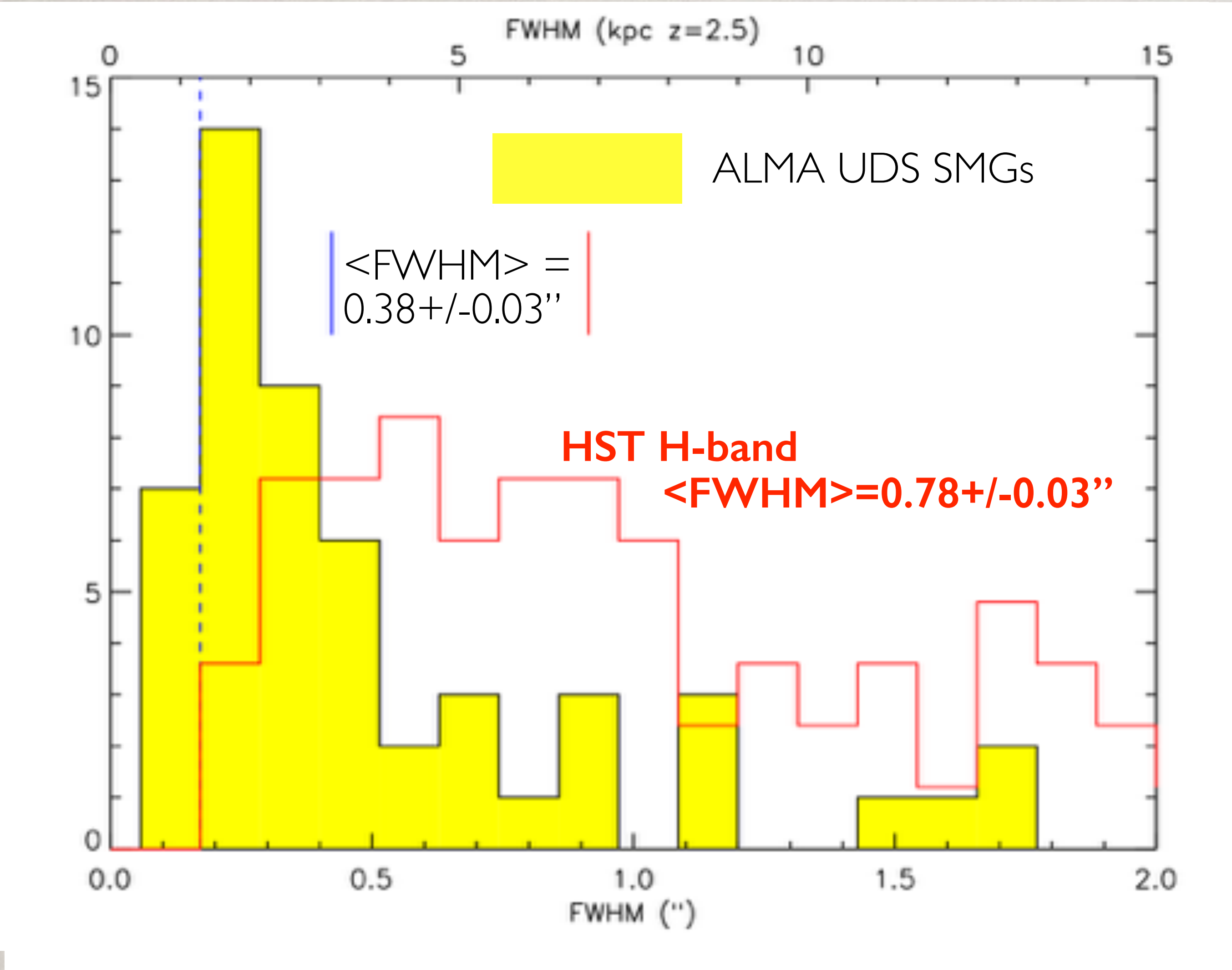
see also: Ikarashi et al. 2015



Resolving emission from many SMGs – typical sizes FWHM ~ 3kpc

Typical SFR ~300M_o/yr so implies SFR surface density ~10–20M_o/yr/kpc^2

Simpson et al. 2014 ApJ in prep



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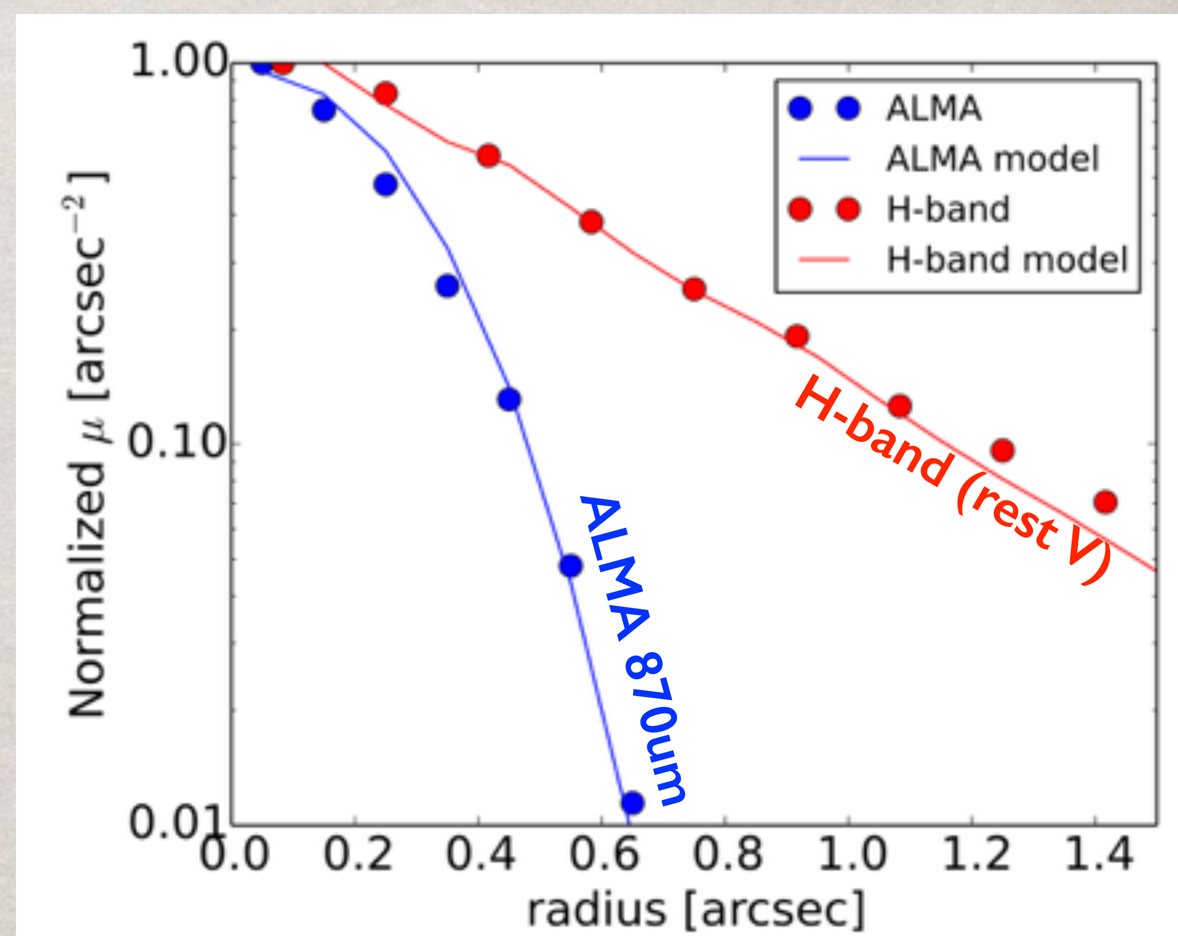
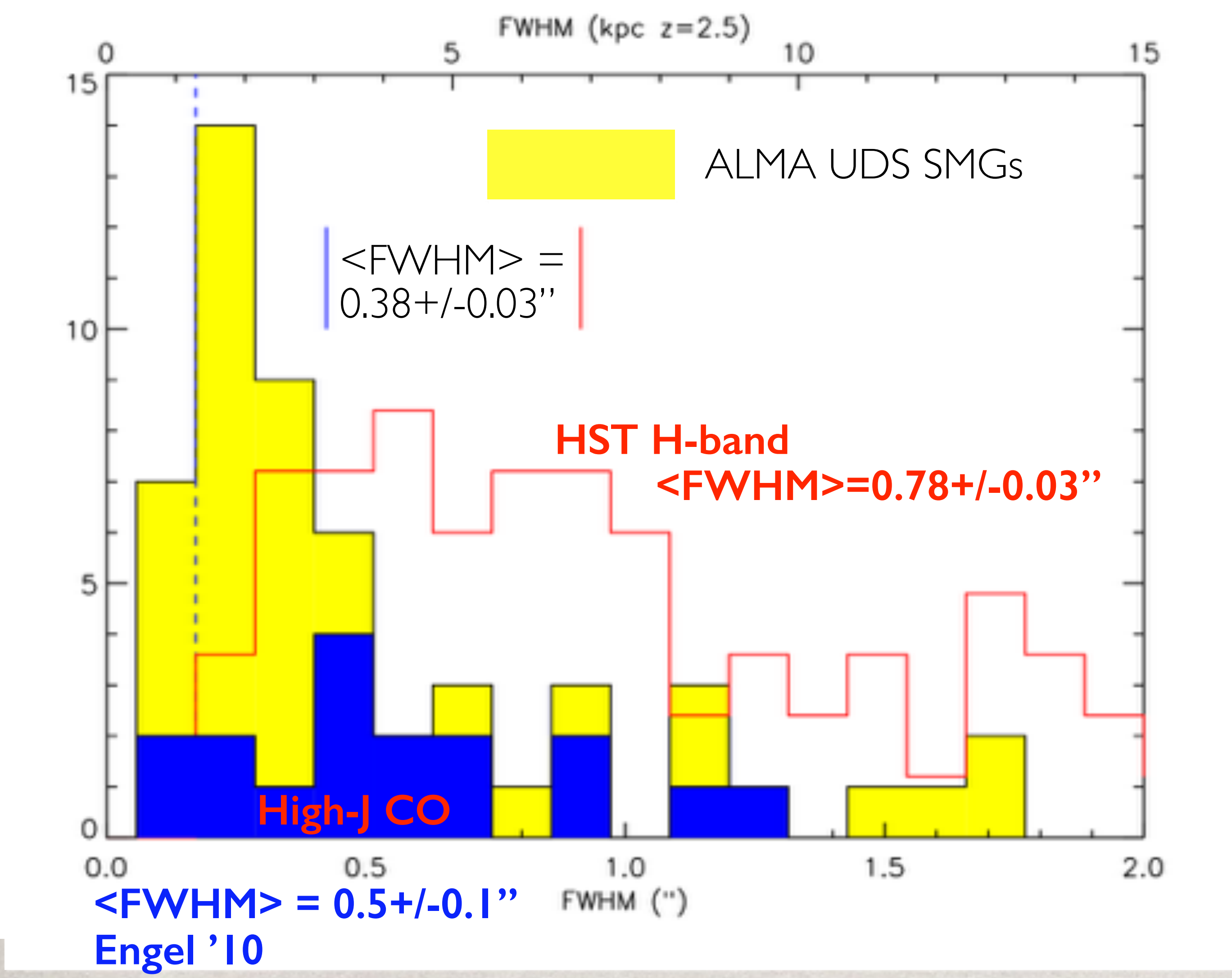
Light Profiles





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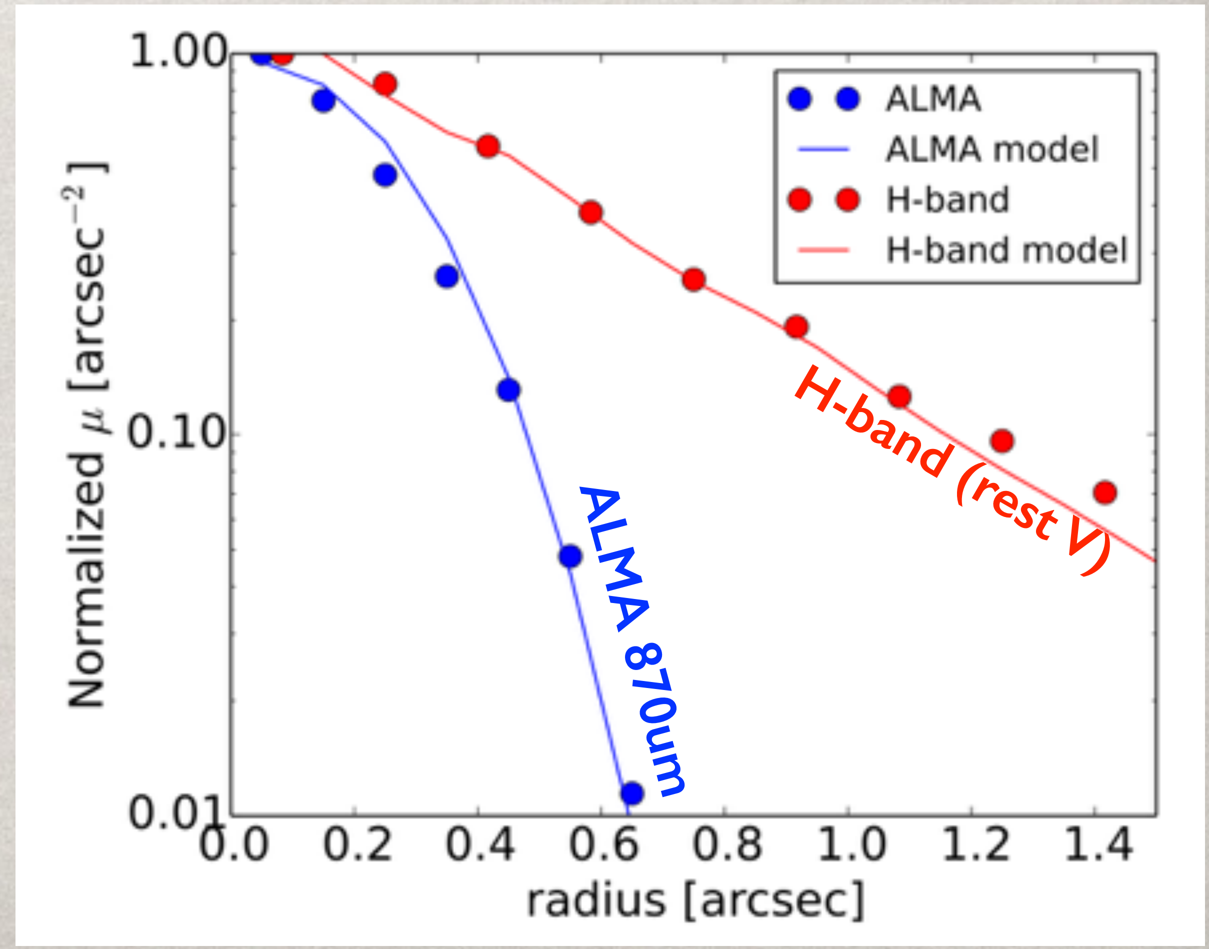


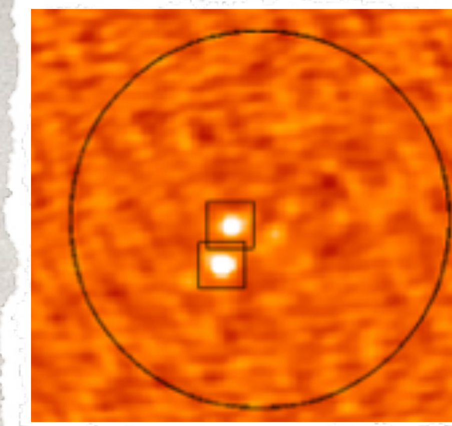
Conclusions

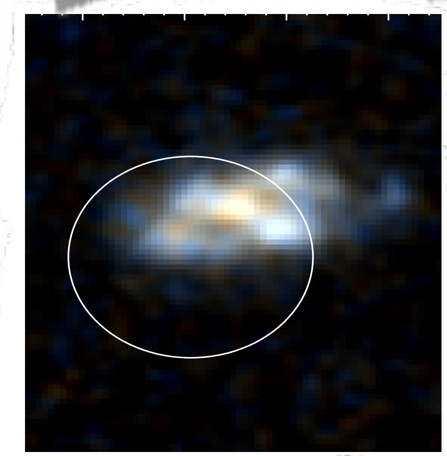
New results (?) and things we thought we knew, but didn't really:

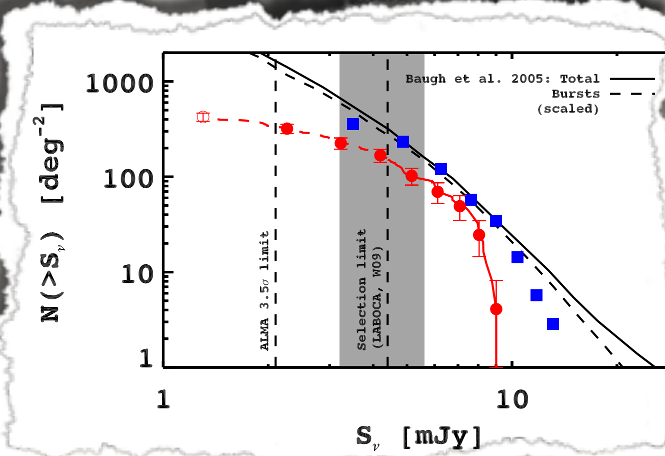
- Many bright submm sources, >10mJy, are multiple SMGs (~50kpc)
- Natural limit? of SFR~$10^3 M_o$/yr for starbursts (few HyLIRGs)
- Median redshift for S_{870um}>2mJy SMGs is z=2.5+/-0.2 (~100% complete).
- Photo-z / spec-z show ≤30% of SMGs at z>3, ≤20% at z>4 – decline in space density beyond z=2-3 is real
- ~10% of SMGs lack counterpart in any other band (z>3–5+?)
- morhologies+dynamics suggest ~50-70% show interactions/mergers (like z=0 population)

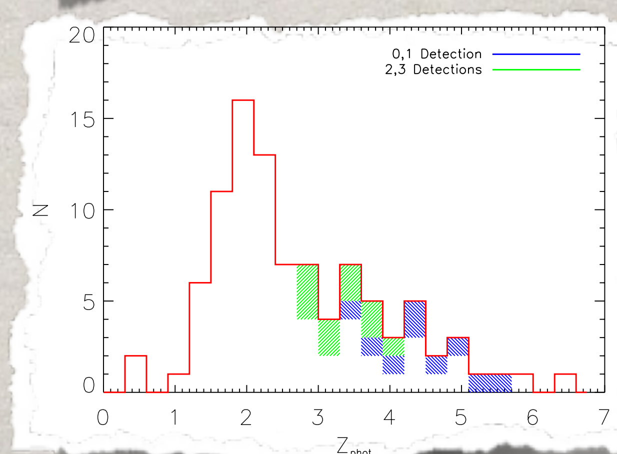
•Faded properties of SMGs are reasonable match to those expected for present-day Elliptical galaxies.

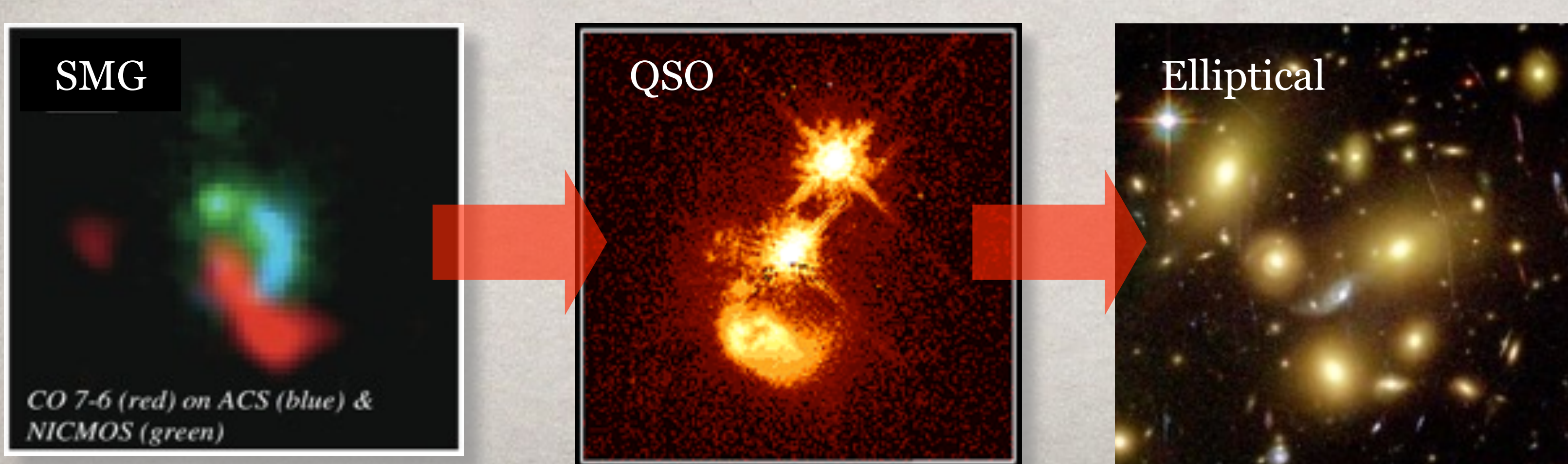
- Latest ALMA data confirms multiplicity and that SF is occurring over several kpc – larger than z ~ 0 ULIRGs











Conclusions

New results (?) and things we thought we knew, but didn't really:

- Many bright submm sources, >10mJy, are multiple SMGs (~50kpc)
- Natural limit? of SFR~$10^3 M_o$/yr for starbursts (few HyLIRGs)
- Median redshift for S_{870um}>2mJy SMGs is z=2.5+/-0.2 (~100% complete).
- Photo-z / spec-z show ≤30% of SMGs at z>3, ≤20% at z>4 – decline in space density beyond z=2-3 is real
- ~10% of SMGs lack counterpart in any other band (z>3–5+?)
- morhologies+dynamics suggest ~50-70% show interactions/mergers (like z=0 population)
- Faded properties of SMGs are reasonable match to those expected for present-day Elliptical galaxies.
- Latest ALMA data confirms multiplicity and that SF is occurring over several kpc – larger than z ~ 0 ULIRGs

The End