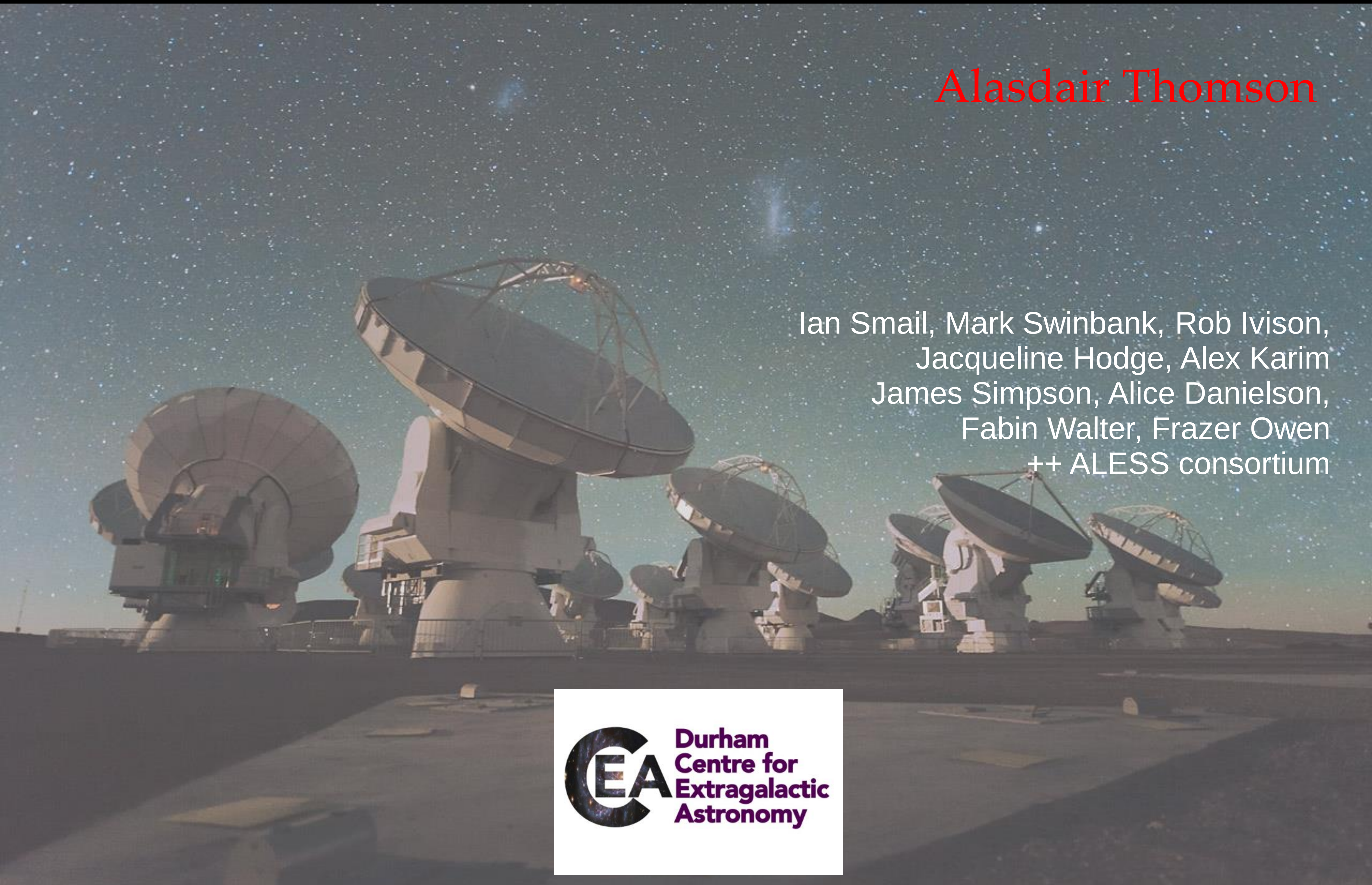
More than LESS: an ALMA follow-up of single-dish identified submillimetre sources



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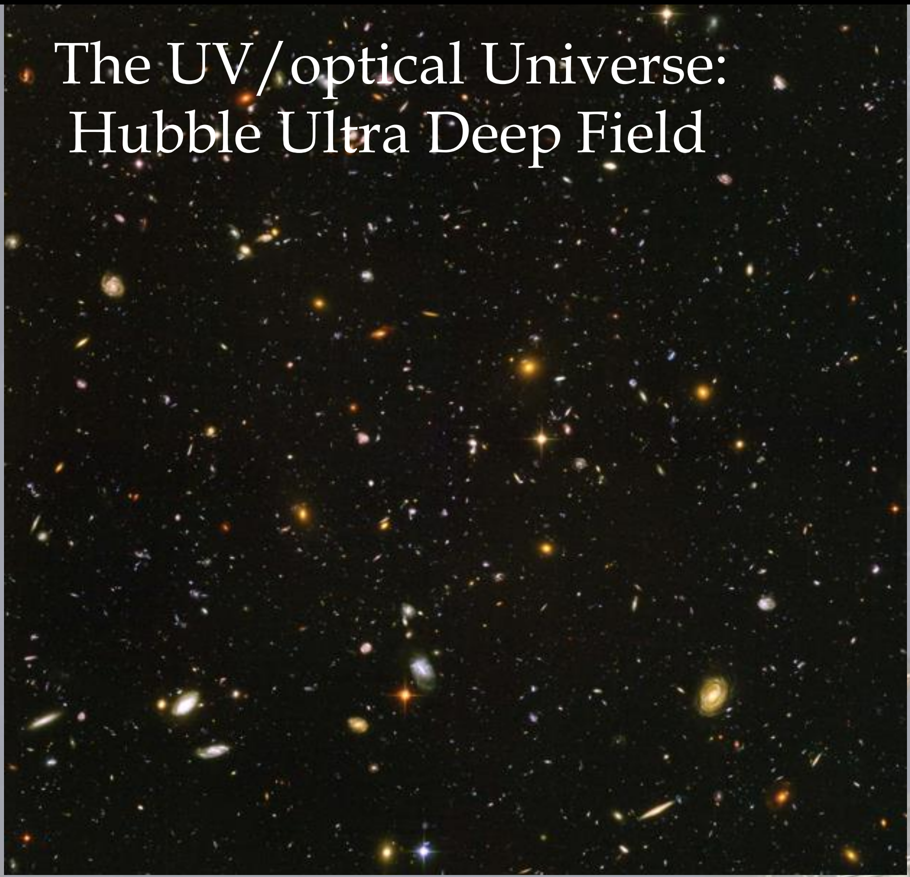
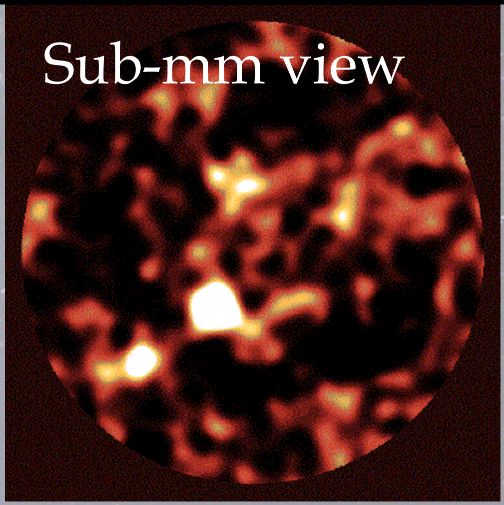
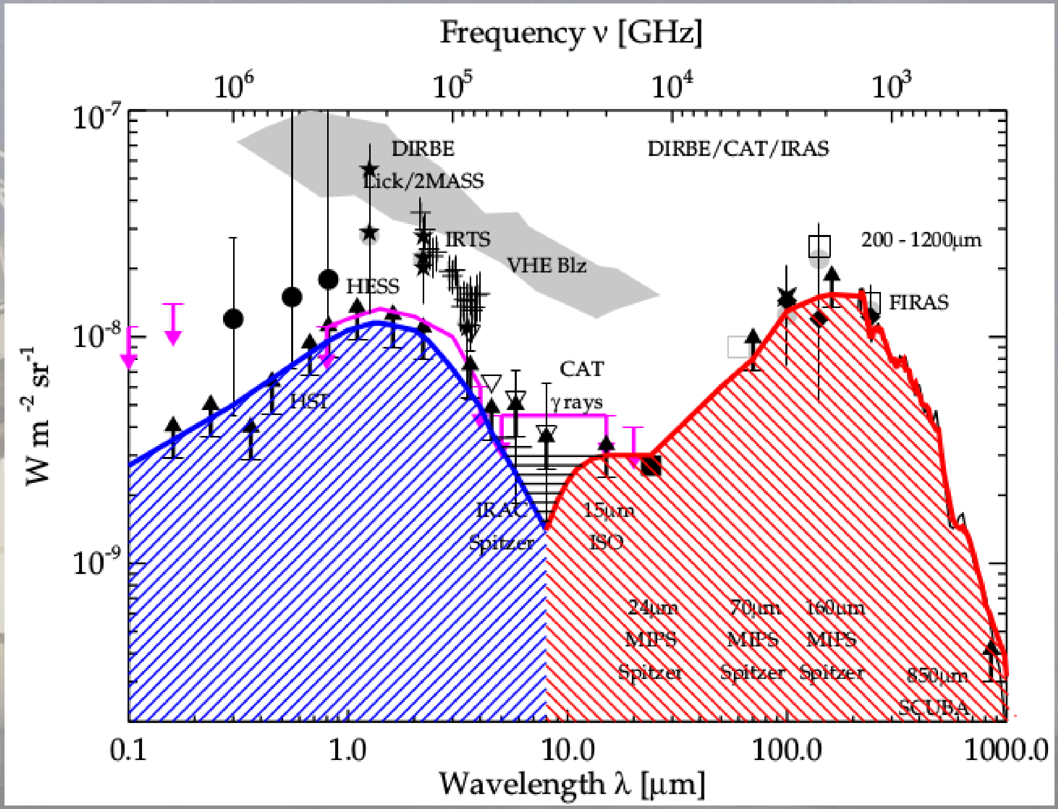
Outline

- Galaxy formation: UV/optical versus FIR/sub-mm
- High-z ULIRGS - submillimetre galaxies (SMGs)
- Pre-ALMA studies of sub-mm sources (e.g. LESS)
- An ALMA (Cycle 0) study of sub-mm sources in ECDFS: ALESS
    - Identifying counterparts to single-dish sub-mm sources
    - Source counts and multiplicity
    - The morphologies of high-z sub-mm sources
    - Redshift distribution
    - FIR/Radio properties
    - The descendants of high-z sub-mm sources
- An ALMA study of sub-mm sources in the S2CLS-UDS
- eMERGE – high-res radio imaging of sub-mm sources in GOODS-N
- Conclusions

The epoch of galaxy formation - sub-mm view

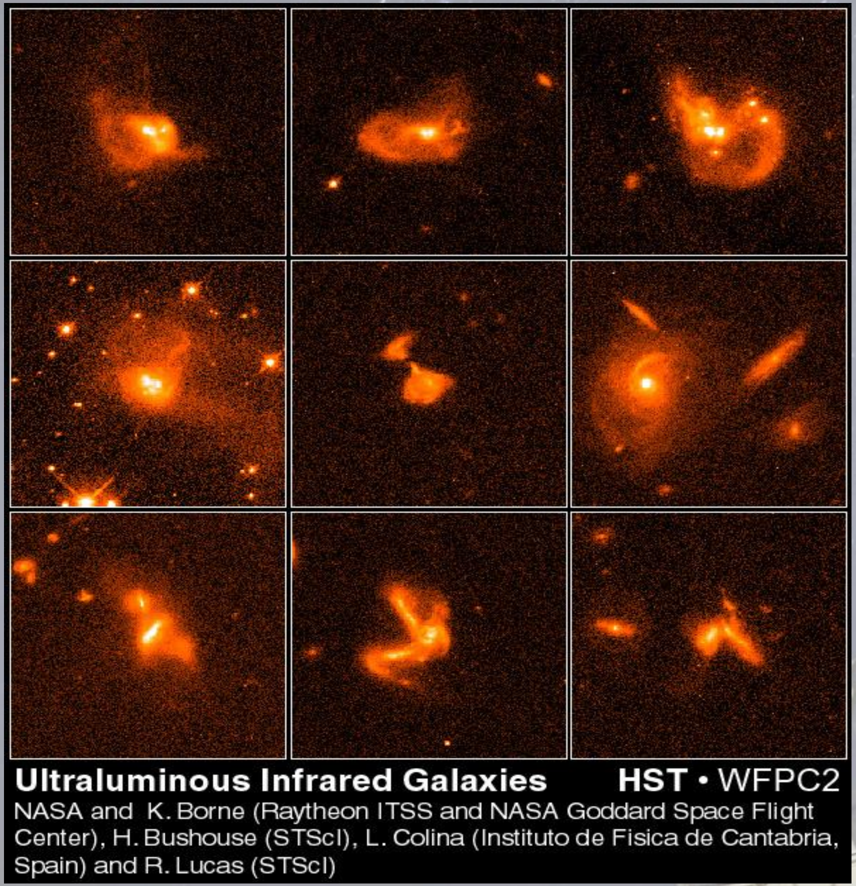


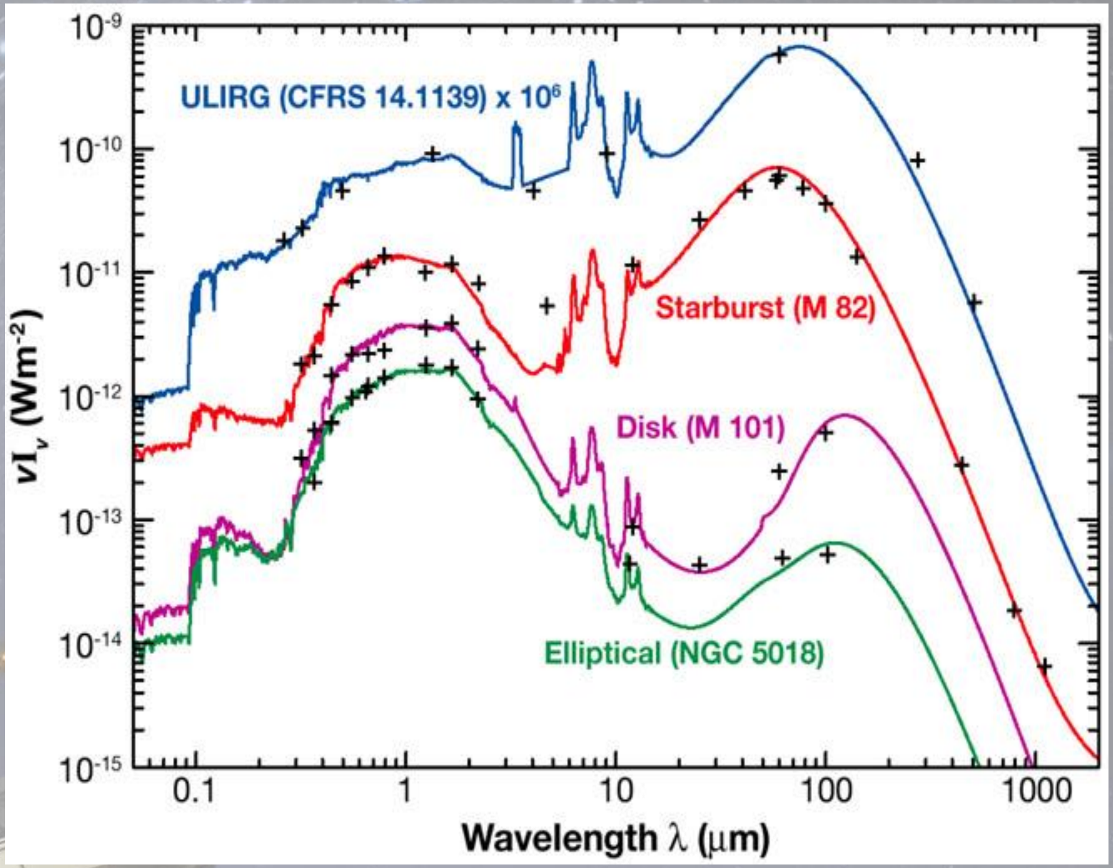




e.g. Fixsen et al, 1998; Dole et al, 2006

The epoch of galaxy formation - sub-mm view

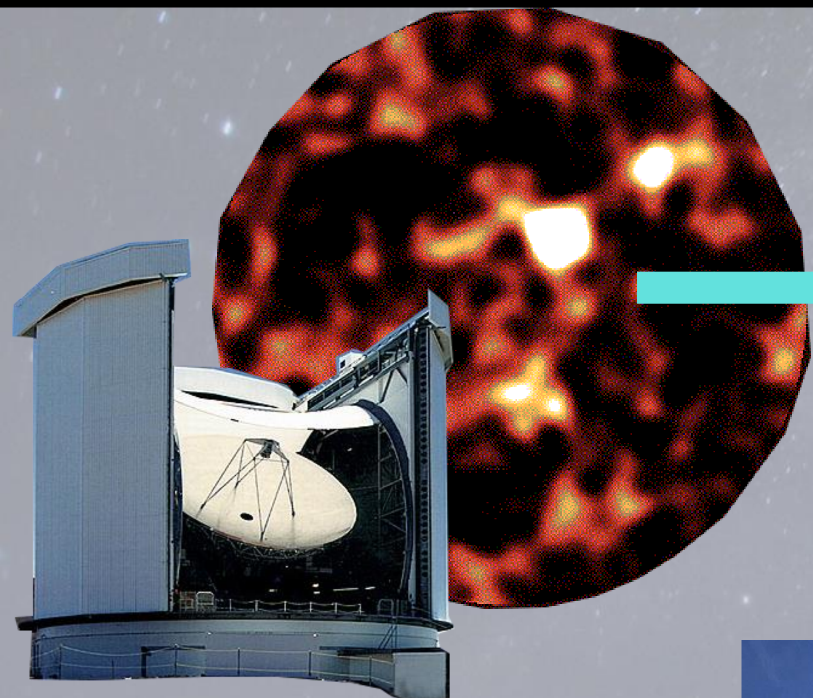


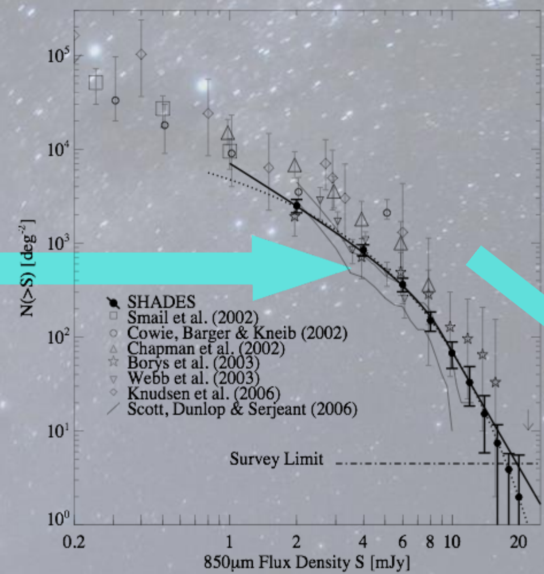


- Rest-frame SEDs peak in the far-IR due to dust-reprocessing of optical/UV starlight
- (Ultra-) luminous: $L_{IR} \geq 10^{12}\ L_\odot$
- Massive: $M_* \geq 10^{11}\ M_\odot$
- SFR ~ 200 – 1000 $M_\odot yr^{-1}$
- Rare: $\log(N/Mpc^3) \sim -6$; 3% of total energy density at z=0 (Magnelli et al, 2011)

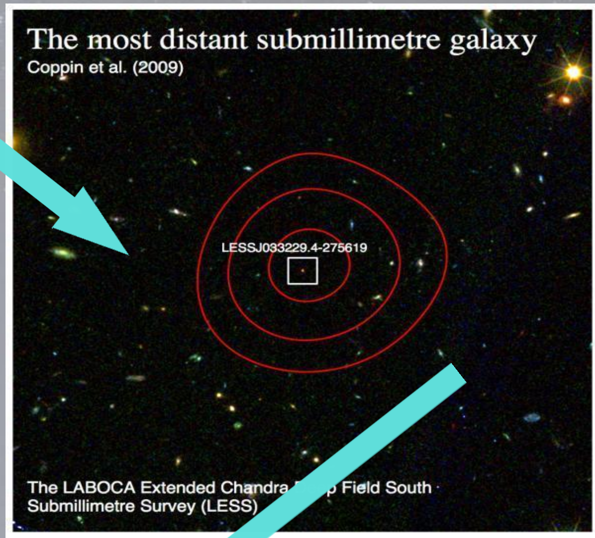
→ can't be responsible for FIRB... or can they?

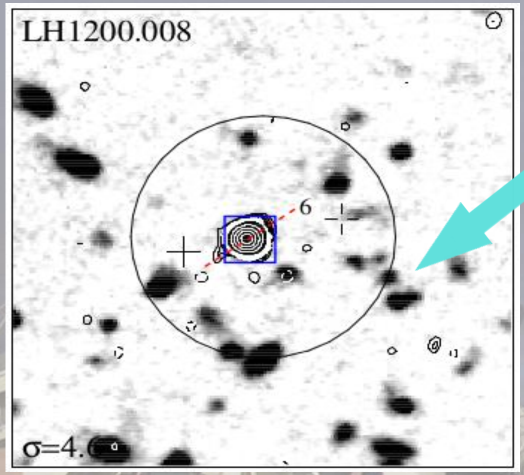
Hunting for high-z ULIRGS (SMGs)

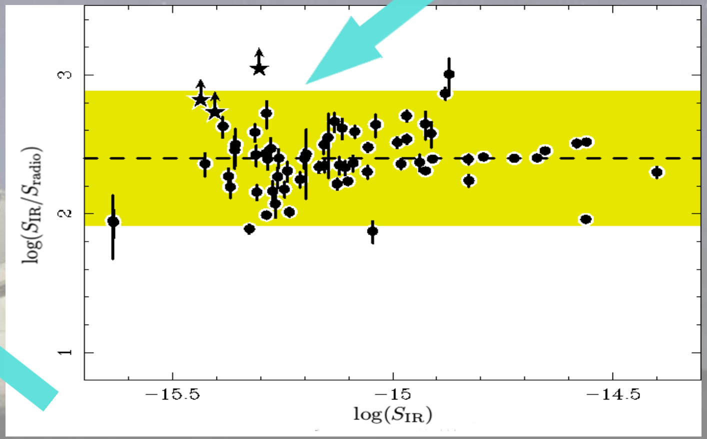




However, λ/D~15", so counterpart identification tricky...



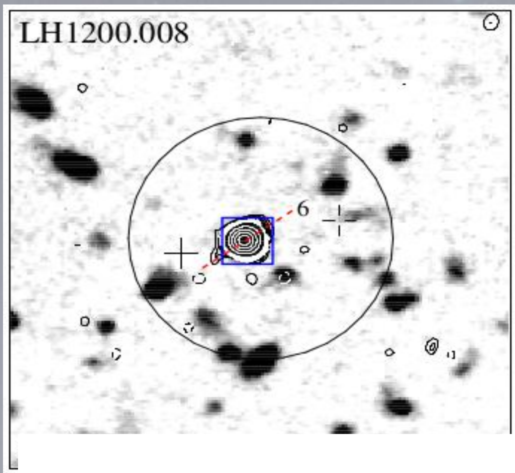


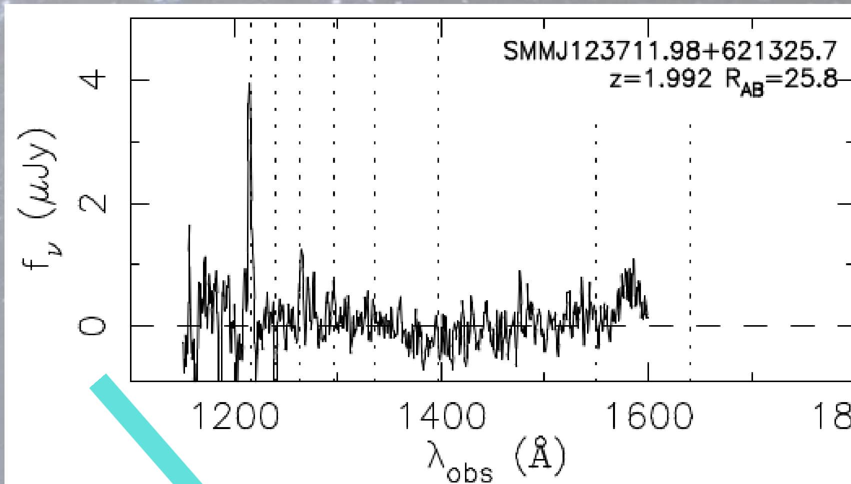


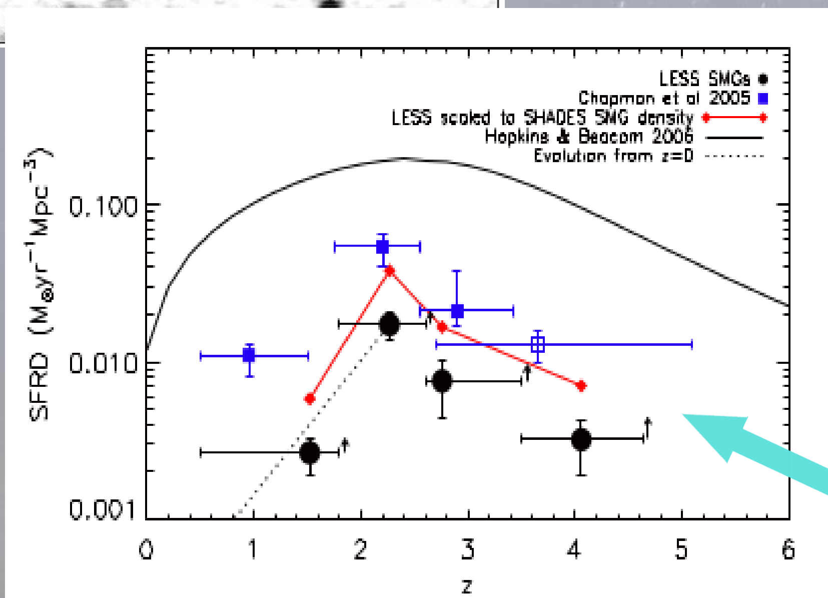
Use radio to pinpoint SMG and begin multiwavelength follow-up in earnest...

Exploit correlation between FIR/radio emission in normal galaxies

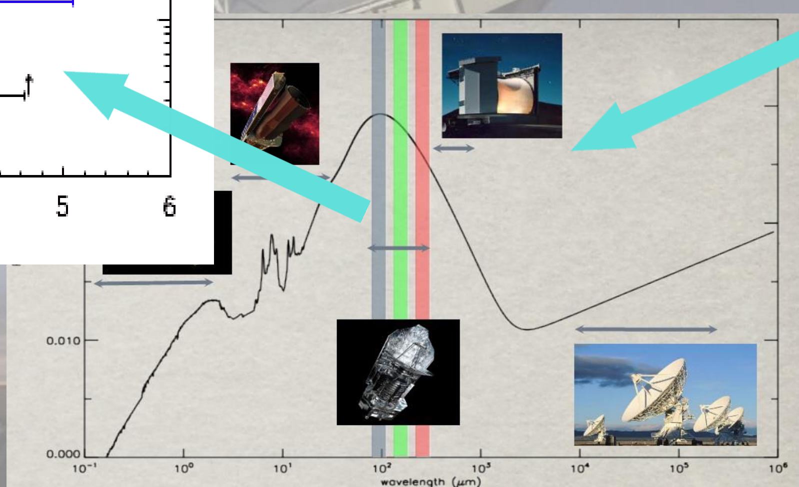
Hunting for high-z ULIRGS (SMGs)

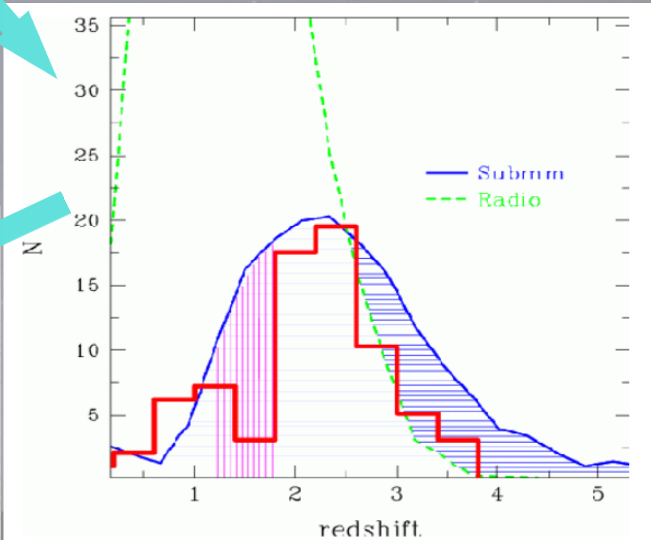






$L_{\odot}$→ SFR > 200 $M_{\odot}$/yr





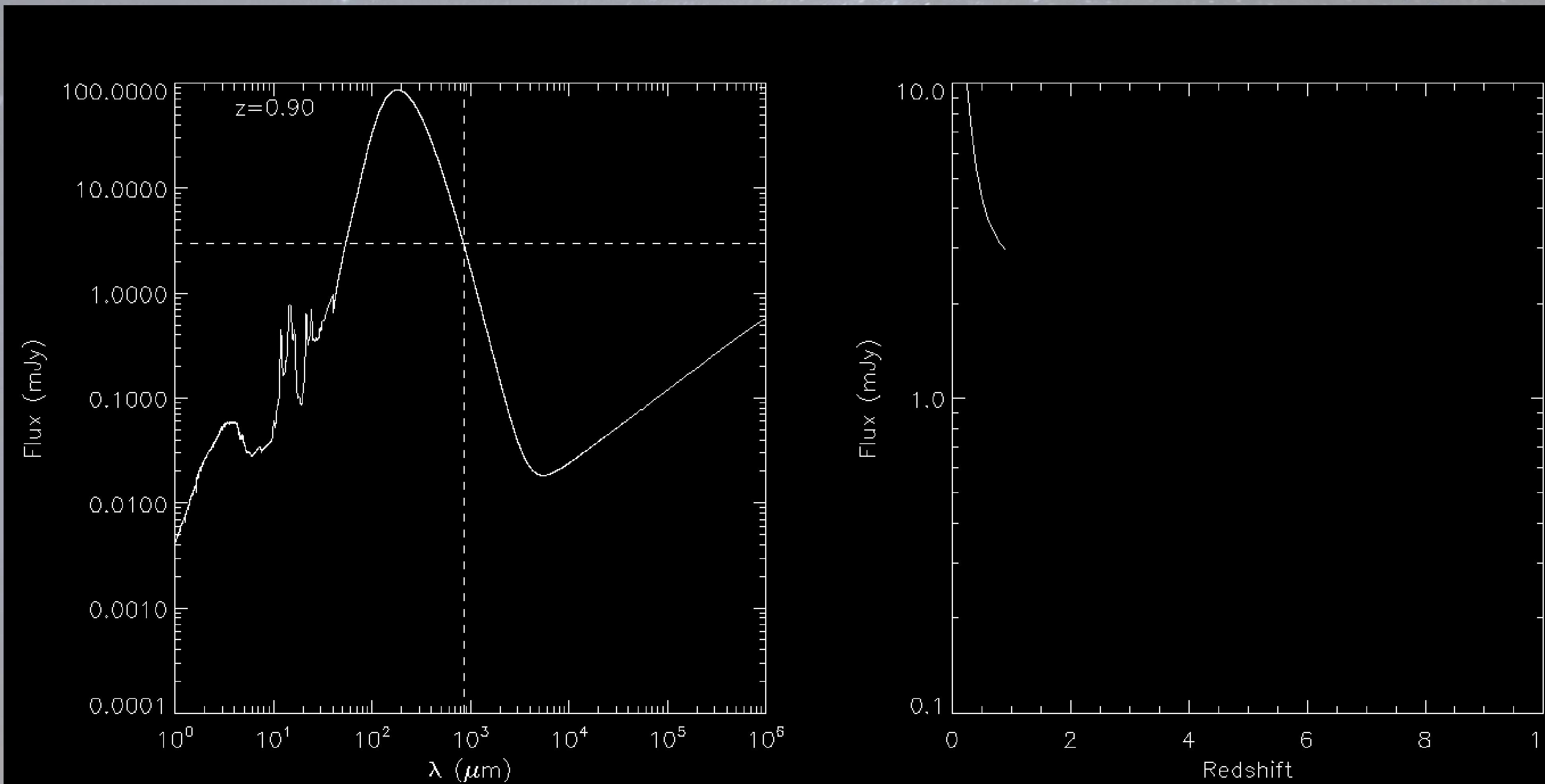
Wardlow et al (2011)
→ SMGs account for
10-40% of SFRD at z=2

Chapman et al (2005)

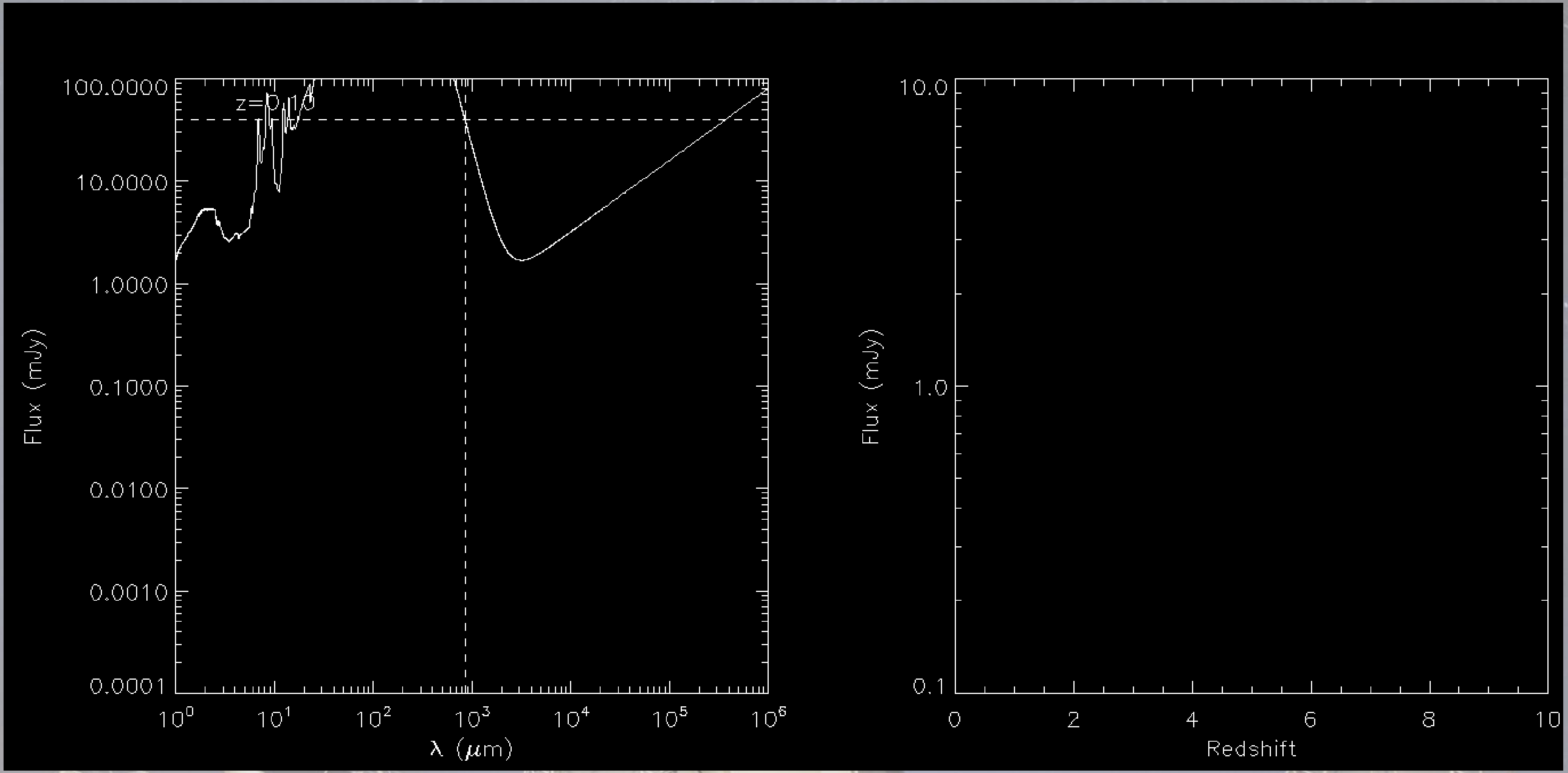
Basic properties of SMGs

- <z> ~ 2.3
- $L_{IR} > 10^{12}L_{\odot} \rightarrow$ SFR > 200 $M_{\odot}$/yr
- $M_{gas} \sim 10^{10}M_{\odot}$
- $M_{*} \sim 10^{11}M_{\odot}$
- σ ~ 200km/s
- In many cases, show disturbed kinematics, suggesting major-merger activity
- 1000x more numerous at z~2 than local ULIRGS
- → contribute ~10s of % of SFRD at peak epoch of star formation

Hunting for high-z ULIRGS: the negative k-correction



Hunting for high-z ULIRGS: the negative k-correction

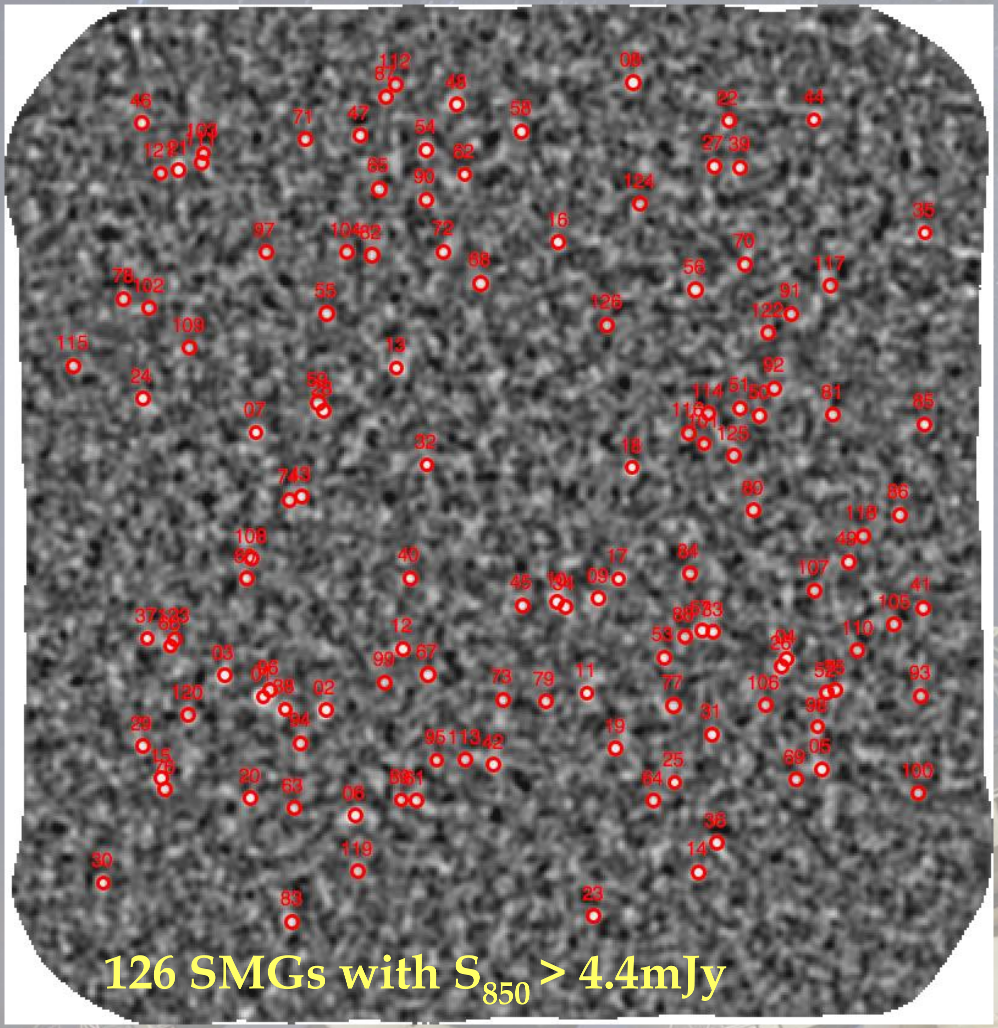


→ Can detect ULIRG-type galaxies in sub-mm bands just as easily at z~7 as in local Universe

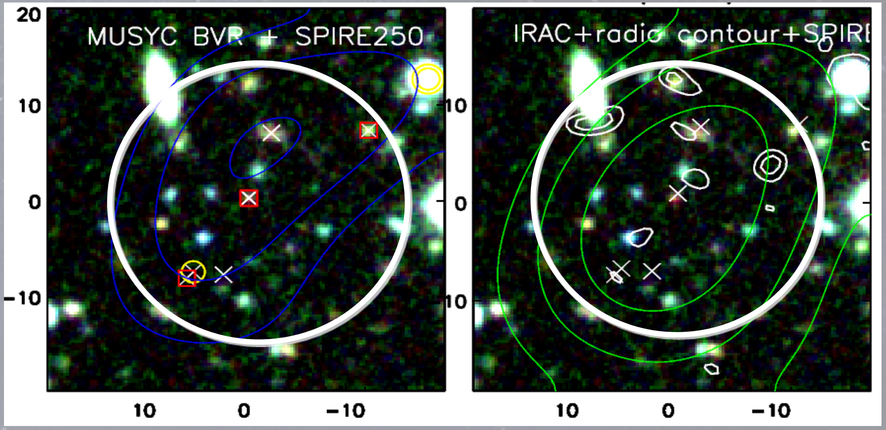
Positive k-correction in radio band

- Far-IR dust emission benefits from negative k-correction...
- ...radio emission, which we used to pinpoint the SMG, does not → cannot detect SMGs in radio continuum beyond z~3
- Is there another way to identify SMG within large single-dish error circle?

The LABOCA Extended Chandra Deep Field South Survey (LESS: Weiss et al. 2009)



LESS is a contiguous and uniform 870-μm survey reaching S_{870}=1.2mJy over ~30x30'



However λ/D~18", so counterpart identifcation potentially tricky...

→ adding *Herschel* data does not improve situation for IDs, since resolution is ~15/25/35" at 250/350/500μm, respectively

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 ALMA LABOCA Extended Chandra Deep Field South Survey (ALESS: Hodge et al. 2013/Karim et al. 2013)

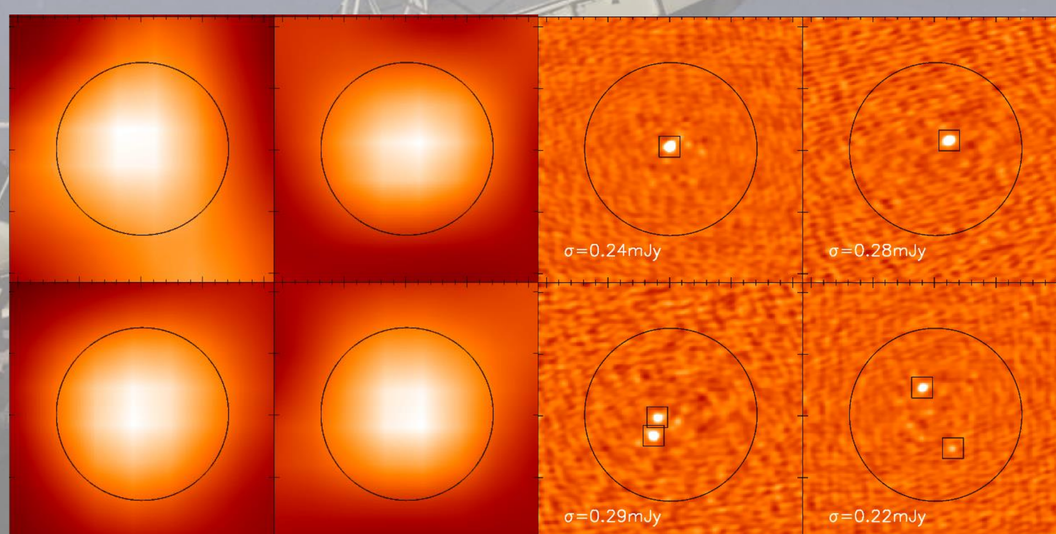
ALMA Cycle 0 program (2011)

<u>Objective:</u> survey all 126 LABOCA sub-mm sources at 870μm to a depth of 0.3mJy in compact configuration

→ 5 min/source (c.f. 350 hours with LABOCA to conduct original survey down to 1.5mJy!)

→ 150m baselines in compact configuration → λ/D ~ 1.4” (200x smaller than the LABOCA beam)

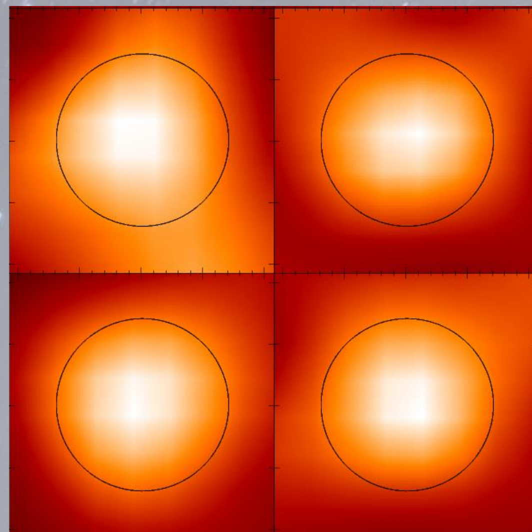
LABOCA ~ 18″

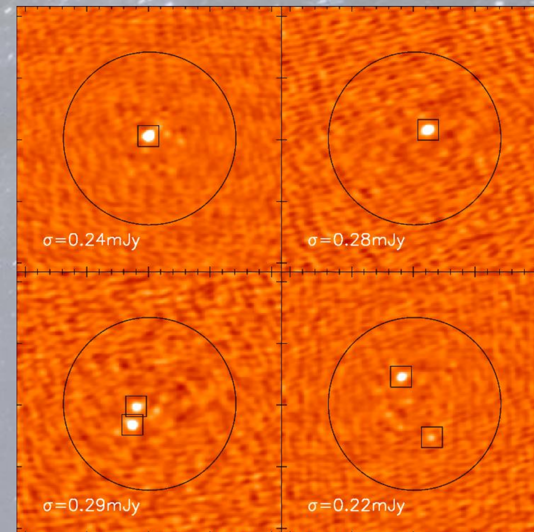


ALMA ~ 1.4″

The ALMA LABOCA Extended Chandra Deep Field South Survey (ALESS: Hodge et al. 2013/Karim et al. 2013)

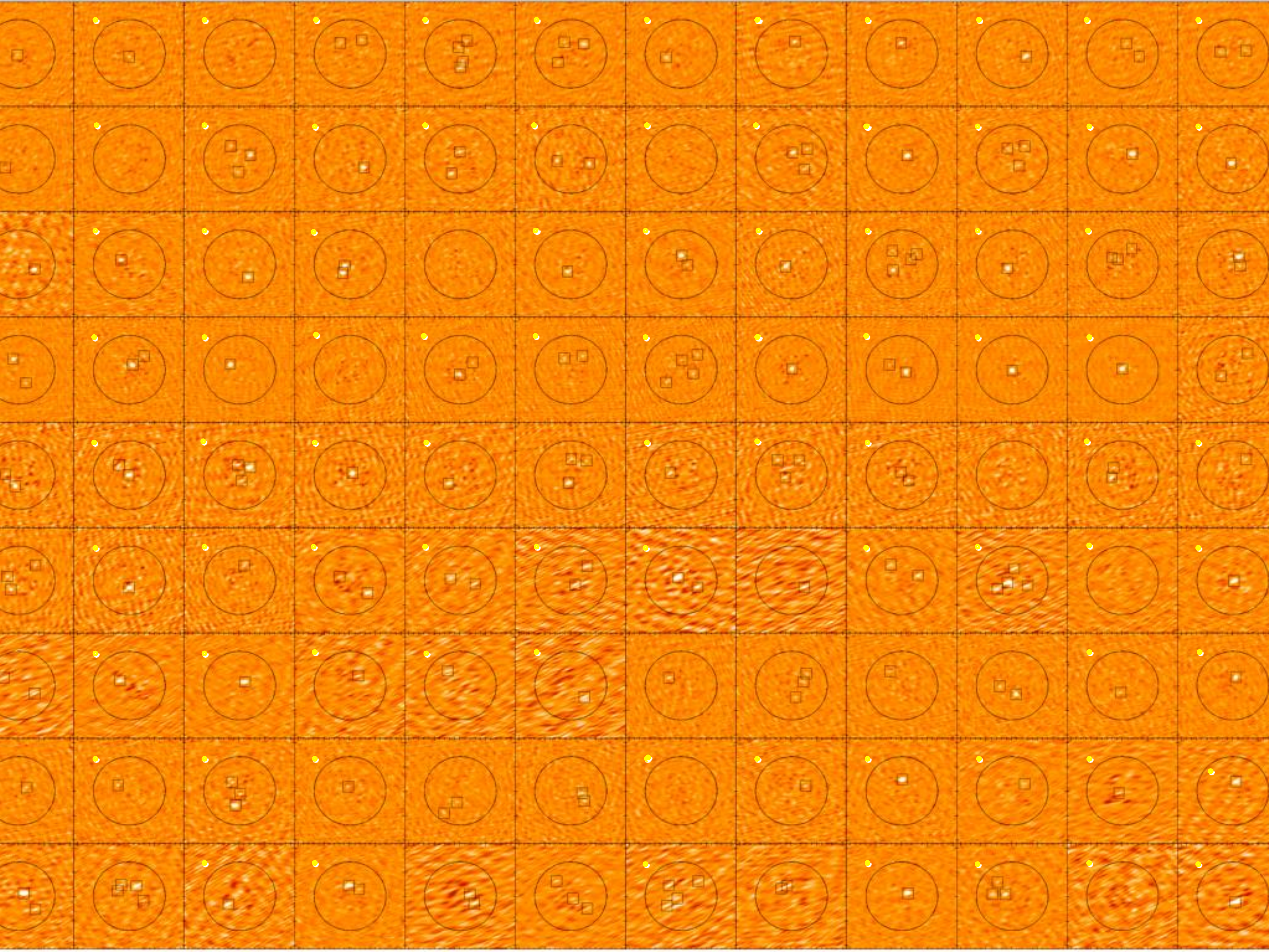
LABOCA ~ 18″



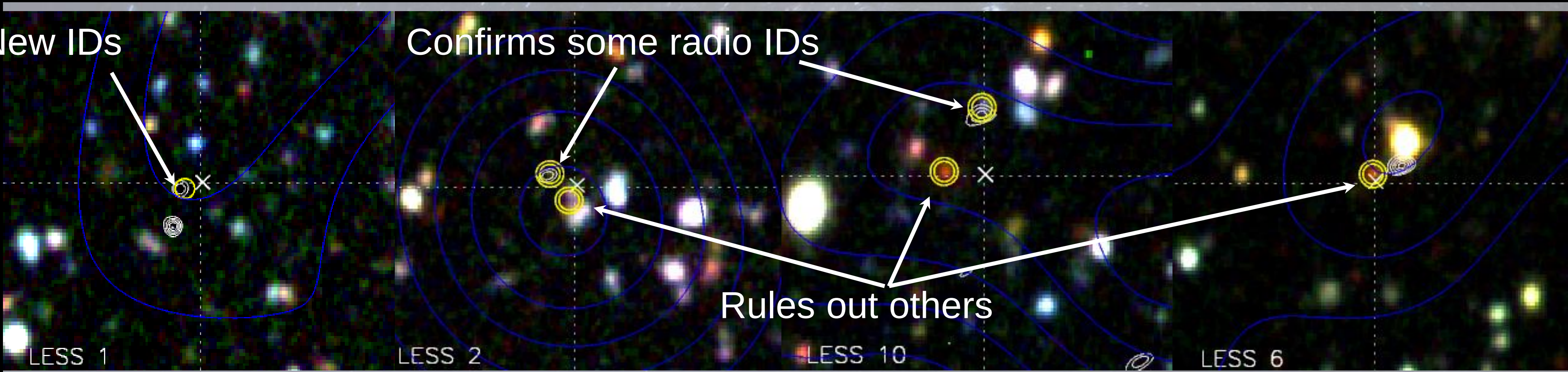


ALMA ~ 1.4″

- 122 ALMA pointings to observe 122 LABOCA SMGs
- ALMA maps ~3x deeper, with ~200x smaller beam than LABOCA
- 88 best ("MAIN") maps have $\sigma < 0.6$mJy/beam and beam axis ratio < 2
- In 69 maps, we detect 99 ALMA sources at $>3.5\sigma$ (multiplicity) with 19 blank maps (20%) -



The ALMA LABOCA Extended Chandra Deep Field South Survey (ALESS: Hodge et al. 2013/Karim et al. 2013)



67% single IDs

22% double IDs

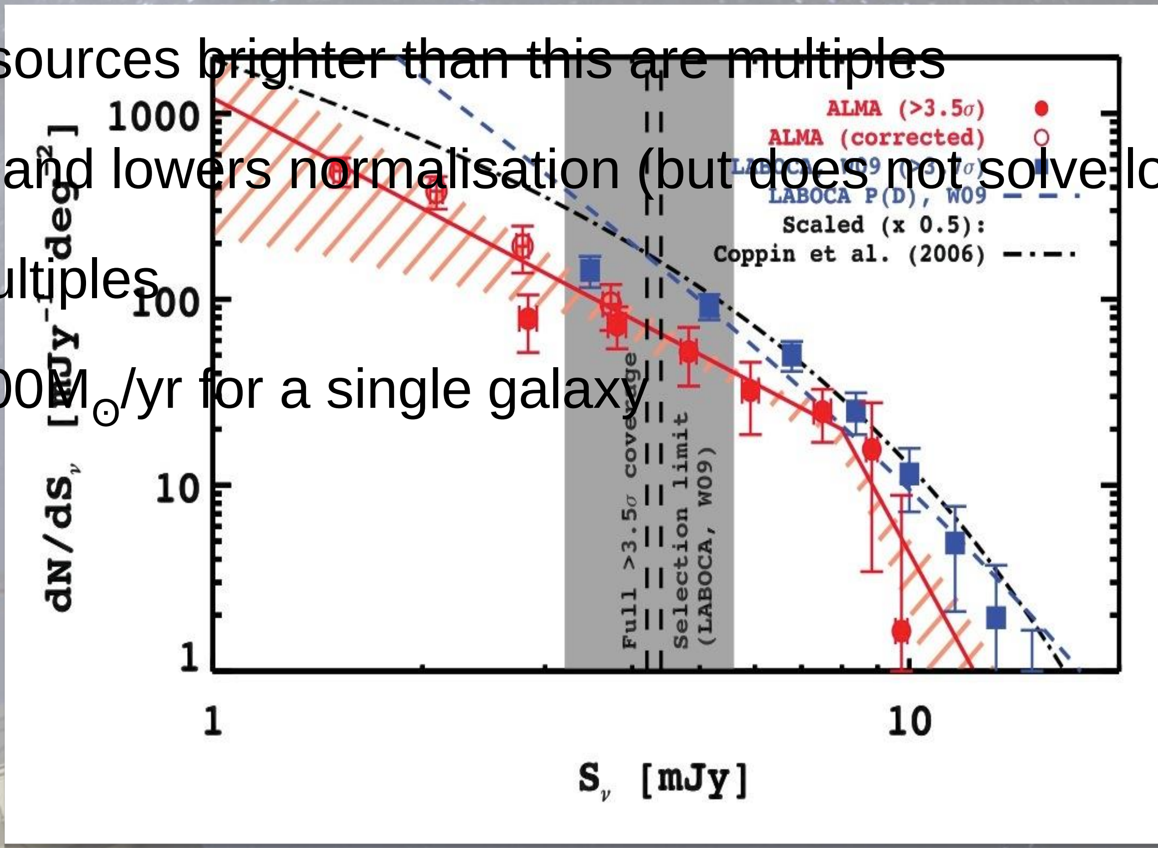
10% >2 IDs or resolved out/blank

Statistical counterpart identification:

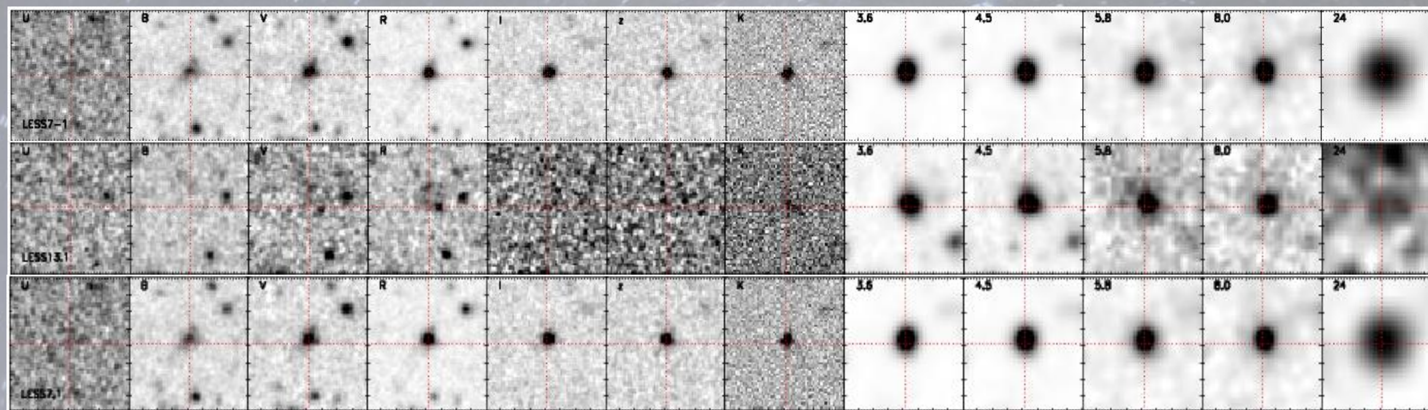
Radio "robust" counterparts: Reliability 80% but Completeness 45%

The ALMA LABOCA Extended Chandra Deep Field South Survey (ALESS: Hodge et al. 2013/Karim et al. 2013)

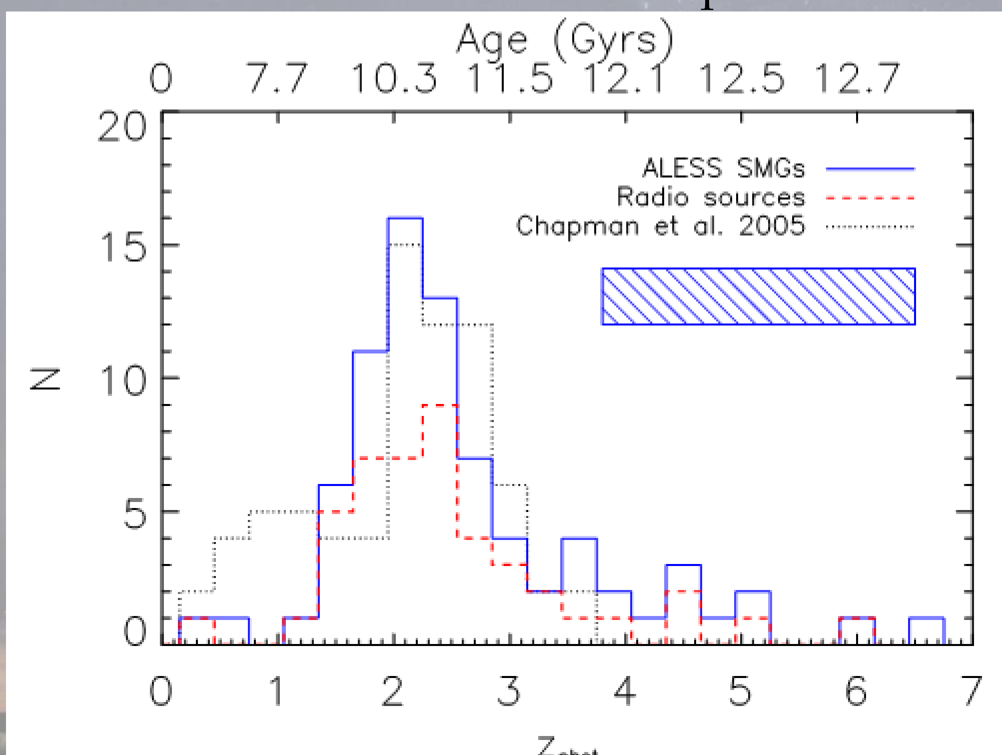
- Flux cutoff at ~10mJy: all LABOCA sources brighter than this are multiples
- Steepens bright-end number count, and lowers normalisation (but does not solve lo
- ~35-50% of sub-mm sources are multiples
- Implies a typical limit in SFR of ~1000$M_\odot$/yr for a single galaxy



An ALMA survey of submillimetre galaxies in the Extended Chandra Deep Field South: redshift distribution (Simpson et al. 2013)



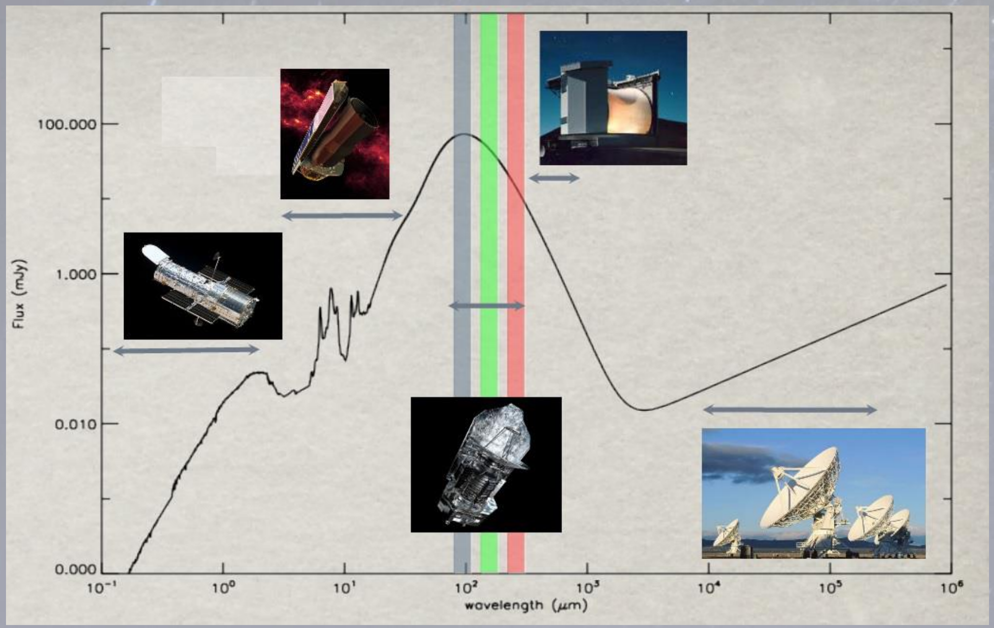
ECDFS deep archival imaging: UBVRIzJHK+IRAC



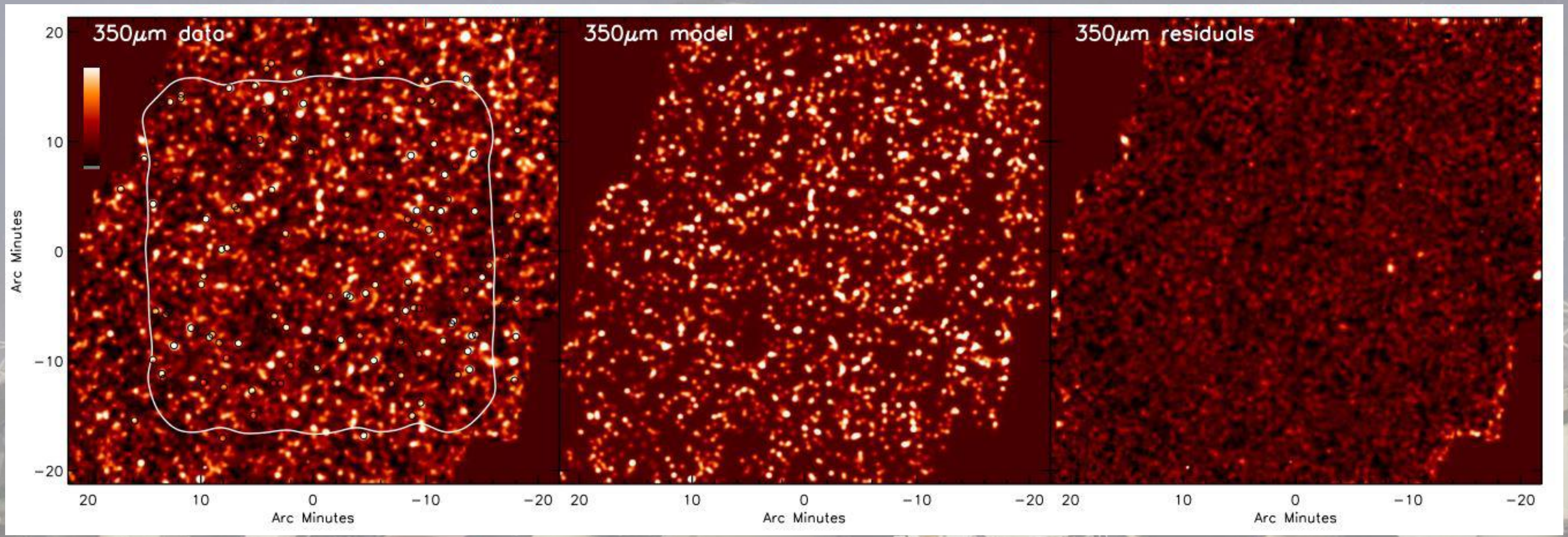
Simpson et al. (2013)

- Of 99 “MAIN” ALMA SMGs, 77 have good photometry in enough bands to determine reliable phot-z's
- Calibrated against 5,900 field galaxies in ECDFS
- ~25 SMGs with spec-z's
- $<z_{phot}> = 2.3 \pm 0.1$
- Tail out to z~6

An ALMA survey of submillimetre galaxies in the Extended Chandra Deep Field South: the far-IR properties of SMGs (Swinbank et al. 2013)



- To properly characterise far-IR SED, need measurements over the dust peak (160-500μm)...
- ...but *Herschel* SPIRE resolution ~15″ at 250μm (35″ at 500μm) → need to deblend SPIRE photometry



Swinbank et al. (2013)

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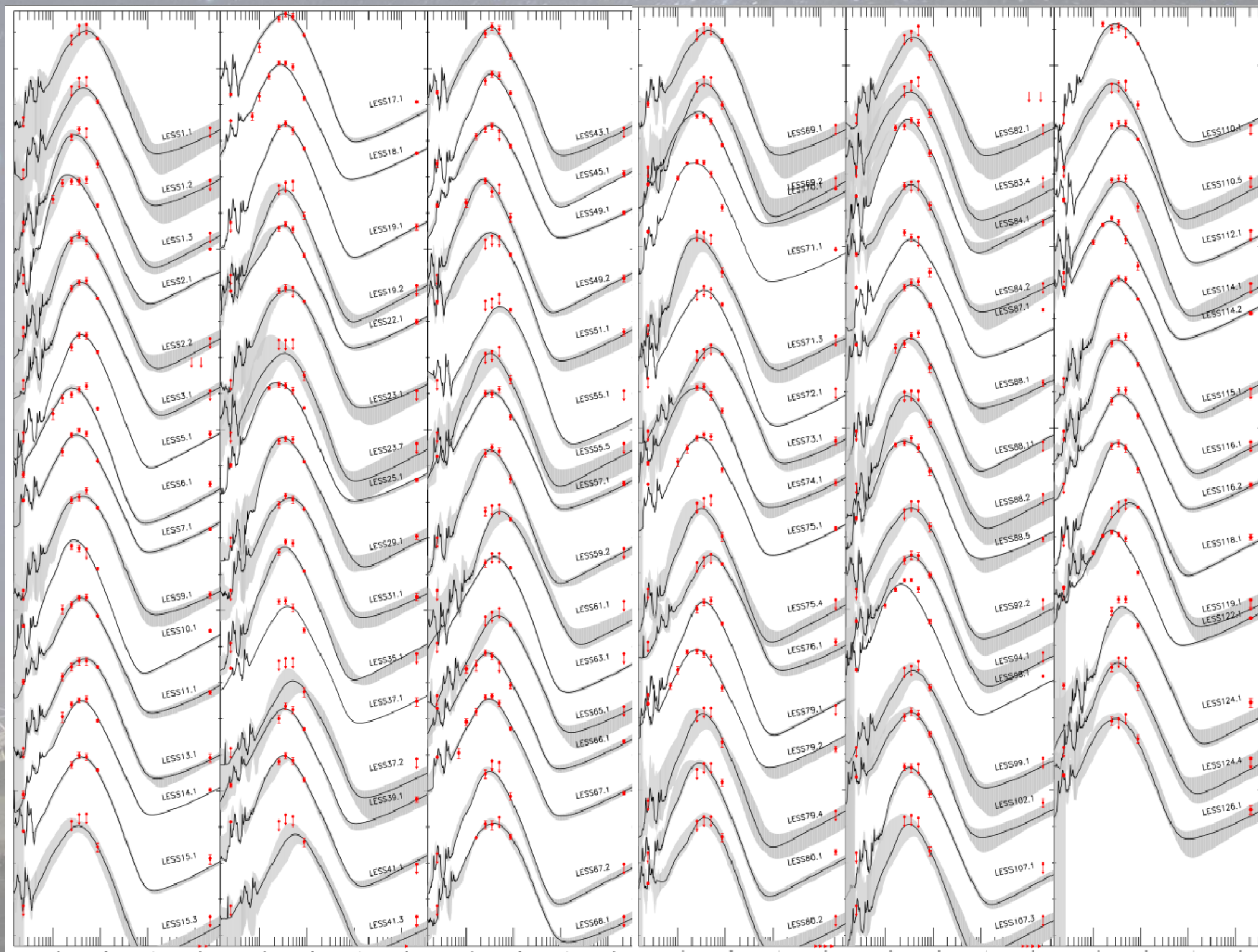

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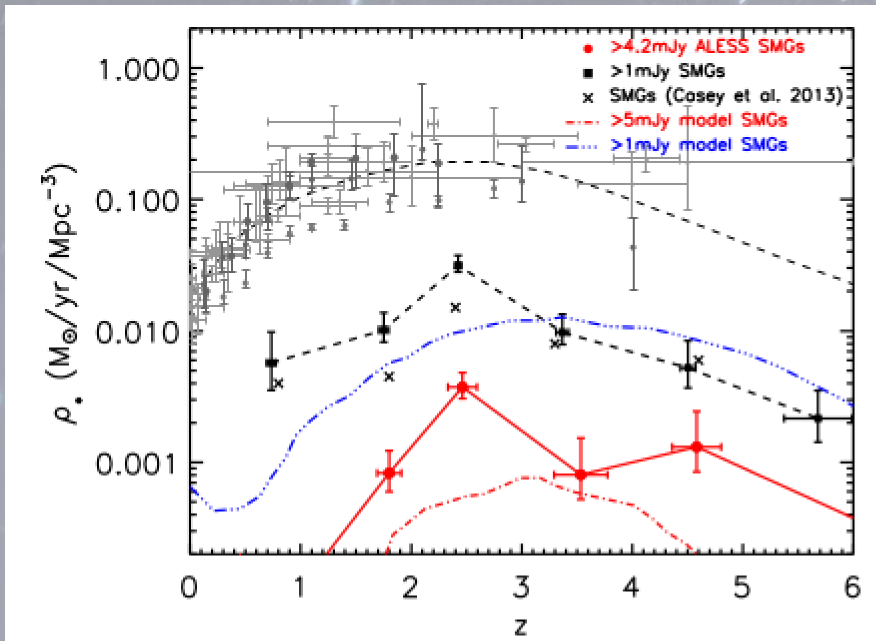
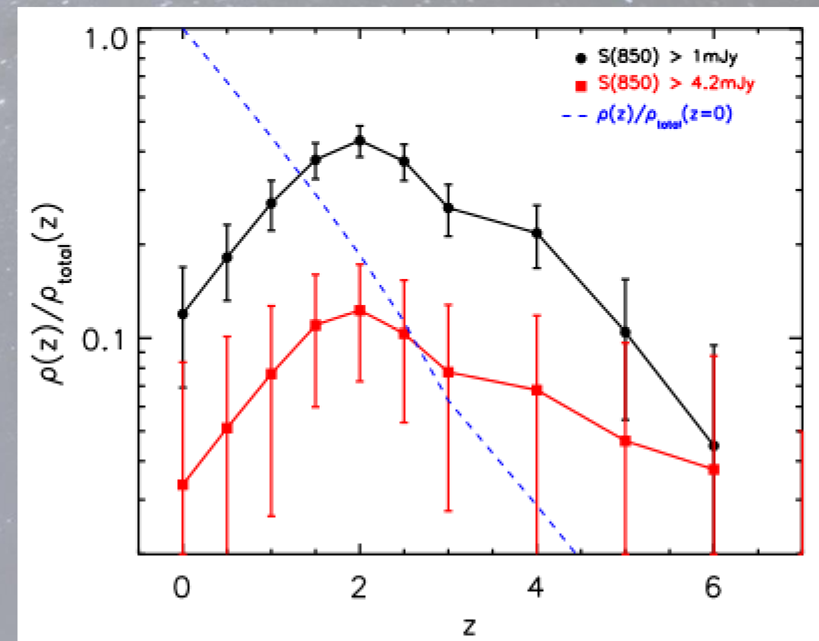
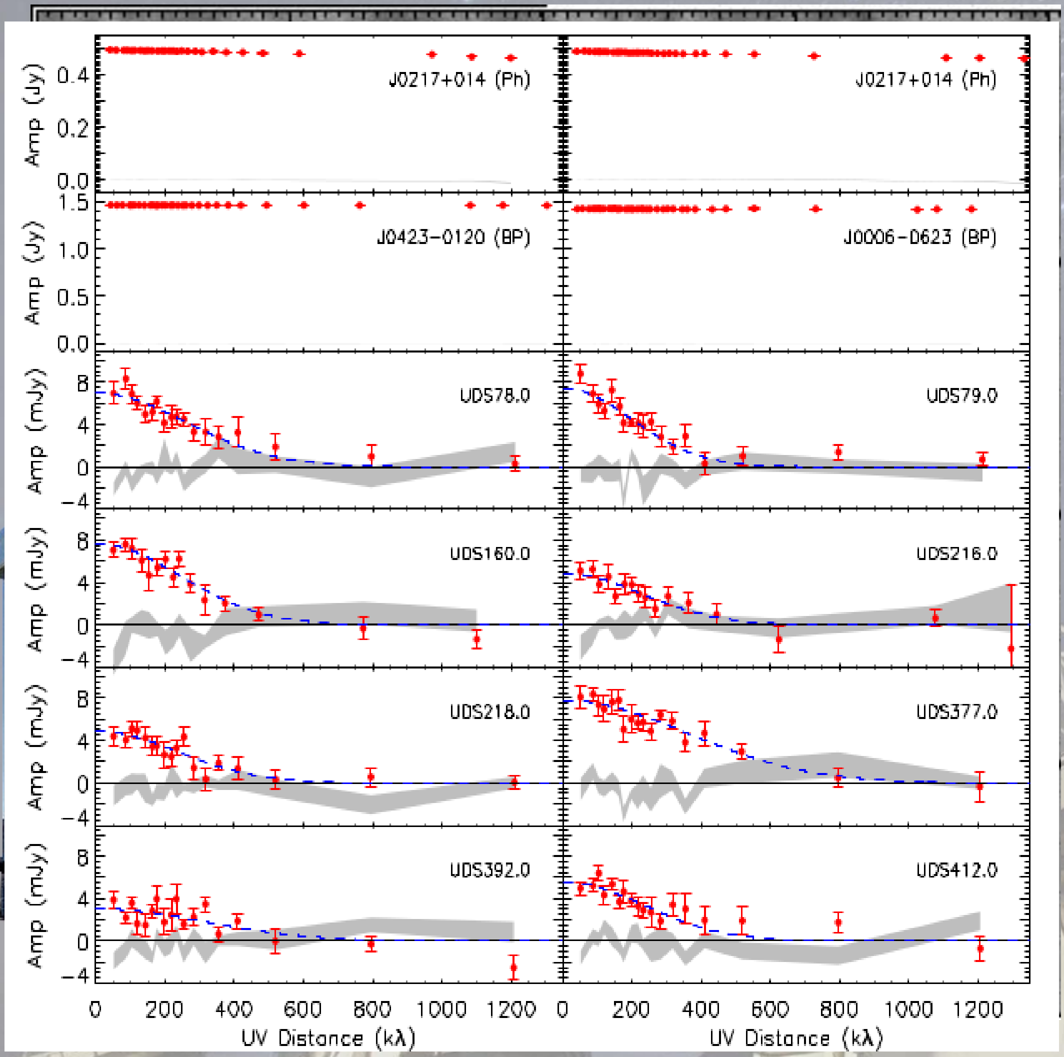


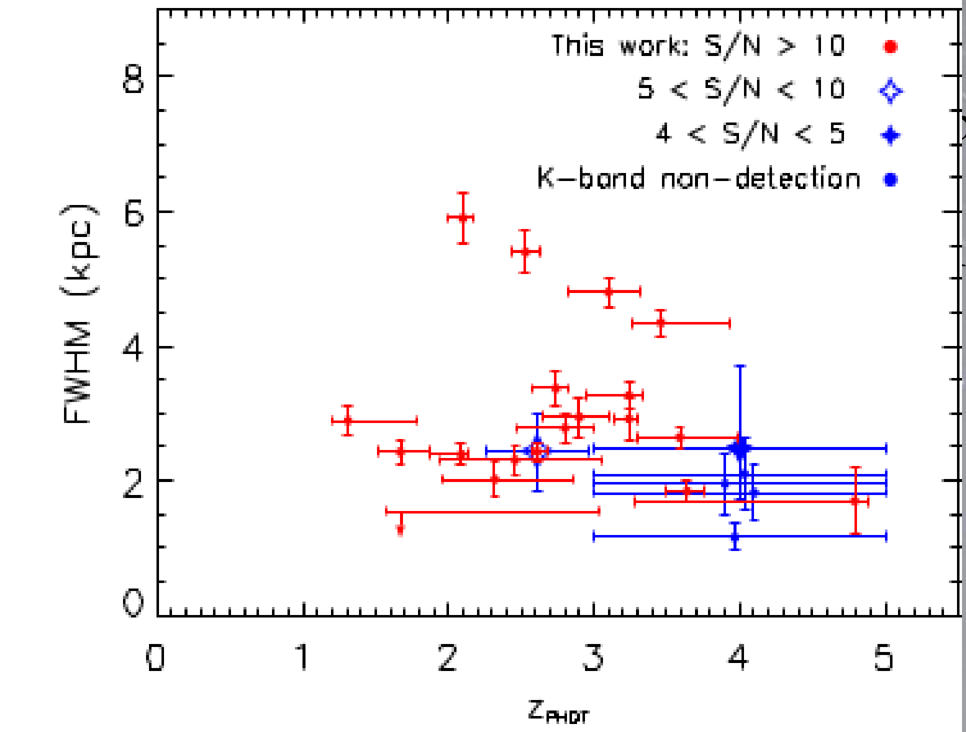


- SMG activity peaks at z=2, contemporaneous with QSO peak (Hopkins et al, 2007)
- Bright (>4mJy) SMGs account for ~2% of SFRD at z=2
- Integrating counts down to 1mJy implies SMGs account for >20% of SFRD at z=2

- Bright SMGs host ~15% of stellar mass at z=2...
- ...but integrating down to 1mJy encompasses > 40% of stellar mass

The SCUBA-2 Cosmology Legacy Survey – ALMA resolves the rest-frame far-IR emission of SMGs (Simpson et al, 2014/15)

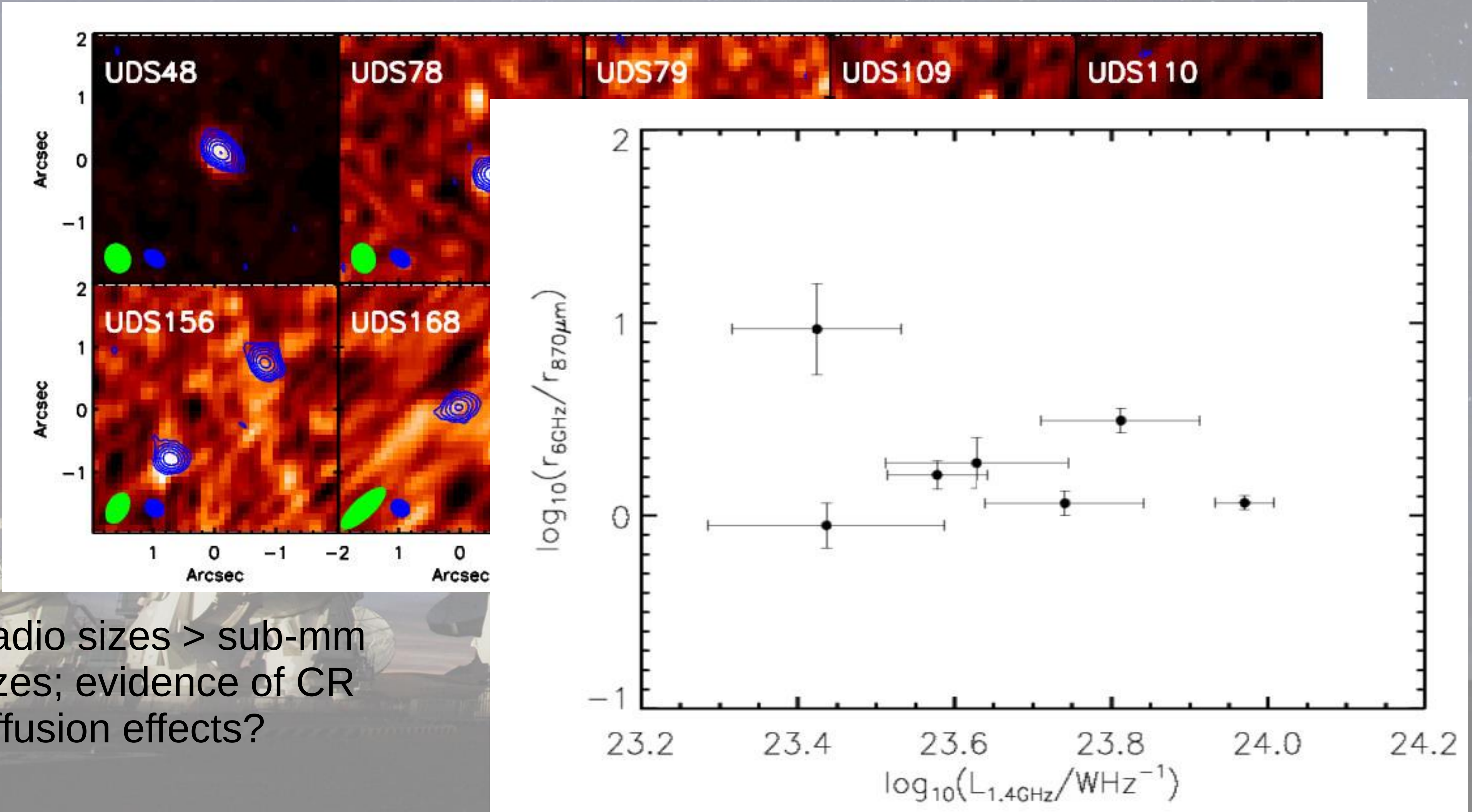




- Median size = 0.30 ± 0.04″ (corresponds to ~2.5kpc)
- Typically ~80% of single-dish flux located in brightest galaxy; cf ~60% for ALESS
- (Slightly) more compact at higher z?

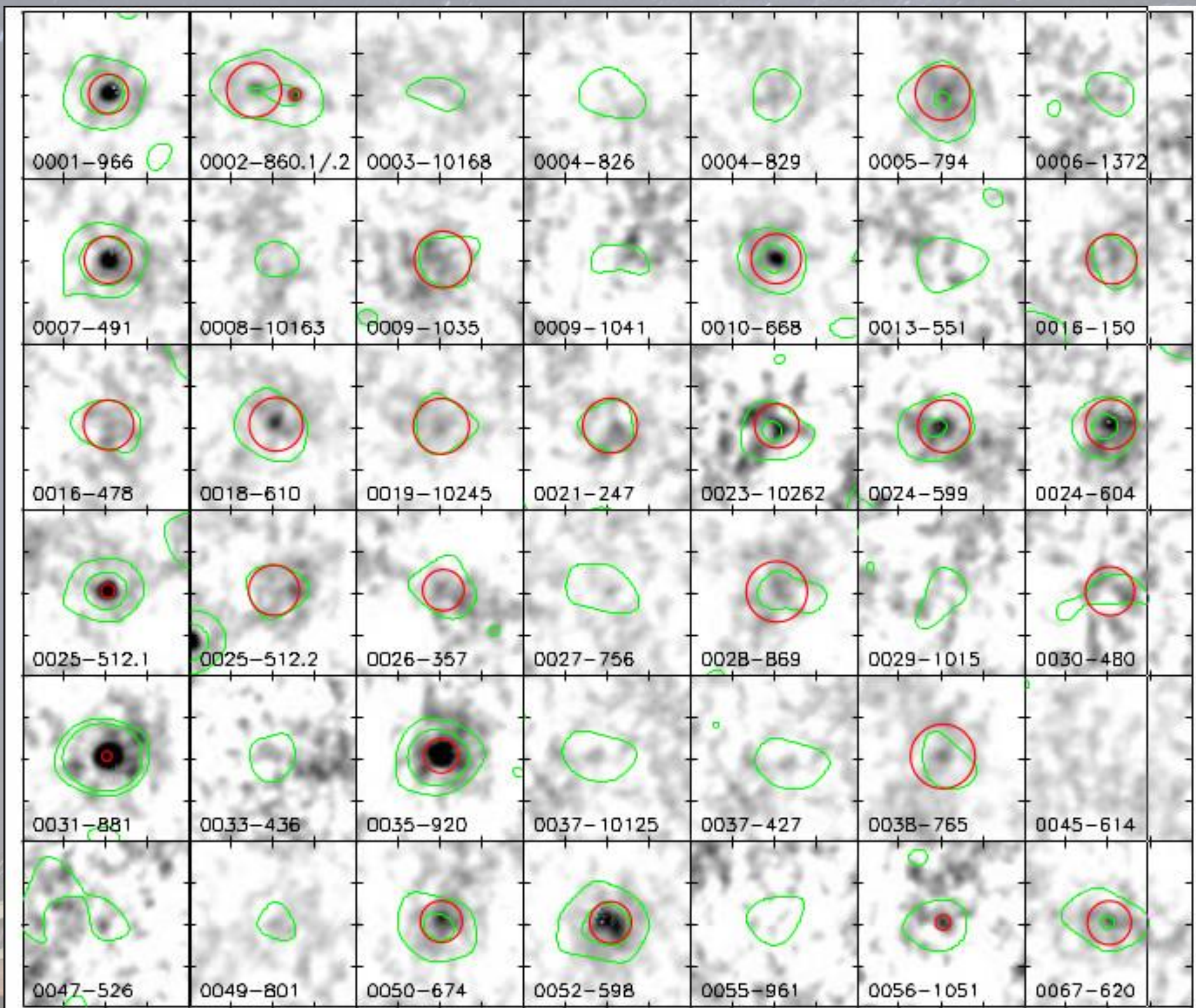
The SCUBA-2 Cosmology Legacy Survey – a comparison of far-IR and radio sizes (Thomson et al. *In prep*)

- SMG sizes ~ ALMA 870μm resolution ~0.3” (Simpson et al. 2015)
- VLA L-band A-conf resolution ~ 1.5” (Arumugam et al. In prep)
- → Need higher frequency/longer baselines to perform morphological comparison
- JVLA C-band, A conf resolution ~ 0.3 (Thomson et, in prep)



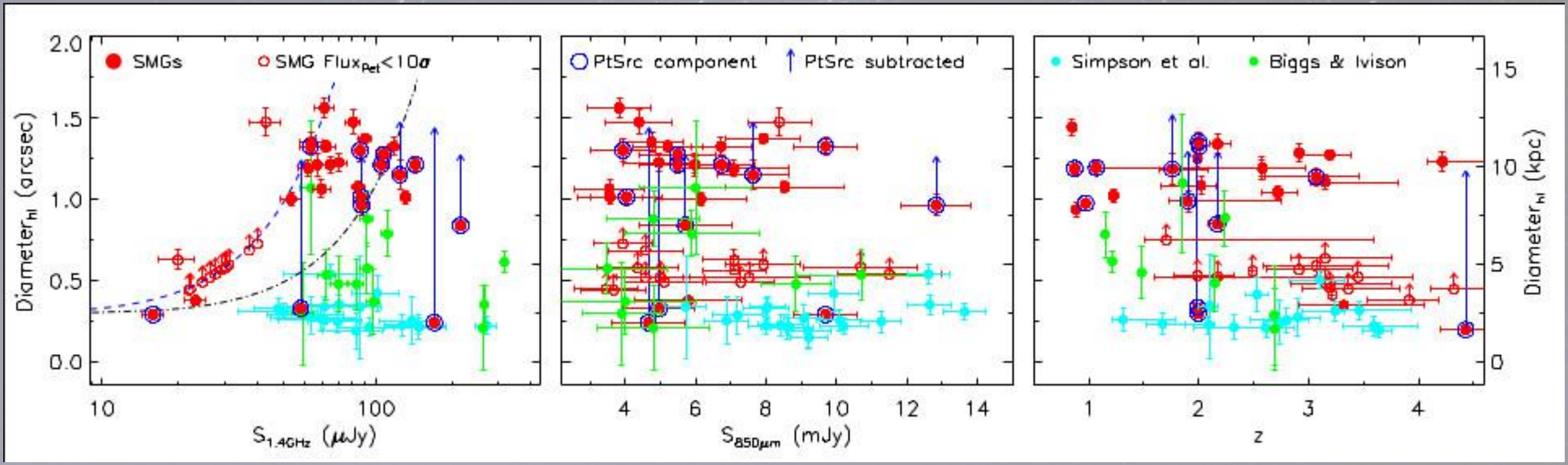
- Radio sizes > sub-mm sizes; evidence of CR diffusion effects?

eMERGE; eMERLIN counterparts to SCUBA-2 sources in GOODS-N (Smail et al, in prep)



- 43 JCMT sources have 1.4GHz counterpart in deep VLA imaging
- Using preliminary eMERGE imaging of field to estimate sizes/morphologies
- Radio sizes in GOODS-N ~10kpc (3x typical ALMA SMG sizes in other fields?!)

eMERGE; eMERLIN counterparts to SCUBA-2 sources in GOODS-N (Smail et al, in prep)



- Radio sizes in GOODS-N ~10kpc (3x typical ALMA SMG sizes in other fields?!) Why?
- CR diffusion effects expected to increase radio sizes (relative to sub-mm) by a few kpc
- Different kinds of beast altogether? (Comparison difficult; ALMA in South, eMERLIN in North…). Nuclear emission suppressed, leading to larger (half light) sizes?
- Something about eMERLIN/ALMA data we don't fully understand?

Conclusions

1) Most bright submm sources, >10mJy, are multiple SMGs

2) Natural limit(?) of SFR~$10^3 M_o$/yr for starbursts (few HyLIRGs)

3) Strategy for ID-ing SMGs using radio/MIR is clean, but low efficiency due in part to confusion from multiple-IDs, also overestimates L_{IR}

4) Median redshift for S_{870um}>2mJy SMGs is z=2.5+/-0.2

5) 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

6) ~10% of SMGs lack counterpart in any other band (z>3–5+?)

7) S_{870um}>1mJy SMGs contribute 20% of SFRD at z=1-4

8) ~50% are disk-like; ~50% show interactions/mergers (Chen et al, 2015)

http://astro.dur.ac.uk/SMG20

SMG20 - Twenty years of Submillimetre Galaxies:

STAR-FORMING GALAXIES AT HIGH REDSHIFTS.

31ST JULY - 2ND AUGUST 2017