Millimeter Survey of Distant Dusty Starburst Galaxies

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IPMU Seminar 2011-10-13

Outline

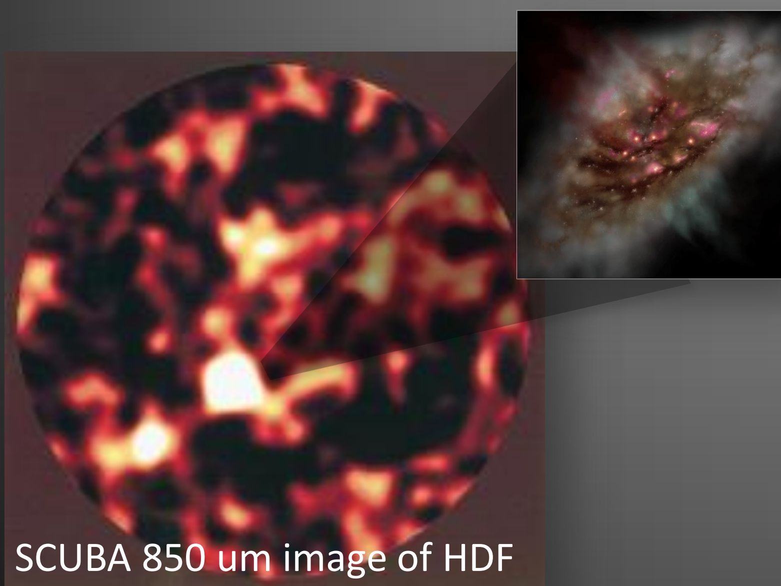
- Introduction
  - Millimeter/submillimeter-bright galaxies (SMGs)
  - Motivations of SMG survey
- 1.1 mm SMG Surveys
  - AzTEC camera on ASTE telescope
    - blank fields & overdense region
  - Results
    - each field
    - combined analysis
- Future Plan
  - ALMA
  - ASTE multi-color camera
  - Nobeyama 45-m telescope wide-band spectrometer

INTRODUCTION

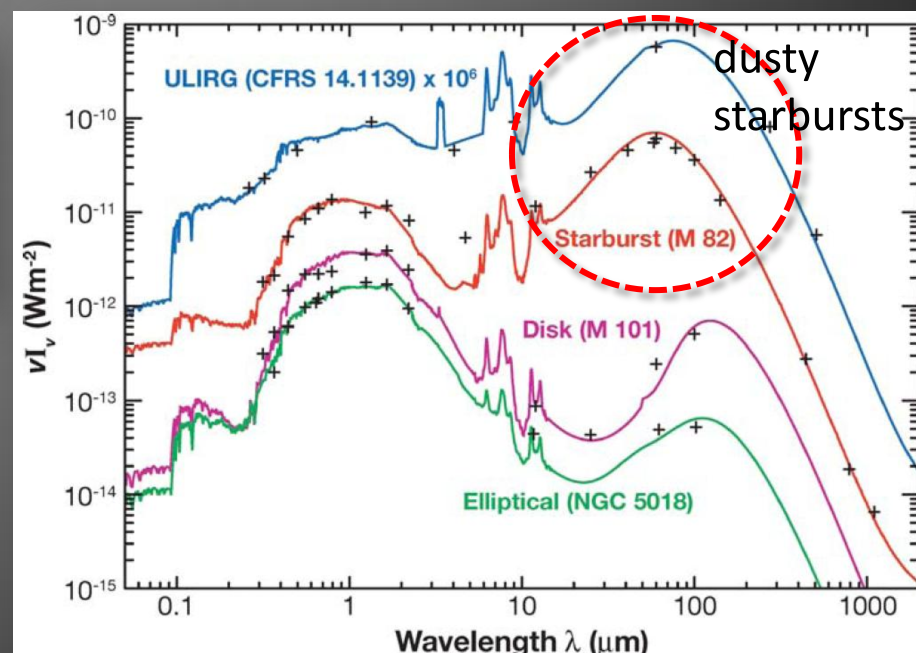
Millimeter/submillimeter-bright Galaxies (SMGs)

- In the late 1990s, 450/850 um deep survey with SCUBA
  - multi-pixel submm camera on JCMT

➔ Discovery of bright submm sources
  - Dust-enshrouded galaxies
  - Most of the energy is emitted at FIR/submm



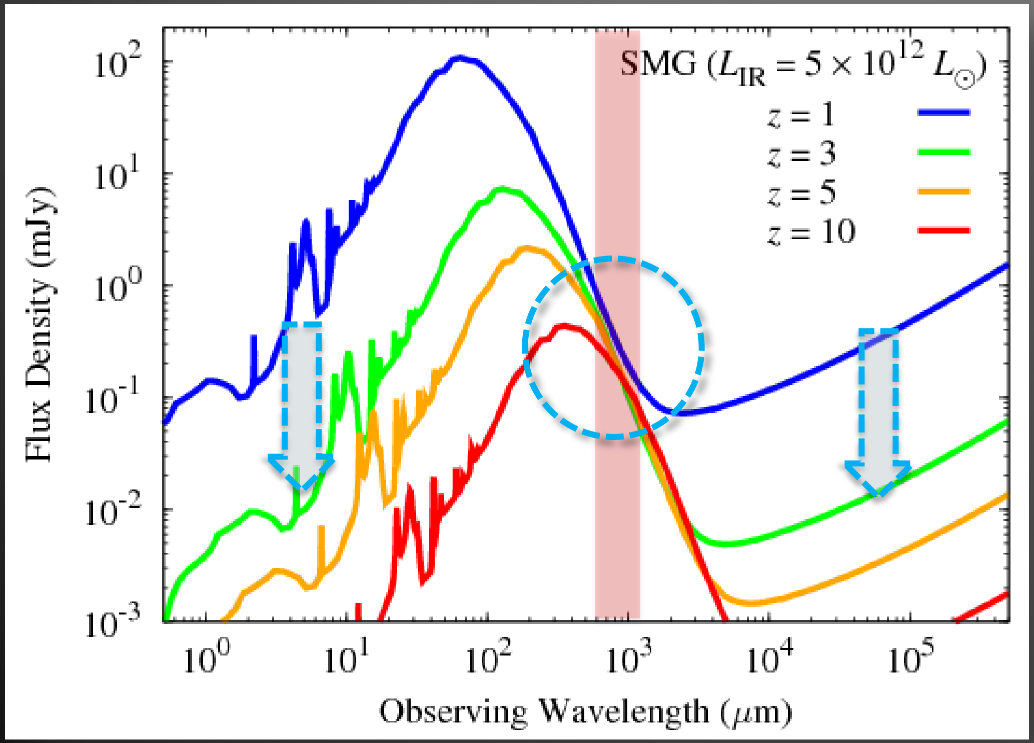
SCUBA 850 um image of HDF
(Hughes+98 Nature 394, 241)

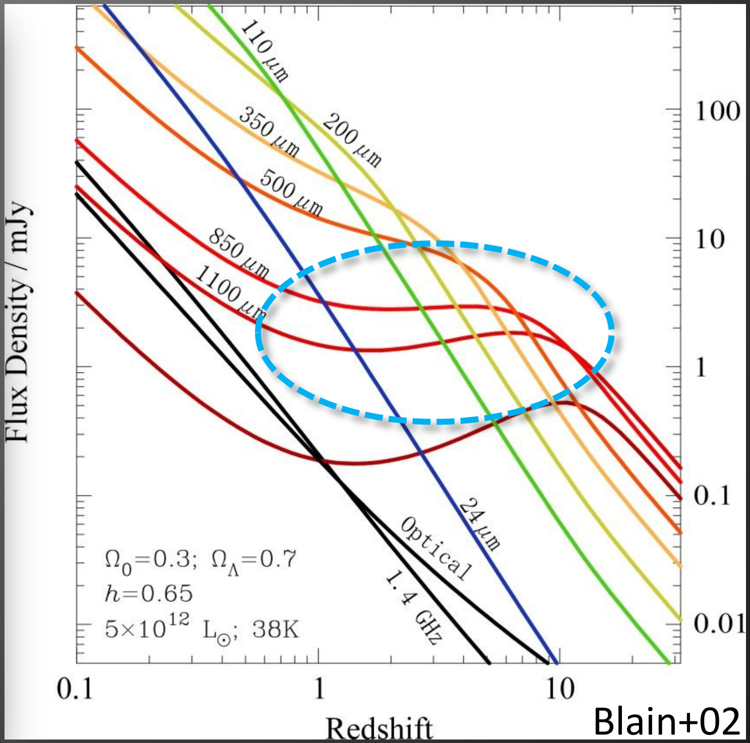


Submillimeter Observation

- Thermal emission from cold dust (~10-100 K)
- Observed flux density of a dusty galaxy is nearly constant because of the negative *K*-correction

➔ Distant galaxies can be detected efficiently (z ~ 10)

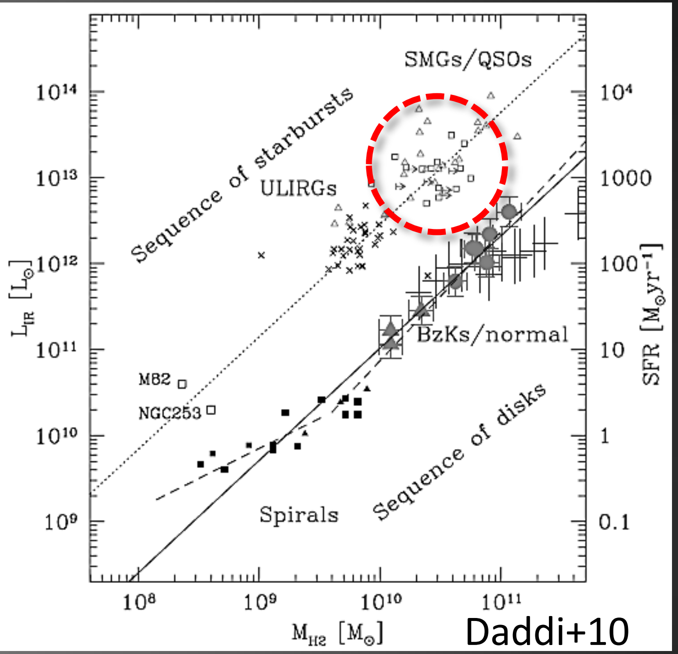




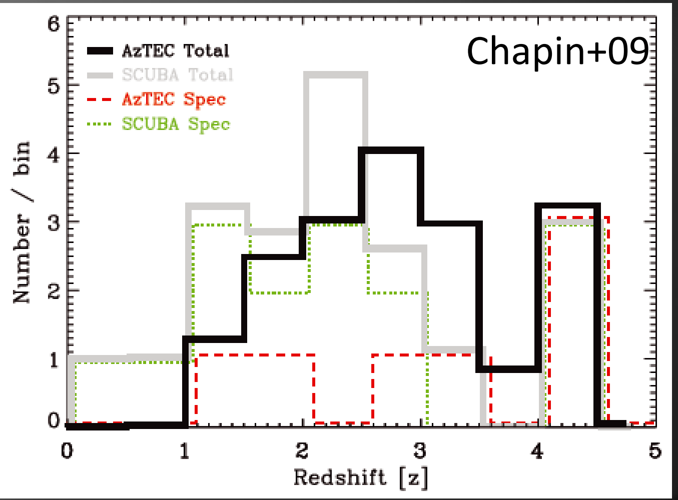
Blain+02

Submillimeter-bright Galaxies (SMGs)

- L(FIR) ~ 10^{13} Lsun
  - a large fraction of SMGs have AGNs
    - ~40-70% (optical/IR/X-ray observations, e.g., Swinbank+04; Alexander+05)
  - contribution of AGN to luminosity is small
  - ➔ Starbursts are the primary power source
- SFR ~ 1000 Msun/yr
- Molecular gas mass ~ 10^{10-11} Msun
- Redshift distribution
  - z ~ 1-4, z_{median} ~ 2.5
    - (e.g., Chapman+05; Aretxaga+08; Chapin+09)
  - several SMGs are found to be at z > 4 and z > 5
    - (e.g., Capak+08; Riechers+10)



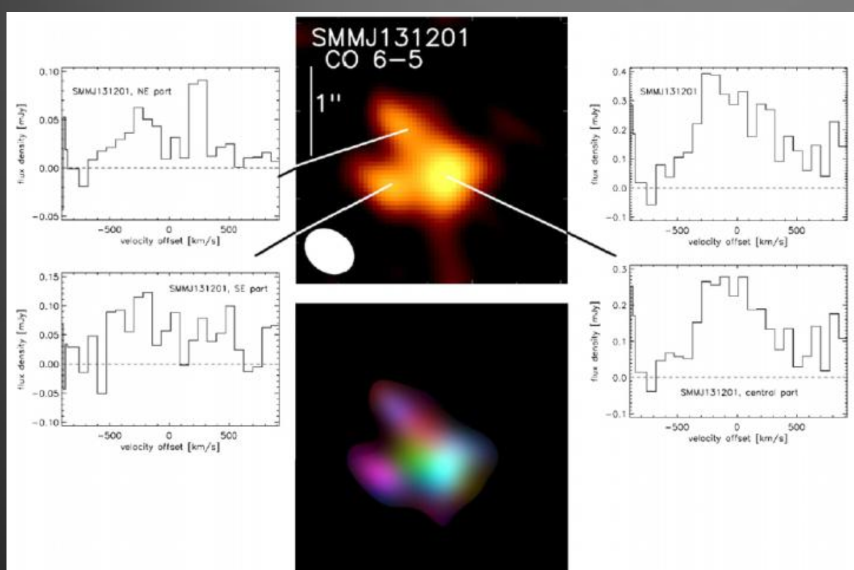
Daddi+10

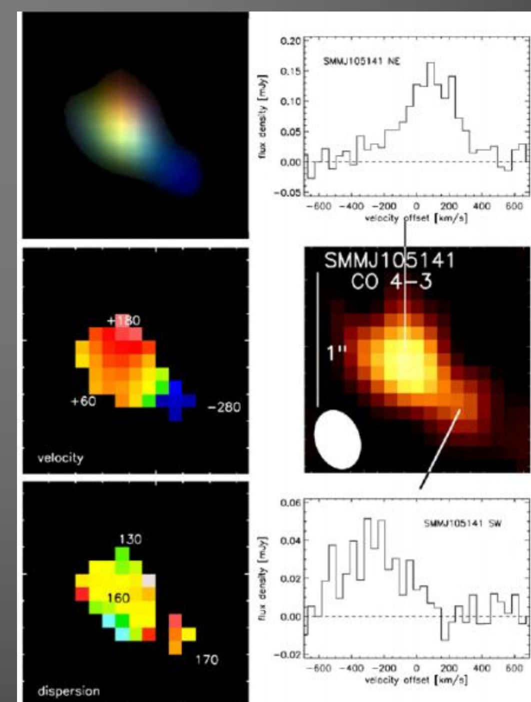


Chapin+09

Submillimeter-bright Galaxies (SMGs)

- Major merger?
  - High-resolution CO observations show signs of mergers
    - (e.g., Tacconi+06, 08, 10; Engel+10)





(Engel+10)

Submillimeter-bright Galaxies (SMGs)

- Massive, intensely star-forming galaxies at high-z
  - *Progenitors of present-day massive ellipticals?*
  - *Evolutionary link between SMGs and QSOs?*

Evolutionary history of SMGs and the relationship with other galaxy populations are largely uncertain...

Motivations of SMG Surveys

1. Relation with other galaxy populations

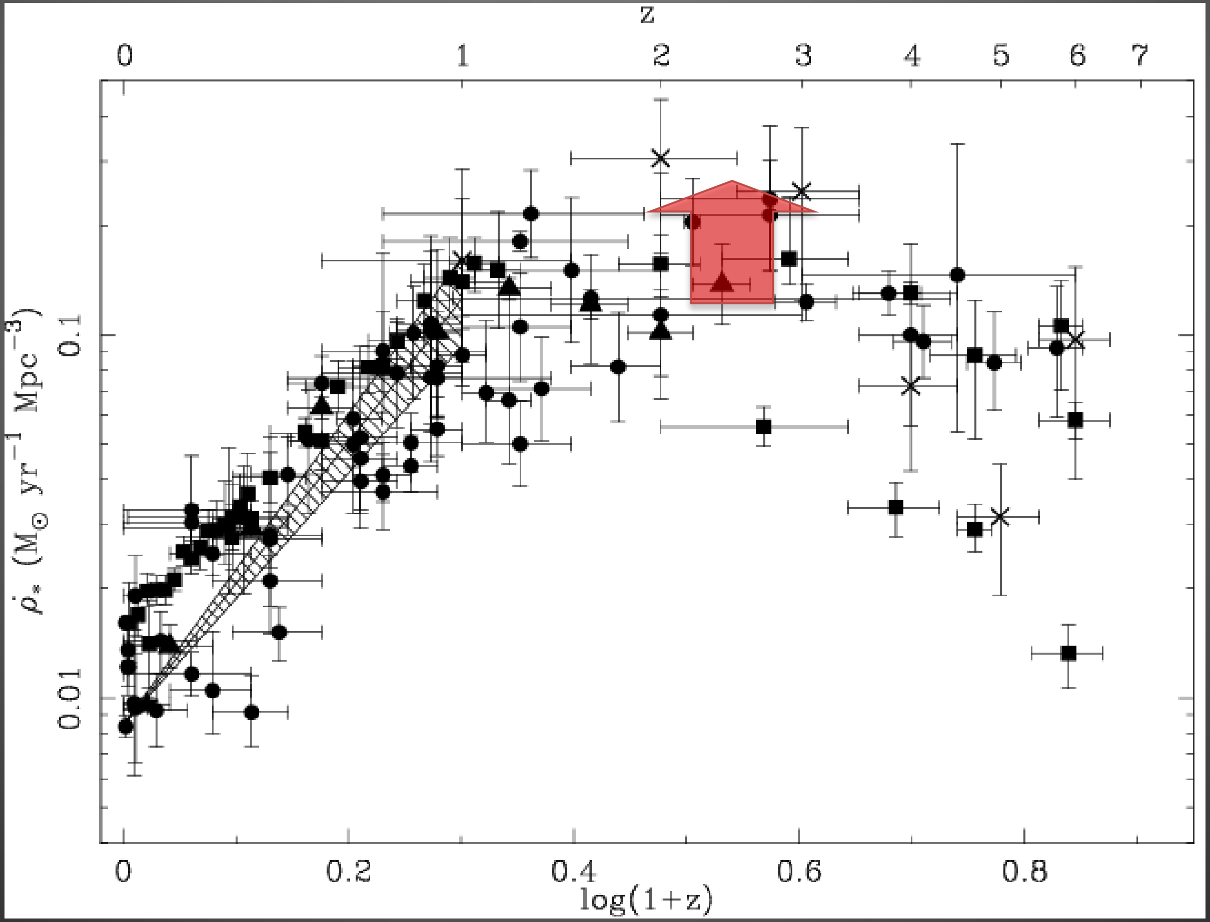
2. Hidden star formation obscured by dust

3. Contribution to cosmic infrared background

4. SMGs in large scale structure

2. Hidden star formation obscured by dust

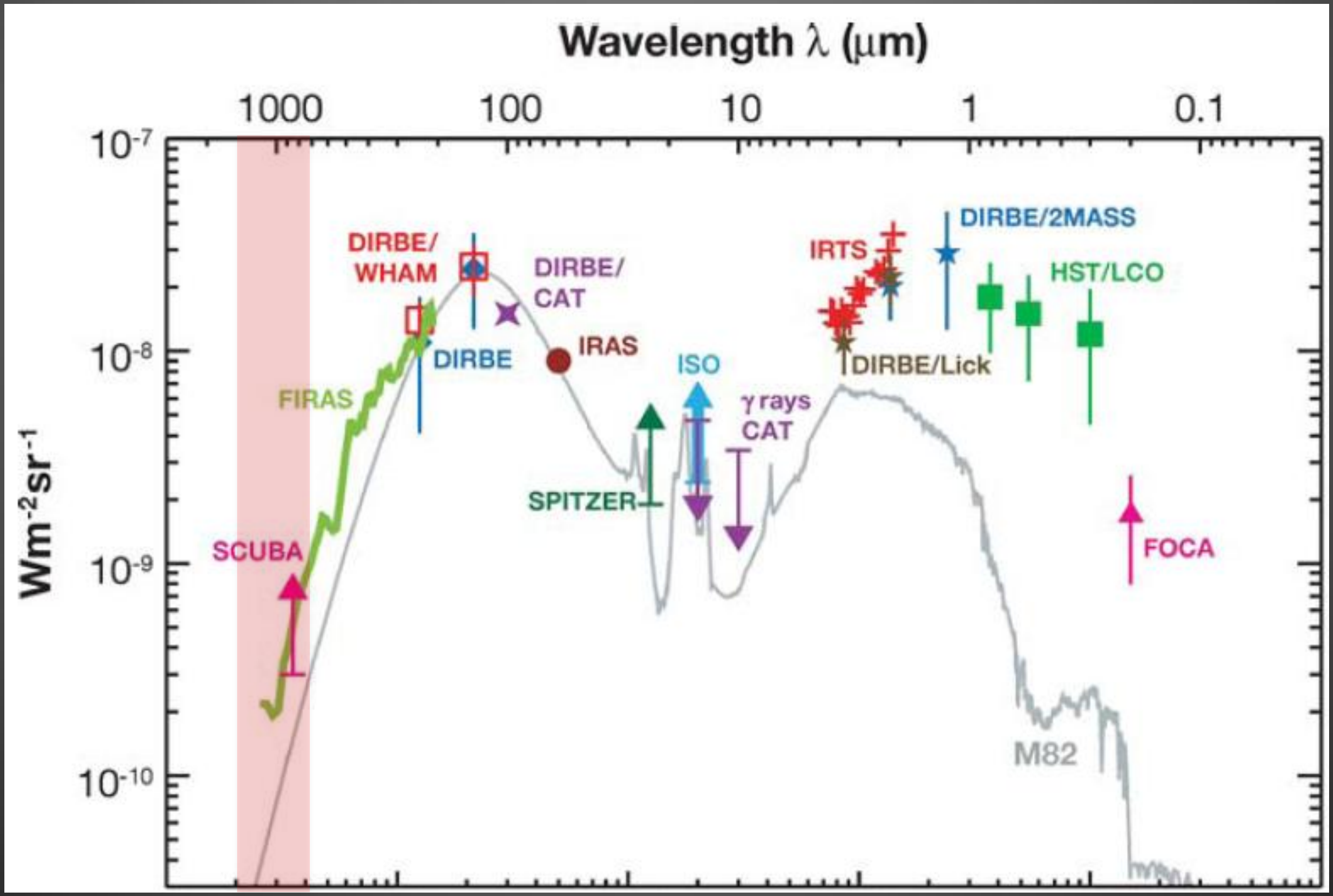
- Contribution of SMGs to cosmic star-formation history



Hopkins & Beacom 06

3. Contribution to Cosmic Infrared Background

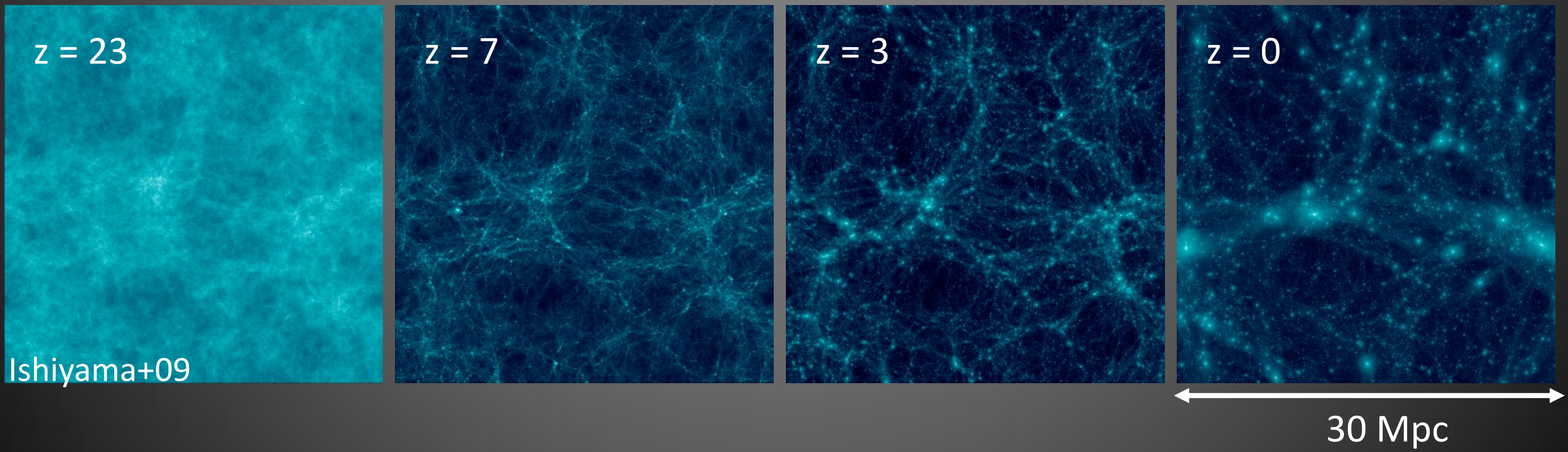
- Contribution of SMGs to the CIB at mm/submm



Lagache+05

4. SMGs in Large Scale Structure

- SMGs reside in massive dark halo?
- SMGs trace high-density peak of dark matter distribution?



AZTEC/ASTE 1.1-MM SURVEYS

AzTEC on ASTE

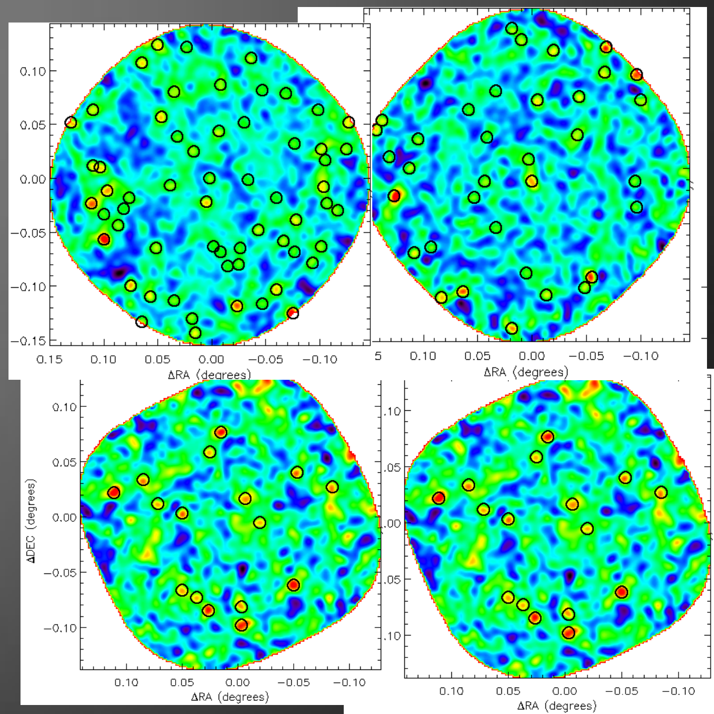
- Atacama Submillimeter Telescope Experiment (ASTE)
  - 10m submm telescope
  - Atacama desert, Chile, 4860 m
- AzTEC camera
  - 144 pixels
  - 1.1 mm wavelength
  - Successful operation on JCMT (2005)
  - 50m Large Millimeter Telescope (LMT) (2011~)

AzTEC/ASTE Surveys

- Survey fields
  - Star-forming regions
  - Nearby galaxies
  - High-z over-dense regions
  - Deep wide-field surveys
    - proto-cluster region: SSA 22
    - blank field: ADF-S, SXDF, COSMOS, GOODS-S, SDF

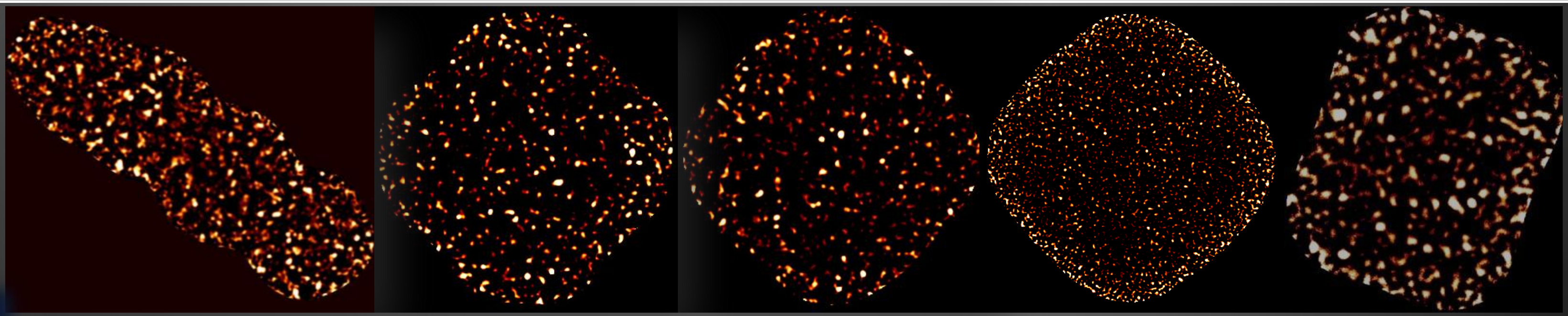
- SMG surveys
    - FOV ~ 8 arcmin
    - Beam size = 30''
  - Total coverage >3 deg^2
  - 1 σ ~ 0.5-1 mJy
  - >1000 sources
  - 10-20 times higher mapping speed compared to SCUBA

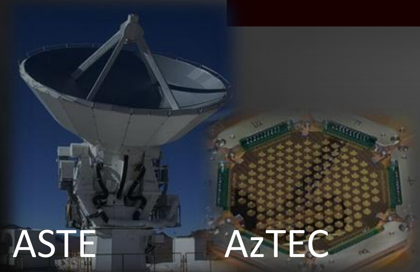
Double or triple the total size of existing surveys!



AzTEC/ASTE Deep Surveys

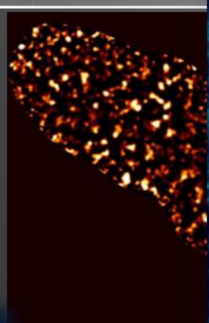
	ADF-S	SXDF	SSA22	COSMOS	GOODS-S
Area (arcmin^2)	909	954	973	2967	350
1σ (mJy)	0.38-0.80	0.52-0.92	0.73-1.3	1.2-2.2	0.53-1.0
>3.5σ source	233	215	125	205	55

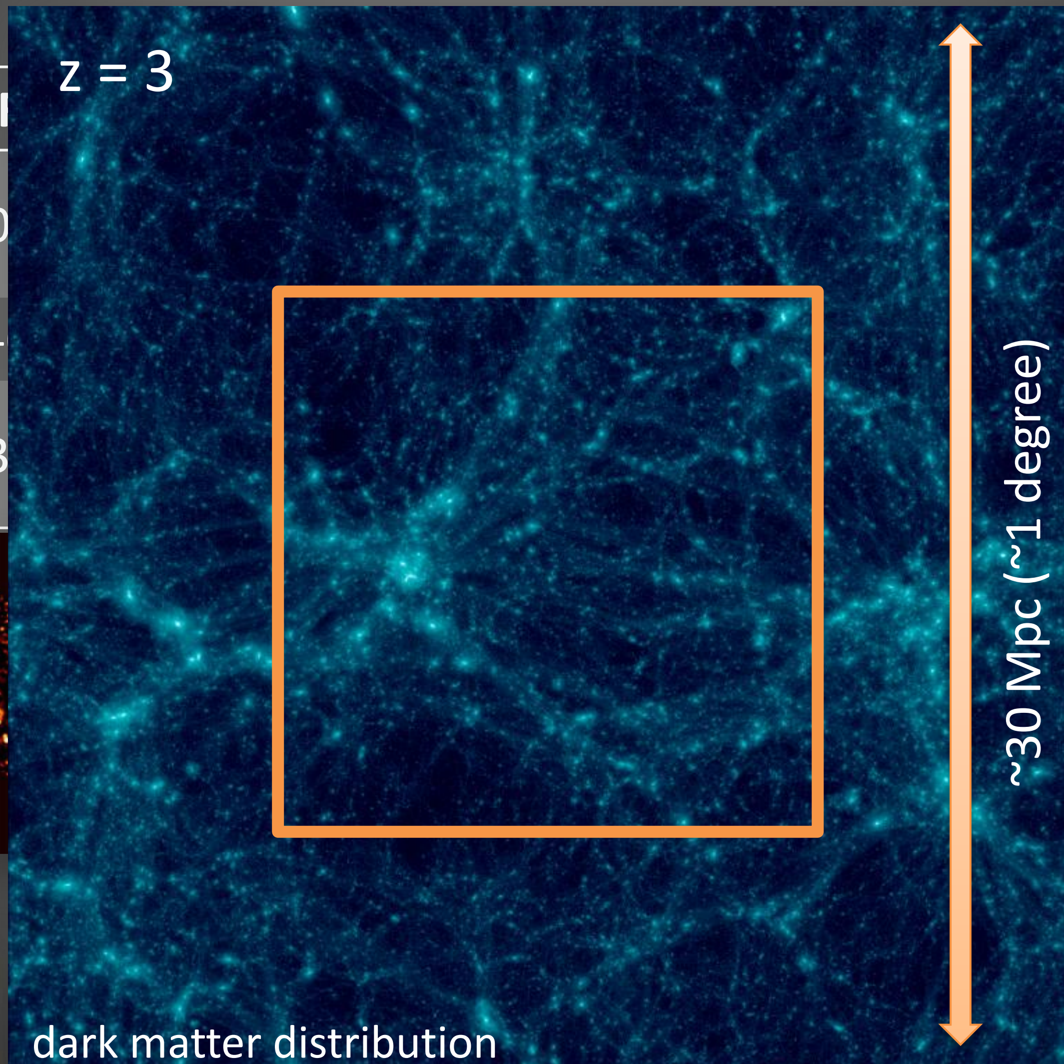


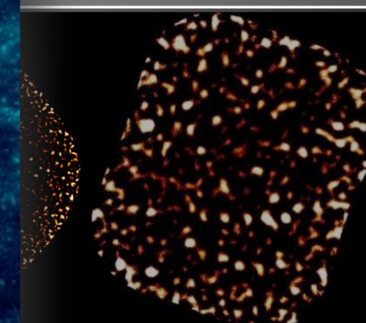


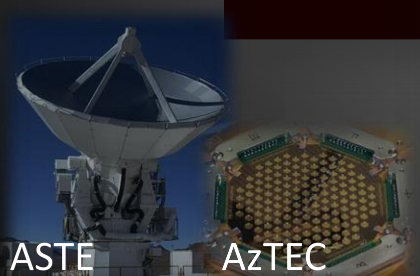
AzTEC/ASTE Deep Surveys

	ADI	GOODS-S
Area (arcmin^2)	90	350
1σ (mJy)	0.38-	0.53-1.0
>3.5σ source	23	55









RESULTS

- Results in each field

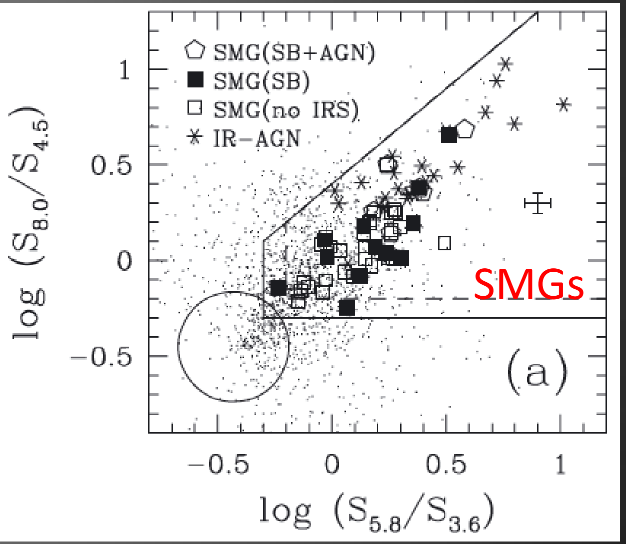
- Combined analysis

Counterpart ID and Redshift Distribution

(Ikarashi et al. in prep.)

- Difficulty in Counterpart ID
  - – large beam size (~30 arcsec)
  - – faint at optical/NIR
- Counterpart ID in SXDF
  - – High-resolution radio image
    - (~< a few arcsec)
  - – IR colors
  - – ~70% of AzTEC sources

(Yun+08)



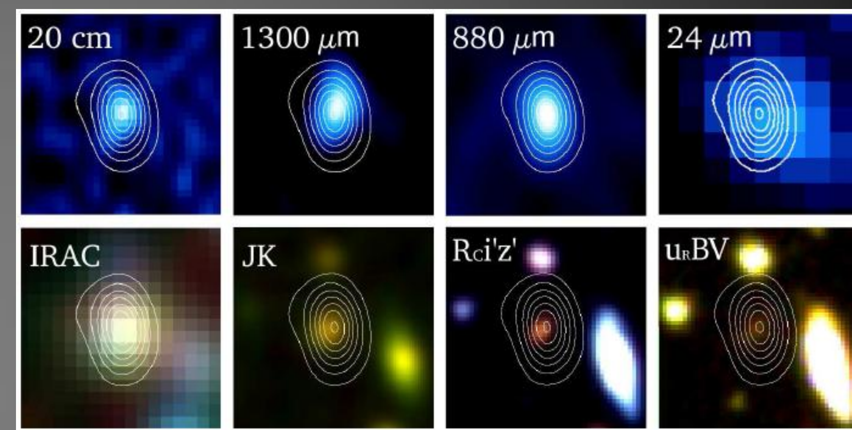
Results 2

Extremely bright source "*Orochi*" in SXDF

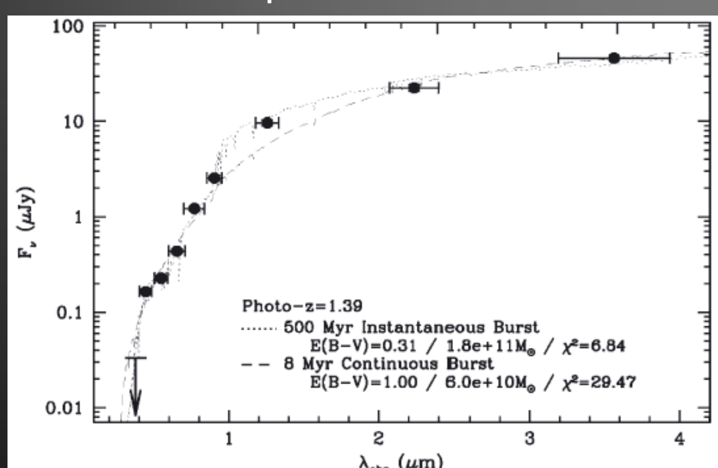
(Ikarashi et al. 2011)

- One of the brightest SMG
  - 34 mJy@1.1mm
  - SED fit

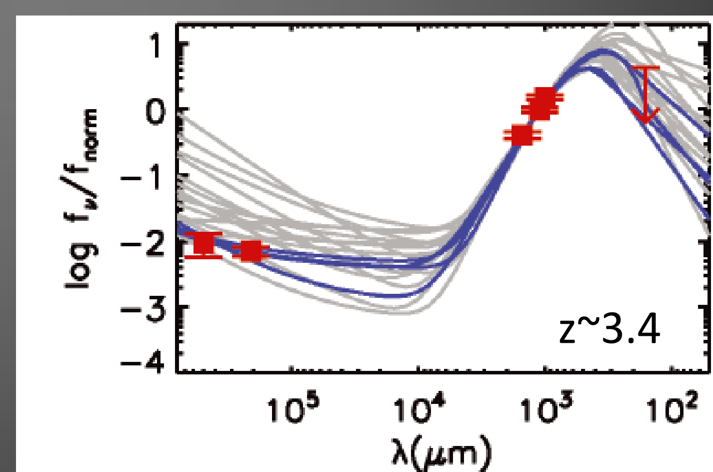
  ➔ a lensed, optically dark SMG at z ~ 3.4 behind a galaxy at z ~ 1.4?



optical-IR SED fit



IR-submm-radio SED fit



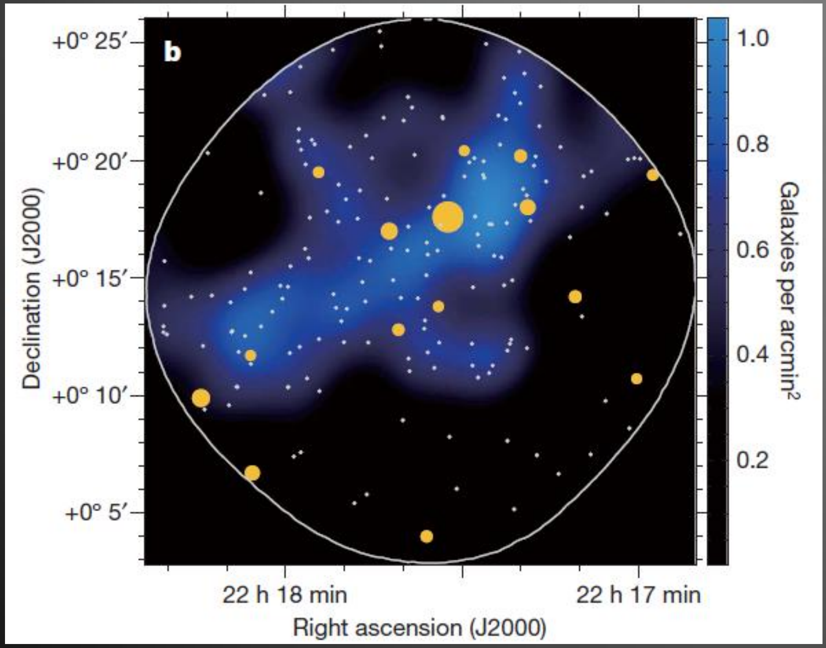
Results 3

Spatial correlation between SMGs and Lyα emitters

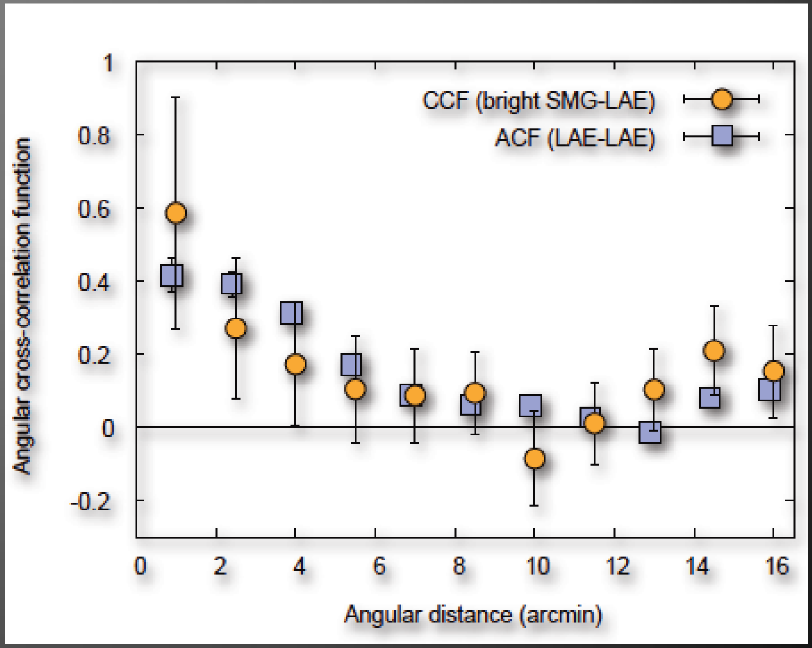
(Tamura et al. 2009)

- Proto-cluster region SSA22 at z=3.09
- Excess in the angular cross-correlation functions between SMGs and LAEs

SMGs (orange) and number density field of LAEs (blue)



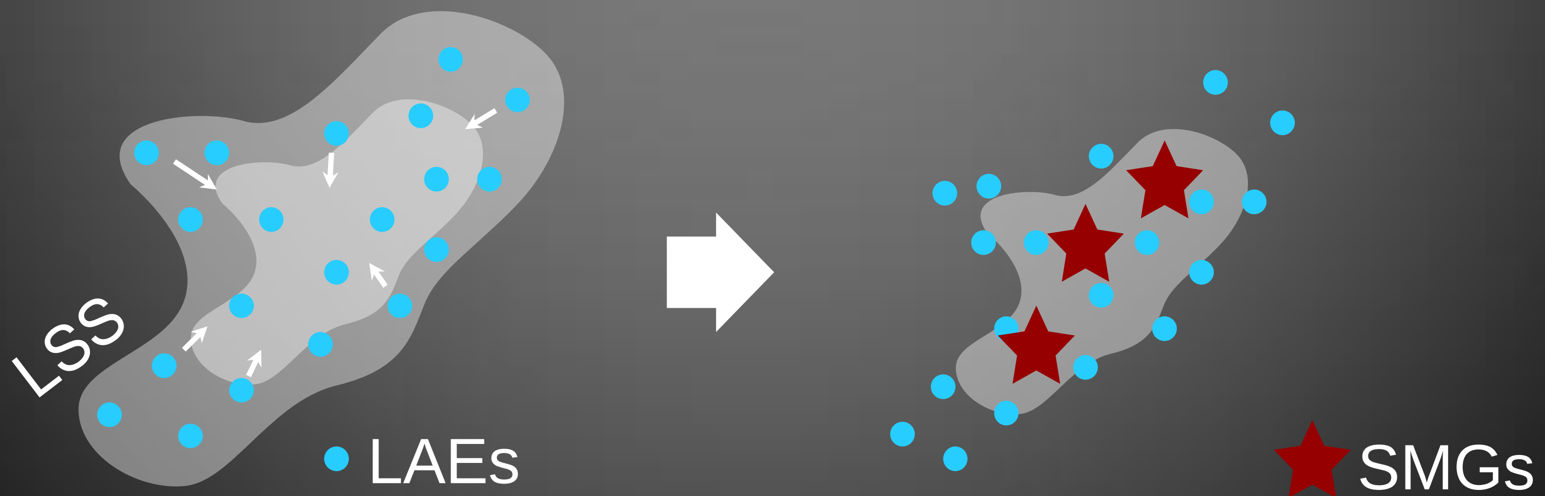
Angular cross-correlation function



Results 3

SMGs form at the bottom of potential well?

- Young, less massive building block (LAEs), which outline the LSS, are accreting towards the center of the LSS,
- Multiple mergers occur at the local peak of DM structure,
- Massive galaxies (SMGs) forming at the bottom of potential well

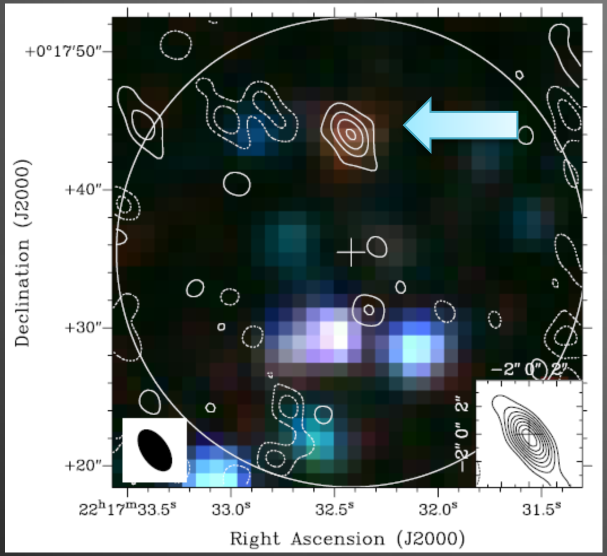


Proto-quasar?

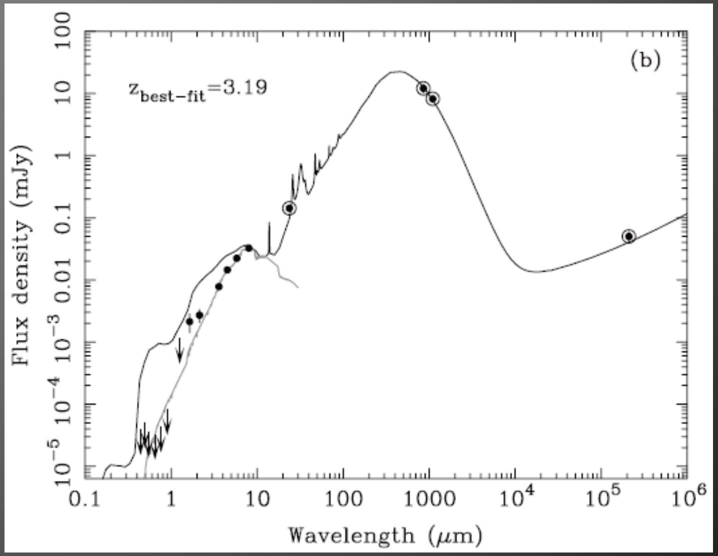
(Tamura et al. 2010)

- SSA22-AzTEC1: Brightest SMG in SSA22
  - Heavily obscured at optical/NIR (Av ~ 3.4mag)
  - Hard X-ray detected
    - Lx~3x10^{44} erg/s
    - N_H~10^{24}cm^{-2}

➔ Transition phase to a quasar with growing SMBH?



SMA 860 μm contours on IRAC



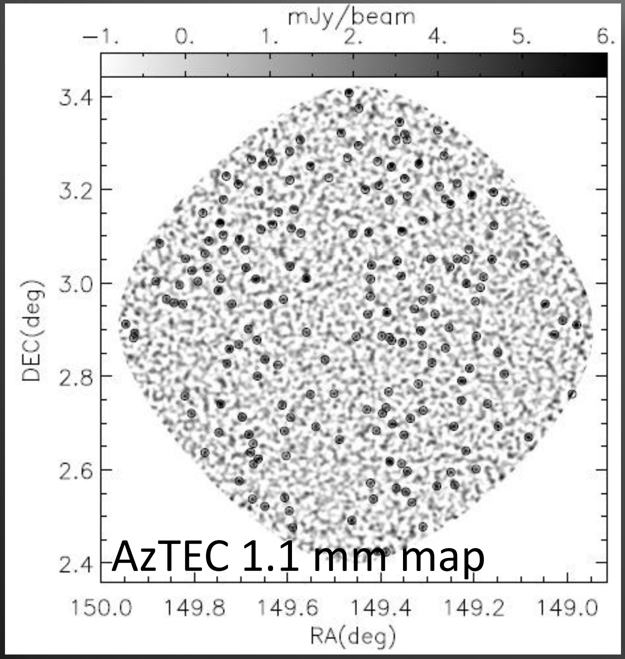
SED fitting

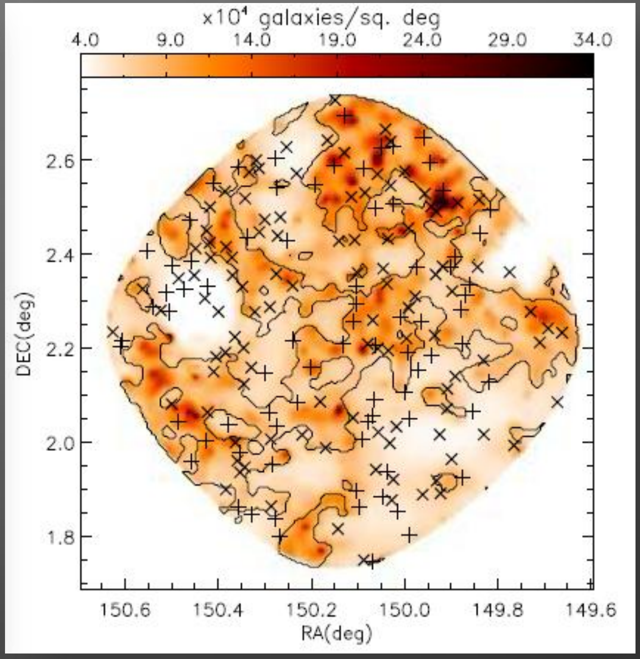
Results 5

Correlation between SMGs and foreground galaxies

- Correlation between bright SMGs (≥5mJy) and $0.6 \le z \le 0.75$ optical galaxies in COSMOS
- Excess in number counts

➔ Galaxy-galaxy and galaxy-group lensing



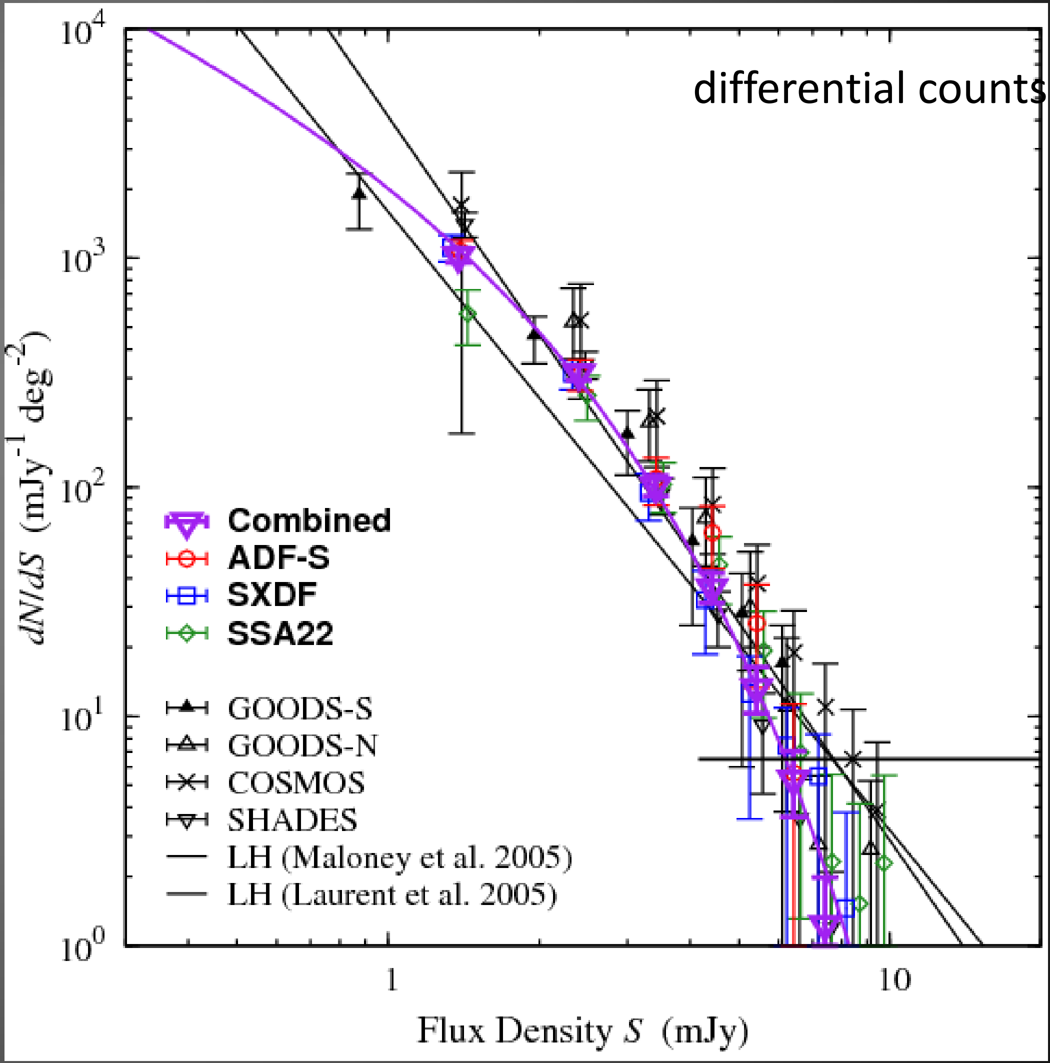


density map of optical/IR galaxies.
x +: AzTEC source (Aretxaga+11)

1.1mm Number Counts

- Average number counts using all available data:
  - ADF-S, SXDF, SSA22, GOODS-N, COSMOS, SHADES
  - Total area ~ 1.5 deg^2
- Most reliable counts down to ~1mJy
- ~10% of Cosmic Infrared Background (CIB) at 1.1mm

➔ Faint sources (<1mJy) largely contribute to CIB

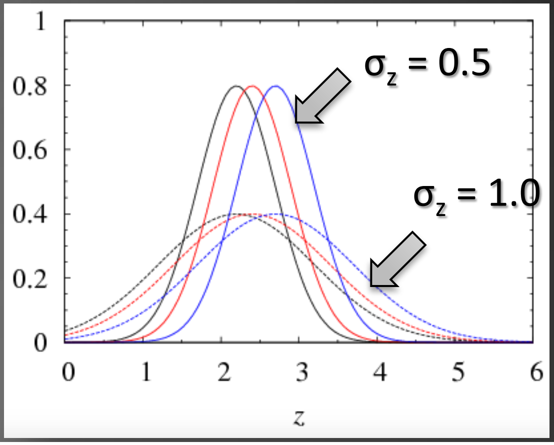


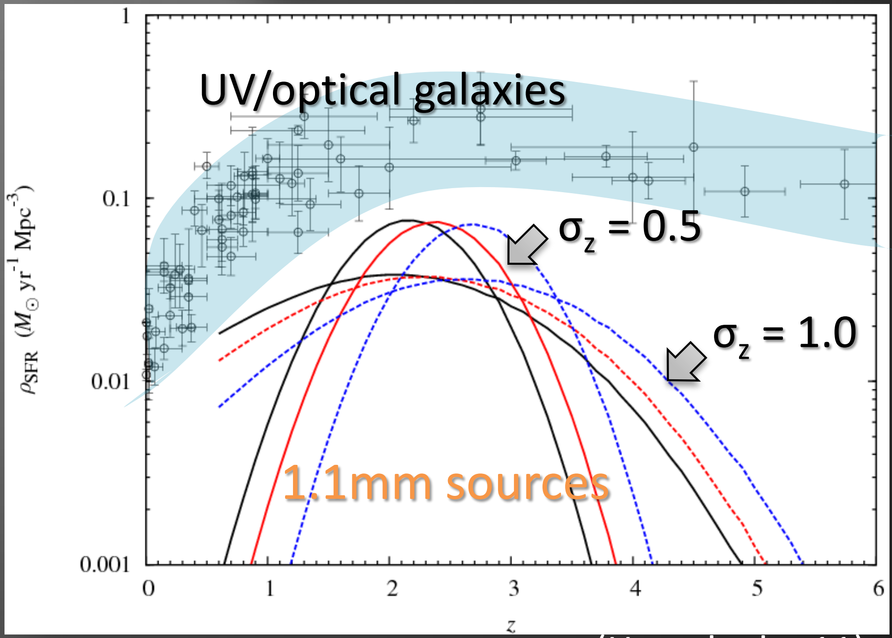
(Hatsukade+11)

Star Formation Rate Density Traced by SMGs

- Integrate number counts (>1mJy) and distribute the total flux according to z distribution
- Assumed z distribution:
  - Gaussian form
    - z_center = 2.2, 2.4, 2.7
    - σ = 0.5, 1.0
    - (e.g., Chapman+05; Aretxaga+07; Chopin+09; Ikarashi+ in prep.)
- ➔ ~1/10 ~ 1/5 of SFRD derived from UV/optically selected galaxies.
  - (e.g., Chapman+05; Aretxaga+07; Dye+08)
- ➔ SMgs contribute ≈10%-20% of SFRD at z~2-3

assumed z distributions



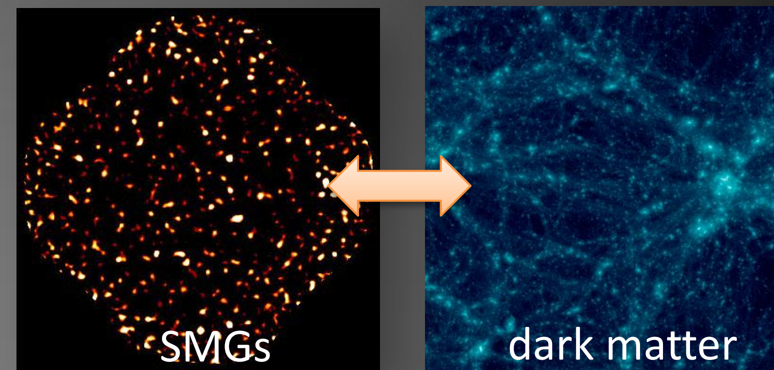


(Hatsukade+11)

(Hatsukade+11)

Clustering Analysis

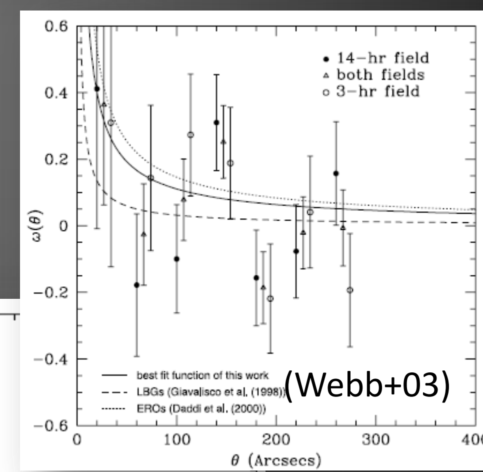
- Density peaks of dark matter are biased
  ➔ Massive galaxies in massive dark halos are clustered

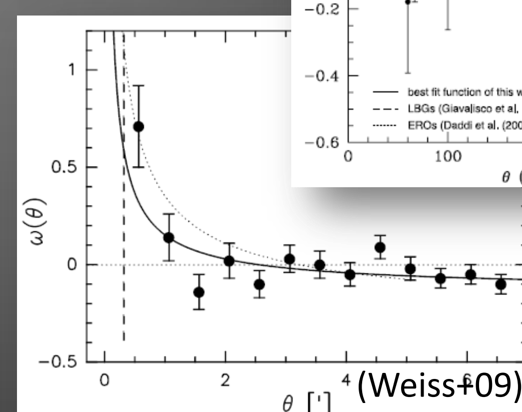


- Clustering measurements ➔
  - Mass of dark halos hosting SMGs
  - Relation with other galaxy populations
- Angular Correlation Function (ACF): $\omega(\theta)$
  - Excess probability of finding a source

$$dP = N^2[1 + \omega(\theta)]d\Omega_1 d\Omega_2,$$

- Previous studies on SMGs
  - tentative detection of strong clustering
    - e.g., Webb+03, Weiss+09, Williams+10

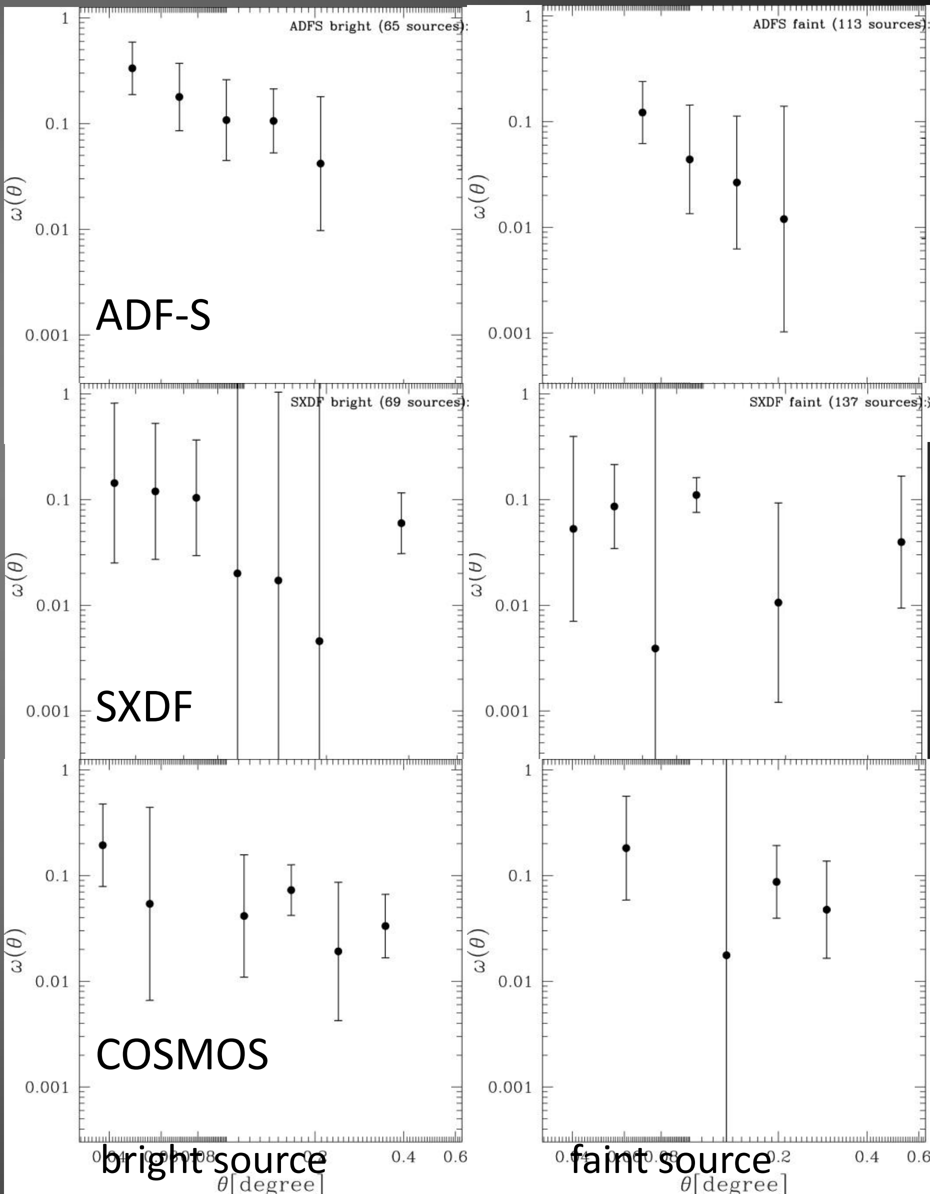




Clustering of SMGs

- Results of ACF
  - tentative detections
  - strong correlation features
    - ADF-S, SXDF
- Bright sources are more strongly clustered

  - Reside in more massive halos
  - Narrower redshift range



(Hatsukade+ in prep)

Clustering of SMGs

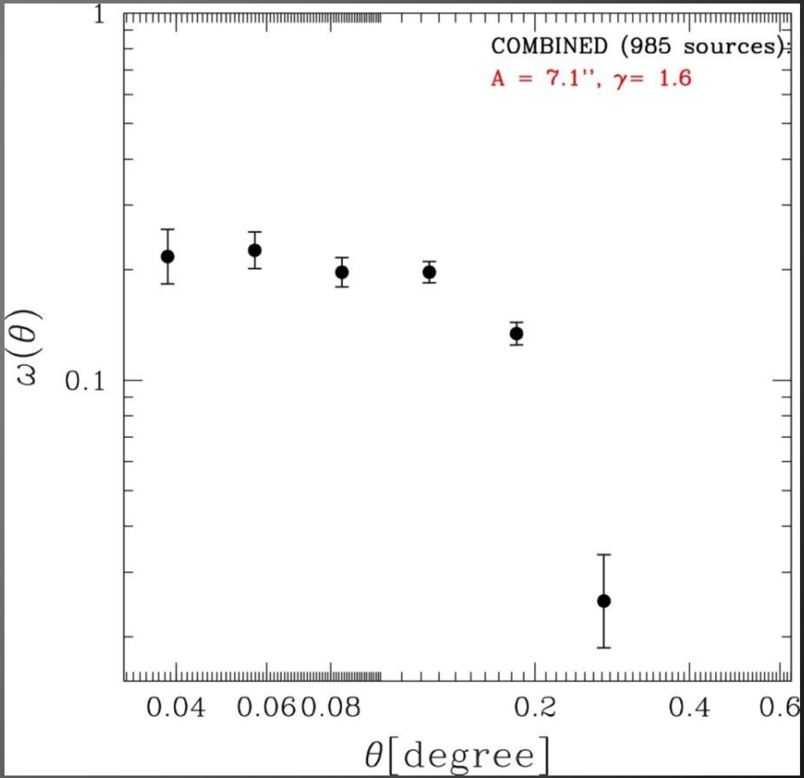
- Combined Analysis
  - Averaging the ACFs of all fields
  - 985 sources in total

- Spatial correlation length (r_0)
  - Angular correlation function is a 2d-projection of spatial correlation function (ξ)

$$\xi(r) = \left(\frac{r}{r_0}\right)^{-\gamma}$$

    - r_0: correlation length; an indicator of clustering strength
  - from angular to spatial correlation
    - redshift distribution (e.g., Chapman+05)
      - Gaussian form centered at z=2.5, σ = 0.5-1.0
    - Formalism of Limber (1953)

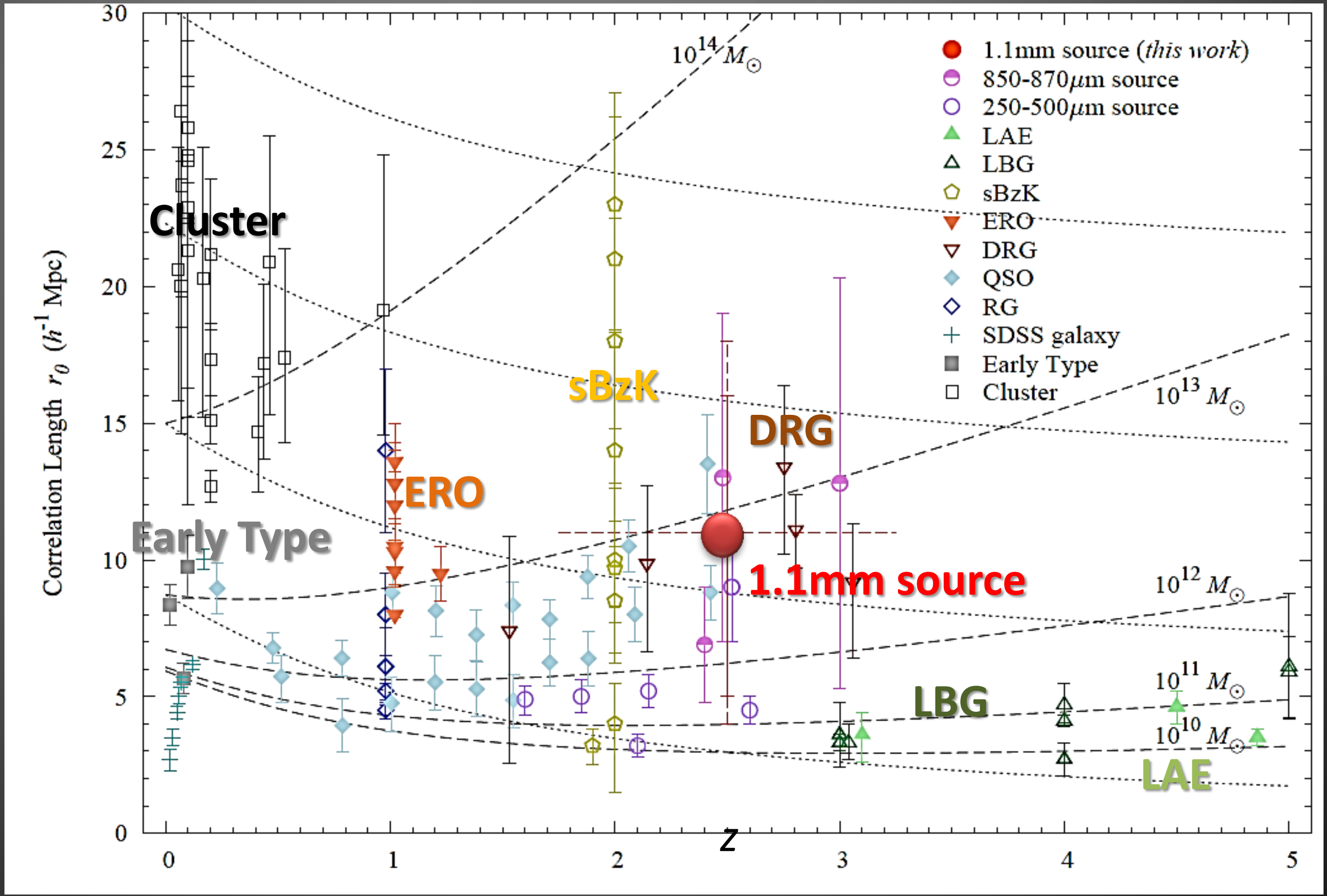
  - ➔ $r_0 \sim$ 11±5 Mpc/h



Comparison with Other Populations

- Mass of Dark Halo hosting SMGs: ~10^{12-13} Msun
- Dark halos hosting SMGs evolve into systems of present clusters

Correlation lengths ($r0$) of various galaxy populations and clusters as a function of redshift



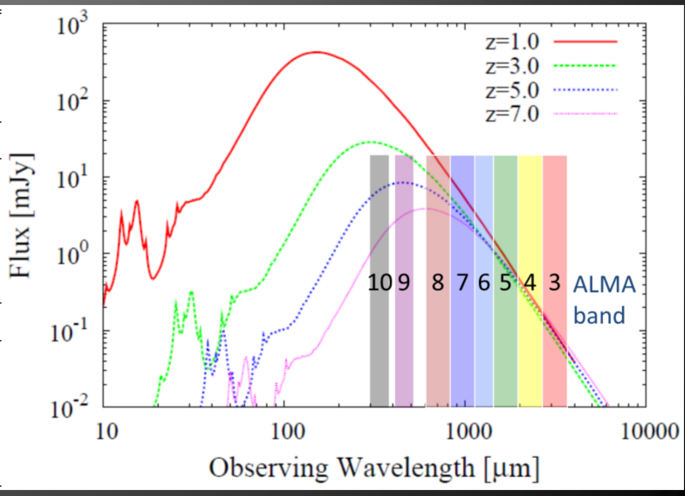
(Hatsukade+ in prep)

FUTURE SUBMM OBSERVATIONS

Atacama Large Millimeter/submillimeter Array (ALMA)

- Early Science (Sep. 2011~)
  - 16 antennas
  - 100, 230, 345, 675GHz
- Full operation
  - 12m x 50 + ACA (7m x 12 + 12m x 4)

Band	Frequency [GHz]	Angular Resolution ["]	Maximum Scale ["]	T_{bc} [mK]	Flux [mJy]	T_{bl} [K]	Field of View ["]
Properties of the Compact Configuration (baselines of ~18 m to ~125 m)							
3	100	5.3	21	0.65	0.14	0.030	62
6	230	2.3	9	1.0	0.20	0.029	27
7	345	1.55	6	1.8	0.37	0.043	18
9	675	0.80	3	15	3.2	0.27	9
Properties of the Extended Configuration (baselines of ~36 m to ~400 m)							
3	100	1.56	10.5	7.6	0.14	0.35	62
6	230	0.68	4.5	11	0.20	0.34	27
7	345	0.45	3.0	20	0.37	0.50	18
9	675	0.23	1.5	175	3.2	3.1	9

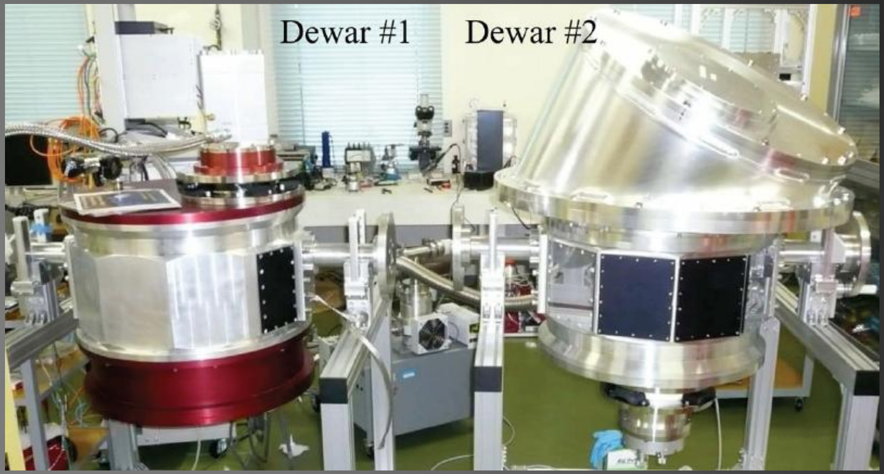


SMG with ALMA

- Redshift distribution
  - ALMA high-resolution ID ➔ spectroscopy at optical/NIR
  - CO, [CII] line spectroscopy
  - ➔ e.g., SFRD, galaxy evolution, clustering,
- Number counts at faint end
  - contribution to CIB
  - ➔ origin of CIB
- High-spatial-resolution imaging
  - spatial distribution of star-forming region in SMG
  - dynamics
  - ➔ nature of SMGs

ASTE New TES Array

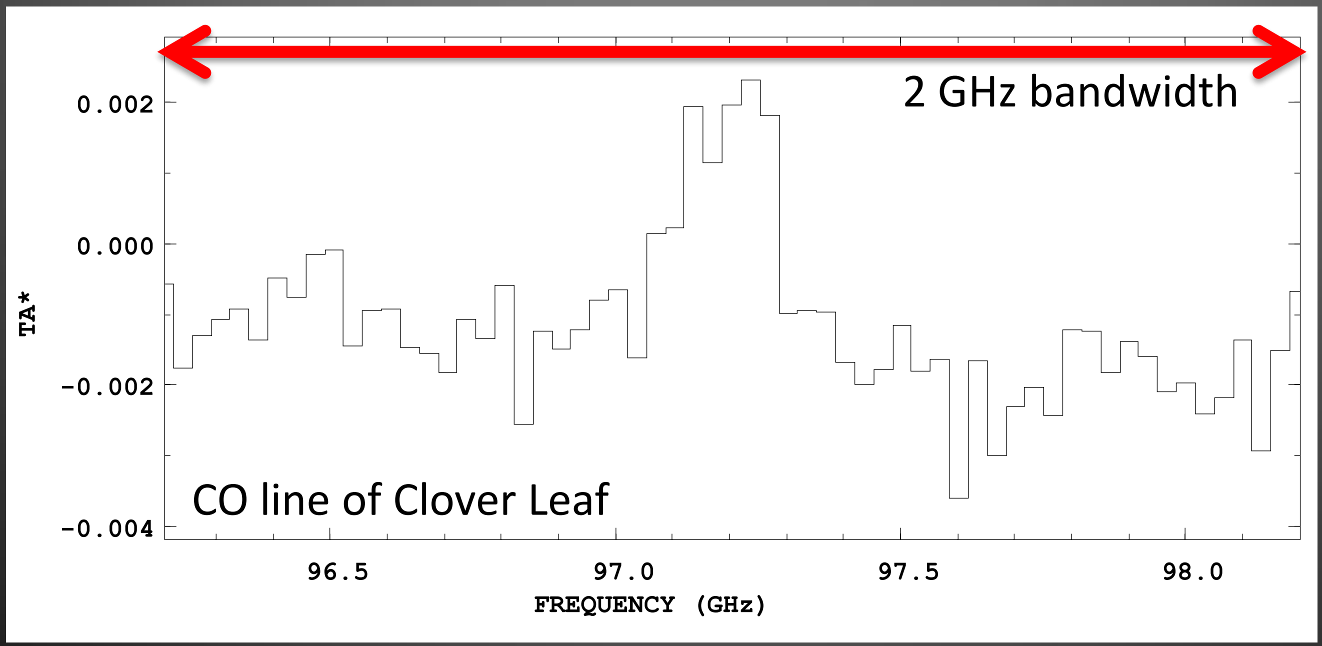
- Multi-color array
  - To be installed at the end of 2011
  - High-sensitivity wide-field surveys



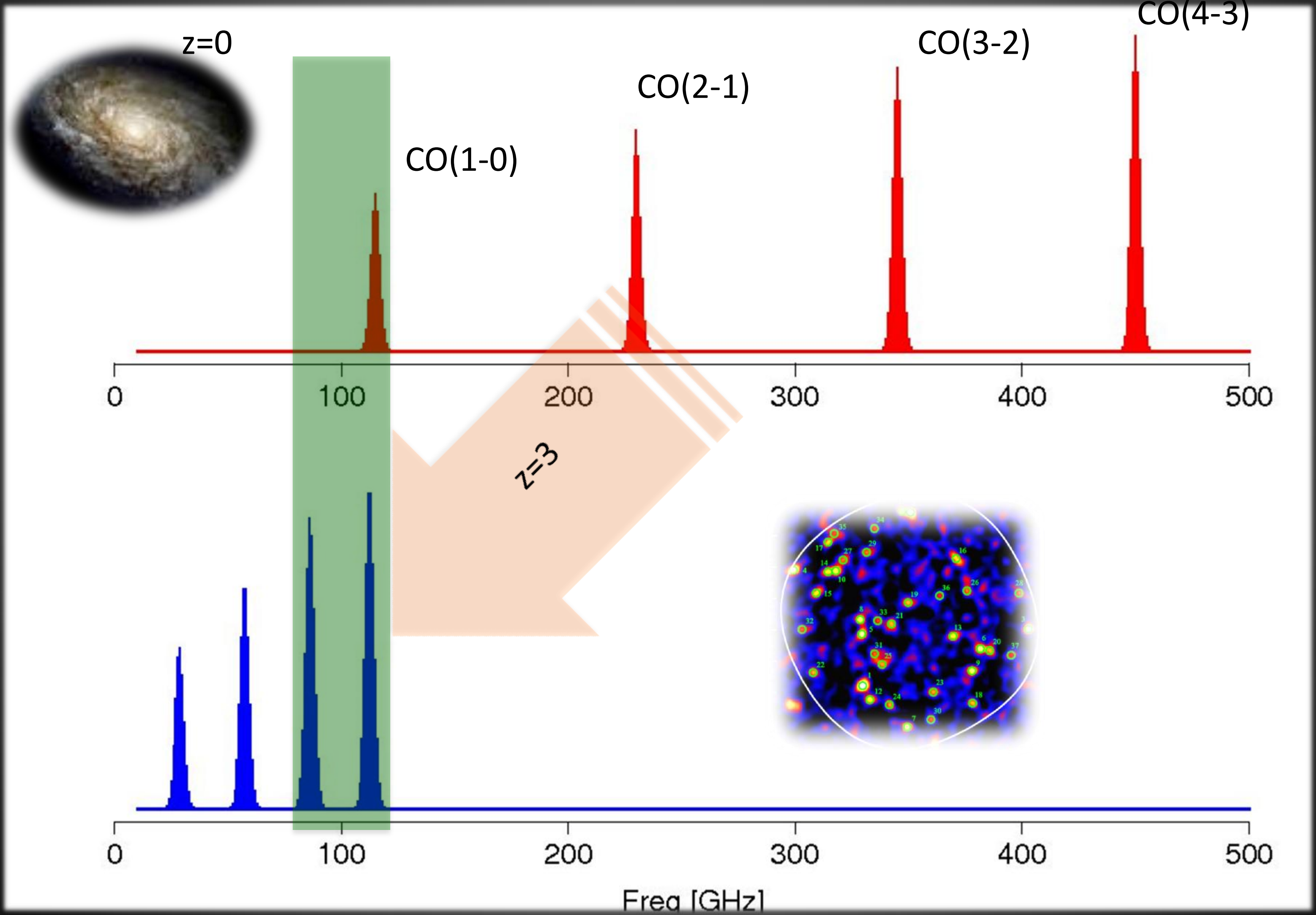
	band	N pixel	beam size	mapping speed
	[um]		[arcsec]	[arcmin^2 mJy^{-2} hr^{-1}]
New TES Array	1100	169	28	30
	850	271	22	~5
	450	881	11	~0.3
AzTEC	1100	144	28	20

Blind CO Search with Nobeyama 45m

- Wide-band spectrometer: SAM45
  - 2 GHz bandwidth x 16 units (= 32 GHz in total)
  - widest among 3-mm wavelength spectrometers



Determine Redshifts of SMGs



Summary

- 1.1mm Deep & wide surveys with AzTEC/ASTE
  - ADF-S, COSMOS, SSA22, SXDF, GOODS-S fields

- Redshift distribution
- Detection of a rare, extremely bright source
- Spatial correlation between SMGs and LAEs
- Proto-quasar candidate

- Most reliable number counts down to faint end (~1 mJy)
  - >1mJy sources contribute ~10% of CIB
  - Fainter sources (<1mJy) largely contribute CIB
  - ≈10%-20% of SFRD at z~2-3

- Clustering of 1.1mm sources
  - Bright sources more strongly clustered
  - Dark halo mass ~10^{12-13} Msun
  - Dark halo hosting SMGs evolve into dark halo of present-day clusters